Astronomical Evidence for Dark Matter

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Ph 135C

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Fun Facts

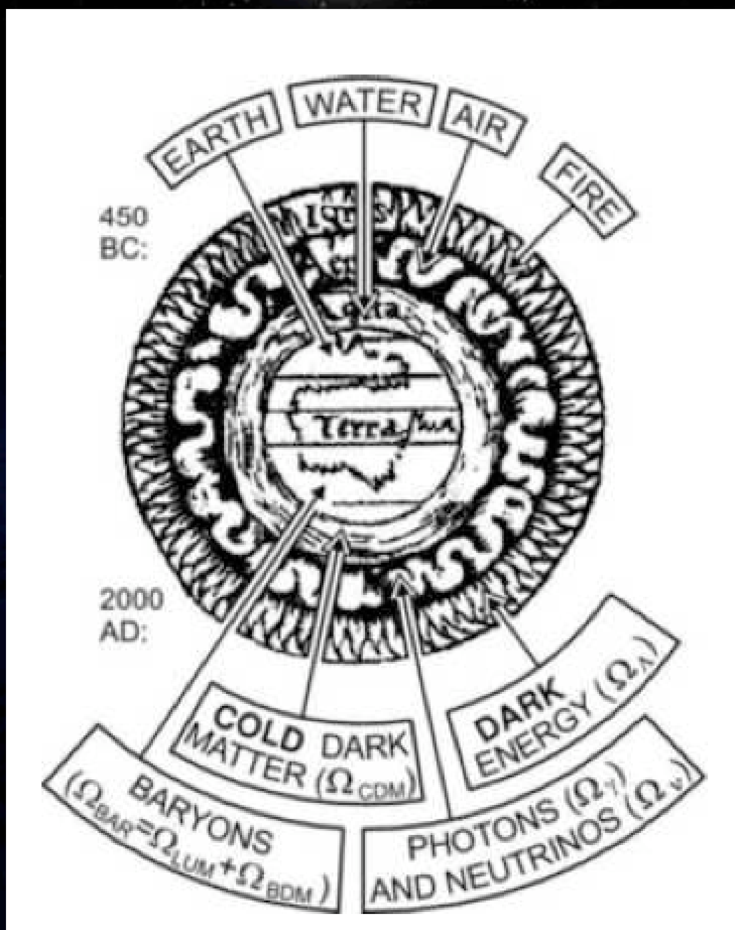
- Franz Zwicky at Caltech first to "discover" dark matter in 1933.
- No more evidence for almost 40 years.
- Most powerful weapon in "Quake 4" is the Dark Matter Gun.
- In Futurama they use dark matter fuel, where "one pound is 10,000 pounds."

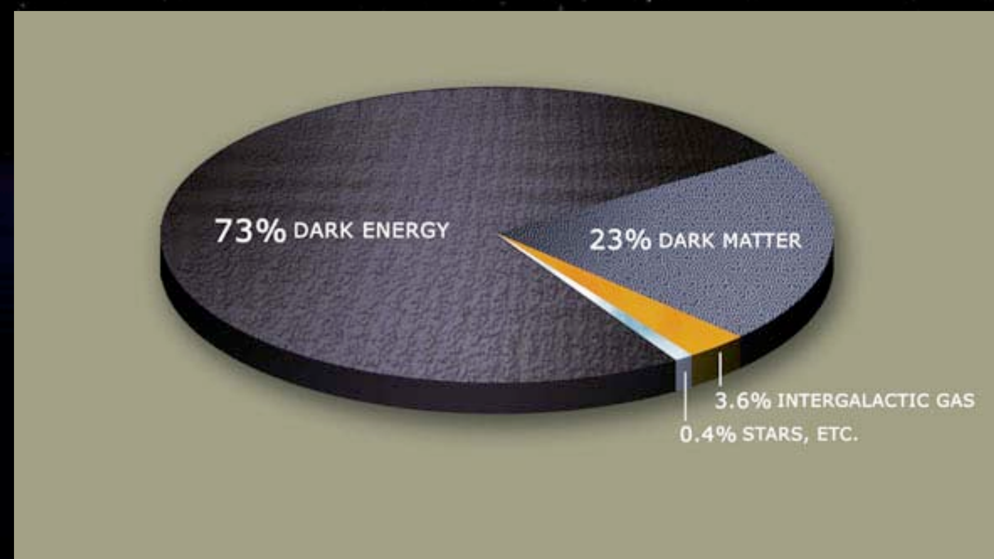
Fun Facts

Optical Dark Matter X-ray Gas
DARK MATTER
Most of the universe can't even be bothered to interact with you.

Current Picture

ΛCDM model



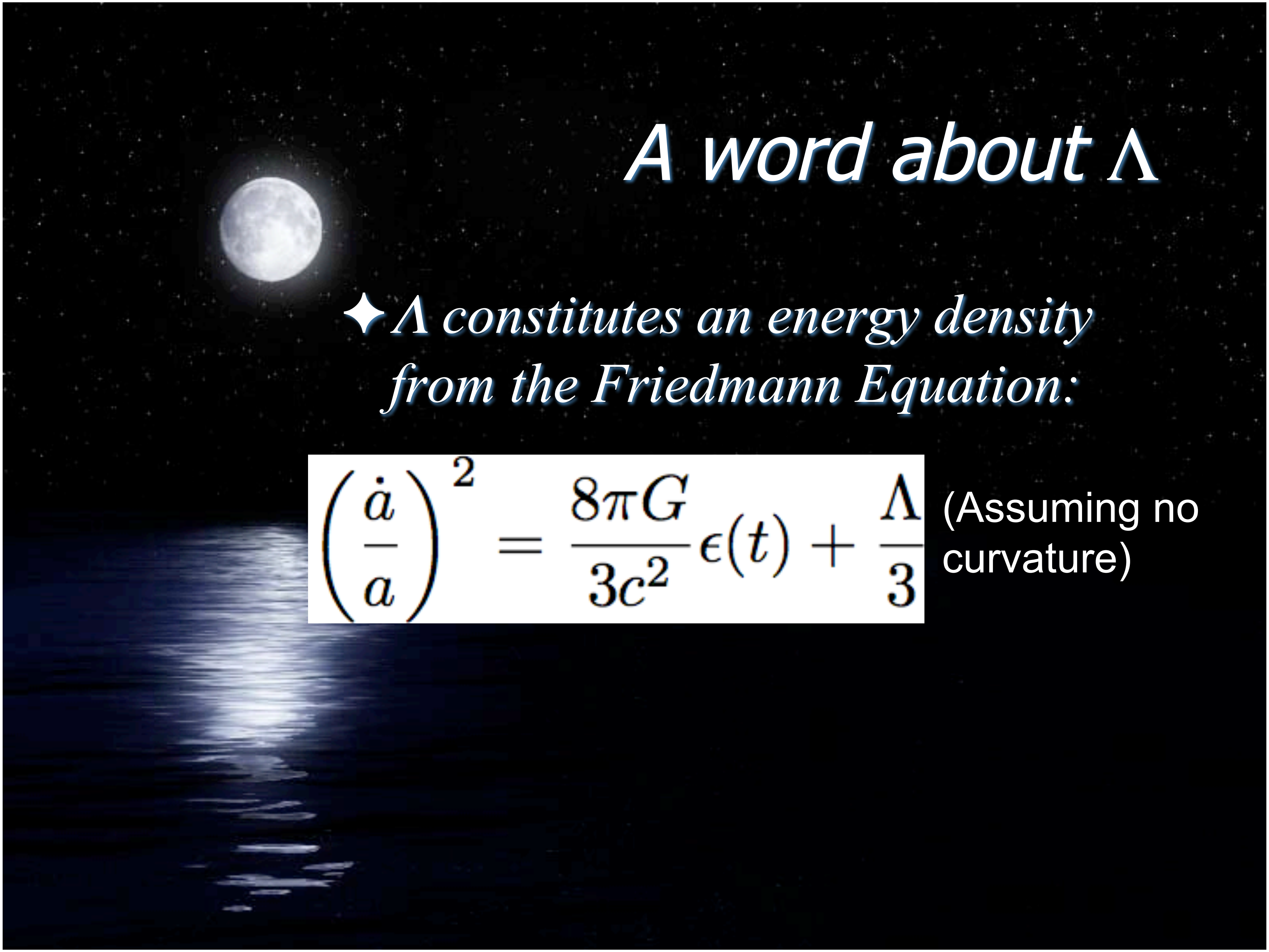


ΛCDM Model

- Λ = cosmological constant

$$G_{ab} + \Lambda g_{ab} = \frac{8\pi G}{c^4} T_{ab}$$

- CDM = cold dark matter (assumed non-baryonic)



A word about Λ

- *Λ constitutes an energy density from the Friedmann Equation:*

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\epsilon(t) + \frac{\Lambda}{3}$$

(Assuming no curvature)

Definitions

- $\rho_C \equiv$ Critical Density
- $\Omega_X \equiv \rho_X/\rho_C$
- $\Omega = 1 \Rightarrow$ flat universe, what ours looks like.


Why DM?
✦Evidence from...
✦Galaxies
✦Galaxy clusters
✦Cosmology

Spiral Galaxies

- Rotation curve:
  - Virial Theorem: $$K = -\frac{1}{2}U$$

$$\frac{1}{2}\frac{GM(r)m}{r} = \frac{1}{2}m(v(r))^2$$

$$v(r) = \sqrt{\frac{GM(r)}{r}}$$

Spiral Galaxies

- ✦Luminous Matter ~ follows:

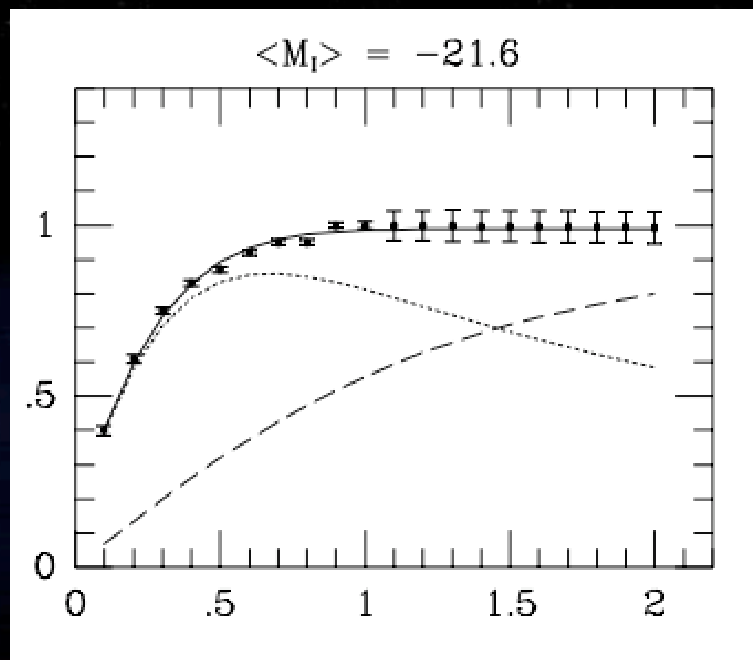
$$I = I_0 e^{-r/R_D}$$

$$M(r) = 2\pi\sigma_0 R_D^2 \left(1 - e^{-r/R_D} - \frac{r}{R_D} e^{-r/R_D}\right)$$

- ✦Asymptotes to constant value

Spiral Galaxies

- Observations:



- Residual fits $\rho \propto \dfrac{1}{a^2 + r^2}$

Galaxy Clusters

- Assuming hydrostatic equilibrium, $\frac{dP}{dr} = -\rho g$

- And cluster is isothermal,

$$P = nkT = \frac{\rho k T}{\mu m_p}$$

- Can derive relation between temp, mass, r:

$$\frac{d \ln \rho}{d \ln r} + \frac{d \ln T}{d \ln r} = -\frac{r}{T}\left(\frac{\mu m_p}{k}\right) g(r)$$

Galaxy Clusters

- Simulation of dynamics:

Galaxy Clusters

- Also with Sunyaev-Zel'dovich Effect.
  - Inverse Compton scattering
  - Sensitive to baryons
  - Spectral distortion:

$$\frac{\Delta T_{RJ}}{T} = -2\frac{k_B \sigma_T}{m_e c^2}\int dl n_e(l) T(l)$$

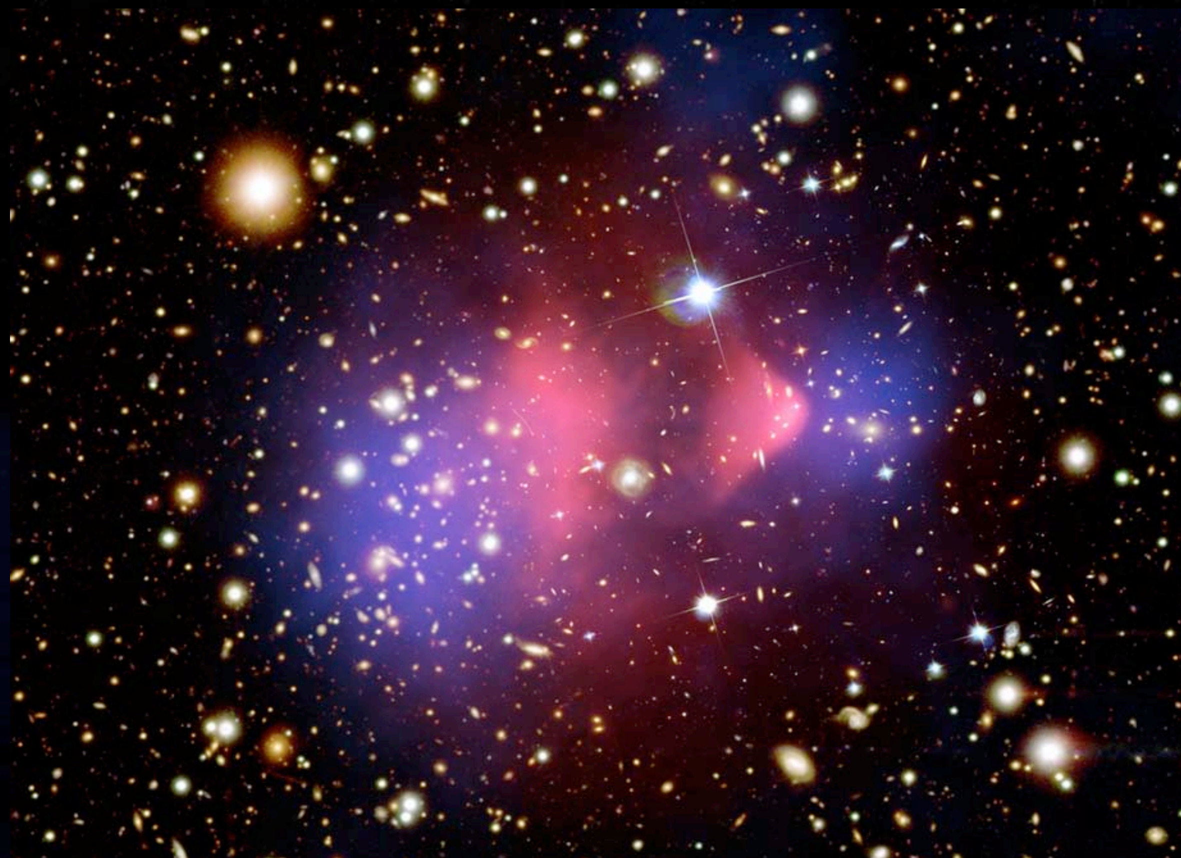
  - Line of sight integral of pressure

Galaxy Clusters

- SZ Effect
  - Compute baryon fraction by comparing SZ to X-ray, virial mass, or gravitational lensing mass.
  - Baryon fraction is around 0.12, comparing with X-ray.

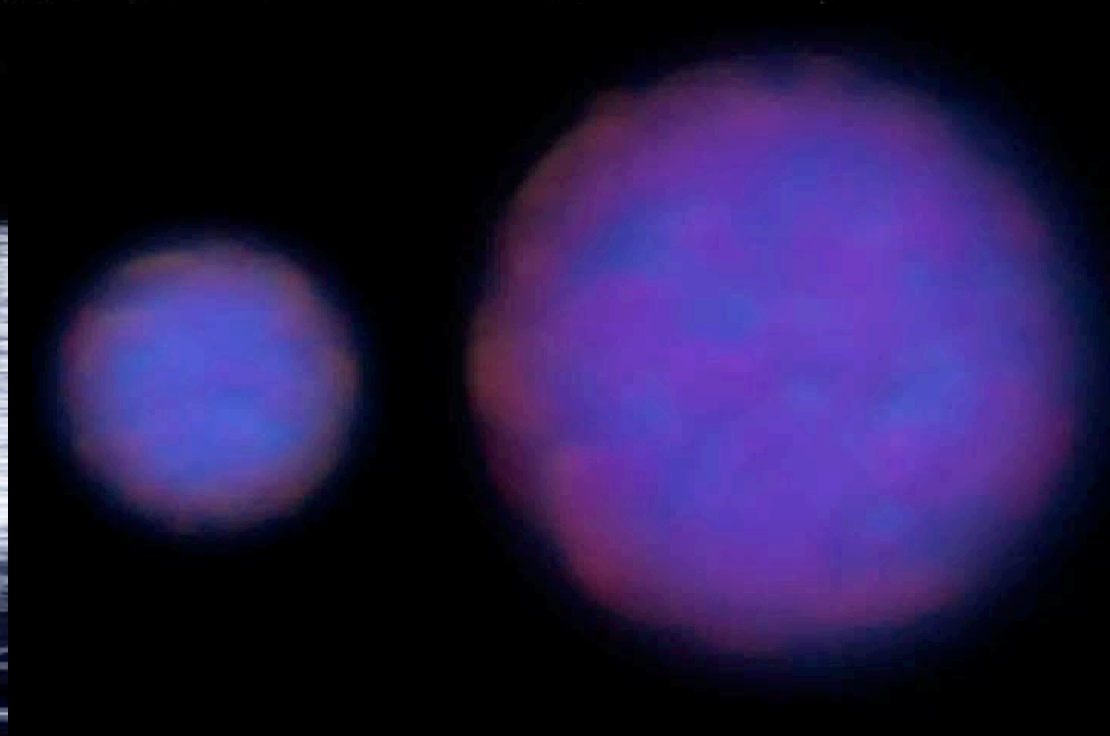
Galaxy Clusters

- Smoking gun: the bullet cluster (pun intended).



Galaxy Clusters

- Bullet Cluster:



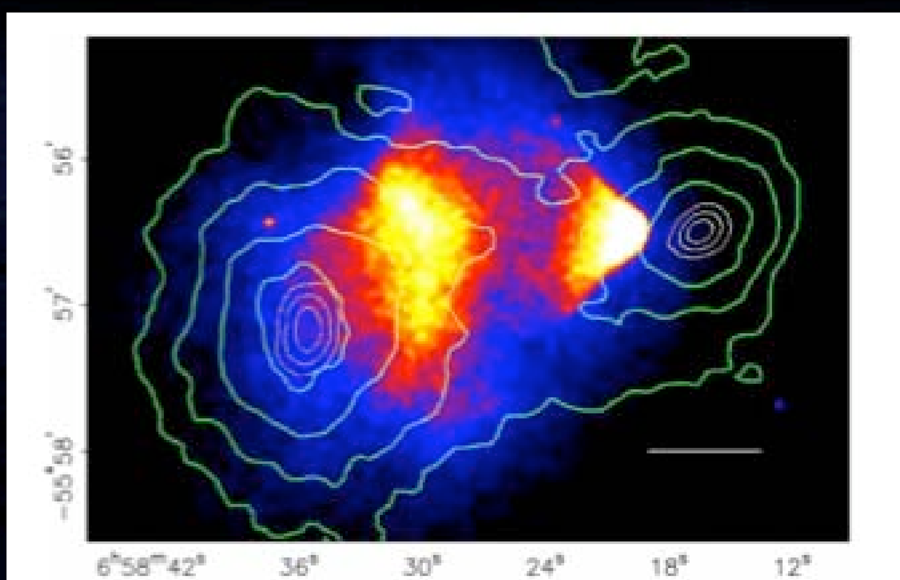
Galaxy Clusters

- Bullet Cluster:

A DIRECT EMPIRICAL PROOF OF THE EXISTENCE OF DARK MATTER *

DOUGLAS CLOWE[1], MARUŠA BRADAČ[2], ANTHONY H. GONZALEZ[3], MAXIM MARKEVITCH[4,5], SCOTT W. RANDALL[4], CHRISTINE JONES[4], AND DENNIS ZARITSKY[1]

ApJ Letters in press



- Weak lensing analysis provides matter contours, X-ray baryonic.
- DM:baryonic ~ 7:1.
- Constrain self-interacting cross section: $\sigma/m < 1\ cm^2\ g^{-1}$

Cosmology

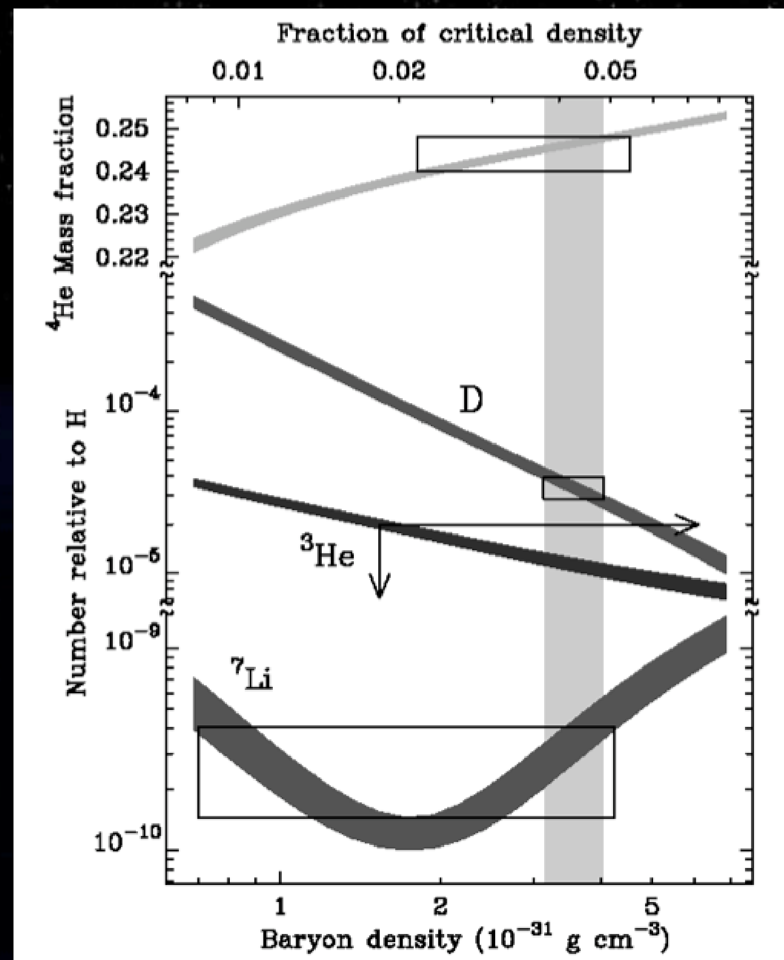
- Good evidence from:
  - Big Bang Nucleosynthesis
  - Cosmic Microwave Background
  - Gravitational Lensing

Big Bang Nucleosynthesis

- Following Maxwell-Boltzmann distribution of protons and neutrons, can compute relative ratio.
- Using nuclear reaction rates, can compute relative abundances of light elements.
- Calculate rate for deuterium synthesis, and higher-mass elements up to Be.

Big Bang Nucleosynthesis

- Abundances of light elements known from theory.
- Measure ratio of light element(s) to H.



Cosmic Microwave Background

- CMB photons from surface of last scattering.
- Density fluctuations left imprint on CMB, creating anisotropies.
- Sensitive to Ω_B, not just Ω_M.

Cosmic Microwave Background

- Compute autocorrelation function of temperature anisotropies.
- First peak highly sensitive to Ω.
- Other peaks sensitive to baryon fraction.

Cosmic Microwave Background

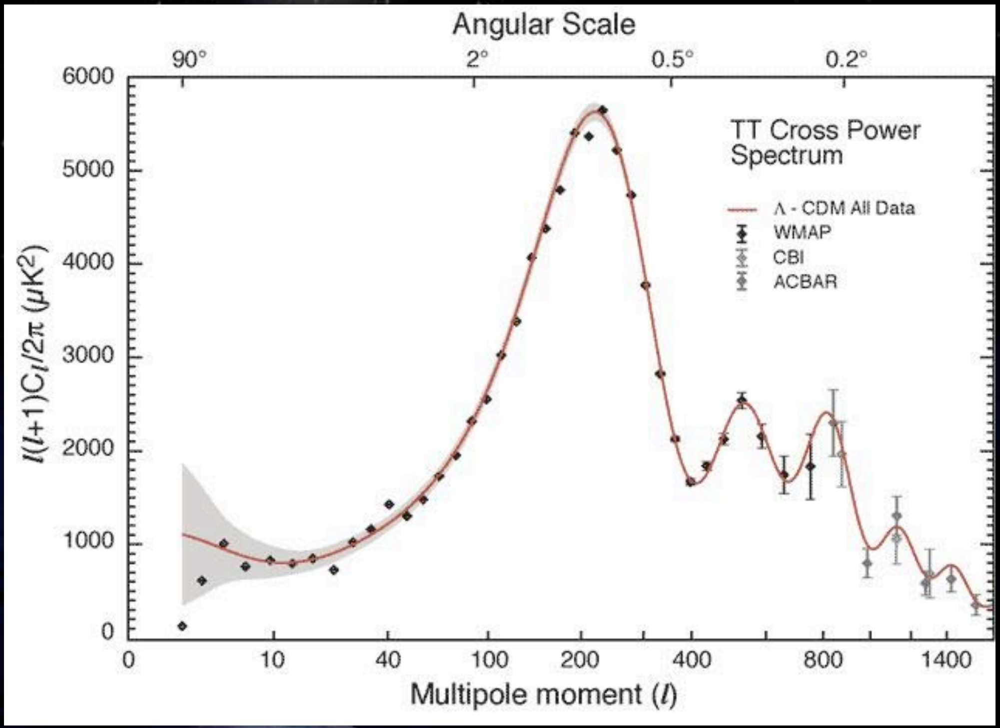
- Temperature autocorrelation function:

$$\frac{\delta T(\hat{x})}{T} = \sum_{l=2}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta, \phi)$$

$$C(\theta) = \left\langle \frac{\delta T(\hat{x}_1)}{T} \frac{\delta T(\hat{x}_2)}{T} \right\rangle$$

$$C(\theta) = \frac{1}{4\pi} \sum_{l=2}^{\infty} (2l+1) C_l P_l(\hat{x}_1 \cdot \hat{x}_2)$$

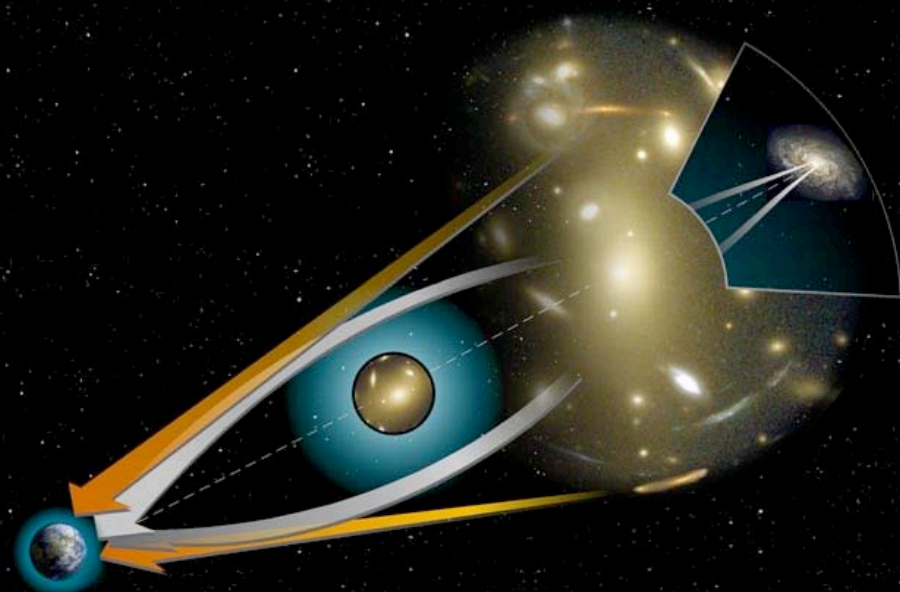
Cosmic Microwave Background



- Left of peak - from dark matter.
- Right of peak - photons and baryons (acoustic oscillations).
- Peak is from maximal compression of photon-baryon fluid.
- Peak sensitive to curvature of universe (should be ~ 1 degree).

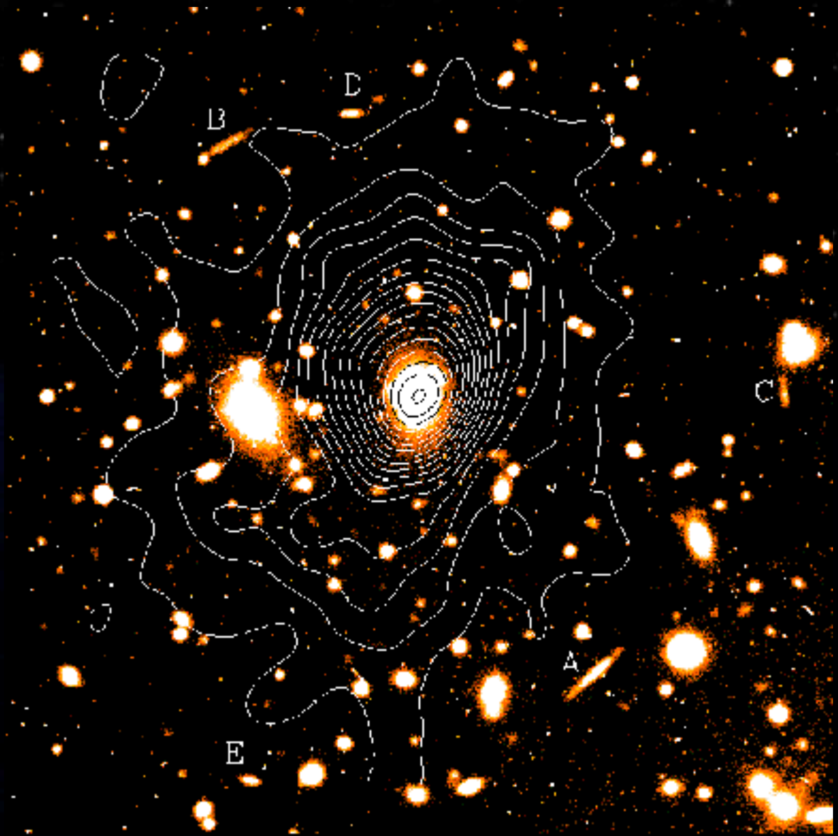
Gravitational Lensing

- Background light sheared by foreground matter distribution.
- Direct probe of dark matter.



Gravitational Lensing

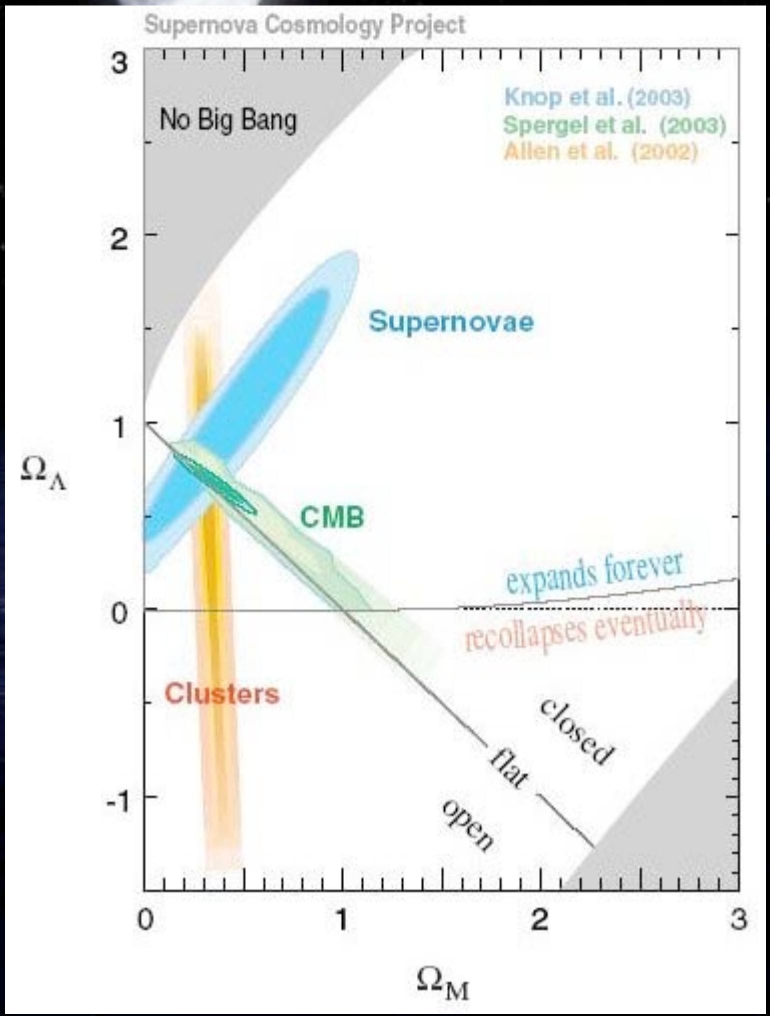
- Can combine with other data (such as optical, X-ray, etc) to infer dark matter.



Results from Cosmology

- Different methods are sensitive in different ways.
- Combine measurements to break degeneracy of cosmological parameters.
- Achieve $\Omega_B \approx 0.044$, $\Omega_M \approx 0.27$, $\Omega_{tot} \approx 1$.

Results from Cosmology



- SN, CMB, Clusters provide different constraints on cosmological parameters.
- Combining information strongly implies $\Omega_M \sim 0.3$

What else could it be?

- Baryonic dark matter?
  - MACHOs - such as failed stars, black holes, etc.
  - Could theoretically account for rotation curves.
  - Fail with Ω_B from BBN, CMB.
  - Would expect microlensing signal.
- Neutrinos?
  - Particle physicists like it since they know they exist.
  - Too hot, cannot form gravitational wells.

What else could it be?

- Modified Newtonian Dynamics?
  - In 1980s, new approach: change gravity.
  - Approach limit of Newtonian gravity for large accelerations, a^2/a0 = g.

$$a_0 \approx 2 \times 10^{-8} h_{50}^2 (P/P_0)^{-1} cm\ s^{-2}$$

  - Worked when there were large uncertainties.
  - Now, need different constant for each cluster.
  - Bullet cluster?

Conclusions

- Dark matter idea around since 1930s.
- Evidence from various scales:
  - Galaxies: rotation curves, velocity dispersion
  - Galaxy clusters: velocity dispersion, X-rays, SZ Effect
  - Cosmology: large scale structure, BBN, CMB, weak lensing
- Other theories cannot explain everything seen.