Dark matter
astrophysical phenomenology

Subir Sarkar

Rudolf Peierls Centre for Theoretical Physics

and

Niels Bohr International Academy, Copenhagen

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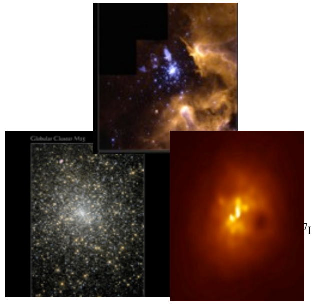
What is the world made of?

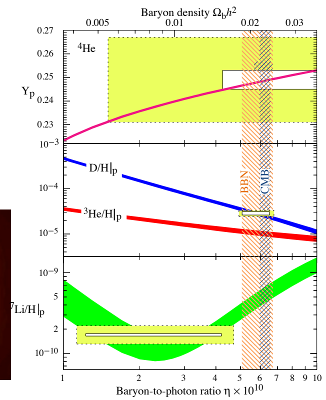
Only geometrical evidence:

$\Lambda \sim H_0^2$, $H_0 \sim 10^{-42}$ GeV

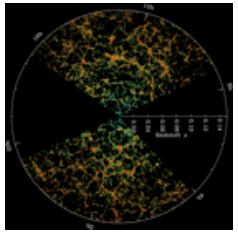
… dark energy is mainly *inferred* from the 'cosmic sum rule':

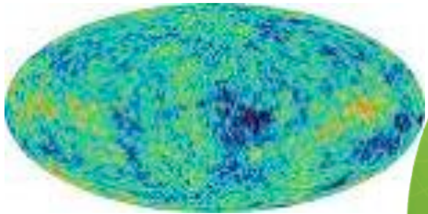
$\mathbf{\Omega_m} + \mathbf{\Omega_k} + \mathbf{\Omega_\Lambda} = 1$

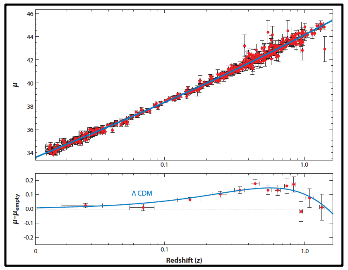


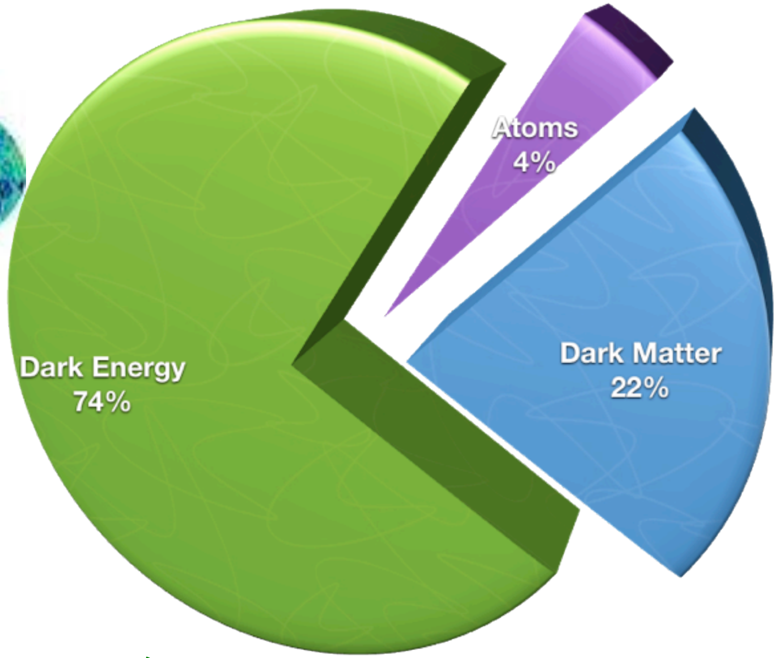


Baryons (but no anti-baryons)

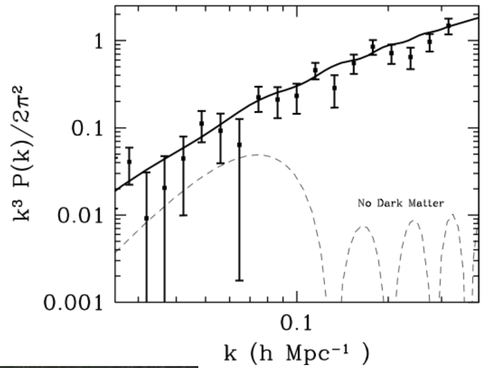






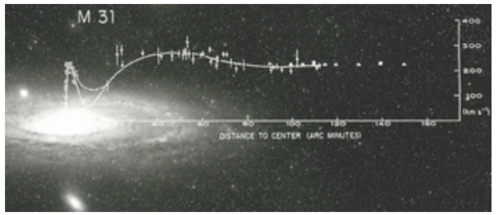


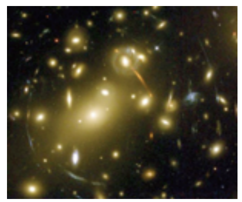
Both geometrical and dynamical evidence (if GR is valid on all scales)



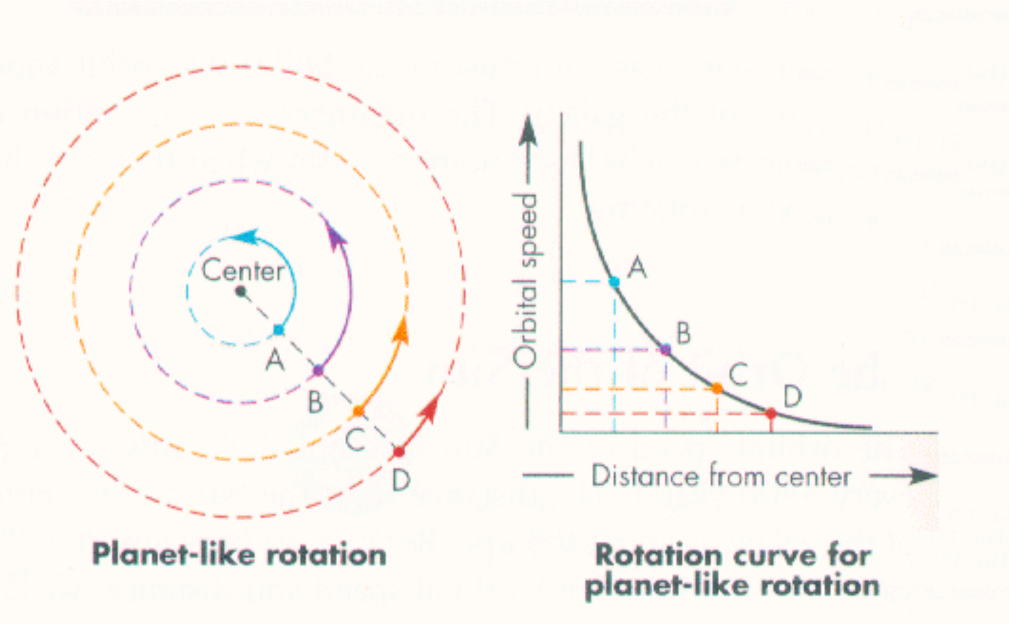
No significant dynamical evidence seen for negative pressure (e.g. late ISW effect)

… is dark energy being faked (e.g. by cosmic inhomogeneity → 'back reaction') ?





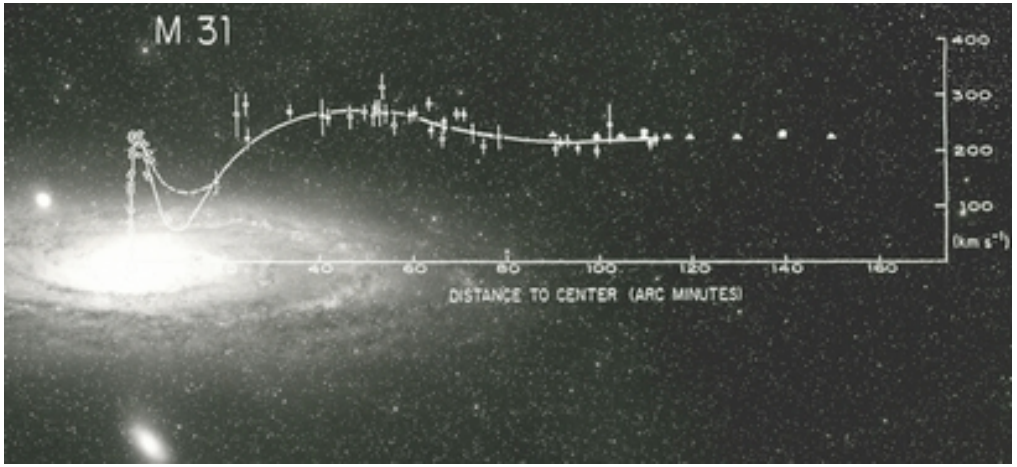
The modern saga of dark matter starts with the rotation curves of spiral galaxies



At large distances from the centre, beyond the edge of the visible galaxy, the velocity would be expected to fall as $1/\sqrt{r}$ if most of the matter is contained in the optical disc

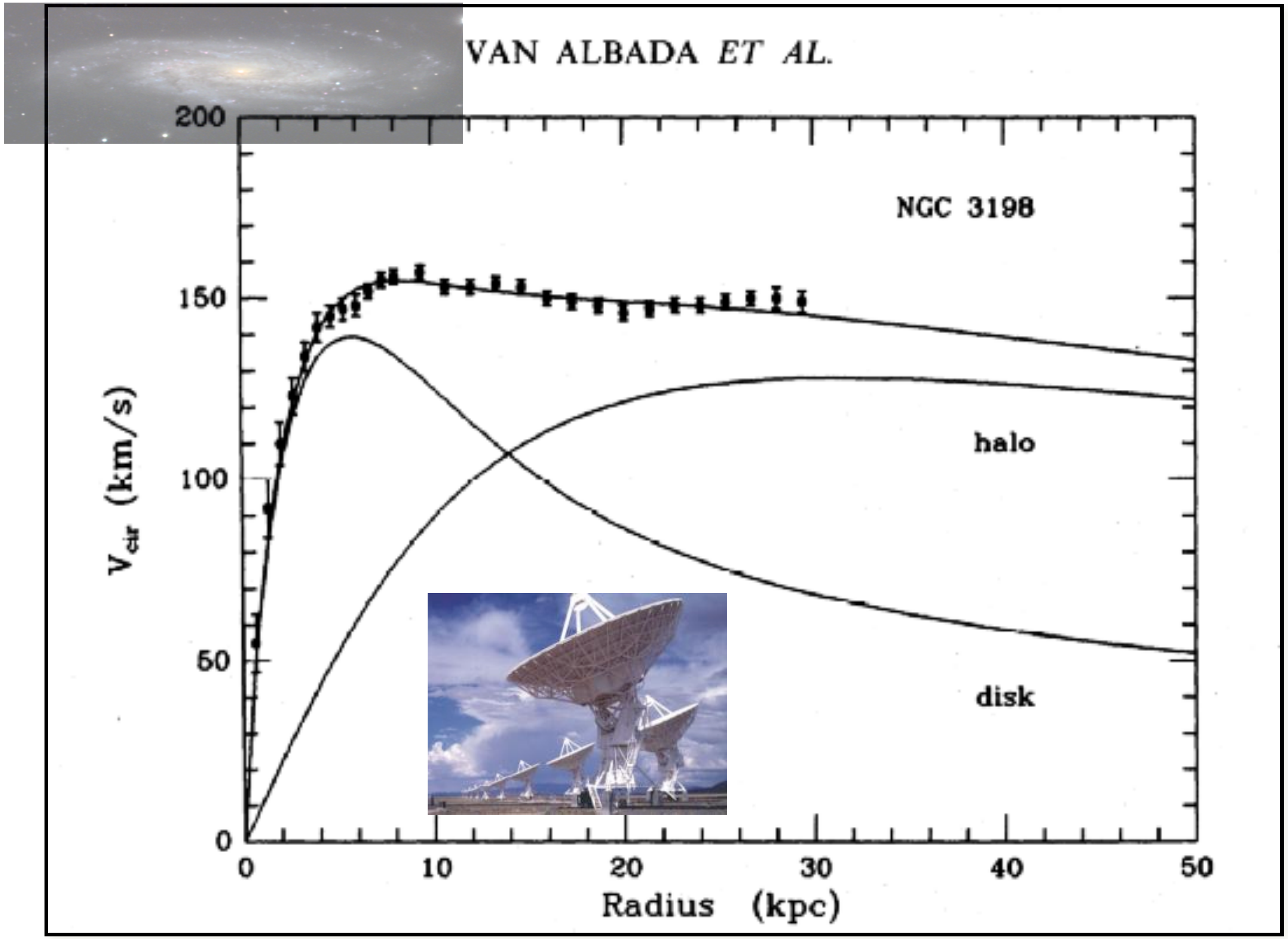
$$v_{\rm circ} = \sqrt{\frac{G_{\rm N} M(<r)}{r}}$$

… but Vera Rubin *et al* (1970) observed that the rotational velocity remains ~constant in Andromeda, implying the existence of an extended (dark) halo



$$v_{\rm circ} \sim \text{constant} \quad \Rightarrow \quad M(<r) \propto r \quad \Rightarrow \quad \rho \propto 1/r^2$$

The really compelling evidence for extended halos of dark matter came from radio astronomical observations in the 1980's of the 21-cm line of neutral hydrogen ... orbiting well beyond the visible disk of the galaxy



To match this, the disk M/L ratio would have to rise significantly in the outer regions

With the $1/r^2$ density profile, the solution of the collisionless Boltzmann equation is the 'Maxwellian distribution', with velocity dispersion:

$$\frac{\partial f}{\partial t} + \mathbf{v}.\frac{\partial f}{\partial \mathbf{x}} - \frac{\partial \Phi}{\partial \mathbf{x}}\frac{\partial f}{\partial \mathbf{v}} = 0$$

$$f(\mathbf{v}) = N \exp\left(-\frac{3|\mathbf{v}|^2}{2\sigma^2}\right)$$

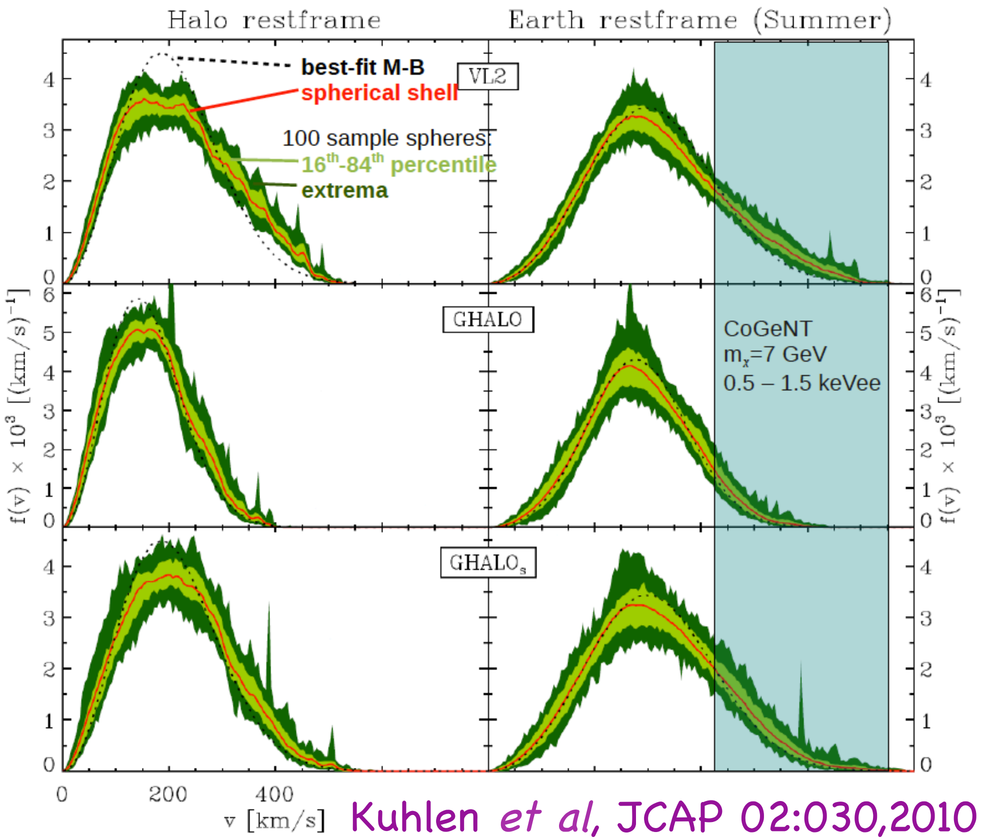
$$\sigma = \sqrt{3/2}\, v_c$$

The 'standard halo model' has $v_c = 220$ km/s and is truncated at $v_{esc} = 544$ km/s (both numbers have large uncertainties)

High resolution numerical simulations however suggest significant deviations from the Maxwellian distribution, particularly at high velocities

(This has significant implications for dark matter detection)

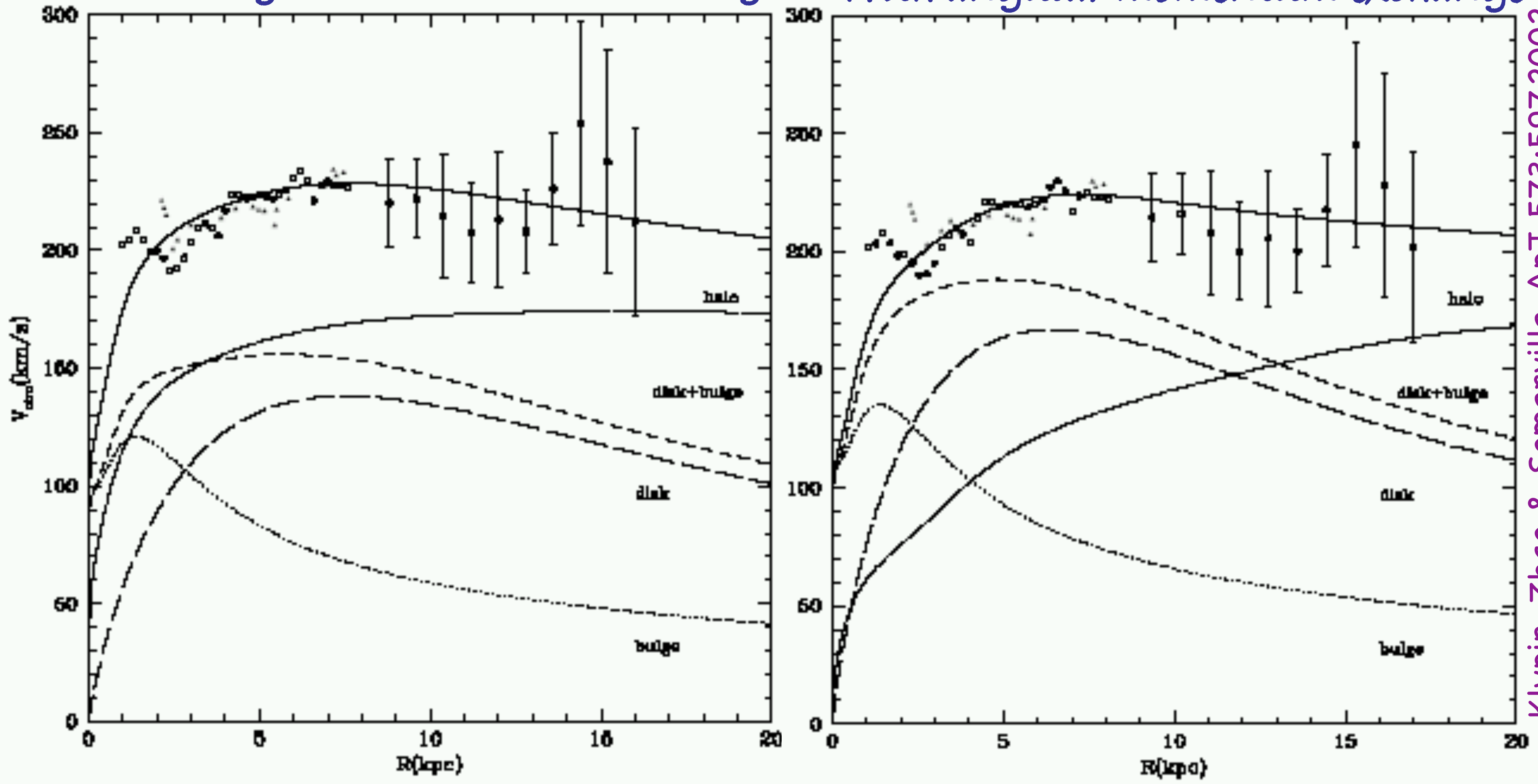
However the `feedback' effect of baryons is probably *more* important



Kuhlen *et al*, JCAP 02:030,2010

More sophisticated modelling needs to account for multiple components and the gravitational coupling between baryonic and dark matter ("disk-halo conspiracy")

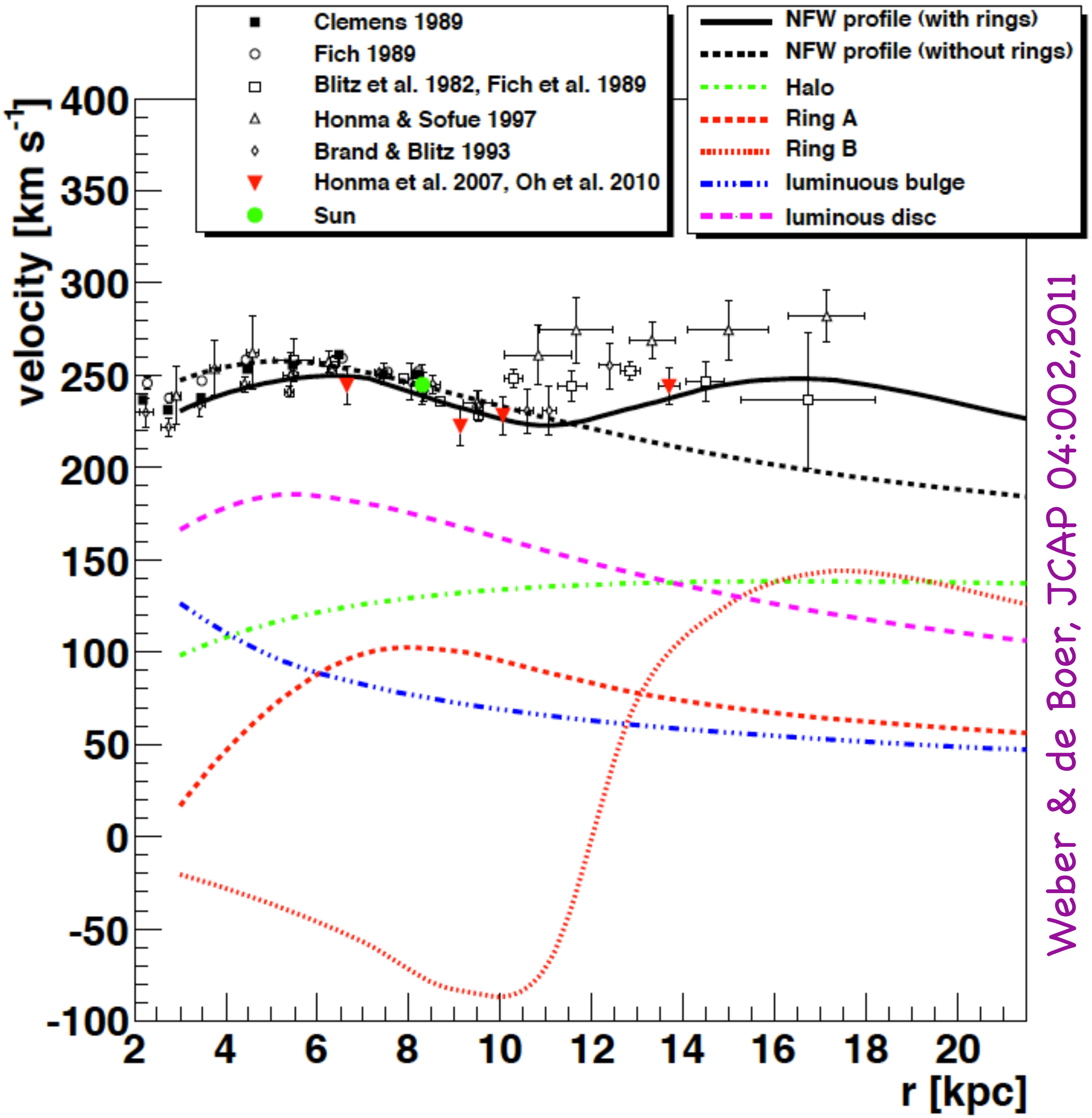
No angular momentum exchange | With angular momentum exchange



Klypin, Zhao & Somerville, ApJ 573:597,2002

The local halo density of dark matter is ~0.3 GeV/cm^3 (factor of ~2 uncertainty)
… a better determination may not be possible until the advent of GAIA (>2014)

Another fit ... where the local halo DM density is 1.3 ± 0.3 GeV cm^{-3} !



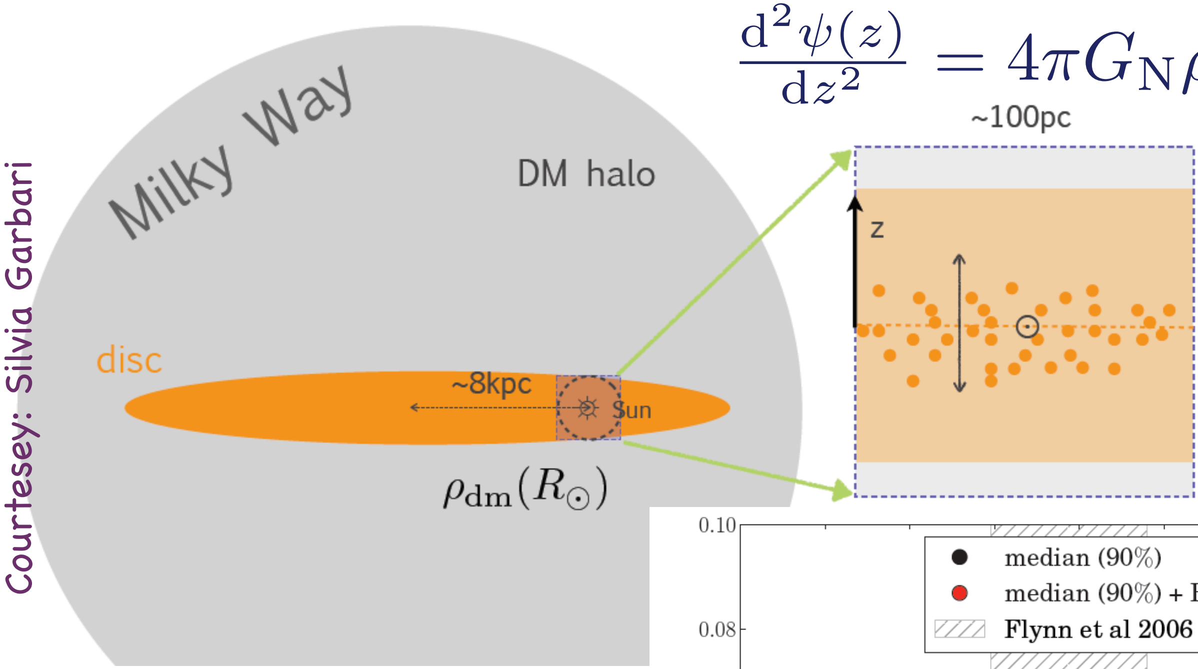
Weber & de Boer, JCAP 04:002,2011

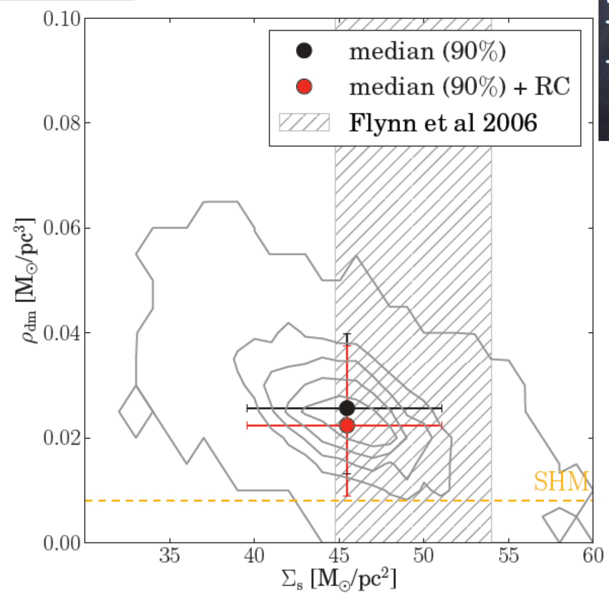
Can also infer local dark matter density by measuring vertical distribution of stars ... pioneered by Kapetyn (1922) and Oort (1932)

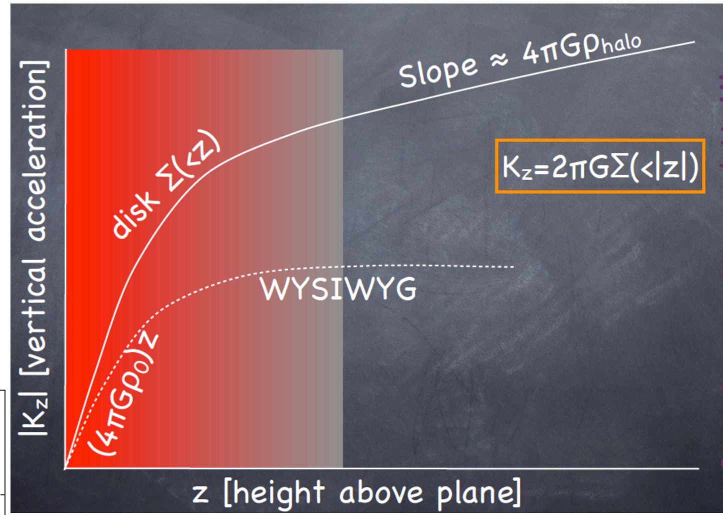
If galaxy is approximated as thin disk, then orthogonal to the Galactic plane:

$$\frac{\mathrm{d}^2\psi(z)}{\mathrm{d}z^2} = 4\pi G_\mathrm{N}\rho_\mathrm{m} \rightarrow \frac{\mathrm{d}\psi(z)}{\mathrm{d}z} = 2\pi G_\mathrm{N}\Sigma_\mathrm{m}$$

Courtesey: Silvia Garbari





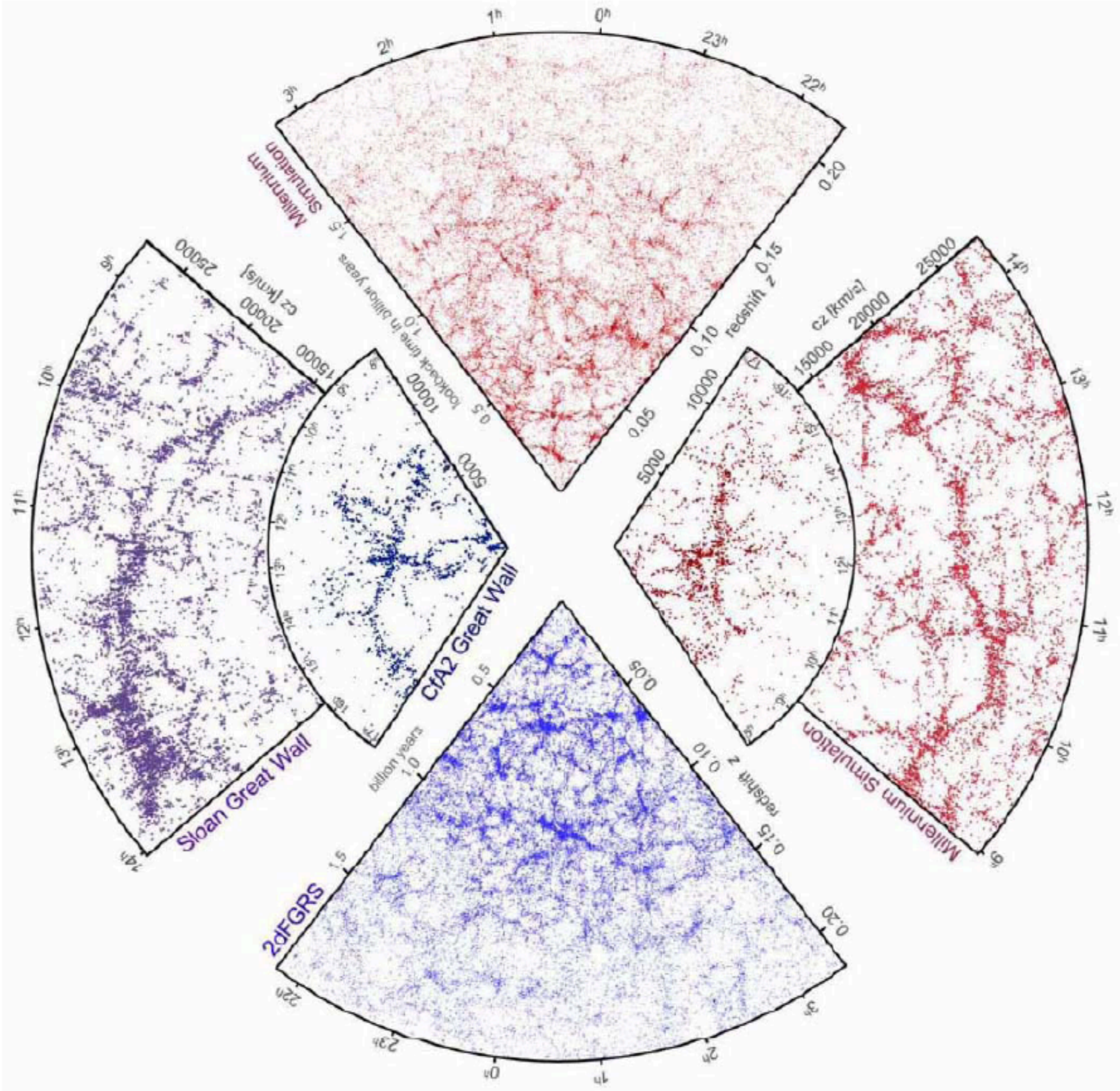


Courtesey: Konrad Kuijken

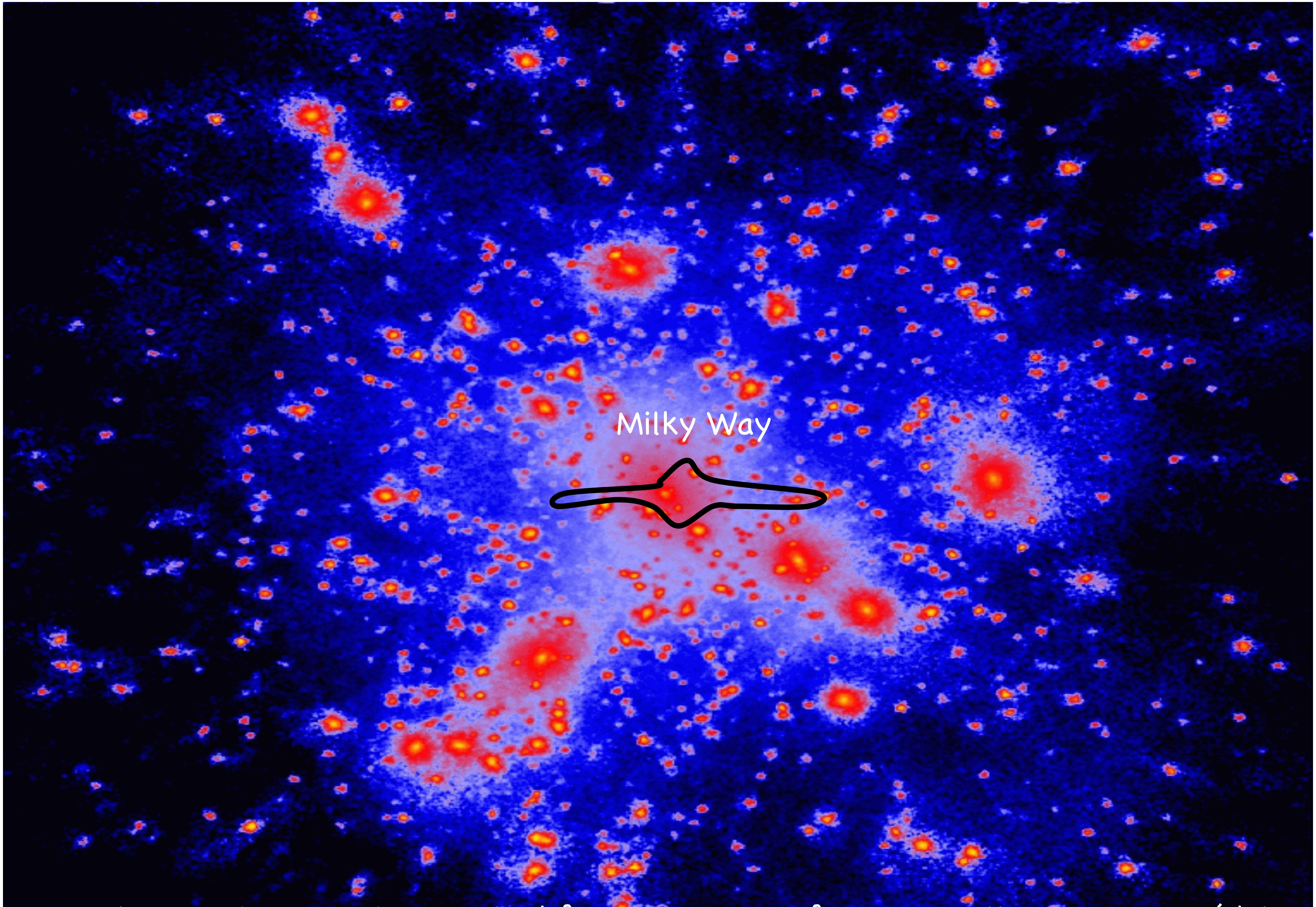
Using data on K-dwarfs (Kuijken & Gilmore 1989) yields: $\rho_\mathrm{DM} = 0.85 \pm 0.6\ \mathrm{GeV/cm^3}$

Garbari, Liu, Read & Lake, MNRAS 425:1445,2012

Such numerical simulations provide a pretty good match to the observed large-scale structure of galaxies in the universe



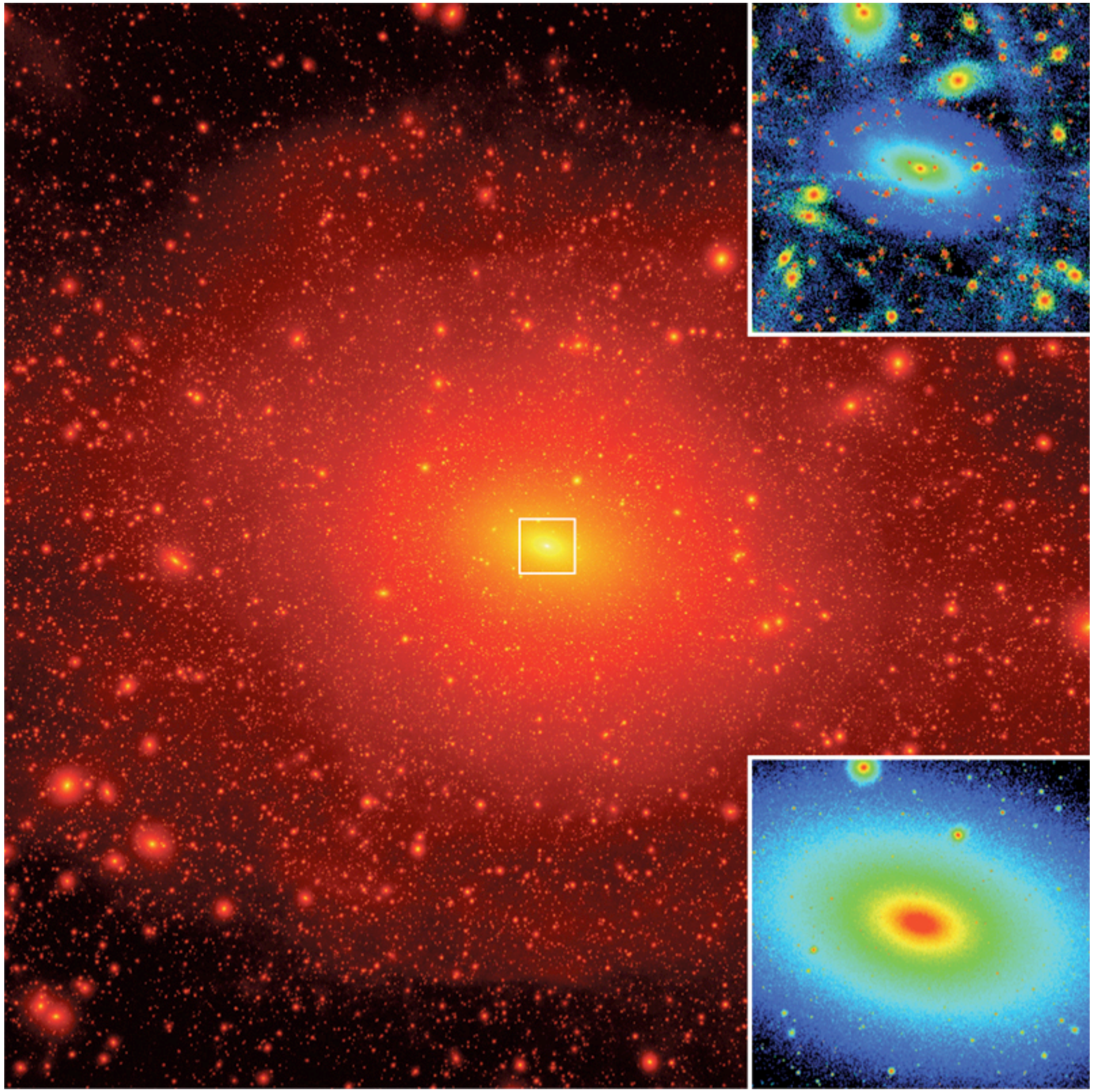
Springel, Frenk & White, Nature 440:1137,2006



A galaxy such as ours has resulted from the merger of many smaller structures, tidal stripping, baryonic infall and disk formation et cetera over billions of years

So the (phase space) structure of the dark halo is complicated ...

Via Lactea II projected dark matter (squared-) density map



phase space

real space

Diemand, Kuhlen, Madau, Zemp, Moore, Potter & Stadel, Nature 454:735,2008

But real galaxies appear simpler than expected!

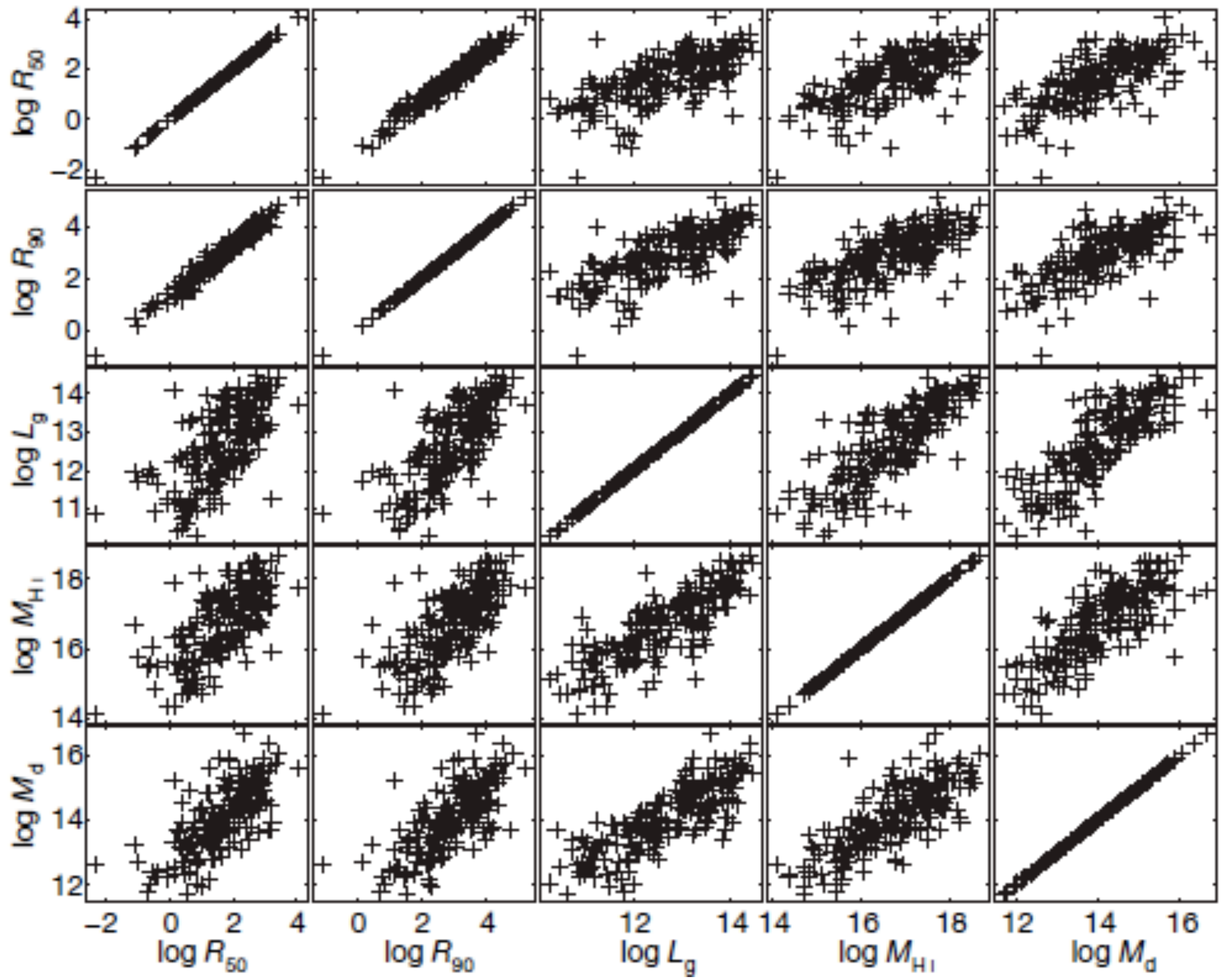
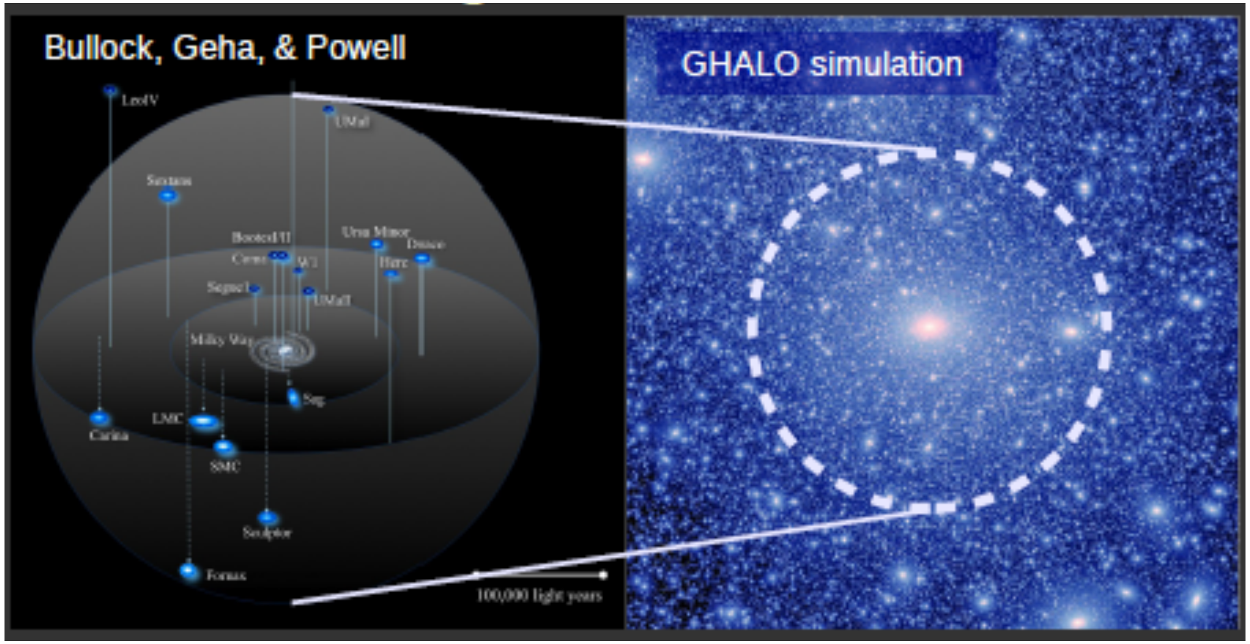
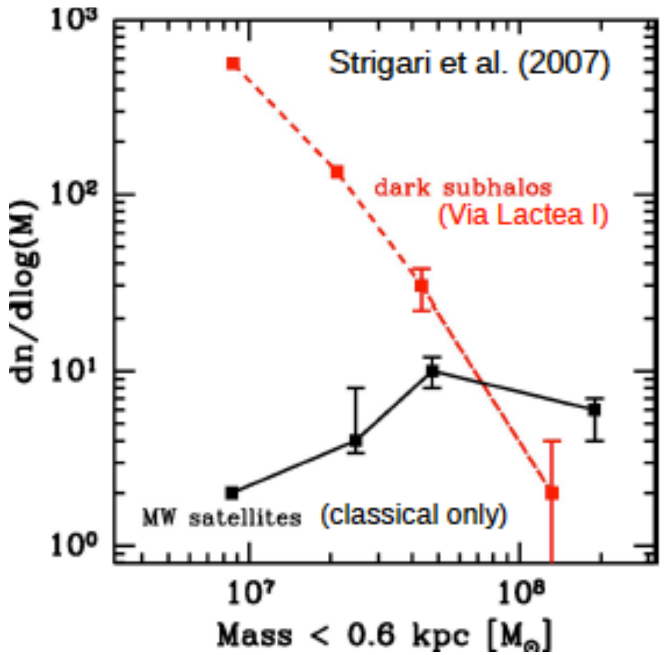


Figure 1 | Scatter plots showing correlations between five measured variables, not including colour. The variables are two optical radii, R_{50} and R_{90} (in parsecs), respectively containing 50 and 90% of the emitted light; and luminosity, L_g; neutral hydrogen mass, $M_{\mathrm{H\,I}}$; and dynamical mass, M_d (inferred from the 21-cm linewidth, the radius and the inclination in the

Disney, Romano, Garcia-Appadoo, West, Dalcanton & Cortese, Nature 455:1082,2008

Moreover whereas the Milky Way does have satellite galaxies and substructure, there is *a lot less* than is expected from the numerical simulations

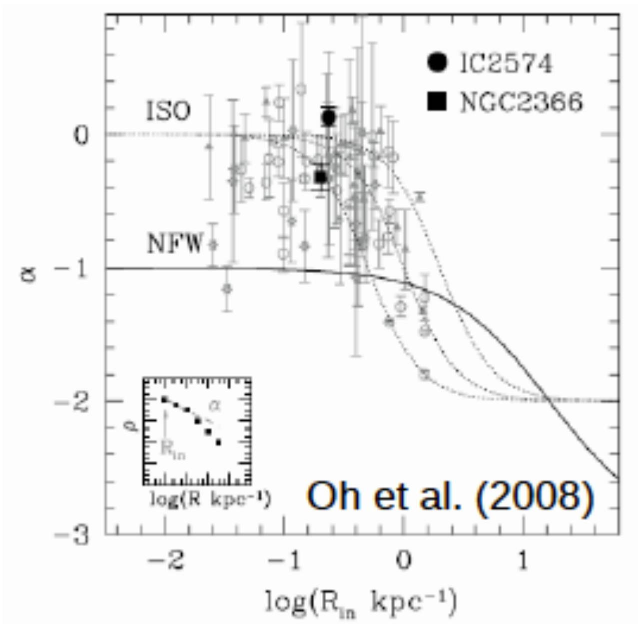




Courtesey: Michael Kuhlen

Also, the density profile of the halo (for collisionless dark matter) is predicted to be \`cuspy' … whereas observations suggest \`cored' isothermal profiles in many cases

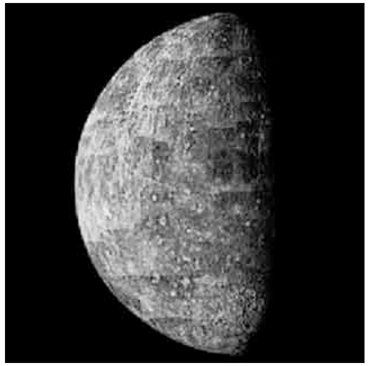
(This could be because of the \`feedback effects' of baryons … simulations are just getting to the point where this can be tested)



Inferences of dark matter are not always right … it may instead be a change in the dynamics

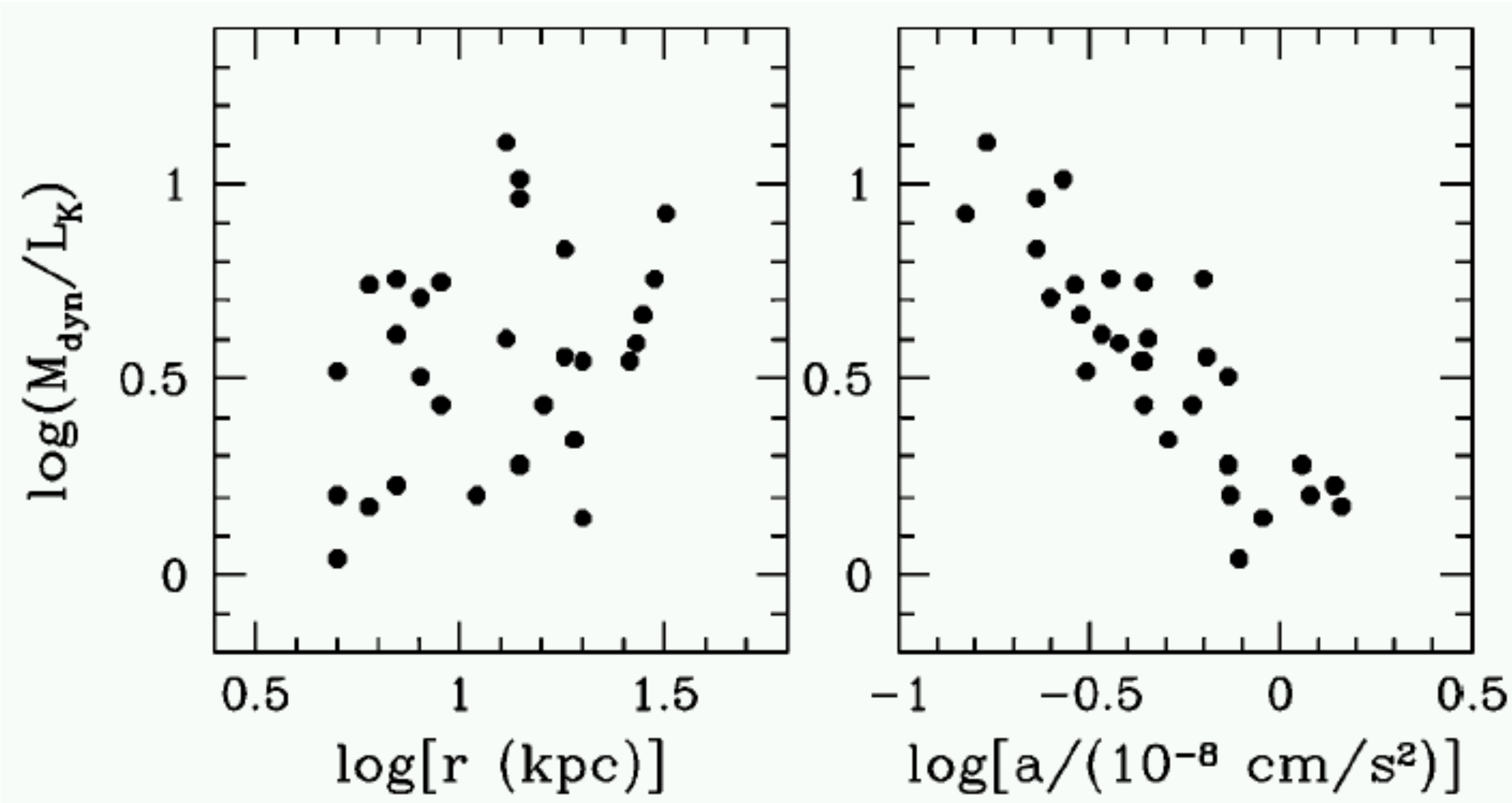
2 Jan 1860: "Gentlemen, I Give You the Planet Vulcan" - French mathematician Urbain Le Verrier announces the discovery of a new planet between Mercury and the Sun, to members of the Académie des Sciences in Paris (following up on his earlier successful prediction of Neptune in 1856)

Some astronomers even see Vulcan in the evening sky!



But the precession of Mercury is not due to a dark planet but because Newton is superseded by Einstein for strong fields … could the same happen for very *weak* gravitational fields?

Dark matter seems to be required only where the test particle acceleration is low (below $a_0 \sim 10^{-8}$ cm/s^2) - it is *not* a spatial scale-dependent effect



What if Newton's law is modified in weak fields?

$$F_N \to \sqrt{\frac{GM}{r^2} a_0}$$

Milgrom, ApJ 270:365,1983

Bekenstein—Milgrom Equation

Suppose $\mathbf{F} = -\nabla\phi$ where

$$\nabla^2\phi_{\rm N} = 4\pi G\rho \quad \to \quad \nabla\cdot[\mu(|\nabla\phi|/a_0)\nabla\phi] = 4\pi G\rho$$

where

$$\mu(x) \to \begin{cases} 1 & \text{for } x \gg 1 \\ x & \text{for } x \ll 1 \end{cases}$$

Then

$$0 = \nabla\cdot[\mu(|\nabla\phi|/a_0)\nabla\phi - \nabla\phi_{\rm N}]$$

implies

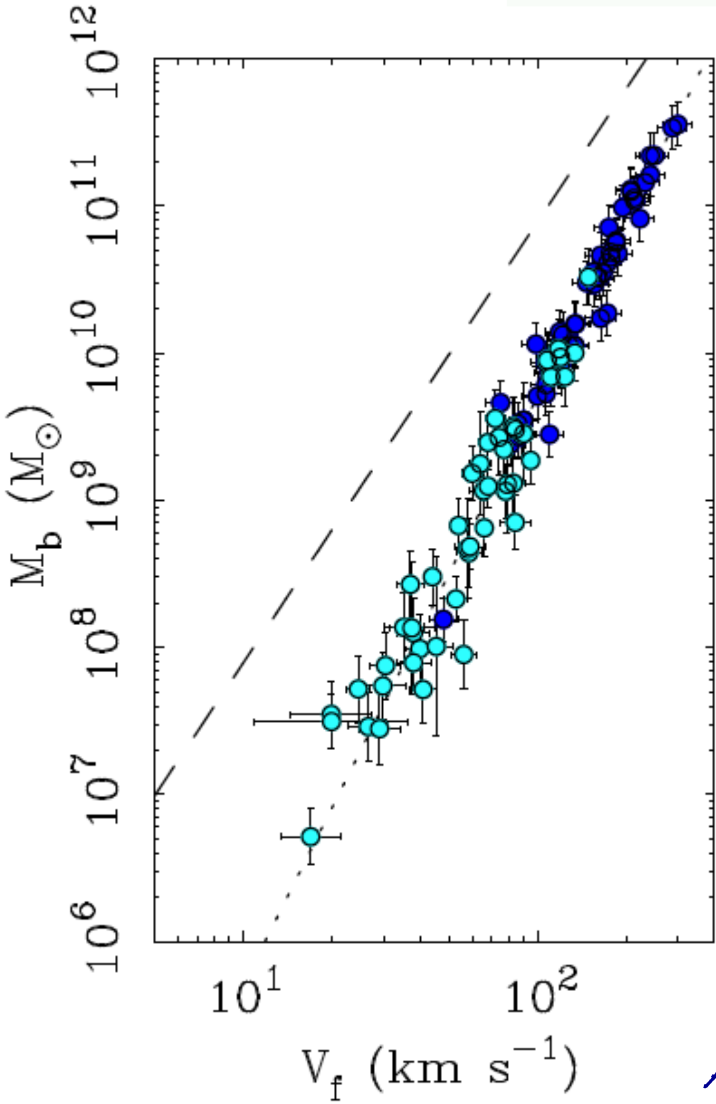
$$\mu(|\nabla\phi|/a_0)\nabla\phi = \nabla\phi_{\rm N} + \nabla\times\mathbf{A}$$

so when $\mathbf{A} \simeq 0$ and $|\nabla\phi| \ll 1$

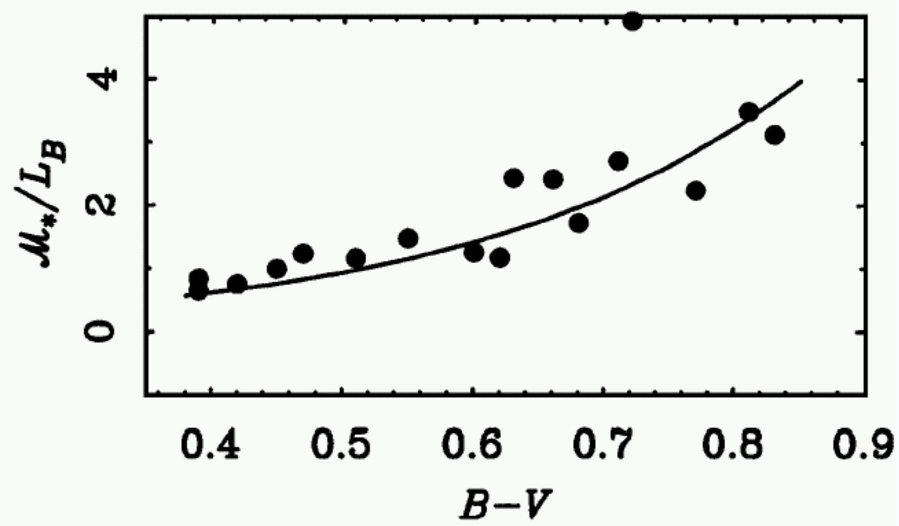
$$g_{r\to\infty} \to -\sqrt{MGa_0}\,\frac{\vec{r}}{r^2} + \mathcal{O}\left(\frac{1}{r^2}\right), \quad \frac{|\nabla\phi|^2}{a_0} = |\nabla\phi_{\rm N}|$$

Milgrom, arXiv:0912.2678

$$\frac{v^4}{r^2} = \frac{GM}{r^2} a_0 \qquad \Rightarrow \qquad M \propto v^4 \quad (\text{Tully–Fisher if } \frac{M}{L} = \text{const})$$



McGaugh, PRL 106:121303,2011



The fitted value of the free parameter (M/L) agrees well with population synthesis models
Sanders & Verheijen, ApJ 503:97,1998

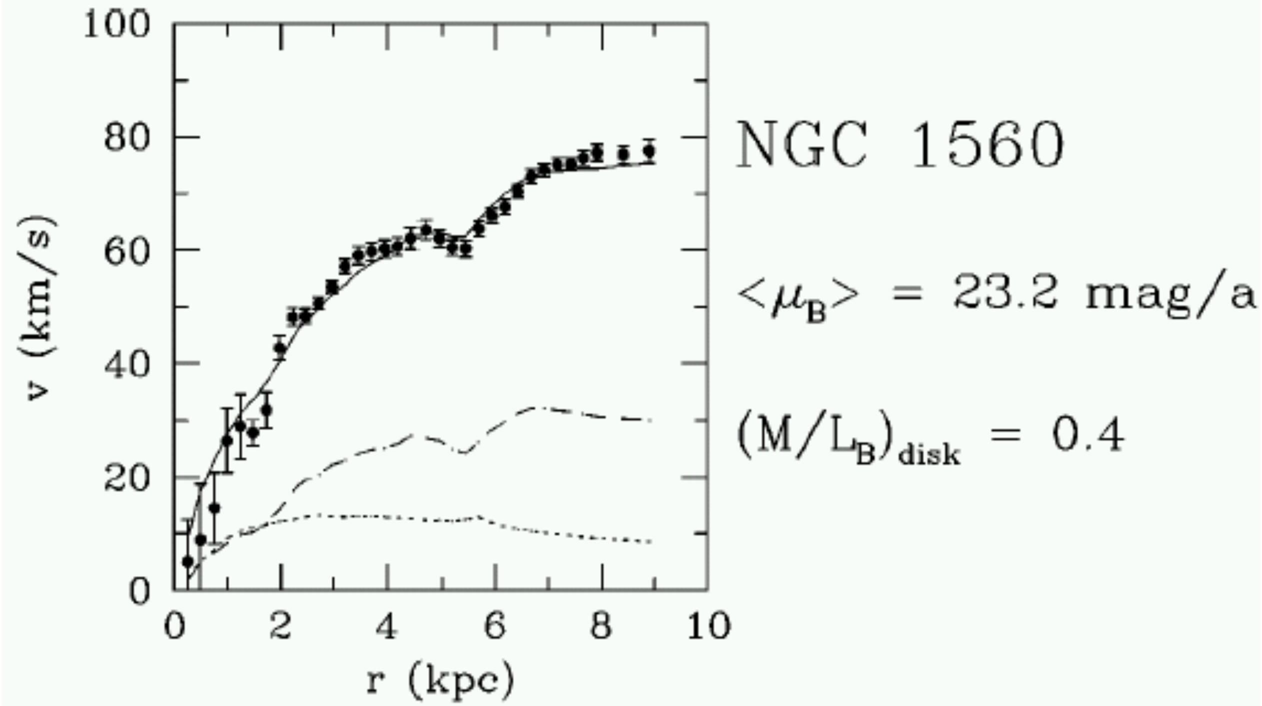
For CDM would expect $M_{\rm vir} = \frac{4\pi}{3} \Delta \rho_{\rm crit} R_{\rm vir}^3$

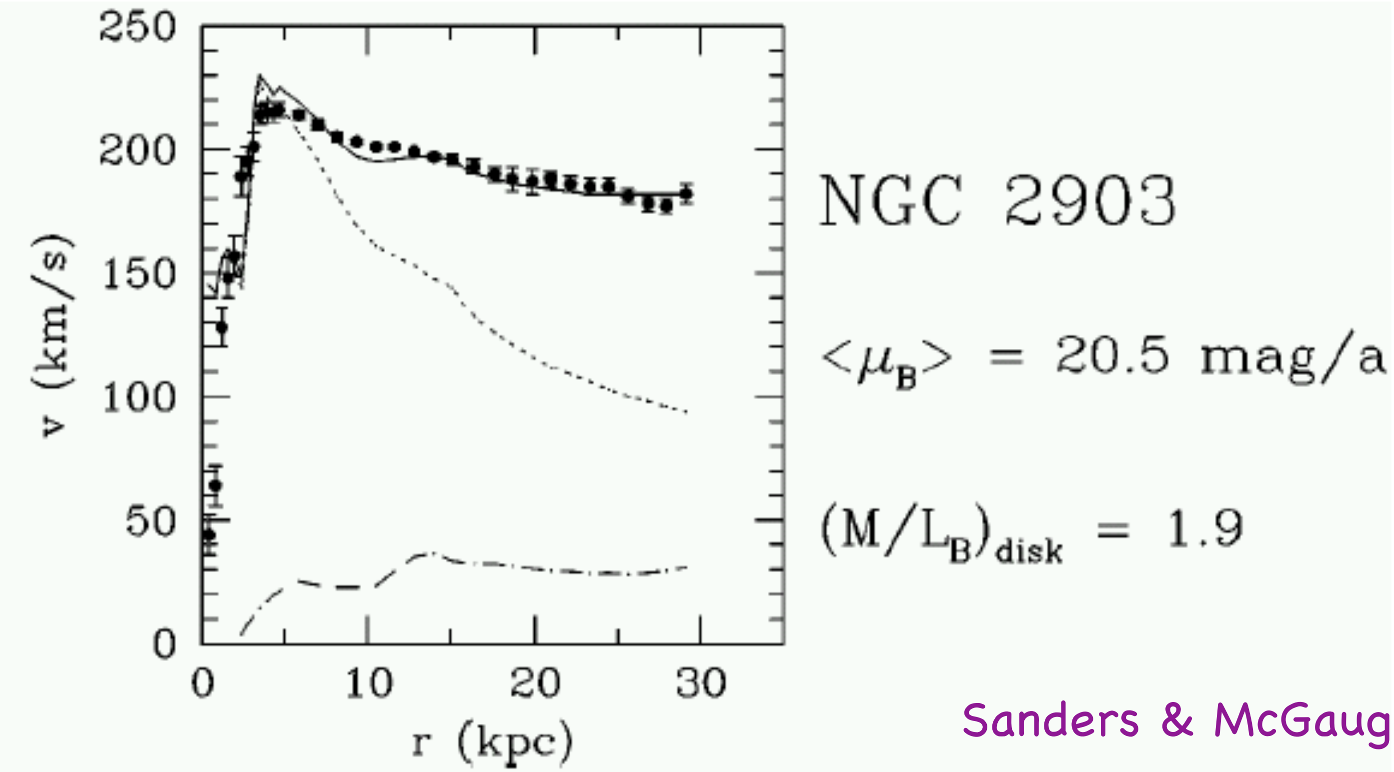
… where Δ is the overdensity in units of the critical density → ~178 in spherical collapse

Also $\frac{V_{\rm vir}^2}{R_{\rm vir}} = \frac{GM_{\rm vir}}{R_{\rm vir}^2} \Rightarrow M_{\rm vir} = (\frac{\Delta}{2})^{-\frac{1}{2}} (GH_0)^{-1} V_{\rm vir}^3$

(Now need to relate M_{vir} to the baryonic mass and V_{vir} to the rotational velocity … this is model-dependent but can it steepen the relationship to the observed one?)

Excellent fits to galactic rotation curves with a_0=1.2x10^{-8} cm s^{-2}

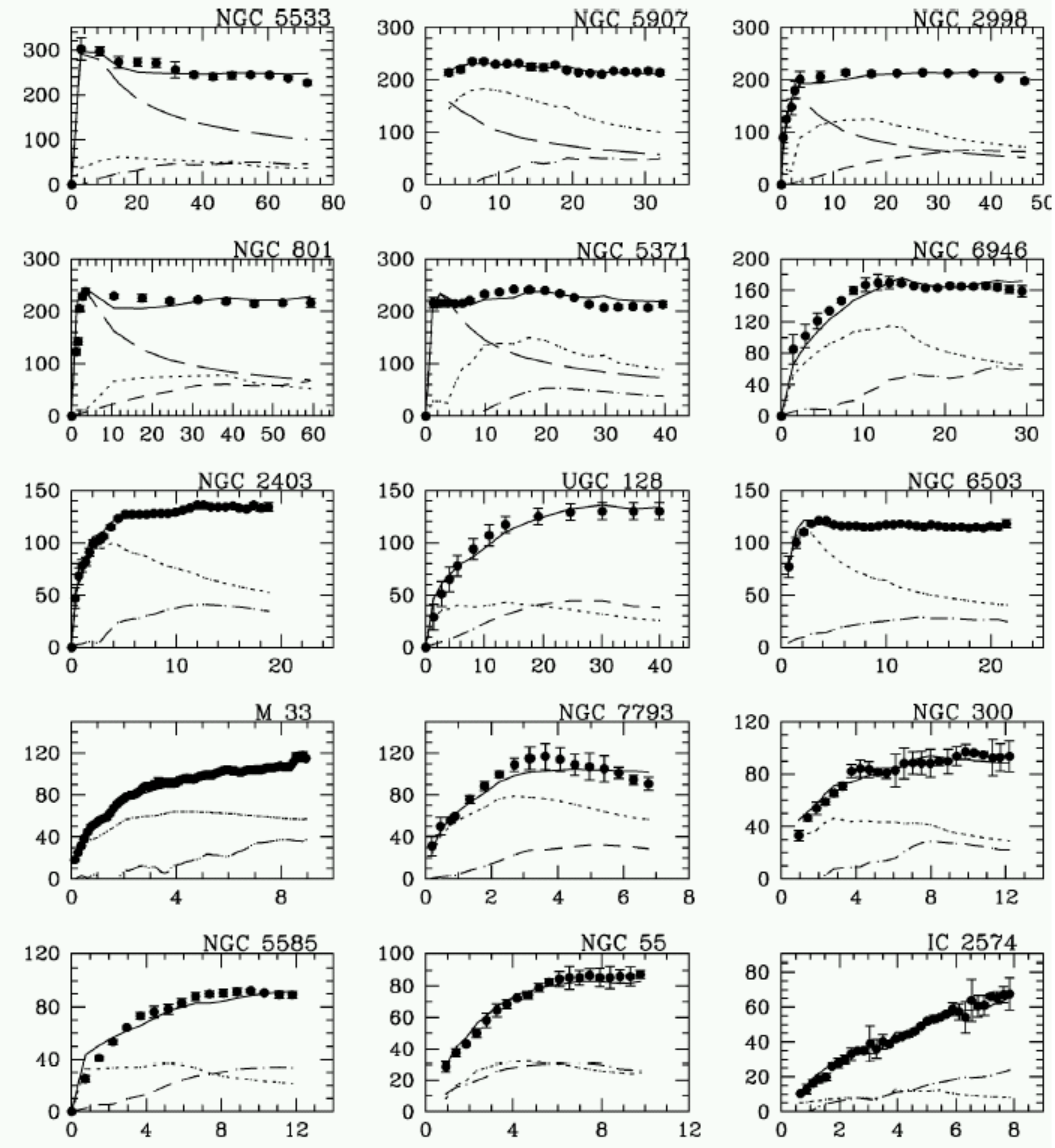




Features in the baryonic disc have counterparts in the rotation curve

Sanders & McGaugh, ARAA 40:093923,2002

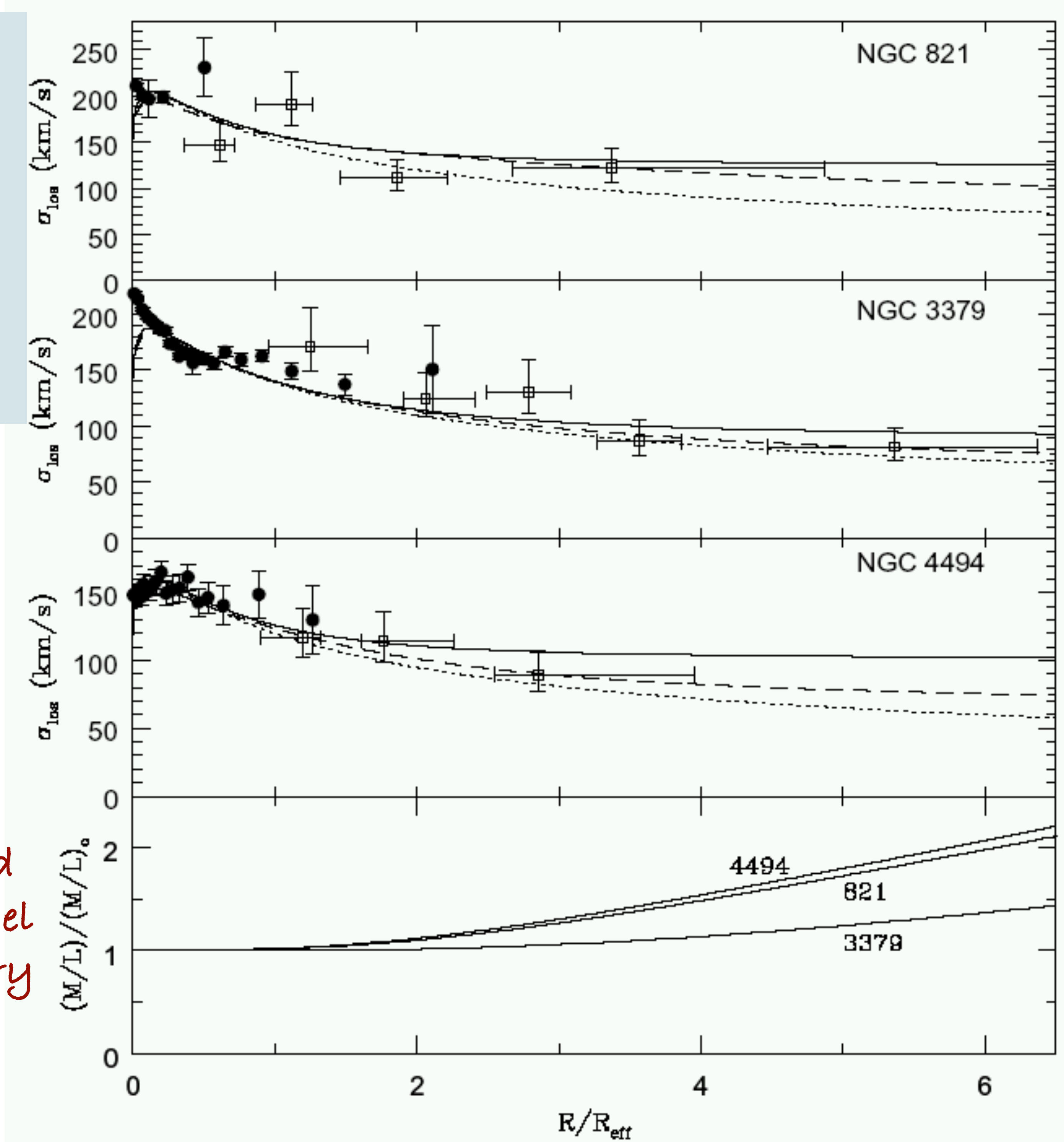
A huge variety of rotation curves is well fitted by MOND



Sanders & Verheijen, ApJ 503:97,1998

… with *fewer* parameters than are required by the dark matter model

Moreover some giant elliptical galaxies do exhibit Keplerian fall-off of the random velocity dispersion, as was predicted by MOND

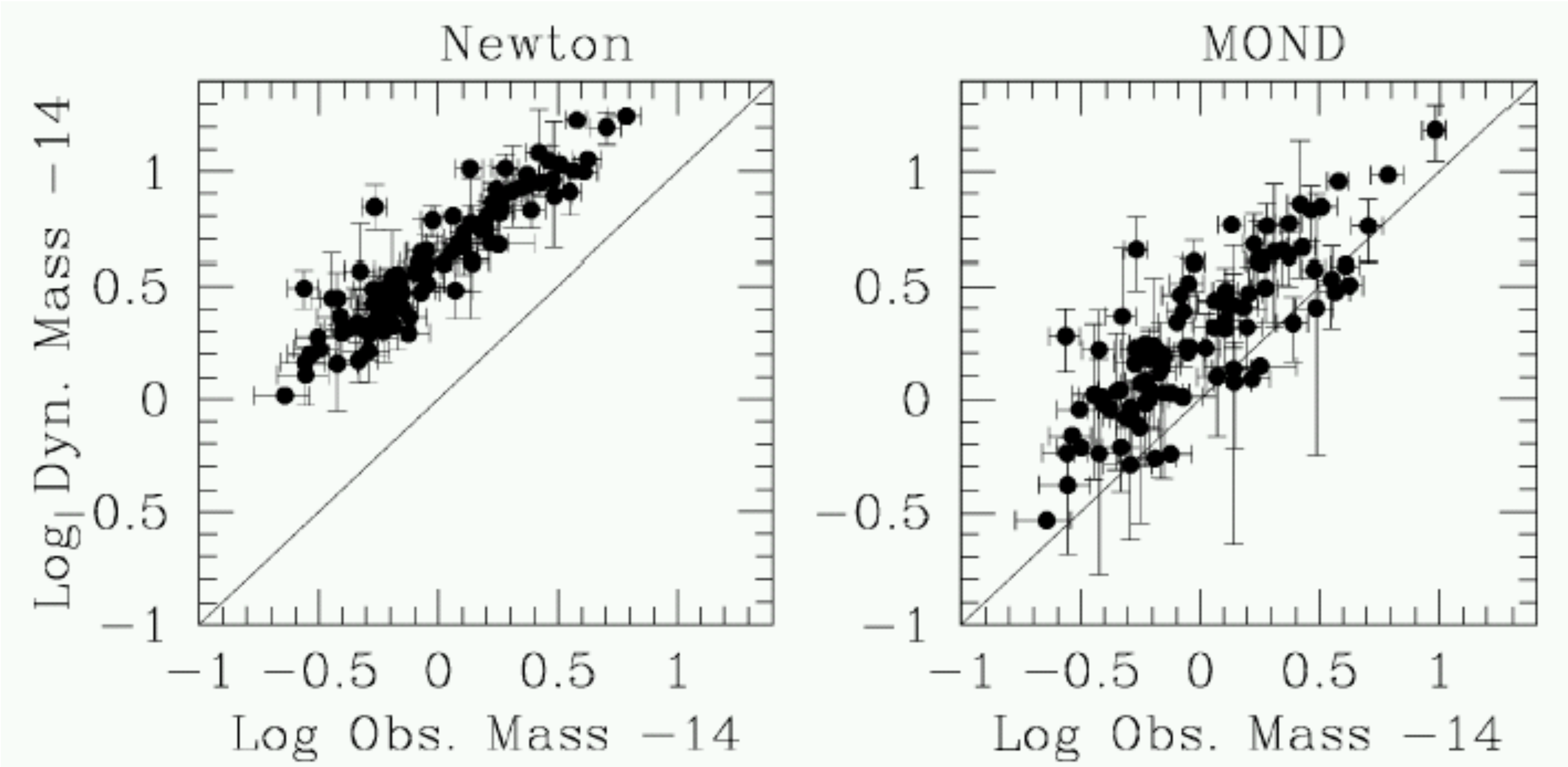


Data:
Romanowsky *et al,*
Science 301:1696,2003

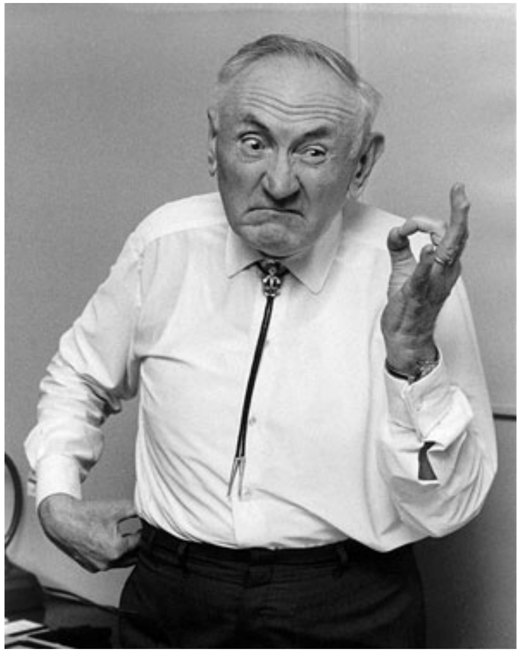
Models:
Milgrom, Sanders,
ApJ 599:L25,2003

(This can be explained in a dark matter model if stellar orbits are very elliptical, Dekel *et al,* Nature 437:707,2005)

However MOND *fails* on the scale of clusters of galaxies



The "missing mass" cannot be accounted for entirely by invoking MOND ... **dark matter is required** (thus vindicating the original proposal of Zwicky)



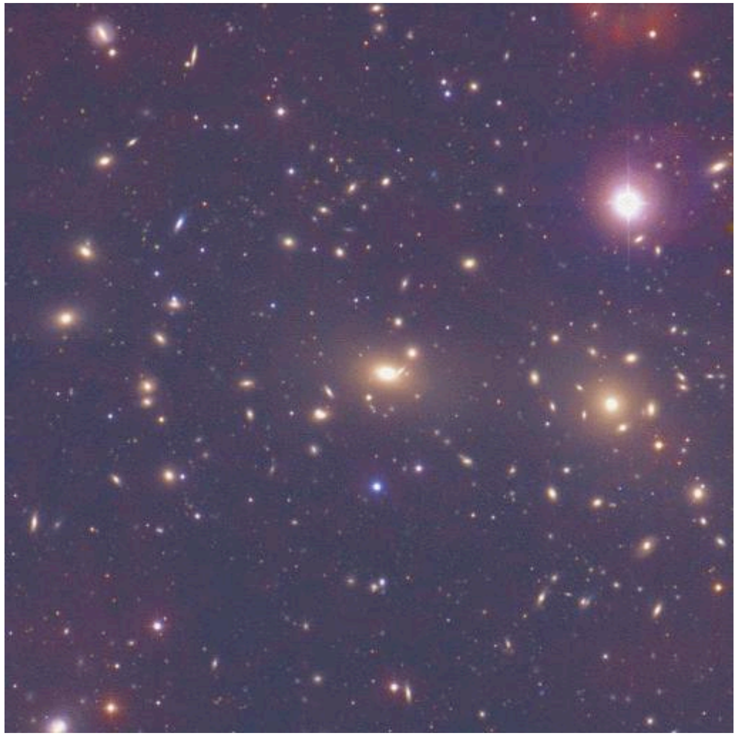
Fritz Zwicky (1933) measured the velocity dispersion in the Coma cluster to be as high as ~1000 km/s ⇒ M/L ~ $O(100)\ M_\odot/L_\odot$

"… If this overdensity is confirmed we would arrive at the astonishing conclusion that dark matter is present (in Coma) with a much greater density than luminous matter"

Virial Theorem: $\langle V \rangle + 2\langle K \rangle = 0$

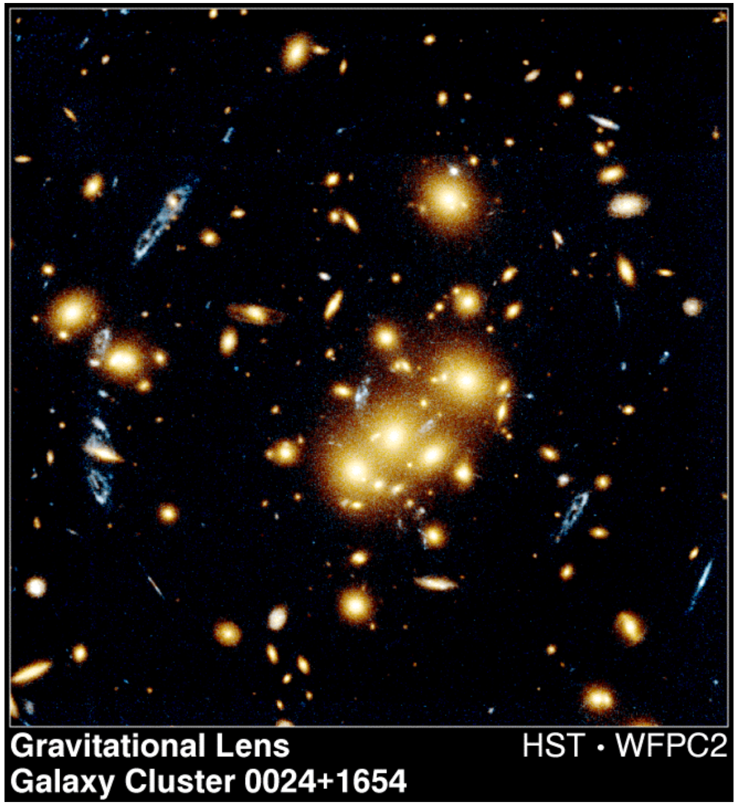
$$V = -\frac{N^2}{2} G_\mathrm{N} \frac{\langle m^2 \rangle}{\langle r \rangle}, \quad K = N \frac{\langle m v^2 \rangle}{2}$$

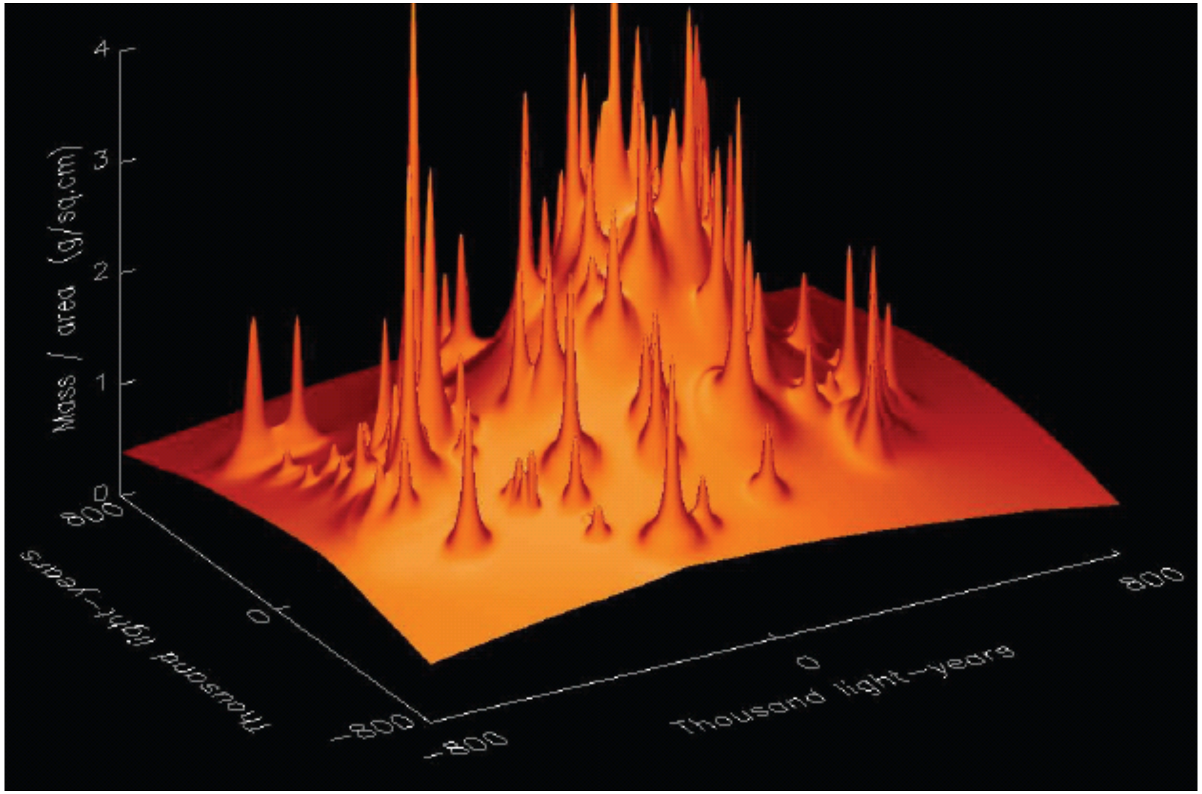
$$M = N\langle m \rangle \sim \frac{2\langle r \rangle \langle v^2 \rangle}{G_\mathrm{N}} \gg \sum m_\mathrm{galaxies}$$



Further evidence comes from observations of **gravitational lensing** of distant sources by a foreground cluster ... enabling the gravitational potential to be reconstructed

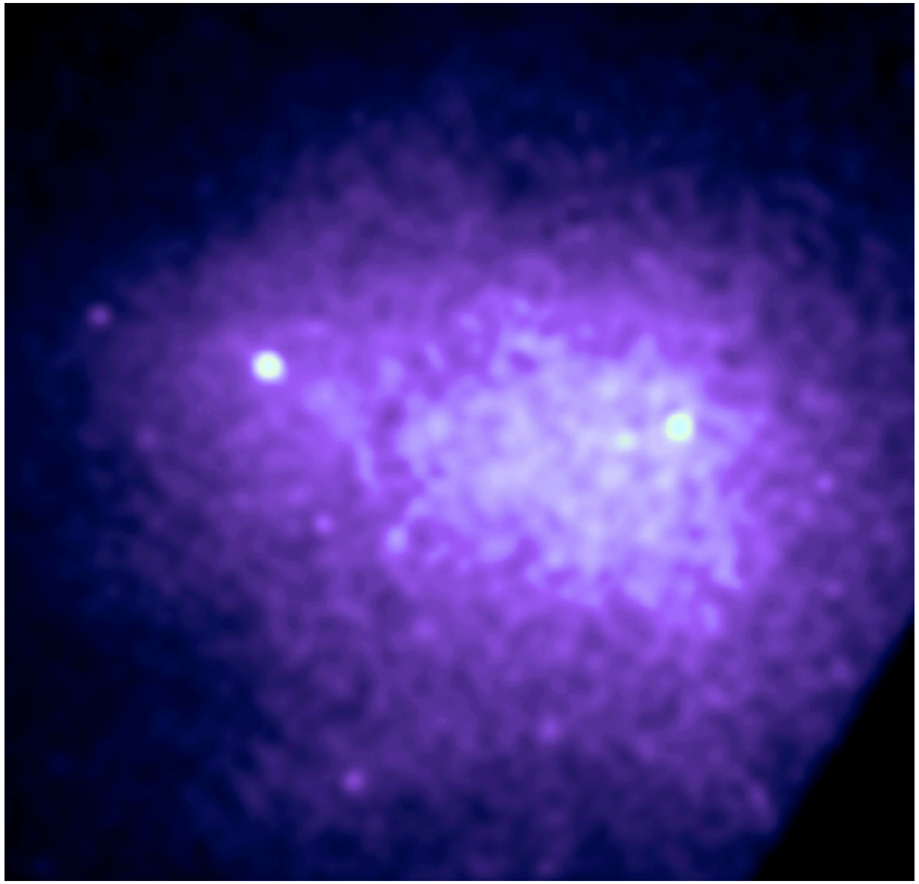
(see: Blandford & Narayan, ARAA 30:911,1992, Wambsgannss, Liv.Rev.Rel.1:12,1998)





This reveals that the gravitational mass is *dominated* by an extended smooth distribution of dark matter

The gravitating mass can also be obtained from X-ray observations of the hot gas in the cluster

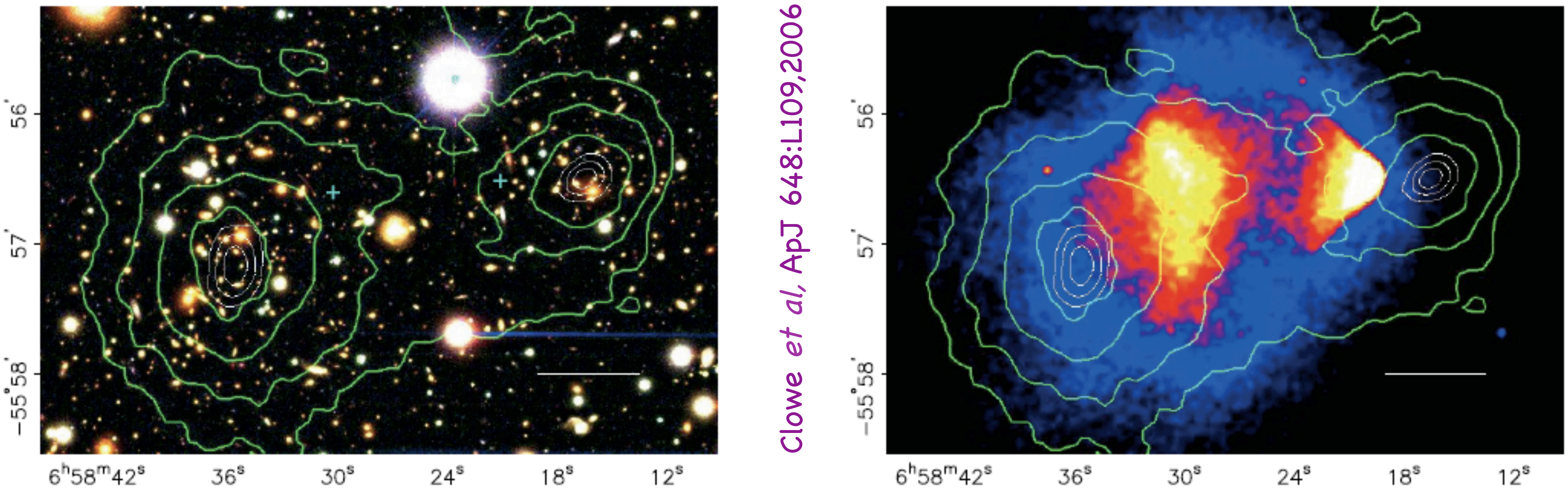


... assuming it is in thermal equilibrium:

$$\frac{1}{\rho_{\rm gas}}\frac{\mathrm{d}P_{\rm gas}}{\mathrm{d}r} = \frac{G_{\rm N}M(<r)}{r^2}$$

The Chandra picture of 1E0657-56 (the 'bullet cluster') shows that the X-ray emitting baryonic matter is displaced from both the galaxies and the dark matter (distribution inferred through gravitational lensing)

... for many this is convincing evidence of dark matter



Clowe *et al*, ApJ 648:L109,2006

FIG. 1.—*Left panel*: Color image from the Magellan images of the merging cluster 1E 0657−558, with the white bar indicating 200 kpc at the distance of the cluster. *Right panel*: 500 ks *Chandra* image of the cluster. Shown in green contours in both panels are the weak-lensing κ reconstructions, with the outer contour levels at $\kappa = 0.16$ and increasing in steps of 0.07. The white contours show the errors on the positions of the κ peaks and correspond to 68.3%, 95.5%, and 99.7% confidence levels. The blue plus signs show the locations of the centers used to measure the masses of the plasma clouds in Table 2.

MOND cannot explain this picture without invoking collisionless dark matter, e.g. ~2 eV mass neutrinos (see: Famae & McGaugh, Liv. Rev. Rel. 15:10,2012)

However 1E0657-56 also poses a *challenge* for ΛCDM cosmology, viz. why is the 'peculiar velocity' so very high (>3000 km/s on a scale of ~5 Mpc)?

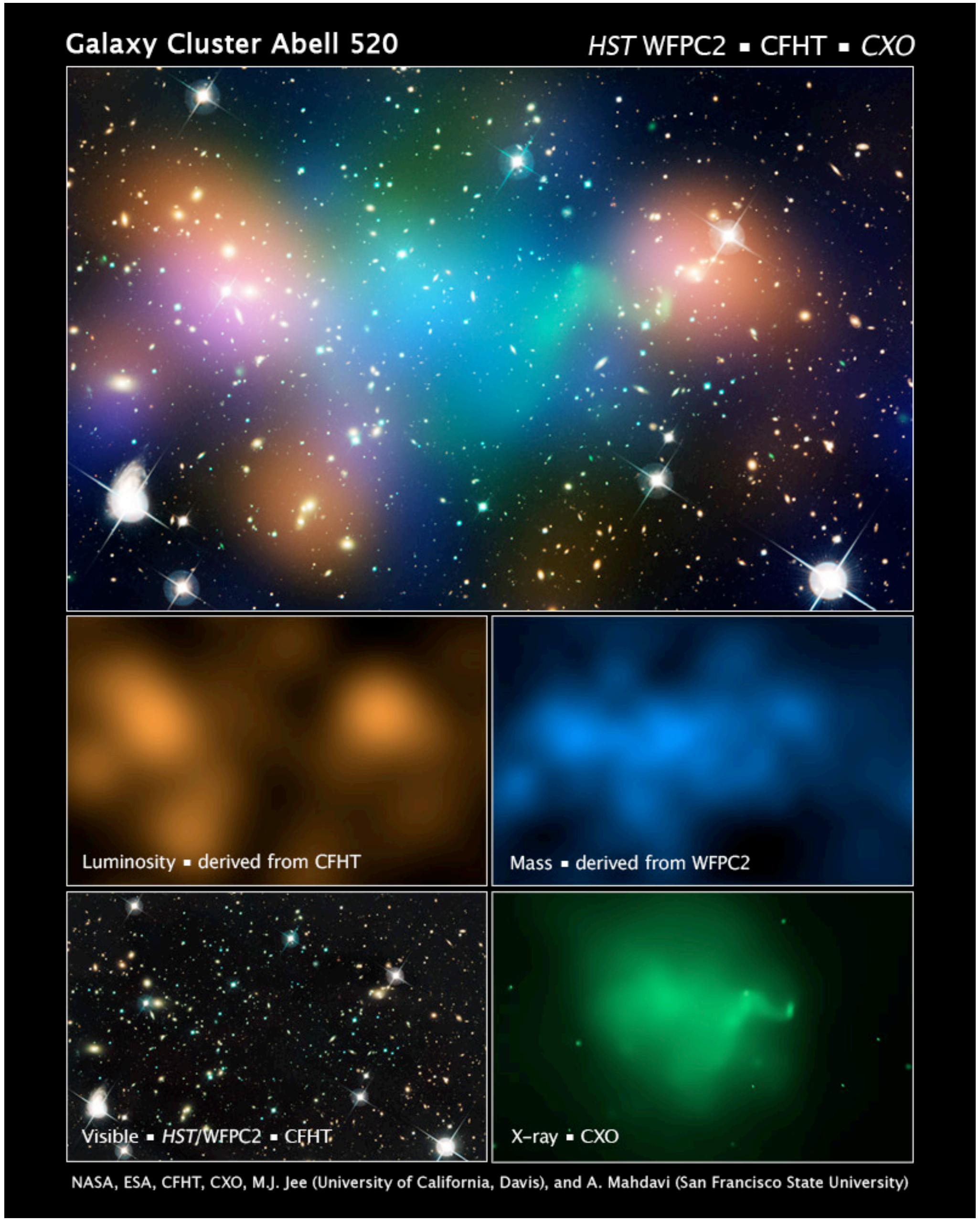
The probability of this collision is of $O(10^{-10})$! (Lee et al, ApJ 718:60,2010)

To muddle the story, another picture of colliding clusters shows that the dark matter is *coincident* with the hot gas and is displaced from the galaxies!

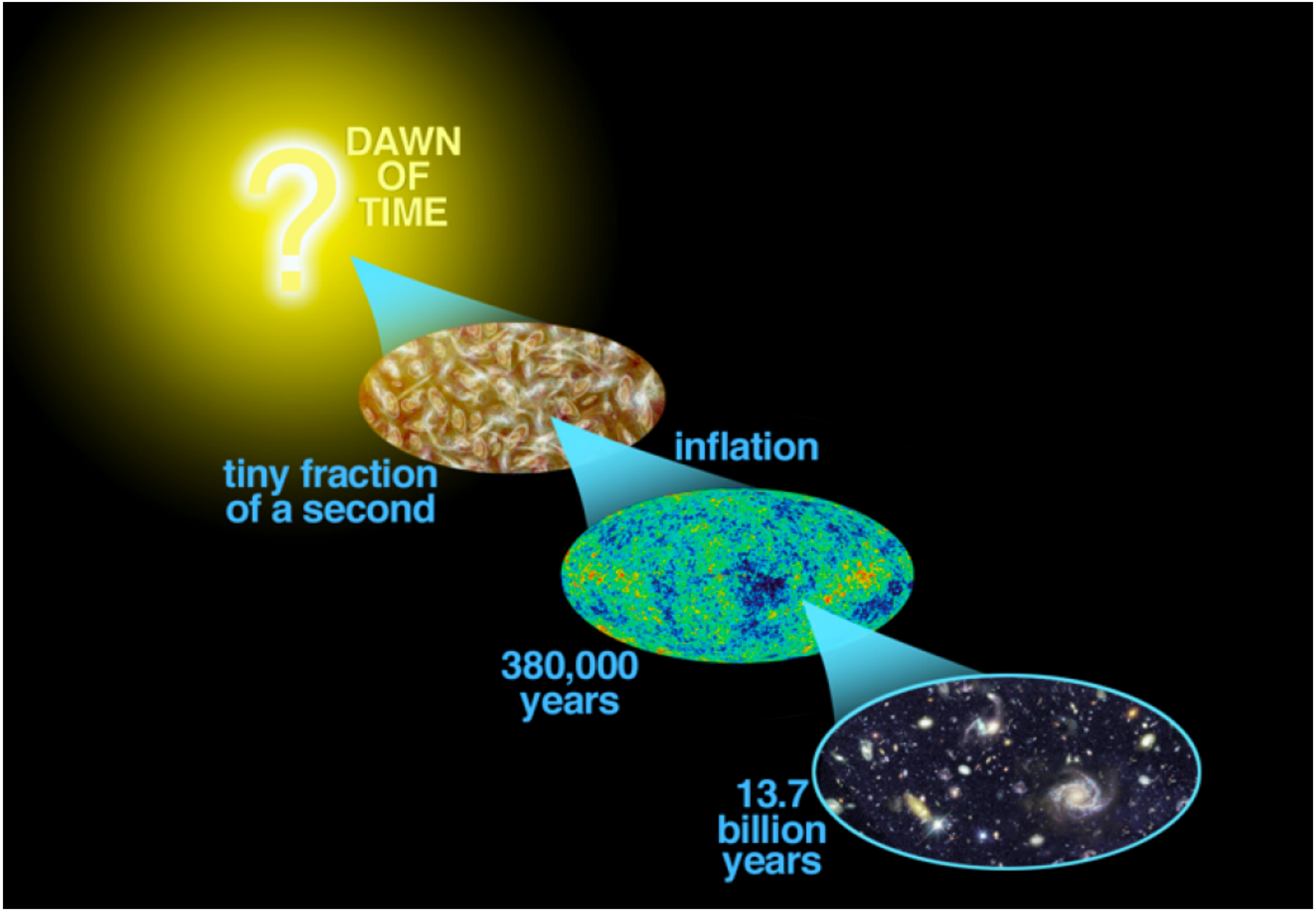
Moreover whereas the 'Bullet Cluster' sets a weak limit on self-interactions: $\sigma \lesssim 2\text{x}10^{-24}$ cm^2/GeV, in Abell 520, the implication is that DM is self-interacting: $\sigma \approx (7\pm2)$ x 10^{-24} cm^2/GeV
Mahdavi *et al*, ApJ 668:806,2007

... but another lensing analysis does not detect the `dark core' and claims consistency with collisionless dark matter
Clowe *et al*, ApJ 758:128,2012

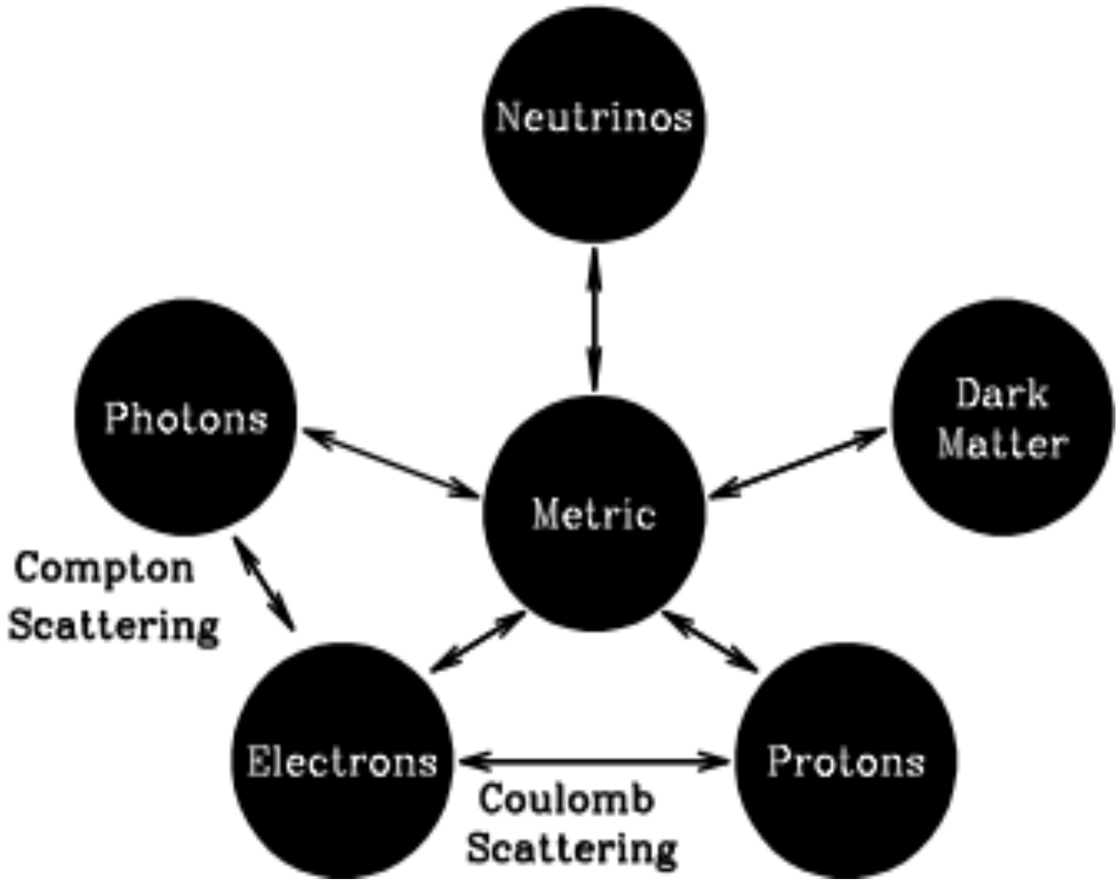
However the light-mass offset observed in Abell 3827 also implies a (weaker) lower limit: $\sigma \gtrsim 8\text{x}10^{-31}$ cm^2/GeV
Williams & Saha, MNRAS 415:448,2011



Perhaps the best evidence for dark matter comes from considerations of structure formation

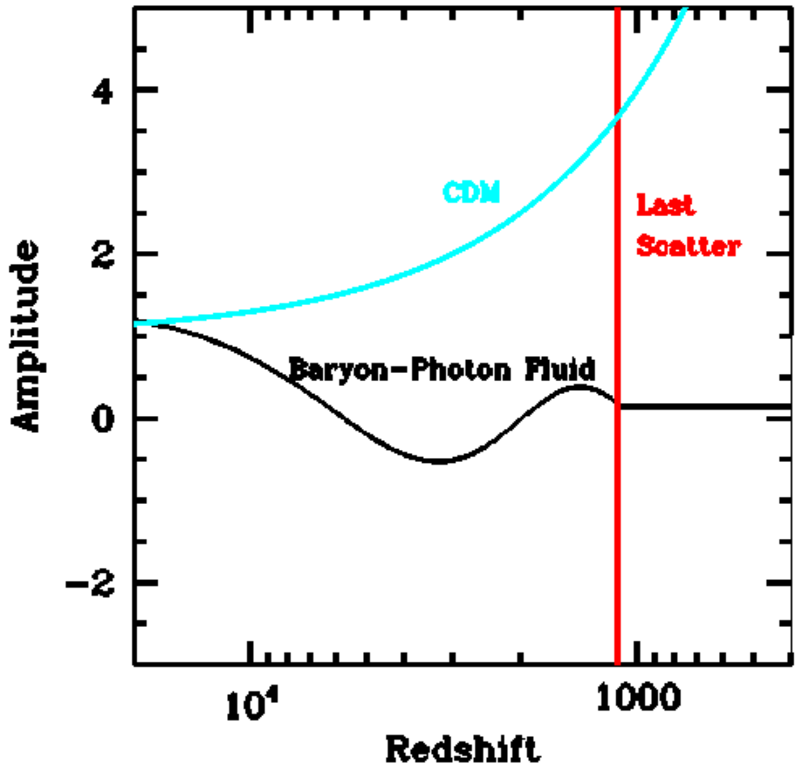


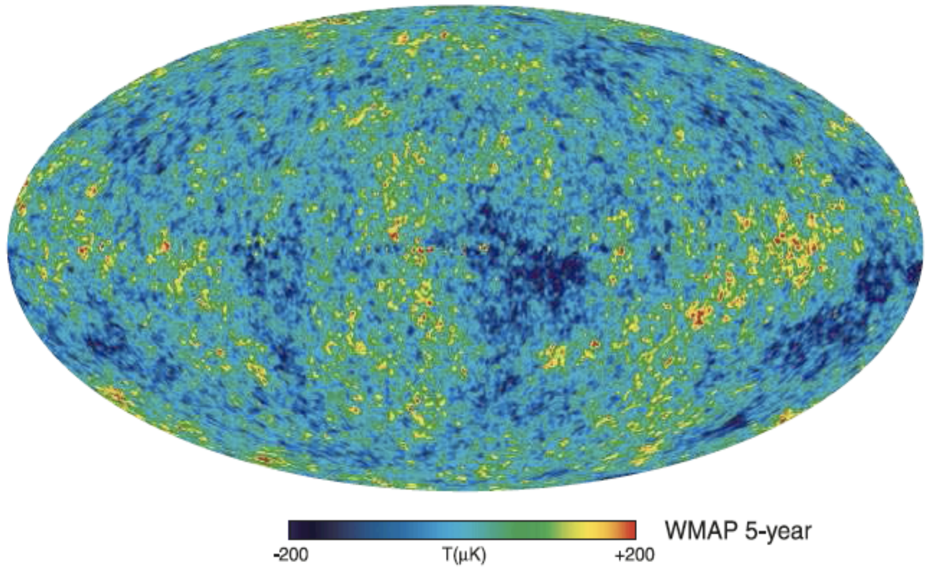
Perturbations in metric (generated during inflation?) induce perturbations in photons and (dark) matter



These perturbations begin to grow through gravitational instability after matter domination

Before recombination, the primordial fluctuations just excite sound waves in the plasma, but can start growing already in the sea of collisionless dark matter ...





These sound waves leave an imprint on the last scattering surface of the CMB as the universe turns neutral and transparent ... sensitive to the baryon & CDM densities

For a statistically isotropic gaussian random field, the **angular power spectrum** can be constructed by decomposing in spherical harmonics:

$$\Delta T(\mathbf{n}) = \sum a_{lm} Y_{lm}(\mathbf{n})$$

$$C_l \equiv \frac{1}{2l+1} \sum |a_{lm}|^2$$

The CMB angular power spectrum is sensitive to cosmological parameters

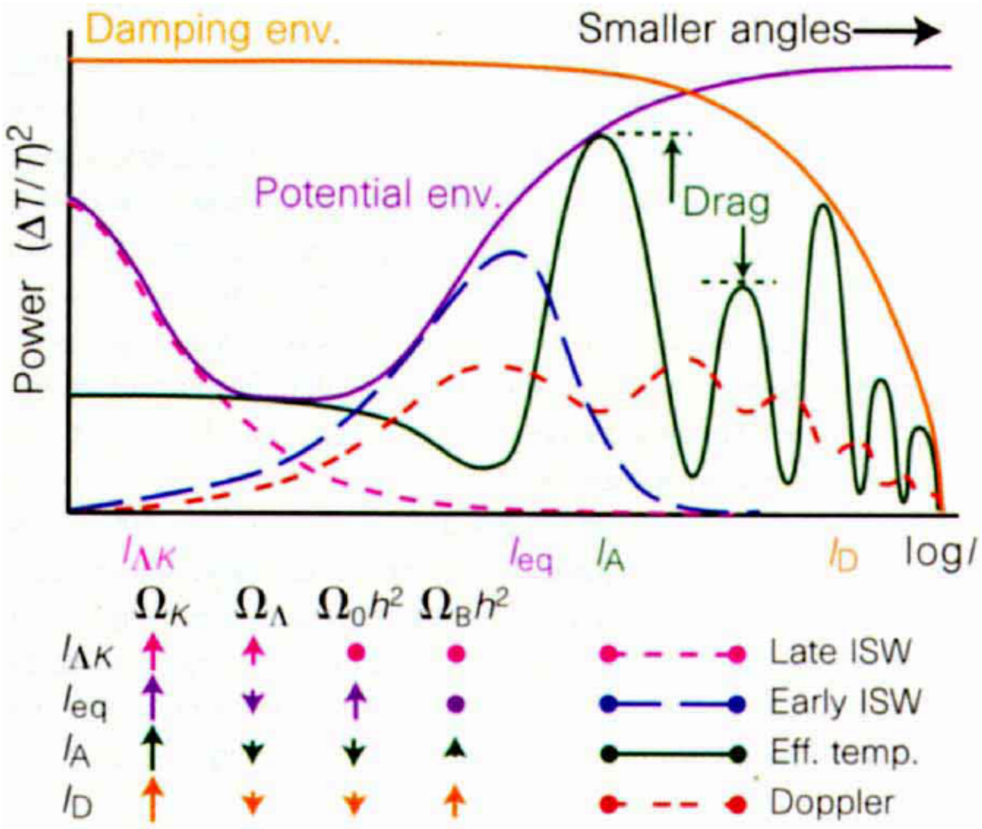


Figure 1 Schematic decomposition of the anisotropy spectrum and its dependence on cosmological parameters, in an adiabatic model. Four fundamental angular scales characterized by the angular wavenumber $l \propto \theta^{-1}$ enter the spectrum: $l_{\Lambda K}$ and l_{eq} which enclose the Sachs-Wolfe plateau in the potential envelope, l_A the acoustic spacing, and l_D the diffusion damping scale. The inset table shows the dependence of these angular scales on four fundamental cosmological parameters: $\Omega_K (\equiv 1 - \Omega_\Lambda - \Omega_0)$, Ω_Λ, $\Omega_0 h^2$ and $\Omega_B h^2$ (see Box 1 for definitions). Baryon drag enhances all compressional (here, odd) maxima of the acoustic oscillation, and can probe the spectrum of fluctuations at last scattering and/or $\Omega_B h^2$. Projection effects smooth Doppler more than effective-temperature features.

Hu, Sugiyama, Silk, Nature 40:171,2002

The Cosmic Microwave Background

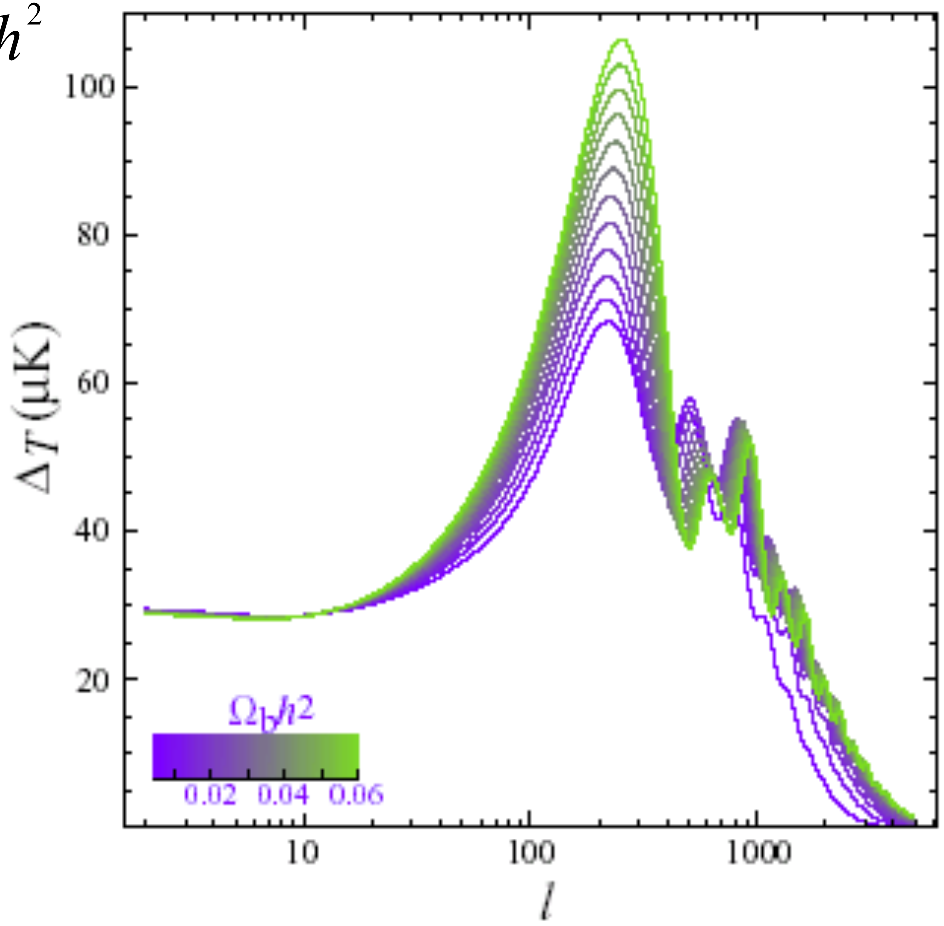
ΔT_ℓ provide independent measure of $\Omega_B h^2$

Acoustic oscillations in (coupled) photon-baryon fluids imprint features at small angles ($< 1^o$) in angular power spectrum

Detailed peak positions, heights, … sensitive to cosmological parameters

e.g. 2nd/1st peak $\Rightarrow$ baryon density

(NB: there are however `degeneracies' e.g. with the shape of the primordial power spectrum of density fluctuations)



WMAP best-fit:

$$\Omega_B h^2 = 0.02273 \pm 0.00062$$

Bond & Efstathiou, ApJ 285:L45,1984
Dodelson & Hu, ARAA 40:171,2002

BBN versus CMB

$\eta_{\rm BBN}$ agrees with $\eta_{\rm CMB}$
allowing for uncertainties in the inferred elemental abundances

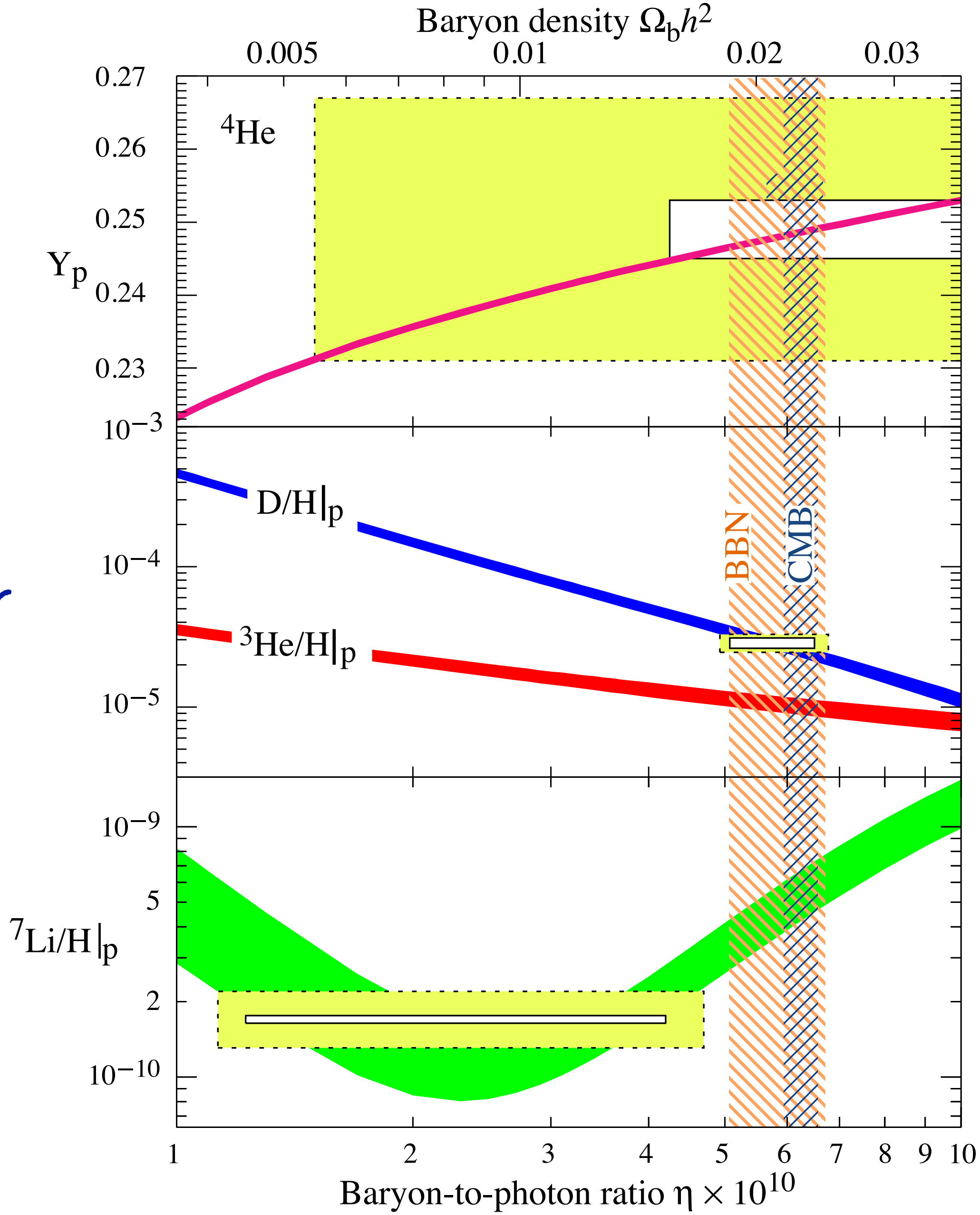
$$4.7 \leq \eta_{10} \leq 6.5 \ (95\% \ \mathrm{CL})$$

Confirms and sharpens the case for (two kinds of) dark matter

Baryonic Dark Matter:
warm-hot IGM, Ly-α, ...

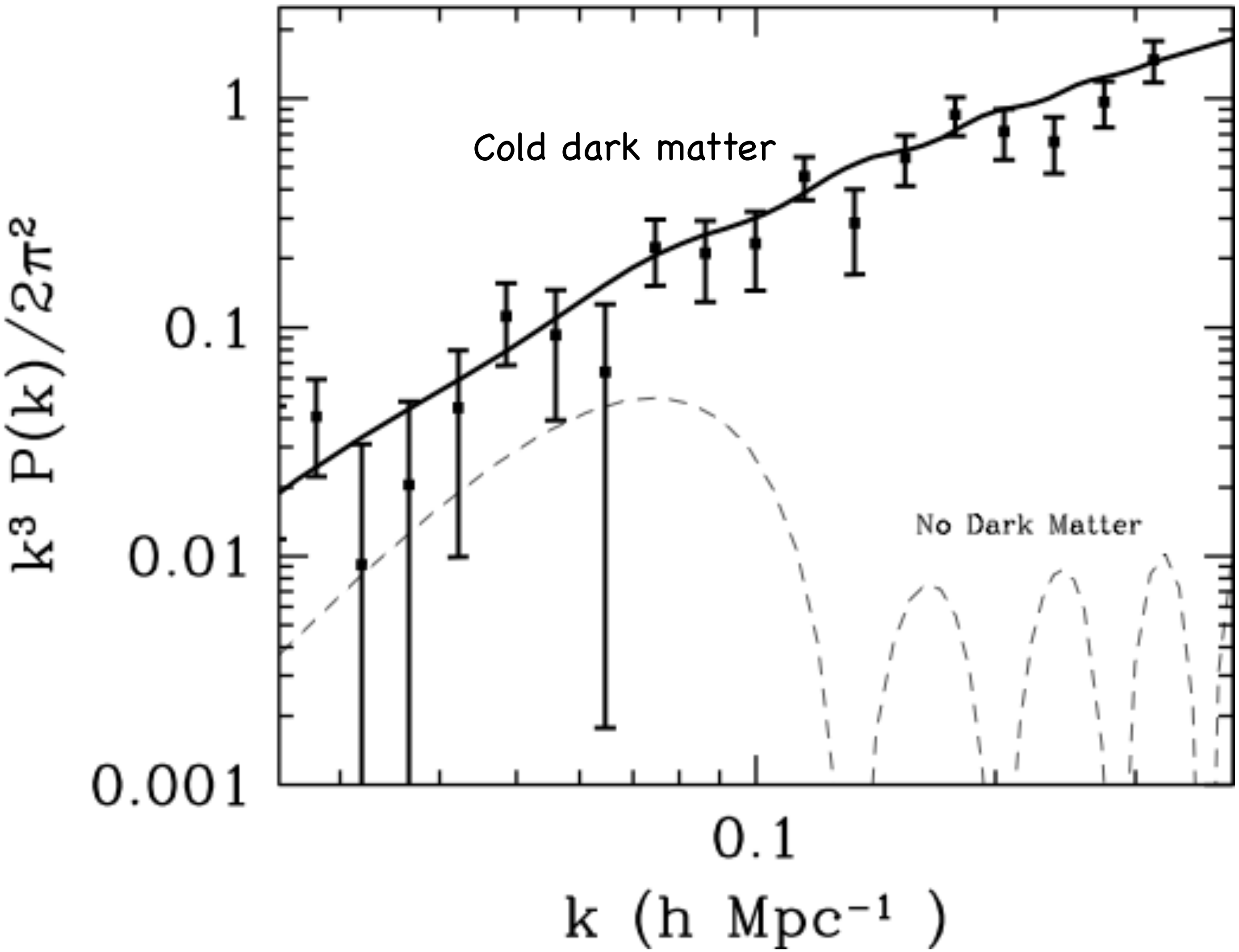
+

Non-baryonic dark matter:
neutralino? technibaryon?
(sterile) neutrino? axion ... ?



Fields & Sarkar (Particle Data Group), PR D86:010001,2012

Moreover the observed large-scale structure *requires* $\Omega_m >> \Omega_B$ if it has resulted from the growth under gravity (GR) of small initial density fluctuations … which left their imprint on the CMB at last scattering



Dodelson & Liguori, PRL 97:231301,2006

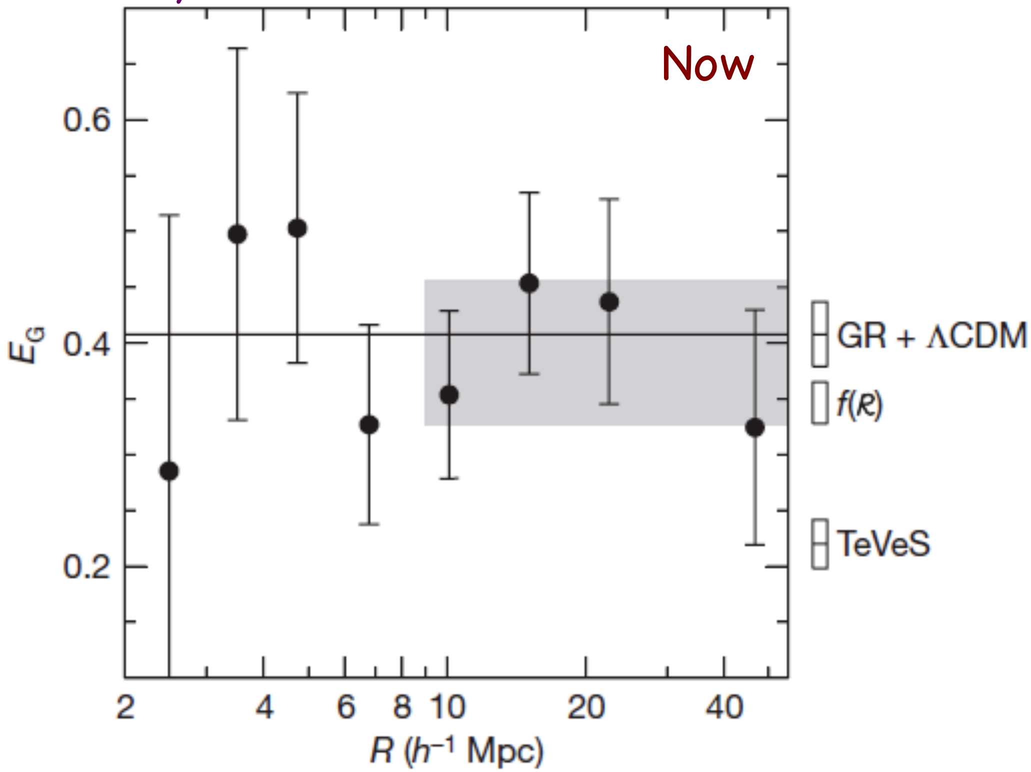
Detailed modelling of WMAP and 2dF/SDSS ⇒ $\Omega_m \sim 0.3$, $\Omega_B \sim 0.05$

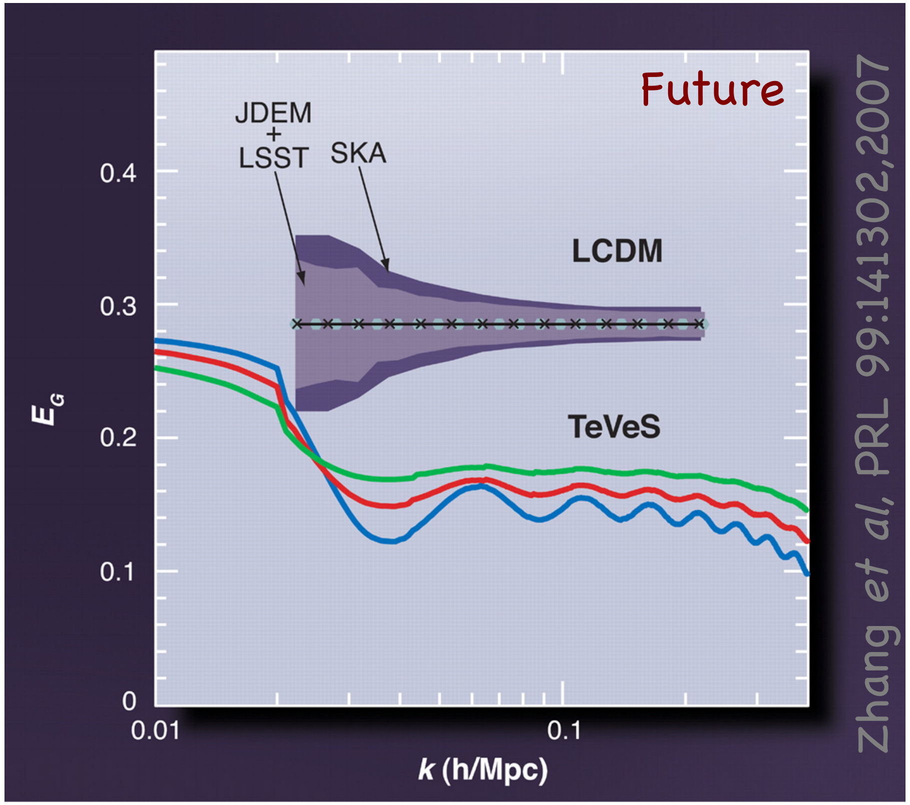
… No MOND-like theory (e.g. TeVeS) can fit the data so well!

Although new gravitational physics (underlying MOND) can in principle provide adequate growth of cosmological structure, there will be an observable distinction – 'gravitational slip' – between General Relativity and the new theory

see: Clifton *et al*, Phys. Rep.513:1,2012

Reyes *et al*, Nature 464:256,2010





This can be tested through measurements of 'weak lensing' (shearing of galaxy shapes) and its cross-correlation with the galaxy density field

Does dark matter exist?

Modified Newtonian Dynamics (MOND) accounts *better* for galactic rotation curves than does dark matter - moreover it predicts the observed correlation between luminosity and rotation velocity: $L \sim v_{rot}^4$ (Baryonic Tully-Fisher relation)

... however MOND *fails* on the scale of galaxy clusters and in particular cannot explain the segregation of 'bright' and 'dark' matter seen in the merging cluster 1E 0657-558

Also MOND is *not* a physical theory – although relativistic covariant theories that yield MOND exist (e.g. 'TeVeS' by Bekenstein) they have not provided as satisfactory an understanding of CMB anisotropies and structure formation, as the standard (cold) dark matter cosmology

... nevertheless good to keep an open mind until dark matter is actually detected by non-gravitational means!