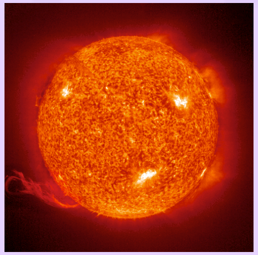
Asymmetric dark matter



and the Sun

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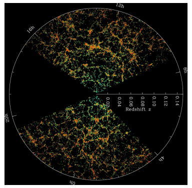
What is the world made of?

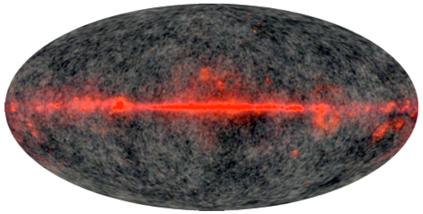
Only **geometrical evidence:**

$\Lambda \sim O(H_0^2)$, $H_0 \sim 10^{-42}$ GeV

… dark energy is *inferred* from the 'cosmic sum rule':

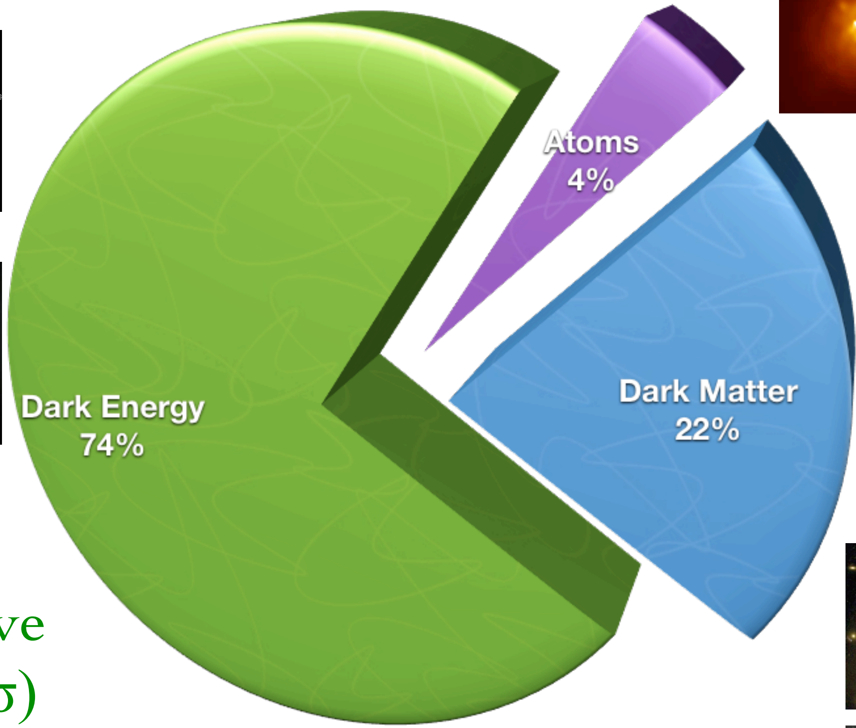
$\Omega_m + \Omega_k + \Omega_\Lambda = 1$

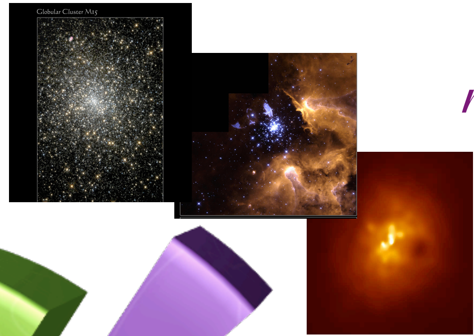




No ***dynamical*** **evidence** of dark energy, e.g. late ISW effect due to negative pressure, seen yet (@ >5σ)

… Is dark energy being faked by inhomogeneity?

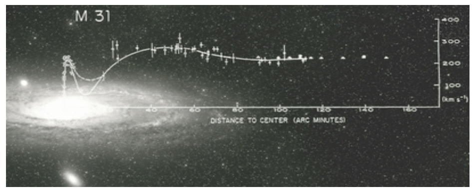




Baryons (but *no* antibaryons)

… the stuff we are made of

Both **geometrical and dynamical evidence found** (assuming GR)



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 $\Omega_B \sim 0.05$

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

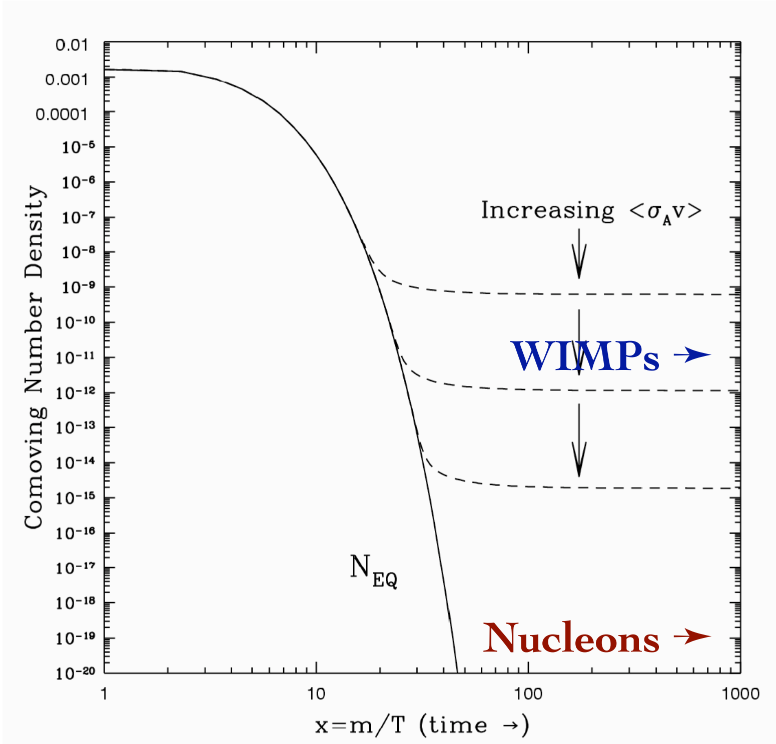
'Freeze-out' occurs when annihilation rate:

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

becomes comparable to the expansion rate

$$H \sim \frac{\sqrt{g}T^2}{M_P}$$ where g = # relativistic d.o.f.

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



$$\frac{n_N}{n_\gamma} = \frac{n_{\bar{N}}}{n_\gamma} \sim 10^{-19}$$ so *need to* 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')?!

Sakharov conditions for baryogenesis:

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

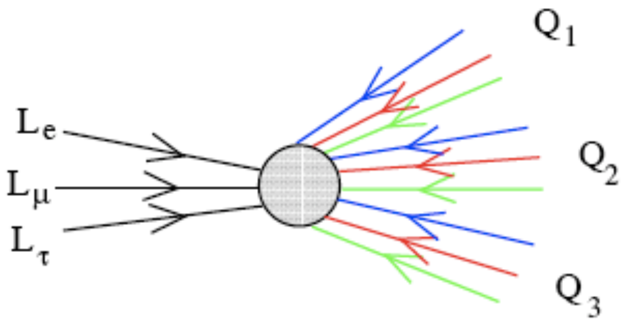
Baryon number violation occurs even in the Standard Model through non-perturbative (sphaleron-mediated) processes … but *CP*-violation is *too weak* (also out-of-equilibrium conditions are not available since the electroweak symmetry breaking phase transition is in fact a 'cross-over')

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

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

Asymmetric baryonic matter



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

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

$\sim 10^{-10}$ for reasonable parameter values

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 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**

… in any case we accept that the only kind of matter which we know certainly *exists* **originated *non*-thermally in the early universe**

What *should* the world be made of ?

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

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

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

… Also true for generic hidden sector matter - 'WIMPless miracle' (Feng & Kumar 2008) since $g_h^2/m_h \sim g_\chi^2/m_\chi \sim F/16\pi^2 M$

But why should the abundance of thermal relics be **comparable** to that of baryons which were born *non*-thermally, with $\Omega_{DM}/\Omega_B \sim 5$?

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 Requires asymmetry	$\Omega_B \sim 10^{-10}$ *cf.* observed $\Omega_B \sim 0.05$
$\Lambda_{\text{Fermi}} \sim G_F^{-1/2}$	Neutralino? Technibaryon?	R-parity? (walking) Technicolour	violated? □ $\tau > 10^{18}$ yr (dim-6 OK)	'Freeze-out' from thermal equilibrium **Asymmetric** (like the *observed* baryons)	$\Omega_{LSP} \sim 0.25$ $\Omega_{LTB} \sim 0.25$

A new particle would *share* in the *B/L* asymmetry if it is charged under a new global *U*(1) symmetry which has a mixed anomaly with the *SU*(2) gauge symmetry (Barr *et al* 1990) **… this can *explain* the ratio of dark to baryonic matter!**

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

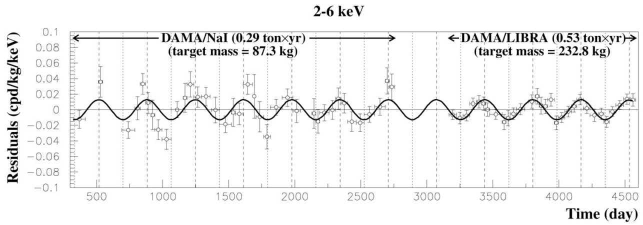
$$\frac{\rho_{\text{DM}}}{\rho_{\text{B}}} \sim \frac{m_{\text{DM}}}{m_{\text{B}}} \left(\frac{m_{\text{DM}}}{m_{\text{B}}}\right)^{3/2} \mathrm{e}^{-m_{\text{DM}}/T_{\text{sphaleron}}} \simeq 5$$

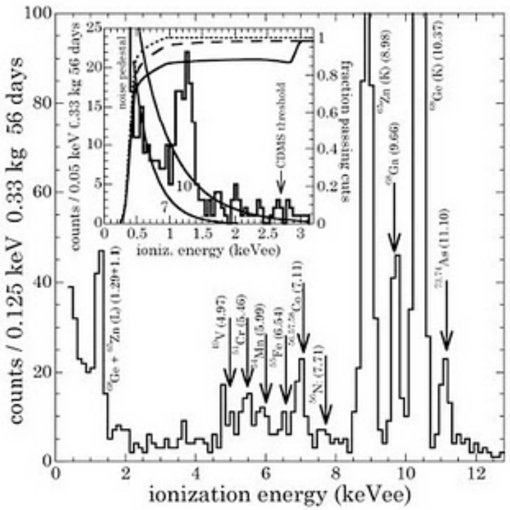
For ~5 GeV mass the required abundance is *even* more natural … and there are candidates (Gelmini *et al* 1987, Raby & West 1987, DB Kaplan 1992, Hooper *et al* 2005, Kitano & Low 2005, DE Kaplan *et al* 2009, Kribs *et al* 2009, Frandsen & Sannino 2010, An *et al* 2010, *etc*)

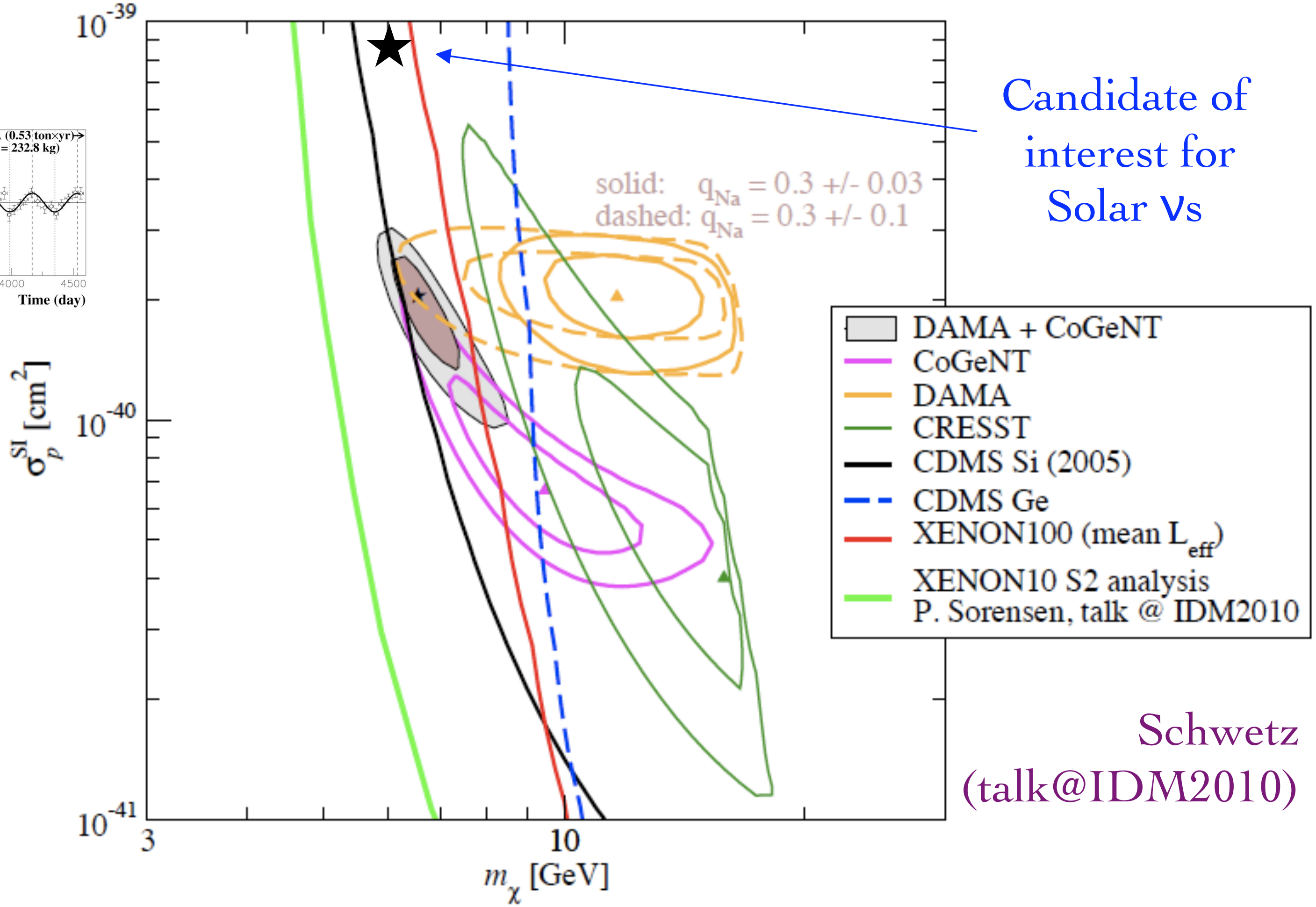
… some with **distinctive collider signatures** (*e.g.* Bai *et al* 2010, Goodman *et al* 2010)

Nuclear recoil detectors are optimised for heavy WIMPs (motivated by SUSY) and have little sensitivity to *low* mass particles ($\Rightarrow O$(keV) recoil energy)

Several experiments have recently reported events close to threshold!



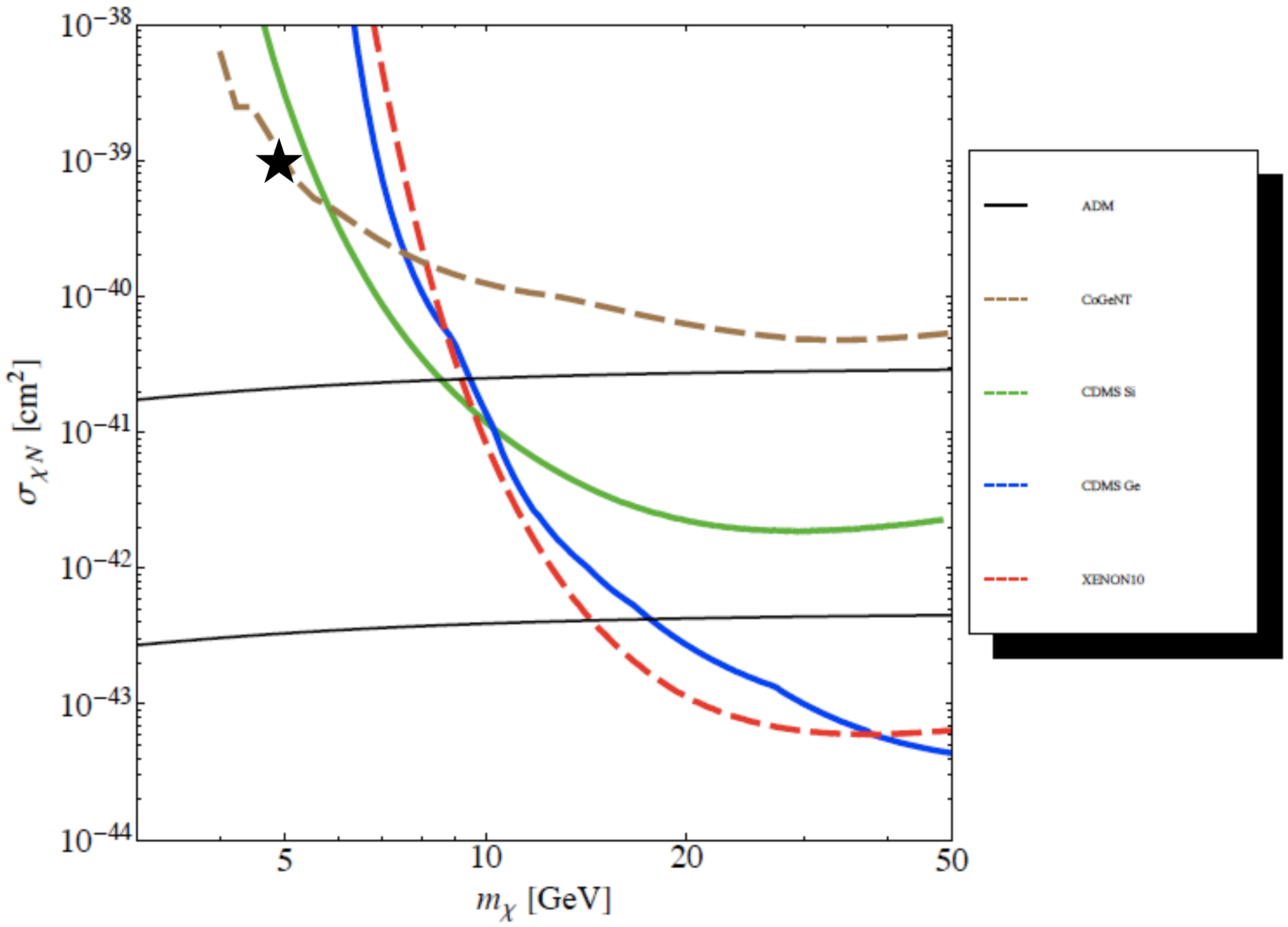




A ~5 GeV dark matter particle may have gone undetected even if its interaction cross-section is as high as ~10^{-39} cm^2

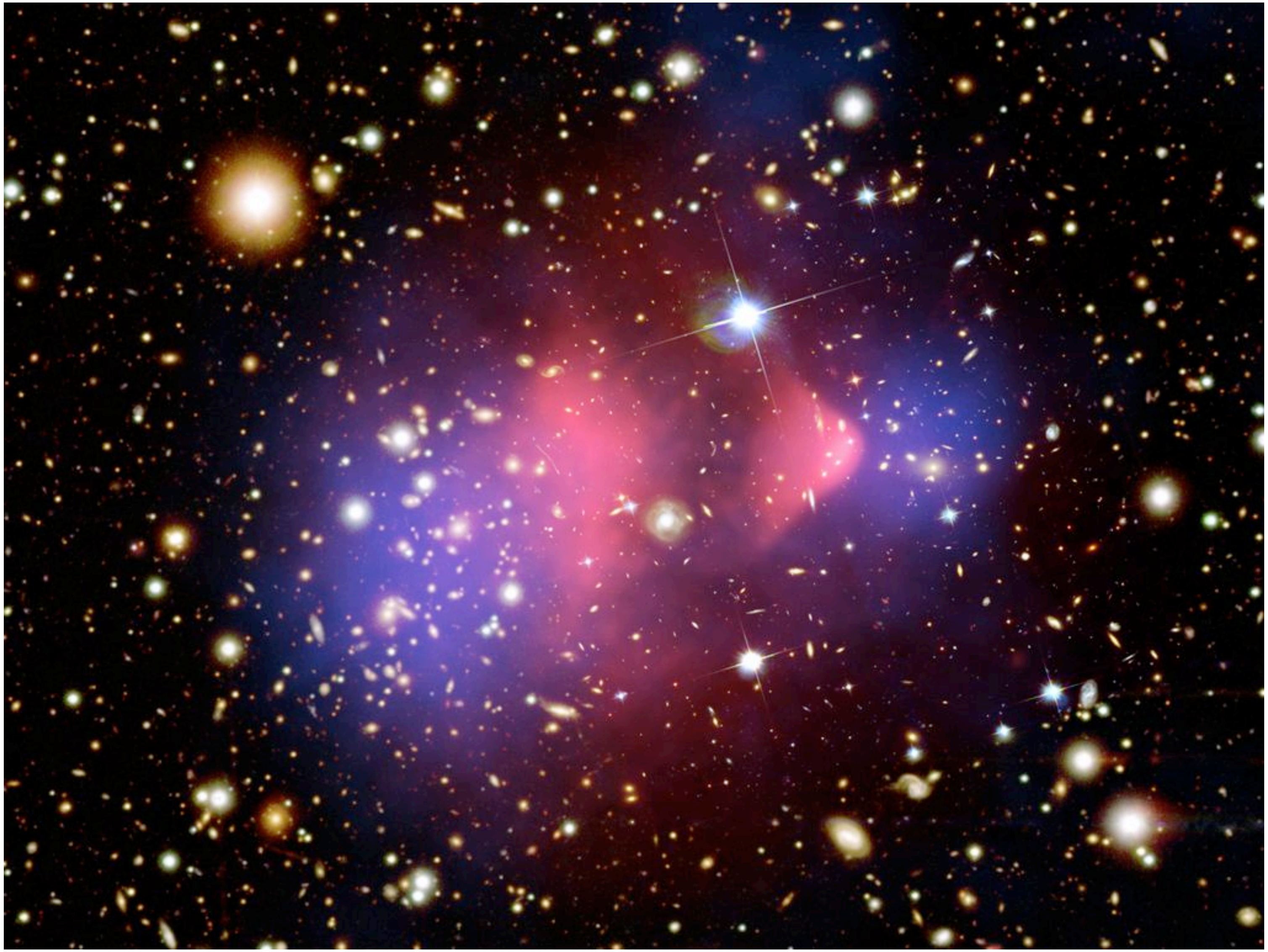
For spin-*dependent* interactions the cross-section can be up to 10^{-36} cm^2

Can get up to ~2 x 10^{-41} cm^2 spin-independent cross-section through Higgs exchange for an 'unbaryon' in walking technicolour (Sannino & Zwicki 2009)



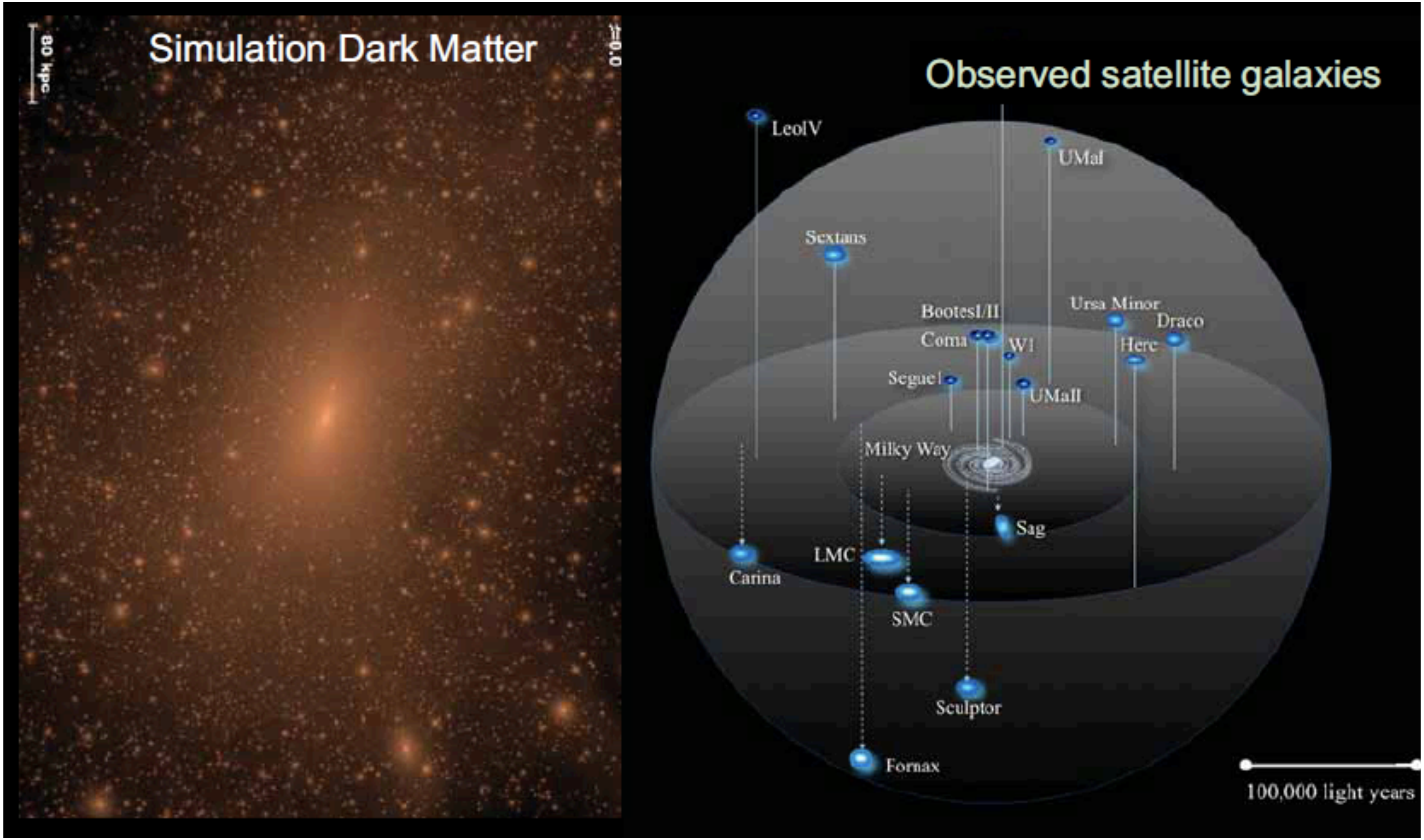
Much larger cross-sections – both SI & SD – can be realised through magnetic moment mediated interactions (Sigurdson *et al* 2006, Gardner 2008, Heo 2009, Masso *et al* 2009, An *et al* 2010, Banks *et al* 2010, Barger *et al* 2010, *etc*)

Such particles would also be naturally **self-interacting** with a typical cross-section: $\sigma_{\chi\chi} \sim \sigma_{nn} (m_n/m_\chi)^2$, where $\sigma_{nn} \sim 10^{-23}$ cm^2



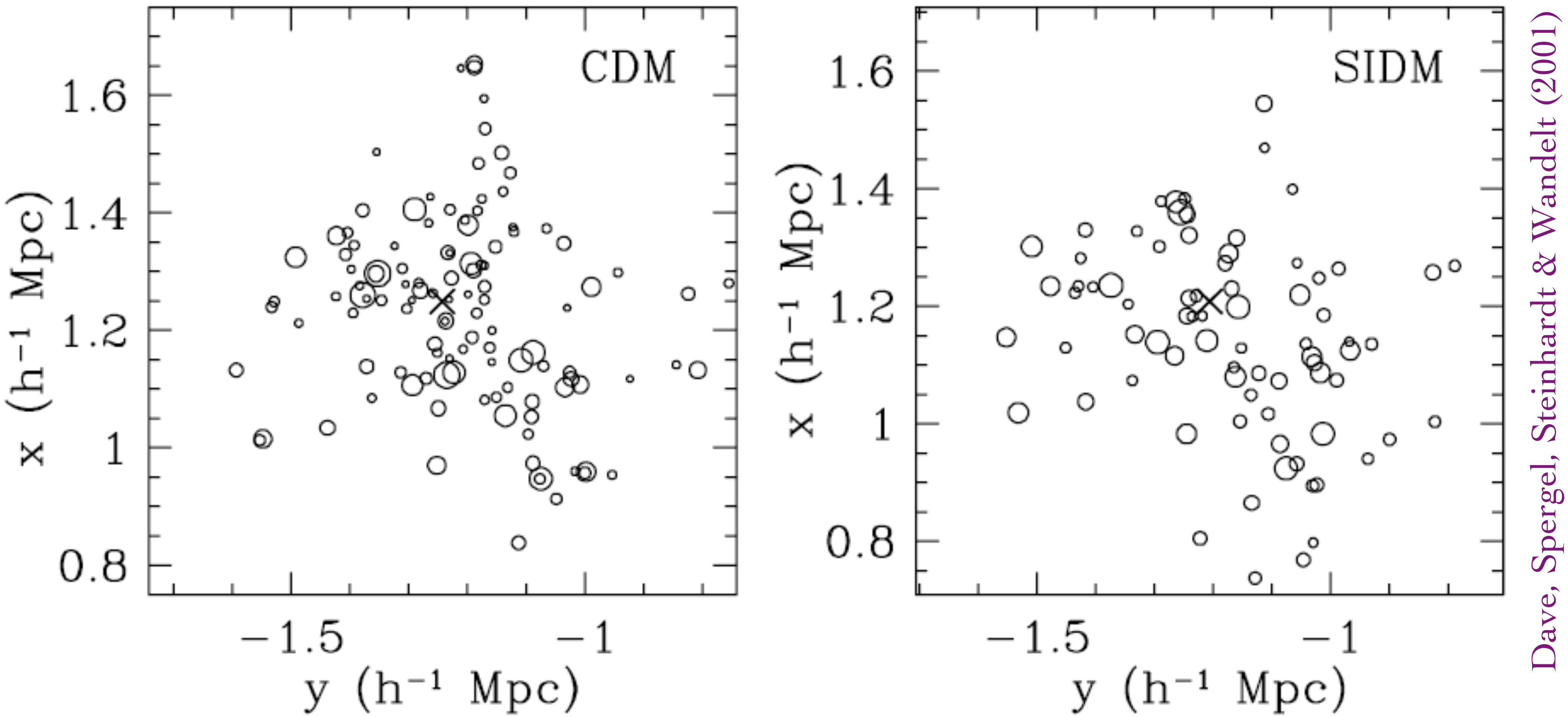
… well below the bound of 2×10^{-24} cm^2/GeV from the 'Bullet cluster'

Self-interacting dark matter was invoked (Spergel & Steinhardt 2000) to reduce excessive substructure in simulations of *collisionless* dark matter …



e.g. the Milky Way has only 25 dwarf galaxies, while ~10^5 are expected

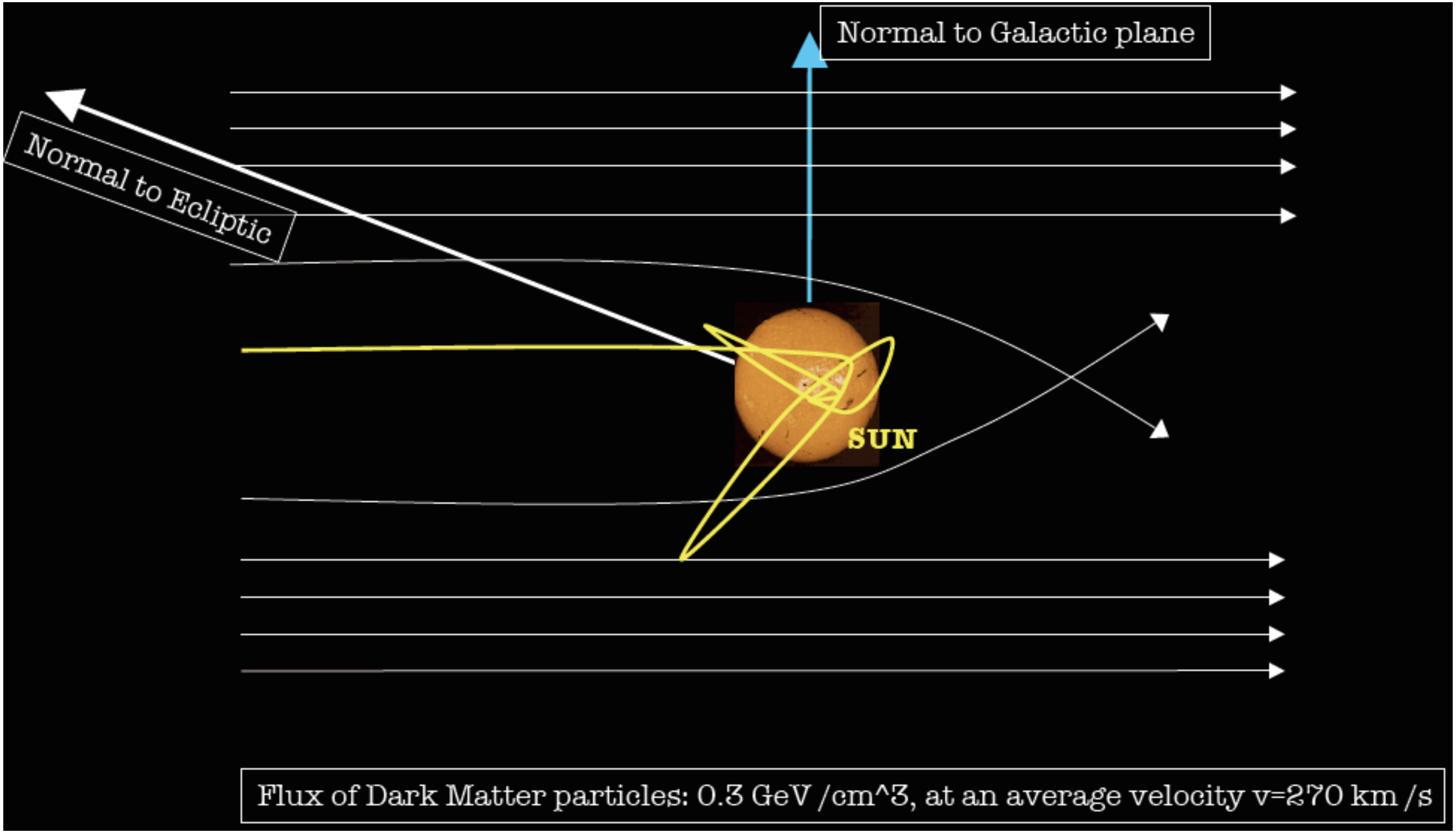
There have been few simulations of *self-interacting* dark matter …



Can be tested through observations of cores *vs.* cusps, halo shape *etc*

Presently we *cannot* require that dark matter must have TeV-scale mass, or be collisionless, or very weakly interacting … or have any annihilation signatures (γ-rays, antiprotons, positrons, neutrinos)!

The Sun has been accreting dark matter particles for ~4.6 x 10^9 yr as it orbits around the Galaxy … these will orbit *inside* affecting energy transport

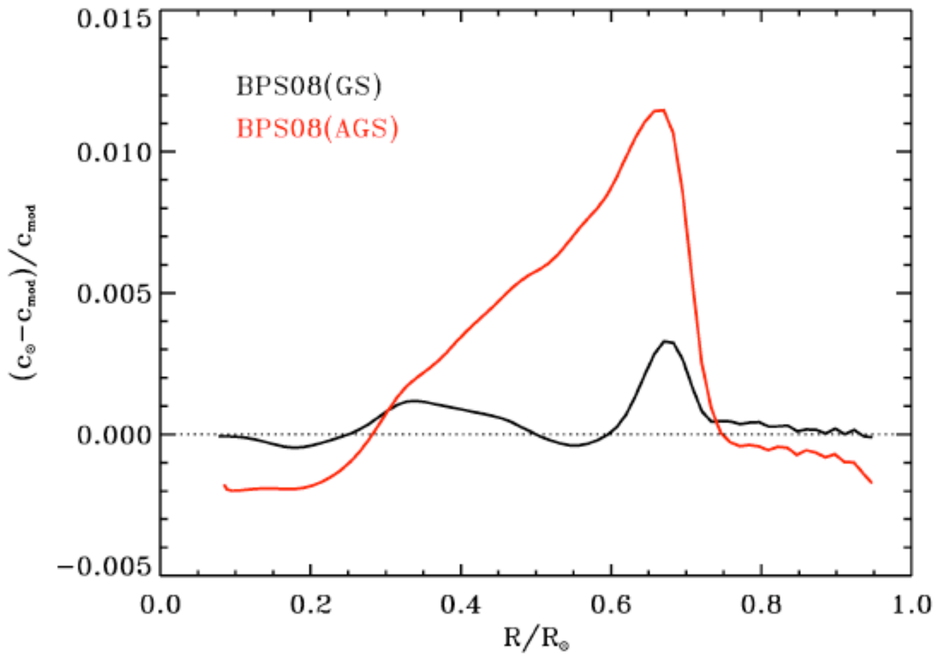


The flux of Solar neutrinos is *very* sensitive to the core temperature and can thus be *reduced* (Steigman *et al* 1978, Faulkner *et al* 1985, Press & Spergel 1985, Gould 1987)

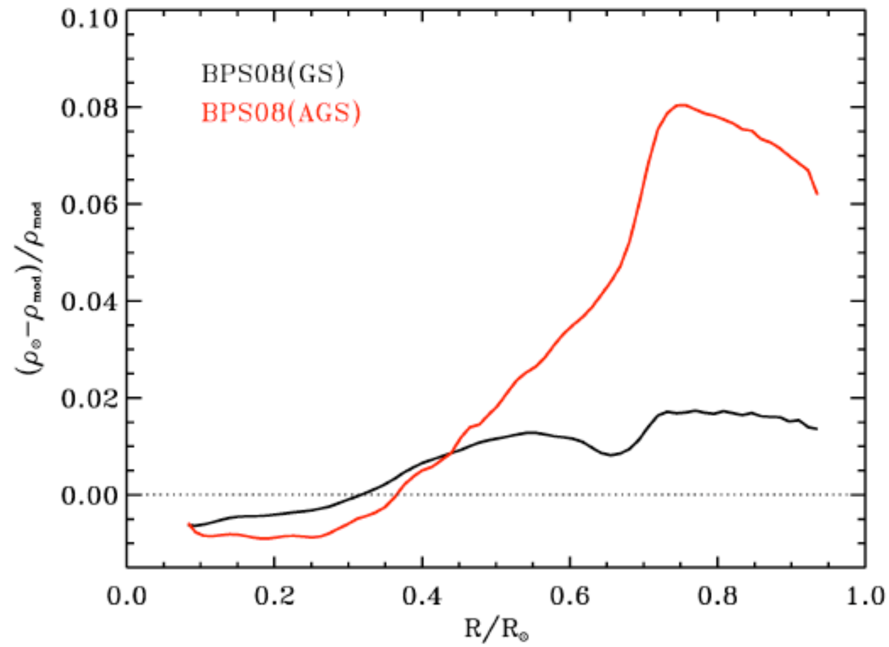
A problem with the standard Solar model

- Asplund, Grevesse & Sauval (2005) have determined new Solar chemical abundances of C, N, O, Ne ('metals') using improved 3D hydrodynamical modeling (tested with many surface spectroscopic observations)
- With these new abundances (30-50% lower metallicity), the previous good agreement between the Standard Solar Model & helioseismology is *broken*

sound speed profile in the Sun



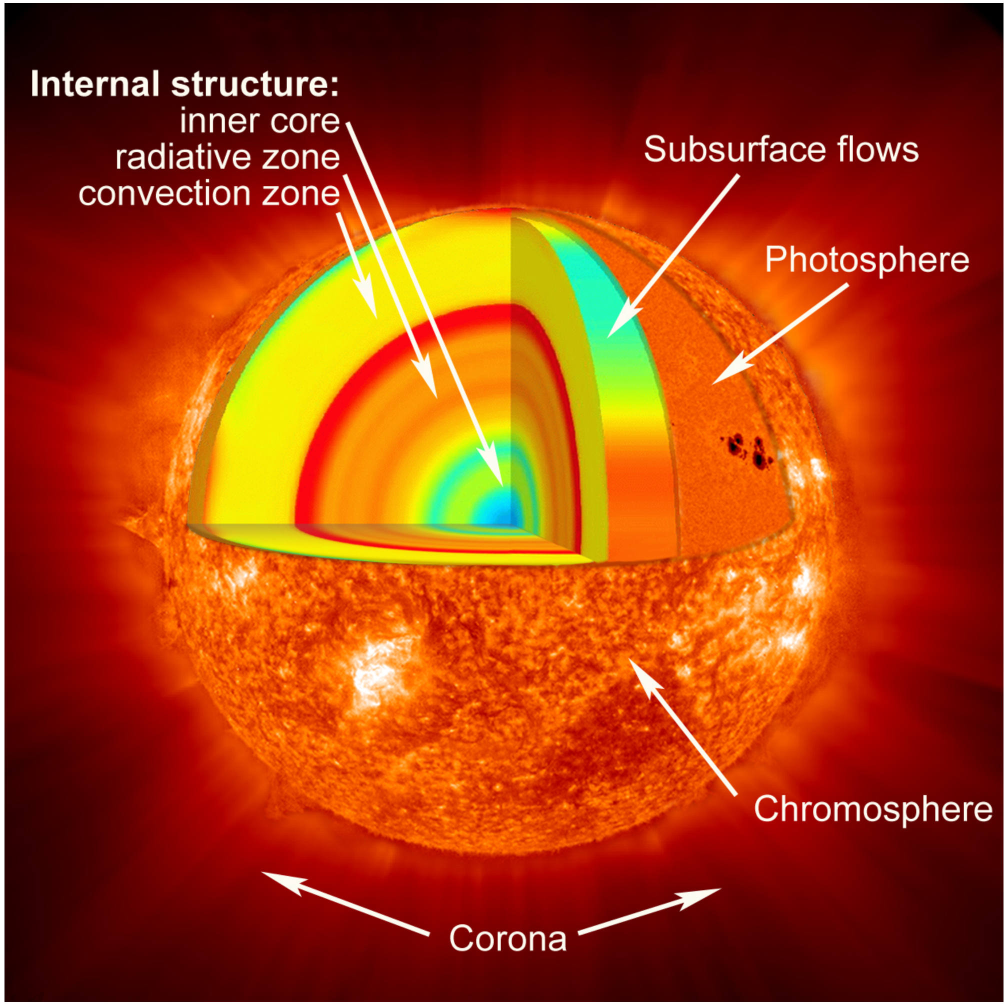
density profile in the Sun



Could light dark matter particles accreted by the Sun solve this problem?

(Villante, talk@TAUP'09, Frandsen & Sarkar 2010)

The particle mass must be ~5-10 GeV to have an effect on energy transport
(too light and they 'evaporate', too heavy and their orbits do not extend out far enough)



Convective zone boundary from helioseismology: $R_{CZ}/R_{\odot} = 0.713 + 0.001$
… too high (by >10σ) in SSM but can be lowered by the required ~1% if

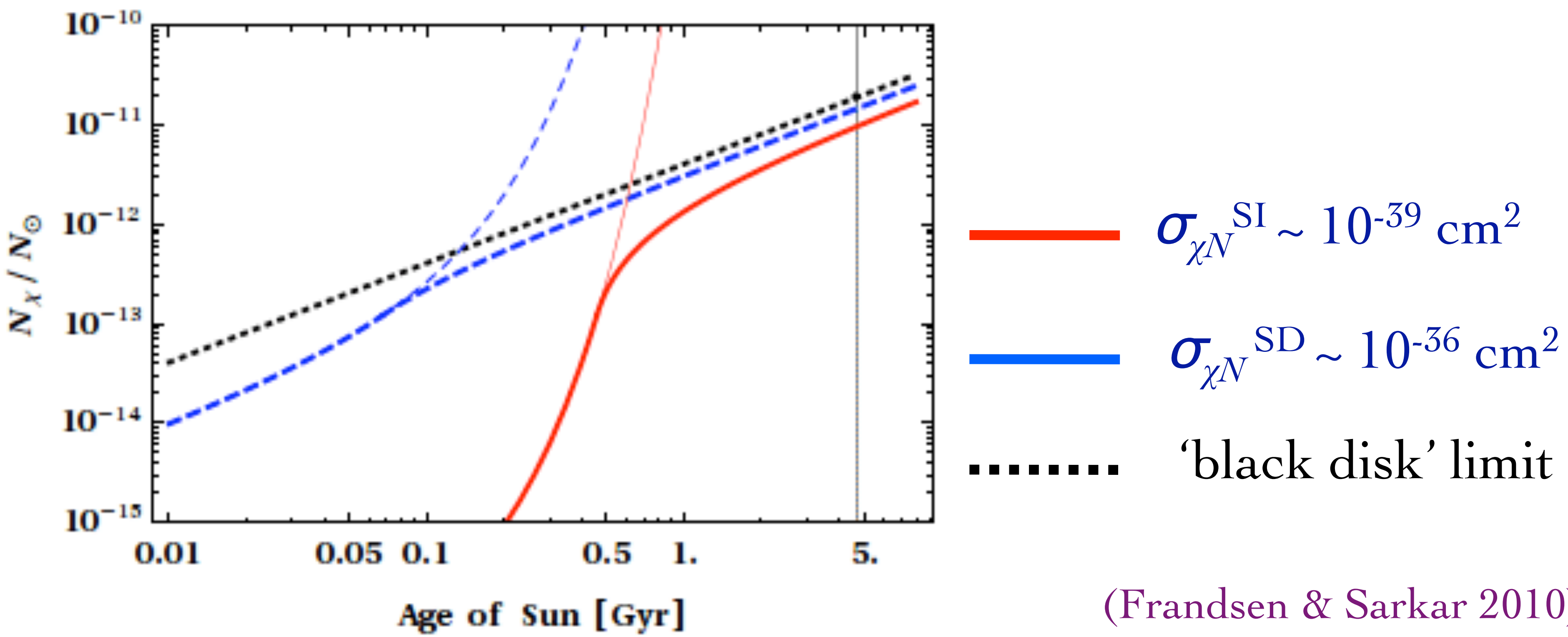
$$(\sigma_{\chi N}/\sigma_{\odot})(N_{\chi}/N_{\odot}) \gtrsim 10^{-14}, \text{ where } \sigma_{\odot} \equiv (m_{N}/M_{\odot})R_{\odot}^{2} \sim 4 \times 10^{-36} \text{ cm}^{2}$$

The abundance of *asymmetric* dark matter is not depleted by annihilation … so grows exponentially (until geometric limit set by Solar radius)

Also self-interactions will *increase* capture rate in the Sun (Zentner 2009)

$$\frac{\mathrm{d}N_\chi}{\mathrm{d}t} = C_{\chi \mathrm{N}} + C_{\chi\chi} N_\chi \quad \Rightarrow \quad N_\chi(t) = \frac{C_{\chi\mathcal{N}}}{C_{\chi\chi}} \left(\mathrm{e}^{C_{\chi\chi} t} - 1\right)$$

Self-capture rate: $C_{\chi\chi} = \sqrt{\frac{3}{2}}\, \rho_{\mathrm{local}}\, s_\chi\, \frac{v_{\mathrm{esc}}^2(R_\odot)}{\bar{v}}\, \langle\phi\rangle\, \frac{\mathrm{erf}(\eta)}{\eta}$

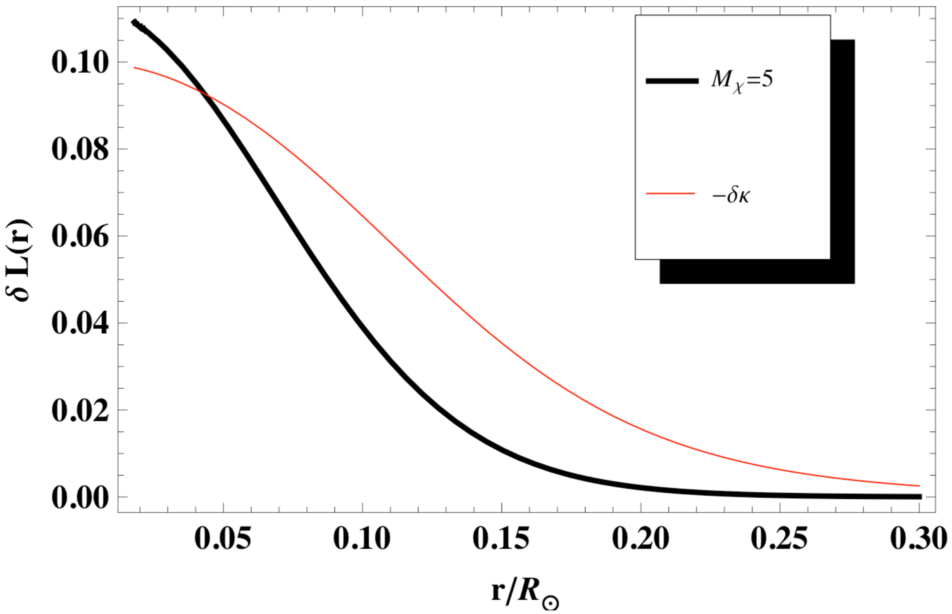


(Frandsen & Sarkar 2010)

ADM will transport heat outward in the Sun: $L_\chi \sim 4 \times 10^{12} L_\odot \frac{N_\chi}{N_\odot} \frac{\sigma_{\chi N}}{\sigma_\odot} \sqrt{\frac{m_N}{m_\chi}}$

… thus affecting the effective opacity : $\delta L(r) \sim -\delta\kappa_\gamma(r) \equiv -\kappa_\chi(r)/\kappa_\gamma(r)$

(Bottino *et al* 2002)



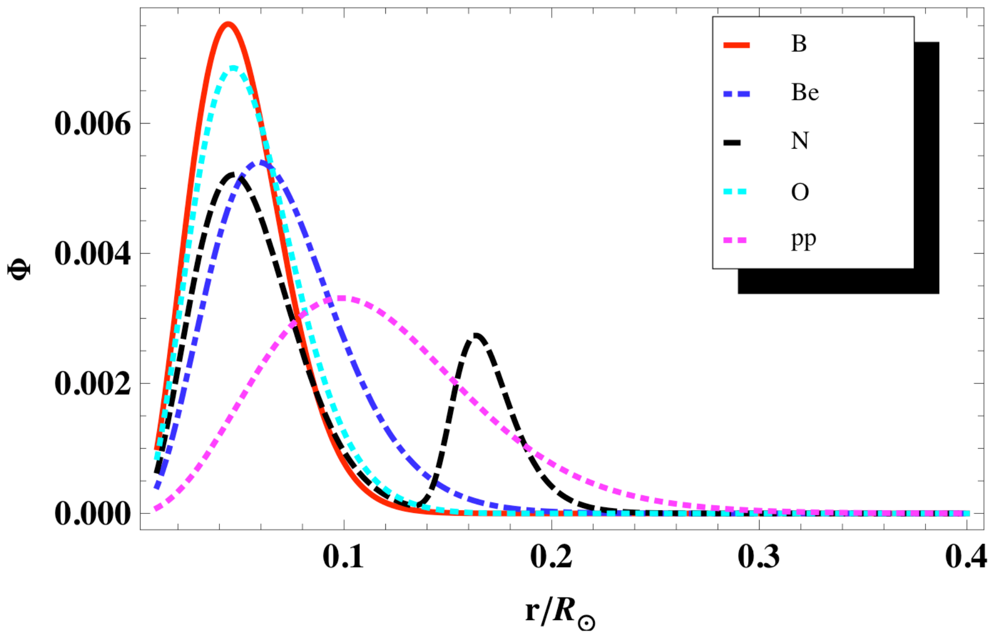
According to the 'Linear Solar model' (Villante & Ricci 2009) a ~10% reduction of the opacity in the core lowers the convective boundary by ~0.7% so will (largely) *restore* agreement with helioseismology

Modification of the luminosity profile will also reduce neutrino fluxes:

$\delta\Phi_B$ = -17%, $\delta\Phi_{Be}$ = -6.7%,

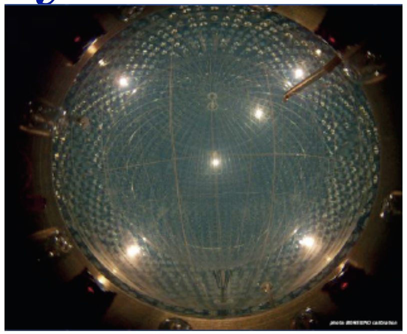
$\delta\Phi_N$ = -10%, $\delta\Phi_O$ = -14%

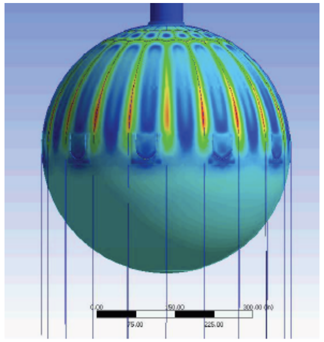
… *testable* by Borexino & SNO$^+$



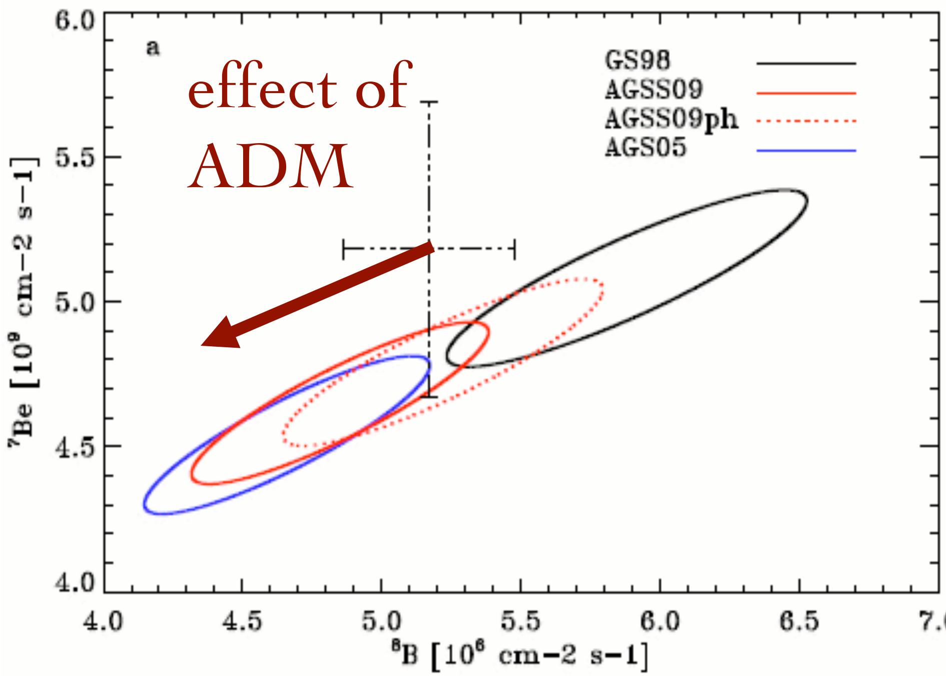
(Frandsen & Sarkar 2010)

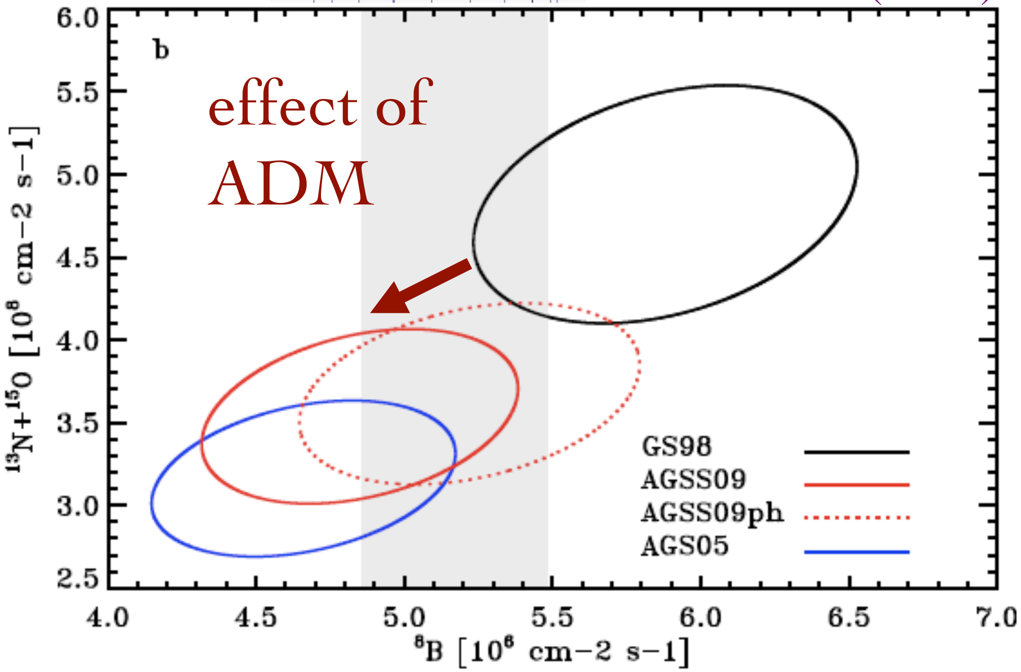
Forthcoming precision measurements of Solar neutrinos by Borexino and SNO⁺ can *test* the model





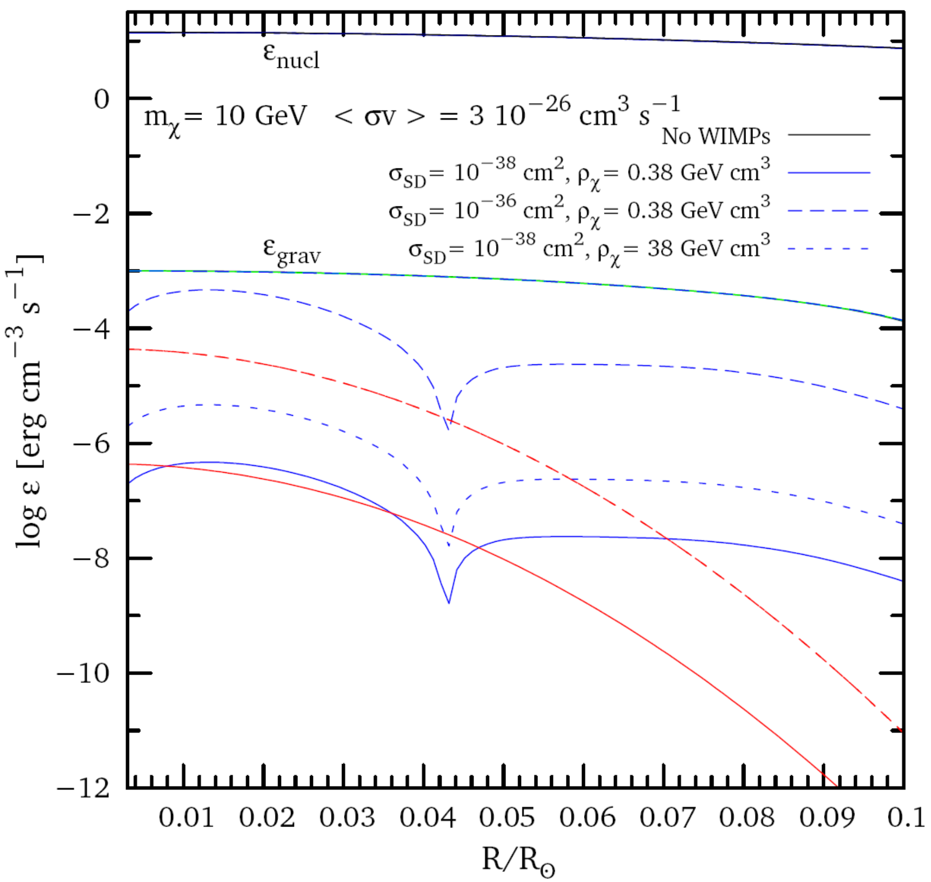
Serenelli (2010)



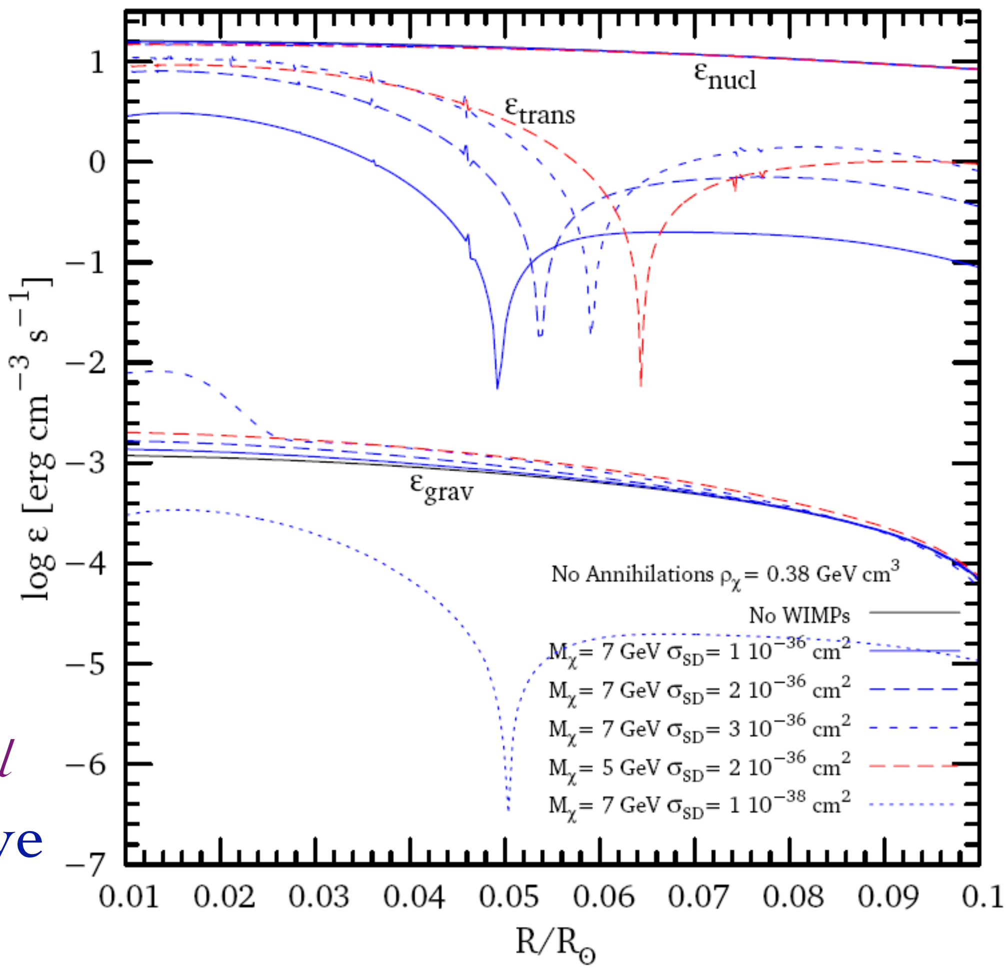


SNO: $\Phi(^8B) = 5.18 \pm 0.29 \times 10^6$ cm^{-2} s^{-1}; **Borexino**: $\Phi(^7Be) = 5.18 \pm 0.51 \times 10^9$ cm^{-2} s^{-1}

Measurement of ^{13}N and ^{15}O fluxes by SNO⁺ will provide additional constraint .. but it may be hard to distinguish between effects of metallicity and dark matter



Using the 'GENEVA code', Taoso *et al* (2010) confirm that the effect on energy transport within the Sun is negligibly small for *annihilating* dark matter



… but can be significant for *asymmetric* dark matter!

However they (also Cumberbatch *et al* 2010) obtain a *smaller* effect than we do from the analytic 'linear Solar model' … this is under investigation

Summary

Asymmetric dark matter is motivated by the observed asymmetry of baryonic matter and the desire to explain why $\Omega_{DM}/\Omega_B \sim \mathcal{O}(1)$

- ~ GeV scale ADM can arise from hidden/mirror/unbaryon sectors

- Such particles are naturally self-interacting

… may solve problems of collisionless CDM on galactic scales

- Direct detection will require $\mathcal{O}$(keV) threshold recoil detectors

… efforts already under way using Xenon, CCDs etc

- Interesting signatures at LHC ('monojets' …)

➢ Large capture rate in Sun ⇒ may solve 'Solar composition problem'

… magnitude of effect is presently disputed (under study)

➢ Can probe through precision measurements of Solar neutrino fluxes

… expect ^{7}Be data soon from Borexino, later ^{13}N + ^{15}O from SNO$^+$

Interesting alternative to dark matter in supersymmetry … experiment will tell!