Probing (Asymmetric) dark matter with Solar neutrino fluxes

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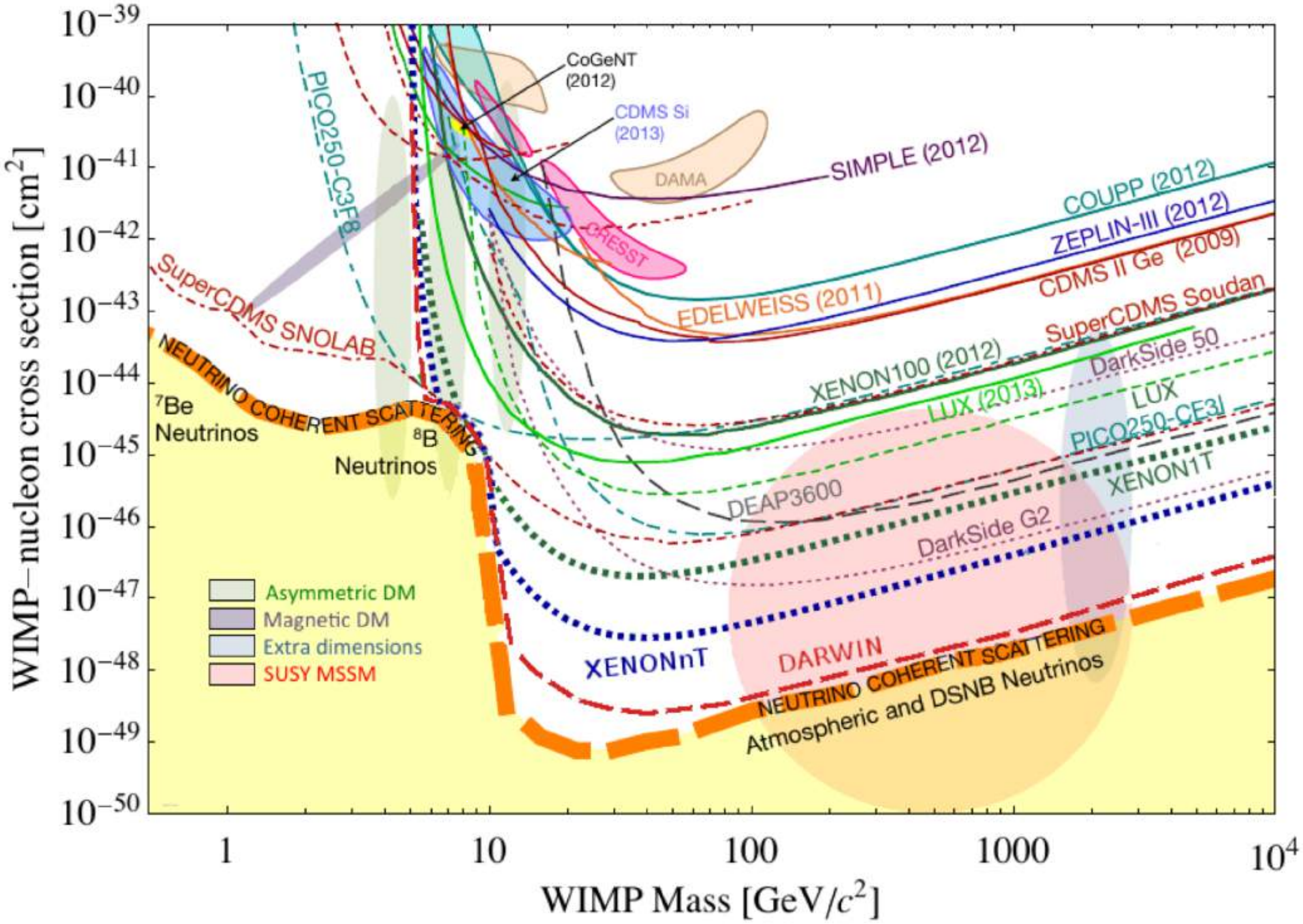
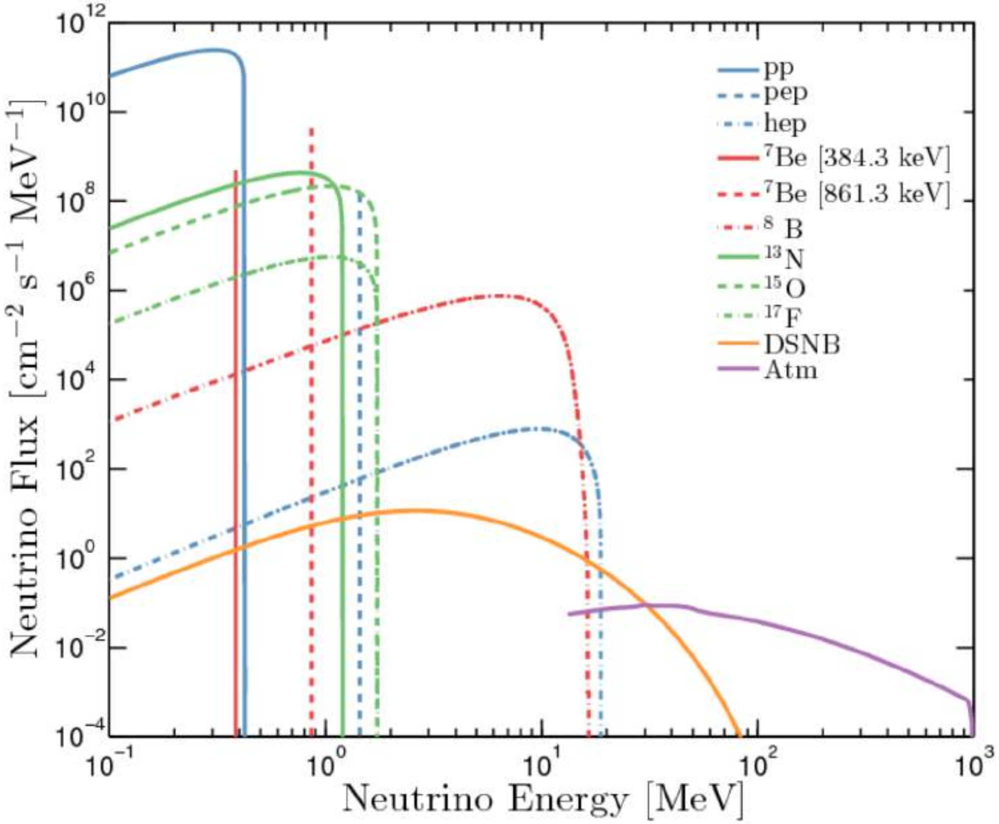
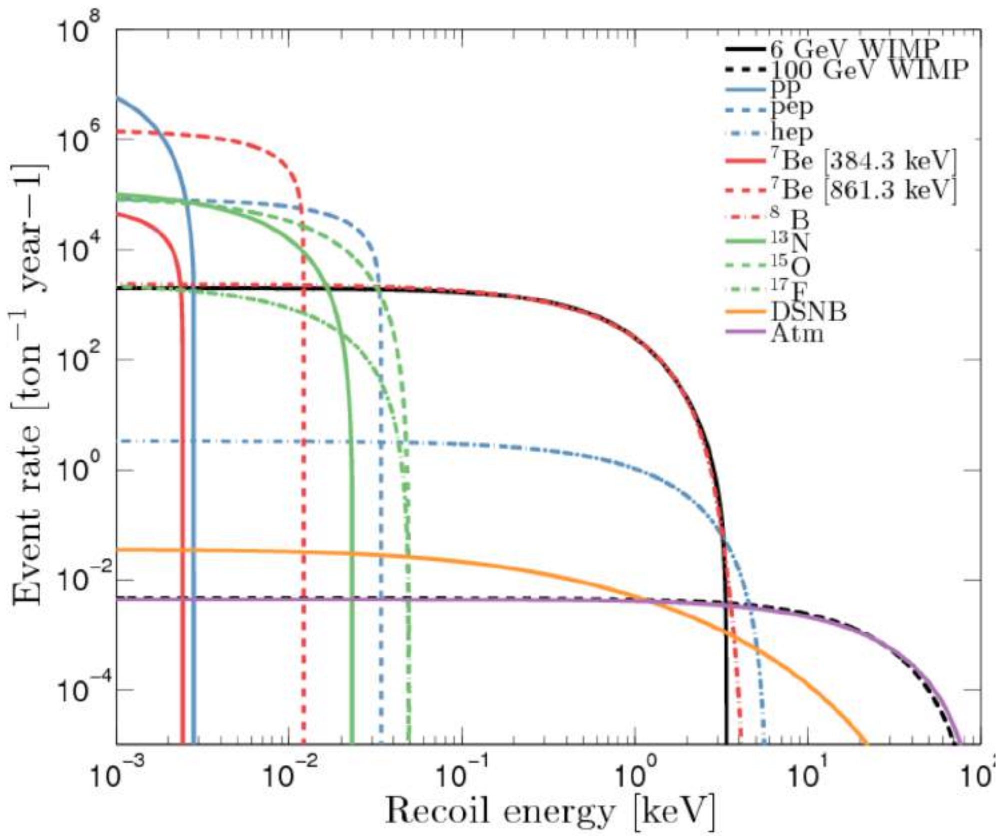


CDM-18 Programme, KITP Santa Barbara, 24 April 2018

Solar & atmospheric neutrino spectra that are backgrounds to direct detection experiments



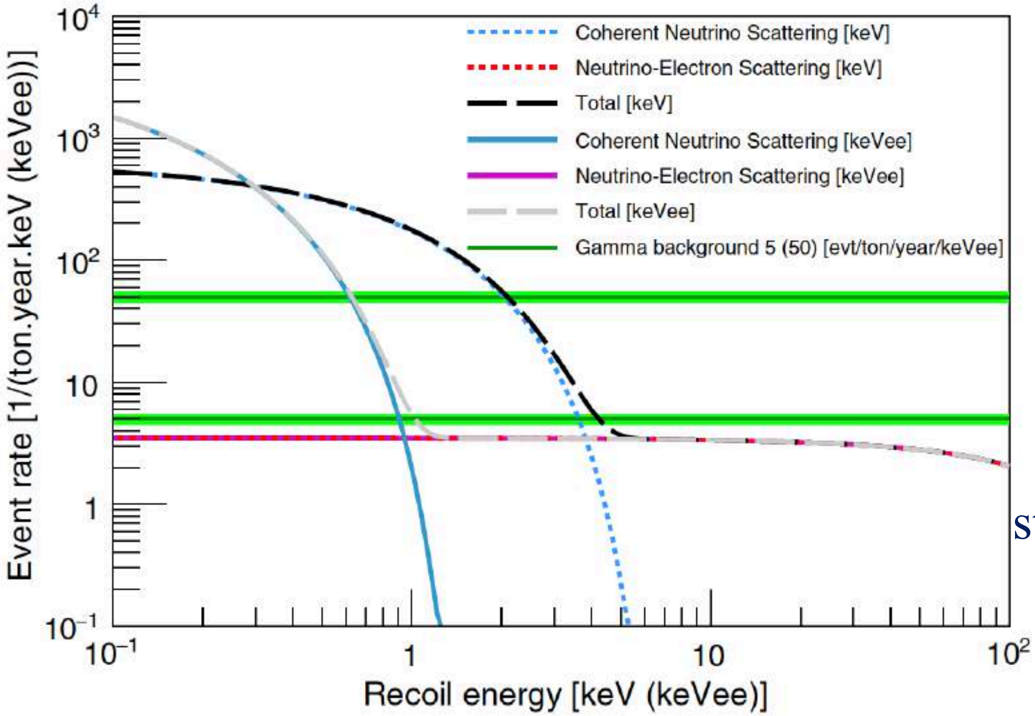
Solar, atmospheric, and the diffuse supernova background. The Solar neutrino fluxes are normalised to the high metallicity standard Solar model. The atmospheric neutrino spectrum is the sum of contributions from electrons, anti-electrons, muons and anti-muons. The diffuse supernova background is the sum of 3 different neutrino temperatures, 3, 5 and 8 MeV.



Xenon scattering event rate as a function of recoil energy for each type of neutrino as well as a 6 GeV WIMP with $\sigma_{\chi-n}$=5×10^{-45} cm^2 (solid black line) and a 100 GeV WIMP with $\sigma_{\chi-n}$=2.5×10^{-49}cm^2 (dashed black line) to show how they overlap with ^{8}B and atmospheric neutrino induced recoils respectively.

O'Hare, Phys.Rev.D**94**:063527,2016

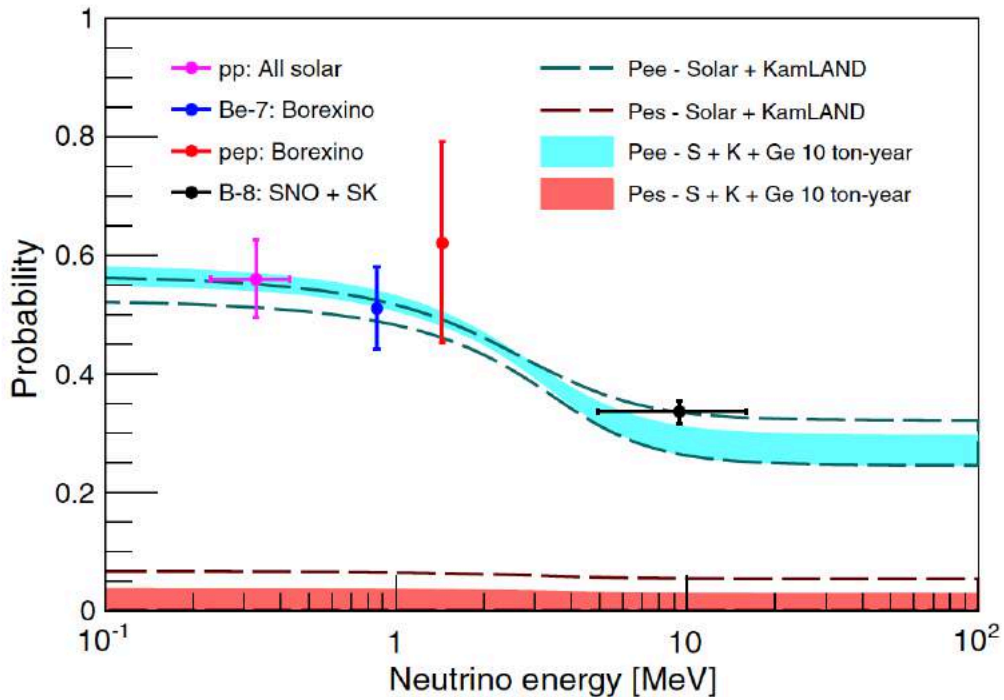
Solar neutrino physics with low-threshold dark matter detectors



Neutrino induced backgrounds in a low threshold Ge dark matter detector as a function of true kinetic energy of the recoil (keV) and ionisation energy (keVee). The ^{8}B induced nuclear recoils (CNS) and the pp induced electronic recoils (ES) are shown as the blue solid and red dashed lines. These event rates have been computed using the high metallicity standard solar model, $P_{ee} = 0.55$ for pp neutrinos and $P_{es} = 0$ at all neutrino energies.Also shown in green is a residual gamma background.

Billard *et al*, PR D**91**:095023,2015

Contours at 95% C.L. on the electron neutrino survival probability P_{ee} (cyan) and transition probability into a sterile neutrino P_{es} (red) as a function of the neutrino energy. The two sets of bands correspond to the case Solar + KamLAND (dashed lines) and to the case Solar + KamLAND + CNS + ES with a background free 10 ton-year exposure (filled contours). Also shown are current constraints on the neutrino-electron survival probability derived assuming no sterile neutrinos.



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 $\Omega_B \sim 0.05$

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

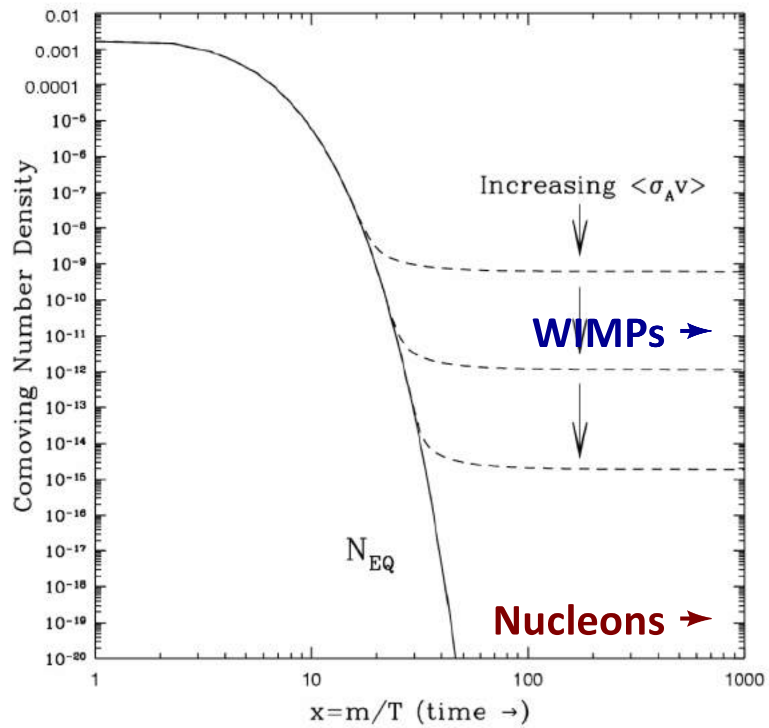
'Freeze-out' occurs when annihilation rate:

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

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')?!

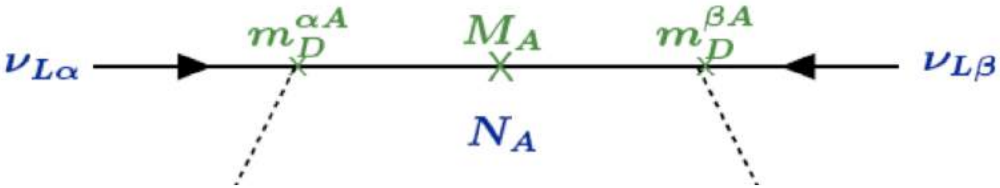
Sakharov conditions for baryogenesis:

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')

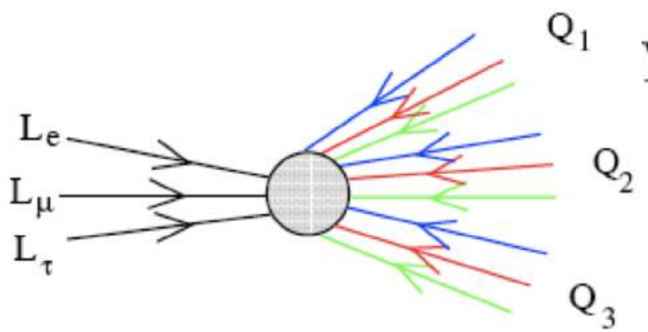
Thus the generation of the observed matter-antimatter asymmetry *requires* new BSM physics (could be related to neutrino masses … **possibly due to violation of lepton number → leptogenesis)**

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



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

Asymmetric baryonic matter



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

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

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

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**

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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?	'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 ?

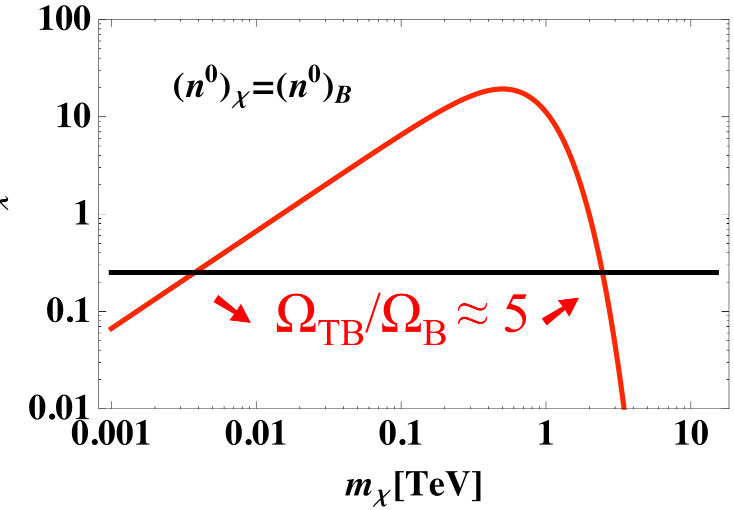
Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
Λ_{QCD}	**Nucleons**	Baryon number	$\tau > 10^{33}$ yr (dim-6 OK)	'Freeze-out' from thermal equilibrium Requires asymmetry	$\Omega_B \sim 10^{-10}$ *cf.* observed $\Omega_B \sim 0.05$
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino? 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!**

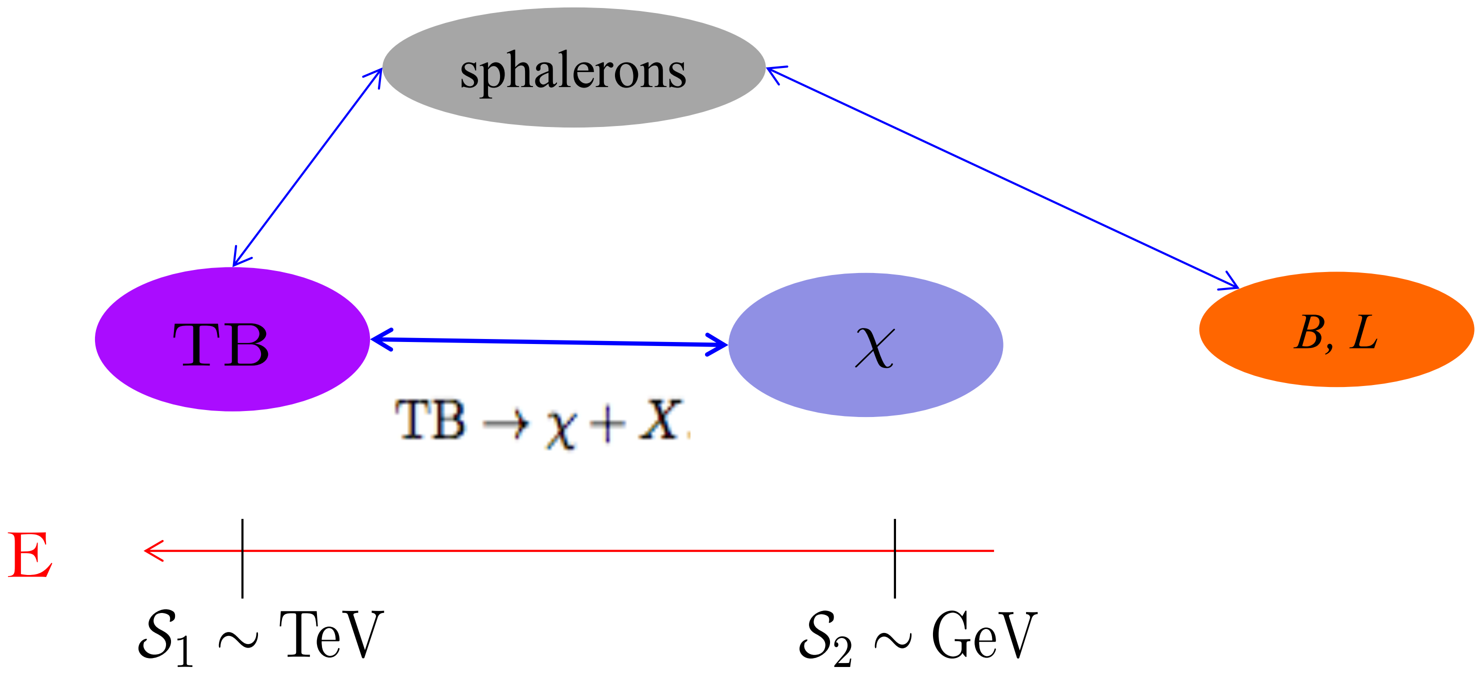
$$\Omega_\chi = (m_\chi/m_B)(n_\chi/n_B)\Omega_B$$

Then a *O*(TeV) mass **technibaryon** can be the dark matter … alternatively a ~few GeV mass **'dark baryon'** in a *hidden sector* (into which the technibaryon decays)

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



Why may we not have seen these particles yet?



S_1 States (constituents) carry weak charges and are connected to sphalerons so inherit any pre-existing fermion asymmetry (➛ baryon asymmetry)

S_2 States are SM singlets (in a hidden sector/hidden valley) but directly connected to the S_1 sector (with scale separation – TeV ➛ GeV – because of different β-function)

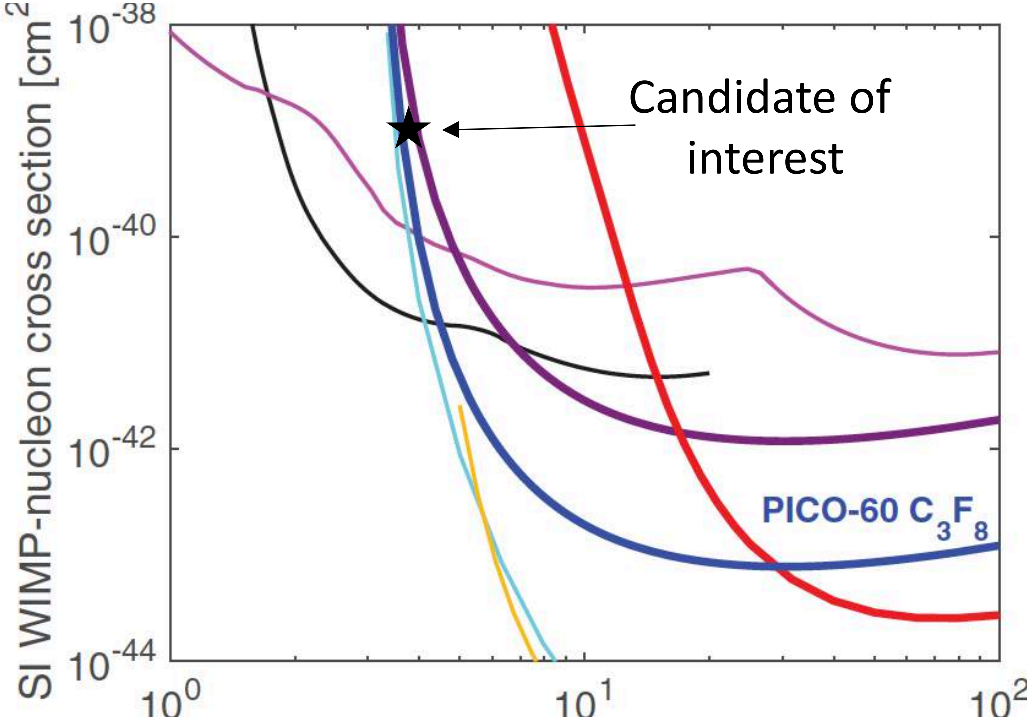
$\mathrm{TB} \to \chi + \mathrm{X}$ is in equilibrium until $T \lesssim T_{\mathrm{sph}}$, then χ decouples and becomes DM

The S_1 states do couple to the SM (so ***ought to show up*** at LHC Run II)

The S_2 states can be searched for only in low threshold nuclear recoil experiments

Frandsen, Sarkar & Schmidt-Hoberg, PR D**84**:051703,2011

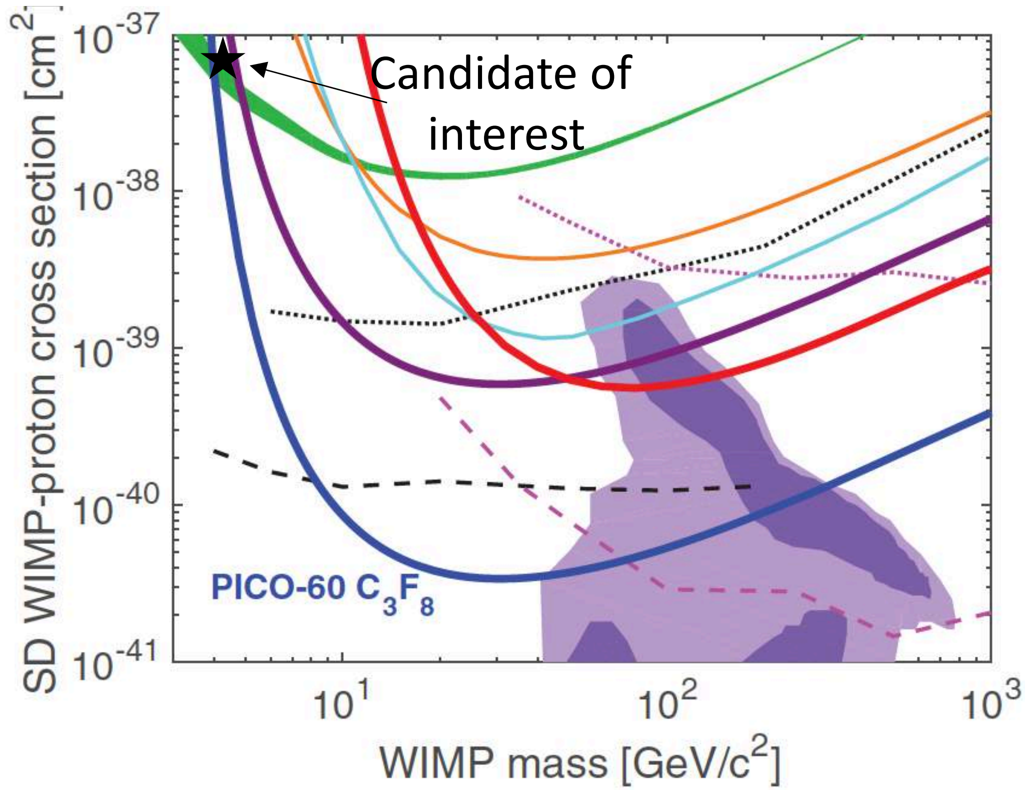
Experiments to directly detect dark matter through nuclear recoil are optimised for heavy WIMPs … they have little sensitivity for low mass particles ⇒ O(keV) recoil energy (where calibration is difficult and the sensitivity falls off *exponentially* … reflecting the Maxwellian tail of the *uncertain* halo velocity distribution



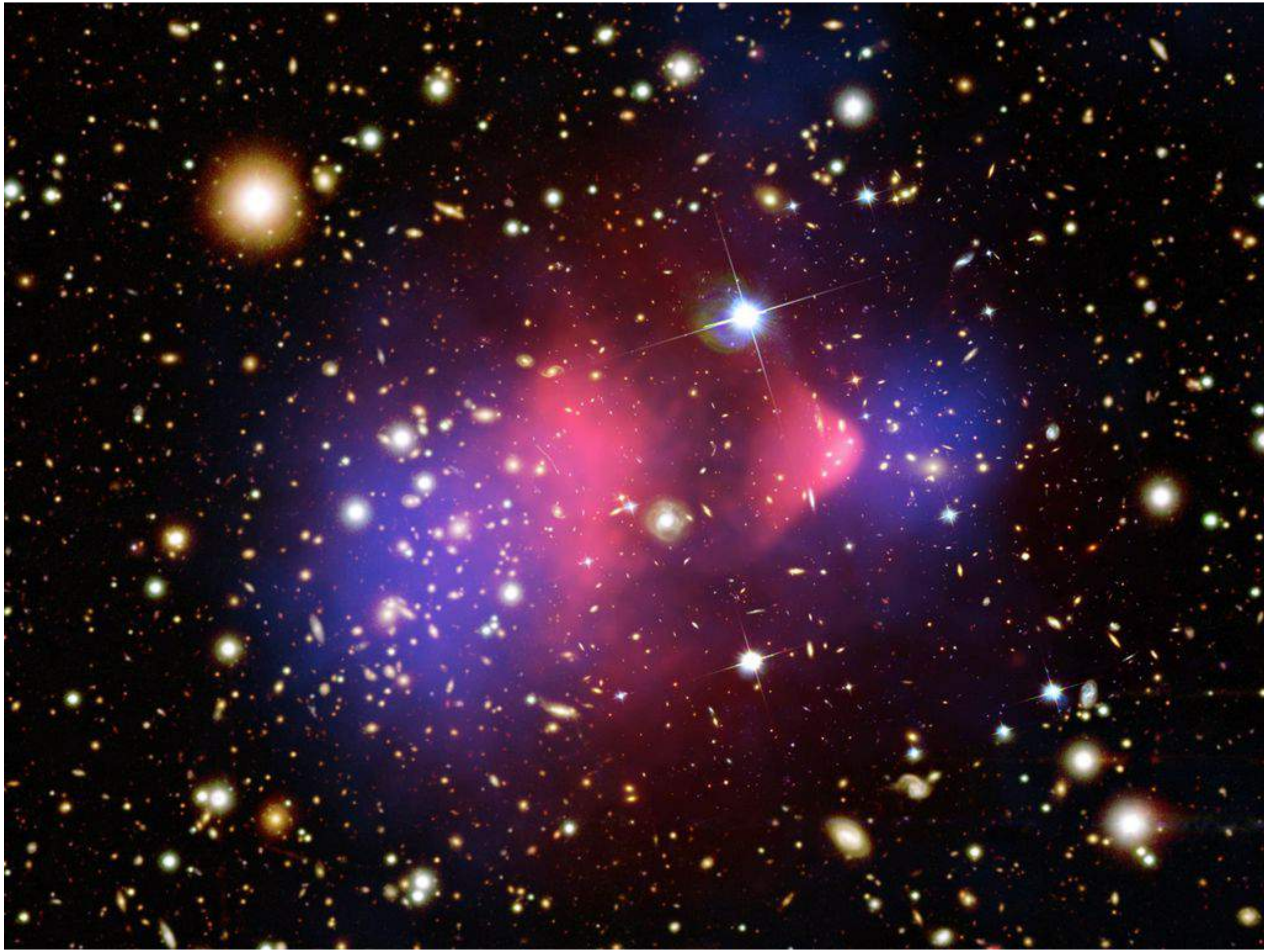
Could a ~4-5 GeV dark matter particle have gone undetected even if its interaction cross-section is as high as $\sim10^{-39}$ cm^2?

… and as high as $\sim10^{-37}$ cm^2 for spin-dependent interactions on protons!

To detect such particles will require very *low* threshold detectors

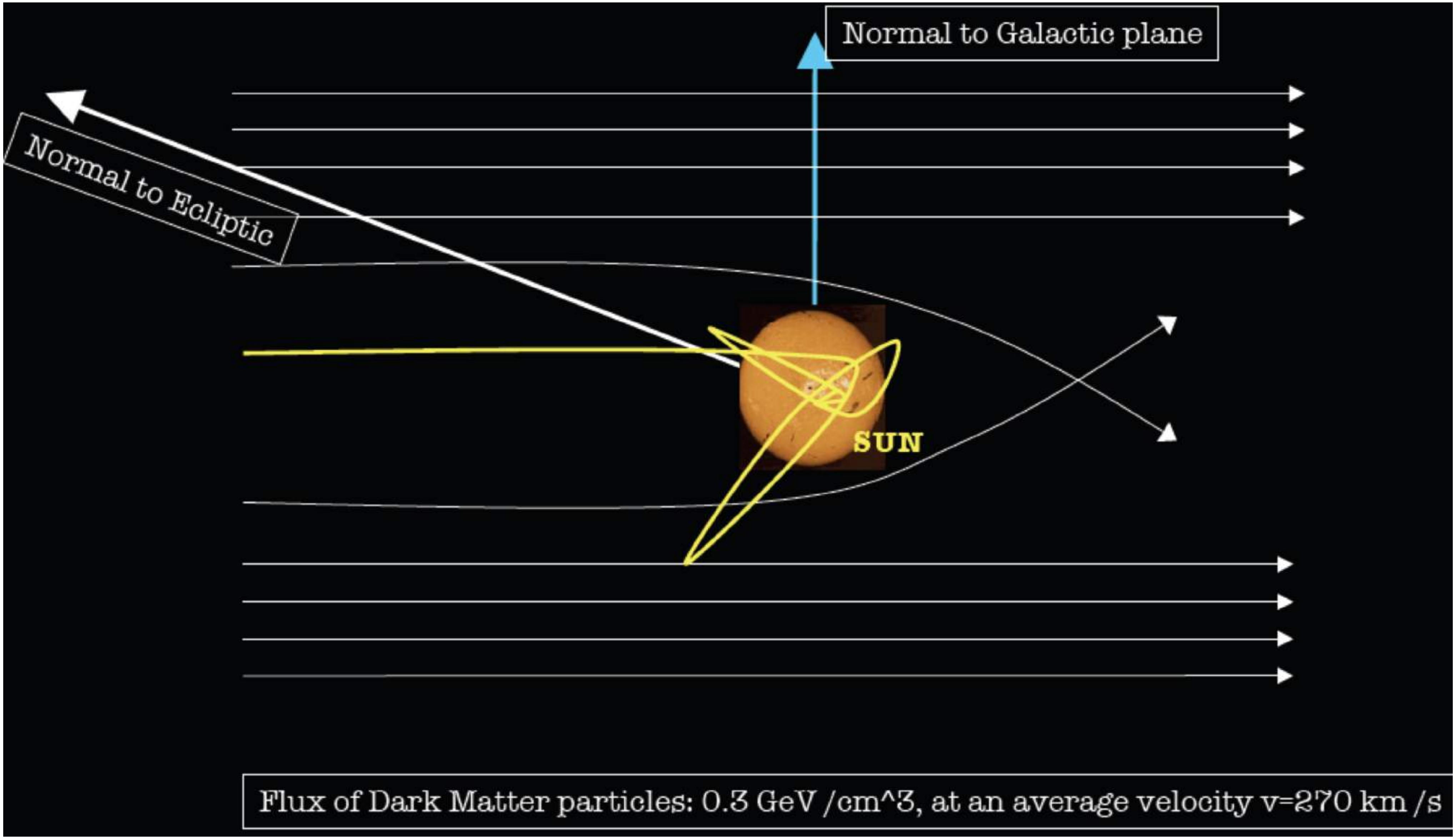


Such particles would also naturally be **self-interacting** with a typical cross-section: $\sigma_{\chi\chi} \sim \sigma_{nn} (m_n/m_\chi)^2$, where $\sigma_{nn} \sim 10^{-23}$ cm^2



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

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

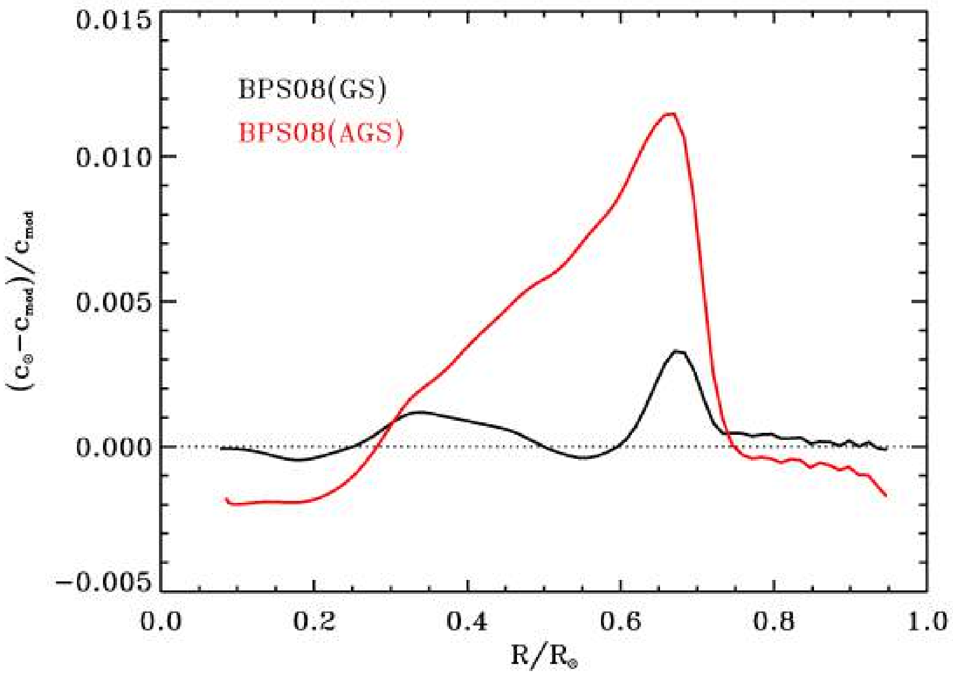


The flux of Solar neutrinos is *very* sensitive to the core temperature and can thus be *reduced* (Steigman *et al* 1978, Faulkner *et al* 1985, Press & Spergel 1985, Gould 1987)

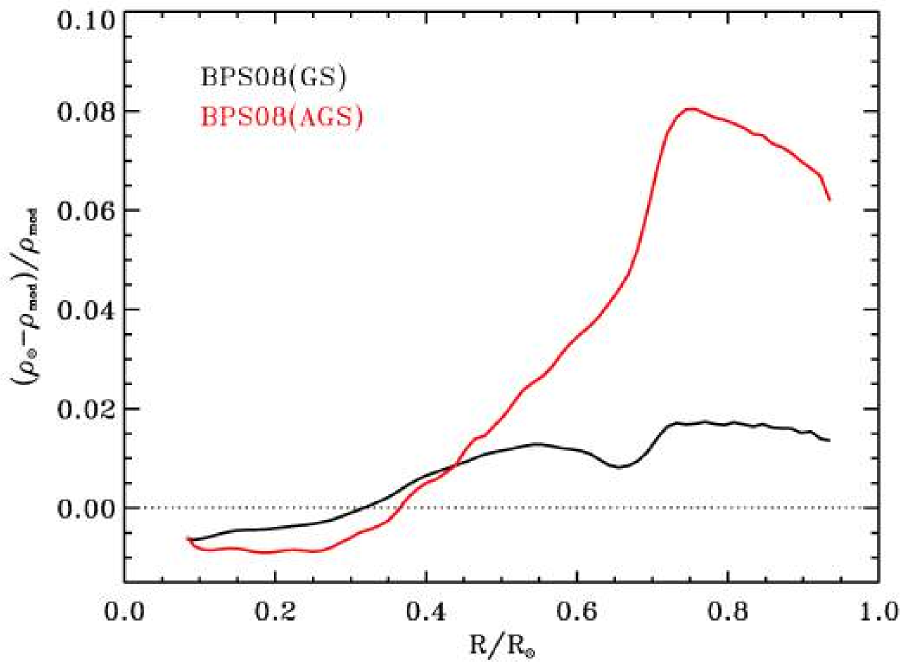
A problem with the standard Solar model

- 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



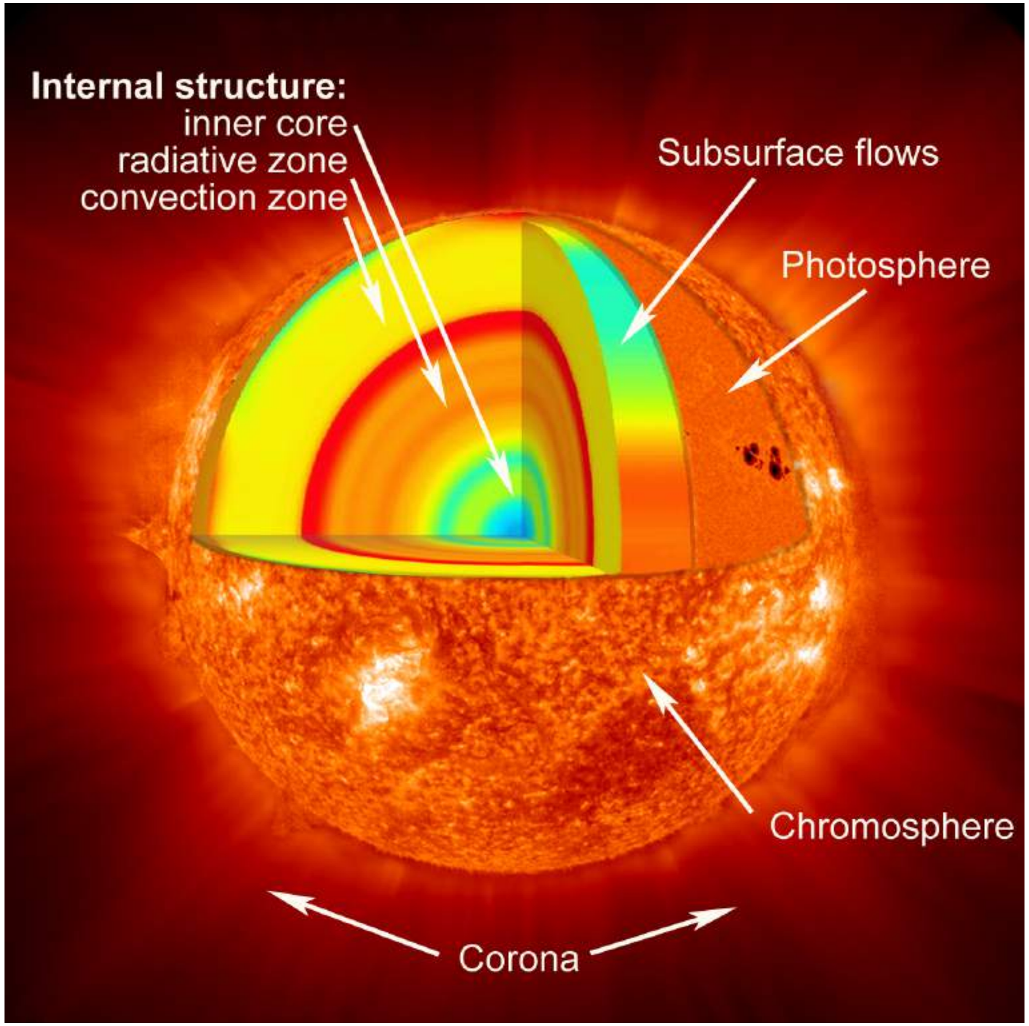
Density profile in the Sun



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

Frandsen & Sarkar, PRL **105**:011301,2010

The particle mass must be ~4-10 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: $R_{\mathrm{CZ}}/R_\odot = 0.713 + 0.001$
… too high (by >6σ!) in SSM but can be lowered by the required ~1% if
$(\sigma_{\chi\mathrm{N}}/\sigma_\odot)(N_\chi/N_\odot) \gtrsim 10^{-14},$ where $\sigma_\odot \equiv (m_\mathrm{N}/M_\odot)R_\odot^2 \sim 4 \times 10^{-36}\ \mathrm{cm}^2$

Capture of dark matter onto stars

$$\Gamma_c = \sum_i \left(\frac{6}{\pi}\right)^{1/2} \frac{\sigma_i \rho_\chi}{\bar{v} m_\chi} \int_0^R 4\pi r^2 \frac{\rho_i(r)}{m_i} \times v_{esc}^2(r) \left[1 - \frac{1 - \mathrm{e}^{-A_i^2(r)}}{A_i^2(r)}\right] dr$$

where $$A_i^2(r) = \frac{3 v_{esc}^2(r)}{2\bar{v}^2} \frac{2}{m_\chi/m_i + m_i/m_\chi - 2}$$

Dark matter forms a thermal core *within* the star, of radius:

$$r_{th} \sim \left[\frac{9kT}{8\pi G \rho_c m_\chi}\right]^{1/2}$$

For the Sun and 5 GeV DM, this is ~4 x 10^9 cm
(compare with Solar radius ~7 x 10^{10} cm)

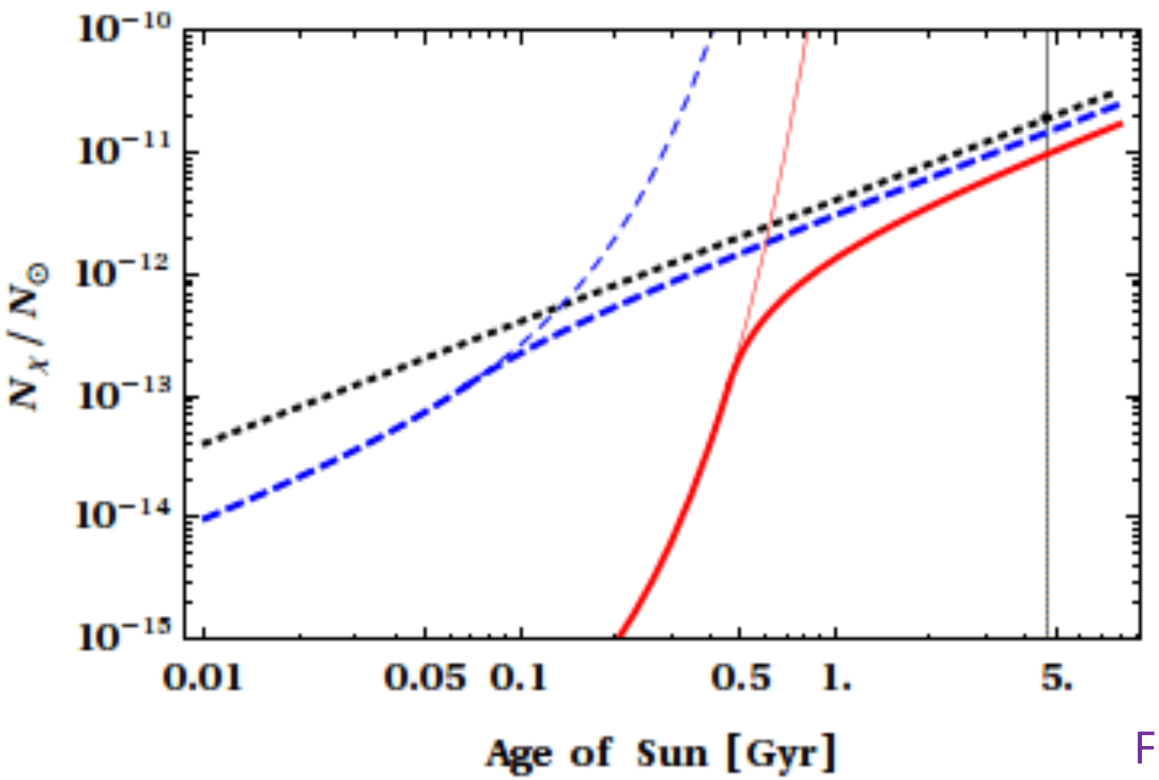
Steigman *et al* (1978), Press and Spergel (1985), Gould (1987), Griest and Seckel (1987)

The abundance of **asymmetric** dark matter is *not* depleted by annihilation … so grows exponentially and is ~independent of scattering cross-section

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

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

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



$N_\chi/N_\odot \sim 10^{-11}$ … i.e. x100 the abundance of a WIMP

$\sigma_{\chi N}{}^{SI} \sim 10^{-39}$ cm^2

$\sigma_{\chi N}{}^{SD} \sim 10^{-36}$ cm^2

'black disk' limit (geometric area)

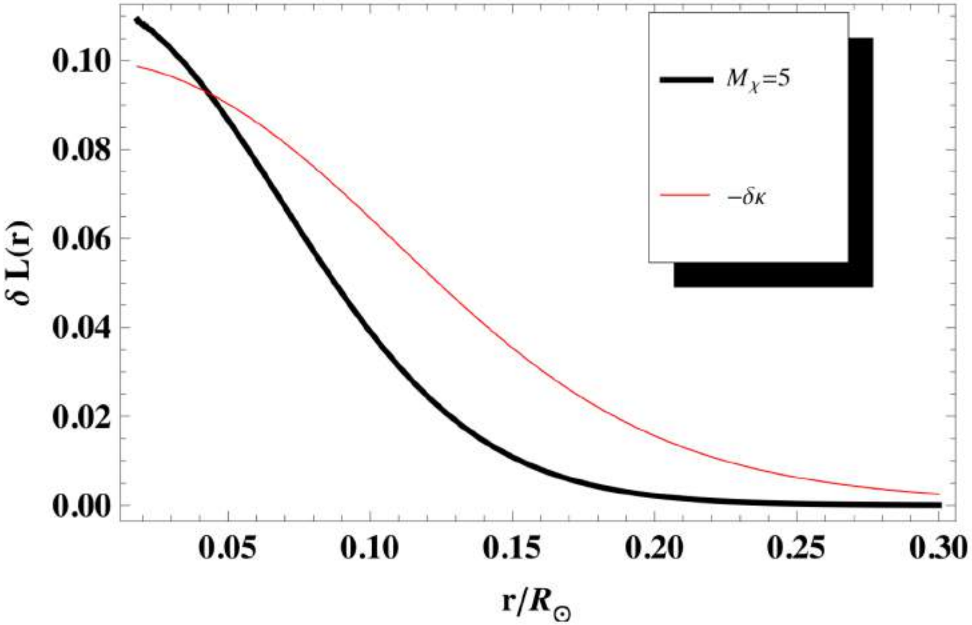
Frandsen & Sarkar, PRL **105**:011301,2010

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)

Frandsen & Sarkar, PRL **105**:011301,2010

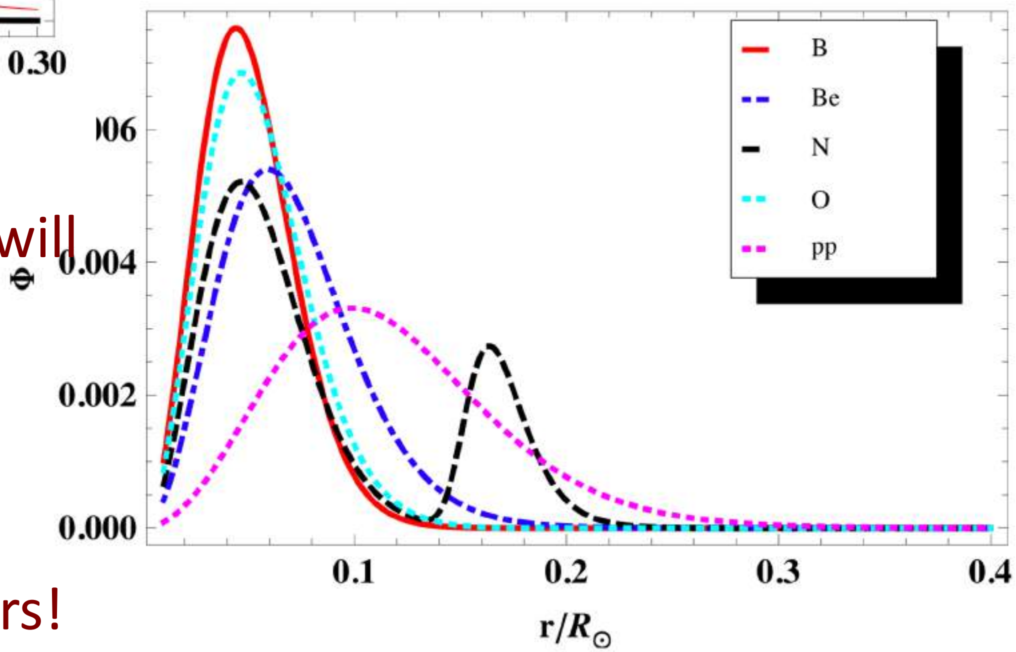


According to the 'Linear Solar model' (Villante & Ricci 2009) a $\sim$10% reduction of the opacity in the core lowers the convective boundary by $\sim$0.7% … so will (largely) *restore* agreement with helioseismology

Modification of the luminosity profile will also reduce neutrino fluxes:

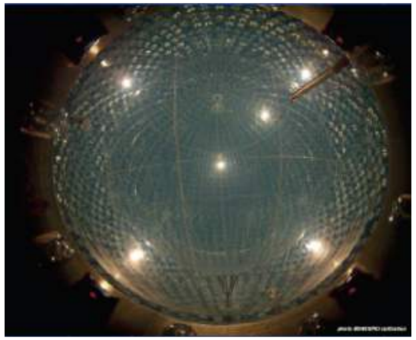
$\delta\Phi_B = -17\%$, $\delta\Phi_{Be} = -6.7\%$,

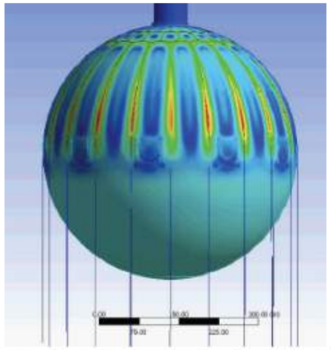
$\delta\Phi_N = -10\%$, $\delta\Phi_O = -14\%$



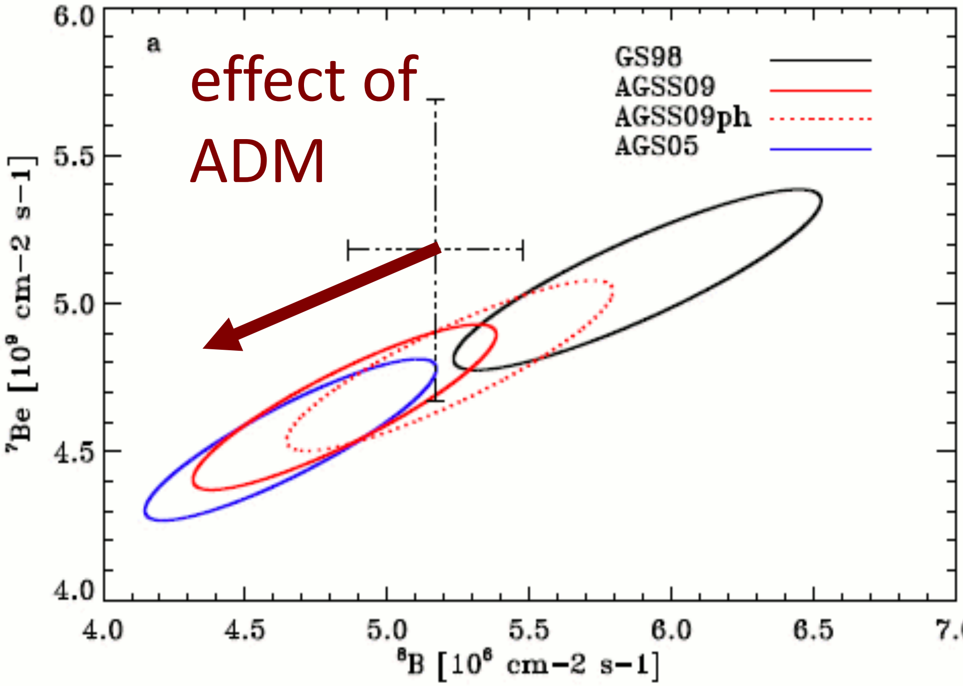
This is *testable* by dark matter detectors!

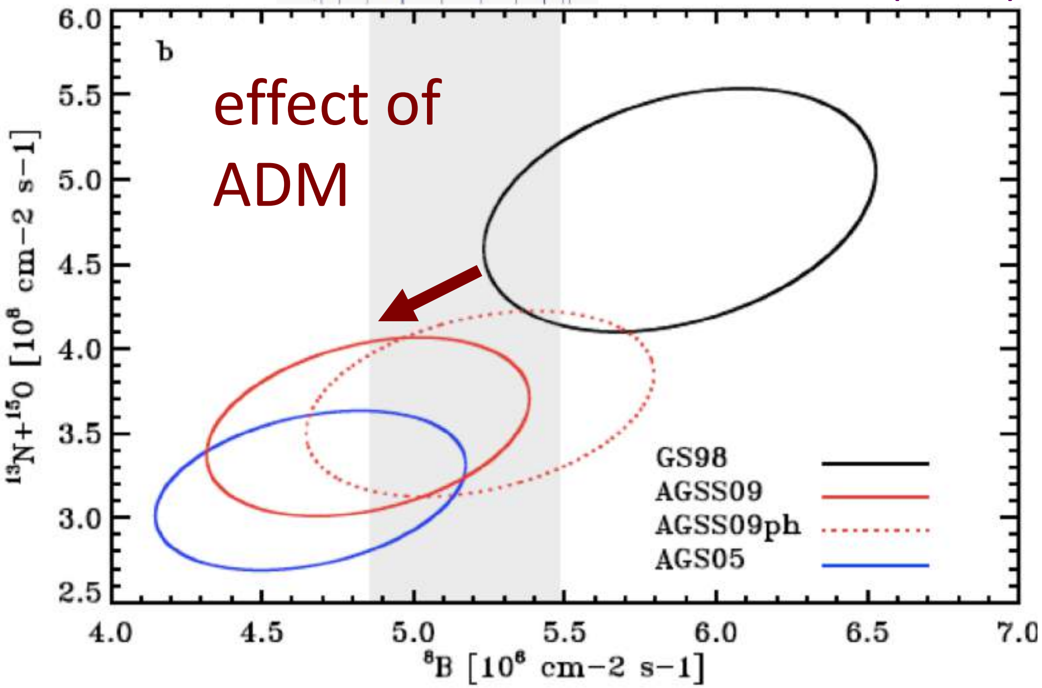
Precision measurements of Solar neutrinos can *test* the model





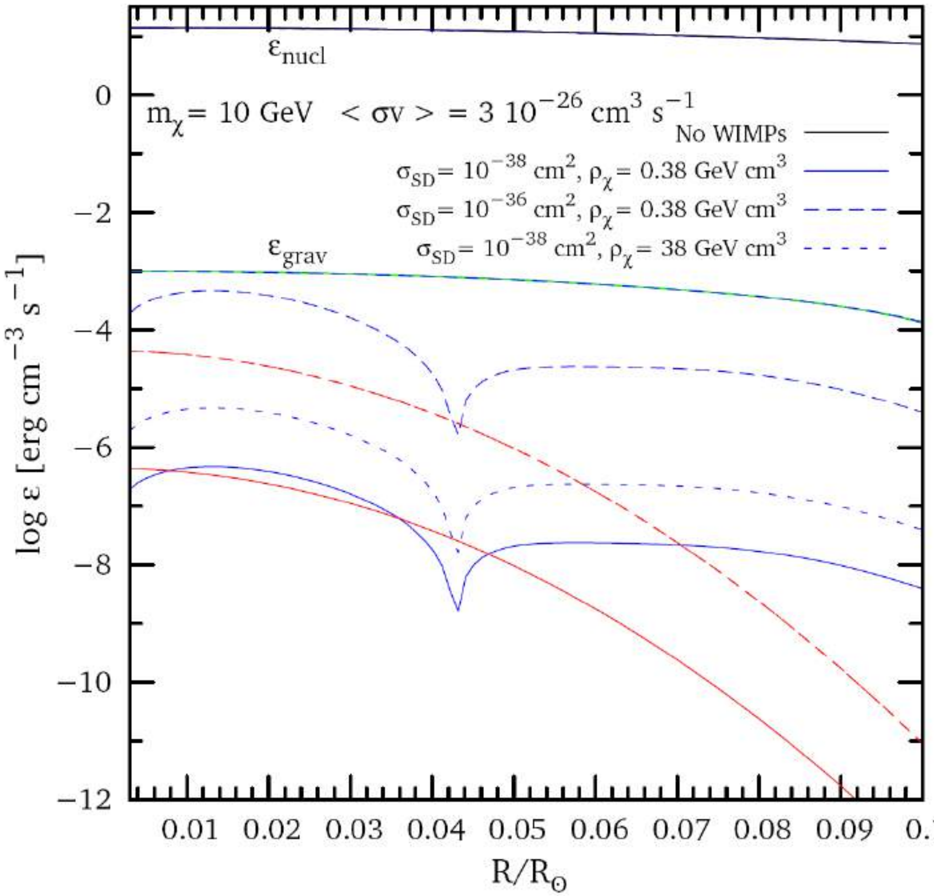
Serenelli (2010)





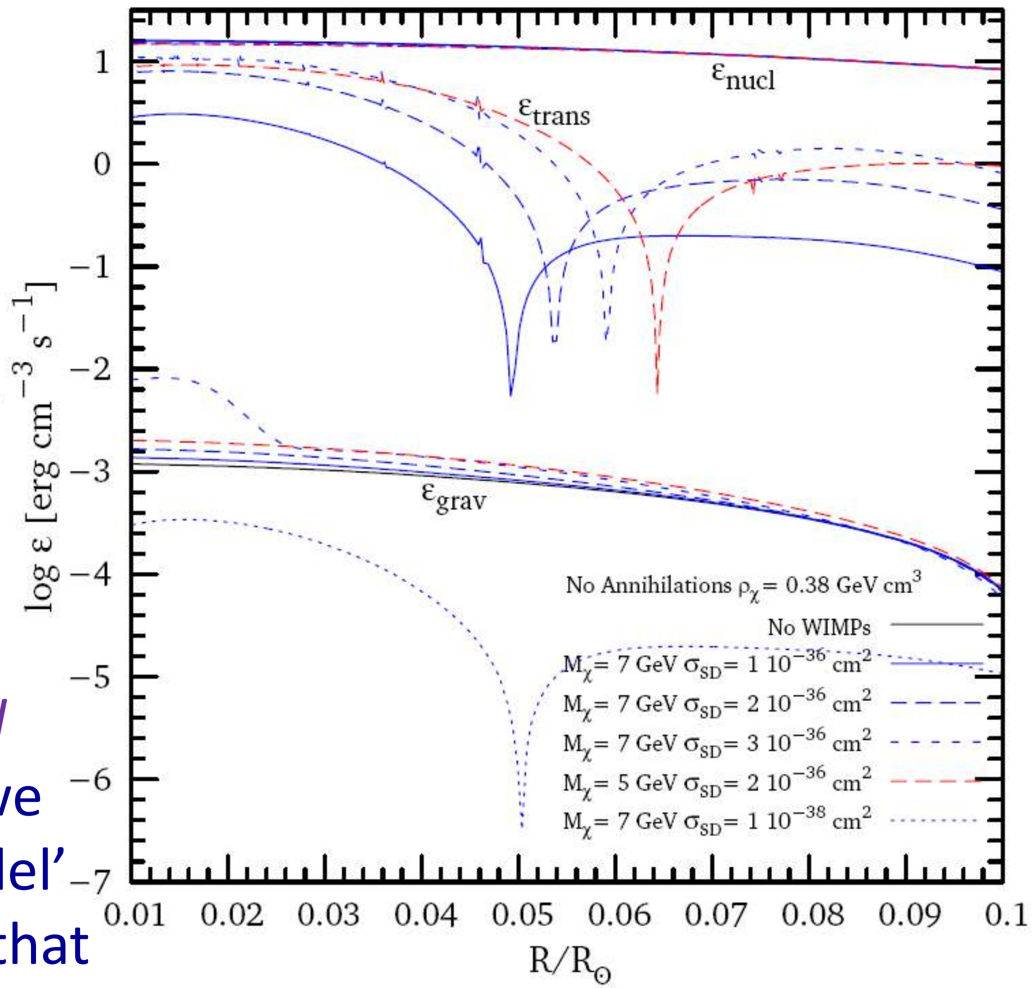
SNO: $\Phi(^8\text{B}) = 5.18 \pm 0.29 \times 10^6\ \text{cm}^{-2}\ \text{s}^{-1}$; **Borexino**: $\Phi(^7\text{Be}) = 5.18 \pm 0.51 \times 10^9\ \text{cm}^{-2}\ \text{s}^{-1}$

Measurement of ^{13}N and ^{15}O fluxes will provide additional constraint … but it may still be difficult to distinguish between effects of metallicity and dark matter



Using the 'GENEVA code', Taoso *et al* (2010) confirmed 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) obtained a *smaller* effect than we did from the analytic 'linear Solar model' … however Vincent *et al* (2015) show that a *stronger* effect comes from momentum-*dependent* scattering with $\sigma \propto q^2$

Summary

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

- $\mathcal{O}$(GeV) mass ADM can arise from hidden/mirror QCD sectors

  - Such particles are naturally self-interacting

… can solve problems of collisionless CDM on galactic scales (if any!)

- Direct detection will require sub-keV threshold recoil detectors

➢ When their sensitivity hits the 'neutrino floor' such detectors may also be also be able to probe asymmetric dark matter *indirectly* through precision measurement of Solar neutrino fluxes

➢ Large capture rate in Sun may also solve 'Solar composition problem'
… magnitude of both problem and solution currently under debate