Asymmetric dark matter

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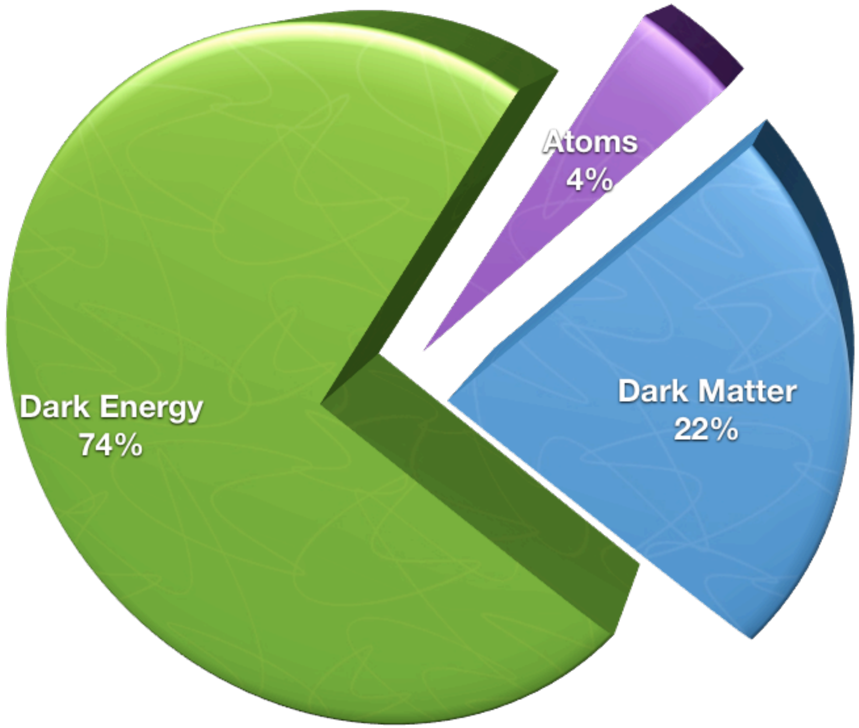
What is the world made of?



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 $\Omega_B \sim 0.05$

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

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

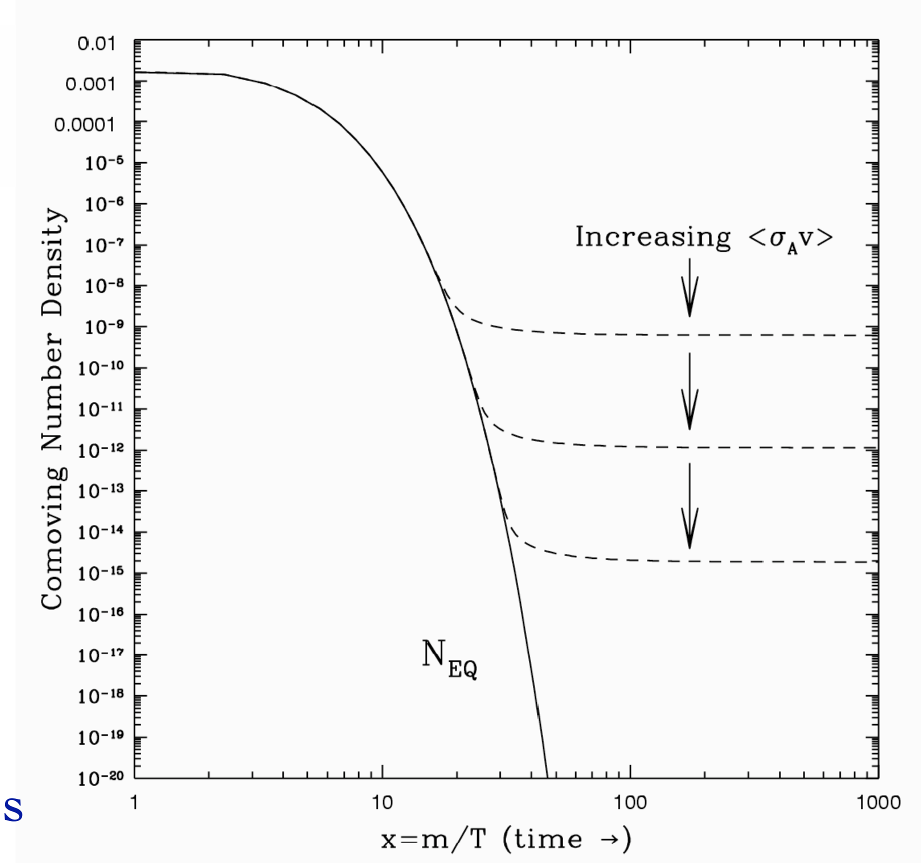
Chemical equilibrium is maintained as long as annihilation rate exceeds the Hubble expansion rate

'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 $T \sim \mathrm{m}_N/45$, 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**: $\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-9}$

Should we not call this the 'baryon disaster'?!

<u>Sakharov conditions for baryogenesis:</u>
1. Baryon number violation
2. *C* and *CP* violation
3. Departure for thermal equilibrium

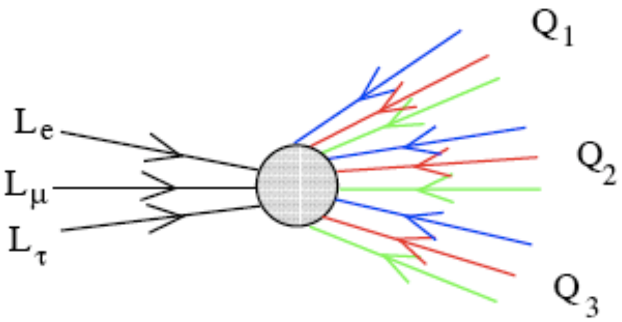
Baryon number violation occurs even in the Standard Model through non-perturbative (sphaleron-mediated) processes … but *CP*-violation is *too weak* (also out-of-equilibrium conditions are not available since the electroweak symmetry breaking phase transition is in fact a 'cross-over')

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

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

Asymmetric baryonic matter



$$
\begin{aligned}
Y_{\Delta B} &= \frac{n_N^{eq}(T \gg M_1)}{s} \sum_\alpha \frac{n_{\ell_\alpha} - n_{\bar{\ell}_\alpha}}{n_N} \times \eta_\alpha \times C \\
&\sim 4 \times 10^{-3} \sum_\alpha \epsilon_{\alpha\alpha} \times \eta_\alpha \times \frac{1}{3}
\end{aligned}
$$

(Courtesey: Sacha Davidson)

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**

… 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 ?

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' is *adequate* to ensure proton stability)	'freeze-out' from thermal equilibrium	$\Omega_{LSP} \sim 0.25$

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

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

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

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? □ $\tau \sim 10^{18}$ yr e^+ excess?!	'Freeze-out' from thermal equilibrium Asymmetric (like the *observed* baryons)	$\Omega_{\text{LSP}} \sim 0.25$ $\Omega_{\text{TB}} \sim 0.25$

A new particle would *share* in the *B*/*L* asymmetry if it is e.g. charged under a new global *U*(1) symmetry which has a mixed anomaly with *SU*(2) gauge symmetry

… 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 (DB Kaplan 1992)

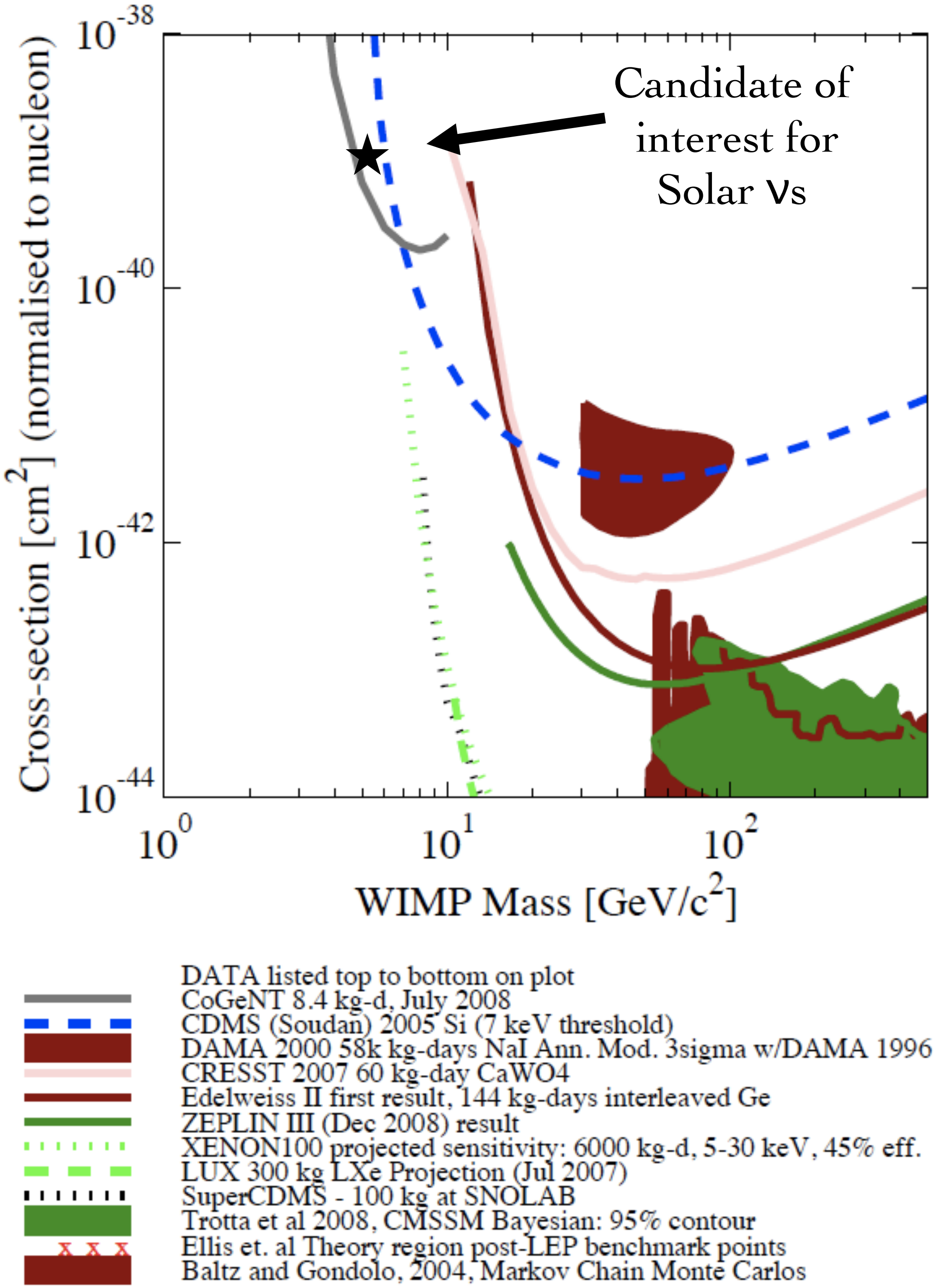
… and there are particle candidates (Hooper *et al* 2005, DE Kaplan *et al* 2009, Kribs *et al* 2009, Frandsen & Sannino 2010, An *et al* 2010) with collider signatures

Experiments to directly detect dark matter through nuclear recoil are optimised for heavy WIMPs (motivated by SUSY) … they have little sensitivity for low mass particles $\Rightarrow$ O(keV) recoil energy

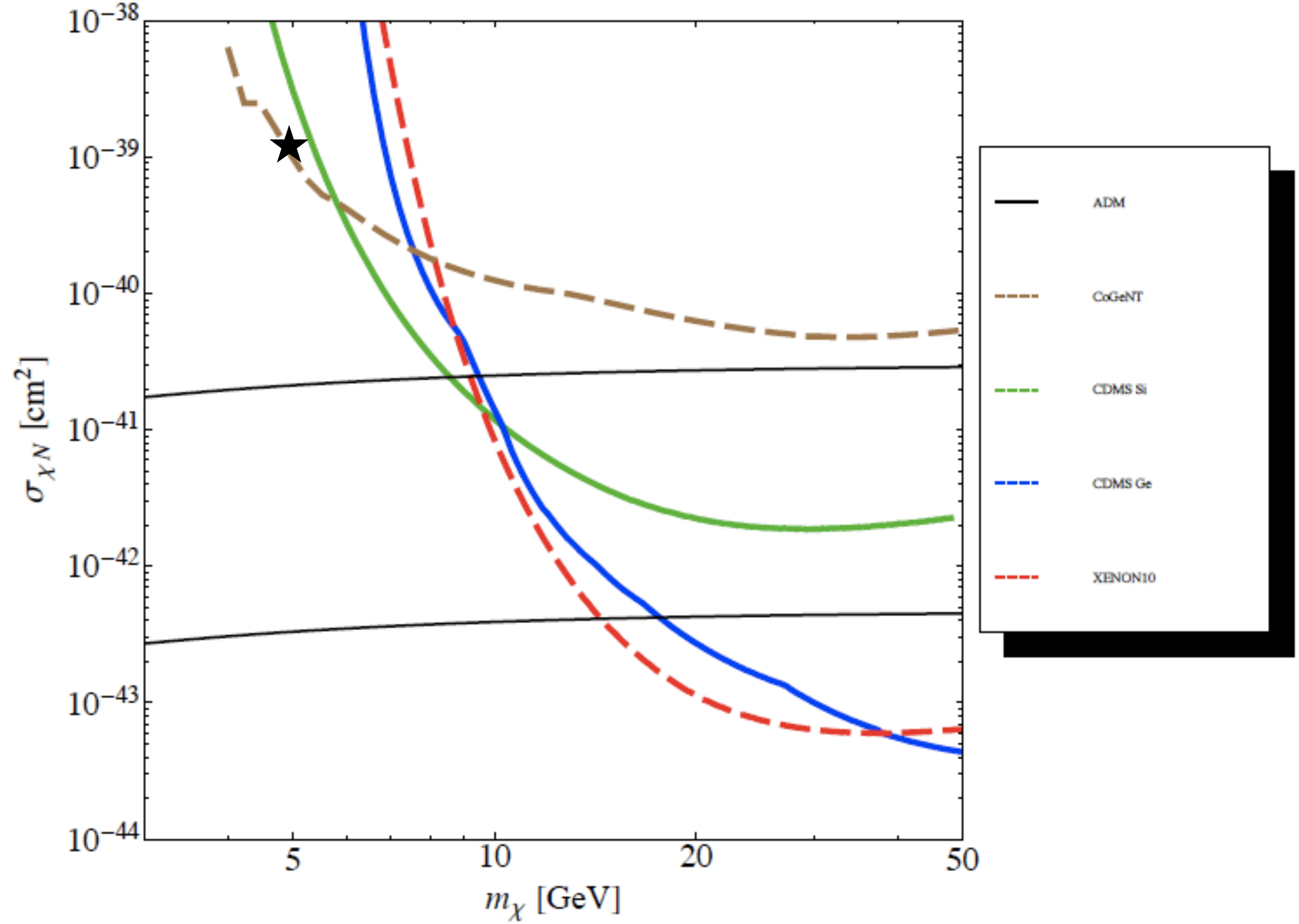
A ~5 GeV dark matter particle would have gone undetected even if its interaction cross-section is as high as ~10^{-39} cm^2

… for spin-dependent interactions the cross-section can be as high as ~10^{-36} cm^2

To detect such particles will require *low* threshold detectors



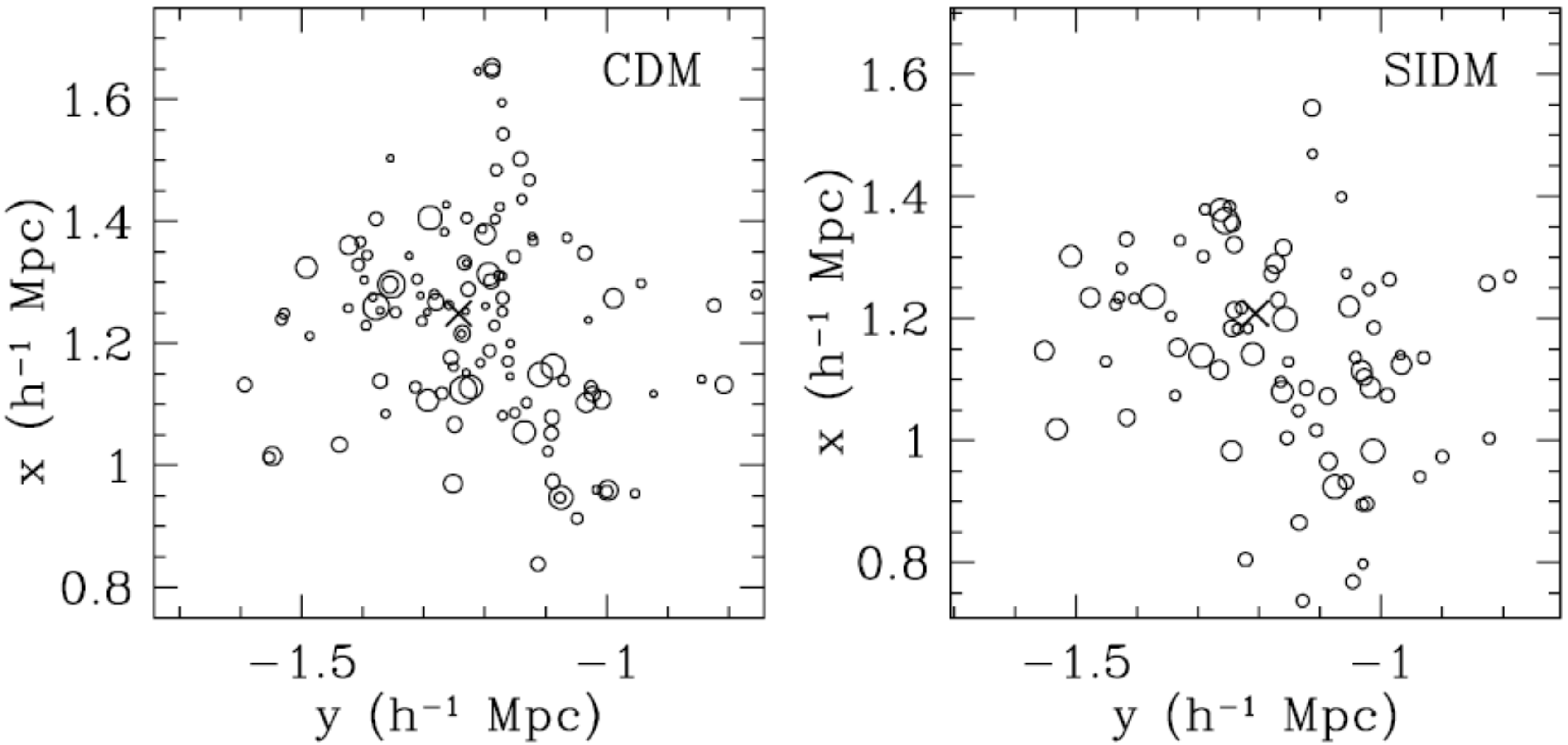
Can get up to ~2 x 10^{-41} cm^2 cross-section through Higgs exchange for an 'unbaryon' in walking technicolour (Sannino & Zwicki 2009)



Larger cross-sections – both SI & SD – can be realised through magnetic moment mediated interactions (An, Chen, Mohapatra, Nussinov & Zhang 2010)

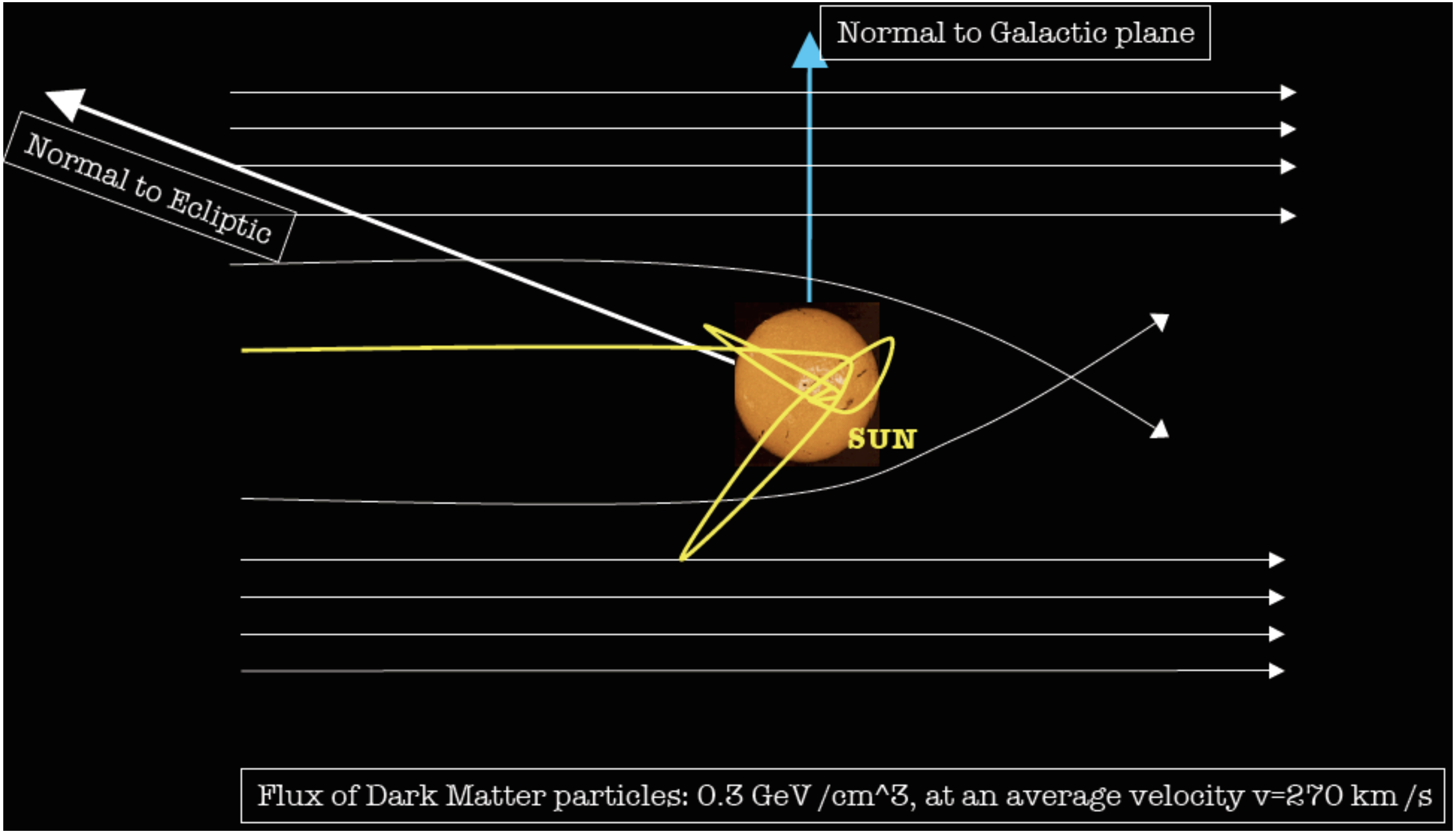
Such particles would also be naturally **self-interacting** with a typical cross-section: $\sigma_{\chi\chi} \sim \sigma_{nn}\,(m_\chi/m_n)^2$, where $\sigma_{nn} \sim 10^{-23}$ cm^2 … this is well below the bound of 2×10^{-24} cm^2/GeV from the colliding 'Bullet cluster'

Self-interactions for dark matter was invoked (Spergel & Steinhardt 2000) to reduce the expected substructure in simulations of collisionless dark matter … which are in disagreement with observations



Dave, Spergel, Steinhardt & Wandelt (2001)

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

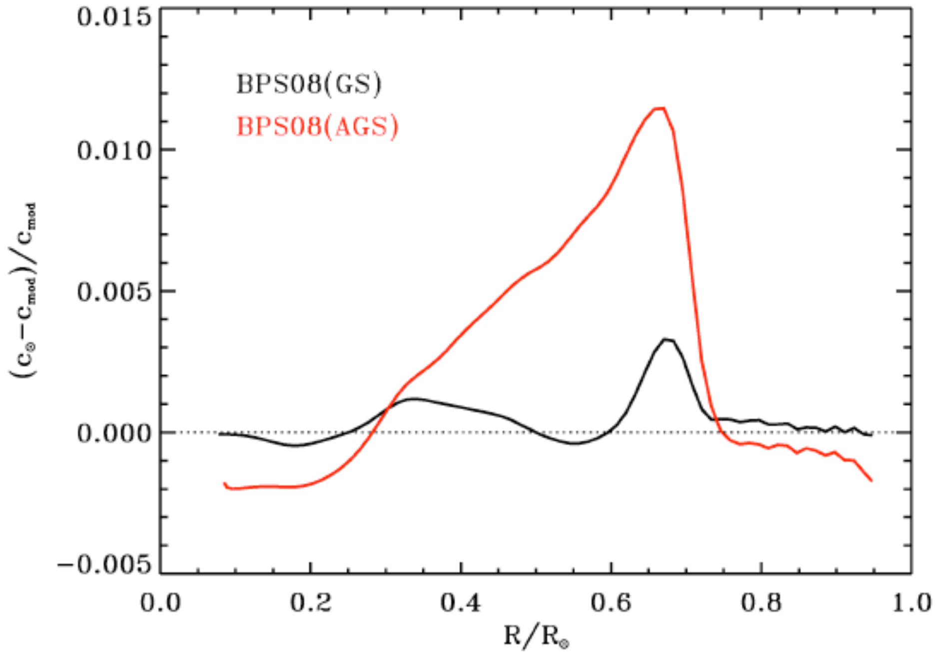


The flux of Solar neutrinos is *very* sensitive to the core temperature and can thus be affected (Faulkner *et al* 1985, Press & Spergel 1985, Gould 1987)

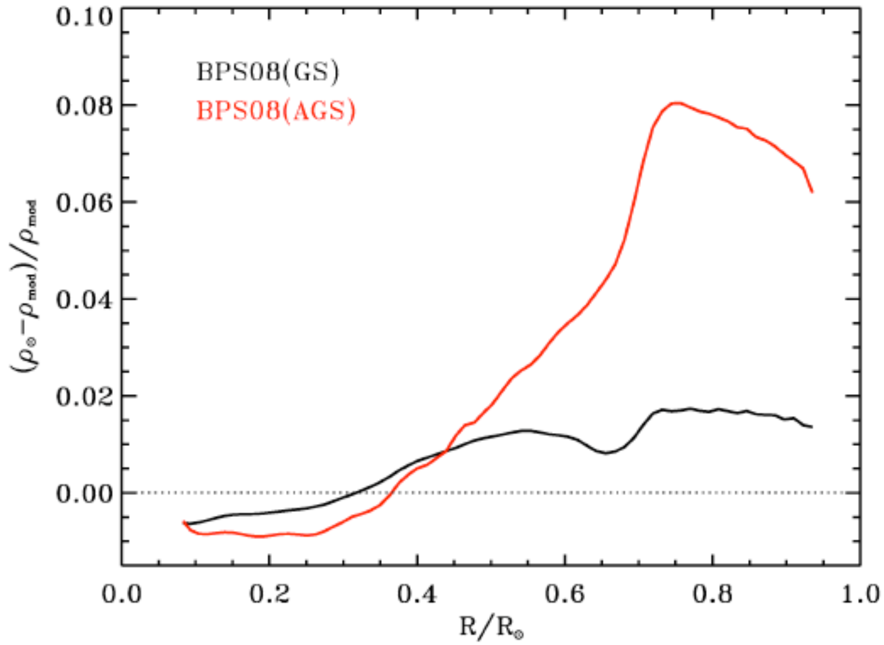
A problem with the standard Solar model

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

sound speed profile in the Sun



density profile in the Sun



Could light WIMPs in the Sun alter the heat transport and solve this problem?

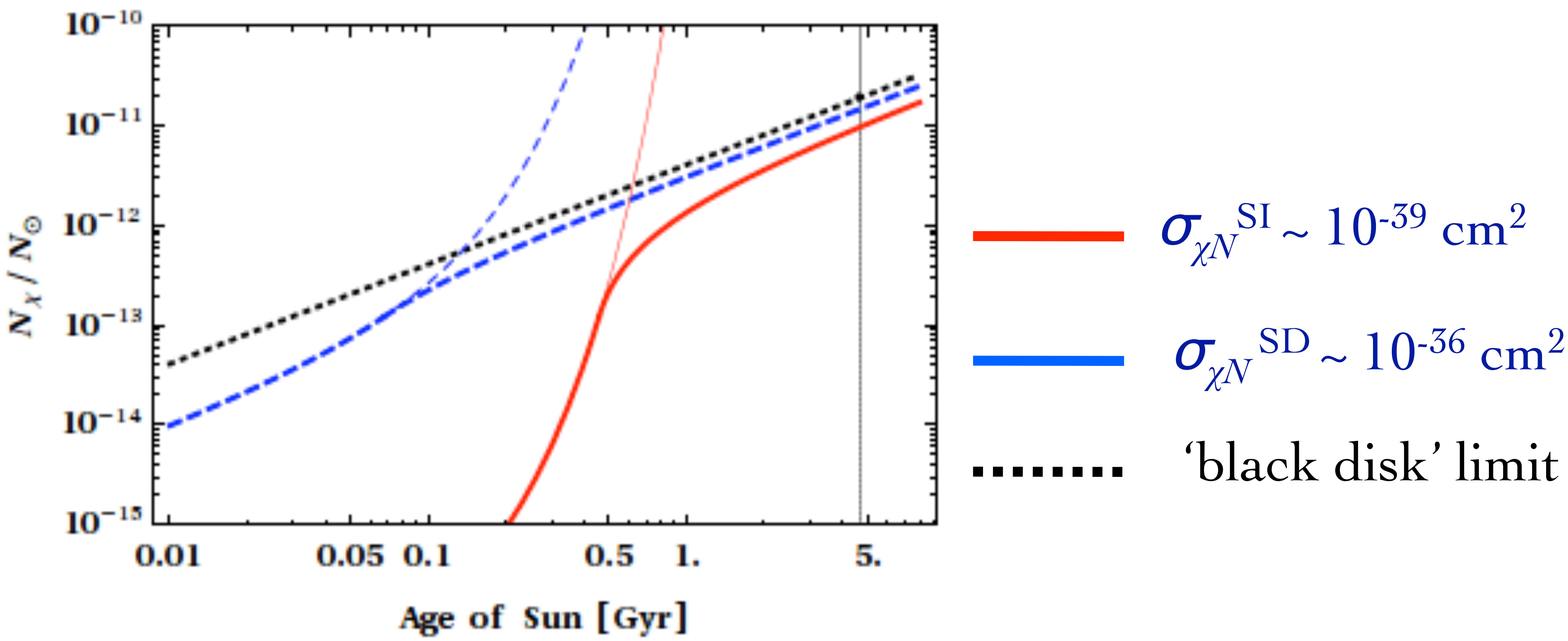
(Villante, TAUP'09)

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

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

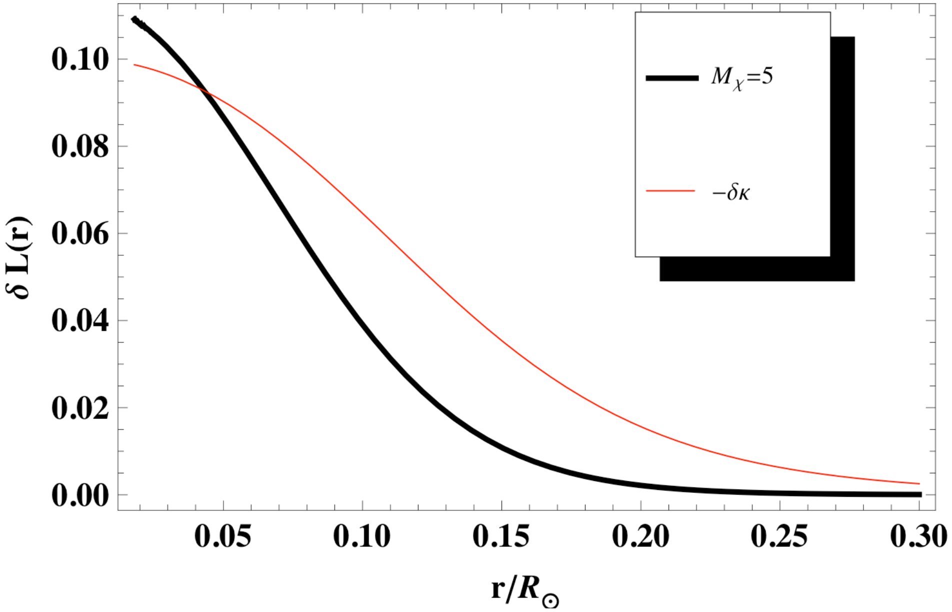
$$\frac{\mathrm{d}N_\chi}{\mathrm{d}t} = C_{\chi\mathrm{N}} + C_{\chi\chi} N_\chi \quad \Rightarrow \quad N_\chi(t) = \frac{C_{\chi\mathcal{N}}}{C_{\chi\chi}} \left(\mathrm{e}^{C_{\chi\chi} t} - 1\right)$$

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

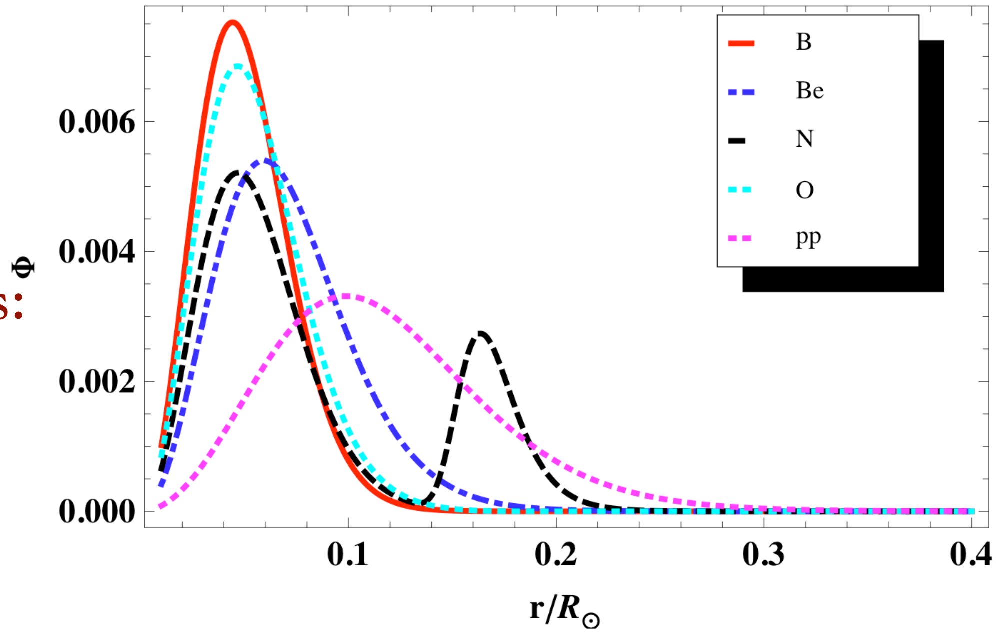


ADM will transport heat outward in the Sun: $L_\chi \sim 4\times 10^{12} L_\odot \frac{N_\chi}{N_\odot}\frac{\sigma_{\chi N}}{\sigma_\odot}\sqrt{\frac{m_N}{m_\chi}}$

… thus affecting the effective opacity : $\delta L(r) \sim -\delta\kappa_\gamma(r) \equiv -\kappa_\chi(r)/\kappa_\gamma(r)$
(Bottino *et al* 2002)

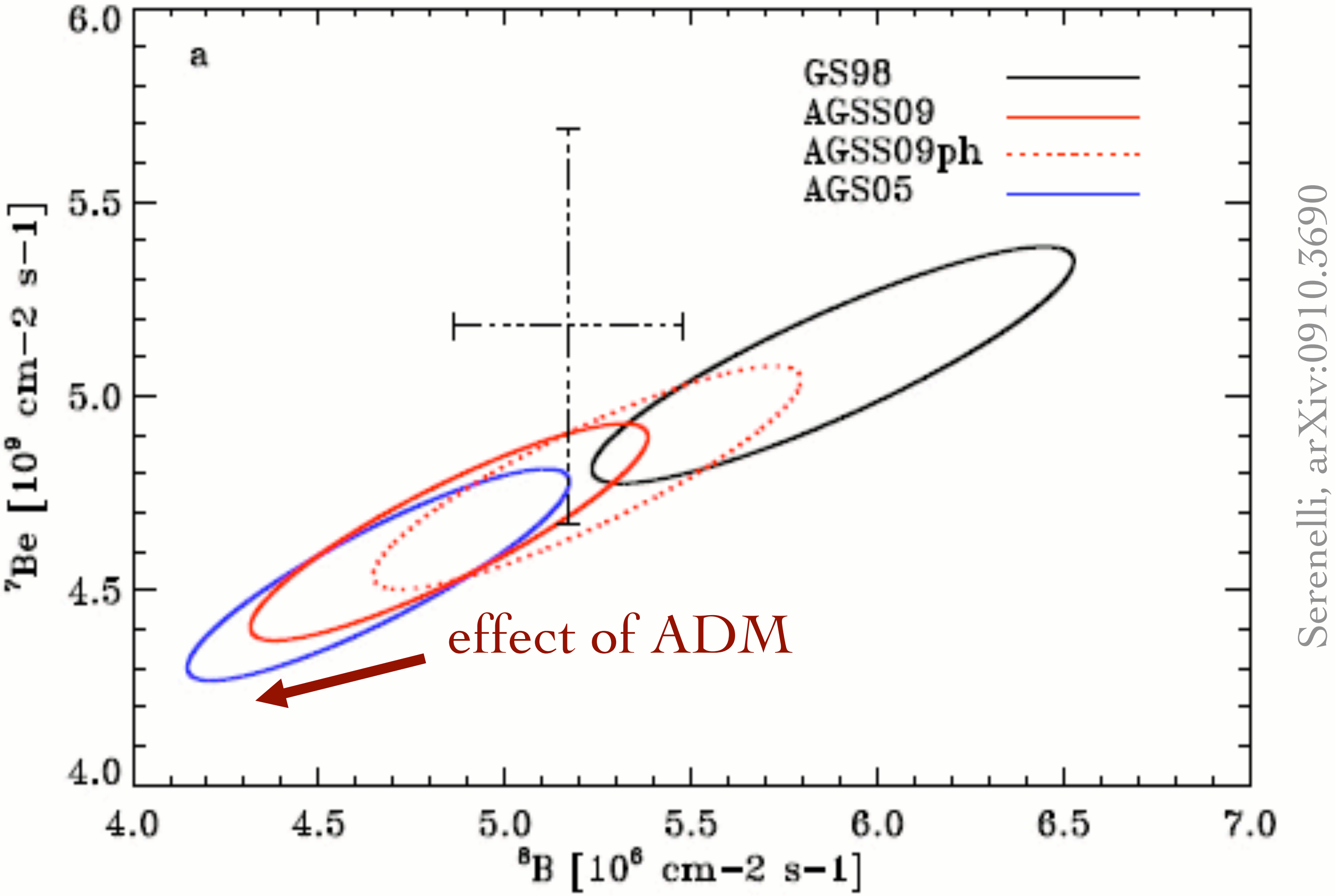


According to the 'Linear Solar model' (Villante & Ricci 2009) a ~10% reduction of the opacity in the core reduces the convective boundary by ~0.7% and *restores* agreement with helioseismology



Modification of the luminosity profile will reduce neutrino fluxes: $\delta\Phi_B$ = -17%, $\delta\Phi_{Be}$ = -6.7%, $\delta\Phi_N$ = -10%, $\delta\Phi_O$ = -14% … *testable* by Borexino & SNO$^+$

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



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

Summary

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

- ~ GeV scale ADM can arise from hidden/mirror/unbaryon sectors (~TeV scale ADM natural in technicolour models for EWSB)

- ~GeV scale ADM is naturally strongly self-interacting … may solve problems for collisionless CDM on Kpc-Mpc scales

- Direct detection will require O(keV) threshold recoil detectors

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

- Can probe through precision measurements of Solar neutrino fluxes

The idea is speculative but eminently falsifiable