Asymmetric dark matter

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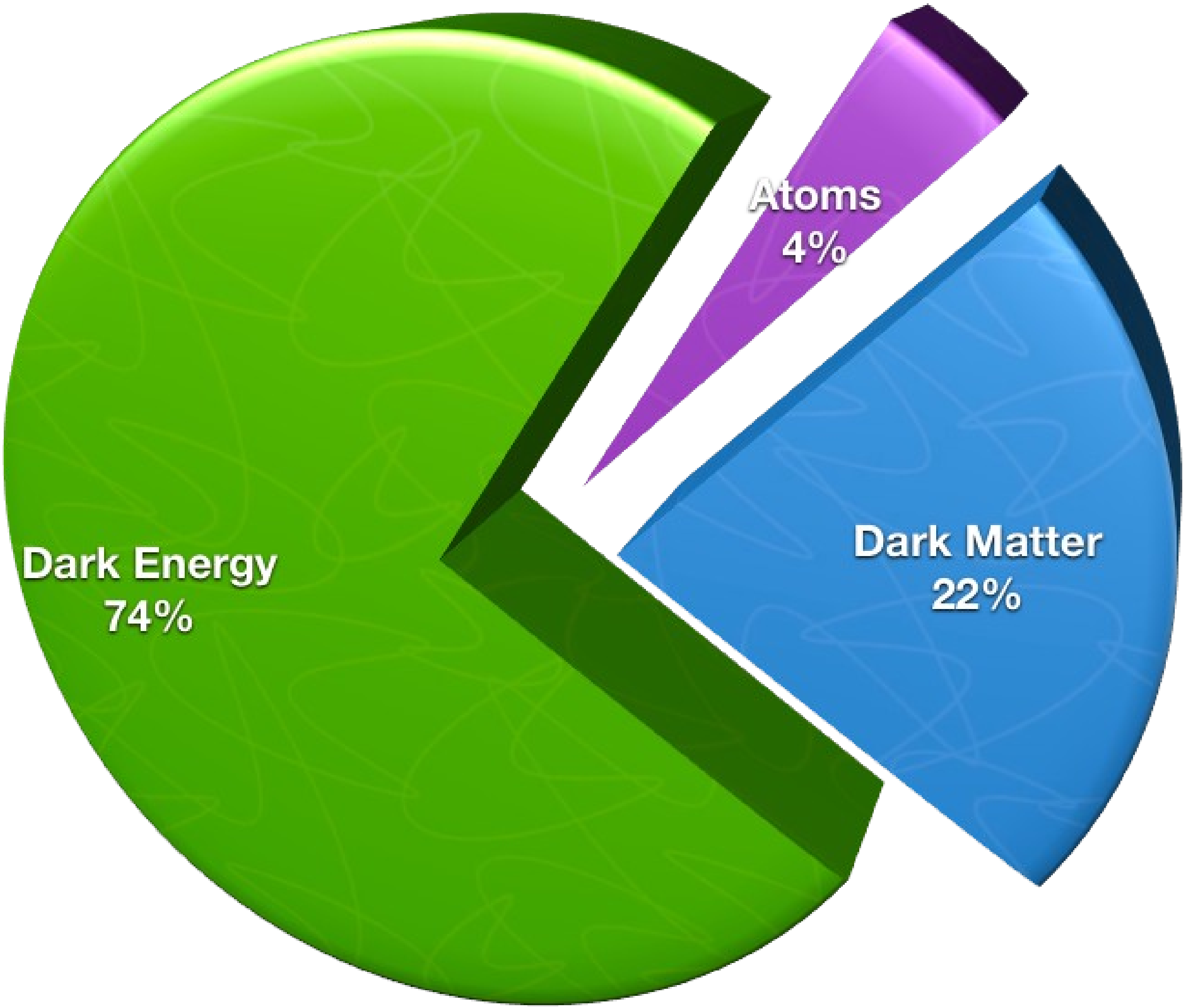
4th Universenet School Lecce
Based in (large) part on talk by S. Sarkar at SUSY2010

Together with
A.Belyaev, S. Sarkar and F. Sannino
arXiv:1007.4839.
S. Sarkar:
Phys.Rev.Lett.105:011301,2010.
F. Sannino:
Phys.Rev.D81:097704,2010.
R. Foadi, F. Sannino
Phys.Rev.D80:037702, 2009.

What is the world made of?



What should the world be made of ?

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
Λ_{QCD}	**Nucleons**	U(1) baryon number	⊗ > 10^{33} yr (dim-6 OK)	'freeze-out' from thermal equilibrium	$\Omega_B \sim 10^{-10}$ cf. observed $\Omega_B \sim 0.05$

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

Chemical equilibrium maintained when annihilaton rate exceeds the Hubble expansion rate

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

'Freeze-out' at T ~ m_N/45, with:

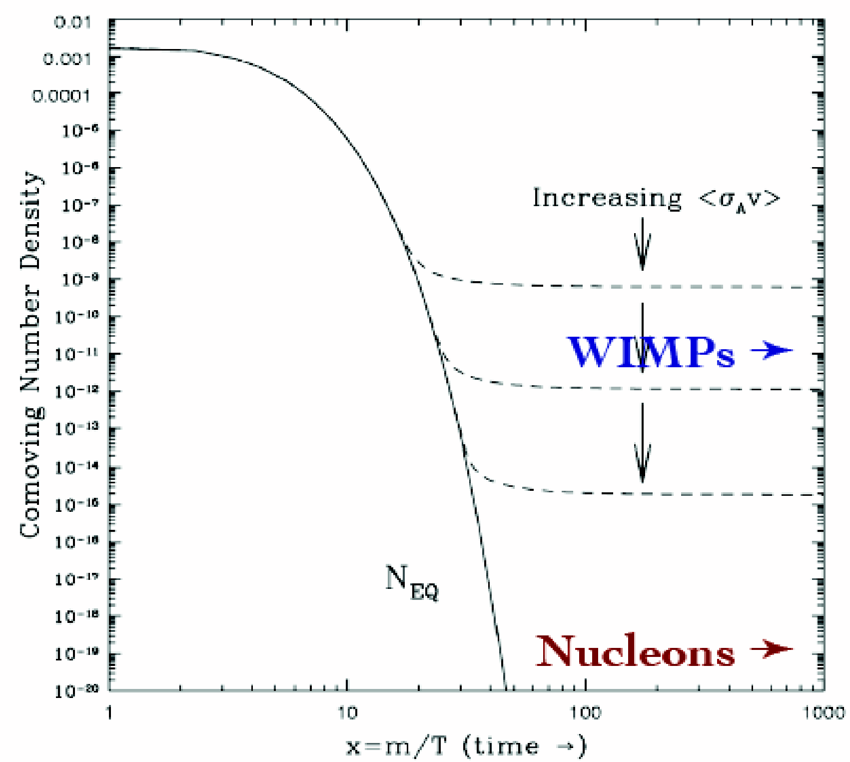
$$\frac{n_N}{n_\gamma} = \frac{n_{\bar{N}}}{n_\gamma} \sim 10^{-19}$$

Observed ratio is 10^9 Times bigger:

A 'baryon disaster'?!

Have to invoke an **asymmetry:**

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



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$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino?	R-parity?	violated?	'freeze-out' from thermal equilibrium	$\Omega_{LSP} \sim 0.3$

For (softly broken) susy we think of the 'WIMP miracle':

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

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

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
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$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino? Technibaryon?	R-parity? U(1) technibaryon number	violated? ?	'freeze-out' from thermal equilibrium Asymmety	$\Omega_{LSP} \sim 0.3$ $\Omega_{TB} \sim 0.3$
$\Lambda_{DB} \sim 5\ \Lambda_{QCD}$	Dark Baryon?	U(1) dark daryon number	?	Asymmetry	$\Omega_{DB} \sim 0.3$

$$\frac{\rho_{\rm DM}}{\rho_{\rm B}} \simeq 6 \sim \frac{m_{\rm DM}}{m_{\rm B}} \left(\frac{m_{\rm DM}}{m_{\rm B}}\right)^{3/2} e^{-m_{\rm DM}/T_{\rm dec|sphaleron}}$$

A TeV scale particle sharing the asymmetry, e.g. a technibaryon, would explain the ratio of dark to baryonic matter... (Nussinov 1985)

Or more naturally a ~5 GeV particle (e.g. a 'dark baryon' from a hidden strong sector)

(Gelmini et al 87, Raby and West 87, DB Kaplan 92, Hooper et al 05, Kitano and Low 05, DE Kaplan et al 09, Kribs et al 09, An et al 10...)

Sakharov conditions for baryogenesis:

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

Any pre-existing fermion asymmetry would be redistributed by the B+L violating processes (which conserve B-L) :

$$\partial_\mu j_i^\mu = \partial_\mu(\bar{\psi}^i \gamma^\mu \psi^i) = \frac{g^2}{8\pi} W^{a\mu\nu} \tilde{W}^a_{\mu\nu} \longrightarrow N^i(T) - N^j(T) = N_0^i - N_0^j .$$

The fermion number in terms of the statistical function c_i and the Chemical potential is:

$$N^i(T) = c_i(m_i, T)\mu_i / T .$$

The fermion violating Processes (sphalerons) Create equal number of fermion doublets:

$$\sum_i \mu_i = 0 .$$

$$\longrightarrow N^i(T) = N_0^i - \frac{\sum_j N_0^j / c_j(m_j, T)}{\sum_j 1/c_j(m_j, T)}$$

(Bahr, Chivukula and Farhi 90)

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'

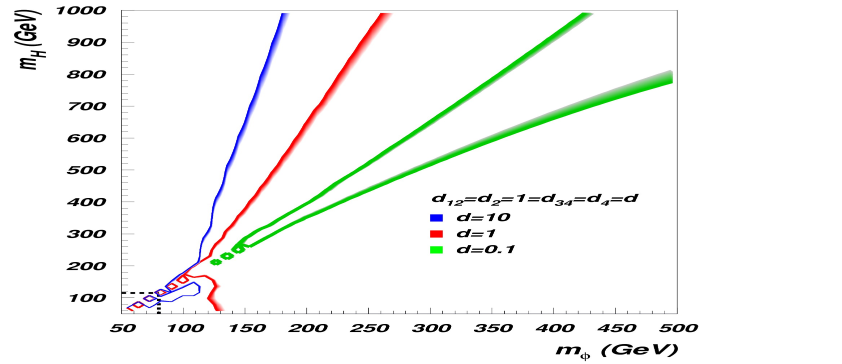
- $\mathcal{R}$ pseudo-real
- $T^0 \sim UD$
- SM singlet GB
- $M_{T^0}^2 \sim -g^2\, F_\Pi^2$

(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:



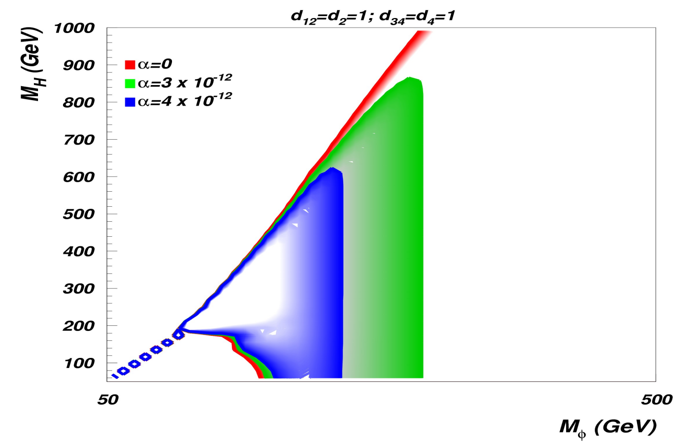
$$\phi \sim \lambda\lambda,$$

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

$$+ \frac{d_2}{\Lambda} m_\phi^2 H \phi^* \phi + \frac{d_3}{2\Lambda^2} H^2 \partial_\mu \phi^* \partial_\mu \phi + \frac{d_4}{2\Lambda^2} m_\phi^2 H^2 \phi^* \phi.$$

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

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

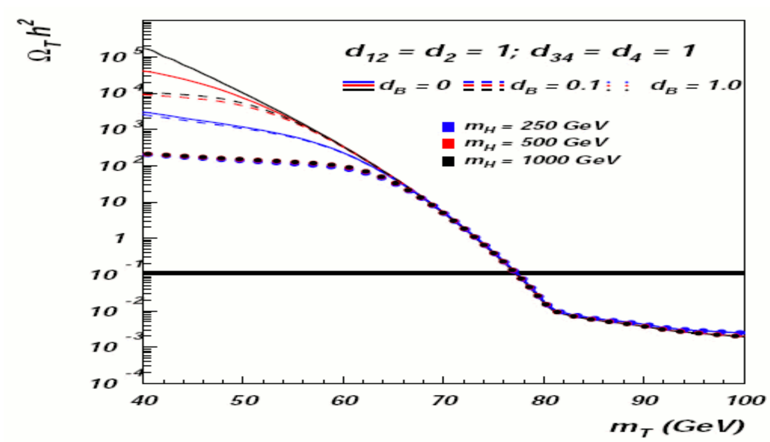


PGB TIMPS with charged constituents, generically have contact Interactions with weak gauge bosons:

$$T \sim UD$$

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

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



What should the world be made of ?

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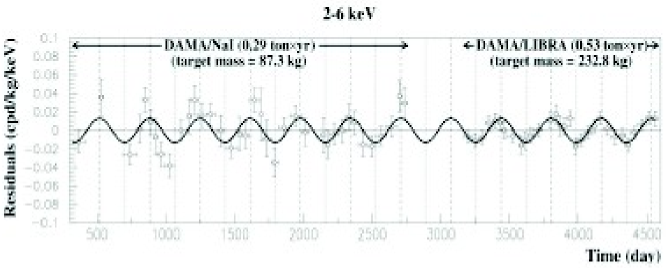
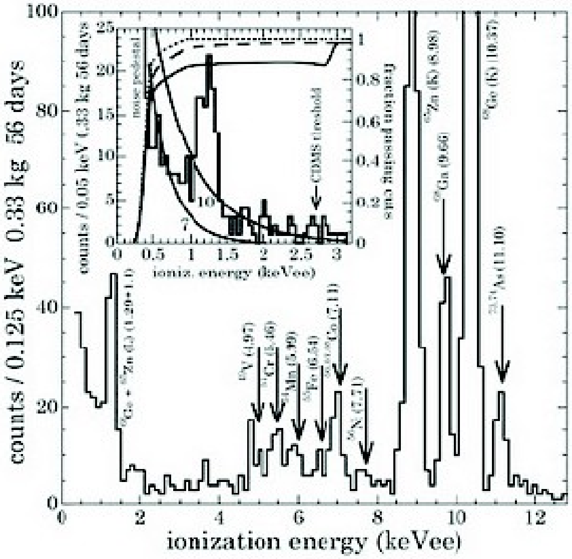
$\sim \Lambda_{Fermi}$	Neutralino	R-parity?	violated?	'freeze-out' from thermal equilibrium	$\Omega_{LSP} \sim 0.3$
$\sim \Lambda_{Fermi}$ ($m > \Lambda_{Fermi}$)	Technibaryon	U(1) technibaryon number	?	Asymmety	$\Omega_{TB} \sim 0.3$
$\sim \Lambda_{Fermi}$ ($m \sim g_W \Lambda_{Fermi}$)	TIMP (PGB)	U(1) technibaryon number	?	(A)symmetry	$\Omega_{TIMP} \sim 0.3$
$\sim 5\ \Lambda_{QCD}$	Dark Baryon?	U(1) dark daryon number	?	Asymmetry	$\Omega_{DB} \sim 0.3$

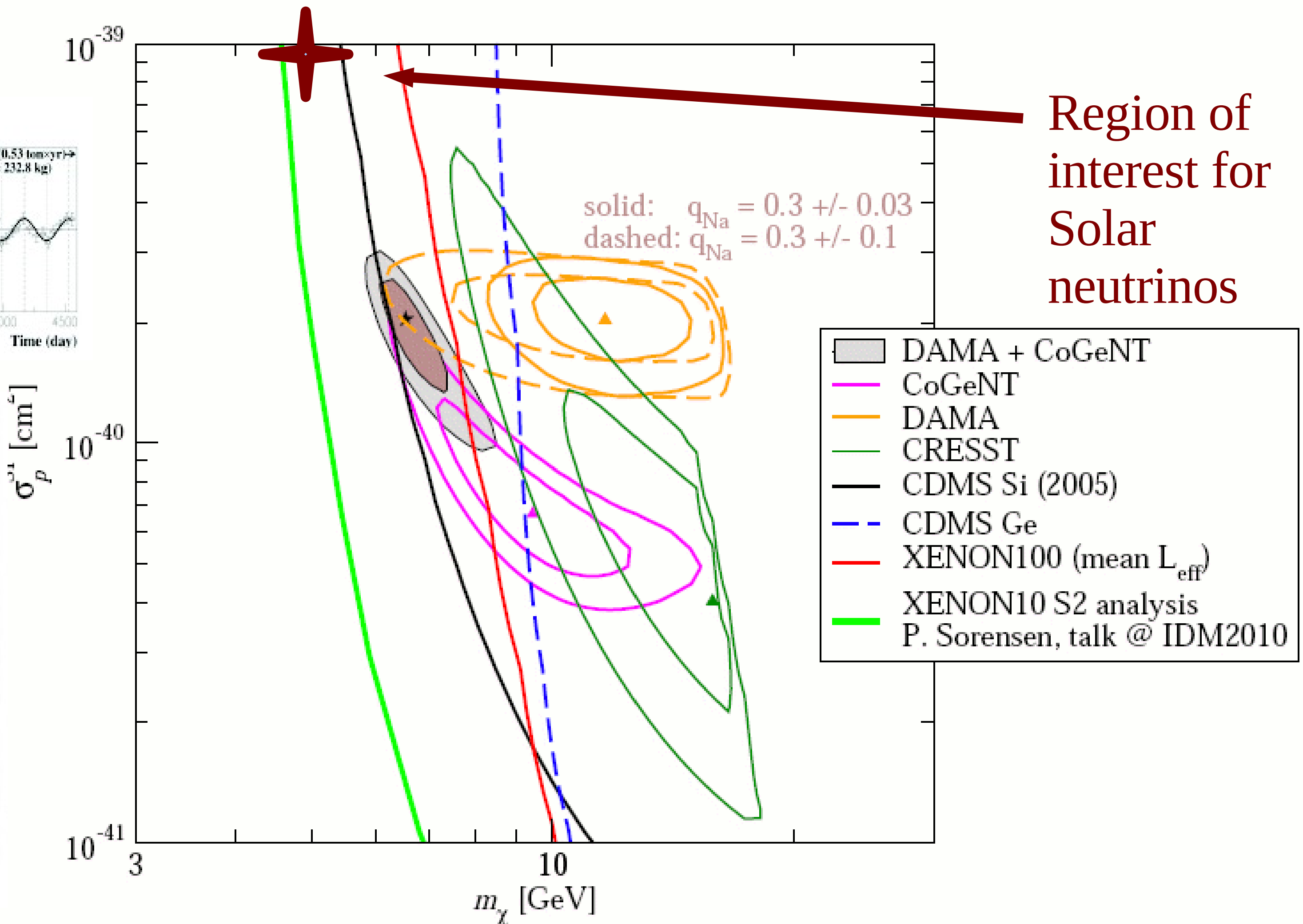
Asymmetric Dark Matter have no annihilation signals of neutrinos, positrons, gamma rays etc... (but may have decay signals)

What are the possible signals?

Several nuclear recoil experiments reported events close to threshold



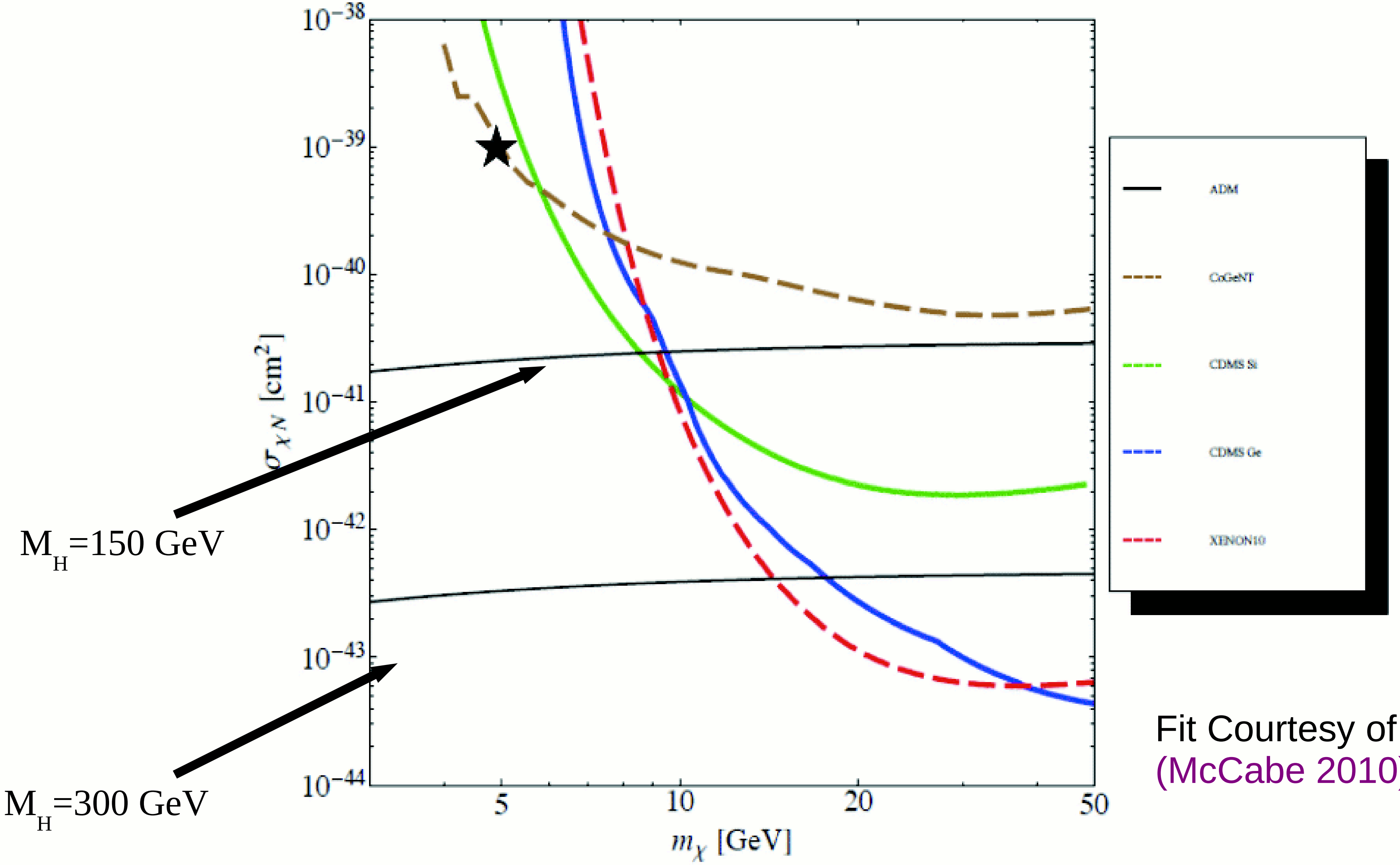




~5 GeV Dark Matter candidates with ~10^{-39} cm^2 spin-independent cross-section remains viable.

Spin-dependent cross-sections up to 10^{-36} cm^2

Higgs exchange can naturally provide up to ~10^{-41} cm^2



Fit Courtesy of C. McCabe (McCabe 2010)

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*)

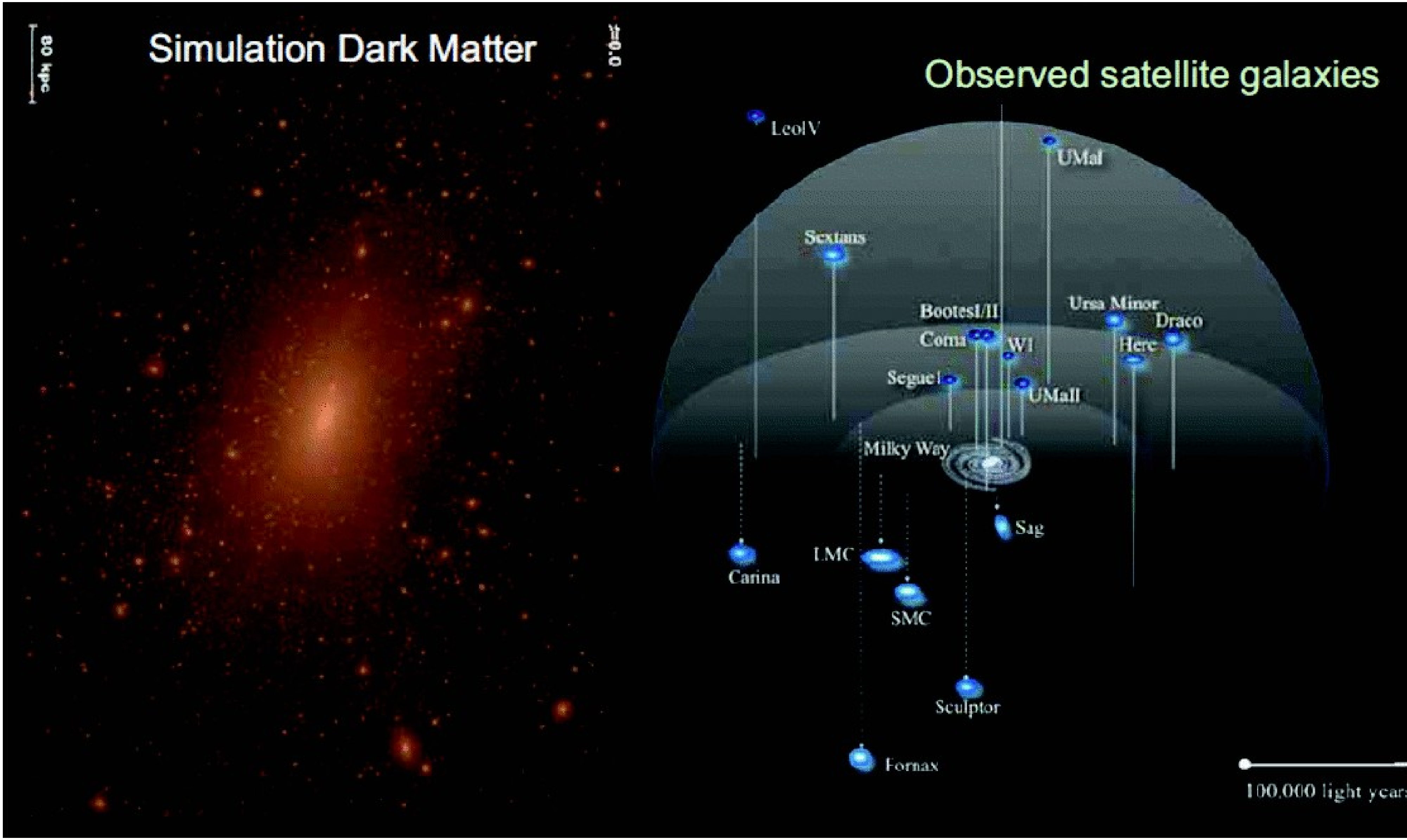
Such particles would also be naturally **self-interacting** with a typical cross-section: $\sigma_{\chi\chi} \sim \sigma_{nn} (m_n/m_\chi)^2$, where $\sigma_{nn} \sim 10^{-23}$ cm^2

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

Long range self-interactions are more tightly constrained by the 'Bullet cluster'

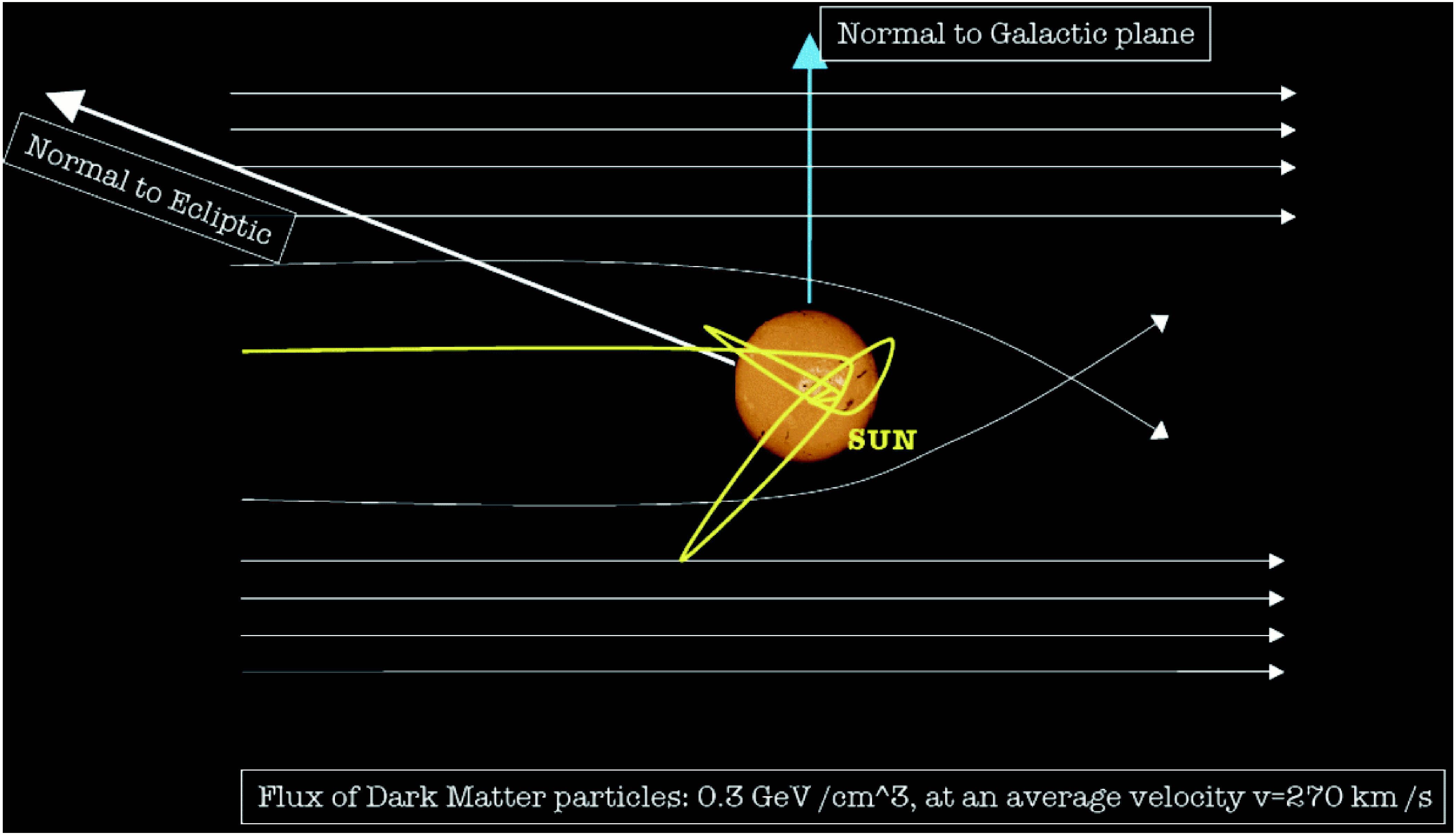
(Feng, Kaplinghat and Yu 10)

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

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

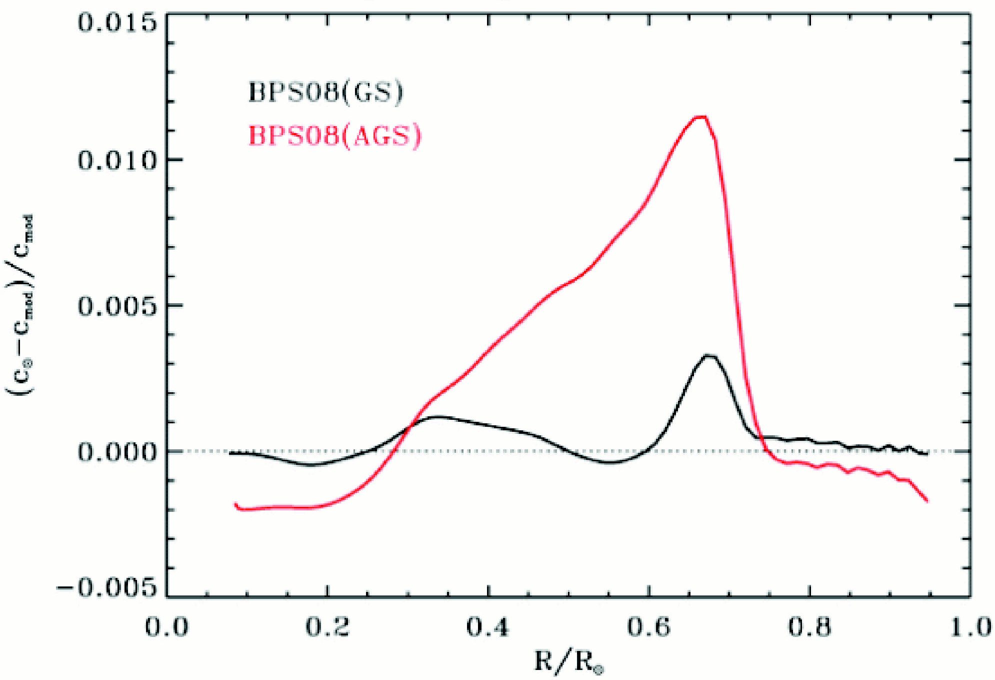


The flux of Solar neutrinos is *very* sensitive to the core temperature and can thus be *reduced* (Steigman *et al* 1978, Faulkner *et al* 1985, Press & Spergel 1985, Gould 1987)

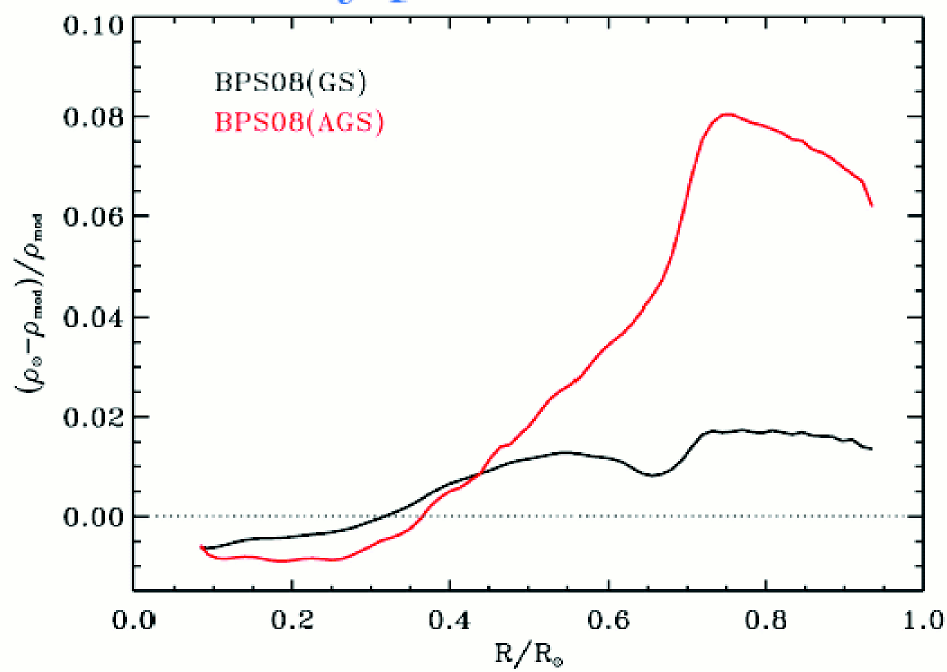
A problem with the standard Solar model

- 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



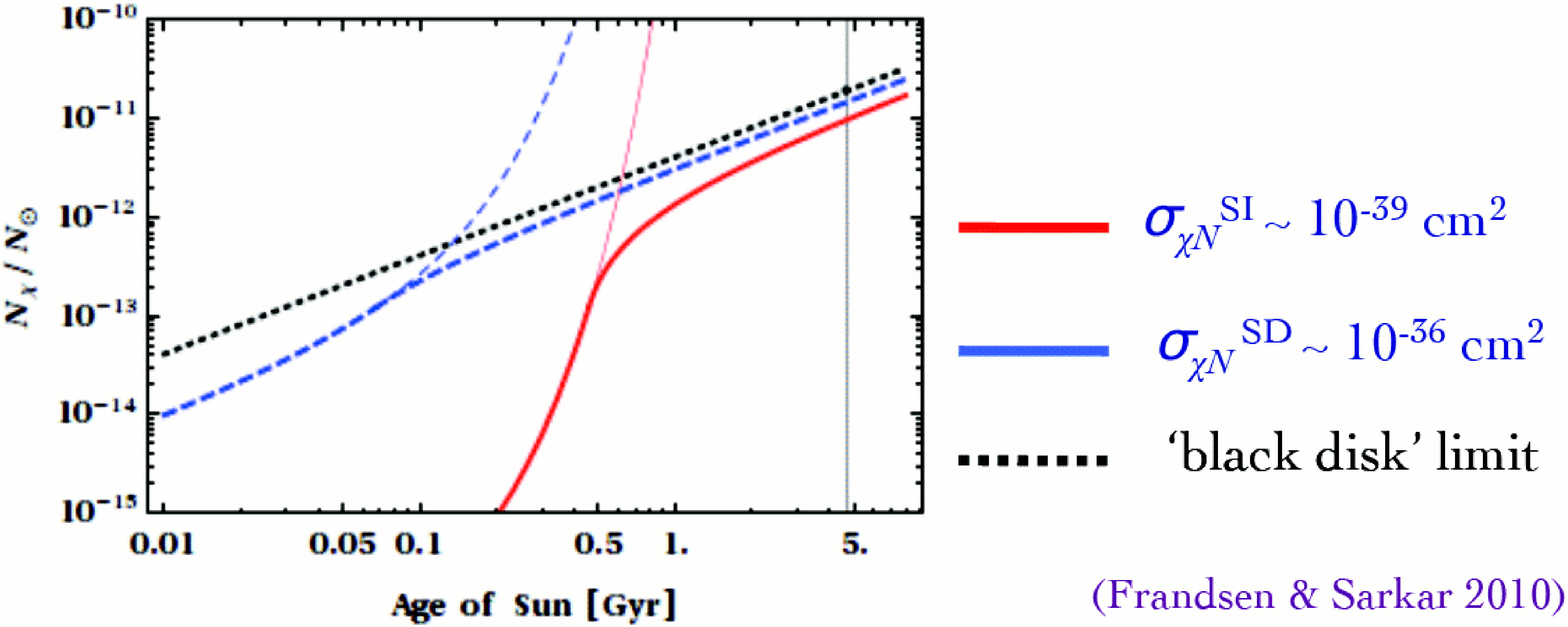
Could light dark matter particles accreted by the Sun solve this problem?
(Villante, talk@TAUP'09, Frandsen & Sarkar 2010)

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

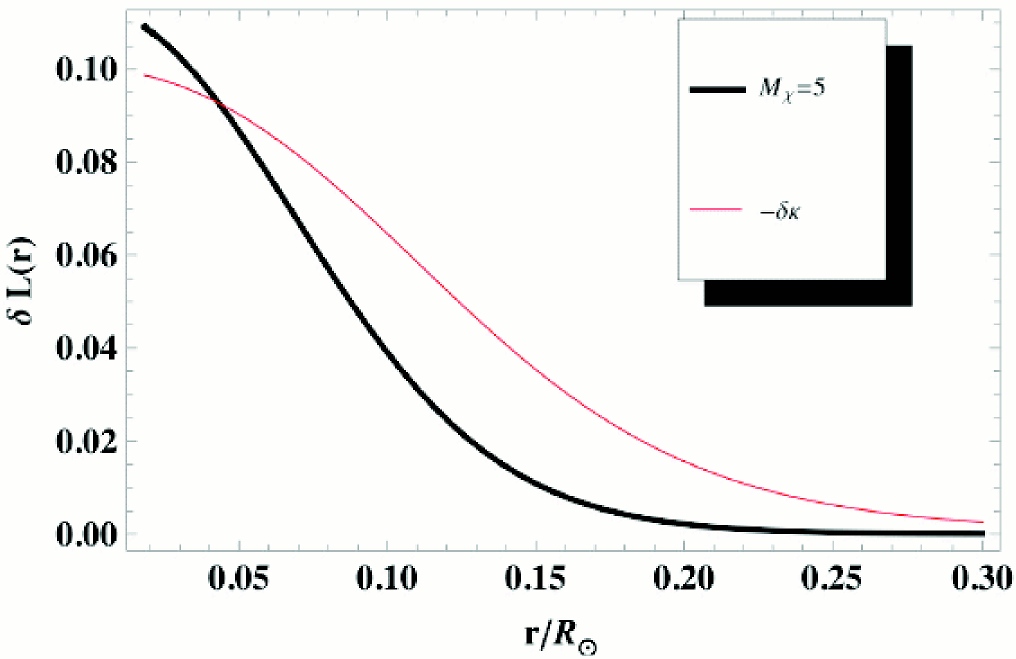


(Frandsen & Sarkar 2010)

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)



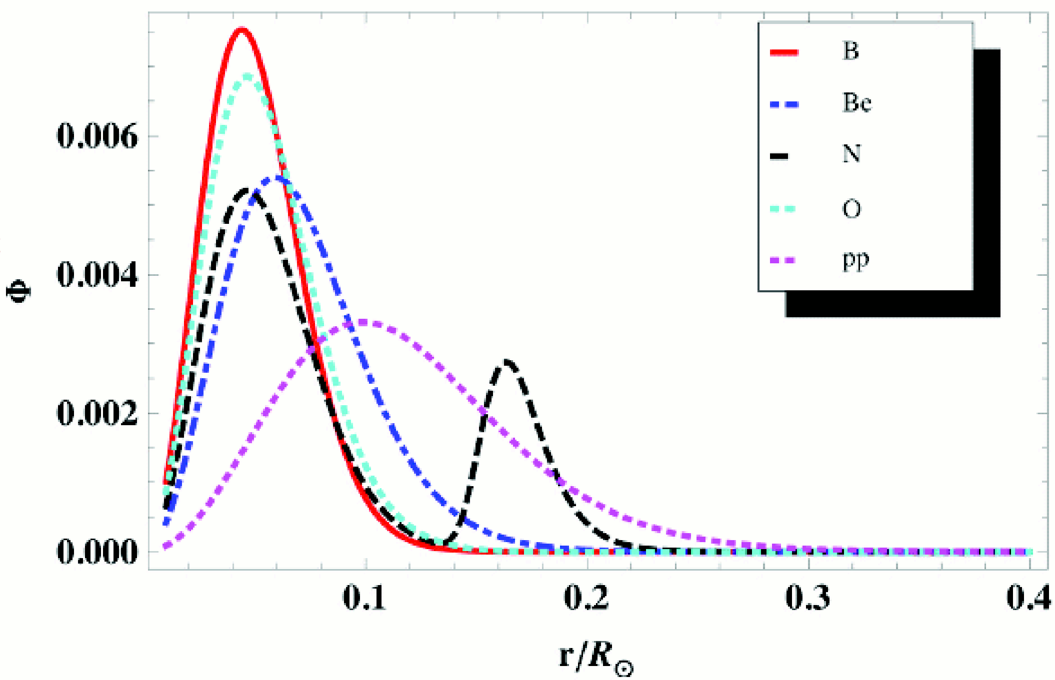
According to the 'Linear Solar model' (Villante & Ricci 2009) a ~10% reduction of the opacity in the core lowers the convective boundary by ~0.7% so will (largely) *restore* agreement with helioseismology

Modification of the luminosity profile will also reduce neutrino fluxes:

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

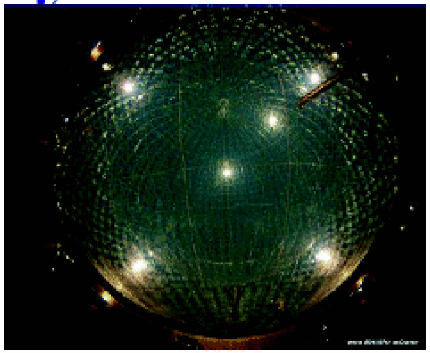
$\delta\Phi_N$ = -10%, $\delta\Phi_O$ = -14%

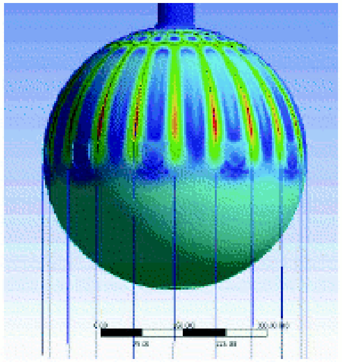
… *testable* by Borexino & SNO$^+$



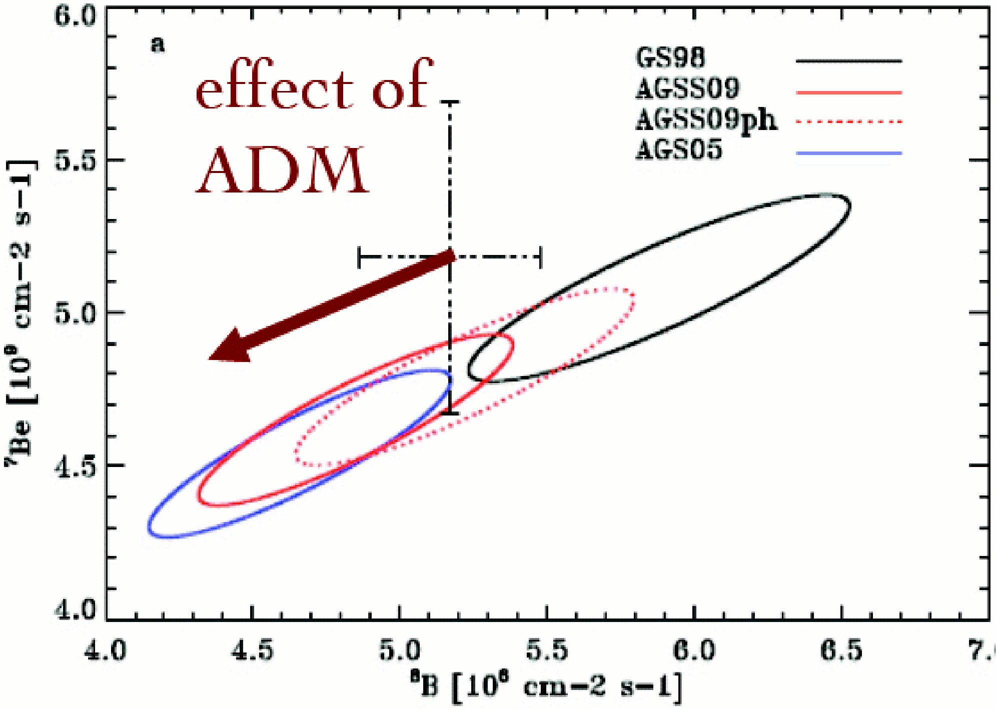
(Frandsen & Sarkar 2010)

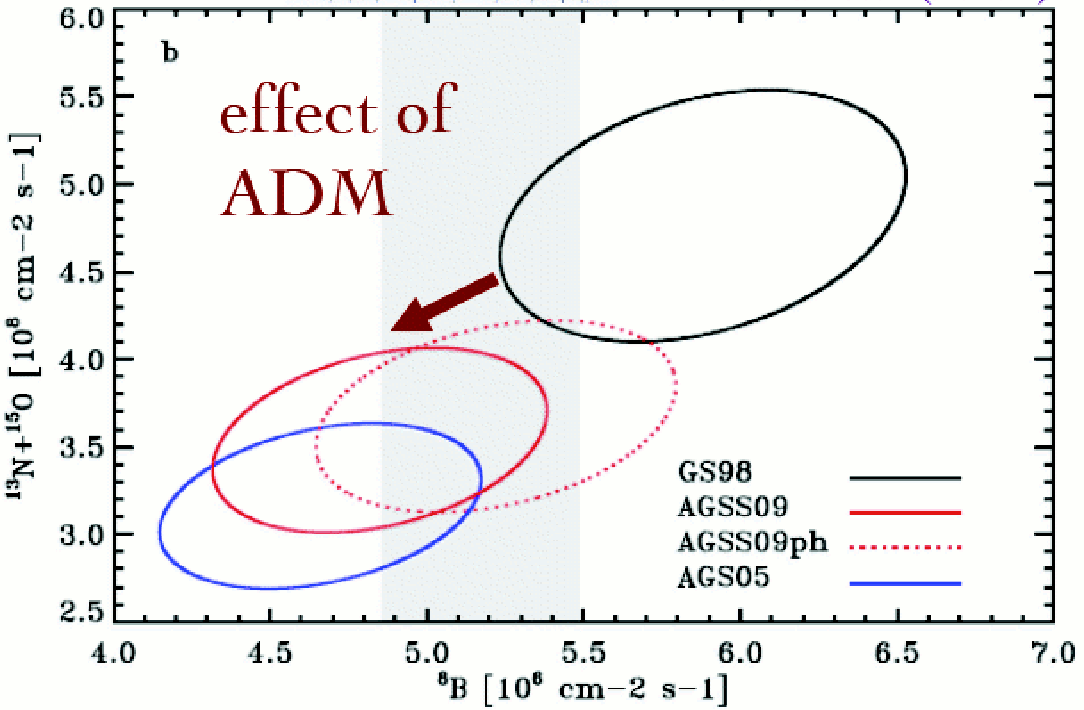
Forthcoming precision measurements of Solar neutrinos by Borexino and SNO+ can *test* the model





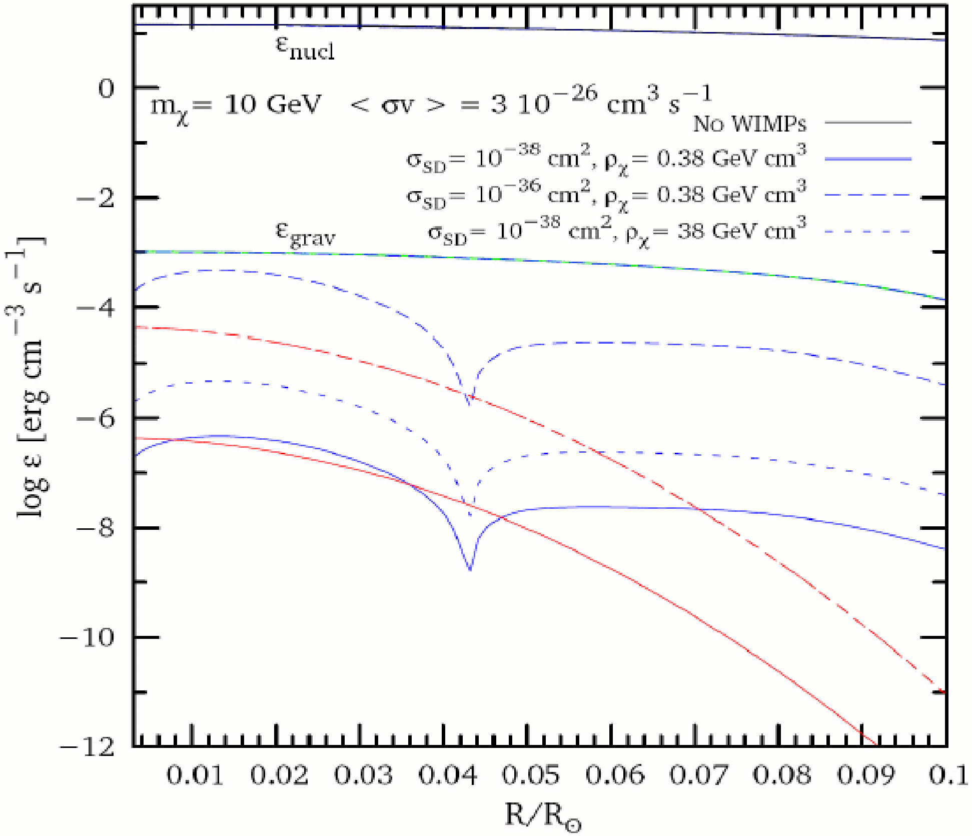
Serenelli (2010)



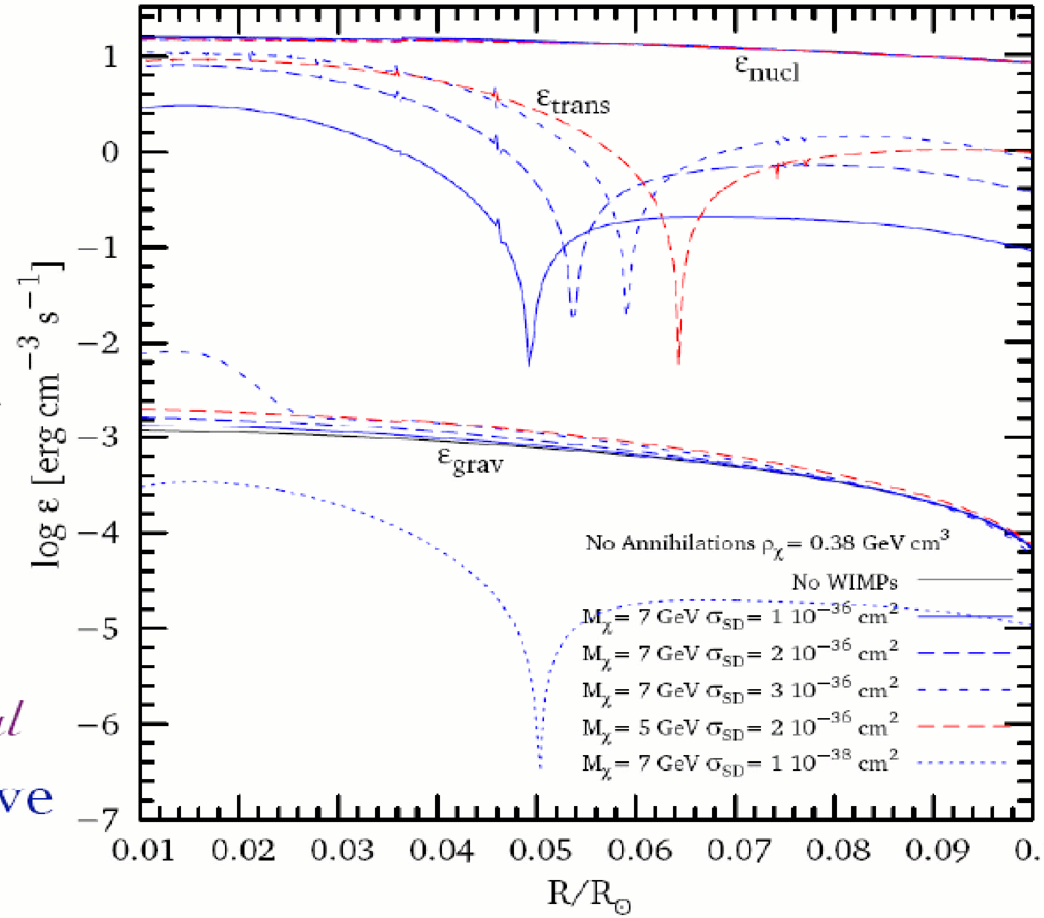


SNO: $\Phi(^8B) = 5.18 \pm 0.29 \times 10^6\ cm^{-2}\ s^{-1}$; **Borexino:** $\Phi(^7Be) = 5.18 \pm 0.51 \times 10^9\ cm^{-2}\ s^{-1}$

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!

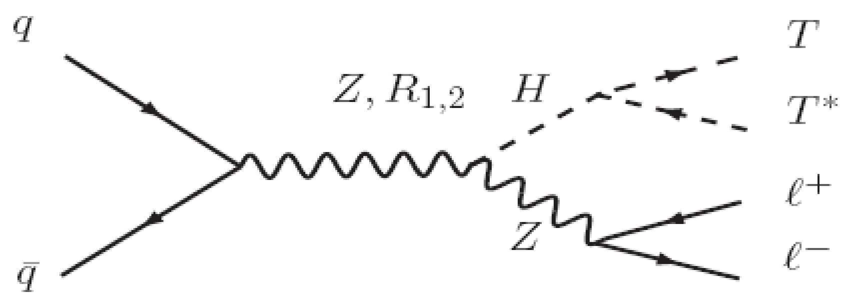
However they (also Cumberbatch *et al* 2010) obtain a *smaller* effect than we do from the analytic 'linear Solar model' … this is under investigation

Recent study of effects of DM on white dwarves and neutron stars, see e.g.

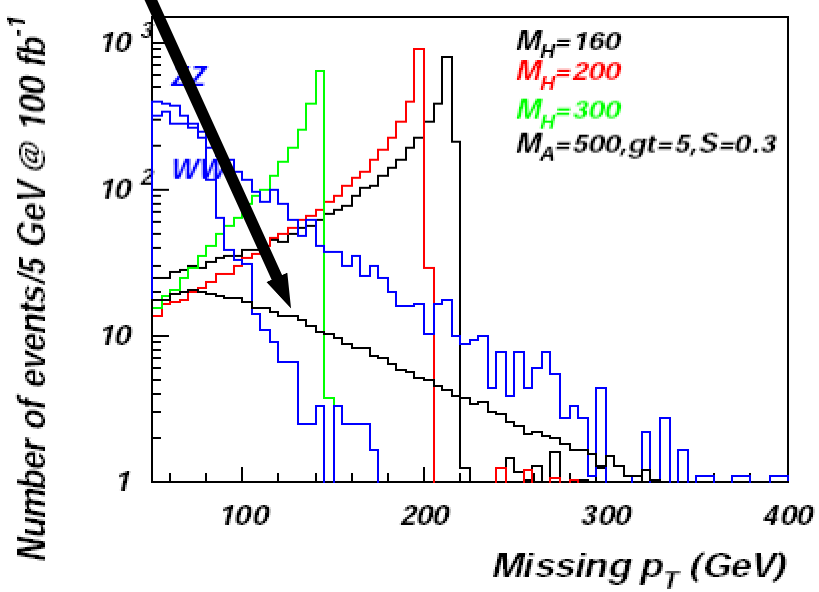
(Fairbairn and McCullough 10 Kouvaris 10)

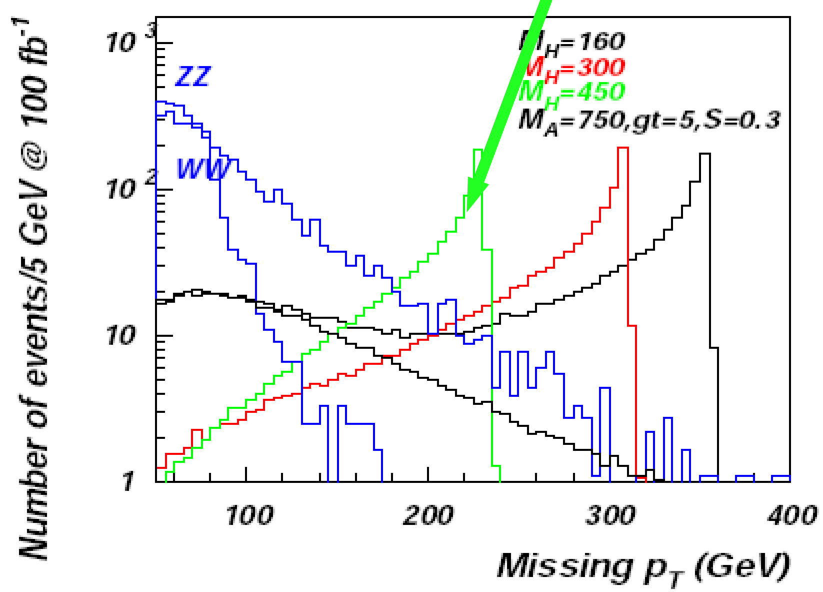
LHC Signals

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 well motivated by the observation of *the asymmetry of baryonic matter* and *explaining* Ω_{DM}/Ω_B

  as well as the *origin, mass and stability* of baryonic matter arising from *Strong Dynamics*

- ~ TeV scale ADM *(Technibaryon)* and ~ 100 GeV scale ADM *(PGB TIMPs)* are natural in Technicolor models of DEWSB.

  ~ GeV scale ADM *(Dark Baryons)* arise from Hidden/Mirror/Unbaryon sectors.

- *Distinct pattern of signatures*

- Absence of annihilation signatures, high possible capture rates in stars, resonance structure in missing energy observables at LHC