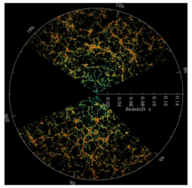
# Subir Sarkar

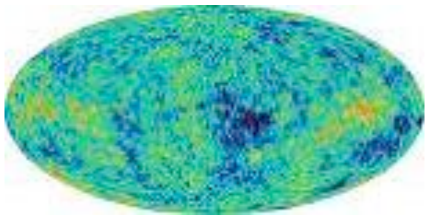
Oxford Physics

- The universe observed
- Reconstructing our thermal history
- Dark matter
- The early universe

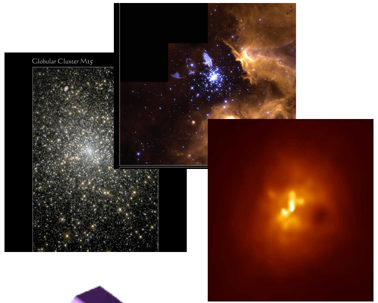
# What is the world made of?

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

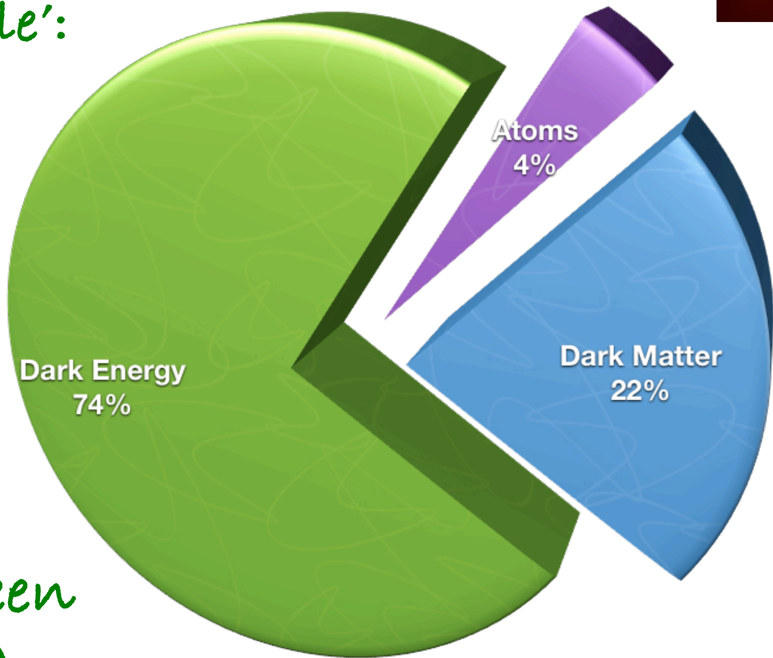




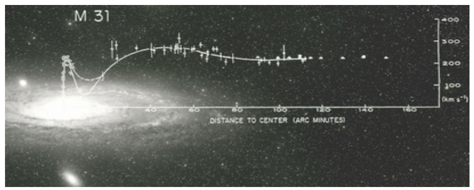
**No significant dynamical evidence** seen (e.g. 'late ISW effect')
… is dark energy being faked by inhomogeneity?



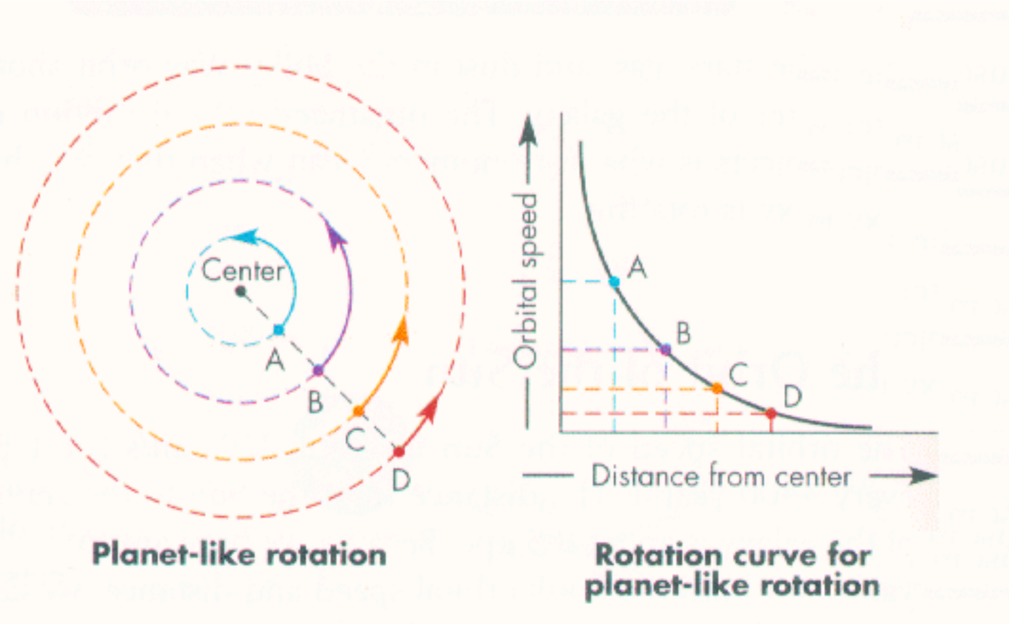
Baryons (but no antibaryons) …




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



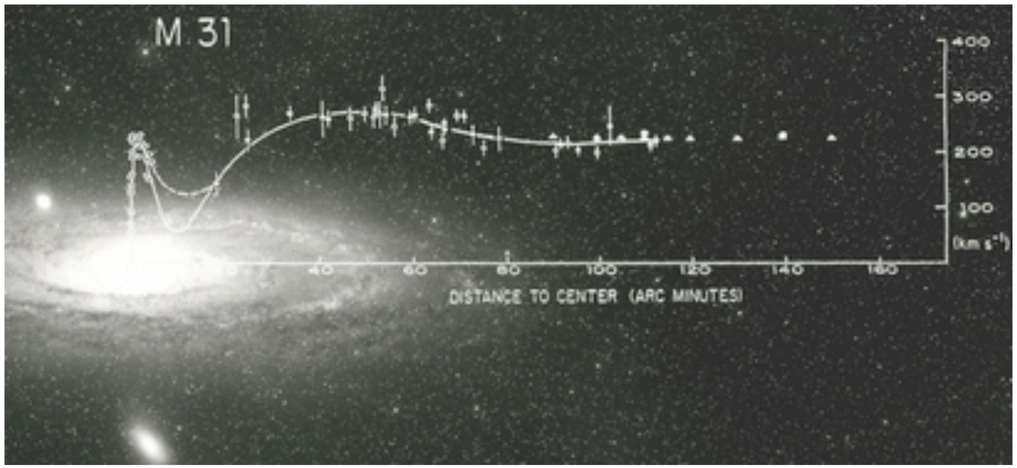
## The modern saga of dark matter starts with the rotation curves of spiral galaxies ...




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

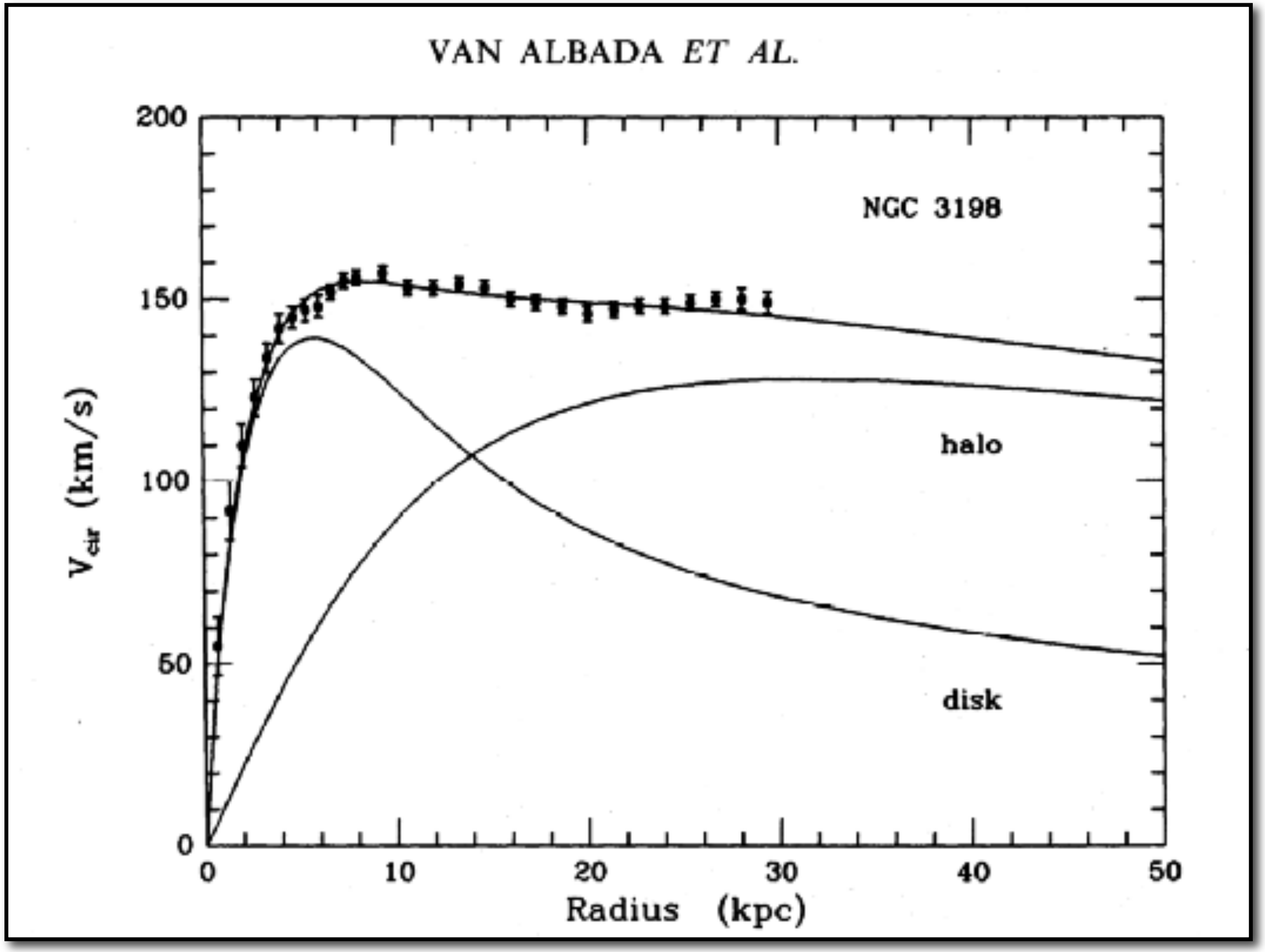
$$v_{\rm circ} = \sqrt{\frac{G_{\rm N} M(< r)}{r}}$$

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

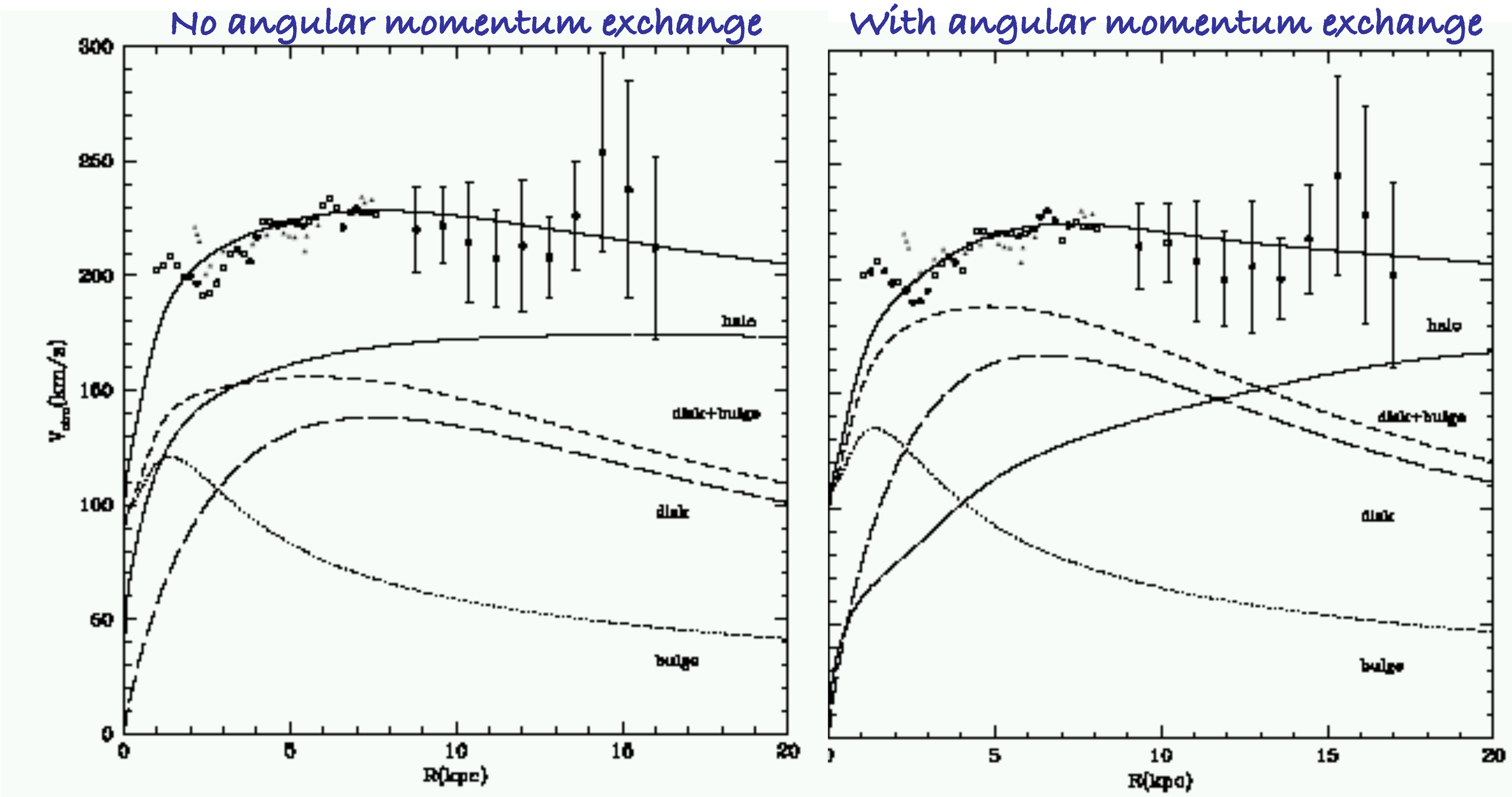



$$v_{\rm circ} \sim \text{constant} \quad \Rightarrow \quad M(< r) \propto r \quad \Rightarrow \quad \rho \propto 1/r^2$$

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

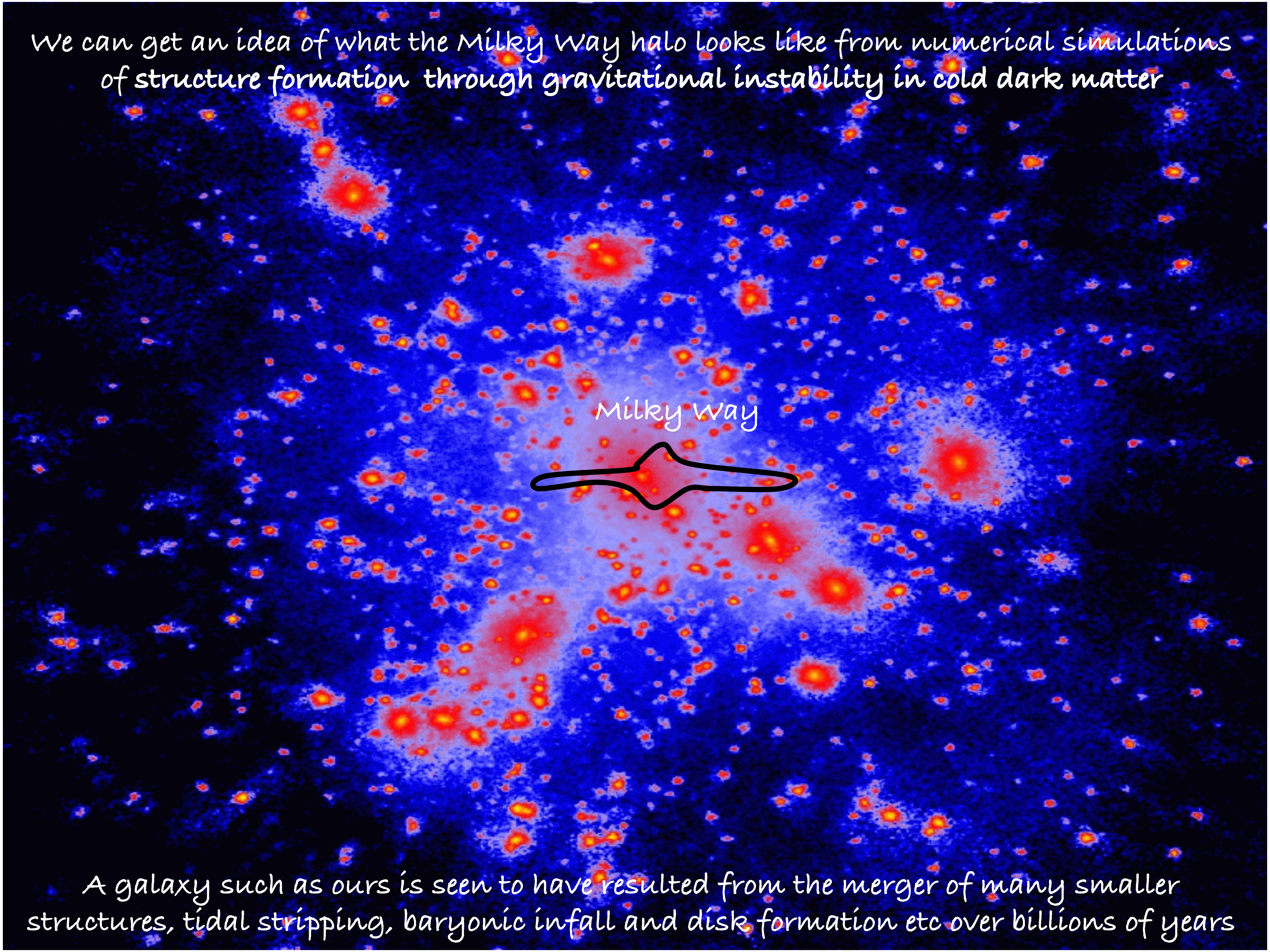


# More sophisticated modelling needs to account for multiple components and the coupling between baryonic & dark matter



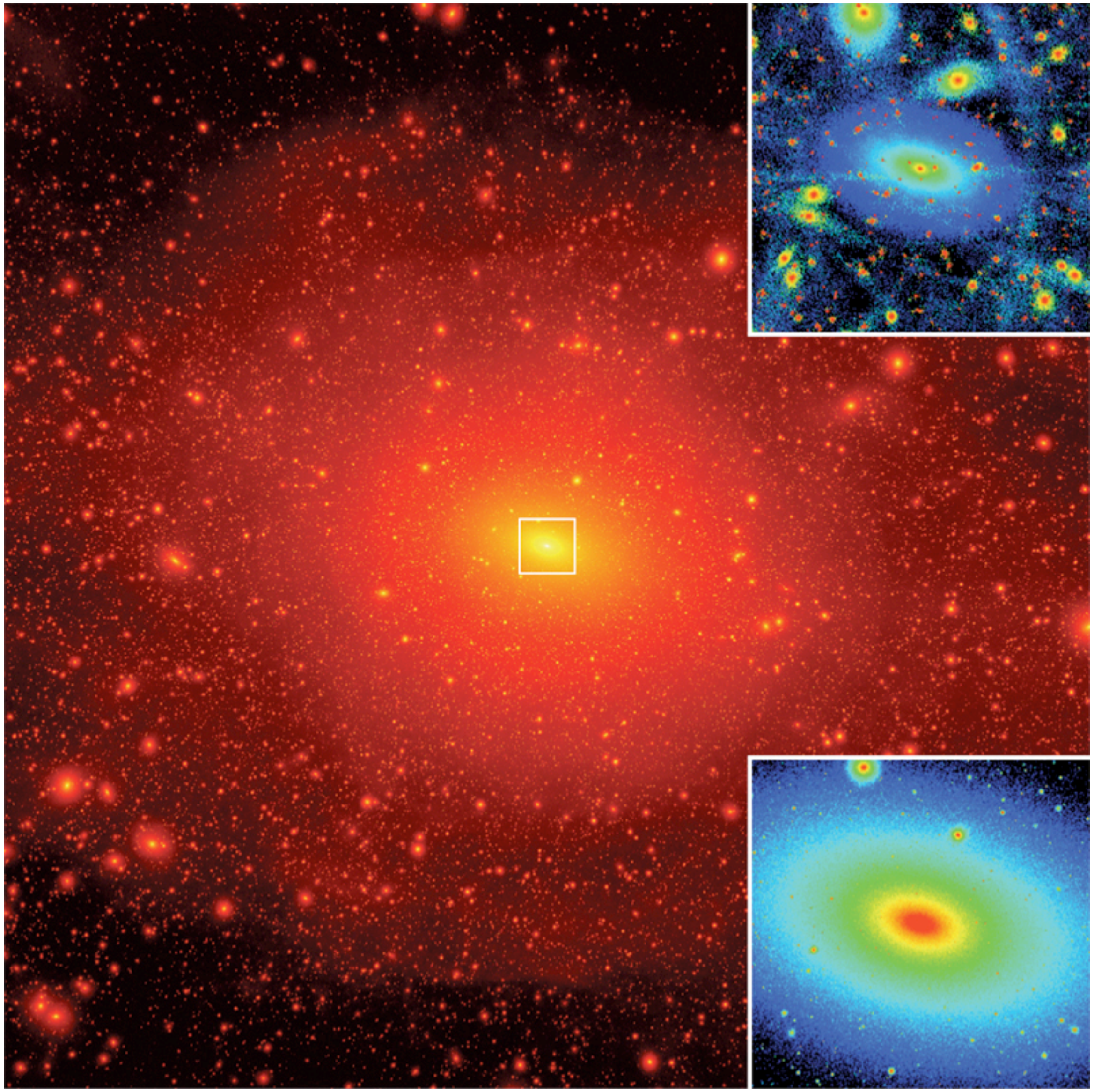

Klypin, Zhao & Somerville [astro-ph/0110390]

The local halo density of dark matter is ~0.3 GeV cm$^{-3}$ (uncertainty x2?)


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!

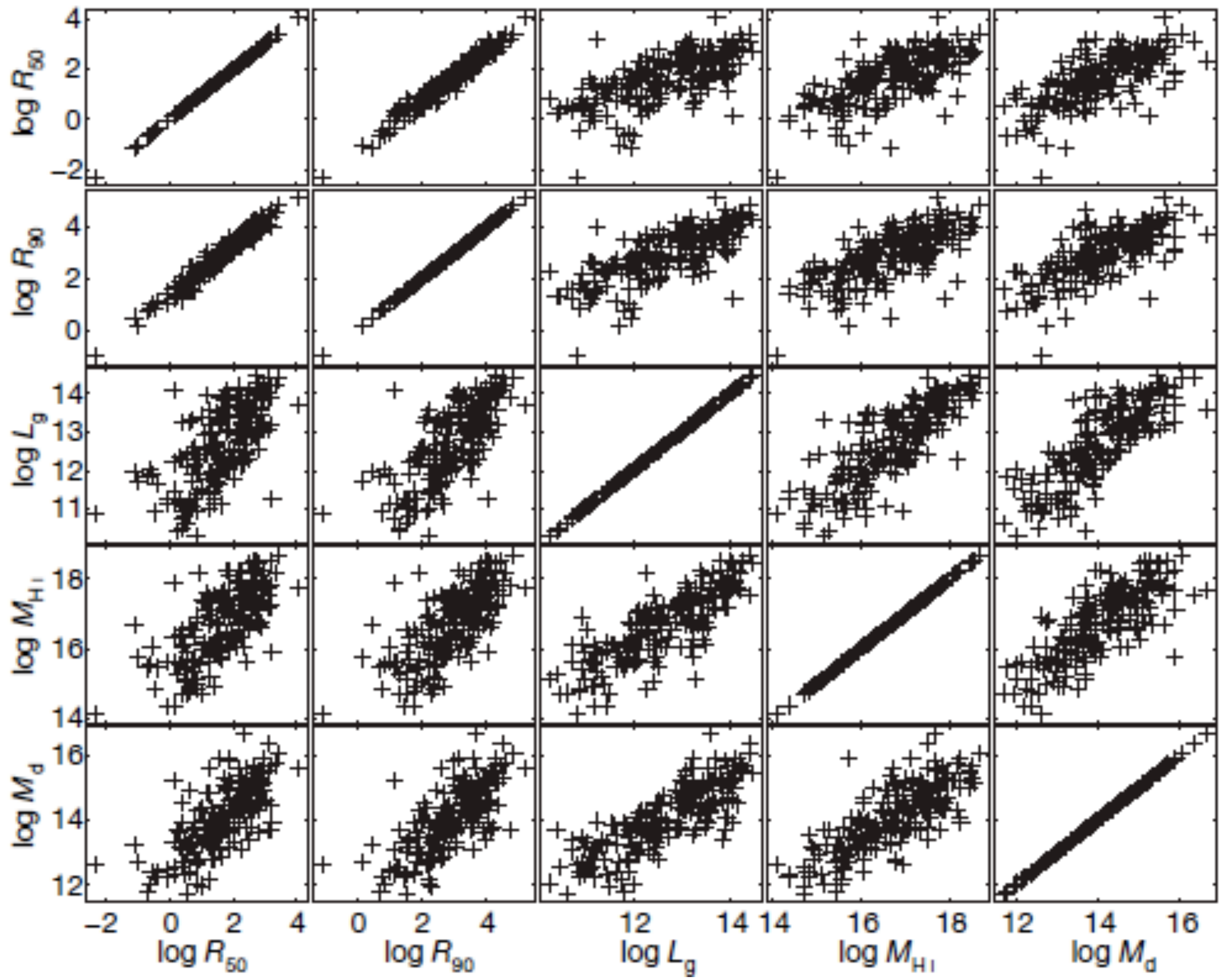
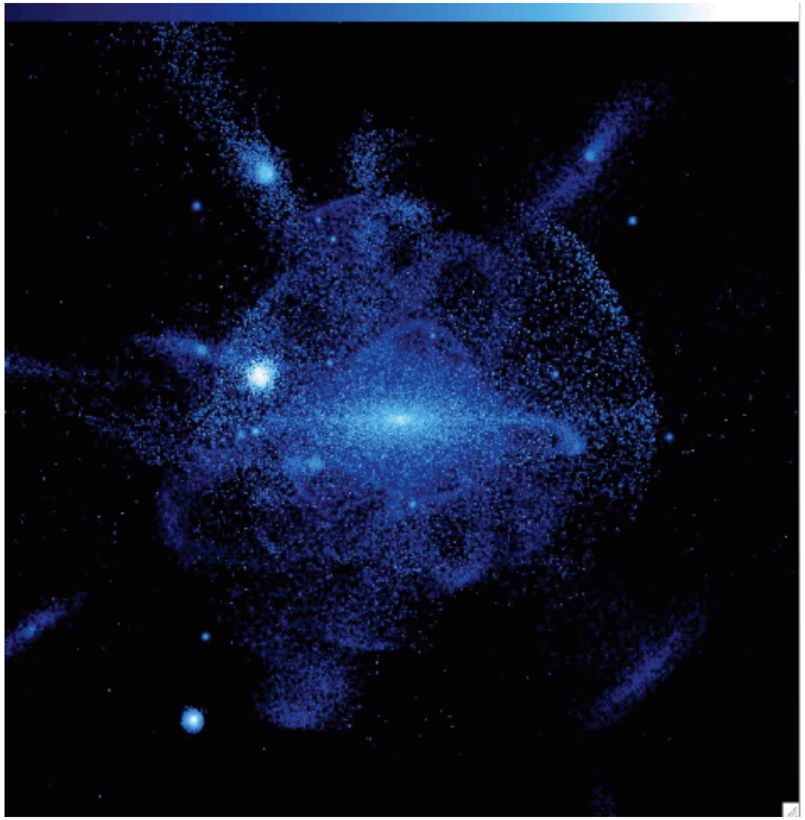
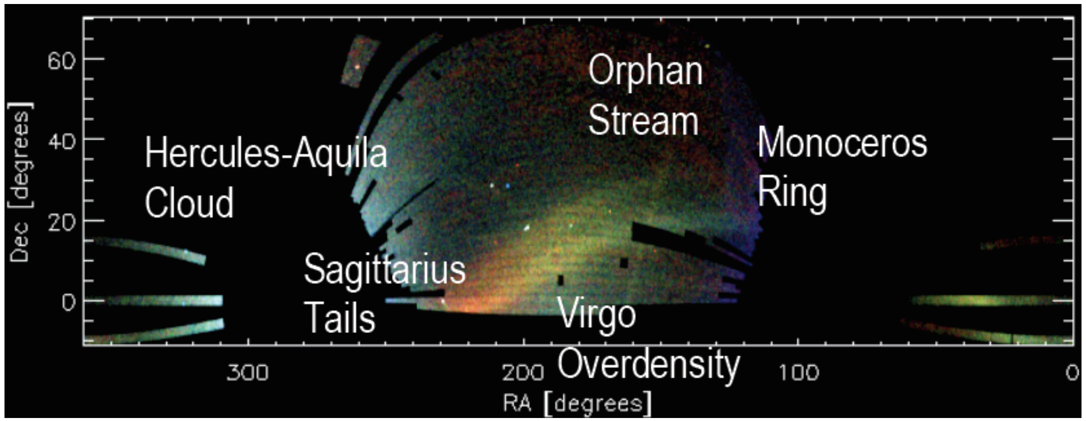



**Figure 1 | Scatter plots showing correlations between five measured variables, not including colour.** The variables are two optical radii, $R_{50}$ and $R_{90}$ (in parsecs), respectively containing 50 and 90% of the emitted light; and luminosity, $L_g$; neutral hydrogen mass, $M_{HI}$; and dynamical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

# Whereas the Galaxy does have satellite galaxies and substructure, it seems to be less than expected from the numerical simulations

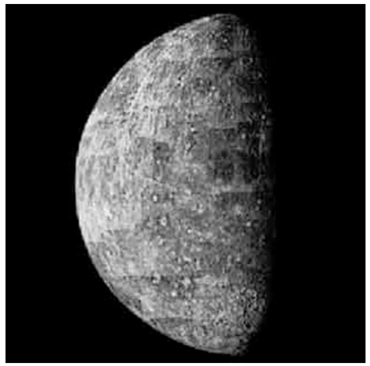




# Inferences of dark matter are not always right ... it may instead be a change in the dynamics

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).

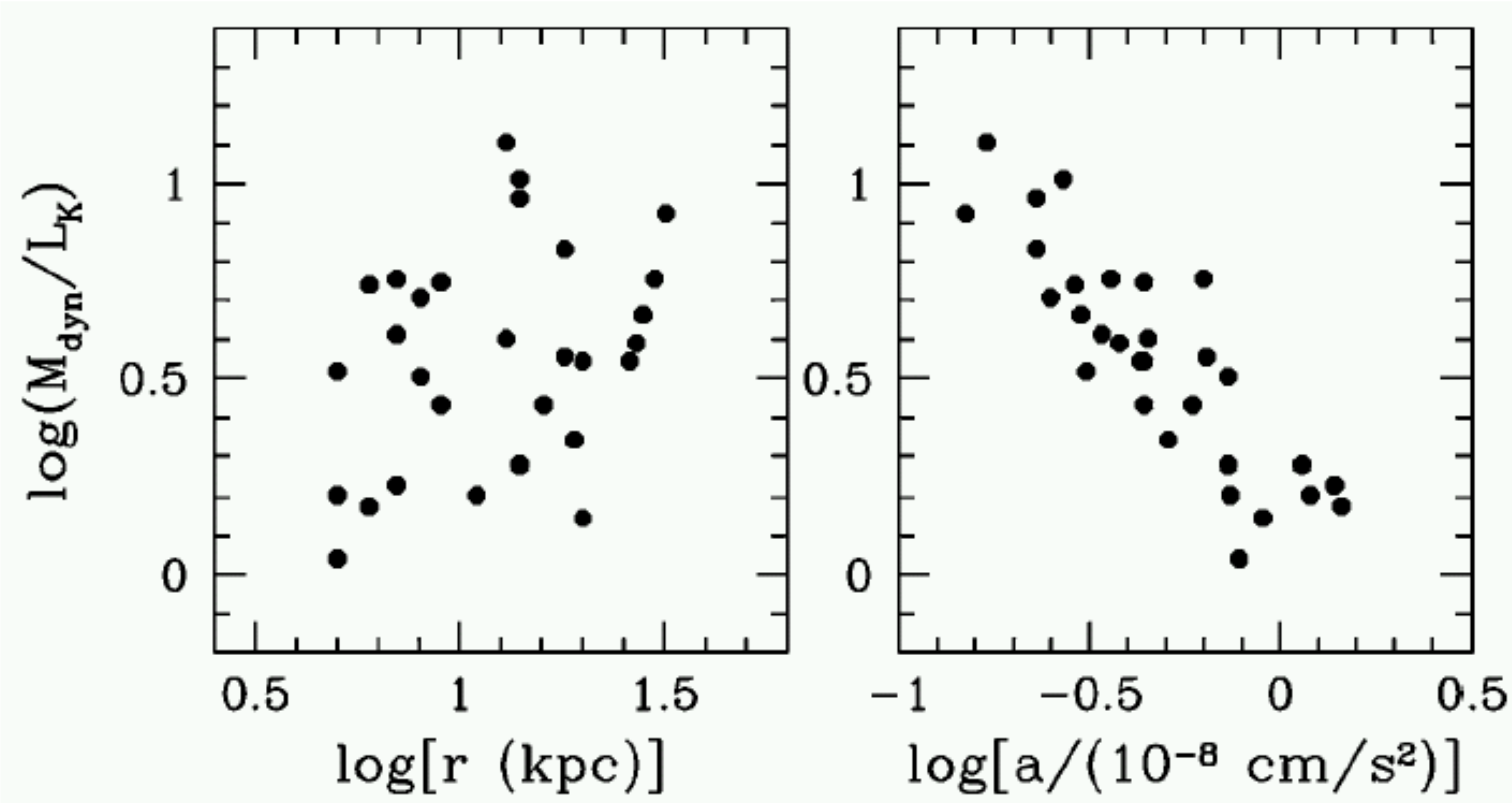
Some astronomers even see Vulcan in the evening sky!



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

# Bekenstein—Milgrom Equation

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

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

where

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

Then

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

implies

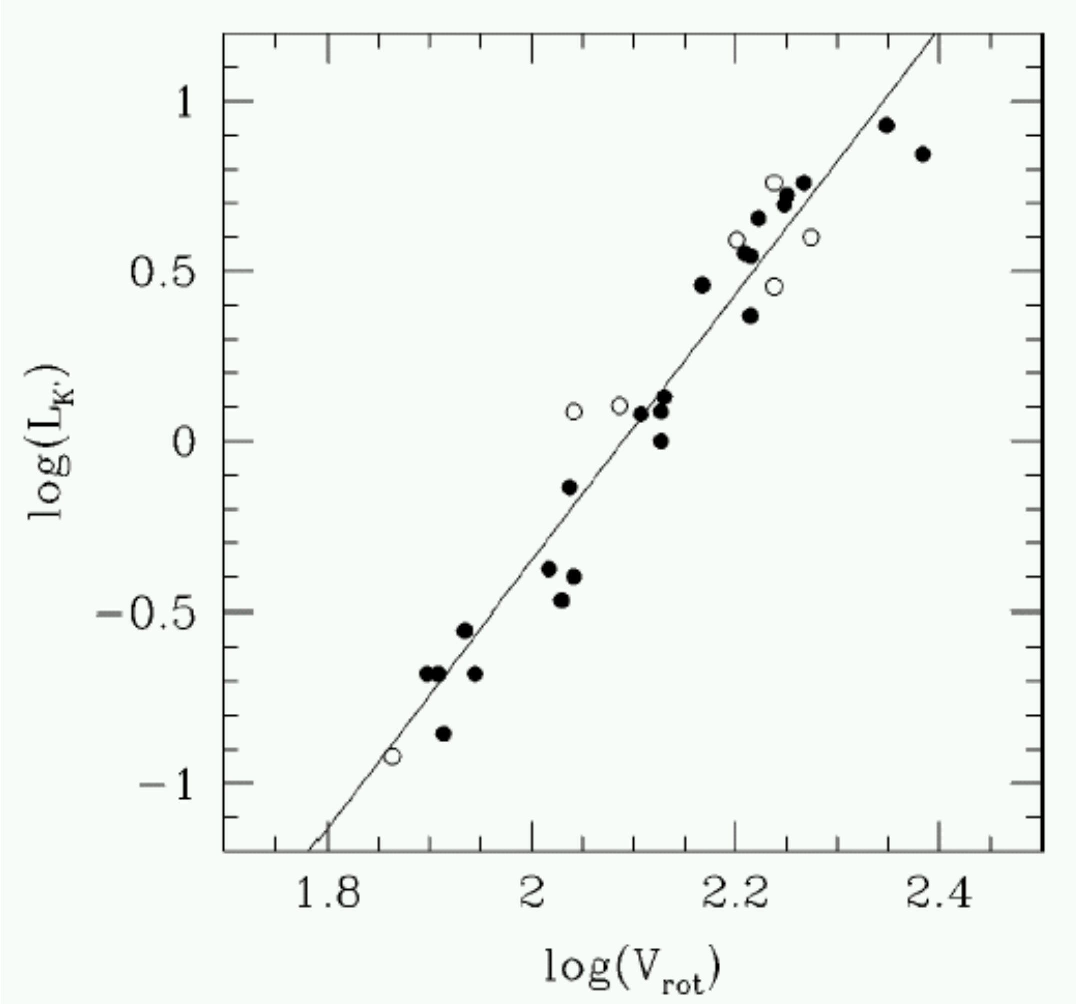
$$\mu(|\nabla\phi|/a_0)\nabla\phi = \nabla\phi_{\rm N} + \nabla\times\mathbf{A}$$

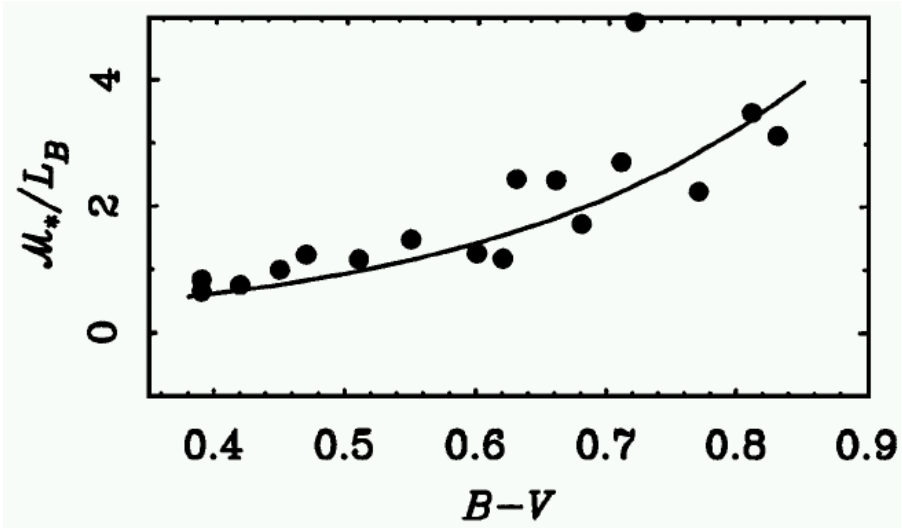
so when $\mathbf{A} \simeq 0$ and $|\nabla\phi| \ll 1$

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

Milgrom [arXiv:0912.2678]

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



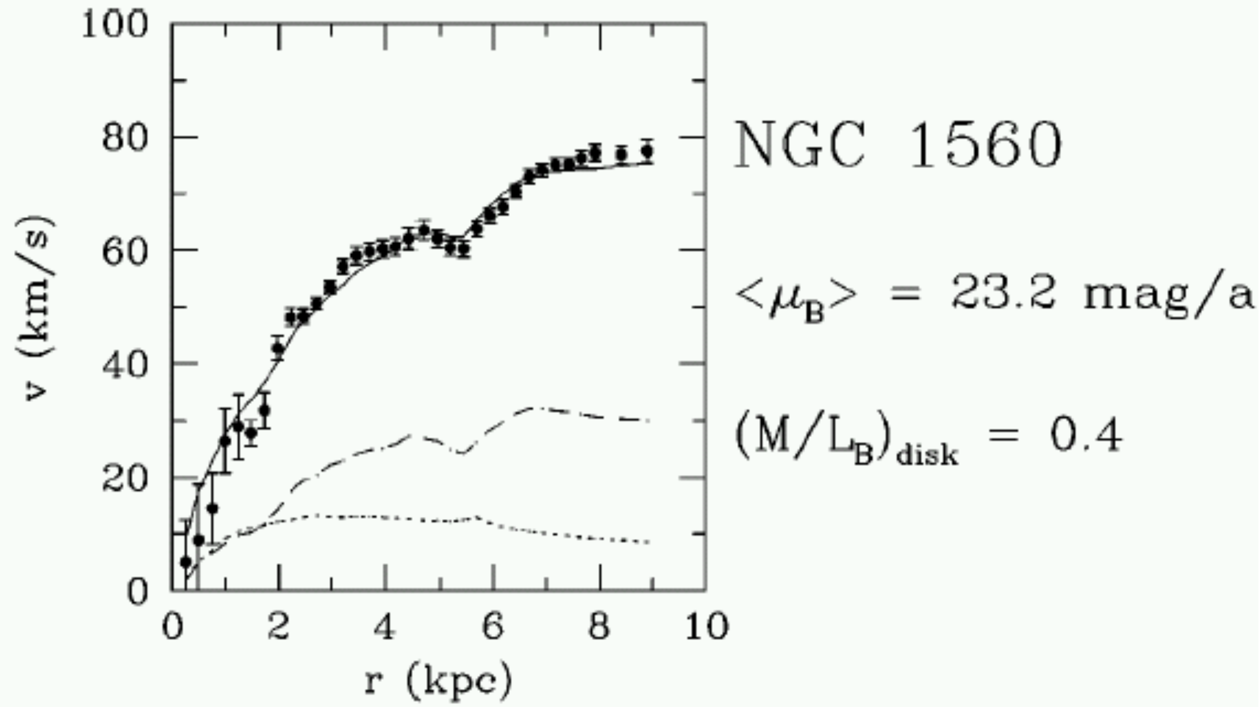



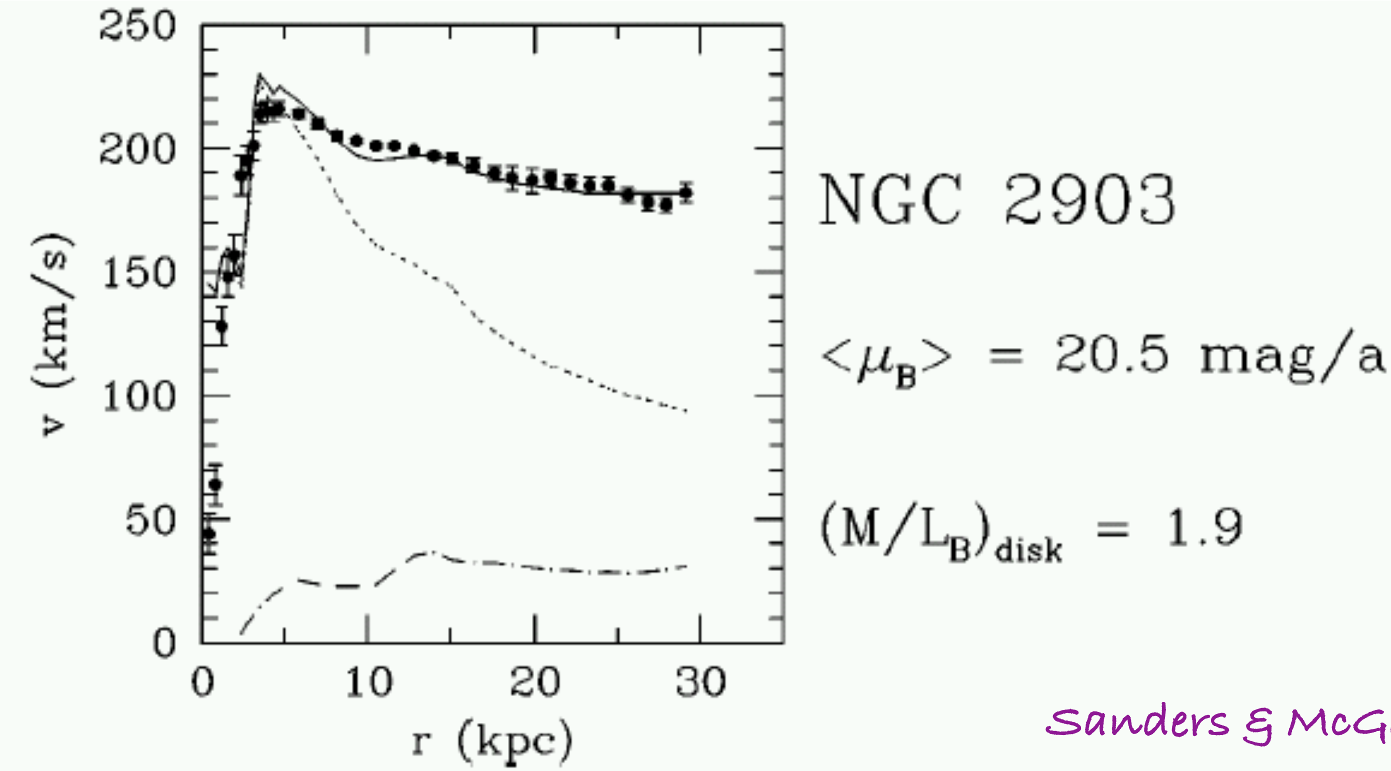

... the fitted value of the only free parameter (M/L) agrees very well with population synthesis models

Sanders & Verheijen [astro-ph/9802240]

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

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



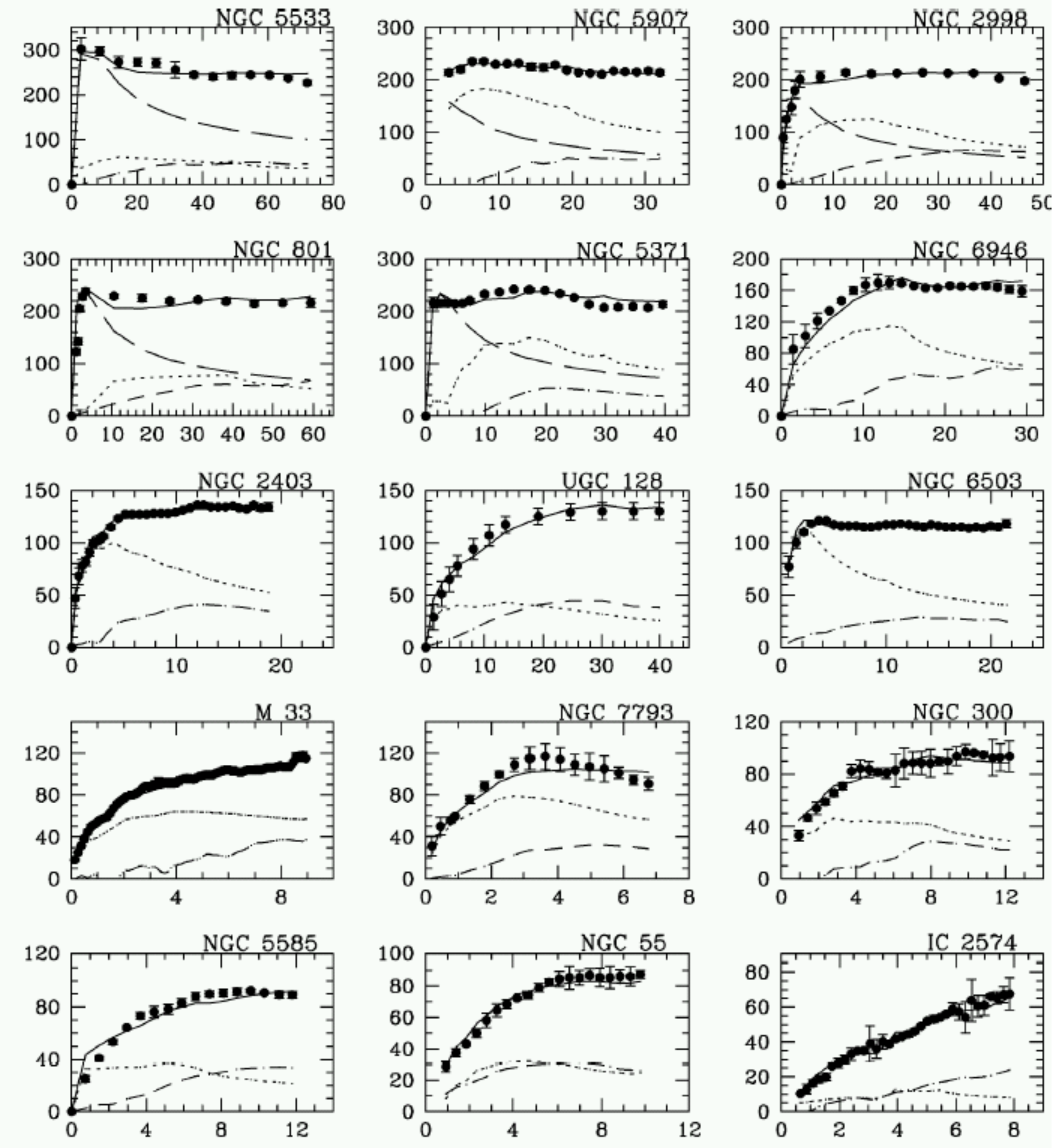




Features in the baryonic disc have counterparts in the rotation curve

Sanders & McGaugh [astro-ph/0204521]

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]

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

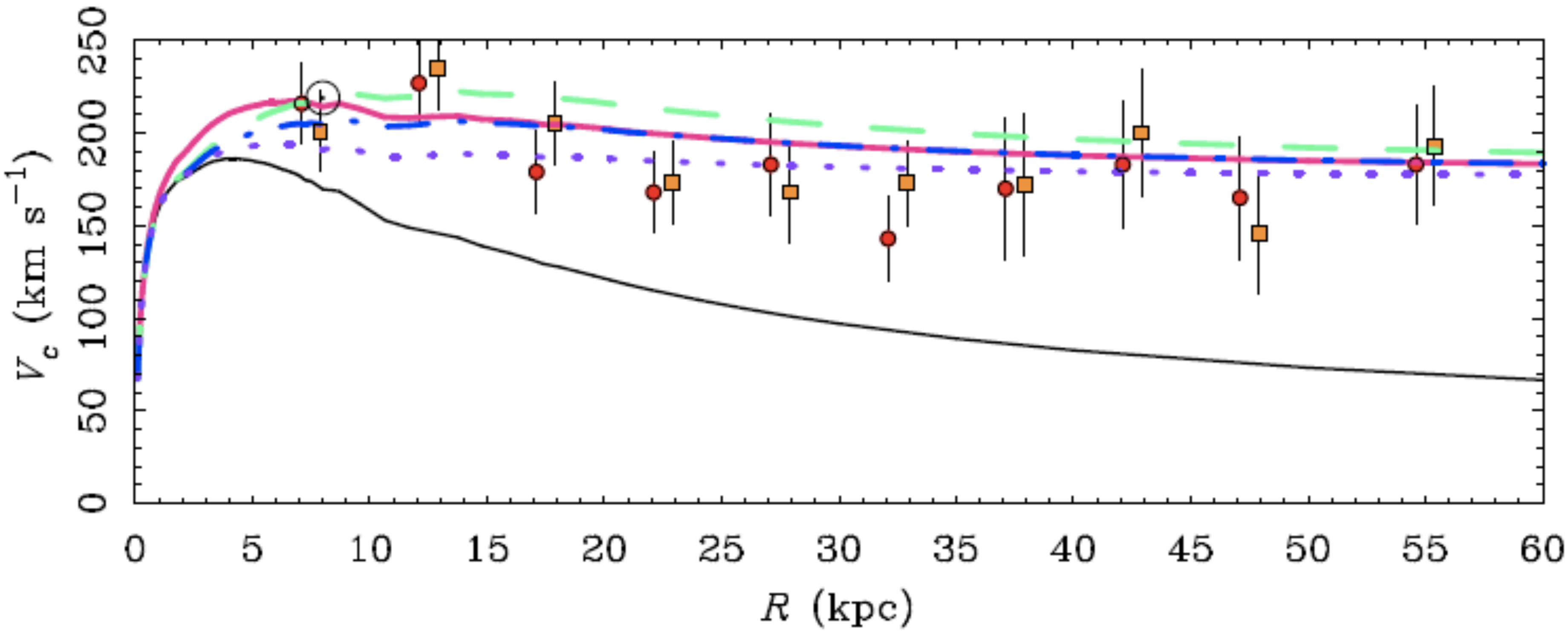



Fig. 7.— The outer rotation curve predicted by MOND for the Milky Way compared to the two realizations of the Blue Horizontal Branch stars in the SDSS data reported by Xue et al. (2008). The data points from the two realizations have been offset slightly from each other in radius for clarity; lines as 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.

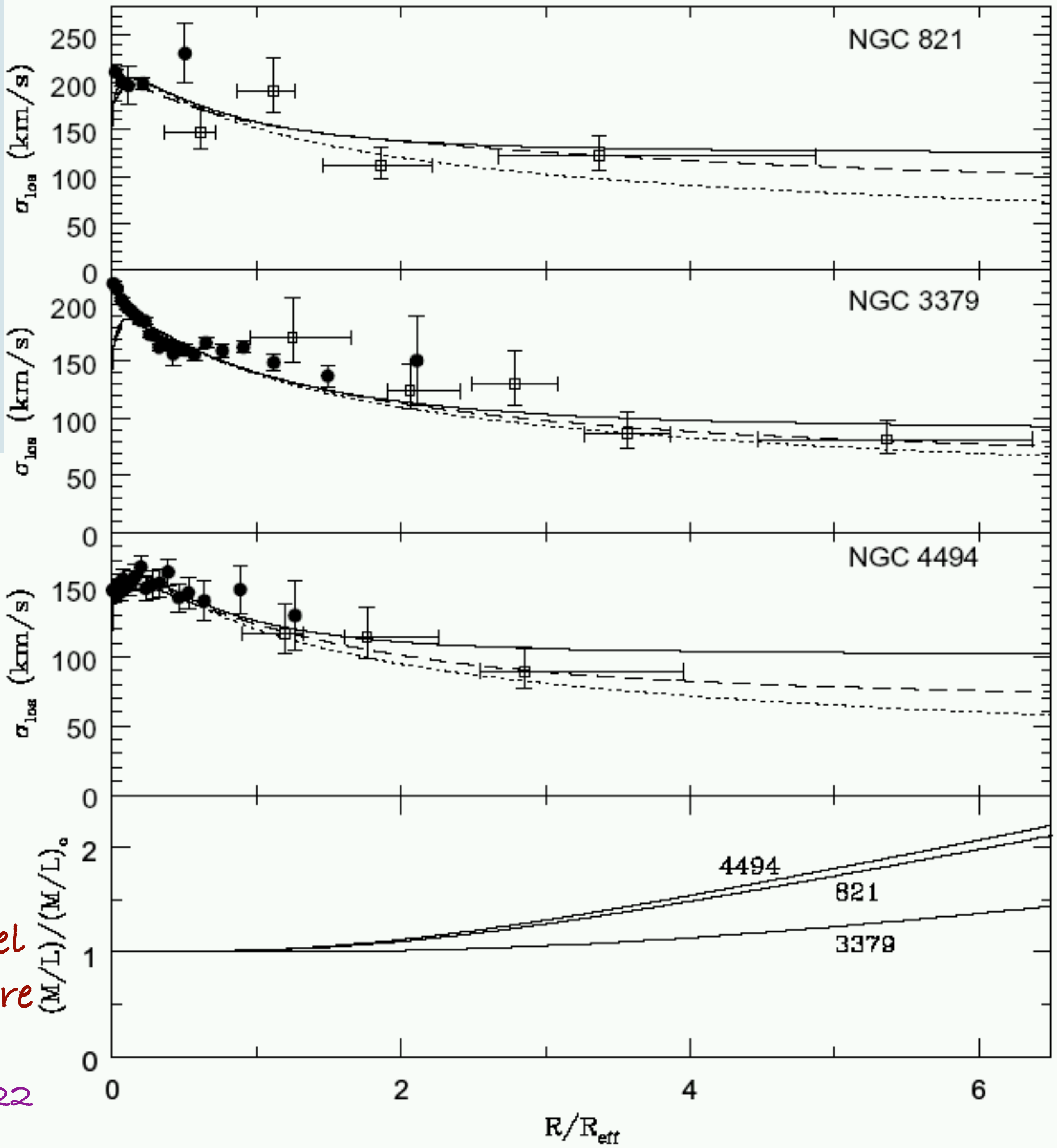
McGaugh (2008)

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

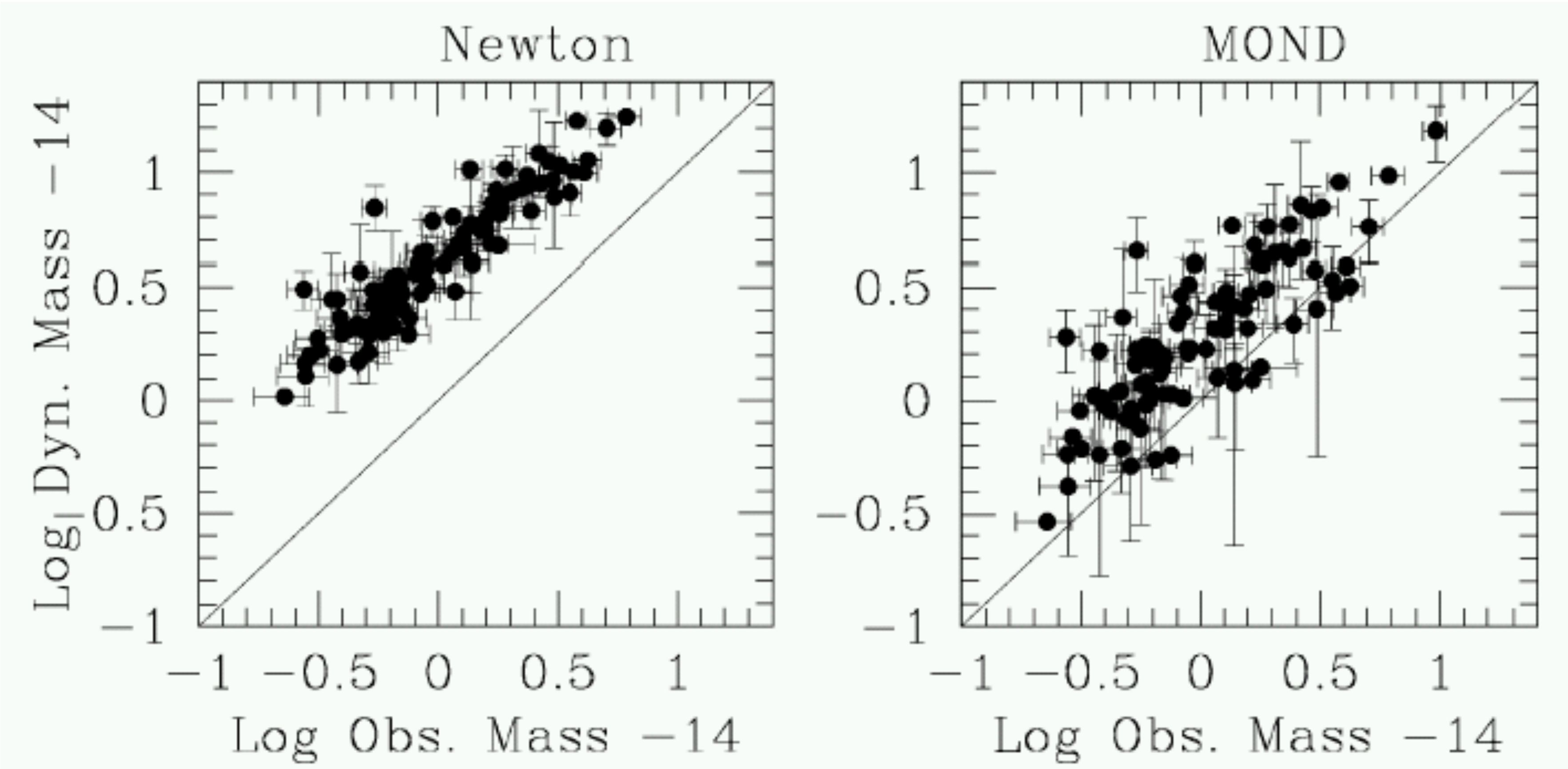
**Data:**
Romanowsky et al [astro-ph/0308518]

**Models:**
Milgrom & Sanders [astro-ph/0309617]

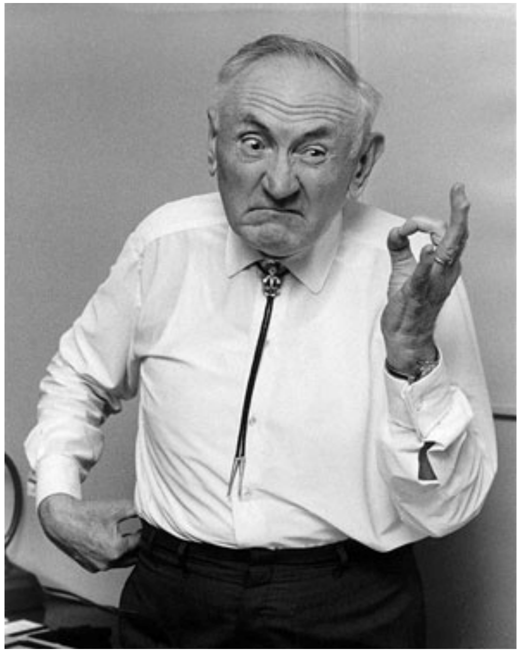
This can be explained in a dark matter model only if stellar orbits are very elliptical
Dekel *et al* astro-ph/0501622



# 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

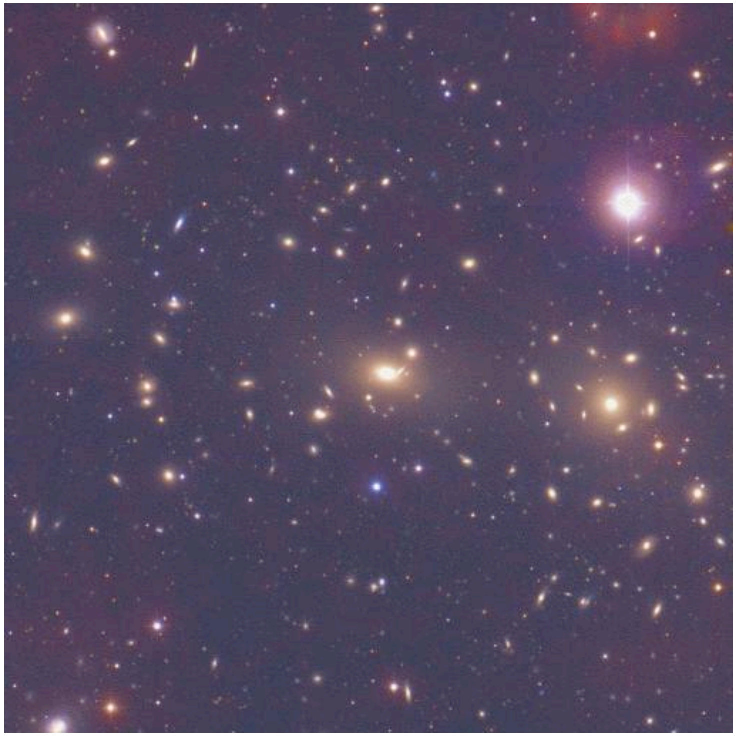
$\Rightarrow M/L \sim O(100)\ M_\odot/L_\odot$

"... 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"

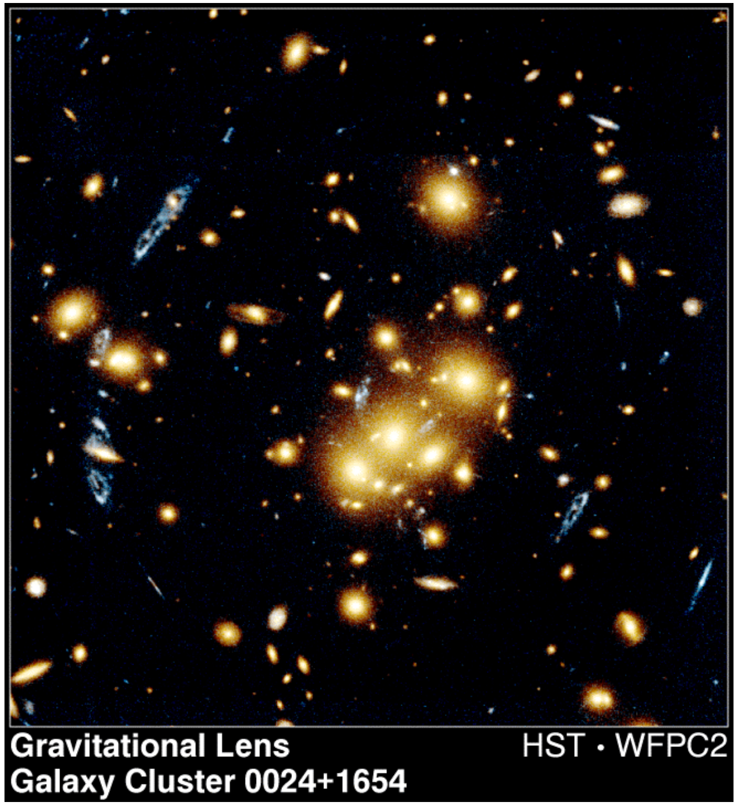
Virial Theorem: $\langle V \rangle + 2\langle K \rangle = 0$

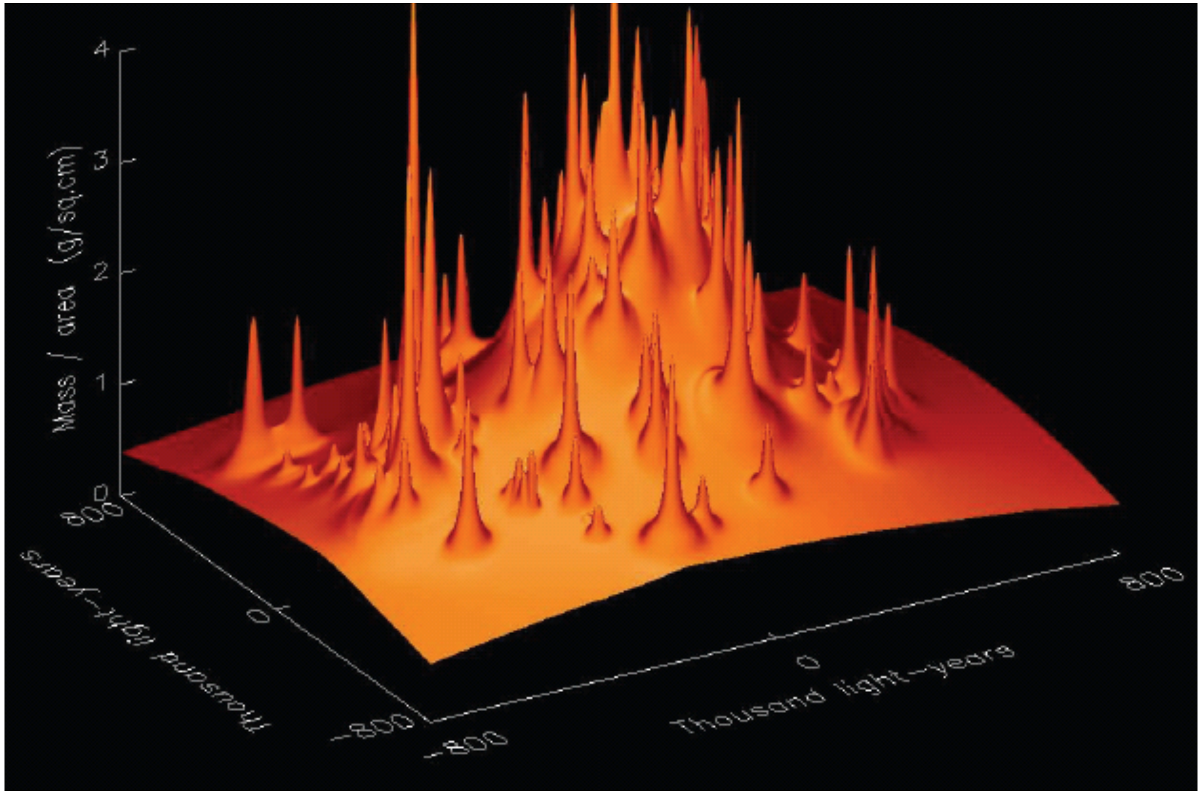
$$V = -\frac{N^2}{2} G_{\mathrm{N}} \frac{\langle m^2 \rangle}{\langle r \rangle}, \quad K = N \frac{\langle m v^2 \rangle}{2}$$

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



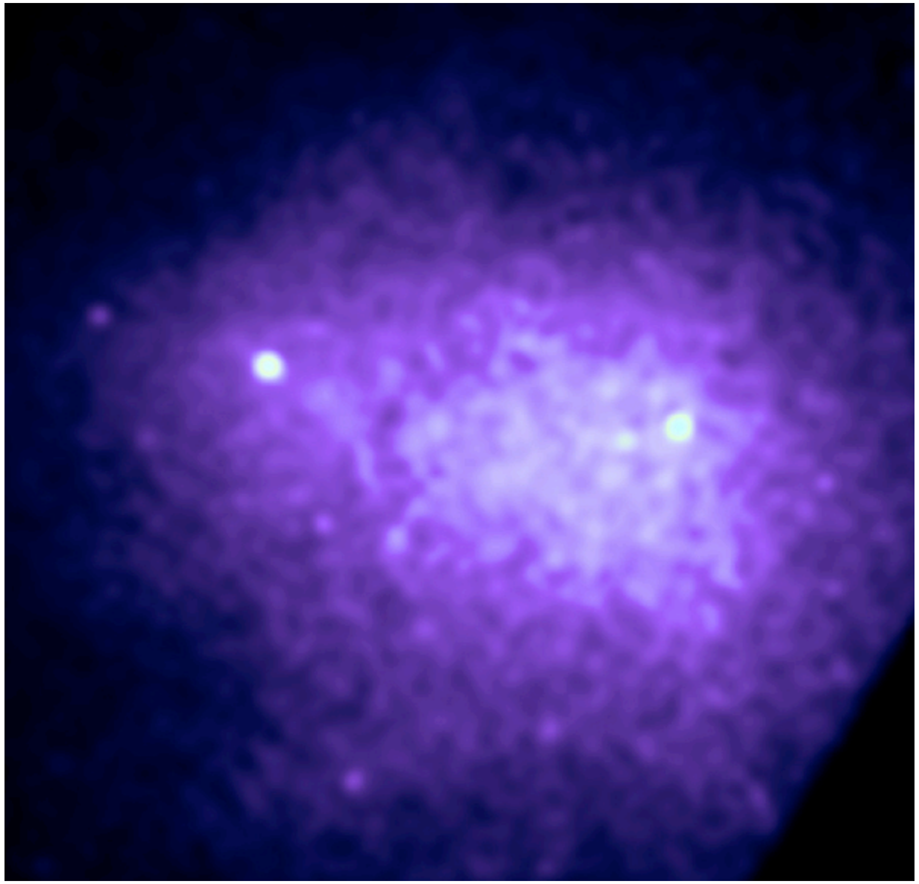
Further evidence comes from observations of **gravitational lensing** of distant sources by a foreground cluster ...
enabling the potential to be reconstructed




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

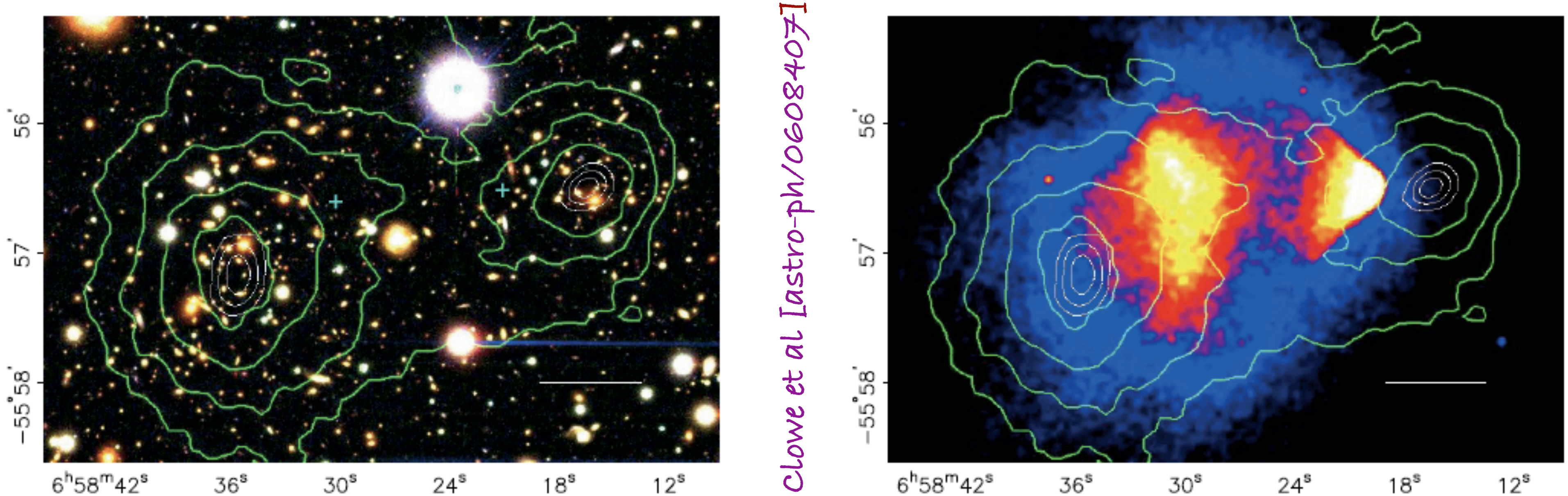


... assuming it is in thermal equilibrium:

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

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**



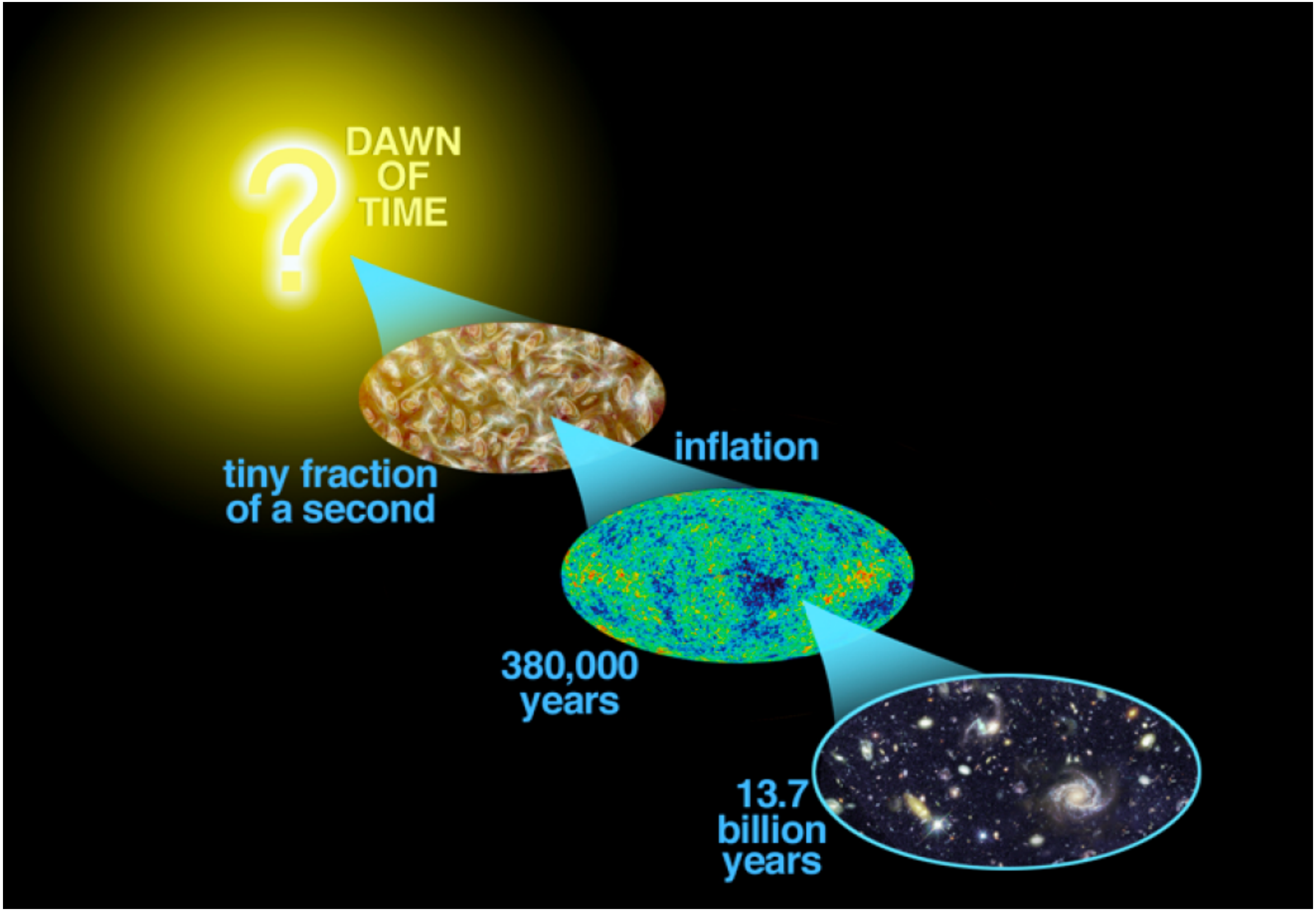

Clowe et al [astro-ph/0608407]

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 $\kappa$ 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 $\kappa$ 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.

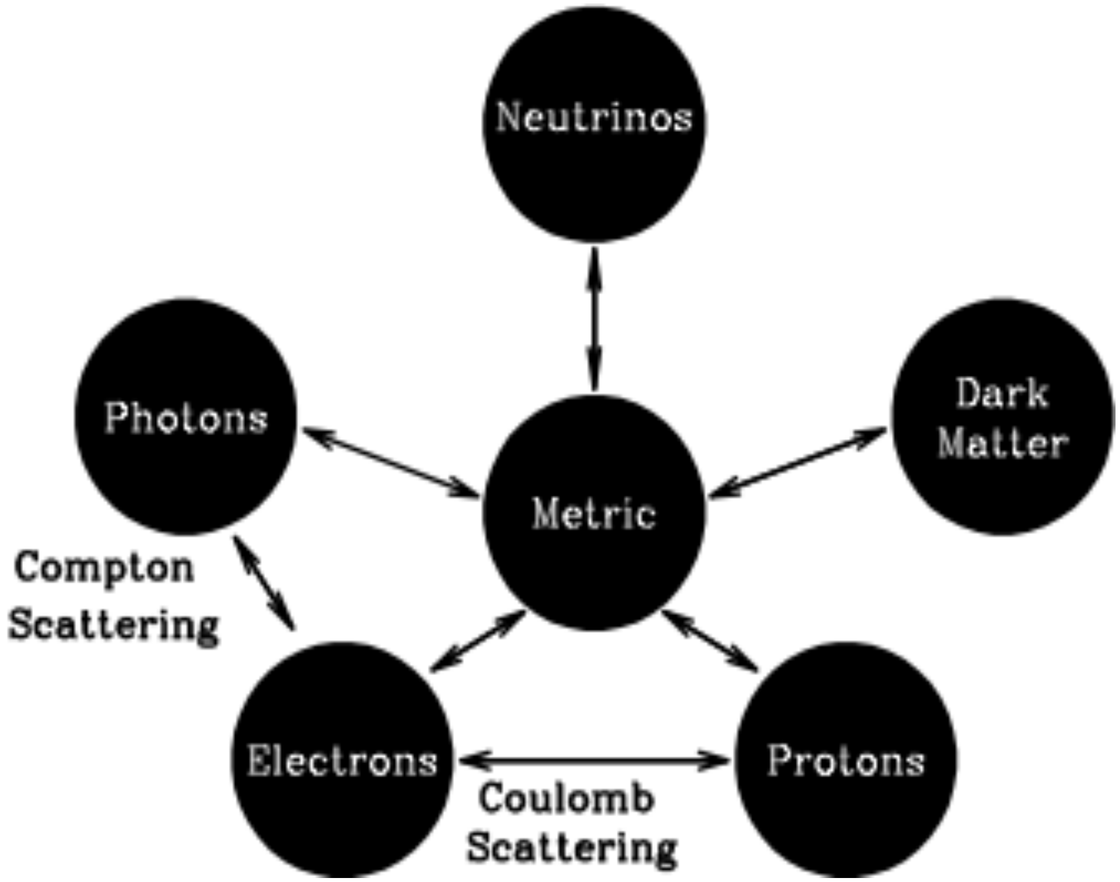
In principle however the alternative theory of gravity which underlies MOND may predict different deflection of light - so the reconstructed gravitational potential may be different

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

Another argument comes from considerations of structure formation in the universe

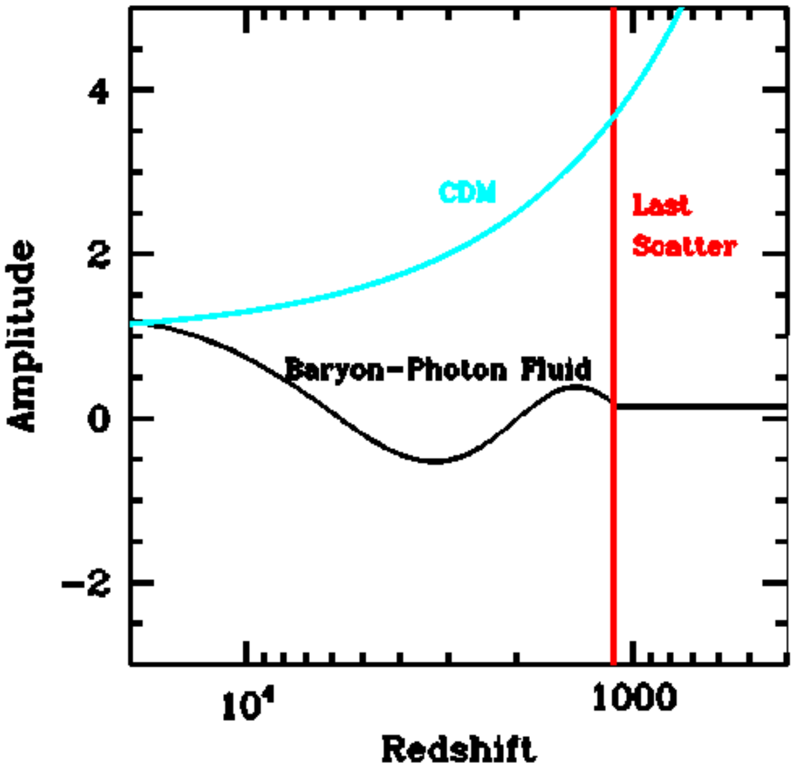


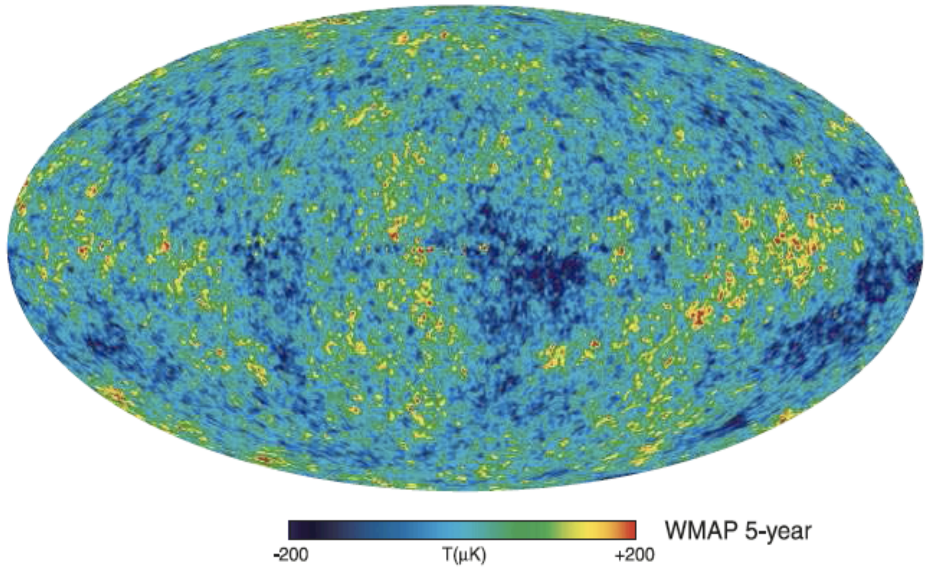
Perturbations in metric (generated during inflation) induce perturbations in photons and (dark) matter




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 …



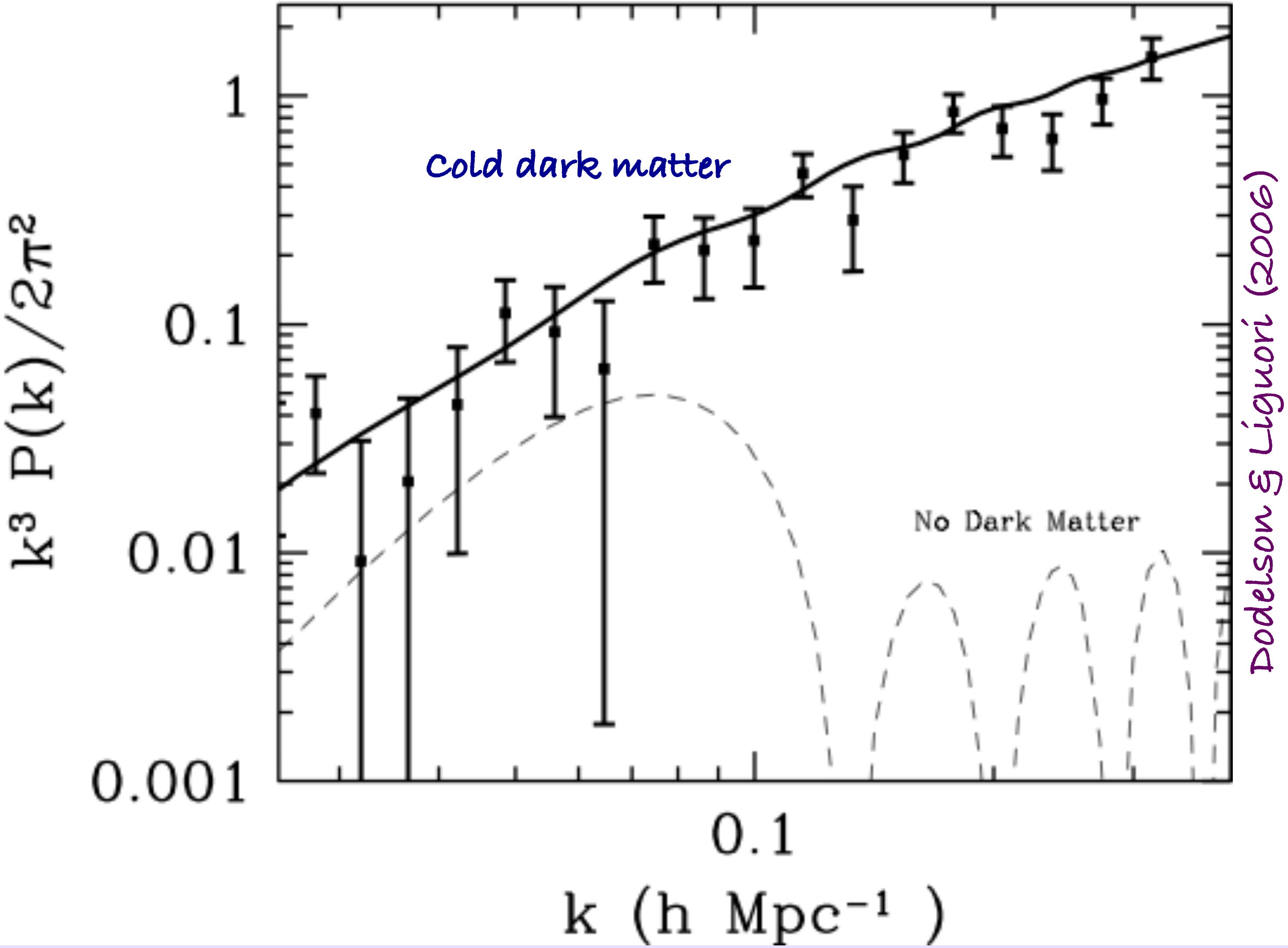

These sound waves leave an imprint on the last scattering surface as the universe turns neutral and transparent … sensitive to the baryon/CDM densities

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

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

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

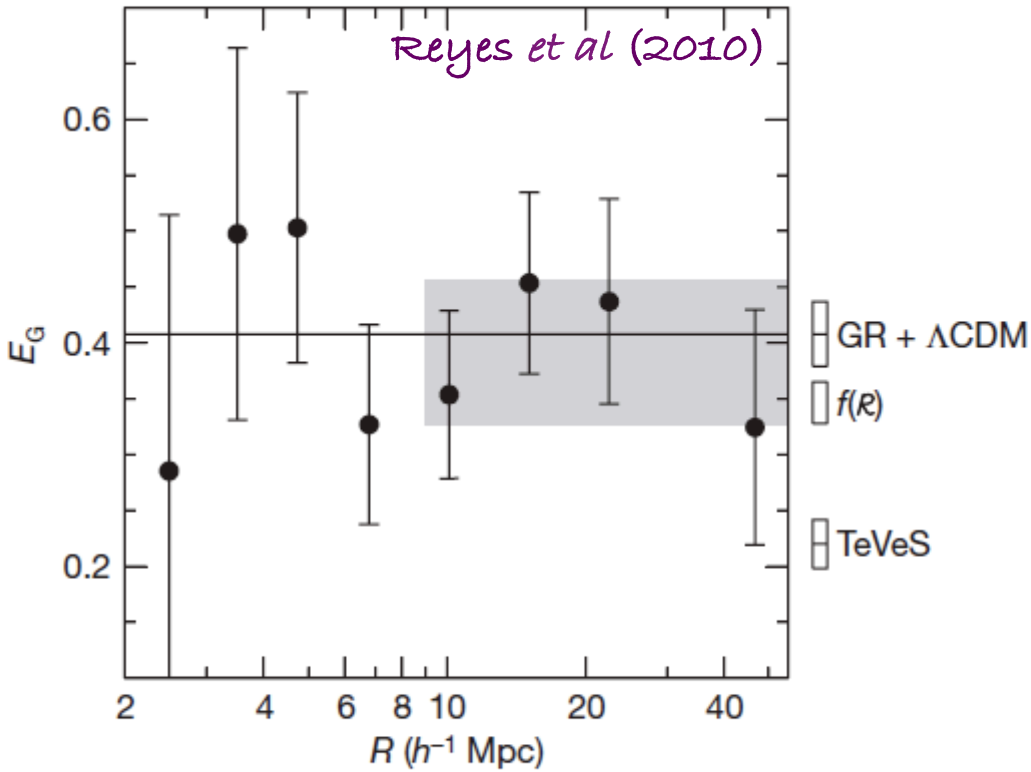
Moreover the observed large-scale structure *requires* $\Omega_m >> \Omega_B$ if it has resulted from the growth under gravity (GR) of small initial density fluctuations … which left their imprint on the CMB at last scattering

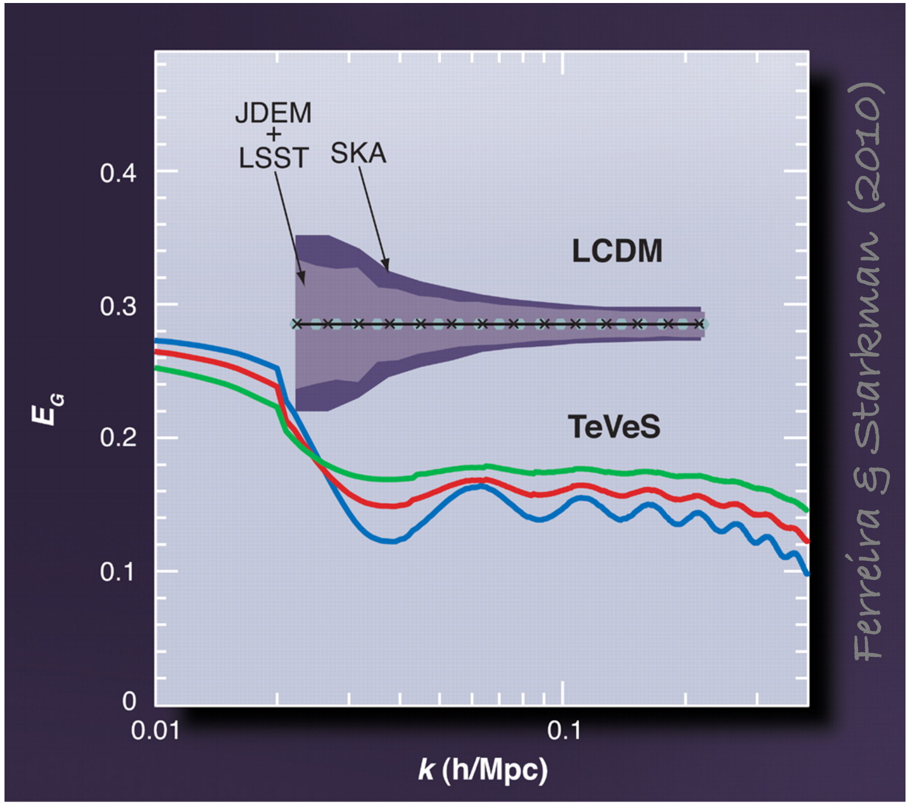



Detailed modelling of WMAP and 2dF/SDSS ⇒ $\Omega_m \sim 0.3$, $\Omega_B \sim 0.05$

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

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




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

# 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: $L \sim v_{rot}^4$ (**"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 – 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!*

Observations indicate that the bulk of the matter in the universe is dark (i.e. dissipationless, ~collisionless, ~cold)

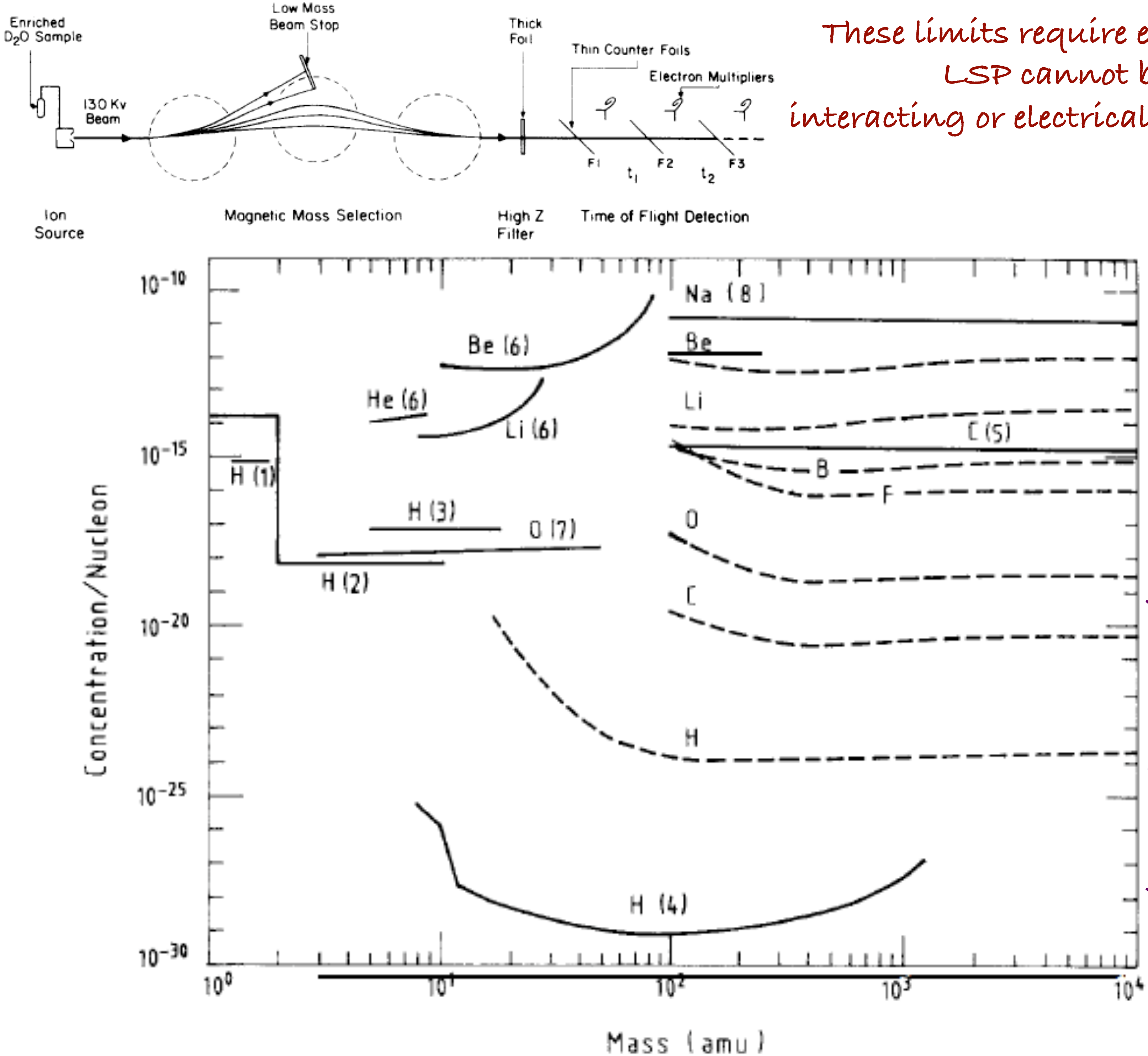
There is a generic expectation that it consists of a new stable particle from physics beyond the Standard Model

... it cannot have electric or colour charge (otherwise would bind to ordinary nuclei creating anomalously heavy isotopes - ruled out experimentally at a high level)

... it cannot couple too strongly to the $Z^0$ (or would have been seen already in accelerator searches)

Underground nuclear recoil detectors are placing restrictive bounds on its elastic scattering cross-section with nucleons ... while indirect searches for gamma-rays, neutrinos and other products of dark matter annihilations (in the Sun, Milky Way, ...) have provided exciting hints!

These limits require e.g. that the LSP cannot be strongly interacting or electrically charged

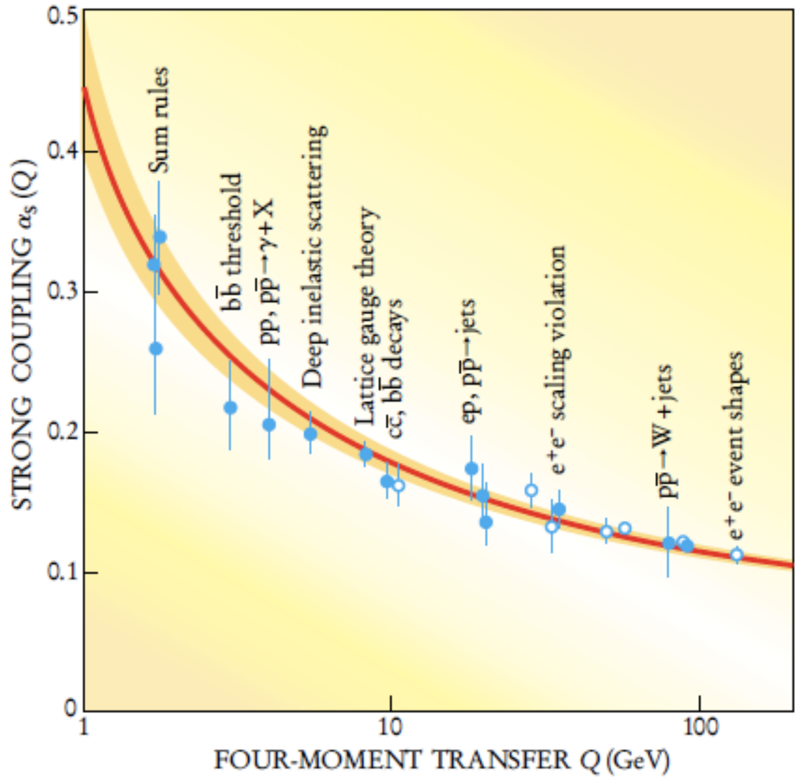


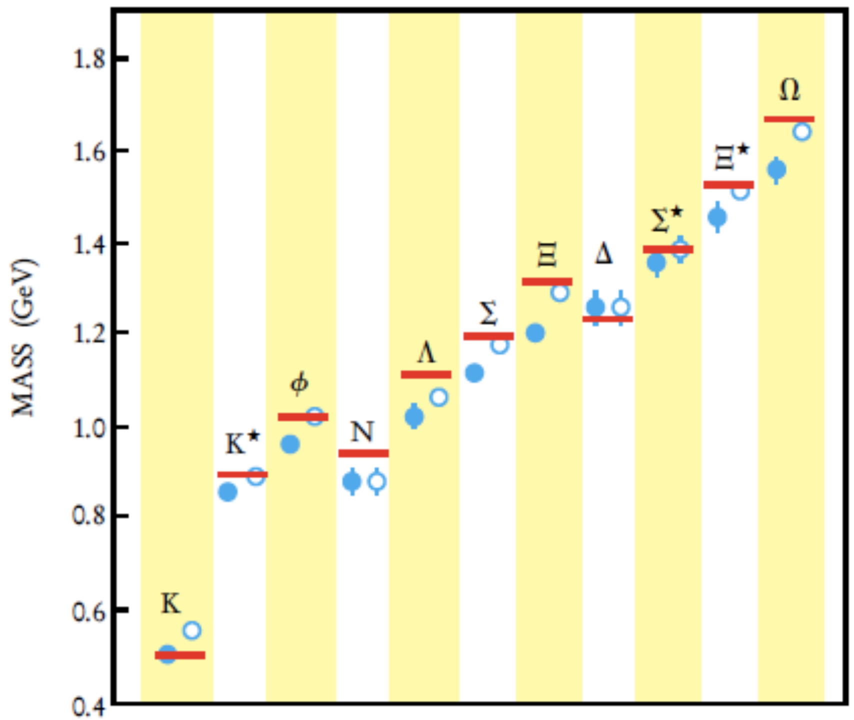

Rich, Lloyd Owen & Spiro, PRep151:239,1987

# What should the world be made of ?

| Mass scale | Particle | Symmetry/ Quantum # | Stability | Production | Abundance |
|---|---|---|---|---|---|
| $\Lambda_{QCD}$ | 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 stable



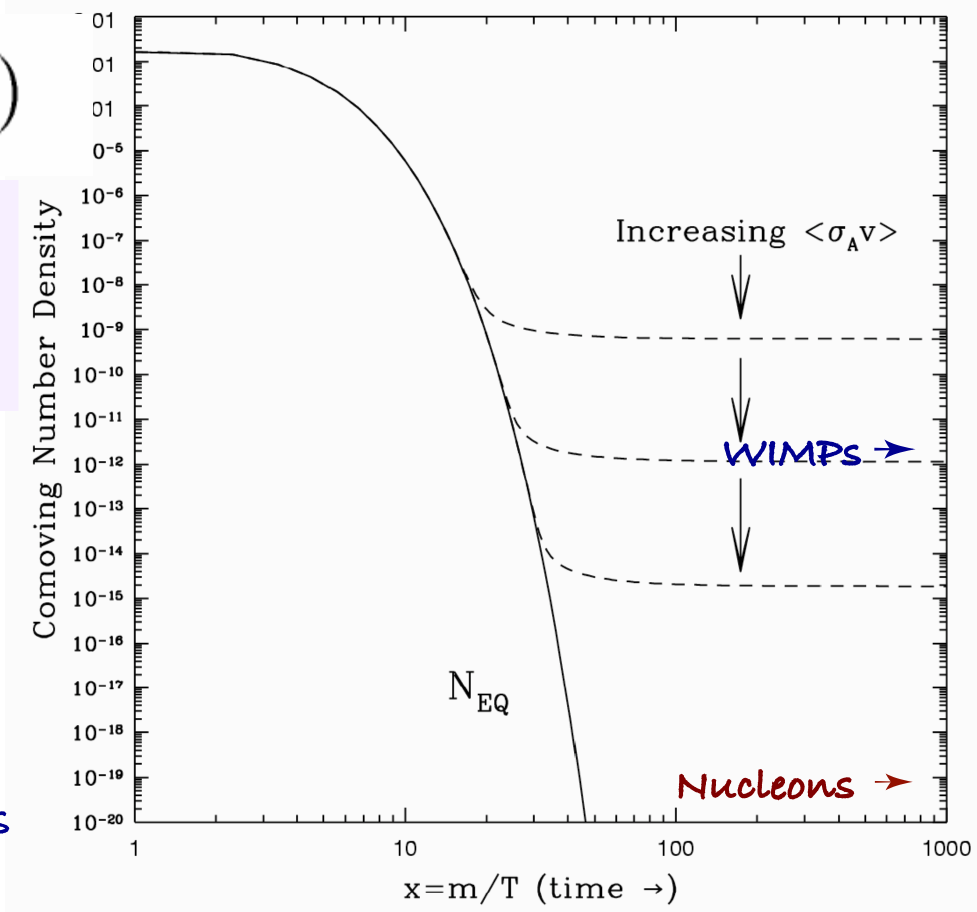




However, in the standard cosmology ~none should be left-over from the Big Bang!

# Thermal Relics

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

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

$$H \sim \frac{\sqrt{g}T^2}{M_P}$$ where g ~ # relativistic species

i.e. 'freeze-out' occurs at T ~ $m_N/45$, 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**: $\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-9}$

**Should we not call this the 'baryon disaster' (cf. 'WIMP miracle')?**

<u>Sakharov conditions for baryogenesis:</u>

1. Baryon number violation
2. C and CP violation
3. Departure for thermal equilibrium

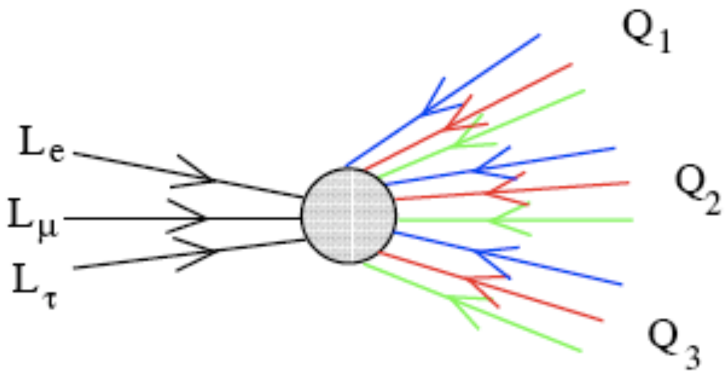
Baryon number violation occurs even in the Standard Model through non-perturbative (sphaleron-mediated) processes … but CP-violation is *too weak* (also the electroweak symmetry breaking phase transition is a 'cross-over' hence not out-of-equilibrium)

Hence the generation of the observed matter-antimatter asymmetry requires new BSM physics (could be related to neutrino masses … **possibly due to violation of lepton number → leptogenesis)**

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


$$\Delta m^2_{atm} = m^2_3 - m^2_2 \simeq 2.6 \times 10^{-3}\mathrm{eV}^2 \qquad \Delta m^2_\odot = m^2_2 - m^2_1 \simeq 7.9 \times 10^{-5}\mathrm{eV}^2$$

# Asymmetric baryonic matter




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

Although **leptogenesis** is not directly testable experimentally (unless the lepton number violation occurs as low as the TeV scale), it is an elegant paradigm for the origin of baryons

**... but in any case we accept that the only kind of matter which we are certain exists, originated *non-thermally* in the early universe**

The Standard $SU(3)_c \times SU(2)_L \times U(1)_Y$ Model provides an exact description of all microphysics (up to some high energy cut-off $M$)

Higgs mass divergence

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

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

The effect of new physics beyond the SM (neutrino mass, nucleon decay, FCNC) → **non-renormalisable operators** suppressed by $M^n$ … which 'decouple' as $M \to M_P$

But as $M$ is raised, the effects of the **super-renormalisable operators** are exacerbated
**Solution for 2nd term → 'softly broken' supersymmetry at $M \sim 1$ TeV**

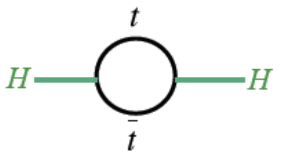
This suggests possible mechanisms for **baryogenesis**, candidates for **dark matter**, … (as also do other proposed extensions of the SM, e.g. new dimensions @ TeV scale)

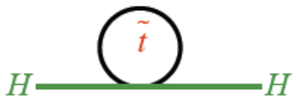
For example, the lightest supersymmetric particle (typically the neutralino $\chi$), if protected against decay by R-parity, is a candidate for thermal dark matter

But if the Higgs is composite (as in **technicolor** models of $SU(2)_L \times U(1)_Y$ breaking) then there is no need for supersymmetry … and light TC states can be dark matter

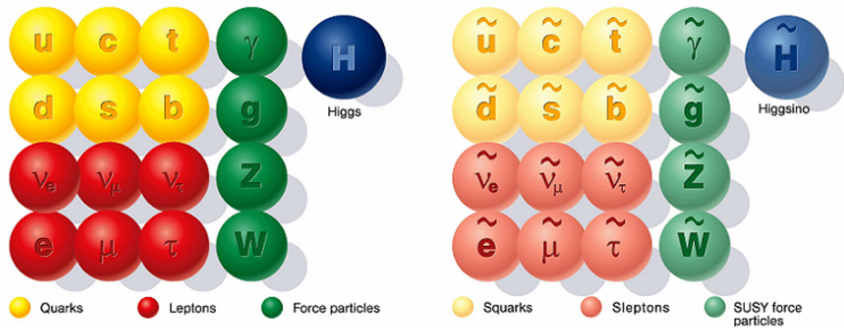
# What should the world be made of ?

| Mass scale | Particle | Symmetry/ Quantum # | Stability | Production | Abundance |
|---|---|---|---|---|---|
| $\Lambda_{QCD}$ | Nucleons | Baryon number | $\tau > 10^{33}$ yr (dim-6 OK) | ~~'freeze-out' from thermal equilibrium~~ Asymmetric baryogenesis | $\Omega_B \sim 10^{-10}$ cf. observed $\Omega_B \sim 0.05$ |
| $\Lambda_{Fermi} \sim G_F^{-1/2}$ | Neutralino? | R-parity? | Violated? (matter parity adequate for p stability) | 'freeze-out' from thermal equilibrium | $\Omega_{LSP} \sim 0.25$ |




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

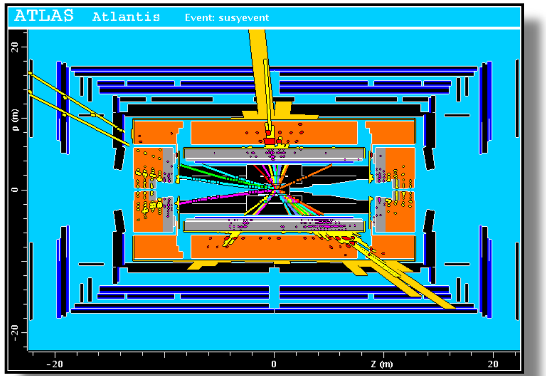


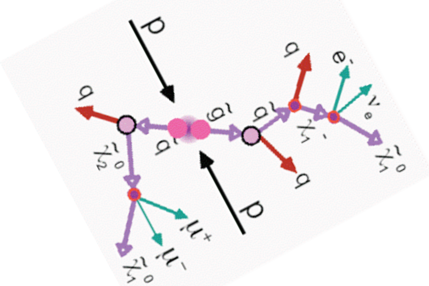

For (softly broken) **supersymmetry** we have the 'WIMP miracle':

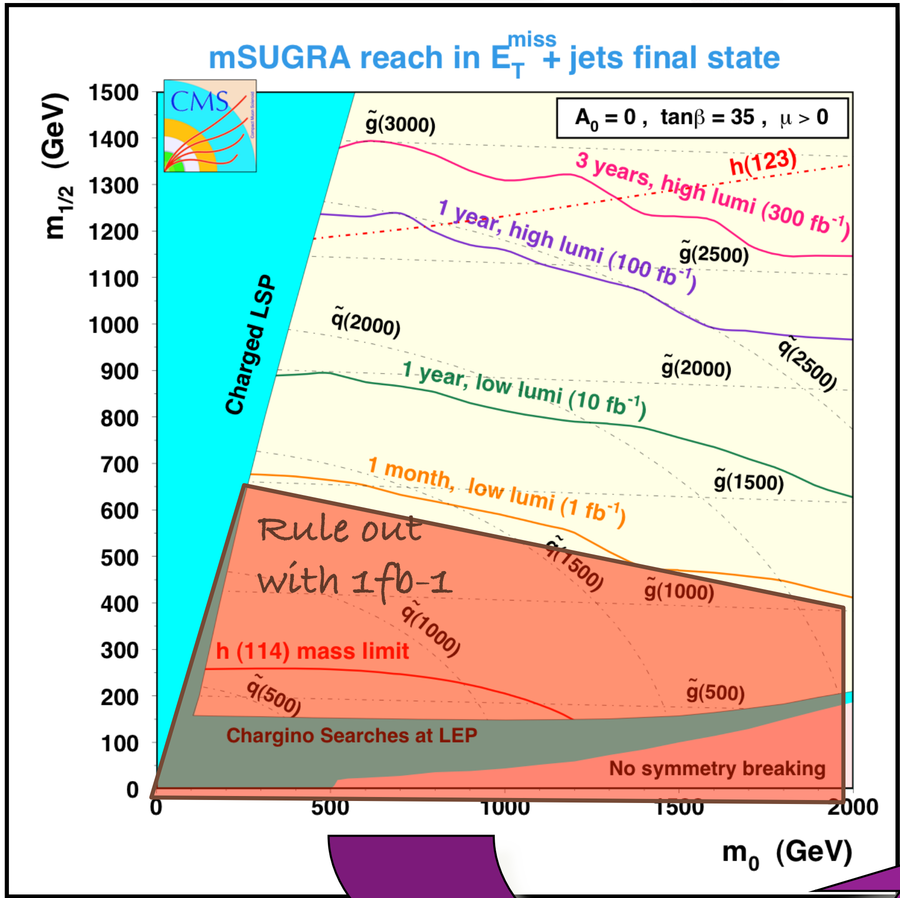
$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27} \mathrm{cm}^{-3} \mathrm{s}^{-1}}{\langle \sigma_{\mathrm{ann}} v \rangle_{T=T_{\mathrm{f}}}} \simeq 0.1 \quad , \text{ since } \langle \sigma_{\mathrm{ann}} v \rangle \sim \frac{g_\chi^4}{16\pi^2 m_\chi^2} \approx 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

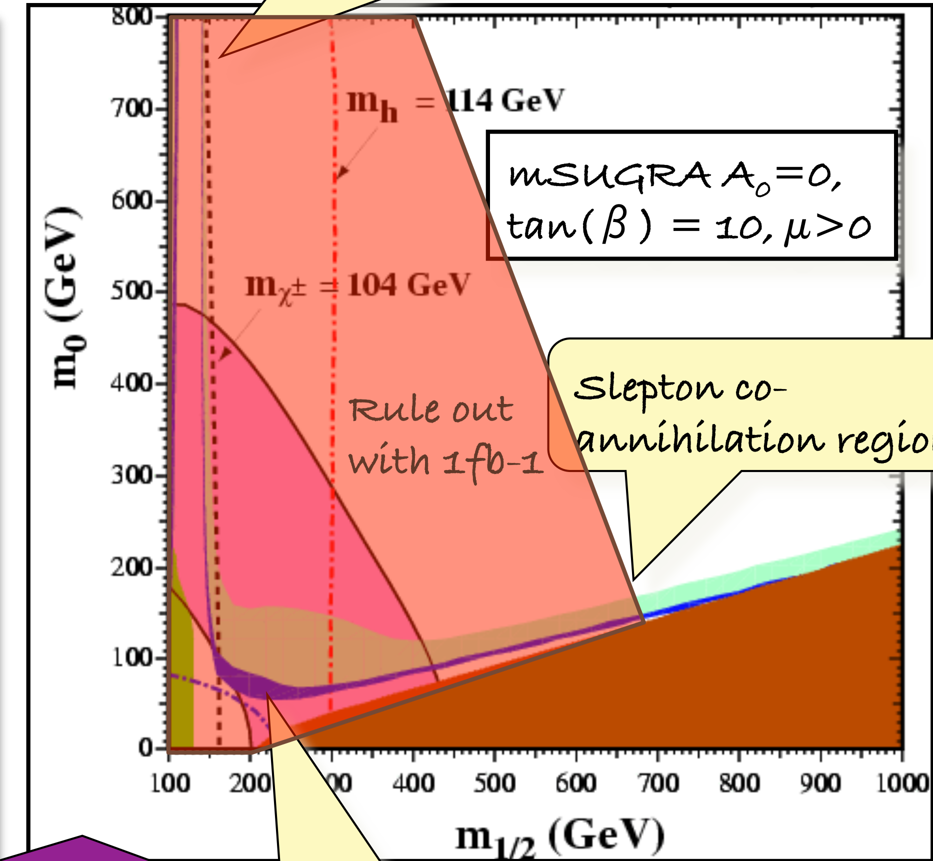
But why should a thermal relic have an abundance comparable to that of baryons?

# LHC reach for SUSY dark matter






'Focus point' region: annihilation to gauge bosons

Slepton co-annihilation region

'Bulk' region: t-channel slepton exchange

WMAP constraints

# What should the world be made of ?

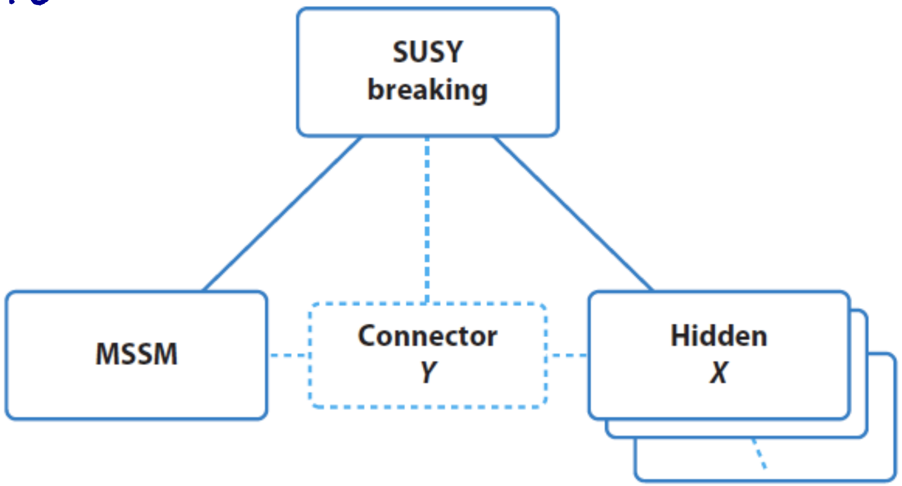
| Mass scale | Particle | Symmetry/ Quantum # | Stability | Production | Abundance |
|---|---|---|---|---|---|
| $\Lambda_{QCD}$ | Nucleons | Baryon number | $\tau > 10^{33}$ yr dim-6 OK | ~~'freeze-out' from thermal equilibrium~~ | $\Omega_B \sim 10^{-10}$ cf. observed $\Omega_B \sim 0.05$ |
| $\Lambda_{Fermi}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

This also yields the 'WIMPless miracle' (Feng & Kumar 2008)

since for generic hidden sector matter: $g_h^2/m_h \sim g_\chi^2/m_\chi \sim F/16\pi^2 M$
which gives required abundance as before

$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27}\mathrm{cm}^{-3}\mathrm{s}^{-1}}{\langle \sigma_{\mathrm{ann}} v \rangle_{T=T_f}} \simeq 0.1$$

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



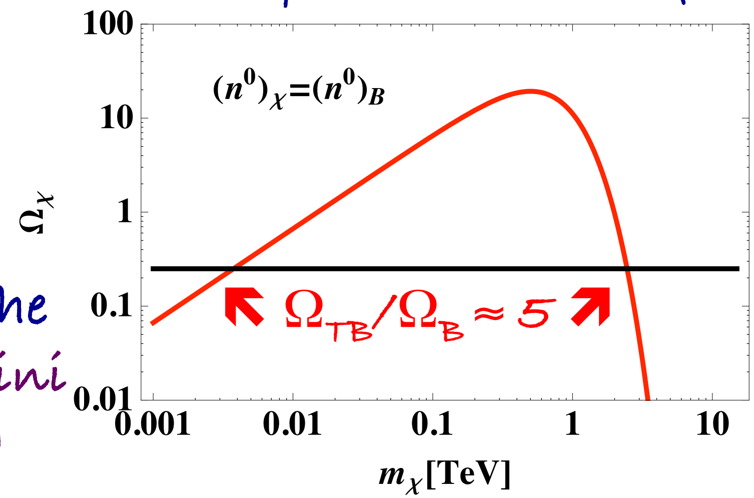
# What should the world be made of ?

| Mass scale | Particle | Symmetry/ Quantum # | Stability | Production | Abundance |
|---|---|---|---|---|---|
| $\Lambda_{QCD}$<br><br>$\Lambda_{QCD'} \sim 5\Lambda_{QCD}$ | Nucleons<br><br>Dark baryon | Baryon number<br><br>$U(1)_{DB}$ | $\tau > 10^{33}$ yr<br><br>? | Asymmetric baryogenesis<br><br>Asymmetric (like baryons) | $\Omega_B \sim 0.05$<br><br>$\Omega_{DB} \sim 0.25$ |
| $\Lambda_{Fermi} \sim G_F^{-1/2}$ | Neutralino?<br><br>Technibaryon? | R-parity?<br><br>(walking) Technicolour | violated?<br>$\tau \sim 10^{18}$ yr<br>$e^+$ excess?! | 'freeze-out' from thermal equilibrium<br>Asymmetric (like baryons) | $\Omega_{LSP} \sim 0.25$<br><br>$\Omega_{TB} \sim 0.25$ |

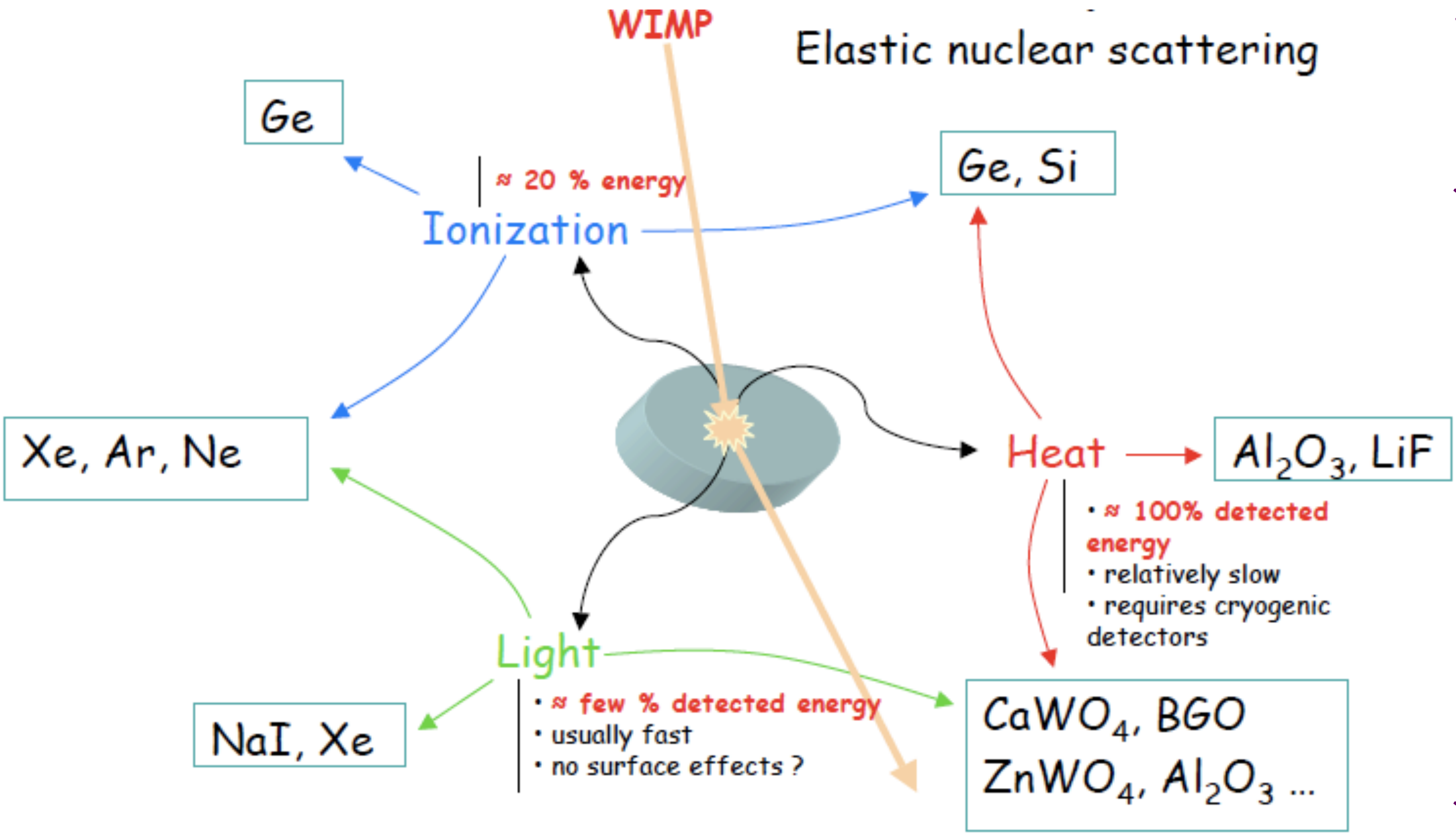
A new EW-scale particle which shares in this asymmetry (e.g. technibaryon) would have the right abundance to be dark matter … and explain the ratio of dark to baryonic matter (Nussinov 1985)

$$\frac{\rho_{\rm DM}}{\rho_{\rm B}} \simeq 6 \sim \frac{m_{\rm DM}}{m_{\rm B}} \left(\frac{m_{\rm DM}}{m_{\rm B}}\right)^{3/2} e^{-m_{\rm DM}/T_{\rm dec|sphaleron}}$$

For 'hidden' baryons with mass of a few GeV the required relic abundance is more natural (Gelmini et al 1987, DB Kaplan 1992, Kaplan et al 2009 …)



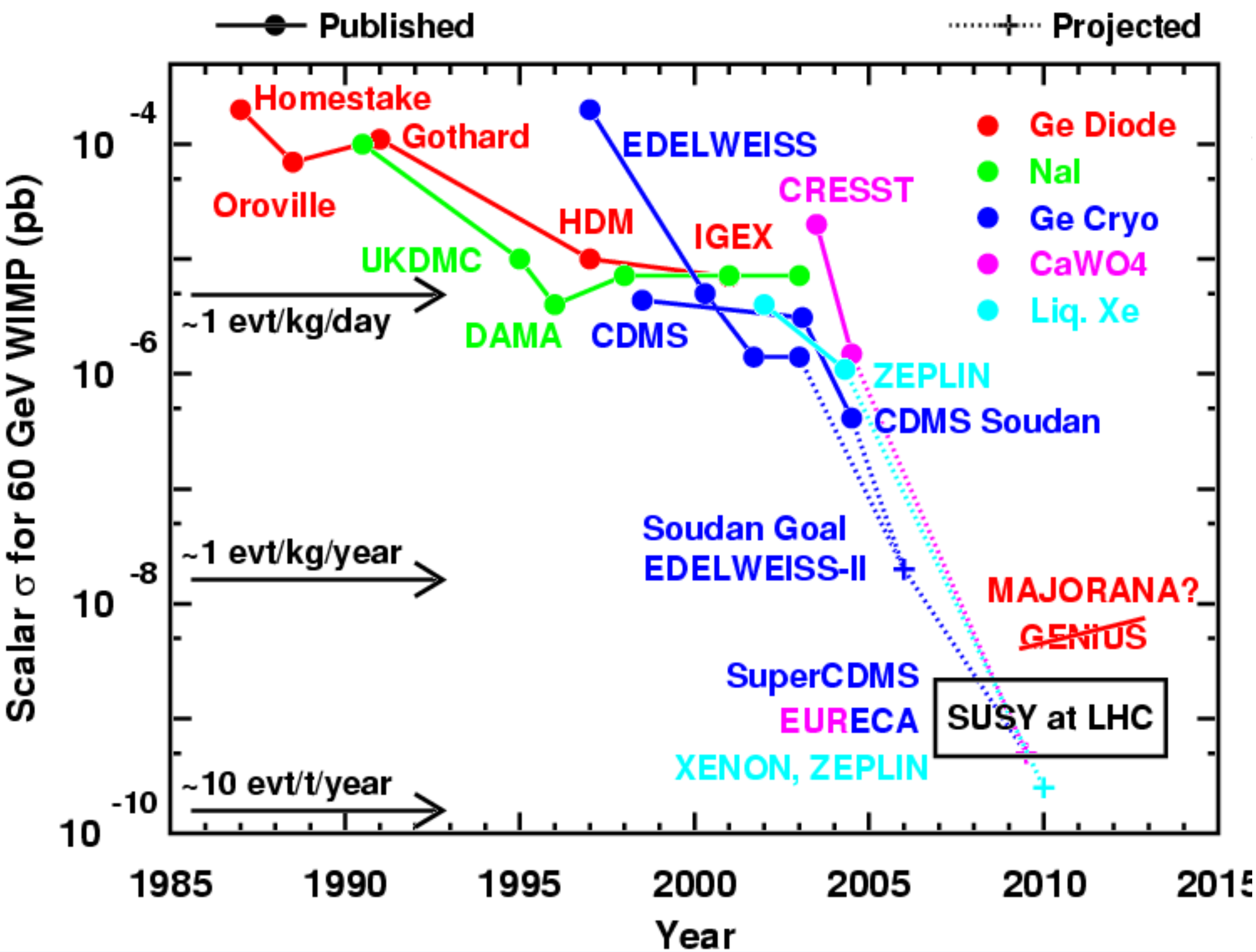
## So can try to detect any passing halo dark matter particles directly, with well-shielded underground experiments




ukier & Stodolsky 1984; Goodman & Witten 1985)

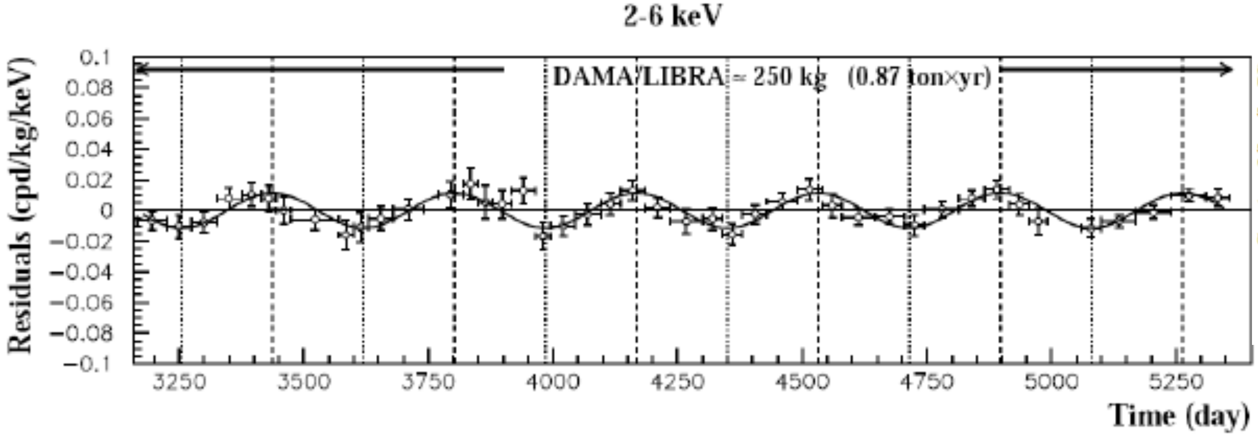
No detection so far ⇒ upper limit of ~$10^{-44}$ $cm^2$ on SI scattering cross-section of ~100 GeV WIMPs, assuming local halo dark matter density ~ 0.4 GeV $cm^{-3}$

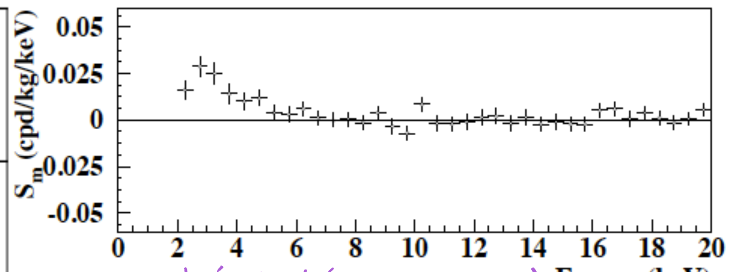
For ~25 years there has been a world-wide race on to detect dark matter ...



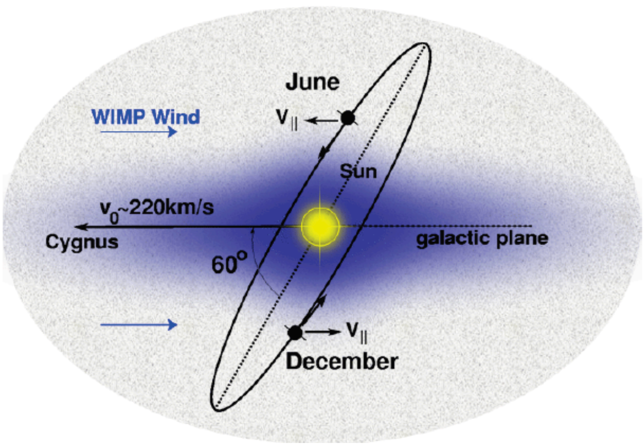

But most of the direct detection experiments have been optimised for ~100 GeV WIMPs (motivated by supersymmetry) ... they are not as sensitive to ~few GeV dark matter particles ⇒ O(keV) recoil energy

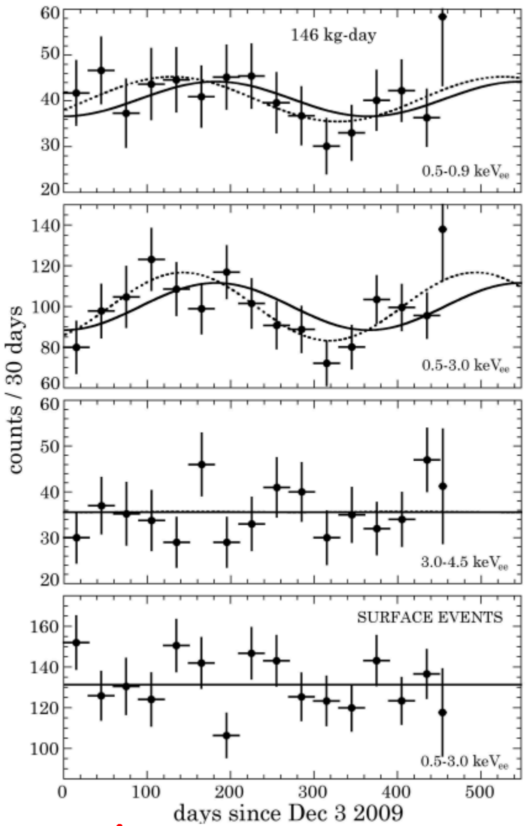
# Some experiments (DAMA, CoGeNT,) have reported modulation signals for ~5-10 GeV mass particles with $\sigma_{SI} \sim 10^{-40}$-$10^{-39}$ cm$^2$!

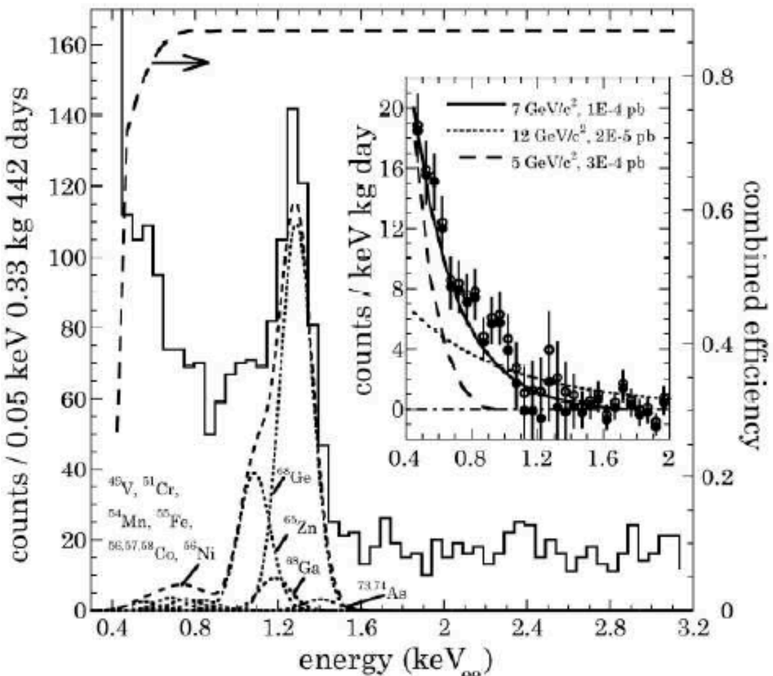



Bernabei et al (2008, 2010)




CoGeNT: Aalseth et al (2010, 2011)

*STOP PRESS* CRESST has just reported >4σ evidence for light dark matter

# Results from 730 kg days of the CRESST-II Dark Matter Search [arXiv:1109.0702]

Sixty-seven events are found in the acceptance region where a WIMP signal in the form of low energy nuclear recoils would be expected. We estimate background contributions to this observation from four sources … Using a maximum likelihood analysis, we find, at a high statistical signicance, that these sources alone are not sufficient to explain the data. The addition of a signal due to scattering of relatively light WIMPs could account for this discrepancy, and we determine the associated WIMP parameters.

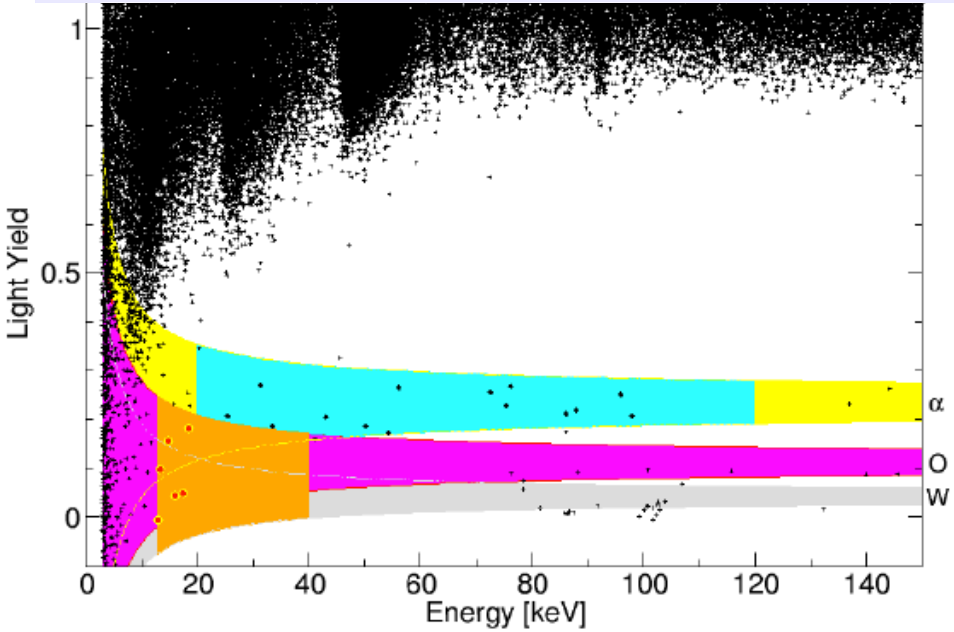



**Fig. 6.** (Color online) The data of one detector module (Ch20), shown in the light yield vs. recoil energy plane. The large number of events in the band around a light yield of 1 is due to electron and gamma background events. The shaded areas indicate the bands, where alpha (yellow), oxygen (violet), and tungsten (gray) recoil events are expected. Additionally highlighted are the acceptance region used in this work (orange), the reference region in the $\alpha$-band (blue), as well as the events observed in these two regions. See text for discussion.

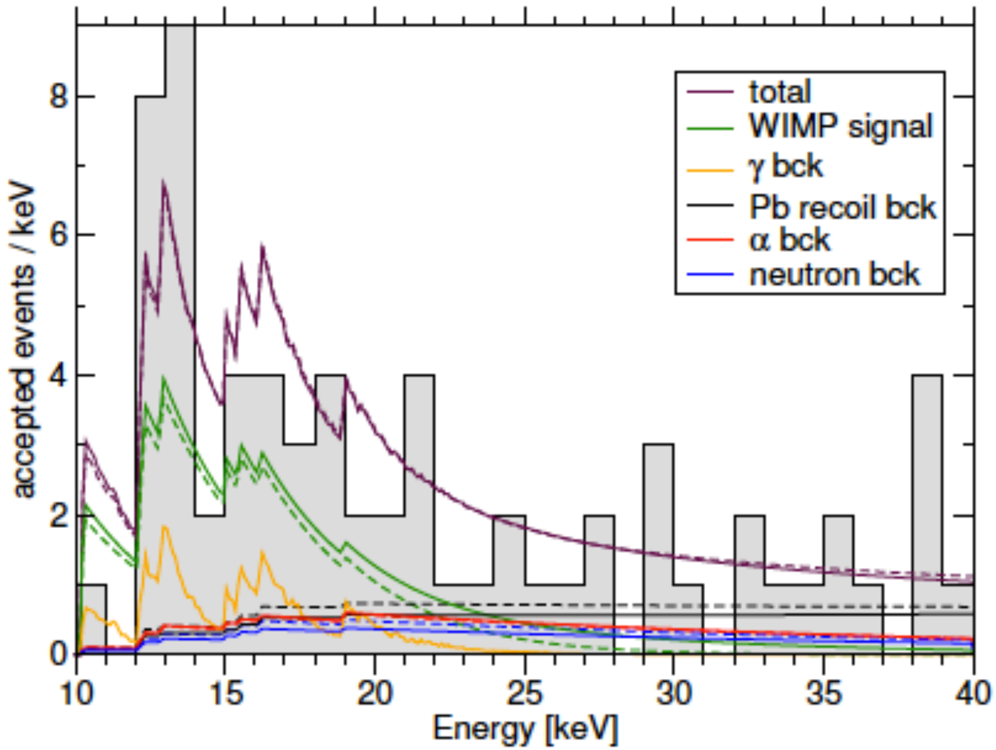
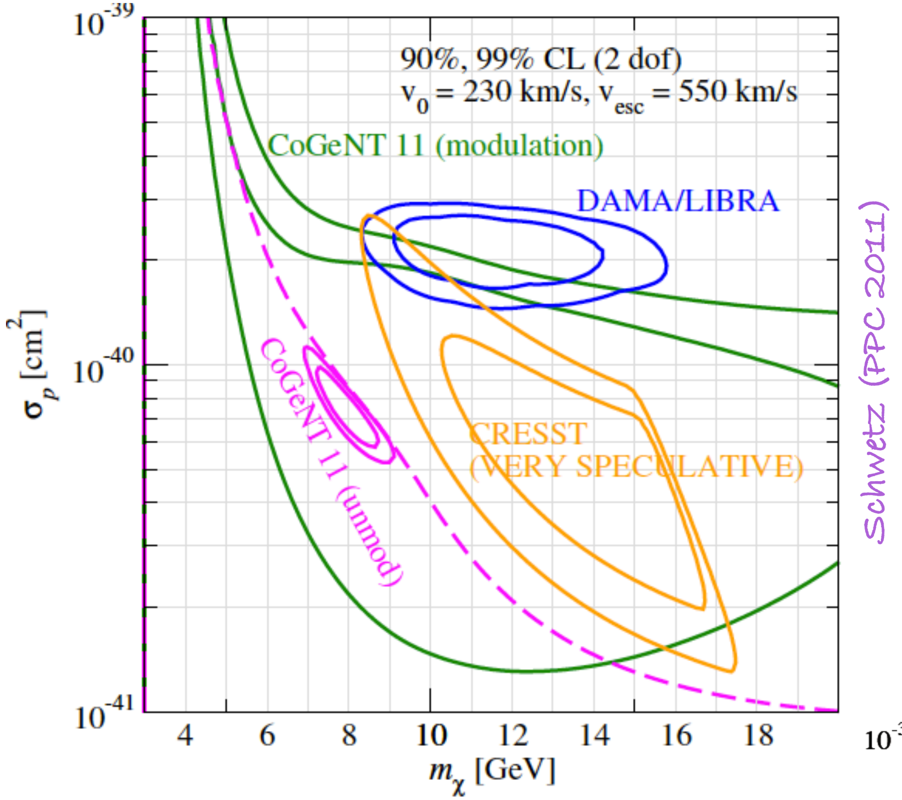
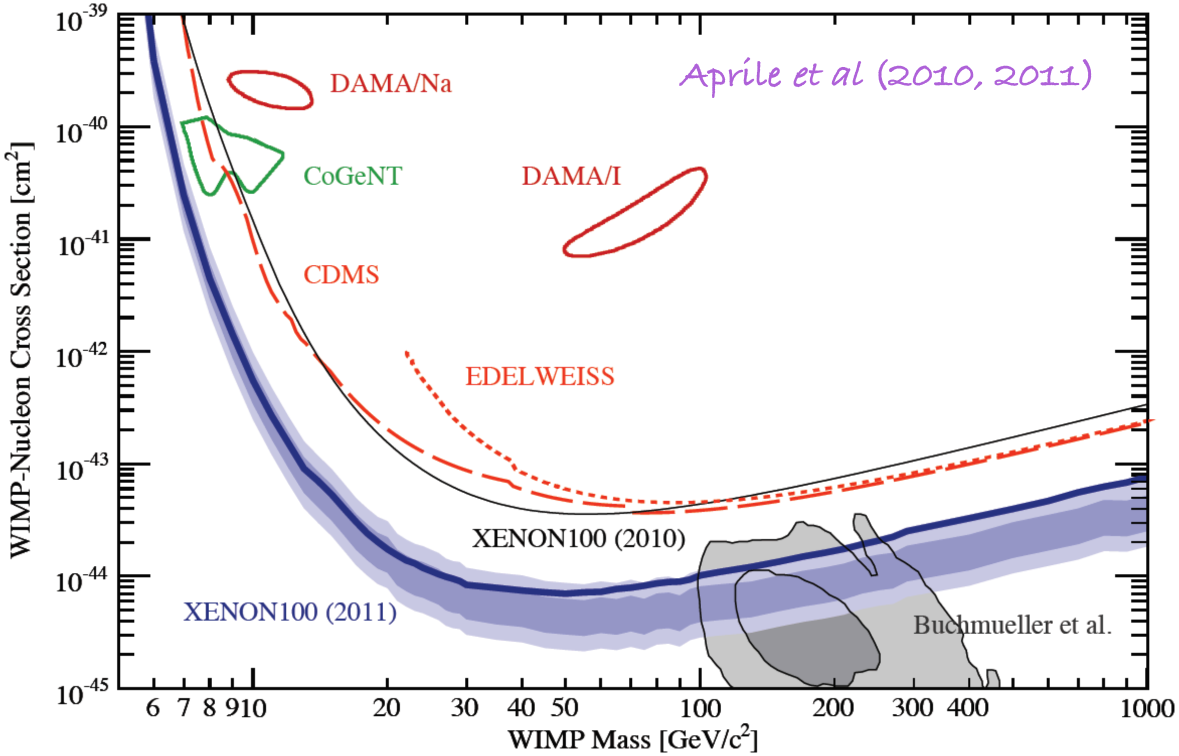



**Fig. 11.** (Color online) Energy spectrum of the accepted events from all detector modules, together with the expected contributions from the considered backgrounds and a WIMP signal, as inferred from the likelihood fit. The solid and dashed lines correspond to the fit results M1 and M2, respectively.




These signals are not quite consistent (for an assumed standard Maxwellian velocity distribution for halo dark matter) ... and are supposedly ruled out completely by data from much bigger experiments like CDMS and XENON-100

This is however hotly disputed - e.g. the efficiency of XENON to detect scintillation light at low recoil energy is rather uncertain ... and so is the CDMS energy scale (Collar et al 2011)



There are several sources of uncertainty in the measured recoil rate:

$$\frac{\mathrm{d}R}{\mathrm{d}E_R}(E_R,t) = M_{\mathrm{tar}} \frac{\rho_\chi}{2\, m_\chi \mu^2} \frac{(f_p Z + f_n(A-Z))^2}{f_n^2} \sigma_n F^2(E_R) \int_{v_{\min}}^{\infty} \mathrm{d}^3 v\, \frac{f_{\mathrm{local}}(\vec{v},t)}{v}$$

Particle physics

Nuclear physics

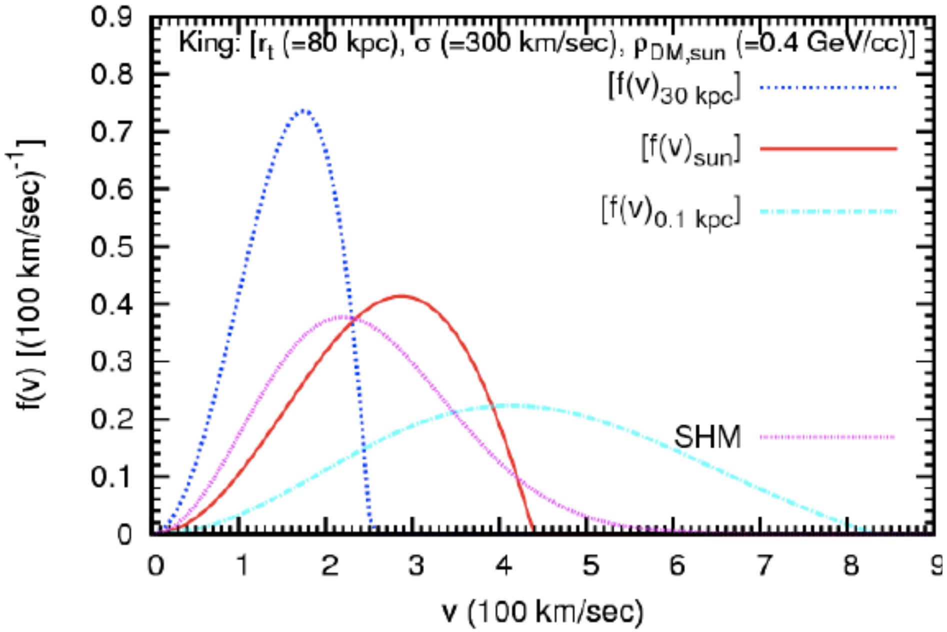
astrophysics

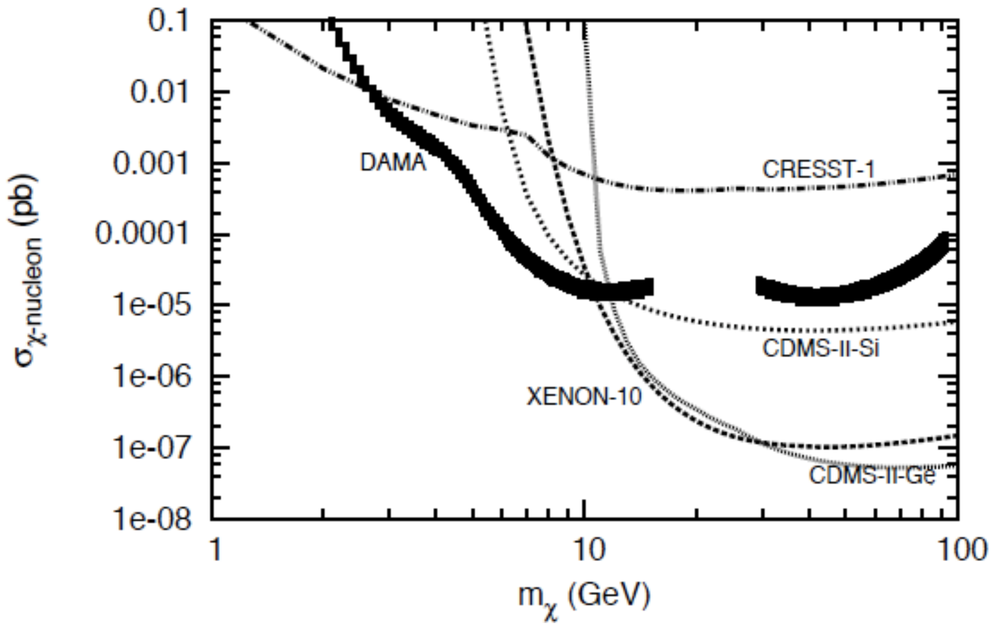
... so can attempt to reconcile the different results by considering whether dark matter might interact with neutrons and protons differently e.g. $f_n/f_p \sim -0.7$ reduces sensistivity of XENON (Giulani 2005, Cheng et al 2010, Feng et al 2011, Frandsen et al 2011) - or have interactions that are mainly inelastic/ momentum dependent/leptophilic/spin-dependent/electromagnetic ... or various combinations of these (many theoretical papers over the past year)

Then there are experimental uncertainties (efficiencies, energy resolution, backgrounds ...) as well as uncertainties in translating measured energies into recoil energies (channelling, quenching ...)

It is becoming increasingly clear that this is not going to be easy!

Another source of uncertainty is the *assumed* velocity distribution of dark matter in the Galaxy … e.g. a non-Maxwellian distribution (determined *self-consistently*, accounting for the effect of baryons) may change the picture (Chaudhury, Bhattacharjee & Cowsik, 2010)

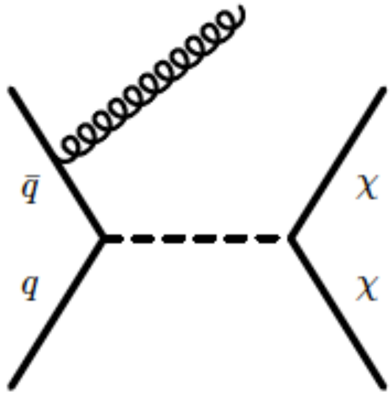


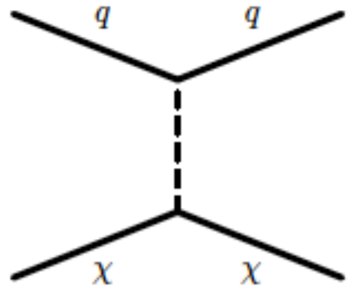

Moreover the escape velocity from the Galaxy and even the Sun's orbital velocity are not known accurately and the local density of dark matter is uncertain by a factor of ~2 … varying these parameters alters the limits

Expect improved measurements from *GAIA* (2012)

Interestingly there is a way to directly measure the coupling of dark matter particles at colliders, by looking for 'monojet' events (Goodman et al 2010, Bai et al 2011, Fox et al 2011) – note this is the same coupling that enters in direct detection




So parametrise all possible dark matter interactions as effective operators, then calculate the expected signal (typically ~10 times smaller than the SM background) and use existing data to set bounds




$$\frac{i\, g_\chi\, g_q}{q^2 - M^2} \left(\bar{q}q\right)\left(\bar{\chi}\chi\right) ,$$ SI, scalar exchange

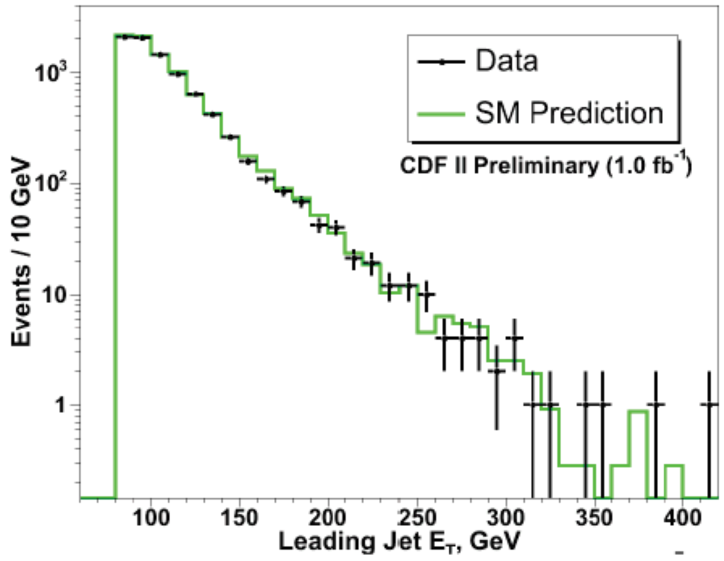
$$\frac{i\, g_\chi\, g_q}{q^2 - M^2} \left(\bar{q}\gamma_\mu q\right)\left(\bar{\chi}\gamma^\mu\chi\right) ,$$ SI, vector exchange

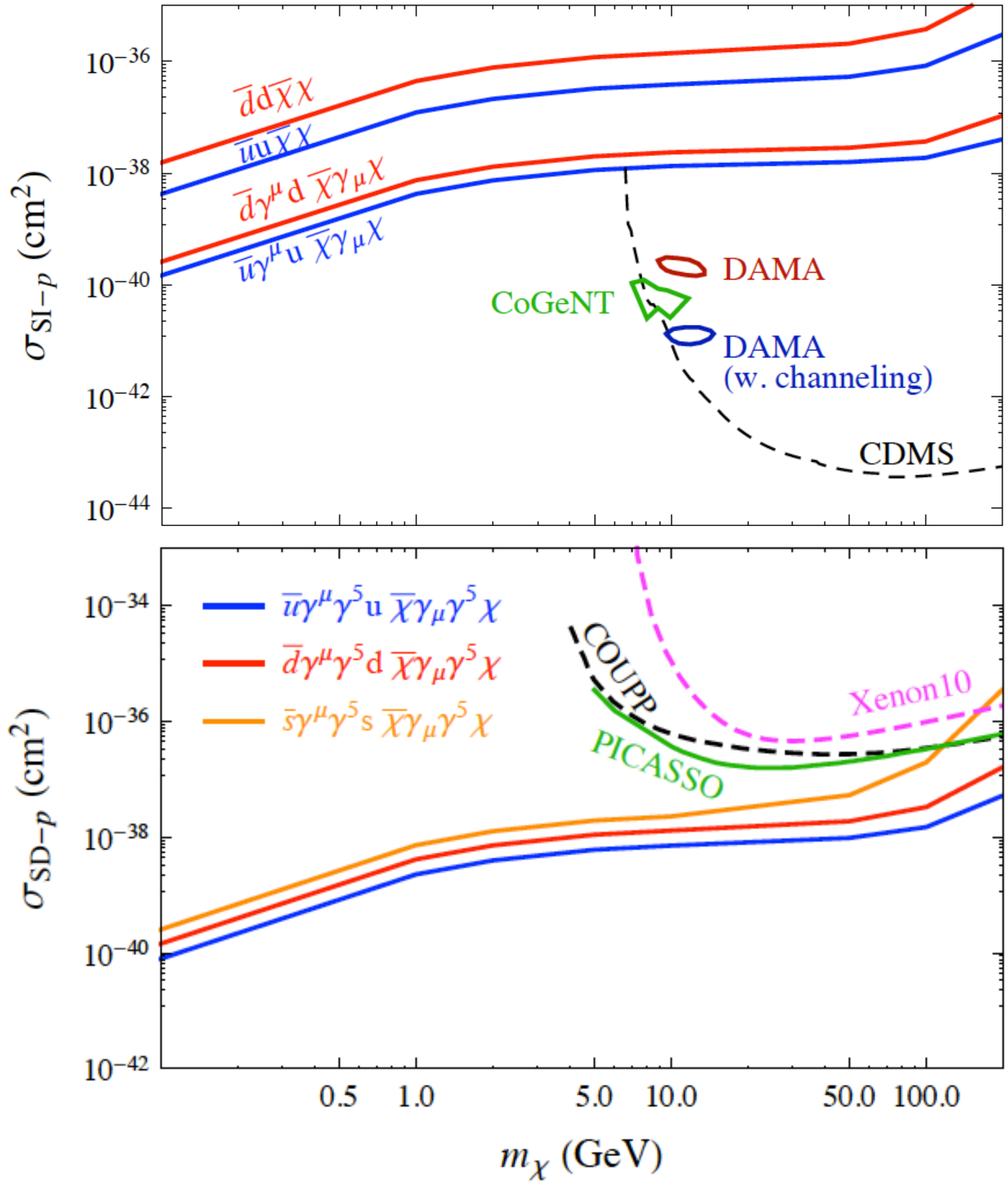
$$\frac{i\, g_\chi\, g_q}{q^2 - M^2} \left(\bar{q}\gamma_\mu\gamma_5 q\right)\left(\bar{\chi}\gamma^\mu\gamma_5\chi\right) ,$$ SD, axial-vector exchange

$$\frac{i\, g_\chi\, g_q}{q^2 - M^2} \left(\bar{q}\gamma_5 q\right)\left(\bar{\chi}\gamma_5\chi\right) ,$$ SD and mom. dep., psuedo-scalar exchange

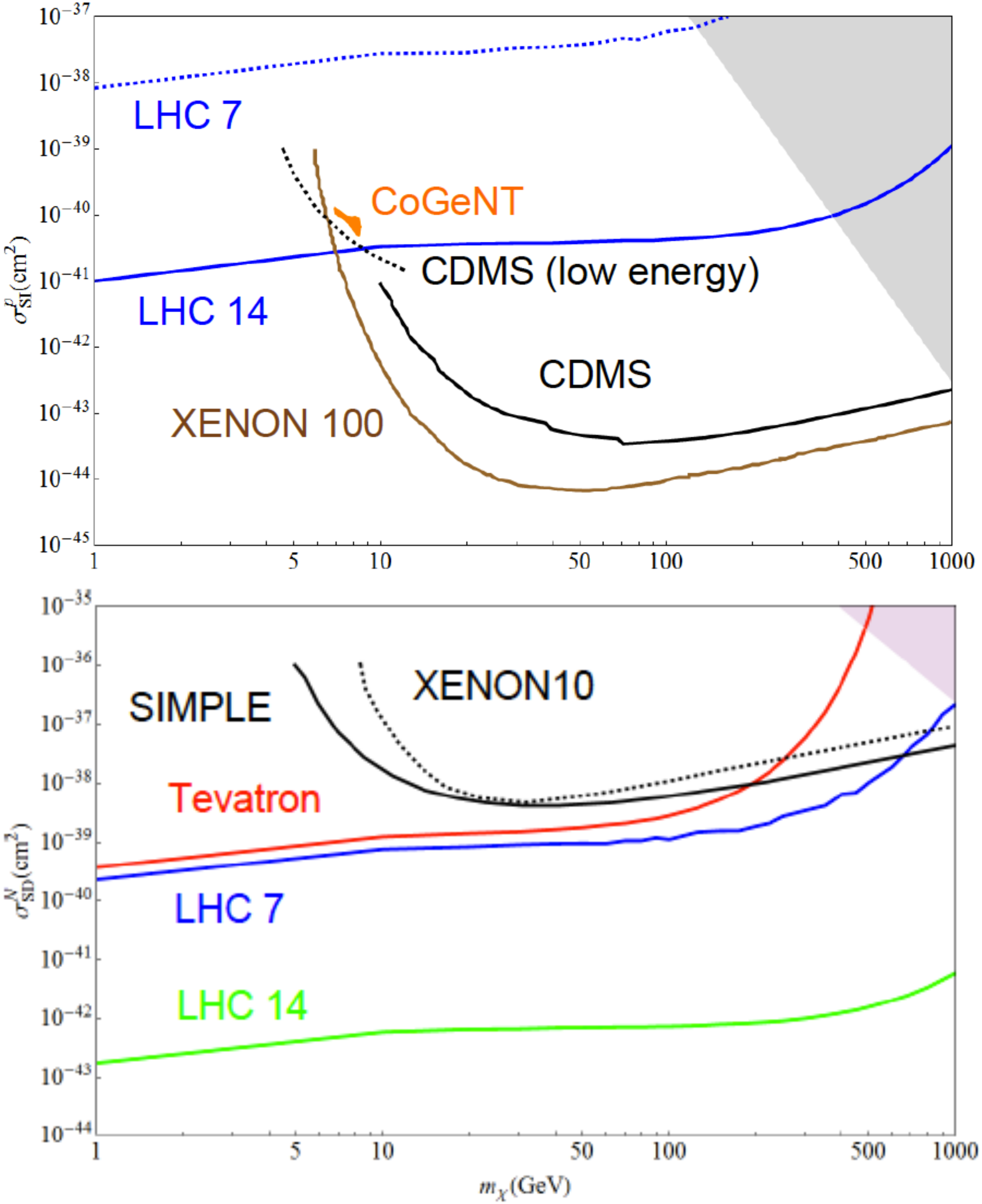
E.g. data from the CDF expt at the Tevatron yield limits which are competitive already with direct detection expts for SD interactions
(Bai, Fox & Harnik 2010)

$$\not{E}_T > 80 \text{ GeV}$$
$$p_T(j1) > 80 \text{ GeV}$$
$$p_T(j2) < 30 \text{ GeV}$$
$$p_T(j3) < 20 \text{ GeV}$$



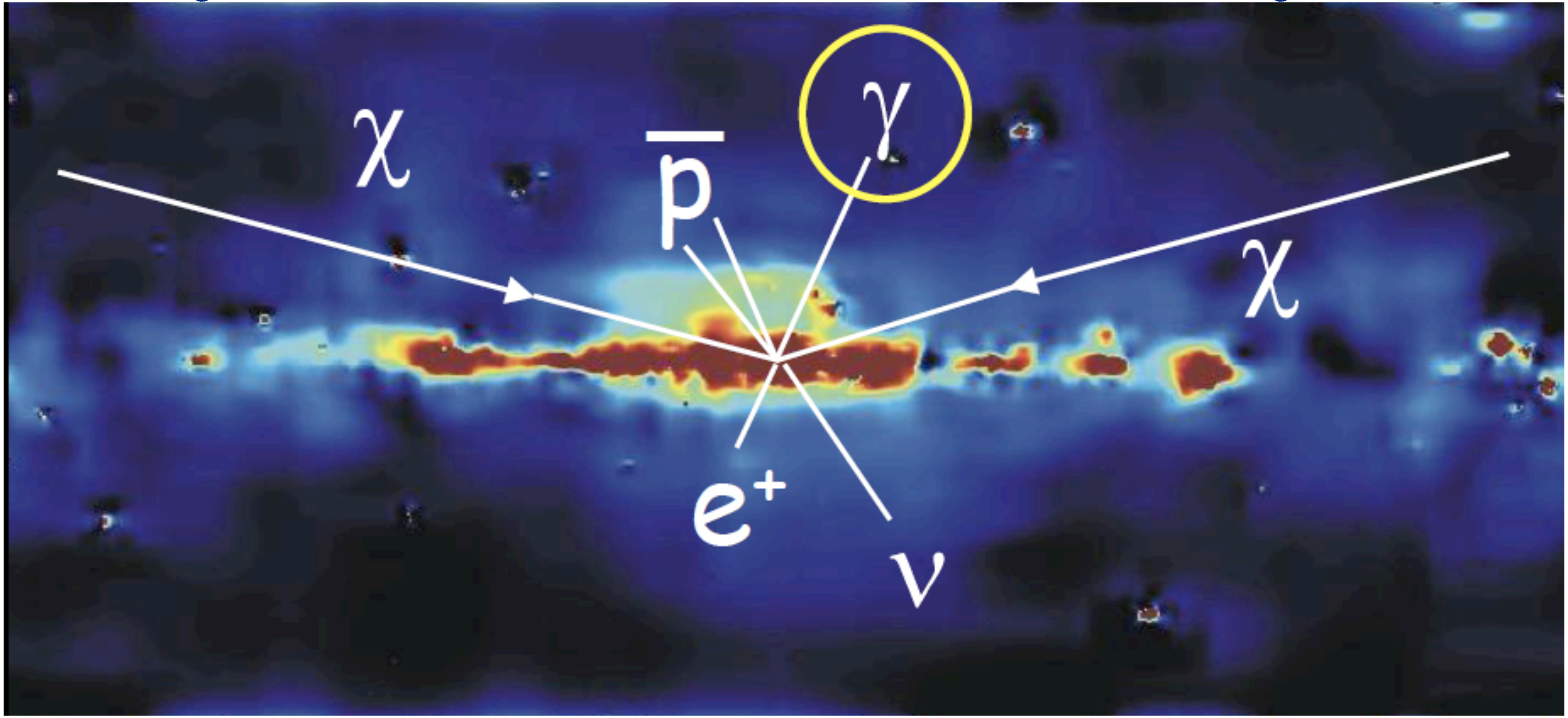



ATLAS and CMS at the LHC are also doing searches for 'monojets' … the expected reach for dark matter couplings is particularly interesting for light dark matter and for spin-dependent couplings (Rajaraman, Sheperd, Tait, Wijangco 2011)




However note that the bounds evaporate if the mediating particle is also light (so cannot be integrated out in EFT)
… so still need direct detection experiments!

# Many techniques for indirect detection … and many claims!




The PAMELA 'excess' ($e^+$), Fermi 'excess' ($e^+ + e^-$), WMAP 'haze' (radio), Fermi 'bubbles' ($\gamma$-ray) … have all been ascribed to dark matter annihilations/decays

These probe dark matter elsewhere in the Galaxy so complement direct detection experiments … but have other systematic uncertainties

# The PAMELA 'anomaly'

**PAMELA** has measured the positron fraction:

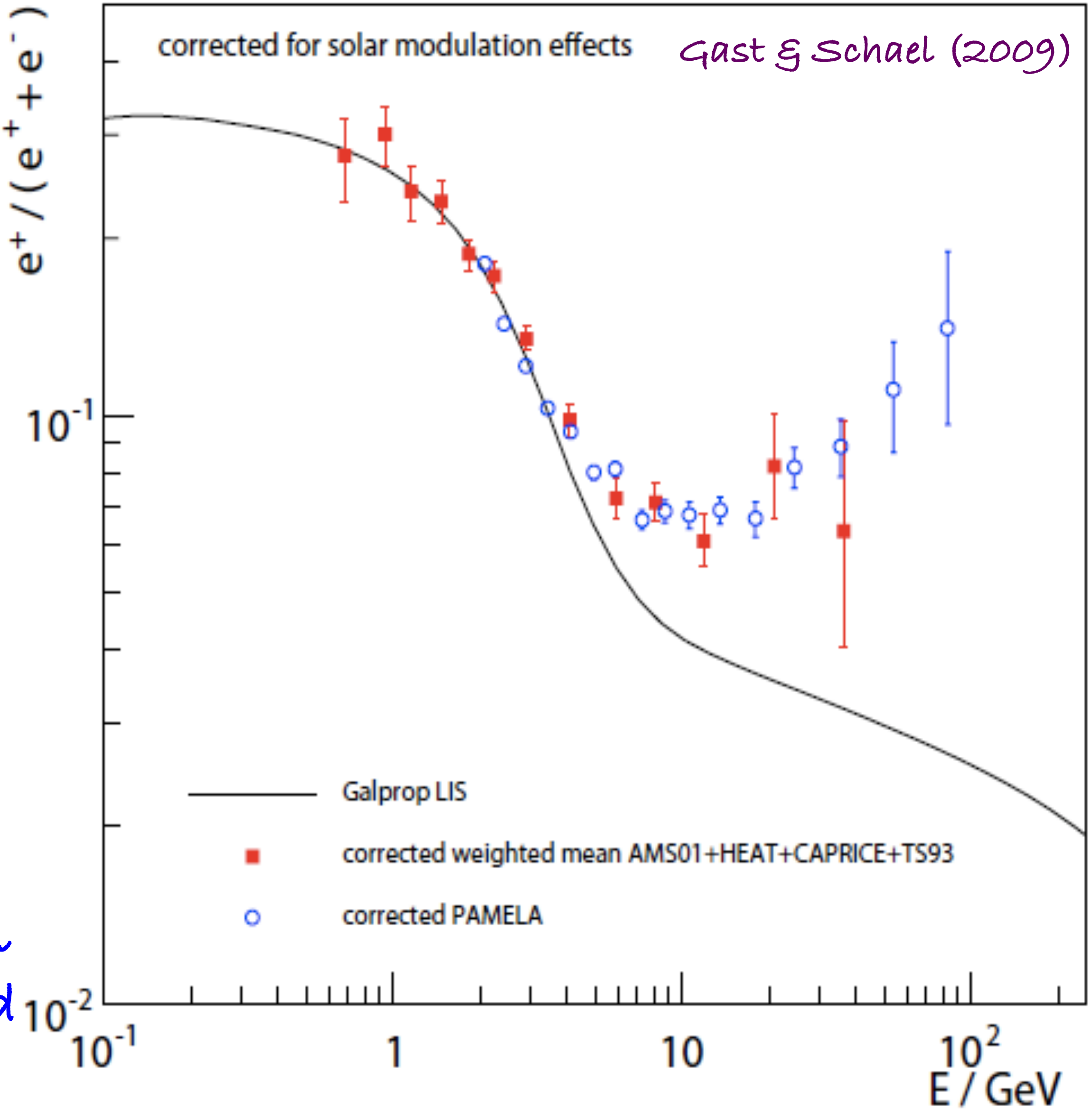
$$\frac{\phi_{e^+}}{\phi_{e^+} + \phi_{e^-}}$$

Anomaly $\Rightarrow$ excess above 'astrophysical bkgd'

Widely attributed to dark matter annihilations/decay: … fits the spectral shape!

However predicted amplitude typically ~10-10$^4$ too small

So need to boost annihilation cross-section by 'Sommerfeld enhancement' due to new long-range force (light boson)

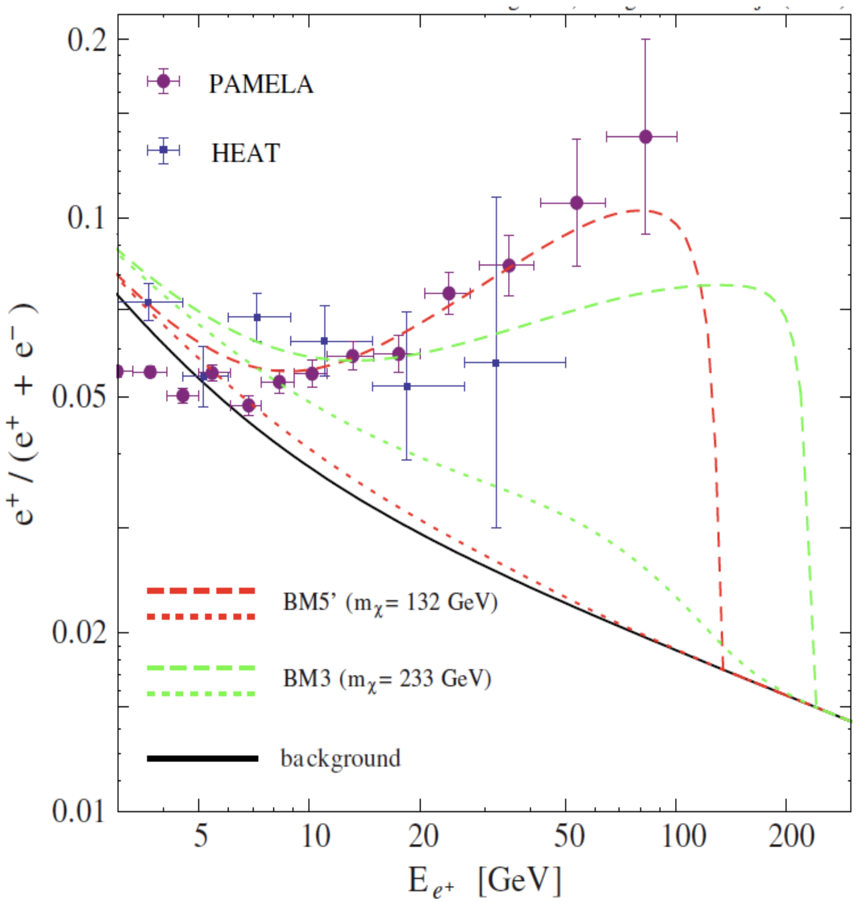


# Dark matter has been widely invoked as the source of the 'excess' $e^+$

## DM annihilation

Rate ~ $n^2_{DM}$

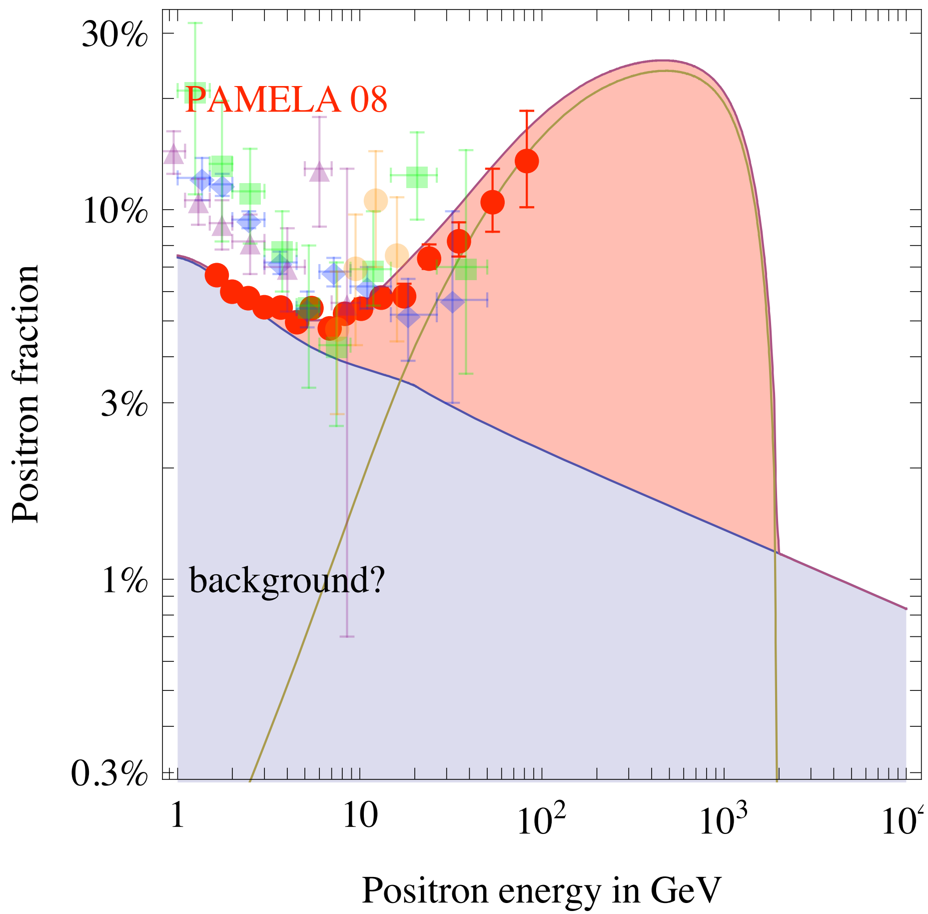
(e.g. few hundred GeV neutralino LSP or Kaluza-Klein state)




## DM decay

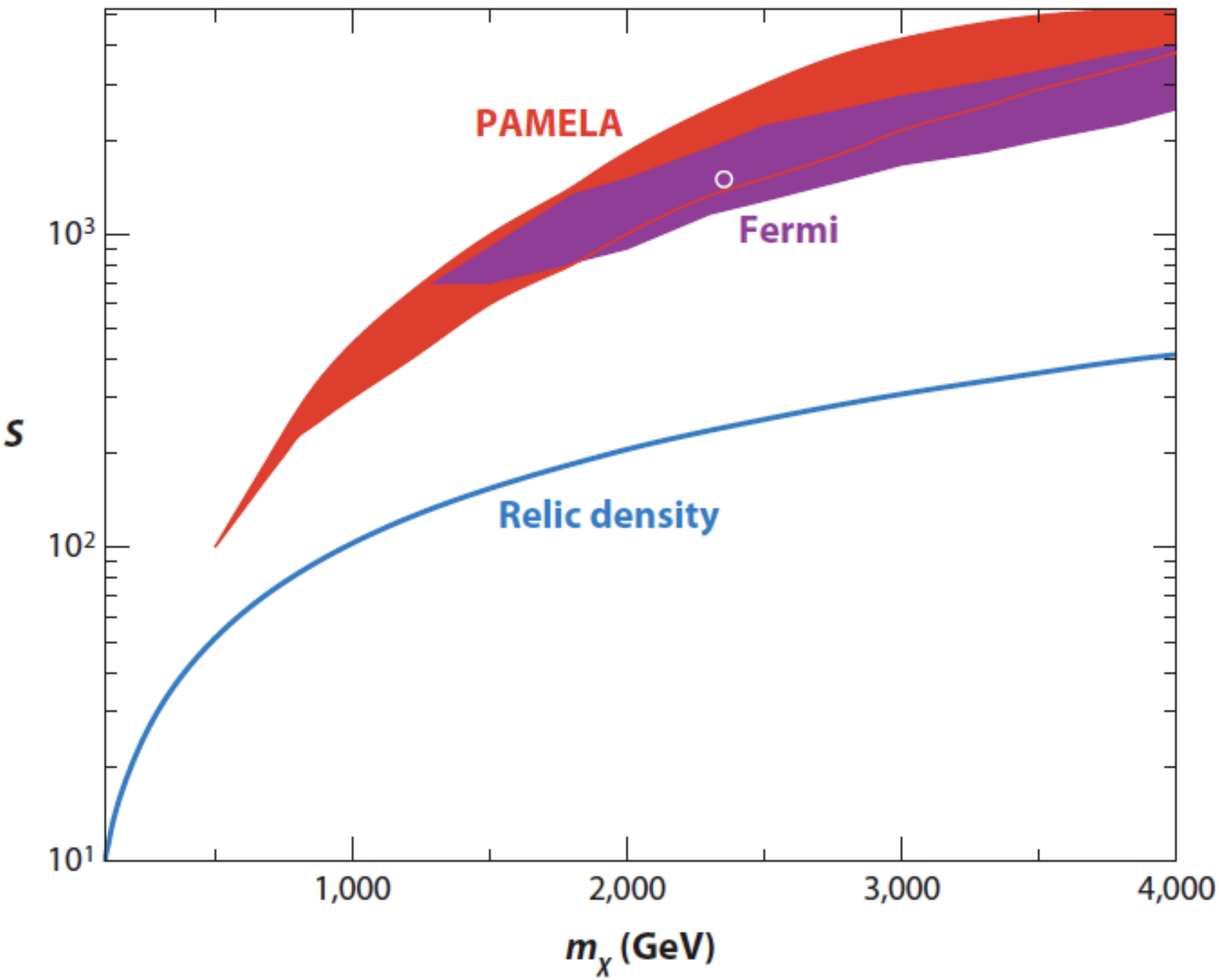
Rate ~ $n_{DM}/\tau_{DM}$

(lifetime ~$10^9$ x age of universe e.g. dim-6 operator suppressed by $M_{GUT}$ for a TeV mass techni-baryon)




Bergström, Bringmann & Edjsö, PR D78:127850,2008    Nardi, Sannino & Strumia, JCAP 0901:043,2009

The 'boost factor' required to match the PAMELA/FERMI data is much higher than the factor of ~few enhancement expected due to clumping of dark matter in the Galaxy

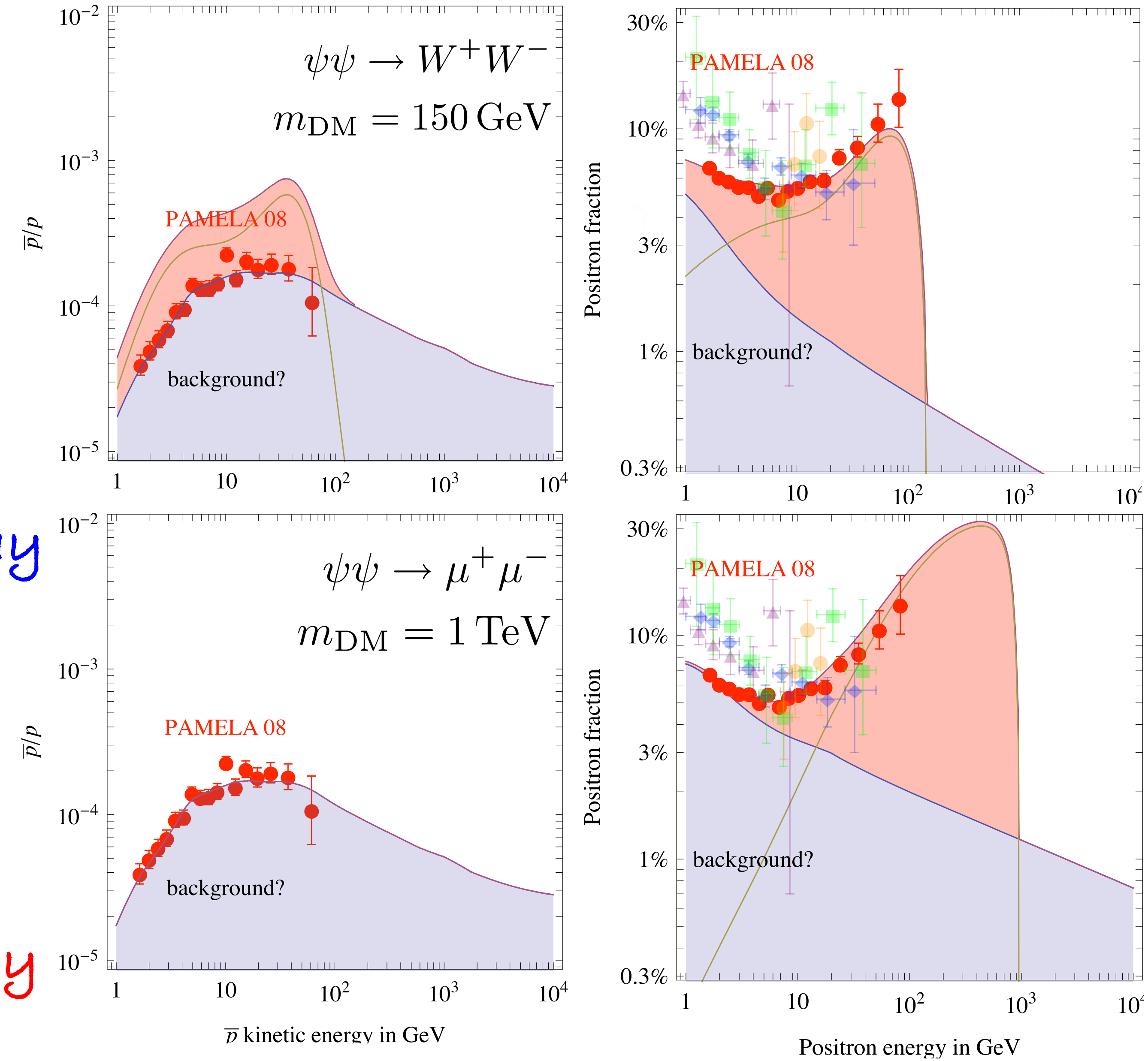


# However the observed antiproton flux is consistent with the background expectation (from cosmic ray propagation in the Galaxy)

This makes dark matter rather unlikely to explain the PAMELA anomaly

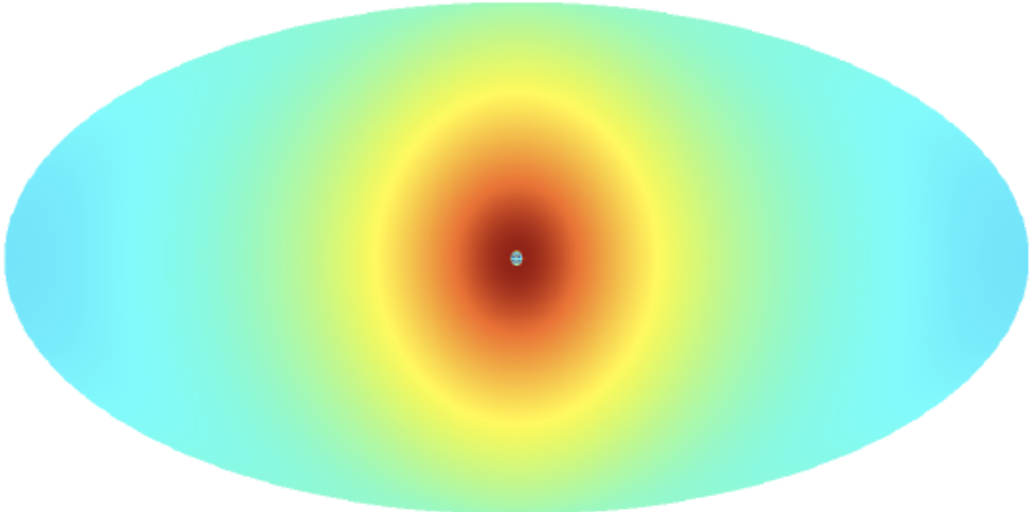
Can fit with DM annihilation or decay only if DM particles are also 'leptophilic'

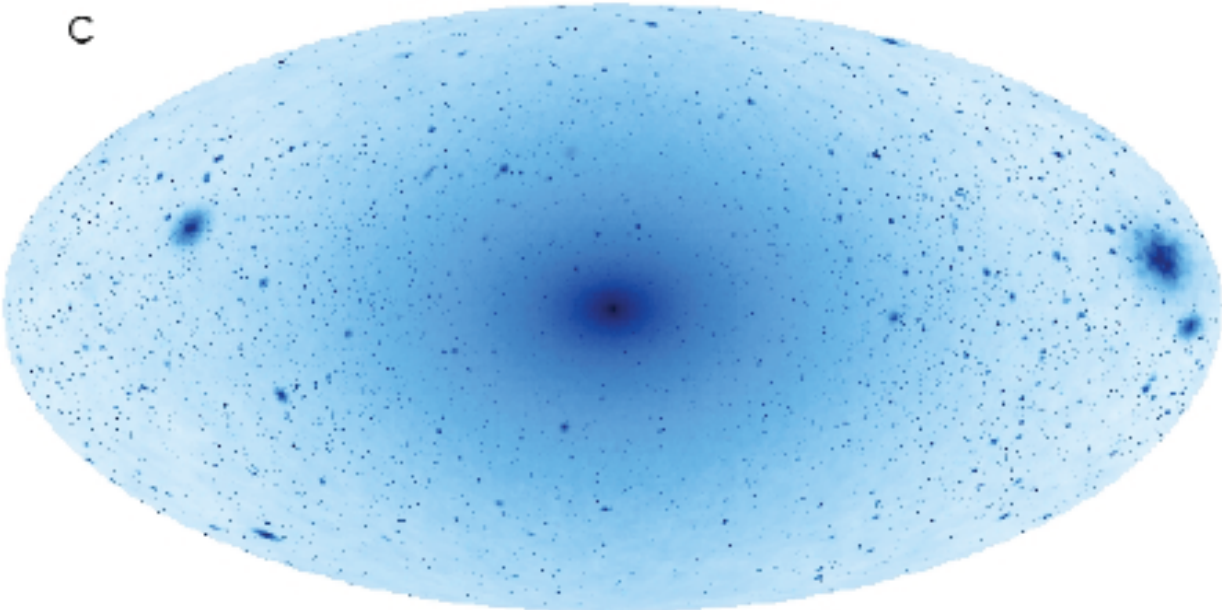
... but such models are increasingly being constrained by limits from Fermi



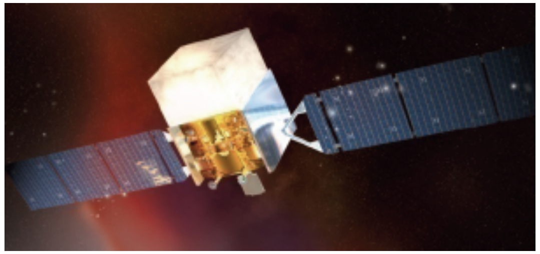

Cirelli et al (2009)

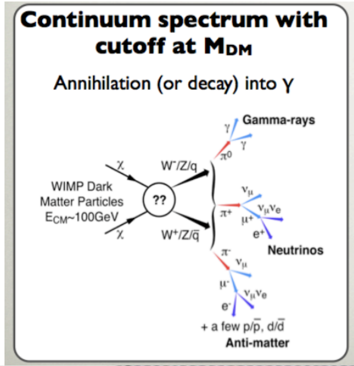
# The best targets for annihilation $\gamma$-rays are expected to be the Galactic Centre and substructure …

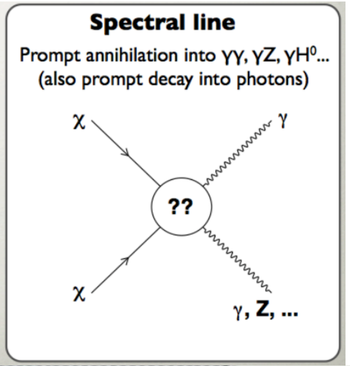


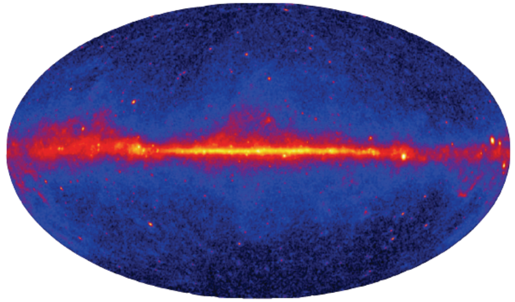


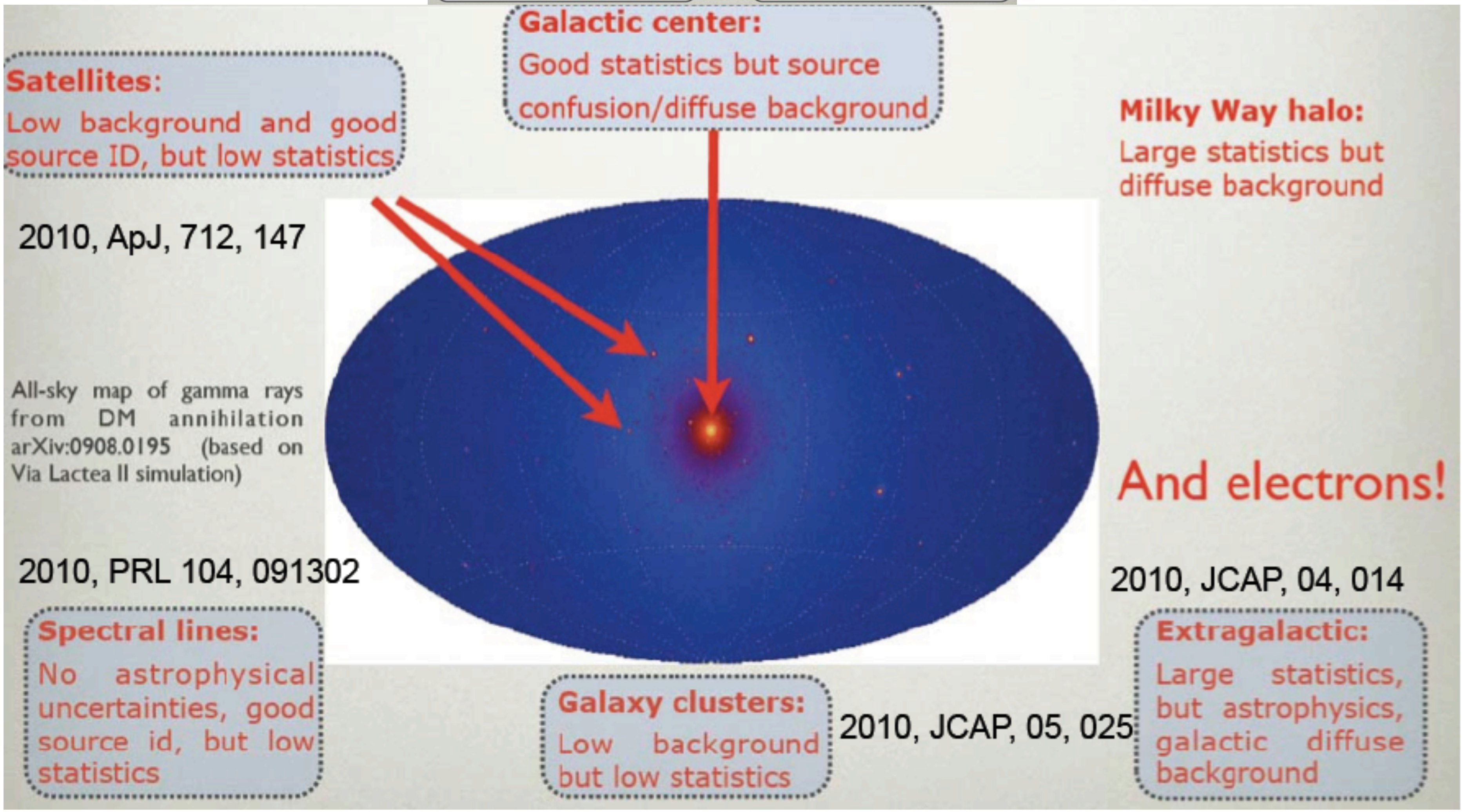
# Fermi has searched for DM signals in a variety of channels … without success



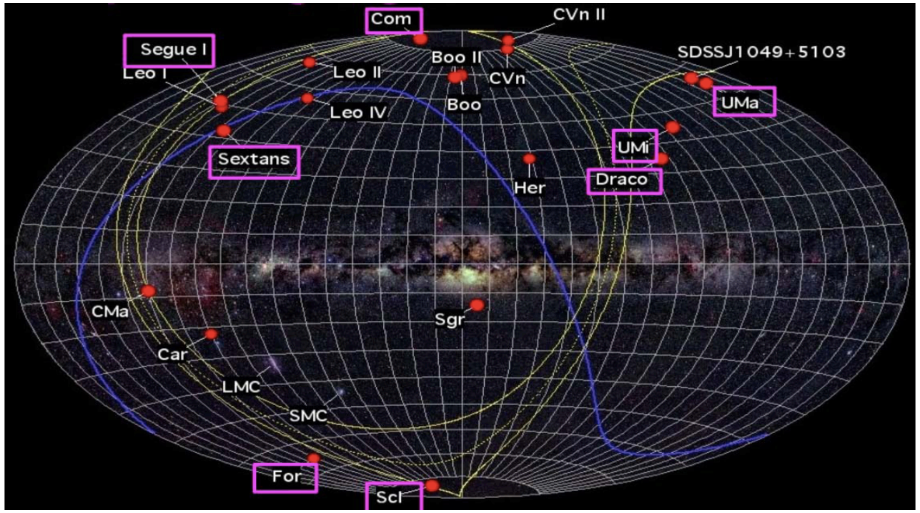


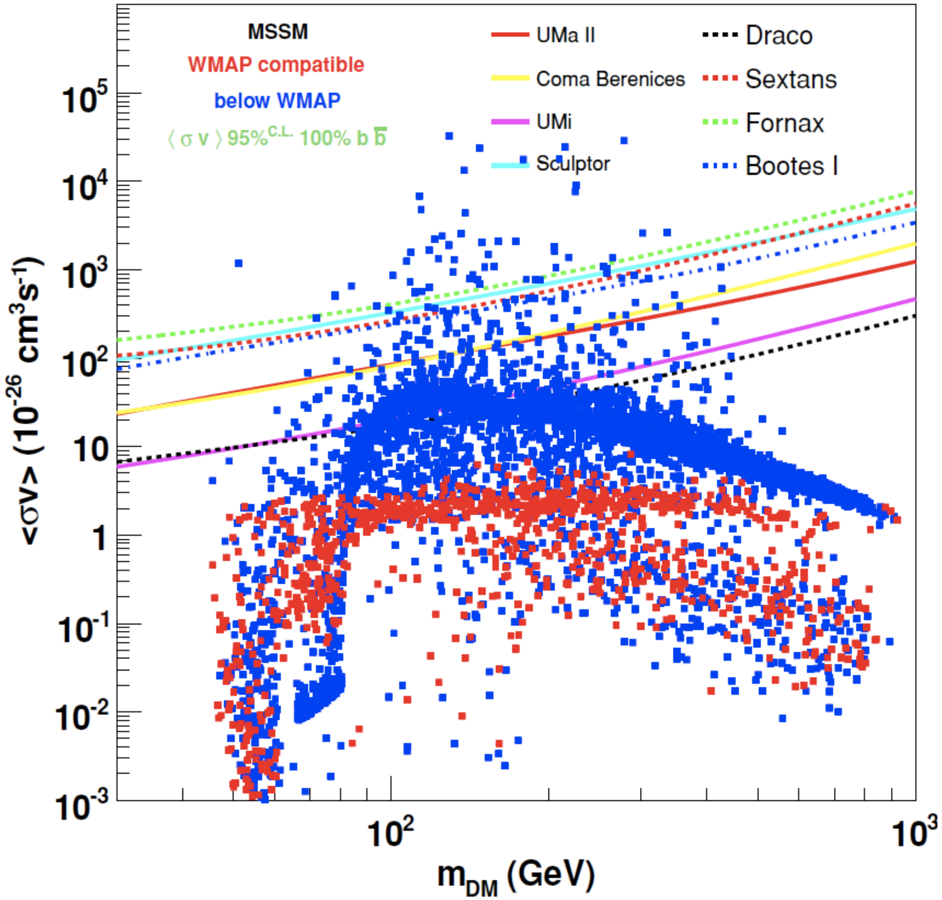



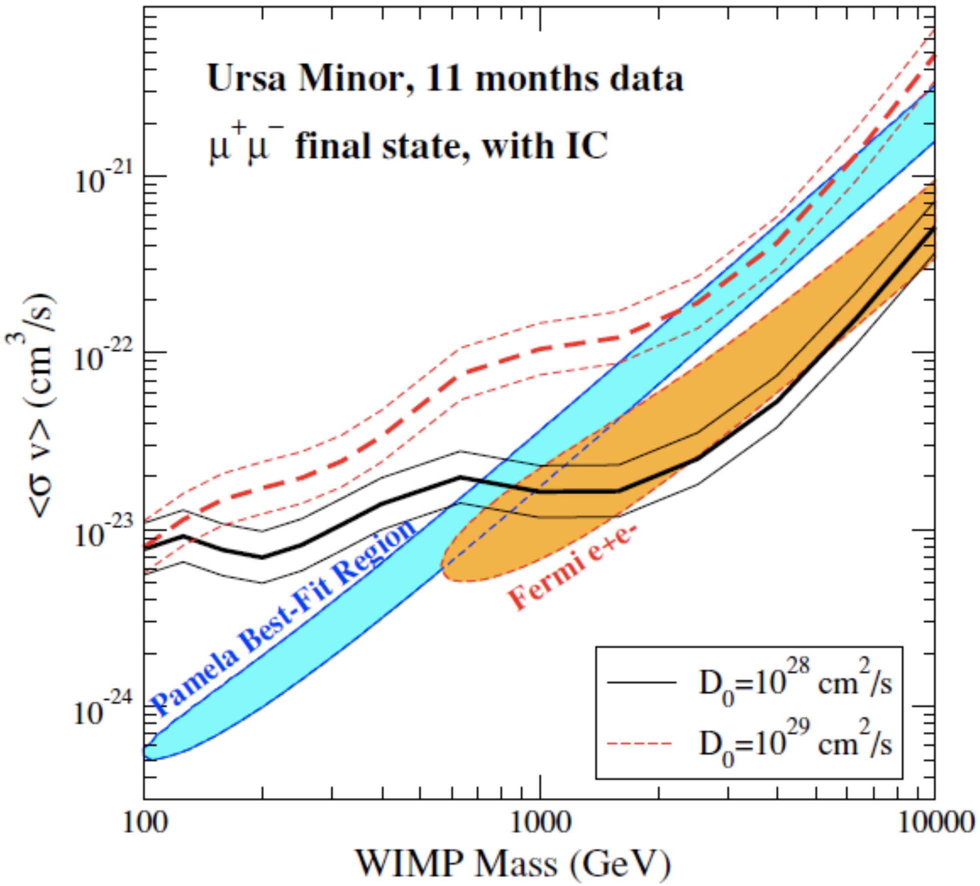





Particularly stringent limits have been set by looking towards dwarf spheroidal galaxies which are satellites of the Milky Way and believed to be highly dark matter dominated …



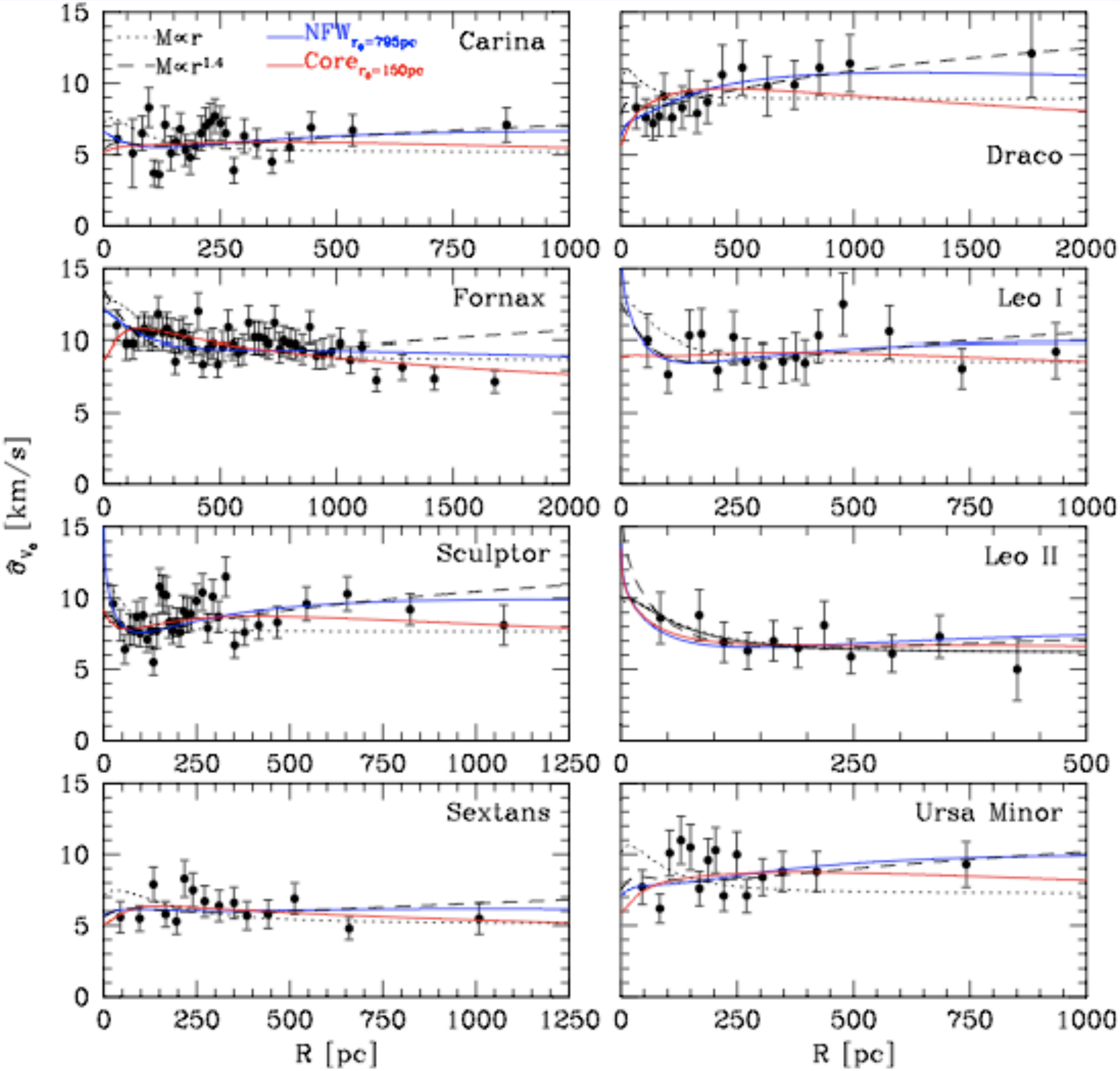



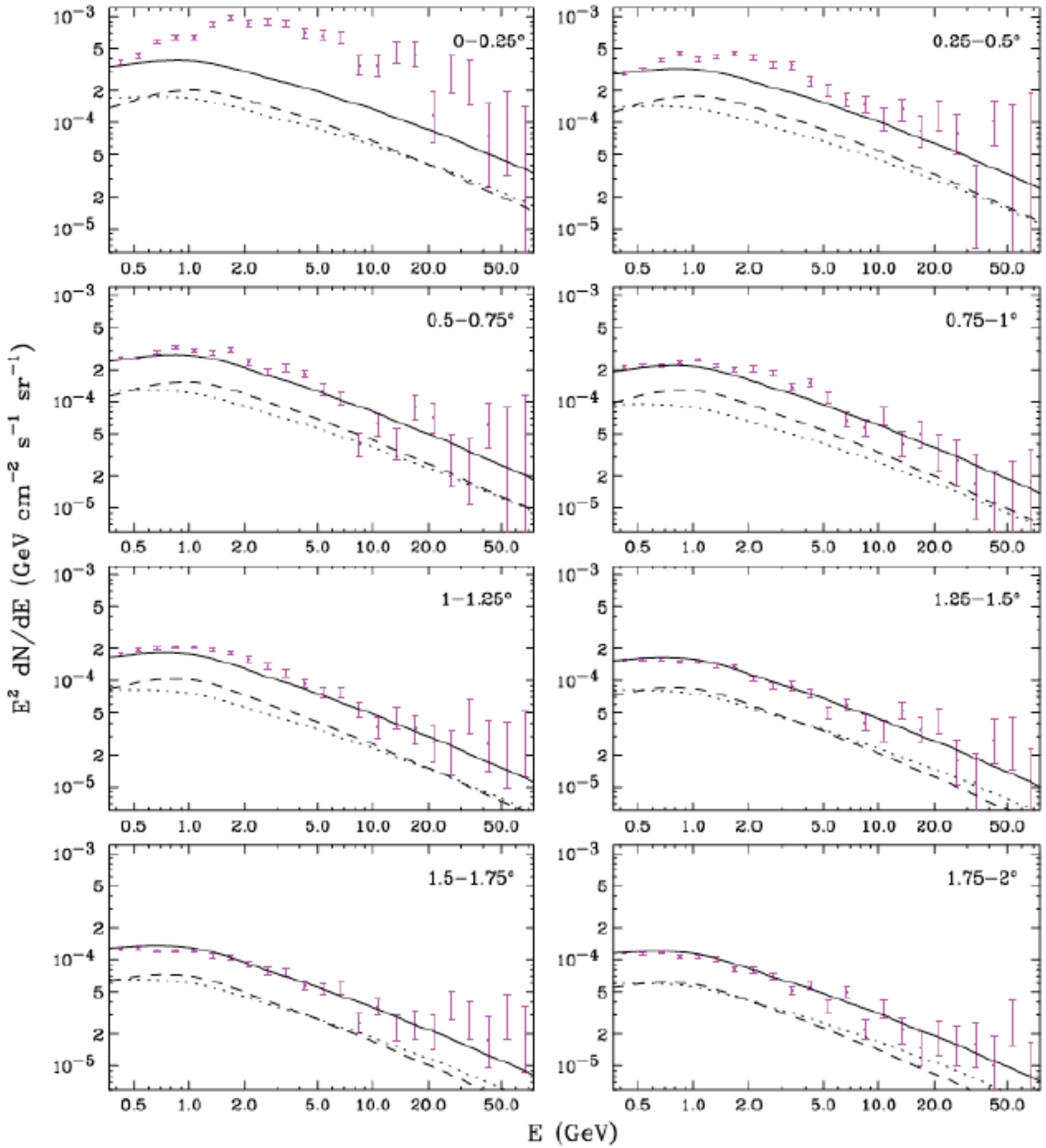
Sensitivity to the annihilation signal from dSphs is however rather dependent on how the dark matter distribution is modelled … cored halos reduce the signal by ~$10^2$ cf. cusps (Evans, Ferrer, Sarkar 2004)

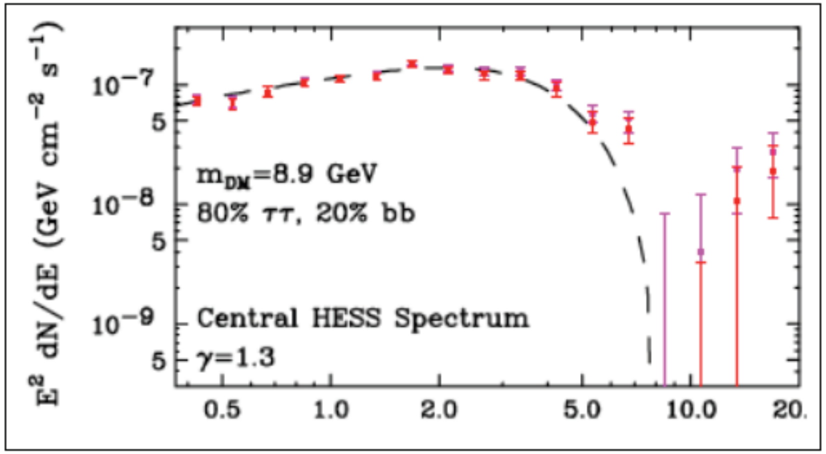
Although current kinematic stellar data is generally not good enough to determine the density profile from the rotation curves (Walker et al 2009),
It has proved possible to demonstrate that at least two dSphs – Fornax and Sculptor – have cores
(Walker & Peñarrubia, 2011)

… this poses a challenge for CDM which predicts cusps



The Galactic Centre is a more promising site for the DM annihilation signal (notwithstanding the astrophysical backgrounds) … indeed it has been claimed that Fermi has seen the signal of ~7-10 GeV DM! (Hooper & Goodenough 2011)

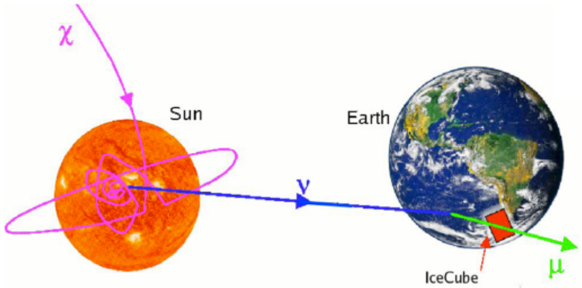


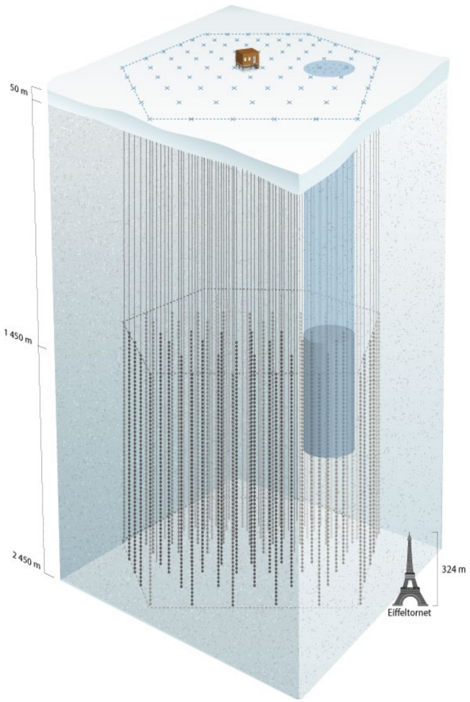



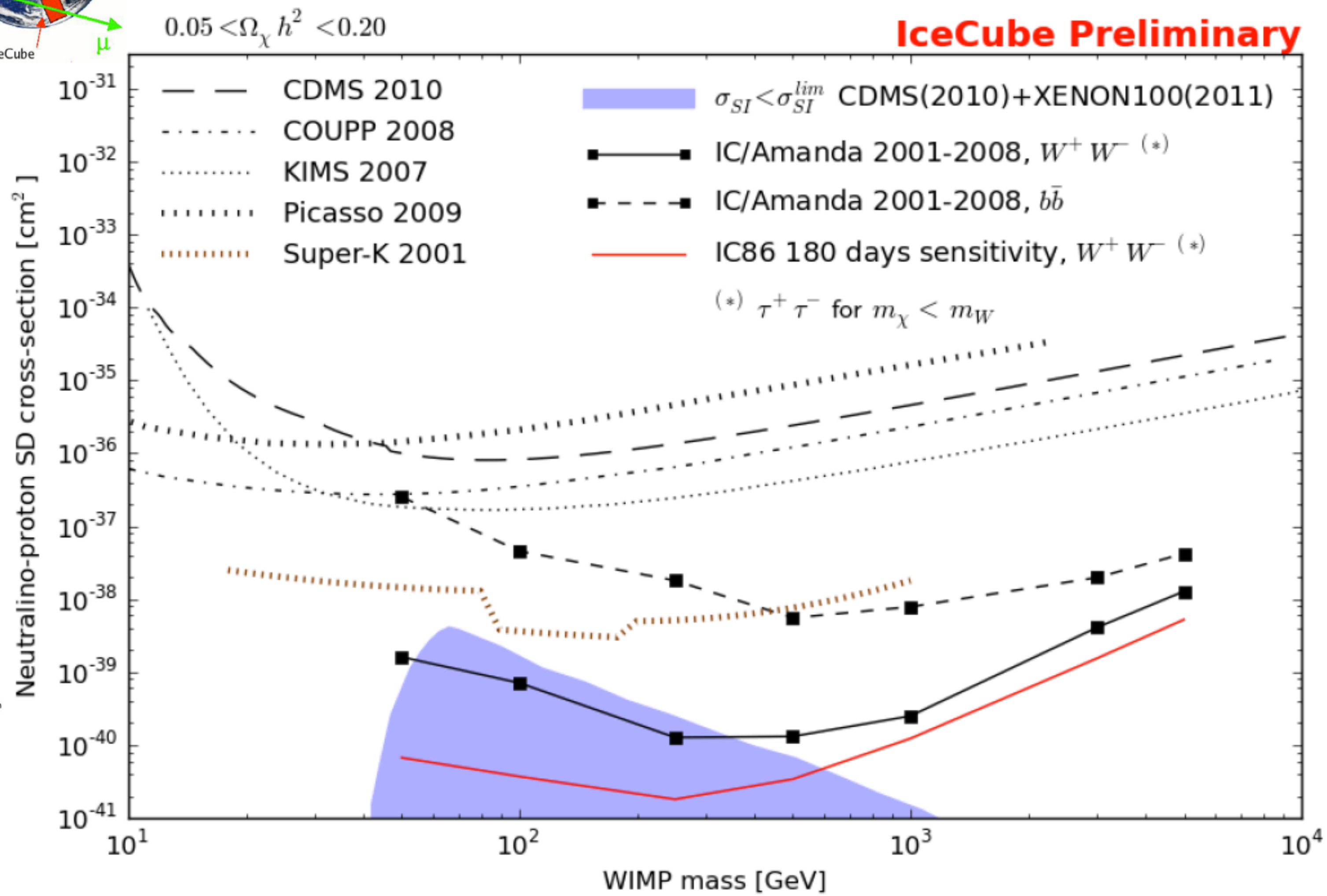

By fitting the observed γ-ray emission to a disk+bulge model ($\pi^0$ + IC emission) they isolate a excess signal in the innermost region (~175 pc) – which has a hard spectrum consistent with dark matter annihilation

… eagerly awaiting checks by the Fermi team

Another discovery channel is high energy neutrinos from annihilation of dark matter accreted by the Sun … most sensitive to spin-dependent interactions (improved with low energy extension of IceCube – DeepCore)



# Axion dark matter

$$\mathcal{L}_{\text{eff}} = M^4 + M^2\Phi^2$$ super-renormalisable

$$+ (D\Phi)^2 + \bar{\Psi} \not{D}\Psi + F^2 + \bar{\Psi}\Psi\Phi + \Phi^2$$ renormalisable

$$+ \frac{\bar{\Psi}\Psi\Phi\Phi}{M} + \frac{\bar{\Psi}\Psi\bar{\Psi}\Psi}{M^2} + \ldots \quad +\theta_{\text{QCD}} F\tilde{F}$$ 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 $\theta_{QCD} < 10^{-6}$

To achieve this without fine-tuning, $\theta_{QCD}$ 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 (later) acquires a mass through its mixing with the pion (the pNGB of QCD): $m_a = m_\pi (f_\pi/f_{PQ})$

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: $f_{PQ} \sim 10^{18}$ GeV

**Hence axion dark matter would need to be significantly diluted – not predictable!**

… or seek anthropic explanation for why $\theta_{QCD}$ is small (Tegmark et al. 2008)

| Mass scale | Lightest stable particle | Symmetry/ Quantum # | Stability ensured? | Production | Abundance |
|---|---|---|---|---|---|
| $\Lambda_{QCD}$ | Nucleons | Baryon number | $\tau > 10^{33}$ yr | 'Freeze-out' from 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 observed baryons) | $\Omega_{DB} \sim 0.3$ |
| $\Lambda_{Fermi} \sim G_F^{-1/2}$ | Neutralino? | R-parity? | violated? | 'freeze-out' from equilibrium | $\Omega_{LSP} \sim 0.3$ |
| | Technibaryon? | (walking) Techni-colour | $\tau \sim 10^{18}$ yr | Asymmetric (like observed baryons) | $\Omega_{TB} \sim 0.3$ |
| $\Lambda_{hidden\ sector} \sim (\Lambda_F M_P)^{1/2}$ | Crypton? hidden valley? | Discrete (very model-dependent) | $\tau \gtrsim 10^{18}$ yr | Varying gravitational field during inflation | $\Omega_X \sim 0.3$? |
| $\Lambda_{see\text{-}saw} \sim \Lambda_{Fermi}^2/\Lambda_{B-L}$ | 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!

# Summary

Experimental situation reminiscent of search for temperature fluctuations in the CMB in the '80s – there were clear theoretical predictions but only upper limits on detection (causing crisis for theory) ...

finally breakthrough that transformed cosmology!

The theoretical expectations for dark matter are not as clear (being based on BSM physics) but there are many experimental approaches and interesting complementarities between them

There are bound to be false alarms but it is a reasonable expectation that the nature of dark matter will soon be determined experimentally