The Abdus Salam
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SUMMER SCHOOL IN COSMOLOGY AND
ASTROPARTICLE PHYSICS

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Strategies for dark matter detection

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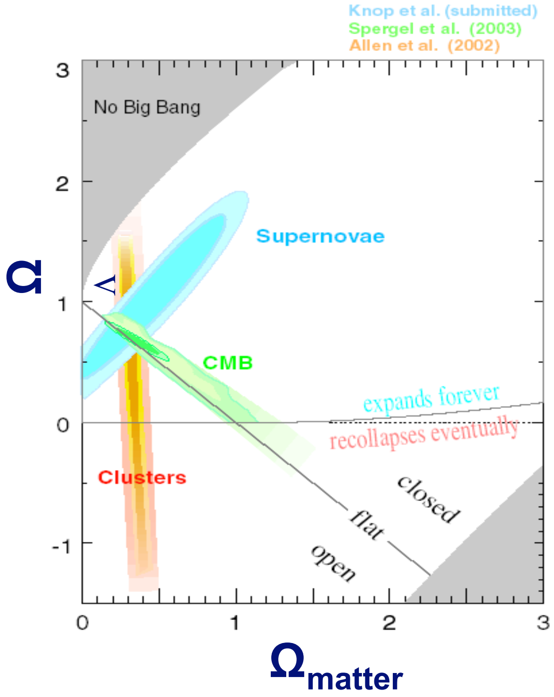
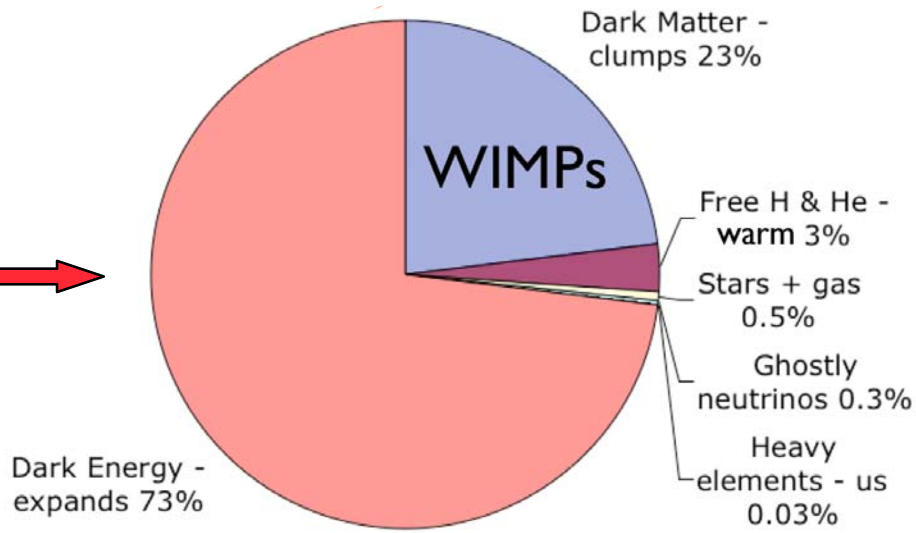
Strategies for Dark Matter Searches

Plan for the 4 lectures

Inputs from Cosmology
Inputs from Gravity

A surprising but consistent picture

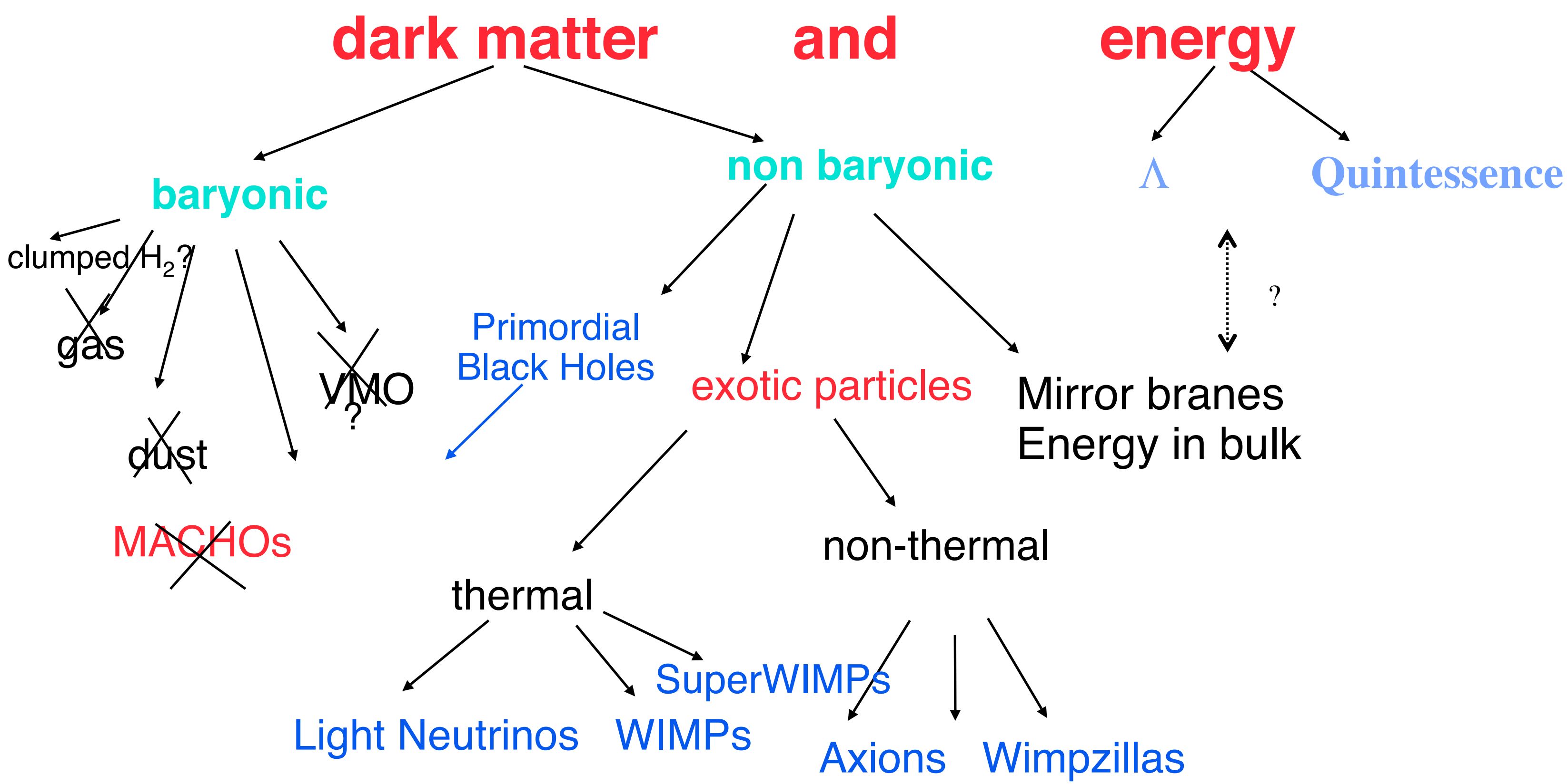




This lecture series: Deciphering the nature of dark matter

A map of the territory!

Current candidate explanations: systematic mapping



Strategies

What generic class(es) to look for?

Fundamental Physics

in particular ≥ 2 justifications
experimental consequences

What approach?

Privilege unambiguous information

minimize "gastrophysics"

Complementary approaches

e.g. Direct detection
Indirect detection
Colliders

What sensitivity goals?

Identify natural scale

+ fine tuning

Previous results

Cross checks

What technology?

Highly discriminative
Large amount of information: rare events ≠ pathological configuration
Identification of background

Highly iterative

Plan of lectures

Lecture 1: Conceptual Framework

Inputs from Cosmology

Inputs from Gravity

Lecture 2: Thermal relics

Inputs from Particle Physics

Thermal relics   Neutrinos

WIMPs

Experimental challenges and broad classes of technologies

Current situation 5 kg: phonon mediated technologies

$1.6\ 10^{-43}$ cm^2 /nucleon (Scalar a.k.a "spin independent")

-> $2\ 10^{-44}$

Lecture 3: Direct Detection of WIMPs

The next stage 25-100kg: $1\ 10^{-45}$ cm^2 /nucleon

Complementarity with the LHC

New technologies 1 ton-5ton-> $1\ 10^{-47}$ cm^2 /nucleon +directionality

Lecture 4: Indirect detection of WIMPs

+ non thermal candidates

An old puzzle: Dark Matter

Solid evidence for Dark Matter

Rotation curves in spiral galaxies
Globular clusters/ gas around elliptical galaxies
Velocity dispersion in clusters
X-ray gas in clusters
Gravitational lensing by clusters
Large scale flows
+ CMBR (if non baryonic)

Same depth of potential wells

Growth of structure

gives the best estimate of the matter density

Large scale structure $\Omega_m = 0.30 \pm 0.1$

Cosmic Microwave Back.

Primordial plasma oscillations

WMAP : $\Omega_m = 0.27 \pm 0.04$

Not obscuration

No infrared emission

nor ad hoc geometry (number of systems)

Mass, Charge, Interactions

Mass: little information from astrophysics

< few 10^6 M_{sun} <= disruption of disks

Stable $\gtrsim$ T_{Hubble}

no recent input of entropy <= CMBR

Electrically neutral

decoupling from photons

unless very heavy (e.g. CHAMPs 10^{12} Gev/c^2)

Limit on interactions

Much weaker than electromagnetic

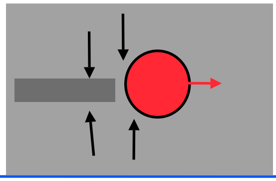
Recently: interacting dark matter => soften

Limits by merging of galaxies

observation of triaxial halos

Dynamic friction

increasing evidence for the need for dynamic



wake effect slowing down large masses

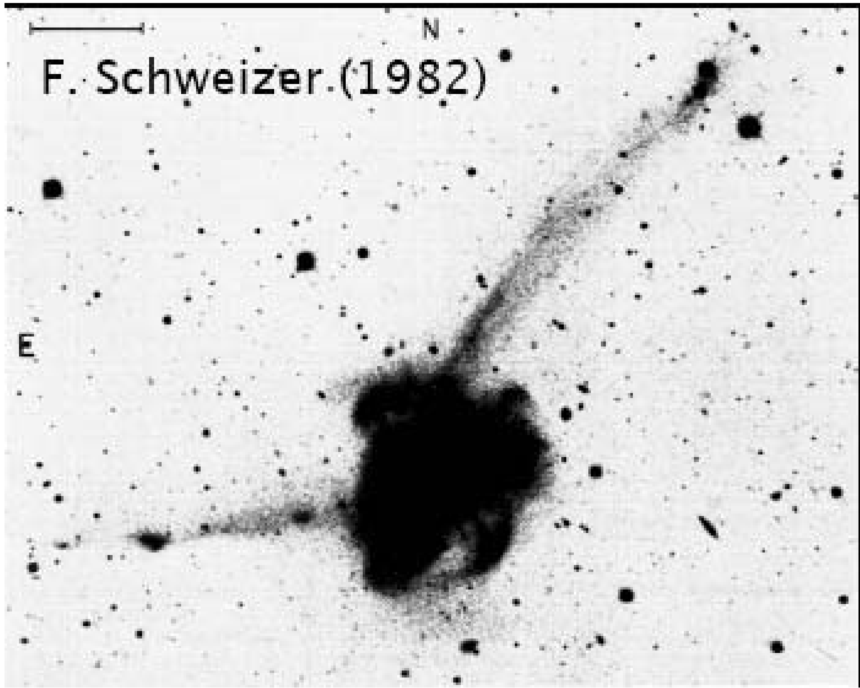
e.g forming bulges by mergers

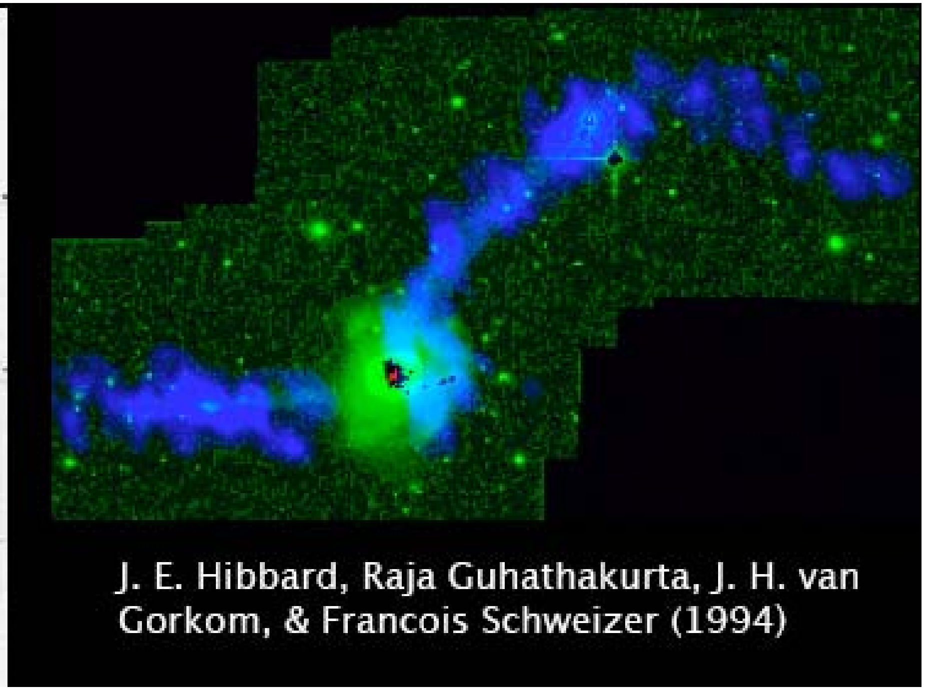
"Physicality" of Dark Matter

Merging of galaxies and formation of bulges

$R^{1/4}$ law: characteristic of elliptical galaxies. The nuclei have already completely merged. Need to effectively surrender their energy and angular momentum to their dark halos.

e.g. NGC 7252





Evidence for Non Baryonic Nature 1

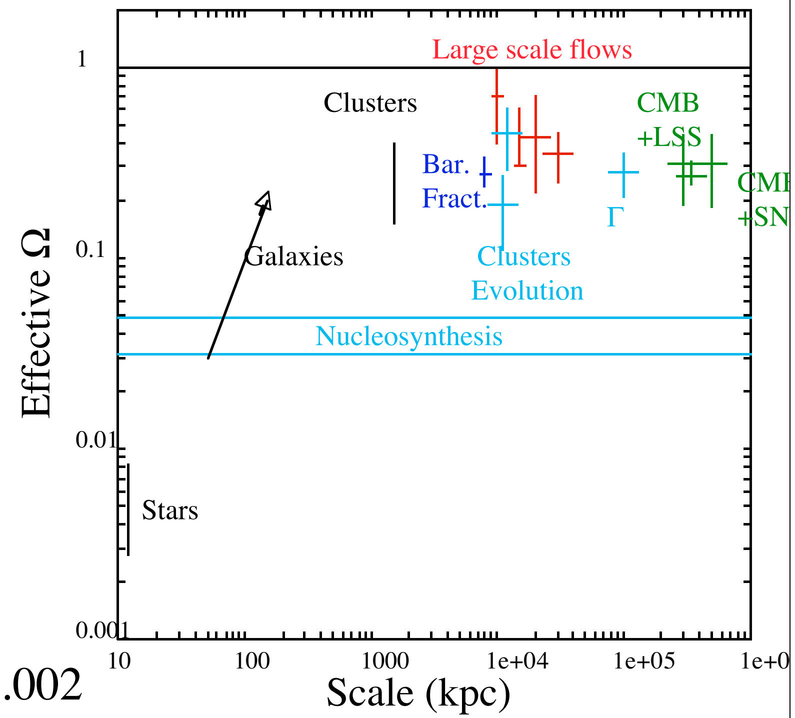
1. Effective Ω_m vs. Ω_b

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

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

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

≠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

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

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

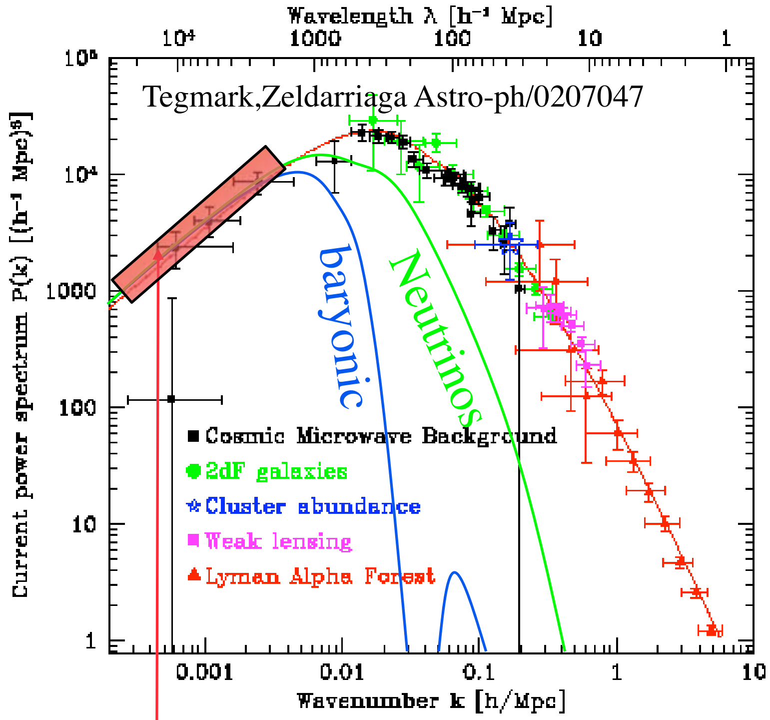
> 12 σ

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

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

$$\sigma_8 = 0.84 \pm 0.04$$

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



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_a forest

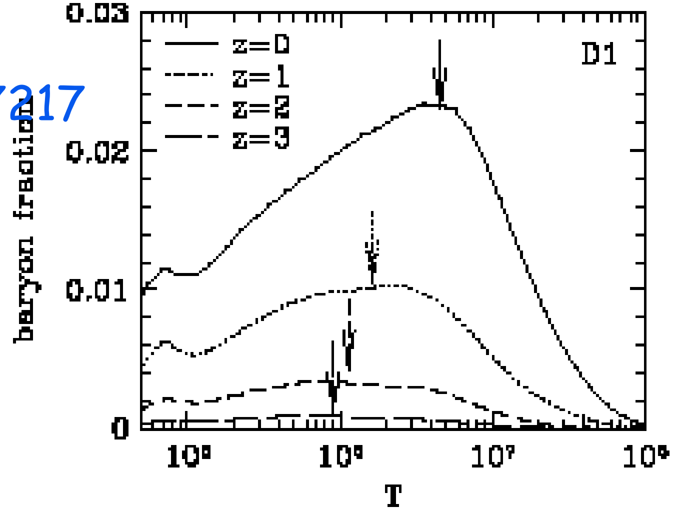
At low redhift: probably in warm hot gas 10^5K <T<10^7K

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

Heated by shocks.

Low density contrast $\delta \approx 30$

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

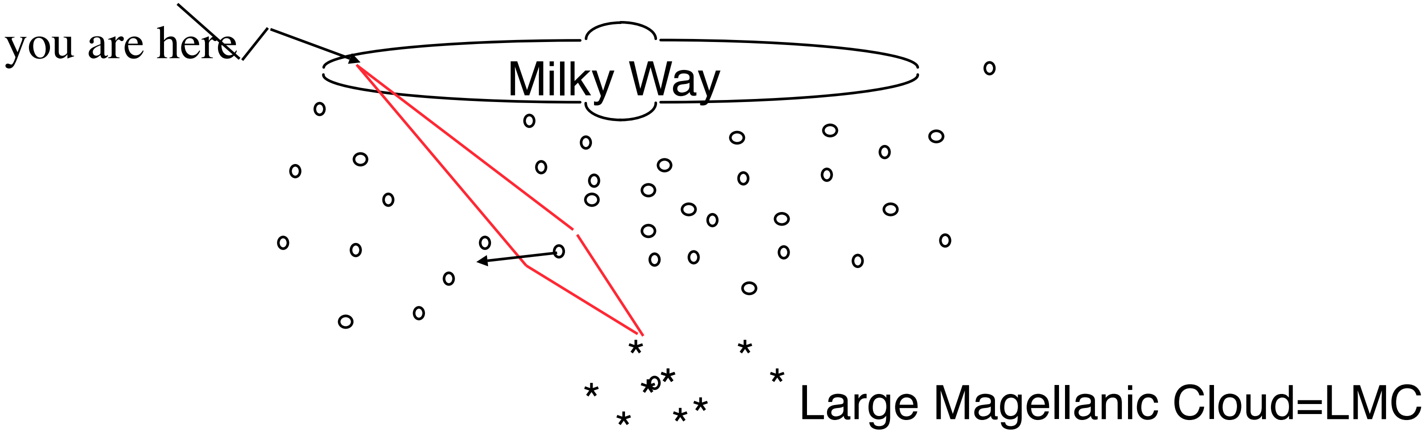
Very fast supernovae, large black holes gobbling up metals to prevent contamination
≠ IR DIRBE observations

MACHOs

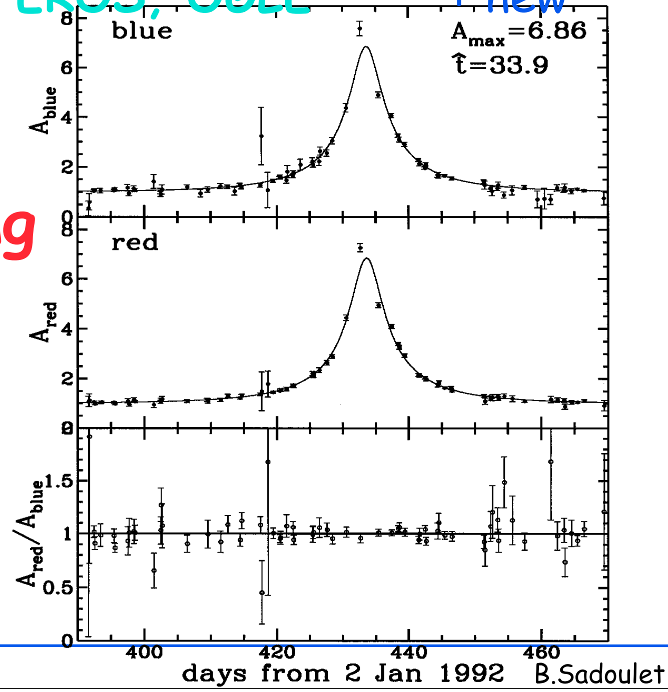
No!...

MACHOs

The basic idea

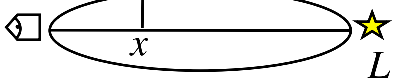


3 main collaborations CfPA MACHO, EROS, OGLE + new groups and M31



Clear demonstration of microlensing

Degeneracy between mass, distance

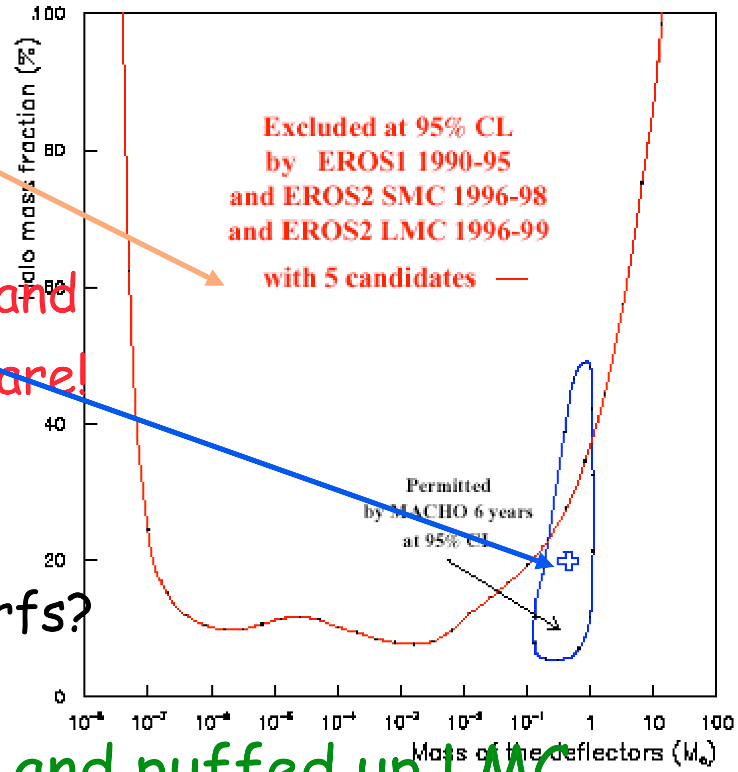


and velocity

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

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**

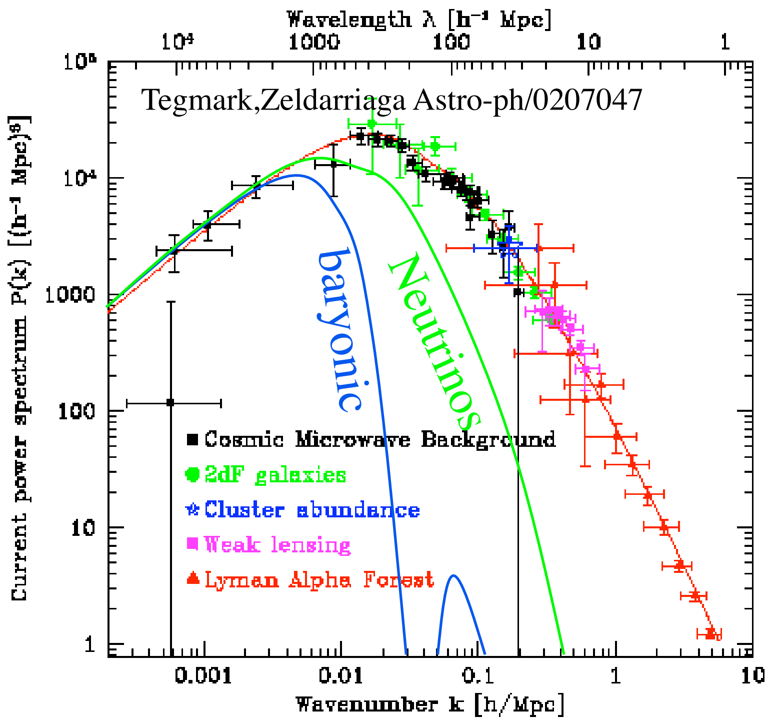
Dark Matter is cold

"Cold"

Non relativistic when comes out of the horizon ≡ time of galaxy formation

≠ light neutrinos ="Hot"

erase density fluctuations at small scale

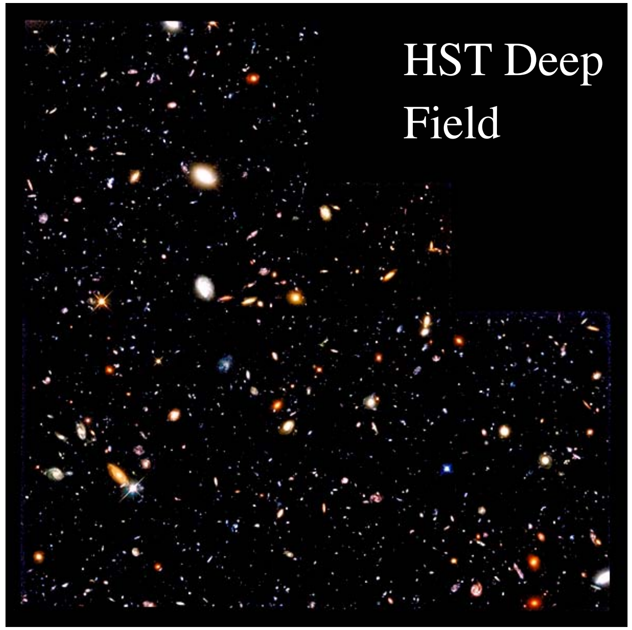


Recurrent appeal to warm dark matter

or "mixed" (Cold +hot)

to soften spectrum
Severely limited by Lyman alpha systems

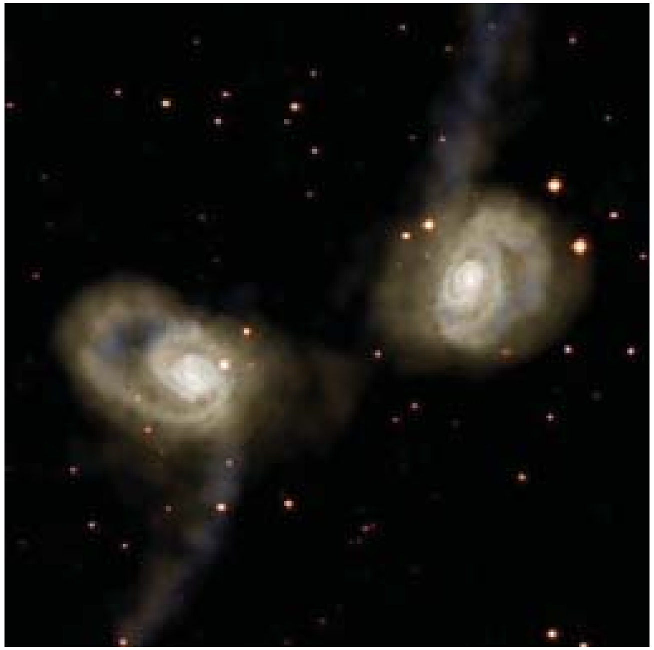
Large Scale Structure



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



Great increase in numerical accuracy

10^{10} particles

e.g.Halo substructure and merging history

Hydrodynamics (although course feedback mechanisms)

Challenges

Too peaked a distribution in center of galaxies

"Cusp problem" :Navaro-Frenk-White profile density $\approx r^{-1}$

Dwarf spheroidals : mostly underestimate of beam smearing

Low surface brightness galaxies (Blitz); when no radial motion $\approx r^{-1}$

Non-circular motions could be caused by nonspherical halos (Navarro & Hayashi).

Large galaxies?

Halo substructure <=Merging histories

"missing satellites"

Loss of gas (Sommerville)

Halo hosting statistics (Gnedin, Klypin, Kravtsov, Zentner)

=> agreement with data.

May be actually an advantage

to explain anomalous flux ratios in radio gravitational lenses (Metcalf)?

Angular momentum problem

Catastrophic loss of angular momentum in current hydrodynamics simulations => difficulty to form spiral galaxies

Formation and role of AGN?

A long history of overcoming challenges

Evolution with red shift

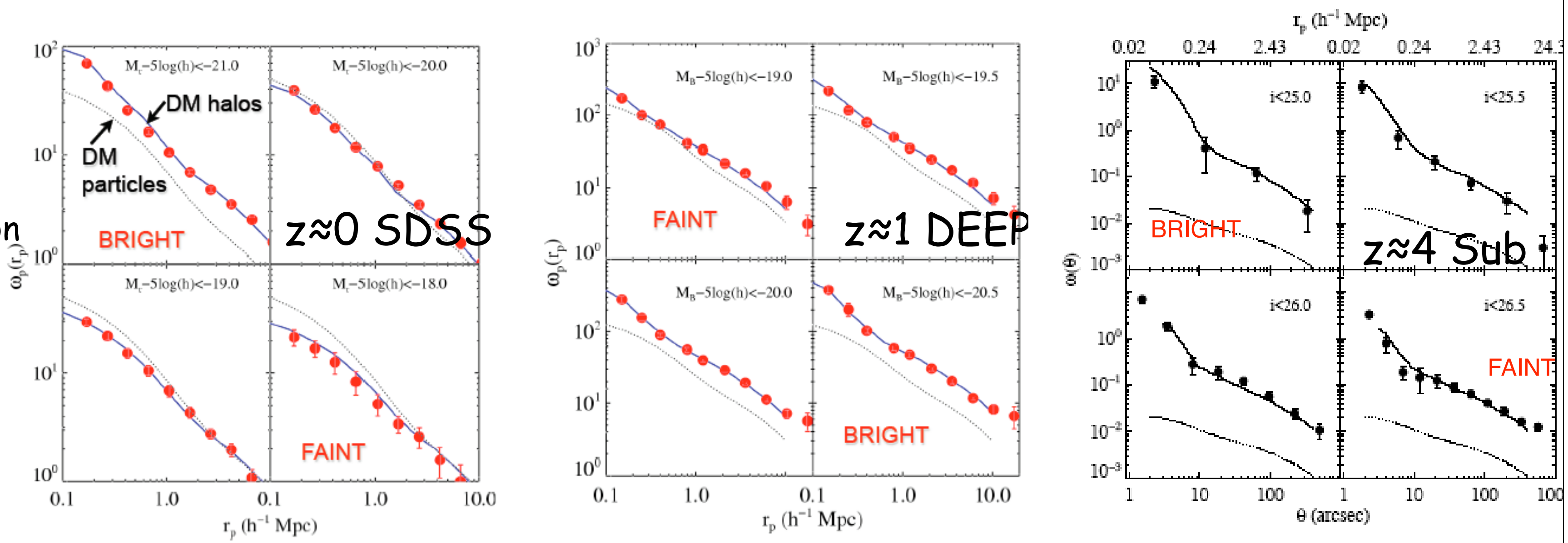
Excellent agreement on all scales

Conroy,Weschsler and Kravtsov Astro ph-05122234

Dark Matter dissipationless simulation

+simple relation between galaxy luminosities and DM halo mass

angular
2-point
correlation
function



Projected separation

Input from Cosmology

What we know:

Dark matter at a variety of scales
Mass, charge, interaction rate, dynamic friction
Non baryonic
Cold

Overall very successful model

Hierarchical merging
However:
- cusp?
- number of satellites?
- angular momentum

What we do not know:

Nature of a fundamental component of structure formation
Nature of dark energy

=> Possibility that we are dealing with epicycles?

Input from Gravity

General success of General Relativity

Tests in solar system
Tests in binary pulsars
$1/r^2$ -equivalence tests in the laboratory

Cosmology provides an excellent demonstration

Formation of structure from perturbations which were temporarily outside the horizon

Challenge from the dark energy

Perfectly OK to have negative pressure and repulsive gravity
But why so small

MOND

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

Till recently no relativistic implementation (Bekenstein)

≠large number of systems where light do not follow mass

Difficulty with dwarfs/low surface brightness galaxies
Polar rings
Increasing evidence for the need for dynamic friction in merging
IE 0657-558 Clowe, Gonzales,Markevitch APJ 604(2004) 596