Dark Matter: The evidence from astronomy, astrophysics and cosmology

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Dark matter has been introduced to explain many independent gravitational effects at different astronomical scales, even at cosmological scales. This review describes more than ten such effects. It is intended for an audience with little or no knowledge of astrophysics or cosmology.

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I Stars near the Galactic disk

- J. H. Oort in 1932 analyzed vertical motions of stars near the Galactic disk and calculated the vertical acceleration of matter.
- Their density and velocity dispersion define the temperature of a ”star atmosphere” bound by a gravitational potential.

- This contradicted grossly the expectations: the density due to known stars was not sufficient:

  the Galaxy should rapidly be losing stars.

- This was the first indication for the possible existence of dark matter in the Galaxy.
- He determined the mass of the Milky Way: 10^{11} solar masses, today understood to be mainly in the halo, not in the disk.

- But dark did not mean non-baryonic, rather invisible gas.
- Note that James Chadwick discovered the neutron in 1932.

II. Virially bound systems

- The total kinetic energy of N objects (stars, galaxies) with average mass m and random peculiar velocities v is

$$E = \frac{1}{2} N m v^2$$

- If the average separation is r, the potential energy of ½ N(N-1) pairings is

$$U = -\frac{1}{2} N(N-1) G m^2 / r$$

- The **virial theorem** states that for a statistically steady, spherical, self-gravitating many-body system

$$E = -\frac{1}{2} U$$

- Thus the total dynamic mass M = Nm of a virial system can be estimated from v, and r from its volume:

$$M = 2 r v^2 / G$$

Large clusters

- Fritz Zwicky noted in 1933 that the galaxies bound in the Coma cluster and other rich clusters move too fast.

- 160 times more mass than the observed luminous mass in the galaxies would be required to keep Coma bound and stop it from disintegrating.

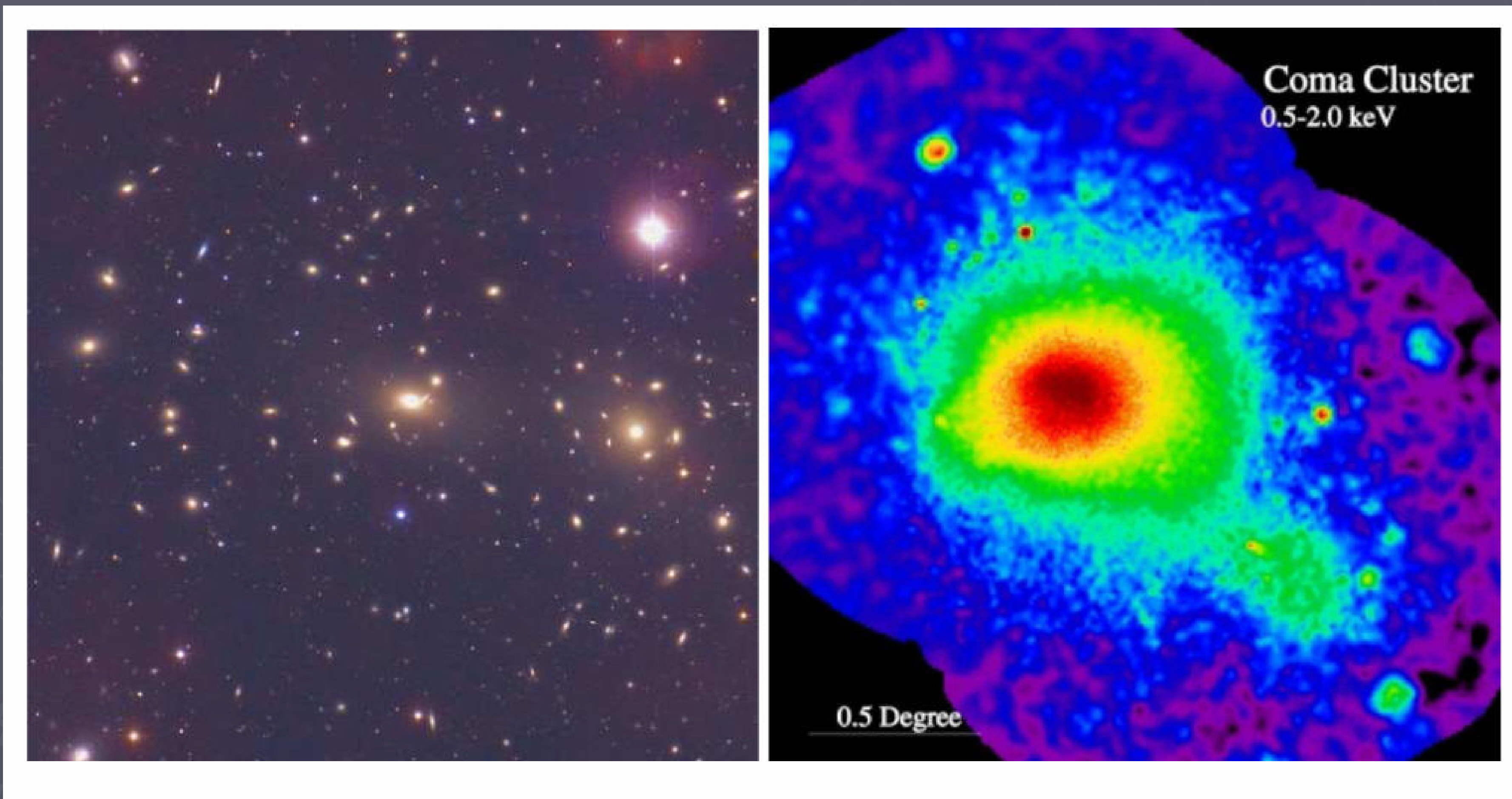
- This was the earliest indication of Dark Matter in an object at cosmological distances.

- But nobody took this seriously for 40 years, infuriating Zwicky.

- The largest virial systems (Coma) contain ~1000 galaxies: 1% stars, 14% gas at 10^8 K, 85% dark matter

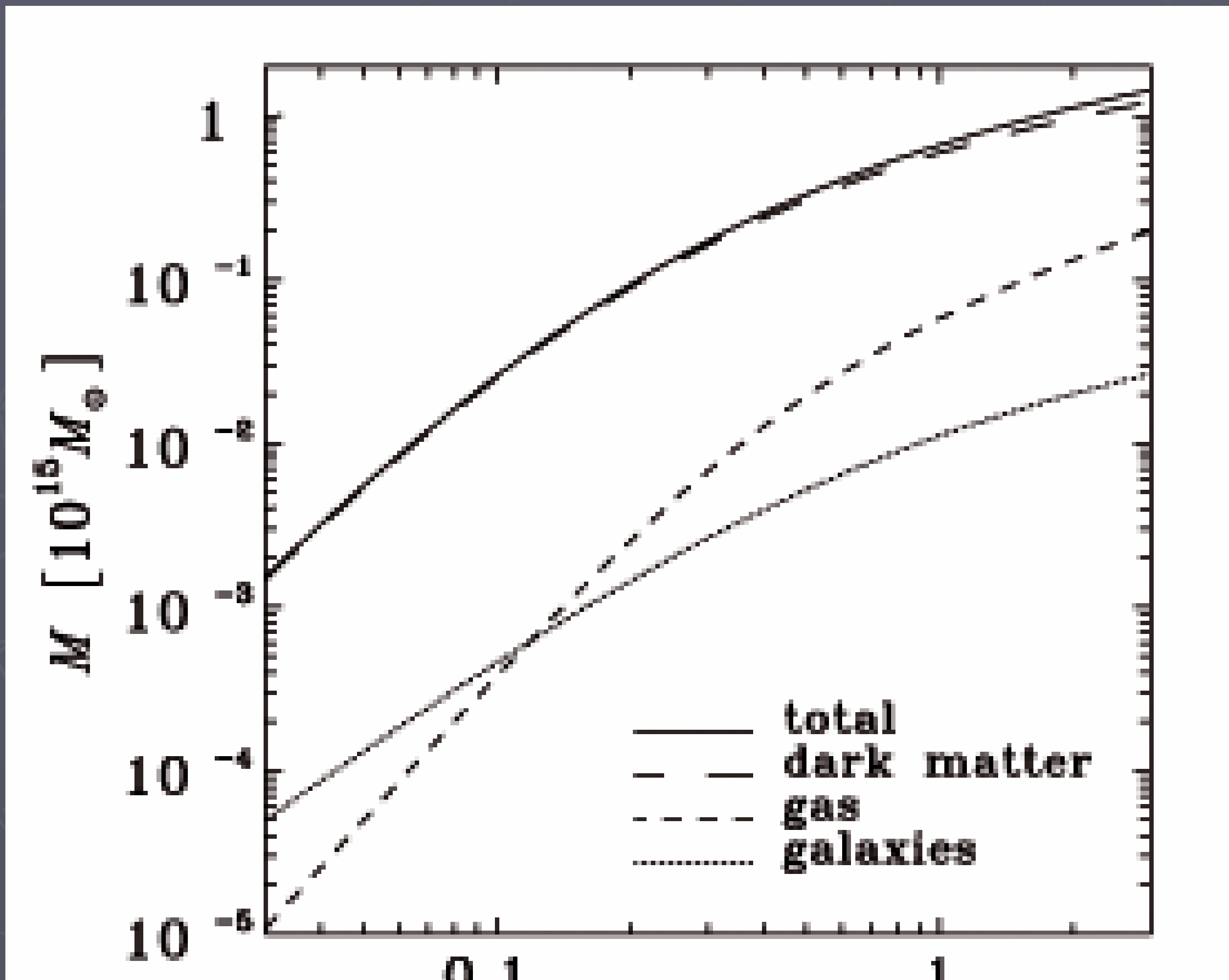
The Coma cluster

optical image X-ray image



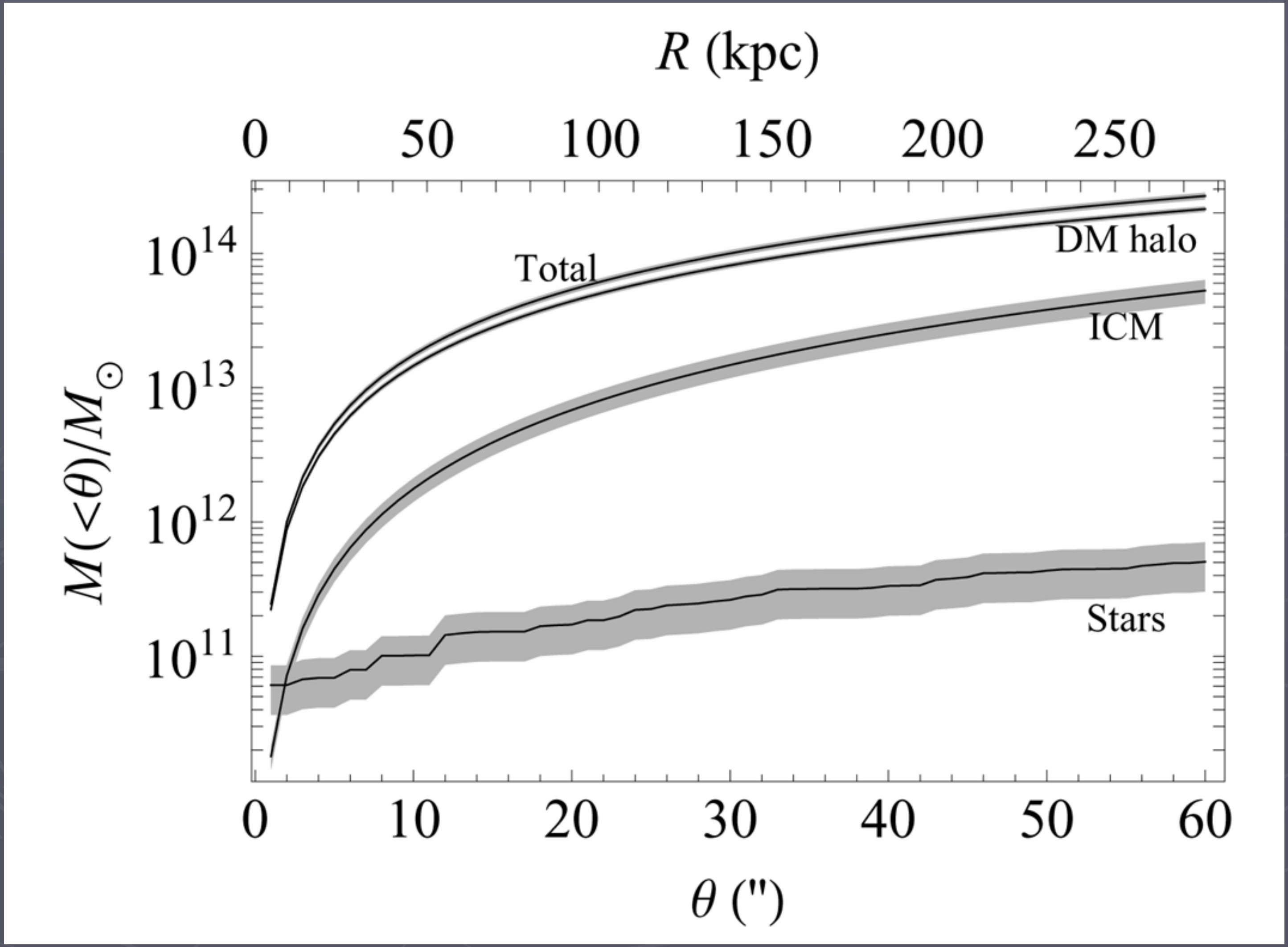
Density profile of the Coma cluster

Lokas & Mamon, MNRAS 343, 401 (2003)



Density profile of the cluster AC 114

Sereno & al., arXiv:0904.0018



Halo core density profiles

? A general parametrization of the DM radial density is

$$\rho_{DM}(r) = \frac{\rho_0}{(r/r_s)^\alpha (1 + r/r_s)^{3-\alpha}}$$

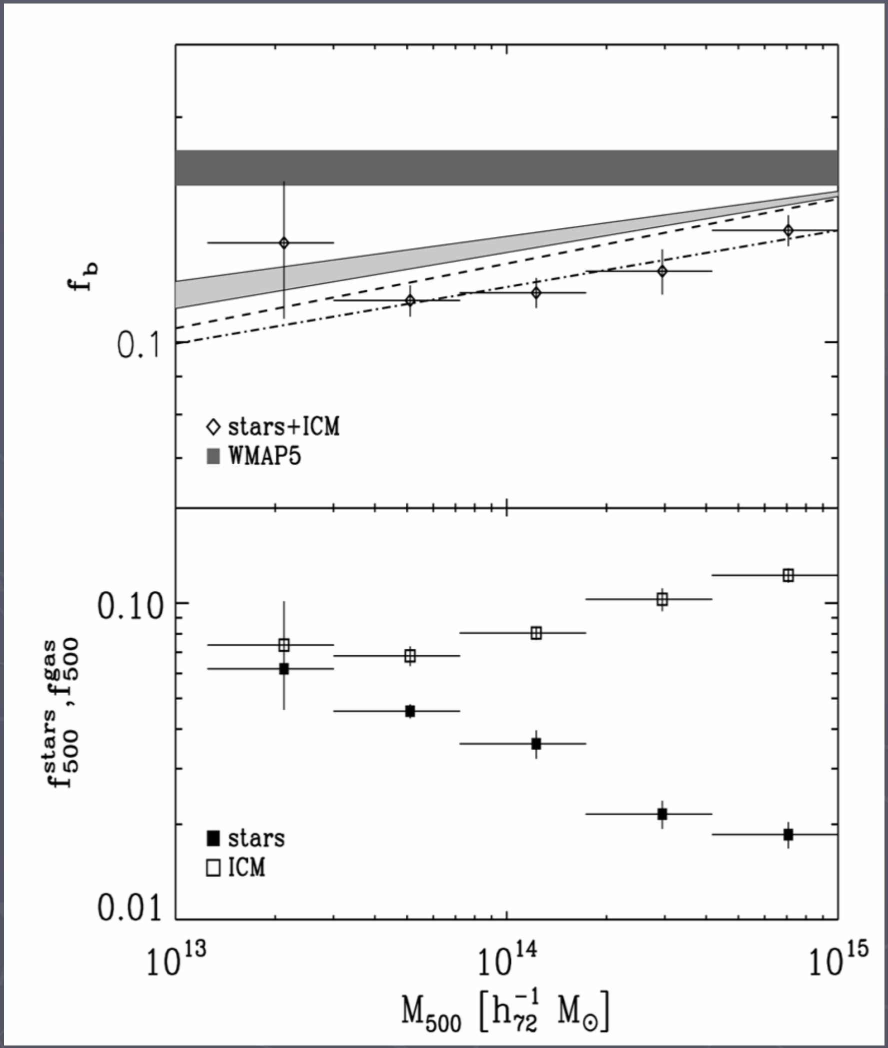
ρ_0 is a constant characteristic density, normalized to give the virial mass inside the virial radius

$\alpha = 1$ is the Navarro-Frenk-Wright cusped profile

$\alpha = 3/2$ is the Moore & al. cusped profile

$\alpha = 0$ is a flat profile

f_b as a function total mass arXiv:0904.0448[astro-ph.CO]



Upper figure

? Dark band: baryonic mass fraction f_b as a function total mass, from WMAP 5.

? Points: fraction f_b of stars and intra-cluster mass as a function of cluster mass in 118 X-ray groups and clusters.

? _._._. Linear fit to the points.

? - - - - f_{gas} corr. for 10% gas depletion

? Grey stripe: Includes also 11-22% constant intra-cluster light correction to star mass. Disagrees with WMAP5.

Lower figure

? Fraction of stars and intra-cluster mass plotted separately.

The Local Group

- The Andromeda galaxy (M31) is falling in towards us, contrary to most other galaxies which are receding.

- Evidently the Galaxy and M31 form a virially bound system which is oscillating, and the potential is dominated by the M31-Milky Way pair.

- Total visible mass of the Galaxy + M31 = 2×10^{11} M_{sun}

- The dynamical mass is affected by the accelerated expansion: Dark Energy reduces the potential energy and modifies the virial mass by 30-50%. Some loosely bound minor galaxies will fly away. arXiv:0902.3871[astro-ph.CO]

- Dynamical mass of the local group = $3.2 – 3.7 \times 10^{12}$ M_{sun}

III. Rotation curves of spiral galaxies

- Spiral galaxies are gravitationally bound systems of stars and interstellar gas which travel around the center in almost circular or elliptical orbits.

- For a galaxy mass M concentrated at radius $r \sim 0$, the circular velocity v at radius r is given by the stability condition:

centrifugal acceleration = gravitational pull

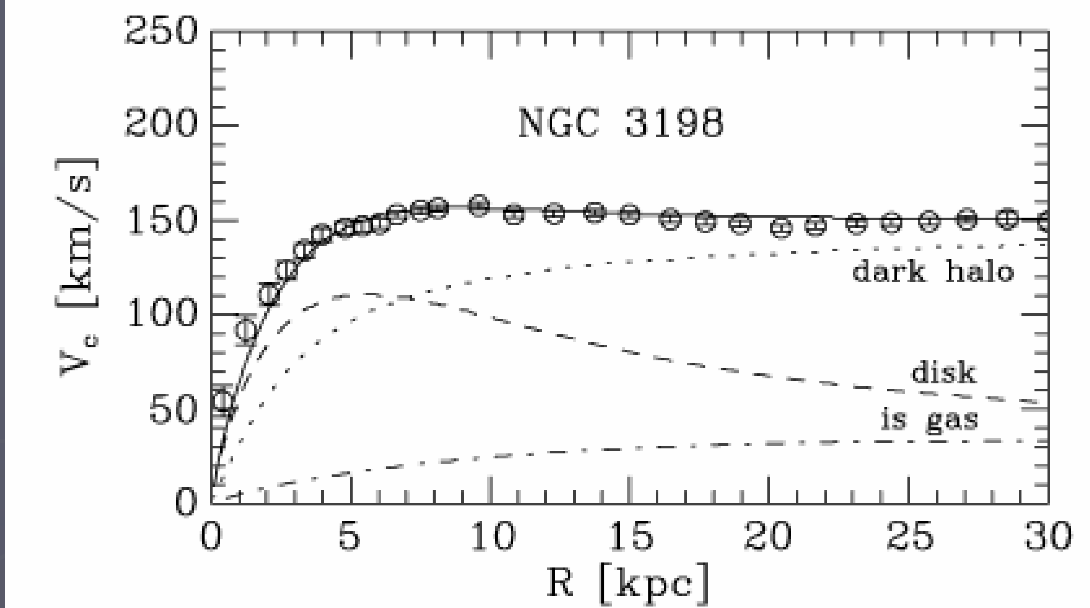
$$v / r = G\, M / r^2 ,$$

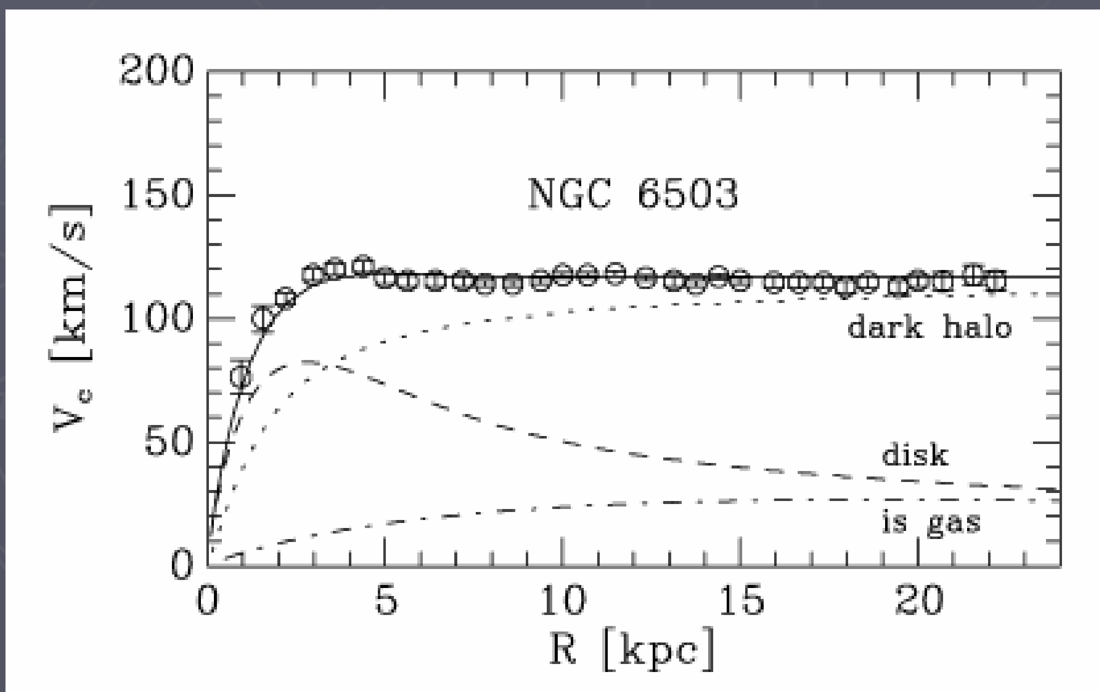
then

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

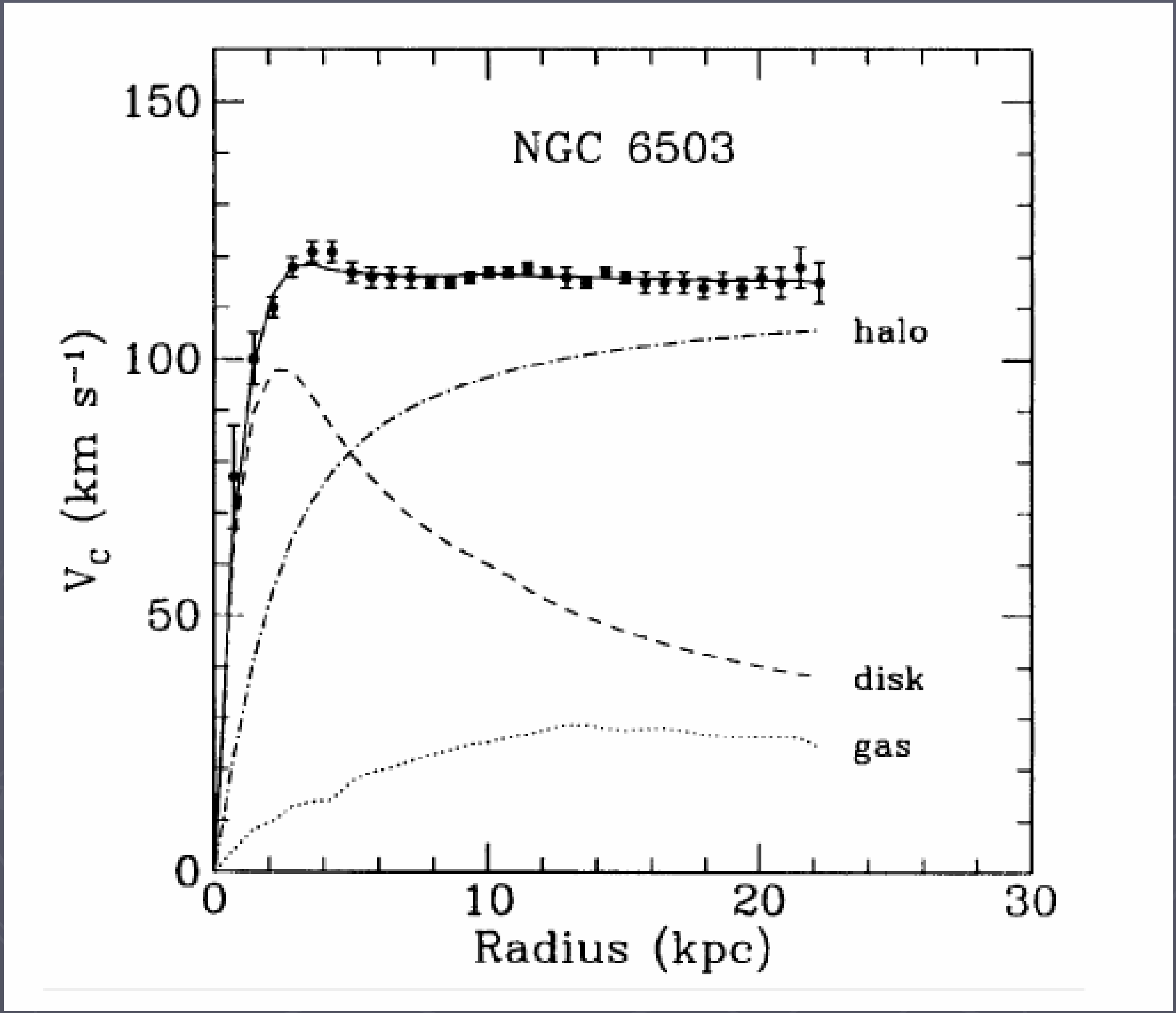
Observations: $v\,(r\,) \sim constant$ Solution: $M = M(r) / r$

- Typically the dark matter is & *50 %* of the total mass.





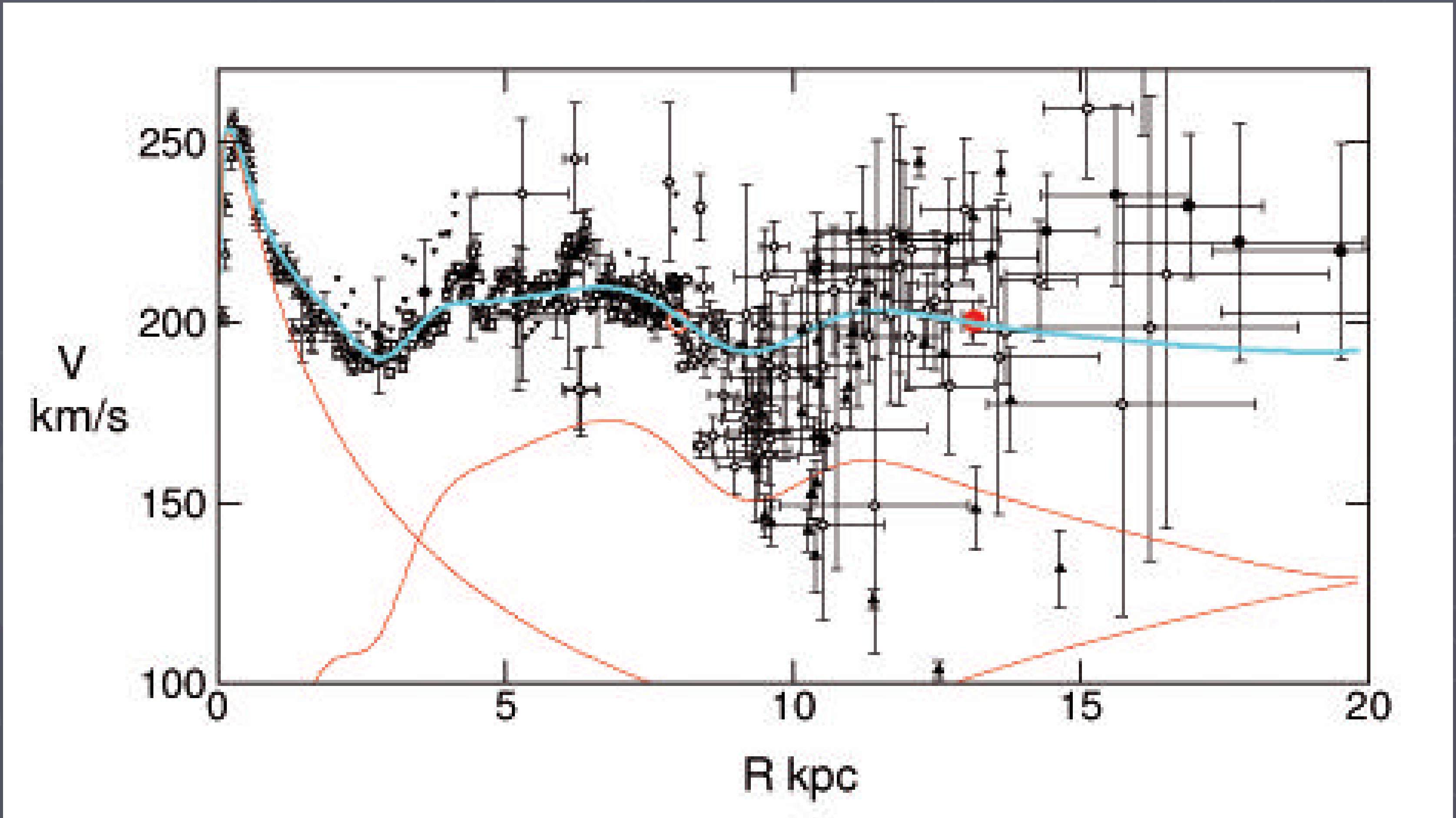
arXiv:astro-ph/0010358


NGC 6503
halo
disk
gas
Vc (km s⁻¹)
150
100
50
0
10
20
30
Radius (kpc)

The Milky way is problematic

arXiv:0811.0859

Red curves, left to right: central bulge, disk+gas, dark matter



IV. Small galaxy groups emitting X-rays

- ? Galaxies that are members of groups are often enveloped in a large cloud of hot gas, visible by its X-ray emission.
- ? From the intensity of this radiation one deduces the mass of gas.
- ? Adding this gas mass to the luminous matter seen, one finds the total amount of baryonic matter, M_b.

- ? The temperature of the gas depends on the strength of the gravitational field, from which the total amount of gravitating matter, M_{grav}, can be deduced.

- ? In many small galaxy groups one finds $M_{grav} / M_b = 3$. Thus a dark halo must be present, ~ *85%* of the total mass.

V. Mass to luminosity ratios M_{sun}/L_{sun}

? The Solar neighbourhood M / L = 2.5-7

? Stellar populations M / L= 1-10

? Dwarf spheroidal galaxies:

Draco 330 § 125, Andromeda IX 93 +120/-50

? Rich clusters on the largest scale M / L = 300 (cf. VII)

? Since the luminosity of the Universe is known, the critical density to close the Universe would require M / L ~ 900

) there is not enough luminous matter to achieve closure,

a large amount of DM is therefore needed.

A special case: Segue 1 (arXiv:0909.3496[astro-ph.CO])

? The ultra-faint dwarf disk galaxy Segue 1 has

baryon mass ~ 1000 M_{Sun}

high stellar velocity dispersion.

Interpretations:

- A thin stellar disk without rotation (and no gas disk) embedded in an axisymmetric DM halo.

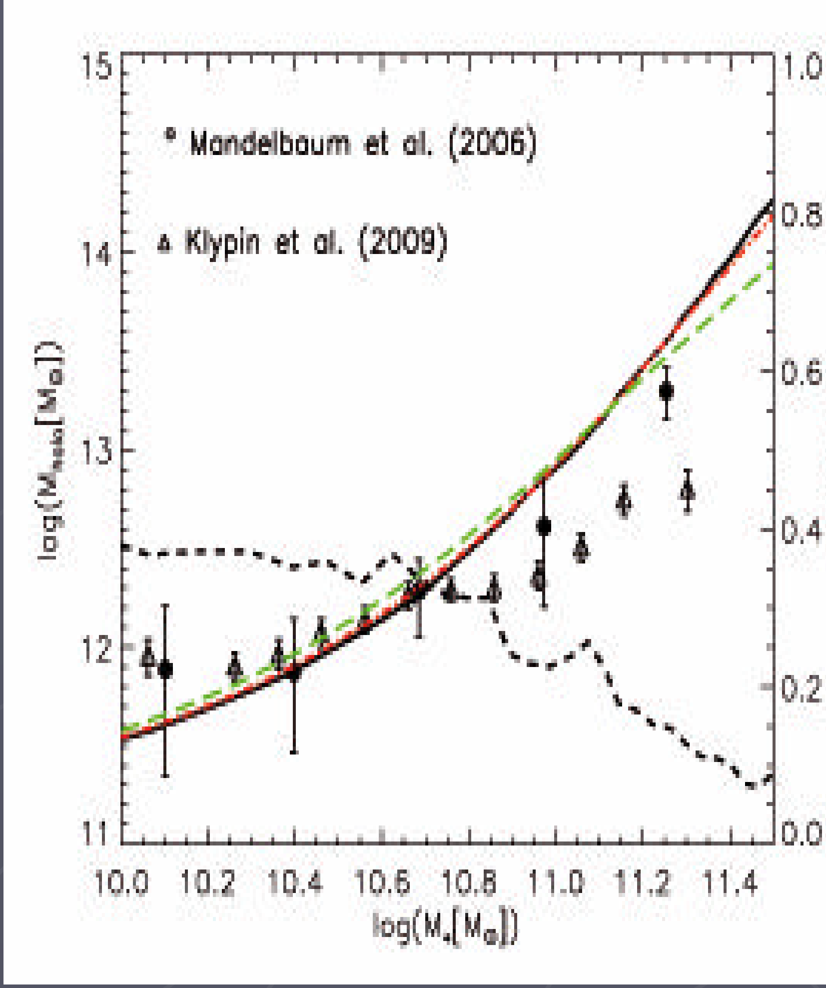
f = (DM halo mass/baryon mass) ~ 200

If the disk rotates f . 2000 .

- If there also is a magnetized gas disk, the DM halo has to confine the effective pressure in the stellar disk and the magnetic Lorentz force in the gas disk, and possible rotation. f could be large.

VI. Mass autocorrelation functions

- If galaxy formation is a local process, then on large scales galaxies must trace mass.
- One derives an accurate relation between galaxy stellar mass and halo dark matter from abundance matching arguments.
- This stellar mass – halo mass relation can be used to populate halos.
- The implied spatial clustering of stellar mass is in remarkably good agreement with direct and precise measurements.
- One concludes that a large amount of matter in the Local Super Cluster is dark.



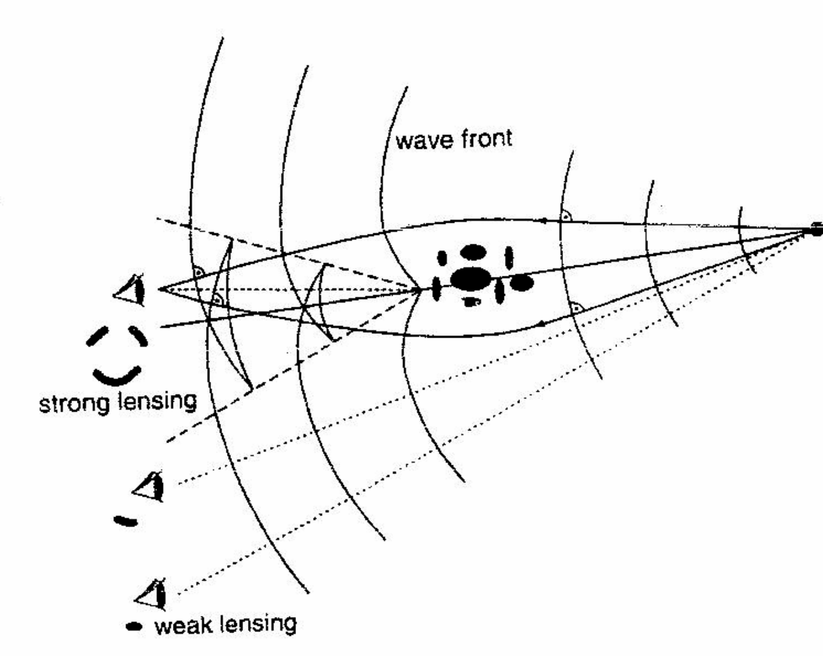
(arXiv:0909.4305[astro-ph.CO])

VII. Strong and weak lensing

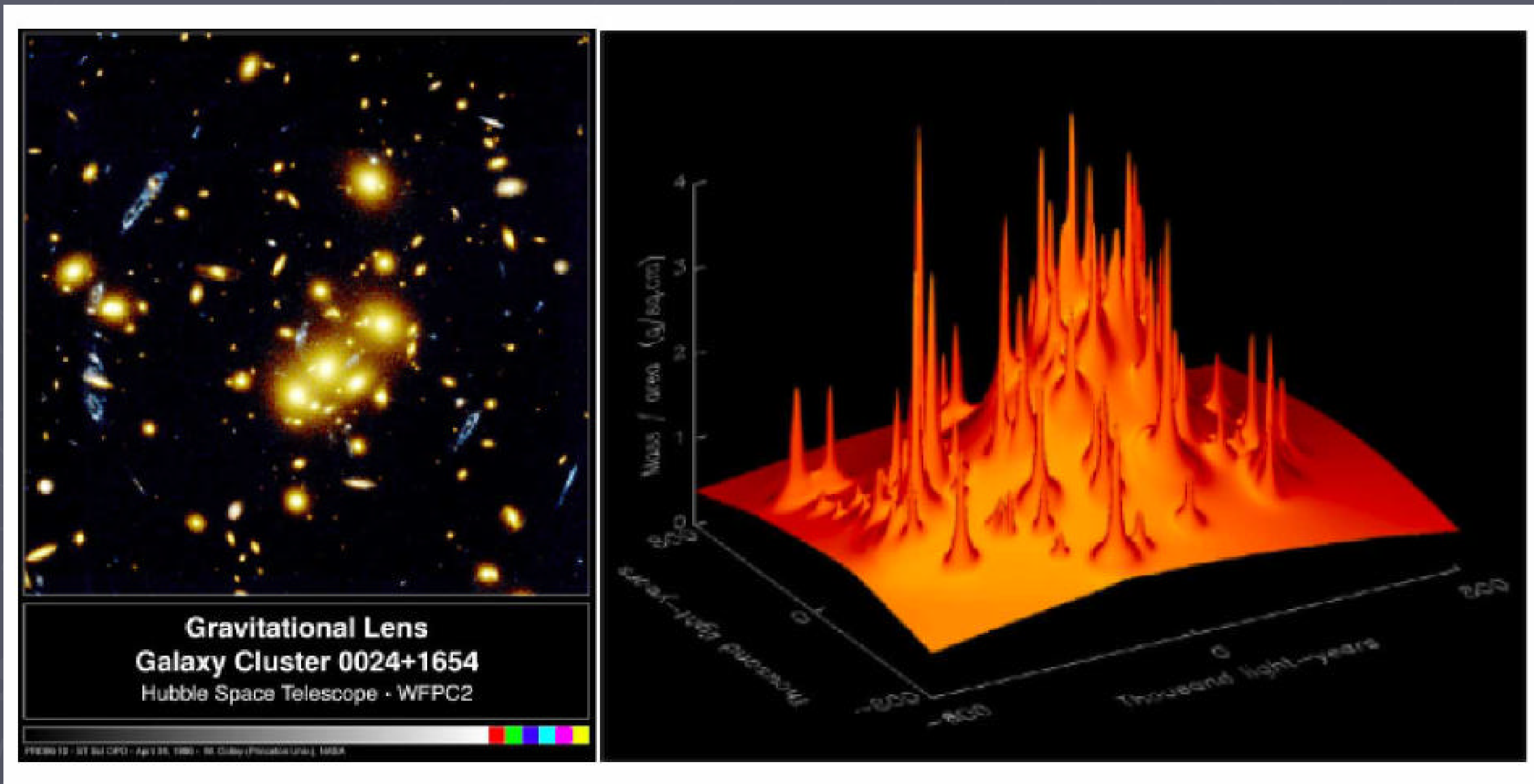
- Strong lensing: A foreground cluster acts as a lens for light rays coming from a background object (galaxy, quasar)

- The object appears as multiple distorted images, from which the mass of the lens can be reconstructed.

- Cosmic shear by Weak lensing: the tidal gravitational field of the large-scale matter distribution distorts all galaxies, making them appear elliptic.

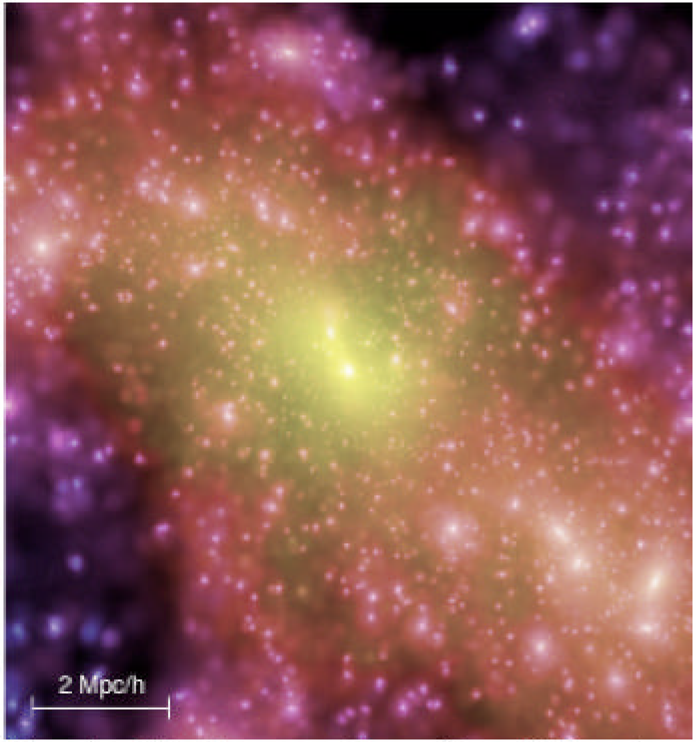


Left: The foreground cluster of galaxies gravitationally lenses the blue backgroun galaxy into multiple images. Right: A computer reconstruction of the lens shows a smooth background component not accounted for by the mass of the luminous objects.



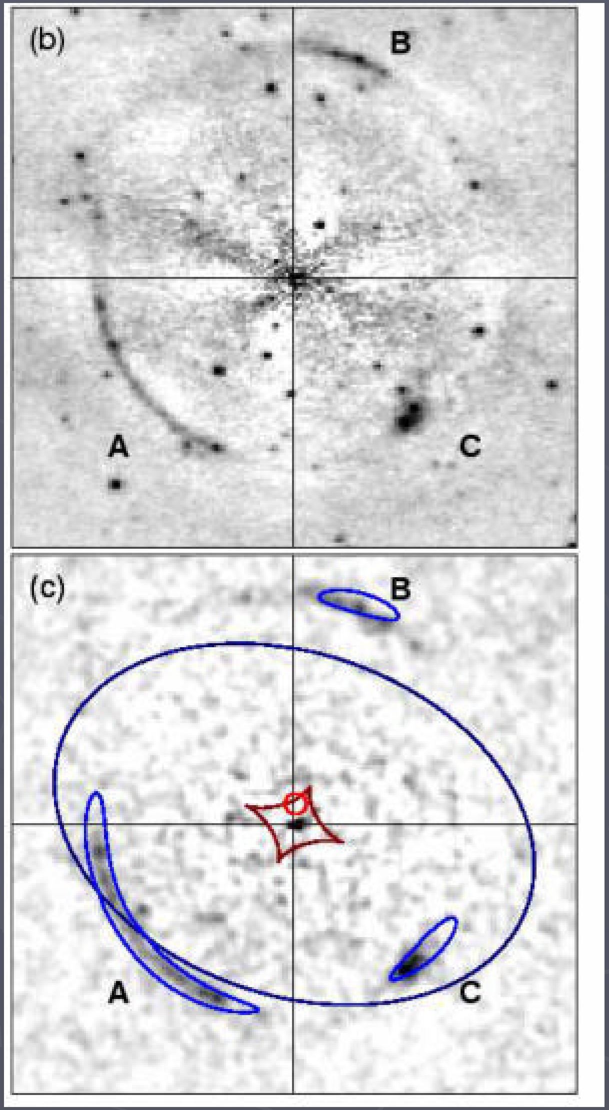
Weak lensing near Abell 1689

Observed dark matter mass map of Abell 1689



Simulated dark matter cluster from Millennium

Strong lensing in elliptical galaxy ESO325-G004



(b) The image is shown after subtracting a smooth boxy-elliptical profile model.

(c) The color-subtracted image with results from a lensing singular isothermal elliptic galaxy.

A, B, C mark the images of the lensed object.

From R.J. Smith & al., Astrophys.J., 625 (2005) L103-L106

R. Massey et al, Dark matter maps reveal cosmic scaffolding, Nature, 445, 286, 2007

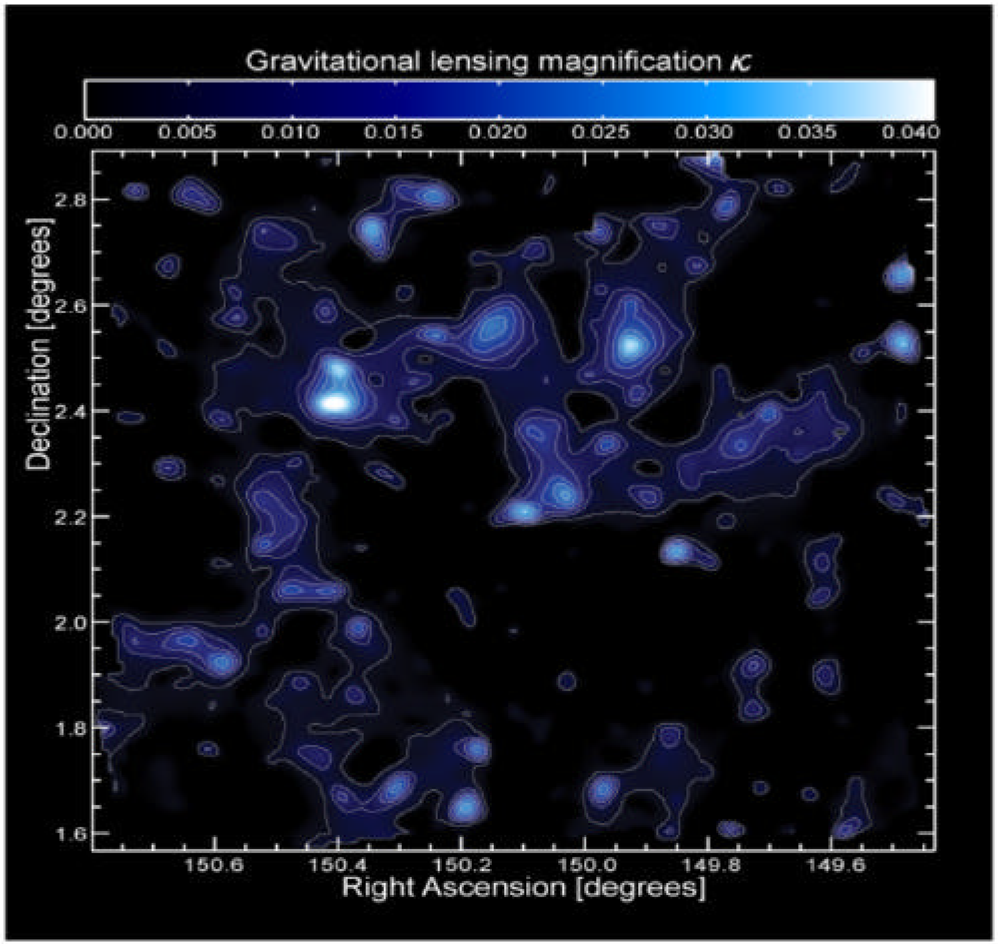
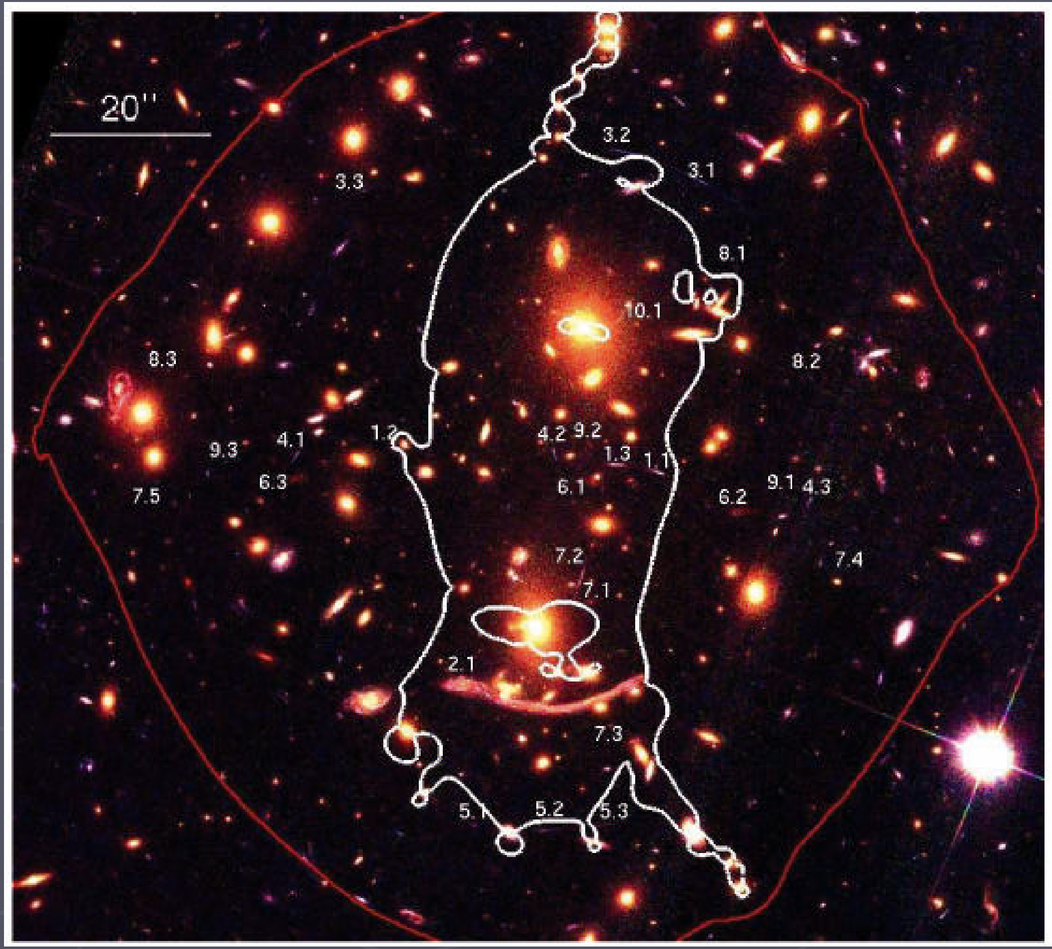


Fig. 6. Map of the dark matter distribution in the 2-square degree COSMOS field by [27]: the linear blue scale shows the convergence field κ, which is proportional to the projected mass along the line of sight. Contours begin at 0.4 % and are spaced by 0.5% in κ.

The first strong lensing analysis of a galaxy cluster, Abell 370

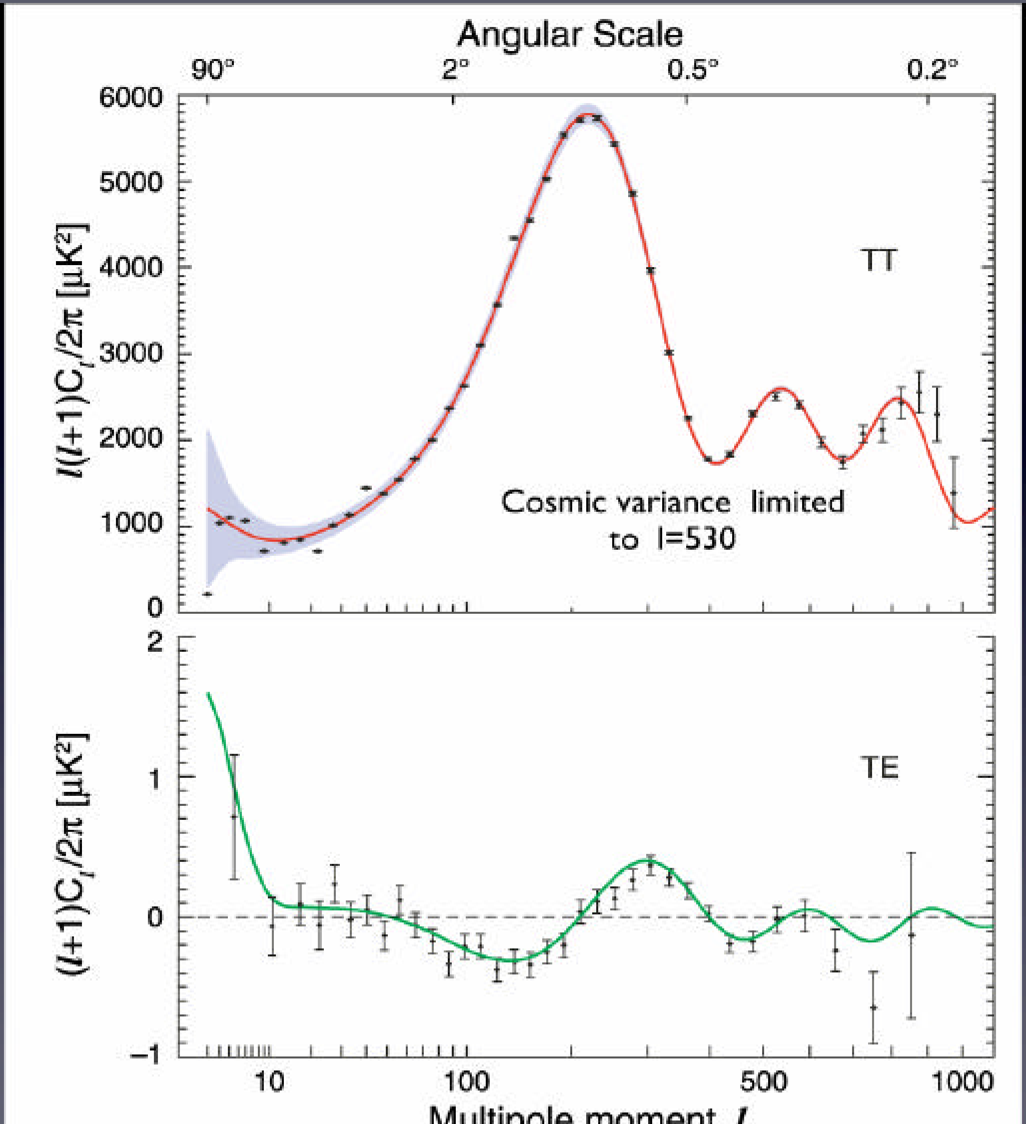
arXiv:0910.5553[astro-ph.CO]



VIII. Cosmic Microwave Background (CMB)

- Baryonic matter feels attractive gravity and is pressure-supported.
- Dark matter only feels attractive gravity, but is pressureless.
- Thus the Doppler peaks in the CMB temperature power spectrum testify about baryonic and dark matter. The position of peak 1 (the angular scale of the sound horizon at decoupling) determines Ω_m .
- The troughs testify about rarefaction caused by the baryonic pressure.
- The ratio of peak 2 to peak 1 determines Ω_b / Ω_m .
- CMB + HST determines $\Omega_m = 0.26$, $\Omega_b = 0.04$, $\Omega_{dm} = 0.22$

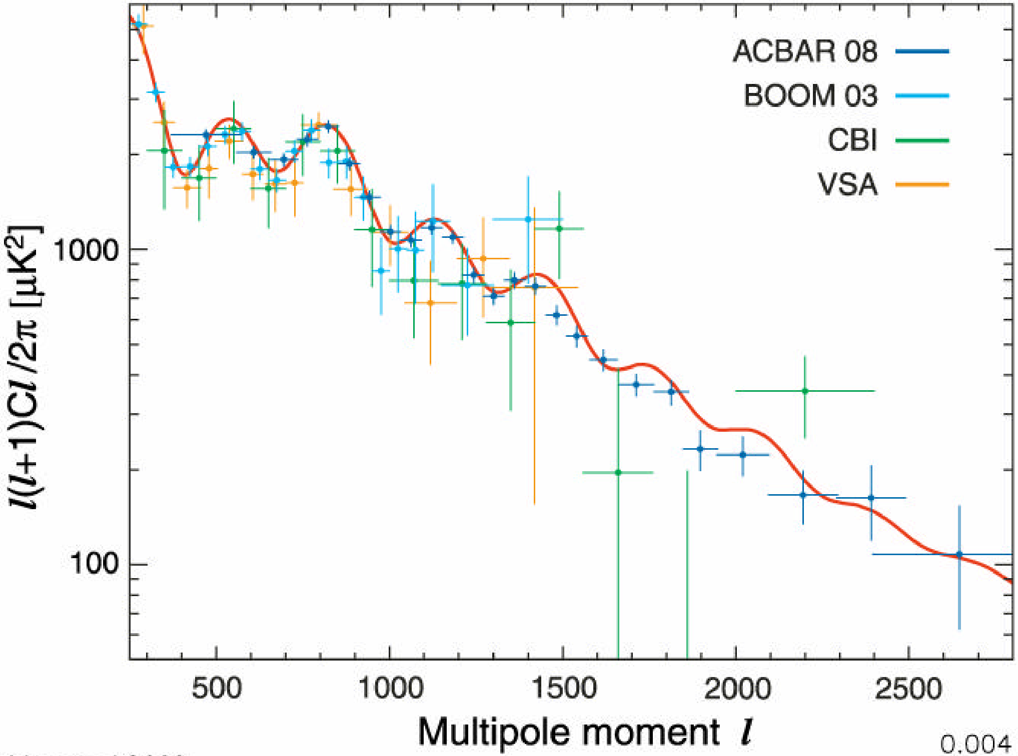
The maps of CMB radiation temperature (TT) and temperature-polarization correlations (TE) from WMAP show anisotropies which can be analyzed by power spectra as functions of multipole moments.



Much improved measurement of the 3rd peak!

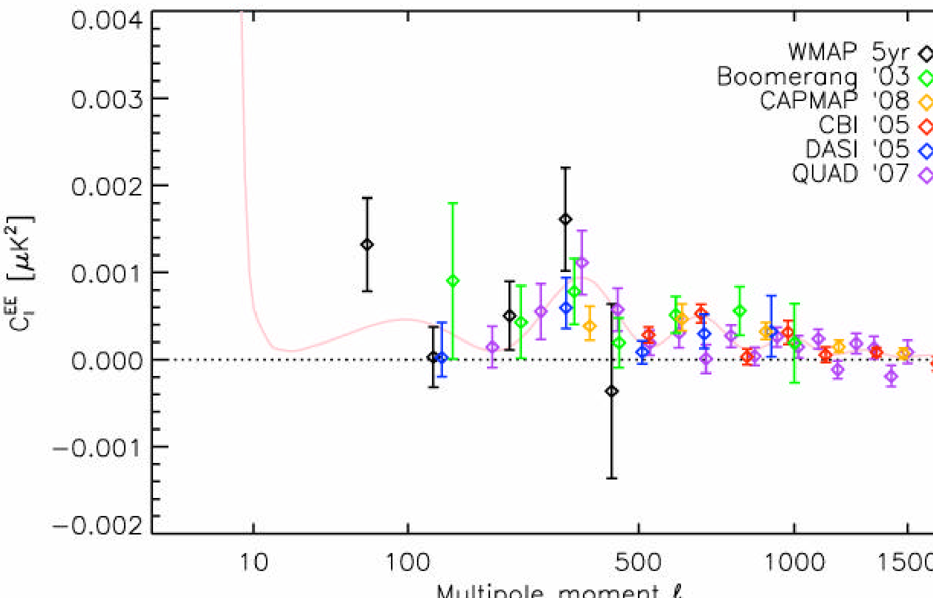
Hinshaw et al 2008

Temp



unkley et al 2008

E-mode Pol



Nolta et al 2008

IX. Baryonic acoustic oscillations (BAO)

- ? The power spectrum of the galaxy distribution exhibits oscillations, caused by acoustic waves in the baryon-photon plasma before recombination at z=1090

- ? The scale of BAO depends on Ω_m and the Hubble constant, *h* , so one needs further information to break the degeneracy.

The result is then

$\Omega_b / \Omega_m = 0.18$ § 0.04

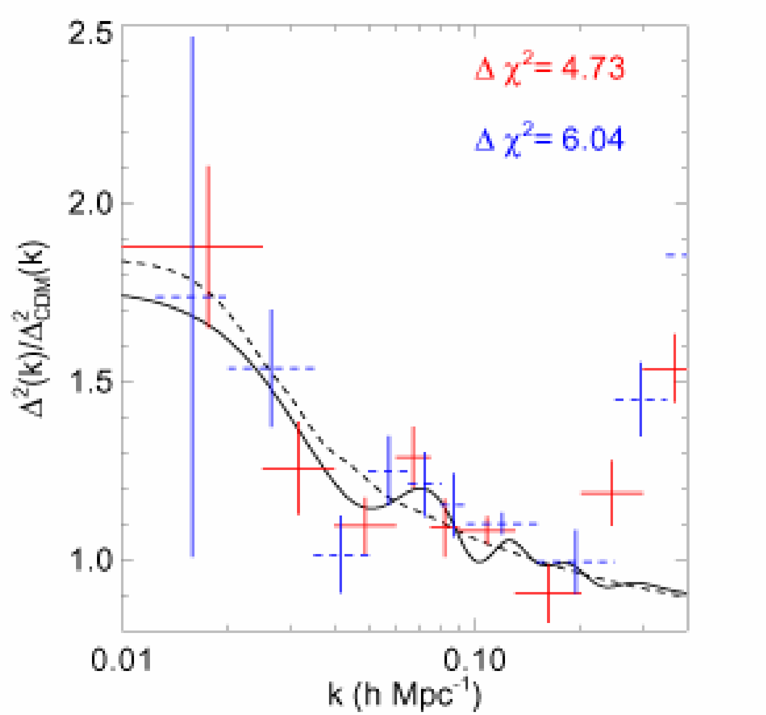


Figure 22. The ratio of the measured power spectrum to th linear CDM power spectrum for our fiducial cosmology (withou baryons). As above, the solid and dashed lines represent binning

X. Galaxy formation in purely baryonic matter

? The expansion speed of the Universe => the critical density $\Omega_{critical}$

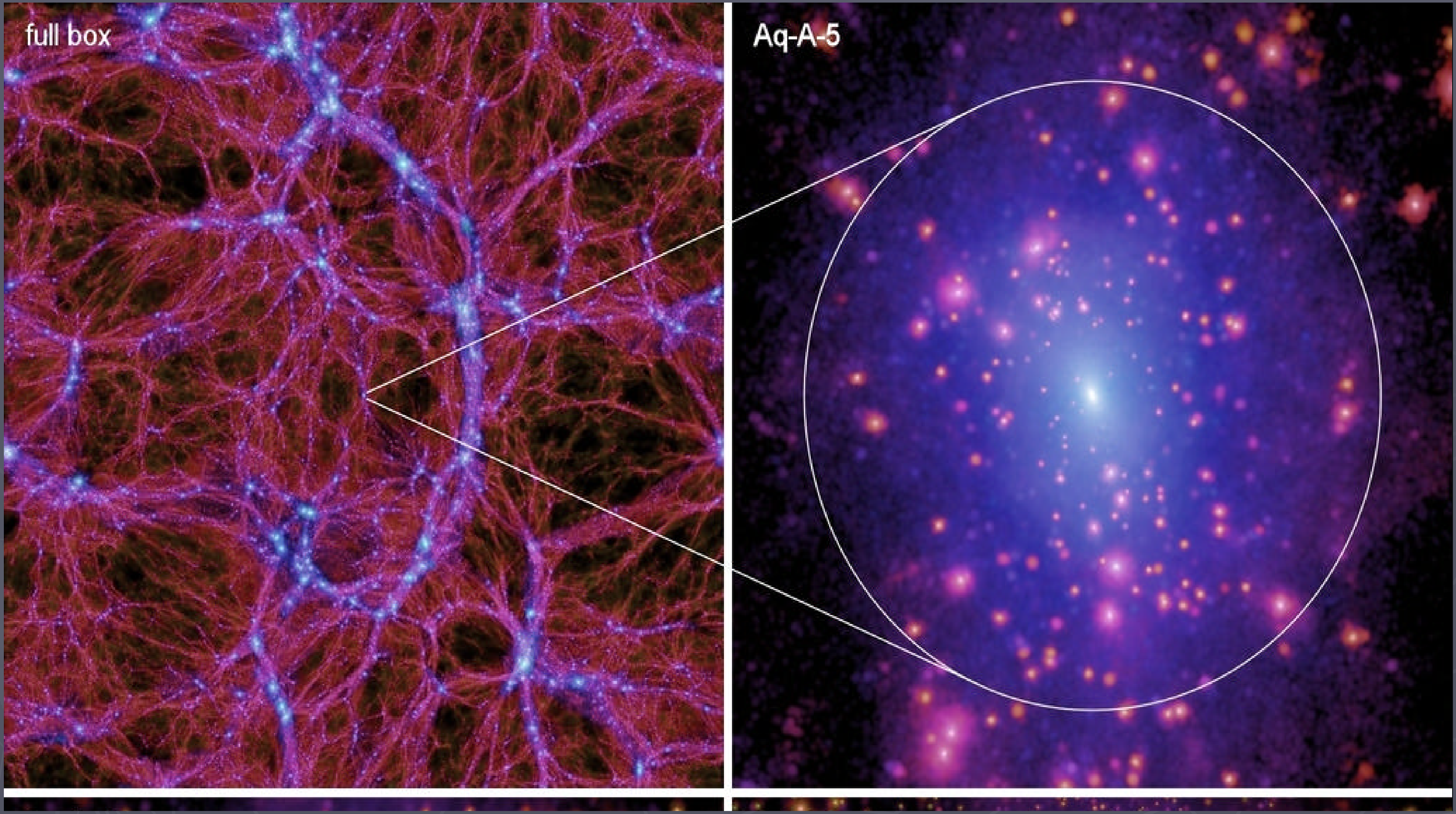
? The mean density of the Universe (baryonic matter in stars, interstellar & intergalactic gas) is only $\Omega_b = 0.046\ \Omega_{critical}$

? The amplitude of the primordial baryon density fluctuations would have needed to be very large in order to form galaxies.

? Fluctuations in the CMB would then also be very large, because they maintain adiabaticity. This would have lead to intolerably large CMB anisotropies today.

) Galaxies could only be formed in the presence of DM which starts to fluctuate early, unhindered by radiation pressure.

XI. Large Scale Structures simulated



Aquarius Simulation, V. Springel et al., Nature 2008

XII. Dark matter from overall fits

- CMB temperature and polarization power spectra (WMAP 5yr)
- Hubble const. $H_0 = 72 \pm 8$ km s^{-1} Mpc^{-1}
- Luminosity distances to 307 SNeIa (HST, SNLS, ESSENCE)
- 6-parameter fit:
  baryons / dark matter =
  $\Omega_b / (\Omega_m - \Omega_b) = 0.20$

E. Komatsu & al., arXiv:0803.0547 and Astrophys. J. Suppl.

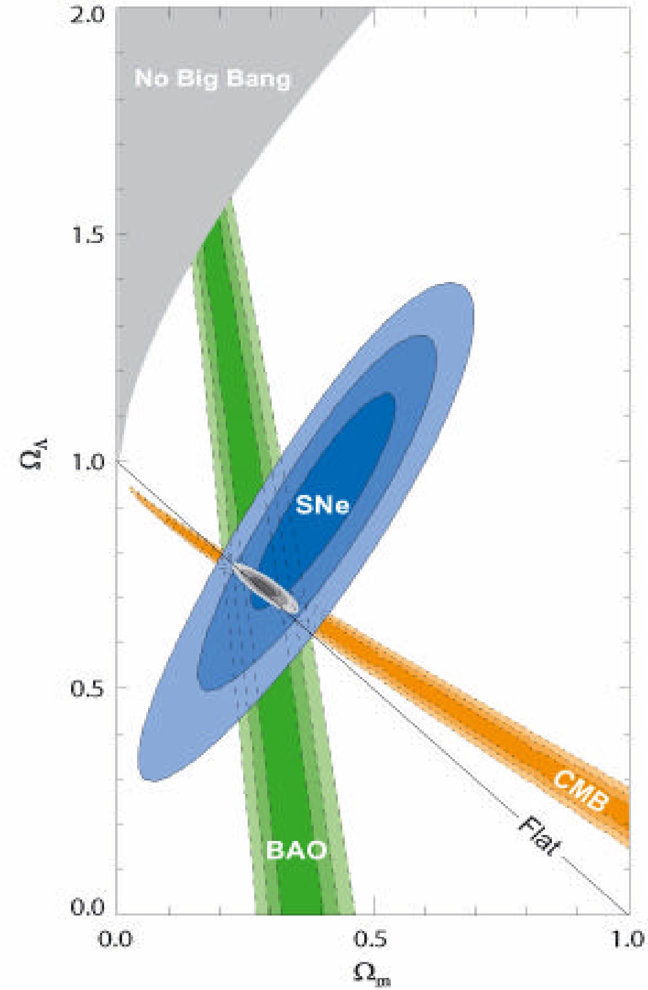


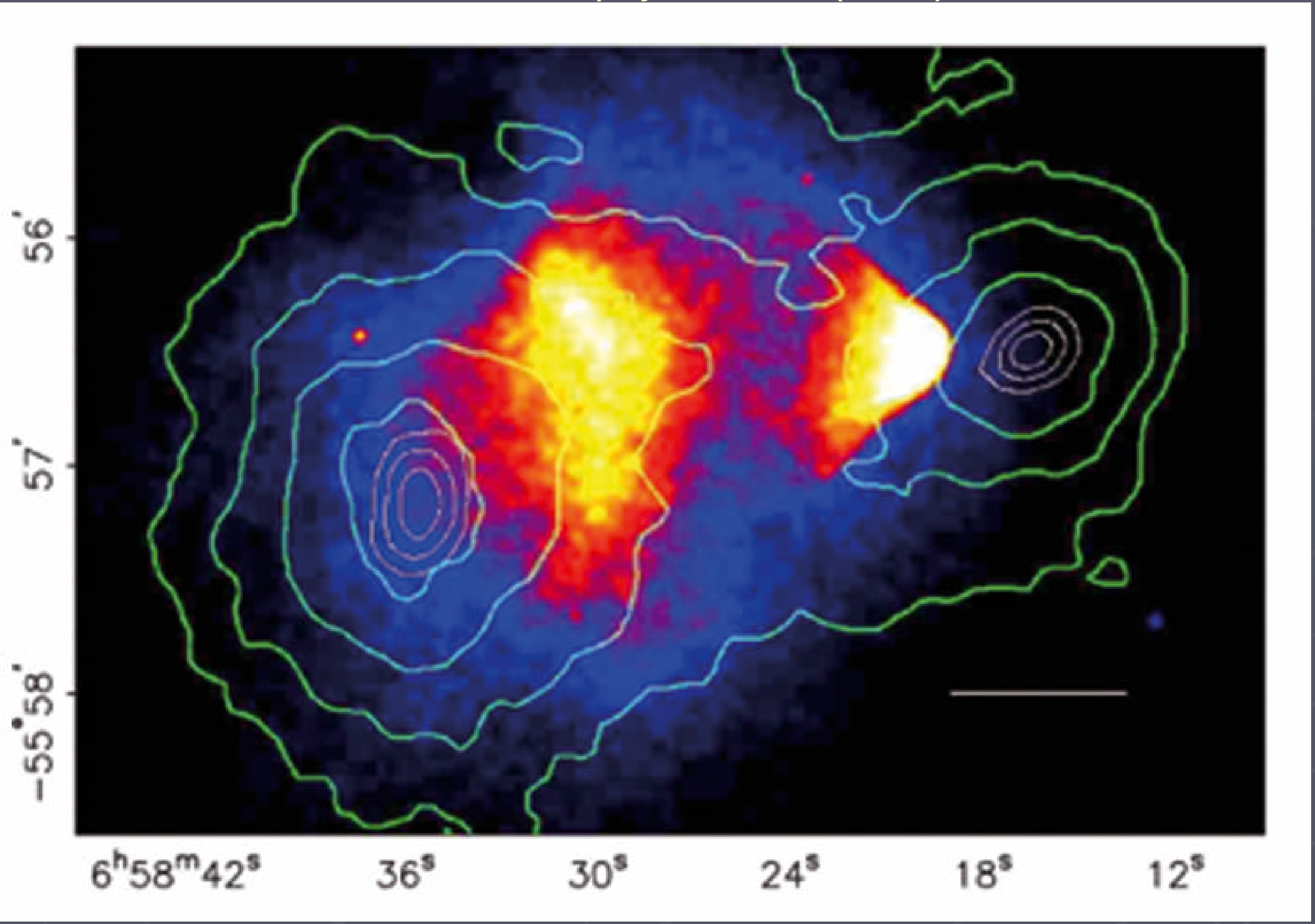
FIG. 15.— 68.3 %, 95.4 % and 99.7% confidence level contours on Ω_Λ and Ω_M obtained from CMB, BAO and the Union SN set as well as their combination (assuming $w = -1$).

XIII. Merging galaxy clusters

- In clusters with recent merging (collisional) activity the positions of the dark matter and the baryonic matter can become temporarily separated.
- The baryonic matter is collisional, hot gas, experiencing ram pressure, and emitting X-rays.
- Dark matter is non-collisional, pressureless, only seen by its gravitational effects on the geometry of space by the weak lensing effect.

The "bullet cluster" IE0657-56

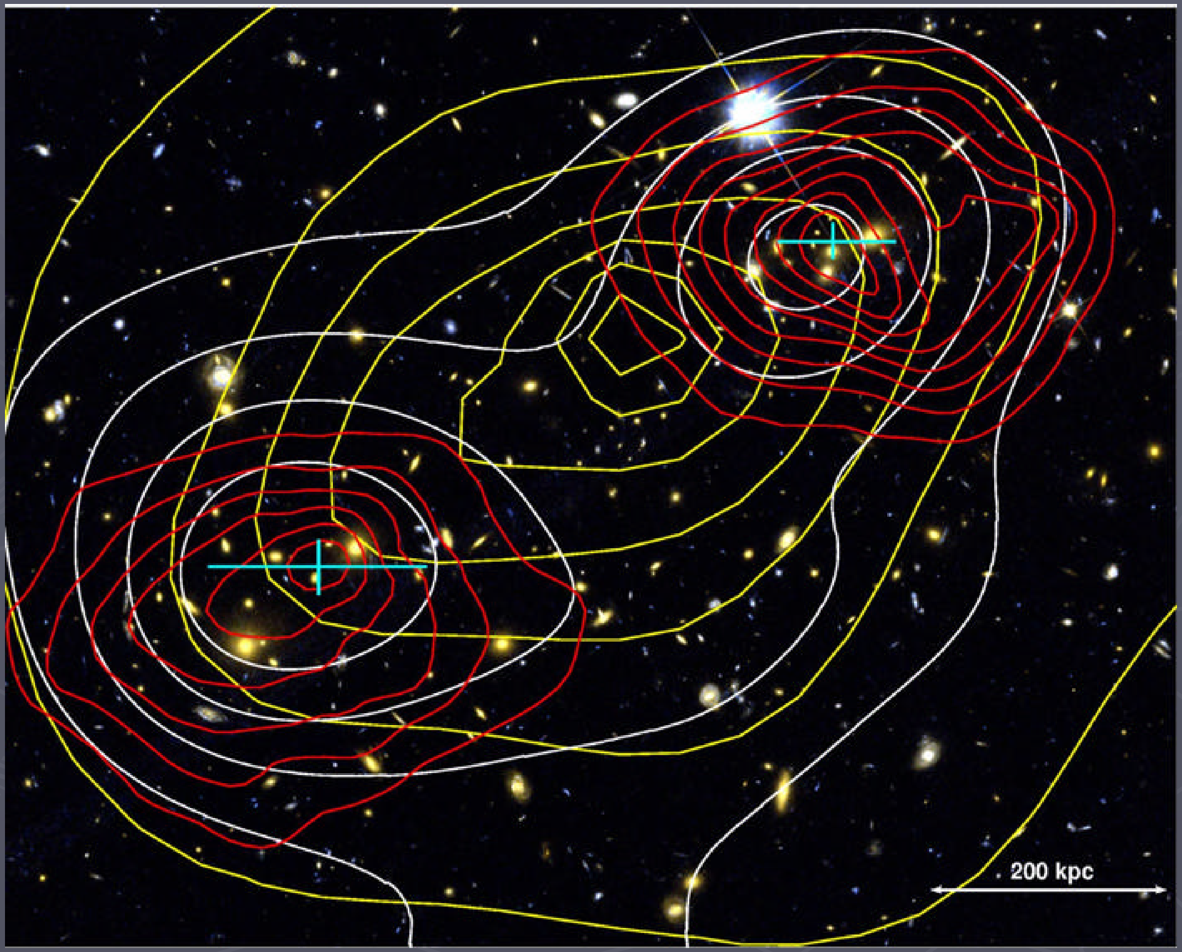
Clowe & al., Astrophys. J. 648 (2006) L109



The post-merging galaxy cluster MACS J0025.4-1222

Bradac & al., arXiv:0806.2320 [astro-ph]

Yellow = X-ray brightness, Red = gravitational field by lensing, White = I-band light



XIV. Conclusions

The nature of Dark matter is not known, but its gravitational influence proves its existence on all scales:

- galaxies
- galaxy groups, small and large
- clusters and superclusters
- CMB anisotropies over the full horizon
- Baryonic oscillations over large scales
- Cosmic shear in the large-scale matter distribution

¡ Thank you !