Darkness Visible

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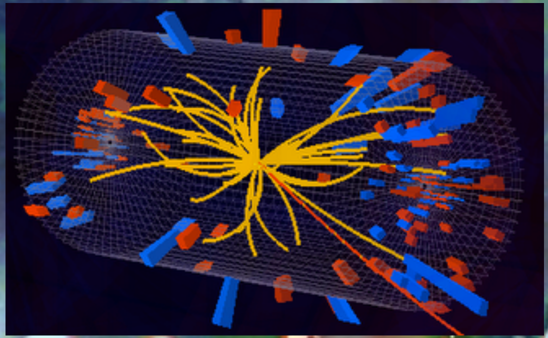


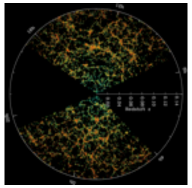
A dungeon horrible, on all sides round.
As one great furnace flamed;
yet from those flames
No light; but rather darkness visible …

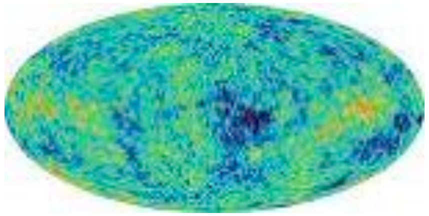
'Paradise Lost' – Milton

Colloquium (to celebrate Raja-ji's 75th birthday), IMSc Chennai, 20th Dec 2011

What is the world made of?

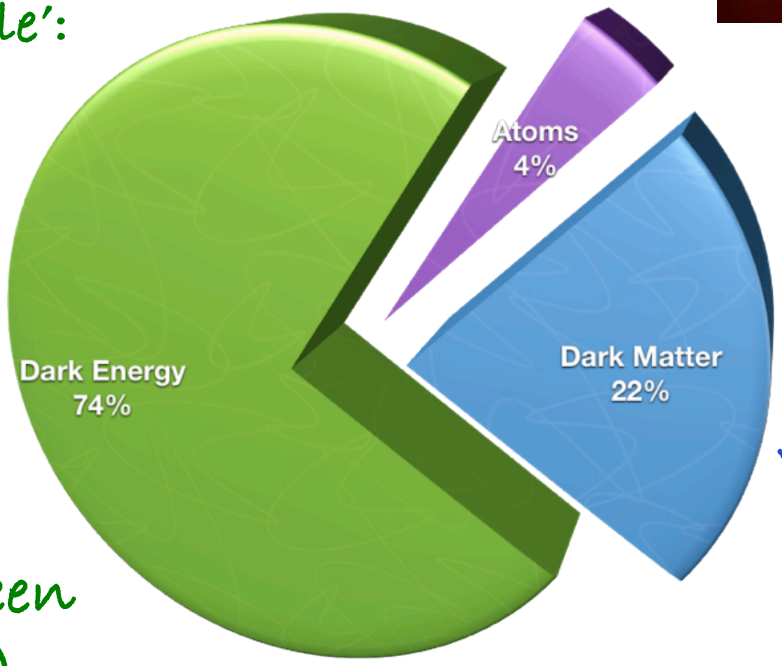
Only geometrical evidence:
$\Lambda \sim O(H_0^2)$, $H_0 \sim 10^{-42}$ GeV
… dark energy is inferred from the 'cosmic sum rule':
$\Omega_m + \Omega_k + \Omega_\Lambda = 1$

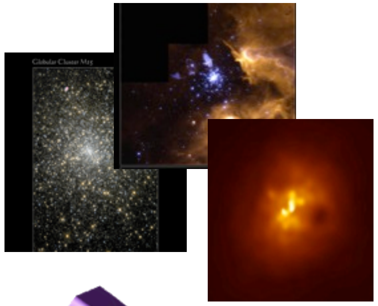




No significant dynamical evidence seen (e.g. 'late ISW effect')

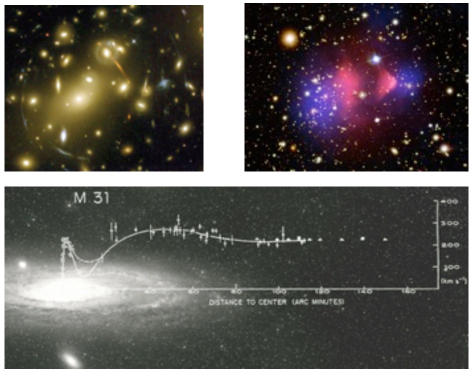
… is dark energy being faked by inhomogeneity?



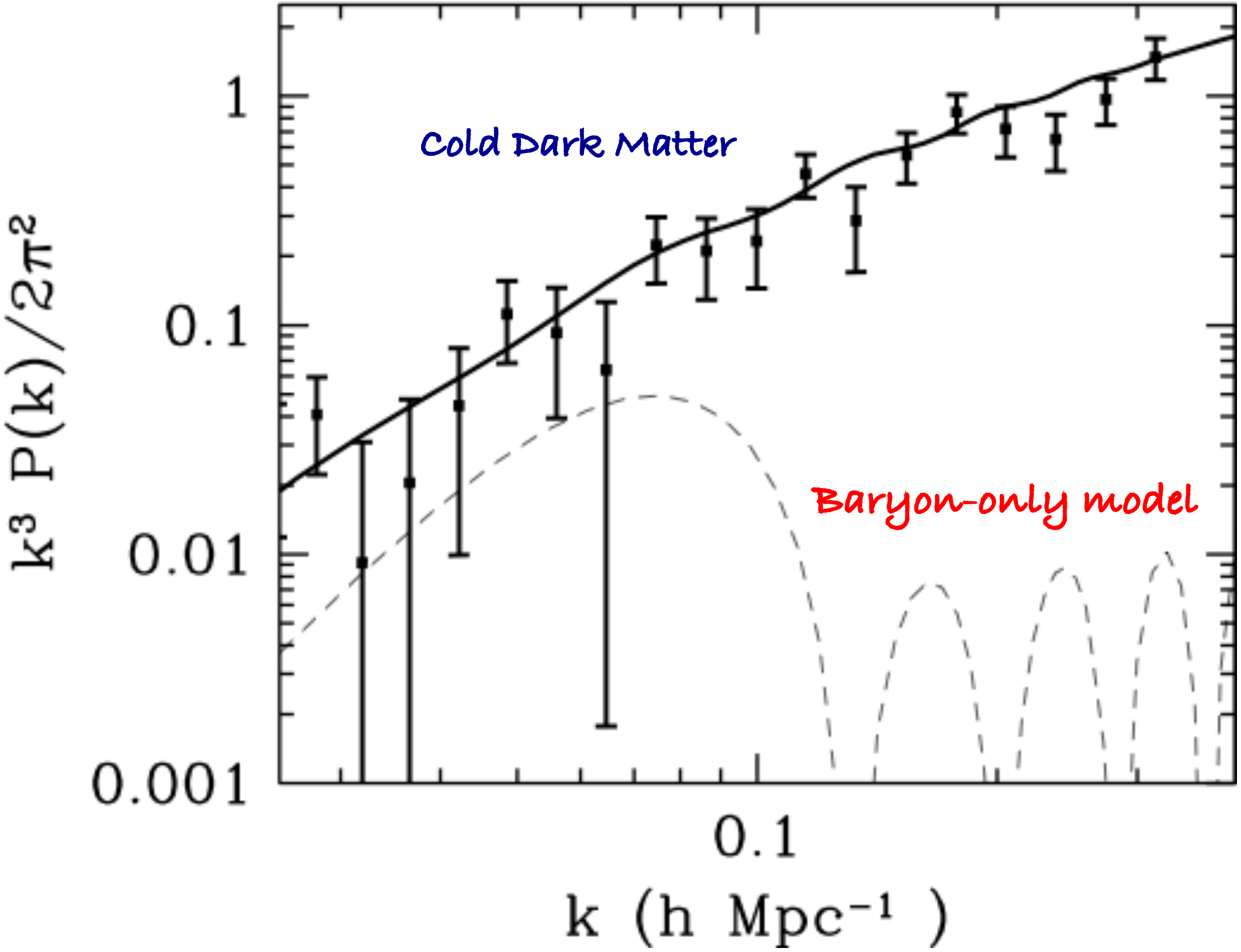


Baryons (but no antibaryons) …

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

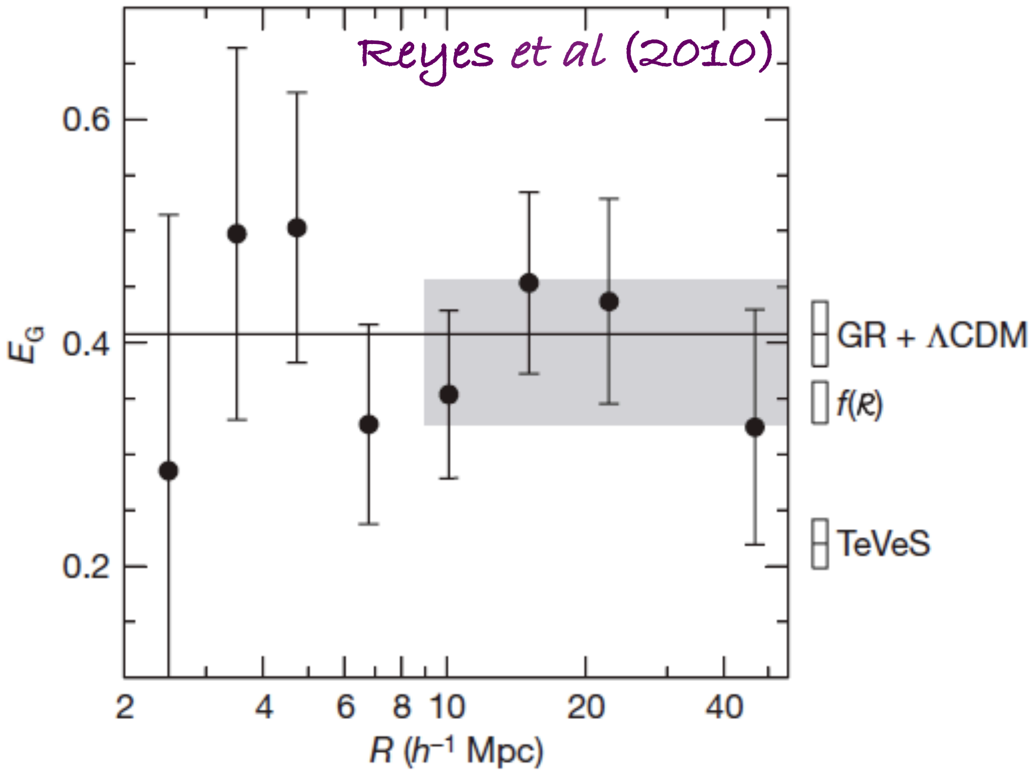


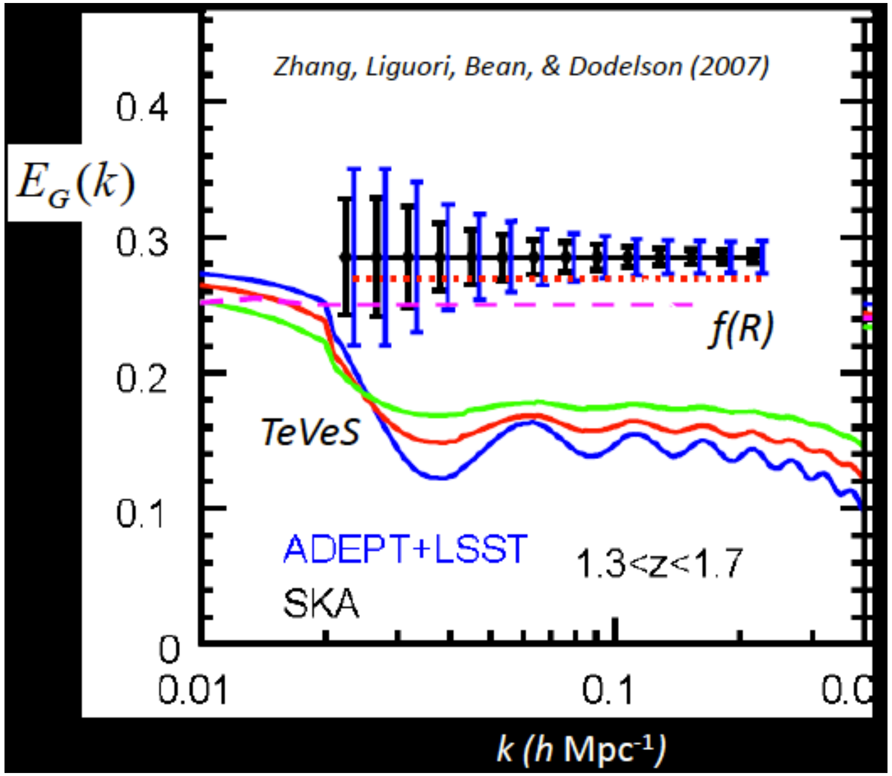
In fact galaxy rotation curves *can* be explained *without* dark matter by **Modified Newtonian Dynamics** (MOND), but the observed large-scale structure *requires* $\Omega_m >> \Omega_B$ … if it has resulted from the growth under gravity of the small initial density fluctuations (which left their imprint on the CMB at last scattering)



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

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

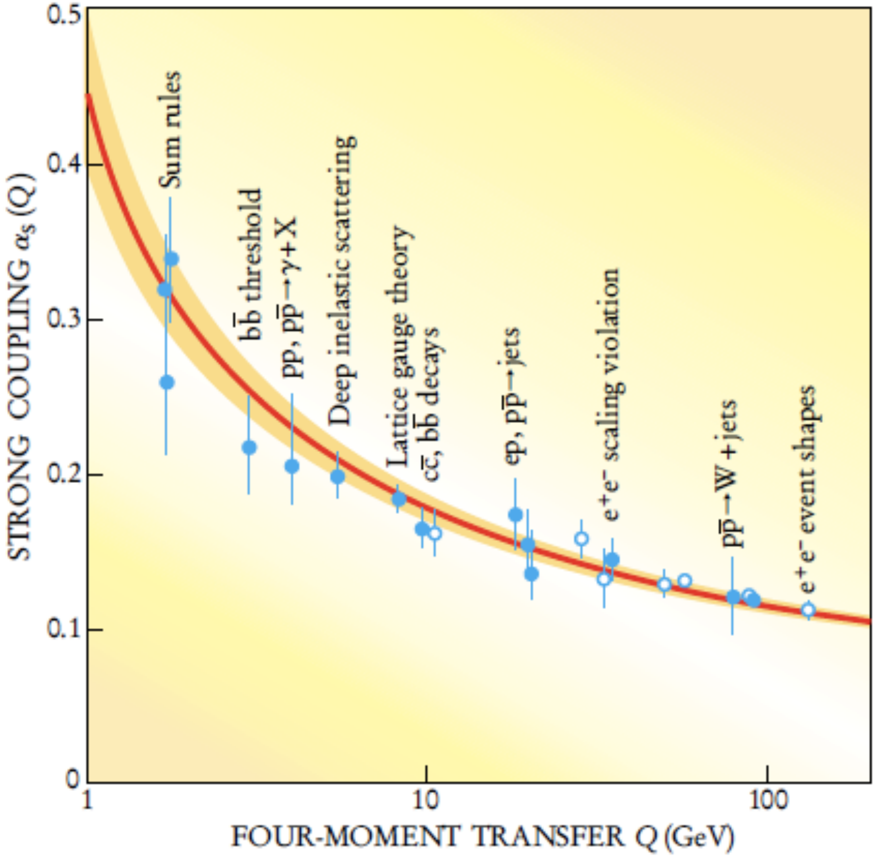




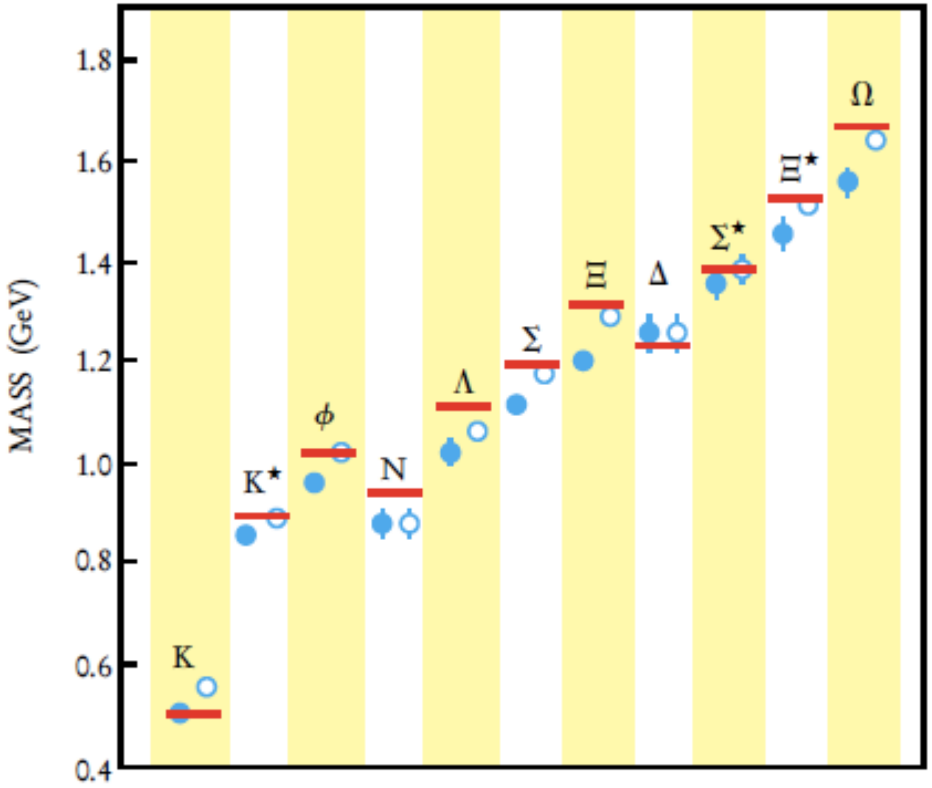
This is testable through measurements of gravitational weak lensing (shearing of galaxy shapes) and its cross-correlation with the galaxy density field

What should the world be made of ?

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



We understand the dynamics of QCD



Courtesey: Frank Wilczek

... and we can calculate the mass spectrum

What do we expect for the symmetric thermal relic abundance of baryons?

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

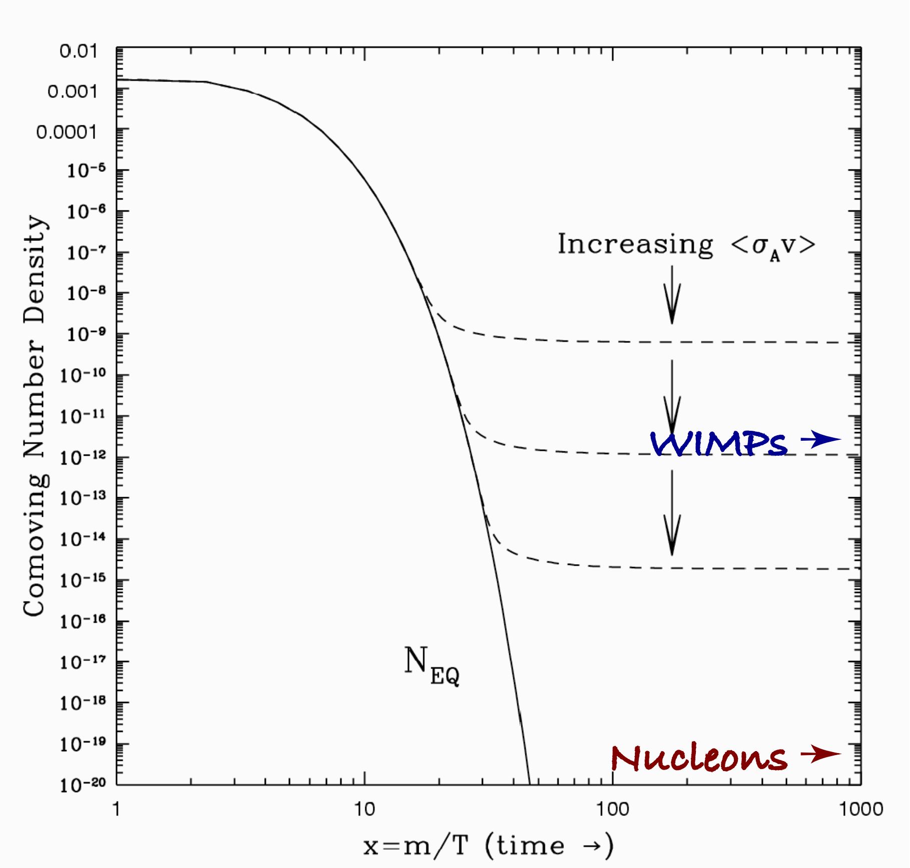
Chemical equilibrium is maintained as long as annihilation rate exceeds the Hubble expansion rate

'Freeze-out' occurs when annihilation rate:

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

becomes comparable to the expansion rate

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



i.e. freeze-out occurs at $T \sim m_N/45$, 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**:

$$\boxed{\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-9}}$$

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

Sakharov conditions for baryogenesis:

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

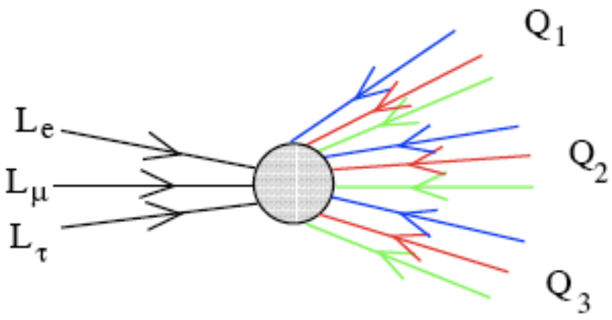
Baryon number violation occurs even in the Standard Model through non-perturbative (sphaleron-mediated) processes … but CP-violation is *too weak* (also the electroweak symmetry breaking phase transition is a 'cross-over' i.e. *not* out-of-equilibrium)

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)**

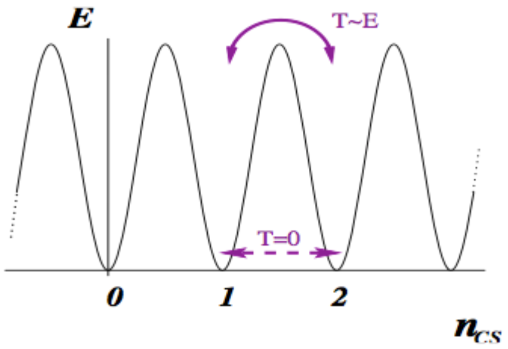
'See-saw': $\mathcal{L} = \mathcal{L}_{SM} + \lambda^*_{\alpha J}\overline{\ell}_\alpha \cdot H N_J - \frac{1}{2}\overline{N_J} M_J N^c_J$ $\quad \lambda M^{-1}\lambda^{\mathrm{T}}\langle H^0\rangle^2 = [m_\nu]$

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

Asymmetric baryonic matter



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

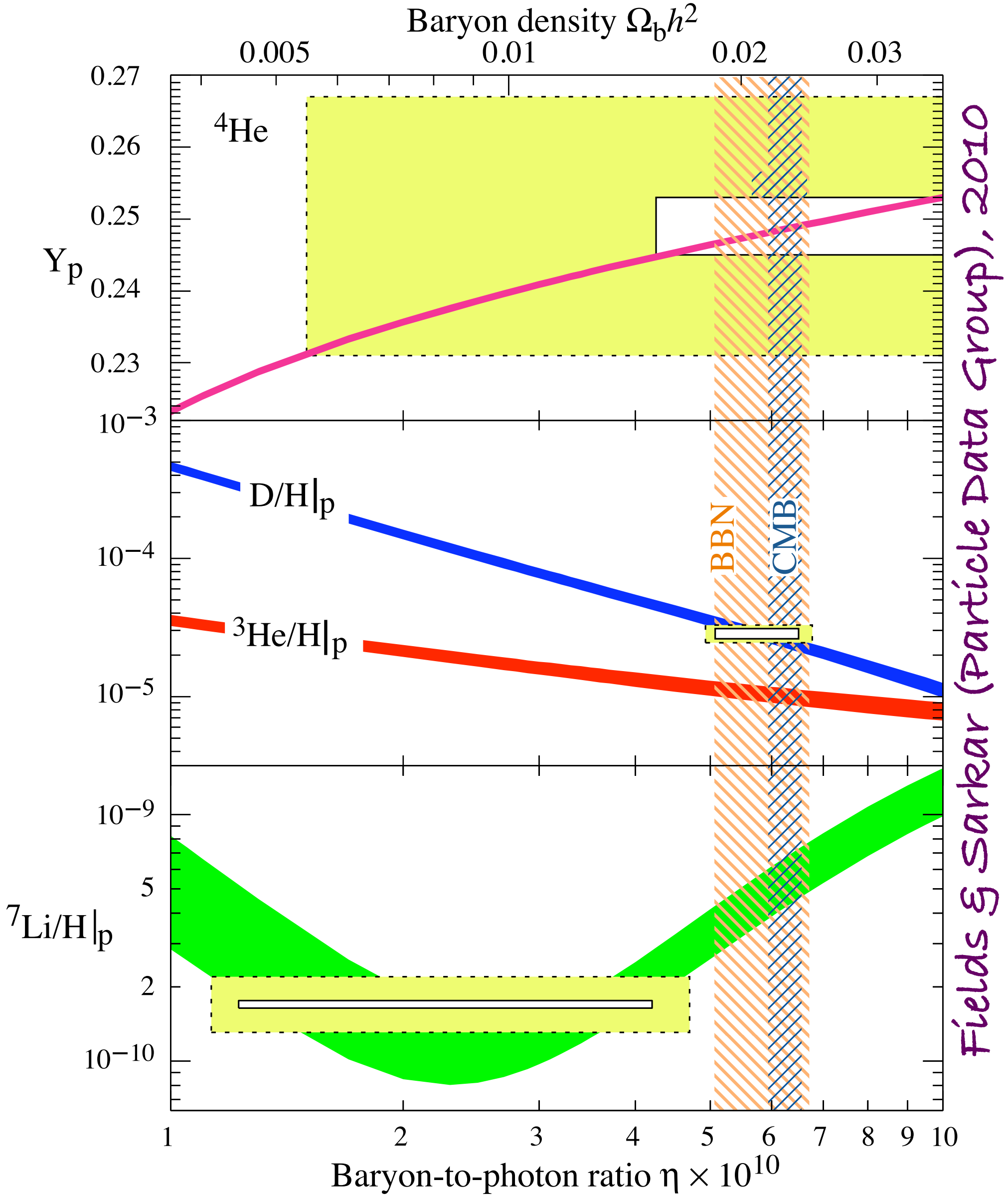


Any primordial lepton asymmetry (e.g. from out-of-equilibrium decays of the right-handed N) would be redistributed by B+L violating processes (which conserve B-L) amongst *all fermions* – **in particular baryons** - which couple to the electroweak anomaly

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

Although vastly overabundant compared to the natural expectation, baryons *cannot* close the universe (BBN ✚ CMB concordance)



Fields & Sarkar (Particle Data Group), 2010

... the dark matter must therefore be mainly *non-baryonic*

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 scale M)

Higgs mass divergence

$$\mathcal{L}_{\rm eff} = M^4 + \boxed{M^2\Phi^2} \qquad m_H^2 \simeq \frac{h_t^2}{16\pi^2}\int_0^{M^2} \mathrm{d}k^2 = \frac{h_t^2}{16\pi^2}M^2$$

super-renormalisable

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

renormalisable

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

non-renormalisable

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 (10^2 new params)

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)

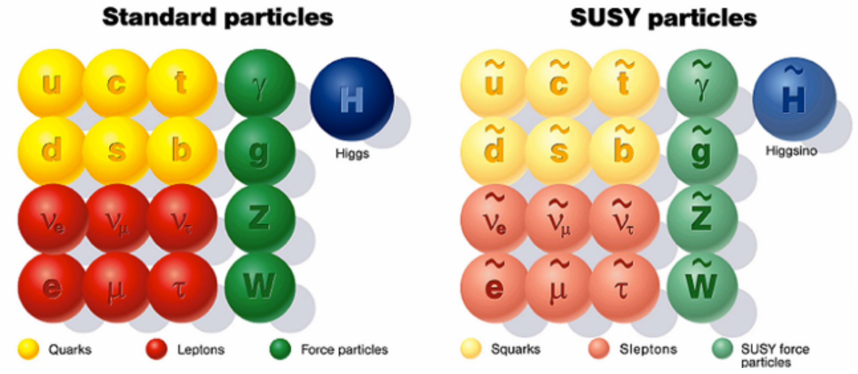
For example, the lightest supersymmetric particle (typically the neutralino χ), *if* protected against decay by R-parity, is a candidate for thermal dark matter

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 the lightest TC state can be dark matter

What should the world be made of ?

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
Λ_{QCD}	Nucleons	Baryon number	$\tau > 10^{33}$ yr (dim-6 OK)	~~'freeze-out' from thermal equilibrium~~ Asymmetric baryogenesis	$\Omega_B \sim 10^{-10}$ 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	$\Omega_{LSP} \sim 0.25$

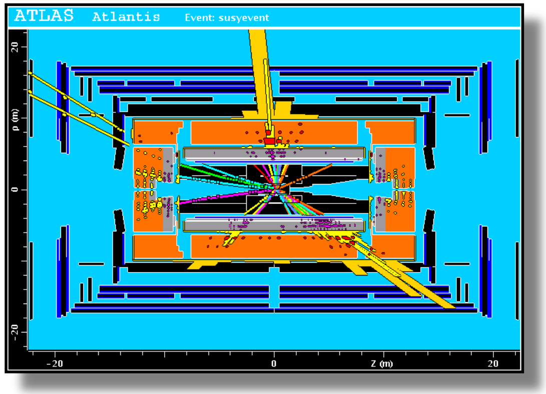
$$L^{SM}_{effective} \supset M_A A_\mu A^\mu + m_f \overline{f_L} f_R + M^2_H |H|^2$$

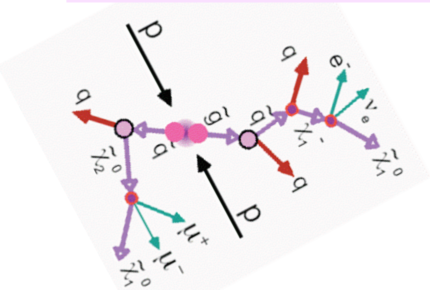


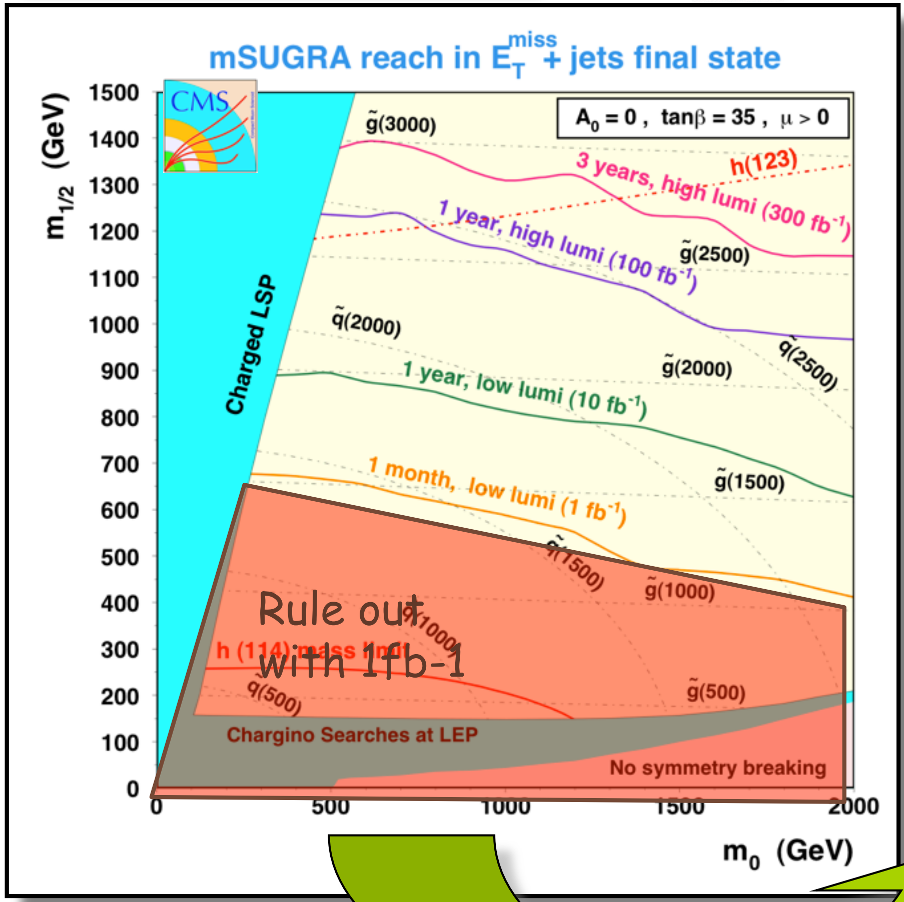
For (softly broken) supersymmetry we have the 'WIMP miracle':

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

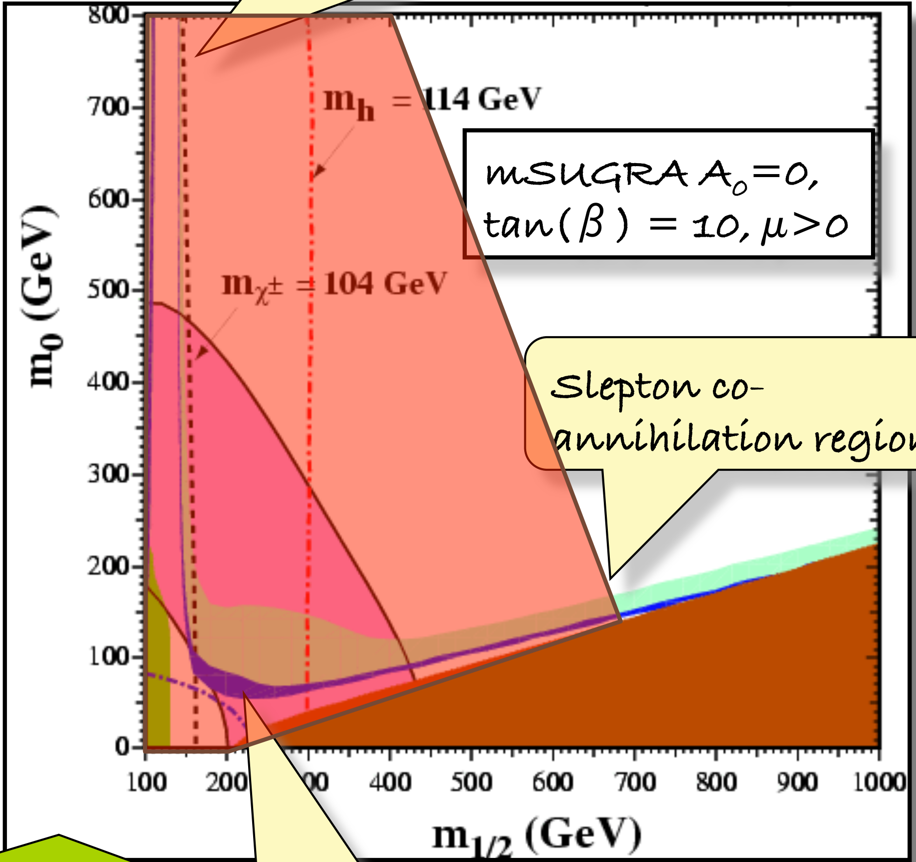
LHC reach for SUSY dark matter







Rule out with 1fb-1



mSUGRA A_0=0, tan(β) = 10, μ>0

'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 ?

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$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino?	R-parity?	violated?	'Freeze-out' from thermal equilibrium	$\Omega_{LSP} \sim 0.25$
	Technibaryon?	(walking) Technicolour	$\tau \sim 10^{18}$ yr e^+ excess?!	Asymmetric (like the observed baryons)	$\Omega_{TB} \sim 0.25$

A new particle can share in the B/L asymmetry if it is charged under a global U(1) symmetry which has a 'mixed anomaly' with SU(2) gauge symmetry ... **thus linking dark to baryonic matter!**

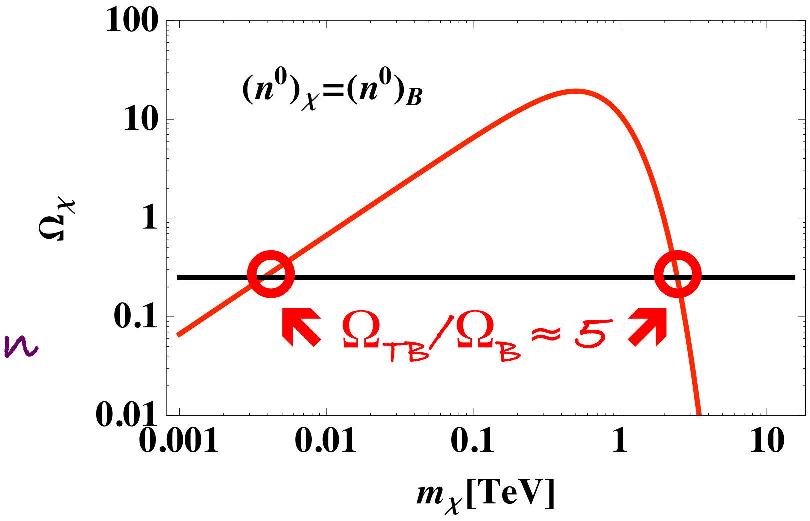
For example a TeV mass technibaryon would have (Nussinov 1985):

$$\frac{\rho_{\mathrm{DM}}}{\rho_{\mathrm{B}}} \sim \frac{m_{\mathrm{DM}}}{m_{\mathrm{B}}} \left(\frac{m_{\mathrm{DM}}}{m_{\mathrm{B}}}\right)^{3/2} \mathrm{e}^{-m_{\mathrm{DM}}/T_{\mathrm{sphaleron}}} \simeq 5$$

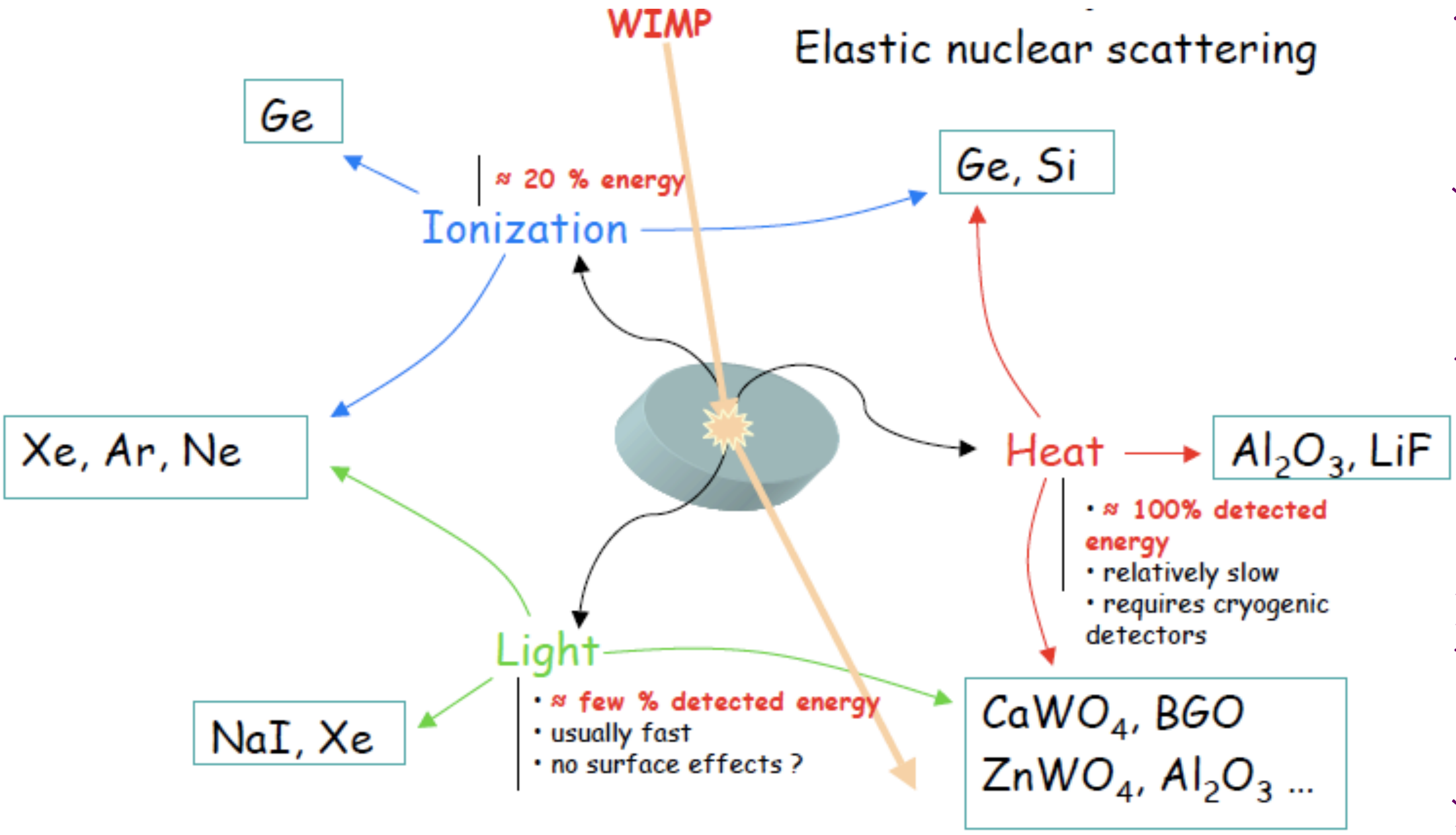
What should the world be made of ?

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
Λ_{QCD}	Nucleons	Baryon number	$\tau > 10^{33}$ yr (dim-6 OK)	~~'Freeze-out' from thermal equilibrium~~ Asymmetric baryogenesis (how?)	$\Omega_B \sim 10^{-10}$ cf. observed $\Omega_B \sim 0.05$
$\Lambda_{QCD'} \sim 5\Lambda_{QCD}$	Dark baryon	$U(1)_{DB}$	?	Asymmetric (like the observed baryons)	$\Omega_{DB} \sim 0.25$
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino?	R-parity?	violated?	'Freeze-out' from thermal equilibrium	$\Omega_{LSP} \sim 0.25$
	Technibaryon?	(walking) Technicolour	$\tau \sim 10^{18}$ yr e^+ excess?!	Asymmetric (like the observed baryons)	$\Omega_{TB} \sim 0.25$

For ~5 GeV mass the abundance is 5 times that of baryons (Gelmini *et al* 1987) and there are candidate particles in hidden sectors (e.g. Kaplan 1992) with characteristic collider signatures



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



WIMP

Elastic nuclear scattering

Ge

≈ 20 % energy

Ionization

Ge, Si

Xe, Ar, Ne

Heat → Al_2O_3, LiF

- ≈ 100% detected energy
- relatively slow
- requires cryogenic detectors

Light

NaI, Xe

- ≈ few % detected energy
- usually fast
- no surface effects ?

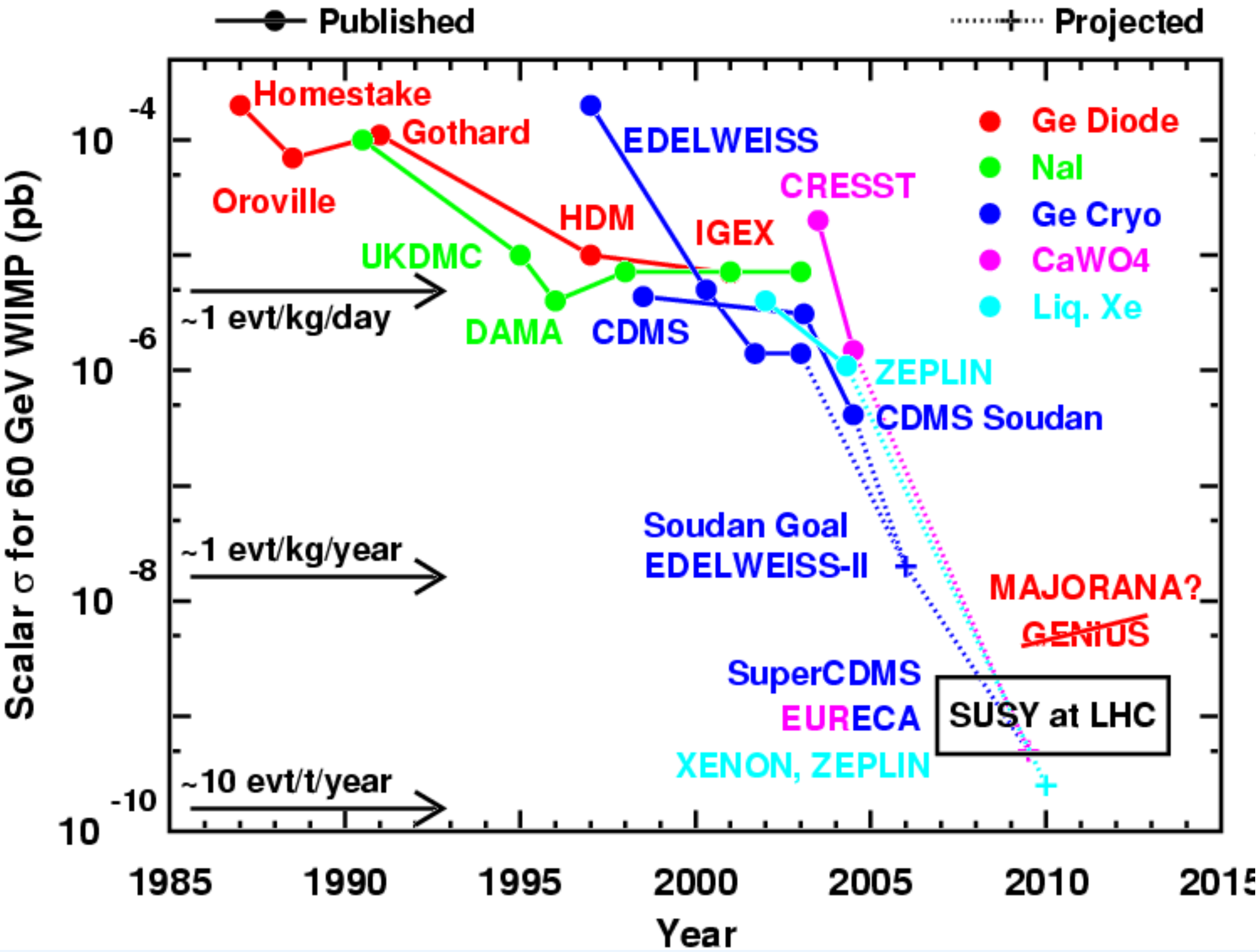
$CaWO_4$, BGO

$ZnWO_4$, Al_2O_3 ...

ukier & Stodolsky 1984; Goodman & Witten 1985)

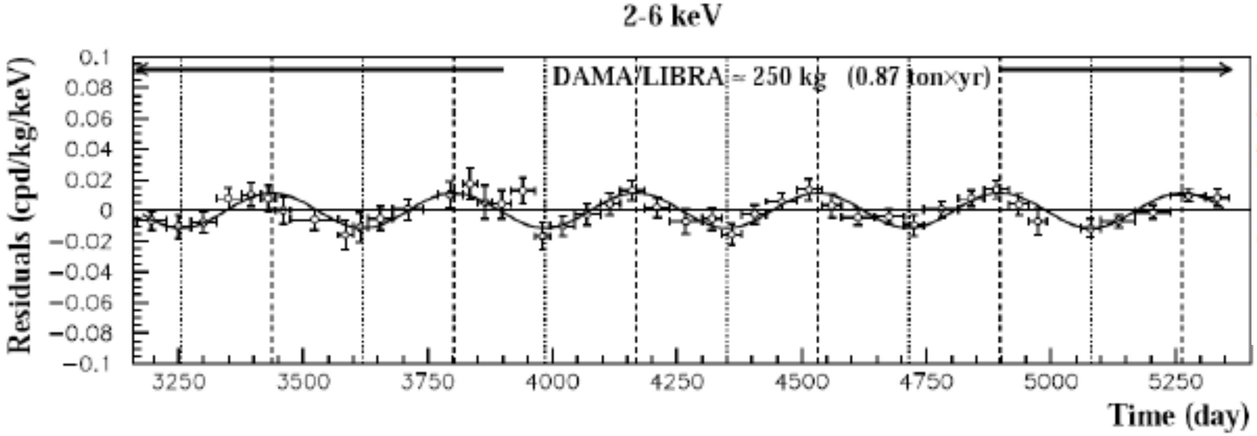
No detection so far ⇒ upper limit of ~10^{-44} cm^2 on SI scattering cross-section of ~100 GeV WIMPs, assuming local halo dark matter density ~ 0.4 GeV cm^{-3}

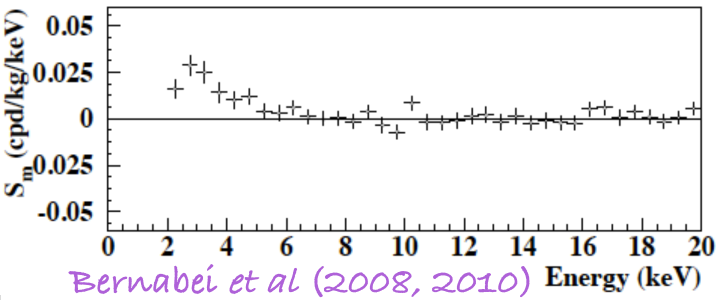
For ~25 years there has been a world-wide race on to detect dark matter …



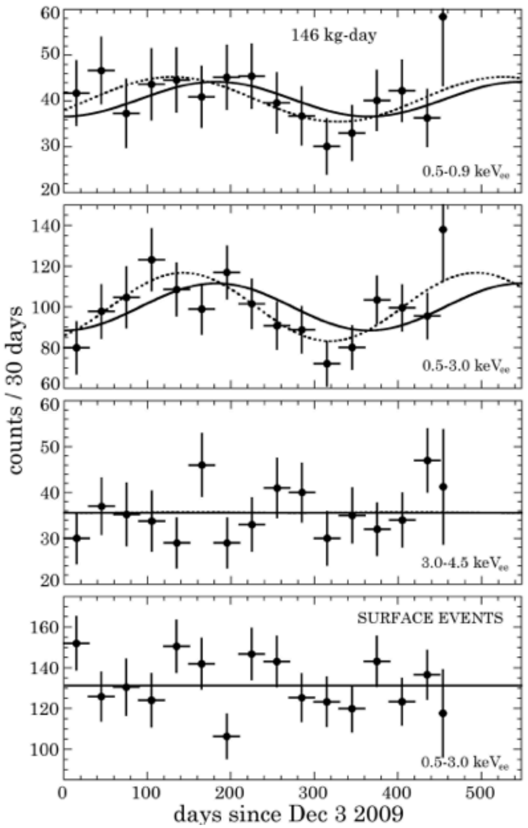
But most of the direct detection experiments have been optimised for ~100 GeV WIMPs (motivated by supersymmetry) … they are not as sensitive to ~few GeV dark matter particles ⇒ O(keV) recoil energy

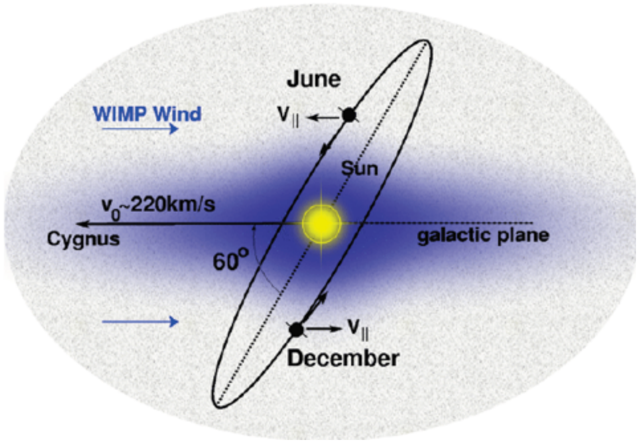
Some experiments (DAMA, CoGeNT,) have reported modulation signals for ~5-10 GeV mass particles with $\sigma_{SI} \sim 10^{-40}$-$10^{-39}$ cm^2!

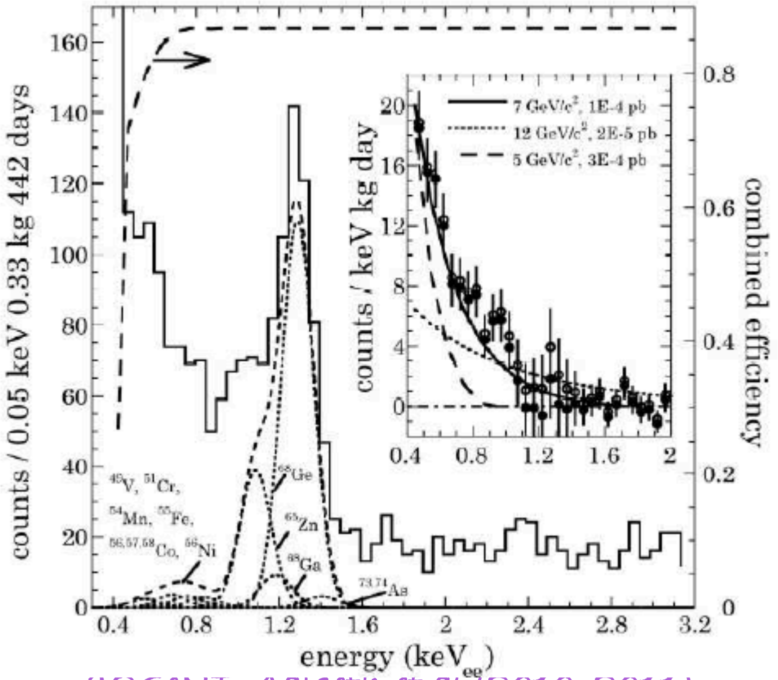




Bernabei et al (2008, 2010)

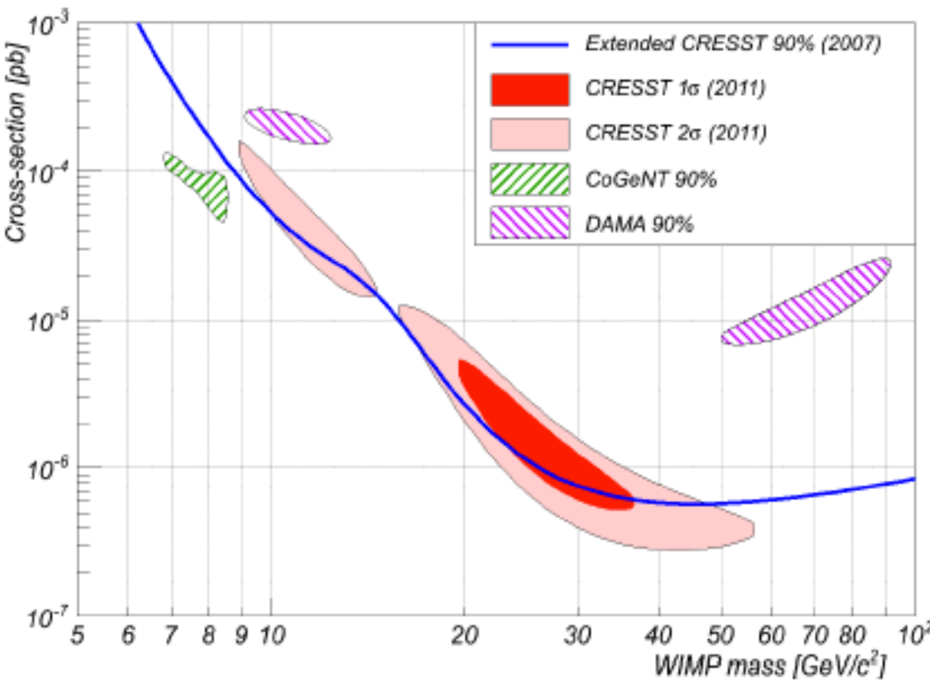






CoGeNT: Aalseth et al (2010, 2011)

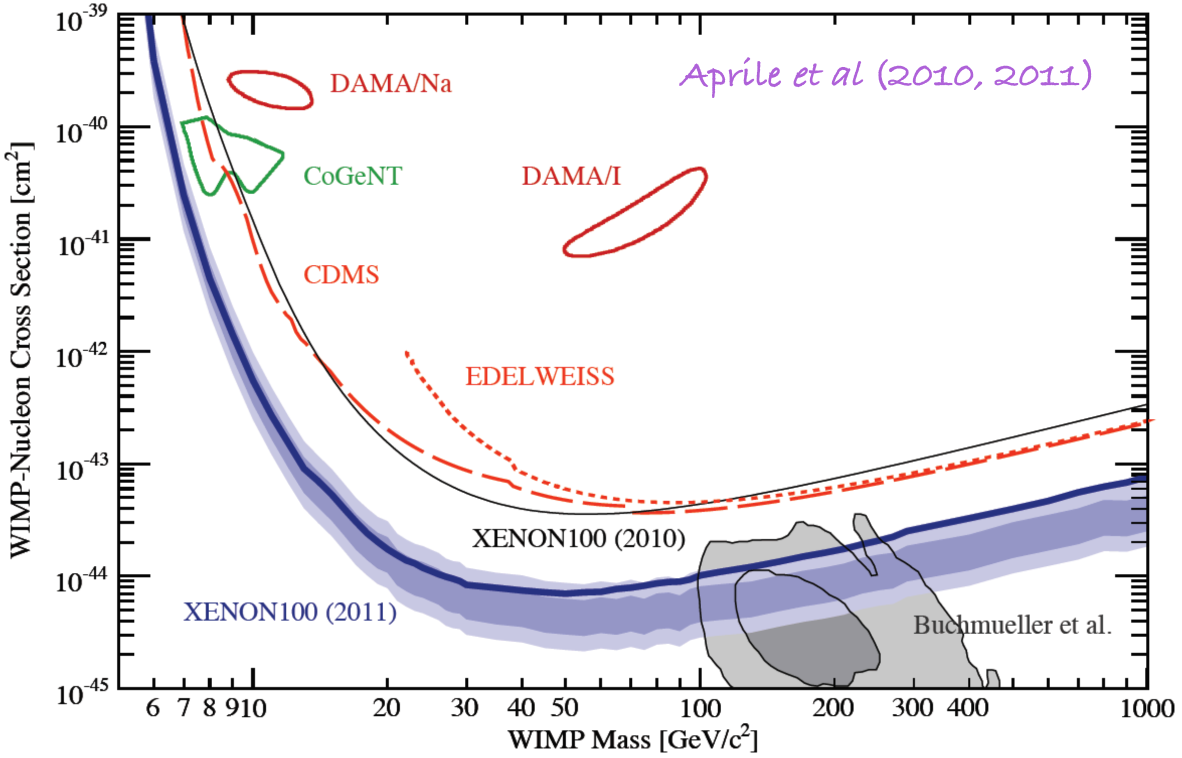
… other experiments e.g. CRESST have also reported 'hints' for light dark matter



Brown et al, arXiv:1109.2589

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)



Aprile et al (2010, 2011)

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

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

Nuclear physics

Particle 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 ...)

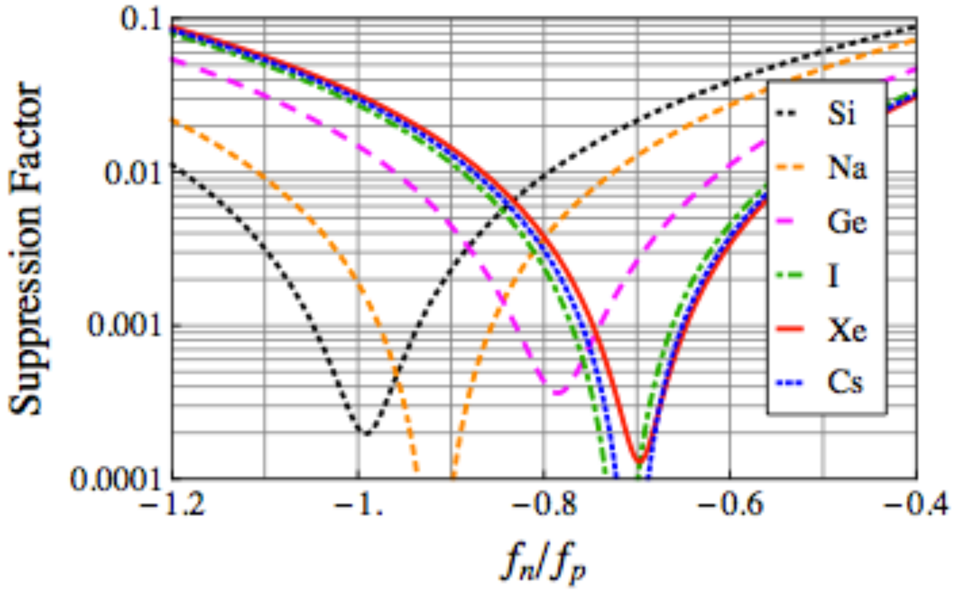
It is becoming increasingly clear that this is not going to be easy!

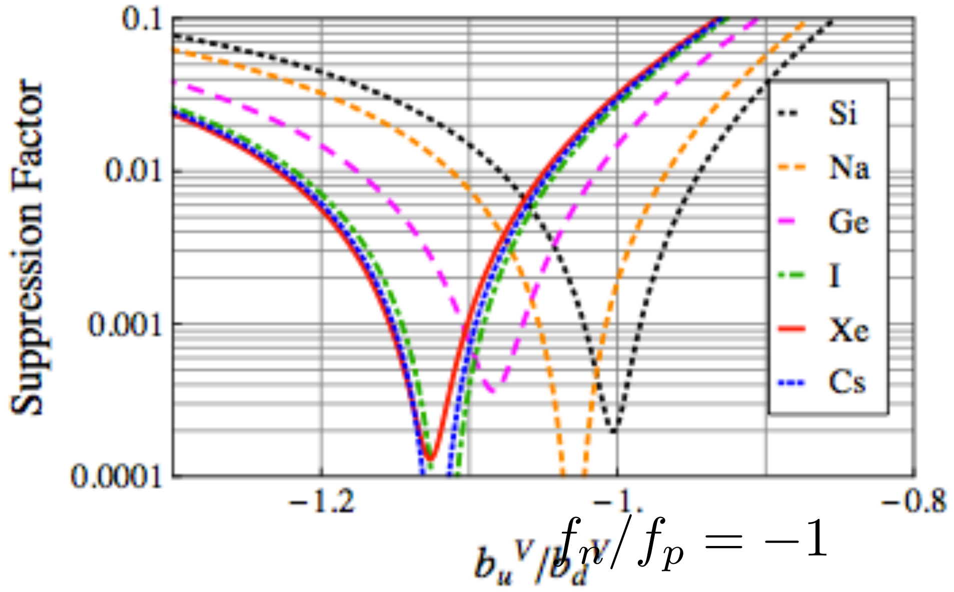
DM-nucleus interactions from vector R

$$\mathcal{L}_R^{\rm NC} = R_\mu \bar{\chi}\gamma^\mu (g_\chi^{\rm V} - g_\chi^{\rm A}\gamma^5)\chi + R_\mu \bar{f}\gamma^\mu (g_f^{\rm V} - g_f^{\rm A}\gamma^5) f$$

Proton/neutron couplings and quark couplings after integrating out R:

$$f_p = 2b_u^{\rm V} + b_d^{\rm V}\ , \quad f_n = 2b_d^{\rm V} + b_u^{\rm V}\ . \qquad b_f^{\rm A,V} = b_{fR}^{\rm A,V} + b_{fZ}^{\rm A,V} = \frac{g_{\chi R}^{\rm A,V}\, g_{fR}^{\rm A,V}}{m_R^2} + \frac{g_{\chi Z}^{\rm A,V}\, g_{fZ}^{\rm A,V}}{m_Z^2}\ .$$





$$f_n/f_p = -1$$

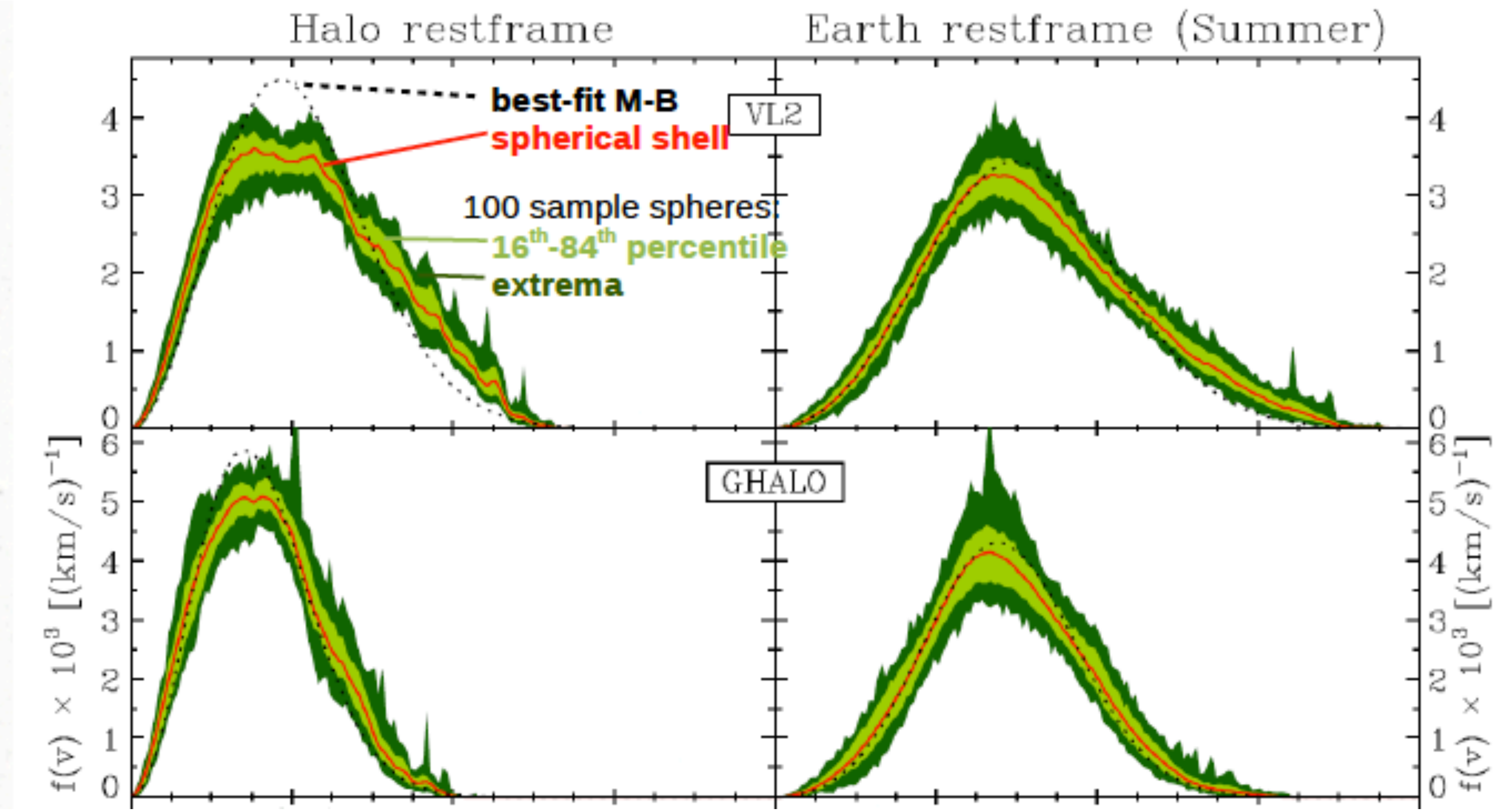
Possible to suppress scattering on a specific target by choosing f_n/f_p appropriately!

$$\sigma_N = \frac{\mu_{\chi N}^2}{\mu_{\chi n}^2}\left(Z\frac{f_p}{f_n} + A - Z\right)^2 \sigma_n$$

If mediator couples to isospin as e.g. QCD rho-meson, then f_n/f_p = -1

(Frandsen, Kahlhoefer, Sarkar, Schmidt-Hoberg, 2011)

Another source of uncertainty is that the DM velocity distribution is assumed to be Maxwellian but is likely to be quite different …



(Kuhlen et al, 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

Expect improved measurements from GAIA (2012)

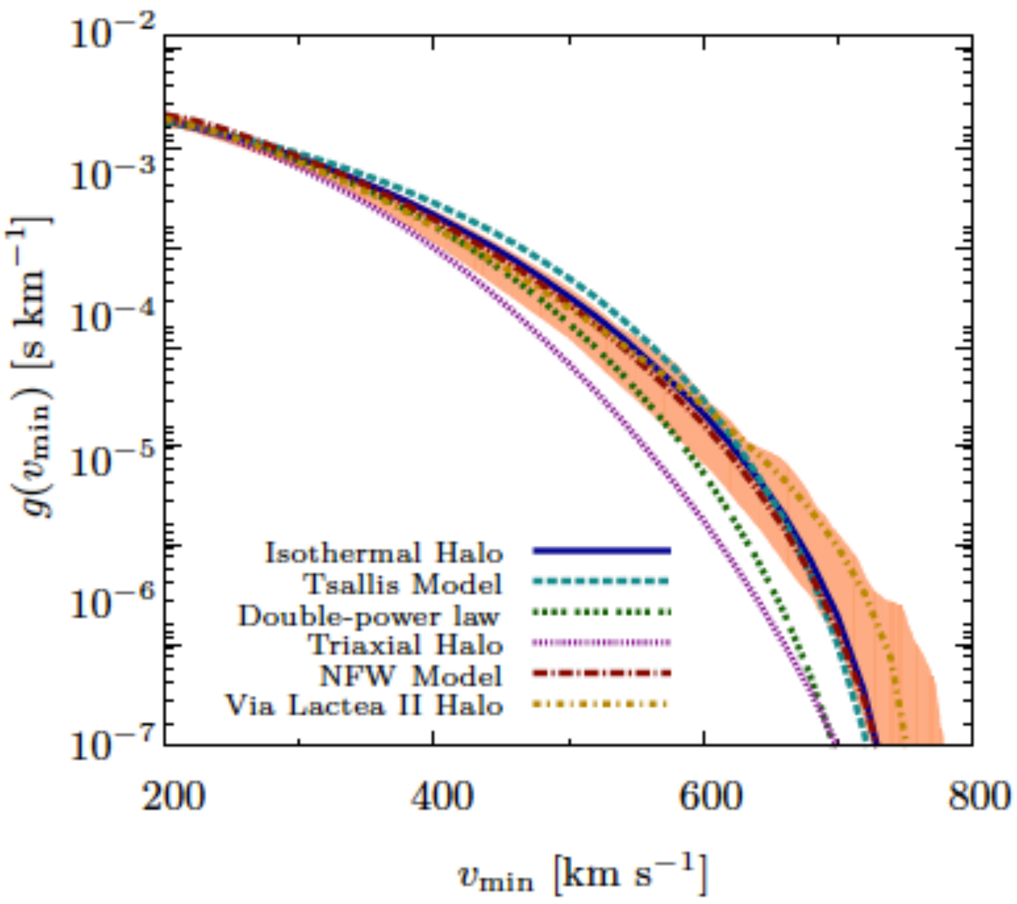
Dark matter density

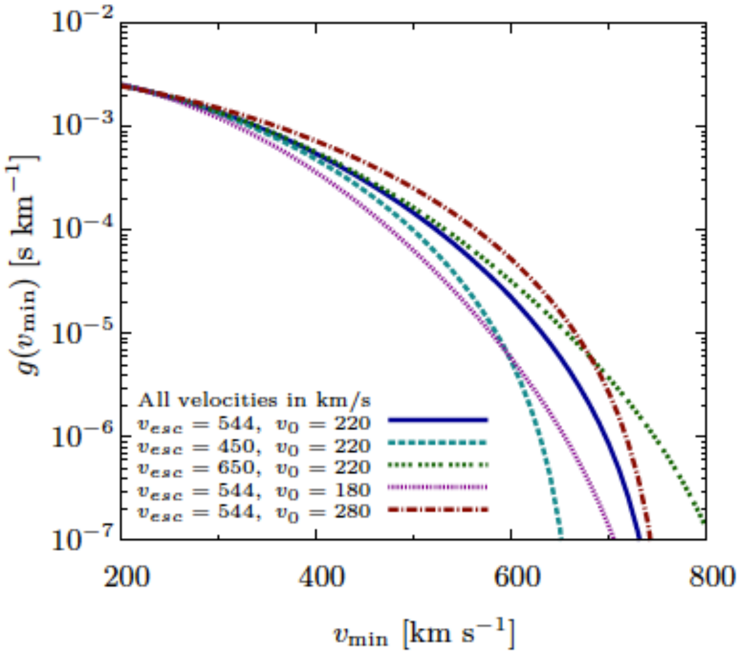
$$\frac{dR}{dE_R} = \frac{\rho\sigma_n}{2m_\chi \mu_{n\chi}^2} A^2 F^2(E_R) g(v_{\min})$$

Velocity integral

$$v_{\min}(E_R) = \sqrt{\frac{m_N E_R}{2\mu^2}}$$

$$g(v_{\min}) = \int_{v_{\min}}^{\infty} \frac{f(\vec{v} + \vec{v}_E(t))}{v} d^3v$$

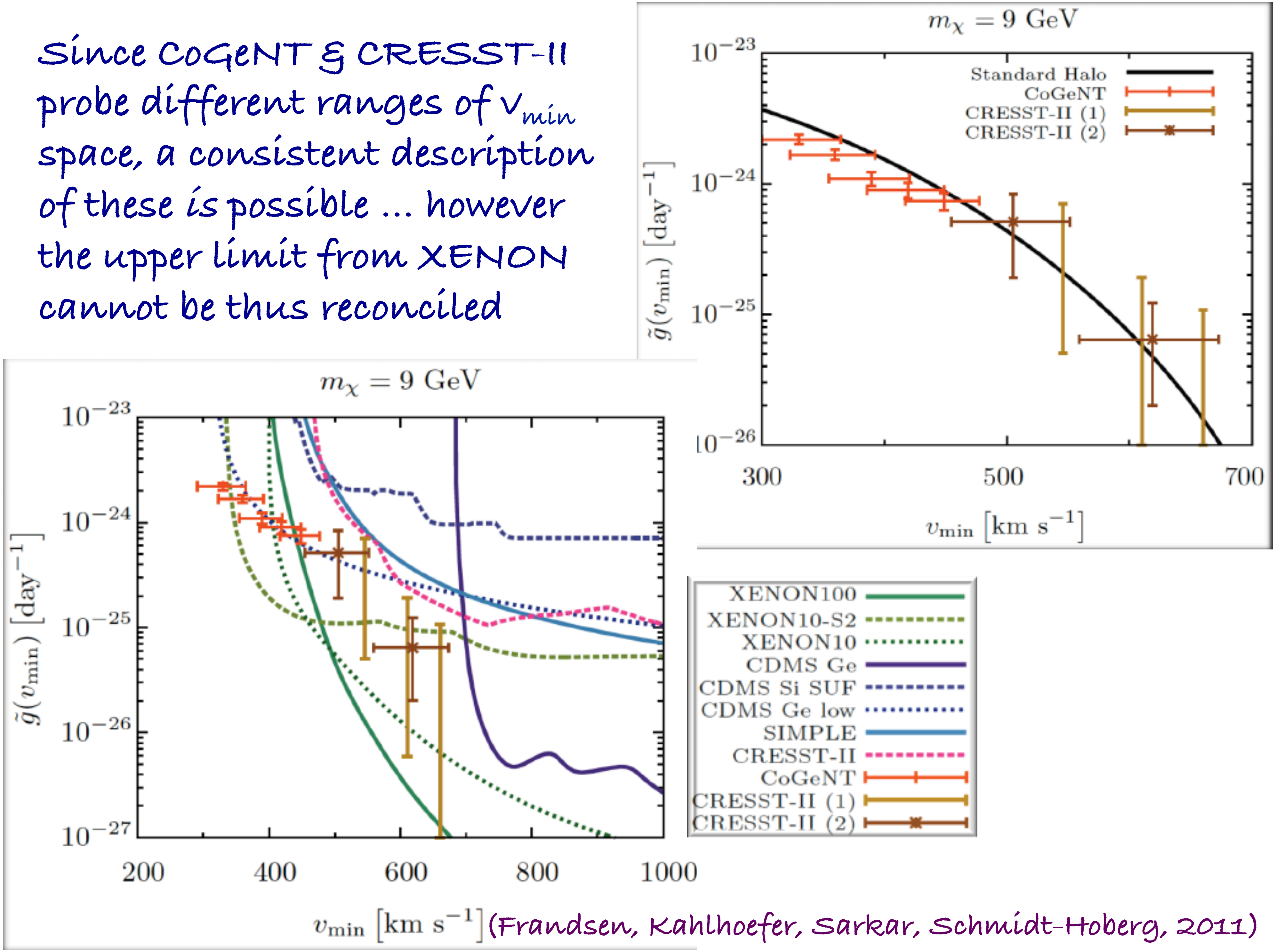




It is just the velocity integral that determines the scattering rate … there is considerable spread amongst various halo models and simulations.

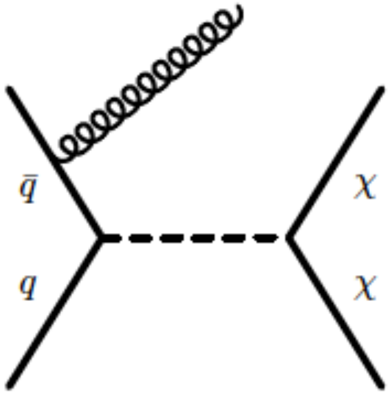
Even for the standard halo model, there are large parameter uncertainties

Since CoGeNT & CRESST-II probe different ranges of v_{min} space, a consistent description of these is possible … however the upper limit from XENON cannot be thus reconciled

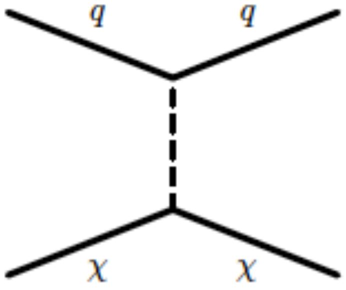


(Frandsen, Kahlhoefer, Sarkar, Schmidt-Hoberg, 2011)

'Monojet' events at colliders directly measure the coupling of dark matter (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



$$\frac{i\, g_\chi\, g_q}{q^2 - M^2}\, (\bar{q} q)\, (\bar{\chi} \chi)\ ,$$

SI, scalar exchange

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

SI, vector exchange

$$\frac{i\, g_\chi\, g_q}{q^2 - M^2}\, (\bar{q} \gamma_\mu \gamma_5 q)\, (\bar{\chi} \gamma^\mu \gamma_5 \chi)\ ,$$

SD, axial-vector exchange

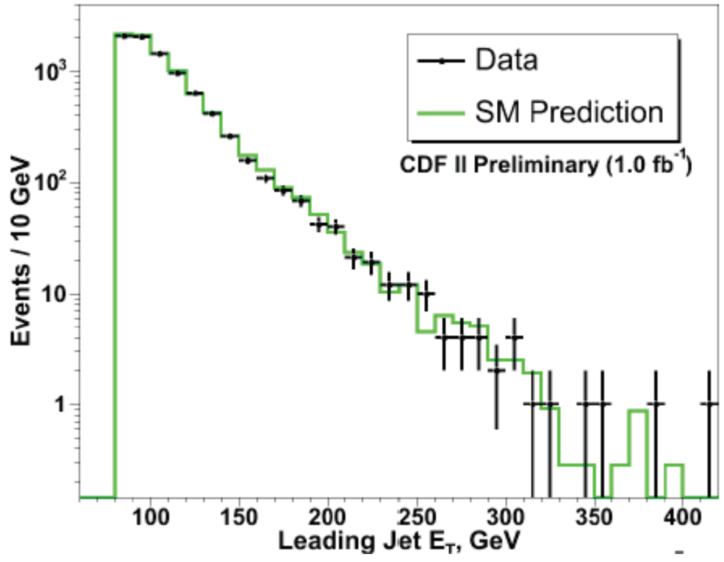
$$\frac{i\, g_\chi\, g_q}{q^2 - M^2}\, (\bar{q} \gamma_5 q)\, (\bar{\chi} \gamma_5 \chi)\ ,$$

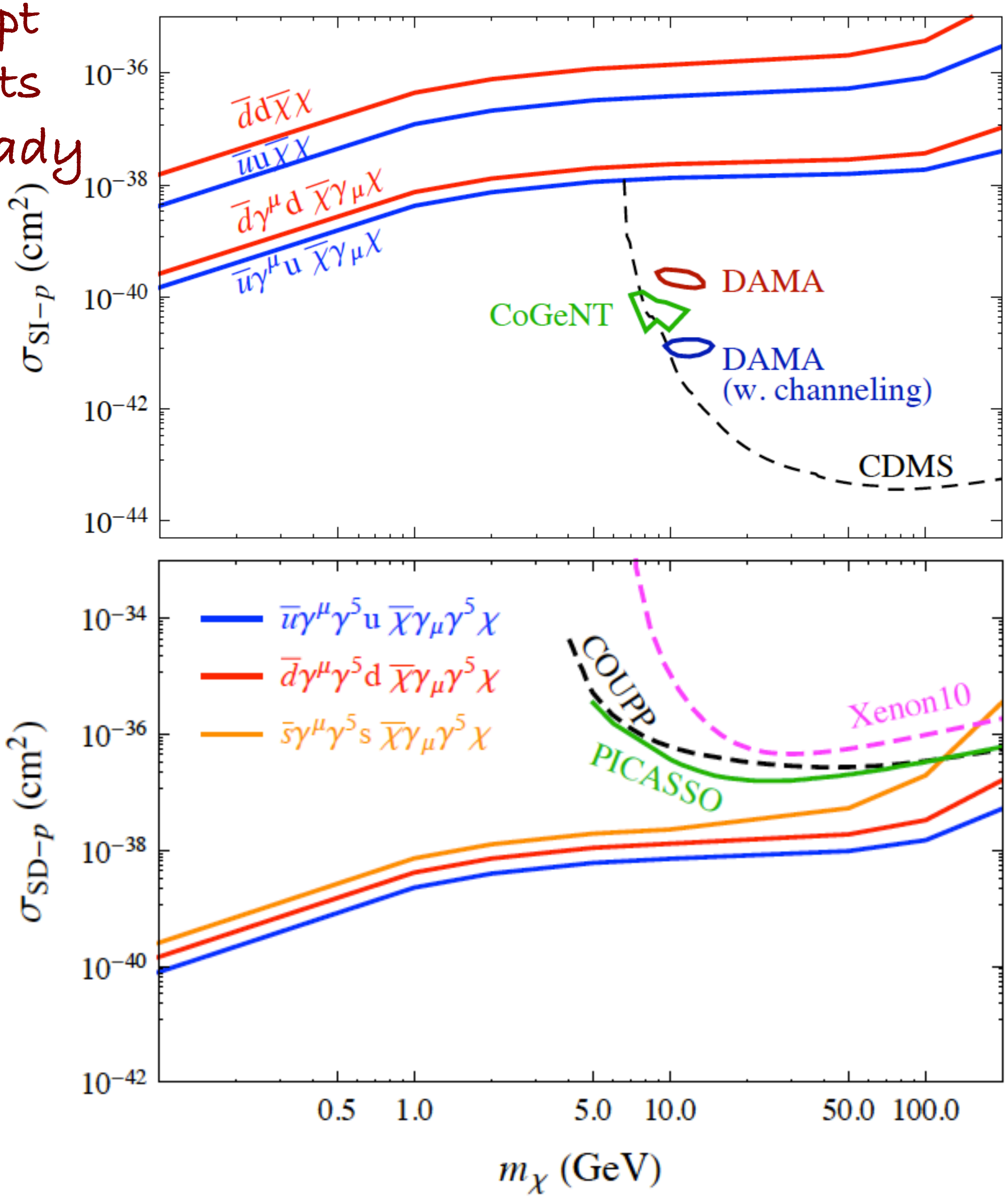
SD and mom. dep., psuedo-scalar exchange

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)

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

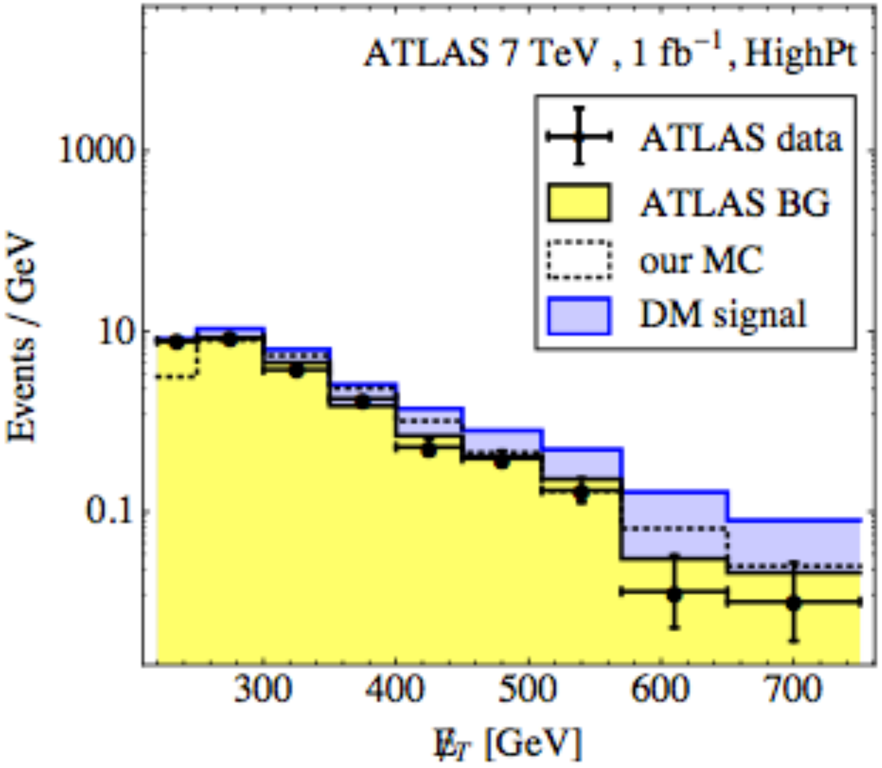


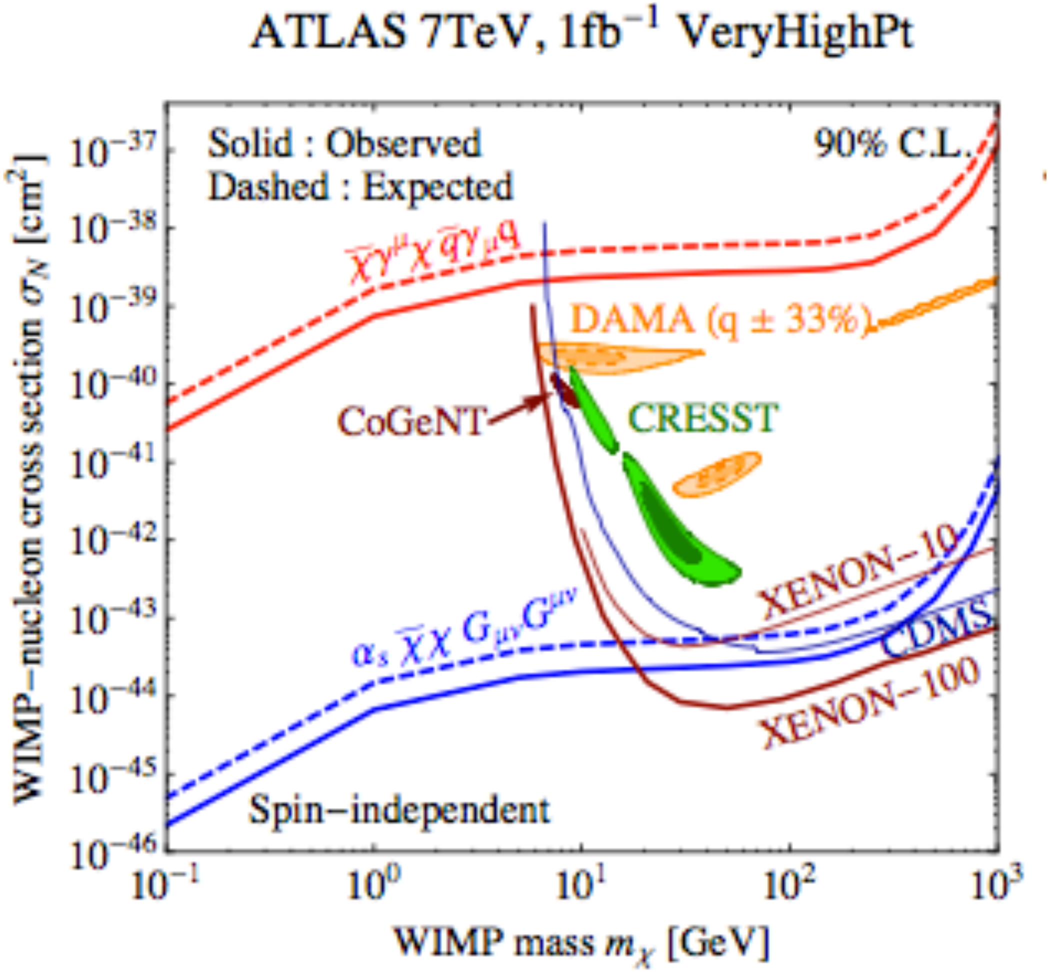


ATLAS and CMS at the LHC are also doing searches for 'monojets' ... the expected reach for dark matter couplings is particularly interesting for light dark matter and for spin-dependent couplings

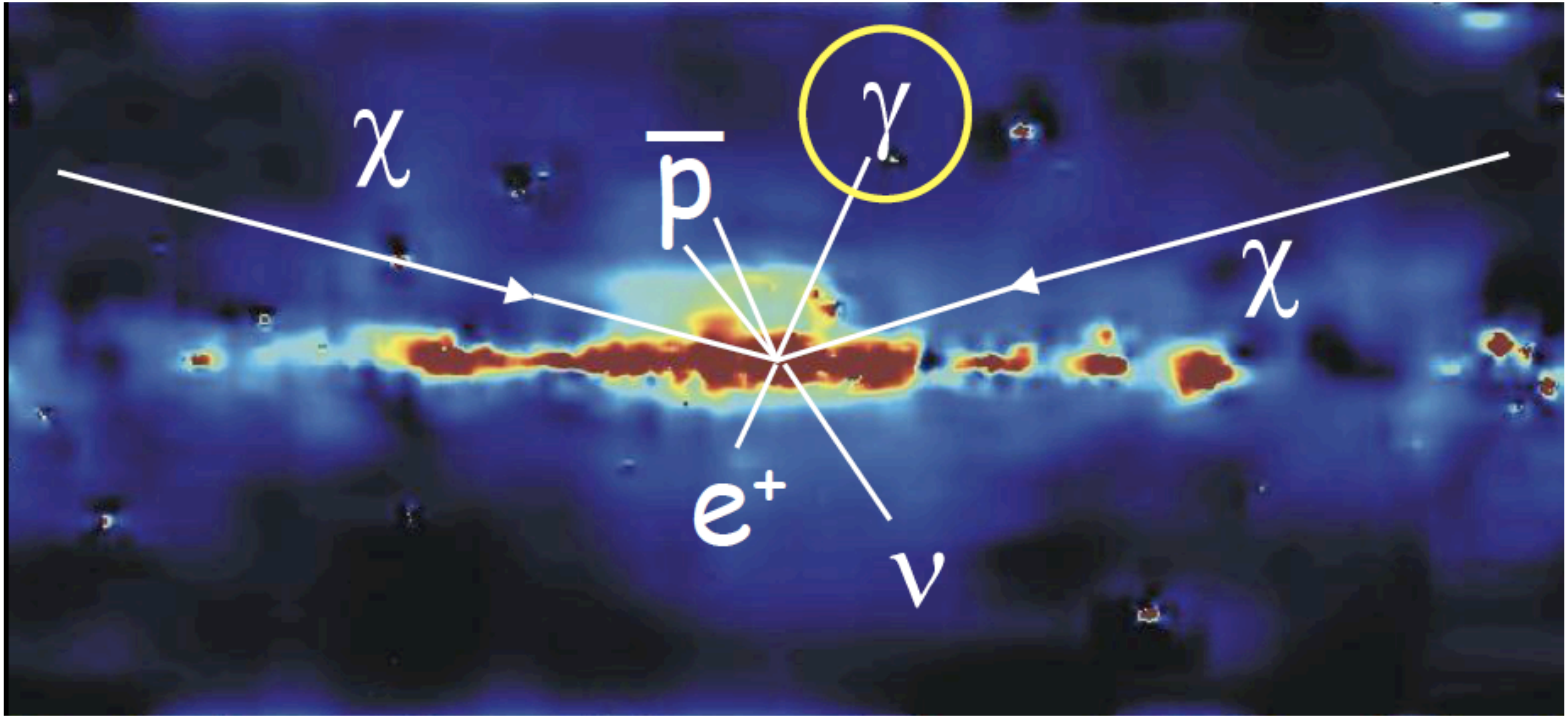
Rajaraman, Sheperd, Tait, Wijangco, '11

ATLAS limits for vector interactions do not yet rule out `best fit regions'





Many techniques for indirect detection ... and many claims!



The PAMELA 'excess' (e^+), Fermi 'excess' ($e^+ + e^-$), WMAP 'haze' (radio), Fermi 'bubbles' (γ-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:

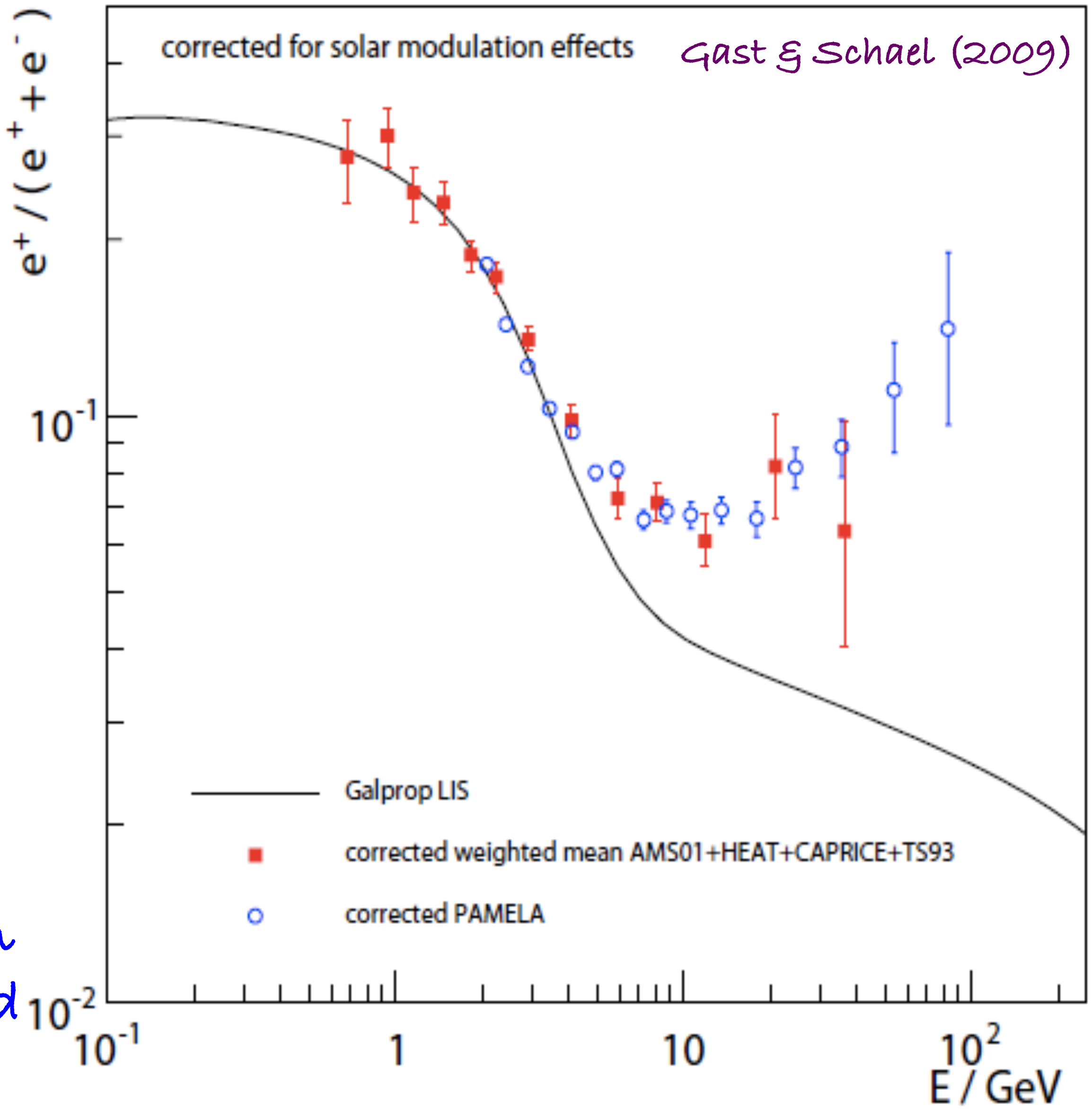
$$\frac{\phi_{e^+}}{\phi_{e^+}+\phi_{e^-}}$$

Anomaly ⇒ excess above ‘astrophysical bkgd’

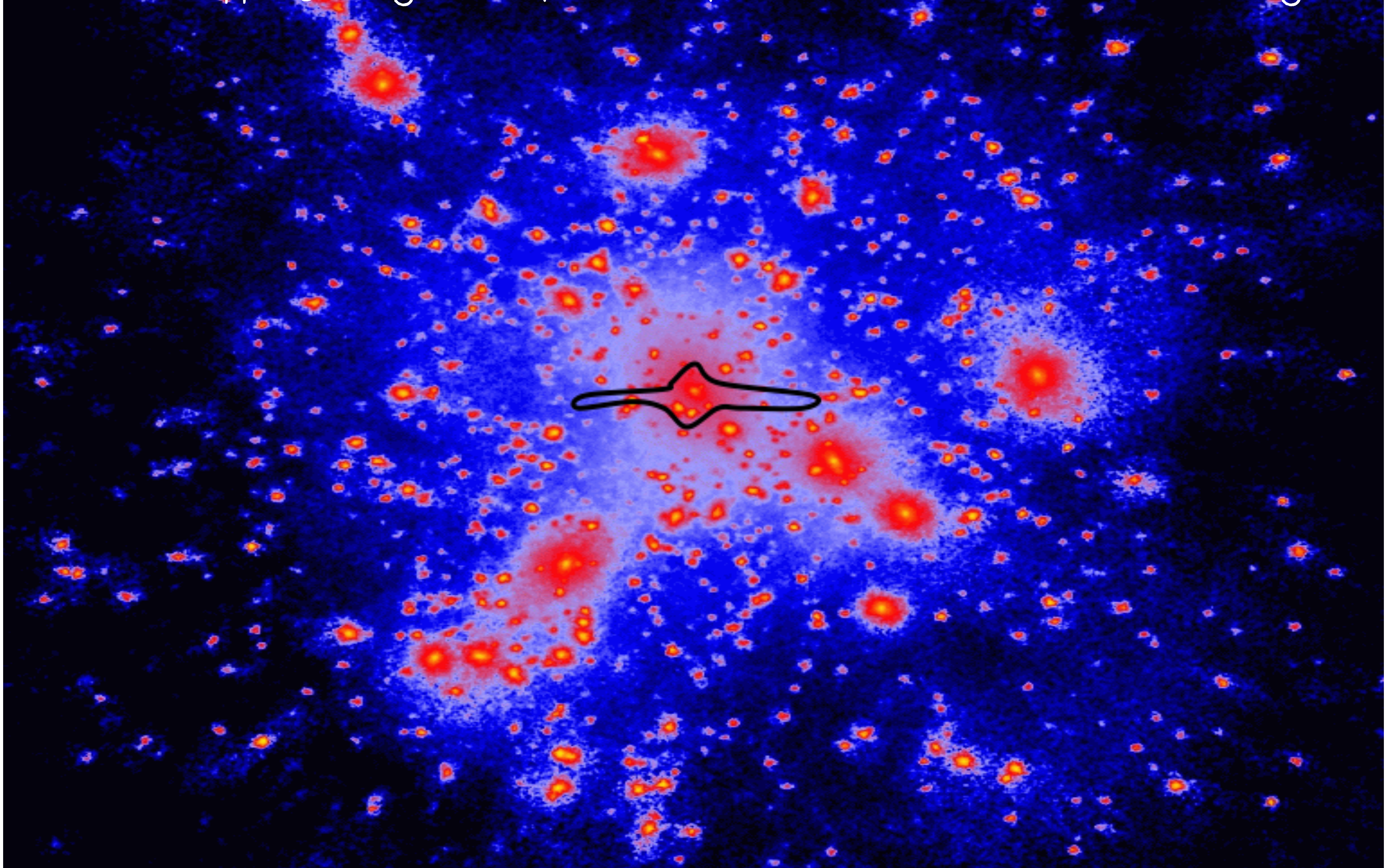
Widely attributed to dark matter annihilations/decay: … fits the spectral shape!

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)



Numerical simulations of structure formation through gravitational instability in cold dark matter show the Milky Way forming from the merger of smaller structures (+ tidal stripping, baryonic infall, disk formation etc) over several billion years



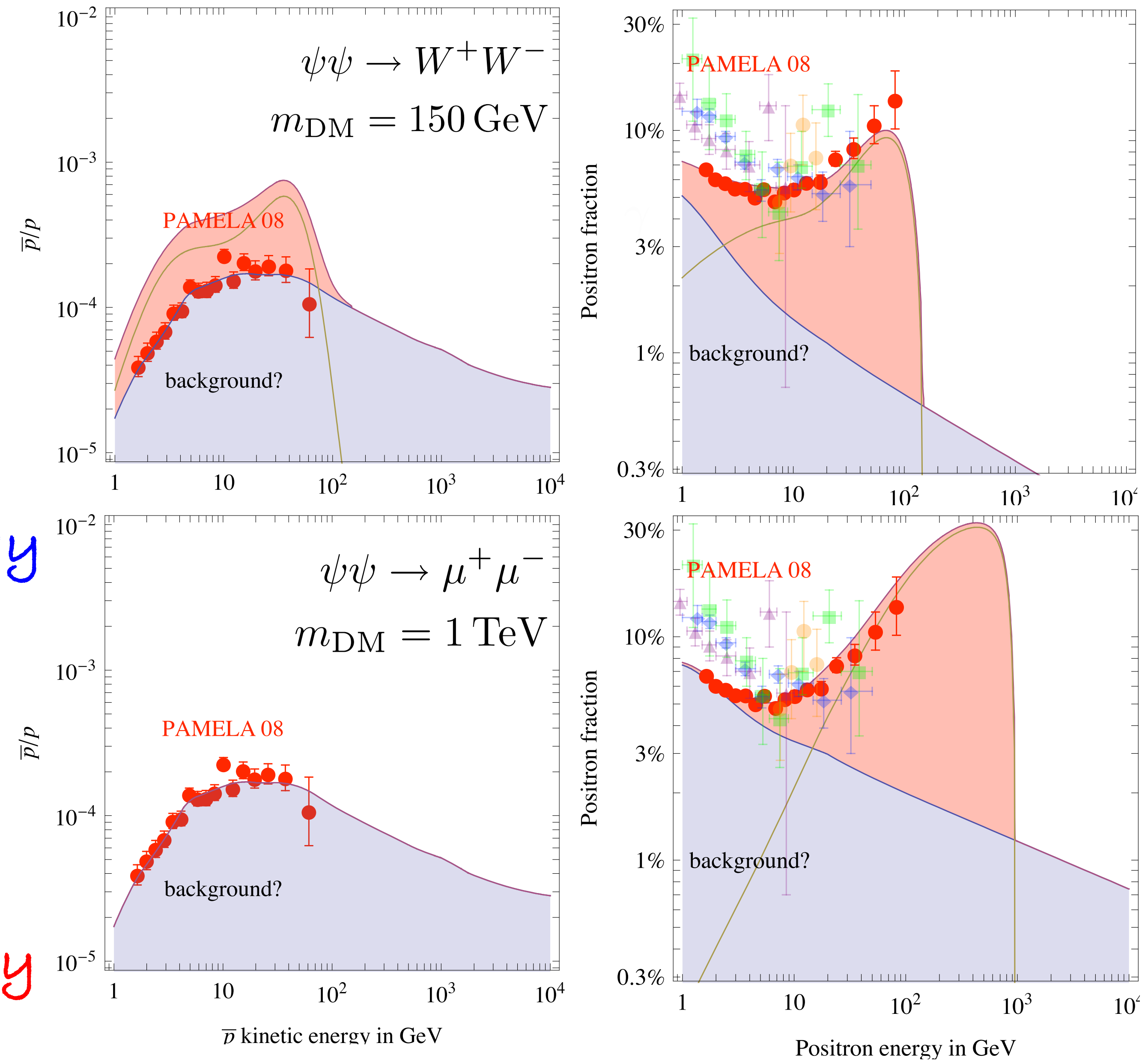
The 'boost factor' due to this clumpiness is < a factor of ~2-10 (Lavalle et al, 2008)

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

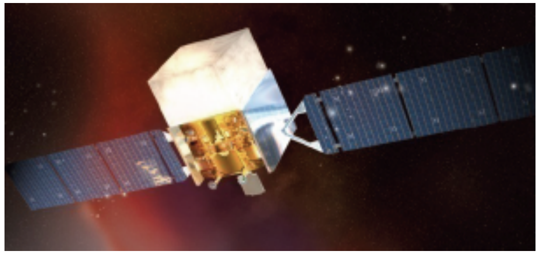
Can fit with DM annihilation or decay only if DM particles are also 'leptophilic'

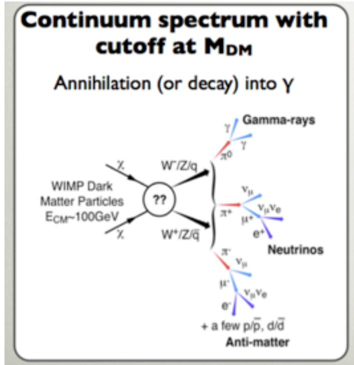
... but such models are increasingly being constrained by limits from Fermi



Cirelli et al (2009)

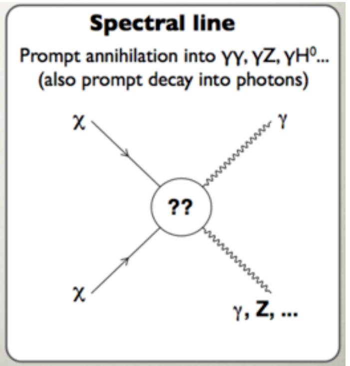
Fermi has searched for DM signals in a variety of channels ... without success





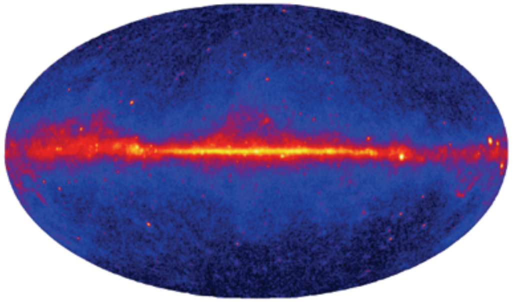
Continuum spectrum with cutoff at M_{DM}

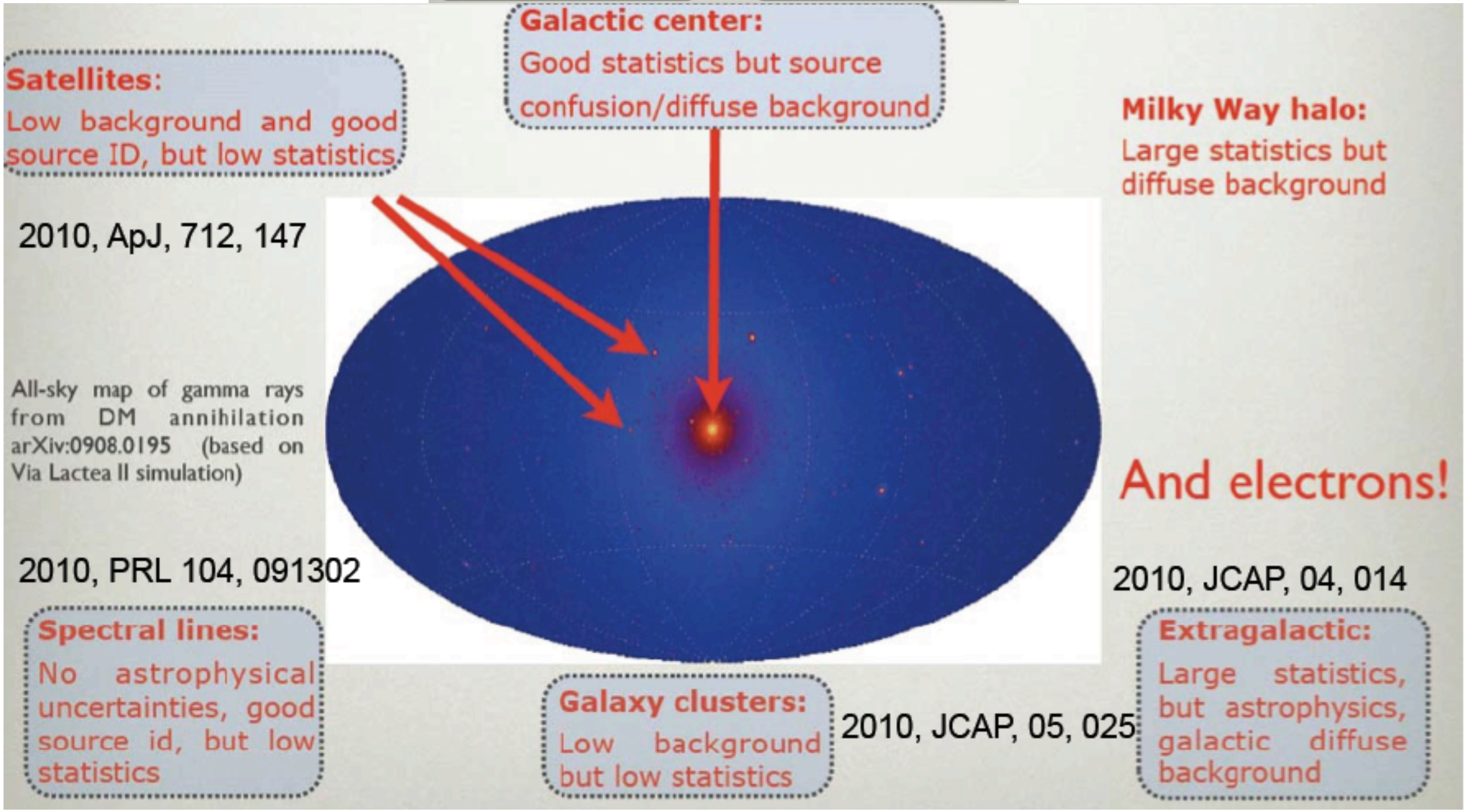
Annihilation (or decay) into γ



Spectral line

Prompt annihilation into γγ, γZ, γH⁰...
(also prompt decay into photons)





Galactic center:
Good statistics but source confusion/diffuse background

Satellites:
Low background and good source ID, but low statistics

Milky Way halo:
Large statistics but diffuse background

2010, ApJ, 712, 147

All-sky map of gamma rays from DM annihilation arXiv:0908.0195 (based on Via Lactea II simulation)

And electrons!

2010, PRL 104, 091302

2010, JCAP, 04, 014

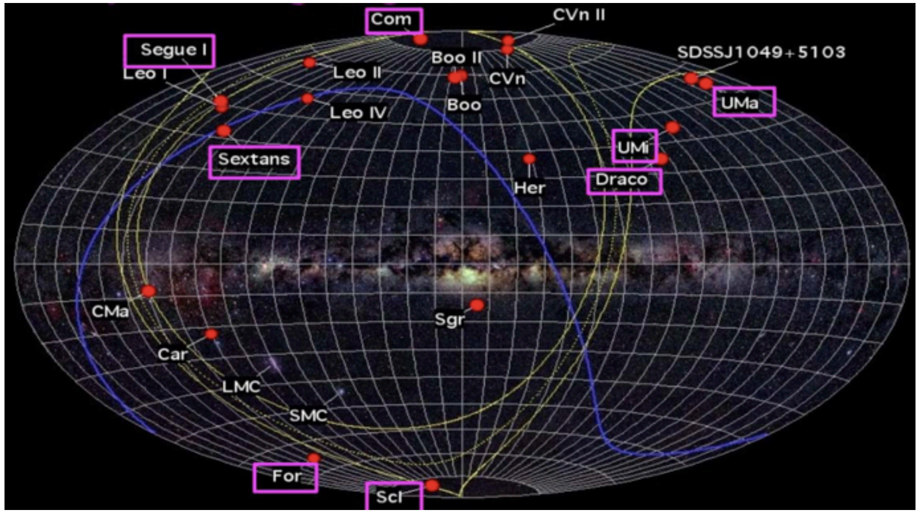
Spectral lines:
No astrophysical uncertainties, good source id, but low statistics

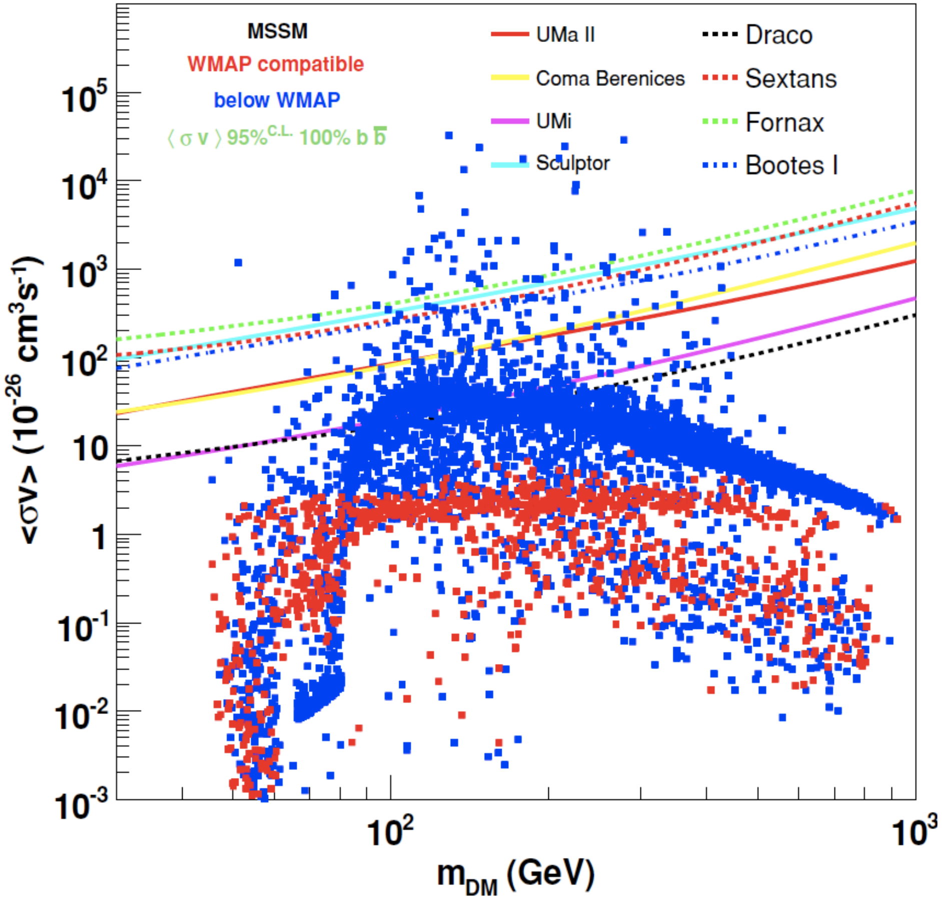
Galaxy clusters:
Low background but low statistics

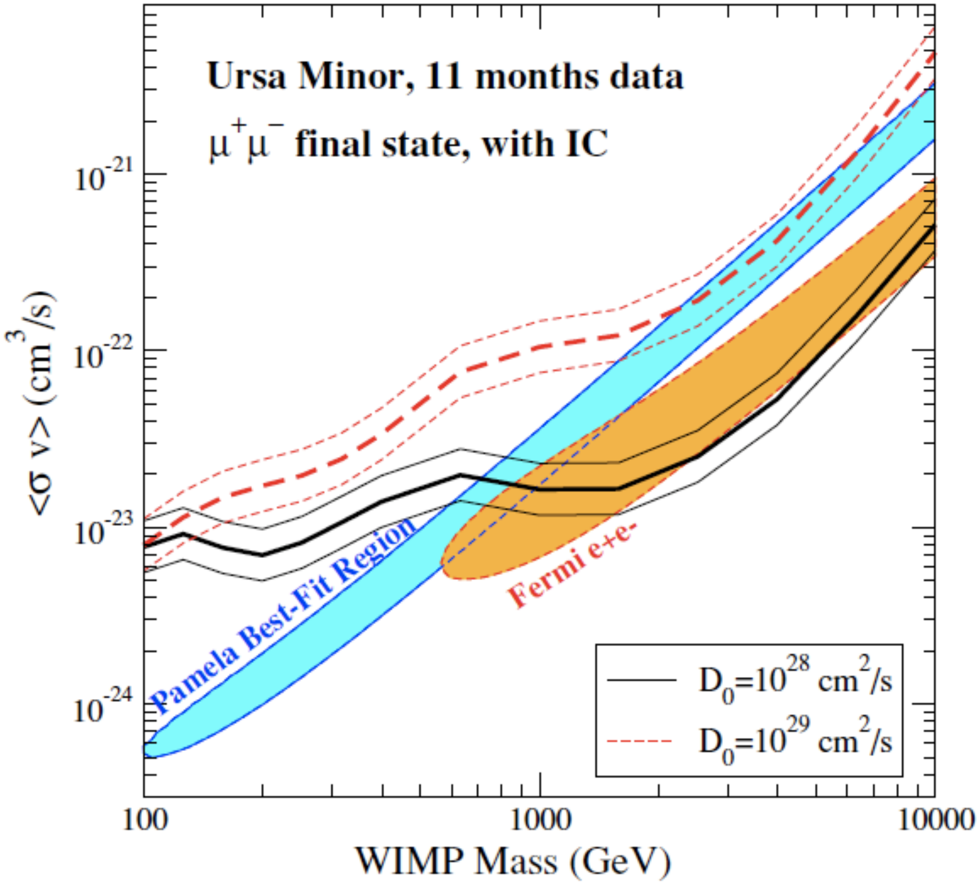
2010, JCAP, 05, 025

Extragalactic:
Large statistics, but astrophysics, galactic diffuse background

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 ...



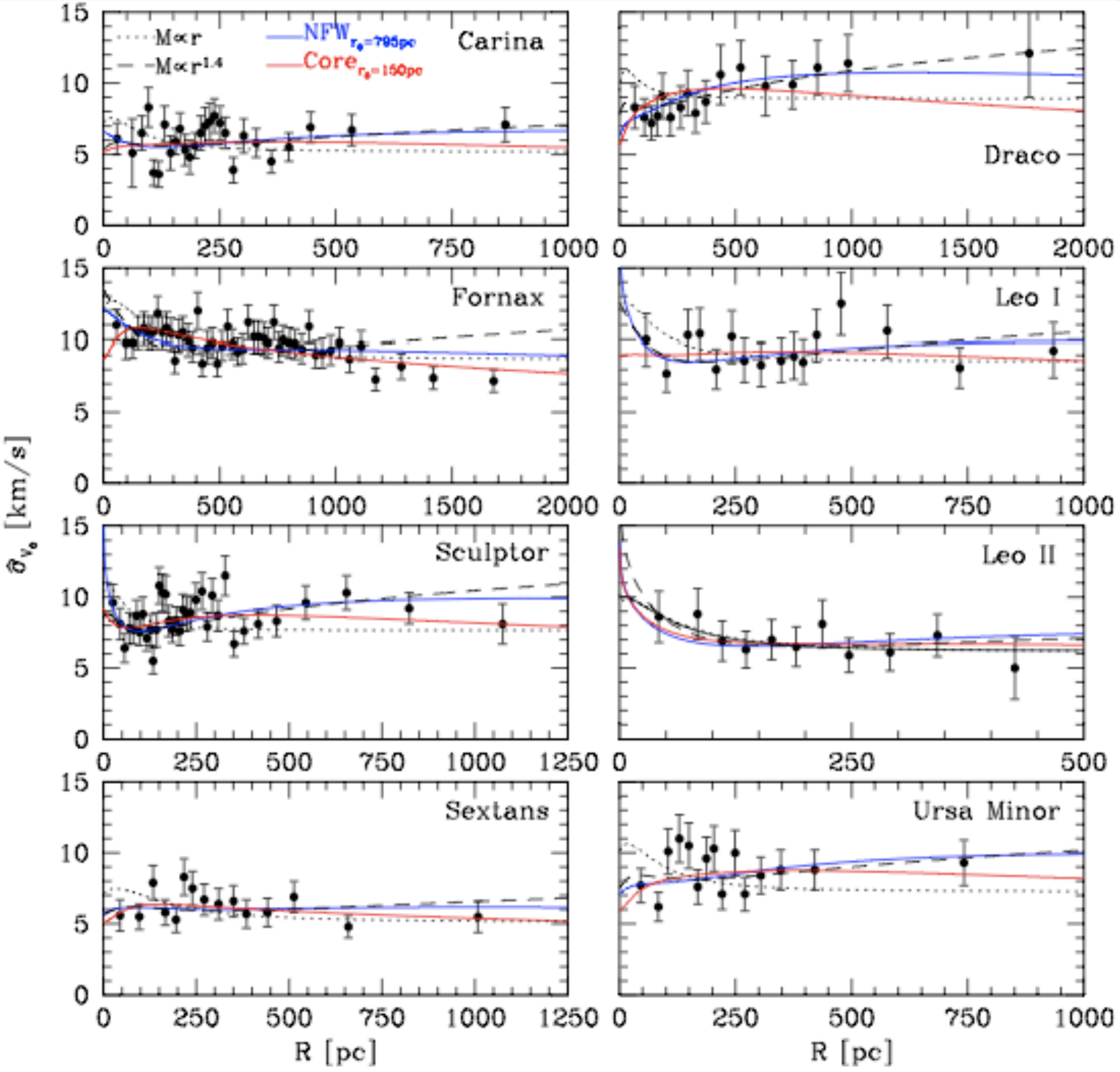




Sensitivity to the annihilation signal from dSphs is however rather dependent on how the dark matter distribution is modelled … cored halos reduce the signal by ~10^2 cf. cusps (Evans, Ferrer, Sarkar 2004)

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)

… challenge for CDM?



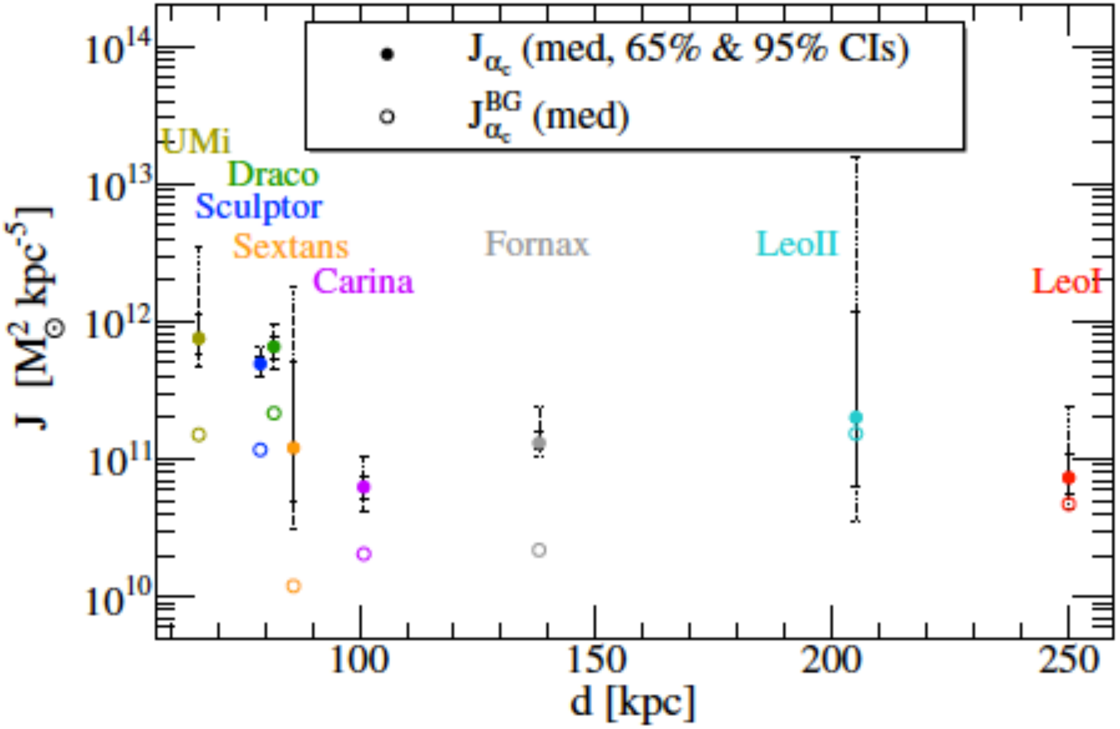
The annihilation signal can be factorised into: particle physics x astrophysics

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\Delta\Omega) = \Phi^{PP}(E_\gamma)\times J(\Delta\Omega)$$

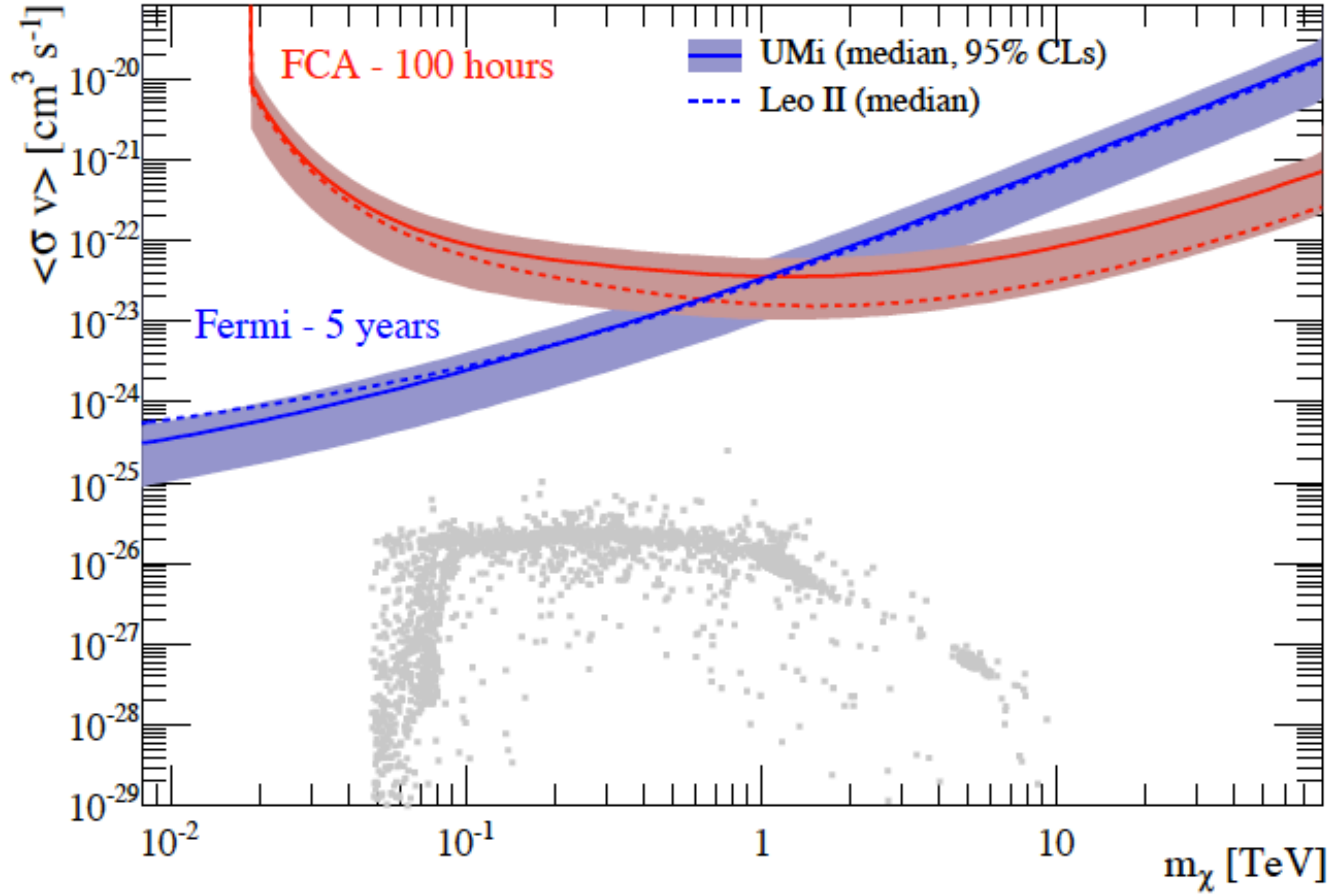
$$\Phi^{PP}(E_\gamma) \equiv \frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi}\frac{\langle\sigma_{\rm ann}v\rangle}{2m_\chi^2}\times\frac{dN_\gamma}{dE_\gamma}$$

$$J = \int_{\Delta\Omega}\int \rho^2_{\rm DM}(l,\Omega)\,dl\,d\Omega.$$

A recent study (walker et al 2011) shows that most authors have *overestimated* the J-factor of the dSphs used in setting limits on annihilating dark matter



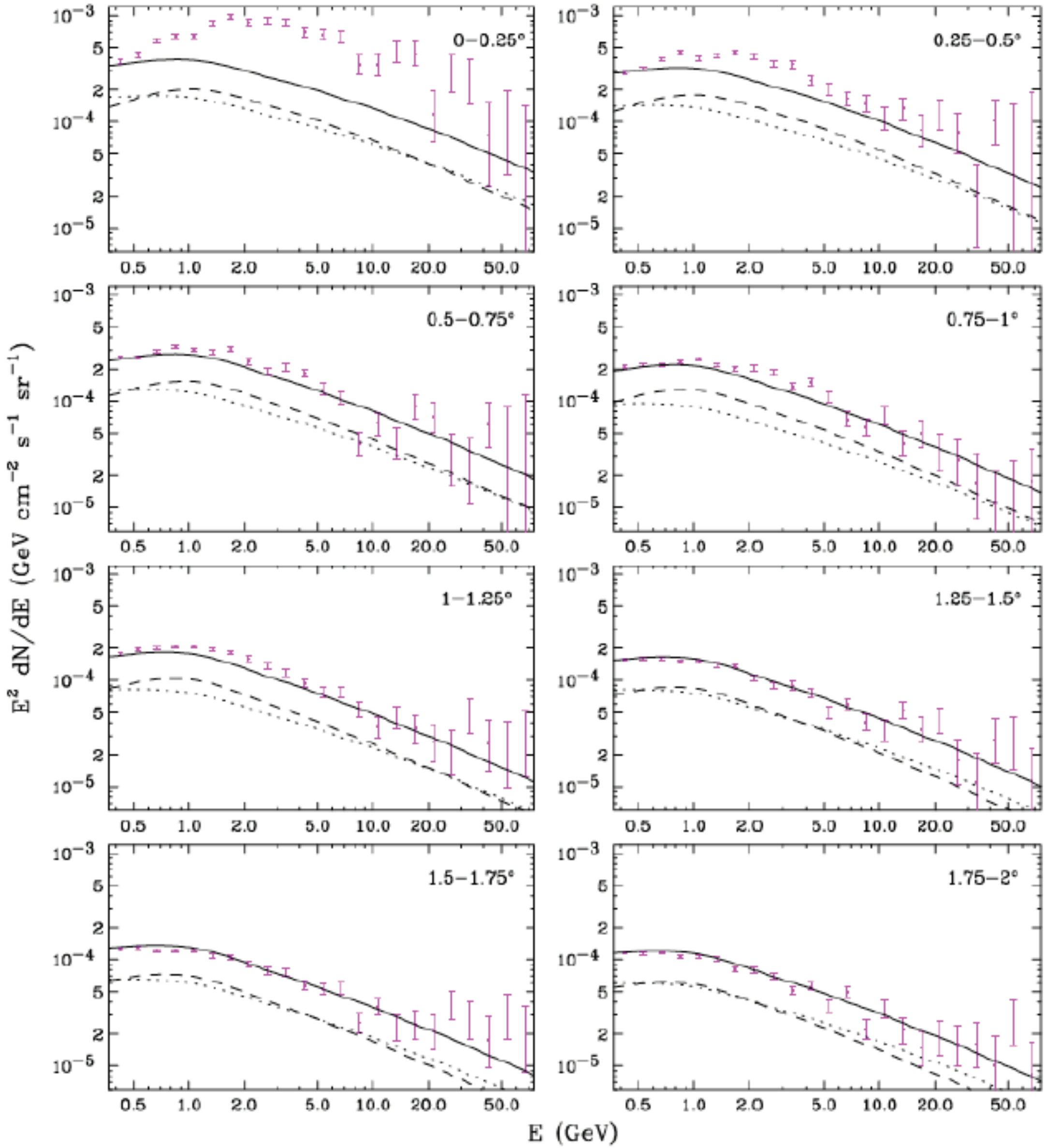
Hence the sensitivity to the annihilation signal that is currently being claimed will actually be reached only after several years operation of Fermi, or by a 'future Cherenkov array (aka CTA)

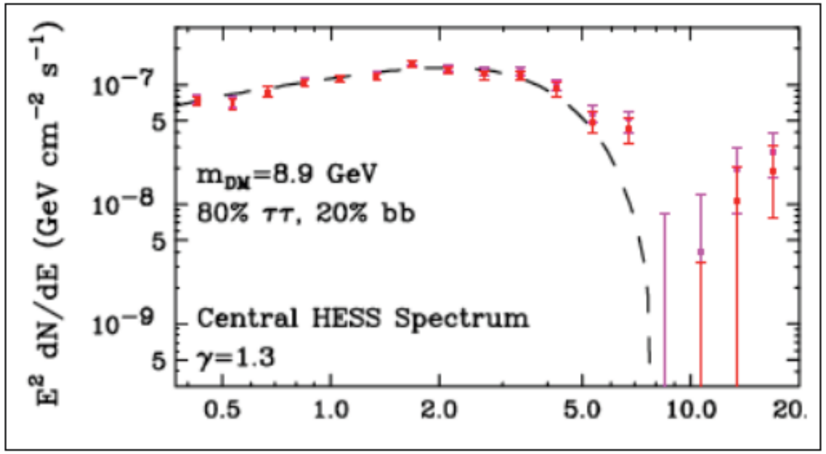


Charbonnier et al 2011

... Can do much better with a dedicated 'Dark Matter Array'

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)

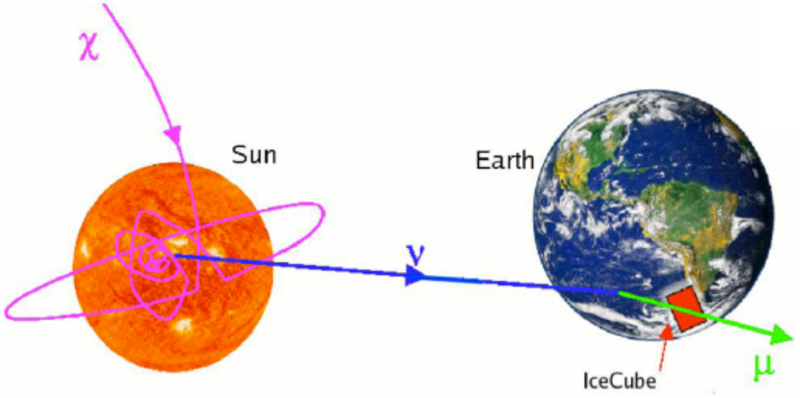




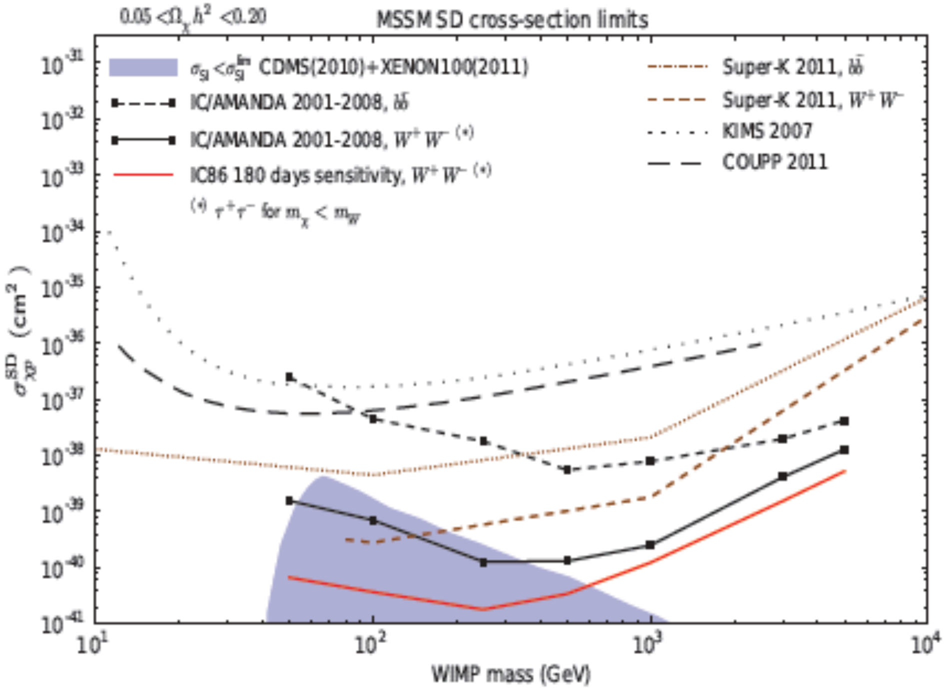
By fitting the observed γ-ray emission to a disk+bulge model (π^0 + IC emission) they isolate a excess signal in the innermost region (~175 pc) – which has a hard spectrum consistent with dark matter annihilation

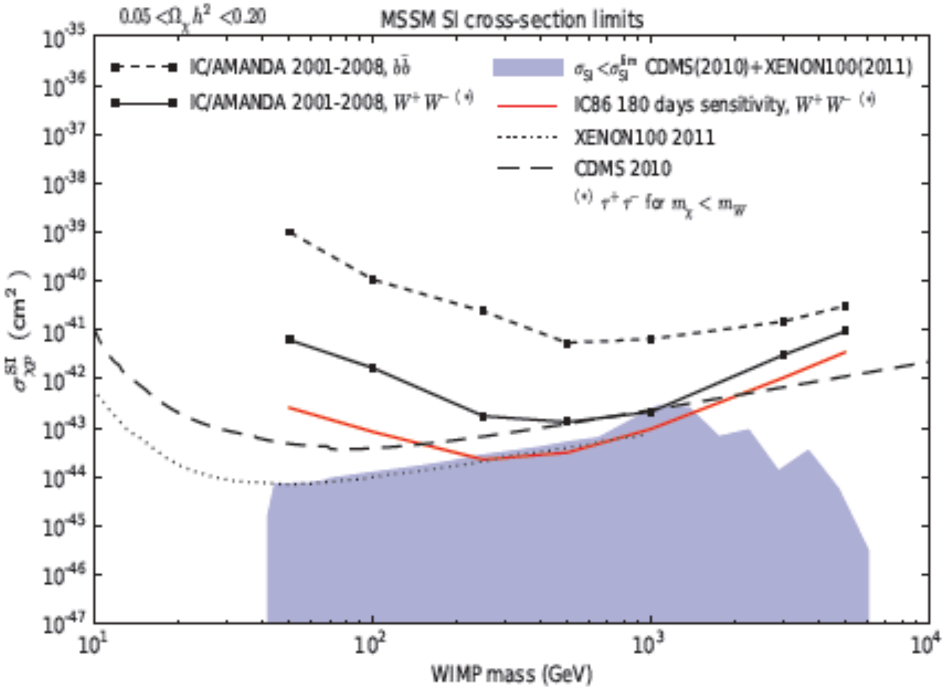
… eagerly awaiting checks by the Fermi team

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)



[arXiv:1112.1840]





Mass scale	Lightest stable particle	Symmetry/ Quantum #	Stability ensured?	Production	Abundance
Λ_{QCD}	Nucleons	Baryon number	$\tau > 10^{33}$ yr	'Freeze-out' from equilibrium Asymmetric baryogenesis – how?	$\Omega_B \sim 10^{-10}$ cf. observed $\Omega_B \sim 0.05$
$\Lambda_{QCD'} \sim 5\Lambda_{QCD}$	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	$\Omega_X \sim 0.3$?
$\Lambda_{see-saw} \sim \Lambda_{Fermi}^2/\Lambda_{B-L}$	Neutrinos	Lepton number	Stable	Thermal (abund ~ CMB photons)	$\Omega_\nu > 0.003$
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 searches in the '80s for temperature fluctuations in the CMB … there were clear theoretical predictions but only upper limits on detection (causing near crisis for theory!)

Finally breakthrough that transformed cosmology!

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