Matter and Energy in the Universe: What We Know and How We Know It

(A Tour of Modern Cosmology)

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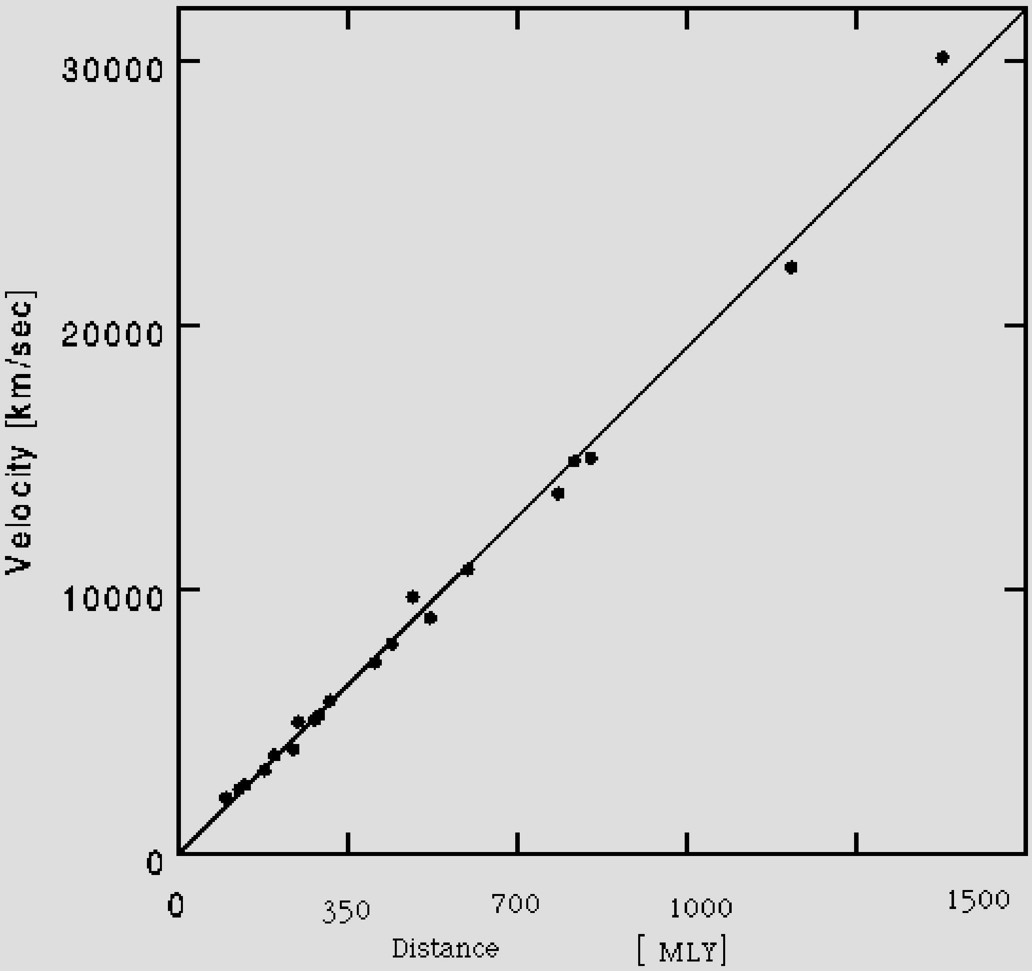
The Universe is Expanding

- **Hubble: galaxies have a "redshift" proportional to their distance from us**
  - **doppler shift in radiation emitted by the galaxy**

$$\frac{\lambda'}{\lambda} = \sqrt{\frac{1+v/c}{1-v/c}} \approx 1 + \frac{v}{c}$$

- **Key fact: as the universe expands, it also cools**
  - **Wavelengths expand along with everything else: longer wavelength (redder) = lower energy**
  - **"co-moving" coordinates expand along with universe**
  - **radiation: T ~ 1 / size**



Evolution of Matter and Radiation Densities with Expansion

- The cosmological scale factor a(t) gives the size as a function of time
- Energy densities:
  - Matter $\rho \propto a^{-3}$
  - Radiation $\rho \propto a^{-4}$
- Vacuum energy is constant!
- Familiar Hubble "constant"

$$H(t) = \frac{\dot{a}}{a}$$

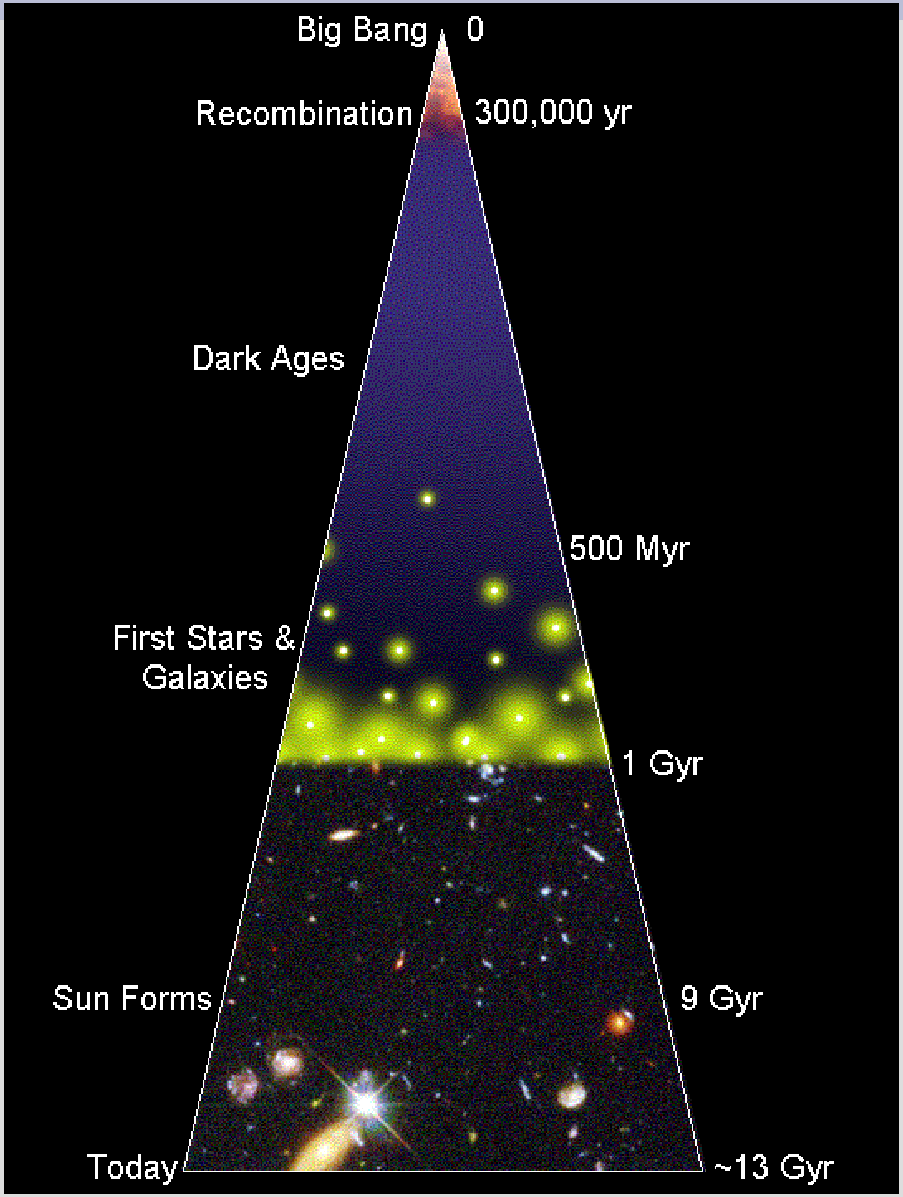
- Einstein's General Relativity gives a(t) given rho:

$$H^2 = \frac{8\pi G}{3}\rho$$

$$\text{radiation}: a(t) \propto t^{1/2}$$

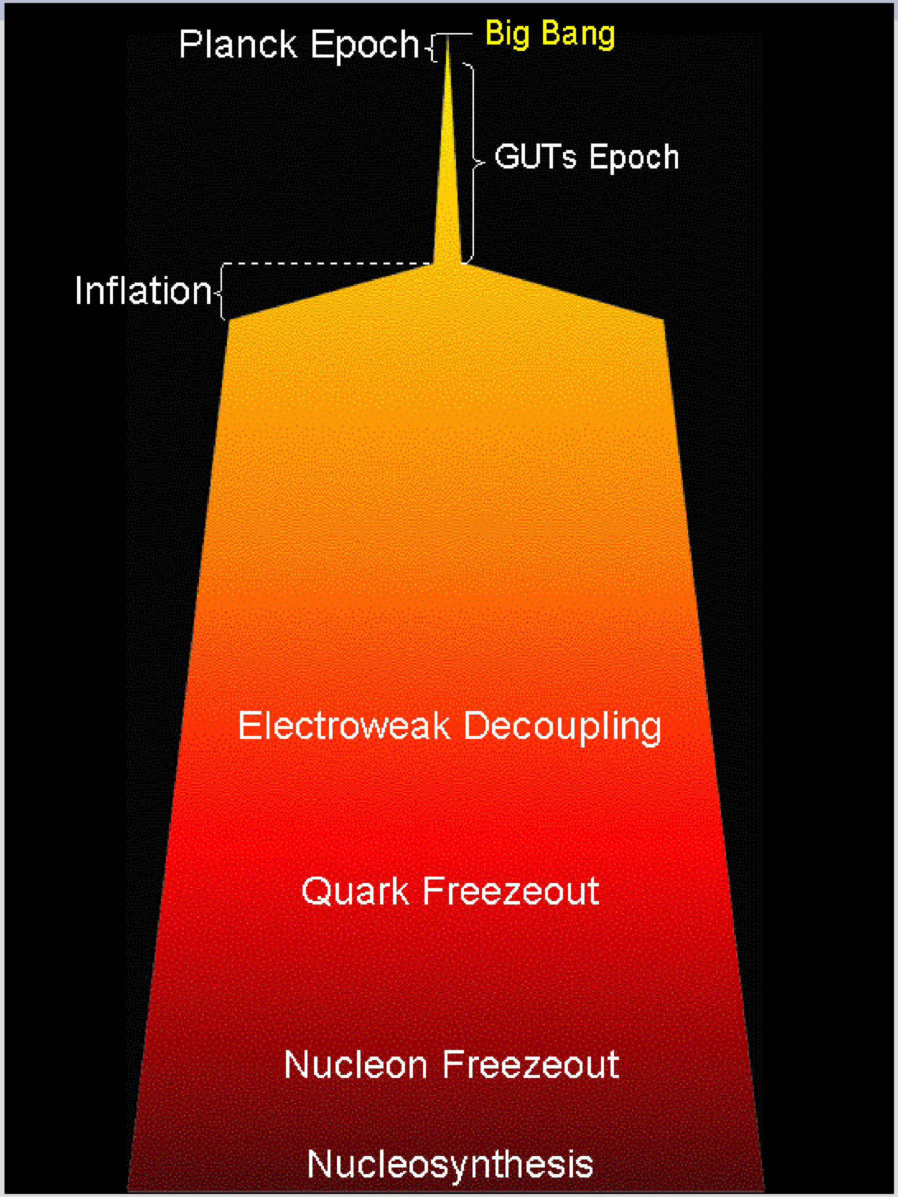
$$\text{matter}: a(t) \propto t^{2/3}$$

$$\text{vacuum}: a(t) \propto e^{Ht}$$



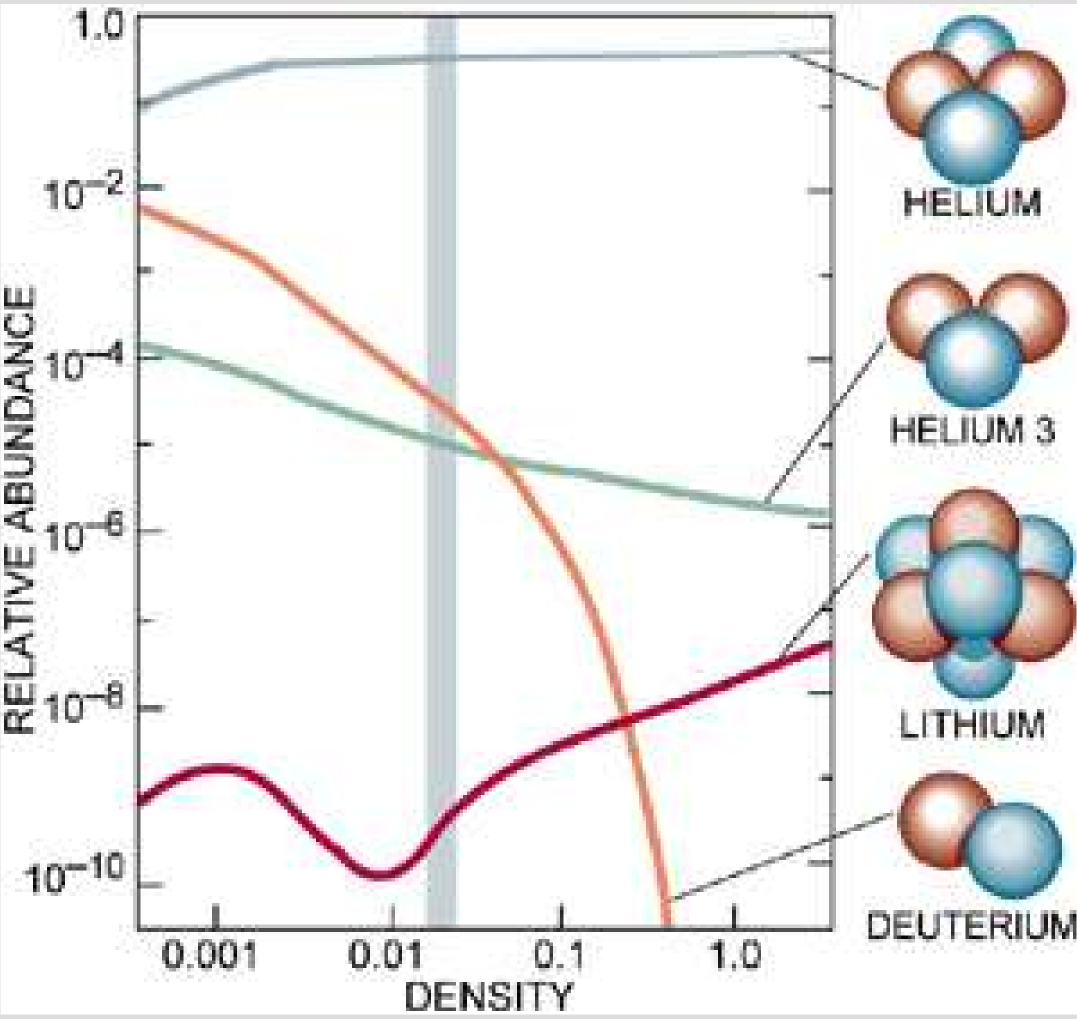
Density of “Normal” Matter in the Universe

- Most of the mass in atoms is in the nucleus
  - protons and neutrons (baryons)
  - electrons are very light
- What is the baryon density in the universe?
  - “Big-bang nucleosynthesis”
- Nuclear reactions common at temperatures of 10 billion deg.
  - Early universe, seconds old
- We have two clocks!
  - Hubble expansion
  - Neutron lifetime
- Use these to constrain density



Big Bang Nucleosynthesis

- Hubble expansion clock
  - radiation dominated universe: $H \sim T^2$
  - photon number density $\sim T^3$
- Neutron lifetime clock
  - mean life 15 minutes
- One input parameter: how many baryons per photon?
  - early on this is all protons and neutrons
- Calculate relative abundances of light isotopes:
  - H, He4, D, He3, Li7
- Now go measure!



Cosmic Deuterium Abundance

- **Deuterium depends on baryon density**
- **It is not made in stars**
- **Deuterium atom is slightly different: energy levels slightly shifted**
  - **deuteron is twice as heavy as proton**
  - **energy shift one part in 3600**
- **Observe both H and D and calculate ratio**
  - **high redshift objects should give a good estimate of the primordial ratio**

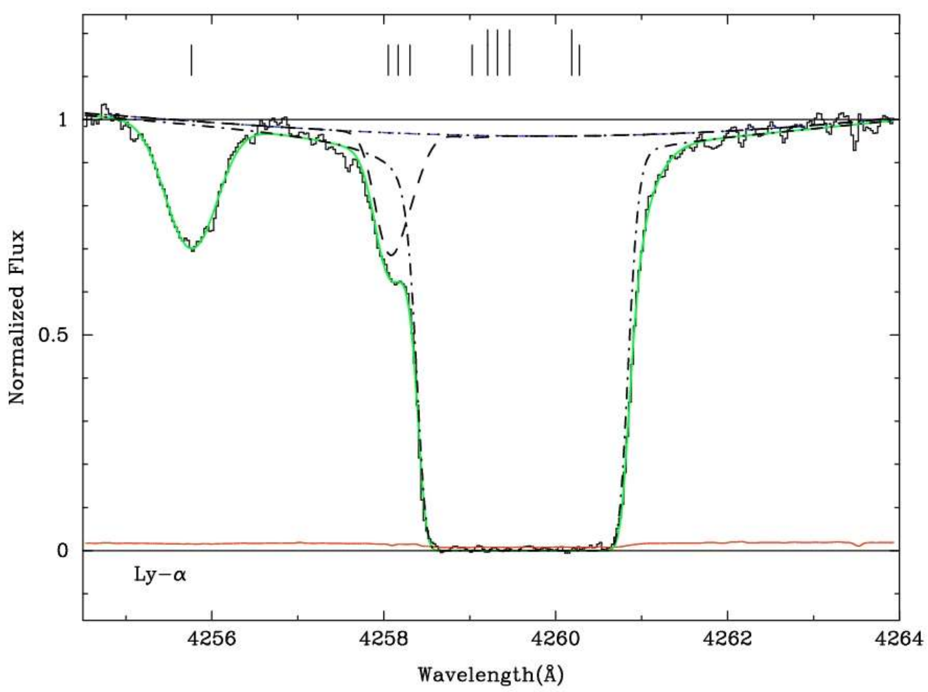


FIG. 6a

Cosmic Densities

- Measure densities relative to the “critical” density
  - h (=0.7) is Hubble constant in units of 100 km / s / Mpc
  - proton mass is 0.938 GeV

$$\rho_c = \frac{3H^2}{8\pi G} = 1.05 \times 10^{-5} h^2 \text{ GeV cm}^{-3}$$

- Density parameters Ω
  - often we use Ωh^2

$$\Omega_X = \frac{\rho_X}{\rho_c}$$

- Ω = 1 is a “flat” universe
- Baryons have Ω=0.044
- This is far less than the total: stay tuned!

- Background radiation left from the hot early universe
  - Photons: Cosmic Microwave Background Ω=0.0001
    - 400 photons / cc
    - “easy” to measure: temperature of the microwave radiation
  - Neutrinos
    - similar number density to photons
    - mass (heaviest) somewhere in the range milli-eV to ~ 2 eV

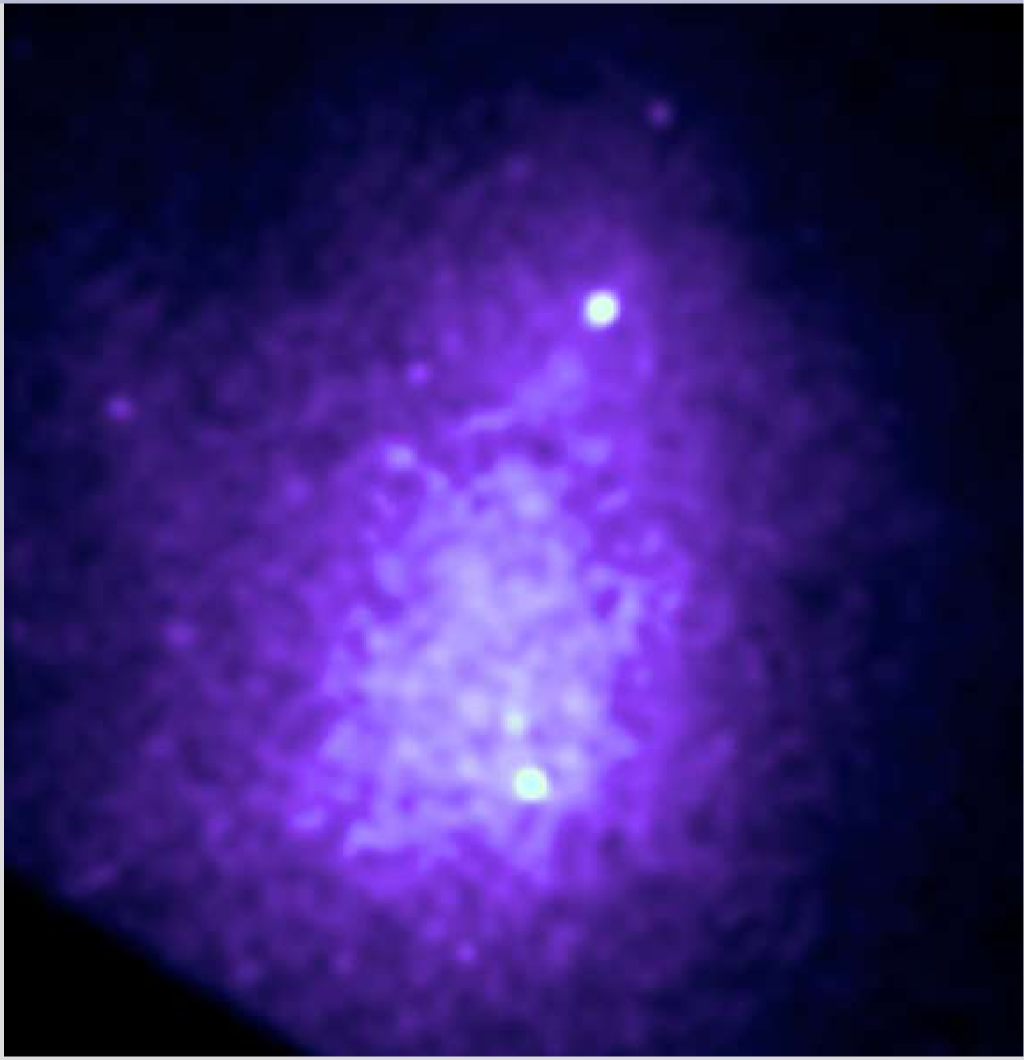
What Are Galaxies Made Of?

- We now know the baryon density: could galaxies be made of baryons?
- Overwhelming evidence indicates “no”
- Oldest evidence from Zwicky (1930s!)
  - M / L in galaxy clusters is 100x or more than solar
  - Light: “easy”
  - Mass from size, velocity and virial theorem

$$\frac{GM}{R} \sim v^2$$

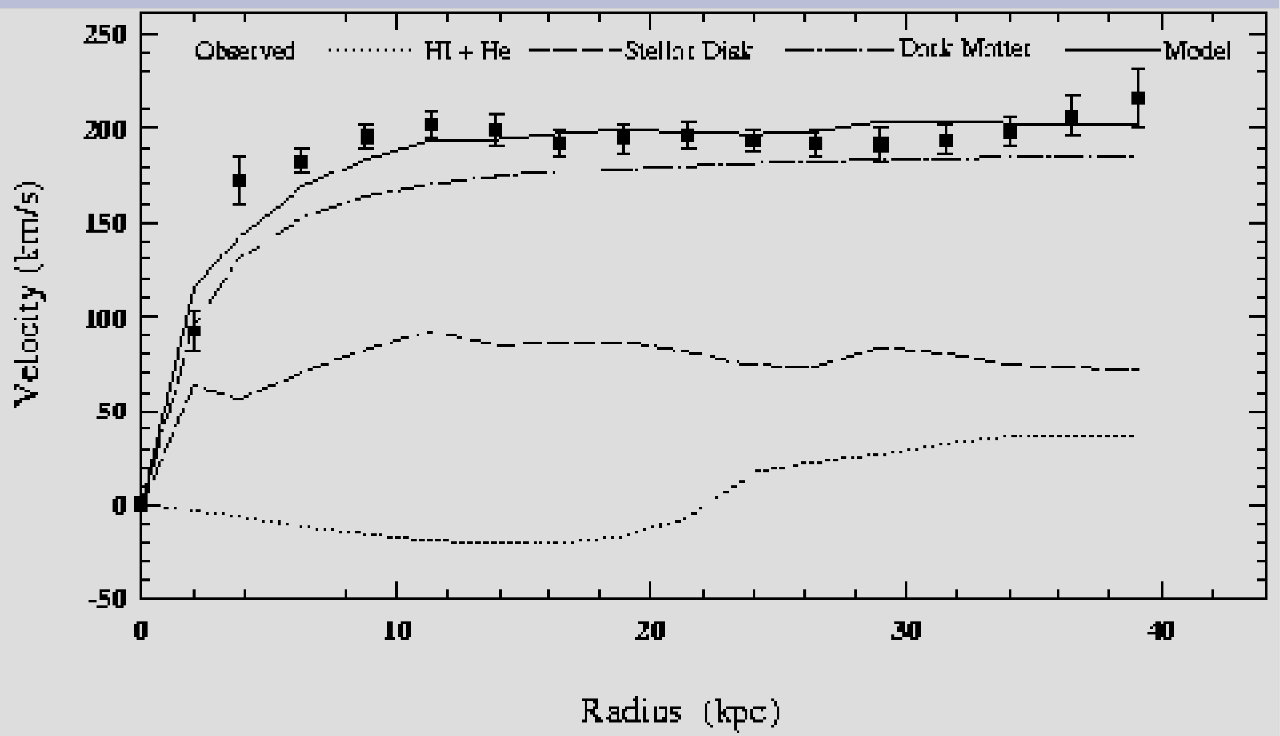
Baryon *Fraction* in Clusters of Galaxies

- Galaxy clusters are rare
  - 1e15 solar masses
  - 1000s of galaxies
  - most baryons are in hot gas
- Gas shines in X-rays
  - how bright? proportional to the total mass in gas
  - how hot? virial theorem again (replace “v” with “T”) and get the total mass
- These disagree: baryons are about 1/5 of the total mass in clusters
- Next: more evidence for “1/5”



Spiral Galaxy Rotation Curves

- Baryons in spiral galaxies mostly in stars; not much gas available
- Stellar density falls exponentially
- Rotation velocities are constant!
  - rho ~ 1 / r² implied
- Doppler shifts used to get velocities
  - Atomic H (21 cm, Hα)
  - Molecules (CO)
- Milky Way rotates at 220 km / s
- Andromeda is a bit faster at 240 km / s

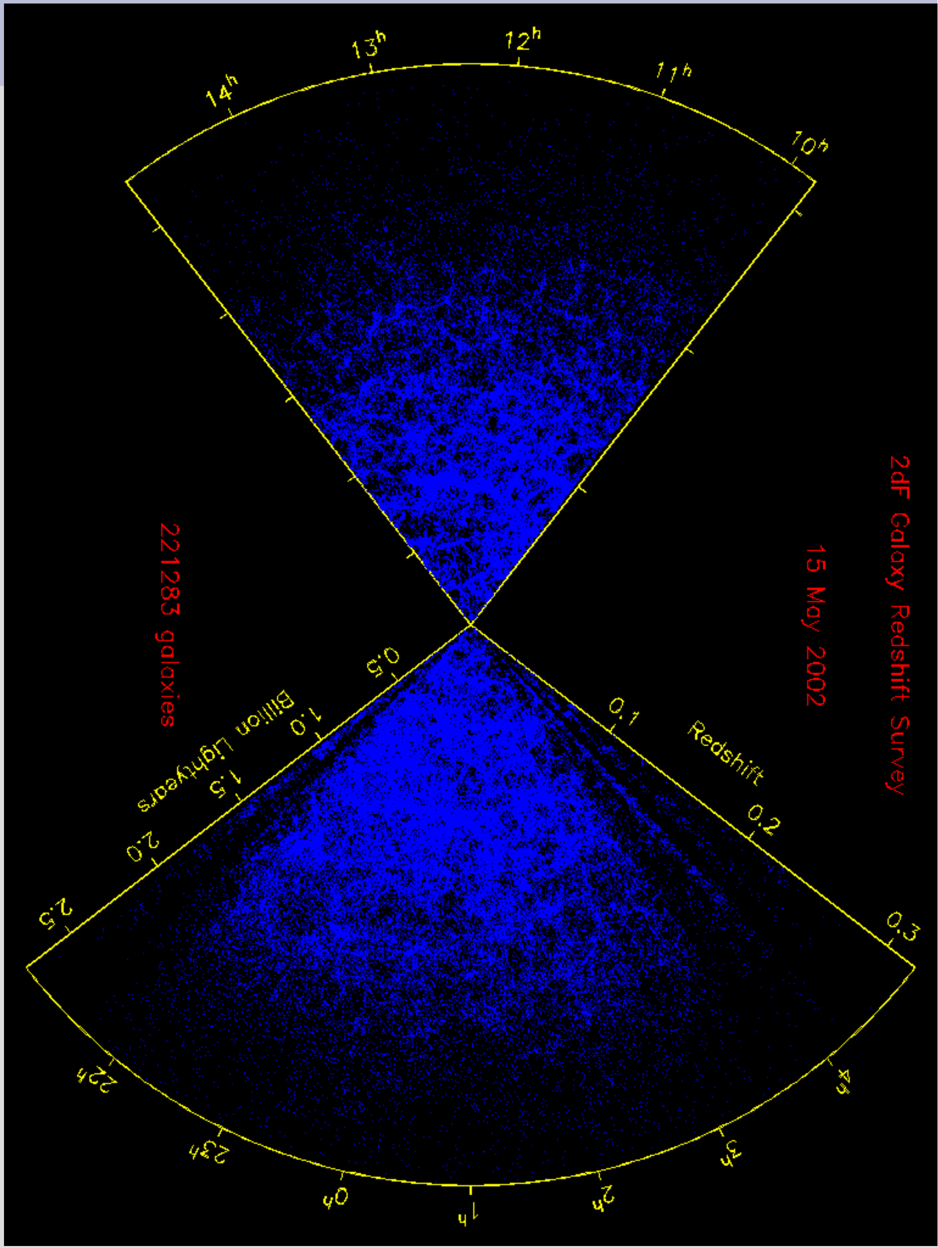


Large Scale Structure

- **How do galaxies cluster on the largest scales?**
  - **measure 100,000+ redshifts**
  - **there is a characteristic scale for the clustering**

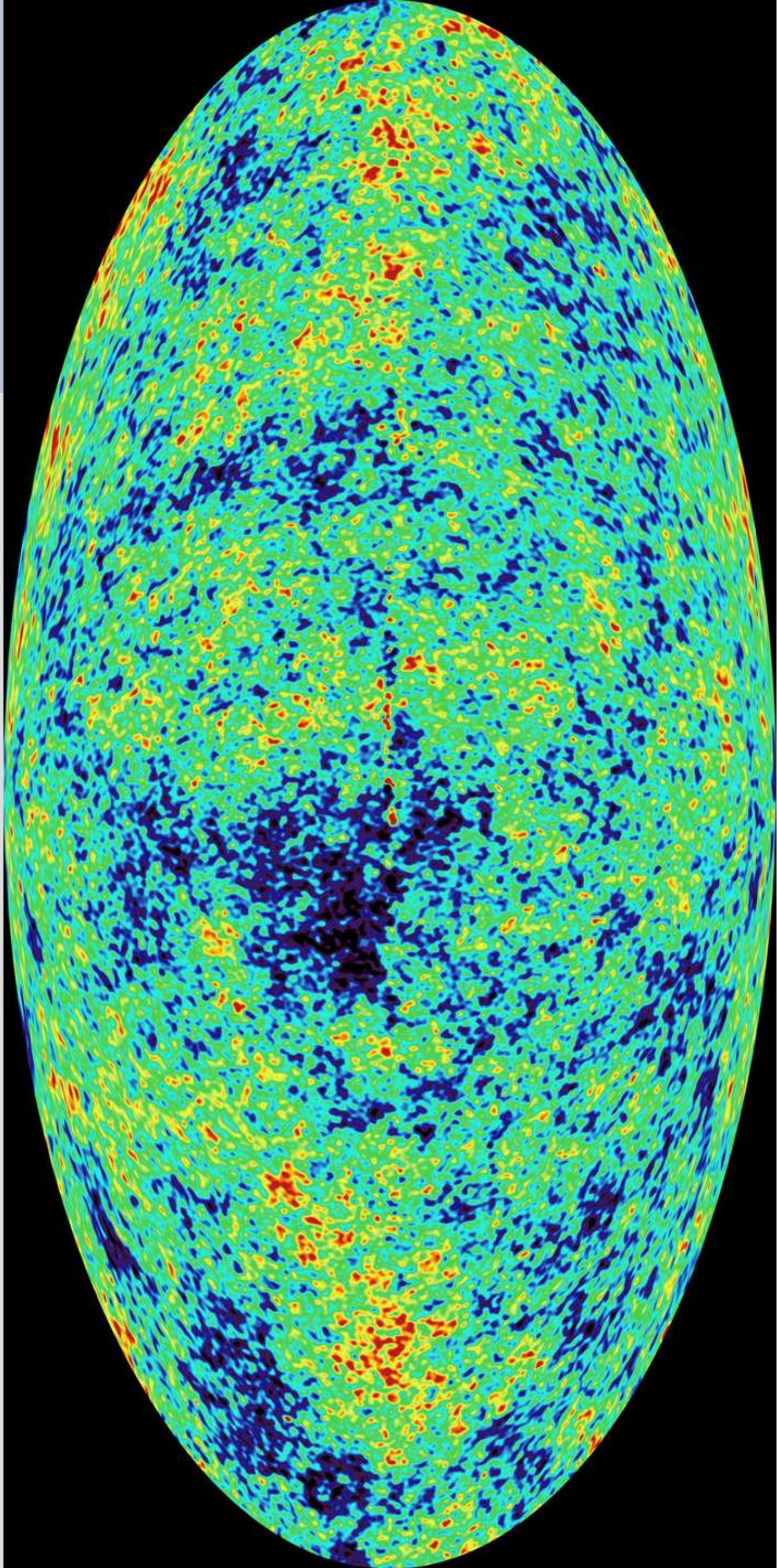
$$R \sim \Omega_{CDM} h$$

  - **Ω=0.3 fits well**
  - **galaxies are made of “cold” matter: neutrinos are too light and must be subdominant**
    - limit is ~1/3 as much as baryons
    - this limits the neutrino mass better than is possible in the lab: m < 0.2 eV



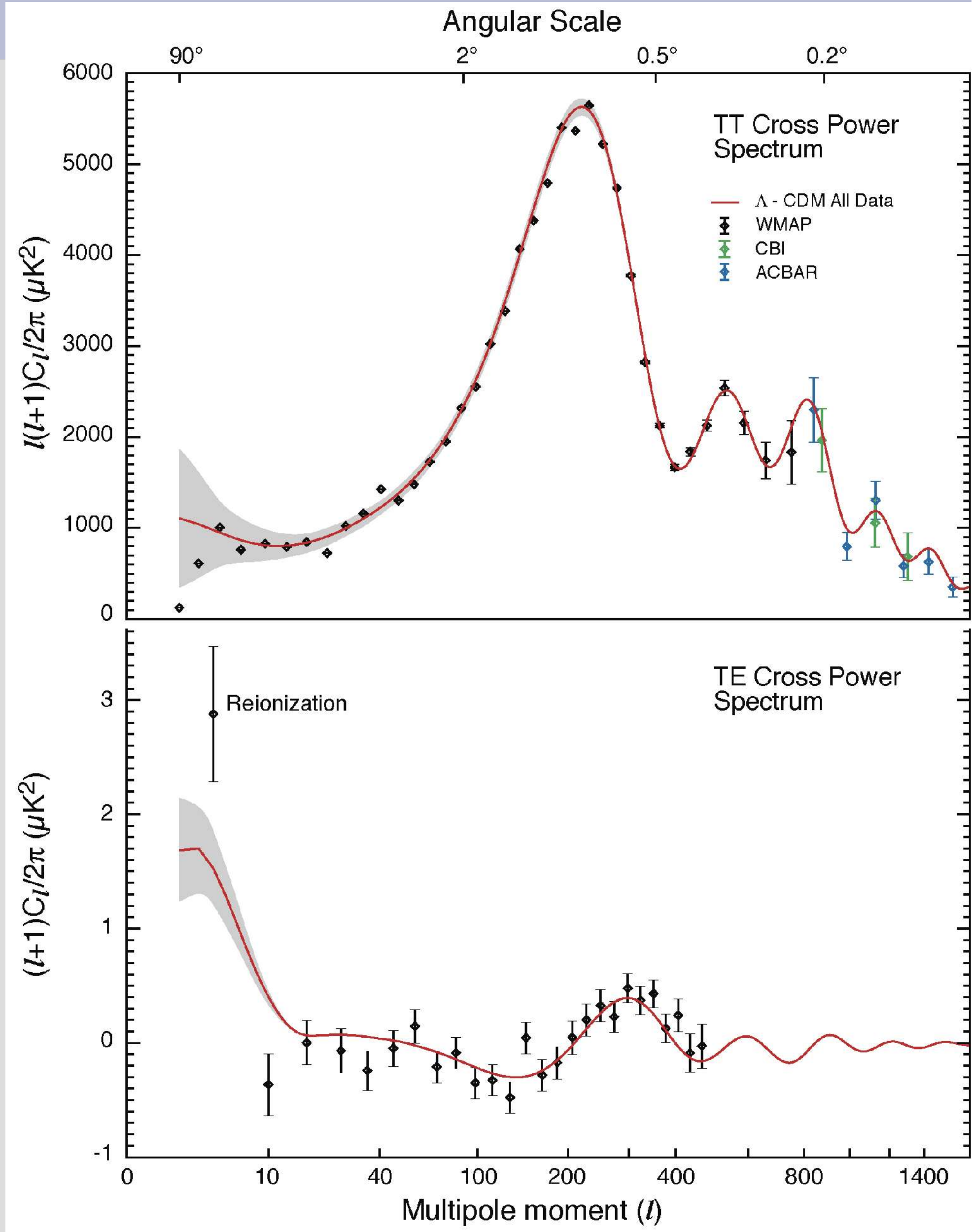
Cosmic Microwave Background

- CMB ties together all these lines of evidence
- Pattern of fluctuations of microKelvin size encodes:
  - baryon density
  - matter density
  - total density
- Acoustic oscillations
  - slightly overdense region wants to collapse under its gravity
  - gas pressure opposes collapse
  - this is an oscillator



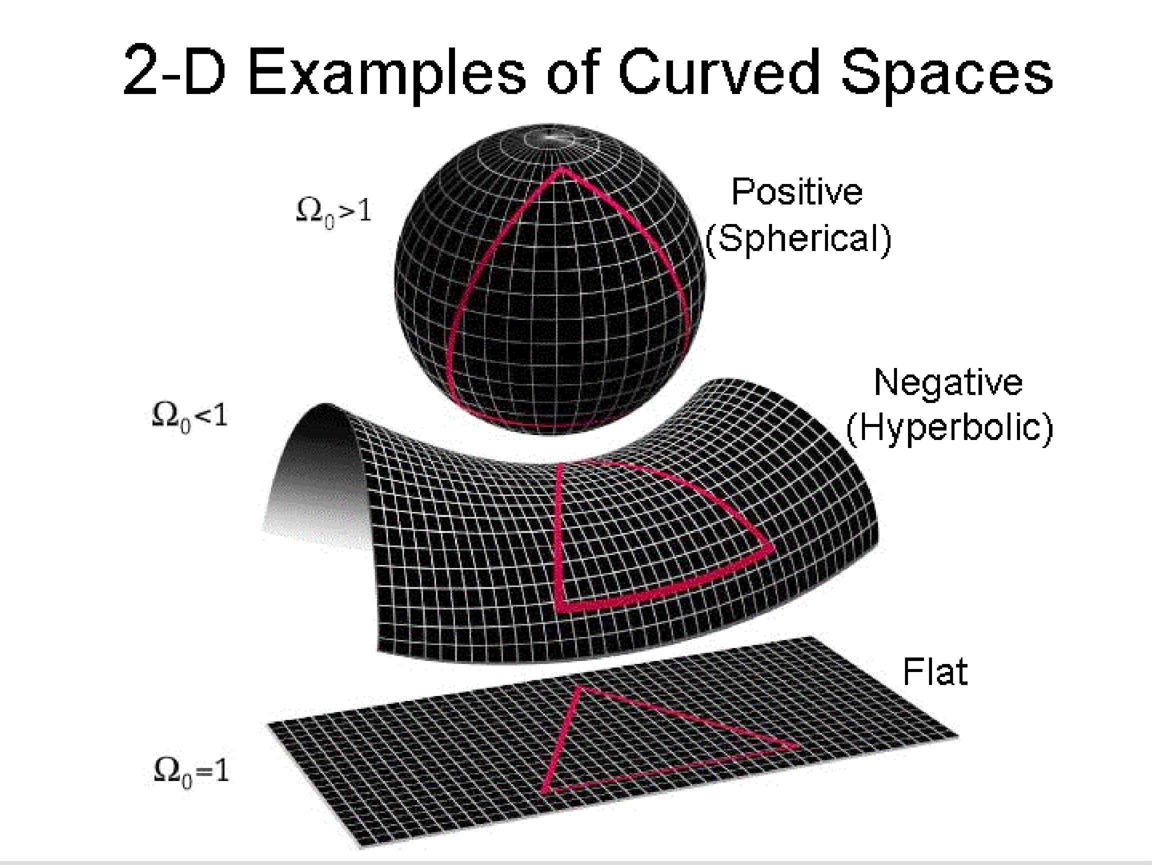
Cosmic Microwave Background II

- The CMB is "emitted" when the universe becomes transparent
  - Hydrogen must recombine: this happens as T falls
  - At emission, CMB has a wavelength of 5 microns (mid-infrared)
- We can calculate the wavelength of oscillations
  - related to age of universe at the time of CMB emission
- From wavelength, we can get the geometry of the universe



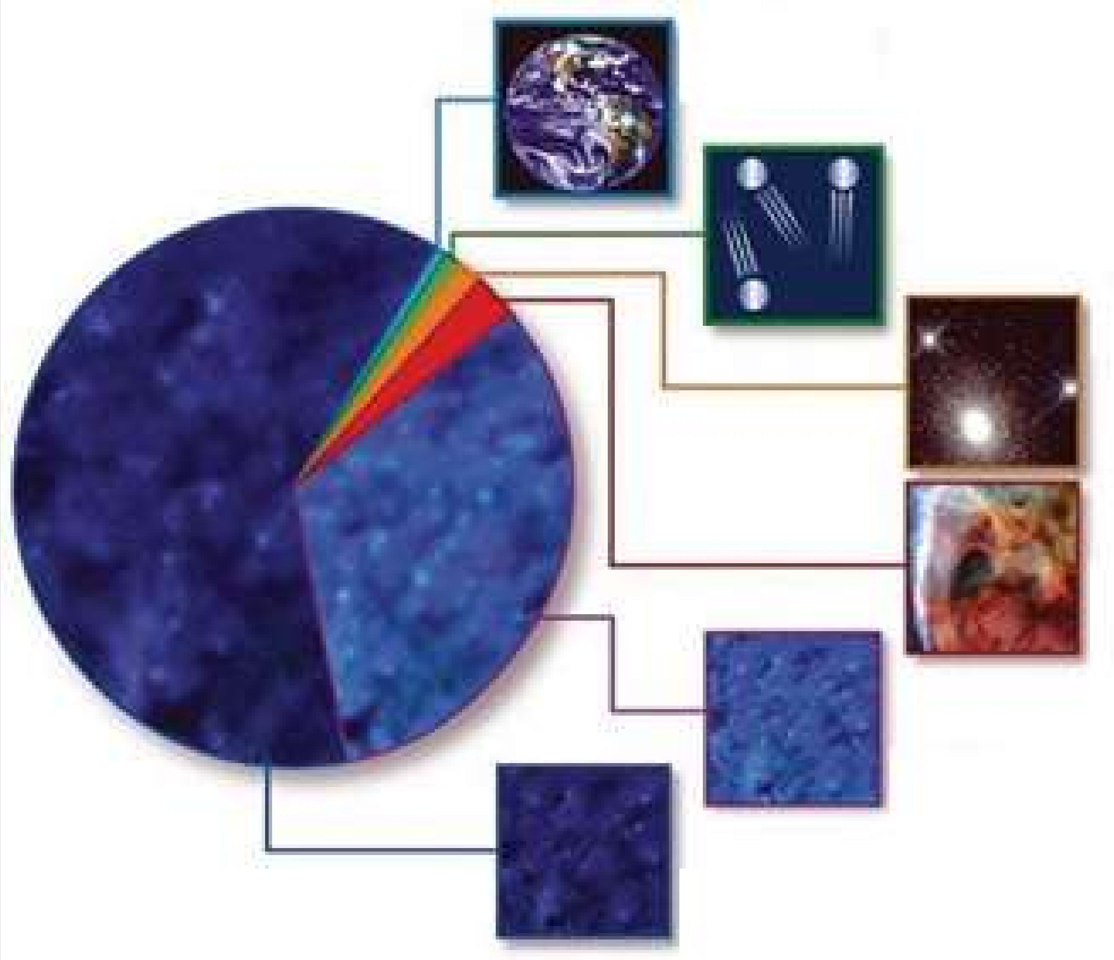
Cosmic Microwave Background III

- Space can be curved
  - positive: objects appear larger than they are
    - parallel lines converge
  - negative: objects appear smaller than they are
    - parallel lines diverge
- We know the redshift of the CMB accurately, and we know how to calculate distance
- CMB tells us that space is flat, and Ω=1
- We're still missing most of the stuff!!!



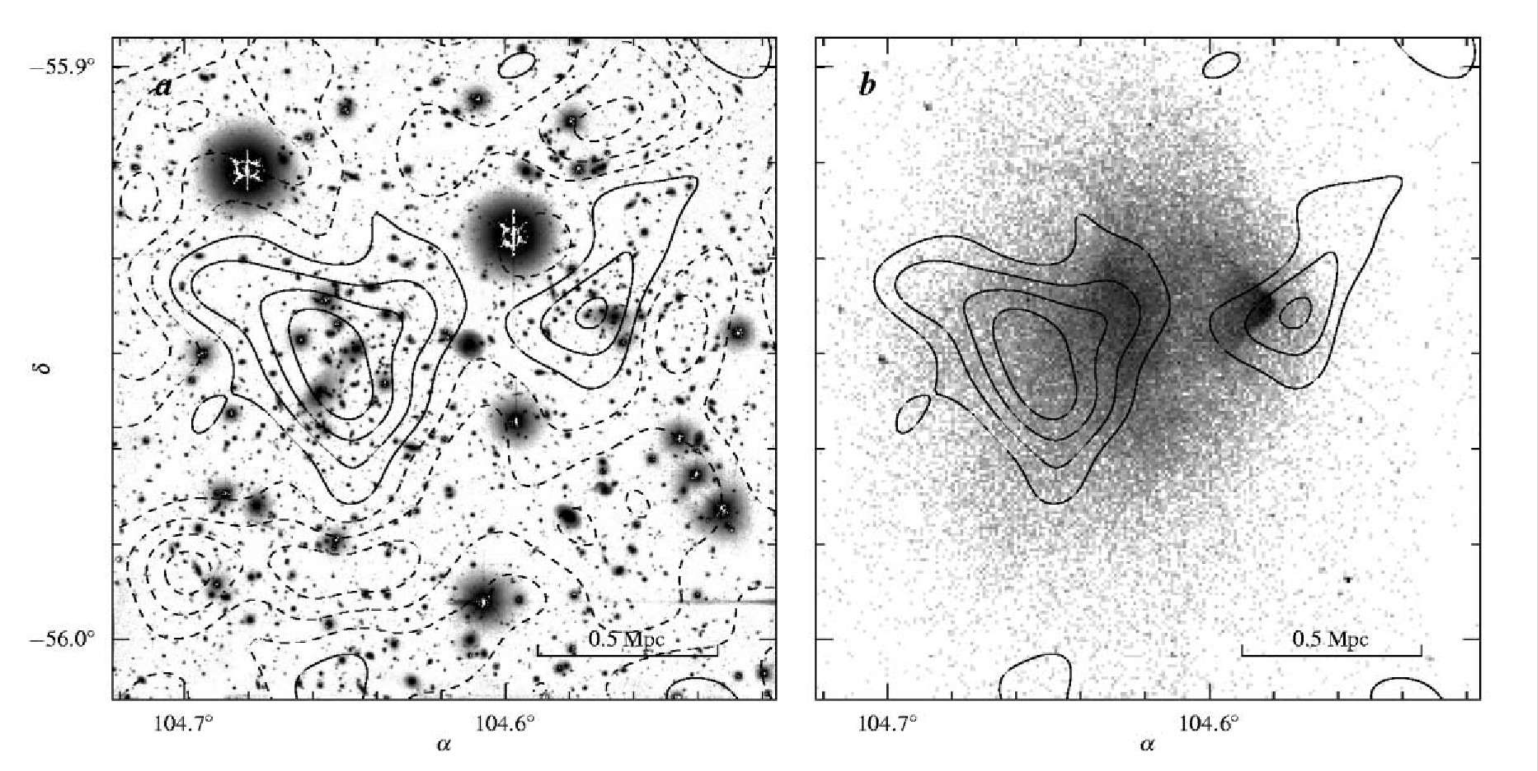
What Are We Missing???

- Baryons: 4%
  - Known to exist
- Neutrinos: < 1.5%
  - Known to exist
- Photons: 0.01 %
  - Known to exist
- Dark Matter: 23%
  - Known to be unknown
- "Dark Energy": 73%
  - This doesn't cluster much



What If We Have Gravity Screwed Up? Could We Not Need Dark Matter?

- MOND (MOdified Newtonian Dynamics)
- Gravitational acceleration has a minimum ~ cH
  - spiral galaxies fit perfectly, clusters have problems
- If baryons and dark matter can be observed to be segregated, there is no hope for MOND



What Could the Dark Matter Be?
Good Candidates from Particle Physics

- Supersymmetry?
  - Fixes a serious problem in the Standard Model
    - Why is the weak force so strong?
- Naturally get particles in the 10 GeV – TeV range
  - lightest new one is stable!
- Repeat the BBN exercise (with new interactions) to get the dark matter density
- Compelling conclusion for massive relic particles:

$$\Omega_X \sim \frac{1}{\sigma} \sim \left(\frac{M}{\mathrm{TeV}}\right)^2$$

- Axions?
  - Fixes a serious problem in the Standard Model
    - Why no electric dipole moments?
- Very light particles
  - micro-milli eV
- Made very cold, never in thermal equilibrium
- As dark matter, can be detected by converting axion to microwave photon in a strong magnetic field
  - and having the best radio ever built!

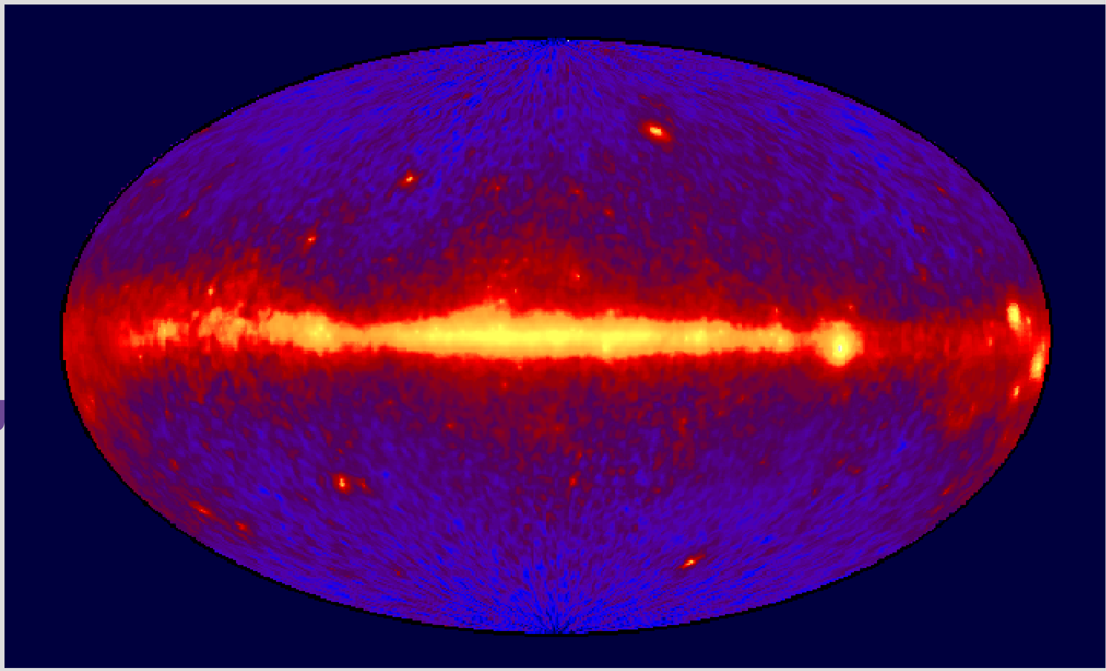
What Could the Dark Matter Be? “Candidates” Not Ruled Out

- Dark Matter is “cold” and nearly non-interacting
  - not difficult to arrange for particles of any mass
- Fluid on galaxy scales
  - discreteness effects appear with DM “particles” of 10,000 solar masses (or so)
  - this is 1e70 eV
- Classical (not quantum) on galaxy scales
  - fermions > 25 eV or so
  - Pauli exclusion principle!
  - bosons > 1e-22 eV
  - no that's not a typo
  - QM wavelength < kpc or so to confine particle to galaxy
- 90+ orders of magnitude uncertainty
- Most of this isn't terribly likely, but until we have data...

Weakly Interacting Massive Particles: (WIMPs)

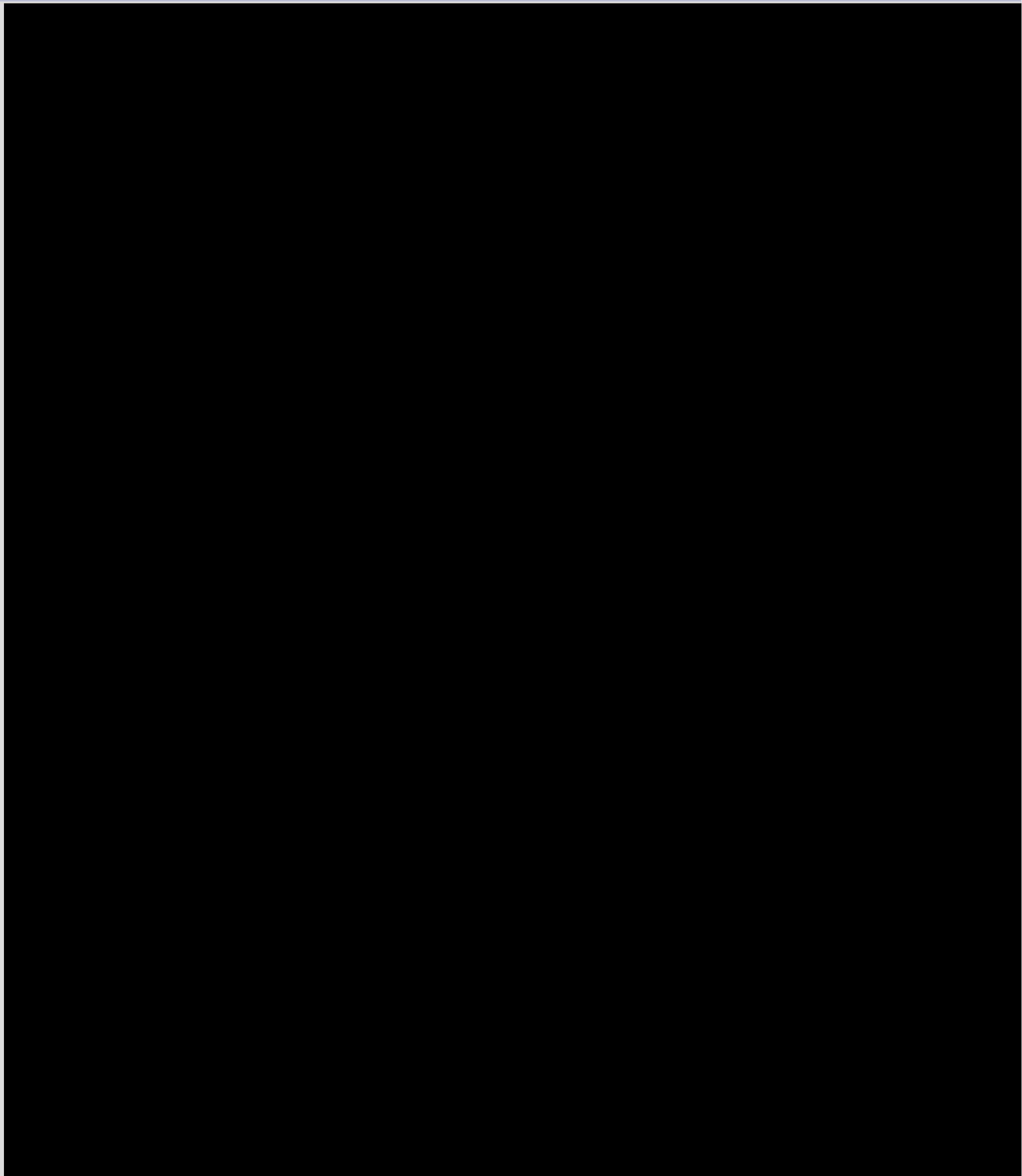
- **100 GeV range: many search strategies:**
  - **accelerators: make dark matter in the lab @ LHC!**
  - **underground: look for dark matter particles making the Milky Way**
    - VERY weakly interacting, moving 200 km / s (go underground to filter out cosmic rays)
  - **in the sky: look for high energy particles coming from (rare) dark matter annihilations**
    - gamma rays, antiprotons, positrons...

EGRET All-Sky Gamma Ray Survey Above 100 MeV



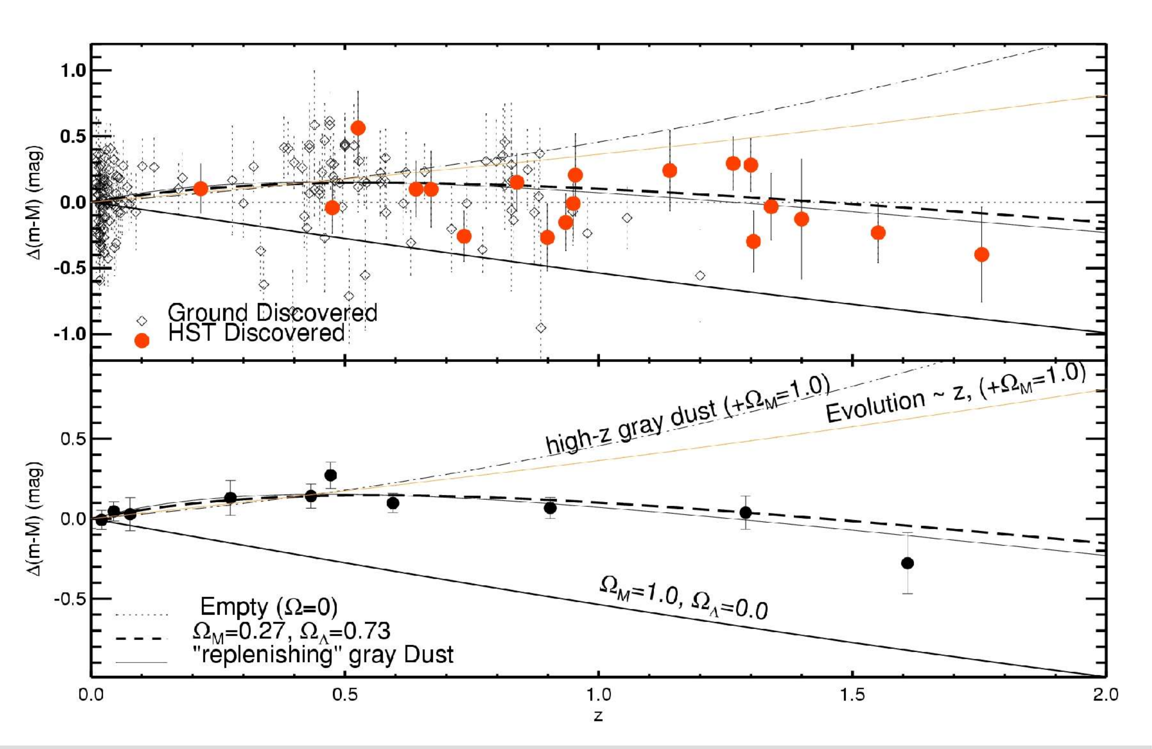
Dark Energy: Even More Mysterious Than Dark Matter

- **Dark Matter, while exotic, could be particles**
  - **we know about particles**
- **Dark Energy doesn't behave like any known form of matter**
  - **it's pressure is negative!**
- **We know from the CMB that the universe is actually dominated by dark energy at the present day**
- **How can we learn more?**



Back To The Hubble Expansion

- **Redshift as a function of distance is not linear**
  - **small deviations from linearity encode the expansion history**
- **In a matter or radiation dominated universe, expansion decelerates**
- **Expansion is now accelerating**
  - **negative pressure required**
  - **same conditions as cosmic inflation in the exceedingly early universe**



The Universe Is Accelerating

- Dark Energy became dominant at z = 0.4
  - deceleration stopped, acceleration began
- The material causing this has p = -rho (or pretty close)
- Quantum mechanics predicts just such a material: the energy of the vacuum
  - the prediction is 120!!! orders of magnitude too large
- We can hope that future measurements clear this up