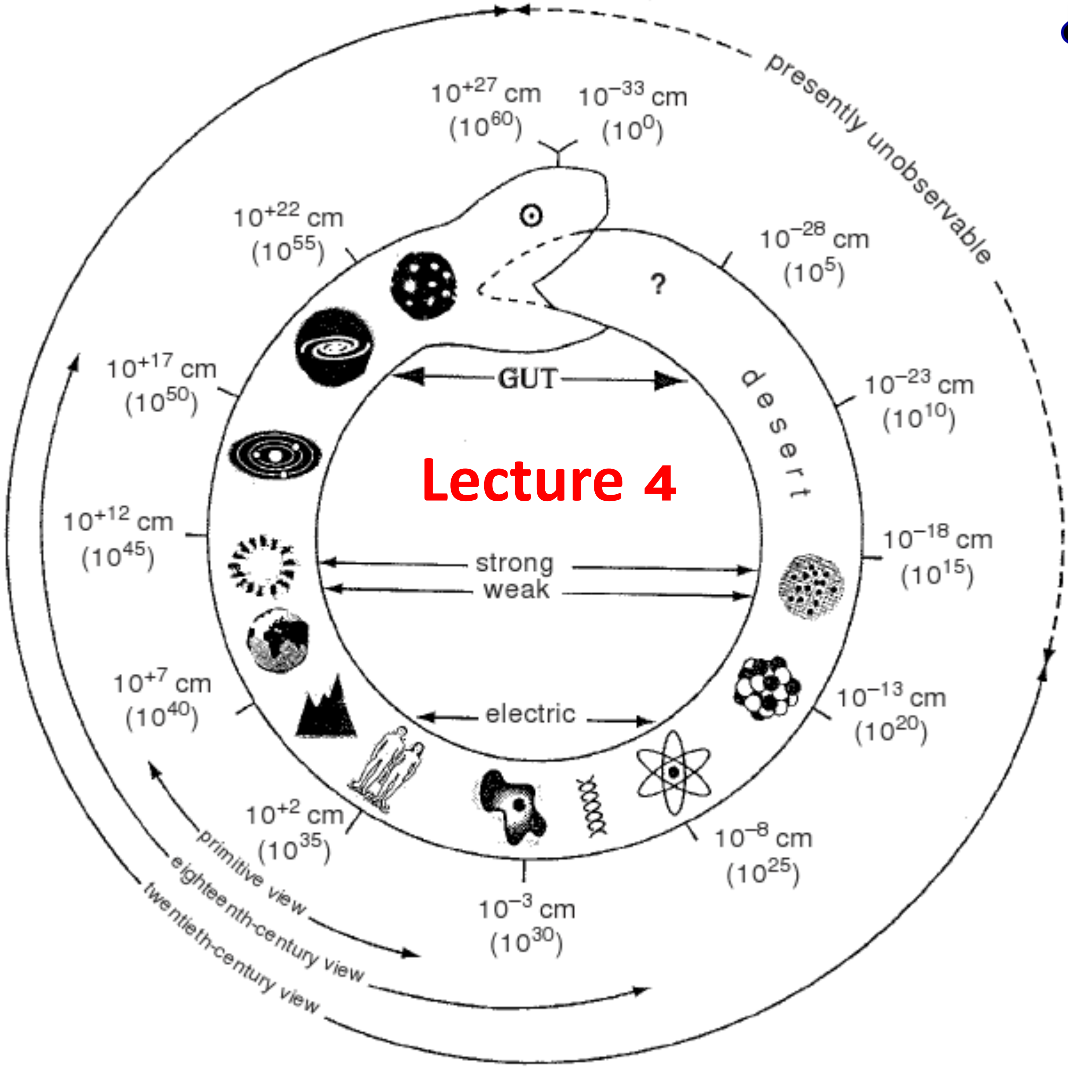
Dark matter

Subir Sarkar

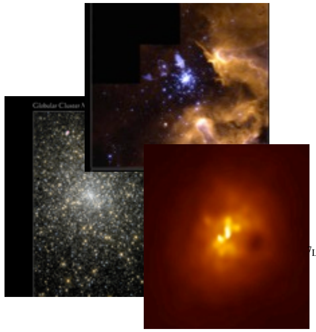


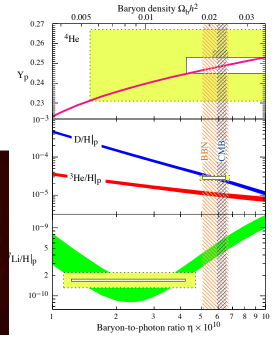
Lecture 4

Taller de Altas Energías, 4-17 September 2016, Benasque

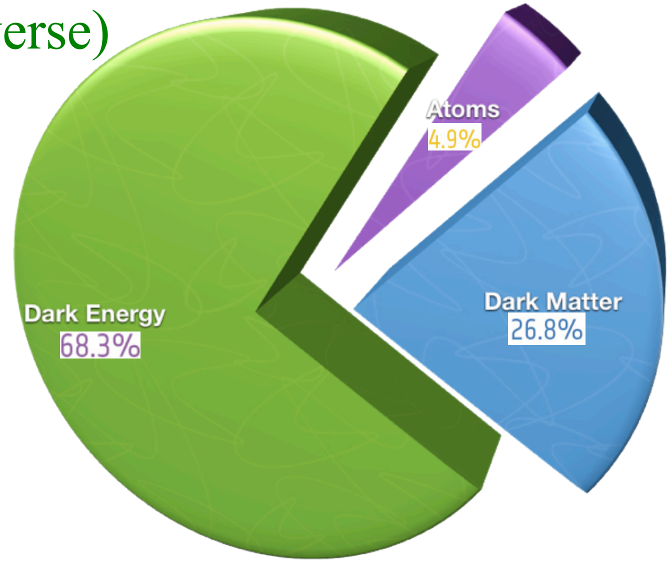
What is the world made of?

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

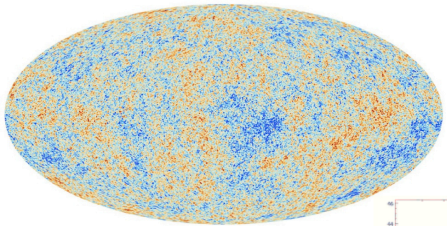


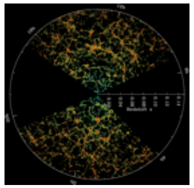


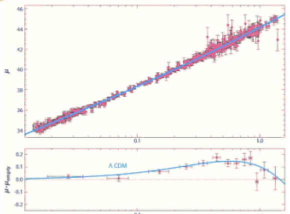
Baryons
(but *no*
anti-baryons)

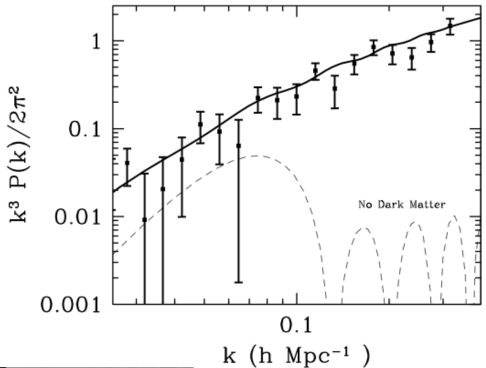


Both geometrical *and*
dynamical evidence for
dark matter (*if* GR valid)

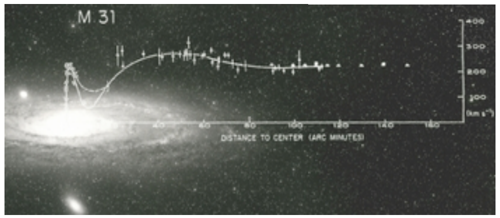


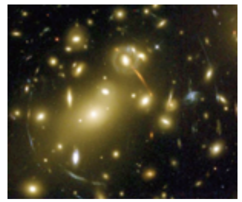




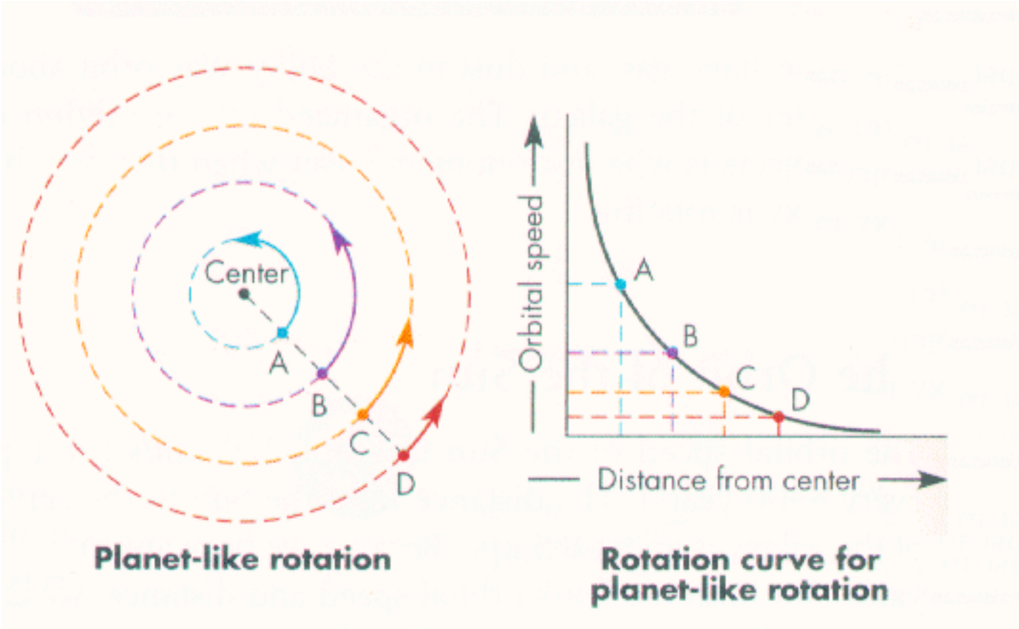


Both the baryon asymmetry and dark matter *require*
new physics beyond the
Standard $SU(3)_c$x$SU(2)_L$x$U(1)_Y$ Model
… dark energy is even more mysterious
(but still lacks compelling *dynamical* evidence)





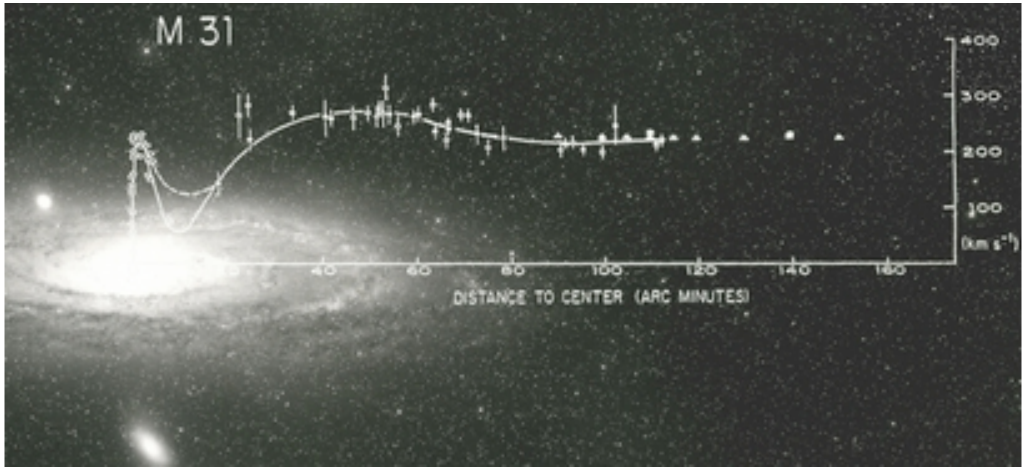
The modern saga of dark matter starts with the rotation curves of spiral galaxies



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

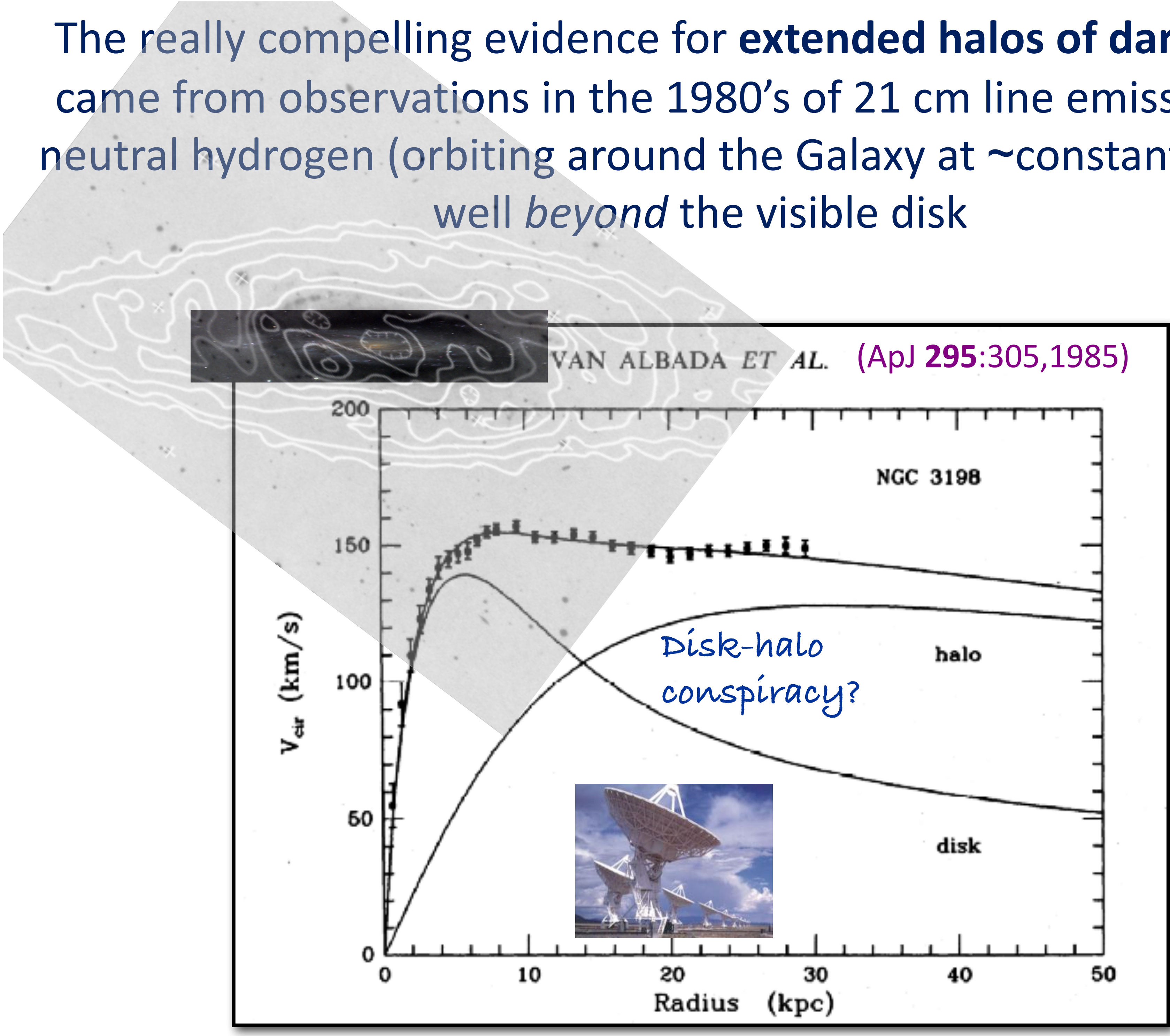
$$v_{\rm circ} = \sqrt{\frac{G_{\rm N} M(<r)}{r}}$$

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

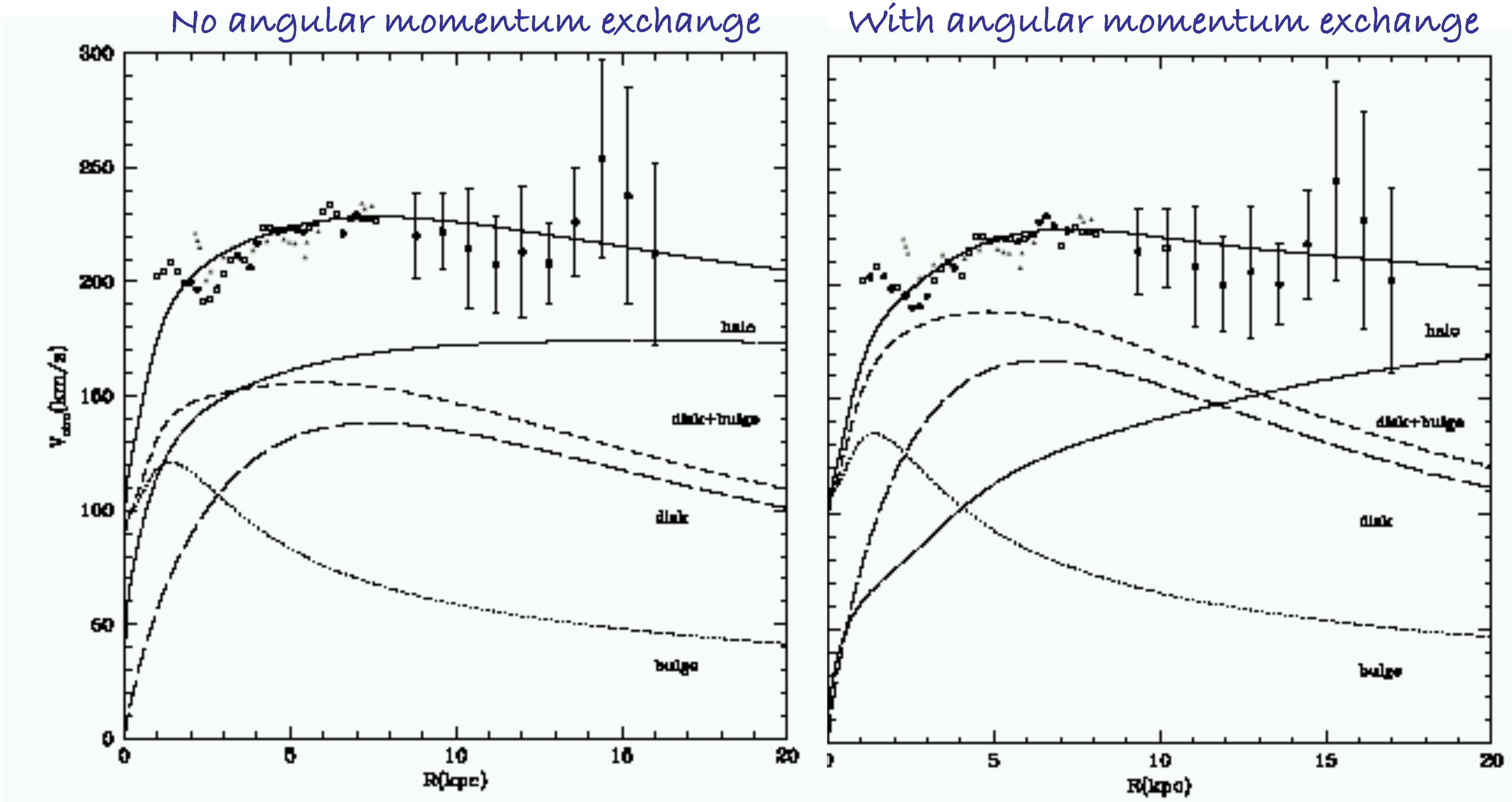


$$v_{\rm circ} \sim {\rm constant} \quad \Rightarrow \quad M(<r) \propto r \quad \Rightarrow \quad \rho \propto 1/r^2$$

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



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



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

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

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

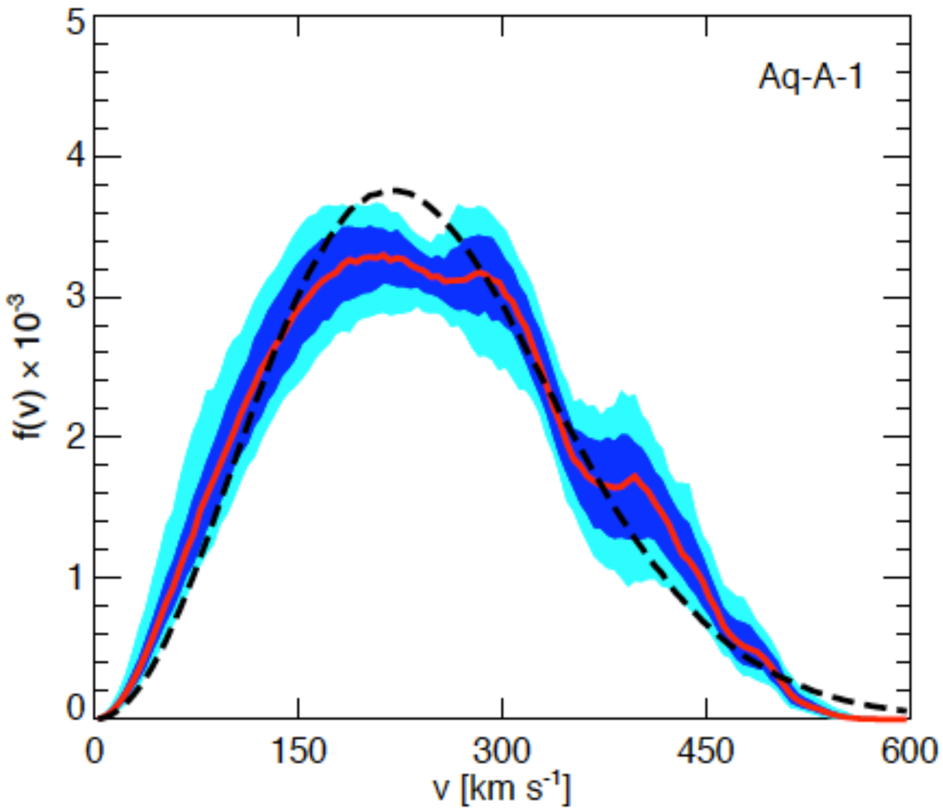
$$\frac{\partial f}{\partial t} + \mathbf{v}.\frac{\partial f}{\partial \mathbf{x}} - \frac{\partial \Phi}{\partial \mathbf{x}}\frac{\partial f}{\partial \mathbf{v}} = 0$$

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

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

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)

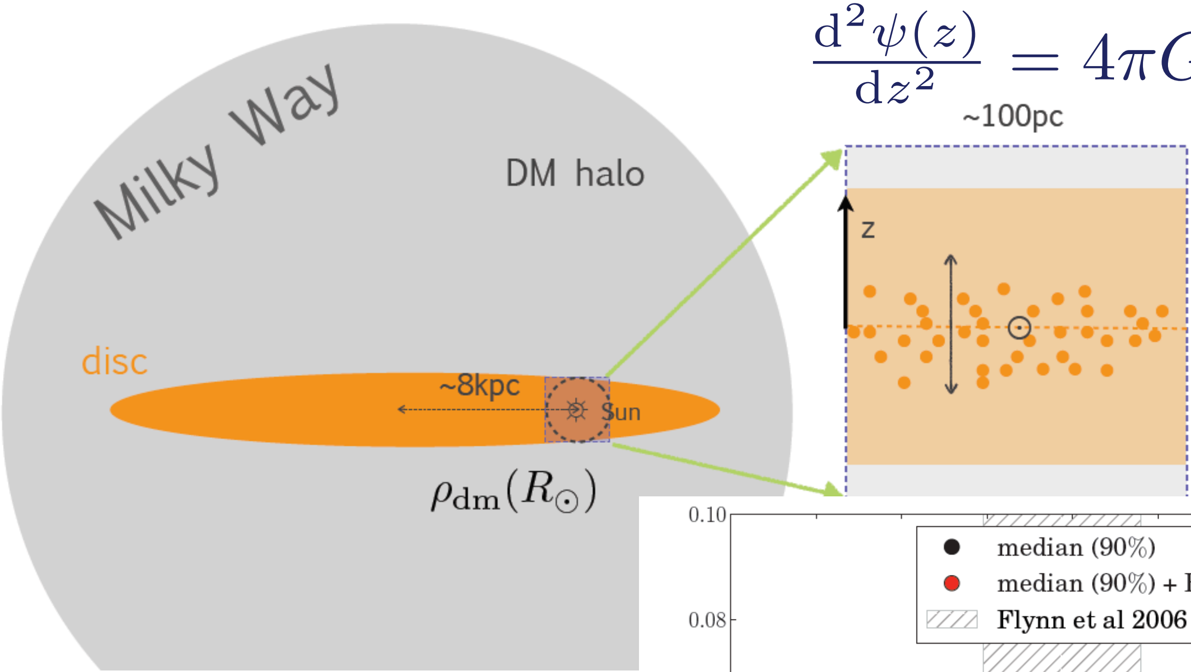


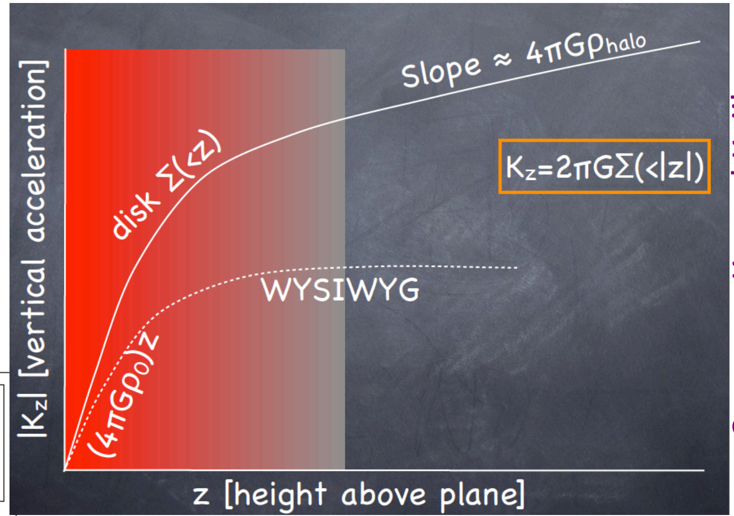
Vogelsberger *et al*, MNRAS **395**:797,2009

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:

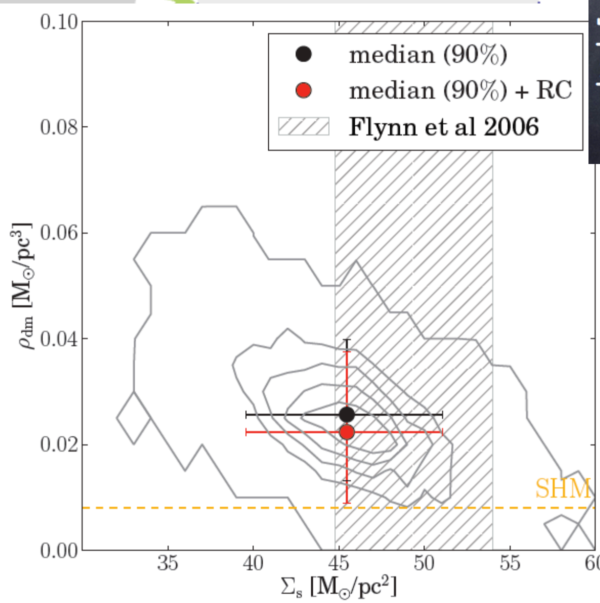
$$\frac{\mathrm{d}^2\psi(z)}{\mathrm{d}z^2} = 4\pi G_\mathrm{N}\rho_\mathrm{m} \rightarrow \frac{\mathrm{d}\psi(z)}{\mathrm{d}z} = 2\pi G_\mathrm{N}\Sigma_\mathrm{m}$$





Courtesy: Konrad Kuijken

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

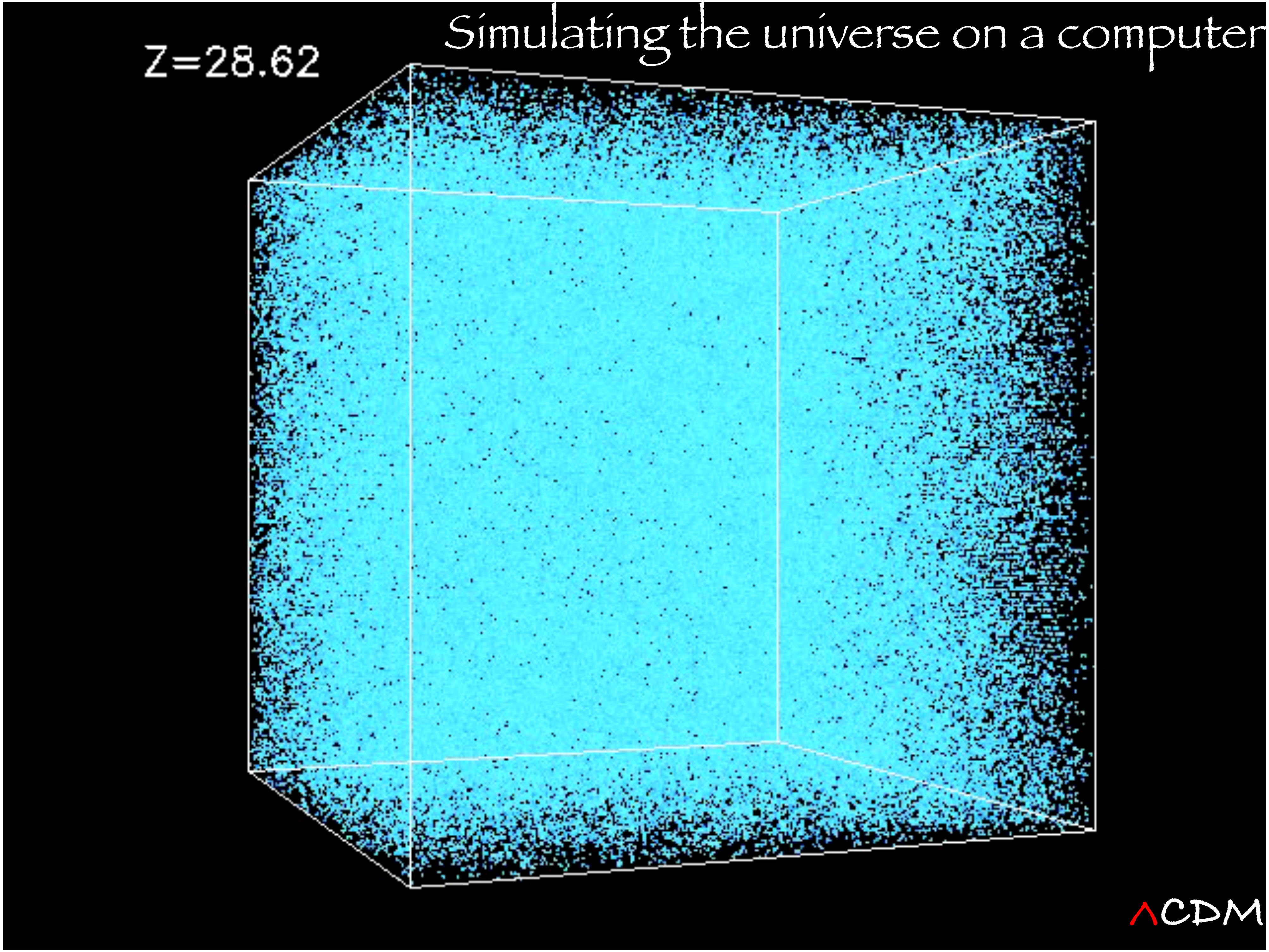


Using data on K-dwarfs (Kuijken & Gilmore, MNRAS **239**:605,1989) found:

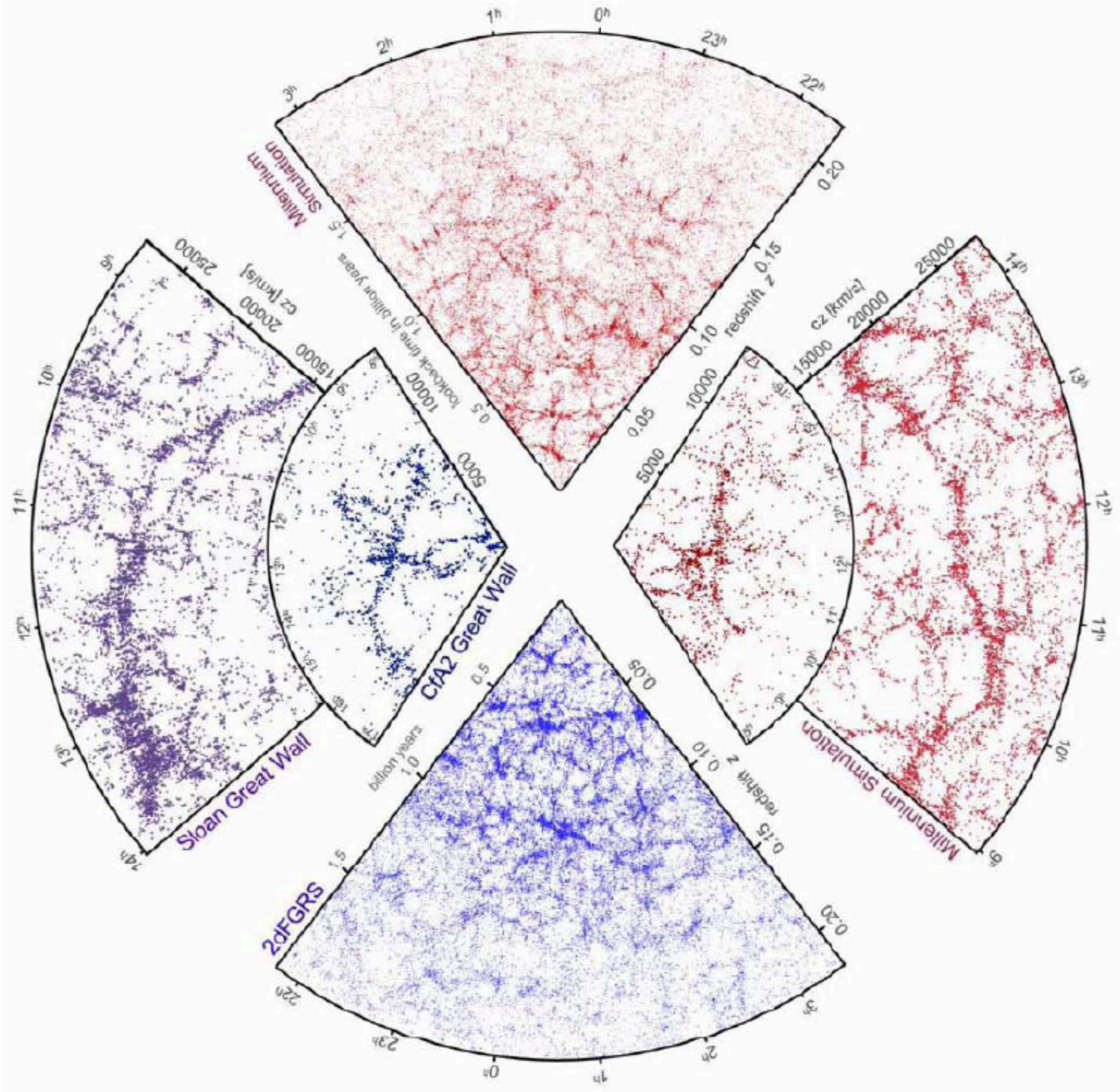
$$\rho_\mathrm{DM} = 0.85 \pm 0.6\ \mathrm{GeV/cm^3}$$

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

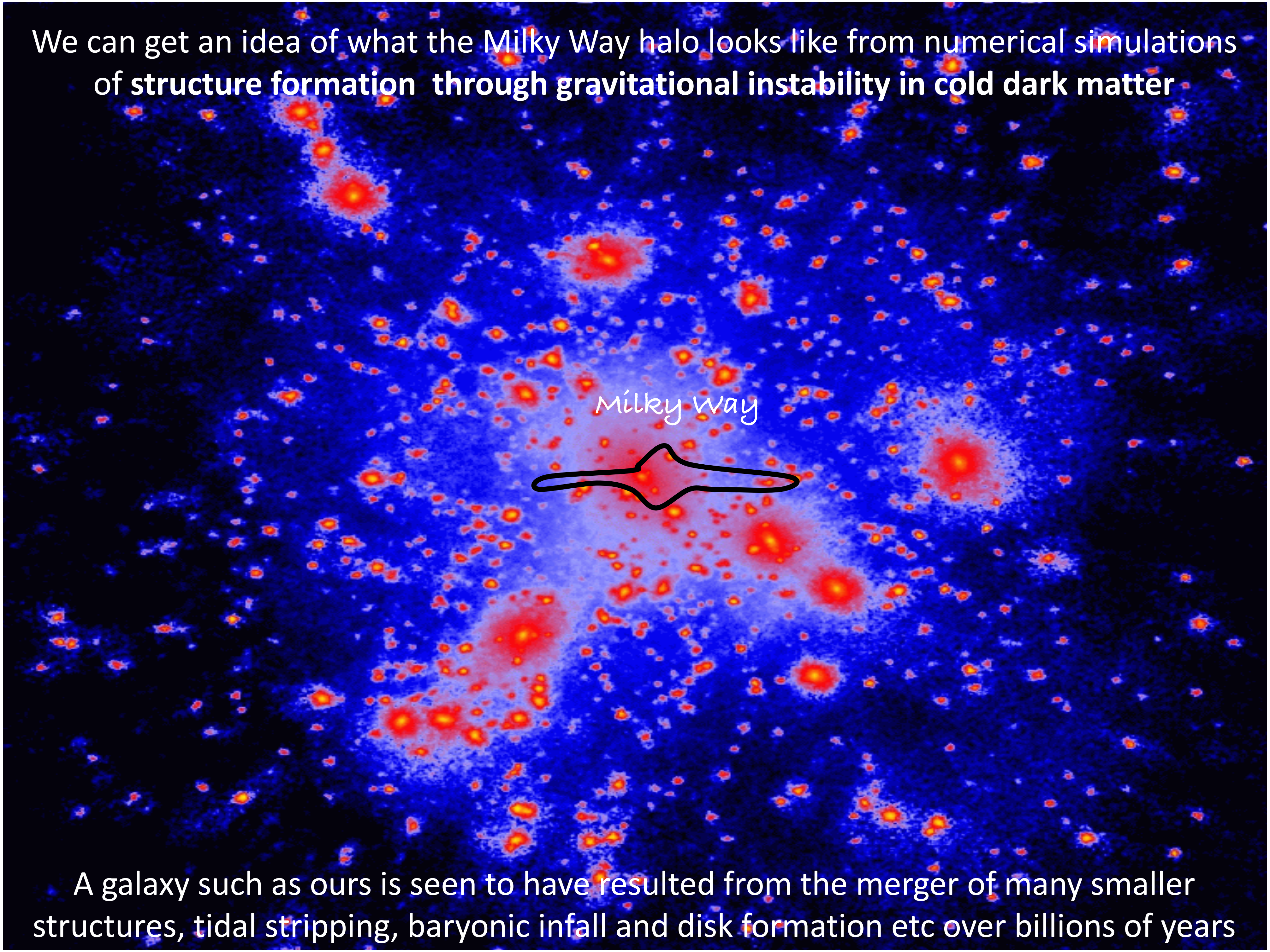
Simulating the universe on a computer



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

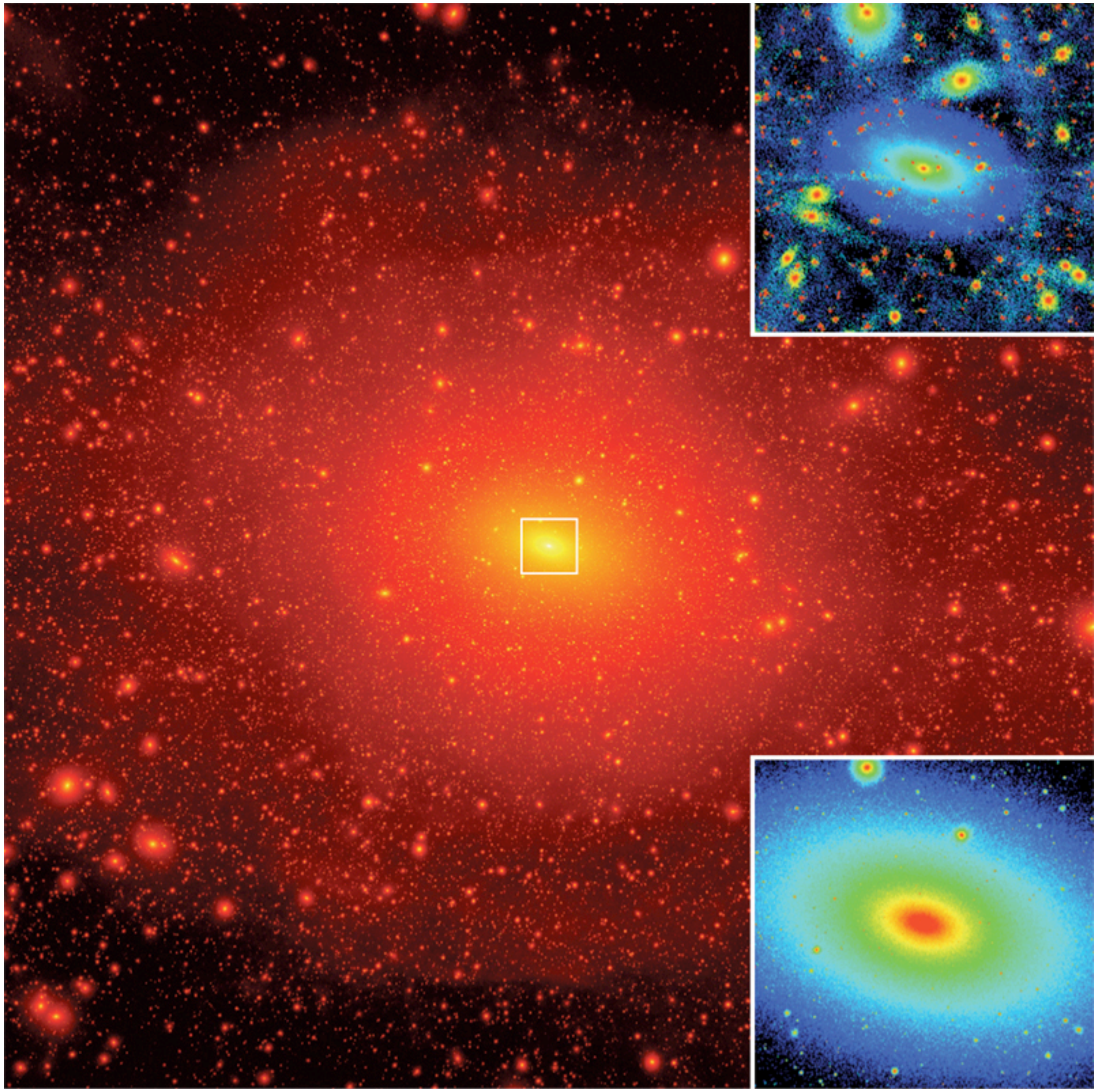


Springel, Frenk & White, Nature **440**:1137,2006


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 seen 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 [arXiv:0805.1244]

But real galaxies appear simpler than expected!

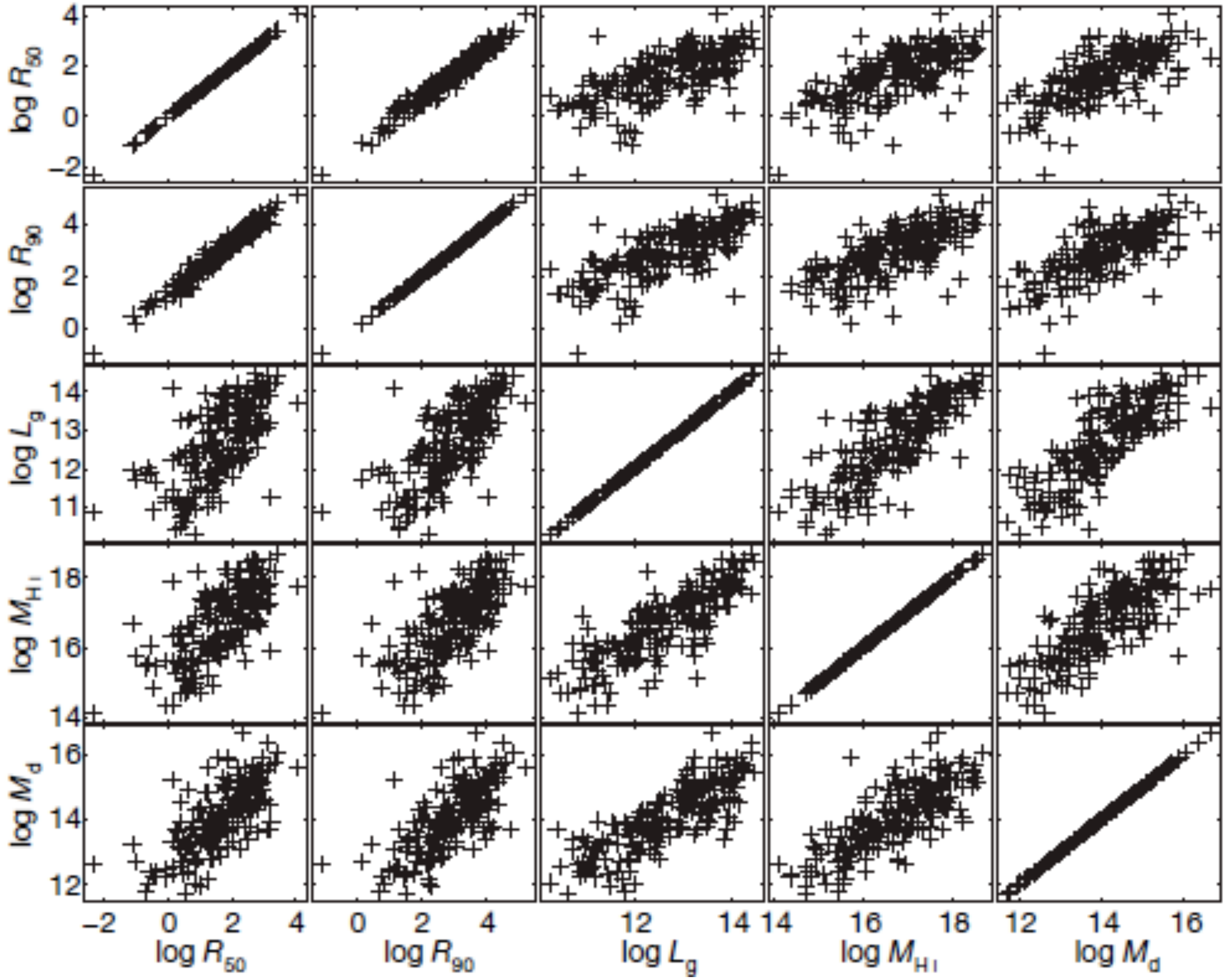
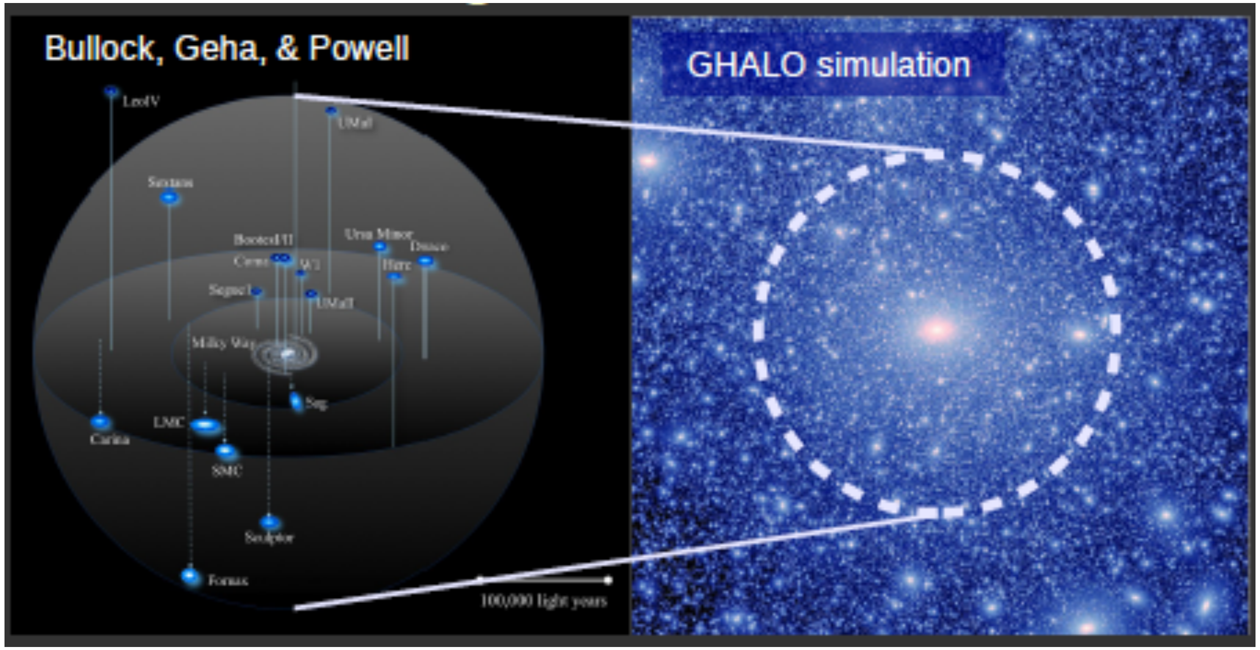
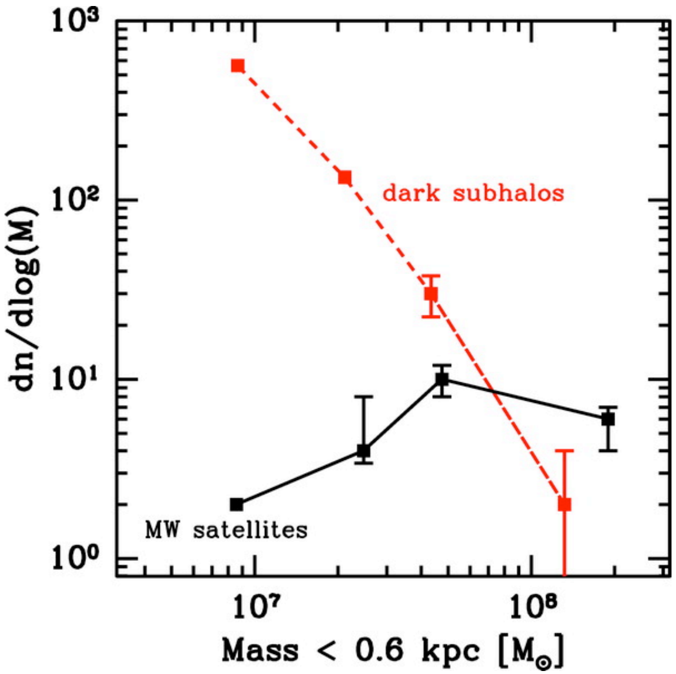


Figure 1 | Scatter plots showing correlations between five measured variables, not including colour. The variables are two optical radii, R_{50} and R_{90} (in parsecs), respectively containing 50 and 90% of the emitted light; and luminosity, L_g; neutral hydrogen mass, M_{HI}; and dynamical mass, M_d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

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

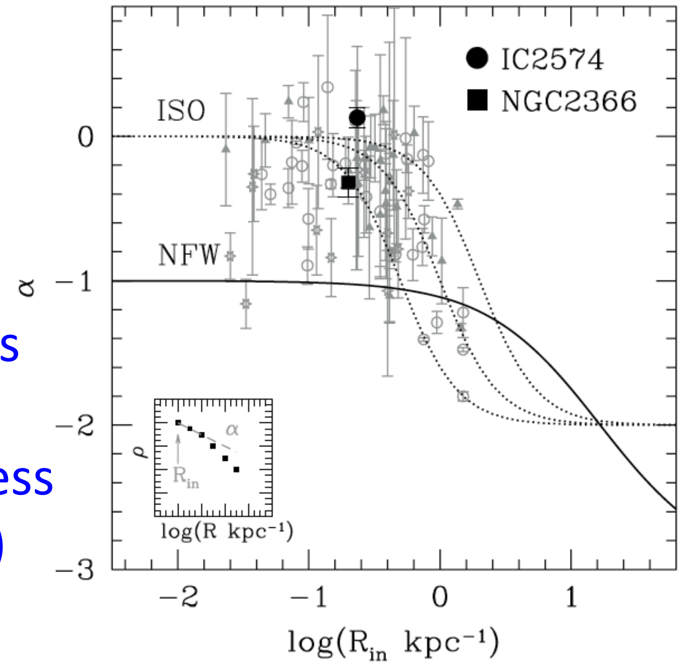
Moreover whereas the Milky Way does have satellite galaxies & substructure, there is a lot less than is expected from the numerical simulations





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



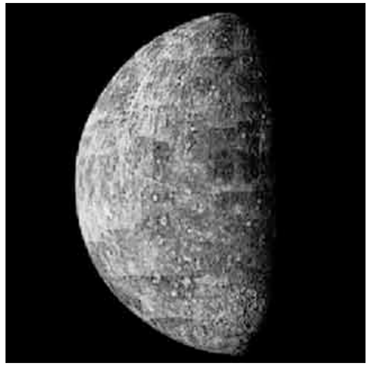
Oh *et al*, AJ **136**:2761,2008

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)

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).

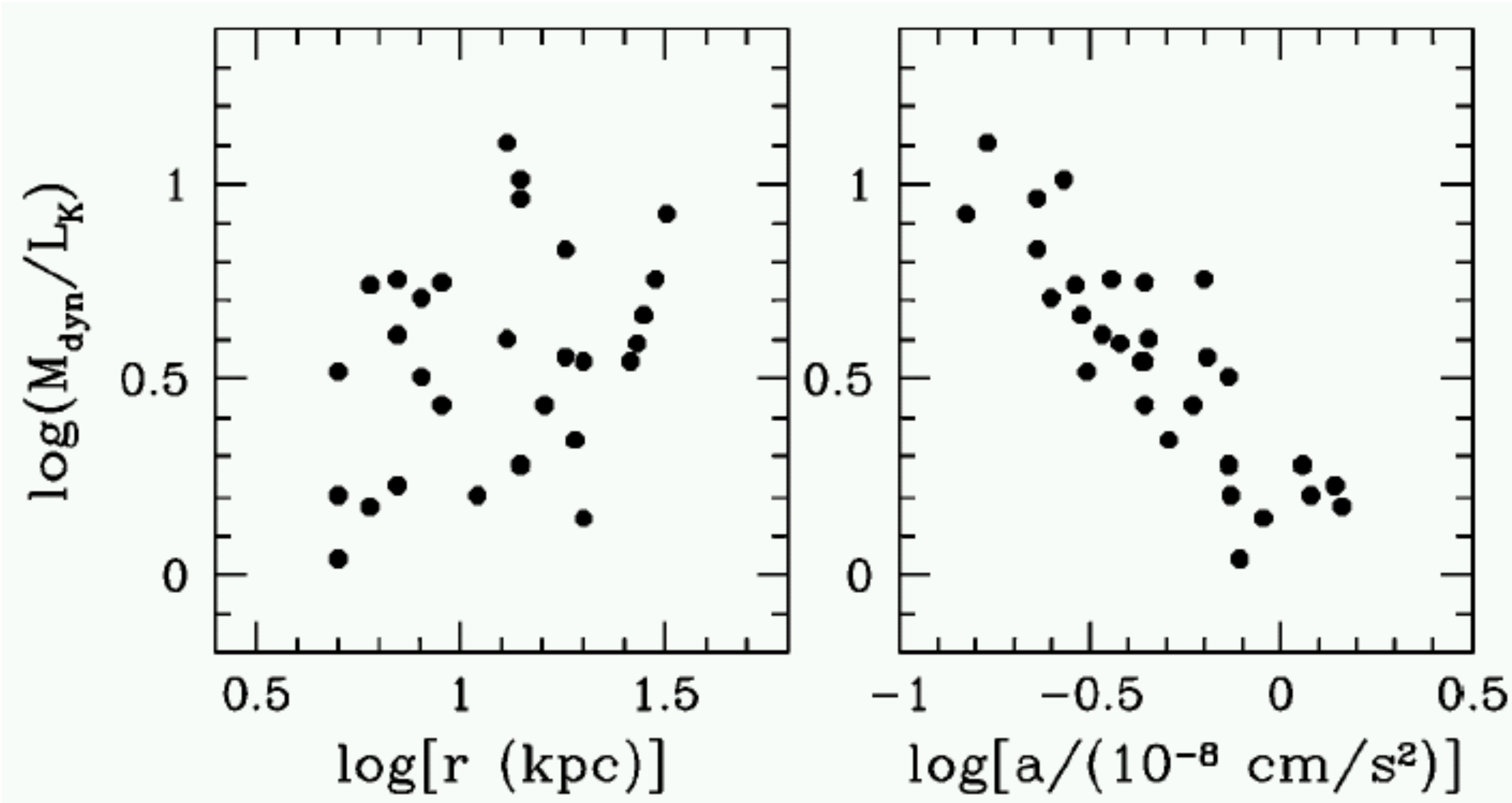
Some astronomers even see Vulcan in the evening sky!



But the precession of Mercury is not due to a dark planet **…**

but because Newton is superseded by Einstein

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



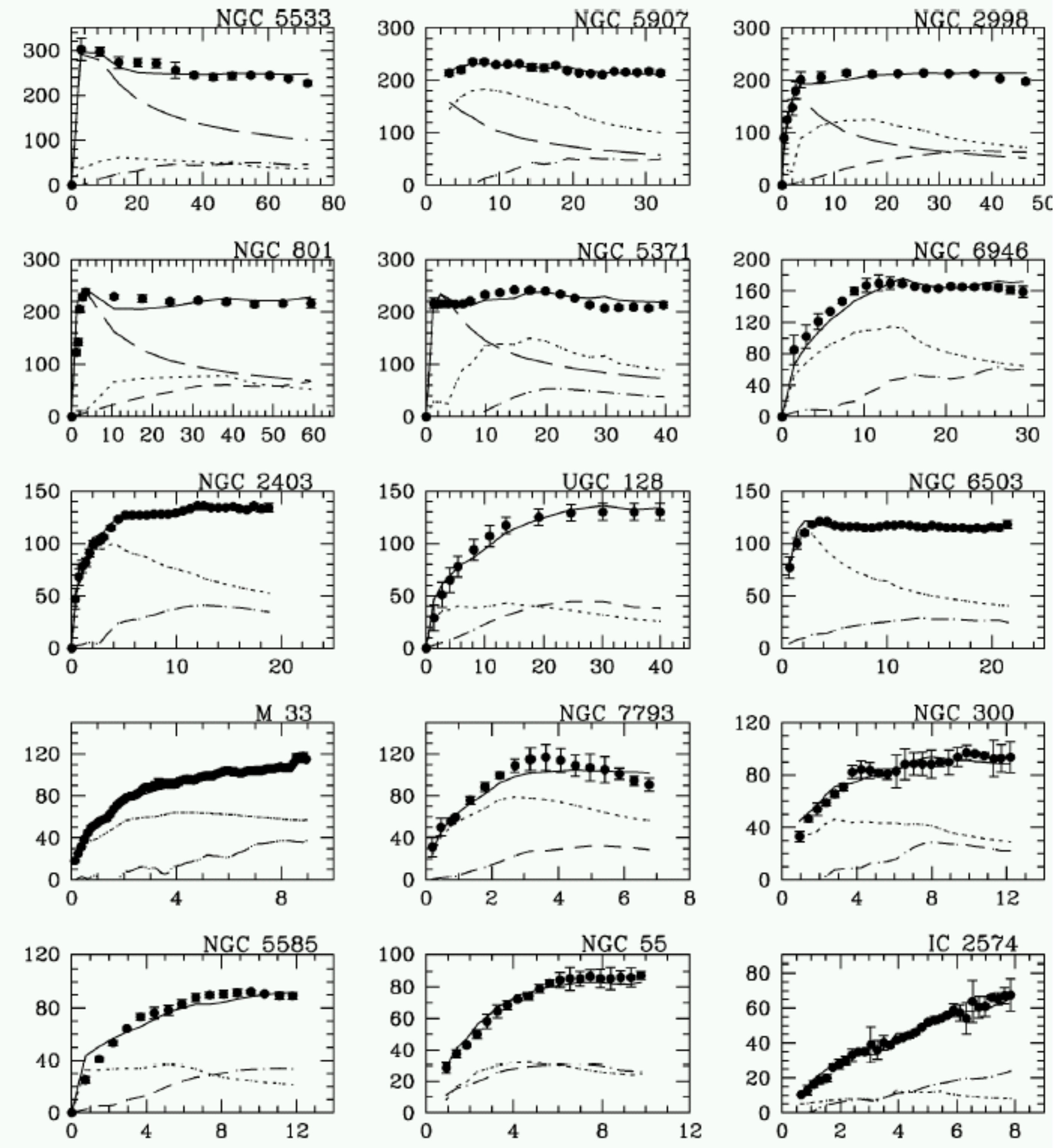
What if Newton's law is modified in weak fields?

$$F_{\rm N} \rightarrow \sqrt{\frac{GM}{r^2}a_0}$$

Milgrom, ApJ 270:365,1983

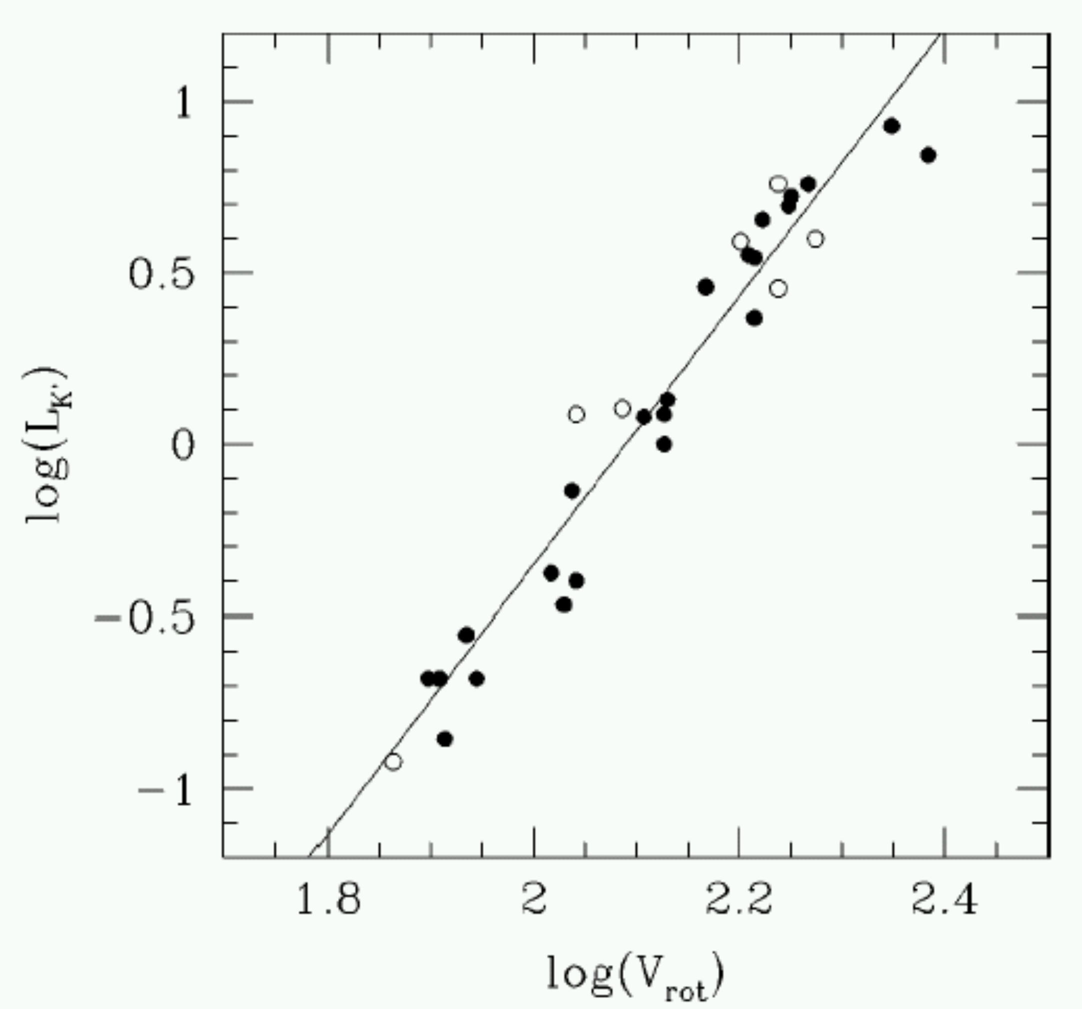
A huge variety of rotation curves is well fitted by MOND

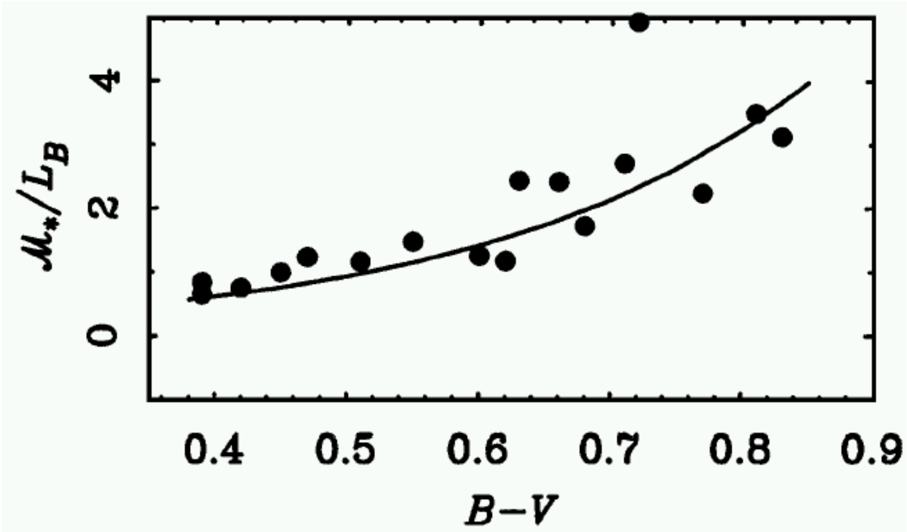
… with fewer parameters than is required by the dark matter model



Sanders & Verheijen [astro-ph/9802240]

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



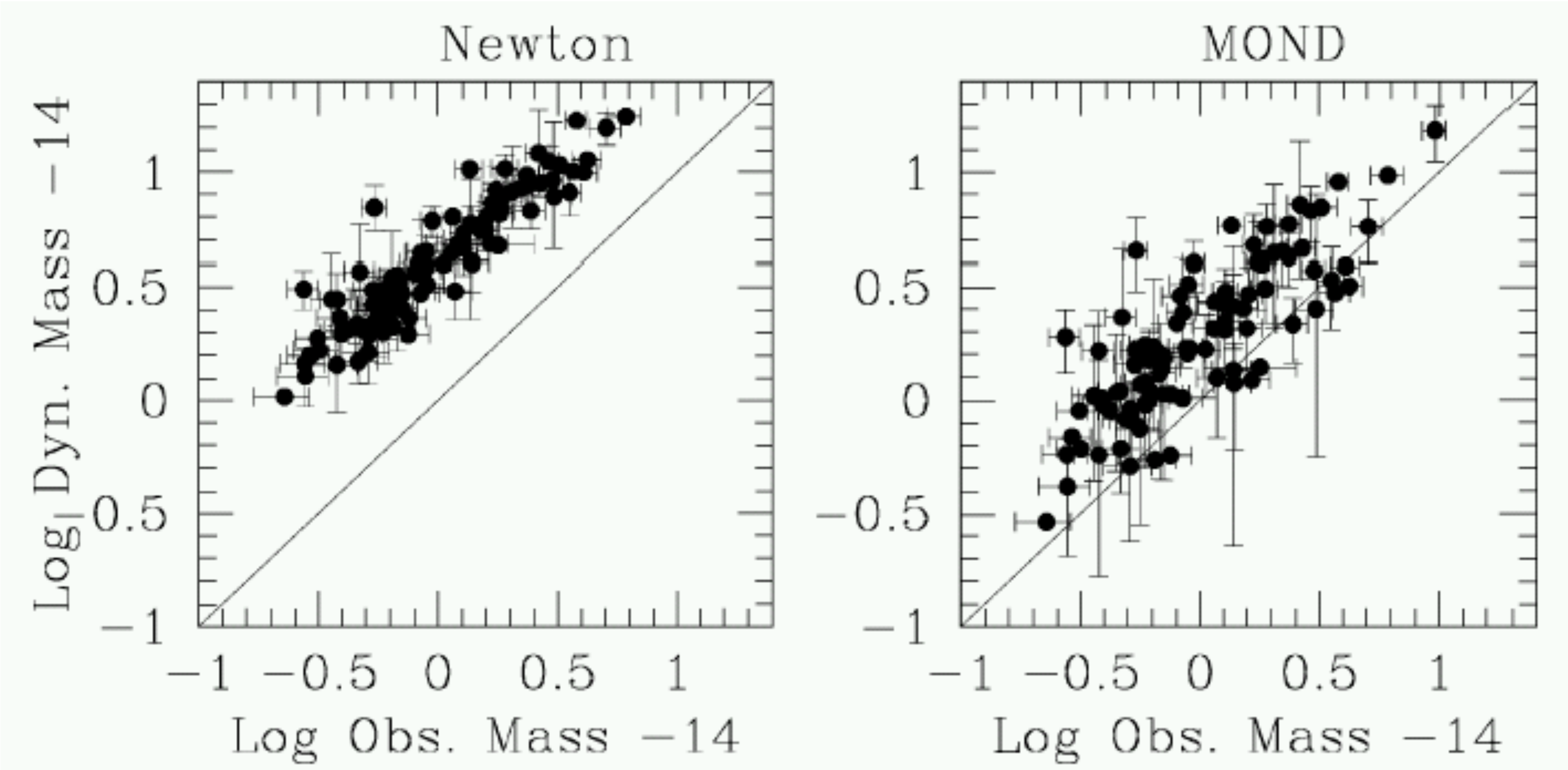


… the fitted value of the only free parameter (M/L) agrees very well with population synthesis models

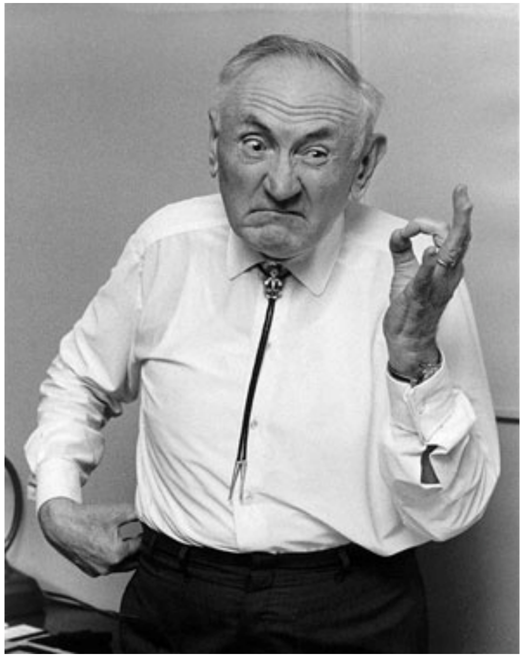
Sanders & Verheijen [astro-ph/9802240]

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

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)



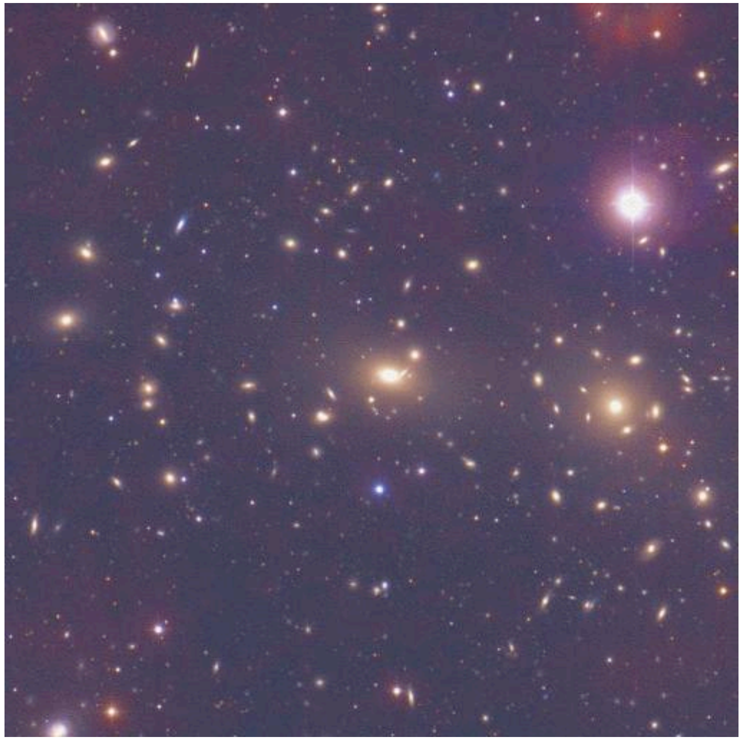
Fritz Zwicky (1933) measured the velocity dispersion in the Coma cluster to be as high as 1000 km/s $\Rightarrow M/L \sim O(100)\ M_\odot/L_\odot$

"… 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"

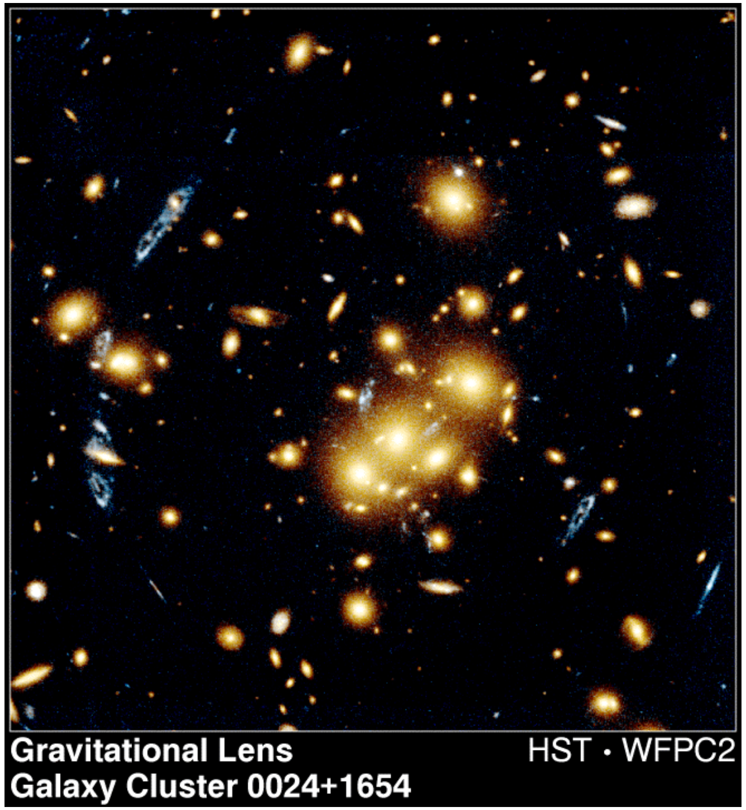
Virial Theorem: $\langle V \rangle + 2\langle K \rangle = 0$

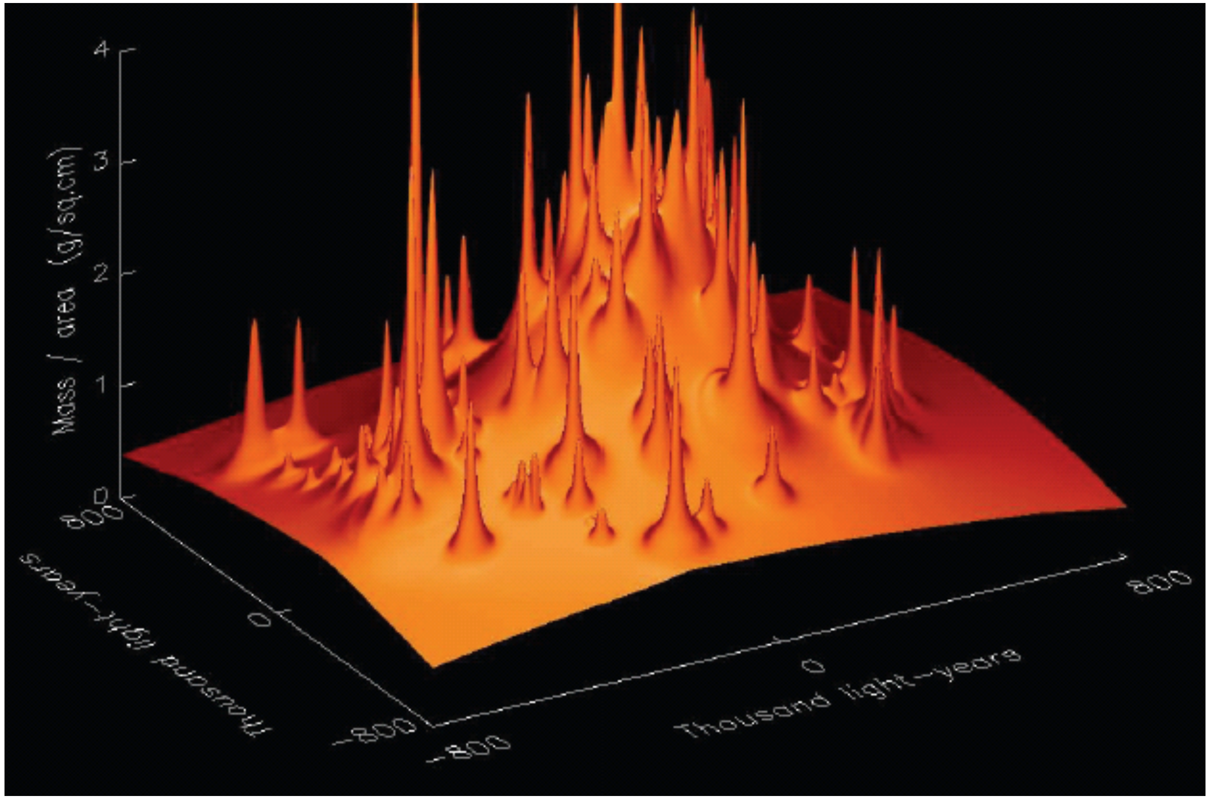
$$V = -\frac{N^2}{2} G_\mathrm{N} \frac{\langle m^2 \rangle}{\langle r \rangle}, \quad K = N \frac{\langle m v^2 \rangle}{2}$$

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



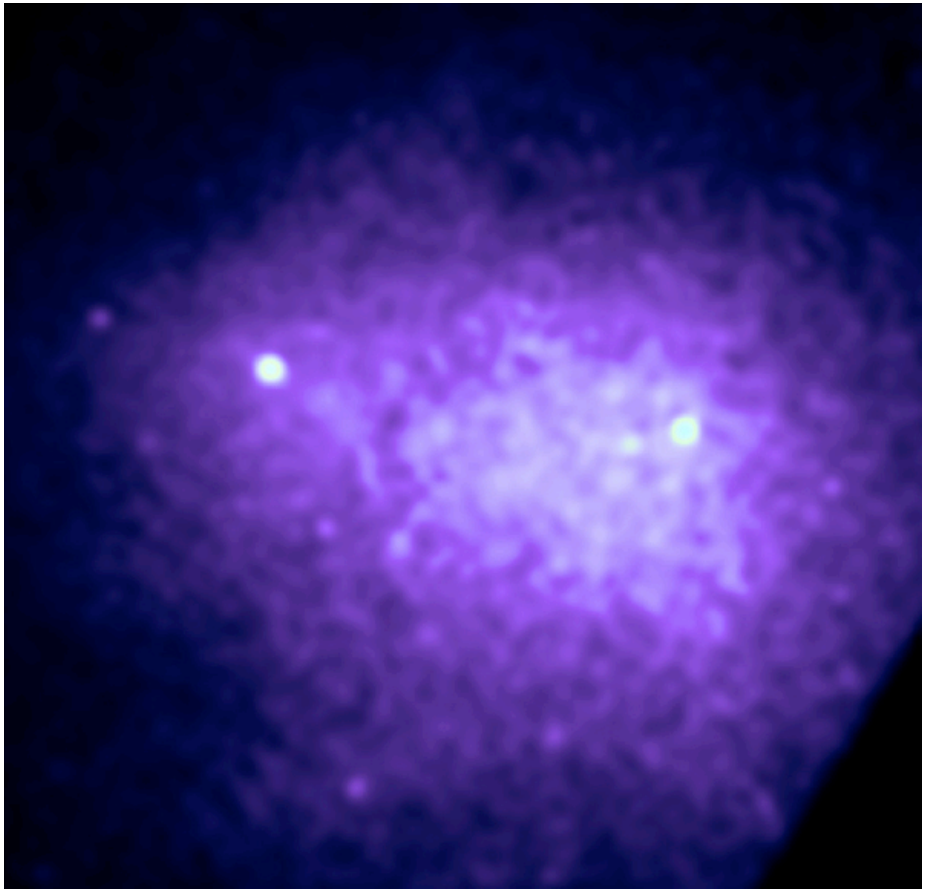
Further evidence comes from observations of **gravitational lensing** of distant sources by a foreground cluster … enabling the potential to be reconstructed





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

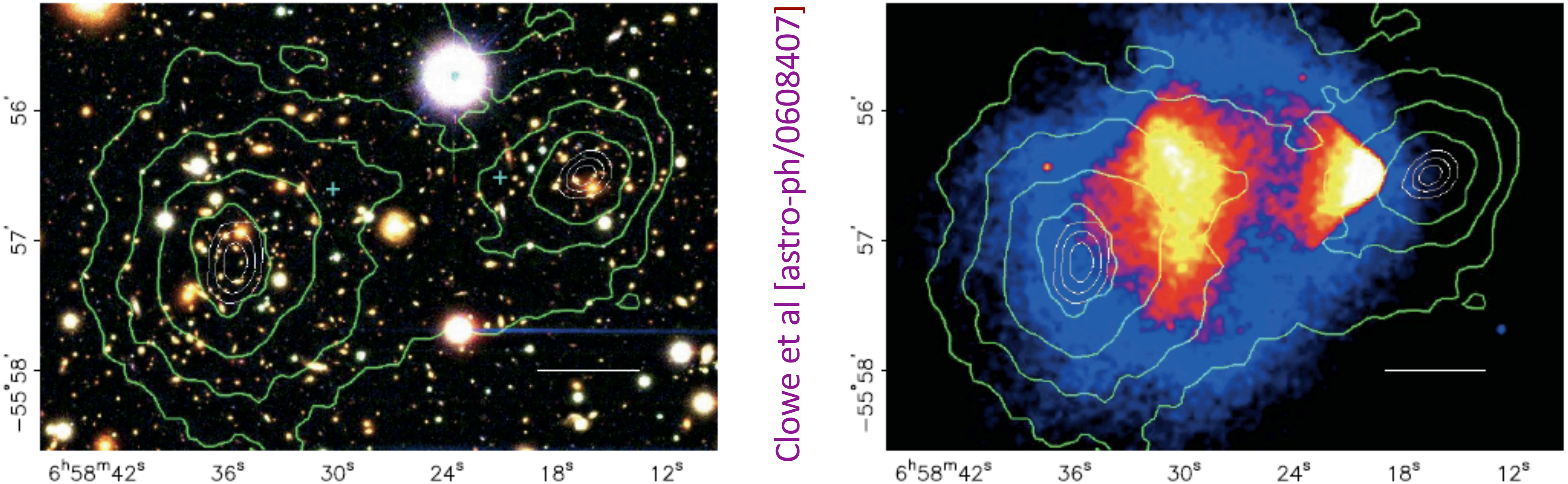


… assuming it is in thermal equilibrium:

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

The Chandra picture of the ‘bullet cluster’ 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



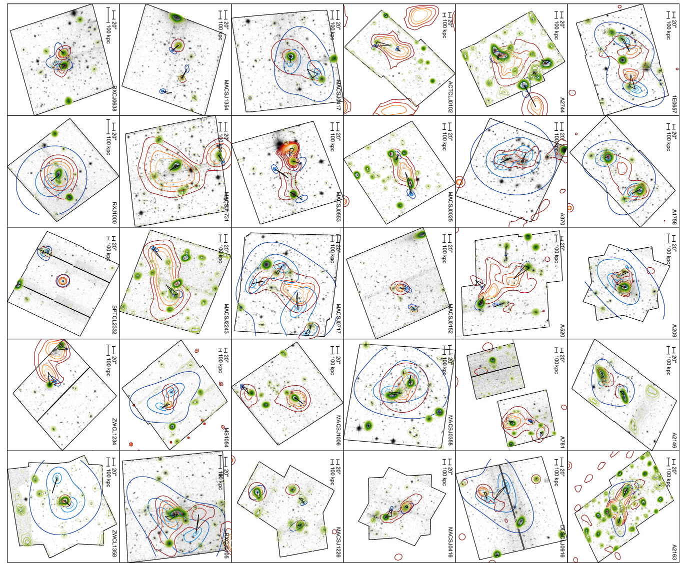
Clowe et al [astro-ph/0608407]

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.

In principle however the alternative theory of gravity which underlies MOND may predict a different deflection of light - so the (self-consistent) reconstructed gravitational potential may be different

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

Colliding clusters



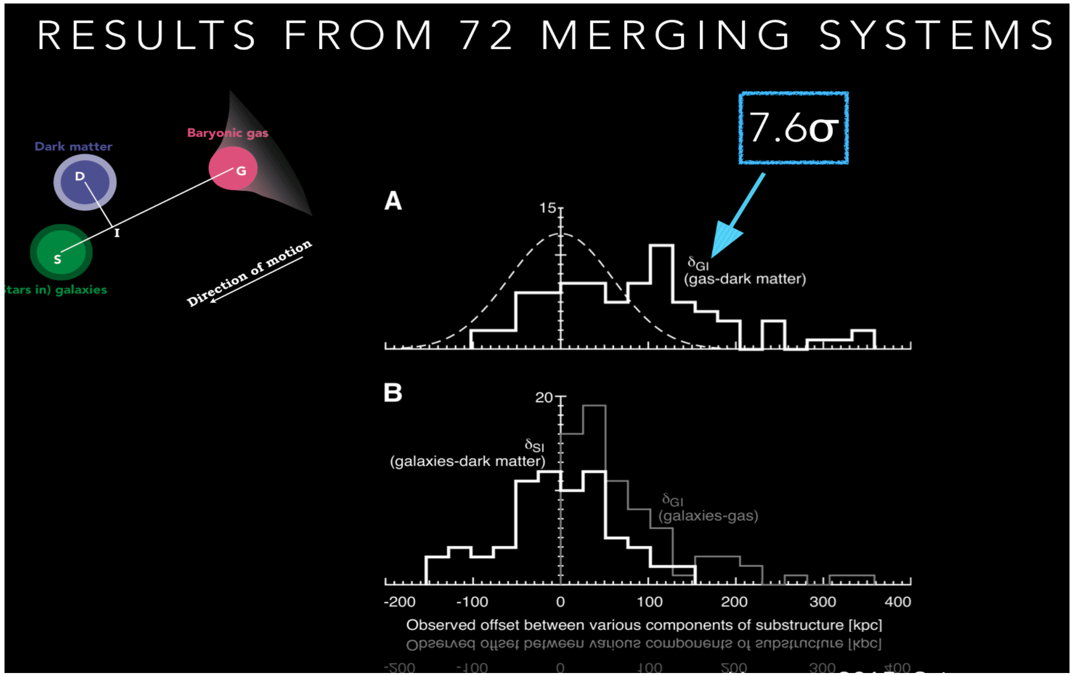
http://www.mergingclustercollaboration.org/

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:

$$\sigma/m_\chi < 0.5 \ \mathrm{cm}^2/\mathrm{g}$$

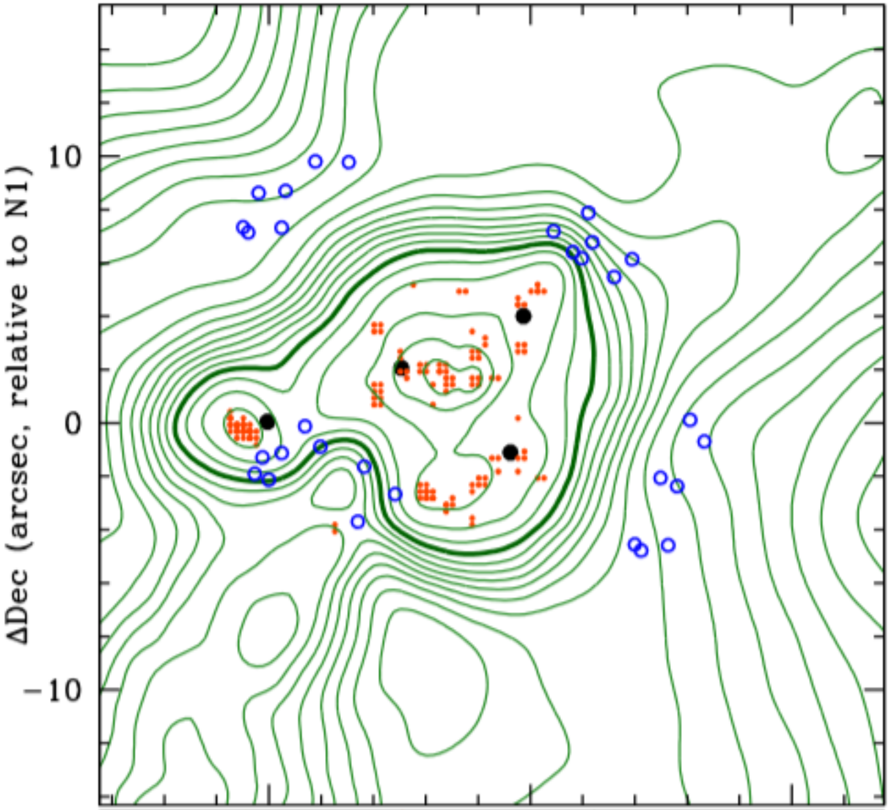
Massey *et al*, 1007.1924; Harvey *et al*, 1305.2117, 1310.1731, 1503.07675



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

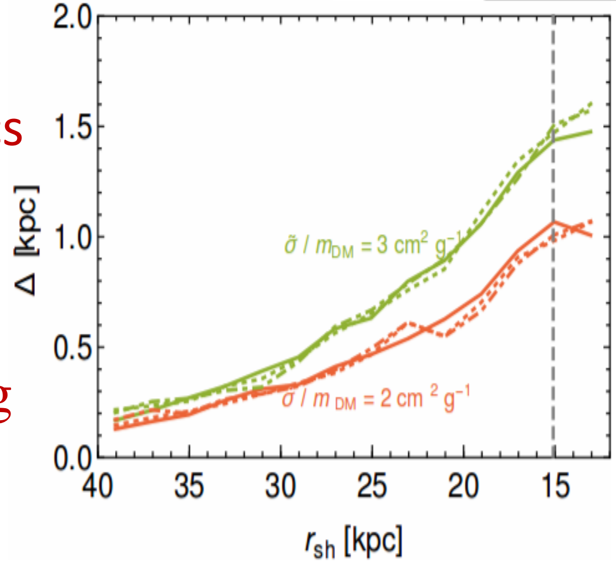
"The best-constrained offset is 1.62 ± 0.48 kpc, where the 68% confidence limit includes both statistical error and systematic biases in mass modelling. [...] With such a small physical separation, it is difficult to definitively rule out astrophysical effects operating exclusively in dense cluster core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

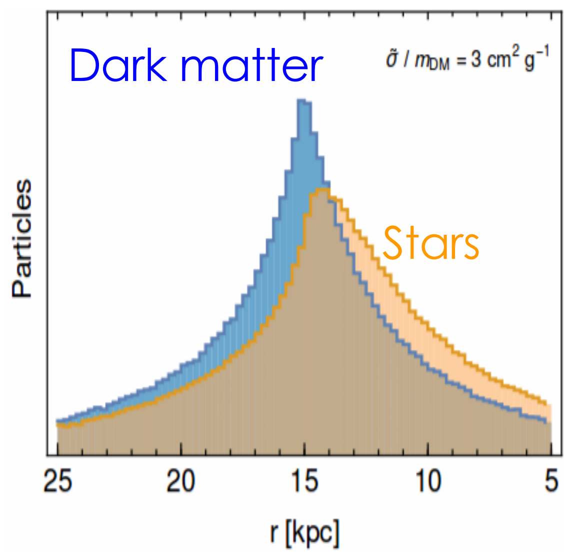
Massey *et al.*,1504.03388



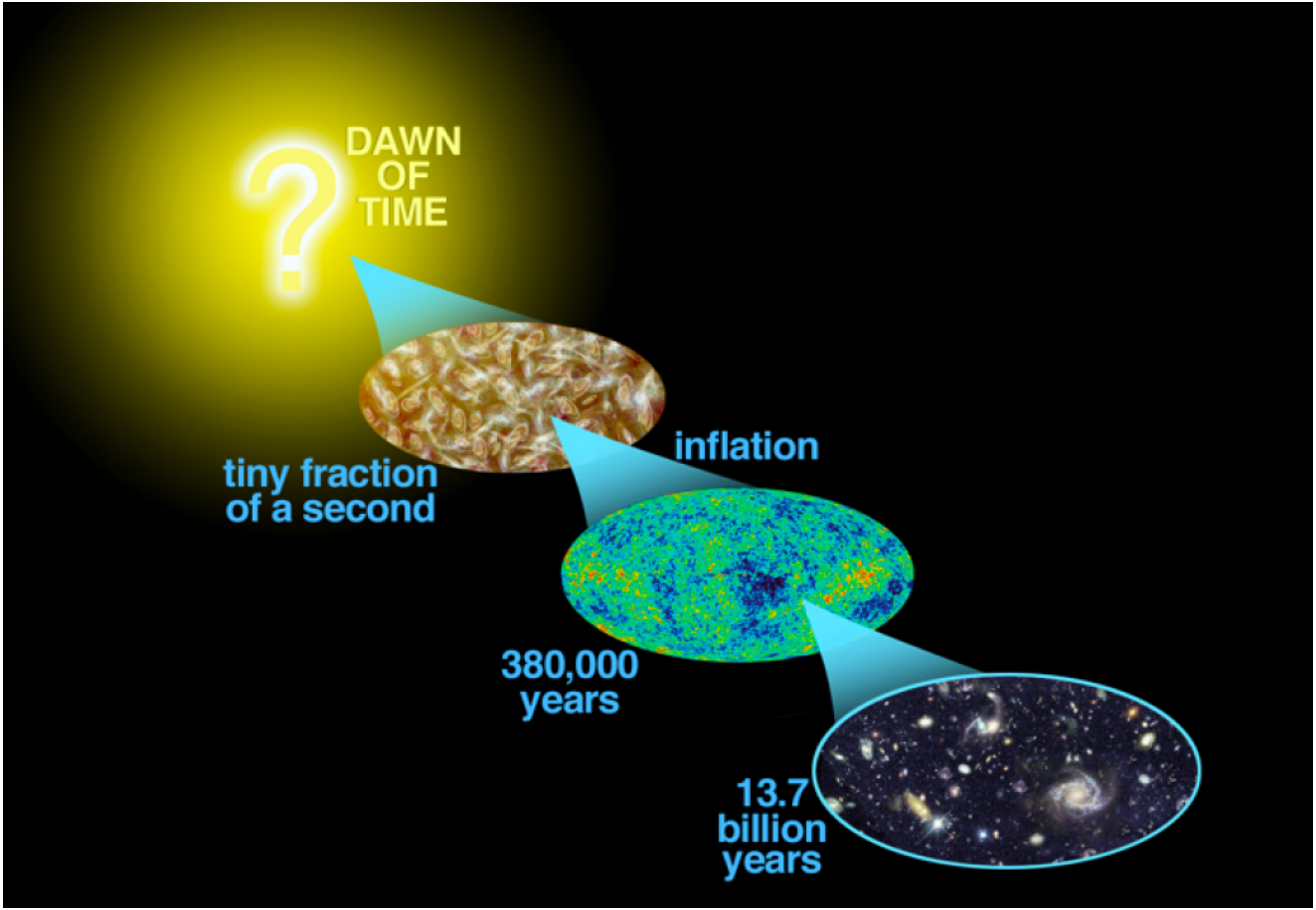
However this is corrected to $\sigma/m \sim 3\ \mathrm{cm}^2/\mathrm{g}$, taking dynamics into account (for long range interactions), whereas for rare contact interactions the required #-secn. is $\sim 1.5\ \mathrm{cm}^2/\mathrm{g}$ i.e. testable in other clusters!

(Kahloefer *et al*, 1504.06576)

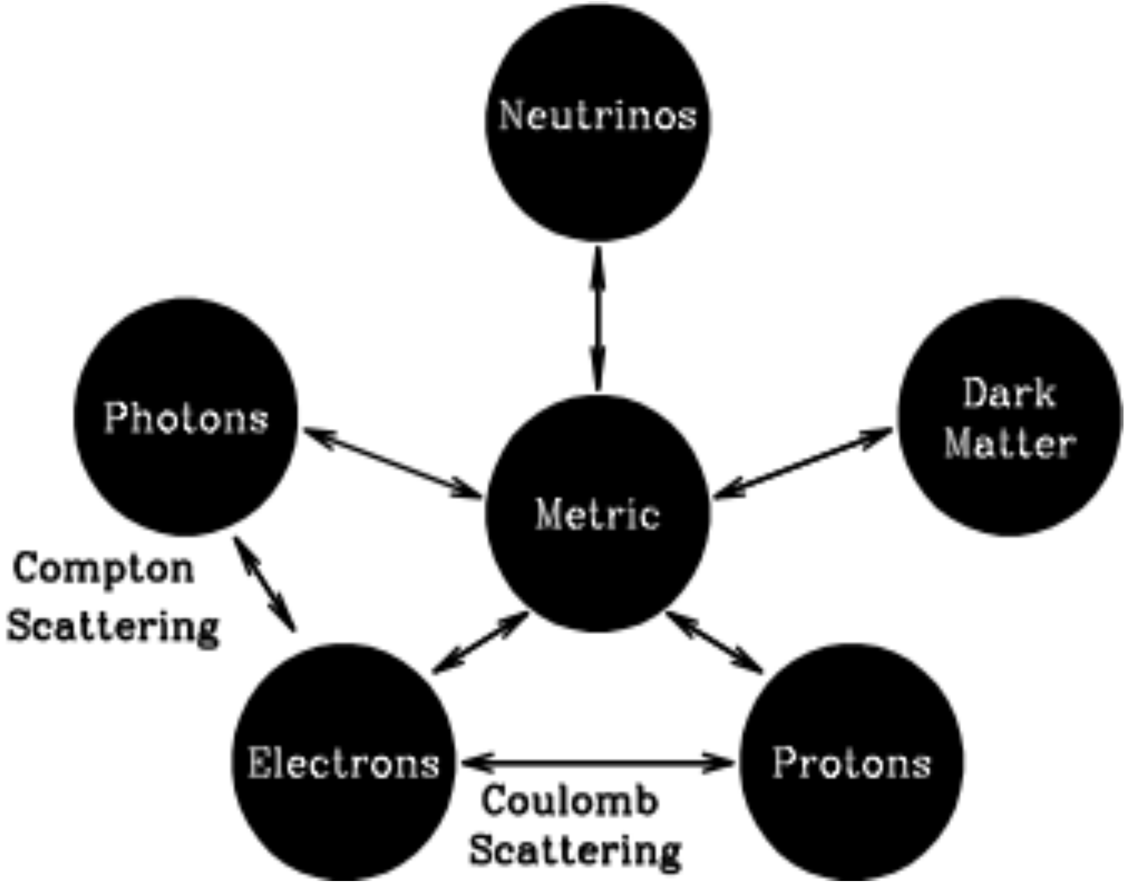




Another argument for dark matter comes from considerations of structure formation

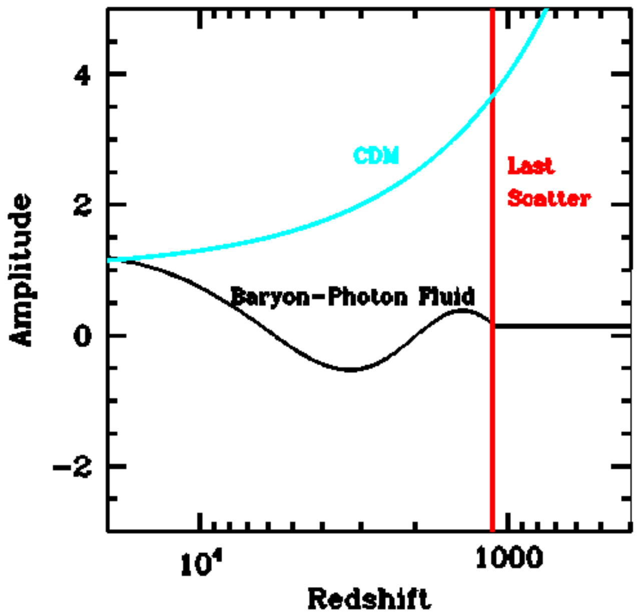


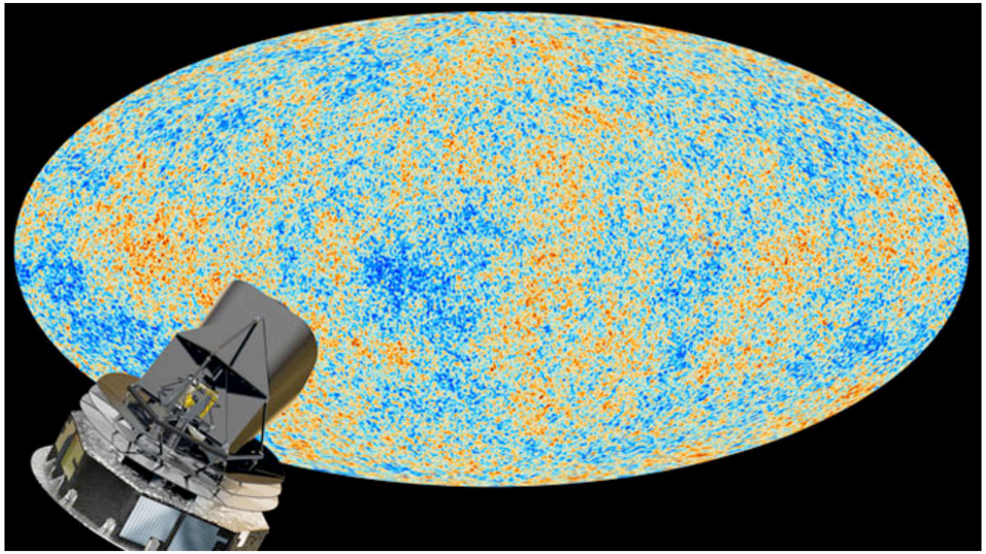
Perturbations in metric (generated during inflation) induce perturbations in photons and (dark) matter



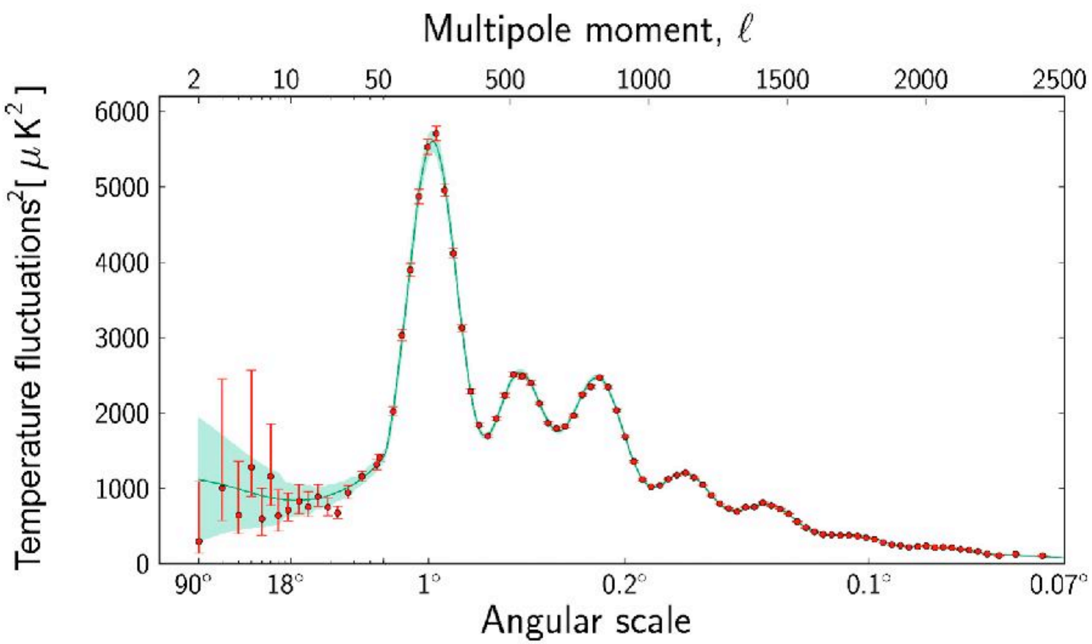
These perturbations begin to grow through gravitational instability after matter domination

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



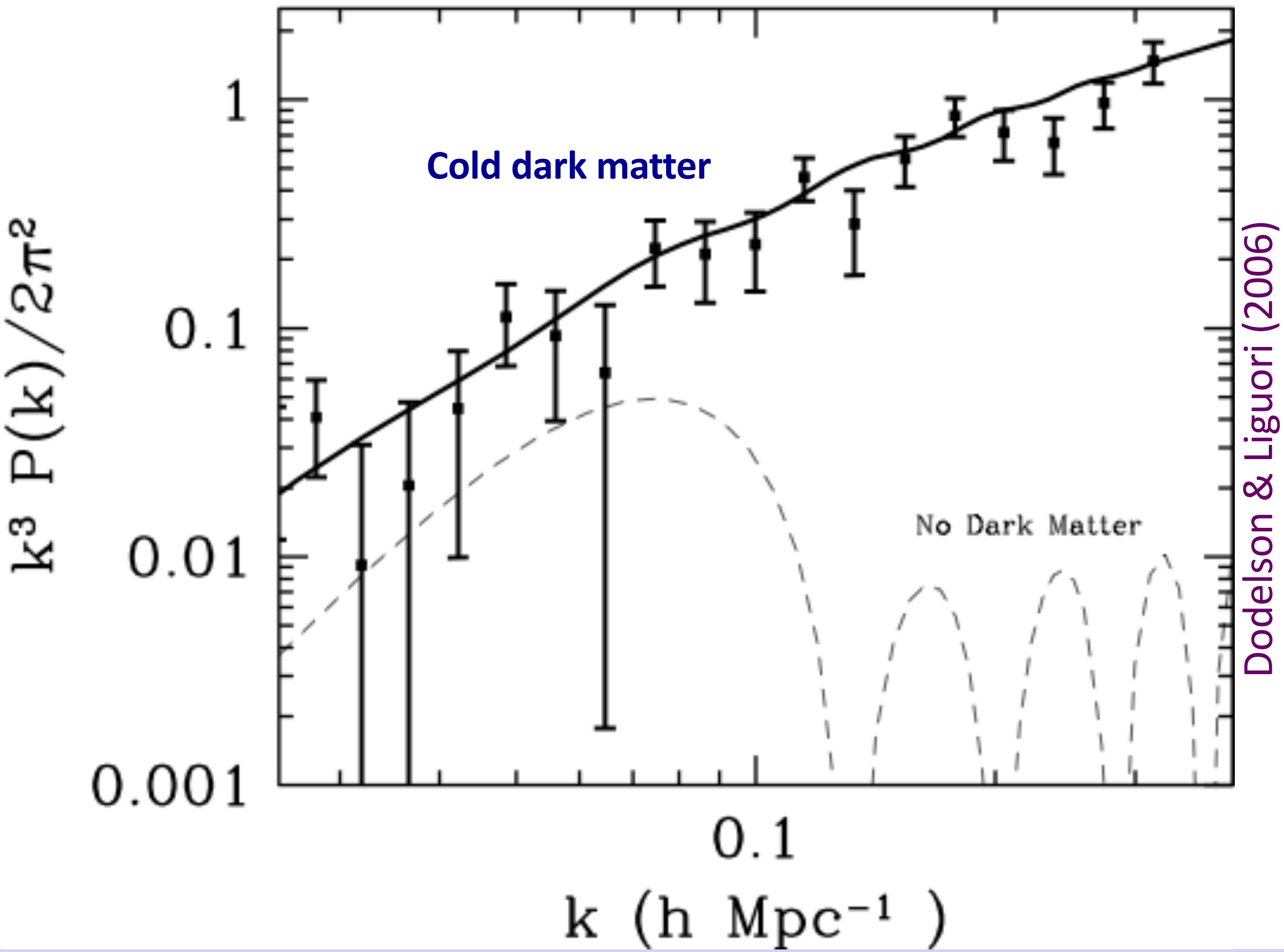


These sound waves leave an imprint on the last scattering surface as the universe turns neutral and transparent … sensitive to the baryon/CDM densities



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* $\Omega_m >> \Omega_B$ 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 (e.g. TeVeS) can fit the data so well

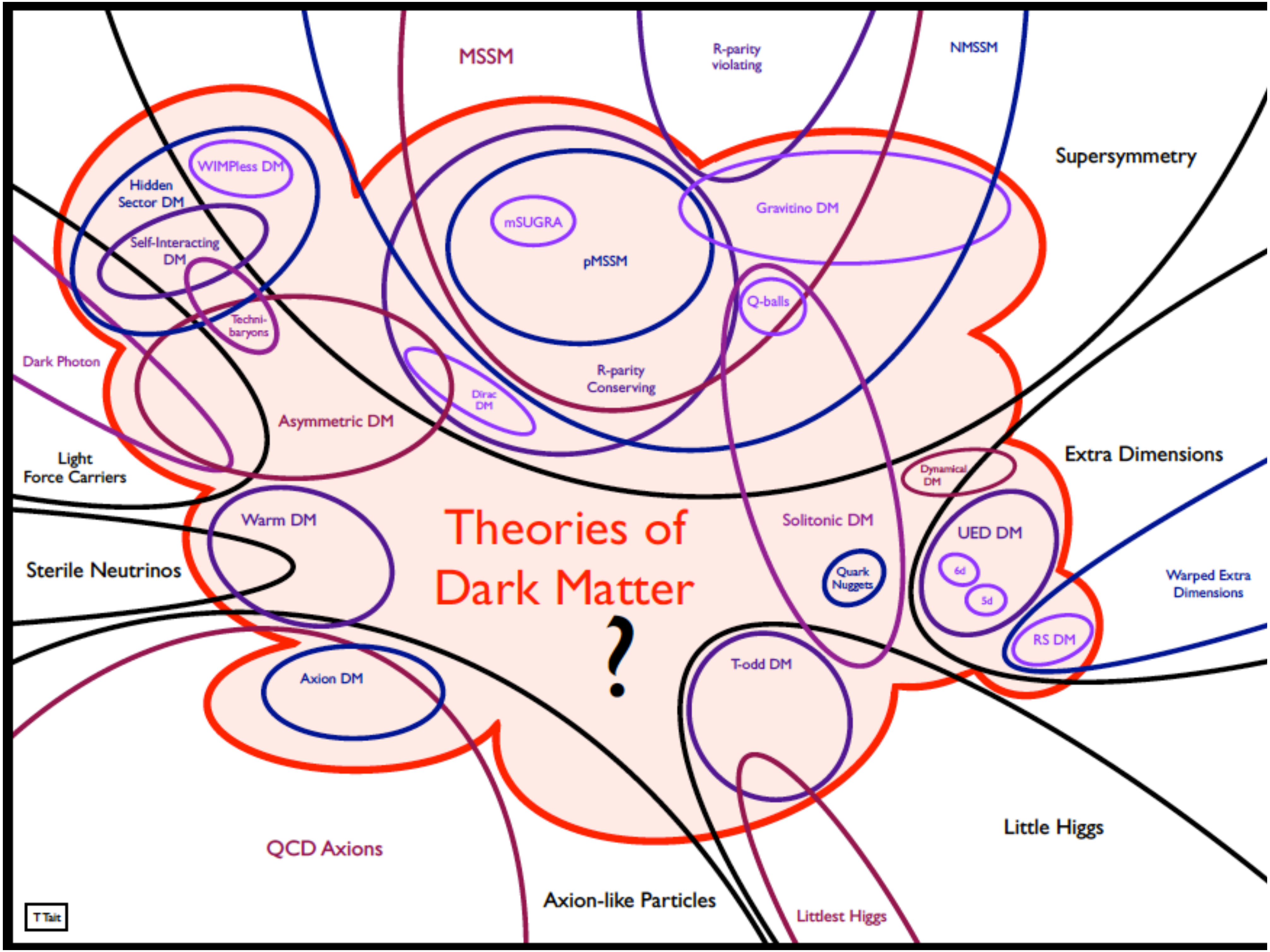
Does dark matter exist?

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: $L \sim v_{\rm rot}^4$ ("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 cluster 1E 0657-558

Also MOND is *not* a physical theory – relativistic covariant theories that yield MOND do exist (e.g. 'TeVeS' by Bekenstein) they have not provided 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 identified in the lab!

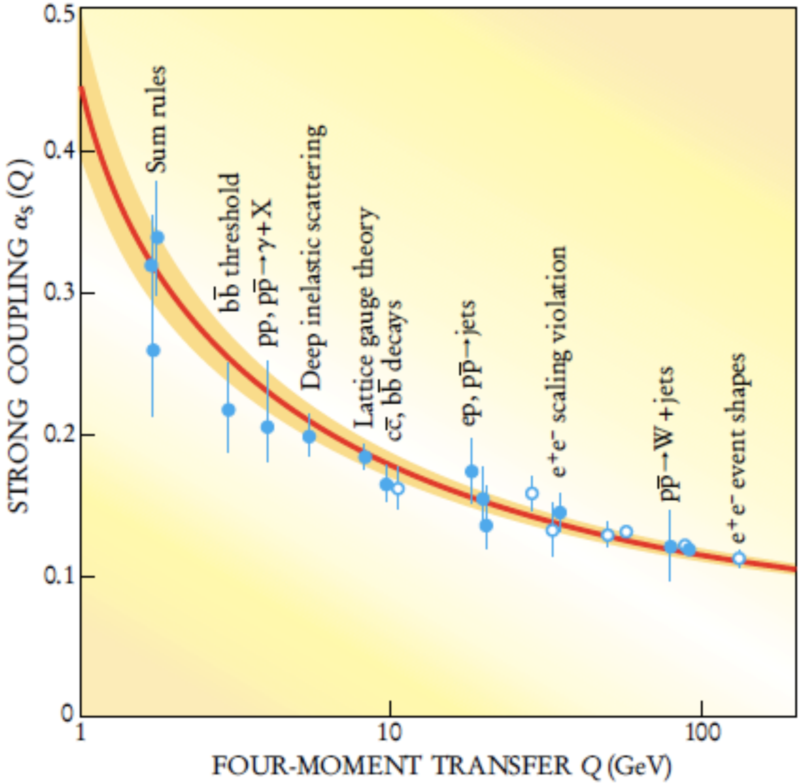


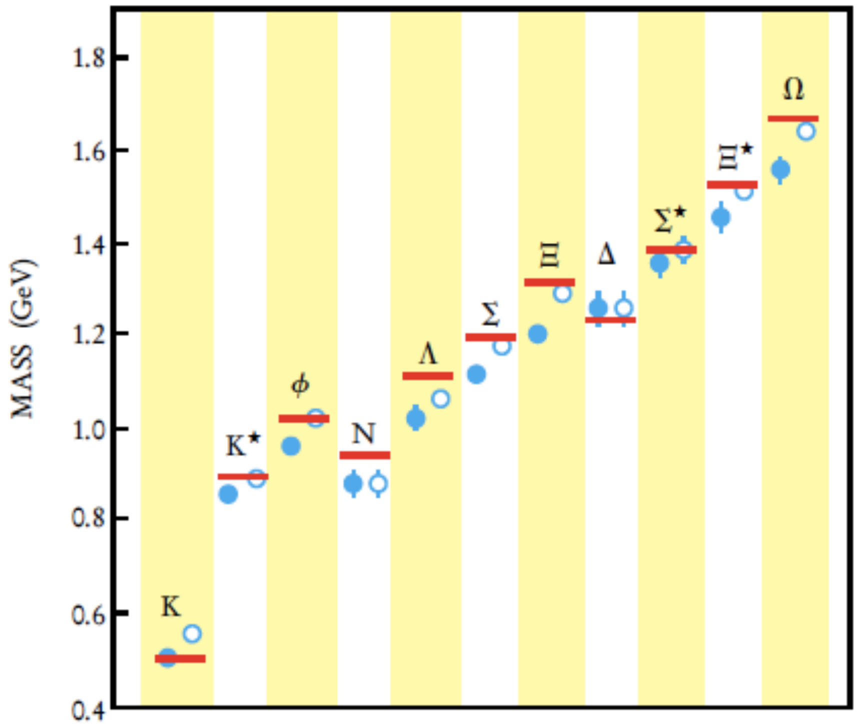
MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-baryons
Dark Photon
Dirac DM
R-parity Conserving
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Theories of Dark Matter
?
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

What *should* the world be made of?

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
Λ_{QCD}	Nucleons	Baryon number	$\tau > 10^{33}$ yr (dim-6 OK)	'freeze-out' from thermal equilibrium	$\Omega_B \sim 10^{-10}$ *cf.* observed $\Omega_B \sim 0.05$

We have a good theory for why baryons are massive and (cosmologically) stable





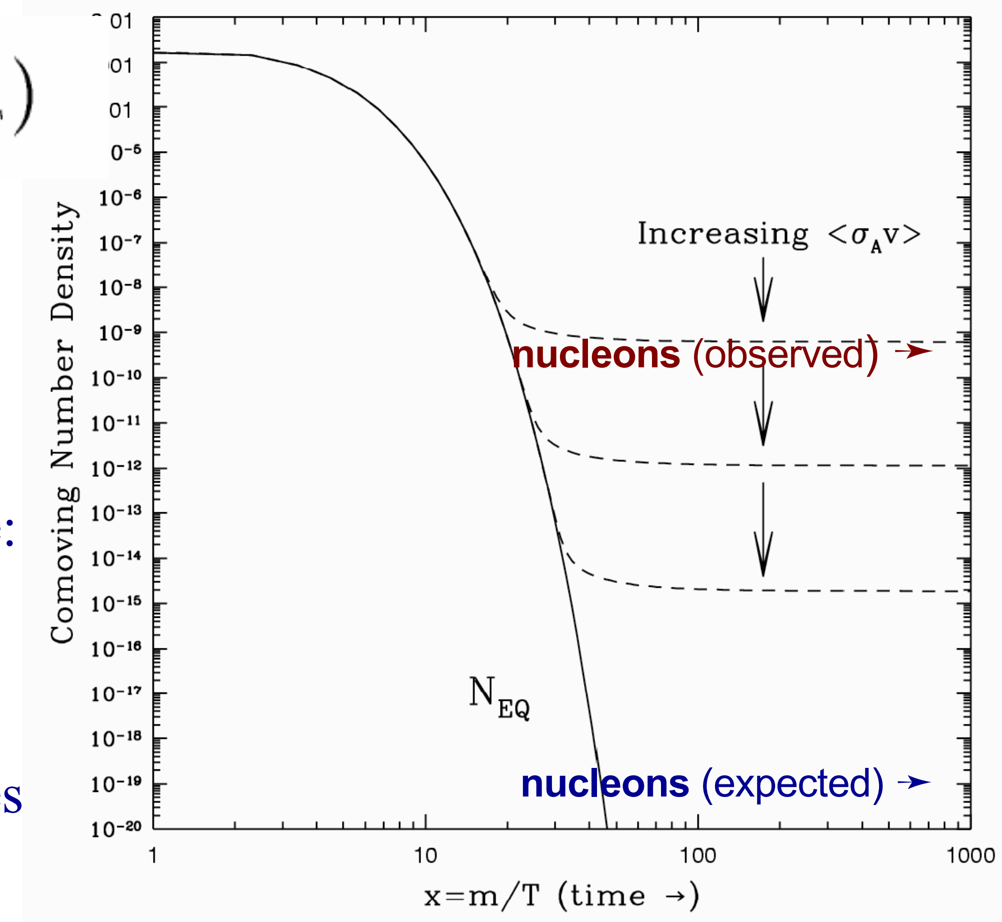
Courtesy: Frank Wilczek, *Physics Today*

However, in the standard cosmology ~none should be left-over from the Big Bang!

What is the expected relic abundance of baryons?

$$\dot{n} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{\mathrm{T}}^2)$$

Chemical equilibrium is maintained as long as annihilation rate exceeds the Hubble expansion rate



'Freeze-out' occurs when annihilation rate:

$$\Gamma = n\sigma v \sim m_N^{3/2} T^{3/2} \mathrm{e}^{-m_N/T} \frac{1}{m_\pi^2}$$

becomes comparable to the expansion rate

$$H \sim \frac{\sqrt{g}T^2}{M_{\mathrm{P}}}$$ where g is # relativistic species

i.e. 'freeze-out' occurs at $T \sim m_{\mathrm{N}}/45$, with: $$\frac{n_N}{n_\gamma} = \frac{n_{\bar{N}}}{n_\gamma} \sim 10^{-19}$$

However the observed ratio is 10^9 times bigger for baryons, and there are no antibaryons, so we must invoke an **initial asymmetry**: $$\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-9}$$

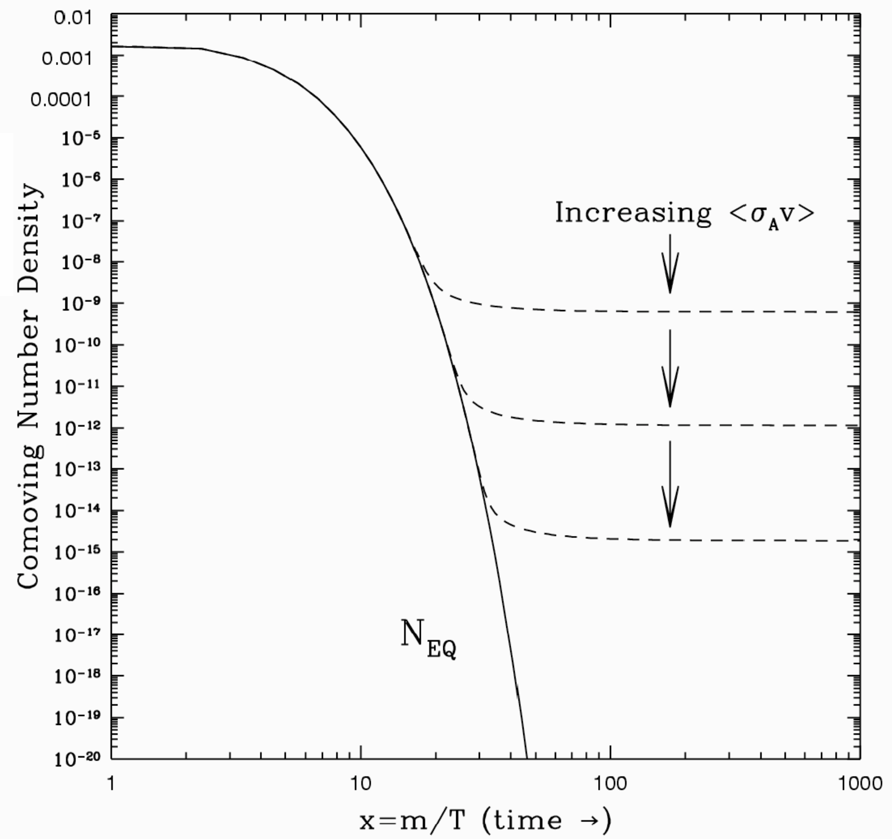
(Note: $\Omega_{\mathrm{B}}/\Omega_{\mathrm{DM}} \sim 1/6$)

Thermal relics

$$\dot{n} + 3Hn = -\langle \sigma v \rangle (n^2 - n_T^2)$$

Chemical equilibrium is maintained as long as the annihilation rate exceeds the Hubble expansion rate

'Freeze-out' can occur either when the annihilating particles are:



- Relativistic: $n \sim n_\gamma$
- Non-relativistic: $n \sim n_\gamma \mathrm{e}^{-m/T}$

$$\text{Example 1}: \quad \sum \Omega_\nu h^2 \simeq m_{\nu_i}/93\text{eV}$$

➛ how might this mass scale arise (e.g. few keV sterile neutrinos)?

$$\text{Example 2}: \Omega_\chi h^2 \simeq \frac{3\times 10^{-27}\text{cm}^3\text{s}^{-1}}{\langle \sigma_{\text{ann}} v \rangle_{T=T_f}}$$

➛ natural DM abundance for Fermi scale mass/coupling ("WIMP miracle")

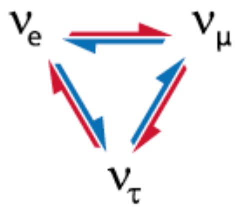
To make the baryon asymmetry requires new physics (‘Sakharov conditions’)

- *B*-number violation
- *CP* violation
- Departure from thermal equilibrium

The SM *allows* *B*-number violation (through non-perturbative – ‘sphaleron-mediated’ – processes) … but *CP*-violation is too *weak* and $SU(2)_L \times U(1)_Y$ breaking is *not* a 1st order phase transition

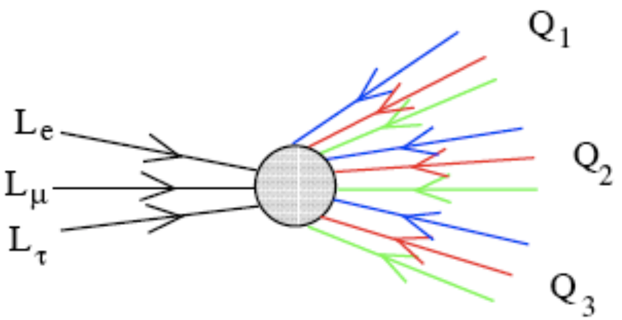
Hence the generation of the observed matter-antimatter asymmetry requires *new* BSM physics … can be related to the observed neutrino masses if these arise from *lepton number* violation → **leptogenesis**

‘See-saw’: $\mathcal{L} = \mathcal{L}_{SM} + \lambda^*_{\alpha J} \overline{\ell}_\alpha \cdot H N_J - \frac{1}{2}\overline{N_J} M_J N_J^c$ $\quad \lambda M^{-1} \lambda^{\mathrm{T}} \langle H^0 \rangle^2 = [m_\nu]$

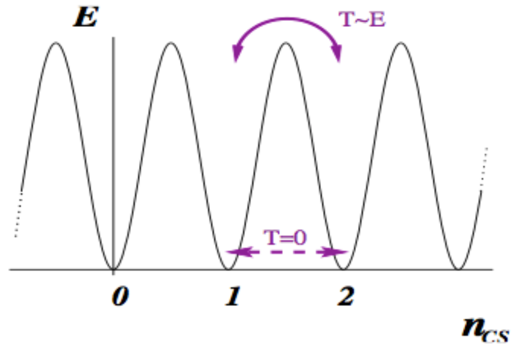


$$\Delta m^2_{atm} = m_3^2 - m_2^2 \simeq 2.6 \times 10^{-3} \mathrm{eV}^2 \qquad \Delta m^2_\odot = m_2^2 - m_1^2 \simeq 7.9 \times 10^{-5} \mathrm{eV}^2$$

Asymmetric baryonic matter



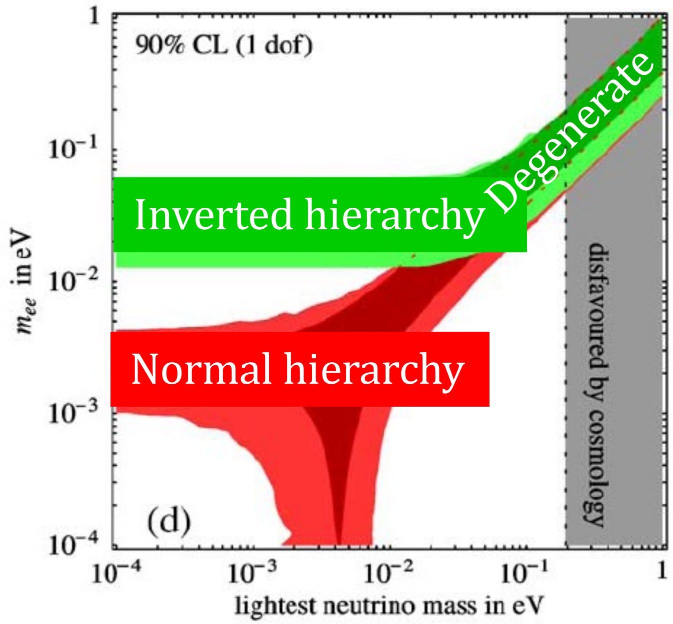
$$\partial_\mu j_i^\mu = \partial_\mu(\bar{\psi}^i \gamma^\mu \psi^i) = \frac{g^2}{8\pi} W^{a\mu\nu} \tilde{W}^a_{\mu\nu}$$



Any primordial lepton asymmetry (e.g. from out-of-equilibrium decays of the right-handed *N*) would be redistributed by *B*+*L* violating processes (which *conserve B-L*) amongst *all fermions* which couple to the electroweak anomaly – in particular **baryons**

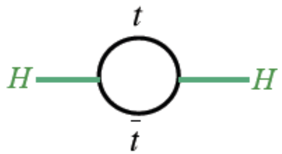
This asymmetry can be shared by any particle that couples to the W (e.g. technibaryons which play a role in dynamical electroweak symmetry breaking)

An essential requirement is that neutrino mass must be Majorana … test by detecting neutrino*less* double beta decay (and measuring the absolute neutrino mass scale)

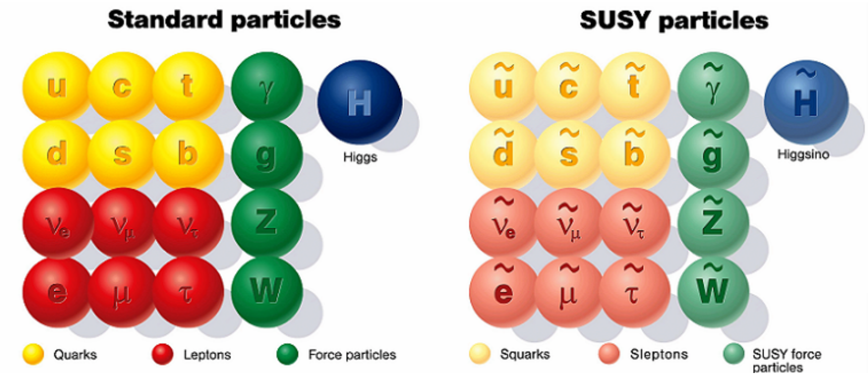


What should the world be made of?

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
Λ_{QCD}	Nucleons	Baryon number	$\tau > 10^{33}$ yr (dim-6 OK)	~~'freeze-out' from thermal equilibrium~~	$\Omega_B \sim 10^{-10}$ *cf.* observed $\Omega_B \sim 0.05$
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino?	R-parity?	violated?	'freeze-out' from thermal equilibrium	$\Omega_{LSP} \sim 0.3$



$$L^{SM}_{effective} \supset M_A A_\mu A^\mu + m_f \overline{f_L} f_R + M_H^2 |H|^2$$



For (softly broken) **supersymmetry** we have the 'WIMP miracle':

$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27} \mathrm{cm}^{-3}\mathrm{s}^{-1}}{\langle \sigma_{\mathrm{ann}} v \rangle_{T=T_\mathrm{f}}} \simeq 0.1, \text{ since } \langle \sigma_{\mathrm{ann}} v \rangle \sim \frac{g_\chi^4}{16\pi^2 m_\chi^2} \approx 3 \times 10^{-26} \mathrm{cm}^3\mathrm{s}^{-1}$$

But why should a *thermal* relic have an abundance comparable to ***non*-thermal** baryons?

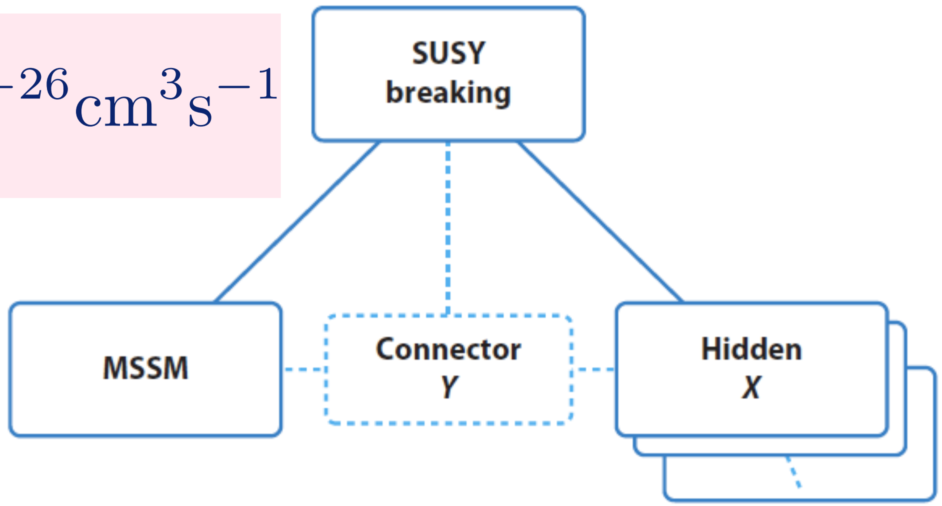
What should the world be made of?

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
Λ_{QCD}	Nucleons	Baryon number	$\tau > 10^{33}$ yr (dim-6 OK)	~~'freeze-out' from thermal equilibrium~~	$\Omega_B \sim 10^{-10}$ *cf.* observed $\Omega_B \sim 0.05$
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino?	R-parity?	violated?	'freeze-out' from thermal equilibrium	$\Omega_{LSP} \sim 0.3$

There is also a 'WIMPless miracle' (Feng & Kumar, PRL **101**:231301,2008) since *generic* hidden sector matter ($g_h^2/m_h \sim g_\chi^2/m_\chi \sim F/16\pi^2 M$) … gives the required abundance as before!

$$\text{since } \langle \sigma_{\rm ann} v \rangle \sim \frac{g_\chi^4}{16\pi^2 m_\chi^2} \approx 3 \times 10^{-26} \mathrm{cm^3 s^{-1}}$$

$$\Omega_\chi h^2 \simeq \frac{3\times10^{-27}\mathrm{cm^3 s^{-1}}}{\langle \sigma_{\rm ann} v \rangle_{T=T_f}} \simeq 0.1$$



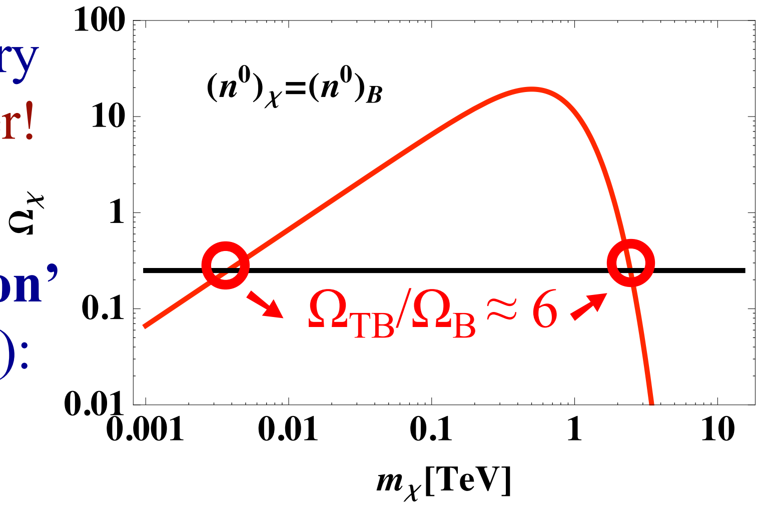
What *should* the world be made of ?

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
Λ_{QCD}	**Nucleons**	Baryon number	$\tau > 10^{33}$ yr (dim-6 OK)	~~'Freeze-out' from thermal equilibrium~~ Asymmetric baryogenesis (how?)	$\Omega_B \sim 10^{-10}$ *cf.* observed $\Omega_B \sim 0.05$
$\Lambda_{QCD'} \sim 6\Lambda_{QCD}$	Dark baryon?	$U(1)_{DB}$	plausible	Asymmetric (like the *observed* baryons)	$\Omega_{DB} \sim 0.3$
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino?	R-parity	violated?	'Freeze-out' from thermal equilibrium	$\Omega_{LSP} \sim 0.3$
	Technibaryon?	(walking) Technicolour	$\tau \sim 10^{18}$ yr e^+ excess?	Asymmetric (like the *observed* baryons)	$\Omega_{TB} \sim 0.3$

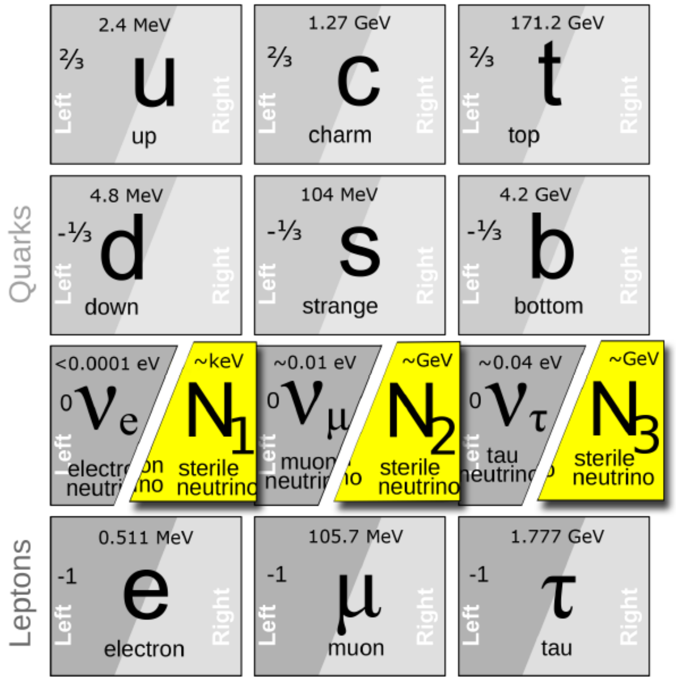
A new particle can naturally *share* in the *B/L* asymmetry if it couples to the *W* … linking dark to baryonic matter!

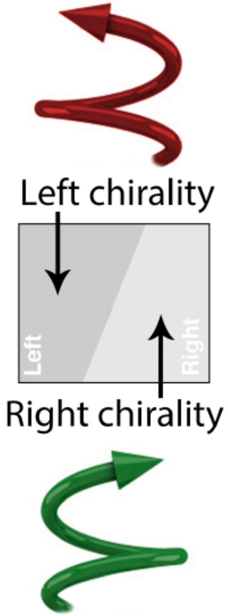
Then a *O*(TeV) mass **technibaryon** can be the dark matter … alternatively a ~5-10 GeV mass **'dark baryon'** in a *hidden sector* (into which the technibaryon decays):

$$\Omega_\chi = (m_\chi \mathcal{N}_\chi / m_B \mathcal{N}_B)\Omega_B$$



Sterile (right-handed) neutrinos can also be the dark matter ...



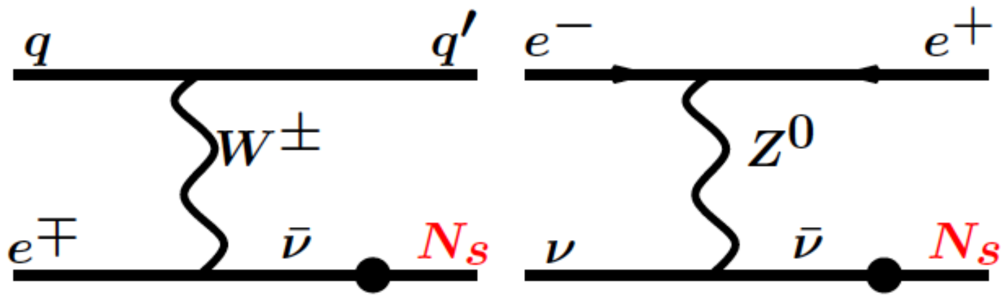


These may mix with the left-handed 'active' neutrinos so would behave as super-weakly interacting particles with an effective coupling: θG_{Fermi}

$$\theta^2_{e,\mu,\tau} \equiv \frac{|M_{\text{Dirac}}|^2}{|M_{\text{Majorana}}|^2} = \frac{\mathcal{M}_{\text{active}}}{\mathcal{M}_{\text{sterile}}}$$

$$\approx 5 \times 10^{-5} \left(\frac{\mathcal{M}_{\text{sterile}}}{\text{KeV}}\right)^{-1}$$

So they will be created when active neutrinos scatter, at a rate $\propto \theta^2 \Gamma_{\text{active}}$



Hence although they may never come into equilibrium, the relic abundance will be of order the dark matter for a mass of order KeV (Dodelson & Widrow, Phys.Rev.D,1993)

Axion dark matter

$$\begin{aligned}\mathcal{L}_{\text{eff}} &= M^4 + M^2\Phi^2 \\ &+ (D\Phi)^2 + \bar{\Psi} \not{D}\Psi + F^2 + \bar{\Psi}\Psi\Phi + V(\Phi) \\ &+ \frac{\bar{\Psi}\Psi\Phi\Phi}{M} + \frac{\bar{\Psi}\Psi\bar{\Psi}\Psi}{M^2} + \ldots\end{aligned}$$

$$\boxed{+\theta_{\text{QCD}} F\tilde{F}}$$

super-renormalisable

renormalisable

non-renormalisable

The SM admits a term which would lead to *CP* violation in strong interactions, hence an (unobserved) electric dipole moment for neutrons → requires $\theta_{\text{QCD}} < 10^{-6}$

To achieve this without fine-tuning, θ_{QCD} must be made a dynamical parameter, through the introduction of a new $U(1)_{\text{Peccei-Quinn}}$ symmetry which must be broken

… the resulting (pseudo) Nambu-Goldstone boson is the **axion** which (subsequently) acquires a mass through its mixing with the pion (the pNGB of QCD): $m_a = m_\pi\, (f_\pi/f_{\text{PQ}})$

(Kim, Phys.Rep.**150**:1,1987, Rev.Mod.Phys.**82**:557,2010; Raffelt, Phys.Rep.**198**:1,1990)

The coherent oscillations of relic axions contain energy density that behaves like CDM with $\Omega_a h^2 \sim 10^{11}$ GeV/f_{PQ} … however the *natural* P-Q scale is: $f_{\text{PQ}} \sim 10^{18}$ GeV

Hence axion dark matter would need to be significantly diluted … i.e. *not* predictable (or seek anthropic explanation for why θ_{QCD} is small - Tegmark *et al* Phys.Rev.D**73**:023505,2006)

What should the world be made of?

Mass scale	Lightest stable particle	Symmetry/ Quantum #	Stability ensured?	Production	Abundance
Λ_{QCD}	**Nucleons**	Baryon number	$\tau > 10^{33}$ yr	'Freeze-out' from thermal equilibrium	$\Omega_B \sim 10^{-10}$ *cf.* observed
				Asymmetric baryogenesis (how?)	$\Omega_B \sim 0.05$
$\Lambda_{QCD'}$ $\sim 5\Lambda_{QCD}$	Dark baryon	$U(1)_{DB}$	?	Asymmetric (like the observed baryons)	$\Omega_{DB} \sim 0.3$
Λ_{Fermi} $\sim G_F^{-1/2}$	Neutralino?	*R*-parity?	violated?	'freeze-out' from thermal equilibrium	$\Omega_{LSP} \sim 0.3$
	Technibaryon?	(walking) Technicolour	$\tau \sim 10^{18}$ yr	Asymmetric (like the observed baryons)	$\Omega_{TB} \sim 0.3$
$\Lambda_{hidden\ sector}$ $\sim(\Lambda_F M_P)^{1/2}$	Crypton? hidden valley?	Discrete (model-dependent)	$\tau \gtrsim 10^{18}$ yr	Varying gravitational field during inflation	$\Omega_X \sim 0.3?$
$\Lambda_{see\text{-}saw}$ $\sim\Lambda_{Fermi}^2/\Lambda_{B\text{-}L}$	**Neutrinos**	Lepton number	Stable	Thermal (like CMB)	$\Omega_\nu > 0.003$
M_{string} M_{Planck}	Kaluza-Klein states? Axions	? Peccei-Quinn	? stable	? Field oscillations	? $\Omega_a \gg 1!$

NO DEFINITE INDICATION FROM THEORY … MUST DECIDE BY EXPERIMENT!

The **Standard $SU(3)_c$ x $SU(2)_L$ x $U(1)_Y$ Model** (viewed as an effective field theory up to some high energy cut-off scale M) describes *all* of microphysics …

$$m_H^2 \simeq \frac{h_t^2}{16\pi^2}\int_0^{M^2} \mathrm{d}k^2 = \frac{h_t^2}{16\pi^2}M^2$$

$$+M^4 + M^2\Phi^2$$

vacuum energy problem

hierarchy problem

super-renormalisable

$$-\mu^2\phi^\dagger\phi + \frac{\lambda}{4}(\phi^\dagger\phi)^2, m_H^2 = \lambda v^2/2$$ → Higgs

$$\mathcal{L}_{\rm eff} = F^2 + \bar{\Psi}\not{D}\Psi + \bar{\Psi}\Psi\Phi + (D\Phi)^2 + V(\Phi)$$

renormalisable

$$\boxed{+\theta_{\rm QCD}F\tilde{F}}$$ → axion?

$$+\frac{\bar{\Psi}\Psi\Phi\Phi}{M} + \frac{\bar{\Psi}\Psi\bar{\Psi}\Psi}{M^2} + \cdots$$

non-renormalisable

neutrino mass

proton decay, FCNC …

New physics beyond the SM ⇒ non-renormalisable operators suppressed by M^n which decouple as $M \to M_P$
… so neutrino mass is small, proton decay is slow → **baryon asymmetry** from 'leptogenesis'?

But as M is raised, the effects of the super-renormalisable operators are *exacerbated*
One solution for Higgs mass divergence → 'softly broken' *supersymmetry* at O(TeV)
… or the Higgs could be *composite* – a pseudo Nambu-Goldstone boson

New TeV-scale physics provides a natural candidate for **dark matter** – e.g. the lightest supersymmetric particle (or techni-baryon or Kaluza-Klein state …)
But there are other possibilities too (axion, sterile neutrino, asymmetric dark matter …)

But the 'cosmological constant' is >10^{60} times higher than the maximum amount of **dark energy** tolerable today … we do *not* understand how the SM couples to gravity!