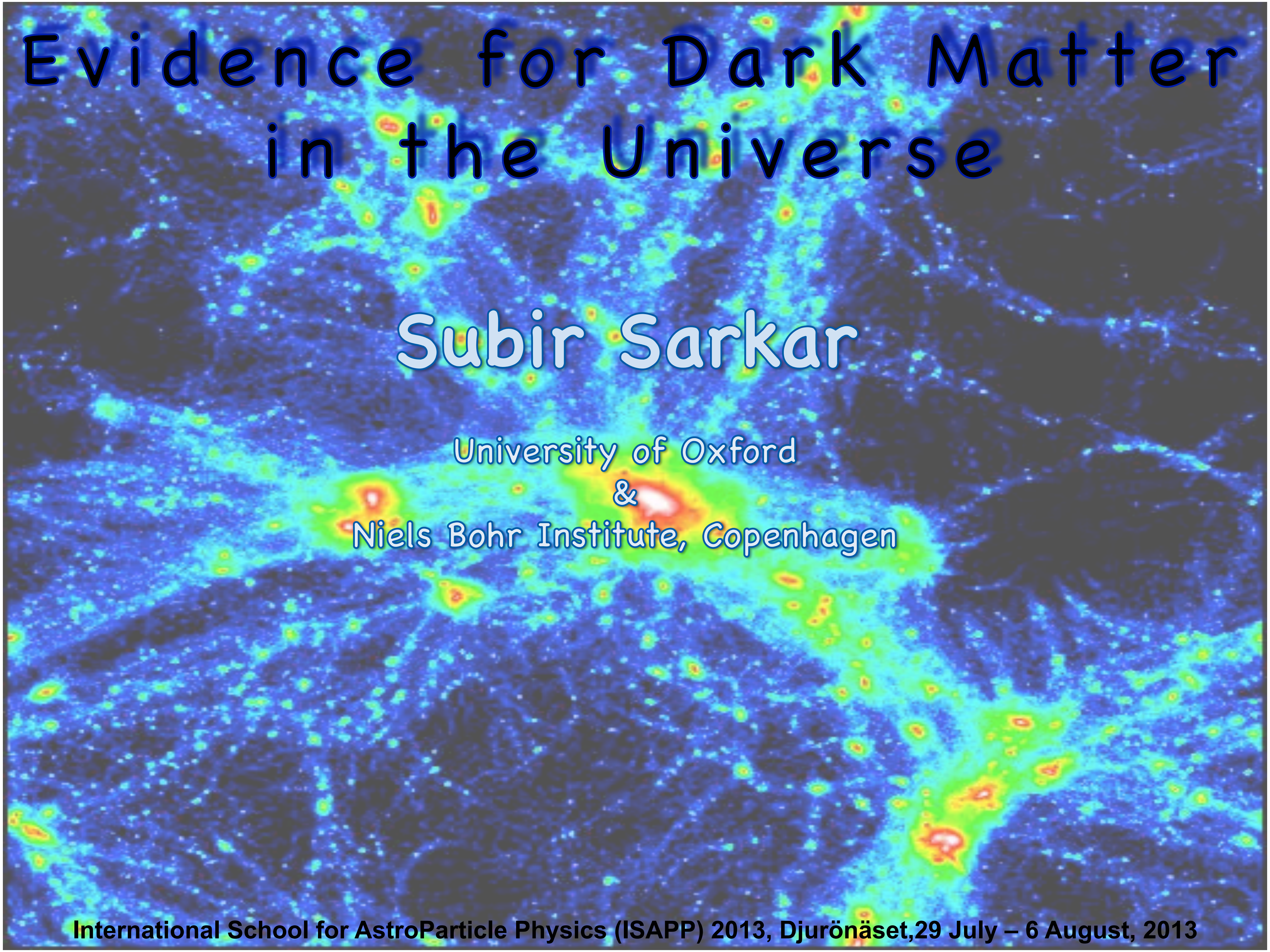

Evidence for Dark Matter in the Universe

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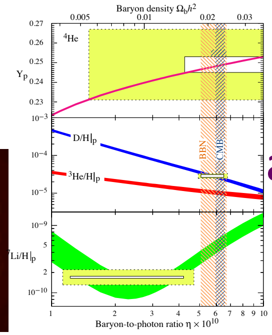
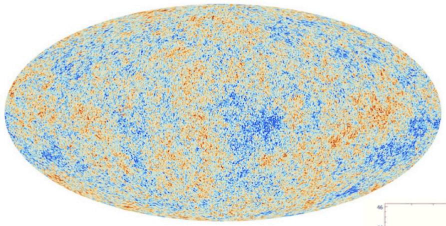
International School for AstroParticle Physics (ISAPP) 2013, Djurönäset,29 July – 6 August, 2013

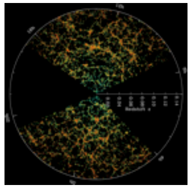
What is the world made of?

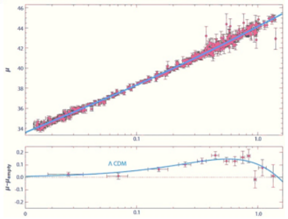


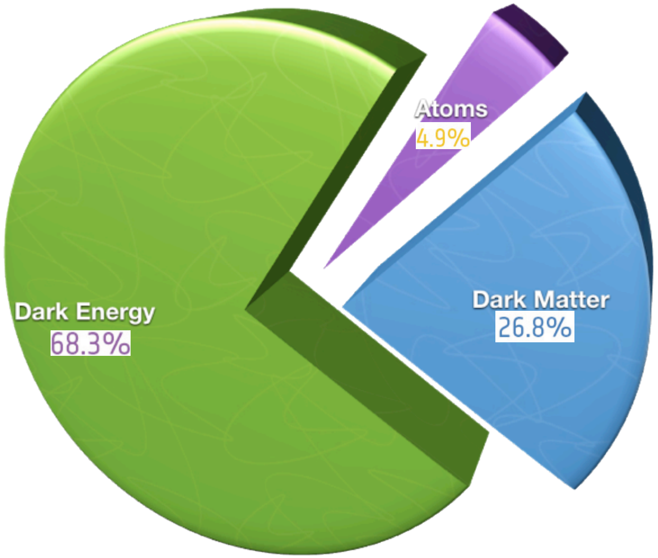
Baryons (*no* anti-baryons)

Mainly geometrical evidence:
$\Lambda \sim O(H_0^2)$, $H_0 \sim 10^{-42}$ GeV
… dark energy is *inferred* from the 'cosmic sum rule':
$\Omega_m + \Omega_k + \Omega_\Lambda = 1$

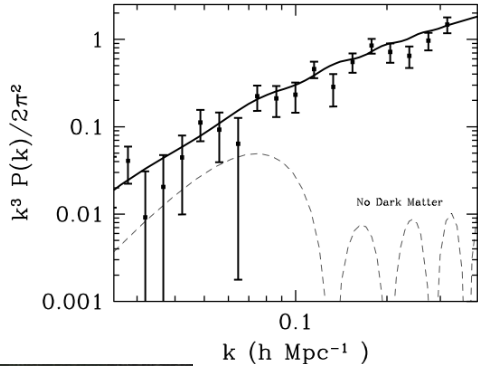




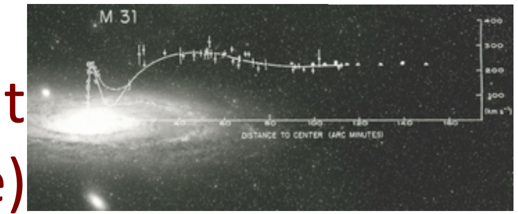


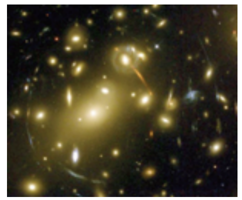


Both geometrical and dynamical evidence (if GR is valid on all scales)



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





23rd Sept 1846: Neptune right where scientists said it would be

Believing in Newton pays off!

NB: John Adams had said so already a year earlier but had not been taken much notice of by the British Astronomer Royal!

The planet Neptune was right where French mathematician Urban Le Verrier predicted it would be when German astronomer Johann Gottfried Galle looked for it

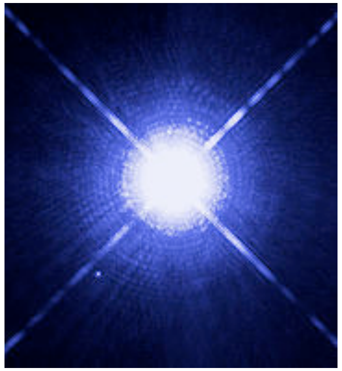
Discovery of dark matter → new (astro)physics

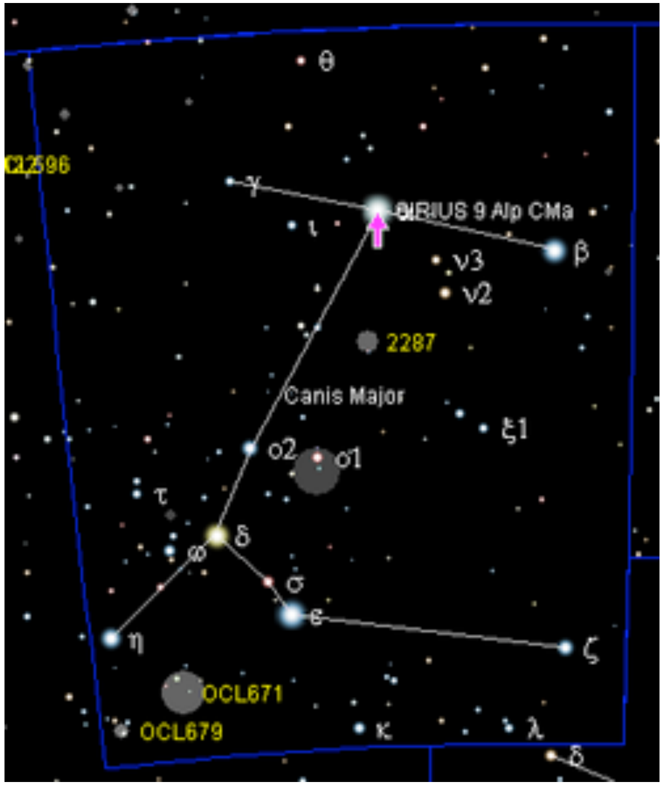
Friedrich Wilhelm Bessel (1832) finds the position of *Sirius* to be oscillating, indicating the presence of an **unseen companion**

Alvan Graham Clark (1862) discovers *Sirius B* visually

Walter Adams (1915) obtains spectrum of *Sirius B* … faint star ~3 times hotter than *Sirius,* hence size ~ Earth but mass ~ Sun

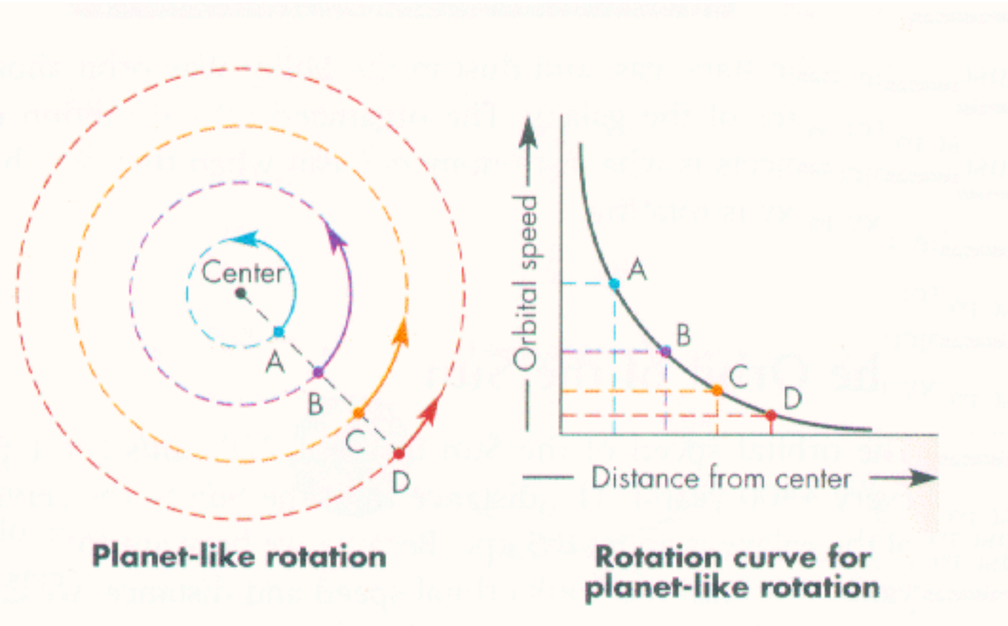
Ralph Fowler (1926) applies quantum ideas to stellar structure … infers that when the Sun exhausts its nuclear fuel it will collapse under gravity until held up by the Pauli exclusion principle (electron degeneracy pressure) …





Subrahmanyan Chandrasekhar (1930) finds stars heavier than $1.4M_{Sun}$ will continue to collapse and *"… one is left speculating on other possibilities"* (→ black holes)

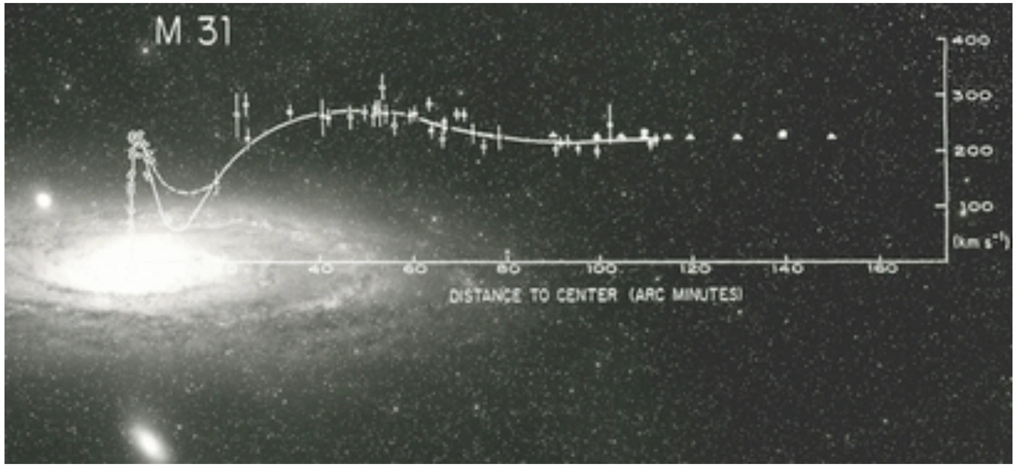
The modern saga of dark matter starts with the rotation curves of spiral galaxies



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

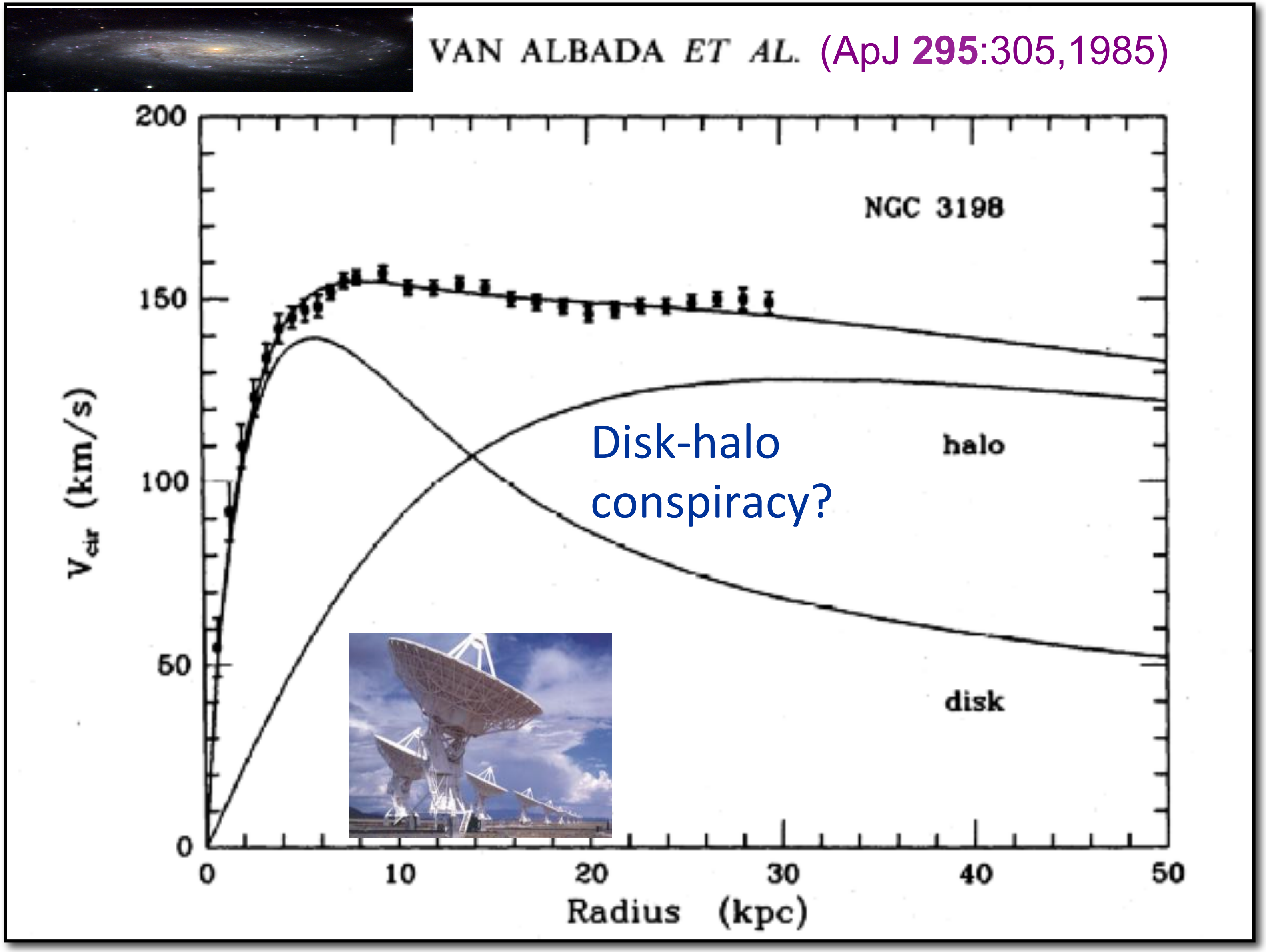
$$v_{\rm circ} = \sqrt{\frac{G_{\rm N} M(< r)}{r}}$$

… but Rubin & Ford (ApJ **159**: 379,1970) observed that the rotational velocity remains ~constant in Andromeda, **implying the existence of an extended dark halo** (earlier Babcock 1939, later Roberts & Whitehurst 1975, Bosma 1978)



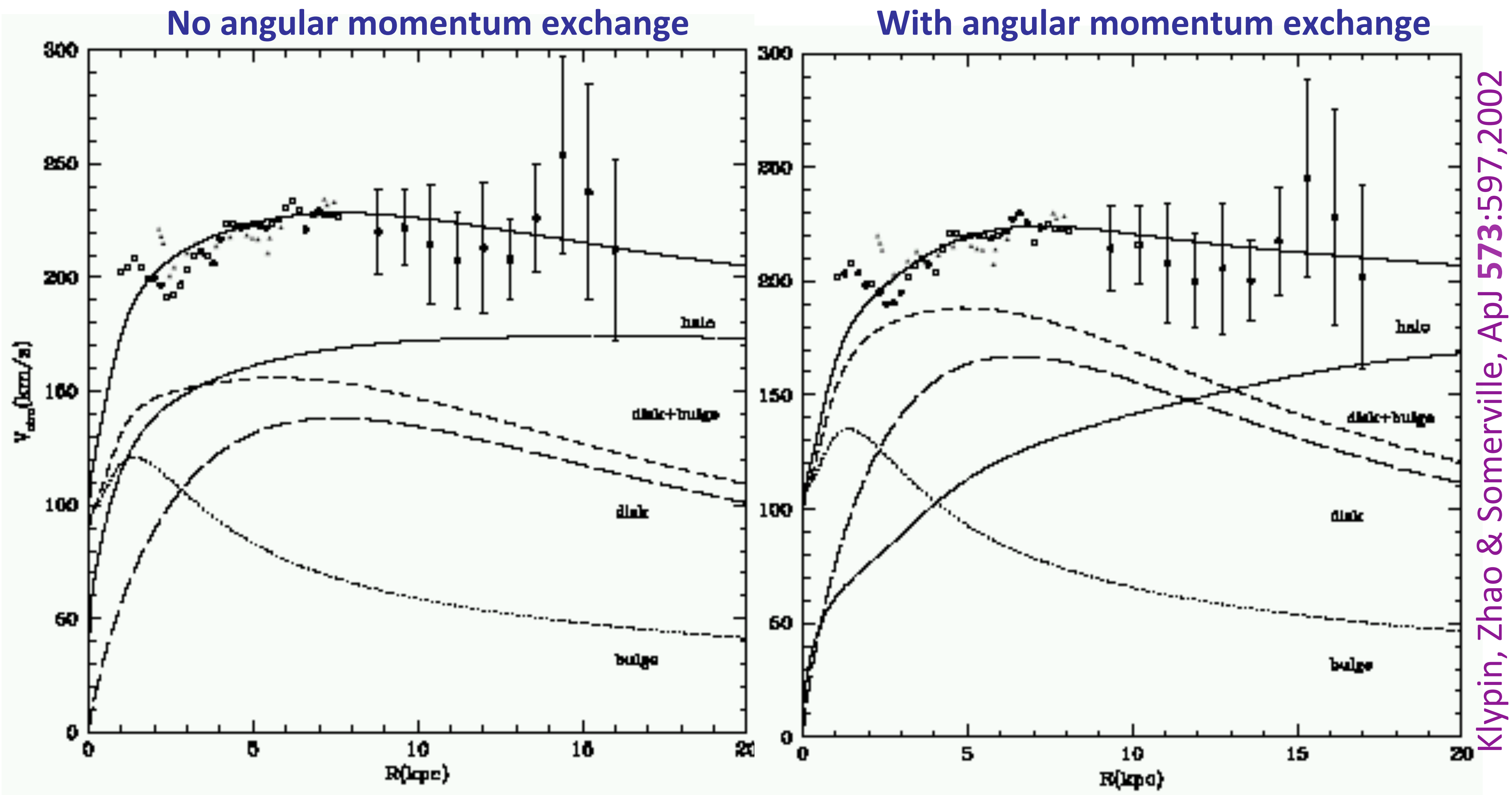
$$v_{\rm circ} \sim {\rm constant} \quad \Rightarrow \quad M(< r) \propto r \quad \Rightarrow \quad \rho \propto 1/r^2$$

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 Galaxy at ~constant velocity) well *beyond* the visible disk



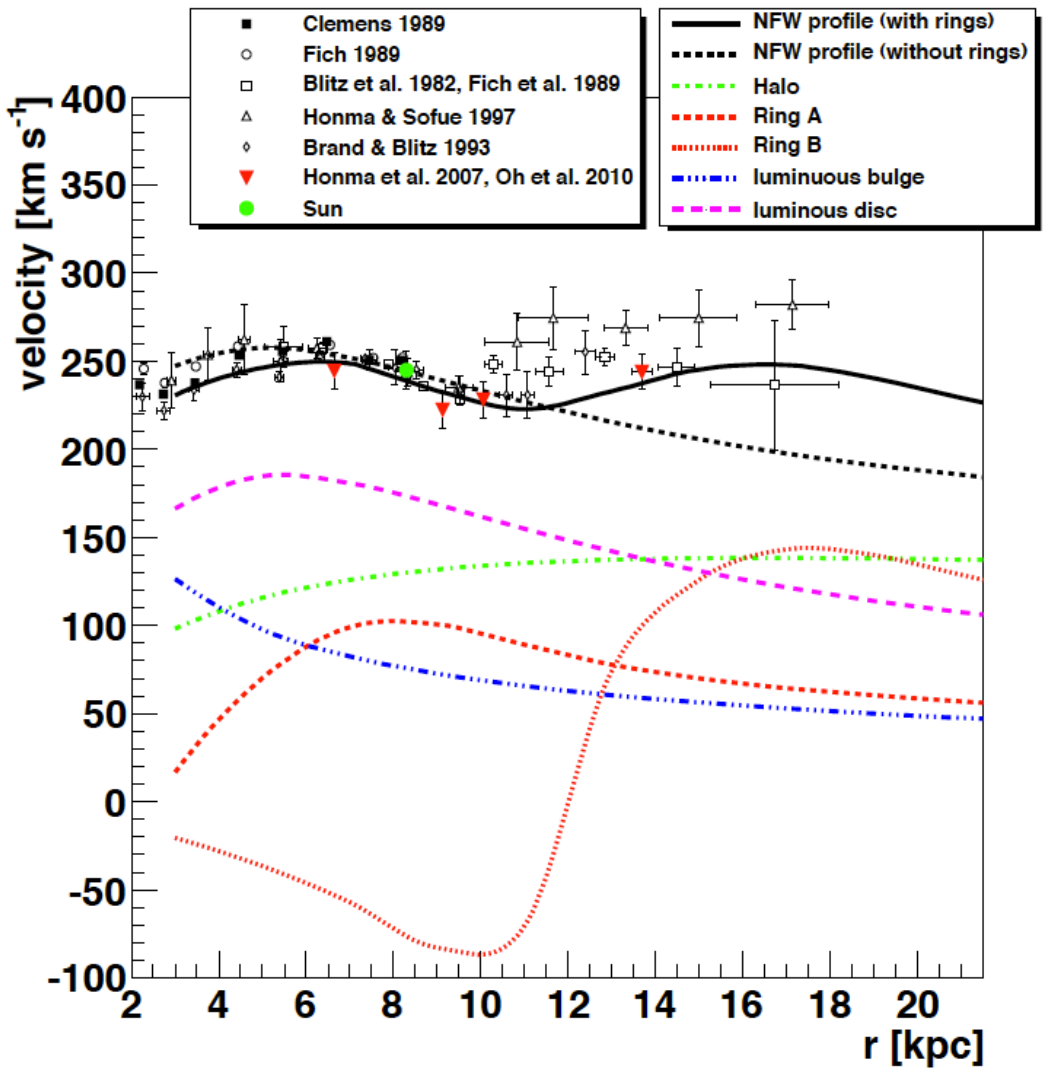
More sophisticated modelling accounts for multiple components and the coupling between baryonic & dark matter (in the ΛCDM cosmology)

No angular momentum exchange | **With angular momentum exchange**



There is considerable ambiguity in making such fits, hence the local halo density of dark matter is uncertain to *at least* a factor of 2 ($\rho_{DM} \sim 0.3 \pm 0.1$ GeV cm^{-3})

Another fit … where the local halo DM density is 4 times higher!



Weber & de Boer, JCAP 04:002,2011

"… the rotation curve is best described by an NFW DM profile complemented by two donut-like DM substructures at radii of 4.2 and 12.4 kpc, which coincide with the local dust ring and the Monocerus ring of stars, respectively … Both regions have been suggested as regions with tidal streams from "shredded" satellites, thus enhancing the plausibility for additional DM. If real, the radial extensions of these nearby ringlike structures enhance the local dark matter density by a factor of four to about 1.3 ± 0.3 GeV/cm^3."

Cored isothermal sphere:

$$\rho_{\rm isothermal} = \frac{\rho_{\rm s}}{\left(1+\frac{r}{r_{\rm s}}\right)^2}$$

Navarro-Frenk-White profile:
(indicated by CDM simulations)

$$\rho_{\rm NFW} = \frac{\rho_{\rm s}}{\frac{r}{r_{\rm s}}\left(1+\frac{r}{r_{\rm s}}\right)^2}$$

Burkert profile:
(fits observations better)

$$\rho_{\rm Burkert} = \frac{\rho_{\rm s}}{\left(1+\frac{r}{r_{\rm s}}\right)\left[1+\left(\frac{r}{r_{\rm s}}\right)^2\right]}$$

Hernquist profile:

$$\rho_{\rm Hernquist} = \rho_{\rm s}\left(\frac{r}{r_{\rm s}}\right)^{-\gamma}\left[1+\left(\frac{r}{r_{\rm s}}\right)^{\alpha}\right]^{\frac{\gamma-\beta}{\alpha}}$$

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

… 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 is obtained by setting $\alpha = 1.5$, $\beta = 2$, $\gamma = 1.5$ *et cetera*

Einasto profile:

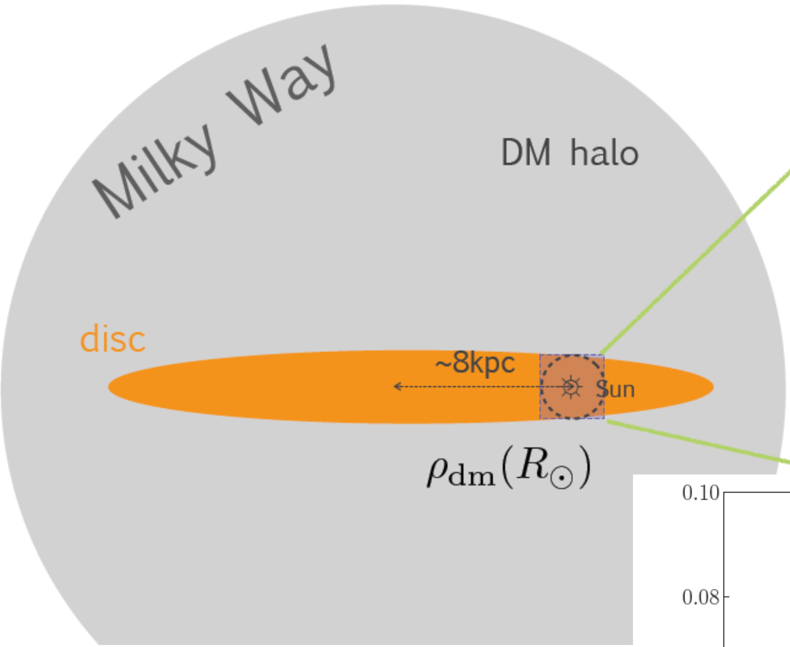
$$\rho_{\rm Einasto} = \rho_{\rm s} \exp\left\{-d_n\left[\left(\frac{r}{r_{\rm s}}\right)^{1/n} - 1\right]\right\}$$

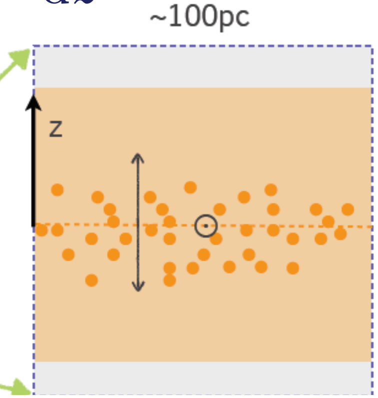
where d_n is defined such that ρ_s is the density at the radius r_s which encloses half the total mass

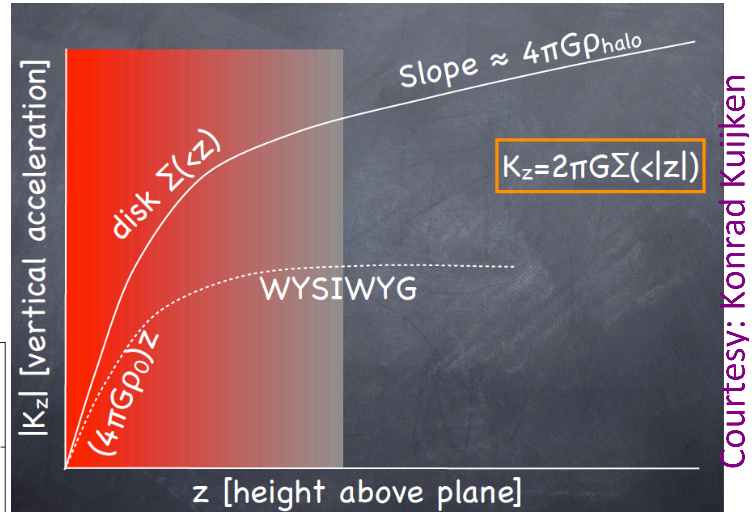
We can infer the *local* dark matter density by measuring vertical distribution of stars … pioneered by Kapetyn (1922) and Oort (1932)

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

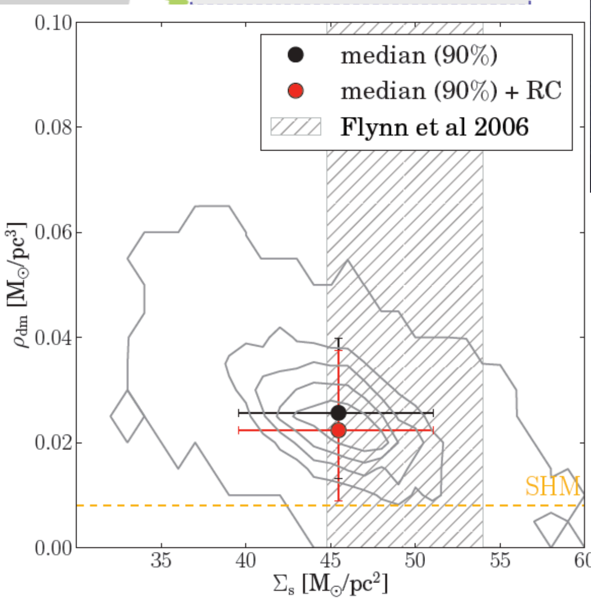
$$\frac{\mathrm{d}^2\psi(z)}{\mathrm{d}z^2} = 4\pi G_\mathrm{N}\rho_\mathrm{m} \rightarrow \frac{\mathrm{d}\psi(z)}{\mathrm{d}z} = 2\pi G_\mathrm{N}\Sigma_\mathrm{m}$$







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



Using data on K-dwarfs (Kuijken & Gilmore, MNRAS **239**:605,1989) yields:
$\rho_\mathrm{DM} = 0.85 \pm 0.6$ GeV/cm^3

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

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

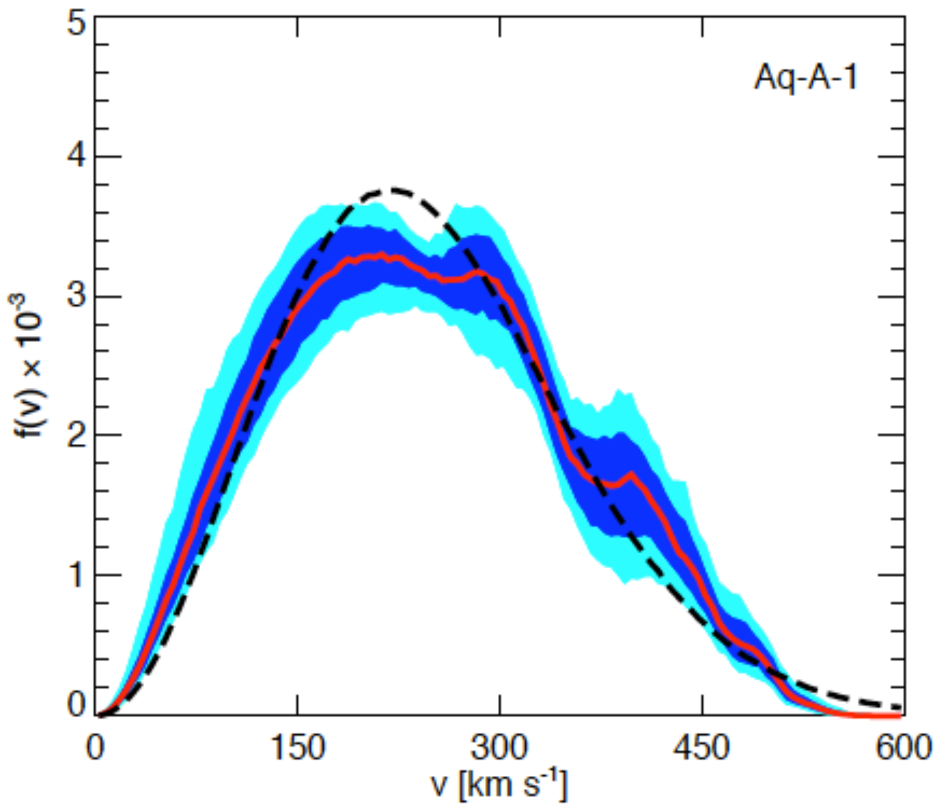
$$\frac{\partial f}{\partial t} + \mathbf{v}.\frac{\partial f}{\partial \mathbf{x}} - \frac{\partial \Phi}{\partial \mathbf{x}}\frac{\partial f}{\partial \mathbf{v}} = 0$$

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

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

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

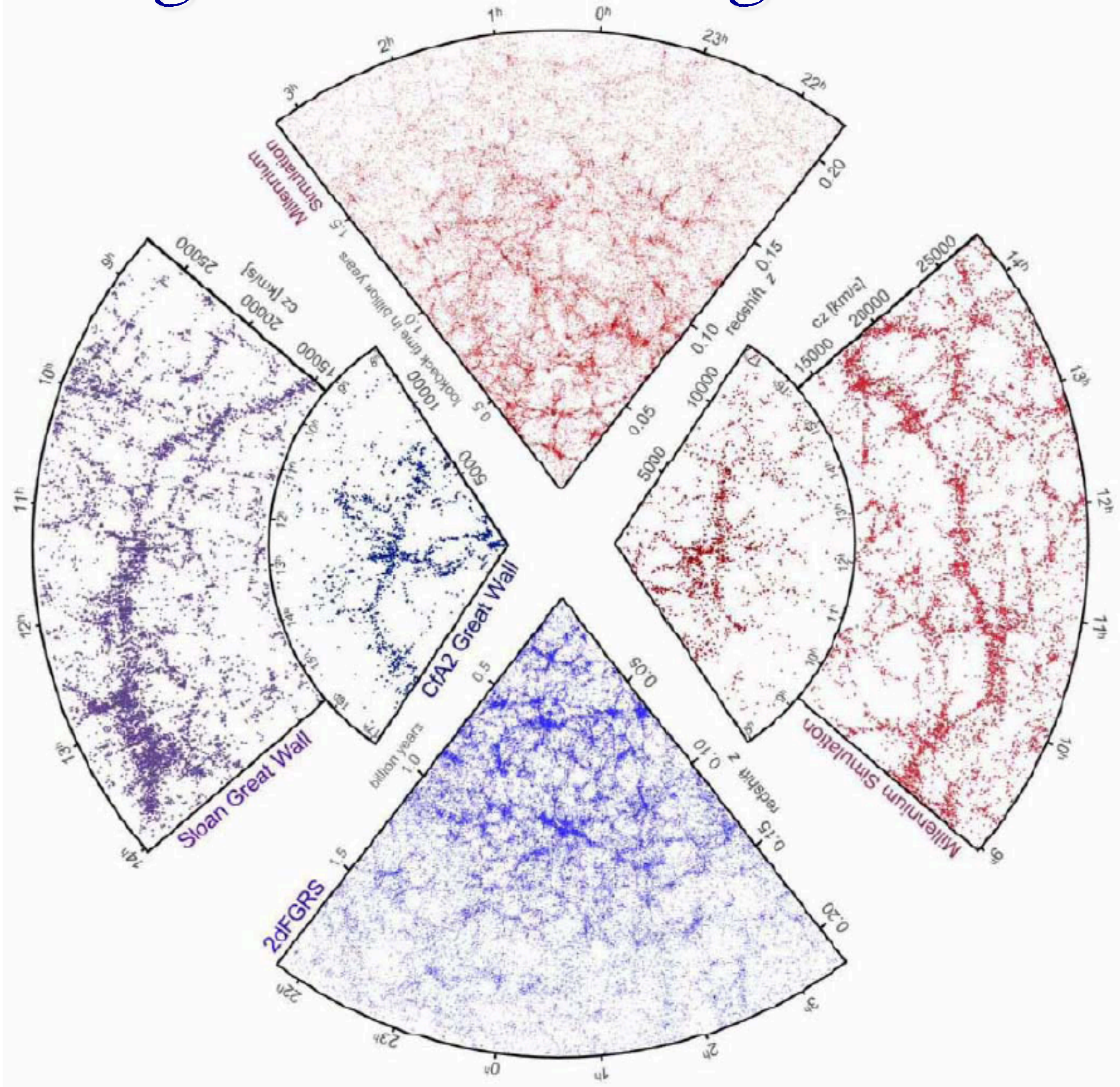
High resolution numerical simulations however suggest significant deviations from the Maxwellian distribution, particularly at high velocities (important implications for direct detection experiments)



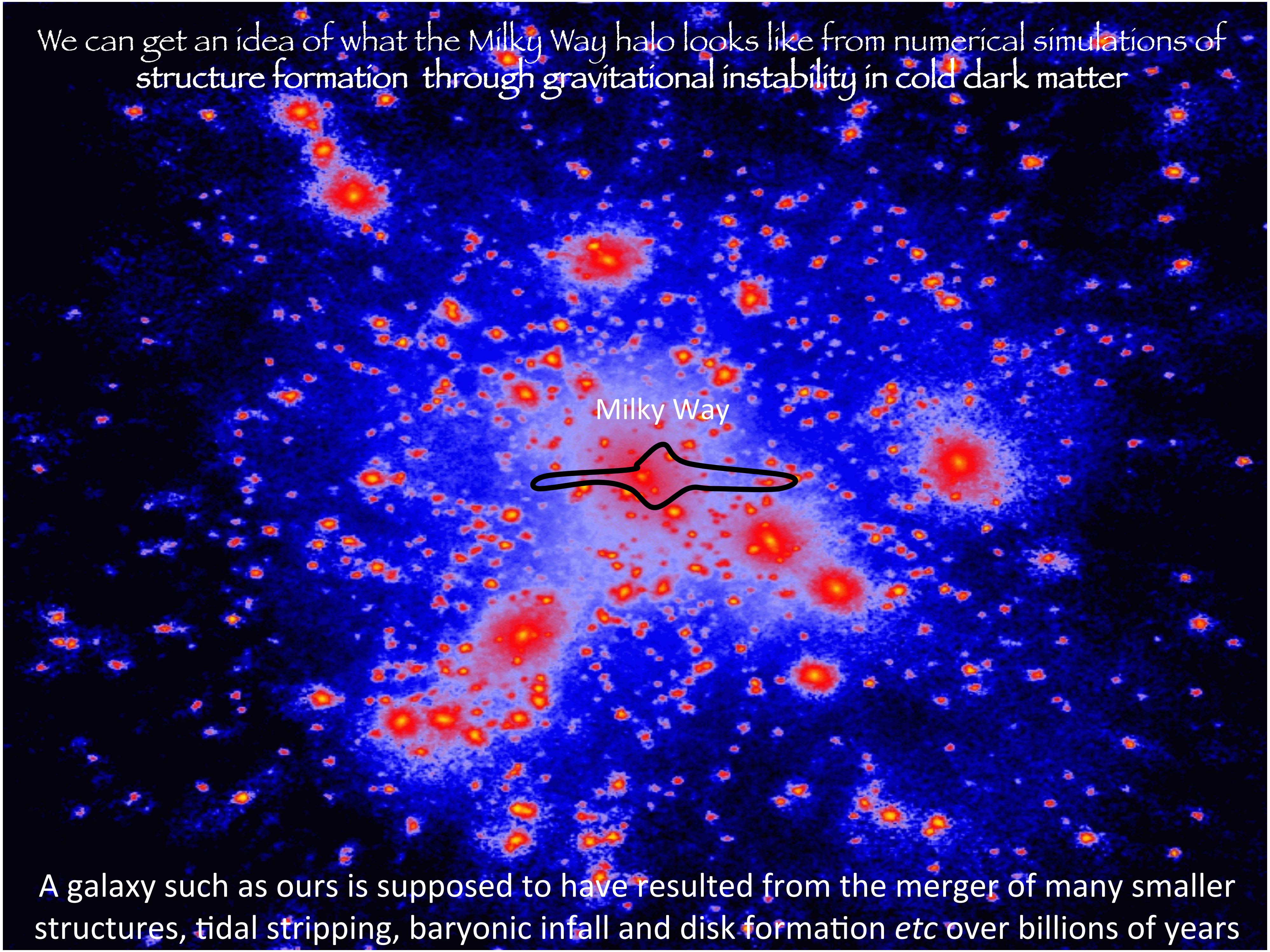
Vogelsberger *et al*, MNRAS **395**:797,2009

Simulating the universe on a computer

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

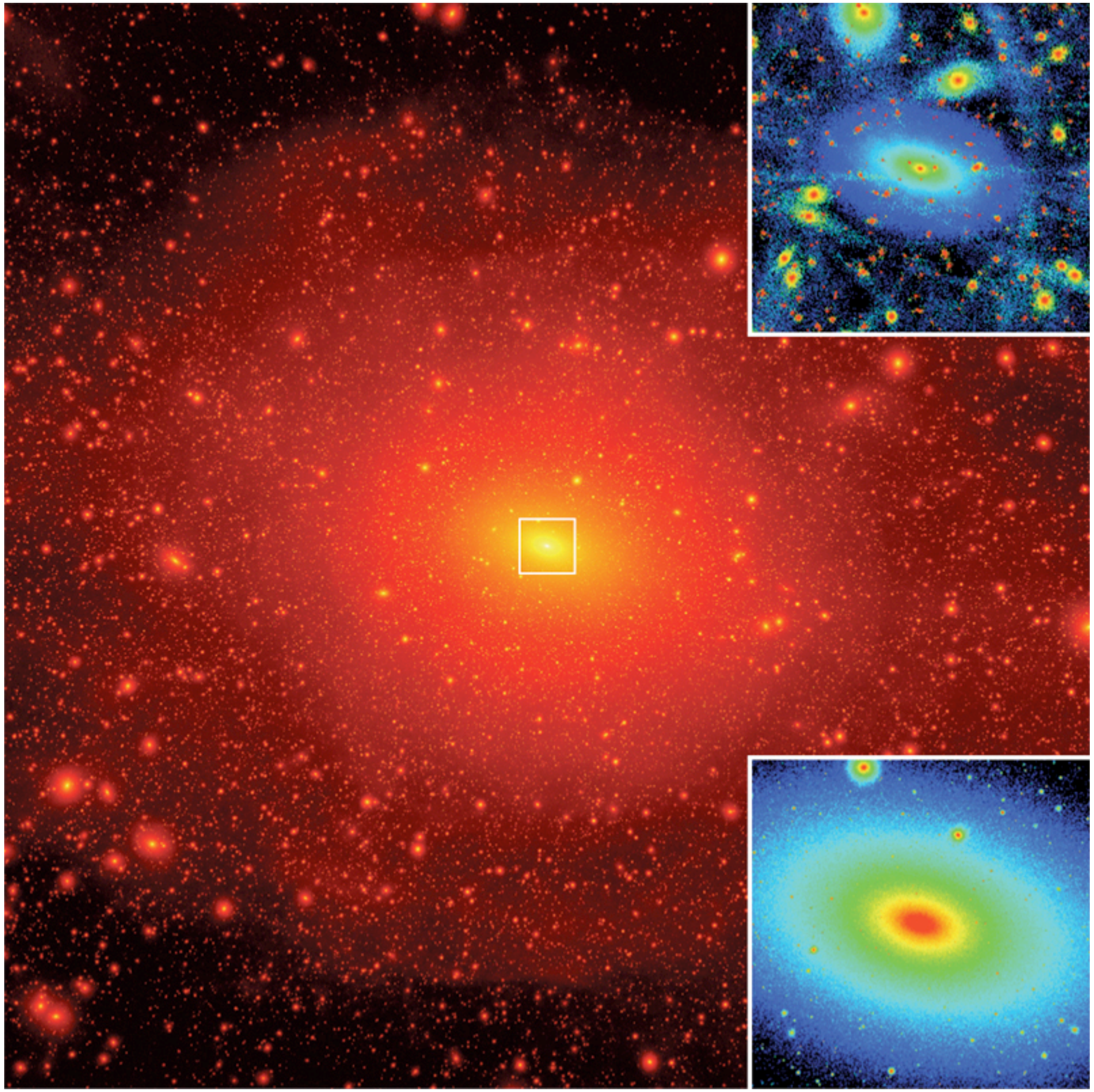


Springel, Frenk & White, Nature **440**:1137,2006


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

So the phase space structure of the dark halo is pretty 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!

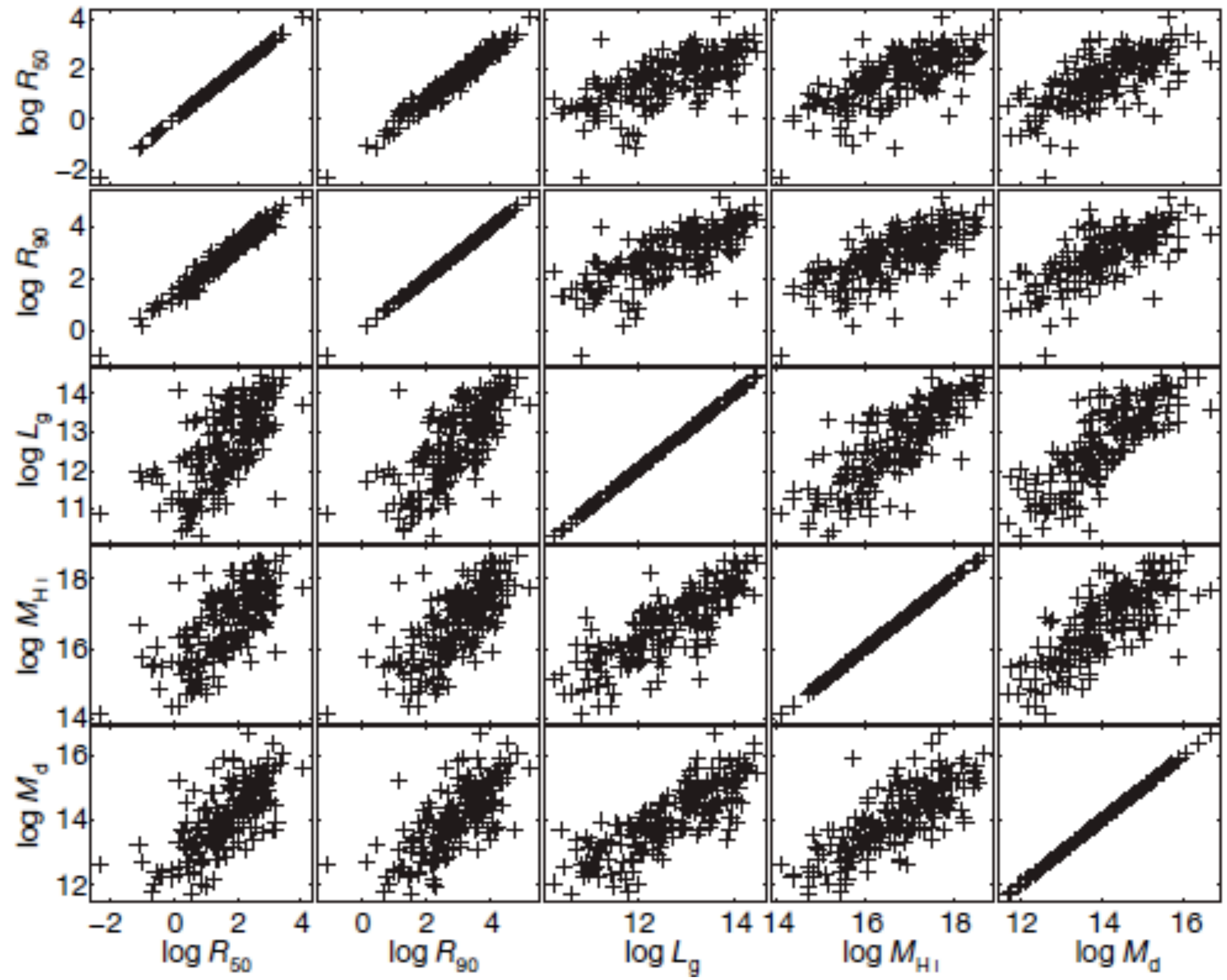
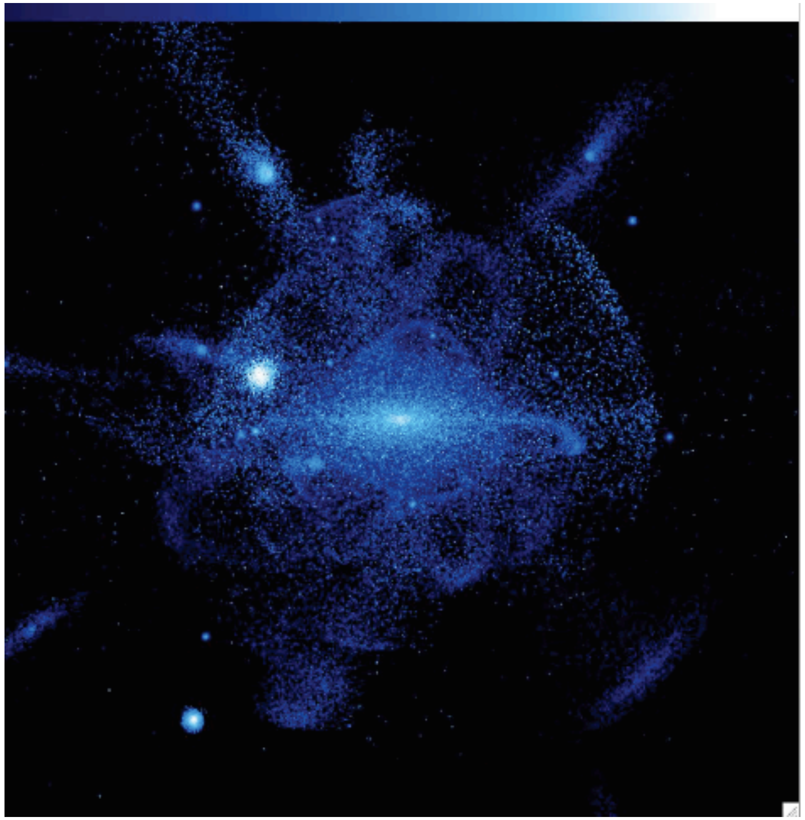


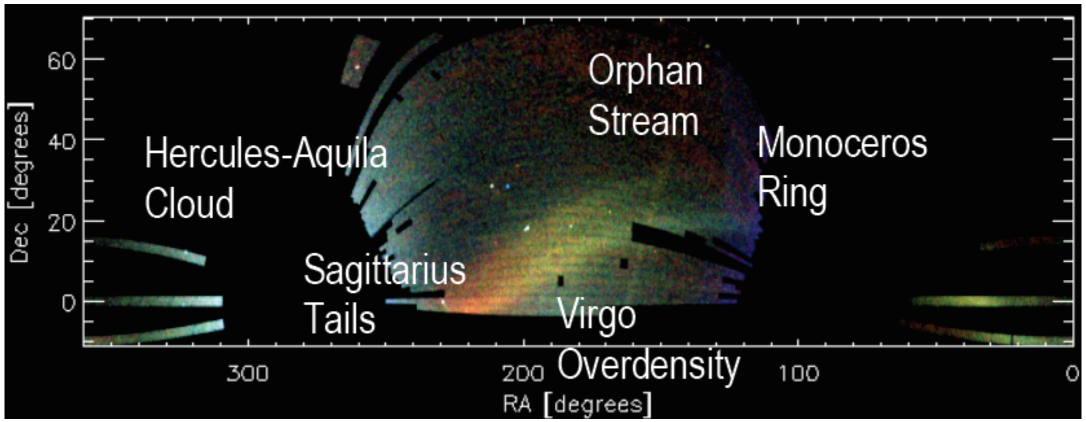
Figure 1 | Scatter plots showing correlations between five measured variables, not including colour. The variables are two optical radii, R_{50} and R_{90} (in parsecs), respectively containing 50 and 90% of the emitted light; and luminosity, L_g; neutral hydrogen mass, $M_{\mathrm{H\,I}}$; and dynamical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

Whereas the Milky Way does have satellite galaxies and substructure, it appears to be a lot less than expected from the numerical simulations

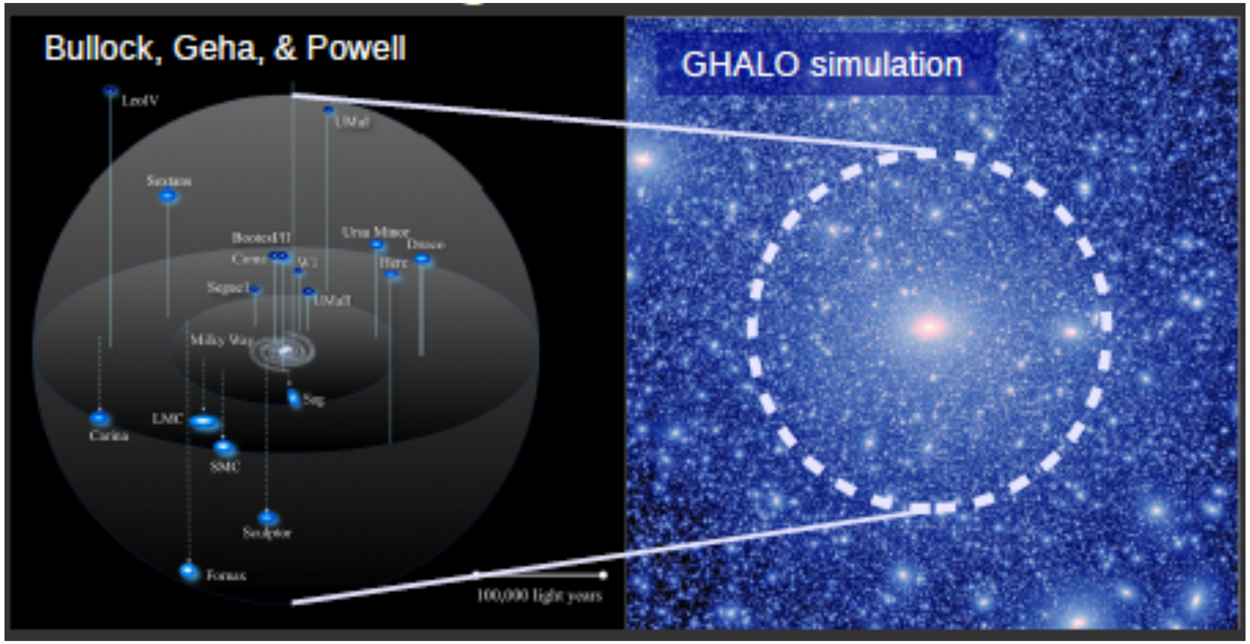


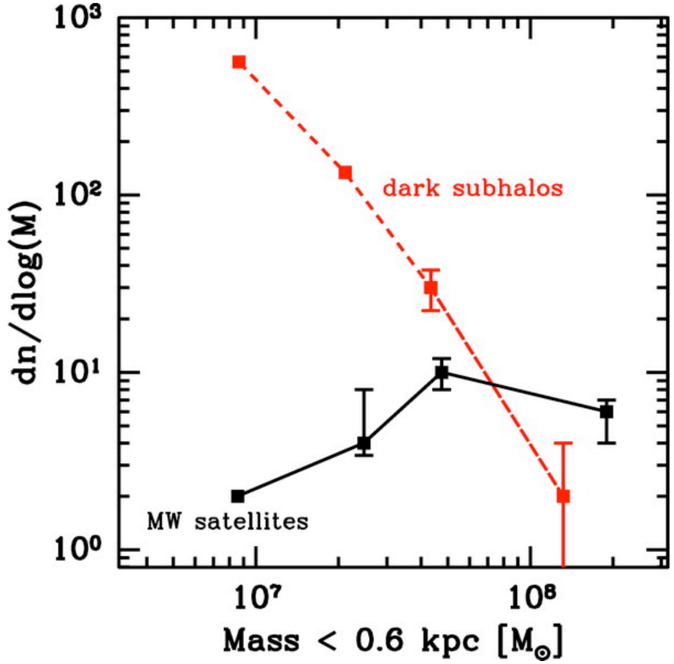
Bullock & Johnston, ApJ **635**:931,2005



http://www.ast.cam.ac.uk/~vasily/sdss/stellar_halo/info.htm

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

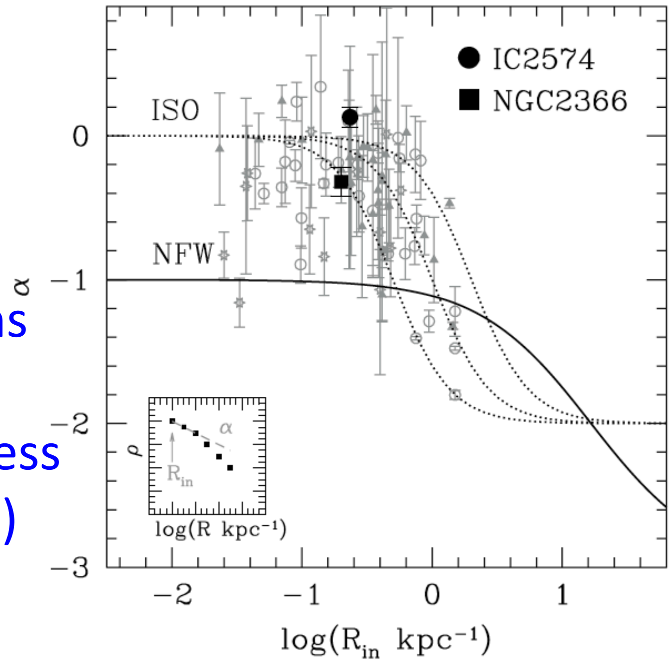




Strigari *et al*, ApJ **669**:676,2007

Also, the halo density profile for collisionless dark matter is predicted to be 'cuspy', whereas observations suggest 'cored' isothermal profiles

This *could* be because of the 'feedback effect' of baryons – computer simulations are just beginning to test this – or it could even be because dark matter is *not* collisionless but self-interacting (or perhaps `warm' rather than cold)

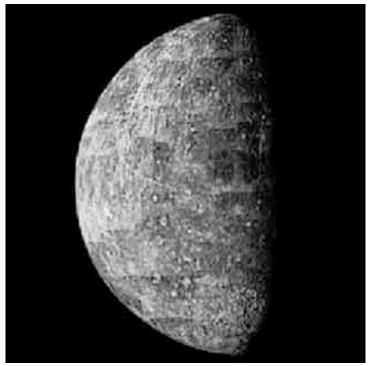


Oh *et al*, AJ **136**:2761,2008

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

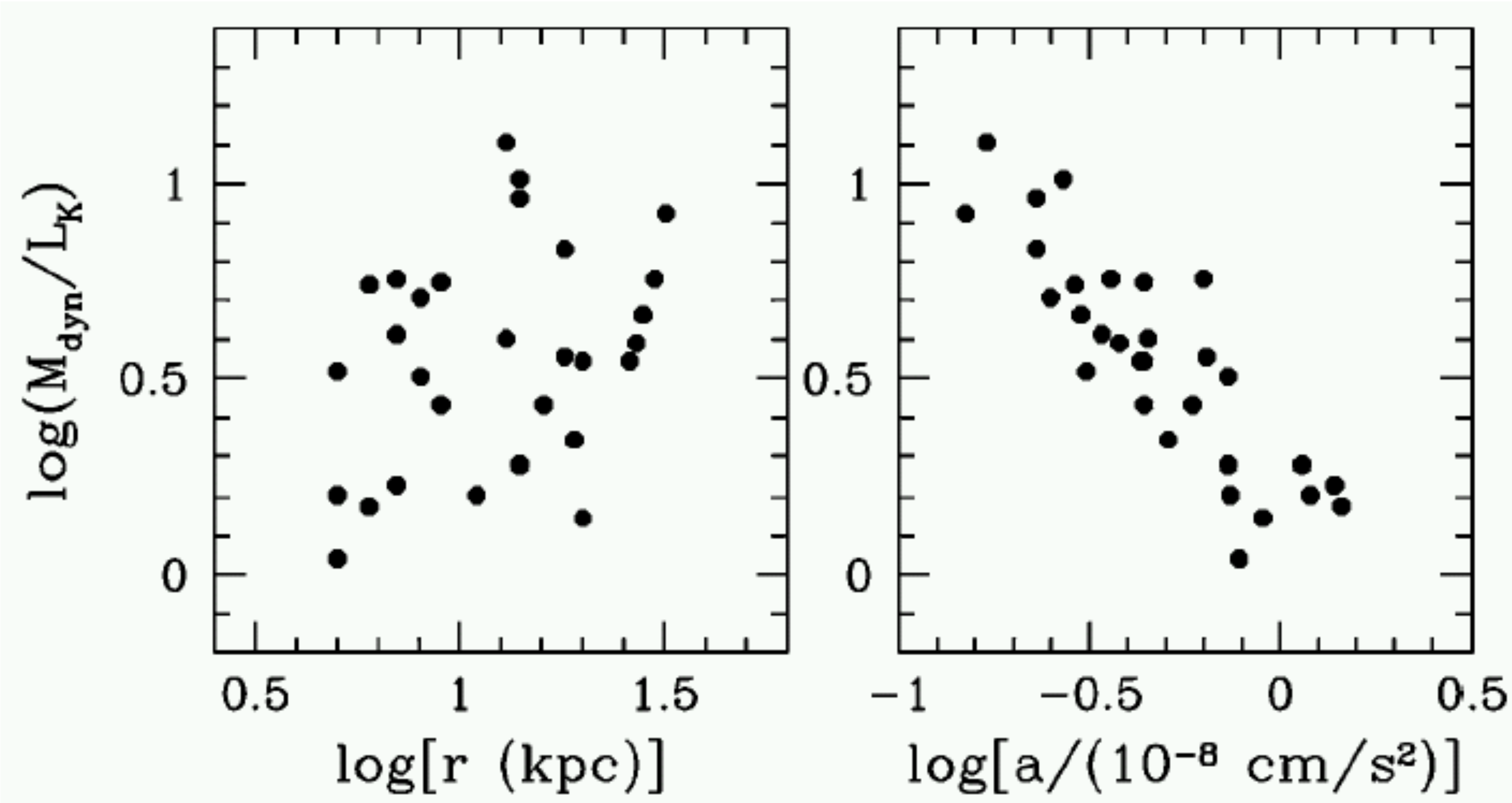
2 Jan 1860: "Gentlemen, I Give You the Planet Vulcan" French mathematician Urbain Le Verrier announces the discovery of a new planet between Mercury and the Sun, to members of the Académie des Sciences in Paris (following up on his earlier successful prediction of Neptune in 1856).

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

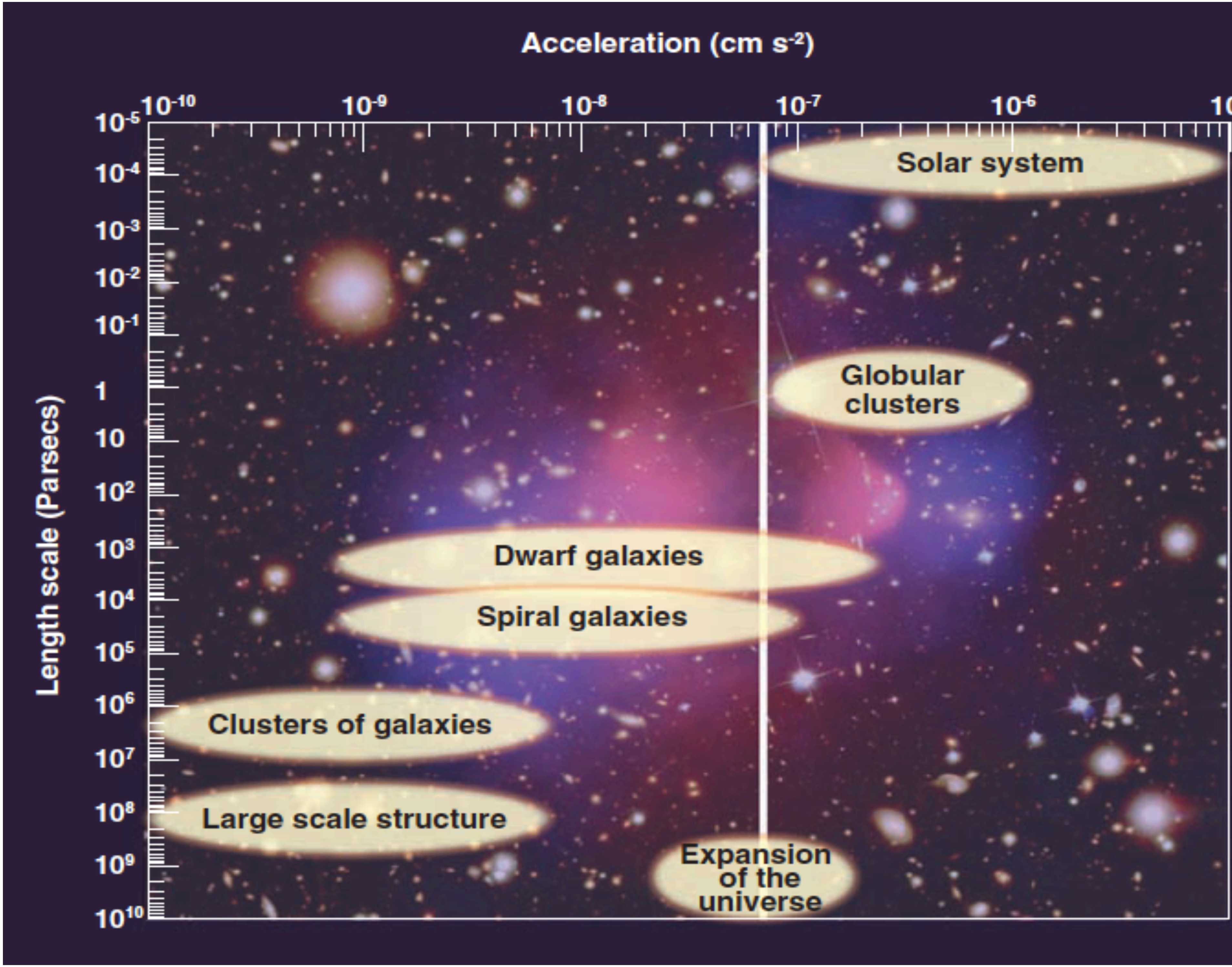
Dark matter appears to be required only where the test particle acceleration is low (below $a_0 \sim 10^{-8}$ cm/s^2) - it is *not* a spatial scale-dependent effect



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



Ferreira & Starkman, Science **326**:812, 2009

Bekenstein—Milgrom Equation

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

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

where

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

Then

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

implies

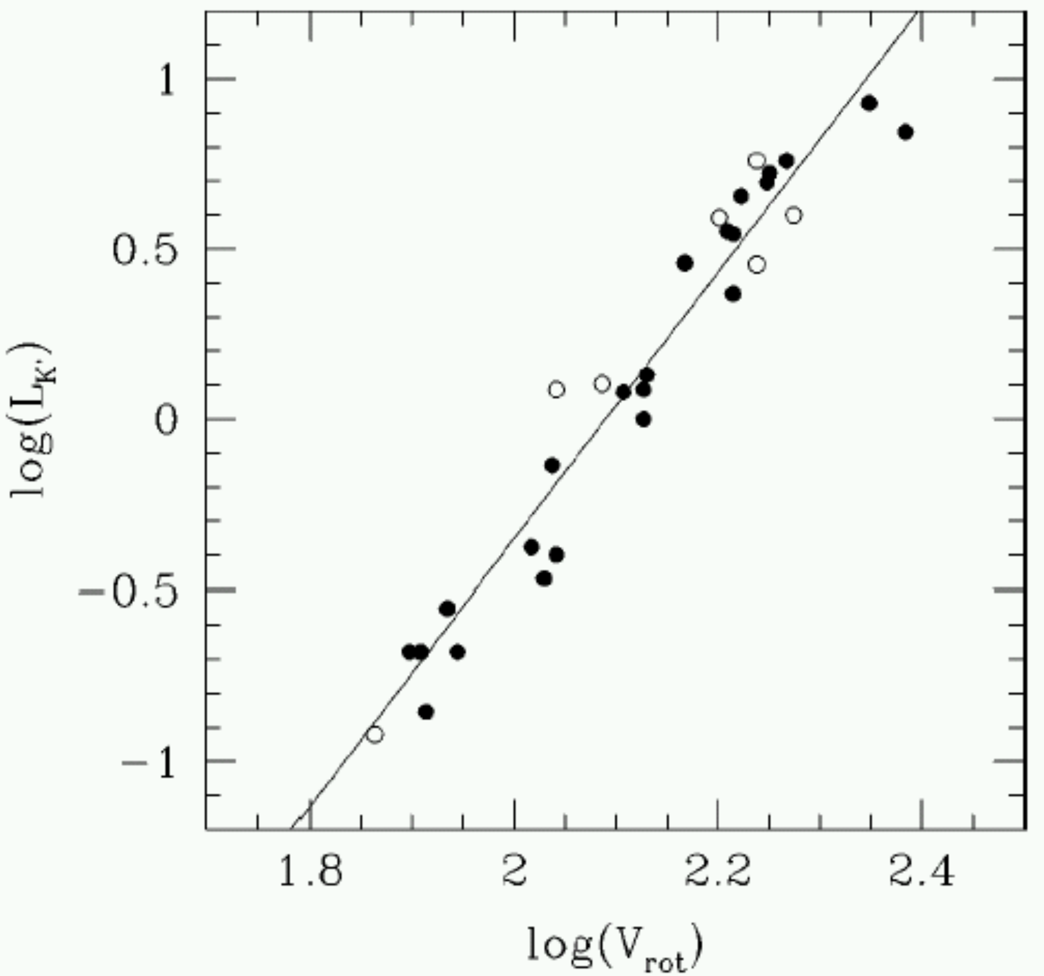
$$\mu(|\nabla\phi|/a_0)\nabla\phi = \nabla\phi_{\rm N} + \nabla\times\mathbf{A}$$

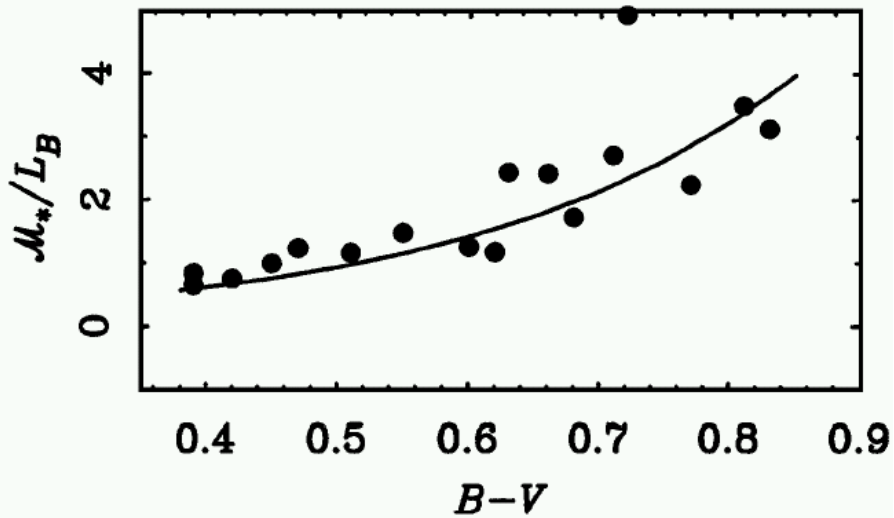
so when $\mathbf{A} \simeq 0$ and $|\nabla\phi| \ll 1$

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

Milgrom, arXiv:0912.2678

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





… 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 DM supposedly has no explanation

In fact, there is a gravitational link between DM and baryons, so is it plausible that the TF relationship might result from baryonic compression during infall?

The answer is ~yes (e.g. Desmond, arXiv:1204.1497)

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

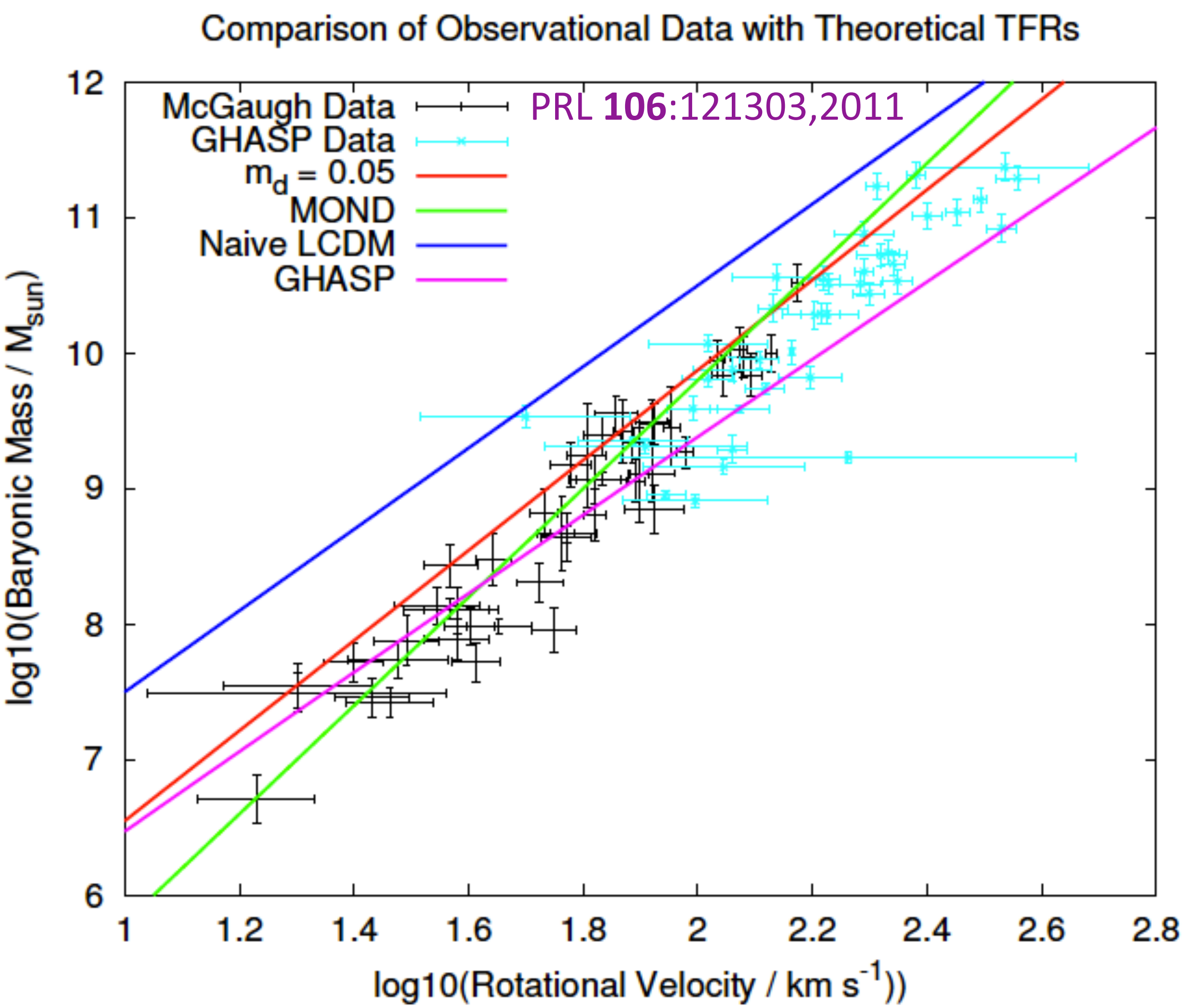
… where Δ is the overdensity in units of the critical density → 178 in spherical collapse

$$\frac{V_{\rm vir}^2}{R_{\rm vir}} = \frac{GM_{\rm vir}}{R_{\rm vir}^2}$$

So can eliminate $R_{\rm vir}$ to get:

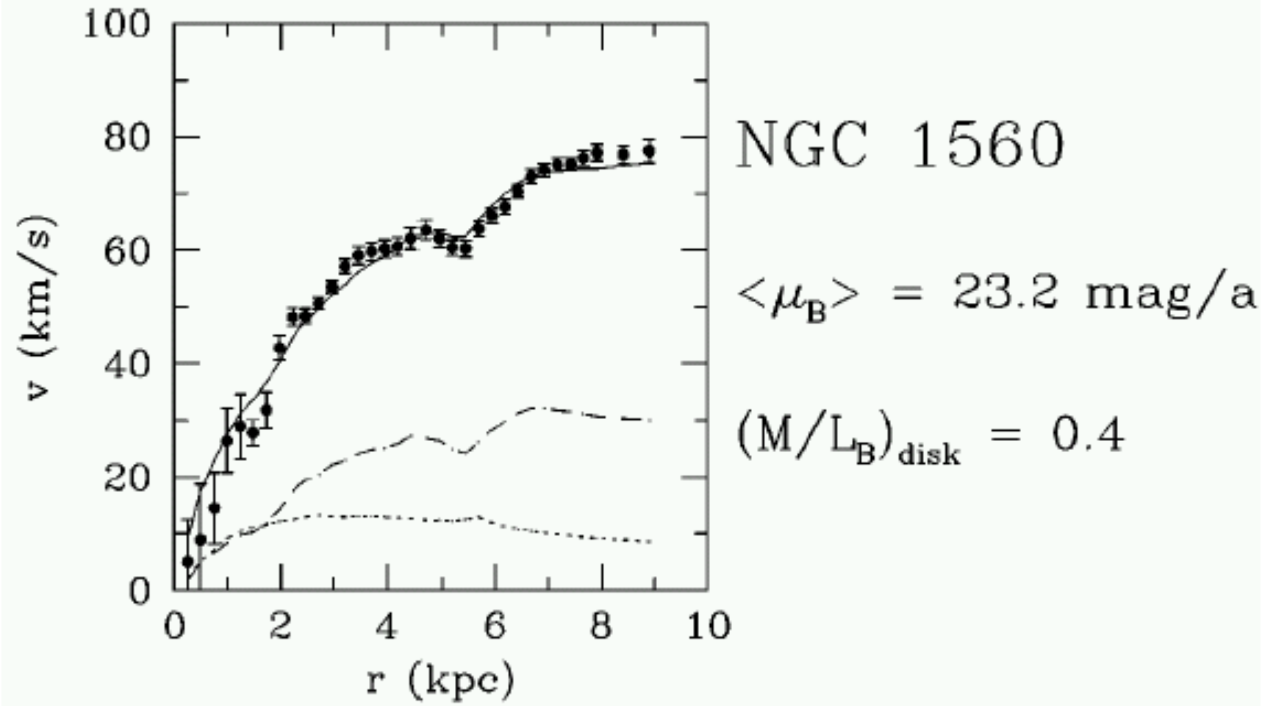
$$M_{\rm vir} = (\frac{\Delta}{2})^{-\frac{1}{2}}(GH_0)^{-1}V_{\rm vir}^3$$

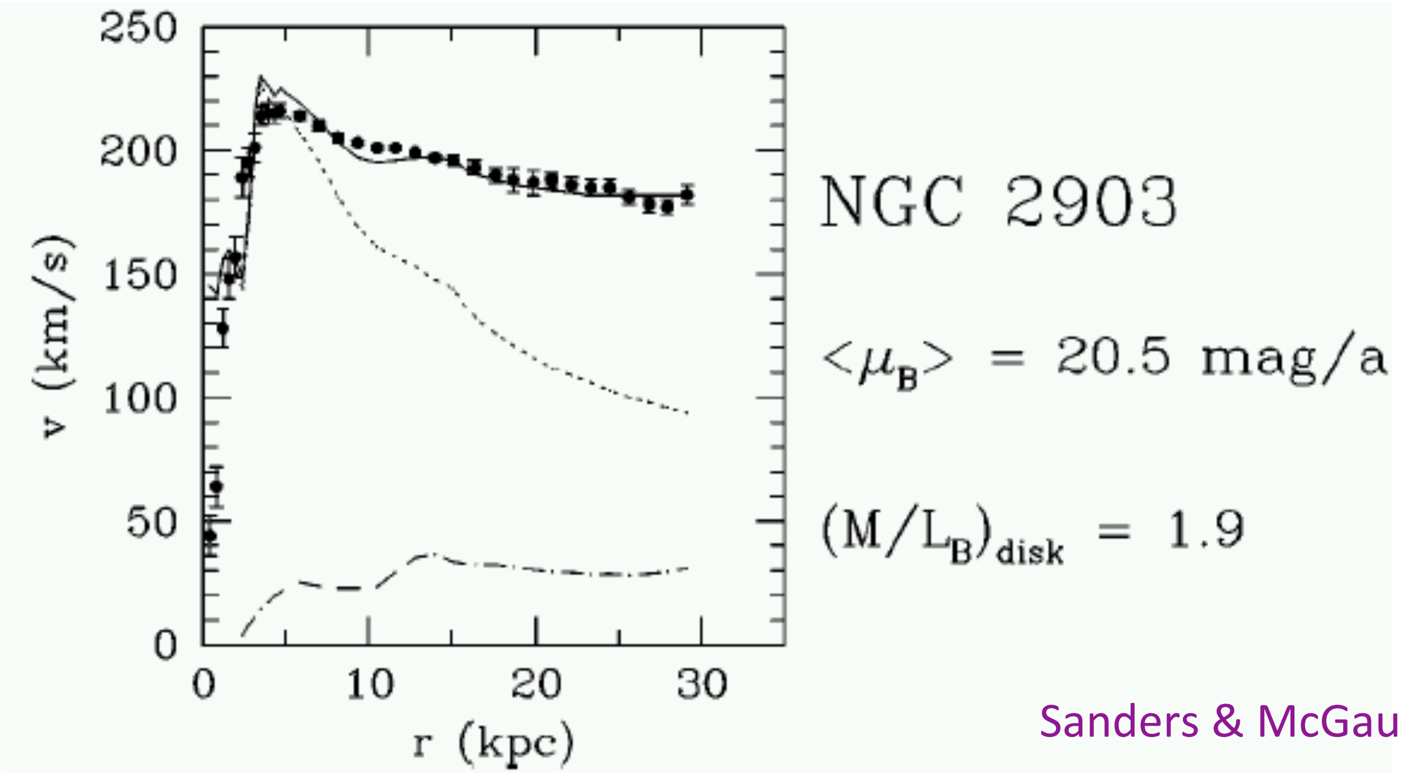
Now need to relate $M_{\rm vir}$ to the baryonic mass and $V_{\rm vir}$ to the rotational velocity … this is somewhat model-dependent



The DM fit to data is *not* as good as MOND’s, however there may well be *selection effects.* In any case it looks plausible that the TF relationship *can* be understood with dark matter!

Excellent fits to galactic rotation curves with $a_0 = 1.2 \times 10^{-8}$ cm s^{-2}



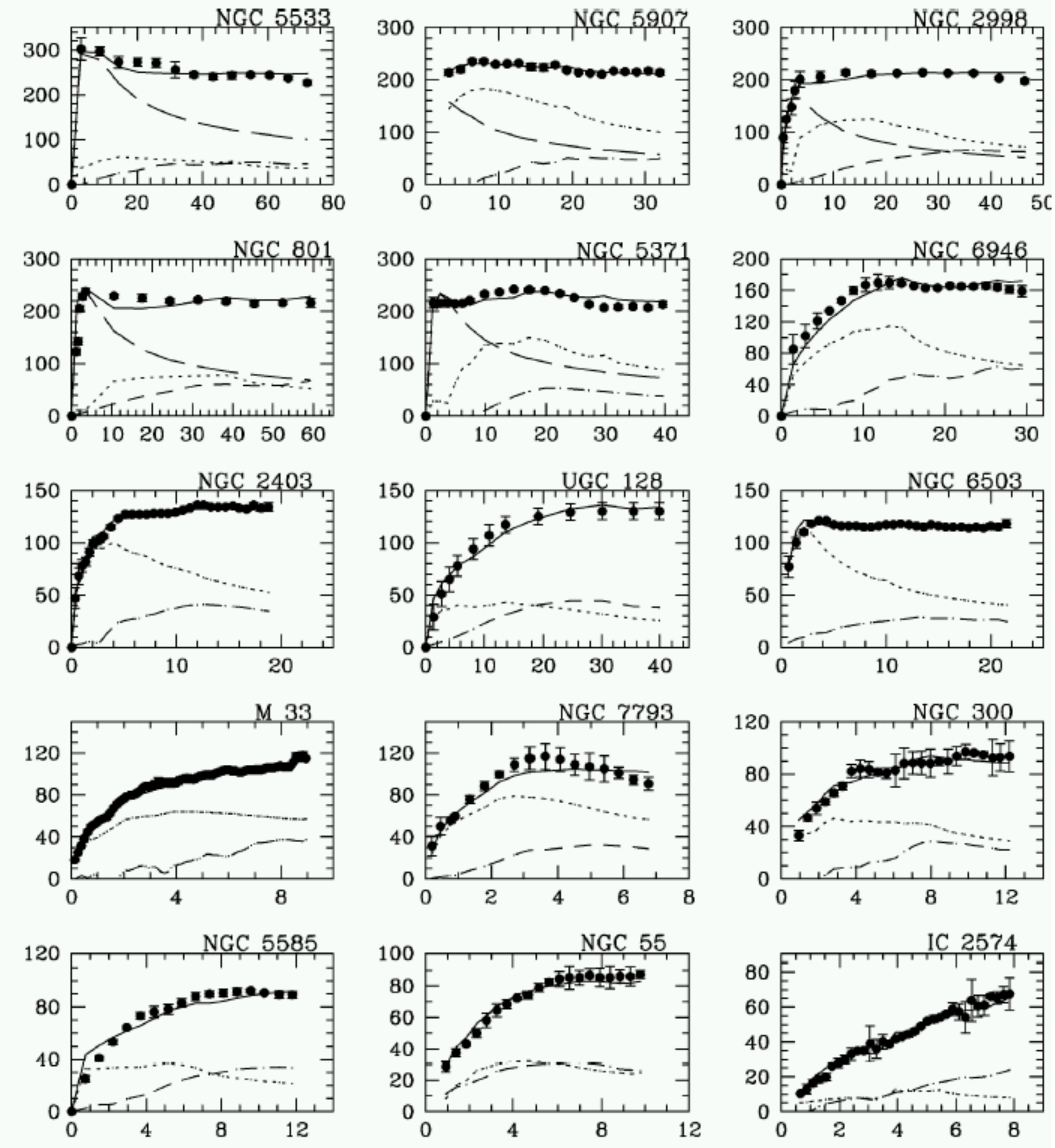


Features in the baryonic disc have counterparts in the rotation curve

Sanders & McGaugh, ARAA **40**:093923,2002

A huge variety of rotation curves is well fitted by MOND

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



Sanders & Verheijen, ApJ **503**:97,1998

The *inferred* rotation curve of the outer Milky Way (a <10^{-8} cm s^{-2}) can be well fitted *without* dark matter

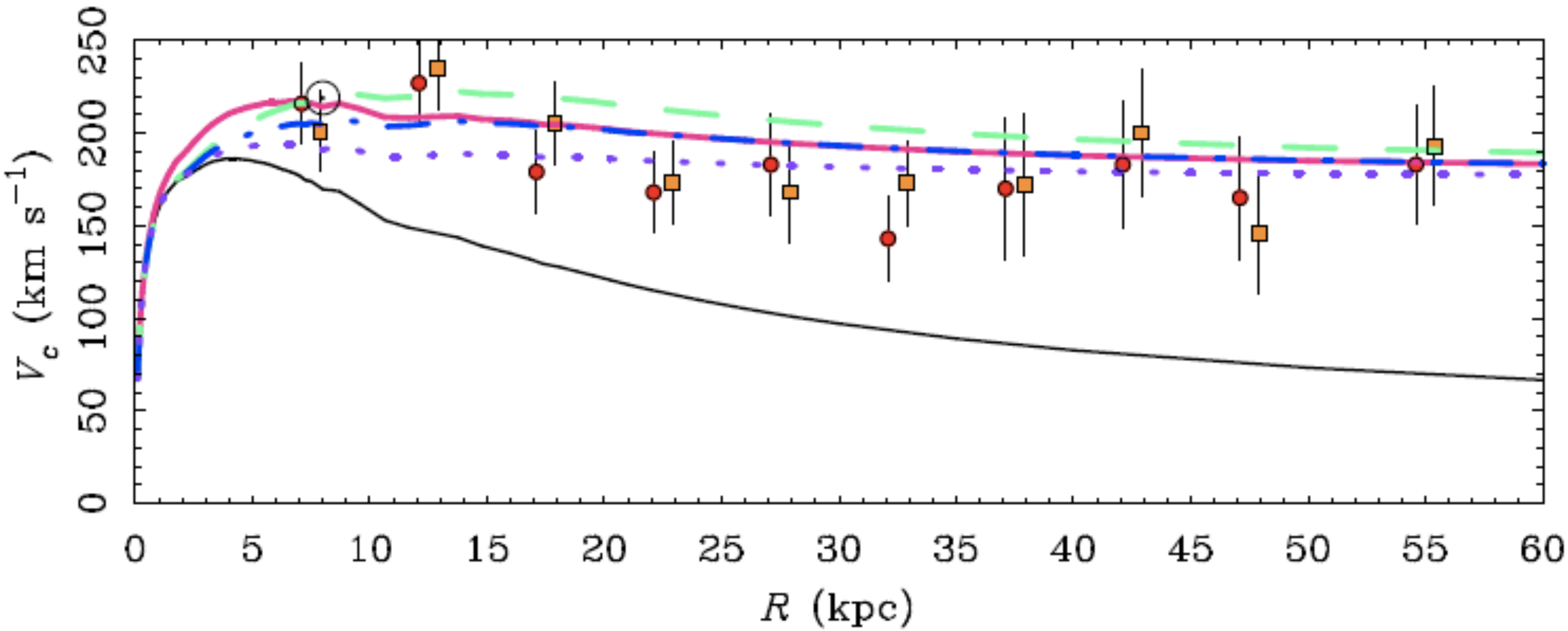


Fig. 7.— The outer rotation curve predicted by MOND for the Milky Way compared to the two realizations of the Blue Horizontal Branch stars in the SDSS data reported by Xue et al. (2008). The data points from the two realizations have been offset slightly from each other in radius for clarity; lines as per Fig. 2. The specific case illustrated has $R_d = 2.3$ kpc, but the rotation curve beyond 15 kpc is not sensitive to this choice. While the data clearly exceed the Newtonian expectation (declining curve), they are consistent with MOND.

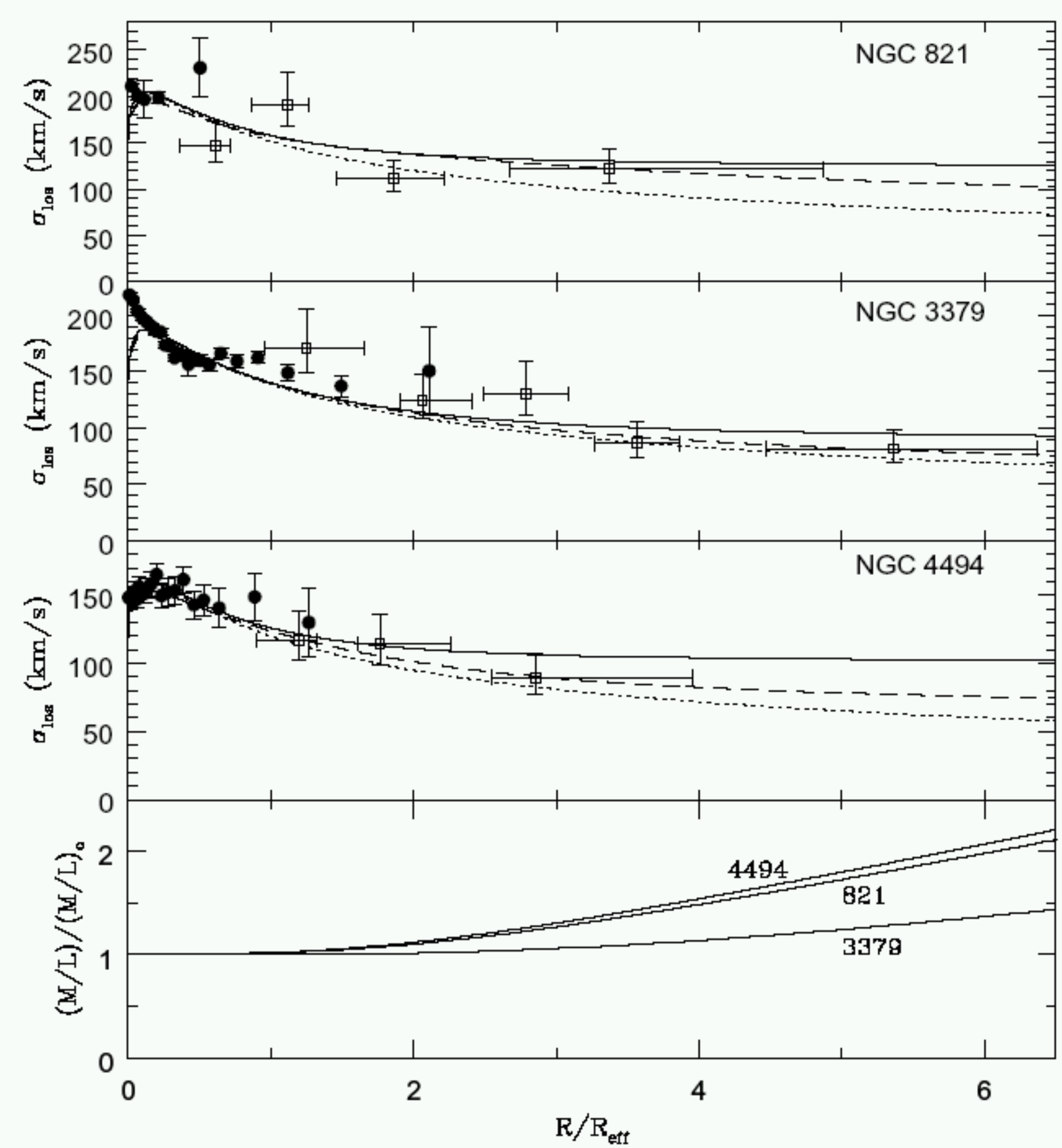
McGaugh, ApJ **683**:137,2008

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

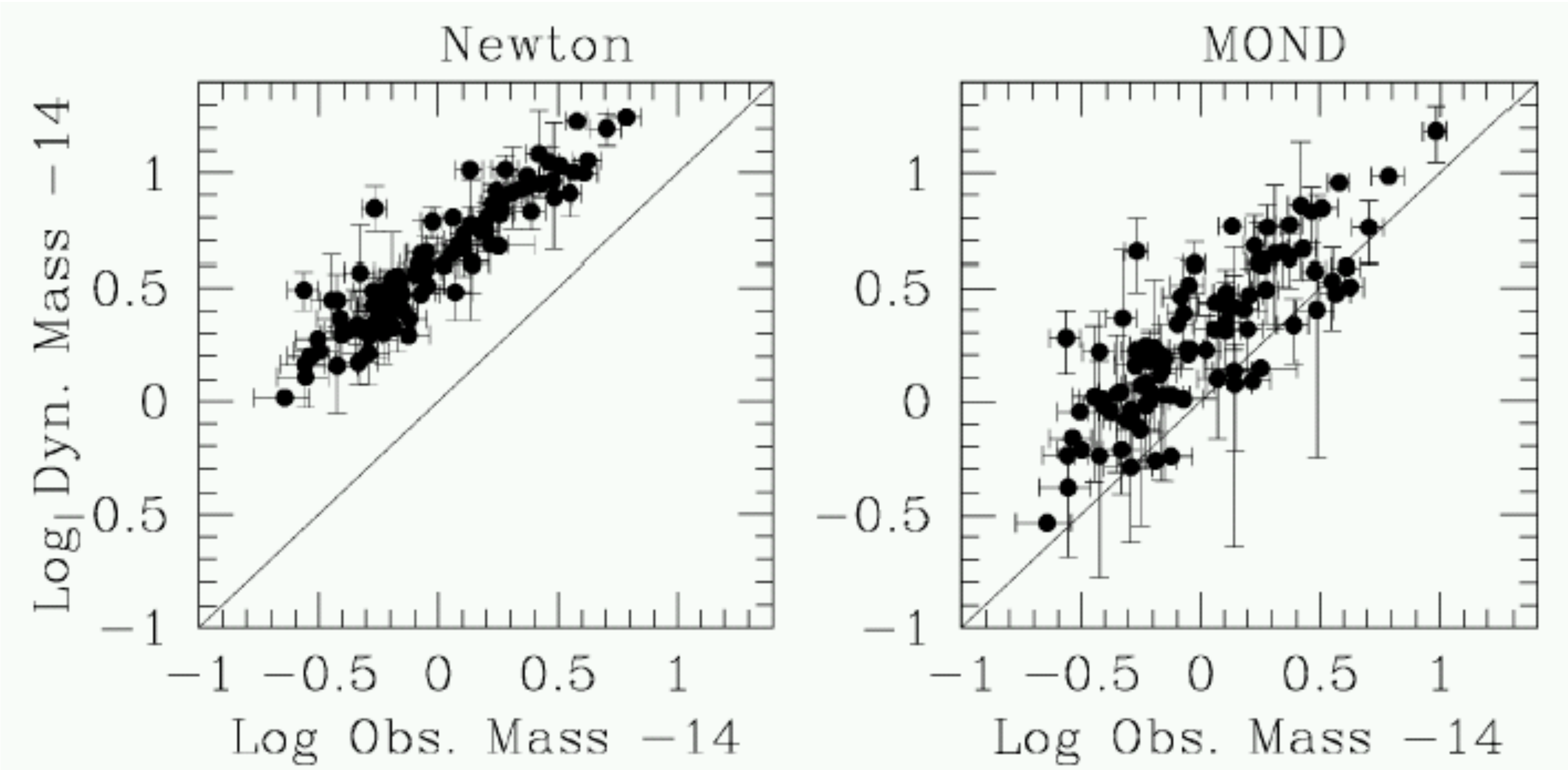
Data:
Romanowsky *et al*, Science 301:1696,2003

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

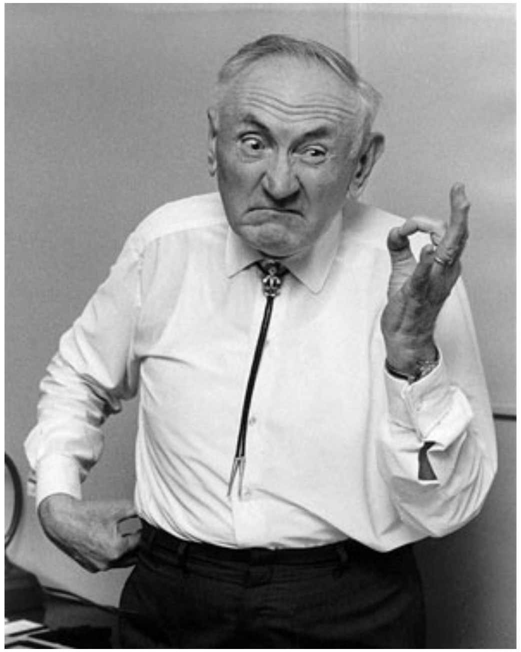
This *can* be explained in a dark matter model if stellar orbits are very elliptical (Dekel *et al*, Nature 437:707,2005)



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

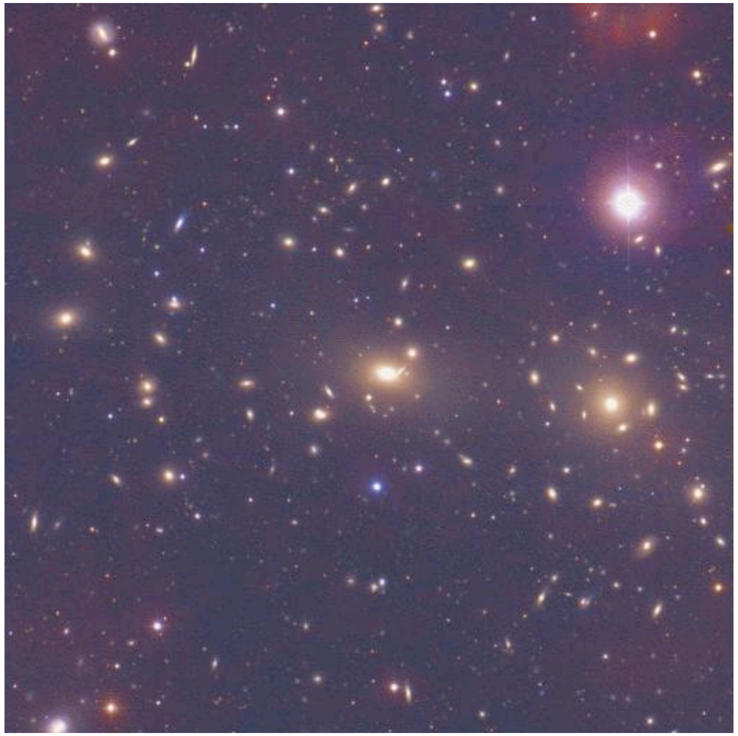
$\Rightarrow M/L \sim O(100)\, M_\odot/L_\odot$

"… 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"

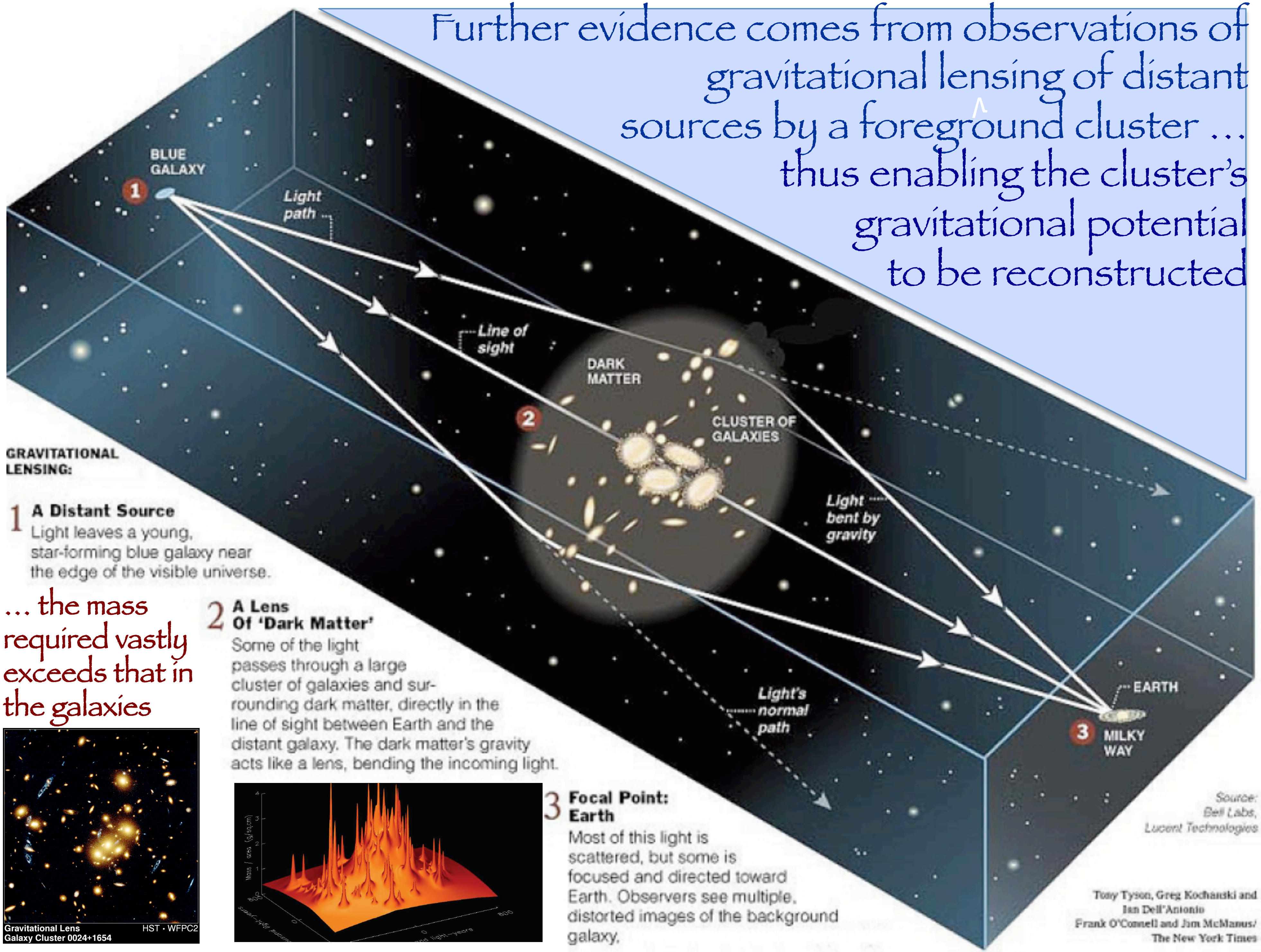
Virial Theorem: $$\langle V\rangle + 2\langle K\rangle = 0$$

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

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

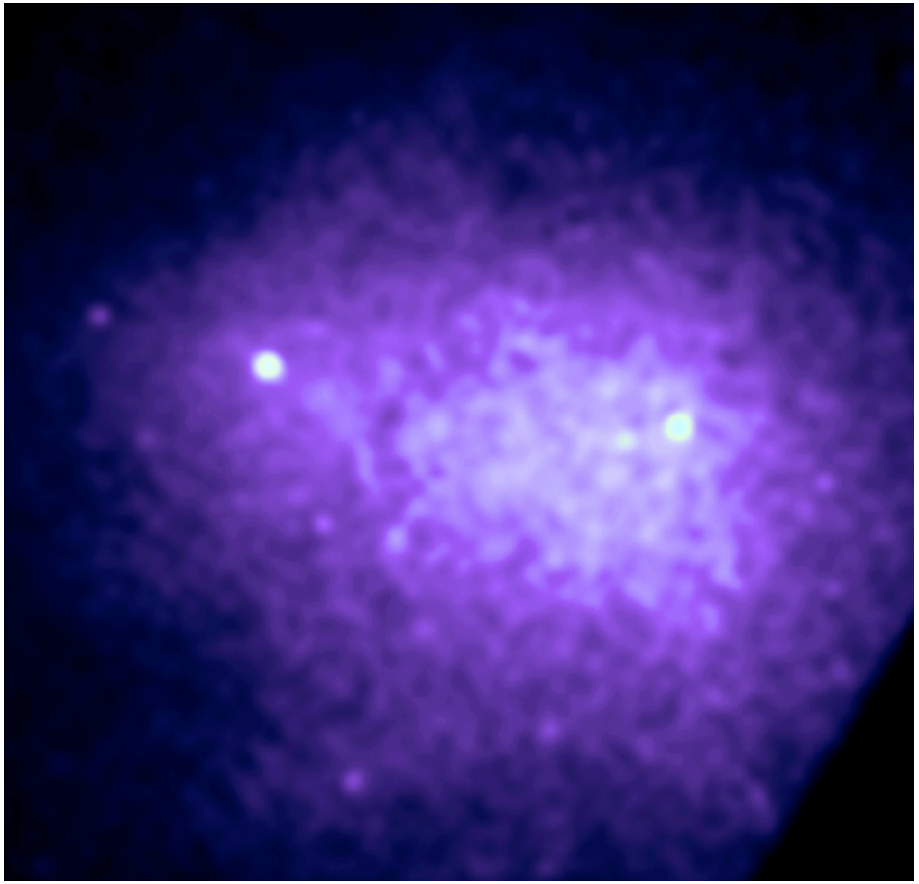


Further evidence comes from observations of gravitational lensing of distant sources by a foreground cluster … thus enabling the cluster's gravitational potential to be reconstructed



… the mass required vastly exceeds that in the galaxies

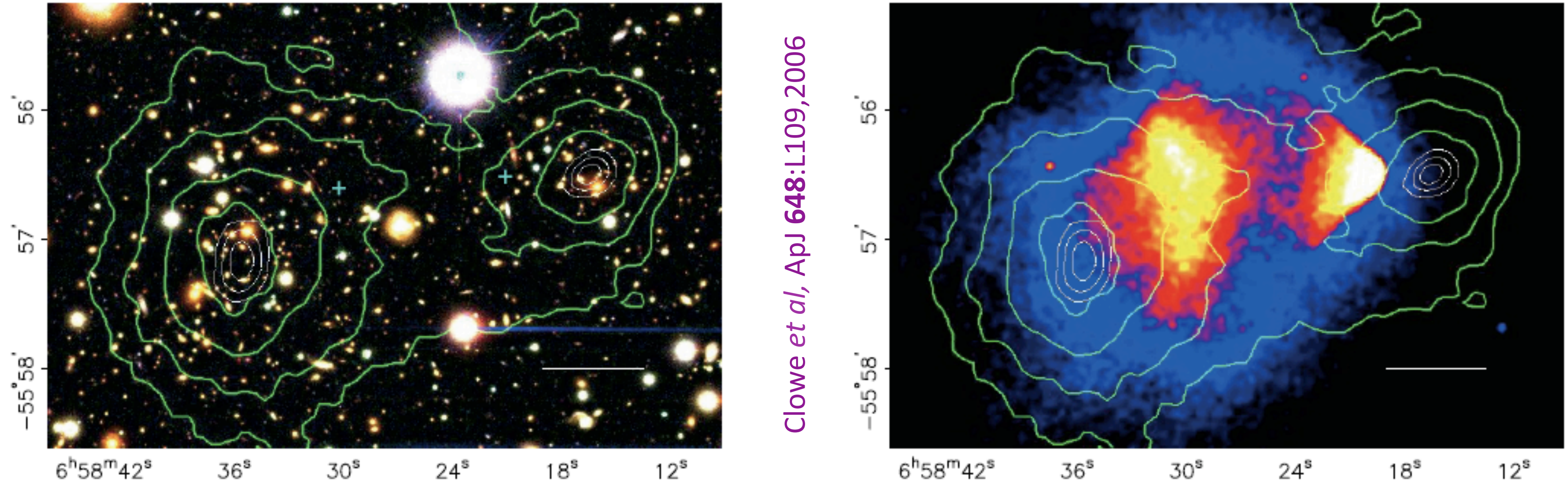
The gravitating mass can also be obtained from X-ray observations of the hot gas in the cluster



… assuming it is in thermal equilibrium:

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

The Chandra picture of the 'bullet cluster' (1E 0657-558) shows that the X-ray emitting baryonic matter is *displaced* from the galaxies and the dark matter (inferred through gravitational lensing) … convincing evidence of dark matter?



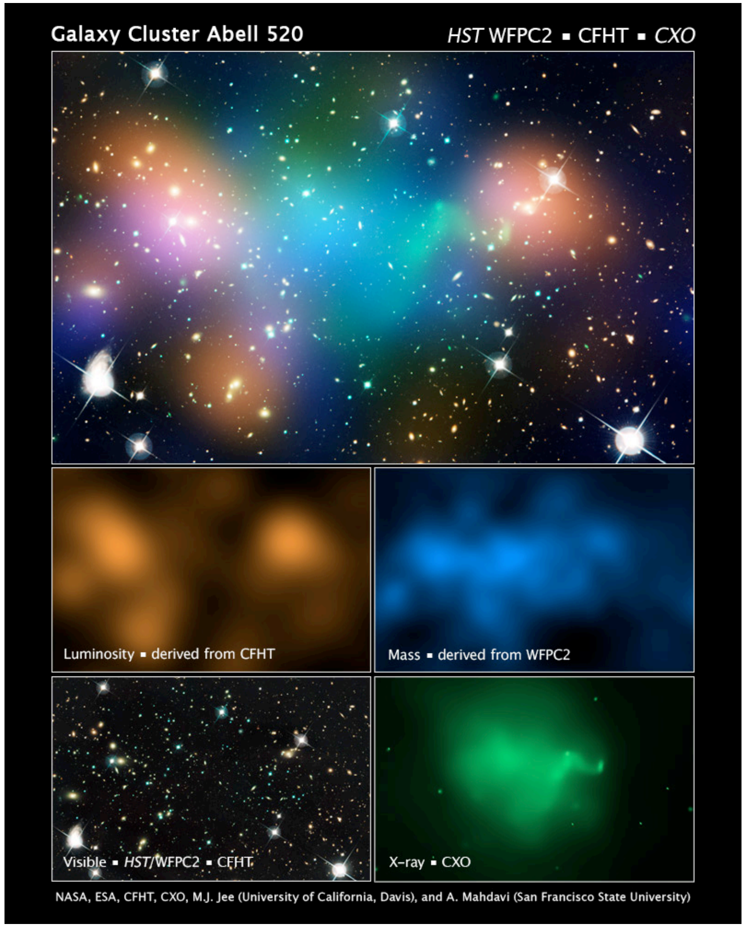
Clowe *et al*, ApJ **648**:L109,2006

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.

The alternative theory of gravity which underlies MOND may predict a different deflection of light - so the reconstructed gravitational potential can be different

… however it has *not* been shown that this can save MOND

To muddle the story, another picture of colliding clusters shows the dark matter (reconstructed from weak lensing) to be partly *coincident* with the hot gas and displaced from the galaxies!

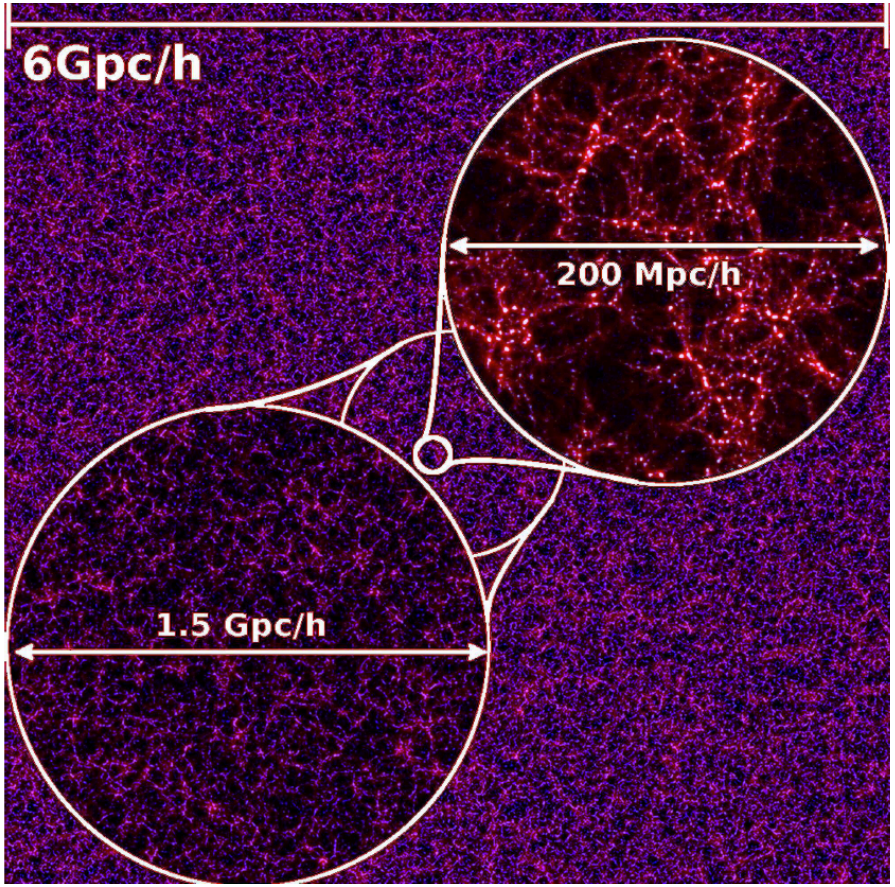


Mahdavi *et al*, ApJ **668**:806,2007

While 1E 0657-558 is often cited as evidence for *collisionless* dark matter, it sets in fact a rather *weak* limit on self-interactions: $\sigma \lesssim 2\text{x}10^{-24}$ cm^2/GeV

However in Abell 520, the inferred dark matter is *coincident* with the X-ray plasma, implying that DM is *self-interacting*: $\sigma \sim 8 \pm 2$ x10^{-24} cm^2/GeV

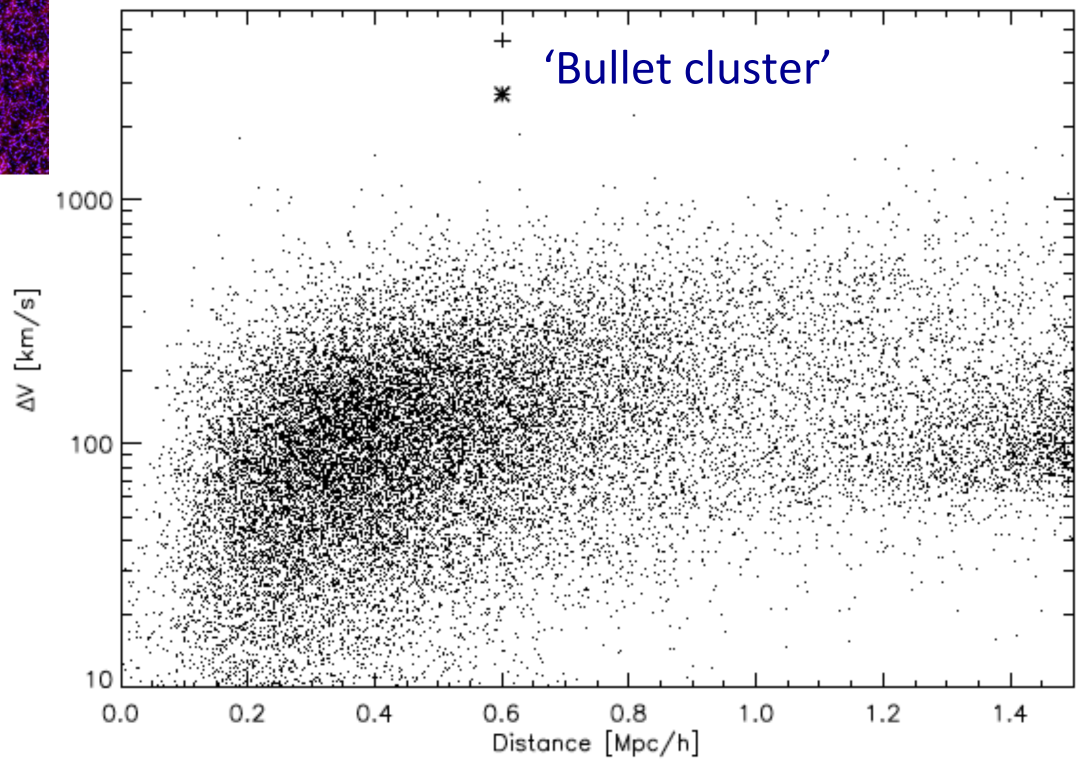
… but uncertainties in the lensing mass reconstruction preclude a definite conclusion (Clowe et al, ApJ 758:128,2012) so there is as yet no hard evidence for self-interactions



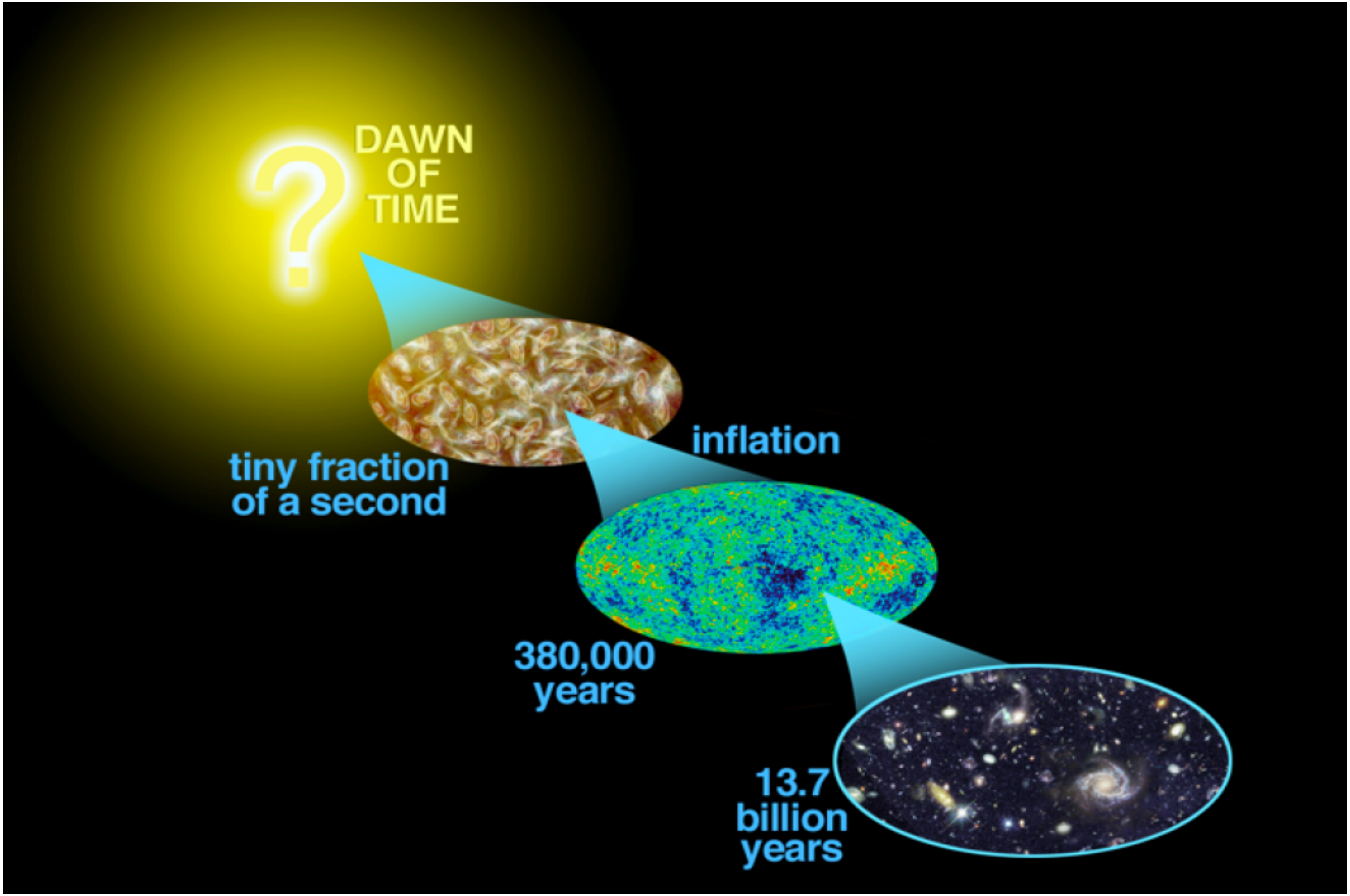
However the 'bullet cluster' poses a *challenge* for ΛCDM cosmology: why is the relative velocity so high (>3000 km/s at an initial separation of ~5 Mpc) … the odds are *tiny* in a gaussian density field (Lee & Komatsu, ApJ **718**:60,2010)

This has been confirmed in the recent Hubble volume 'Jubilee' simulation which does not find a *single* system like the 'bullet cluster' … yet nine such systems have by now been observed!

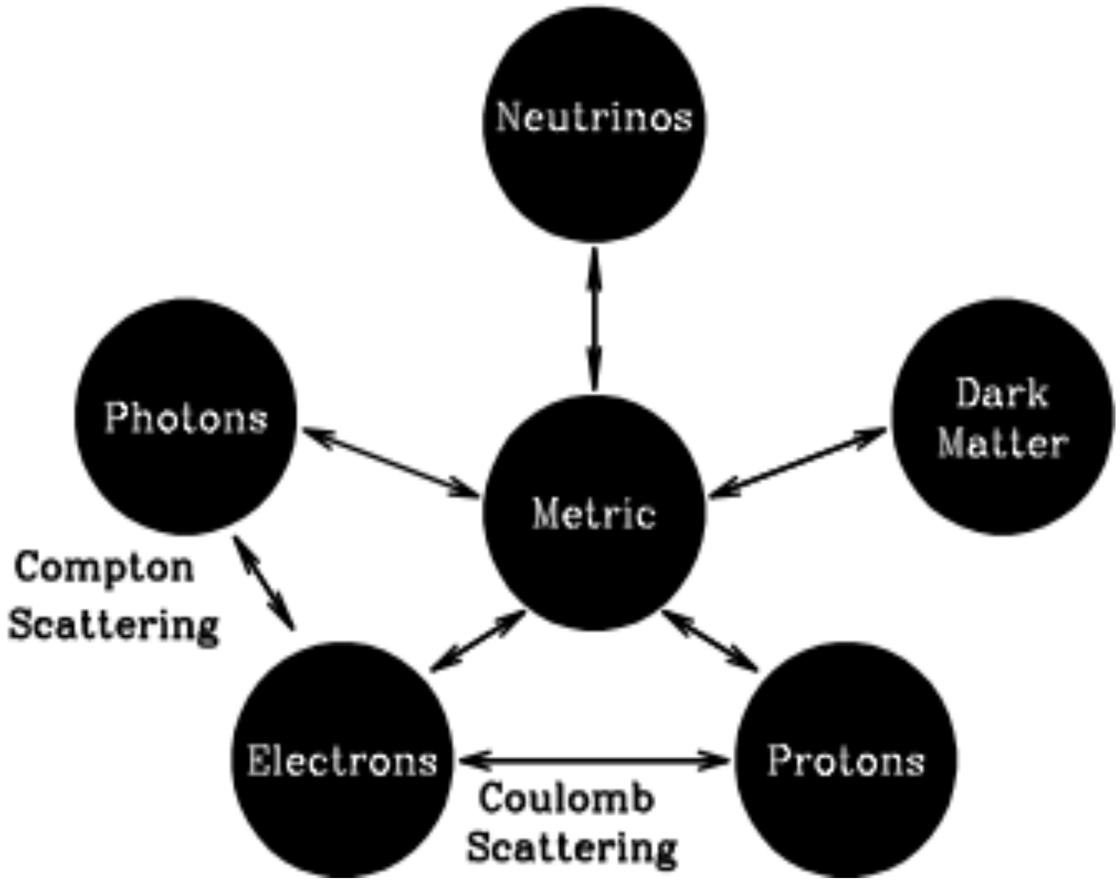
Watson *et al*, arXiv:1305.1976



A compelling argument for the dominance of dark matter over baryonic matter comes from considerations of structure formation in the universe

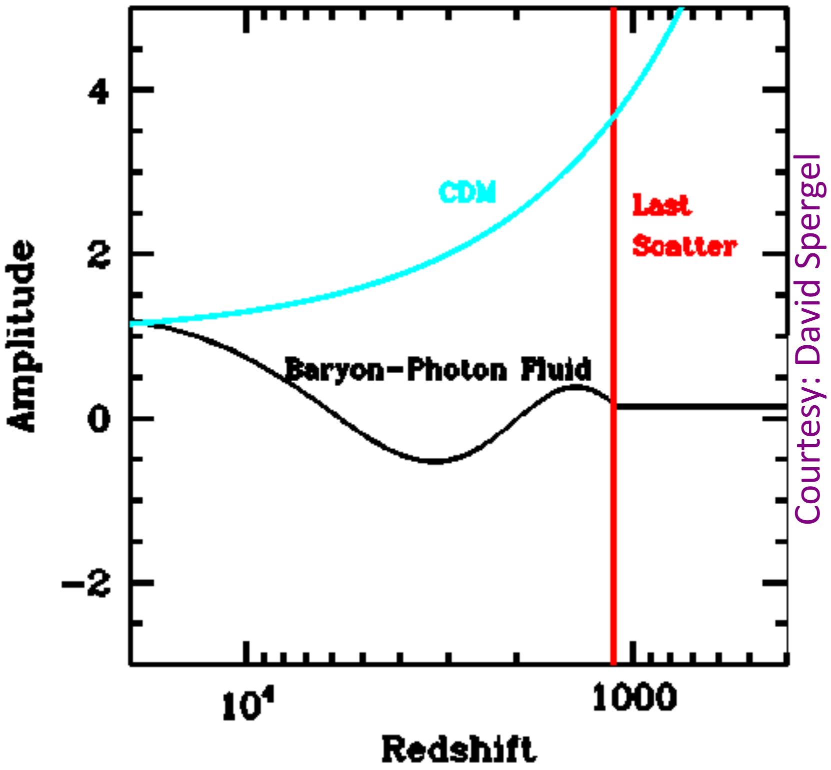


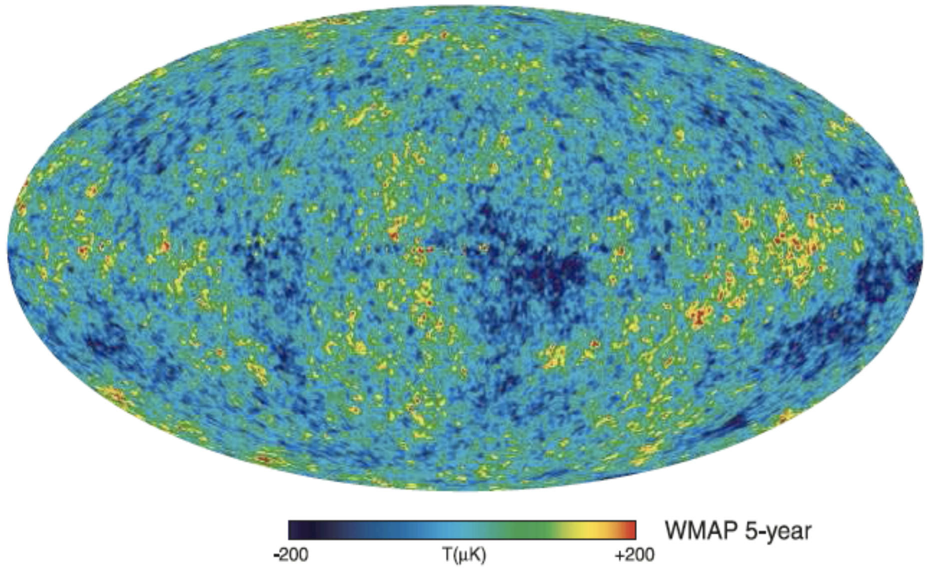
Perturbations in metric (generated during inflation) induce perturbations in photons and (dark) matter



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 …





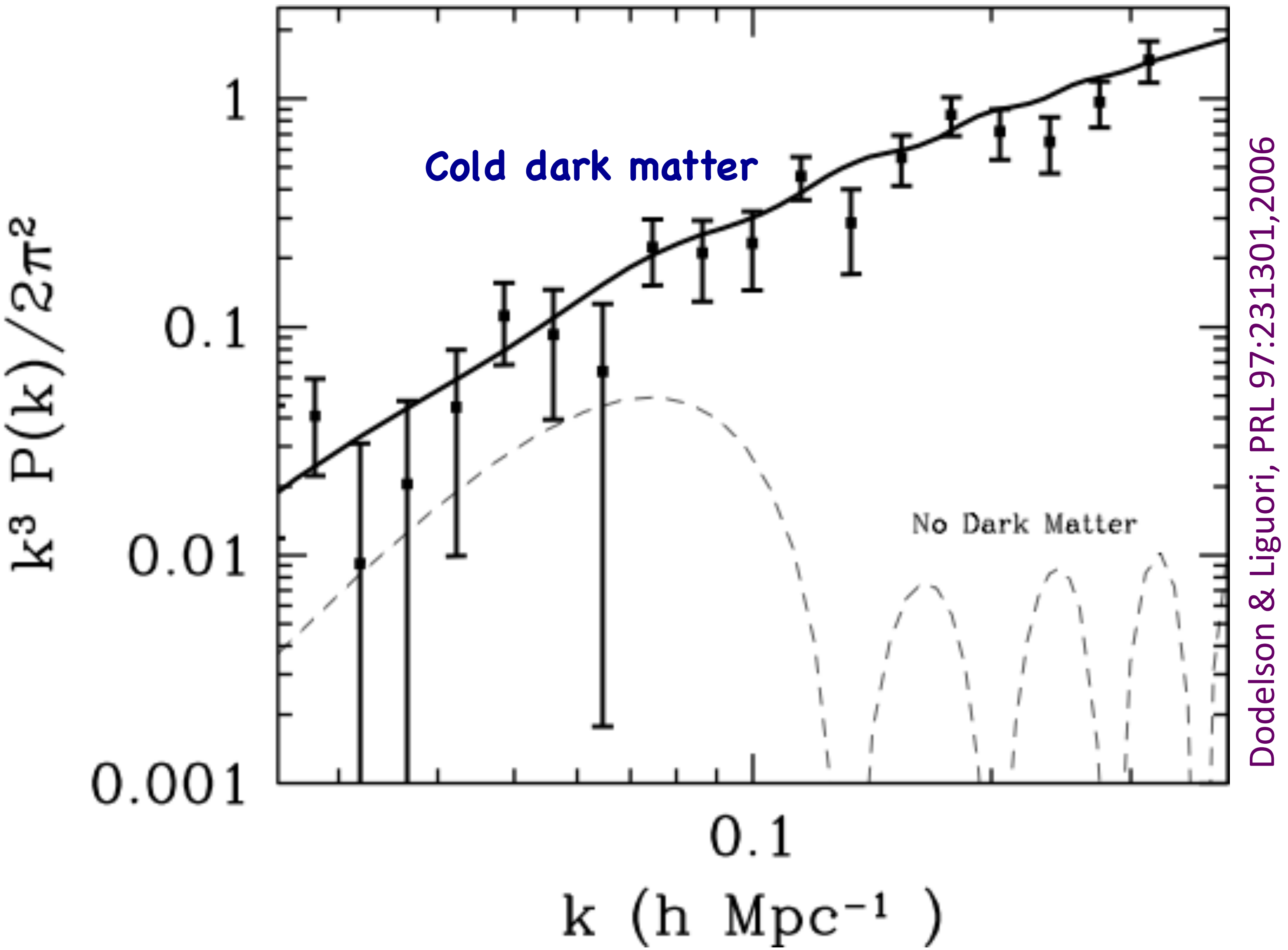
These sound waves leave an imprint on the last scattering surface of the CMB as the universe turns neutral and transparent … sensitive to the baryon/CDM densities

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 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 have left their imprint on the CMB at last scattering



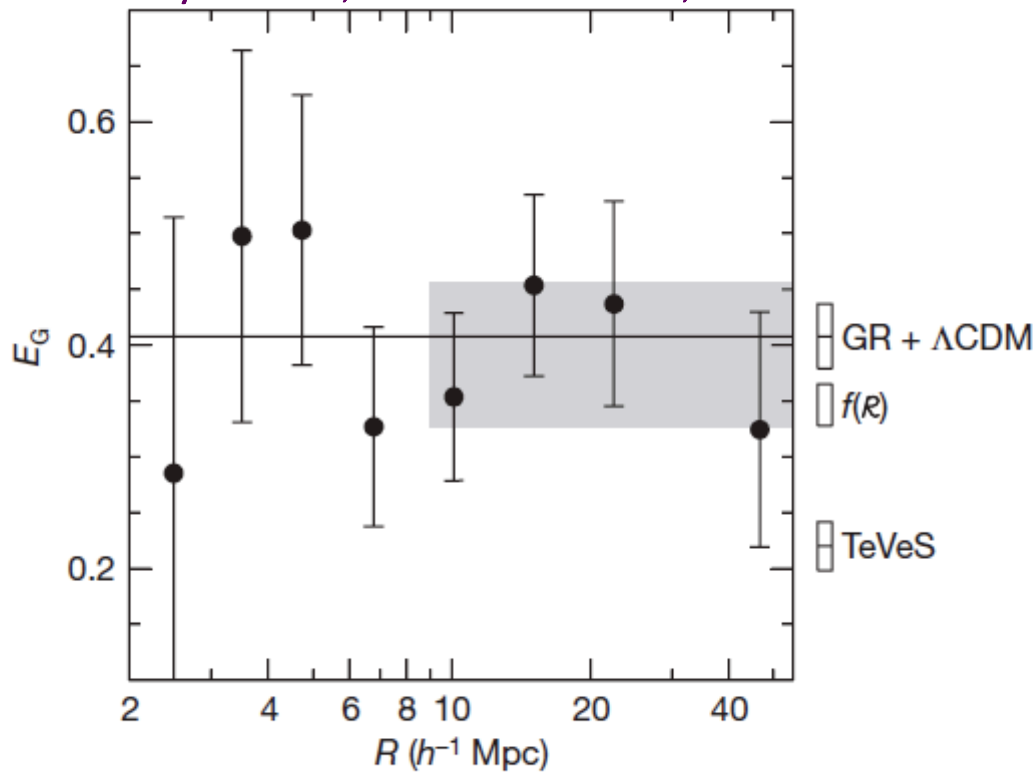
Detailed modelling of WMAP and 2dF/SDSS ⇒ $\Omega_m \sim 0.3, \Omega_B \sim 0.05$

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

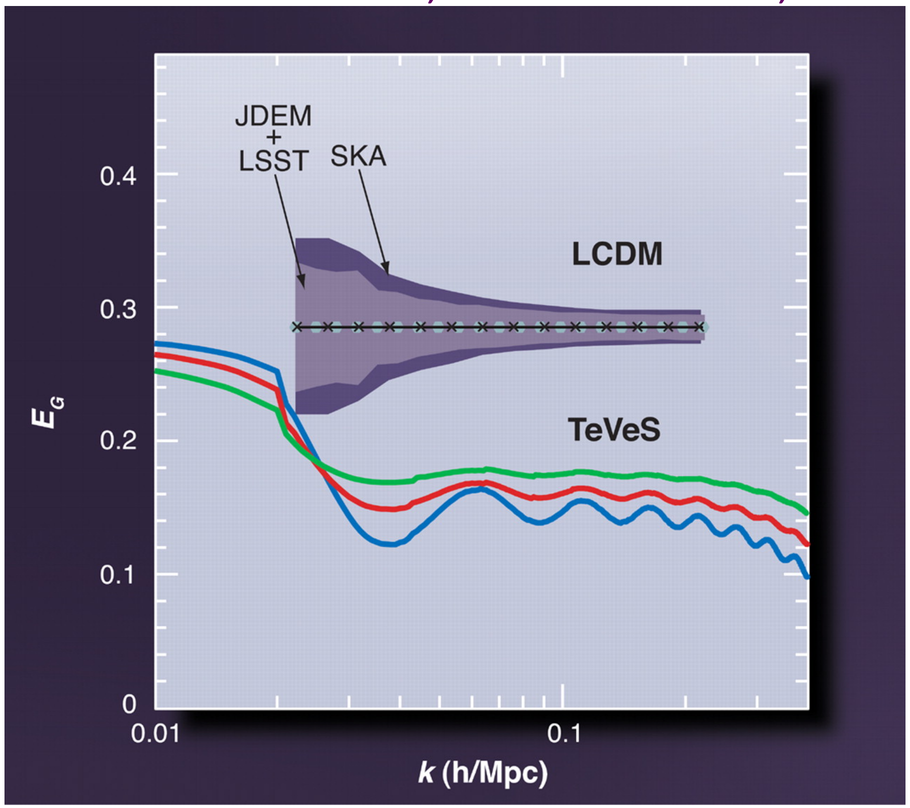
Although *new* gravitational physics (underlying MOND) can in principle provide adequate growth of cosmological structure, there is in general an observable distinction – the 'gravitational slip' – between GR and modified gravity

(for a review see: Clifton *et al*, Phys. Rep.**513**:1,2012)

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

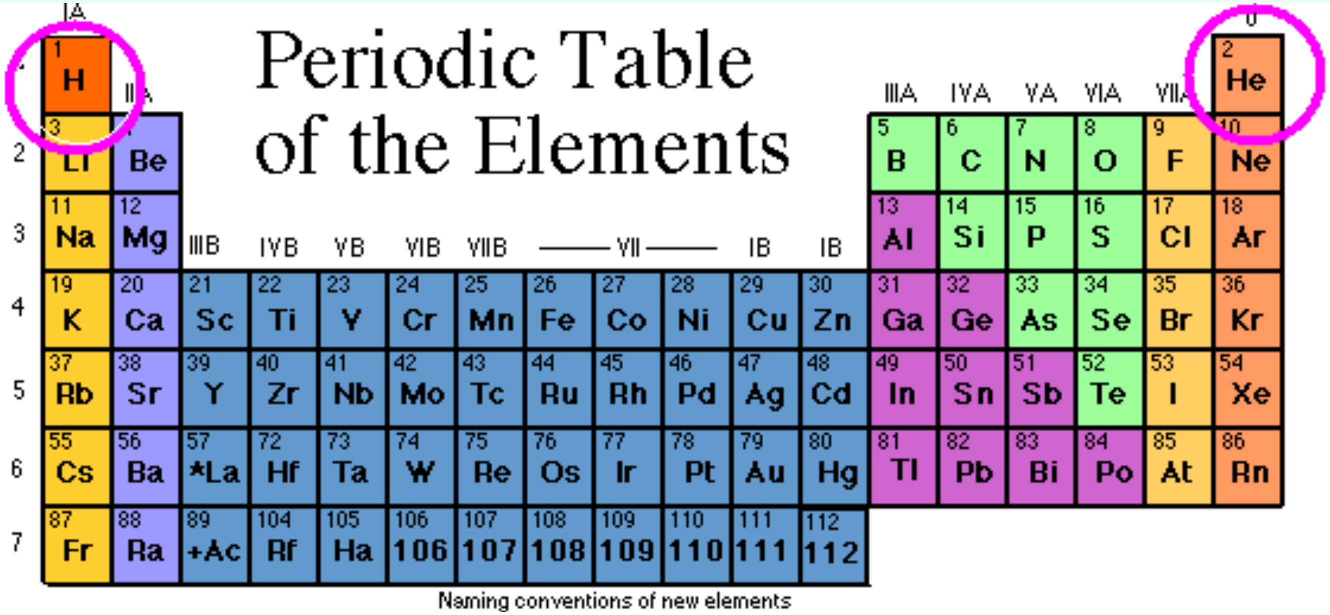


Ferreira & Starkman, Science **326**:812,2009



This can be tested through cross-correlation of weak lensing (shearing of galaxy shapes) with the galaxy density field (Zhang *et al*, PRL **99**:141302,2007)

Matter is made mainly of hydrogen (~75%) and helium (~25%)
+ traces of heavier elements

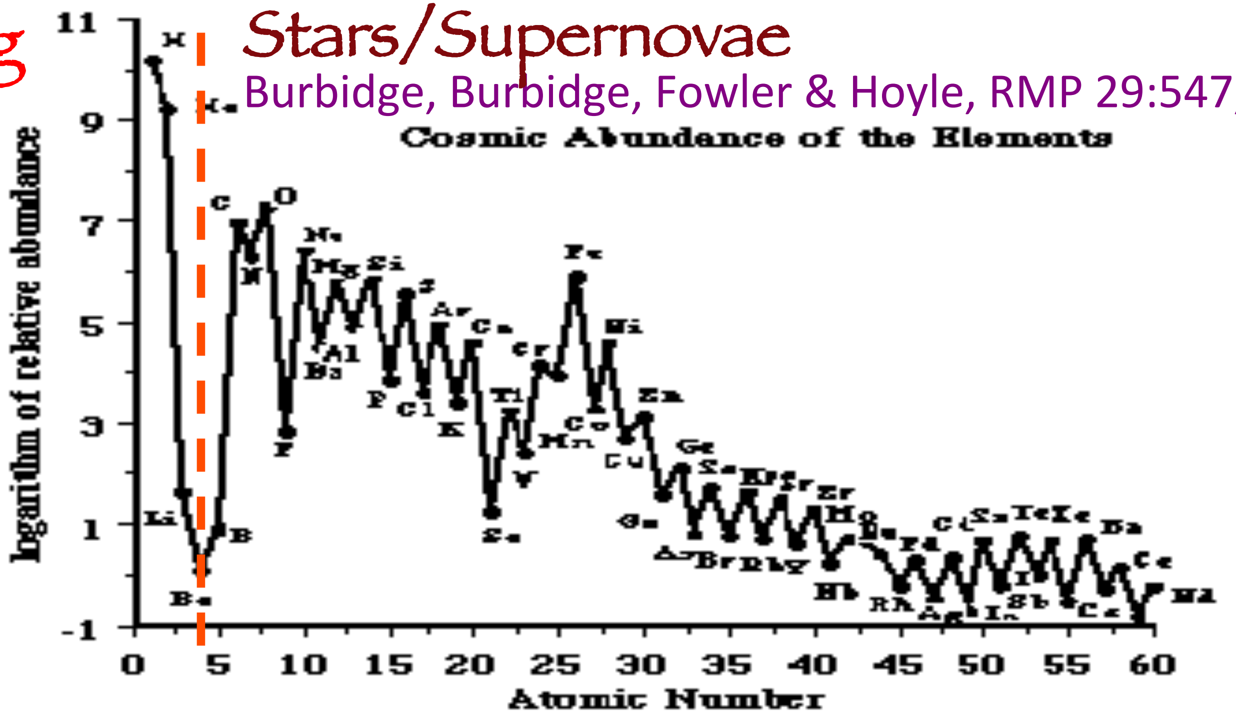


Big Bang

Alpher, Herman & Gamow, PR**74**:1198, 1948

Stars/Supernovae

Burbidge, Burbidge, Fowler & Hoyle, RMP 29:547,1957



Weak interactions and nuclear reactions in expanding, cooling universe

(Hayashi 1950, Alpher, Follin & Herman 1953, Peebles 1966, Wagoner, Fowler & Hoyle 1967)

Dramatis personae:

Radiation (dominates) $\gamma, e^{\pm}, 3\nu\bar{\nu}$

Matter n, p

baryon-to-photon ratio (only free parameter) $n_{\rm B}/n_\gamma \equiv \eta \simeq 2.74 \times 10^{-8}\Omega_{\rm B}h^2$

Initial conditions: T >> 1 MeV, t << 1 s

n-*p* weak equilibrium: $n + \nu_e \leftrightarrow p + e^-$

neutron-to-proton ratio: $p + \nu_e \leftrightarrow n + e^+$

Weak freeze-out: $T_{\rm f}$ ~ 1 MeV, $t_{\rm f}$ ~ 1 s

$\tau_{\rm weak}(n \leftrightarrow p) \geq t_{\rm universe} \Rightarrow T_{\rm freeze\text{-}out} \sim \left(G_N / G_F^2\right)^{1/3}$

which fixes: $n/p = e^{-(m_n - m_p)/T_{\rm f}} \approx 1/6$

Deuterium bottleneck: T ~ 1 → 0.07 MeV

D created by $np \rightarrow D\gamma$

but destroyed by high-E photon tail: $D\gamma \rightarrow np$

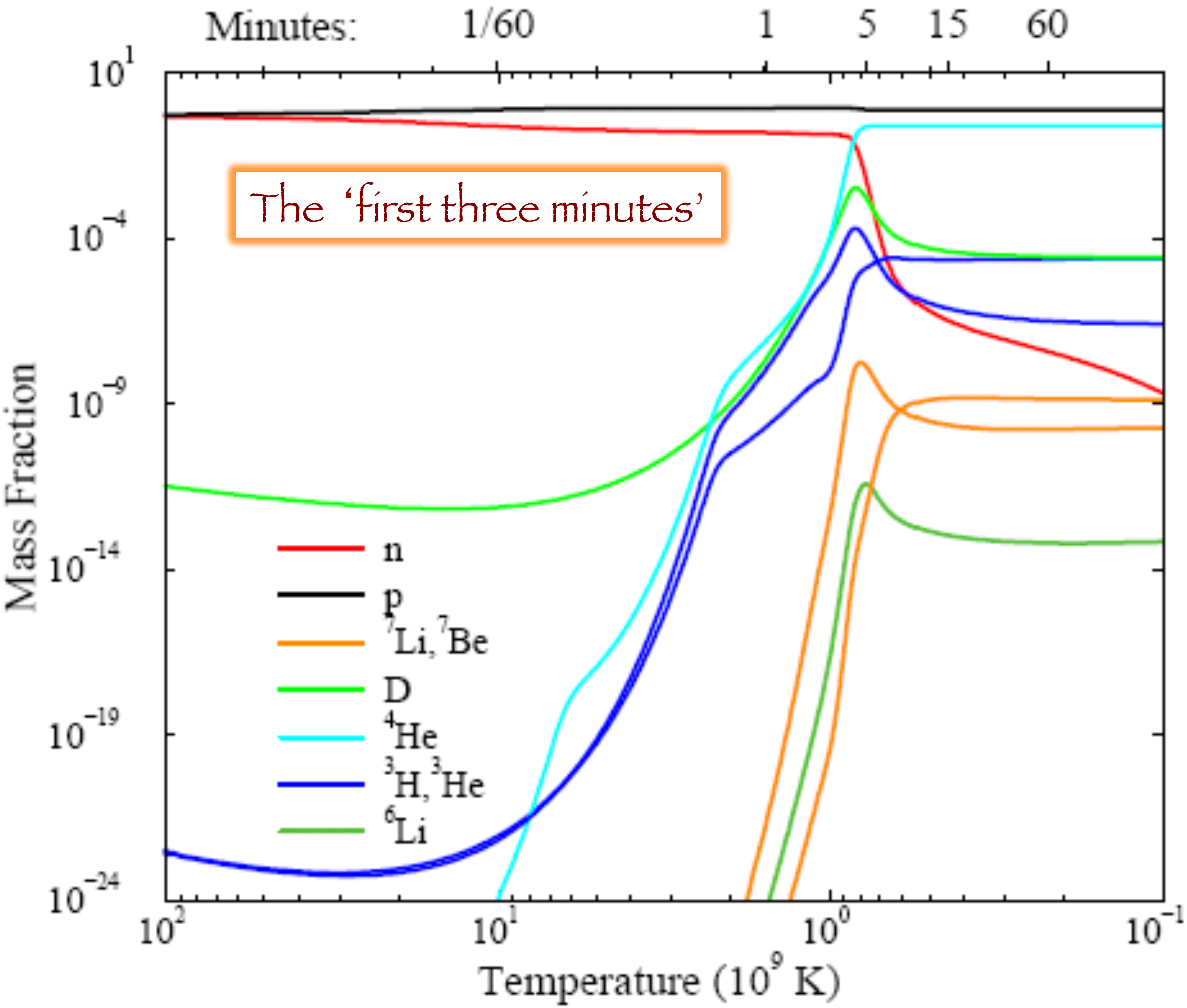
so nucleosynthesis halted until: $T_{\rm nuc} \sim \Delta_{\rm D}/\text{-}\ln(\eta)$

Element synthesis: $T_{\rm nuc}$ ~ 0.07 MeV, $t_{\rm nuc}$ ~ 3 min

(meanwhile n/p → 1/7 through neutron β-decay)

nearly all n → ^{4}He ($Y_{\rm P}$ ~ 25% by mass) + left-over traces of D, ^{3}He, ^{7}Li (with ^{6}Li/^{7}Li ~ 10^{-5})

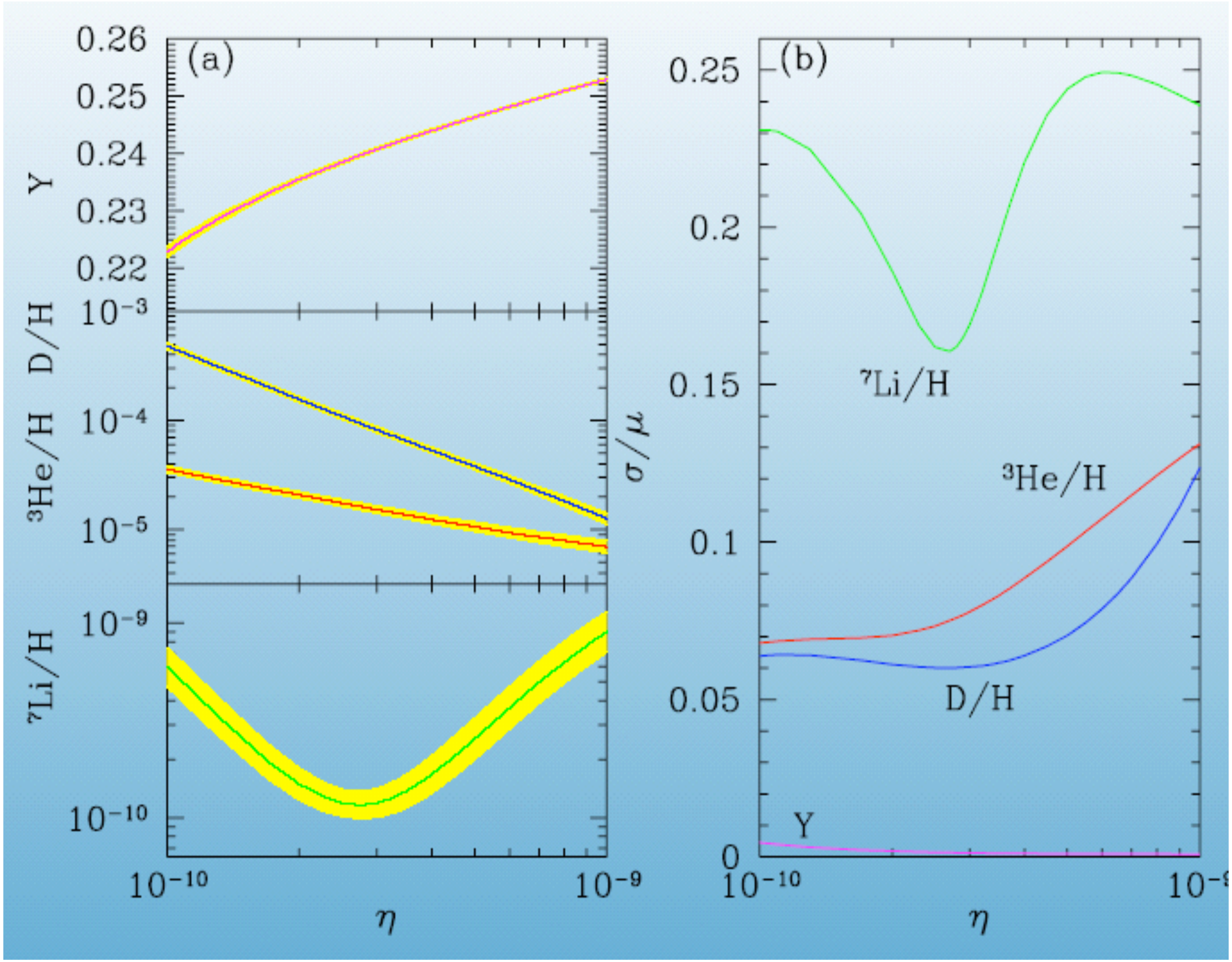
No heavier nuclei formed in standard, homogeneous hot Big Bang … must wait for stars to form after a ~billion years and synthesise all the other nuclei in the universe (s-process, r-process, …)



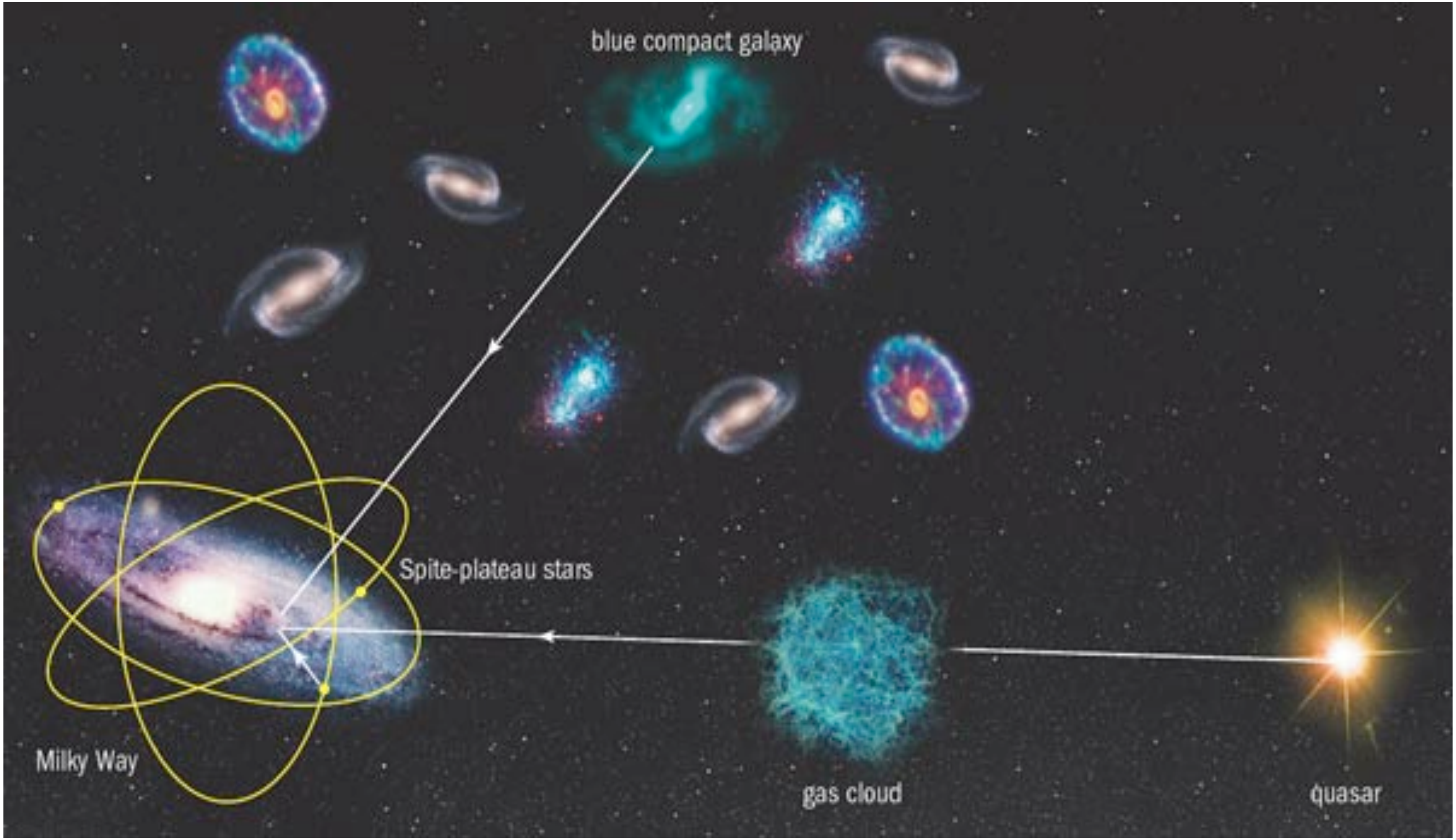
Minutes: 1/60 1 5 15 60
The 'first three minutes'
Mass Fraction
10^1
10^-4
10^-9
10^-14
10^-19
10^-24
10^2
10^1
10^0
10^-1
Temperature (10^9 K)
n
p
7Li, 7Be
D
4He
3H, 3He
6Li

BBN Predictions

line widths ⇒ theoretical uncertainties (neutron lifetime, nuclear cross sections)



Inferring primordial abundances



Inferred primordial abundances

^{4}He observed in extragalactic HII regions:

$$Y_p = 0.249 \pm 0.009$$

^{2}H observed in quasar absorption systems (and ISM):

$$D/H|_p = (2.84 \pm 0.26) \times 10^{-5}$$

^{7}Li observed in atmospheres of dwarf halo stars:

$$Li/H|_p = (1.7 \pm 0.02^{+1.1}_{-0}) \times 10^{-10}$$

(^{3}He can be both created & destroyed in stars … so primordial abundance *cannot* be reliably estimated)

Systematic errors have been re-evaluated based on scatter in data
(see Particle Data Group, J. Phys.G37:075021,2010)

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

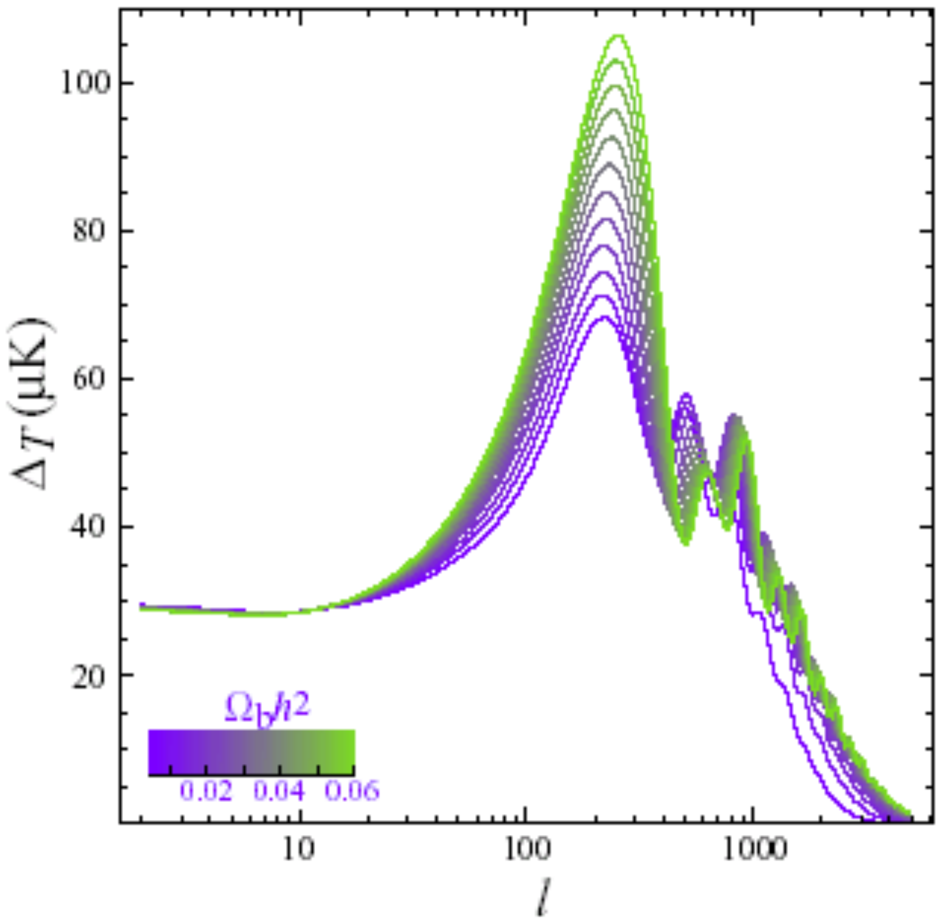
Detailed peak positions, heights, …

sensitive to cosmological parameters

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

e.g. WMAP-5 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

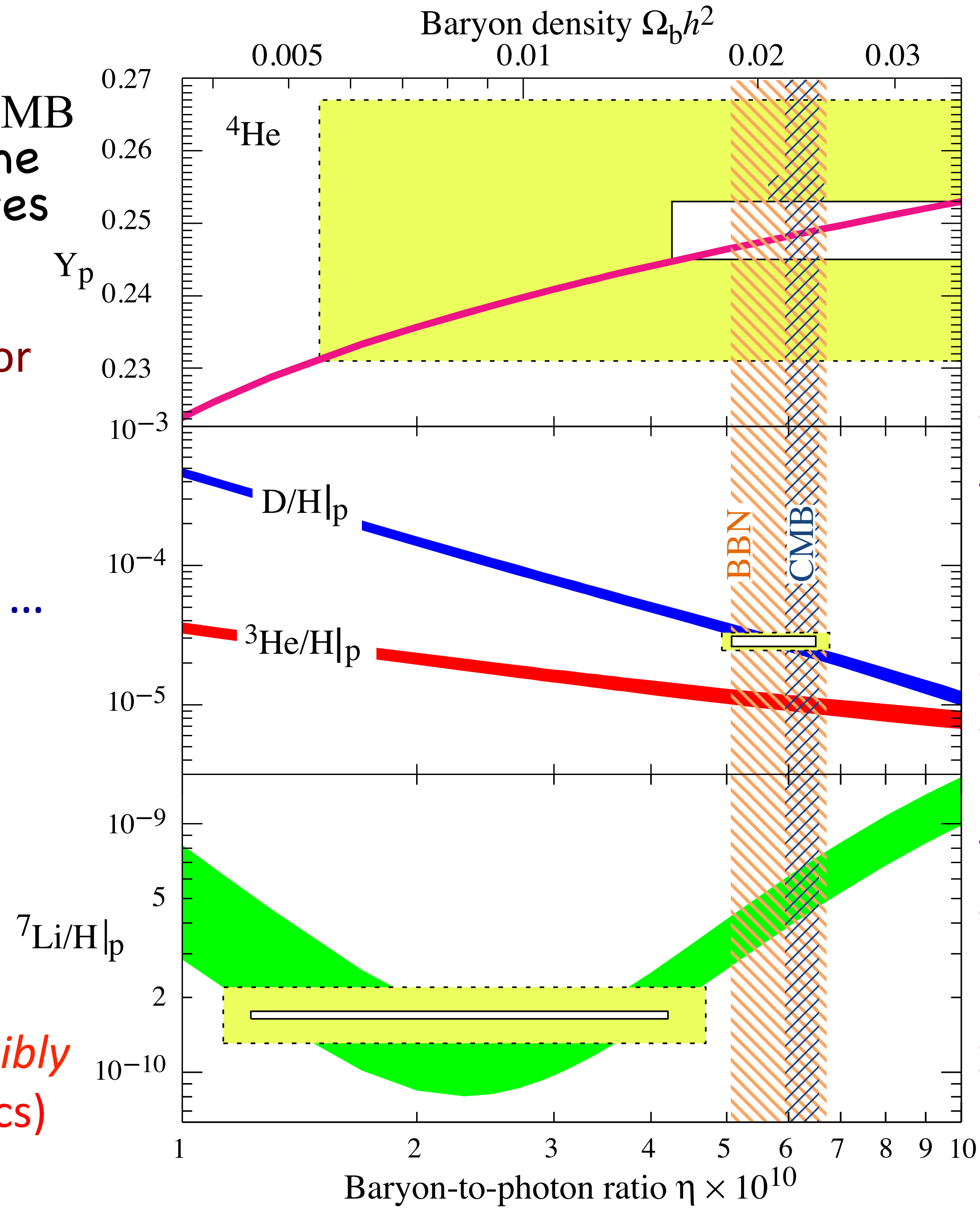
η_{BBN} is in agreement with η_{CMB} allowing for uncertainties in the *inferred* elemental abundances

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

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

Baryonic Dark Matter:
warm-hot IGM, Ly-α , X-ray gas …
+
Non-baryonic dark matter: ?

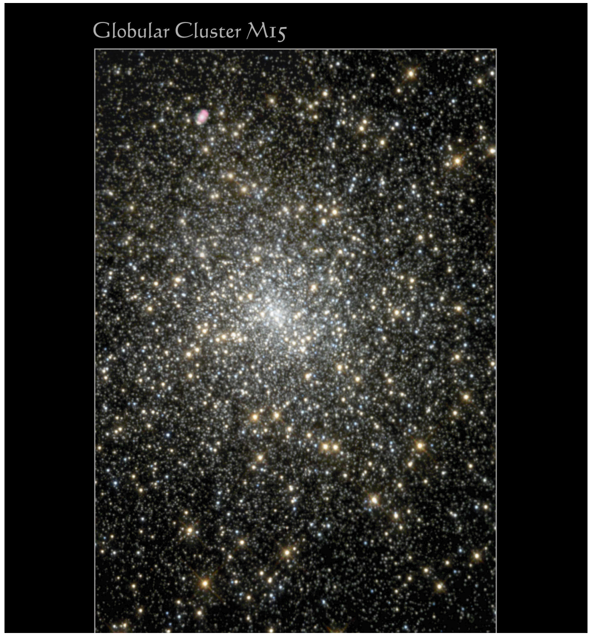
(There is a "lithium problem" *possibly* indicative of non-standard physics)



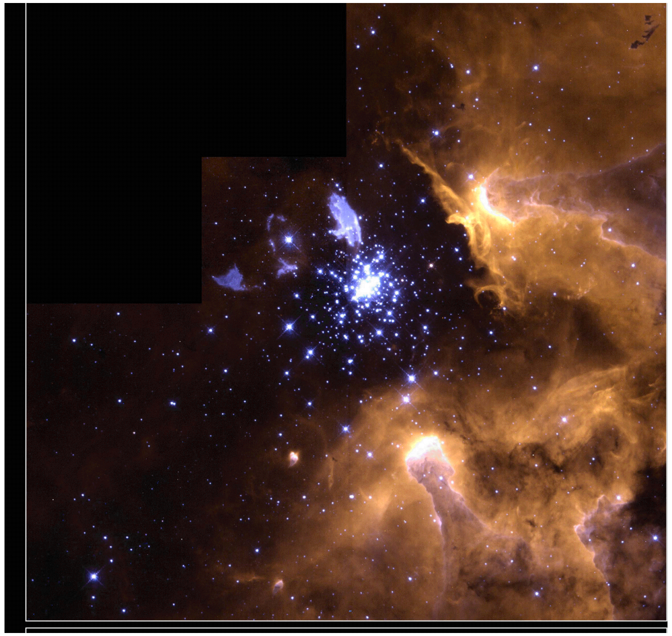
Fields & Sarkar (Particle data Group), Phys.Rev.D86:1,2012

We know that *some* baryons must be dark because BBN requires $\Omega_B \sim 0.02h^{-2}$, whereas $\Omega_{luminous} \sim 0.024h^{-1}$

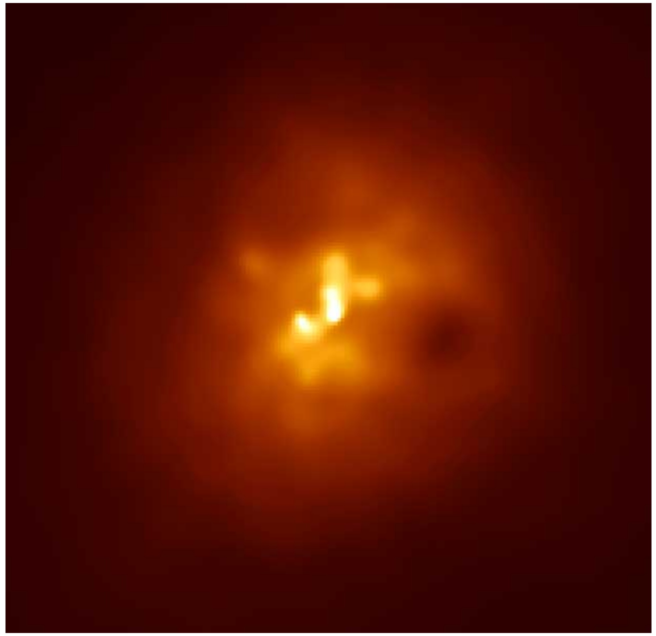
Stars
$\Omega \sim 0.005$



Interstellar gas
$\Omega \sim 0.005$



Hot gas in clusters
$\Omega \sim 0.03$



Cosmological observations indicate $\Omega_m \sim 0.3$ so most of the matter in the universe must be dark and *non-baryonic*

Is it possible that **dark matter** is illusory?

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: $L \sim v_{\rm rot}^{4}$ ("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 'Bullet' 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 identified!