Course Description

Part III Astrophysics: Galaxies
Lent Term 2011:

Mon, Wed, Fri. 11am. MR11

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Office phone: 01223 330803

Galaxies

Lecture 1: Overview

- Intro to course
- Detail on Topics covered
- Historical Overview
- Overview of course

Intro to course

- Galaxies provide laboratories for a wide range of astrophysical phenomena:
- stellar dynamics, gas dynamics, dark matter, and stellar and chemical evolution.
- Moreover the problem of the formation and evolution of galaxies stands as one of the most important challenges to 21st century astrophysics.

Intro to course

- Part of this subject has traditionally been covered in the Part III course Astrophysical Dynamics,
  - covers basic stellar dynamics theory and selected applications to galaxies and galactic systems.
- This course, **Galaxies**, is designed as a companion to the Dynamics course.
- It includes a comprehensive introduction to the observed structural, kinematical, and evolutionary properties of galaxies and the relevant theoretical models.

Textbooks

- The main text for this course is Galactic Astronomy by Binney and Merrifield (Princeton University Press, 1998).
  - companion volume to Galactic Dynamics by Binney and Tremaine (Princeton University Press, 2007), which serves as the text for the Part III Astrophysical Dynamics course.
- We will cover the topics in a different order
  - first ~half of the course covering the basic structural and kinematical properties of galaxies
  - second ~half covering stellar populations and galaxy evolution, beginning in the solar neighbourhood and ending with cosmological lookback studies.

Textbooks

- The two- volume set of books provides a comprehensive coverage of galaxies from an observational and theoretical perspective
  - Both are highly recommend for those who plan to continue work in the field at the postgraduate level and beyond.
- An excellent supplemental text is "Galaxies in the Universe" by Sparke and Gallagher (Cambridge University Press, 2007). It covers much of the same material as the pair of Princeton series texts, but at a somewhat lower level.
- "Galaxies and Galactic Structure" by Elmegreen provides a good qualitative introduction to the subject.

Example Sheets and Classes

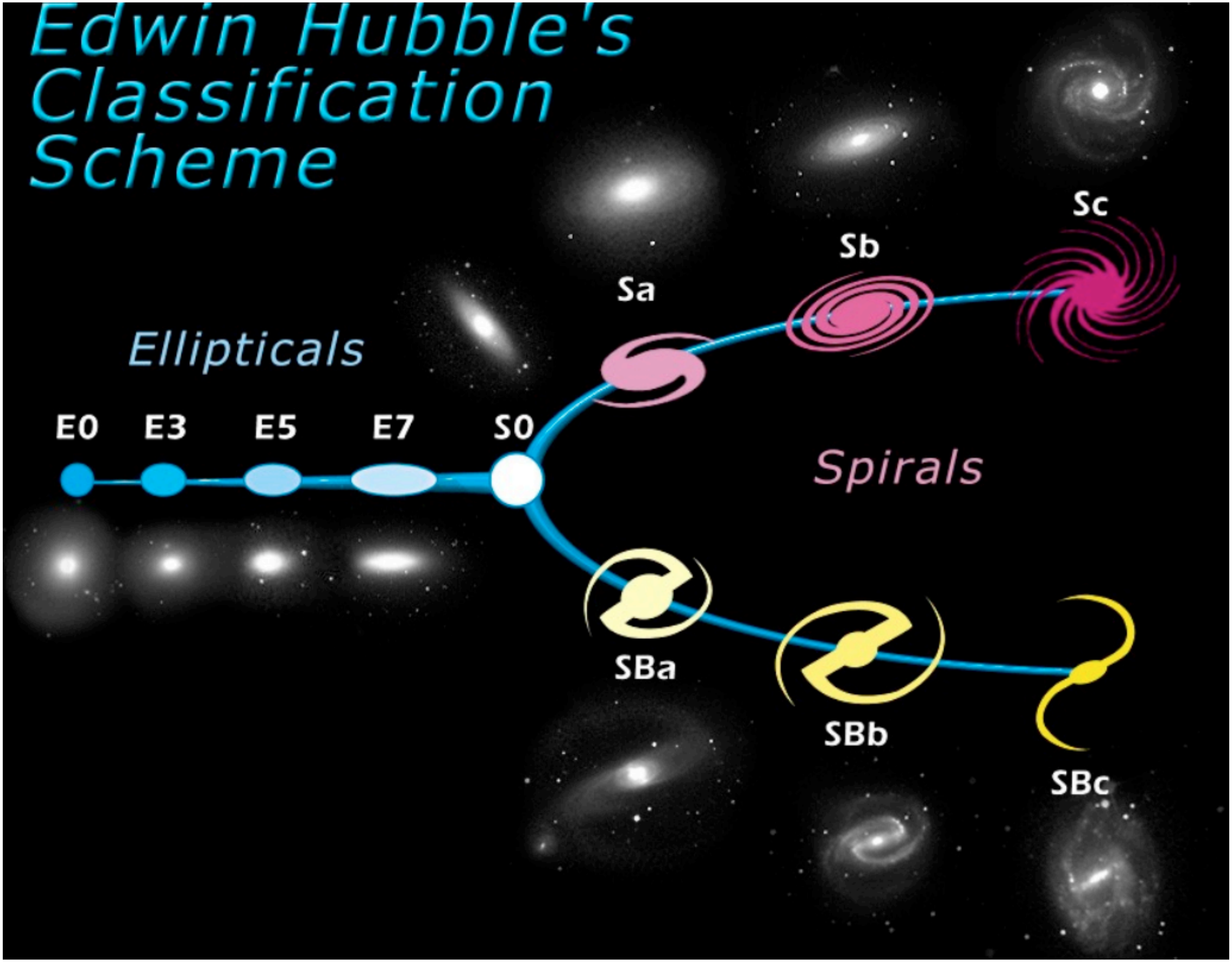
- There are four example classes associated with this course, three to be held during Lent term and one early in the Easter term, on dates and times TBD. The instructor for these classes will be Dr. Dan Stark (dps@ast.cam.ac.uk).
- Example sheets will be distributed in advance in the lectures. The material in the example classes will provide more in-depth coverage of some of the mathematical material in the course and provide examples of the types of questions that may appear on the course examination.

Examination

- The examination for this course is tentatively scheduled for June 3, 2011 at 13:30pm. The examination will mainly consist of problems with the choice of an essay question.
- Although the emphasis in the problems will be on mathematical and physical concepts and derivations, you may also be asked to relate the results to observations of galaxies as discussed in the lectures.
- The examination will be "open book", meaning that you may bring handwritten class notes to the examination (but not printed lecture notes, photocopied material, or calculators).

Topics

- Background, historical introduction
  - galaxy catalogs, atlases, and databases
- Form and classification
  - morphological classification systems
  - quantitative and physical classification systems
- Photometric and physical structure
  - luminosity function
  - spheroids & disks
- Interstellar media in galaxies
- Kinematics, dynamics
  - internal kinematics and dynamics
  - scaling laws and the fundamental plane
  - dark matter



Edwin Hubble's
Classification
Scheme
Ellipticals
E0
E3
E5
E7
S0
Sa
Sb
Sc
Spirals
SBa
SBb
SBc

Topics: stellar content and evolution

- The extragalactic distance scale
- Chemical evolution models
- The Solar neighborhood
  - stellar statistics, luminosity function, IMF
  - disk population: ages, abundances, orbits
- The Galactic halo and bulge (near-field cosmology)
  - field stars
  - formation scenarios: instantaneous collapse vs hierarchical formation

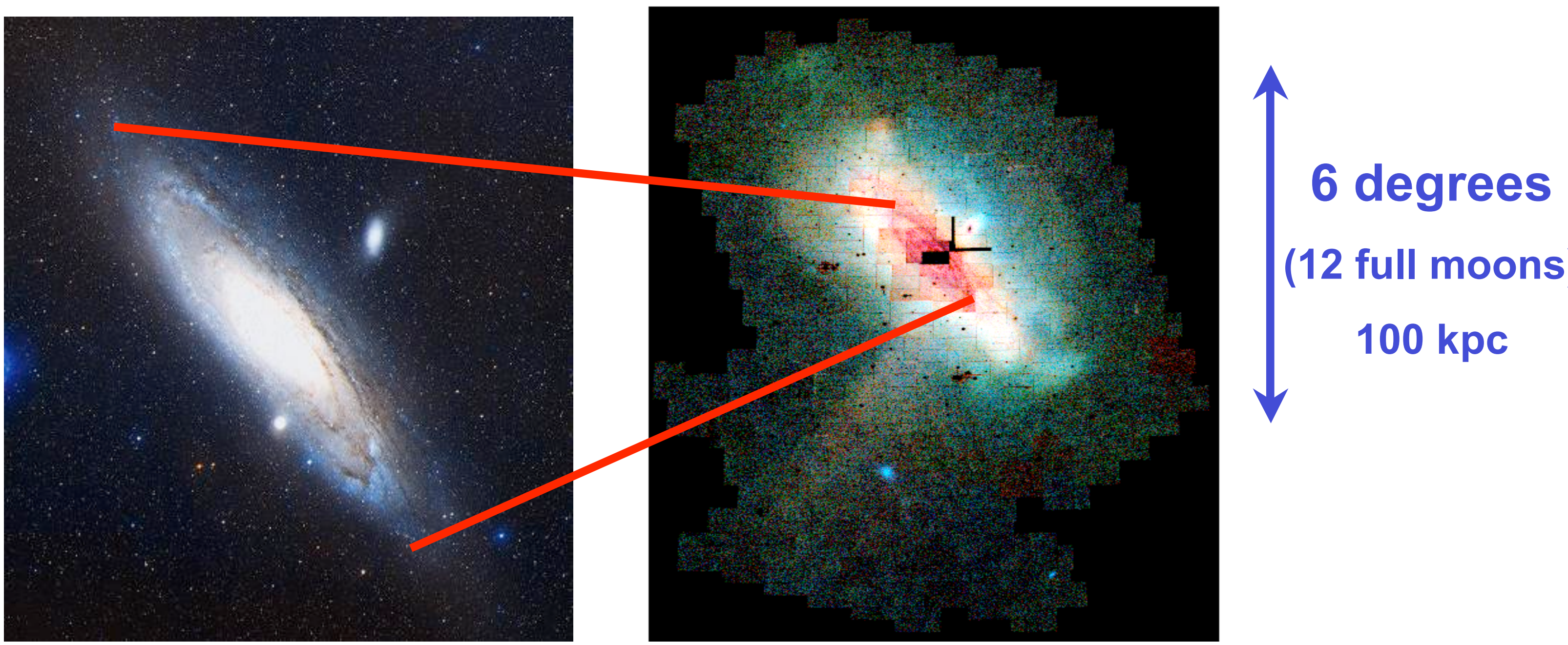
Topics: stellar content and evolution

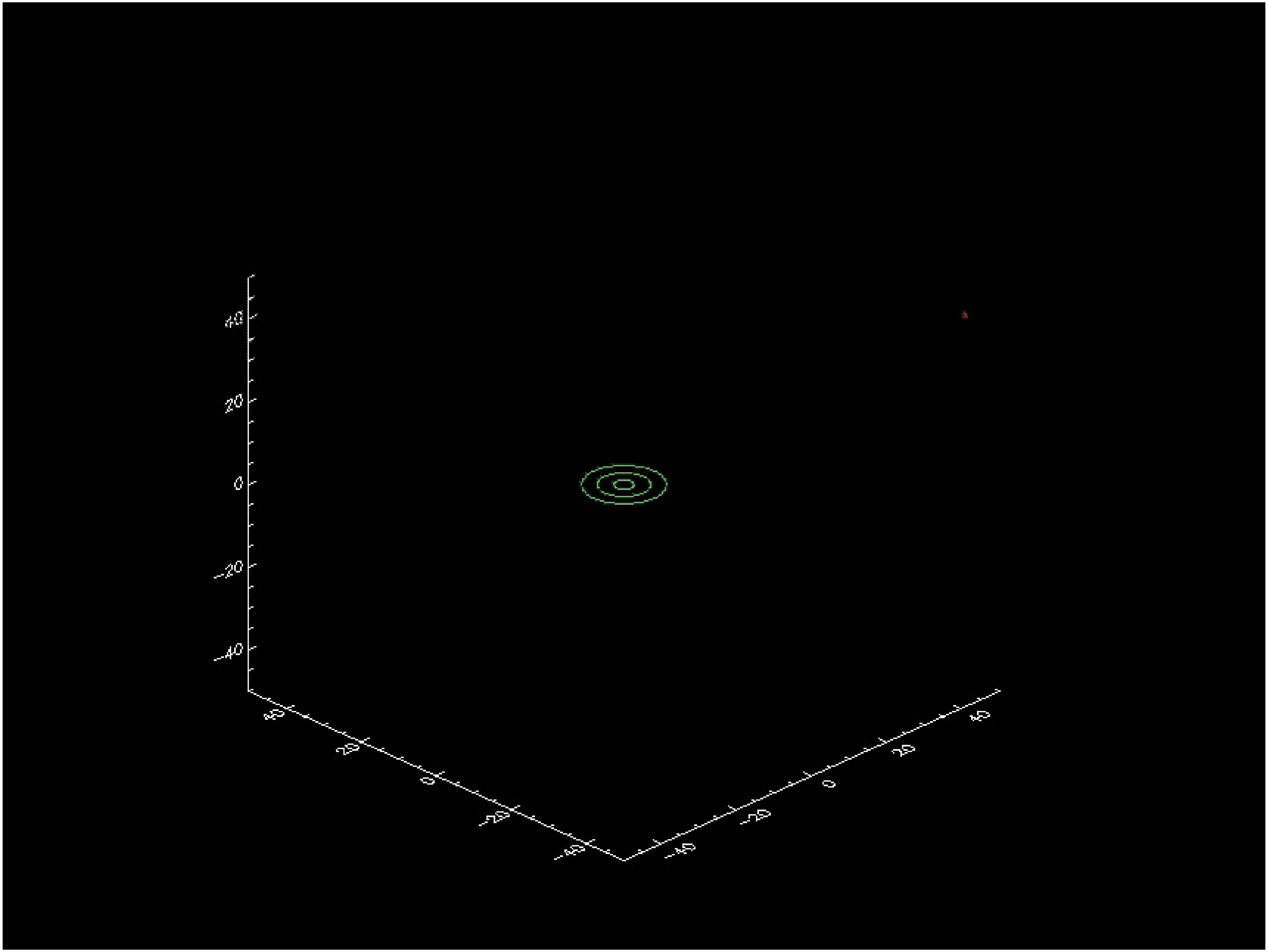
- Stellar populations in nearby galaxies
  - resolved stellar populations in nearby galaxies
  - diagnostics of star formation rates and histories
  - spectral and evolutionary synthesis
  - star formation properties of the Hubble sequence
  - environmental influences and starbursts
  - chemical abundances and evolution

Fossil Record of Galaxy Formation: M31 (Andromeda)

Classical (Palomar) view of M31

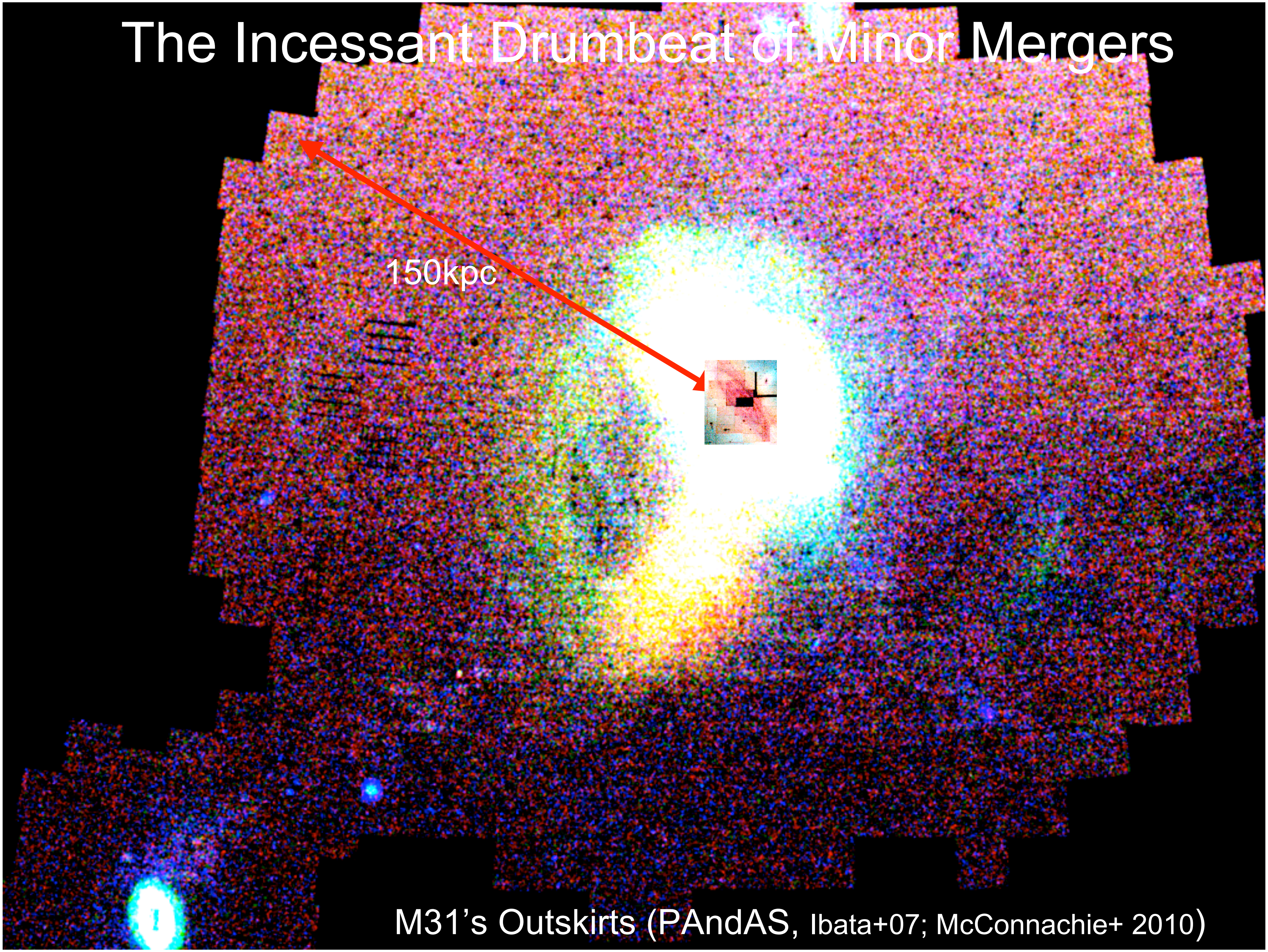
Modern (wide-field CCD) view of M31 (Irwin+05)



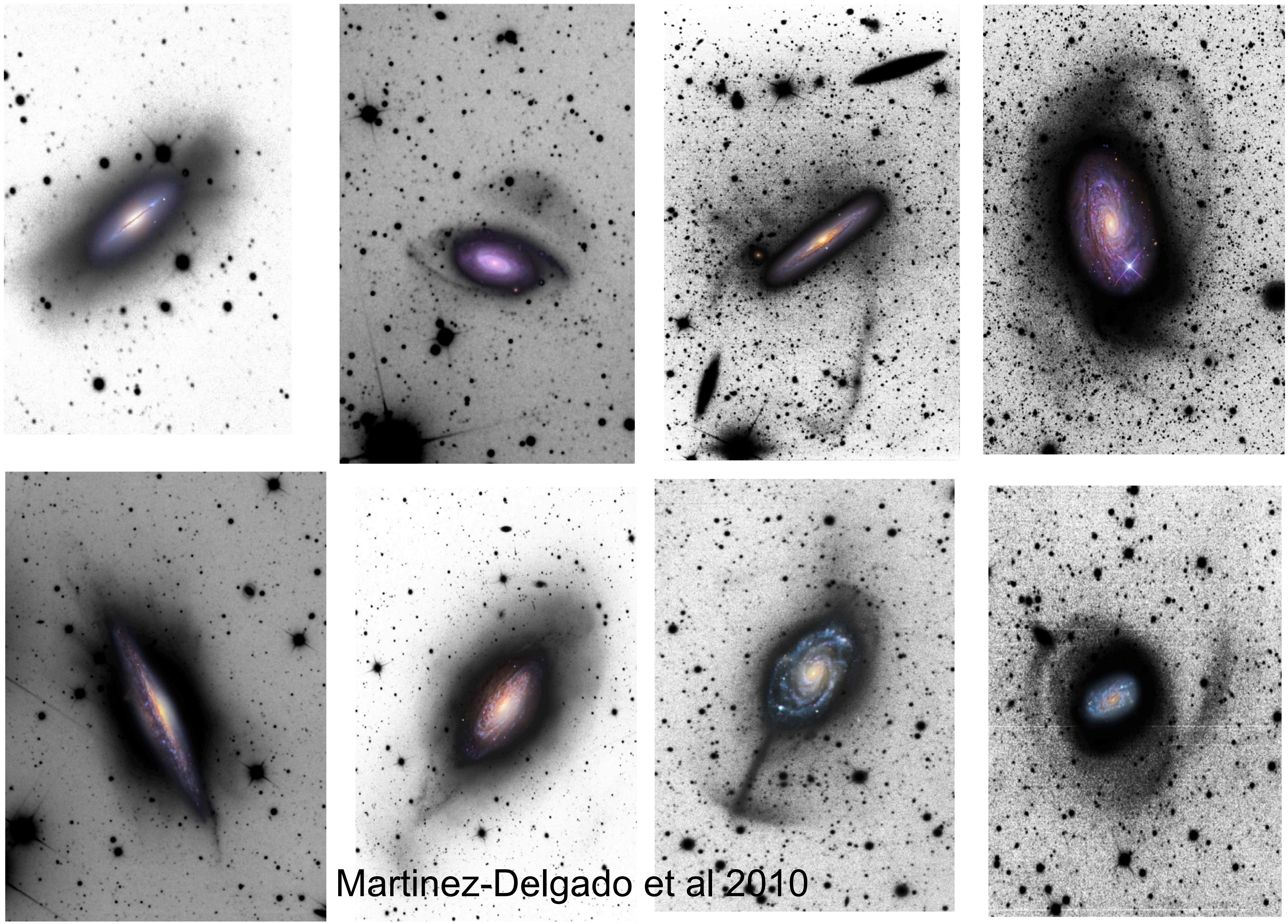


40
20
0
-20
-40
40
20
0
-20
-40
-40
-20
0
20
40

The Incessant Drumbeat of Minor Mergers



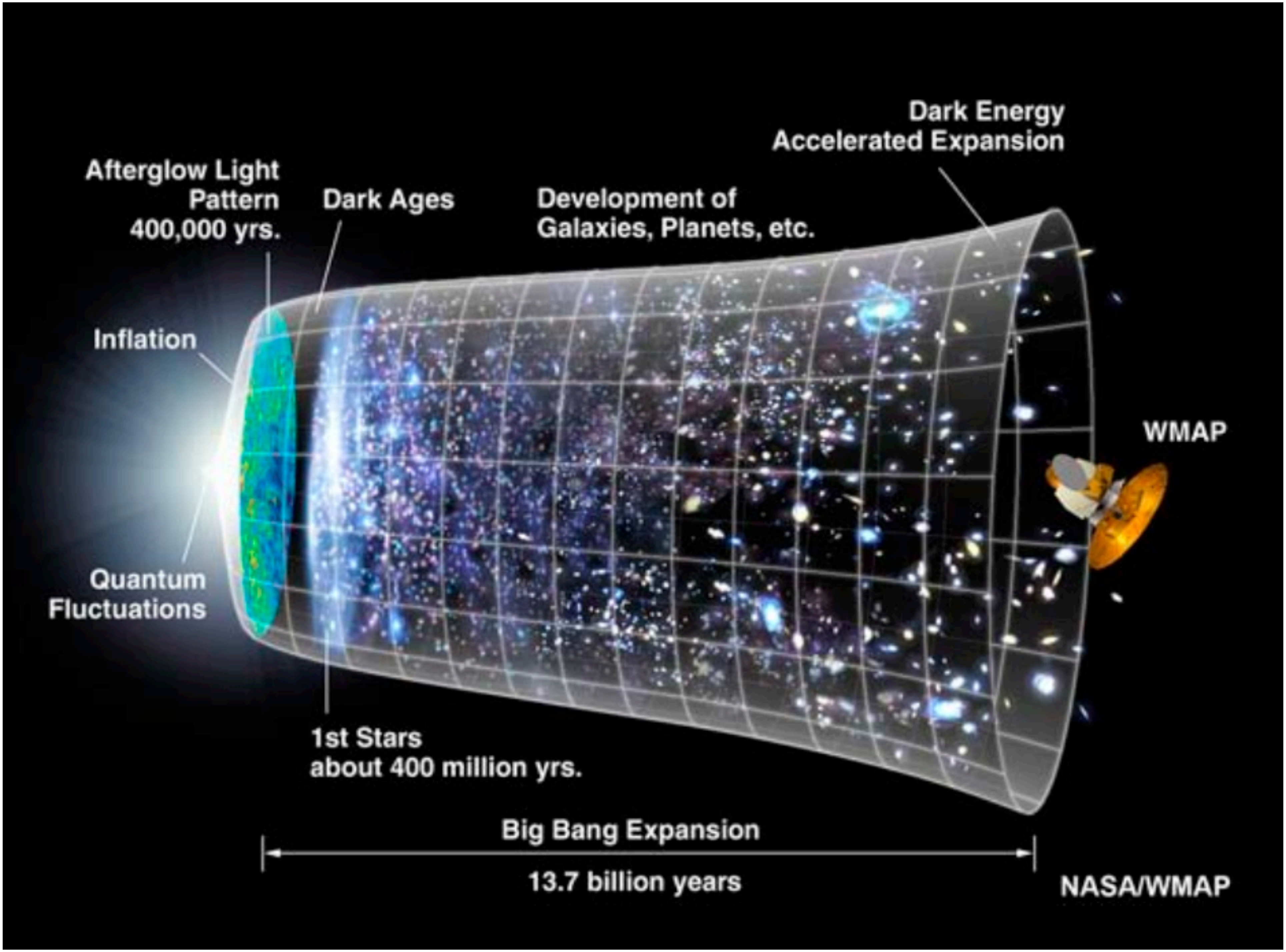
M31's Outskirts (PAndAS, Ibata+07; McConnachie+ 2010)

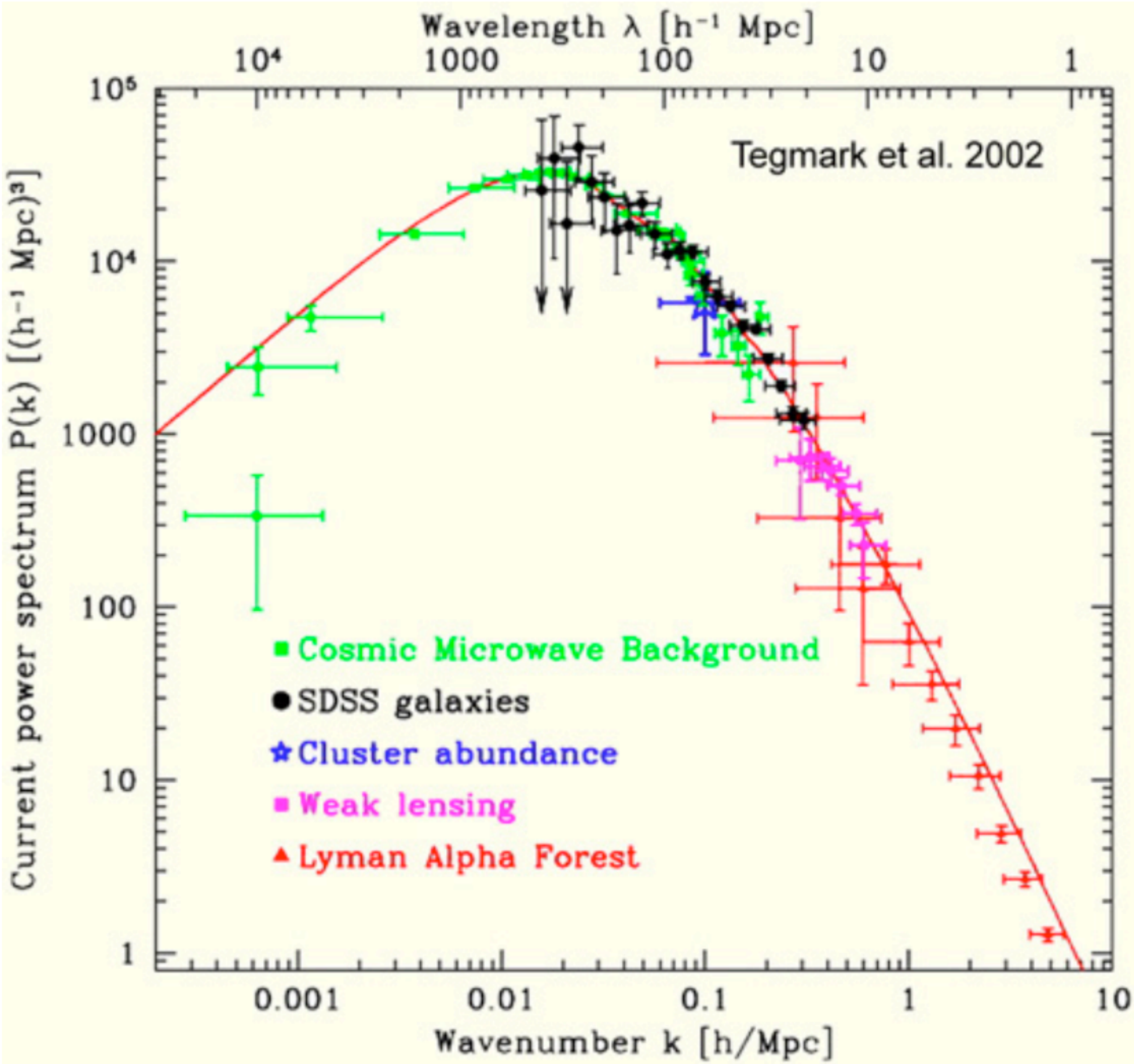


Martinez-Delgado et al 2010

Topics: Galaxy Formation and Evolution

- 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 -- ***Cosmology***
- In a hierarchical Universe massive galaxies are predicted to be the result of the successive mergers of less massive galaxies (White and Rees 1978).


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP

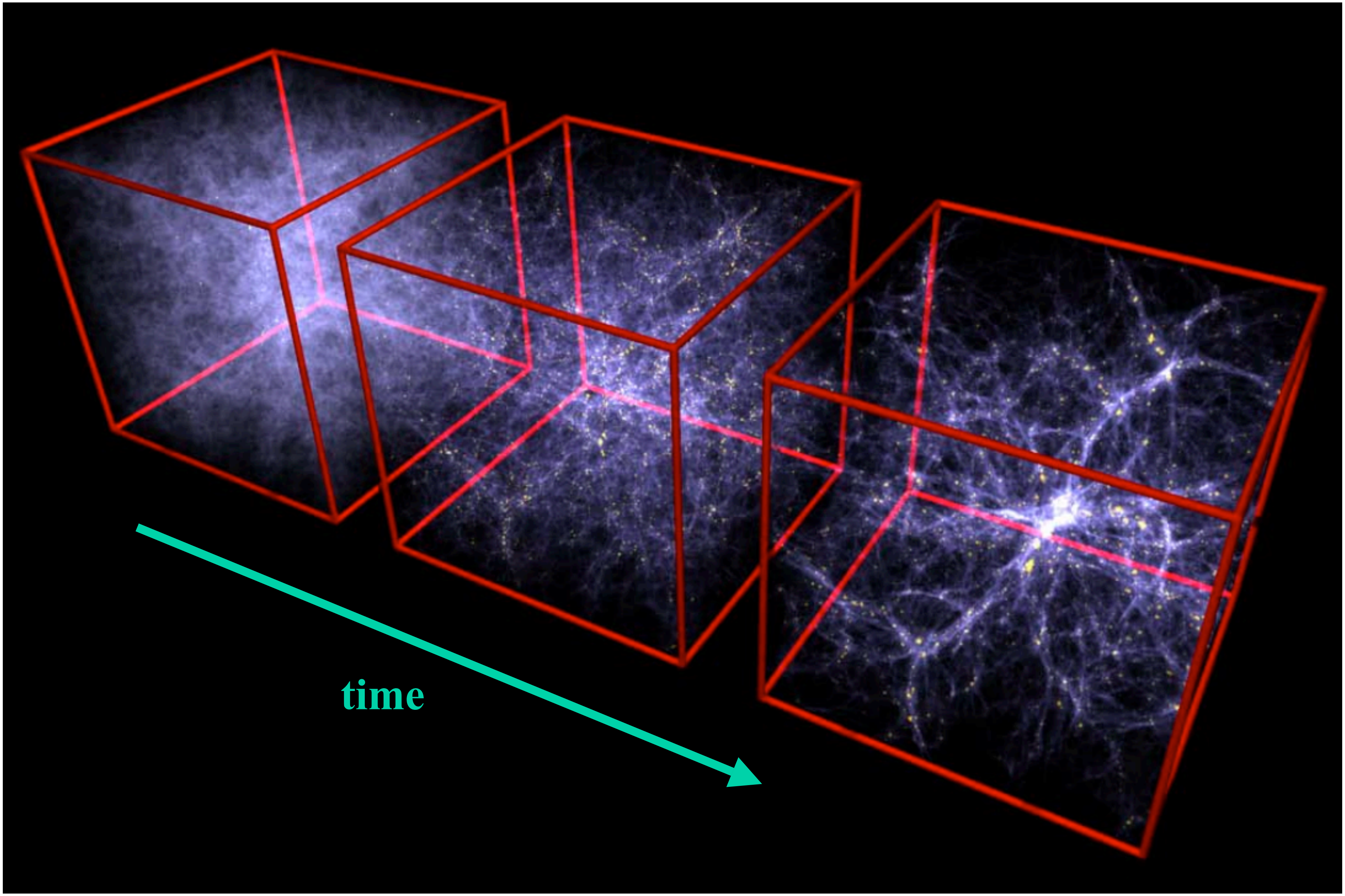


Wavelength λ [h⁻¹ Mpc]
10⁴
1000
100
10
1
10⁵
10⁴
1000
100
10
1
Tegmark et al. 2002
Current power spectrum P(k) [(h⁻¹ Mpc)³]
Cosmic Microwave Background
SDSS galaxies
Cluster abundance
Weak lensing
Lyman Alpha Forest
0.001
0.01
0.1
1
10
Wavenumber k [h/Mpc]

Topics: Galaxy Formation and Evolution

- Instantaneous collapse (ELS) picture
  - galaxies form from single protogalactic clouds
  - formation of all principal components (mass, gas, stars, metals) begins simultaneously
  - galaxy type dictated mainly by angular momentum and mass of protogalactic cloud
  - galaxy type imprinted at birth- no subsequent changes

- Cold Dark Matter (CDM) hierarchical picture
  - galaxies grow from merging of small protogalactic fragments, plus accretion of intergalactic gas
  - formation is continuous, with assembly of mass, gas, stars, metals only indirectly coupled
  - galaxy type determined by cloud mass, merger history, local environment
  - major transformations in type possible

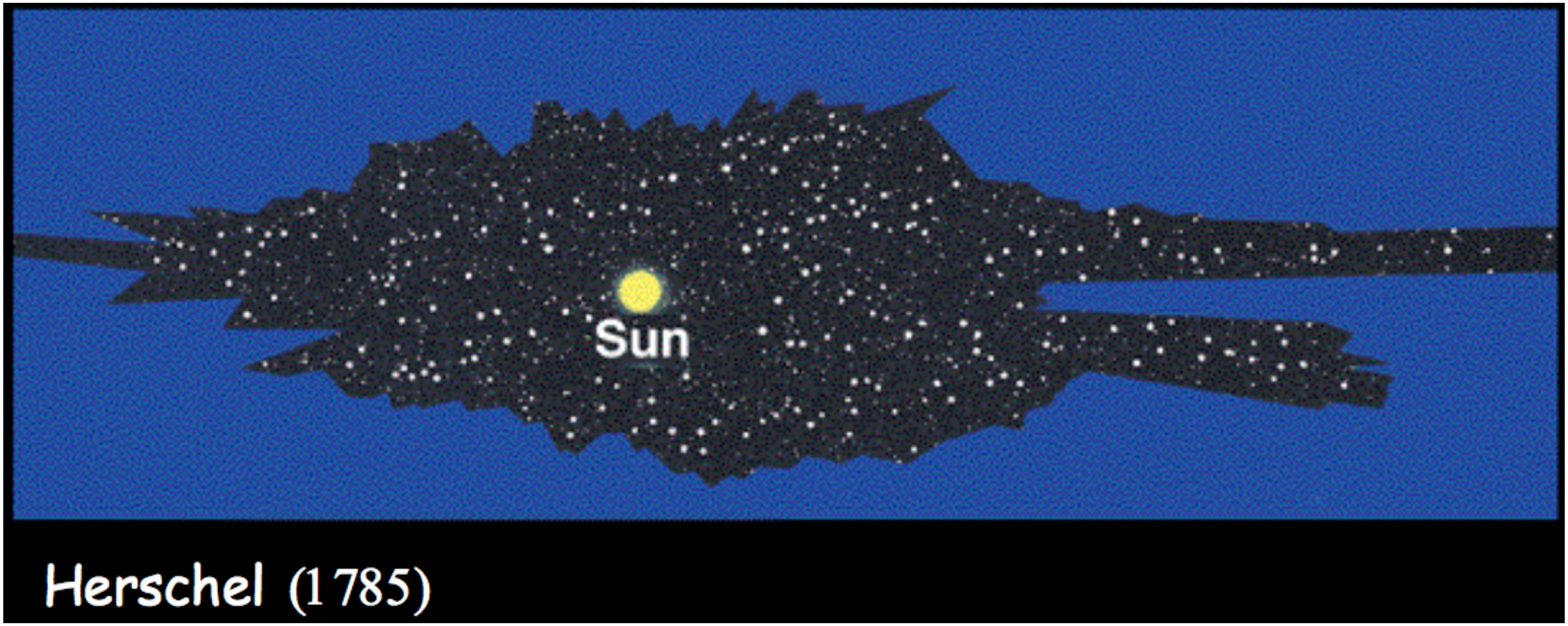

time

Historical Introduction

- A good *modern* working definition of a galaxy is a population of stars, gas and dust bound gravitationally within a dark matter halo (TBD).
- The early history of galaxy studies led up to and culminated in Hubble's confirmation that they are stellar systems external to our own Galaxy and that they are receding from us (Hubble's expansion law - 1929)
- This marked a turning point towards the beginning of galaxy "evolution" studies as we know it now.

Historical Introduction

- 1610 Galileo resolves Milky Way into stars
- 1755 Kant introduces island universe hypothesis for Milky Way
- 1785 Herschel makes first mapping of MW structure
- 1800's thousands of galaxies catalogued, but nature misunderstood
- 1918 Shapley uses Cepheid distances to globular clusters to show that Galactic center is 15 kpc from Sun, MW diameter ~100 kpc
- 1922 Kapteyn models MW: R ~ 10 kpc, roughly centered on Sun (the *observable* Universe)



Astronomers were trying to determine the structure of our galaxy
(which was thought to be the known Universe)
and locate the relative position of the Sun in the vast array of stars.

“spiral nebulae” (galaxies)

- Some astronomers postulated that they were island universes just like our own Galaxy (but they had no proof)
- most astronomers suspected they were part of our own Galaxy, just like other nebulae and clusters.
- But recent studies had shown them to have very high radial velocities.
- If only astronomers could determine the distance to these spiral nebulae, their nature could be tied into the structure of the Galaxy.

Shapley (1917-8)

- use the centroid of globular cluster system to define Galactic center

globular cluster M2

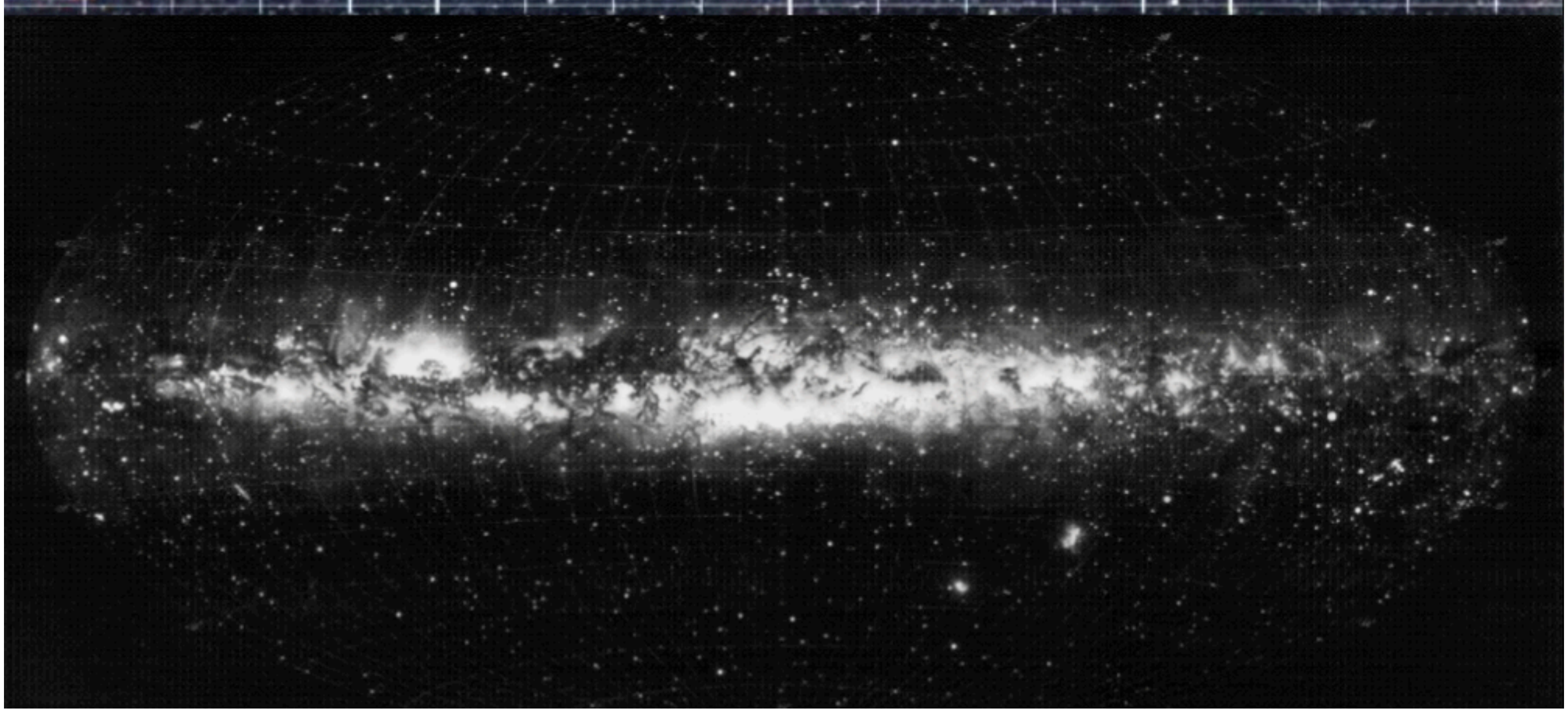
Shapley's Milky Way

- **Harlow Shapely (1914)** began studying globular clusters (associations of stars)
- Noted they were widely distributed above and below the galactic equator.
- Yet largely concentrated around one hemisphere in galactic longitude.
- this skewing in galactic longitude was unique to globular clusters and no other type of object – nebulae, open clusters, double stars, etc.

- Determined the distances to the globular clusters using a the newly found technique, the **period-luminosity relation**.
- 1916: found the distance to M13 as 30kpc, which placed it well outside the size of Kapteyn's Universe.
- Since the globular clusters were of probably similar size,
  and if they are outside of our galaxy but associated with it,
  then their distribution might suggest that we - *not they* – are in a skewed position !!

- Perhaps the Sun is located toward the edge of an enormous system, **5 times larger** than previously thought, defined by the globular clusters.

Modern view of our Milky way

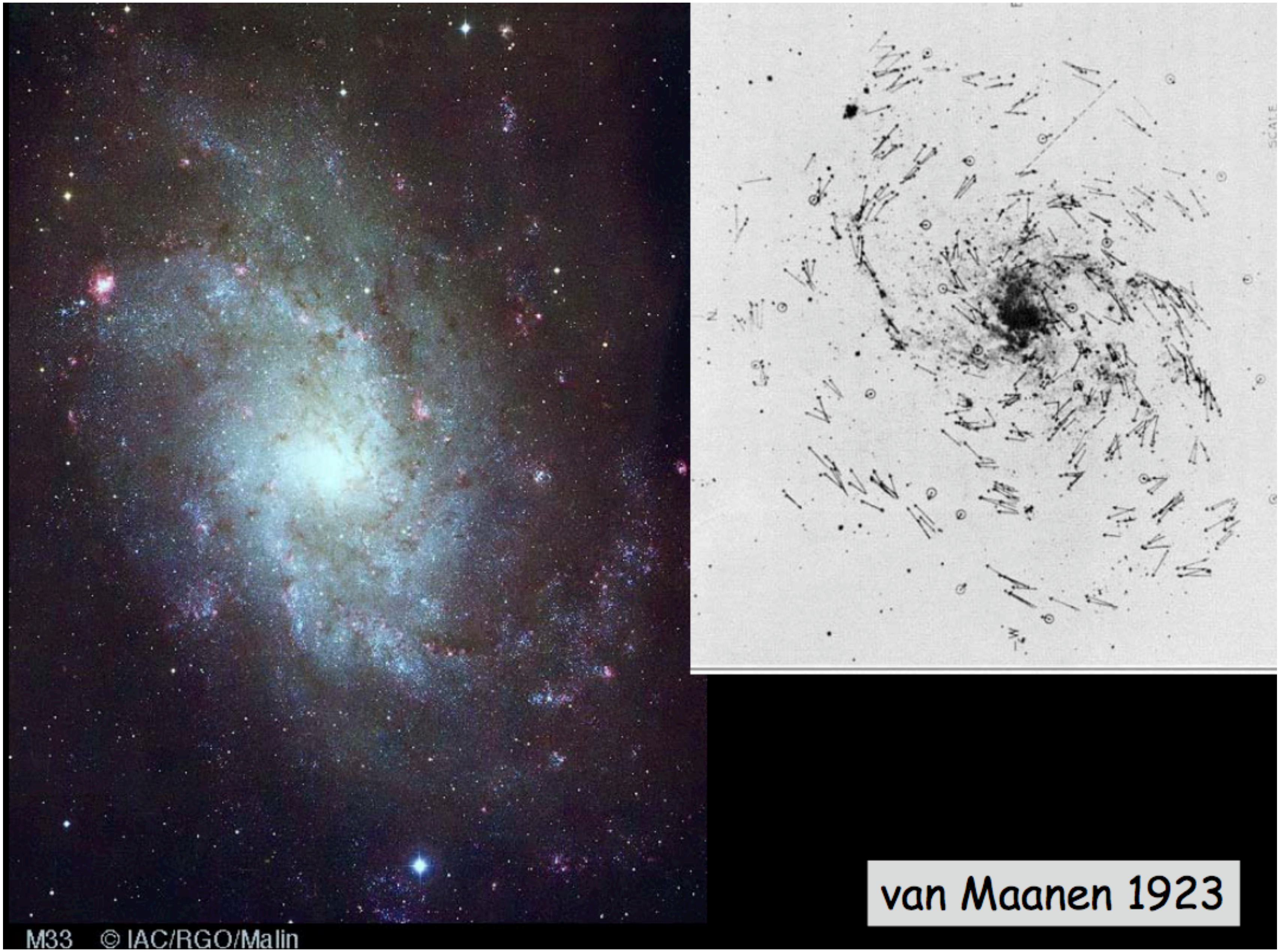


Historical Introduction

- 1918 Curtis notes similarity of edge-on "nebulae" (galaxies) to Milky Way
- 1920 Shapley-Curtis debate on nature of spiral nebulae
- 1924 Hubble detects Cepheid variables in M31, confirming extragalactic nature of galaxies
- 1928 Oort measures solar orbit (from motions of stars), deduces mass of Milky Way
- 1929 Hubble & Humason discover linear expansion of universe
- 1930 Trumpler discovers diffuse interstellar extinction (more accurate distance scales)

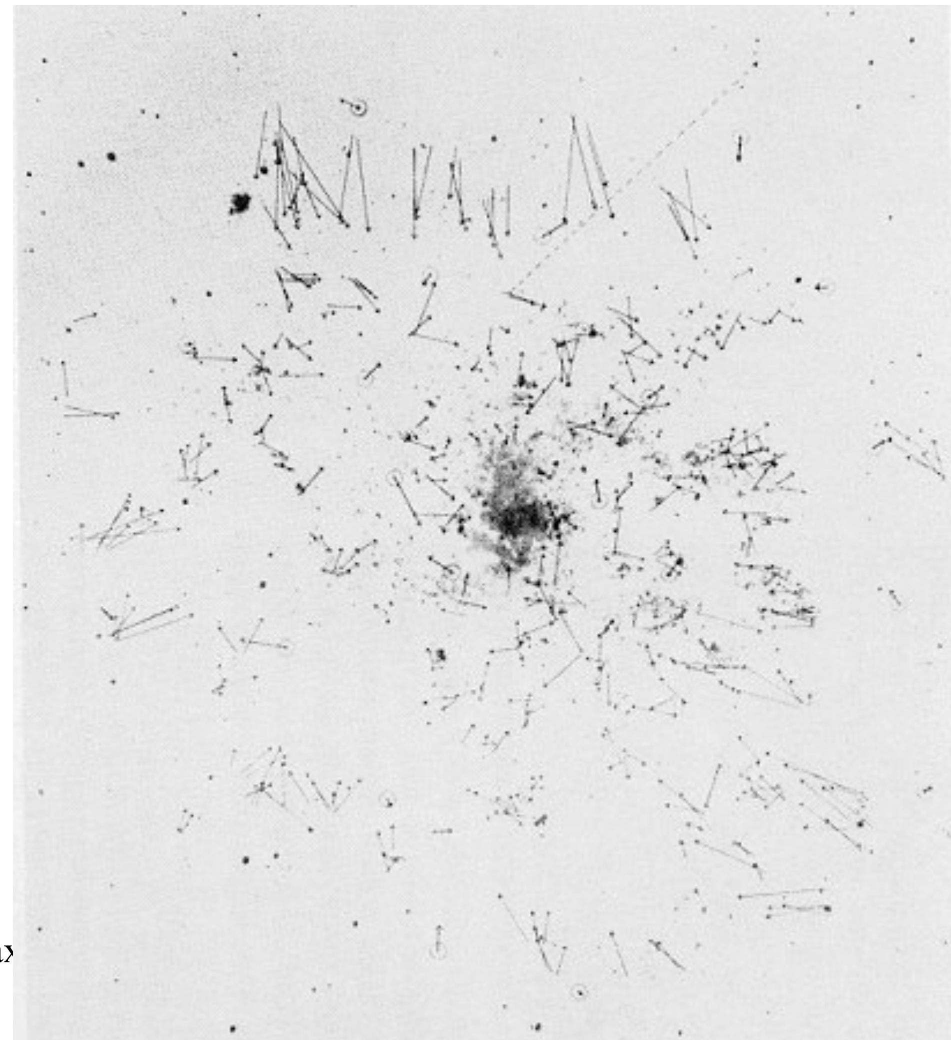

NGC 891
NGC 4631

Rotation of the Spiral Nebulae?

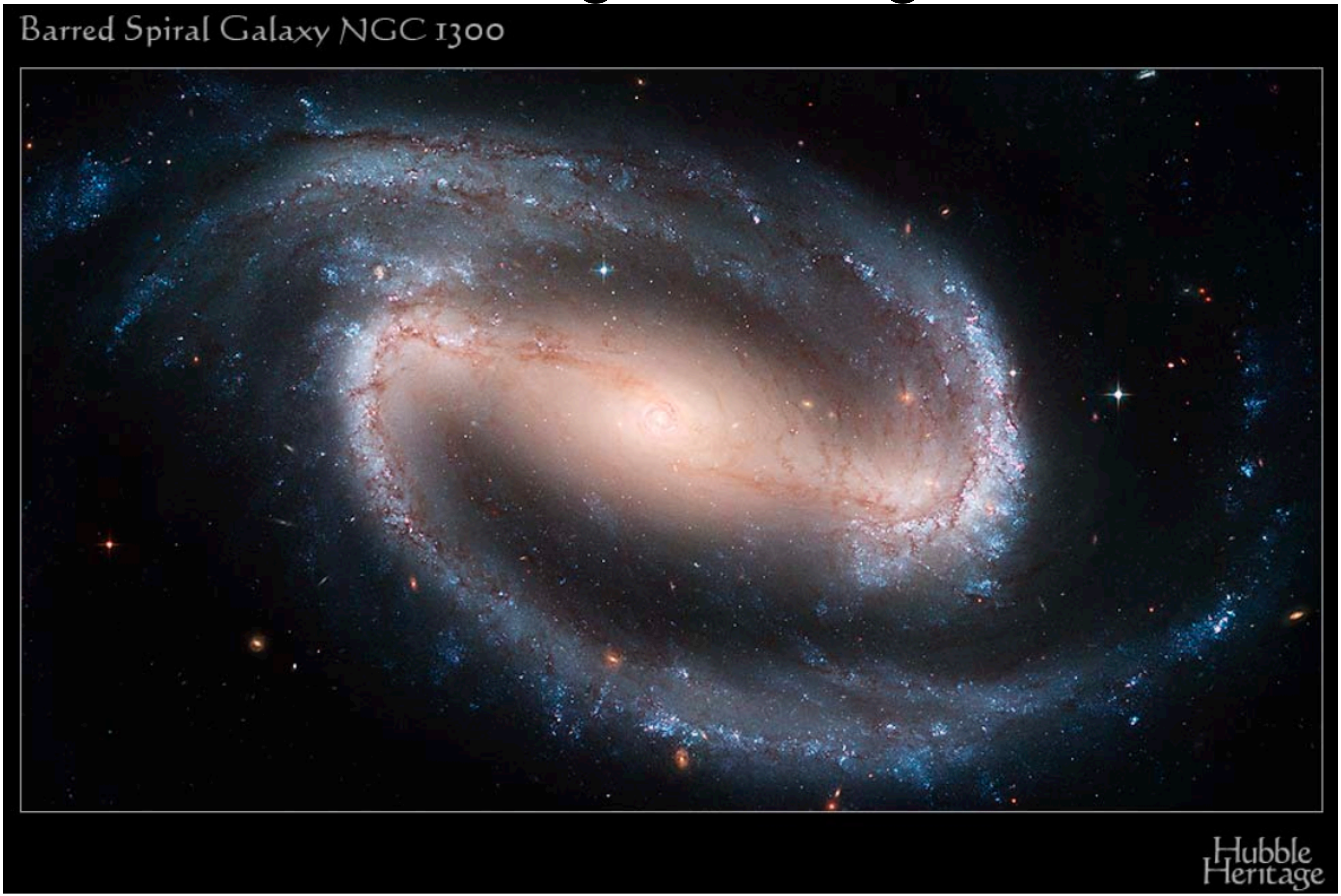


Lundmark 1921: failed to see rotation in same galaxy (M33)

- This was thought to be a more reasonable finding if indeed they were at great distances
- Debate raged about whether the spiral nebulae could be island universes

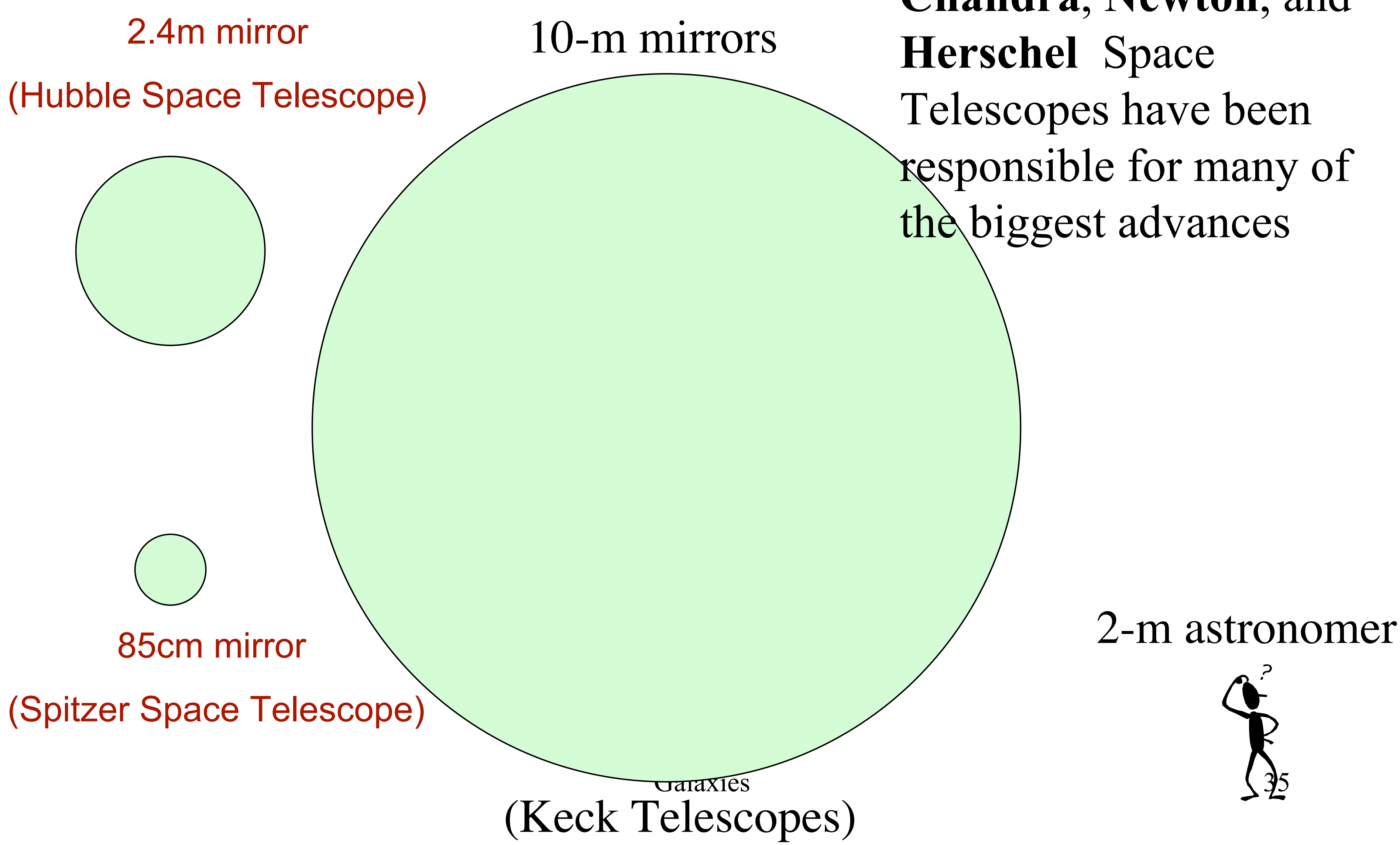


External 'local' galaxies in great detail

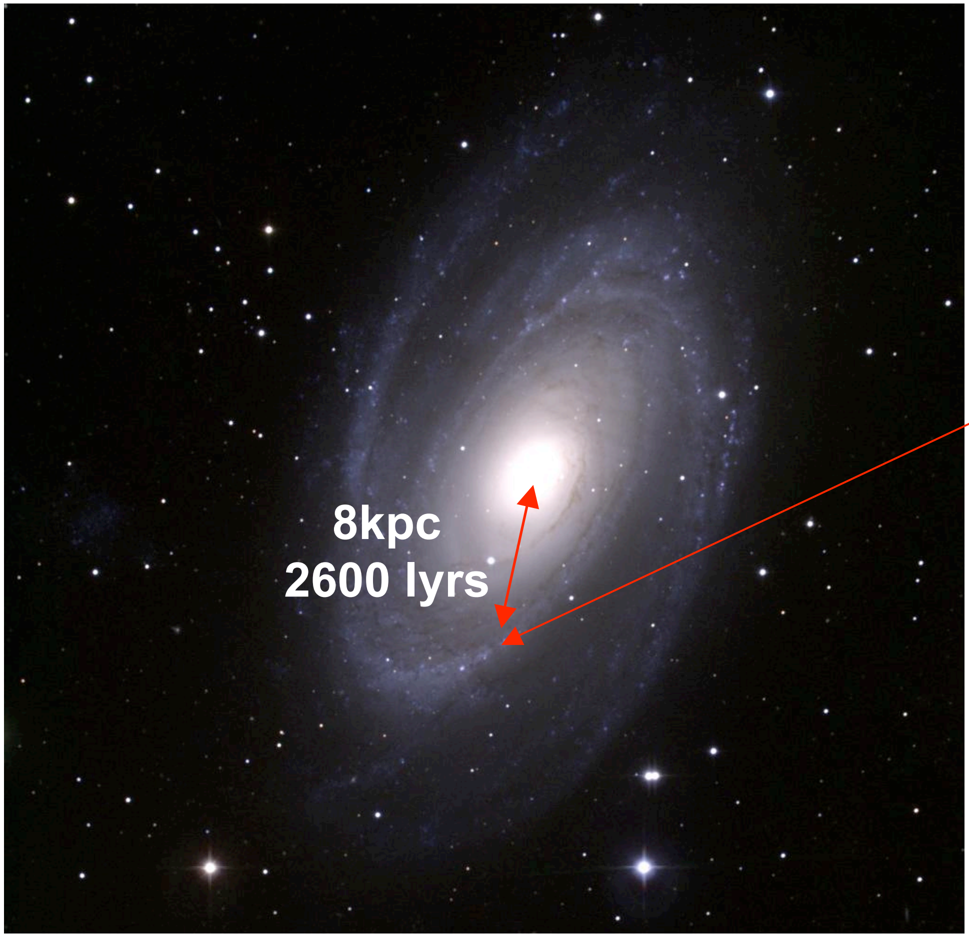


A modern view: past decade of discovery: laboratory for studying galaxy evolution

The **Keck, VLT, Gemini** Optical Telescopes along with the **Hubble**, **Spitzer**, **Chandra**, **Newton**, and **Herschel** Space Telescopes have been responsible for many of the biggest advances

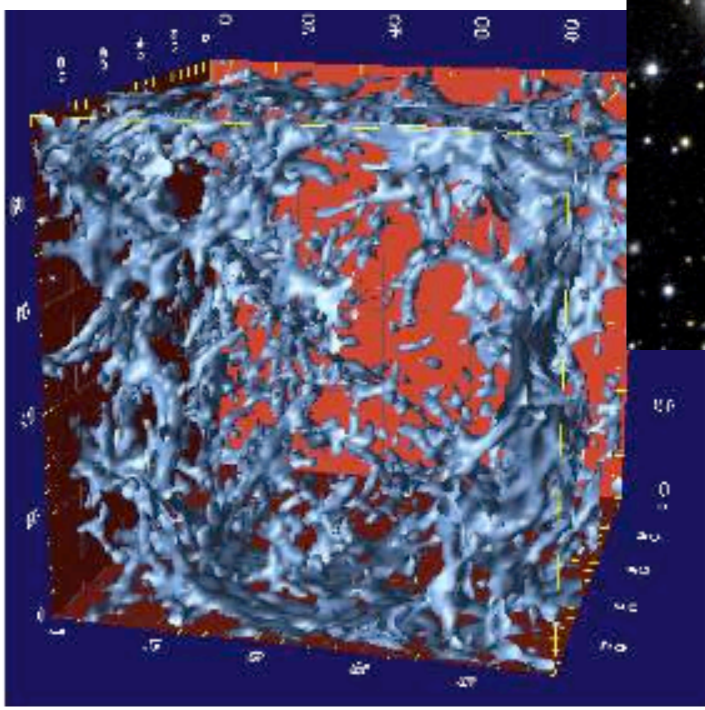


The Sun and Solar System live in a large Spiral Galaxy with a 100 million "sun" black hole at the centre

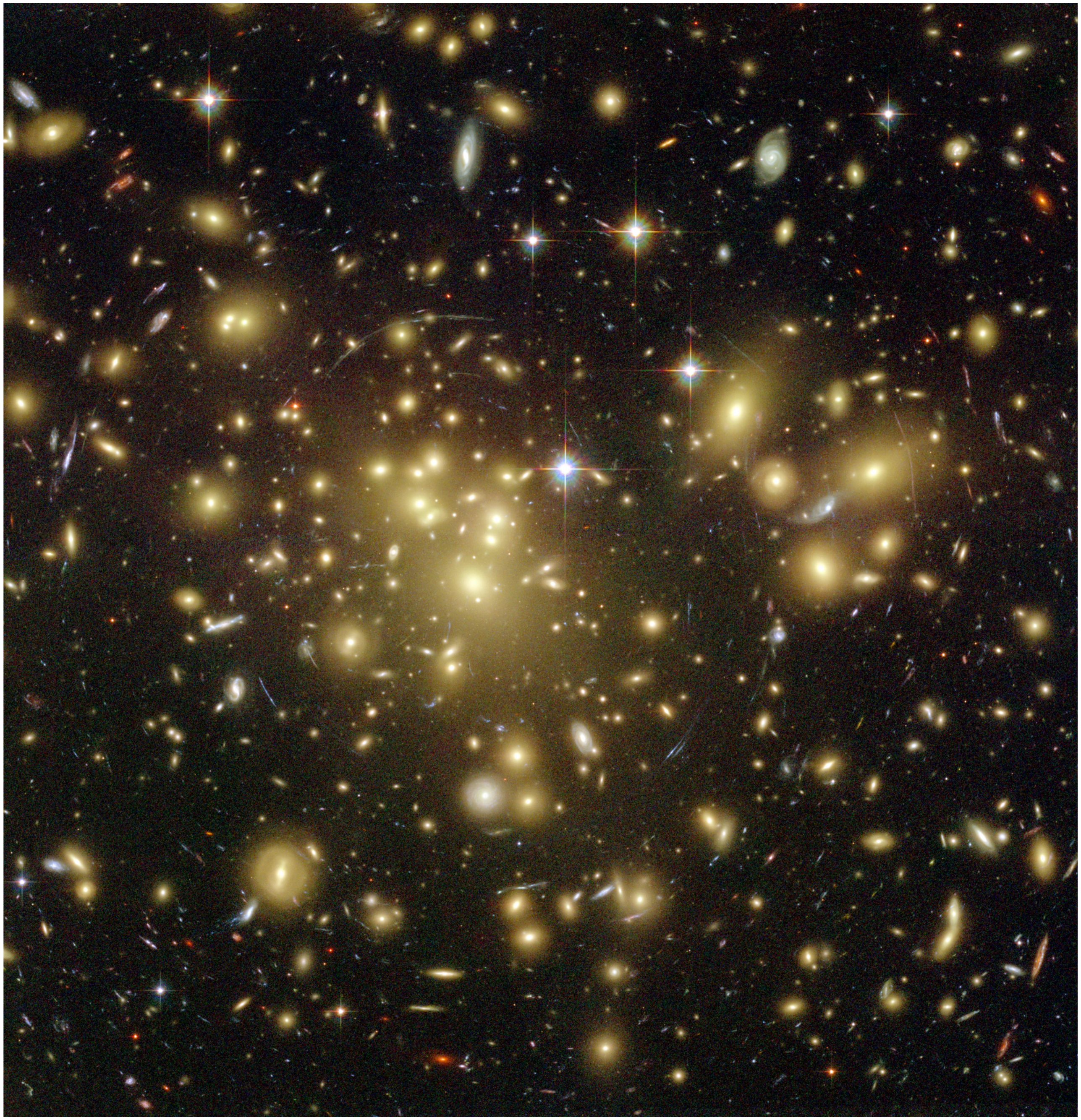


- A large spiral galaxy like the Milky Way Galaxy contains around *100 billion* stars, with a **total mass** of ~10^{12} "solar masses"
  - a galaxy is a big group of stars, gas and dark matter.
- We live in the suburbs
- Hard to comprehend the size, shape, and age of the Universe ;-(
- Speed of light as a *time machine* allows us to study it!

The Milky Way Galaxy is a member of a small group of Galaxies (M31 & M33 are other two big galaxies)



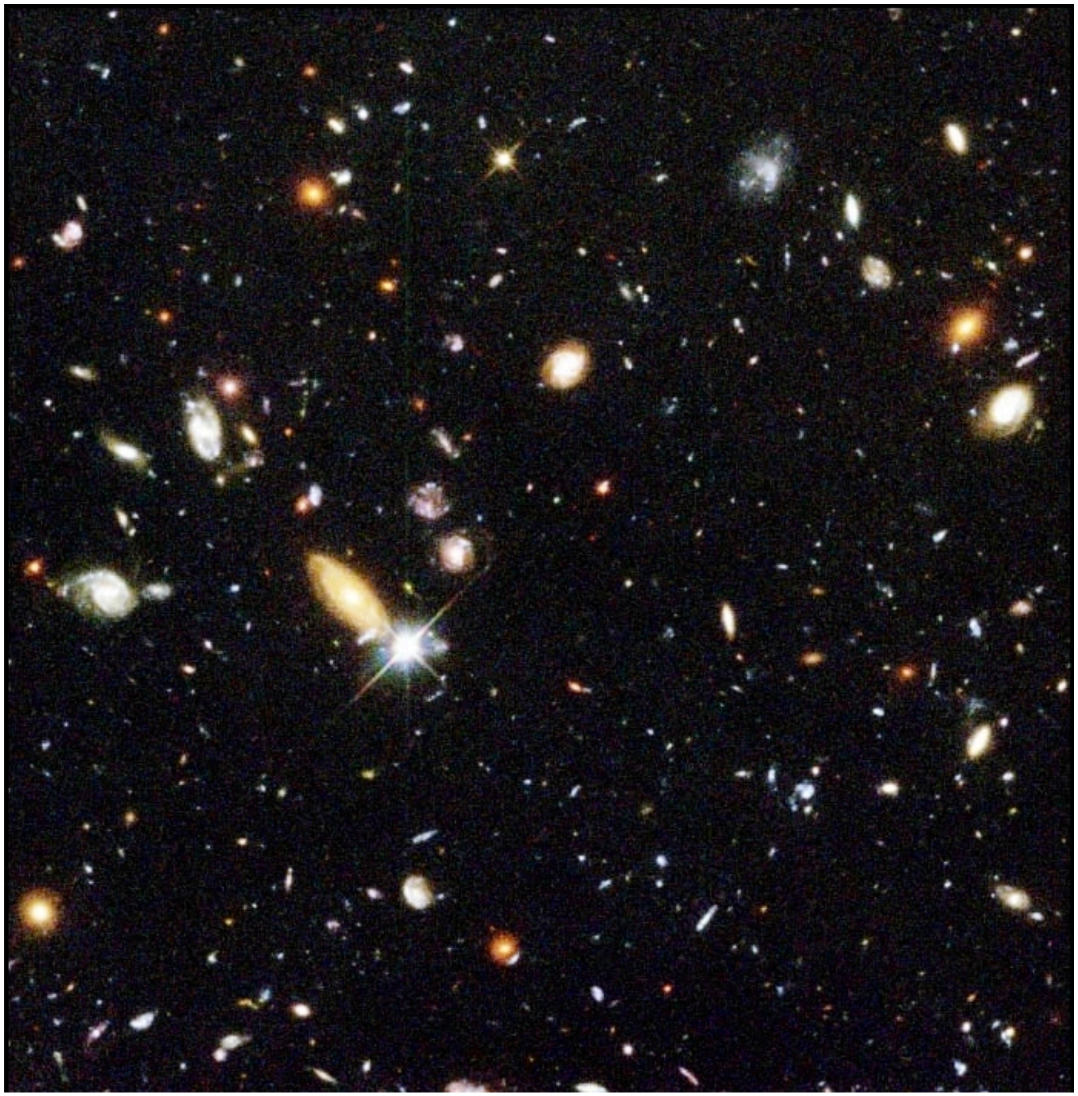
The Local Group is falling into the Local Super Cluster



There are much larger concentrations of galaxies

"Rich" Galaxy Clusters (this one seen about 1/4 the way back to Big Bang)

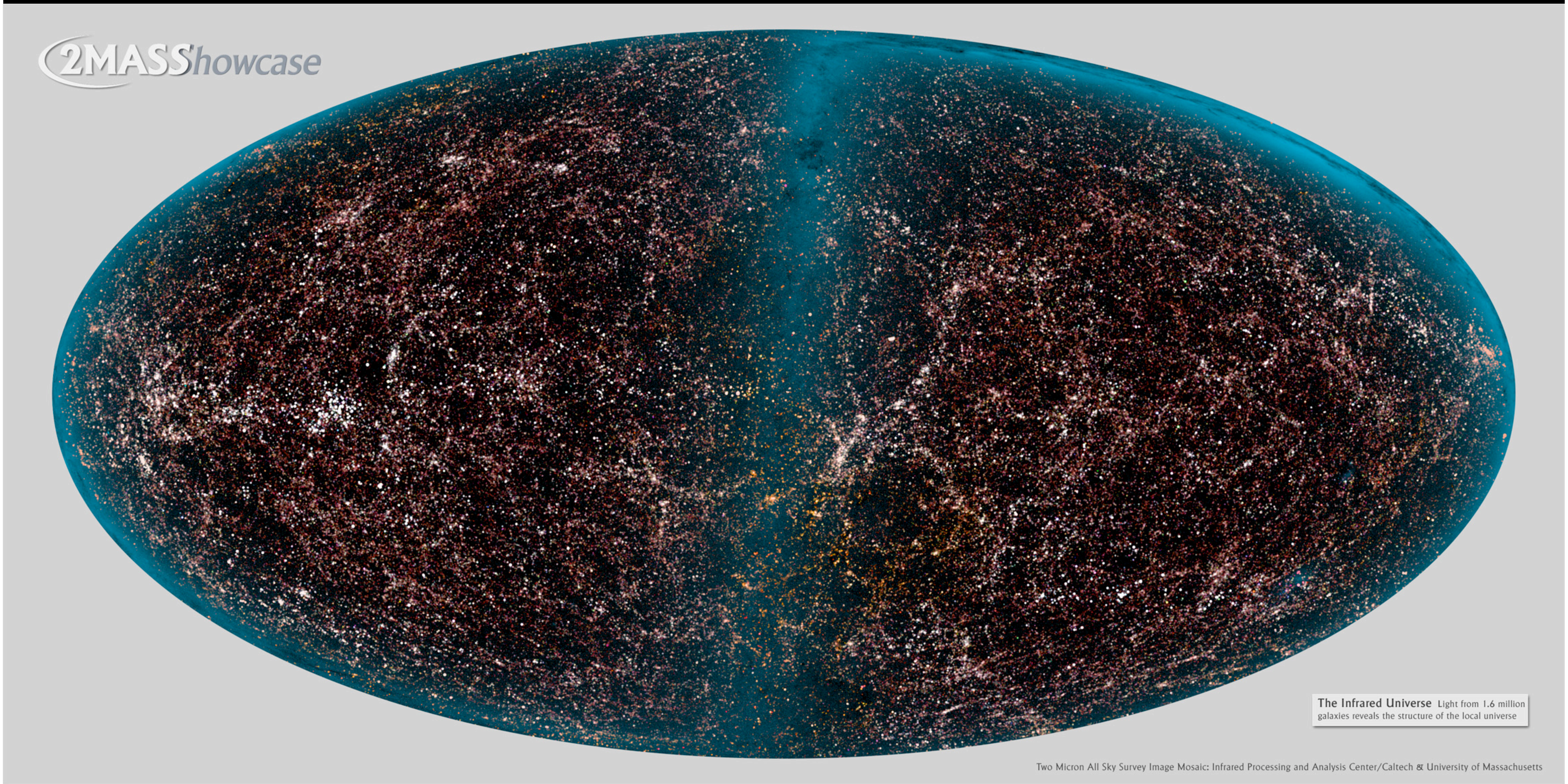
Cluster galaxies evolve differently/faster than field galaxies



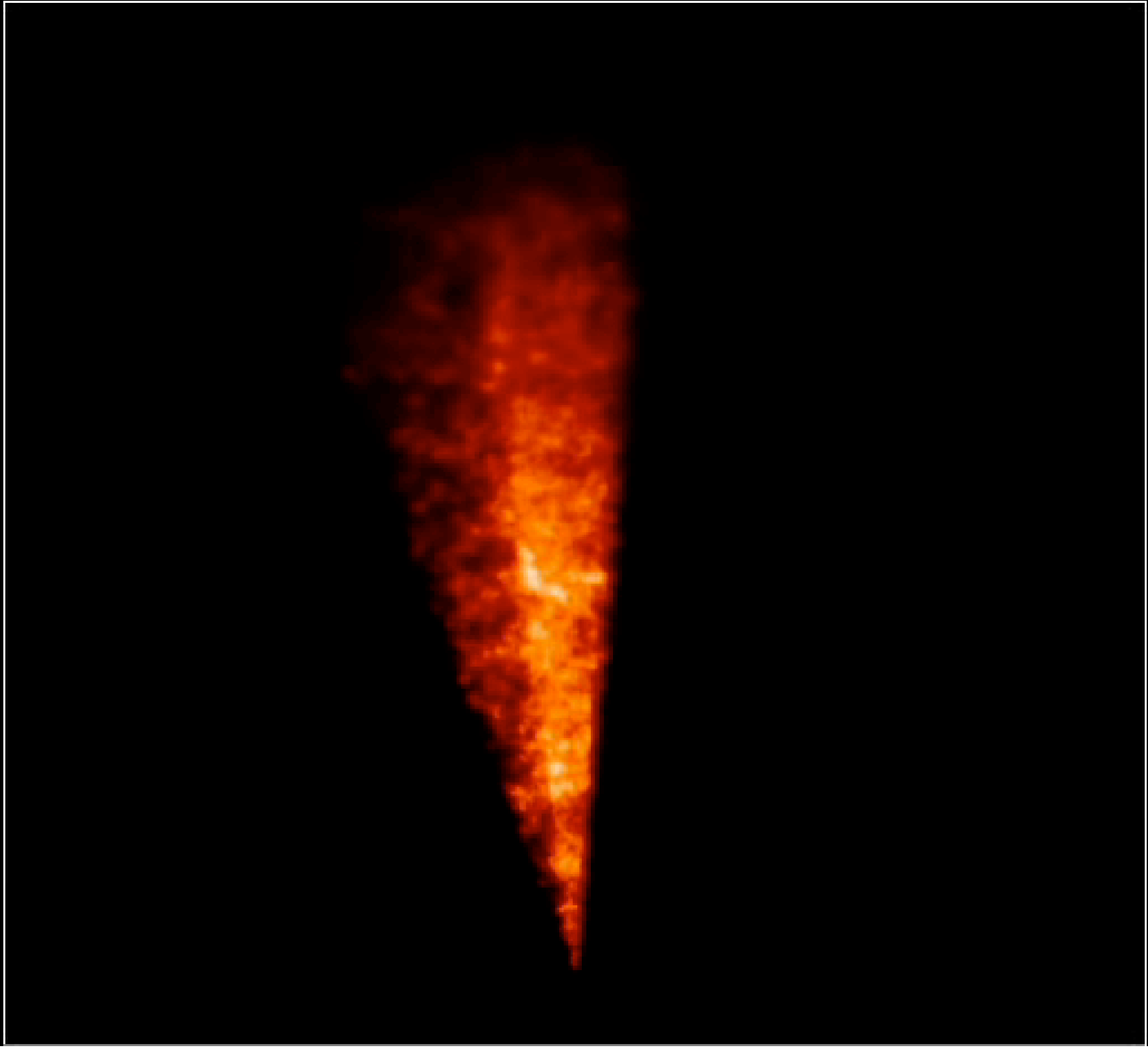
All the galaxies in the cluster represent only a tiny fraction of the total number of galaxies in the Universe (several billions)

(The Hubble Space Telescope DEEP field)

Large-Scale Structure of local galaxies
All-sky surveys



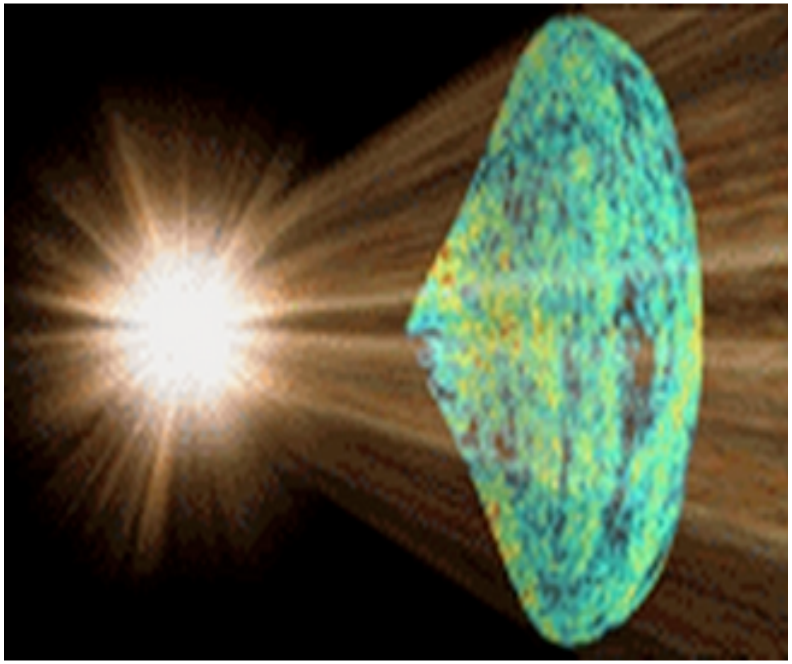
2dF redshift survey: LSS out to large distances



The big picture - the history of the Universe

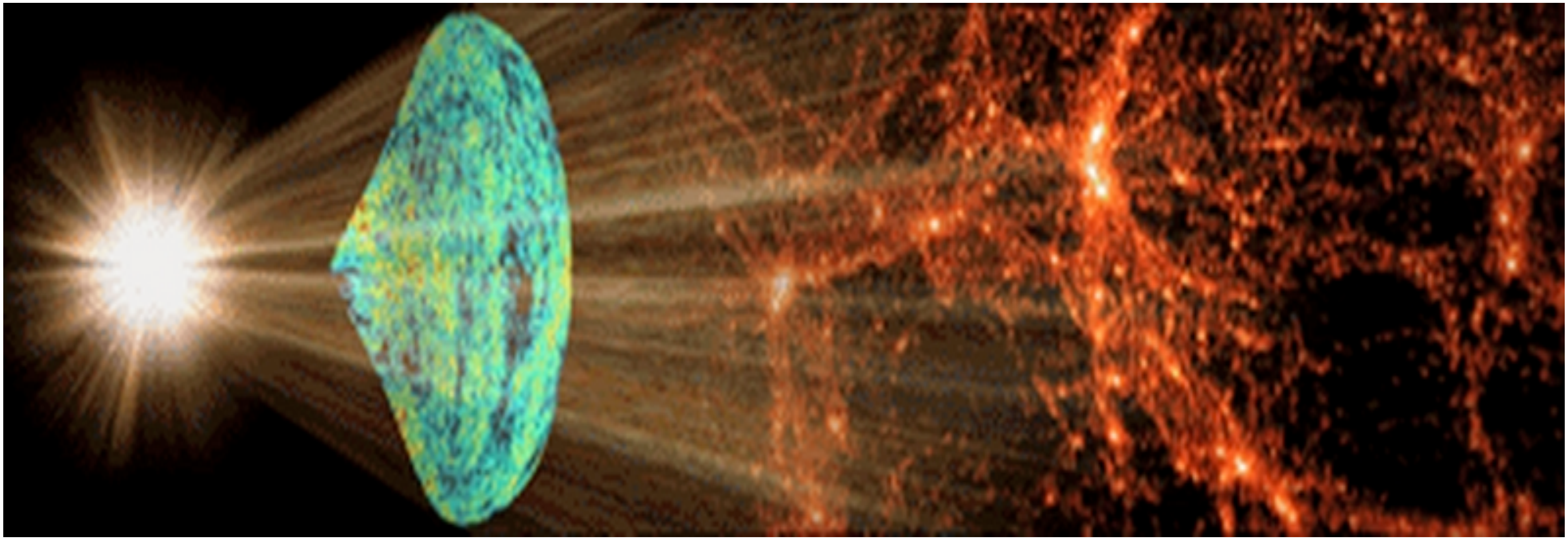
- The big bang (Quantum Gravity at work) …
  What comes before ??????
  - Our physics is not good enough yet to tell us!

The "*seeds*" of galaxies



- The Cosmic Microwave Background, 400,000 yrs after Big Bang: light and matter have "decoupled" (well understood physics: COBE/WMAP satellites)
  - The first "easily observable" Universe

Galaxy Formation? (when/how do the stars form?)



- Starting ~1 billion years after the big bang, the first recognizable (now detectable!) "galaxies" started to form.
- Gas falling into overdensities of Dark Matter … cools, compresses, forms stars.
- Small galaxies *merge* to form bigger galaxies

Galaxy Evolution - Dark Matter and Gravity

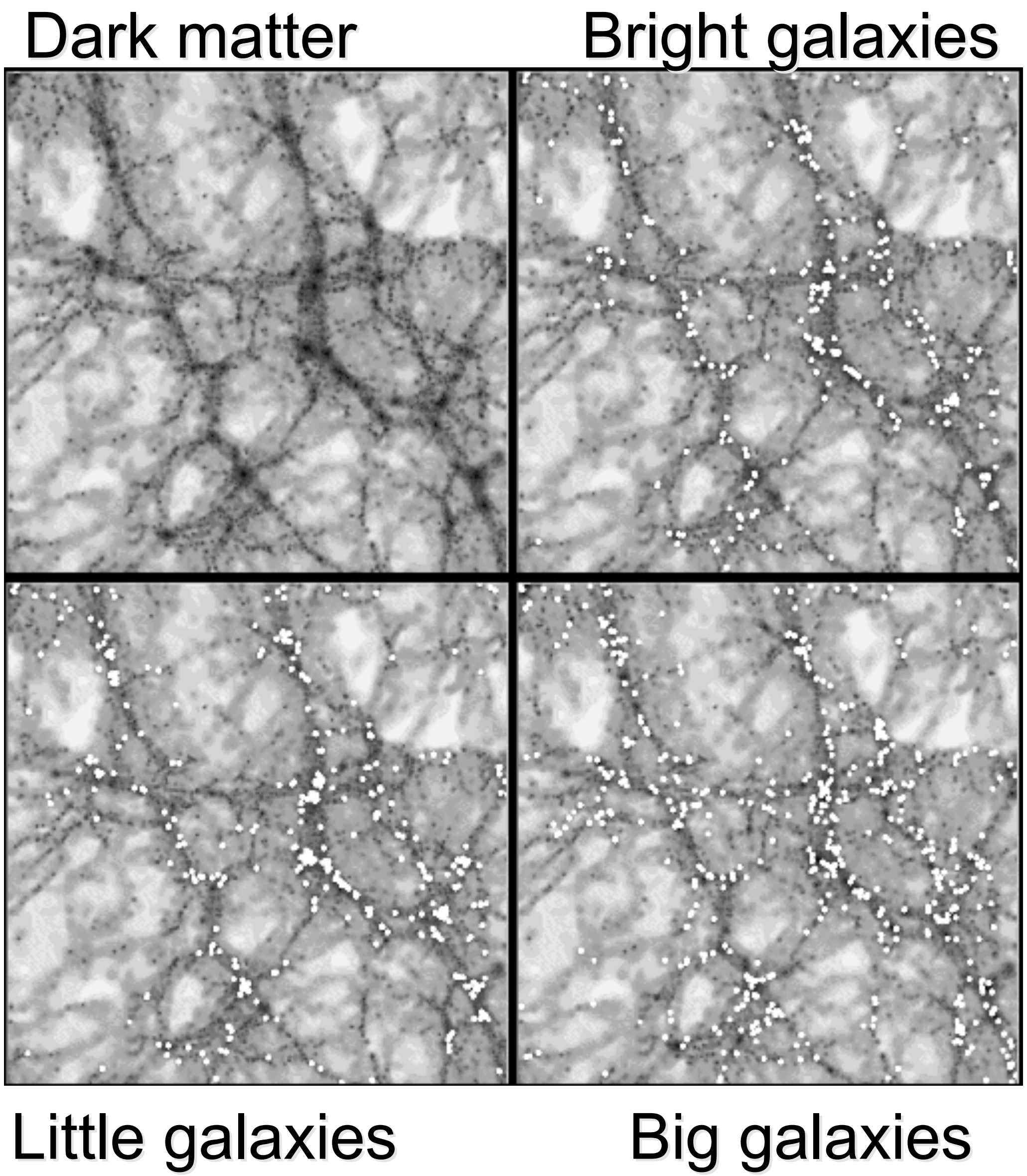
THEORY OF GALAXY FORMATION and EVOLUTION:
with baryons - the stuff we can see!

Current Theories
-gas cooling
-star formation
-feedback/outflows
-galaxies merging

•Difficulty *predicting* how galaxies form …

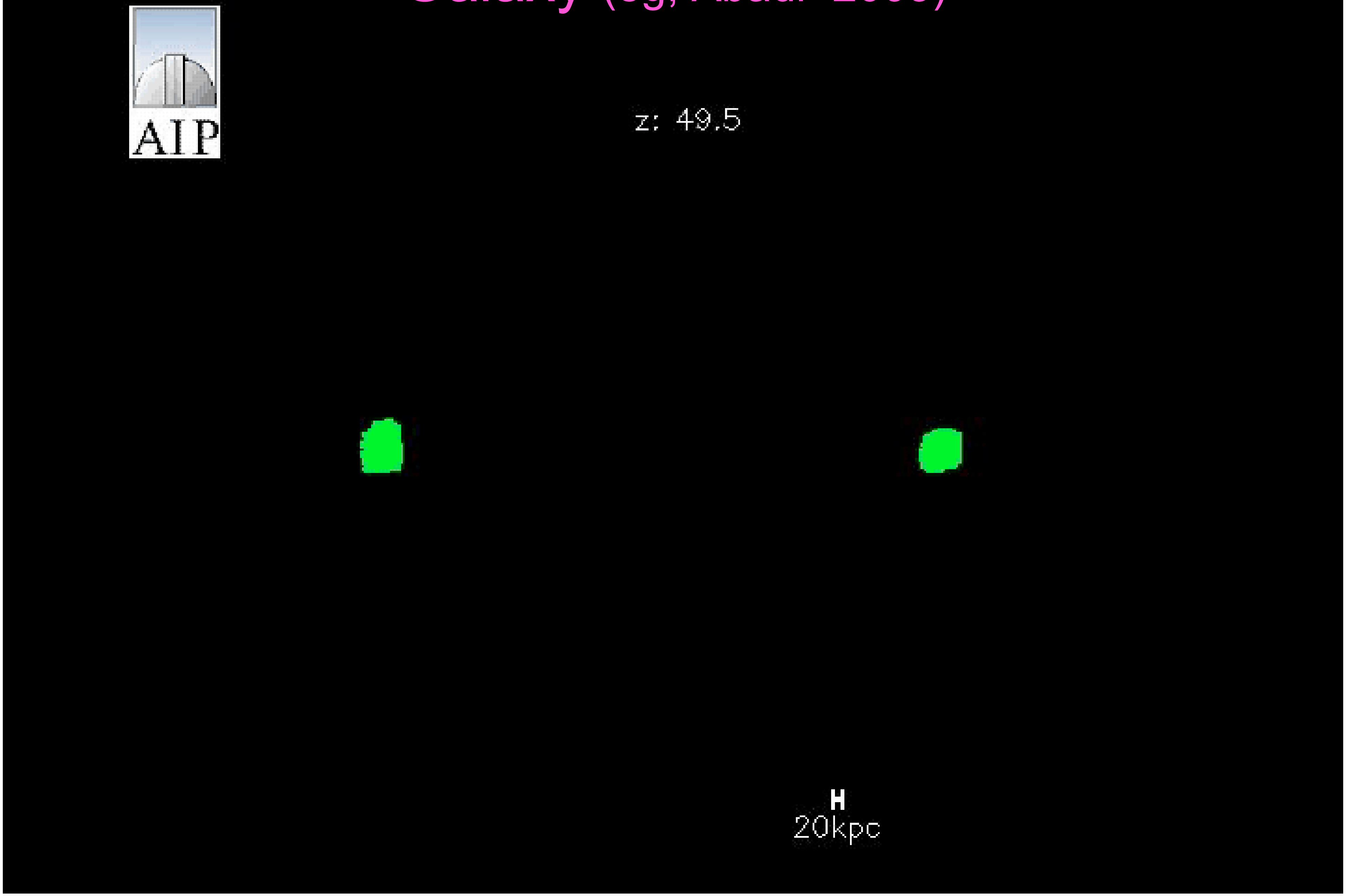
•Don't even know about all the galaxies at different times and their basic properties (gas supplies, stellar masses, star formation histories)!

•**Need observations**



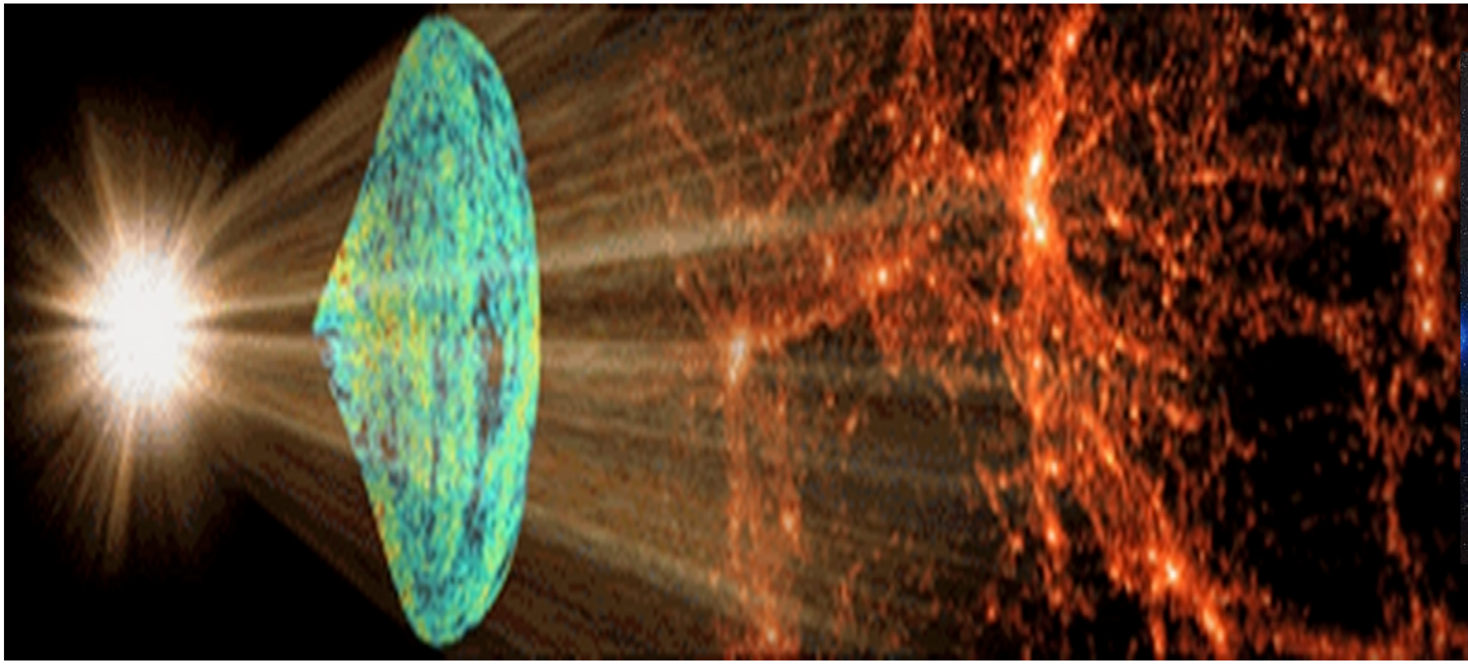
(Kauffmann et al. 1998)

Add gas (hydrodynamics) to build big Spiral Galaxy (eg, Abadi+2003)



Context: *Hierarchical Galaxy Formation*

(How/when are the galaxy components assembled?)



Big Bang … Cosmic Microwave Background …

… Galaxy Formation and Evolution … **Fossil Records today!**

Local galaxies *(MW, Andromeda) are ideal laboratories to study archeology.*

Optical,Infrared,Radio/millimetre allow studies of distant forming galaxies;

End lecture 1

Galaxies

Lecture 2: Review ; Galaxy Classification

- Review of some basic astronomy concepts needed

Classification

- Hubble tuning fork
- Other schemes

http://www.ast.cam.ac.uk/~schapman/Part3Galaxies/

The Magnitude Scale

- $L = 4\pi d^2 f$ – where L is the intrinsic luminosity, d is the distance and f is the flux measured by the observer. [assumes that the source radiates isotropically – good approximation for most galaxies and stars]
- For historical reasons the apparent brightness (= measured flux) of sources is specified using a magnitude scale
- Definition:

$$m_\lambda = -2.5 \times \log_{10} f + \text{constant}$$

where m_λ is the "apparent magnitude". The flux, f, is measured within a well-defined magnitude range, with standard "passbands" indicated by "λ" or similar, e.g. $m_B = m(B) = B = \mathit{B}$ all used for B-band magnitude

$$m_\lambda = -2.5 \times \log_{10} f + \text{constant}$$

- The minus sign, "-", is important – fainter objects have large values of m
- The constant that defines the zero-point of the scale was defined historically such that the bright visible star Vega (αLyr) has zero-magnitude in all passbands. Thus, for Vega

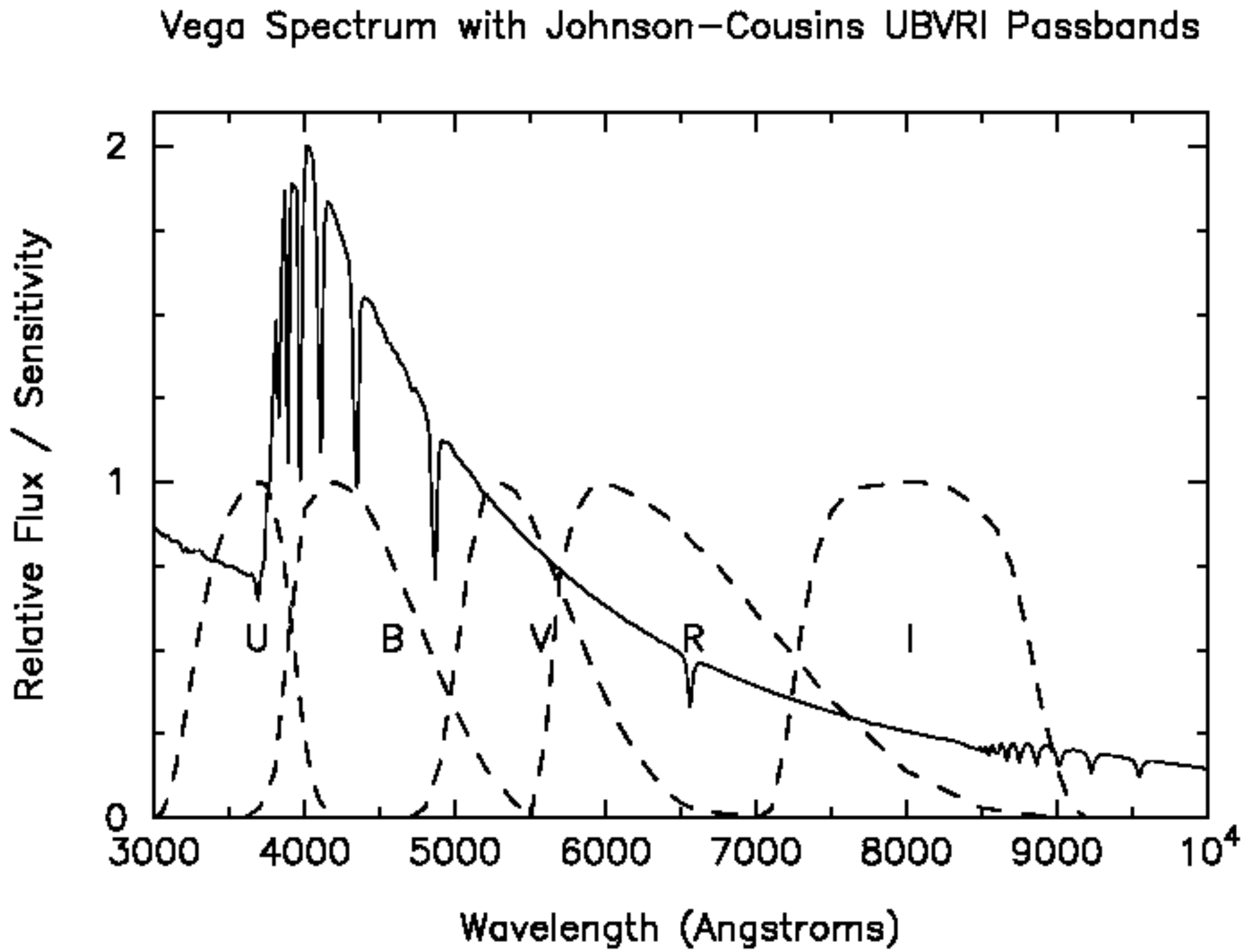
$$m_B = m_V = m_R = \ldots = m_K = 0.0$$

where the subscripts indicate passbands that span the optical through near-infrared region (400-2500nm)

Astronomers use of the "magnitude" system causes disbelief in many a physicist(!) but even today the system is essentially unchanged from that set up originally

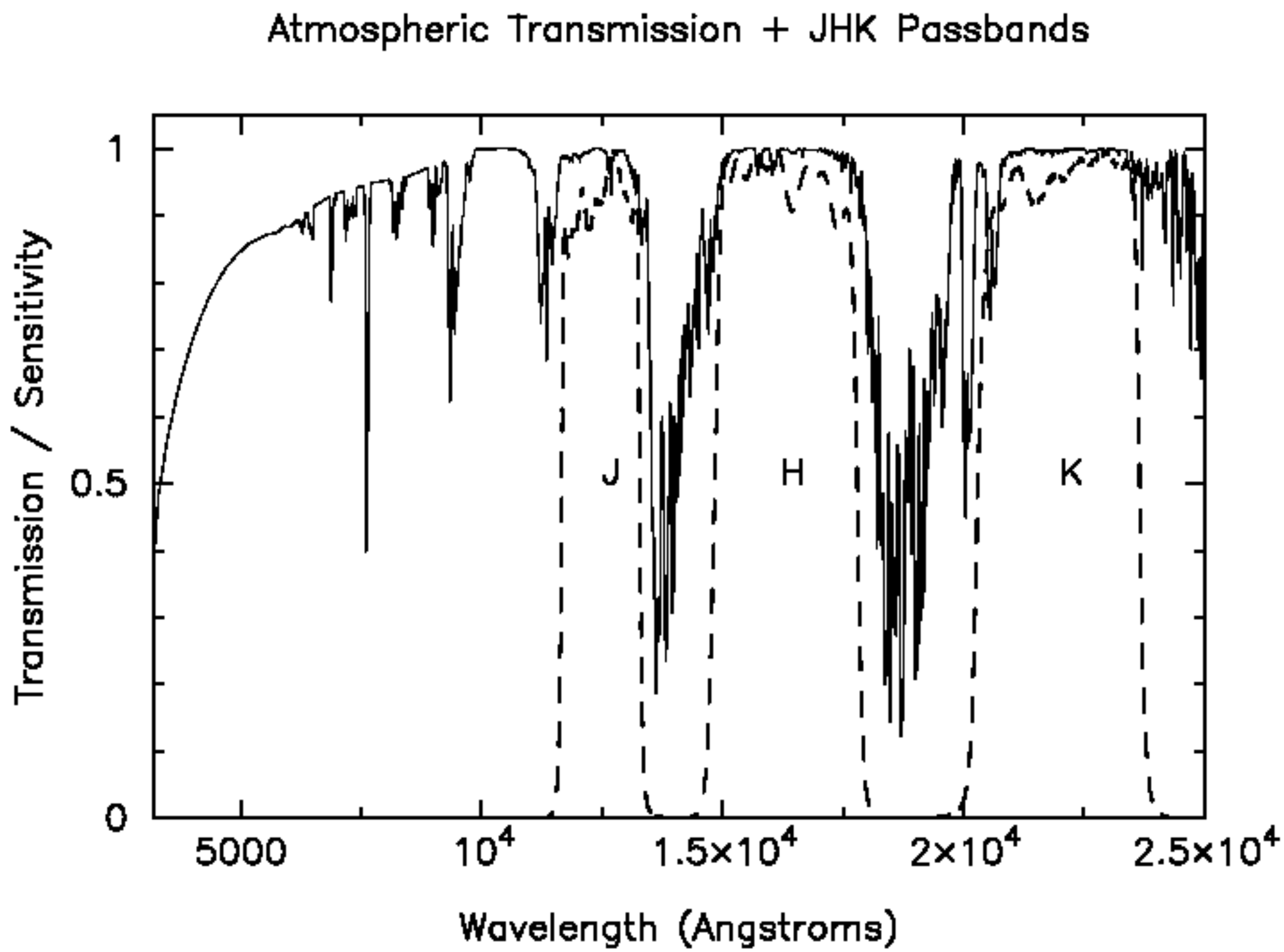
- The AB magnitude system has a common «zeropoint» at all wavelengths giving a more useful magnitude scale to flux conversion:

$$M_{AB} = -2.5\ \lg(f)\ -48.6 \qquad f\ [\text{ergs/s/cm}^2\text{/Hz}]$$


Vega Spectrum with Johnson—Cousins UBVRI Passbands
Relative Flux / Sensitivity
Wavelength (Angstroms)
U
B
V
R
I
0
1
2
3000
4000
5000
6000
7000
8000
9000
10^4

Standard Passbands in the Visible and Near-infrared

Passband	λ_{eff} (nm)	Comment
U	360	Shortest possible from ground
B	440	visible
V	550	visible
R	650	visible
I	750	
Z	850	
J	1200	near-infrared
H	1600	near-infrared
K	2200	limited by thermal emission


Atmospheric Transmission + JHK Passbands
Transmission / Sensitivity
1
0.5
0
J
H
K
5000
10^4
1.5×10^4
2×10^4
2.5×10^4
Wavelength (Angstroms)

Apparent Magnitudes

Object	m_V
Sun	-26.7
Venus (brightest)	-4.5
Sirius (brightest star)	-1.4
Vega	0.0
Faintest star (from Cambridge street)	3.5
M31 (brightest galaxy)	3.5
Faintest star (dark site, dark-adapted)	6.0
Brightest quasar	12.0
Dark night sky (surface brightness)	21.5□″
Faintest object detected	30.0

Absolute Magnitudes and Distance

- Absolute magnitude is defined as the magnitude an object would have if observed at a distance of 10pc
- Absolute magnitudes are indicated using capital letters e.g. M_V is the V-band absolute magnitude
- Absolute magnitude is astronomers' scheme for quantifying the luminosity of objects, $L = 4\pi d^2 f$, and provides a convenient measure of the distance of an object via the "distance modulus" (DM)

$$DM = m - M = -2.5 \log f_d + 2.5 \log f_{10}$$

$$= -2.5 \log (f_d / f_{10})$$

Useful for local volume of galaxies, but less sensible for cosmological distances. IE: M31 (Andromeda) has a DM=24, Virgo cluster has DM=31

From inverse-square law, $f \propto 1/d^2$, and

$$f_d / f_{10} = (10/d)^2$$

and $$m - M = -2.5 \log (10/d)^2$$

Distance modulus: $DM = m - M = 5 \log d - 5$

or $d = 10^{(m-M+5)/5}$ pc

If absolute magnitude for an object known then can measure apparent magnitude, m, and calculate distance, d.

CAUTION: 'd' in a cosmological context is "Luminosty Distance" TBD

[Will drop explicit base for "log"s, "log" = "$\log_{10}$"]

Blackbody Radiation

Spectrum of blackbody as a function of temperature, T:

$$B_\lambda(T) = B(\lambda, \mathrm{T}) = \frac{2hc^2/\lambda^5}{e^{hc/\lambda kT} - 1}$$

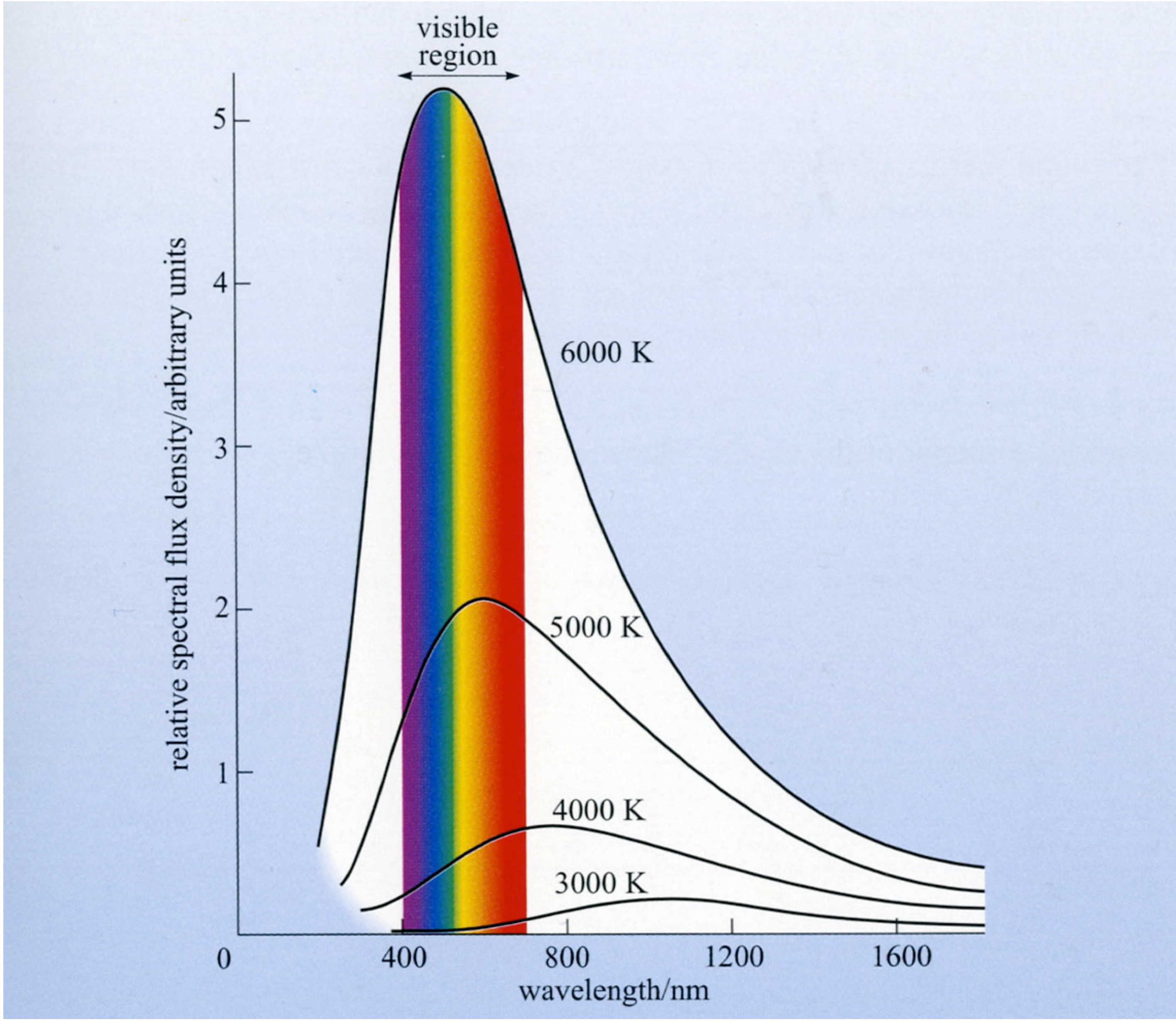
where h is Planck's constant and c is the velocity of light with common units in astronomy, ergs cm^{-2} A^{-1} sr^{-1} s^{-1} or Watts m^{-2} nm^{-1} sr^{-1} Alternatively, in terms of frequency, υ:

$$B_\nu(T) = B(\nu, \mathrm{T}) = \frac{2h\nu^3/c^2}{e^{h\nu/kT} - 1}$$

units, ergs cm^{-2} Hz^{-1} sr^{-1} s^{-1} or Watts m^{-2} Hz^{-1} sr^{-1}

The blackbody spectrum is strongly peaked – most energy emitted within narrow wavelength (frequency) range

Blackbody curves for different T



Wien’s Displacement Law

From the blackbody distribution can show that the wavelength at which the function peaks and the Temperature of the blackbody are simply related by:

$$\lambda_{max} \times T = 0.290 \qquad \text{(cm K)}$$

Wien’s Law is extraordinarily useful and worth remembering

(How would you derive it?)

Wien's Displacement Law

T (K)	λ (μm)	Source
20	145	Molecular cloud
293	9.9	Room temperature
1000	2.9	Brown dwarf
3400	0.85	Red giant
5800	0.50	Sun
40000	0.07	O star

Ratio of fluxes in two passbands uniquely determines the temperature of a blackbody

In terms of the magnitude system, the difference between magnitudes in two passbands gives the "colour index" or "colour" of an object, e.g. measures in the B and V band

$$B = -2.5 \log f_B + \text{const}$$
$$V = -2.5 \log f_V + \text{const}$$

$$B\text{-}V = -2.5 \log (f_B/f_V)$$

and the B-V colour thus measures T

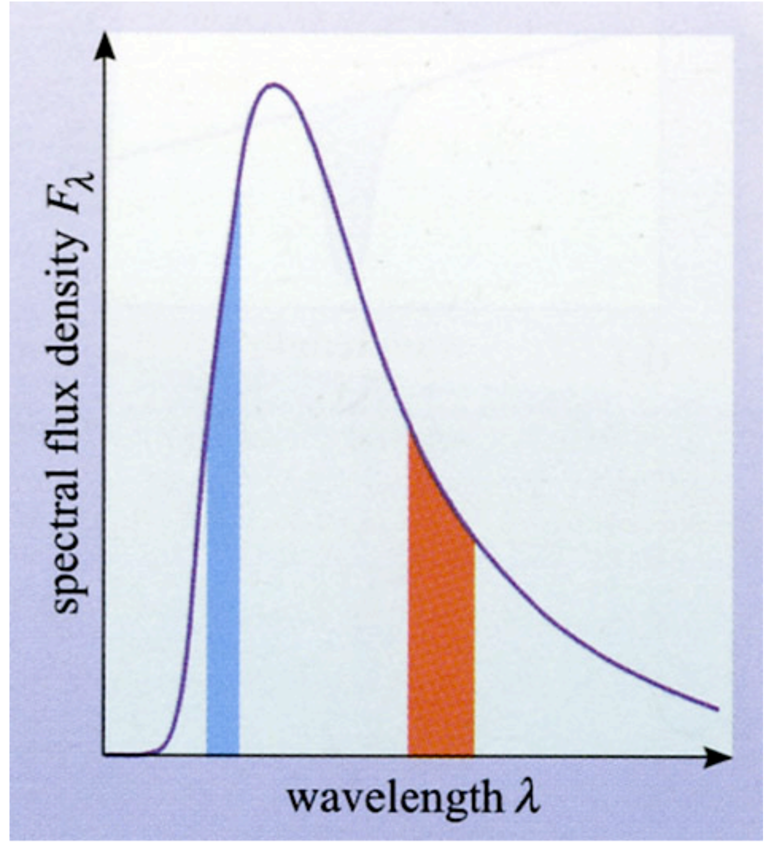


Figure 3.19 The photometric method of obtaining photospheric temperatures. The ratio of the amount of energy measured in two different wavelength regions (shaded) is uniquely defined by the temperature if the object emits like a black body.

Colours of Galaxies and Stars

It follows from the definition of the zero-point for the magnitude system that for Vega all colours have zero values, i.e. U-B = B-V = V-R = V-I =…= J-K = 0.0

Conventionally, all colours are specified in sense blue-red

Thus, objects with redder spectral energy distributions than Vega have positive colours, e.g. for the Sun, B-V=0.6

Objects with bluer spectral energy distributions than Vega have negative colours, e.g. for an O star, B-V≈-1.0

B-V colours most common for historical reasons (photographic emulsions) but longer baseline often better

Most stellar spectra are well approximated by blackbodies.
Galaxy light (in optical) is an integration of the individual stars' light.

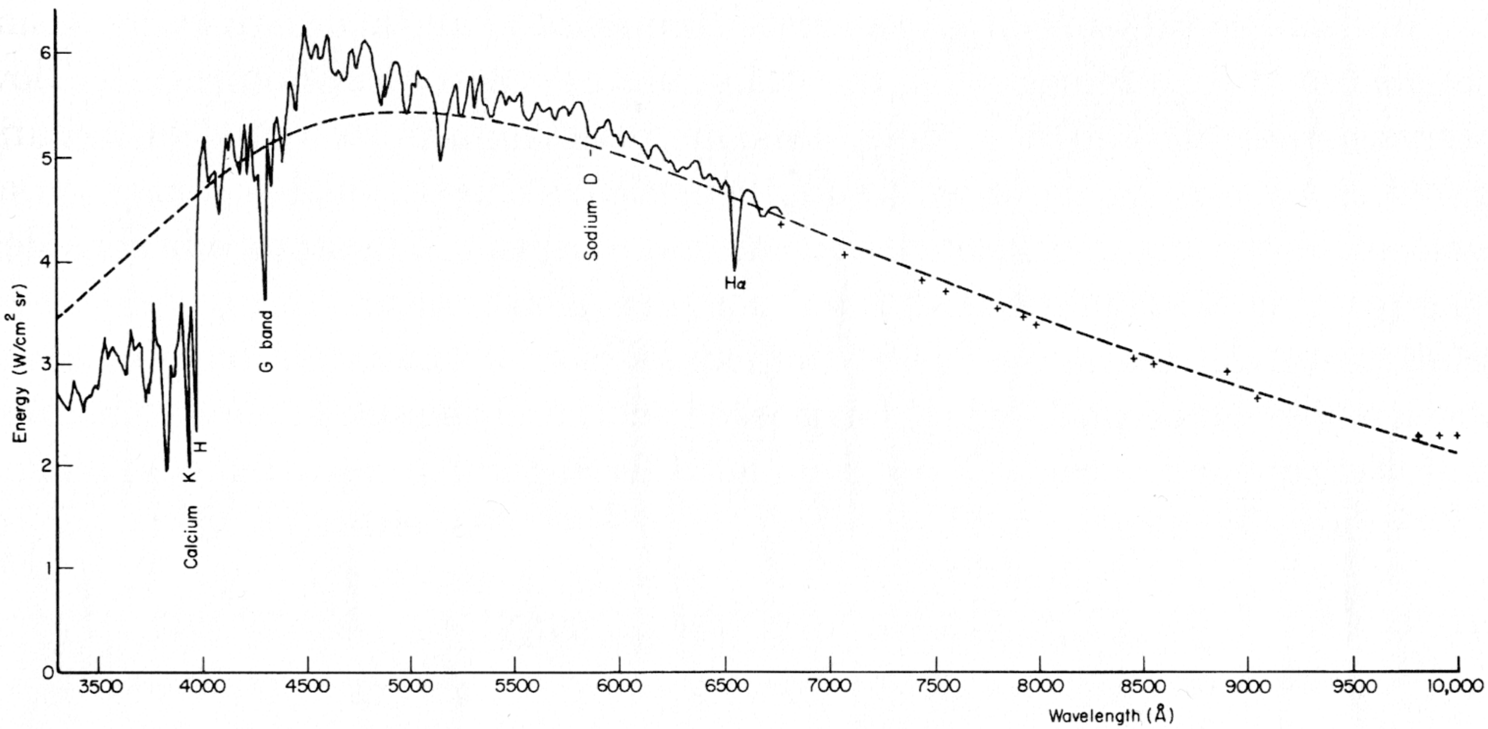


Figure 9.5 The spectrum of the Sun. The dashed line is the curve of an ideal blackbody having the Sun's effective temperature. (Figure from Aller, *Atoms, Stars, and Nebulae*, Revised Edition, Harvard University Press, Cambridge, MA, 1971.)

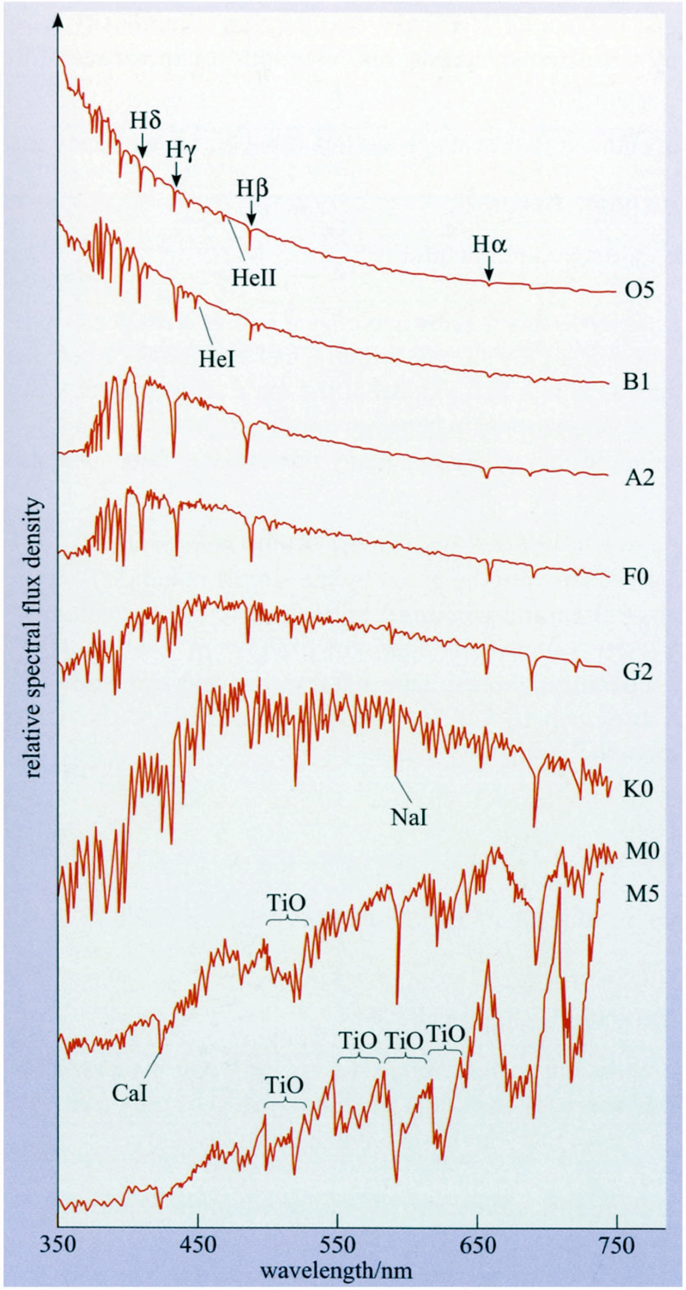
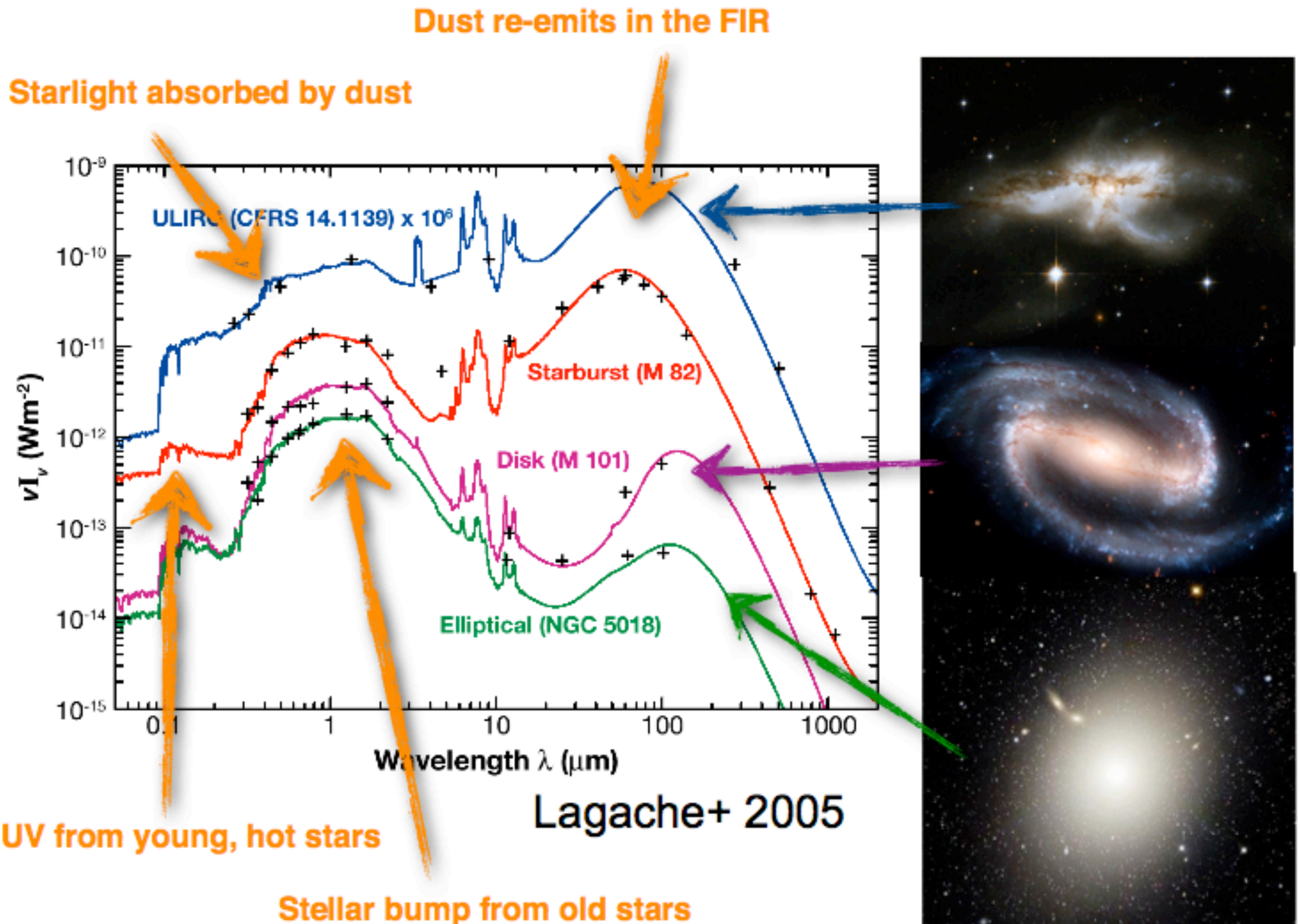


Figure 3.26 The stellar absorption spectra given in Figure 3.25 are more usually presented as graphs of relative flux density versus wavelength for ease of identification of the prominent absorption lines. The spectra have been plotted without spectral flux density scales and displaced vertically for clarity. (Kaufmann and Freedman, 1998)



Dust re-emits in the FIR
Starlight absorbed by dust
ULIRG (CFRS 14.1139) x 10^6
Starburst (M 82)
Disk (M 101)
Elliptical (NGC 5018)
10^-9
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
νI_ν (Wm^-2)
0.1
1
10
100
1000
Wavelength λ (μm)
UV from young, hot stars
Stellar bump from old stars
Lagache+ 2005

Stefan Boltzmann Law: Approximating Galaxies and Stars as Blackbodies

- Integrate the blackbody spectrum over all wavelengths

$$\int B_\lambda(T)d\lambda = \sigma\ T^4$$

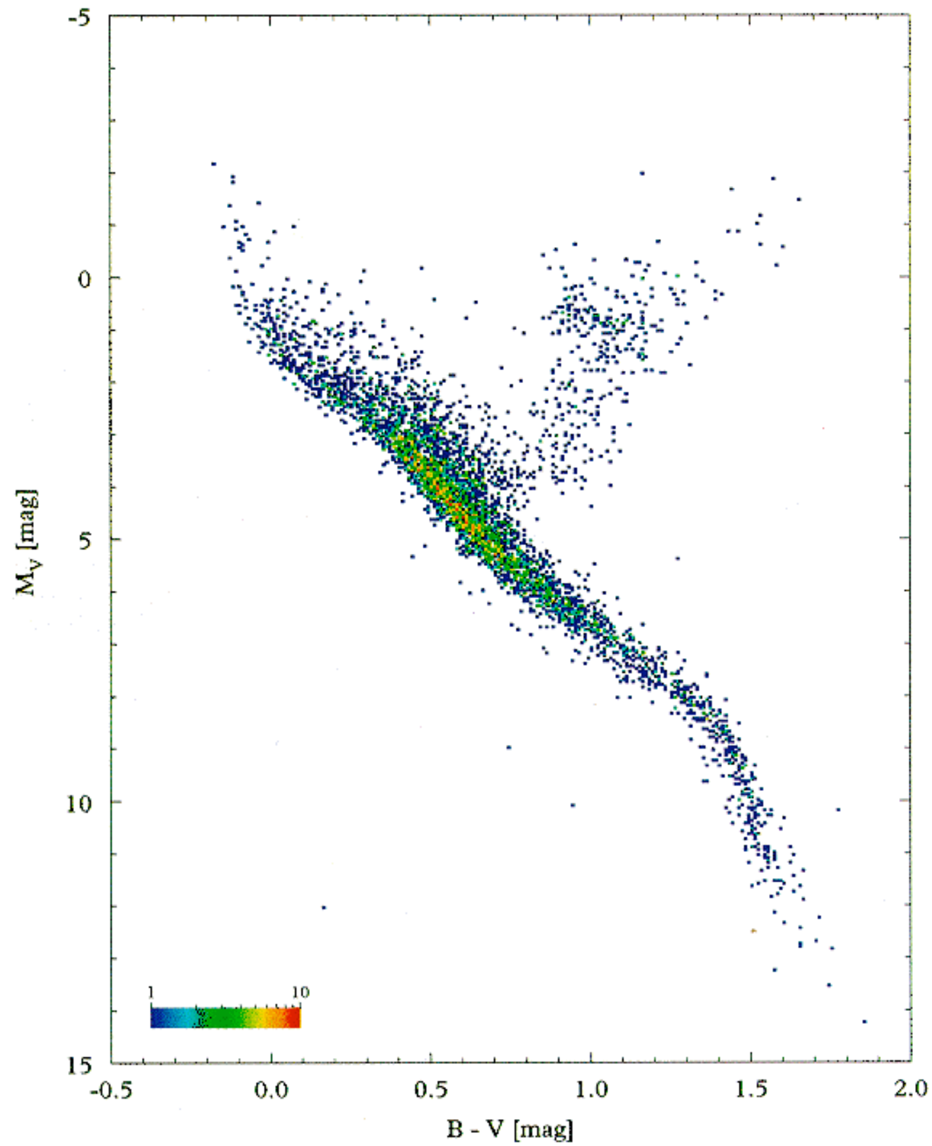
where σ is the Stefan-Boltzmann constant.

- If surface element of a galactic component (the photosphere of stars; cool dust emission) emits like a blackbody then

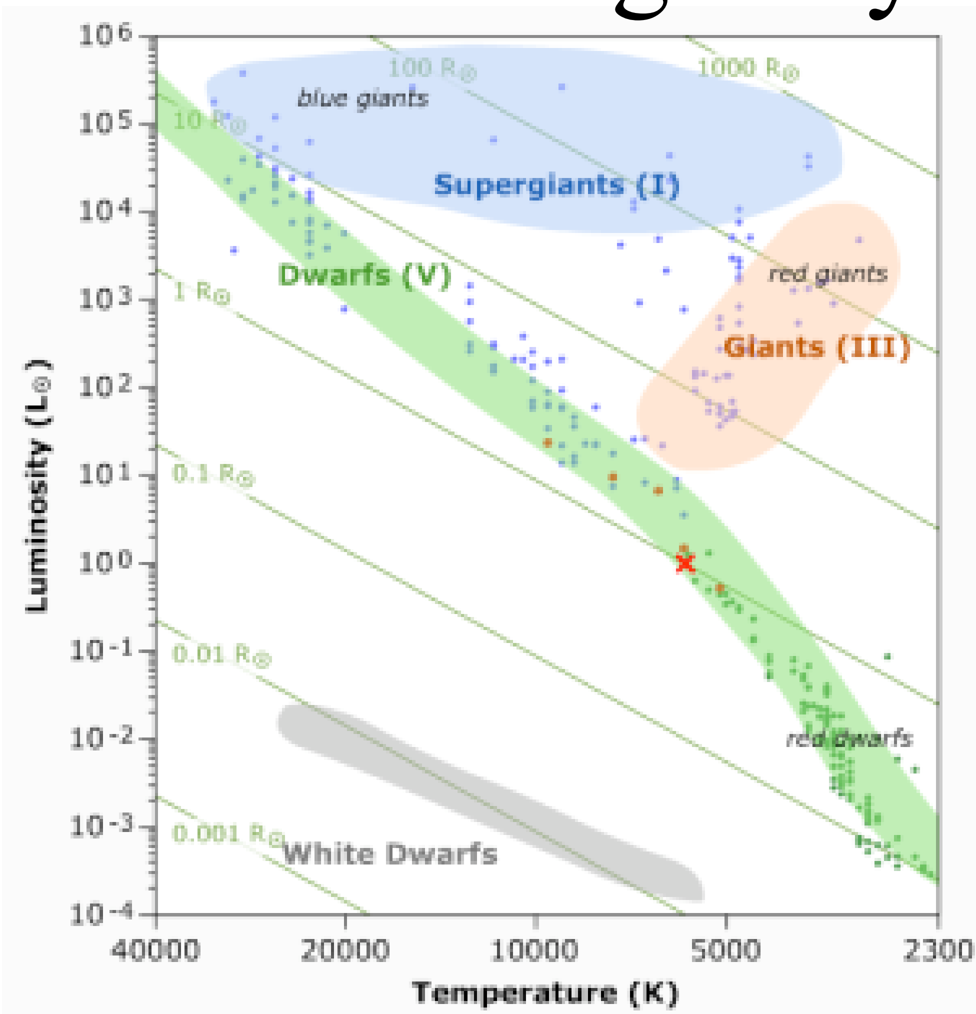
$$L = 4\ \pi\ R^2\ \sigma\ T_e^{\,4}$$

relates luminosity, L, radius, R, and effective temperature, T_e of the component. None are in fact perfect blackbodies and T_e is the temperature (minimum radius R) would have if it were a blackbody.

Hertzsprung-Russell diagram from HIPPARCOS satellite – bright, nearby stars.



HR diagram: stellar evolution = galaxy evolution



Evolved versus 'young' galaxies

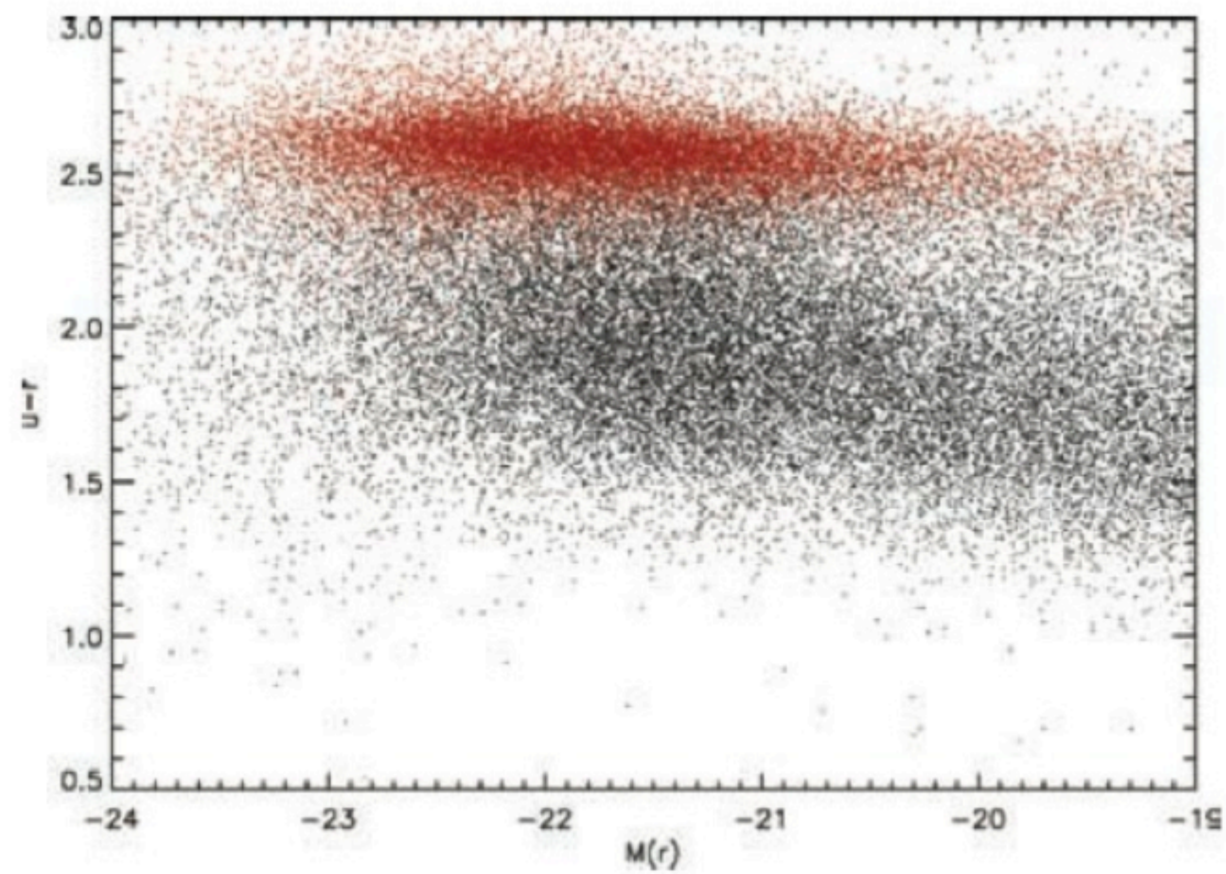
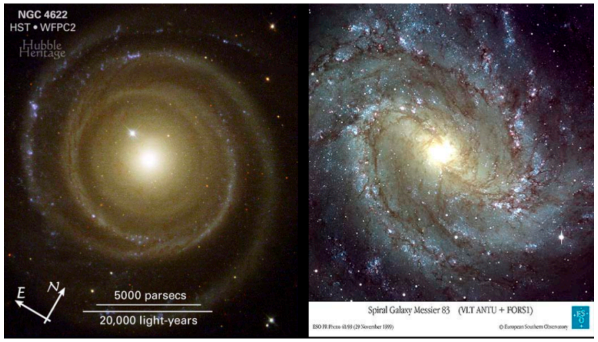
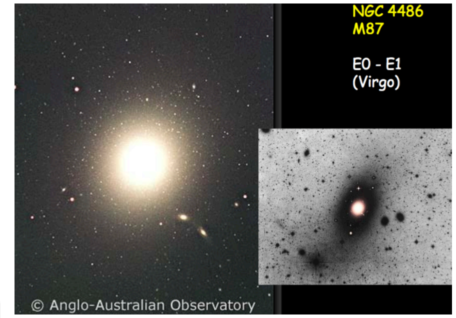


Figure 9. Colour–magnitude diagram for galaxies in the weighted super-clean combined spirals sample. Systems classified as spiral are shown in black, those classified as elliptical in red.



Galaxy Classification

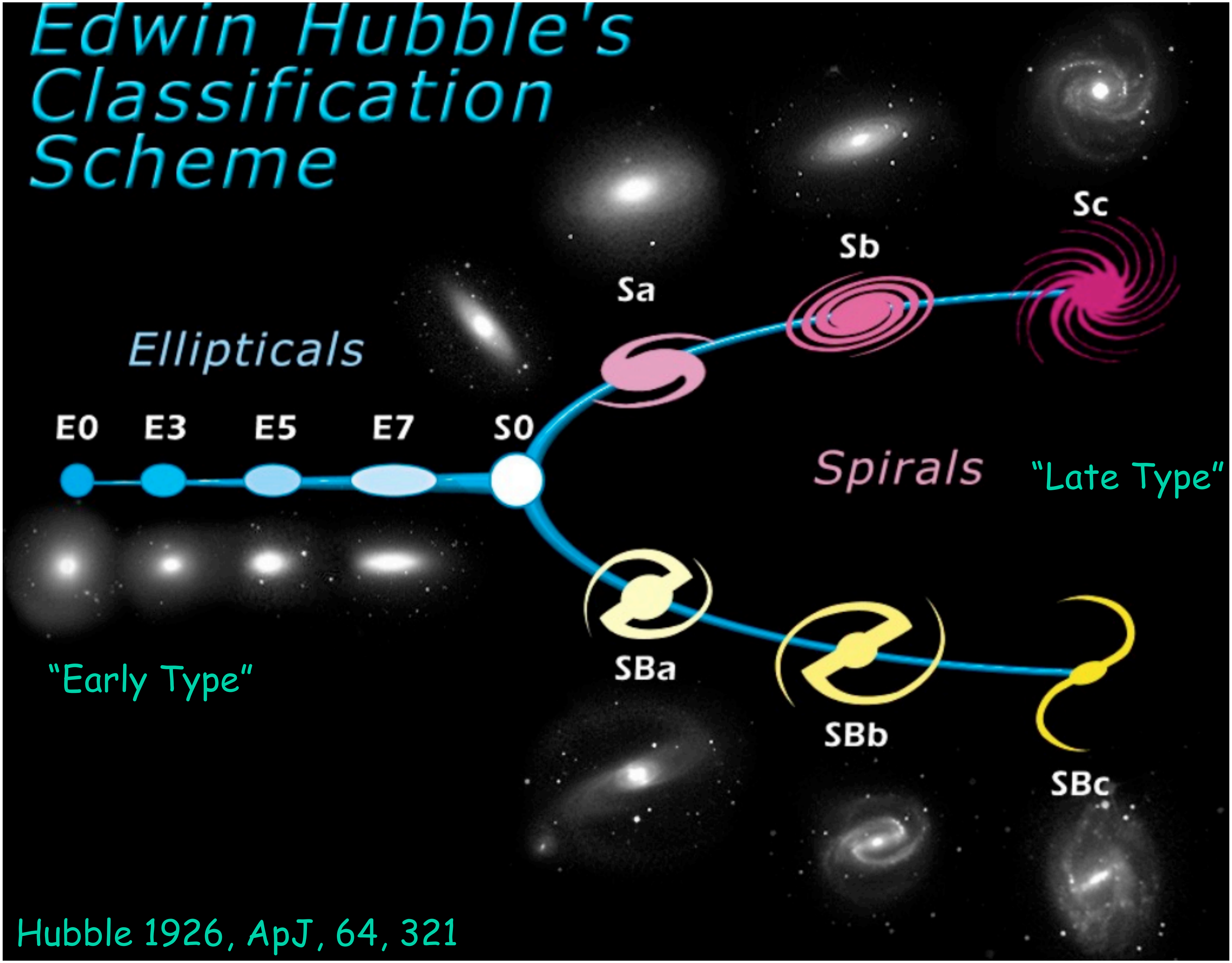


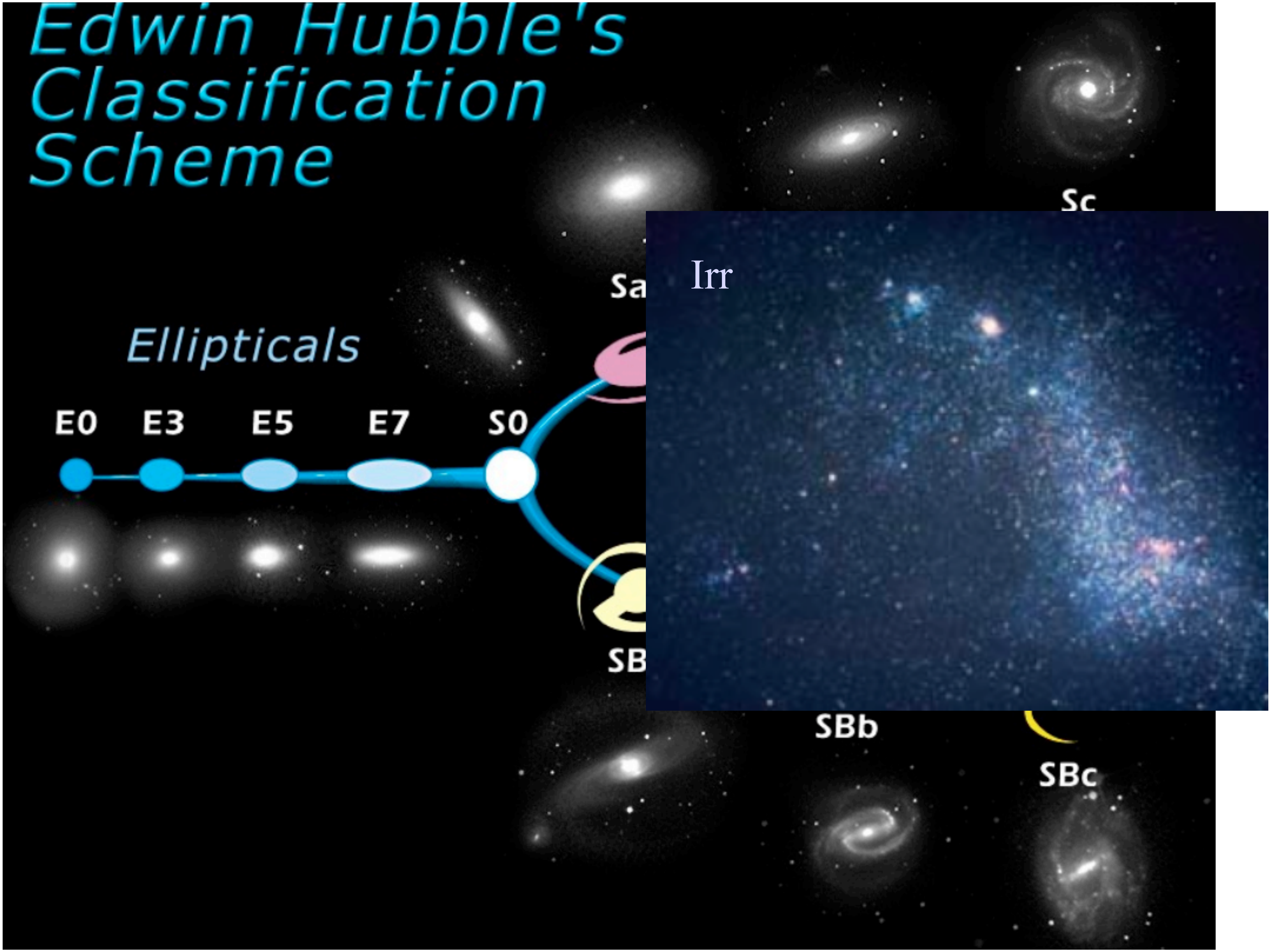
Considerations:

1) Different libraries of galaxy images are liable to lead to the identification of different classes
2) It makes no sense to compare a B-band image of one galaxy with a R-band image of another. Or a shallow image of one with a deep image of another.
   Essential that library of images be homogeneous.
   Acute problem for studying galaxies over cosmological distances!
3) Scheme should reflect what is 'physically important' rather than superficial details.
4) Criteria used to assign a galaxy to a class should permit a unique classification in each case.

Morphology: the two-dimensional physical appearance of galaxies

- The first systematic attempts to study galaxies focussed upon understanding the range of shapes they presented.
- Hubble - though not the first - presented what is arguably the most complete yet simple classification of galaxies based upon their visible appearance: the Hubble sequence.


Edwin Hubble's Classification Scheme
Ellipticals
E0
E3
E5
E7
S0
Sa
Sb
Sc
Spirals
"Late Type"
SBa
SBb
SBc
"Early Type"
Hubble 1926, ApJ, 64, 321


Edwin Hubble's
Classification
Scheme
Ellipticals
E0
E3
E5
E7
S0
Sa
Sc
SB
SBb
SBc
Irr

Why Begin with Classification?

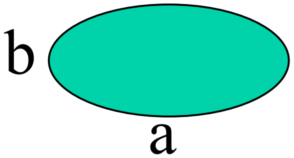
- The Hubble system forms the basic vocabulary of the subject.
- The Hubble sequence of galaxy types reflects an underlying physical and evolutionary sequence.
  - provides an overview of integrated properties
  - reproducing the variation in these properties along the Hubble sequence is a major (unsolved) challenge for galaxy formation/evolution theory

Hubble Sequence

- An important aspect of the Hubble sequence is that many intrinsic properties of galaxies, such as **luminosity**, **colour**, and **gas content**, change systematically along this sequence.
- In addition, disks and ellipsoids most likely have very different formation mechanisms.
- Therefore, the morphology of a galaxy, or its location along the Hubble sequence, is directly related to its formation history.

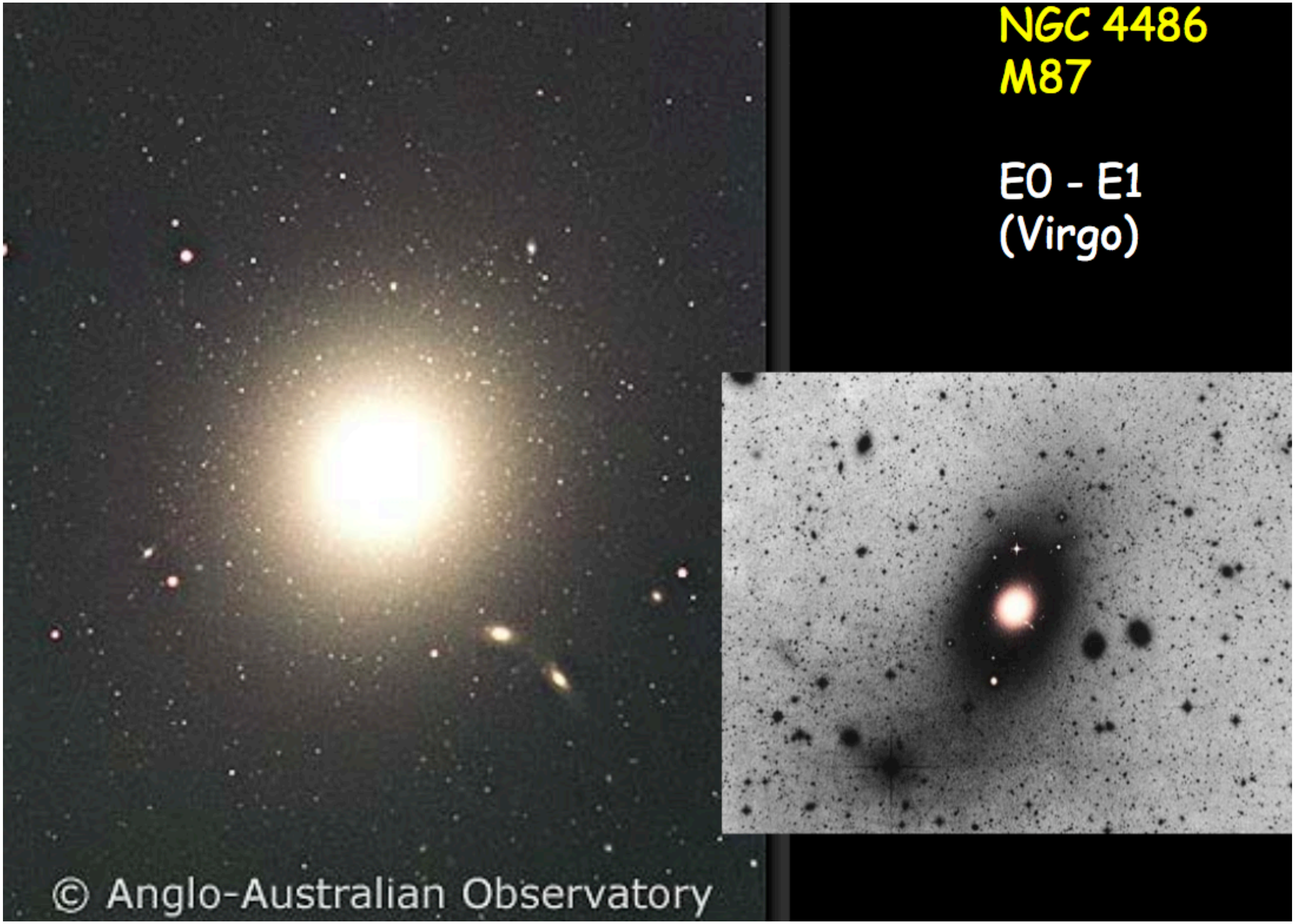
Hubble Sequence - Ellipticals

- The sequence is an interesting mix of quantitative and qualitative criteria:
- Smooth, elliptical galaxies showing no evidence of a disk
  - Relatively little evidence of gas, dust
  - subtypes defined by projected flattening, labelled with a number of E0 to E7 with the number computed as **10 x (1 - b/a),**
    - **b** and **a** are the minor and major axis lengths.



Hubble Sequence - Ellipticals

- An S0 or lenticular galaxy is a bulge dominated galaxy with a smooth, purely stellar disk.
- introduced in 1936 revision of system
- IE: disk and bulge but no spiral structure


NGC 4486
M87
E0 - E1
(Virgo)
© Anglo-Australian Observatory

Hubble Sequence - Spirals

- Spiral galaxies are classified by more qualitative criteria such as the prominence and tightness of spiral arms and the presence of a central bar.
- flattened disk + central bulge (usually)
- two major subclasses: normal and barred

Subtypes Sa, Sb, Sc distinguished by 3 criteria

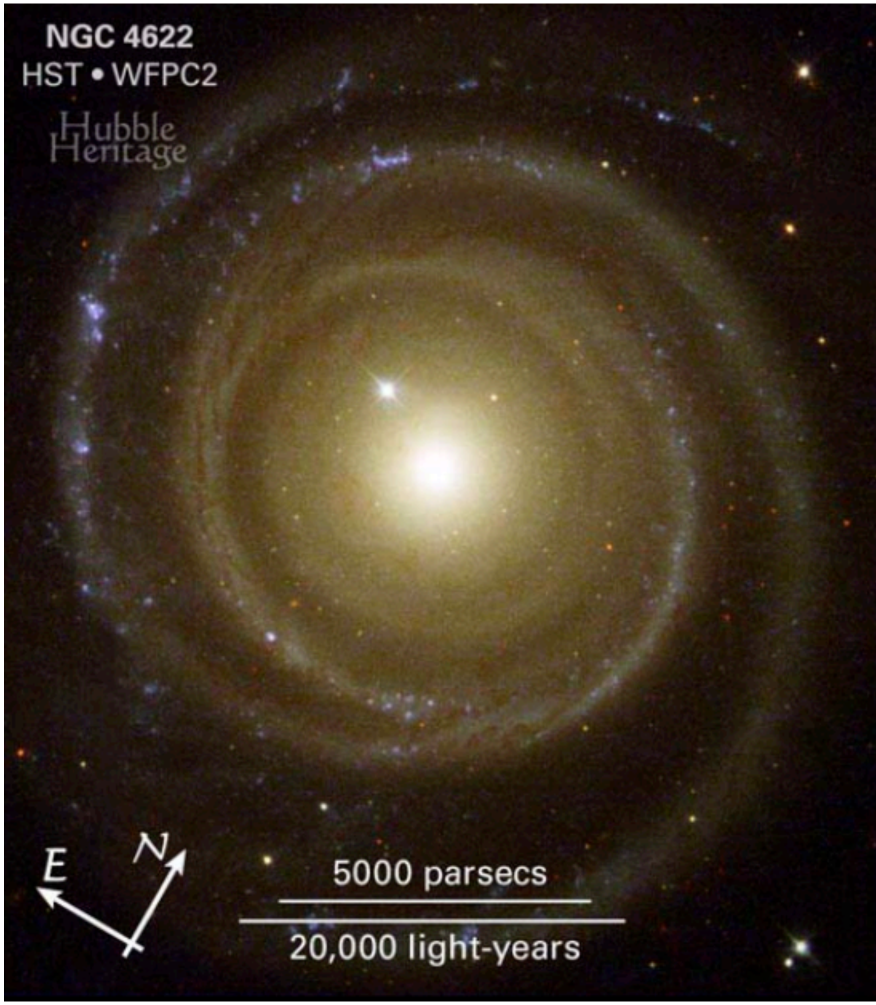
- bulge/disk luminosity ratio
  - B/D ranges from >1 (Sa) to <0.2 (Sc)
- spiral arm pitch angle
  - ranges from 1-7^o (Sa) to 10-35^o (Sc)
- "resolution" of disk into knots, HII regions, stars

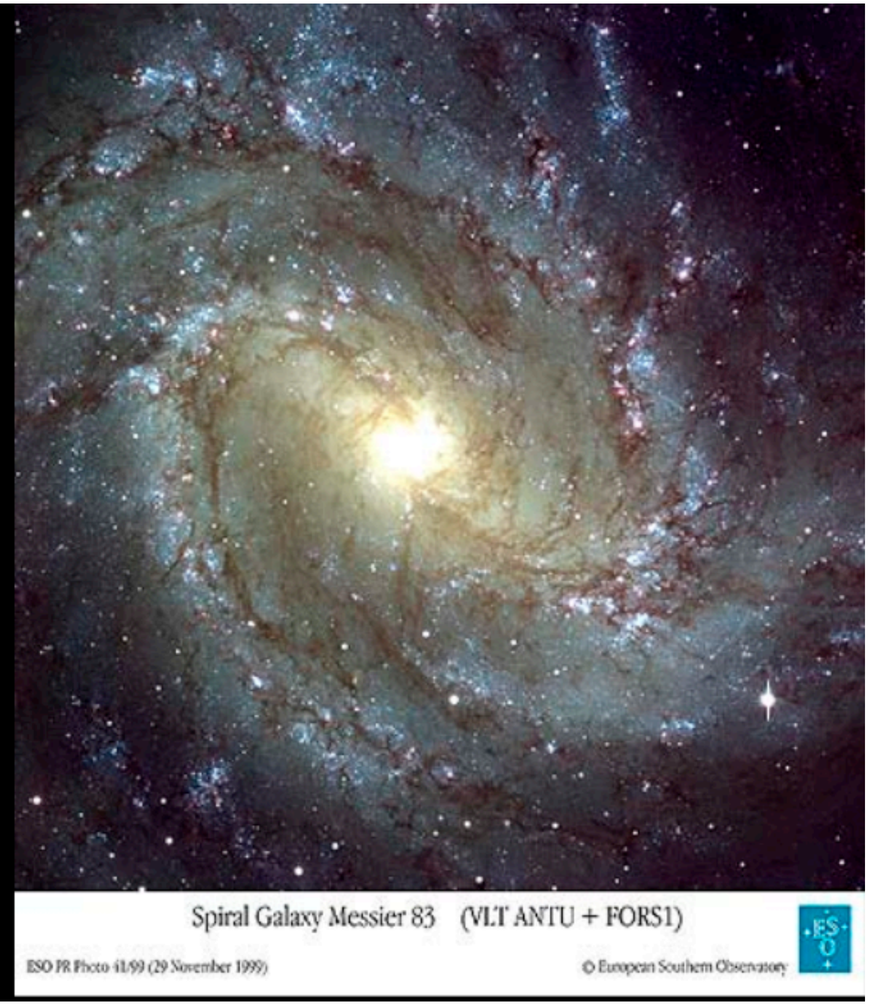
Hubble Sequence - Spirals

- these three criteria are not necessarily consistent!

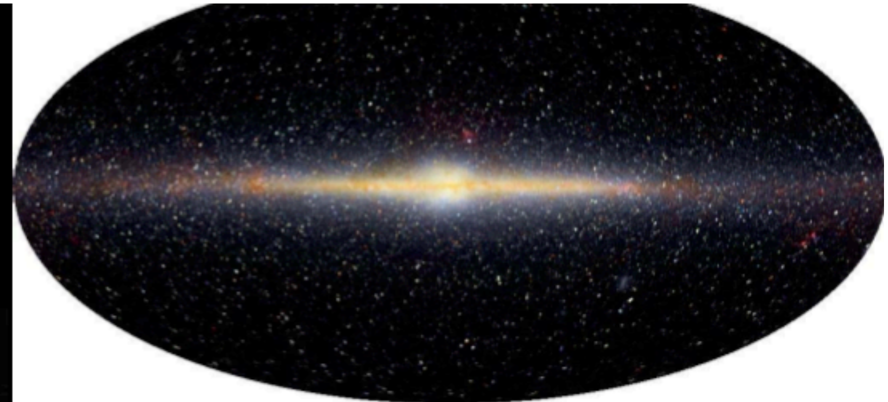
Each reflects an underlying physical variable:

- B/D ratio ---> spheroid/disk mass fractions
- pitch angle ---> rotation curve of disk, mass concentration
- resolution ---> star formation rate
- Hubble's system is simple yet subjective - in that it is dependent upon human visual classification.
- However, as numerous supporters of visual classification have remarked, the eye is exceptionally adept at recognizing and classifying two dimensional structures.


NGC 4622
HST • WFPC2
Hubble Heritage
E
N
5000 parsecs
20,000 light-years


Spiral Galaxy Messier 83 (VLT ANTU + FORS1)
ESO PR Photo 41/99 (29 November 1999)
© European Southern Observatory

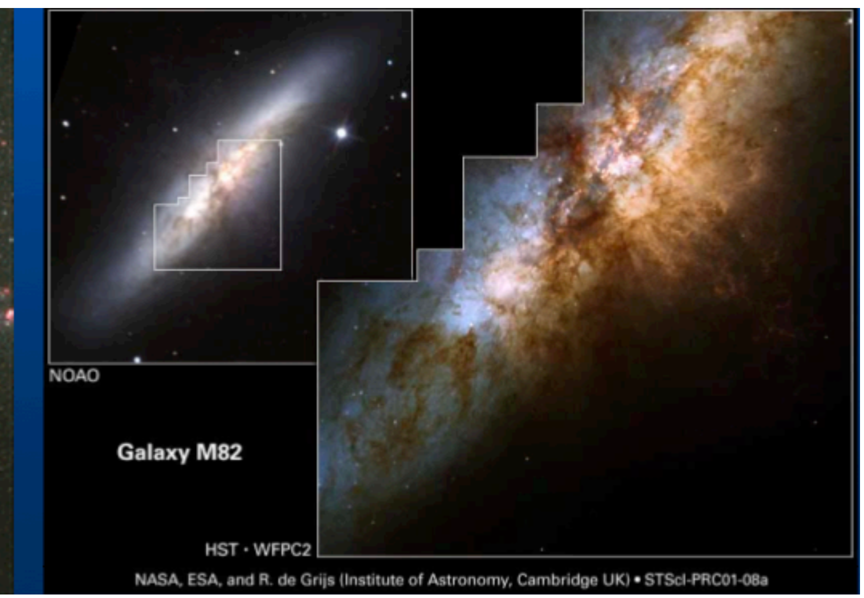
The Sombrero Galaxy (VLT ANTU + FORS1)



Spiral Galaxy NGC 4945

Hubble Sequence - Irr's

- Irregular galaxies
  - little or no spatial symmetry
  - two major subtypes
    - Irr I: highly resolved (e.g., Magellanic Clouds)
    - Irr II: smooth but chaotic, disturbed (e.g., M82)



Hubble Sequence - others?

- Unclassifiable galaxies?
  - ~2% of galaxies cannot be classified as E, S, Irr
  - predominantly disturbed or interacting systems

NGC 5128 = Cen A

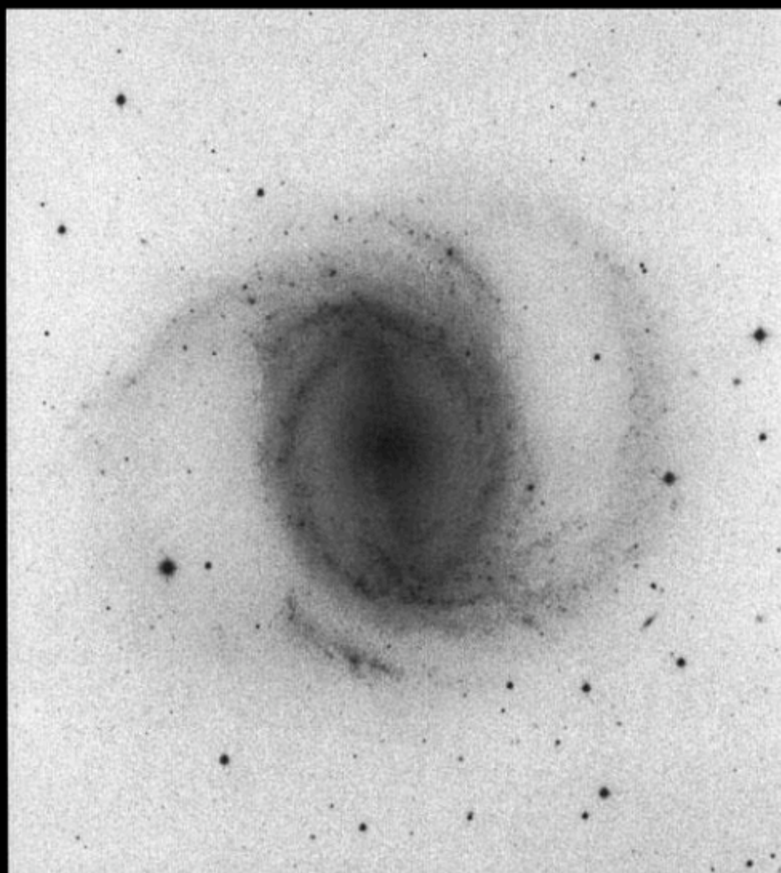
NGC 4038/9 = “Antennae”

Extended Hubble Sequence

- Revised Hubble system
  - de Vaucouleurs 1958, Handbuch der Phys, 53, 275
  - de Vaucouleurs 1964, Reference Catalog of Bright Galaxies (RC1)
- goal: retain basic system, add more information
- mixed types: E/S0, Sab, Sbc, etc
- intermediate barred: SA, SAB, SB
- extended types: Sd, Sm, Sdm
- inner rings: S(r) , S(s)
- outer rings: (R) S
- Magellanic spirals, irregulars: Sm, Im

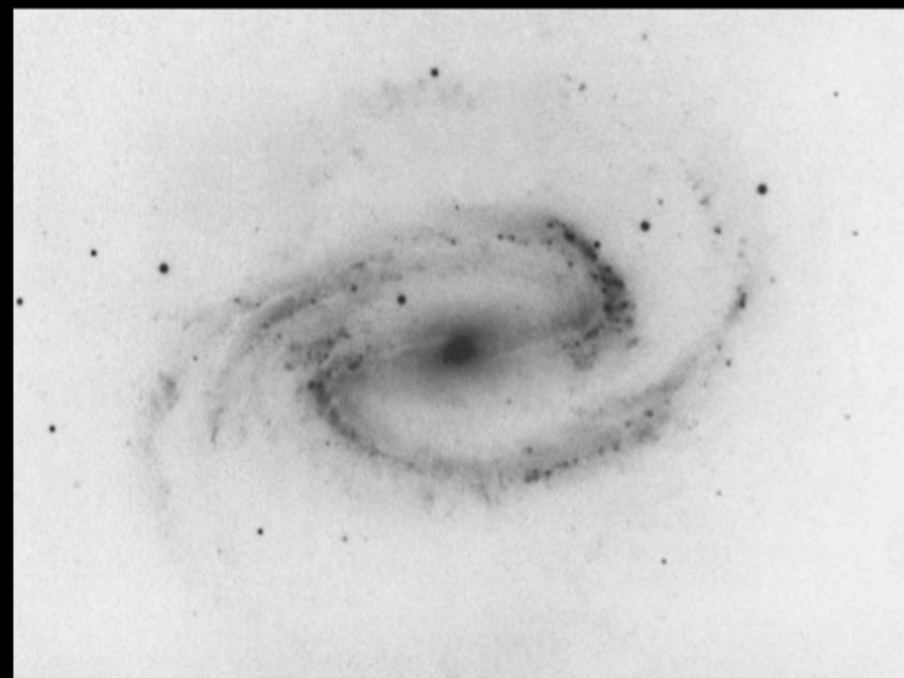
NGC 1433

(R)SB(r)ab



NGC 1300

SB(rs)bc

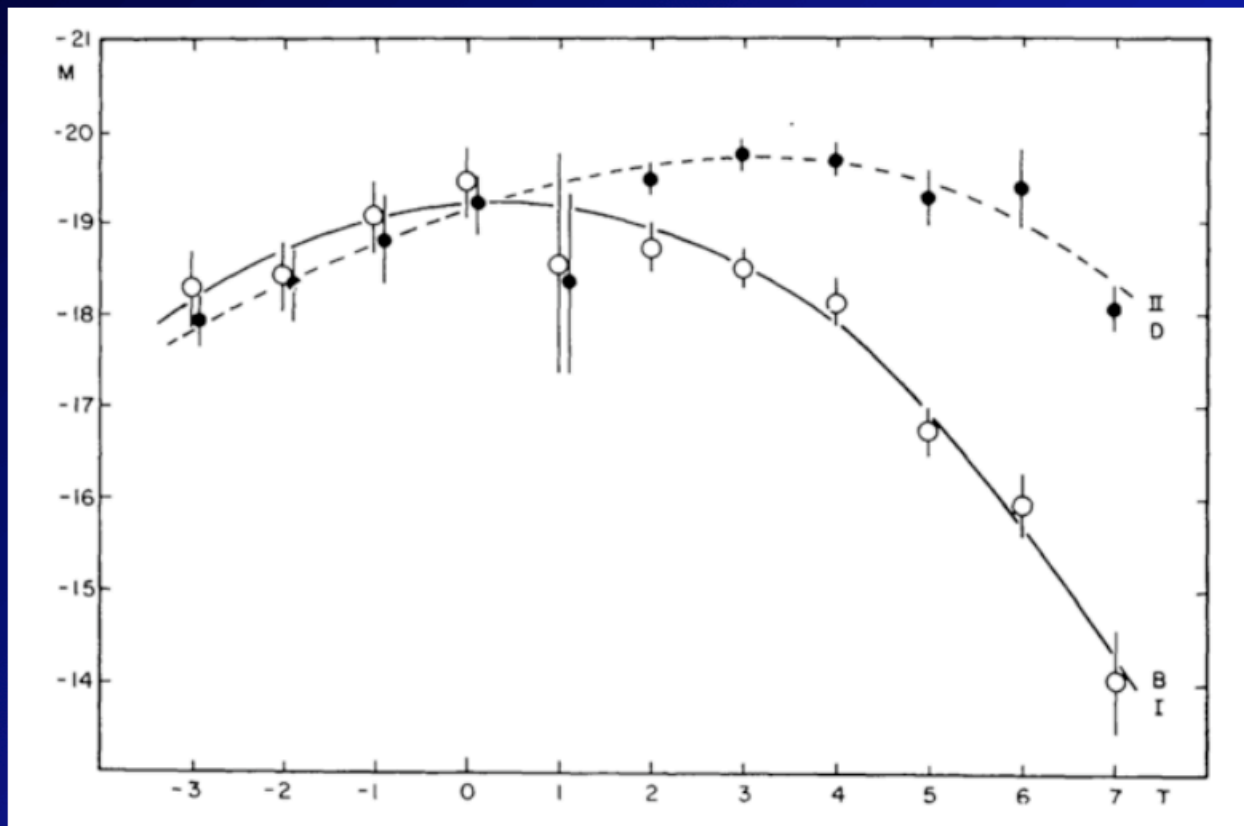


Extended Hubble Sequence

- Attempts have been made to quote Hubble's scheme as a numerical sequence, T-types.
- Physical quantities such as relative fractions of bulge and disk light do correlate with T-type.
- However, T-types remain a subjective, relative classification scheme, i.e. there is no absolute "elliptical" or "spiral" reference. There is no absolute "ground truth" for purely visual classification schemes.

T-types: quantitative morphology?

Magnitude



Disk

Bulge

Numerical Hubble stage

Hubble stage T	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10
de Vaucouleurs class[4]	cE	E	E$^+$	S0$^-$	S0^0	S0$^+$	S0/a	Sa	Sab	Sb	Sbc	Sc	Scd	Sd	Sdm	Sm	Im
approximate Hubble class[5]	E			S0			S0/a	Sa	Sa-b	Sb	Sb-c	Sc			Sc-Irr	Irr I	

Other Classification Systems

- Luminosity classification (DDO system)
  van den Bergh 1960, ApJ, 131, 215
- goal: use morphology to subdivide galaxies by absolute luminosity and mass
  – basic criterion is spiral arm “development” (arm length, continuity, relative width)
- secondary criterion surface brightness (dwarfs)
- roman numeral designation after Hubble type
  – Sc I, I-II, II, II-III, III, III-IV, IV
  – Sb I, I-II, II, II-III
  – Ir IV-V, V
- mean M_B ranges from -21 (I) to -16 (V)

NGC 1232: SBc I

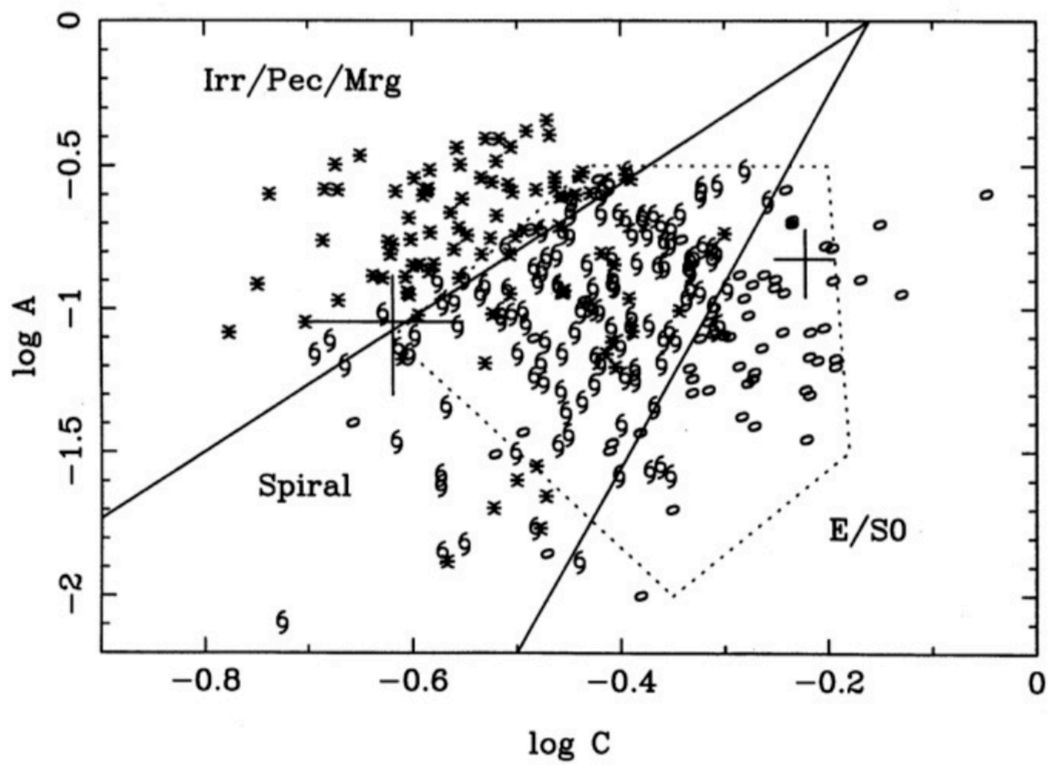
NGC 598 = M33 Sc II-III

Quantitative Classification

- Numerous "machine-based" or automated morphological classification schemes have been proposed.
- automated classification is needed for very large imaging or spectroscopic surveys (e.g., Sloan Digital Sky Survey = SDSS)
- can obtain objective measures, that are less susceptible to systematic or subjective effects
- the current morphological sequence may not be representative of galaxies at earlier cosmic epochs
- since many physical and spectral properties of galaxies correlate with type, a physical classification system can be created
- parametric classifications provide information on the dimensionality of the galaxy parameter space

Quantitative Classification

- Abraham et al. 1994, ApJ, 432, 75
- Abraham et al. 1996, MNRAS, 279, L49
- simple 2-parameter system
- concentration index C --> ratio of fluxes in two isophotal regions
- asymmetry index A --> flip image, subtract from initial image, measure fraction of residual flux



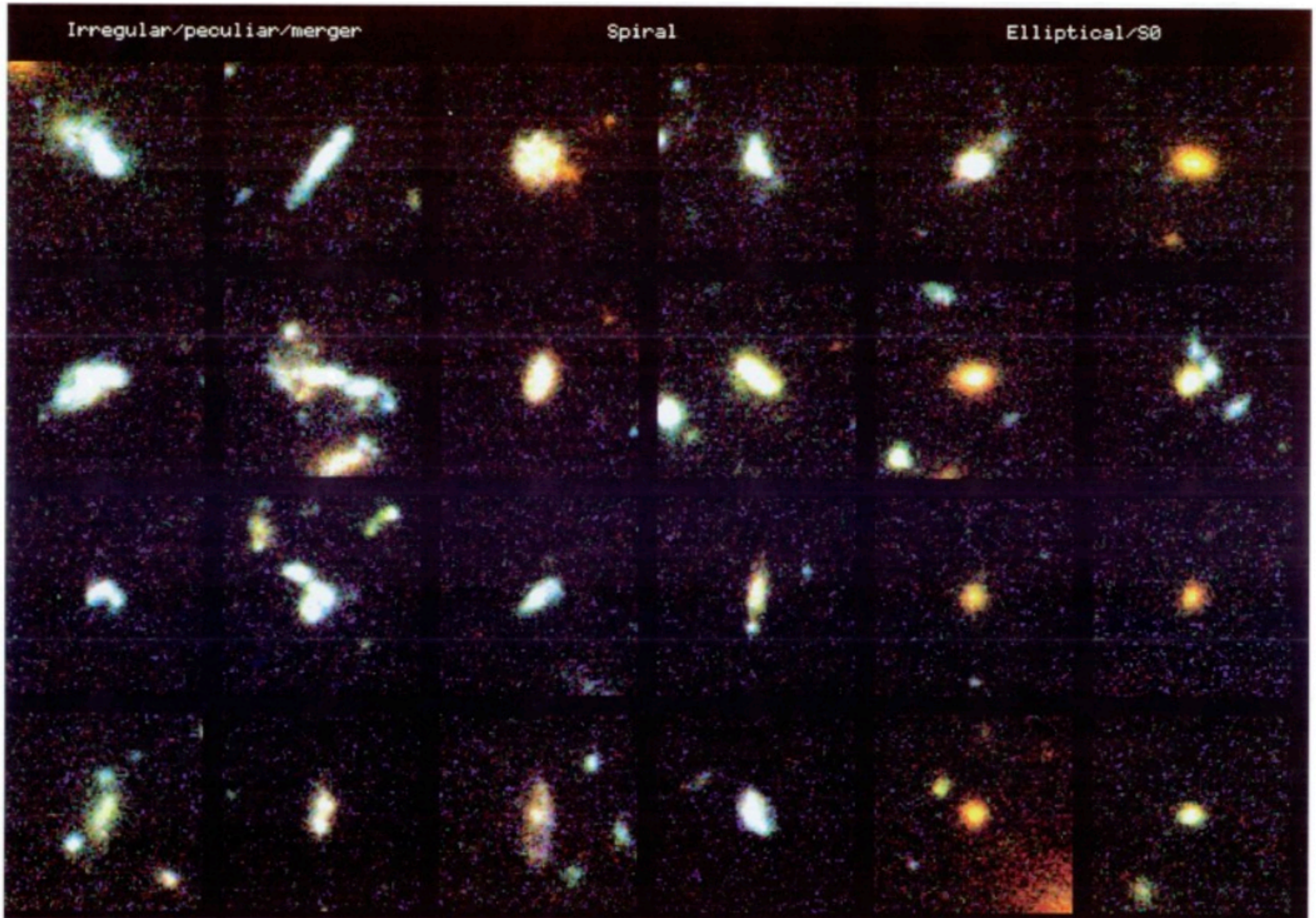


Figure 3. Montage of $I > 23$ galaxies from the HDF with: irregulars/peculiars/mergers – columns 1 and 2; spirals – columns 3 and 4; and E/S0 – columns 5 and 6. Images were selected on the basis of the A–C classifier (see Fig. 1).

Galaxies

Lecture 3: Parametric Classification; Galaxy Profiles

- Parametric Classification schemes
  - PCA; quantitative spectral classes
- Photometric structure
- Surface brightness profiles

Parametric Classification

- Basic Idea: Hubble type correlates with several integrated properties of galaxies (e.g., bulge fraction, gas fraction, color, star formation rate, angular momentum …
- Goal: define a physical classification in an n-space of galaxy properties
- Use correlations between these parameters to analyze the number of independent variables that define galaxy properties

Principal component analysis (PCA)

- a mathematical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of uncorrelated variables called **principal components**.
- The number of principal components is less than or equal to the number of original variables.
- This transformation is defined in such a way that the first principal component has as high a variance as possible (that is, accounts for as much of the variability in the data as possible)
- each succeeding component in turn has the highest variance possible under the constraint that it be orthogonal to (uncorrelated with) the preceding components.

Principal component analysis (PCA)

Djorgovski 1992, in Cosmology and Large Scale Structure of the Universe, ASP Conf Ser, 24, 19; also see Box 4.2 (p207) of BM

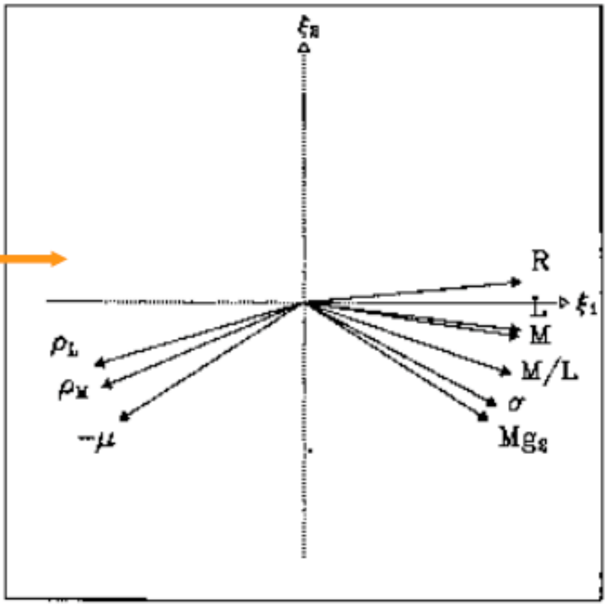
- select a set of measured parameters for the galaxy set, and normalize the ranges to unity
- compute the correlation coefficient for each pair of parameters (normalize each variable to full range of unity

$$rij = \frac{N\Sigma(xy) - \Sigma x \Sigma y}{[N\Sigma x^2 - (\Sigma x)^2]^{1/2}\ [N\Sigma y^2 - (\Sigma y)^2]^{1/2}}$$

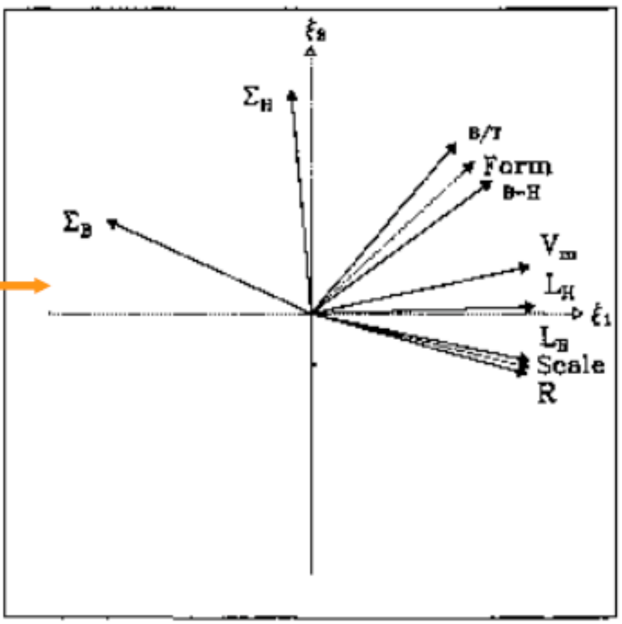
PCA ctd.

- construct a correlation matrix of these coefficients, dimension n x n, where n is the number of parameters measured
- diagonalize the correlation matrix and solve for its eigenvalues and eigenfunctions
  - each eigenfunction is a linear combination of galaxy properties, representing an independent degree of variability (or noise)
  - the corresponding eigenvalues represent the fraction of observed variation of galaxy properties in each of these eigenfunctions
  - NB: This formalism should be familiar from Lagrangian mechanics, e.g., solving for normal modes of an oscillating system

- when applied to elliptical galaxies:
  - most (~80%) of the variance is in a single parameter (mass/luminosity/ radius/velocity dispersion/color/line strength)
  - virtually all of the remaining variance is in a second parameter (ellipticity, rotation...) --> <u>the fundamental plane</u>



- when applied to spiral galaxies:
  - two parameters needed (Hubble type, luminosity/mass)

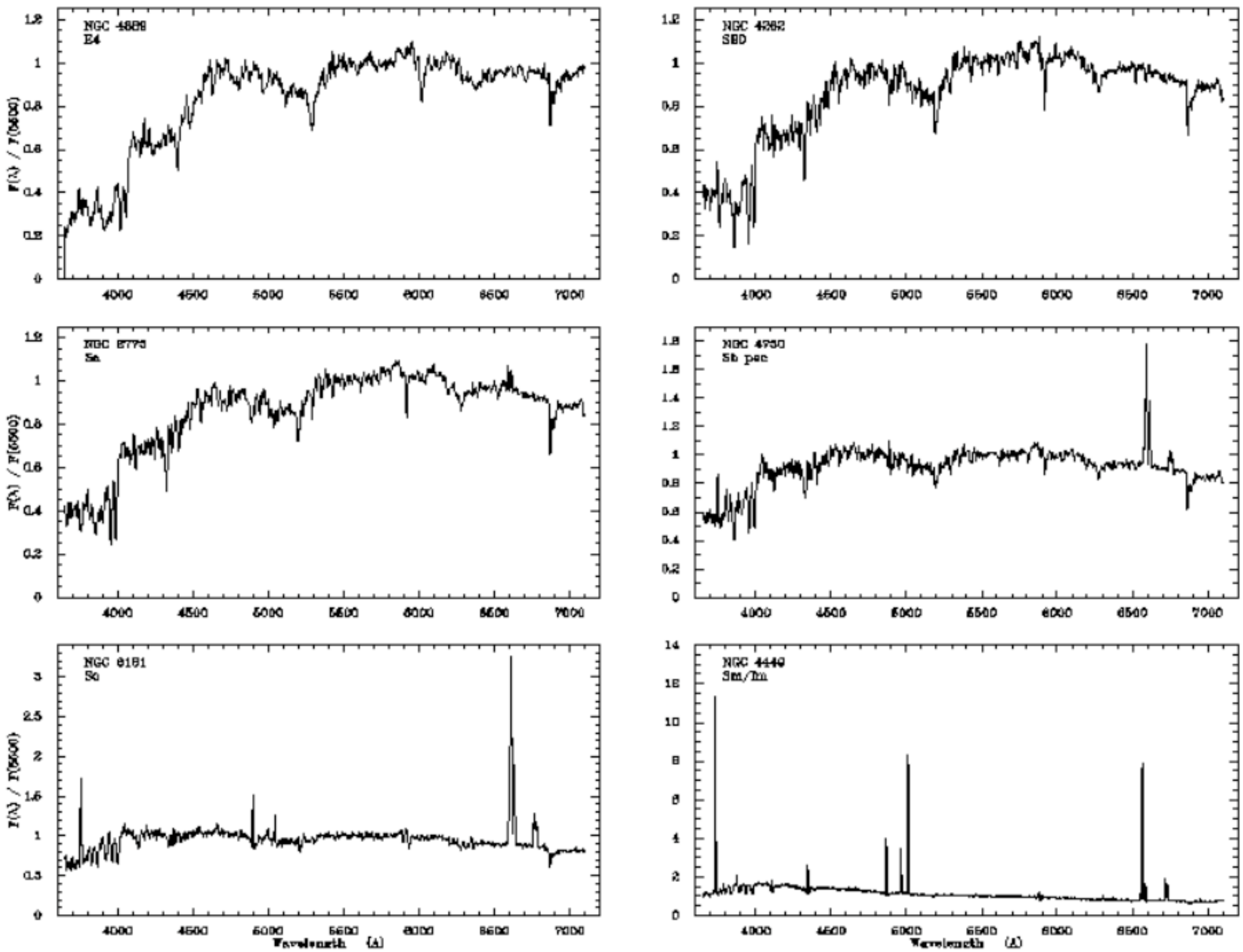


Djorgovsky 1992

Quantitative *spectral* classification

Kennicutt 1992, ApJS, 79, 255 Zaritsky, Zabludoff, Willick 1995, AJ, 110, 1602

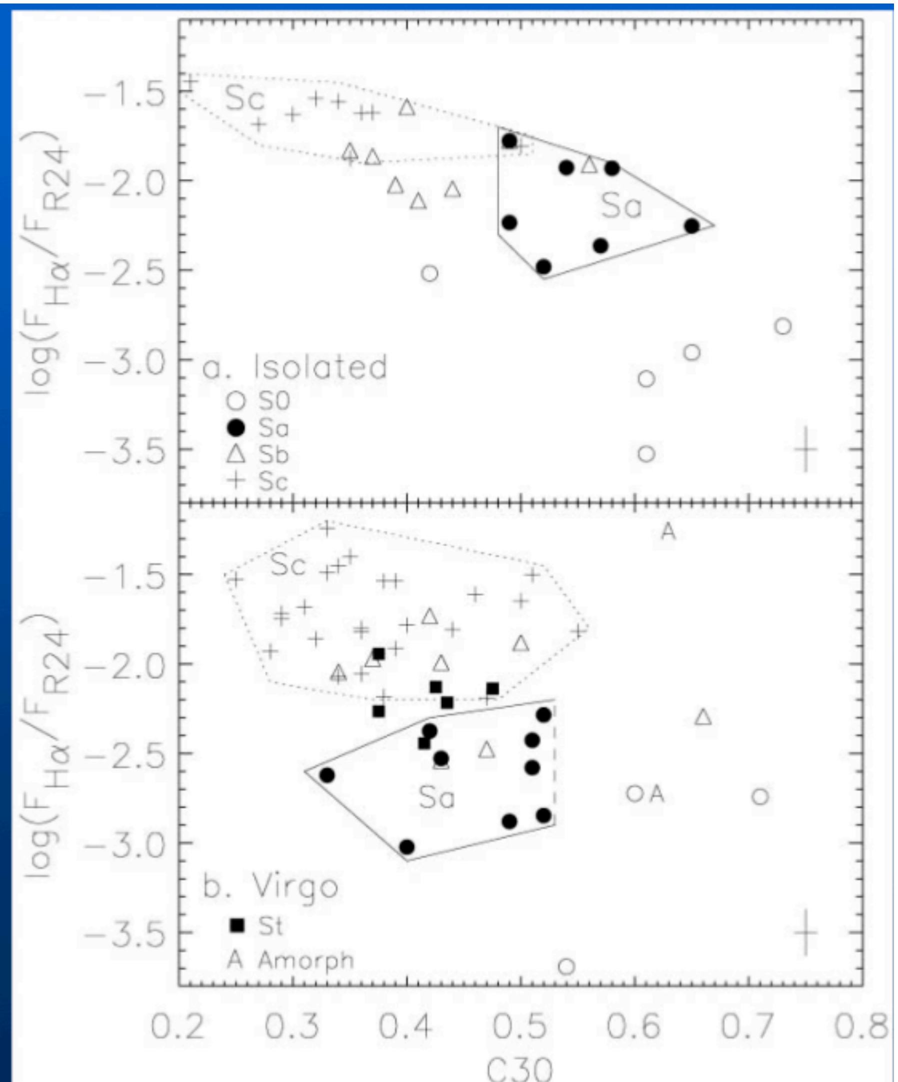
- galaxy spectra correlate strongly with Hubble type
  - Morgan & Mayall (1957) developed a morphological classification system (Yerkes system) based on galaxy spectra (PASP, 69, 291)
- principle component analysis shows that most of the variation is due to 2 parameters (eigenfunctions)
  - change in absorption spectrum: A stars vs K stars
  - change in emission line strength vs continuum + absorption
- fit each galaxy spectrum to these eigenspectra (maximum liklihood), measure spectral indices
- classifications are independent of morphology, but one can correlate spectral vs morphological types


NGC 4889
E4
NGC 4262
SB0
Sa
NGC 4750
Sb pec
NGC 6181
Sc
NGC 4449
Sm/Im
Wavelength (Å)

morphology/spectral classification

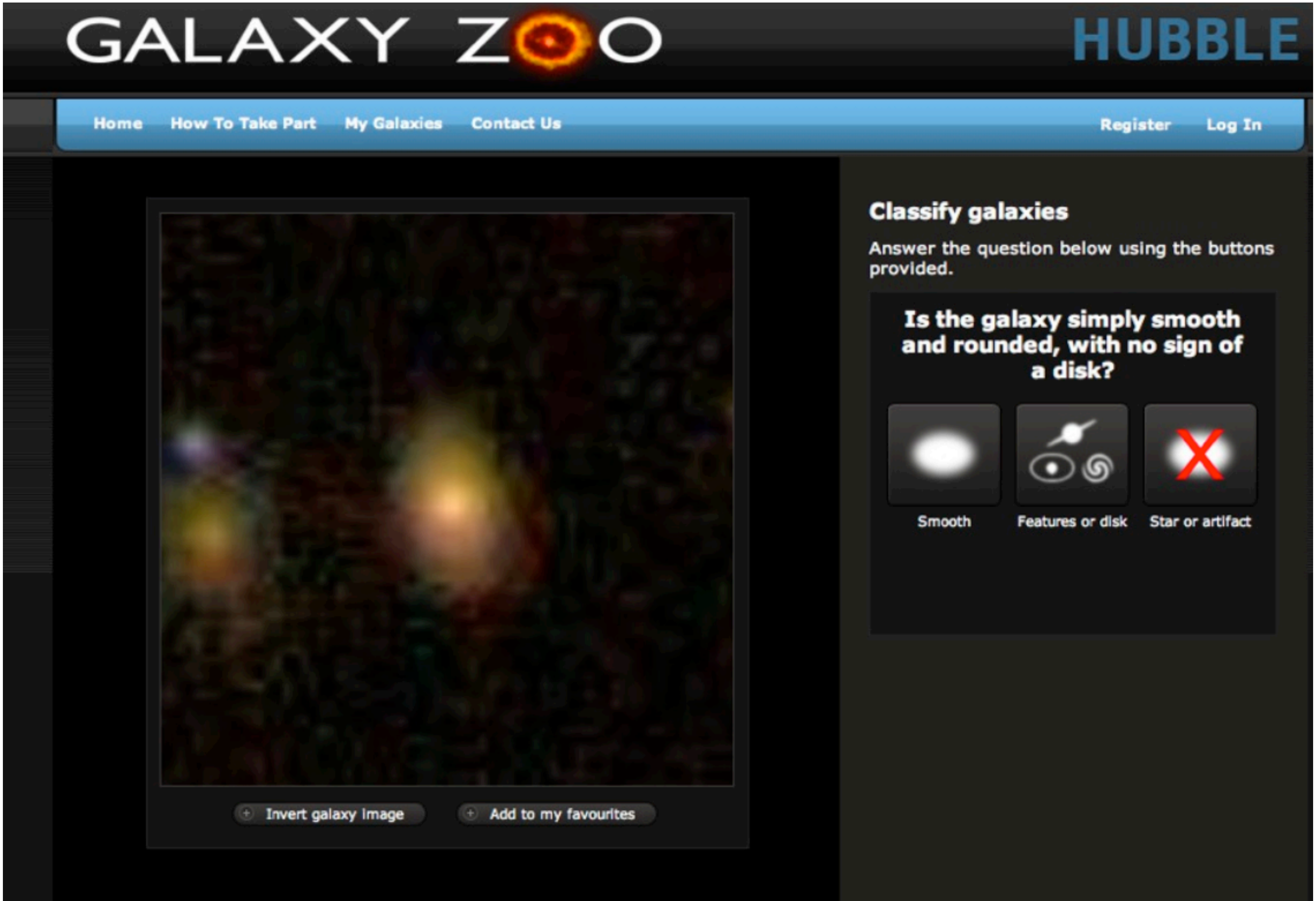
Koopman & Kenney 1998, ApJ, 497, L5

- question: Does galaxy cluster environment (Virgo) affect spiral galaxy evolution?
- hybrid system
  - define emission-line spectral index (scales as SFR per unit red luminosity)
  - correlate with concentration index, to remove subjectivity of morphological types
- result: Virgo cluster contains galaxy population not found elsewhere



Classification of Galaxies

- Ultimately all classification schemes, whether human or machine based, are fallible. However, machine based schemes are certainly more repeatable, i.e. you and I can run the same classification script even though our by-eye results may not agree.
- A notable development in this field though is the advent of Galaxy Zoo (Lintott et al. 2008): a large human based classification of the morphology of SDSS galaxies.
  - The size of the data set and hard work of the classifiers has allowed serious attempts to be made to understand the biases involved in human classification.

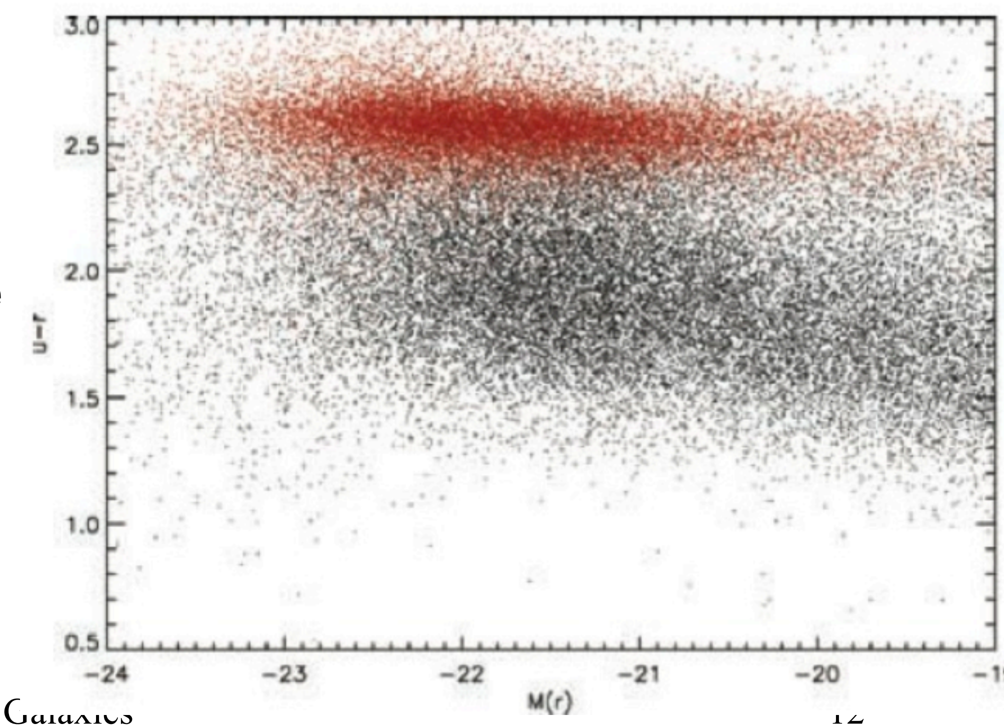

GALAXY ZOO
HUBBLE
Home
How To Take Part
My Galaxies
Contact Us
Register
Log In
Classify galaxies
Answer the question below using the buttons provided.
Is the galaxy simply smooth and rounded, with no sign of a disk?
Smooth
Features or disk
Star or artifact
Invert galaxy image
Add to my favourites

Galaxy colour-bimodality and classification

- one broad result should be emphasized: what may be termed the **morphology-colour** relation. Elliptical galaxies are typically redder in colour than spirals. This phenomenon is also known as colour-bimodality.
- Simply put, the forces that shape the morphology of a galaxy must also influence its star formation history.
- For, as we shall see later, the integrated star formation history is the prime driver of its integrated colour.

Class	Button	Description
1		Elliptical galaxy
2		Clockwise/Z-wise spiral galaxy
3		Anti-clockwise/S-wise spiral galaxy
4		Spiral galaxy other (eg. edge on)
5		Star or Don't Know (eg. artefact)
6		Merger

Table 1. Galaxy Zoo classification categories showing schematic symbols as used on the site.



Photometric Structure

Photometric Structure: Motivation

- unlike more familiar dynamical systems (e.g., solar system, stellar systems), the orbital properties of stars in galaxies are not determined by few-body dynamics, but rather by the mass distribution and dynamical history of the system as a whole
- most relevant dynamical timescales in galaxies lie between two limiting cases:
  - crossing time: time for a typical star to cross the system $\tau_{cross} = R/v$
  - relaxation time: time for the system of stars to randomize orbits and attain an equilibrium configuration
    - derive by computing frequency of 2-body gravitational encounters and typical change in kinetic energy in each encounter; relaxation time is that required for sum of δv^2 to be comparable to typical orbital velocity v
    - $\tau_{relax} \sim (N / 6 \ln(N/2))\ (R/v) = N / (6 \ln(N/2))\ \tau_{cross}$ where N is number of stars in system

Relaxation timescale

- Idea: given enough time, molecules of air will spread themselves out evenly in a room
  - Particles exchange energy and momentum during "collisions" (close encounters)
  - Force between them is much stronger than the force each feels from all other molecules together.
- Similarly, can think of galaxy gravitation potential $\Phi(x)$, as sum of
  - 1) smooth component averaged over region with many stars,
  - 2) remainder: very deep potential well around each star.

Relaxation timescale

- Average time between **<u>strong close encounters</u>**
- Stars mass *m*, move in random directions, speed V
- At approach, KE increases to match change in PE
- Defined as

  change in PE > starting KE
- r_s is strong encounter radius

  (for Sun this is ~few AU!)

  (with ~30 km/s typical near Sun)

$$\frac{Gm^2}{r} \geq \frac{mV^2}{2}$$

$$r < r_s \equiv \frac{2Gm}{V^2}$$

Relaxation timescale

- Happens rarely: sun has not had strong encounter in past ~5 Gyr
- Imagine cylinder radius r_s length Vt
- n stars per unit volume, 1 encounter in time t_s with

  $$n\pi r_s^2 V t = 1$$

$$t_s/(4x10^{12}\,yr) = \frac{V^3}{4\pi G^2 m^2 n}$$

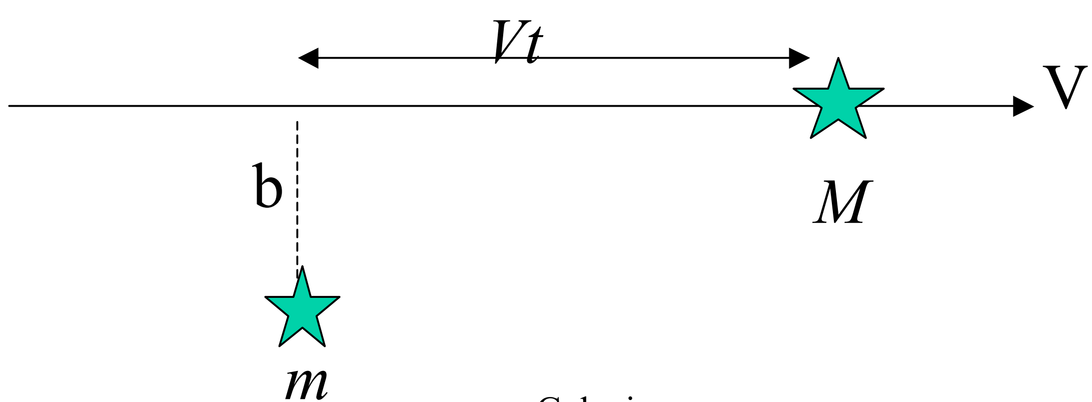
- Around Sun $n \sim 0.1\ pc^{-3}$ and $t_s \sim 10^{15}$ yrs!
- Conclude that strong encounters are only important in dense cores of globular clusters, and in galactic nuclei

$$\approx \left(\frac{V}{10km/s}\right)^3 \left(\frac{m}{Msun}\right)^{-2} \left(\frac{n}{1pc^{-3}}\right)^{-1}$$

Relaxation timescale

Distant weak encounters

- Gravity always attractive, and star pulled toward other stars no matter how far away
- Cumulative pull of distant stars effective in changing stars direction over time
- Weak force implies stars hardly deviate from original path
- Use impulse approximation, calculating force star would feel as they continue on undisturbed path
- Star mass *M,* moving at speed V along path that passes distance *b* from a 'stationary' star of mass *m*



Relaxation timescale

- Measure time from point of closest approach, perpendicular force is

$$F_{\perp} = \frac{GmMb}{(b^2 + V^2 t^2)^{3/2}} = M\frac{dV_{\perp}}{dt}$$

- Integrate over time, find that long after encounter, *M* has speed …

$$\Delta V_{\perp} = 1/M\int_{-\infty}^{\infty} F_{\perp}(t)dt = \frac{2Gm}{bV}$$

- In this approximation, speed V of M along original direction is unaffected - path of M is bent through angle α ...

$$\alpha = \frac{\Delta V_{\perp}}{V} = \frac{2Gm}{bV^2}$$

- Momentum in direction F_{perp} must be conserved, so star m is also moving at 2Gm/bV
- V_{perp} must be small compared with V for valid approximation, thus weak encounter requires b to be much larger than r_s (strong encounter radius)

$$b >> \frac{2G(m+M)}{V^2}$$

Relaxation timescale

- During *t,* number of stars m passing M with separations from b to b + Δb is

  n . Vt 2πb Δb (their volume)

- Multiply by v_{perp} (previous slide) and integrate over b gives the expected squared speed: after time t …

$$\left\langle \Delta V_{\perp}^{2} \right\rangle = \int_{b_{\min}}^{b_{\max}} nVt \left(\frac{2Gm}{bV} \right)^{2} 2\pi b.db$$

$$= \frac{8\pi G^{2} m^{2} nt}{V} \ln\left(\frac{b_{\max}}{b_{\min}} \right)$$

Relaxation timescale

- After time t_{relax}, such that $\langle \Delta V_p^2 \rangle = V^2$, the star's expected speed perpendicular to its original path becomes ~equal to original forward speed
  - The memory of its initial path has been lost
  - Define $\Lambda = b_{max}/b_{min}$, we find this relaxation time is much shorter than the strong encounter time t_s (previous slides) …

$$t_{relax} = \frac{V^3}{8\pi G^2 m^2 n \ln\Lambda} = \frac{t_s}{2\ln\Lambda}$$

$$\approx \frac{2x10^9\,yr}{\ln\Lambda}\left(\frac{V}{10\,km/s}\right)^3\left(\frac{m}{Msun}\right)^{-2}\left(\frac{n}{1000\,pc^{-3}}\right)^{-1}$$

Not obvious what to use for Λ. Can't have $b < r_s$!

Take $b_{min} = r_s$ and b_{max} equal to size of stellar system

For Sun b_{max} ~ 300pc to 30kpc, and $\ln\Lambda$ = 18–22 (exact values not important)

Relaxation timescale

- In an isolated cluster of N stars, mass m, moving at speed V, average star separation is ~1/2 R (size of the system).
- Using the virial theorem: 2<KE> = -<PE>

$$\frac{1}{2}NmV^2 \approx \frac{G(nm)^2}{2R}, \quad so \quad \Lambda = R/rs \sim \frac{GmN}{V^2}.\frac{V^2}{2Gm} \sim N/2$$

- The crossing time t_{cross} ~ R/V; since $N=4n\pi R^3/3$, we have

$$\approx \frac{t\_relax}{t\_cross} \sim \frac{V^4R^2}{NG^2m^2\ln\Lambda} \sim \frac{N}{6\ln(N/2)}$$

Dynamical Timescales of Stellar Systems

- Examples: (1 km/sec = 1 pc per 10^6 years)
  - open star cluster: N ~ 1000 R ~ 10 pc v ~ 1 km/sec
    - τ_{cross} = 10/1 = 10 Myr
    - $\tau_{relax} \sim 18\tau_{cross} \sim$ 200 Myr
  - globular star cluster: N ~ 10^5 R ~ 10 pc v ~ 10 km/sec
    - τ_{cross} = 10/10 ~ 1 Myr
    - $\tau_{relax} \sim 1100\tau_{cross} \sim$ 1 Gyr
  - Milky Way: N ~ 10^{11} R ~ 10,000 pc v ~ 200 km/sec
    - τ_{cross} = 10000/200 = 50 Myr
    - $\tau_{relax} \sim 5 \times 10^8 \tau_{cross} \sim 2.5 \times 10^{16}$ yr

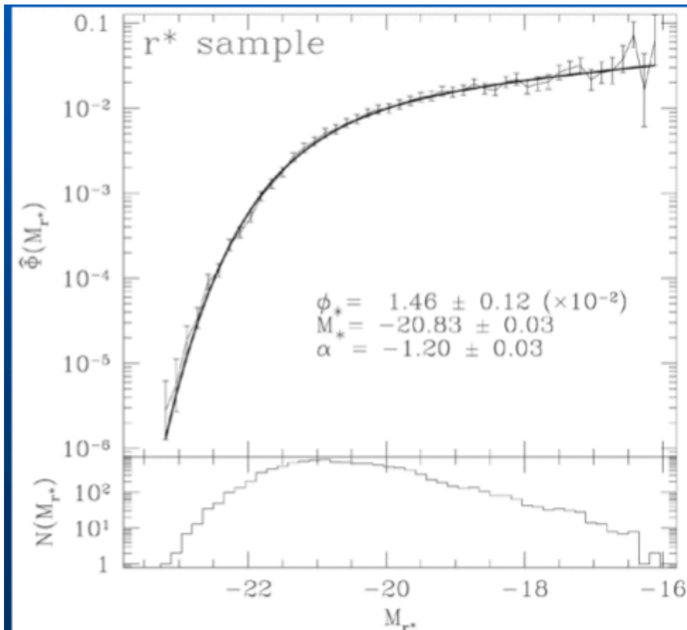
- implication: galaxies have dynamical memory!
- present structure reflects dynamical history over >10 Gyr

Luminosity Functions

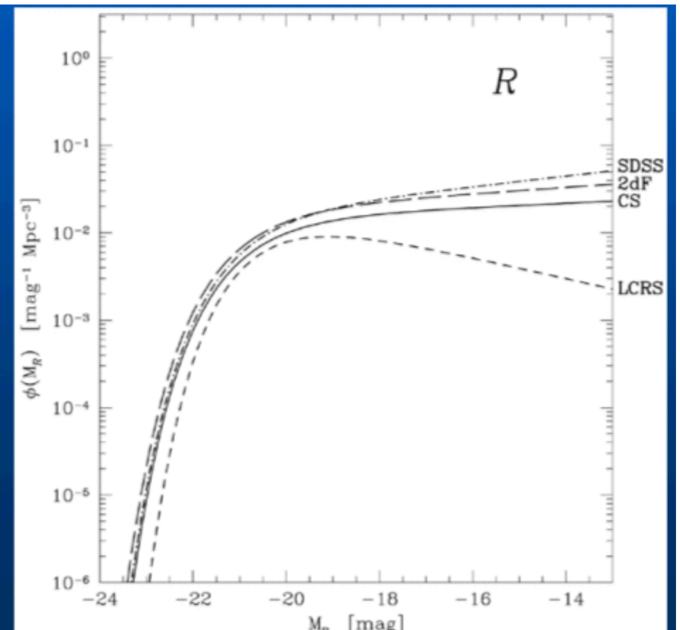
- galaxies span enormous luminosity range: M_B= -24 to -10
- luminosity distribution well constrained for M_B< -15
- parametrization: Schechter 1976, ApJ, 203, 297

$$\Phi(L)\, dL = \Phi(L^*) \; (L/L^*)^{\alpha}\, e^{-L/L^*}\, d(L/L^*)$$

where ϕ_* is a characteristic density, L_* is a characteristic luminosity and α is a faint-end slope.



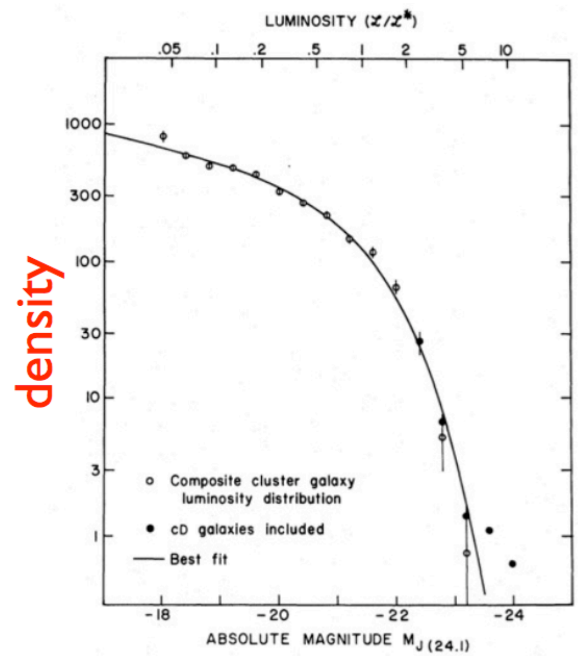
Blanton et al 2001, AJ, 121, 2358 (SDSS)



Brown et al 2001, AJ, 122, 297 (CfA)

Luminosity Functions

- The luminosity function (LF) describes the space density of galaxies per unit luminosity as a function of luminosity.
- Galaxy populations are almost universally described by the Schechter (1976) function
  - can be thought of as a composite function consisting of a faint end power law of slope alpha and a bright exponentially declining form.
  - Current redshift (distance) surveys provide the following best-fitting parameters for the B-band luminosity function of:
  - $\phi_* = 5.5 \times 10^{-3}$ gals Mpc^{-3} $L^* = 2 \times 10^{10} L_\odot$ or $M^* = -20.6$.



Galaxies

Lecture 4: Luminosity Function and Galaxy Profiles

- Luminosity function and galaxy formation
- Photometric structure
- Surface brightness profiles
- Size of galaxies

GOALS:

- Ultimately we want to understand how galaxies form, evolve, and produce the Hubble diagram today
- Relaxation timescale very long! … suggests that studying **galaxy morpology, structure** and **radial profile** will unearth fossil records of the formation history
- The luminosity function of galaxies has also provided a lot of unexpected clues to how galaxies form

- All of these are strong motivations for carefully studying the properties of 'local' galaxies in as much detail as possible.

Dynamical Timescales of Stellar Systems

- Examples: (1 km/sec = 1 pc per 10^6 years)
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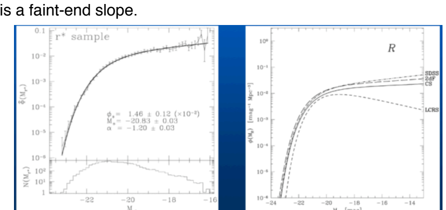

Blanton et al 2001, AJ, 121, 2358 (SDSS) Brown et al 2001, AJ, 122, 297 (CfA)

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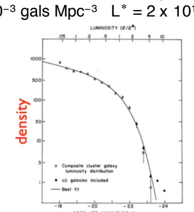


Luminosity Functions

- The total density of galaxies is:

$$\Phi = \int_0^\infty \phi(L')\, dL' = \Gamma(\alpha+1)\, \phi^*,$$

- where Γ(a) is the Gamma function. Note that this integral diverges for α<-1, in which case the alternative form should be used:

$$\Phi(>L) = \int_L^\infty \phi(L')\, dL' = \Gamma(\alpha+1, L/L^*)\, \phi^*,$$

- where Γ(a, b) is the incomplete Gamma function.

Luminosity Functions

- The luminosity density of galaxies is

$$\mathcal{L} = \int_0^\infty L\ \phi(L)\ \mathrm{d}L = \phi^* L^* \Gamma(\alpha + 2).$$

- Taking $\alpha = -1$ gives $\Gamma(\alpha + 2) = \Gamma(1) = 1$ and $L = \phi_* L_* = 1.1\times10^8\ L_\odot \mathrm{Mpc}^{-3}$.

Luminosity Functions

- Mulitplying the LF by a single M/L ratio (see Dark Matter later) generates a very simple galaxy mass function.
- Why does the crude galaxy mass function deviate from the expectation of a dark matter mass function at the high- and low-mass ends?
- This is similar to the question of what determines the maximum and minimum mass of a galaxy?
- Answers include supernova driven mass loss and AGN moderated feedback.

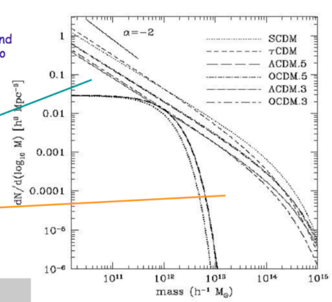
Galaxy Evolution - Dark Matter and Gravity

- NB: the luminosity and mass functions do not match those expected for dark matter haloes
- feedback processes may determine shape of galaxy mass, luminosity functions
- understanding galactic-scale SF and "gastrophysics" is the missing link to understanding galaxy formation, evolution

Somerville & Primack 1999, MNRAS, 310, 1087

gas ejection in winds?
inefficient star formation?

gas ejection from AGNs or superwinds?
gas exhaustion?

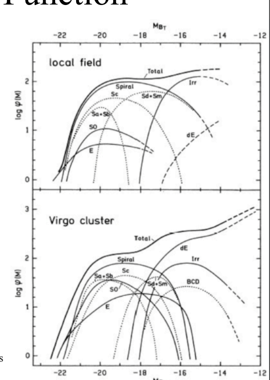


cf Di Matteo, Springel, Hernquist 2004, Nature, 443, 604

Luminosity Function

- The LF can be applied across all galaxy types or split by galaxy properties
- Form of LF at faint luminosities still uncertain, controversial
- LF is strong function of galaxy type
- LF probably is dependent on galaxy environment

Binggeli, Sandage, Tammann 1988, ARAA, 26, 509



Theory: Structure of Galactic Spheroids

Radial structure:

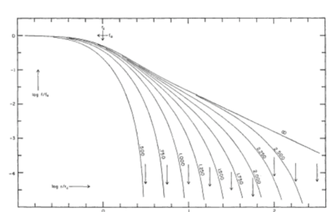
- if we approximate spheroids as relaxed, purely stellar systems, stellar dynamical theory provides a semi-empirical description (King 1962, AJ, 67, 471)
  - *Look at this in detail in Lec_5*
- profile follows isothermal profile ($\rho \sim 1/r^2$) over several magnitudes in surface brightness
- central core, with projected brightness

$I(r) = I_0 / (1 + r/r_c)$

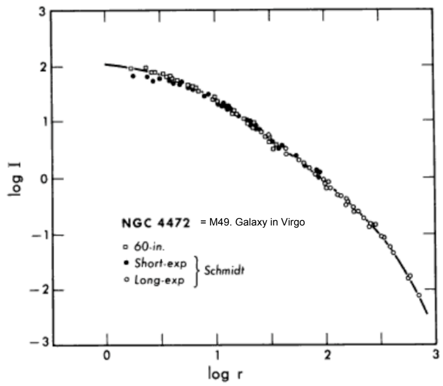
r_c -> core radius

- King model also requires outer truncation, parametrized by a tidal radius

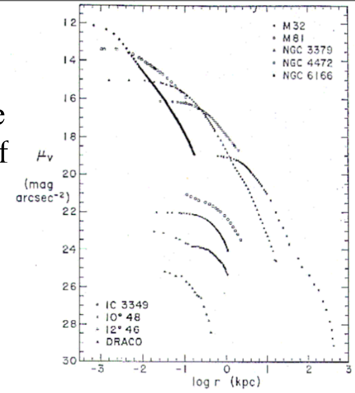
c -> log (r_t / r_c)



King 1966, AJ, 71, 64



King models are reasonable descriptions of a range of spheroid classes

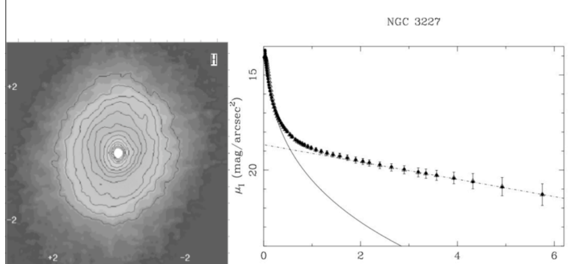


see: Kormendy (1985)

Surface brightness profiles

- One could think of this as one-dimensional morphology where the intensity per unit surface area is expressed via an analytic function.
- Surface brightness data is generated by averaging along elliptical isophotes to generate 1D elliptically averaged light profiles.

Surface brightness profiles



Chapman et al. (2000)

Surface Brightness

- Surface brightness is quoted in $L_\odot pc^{-2}$,
- i.e. $1 L_\odot pc^{-2} = (3.86 \times 10^{24}$ W$)/(3.09 \times 10^{16}$ m$)^2 = 4.05 \times 10^{-7}$ Wm^{-2} .
- The B-band solar magnitude is $M_{B,\odot} = 5.48$ and 1 pc at 10 pc subtends 0.1 radians (20626.5 arcseconds).
- Expressing $L_\odot pc^{-2}$ in magnitudes per square arcsecond gives

$\mu_B = -2.5 \log(L/pc^2)$
$= M_{B,\odot} + 5 \log(20626.5)$
$= 27.05$ *B* magnitudes per square arcsecond (at 10 pc).

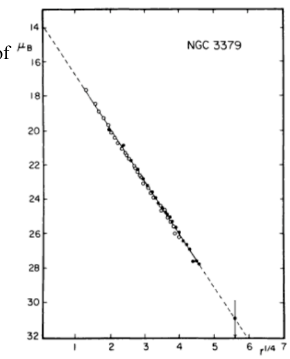
Empirical luminosity laws

- Generally, features such as spiral arms and dust lanes average out in this process (though as will be seen some ripples and bumps can remain).
- Simplistically:
  - *Spiral galaxy disks* display surface brightness profiles that are well fit by **exponential** intensity profiles
  - *Elliptical galaxies* are fit by a **de Vaucouleurs** (1948) or **$R^{1/4}$** intensity profile.

Empirical luminosity laws

- Hubble (1926) profile
  $I(r) = I_0 / (1 + r/r_o)^2$
- de Vaucouleurs $r^{1/4}$ law
  $\log I(r)/I_0 = (r/r_e)^{1/4} - 1$
  where r_e -> effective radius
  (radius containing half of integrated luminosity)
- although the $r^{1/4}$ law is empirical in origin, n-body simulations of merging/forming spheroids can reproduce the profile

de Vaucouleurs profile:
Good fit to outer regions of spheroidal galaxies (ellipticals)



de Vaucouleurs, Capaccioli 1979, ApJS, 40, 699

Surface brightness (spirals)

- Exponential (spiral) intensity profile:
  $I(R) = I_0 \exp(-R/r_s)$,
- where I_0 is the central intensity and r_s is a scale length.
- Expressed in magnitudes
  $\mu(R) = \mu_0 + 1.086(R/r_s)$

where 1.086 = 2.5 log e.

Sersic Luminosity Profiles

- Sersic 1968, Atlas de Galaxias Australes (Cordoba: Obs. Astr. Cordoba) BM Box 4.1 (p187)
- the de Vaucouleurs law is a specific form of a more generalized law:
  $\log I(r)/I(r_e) = -b_n [(r/r_e)^{1/n} - 1]$
  where r_e -> effective radius

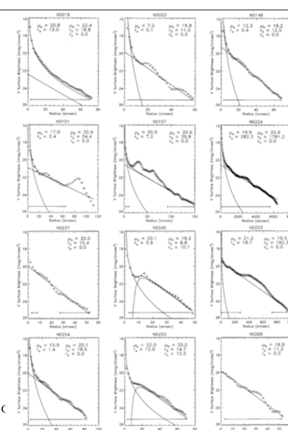
('b' chosen so radius contains half of integrated luminosity)

- case n = 4: de Vaucouleurs $r^{1/4}$ law
- case n = 1: exponential (disc) law
- intermediate cases do exist (e.g., pseudo-bulges)
- a galaxy can be fitted with a sum of Sersic profiles (one for each distinct component)

Surface Brightness Profiles

- In practice many galaxies display a surface brightness profile that is best described by a superposition of two intensity profiles.
- This is achieved by fitting a galaxy with each profile applied over a selected range of radii,
  - e.g. $R^{1/4}$ over inner radii and exponential over outer radii.
- Such an approach is referred to as bulge-disk decomposition.

Surface Brightness Profiles



Surface brightness

- Surface brightness can be expressed as
- $L_{Total} / 2\pi R_e^2$ where R_e is the half-light radius.
- Using this simple definition, both spirals and ellipticals display surface brightnesses of order 100 $L_\odot pc^{-2}$ or $\mu_B = 22$.
- Central values of surface brightness can differ greatly,
- e.g. of order a few hundred $L_\odot\ pc^{-2}$ for spirals to $\sim 10^4\ L_\odot\ pc^{-2}$ for ellipticals.

Size of galaxies

- A closely related topic is the idea of the total size of a galaxy.
- The detectable extent of a galaxy on a detector is determined by the radius at which the surface brightness approaches the effective surface brightness of the combined sky plus detector noise.
- This isophotal area can be thought of as a lower limit on the size of a galaxy.

Size of galaxies

- One could simply integrate the relevant surface brightness profile to infinite radius. However, this
- a) requires obtaining an accurate determination of the SB profile
- b) assumes that the profile can be reasonably extrapolated beyond the isophotal radius.
- An alternative, practical approach is to determine a radius based upon a statistical analysis of the light distribution in the galaxy itself.
- This has the advantage that the radius is model independent and can be computed for galaxies where only a few tens (or less) of pixels are detected above the isophotal threshold.
- This is the idea behind the Kron (1980) and Petrosian (1976) radii.

Surface brightness

Total luminosity: $L_T = \int_0^\infty 2\pi R I(R) \mathrm{d}R.$

Half light radius: $L(R_e) = \int_0^{R_e} 2\pi R I(R) \mathrm{d}R = 0.5 L_T.$

Kron radius: twice the image moment radius

$$R_K = \frac{\int R^2 I(R) \mathrm{d}R}{\int R I(R) \mathrm{d}R}.$$

Typically, $L(R_K) \sim 90\%\ L_T$.

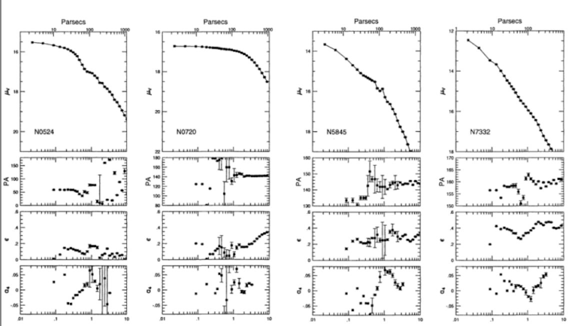
Petrosian radius:

$$I(R_P) = 0.2 \frac{L(R_P)}{\pi R_P^2}.$$

One inverts the equation to obtain R_P . Typically, $L(R_P) \sim 90\%\ L_T$

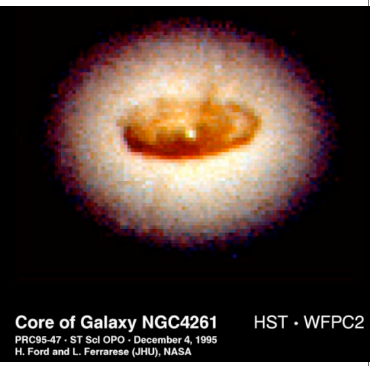
Core structure of spheroid galaxies

- Lauer et al. 1995, AJ, 110, 2622 (*Nuker* team)
- Jaffe et al. 1995, AJ, 108, 1567
- **subject revolutionized by HST - resolution at larger distances where typical ellipticals live**
- luminous galaxies show strong turnover in inner ~100 pc cores; or "shallow cusps"
- lower luminosity galaxies show continued (1/r) increase in brightness into the galactic centers
- few ellipticals show asymptotic flat brightness profile in center



Lauer et al. 1995, AJ, 110, 2622

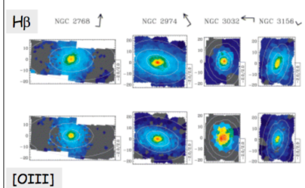
- Many spheroids possess nuclear discs with gas, dust

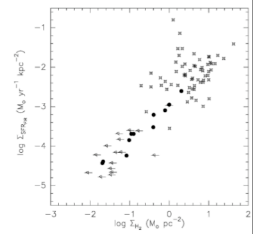


Ellipticals with faint disks

SAURON Sample

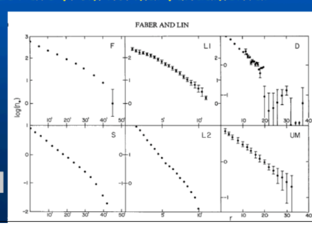
- 48 E/S0 galaxies observed (43 in CO)
- 75% detected in Hβ (16/24 E, 20/24 S0), 28% detected in CO
- typical SFRs of order 0.01-1 $M_{\odot}$/yr
- disk-averaged SF properties extend Schmidt law for spirals





dSph galaxies: mini-ellipticals?

- Dwarf spheroidal galaxies show different radial structure
  - radial profiles fitted better with King profiles (like star clusters) or exponential profiles (like discs)
  - these galaxies also have distinct dynamical properties, and deviate from normal fundamental plane



Faber & Lin 1983,ApJ, 266, L17

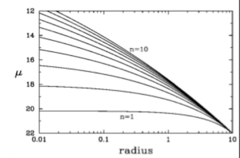
Leo I dSph M_V = -11.9

Elliptical Galaxies

Lectures 5-7: 3D structure of ellipticals, their stars, a physical understanding, and their formation mechanisms

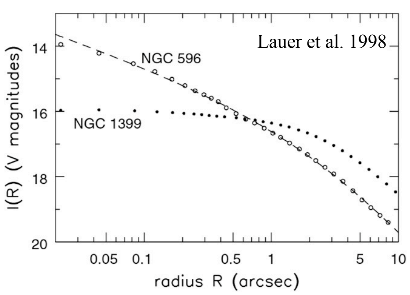
- **3D structure of ellipticals & scaling relations**
- Stellar populations in Ellipticals,
- cusps/cores and clues to the formation of E's
- Collisionless Boltzmann Equation
- Isothermal sphere and King model
- Violent relaxation (rapid change in potential)
- Relation to observed Sersic profiles
  - Sersic index varies with Elliptical luminosity

Parameterization of the Surface Brightness Profiles:



- Sersic law (Sersic 1968):
  $I(R) = I_e \exp(-b_n[R/R_e)^{1/n} - 1])$
- Has a number of attractive features for parameterizing both the small - and large-scale profiles of E/dE galaxies:
  - Accounts for the profiles' curvature on kpc-scales
  - Parameters are robust against radial range of data (Graham et al. 2003)
  - Integrals for r->infinity converge (c.f., Nuker law)

Cores/Cusps



Elliptical Galaxies

Inferring the density from the surface brightness

- The surface brightness profile, which essentially traces the distribution of stars, can be used to infer the underlying 3D matter density distribution.
- The projected stellar surface density distribution is the integral over the 3D stellar density distribution.
- This in turn can be viewed as the total matter 3D density distribution scaled by a suitable mass-to-light ratio
  - (in practice the use of a single M/L may be simplistic, though useful, assumption).

Elliptical Galaxies

- So what can we learn about the underlying 3D matter density distribution from the radial distribution of starlight alone?
- Consider a power law distribution of 3D density, e.g. $\rho \propto r^{-\gamma}$. The projected surface brightness distribution will be a scaled version of the projected density, i.e.

$$I(R) \propto \int_0^\infty (z^2 + R^2)^{-\gamma/2} \mathrm{d}z$$

where the z -axis is defined by the line-of-sight to the observer.

3D structure

- Taking g = z /R, this integral becomes

$$\int_0^\infty \frac{R\ \mathrm{d}g}{R^\gamma (g^2+1)^{\gamma/2}} = R^{-\gamma+1} G(\gamma)$$

where G(γ) depends only on γ.

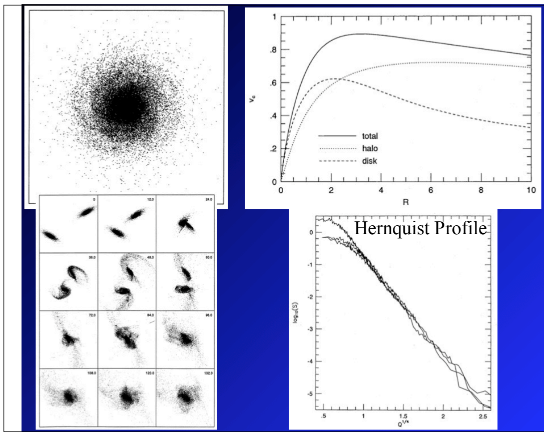
Therefore a power-law 3D density of slope –γ projects onto a surface density profile of slope –γ + 1.

(likewise King models have similar behaviour from 3D density to 2d surface density profile)

- One of the drawbacks of the de Vaucouleurs surface brightness distribution is that it does not have an analytic counterpart in 3D density.
- Various density profiles have been suggested that provide a good match to observed surface brightness profiles when projected, e.g. the Hernquist (1992) profile

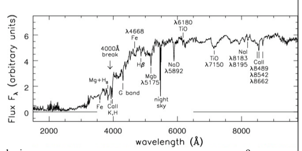
$$\rho(r) = \frac{M}{2\pi} \frac{r_c}{r(r + r_c)^3}$$

- The Hernquist model is particularly appealing as it arises from the numerical simulation of the merger of two equal mass disk galaxies, each embedded within a dark matter halo.



Relation to orbital properties

- The 2D shapes of elliptical galaxies results from the 3D distribution of stars.
- This in turn may be thought of as a reflection of the 3D orbital structure of the galaxy.
- The debate as to the orbital structure of bright ellipticals was eventually resolved via resolved absorption line spectroscopy during the 1970s and early 1980s.
- Ellipticals are not isotropic systems whose 2D morphology arises from rotational flattening.
- They are slow rotators compared to their random velocity dispersion.



Relation to orbital properties

- The 2D morphology of bright ellipticals results from an anisotropic mix of stellar orbits.
- As the stellar orbits are incoherent (both positive and negative along the line of sight) let us consider the mean square velocity $\langle v^2 \rangle$ along each axis.
- We refer to the mean square velocity along each axis as σ^2 (i.e. $\langle v_x^2 \rangle = \sigma_x^2$ where σ is the velocity dispersion).
- Consider a galaxy rotating in the x-y plane (i.e. about the z -axis) with a rotational velocity V .
- The velocity dispersions are isotropic, i.e. $\sigma_x^2 = \sigma_y^2 = \sigma_z^2$.

Orbital properties

- The radial extent of stars along each axis should be proportional to their kinetic energies.
- Assuming we view the system from the y-axis (side on), then a non zero axis ratio should result from rotational flattening according to

$$\frac{b}{a} \approx \frac{K_z}{K_x} \approx \frac{\sigma_z^2}{V^2 + \sigma_x^2}$$

- The 1D velocity dispersion $\sigma_r = \sigma_y$ which is equal to the other components following our isotropy condition.

- We therefore have

$$\frac{b}{a} \approx \frac{\sigma_r^2}{V^2 + \sigma_r^2},$$

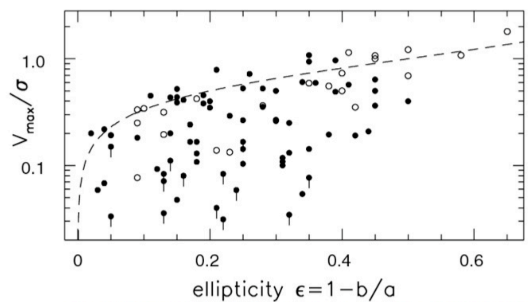
- which can be re-arranged to yield

$$\left(\frac{V}{\sigma}\right)^2 \approx \left(\frac{a}{b} - 1\right) = \frac{\epsilon}{1 - \epsilon}$$

- where $\epsilon = 1 - b/a$ is the observed ellipticity.

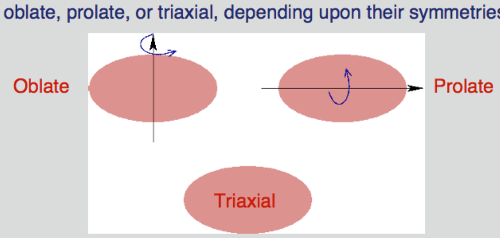
Orbital properties

- As can be seen (next slide), to obtain b/a = 0.5 (an E5 elliptical) requires V /σ ≈ 1.
- As a typical bright elliptical may display σ = 250kms^{-1} this means it would have to rotate as fast as a massive spiral !!!
- In practice most bright ellipticals rotate much slower than this limit.
- One concludes that rotational flattening does not contribute to the 2D shapes of ellipticals
- And that they are instead caused by anisotropic orbits.



Dynamics of elliptical galaxies

Galaxies that appear elliptical on the sky may be intrinsically oblate, prolate, or triaxial, depending upon their symmetries:



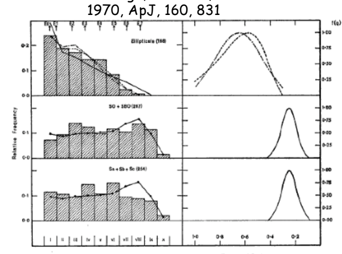
For an individual galaxy, can't determine from an image what the intrinsic shape of the galaxy is.

Orbits of stars differ substantially in different types.

3-Dimensional Form of Spheroids

- Approximated 3D forms as oblate or prolate spheroids
- Get distribution if true flattenings can be determined (detailed kinematics?)
- Photometric and kinematic tests more consistent with oblate geometry

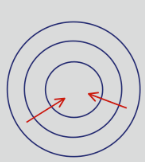
Sandage, Freeman, Stokes 1970, ApJ, 160, 831



Orbits in elliptical galaxies

Classification of stellar orbits in elliptical galaxies is much more complicated than for disk galaxies. Most important distinction is between **axisymmetric galaxies** (prolate or oblate) and **triaxial galaxies**.

In an axisymmetric galaxy, there is a plane, perpendicular to the symmetry axis, in which gravitational force is central.



No azimuthal force, so component of angular momentum about symmetry axis (say, z-axis) is conserved

$$L_z = m(\mathbf{r} \times \mathbf{v})_z$$

Only stars with L_z=0 can reach center, other stars must avoid the center.

Orbits in elliptical galaxies

Triaxial potential: energy is conserved but not L_z

Simple example is the potential:

$$\Phi(\mathbf{x}) = \frac{1}{2}\left[\omega_x^2 x^2 + \omega_y^2 y^2 + \omega_z^2 z^2\right]$$

…which is the potential inside a uniform density ellipsoid. ω_x etc are constants. Star in this potential follows harmonic motion in each of the x,y,z directions *independently*.

Unless ω_x, ω_y and ω_z are rational multiples of each other (eg 1:2:7) orbits never close - star completely fills in a rectangular volume of space in the galaxy.

Example of a **box orbit**.

Orbital properties

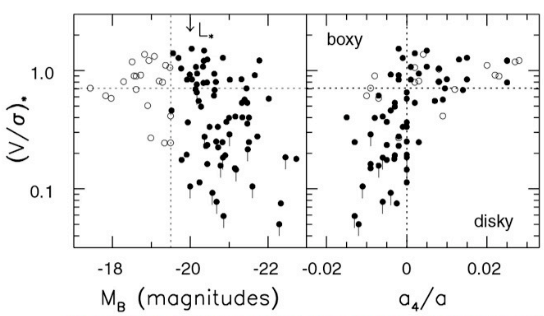
- Clearly some ellipticals do rotate to the extent that *rotational flattening* contributes to their morphology.
- These are generally lower luminosity ellipticals and their morphologies as often referred to as "disky" (as opposed to the "boxy" bright ellipticals) – thought to indicate a rotating stellar disk.

- At the 1-2% level most spheroids show systematic deviations from elliptical isophotes
  - parametrize in terms of Fourier terms:

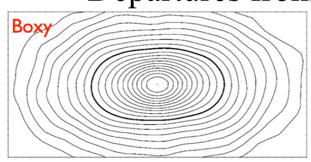
$$I(\theta) = a_0 + a_2 \cos(2\theta) + a_4 \cos(4\theta) + ...$$

- $a_4 = 0$ pure ellipse
- $a_4 < 0$ "boxy"
- $a_4 > 0$ "discy"

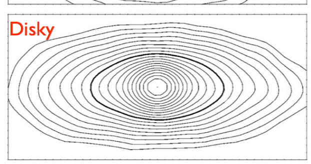
- a_4 correlates with kinematic properties (i.e., discy galaxies rotate faster)
- it also correlates with most other properties along the fundamental plane



Departures from ellipticity



Boxy ellipticals suggest some degree of triaxiality.

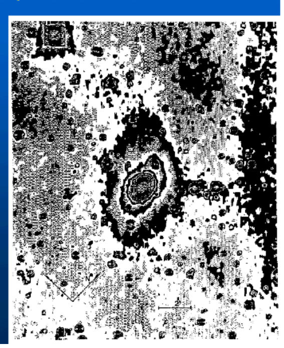


In the limit, S0 galaxies could be considered the extreme of 'disky' ellipticals

- High S/N images reveal significant departures s from elliptical geometry
  - isophotal twists
  - ellipticity variations
  - "boxy" isophotes
  - "discy" isophotes

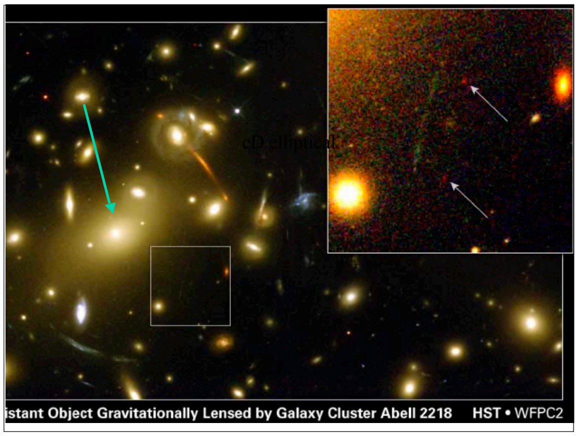
NGC 1600 →

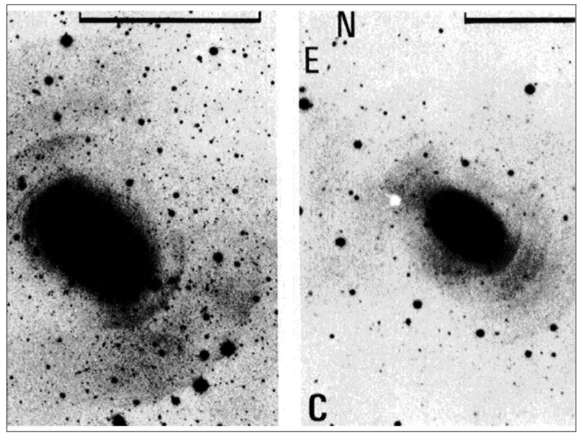
Barbon et al. 1984, A&A, 137, 166

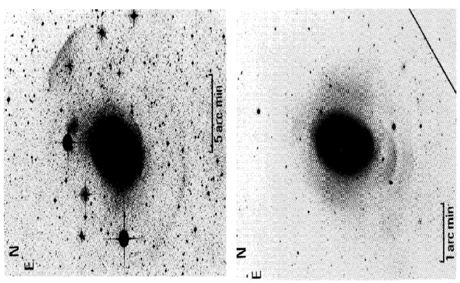


- **Shells** Malin & Carter 1983, ApJ, 274, 534
  - faint(!) azimuthal shells are observed around a large fraction of elliptical galaxies
  - shells are characterized by sharp edges, caustic structure
  - galaxies with prominent shells have systematically bluer colors, evidence of intermediate age stars in spectra
  - numerical simulations suggest shells are tidal remnants of satellite galaxy accretion, minor mergers
- **cD Galaxies**
  - some luminous elliptical galaxies possess very extended power-law envelopes, extending up to »100 kpc in radius
  - predominantly seen in central galaxies in rich clusters
  - multiple nuclei very common
  - probably built up from multiple captures and mergers with neighboring galaxies --> "galactic cannibalism"

Yerkes classifications: "c" in "cD" refers to galaxies being very large, hence *supergiant*, "D" refers diffuse. A backformation of "cD" is frequently used to mean *central Dominant galaxy.*







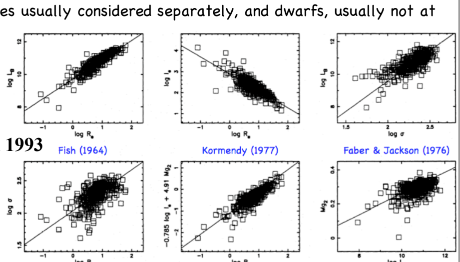
Malin & Carter 1983, ApJ, 274, 534

- Shells have been used to constrain stellar orbits and potential of ellipticals

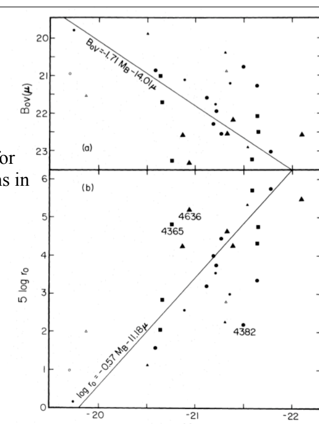
SCALING RELATIONS in Elliptical Galaxies

- Luminous (Giant = Normal = Ordinary) galaxies obey a well-defined set of **scaling relations** between their *photometric* and *kinematic* structural parameters:
- e.g., Fish (1964), Faber & Jackson (1976), Kormendy (1977), Binggeli, Sandage & Tammann (1984), Dressler et al. (1987), Djorgovski & Davis (1987), and many, many others.
- Late-types usually considered separately, and dwarfs, usually not at all.

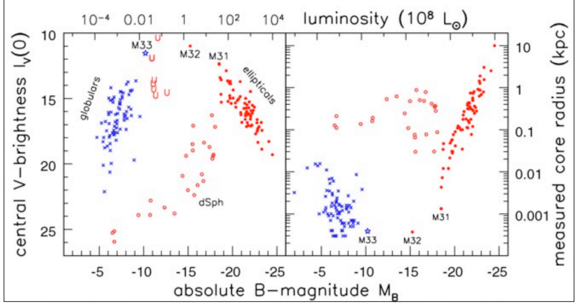
Guzman et al 1993



Kormendy 1977
Early suggestions for parameter correlations in Ellipticals



- Ellipticals, dSphs, and globular star clusters are not all obviously an extension of the same spheroid sequence … (dSphs later lecture)



Faber-Jackson and the virial theorem

- Faber and Jackson (1976) determined (empirically) that the luminosity of bright ellipticals is related to their velocity dispersion via

  $L \propto \sigma_r^n$ with $3 < n < 5$.

- More luminous ellipticals are more massive.

Faber-Jackson and the virial theorem

- One can take a simple approach to the FJ relation by noting that
- $v^2 \propto GM/R$ (virial theorem) and $L \propto I_e R_e^{\ 2}$
- This indicates that $L \propto v^4 / (I_e (M/L)^2)$,

which nominally reproduces the FJ relation (if both the M/L ratios and surface brightness properties are relatively constant for bright ellipticals).

Faber-Jackson and the virial theorem

- As we have noted, the FJ relation is a reflection of the virial theorem applied to elliptical galaxies, assuming that their surface brightnesses and mass-to-light ratios are relatively constant.
- Beginning with the virial theorem we can write $2K + U = 0$
- For the kinetic energy of the system we have

$$K = \frac{1}{2}\sum_i m_i v_i^2 = \frac{1}{2}M\langle v^2\rangle$$

Faber-Jackson and the virial theorem

- We further note that $\langle v^2 \rangle = \sigma^2 = 3\sigma_r^2$, where σ_r is the 1D velocity dispersion. The potential energy takes the form

$$U = \sum_{i>j} -\frac{Gm_i m_j}{|r_i - r_j|} = -\frac{GM^2}{r_g}$$

where r_g is a weighted average separation of the stars in the galaxy.

Faber-Jackson and the virial theorem

- Generally we may write

$$U = -\alpha\frac{GM^2}{R_e}$$

- where α is a constant of order unity whose value depends upon the form of the density profile.
- We can therefore write

$$3M\sigma_r^2 = \alpha\frac{GM^2}{R_e}$$

$$M = \frac{3\sigma_r^2 R_e}{\alpha G}$$

$$L = \frac{3\sigma_r^2 R_e}{\alpha G(M/L)}$$

$$L \propto \frac{\sigma_r^2 R_e}{(M/L)} \quad \text{but we also have } L \propto I_e R_e^2$$

$$L \propto \frac{\sigma_r^2 (L/I_e)^{1/2}}{(M/L)}$$

$$L \propto \frac{\sigma_r^4}{I_e^2 (M/L)^2}.$$

- Which corresponds to the FJ relation assuming that I_e and *M/L* are relatively constant for bright ellipticals.

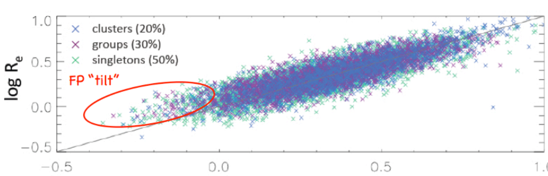
The Fundamental Plane

- Djorgovski and Davis (1987) were among a number of researchers to note that two parameter scaling relations
  - Faber-Jackson sigma-L
  - Kormendy (core/cusp surface brightness, vs L)

  contained real scatter in which the residuals in one plot correlated with those on the other.
- This suggested the existence of a *three parameter* relation encompassing the above relationships,
  - i.e. a tilted plane of points in 3D of which the FJ and Kormendy relations are 2D projections.

Es/S0s and the Fundamental Plane

- Edge-on projection of the Fundamental Plane for 10K early-type galaxies from the 6dFGS (Colless et al. 2009; www.aao.gov.au/6dFGS).
- Note: does not include "dwarfs" (i.e., the sample has a mass cutoff of 1010.5 solar masses).



The Fundamental Plane

- The Fundamental Plane (FP) relation for bright ellipticals takes the form

log Re = 1.4 log σ_e + 0.36Σ_e + constant,

- where σ_e is the 1D velocity dispersion measured within R_e and $\Sigma_e = -2.5 \log I_e$

The Fundamental Plane

- The FP relation can be reconstructed using the following arguments

$$R_e^2 = \frac{L}{2\pi I_e}$$

$$R_e = \frac{M}{c\sigma_e^2}$$

with this second equation being a statement of virial equilibrium and ***c*** denoting a combination of physical constants.

The Fundamental Plane

- Dividing these two equations one obtains

$$R_e = \left(\frac{c}{2\pi}\right)\left(\frac{M}{L}\right)^{-1} \sigma_e^2 I_e^{-1}$$

$$\log R_e = 2\log\sigma_e - \log I_e + \log\left[\frac{2}{2\pi}\left(\frac{M}{L}\right)^{-1}\right]$$

$$\log R_e = 2\log\sigma_e - 0.4\Sigma_e + \log\left[\frac{2}{2\pi}\left(\frac{M}{L}\right)^{-1}\right]$$

which is close to but not exactly equal to the observed FP relation.

The Fundamental Plane

- We conclude that

1. Bright ellipticals are in virial equilibrium.
2. To 1st order M/L ratios and structural parameters are very similar.
3. Therefore, their stellar populations, ages and DM properties are very similar.
4. To obtain an exact match to observed FP data requires $M/L \propto M^{0.2}$, i.e. massive ellipticals are slightly older than less massive counterparts.