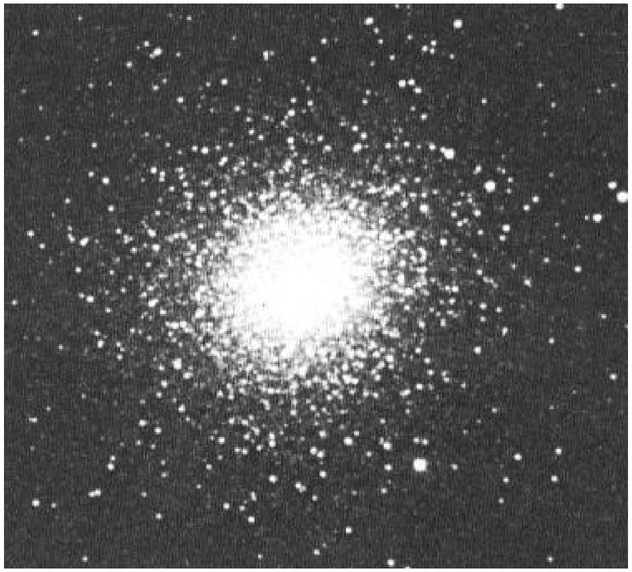
Physics 661

Particle Physics Phenomenology

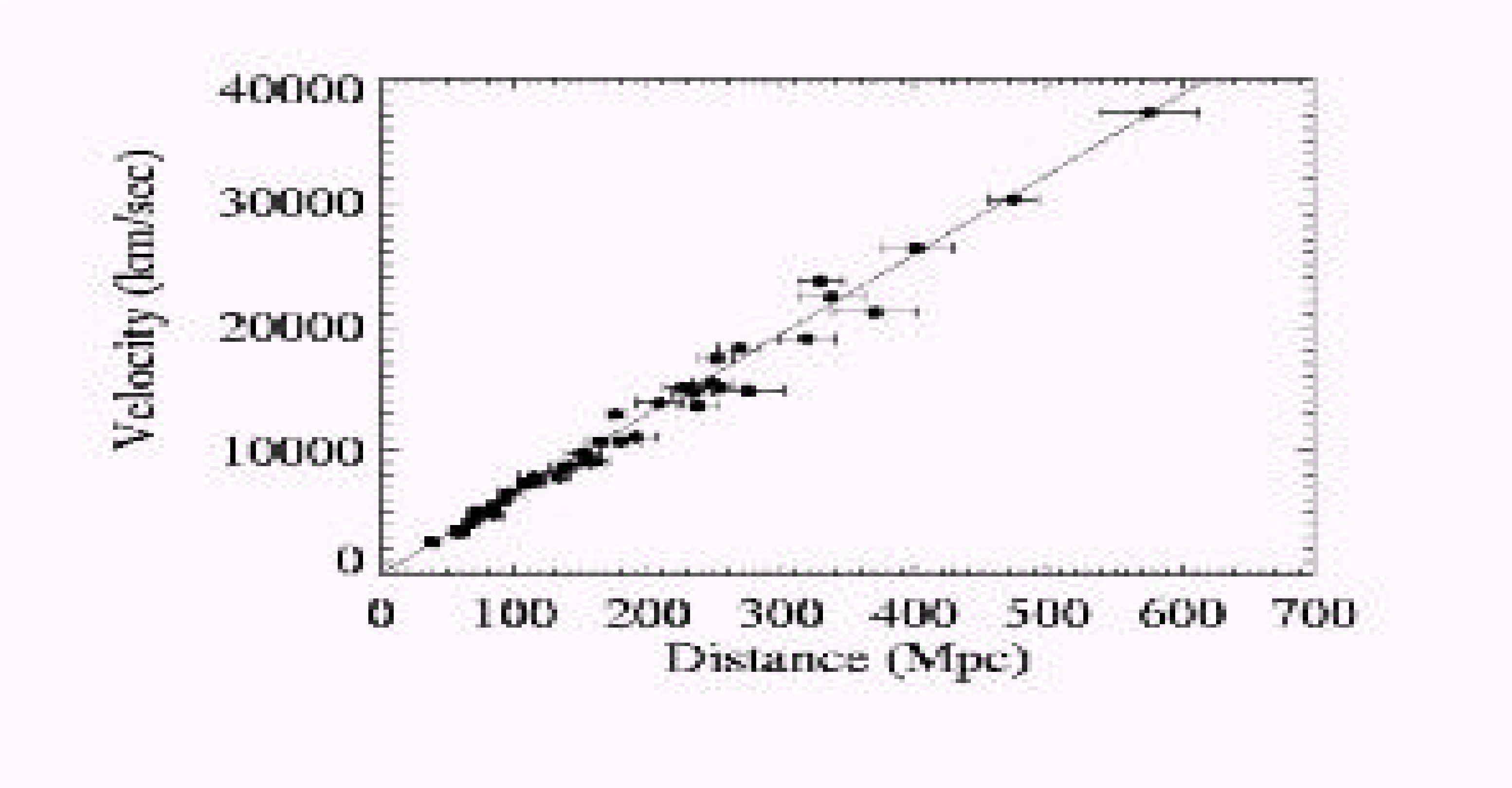
October 2, 2003

Hot Big Bang Model

- Evidence for theory:
  - Present expansion of the Universe
  - Existence of cosmic microwave background radiation
  - Relative abundance of light elements
- Furthermore, oldest objects (globular clusters) no older than ~15 x 10^9 years



Expansion of the Universe

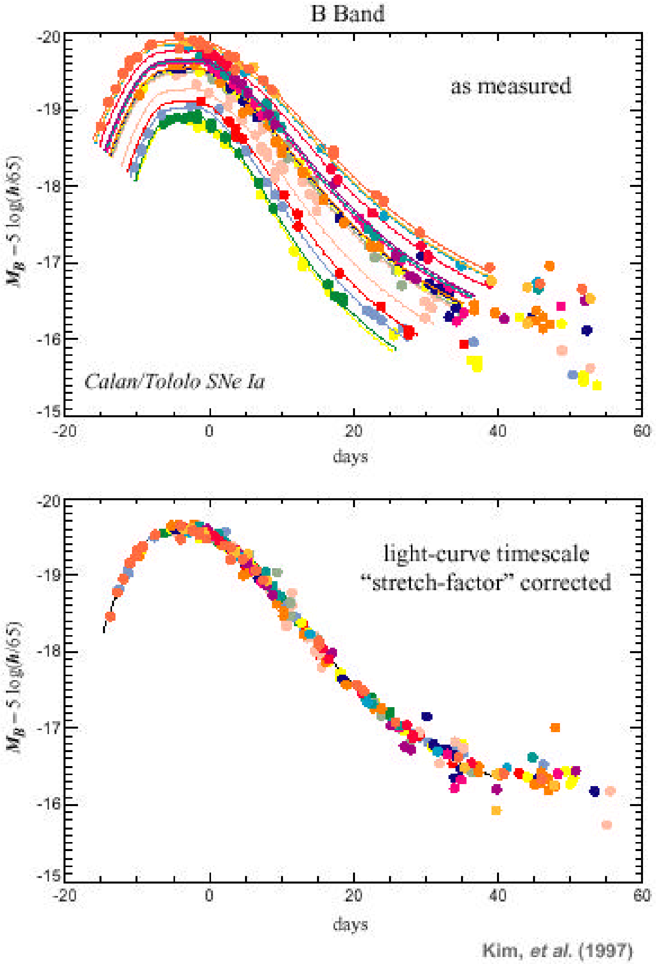


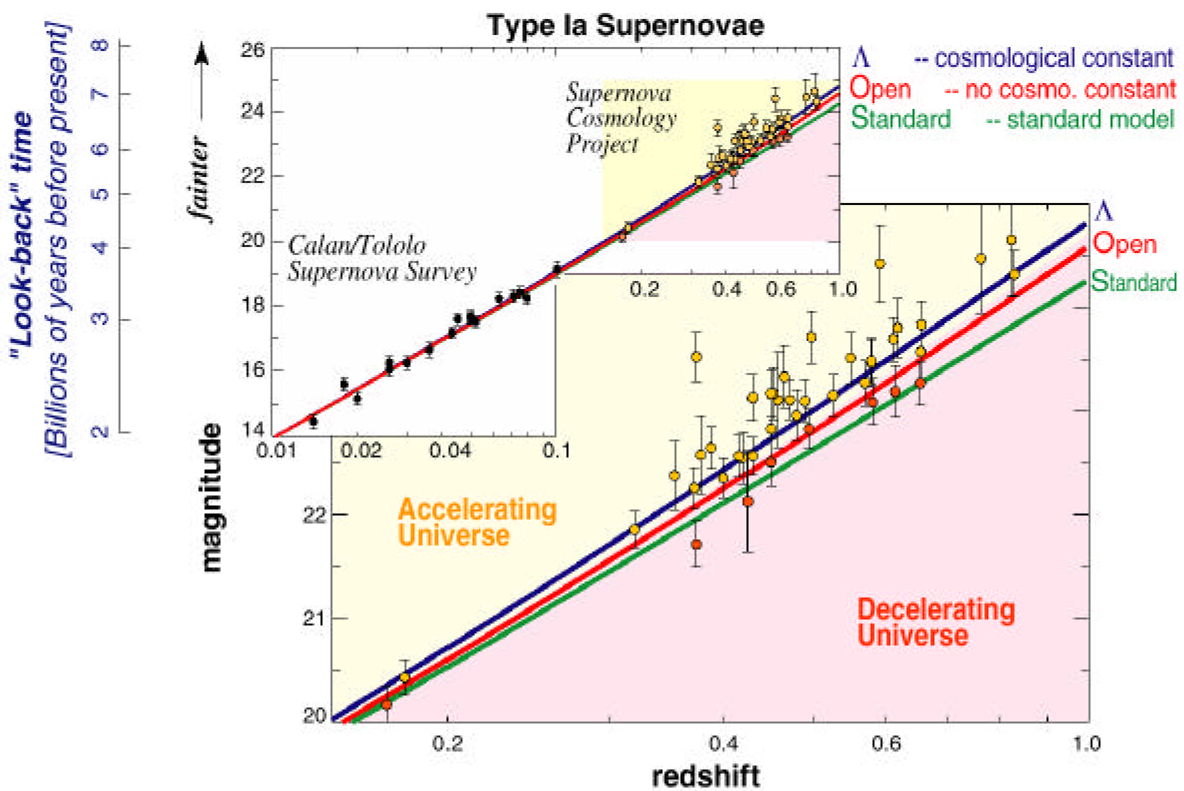
$H_0 = 65 \pm 5$ km/s/Mpc

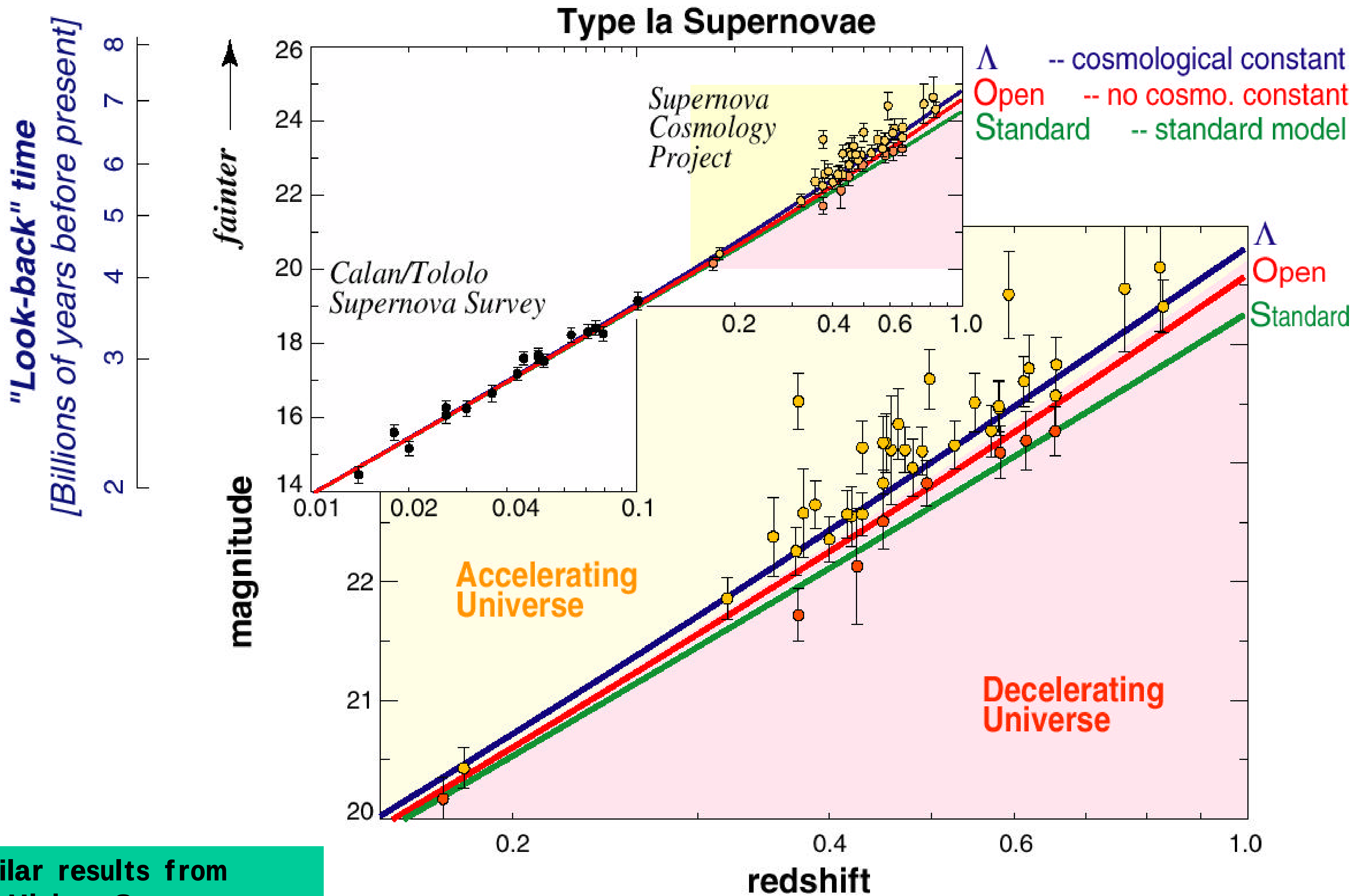
$\equiv h \bullet 100$ km/s/Mpc (1 pc = 3.26 light-years)

Expansion of the Universe

Use type Ia Supernovae corrected candles to measure the expansion rate. Ground-based work thus far has uncovered a major surprise:



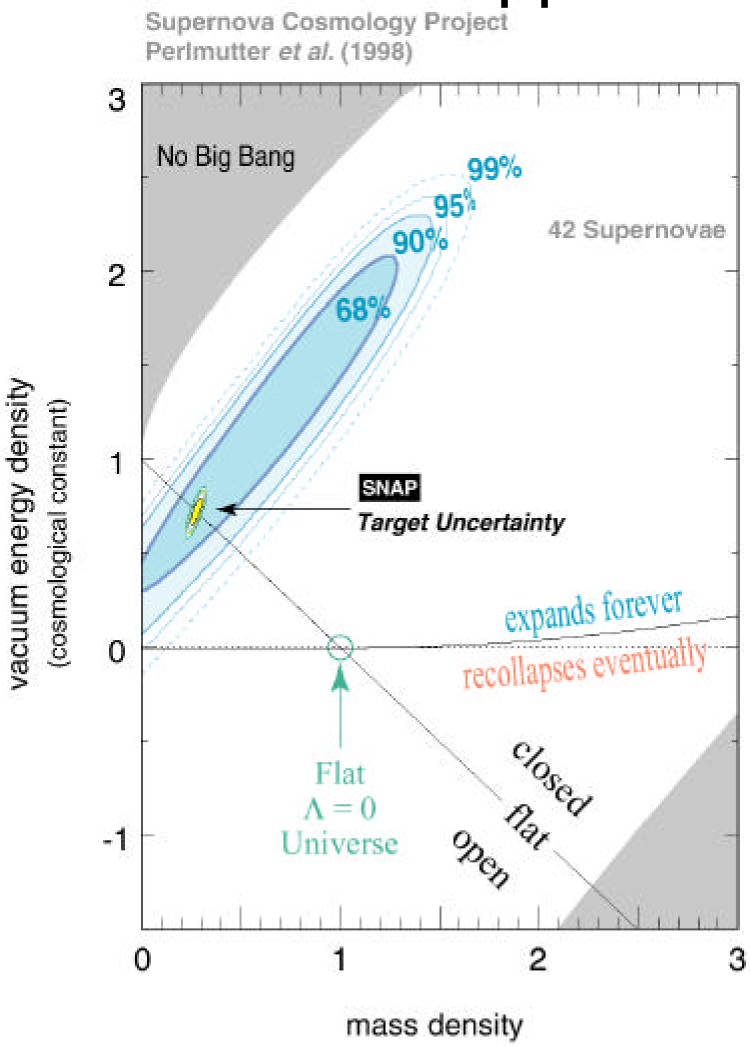




Similar results from the High-z Supernova Search Team (e.g., Riess et al AJ116(1998))

Implications of expansion rate

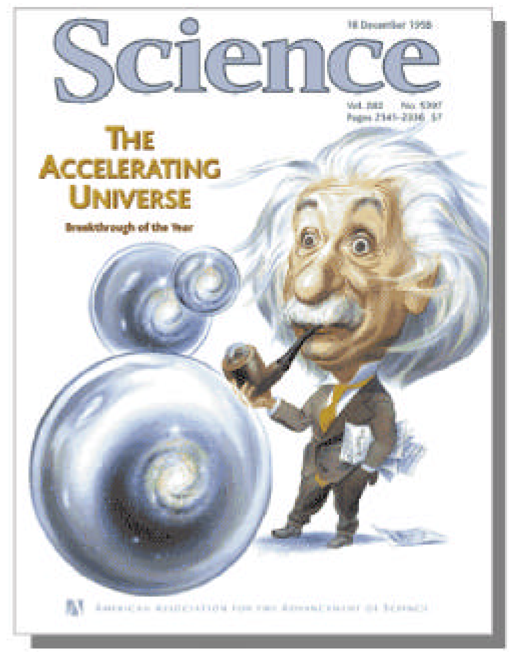
Contrary to expectation, the expansion of the Universe appears to be ***increasing*** with time!



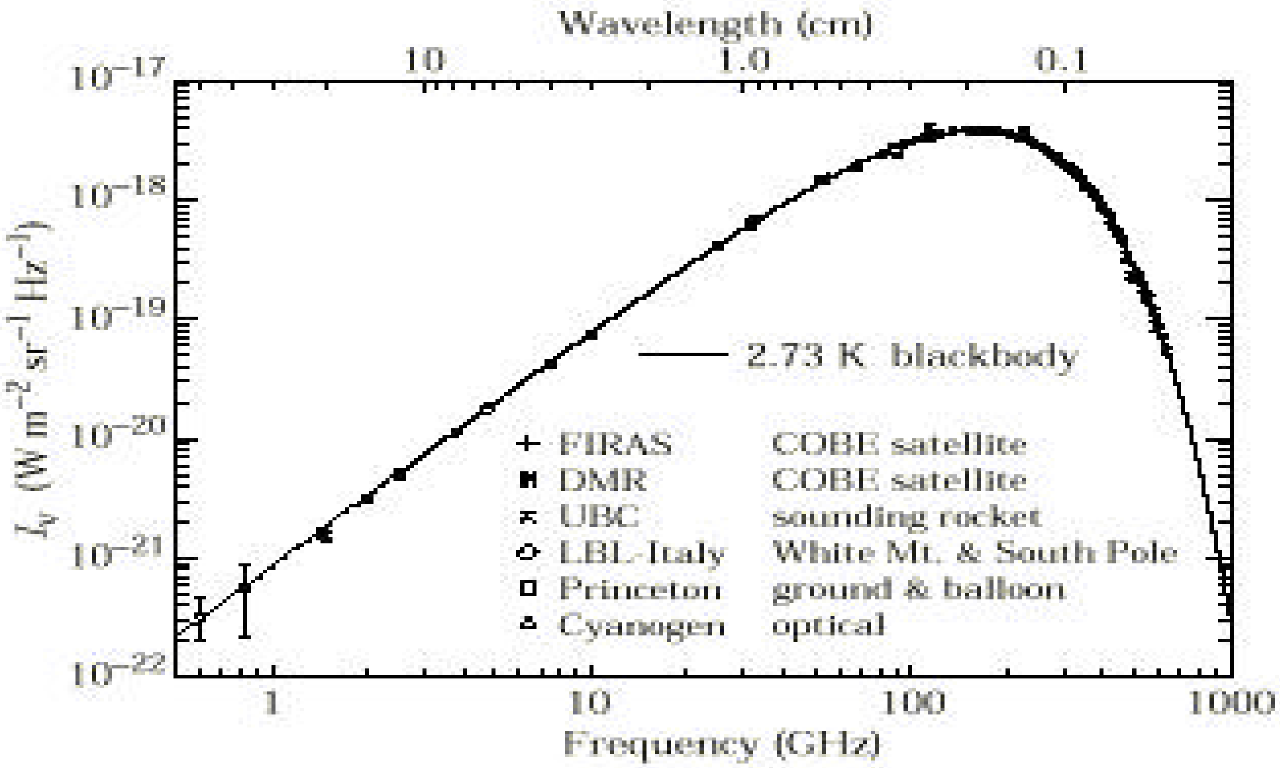
This could be due to a non-zero cosmological constant, a manifestation of non-zero vacuum energy….

… or systematic effects yet to be understood.

This result has raised fundamental questions and begs further investigation.

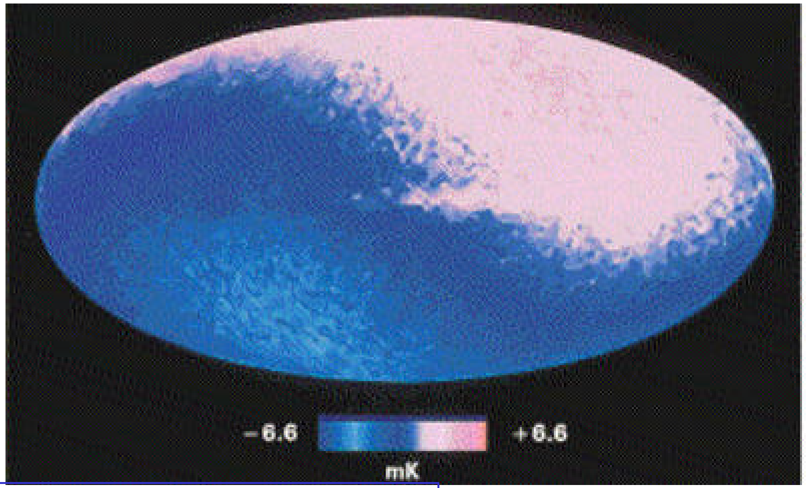


Cosmic microwave background radiation

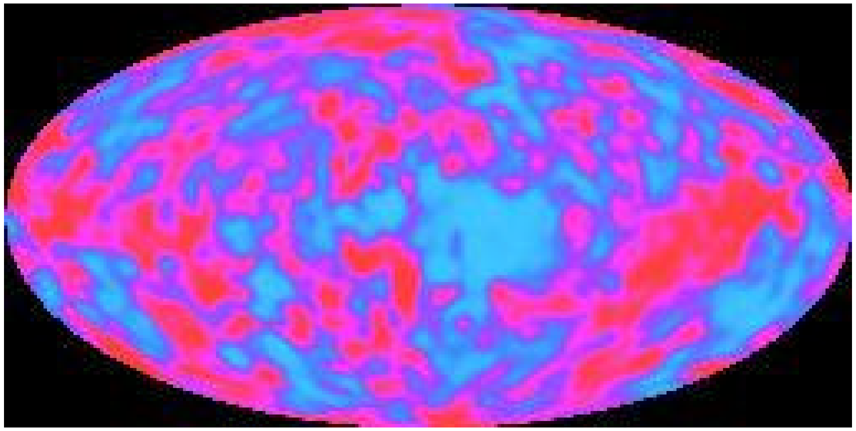


Cosmic microwave background radiation

micro-Kelvin fluctuations



milli-Kelvin fluctuations

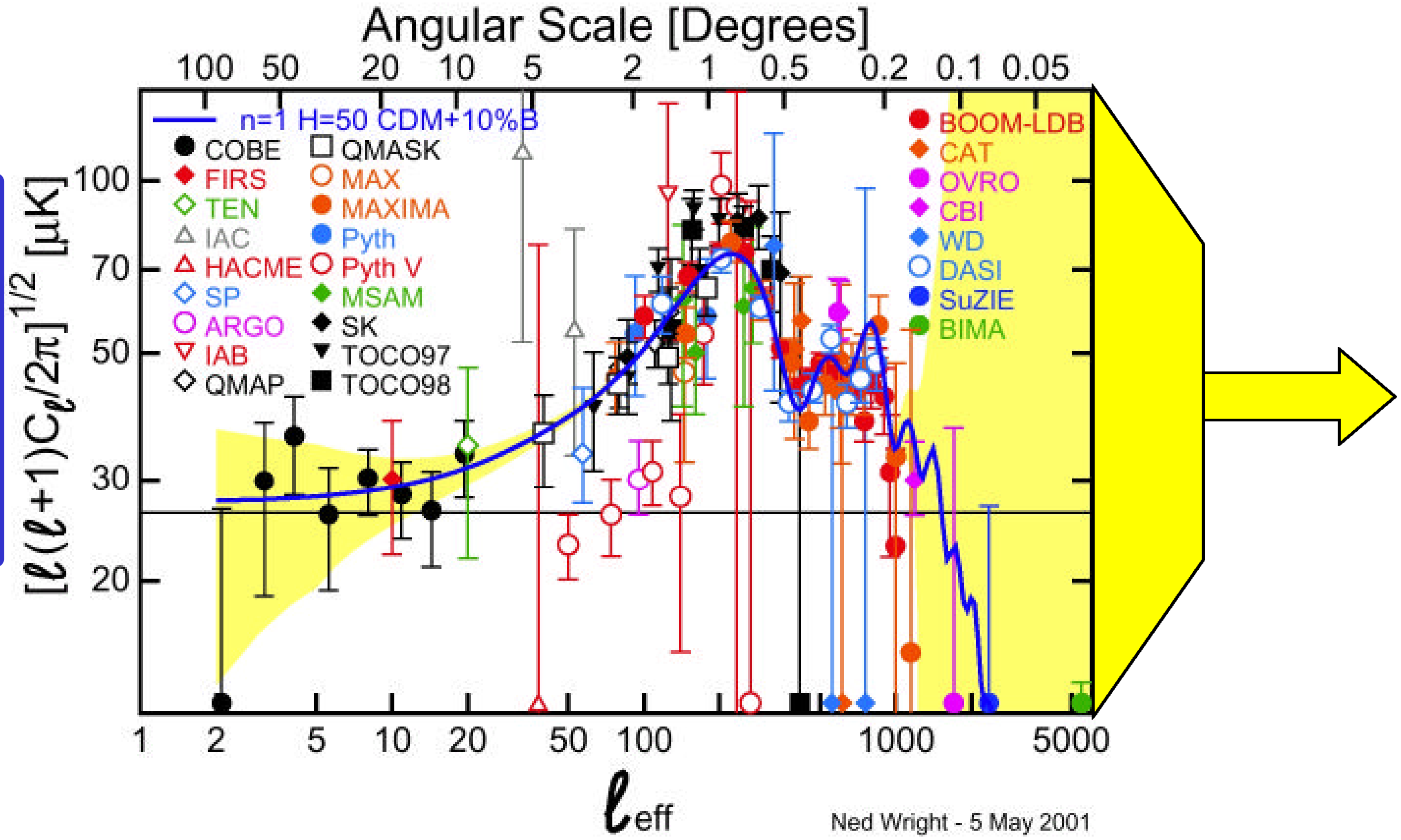


We can quantify these fluctuations ⇒

Cosmic Microwave Background

Recent results add to the growing collection of measurements from the ground, balloons, and space:

$$\frac{\Delta T(\theta,\phi)}{T} = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta,\phi)\,.$$

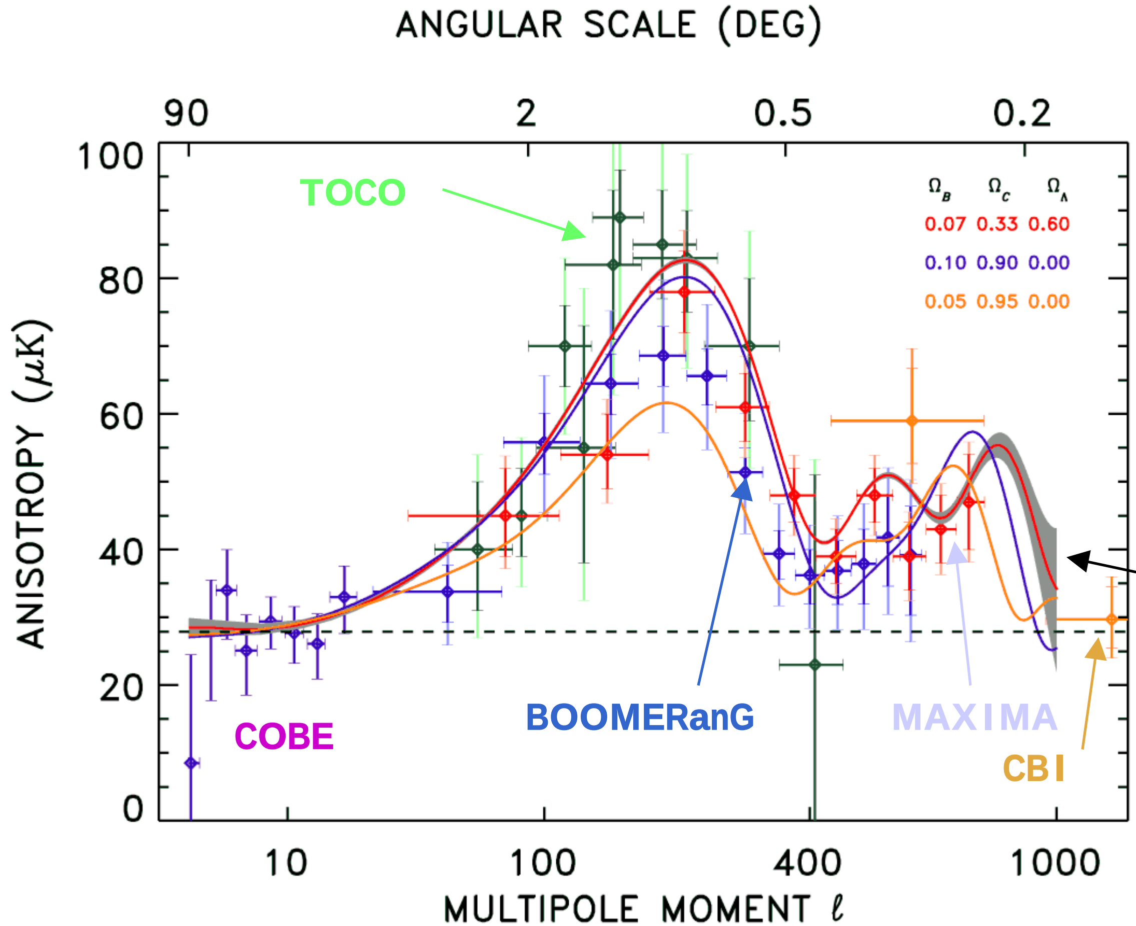


Amazing that we can see this – foreground removal!

See http://www.astro.ucla.edu/~wright/intro.html

and http://www.hep.upenn.edu/~max/ and links therein

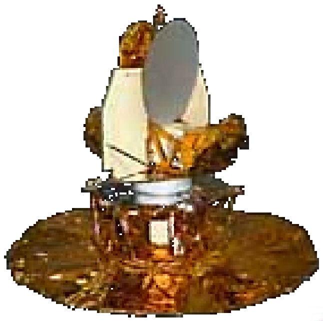
Cosmic Microwave Background



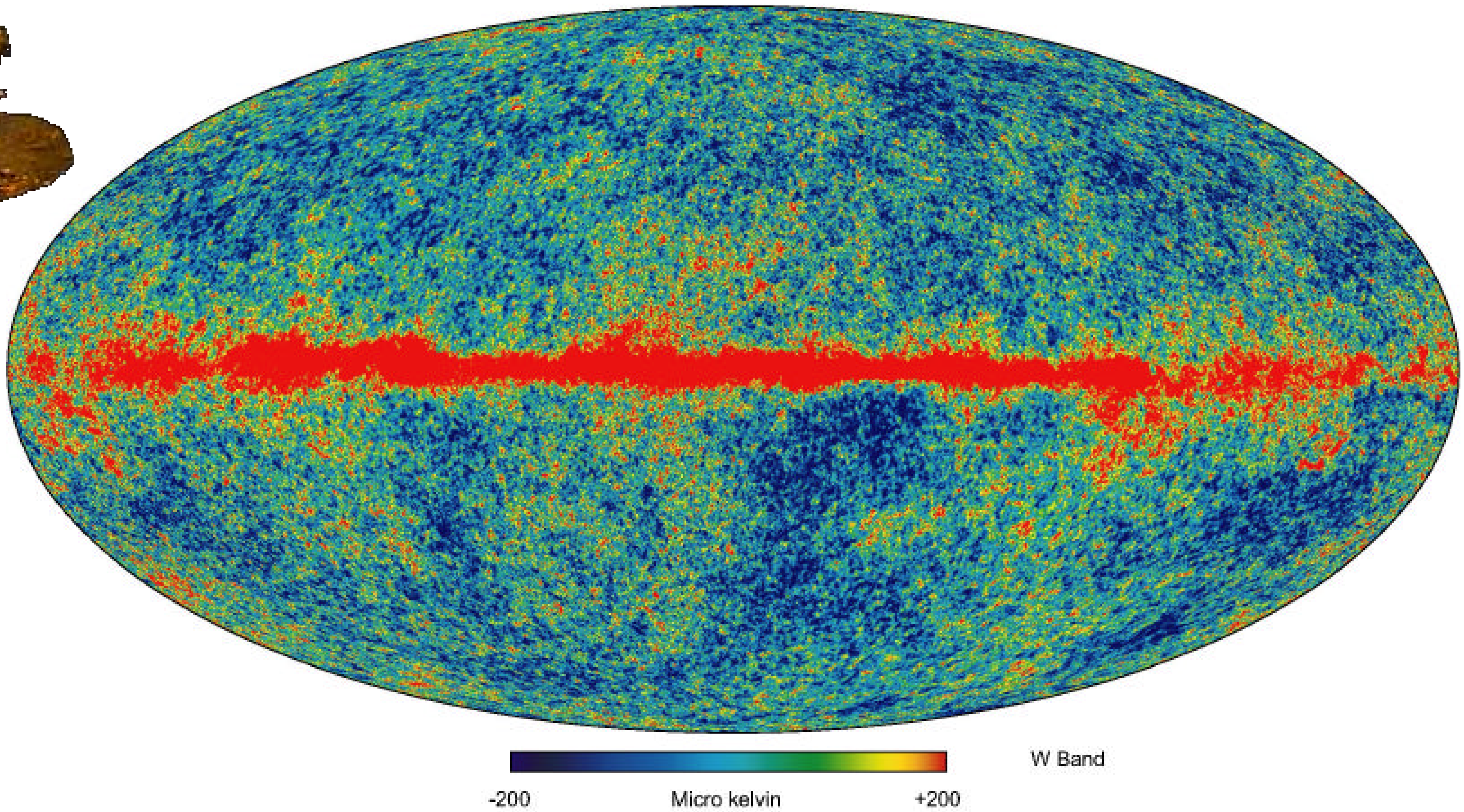
Expected MAP precision shown as the gray band.
Launched June, 2001

Entering the era of precision cosmology. Many experiments (e.g., PLANCK, PIQUE, …) over the next decade will measure the strength of higher acoustic peaks and polarization anisotropy.

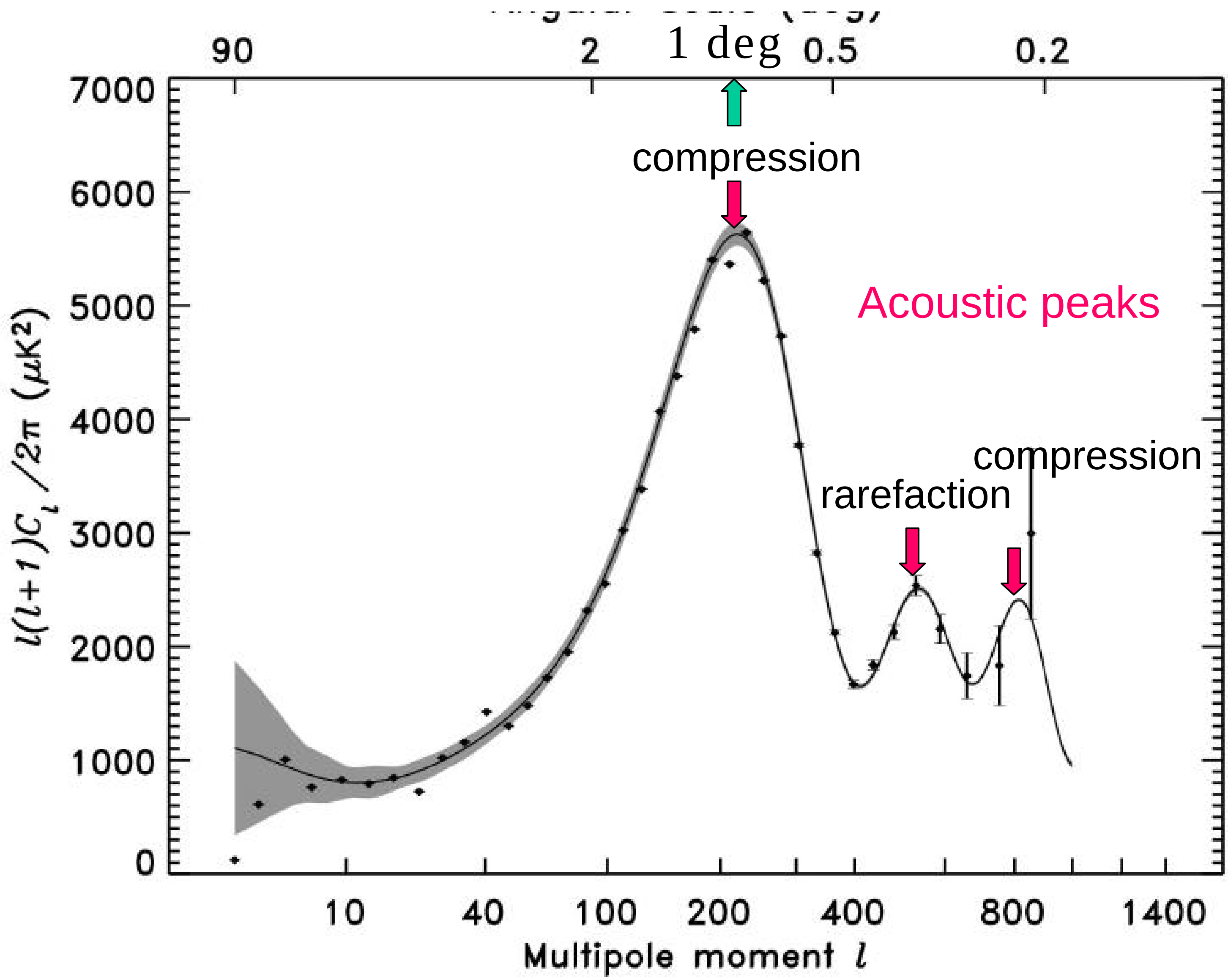
Cosmic microwave background radiation



WMAP,
2003



Cosmic Microwave Background



WMAP fits

WMAP only (TT+TE), flat LCDM (Spergel et al. 2003)

CMB appears to be Gaussian. (Komatsu et al.)

- 15% of CMB was re-scattered in a reionized universe.
- The estimated reionization redshift ~20,
  or 200 million years after the Big-Bang.

Flat LCDM still fits:

6 parameters fit *1348 points*

$$\frac{c^2}{n} = \frac{1431}{1342} = 1.07$$

DM density $(2.25 \pm 0.38) \times 10^{-27}$ Kg/m^3

atomic density $(2.7 \pm 0.1) \times 10^{-7}\, cm^{-3}$

$h = (6.5^{+0.4}_{-0.3}) \times 10^{-10}$

Age at decoupling $372 \pm 14 Kyr$

Age 13.4 ± 0.3 Gyr

$s_8 = 0.9 \pm 0.1$

$z_{reion} \approx 17$

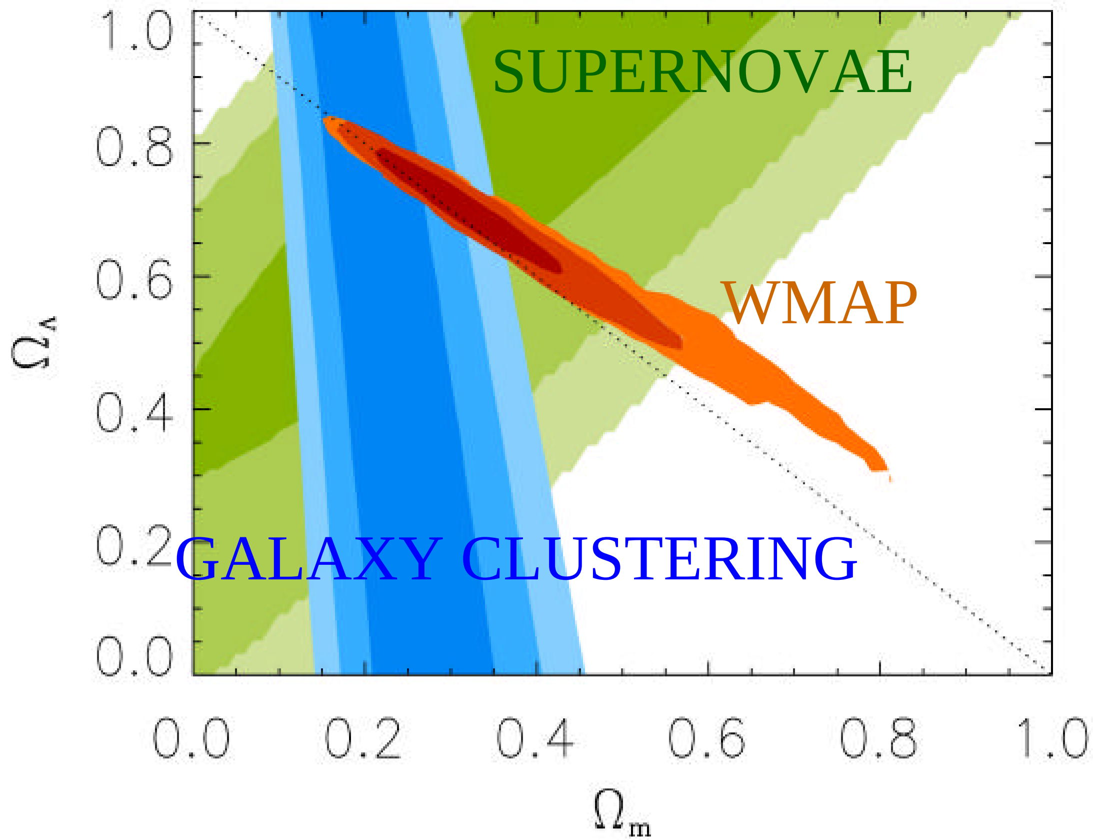
$1s$ marginalized

Fits not only the CMB but also a host of other cosmological observations.

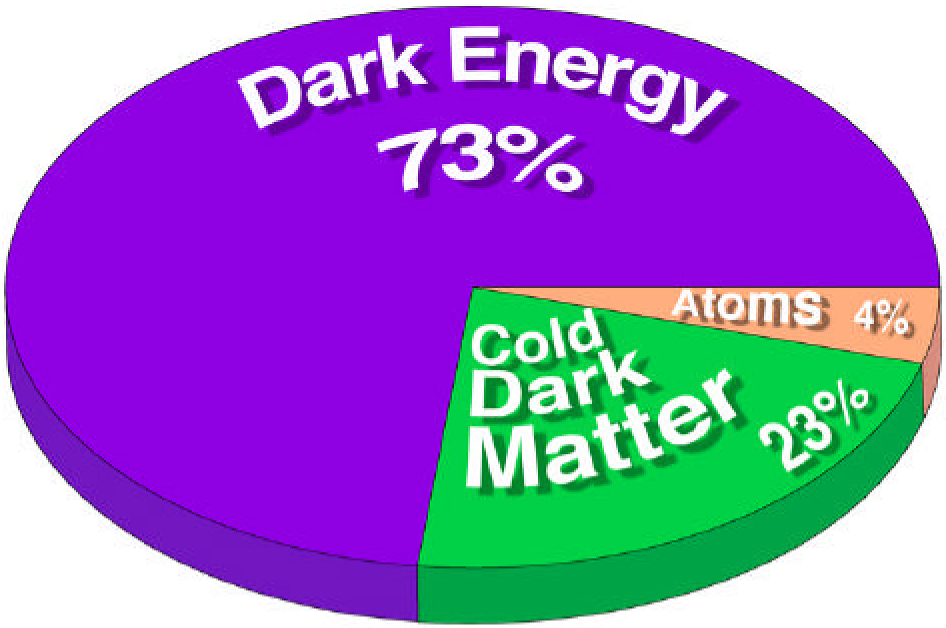
Fluctuations and a Flat Universe

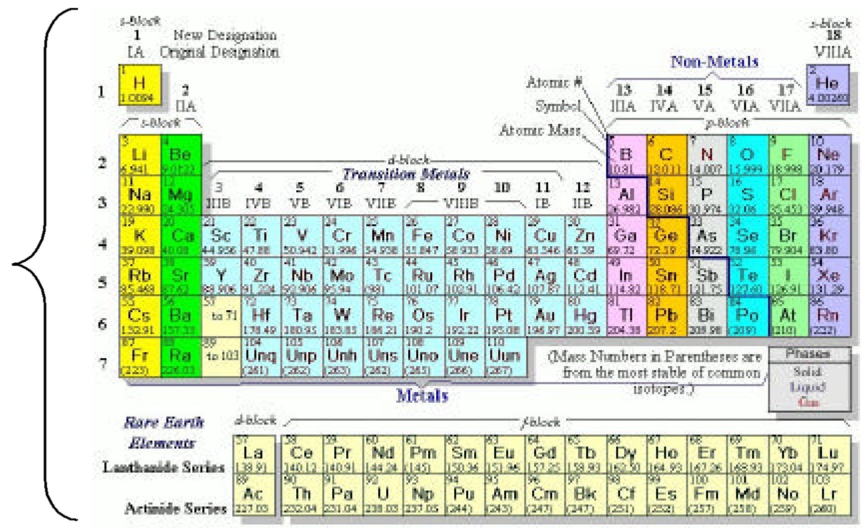
Fluctuations measured by WMAP are consistent with

$\Omega_\Lambda + \Omega_M = 1.0$



We (and all of chemistry) are a small minority in the Universe.

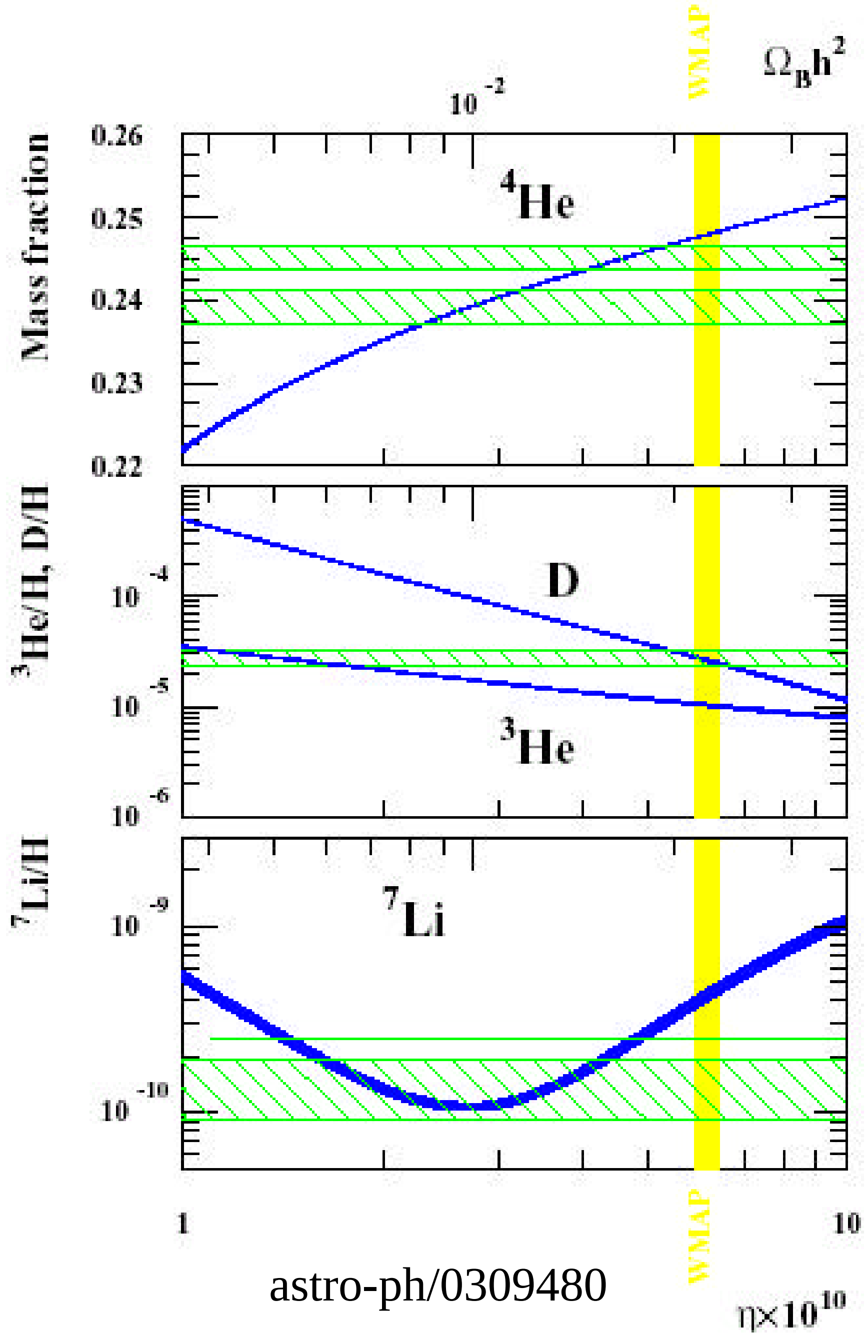




Relative abundances

$$\eta_{10} = \eta \times 10^{10}$$
$$= n_B / n_\gamma \times 10^{10}$$
$$\approx 6.1 \text{ (WMAP)}$$

(baryon to photon ratio)

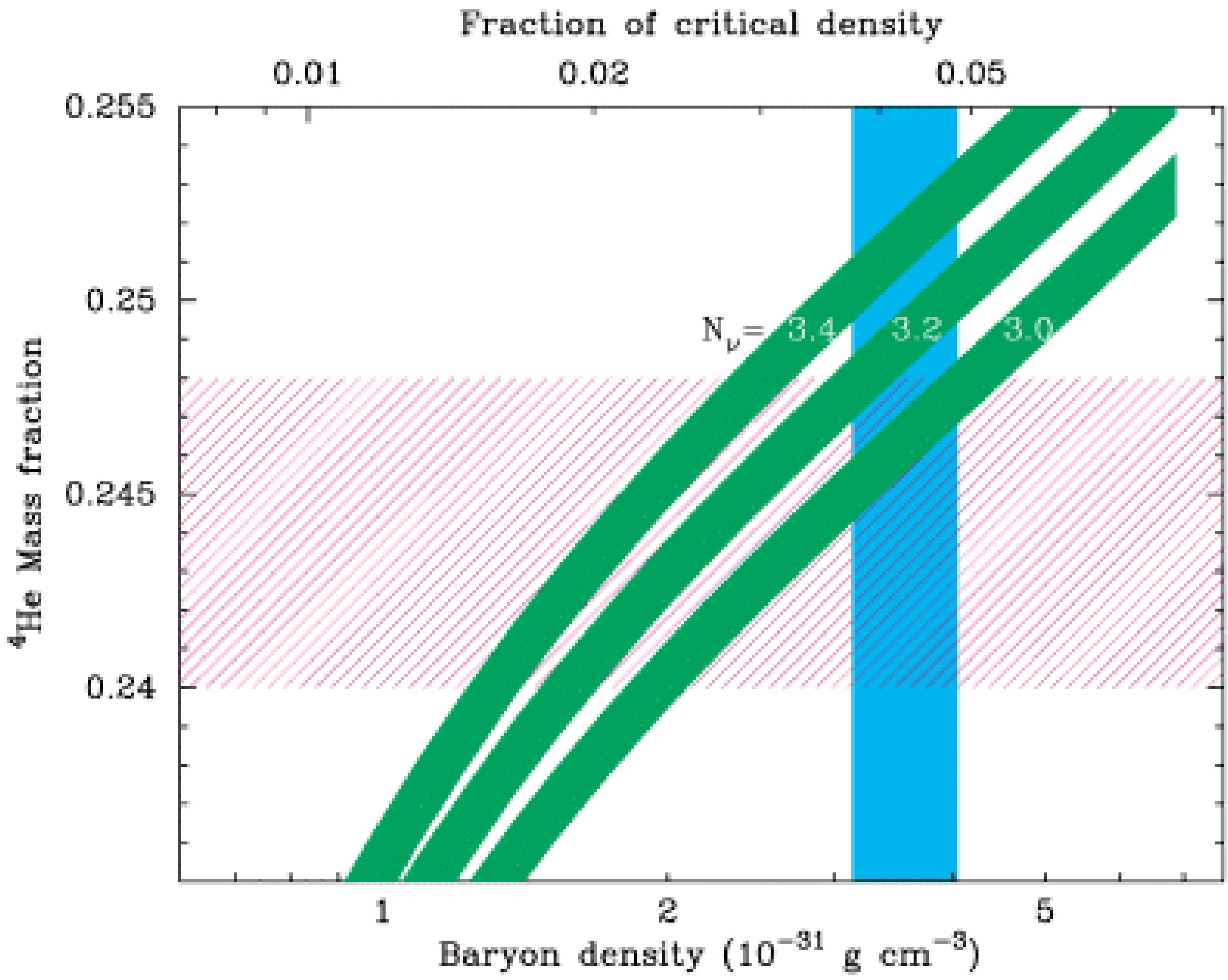


astro-ph/0309480

Baryonic Matter

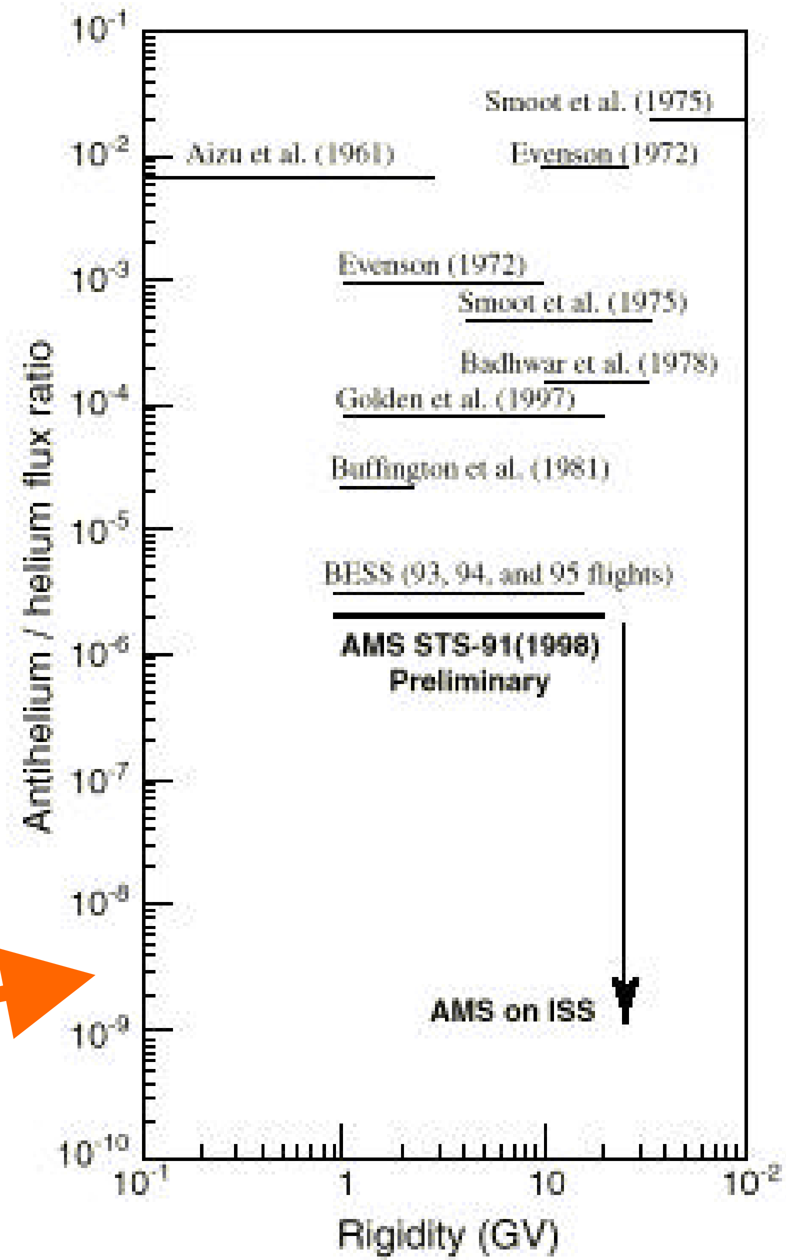
- Dominated by hydrogen and helium
  - helium abundance (~24%) too large to have been produced in stars
- $\eta_B = n_B \, / \, n_\gamma \approx 10^{-9}$
  - reveals early universe matter/antimatter asymmetry
- abundances of light elements consistent with theory
  - constrains number of neutrino species

Constrained number of neutrino species



Antimatter limits

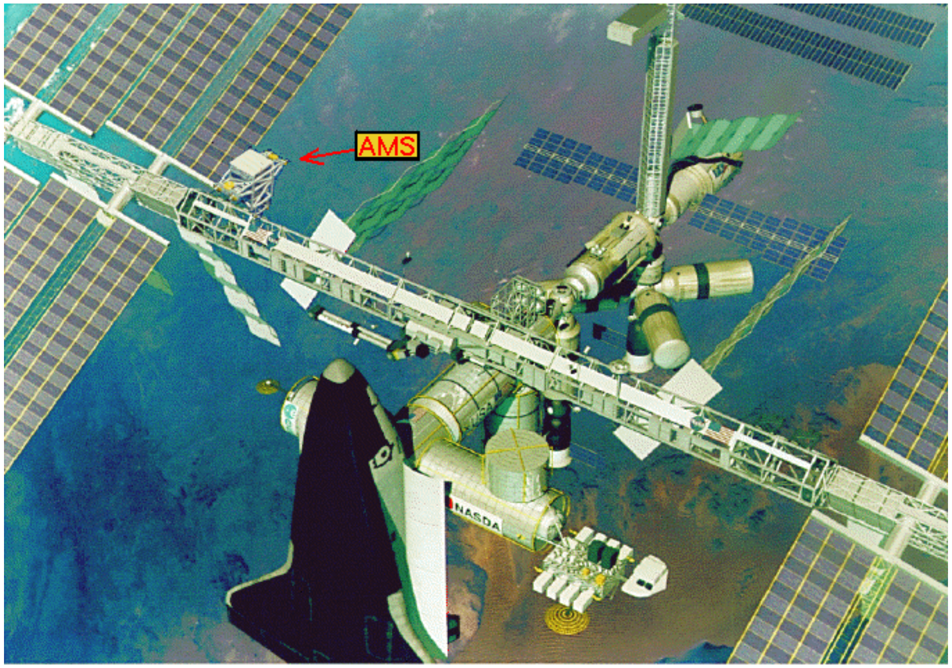
- Data indicates antimatter is rare in the present Universe
- 1998 AMS space shuttle data

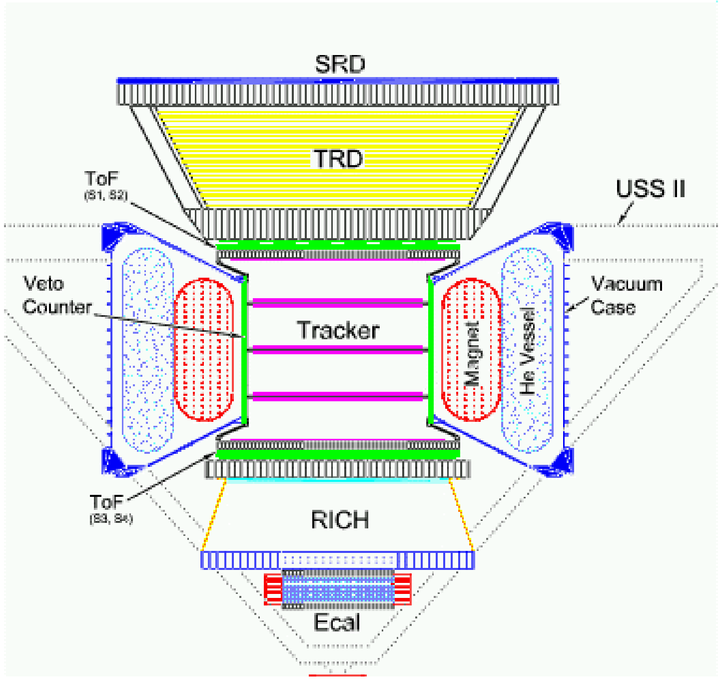


Alpha Magnetic Spectrometer

An experiment to search in space for dark matter, missing matter & antimatter on the international space station.

Successful shuttle experiment flight of AMS1 in June 1998. Manifested on shuttle flight to the ISS in 2005.





See http://ams.cern.ch/AMS/ams01_homepage.html

Antimatter

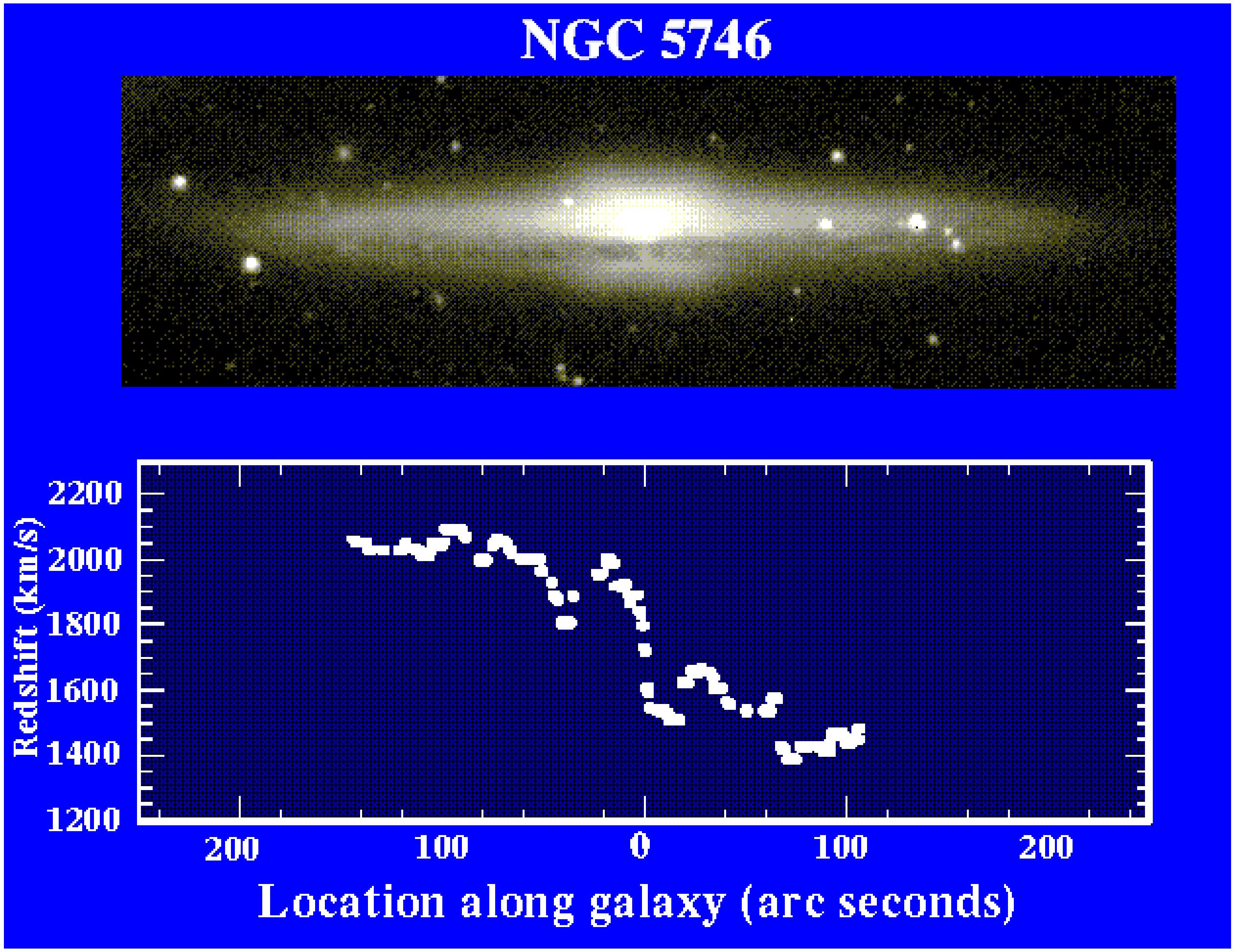
- Antimatter should have been created equally with matter at the beginning
- It does not exist today, because if it did we would observe powerful bursts
- It annihilated away early, but only after an asymmetry between matter and antimatter developed:

$$\eta_B = n_B / n_\gamma \approx 10^{-9}$$

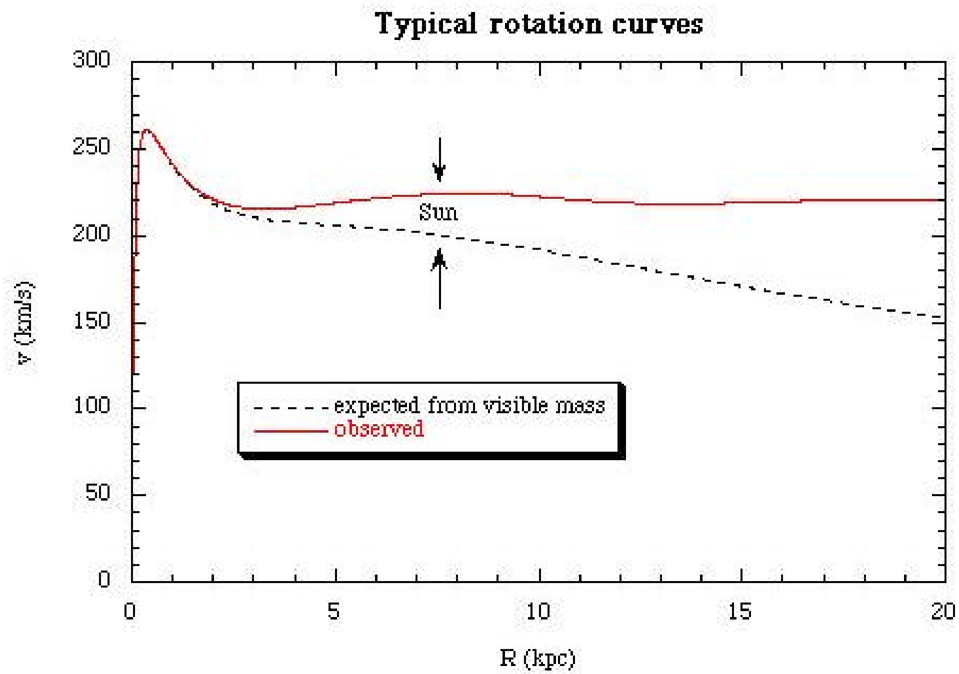
(how did this come about?)

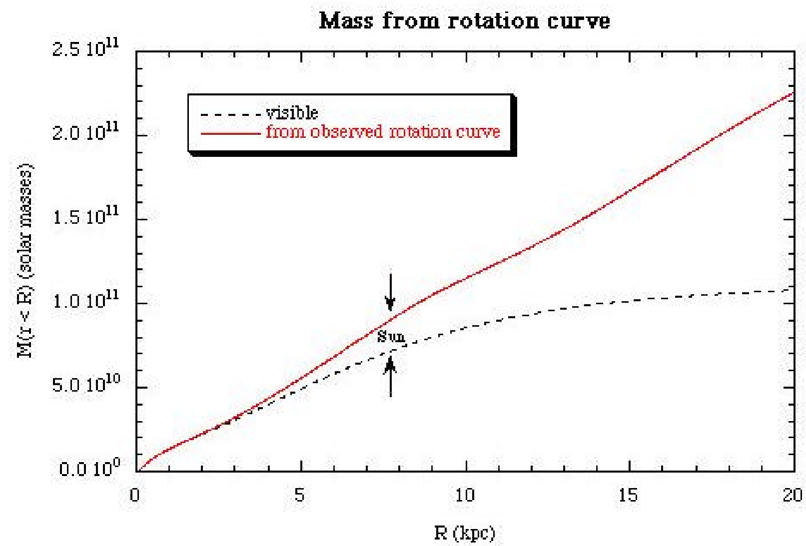
Dark Matter

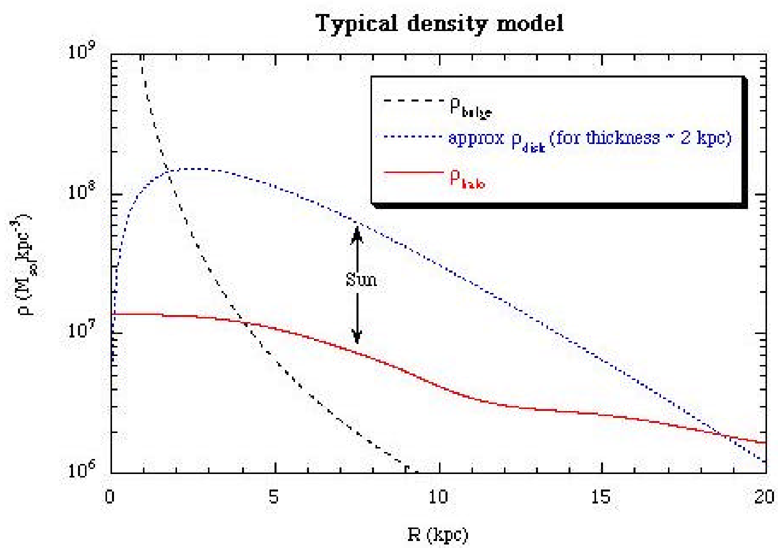
Galactic rotation curves reveal dark matter



Dark Matter







From:
http://hepwww.rl.ac.uk/ukdmc
/dark_matter/rotation_curves.html

Dark Matter

What is it?

- ordinary matter (some is, not much)
- axions?
- massive neutrinos?
- neutralinos?
- monopoles?
- primordial black holes?

The Crisis in Particle Physics

- Universe is dominated by Dark Energy
- and even Dark Matter dominates baryonic matter
- This is a challenge to the Standard Model of particle physics since nonbaryonic dark matter, massive neutrinos, and dark energy are not part of the Standard Model

What might we achieve in the next 20 years?

- Discover the Higgs
- Discover supersymmetry
- Solve the hierarchy problem
- Directly detect dark matter
- Understand dark-matter dynamics
- Discover axions
- Solve the cosmological constant problem
- Measure the equation of state of the dark energy
- Verify/disprove inflation
- Understand the origin of large-scale structure
- Understand the baryon asymmetry
- Understand neutrino masses and mixings
- Detect gravitational waves
- Understand gamma-ray bursts
- Discover extra spatial dimensions
- Quantize gravity
- Explain ultra-high-energy cosmic rays
- Understand CP violation (and P violation)
- Discover baryon-number violation
- Detect violations of Lorentz invariance, CPT, the Principle of Equivalence, Newton's law of gravity