Asymmetric dark matter

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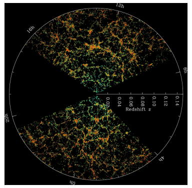
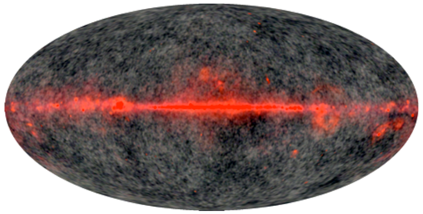
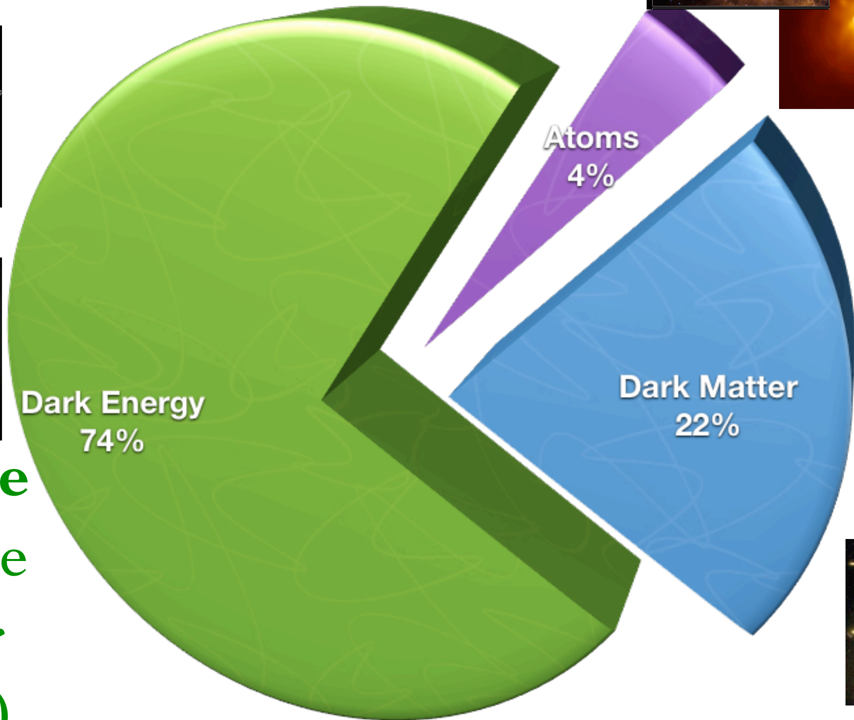
What is the world made of?

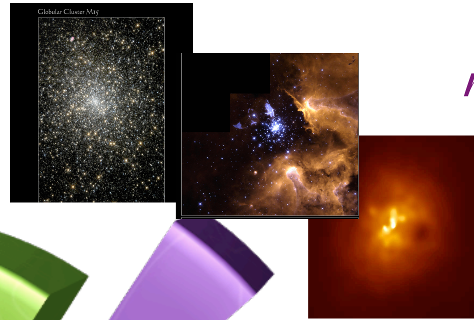
***Only* geometrical evidence:**
$\Lambda \sim O(H_0^2)$, $H_0 \sim 10^{-42}$ GeV
… dark energy is *inferred* from the 'cosmic sum rule':
$\Omega_m + \Omega_k + \Omega_\Lambda = 1$





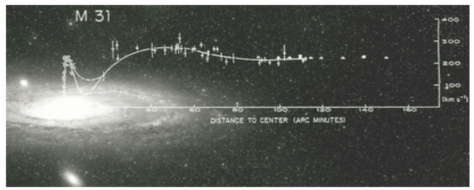
No *dynamical* evidence of dark energy (e.g. late ISW effect) seen so far (with >5σ significance)
… Could dark energy be faked by inhomogeneity?





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 $\Omega_B \sim 0.05$

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

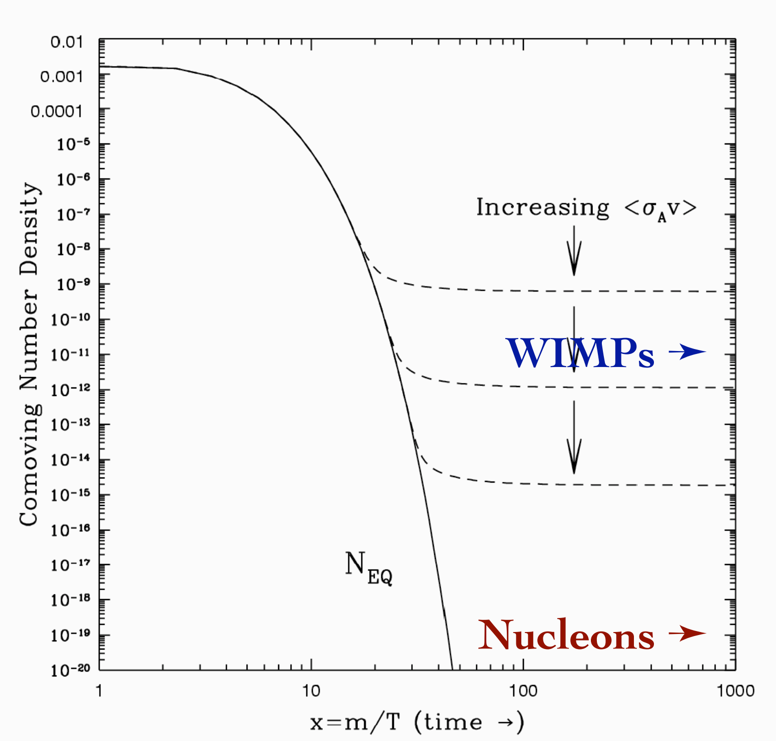
'Freeze-out' occurs when annihilation rate:

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

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

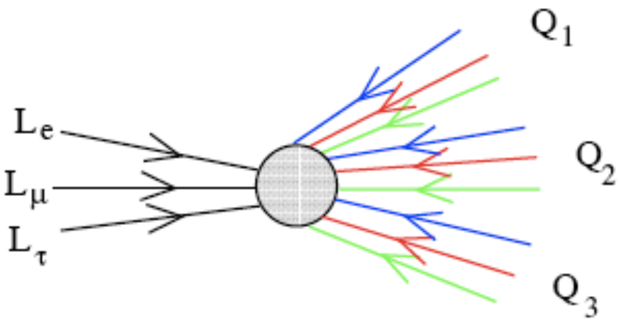
Baryon number violation occurs even in the Standard Model through non-perturbative (sphaleron-mediated) processes … but *CP*-violation is *too weak* (also out-of-equilibrium conditions are not available since the electroweak symmetry breaking phase transition is in fact a 'cross-over')

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



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

(Davidson *et al*, Phys.Rep.466:105,2008)

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 $\Omega_B \sim 0.05$
$\Lambda_{\mathrm{Fermi}} \sim G_F^{-1/2}$	Neutralino?	R-parity?	violated? ('matter parity' *adequate* to ensure proton stability)	'freeze-out' from thermal equilibrium	$\Omega_{\mathrm{LSP}} \sim 0.25$

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

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

… 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 $\Omega_{\mathrm{DM}}/\Omega_B \sim 5$?

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~~ Asymmetric baryogenesis	$\Omega_B \sim 10^{-10}$ *cf.* observed $\Omega_B \sim 0.05$
$\Lambda_{\mathbf{Fermi}} \sim G_F^{-1/2}$	Neutralino? Technibaryon?	R-parity? (walking) Technicolour	violated? □ $\tau \sim 10^{18}$ yr e^+ excess?!	'Freeze-out' from thermal equilibrium Asymmetric (like the *observed* baryons)	$\Omega_{LSP} \sim 0.25$ $\Omega_{TB} \sim 0.25$

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):

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

What *should* the world be made of ?

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

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 ~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

TIMPs

TIMP: Complex scalar, charged under the $U(1)_{TB}$ symmetry (Gudnason, Kouvaris and Sannino 05)

$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2}\right)^T \ , \quad U_R^{+1/2} \ , \ D_R^{-1/2} \ ; \quad \lambda^f \ .$$

'iTIMP'

- $\mathcal{R}$ real
- $T^0 \sim UD$
- Iso-singlet GB
- $M_{T^0} \sim g\, F_\Pi$

(M.T.F and F.Sannino 09)

'TIMP'

- 4 of $SU(4)$
- $UDUD$
- SM singlet
- $M_T \sim N_{TC}^{3/2} F_\Pi$

(Bahr, Chivukula and Farhi 90; Nussinov 92)

'TIMP'

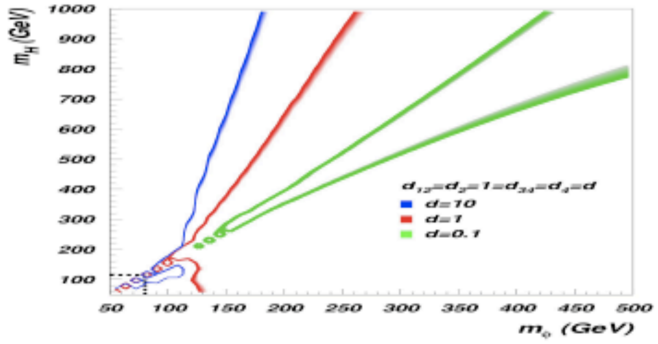
- $\mathcal{R}$ pseudo-real
- $T^0 \sim UD$
- SM singlet GB
- $M_{T^0}^2 \sim -g^2\, F_\Pi^2$

(Ryttov and Sannino 08; Foadi, M.T.F and Sannino 09)

Arise as GB from breaking of the technicolor chiral symmetries.
Stable as they carry technibaryon number.
Composite states neutral but constituents may be charged.
Receive mass from 'vacuum alignment', i.e. electroweak mass contribution.

TIMPS

PGB TIMPS have derivatively suppressed couplings: Can TIMPs have a symmetric relic density?
If constituents are uncharged they can:

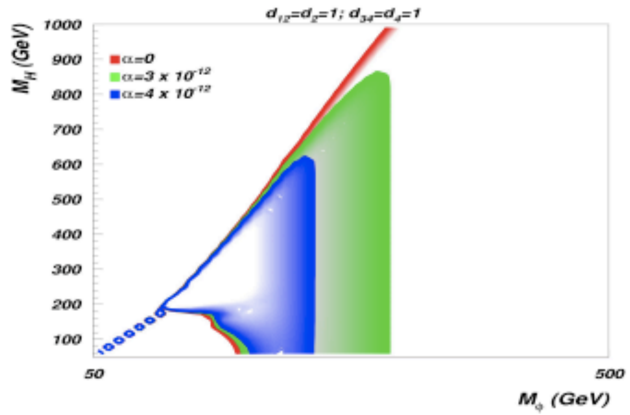


$$\phi \sim \lambda\lambda,$$

$$\mathcal{L} = \partial_\mu \phi^* \partial_\mu \phi - m_\phi^2 \phi^* \phi + \frac{d_1}{\Lambda} H \partial_\mu \phi^* \partial_\mu \phi \qquad (2)$$
$$+ \frac{d_2}{\Lambda} m_\phi^2 H \phi^* \phi + \frac{d_3}{2\Lambda^2} H^2 \partial_\mu \phi^* \partial_\mu \phi + \frac{d_4}{2\Lambda^2} m_\phi^2 H^2 \phi^* \phi.$$

Adding by hand an asymmetry still enhances the available parameter space:

(Griest and Seckel 86, Hooper, March-Russel and West)

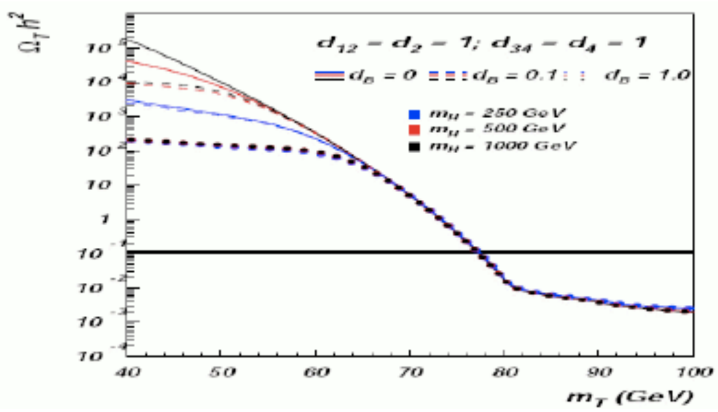


PGB TIMPS with charged constituents, generically have contact Interactions with weak gauge bosons:

$$T \sim UD$$

$$L_{WW,ZZ} = -\frac{T^* T}{2} \mathrm{Tr}\left[d_W\, W_\mu W^\mu + d_Z\, Z_\mu Z^\mu\right]$$

(Belyaev, M.T.F, Sannino and Sarkar 10)

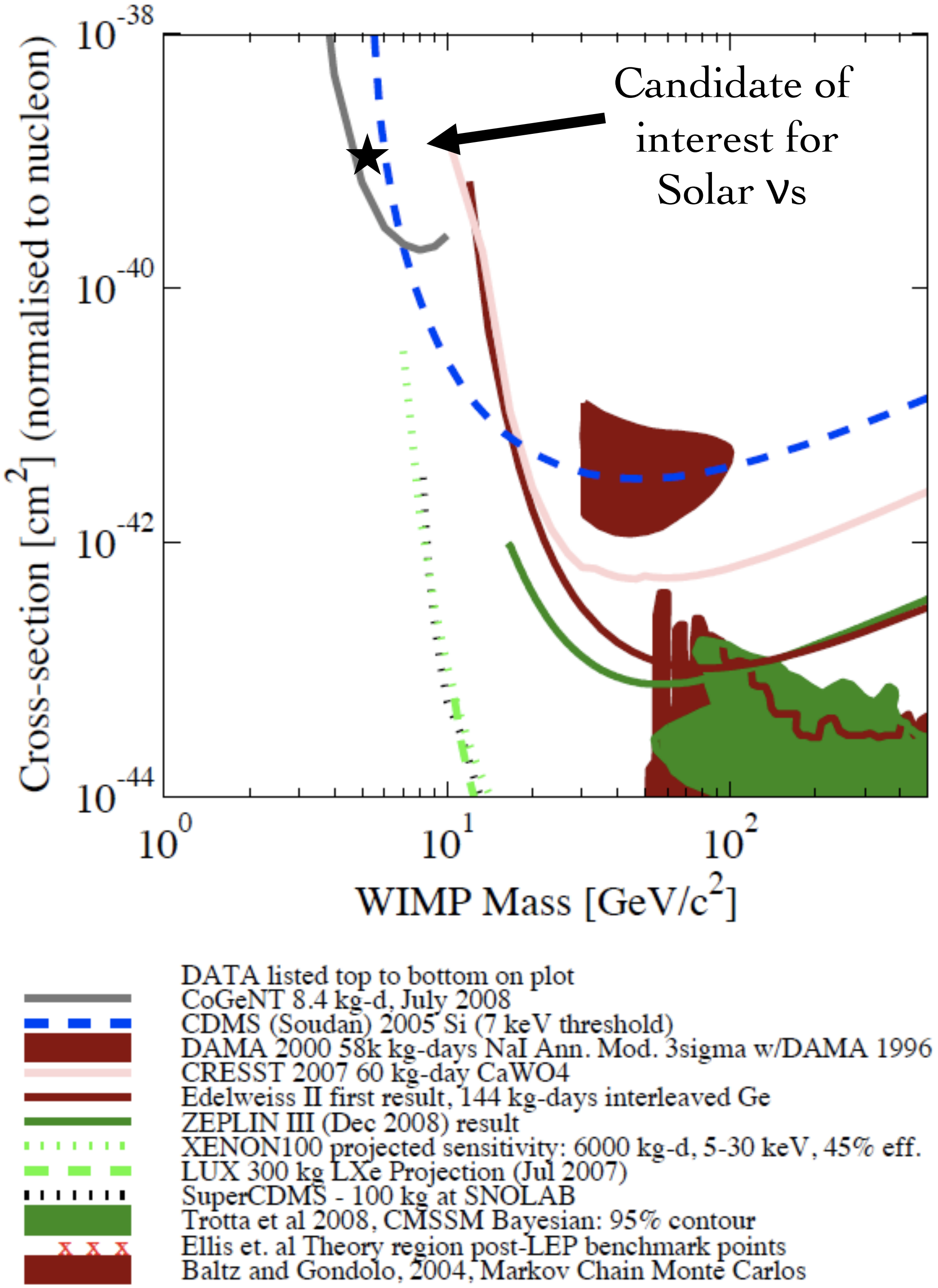


Experiments to directly detect dark matter through nuclear recoil are optimised for heavy WIMPs (motivated by SUSY) … they have little sensitivity for low mass particles $\Rightarrow O(\mathrm{keV})$ recoil energy

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

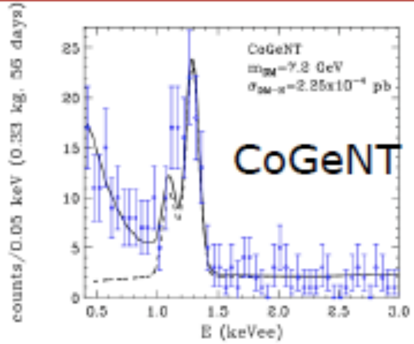
… for spin-dependent interactions the cross-section can be as high as ~10^{-36} cm^2

To detect such particles will require *low* threshold detectors

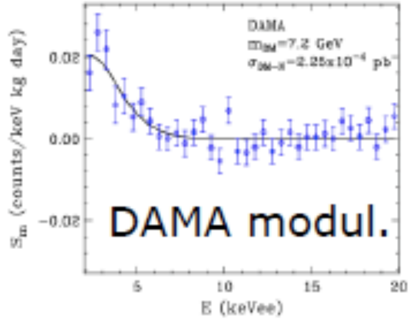


Low Mass WIMPs

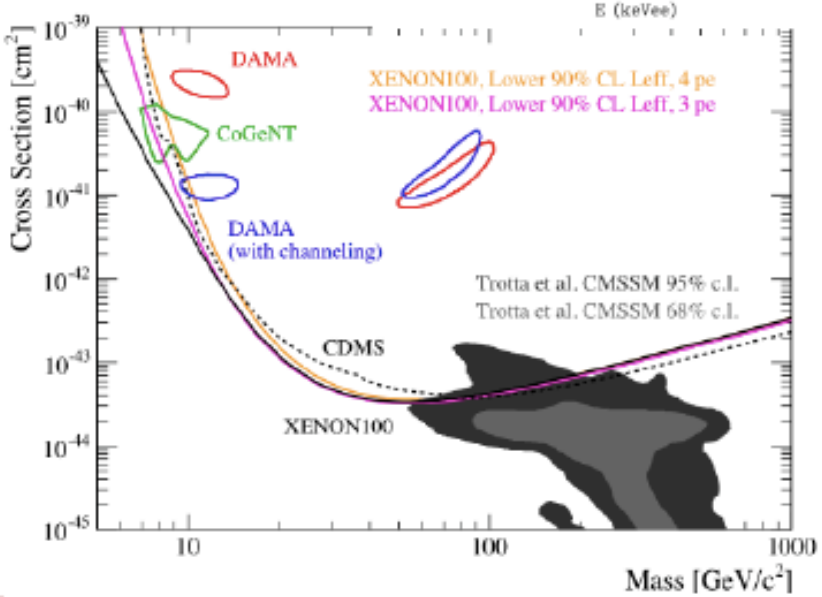
- Observed excess at low energy, close to experimental thresholds, in DAMA/LIBRA (annual modulation in NaI) and CoGeNT (high-resolution Ge, ionization-only) [Aalseth et al, arXiv 1002.4703]



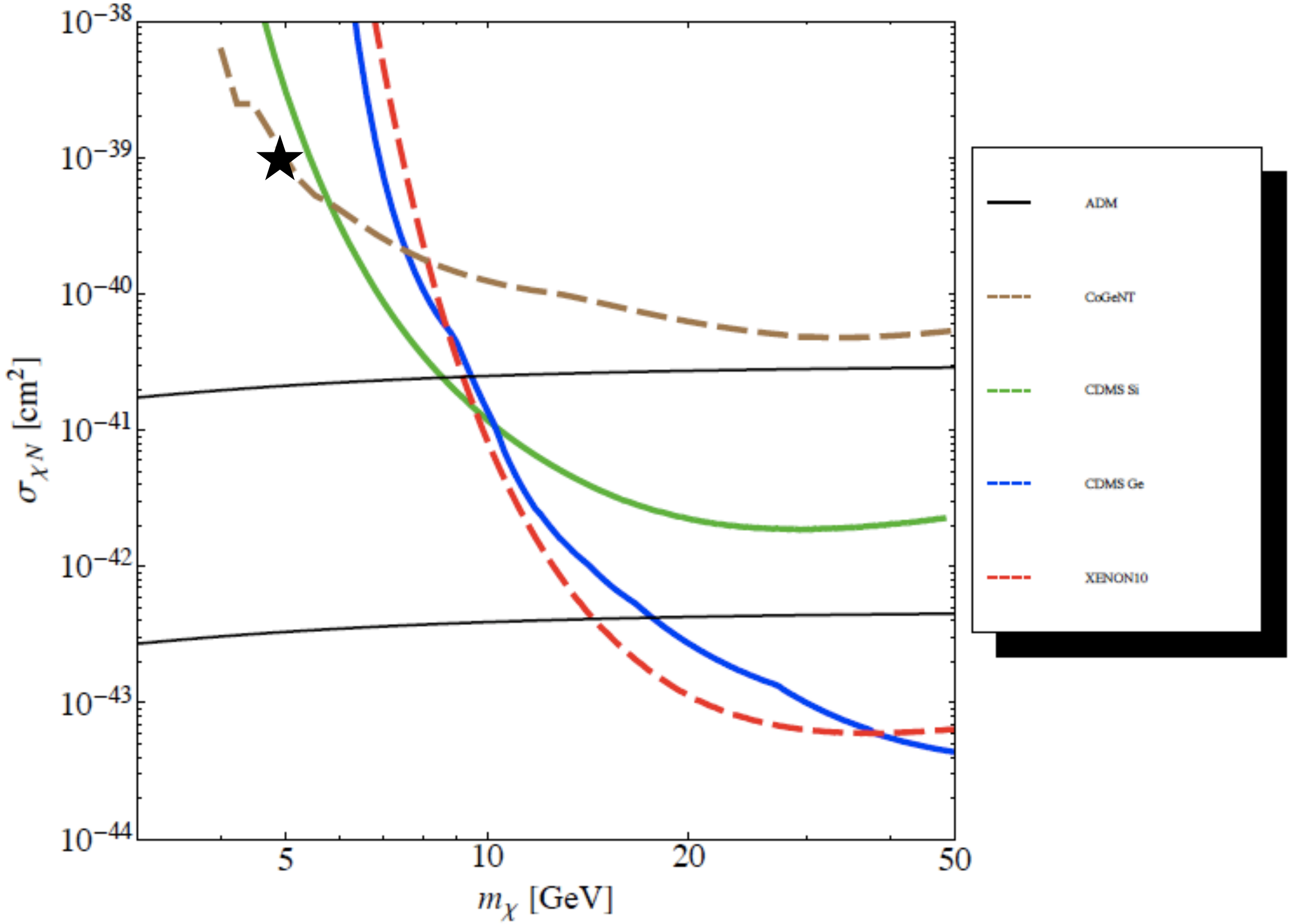
- Interpretation as M < 10 GeV WIMP? Inconsistent with XENON-100 [Aprile et al, subm. PRL, arXiv:1005.0380].



- Inconsistency avoided by questioning the precision of the calibration of the light yield for Xe recoils picture [Savage et al, arXiv 1006.0972, Hooper et al, arXiv 1007.1005]
- Contradictory hints, require further investigations (& low thresholds)
- Emerging consensus: channeling of lattice ions no longer relevant [Bozorgnia et al, arXiv 1006.3110]

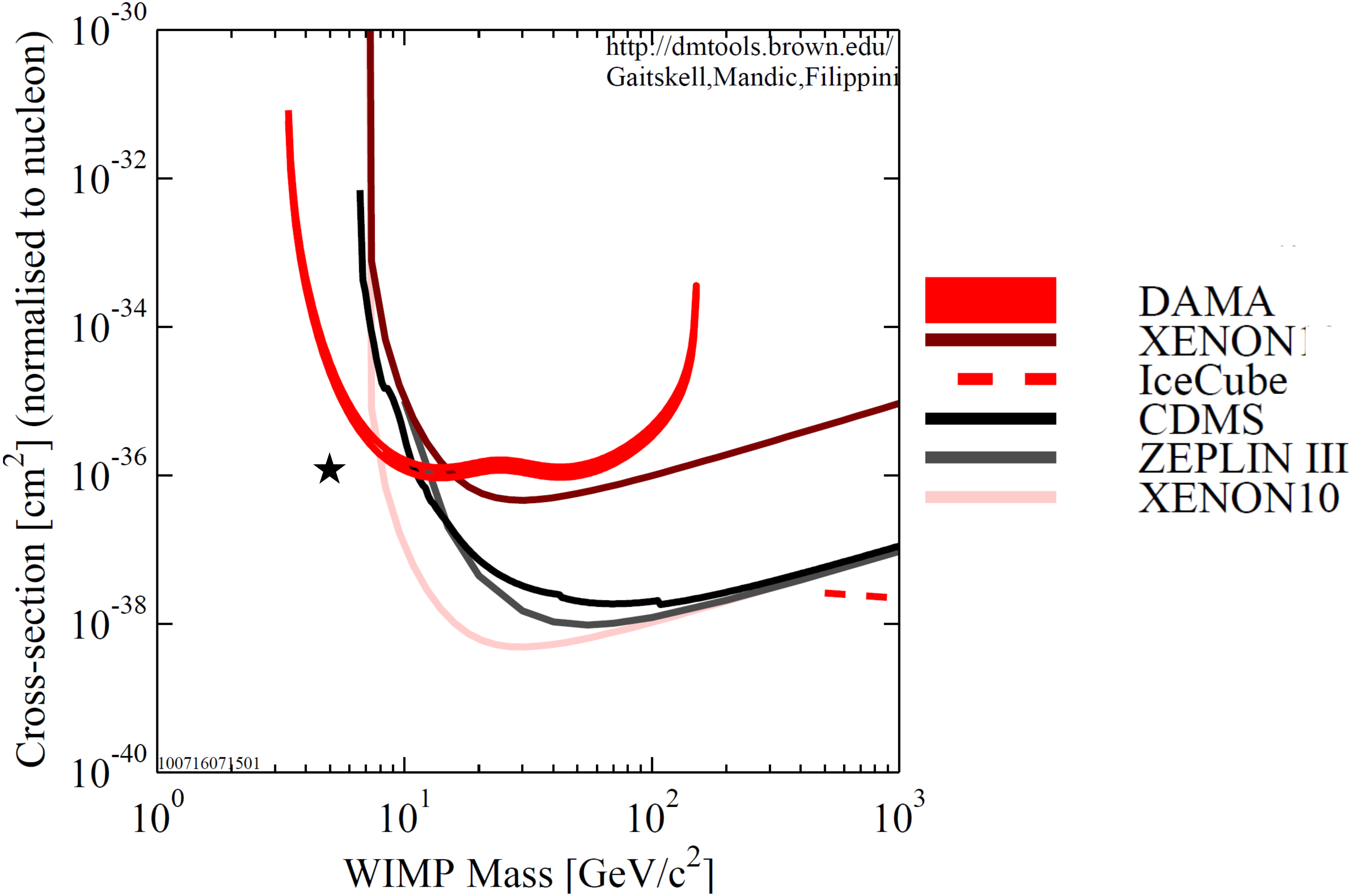


Can get up to ~2 x 10^{-41} cm^2 spin-independent cross-section through Higgs exchange for an 'unbaryon' in walking technicolour (Sannino & Zwicki 2009)

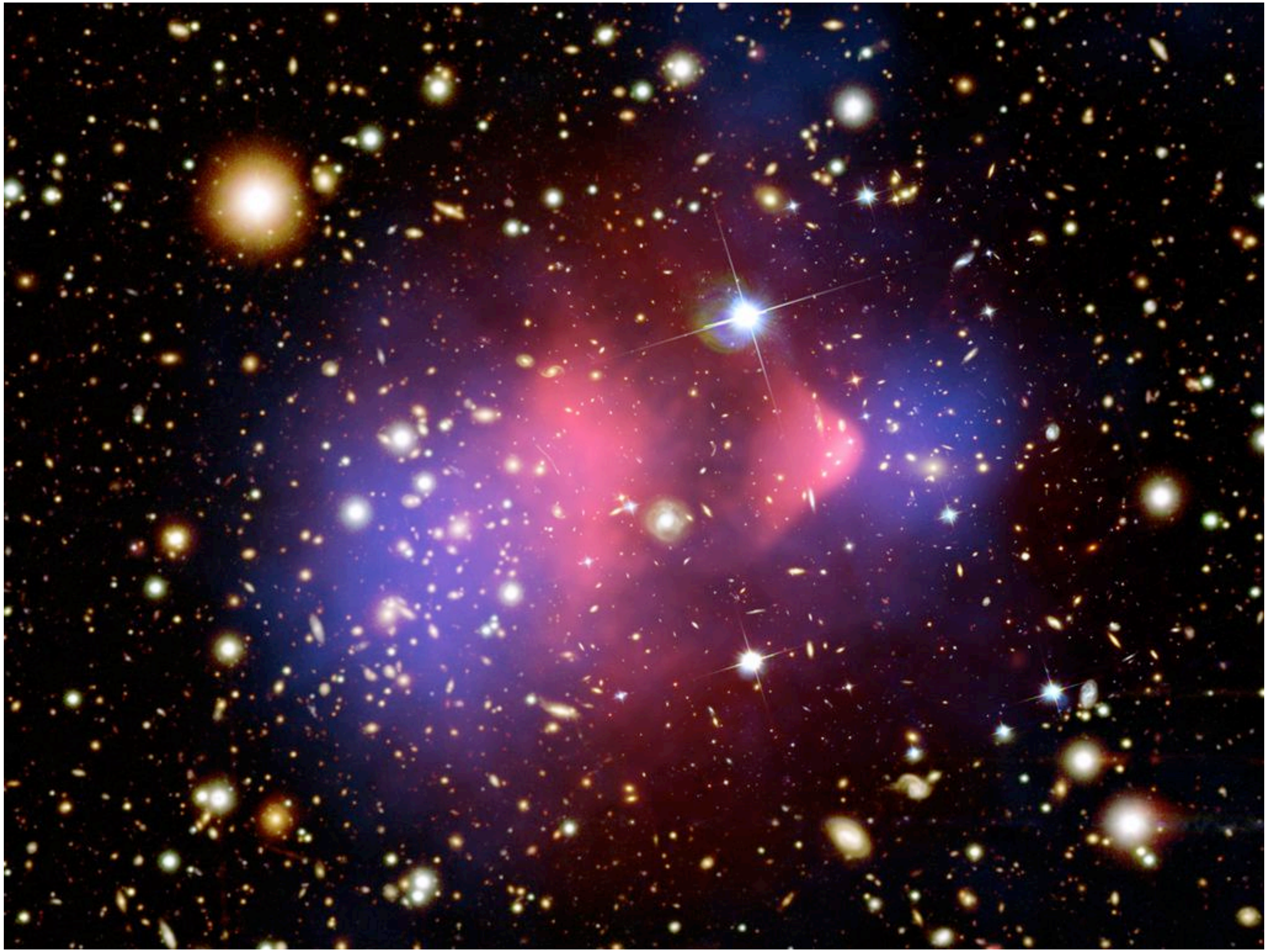


Much larger cross-sections – both SI & SD – can be realised through magnetic moment mediated interactions (Sigurdson *et al* 2006, Gardner 2008, Heo 2009, Masso *et al* 2009, An *et al* 2010, Banks *et al* 2010, Barger *et al* 2010, *etc*)

Current experimental limits on spin *dependent* DM-nucleon cross-section

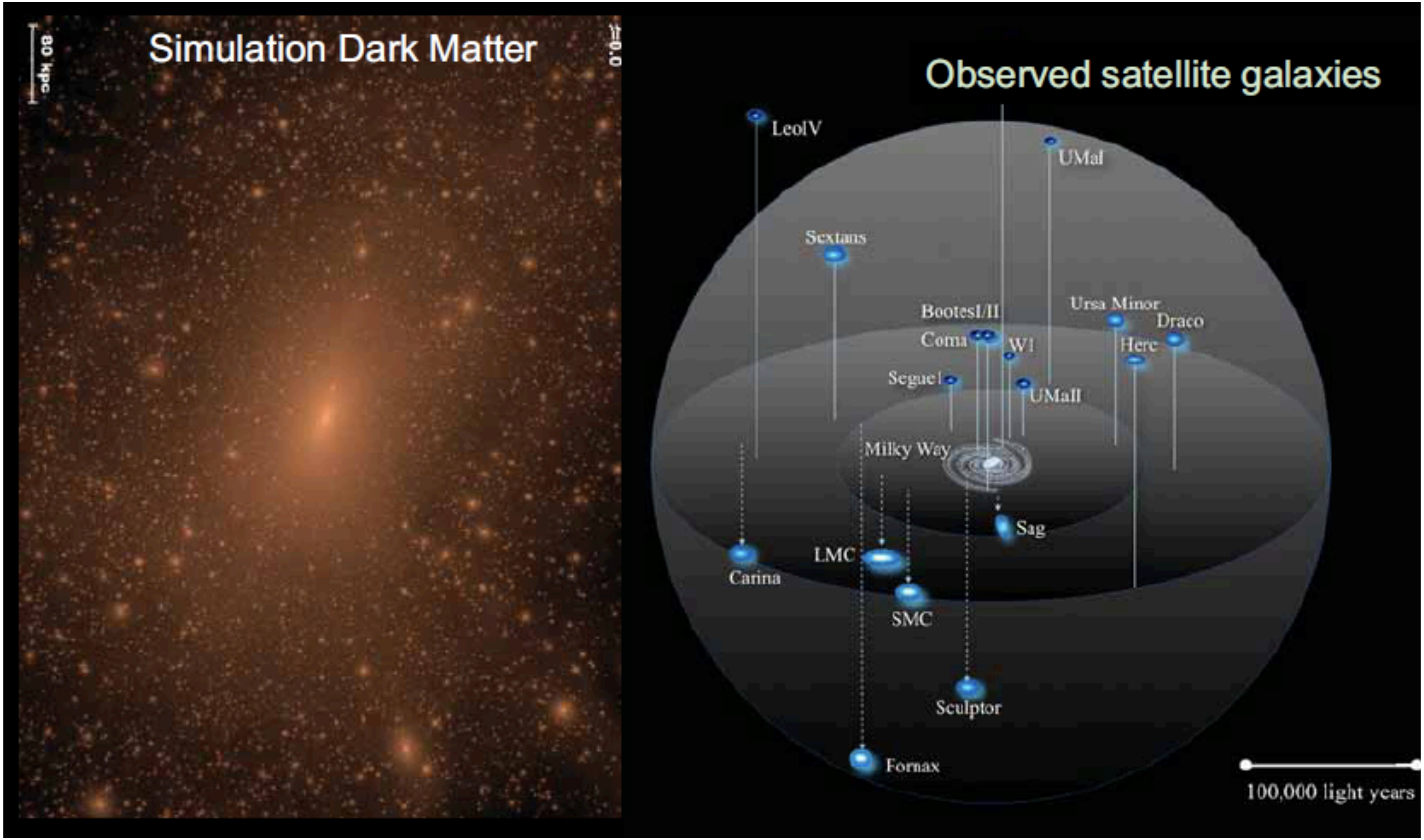


Such particles would also be naturally **self-interacting** with a typical cross-section: $\sigma_{\chi\chi} \sim \sigma_{nn} (m_n/m_\chi)^2$, where $\sigma_{nn} \sim 10^{-23}$ cm^2



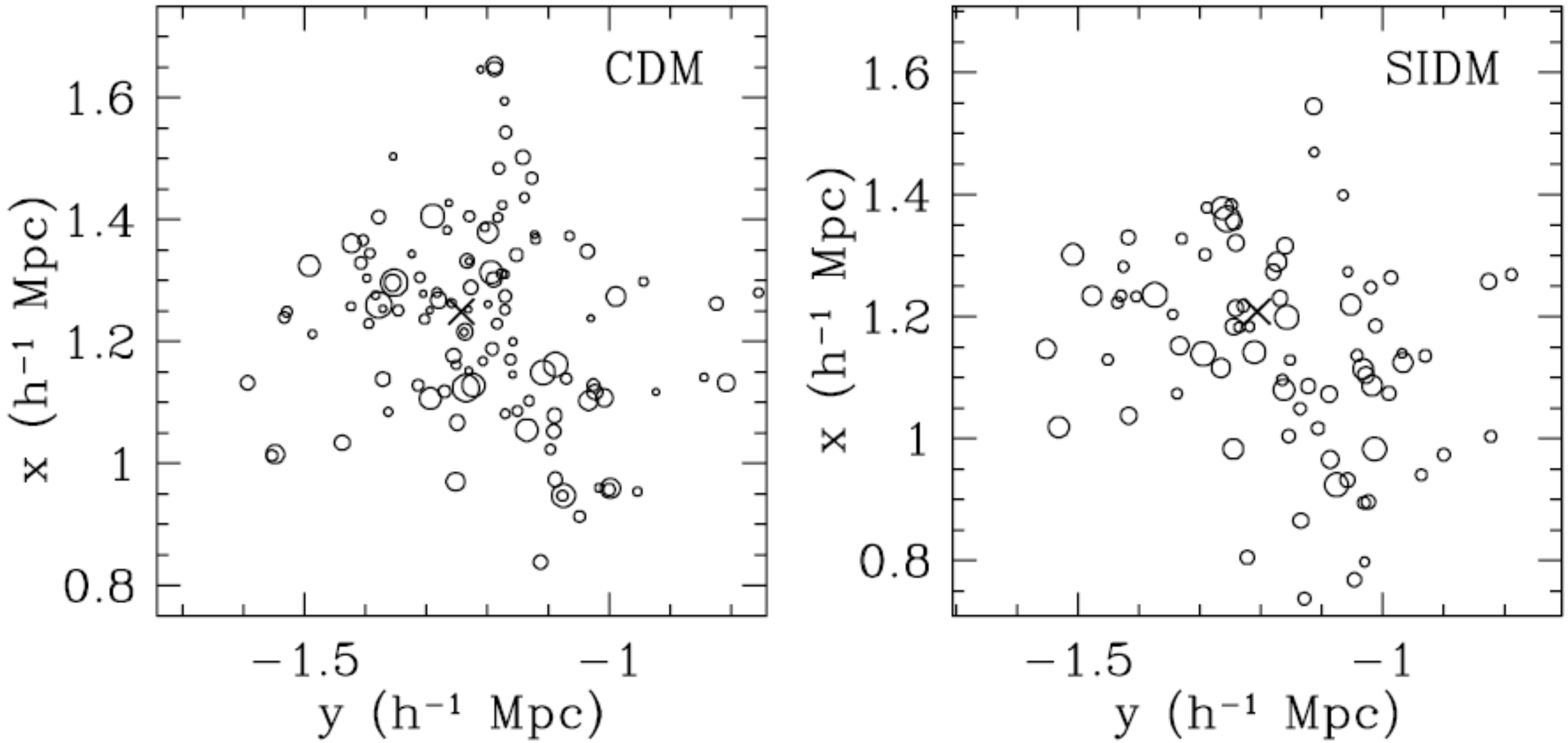
… well below the bound of 2×10^{-24} cm^2/GeV from the 'Bullet cluster'

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

Substructure is indeed reduced in numerical simulations done so far …
however the (important) effect of baryons was not included



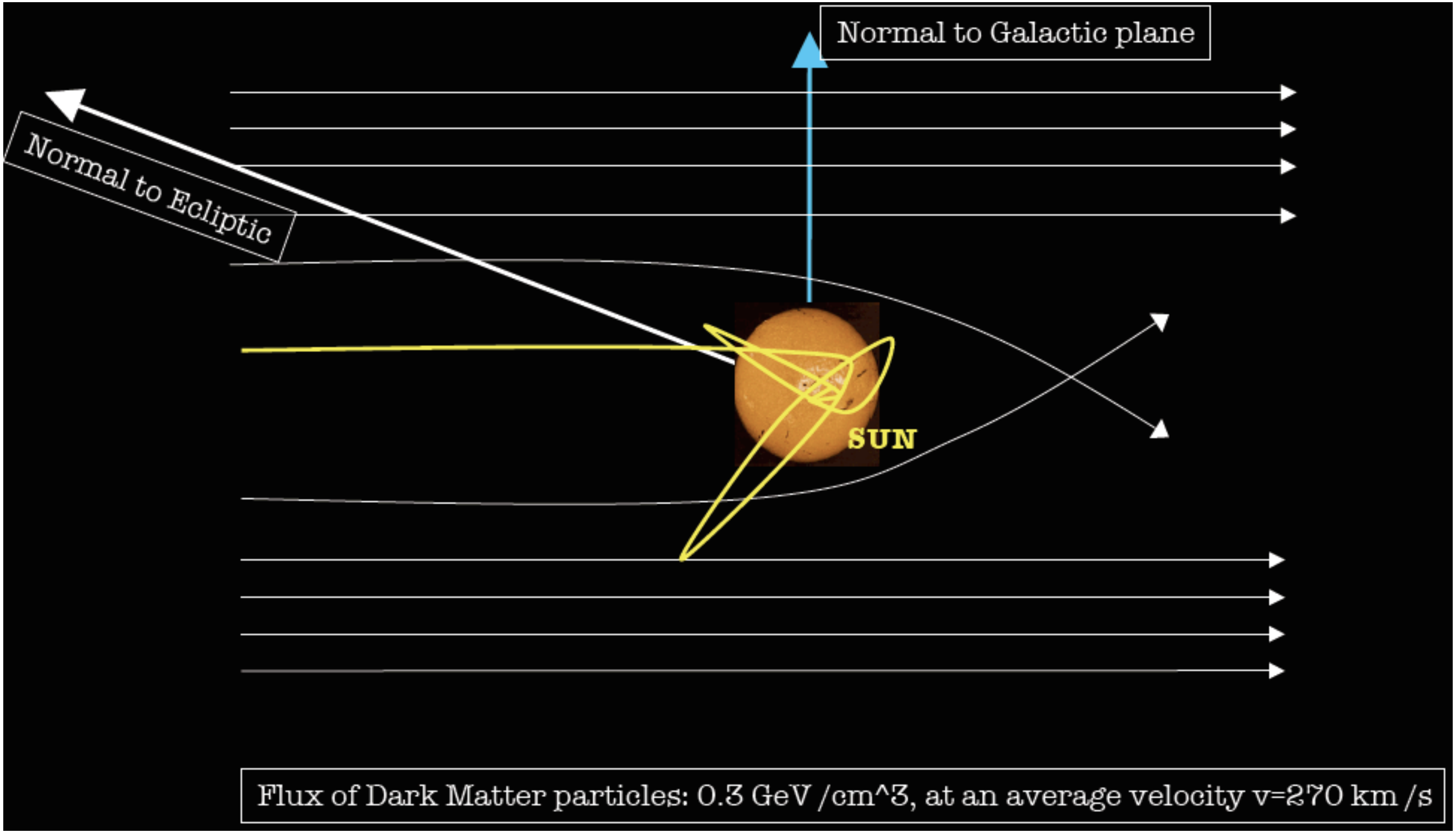
Dave, Steinhardt, Spergel & Wandelt (2001)

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

Feng, Kaplinghat & Yu (2010)

Presently we *cannot* require that dark matter must have TeV-scale mass, or be collisionless, or very weakly interacting … or have any annihilation signatures

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

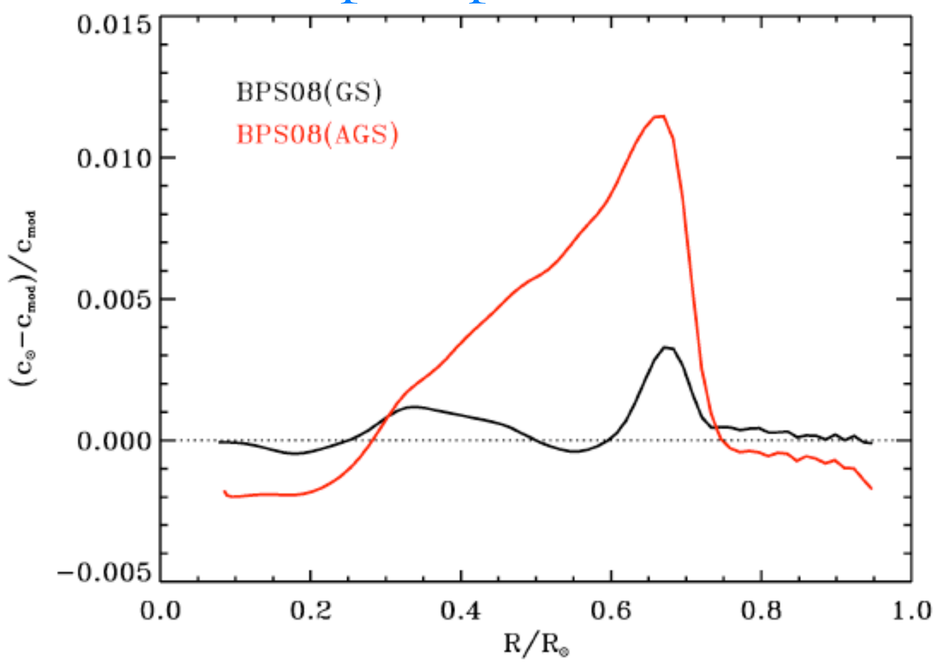


The flux of Solar neutrinos is *very* sensitive to the core temperature and can thus be affected (Faulkner *et al* 1985, Press & Spergel 1985, Gould 1987)

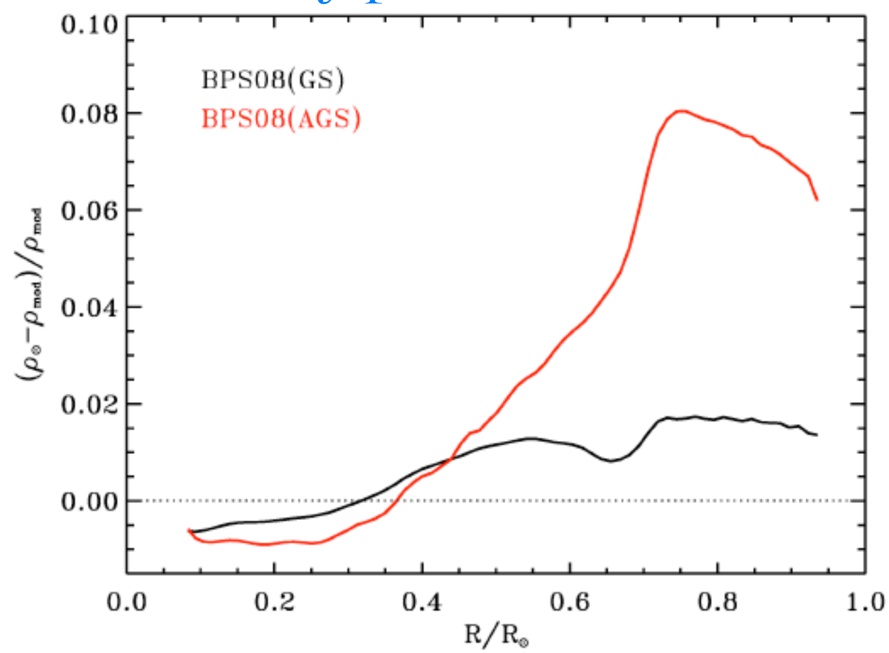
A problem with the standard Solar model

- 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

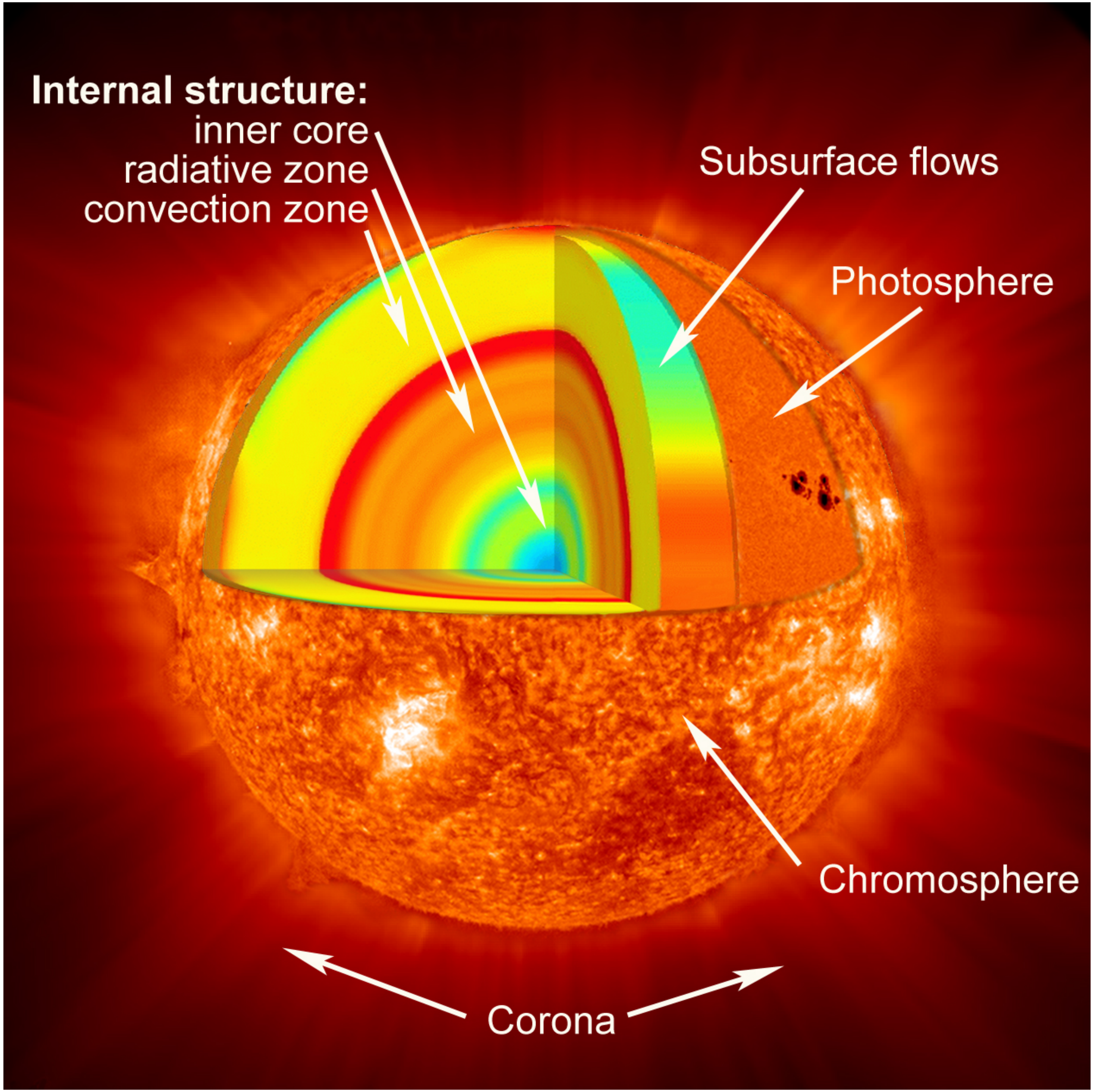


density profile in the Sun



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

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

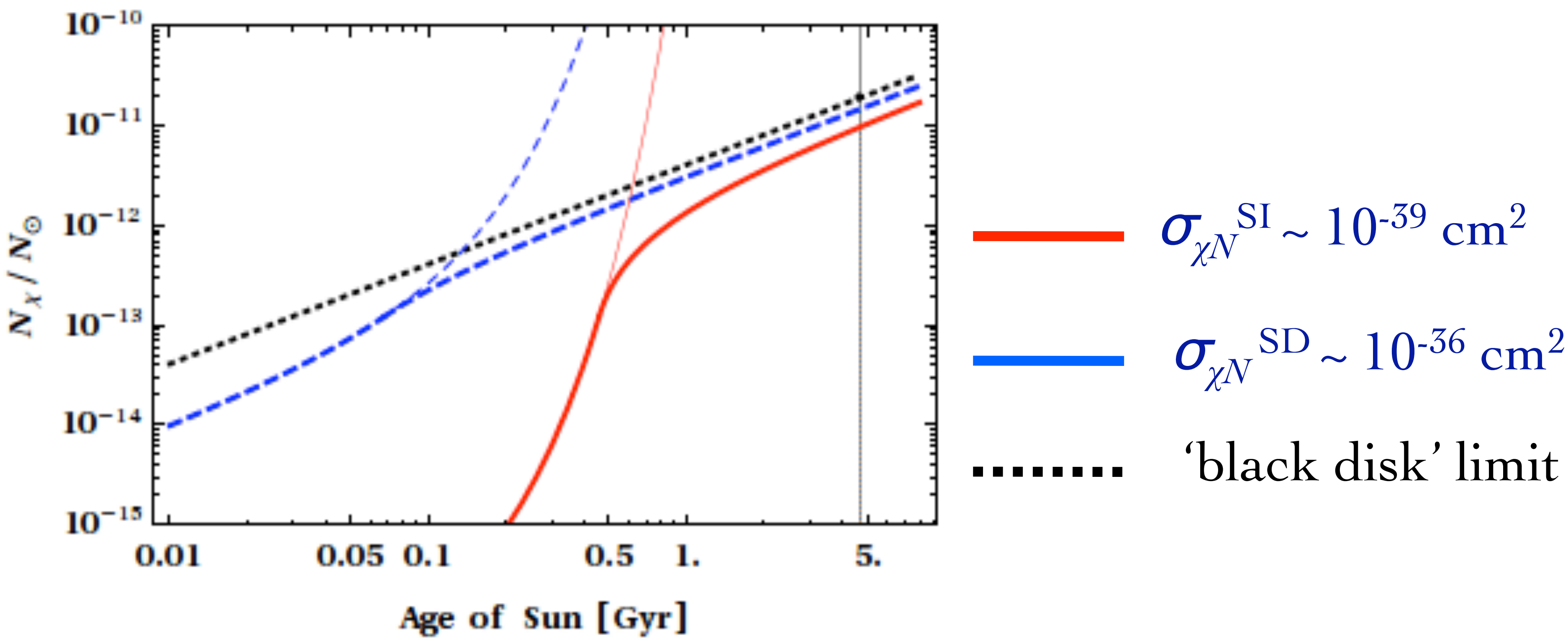

Internal structure:
inner core
radiative zone
convection zone
Subsurface flows
Photosphere
Chromosphere
Corona

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)

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

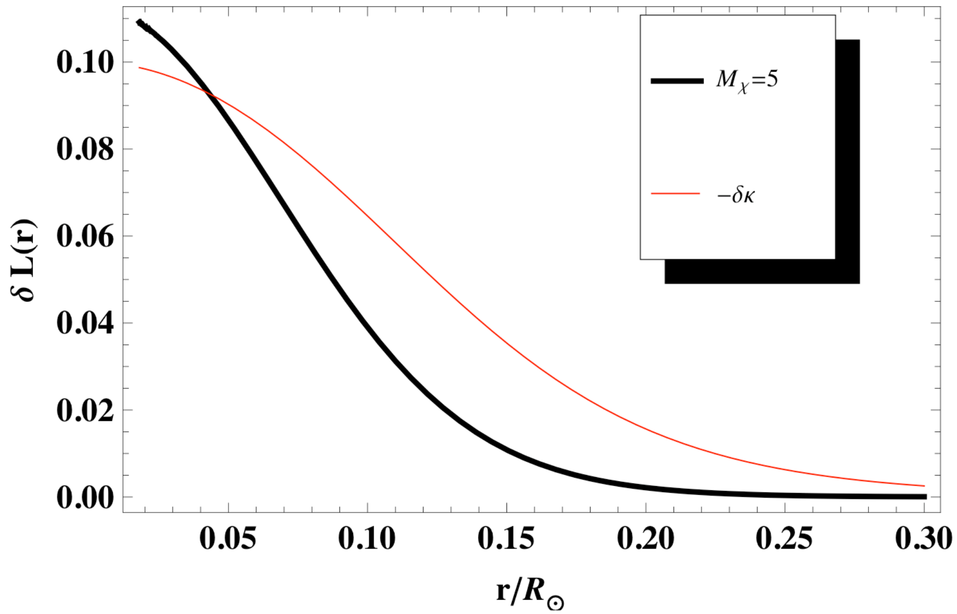
Self-capture rate: $C_{\chi\chi} = \sqrt{\frac{3}{2}}\, \rho_{\rm local}\, s_\chi\, \frac{v_{\rm esc}^2(R_\odot)}{\bar{v}} \langle\phi\rangle \frac{\mathrm{erf}(\eta)}{\eta}$



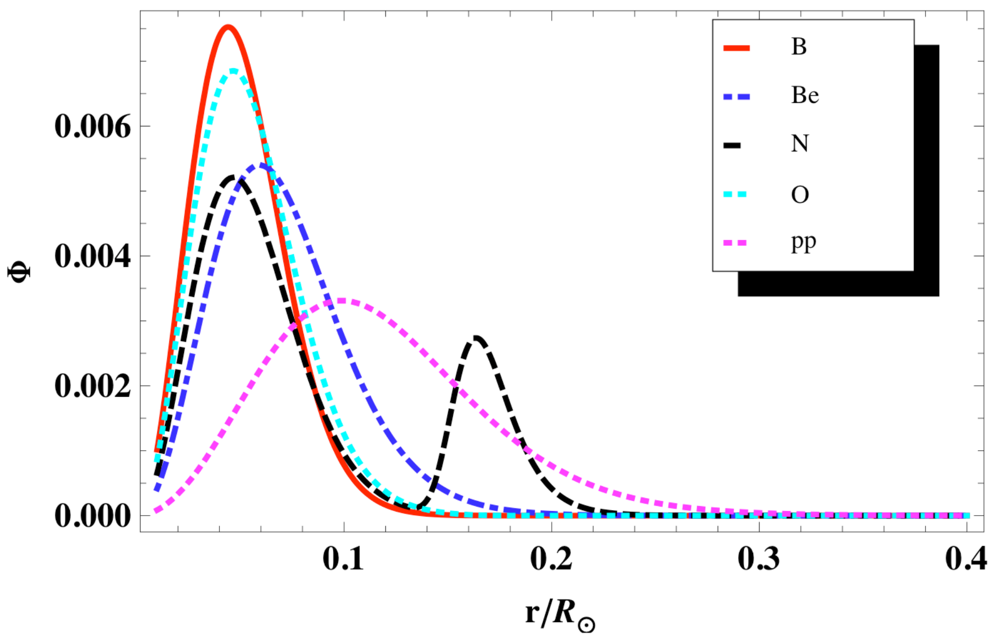
ADM will transport heat outward in the Sun: $L_\chi \sim 4 \times 10^{12} L_\odot \frac{N_\chi}{N_\odot} \frac{\sigma_{\chi N}}{\sigma_\odot} \sqrt{\frac{m_N}{m_\chi}}$

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

(Bottino *et al* 2002)

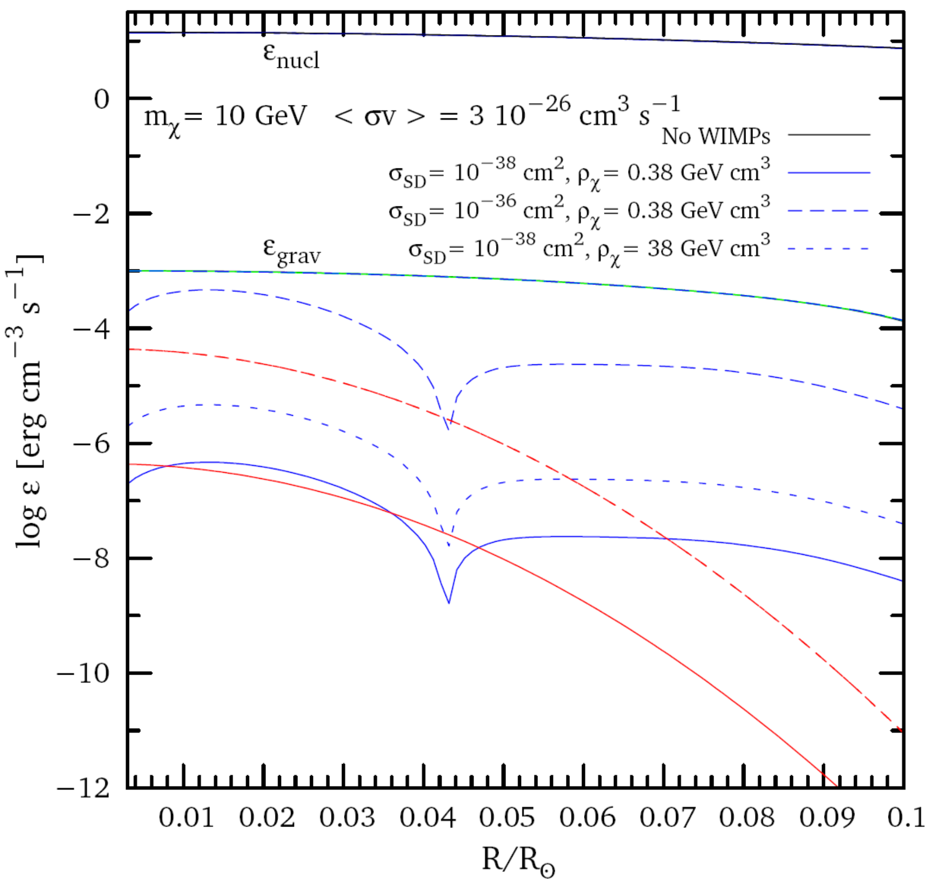


According to the 'Linear Solar Model' (Villante & Ricci 2009), a ~10% reduction of the opacity in the core will reduce the convective boundary by ~0.7% and *restore* agreement with helioseismology

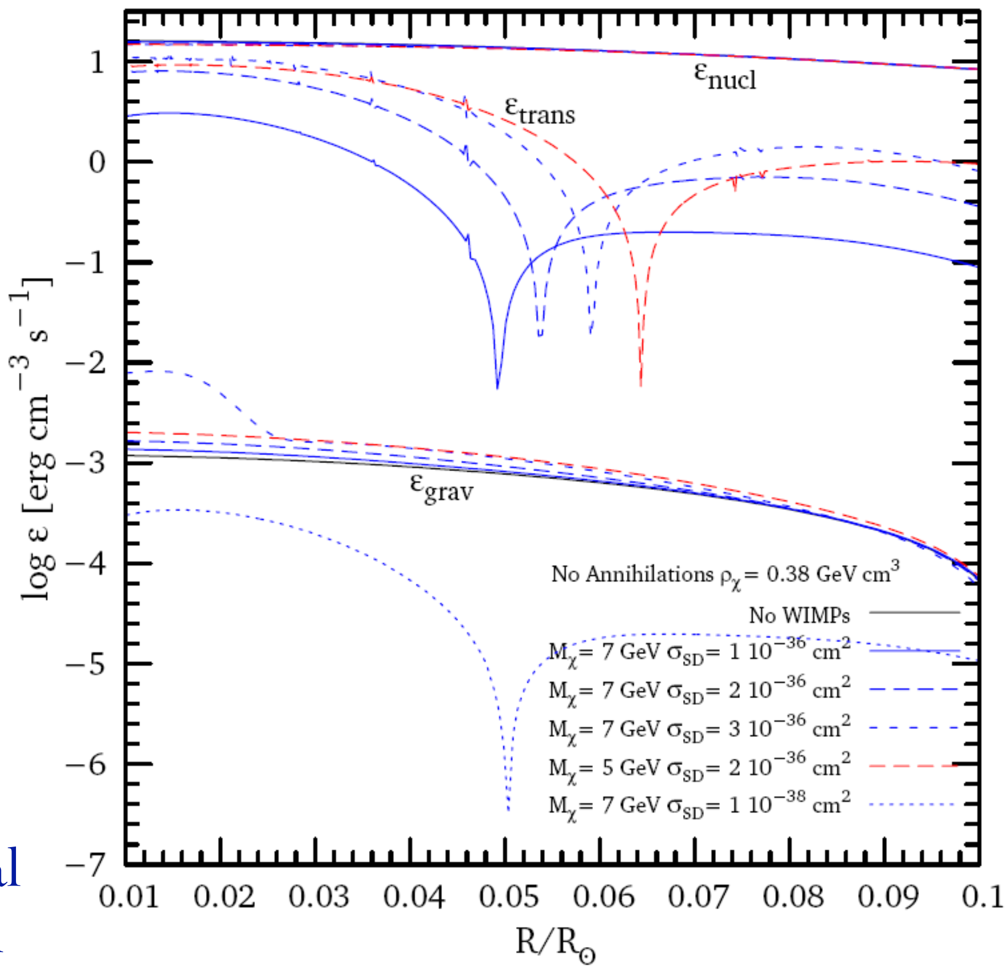


Modification of the luminosity profile will reduce ν fluxes: $\delta\Phi_B$ = -17%, $\delta\Phi_{Be}$ = -6.7%, $\delta\Phi_N$ = -10%, $\delta\Phi_O$ = -14% … *testable* by Borexino & SNO$^+$

(Frandsen & Sarkar 2010)



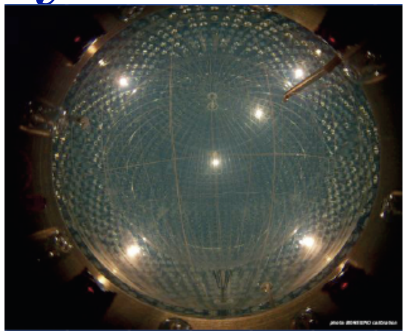
Using the GENEVA code to evolve the Sun, Taoso *et al* (2010) confirm that the effect on energy transport within the Sun is negligibly small for *annihilating* dark matter

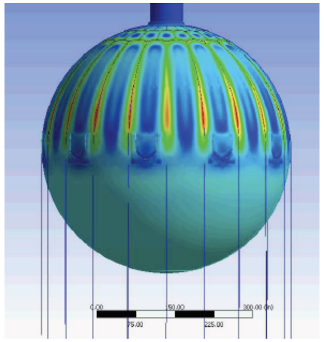


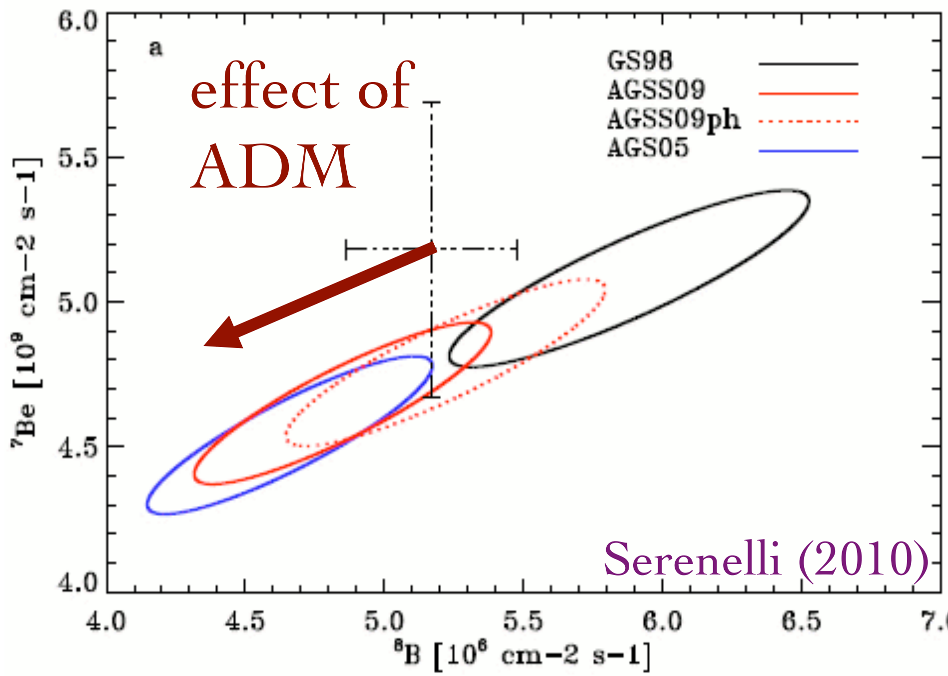
… but a significant effect is seen for *asymmetric* dark matter (although not as far out as the convective boundary)

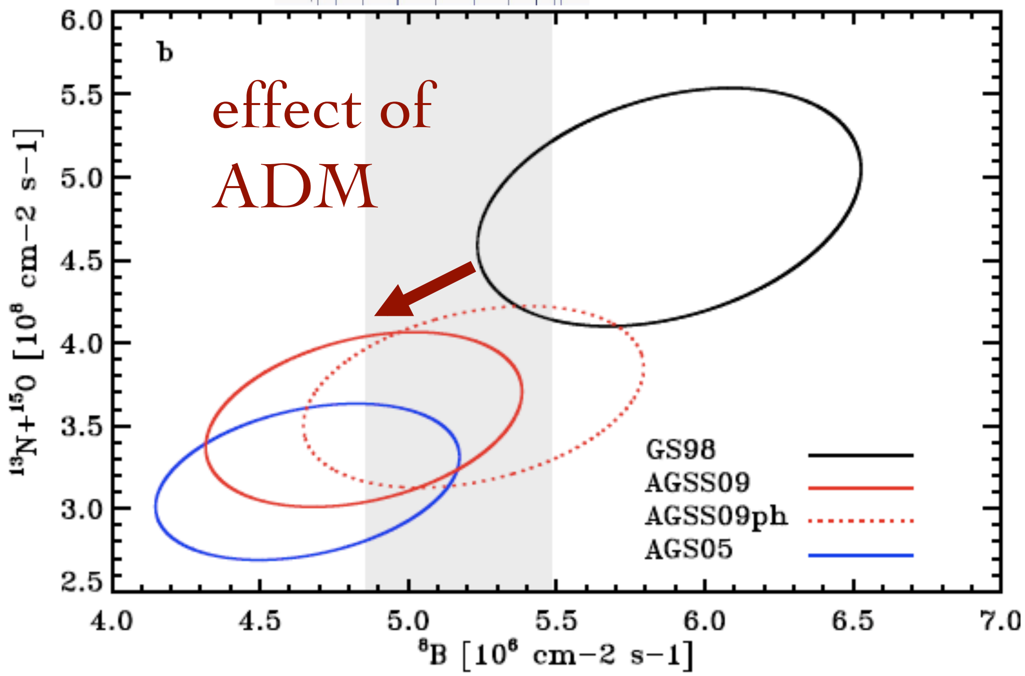
Cumberbatch *et al* (2010) also obtain a *smaller* effect than we do from a numerical Solar model … this is under investigation (Particles as light as 5 GeV are hard to simulate)

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







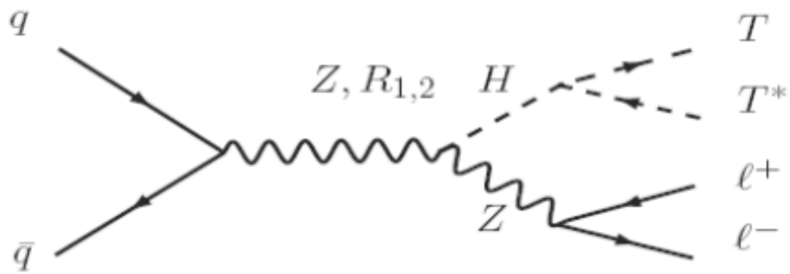


SNO: $\Phi(^8B) = 5.18 \pm 0.29 \times 10^6\ cm^{-2}\ s^{-1}$; **Borexino**: $\Phi(^7Be) = 5.18 \pm 0.51 \times 10^9\ cm^{-2}\ s^{-1}$

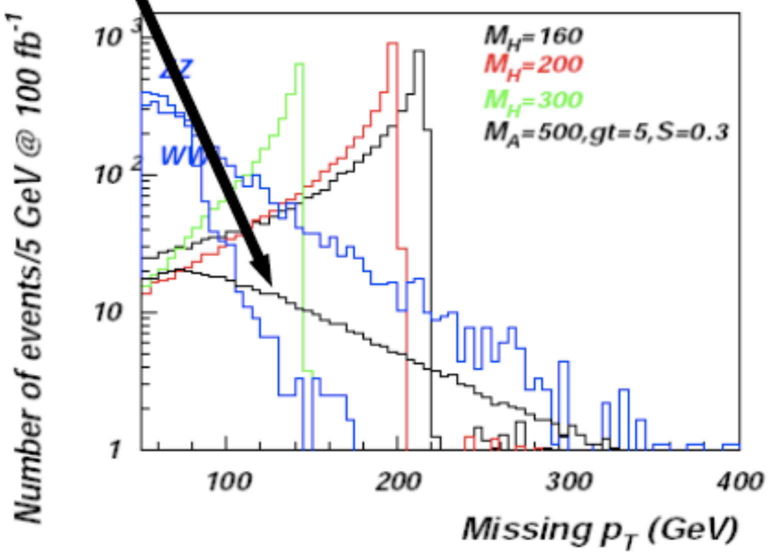
Measurement of ^{13}N and ^{15}O fluxes by SNO+ will provide additional constraint .. but it may be hard to distinguish between effects of metallicity and dark matter

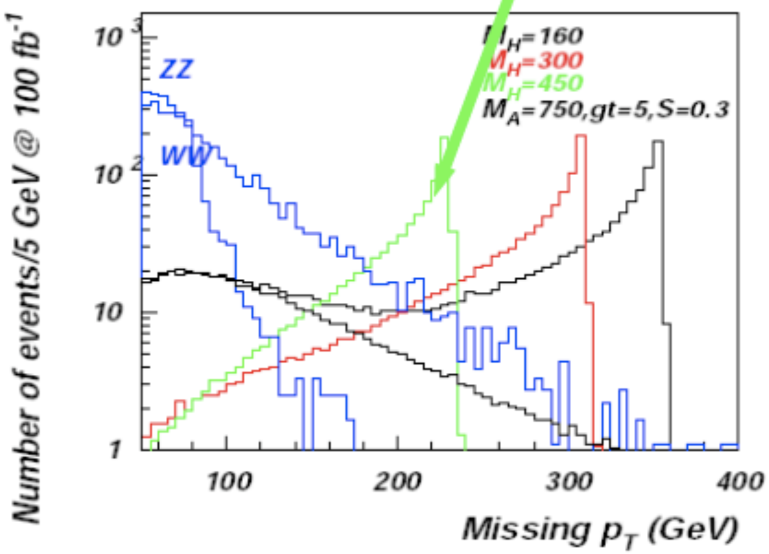
LHC Signals

SM-like Higgs
Decaying 'invisibly'
e.g. to 'dark baryon'



Resonance peaks from
composite Higgs
decaying 'invisibly', e.g.
TIMPs or dark baryons





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!