Discovering dark matter

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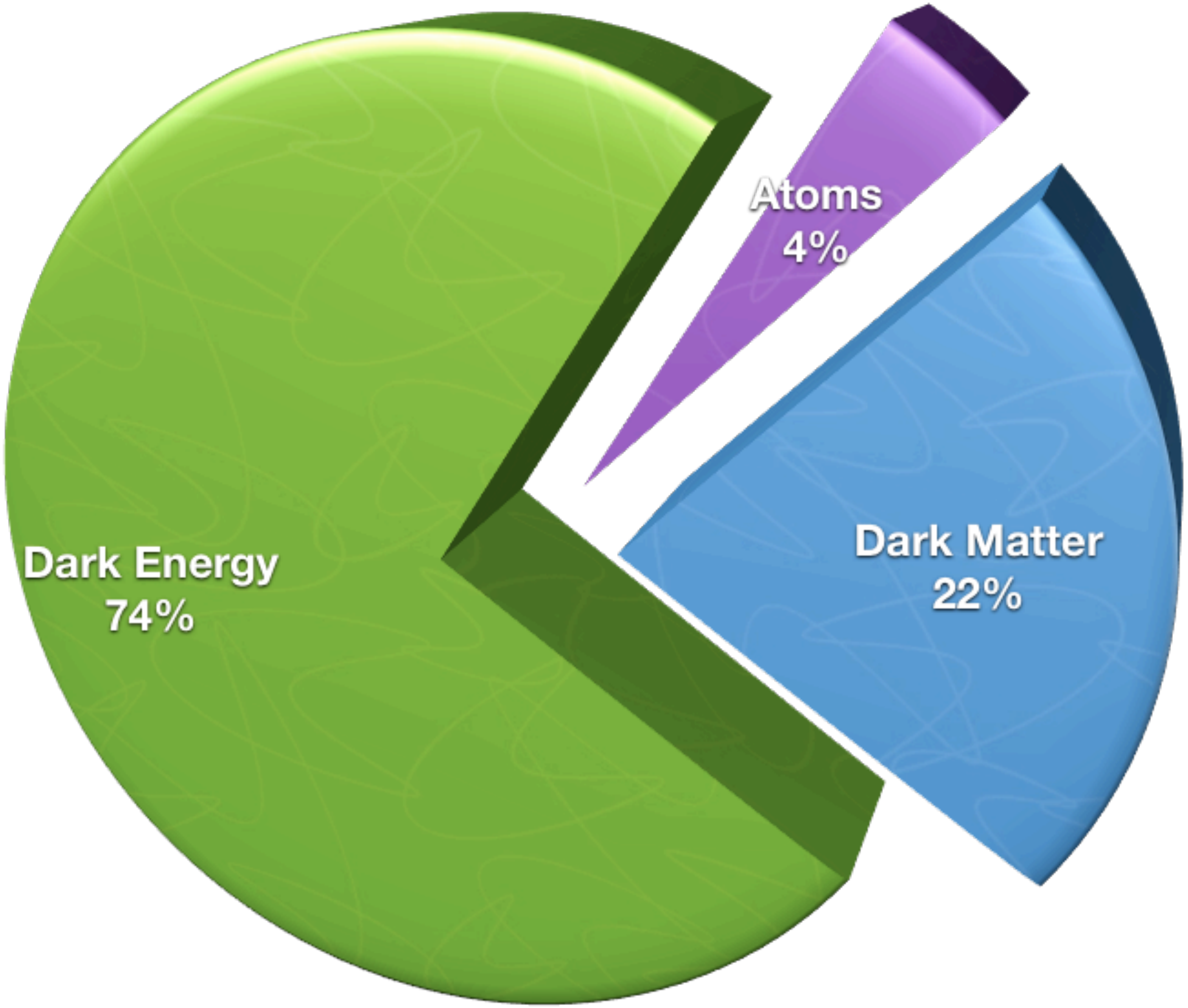
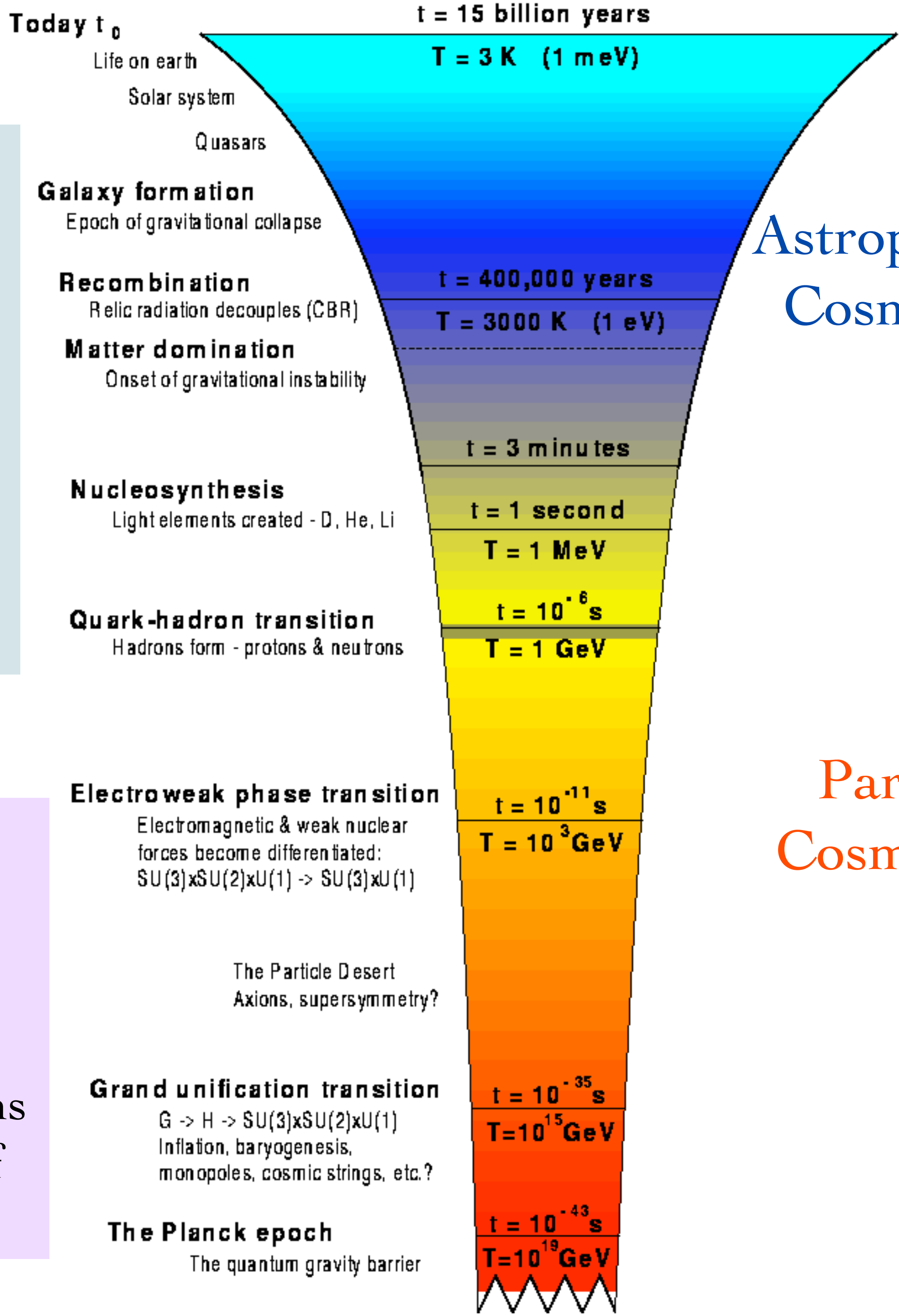
What is the world made of?



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 $\Omega_B \sim 0.05$

On the basis of SM physics, the evolution of the universe can be extrapolated into our past, fairly reliably up to the big bang nucleosyntheis era and (with some caveats) back through the chiral/QCD phase transition up to the electroweak unification epoch



Astrophysical Cosmology

Particle Cosmology

But *new* physics is needed to:

a) account for the asymmetry between matter & antimatter,
b) to explain dark matter, and
c) generate density fluctuations which seeded the formation of large-scale structure.

Thermal Relics

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

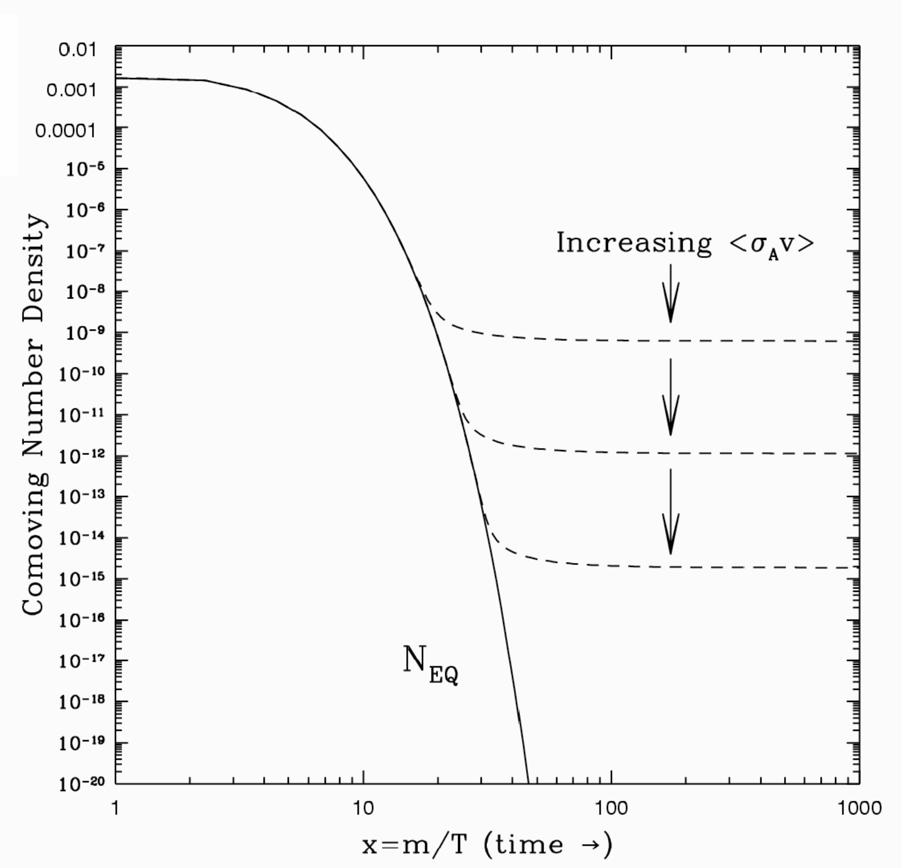
Chemical equilibrium is maintained as long as annihilation rate exceeds the Hubble expansion rate

'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 ~ # relativistic species



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

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

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

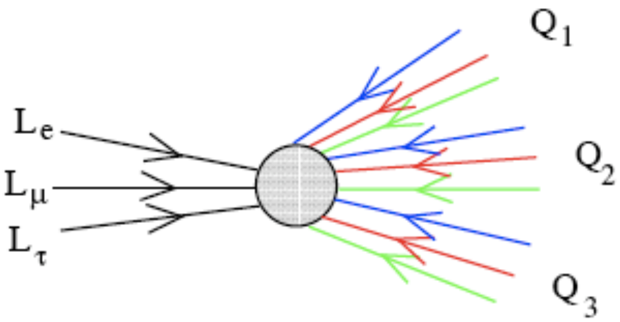
Baryon number violation occurs even in the Standard Model through non-perturbative (sphaleron-mediated) processes … but CP-violation is *too weak* (also out-of-equilibrium conditions are not available since the electroweak symmetry breaking phase transition is a ‘cross-over’)

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

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

Asymmetric baryonic matter



$$Y_{\Delta B} = \frac{n_N^{eq}(T \gg M_1)}{s} \sum_\alpha \frac{n_{\ell_\alpha} - n_{\bar{\ell}_\alpha}}{n_N} \times \eta_\alpha \times C$$

$$\sim 4 \times 10^{-3} \sum_\alpha \epsilon_{\alpha\alpha} \times \eta_\alpha \times \frac{1}{3}$$

Any pre-existing fermion asymmetry would be redistributed by the *B*+*L* violating processes (which conserve *B*-*L*) among all particles with electroweak couplings

Although leptogenesis is not directly testable (unless the lepton number violation occurs as low as the TeV scale), it provides an elegant paradigm for the origin of baryons
… so we accept that the only kind of matter which we know exists originated non-thermally in the early universe

What *should* the world be made of ?

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$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino?	R-parity?	violated?	'freeze-out' from thermal equilibrium	$\Omega_{LSP} \sim 0.3$

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

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

But why is the abundance of thermal relics **comparable** to that of baryons which were born *non*-thermally, with $\Omega_{DM}/\Omega_B \sim 6$?

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$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino? Technibaryon?	R-parity? (walking) Technicolour	violated? $\tau \sim 10^{18}$ yr e^+ excess?!	'freeze-out' from thermal equilibrium Asymmetric (like the *observed* baryons)	$\Omega_{LSP} \sim 0.3$ $\Omega_{TB} \sim 0.3$

A new electroweak-scale mass 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)

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

If the mass is a few GeV e.g. 'unbaryon' of walking technicolour (Sannino 2009) then the required relic abundance is obtained even more naturally (Frandsen *et al* 2009)

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$\Lambda_{hidden\ sector} \sim (\Lambda_F M_P)^{1/2}$ $\Lambda_{see\text{-}saw} \sim \Lambda_{Fermi}^2/\Lambda_{B-L}$	Crypton? (hidden valley, sequestered) **Neutrinos**	Discrete (*very* model-dependent) Lepton number	$\tau \sim 10^{18}$ yr Stable	Varying gravitational field during inflation Thermal (like CMB)	$\Omega_X \sim 0.3$? $\Omega_\nu > 0.003$
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!

Discovery of dark matter ➔ new (astro)physics

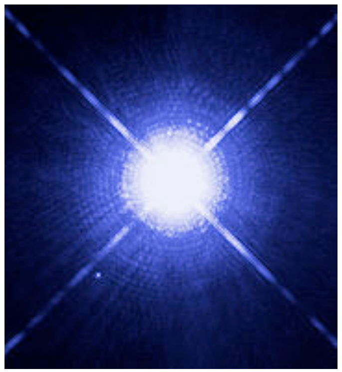
Friedrich Wilhelm Bessel (1832) finds the position of *Sirius* to be oscillating, indicating the presence of an unseen companion

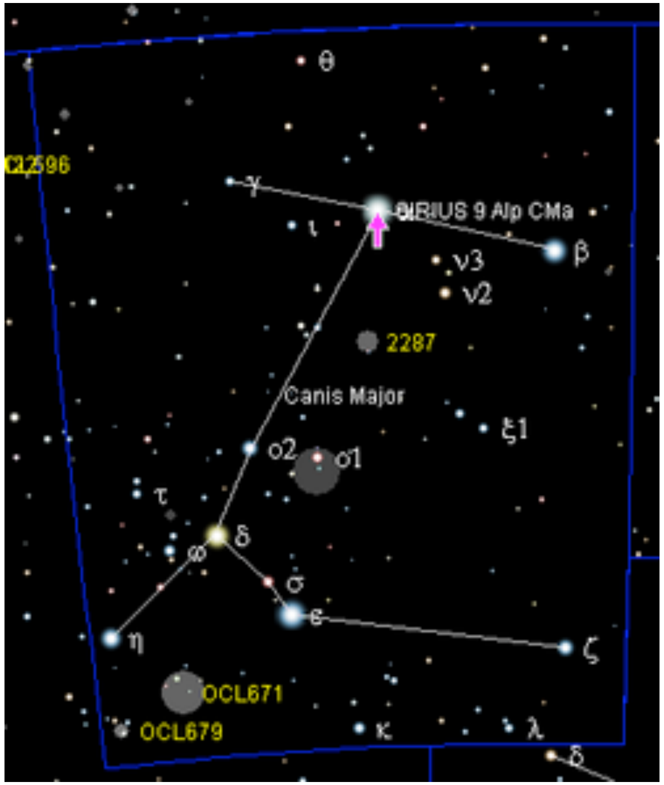
Ivan Clark (1862) discovers *Sirius B* visually

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

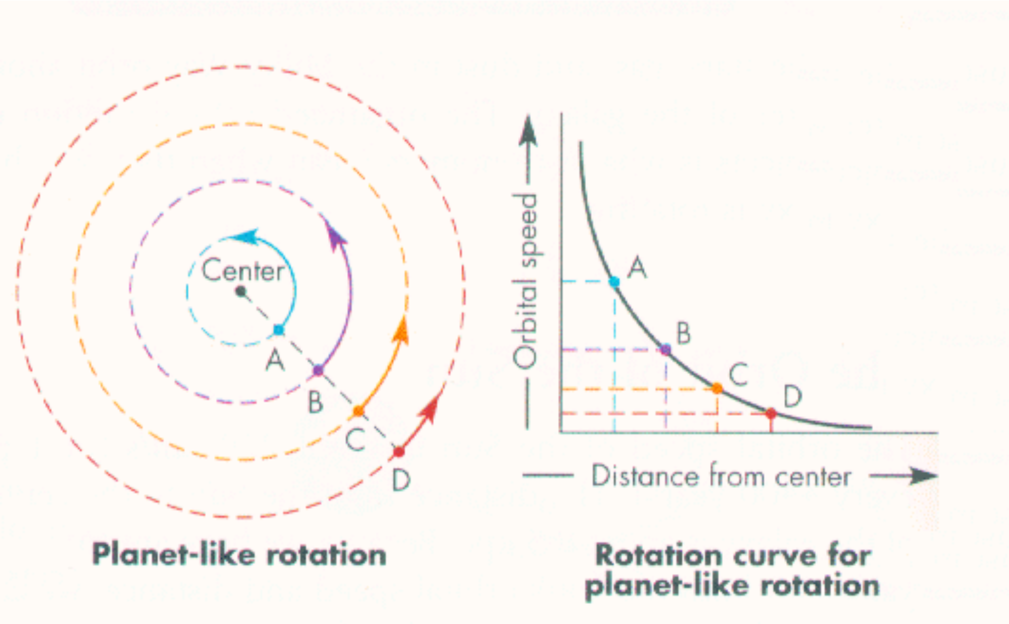
Subrahmanyan Chandrasekhar (1930) applies quantum ideas to stellar structure … infers that when the Sun exhausts its nuclear fuel it will collapse under gravity until held up by Pauli exclusion principle (electron degeneracy pressure)

… but stars heavier than $1.4M_0$ will continue to collapse and "*… one is left speculating on other possibilities*" (neutron stars and black holes!)





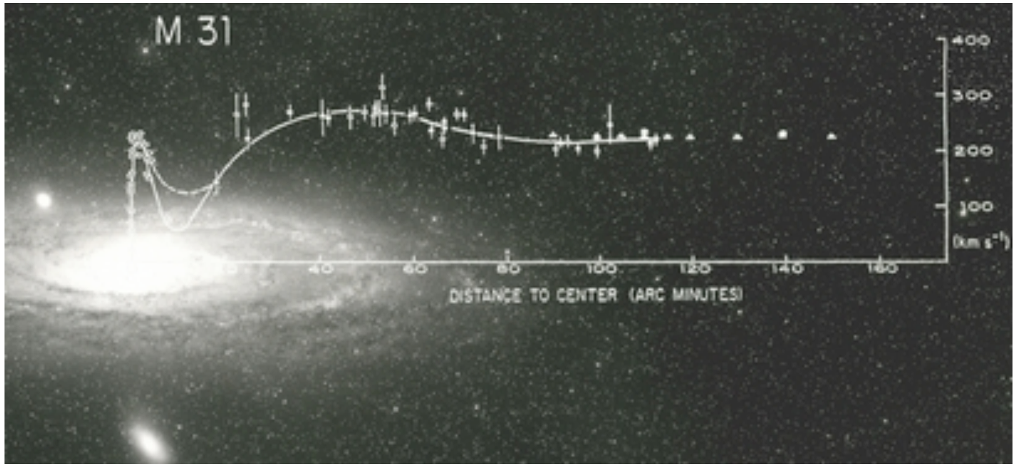
The modern saga of dark matter starts with the rotation curves of spiral galaxies …



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

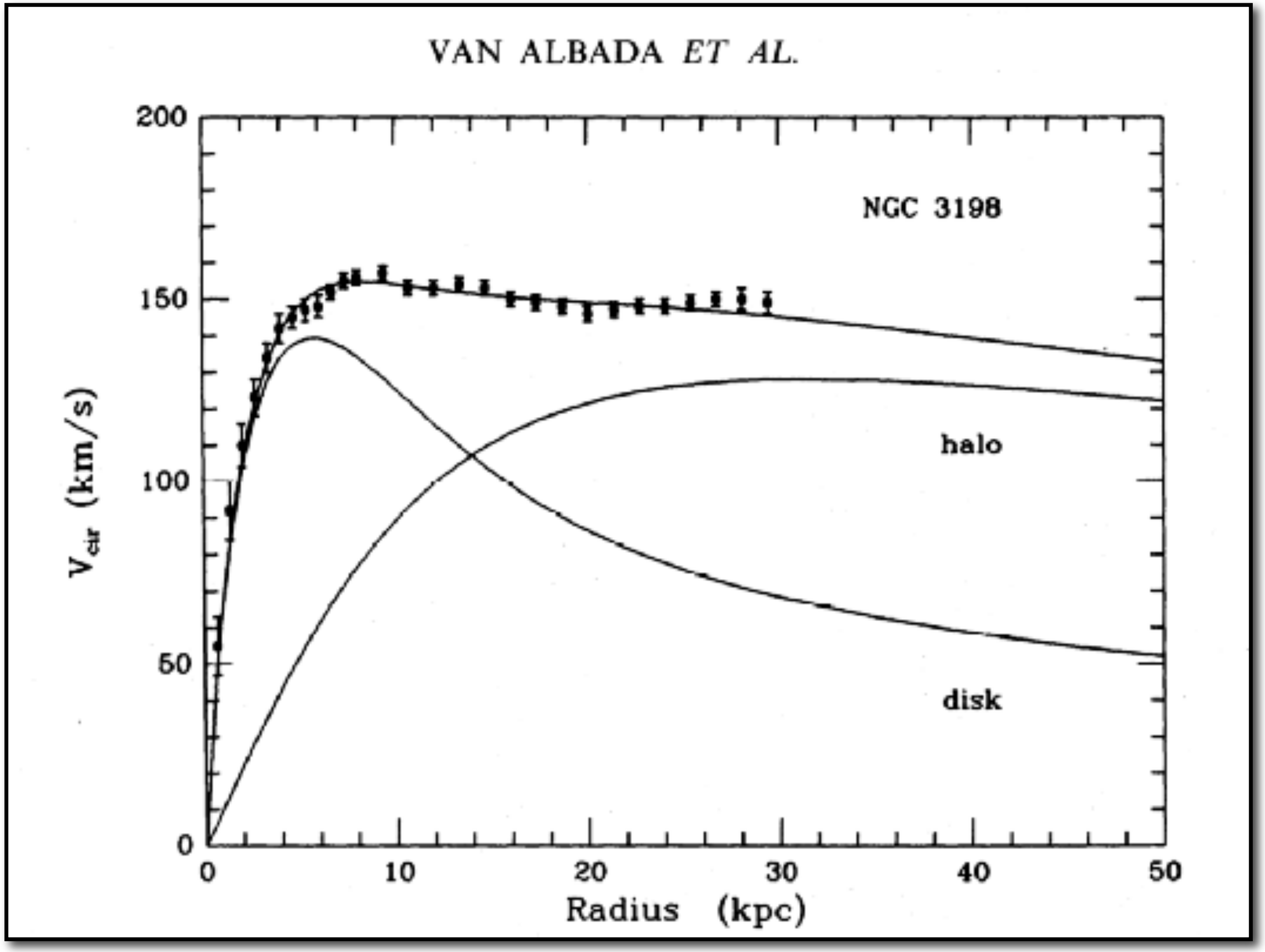
$$v_{\rm circ} = \sqrt{\frac{G_{\rm N} M(<r)}{r}}$$

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

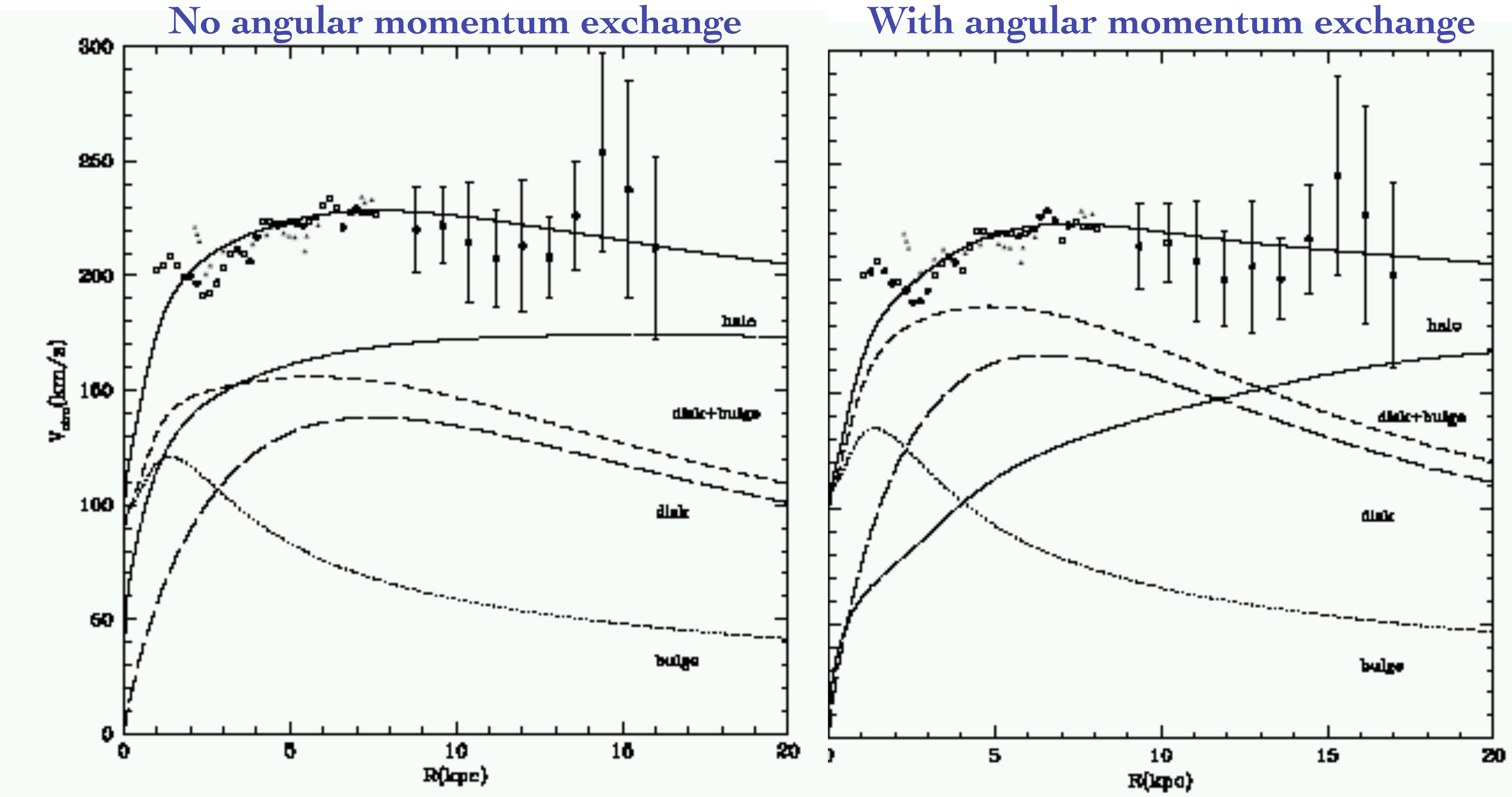


$$v_{\rm circ} \sim {\rm constant} \quad \Rightarrow \quad M(<r) \propto r \quad \Rightarrow \quad \rho \propto 1/r^2$$

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



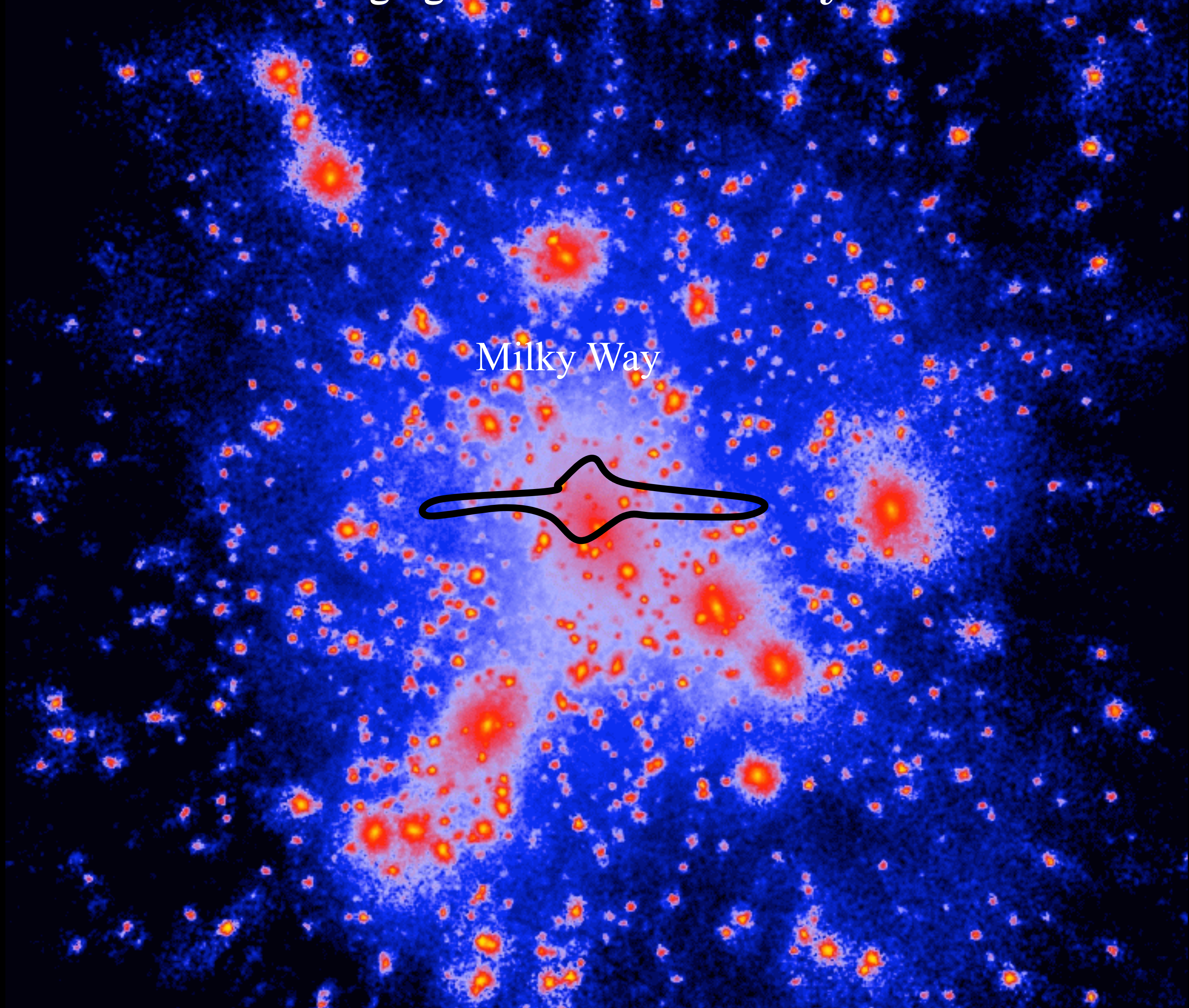
More sophisticated modelling needs to account for multiple components and the coupling between baryonic & dark matter



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

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

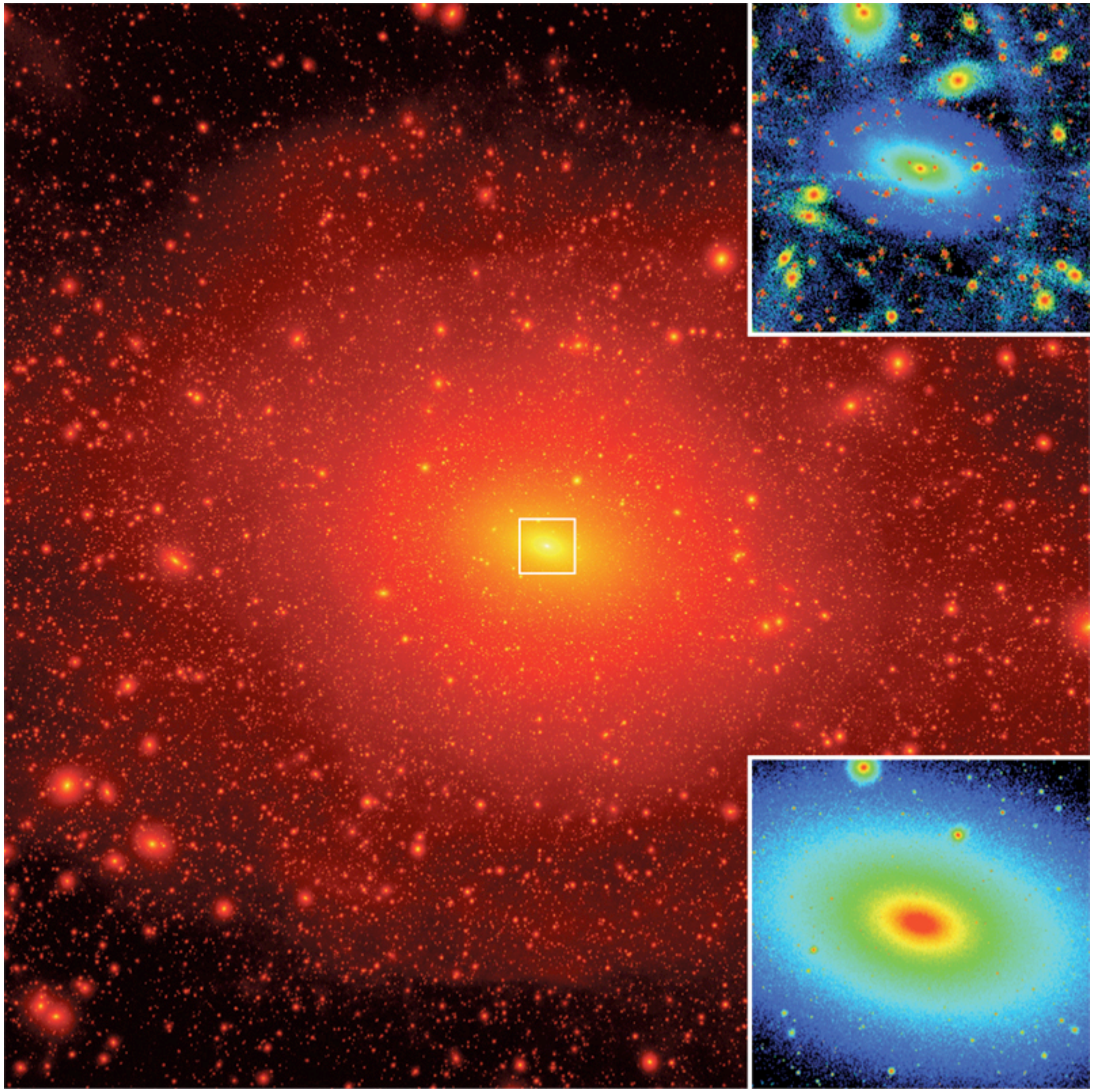
We can get an idea of what the Milky Way halo looks like from numerical simulations of **structure formation through gravitational instability in cold dark matter**



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

So the phase space structure of the dark halo is 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!

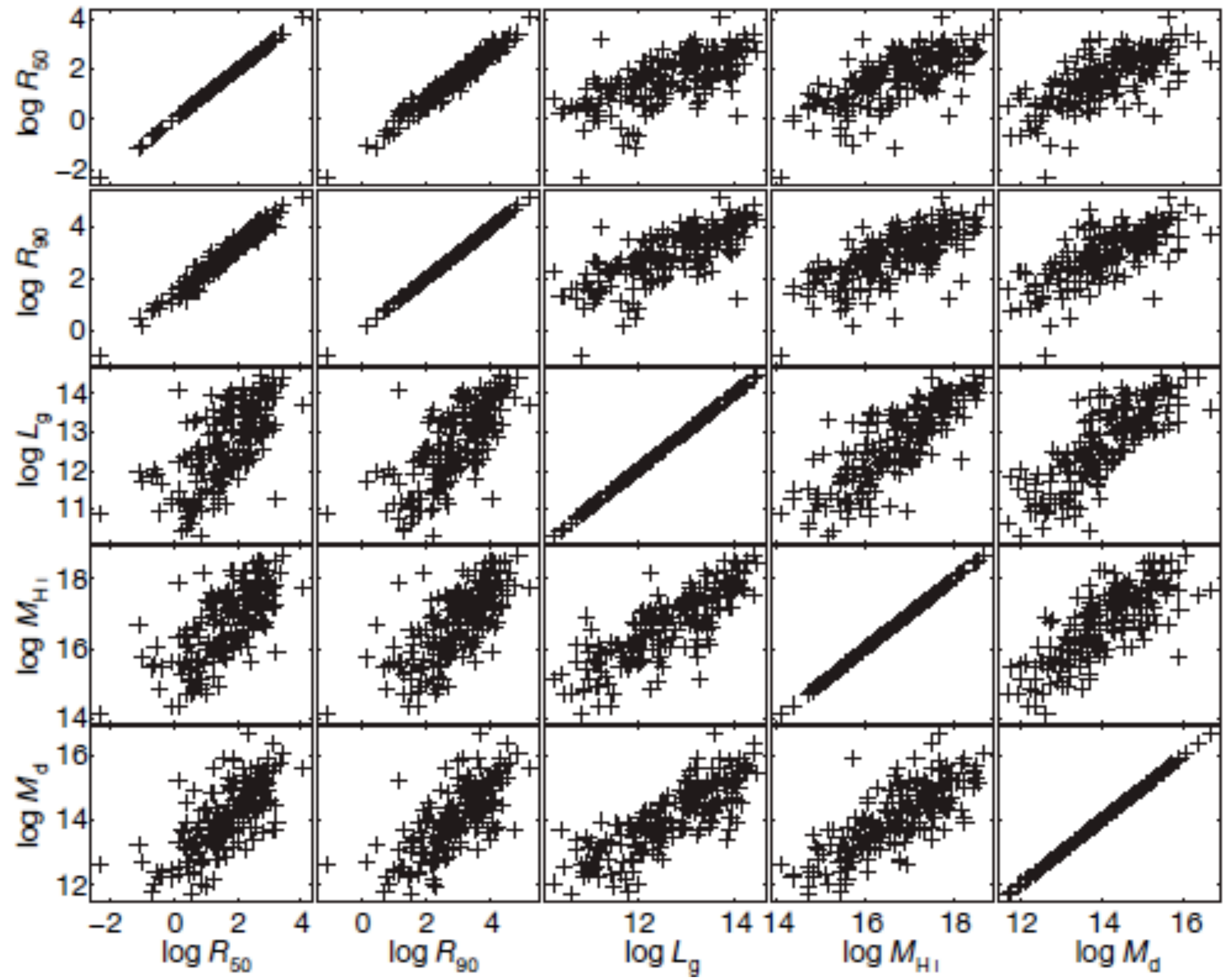
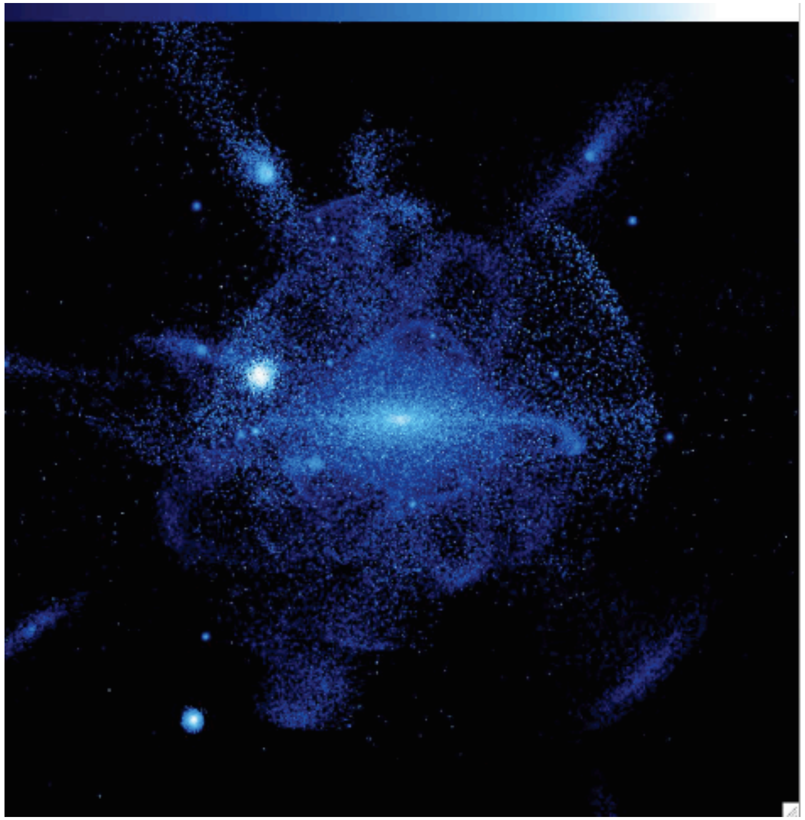
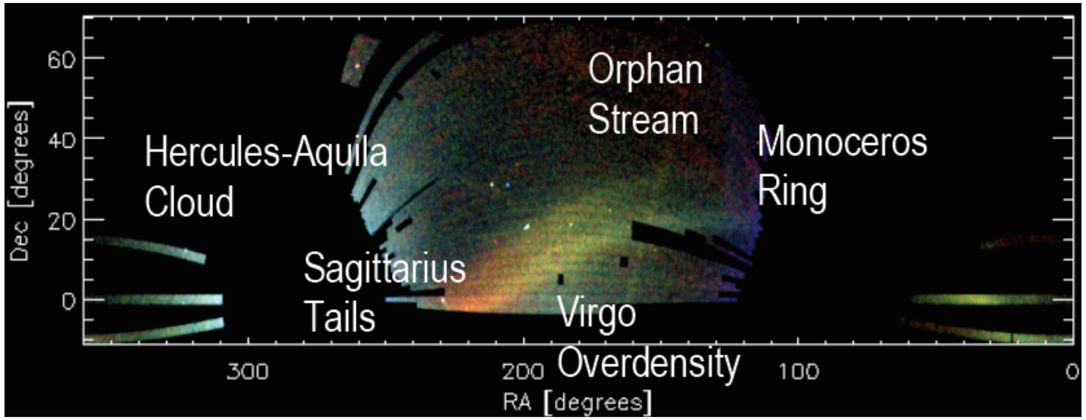


Figure 1 | Scatter plots showing correlations between five measured variables, not including colour. The variables are two optical radii, R_{50} and R_{90} (in parsecs), respectively containing 50 and 90% of the emitted light; and luminosity, L_g; neutral hydrogen mass, M_{HI}; and dynamical mass, M_d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

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

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

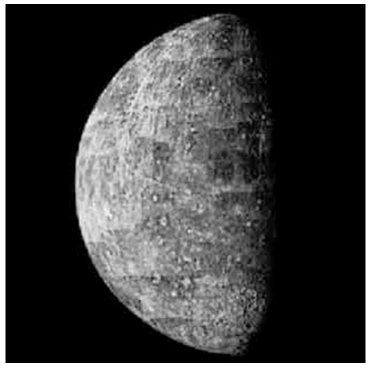




Inferences of dark matter are not always right …
it may instead be a change in the *dynamics*

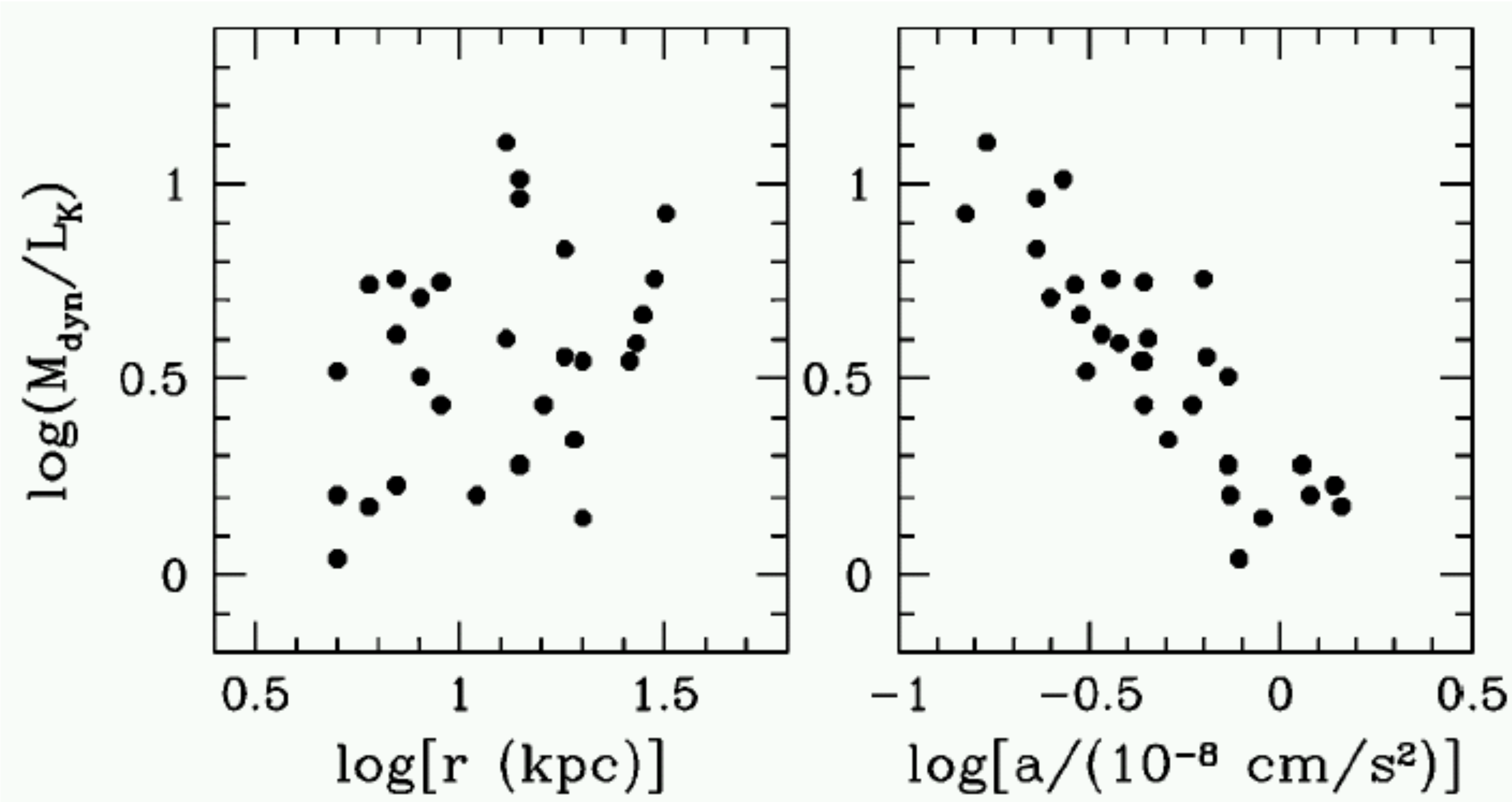
2 Jan 1860: *"Gentlemen, I Give You the Planet Vulcan"*
French mathematician Urbain Le Verrier announces the discovery of a new planet between Mercury and the Sun, to members of the Académie des Sciences in Paris (following up on his earlier successful prediction of Neptune in 1856).

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 (1983)

Bekenstein – Milgrom Equation

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

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

where

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

Then

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

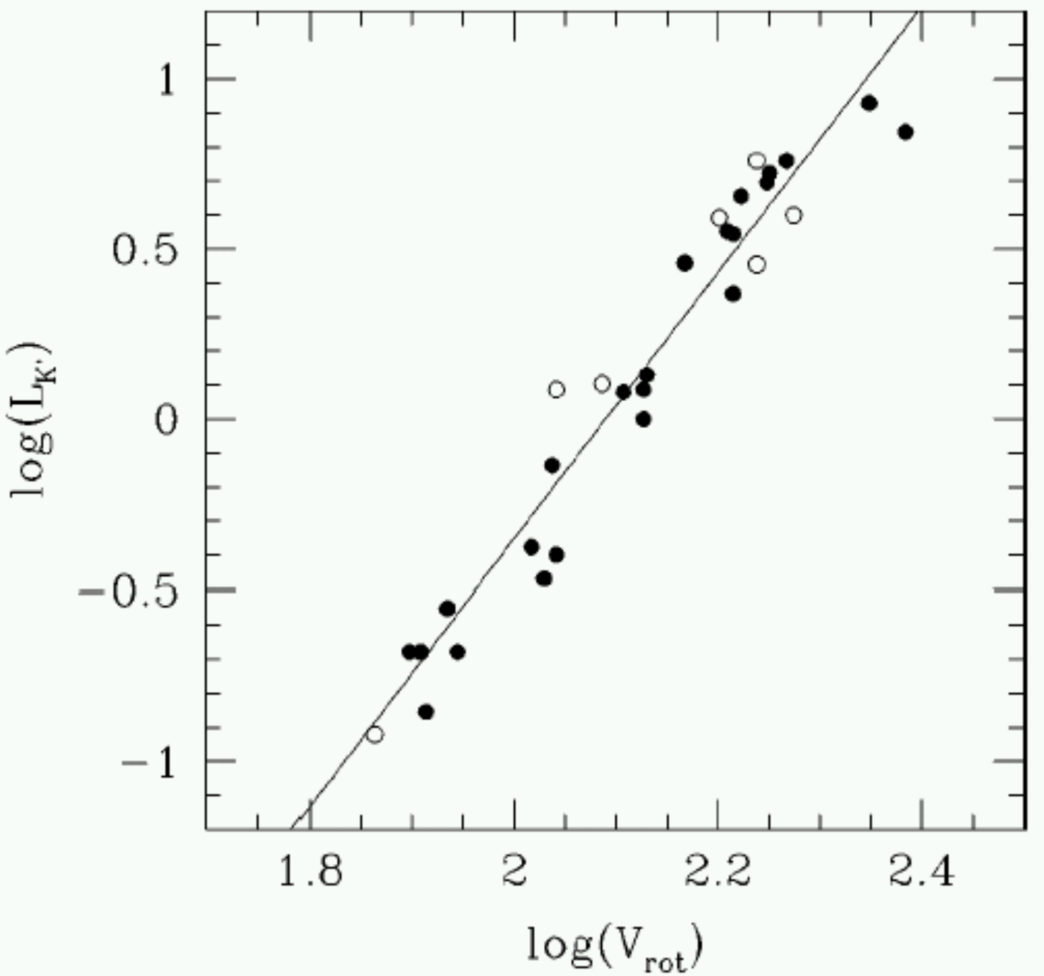
implies

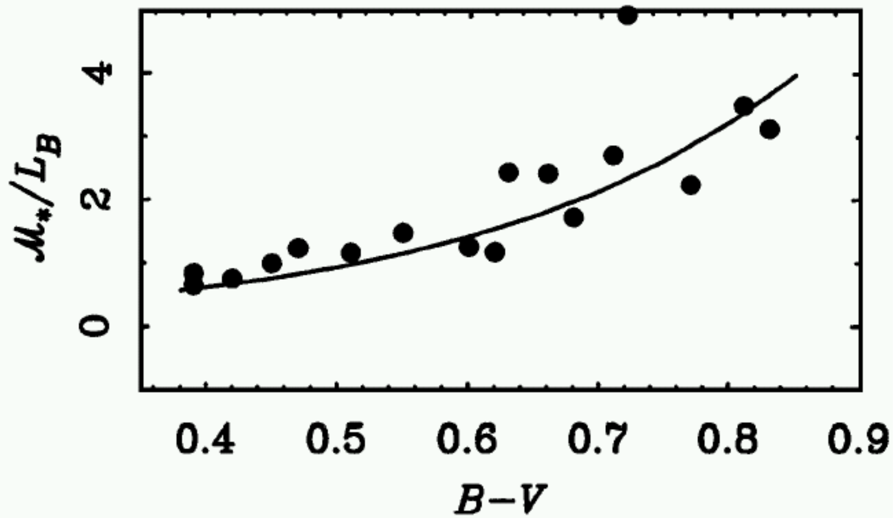
$$\mu(|\nabla\phi|/a_0)\nabla\phi = \nabla\phi_\mathrm{N} + \nabla\times\mathbf{A}$$

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

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

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



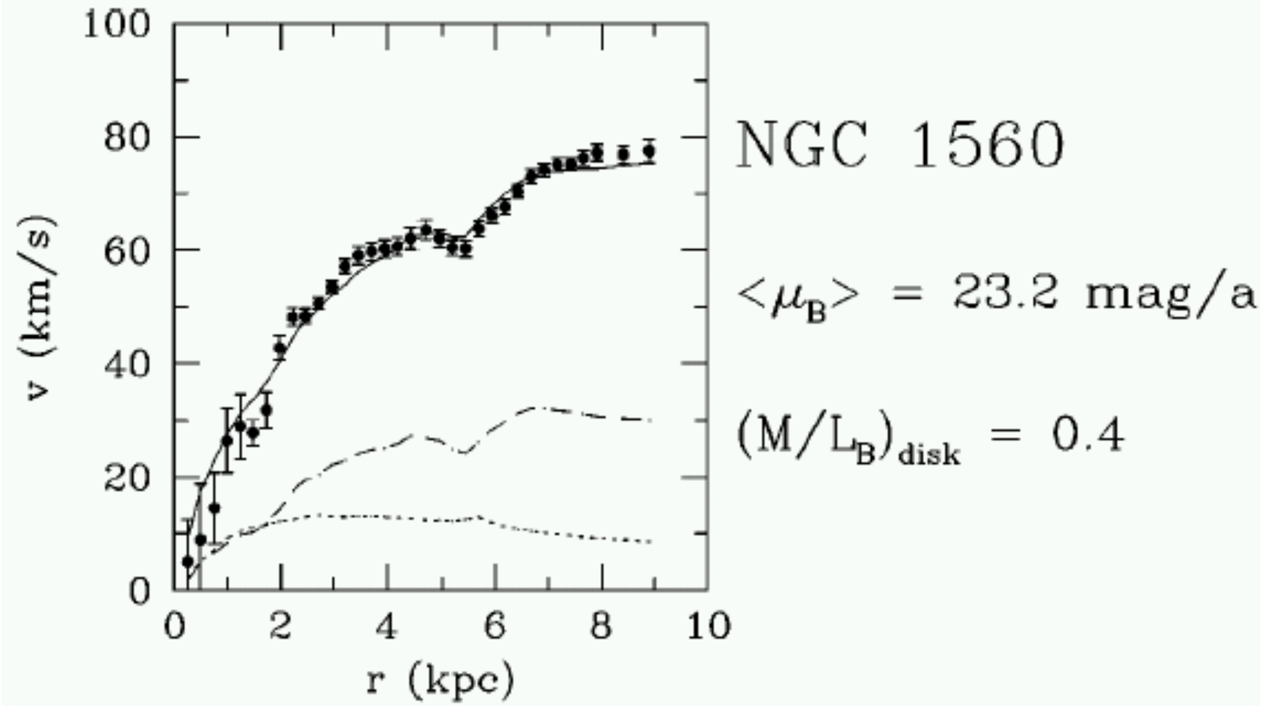


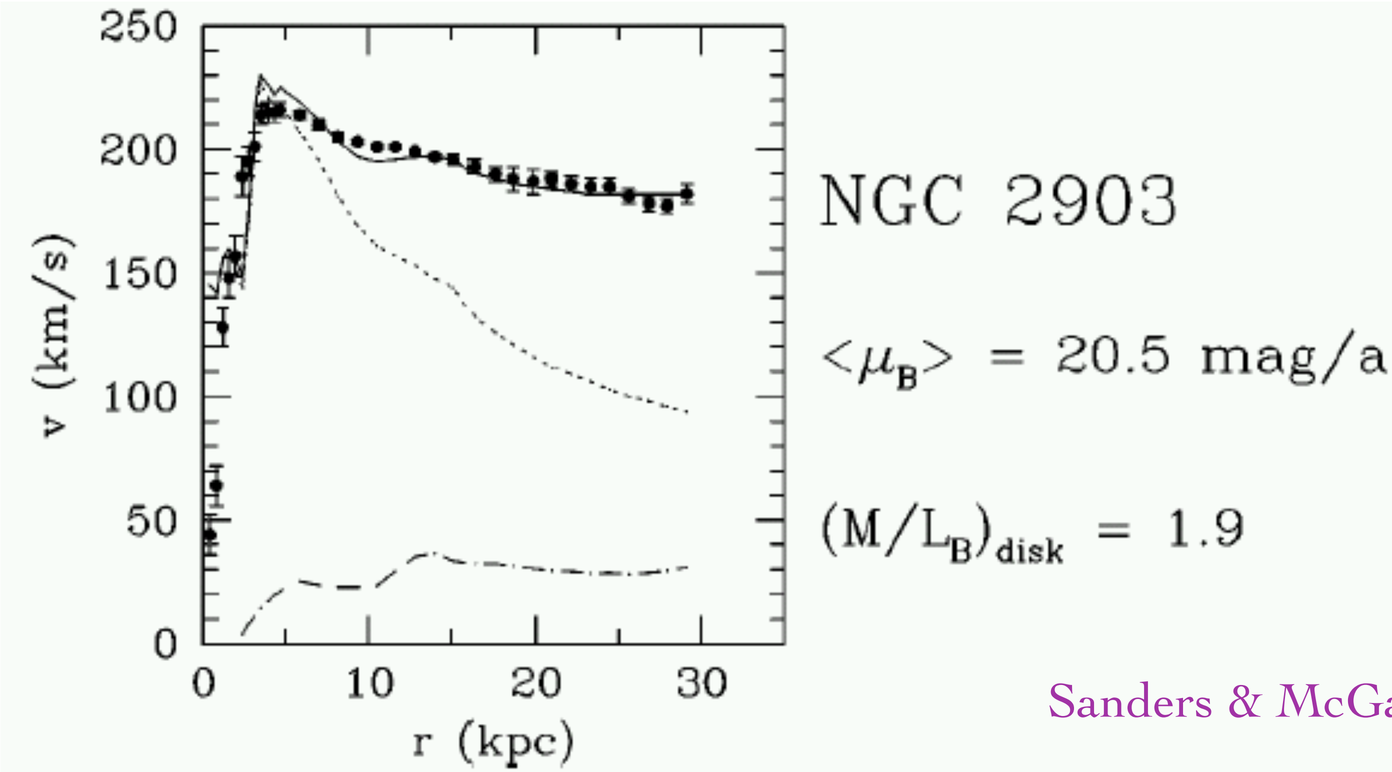
… the fitted value of the only free parameter (M/L) *agrees very well* with population synthesis models

Sanders & Verheijen [astro-ph/9802240]

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

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



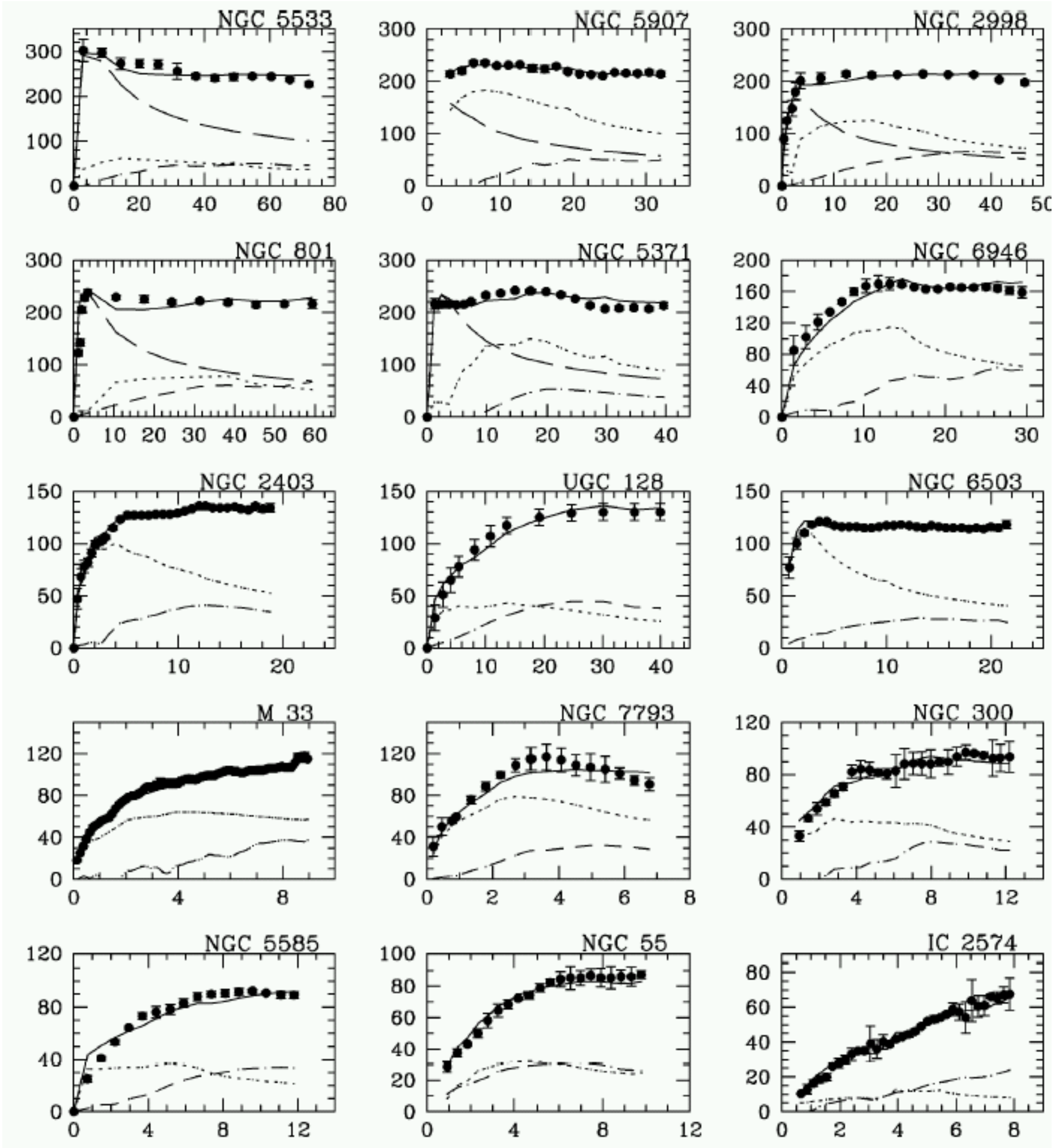


Features in the *baryonic* disc are clearly reproduced

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

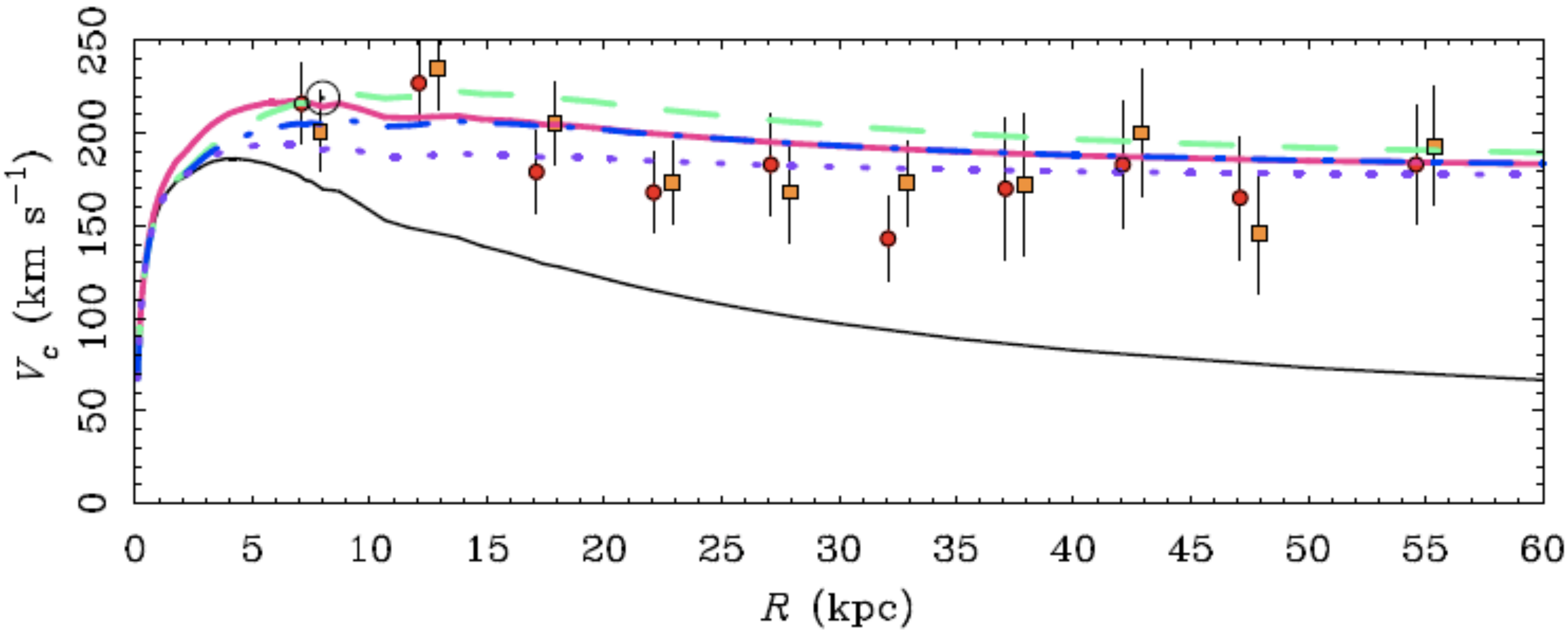


Fig. 7.— The outer rotation curve predicted by MOND for the Milky Way compared to the two realizations of the Blue Horizontal Branch stars in the SDSS data reported by Xue et al. (2008). The data points from the two realizations have been offset slightly from each other in radius for clarity; lines as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

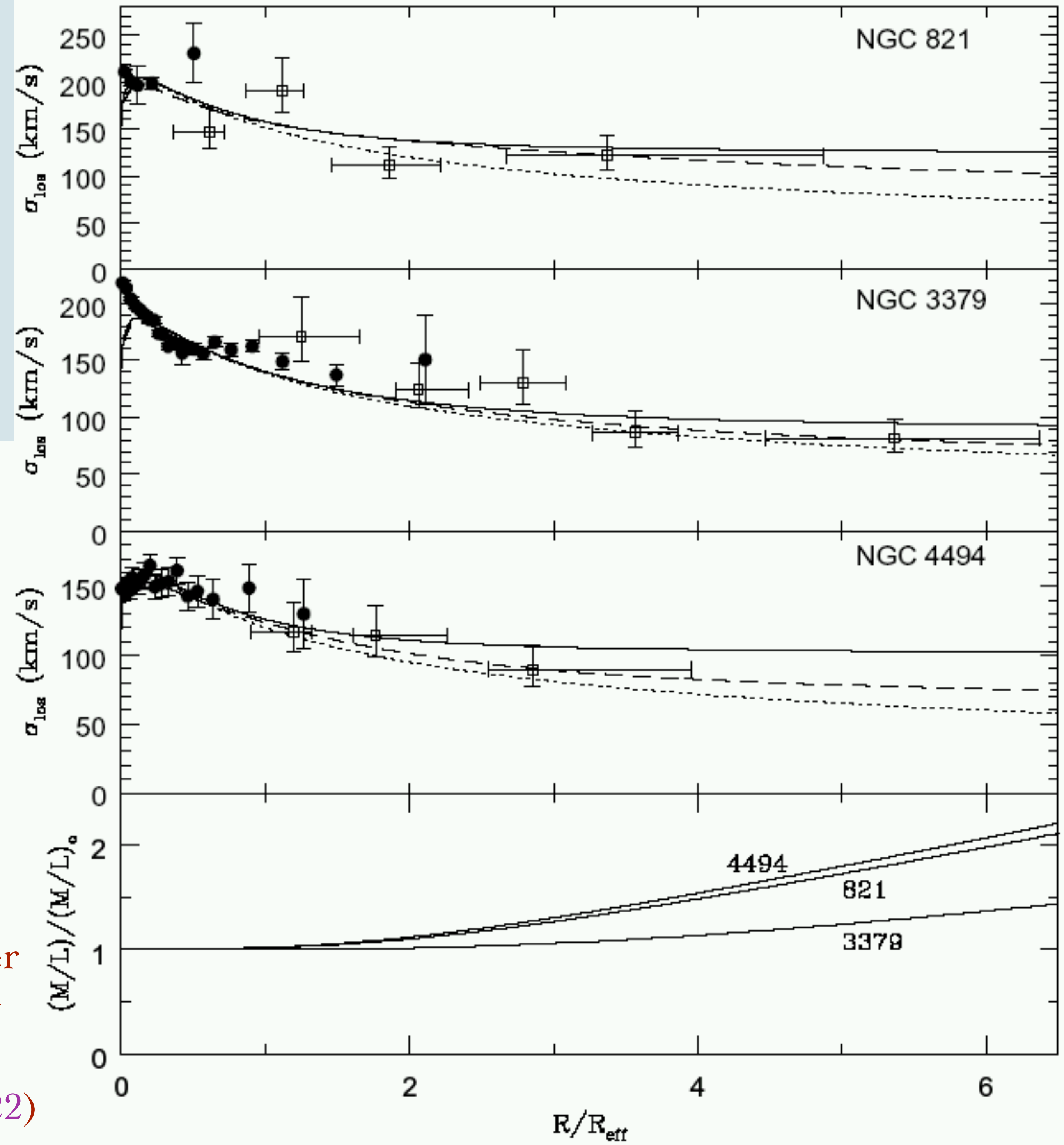
McGaugh [arXiv:0804.1314]

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

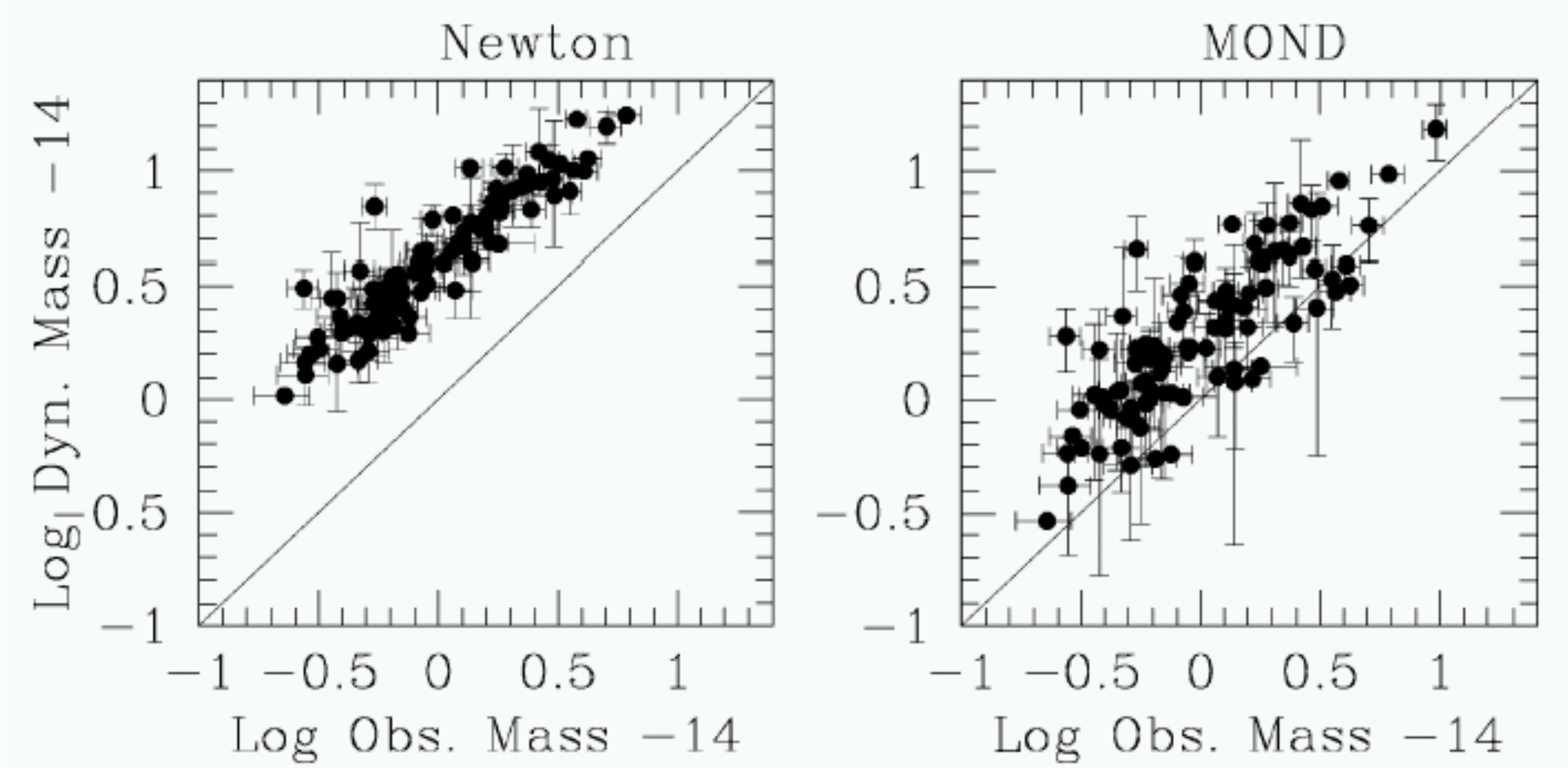
Data:
Romanowsky *et al* [astro-ph/0308518]

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

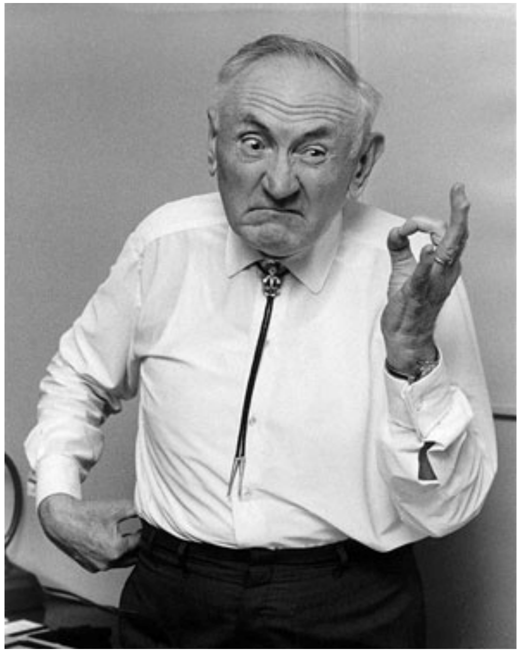
However this can also be explained in a dark matter model if stars are on very elliptical orbits …
Dekel *et al* [astro-ph/0501622)



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)



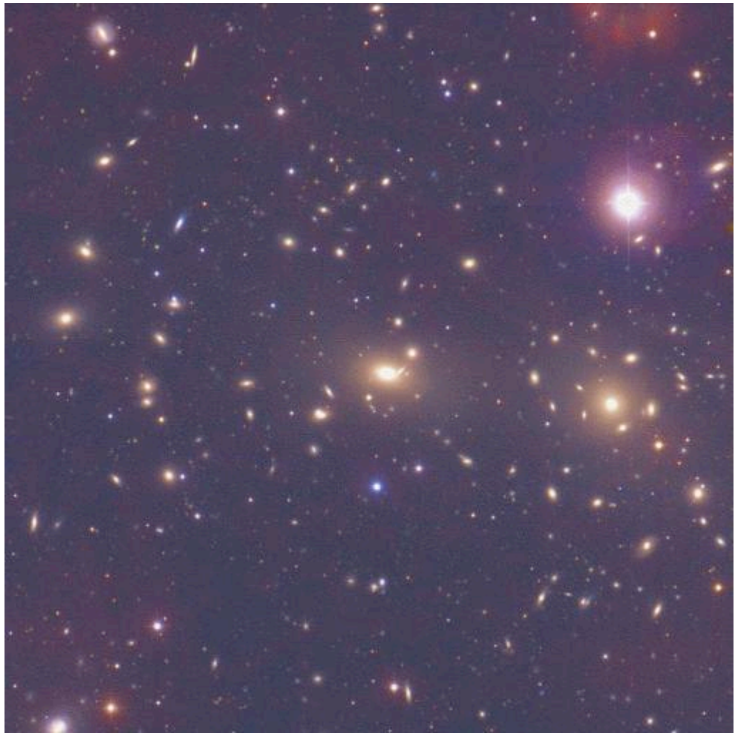
Fritz Zwicky (1933) measured velocity dispersion in the Coma cluster to be ~1000 km/s ➔ M/L ~O(100) Mo/Lo

"… 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"

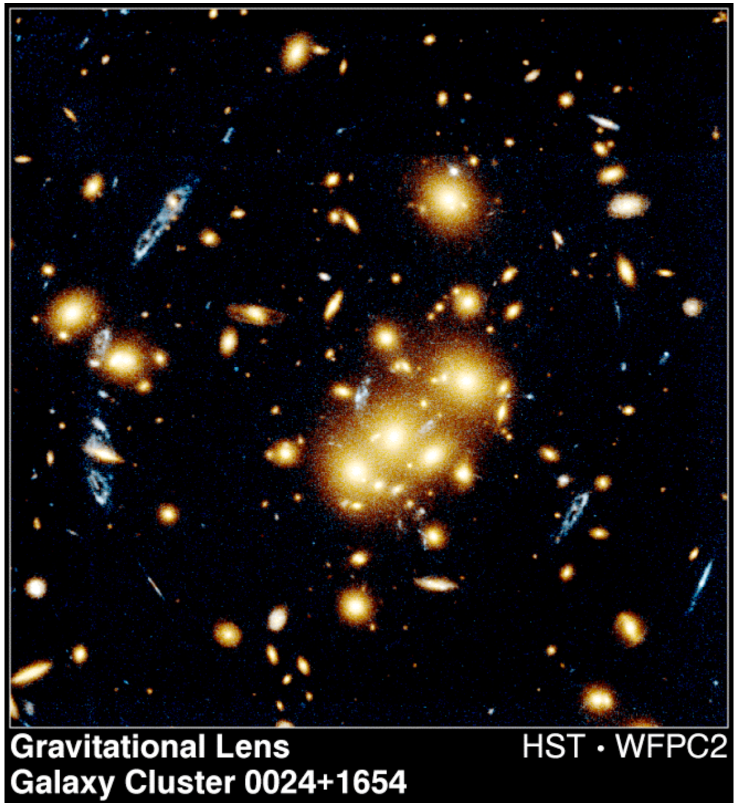
Virial Theorem: $\langle V \rangle + 2\langle K \rangle = 0$

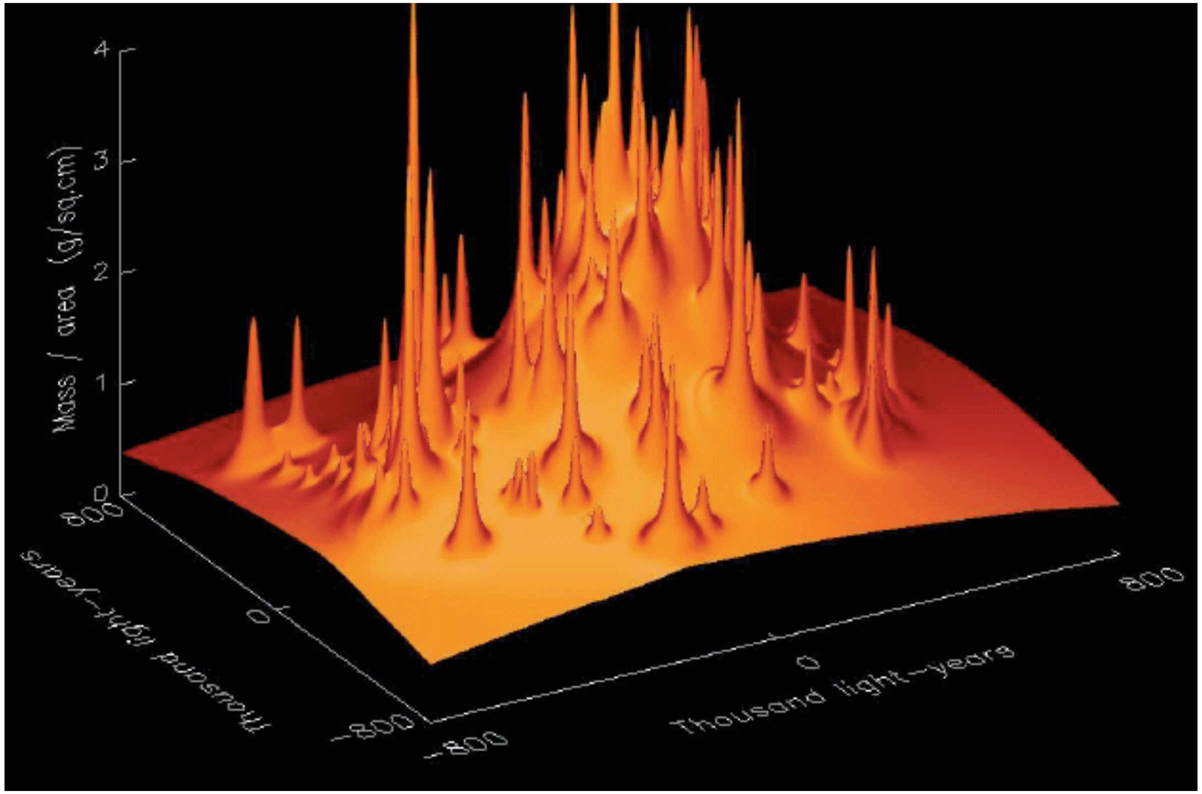
$$V = -\frac{N^2}{2} G_{\mathrm{N}} \frac{\langle m^2 \rangle}{\langle r \rangle}, \quad K = N \frac{\langle m v^2 \rangle}{2}$$

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



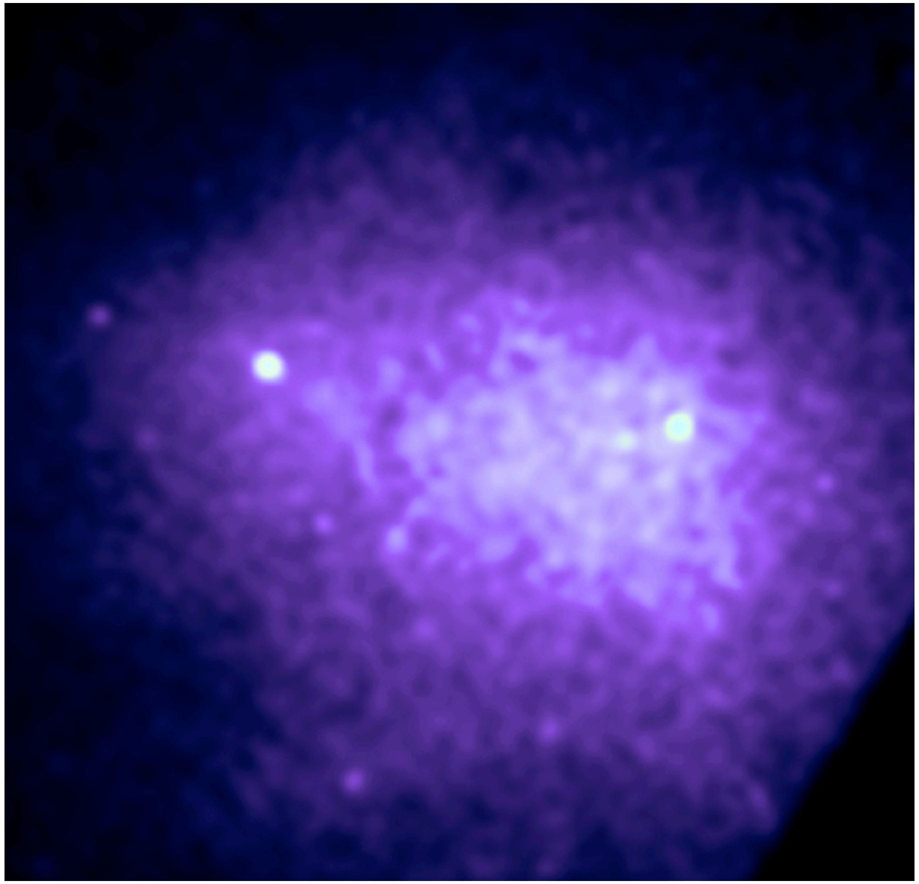
Further evidence comes from observations of **gravitational lensing** of distant sources by a foreground cluster … enabling the potential to be reconstructed





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

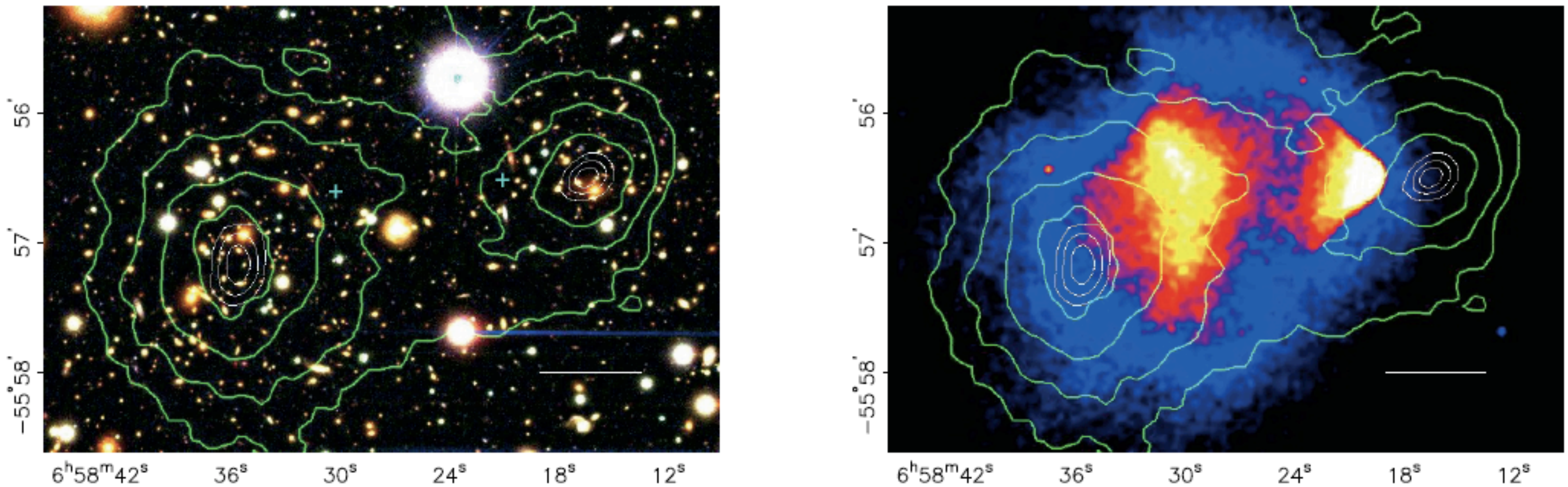
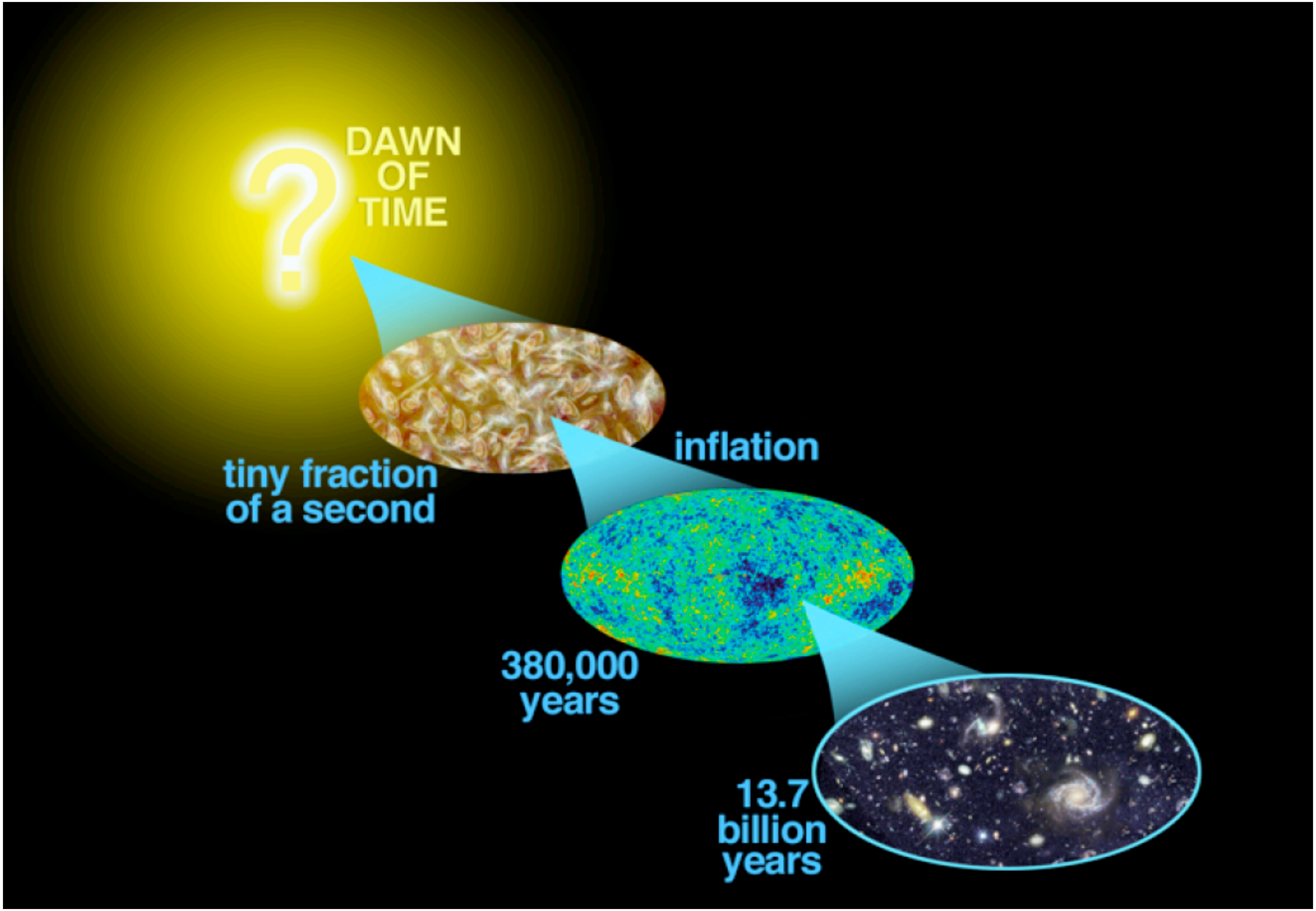


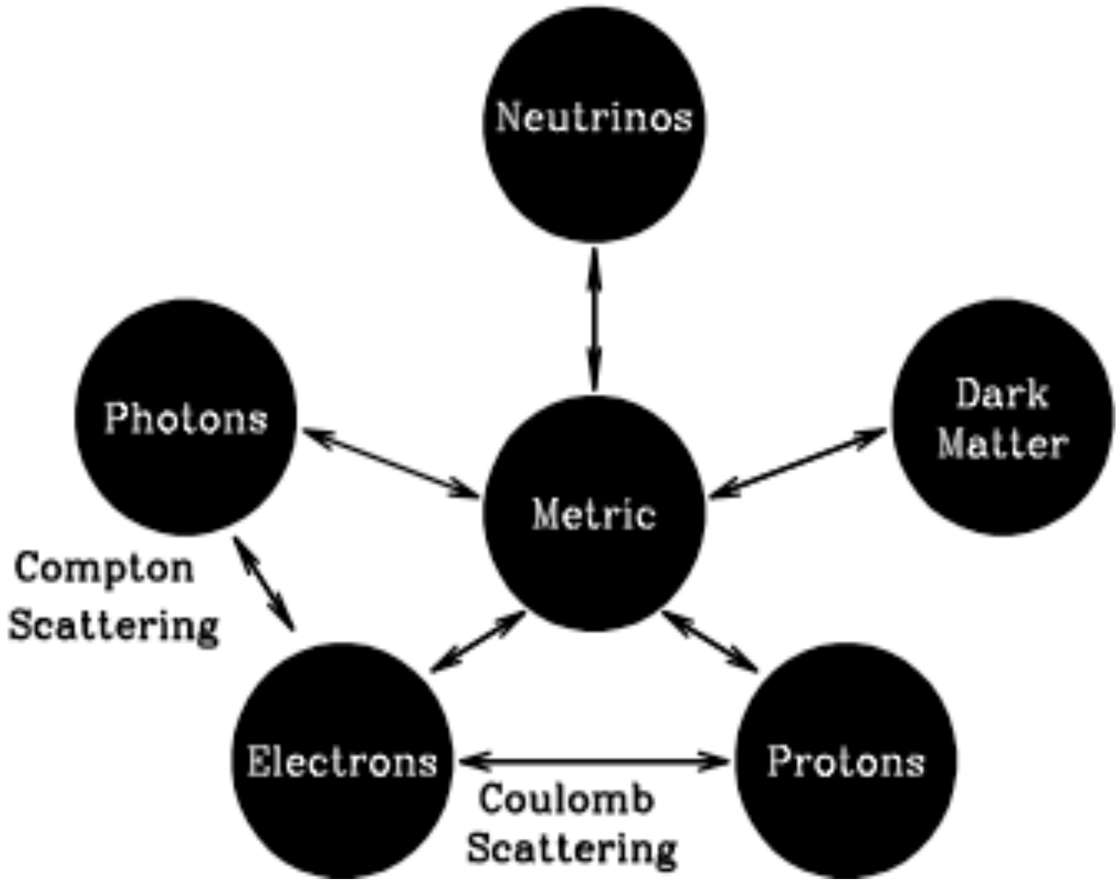
FIG. 1.—*Left panel*: Color image from the Magellan images of the merging cluster 1E 0657−558, with the white bar indicating 200 kpc at the distance of the cluster. *Right panel*: 500 ks *Chandra* image of the cluster. Shown in green contours in both panels are the weak-lensing κ reconstructions, with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

Clowe *et al* [astro-ph/0608407]

Another argument comes from considerations of structure formation in the universe

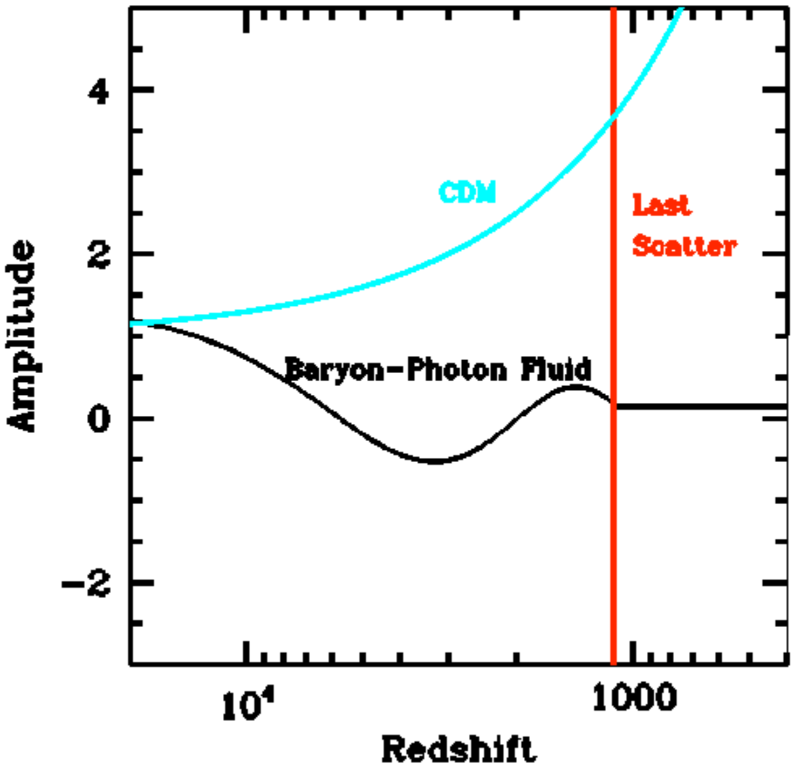


Perturbations in metric (generated during inflation) induce perturbations in photons and (dark) matter

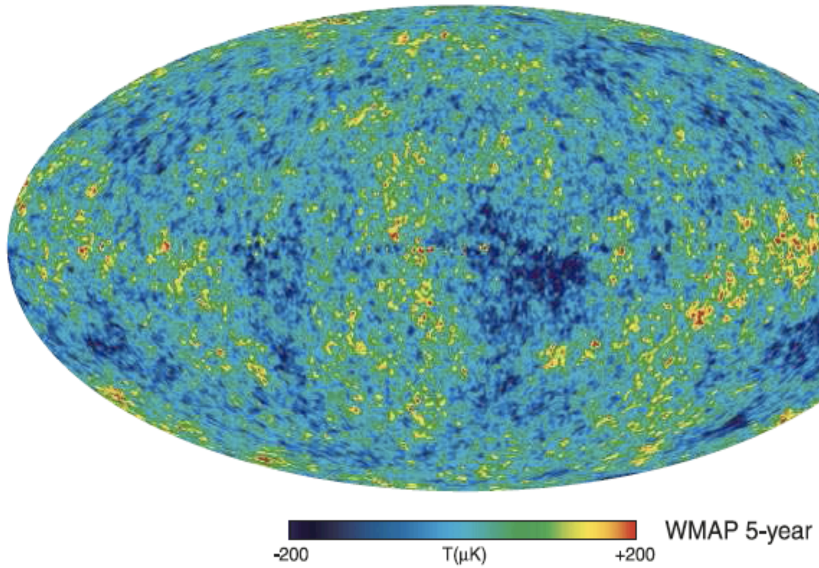


These perturbations begin to grow through gravitational instability after matter domination

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



Courtesey David Spergel



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:

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

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

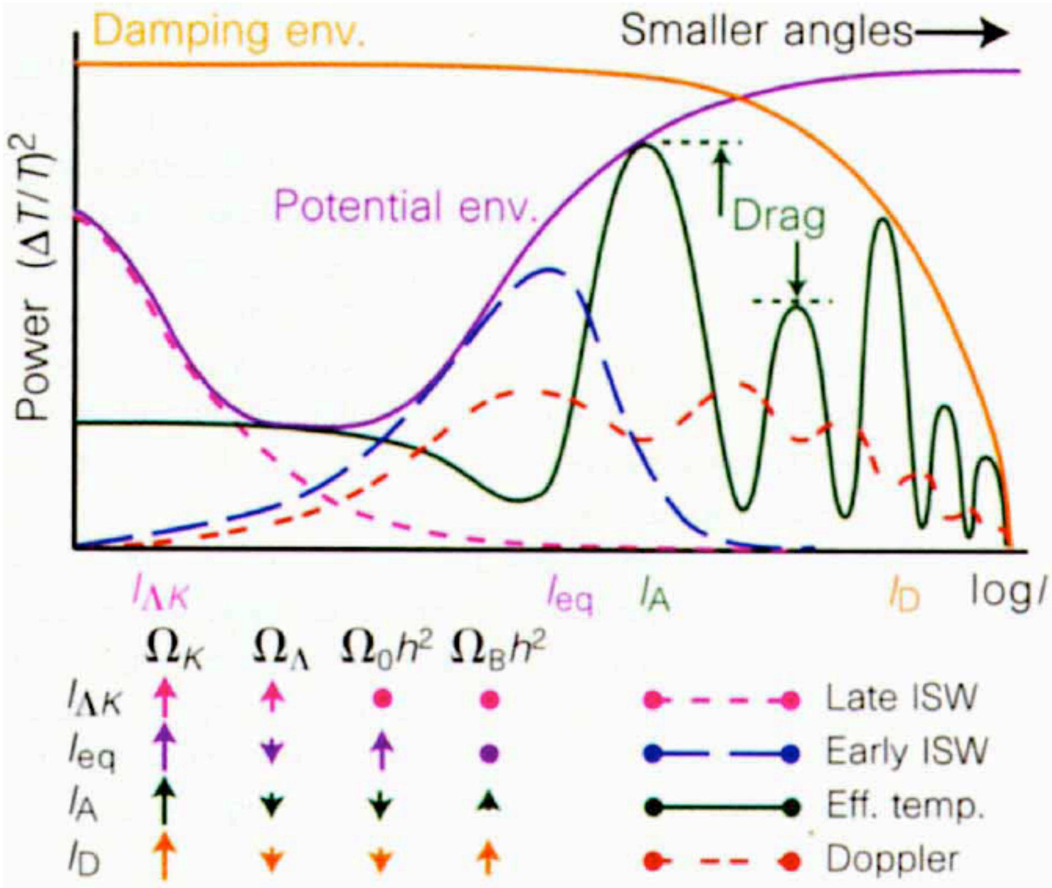


Figure 1 Schematic decomposition of the anisotropy spectrum and its dependence on cosmological parameters, in an adiabatic model. Four fundamental angular scales characterized by the angular wavenumber $l \propto \theta^{-1}$ enter the spectrum: $l_{\Lambda K}$ and l_{eq} which enclose the Sachs-Wolfe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

Hu, Sugiyama, Silk [astro-ph/9604166]

The Cosmic Microwave Background

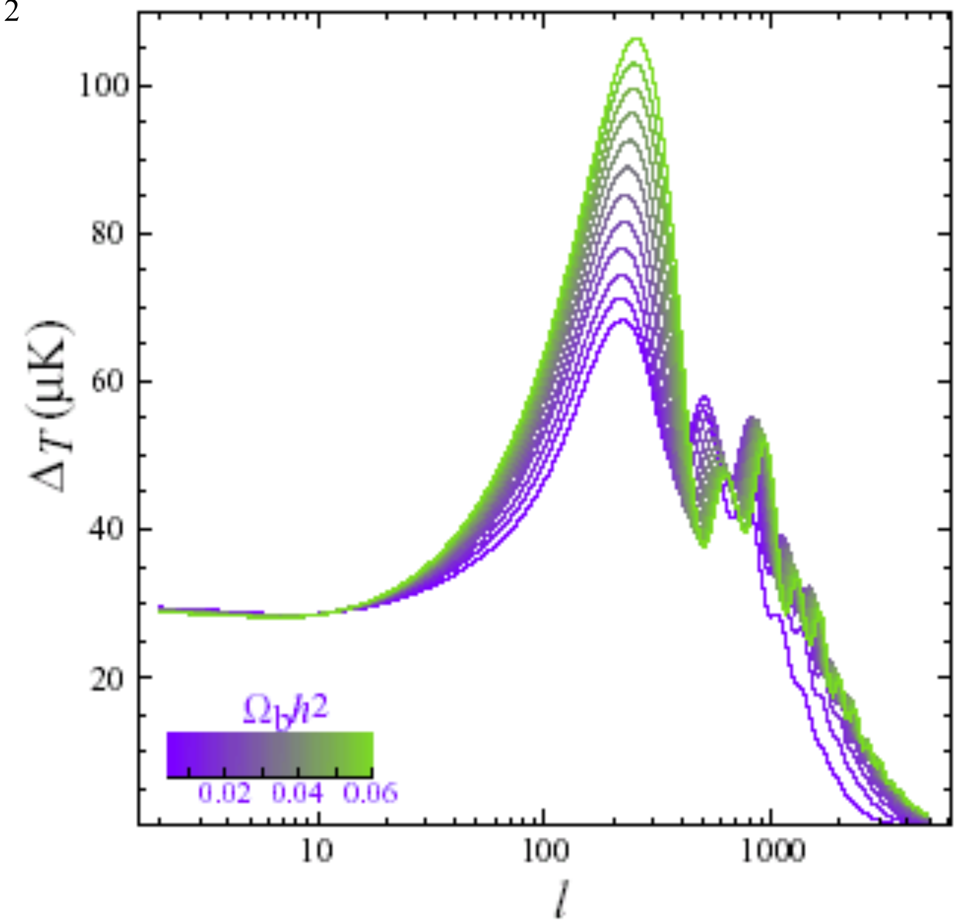
ΔT_ℓ provide *independent* measure of $\Omega_B h^2$

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 ⇒ baryon density

WMAP-5 best-fit:

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



Bond & Efstathiou (1984)
Dodelson & Hu (2003)

BBN versus CMB

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

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

This implies $\Omega_B \sim 0.02h^{-2}$, whereas $\Omega_{luminous} \sim 0.024h^{-1}$

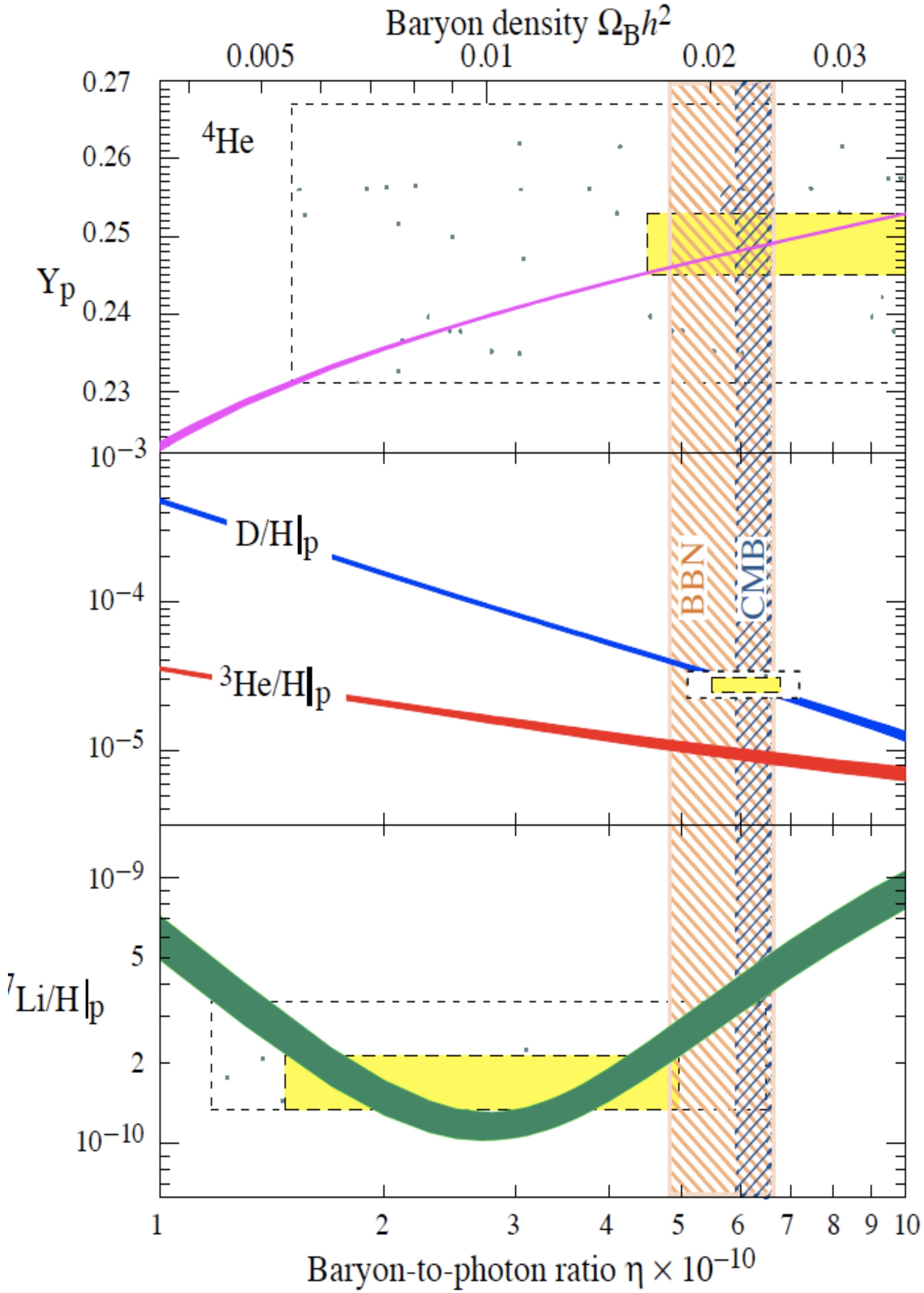
Confirms and sharpens the case for **(*two* kinds of) dark matter**

Baryonic Dark Matter:
warm-hot IGM, Ly-α , X-ray gas …

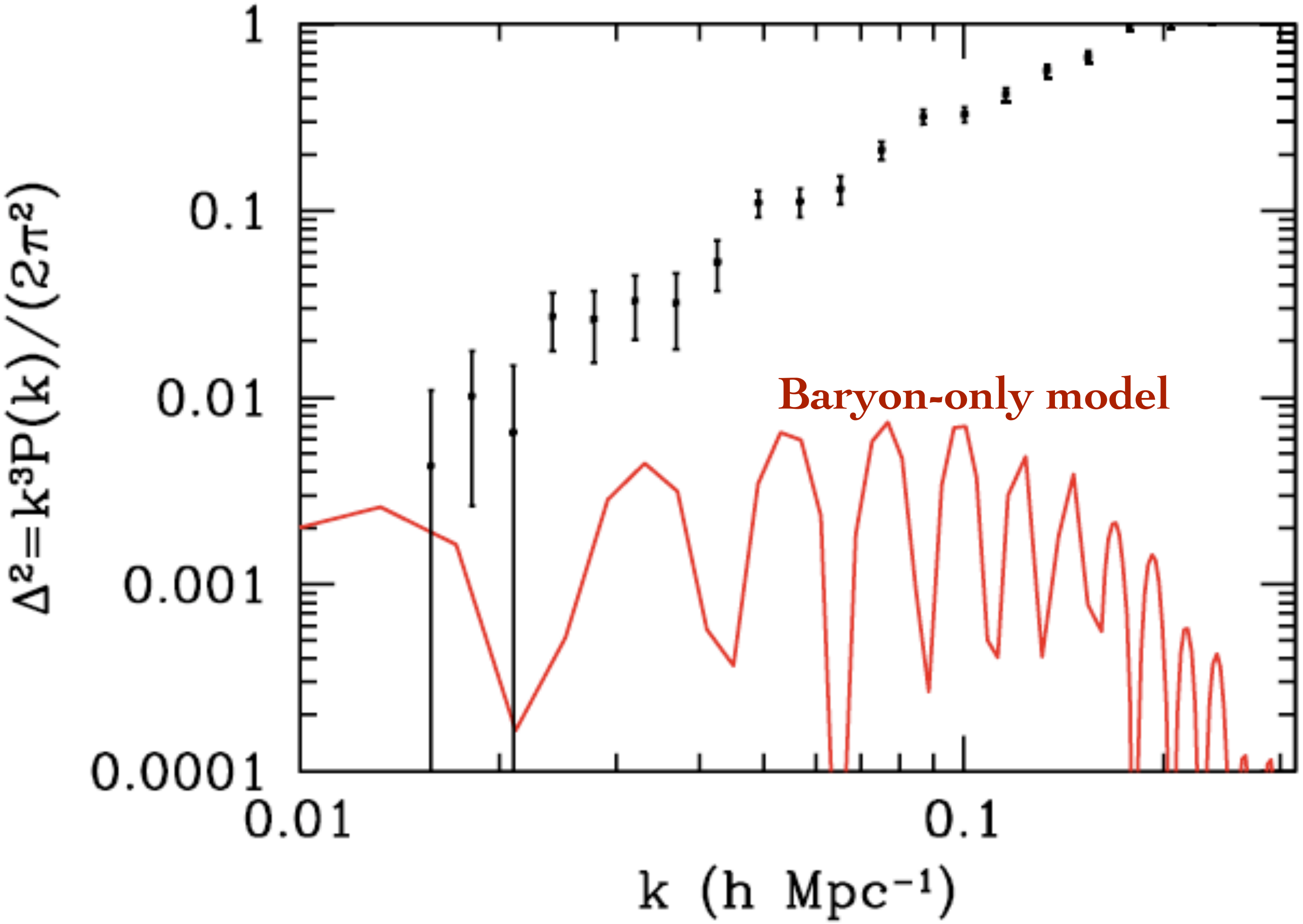
+

Non-baryonic dark matter:
neutralino? axion? …

Particle data Group: Fields & Sarkar (2008)



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



Dodelson & Liguori [astro-ph/0608602]

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

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 dark matter cosmology

Essential to undertake new probes of MOND, e.g. 'Pioneer anomaly', gravitational lensing, …

Confirmation of general relativity on large scales from weak lensing and galaxy velocities

Nature 464:256,2010

Reinabelle Reyes[1], Rachel Mandelbaum[1], Uros Seljak[2,3,4], Tobias Baldauf[2], James E. Gunn[1], Lucas Lombriser[2] & Robert E. Smith[2]

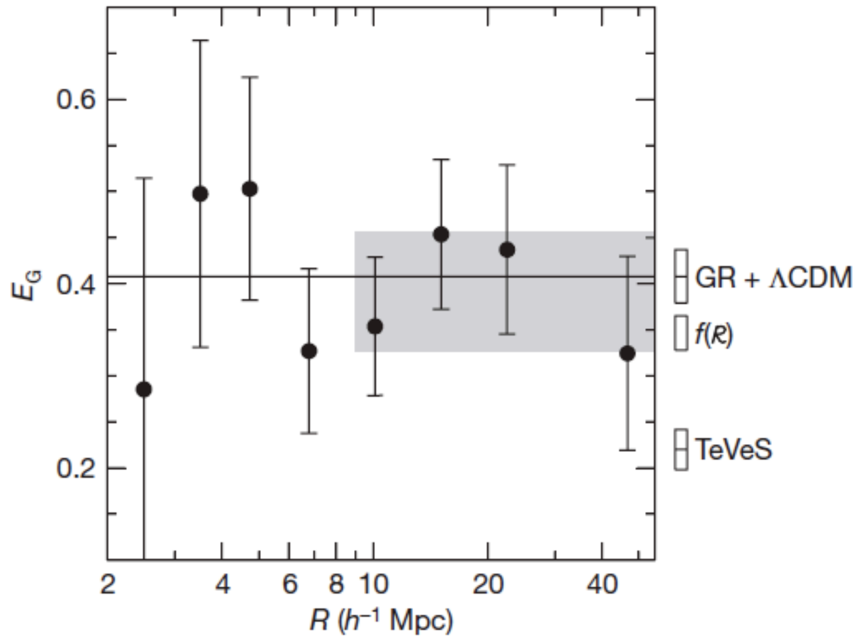


Figure 2 | Comparison of observational constraints with predictions from general relativity and viable modified theories of gravity. Estimates of $E_G(R)$ with error bars (1σ) including the statistical error in the measurement of β (ref. 14). The grey shaded region is the 1σ envelope of the mean E_G on scales $R = 10h^{-1}$–$50h^{-1}$ Mpc, where the systematic effects are least important (Supplementary Information). The horizontal line shows the mean prediction of general relativity, $E_G = \Omega_{m,0}/f(z)$, at the effective redshift of the measurement, $z = 0.32$. On the right-hand side of the panel, labelled vertical bars show the predicted ranges from three different gravity theories: general relativity (GR) plus Λ cold dark matter (ΛCDM) model ($E_G = 0.408 \pm 0.029$ (1σ)); a class of cosmologically interesting models in $f(R)$ theory with Compton-wavelength parameters[21] $B_0 = 0.001$–0.1 ($E_G = 0.328$–0.365); and a tensor–vector–scalar (TeVeS) model[1] designed to match existing cosmological data and to produce a significant enhancement of the growth factor ($E_G = 0.22$, shown with a nominal error bar of 10% for

All these observations indicate that the bulk of the matter in the universe is *dark* (dissipationless, collisionless, mainly cold)

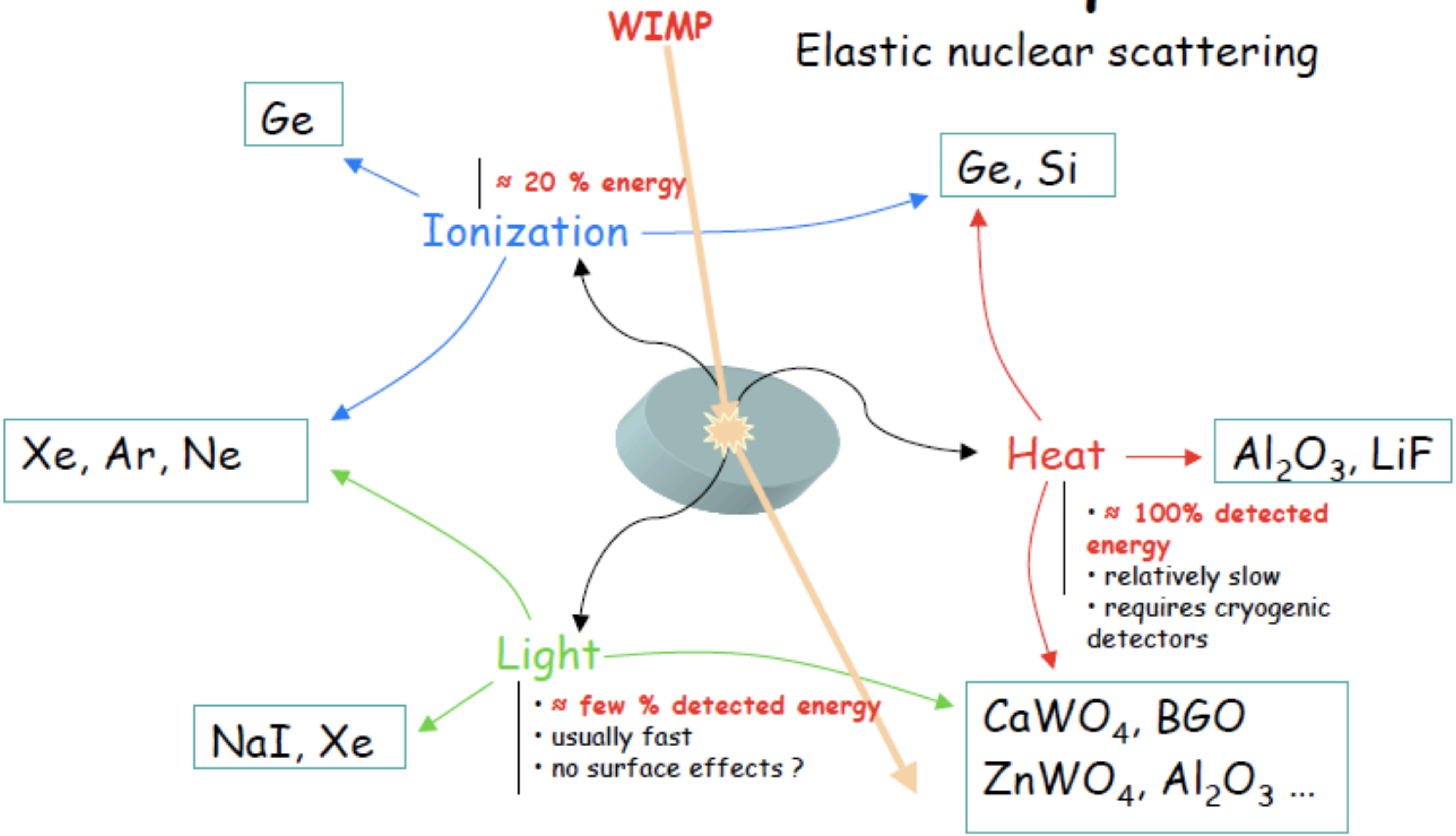
There is a generic expectation that it consists of a new stable particle from *physics beyond the Standard Model*

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

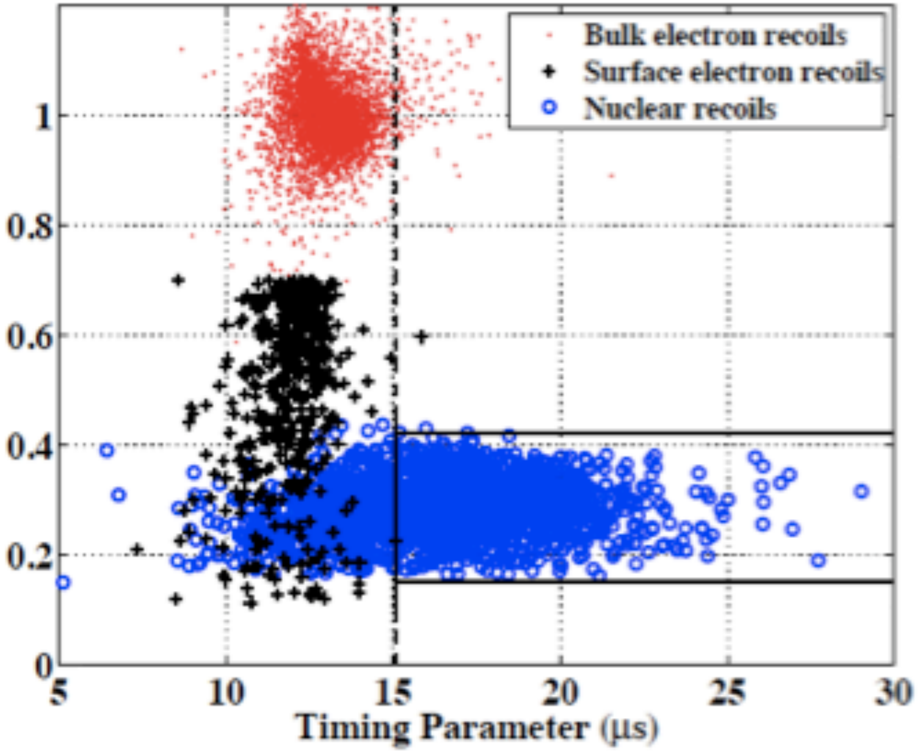
… it cannot couple too strongly to the Z^0 (or would have been seen already in accelerator searches)

Underground nuclear recoil detectors are placing increasingly restrictive bounds on its elastic scattering cross-section with nucleons … however there have been some tantalising results of late

Direct detection techniques

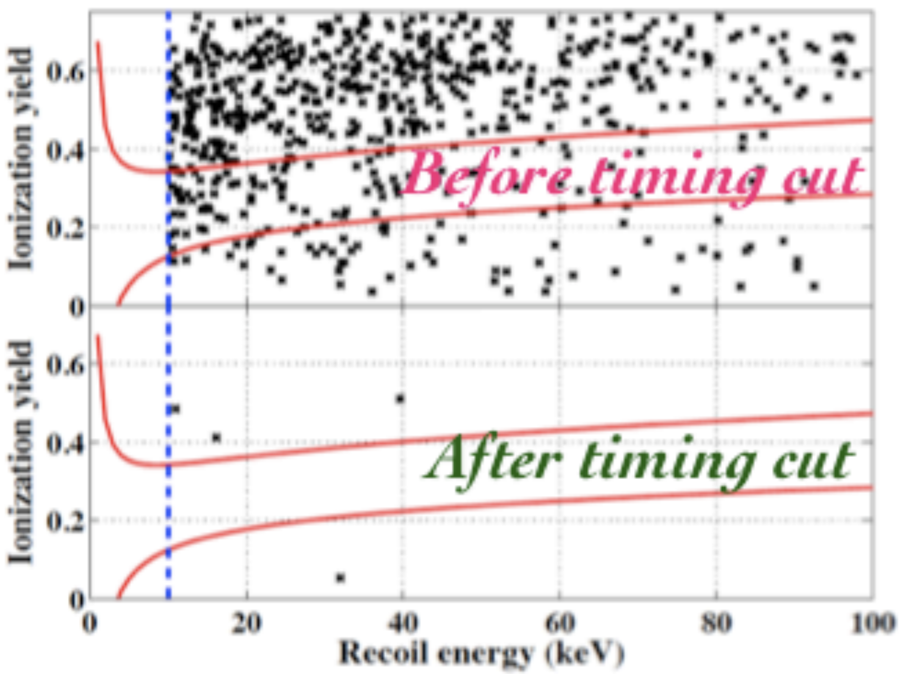


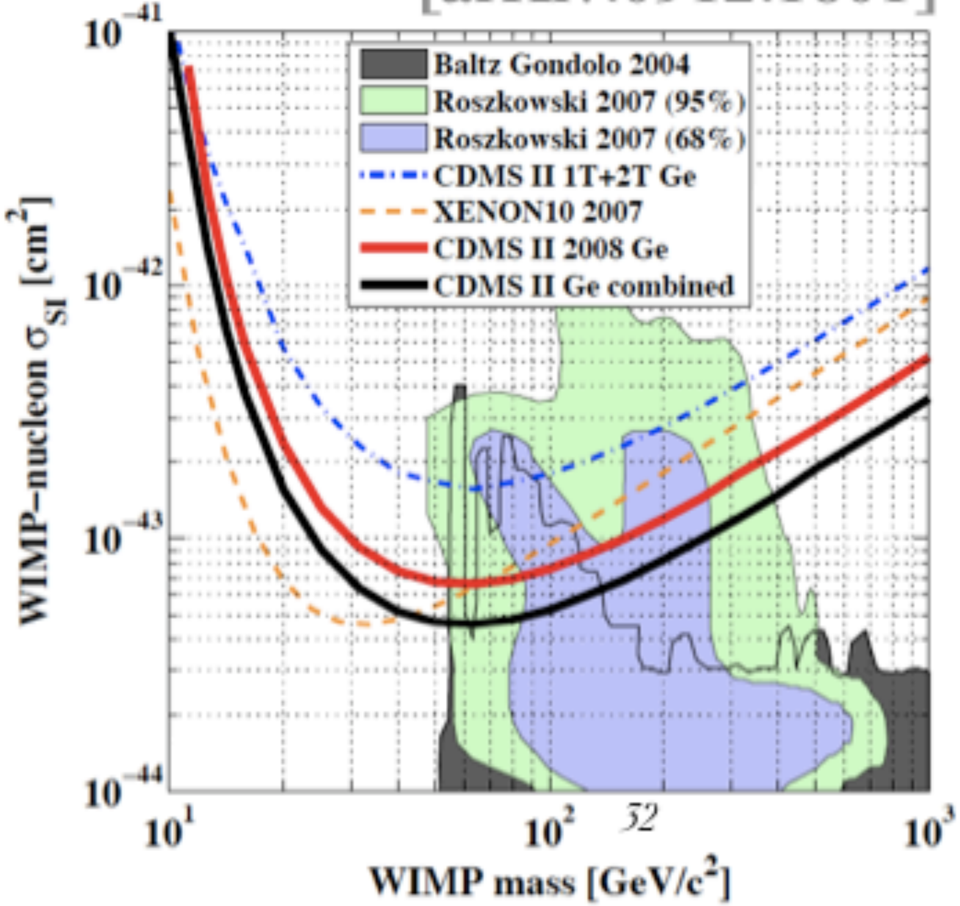
(Drukier & Stodolsky 1984; Goodman & Witten 1985)



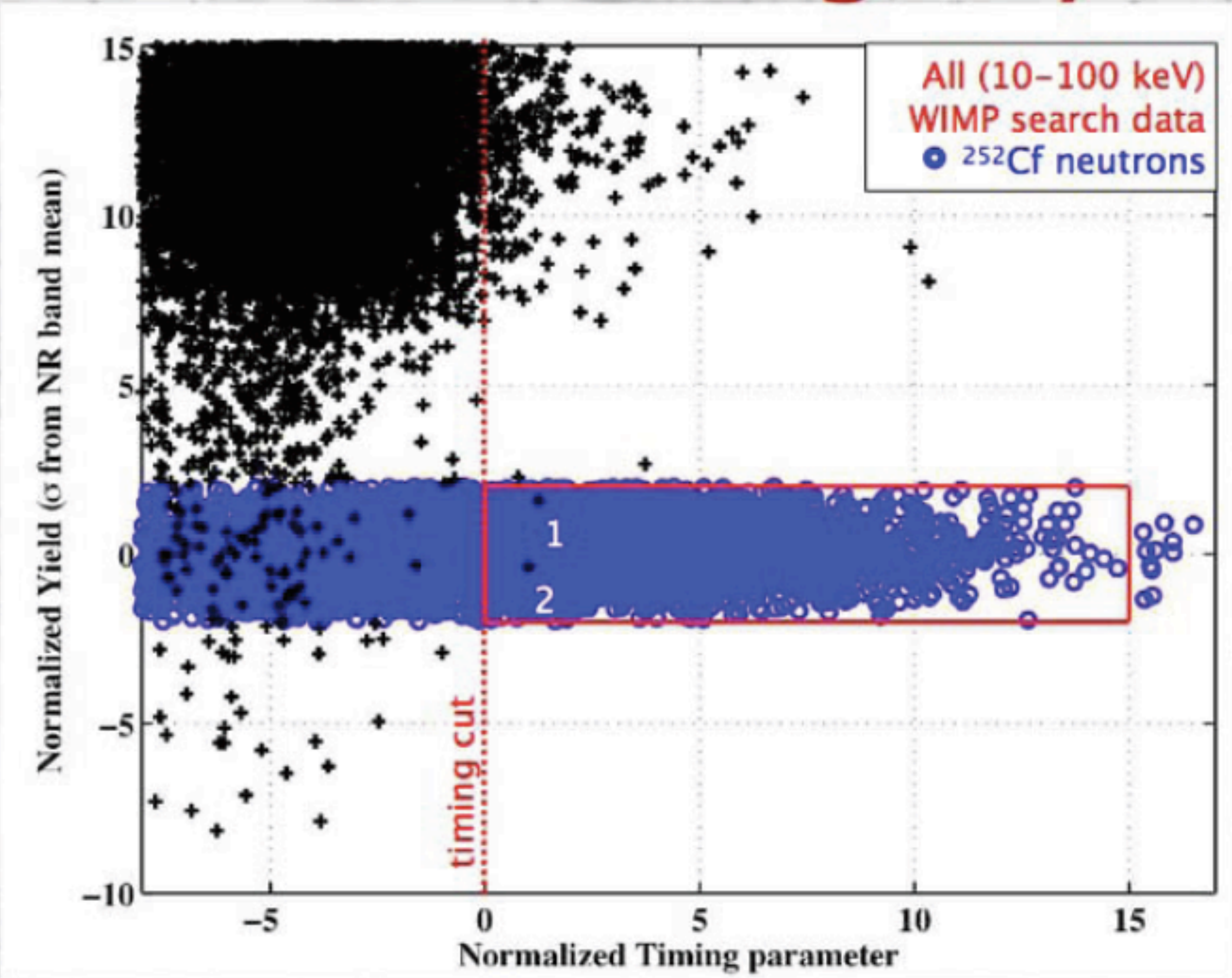
Nuclear recoil detectors (cryogenic and noble liquid) have set stringent limits on spin-*indepependent* elastic scattering cross-sections (it is crucial to distinguish between dark matter and neutron recoil events)

[arXiv:0912.1601]





CDMS-II Results (191 kg.d)

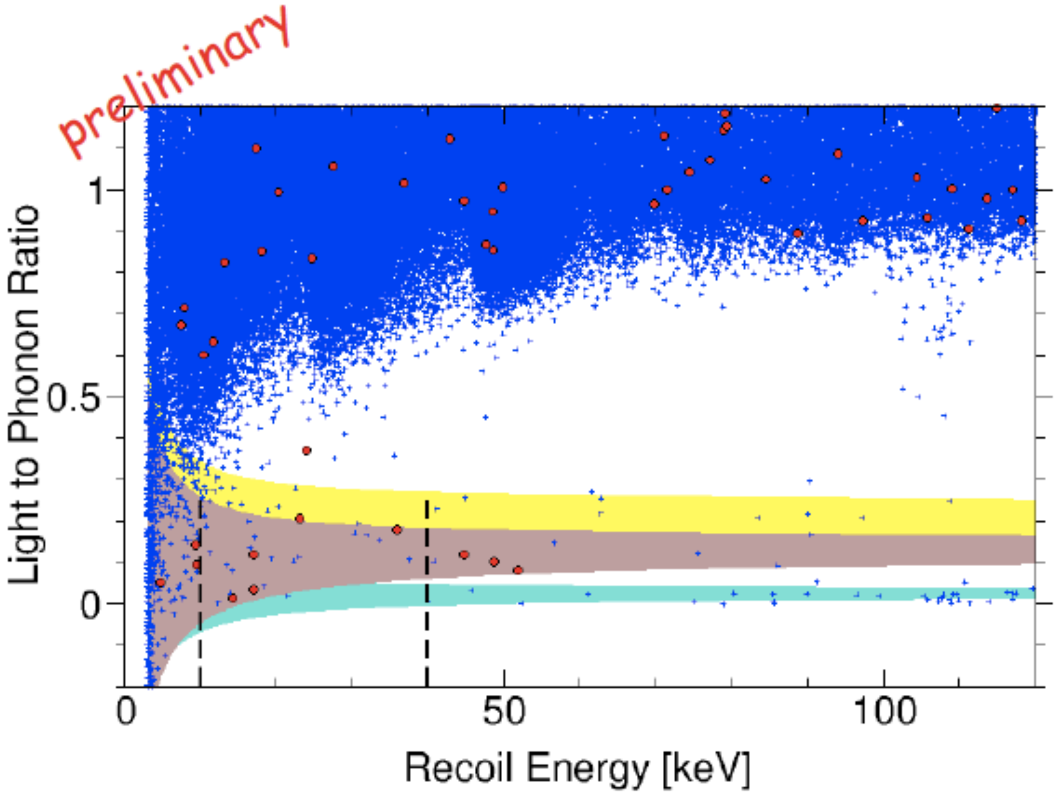


- 2 events passing all cuts
- Blinded background estimate of 0.6 ± 0.1 events

[arXiv:0912.3592]

What is going on in the Oxygen Band

Several detectors added



- Rate in all detectors equal within statistics
- decrease summer winter there but statisticallly not yet significant

Neutrons ?

- Rate to high for external neutrons
- „internal“ neutron source only if low energetic

Low mass WIMPs ??

A combined analysis of all recoil-bands is in preparation

More statistics is needed

CRESST

Evidence for 'light' WIMP dark matter?

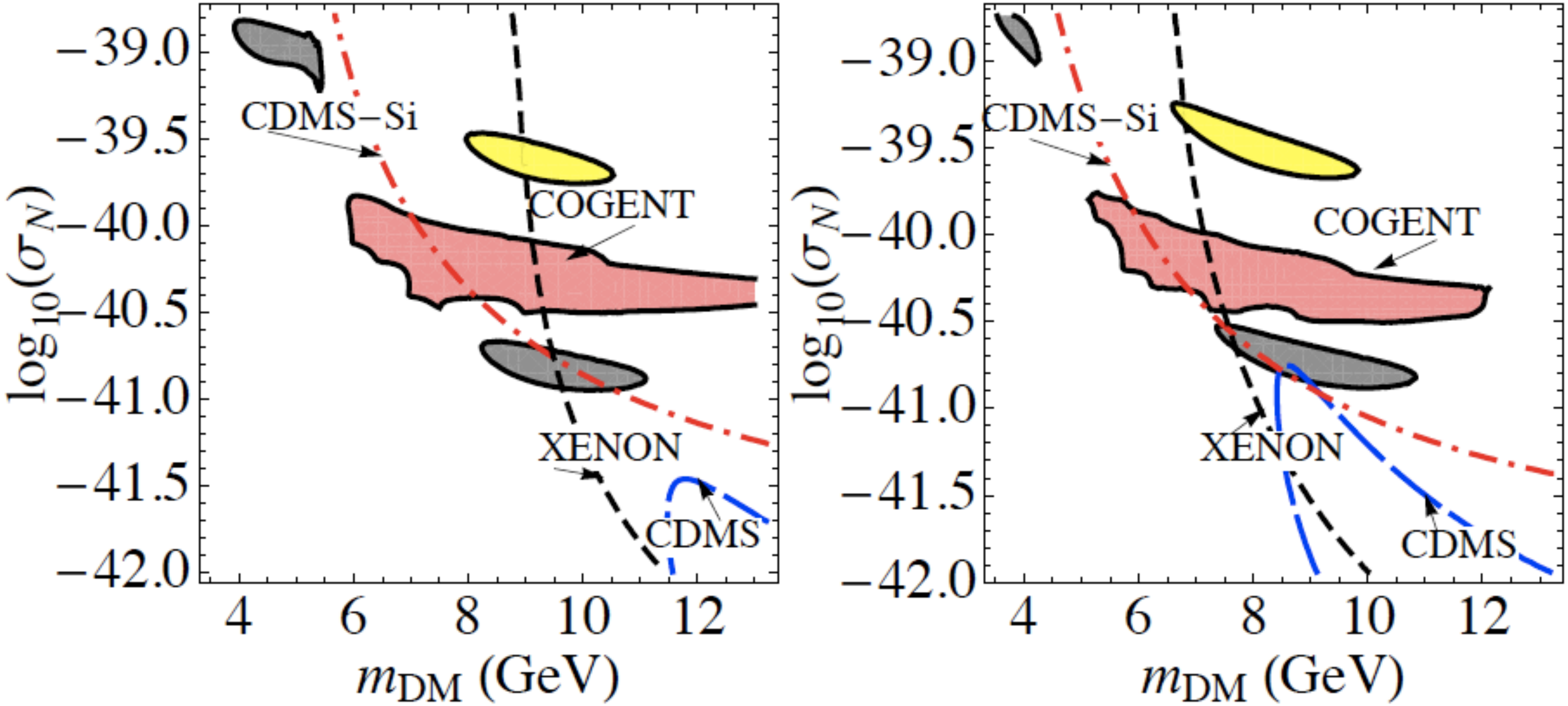
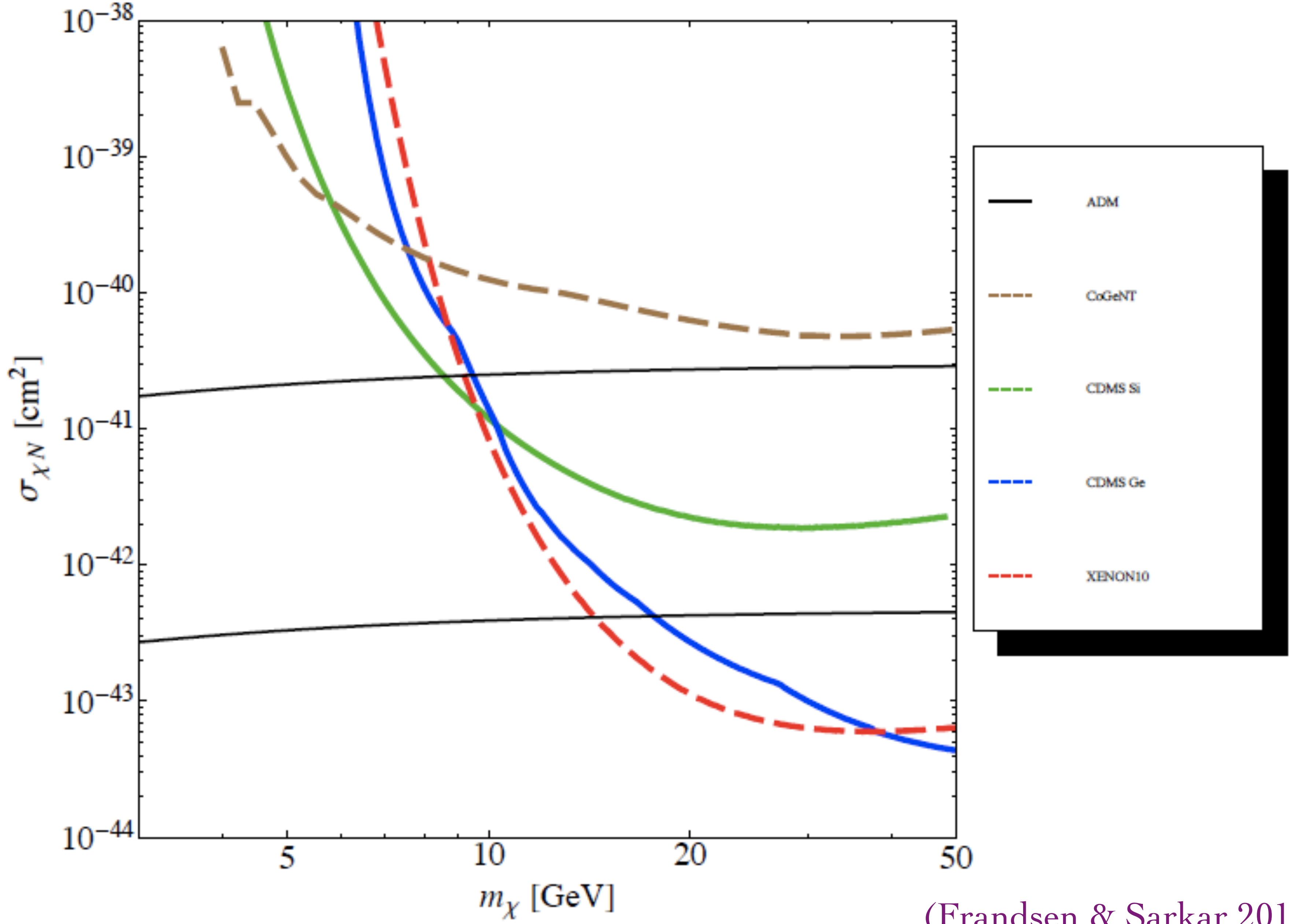


FIG. 1: The regions in the elastic scattering cross section (per nucleon), mass plane in which dark matter provides a good fit to the CoGeNT excess, compared to the region that can generate the annual modulation reported by DAMA (darker grey regions). In this figure, we have adopted $v_0 = 270$ km/s and use two values of the galactic escape velocity: $v_{\rm esc} = 490$ km/s (left) and $v_{\rm esc} = 730$ km/s (right). In calculating the DAMA region, we have treated channeling as described in Ref. [23]. If a smaller fraction of events are channeled in DAMA than is estimated in Ref. [23], the DAMA region will move upward, toward the yellow regions (near $\sigma_N \approx 10^{-39.5}$ cm^2, which include no effects of channeling), improving its agreement with CoGeNT. Also shown is the 90% C.L. region in which the 2 events observed by CDMS can be produced. If the escape velocity of the galaxy is taken to be relatively large, this region can also approach those implied by CoGeNT and DAMA. Constraints from the null results of XENON10 and the CDMS silicon analysis are also shown. For the XENON10 constraint, we have used the lower estimate of the scintillation efficiency (at 1σ) as described in Ref. [24].

Fitzpatrick, Hooper & Zurek, arXiv:1003.0041

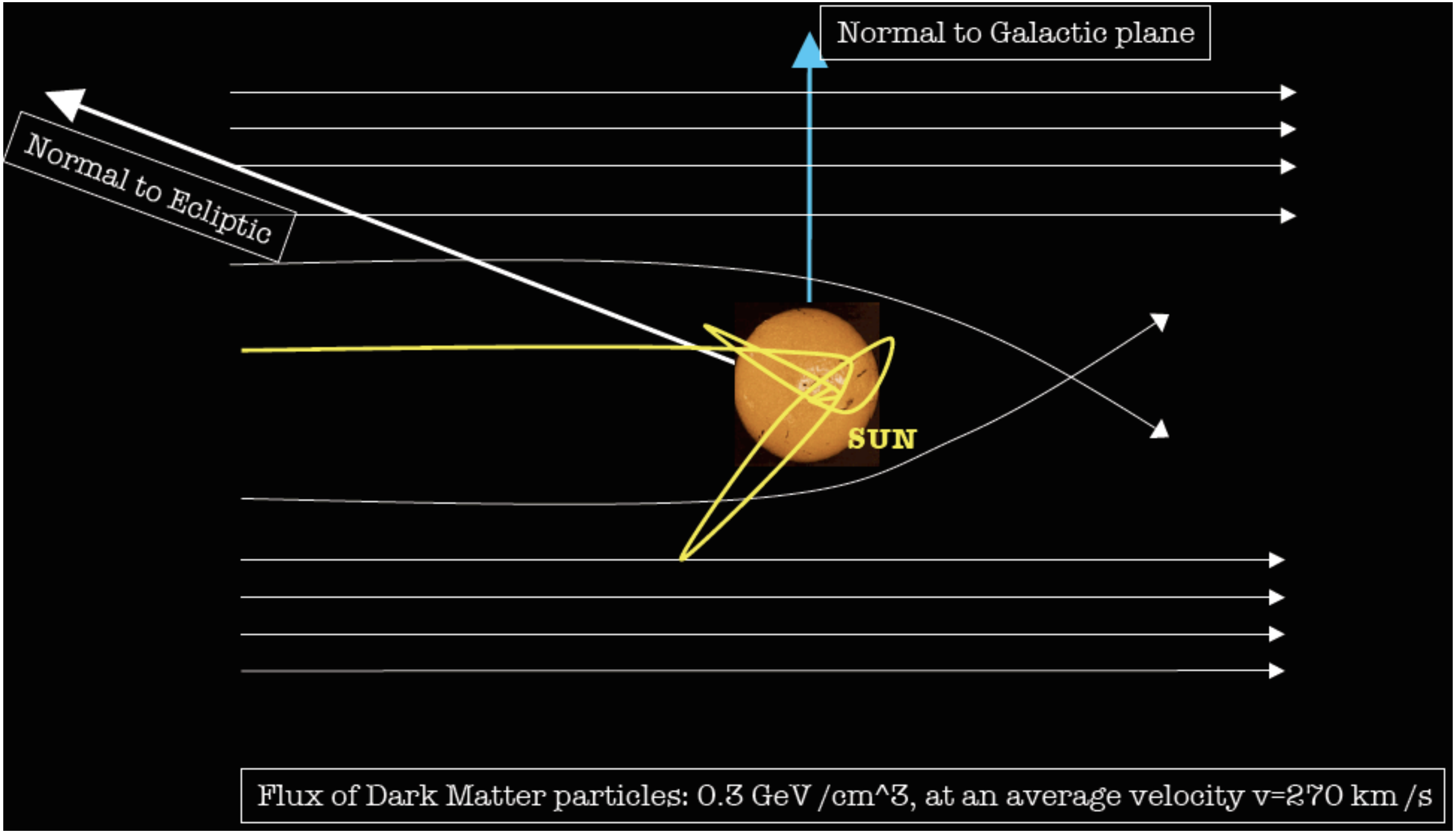
Interestingly, this is just the range of mass and cross-section (through Higgs exchange) that would be expected for an 'unbaryon' in walking technicolour



(Frandsen & Sarkar 2010)

The Sun has been accreting dark matter particles for ~5 x 10^9 yr as it orbits around the Galaxy … these will orbit *inside* affecting energy transport

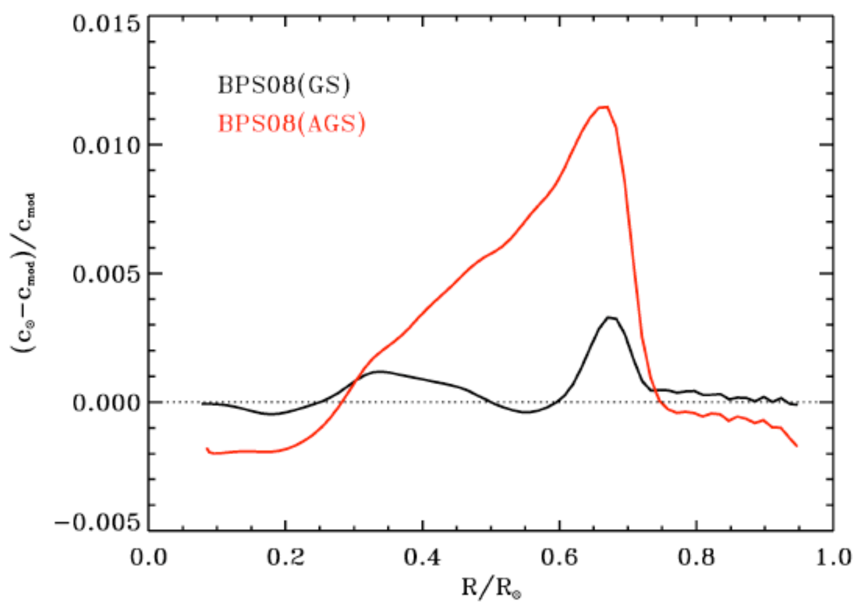
The flux of Solar neutrinos is very sensitive to the core temperature and can be thus affected (Faulkner *et al* 1985, Press & Spergel 1985)



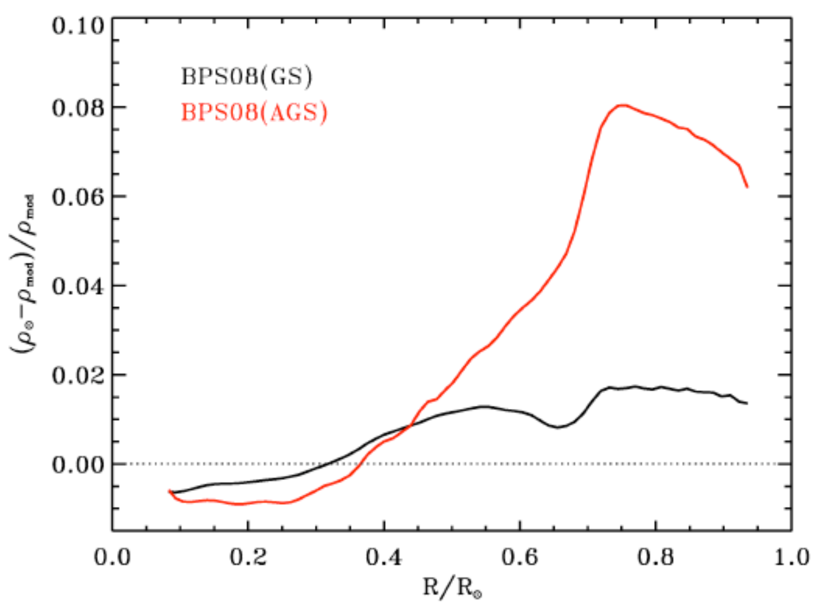
Helioseismology and Solar Metallicity
A New Problem with Solar Models

- Asplund, Grevesse and Sauval determined new solar chemical abundances (metallicity) in 2005 using improved 3D hydrodynamical modeling (tested with many surface spectroscopic observations)
- with these new chemical abundances in solar models (lower metallicity), the previous excellent agreement between model calculations and helioseismology is broken

new C, N, O, Ne abundances lower by 30-50%

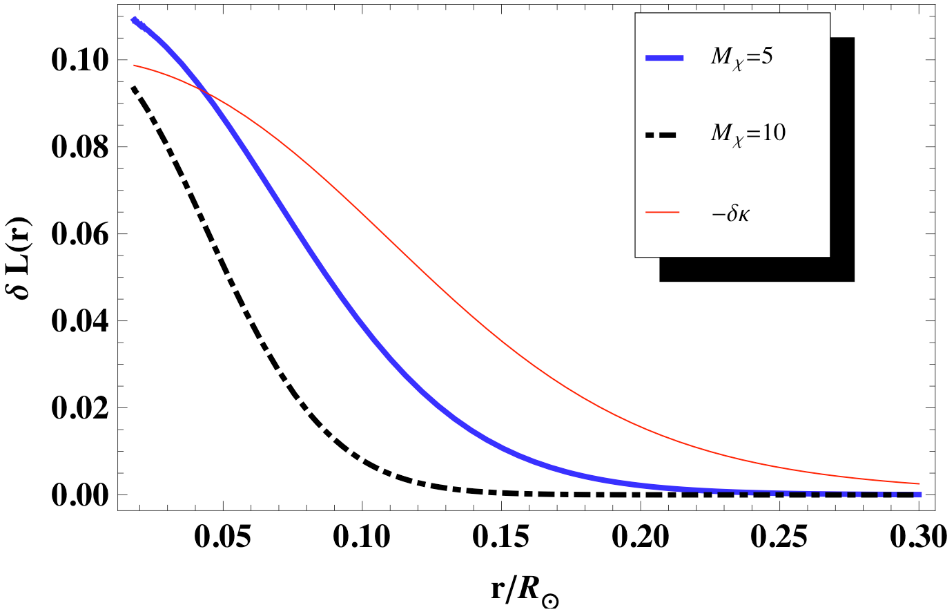


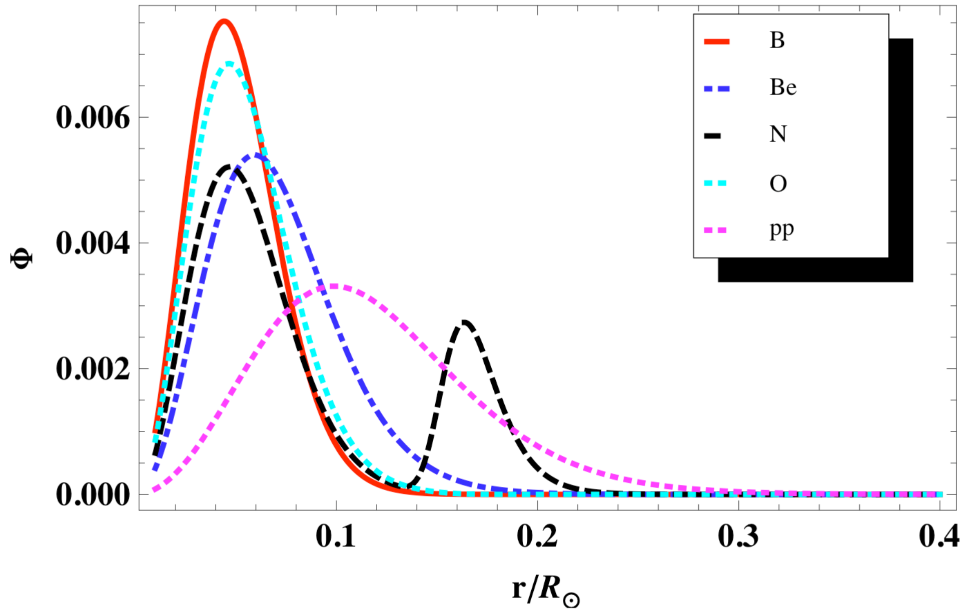
sound speed profile in the Sun



density profile in the Sun

If such 5-10 GeV mass particles are *asymmetric*, their abundance in the Sun will not be depleted by annihilations … in fact it will grow *exponentially* if they have self-interactions (which would also help to explain the paucity of cosmic structure on sub-Galactic scales)

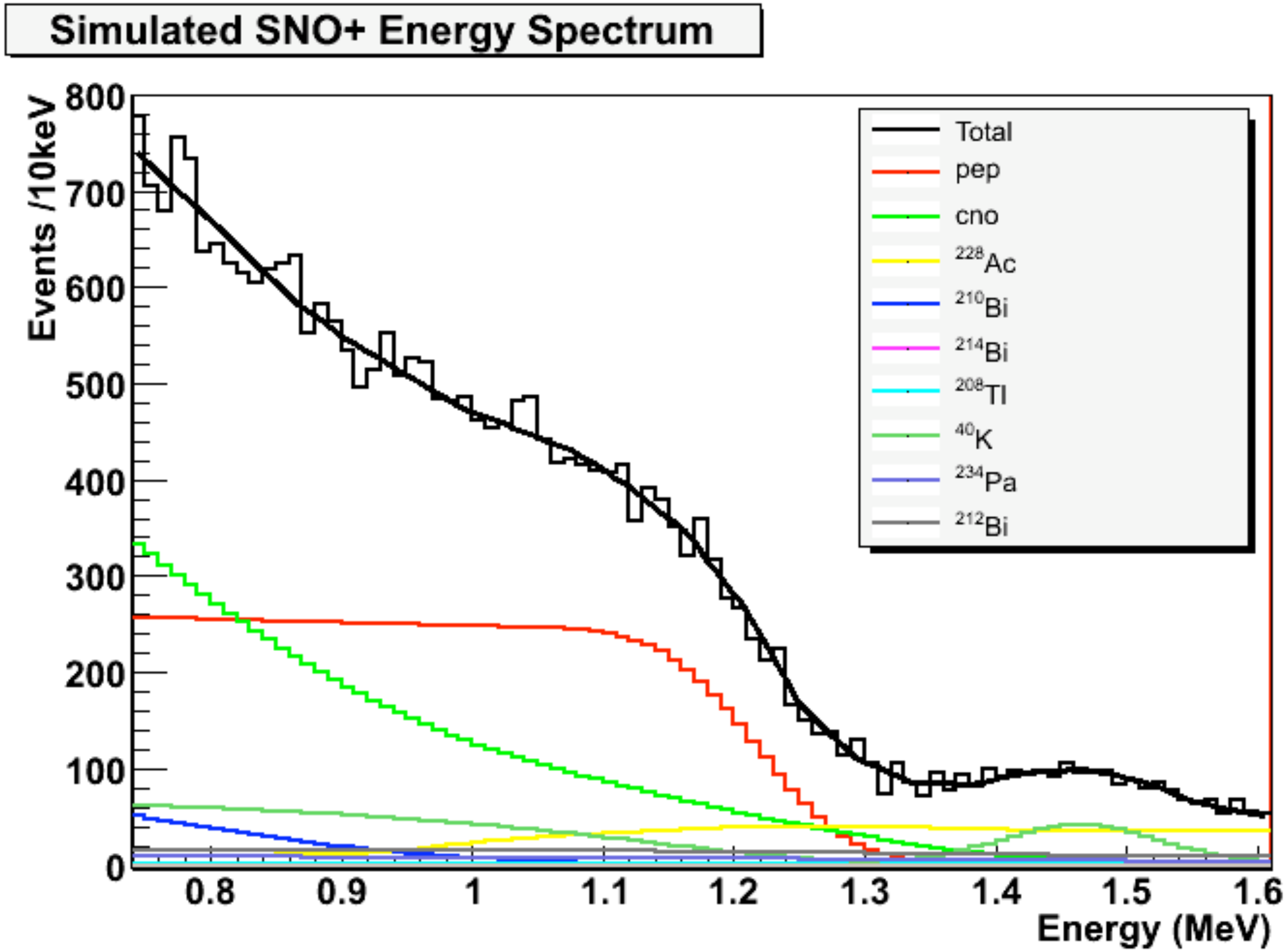




The Solar temperature will be affected in the core where neutrinos are produced and alter their fluxes … this can tested by SNO+ / Borexino

(Frandsen & Sarkar, arXiv:1003.4505)

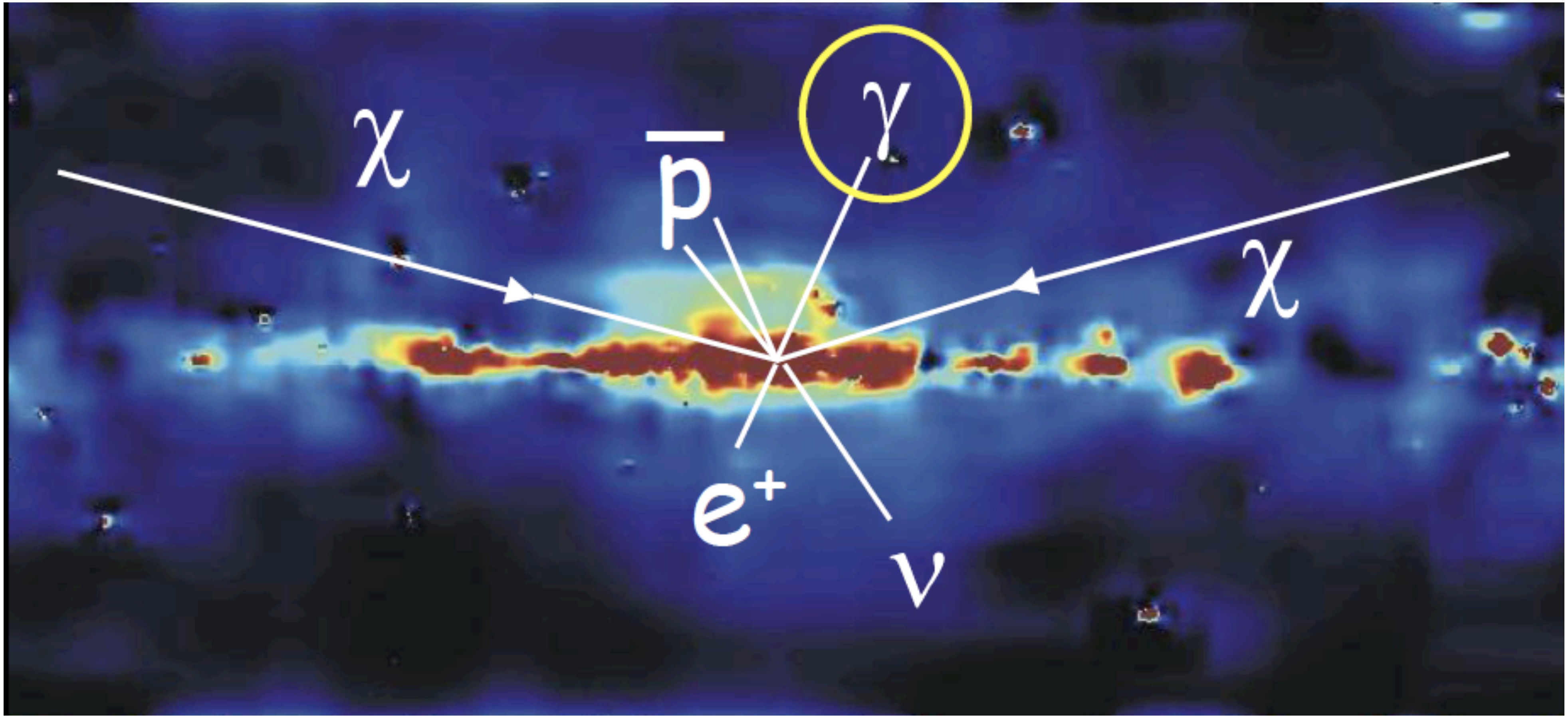
SNO+ pep and CNO Solar Neutrino Signals



CNO extracted with ±6% uncertainty (assuming target background levels ^{210}Bi and ^{210}Po, U, Th, ^{40}K achieved) in three years

3600 *pep* events/(kton·year), for electron recoils >0.8 MeV

Many techniques for indirect detection … and many claims!



The WMAP 'haze' (radio), PAMELA 'excess' (e^+) … have been ascribed to dark matter annihilations or decays

These offer probes of DM distribution at other locations in the Galaxy so usefully complement direct detection experiments

The *PAMELA* ‘anomaly’

PAMELA has measured the positron fraction:

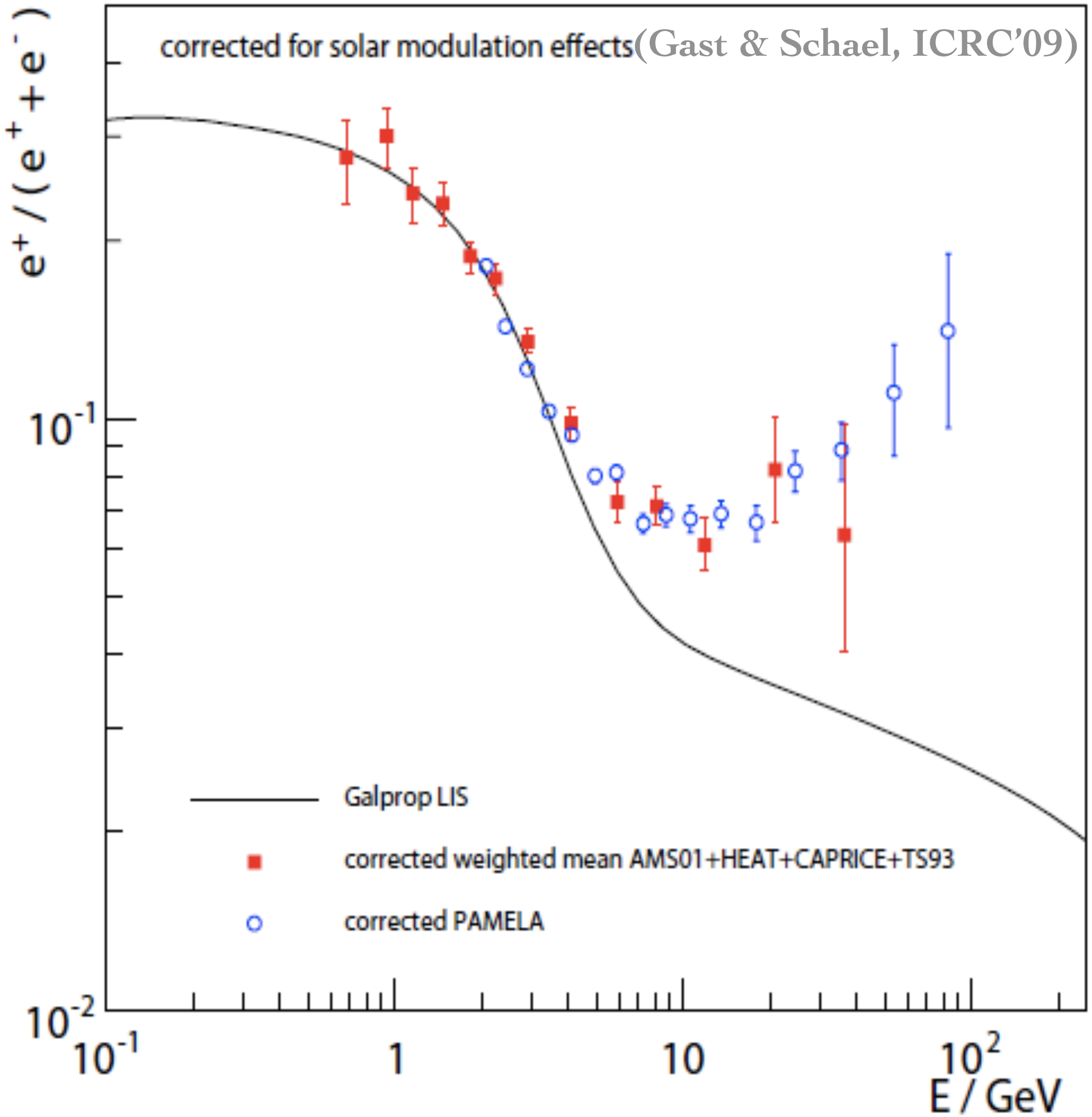
$$\frac{\phi_{e^+}}{\phi_{e^+} + \phi_{e^-}}$$

Anomaly $\Rightarrow$ excess above ‘astrophysical background’

Source of anomaly:

- Dark matter?
- Pulsars?
- Supernova remnants?

… over 400 citations



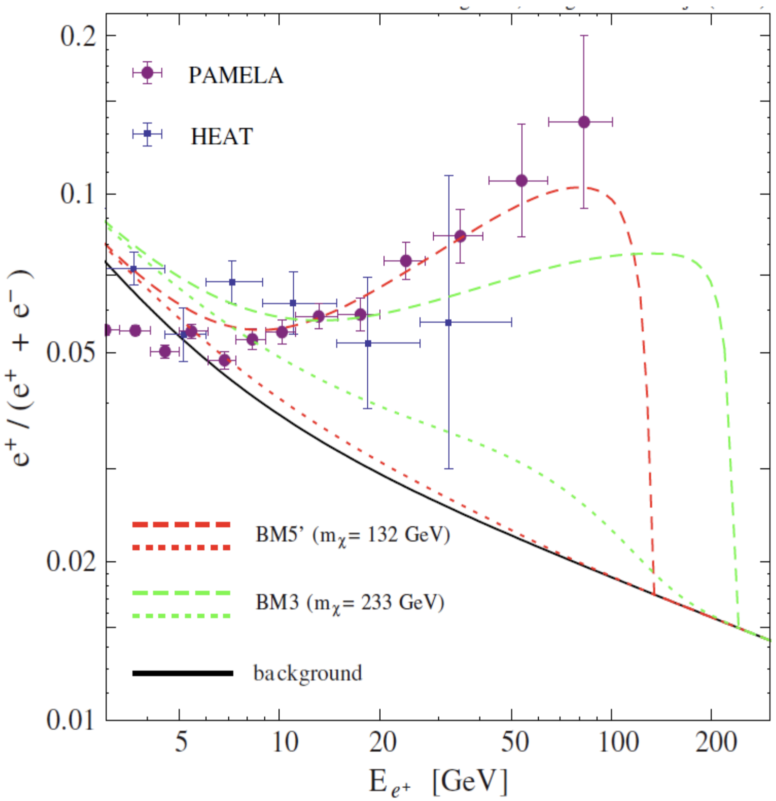
Nature 458:607,2009

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

DM annihilation

Rate $\propto n_{\rm DM}^2$

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

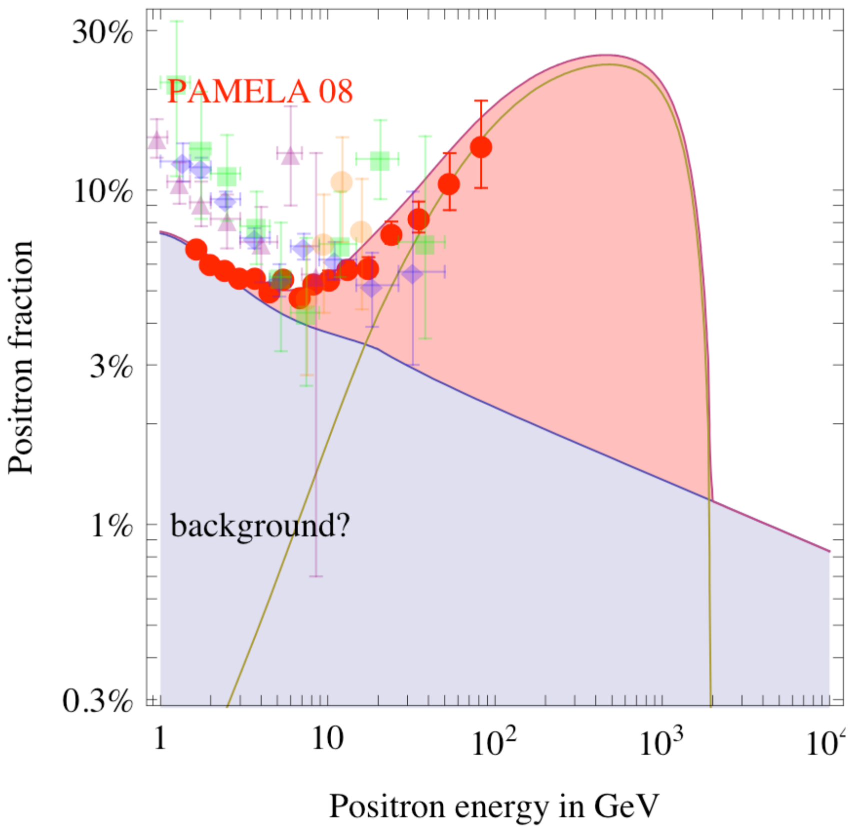


Bergström, Bringmann & Edjsö, PR D78:127850,2008

DM decay

Rate $\propto n_{\rm DM}/\tau_{\rm DM}$

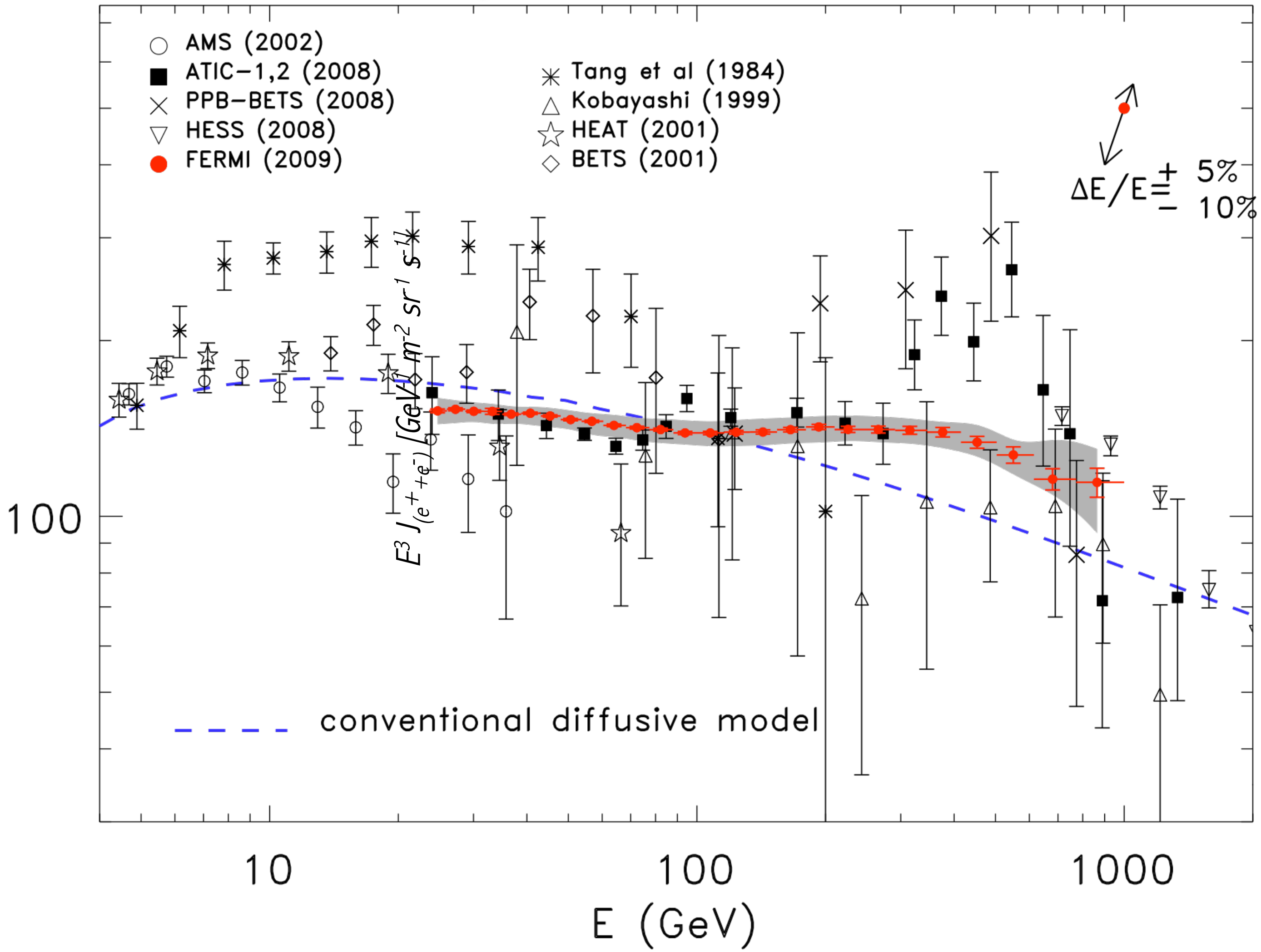
(lifetime ~10^9 x age of universe e.g. dim-6 operator suppressed by $M_{\rm GUT}$ for a TeV mass techni-baryon)



Nardi, Sannino & Strumia, JCAP 0901:043,2009

Fermi

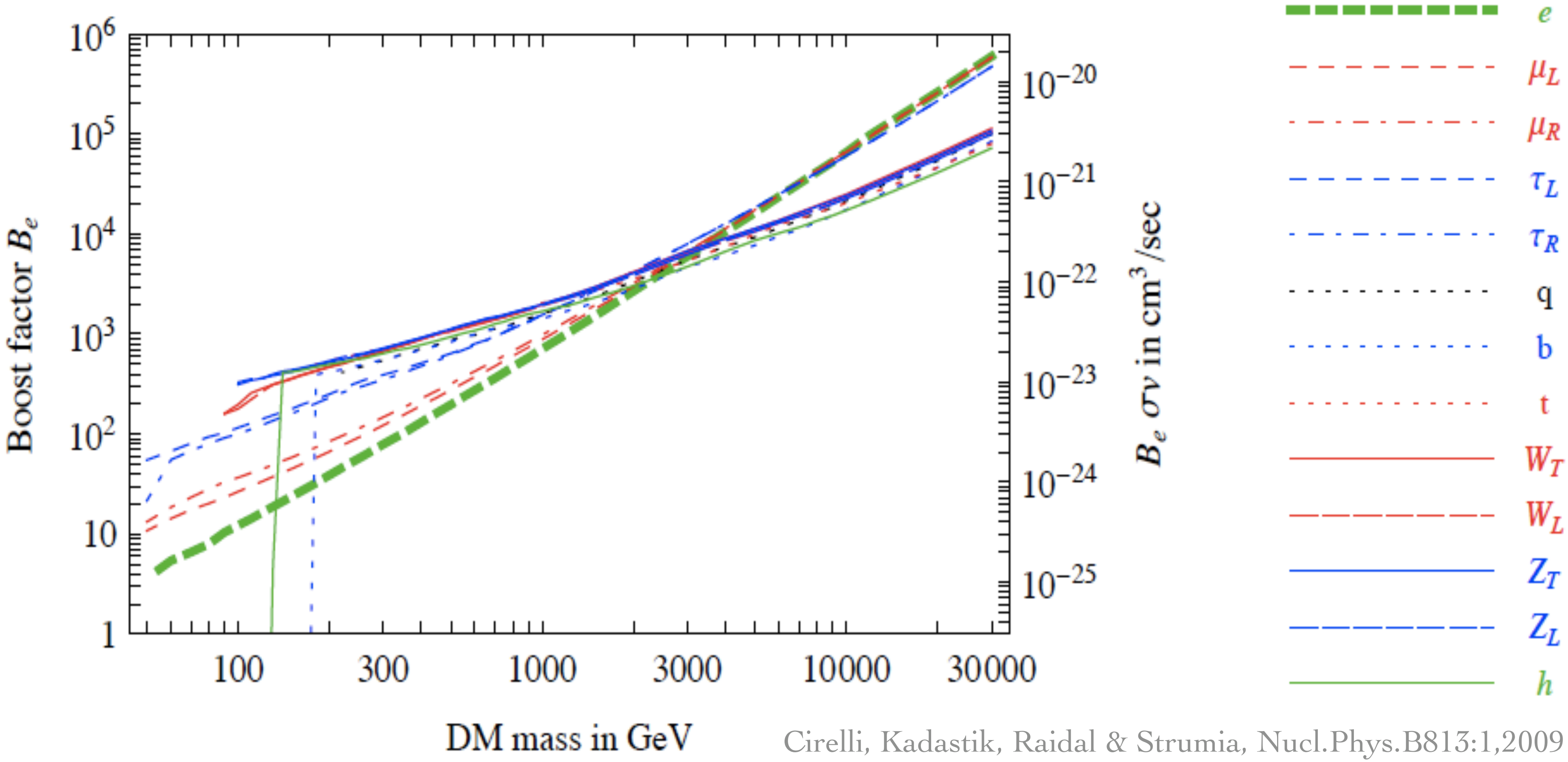
The ~~ATIC~~ excess



Dark matter has also been invoked to explain the excess $e^{\pm}$ over expectations seen by Fermi (there is no confirmation of the peak seen earlier by ATIC-2)

But DM annihilation rate requires huge 'boost factor' to match flux

➔ would imply in general negligible relic abundance unless strong velocity dependence (e.g. 'Somerfeld enhancement') of annihilation #-section is invoked (this requires hypothetical light gauge bosons to provide new long range force)



Cirelli, Kadastik, Raidal & Strumia, Nucl.Phys.B813:1,2009

... no such problem for decaying dark matter models (just tune lifetime!)

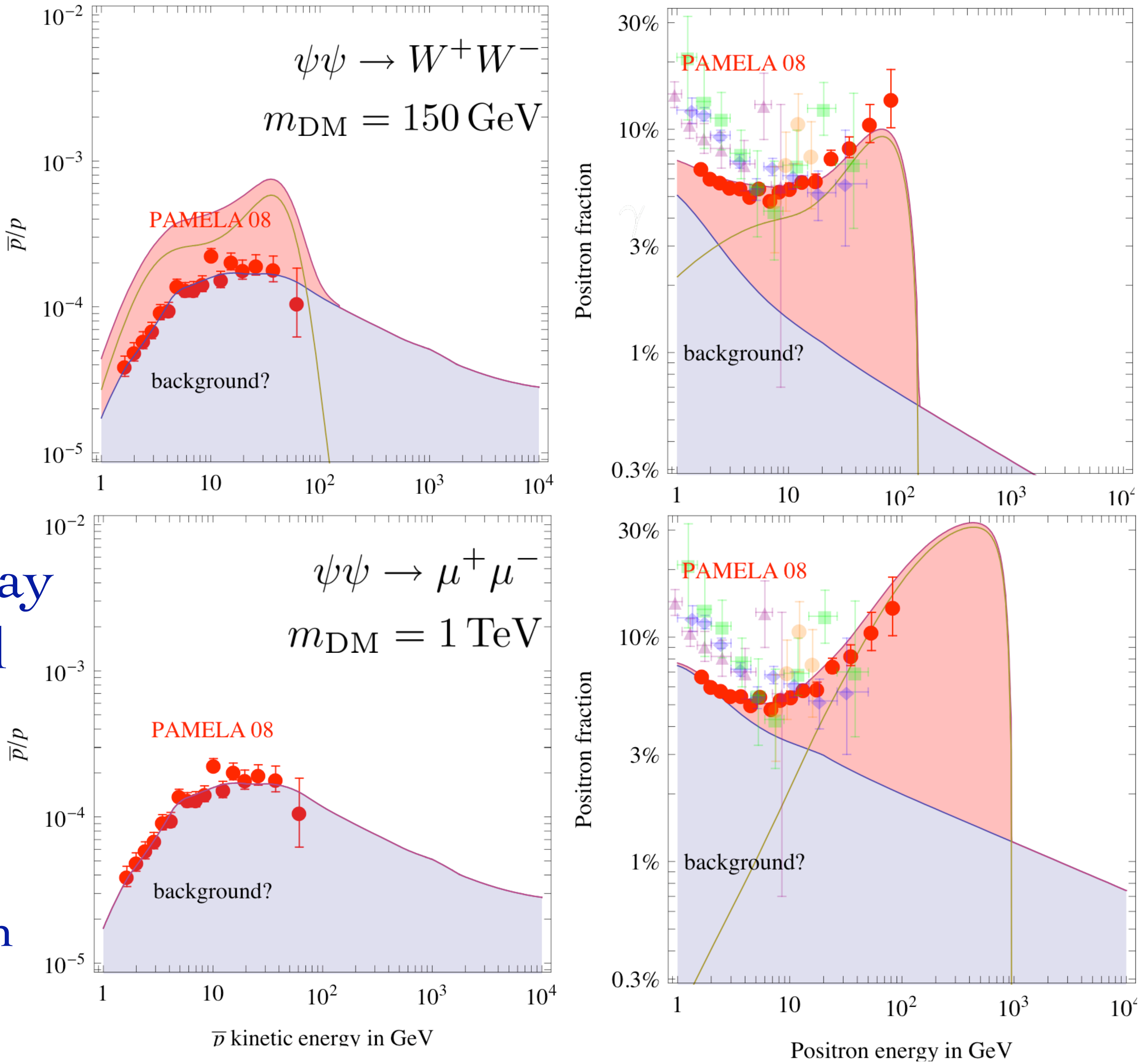
But the observed antiproton flux is *consistent* with the background expectation (from standard cosmic ray propagation in the Galaxy)

This is a serious constraint on *all* dark matter models of the PAMELA anomaly

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

... rather contrived!

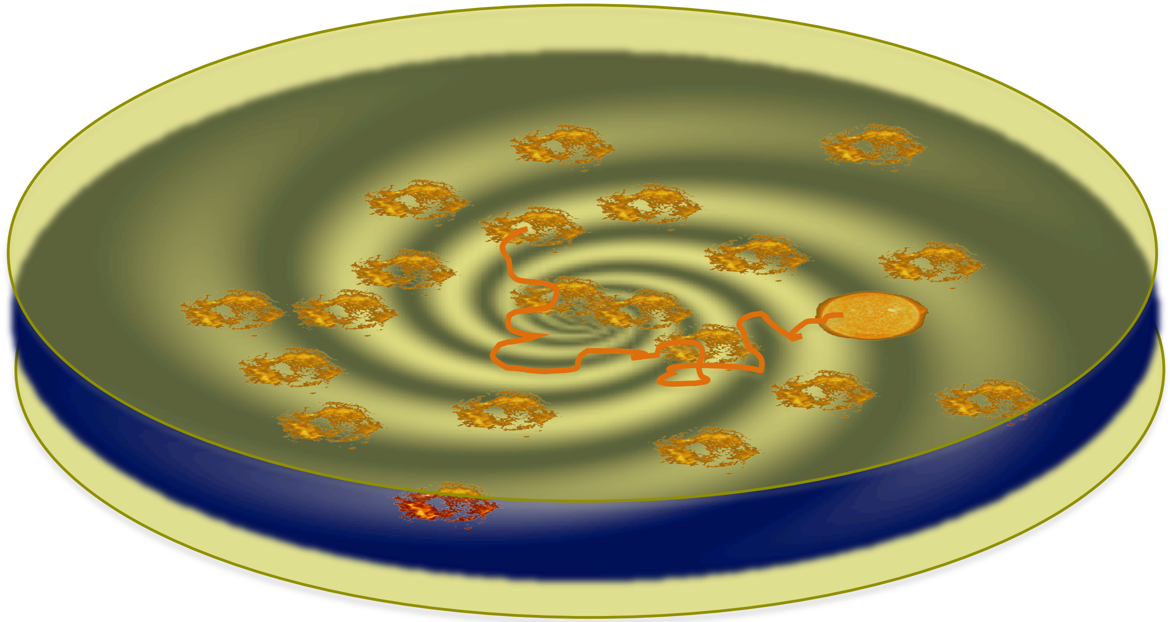
(nevertheless many such models proposed)



Cirelli et al, Nucl.Phys.B813:1,2009

The standard model for Galactic cosmic ray origin

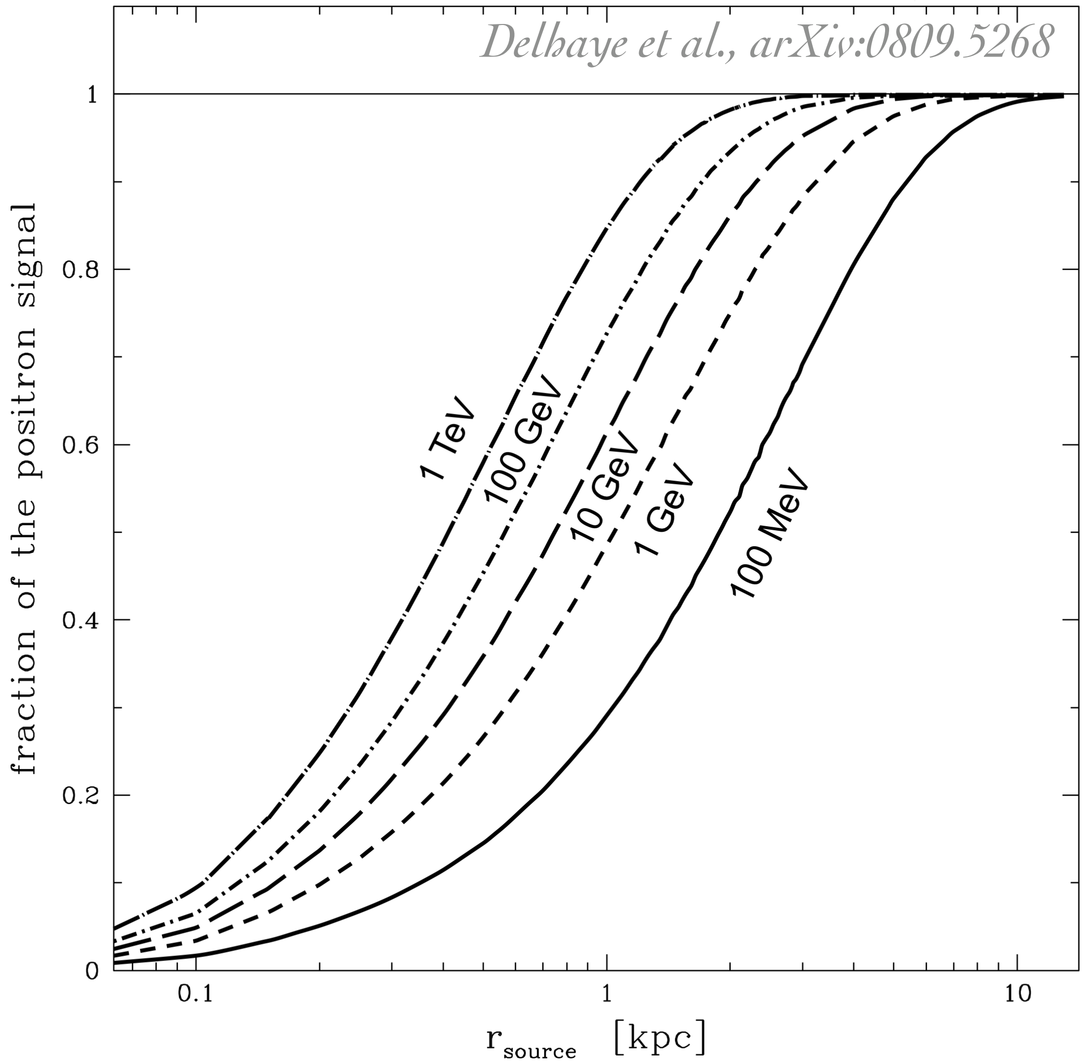
- ❑ SNR shock waves accelerate relativistic particles by Fermi mechanism
- ➩ power law spectrum (synchrotron radio/X-ray + γ-ray emission)
- ❑ Diffusion through magnetic fields in Galaxy (disk + halo)



- ❑ Secondary production during propagation: $\bar{p}, e^+, N'$
- ❑ $e^{\pm}$ lose energy through synchrotron and inverse Compton scattering

Measurables: Energy spectra of individual species + diffuse radiation

However $e^{\pm}$ lose energy readily during propagation, so only *nearby* sources dominate at high energies …
the usual background calculation is then *irrelevant*



$$\tau \simeq 5 \cdot 10^5 \mathrm{yr} \left(\frac{1\,\mathrm{TeV}}{E} \right)$$

Are there any primary sources of positrons (with a hard spectrum) in our Galactic neighbourhood?

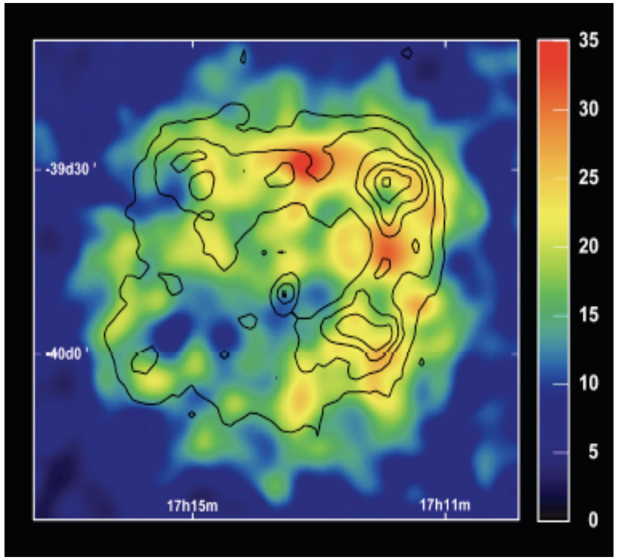
A nearby cosmic ray accelerator?

Rise in e^+ fraction could be due to secondaries being produced *during* acceleration … which are then accelerated along with the primaries

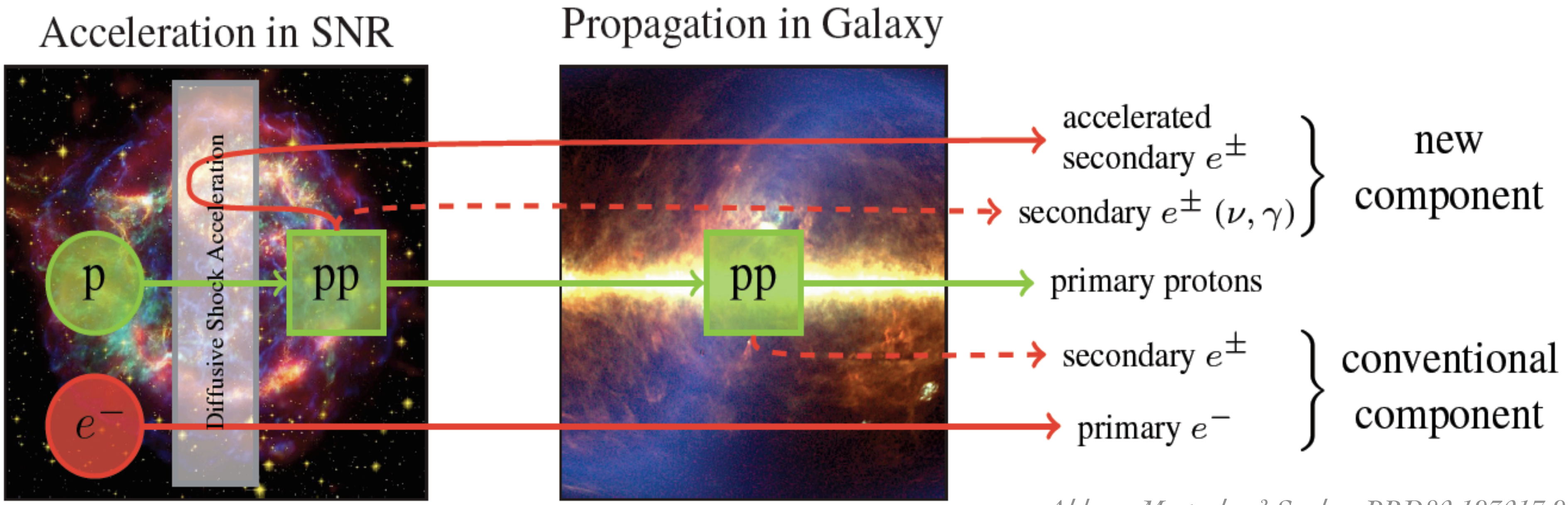
(Blasi, PRL 103:051104,2009, Fujita *et al*, PRD80:063003,2009)

… generic feature of a *stochastic* acceleration process, if $\tau_{acc} > \tau_{1\rightarrow 2}$ (Cowsik 1979, Eichler 1979)

This component *naturally* has a harder spectrum and fits *PAMELA* data (with just 1 free parameter)



RXJ1713.7-3946, HESS



Ahlers, Mertsch & Sarkar, PRD80:123017,2009

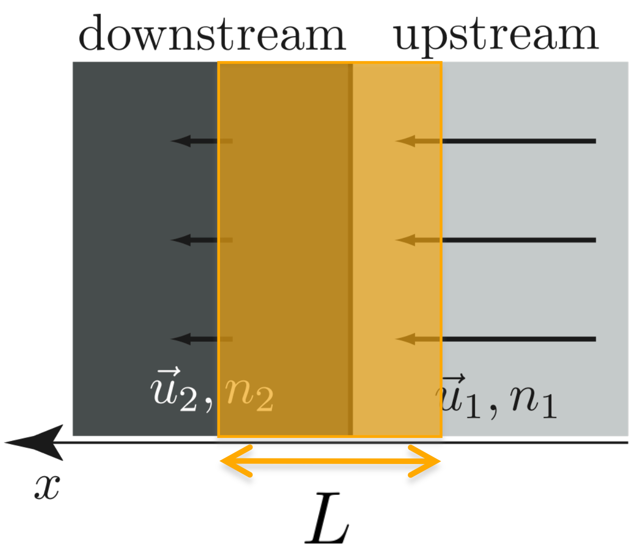
Diffusive (1st-order Fermi) shock acceleration

Consider flux:

$$\Phi(p) = \int \mathrm{d}^3x \, \frac{4\pi p^2}{3} f(p)(-\nabla \cdot \vec{u})$$

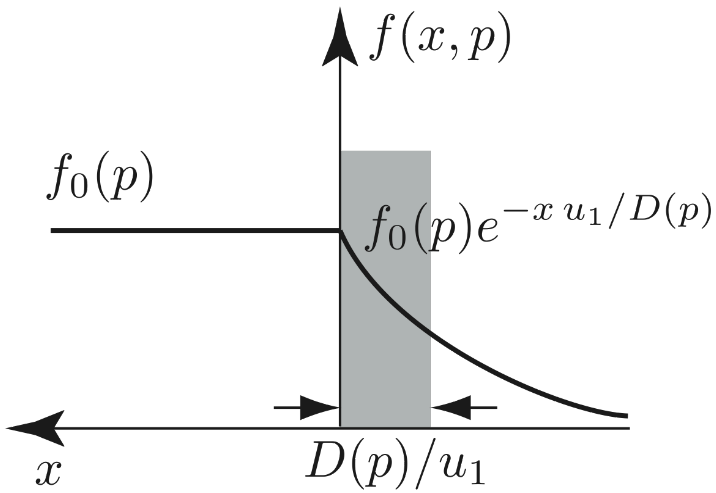
Conservation equation:

$$\underbrace{\frac{\partial}{\partial t}\left(4\pi p^2 f^0(p) L\right)}_{\textit{density change}} + \underset{\textit{acceleration}}{\frac{\partial \Phi}{\partial p}} = \underbrace{-4\pi p^2 f^0(p) u_2}_{\textit{convection}} + \underset{\textit{injection}}{Q(p)}$$



Steady state: $\dfrac{u_1 - u_2}{3} p \dfrac{\partial f}{\partial p} + u_1 f = 0$

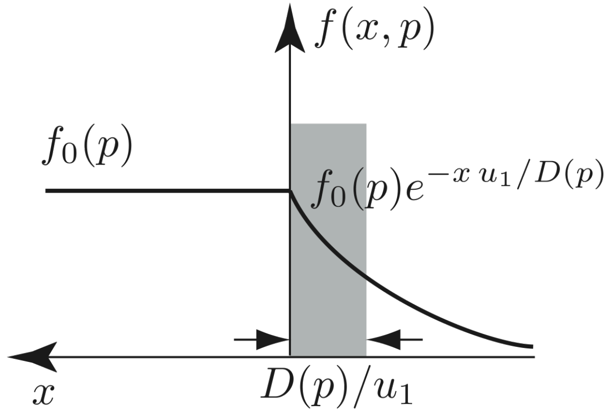
$$\Rightarrow f(p) \propto p^{-3u_1/(u_1 - u_2)} = p^{-\gamma}$$



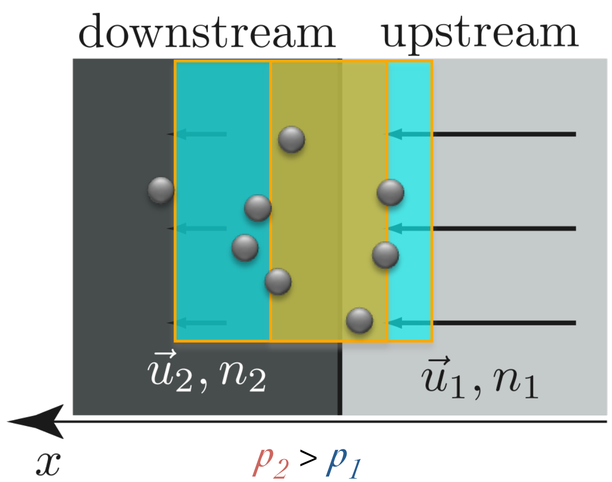
DSA with secondary production

- Secondaries are produced with primary spectrum (Feymann scaling):

$$q_{e^\pm} \propto f_{\rm CR} \propto p^{-\gamma}, \quad \gamma = \frac{3r}{r-1} \qquad r = \frac{u_1}{u_2} = \frac{n_2}{n_1}$$



- Only particles with $|x| \lesssim D(p)/u$ are accelerated



- Bohm diffusion: $D(p) \propto p$

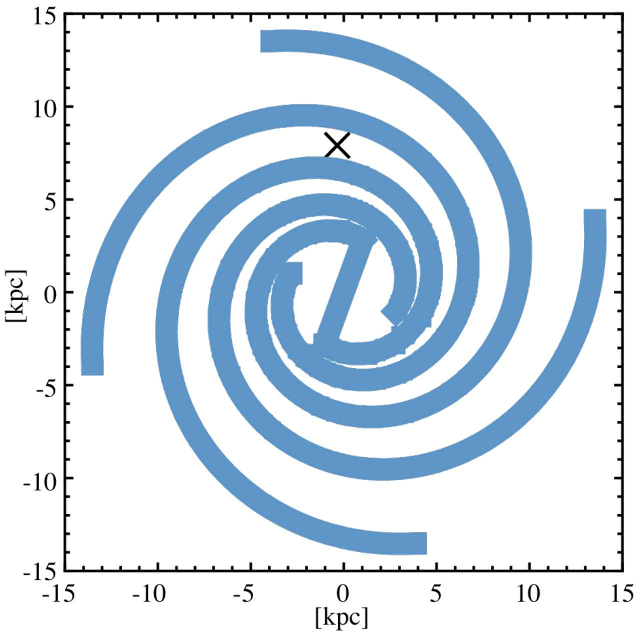
- Fraction of accelerated secondaries is $\propto p$

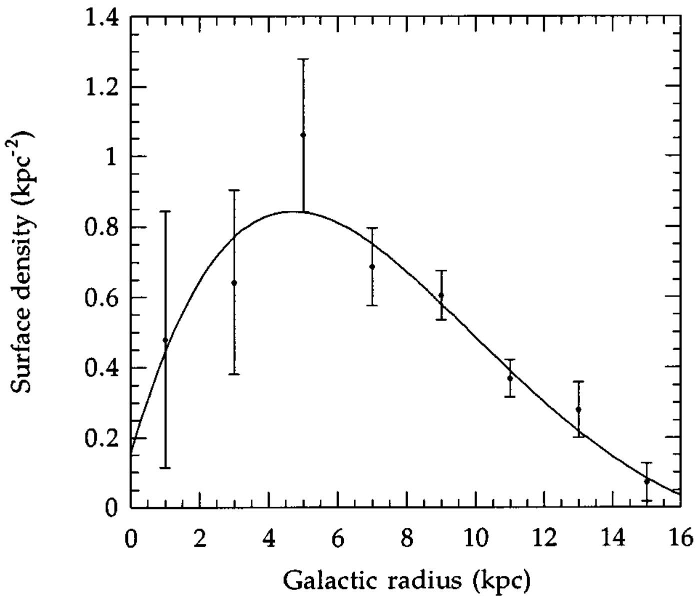
- **Steady state spectrum**

$$n_{e^\pm} \propto q_{e^\pm} \left(1 + \frac{p}{p_0}\right) \propto p^{-\gamma} + p^{-\gamma+1}$$

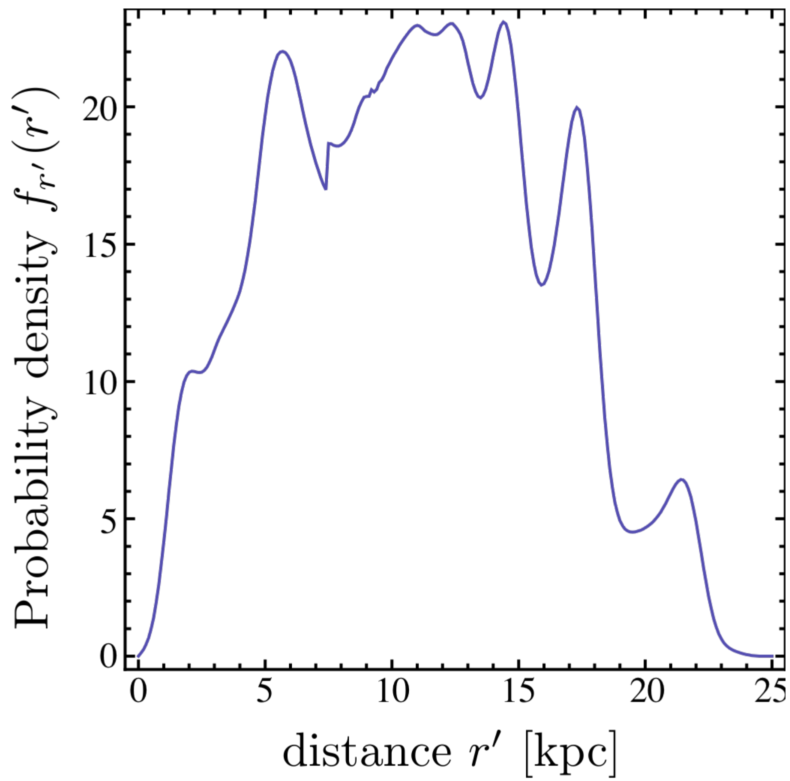
➔ *rising positron fraction at source!*

Statistical distribution of sources





Case & Bhattacharya, ApJ 504:761,1998

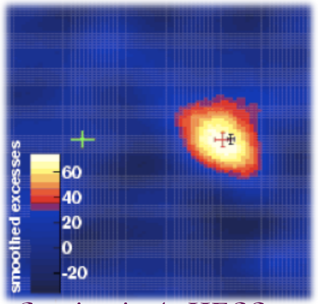


Strategy:

- Draw source positions from this distribution
- Calculate total $(e^+ + e^-)$ flux
- The best fit to data is likely to be closest to real distribution

Ahlers, Mertsch & Sarkar, PRD80:123017,2009

Normalising the source spectra



Cassiopeia A, HESS

Normalisation of primary e^- : fit absolute e^- flux at low energies

Normalisation of secondary $e^\pm$: $p + p \rightarrow \begin{cases} \pi^0 + \ldots & \rightarrow \quad 2\gamma + \ldots \\ \pi^\pm + \ldots & \rightarrow \quad e^\pm + \ldots \end{cases}$

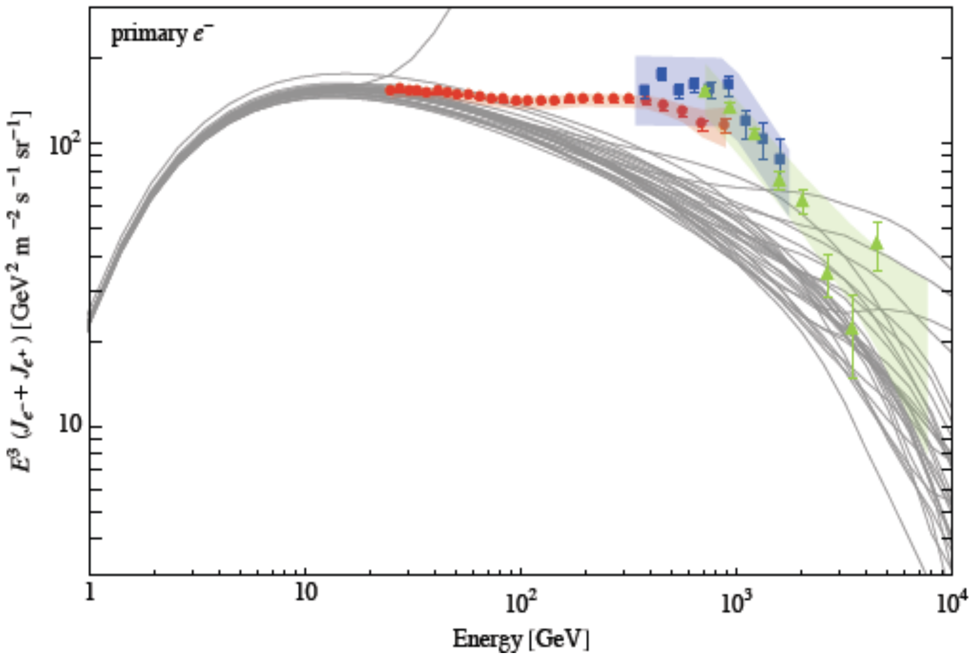
Source	Other name(s)	Γ	$J^0_\gamma \div 10^{-12}$ [(cm^2 s TeV)$^{-1}$]	$E_{\max}$ [TeV]	d [kpc]	$Q^0_\gamma \div 10^{33}$ [(s TeV)$^{-1}$]
HESS J0852−463	RX J0852.0-4622 (Vela Junior)	2.1 ± 0.1	21 ± 2	> 10	0.2	0.10
HESS J1442−624	RCW 86, SN 185 (?)	2.54 ± 0.12	3.72 ± 0.50	$\gtrsim 20$	1	0.46
HESS J1713−381	CTB 37B, G348.7+0.3	2.65 ± 0.19	0.65 ± 0.11	$\gtrsim 15$	7	3.812
HESS J1713−397	RX J1713.7-3946, G347.3-0.5	2.04 ± 0.04	21.3 ± 0.5	17.9 ± 3.3	1	2.55
HESS J1714−385	CTB 37A	2.30 ± 0.13	0.87 ± 0.1	$\gtrsim 12$	11.3	13.3
HESS J1731−347	G 353.6-07	2.26 ± 0.10	6.1 ± 0.8	$\gtrsim 80$	3.2	7.48
HESS J1801−233[a]	W 28, GRO J1801-2320	2.66 ± 0.27	0.75 ± 0.11	$\gtrsim 4$	2	0.359
HESS J1804−216[b]	W 30, G8.7-0.1	2.72 ± 0.06	5.74	$\gtrsim 10$	6	24.73
HESS J1834−087	W 41, G23.3-0.3	2.45 ± 0.16	2.63	$\gtrsim 3$	5	7.87
MAGIC J0616+225	IC 443	3.1 ± 0.3	0.58	$\gtrsim 1$	1.5	0.156
Cassiopeia A		2.4 ± 0.2	1.0 ± 0.1	$\gtrsim 40$	3.4	1.38
J0632+057	Monoceros	2.53 ± 0.26	0.91 ± 0.17	N/A	1.6	0.279
Mean		~ 2.5		$\gtrsim 20$		~ 5.2
Mean, excluding sources with $\Gamma > 2.8$		~ 2.4		$\gtrsim 20$		~ 5.7
Mean, excluding sources with $\Gamma > 2.6$		~ 2.3		$\gtrsim 20$		~ 4.2

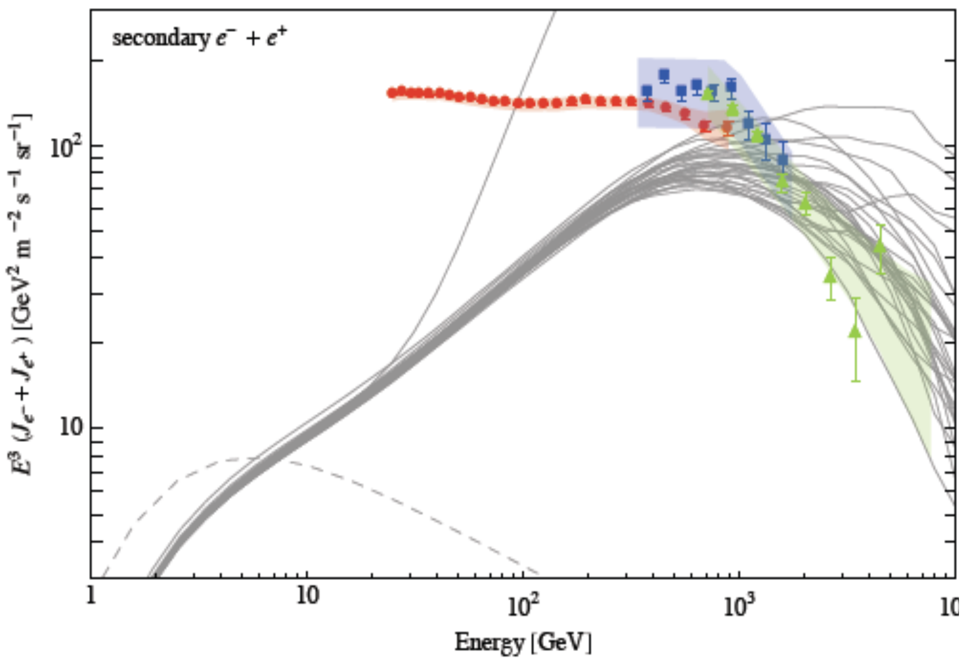
Ahlers, Mertsch & Sarkar, PRD80:123017,2009

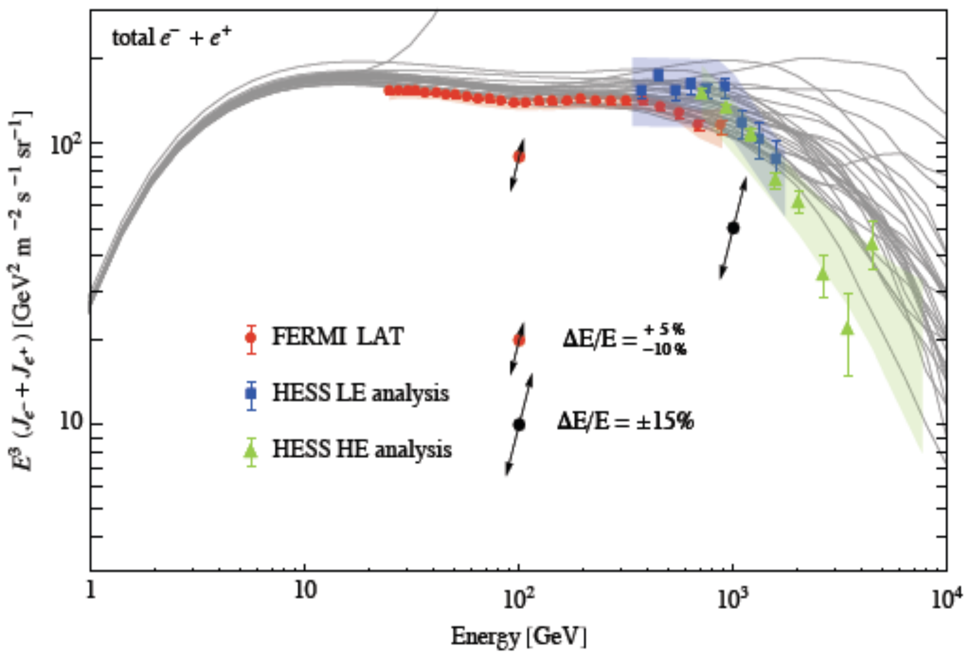
Fitting the $e^+ + e^-$ flux

The propagated primary e^- spectrum is much too steep to match the Fermi LAT data ... but the accelerated secondary $e^+ + e^-$ component has a harder spectrum so fits the 'bump'!

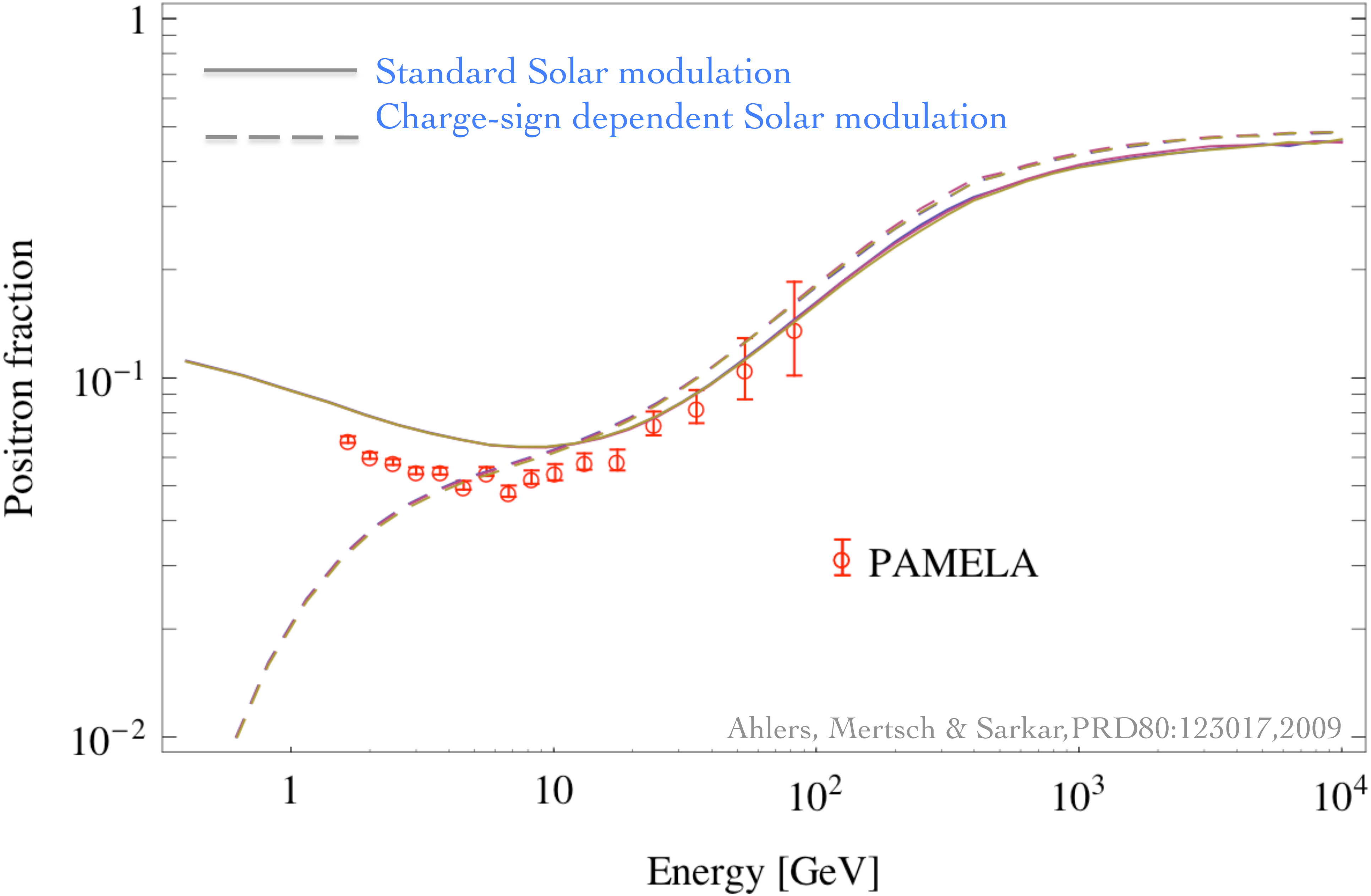
Ahlers, Mertsch & Sarkar,PRD80:123017,2009







The *predicted* positron fraction



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 (on verge of 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 some false alarms but it is a reasonable expectation that the nature of dark matter will be clarified soon experimentally