# Strong dynamics for dark matter and electroweak symmetry breaking

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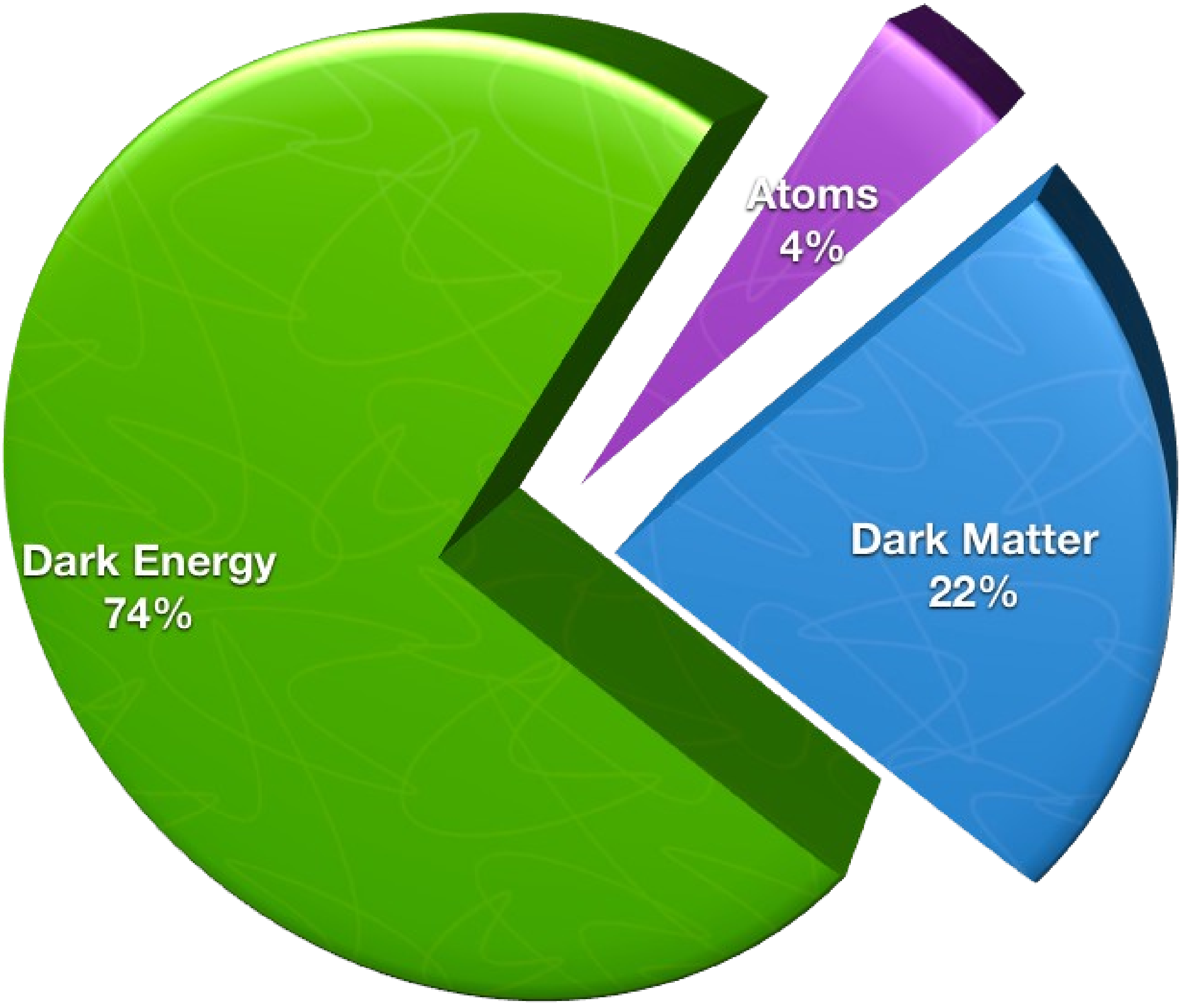
# What is the world made of?



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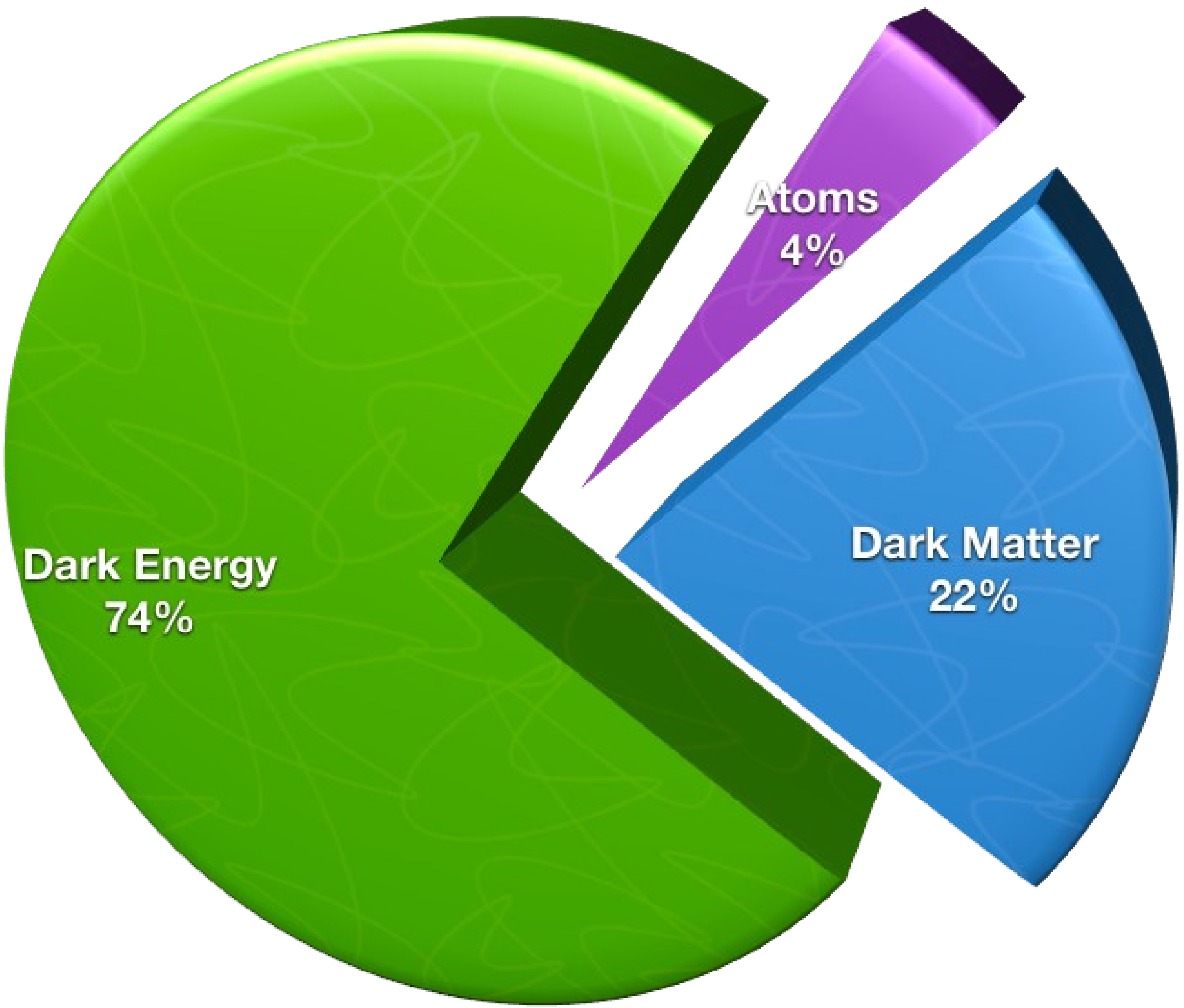



Baryons but no anti-baryons

Baryon mass (mainly) dynamical

# What *should* the world be made of ?

| Mass scale | Particle | Symmetry/ Quantum # | Stability | Production | Abundance |
|---|---|---|---|---|---|
| $\Lambda_{QCD}$ | **Baryons** | U(1) baryon number | ⊗ > $10^{33}$ yr (dim-6 OK) | 'freeze-out' from thermal equilibrium<br><br>asymmetry | $\Omega_B \sim 10^{-10}$<br><br>$\Omega_B \sim 0.05$ |

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

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:

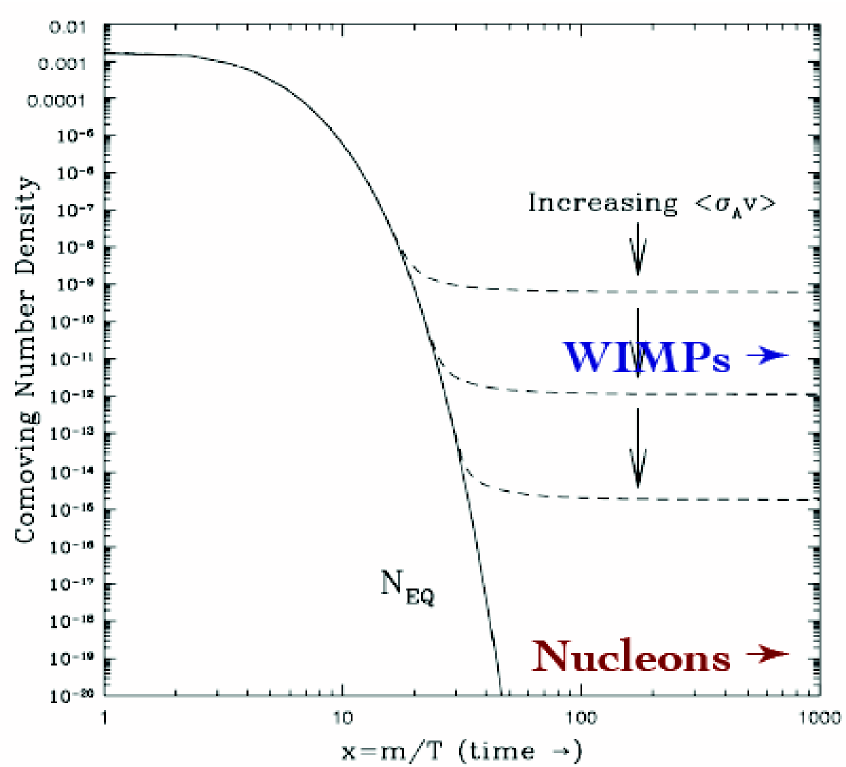
$$\frac{n_N}{n_\gamma} = \frac{n_{\bar{N}}}{n_\gamma} \sim 10^{-19}$$

Observed ratio is $10^9$ times bigger:

***A 'baryon disaster'?!***

Have to invoke an **asymmetry:**

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



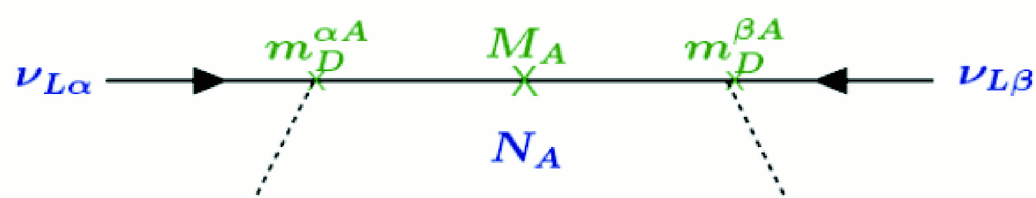
<u>**Sakharov conditions for baryogenesis:**</u>

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')

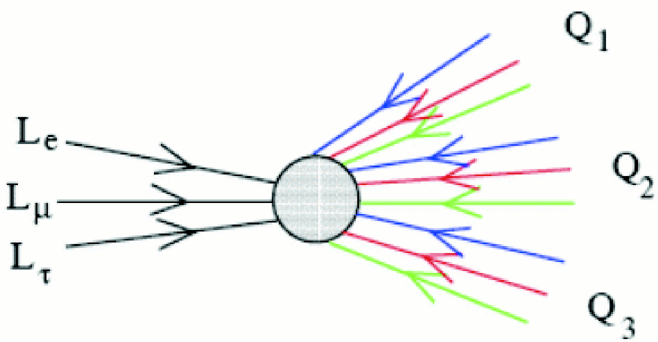
Thus the generation of the observed matter-antimatter asymmetry *requires* new BSM physics (could be related to neutrino masses … **possibly due to violation of lepton number → leptogenesis)**

'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




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

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

$$\sim 10^{-10} \text{ for reasonable parameter values}$$

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 ?

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| $\Lambda_{QCD}$ | **Nucleons** | U(1) baryon number | ⊗ > $10^{33}$ yr (dim-6 OK) | 'freeze-out' from thermal equilibrium<br>asymmetry | $\Omega_B \sim 10^{-10}$<br>$\Omega_B \sim 0.05$ |
| $\Lambda_{Fermi} \sim G_F^{-1/2}$ | Neutralino? | R-parity? | violated? | 'freeze-out' from thermal equilibrium | $\Omega_{LSP} \sim 0.3$ |

In (softly broken) susy we could have a 'WIMP miracle':

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

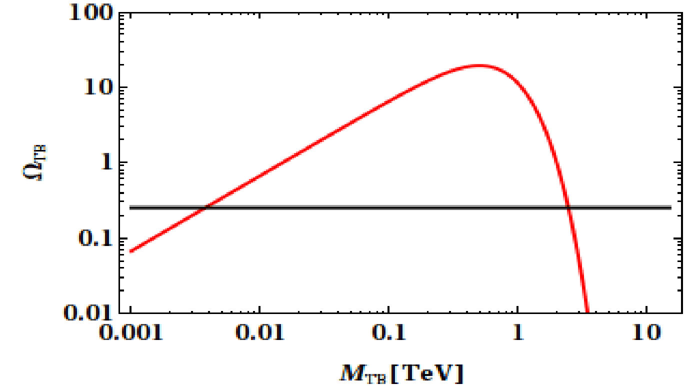
But why then is the abundance of thermal relics **comparable** to that of baryons born non-thermally, with $\Omega_{DM}/\Omega_B \sim 5$?

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, ...)

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| $\Lambda_{TC} \sim \Lambda_{Fermi}$<br>$\Lambda_{DB} \sim 5\,\Lambda_{QCD}$ | Technibaryon?<br>Dark Baryon? | U(1) techibaryon<br>U(1) dark baryon number | | Asymmetry | $\Omega_{TC} \sim 0.3$<br>$\Omega_{DB} \sim 0.3$ |

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:

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

$$\sum_i \mu_i = 0 .$$

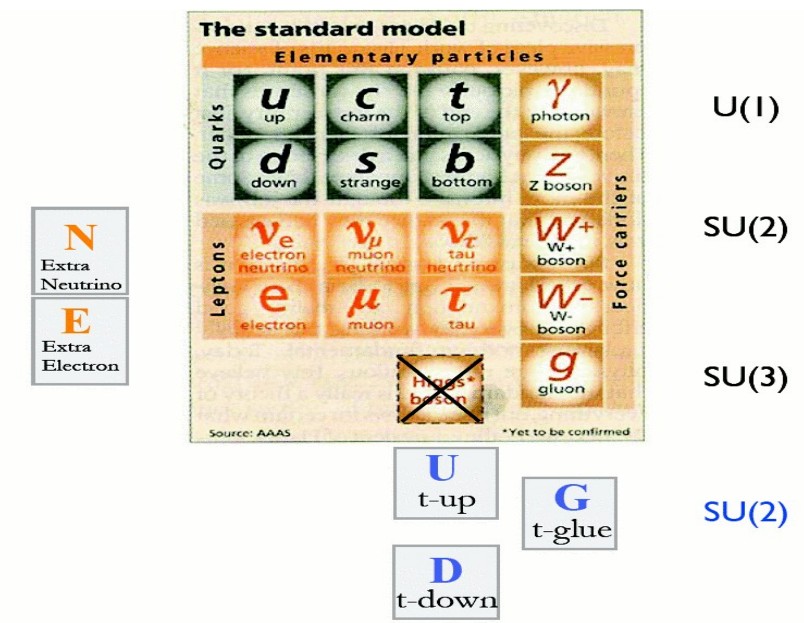
(Bahr, Chivukula & Farhi 90; Harvey and Turner 90)

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

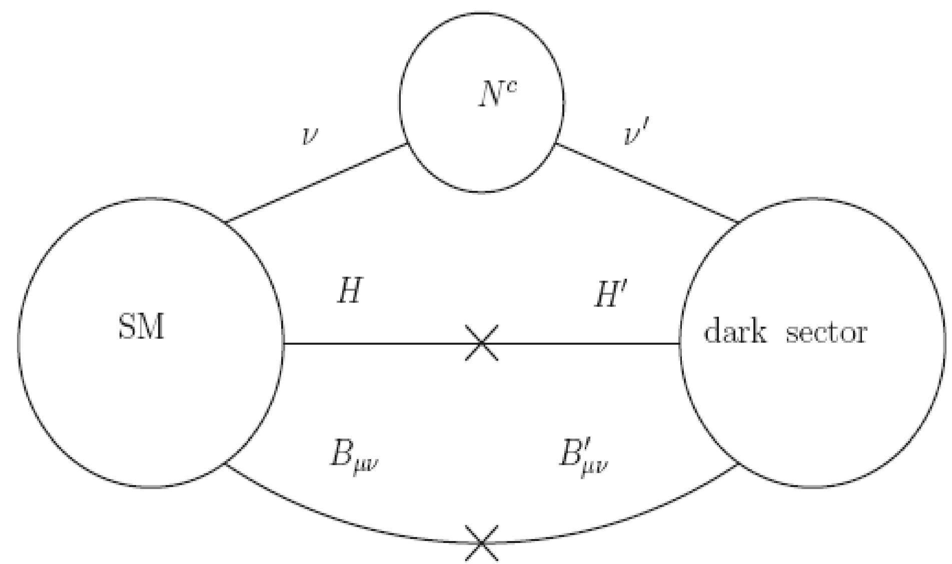
Minimal (Walking) Technicolour




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

GeV scale ADM e.g. from a

Dark mirror sector/world




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*

# Minimal Walking Technicolor

## Dark Matter and LHC Phenomenology

Mads Toudal Frandsen

University of Oxford

Sussex, October 25$^{\mathrm{th}}$ 2010

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# Outline

# Technicolor

**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.

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Example: Scaled-up QCD !

# Technicolor

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$$G_{SM} \to SU(3)_{\rm c} \times SU(2)_{\rm W} \times U(1)_{\rm Y} \times G_{\rm TC} \ .$$

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

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

# Technicolor dark matter

## Technocosmology (Nussinov 85)

Lightest Technibaryon as Asymmetric Dark Matter

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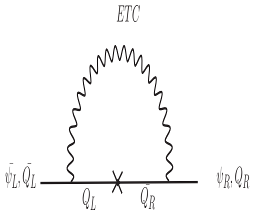
- Or 'Dark Baryon' with $m_{TB} \sim 5 - 10 GeV$ ?

(D.B.Kaplan 92; An, Chen, Mohapatra and Zhang 09; D.E.Kaplan, Luty and Zurek 09; Fitzpatrick, Zurek and Hooper 10; M.T.F and Sarkar 10)

# Extended Technicolor and fermion masses

**ETC:** (Eichten and Lane 80)

New gauge theory with SM and TC fermions in the same multiplet.




1. Four fermion operators:

$$\alpha \frac{\bar{Q}Q\bar{Q}Q}{\Lambda_{ETC}^2} + \beta \frac{\bar{Q}Q\bar{\psi}\psi}{\Lambda_{ETC}^2} + \gamma \frac{\bar{\psi}\psi\bar{\psi}\psi}{\Lambda_{ETC}^2} + \dots$$

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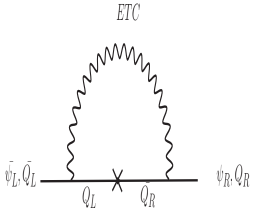


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Fermion masses:

$$M_\psi \sim \frac{\langle \bar{Q}Q \rangle_{ETC}}{\Lambda_{ETC}^2} \sim d(R_{TC}) \frac{\Lambda^{3-\gamma}\Lambda_{ETC}^{\gamma}}{\Lambda_{ETC}^2}$$

(Holdom 81, 85; Yamawaki, Bando and Matumoto 86; Appelquist, Karabali and Wijewardhana 86; Hill and Simmons 02)

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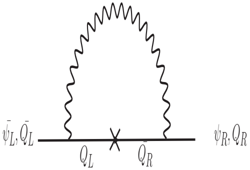


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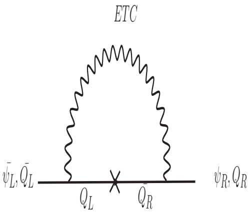


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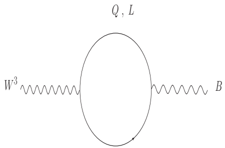
3. Focus on Technicolor sector

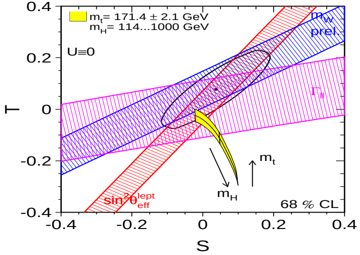
# Constraints from LEP

1. A minimal matter content in the TC sector is favored:

$$S \equiv -16\pi\Pi'_{W^3B}(0) \ , \ \ T \equiv \frac{4\pi}{s_W^2 c_W^2 M_Z^2}(\Pi_{W^1W^1}(0) - \Pi_{W^3W^3}(0))$$




$$S_{\rm naive} = N_D \frac{d(R_{\rm TC})}{6\pi}$$




(Kennedy and Lynn 89; Peskin and Takeuchi 90; Altarelli and Barbieri 91)

# Minimal Technicolor Theory Space

Minimal Technicolor: 2 Dirac Flavors. No QCD charges.

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

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- $F$ of $SO(N)$

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$$\begin{pmatrix} \Pi & T_i \\ T_i^* & \Pi^T \end{pmatrix}$$

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# Dark Matter from Minimal Technicolor

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

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**'iTIMP'**

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

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# Dark Matter from Minimal Technicolor

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

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

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- 4 of $SU(4)$

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(Other candidates in MT: Gudnason, Kouvaris and Sannino 05; Kainulainen, Virkajärvi and Tuominen 06, 09, 10; Kouvaris 07; Khlopov and Kouvaris 08)

# Direct detection

- Charge radius
  $\mathcal{L}_B = ie\frac{d_B}{\Lambda^2} T^* \overleftrightarrow{\partial_\mu} T \, \partial_\nu F^{\mu\nu}$ .
  (Bagnasco, Dine and Thomas 93)
- Composite Higgs $\mathcal{L}_H = d_H v_{ev} T^* T H, \frac{d_{13}}{\Lambda} \; H \partial_\mu T^* \partial_\mu T$ .
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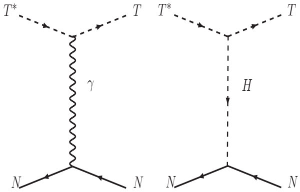

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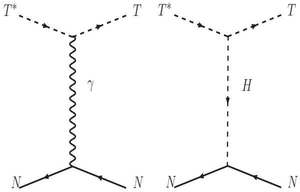


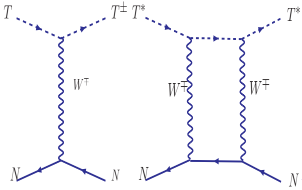

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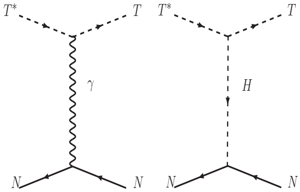
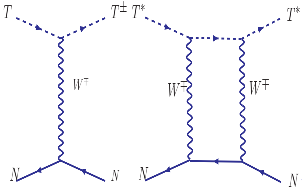
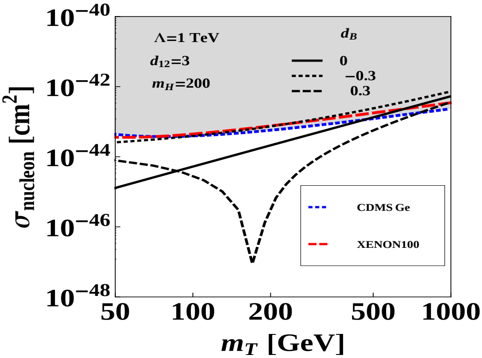
- For colored baryons: Gluonic polarizabilities
  (Nussinov 92 ; Chivukula et al 92)
- For spin-1/2 baryons: Dipole moments
  (Nussinov 92 ; Bagnasco, Dine and



# Direct Detection Limits on TIMPs

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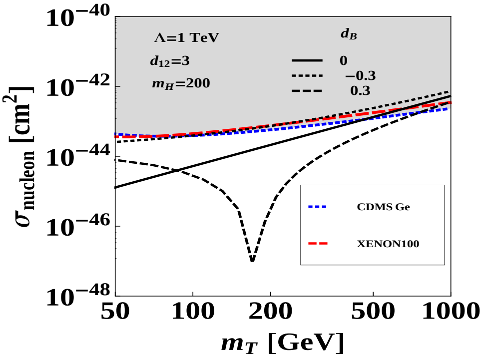


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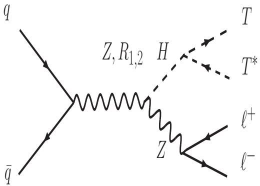
- Indirect detection of Decaying Dark Matter: (Nardi, Sannino and Strumia 09)

# LHC signatures of (i)TIMPs

- (i)TIMP Invisible Higgs (Foadi, M.T.F and Sannino 08 ; Godbole, Guchait, Mazumdar, Moretti and Roy 03).



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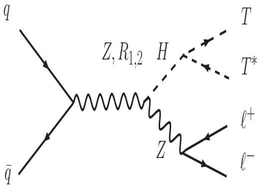


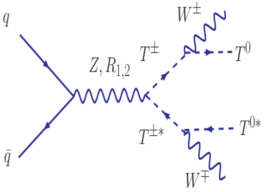

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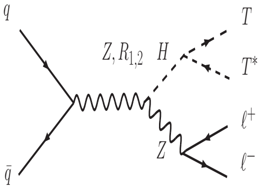
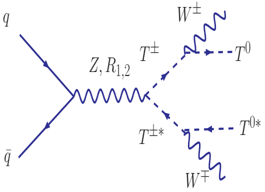
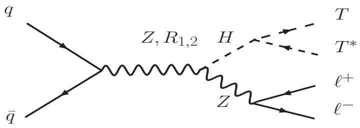
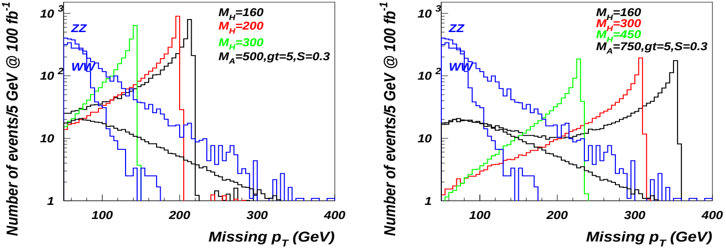



- Note: The same signatures from a new stable heavy lepton!
  (M.T.F, Masina and Sannino 09 ; Antipin, Heikinheimo, Tuominen 09)

# (i)TIMP missing energy signals

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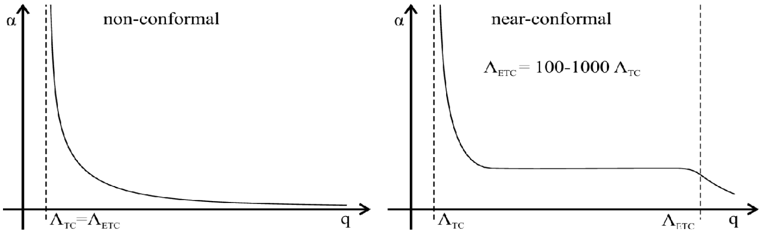
# Walking Technicolor




1. TC sector: Walking reduces the full S-parameter (Sundrum and Hsu 92; Appelquist and Sannino 98; Harada, Kurachi and Yamawaki 03; Kurachi and Shrock 06)

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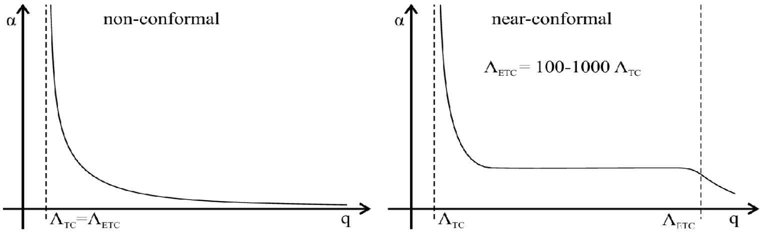


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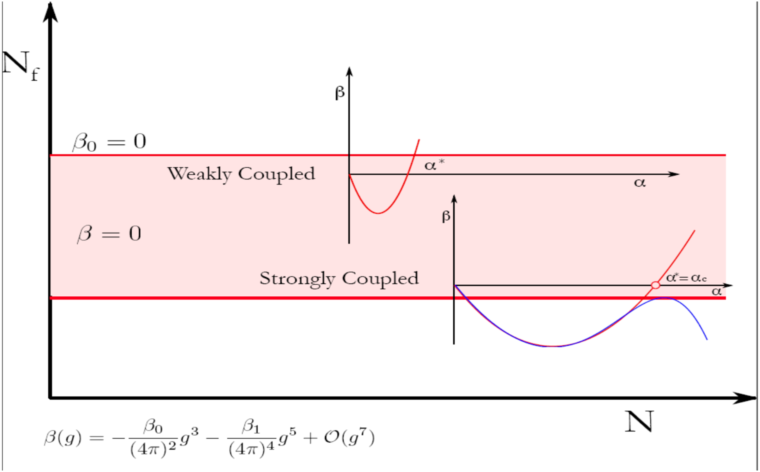
2. ETC sector: Walking reduces tension between SM fermion masses and FCNC's
   (Holdom 81, 85; Yamawaki, Bando and Matumoto 86; Appelquist, Karabali and Wijewardhana 86)

# Conformal window and Walking




(Fig:Sannino, cp3-origins 09)

# ETC fermion masses and Walking

1. Four fermion operators:

$$\alpha\frac{\langle\bar{Q}Q\rangle\bar{Q}Q}{\Lambda^2_{ETC}}+\beta\frac{\langle\bar{Q}Q\rangle\bar{\psi}\psi}{\Lambda^2_{ETC}}+\gamma\frac{\bar{\psi}\psi\bar{\psi}\psi}{\Lambda^2_{ETC}}+\dots$$

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$$< \bar{Q}Q >_{ETC} \sim \left(\frac{\Lambda_{ETC}}{\Lambda_{TC}}\right)^{\gamma(\alpha^*)} < \bar{Q}Q >_{TC}$$

(Holdom 81, 85; Yamawaki, Bando and Matumoto 86; Appelquist, Karabali and Wijewardhana 86)

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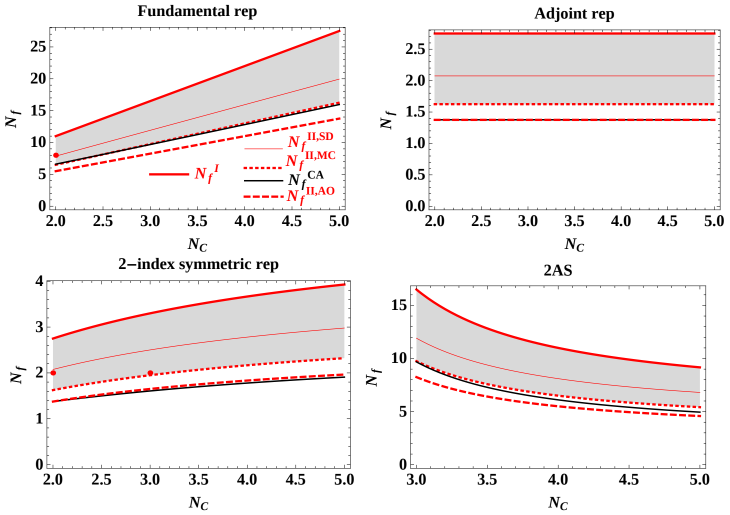
4. (Too) Naively $\Lambda_{ETC}>10^3\,TeV$ to suppress FCNC's:
(King 89; Evans and Ross 94; Appelquist and Shrock 02; Evans and Sannino 05; Christensen, Piai and Shrock 06)

# Analytical approaches to the conformal window

1. Ladder approximation: $\alpha_c = \frac{\pi}{3C_2(\mathrm{R})}$ , $\frac{\alpha^*}{4\pi} = -\frac{\beta_0}{\beta_1}$.
   (Appelquist, Lane and Muhanta 88; Cohen and Georgi 89; Sannino and Tuominen 04; Dietrich and Sannino 06; Ryttov and Sannino 07)
2. All-orders beta function conjecture(s)
   (Ryttov and Sannino 08; Antipin and Tuominen 09; Dietrich 09)
3. Dualities
   (Sannino 09)
4. Compactification approach
   (Unsal and Poppitz 09; Ogilvie and Myers 09;)
5. Worldline formalism
   (Armoni 09)
6. Holography (Hong and Yee 06; Alvares, Evans, Gebauer and Weatherill 09)
7. Metric Confinenement MC and Causal Analytic couplings
   (Oehme and Zimmerman 80; Nishijima 86; Oehme 1990; Gardi and Grunberg 98; M.T.F, Pickup and Teper 10)

# Conformal window lower bounds: MC and AO




(M.T.F, T. Pickup and M. Teper 10).

# Some Minimal Models of Walking Technicolor

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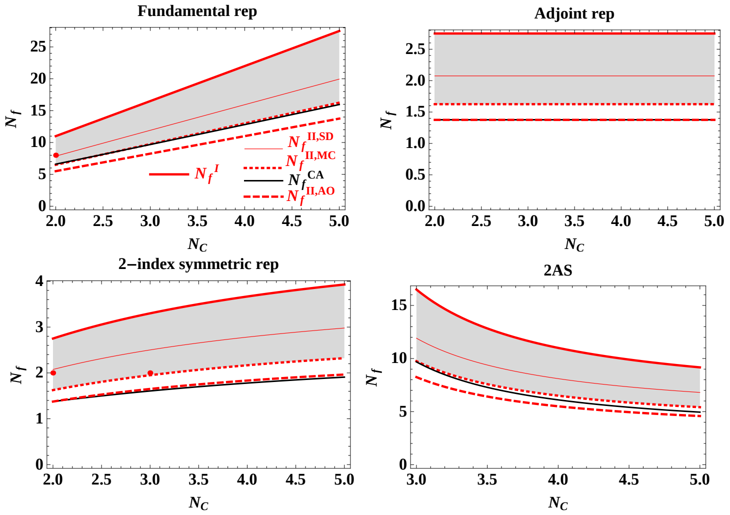
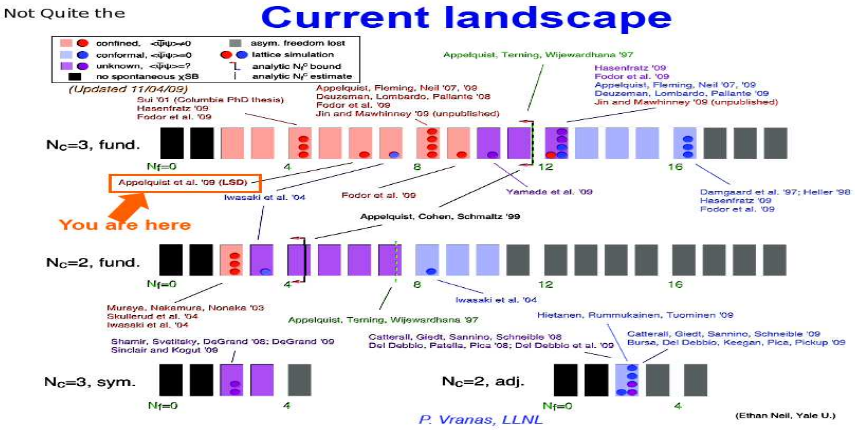



(M.T.F, T. Pickup and M. Teper 10).

# Lattice simulations




(Dedicated collaborations: Lattice Strong Dynamics (US) ; Strong BSM (EU) )

# EFT for strong dynamics @ LHC

**common sector:**

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

- New states: Lightest (axial)-vector triplets and scalar

$$R_1^{\pm,0},\ R_2^{\pm,0},\ H. \quad \text{TIMPs}$$

- Input parameters and constraints:

$$e,\ G_F,\ M_Z;\ S,\ \text{Sum Rules.}$$

- Main free parameters:

$$M_A,\ \tilde{g},\ M_H.$$

(Appelquist, Da Silva and Sannino 99; Foadi, M.T.F, Ryttov and Sannino

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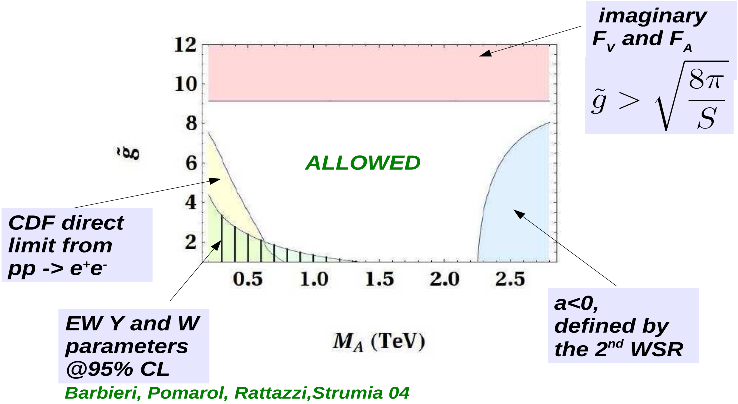
(Appelquist, Da Silva and Sannino 99; Foadi, M.T.F, Ryttov and Sannino

- EFTs for 'BESS' models, '3-site/4-site' models and LSTC

(Casalbuoni, Deandrea, De Curtis, Dominici, Gatto, Grazzini 95; He et al 08; Lane and Martin 09)

# Parameter space




(Foadi, M.T.F and Sannino 07 ; Belyaev, Foadi, M.T.F, Järvinen, Pukhov, Sannino 08)

# Mass spectrum, imposing $S$ and WSR1

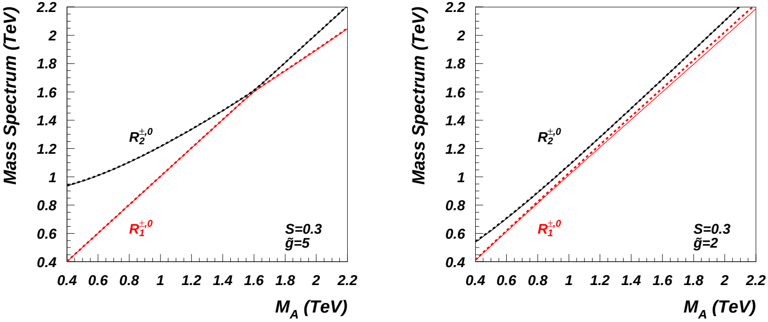
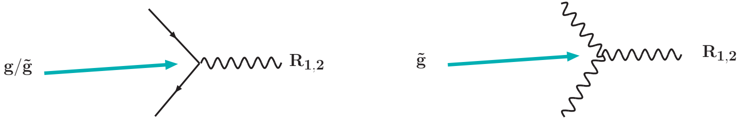



Figure: $R_{1,2}$ spectrum.

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

# LHC Phenomenology

- Basic phenomenology controlled by $\tilde{g}$, $M_A$, $M_H$.



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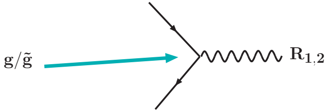


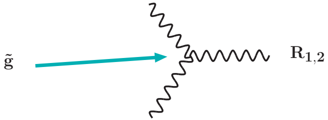


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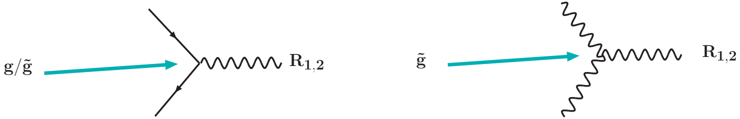


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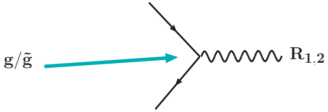


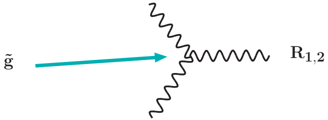


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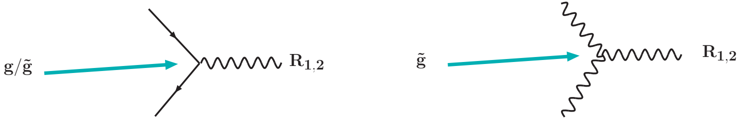


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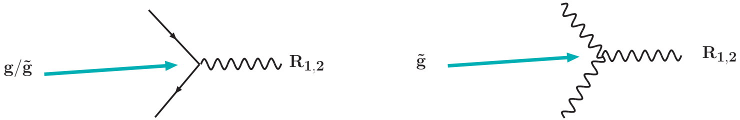


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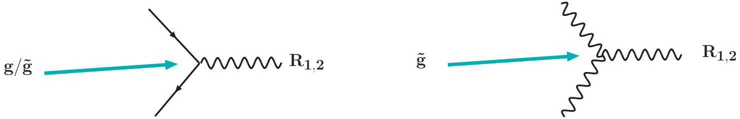


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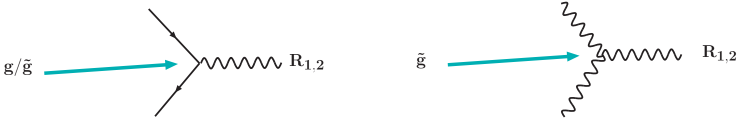


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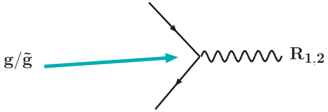


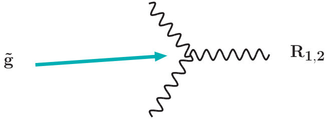


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  - boosted tops, W, Z and H
- Lattice can (in principle) narrow down parameter space for each model
  - MWT/OMT, NMWT, UMT etc...

# Vector Production

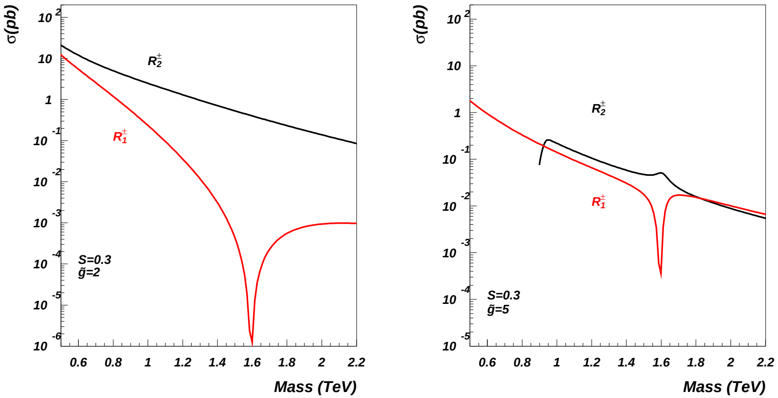



Figure: DY production of $R_{1,2}$.

(Belyaev, Foadi, M.T.F, Järvinen, Pukhov, Sannino 08)

# Vector BRs

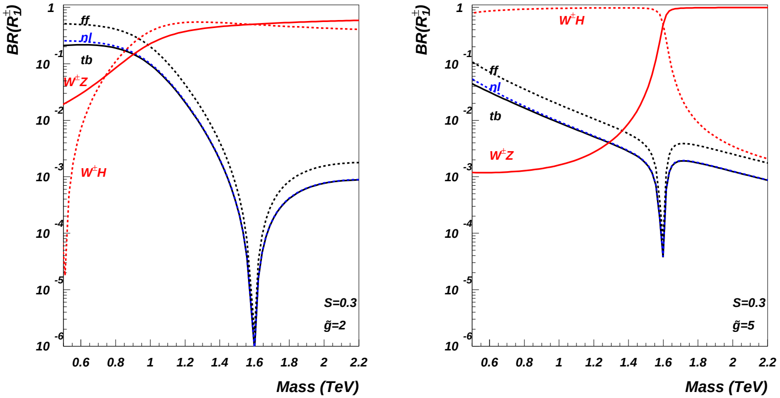



Figure: BR's of $R_1$.

(Belyaev, Foadi, M.T.F, Järvinen, Pukhov, Sannino 08)

# $\ell^+\ell^-$ signature @ LHC using CalcHEP

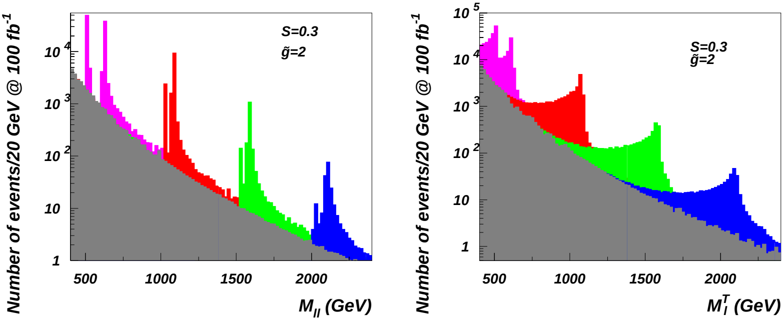



Figure: Left: Dilepton invariant mass distributions $M_{\ell\ell}$ for $pp \to R^0_{1,2} \to \ell^+\ell^-$
Right: Single lepton transverse mass distributions $M^T_\ell$ $pp \to R^\pm_{1,2} \to \ell^\pm$

(Belyaev, Foadi, M.T.F, Järvinen, Pukhov, Sannino 08)

# Results for *tb*

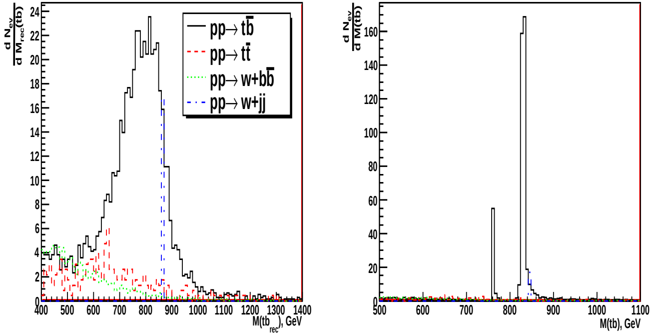
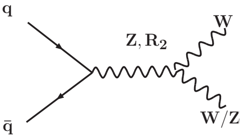
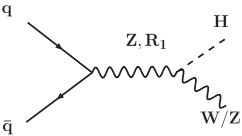


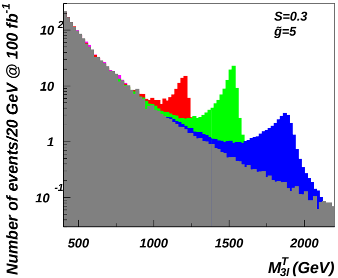

Figure: Reconstructed (left plot) and partonic (right plot) invariant mass of top and b-quarks after final cuts. Distributions normalized to 30 $\mathrm{fb}^{-1}$.

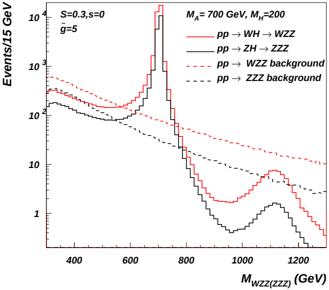
(A. Belyaev, M.T.F and A.Sherstnev in preparation)

# Di-boson vs Higgs-strahlung



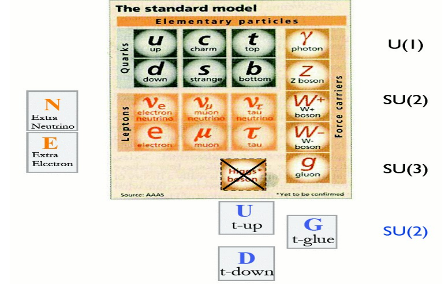



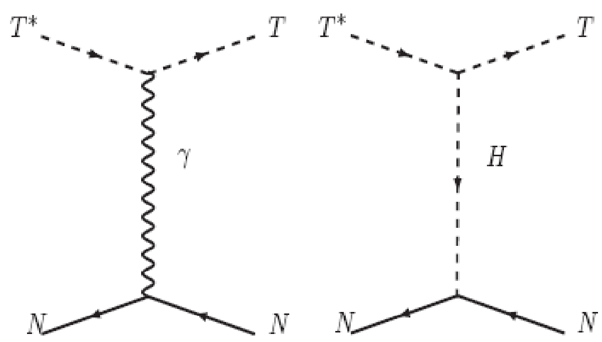




(Belyaev, Foadi, M.T.F, Järvinen, Pukhov, Sannino 08)

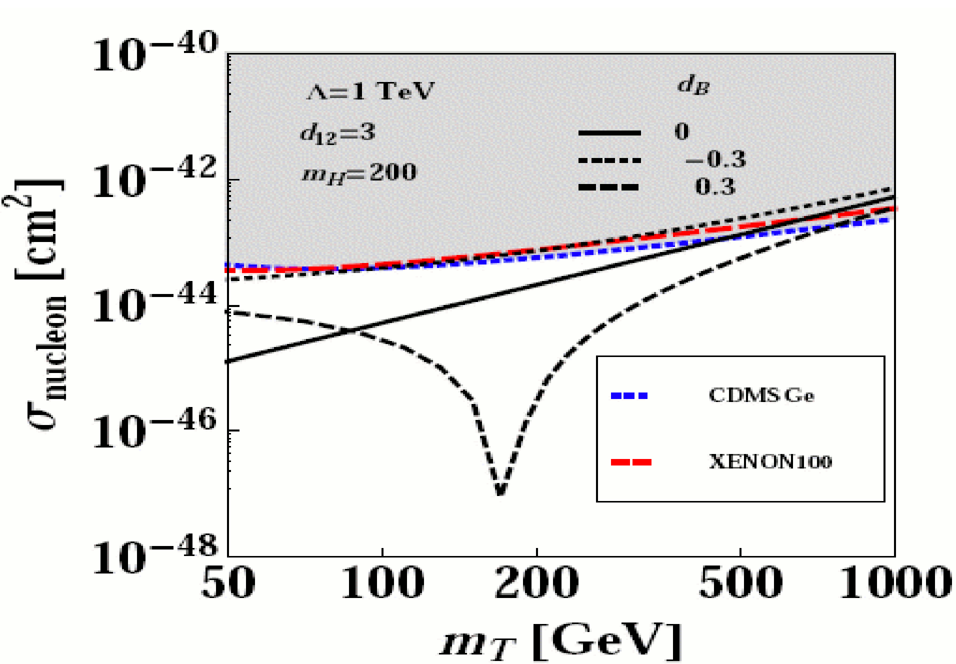
# Detection of TIMPs




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




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

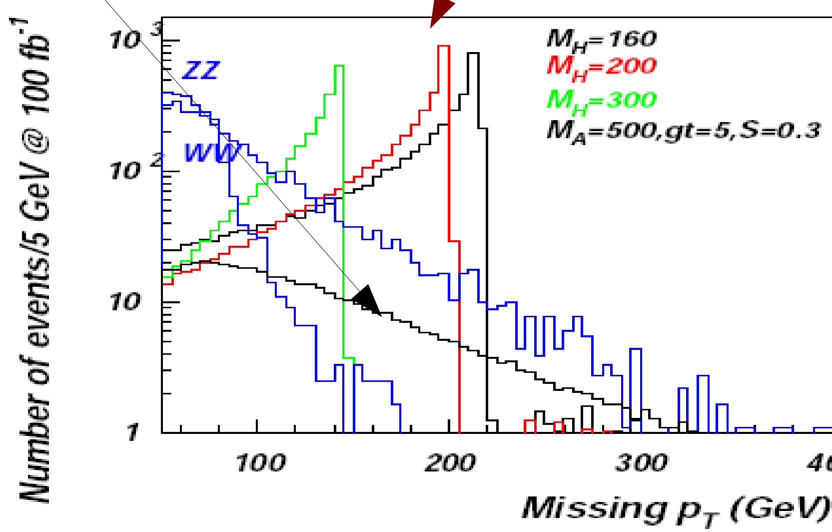



(Belyaev, M.T.F, Sarkar & Sannino 10)

At LHC Resonance structures expected.

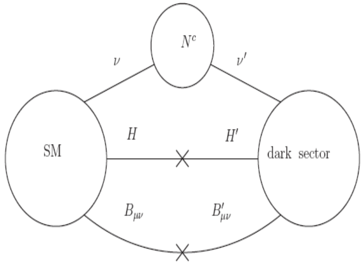
Resonance peaks from composite Higgs decaying 'invisibly', e.g. TIMPs or dark baryons

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



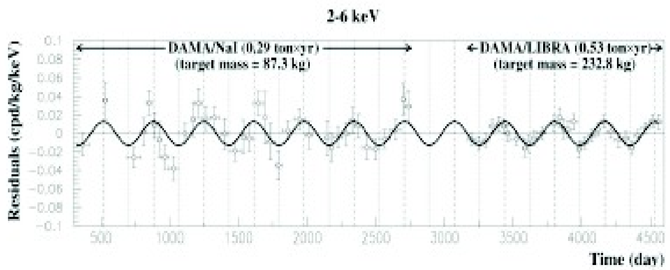

(Foadi, M.T.F and Sannino 09; Davoudiasl, Han and Logan 04; Godbole, Guchait, Mazumdar, Moretti and Roy 03)

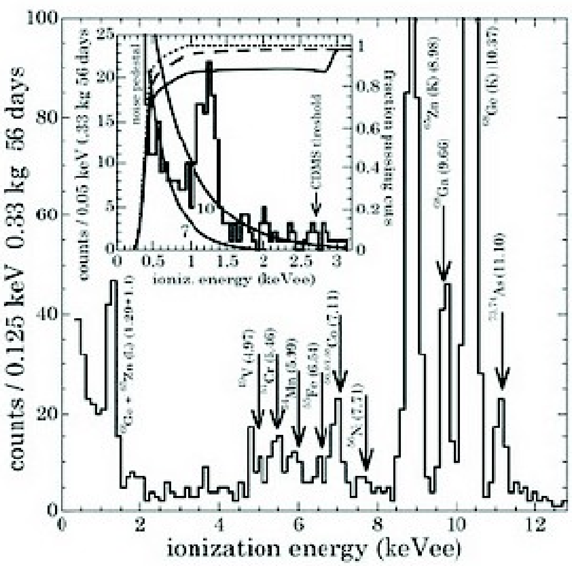
# Back to light ADM

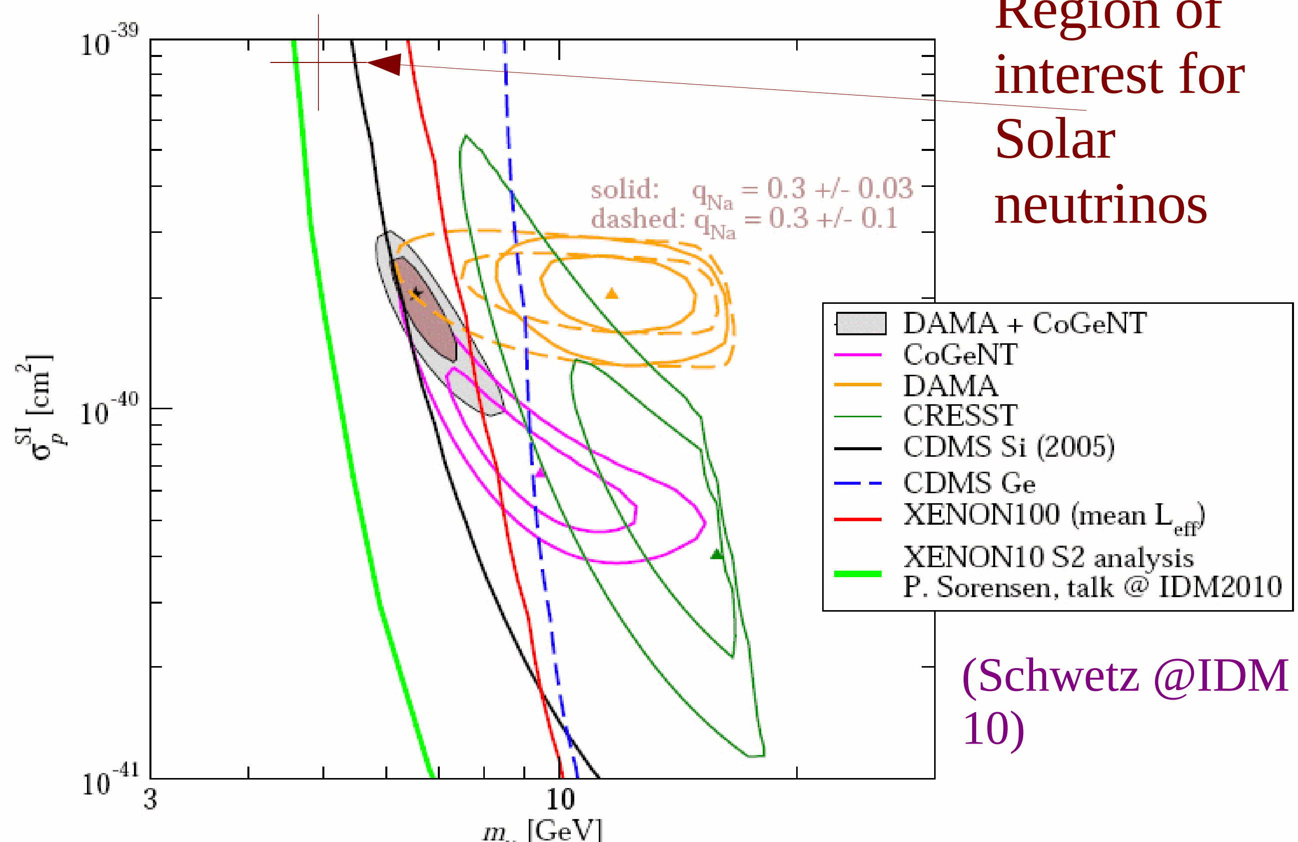



Most nuclear recoil experiments optimized to heavy WIMPs with little sensitivity to low mass particles O(keV) recoil energies

Recently several experiments have reported events close to threshold



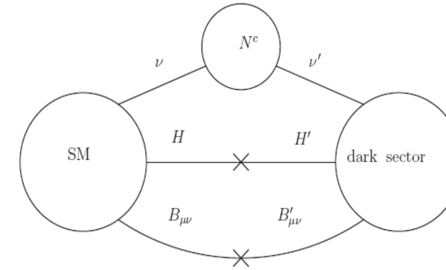

Region of interest for Solar neutrinos

(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$^2$

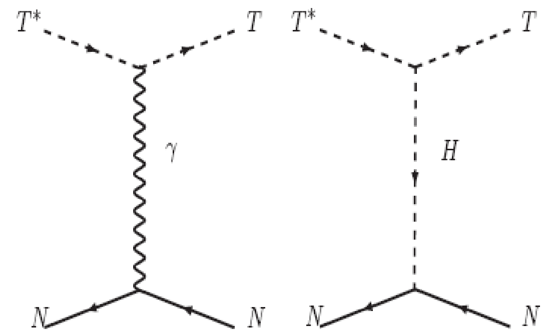
# Signatures of light ADM




Similar to TIMPs light ADM may be a composite scalar or fermion

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

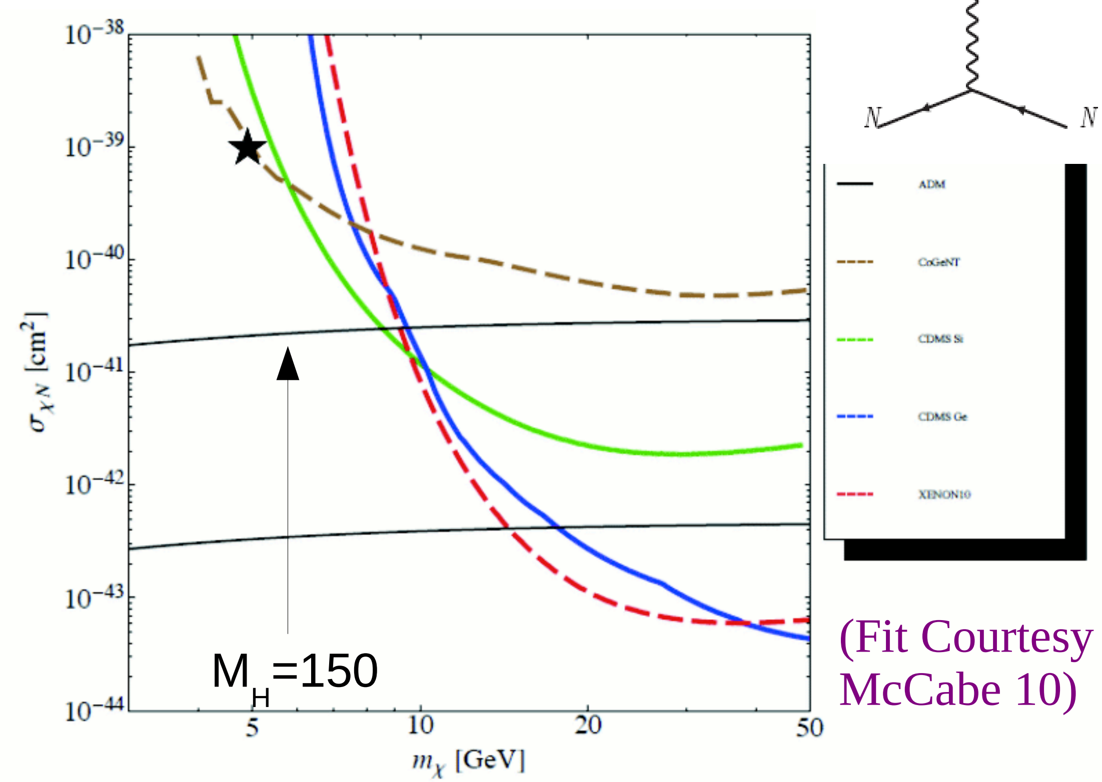
$$\sigma^{H}_{\rm nucleon} = \frac{\mu^2}{2\pi}\left[\frac{d_H f m_N}{m_H^2 m_\phi v}\right]^2$$




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

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

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




(Fit Courtesy of McCabe, McCabe 10)

(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 like for TIMPs incl 'monojets'

(Goodman et al 10, Bai, Fox & Harnik 10)

# Astrophysical aspects of light ADM

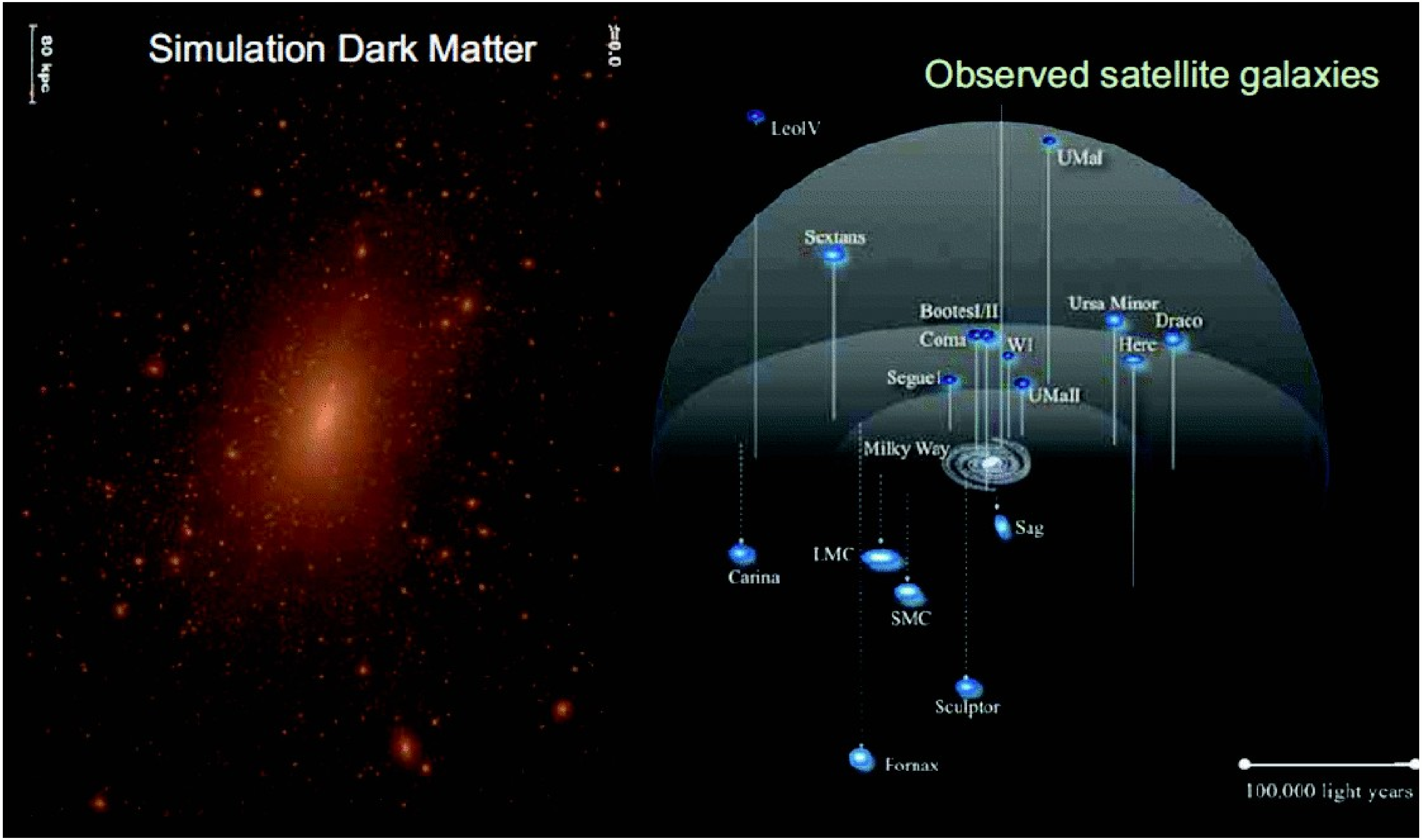
Such particles would also be naturally **self-interacting** with a typical cross-section: $\sigma_{\chi\chi} \sim \sigma_{nn} (m_n/m_\chi)^2$, where $\sigma_{nn} \sim 10^{-23}$ cm$^2$

… well below the bound of $2\times10^{-24}$ cm$^2$/GeV from the 'Bullet cluster'

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

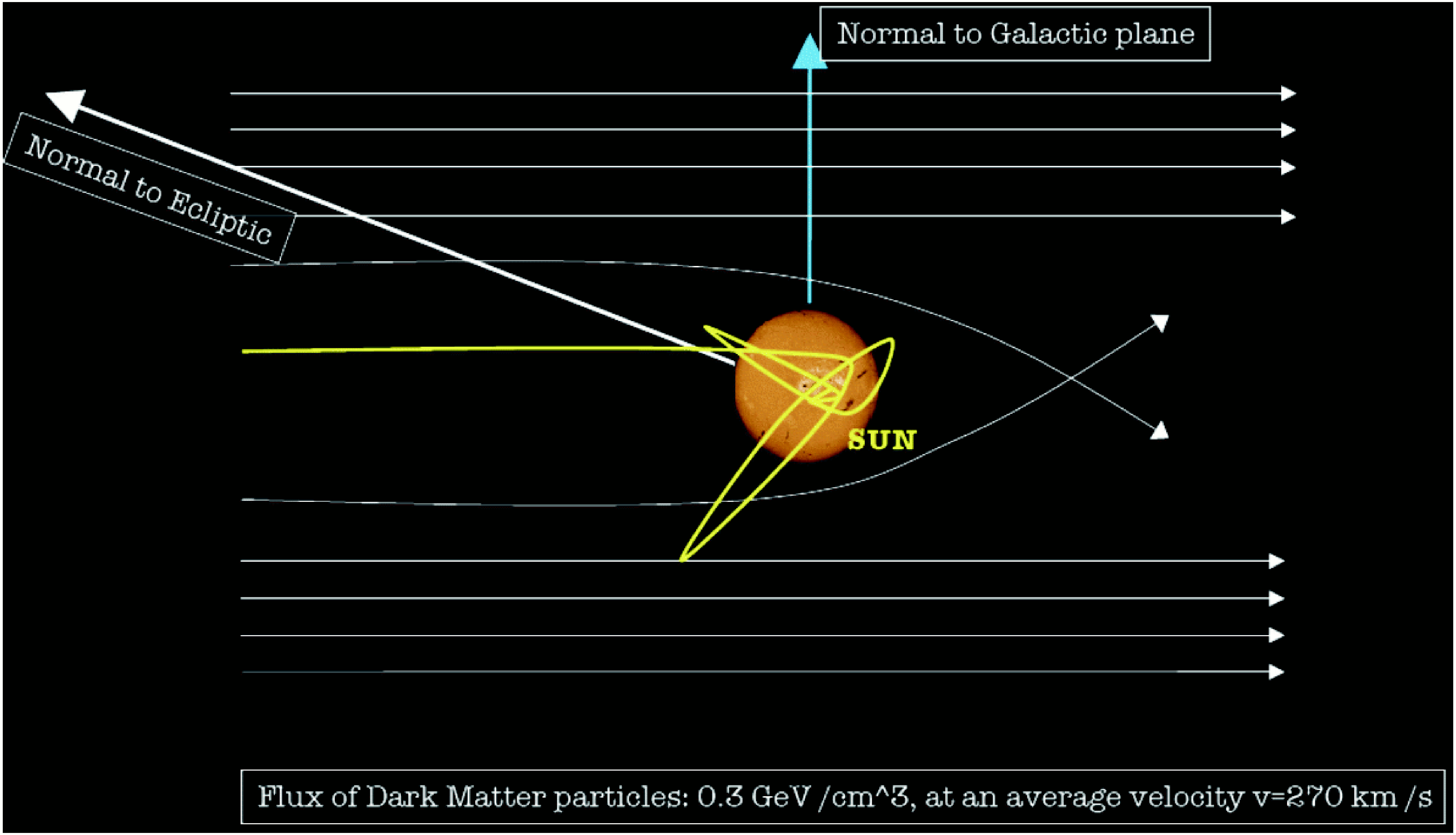
(Feng, Kaplinghat and Yu 10)

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



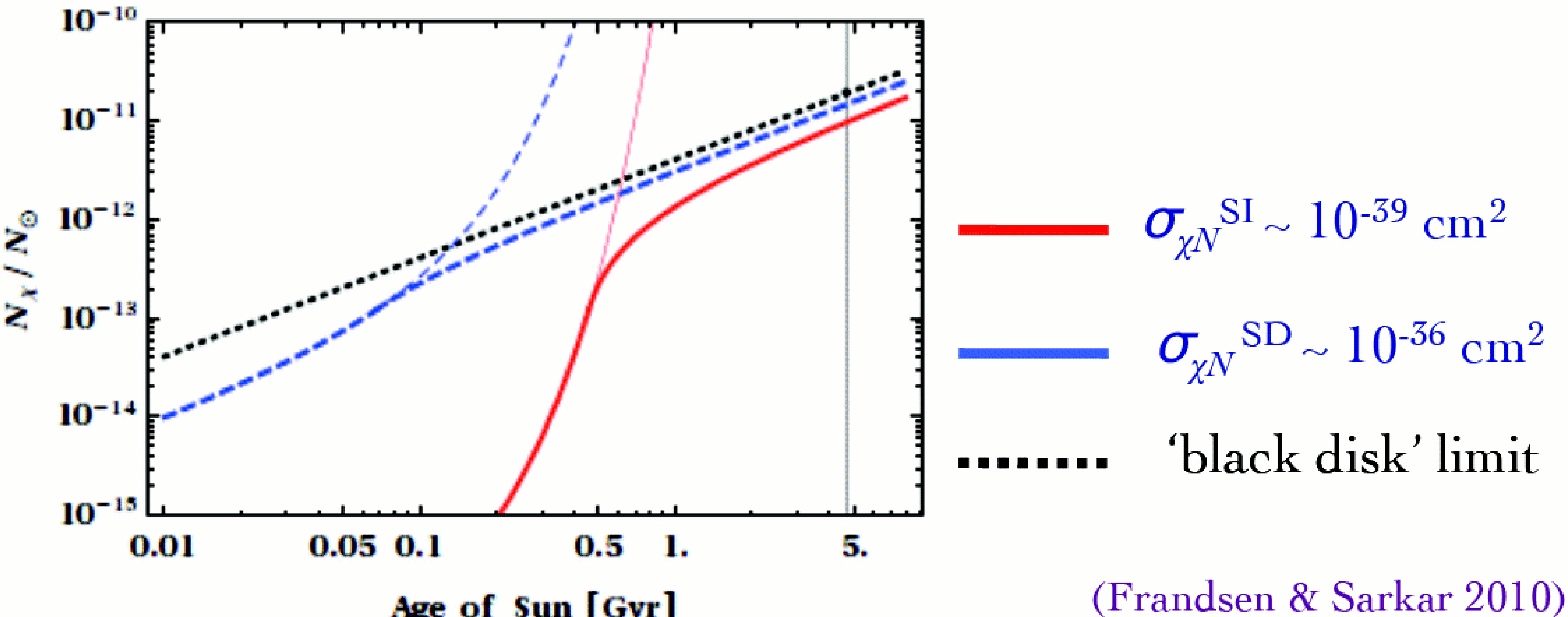

The flux of Solar neutrinos is *very* sensitive to the core temperature and can thus be *reduced* (Steigman *et al* 1978, Faulkner *et al* 1985, Press & Spergel 1985, Gould 1987)

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

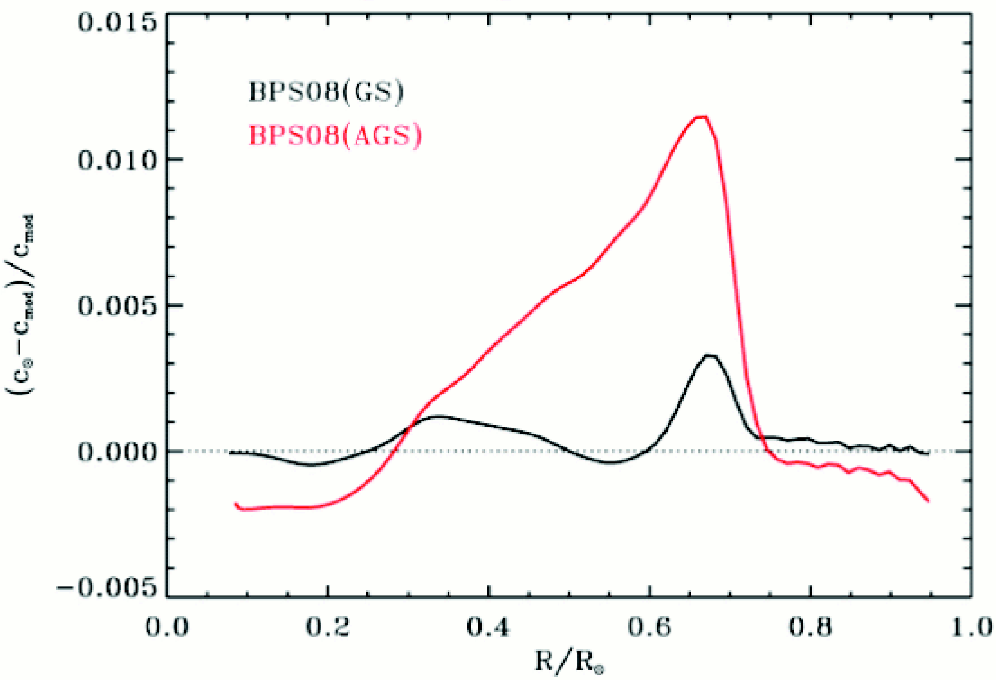



(Frandsen & Sarkar 2010)

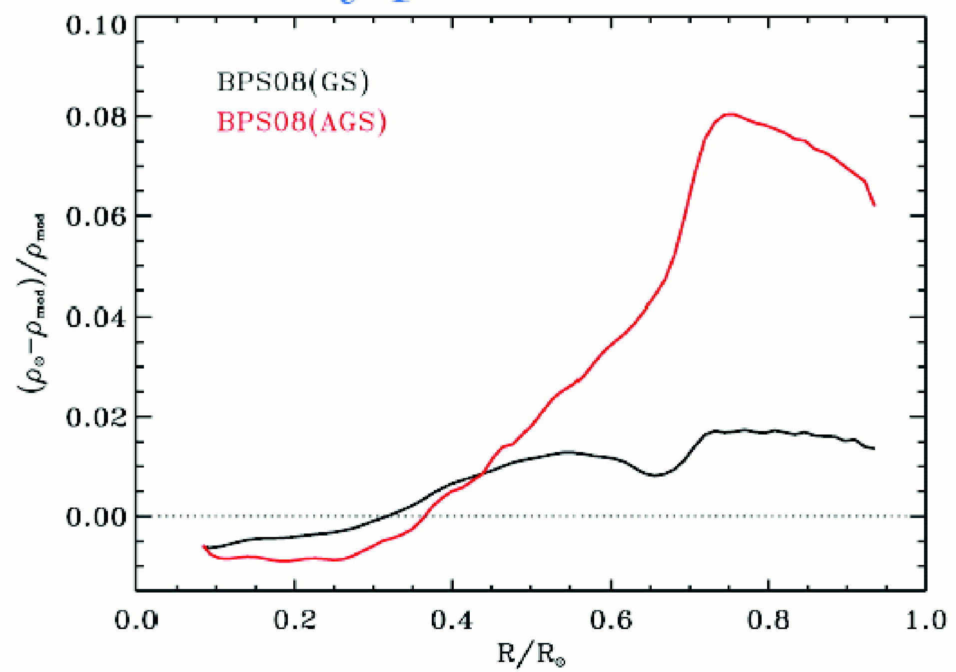
# A problem with the standard Solar model

- 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

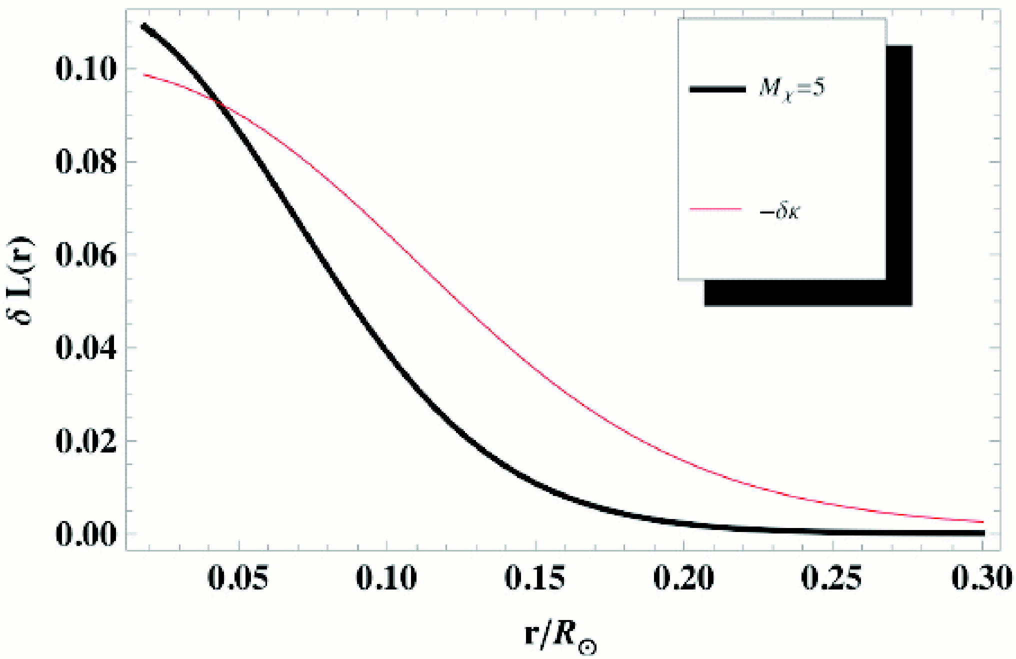



Could light dark matter particles accreted by the Sun solve this problem?
(Villante, talk@TAUP'09, Frandsen & Sarkar 2010)

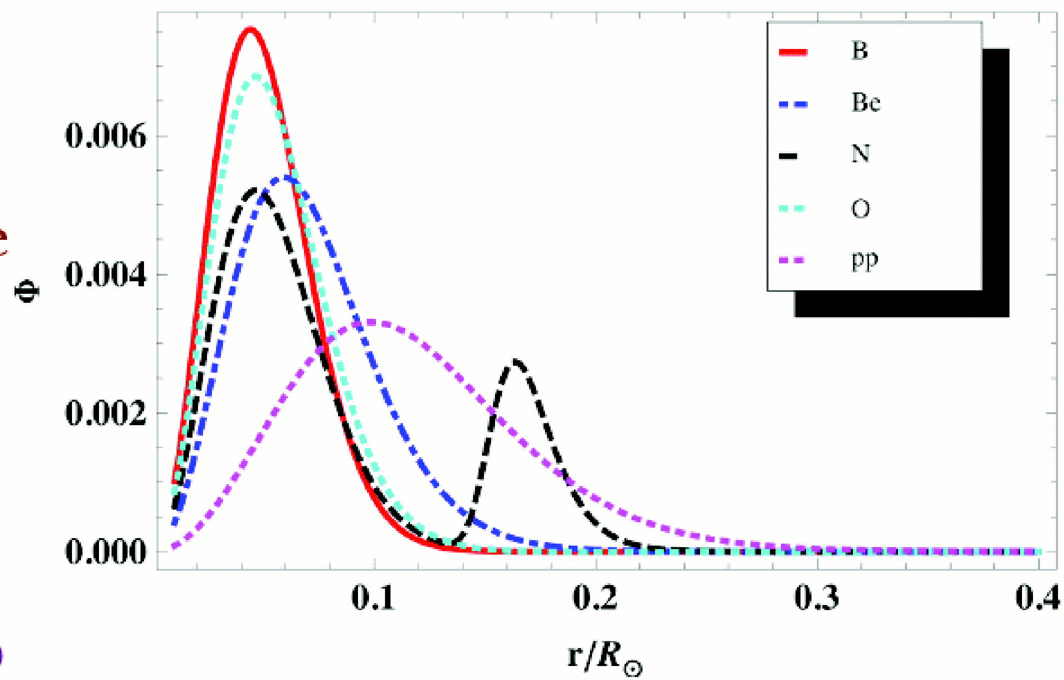
ADM will transport heat outward in the Sun: $L_\chi \sim 4 \times 10^{12} L_\odot \frac{N_\chi}{N_\odot} \frac{\sigma_{\chi N}}{\sigma_\odot} \sqrt{\frac{m_N}{m_\chi}}$

… 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:

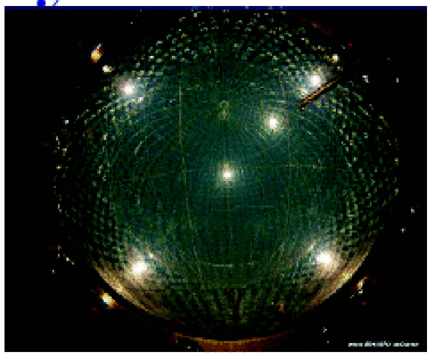
$\delta\Phi_B$ = -17%, $\delta\Phi_{Be}$ = -6.7%,

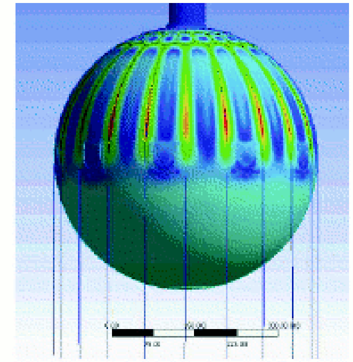
$\delta\Phi_N$ = -10%, $\delta\Phi_O$ = -14%

… *testable* by Borexino & SNO+

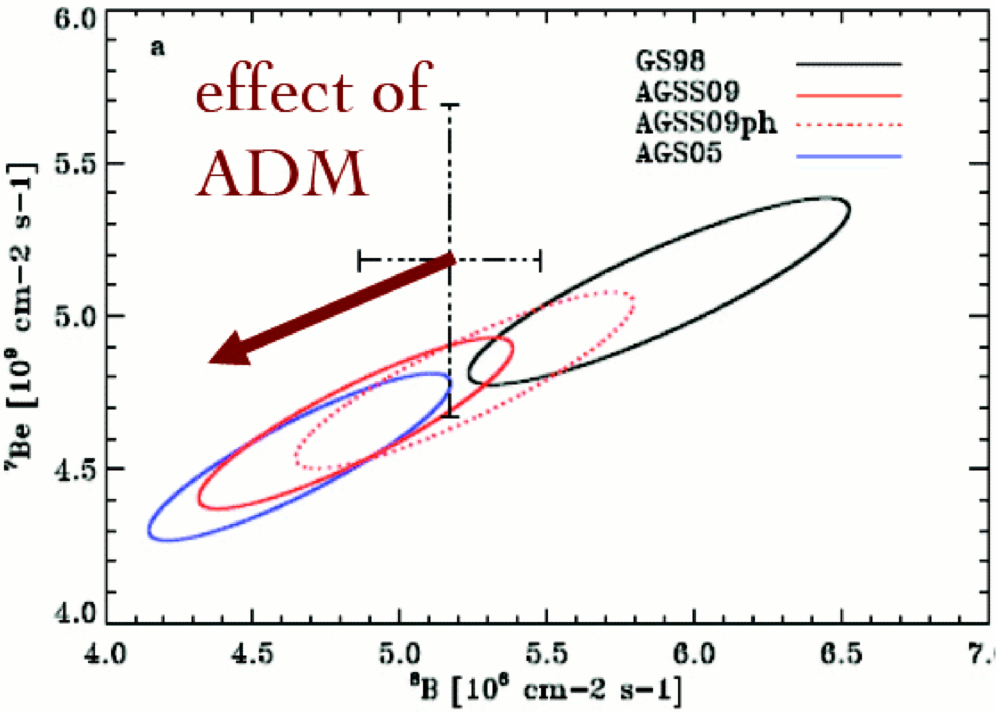
(Frandsen & Sarkar 2010)

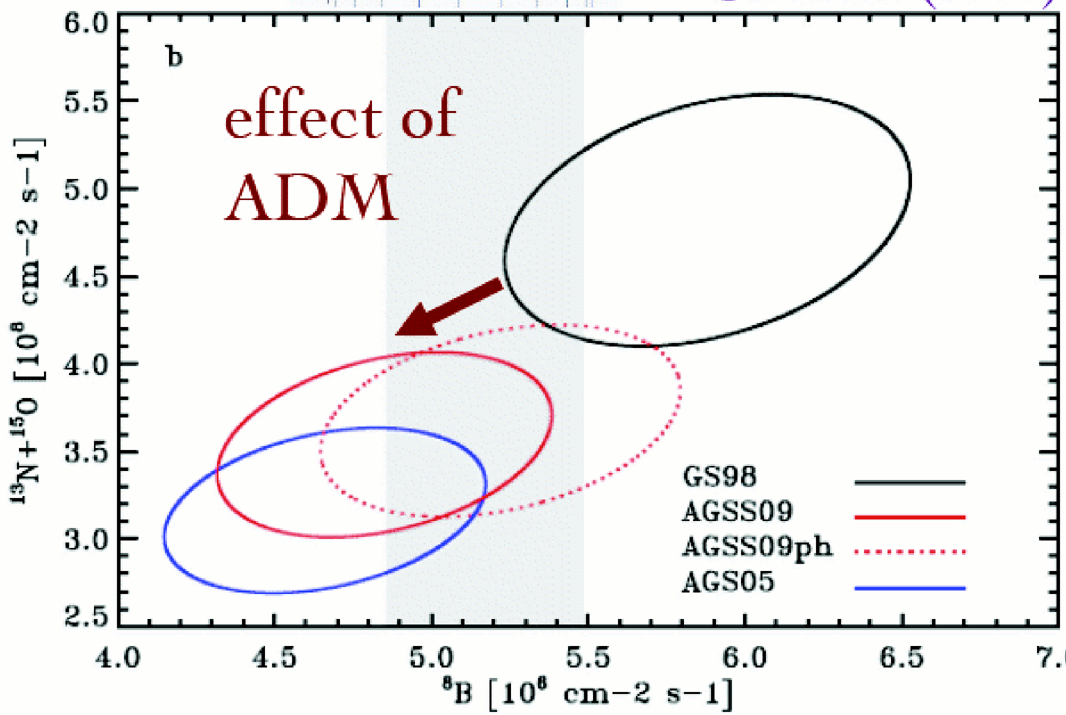
# Forthcoming precision measurements of Solar neutrinos by Borexino and SNO+ can *test* the model





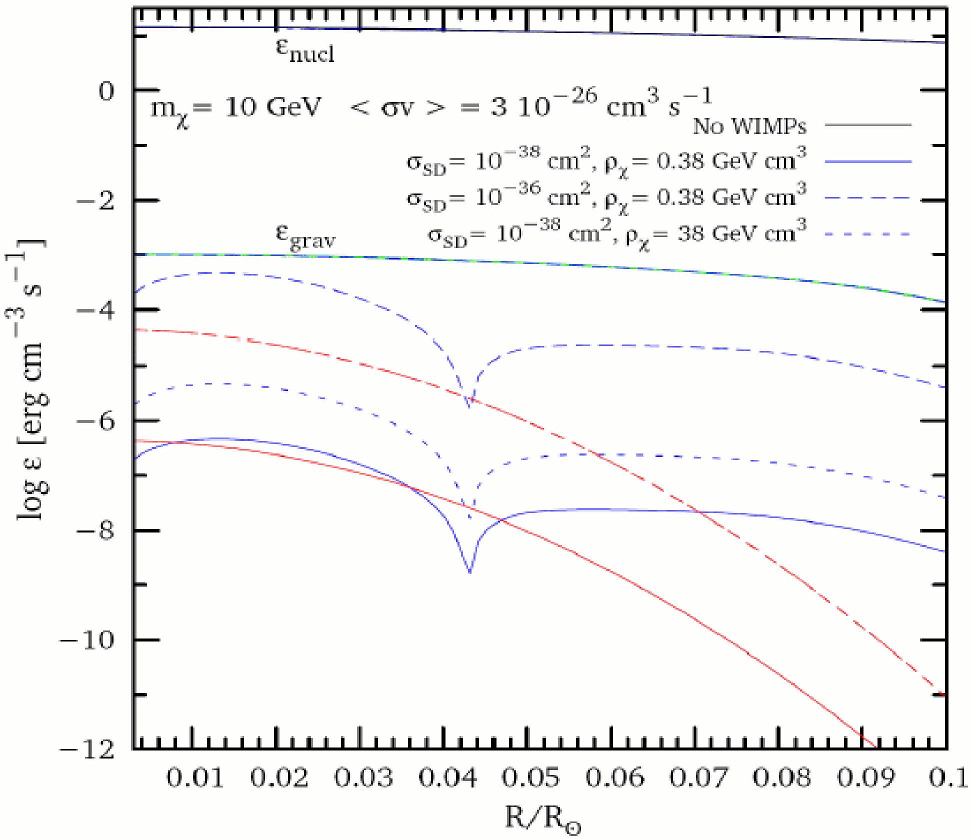
Serenelli (2010)



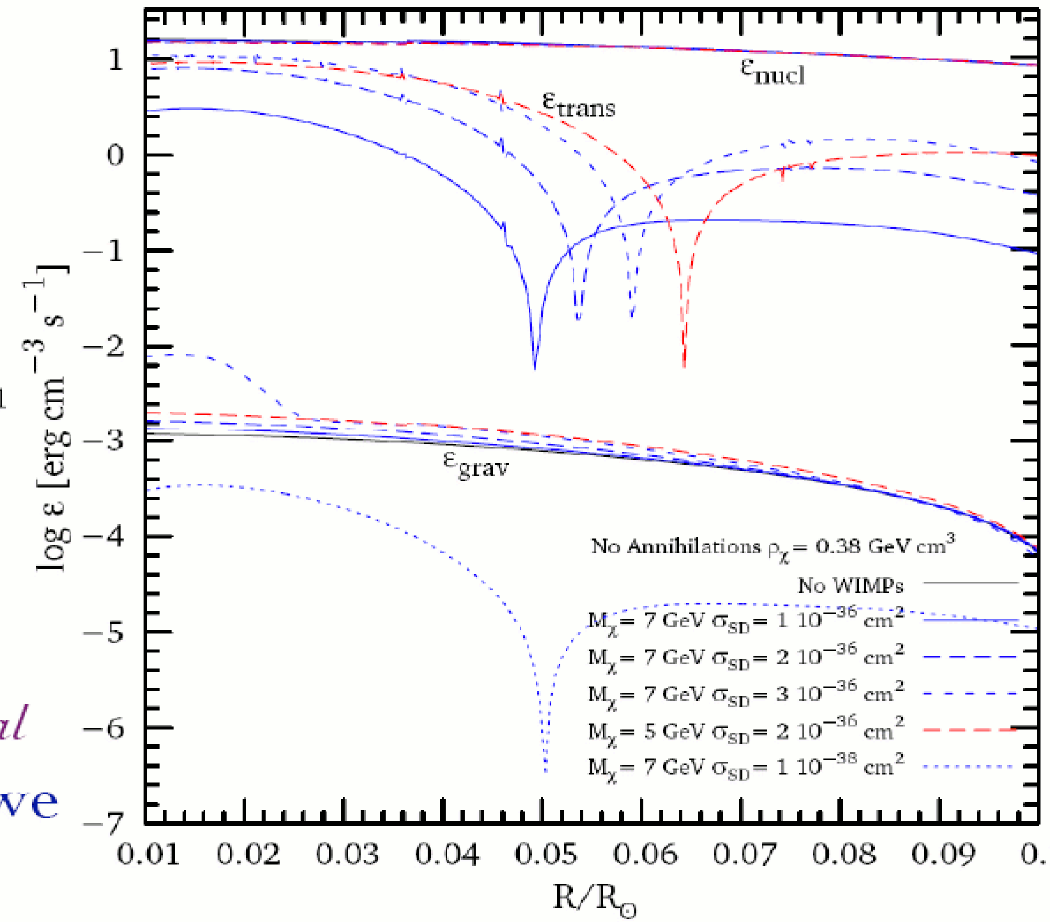




**SNO**: $\Phi(^8B) = 5.18 \pm 0.29 \times 10^6$ cm$^{-2}$ s$^{-1}$; **Borexino**: $\Phi(^7Be) = 5.18 \pm 0.51 \times 10^9$ cm$^{-2}$ s$^{-1}$

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

(Fairbairn and McCullough 10; Kouvaris 10)

# Summary

- Asymmetric Dark Matter motivated by the *asymmetry of baryonic matter* and the wish to *explain why* $\Omega_{DM} / \Omega_B \sim O(1)$
- *Technicolor is a natural and dynamical model of EWSB*
- ~ 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 strong dynamics in Hidden/Mirror/Unbaryon sectors, and is motivated in addition by problems in structure formation and potentially in helioseismology.
- *Variety of signatures can test the scenarios*

# DM Production mechanisms

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

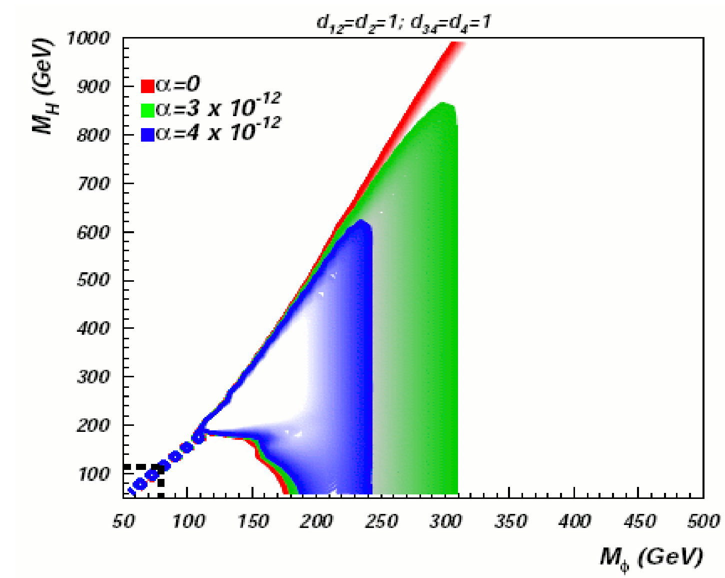
$$\mathcal{L} = \partial_\mu \phi^* \partial_\mu \phi - m_\phi^2 \phi^* \phi + \frac{d_1}{\Lambda} H \partial_\mu \phi^* \partial_\mu \phi + \frac{d_2}{\Lambda} m_\phi^2 H \phi^* \phi + \frac{d_3}{2\Lambda^2} H^2 \partial_\mu \phi^* \partial_\mu \phi + \frac{d_4}{2\Lambda^2} m_\phi^2 H^2 \phi^* \phi.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

Symmetric vs. asymmetric relics

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

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

(Griest & Seckel 85)



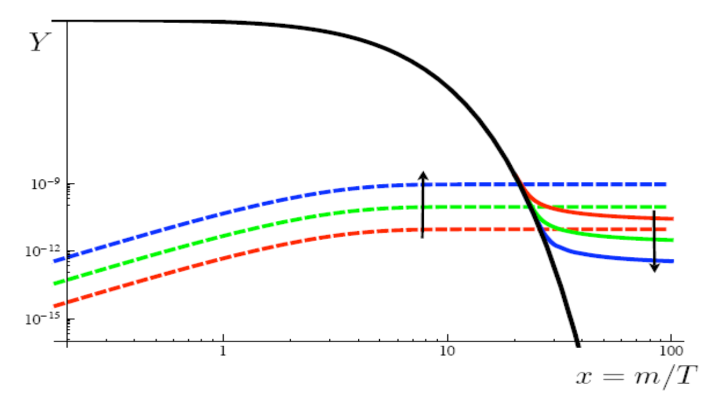

(Belyaev, M.T.F, Sarkar & Sannino 10)

Freeze out vs. freeze-in

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

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

(Asaka, Ishiwata & Moroi 05)




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