Bernard Sadoulet
Dept. of Physics /LBNL UC Berkeley
UC Institute for Nuclear and Particle
Astrophysics and Cosmology (INPAC)

Search for Dark Matter

Lecture 1: The dark side of the universe

An old problem: Dark Matter 1933

Observed at a variety of scales

The uninvited guest: Dark Energy 1998

Acceleration of the universe expansion => $p \approx -\rho$

The standard model of cosmology

Most of the dark matter is not baryonic

Rough Outline of Lecture Series

Lect. 1: The Dark Side of the Universe

Dark Matter

Dark Energy

"Standard" model of Cosmology

Lect. 2: Thermal particle candidates

Light neutrinos: cosmological limits on the mass

Weakly Interactive Massive Particles: generic properties

Lect. 3+4: WIMP detection

Elastic scattering: strategies and current results

Indirect detection through annihilation products

Lect. 5: Non thermal candidates

Axions, WIMPZILLAS

Do we understand gravity?

The extravagant universe

How can we experimentally help

The Dark Side of the Universe

Last 10 years of cosmology

- >99% of the energy in the universe is dark
- 96% appears to be in new forms of matter/energy
  - And we have no clue!

Fundamental problem in Cosmology

- Always the risk for some Astrophysics confusing the issue
- However increasing precision of cosmological information
  + increasing ability to disentangle "Gastrophysics"

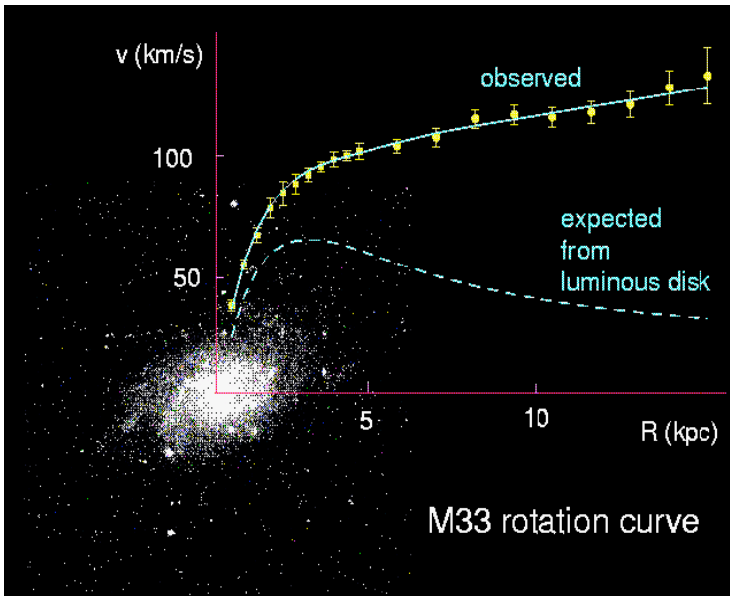
Deeply related to Fundamental Physics

- Particle Physics (supersymmetry, neutrinos, baryogenesis)
- Gravity / Additional dimensions

Obviously central problem in science!

Dark Matter on Galaxy scales 1

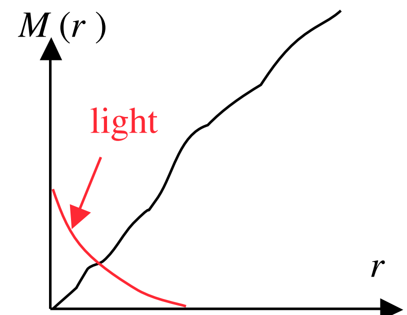
Spiral galaxies



For spherical stationary distribution

$$\frac{v^2}{r} = G\frac{M(r)}{r^2}$$

$v^2 = \text{constant}$ => enclosed mass $M(r) \propto r$



True for hundreds of galaxies

Non flat rotation curves linked to tidal interaction

Non spherical corrections small and ad hoc

Elliptical galaxies

Similar evidence: Star velocity dispersion

Temperature of x ray gas

Globular clusters

Dark Matter on Galaxy scales 1

Amount?

Measure mass M by rotation curves/ virial method, and luminosity L

$$\rho = \left\langle \frac{M}{L} \frac{dL}{dV} \right\rangle \approx \left\langle \frac{M}{L} \right\rangle \left\langle \frac{dL}{dV} \right\rangle \quad \Rightarrow \quad \Omega = \frac{\left(\frac{M}{L}\right)_{\text{sun unit}}}{1500h}$$

Luminosity Function dL/dV

Galactic Halos $M/L>30h \Rightarrow \Omega_m > .02$

lower limit!

Distribution

Dark matter(mass) does not appear to trace light!

More or less spherical halos ≠ disk

polar rings, x ray emission

Some dwarf galaxies seem to have lost most of their gas

Probably also explains lack of visible sub-halo structure

but seen in mini-lensing

Controversy about cusp at the center

Predicted by low resolution cold dark matter models

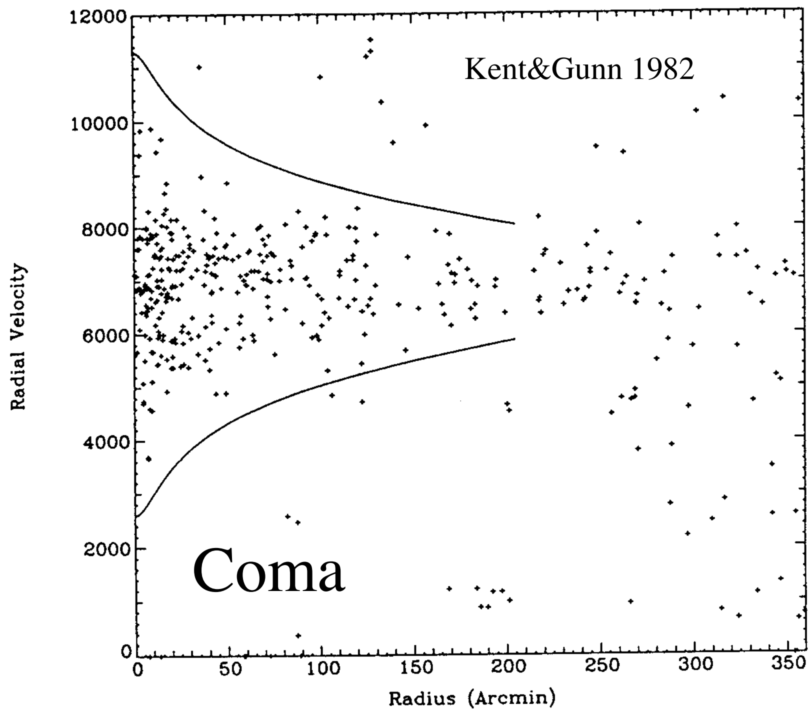
+ initial problem observation accuracy

New simulations appear less cuspy, + experimental variability

$$\rho(r) \propto \frac{1}{r\left(1+\frac{r}{r_s}\right)^2}$$

Dark Matter in Clusters 1

1)Virial velocity

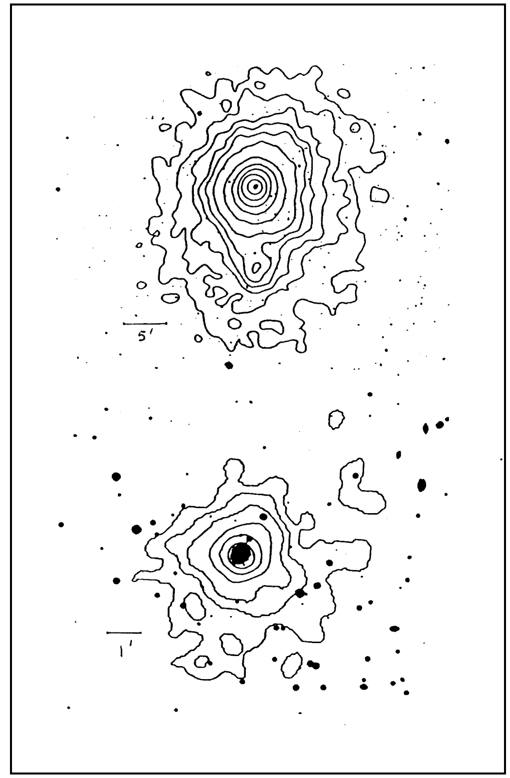


$$\langle K \rangle = -\frac{1}{2}\langle W \rangle$$

2)X ray gas

Mass in gas>> mass in stars

Abell 85, at two different resolutions (top with the Einstein Satellite IPC, bottom with the HRS). (From W. Forman and C. Jones, 1982.)



$$\langle 3/2 k_B T \rangle \approx -\frac{1}{2}\langle W \rangle$$

or better

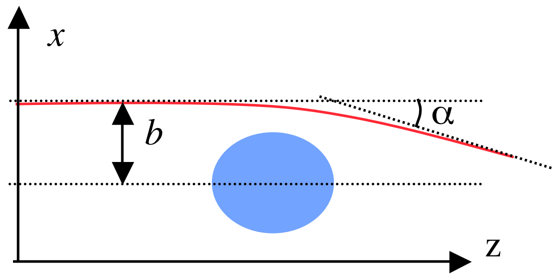
$$\text{Hydrodynamic equilibrium}: \rho_T(\vec{r}) = \sqrt{-\frac{\nabla_{\vec{r}}^{\ 2} p\left[\rho_b(\vec{r}), T_e(\vec{r})\right]}{4\pi G}}$$

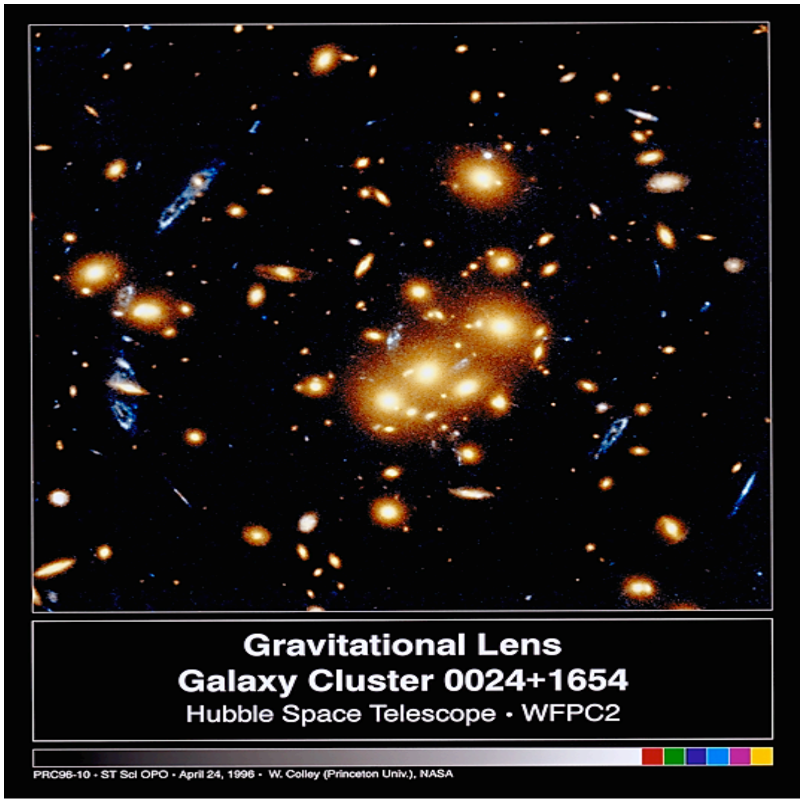
Also Sunyaev Zel'dovich up-scattering of Cosmic Microwave photons

Dark Matter in Clusters 2

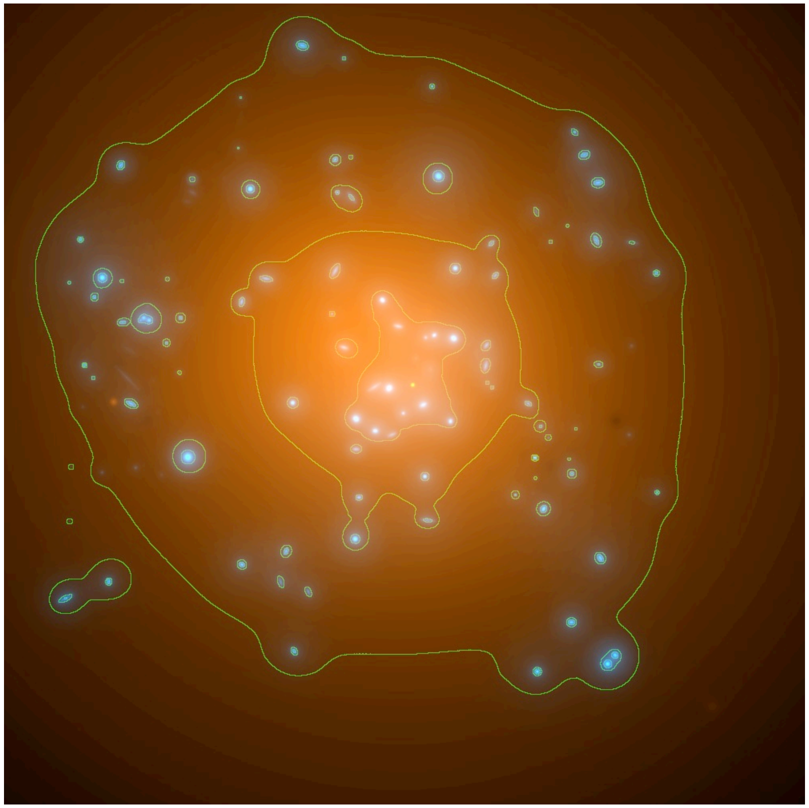
3) Gravitational lensing

$$\alpha = \frac{2}{c^2}\int_{-\infty}^{+\infty} dz \frac{\partial \varphi}{\partial x}$$





CL0024+1654



(Dark Matter) Mass reconstruction

Dark Matter in Clusters 3

Concordance

Virial velocities | > 10 times more mass than in gas (>> stars)

X ray intensity+temperature

Sunyaev Zel'dovich+T_g

Gravitational lensing | => same depth of potential (±factor 2)

Note: some discrepant systems but usually appear not completely relaxed after recent merger.

=>Amount

Clusters *M/L>225h* => Ω_m >.15

Distribution

Similar distribution of dark matter and gas: diffuse

$$\rho(r) \propto \frac{1}{r\left(1+\frac{r}{r_s}\right)^2}$$

Cusp controversy also:

- Original CDM predictions of Navarro,Frenk,White not confirmed
- In particular in 1 cluster: radial arc seen by VanThieu, R.Ellis (02)incompatible with cusp
- Can be destroyed by mergers/dynamic friction

Dark Matter in Clusters 4

Clusters +Nucleosynthesis give an upper limit for Ω_m!

Coma baryon inventory (S. White and C. Frenk ApJ 379(1991) 52)

Measure M_b from stars and gas and M_t from x rays

The ratio M_b/M_t should be representative of the background ratio

Correction for baryon enhancement in collapse (<1.4)

$$\left(\frac{M_b}{M_t}\right)_{\text{background}} \equiv \frac{\Omega_b}{\Omega_m} \geq 0.015 + 0.08 h^{-\frac{3}{2}}$$

Stars X ray gas

Use of the primordial nucleosynthesis to fix Ω_b. (Upper limits because of hidden gas)

$$\Omega_m \leq \frac{0.02}{h^2} \frac{1}{\left(0.015 + 0.08 h^{-\frac{3}{2}}\right)} \approx 0.3$$

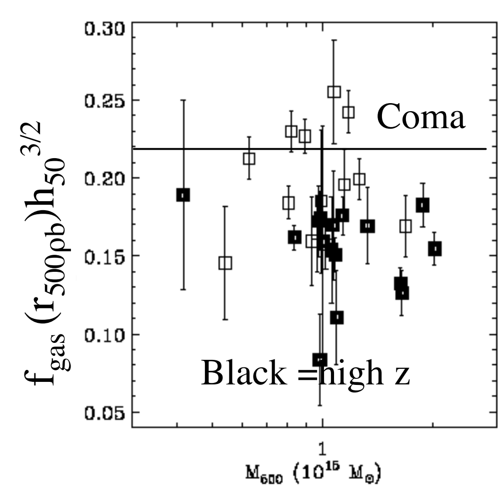
Other clusters ?

Should be the same!

Ex: 36 clusters from ROSAT

S Ettori, A.C Fabian astro-ph/9901304

Unfortunately wrong cosmology(Ω_m=1, Ω_Λ=0)



Appear constant to ± 20%

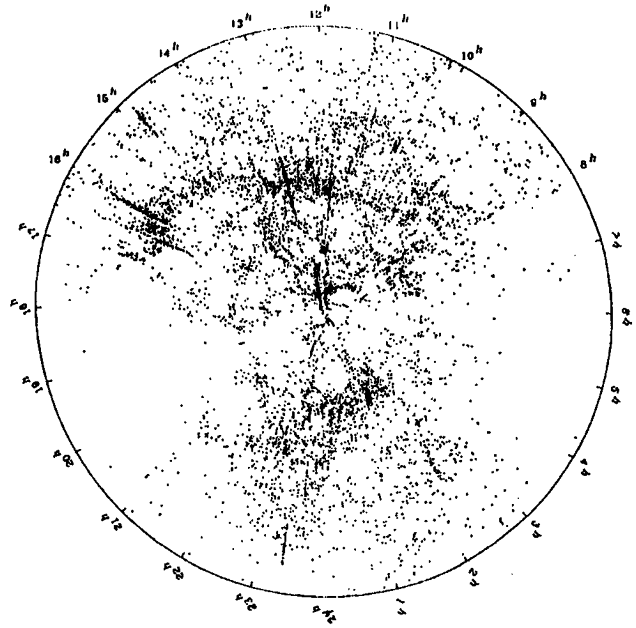
If no hidden baryon,

$$\Omega_m = 0.29 \pm .05$$

Dark Matter at Large Scale 1

Filamentary structure

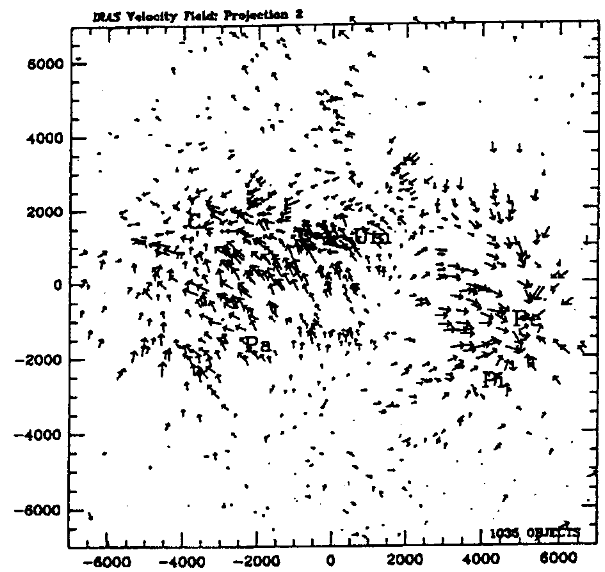
Plot a radial distance a redshift



J. Huchra and M. Geller, 1989

Streaming velocity field

take off Hubble expansion



M. A. Strauss and M. Davis, 1987
result of a model fitting IRAS galaxy density and radial velocity

General idea:given observed density fluctuations, the gravitational forces needed either to form bubbles or to accelerate galaxies to this speed over the age of the universe require relatively high Ω.

+ Redshift dependence, e.g., of clusters

Dark Matter at Large Scales 2

Peculiar velocities

Starting with $\delta\rho = \rho_m - \langle \rho_m \rangle$ it can be shown easily (e.g. Peebles 92)

$$\vec{v}(\vec{r},t_o) = \underbrace{\frac{2}{3}\frac{1}{\Omega_{mo}H_o}}_{\text{effective time}} f \underbrace{\left(-\vec{\nabla}_r \int \frac{G\delta\rho(\vec{r}',t_o)}{|\vec{r}'-\vec{r}|} d^3\vec{r}'\right)}_{\text{current acceleration}} \quad \text{with } f \approx \Omega_{mo}^{\ 0.6} \approx \text{independent of } \Lambda$$

We measure $\vec{z} = \frac{H_o\vec{r}}{c}$ and the galaxy number fluctuation, $\frac{\delta n}{n}$ not $\frac{\delta\rho}{\rho_m}$

Assuming $\frac{\delta n}{n} = \mathrm{b}\,\frac{\delta\rho}{\rho_m}$ where b is the biasing factor, we obtain

$$\vec{v}(\vec{r},t_o) \propto \frac{\Omega_{mo}^{\ 0.6}}{b}\left(-\vec{\nabla}_z \int \frac{\delta n(\vec{z}',t_o)}{n|\vec{z}'-\vec{z}|} d^3\vec{z}\right)$$

Apply to

with appropriate technical tricks to deal with redshift space, radial velocities

1) *Our velocity* with respect to microwave background
2) *Radial peculiar velocities*
3) *Flattening* of radial velocities around clusters <= pull (Redshift distortion)

$$\beta = \Omega_m^{\ 0.6}/b = \begin{matrix} 0.5-0.7 & \text{Infrared b} \approx 1? \\ 0.4\text{-}0.6 & \text{Optical b} \approx 1.2? \end{matrix} \Rightarrow \Omega_m = 0.25-0.5$$

Dark Matter at Large Scale 3

Evolution of clusters with redshift

Depends strongly on Ω_m!

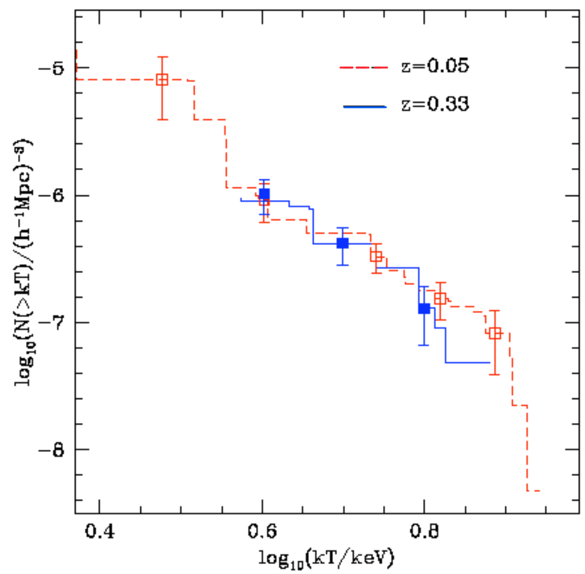
The observed weak dependence show that Ω_m<1

Eke et al. (1998)

$$\Omega_m = 0.45^{+0.18}_{-0.16}$$

N. Bahcall et al. (2002)

$$\Omega_m = 0.19^{+0.08}_{-0.07}$$

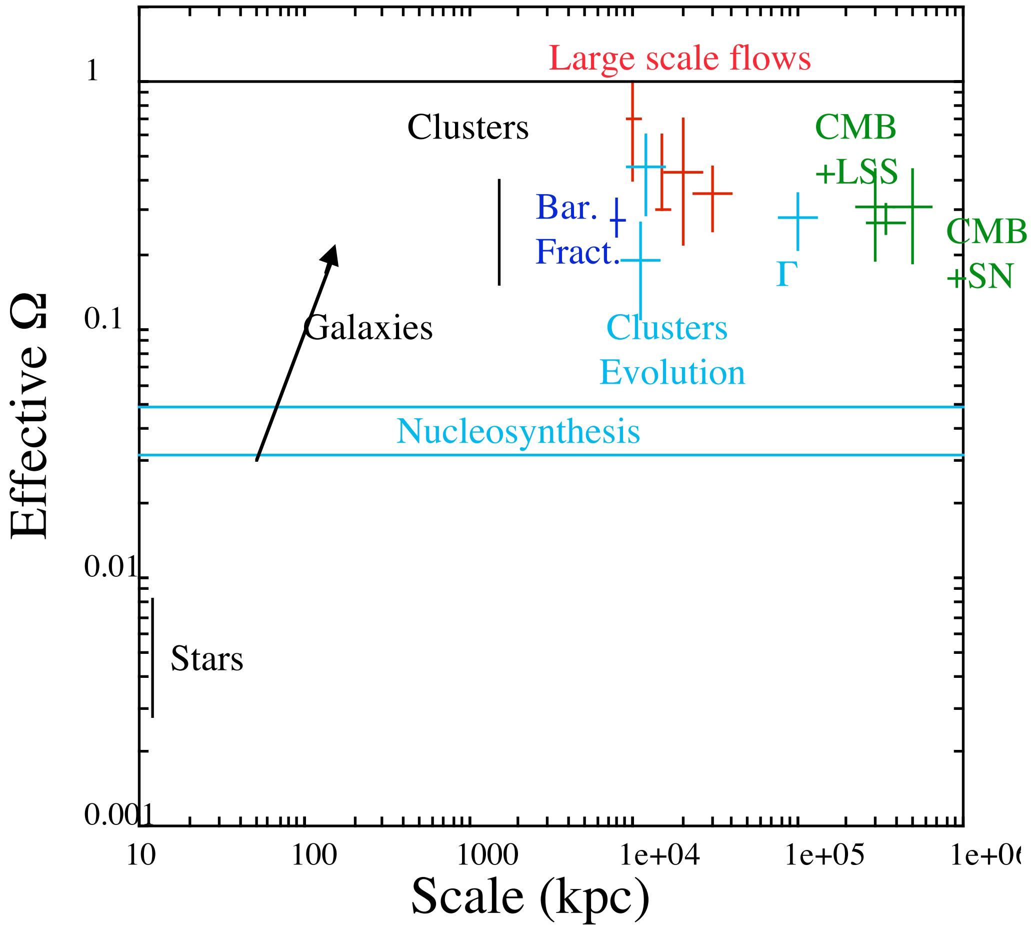


Peak of the power spectrum

Depends on the size of the horizon at the onset of matter dominance

$$\Gamma \approx \Omega_m h \approx 0.2 \pm 0.05$$

Putting All Together



2002

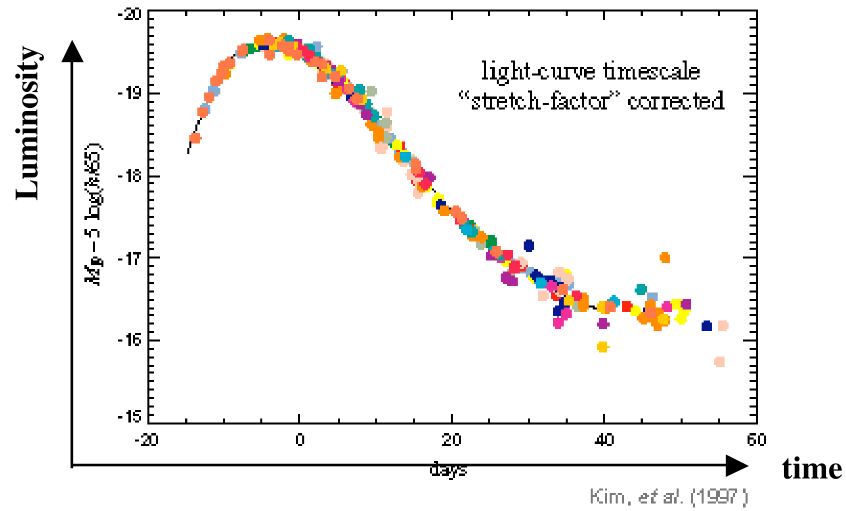
M.Turner $\Omega_m = 0.33^{+0.035}_{-0.035}$

N. Bahcall $\Omega_m = 0.20^{+0.05}_{-0.025}$

The Uninvited Guest: Dark Energy

An accelerating universe?

Supernovae Type Ia
at high redshift (2 groups)
$\Omega_m - \Omega_\Lambda$
Distant supernovae appear dimmer than expected in a flat universe



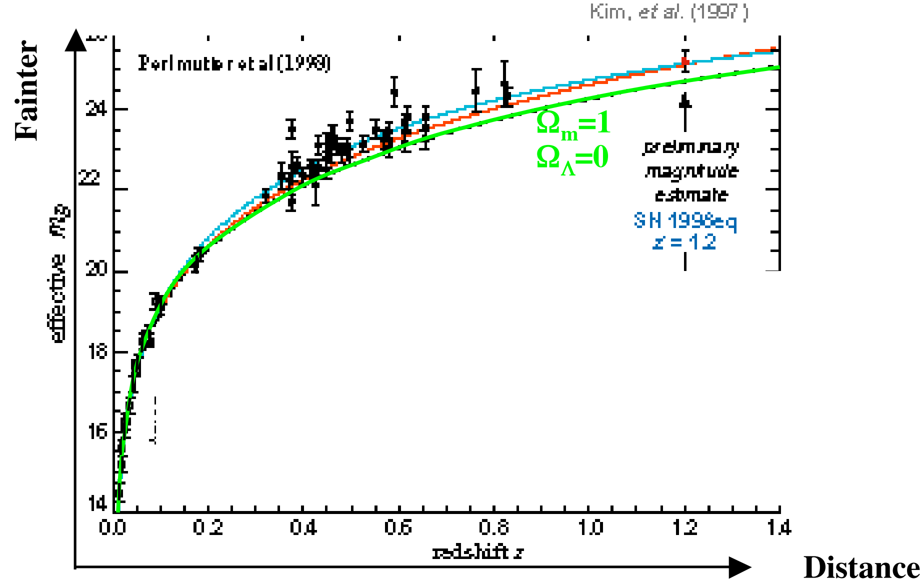
Potential problems

Are supernova properties really constant?
Dust?

Interpretation within conventional framework

Large negative pressure

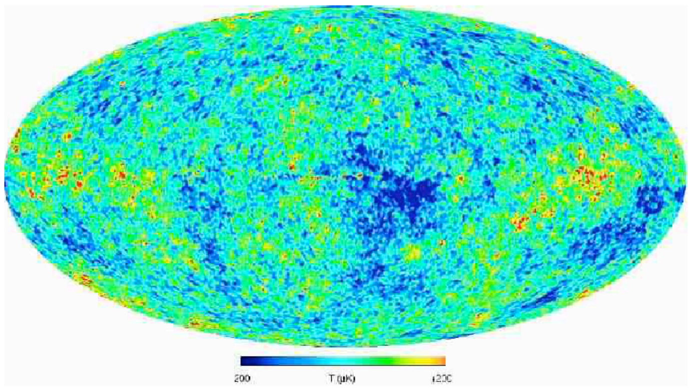
$$\underbrace{a}_{\text{acceleration}} = \frac{G}{r^2} \underbrace{\frac{1}{c^2}\left(\underbrace{u}_{\text{energy density}} + 3 \underbrace{p}_{\text{pressure}} \right)}_{\text{GR gravitational mass}} V$$

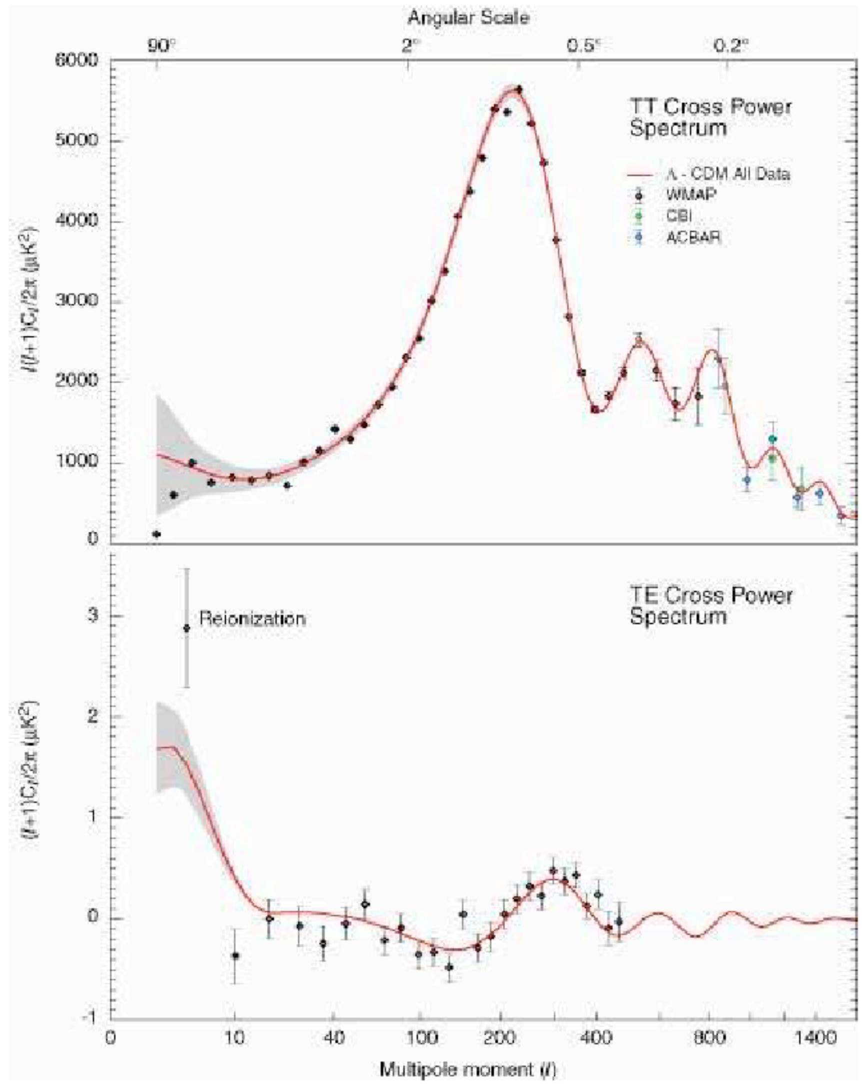


Gravity becomes repulsive!

Oscillations of the Primordial Plasma

WMAP ΔT

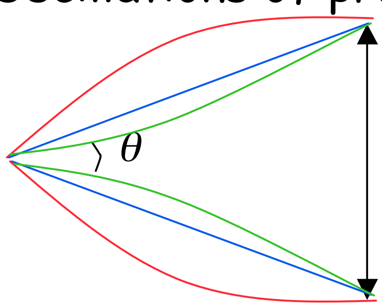




Complex pattern

Analyze into angular frequency content

Oscillations of primordial plasma

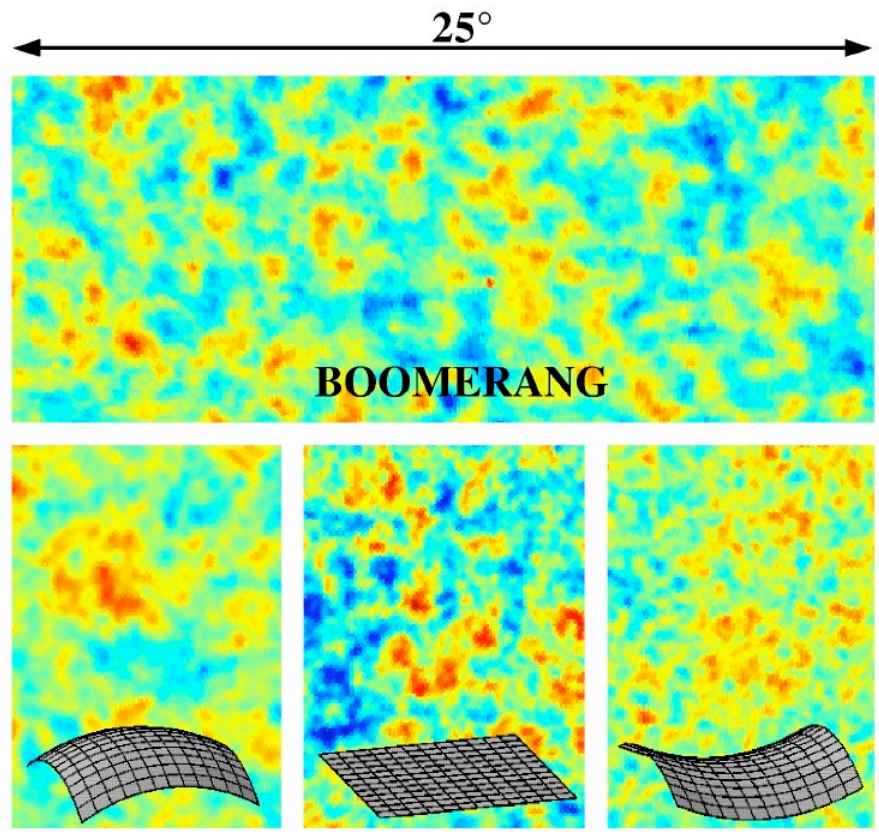


Physical dimension known

=> Measure angle => Geometry

The Geometry of the Universe

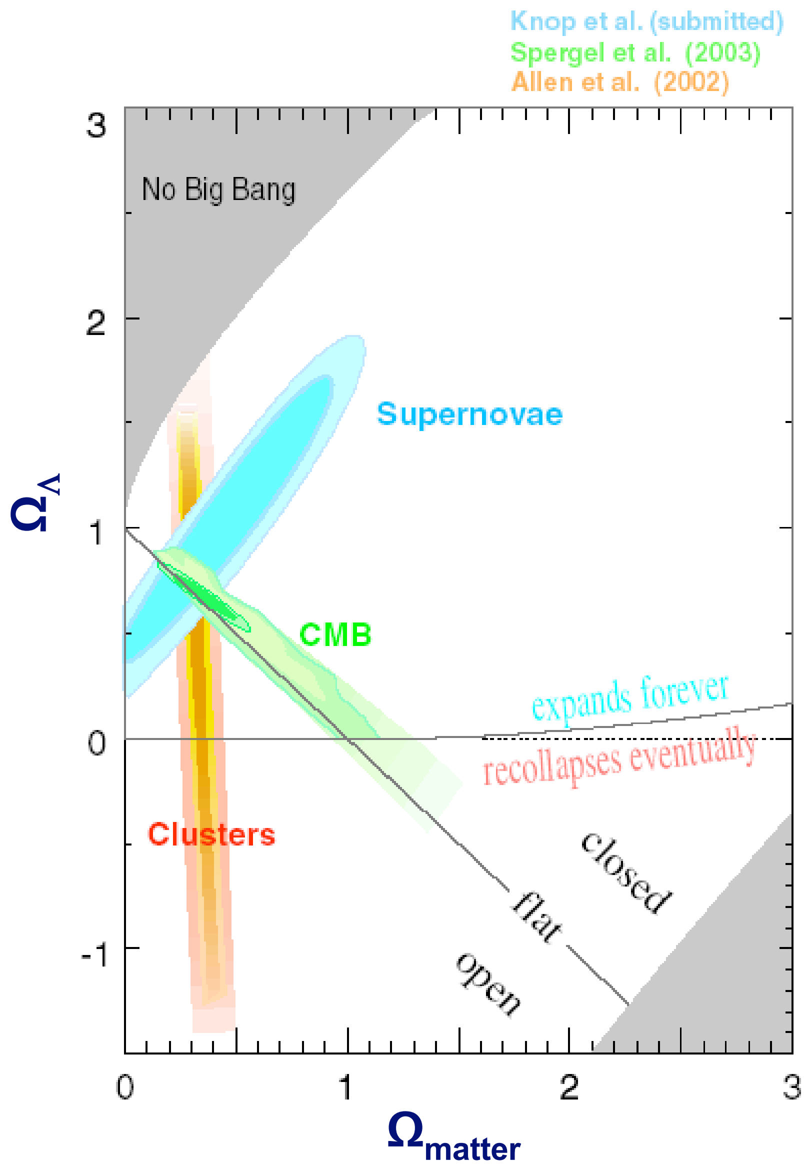
Boomerang



Angular size implies that the geodesics are straight:
=> Universe is spatially FLAT

$$\text{WMAP}: \ \Omega_{tot} = 1.02 \pm 0.02$$

Standard Model of Cosmology



Supernovae "confirmed"

by the fact that in standard cosmology we need a non clumping component which appeared late

CMBR amplitude of the acoustic peaks $\Omega_m \approx 0.3 < \Omega_{tot} \approx 1$

Upper limits on Ω_m

- Peak of the Large Scale structure power spectrum
- Baryon content of clusters

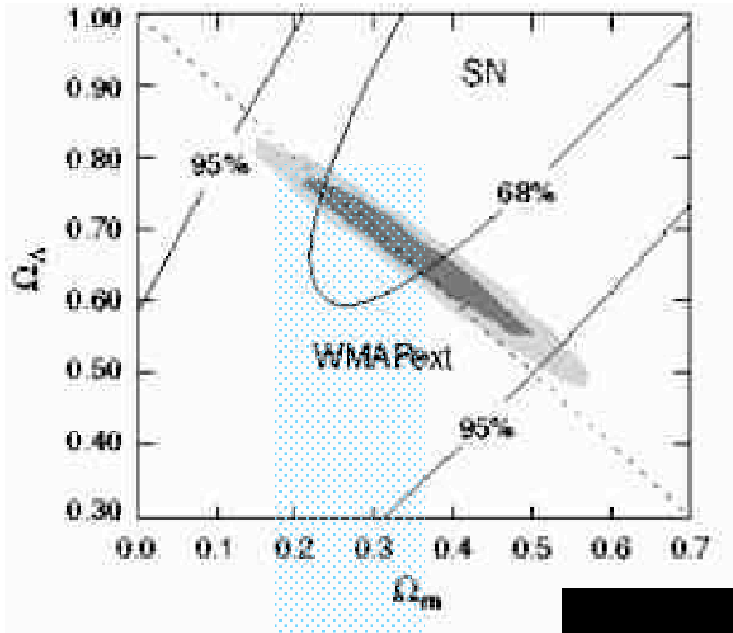
+ Nucleosynthesis $\Omega_m < 0.29 \pm 0.05$

- Cluster evolution

But this deficit $\Omega_m < \Omega_{tot}$ does not imply acceleration ≠SN

The Cosmic Mix

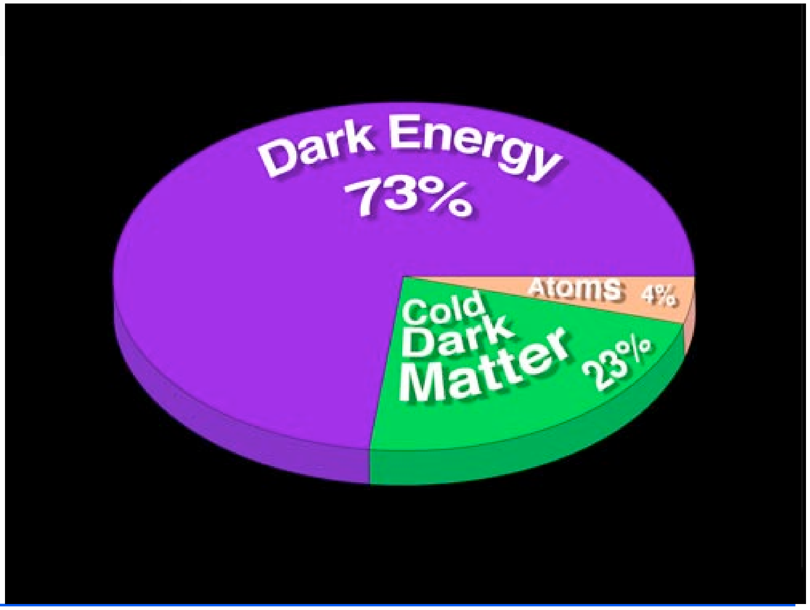
Zooming in



WMAP + flat :
$\Omega_m = 0.27 \pm 0.04$
$\Omega_\Lambda = 0.73 \pm 0.04$

Taking into account amounts of baryons

Nucleosynthesis (5 D/H systems) $\Omega_b h^2 = 0.020 \pm .002$
Cosmic Microwave Background $\Omega_b h^2 = 0.024 \pm .001$
=> $\Omega_b = 0.04 \pm 0.008$ rms



Evidence for Non Baryonic Nature 1

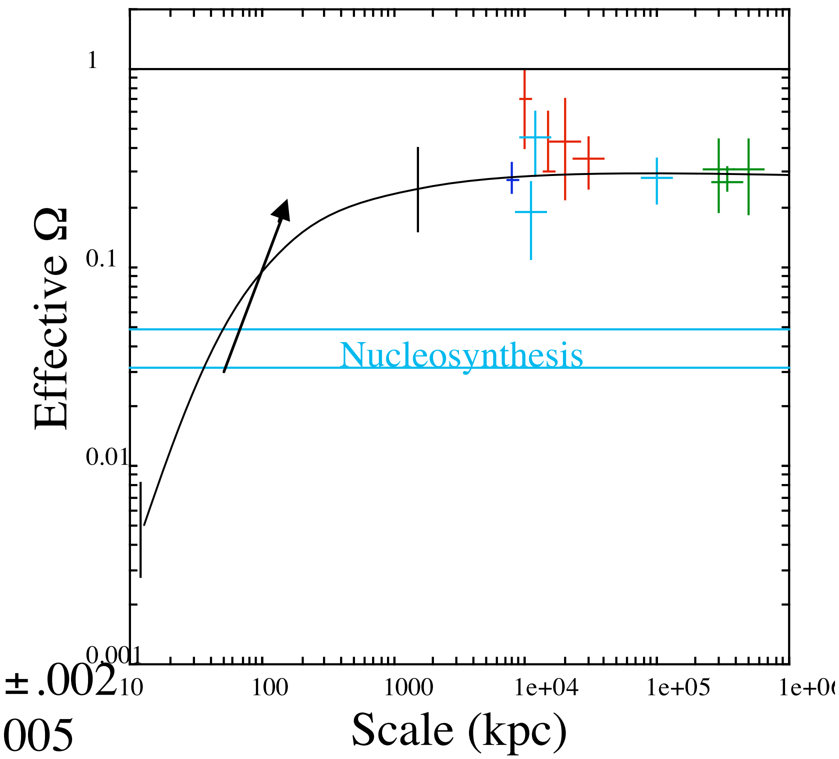
1. Effective Ω_m vs. Ω_b

LSS: Various estimates of Ω_m at large scale. e.g 2002

$$\text{M.Turner} \quad \Omega_m = 0.33^{+0.035}_{-0.035}$$

$$\text{N. Bahcall} \quad \Omega_m = 0.20^{+0.05}_{-0.025}$$

≠Two independent estimations of the average density in baryons



Nucleosynthesis (5 D/H systems) $\Omega_b h^2 = 0.020 \pm .002$

Cosmic Microwave Background $\Omega_b h^2 = 0.02 \pm .005$

=> $\Omega_b = 0.04 \pm 0.008$ rms

dominated by uncertainty on H_o

Large discrepancy (6-7σ's!)

CMB alone requires non baryonic dark matter

Ratio of even/odd peaks

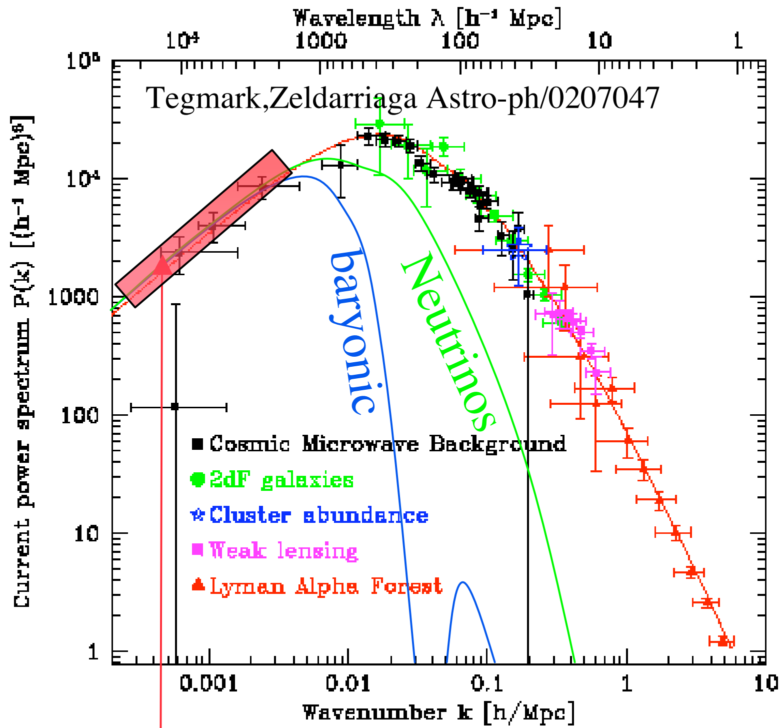
WMAP + adiabatic + flat + no tensor :

$$\left.\begin{array}{r}\Omega_b h^2 = 0.024 \pm 0.001 \\ \Omega_m h^2 = 0.14 \pm 0.02\end{array}\right| \Rightarrow \approx 6\sigma$$

Evidence for Non Baryonic Nature 2

2. Comparison of CMB ΔT/T and large scale structure

CMB Power spectrum +
adiabatic fluctuations +spatial flatness



WMAP+ACBAR+CBI+2° Field +Lyman$_\alpha$
+ Λ CDM

$$\Omega_m h^2 = 0.135 \begin{matrix} +.008 \\ -0.009 \end{matrix}$$

$$\Omega_b h^2 = 0.0224 \pm 0.0009$$

> 12 σ

$$h = 0.71 \begin{matrix} +.04 \\ -0.03 \end{matrix}$$

$$n_s\left(0.05\,\mathrm{Mpc}^{-1}\right) = 0.93 \pm 0.03$$

$$\sigma_8 = 0.84 \pm 0.04$$

$$\tau = 0.17 \pm .06 \text{ (Temperature Polarization cross correlation)}$$

We need non baryonic dark matter for structure formation!

Evidence for Non Baryonic Nature 3

3. Implausible efficiency of hiding baryons

e.g. Baryonic content of clusters: ≈ 13% × $(h/0.72)^{-1.5}$

If totally baryonic, we would need to hide >87% of baryons in MACHOs/black holes: We do not know any "star" formation process which is that efficient!

We expect the baryons to warm up!

Where are the Dark baryons?

At high redshift, compatible with Ly_α forest

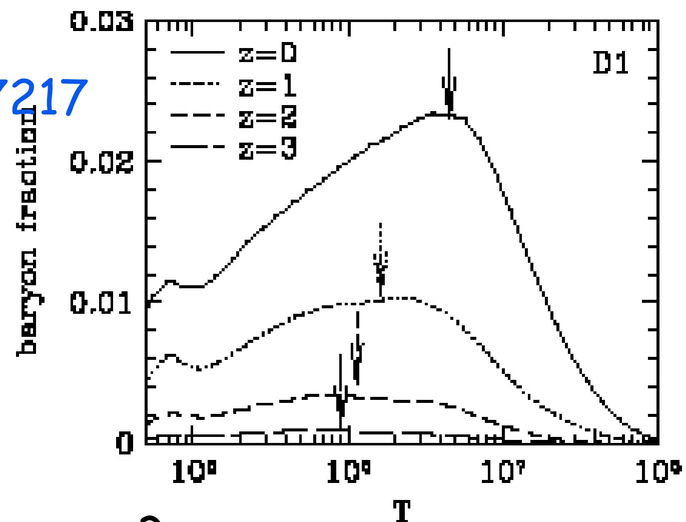
At low redhift: probably in warm hot gas 10^5K <T<10^7K

Davé, Cen, Ostriker et al Astro-ph/0007217

Heated by shocks.

Low density contrast δ≈30

around dense objects, filaments



Challenging (foreground)

XMM? High resolution Xray spectroscopy?

Evidence for Non Baryonic Nature 4

4. We do no see enough dark baryons to give $\Omega_m \approx 0.3$

Independently from nucleosynthesis

Non ionized gas

Gunn Peterson Astr. Phys. J. 142(1965) 1633

No trough

Totally ionized gas

≠ y parameter CMBR

X ray extragalactic background

Dust

Infrared radiation

H snowballs

Would evaporate

Very Massive Objects

Very fast supernovae, large black holes gobbling up metals to prevent contamination

≠ IR DIRBE observations

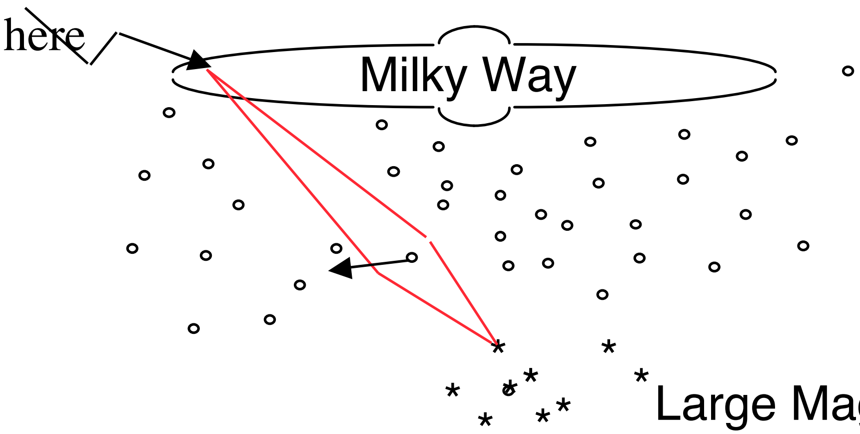
MACHOs

No!...

MACHOs

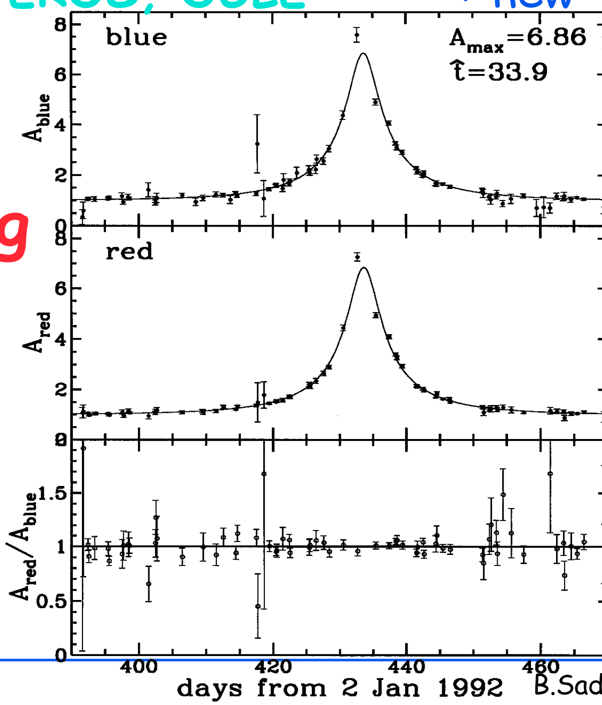
Massive Compact Halo Objects

The basic idea



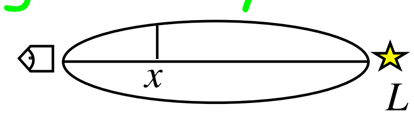
3 main collaborations

CfPA MACHO, EROS, OGLE + new groups and M31



Clear demonstration of microlensing

Degeneracy between mass, distance and velocity

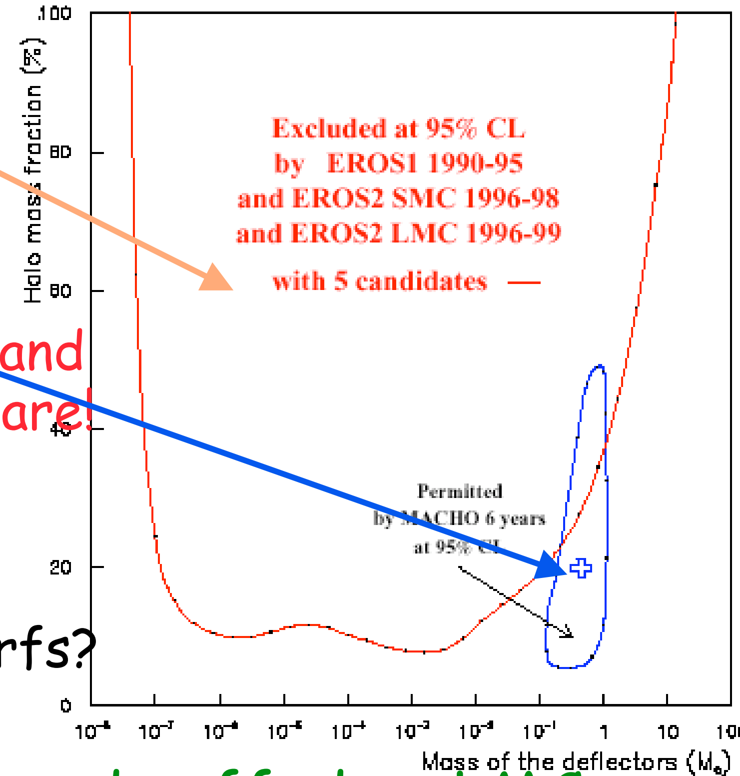


$$\tau \propto \int \rho(x) \frac{x(L-x)}{L} dx \qquad \Delta t \propto \sqrt{\frac{mx(L-x)}{v_\perp^2 L}}$$

MACHOs

No small LMC/SMC duration events

=> Dark Matter≠Brown Dwarfs



Puzzling long duration LMC events

- Degeneracy between velocity,distance and mass We do not know where the lenses are!
- Even if distributed as halo:
  MACHO Group result: fraction≈20%
  8% ≤fraction≤50% 95% CL
  Mass is 0.5 M_{sun}: Stars! Old white dwarfs?
  may have been detected!

- Also compatible with no MACHO and puffed up LMC
  <= tidal interactions with the Milky Way
  - The few lenses whose positions are known are in the host galaxies, not in the halo!
  - Long duration events (2) towards SMC
  - Not enough events in SMC compared to LMC

2nd generation: **EROS II, OGLE II, SuperMachos ,Stellar Interferometric Mission**

Dark Matter Appears Physical 1

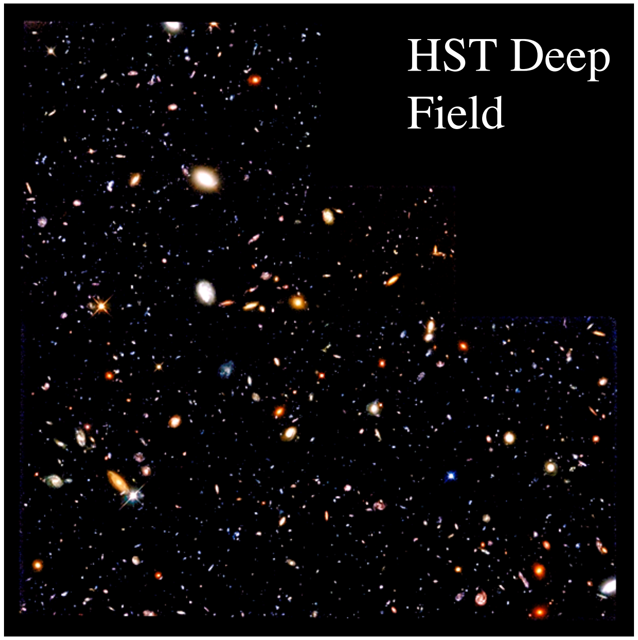
≠ **Recurring arguments dismissing dark matter**

Not a problem of obscuration

reemission on the infrared

Multiplicity of systems argues against *ad hoc elliptical* geometries to explain rotation curves and would not explain virial velocities

Non baryonic dark matter is an essential ingredient of our understanding of structure formation



Galaxy scale: disk + halo

Intermediate scale: hierarchical merging

Power spectrum

Amazing first approximation

Difficulties at very small scale?

Halo substructure: may actually be a success

Cusps: likely to be combination of simulation inaccuracy and astrophysics

Too early to imply new properties of dark matter particles

e.g. self interacting, fuzzy or decaying

Angular momentum

C. Frenk: examples of the many crises that CDM has weathered

Dark Matter Appears Physical 2

Not a simple failure of our theory of gravity

e.g. Modified Newtonian Dynamics (Milgrom)

clever way to deal with multiplicity of scale by working with acceleration: gravity will become stronger below a certain threshold

Milgrom M., 1995, Astrophys. J. 455, 439. & 1997, Astrophys. J. 478, 7.

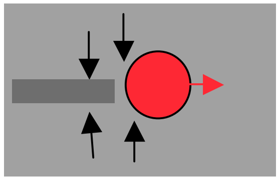
Sanders, R.H., 1996, Astrophys. J. 479, 659,1997, Astrophys. J., 480, 492

but

large number of systems where light do not follow mass

difficulty with dwarfs/low surface brightness galaxies

increasing evidence for the need for dynamic friction



wake effect slowing down large masses

e.g forming bulges by mergers

More fundamentally not a relativistic theory

=> No possibility for rigorous calculations

A map of the territory!

Current candidate explanations: systematic mapping