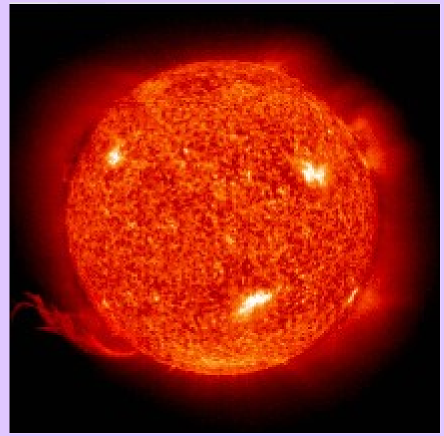
Asymmetric Dark Matter



and the SUN

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Together with Subir Sarkar
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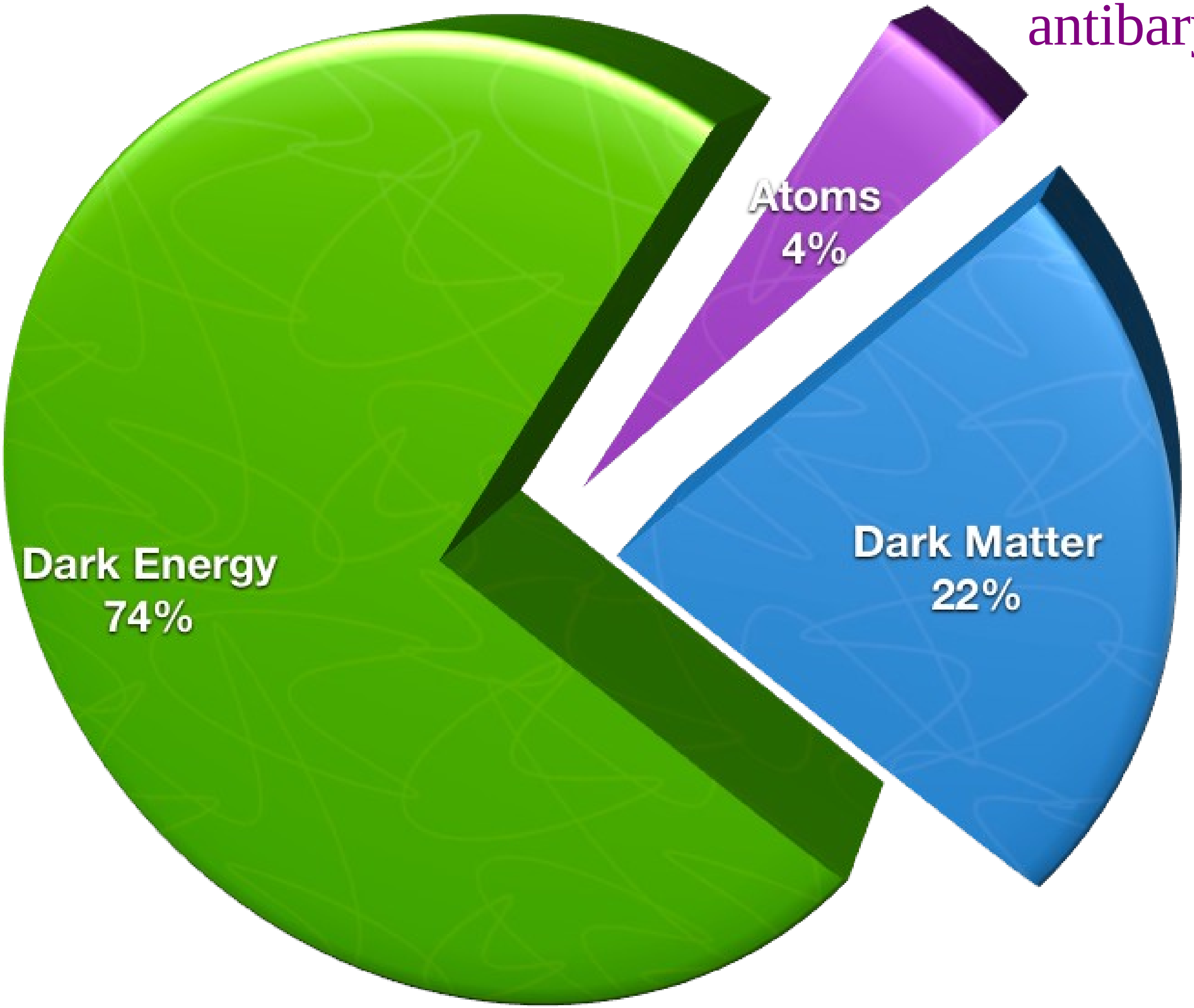
PHYSYN, October 5th 2010
Some slides taken from S. Sarkar @ SUSY10

What is the world made of?



Baryons but no antibaryons

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 $\Omega_B \sim 0.05$

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

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:

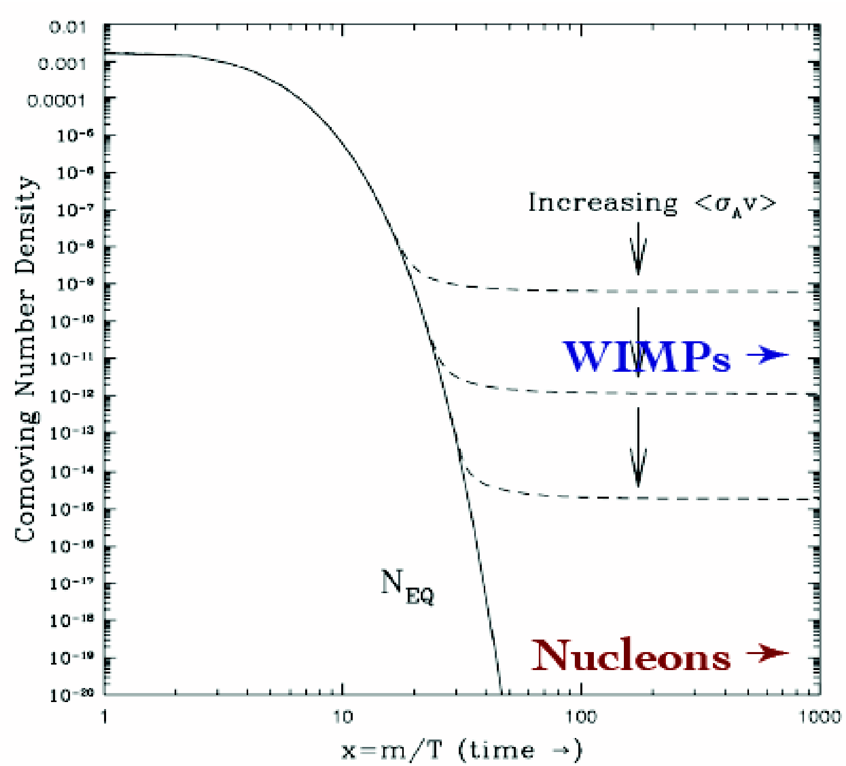
$$\frac{n_N}{n_\gamma} = \frac{n_{\bar{N}}}{n_\gamma} \sim 10^{-19}$$

Observed ratio is 10^9 times bigger:

A 'baryon disaster'?!

Have to invoke an **asymmetry:**

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



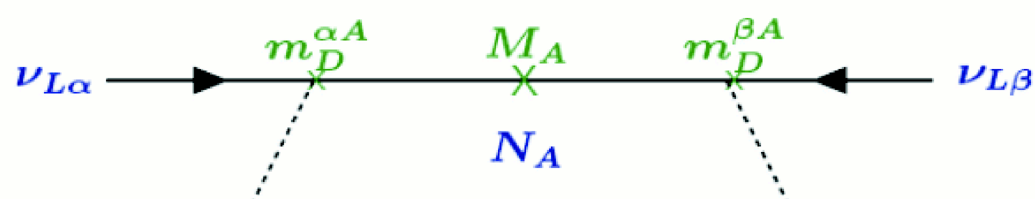
<u>Sakharov conditions for baryogenesis:</u>

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')

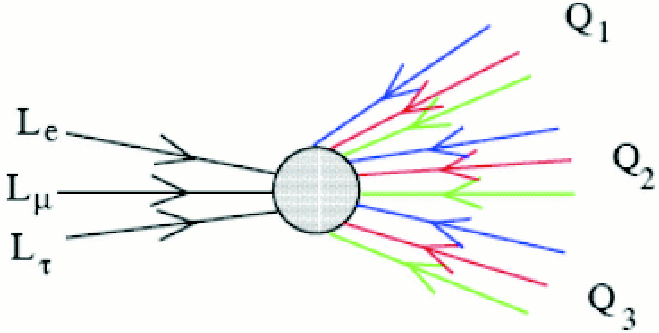
Thus the generation of the observed matter-antimatter asymmetry *requires* new BSM physics (could be related to neutrino masses … **possibly due to violation of lepton number → leptogenesis)**

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



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

Asymmetric baryonic matter



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

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

$\sim 10^{-10}$ 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**

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 asymmetry	$\Omega_B \sim 10^{-10}$ $\Omega_B \sim 0.05$
$\Lambda_{Fermi} \sim G_F^{-1/2}$	Neutralino?	R-parity?	violated?	'freeze-out' from thermal equilibrium	$\Omega_{LSP} \sim 0.3$

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

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

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

What *should* the world be made of ?

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
Λ_{QCD}	**Nucleons**	U(1) baryon #	⊗ > 10^{33} yr (dim-6 OK)	'freeze-out' from thermal equilibrium **Asymmetry**	$\Omega_B \sim 10^{-10}$ $\Omega_B \sim 0.05$
$\Lambda_{TC} \sim \Lambda_{Fermi}$ $\Lambda_{DB} \sim 5\,\Lambda_{QCD}$	**Technibaryon? Dark baryon?**	**U(1) technibaryon # U(1) dark baryon #**	**violated?**	**Asymmetry**	$\Omega_{DB} \sim 0.3$
Λ_{Fermi}	Neutralino?	R-parity?	violated?	'freeze-out' from thermal equilibrium	$\Omega_{LSP} \sim 0.3$
$f_a/M_{Planck} < 10^{-9}$	Axion?	Peccei-Quinn	Stable	Field oscillations (non-thermal)	$\Omega > 0.3$?
$\Lambda_{Fermi}/M_{Planck}$	Sneutrino?	R-parity?	violated?	Freeze-In	$\Omega_{DM} \sim 0.3$

No definite indication from theory...must decide by experiment, but:

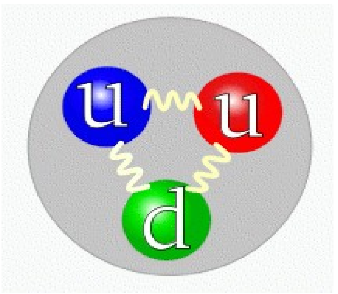
Asymmetric Dark Matter from new strong interactions motivated by known *stability, mass and asymmetric origin* of baryons from QCD strong interactions.

Such light ADM could have an effect on solar observables – helioseismology and solar ν

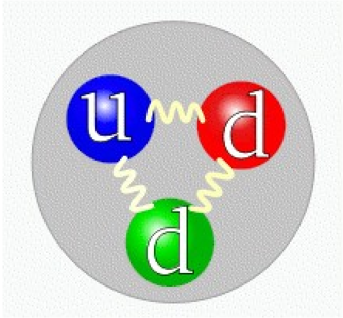
Asymmetric Dark Matter

The baryons are *composite and massive* due to the strong dynamics of QCD. The proton stability is due to a global continuous $U(1)_B$

Proton



Neutron



Minimal chiral symmetries: 3 GB's + Custodial + DM.

$$SU_L(2) \times SU_R(2) \times U_{TB}(1) \rightarrow SU_V(2) \times U_{TB}(1) \ .$$

...without Higgs interactions the neutron is the lightest stable baryon

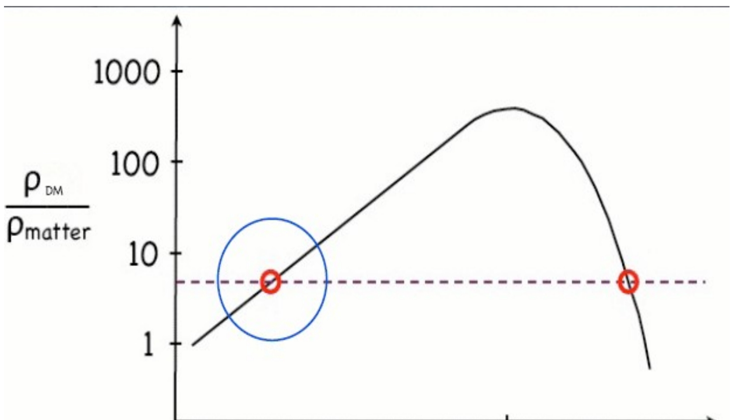
This *motivates* New Strong Dynamics as the origin of ADM

We can hope to understand *why* $\Omega_{DM} / \Omega_B \sim O(1)$

Two natural scales:

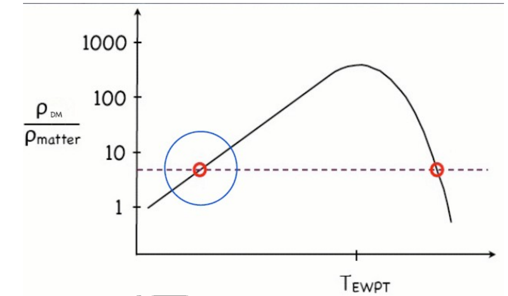
$\sim \Lambda_{Fermi}$ *ADM and DEWSB from Technicolour*

$\sim \Lambda_{QCD}$ *Light ADM*



(Zurek @ SUSY10)

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



$$\Omega_{TB}/\Omega_B = m_{TB}/m_B \times n_{TB}/n_B$$

- From initial $n_B \sim n_{TB}$:

$$\Omega_{TB}/\Omega_B \sim m_{TB}/m_B \times (m_{TB}/T_{sphaleron})^{3/2} e^{-m_{TB}/T_{sphaleron}}$$

$$T_{sphaleron} \sim v_{EW} ,$$

(Bahr, Chivukula and Farhi 90)

Even more naturally is 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, Sannino and Zwicky 09, An et al 10, M.T.F & Sarkar 10, ...)

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 Asymmetry	$\Omega_B \sim 10^{-10}$ $\Omega_B \sim 0.05$
$\Lambda_{TC} \sim \Lambda_{Fermi}$ $\Lambda_{DB} \sim 5\ \Lambda_{QCD}$	Technibaryon? Dark Baryon?	U(1) techibaryon # U(1) dark baryon #		Asymmetry	$\Omega_{DB} \sim 0.3$

Is it natural to have similar initial asymmetry in the visible and dark sector?

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 N ^{i} terms of the statistical function c_i and the Chemical potential μ is:

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

The fermion number 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 & Farhi 90; Harvey and Turner 90)

It is natural to have similar initial asymmetry in the visible and dark sector!

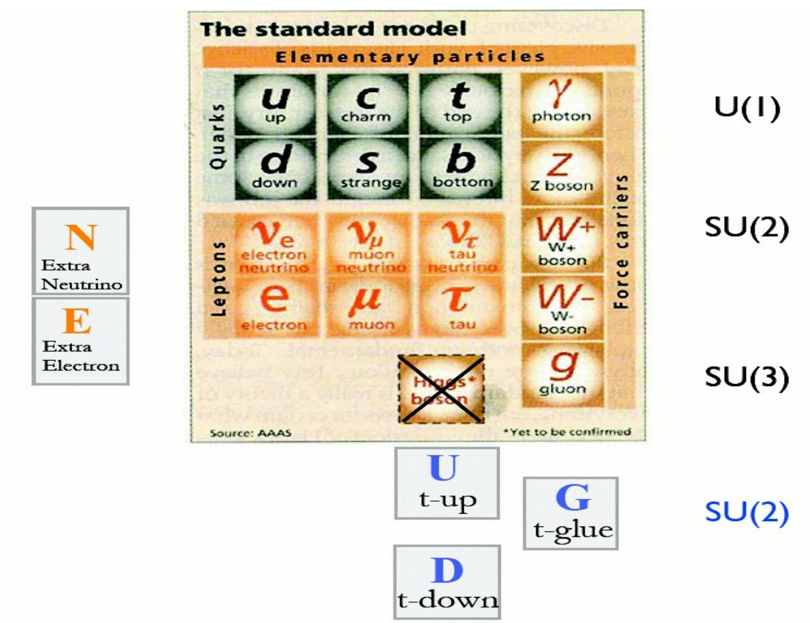
If composite ADM is electrically neutral but has constituents with EW charges, sphalerons may distribute the asymmetry among baryons and dark matter

Can we construct natural explicit models?

EW scale ADM from Technicolor models

GeV scale ADM e.g. from a

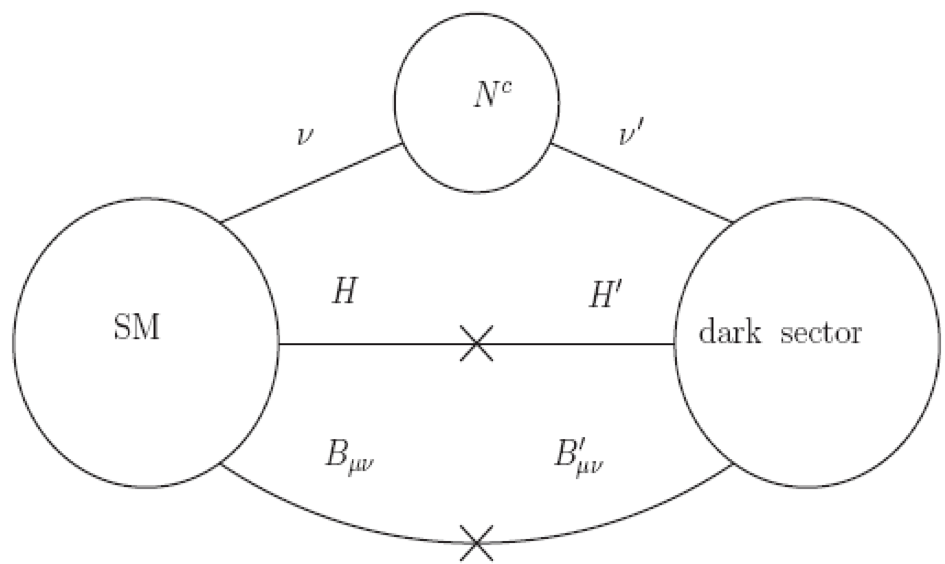
Minimal (Walking) Technicolour



(From Sannino @ SUSY10)

Technicolour *breaks the electroweak symmetry* and the technifermions can *form composite ADM*

Dark hidden/mirror sector



(From An et al 10)

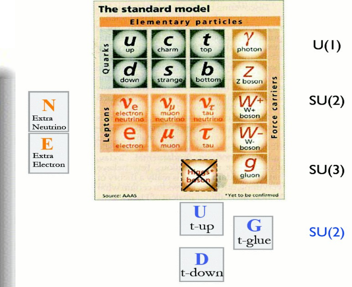
A dark mirror sector (e.g. a complete copy of the SM) is coupled via Higgs-Mirror Higgs and heavy right handed neutrinos which *generate neutrino masses in the SM* and *provide leptogenesis of matter in the SM as well as ADM from the mirror sector*

Technicolor: (Weinberg 78, Susskind 78)

1. In the SM without a Higgs, QCD breaks the EW symmetry:

$$\langle \bar{u}_L u_R + \bar{d}_L d_R \rangle \neq 0 \quad \rightarrow \quad M_W = \frac{g f_\pi}{2} .$$

2. Consider a new strongly interacting gauge theory with $F_\Pi^{TC} = v_{EW} = 246\, GeV$.
3. Let the electroweak gauge group be a subgroup of the chiral symmetry group.



TECHNOCOSMOLOGY – COULD A TECHNIBARYON EXCESS PROVIDE A "NATURAL" MISSING MASS CANDIDATE?

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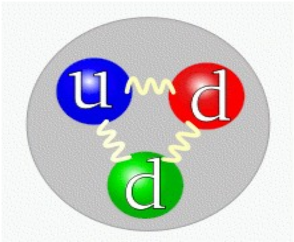
Received 7 October 1985

'Techni-neutron'



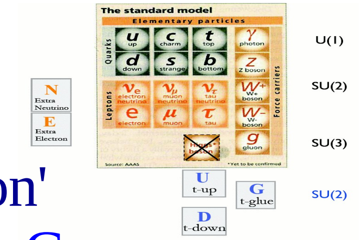
It is pointed out that if: (a) at least one technibaryon is very stable ($\tau \geqslant 10^{20-25}$ yr) and (b) a technibaryon excess is built up at the early stages of the big bang with magnitude comparable to the normal baryonic matter asymmetry $\epsilon_B \approx \epsilon_{TB}$ then stable technibaryons can account for the missing mass and most naturally explain why $\rho_B \approx 10^{-2} \rho_{crit}$.

The most obvious technicolor/technibaryon scenarios, scaled up versions of QCD with 'techni-neutron' dark matter are ruled out:

Precision EW parameters too large S ~ O(1)

DM scattering on nuclei too large → $\sigma = (G_F^2/2\pi)(n_{TC})^2 m_\rho^2 \approx 10^{-32}\ \text{cm}^2$

Techni-Interacting Massive Particles



Technibaryon ADM is much more general than a QCD-like 'techni-neutron'

Consider a general minimal (2 techniflavors) TC theory with gauge group G_{TC}

TIMP: Complex scalar, charged under the $U(1)_{TB}$ symmetry

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

'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)

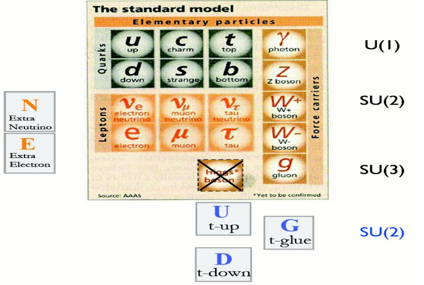
TIMPs arise as Goldstone Bosons from the technicolour chiral symmetries → they can be light ~ O(100) GeV when EW interactions are taken into account

They are stable as they carry $U(1)_{TB}$ technibaryon number

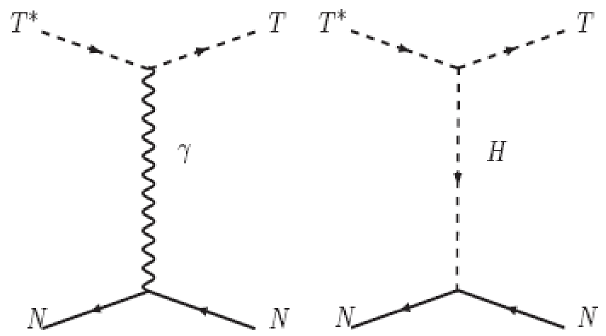
Composite states neutral but constituents may be charged as above

Precision EW parameters and DM scattering on nuclei ok for these TIMPs

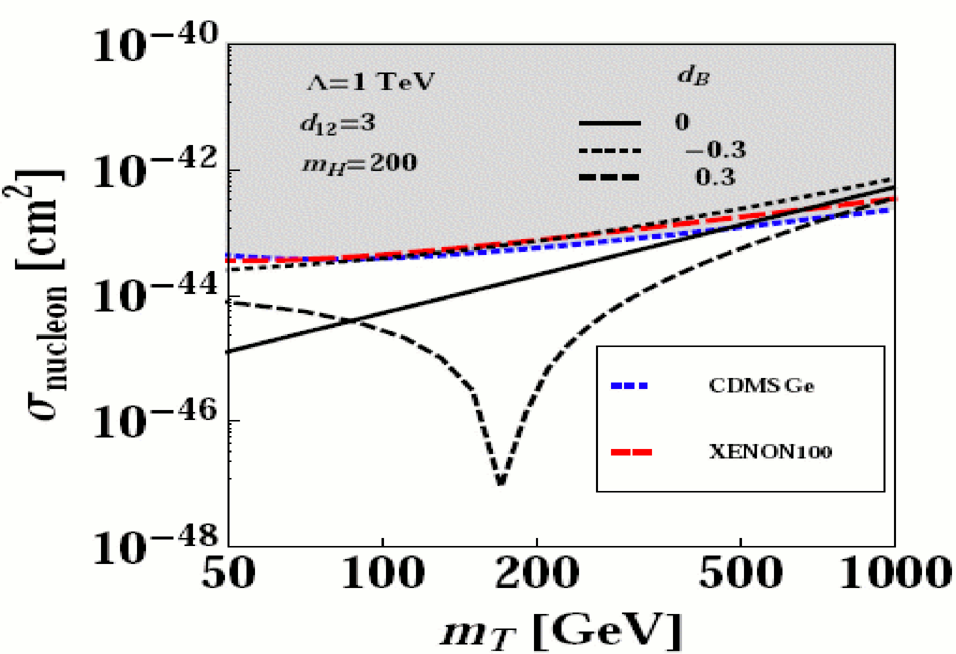
Detection of TIMPs



TIMPs are accesible in direct detection & collider experiments
Can systematically study relvant operators (similarly for light ADM)



$$\sigma_{\mathrm{p}}^{\gamma} = \frac{\mu^2}{4\pi}\left[\frac{8\pi\,\alpha\,d_B}{\Lambda^2}\right]^2 \qquad \sigma^{H}_{\mathrm{nucleon}} = \frac{\mu^2}{2\pi}\left[\frac{d_H\,f\,m_N}{m_H^2 m_\phi v}\right]^2$$

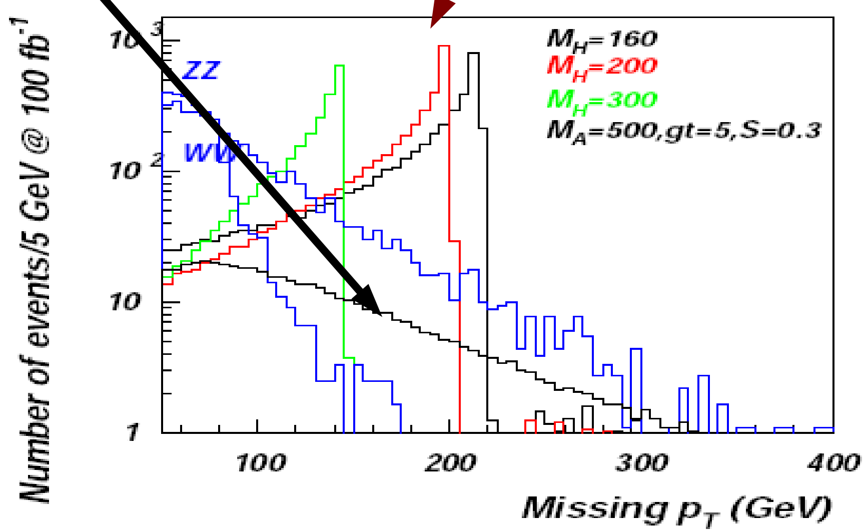


(Belyaev, M.T.F, Sarkar & Sannino 10)

At LHC Resonance structures expected.

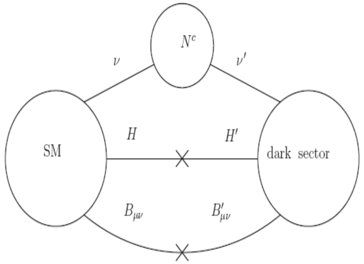
Resonance peaks from composite Higgs decaying 'invisibly', e.g. TIMPs or dark baryons

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



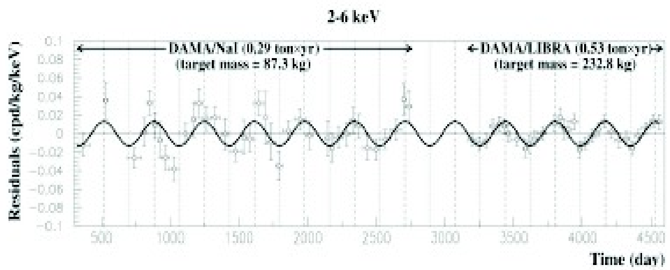
(Foadi, M.T.F and Sannino 09; Davoudiasl, Han and Logan 04; Godbole, Guchait, Mazumdar, Moretti and Roy 03)

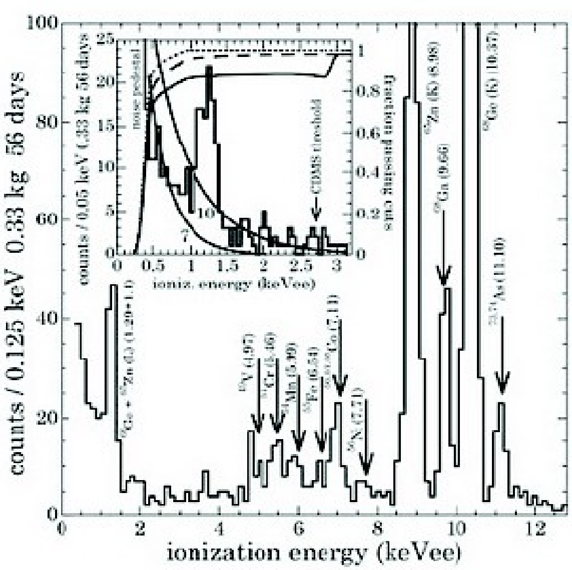
Back to light ADM

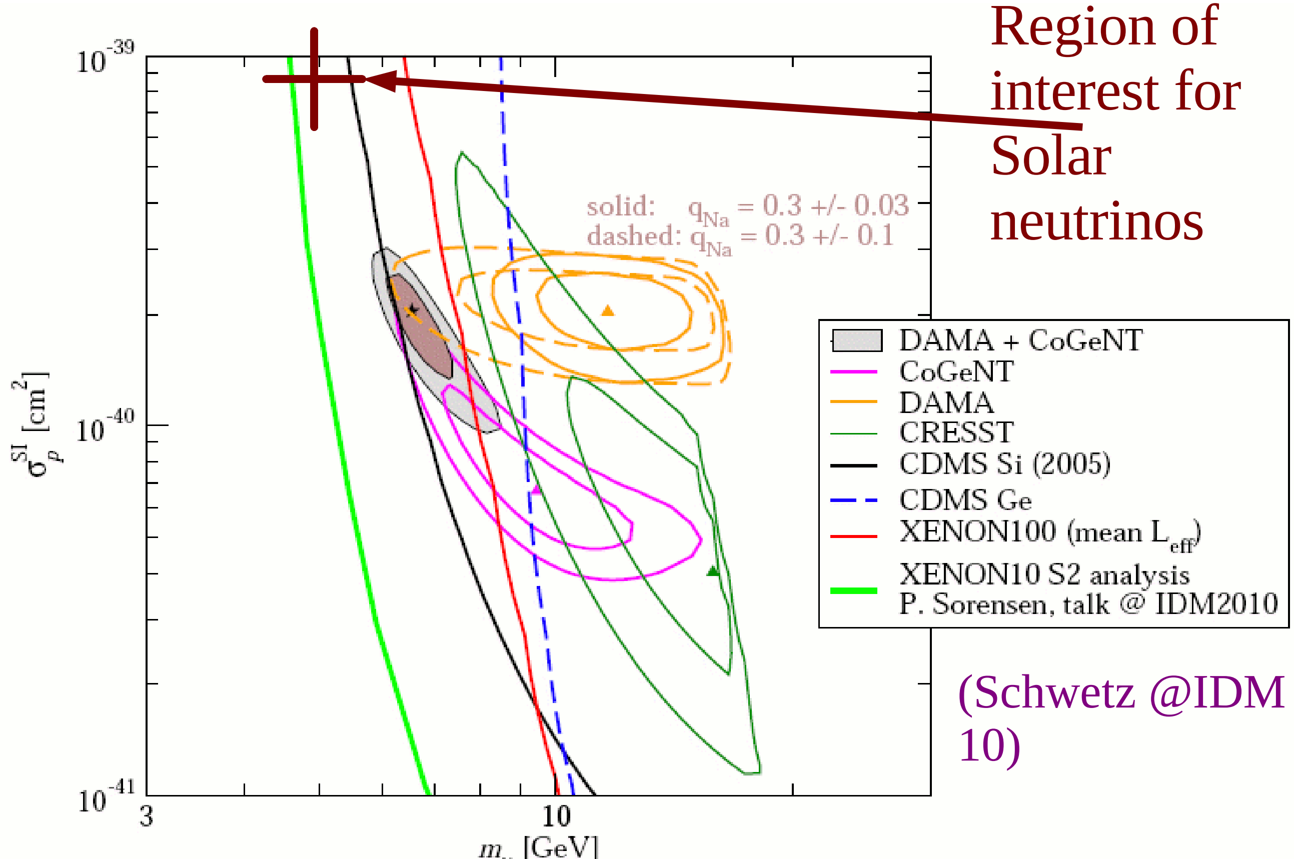


Most nuclear recoil experiments optimized to heavy WIMPs with little sensitivity to low mass particles O(keV) recoil energies

Recently several experiments have reported events close to threshold







Region of interest for Solar neutrinos

(Schwetz @IDM 10)

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

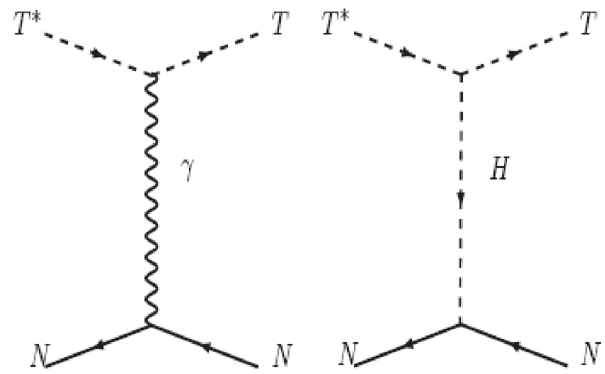
Spin-dependent cross-sections up to ~ 10^{-36} cm^2 remain viable

Signatures of light ADM

Light ADM may be a composite scalar or fermion

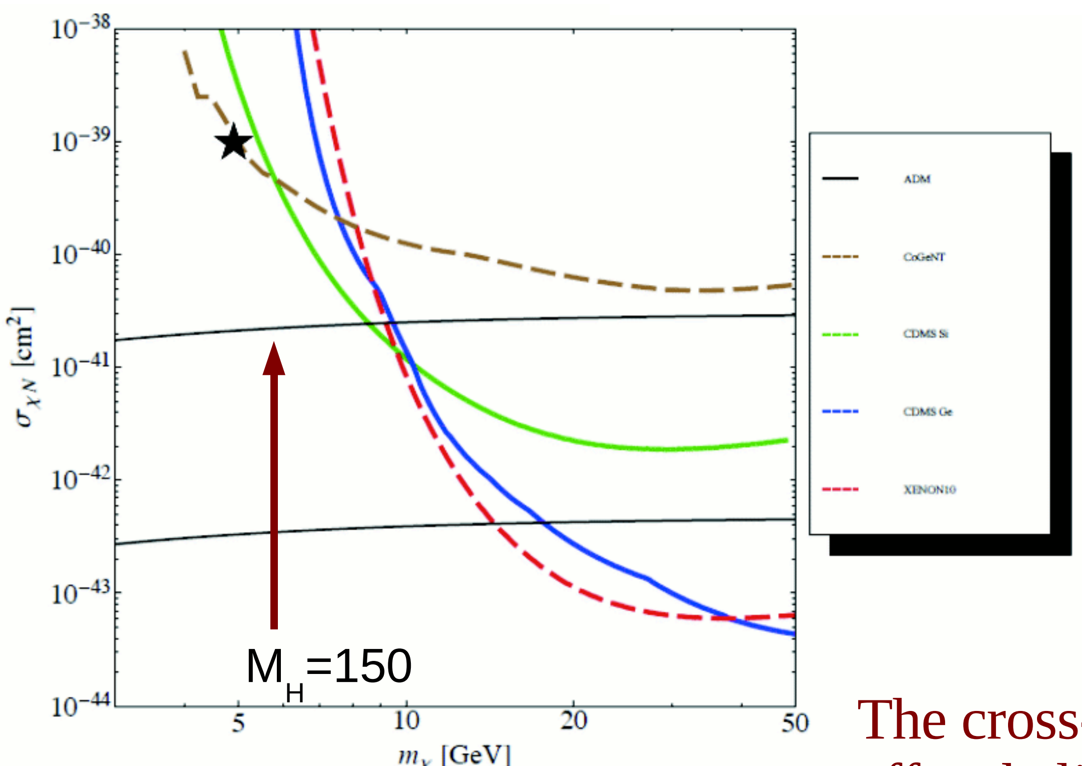
Charge radius can naturally provide up to ~10^{-39} cm^2

$$\sigma_{\rm P}^{\gamma} = \frac{\mu^2}{4\pi}\left[\frac{8\pi\,\alpha\,d_B}{\Lambda^2}\right]^2$$



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

$$\sigma_{\rm nucleon}^{H} = \frac{\mu^2}{2\pi}\left[\frac{d_H f m_N}{m_H^2 m_\phi v}\right]^2$$



(Fit Courtesy of C. McCabe, McCabe 10)

Large SI and SD cross-sections of fermionic ADM can be realized via charge radius and magnetic moment interactions

(Sigurdson et al 2006, Gardner 08, Heo 09, Masso et al 09, An et al 10, Banks et al 10, Barger et al 10...)

Interesting LHC signatures incl 'monojets' (Goodman et al 10, Bai, Fox & Harnik 10)

The cross-sections required - in principle – to affect helioseismology and solar ν's are possible.

Astrophysical aspects of light ADM

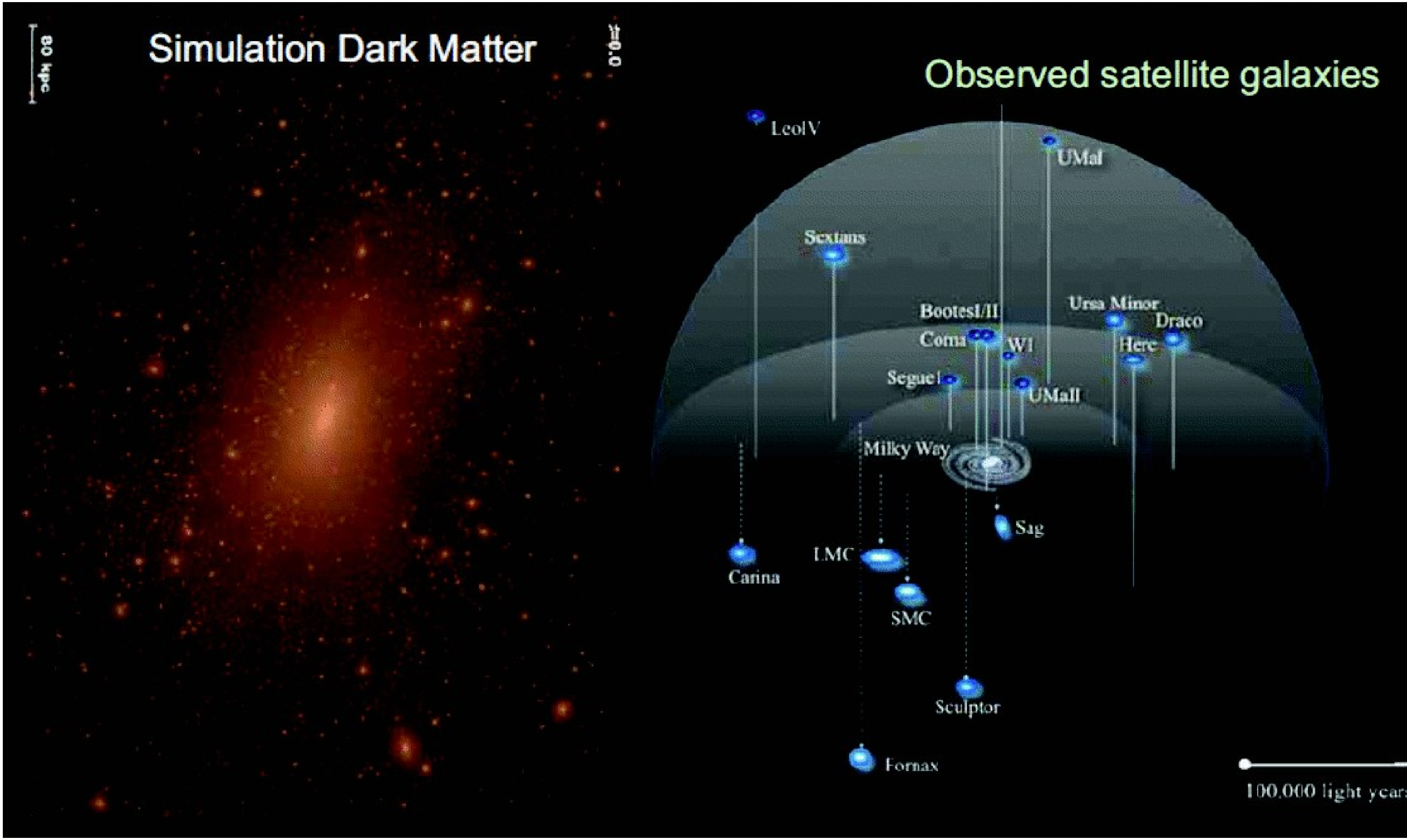
Such particles would also be naturally **self-interacting** with a typical cross-section: $\sigma_{\chi\chi} \sim \sigma_{nn} (m_n/m_\chi)^2$, where $\sigma_{nn} \sim 10^{-23}$ cm^2

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

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

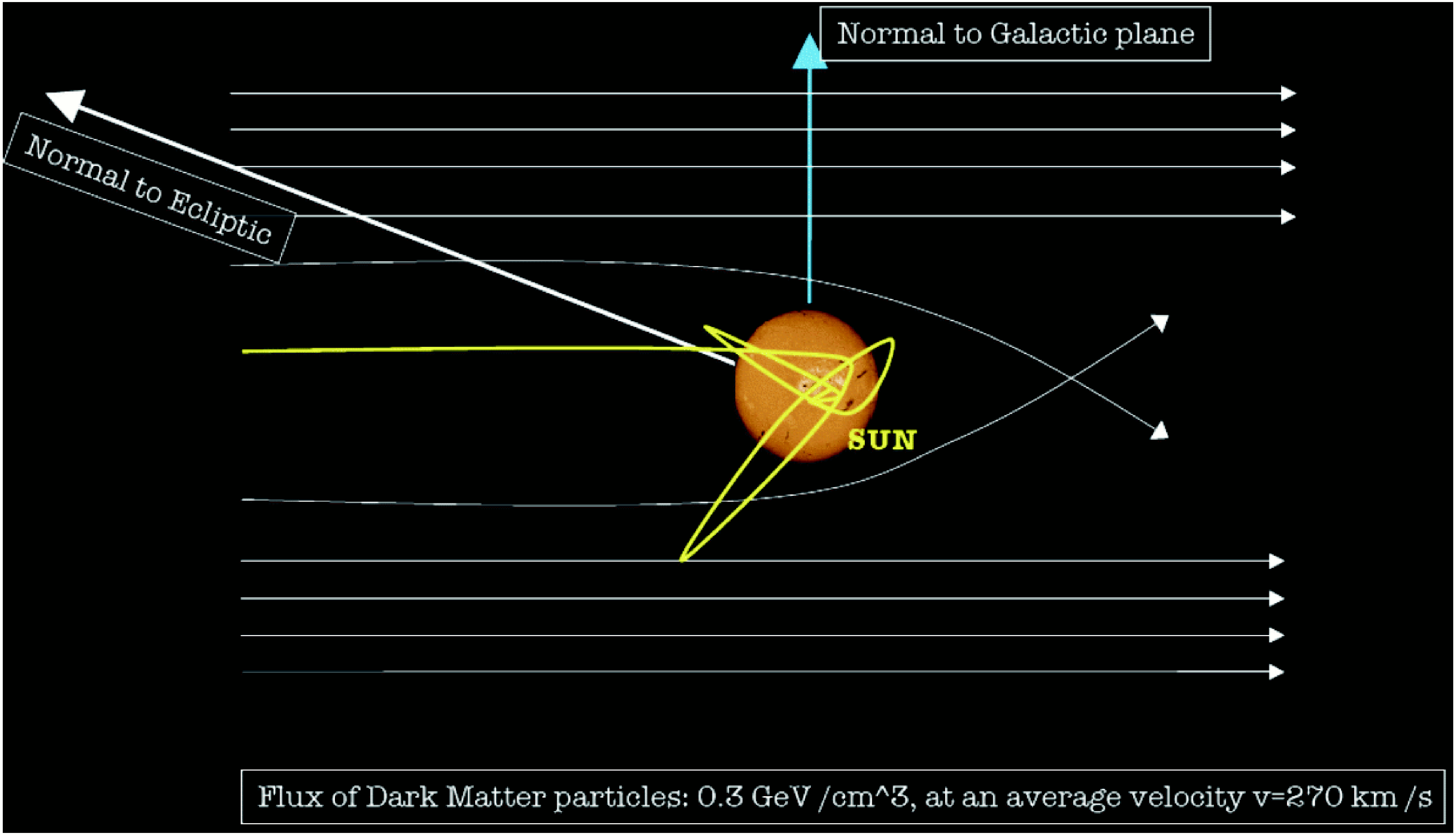
(Feng, Kaplinghat and Yu 10)

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)

Limits on capture and effects in the sun

The 'black disc' rate $\Gamma = \pi R^2_{Sun} n_\chi v * v_{esc}^2 / v^2$ is an upper bound on the maximal captured population of DM in the sun $N_\chi / N_{protons} \sim 10^{-11}$

(Press and Spergel 85)

Without large self-interactions we need $\sigma_{\chi,proton} \sim 4\ 10^{-36}\ cm^2$ to achieve the black disc rate

If the DM is annihiltating the population will be depleted → steady state abundance.

If the DM mass < 3.8 GeV the population will be depleted by 'evaporation' (Gould 85)

If the DM mass is large the population will be highly centralized in the sun

$$r_x = \left(\frac{9}{4\pi}\frac{kT_c}{G\rho_c m_p}\right)^{1/2}\sqrt{\frac{m_p}{m_x}} \approx 9.0\times 10^9\ \mathrm{cm}\sqrt{\frac{m_p}{m_x}} \approx 0.13\ R_\odot \sqrt{\frac{m_p}{m_x}}\ .$$

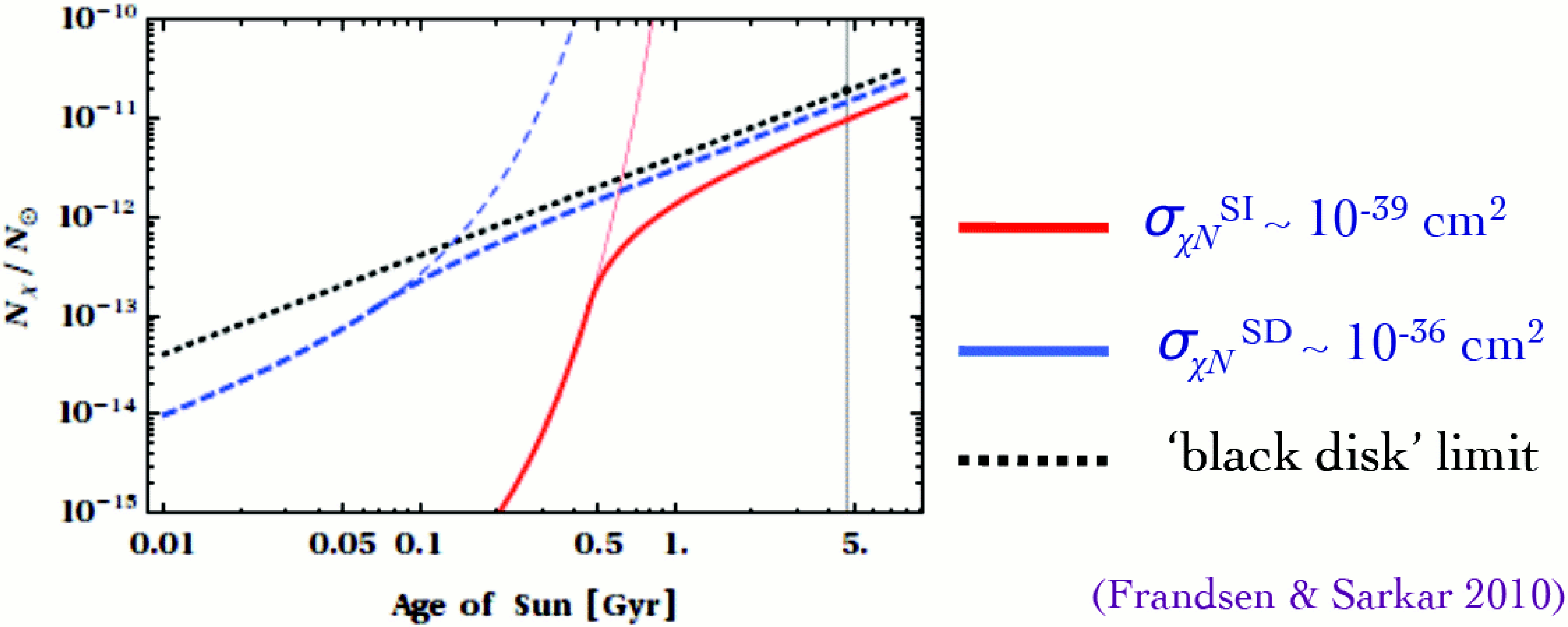
(Spergel and Press 85)

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

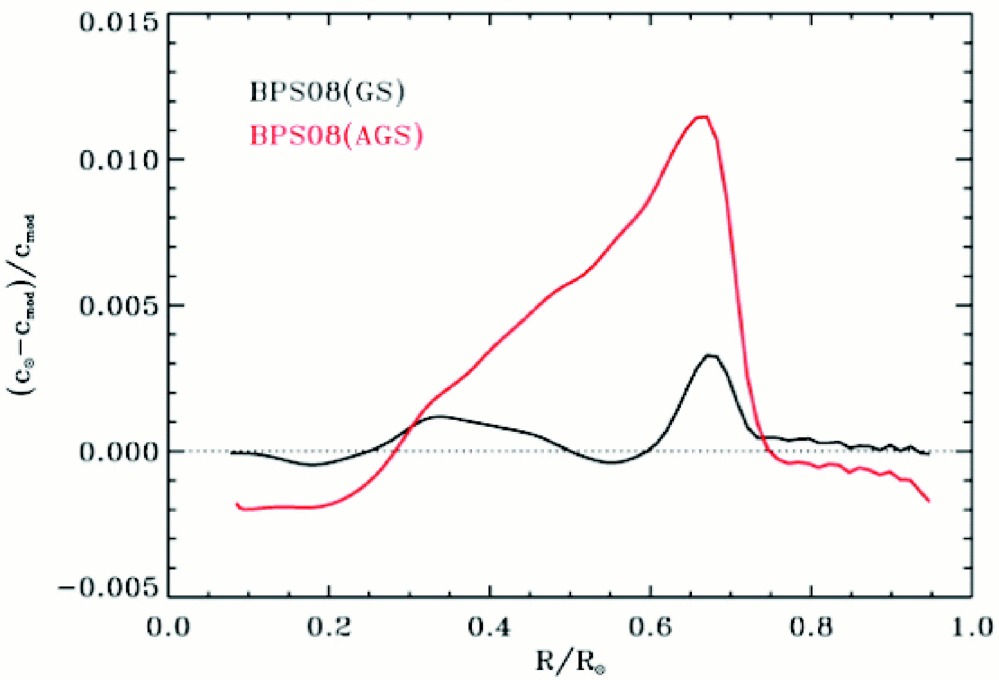


(Frandsen & Sarkar 2010)

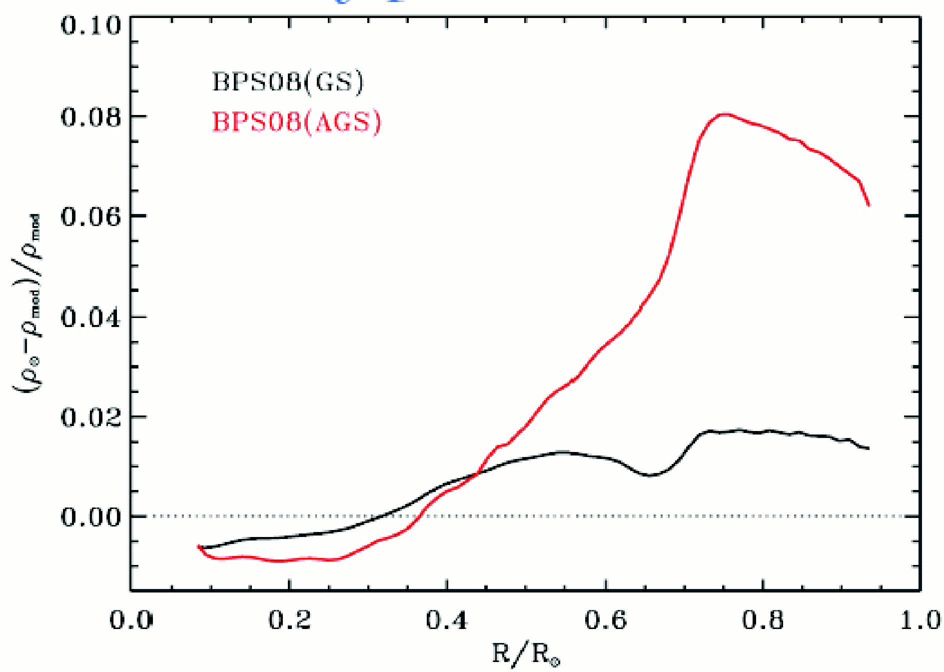
A problem with the standard Solar model

- 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



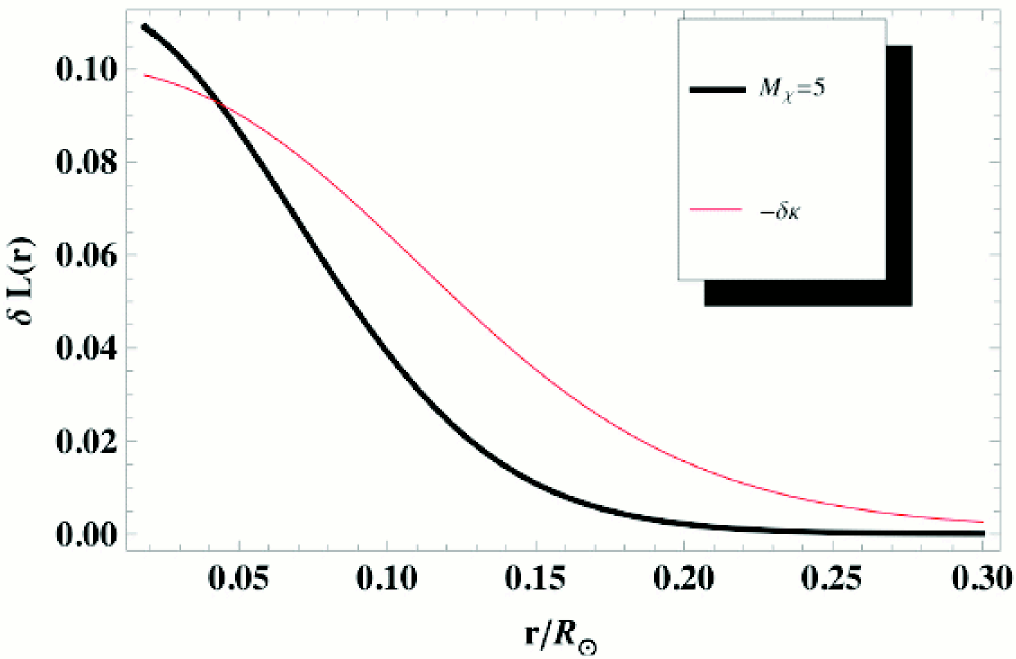
Could light dark matter particles accreted by the Sun solve this problem?

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

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)



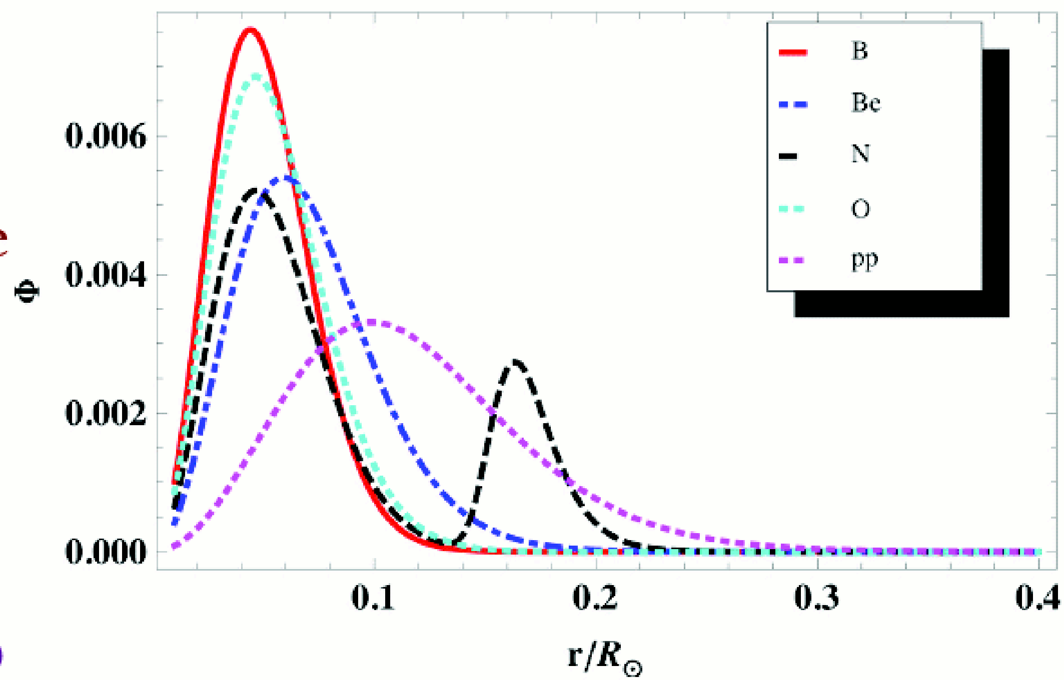
According to the 'Linear Solar model' (Villante & Ricci 2009) a ~10% reduction of the opacity in the core lowers the convective boundary by ~0.7% so will (largely) *restore* agreement with helioseismology

Modification of the luminosity profile will also reduce neutrino fluxes:

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

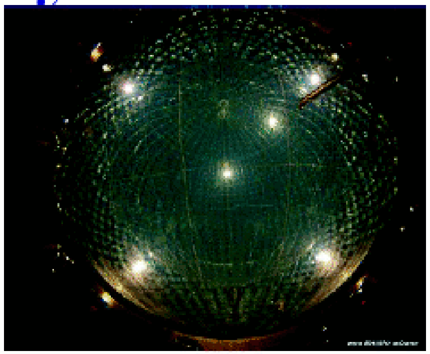
$\delta\Phi_N$ = -10%, $\delta\Phi_O$ = -14%

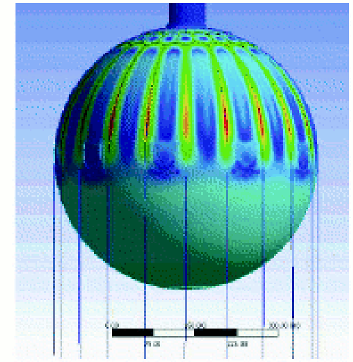
… *testable* by Borexino & SNO+



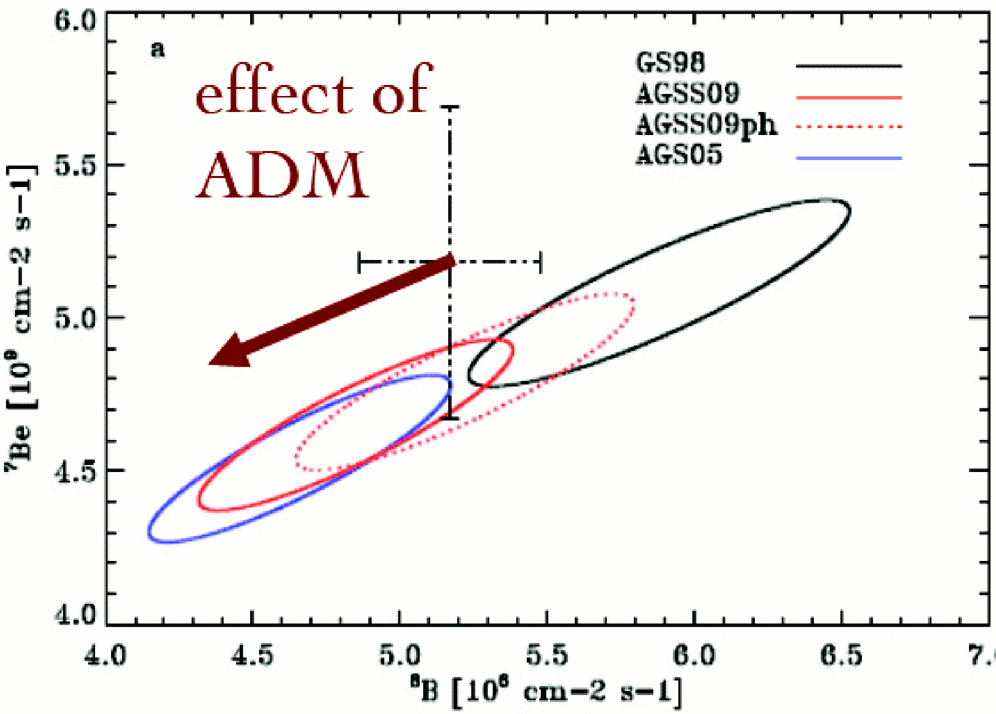
(Frandsen & Sarkar 2010)

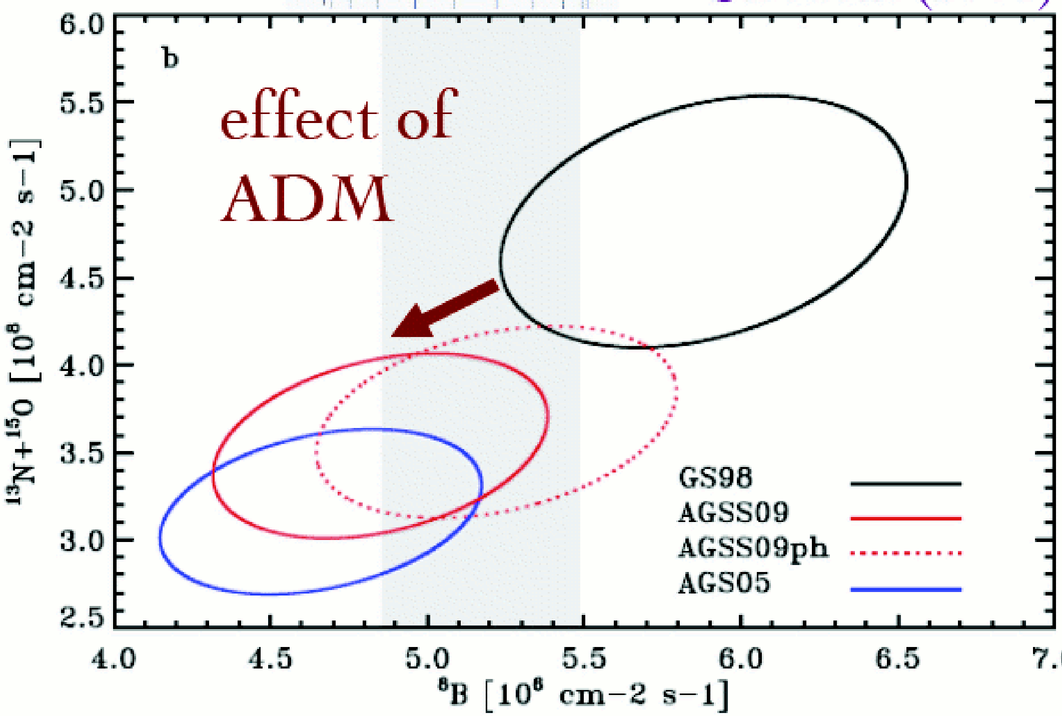
Forthcoming precision measurements of Solar neutrinos by Borexino and SNO$^+$ can *test* the model





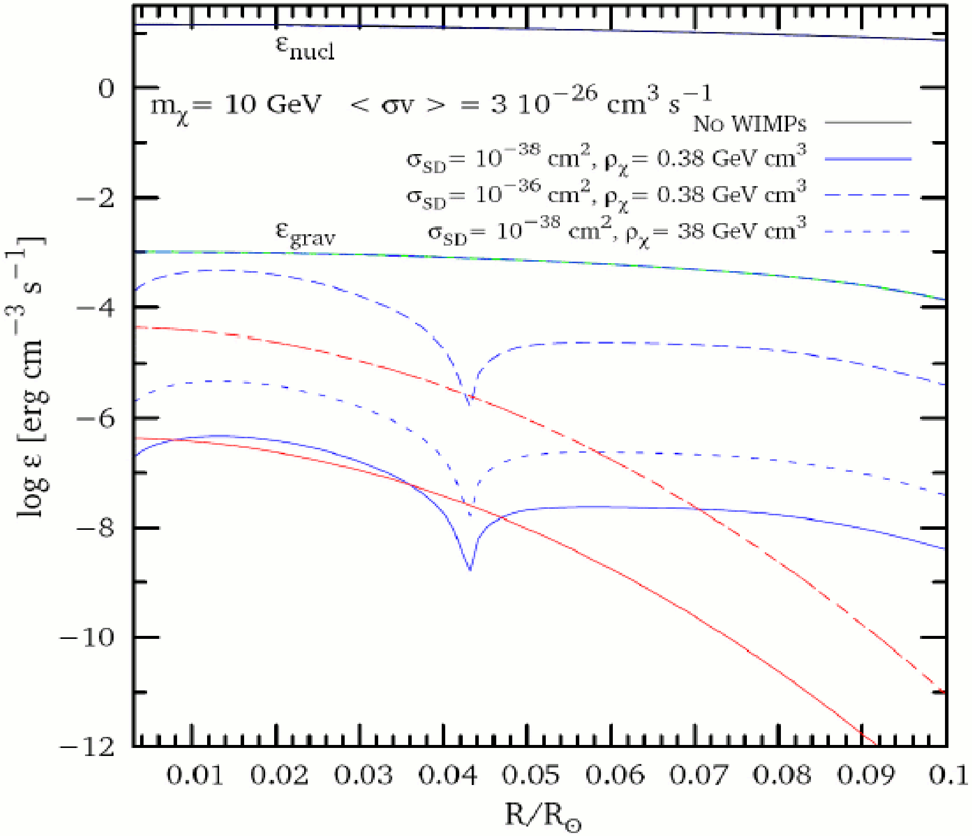
Serenelli (2010)



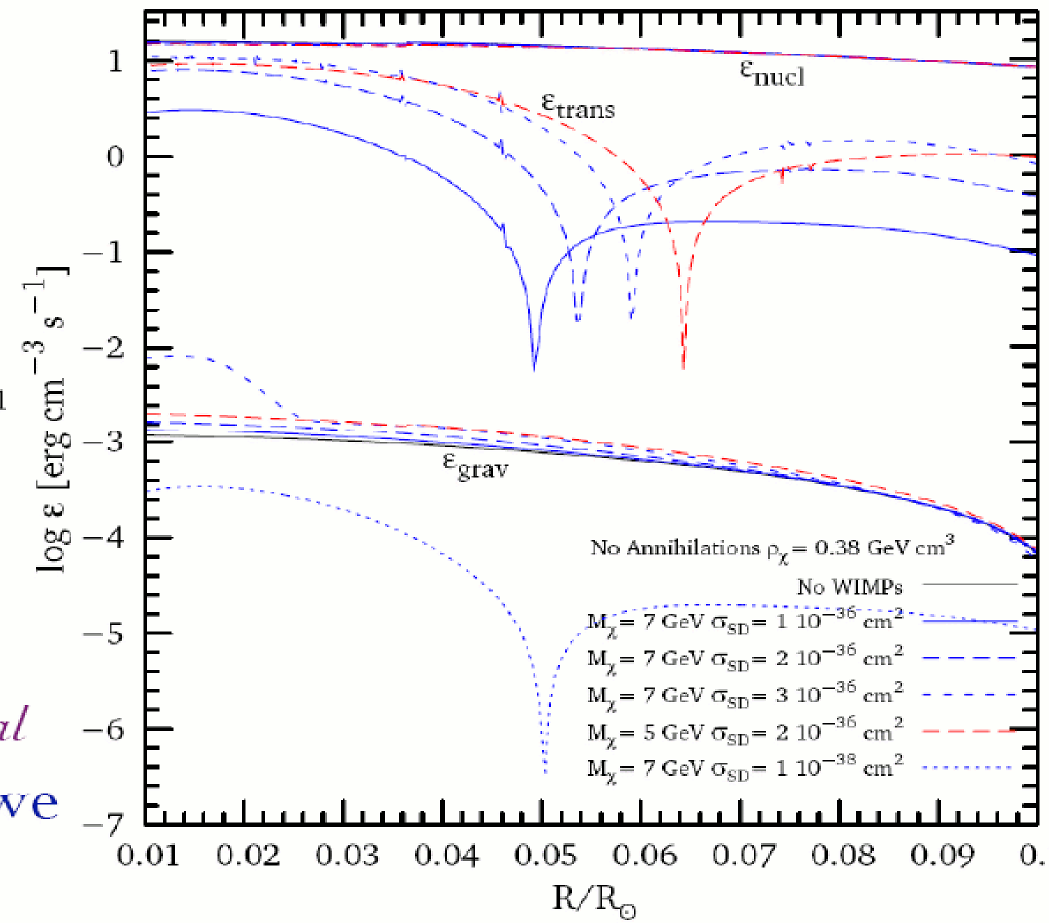


SNO: $\Phi(^8B) = 5.18 \pm 0.29 \times 10^6\ cm^{-2}\ s^{-1}$; **Borexino**: $\Phi(^7Be) = 5.18 \pm 0.51 \times 10^9\ cm^{-2}\ s^{-1}$

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 small frequency separation and Gravity modes (assuming very large cross-sections)

(Cumberbatch et al 10; Lopes & Silk 10)

Summary

- Asymmetric Dark Matter is motivated by *the asymmetry of baryonic matter, mass and stability* and the wish to *explain why* $\Omega_{DM} / \Omega_B \sim O(1)$,
- ~ TeV scale ADM *(Technibaryon)* and

  ~ 100 GeV scale ADM *(pseudo Goldstone Boson TIMPs)*

  arise in (Minimal Walking) Technicolor models of DEWSB.

  ~ GeV scale ADM *(Dark Baryons)*

  arise from Hidden/Mirror/Unbaryon sectors, and impacts
- Structure formation – explains the paucity of structuve on < 1 Mpc ?
- Solar physics – alleviates (parts) of the solar composition problem and modifies solar ν fluxes. More detailed study needed
- Direct detection – Challenging (...compatible with recently claimed hints of signals?)

DM Production mechanisms

Illustrative and simple model: A complex composite scalar $\phi \sim \lambda\lambda,$

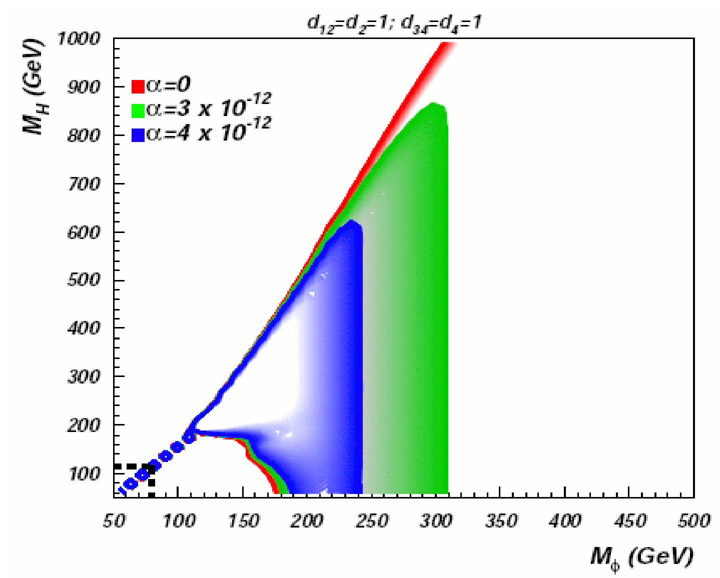
$$\mathcal{L} = \partial_\mu \phi^* \partial_\mu \phi - m_\phi^2 \phi^* \phi + \frac{d_1}{\Lambda} H \partial_\mu \phi^* \partial_\mu \phi \qquad (2)$$
$$+ \frac{d_2}{\Lambda} m_\phi^2 H \phi^* \phi + \frac{d_3}{2\Lambda^2} H^2 \partial_\mu \phi^* \partial_\mu \phi + \frac{d_4}{2\Lambda^2} m_\phi^2 H^2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

Symmetric vs. asymmetric relics

$$\frac{\mathrm{d}Y_-}{\mathrm{d}x} = \lambda x^{-2} \left[Y_-^{\mathrm{eq}} (Y_-^{\mathrm{eq}} + 2\alpha) - Y_- (Y_- + 2\alpha) \right]$$

$$\Omega_\phi h^2 = 5.5 \times 10^8 (Y_{-\infty} + \alpha) \frac{m_\phi}{\mathrm{GeV}}$$

(Griest & Seckel 85)



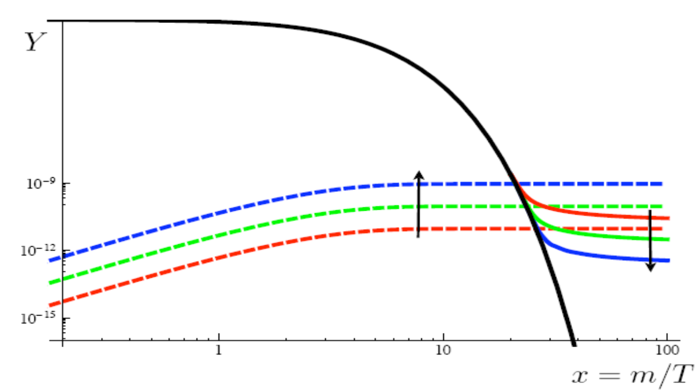
(Belyaev, M.T.F, Sarkar & Sannino 10)

Freeze out vs. freeze-in

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

$$\dot{n}_{\tilde{\nu}_R} + 3H n_{\tilde{\nu}_R} = C_{\mathrm{decay}}$$

(Asaka, Ishiwata & Moroi 05)



(Hall, Jedamzik, March-Russel and West 10)