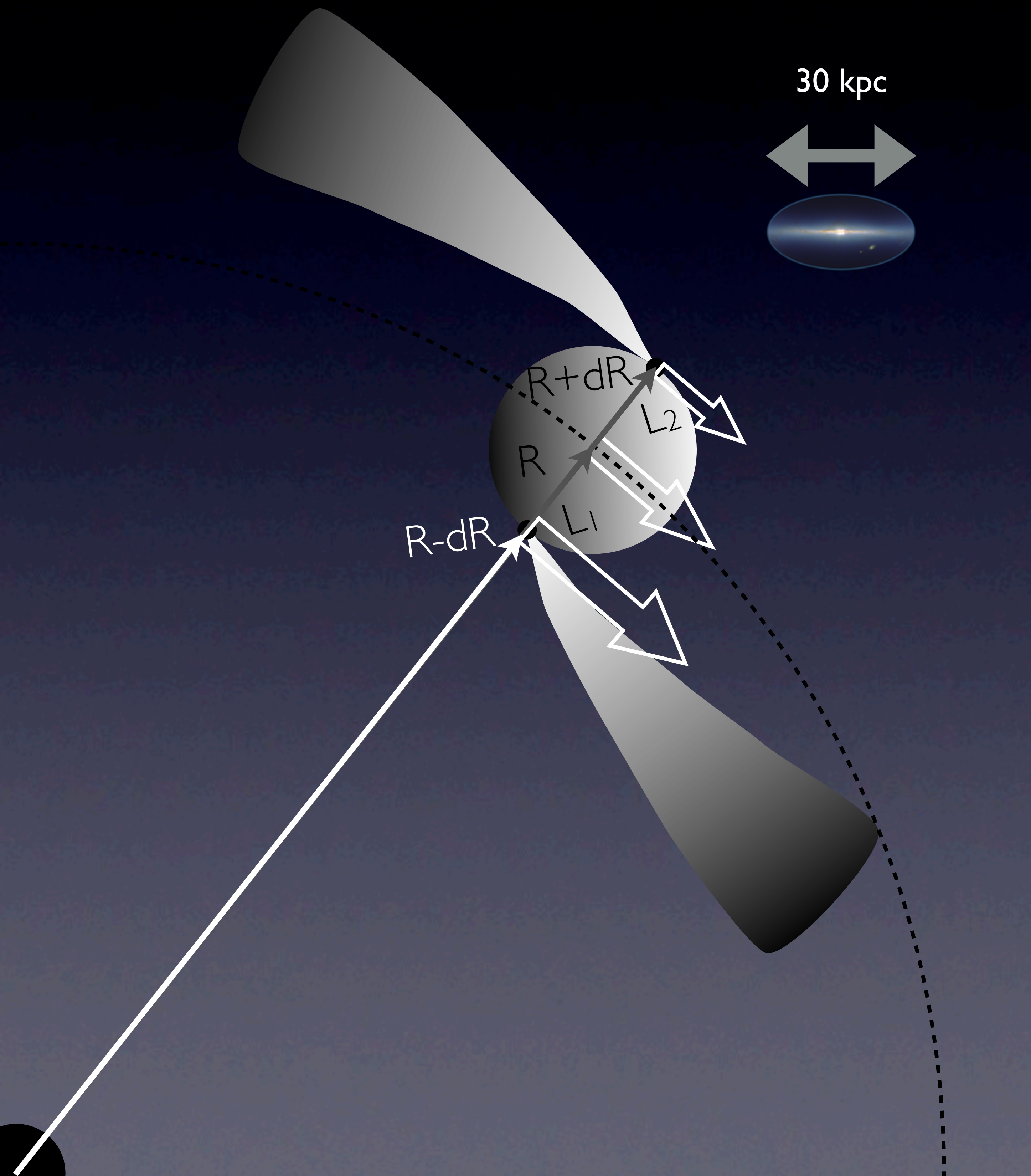
Stellar Content and Evolution of Galaxies

Vasily Belokurov, vasily@ast.cam.ac.uk

Tidal Streams



by Bullock & Johnston

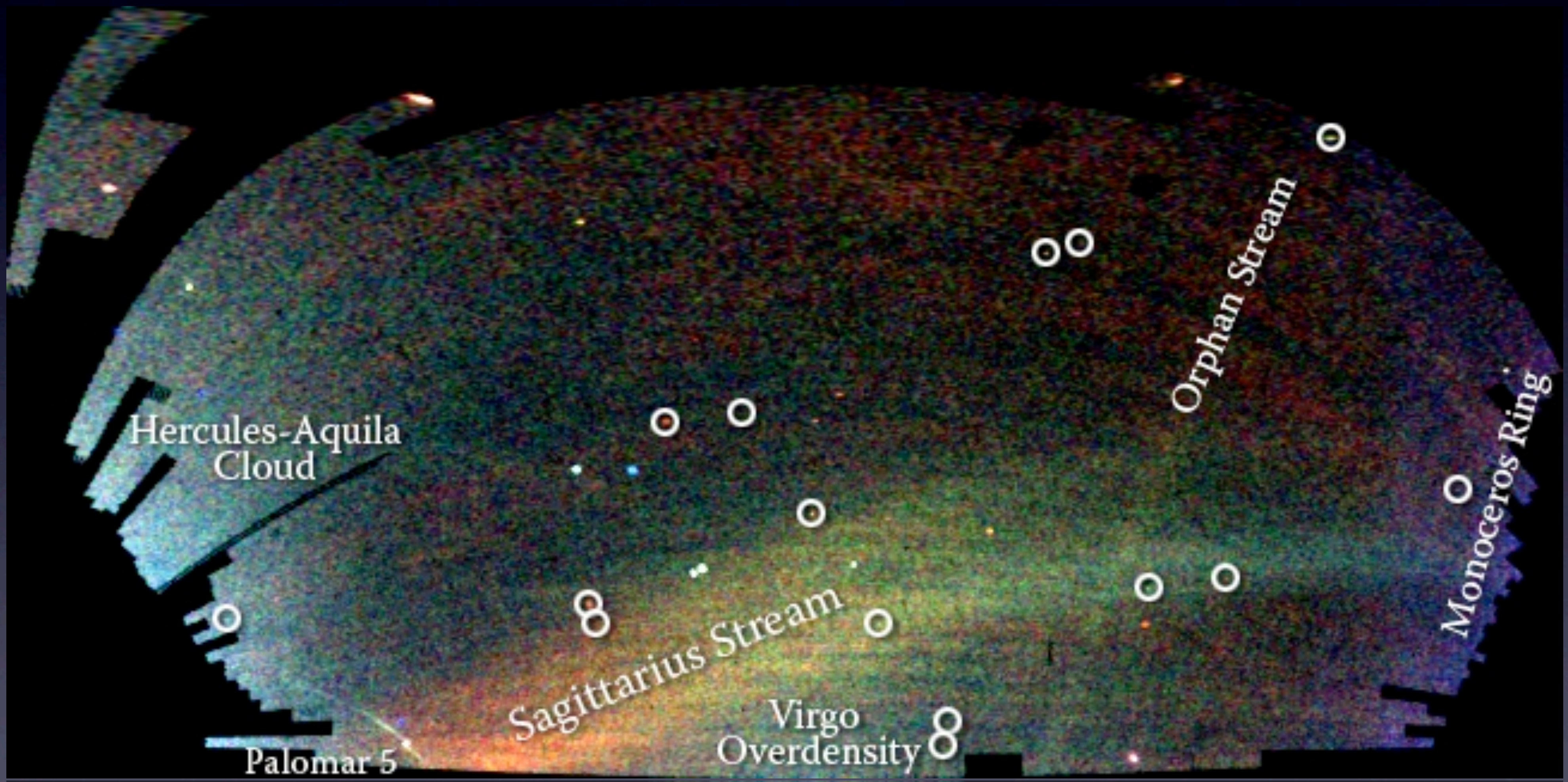
Tidal Streams

"Field Of Streams" in the Milky Way' s halo

by V. Belokurov & SDSS

Tidal Streams

"Field Of Streams" in the Milky Way' s halo

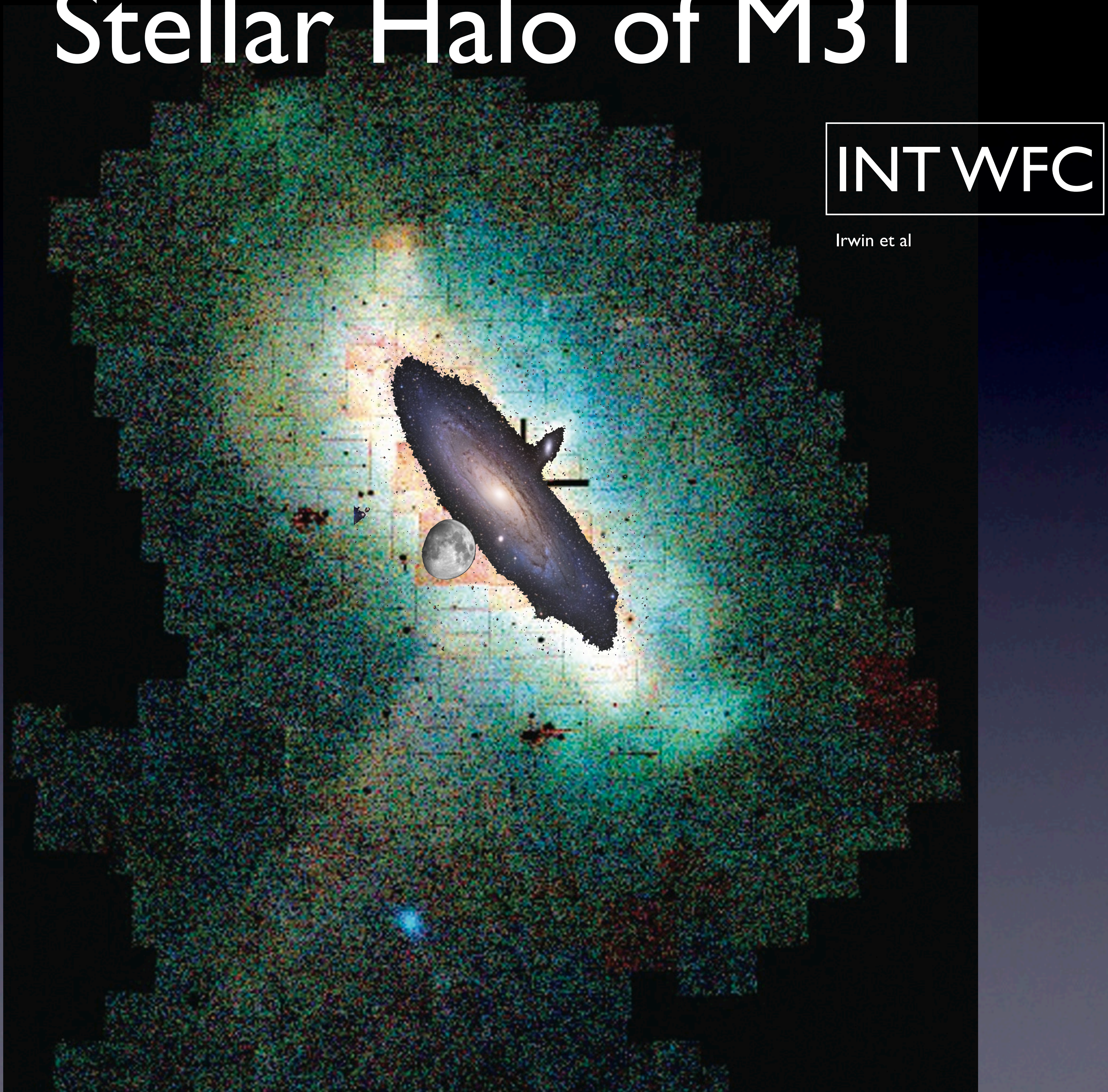


by V. Belokurov & SDSS

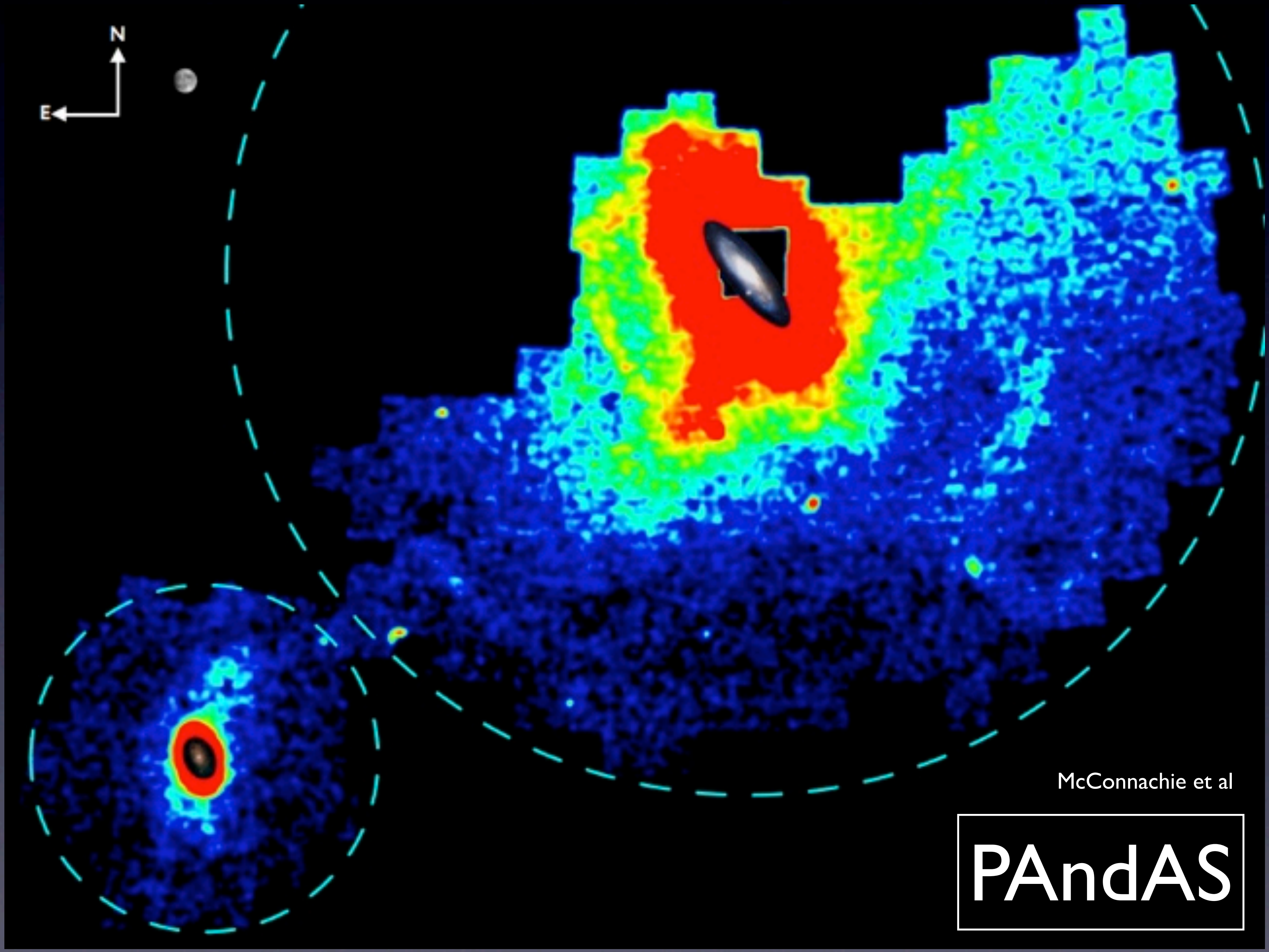
Andromeda galaxy = M31

by Adam Block and Tim Puckett

Stellar Halo of M31



Stellar Halo of M31 and M33



Resolved Stellar Populations in Galaxies

Component	Mv	Distance Limits (Mpc) Spectra (V<22)	GB Imaging (V<24)	HST Imaging (V<27)
A Supergiants	-10	25	60	250
OB, M Supergiants	-8	10	25	100
Red Giant Tip	-3	1	3	10
Cepheids	-4	2	5	20
RR Lyrae, HB	0	0.25	0.6	2
MS Turnoff	+5	0.025	0.06	0.25

The Local Group

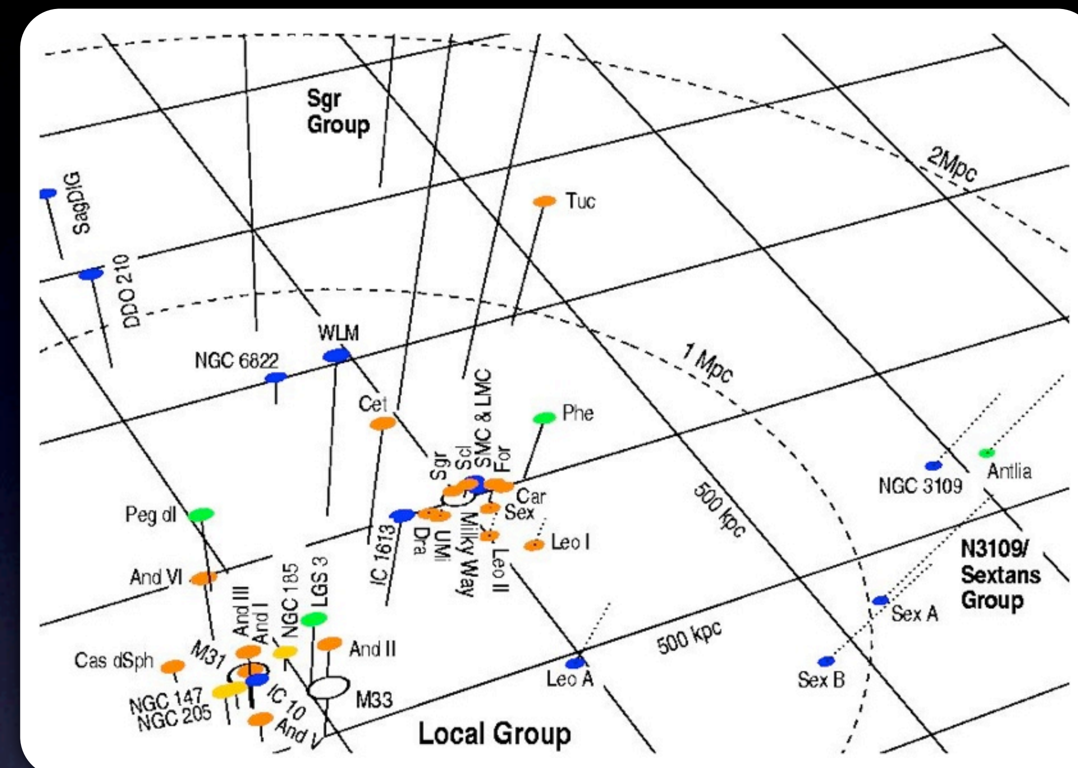
TABLE 2

DATA ON LOCAL GROUP GALAXIES

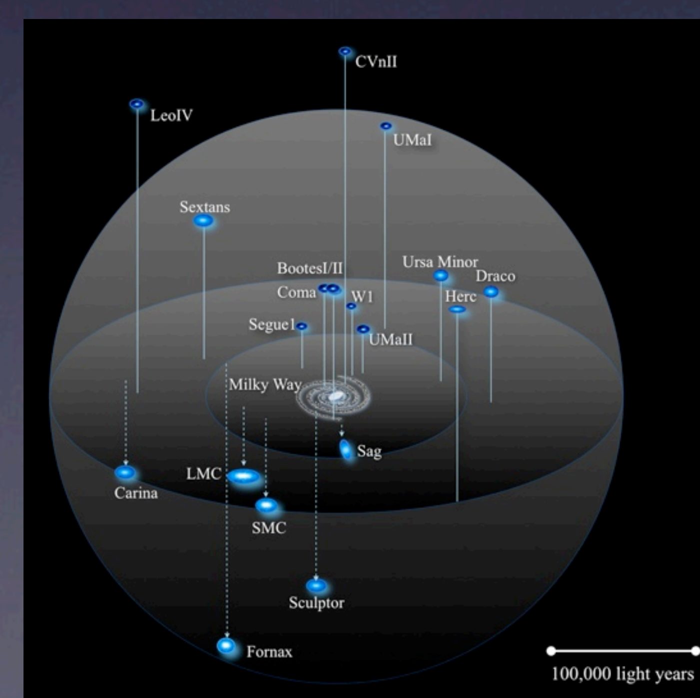
Name	Alias	Type	M_V	D (Mpc) Galaxy	D (Mpc) Local Group
WLM	DDO 221	Ir IV–V	−14.4	0.95	0.81
IC 10	UGC 192	Ir IV:	−16.3	0.66	0.27
Cetus		dSph	−10.1	0.78	0.62
NGC 147	UGC 326	Sph	−15.1	0.66	0.22
And III...........	A0032+36	dSph	−10.2	0.76	0.31
NGC 185	UGC 396	Sph	−15.6	0.66	0.22
NGC 205	M110	Sph	−16.4	0.76	0.31
M32	NGC 221	E2	−16.5	0.76	0.31
M31	NGC 224	Sb I–II	−21.2	0.76	0.30
And I............	A0043+37	dSph	−11.8	0.81	0.36
SMC		Ir IV/IV–V	−17.1	0.06	0.48
Sculptor		dSph	− 9.8	0.09	0.44
Pisces............	LGS 3	dIr/dSph	−10.4	0.81	0.42
IC 1613		Ir V	−15.3	0.72	0.47
And V...........		dSph	− 9.1	0.81	0.37
And II...........		dSph	−11.8	0.68	0.26
M33	NGC 598	Sc II–III	−18.9	0.79	0.37
Phoenix		dIr/dSph	− 9.8	0.40	0.59
Fornax		dSph	−13.1	0.14	0.45
LMC		Ir III–IV	−18.5	0.05	0.48
Carina		dSph	− 9.4	0.10	0.51
Leo A	DDO 69	Ir V	−11.5	0.69	0.88
Leo I	Regulus	dSph	−11.9	0.25	0.61
Sextans		dSph	− 9.5	0.09	0.51
Leo II	DDO 93	dSph	−10.1	0.21	0.57
Ursa Minor......	DDO 199	dSph	− 8.9	0.06	0.43
Draco	DDO 208	dSph	− 8.6	0.08	0.43
Milky Way	Galaxy	S(B)bc I–II	−20.9:	0.01	0.46
Sagittarius		dSph(t)	−13.8::	0.03	0.46
SagDIG		Ir V	−12.0	1.18	1.29
NGC 6822		Ir IV–V	−16.0	0.50	0.67
Aquarius	DDO 210	V	−10.9	0.95	0.95
Tucanae		dSph	− 9.6	0.87	1.10
Cassiopeia	And VII	dSph	−12.0	0.69	0.29
Pegasus	DDO 216	Ir V	−12.3	0.76	0.44
Pegasus II	And VI	dSph	−11.3	0.78	0.38

NOTE.—Galaxies are listed in order of increasing right ascension.

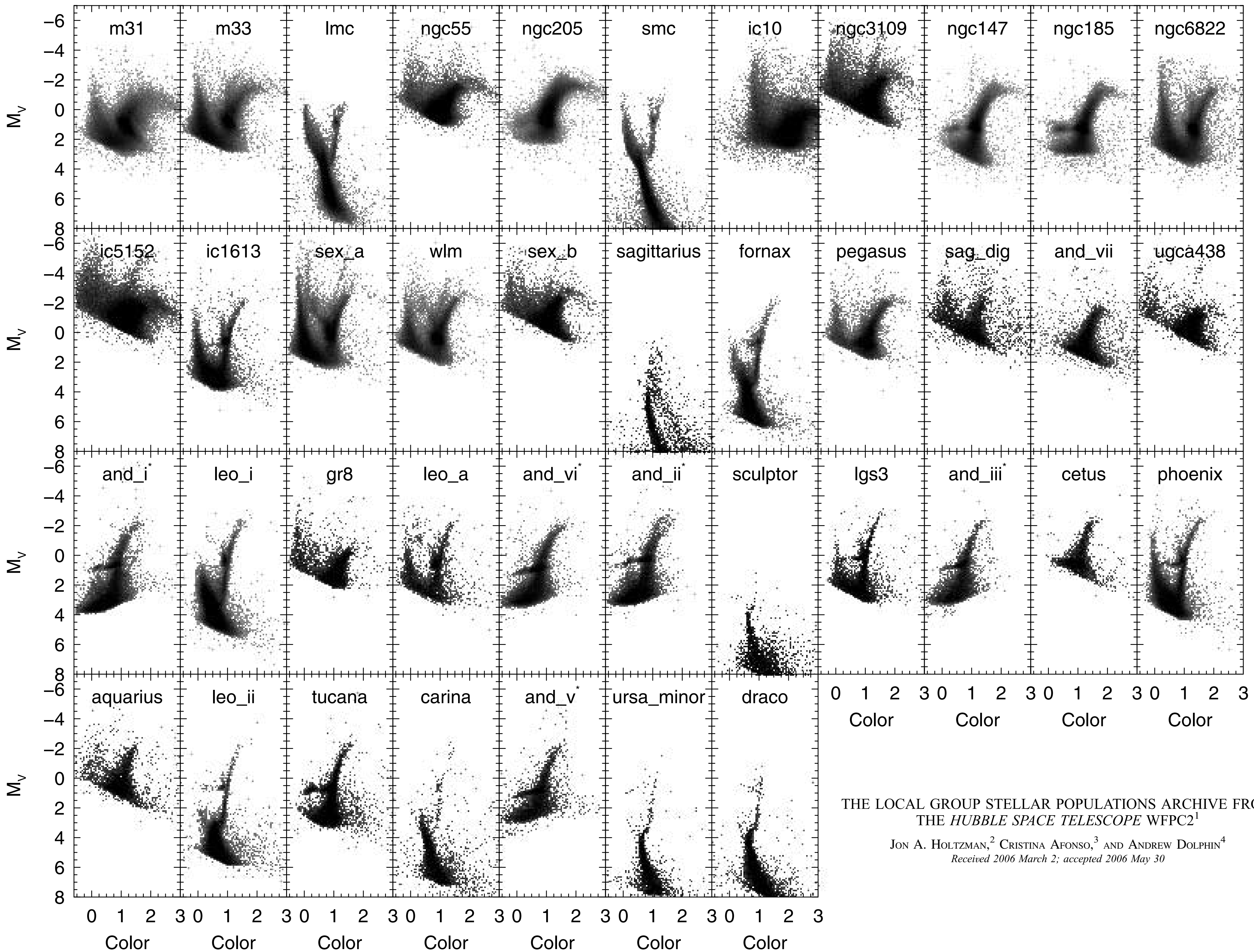
van den Bergh, 2000, PASP



E. Grebel, IAU Symposium 192



The Local Group

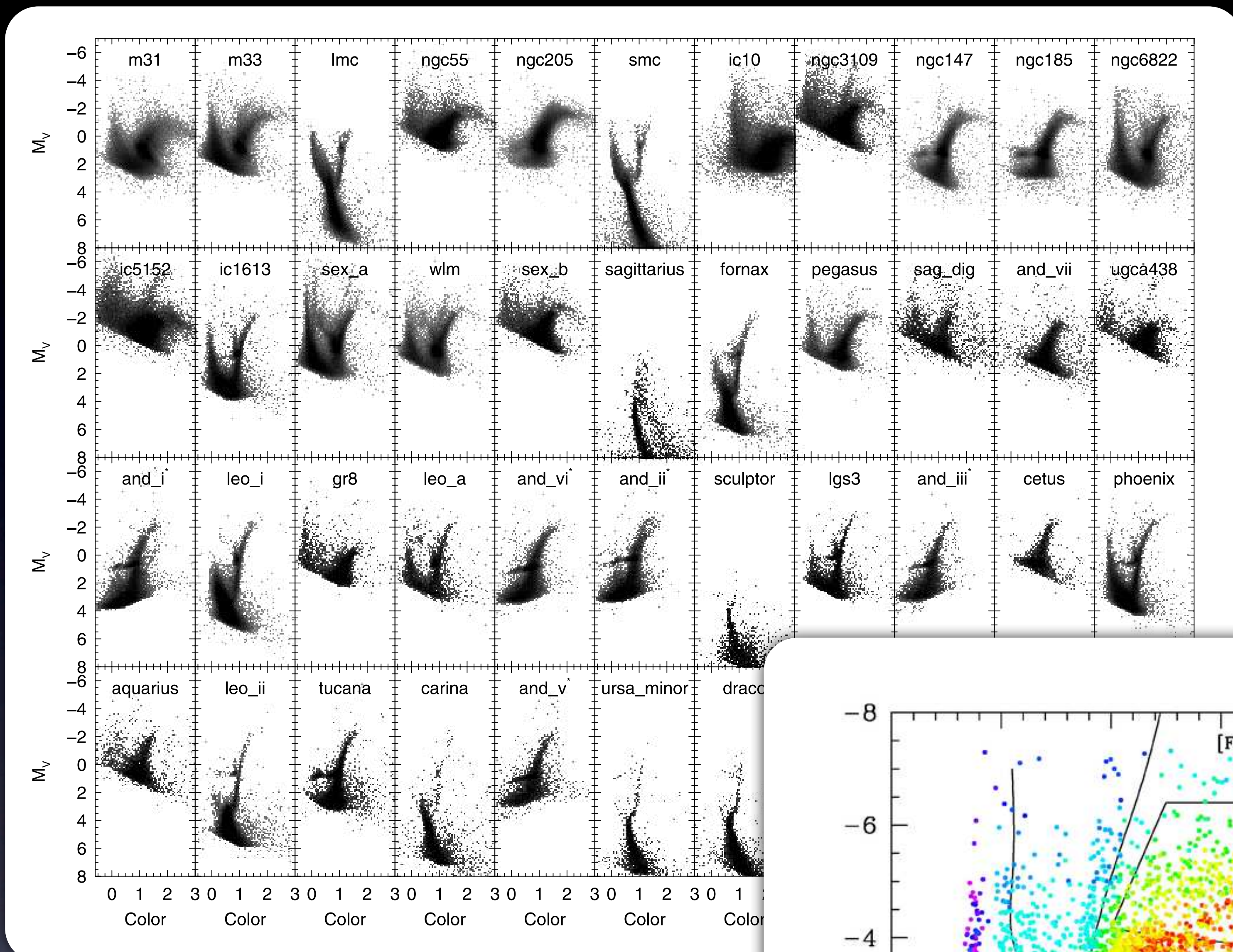


THE LOCAL GROUP STELLAR POPULATIONS ARCHIVE FROM THE *HUBBLE SPACE TELESCOPE* WFPC2[1]

Jon A. Holtzman,[2] Cristina Afonso,[3] and Andrew Dolphin[4]

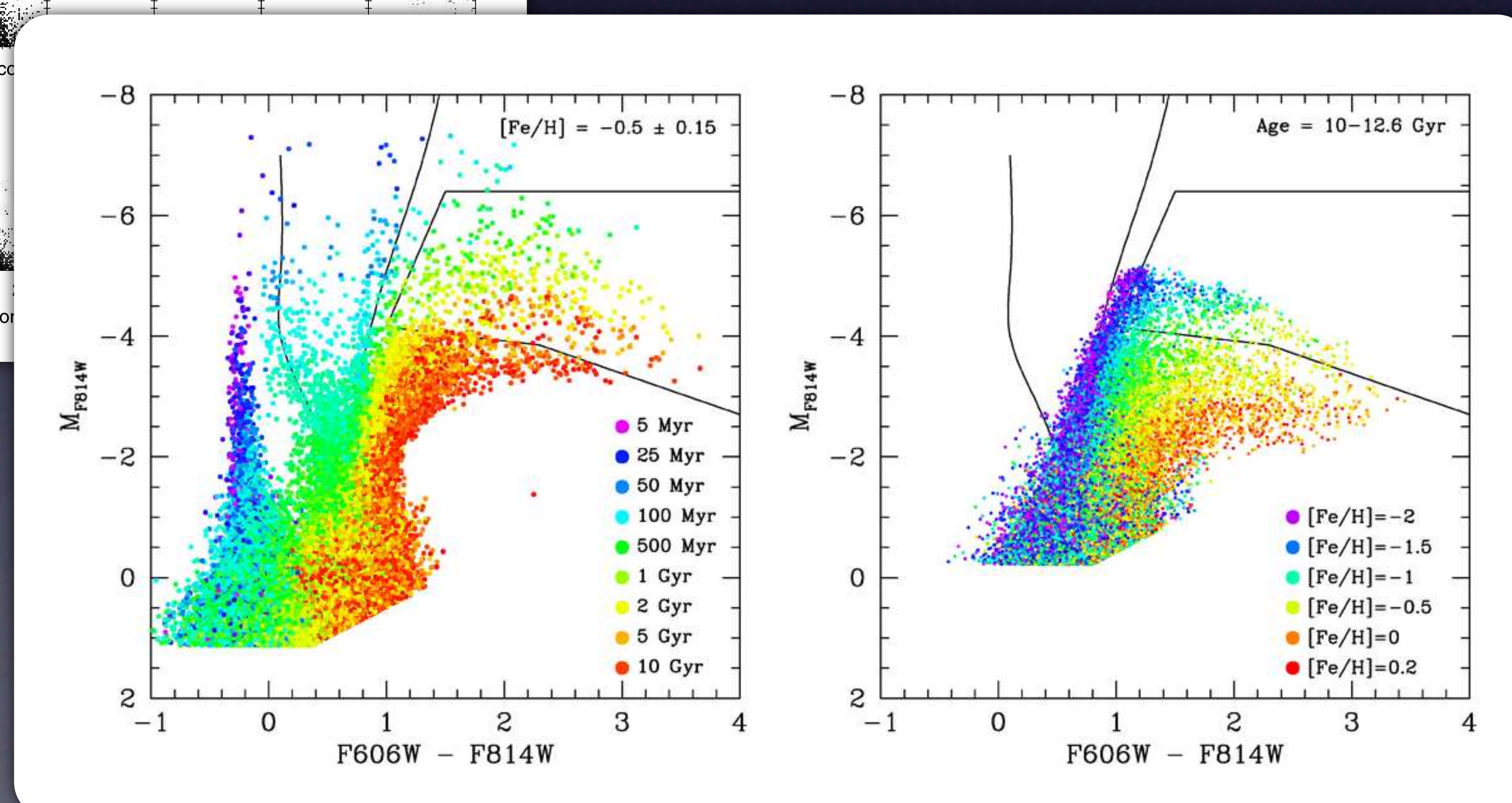
Received 2006 March 2; accepted 2006 May 30

The Local Group

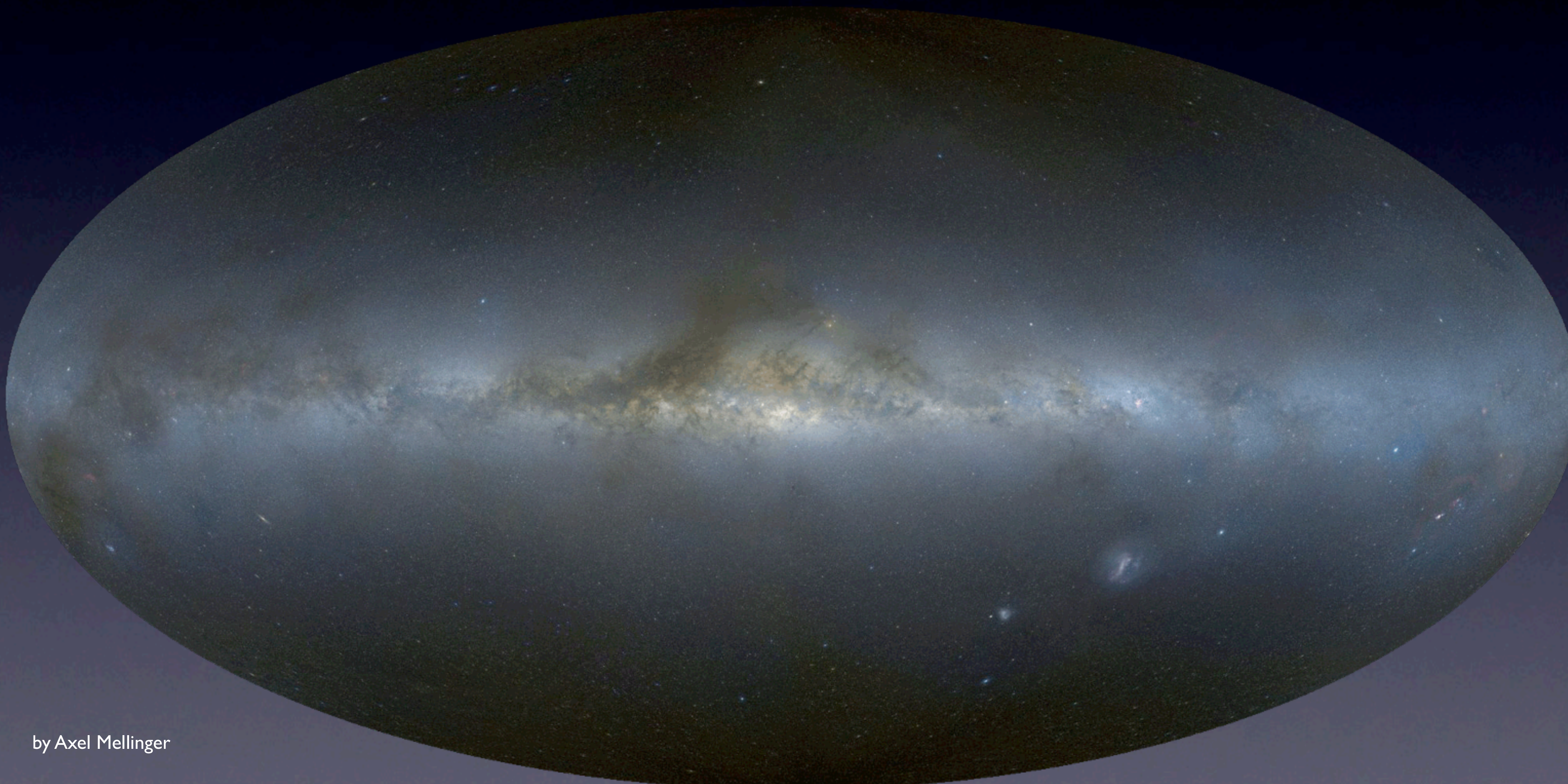


ANGST

The ACS Nearby Galaxy Survey Treasury

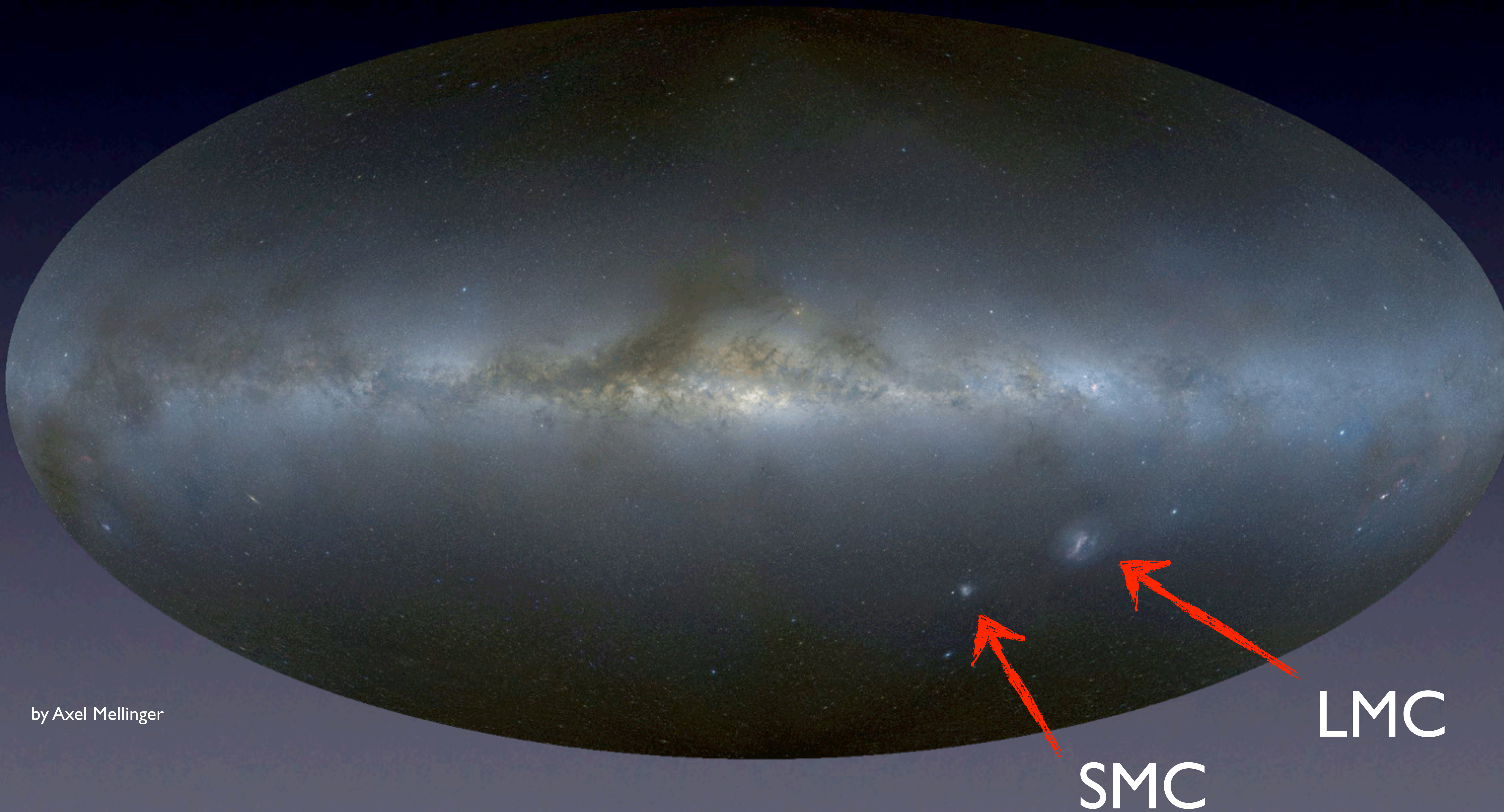


Large and Small Magellanic Clouds



by Axel Mellinger

Large and Small Magellanic Clouds



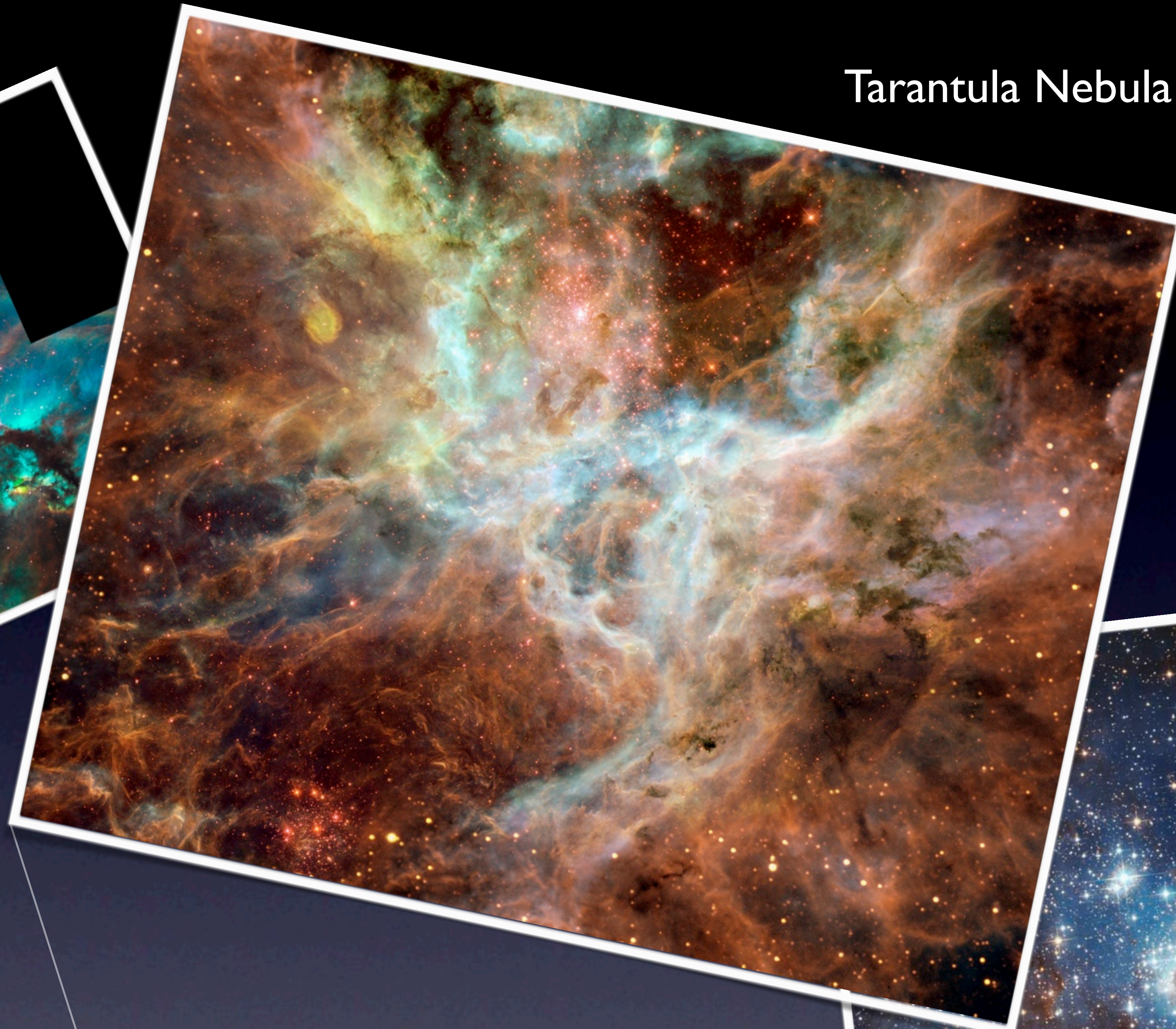
by Axel Mellinger

LMC

by Robert Gendler

Seahorse Nebula

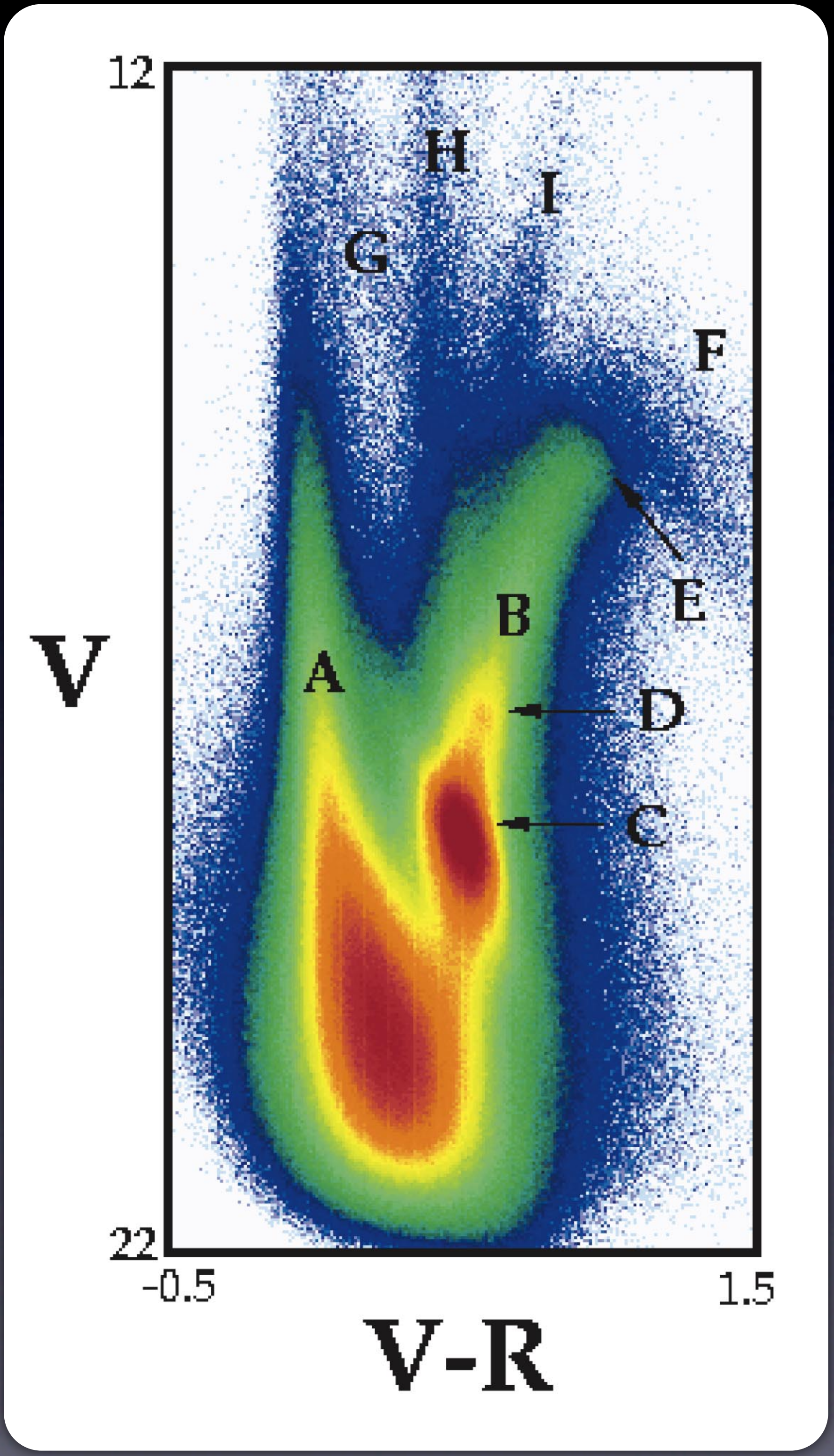
Tarantula Nebula



LH 95

NGC 1850

Stellar Populations in the LMC

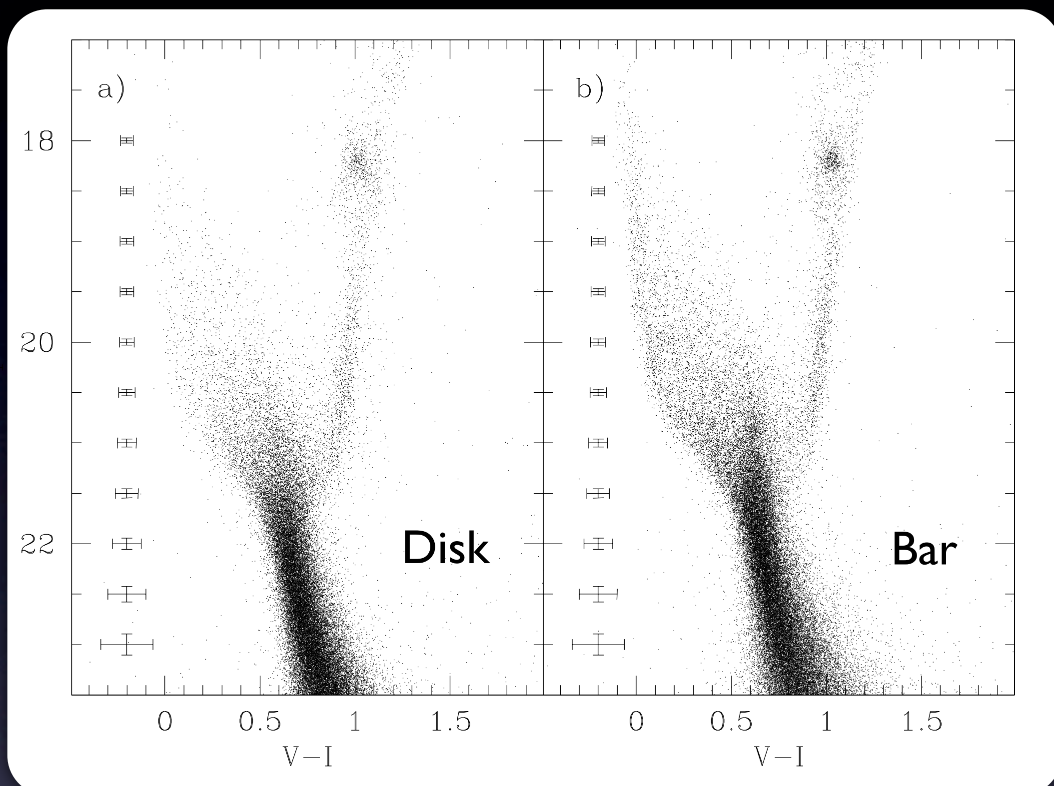


A - The Main Sequence
B - The Giant Branch
C - The Horizontal Branch Red Clump
D - The Asymptotic Giant Branch Bump
E - The Tip Of The Red Giant Branch
F - The Asymptotic Giant Branch
G - The Blue Supergiants
H - Foreground Galactic Disk
I - The Red Supergiants

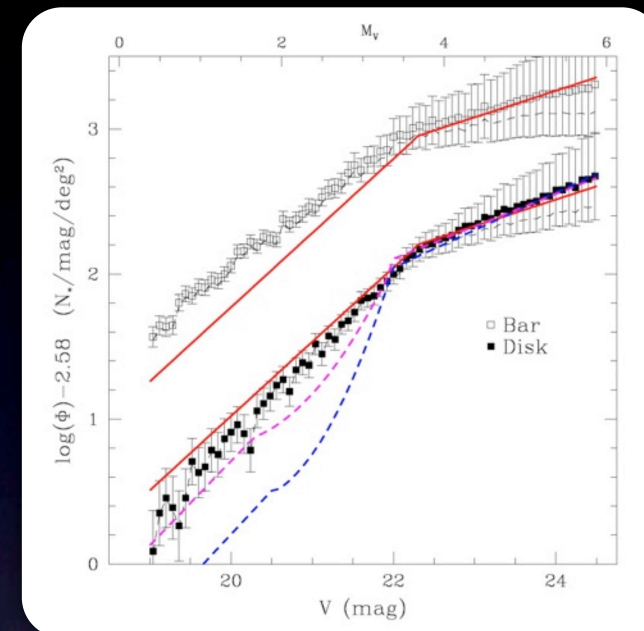
Alcock et al 2000, AJ

Stellar Populations in the LMC

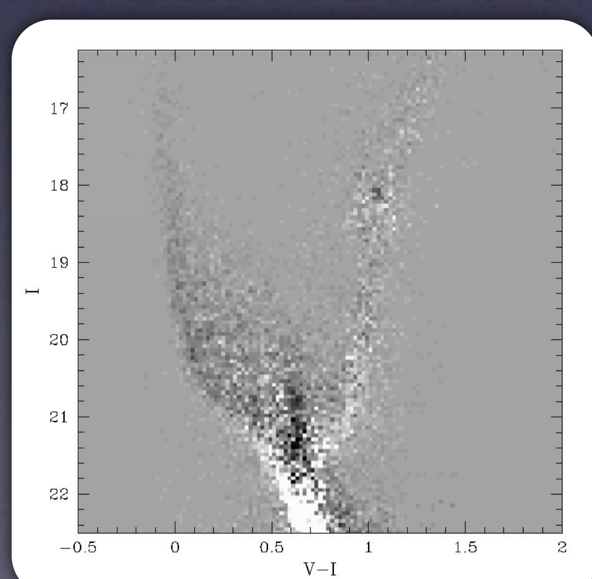
CMD



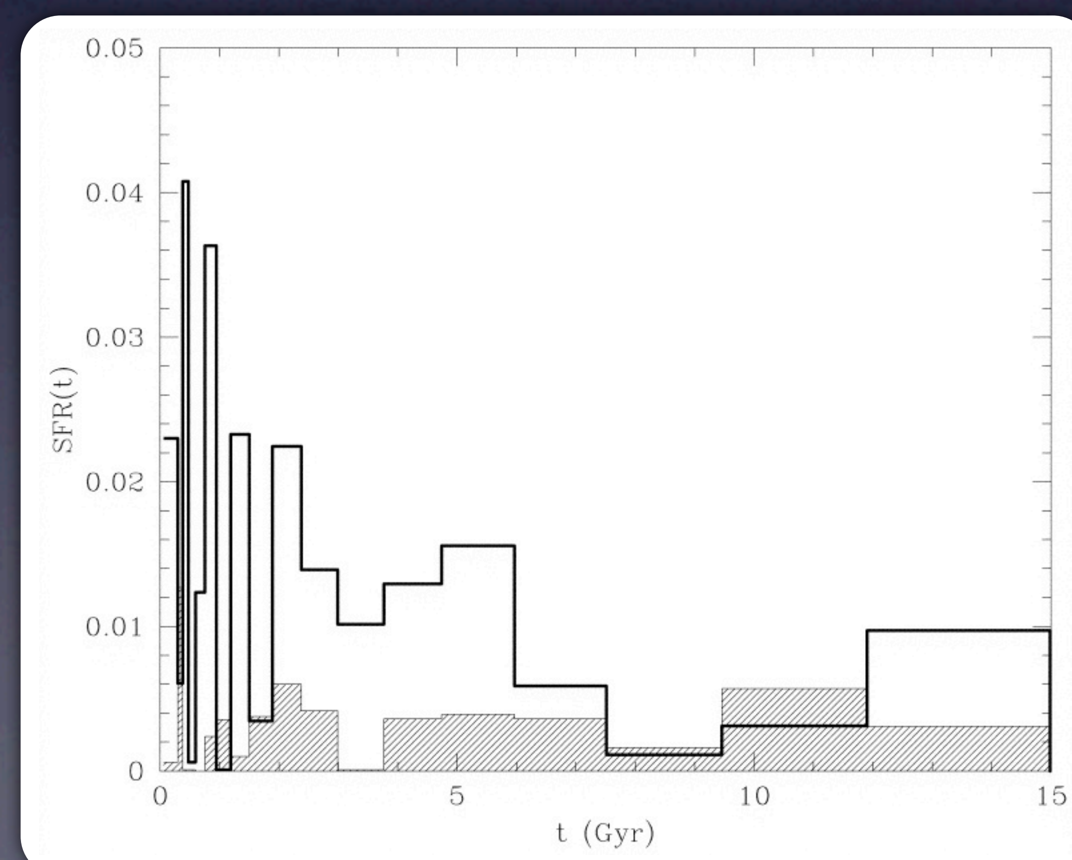
Luminosity Function



Hess Difference



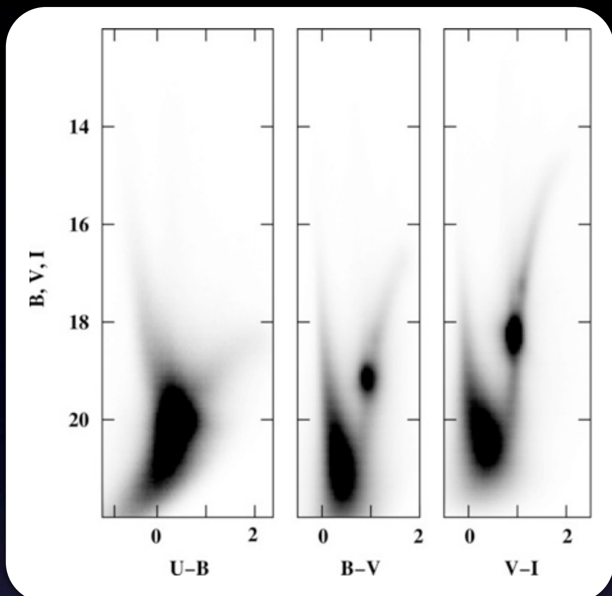
Star Formation Rate

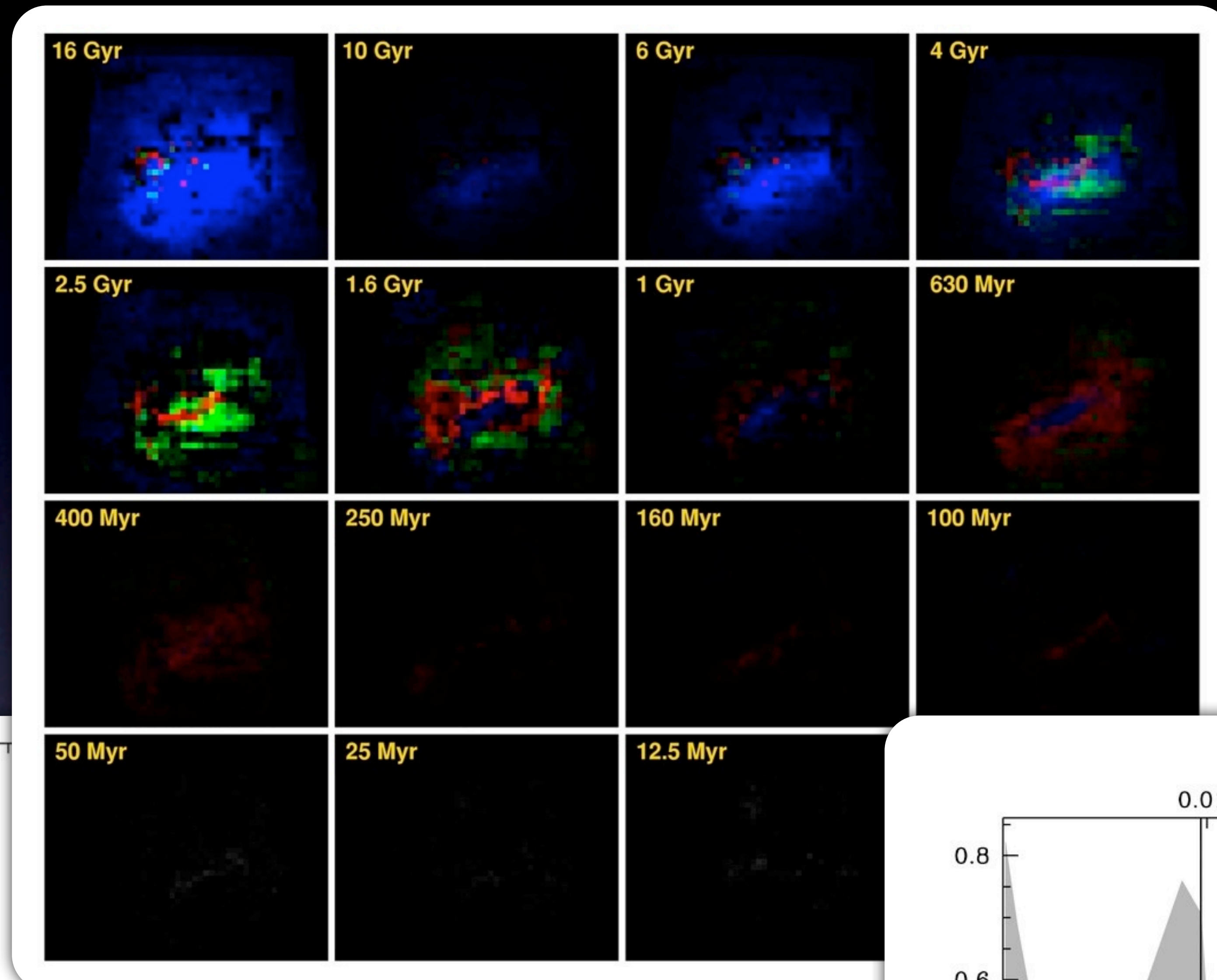


Smecker-Hane et al 2002, ApJ

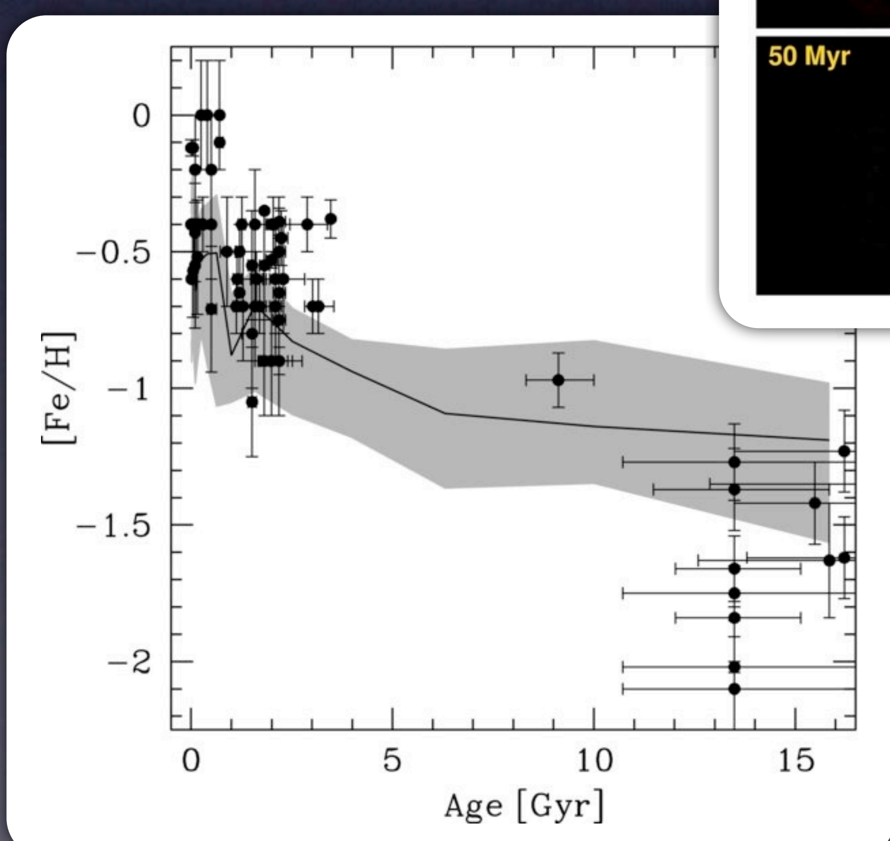
Stellar Populations in the LMC

Example CMDs

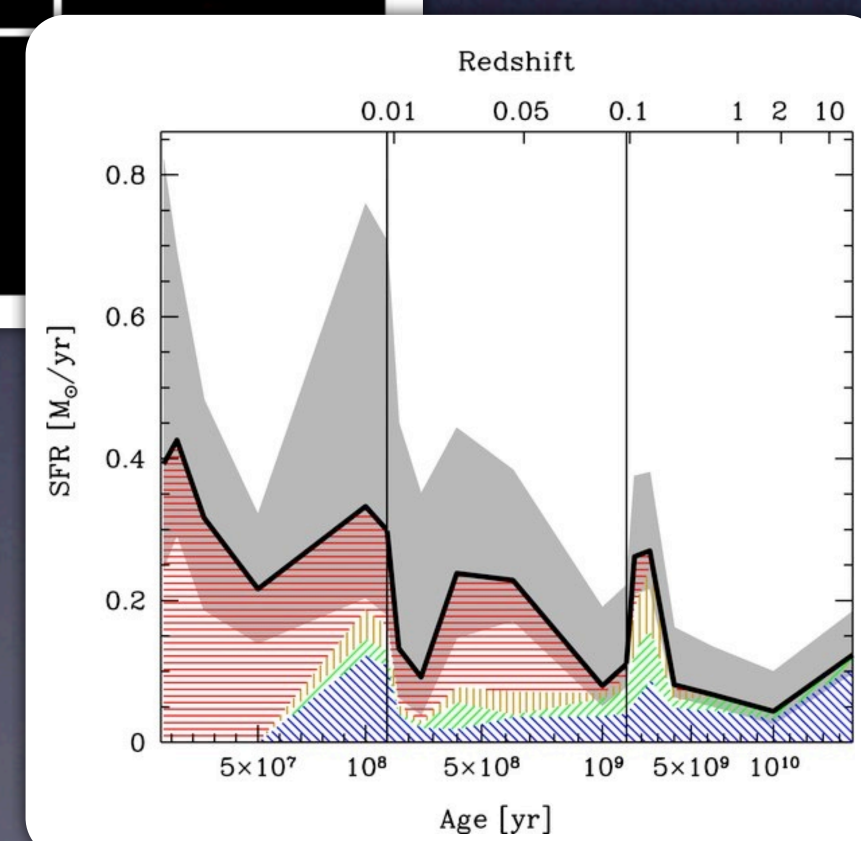




Globular Clusters



SFR



Harris and Zaritsky, 2009, AJ

LMC: Results

- Field stars
  - LMC contains outer halo of old field stars and globular clusters
  - evidence for large star formation events 3-10 Gyr ago
  - peak in star formation occurred in last 3 Gyr
- Clusters and asssociations
  - age distribution is bimodal, with gap between 3-10 Gyr (field stars show different behavior)
  - LMC contains population of massive young “blue globular clusters”, and supergiant HII regions

Dwarf Spheroidal Galaxies

Draco

Mischa Schirmer

Carina

AAO

Fornax

ESO/Digitized Sky Survey 2

Leo I

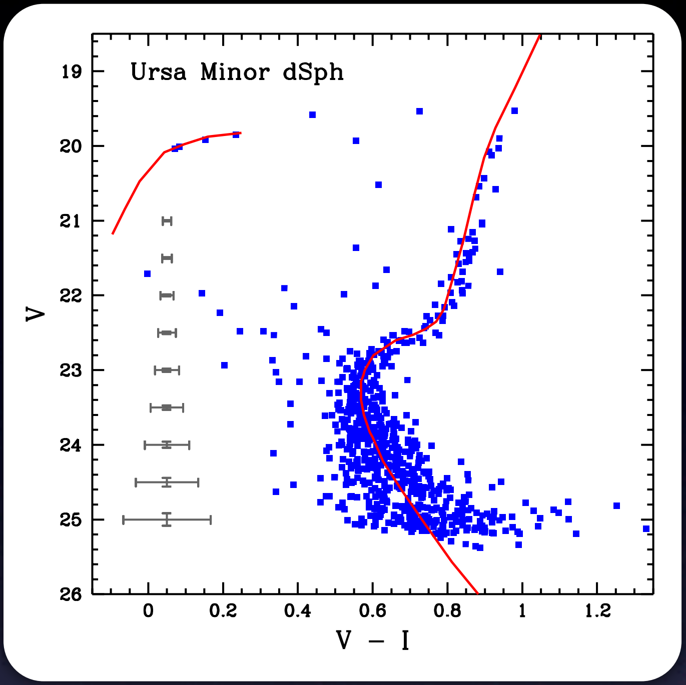
Leo II

SDSS

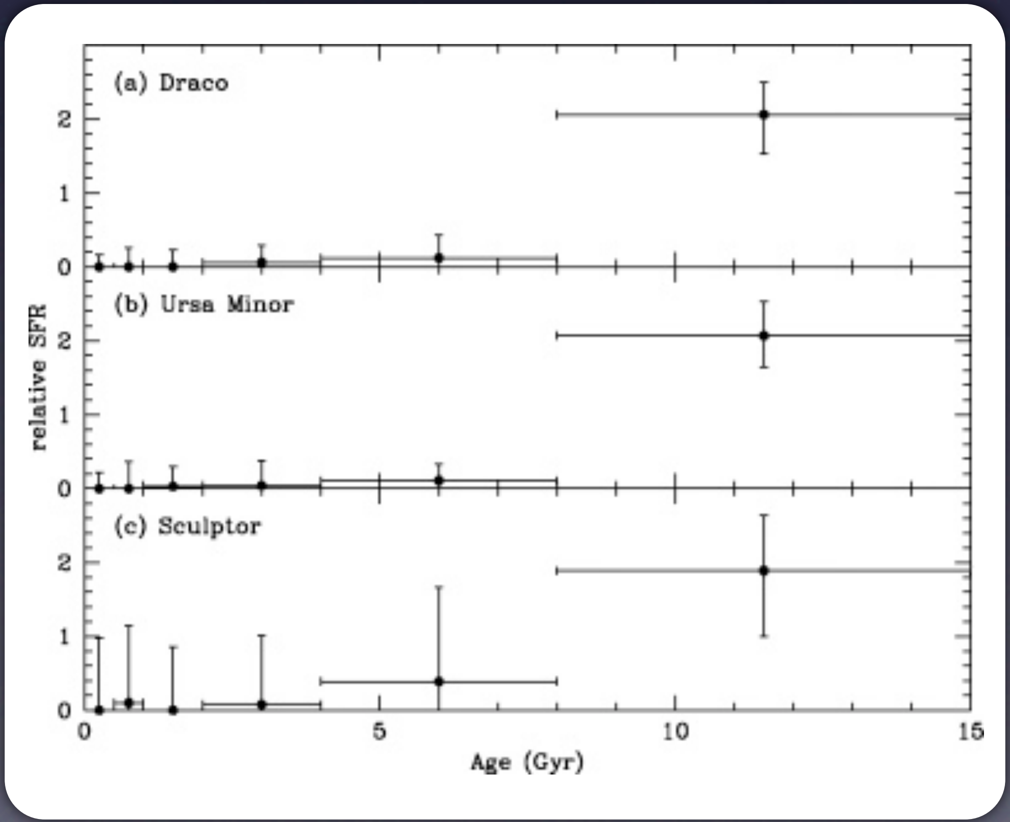
Dwarf Spheroidal Galaxies

- SF history from HST CMDs
- young population is absent (by definition)
- old population ubiquitous
  - at least one purely old galaxy (Ursa Minor) -------->
- intermediate-age population varies from 0% --> >90%

Mighell & Burke, 1999, AJ



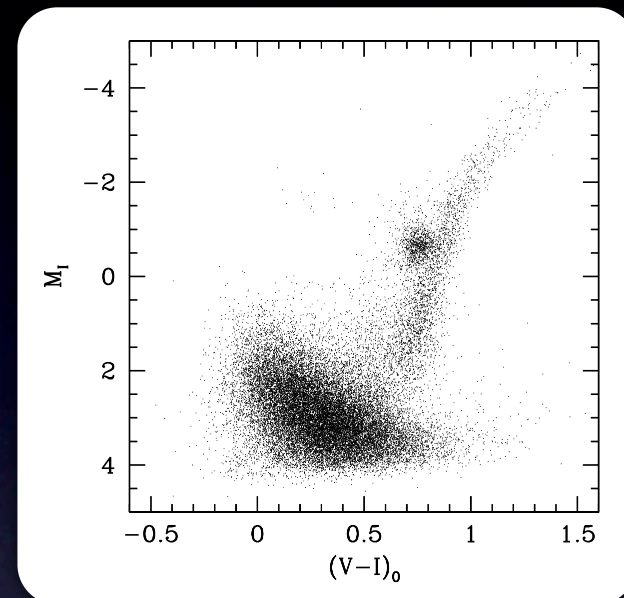
Dolphin, 2002, MNRAS



Dwarf Spheroidal Galaxies

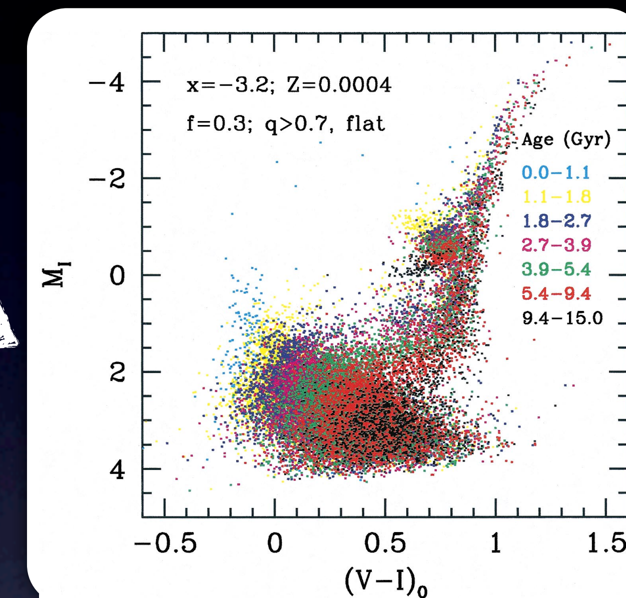
Leo I

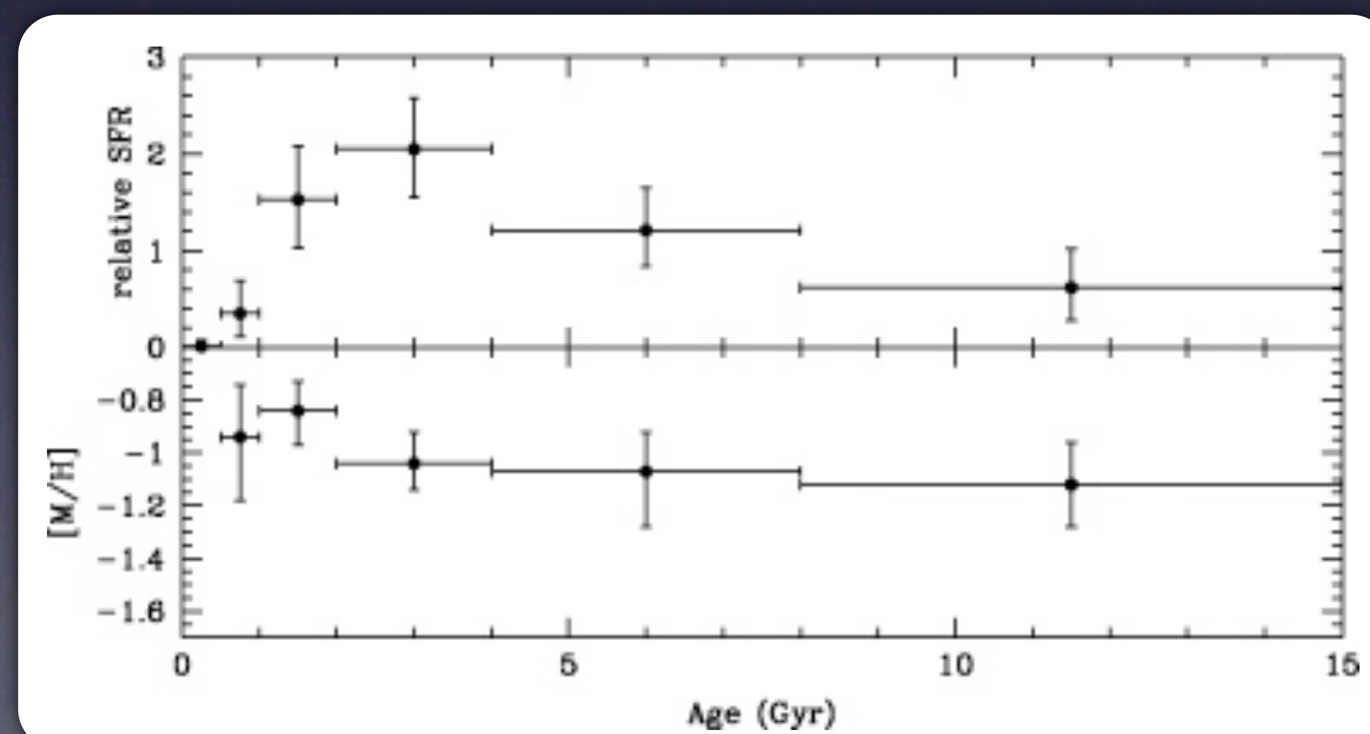
Data



Gallart er al, 1999, AJ

Model





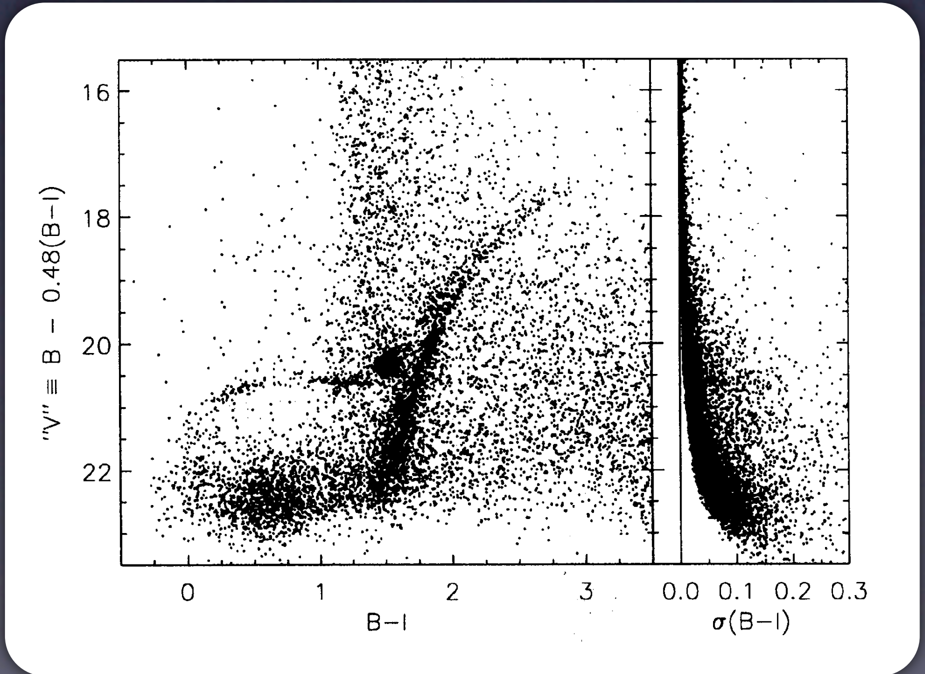
Steady star formation up to 1 Gyr ago

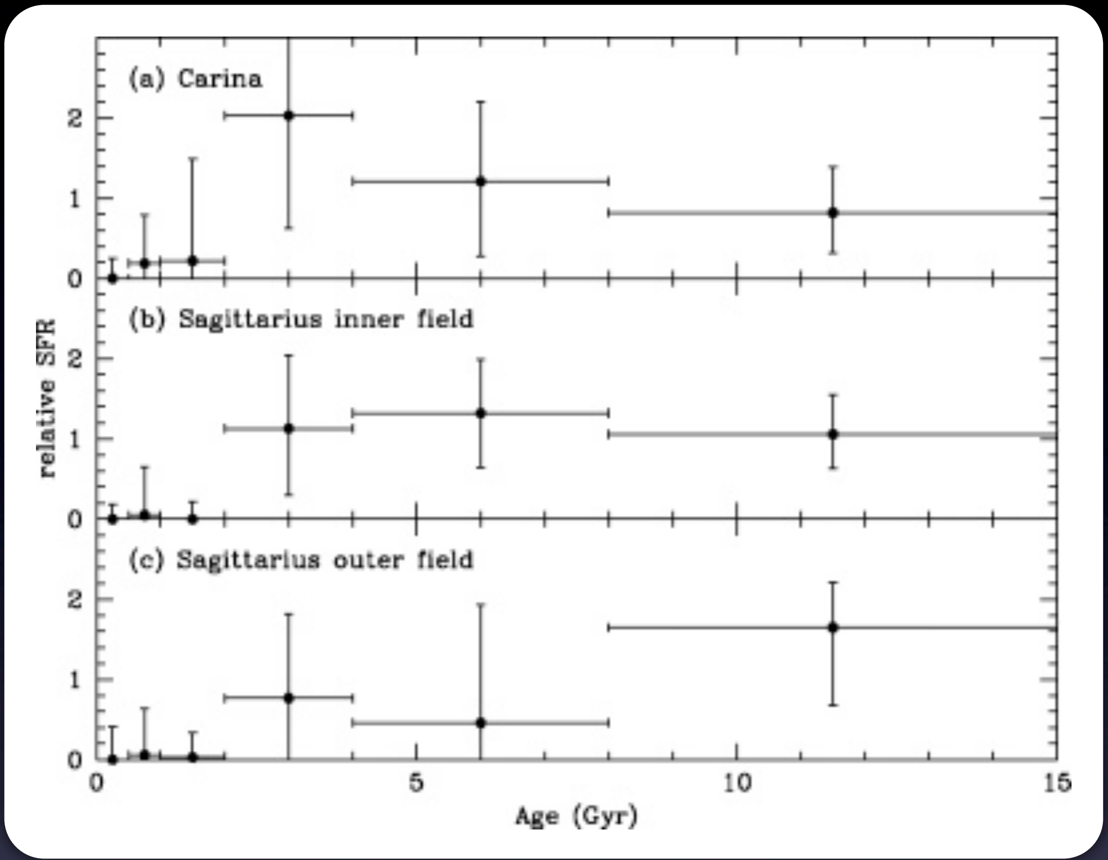
Dolphin, 2002, MNRAS

Dwarf Spheroidal Galaxies

Carina

Smecker-Hane et al, 1994, AJ



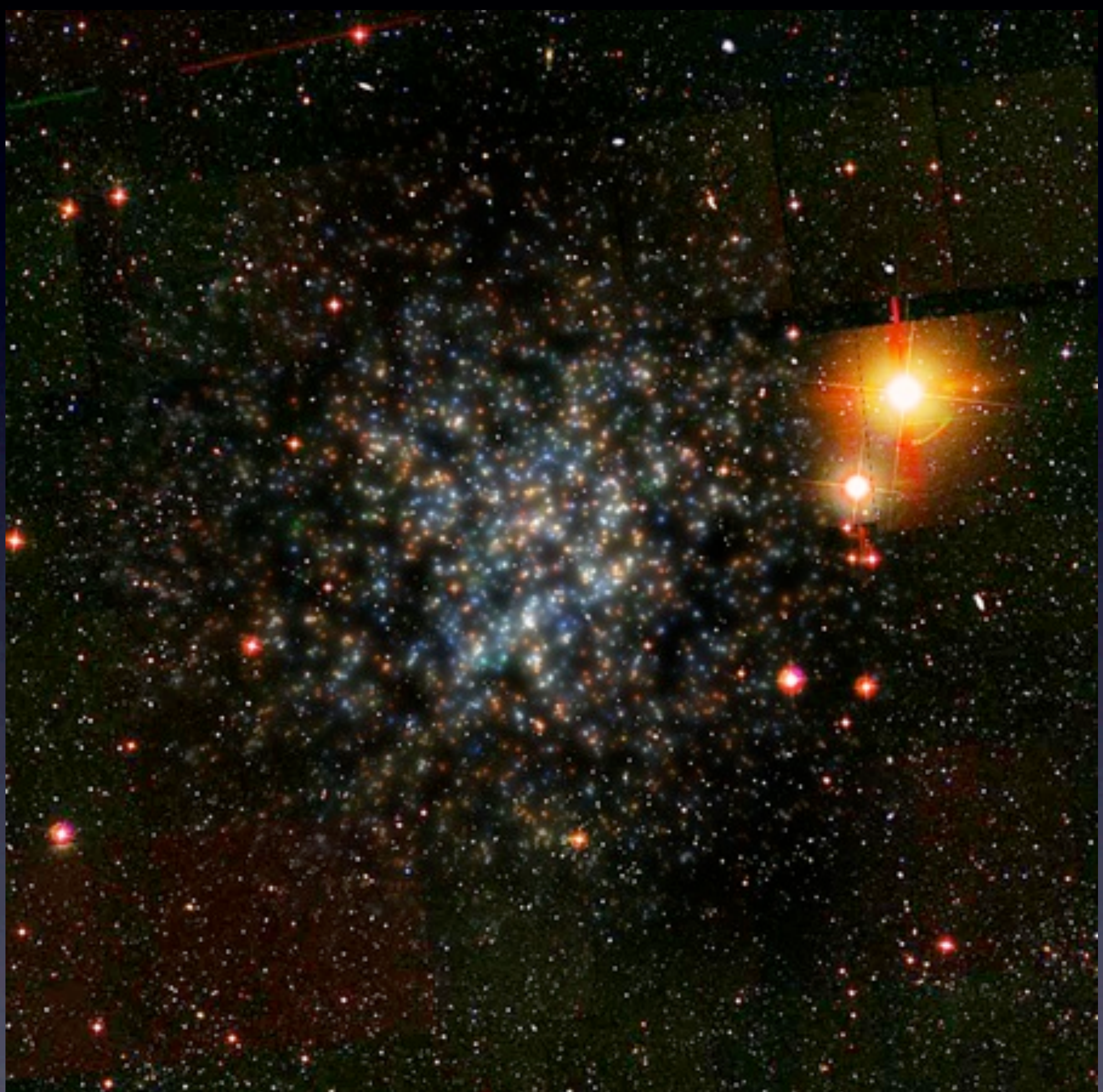


Dolphin, 2002, MNRAS

Several episodes of star formation

Ultra Faint Dwarfs

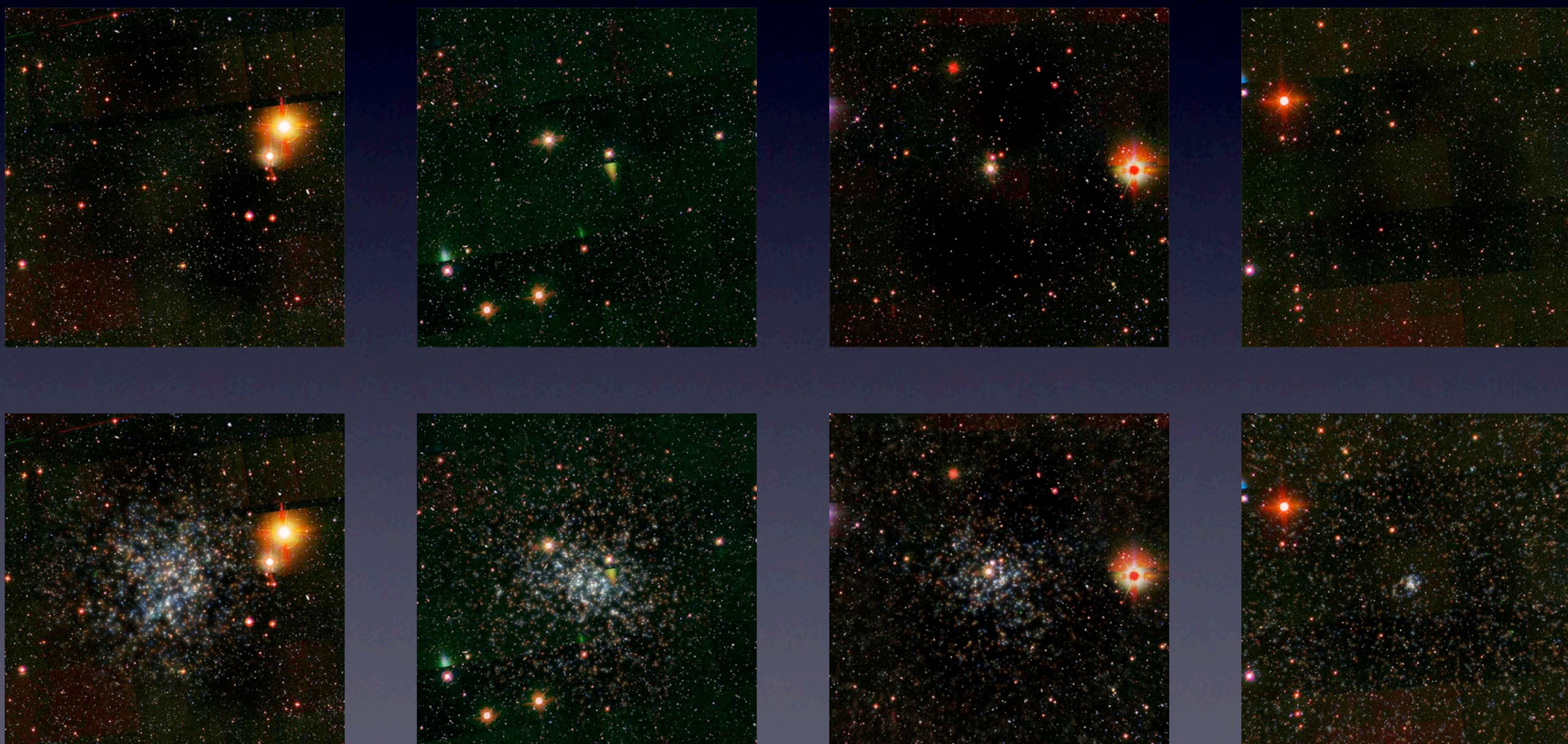
original SDSS image



“enhanced” SDSS image

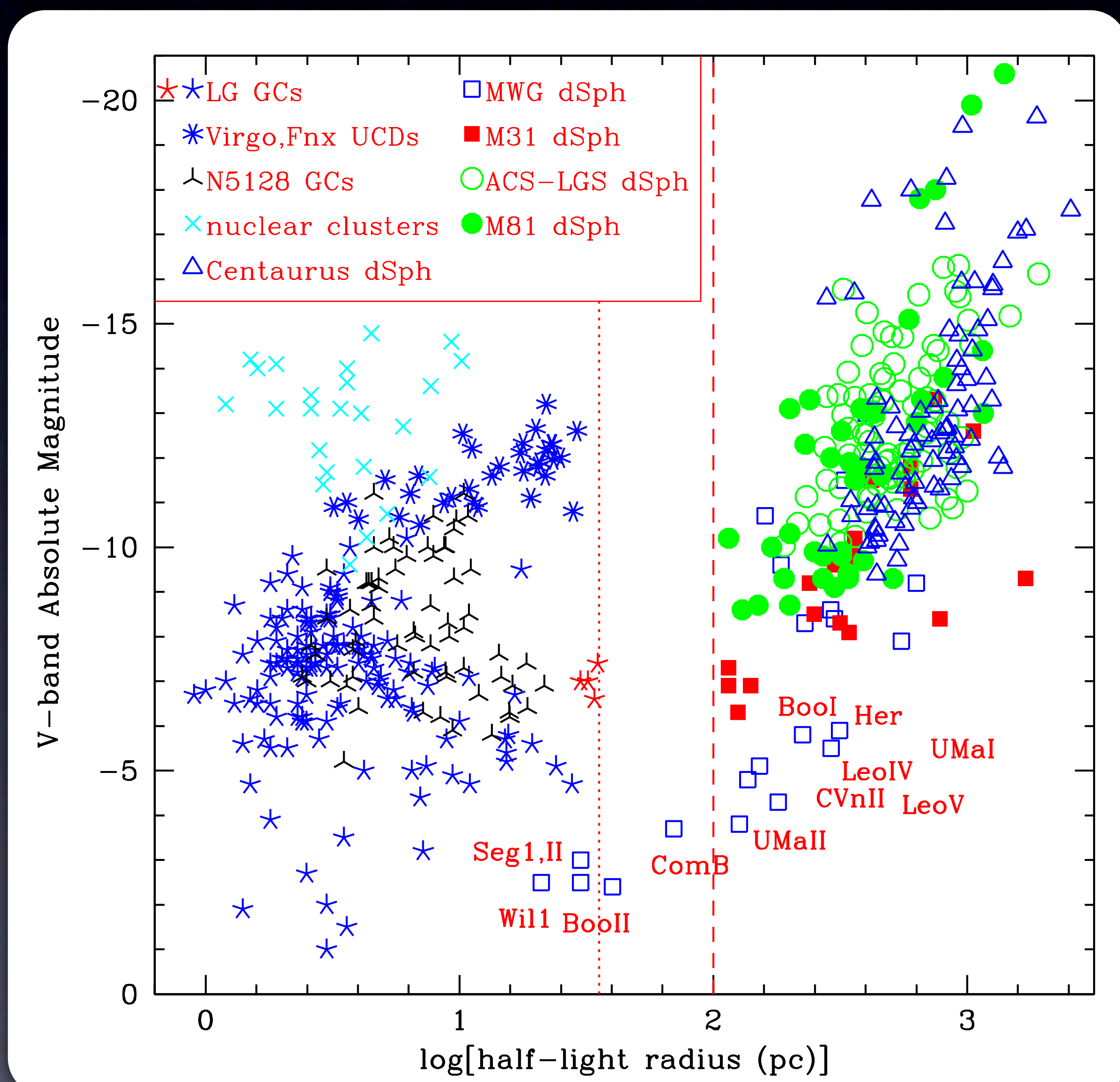
Ultra Faint (Invisible) Dwarfs

Bootes I | Canes Venatici I | Coma | Canes Venatici II

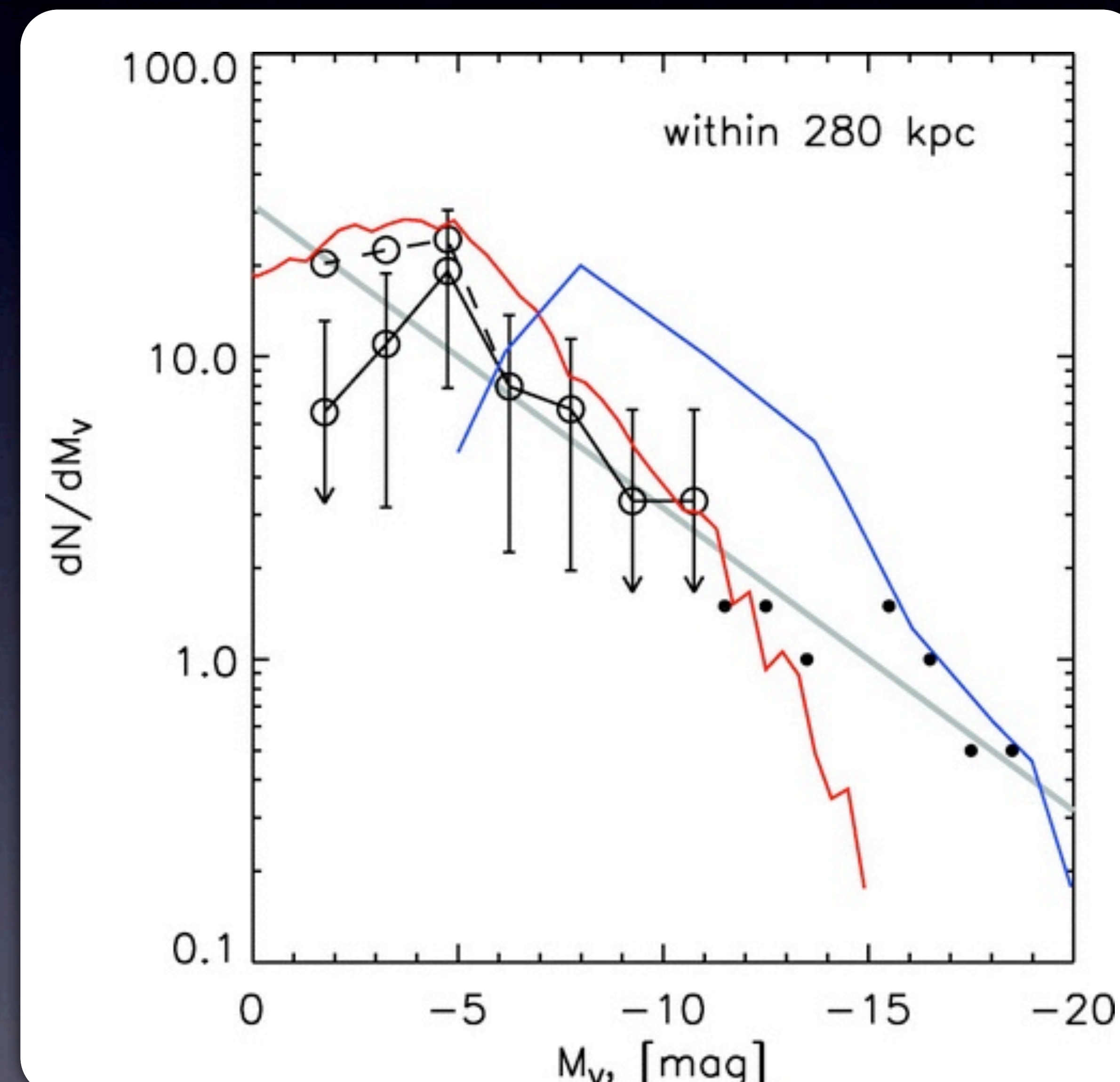


Belokurov et al., 2007, ApJ

Ultra Faint Dwarfs

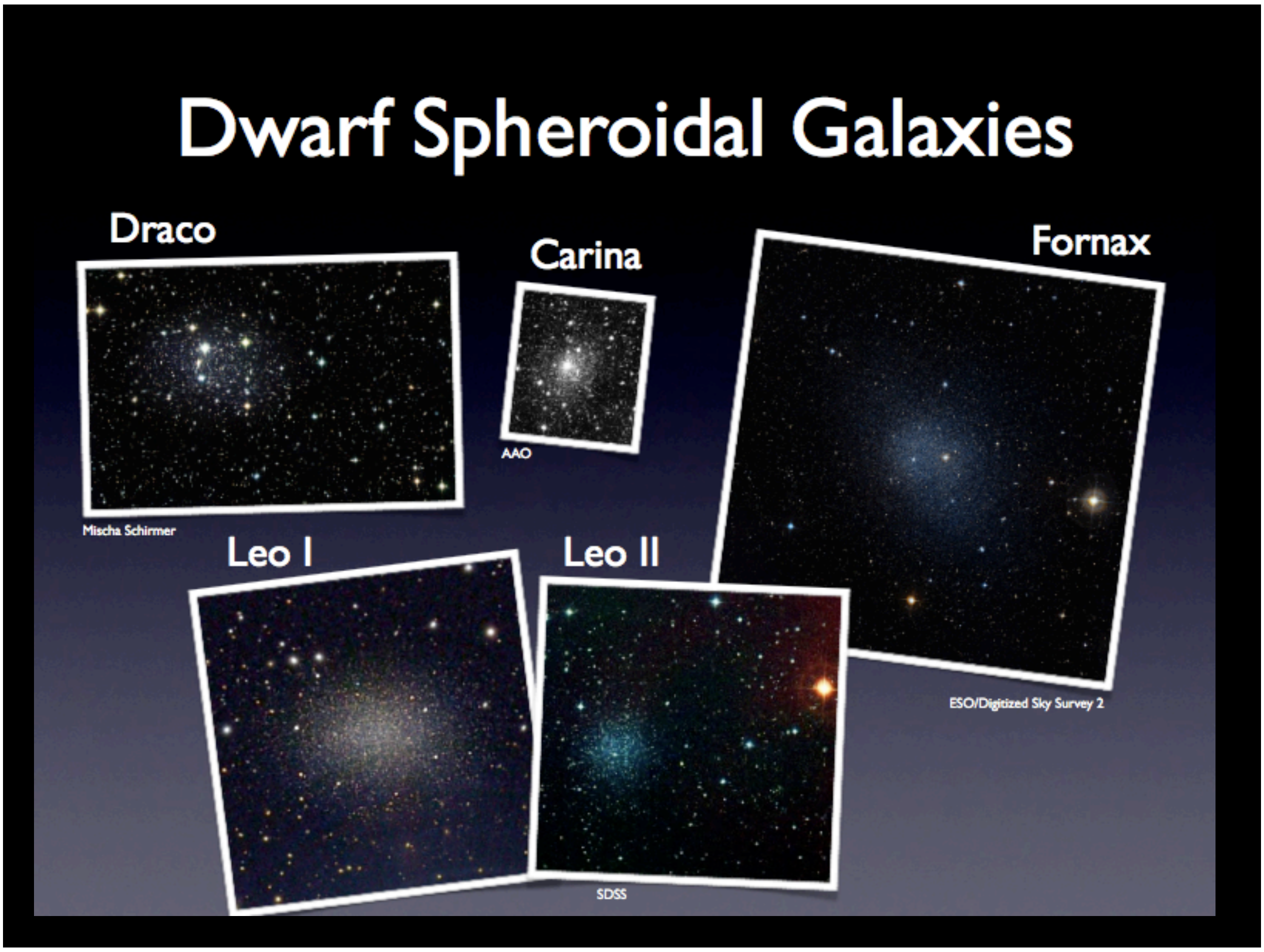


Luminosity Function



Koposov et al., 2008, ApJ


dwarf galaxies
The Dark side of galaxies
Jorge Peñarrubia
jorpega@ast.cam.ac.uk


Dwarf Spheroidal Galaxies
Draco
Carina
Fornax
AAO
Mischa Schirmer
Leo I
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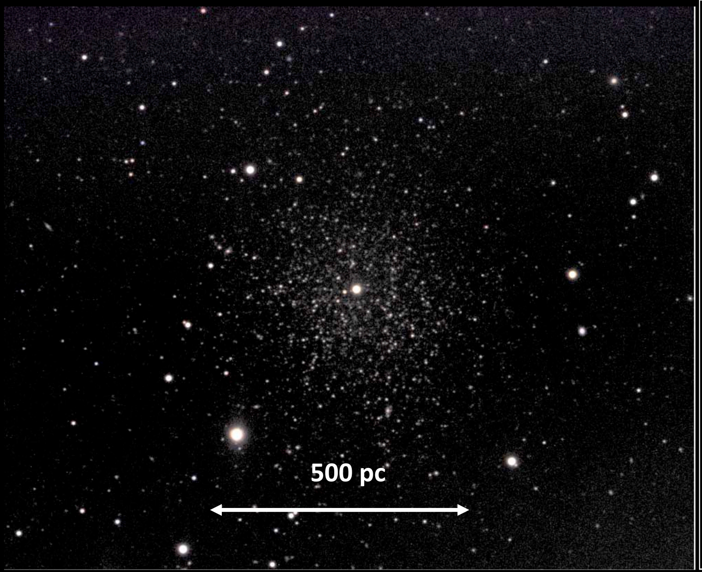
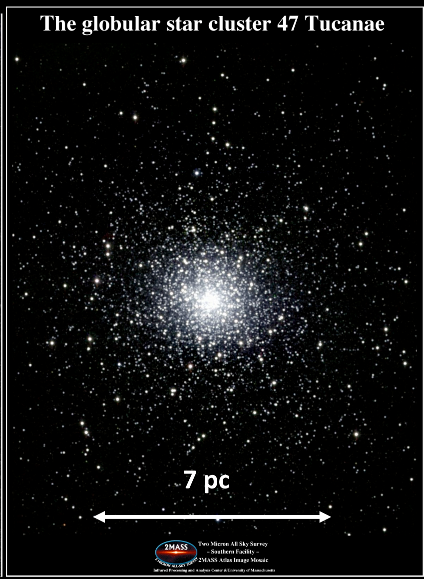
SDSS

Dwarf Galaxies: DM laboratories





Leo II
Mv = -9.6
σ = 7 km/s

$M_{dyn} \sim 2\,\sigma^2\, r / G$

47 Tucanae
Mv = -9.4
σ = 11.6 km/s

Dwarf Galaxies in CDM

- Most DM-dominated objects in the Universe (stars=tracers of the potential)
- Lowest-mass haloes that were able to retain gas and form stars
- Stellar populations as old as the Universe

↓

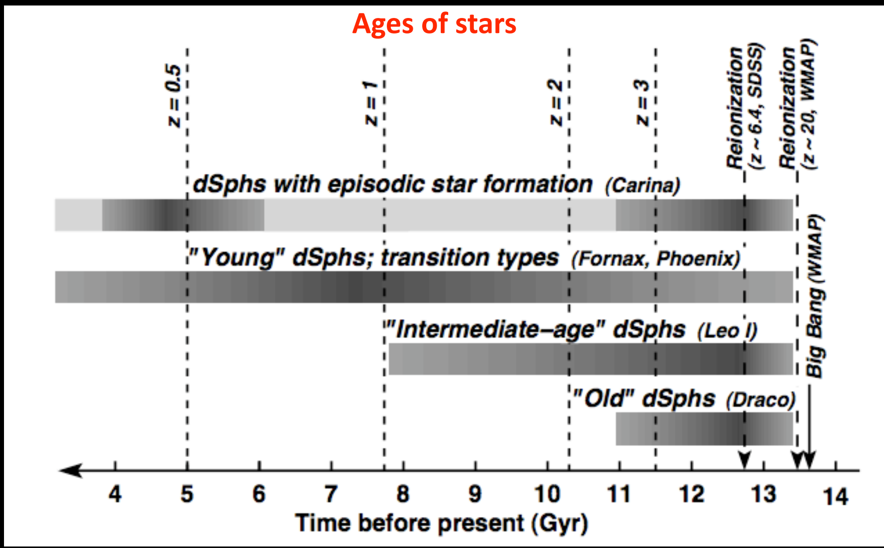
- **Nature of dark matter (test paradigm!)**
- **Star formation at z>>0**

Sculptor

≡

stars ≡ mass-loss tracers of the **DM potential**

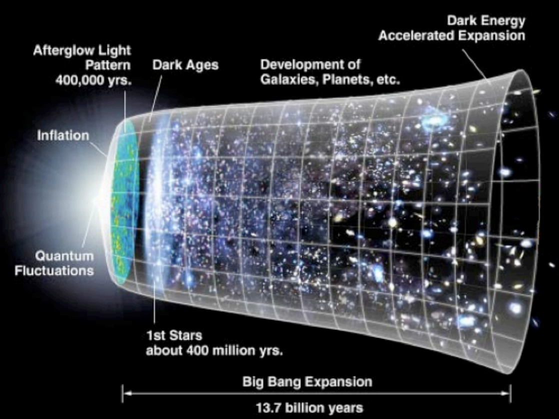
Stars in Dwarf Galaxies



Grebel et al. (2005)

All dwarfs contain stars as old as the Universe

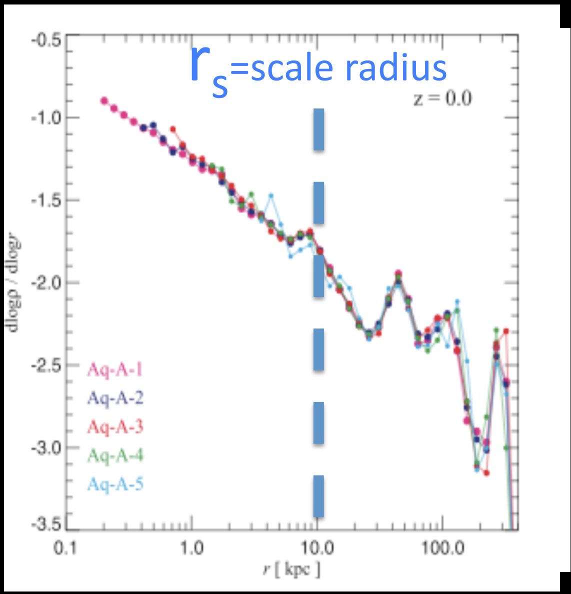
Cold Dark Matter cosmogony



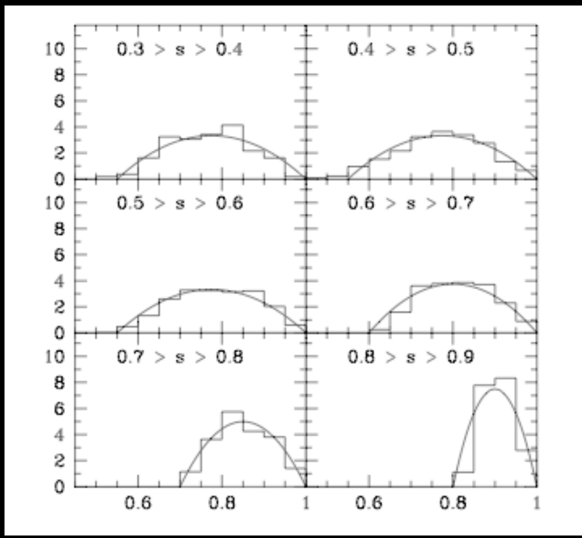
Springel et al. (2008) Aquarius Simulation (10^{10} particles)

Cold Dark Matter cosmogony

CDM paradigm predictions:
- dark matter haloes follow a universal density profile (NFW)
- dark matter haloes have a triaxial shape



Springel et al. (2008) Aquarius Simulation (10^{10} particles)



Allgood et al (2008)

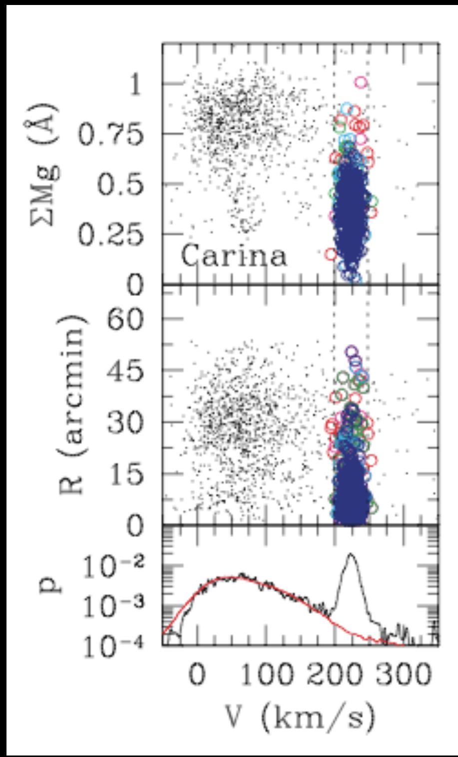
(s=c/a ; p=b/a)

Testing CDM predictions in dSphs

position, velocity metallicity of hundreds of individual stars

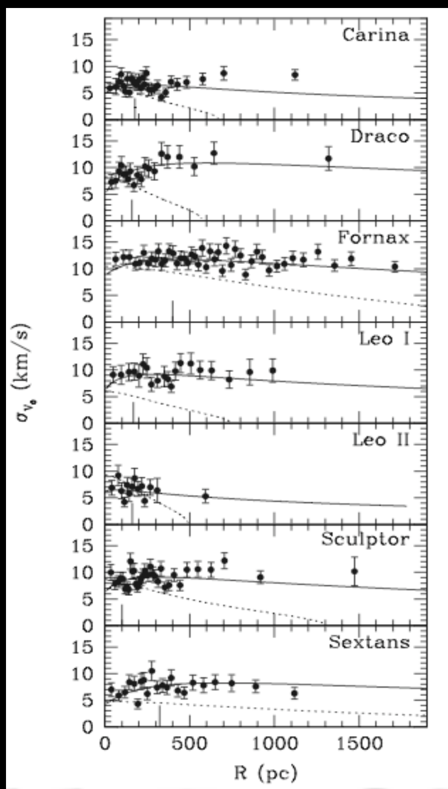
Testing CDM predictions in dSphs

position, velocity metallicity of hundreds of individual stars



Testing CDM predictions in dSphs

position, velocity metallicity of hundreds of individual stars



Walker et al. 2007

Dynamical modelling

$f(\mathbf{x}, \mathbf{v}, t) d^3x d^3v$ Distribution function

$\dot{\mathbf{v}} = -\nabla\Phi$ Poisson equation

$\frac{df}{dt} = 0$ continuity equation

Collision-less Boltzmann equation

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f - \nabla\Phi \cdot \frac{\partial f}{\partial \mathbf{v}} = 0$$

Dynamical modelling

Approximation #1: Dynamical equilibrium $\frac{\partial f}{\partial t} = 0$

Approximation #2: DF → Moments $\int v_j d^3v \quad \times$

$$\int v_i v_j \frac{\partial f}{\partial x_i} d^3v - \frac{\partial \Phi}{\partial x_i} \int v_j \frac{\partial f}{\partial v_i} d^3v = 0$$

Dynamical modelling

Definitions:

$$\nu \equiv \int f d^3v$$ stellar density

$$< v_i > \equiv \frac{1}{\nu} \int v_i f d^3v$$ mean velocity

$$\sigma^2_{i,j} \equiv < v_i v_j > - < v_i > < v_j >$$ velocity dispersion tensor

$$\sigma_{i,j} = \delta_{i,j}\sigma_{i,i}$$ (diagonalized)

Jeans equations

(see e.g Binney & Tremaine 1987; S.4.2)

$$\int v_i v_j \frac{\partial f}{\partial x_i} d^3v - \frac{\partial \Phi}{\partial x_i} \int v_j \frac{\partial f}{\partial v_i} d^3v = 0$$

divergence theorem: $$\int g(\nabla \cdot \mathbf{f}) d^3x = \int g(\mathbf{f} \cdot \mathbf{n}) d^2x - \int (\mathbf{f}\nabla) g d^3x$$

$$\int v_j \frac{\partial f}{\partial v_i} d^3v = \int v_j (f v_i) d^2v - \int f \frac{\partial v_j}{\partial v_i} d^3v = -\int f \delta_{i,j} d^3v = -\delta_{i,j}\nu$$

(right term)

$$\int v_i v_j \frac{\partial f}{\partial x_i} d^3v = \frac{\partial}{\partial x_i} \int v_i v_j f d^3v = \frac{\partial (< v_i v_j > \nu)}{\partial x_i}$$

(left term)

Jeans equations

(see e.g Binney & Tremaine 1987; S.4.2)

$$\int v_i v_j \frac{\partial f}{\partial x_i} d^3v - \frac{\partial \Phi}{\partial x_i} \int v_j \frac{\partial f}{\partial v_i} d^3v = 0$$

$$\frac{\partial(\nu < v_i v_j >)}{\partial x_i} + \nu \frac{\partial \Phi}{\partial x_j} = 0$$

Approximation ＃3： System is in equilibrium $(<v_i>=0)$

$$\frac{\partial(\nu \sigma_{i,i}^2)}{\partial x_i} + \nu \frac{\partial \Phi}{\partial x_j} = 0$$

diagonalized ref. frame
$(\sigma_{i,j}=0 \;\; i \neq j)$

Jeans equations in spherical coord.

$$\frac{\partial(\nu \sigma_{i,i}^2)}{\partial x_i} + \nu \frac{\partial \Phi}{\partial x_j} = 0$$

Approximation ＃4： System has spherical symmetry

$$\frac{d(\nu \sigma_r^2)}{dr} + \frac{\nu}{r}\left[2\sigma_r^2 - \sigma_t^2\right] + \nu \frac{d\Phi}{dr} = 0$$

Definition:

$$\beta \equiv 1 - \frac{\sigma_t^2}{2\sigma_r^2}$$ velocity anisotropy $(\sigma_t^2 \equiv \sigma_\theta^2 + \sigma_\phi^2)$

$$\frac{d(\nu \sigma_r^2)}{dr} + 2\frac{\beta \nu \sigma_r^2}{r} + \nu \frac{d\Phi}{dr} = 0$$

Modelling of dSphs

$$\frac{d(\nu\sigma_r^2)}{dr} + 2\frac{\beta\nu\sigma_r^2}{r} + \nu\frac{d\Phi}{dr} = 0$$

1. velocities and density profiles are projected quantities
2. **β unknown** (!!)
3. $\Phi = \Phi_{DM}$

$$\Sigma(R) = 2\int_R^\infty \frac{\nu r dr}{\sqrt{r^2 - R^2}}$$

$$\sigma_p^2(R) = \frac{2}{\Sigma(R)}\int_R^\infty \frac{\nu\sigma_r^2 r dr}{\sqrt{r^2 - R^2}}$$

} observational constraints

Modelling of dSphs: 1- Isotropic models

(β=0)

$$\frac{d(\nu\sigma_r^2)}{dr} + 2\frac{\beta\nu\sigma_r^2}{r} + \nu\frac{d\Phi}{dr} = 0$$

$$\sigma_r^2(r) = \frac{1}{\nu}\int_r^\infty \nu\frac{d\Phi}{dr}dr$$

$$\Phi = -V_{\max}^2 \frac{r_{\max}}{r}\ln[1 + r/r_s]$$

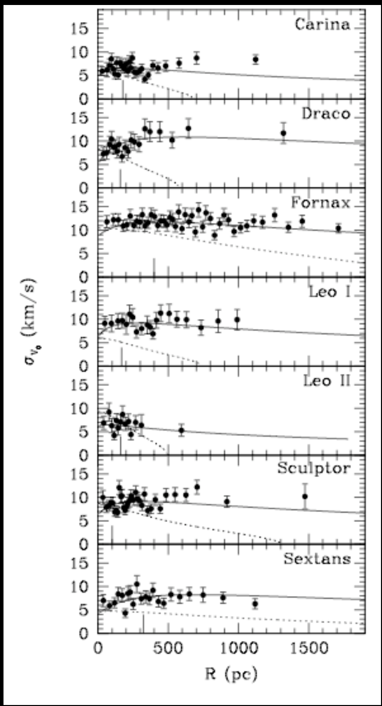
NFW potential (CDM prior)

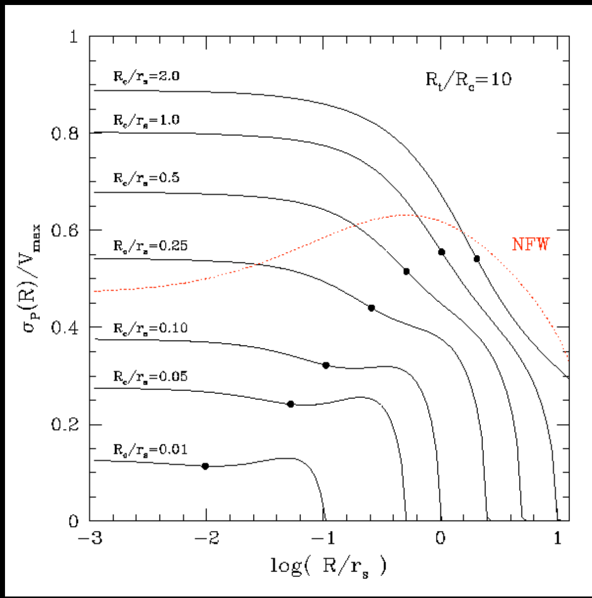
$$\nu = \frac{K}{x^2}\left[\frac{\cos^{-1}(x)}{x} - \sqrt{1 - x^2}\right]$$

$$x = \frac{1 + (r/r_k)^2}{1 + (r_t/r_k)^2}$$

King density profile (obs. prior)

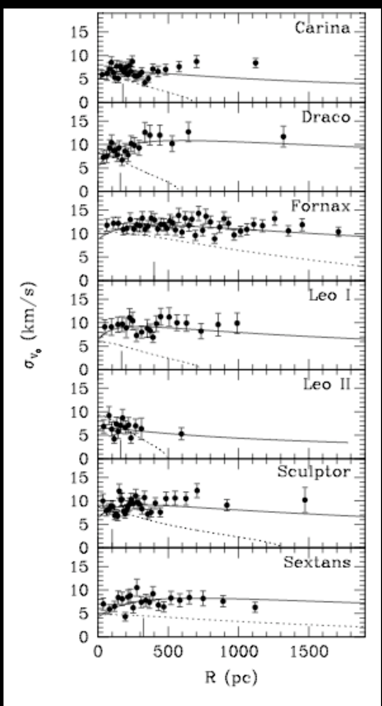
Modelling of dSphs: 1- Isotropic models

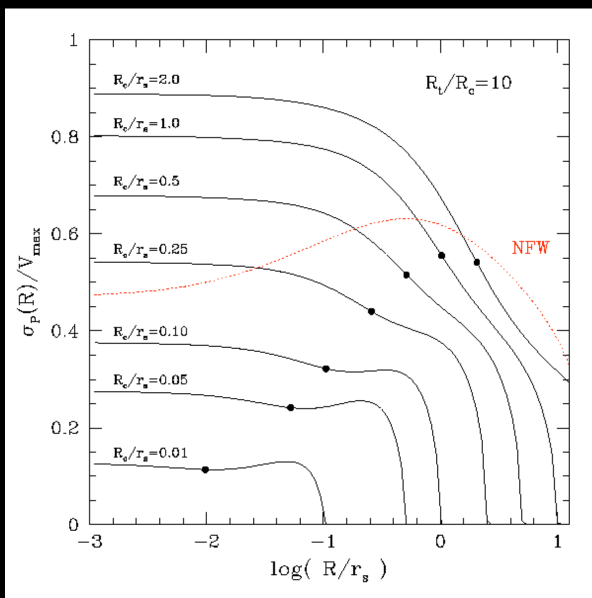




r_s, V_{max}??

Modelling of dSphs: 1- Isotropic models

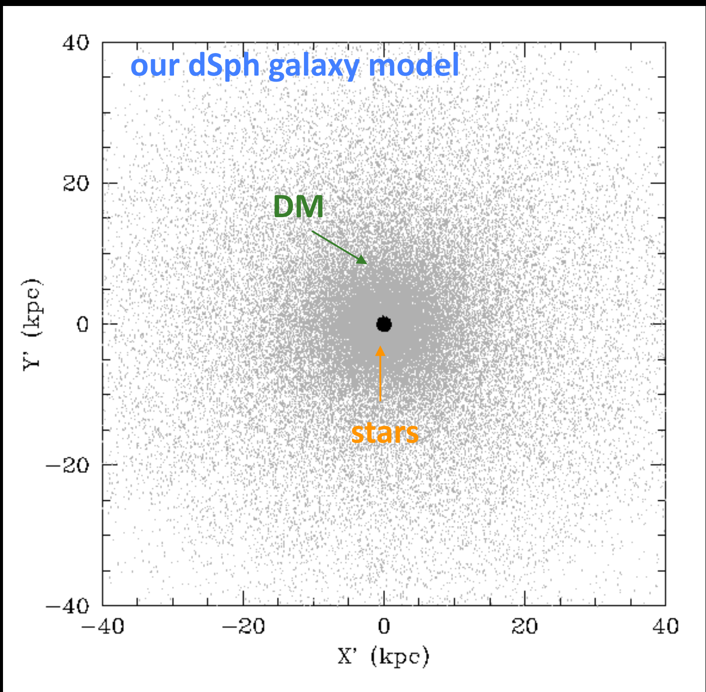




r_s, V_{max}??

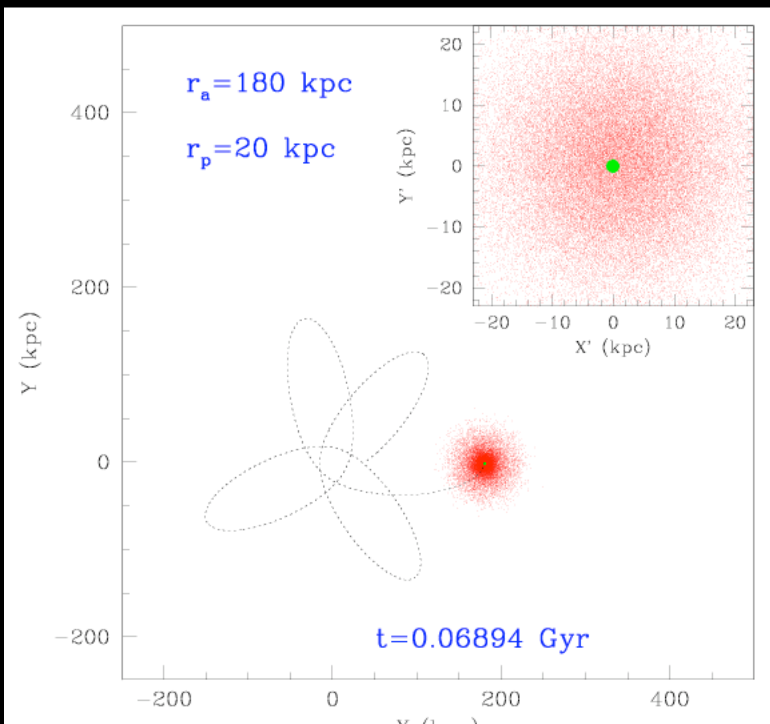
(flat) velocity dispersion profiles indicate r_k/r_s<<1

Modelling of dSphs: 1- Isotropic models



stars are deeply embedded in DM potential wells

Modelling of dSphs: 1- Isotropic models



Peñarrubia et al. 2008

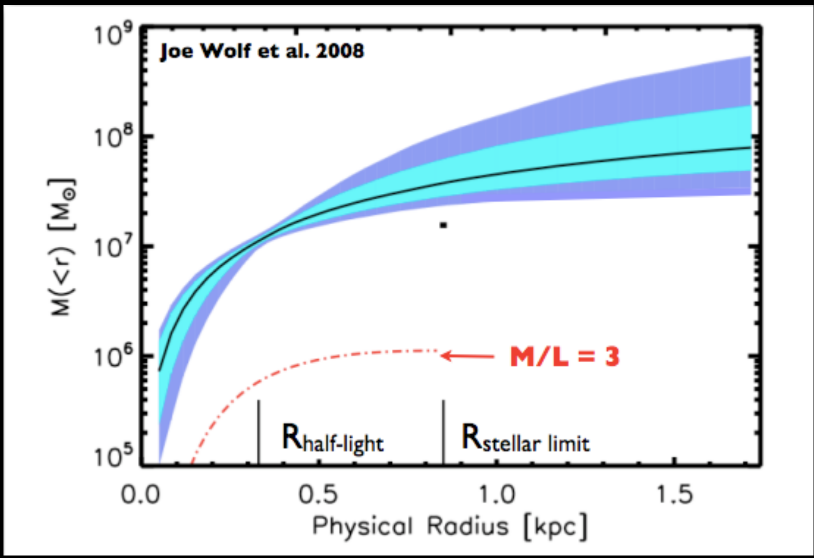
stars are deeply embedded in DM potential wells

Extreme resilience to external tidal forces

Modelling of dSphs: 2- ANisotropic models

β – Φ degeneracy

$$\sigma_r^2 = \frac{1}{r^{2\beta}\nu}\int_r^\infty r^{2\beta}\nu\frac{d\Phi}{dr}dr$$



$$\frac{d\Phi}{dr} = \frac{GM(r)}{r^2}$$

Modelling of dSphs: 2- ANisotropic models

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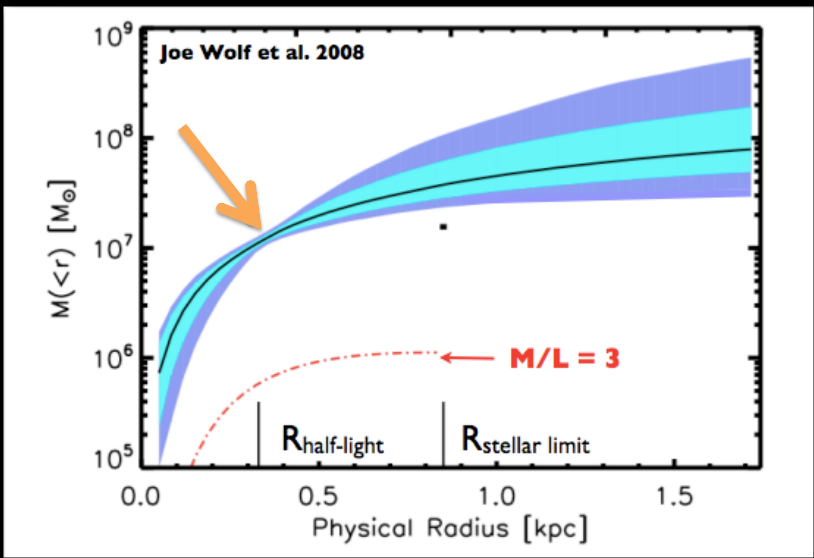

$$\frac{d\Phi}{dr} = \frac{GM(r)}{r^2}$$

degeneracy very small at $R \sim R_{half}$

accurate $M(R_{half})$

Modelling of dSphs: 2- ANisotropic models

β – Φ degeneracy

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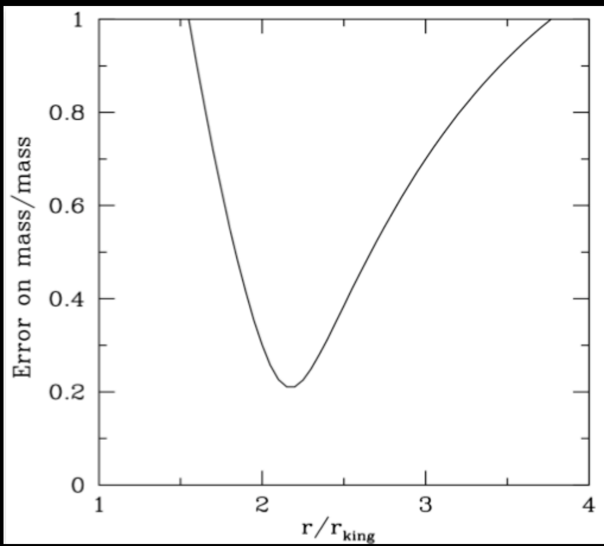
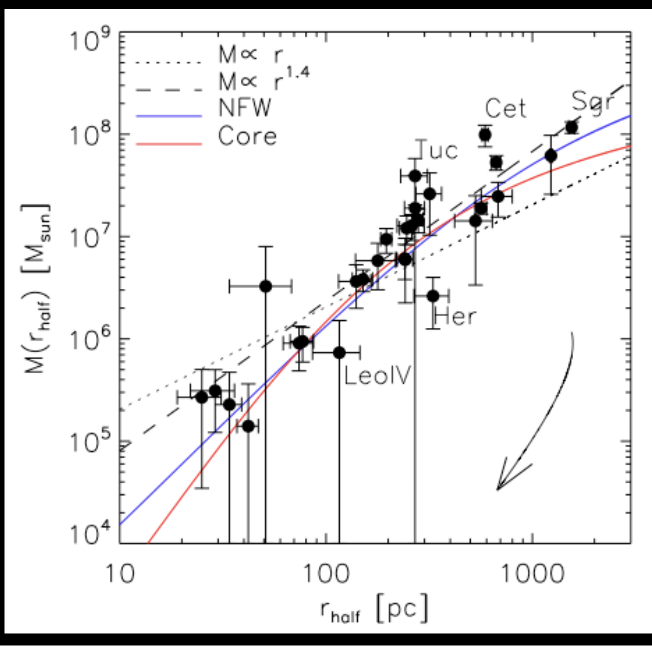


degeneracy very small at R~R_{half}

accurate M(R_{half})

dSphs in cosmology

we cannot test the universal density profile predicted by CDM using Jeans models… but we can measure M(R_{half})



walker et al. (2009)

dSphs in cosmology

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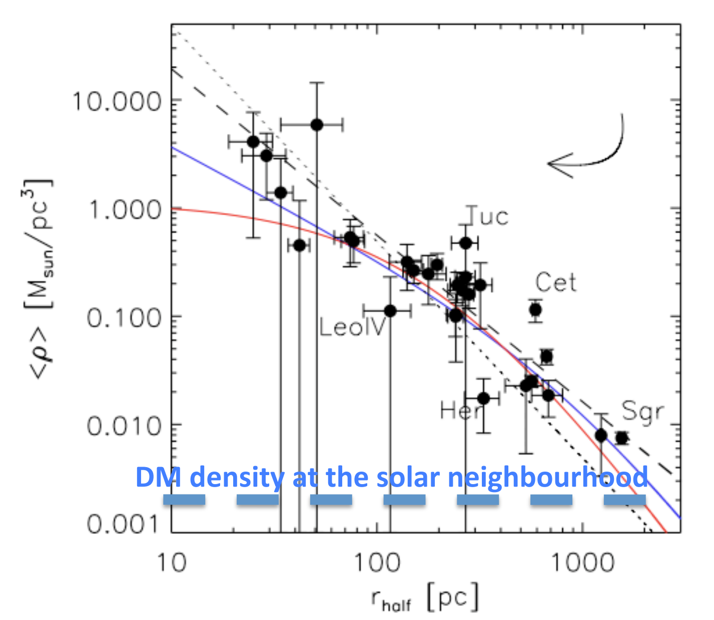


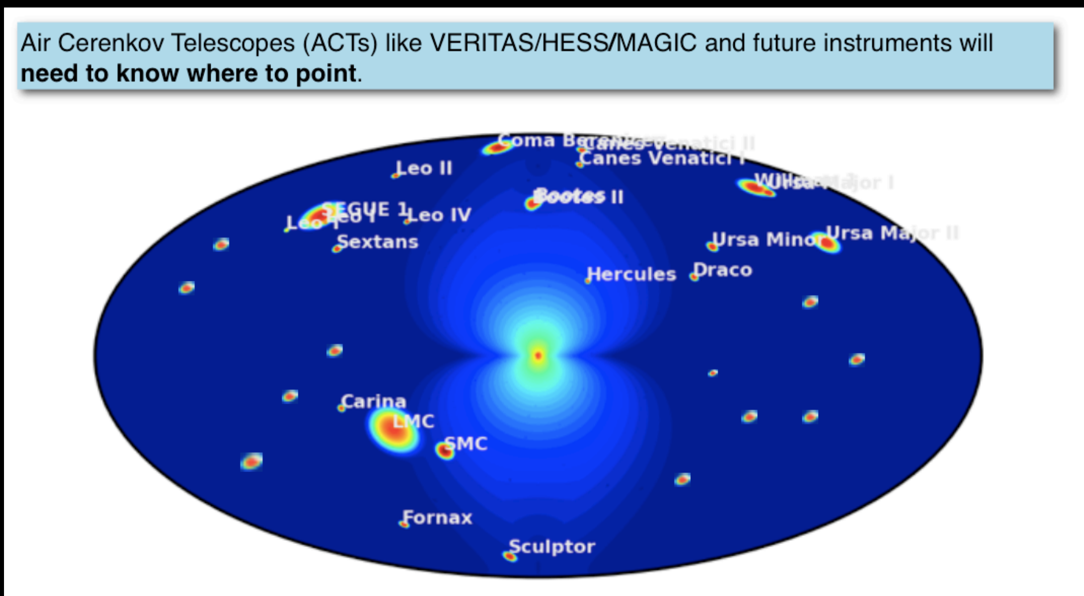
dSphs are the galaxies with the highest DM densities in the known Universe

walker et al. (2009)

dSphs in cosmology

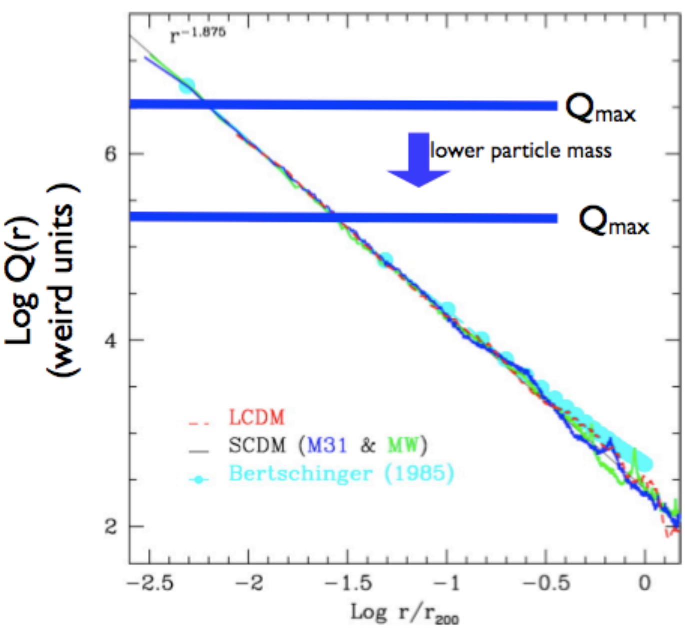
$$\mathrm{Flux}_\gamma \propto \int_V \rho(r)^2 \frac{dr}{D^2}$$

best targets for indirect DM detection instruments



dSphs in cosmology

Phase space profile of WDM halos: must break @ small r



Martinez, JSB, Kaplinghat, Strigari, Simon, in prep

Note: self-consistent Q(r) profiles that have a maximum cannot be a power-law at large r. The figure to the left is just descriptive.

dSphs in cosmology

Phase Space Densities:

$Q = \rho/\sigma^3$

CDM $Q_{CDM} \approx 7\times10^{14}\left(\frac{m_{cdm}}{100GeV}\right)^{3/2} M_{sun}\,pc^{-3}(km/s)^{-3}$

Neutrino WDM $Q \approx 5\times10^{-4}\left(\frac{m}{keV}\right)^{4} M_{sun}\,pc^{-3}(km/s)^{-3}$

Dark matter from decays (non-thermal) $Q \approx 10^{-6}\left(\frac{10^{-3}}{\Delta m/m_{DM}}\right)^{3}\left(\frac{z_{decay}}{1000}\right)^{3} M_{sun}\,pc^{-3}(km/s)^{-3}$

e.g. SuperWIMPS

Strigari, Kaplinghat, JSB 07

Ultra-faint dSphs show a Q_{max}

$Q_{max} = \langle\rho\rangle/\sigma_*^3 \sim 5\ M_{sol}\ pc^{-3} / (3\ km\ s^{-1})^3 \sim 0.5\ M_{sol}\ pc^{-3} / (km\ s^{-1})^3$

$m_{WDM} > 5.6$ ev

Galaxies

Lecture 16: Extra-galactic distance scale

- Cosmology
- The search for H_0

A Universe of galaxies

- Stars exist in galaxies but galaxies are distributed throughout the Universe.
  - Therefore, to understand questions such as the physical origins of galaxies, distances to galaxies and the ages of stars in galaxies one must consider the fundamental properties of the Universe in which they exist.
- Some recent **observational developments** have been:
  - the 3/4-century long uncertainty in H_o is now over: H_o = 72 +- 5 km s^{-1} Mpc^{-1}
  - the long search for a decent standard candle is also over: SNIa seem to work well
  - COBE & WMAP have now measured the CMB spectrum & anisotropy with high accuracy
  - 2dFGRS & SDSS have recently mapped cosmologically significant local structures
  - observations at z ~1-6 are almost routine, and probe a significant slice of cosmic history

Cosmology

- In close partnership, **theoretical developments** and their applications are increasingly robust:
- The cosmic **constituents** and their **relative proportions** have been ascertained
  - Ω_Λ = 0.73 +- 0.02 : dark energy dominates the current universe
  - Ω_{DM} = 0.26 0.02 : dark matter is very important, particularly in structure formation
  - Ω_b = 0.04 0.01 : baryons are a trace (though vital!) component
  - Ω_γ = 5.0 x 10^{-5} : CMB photons reveal an early hot phase
  - Ω_ν = 3.4 x 10^{-5} : CNB neutrinos are predicted, but have not yet been observed
- An "ordinary" FRW cosmological **world model** has emerged as being completely adequate
  - The FRW parameters have been measured -> **"The Concordance Model"**
  - This yields a reliable framework for charting cosmic history -- ie we now know t(z)
  - A number of puzzles are removed by invoking an early period of inflation.

Cosmology

- A detailed theory exists tracing the **average** conditions from very early times
  - a fairly full description of t < 1s exists, though it is not yet well tested
  - nucleosynthesis at t ~ 1-5 mins nicely recovers the observed light element abundances
  - (in fact, this measures conditions at t ~ 1s, when the neutron/proton ratio was fixed)
  - the theory accurately describes recombination at ~1/2Myr and the origin of the CMB
- A detailed theory now exists which describes the **growth of perturbations**
  - Starting from inflation, a natural **spectrum of fluctations** can be followed to z~1000
  - here it matches the CMB anisotropies in great detail
  - it can then be followed to z=0, where it accurately matches **local structure**

Cosmology

- After thousands of years of wild speculation, the true story of creation is finally emerging
  - we are living through (and participating in!) a historic period of intellectual growth
  - in the future, our time will be recalled much like that of Copernicus, Newton, or Darwin.
- let's regain some humility by recalling:
  - we have **no idea** what the dark matter or dark energy are actually made of (ie 96% !)
  - although inflation is a promising idea, it is **far from proven** and its cause is unknown
  - the origin of the baryon asymmetry is only guessed at
  - why particular cosmological values are favoured is unknown beyond anthropic arguments.
  - why there is **something** and not **nothing** is as unknown now as it was in Aristotle's day.
  - Of course, these (and many other) puzzles are not really bad news at all: they signify a rich subject in good health,

Cosmology

- Understandably, Cosmology has attracted enormous interest and effort
- The subject is now mature and sophisticated -- much is well beyond our/my range
- Our aim will be to **outline the overall framework relevant to this course**, while **ignoring details**
- Following homogeneous Cosmology, we are ready to start discussing **inhomogeneities**
- These provide the starting point for our next topics: **structure and galaxy formation**.

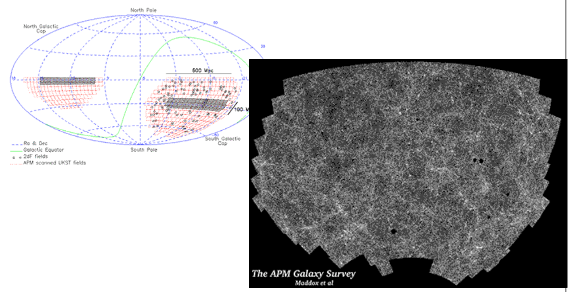
Cosmology: Global Properties

1) Large Scale Isotropy

- To humans, the universe seems **highly anisotropic**
  - down is solid, up is the sky, with the sun, moon, & stars in specific directions
  - even statistically, stars prefer the MW while bright galaxies cluster in Virgo and Coma
- Only at **much fainter levels** and **much greater distances** does isotropy begin to emerge
  - 2 million faint (m_J < 17) galaxies cover ~1 sr with only slight structure visible
  - 31,000 radio sources (typical z ~ 1) uniformly cover the northern hemisphere
  - the CMB with the galaxy & dipole removed is isotropic to one part in 10^5
- At faint levels (i.e. large scales) the Universe seems **remarkably isotropic**

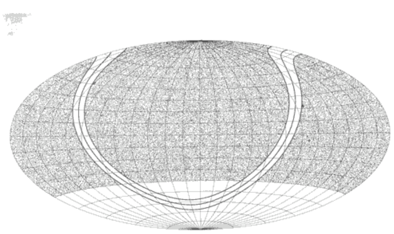
Cosmology

- The APM survey of 2 million galaxies (m_J < 17)



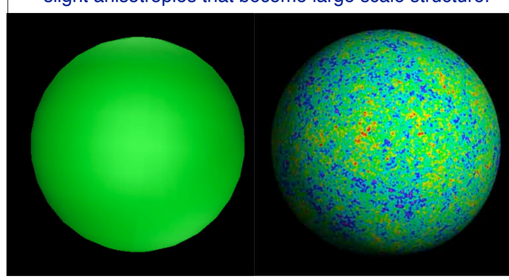
Cosmology

- Distribution of 31,000 radio sources in the northern hemisphere (from Jim Condon)



Cosmology

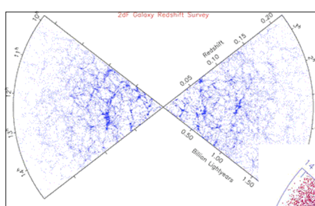
- Representation of CMB -- after removal of dipole and MW emission
- WMAP image of the CMB, contrast stretched to show the slight anisotropies that become large scale structure.

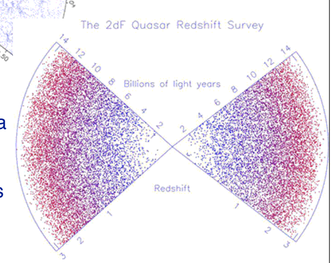


Cosmology

2) Large Scale Homogeneity

- **The Universe looks, statistically, the same from all locations**
- Can show that: isotropy + cosmological principle = **homogeneity**
  - all locations are (statistically) equivalent (eg, have same mean density)
- This is sometimes extended to postulate that the laws of physics are also global
  - The observations of familiar spectral features in distant galaxies certainly supports this
- Homogeneity only sets in on **large enough scales**, somewhere between 100 Mpc & 1 Gpc
- On smaller scales, of course, one encounters much **inhomogeneity** (next)
- This leads to a heart warming conclusion: Right "now", a civilization 1000 Gpc away (ie, **well beyond our horizon**)
  - sees microwave background; high-z QSOs; and distant young galaxies
  - is surrounded by sheets & voids of mature galaxies
  - finds local galaxies with their stars and planets to be much like ours.
- Far from being bizarrely remote; the distant Universe would be remarkably familiar.





- 2dF Quasar survey. Although there is clearly a change with epoch (redshift) at any given redshift, the distribution is homogeneous

Cosmology

3) Small Scale Structure

- The Universe's small scale **inhomogeneity** is much more obvious than its global **homogeneity**.
  - At first sight this is a rather puzzling fact: why isn't the Universe just fully one or the other?
  - And why is there a special length scale that marks the boundary between the two?
- The inhomogeneity appears as a **heirarchy of structures**: stars; galaxies; clusters; tapestry
  - Out of almost perfectly uniform gas comes all these rich forms, each with its own character -- a remarkable and profound property of our Universe.
- Our cosmology must explain this **origin and development of structure**.

Expansion: the Hubble Law

- As soon as galaxy spectra were measured it became clear that most were **redshifted**
  - In 1929 Hubble found a "roughly linear" relation between redshift and distance: cz~d as data improved, this relation was confirmed and has strengthened ever since
- Don't confuse ***establishing*** the linear relation with ***measuring*** its gradient: It took ~75 years to achieve 10% uncertainty in the gradient, H_o (slides below)
  - This is primarily because calibrating the distance scale is notoriously difficult. The current best estimate for H_o is 72+- 5 km/s/Mpc (72 x 10^{-6} Myr^{-1} in psm units)
  - Note, it is still customary to quote measurements scaled to h = 100 km/s/Mpc:
  - E.g., "The luminosity of M87 is 2.3 x 10^{11} h^{-2} Lsun"

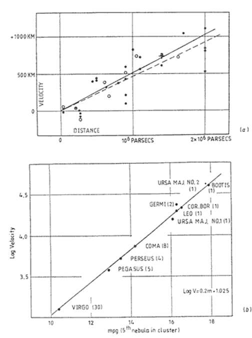


Fig. 1.2. (a) Hubble's first velocity–distance relation for nearby galaxies (Hubble 1929). The filled circles and the full line represent a solution for the solar motion using the nebulae individually; the open circles and the dashed line is a solution combining the nebulae into groups. (b) The velocity–apparent magnitude relation for the fifth brightest members of clusters of galaxies, corrected for galactic obscuration (Hubble and Humanson 1934). Each cluster velocity is the mean of the radial velocities of galaxies in the cluster, the number of galaxies being indicated by the figure in brackets. (See Sect. 2.3 for a discussion of the use of apparent magnitudes to measure distances in this relation.)

Expansion: Hubble Law

- Note also that there is always some small scatter (~few 100 km/s) in the Hubble relation
- galaxy redshifts have **two** components:

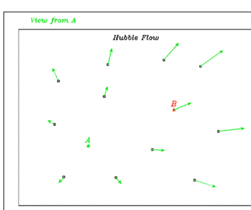
1. the global "Hubble Flow" (arising from cosmic expansion)
2. a small "peculiar" velocity (arising as the galaxy responds to the gravity of its neighbors).
   - ["peculiar" comes from Latin: "peculium", meaning "private property" - specific to it alone]

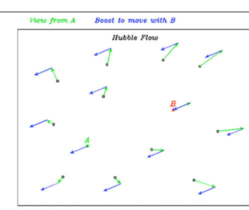
Expansion: everyone sees the same law

- At first glance the Hubble Law seems to violate the Cosmological Principle:
  - galaxies appear to move radially away from **us** suggesting we are somehow central
  - However, its linear form ensures that **all** locations witness the same relation:
- Consider two (vector) locations **k** and **p** and the vector field: **v** = H **r** centered on us (at O)
  - We see p move at $\mathbf{v}_p$ = H **p**; so how does an observer located on **k** see p move? use primes to denote values measured by k:

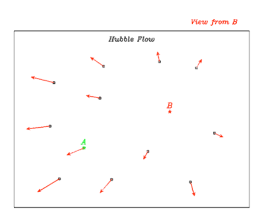
$$\mathbf{p'} = \mathbf{p} - \mathbf{k} \quad \text{and} \quad \mathbf{v'}_p = \mathbf{v}_p - \mathbf{v}_k = H\mathbf{p} - H\mathbf{k} = H(\mathbf{p} - \mathbf{k}) = H\mathbf{p'}$$

Hence, for any point **p**, k sees a Hubble Law: $\mathbf{v'}_p$ = H **p'** ;if we see v = Hr then so does everyone else; cosmological principle still holds true
  - Since everyone witnesses the same Hubble Law, we conclude that: -> the **Universe itself** is undergoing **isotropic expansion** with form **v** = H **r** …. a remarkable and profound result.





- Hubble velocities as seen in A's frame
- Boost (blue vector) to B's frame
- Resultant (red) velocities seen by B: B sees the same Hubble law as A



The Scale Factor a(t) & Comoving Coordinates

consider the (possibly curved) grid and its expansion separately

- First notice that the **Hubble law preserves shapes**: patterns of galaxies becomes bigger patterns
  - for a set of *i* points, cosmic expansion gives: $\mathbf{r}_i(t) = a(t)\, \mathbf{r}_i(t_o)$, for a fiducial time t_o
- Here, a(t) is a universal scalar function of time, and is called **the scale factor**
  - a(t) simply tracks how the separation of galaxies changes over time
  - **Finding the form for a(t) is a holy grail in cosmology.**
- Sensibly, we assign the **current** time special status:
  t_o = now; $a(t_o) = 1$ and $\mathbf{r}(t_o) = \mathbf{r_o}$ … Hence:
  - the current values, $\mathbf{r_o}$, provide the coordinate grid, and are called **comoving coordinates** as the grid expands, the comoving coordinates **do not change**
  - at any time, the **physical coordinate** of an object is: $\mathbf{r} = a(t)\, \mathbf{r_o}$
  - by setting $a(t_o) = 1$, we ensure that in the past, a < 1 while in the future a > 1.

Expansion

- For example, at the time of recombination, a~ 0.001
  The **comoving distance** to proto-M87 is still 15 Mpc, but its **physical distance** is only 15 kpc.
- Notice that **r** and $\mathbf{r_o}$ are both **proper distances**: they tell us how many **non-expanding** rulers fit end-to-end from here to the galaxy.
- You have also seen several **pseudo-distances**: eg luminosity & angular diameter distance; D_L, D_A.
  - these are not true (proper) distances, but convenient **functions** of distance.
- **Warning**: symbol conventions for physical/comoving/pseudo distances varies greatly
  - For consistency: r = physical; r_o = comoving; D = pseudo.

The Hubble Parameter: H(t)

- With expanding coordinate grid, how does H fit in?
  - take time derivatives of $\mathbf{r}(t) = a(t) \times \mathbf{r}(t_o)$:

  $d\mathbf{r}/dt = \mathbf{v}(t) = da/dt \times \mathbf{r}(t_o) = (1/a)\, da/dt\, \mathbf{r}(t)$
- But this is simply:
  $\mathbf{v}(t) = H(t)\, \mathbf{r}(t)$ with $H(t) = (1/a)\, da/dt$
- we have found that the Hubble relation applies **at all times**
- $H(a) = H(t) = 1/a\, da/dt$ *and* $dr/dt = v = H r$
- In general, H(t) and a(t) both vary with time
- For the current epoch, we write $H(t_o) = H_o$ and it has units of inverse time

The Velocity-Distance Relation & The Hubble Law

- there are **two** apparently similar relations.
  - the **theoretical "proper" velocity-distance** relation: v = H r
  - the **observational redshift-distance** "Hubble Law": cz = H D
- These are, in fact, somewhat different.
- The theoretical relation v = H r is **globally exact**, though it is observationally inaccessible:
  - both v and r are "proper" quantities, ie as measured in a local rest frame.
  - For example for r: how many **non-expanding** rulers must be laid down between us and the galaxy?
    - after 1 second, v additional rulers must be laid down, where v = H r.
  - notice that the values are all measured **at the same cosmic time**:
  - we deal with distant galaxies **as they <u>are</u>**, right now, not **as we see them**.

Expansion

- The Hubble Law is strictly observational:
  - $1 + z = \lambda_{obs}/\lambda_{em} = a(t_o) / a(t_e) = 1 / a(t_e)$
    and cz rather than v(z) is sometimes taken as a "Doppler velocity"
  - D is usually a luminosity distance, which matches the **proper distance** only at low z.
  - both z and D apply to the **time when the light set out**, not the **current time** during the light's journey, the galaxy moved further away and, possibly, slowed down
- At high z, several factors **break linearity** (e.g. redshift distortions), indeed this deviation is used to measure q_o.
- At low redshift the Hubble Law and the velocity-distance relation **look the same**
- Cosmic expansion is best described by v = Hr; it is exact and holds everywhere at all times
- the Hubble Law, cz = H D, only provides imperfect observational access to this cosmic expansion.

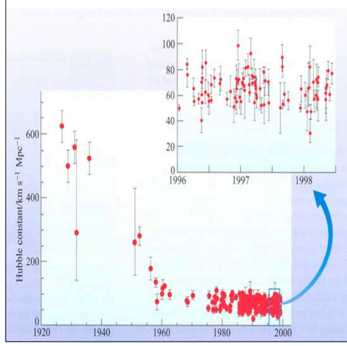
The Hubble Sphere

- push the velocity-distance law to great distances:
  For H_o = 100 km/s/Mpc, we have :
  - at r = 10 Mpc, v = 10^3 km/s
  - at r = 10 Gpc, v = 10^6 km/s
  - at r = 1000 Gpc, v = 10^8 km/s
- velocities are **faster than light**: special relativity **does not apply** to this motion: it arises from **expansion <u>of</u> space**, not **motion <u>through</u> space**.
  - Can we see the galaxies which recede faster than light?
  - The light they emit moves **through space** at speed c towards us but over time the wavefronts get **further from us**, at speed v - c > 0
    … we will never see them!
- There is a critical distance $r_{H,o} = c/H_o = 3.0\, h^{-1}$ Gpc which is now receding at $v = H_o\, r_{H,o} = c$
- $r_{H,o} = c/H_o$ is called the **Hubble distance**; where, right now, galaxies recede at *c*
- For constant rate of expansion, we will ultimately see everything inside a sphere of radius $r_{H,o}$

Extragalactic Distance Scale

- Accurate distances fundamental for characterising structural and evolutionary properties of galaxies
  - many scaling laws and other correlations are so tight that scatter is limited by precision of distances
- Progress in subject has been driven by cosmology (calibration of Hubble constant, cosmological standard candles)
- Application of velocity-distance relation provides accurate (<few percent) distances for d > 100 Mpc,
  - but for nearer galaxies, departures from Hubble flow (up to >100%!) require determination of individual distances
- Rather than consider the full history, we shall summarize the current (1995 - 2010) situation.

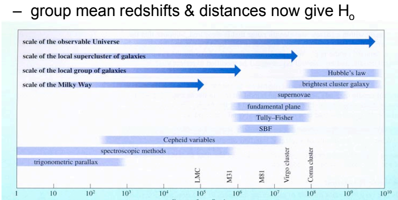
H0



- estimates of the current Hubble parameter, H_o have changed dramatically since Hubble's original estimate near 550 km/s/Mpc.
- The greatest change came in 1952 when Walter Baade recognised the difference between Pop-I and Pop-II Cepheid variables, and the distance scale changed by a factor of two "overnight".
- tendency in the 1980s for there to be two consistently different values -- the "low" value near 50 (Sandage et al), and the high value near 100 (de Vaucouleurs et al).

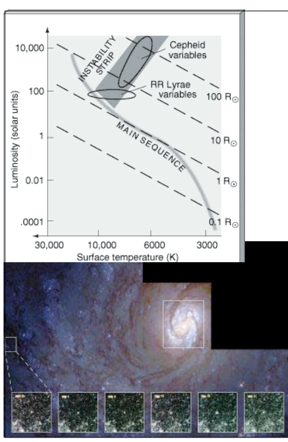
Hubble Law: 3 measurement rungs

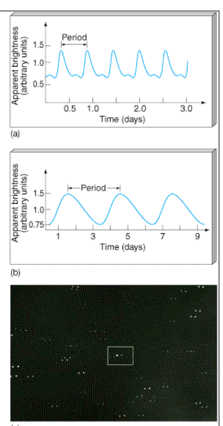
- Use the Hipparcos satellite to get trigonometric parallaxes of nearby Cepheids
  - calibrate Period-Luminosity (PL) relation
- Use HST to get Cepheid distances to nearby (<25 Mpc) galaxies
  - calibrate Tully-Fisher (TF) & Fundamental-Plane (FP) (& other) methods
- Use TF, FP (& other) distances to groups where peculiar velocities are unimportant.
  - group mean redshifts & distances now give H_o



Cepheid Variables

- class of pulsating stars defines a tight period-luminosity(-color) relation
- measure **period** to get luminosity and hence **distance**
- they are **luminous** stars (M: -8 to -12) and hence can be seen to considerable distances (~25 Mpc by HST) (however, also rare)
- Historically, the PL relation was calibrated by Main Sequence fitting to open clusters containing Cepheids
- Hipparcos provides direct **trigonometric calibration** (eg Perryman et al 1997) however, this calibration still needs to be improved (eg using future astrometric missions SIM, GAIA).
- The distance to the LMC plays a **very important role** (and also still needs to be improved)
  - it contains enough Cepheids to define the PL relation in m (not M)
  - hence extragalactic Cepheids yield **relative distances** to the LMC
  - the current best estimate for the LMC is: m-M = 18.50+-0.13 **=** 50+-3.2 kpc (uses E(B-V) = 0.1)
- the HST Key Project has now measured Cepheids in galaxies out to ~25 Mpc. These galaxies were then used to calibrate the following methods:



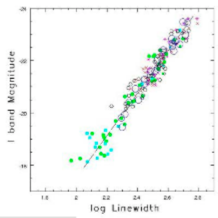


Secondary indicators of H0

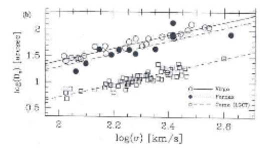
- **TF: Tully-Fisher Relation** This is a luminosity-linewidth relation for **spirals**
  - scatter is minimum in the near IR (I, H), hence the method is often referred to as "IR-TF"
  - about 20 spirals now have Cepheid distances
  - about 25 groups/clusters out to 10,000 km/s have TF distances H_o = 71+-8 (eg Sakai et al 1999,2000)
- **FP: Fundamental Plane Relation** This is a refinement of the luminosity-linewidth (Faber-Jackson) relation for **ellipticals**
  - Either D_n- σ (isophotal diameter/dispersion) or surface brightness/radius/dispersion relations
  - since no Cepheids in Es, calibration uses Es in **groups** with Cepheid distances (eg Virgo, Fornax, Leo)
  - many groups/clusters out to 10,000 km/s now have FP distances H_o = 78+-10 (eg Mould et al 1996; Kelson et al 1999)

Secondary Distance Indicators

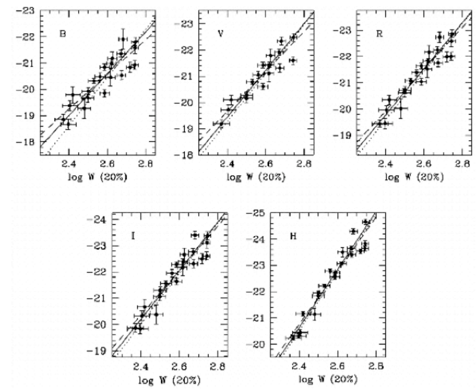
- Calibrate multiple methods to reduce risk of systematic errors



Tully-Fisher relation



D_n-σ relation – fundamental plane

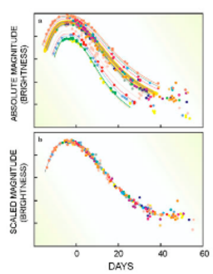


Sakai et al. 2000, ApJ, 529, 698

TF in HST Key Project

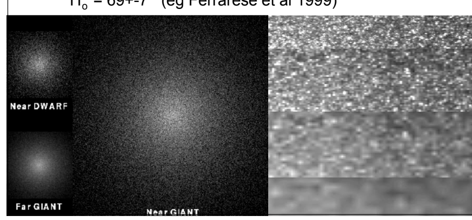
Hubble law

- **SNIa: WD binary thermonuclear detonation**
- These are very luminous, so well suited to q_o studies (high z), but also useful for H_o (lower z)
- the light curves **aren't** all the same; but peak luminosity correlates with fading rate (and color)
- unfortunately, very few SNIa have ocurred in galaxies with Cepheid distances calibration **not** ideal
  H_o = 68+- 6 (eg Gibson et al 1999)



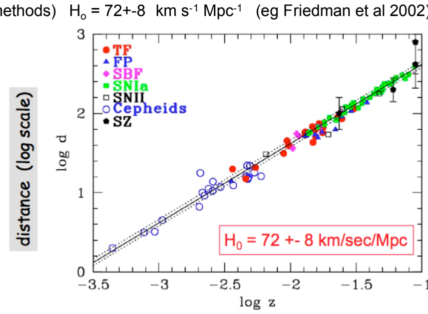
SBF: Surface Brightness Fluctuations

- Consider a set of CCD pixels recording the light from an E galaxy, each one with **perfect** S/N ratio
  - there is still **variation** between the pixels because of sqrt(N) fluctuations in # stars
  - Although the **mean** surface brightness is independent of distance, the **variation** is not
  - nearer galaxies have **fewer** stars per pix -> **larger** variation.
- difficulties: contamination by GCs; color/population dependency; calibration.
- HST can use this method out to about 7000 km/s
  H_o = 69+-7 (eg Ferrarese et al 1999)



HST Key Project

- combines all these methods (plus GC & PN luminosity function methods) H_o = 72+-8 km s^{-1} Mpc^{-1} (eg Friedman et al 2002)



Direct methods: **Expanding Photosphere Method**

- In blackbody approximation, Stefan-Boltzmann law states: $L_{bol} = 4\pi R^2 \sigma T^4$ $f_{bol} = 4\pi\alpha^2\sigma T^4$ where angular size α= R/d
  - but measuring the spectral linewidths with time gives $V_{exp}(t)$, which can be integrated to measure R(t).
  - This provides a direct physical determination of the distance d.
- This Baade-Wesselink method was originally developed to calibrate the luminosities of RR Lyrae and Cepheid variable stars
  - EPM distances now available for SN II out to 14,000 km/s (check) H_o = 73+-11 (eg Schmidt et al 1994)
  - Real applications to supernovae complicated by non-blackbody shape of spectrum, bolometric corrections, and difference between line-emitting/absorbing surface and photosphere. But these can be modelled.

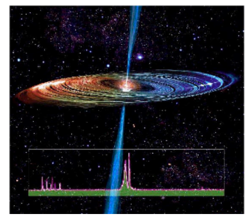
Direct estimates

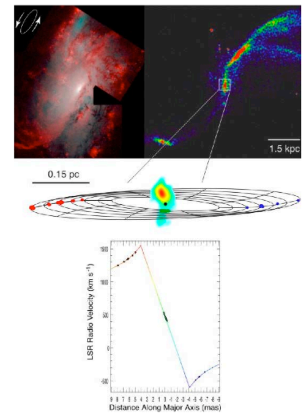
- **VLBI Masers in Nuclear Gas Disks**
- So far, only one good example of this method exists: NGC 4258, Miyoshi et al 1995
- a compact (~1pc) molecular disk orbits central black hole VLBI of H_2O masers gives (Keplerian) velocities and proper motions distance, by comparing linear and angular velocities
- this method has good potential for future (more distant) objects
- (e.g., at z > 0.5 it would give H_o and q_o).

H_2O Masers in NGC 4258

- combination of maser radial velocities and proper motions from VLBI gives trigonometric distance

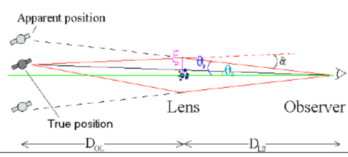
- Keplerian falloff in velocity with distance provides precise BH mass





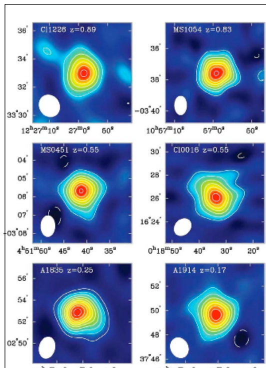
Gravitational Lensing Time Delays

- recall scattering calculation for 2-body interactions: $\delta v = 2GM/bv$ so scattering angle $\alpha = \delta v/v = 2GM/bv^2$
- GR shows for light $\alpha = \delta v/c = 4GM/bc^2$ … twice classical result!
- 2 QSO images have different light paths with different physical lengths this path difference is given by the time delay between QSOs light curved (via cross-correlation).
- the calculated path difference depends on projected mass density and **linear scale** distance by comparing observed angular scale and calculated linear scale
- About 10 now done H_o ~60 - 65 (puzzlingly low).



SZ: Sunyaev-Zeldovich Effect in Clusters

- Hot electrons in galaxy cluster ICMs do two things:
- they generate X-rays via bremsstrahlumg:
- $L_x \sim n_e^2 r_c^3 T_x^{1/2}$
- they Compton scatter CMB photons:
- $(dT/T)_{CMB} \sim n_e r_c T_x$
- you can solve for r_c and compare with θ_c to get a distance H_o = 60 - 65 (eg Birkinshaw 1998) also puzzlingly low.

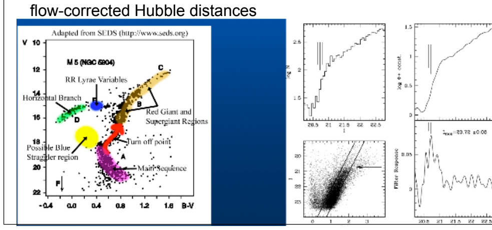


- magnitude of the SZ decrement is a function of the IGM density, temperature, and radius of the cluster
- measurements of the thermal X-ray emission of cluster constrain density, temperature, and angular radius
- combination provides a physical measurement of cluster distance, subject to assumptions about 3D geometry and density structure

Carlstrom et al. 2002, ARAA 40, 643

Distances to Local Galaxies

- Hubble expansion distance is useless for d < 10 Mpc, and subject to large local flow corrections out to >100 Mpc
- secondary candles used in H0 calibration can be used to infer direct distances (SBF, Tully-Fisher relation, Dn-σ relation, PNLF, SNIa, EPM)
- for local galaxies, several stellar standard candles are available (e.g., Cepheids, RR Lyraes, red giant branch tip)
- above are used to calibrate local deviations from Hubble flow, and provide flow-corrected Hubble distances



Possible Concerns

- Why do the more distant (lensing & SZ) methods seem to give systematically low values for H_o?
  - Perhaps we live in a void with higher local H_o than the global value? The answer is "probably not", for several reasons:
  - the most distant TF work is now out to 15,000 km/s (200 Mpc) which is hardly local
  - the Hubble relation is **linear** from 100 to 1000 Mpc
  - from CMB anisotropies, the incidence of voids of size 10^4 km/s is quite rare
- The local value is probably within a few percent of the global value …
- Why the more distant estimates seem to yield low values is not yet understood.
- Spergel et al (2003) used this HST Key Project value for their WMAP concordance model. Many people now adopt this as the (currently) favoured value.

Galaxies

Lecture 17: galaxy interactions continued

- Tidal evaporation (tidal tails)
- Impulse approximation

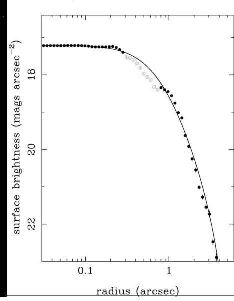
Tidally Driven Evaporation: Truncation and Disruption

- The outer luminosity profiles of globular clusters are **often sharply truncated**
  - Naively, this is puzzling since stellar systems don't naturally have "edges"
- The reason: outer stars become more bound to the galaxy than to the GC potential
- This is an example of **Tidal Stripping** or **Tidal Truncation**

  (Similar effects are seen in some cluster galaxies)

Tidal Radius

- Number counts (with King profile fit), showing a steep cutoff beyond the tidal radius



(i) Tidal (Jacobi/Roche) Limit

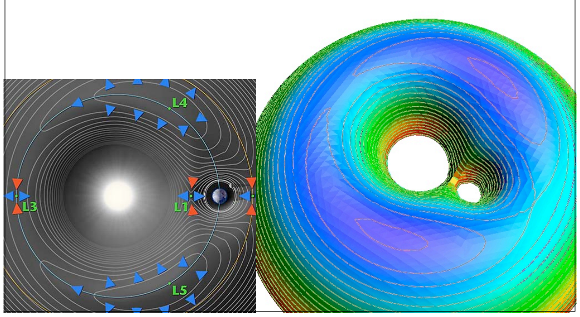
- How far must a star "wander" from its satellite before it is lost to the galaxy ?
  - If you answer: "where the r^{-2} force of the satellite and galaxy are balanced" you would be **wrong**
  - You forgot to include the fact that the satellite is **also orbiting the galaxy**
  - The satellite and galaxy are "fixed" only in a **rotating frame**, in which **pseudo-forces** are also important.
- In this rotating frame, the star's energy $E = 1/2\mathbf{V}^2 + \Phi(\mathbf{r})$ **is not conserved** (recall, space probes can use planets to gain energy in a "gravitational slingshot")
- Instead, the **Jacobi Integral** $E_J = 1/2\mathbf{V}^2 + \Phi_{eff}(\mathbf{r})$ **<u>is</u> conserved**; where we have again introduced the **effective potential** in a rotating frame:

  $$\Phi_{eff}(\mathbf{r}) = \Phi(\mathbf{r}) - 1/2\,|\,\Omega \times \mathbf{r}\,|^2$$

  where Ω refers to the satellite's orbit and **r** has origin at the Centre of Gravity (~ galaxy centre)

(i) Tidal (Jacobi/Roche) Limit

- contour plot of $\Phi_{eff}(\mathbf{r})$ for two point masses:



(i) Tidal (Jacobi/Roche) Limit

- Note the 5 **Lagrange points**: maxima in Φ_{eff} where stars are **stationary** (in the rotating frame)
  - L1 is the deepest; L1, L2, L3 are **unstable**; L4, L5 are **stable** (although L4, L5 are maxima, coriolis force keeps objects in a slow "epicyclic orbit" around them)
- Consider the simplest case: two point masses: a small satellite in circular orbit about a massive galaxy (ie m<<M)
  - evaluate Φ_{eff} along a line connecting m and M (separation R), with origin at m:

  $$\Phi_{eff}(x) = -GM/|R-x| - Gm/|x| - 1/2\,\Omega^2(x-R)^2$$

- Now find the turning points :
  - substitute for $\Omega^2 = GM/R^3$; differentiate w.r.t. x; set to zero and solve for $x = r_J$:
- $r_J = R(m/3M)^{1/3}$ is the **Jacobi Limit** (also called the tidal or Roche radius, or Hill radius)

(i) Tidal (Jacobi/Roche) Limit

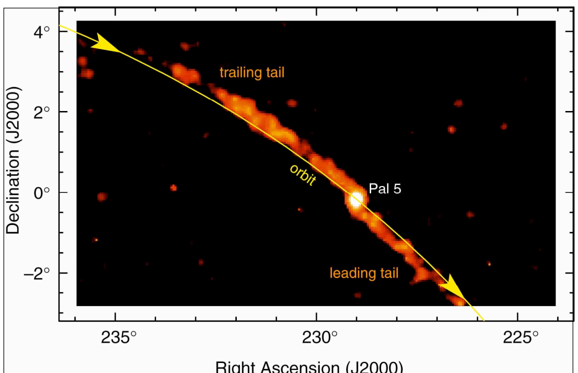
- If we re-calculate for the case of a galaxy with isothermal (flat V_{rot}) galaxy halo, we get:
  $r_J = R(m / 2M)^{1/3}$
- In general, a useful approximation is that r_J marks the point at which:
  - the orbital period of the satellite about the galaxy is similar to
  - the orbital period of a star about the satellite (in the absence of the galaxy).
- In practice, measured ***tidal radii*** agree **only roughly** with our simple expression for r_J.
  - The derivation should be considered as indicative rather than predictive.

(ii) Satellite Evaporation and Possible Destruction

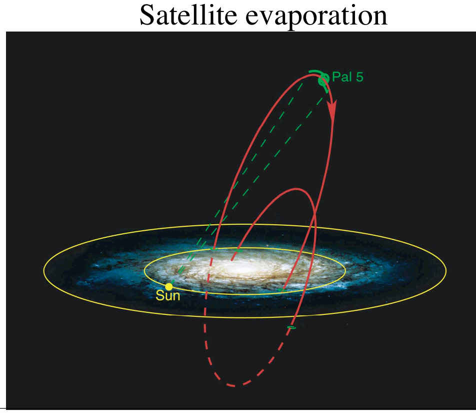
- The value of Φ_{eff} at r_J divides stars into those which can escape from those which cannot
  - Consider a satellite star with E_J moving away from the satellite: V is decreasing as the star approaches the contour $\Phi_{eff} = E_J$, V approaches zero and the star turns around
  - Clearly, if $E_J > \Phi_{eff}(r_J)$ then the star **crosses the critical contour**
  - **If** this happens to be near L1 (or L2), the star proceeds "down hill" **and is lost from the satellite**
  - Thus, over time we expect to lose all stars with $E_J > \Phi_{eff}(r_J)$
- The satellite **evaporates**, in the sense that it is losing stars with the highest energy
  - Unlike the slow evaporation of an isolated cluster, when stars scatter into orbits with $V > V_{esc}$ … tidal evaporation is **independent of scattering within the cluster**:
  - even **bound stars** (ie E < 0 for an isolated satellite) can have $E_J > \Phi_{eff}(r_J)$ and can be lost

(ii) Satellite Evaporation and Possible Destruction

- For a satellite which is **approaching** a galaxy, r_J and $\Phi_{eff}(r_J)$ continually decrease:
  - the cluster may lose an ever increasing number of stars.
- Recall from elliptical galaxy lectures that **most** stars are marginally bound (ie N(E) peaks near E~0):
  - a small decrease in $\Phi_{eff}(r_J)$ can result in the loss of many stars.
- Nice examples of tidal evaporation
  - MW globular cluster Palomar 5: (next slides)
  - simulation of the tidal destruction of a dwarf satellite by Kathryn Johnston (Columbia University)



Satellite evaporation



Galaxy Interactions

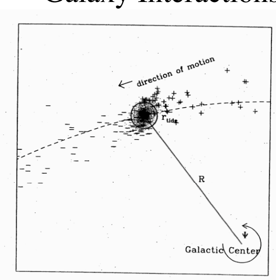


Fig. 3.— Snapshot of particle positions in the orbital plane of a simulation of a tidal encounter. The dots label particles still bound to the satellite, and the "-" and "+" signs label those unbound on orbits with lower and higher energy than the satellite orbit respectively. The dashed line shows the satellite's path. The bold circle shows the physical scale calculated from equation (3). JOHNSTON (1998)

Galaxies stable against tidal stripping?

- Consider the tidal stability of two satellites of the MW: the LMC and the Sagittarius dwarf
- $r_J = R(m / 2M)^{1/3}$
- LMC: Taking $m_{LMC} = 10^{10}$ M⊙, R = 50 kpc, M_{MW} (< R) = 5 x 10^{11} M⊙

$r_{J,LMC}$ = 50 kpc x $[10^{10} /(2 \times 5 \times 10^{11})]^{1/3} \approx$ 11 kpc.

- The physical extent of the LMC is approximately 5 kpc and we conclude that it is stable against tidal stripping.

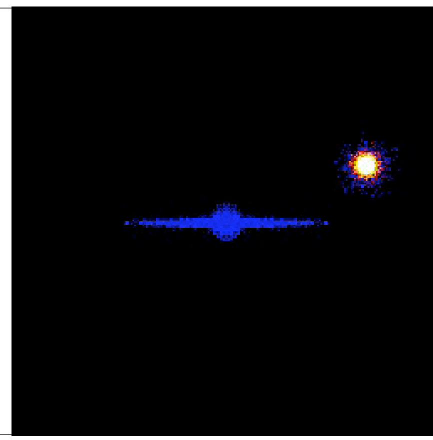
Galaxies stable against tidal stripping

- Sagittarius Dwarf Elliptical Galaxy.
- The mass of the Sag DEG is not well known.
  - Take L_{Sag} = 8 x 10^7 L⊙ and M/L >~ 10 (not unreasonable for dwarf galaxies).
  - Also take R = 20 kpc and M (< R) = 2 x 10^{11} M⊙. One then obtains

$r_{J,Sag}$ = 20 kpc x $[8\times10^8 /(2 \times 2 \times 10^{11})]^{1/3} \approx$ 2.5 kpc.

The long axis of the Sag DEG is 2.6 kpc in extent and we conclude that this system is being actively stripped in the tidal field of the MW.

Merging of Sag DEG



Merging timescales and tidal stripping

- Clearly the merging timescales and degree of tidal stripping will depend on the orbit of the satellite -- e.g., circular or plunging -- and distance from host.
- Although stellar streams can exist for a long time, the parent structures –– the dwarf galaxies themselves –– can merge with the primary galaxy over much shorter timescales.
- Recall that dynamical friction enables this process (lec13) -- resulting from the integrated effect of numerous weak stellar encounters between the satellite and primary.

Merging Timescale

- Recall, $F_{\rm drag} = -\frac{4\pi G^2 M^2 nm \ln\Lambda}{V^2} = -\frac{4\pi G^2 M^2 \rho \ln\Lambda}{V^2}$
- The merging timescale from dynamical friction may be defined as the time required to slow the satellite to zero velocity, i.e. t_{merge} ~ v / dv/dt
- One notes that $t_{merge} \propto 1/m_g$,
  - i.e. more massive systems consumed faster than less massive.
  - Dwarf galaxies are consumed faster than GCs.
- $t_{merge} \propto 1/\rho_*$, i.e. denser galaxies consume their satellites more rapidly.
- For a satellite galaxy with v = 200 kms^{-1} and M_g = 10^{10} M⊙ orbiting a galaxy at R = 10 kpc and M (< R) = 10^{11} M⊙ (remember ρ_* = 10^{11} M⊙/4/3π(10 kpc)^3): t_{merge} ~ 3 x 10^8 yrs.
  - could refine this calculation further but, for instance, taking M_g = 10^8 M⊙, i.e. more applicable to the Sagittarius DEG, one obtains t_{merge} ~ 10^{10} yrs.
- This indicates that it is reasonable to observe dwarf galaxies in close proximity to giants in the LG today
  - the merging time is of the order of the age of the Universe.

Adiabatic Approximation (Slow Encounter)

- During a tidal encounter, the orbits of many stars are significantly affected.
  - However, some orbits are **not** greatly affected: those for which $t_{orbit} << t_{encounter}$
  - As the tidal field slowly changes, the orbit responds slowly and **reversibly**
    - cf the response of the moon's orbit during the year as the Earth's distance to the sun changes
  - This type of response is called **adiabatic**
- If the encounter is a "flyby", the tidal field first grows, then decays
  - the rapid orbits slowly modify, but then **return to their original form**
  - Thus, stars on rapid orbits near galaxy centres are **not greatly affected** by tidal encounters (unless, of course, the encounter proceeds to become a merger)

Impulse Approximation (Fast Encounter: Tidal Shocks)

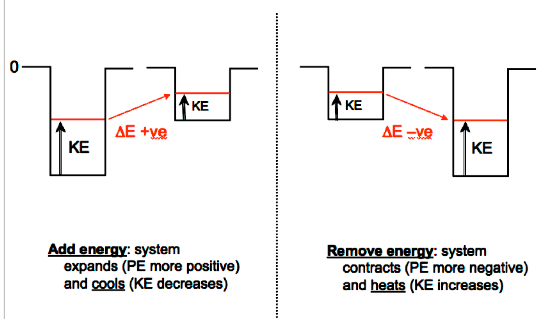
- The opposite extreme occurs when $t_{orbit} >> t_{encounter}$
  This occurs when $V_{internal} << \Delta V_{encounter}$
- In this case **stars don't move much during the encounter**
  - no change in PE : $\Delta PE \sim 0$
- However, they do feel **an impulse**, (ie, a force acting over a short time)
  - changes in both global and internal velocities: $\Delta \mathbf{V}_{CM}$ and $\Delta \mathbf{V}_{internal}$ (B&T p434-435)
  - so internal KE **does change**: KE ~ $1/2 \sum m \Delta V_{int}^2$ (note: always +ve)
  - … The effect of the tidal impulse is to **heat** the stars
- We say the system has experienced a **tidal shock**

Impulse Approximation (Fast Encounter: Tidal Shocks)

How does the system respond (relax) **after** experiencing the tidal shock ?

- Loosely speaking: the increased KE causes the system to **expand** and **cool** (self gravitating star systems have -ve specific heat: eg, Collapsing gas cloud radiates energy, collapses further, and **heats up**.)
- More formally: using subscripts o="original", i="initially after encounter", and f="finally after relaxation"
  - Virial theorem applies to the original and final relaxed systems: $E_o = -KE_o$ and $E_f = -KE_f$
  - immediately following the encounter we have: $KE_i = KE_o + \Delta KE$ and $E_i = E_o + \Delta KE = -KE_o + \Delta KE$
  - following relaxation, we have: $E_f = E_i$ -> $-KE_f = -KE_o + \Delta KE$ giving $KE_f = KE_o - \Delta KE$
- from original to final, the system has indeed **cooled**, by an amount ΔKE
- since the shock **heats** the original system by ΔKE, then **during relaxation** (i to f) the system cools by $-2\Delta KE$ (ie $KE_f = KE_i - 2\Delta KE$)
- of course, the system has also **expanded**, increasing the final PE by ΔKE

Negative Specific Heat



Impulse Approximation (Fast Encounter: Tidal Shocks)

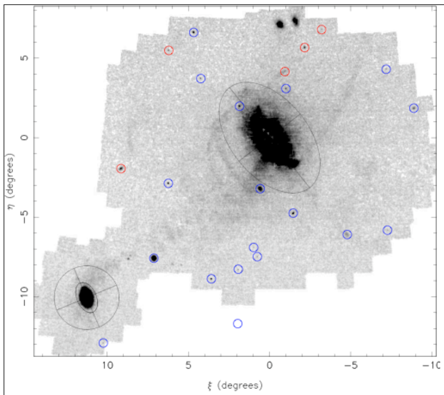
- Since the stars receive energy, some may become **unbound** (E > 0)
  - these are lost from the system: they **evaporate**
  - If there are **repeated** tidal shocks, a cluster may be disrupted and **disintegrate**

Finally, if the encounter is distant, the **"tidal approximation"** applies: (B&T p 437- … detailed theory, depending on properties of host/satellite)
  - tidal approximation applies when the impact parameter is much larger than a typical radii of the galaxies
- *eg*, velocity change ΔV_2 in the stars of dwarf galaxy after a fast interaction with a perturber of (point) mass M_1 scales with the dwarf galactocentric radius R at distance b with speed V
  - $\Delta V_2 \sim 2GM_1R / b^2V$; change in its energy is $\Delta E_2 \sim (G^2M^2r^2) / b^4V^2$ … all the energy absorbed is kinetic
  - it is left elongated, long axis pointing to the point of closest approach (cf lunar tides) … first order terms we've ignored above.

Impulse Approximation (Fast Encounter: Tidal Shocks)

Examples

- Open clusters are shocked by the passage of Dense Molecular Clouds (DMCs)
  - there are very few old open clusters
  - most have evaporated from repeated shocks on a timescale ~5×10^8 yr.
- Globular Clusters are shocked when they pass through the MW disk
  - can lead to evaporative disruption (depends on where in the disk)
  - Eg, for GC with σ = 5 km/s, r = 10pc, V_p = 170 km/s crossing at ~3.5 kpc,
  - disruption timescale is 6×10^9 yr



dSph galaxies viewed 'complete' for the first time in the Local Group in the M31 subgroup: (Irwin+)

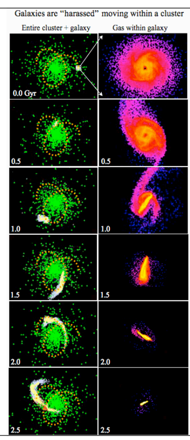
Tidal debris left as evidence of the accretion history

Impulse Approximation (Fast Encounter: Tidal Shocks)

- Tidal shocking of galaxies in galaxy clusters is termed: **galaxy harassment**
  - disks are **heated** they get thicker and Toomre's Q parameter increases (see lecture12)
  - spiral arm formation is therefore suppressed
  - appear to have **earlier** Hubble types (eg, Sb or Sa)
- Also, stars and dark matter expand and are lost to the galaxy but join the cluster
- Gas, however, loses AM and goes to the center to trigger a starburst (next slide shows process in action):

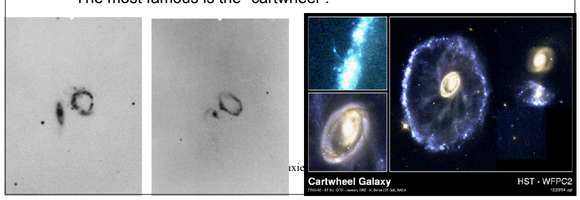
Impulse Approximation (Fast Encounter: Tidal Shocks)

- Left column shows the path of a single galaxy through the galaxy cluster.
- As it is subject to tidal shocks passing the other galaxies, the stars and dark matter are heated and some are lost to the tidal field of the entire cluster.
- The evaporated stars and dark matter form a long tail.
- Right column zooms in on the **gas** in the galaxy, which steadily evolves via shocks and cooling and gravitational torques, into a compact nuclear disk.
- This disk likely gives rise to a high star formation rate.



Impulse Approximation (Fast Encounter: Tidal Shocks)

- Ring galaxies are formed from tidal shocks
  - Perturber passes rapidly through & close to center of a disk galaxy ($V >> V_c$)
  - shock induces $\Delta V_r \sim \pi V_c (V_c / V)$ radially inwards for **all stars**
  - this sets up **synchronised** epicyclic motion
  - (recall, velocity perturbations to orbiting stars yield epicyclic motion)
  - the response is an **expanding circular density wave** -> a ring !
  - these density waves can, of course, trigger star formation …. The most famous is the "cartwheel":



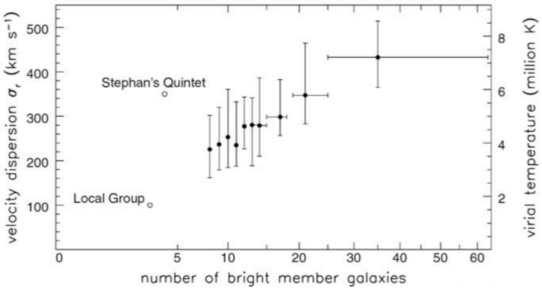
Dwarf galaxy chemistry and SF history

- Dwarf galaxies are low metallicity objects
  - down to 1/10th to 1/30th solar.
  - This is due to the binding energy of metals produced in SNe ejecta. (e.g., Dekel and Silk)
- All dwarf elliptical and spheroidal galaxies contain old stars.
  - However, many contain younger stellar populations associated with both short and extended periods of star formation.
- No dwarf ellipticals or spheroidals contain stars younger than 2-3 Gyr.
- There is no clear pattern to the star formation histories of such dwarf galaxies.
- They appear to be stochastic and potentially driven by interactions with the giant galaxies in the LG.

Dsphs and the Local Group in context

- The LG can be thought of as a low mass group of galaxies.
- Such structures may well dominate the mass density of galaxies in the Universe (Fukugita et al. 1998 -- counting both gas and galaxies).
- The LG is therefore a small part of a steadily increasing scale of structure in the Universe -- see upcoming lectures.
- This is confirmed observationally and within computational N -body simulations.
- N -body simulations are important because they predict the distribution of dark matter halos -- both parent and satellite -- within computational analogues of the LG.

The local group as part of the (local) large scale structure



Dsphs and the Local Group in context

- Since Klypin et al. 1999 (and Moore et al. 1999) it has been realized that such DM-only simulations over predict the abundance of DM halos as a function of mass (the halo mass function) compared to observations.
- The "Missing satellite" problem has been discussed from two perspectives:
  - firstly, the cold dark matter hypothesis underpinning the computer simulations may be flawed at some level.
    - Solutions include mixing warm and cold dark matter to simulations to modulate the halo distribution.
  - Alternatively, our census of the LG dwarf galaxy population may be incomplete.
    - This is plausible given both the low luminosity and the fragility to disruption of dwarf galaxies.

No. 1, 1999 WHERE ARE GALACTIC SATELLITES? 85

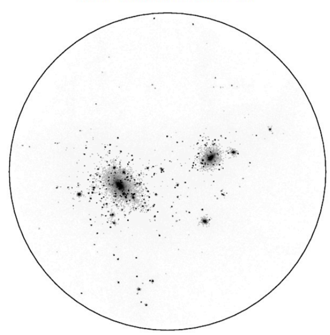
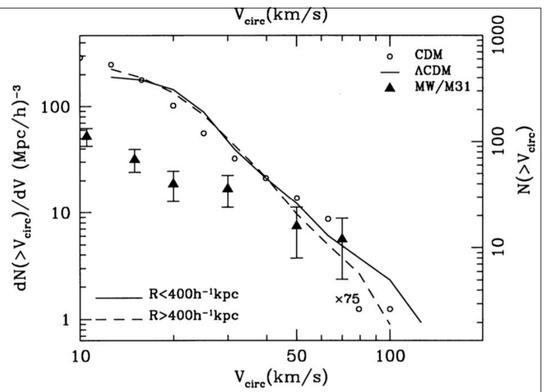


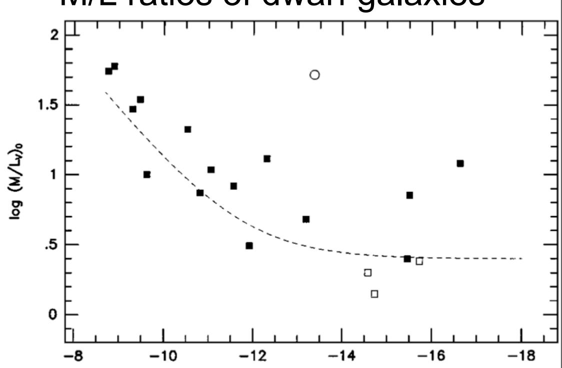
FIG. 2.—Distribution of DM particles inside a sphere of radius 1.5 h^{-1} Mpc (*solid circle*) for a small group of DM halos (similar in mass to the Local Group) in the ΛCDM simulation. The group consists of two massive halos with circular velocities of 280 and 205 km s^{-1} (masses of 1.7×10^{12} and 7.9×10^{11} h^{-1} $M_\odot$ inside a 100 h^{-1} kpc radius) and 281 halos with circular velocities greater than 10 km s^{-1} inside 1.5 h^{-1} Mpc. The distance between the halos is 1.05 h^{-1} Mpc. To enhance the contrast, we have color coded DM particles on a gray scale according to their local density: the intensity of each particle is scaled as the logarithm of the density, where the density was obtained using a top-hat filter with 2 h^{-1} kpc radius.



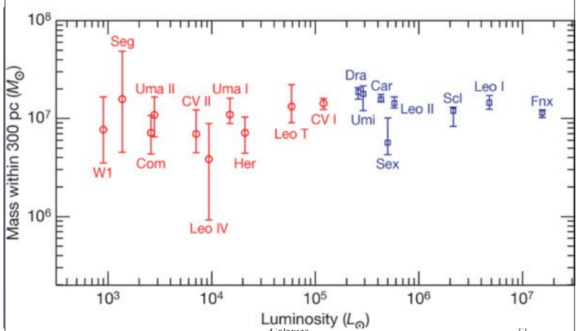
Dsphs and the Local Group in context

- Furthermore, consideration of the M/L ratio of dwarf galaxies as a function of luminosity indicates that dwarf galaxies may reside in approximately constant mass halos with steadily increasing M/L ratios as a function decreasing luminosity.
- This in turn may be related to the efficiency of star formation in very low mass galaxies.
  - One of the lowest luminosity dwarf galaxy candidate in the LG is Segue 1 (Belokurov et al 2009)
    - luminosity L_V = 340 L⊙ (approximately that of a single red giant star)
    - mass M = 4.3 x 10^5 M⊙. The implied M/L ratio is greater than 1000
- Observations of such systems are challenging in a number of ways:
  - the velocity of Segue 1 with respect to the Earth is 206 kms^{-1} and the velocity dispersion, measured from ~tens of stars, is ~ 3.5 kms^{-1}.
  - In addition, the debate continues as to whether such "galaxies" are bound or are in the process of disruption.
- However, overall these observations may point to a mass threshold, below which a galaxy will either no longer form stars, or it will form them but not retain them.
- Only when this question is understood will the missing satellite problem be considered answered.

M/L ratios of dwarf galaxies



All dsphs have the same mass? E.g, Strigari et al. 2007



Galaxies 37

Galaxies

Lecture 18: Galaxy formation

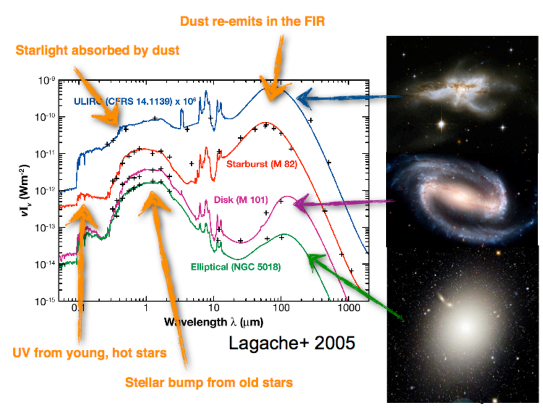
- Concepts of galaxy formation
- Initial look at what's there at high redshift
- The Semi-analytic approach to gal form

Concepts of galaxy formation

- Stellar evolution
- Chemical evolution
- Structure formation and evolution
  - Dark matter
  - Baryonic matter: hydrodynamic
- Evolution in clusters: different/accelerated
- Identifying early galaxies, galaxy formation
  - Evolution in luminosity, size, stellar content, AGN
- …

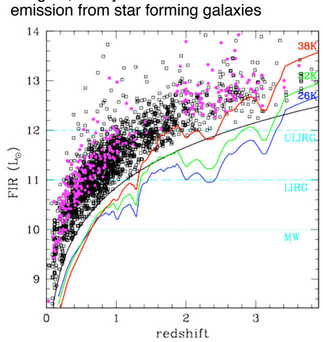
First, what galaxies do we find at high redshift?

- We're now quite familiar with local galaxies
  - Elliptical/spheroidal versus Disc galaxies
  - Huge range in luminosity function
    - Giant ellipticals down to dwarf spheroidals
- At high redshifts, we're increasingly pushed to more luminous galaxies
- Other difficulties (technical/atmospheric hurdles)



Example: Ultra-Deep VLA Radio Survey

- 5sigma, 10uJy limit -- uniform selection from simple synchrotron radio emission from star forming galaxies



MW to z=0.4
10xMW to z=1.5,
100xMW to z=3
1000xMW to "any" redshift

Bias in detailed understanding -- optically brighter counterparts with spectroscopic bias

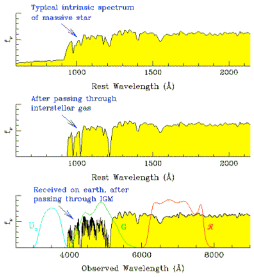
Note much more complicated selection effects at 24microns (compare previous slide)

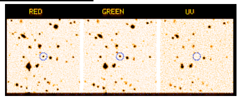
This is not true at submm wavelengths (the only such case)!!!

What do galaxies look like at high-z

- Cosmological distances
  - Because the
    - Universe is smaller in the rest frame
    - Photons have lost energy along the way
- "k-correction"
  - $k(z) = 2.5\log_{10}(1+z) - 2.5\log_{10}\{ (\int L_\lambda[\lambda/(1+z),t_0]d\lambda) / \int L_\lambda[\lambda,t_0]d\lambda \}$
    - Accounts for changes in wavelength of light due to z
- Redshift issues
  - Rest frame vs observed
  - Varying metallicity/extinction

High-z galaxies -- Photometric Pre-selection: UV

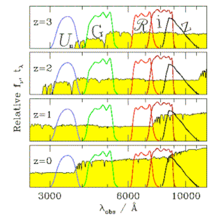


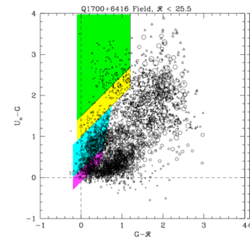


- ~50 objects/square arcmin down to R=25. How do you pick out the high-redshift galaxies?
- Lyman discontinuity at *rest-frame* 912 A gives z~3 galaxies very distinctive *observed* UGR colors

(Steidel et al. 1992, 1993, 1995, 1996, 2003)

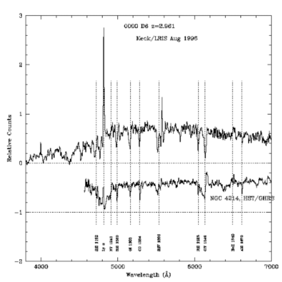
z>1.5 Rest-UV Color Selection





- z~3 UGR Lyman Break criteria, adjusted for z~2 (Adelberger et al. 2004)
- Spectroscopic follow-up with optimized UV-sensitive setup (Keck I/LRIS-B)
- ~1000 galaxies at z~3, >750 galaxies with spectroscopic redshifts at z=1.4-2.5, in what was previously called the Redshift Desert

Measuring Redshifts: z~3



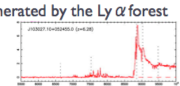
High redshift

- Lyα em/abs, interstellar abs at z>2.5
- At z =1.4-2.5, these features are in the near UV, while strong rest-frame optical emission lines have shifted into the near-IR
- Increasing observational challenges

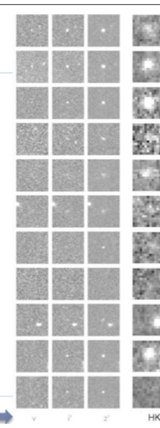
Out to very high redshifts z>6

Detecting High-z Galaxies

- "Dropouts" (Steidel, Pettini, Hamilton 1995)
  - Lyman break at 912 A ➔ dropoff in continuum flux, just shortward of Ly α line ➔ select filters accordingly
  - Absorption generated by the Ly α forest



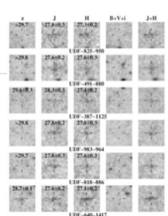
- Examples
  - Stanway et al (2005) ➔ surface density of i-band dropouts (HST, Keck)
    - z~6 star-bursting galaxies
    - No X-ray detections ➔ no quasars
    - Tiny sizes ~ 1.5 kpc
    - SFR ~ 10-25 M yr-1

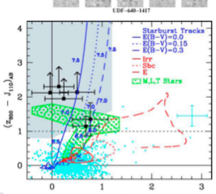


Increasing contamination from stars at z>7

Detecting High-z Galaxies

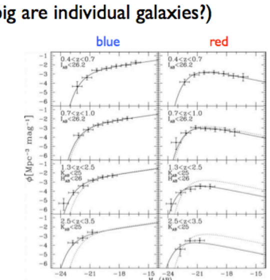
- "Dropouts"
  - Lyman break at 912 A ➔ dropoff in continuum flux, just shortward of Ly α line ➔ select filters accordingly
- Examples
  - Bouwens et al (2005) ➔ Near-IR spectrophotometry
    - z–J > 0.85 mag
      - z filter at 8500 A = 0.85 microns
      - J filter at 1.1 microns
    - no detection below 8500 A (z~7.3)
    - 5 sources with H (1.6microns) ~ 27 mag
      - Corresponds to rest-frame UV ➔ L*-like galaxies
    - No luminosity evolution as compared to z~3.8 sample
      - Account for redshift distance/size





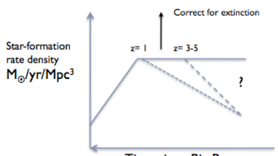
Metrics of evolution

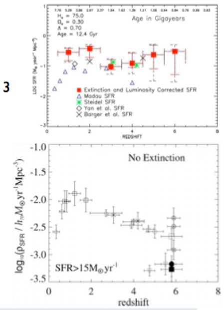
- Luminosity function/mass function
- Size distribution (i.e. how big are individual galaxies?)
  - Morphology distribution
- Star formation/stellar mass



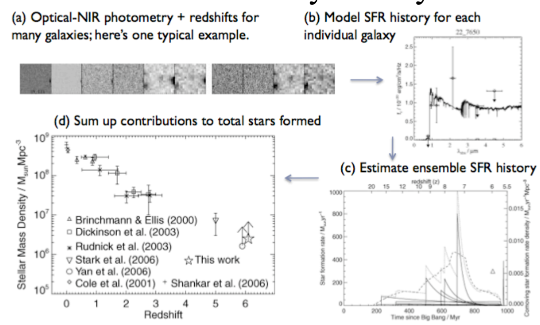
Star formation history of the Universe

- What fraction of stars formed when?
- Measure SFR at a variety of redshifts
  - Metrics for measuring the SFR….
    - Hα, radio continuum ➔ local
    - [O II]3727 at intermediate redshifts ➔ z ~ 3
    - UV continuum at high redshifts
    - (SKA will use radio continuum)





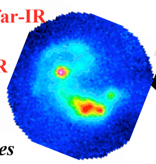
Mass assembly history

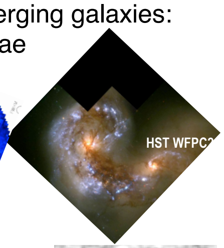


e.g. Eyles et al. 2006

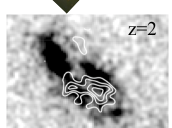
Are we missing some high-z galaxies? Luminous, dust obscured, merging galaxies: e.g.,The Antennae

- **Distinct opt/UV and far-IR luminosity**
- **90% emitted at far-IR**
- **Dust obscures UV; *absorbs* and *re-radiates* at longer wavelengths (~100-200 microns)**





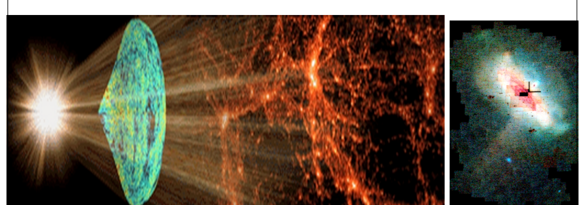
At redshift ~1-3, we can find luminous analogs to the Antennae using radio & millimetre/ far-IR (later)



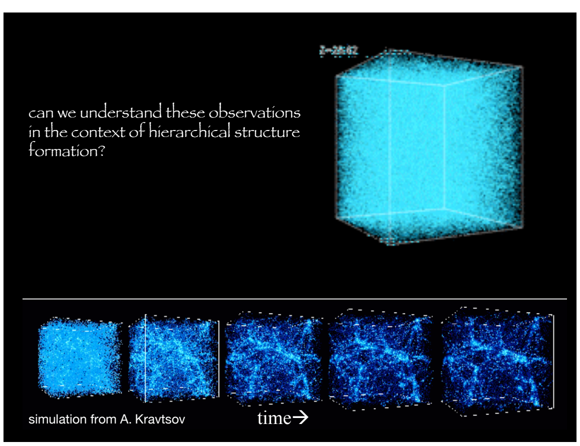
Radio contours ~1000xMW luminosity!

Context: *Hierarchical Galaxy Formation*

(How/when are stars formed and galaxy components assembled?)



Big Bang … Cosmic Microwave Background … … Galaxy Formation and Evolution … Fossil Records today!



Summary of understanding at high-z

- At high redshift galaxies were
  - Smaller, lumpier, and presumably more gas rich
  - Bluer and dustier
  - More actively forming stars (per unit mass)
  - Not as concentrated in clusters
- *What we would like to know:*
  - When and how quickly did gas settle into dark matter potentials?
  - When, where, and how did the gas get converted into stars?
  - When and how did the merging process of galaxies develop?
  - What is the relative importance of gas accretion versus merging?
  - How rapidly are galaxies still (trans)forming today?

How we think structure formed

- Process:
  - Start with distribution of fluctuations (i.e. dark matter halos)
  - Fill with baryons and let "gastrophysics" happen
    - Virialization of gas
    - Radiative cooling ➔ disk formation
    - Photoionization from background
    - Star-formation ➔ feedback
    - Chemical evolution
- What is the dark matter: *hot, warm, or cold?* (how long relativistic?)
- Hot Dark Matter (*top down*)
  - Neutrinos w/ E~10 eV ➔ $mc^2 = 3k_BT$ (non-relativistic) occurs at $z \sim 2\times10^4$
    ➔ Universe is hot, Jeans mass is large ➔ $M \sim 10^{15} M_\odot$ (i.e. cluster masses)
    ➔ density fluctuations < $10^{15} M_\odot$ are damped out
  - 1st structures to form are large clusters
  - galaxies form from fragmentation of larger structures (like star-formation)

  } Zeldovich pancakes
- Cold Dark Matter (*bottom up*)
  - Post recombination temperature ➔ $M_J \sim 10^5 M_\odot$
  - 1st structures to form were small

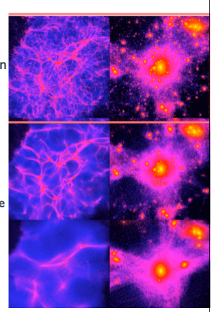
Jeans mass and length:
$M_J = (\pi\lambda_J 3/6)\,\rho$
$\lambda_J = (c_s/(3)^{1/2})(3\pi/8G\rho)^{1/2}$

First, what kind of dark matter?

ICC

What kind of dark matter?

- Well, Hot or Cold?
  - Hot ➔ hard to make stars/galaxies so much younger than clusters
    - we also see evolution/growth in galaxy clusters at z ~ 0.7
  - Hot ➔ too easily makes large flattened things
  - Cold ➔ structure on all scales forms at same time
  - Cold ➔ matches galaxy two-point correlation
- CDM the winner
  - Hierarchical formation ➔ building galaxies via merging of large numbers of small galactic systems ➔ described via a "merger tree"



Context: *Hierarchical Galaxy Formation*

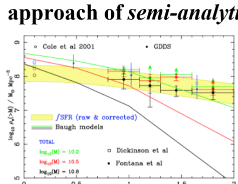
HOW TO PROCEED?

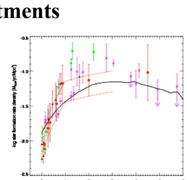
1) Full hydro-dynamical simulation … compare to observations
2) Approximate some/most of the physics: but difficult to produce a model consistent with all observations.
   - SUCCESS using many tunable parameters:
   - **Durham: GALFORM (Baugh et al. 2005); Sommerville et al. (2000)**
   - **Bullock&Johnston 2005: stellar disks, halos, Local Group substructure**
3) Study "High-redshift" (z=1--6+) populations in many ways
   - Try to connect populations in TIME.
   - Short timescale: Star Bursts/ Black Hole growth
   - Long timescale: TOOLS:
     - Masses/Clustering (difficult but doable)
     - Volume densities (bad -- mergers)
     - Chemical evolution (hard at high-z)
4) Study Local Group galaxies, ARCHEOLOGY -- FOSSIL RECORD
   - Dissect galactic components by kinematics and chemistry (age?),
     … and try to piece evolution together

Key questions in galaxy formation

- **what is stellar mass buildup, cosmic star formation history, and chemical evolution?**
- **how is this related to build-up of structure in the dark matter?**

These have motivated a 'get me to the answer fast' approach of *semi-analytic* treatments

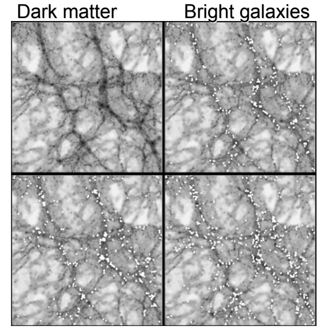




***GALAXY FORMATION and EVOLUTION*: with baryons**
The semi-analytic approach

N-body + semi-analytic
-gas cooling
-star formation
-SNe feedback
-galaxy mergers
within halos

•Success reproducing observed parameters at z=0.
•High-z objects of various classes continue to be problematic -- LBGs, SMGs,
(e.g., Sommerville et al. 2000; Baugh et al. 2005)



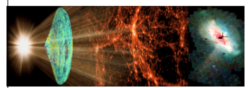
(Kauffmann et al. 1998)

Galaxies

Lecture 19: Galaxy formation

- The Semi-analytic model (SAM) approach to galaxy formation

Context: *Hierarchical Galaxy Formation*



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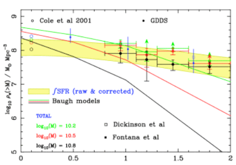

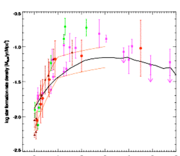

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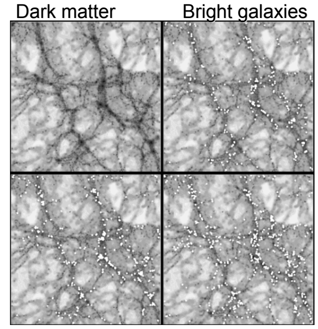


(Kauffmann et al. 1998)

Advantages

- Follows complicated baryonic physics through simple (averaged) prescriptions
- Computationally cheap
- Cosmological scale simulation (as opposed to hydro-simulations which effectively include more real physics, but have to invoke ad hoc initial conditions)

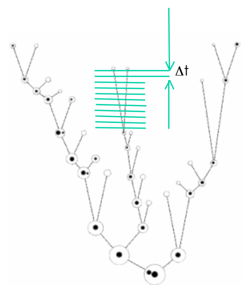
Galaxy formation in the Cold Dark Matter (CDM) model: key physical processes

- **Assembly of dark matter halos**
- Shock-heating and radiative cooling of gas within halos
- Star formation and feedback
- Production of heavy elements
- Galaxy mergers

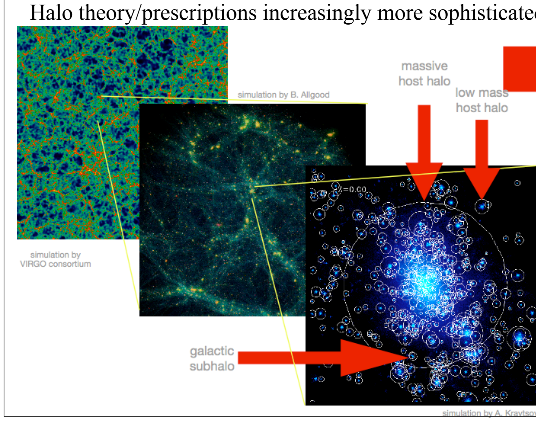
Early SAM attempts at halo merger trees

(e.g. as used in Sommerville&Primack 1999)

- Monte Carlo technique to calculate merger tree (i.e. allow mass loss, and merger event z chosen randomly).
- Normalized to Sheth-Tormen halo mass function - we'll look at this in more detail next.
- Grid of 50 halos
- Halo = Singular Isothermal Sphere (sets density profile), virialized
- $V_c(r_{VIR})$ ~ size of Halo

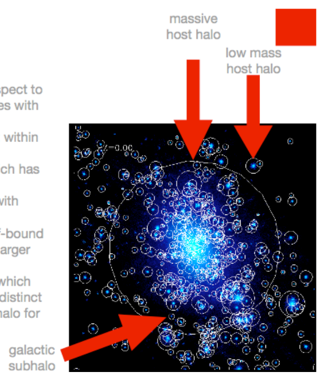


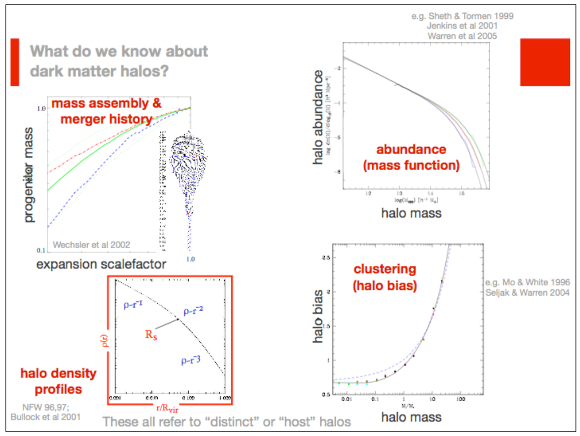
Halo theory/prescriptions increasingly more sophisticated



What is a halo?

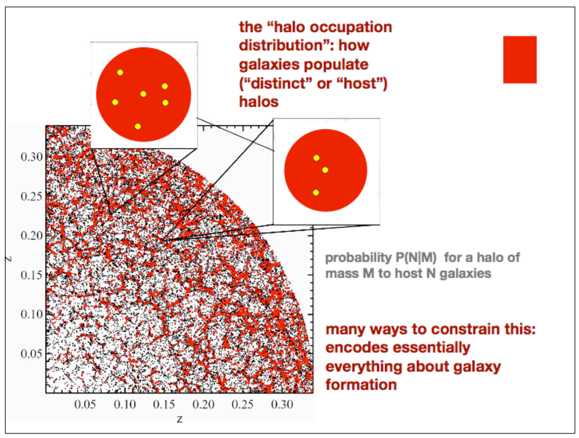
- a halo is typically defined by an overdensity delta (eg 200) with respect to the background density (sometimes with respect to the critical density)
- "distinct" halo: a halo which is not within the virial radius of a larger halo
- "parent" or "host" halo: a halo which has subhalos within its virial radius (sometimes used interchangably with distinct)
- "subhalo" or "satellite" halo: a self-bound object within the virial radius of a larger halo
- "galactic halo": the smallest halo which surrounds a galaxy. this halo is a distinct halo for central galaxies, or a subhalo for satellite galaxies





The Halo Model

- the halo model is the modern way to calculate the clustering of mass or cosmological objects that have some relation to mass
- ***use information about the clustering of mass extracted from dark matter simulations***
- Typical inputs to the halo model are:
  - The halo mass function
  - Halo clustering
  - Halo profiles
- To calculate the clustering of galaxies (quasars, etc etc), one needs a model for how they are connected to dark matter halos.
- *The basic assumption*: all galaxies live in halos
- For calculating this clustering, can use either analytic approximations or directly populate halos in a simulation: **halo occupation distribution**



Physics for Each Halo

Cooling of gas by radiation

Disc formation

Reheating – SN feedback

Star formation

Stellar population synthesis models

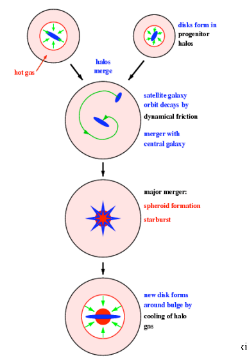
Dust absorption

Chemical evolution

Galaxy morphologies

Galaxy distribution, evolution (stripping etc)

Galaxy formation made simple



- gas cools to make disks
- halos merge
- galaxies merge by dynamical friction
- major mergers make galactic spheroids from disks
- mergers trigger starbursts
- spheroids can grow new disks

Example Star Formation Prescriptions

$$\dot{m}_* = \frac{m_{\rm cold}}{\tau_*}$$

- SFR-disks

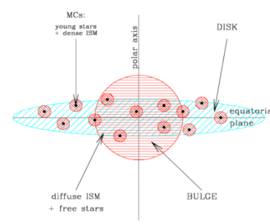
$$\tau_* = \tau_*^0$$

- SFR-mergers

$$\tau_* = \tau_*^0 \tau_{\rm dyn} \qquad \tau_{\rm dyn} \sim \frac{r_{\rm disc}}{V_c}$$

Modelling the stars & dust

- **Dust** affects the way galaxies look - especially at higher redshifts
- **dust** in **diffuse medium** and **molecular clouds**
- stars form in clouds and leak out
- stellar emission from **population synthesis**
- **radiative transfer** of starlight through dust distribution
- **heating** of dust grains –> **dust temperature distribution**

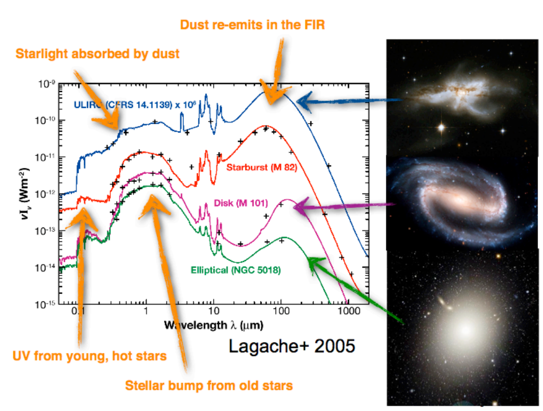


GRASIL code: Silva etal 1998, Granato etal 2000

More details of dust modelling

- Physical model for dust grains, chosen to reproduce local ISM extinction law
- Mixture of graphite & silicate grains, with distribution of grain sizes
- Includes PAHs (polycyclic aromatic hydrocarbons)

- Assume dust/gas proportional to gas metallicity
- Optical depth for dust depends on both *dust mass* and *galaxy radius*
    - these are both predicted by the galaxy formation model



Model for radio emission

- Free-free radiation from HII regions ionized by young stars
  - production rate of ionizing ctm photons, $\nu^{-0.1}$ because of opacity coef

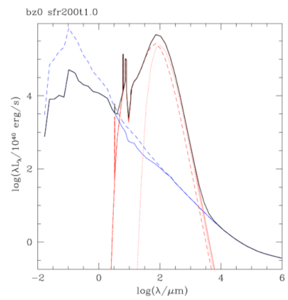
$$L_{\nu,free-free} \propto \dot{N}_{Lyc}\nu^{-0.1}$$

- Synchrotron radiation from relativistic electrons accelerated in supernova remnants
  - assume constant fraction of SN energy radiated

$$L_{\nu,sync} \propto \dot{N}_{SN}\nu^{-\alpha} \qquad \alpha \approx 0.8$$

(Bressan, Silva & Granato 2002)

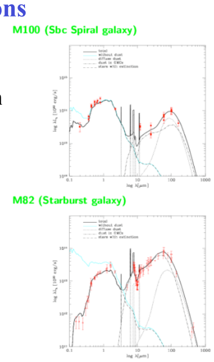
Example Model SED



- starlight with dust extinction
- emission from diffuse dust + molecular clouds
- total including radio emission (thermal + synchrotron)

SEDs from dust model – comparison with observations

- model predicts **galaxy spectrum** from **far-UV** to **millimetre**
- accurately reproduces **observed spectral energy distributions (SEDs)** for nearby **normal** and **starburst** galaxies



Silva et al 1998

Modern SAMs

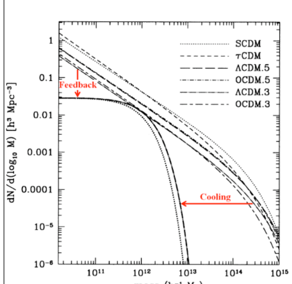
Assumptions:

Most star formation occurs in galactic discs
Major mergers drive larger, higher efficiency starbursts
Galactic spheroids form only in major mergers
Gas cools only onto the central galaxy in any halo
Star formation and feedback parameters set by local data

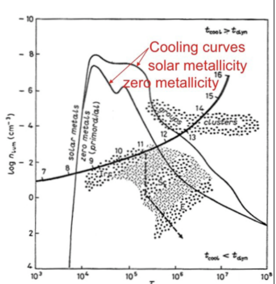
Reproduced Observations:

Trends in galaxy luminosity , gas content , morphology
Early-type galaxies populate higher density environments

Most halos do not host galaxies



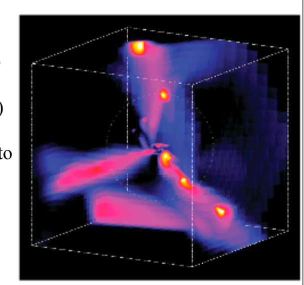
Somerville and Primack (1999)



- *Gas cooling in detail next lecture*
- Galaxy formation is efficient only for halos roughly in the mass range $10^8 - 10^{12}$ $M_\odot$

Cold Flows (Dekel et al. 2009)

Hydrodynamical simulations:
- Suggest a mechanism for gas to *flow* in 'cold' along filaments/streams (~freefall time)
- Rather than being shock heated to virial temperature as it falls into halo as was previously assumed
- In halos with $M<M_{crit}$, some fraction of gas can settle quickly to centre and form stars
- "solves" problems with rapid star formation ('bursts') at high redshifts

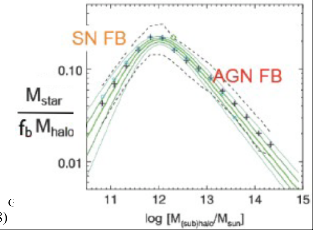


Additional SAM processes

Process or Assumption	Helps to
Dust extinction	Reproduce observed luminosity functions
AGN feedback	Not overproduce very luminous galaxies
AGN feedback & Supernova feedback	Quench star formation Reproduce galaxy color bimodality
Critical halo mass $M_{shock} \sim 10^{12}\ M_{\odot}$	Quench star formation

$M_h < M_{shock}$ halos
Gas can enter in cold streams and form stars efficiently

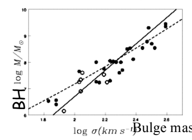
$M_h > M_{shock}$ halos at $z < 2$
Entering gas is shock-heated and cannot form stars efficiently



Somerville et al. (2008)

Feedback from AGN: the missing link?

- Star formation at z>2 forms the galaxy bulges/spheroids
- tight observed relation between M_{bulge} and M_{BH}
  - How do we achieve this?
- energy emitted expected to be proportional to M_{BH}
- Feedback: Regulation mechanism to shut off the fuel supply to the BH and terminate star formation in surrounding galaxy.
- Hydro-simulations suggest AGN is the easiest way to achieve required feedback
- (NOTE: feedback has been a blackbox for SAMs … they don't care how you achieve it, just tune it to match observations)



Di Matteo, Springel & Hernquist 2005 Nature

AGN feedback by momentum-driven winds

- Large-scale galactic winds driven by momentum deposition.
- Momentum injection provided by radiation pressure produced by continuum absorption and scattering of photons on dust grains
- Radiation from either **AGN** or **starbursts**

- Eddington luminosity limit model (Murray, Quataert & Thompson 2005)
- gravitational potential: isothermal sphere with (gas density) mass profiles: $M_g(r) = \frac{2 f_g \sigma^2 r}{G}$

- gas surrounding a point source with luminosity L modeled as spherical, optically-thick shell
- momentum deposition rate: $\frac{dP}{dt} = M_g(r)\frac{dV}{dt} = -\frac{GM(r)M_g(r)}{r^2} + \frac{L(t)}{c}$
- critical luminosity is then: $L_{crit} = \frac{4 f_g c}{G}\sigma^4$
- If $L(t) < L_{crit}$ then effective gravity reduced by momentum deposition of radiation
- For $L(t) > L_{crit}$ gas moves outwards in radiation-pressure driven outflow

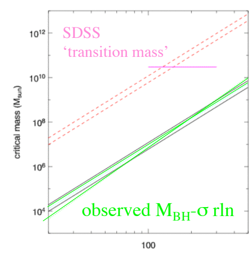
AGN feedback by momentum-driven winds

- Critical luminosity for outflow
- together with an assumed Eddington limited luminosity from AGN (accretion disc) allows the M_{BH}-σ relation to be achieved in the SAMs

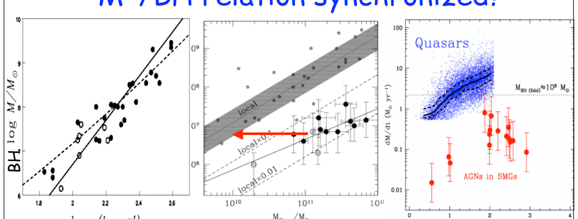
$$L_{crit} = \frac{4 f_g c}{G}\sigma^4$$ Murray, Quataert & Thompson 2005

$$L_\bullet = \eta_{Edd} L_{Edd}$$

$$M_{\bullet,crit}/M_{sun} = 0.12\eta_{Edd}^{-1}\left(\frac{f_g}{0.1}\right)\left(\frac{\sigma}{km/s}\right)^4$$



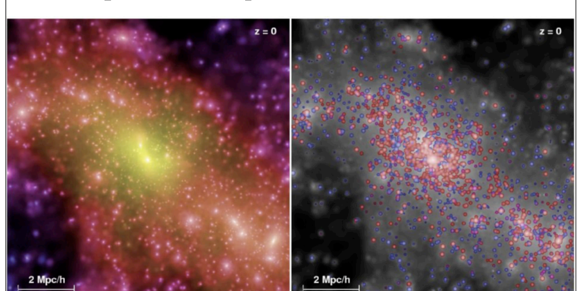
M*/BH relation synchronized?



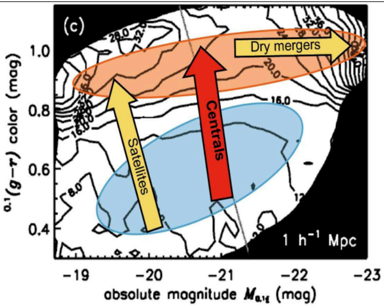
- At z=2 SMBH's "observed" as needing to grow substantially
- BH growth mostly ***after*** the obscured, starburst luminous phase (spheroid formation)
- Subsequent phase of rapid BH growth …. QUASARS!

(Alexander, Chapman, et al. Nature, 2005; Borys, Chapman, et al. 2005)

Importance of quenched star formation



The central galaxies are all red, which is consistent with observations.



Galaxy Evolution

Satellite galaxies

Star formation quenches
Gas accretion ceases
Become red

Central galaxies

Join the red sequence if either:
- Form a supermassive black hole
- Halo mass exceeds M_{shock}
- Become satellite galaxies in clusters

Dry mergers

Most massive reds
Form through mergers of reds
(Blues are not massive enough)

Important (controversial) features of Durham GALFORM model

• NOTE: SAMs are not an 'established' theory. Constantly evolving models, and fierce competition between groups to find new angles and explain new observational phenomena.

Durham GALFORM model:

• starbursts triggered by minor and major mergers

• seem to require Top-heavy IMF in bursts

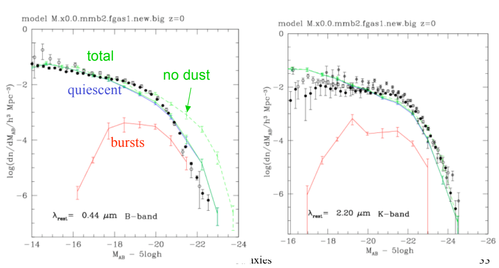
$$dN/d\ln m \propto m^{0} \text{ instead of } dN/d\ln m \propto m^{-1.5}$$

• fraction of star formation in bursts increases with redshift

Cole et al 2000; Granato et al 2000; Baugh et al 2005; Lacey et al. 2008

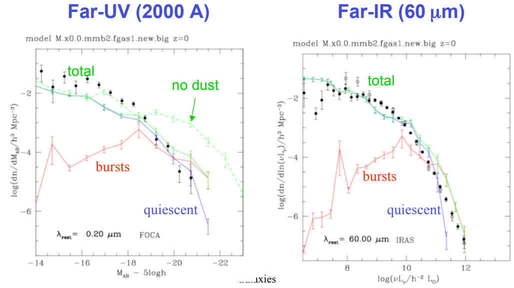
Durham model: Present-day galaxy luminosity functions in optical & near-IR

B-band K-band

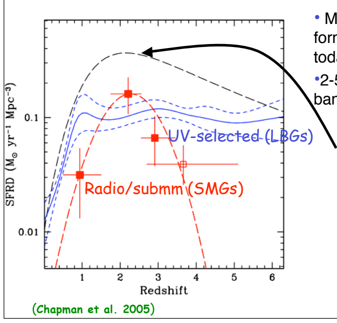


Present day luminosity functions in far-UV & far-IR

Far-UV (2000 A) Far-IR (60 μm)



The Star Formation History of the Universe



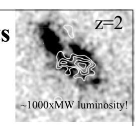
• Millimeter/Radio galaxies could form most of the stars we see today in big bursts

• 2-5 billions years after the big bang, z=1.5-3.5

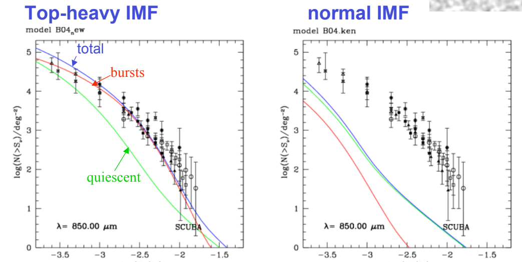
Total estimated from integrated background light.

SMG population potentially very important for forming bulk of stars in big elliptical galaxies.

Durham model: Sub-mm source counts -- reproducing extremely luminous starbursts



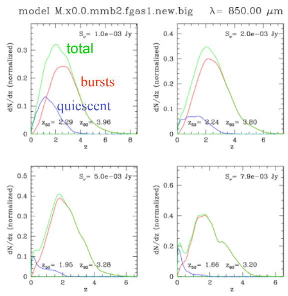
Top-heavy IMF normal IMF



Sub-mm counts too low by factor ~30 for normal IMF

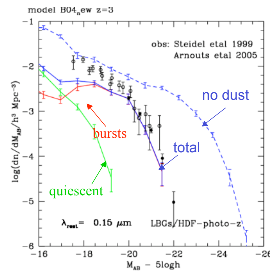
Redshift distribution of sub-mm sources (extremely luminous starbursts)

- model predicts **median z~2** for S(850)=1-10 mJy (100-1000x MW)
- **consistent with observational constraints** (e.g. Chapman etal 2005, z(median)=2.4 at S~5mJy, 500xMW)
- Problem is that top-heavy IMF means no long-lived stars form in burst!

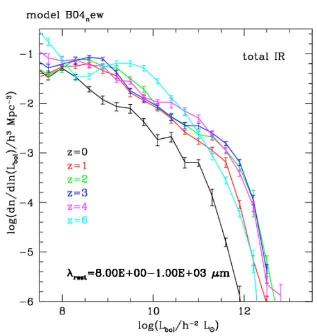


Rest-frame UV: Lyman-break galaxies at z~2-6

LBGs *(UV-selected galaxies from dropout technique)* **too faint for normal IMF, once include dust extinction**



Evolution of total (0.3-1000 μm) LF



- traces dust-obscured star formation
- combine with UV to determine star formation history
- Brightens by factor ~10 from z=0 to z~3
- declines beyond z~4

Final issues:

- Star Bursts (and modified prescription for star formation) more important at z=1-3
  - Quiescent star formation timescale longer in disks … make mergers at high-z more gas rich
  - Triggering of bursts by minor & major mergers
  - Top-heavy IMF ?
  - Feedback from AGN radiation pressure regulates BH growth and star formation
- But bursts don't produce the stars in z=0 galaxies … these are formed in disks and rearranged.
- Controversial IMF changes, but form of changed IMF not important
- NOTE: top-heavy IMF does help to solve other problems:
  - Theoretical evidence that IMF may be different at high-z
  - Metal content of intra-cluster medium
  - Stellar absorption line strengths in Ellipticals.

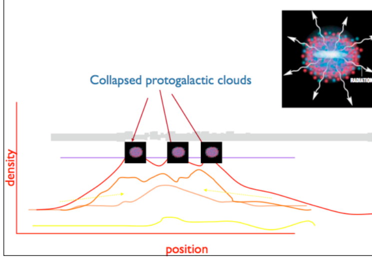
Galaxies

Lecture 20: galaxy formation: gas cooling

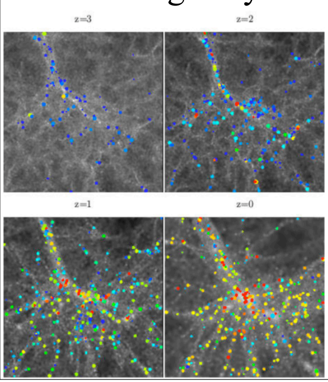
- Outline of basic paradigm
- Gas cooling onto halos
- Next: disc formation - ang.momentum in halos and galaxies
- And: detailed halo properties and origin of (sub)structure

galaxy formation

- gravitationally bound structures, and hence galaxies occur at the peaks in the density distribution … to be discussed



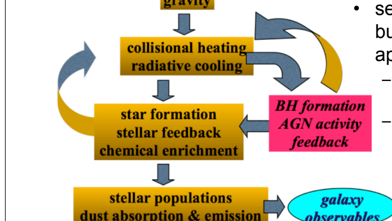
galaxy evolution



Heuristically, we saw that SAMs can paste recipes for galaxy physics into DM halo simulations and *sort of* get observed properties of galaxies correct from early Universe to the present.

Lets look in more detail at where these recipes come from.

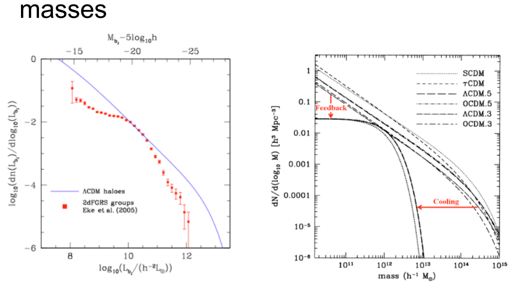
Kauffmann, Diaferio, Colberg & White 1999



- simulation: solve equations of physics (e.g., gravity, thermo, hydro, etc.) using particles or mesh cells
- semi-analytic: trace bulk quantities using approximations.
  - usually Monte-Carlo based
  - no spatial information unless you combine with simulations

galaxy formation

- galaxy formation is not equally efficient at all masses



Core condensation in heavy halos: a two-stage theory for galaxy formation and clustering

S. D. M. White and M. J. Rees *Institute of Astronomy, Madingley Road, Cambridge*

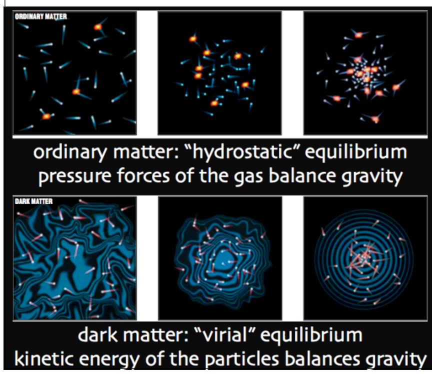
Received 1977 September 26

Summary. We suggest that most of the material in the Universe condensed at an early epoch into small 'dark' objects. Irrespective of their nature, these objects must subsequently have undergone hierarchical clustering, whose present scale we infer from the large-scale distribution of galaxies. As each stage of the hierarchy forms and collapses, relaxation effects wipe out its substructure, leading to a self-similar distribution of bound masses of the type discussed by Press & Schechter. The entire luminous content of galaxies, however, results from the cooling and fragmentation of residual gas within the transient potential wells provided by the dark matter. Every galaxy thus forms as a concentrated luminous core embedded in an extensive dark halo. The observed sizes of galaxies and their survival through later stages of the hierarchy seem inexplicable without invoking substantial dissipation; this dissipation allows the galaxies to become sufficiently concentrated to survive the disruption of their halos in groups and clusters of galaxies. We propose a specific model in which $\Omega \sim 0.2$, the dark matter makes up 80 per cent of the total mass, and half the residual gas has been converted into luminous galaxies by the present time. This model is consistent with the inferred proportions of dark matter, luminous matter and gas in rich clusters, with the observed luminosity density of the Universe and with the observed radii of galaxies; further, it predicts the characteristic luminosities of bright galaxies and can give a luminosity function of the observed shape.

two-stage galaxy formation

- Gas cools in virialized dark matter 'halos'. Physics of halos is nonlinear, but primarily gravitational.
- Complicated gastrophysics (star formation, supernovae enrichment, etc.) mainly determined by local environment (i.e., by parent halo), not by surrounding halos.

Separating light from dark matter



Gas cooling

- Cooling rate from collisional ionization is strong function of temperature and metallicity, so cooling rate is function of position in halo (~ radius from centre)
- Cooling by Bremsstrahlung continuum dominates at $T>10^8$ K, metal line-cooling important at 10^7-10^8 K
- Cooling rate defines time; since rate depends on radius, cooling time depends on radius
- Gas cools within "cooling radius":
  - radius where cooling time = $t_{Universe}$

Gas cooling

- halos are spherically symmetric
- hot gas initially follows the dark matter distribution
- gas is shock heated to virial temperature
- collisional equilibrium assumed

$2K + W = 0$ ….

$2 \times 3M_{gas}k_BT / 2\mu m_p - 3GM_{gas} M / 5r_{cl}$

$$T_{vir}(r) = \frac{1}{2}\frac{\mu m_p}{k_B}V_c^2(r) = 35.9\left[\frac{V_c^2(r)}{\text{km s}^{-1}}\right] K$$

where $\mu m_p = \rho_g/n = 4/(8-5Y)$.

White & Frenk 1991 … considering a truncated halo, radius r (as SIS has infinite mass)

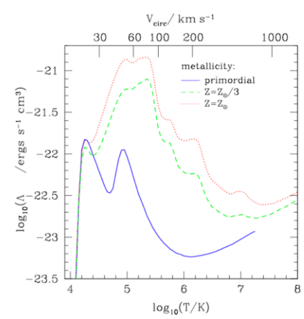
Gas cooling - cooling function

$$\Lambda(T) \equiv \frac{C}{n_H^2} \quad \frac{\text{erg s}^{-1}\text{ cm}^{-3}}{\text{cm}^{-6}}$$

where C is total cooling rate per unit volume, n_H is number density of hydrogen atoms

Thus defined, Λ is independent of gas density for an optically thin gas.

- cooling depends on the metallicity of the gas
- Bremsstrahlung (free-free) $T>10^8$ K …. $\Lambda \sim T^{1/2}$
- metal line-cooling 10^7-10^8 K
- H, He peaks (blue) 10^4, 10^5 K
- Heavier element peaks for more enriched gas
- $T<10^4$ K, most of electrons have recombined and cooling due to collisional excitation drops precipitously



Gas cooling

$$t_{cool} \equiv \frac{\rho\varepsilon}{C} = \frac{3nk_BT}{2n_H^2\Lambda(T)_H} \approx 3.3\times10^9\frac{T_6}{n_{-3}\Lambda_{-23}(T)}\,yr$$

- Cooling time for gas at temperature T and density n as a result of radiative cooling; ε is internal E / unit mass.
- ideal gas with γ=5/3
- For 10^{11} M_{sun} protogalaxy has n_{-3}~5.5 and Λ_{-23}~0.5 (primordial gas) … t_{cool} ~ 7.4×10^8 yr
- Roughly twice free-fall time t_{ff}= sqrt(3π/32Gρ)

White & Frenk 1991

$$n_e^2(r)\Lambda_{cool}(T)\tau_{cool} = \frac{3}{2}n(r)k_BT$$

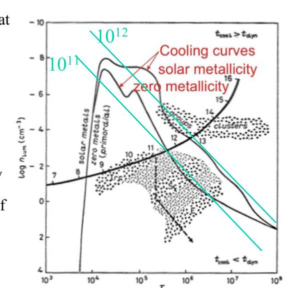
$$\eta \equiv \frac{n_e}{n_{tot}} = \frac{4(Y^{-1}-1)+2}{8(Y^{-1}-1)+3}.$$

$$\tau_{cool} = \frac{3}{4}\frac{(\mu m_p)^2}{\eta^2}\frac{V_c^2(r)}{\rho_g(r)\Lambda_{cool}(T)}$$

- for an assumed gas density profile, can solve for 'cooling radius' …. r_{cool}

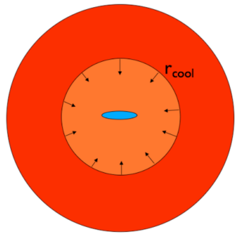
Gas cooling

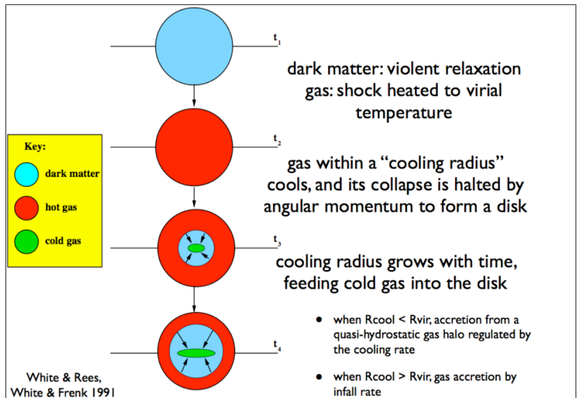
- Locus of $t_{cool} = t_{ff}$ in n-T plane
- Separates clouds that can cool effectively ($t_{cool} << t_{ff}$) from those that cannot
- Loci of constant M_{gas} shown (in M_{sun} units)
- Gas density higher with higher redshift
- Primordial gas $M>10^{11}$ cannot cool effectively at any *z*
- For enriched gas $M>10^{12}$
  - Clusters and groups at present usually contain large amounts of hot gas
- Critical cooling mass similar to that of most massive galaxies
  - Suggests physics of cooling plays an important role in limiting the mass of galaxies (e.g. White & Rees 1978)

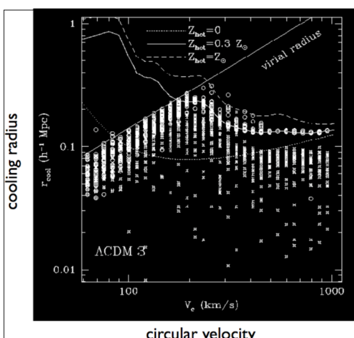


galaxy evolution

- White & Rees model (standard semi-analytic)
- cooling rate defines cooling time
- radius where cooling time $t_{cool} = t_{Universe}$ define the "cooling radius" within which gas cools







Sommerville & Primack 1999

- Diagonal line show the r_{virial}
- Curved lines show cooling radius for different metallicities
- Open circles are application of 'static' halo model within merger trees; crosses show dynamic halo model
- Earlier conversion of gas from hot to cold phase, and reheating of hot gas by halo mergers, results in lower cooling efficiency for large halos

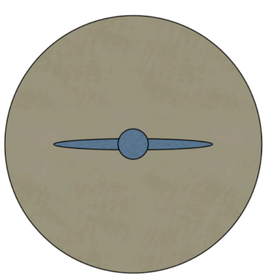
Cooling Catastrophe

- Prescription for cooling straightforward, but there is a problem: cooling times in centres of massive halos extremely short ($T \sim m^{2/3}$)
- Prescription leads to massive, luminous central galaxies which are NOT observed
- Solution: switch-off cooling BY HAND in all halos with $\sqrt{GM_{vir}/R_{vir}} > 350$ km/s
- or, come up with some other way to do it...

Simple picture of Hubble type

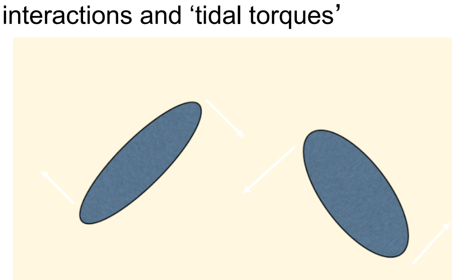
- What happens to gas which cools in halo?

- Two parts to galaxies: bulge and disk
- Ellipticals all bulge, Sd galacies basically all disk



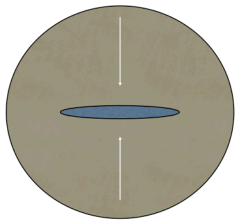
Disc galaxy formation

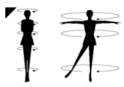
- clumps gain angular momentum from interactions and 'tidal torques'



Disc galaxy formation

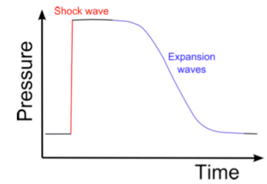
gas collapses to form a disk





Shocks in collapsing, cooling gas

- Basic idea of shocks:
  - occurs in supersonic motion of a fluid:
  - sound waves traveling against the flow cannot travel and pressure builds, creating a high pressure shock wave
  - a sharp increase in density, pressure, temperature and speed at the shock

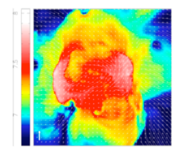


Shocks in cosmology

- Virial Shocks
- Shocks in merging clusters
- Shocks in moderately dense filaments -- heat the IGM
- Shocks in the ISM and ICM from eg. SN or other energy sources

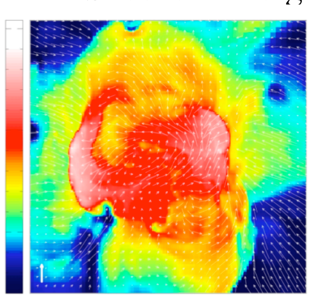
Shocks

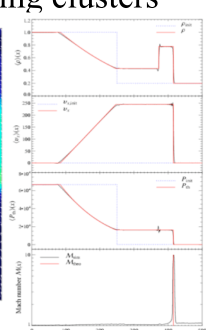
Virial Shock Heating



- as halos collapse, the dark matter undergoes violent relaxation
- within the virial radius, dm shells cross and the pressure of the gas increases, prevents shell crossing of the gas
- gas is infalling at greater than the sound speed. pressure makes this velocity vanish at the center.
- because it's supersonic, info about the boundary condition can't propagate outwards, and a shock is created.
- as the shock propagates outwards, gas that crosses the shock is heated. this increases the sound speed and makes the interior flow subsonic.
- net result is transfer of KE of the collapse into thermal energy of the gas
- in order to persist, the gas internal to the shock has to have pressure.

Shocks in merging clusters

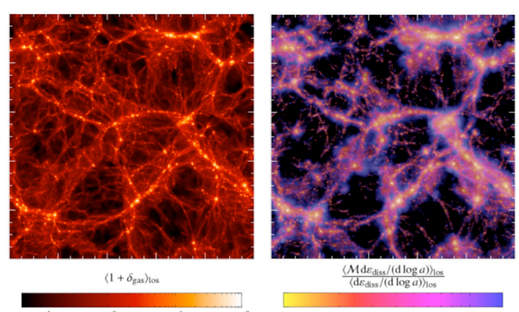




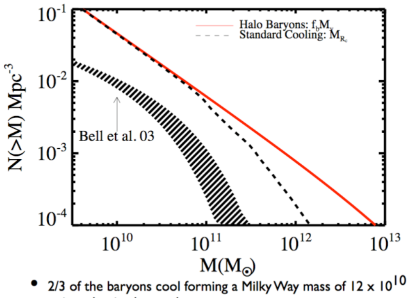
A gas velocity map overlayed on the emission-weighted temperature map of the cluster undergoing major merger z=0.43. The map shows the average projected velocity and entropy in a 125h-1kpc (comoving) slice centered on central density peak. The size of the region shown is 8h-1Mpc.

Structure formation shocks can be studied in situ in SPH

SHOCK STRENGTH DISTRIBUTION, WEIGHTED BY DISSIPATION RATE



Two phase cooling



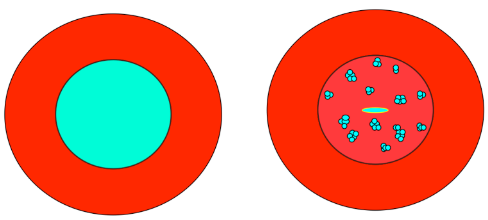
- 2/3 of the baryons cool forming a Milky Way mass of 12 x 10^{10}, twice what is observed.
- Supernova feedback is invoked to blowout half of the Milky Ways while not destroying the thin disk.

A Maller

Two phase cooling

- A cooling plasma is hydrodynamically unstable (Field 1965)
- Higher density regions will cool faster, becoming denser and therefore cooling faster. Low density regions won't cool as quickly, will expand into the space left by the high density regions, thus decreasing their density and the rate that they cool.
- One ends up with a two phase medium of low density hot gas and warm clouds.

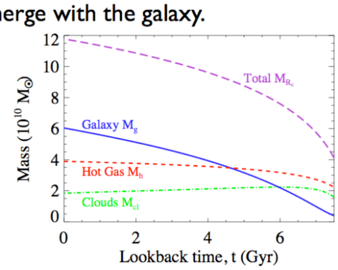
Two phase cooling



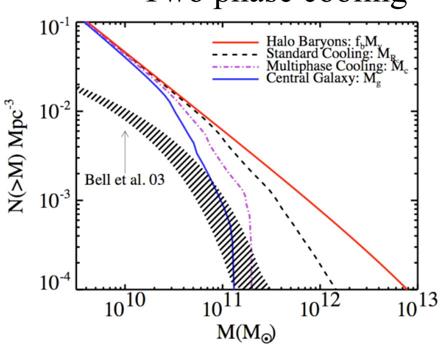
Two phase cooling

Clouds will move around in the halo until they collide or lose energy from ram pressure. Only then will they merge with the galaxy.

$$M_h \propto \rho_c R_c^3$$

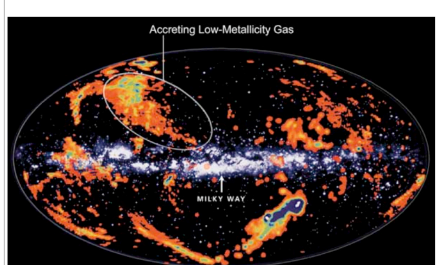


Two phase cooling



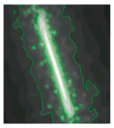
- Multi-phase cooling seems to predict this cutoff naturally.

Two phase cooling

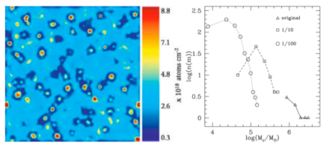


High Velocity Clouds: HI clouds detected around our galaxy not associated with the disk.

Two phase cooling



density in a pure disk galaxy



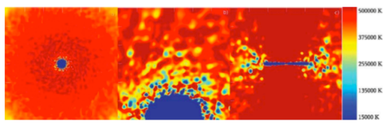


Figure 9. Temperature maps of the gas in slices through the centre of the standard M33 simulation after 2.1 Gyr. Panels (a) and (b) show 200 and 32 kpc regions, respectively. Panel (c) shows a 40-kpc slice perpendicular to the disc plane.

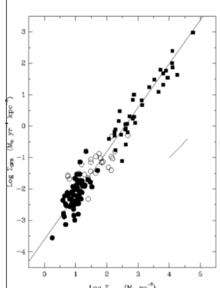
Kaufmann et al 2006

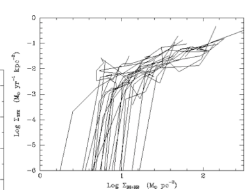
Two phase cooling

- When gas cools we expect a two phase medium to arise.
- To survive warm clouds must have masses of 10^5 - 10^8 solar masses.
- To get the observed Milky Way mass clouds must have masses of 10^6-10^8
- To match the observed properties of high velocity clouds requires cloud masses of 3-7 x 10^6 solar masses.
- A similar range of cloud masses is needed to produce quasar absorption systems.
- Irrespective of the cloud mass, the hot low density core sets an upper limit on the amount of mass that can cool of 2 x 10^{11} solar masses explaining the exponential cutoff in the Luminosity function.

Star formation

star formation





$\dot{\Sigma}_* = C\, \Sigma_g^{\ 1.5}$

above critical threshold

Kennicutt 1989, 1998;
Martin & Kennicutt 2001

Star formation

- SFR $\varphi = \alpha\, M_{cold}/t_{dyn} = \alpha\, M_{cold}(10V_{vir}/R_{vir})$
- Note $t_{dyn} = R_{vir}/10V_{vir}$ ~ 0.01/H ~ 0.01 $t_{Universe}$
- because $GM/R = V^2$ so $(4\pi G/3)(3M/4\pi R^3) = (4\pi G/3)200\rho_{crit} = (V/R)^2$
- But $\rho_{crit} = (3H^2/8\pi G)$ so $(10H)^2 = (V/R)^2$
- Fudge factor $\alpha = \alpha_0\, (V_{vir}/220\ \mathrm{km/s})^{\alpha_1}$
- Makes star formation efficiency depend on halo circular velocity *and* redshift (at fixed V, R is smaller at high z, so SFR φ is larger)

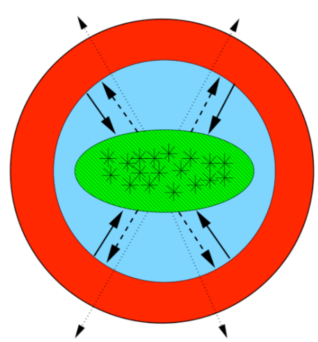
Star formation

$$dm_*/dt = m_{cold}/[\tau_0\, t_{dyn}\, (1+z)^{\gamma}]\ (V_0/V_c)^{\alpha}$$

- τ_0 set by fitting present-day luminosity and gas fraction
- degeneracies in scaling with redshift can be broken by high redshift observations

e.g. Kauffmann et al. 1999; rss & Primack 1999,
Kauffmann & Haehnelt 2000;
Cole et al. 2001; rss, Primack & Faber 2001

feedback



Feedback

- Energy input from stars which form and then explode as SNae will heat gas, preventing further cooling:

$$\Delta M_{reheat} = \varepsilon\ (4/3)\ (\eta_{SN} E_{SN}/V_{vir}^2)\ \Delta M_{star}$$

Uncertainties

- η_{SN}: number of SNae per solar mass in stars, depends on IMF ($\sim 0.0063/M_{sun}$)
- E_{SN}: energy released per SN ($\sim 10^{51}$ ergs)
- ε: efficiency of process(!)
- Is reheating local? Global?
- Does energy leave halo (e.g., SN winds may exceed escape velocity of low mass halos)?

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Feedback

- in presence of UV ionizing background, halos with virial temp < background radiation field are unable to accrete gas (σ < 30-50 km/s)
- gas can be "boiled out" of halos (σ<20 km/s)
- cooling function modified (cooling suppressed at low T)

eg. Somerville 2002
Benson et al. 2002

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Feedback
Ejection vs. Retention

- Retention: shocked material is reheated to virial temperature, and is then again available for cooling
- Ejection: $\Delta M_{back} = \gamma\ M_{eject}\ (V/R)\ \Delta t$ (ejected gas falls back on a timescale determined by γ; mainly purpose is to remove some of gas from the cooling reservoir)
- Winds: $dM_{wind}/dt = c\varphi$ (wind strength scales with SFR ~ observed)

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Galaxies
Lecture 21: disc galaxy formation

- Angular Momentum in Halos & Galaxies
- Relation to disc galaxy formation
- Problems with simulating disc galaxies

Angular Momentum in halos and discs

- Tidal torque theory
- Halo spin
- The angular momentum distribution in halos
- Gas condensation & Disc formation
- The AM problems
- gas AM vs dark matter AM

how do galaxies get their spin?

Halo spin parameter

- Important property of a dark matter halo is its angular momentum (AM)
- Hoyle (1949) suggested (and Efstathiou & Jones 1979 demonstrated) asymetric collapse in an expanding Universe produces objects with significant AM.
- Parametrized through spin parameter

$$\lambda = \frac{J|E|^{1/2}}{GM^{5/2}}$$

- Where J, E, M are total AM, energy and mass of the halo
- For an isolated system, all these quantities are conserved during dissipationless gravitational collapse, and so therefore is λ itself.

$\lambda = \frac{J|E|^{1/2}}{GM^{5/2}}$ Halo spin parameter

- Spin parameter thus defined is roughly the square root of the ratio between the rotational and the total energy of the system
- So characterizes the overall importance of AM relative to random motion in the DM halo.
- Energy of spherical DM halo from virial theorem:

$$E = -4\pi \int_0^{rh} \frac{\rho(r)V_c^2(r)}{2} r^2 dr \equiv -\frac{M_h V_h^2}{2} F_E$$

- Where $V_h = V_c(r_h)$ is the circular velocity at r_h and F_E is a parameter that depends on halo's density distribution
- F_E=1 for SIS; can be calculated analytically for an NFW halo in terms of the concentration parameter c

$$F(E) = c/2 \frac{[1 - 1/(1+c)^2 - 2\ln(1+c)/(1+c)]}{[c/(1+c) - \ln(1+c)]^2}$$

$\lambda = \frac{J|E|^{1/2}}{GM^{5/2}}$ The spin parameter

- In literature, we find alternative definition of the spin parameter which avoids the need to calculate halo energy explicitly

$$\lambda' = \frac{J}{2MV_h r_h}$$

- This spin parameter related to above through

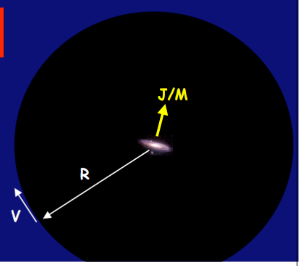
$\lambda' = \lambda F_E^{-1/2}$

The spin parameter

Spin parameter $\lambda \sim \frac{J/M}{RV}$

Conservation of specific angular momentum $const. = J/M \sim \lambda R_{\rm virial} V \sim R_{\rm disk} V$

→ $\frac{R_{\rm disk}}{R_{\rm virial}} \sim \lambda$



The spin parameter

$$\lambda \equiv \frac{J E^{1/2}}{G M^{5/2}}$$

Peebles 76

$$\lambda' = \frac{J}{\sqrt{2} M V R}$$

Bullock et al 01

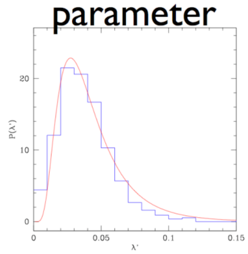
approximately: rotational support in units of the virial velocity dispersion

- typical values are 0.02-0.11

Barnes & Efstathiou 87, Ryden 88, Warren et al 92, Steinmetz & Bartelman 95, Cole & Lacey 96, Gardner 01, Bullock et al 01, Maccio et al 06

distribution of the spin parameter

lognormal distribution



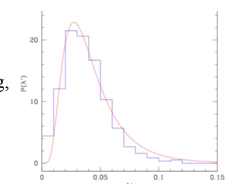
$$\lambda' = \frac{J}{\sqrt{2} M V R}$$

doesn't depend on M, z, cosmology

Bullock et al 01

Distribution of spin parameter

- Median and width of log-normal distribution depend only weakly on halo mass, redshift and cosmology
- At all halo masses, tendency for halos with higher spin to be in denser regions and thus to be more strongly clustered.
- Distribution is broad (factor of 5 from 10th to 90th percentiles)
- Median spin small
  - DM halos are mainly suported by random motions of particles rather than rotation
- We will see that λ of a self-gravitating, rotationally supported disc is ~0.4 (~10x larger than DM halo).



Tidal-Torque Theory

angular momentum in Eulerian patch $\vec{L}(t) = \int_{\gamma\ \rm Eulerian} \rho(\vec{r},t)\,[\vec{r}(t) - \vec{R}_{cm}(t)] \times [\vec{v}(t) - \vec{V}_{cm}(t)]\ d^3 r$

comoving coordinates $\vec{x} \equiv \vec{r}/a \quad \vec{v} \equiv a\dot{\vec{x}} \quad \delta \equiv \rho/\bar{\rho}(t) - 1$

$$\vec{L}(t) = \bar{\rho}(t) a^3(t) \int_\gamma [1 + \delta(\vec{x},t)]\,[\vec{x}(t) - \vec{X}_{cm}(t)] \times \dot{\vec{x}}\, d^3 x$$

const. in m.d.

displacement from Lagrangian q to Eulerian x $\vec{q} \rightarrow \vec{x} \quad \vec{x}(\vec{q},t) = \vec{q} - \vec{S}(\vec{q},t)$

laminar flow $1 + \delta[x(q,t)] = J^{-1}_{acobian}(q,t) \rightarrow (1+\delta) d^3 x = d^3 q$

for small fluctuations, the mapping q--x is reversible

continuity eq. implies $\vec{L}(t) = \bar{\rho}_0 a_0^3 \int_{\Gamma\ \rm Lagrangian} [(q - \bar{q}) + (S(q,t) - \bar{S})] \times \dot{S}(q,t)\, d^3 q$

average over q in _

Zel'dovich approximation $S(q,t) = -D(t)\nabla\phi(q) \quad \phi(q) = \varphi_{\rm grav}(q,t)/[4\pi G \rho(t) a^2(t) D(t)] \rightarrow \vec{S} // \dot{\vec{S}}$

$$\vec{L}(t) = -a^2(t)\dot{D}(t)\ \bar{\rho}_0 a_0^3 \int_\Gamma (q - \bar{q}) \times \nabla\varphi(q)\ d^3 q$$

in a flat universe $a^2 \dot{D} \propto D^{3/2} \propto t$ in EdS

2nd-order Taylor expansion of potential about q_{cm}=0 $\phi(\vec{q}) \approx \phi(0) + \left.\frac{\partial \phi}{\partial q_i}\right|_{\vec{q}=0} q_i + \frac{1}{2} \left.\frac{\partial^2 \phi}{\partial q_i \partial q_j}\right|_{\vec{q}=0} q_i q_j \quad \vec{q} \equiv \vec{q} - \bar{\vec{q}}$

$$L_i(t) = a^2(t)\dot{D}(t)\ \varepsilon_{ijk} D_{jl} I_{lk}$$

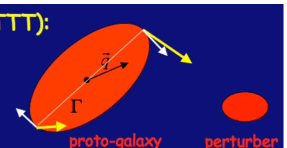
Deformation tensor $D_{jl} \equiv -\left.\frac{\partial^2 \phi}{\partial q_j \partial q_l}\right|_{q=q_{cm}=0}$ Inertia tensor $I_{lk} \equiv \bar{\rho}_0 a_0^3 \int_\Gamma q_l q_k d^3 q$ antisymmetric tensor ε_{ijk}

The origin of angular momentum

- angular momentum comes from gravitational coupling of the quadrupole moment of the protohalo's mass distribution with the tidal field.
- torque depends on the misalignment.

Tidal Torque Theory (TTT):

Peebles 1976 White 1984



Result:

$$J_i \propto t\ \varepsilon_{ijk} T_{jl} I_{lk}$$

Tidal: $T_{ij} = -\frac{\partial^2 \phi}{\partial q_i \partial q_j}$ Inertia: $I_{ij} = \rho_0 a_0^3 \int_\Gamma q_i q_j\ d^3 q$

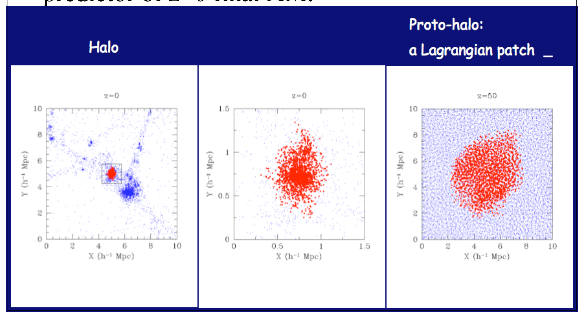
Tidal-Torque Theory

- Angular momentum in protohalos grows linearly with time.
- AM growth stops once a protogalaxy separates from the overall expansion and starts to collapse (when linear theory ends)
- AM depends strongly on mass, weakly on time of collapse

- Linear theory above gives some idea about acquisition of AM during early stages of collapse of DM halos in cosmological density field
- This AM may not correspond to final AM of DM halo because during *late stages of non-linear collapse*, and due to *mergers with other halos*, significant AM gained.
- Porciani+2002 => linear AM is poor predictor of final AM

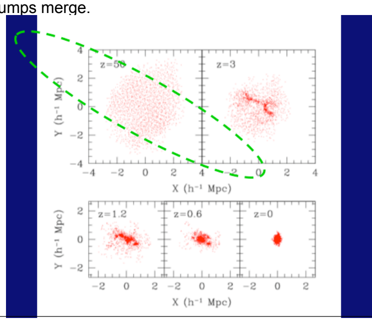
Stages in growth

- z~50 linear theory prediction of AM, not a great predictor of z=0 final AM.



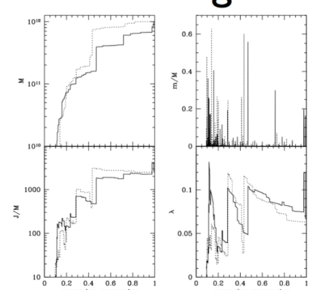
Stages in halo formation Porciani, Dekel & Hoffman 02

- first collapse along major axis of inertial & tidal field
- filament breaks into clumps.
- clumps merge.



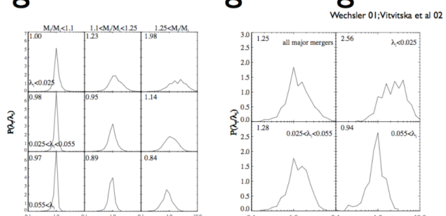
angular momentum growth through mergers

Wechsler 01;Vitvitska et al 02



angular momentum growth through mergers

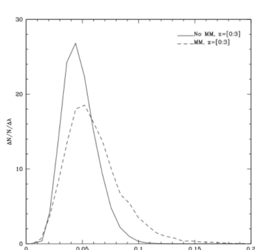
Wechsler 01;Vitvitska et al 02



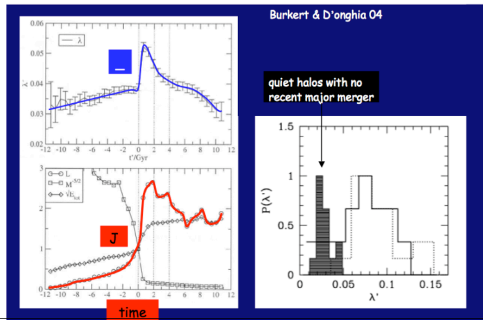
basic picture: growth of spin in halos is a random walk

much of spin-up comes from a sequence of minor mergers

Growth of AM through mergers: major versus minor



angular momentum growth through mergers

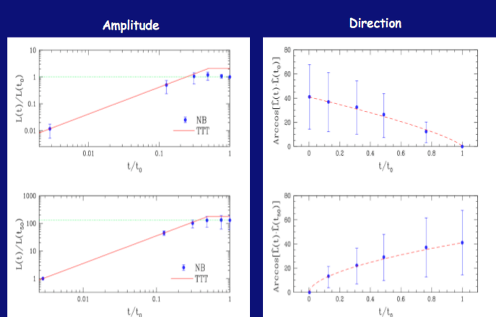


Alignments of AM in halos

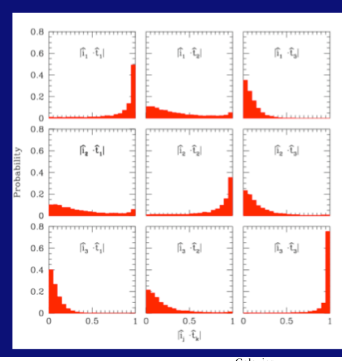
- Direction of AM vector strongly aligned with minor axis of halo
  - Median misalignment angle of ~25deg (Bailin&Steinmetz05)
- On larger scales, DM halos embedded in nonlinear 2D sheets have strong tendency for AM vector to align with sheet (Hahn+2007)
- Alignment between AM vectors of neighbour DM halos:
  - Weak tendency for massive halos (>5x10^{12} Msun) to AM vectors antiparallel to those within a few Mpc
  - But for less massive halos and larger distances, correlation is zero

TTT vs. Simulations: Amplitude Growth Rate

Porciani, Dekel & Hoffman 02



TTT vs Simulations (Porciani, Dekel & Hoffman 2002)



Alignment of T and I:
Spin originates from the residual misalignment.
Small spin !

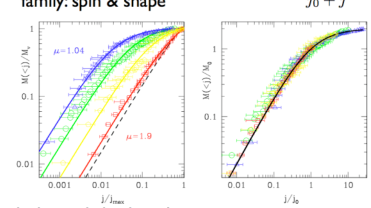
Internal Angular Momentrum Distribution

- Spin parameter describes total AM of DM halo, but contains no information regarding the *distribution* of AM within halo
- This *specific AM distribution* is important for modeling the mass distribution of disc galaxies
- Bullock+2001a,b measured specific AM distributions of DM halos, and found simple functional forms describe them
- specific AM scales roughly with radius ($j \sim$ r), or enclosed (cumulative) mass M(<j) ~ j … it follows a power law over most of mass and flattens at large j

angular momentum profiles

a two-parameter family: spin & shape

$$M(<j) = M_v \frac{\mu j}{j_0 + j}$$

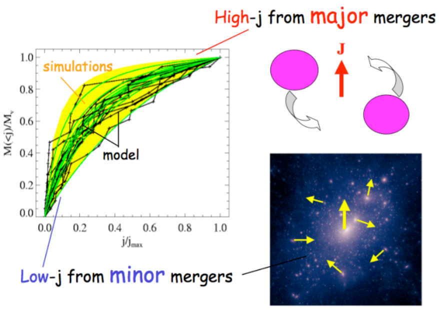


high spin halos have J more evenly distributed

Bullock et al 01

High-λ halos tend to have high μ, corresponding to a narrower, more uniform j-distribution

Internal J



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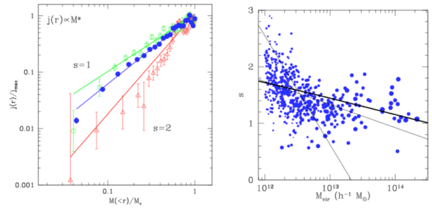
Maller, Dekel & Somerville 02

Radial profile of *j*

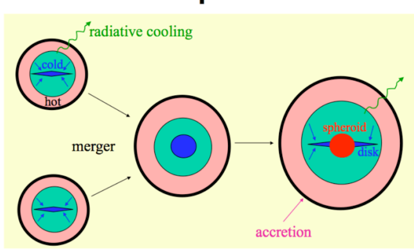
When averaged over spherical shells encompassing mass M, the halo j profiles are fitted by $j(M) \sim M^s$ with s=1.3+-0.3



~>10% have significant misalignment between shells

Bullock et al 01

basic picture



morphology is a transient feature of galaxies set by its merging history

disks are formed during quiet periods

classic disk formation picture

- gas initial well mixed in a smoothly rotating halo
- angular momentum exists due to tidal torques
- falls in to form an angular momentum-supported exponential disk
- assumes that the specific angular momentum of the disks are the same as their host halos

Fall & Efstathiou 1980, Blumenthal et al 1986, Mo, Mao & White 1998

Formation of Disc w/o halo?

- Spiral galaxies supported by rotation $\lambda = \frac{J|E|^{1/2}}{GM^{5/2}}$
- Rotation curves for discs studied previously, and total AM is

$$J_d = 2\pi \int_0^\infty V_c(R)\Sigma(R)R^2 dR \approx 1.11 G^{1/2} M_d^{3/2} R_d^{1/2}$$

- Virial theorem -> $E = -2\pi \int_0^\infty \frac{V_c^2(R)}{2}\Sigma(R) R dR \approx -0.147 G M_d^2 R_d^{-1}$
- λ ~0.4 in observed disc galaxies, but theory suggests λ~0.01 - 0.1, median ~0.035
- Yields estimate of collapse time of gas cloud that forms the disc $\lambda = \lambda_i (R/R_i)^{-1/2}$
- Mass and J conserved, but binding energy -E increases proportional to R^{-1}.
- Suggests R/R_i~70. For MW, R~10kpc M~5x10^{10}Msun, R_i~700kpc
- Free-fall time ~ sqrt(3π/32Gρ)~4x10^{10}yr
- Longer than age of U.

Formation of disc with halo

- Very different if gas contracts in a massive DM halo
- Consider a halo with a circular velocity independent of radius ($\rho \sim r^{-2}$)
- Assume gas cools and flows inward conserving specific AM
- Implies gas a radius R in disc came from $R_i = R(V_c/V_{rot},i)$ where V_{rot},i is the typical initial rotation velocity of the gas at radius R_i
- From before, specific AM scales roughly with radius ($J_s \sim r$)
- SIS halo, $V_{rot}(r) = \eta V_c$, η a constant related to λ
- Truncating at large radius (finite mass) $\lambda = 2^{-3/2} \eta$
- λ=0.05 corresponds to η ~0.14
- Assume gas in DM halo has same J_s distribution as DM (both have experienced same tidal torques)
- Gas now only has to collapse by factor 1/ η =1/.14 ~ 7 to bring rotation speed up to V_c
- Reduced collapse factor by x10 … and $t_{ff} \sim 10^9$ yr
- Simple argument gives strong support for presence of extended DM halos (independent of dynamical arguments)

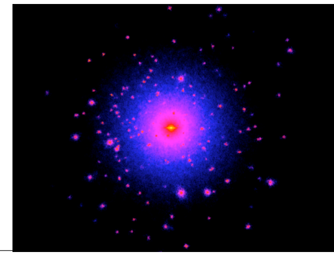
classic disk formation picture

Mo, Mao & White 1998

- gas initially well mixed in a smoothly rotating halo
- mass of the disk is a fixed fraction of the halo mass
- angular momentum is a fixed fraction of the halo AM
- disk is thin with an exponential surface density
- only dynamically stable systems can be disks.
- falls in to form an angular momentum-supported disk
- gives an estimate for the sizes & rotation curves of disks

Real disc galaxies?

- That's all well and good. But does it have anything to do with galaxies?
- … a perpetual problem to form realistic disk galaxies in cosmological simulations



Calculation of MW-like disc

- Assume formation and growth of the disc is a slow, adiabatic process => end state is independent of the exact formation history … focus on static models of end states.
- Consider dissipational collapse of gas cloud with some initial AM
- Radiative cooling very effective provided cloud is dense enough and has $T>10^4$ K
- Radiates away binding energy and contracts, approaching state where E is as low as possible
- Assume cloud will conserve its AM, as radiation field from cooling is roughly isotropic, thus shouldn't carry away much AM.
- Preferred end state is a rotating disc, since AM of all mass elements points in the same direction
- In the absense of viscosity or non-axisymmetric structure, each mass element of the cloud will conserve its own specific AM, *j*, so end state is disc with Σ related to initial AM distribution.

Idealized case

- First, ignore self-gravity of disc, and take SIS DM halo $\rho(r) = V^2_{vir}/(4\pi G r^2)$
- V_{vir} defined that average density within is Δ_{vir} times critical density for closure: for ΛCDM, $\Delta_{vir}\sim100$ at $z=0$ (depends on cosmology and redshift, following spherical collapse model -- next lecture)
- $\rho_{crit} = 3H^2(z)/8\pi G$ $\quad r_{vir} = \sqrt{\frac{2}{\Delta_{vir}(z)}}\frac{V_{vir}}{H(z)} \quad M_{vir} = \sqrt{\frac{2}{\Delta_{vir}(z)}}\frac{V^3_{vir}}{GH(z)}$
- Independent of density profile of DM halo
- Assume mass settling into disc a fixed fraction m_d of the halo mass

  $M_d \sim 1.3\times10^{11} h^{-1}\, Msun\, (m_d/0.05)\, (V_{vir}/200 km/s)^3\, \xi^{-1}(z)$

  where $\xi^{-1}(z) = (\Delta_{vir}/100)^{1/2}\, H(z)/H_0$
- Disc infinitesimally thin and has $\Sigma(R) = \Sigma_0 \exp(-R/R_d)$
- Without self-gravity, rotation curve flat at V_{vir}, and AM given by

$$J_d = 2\pi\int_0^\infty V_c(R)\Sigma(R)R^2 dR = 2M_d R_d V_{vir}$$

- Assume AM a fraction of halo $J_d = j_d J_{vir}$, with J_{vir} related to λ :

$$R_d = \frac{\lambda G M_{vir}^{3/2}}{2V_{vir}|E|^{1/2}}(j_d/m_d)$$

Idealized case ctd…

- Total energy of SIS DM halo from virial thm $E = M_{vir}V^2_{vir}/2$

Get $$R_d = \frac{1}{\sqrt{2}}\frac{j_d}{m_d}\lambda r_{vir} \approx 10_{\rm kpc}\frac{j_d}{m_d}\frac{\lambda}{0.05}\frac{V_{vir}}{200_{\rm km/s}}\frac{1}{\xi(z)}$$

And $$\Sigma_0 \approx 207 M_{\rm Sun/pc2}\frac{m_d}{0.05}\left(\frac{j_d}{m_d}\right)^{-2}\left(\frac{\lambda}{0.05}\right)^{-2}\left(\frac{V_{vir}}{200_{\rm km/s}}\right)\xi(z)$$

Relates disc properties to DM halo (V_{vir} and λ), where $m_d=M_d/M_{vir}$ & $j_d=J_d/J_{vir}$ depend on details of disc forming processes (efficiencies, cooling, feedback)

Commonly assume $j_d\sim m_d$ (specific AM of material forming disc is same as halo (as baryons experience same tidal forces as DM).

For MW parameters for V,M,R: get $m_d\sim0.01$, λ~0.011

Cosmological baryon fraction $f_{bar}\sim0.17$, suggests an efficiency $\varepsilon = m_d/f_{bar}\sim0.07$ (ie, 93% of baryons never cooled or were expelled by feedback)

… But feedback not expected to be efficient in large halos

… And λ~0.01 rare (typical λ~0.035, and <3% of halos have λ<0.011)

Alternatively, can form disc with MW scale ~3.5kpc in halo with λ~0.05 if $j_d\sim0.2m_d$

Problems with Idealized case

…. Disc has lower *j* than DM halo. Should occur if disc grows preferentially from low *j* material, or if baryons transfer significant AM to DM halo during cooling

In fact some 'adiabatic contraction' is thought to occur

- However, a big problem is that H(z) and ΛCDM means disc galaxy at z=1 will have a scale length 70% smaller than a disc galaxy in a halo of the same V_{vir} and λ at z=0
  - Blindingly obvious in SPH simulations 10yrs ago!
- Simulations have shown that λ doesn't evolve strongly with z, this is completely inconsistent with recent HST observations of discs at z~1 (which are only marginally smaller than discs of similar mass today)
- Idealized case above thus has **3 serious problems:**
  - 1) Disc mass fraction much smaller than universal baryon fraction
  - 2) Discs form in halos with very low spin parameters
  - 3) Small disc scales

Example disc formation with Bullock et al. 2001 universal *j*- profile explicitly:

- Disc profile obtained from Halo *j* distribution, has same problems

Assume the gas follows the halo j distribution $M_{gas}(<j) = f\,M(<j)$

Assume conservation of j during infall from halo to disk.

In disk: $j(r) = Vr = [GM(r)r]^{1/2}$

In disk: lower j at lower r $M_{halo}(<j) \rightarrow m_{disk}(r)$

$$M_{halo}(<j) = M_{vir}\frac{\mu j}{j_0 + j} \quad \mu > 1 \;\rightarrow\; m_d(r) = f\mu M_v \frac{j(r)}{j_0 + j(r)} \quad j(r) < j_{max}$$

Assume isothermal sphere
No adiabatic contraction

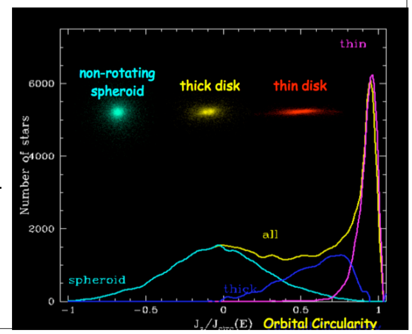
$$M \propto r \quad \rightarrow \quad j(r) = rV(r) = rV_{vir}$$

$$\rightarrow\; m_d(r) = f\mu M_v \frac{r}{r_d + r} \quad r < r_{max} \qquad r_d = \sqrt{2}\lambda' R_v b^{-1}(\mu) \quad r_{max} = r_d/(\mu - 1)$$

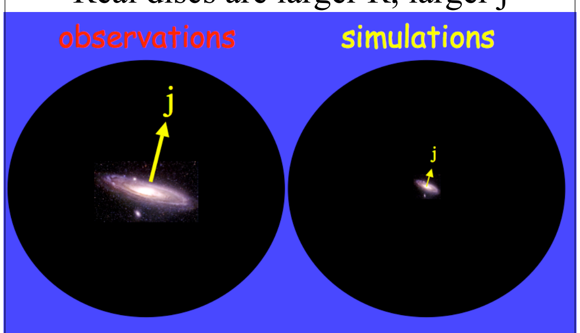
$$\Sigma_d(r) = \frac{f\mu M_v}{2\pi}\frac{r_d}{r(r_d + r)^2}$$

Dynamical components of a simulated disc galaxy

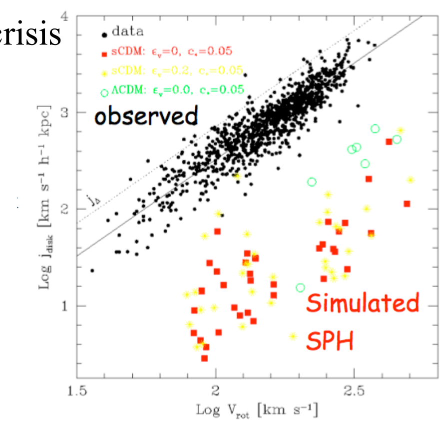
basic picture, that the various components are set by the merging history is probably right.



Real discs are larger R, larger j



Spin crisis



Solutions to Idealized case

- If we account for disc self-gravity $Vc^2 = V_{c,d}(r)^2 + GM_{h,ac}(r)/r$, and use more realistic DM halo profile, and include adiabatic contraction with transfer of baryon AM to DM halo

… Strongly boost circular velocity at a few disc scale lengths (~10kpc in MW)

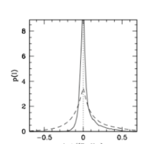
  - Disc galaxy of a given Vrot resides in a less massive halo than simple model
  - Given disc mass requires a larger m_d … so closer to f_{bar} … solution to (1)
  - Less massive halo has smaller r_{vir}, so a given r_d => larger λ ... solution to (2)

- If $\mathbf{j_d \sim m_d}$, can almost get realistic size discs, but still require significant feedback
  - Baryons have to largely conserve their specific AM when cooling … the more this isn't true, the more feedback is required … sort of solution to (3)

- Finally, this static model cannot of course describe SF history of the disc galaxy, or make predictions regarding radial age and metallicity gradients … need to follow the actual assembly of disc over time (see examples#4).

are DM & galaxy J really the same?

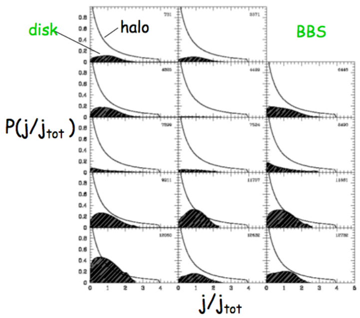
not likely.
see van den Bosch et al 02, Wise & Abel



although the two components experience the same torques and the same merging processes, they undergo very different relaxation, heating, etc.
dm: violent relaxation; gas: shock heating + feedback

remember, standard model assumes specific angular momentum conservation

Observed j distribution in dwarfs



Low $f_{baryons} \approx 0.03$

Missing low j

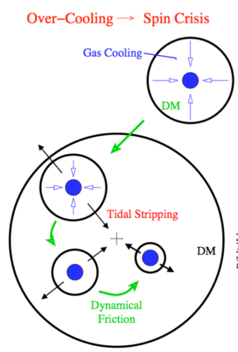
High $\lambda_{baryons} \approx 0.07$

van den Bosch, Burkert & Swaters 2002

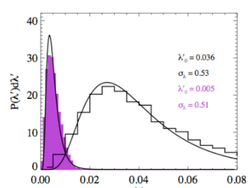
angular momentum problems

- the observed spin component of galaxies is comparable or larger to that of dm halos, but cooling of the baryons should make it smaller
- baryons in observed dwarfs seem to lack the low-j and high-j tails of the distribution of angular momentum for dark halos

Problem in dwarf galaxies:



j-rich mass is stripped off
compact baryonic component survives and loses j as it sinks to the center



if cooling is the problem, maybe heating is the solution

Maller & Dekel 02

if cooling is the problem, maybe heating is the solution…

Supernova Feedback: V_{SN} (Dekel & Silk 86; Dekel & Woo 03)

Energy fed to the ISM during the "adiabatic" phase:

$$E_{SN} \approx \nu \varepsilon \, \dot{M}_* \, t_{rad} \quad \propto M_* \, (t_{rad}/t_{ff})$$

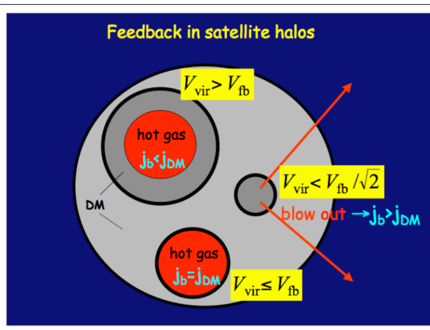
$$\dot{M}_* \approx M_*/t_{ff}$$

≈ 0.01 for $\Lambda \propto T^{-1}$ at $T \sim 10^5 K$

Energy required for blowout:

$$E_{SN} \approx M_{gas} V^2$$

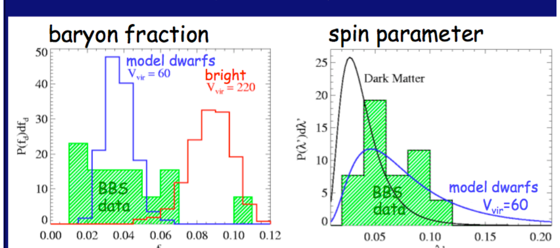
$$\rightarrow \; V_{crit} \approx 100 \text{ km/s} \quad \rightarrow \; M_{*crit} \approx 3\times10^{10} M_\odot$$



in small satellites heating can blow out gas, low j preferentially

Model vs Data (Maller & Dekel 02)

BBS data: 14 dwarfs, van den Bosch, Burkert & Swaters 02



One free parameter in model: $V_{feedback} \cong 90 \text{ km s}^{-1}$