Asymmetric dark matter

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with Mads Frandsen:

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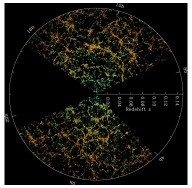
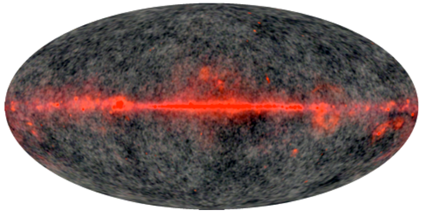
With Alexander Belyaev, Mads Frandsen & Francesco Sannino:

arXiv:1007.4839 (*Phys. Rev. D*, to appear)

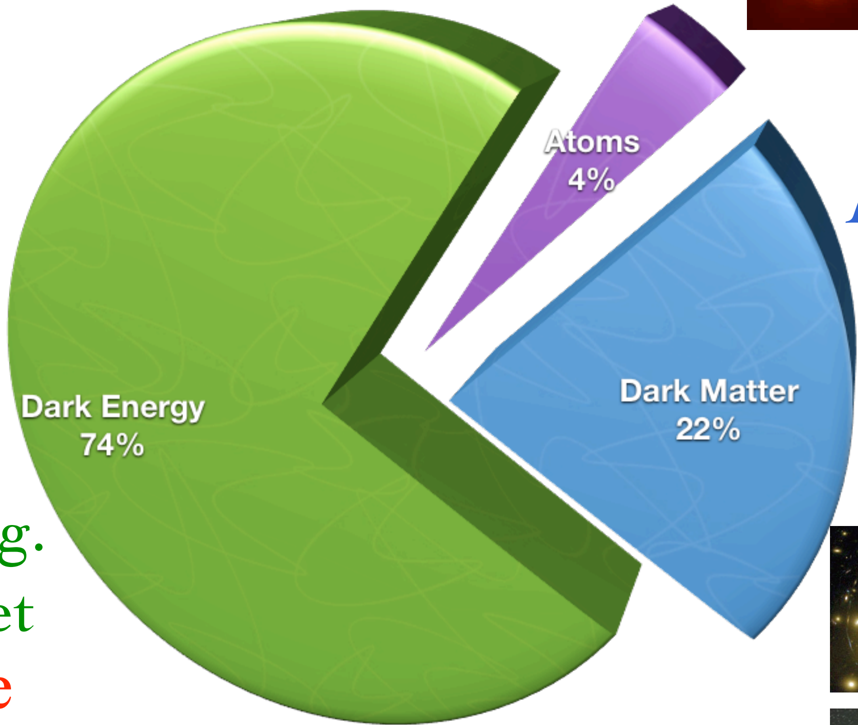
What is the world made of?

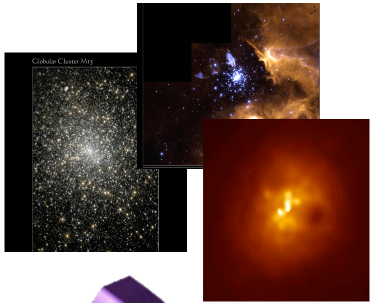
***Only* geometrical evidence:**
$\Lambda \sim O(H_0^2)$, $H_0 \sim 10^{-42}$ GeV
… dark energy is *inferred* from the 'cosmic sum rule':
$\Omega_m + \Omega_k + \Omega_\Lambda = 1$





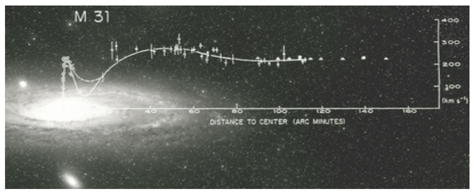
No convincing *dynamical* evidence (e.g. late ISW effect) seen yet
… Could dark energy be faked by inhomogeneity?





Baryons (but *no* antibaryons) … the stuff *we* are made of

***Both* geometrical** and **dynamical** evidence (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 $\Omega_B \sim 0.05$

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

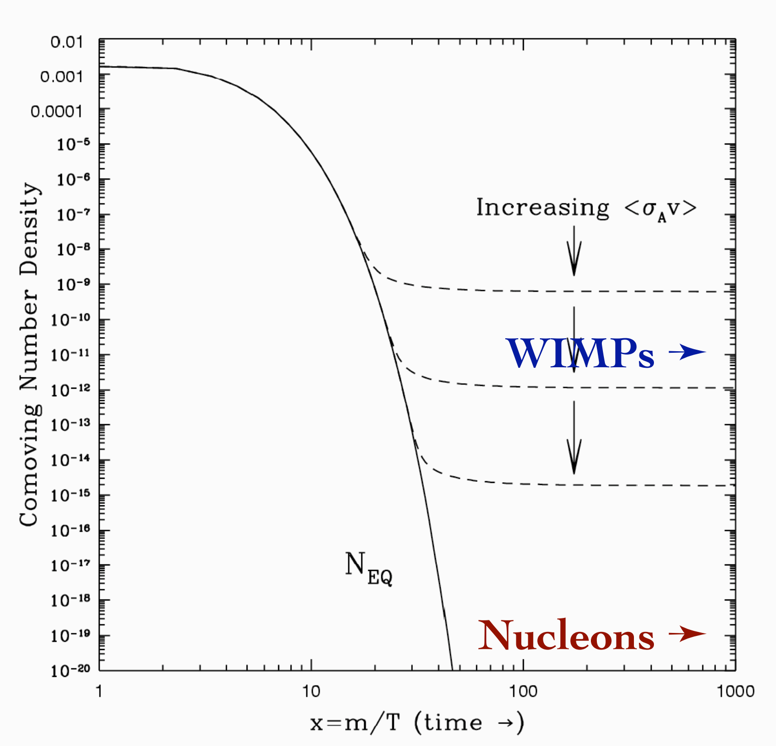
'Freeze-out' occurs when annihilation rate:

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

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 *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' (*cf.* 'WIMP miracle')?!

<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')

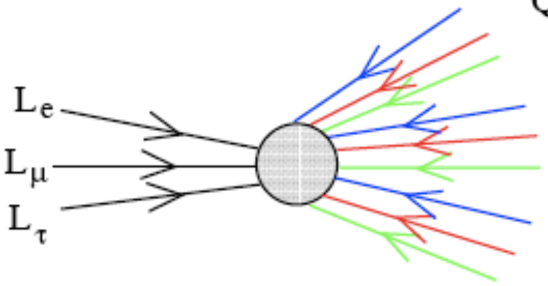
Thus the generation of the observed matter-antimatter asymmetry *requires* new BSM physics (could be related to neutrino masses … **possibly due to violation of lepton number ➝ leptogenesis)**

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

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

Asymmetric baryonic matter

(Barr *et al*, PL B241:387,1990)



Q_1 $$\partial_\mu j_i^\mu = \partial_\mu(\bar{\psi}^i \gamma^\mu \psi^i) = \frac{g^2}{8\pi} W^{a\mu\nu} \tilde{W}^a_{\mu\nu} \Rightarrow N^i(T) - N^j(T) = N_0^i - N_0^j$$

Q_2 $$N^i(T) = c_i(m_i, T)\mu_i/T \quad + \quad \sum_i \mu_i = 0$$

Q_3 $$\Rightarrow \quad N^i(T) = N_0^i - \frac{\sum_j N_0^j / c_j(m_j, T)}{\sum_j 1/c_j(m_j. T)}$$

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* originated *non*-thermally in the early universe

The **Standard $SU(3)_c$ x $SU(2)_L$ x $U(1)_Y$ Model** provides an exact description of all *microphysics* (up to some high energy cut-off scale *M*)

Higgs mass divergence

$$\mathcal{L}_{\rm eff} = M^4 + M^2\Phi^2 \quad \textbf{super-renormalisable}$$

$$+ (D\Phi)^2 + \bar{\Psi} \not{D}\Psi + F^2 + \bar{\Psi}\Psi\Phi + \Phi^2 \quad \textbf{renormalisable}$$

$$+ \frac{\bar{\Psi}\Psi\Phi\Phi}{M} + \frac{\bar{\Psi}\Psi\bar{\Psi}\Psi}{M^2} + \ldots \quad \textbf{non-renormalisable}$$

The effects of *new* physics beyond the SM (neutrino mass, nucleon decay, FCNC ...) → **non-renormalisable operators** suppressed by M^n … which 'decouple' as $M \rightarrow M_P$

But as *M* is raised, the effects of the **super-renormalisable operators** are *exacerbated*
Solution for Higgs (quadratic) mass divergence → softly broken supersymmetry at $M \sim 1$ TeV

This suggests possible mechanisms for **baryogenesis**, candidates for **dark matter**, … (as also do other proposed extensions of the SM, e.g. new dimensions @ TeV scale)

For example, the lightest supersymmetric particle (typically the neutralino χ), *if* protected against decay by *R*-parity, is a candidate for thermal dark matter

But if the Higgs is ***composite*** (as in technicolor models of $SU(2)_L$ x $U(1)_Y$ breaking) then there is *no need* for supersymmetry … and light TC states can be dark matter

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

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

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

Also true for *generic* hidden sector matter: 'WIMPless miracle'
(Feng & Kumar 2008) … because $g_h^2/m_h \sim g_\chi^2/m_\chi \sim F/16\pi^2 M$

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~~ Asymmetric baryogenesis	$\Omega_B \sim 10^{-10}$ *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)	$\Omega_{LSP} \sim 0.25$ $\Omega_{TB} \sim 0.25$

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 (dim-6 OK)	~~'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 (Gelmini *et al* 1987) … and there are candidate particles (Kaplan 1992, Hooper *et al* 2005, Kaplan *et al* 2009, Kribs *et al* 2009, Frandsen & Sannino 2010, An *et al* 2010) with distinctive 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)

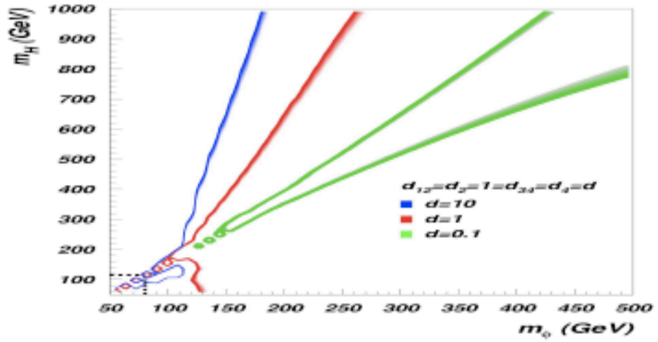
Arise as GB from breaking of the technicolor chiral symmetries.
Stable as they carry technibaryon number.
Composite states neutral but constituents may be charged.
Receive mass from 'vacuum alignment', i.e. electroweak mass contribution.

TIMPS

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

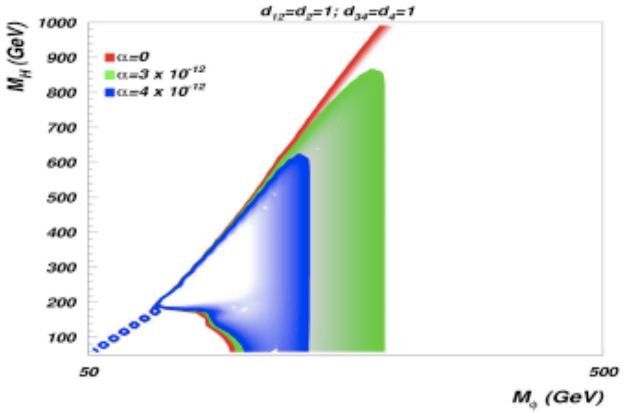
$$\phi \sim \lambda\lambda,$$

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



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

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

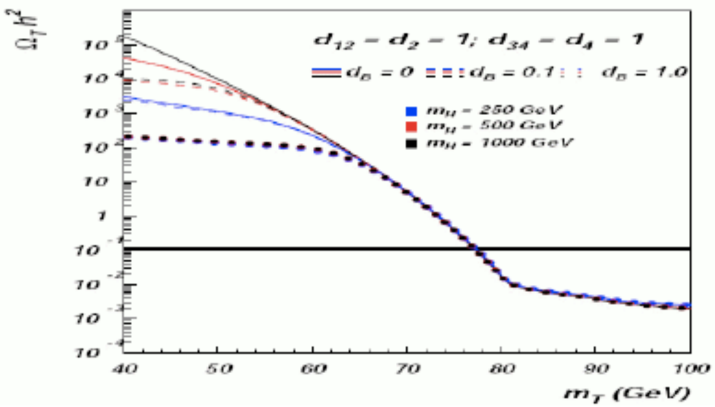


PGB TIMPS with charged constituents, generically have contact Interactions with weak gauge bosons:

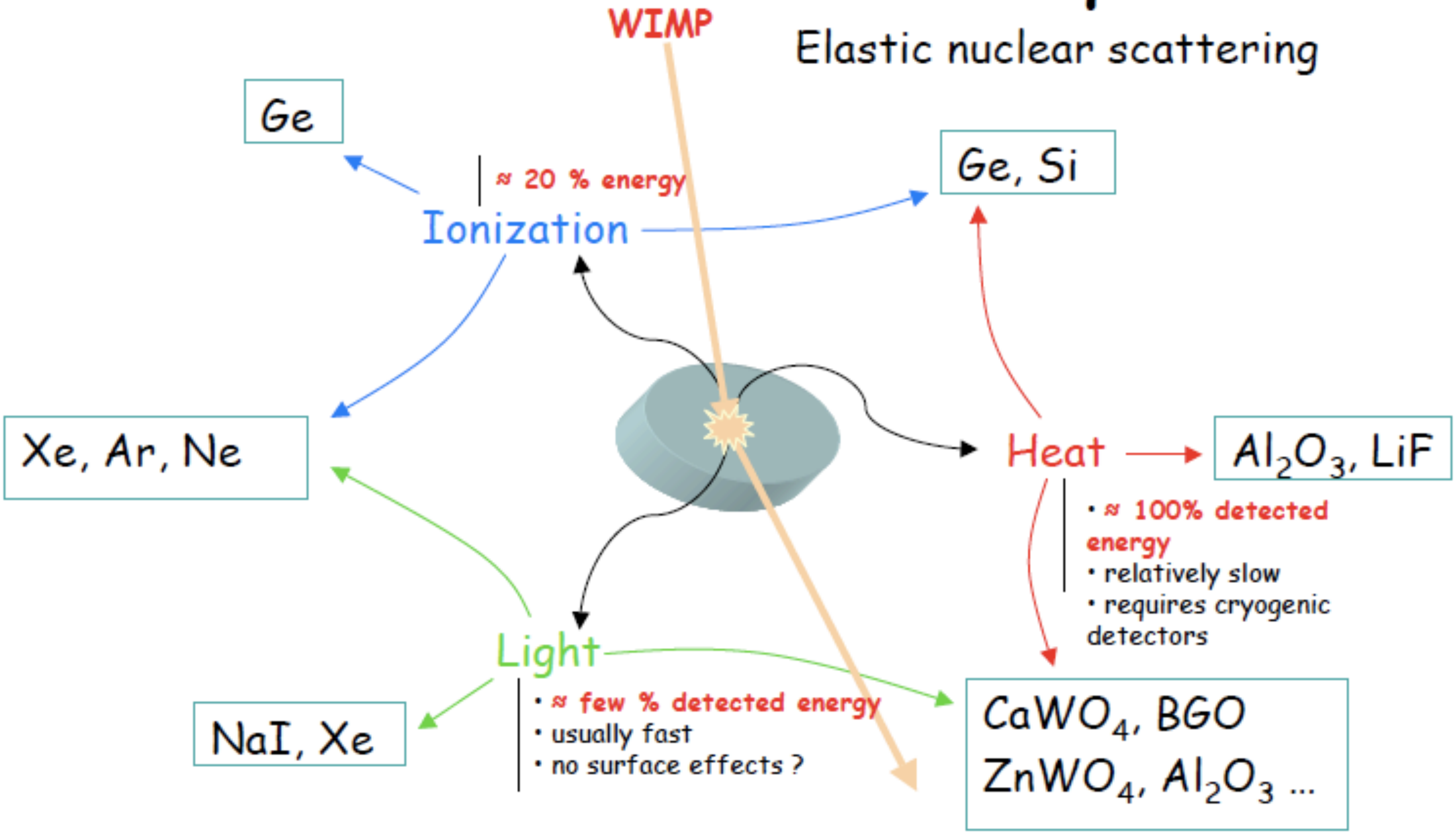
$$T \sim UD$$

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

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



Direct detection techniques



(Drukier & Stodolsky 1984; Goodman & Witten 1985)

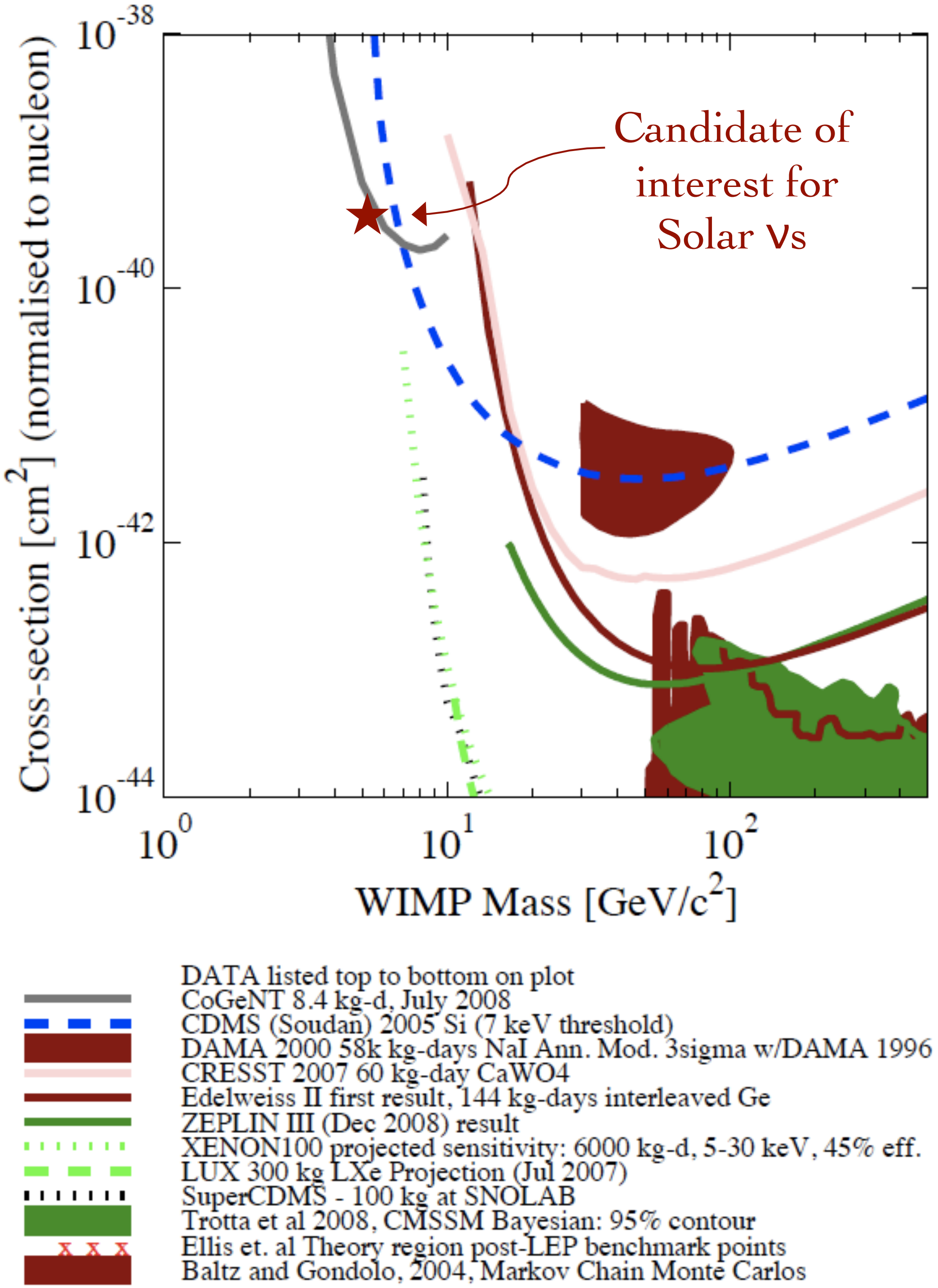
No detection so far … upper limits (~10^{-43} cm^2) on scattering cross-section of ~100 GeV WIMPs, assuming local halo dark matter density ~ 0.4 GeV cm^{-3}

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 ⇒ O(keV) recoil energy

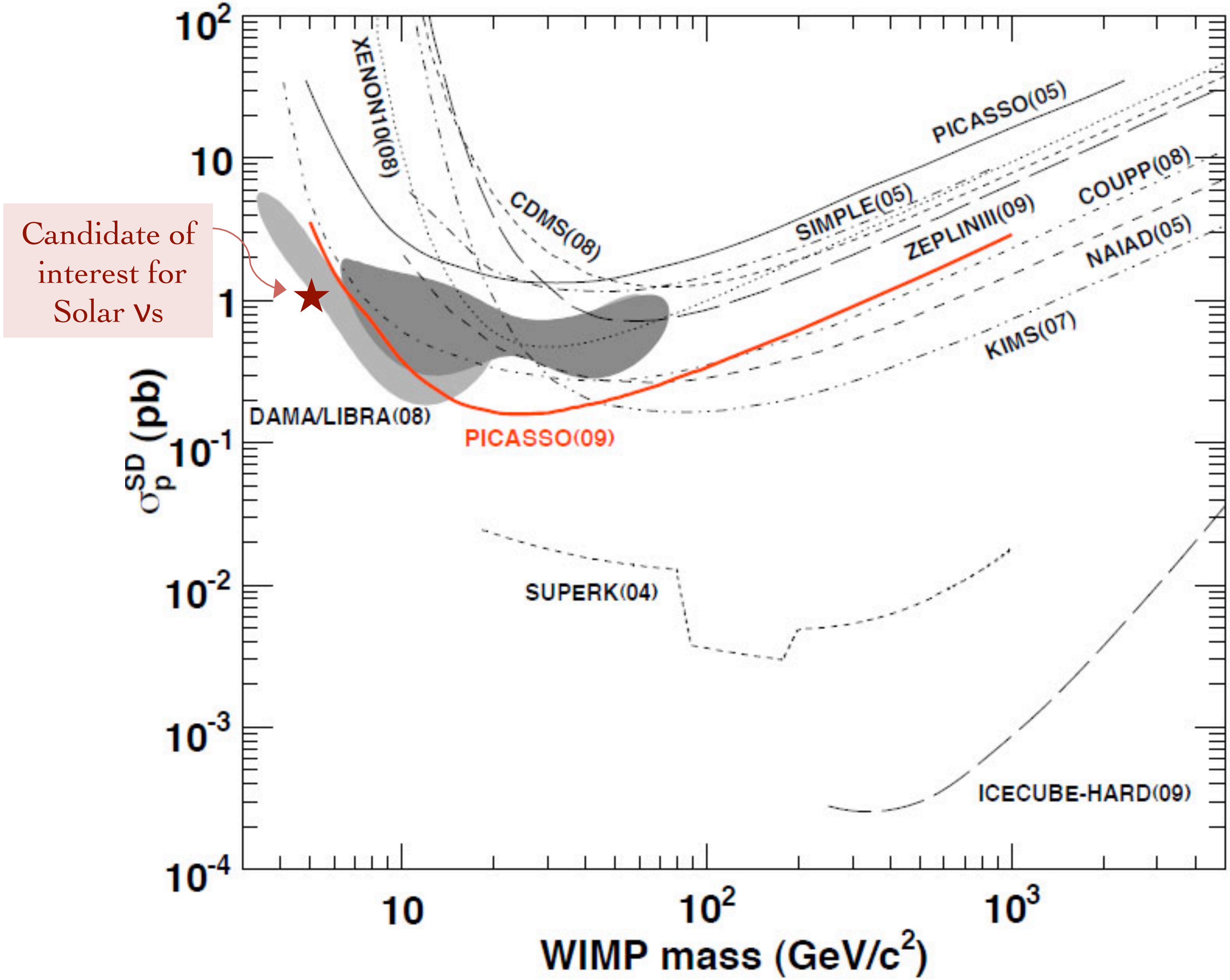
A ~5 GeV dark matter particle may have gone undetected even if its interaction cross-section is as high as ~10^{-40}-10^{39} cm^2

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

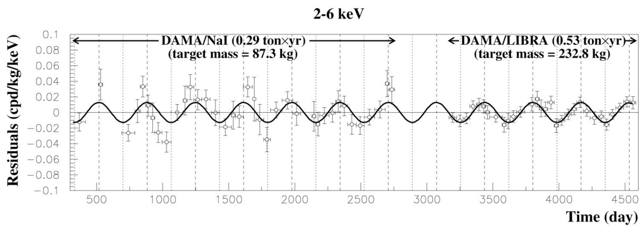
To detect such particles will require *low* threshold detectors

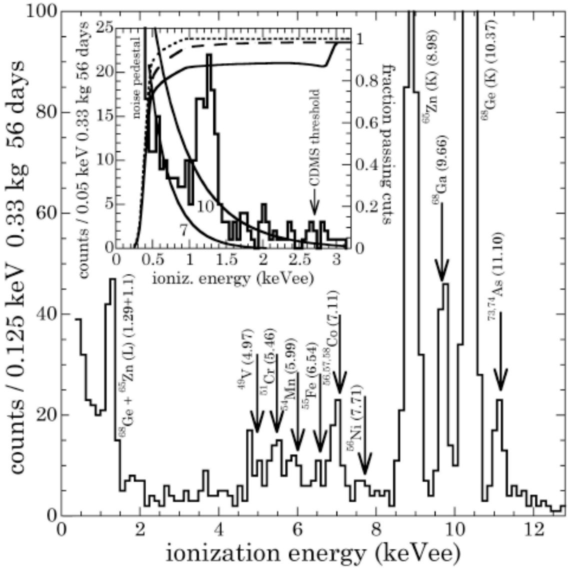


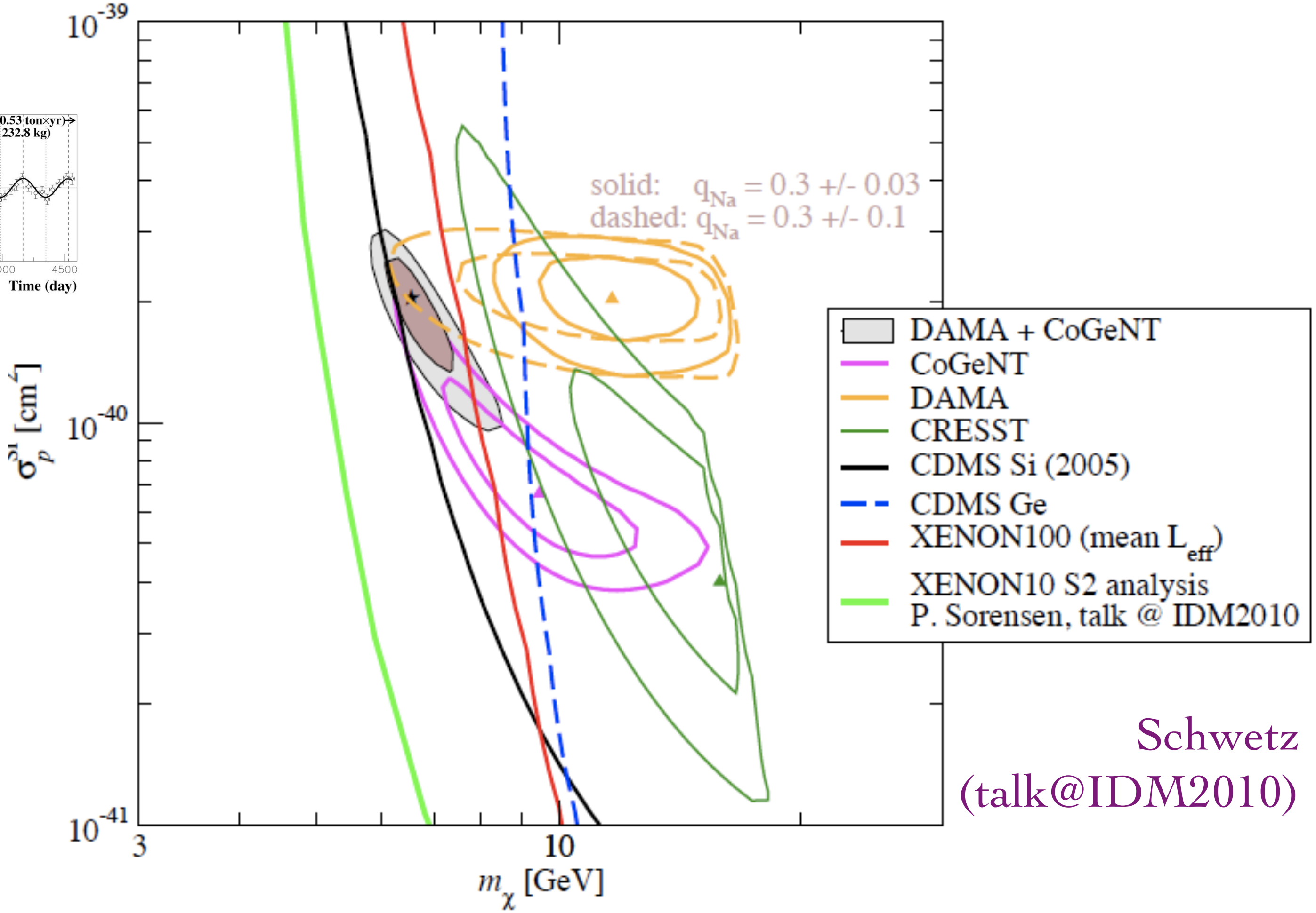
Current experimental limits on spin *dependent* DM-nucleon cross-section



Some experiments (CoGeNT, DAMA, …) have reported *possible* signals for **~5-10 GeV** mass dark matter with $\boldsymbol{\sigma_{SI} \sim 10^{-40}\text{-}10^{-39}\ \mathrm{cm}^2}$!

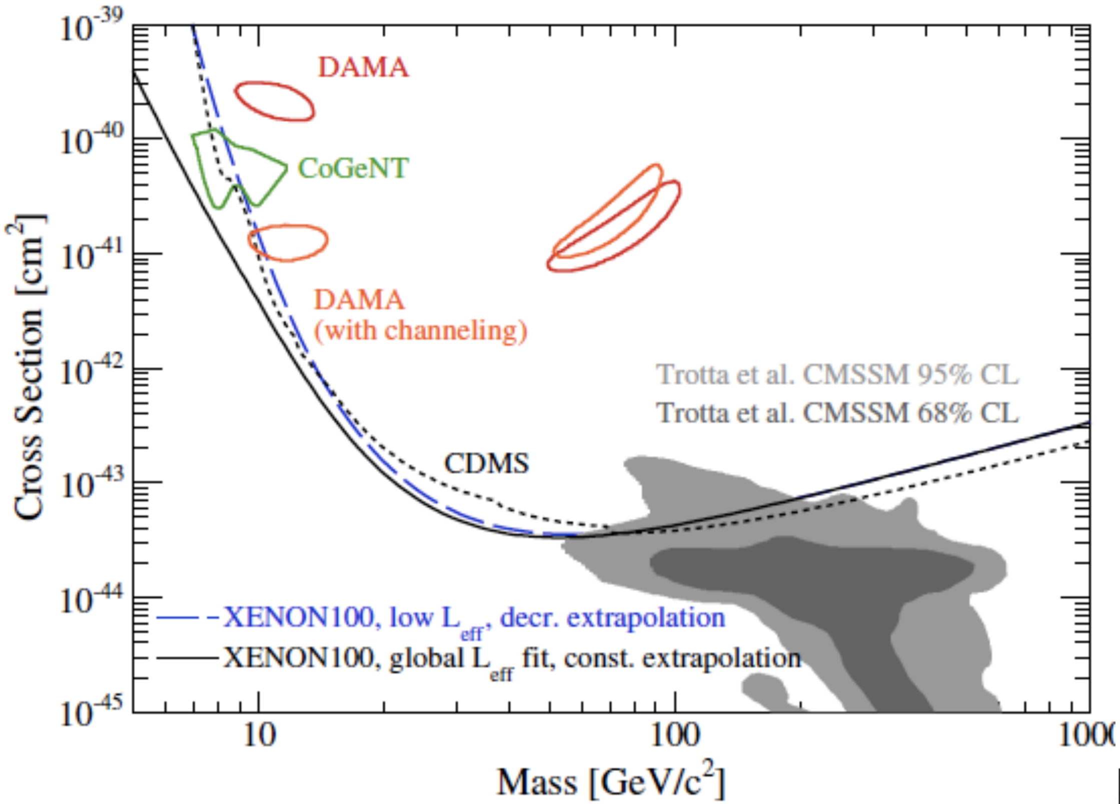


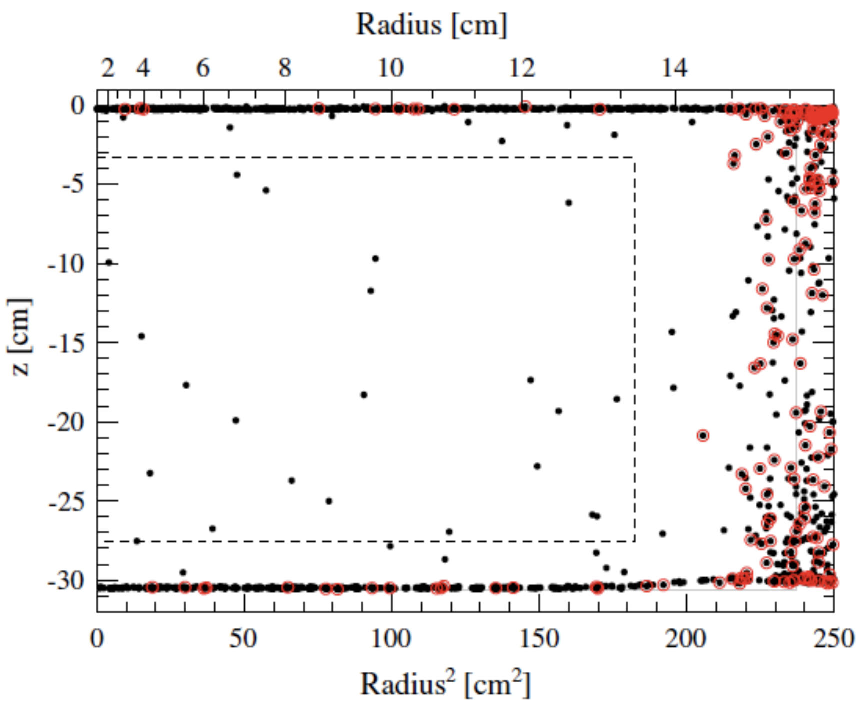


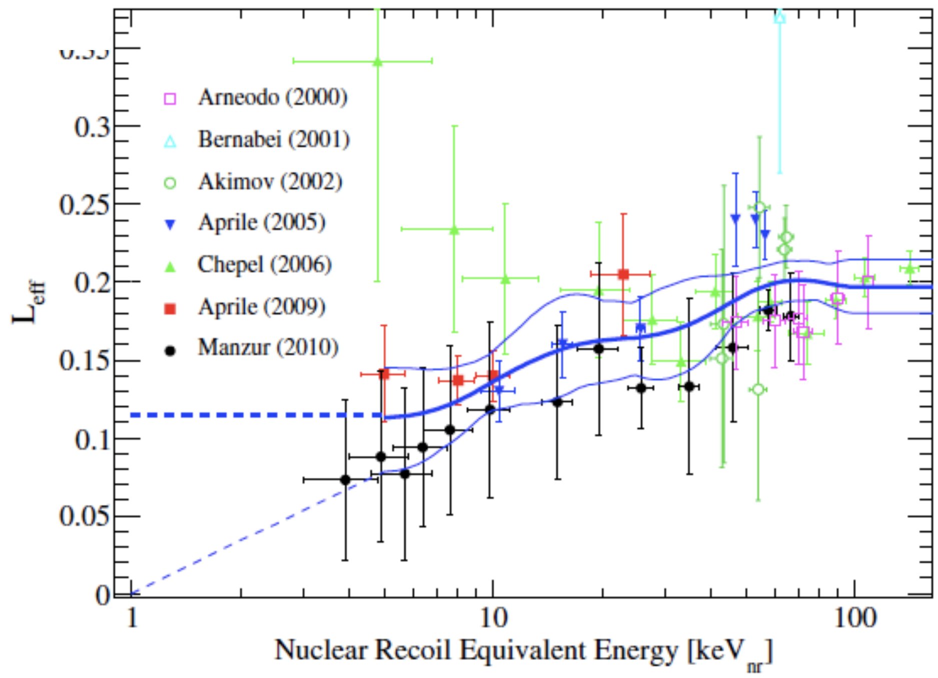


Schwetz
(talk@IDM2010)

Efforts are currently underway to test these claims with *low threshold* detectors (XENON, CCDs …)

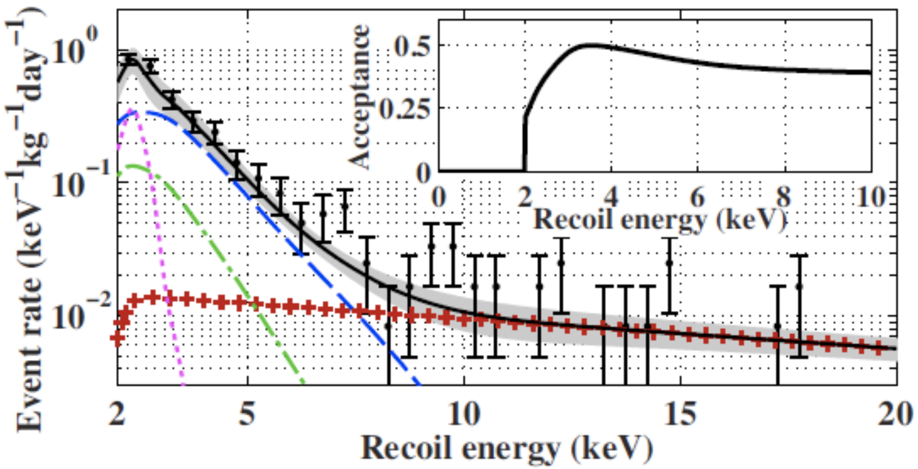






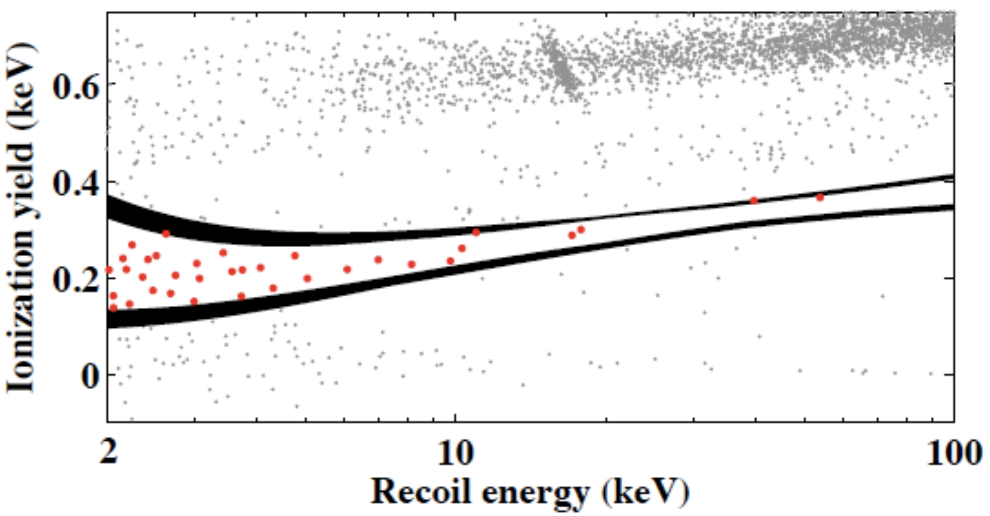
Xenon-100 claims to rule this out, however their bounds are subject to uncertainties in the scintillation light yield at low threshold …

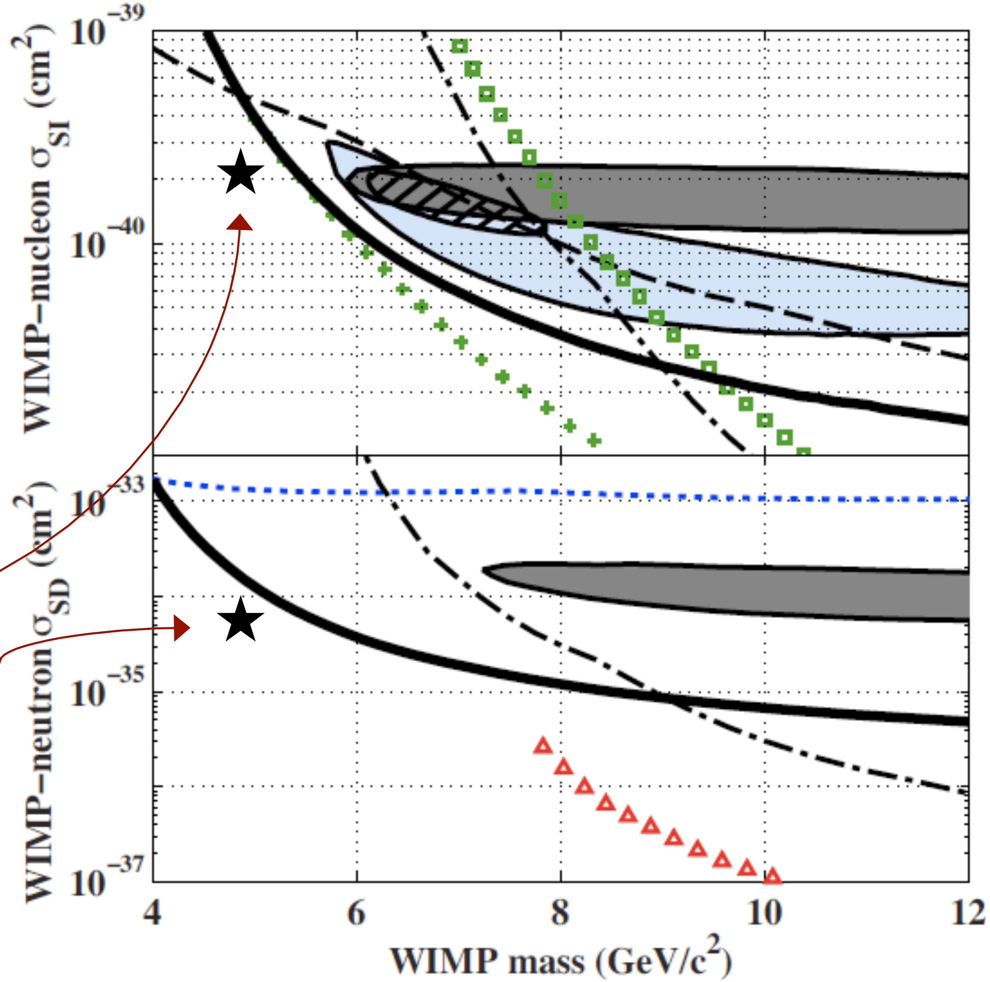
PRL 105, 131302 (2010)



CDMS-II says it has ruled out CoGeNT and DAMA …

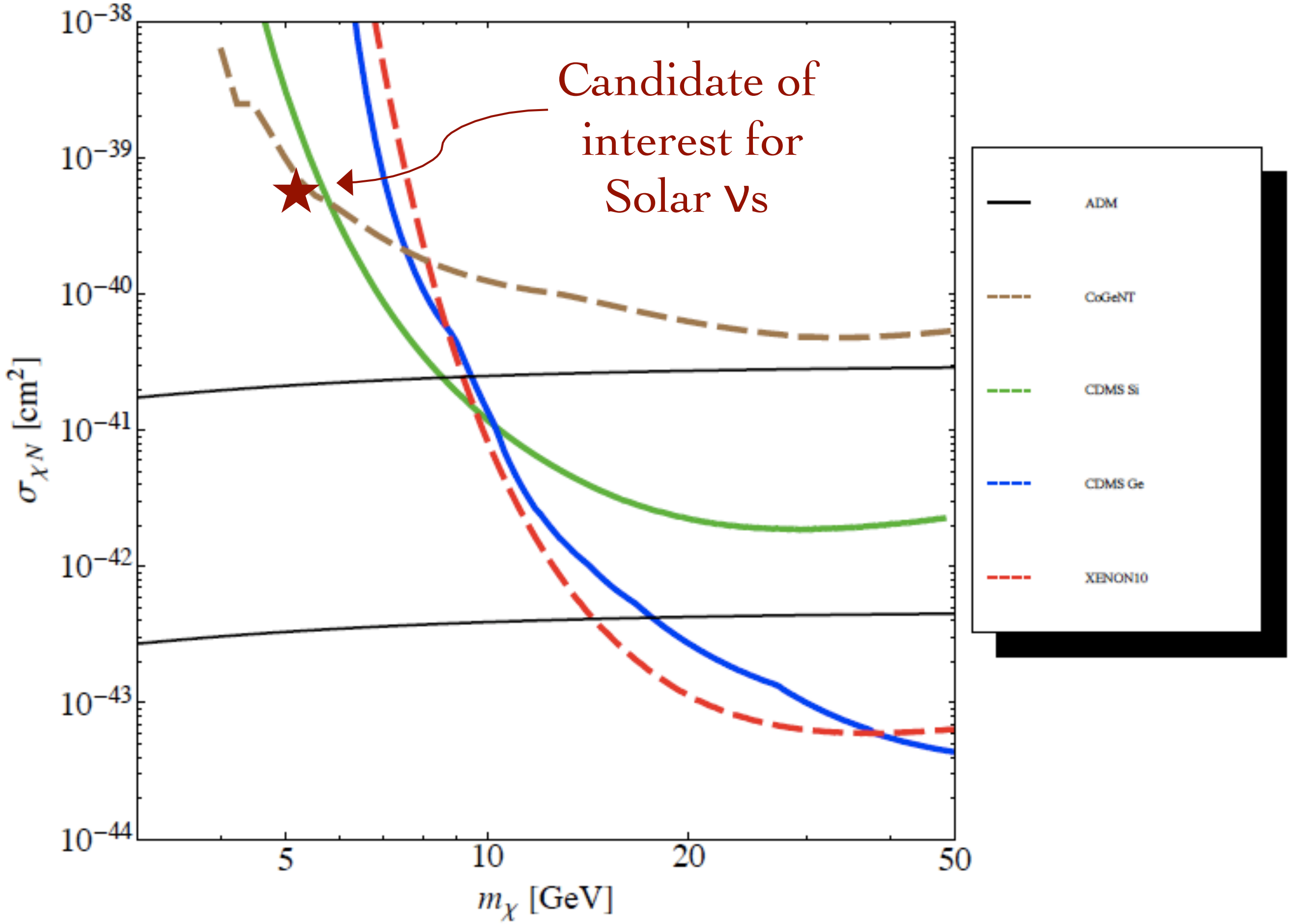
[arXiv:1011.2482]





However the 5 GeV particle candidate of interest is still unconstrained…

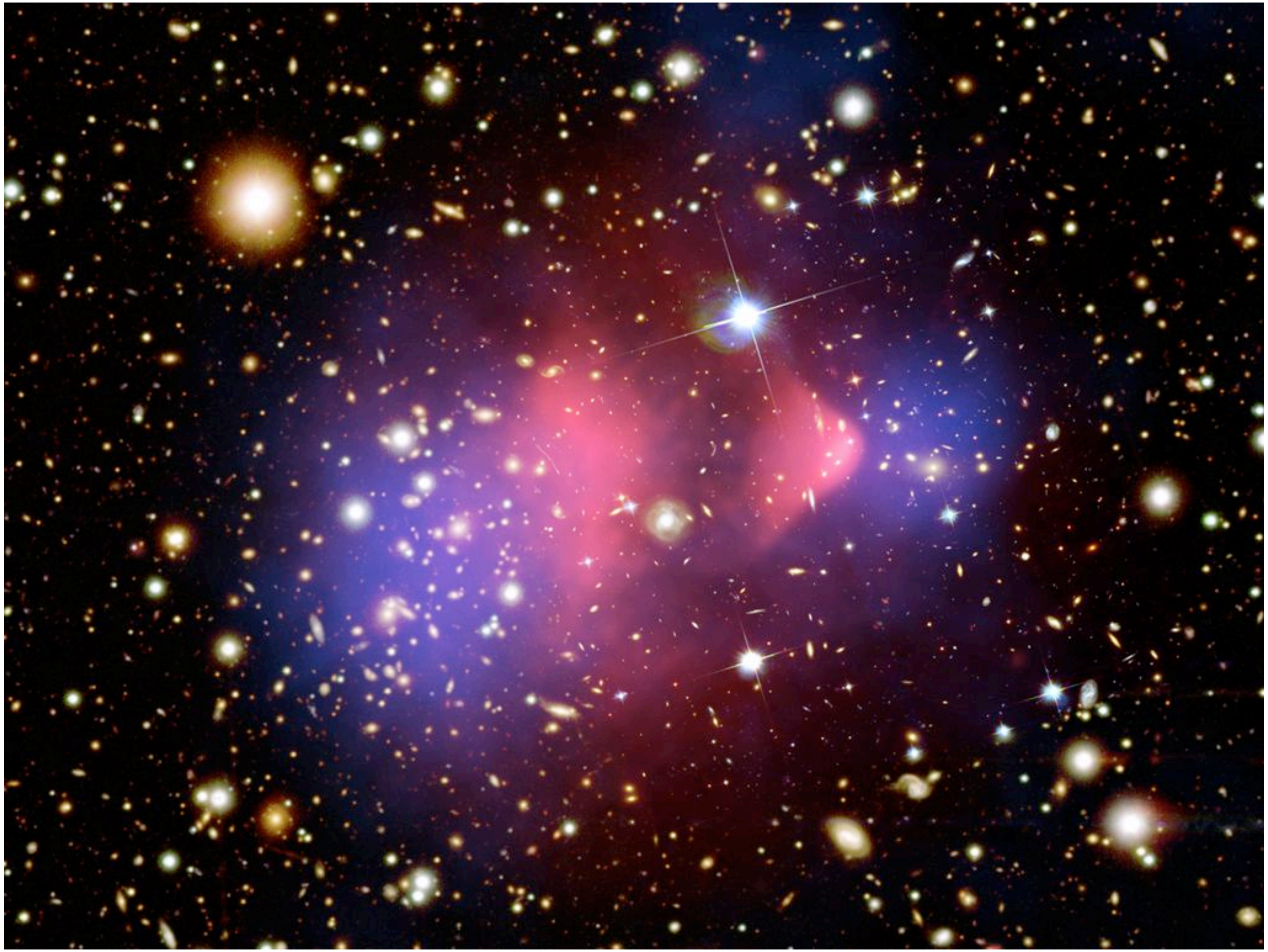
Can get up to ~2 x 10^{-41} cm^2 spin-independent cross-section through Higgs exchange for an 'unbaryon' in walking technicolour (Sannino & Zwicki 2009)



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, …)

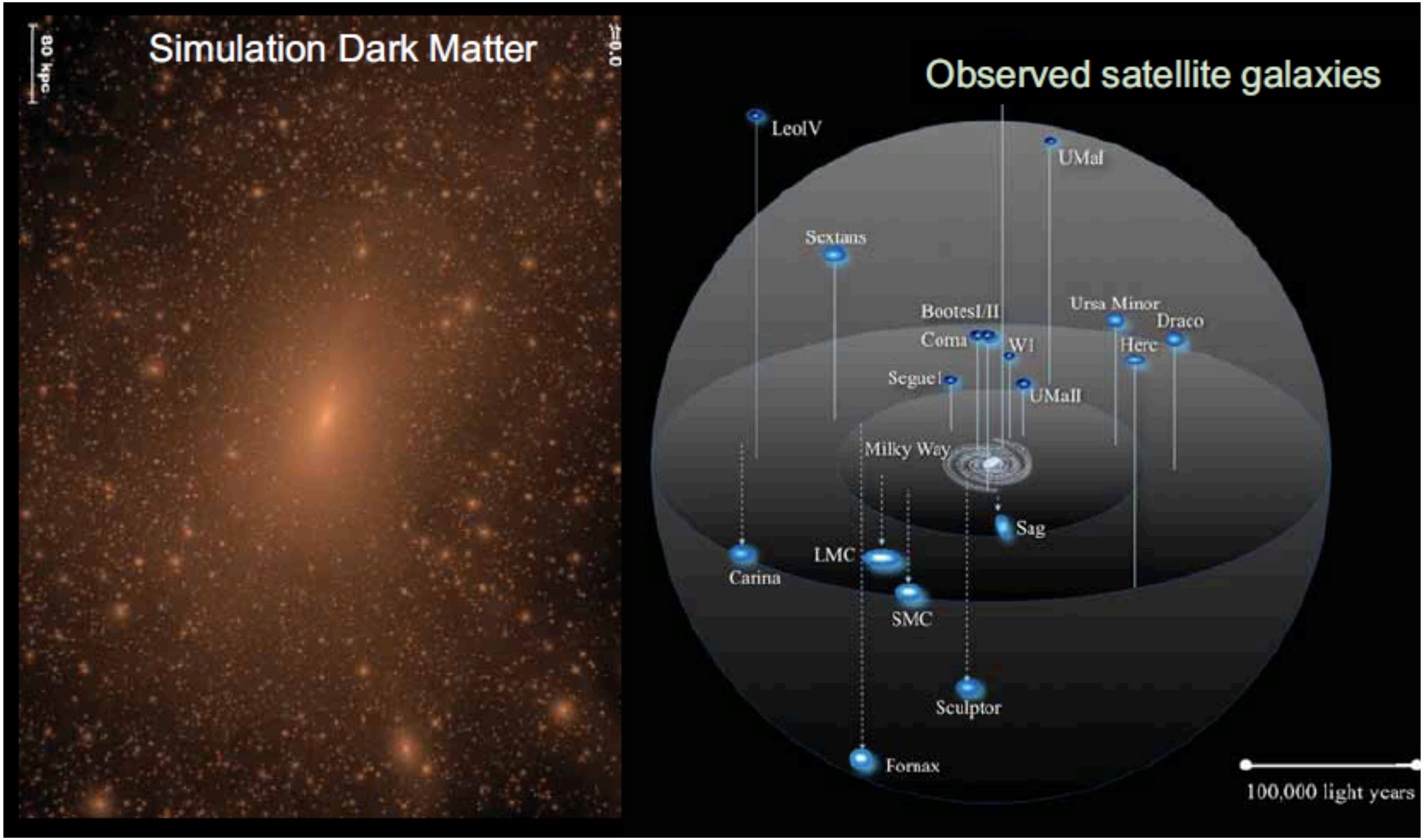
NB: Only DAMA is sensitive to electron recoils due to such *em* interactions

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



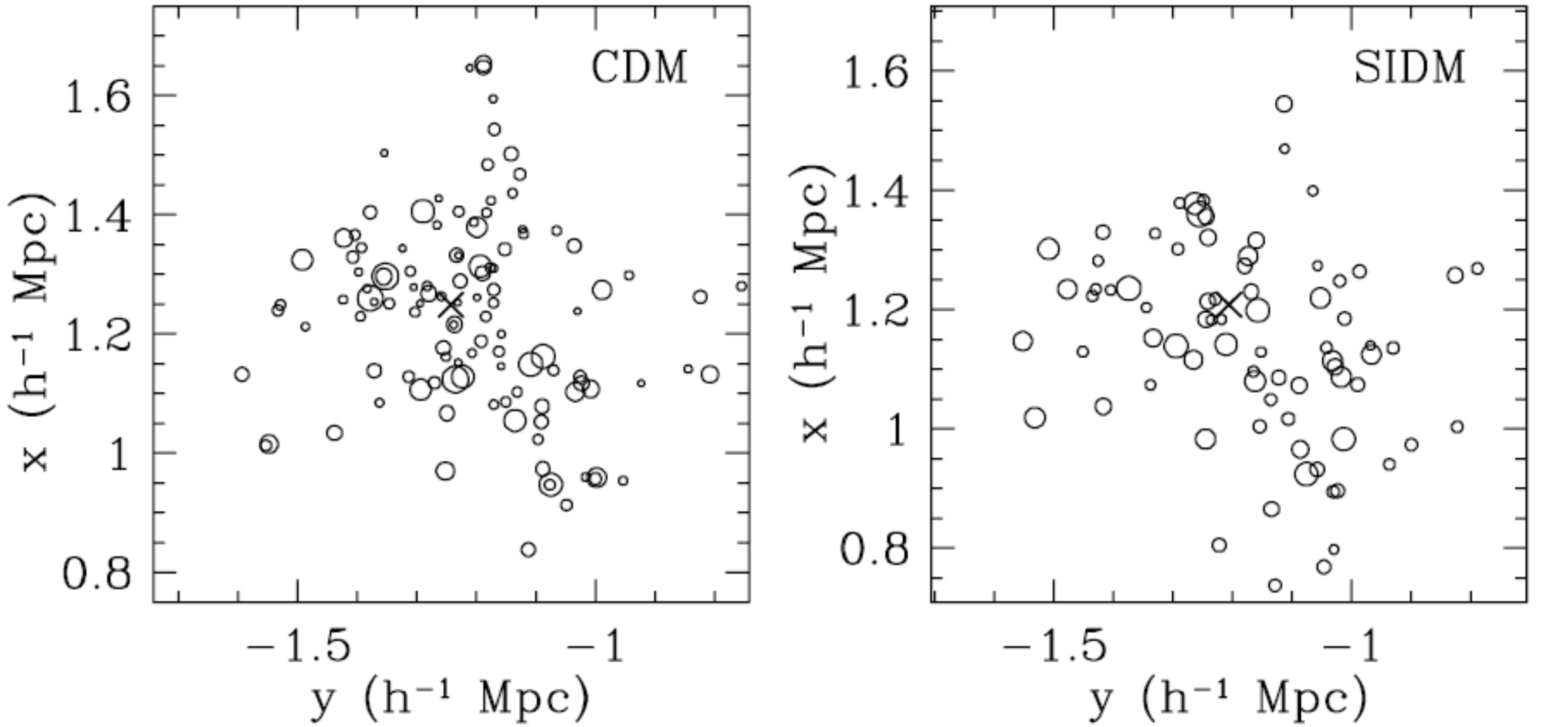
… well below the bound of 2×10^{-24} cm^2/GeV from the 'Bullet cluster'

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 >10^3 are expected

Only one numerical simulation done so far of SIDM … however the (important) effect of baryons was not included – more studies needed



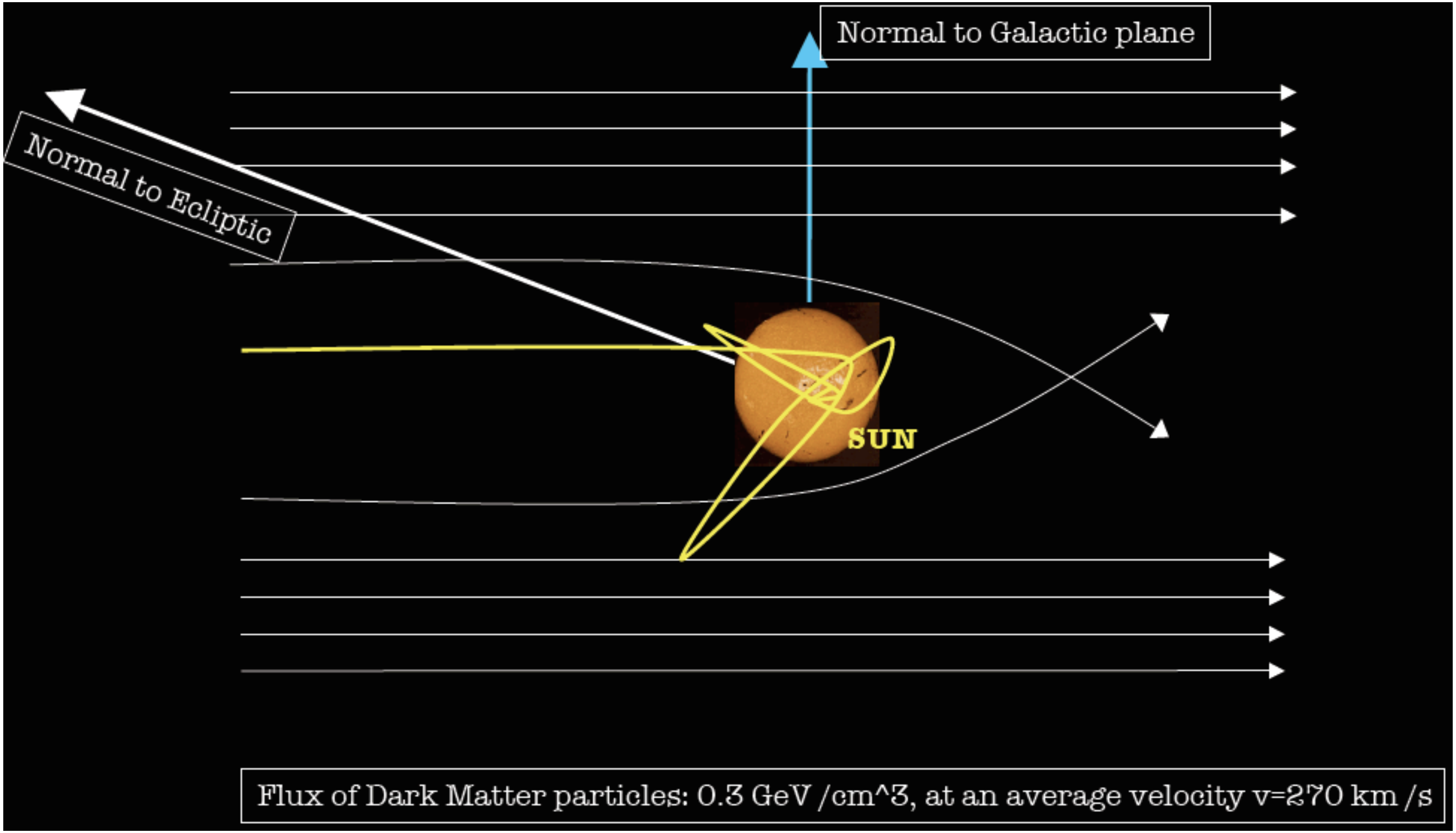
Dave, Steinhardt, Spergel & Wandelt (2001)

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

Firmani, D'Onghia, Avila-Reese, Chinarini & Hernandez (2000), Feng, Kaplinghat & Yu (2010)

Presently we *cannot* assert that dark matter must have Fermi-scale mass, or be collisionless, or be 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

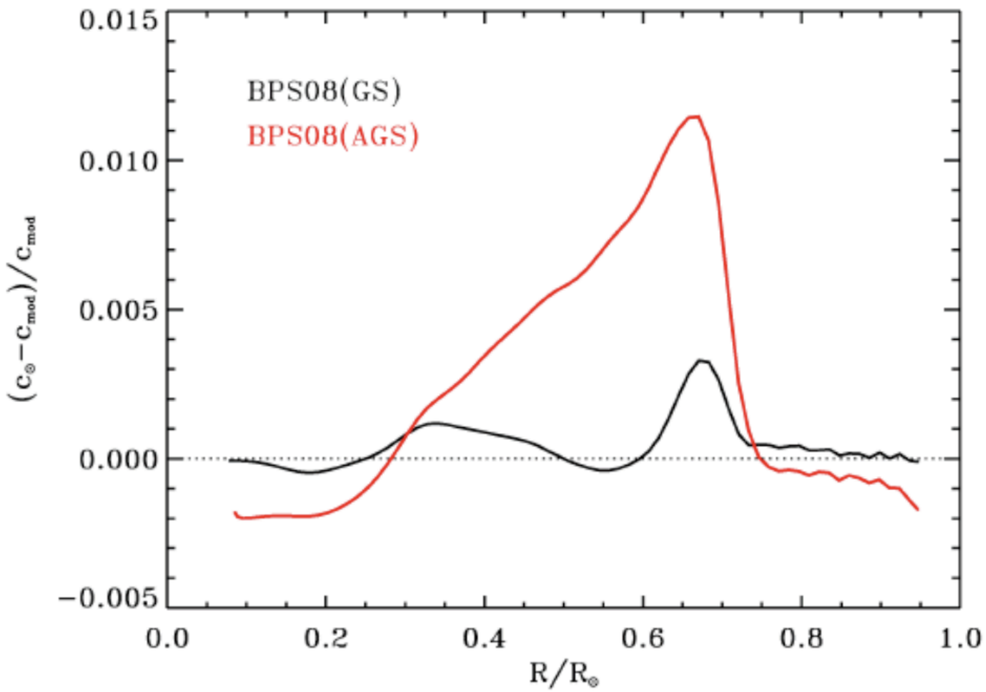


The flux of Solar neutrinos is *very* sensitive to the core temperature and can thus be affected (Faulkner *et al* 1985, Press & Spergel 1985, Gould 1987)

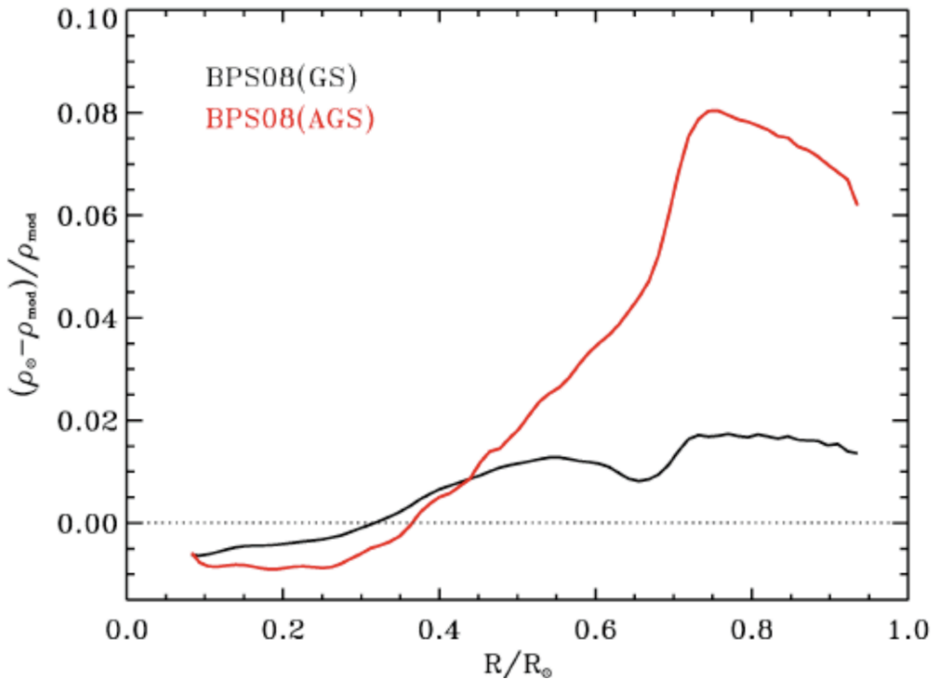
A problem with the standard Solar model

- Asplund, Grevesse & Sauval (2005) have determined new Solar chemical abundances 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



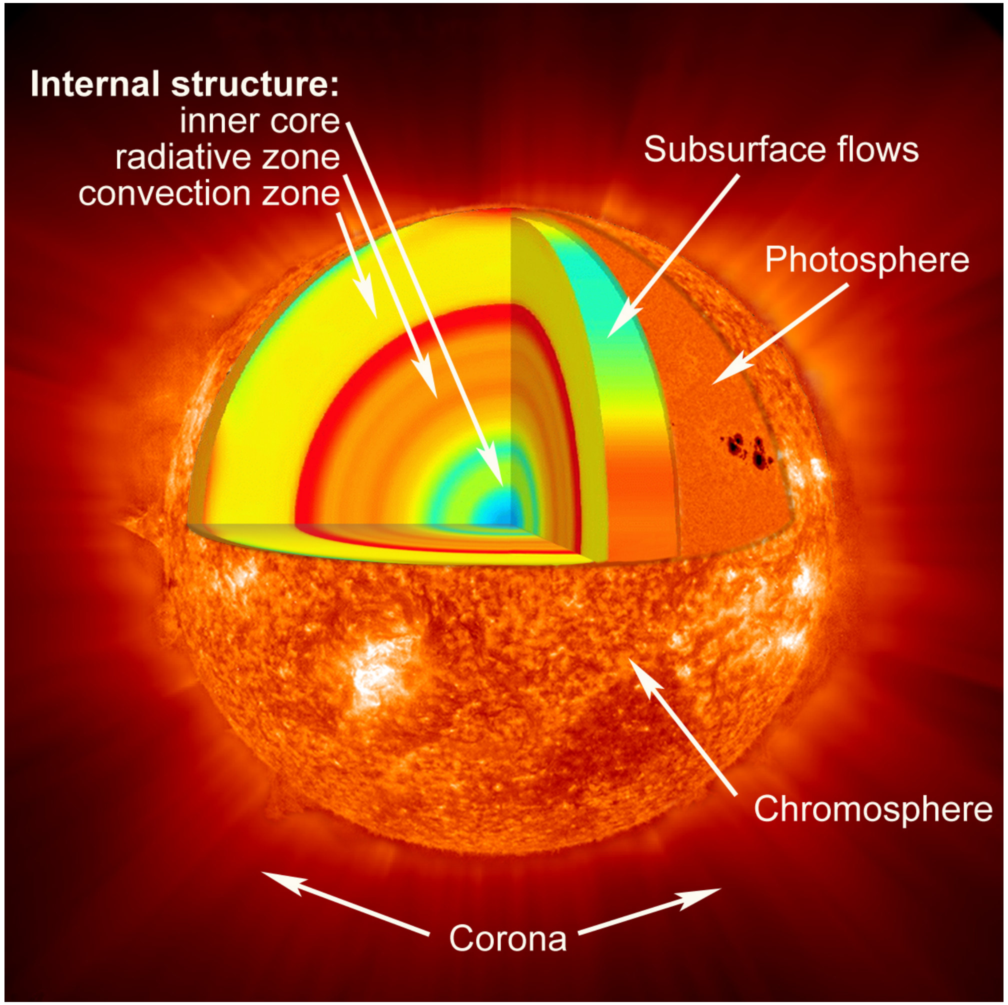
density profile in the Sun



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

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

The particle mass must be ~5-10 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: $R_{CZ}/R_{\odot}$ = 0.713 + 0.001
… too high (by >10σ) in SSM but can be lowered by the required ~1% if

$$(\sigma_{\chi N}/\sigma_{\odot})(N_{\chi}/N_{\odot}) \gtrsim 10^{-14}, \text{ where } \sigma_{\odot} \equiv (m_{N}/M_{\odot})R_{\odot}^{2} \sim 4 \times 10^{-36} \text{ cm}^{2}$$

Capture of dark matter by 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 thermal core within the star of radius:

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

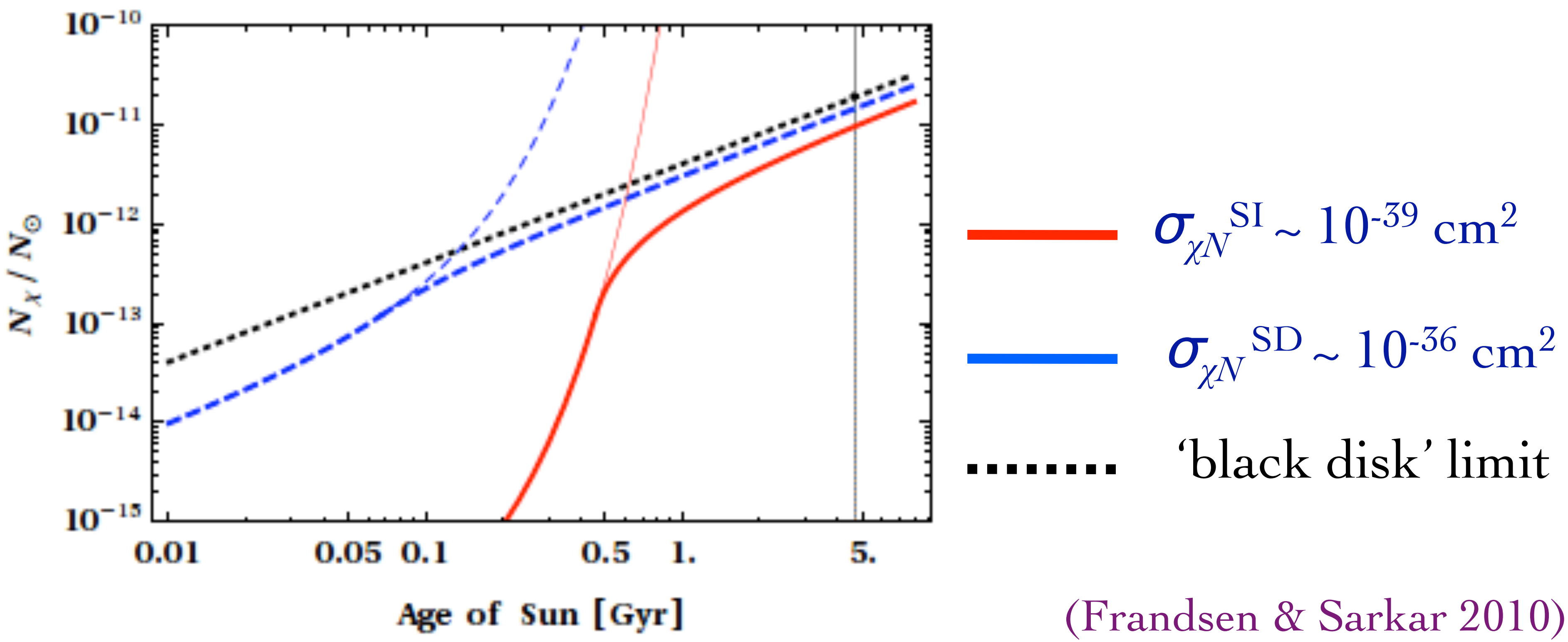
For the Sun and 5 GeV DM, this is ~ 4 x 10^9 cm (orbit period ~ 10^4 s)
… compare with Solar radius ~7x10^{10} cm (thermal diffusion time ~10^{15} s)

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 … also self-interactions *raise* (self-) capture rate (Zentner 2009) so abundance grows *exponentially* (until geometric limit set by Solar disk)

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

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

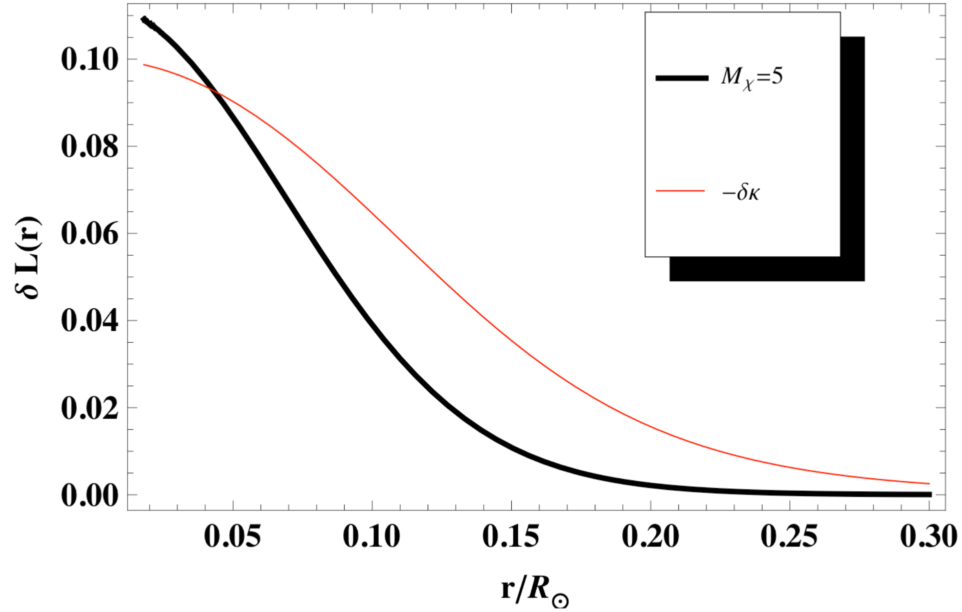


(Frandsen & Sarkar 2010)

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

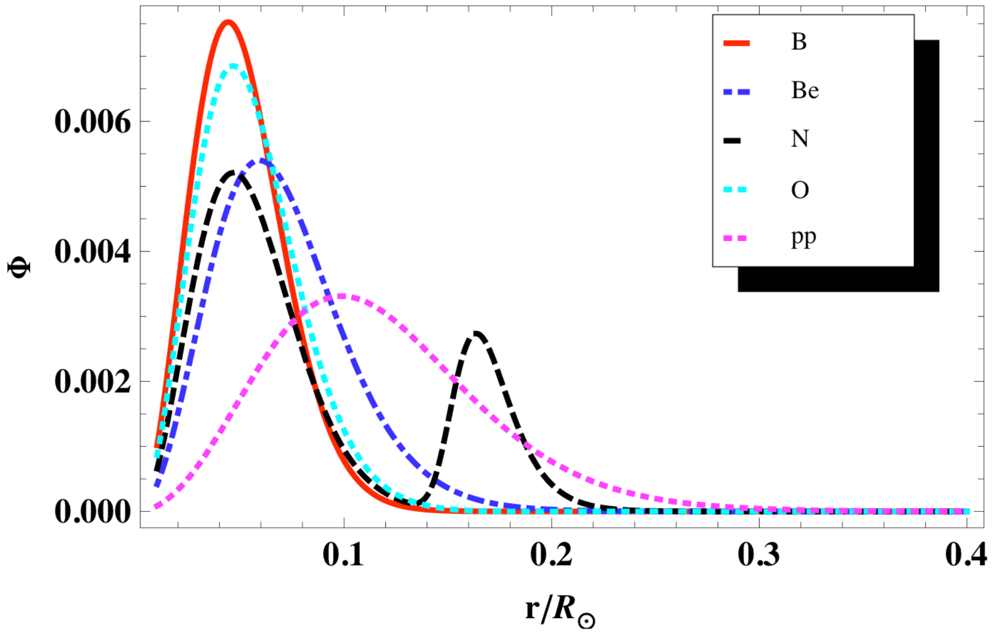
(Bottino *et al* 2002)



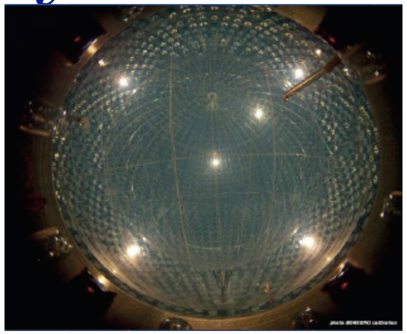
According to the 'Linear Solar Model' (Villante & Ricci 2009), a ~10% reduction of the opacity in the core will reduce the convective boundary by ~0.7% and *restore* agreement with helioseismology

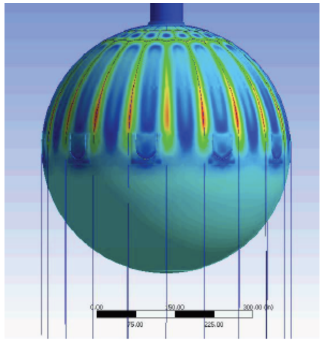
Modification of the luminosity profile will reduce the ν fluxes:
$\delta\Phi_B$ = -17%, $\delta\Phi_{Be}$ = -6.7%,
$\delta\Phi_N$ = -10%, $\delta\Phi_O$ = -14% …
testable by Borexino & SNO+

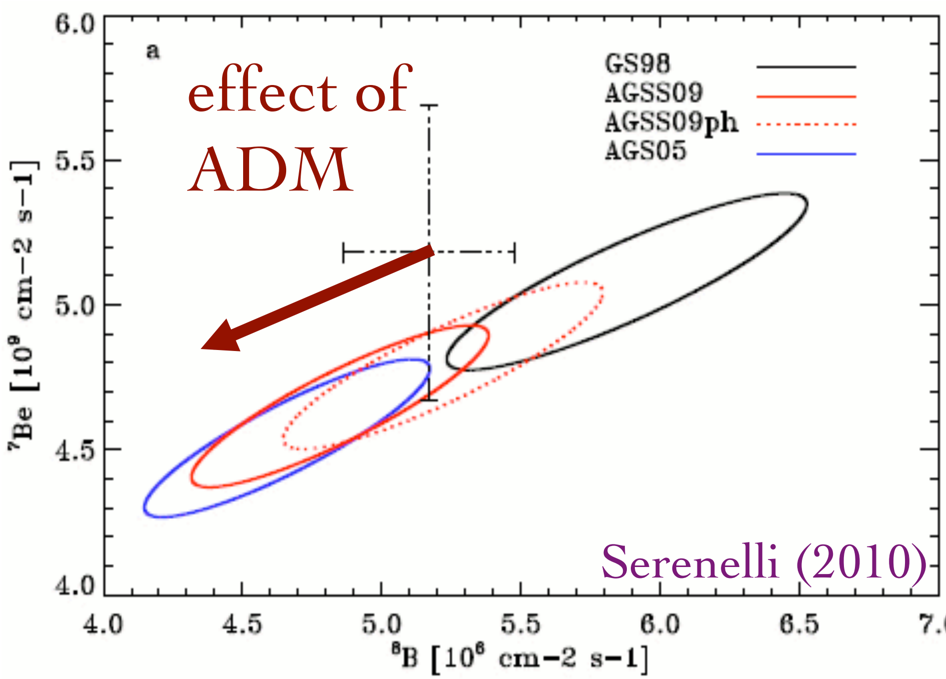
(Frandsen & Sarkar 2010)

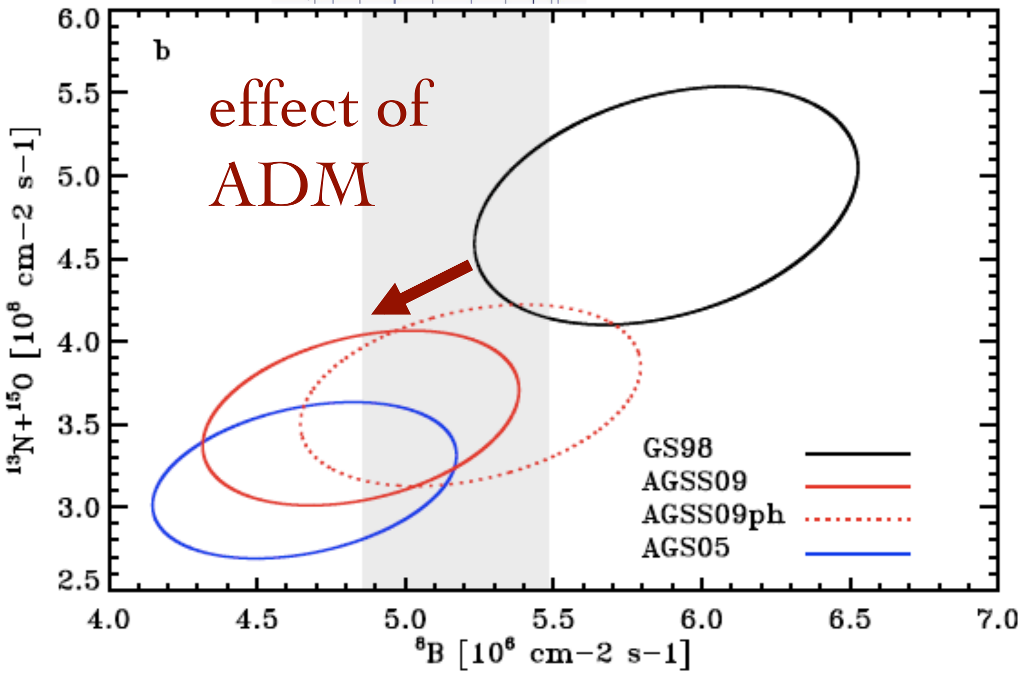


Forthcoming precision measurements of Solar neutrinos by Borexino and SNO+ can *test* the model









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 will be hard to distinguish between effects of metallicity and dark matter

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', invisible decays …)

➢ 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 SUSY dark matter … experiment will tell!