What We Don't Know:

Open Questions in Fundamental Physics

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Big Questions

As we know,
There are known knowns.
There are things we know we know.
We also know
There are known unknowns.
That is to say
We know there are some things
We do not know.
But there are also unknown unknowns,
The ones we don't know
We don't know.

Donald Rumsfeld, 2003

Known Knowns

- Quarks are confined.
- The masses of the hadrons are determined by QCD.

(Known. But we’re still not smart enough to do the math)

Known Unknowns

- What is the Higgs particle?
- Do gravity waves exist?
- Is Nature supersymmetric?
- Are the forces unified?
- What is dark matter?
- How long does the proton live?
- Are the constants of Nature truly constant?
- Do black holes lose information?
- What is the quantum theory of gravity?
- What is dark energy?

(We at least expect these questions to have an answer)

Unknown Unknowns

- Why is there more matter than anti-matter?
- Why is gravity so *very very* weak?
- Why is the universe so big and flat?
- Why are there four macroscopically large dimensions?
- What is measurement in quantum theory?
- Is there a beginning of time?
- What gave rise to the arrow of time?

(It’s not even clear these questions have a sensible answer)

The Plan

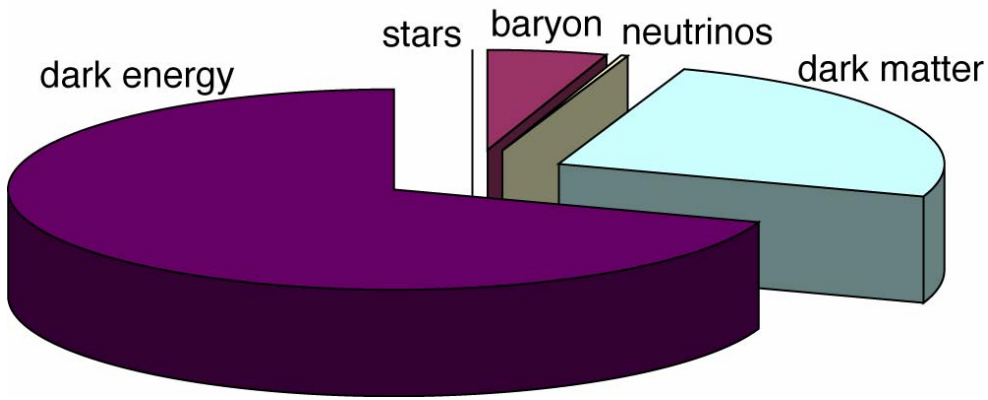
- I'll concentrate on just two of these questions:
  - What is dark matter?
  - What is dark energy?

- The first probably has a rather simple answer.
- The second is harder and possibly holds the key to the greatest problems of all….


Astro-Porn: Hubble ultra-deep field

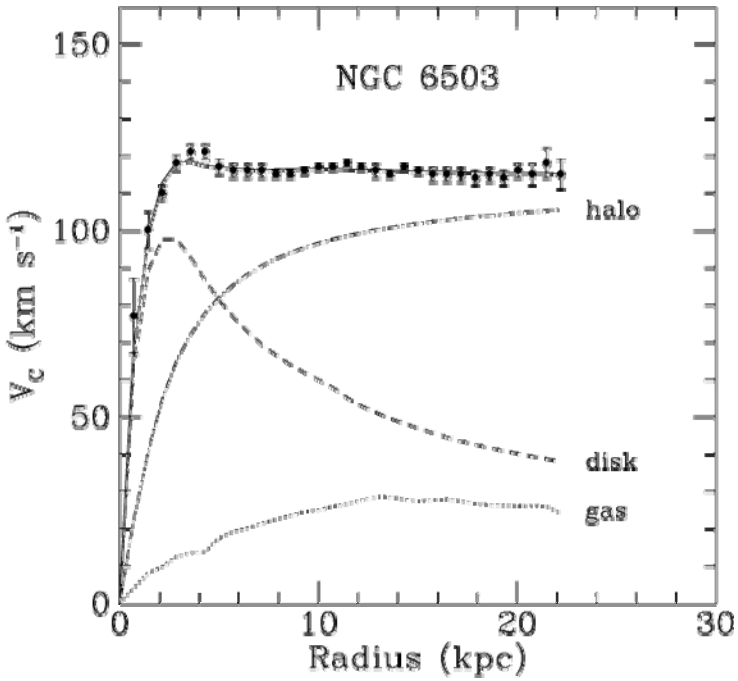
Energy Budget of the Universe

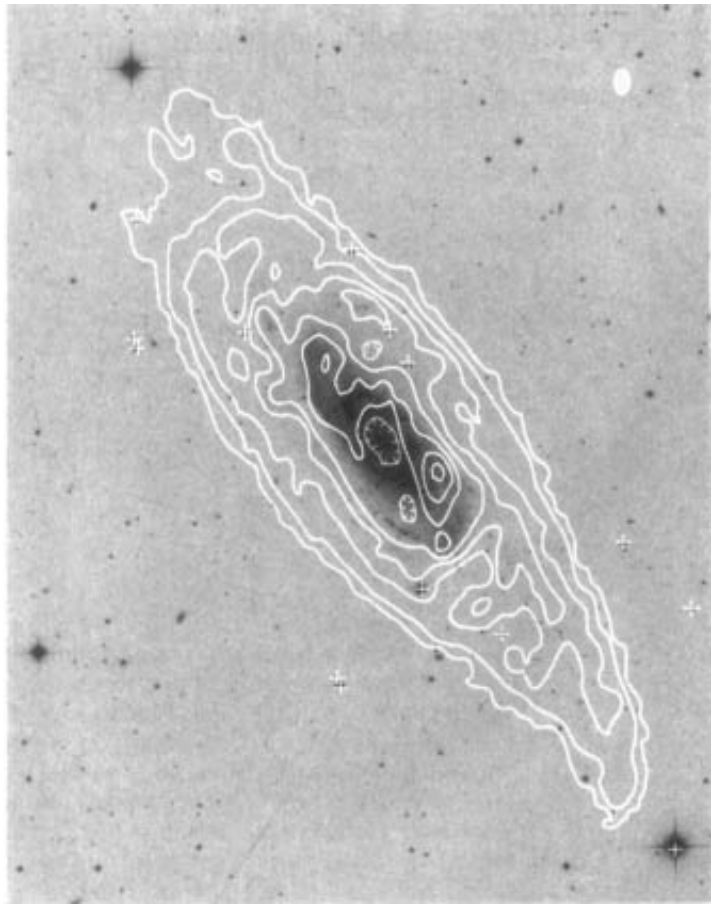
- Ordinary matter (electrons and protons) ~5%
- Dark Matter ~25%
- Dark Energy ~70%
- Anti-Matter 0%



Evidence for Dark Matter

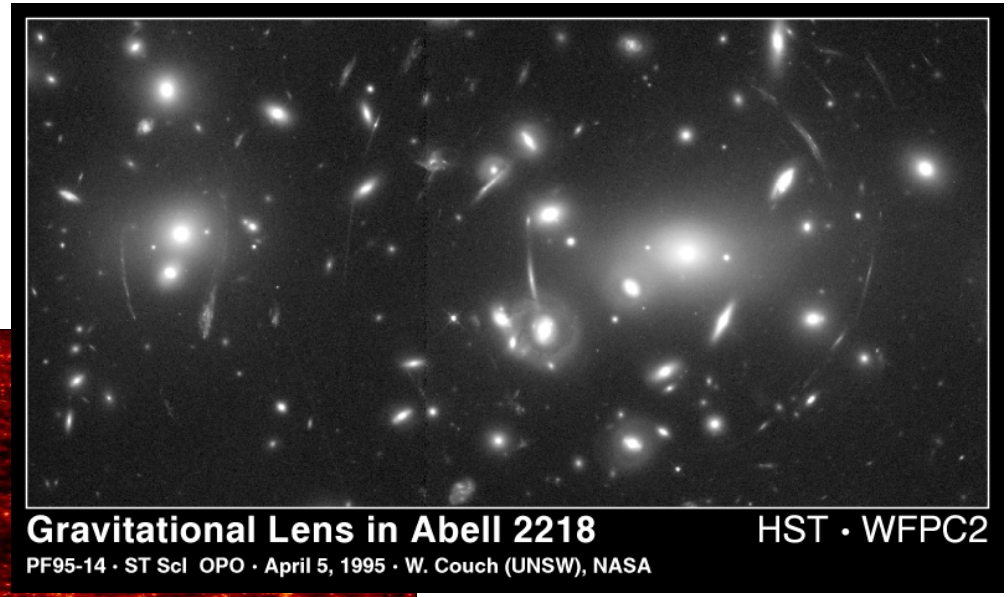
- Galaxy Rotation Curves

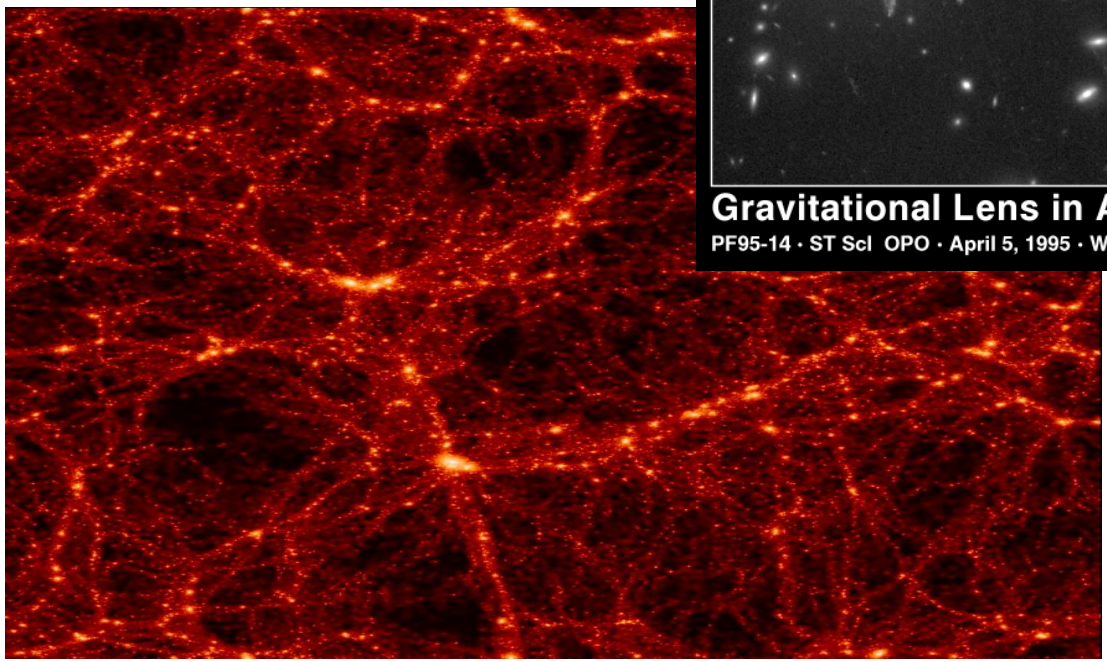




More Evidence for Dark Matter

Gravitational Lensing





Structure Formation

So What *is* Dark Matter

- The evidence for dark matter is now overwhelming
  - galactic rotation curves, structure formation, gravitational lensing, motion of galactic clusters, stability of spiral galaxies, CMB….
- We don't know what it is…….but we may soon find out!
- A rough calculation tells us how much dark matter is left from the big bang. This depends on its interactions and its mass. If we *assume* weak interactions, we find the mass

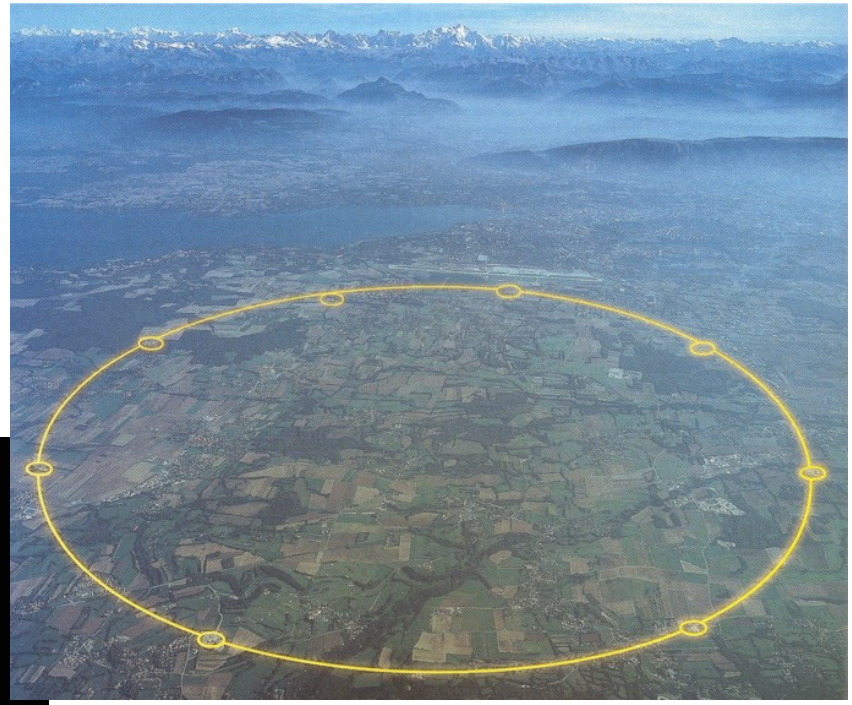
$$M \sim 1\ TeV \sim 10^{-23} Kg$$

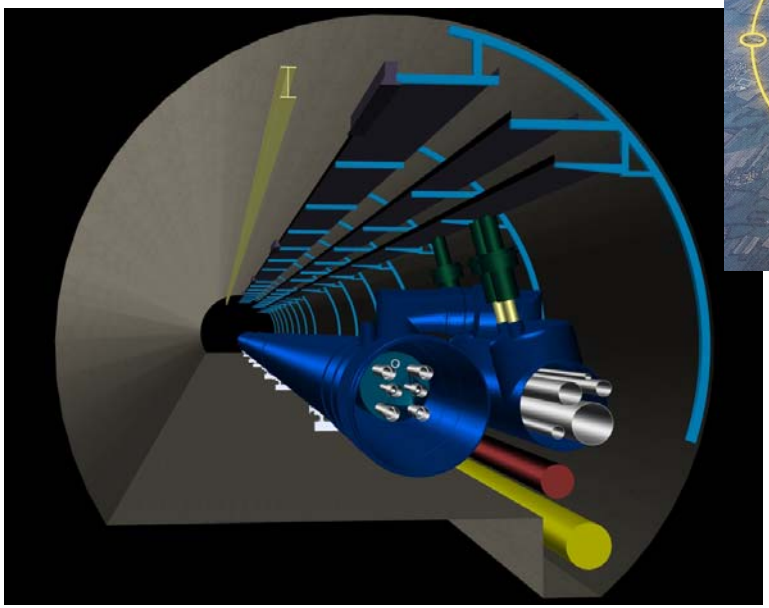
- This is the mass scale associated with electroweak symmetry breaking and Higgs boson physics, where we have good reason to find a plethora of further particles…..

Dark matter in the lab?

The Large Hadron Collider in CERN, Geneva turns on in 2007.

It will create particles with energies in the range of M=1 TeV !





Perhaps we will soon create dark matter in the lab.

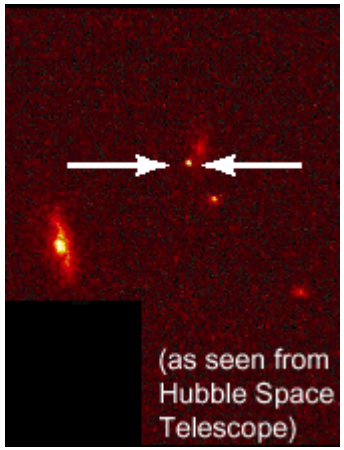
Dark Energy

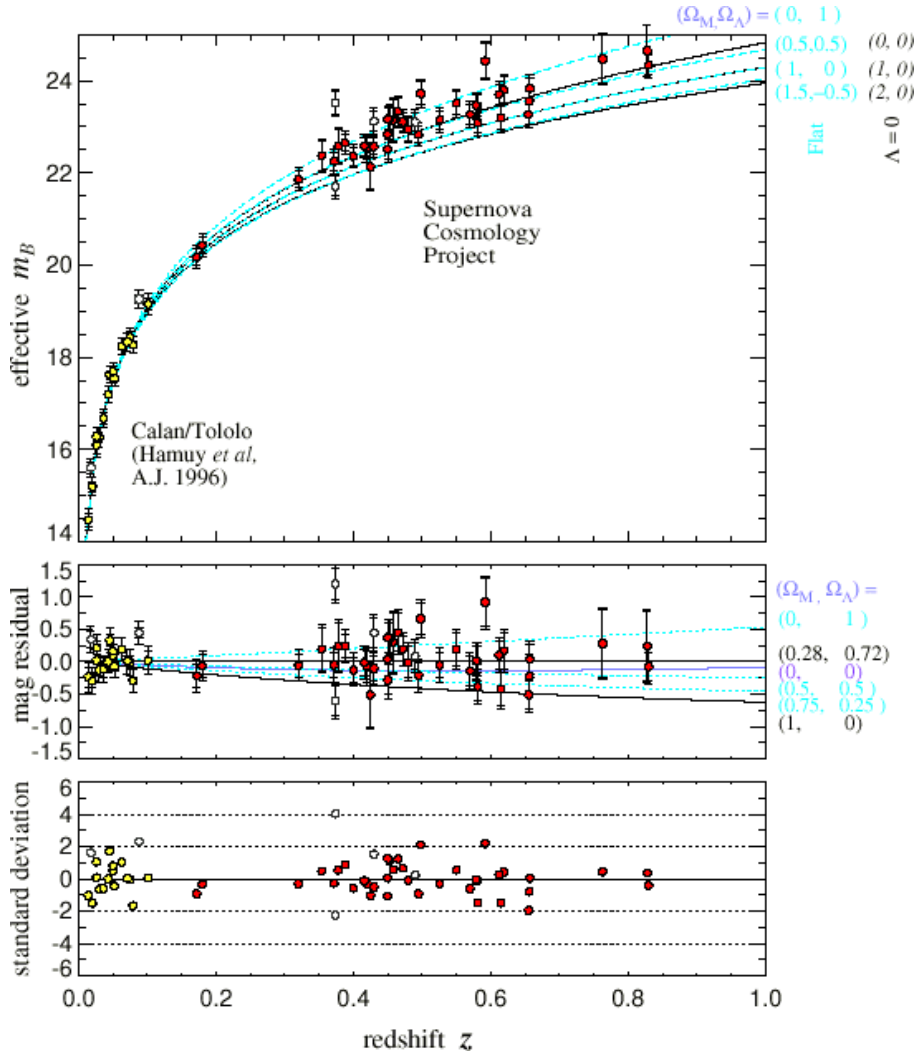
a.k.a the cosmological constant

- Dark Energy is an anti-gravitational force-field spread throughout the universe.
- It is causing the expansion of the universe to speed up.
- It is currently 70% of the energy in the universe. It is taking over!
- We are completely clueless about it’s microscopic origin!

The Expansion of the Universe

In the late 1990's, studies of supernovae suggested that the expansion of the universe is accelerating.

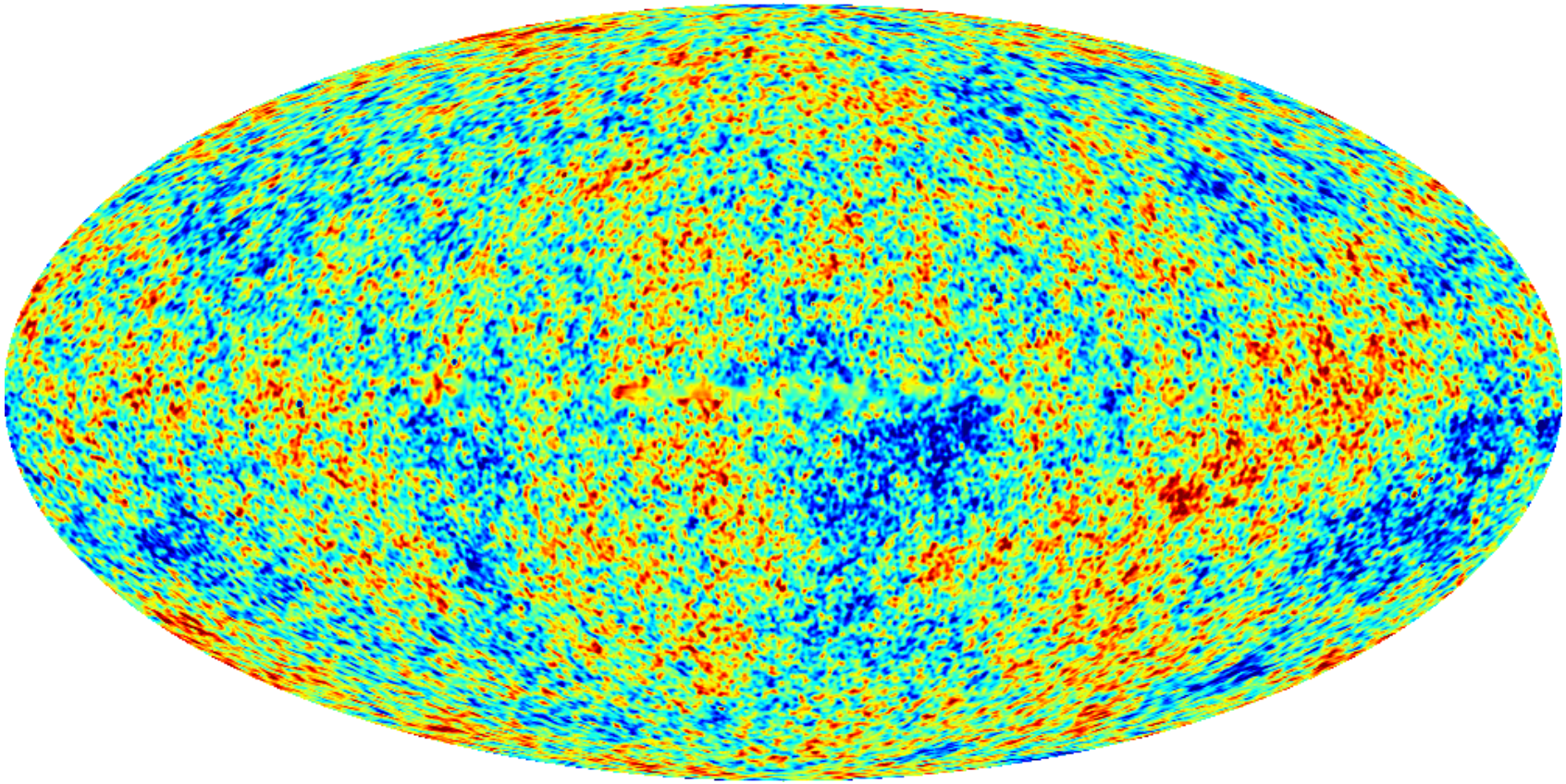




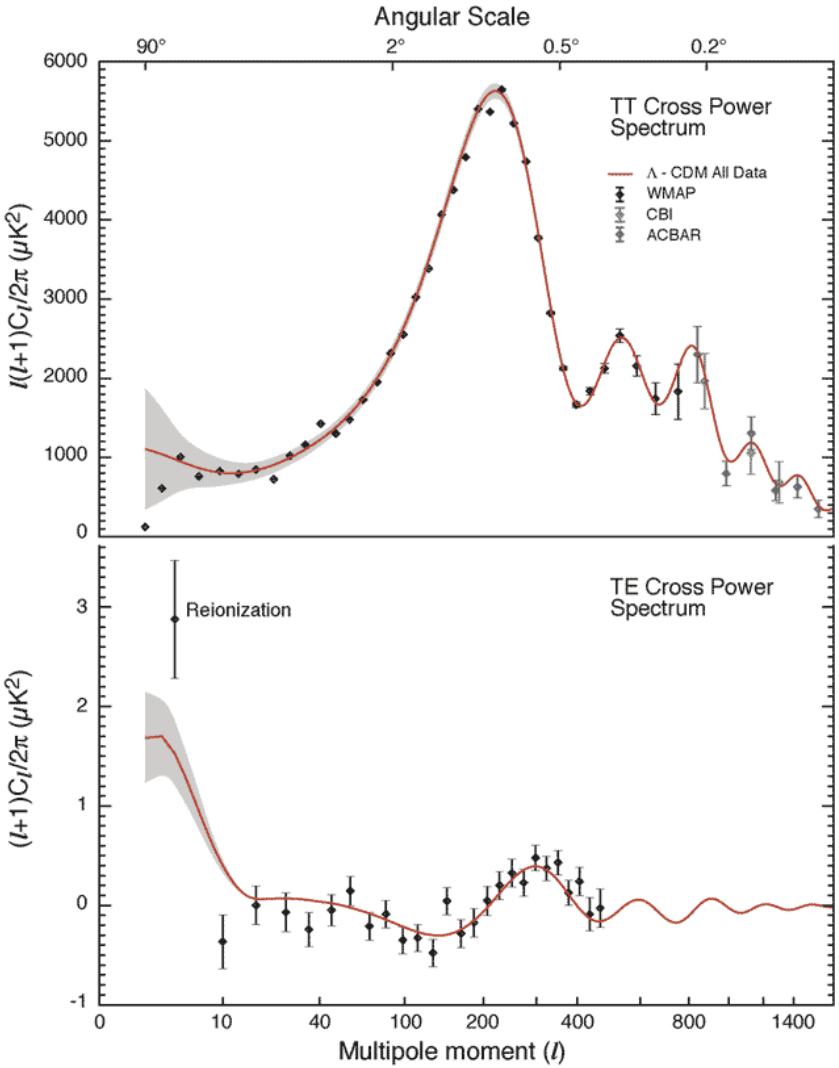
The Cosmic Microwave Background

- When the temperature of Universe was higher than about 3000K, all atoms (mostly hydrogen and helium) were ionized.
- Photons cannot travel in this plasma. They scatter off unbound electrons.
- As the universe cools, atoms form. These are neutral and photons can now travel more freely
- We see these photons in the sky, red-shifted cosmic expansion. They are the photons from the fireball of the big bang.

Cosmic Microwave Background



Cosmic Microwave Background



The astonishing data from the WMap Satellite (2002)

The “acoustic peaks” are formed by the plasma sloshing around in the universe, almost 14 billion years ago.

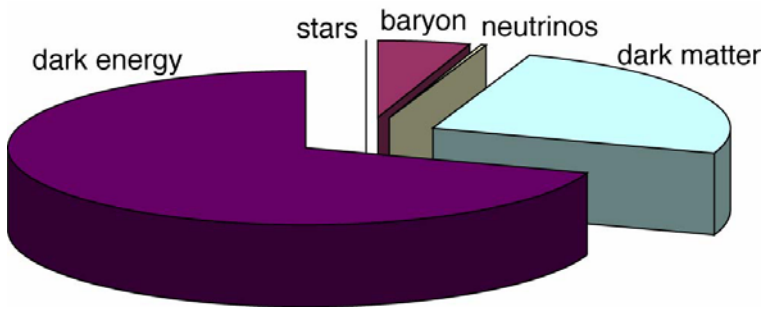
The exact position and shapes of the peaks depends sensitively on the amount of dark matter and dark energy

Dark Energy

- We now have several pieces of evidence to show that dark energy comprises 70% of the energy of the universe.
  - supernovae, CMB, galaxy clusters, ages of globular clusters
- While normal matter dilutes as the universe expands, dark energy stays constant. It's taking over the universe!
- The amount of dark energy is 0.001 eV per 1 mm cubed. It's tiny. But its everywhere and it adds up!

Comparison to Theory

- Can we explain this theoretically?

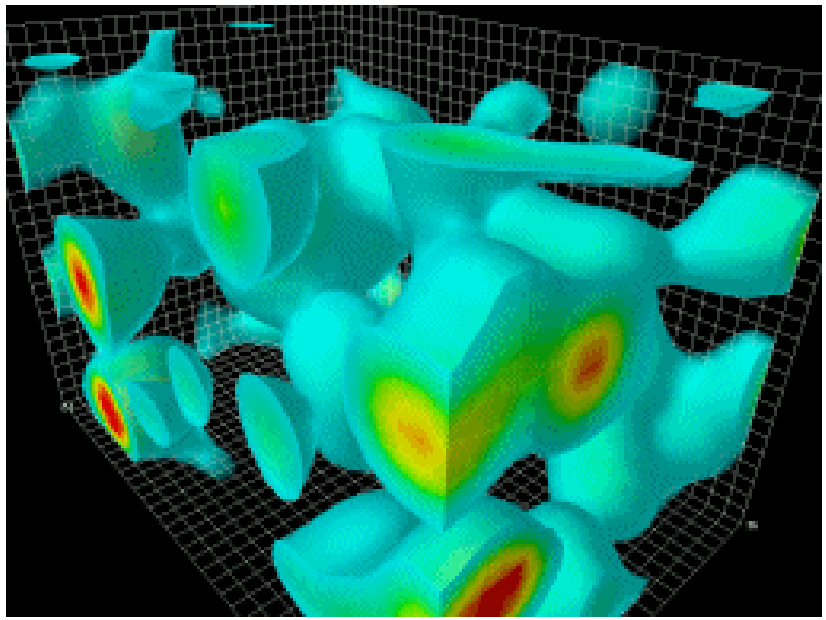


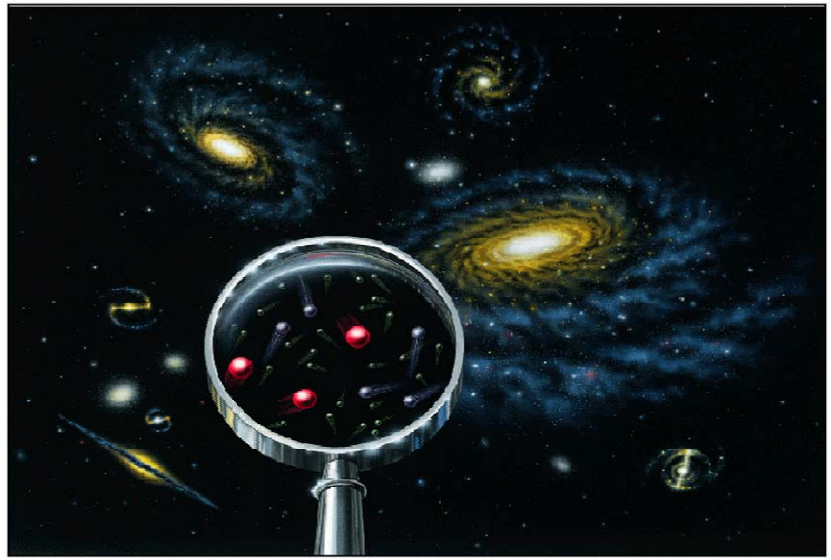
  - For dark matter, there's a conceptually simple answer: there's some new particle (or particles) that we haven't seen as light passes through them. (Neutrinos already have this property….it's not too hard to imagine others do as well)

  - For dark energy, the situation is different. It turns out that theory does predict dark energy. It predicts a hell of a lot of it!

Dark Energy as Vacuum Fluctuations

Quantum theory implies that the vacuum of space is alive with particle anti-particle pairs, constantly popping in and out of creation.





These contribute in exactly the same way as dark energy! They cause the expansion of the universe to accelerate.

Dark Energy as Vacuum Fluctuations?

- This sounds great….we can explain the acceleration of the universe in terms of Heisenberg's uncertainty principle!!
- **EXCEPT,** when you calculate, you find that the theoretical prediction for dark energy is:

$$\Lambda_{\text{prediction}} = 10^{120}\Lambda_{\text{observed}}$$

- This is possibly the biggest discrepancy in the history of science!!!

(If we assume a new symmetry between bosons and fermions, known as supersymmetry, then we do much much better: $\Lambda_{\text{prediction}} = 10^{60}\Lambda_{\text{observed}}$)

So What *is* Dark Energy?

- We don't know!
- Quite possibly there is something very fundamental and deep that we don't understand about gravity, manifesting itself as an accelerating universe

- This paradox potentially compares to the great mysteries our predecessors struggled with:

  - Failure to detect the motion of the earth through the ether
  - Failure to understand why the electron doesn't spiral into the atom

The resolution of the dark energy problem should lead to an equally profound revolution in the way we view the universe.

Some Proposed Crazy Ideas

- Gravity is Wrong
  - While particle (quantum) physics has been tested to 10^{-17}cm, gravity has been tested only to 0.1 mm! If gravity stops working at this scale, it only responds to some vacuum fluctuations. We find roughly the right dark energy!

Some Proposed Crazy Ideas

- The Anthropic Principle (dear God)
  - You can compute how large the dark energy can be and still allow galaxies to form. You find that we're living life on the edge!
  - The basic idea: there are many universes, in each of which the laws of physics are different. Most have lots of dark energy. But then, most don't have us.

Some Proposed Crazy Ideas

- Holography
  - The world is really a hologram. We think we move in 3 spatial dimensions, but we don't really. It's an illusion: we move in 2 dimensions…
  - This crazy idea finds it's root in old work of Stephen Hawking and was first proposed by Gerard 't Hooft. It has recently found some vindication in string theory. The resultant thinning of the degrees of freedom may help solve the dark energy problem.

What is Dark Energy Really?

- Probably none of the above.
- Answer left as a homework exercise.