

Dark matter: astrophysical evidence

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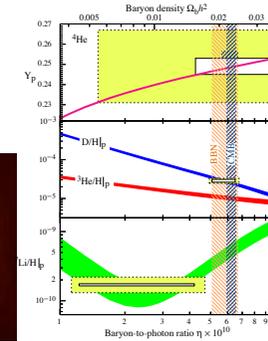
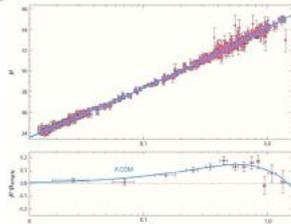
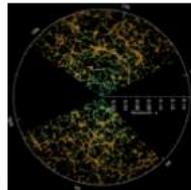
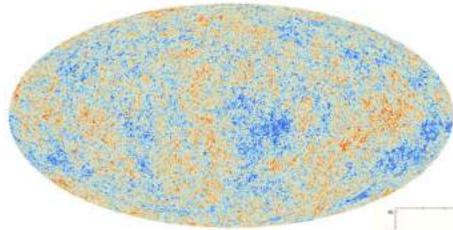


21st International School of Cosmic Ray Astrophysics, Erice, 1-7 August 2018

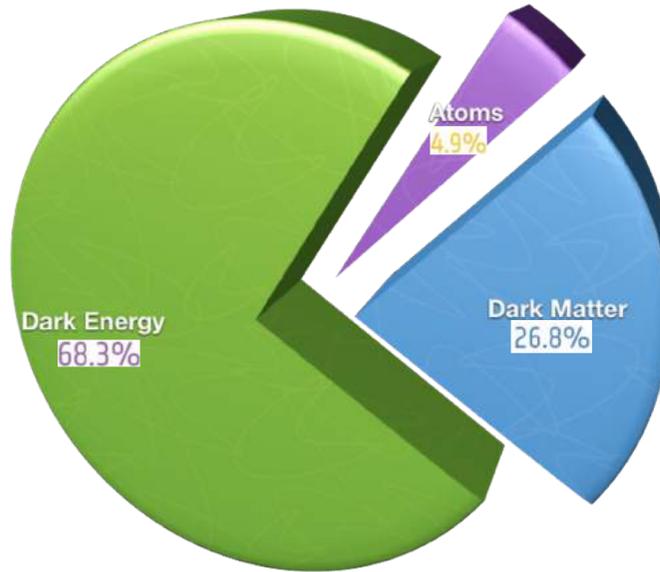
What is the world made of?

Mainly geometrical evidence:
 $\Lambda \sim O(H_0^2)$, $H_0 \sim 10^{-42} \text{ GeV}$
 ... dark energy is *inferred* from
 the 'cosmic sum rule':

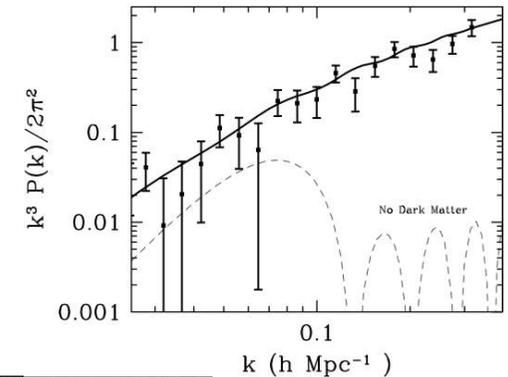
$$\Omega_m + \Omega_k + \Omega_\Lambda = 1$$



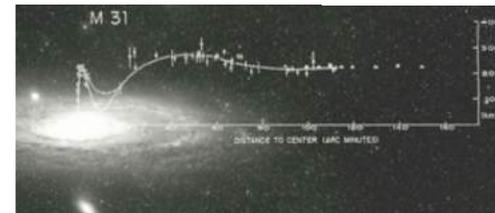
Baryons (*no*
anti-baryons)



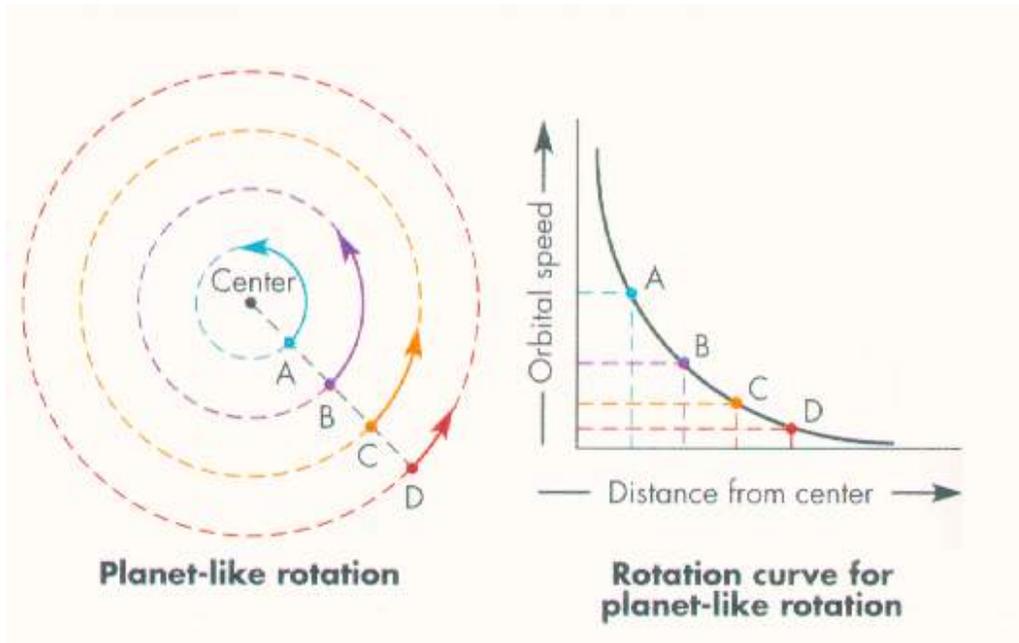
Both geometrical
and dynamical
evidence (assuming
GR to be valid)



Both the baryon asymmetry and dark matter
require that there be *new physics* beyond the
Standard $SU(3)_c \times SU(2)_L \times U(1)_Y$ Model
... dark energy is even more mysterious (but as
yet lacks compelling *dynamical* evidence)



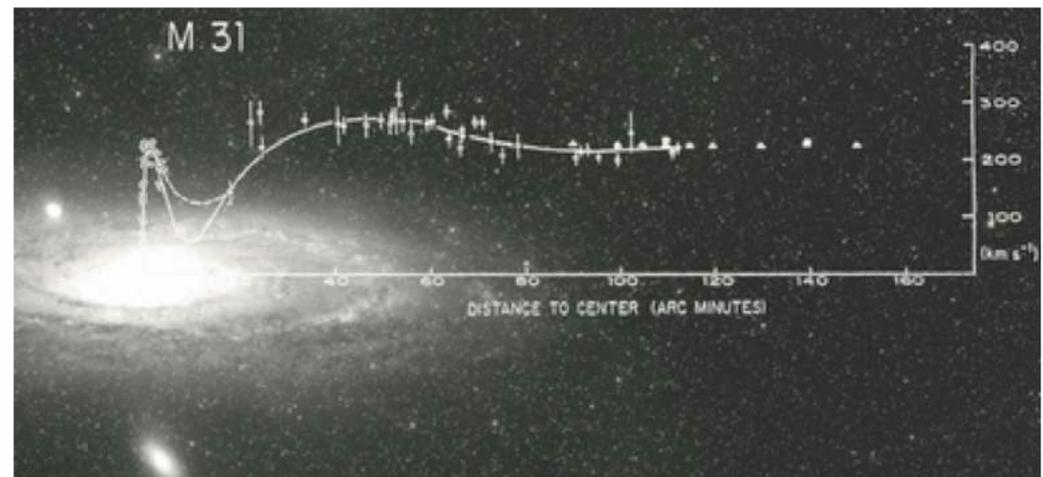
The modern saga of dark matter starts with the rotation curves of spiral galaxies



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

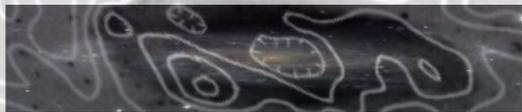
$$v_{\text{circ}} = \sqrt{\frac{G_N M(< r)}{r}}$$

... but Rubin & Ford (ApJ **159**:379,1970) observed that the rotational velocity remains \sim constant in Andromeda – interpreted *later* as implying the existence of an extended (dark) ‘corona’ or halo ...

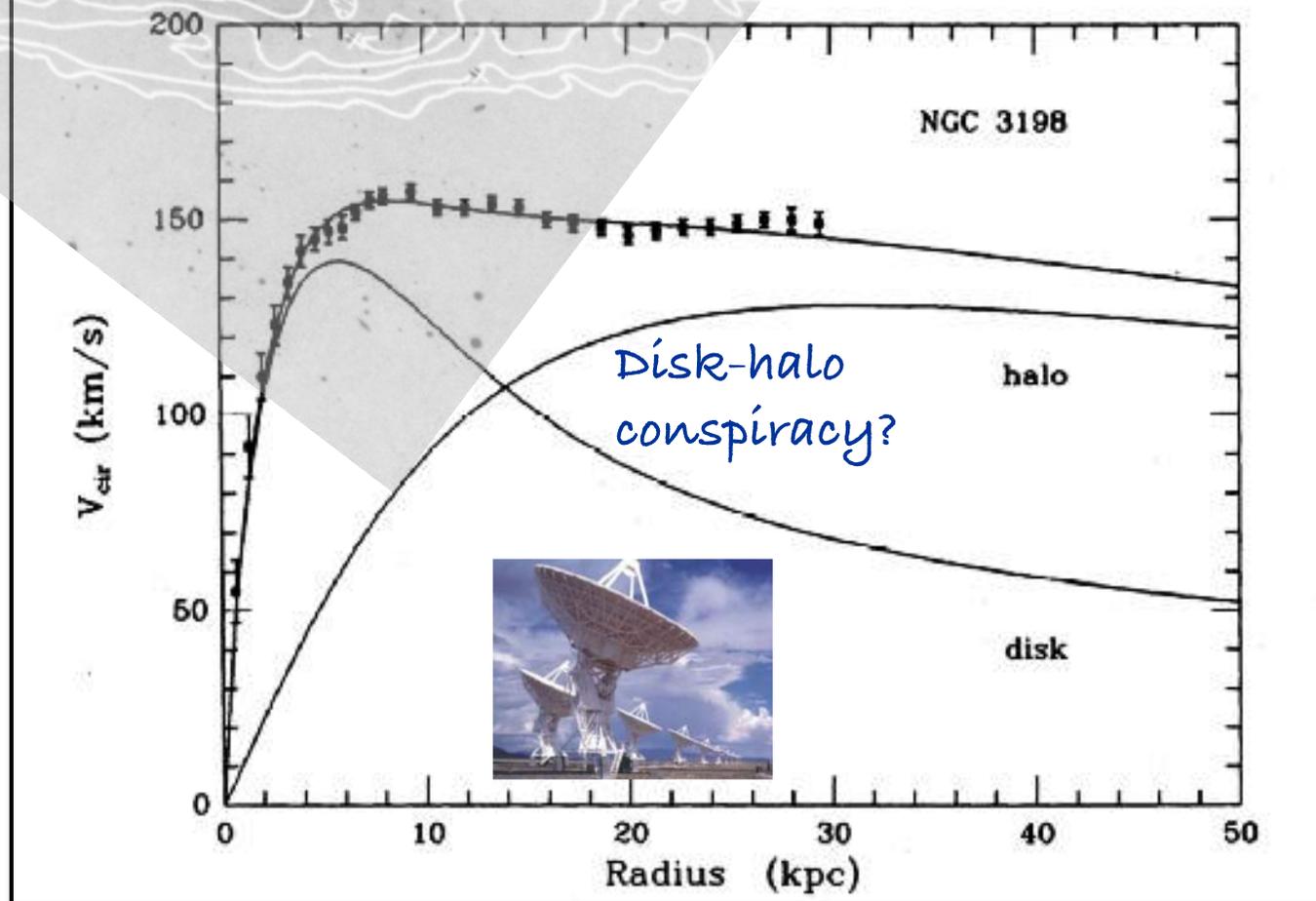


$$v_{\text{circ}} \sim \text{constant} \quad \Rightarrow \quad M(< r) \propto r \quad \Rightarrow \quad \rho \propto 1/r^2$$

The really *compelling* evidence for **extended halos of dark matter** came from observations in the 1980's of 21-cm line emission from neutral hydrogen (orbiting around the Galaxy at \sim constant velocity) *well* beyond the visible disk

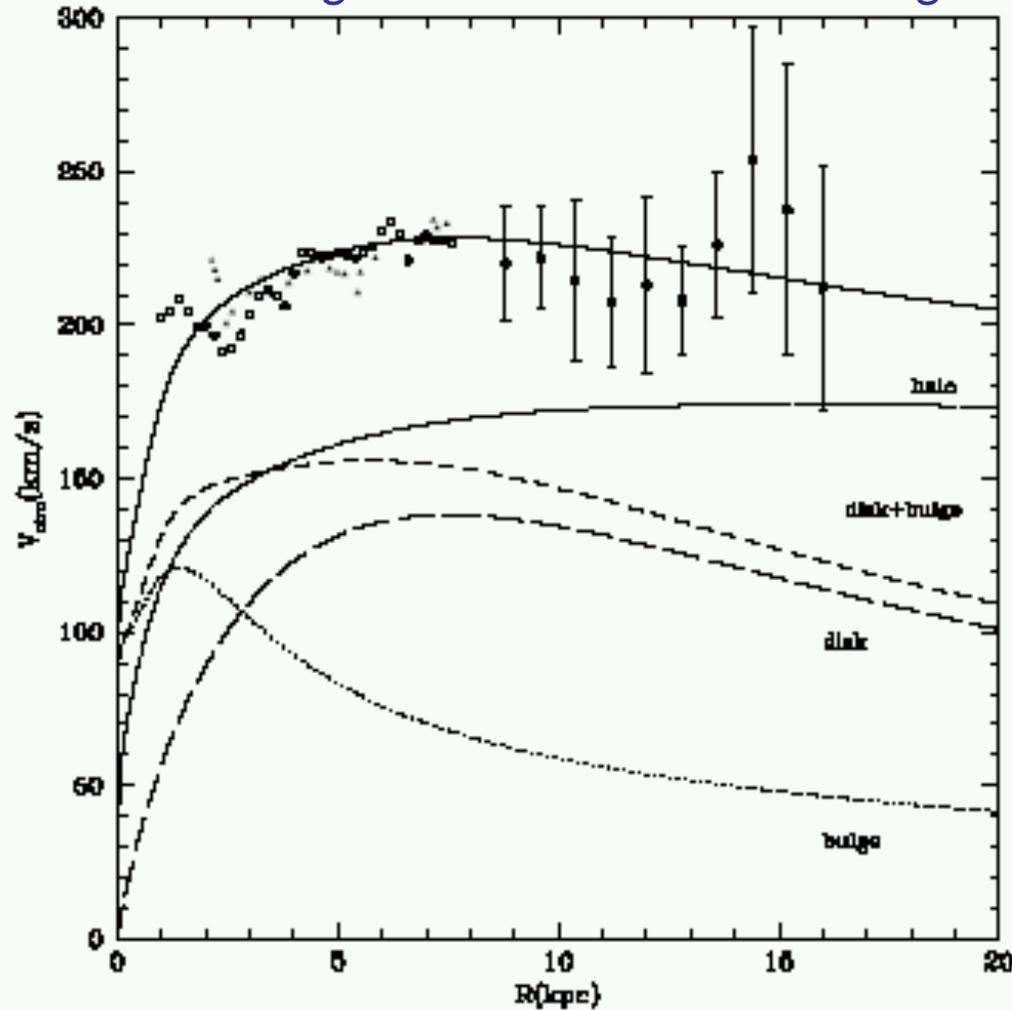


VAN ALBADA *ET AL.* (ApJ 295:305,1985)

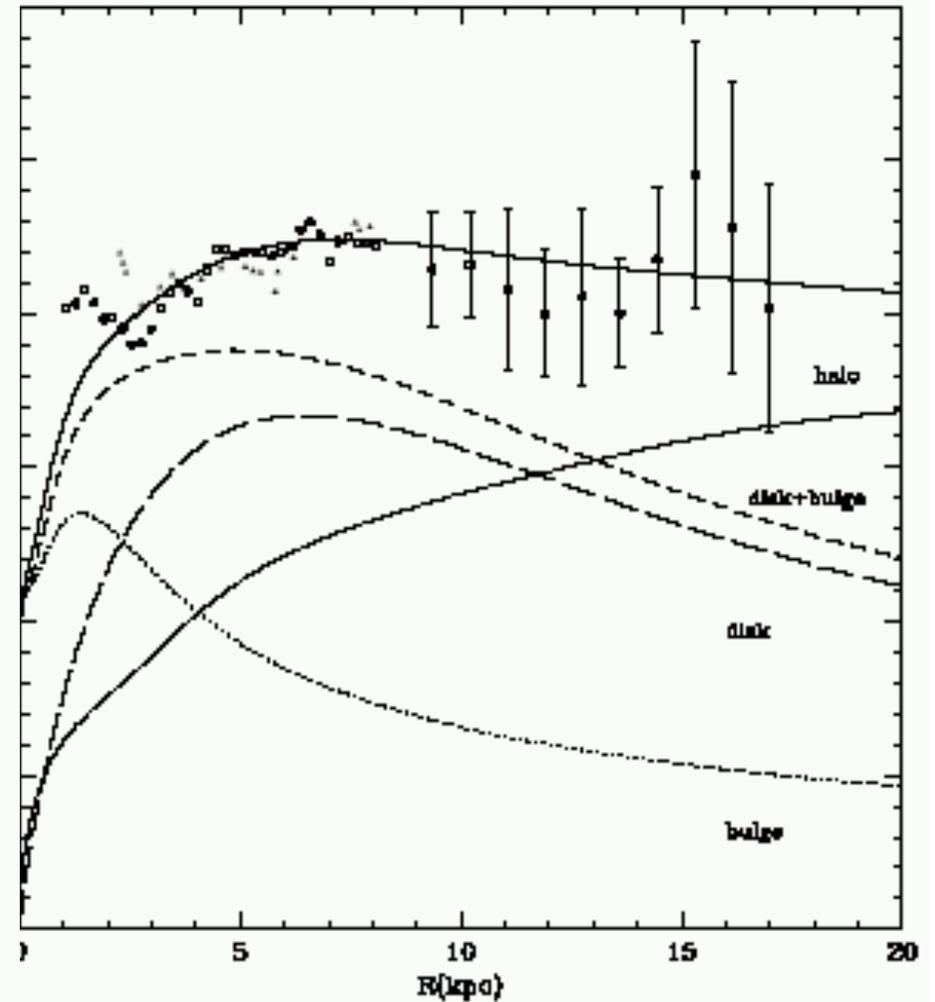


More sophisticated modelling accounts for multiple components and the gravitational coupling between baryonic & dark matter

No angular momentum exchange



With angular momentum exchange



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

The *local* halo dark matter density is inferred to be $\sim 0.3 \text{ GeV cm}^{-3}$ (uncertainty x2)

With the $1/r^2$ density profile, the solution of the *collisionless* Boltzmann equation is the ‘Maxwellian distribution’:

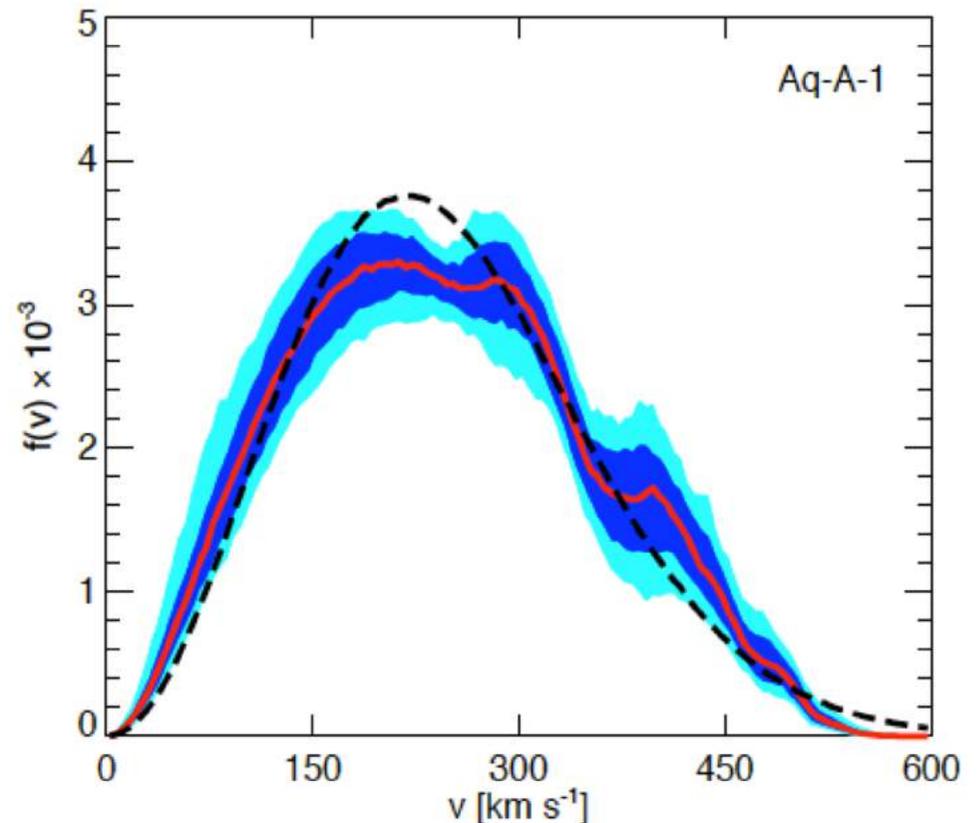
The ‘standard halo model’ has $v_c = 220$ km/s and is truncated at $v_{\text{esc}} = 544$ km/s (both numbers have large observational uncertainties)

High resolution numerical simulations however suggest significant deviations from the Maxwellian distribution, particularly at high velocities (this has important implications for direct detection experiments)

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

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

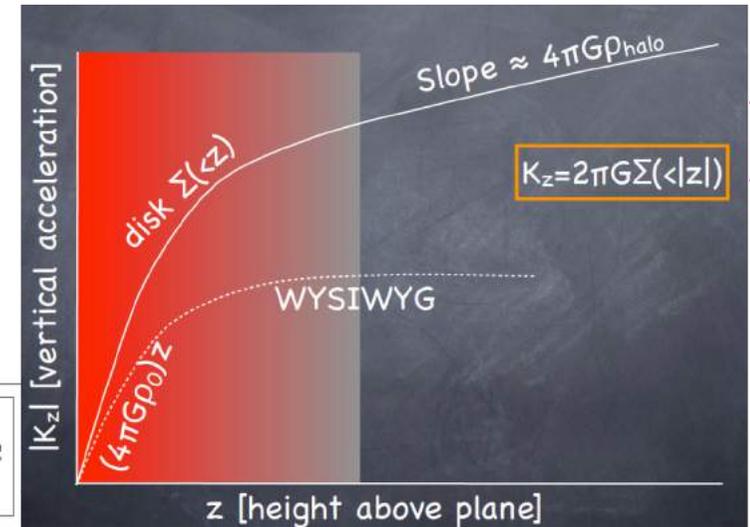
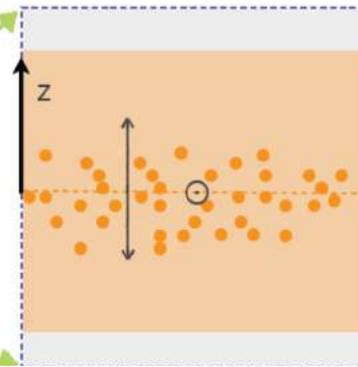
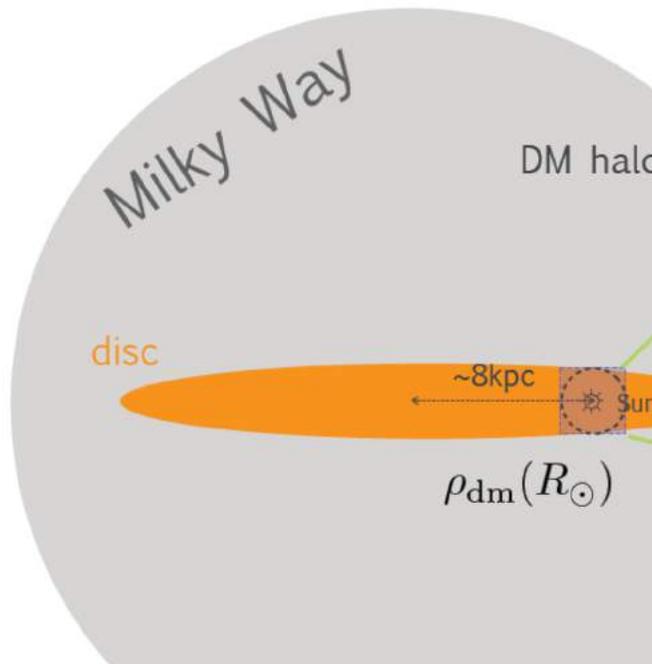
$$\sigma = \sqrt{3/2} v_c$$



We can infer the *local* dark matter density by measuring vertical distribution of stars ... pioneered by Kapetyn (1922) and Oort (1932)

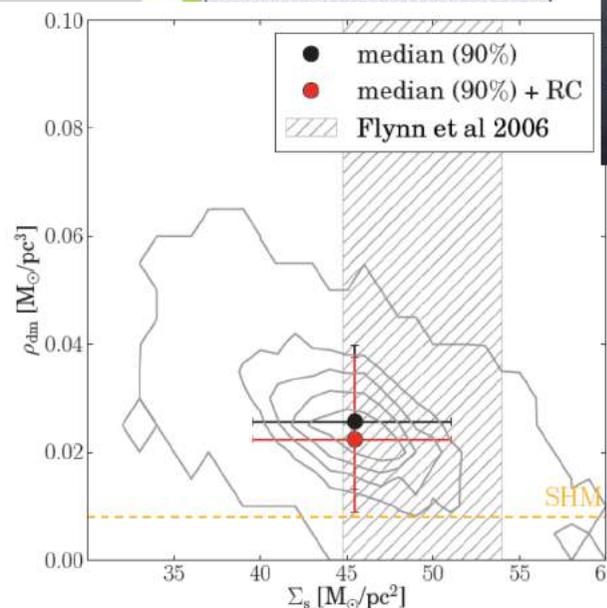
If galaxy is approximated as thin disk, then orthogonal to the Galactic plane:

$$\frac{d^2\psi(z)}{dz^2} \underset{\sim 100\text{pc}}{=} 4\pi G_N \rho_m \rightarrow \frac{d\psi(z)}{dz} = 2\pi G_N \Sigma_m$$



Courtesy: Konrad Kuijken

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



Using data on K-dwarfs
(Kuijken & Gilmore, MNRAS
239:605,1989) found:
 $\rho_{\text{DM}} = 0.85 \pm 0.6 \text{ GeV}/\text{cm}^3$
... update expected from GAIA

Bidin *et al* (ApJ **747**:101,2012) claimed $\rho_{\text{DM}} < 0.04 \text{ GeV}/\text{cm}^3$, because of the *incorrect* assumption that the rotational velocity is independent of galactocentric radius at *all* z (Bovy & Tremaine, ApJ **756**:89,2012)

Modelling dark matter halos

Cored isothermal sphere: $\rho_{\text{isothermal}} = \frac{\rho_s}{\left(1 + \frac{r}{r_s}\right)^2}$

Navarro-Frenk-White profile: $\rho_{\text{NFW}} = \frac{\rho_s}{\frac{r}{r_s} \left(1 + \frac{r}{r_s}\right)^2}$
(indicated by CDM simulations)

Burkert profile: $\rho_{\text{Burkert}} = \frac{\rho_s}{\left(1 + \frac{r}{r_s}\right) \left[1 + \left(\frac{r}{r_s}\right)^2\right]}$
(fits observations better)

Einasto profile:
 $\rho_{\text{Einasto}} = \rho_s \exp \left\{ -d_n \left[\left(\frac{r}{r_s}\right)^{1/n} - 1 \right] \right\}$

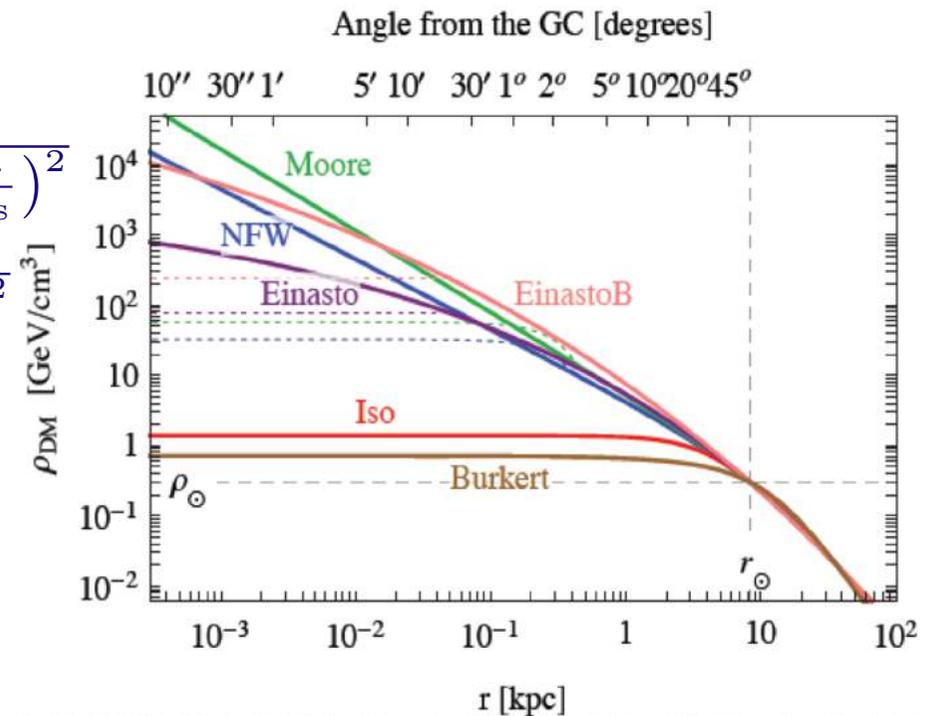
where d_n is defined such that ρ_s is the density at the radius r_s enclosing half the total mass

... more generally define the **Hernquist profile:** $\rho_{\text{Hernquist}} = \rho_s \left(\frac{r}{r_s}\right)^{-\gamma} \left[1 + \left(\frac{r}{r_s}\right)^\alpha\right]^{\frac{\gamma-\beta}{\alpha}}$

Here r_s is a characteristic scale and α controls the sharpness of the transition from the inner slope $\lim_{r \rightarrow 0} d \ln(\rho) / d \ln(r) = -\gamma$ to the outer slope $\lim_{r \rightarrow \infty} d \ln(\rho) / d \ln(r) = -\beta$

... e.g. the NFW profile corresponds to choosing $\alpha = 1, \beta = 3, \gamma = 1$, whereas a cored isothermal profile corresponds to choosing $\alpha = 1, \beta = 2, \gamma = 0$, and a Moore profile corresponds to $\alpha = 1.5, \beta = 2, \gamma = 1.5$ etc

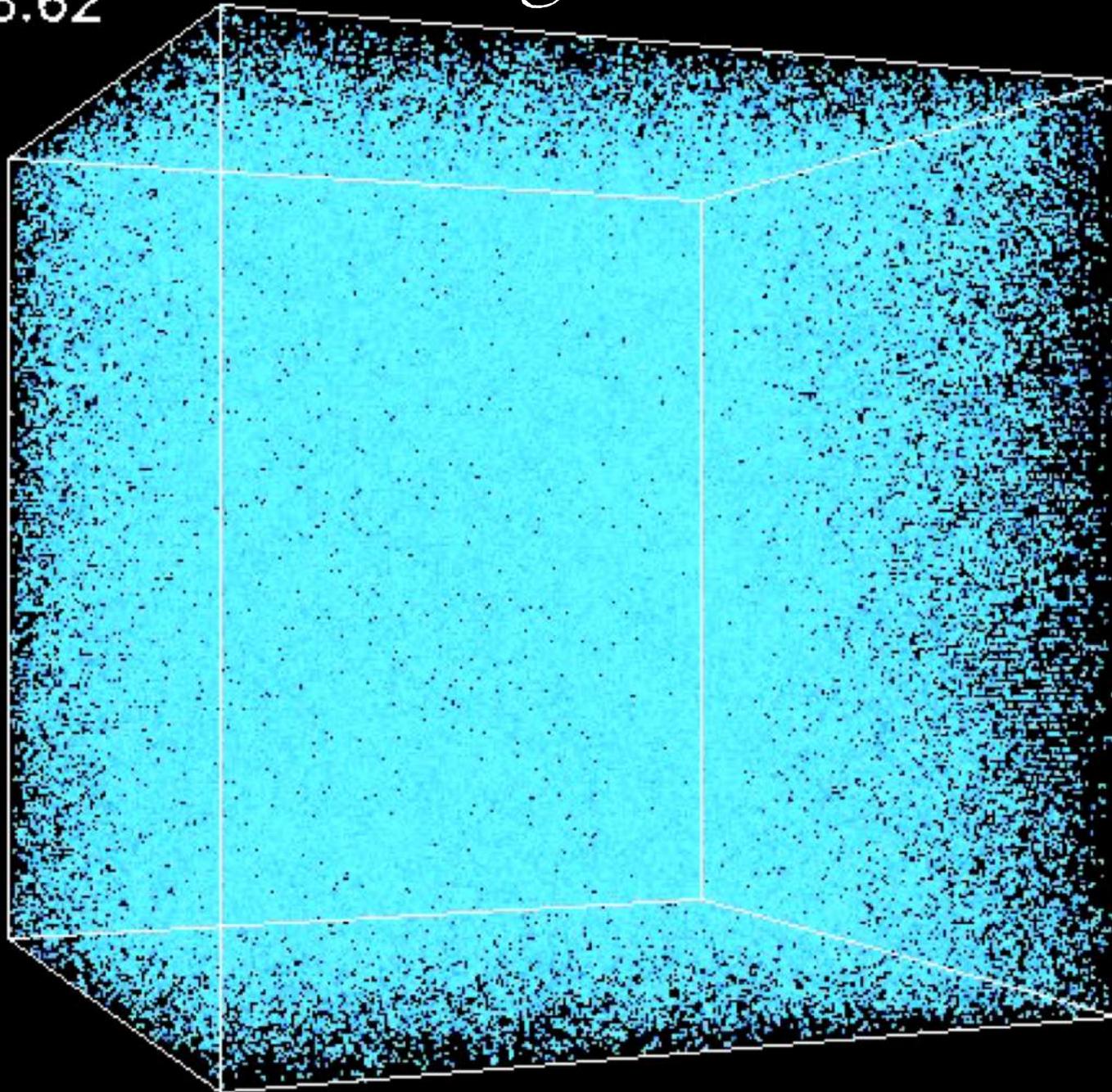
For the Milky Way, the fit parameters are:



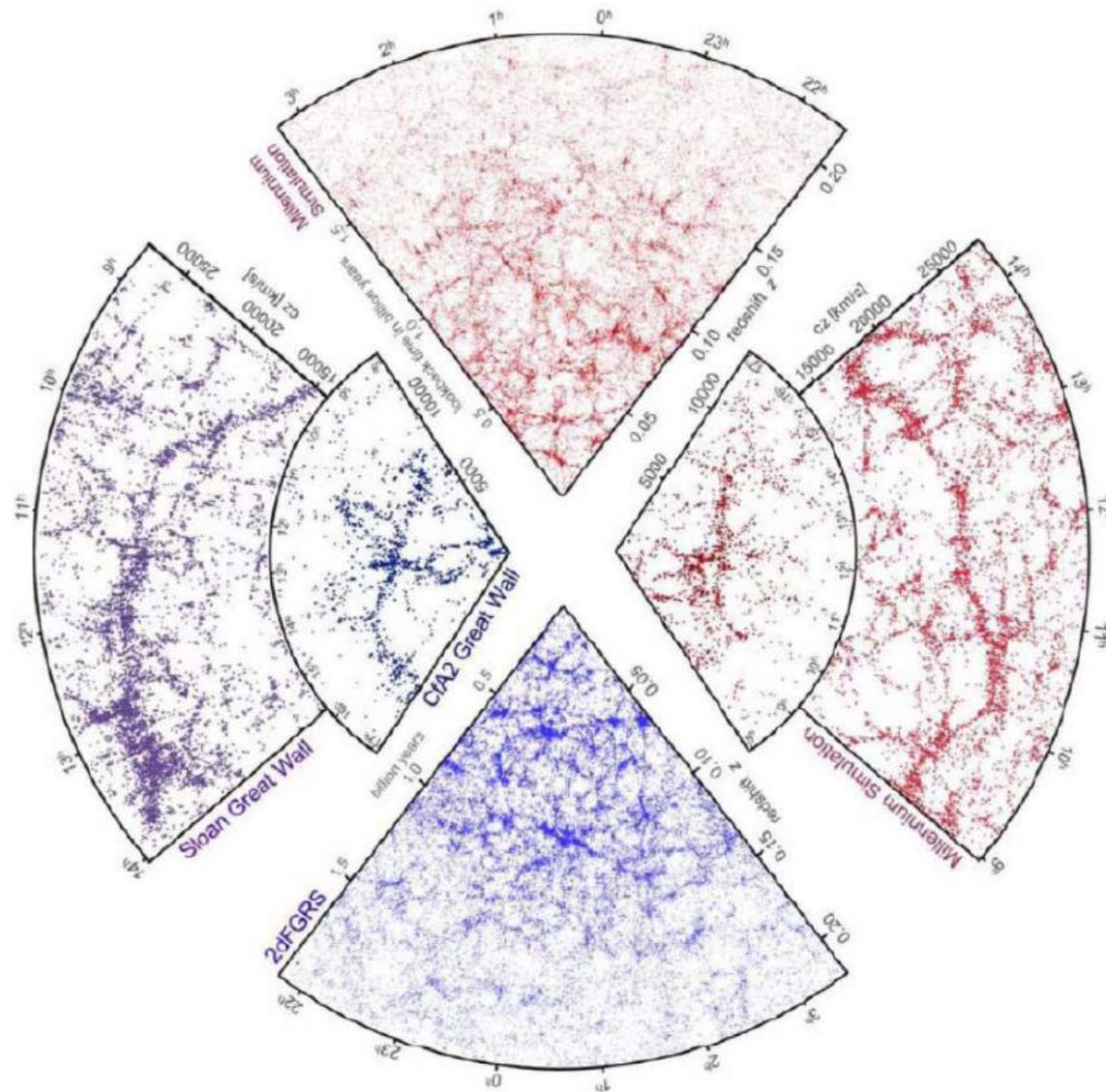
DM halo	α	r_s [kpc]	ρ_s [GeV/cm ³]
NFW	–	24.42	0.184
Einasto	0.17	28.44	0.033
EinastoB	0.11	35.24	0.021
Isothermal	–	4.38	1.387
Burkert	–	12.67	0.712
Moore	–	30.28	0.105

Simulating the universe on a computer

$Z=28.62$



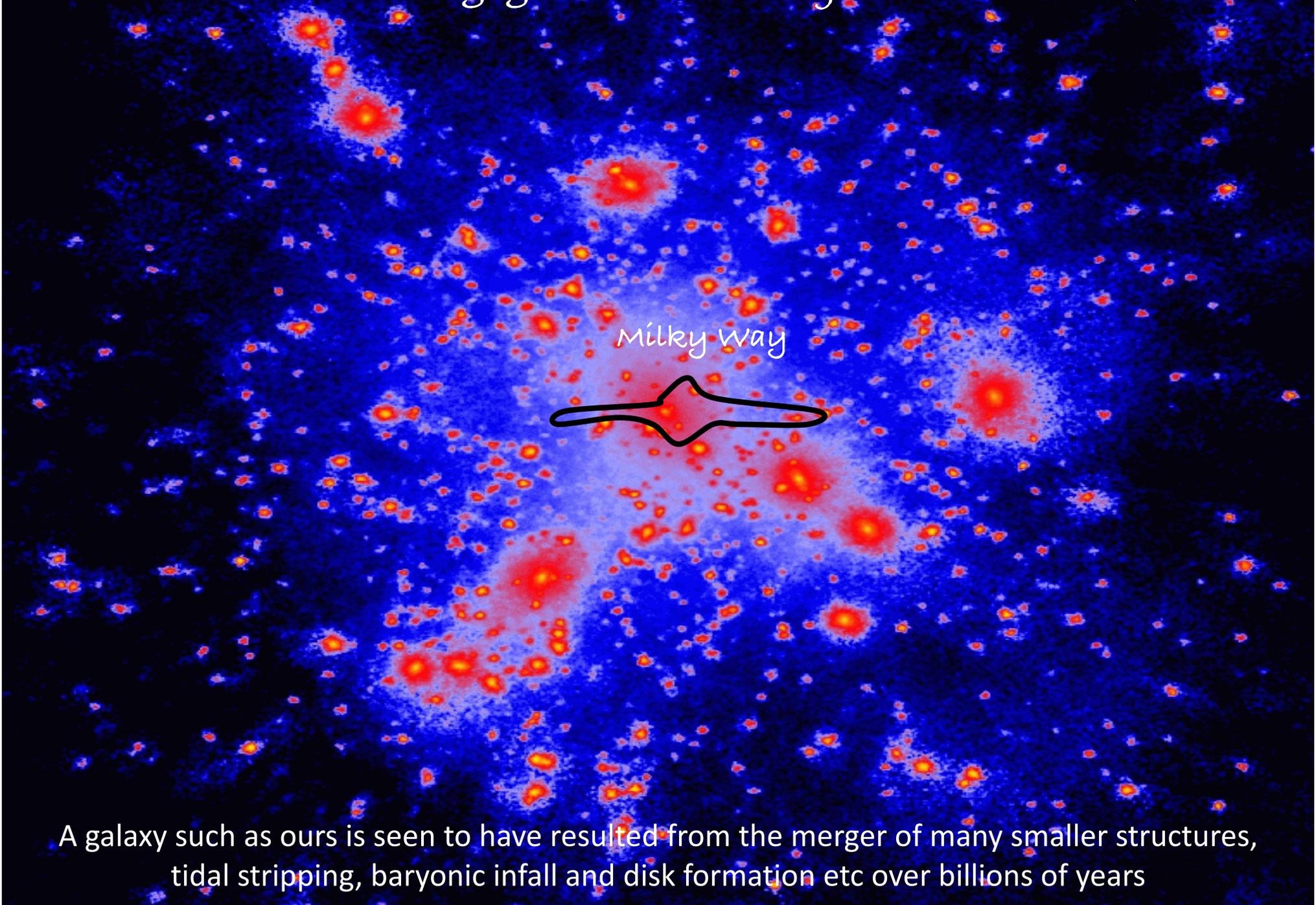
Such numerical simulations provide a pretty good match to the observed large-scale structure of galaxies in the universe



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

The dark matter particles are assumed to be *cold* (non-relativistic at decoupling) & *collisionless* ... this is true of both weakly interacting massive particles (WIMPs) and ultralight axions!

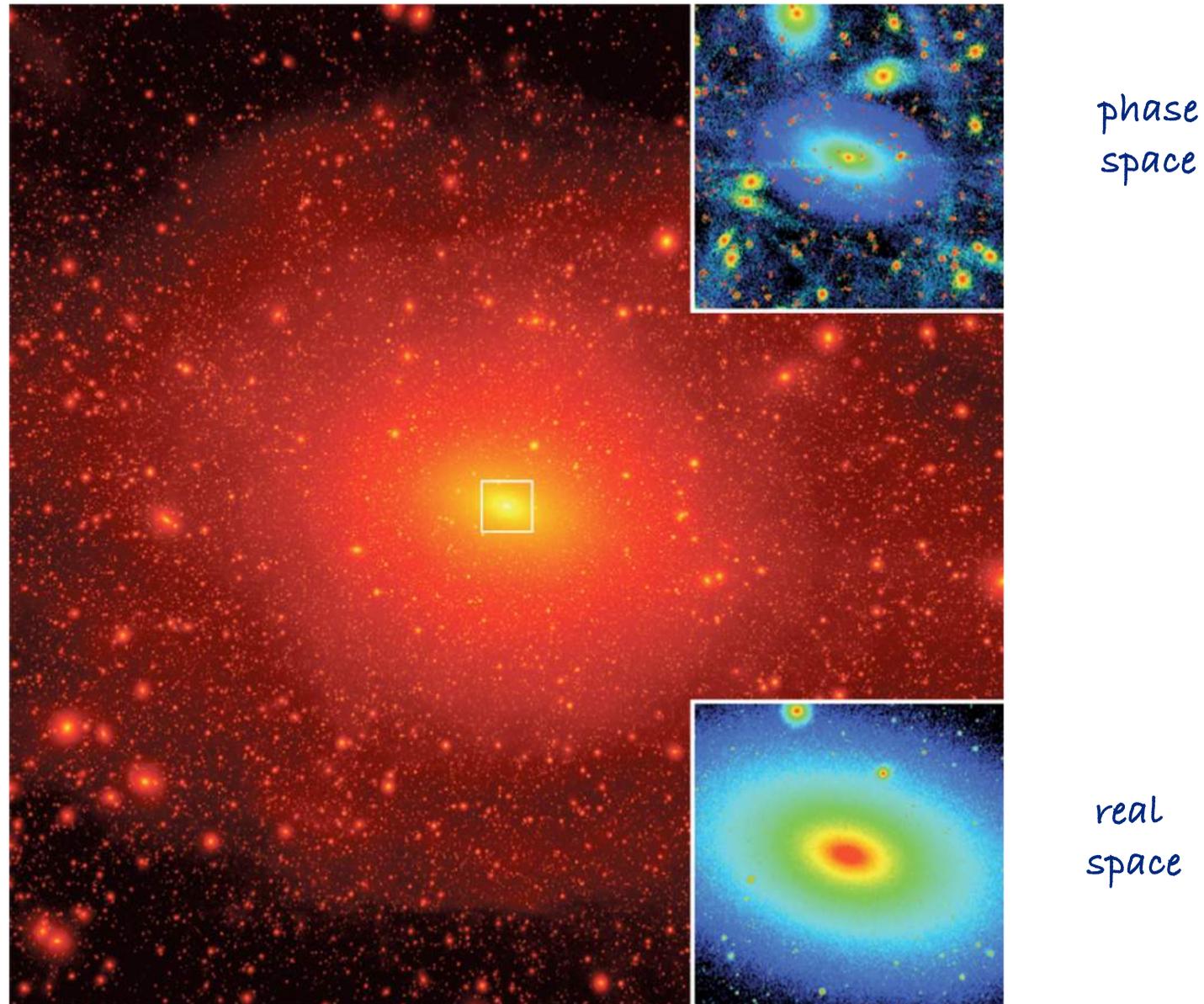
We can get an idea of what the Milky Way halo looks like from numerical simulations of structure formation through gravitational instability in cold dark matter (CDM)



A galaxy such as ours is seen to have resulted from the merger of many smaller structures, tidal stripping, baryonic infall and disk formation etc over billions of years

The phase space structure of the dark CDM halo is pretty complicated

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



But real galaxies appear much simpler than expected!

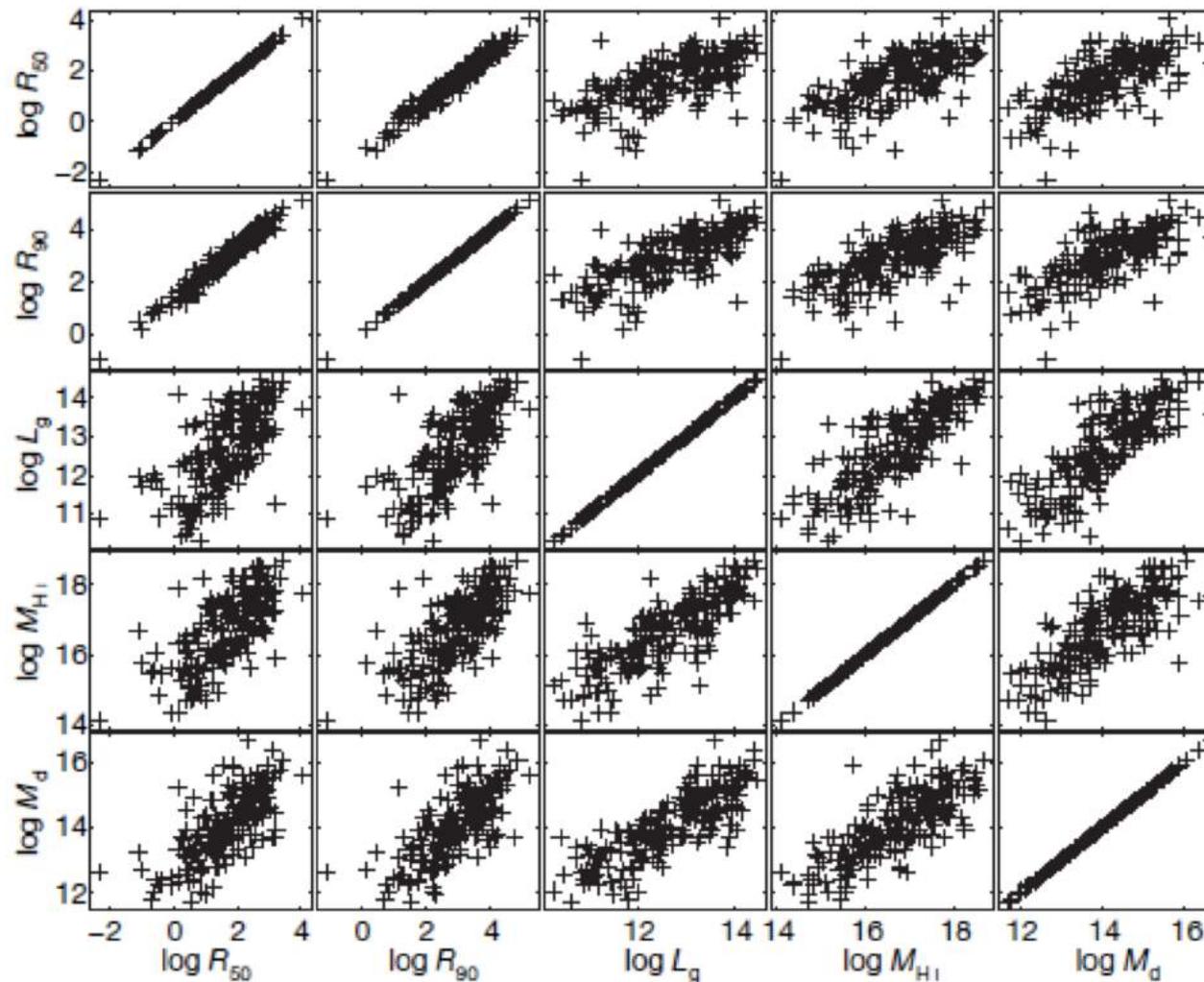


Figure 1 | Scatter plots showing correlations between five measured variables, not including colour. The variables are two optical radii, R_{50} and R_{90} (in parsecs), respectively containing 50 and 90% of the emitted light; and luminosity, L_g ; neutral hydrogen mass, $M_{H I}$; and dynamical mass,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

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



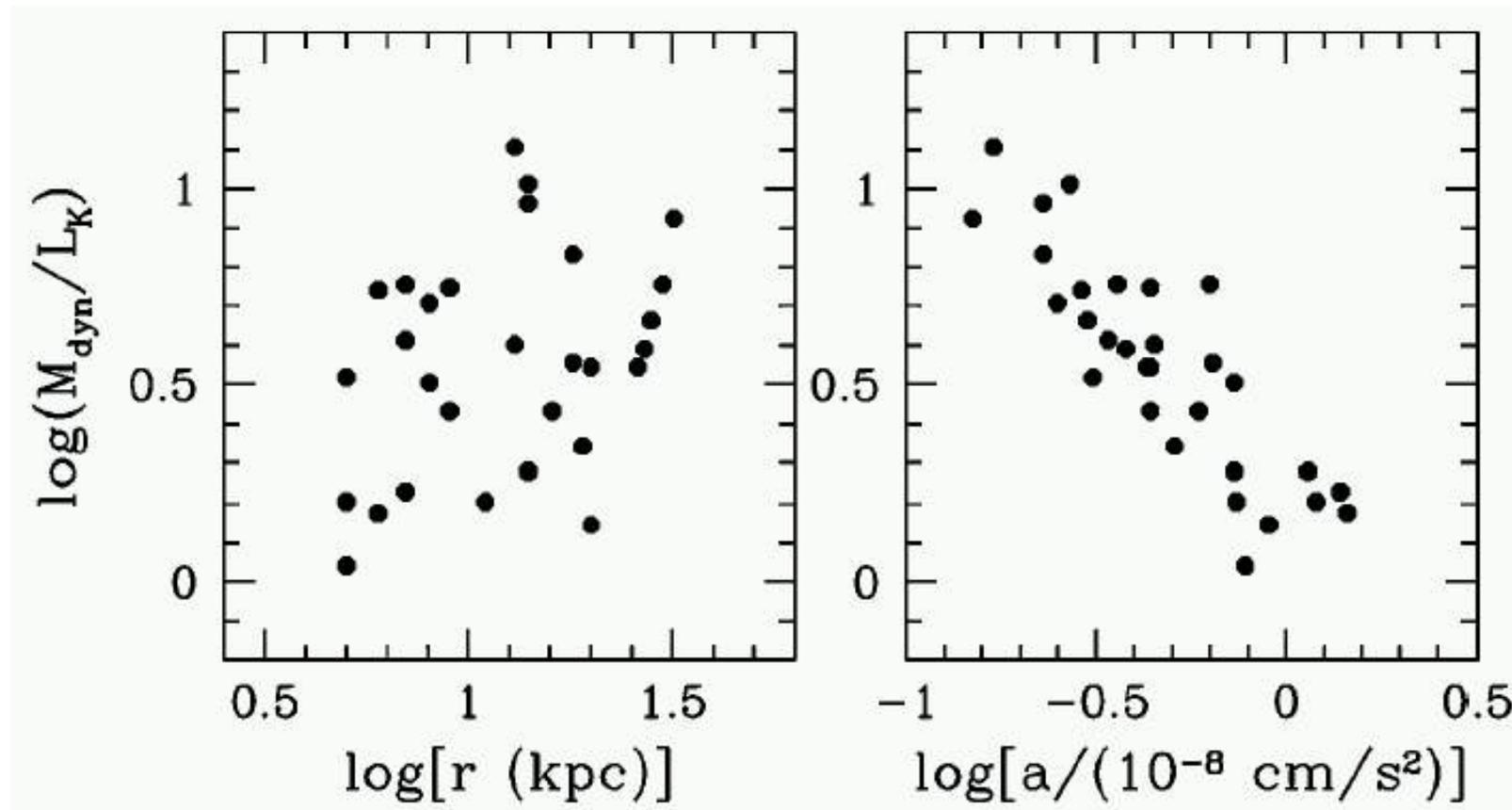
2nd January 1860: “*Gentlemen, I Give You the Planet Vulcan*” French mathematician Urbain Le Verrier announces the discovery of a new planet between Mercury and the Sun, to members of the Académie des Sciences in Paris (following up on his earlier prediction of Neptune in 1856).

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

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

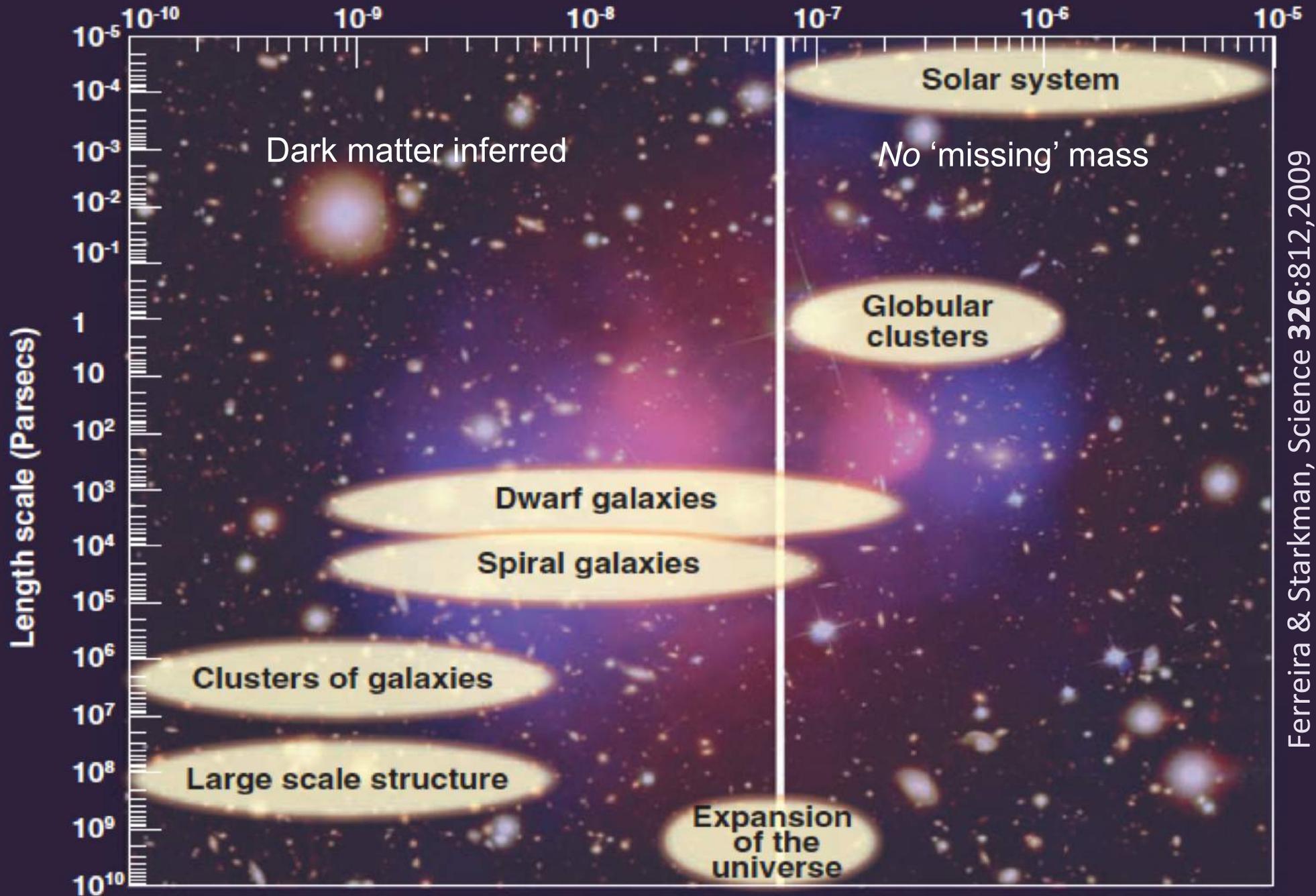


What if Newton's law is modified in weak fields?

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

Milgrom, ApJ **270**:365,1983

Acceleration (cm s^{-2})



Bekenstein—Milgrom Equation

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

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

where

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

Then

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

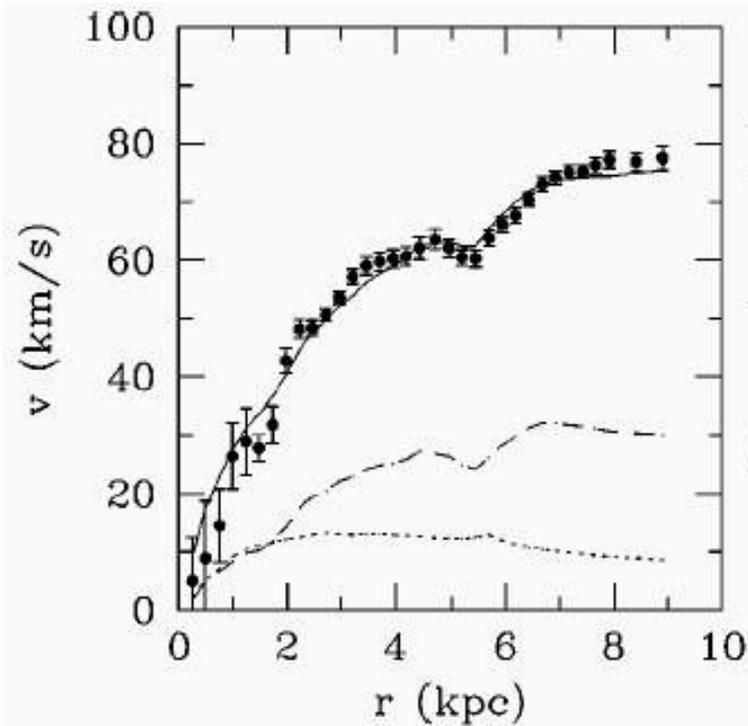
implies

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

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

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

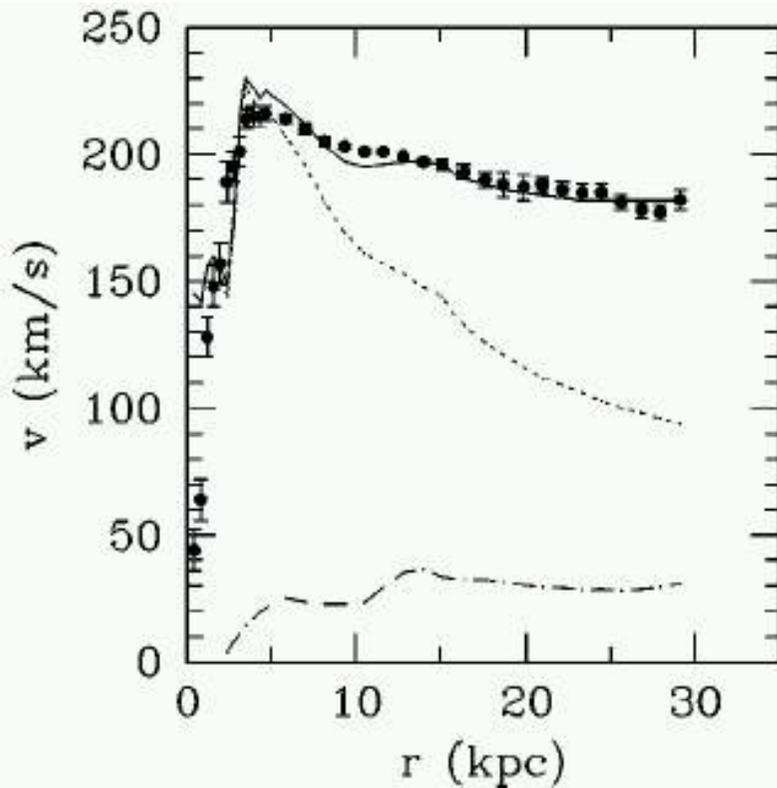
MOND fits *all* galactic rotation curves with $a_0 = 1.2 \times 10^{-8} \text{ cm s}^{-2}$



NGC 1560

$\langle \mu_B \rangle = 23.2 \text{ mag/a}$

$(M/L_B)_{\text{disk}} = 0.4$



NGC 2903

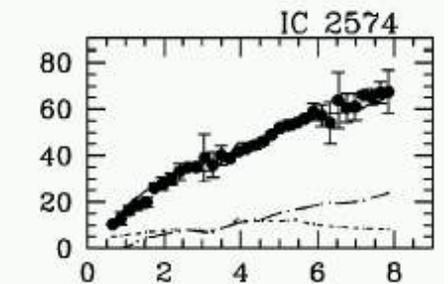
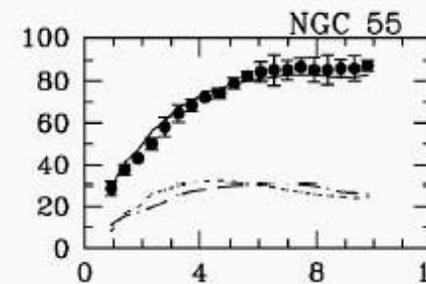
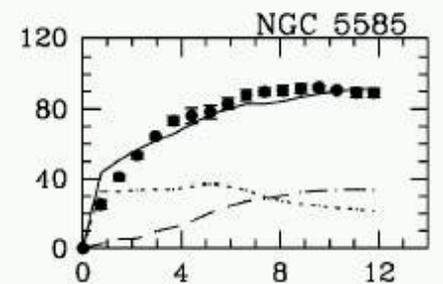
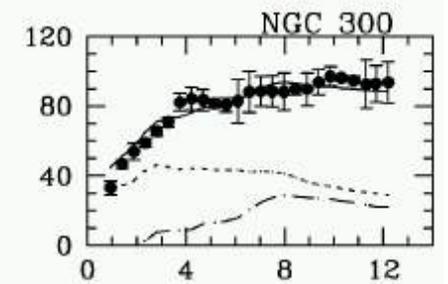
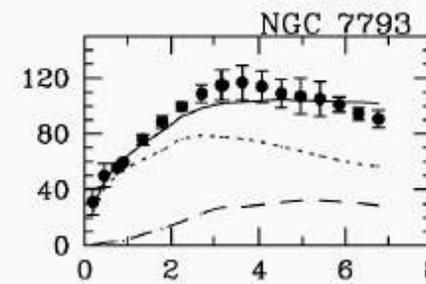
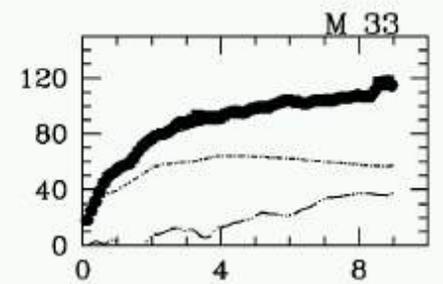
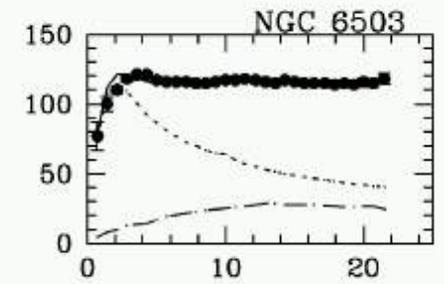
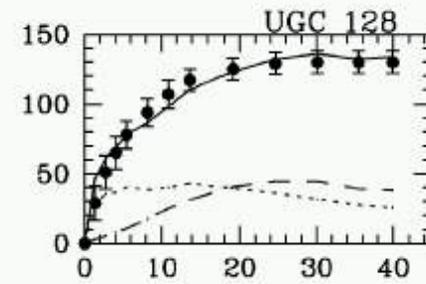
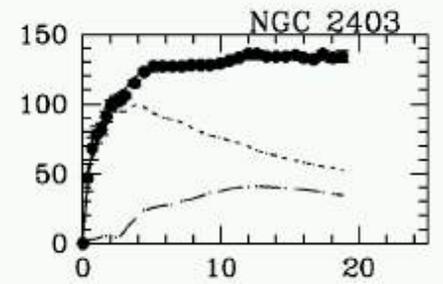
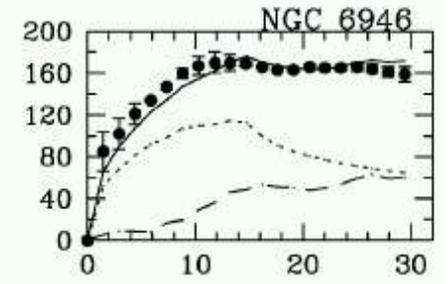
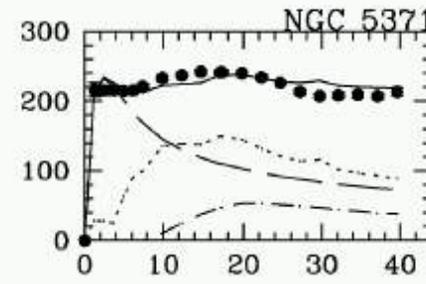
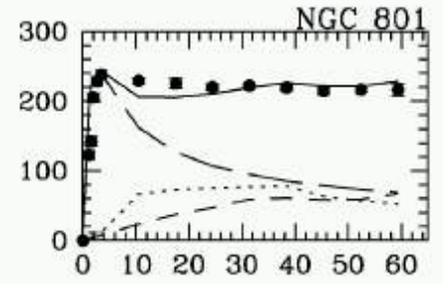
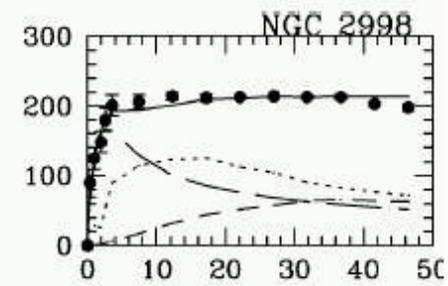
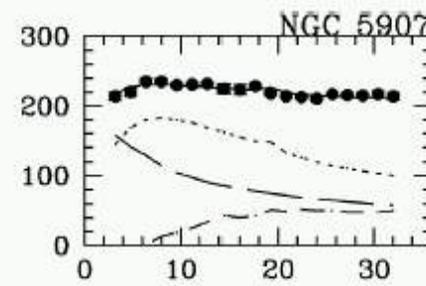
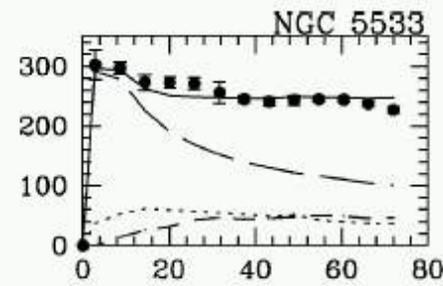
$\langle \mu_B \rangle = 20.5 \text{ mag/a}$

$(M/L_B)_{\text{disk}} = 1.9$

Features in the baryonic disc have *counterparts* in the rotation curve

A huge variety of rotation curves is well fitted by MOND

... with *fewer* parameters than is required by the dark matter model



Moreover some giant ellipticals *do* exhibit Keplerian fall-off of the random velocity dispersion, as MOND predicts

Data:

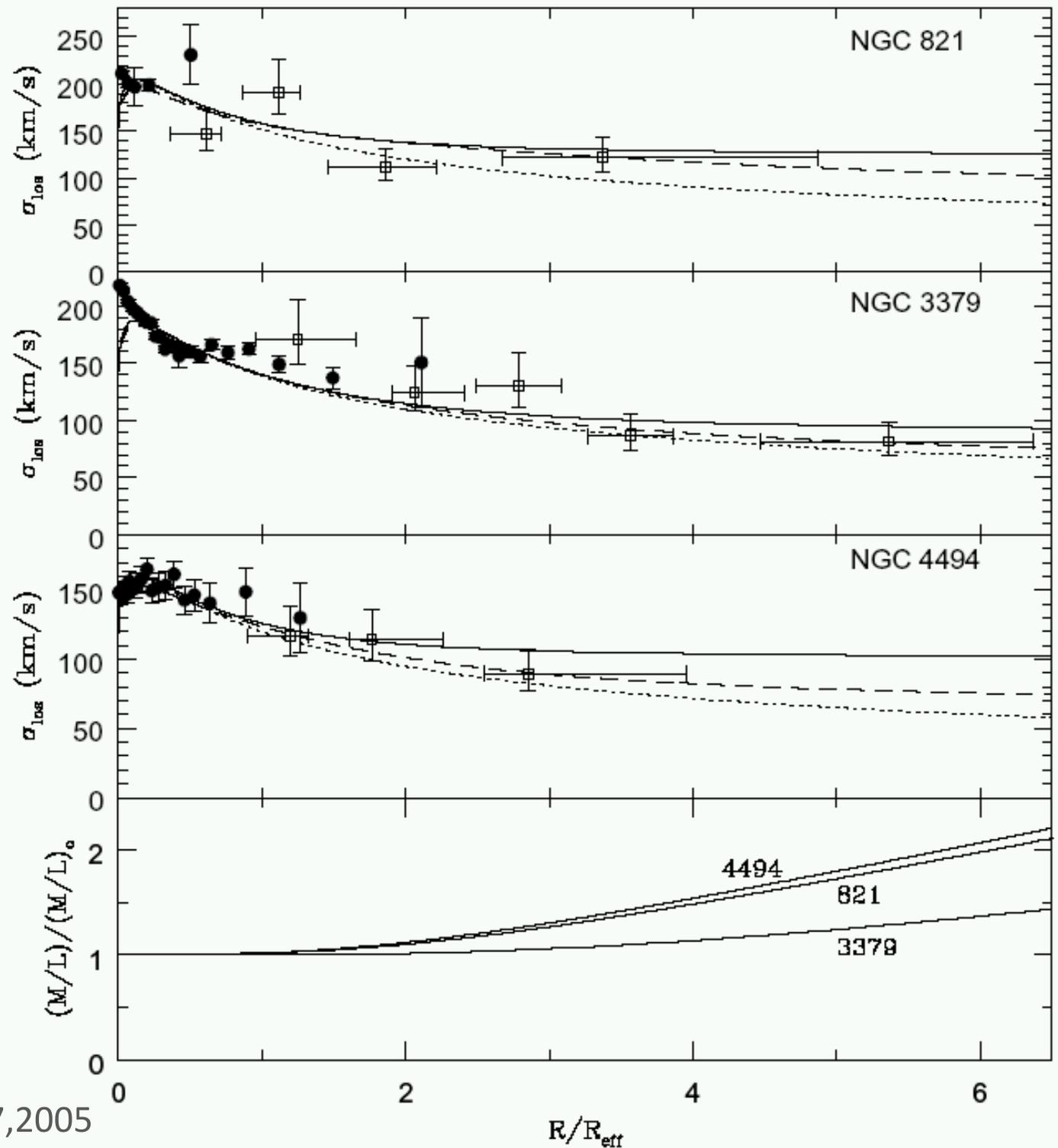
Romanowsky *et al*,
Science **301**:1696,2003

Models:

Milgrom & Sanders
ApJ **599**:L25,2003

This can be explained in a dark matter model only if stellar orbits are *very elliptical*

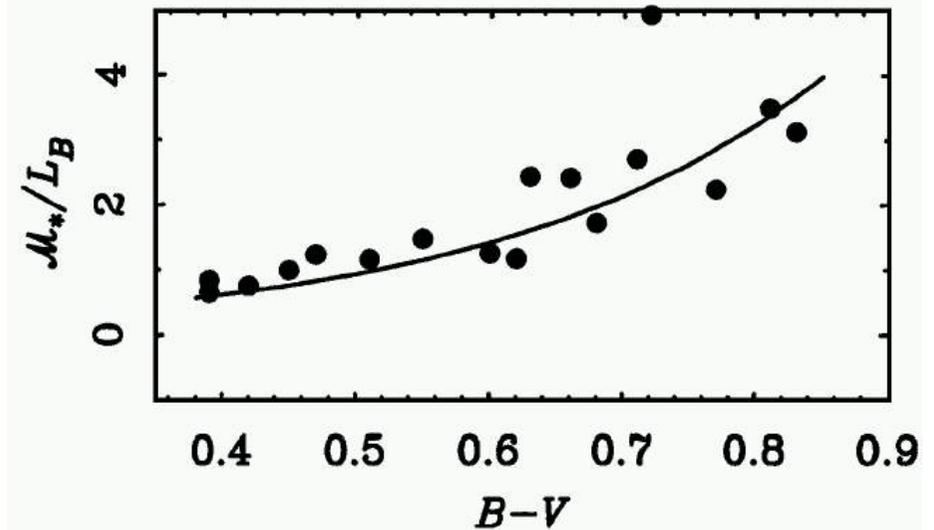
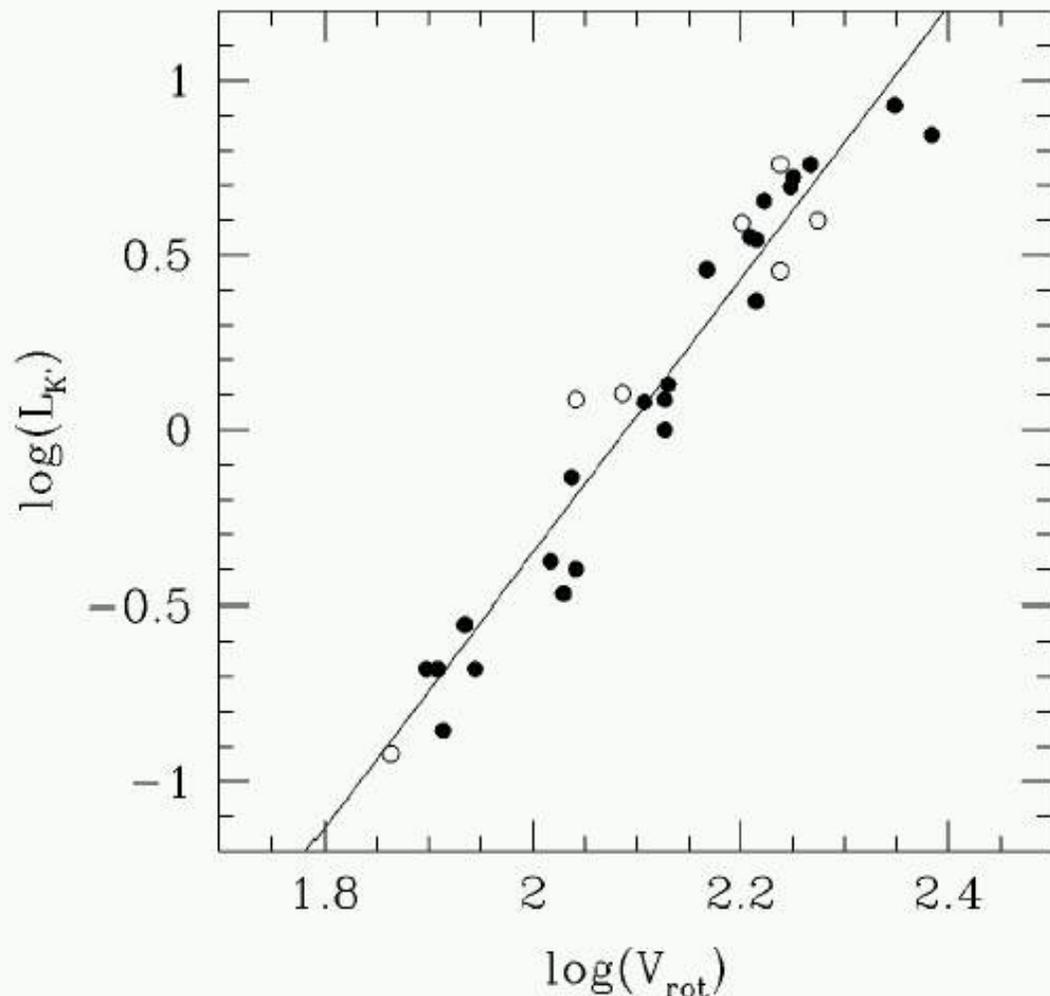
Dekel *et al*, Nature **437**:707,2005



Simply squaring the MOND ansatz $F_N \rightarrow \sqrt{\frac{GM}{r^2} a_0}$ predicts a known astronomical law

$$\frac{v^4}{r^2} = \frac{GM}{r^2} a_0$$

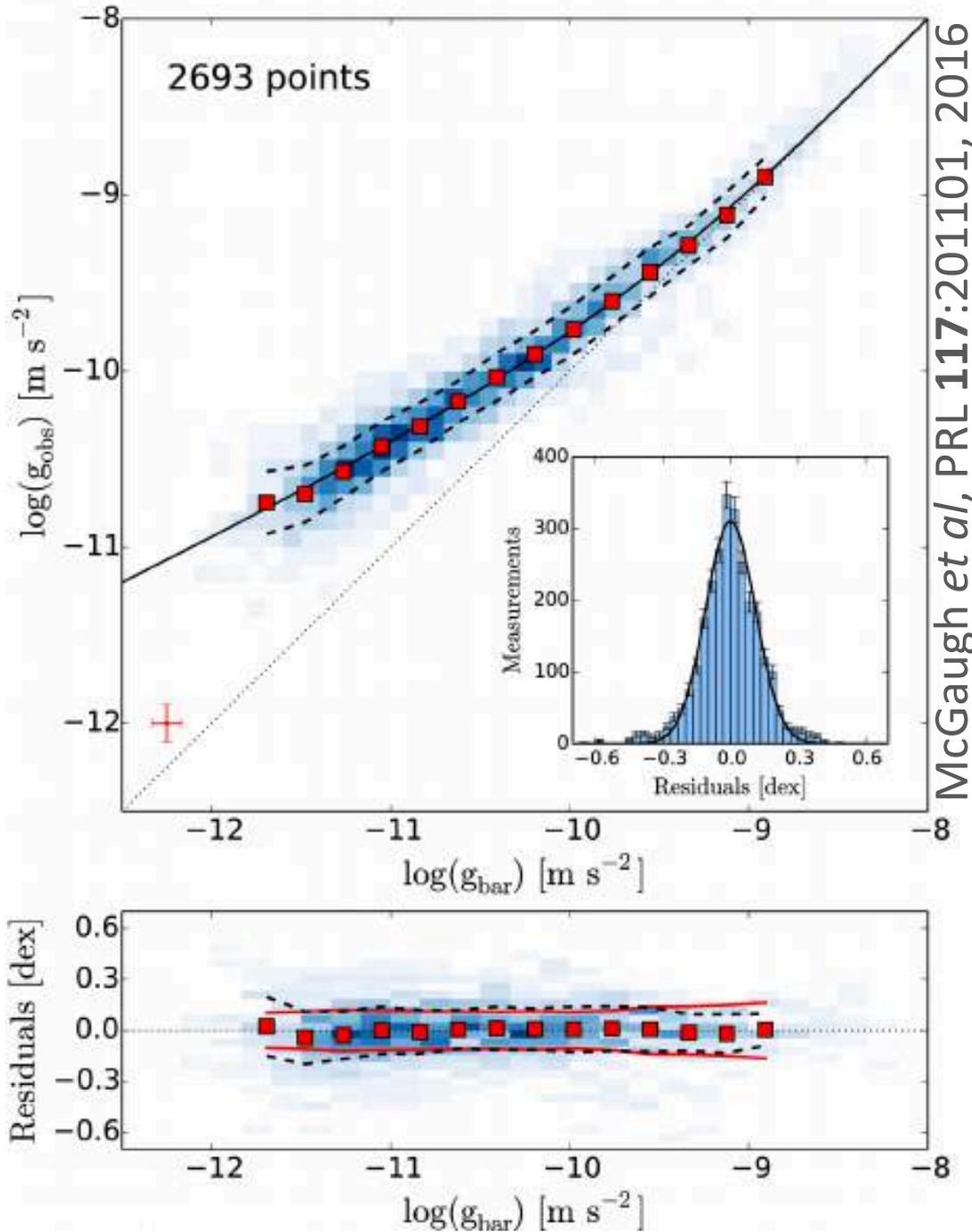
$$\Rightarrow M \propto v^4 \quad (\text{Tully-Fisher if } \frac{M}{L} = \text{const})$$



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

This is an impressive correlation for which dark matter has *no* simple explanation

Recently this has gained new prominence as the ‘MDAR relationship’



153 disk galaxies (SPARC set)
measured at multiple radii

$$g_{\text{obs}} = \mathcal{F}(g_{\text{bar}})$$

$$= \frac{g_{\text{bar}}}{1 - e^{-\sqrt{g_{\text{bar}}/g_{\dagger}}}}$$

$$g_{\dagger} = (1.2 \pm 0.24) \times 10^{-10} \text{m s}^{-2}$$

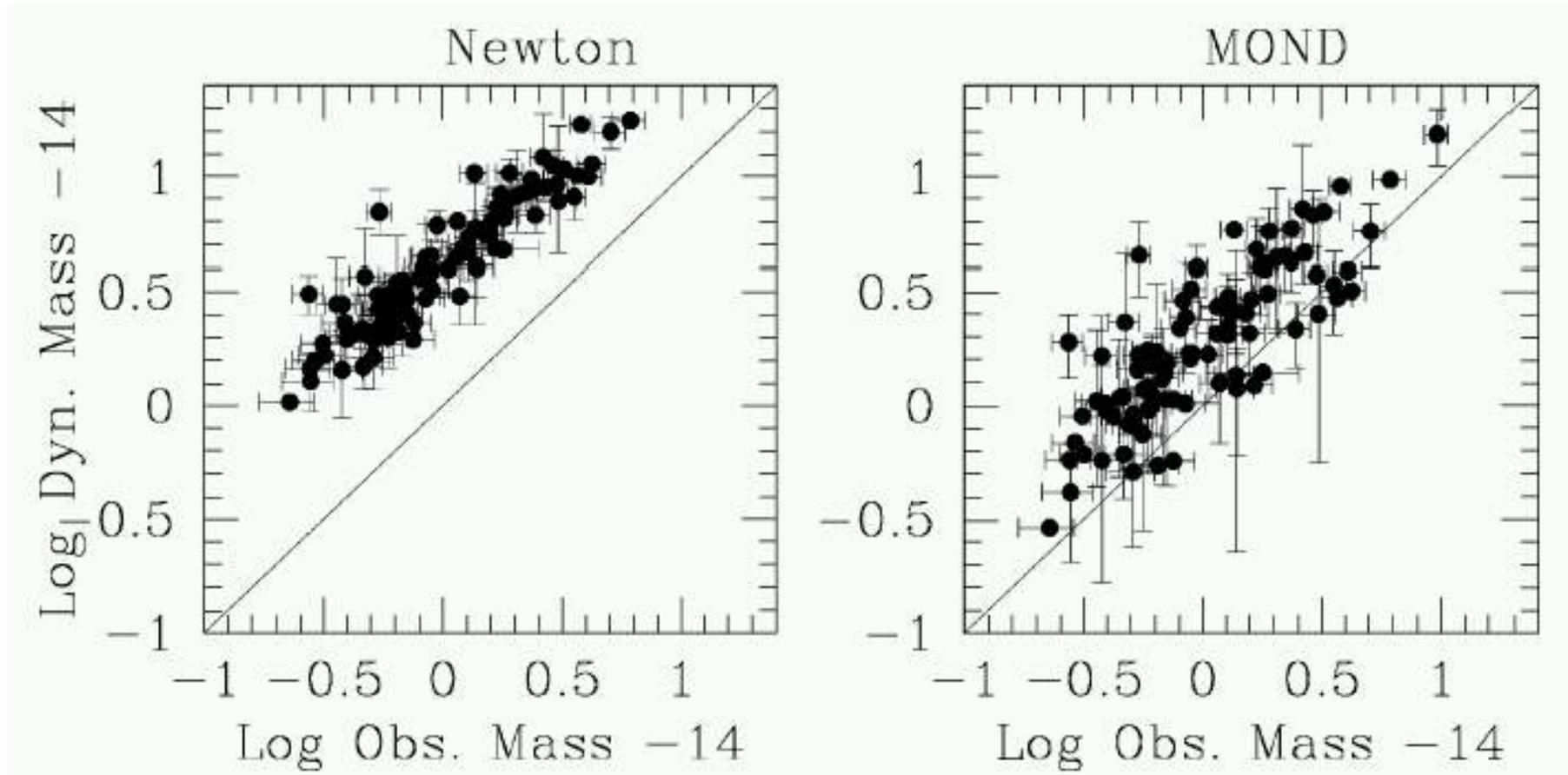
The functional form is *not* unique, e.g.

$$\mathcal{F}(y) = [1 + \sqrt{(1 + 4/y)}]/2$$

which follows from $\mu(x) = x/(1+x)$, fits just as well (Milgrom, 1609.06642)

Can CDM simulations *including* baryon physics predict this curve?

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 $\Rightarrow M/L \sim O(100) M_{\odot}/L_{\odot}$

“... 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”

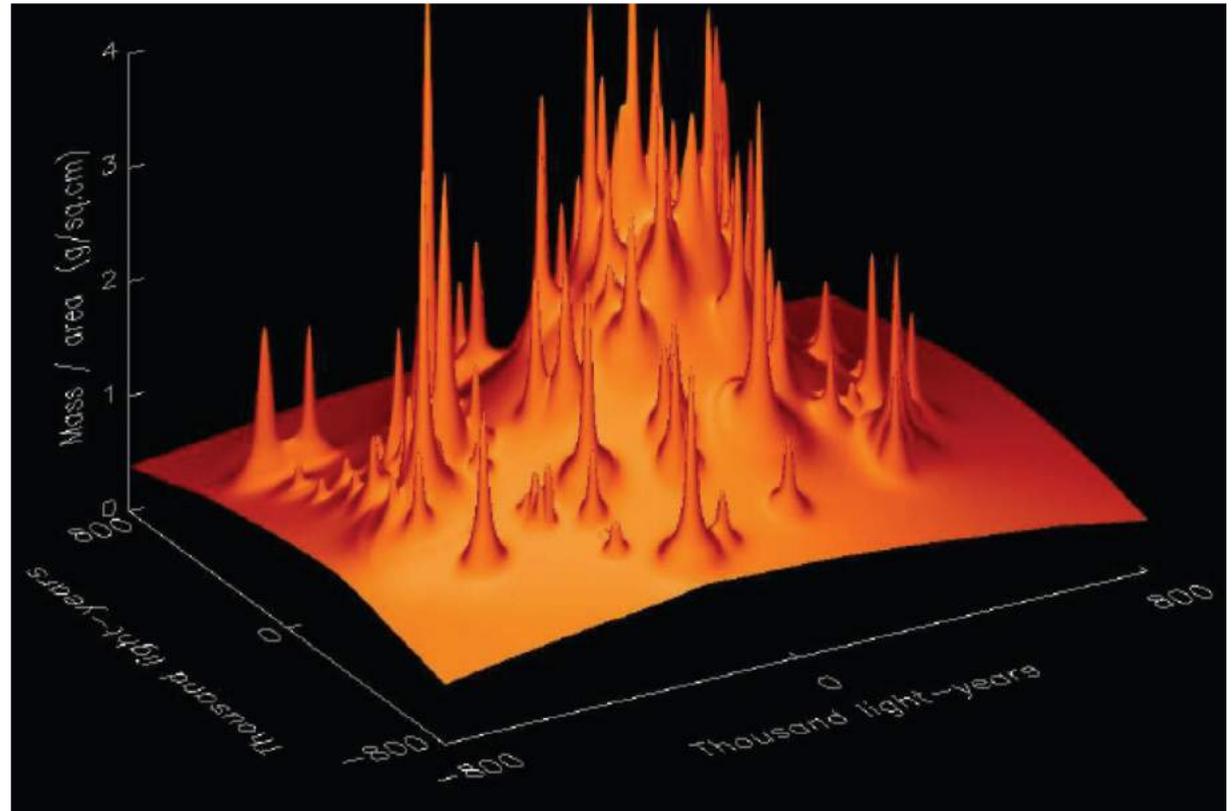
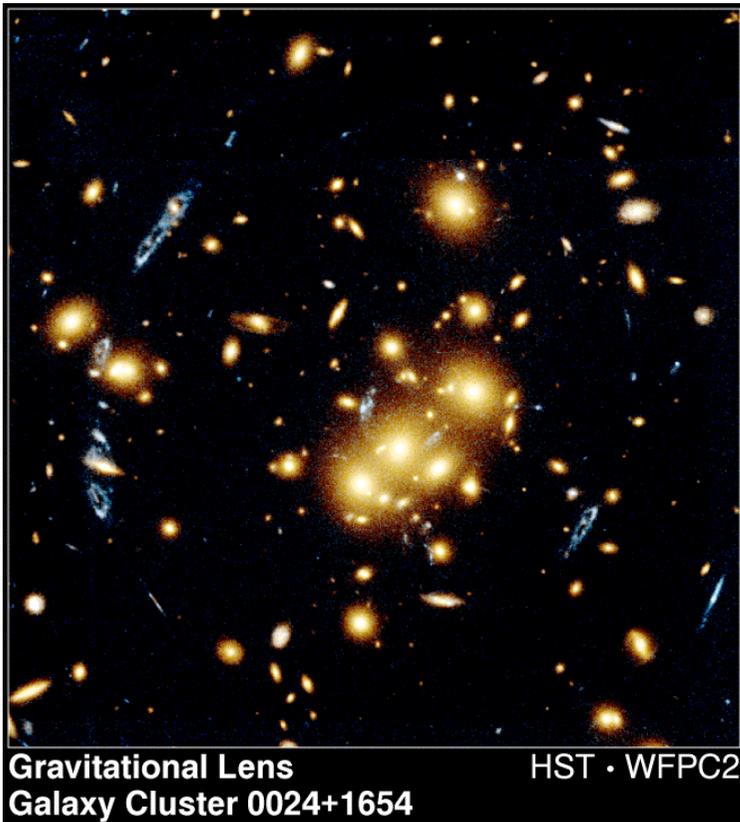
Virial Theorem: $\langle V \rangle + 2\langle K \rangle = 0$

$$V = -\frac{N^2}{2} G_N \frac{\langle m^2 \rangle}{\langle r \rangle}, \quad K = N \frac{\langle mv^2 \rangle}{2}$$

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

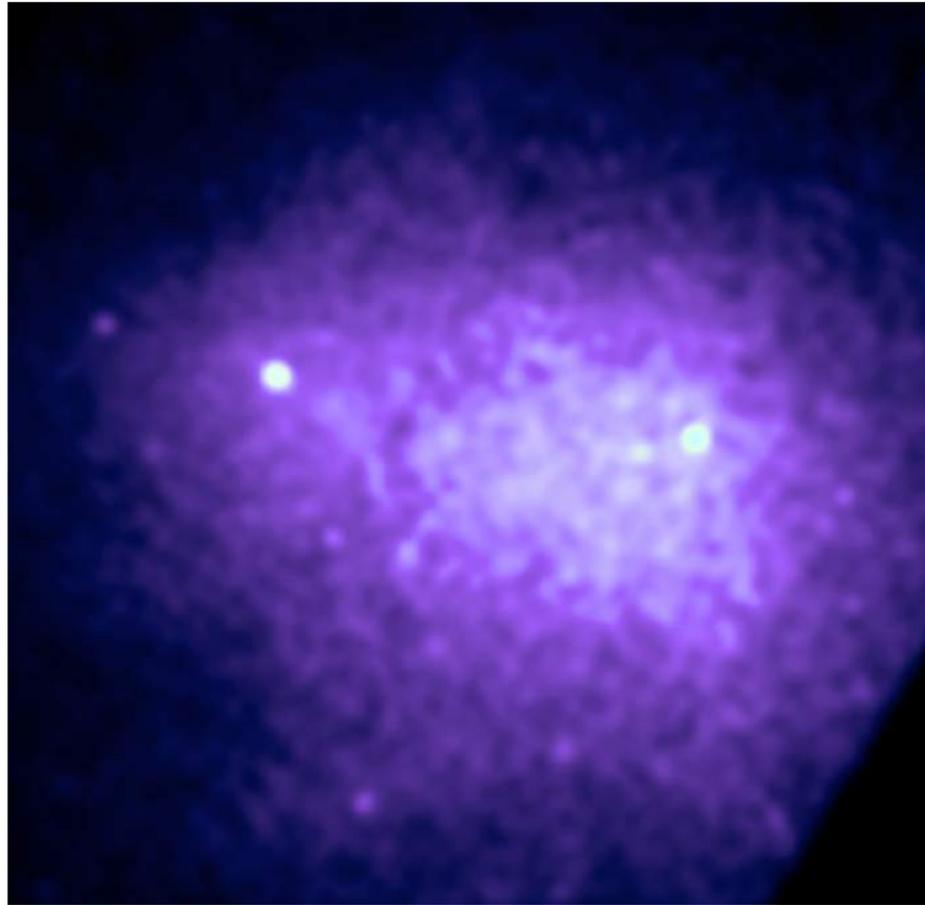


Further evidence comes from observations of **gravitational lensing** of distant sources by a foreground cluster ... enabling the potential to be reconstructed



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:

$$\frac{1}{\rho_{\text{gas}}} \frac{dP_{\text{gas}}}{dr} = \frac{G_N M(< r)}{r^2}$$

The Chandra picture of the ‘bullet cluster’ shows that the X-ray emitting baryonic matter is displaced from the galaxies and the dark matter (inferred through gravitational lensing) ...
for many this is convincing evidence of dark matter

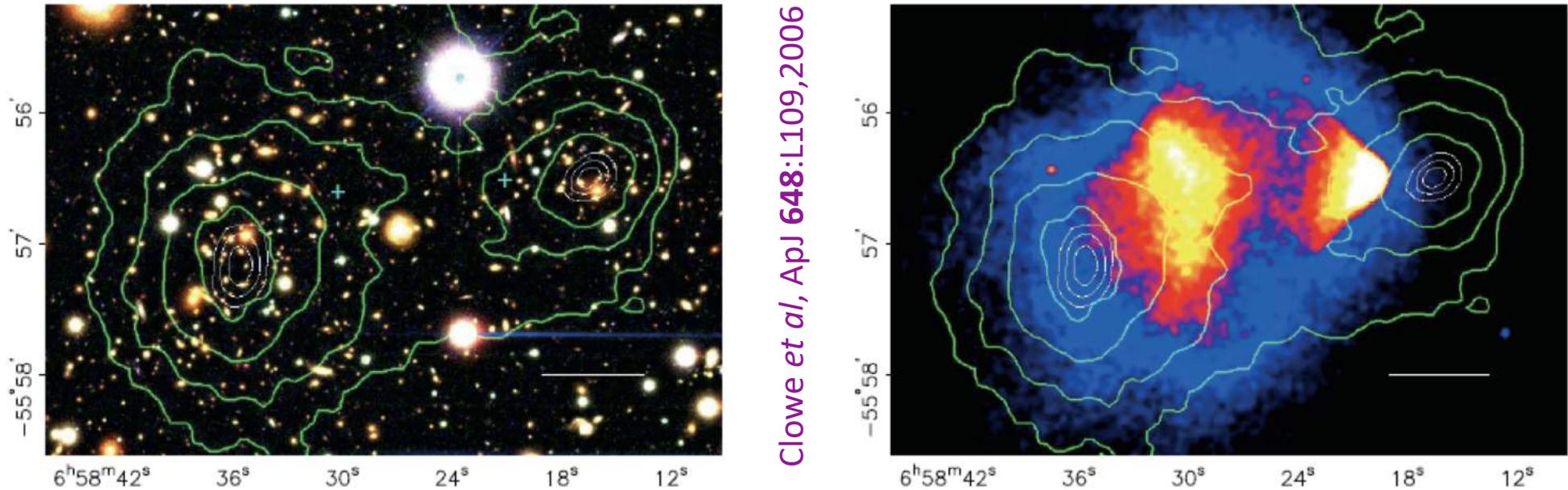


FIG. 1.—*Left panel:* Color image from the Magellan images of the merging cluster 1E 0657–558, with the white bar indicating 200 kpc at the distance of the cluster. *Right panel:* 500 ks *Chandra* image of the cluster. Shown in green contours in both panels are the weak-lensing κ reconstructions, with 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.

However this is nothing new ... it was known *already* that MOND fails (by a factor of ~ 2) to explain the ‘missing matter’ in galaxy clusters (Moreover the rather high relative velocity of the merging clusters is a puzzle in the Λ CDM cosmology as well – only ~ 0.1 such systems are expected (Kraljic & Sarkar, JCAP 04:050,2015))

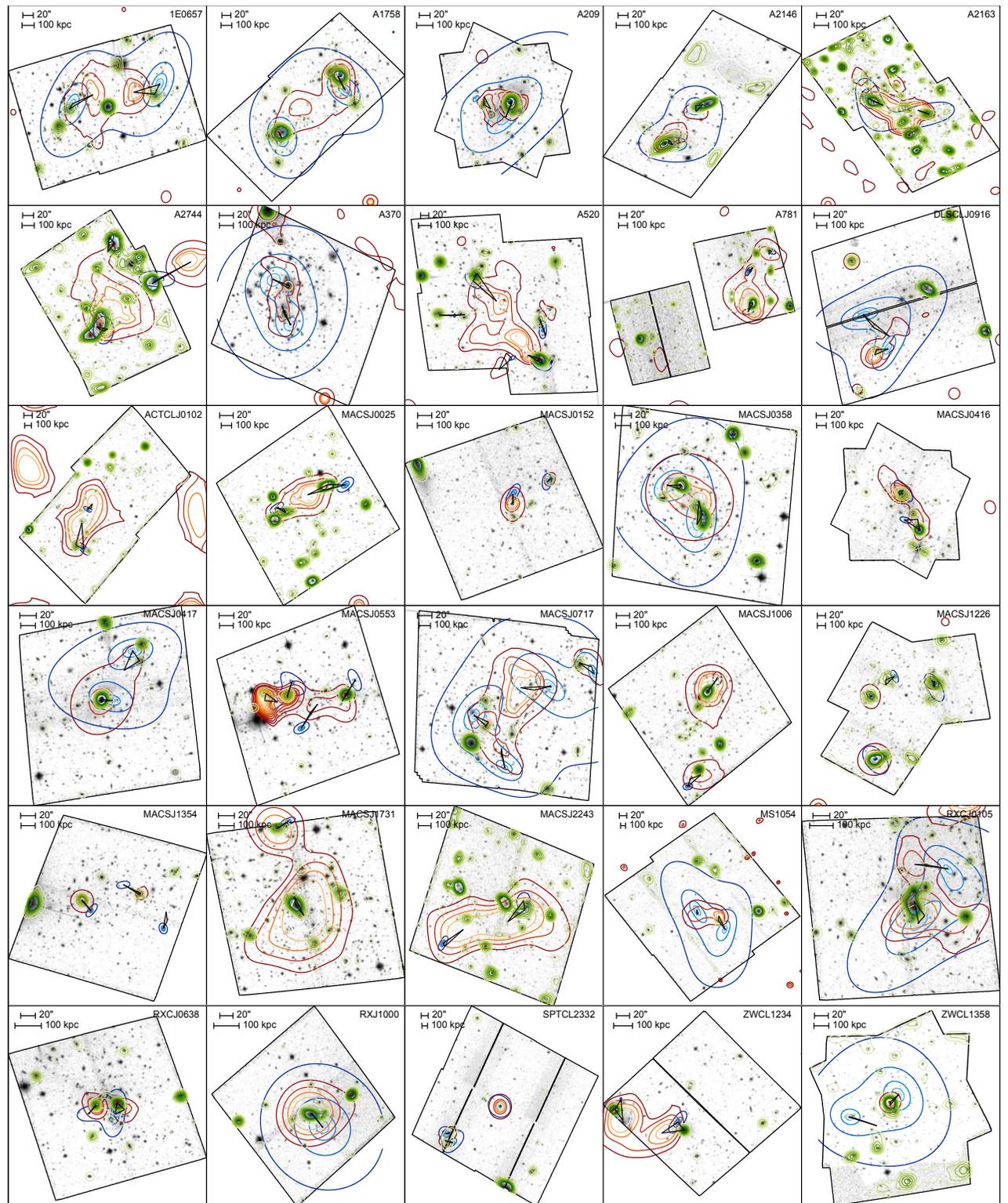
Colliding Clusters

There have been several studies on constraining DM self-interactions via the observation of merging galaxy clusters

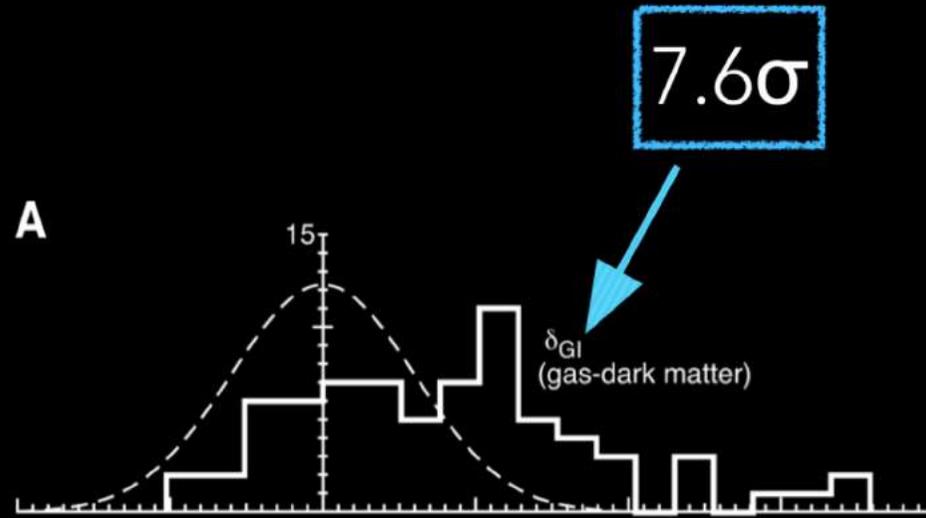
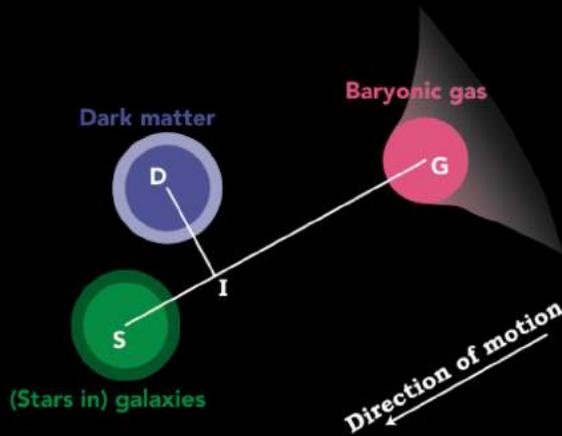
Through statistical analysis of a large number of gravitationally lensed clusters in the Chandra catalogue, the DM self-interaction is bounded as:

$$\sigma/m_\chi \lesssim 1 \text{ cm}^2/\text{g}$$

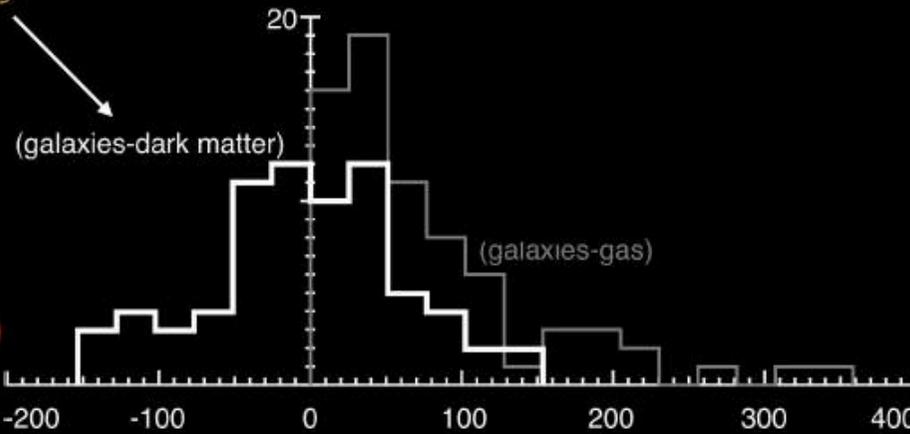
Harvey *et al*, Science
347:6229,2015



RESULTS FROM 72 MERGING SYSTEMS



$5.8 \pm 8.2 \text{ kpc}$

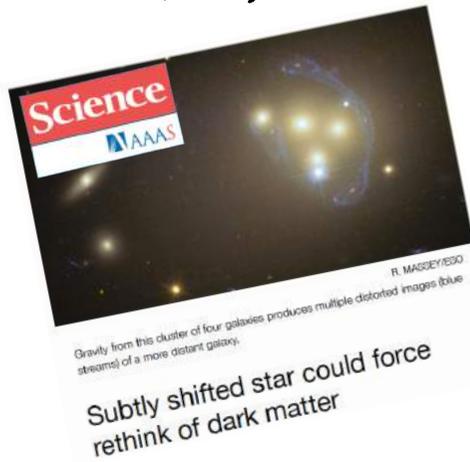


$25 \pm 29 \text{ kpc}$
(Bullet Cluster)

Observed offset between various components of substructure [kpc]

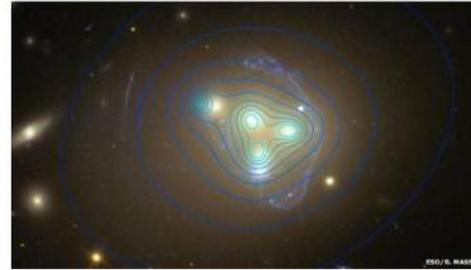
-500 -400 0 100 200 300 400

But in A3827 an offset was observed between a galaxy and its DM halo!



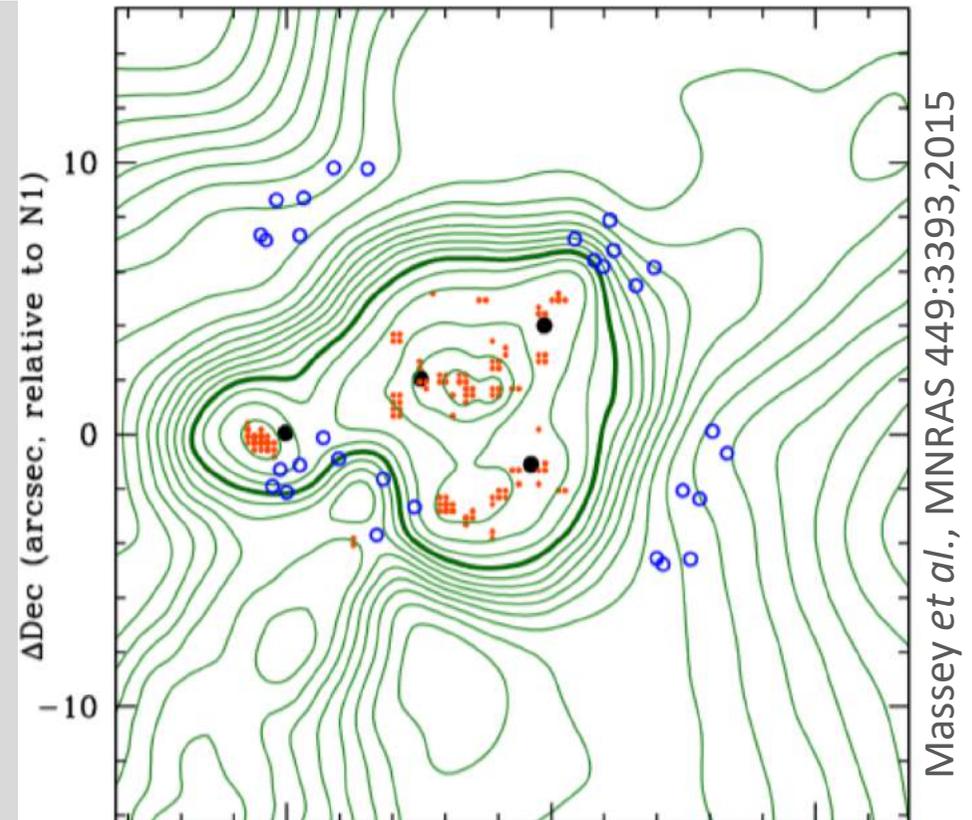
Dark matter becomes less 'ghostly'

By Paul Rincon
Science editor, BBC News website
15 April 2015 | Science & Environment



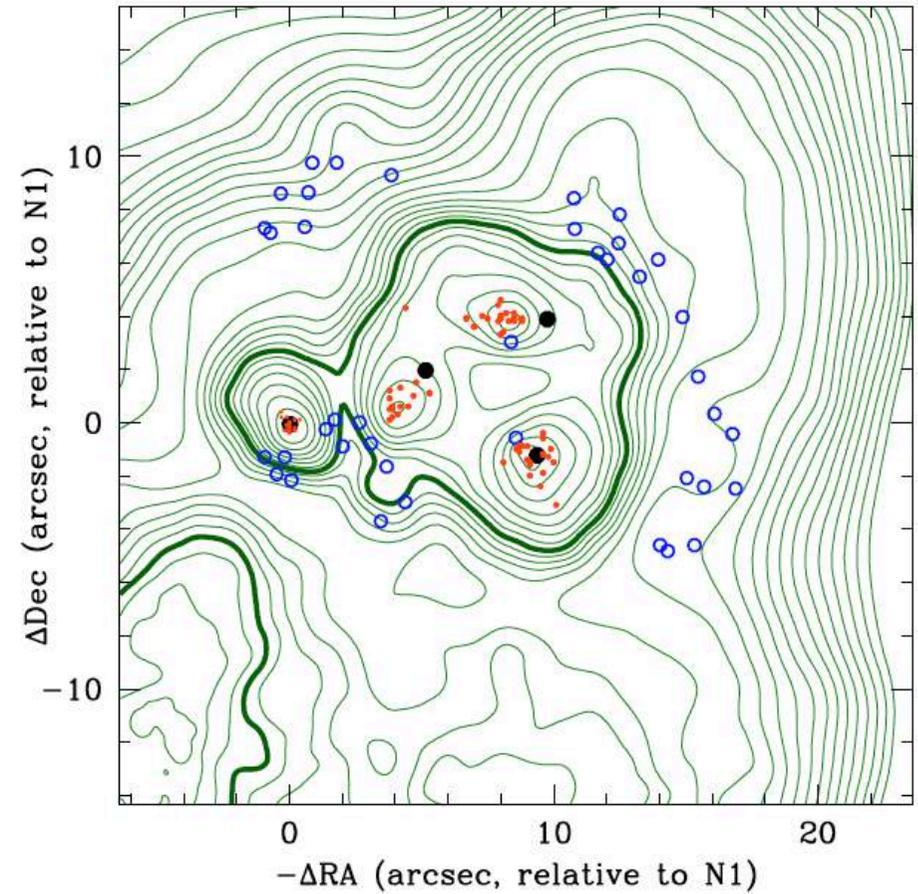
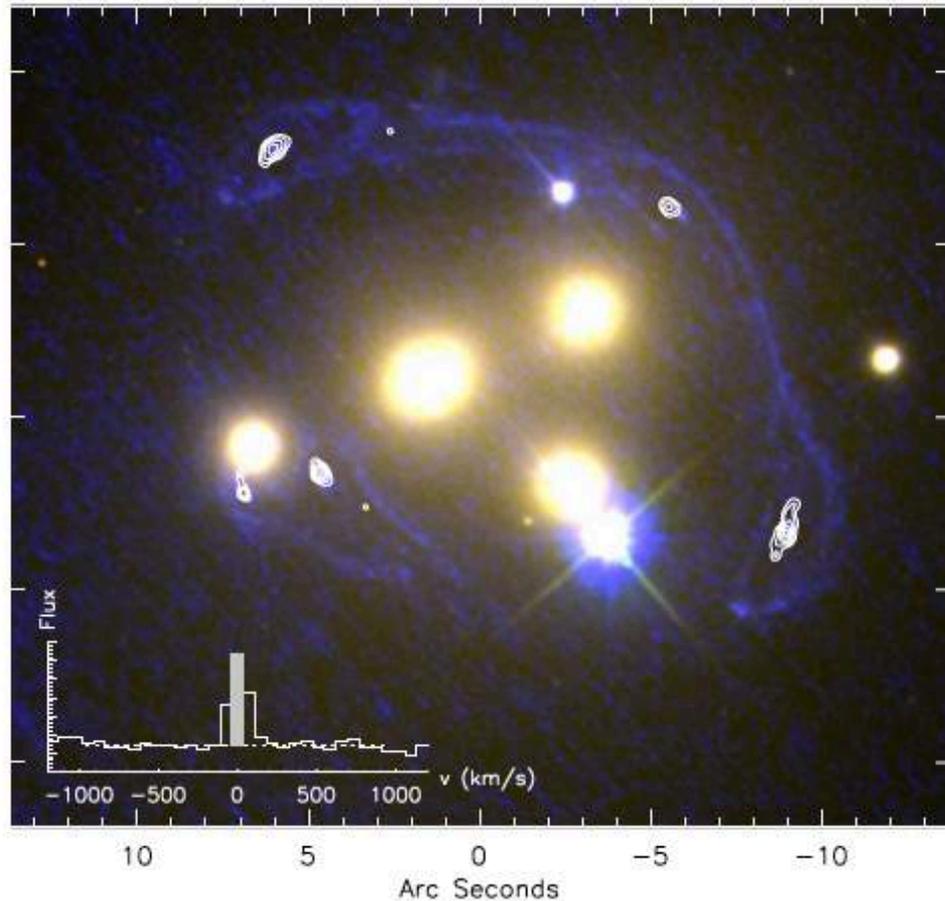
The behaviour of dark matter associated with 4 bright cluster galaxies in the 10 kpc core of Abell 3827

“The best-constrained offset is 1.62 ± 0.48 kpc, where the 68% confidence limit includes both statistical error and systematic biases in mass modelling. [...] With such a small physical separation, it is difficult to definitively rule out astrophysical effects operating exclusively in dense cluster core environments – but if interpreted solely as evidence for self-interacting dark matter, this offset implies a cross-section $\sigma/m = (1.7 \pm 0.7) \times 10^{-4} \text{ cm}^2/\text{g} (t/10^9 \text{ yr})^{-2}$ where t is the infall duration.”



... corrected to $\sigma/m \sim 1.5 \text{ cm}^2/\text{g}$, accounting for dynamics (Kahlhoefer et al, MNRAS 452:L54,2015)

But with new data from ALMA the offset in Abell 3827 has disappeared!
Now that the counterparts of the many multiply-imaged star-forming knots are better identified, the lensing reconstruction is more secure and uncertainties are reduced

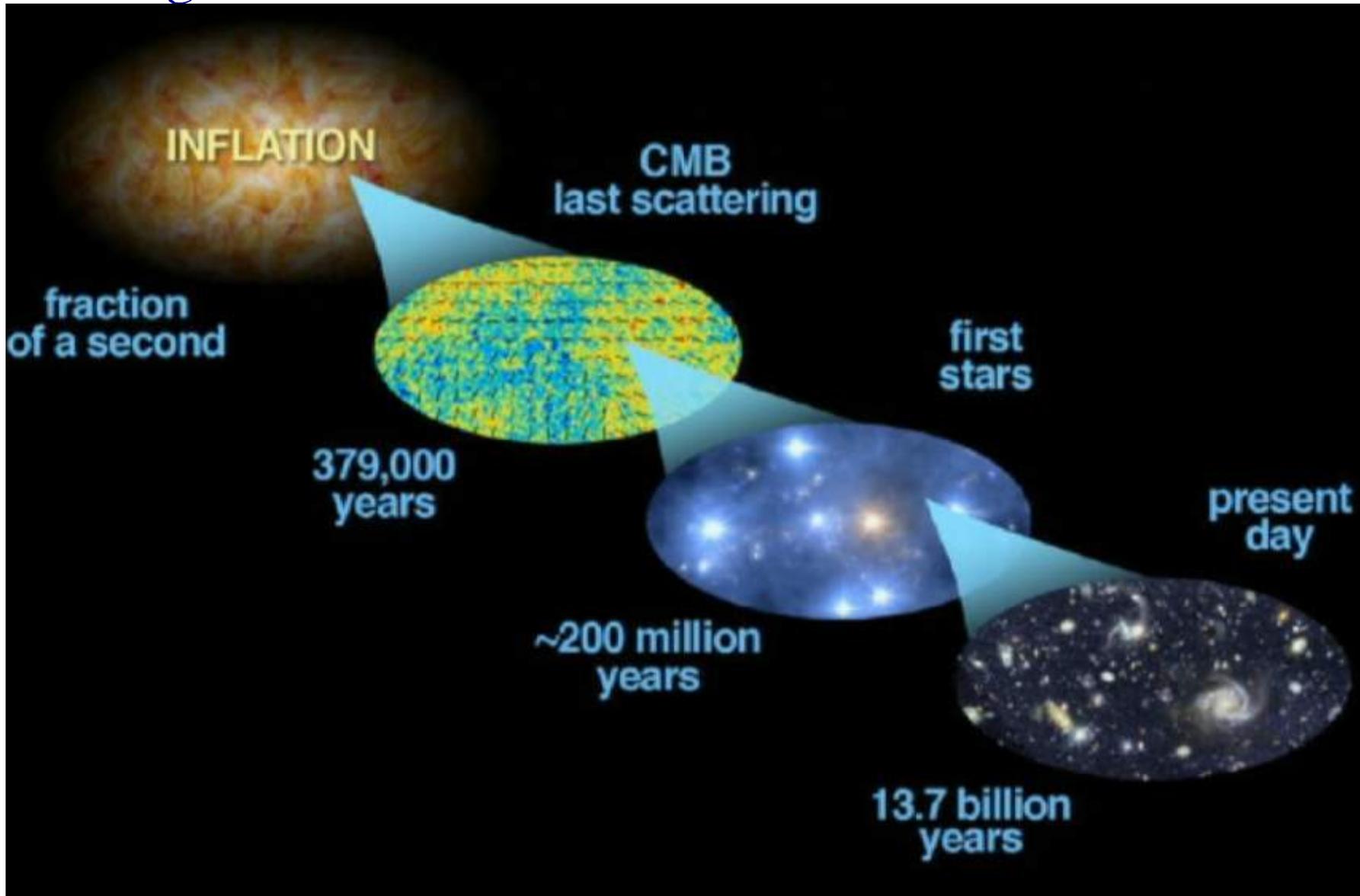


Massey et al., MNRAS 477:669,2017

Nevertheless arguments continue to be made in support of dark matter having self-interactions (which may be *velocity-dependent*) e.g. from observations of cores in dwarf spheroidal/low surface brightness galaxies, cluster mergers (e.g. A520), etc

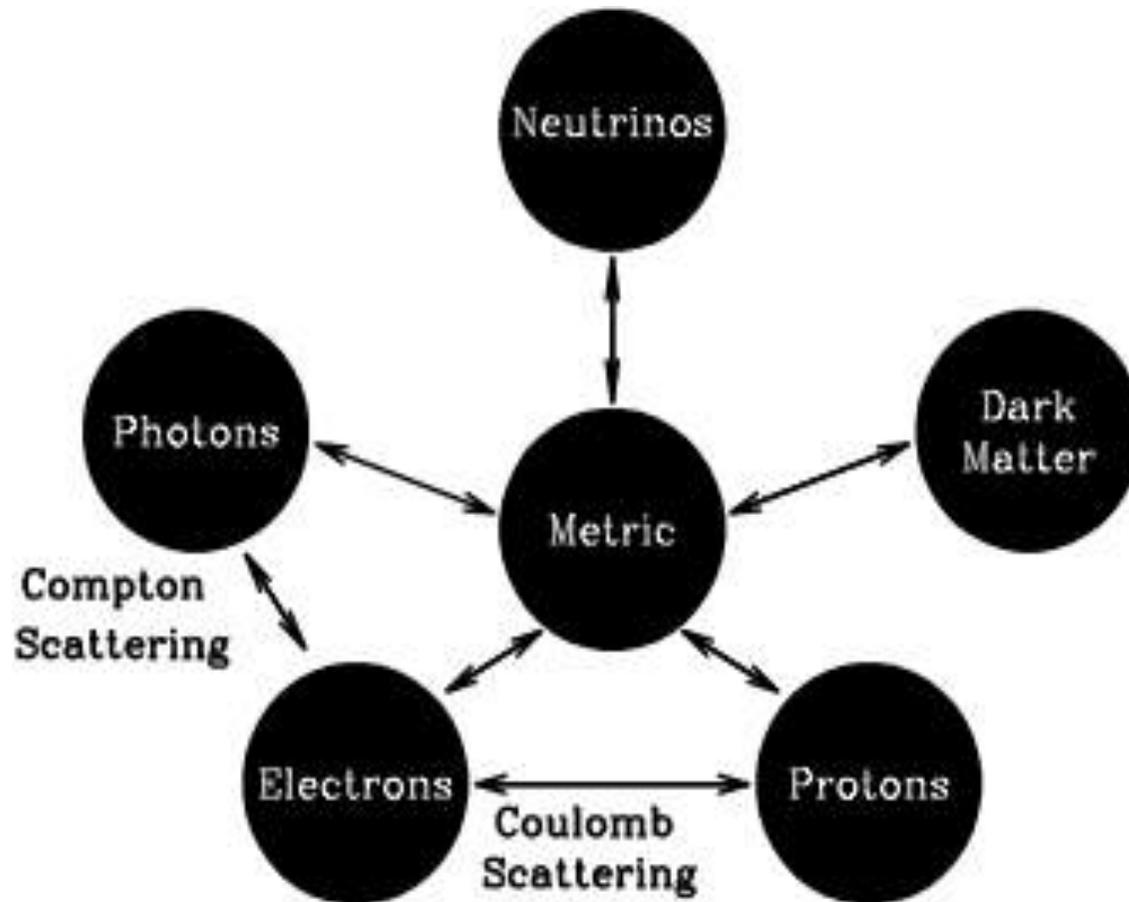
Astronomical observations may provide the clue to the particle nature of dark matter!

Another argument for DM comes from considerations of structure formation



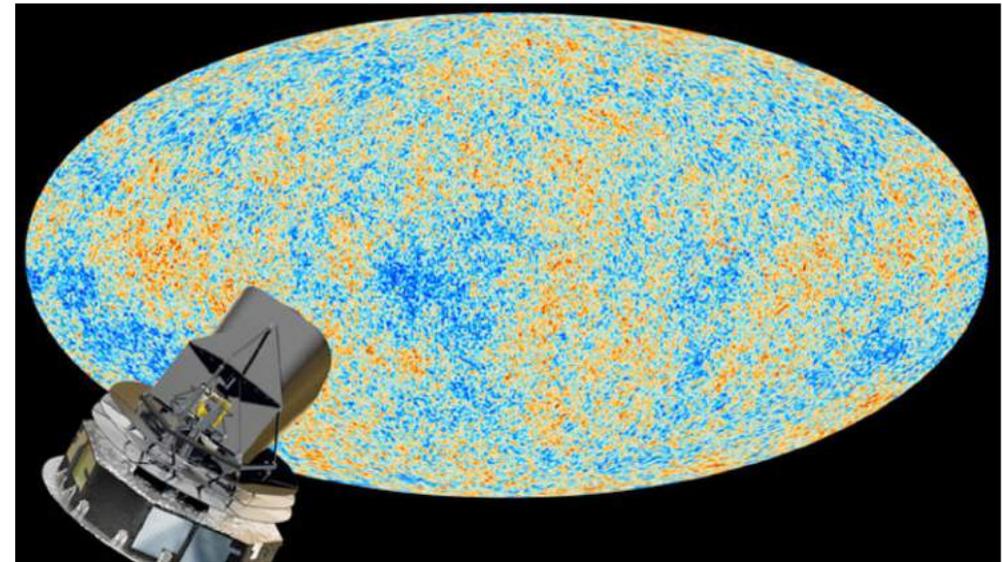
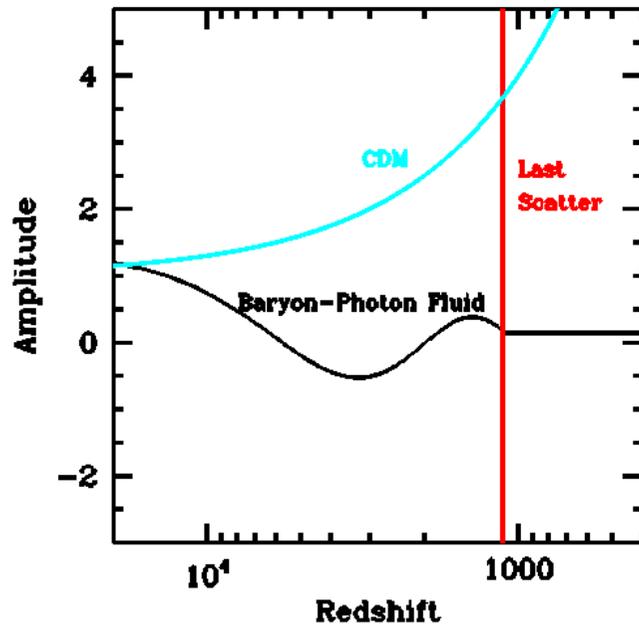
These temperature fluctuations are understood as due to **scalar density perturbations** with an \sim scale-invariant spectrum which were generated during an early phase of inflationary expansion ... these perturbations have subsequently grown into the **large-scale structure** of galaxies observed today through **gravitational instability** in a sea of **dark matter**

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



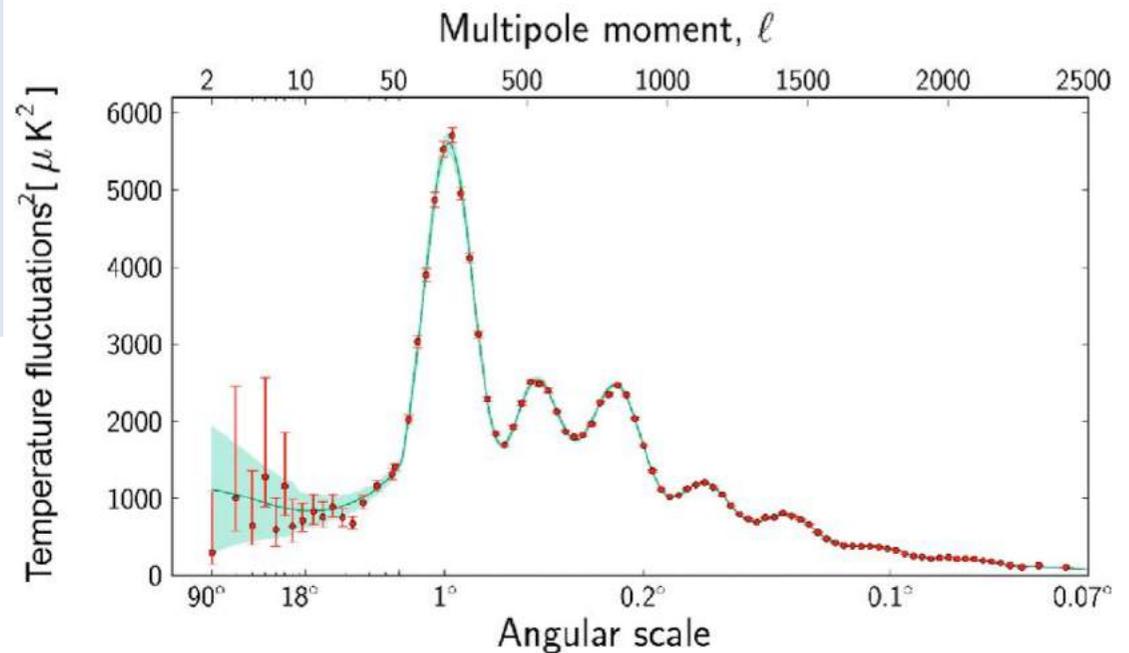
These perturbations begin to grow through gravitational instability after matter domination

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

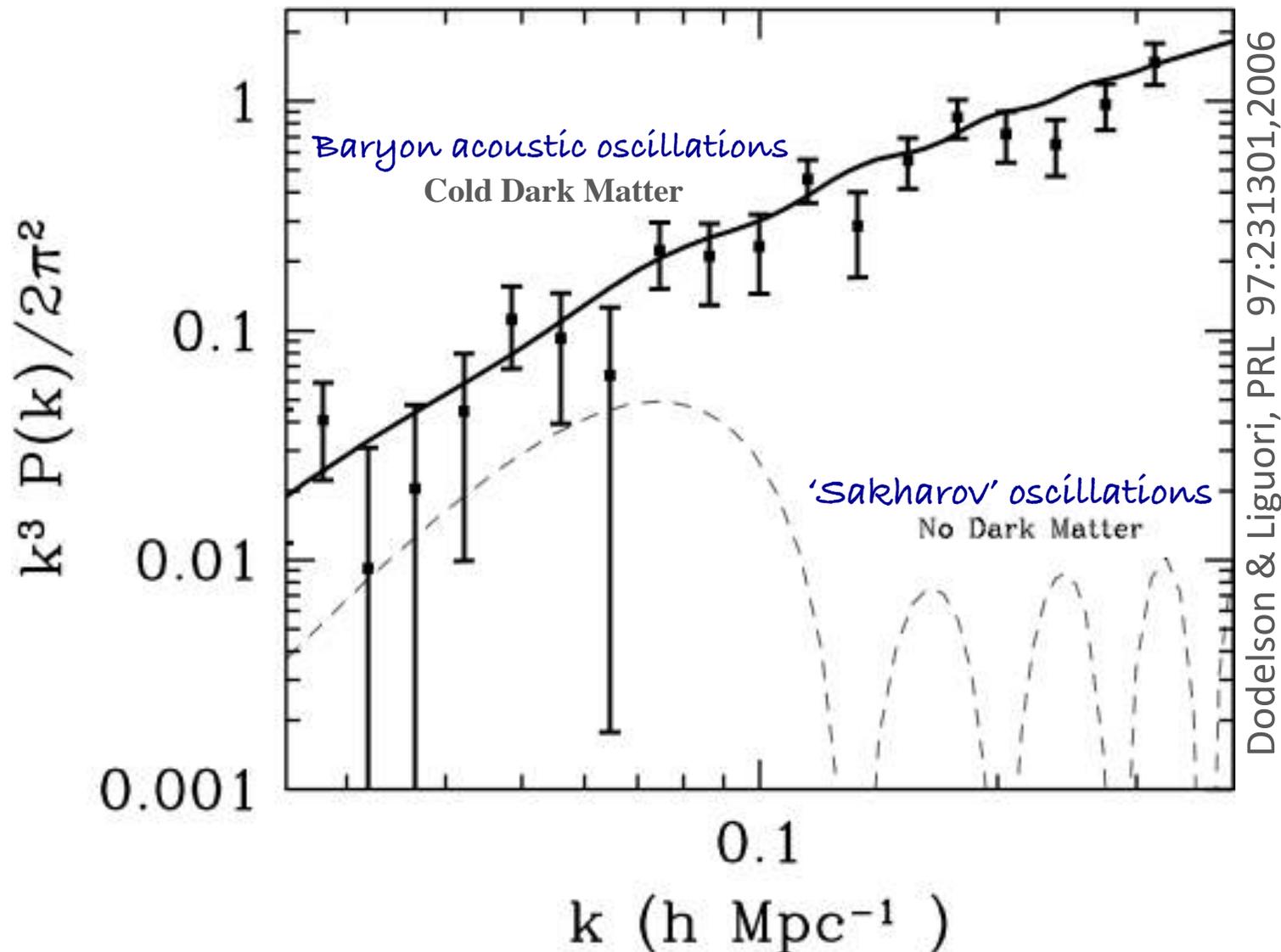


These sound waves leave an imprint on the last scattering surface as the universe turns neutral and transparent ... sensitive to the baryon/CDM densities

The angular power spectrum of the fluctuations can be well described only if dark matter dominates over baryonic matter ('Silk damping')

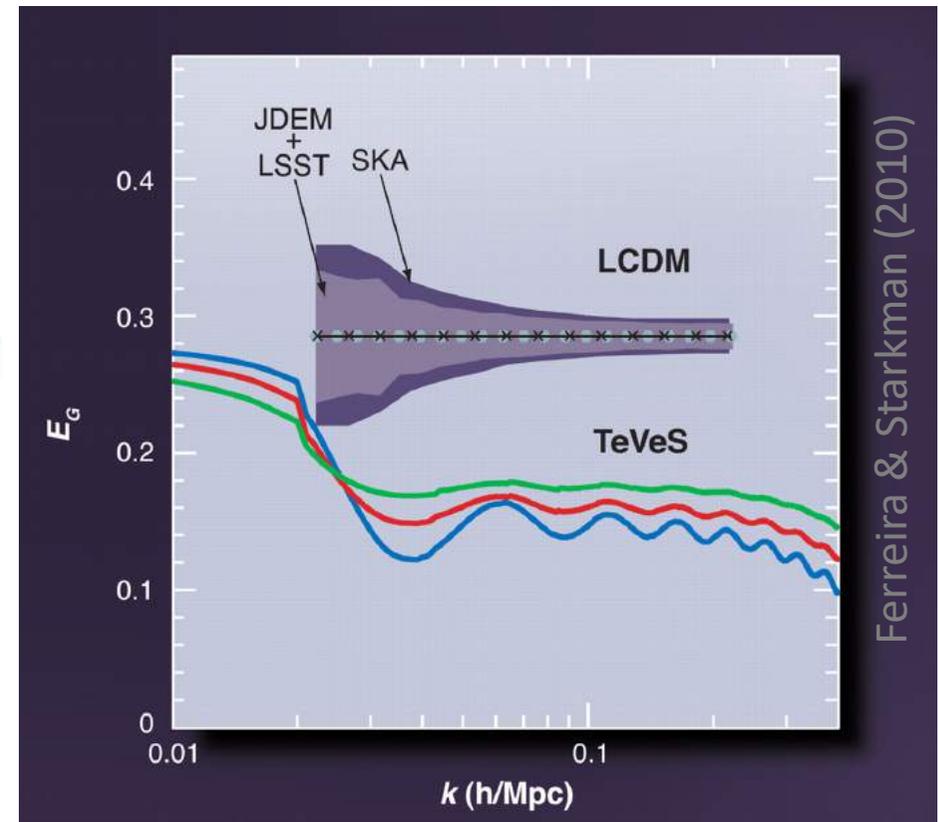
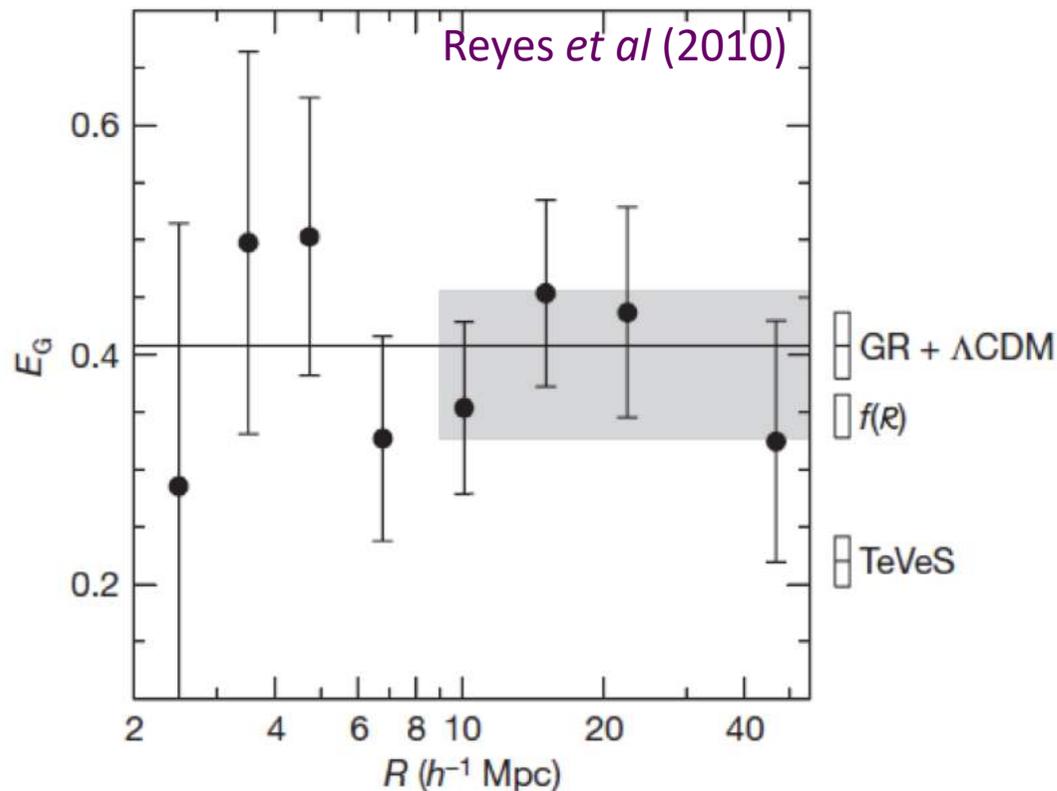


The observed large-scale structure *requires* $\Omega_m \gg \Omega_B$ if it has resulted from the growth under gravity (described by general relativity) of small initial density fluctuations ... which left their imprint on the CMB at last scattering



Detailed modelling of WMAP/Planck and 2dF/SDSS $\Rightarrow \Omega_m \sim 0.3, \Omega_B \sim 0.05$
 ... No MOND-like theory can enable such calculations and fit the data so well

Although *new* gravitational physics (underlying MOND) can in principle account for the growth of cosmological structure, there will always be an *observable* distinction – the ‘gravitational slip’ – between GR and the new theory



This is measurable via weak lensing (shearing of galaxy shapes) and its cross-correlation with the galaxy density field ... with forthcoming telescopes

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: $L \sim v_{\text{rot}}^4$ (“Tully-Fisher relation”)

... however MOND *fails* on the scale of galaxy clusters and cannot naturally explain the segregation of ‘bright’ and ‘dark’ matter seen in merging clusters (e.g. 1E 0657-558)

MOND is *not* a physical theory – relativistic covariant theories that yield MOND exist (e.g. ‘TeVeS’ by Bekenstein, Phys.Rev.D**70**:083509,2004) but they do *not* provide as satisfactory an understanding of CMB anisotropies and structure formation, as has the standard (cold) dark matter cosmology

... *nevertheless you may like to keep an open mind until dark matter is actually detected (non-gravitationally)!*