Asymmetric dark matter

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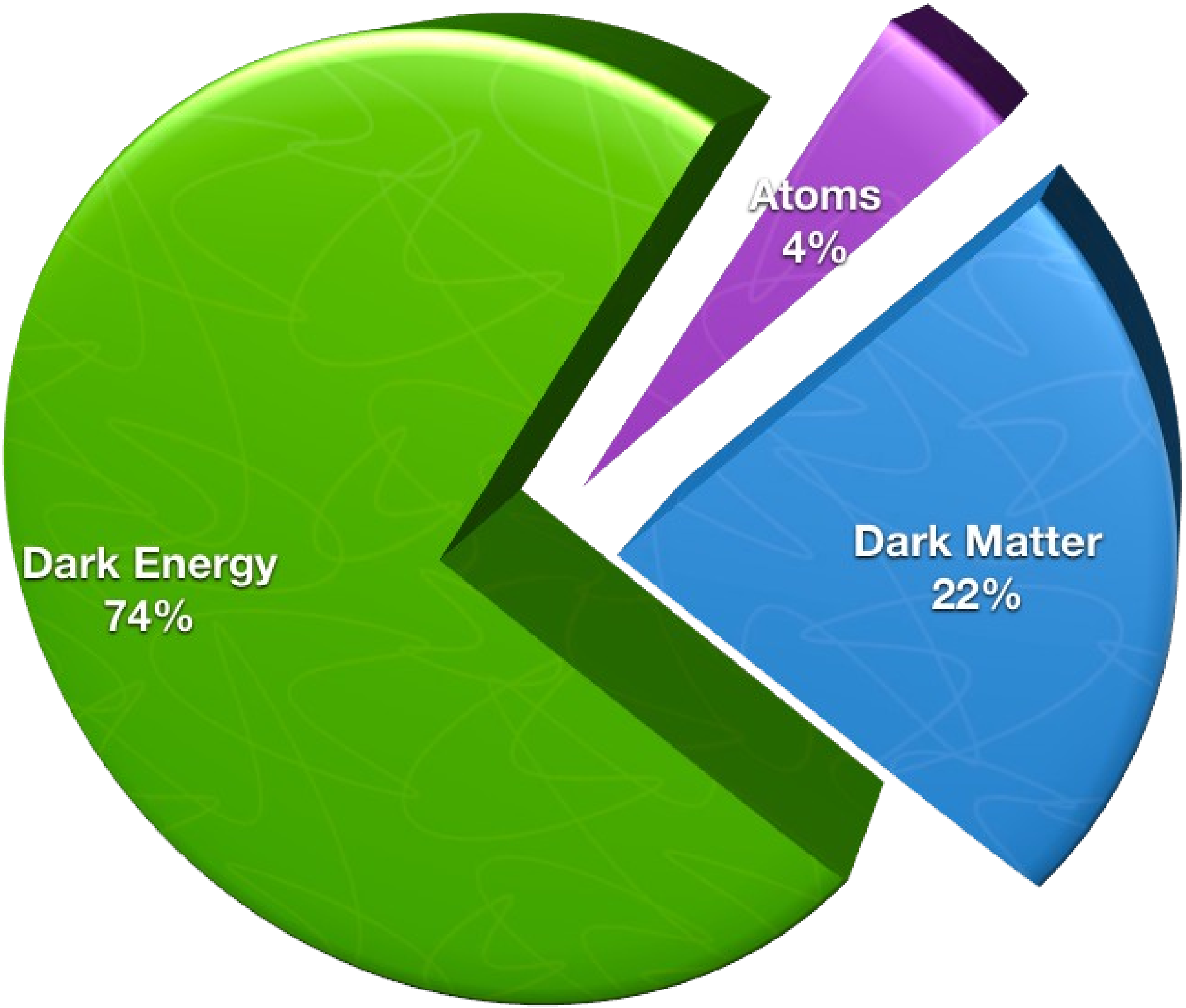
Outline

- *Asymmetric Dark Matter*
- Symmetric vs Asymmetric Cold Dark Matter
- Direct Detection and Models of Light Asymmetric Dark Matter
- *Indirect Detection: Capture in the sun*
- Helioseismology and neutrino fluxes
- *Summary*

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	$\otimes > 10^{33}$ yr (dim-6 OK)	'freeze-out' from thermal equilibrium	$\Omega_B \sim 10^{-10}$ cf. observed $\Omega_B \sim 0.05$

Thermal Relics

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

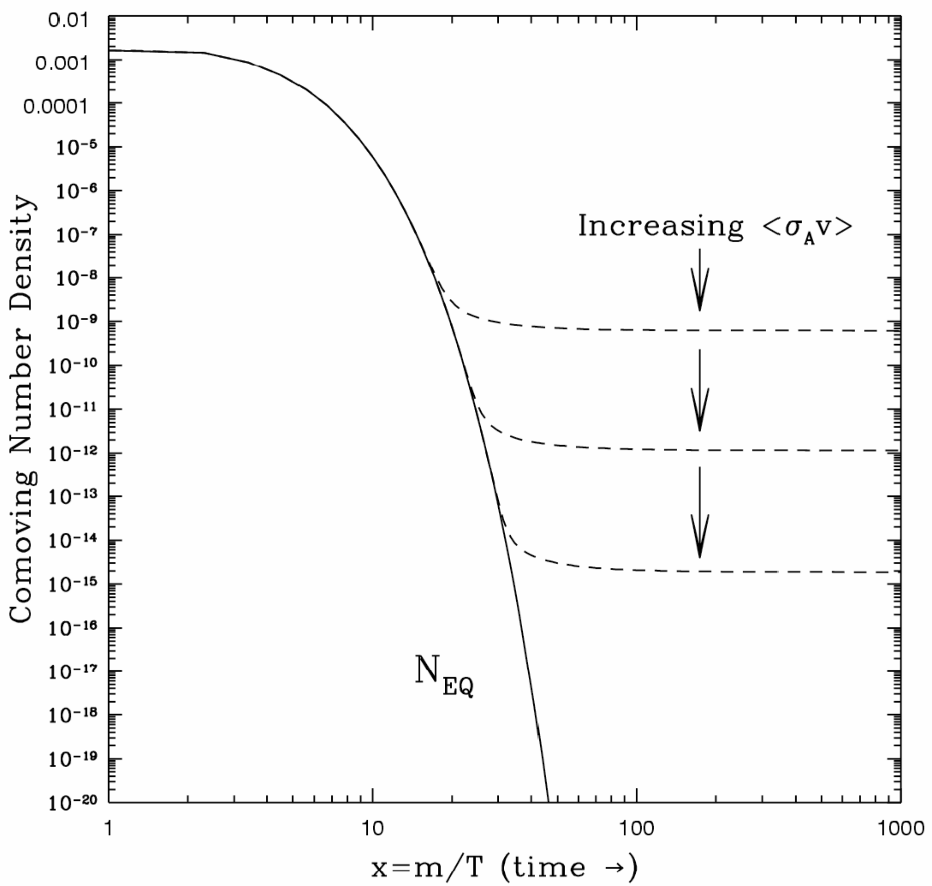
Chemical eq. maintained when ann rate exceeds the Hubble expansion rate

'Freeze-out' 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 expansion rate

$$H \sim \frac{\sqrt{g}T^2}{M_{\mathrm{P}}}$$ where g ⇨ # relativistic species



i.e. 'freeze-out' at T ~ m_N/45, with:

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

The observed ratio is 10^9 times bigger for baryons, and there are no antibaryons, so we must invoke an **initial asymmetry**:

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

Sakharov conditions for baryogenesis:

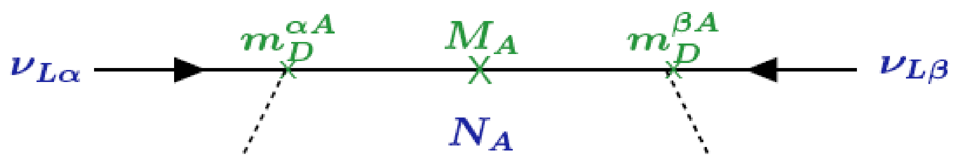
1. Baryon number violation
2. C and CP violation
3. Departure for thermal equilibrium

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

Thus 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)**

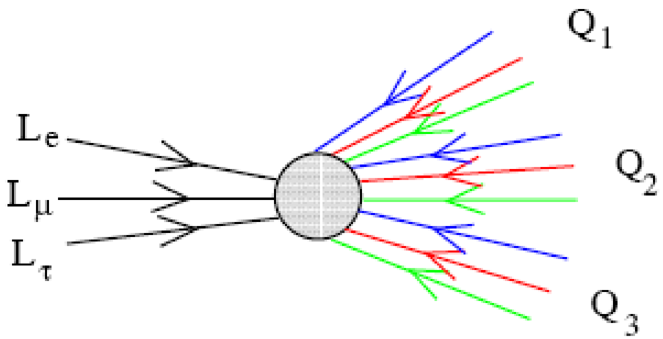
‘See-saw’:

$$\mathcal{L} = \mathcal{L}_{SM} + \lambda^*_{\alpha J}\overline{\ell}_\alpha \cdot H N_J - \frac{1}{2}\overline{N_J} M_J N^c_J \qquad \lambda M^{-1}\lambda^{\mathrm{T}}\langle H^0\rangle^2 = [m_\nu]$$



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

Asymmetric baryonic matter



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

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

Any pre-existing fermion asymmetry would be redistributed by the B+L violating processes (which conserve B-L) among all particles with electroweak couplings

Although leptogenesis is not directly testable (unless the lepton number violation occurs as low as the TeV scale), it provides 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	$\otimes$ > 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	$\Omega_{LSP} \sim 0.3$

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

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

Why 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
Λ_{QCD}	**Nucleons**	Baryon number	⊗ $> 10^{33}$ yr (dim-6 OK)	'freeze-out' from thermal equilibrium	$\Omega_B \sim 10^{-10}$ cf. observed $\Omega_B \sim 0.05$
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino? Technibaryon?	R-parity? U(1) Technibaryon #	violated? $\tau \sim 10^{18}$ yr e^+ excess?! (Sannino et al 08)	'freeze-out' from thermal equilibrium Asymmetric (like the observed baryons)	$\Omega_{LSP} \sim 0.3$ $\Omega_{TB} \sim 0.3$

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

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

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
Λ_{QCD}	**Nucleons**	Baryon number	⊗ > 10^{33} yr (dim-6 OK)	'freeze-out' from thermal equilibrium	$\Omega_B \sim 10^{-10}$ cf. observed $\Omega_B \sim 0.05$
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino? Technibaryon?	R-parity? (walking) Technicolour	violated? $\tau \sim 10^{18}$ yr e^+ excess?!	'freeze-out' from thermal equilibrium Asymmetric (like the observed baryons)	$\Omega_{LSP} \sim 0.3$ $\Omega_{TB} \sim 0.3$
$\Lambda_{DB} \sim 5\,\Lambda_{QCD}$	Dark Baryon	Dark Baryon #	?	Asymmetric	$\Omega_{DB} \sim 0.3$

...or a 5 GeV 'dark baryon'.
In this case with no Boltzmann suppresion:

(Kaplan 1990)

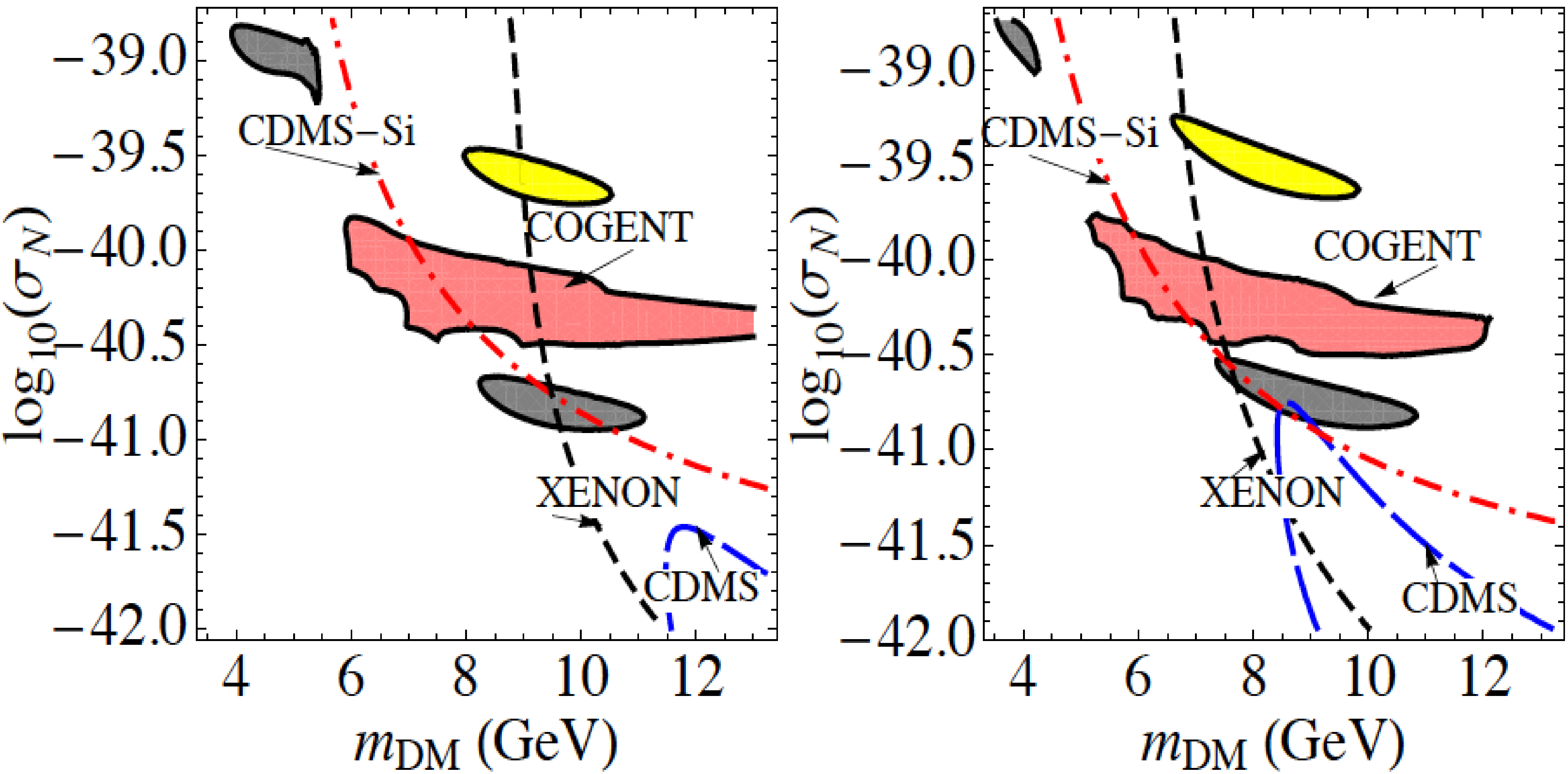
$$\frac{\Omega_{DB}}{\Omega_B} = \frac{m_{DB}}{m_B}$$

Direct Detection

Evidence for ‘light’ WIMP dark matter?

(Dama, Bernabei et al 08;
CDMS-II, Ahmed et al 09;
CoGeNT, Aalseth et al 10;)

(Kopp, Schwetz and Zupan 09; Farina, pappadopulo and Strumia 09; Fitzpatrick, Hooper and Zurek 09:)



Models of TeV and GeV scale ADM

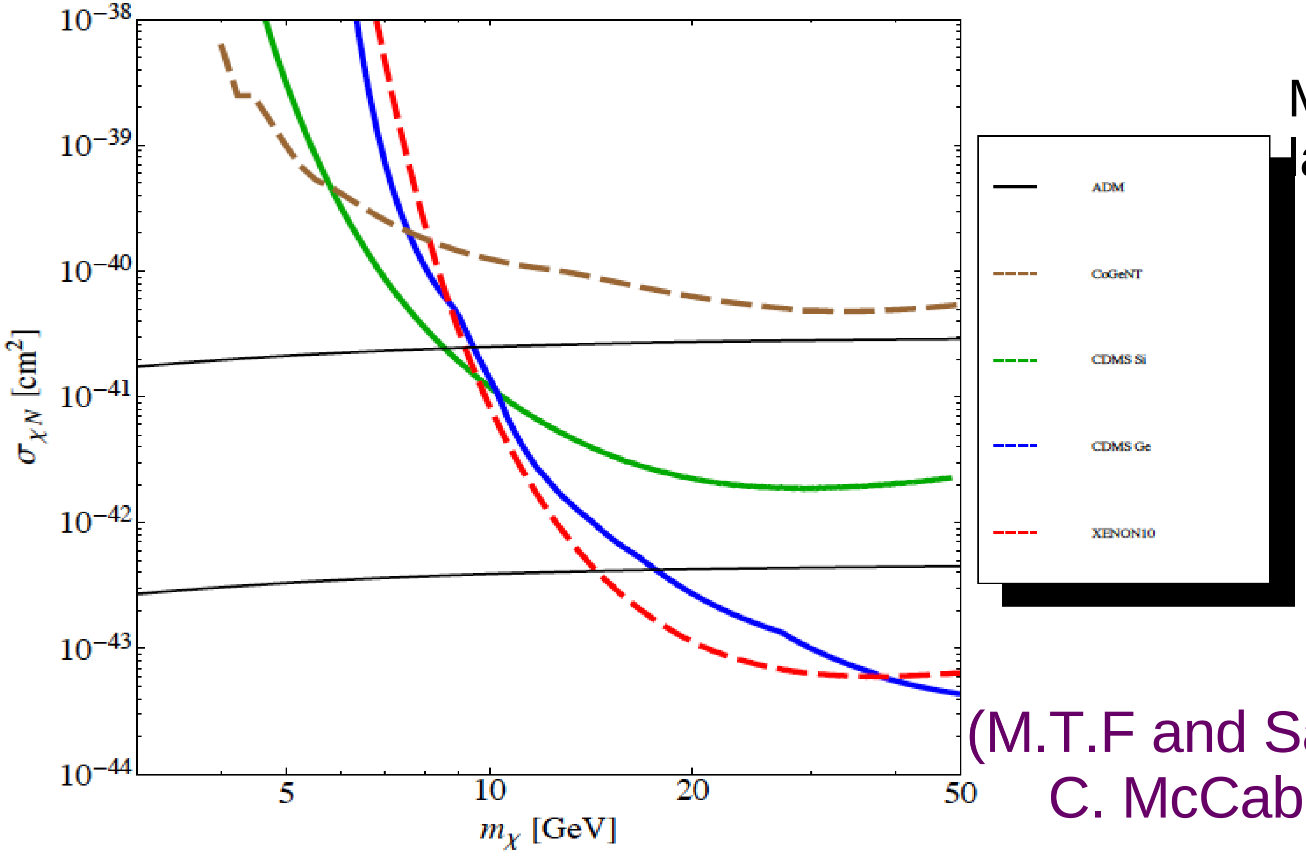
- Unbaryons or Dark Mirror baryons
- Interactions with SM through Higgs Exchange

and (for Dirac fermion) magnetic moments

(Sannino and Zwicky 09)

(M.T.F and Sarkar 10)

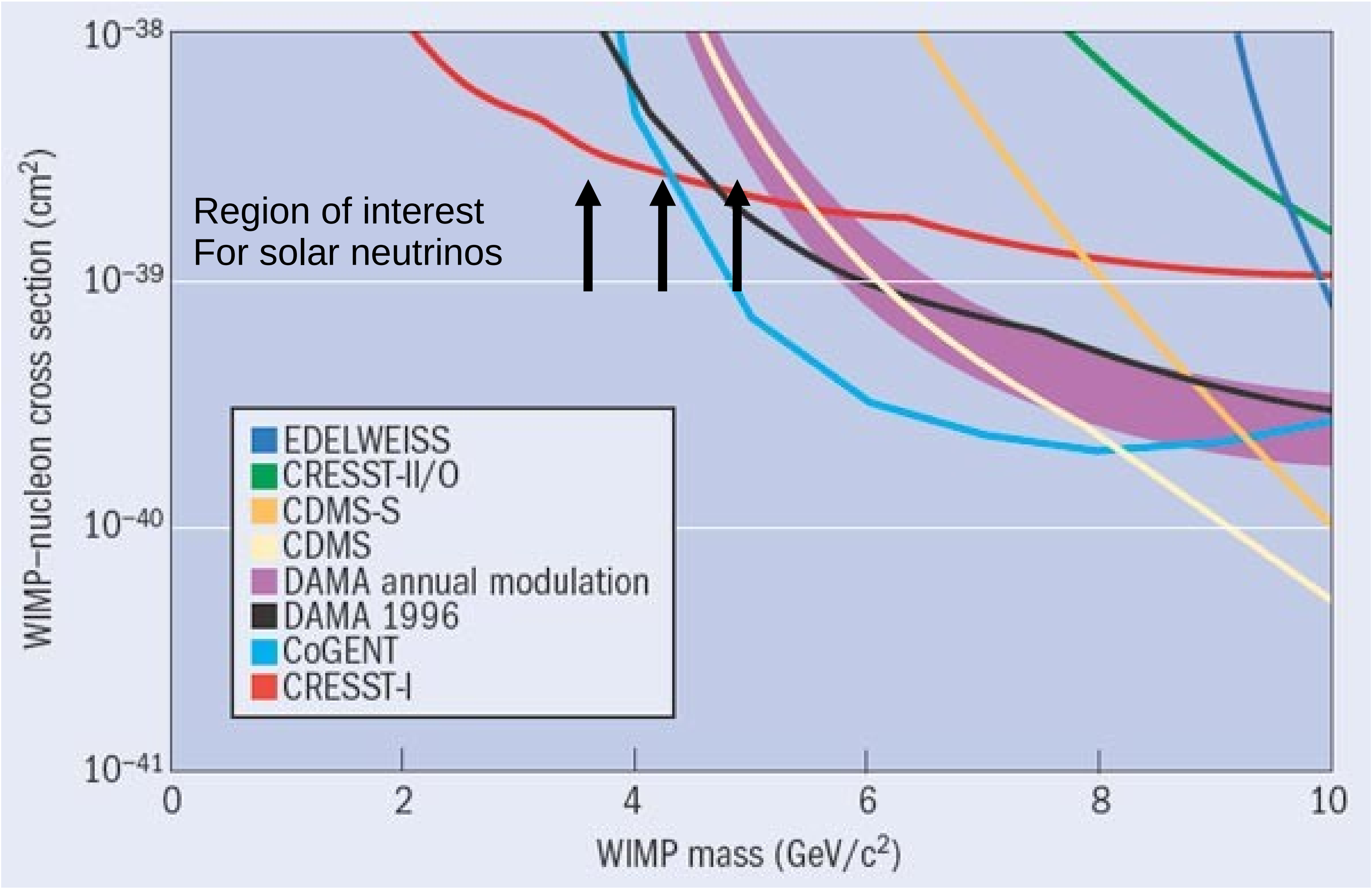
(An et al 2010)



Magnetic moments can provide large SI/SD cross-sections

(An et al 2010)

(M.T.F and Sarkar 10; Data courtesy of C. McCabe and M. McCullough)



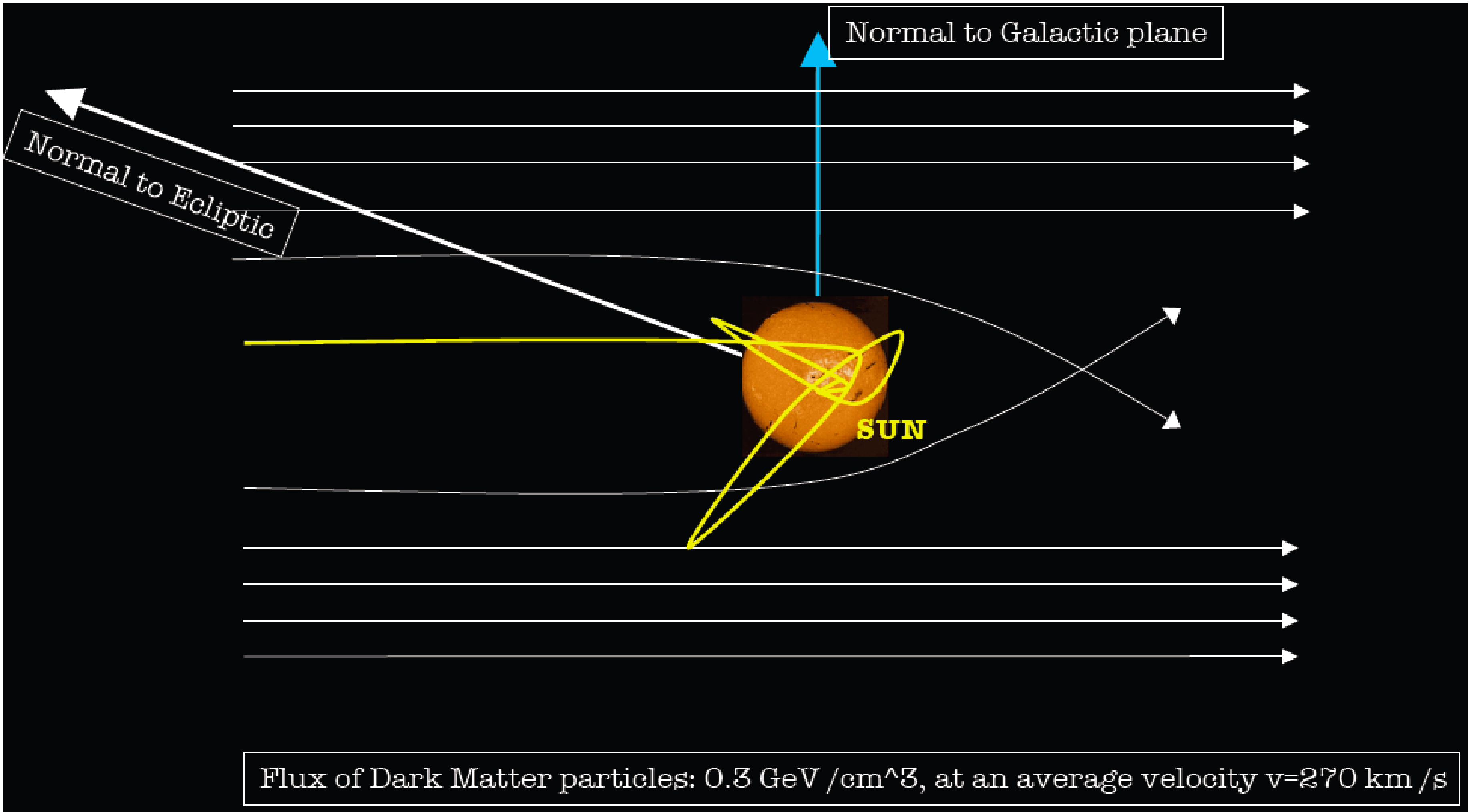
SI and SD cross-sections similar for capture in the sun, but limits on SD much weaker~

$\sigma \sim 10^{-36}\, cm^2$

Indirect Detection–Capture in the Sun

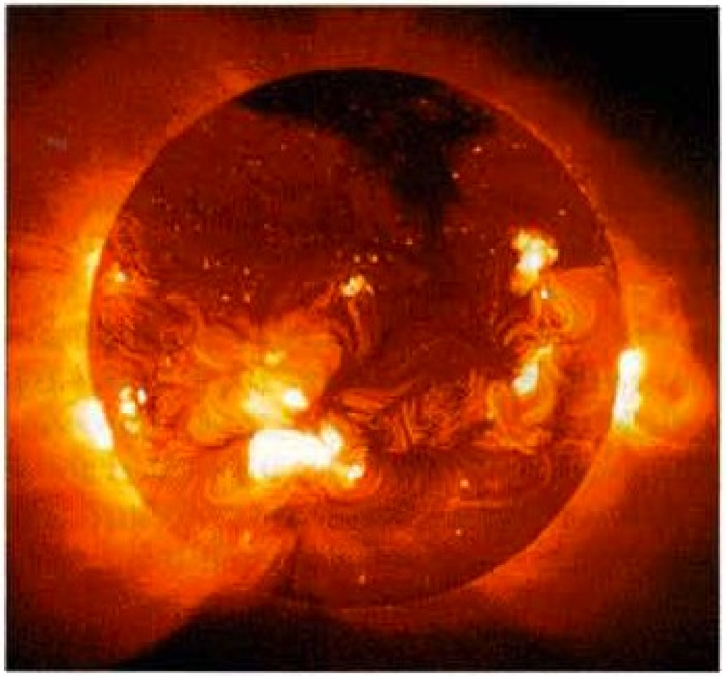
The Sun has been accreting dark matter particles for ~5 x 10^9 yr as it orbits around the Galaxy … these will orbit inside affecting energy transport

Solar neutrino flux is very sensitive to the core temperature (Faulkner et al 1985, Press & Spergel 1985)



Chemical controversy at the solar surface

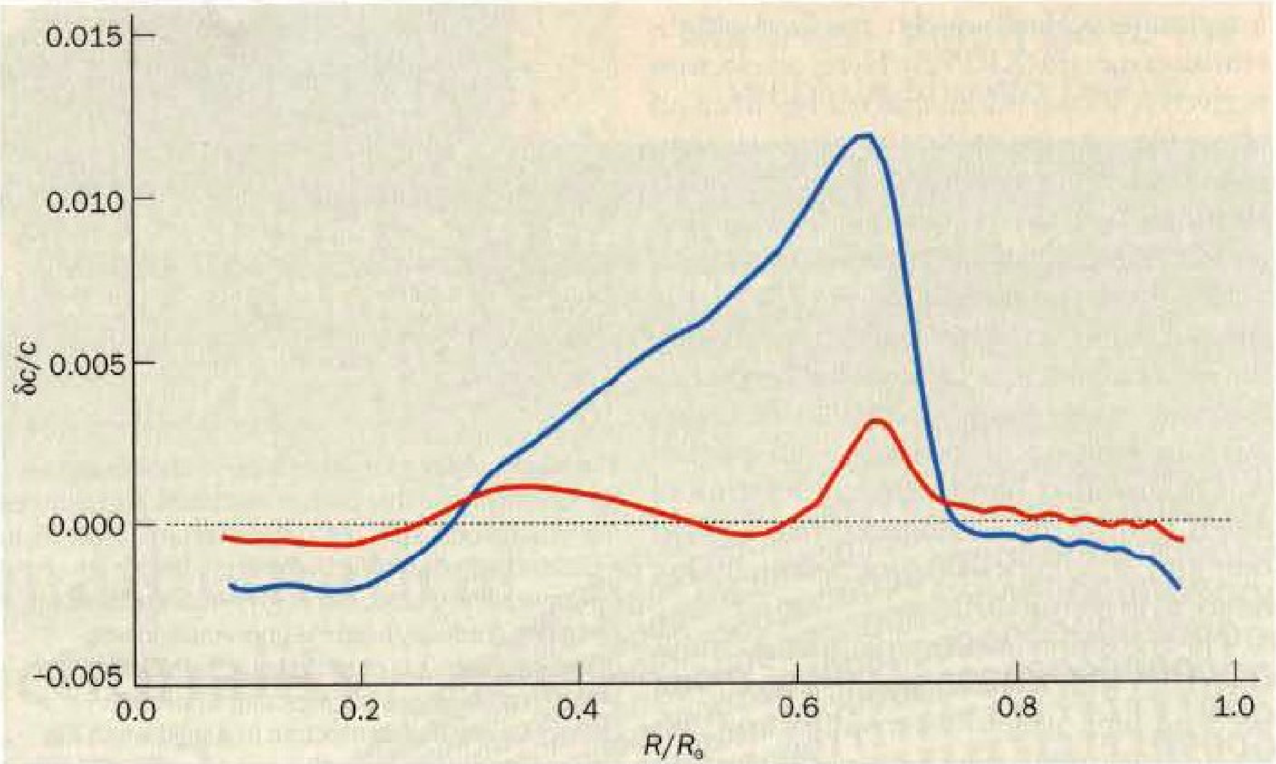
Improved measurements of elemental abundances suggest that something might be wrong with our model of the Sun



An accurate model of the Sun is crucial for our understanding of more-distant stars.

From **John N Bahcall** at the Institute for Advanced Study, Princeton, New Jersey, US

My personal guess is that it may take years before we stumble upon the key to resolving the mystery of why the improved measurements of element abundances cause solar models to disagree with helioseismological measurements while older measurements agree extraordinarily well. However, scientists love a conflict between theory and observation because they are guaranteed to learn something interesting by resolving it. We are puzzled, but we are having fun.

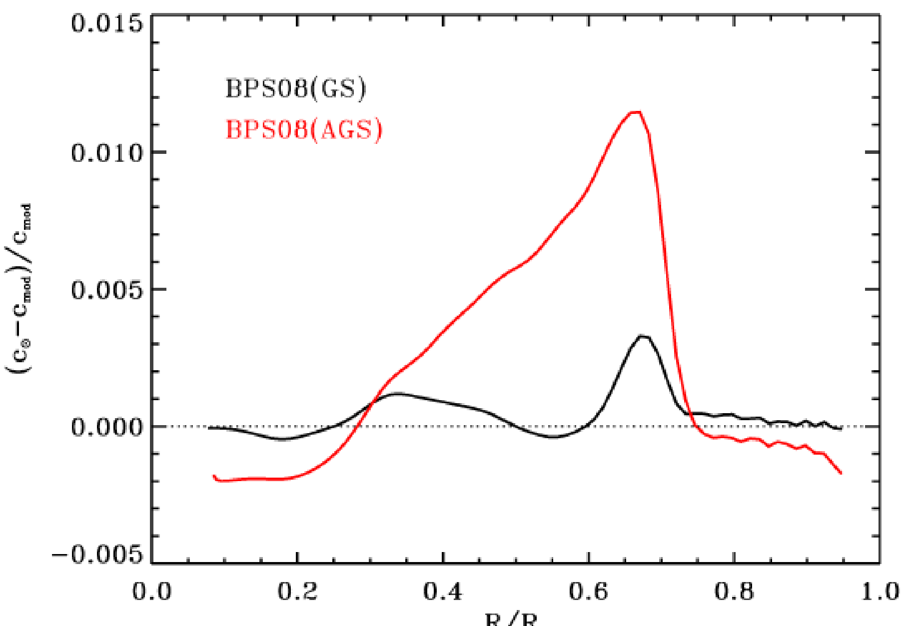


Solar puzzle – measurements of the speed of sound in the solar interior provide a stringent test of the solar model. This plot shows the fractional difference in the speed of sound (c) between the measured and predicted values as a function of the solar radius ($R_{\odot}$) (the dashed line represents perfect agreement between theory and observation). When the older heavy-element abundances are used in the model (red) the measured sound speeds agree much better with the calculations than they do when the new, lower values are used (blue).

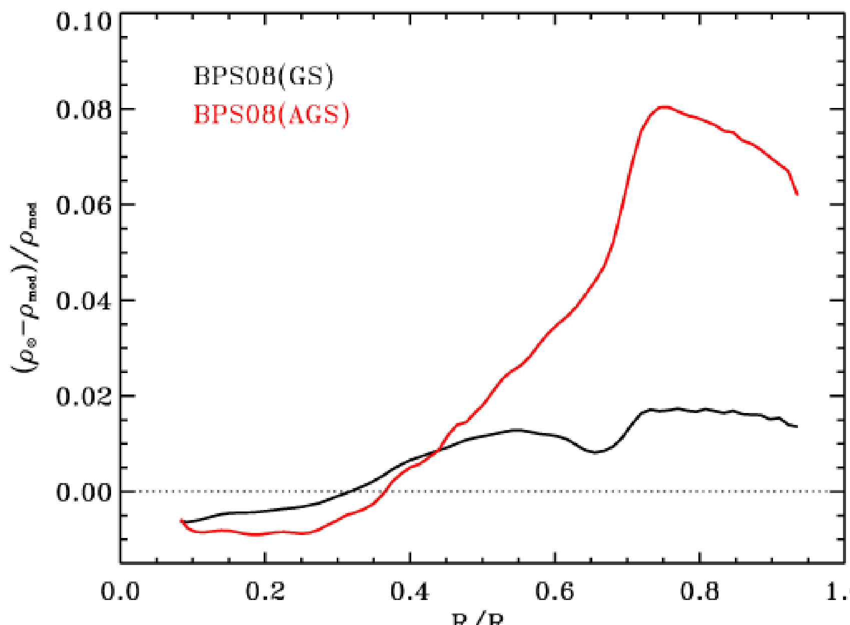
Helioseismology and Solar Metallicity
A New Problem with Standard Solar Models (SSM)

- Asplund, Grevesse and Sauval determined new solar chemical abundances (metallicity) in 2005 using improved 3D hydrodynamical modeling (tested with many surface spectroscopic observations) AGS05 vs GS98
- with these new chemical abundances in solar models (lower metallicity), the previous excellent agreement between SSM calculations and helioseismology is broken

new C, N, O, Ne abundances lower by 30-50%



sound speed profile in the Sun



density profile in the Sun

$R_{CZ} = (0.713 +/- 0.001)\, R_{sun}$ (Antia & Basu 1997)

AGS05 SSM 15 sigma larger

Self-interactions can increase capture in the sun (Zentner 09)

The abundance of ~5 GeV ADM in the Sun will not be depleted by annihilations …naturally large self-int (M.T.F & Sarkar 10; Taoso et al 10)

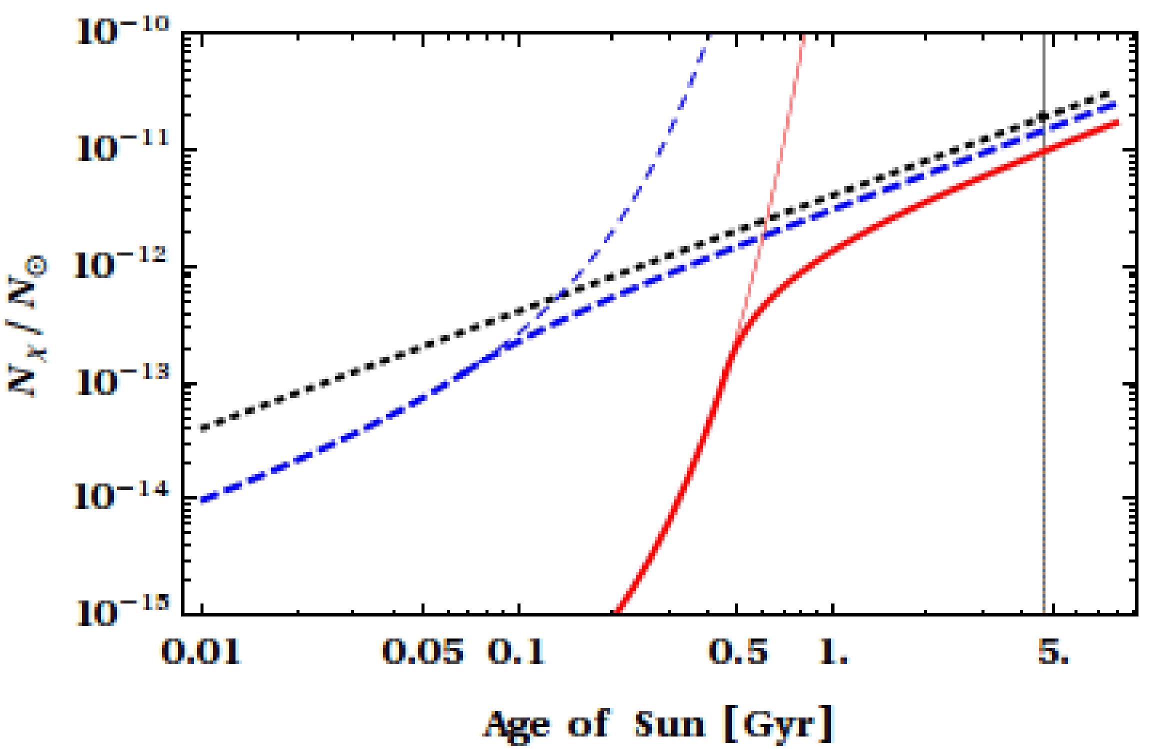
$$\sigma_{\chi\chi} = m_n^2 / m_\chi^2 \sigma_{nn}, n = neutron$$

Abundance grows exponentially:

$$\sigma_{\chi\chi} = 10^{-23} cm^2$$

At the bound of recent study of Bullet Cluster

(Wandelt et al 08)



$$\frac{dN_\chi}{dt} = C_{\chi N} + C_{\chi\chi} N_\chi.$$

$$N_\chi(t) = \frac{C_{\chi\mathcal{N}}}{C_{\chi\chi}} \left(e^{C_{\chi\chi} t} - 1\right),$$

$\sigma_{\chi N}^{SI} = 10^{-37} cm^2$

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

Black Disk Limit

(Self-interacting ADM would also help to explain the paucity of cosmic structure on sub-Galactic scales) (Spergel & Steinhardt 2000)

Effects of light ADM in the Sun

DM affects the solar luminosity,
Non-local heat transport:

$$L_\chi \sim 4 \times 10^{12} L_\odot \frac{N_\chi}{N_\odot} \frac{\sigma_{\chi \mathrm{N}}}{\sigma_\odot} \sqrt{\frac{m_\mathrm{N}}{m_\chi}}$$

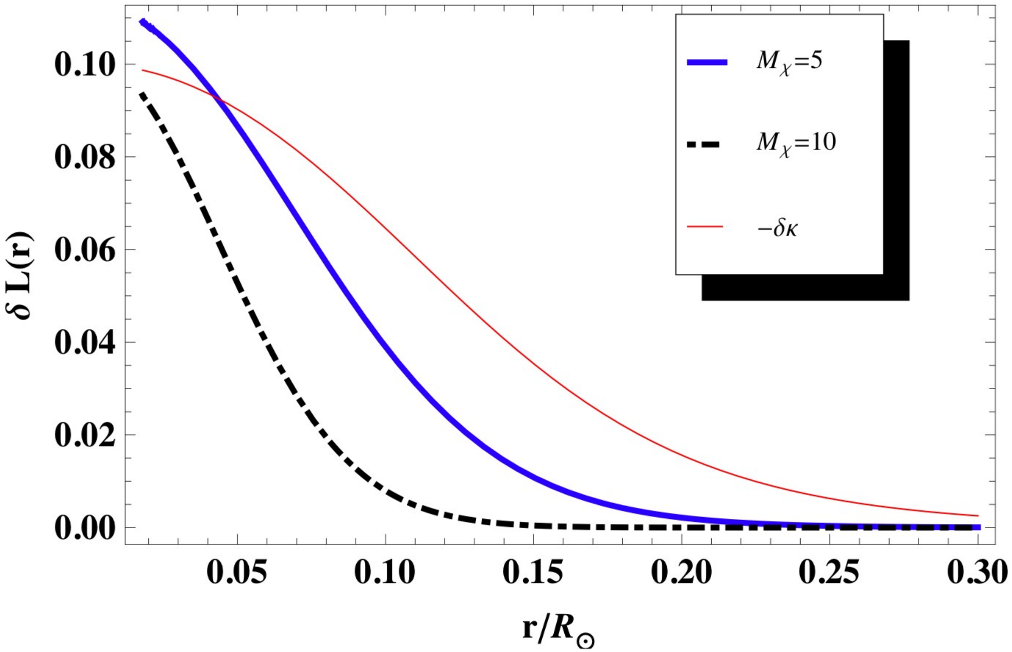
(Press & Spergel 1985)

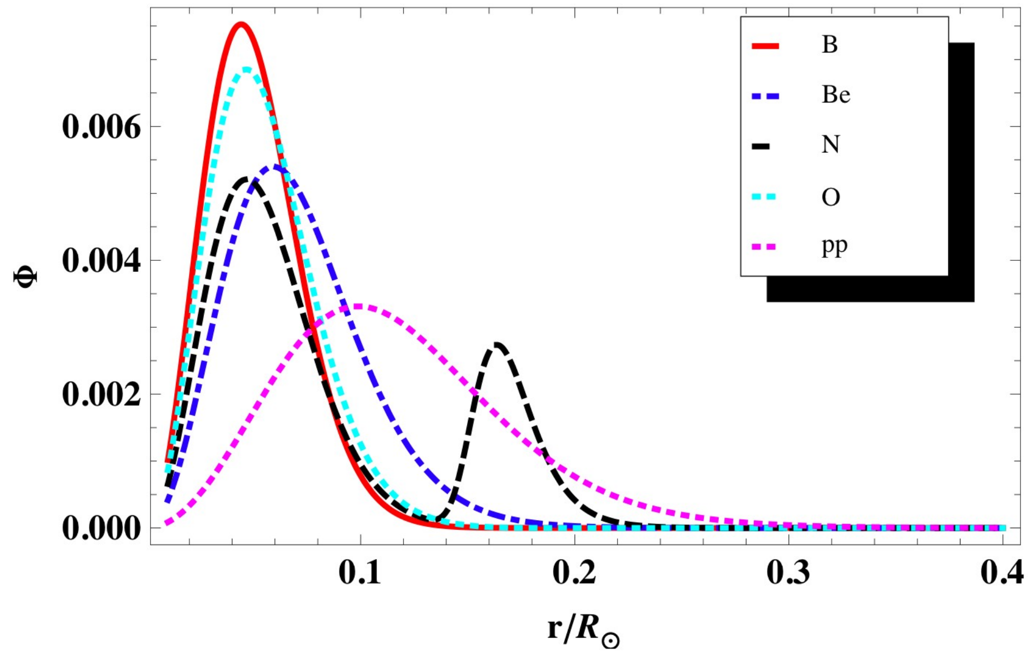
Effectively the solar opacity is modified

$$\delta L(r) \sim -\delta\kappa_\gamma(r) \equiv -\kappa_\chi(r)/\kappa_\gamma(r)$$

(Gould & Raffelt 1985 Bottino et al 2002)

(M.T.F & Sarkar 2010)





The core Solar temperature and neutrino fluxes altered… this can tested by SNO+ / Borexino

Linear Solar Models

(Villante & Ricci 2009, 2010; See Villantes talk TAUP 2009)

- SSMs provide a good approximation of the real sun. Small modifications are likely to explain disagreement with helioseismology.

- We can expand linearly the solar models around the SSM and calculate:

$$\delta(\text{output}) = L\left[\delta(\text{input})\right]$$

$$\delta(\text{input}) = \delta\kappa,\ \delta\varepsilon,\ \text{new effects} \ldots$$
$$\delta(\text{output}) = \delta u,\ \delta R_b,\ \delta\Phi_\nu,\ \delta Y_{ph}\ \ldots$$

$$\frac{d\delta m}{dr} = \frac{1}{r_m}[\delta\rho - \delta m]$$
$$\frac{d\delta P}{dr} = \frac{1}{r_P}[\delta m + \delta\rho - \delta P]$$
$$\delta P = \left[P_\rho\delta\rho + P_T\delta T + P_Y\Delta Y\right]$$
$$\frac{d\delta l}{dr} = \frac{1}{r_l}\left[(1+\varepsilon_\rho)\delta\rho + \varepsilon_T\delta T + \varepsilon_Y\Delta Y + \varepsilon_i\delta X_i - \delta l + \delta\varepsilon\right]$$
$$\begin{cases} \dfrac{d\delta T}{dr} = \dfrac{1}{r_T}\left[\delta l + (\kappa_T - 4)\delta T + (\kappa_\rho + 1)\delta\rho + \kappa_Y\Delta Y + \kappa_i\delta X_i + \delta\kappa\right] & \text{Radiative} \\ \dfrac{d\delta T}{dr} = \dfrac{1}{r_T}[\delta m + \delta\rho - \delta P] & \text{Convective} \end{cases}$$

write: $h(r) = \overline{h}(r)[1 + \delta h(r)]$ $\quad h = l, m, T, P, \rho$

$$Y(r) = \overline{Y}(r) + \Delta Y(r)$$
$$X_i(r) = \overline{X}_i(r)[1 + \delta X_i(r)]$$

where $r_h = \left[\dfrac{d\ln(\overline{h})}{dr}\right]^{-1}$ and $P_h = \left[\dfrac{d\ln(P)}{d\ln(h)}\right]$, $\varepsilon_h = \left[\dfrac{d\ln(\varepsilon)}{d\ln(h)}\right]$, $\kappa_h = \left[\dfrac{d\ln(\kappa)}{d\ln(h)}\right]$

The response of sound speed to δk(x)

(From Villante TAUP 09
See also Lopes, Silk & Hansen 01;
Lopes, Bertone & Silk 02)

Sound speed is sensitive to differential opacity modifications:

$$\left(\delta\kappa_{outer} - \delta\kappa_{inner}\right)$$

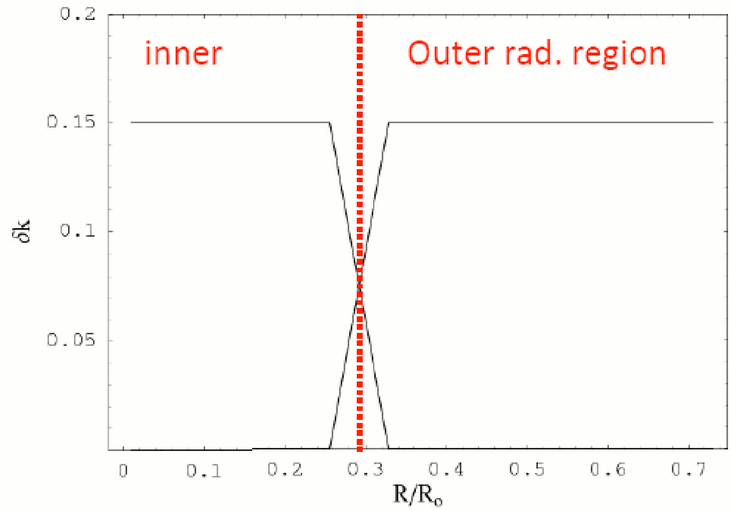
Discrepancy with helioseismic data is solved by:

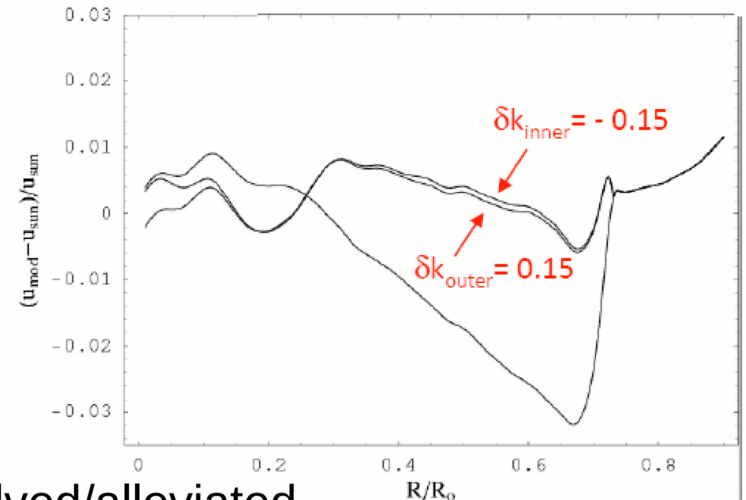
$$\left(\delta\kappa_{outer} - \delta\kappa_{inner}\right) \approx 0.15$$

As an example:

-15% increase of opacity in the outer radiative region (increase metals ...)

- 15% decrease of opacity in the inner radiative region (??? few GeV WIMP in the solar core ???)



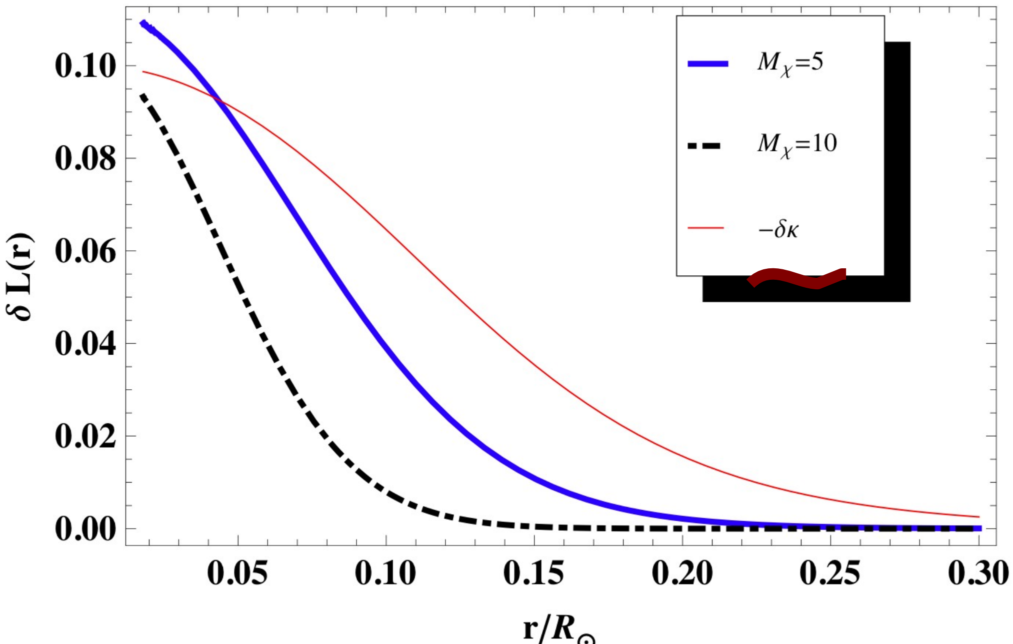


Discrepancy for the convective radius is also solved/alleviated
With same modification.

Convective radius measured from Helioseismology: $R_{CZ} = 0.713\, R_{sun} +/- 0.001$

Convective radius inferred from the AGS05 SSM: $R_{CZ} = 0.728\, R_{sun} +/- 0.0037$

(Bahcall, Serenelli & Basu 05)



	OPA1		OPA2	
	SM	LSM	SM	LSM
$\Delta Y_{\rm ini}$	0.016	0.017	-0.0056	-0.0058
$\delta Z_{\rm ini}$	-0.018	-0.016	0.000	-0.001
$\Delta Y_{\rm b}$	0.014	0.014	-0.0037	-0.0036
$\delta Z_{\rm b}$	-0.018	-0.018	0.0049	0.0047
$\delta R_{\rm b}$	-0.0020	-0.0020	-0.0067	-0.0070
$\delta \Phi_{\rm pp}$	-0.011	-0.010	0.0045	0.0052
$\delta \Phi_{\rm Be}$	0.13	0.13	-0.067	-0.064
$\delta \Phi_{\rm B}$	0.27	0.27	-0.17	-0.17
$\delta \Phi_{\rm N}$	0.14	0.14	-0.10	-0.094
$\delta \Phi_{\rm O}$	0.21	0.22	-0.14	-0.14

Recent Numerical Studies W/ maximal SD cross-section but different numerical/analytical approaches

(Cumberbatch et al 10; Taoso et al 10)

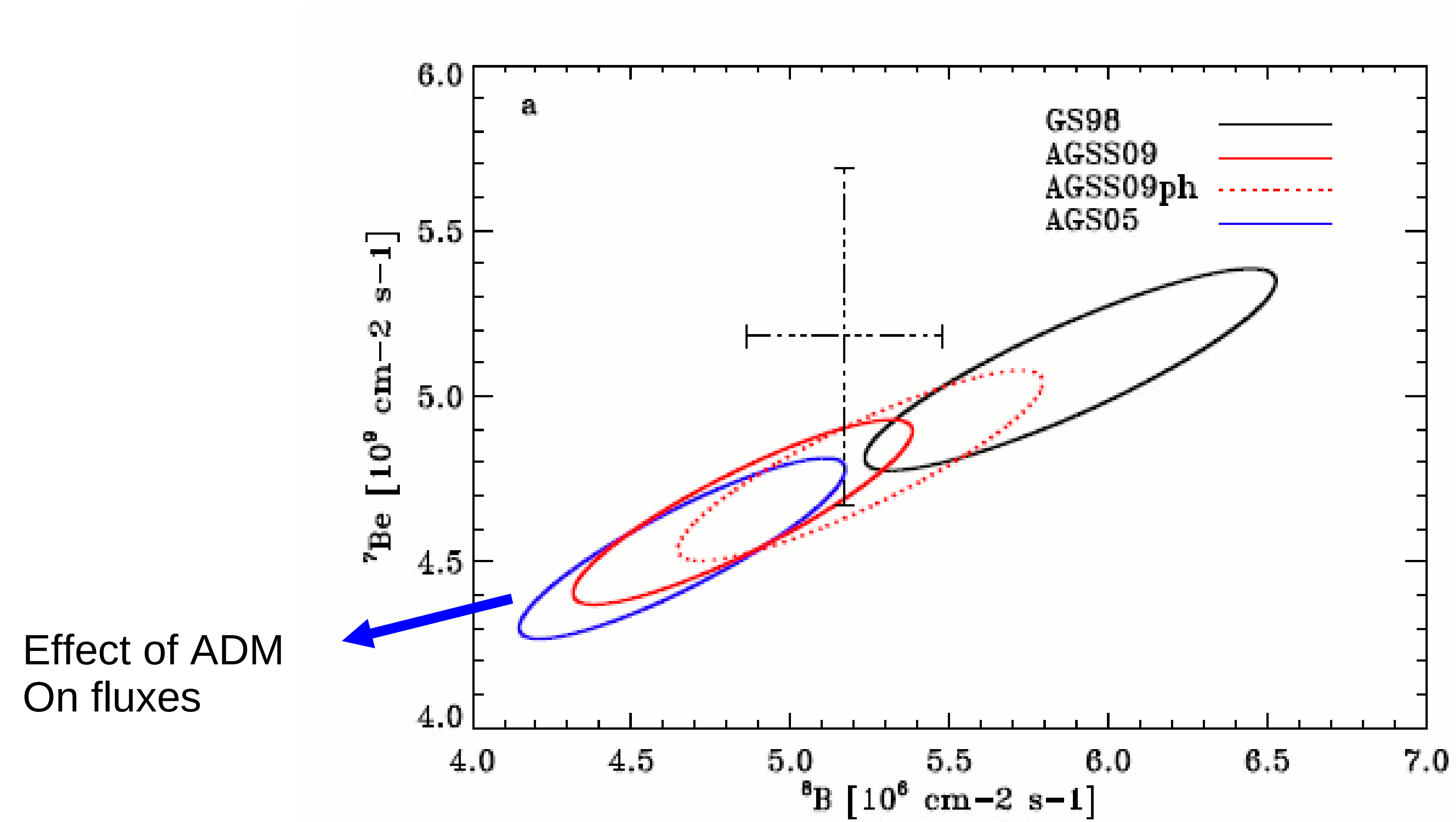
<u>Cumberbatch et al</u> finds smaller variation on
Convective Radius, Larger variations on Boron neutrinos

<u>Taoso et al</u> find virtually no effect on Convective Radius and neutrino fluxes

<u>Villante</u> finds 15% opacity variation (as from e.g. ADM) restores agreement with Helioseismology within LSM approach.
Effect on Neutrino fluxes and Helium abundance can constrain/rule out this scenario

(Villante 10)

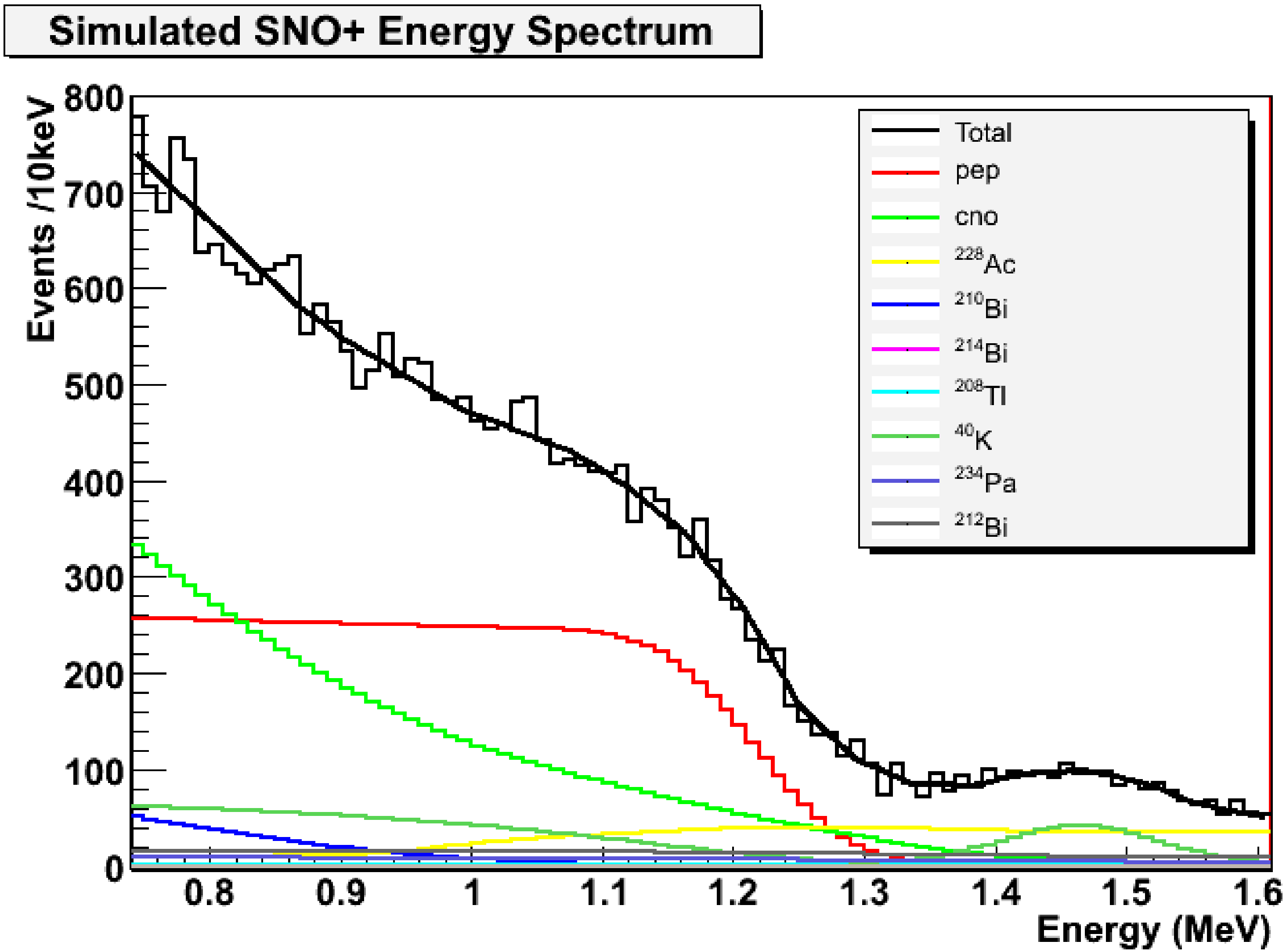
Neutrino flux measurements can constrain/rule out light ADM scenario



$\Phi(8^B) = (5.18 +/- 0.29)\, x\, 10^6 cm^{-2} s^{-1}$ (SNO, Aharmin et al 08)

$\Phi(8^B) = (5.18 +/- 0.29)\, x\, 10^6 cm^{-2} s^{-1}$ (Borexino, Arpesella et al 08)

SNO+ pep and CNO Solar Neutrino Signals



CNO extracted with ±6% uncertainty (assuming target background levels ^{210}Bi and ^{210}Po, U, Th, ^{40}K achieved) in three years

3600 pep events/(kton·year), for electron recoils >0.8 MeV

Summary

- *Asymmetric Dark Matter is motivated by wanting to explain* Ω_{DM}/Ω_B
- ~ TeV scale ADM natural in Technicolor models of DEWSB.

~ GeV scale ADM arise from Hidden/Mirror/Unbaryon sectors.

- *Direct and indirect detection challenging*
- ~ GeV scale ADM ('Dark Baryon') naturally strongly self-interacting
- Motivated by structure formation on Kpc-Mpc scales
- Large capture rates in the sun, possible solution of the solar composition problem
- Probed by neutrino flux measurements - Interesting benchmark for Direct Detection and neutrino flux experiments