MATERIA OSCURA: EVIDENZA OSSERVATIVA, RILEVANZA COSMOLOGICA E NATURA FISICA

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ABSTRACT

Assuming KNOWN physical laws,

- I first discuss OBSERVATIONAL evidence of dark matter in galaxies and clusters.
- Next, I analyze the COSMOLOGICAL RELEVANCE of these results.
- Finally, I combine this information with COSMOLOGICAL observations to draw conclusions about the AMOUNT and NATURE of the dark matter in the Universe.

1 – INTRODUCTION

All informations about the Universe are carried by photons. Of course, we do not see most of photons emitted by astronomical objects …. MOST of matter in the Universe is DARK.

Why bother? In fact, people did not. Until it become clear that most of DM is TOTALLY DIFFERENT from luminous matter.

Actually, structure formation THEORY combined with CMB OBSERVATIONS …. Universe dominated by NONBARYONIC DM.

Quite remarkably, elementary particle-physics offers REALISTIC – even if so far undetected – candidates for NBDM: axions, neutralinos, ecc.

Equally remarkably is that the NBDM scenario is in agreement with OBSERVATIONAL evidence for DM in galaxies and clusters.

Surprisingly, consistency with cosmological observations requires the existence of a still LARGER amount of DARK ENERGY i.e. dark stuff with NEGATIVE pressure producing ACCELERATED cosmic expansion.

Regretfully, elementary particle-physics offers NO natural candidates for DE.

Throughout I assume that gravity is described by general relativity with Einstein lagrangian.

2 – ASTROPHYSICAL STRATEGY

Basically 2 methods allow for the discovery of DM in galaxies and clusters.

DYNAMICAL ANALYSIS – It rests upon gravitational effects produced by DM on LUMINOUS matter. Amount and morphology of DM estimated from the dynamical behaviour of TRACERS.

Early history of dynamical analysis:

1844 (Bessel), tracer = Sirius, DM = Sirius B.

1846 (Adams, Le Verrier), tracer = Urans, DM = Neptune.

1932 (Oort), tracer = stars near the Sun, DM = local DM.

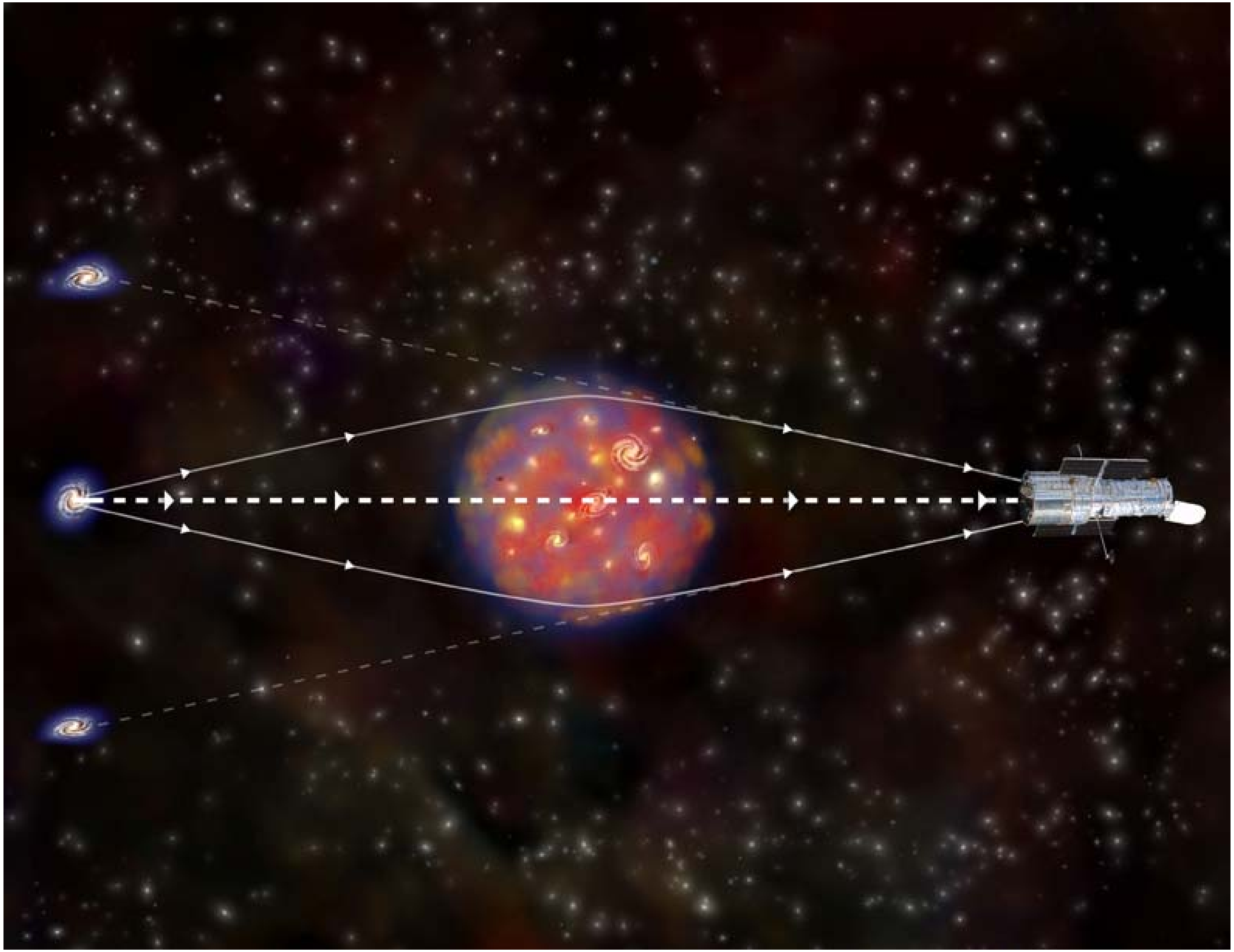
1933 (Zwicky), tracer = galaxies in Coma, DM = DM in Coma.

1936 (Smith), tracer = galaxies in Virgo, DM = DM in Virgo.

GRAVITATIONAL LENSING – Based on gravitational effects caused by DM on propagation of LIGHT. Any mass distribution gives rise to space CURVATURE …. distortion of light rays …. mass distribution acts like a LENS changing shape, brightness and number of observed images. So LENS MASS can be determined from observed properties of

IMAGES.

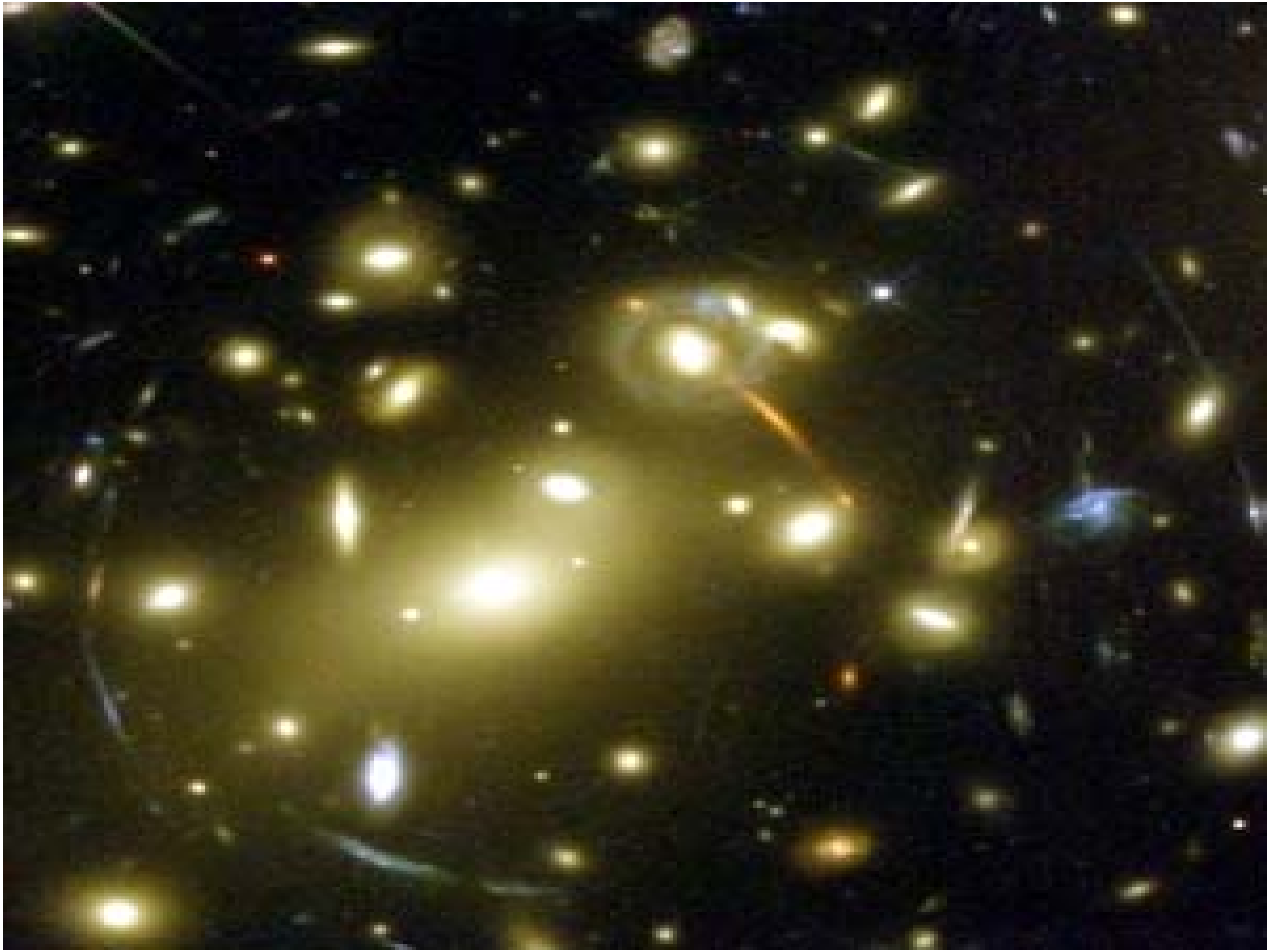
STRONG LENSING – Caustic effect. Suppose lens axially-symmetric along the optical axis. Then EINSTEIN CAUSTIC = point on optical axis beyond the lens …. image of a POINT source on Einstein caustic is EINSTEIN RING. That becomes 2 GIANT ARCS for an EXTENDED source. In either case, magnification is



DRAMATIC and observations yield LENS MASS inside Einstein ring. Now small PERTURBATION of axial symmetry …. large demagnification of 1 arc and small change in estimated mass. Hence 1 GIANT ARC is observational signature of strong lensing. Since 1986 giant arcs have been observed around clusters and elliptical galaxies. Clearly strong lensing

happens only OCCASIONALLY.

WEAK LENSING – When source not close to caustic no dramatic effect occurs. Still, images of ALL sources near projected lens position are distorted weakly but according to a COHERENT pattern. Imagine a RANDOM distribution of extended sources. NO lensing …. observed images are ISOTROPICALLY distributed ….



NO net polarization in observed pattern. Because of lensing, images are SQUEEZED along projected lens-source direction and STRETCHED along the perpendicular one …. lens surrounded by a configuration of ARCLETS with net TANGENTIAL polarization proportional to the lens MASS.

Shape of sources UNKNOWN …. statistical

study of arclets necessary to quantify net polarization and lens mass. Since 1987 arclets have been detected around clusters and isolated galaxies.

MASS-TO-LIGHT RATIOS – For galaxies and clusters I consider Q = (TOTAL mass M /optical luminosity) and q = (LUMINOUS mass m /optical luminosity). Both are expressed in solar units. q is determined from stellar evolution models without new observations and q = 6.5 – 1 along the Hubble sequence. Q can be determined by OBSERVATIONS only. Since M/m = Q/q, the knowledge of Q yields the amount of DM in a given galaxy (same for clusters).

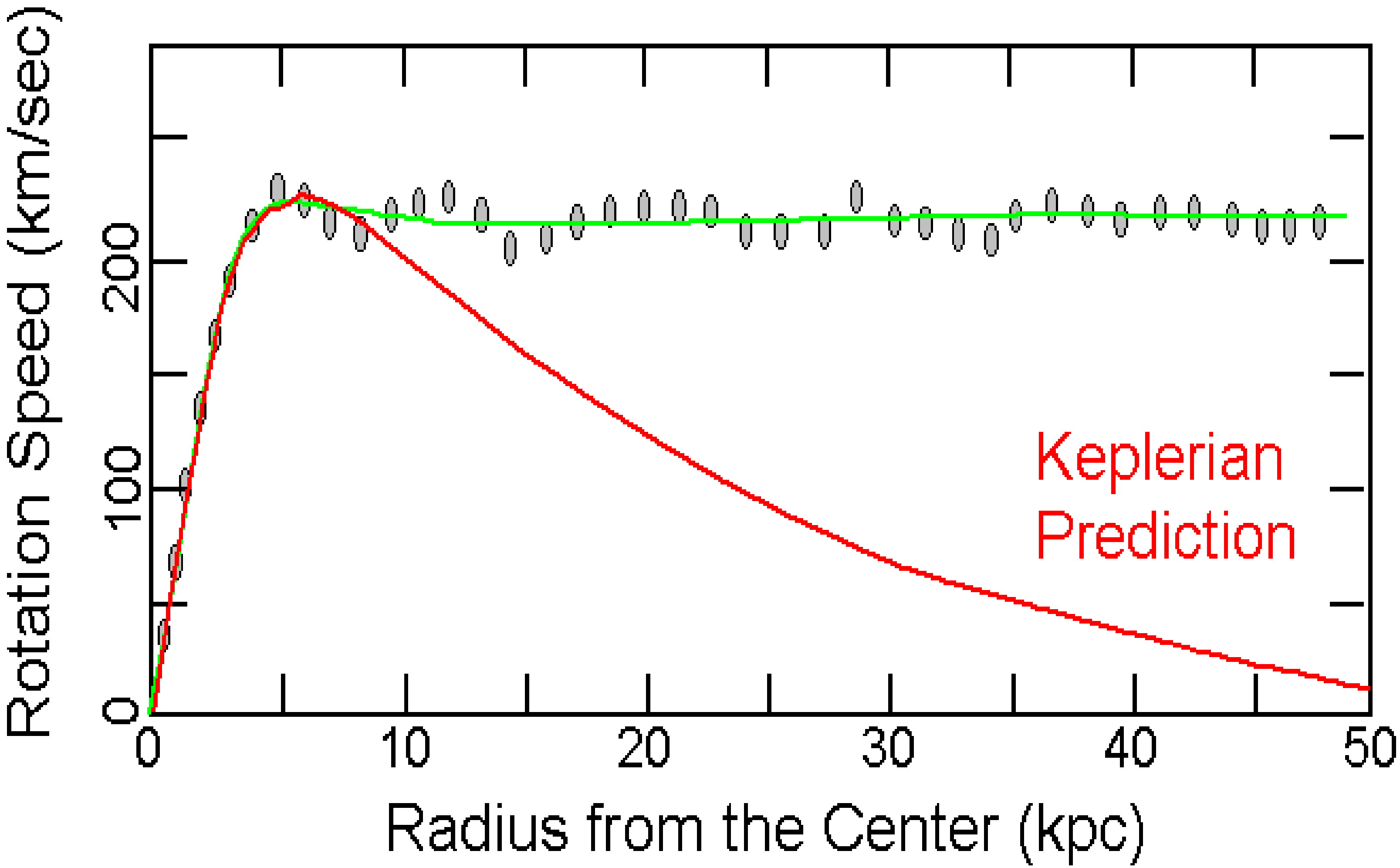
3 – DARK MATTER IN GALAXIES

Best evidence for DM in galaxies comes from study of SPIRAL galaxies.

Their LUMINOUS component consists of a central bulge and a disk made of stars and cold HI clouds. Radius of stellar disk 10 – 20 kpc while that of gaseous disk twice as large. Disk dynamically COLD …. ordered motion of stars and gas clouds on CIRCULAR orbits.

- DYNAMICAL ANALYSIS with stars as tracers …. ROTATION CURVE = circular velocity vs. galactocentric distance. Observations based on Doppler shift of optical spectral lines. With only LUMINOUS matter the rotation curve is KEPLERIAN. Yet observations …. FLAT behaviour at large radii …. DM exists and dominates outer region …. DARK HALO.

Observed *vs.* Predicted Keplerian



This method works out to optical radius only.

- DYNAMICAL ANALYSIS with HI clouds as tracers. Observations based on Doppler shift of 21 cm emission line. Same method and results as before, but now out to twice optical radius.

Assuming SPHERICAL symmetry, flat rotation curves …. dark halo described by

SINGULAR ISOTHERMAL SPHERE model i.e. M grows like r.

However assuming only AXIAL symmetry a DEGENERACY exists: any flattening can be consistent with flat rotation curves. Still, flattening can be determined by measuring THICKNESS of gaseous disk, fixed by competition between thermal pressure and gravitational force. Typically flattening =

0.6 – 1 …. spherical symmetry is a good approximation.

Accordingly optical observations …. amount of DM inside optical radius ≈ amount of luminous mass. Radio observations …. larger values for amount of DM ….

What is the total mass of dark halos?

- DYNAMICAL ANALYSIS with satellite galaxies. A sample of primaries and satellites is considered. Assuming all primaries produce SIMILAR effects …. ALL satellites can be attributed to a SINGLE primary of total mass M. By a STATISTICAL version of virial theorem M can be estimated as

$$M = \frac{4}{GN} \sum_{\alpha=1}^{N} v_{r,\alpha}^{2} r_{\alpha}$$

Typically one finds halo extension up to 200 kpc and Q $\approx$ 100 q.

- WEAK LENSING. Net polarization of arclet pattern around a SINGLE spiral too small to be measured. So one considers a sample of spirals (lenses) and measures orientation of nearest arclet. Assuming all lenses produce SIMILAR effects …. ALL arclets can be attributed to a SINGLE lens. Resulting M in agreement with above values.

OTHER types of galaxies (ellipticals, lenticulars, irregulars) can be analyzed by similar methods. The following results for the mass-to-light ratios are achieved.

SPIRALS

$$\overline{Q_S} \approx 100$$

ELLIPTICALS

$$\overline{Q_E} \approx 300$$

LENTICULARS

$$\overline{Q_{S0}} \approx 200$$

IRREGULARS

$$\overline{Q_{IRR}} \approx 100$$

4 – DARK MATTER IN CLUSTERS

Because DM is contained in galaxies it is AUTOMATICALLY present in clusters. Still there can be FURTHER DM in intracluster space.

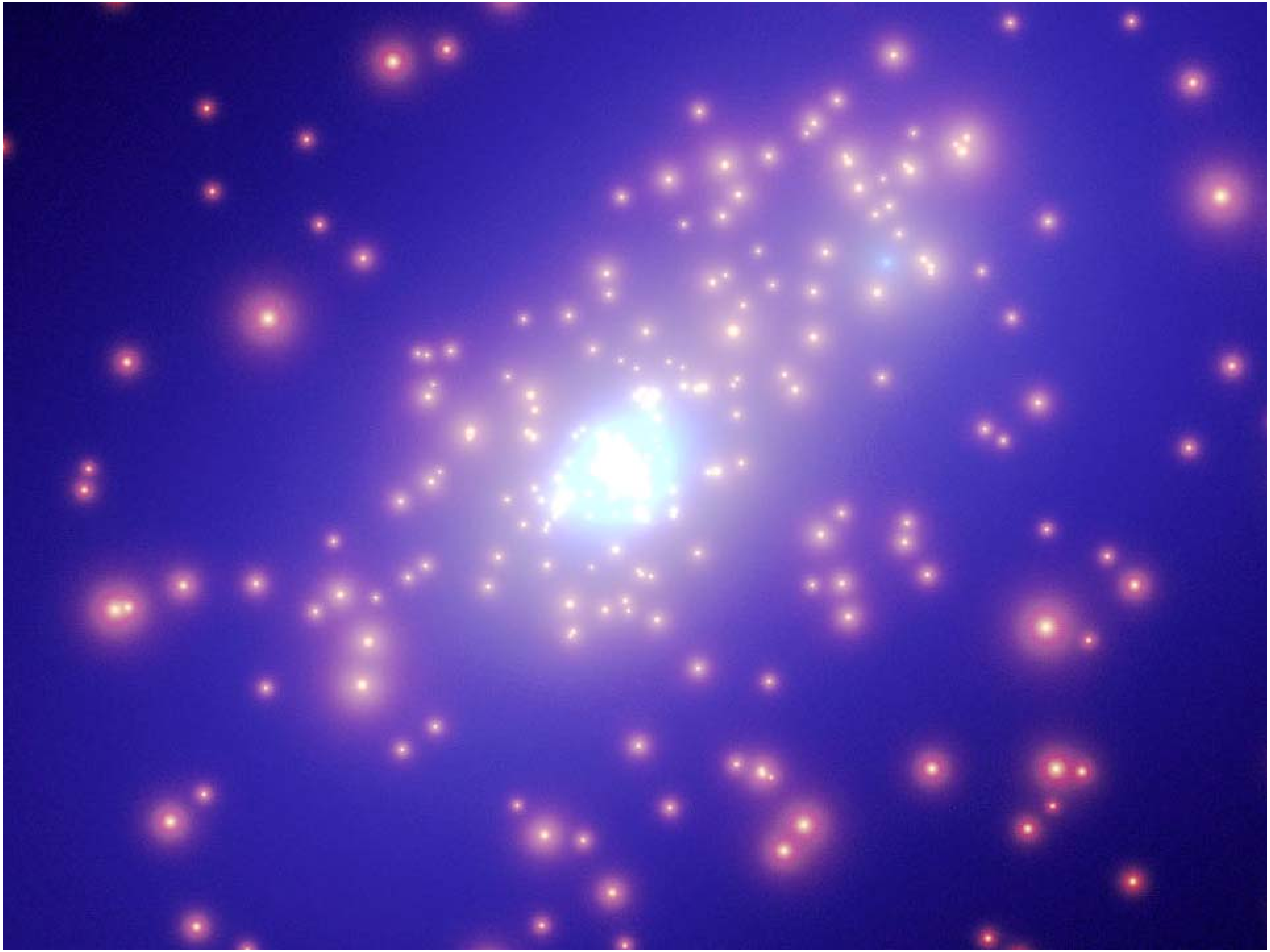
GLOBAL analysis of DM in clusters rests upon 4 techniques which lead to cluster MASS determination.

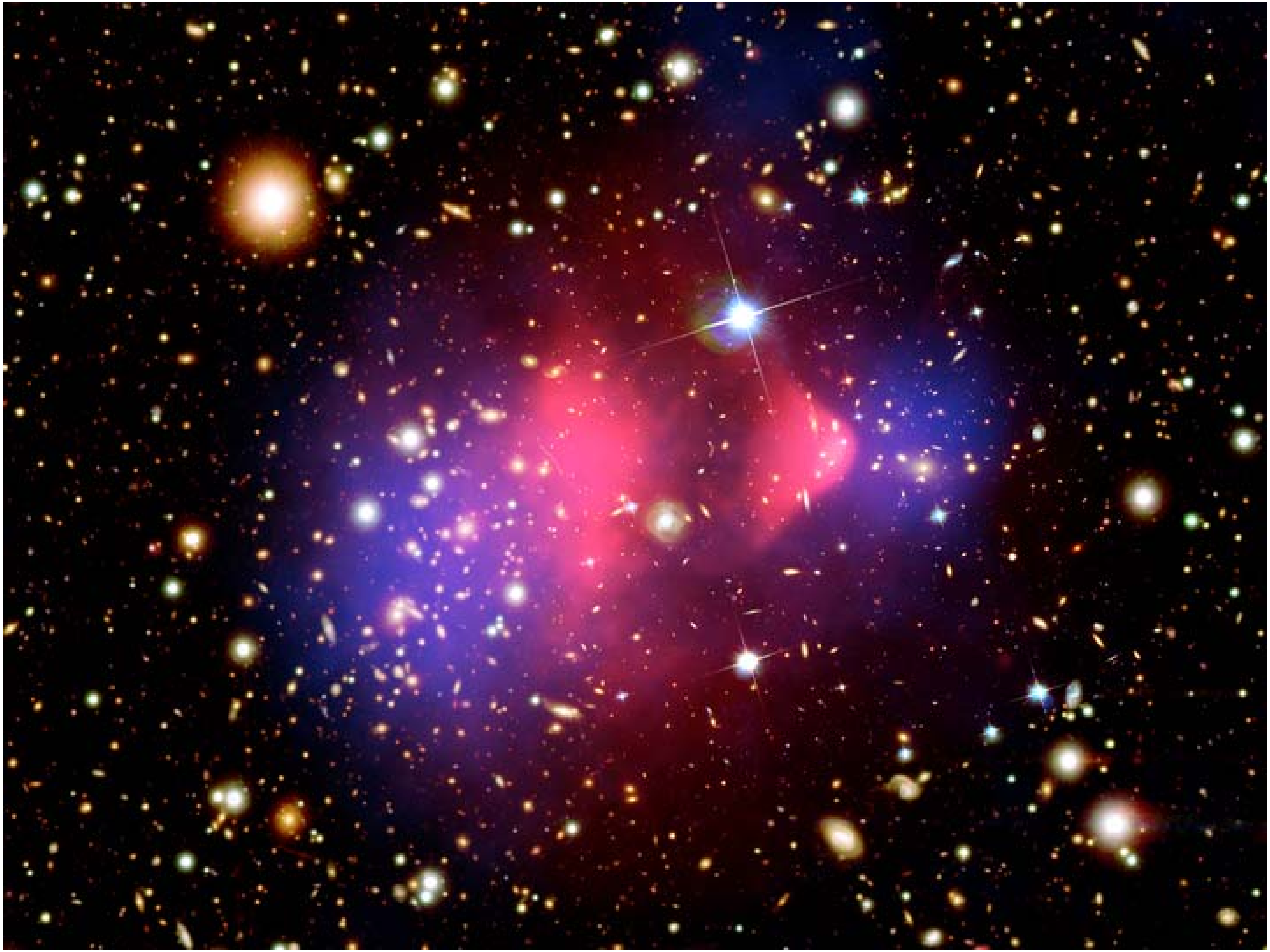
- DYNAMICAL ANALYSIS based on VIRIAL THEOREM assuming cluster equilibrium.

- DYNAMICAL ANALYSIS based on hot X-ray emitting GAS assumed in hydrostatic equilibrium ….. X-ray emissivity CONSTANT on equipotential surfaces.
- STRONG LENSING based on giant arcs (lens = cluster, sources = background galaxies).
- WEAK LENSING based on statistical analysis of arclet configuration (lens =

cluster, sources = background galaxies).

All these methods yield CONSISTENT results. They are ALSO in agreement with previous information about DM in galaxies provided ALL cluster DM is ORIGINALLY associated with GALAXIES i.e. there is NO intrinsec intracluster DM …. structures form according to BOTTOM-UP SCENARIO: OK with N-body simulations.





5 – COSMOLOGY

Standard big-bang model based on Einstein gravity with possibly a cosmological term.

MATTER = anything with positive energy and pressure.

DARK ENERGY = anything with positive energy and NEGATIVE pressure …. cosmological constant accounts for DE associated with VACUUM.

An EMPTY Universe would expand at CONSTANT rate. Cosmic expansion would be DECELERATED for a MATTER dominated Universe because ordinary gravity is attractive. Cosmic expansion would be ACCELERATED if DE dominates. I set

$$\Omega = \Omega_M + \Omega_\Lambda$$

6 – COSMOLOGICAL RELEVANCE OF ASTROPHYSICAL ANALYSIS

Observations yield GALAXY LUMINOSITY FUNCTION = average number of galaxies of Hubble type X per unit volume per unit luminosity … $\dot{j}_X \equiv$ AVERAGE LUMINOSITY DENSITY produced by galaxies of type X.

Actually, galaxies generate WHOLE cosmic luminosity in OPTICAL band (not so in other bands) …. $j = \sum j_X$ = average COSMIC luminosity density in optical band.

Relevance of M/L: converts luminosity of an object into its MASS. What is M/L for WHOLE galaxy population?

$$\frac{M}{L} = \frac{\sum_X \left(\frac{M}{L}\right)_X j_X}{\sum_X j_X}$$

- Consider first q for LUMINOUS matter. Then

$$q = \frac{\sum_X q_X\, j_X}{\sum_X j_X}$$

Hence the contribution of LUMINOUS matter in galaxies to average COSMIC density is

$$\rho_* = q \quad j$$

which gives

$$\Omega_* \approx 0.005$$

- Consider next Q for TOTAL matter. Again we have

$$Q = \frac{\sum_{X} Q_X \, j_X}{\sum_{X} j_X}$$

Accordingly the contribution of TOTAL matter in galaxies to average COSMIC density is

$$\rho = Q \quad j$$

leading to

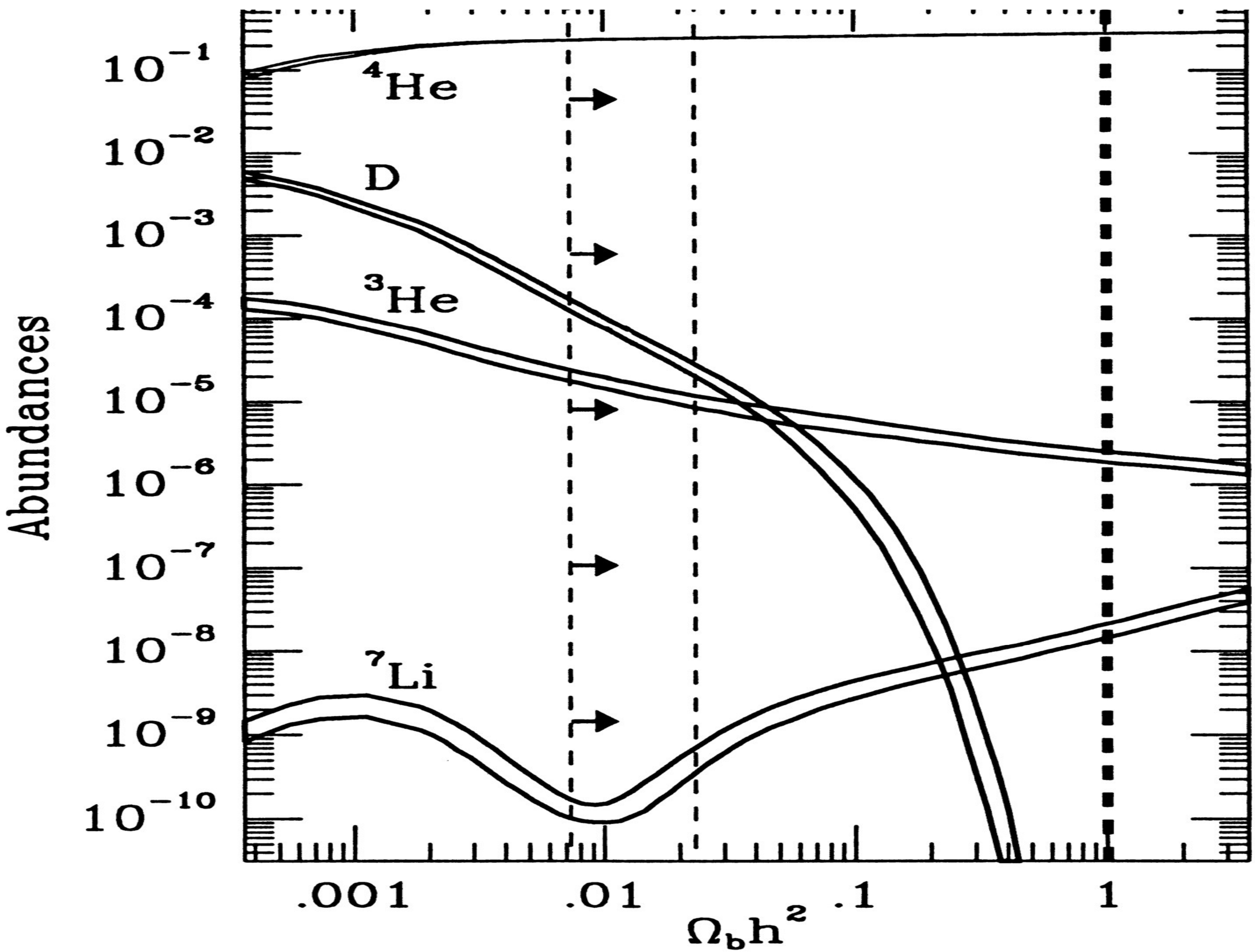
$$\Omega_G \approx 0.20 - 0.30$$

7 – PRIMORDIAL NUCLEOSYNTHESIS

Light element i.e. deuterium, helium and lithium form in the early Universe when $T \approx 10^9 K$ (100 s after the big bang). Light element abundances depend ONLY on Ω_B (assuming 3 light neutrino flavours).

AGREEMENT between theory and observations demands

$$\Omega_B \approx 0.04 - 0.05$$


Abundances
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
^{4}He
D
^{3}He
^{7}Li
.001
.01
.1
1
$\Omega_b h^2$

8 – COSMIC MICROWAVE BACKGROUND

When T = 3000 K ($3 \cdot 10^5$ yr after the big bang) the Universe becomes neutral because atoms form (recombination). Compton scattering becomes irrelevant and radiation decouples from ordinary matter undergoing adiabatic expansion and cooling. The equilibrium (blackbody) spectrum is preserved but all frequencies are systematically lowered. Today the

CMB temperature is 2.7 K and its contribution to energy budget is negligible.

Small-scale (angle < 1 degree) temperature fluctuations are present in the CMB with

$$\frac{\Delta T}{T} \approx 10^{-5}$$

Their statistical analysis yields 2 basic informations.

- POSITION of the FIRST acoustic peak in CMB angular power spectrum implies

$$\Omega_M + \Omega_\Lambda \approx 1$$

- RATIO of HEIGHTS of odd to even peaks in CMB angular power spectrum entails

$$\Omega_B \approx 0.045$$

in good agreement with primordial nucleosynthesis result.

9 – STRUCTURE FORMATION

Galaxies and clusters must have formed a long time after the big bang. Structure formation theory is based on the paradigm of GRAVITATIONAL INSTABILITY: initial density fluctuations grow during cosmic expansion to produce observed structure today.

Density fluctuations of BARYONS cannot grow until recombination because of

FREE STREAMING of photons. Existence of structure demands

$$\frac{\Delta\rho}{\rho} \approx 1-10$$

TODAY. Clearly the density is controlled by COSMIC EXPANSION while the relative density by SELF-GRAVITY. For

$$\frac{\Delta \rho}{\rho} < 1$$

self-gravity is negligible. In such a regime

$$\frac{\Delta \rho}{\rho} \propto \frac{1}{1+z}$$

Therefore going backward in time, at RECOMBINATION we should have

$$\frac{\Delta\rho}{\rho} \approx 10^{-3} - 10^{-2}$$

which means CMB temperature fluctuations

$$\frac{\Delta T}{T} \approx 10^{-3} - 10^{-2}$$

TOO BIG by a factor of 100.

Turning the argument around, NBDM is NECESSARY to explain structure formation without conflicting with CMB observations.

Difficult to quantify how much NBDM is needed but certainly

$$\Omega_M > 0.20$$

Actually 2 scenarios are possible.

- HOT NBDM for particles RELATIVISTIC at decoupling …. TOP-DOWN mechanism: clusters form first and galaxies next by fragmentation …. LARGE amount of intracluster DM.
- COLD NBDM for particles NONRELATIVISTIC at decoupling …. BOTTOM-UP mechanism: galaxies form

first and clusters next by hierarchical merging …. SMALL amount of intracluster DM.

N-BODY simulations show that BOTTOM-UP scenario is realized in nature …. NBDM must be COLD.

10 – COSMIC DARK MATTER

LUMINOUS matter, necessarily BARYONIC

$$\Omega_* \approx 0.005$$

BARYONIC matter

$$\Omega_B \approx 0.045$$

…. BARYONIC DM (90 % of baryons).

Matter in GALAXIES

$$\Omega_G \approx 0.20 - 0.30$$

…. Galaxies are dominated by NBDM ….
OK with structure formation theory.

Yet

$$\Omega - \Omega_G \approx 0.70 - 0.80$$

totally UNACCOUNTED. We are used to think galaxies as building blocks of the Universe but we are in error …. MOST of cosmic stuff lies OUTSIDE galaxies.

PRESUMABLY that stuff should be NBDM DIFFUSED in intergalactic space.

However even this option turns out to be wrong.

- Why does such stuff NOT collapse into galaxies like other NBDM?
- Regular clusters are believed to be FAIR SAMPLES of whole Universe …. their

COMPOSITION should trace the mean COSMIC composition …. cluster baryon fraction should obey the relation

$$f_B \approx \frac{\Omega_B}{\Omega_M}$$

Observations yield $f_B \geq 0.15 - 0.21$

which entails

$$\Omega_M \leq 0.21 - 0.30$$

Thus we see that

$$\Omega_M \approx \Omega_G$$

which implies that ALL cosmic MATTER is indeed in GALAXIES. But

$$\Omega - \Omega_M \approx 0.70 - 0.80$$

…. MOST of cosmic stuff NOT even matter ….

WHAT is the UNIVERSE made of ?

11 – ACCELERATED COSMIC EXPANSION

A breakthrough came in april 1998 from a study of cosmic expansion based on observations of a sample of TYPE IA SUPERNOVAE at different z. They are believed to be STANDARD CANDLES i.e. their absolute luminosity is supposed KNOWN. Then

- measuring apparent luminosity …. distance d,

- measuring z from host host galaxy …. recession velocity v.

  Plotting v vs. d we get informations on cosmic expansion. It was believed to find

  d SMALLER than predicted by linear Hubble law owing to cosmic DECELERATION produced by gravitational attraction. Data showed the opposite …. ACCELERATED expansion.

Quantitatively

$$\Omega_\Lambda \approx 1.40 \cdot \Omega_M + 0.35$$

12 – COSMIC SCENARIO

PRESENT Universe is DOMINATED by DE. Its negative pressure produces a REPULSIVE gravity responsible for ACCELERATED cosmic expansion.

At least 2 questions arise.

- Previous astrophysical analysis neglected DE. Is that correct? YES. DE is self-repulsive …. SMOOTHLY distributed in the Universe …. DE contribution to galaxies indeed NEGLIGIBLE.

- Is DE really the MISSING stuff ? Combining

$$\Omega_M \approx \Omega_G \approx 0.20 - 0.30$$

with

$$\Omega_\Lambda \approx 1.40 \cdot \Omega_M + 0.35$$

we get

$$\Omega_{\Lambda} \approx 0.63 - 0.77$$

which quantifies the amount of DE. Hence

$$\Omega = \Omega_{M} + \Omega_{\Lambda} \approx 0.83 - 1.07$$

in AGREEMENT with

$$\Omega = 1$$

ALL cosmic stuff is now accounted for.

13 - CONCLUSIONS

A CONSISTENT cosmic scenario emerges. HOWEVER our UNDERSTANDING of the composition of the Universe is quite POOR.

- 90 % of the baryons are not luminous …. BARYONIC DARK MATTER …. What is its form?
- DOMINANT form of MATTER is NONBARYONIC …. What kind of elementary particles?
- DOMINANT constituent of the Universe is NOT even matter …. What is DE?

Details are explained in: M. R. “Aspetti Astrofisici della Materia Oscura” (Bibliopolis, Napoli, 2004); M. R. “Astrophysical Aspects of Dark Matter” (Cambridge University Press, Cambridge, 2008).