

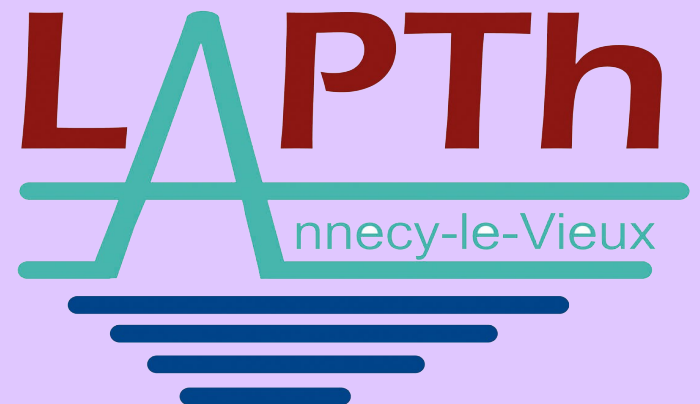
Asymmetric dark matter from



and New Strong Dynamics

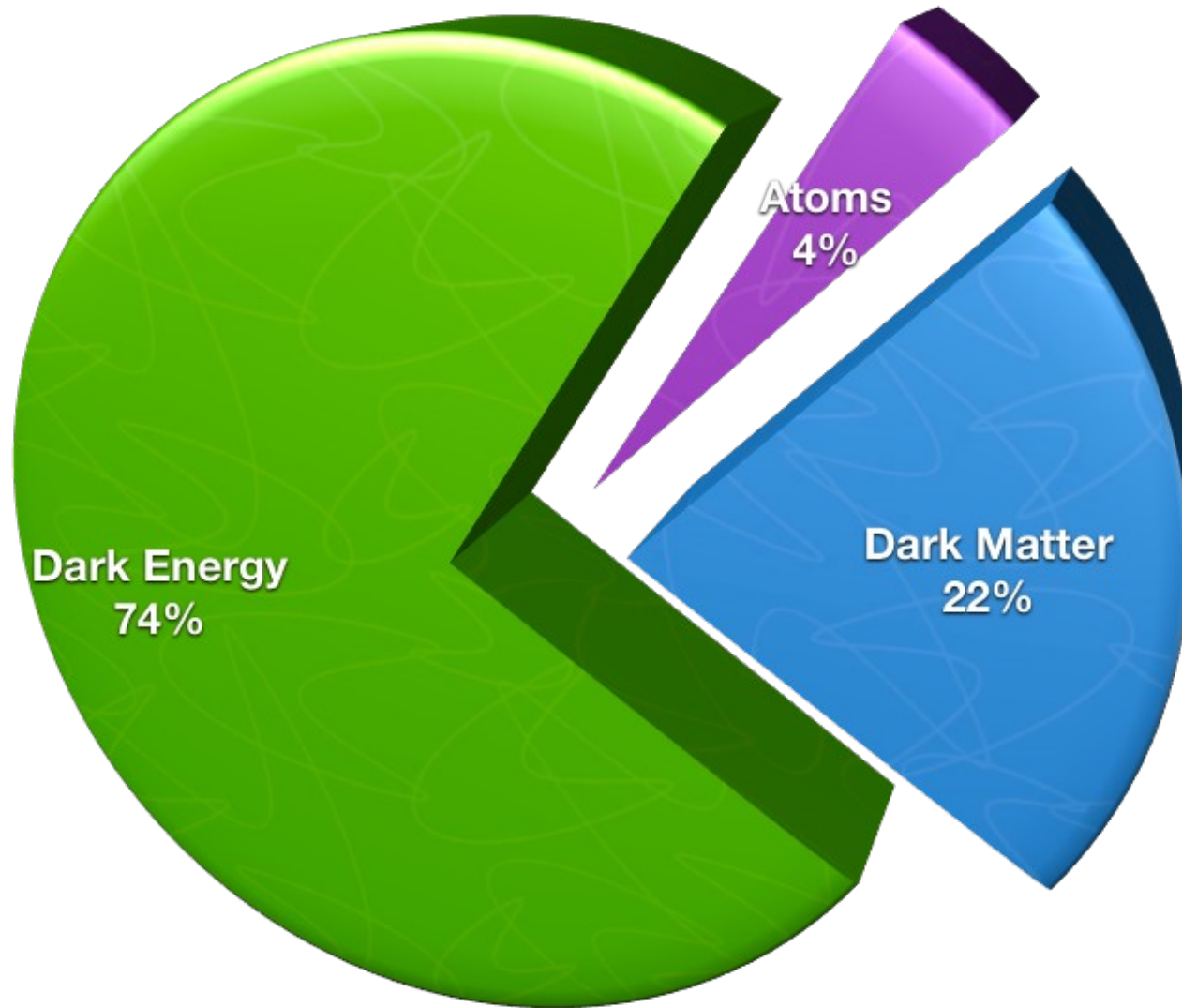
Mads Toudal Frandsen

Rudolf Peierls Centre for Theoretical Physics

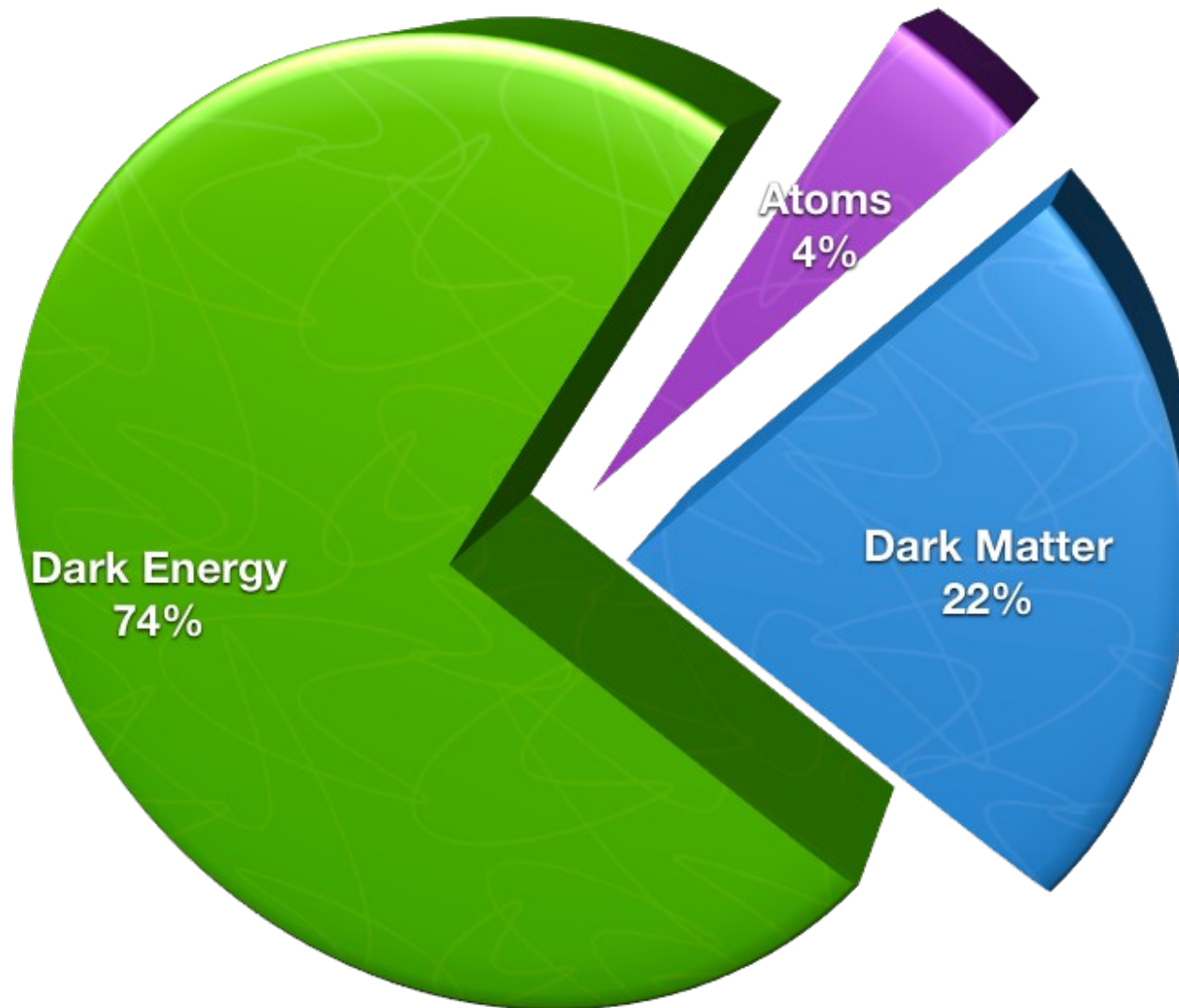


November 5th 2010

What is the world made of?



What is the world made of?



Baryons but no anti-baryons

Baryon mass (mainly) from strong dynamics

$$\Omega_{\text{DM}}/\Omega_{\text{B}} \sim \text{O}(1)$$

What *should* the world be made of ?

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

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

Chemical equilibrium maintained
when annihilation rate exceeds
the Hubble expansion rate

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

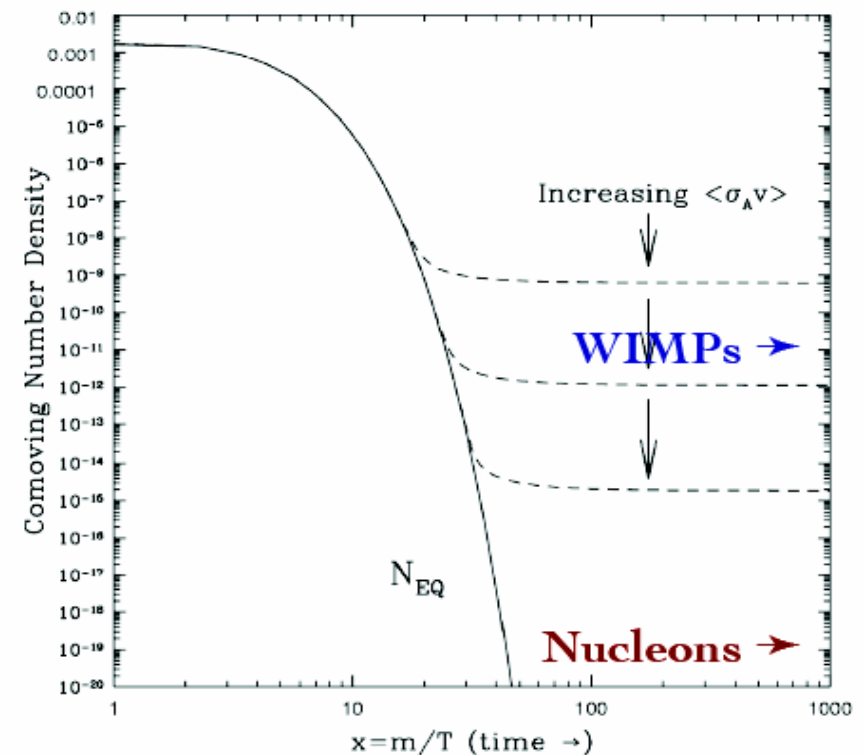
'Freeze-out' at $T \sim m_N/45$, with:

$$\frac{n_N}{n_\gamma} = \frac{n_{\bar{N}}}{n_\gamma} \sim 10^{-19} \quad \text{Observed ratio is } 10^9 \text{ times bigger:}$$

A 'baryon disaster'?!

Have to invoke an
asymmetry:

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



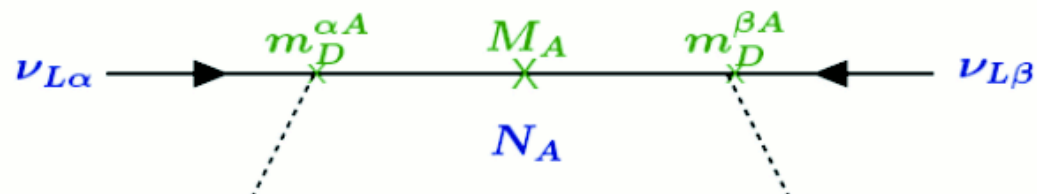
Sakharov conditions for baryogenesis:

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* (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 $\rightarrow$ leptogenesis**)

‘See-saw’: $\mathcal{L} = \mathcal{L}_{SM} + \lambda_{\alpha J}^* \bar{\ell}_{\alpha} \cdot H N_J - \frac{1}{2} \bar{N}_J M_J N_J^c \quad \lambda M^{-1} \lambda^T \langle H^0 \rangle^2 = [m_{\nu}]$



$$\Delta m_{atm}^2 = m_3^2 - m_2^2 \simeq 2.6 \times 10^{-3} \text{eV}^2 \quad \Delta m_{\odot}^2 = m_2^2 - m_1^2 \simeq 7.9 \times 10^{-5} \text{eV}^2$$

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) :

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

The fermion number N^i terms of the statistical function c_i and the

Chemical potential μ is:

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

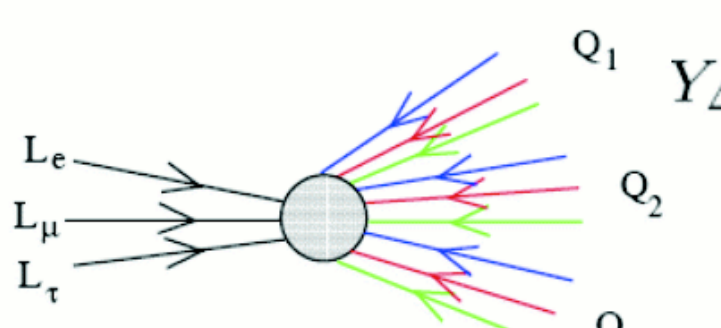
The fermion number violating processes (sphalerons) create equal number of fermion doublets:

$$\sum_i \mu_i = 0.$$

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

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

Asymmetric baryonic matter



$$\begin{aligned}
 Y_{\Delta B} &= \frac{n_N^{eq}(T \gg M_1)}{s} \sum_{\alpha} \frac{n_{\ell_{\alpha}} - n_{\bar{\ell}_{\alpha}}}{n_N} \times \eta_{\alpha} \times C \\
 &\sim 4 \times 10^{-3} \sum_{\alpha} \epsilon_{\alpha\alpha} \times \eta_{\alpha} \times \frac{1}{3} \\
 &\sim 10^{-10} \text{ for reasonable parameter values}
 \end{aligned}$$

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	$\otimes > 10^{33} \text{ yr}$ (dim-6 OK)	'freeze-out' from thermal equilibrium asymmetry	$\Omega_{\text{B}} \sim 10^{-10}$ $\Omega_{\text{B}} \sim 0.05$
$\Lambda_{\text{Fermi}} \sim$ $G_{\text{F}}^{-1/2}$	Neutralino?	R-parity?	violated?	'freeze-out' from thermal equilibrium	$\Omega_{\text{LSP}} \sim 0.3$

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

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

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

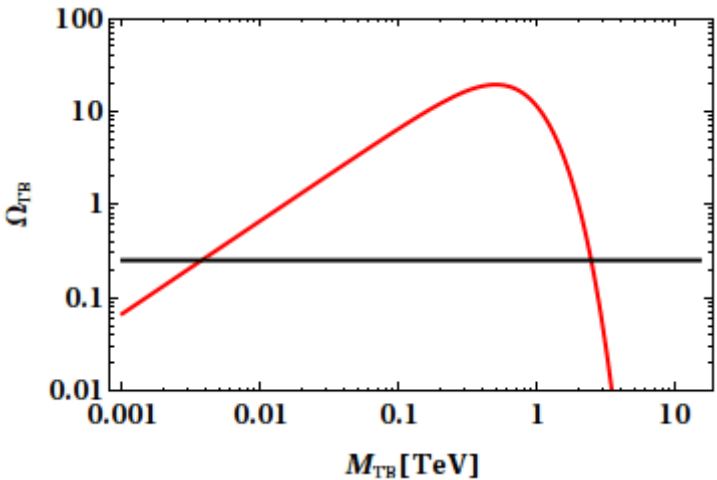
A TeV scale particle sharing the asymmetry (e.g. a technibaryon) could explain the ratio of dark to baryonic matter... (Nussinov 1985)

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

• From initial $n_B \sim n_{TB}$:

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

$$T_{sphaleron} \sim v_{EW} \; , \qquad \text{(Bahr, Chivukula and Farhi 90)}$$



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	$\otimes > 10^{33}$ yr (dim-6 OK)	'freeze-out' from thermal equilibrium Asymmetry	$\Omega_B \sim 10^{-10}$ $\Omega_B \sim 0.05$
$\Lambda_{\text{TC}} \sim \Lambda_{\text{Fermi}}$	Technibaryon?	U(1) techibaryon	?	Asymmetry	$\Omega_{\text{TC}} \sim 0.3$
$\Lambda_{\text{DB}} \sim 5 \Lambda_{\text{QCD}}$	Dark Baryon?	U(1) dark baryon number			$\Omega_{\text{DB}} \sim 0.3$

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) :

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

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:

$$\sum_i \mu_i = 0.$$

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

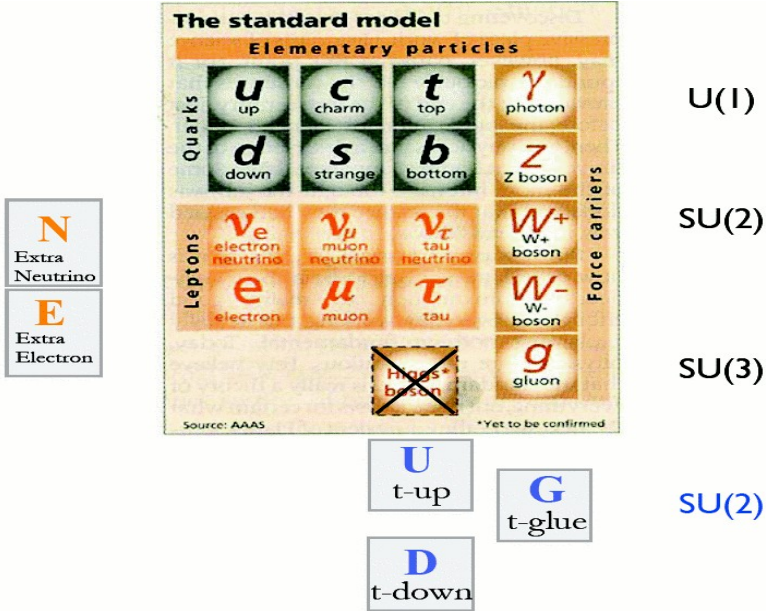
(Bahr, Chivukula & Farhi 90;
Harvey and Turner 90)

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

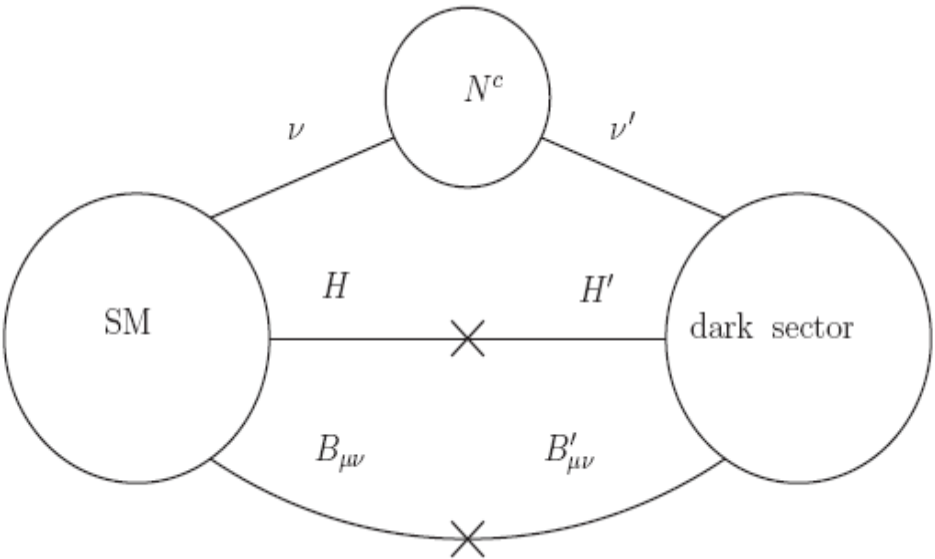
Minimal (Walking) Technicolour



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*

Technicolor Dark matter and LHC Phenomenology

Mads Toudal Frandsen

LAPTh

Annecy-le-Vieux, November 5th 2010
m.frandsen1@physics.ox.ac.uk

Outline

- 1 Technicolor and Technibaryon Dark Matter
- 2 Minimal Walking Technicolor and (i)TIMPs
- 3 LHC Phenomenology of MWT and (i)TIMPs

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 $F_\Pi^{TC} = v_{EW} = 246 \text{ GeV}$.
- 3 Let the electroweak gauge group be a subgroup of the chiral symmetry group.

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 $F_\Pi^{TC} = v_{EW} = 246 \text{ GeV}$.
- 3 Let the electroweak gauge group be a subgroup of the chiral symmetry group.

Example: **Scaled-up QCD** !

Technicolor

- 1 The SM gauge group is augmented:

$$G_{SM} \rightarrow SU(3)_c \times SU(2)_W \times U(1)_Y \times G_{TC} .$$

Technicolor

- 1 The SM gauge group is augmented:

$$G_{SM} \rightarrow SU(3)_c \times SU(2)_W \times U(1)_Y \times G_{TC} .$$

- 2 The Higgs sector of the SM is replaced:

$$\mathcal{L}_{Higgs} \rightarrow -\frac{1}{4}F_{\mu\nu}^a F^{a\mu\nu} + i\bar{Q}_L \gamma_\mu D^\mu Q_L + i\bar{Q}_R \gamma_\mu D^\mu Q_R + \dots$$

Technicolor

- 1 The SM gauge group is augmented:

$$G_{SM} \rightarrow SU(3)_c \times SU(2)_W \times U(1)_Y \times G_{TC} .$$

- 2 The Higgs sector of the SM is replaced:

$$\mathcal{L}_{Higgs} \rightarrow -\frac{1}{4}F_{\mu\nu}^a F^{a\mu\nu} + i\bar{Q}_L \gamma_\mu D^\mu Q_L + i\bar{Q}_R \gamma_\mu D^\mu Q_R + \dots$$

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

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

Technicolor dark matter

Technoc cosmology (Nussinov 85)

Lightest Technibaryon as Asymmetric Dark Matter

Technicolor dark matter

Technoc cosmology (Nussinov 85)

Lightest Technibaryon as Asymmetric Dark Matter

- The LTB abundance:

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

Technicolor dark matter

Technocosmology (Nussinov 85)

Lightest Technibaryon as Asymmetric Dark Matter

- The LTB abundance:

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

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

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

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

(Chivukula and Walker 90; Bahr, Chivukula and Farhi 90; Harvey and Turner 90; Ellis et al 95; Sarkar 95; Gudnason, Kouvaris and Sannino 05)

Technicolor dark matter

Technoc cosmology (Nussinov 85)

Lightest Technibaryon as Asymmetric Dark Matter

- The LTB abundance:

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

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

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

$$T_{\text{sphaleron}} \sim v_{EW}, \quad M_{TB} \sim \text{TeV}$$

(Chivukula and Walker 90; Bahr, Chivukula and Farhi 90; Harvey and Turner 90; Ellis et al 95; Sarkar 95; Gudnason, Kouvaris and Sannino 05)

Technicolor dark matter

Technocosmology (Nussinov 85)

Lightest Technibaryon as Asymmetric Dark Matter

- The LTB abundance:

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

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

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

$$T_{sphaleron} \sim v_{EW}, \quad M_{TB} \sim TeV$$

(Chivukula and Walker 90; Bahr, Chivukula and Farhi 90; Harvey and Turner 90; Ellis et al 95; Sarkar 95; Gudnason, Kouvaris and Sannino 05)

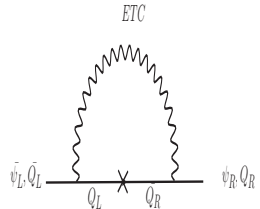
- Scaled up 'technineutron' now ruled out by recoil experiments

$$\sigma_{TN,p} \sim 10^{-32} \text{ cm}^2$$

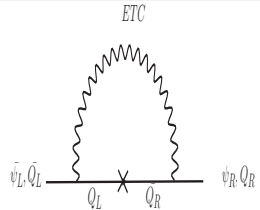
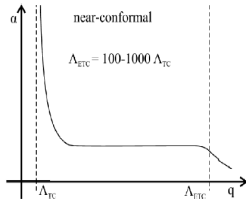
Extended Technicolor and fermion masses

ETC: (Eichten and Lane 80)

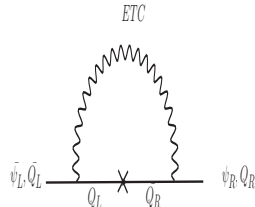
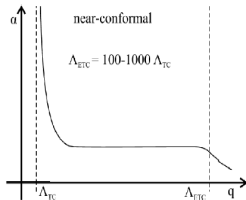
New gauge theory with SM and TC fermions in the same multiplet.



Extended Technicolor and fermion masses



Extended Technicolor and fermion masses

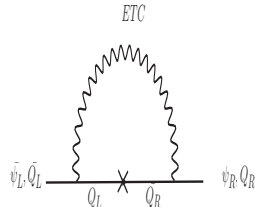
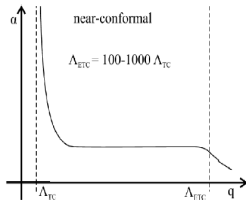


- 1 Four fermion operators:

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

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

Extended Technicolor and fermion masses



- 1 Four fermion operators:

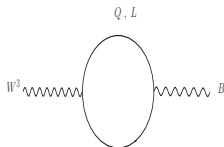
$$\alpha \frac{\bar{Q}Q\bar{Q}Q}{\Lambda_{ETC}^2} + \beta \frac{\bar{Q}Q\bar{\psi}\psi}{\Lambda_{ETC}^2} + \gamma \frac{\bar{\psi}\psi\bar{\psi}\psi}{\Lambda_{ETC}^2} + \dots$$

- 2 (Too!) Generically $\Lambda_{ETC} > 10^3 \text{ TeV}$ to suppress FCNC's:
 (King 89; Evans and Ross 94; Appelquist and Shrock 02; Evans and Sannino 05; Christensen, Piai and Shrock 06)
- 3 Focus on Technicolor sector

Constraints from LEP

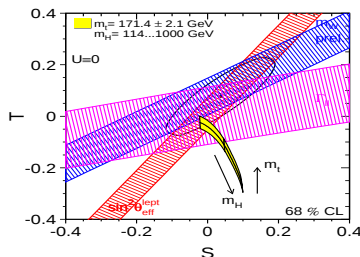
- 1 A minimal matter content in the TC sector is favored:

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



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

$$S = S_{\text{naive}}(1 + \delta)$$



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

Minimal Technicolor Theory Space

2 EW charged Dirac Flavors. No QCD charges.

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

Minimal Technicolor Theory Space

2 EW charged Dirac Flavors. No QCD charges.

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

'Orthogonal TC'

'QCD TC'

'Symplectic TC'

Minimal Technicolor Theory Space

2 EW charged Dirac Flavours. No QCD charges.

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

'Orthogonal TC'

- $\mathcal{R}$ real

'QCD TC'

- $\mathcal{R}$ complex

'Symplectic TC'

- $\mathcal{R}$ pseudo-real

Minimal Technicolor Theory Space

2 EW charged Dirac Flavours. No QCD charges.

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

'Orthogonal TC'

- $\mathcal{R}$ real
- F of $SO(N)$

'QCD TC'

- $\mathcal{R}$ complex
- F of $SU(N)$

'Symplectic TC'

- $\mathcal{R}$ pseudo-real
- F of $Sp(2N)$

Minimal Technicolor Theory Space

2 EW charged Dirac Flavors. No QCD charges.

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

'Orthogonal TC'

- $\mathcal{R}$ real
- F of $SO(N)$
- $SU(4)/SO(4)$

'QCD TC'

- $\mathcal{R}$ complex
- F of $SU(N)$
- $G_{GB}: SU(2)$

'Symplectic TC'

- $\mathcal{R}$ pseudo-real
- F of $Sp(2N)$
- $SU(4)/Sp(4)$

Minimal Technicolor Theory Space

2 EW charged Dirac Flavors. No QCD charges.

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

'Orthogonal TC'

- $\mathcal{R}$ real
- F of $SO(N)$
- $SU(4)/SO(4)$
- $3_{\Pi} \oplus 3 \oplus \bar{3}$

'QCD TC'

- $\mathcal{R}$ complex
- F of $SU(N)$
- $G_{GB}: SU(2)$
- 3_{Π}

'Symplectic TC'

- $\mathcal{R}$ pseudo-real
- F of $Sp(2N)$
- $SU(4)/Sp(4)$
- $3_{\Pi} \oplus 1 \oplus \bar{1}$

Minimal Technicolor Theory Space

2 EW charged Dirac Flavours. No QCD charges.

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

'Orthogonal TC'

- $\mathcal{R}$ real
- F of $SO(N)$
- $SU(4)/SO(4)$
- $3_{\Pi} \oplus 3 \oplus \bar{3}$

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

'QCD TC'

- $\mathcal{R}$ complex
- F of $SU(N)$
- $G_{GB}: SU(2)$
- 3_{Π}

$$\Pi = \begin{pmatrix} \Pi^0 & \Pi^+ \\ \Pi^- & \Pi^0 \end{pmatrix}$$

'Symplectic TC'

- $\mathcal{R}$ pseudo-real
- F of $Sp(2N)$
- $SU(4)/Sp(4)$
- $3_{\Pi} \oplus 1 \oplus \bar{1}$

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

Minimal Technicolor Theory Space

2 EW charged Dirac Flavors. No QCD charges.

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

'Orthogonal TC'

- $\mathcal{R}$ real
- F of $SO(N)$
- $SU(4)/SO(4)$
- $3_{\Pi} \oplus 3 \oplus \bar{3}$

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

$$T_i = \begin{pmatrix} T^0 & T^+ \\ T^- & T^{0*} \end{pmatrix}$$

'QCD TC'

- $\mathcal{R}$ complex
- F of $SU(N)$
- $G_{GB}: SU(2)$
- 3_{Π}

$$\Pi = \begin{pmatrix} \Pi^0 & \Pi^+ \\ \Pi^- & \Pi^0 \end{pmatrix}$$

'Symplectic TC'

- $\mathcal{R}$ pseudo-real
- F of $Sp(2N)$
- $SU(4)/Sp(4)$
- $3_{\Pi} \oplus 1 \oplus \bar{1}$

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

$$T_s = \begin{pmatrix} T^0 & 0 \\ 0 & T^{0*} \end{pmatrix}$$

Dark Matter from Minimal Technicolor

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

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

Dark Matter from Minimal Technicolor

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

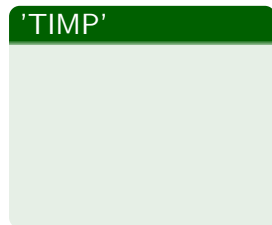
$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2} \right)^T, \quad U_R^{+1/2}, D_R^{-1/2}; \lambda. \quad (1)$$



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



(Bahr, Chivukula and
Farhi 90; Nussinov 92)



(Ryttov and Sannino
08; Foadi, M.T.F and
Sannino 09)

Dark Matter from Minimal Technicolor

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

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

'iTIMP'

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

'TIMP'

• 4 of $SU(4)$

(Bahr, Chivukula and
Farhi 90; Nussinov 92)

'TIMP'

(Ryttov and Sannino
08; Foadi, M.T.F and
Sannino 09)

Dark Matter from Minimal Technicolor

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

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

'iTIMP'

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

'TIMP'

- 4 of $SU(4)$
- $U_L D_L U_L D_L$

(Bahr, Chivukula and
Farhi 90; Nussinov 92)

'TIMP'

(Ryttov and Sannino
08; Foadi, M.T.F and
Sannino 09)

Dark Matter from Minimal Technicolor

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

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

'iTIMP'

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

'TIMP'

- 4 of $SU(4)$
- $U_L D_L U_L D_L$
- SM singlet

(Bahr, Chivukula and
Farhi 90; Nussinov 92)

'TIMP'

(Ryttov and Sannino
08; Foadi, M.T.F and
Sannino 09)

Dark Matter from Minimal Technicolor

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

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

'iTIMP'

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

'TIMP'

- 4 of $SU(4)$
- $U_L D_L U_L D_L$
- SM singlet
- $M_T \sim N_{TC}^{3/2} F_\Pi$

(Bahr, Chivukula and
Farhi 90; Nussinov 92)

'TIMP'

(Ryttov and Sannino
08; Foadi, M.T.F and
Sannino 09)

Dark Matter from Minimal Technicolor

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

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

'iTIMP'

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

'TIMP'

- 4 of $SU(4)$
- $U_L D_L U_L D_L$
- SM singlet
- $M_T \sim N_{TC}^{3/2} F_\Pi$

(Bahr, Chivukula and
Farhi 90; Nussinov 92)

'TIMP'

(Ryttov and Sannino
08; Foadi, M.T.F and
Sannino 09)

Dark Matter from Minimal Technicolor

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

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

'iTIMP'

- $\mathcal{R}$ real

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

'TIMP'

- 4 of $SU(4)$
- $U_L D_L U_L D_L$
- SM singlet
- $M_T \sim N_{TC}^{3/2} F_\Pi$

(Bahr, Chivukula and
Farhi 90; Nussinov 92)

'TIMP'

- $\mathcal{R}$ pseudo-real

(Ryttov and Sannino
08; Foadi, M.T.F and
Sannino 09)

Dark Matter from Minimal Technicolor

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

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

'iTIMP'

- $\mathcal{R}$ real
- $T^0 \sim U_L D_L$

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

'TIMP'

- 4 of $SU(4)$
- $U_L D_L U_L D_L$
- SM singlet
- $M_T \sim N_{TC}^{3/2} F_\Pi$

(Bahr, Chivukula and
Farhi 90; Nussinov 92)

'TIMP'

- $\mathcal{R}$ pseudo-real
- $T^0 \sim U_L D_L$

(Ryttov and Sannino
08; Foadi, M.T.F and
Sannino 09)

Dark Matter from Minimal Technicolor

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

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

'i'TIMP'

- $\mathcal{R}$ real
- $T^0 \sim U_L D_L$
- Iso-spin 0 GB

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

'TIMP'

- 4 of $SU(4)$
- $U_L D_L U_L D_L$
- SM singlet
- $M_T \sim N_{TC}^{3/2} F_\Pi$

(Bahr, Chivukula and Farhi 90; Nussinov 92)

'TIMP'

- $\mathcal{R}$ pseudo-real
- $T^0 \sim U_L D_L$
- SM singlet GB

(Ryttov and Sannino 08; Foadi, M.T.F and Sannino 09)

Dark Matter from Minimal Technicolor

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

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

'iTIMP'

- $\mathcal{R}$ real
- $T^0 \sim U_L D_L$
- Iso-spin 0 GB
- $M_{T^0} \sim g F_\Pi$

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

'TIMP'

- 4 of $SU(4)$
- $U_L D_L U_L D_L$
- SM singlet
- $M_T \sim N_{TC}^{3/2} F_\Pi$

(Bahr, Chivukula and Farhi 90; Nussinov 92)

'TIMP'

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

(Ryttov and Sannino 08; Foadi, M.T.F and Sannino 09)

Dark Matter from Minimal Technicolor

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

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

'iTIMP'

- $\mathcal{R}$ real
- $T^0 \sim U_L D_L$
- Iso-spin 0 GB
- $M_{T^0} \sim g F_\Pi$

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

'TIMP'

- 4 of $SU(4)$
- $U_L D_L U_L D_L$
- SM singlet
- $M_T \sim N_{TC}^{3/2} F_\Pi$

(Bahr, Chivukula and
Farhi 90; Nussinov 92)

'TIMP'

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

(Ryttov and Sannino
08; Foadi, M.T.F and
Sannino 09)

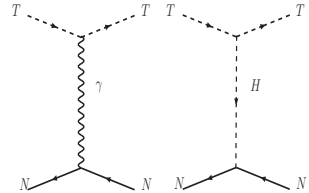
(Other candidates in MT: Gudnason, Kouvaris and Sannino 05; Kainulainen, Virkajarvi and Tuominen 06, 09, 10; Kouvaris 07; Khlopov and Kouvaris 08)

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)



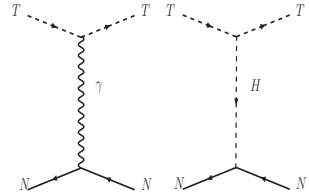
- Composite Higgs $\mathcal{L}_H^{Yuk} = d_H v_{ev} T^* T H$ or
 $\mathcal{L}_H^{GB} = \frac{d_{13}}{\Lambda} H \partial_\mu T^* \partial_\mu T$. (M.T.F and Sannino 09)

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)



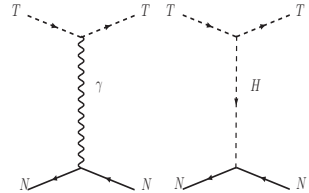
- Composite Higgs $\mathcal{L}_H^{Yuk} = d_H v_{ev} T^* T H$ or
 $\mathcal{L}_H^{GB} = \frac{d_{13}}{\Lambda} H \partial_\mu T^* \partial_\mu T$. (M.T.F and Sannino 09)
- For colored baryons: Gluonic polarizabilities
 (Nussinov 92 ; Chivukula et al 92)

Direct detection

- Charge radius

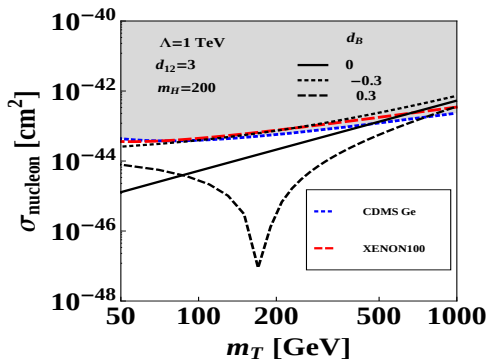
$$\mathcal{L}_B = ie \frac{d_B}{\Lambda^2} T^* \overleftrightarrow{\partial}_\mu T \partial_\nu F^{\mu\nu} .$$

(Bagnasco, Dine and Thomas 93)



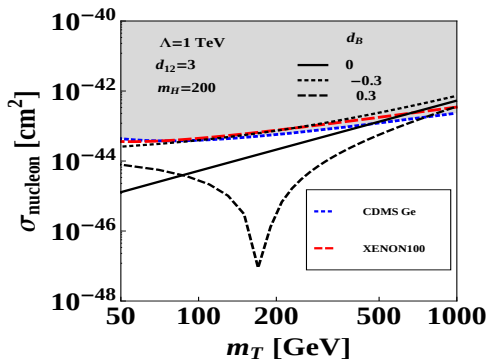
- Composite Higgs $\mathcal{L}_H^{Yuk} = d_H v_{ev} T^* T H$ or $\mathcal{L}_H^{GB} = \frac{d_{13}}{\Lambda} H \partial_\mu T^* \partial_\mu T$. (M.T.F and Sannino 09)
- For colored baryons: Gluonic polarizabilities (Nussinov 92 ; Chivukula et al 92)
- For spin-1/2 baryons: Dipole moments (Nussinov 92 ; Bagnasco, Dine and Thomas 93)

Direct Detection Limits on TIMPs



(Foadi, M.T.F and Sannino 09; Belyaev, M.T.F, Sannino and Sarkar; Exclusion limits courtesy of C. McCabe 10)

Direct Detection Limits on TIMPs

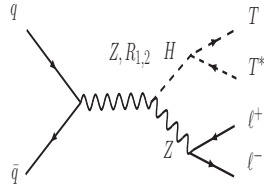


(Foadi, M.T.F and Sannino 09; Belyaev, M.T.F, Sannino and Sarkar; Exclusion limits courtesy of C. McCabe 10)

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

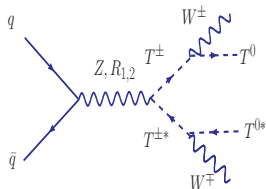
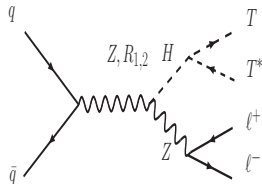
LHC signatures of (i)TIMPs

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



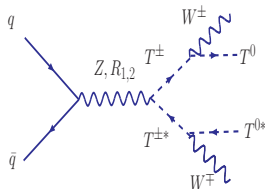
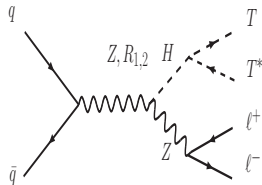
LHC signatures of (i)TIMPs

- (i)TIMP Invisible Higgs
 (Foadi, M.T.F and Sannino 08 ;
 Godbole, Guchait, Mazumdar,
 Moretti and Roy 03).
- **i**TIMP 'Antlers'
 (M.T.F and Sannino 09 ; Han, Kim
 and Song 09)



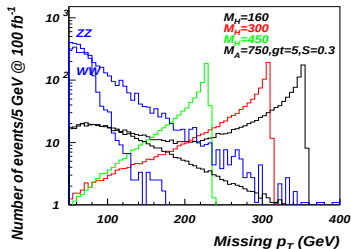
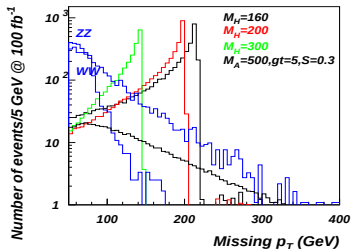
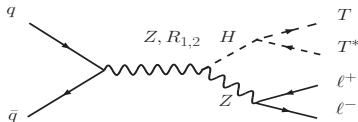
LHC signatures of (i)TIMPs

- (i)TIMP Invisible Higgs
 (Foadi, M.T.F and Sannino 08 ;
 Godbole, Guchait, Mazumdar,
 Moretti and Roy 03).
- iTIMP 'Antlers'
 (M.T.F and Sannino 09 ; Han, Kim
 and Song 09)



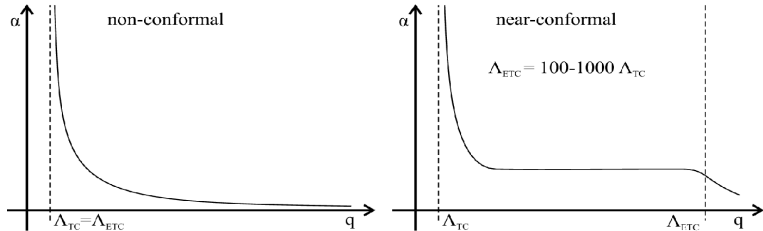
- Note: The same signatures from a new stable heavy lepton!
 (M.T.F, Masina and Sannino 09 ; Antipin, Heikinheimo, Tuominen 09)

(i)TIMP missing energy signals



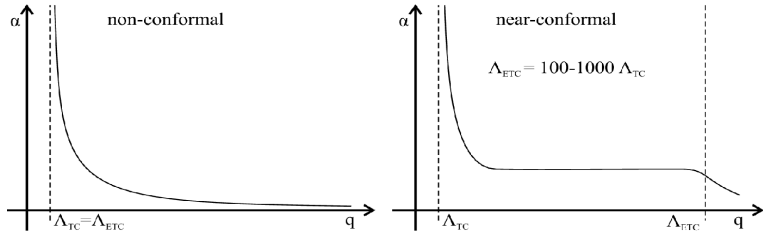
(Foadi, M.T.F and Sannino 08; Godbole, Guchait, Mazumdar, Moretti and Roy 03).

Walking Technicolor



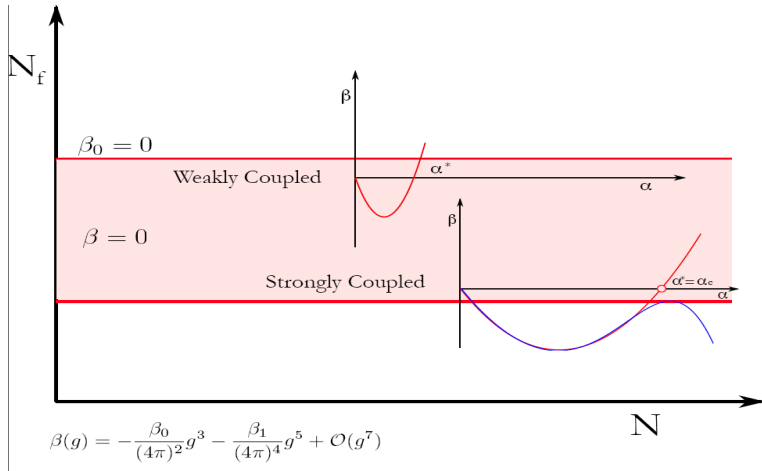
- 1 TC sector: Walking reduces the full S-parameter
(Sundrum and Hsu 92; Appelquist and Sannino 98; Harada, Kurachi and Yamawaki 03; Kurachi and Shrock 06)

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)
- 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:

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

ETC fermion masses and Walking

- 1 Four fermion operators:

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

- 2 Fermion masses:

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

ETC fermion masses and Walking

- 1 Four fermion operators:

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

- 2 Fermion masses:

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

- 3 Condensate enhancement from Walking:

$$\langle \bar{Q}Q \rangle_{ETC} \sim \left(\frac{\Lambda_{ETC}}{\Lambda_{TC}} \right)^{\gamma(\alpha^*)} \langle \bar{Q}Q \rangle_{TC}$$

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

ETC fermion masses and Walking

- 1 Four fermion operators:

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

- 2 Fermion masses:

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

- 3 Condensate enhancement from Walking:

$$\langle \bar{Q}Q \rangle_{ETC} \sim \left(\frac{\Lambda_{ETC}}{\Lambda_{TC}} \right)^{\gamma(\alpha^*)} \langle \bar{Q}Q \rangle_{TC}$$

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

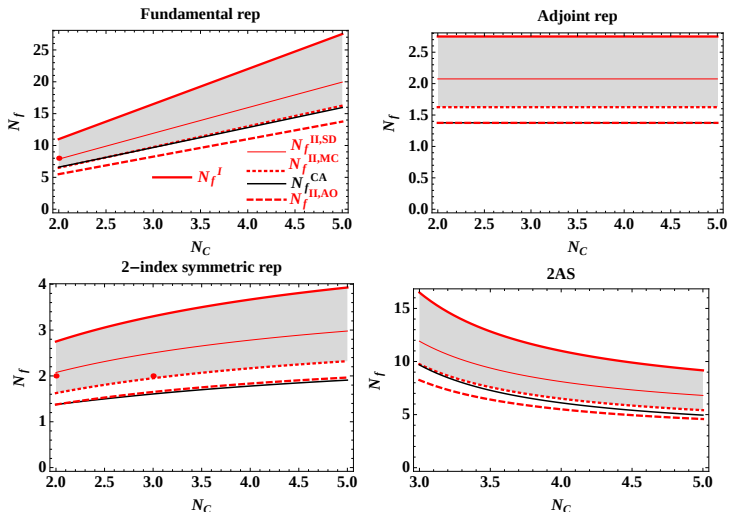
- 4 (Too) Naively $\Lambda_{ETC} > 10^3 \text{ TeV}$ to suppress FCNC's:

(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: $\alpha_c = \frac{\pi}{3C_2(R)}$, $\frac{\alpha^*}{4\pi} = -\frac{\beta_0}{\beta_1}$.
(Appelquist, Lane and Muhanta 88; Cohen and Georgi 89; Sannino and Tuominen 04; Dietrich and Sannino 06; Rytto and Sannino 07)
- 2 All-orders beta function conjecture(s)
(Rytto 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 Confinement 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

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

Some Minimal Models of Walking Technicolor

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

MWT model: (Sannino and Tuominen 04)

$G_{TC} = SU(2)$. $\mathcal{R} = Adj$. Leptons.

(Dietrich, Sannino and Tuominen 05)

Some Minimal Models of Walking Technicolor

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

MWT model: (Sannino and Tuominen 04)

$G_{TC} = SU(2)$. $\mathcal{R} = Adj$. Leptons.
(Dietrich, Sannino and Tuominen 05)

OMT model

- $G_{TC} = SO(4)$

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

NMWT model

- $G_{TC} = SU(3)$

(Sannino and
Tuominen 04)

UMT model

- $G_{TC} = SU(2)$

(Ryttov and Sannino
08)

Some Minimal Models of Walking Technicolor

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

MWT model: (Sannino and Tuominen 04)

$G_{TC} = SU(2)$. $\mathcal{R} = Adj$. Leptons.
(Dietrich, Sannino and Tuominen 05)

OMT model

- $G_{TC} = SO(4)$
- $\mathcal{R} = F$

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

NMWT model

- $G_{TC} = SU(3)$
- $\mathcal{R} = 2S$

(Sannino and
Tuominen 04)

UMT model

- $G_{TC} = SU(2)$
- $\mathcal{R} = F, Adj$

(Ryttov and Sannino
08)

Some Minimal Models of Walking Technicolor

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

MWT model: (Sannino and Tuominen 04)

$G_{TC} = SU(2)$. $\mathcal{R} = Adj$. Leptons.
(Dietrich, Sannino and Tuominen 05)

OMT model

- $G_{TC} = SO(4)$
- $\mathcal{R} = F$
- iTIMP

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

NMWT model

- $G_{TC} = SU(3)$
- $\mathcal{R} = 2S$

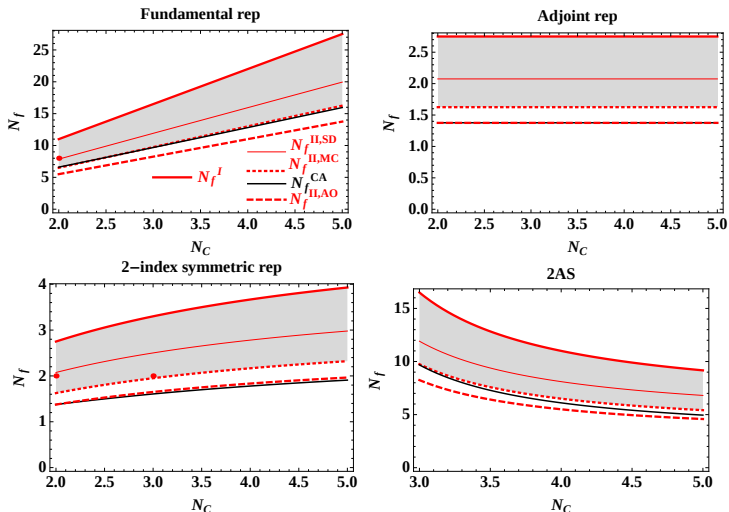
(Sannino and
Tuominen 04)

UMT model

- $G_{TC} = SU(2)$
- $\mathcal{R} = F, Adj$
- TIMP

(Ryttov and Sannino
08)

Conformal window lower bounds: MC and AO

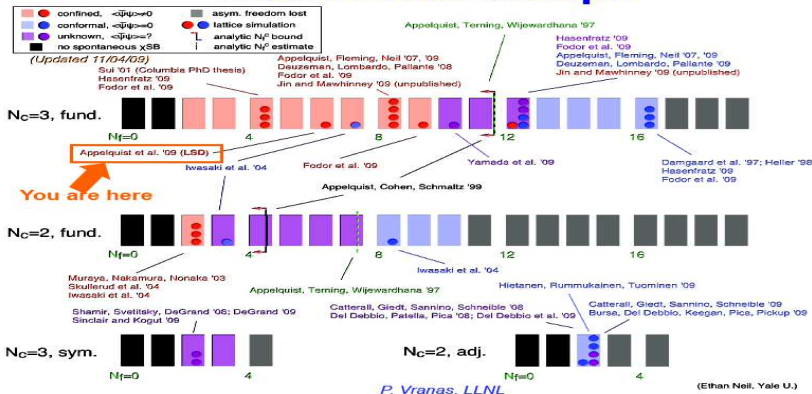


(M.T.F, T. Pickup and M. Teper 10).

Lattice simulations

Not Quite the

Current landscape



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

EFT for strong dynamics @ LHC

common sector:

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

- 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, Rytto and Sannino

EFT for strong dynamics @ LHC

common sector:

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

- 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:

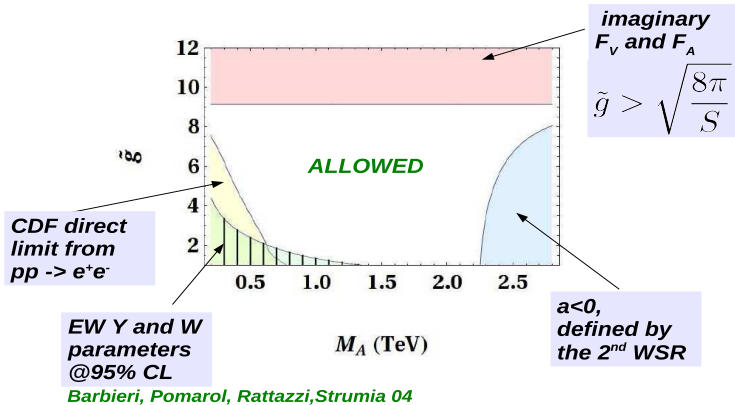
$$M_A, \tilde{g}, M_H.$$

(Appelquist, Da Silva and Sannino 99; Foadi, M.T.F, Rytov 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 WSR_1

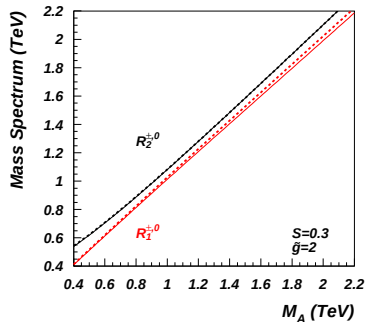
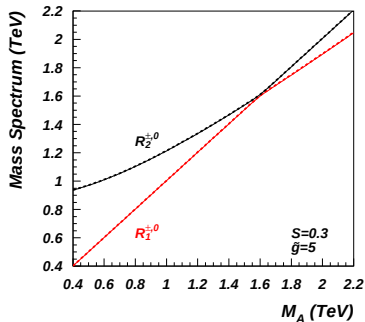
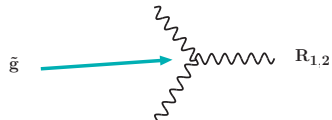
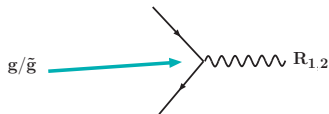


Figure: $R_{1,2}$ spectrum.

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

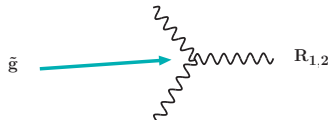
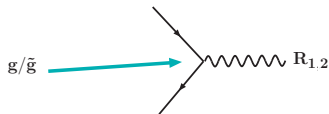
LHC Phenomenology

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



LHC Phenomenology

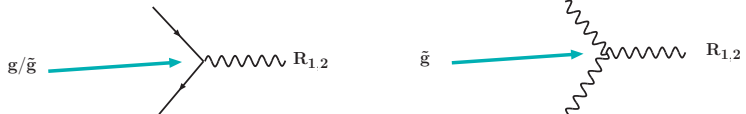
- Basic phenomenology controlled by $\tilde{g}$, M_A , M_H .



- Different decay channels probe R_1 , R_2 and H .

LHC Phenomenology

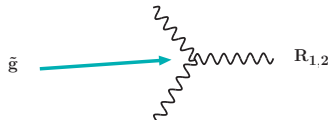
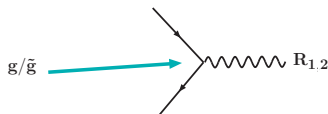
- Basic phenomenology controlled by $\tilde{g}$, M_A , M_H .



- Different decay channels probe R_1, R_2 and H .
 - Di-lepton: $R_{1,2}^0 \rightarrow \ell^+ \ell^-$. Single top: $R_{1,2}^\pm \rightarrow tb$

LHC Phenomenology

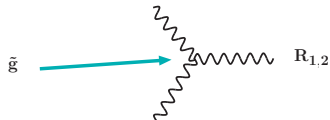
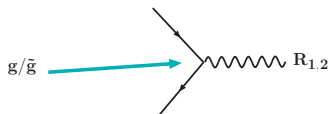
- Basic phenomenology controlled by $\tilde{g}$, M_A , M_H .



- Different decay channels probe R_1 , R_2 and H .
 - Di-lepton: $R_{1,2}^0 \rightarrow \ell^+ \ell^-$. Single top: $R_{1,2}^\pm \rightarrow tb$
 - Di-boson: $R_2 \rightarrow ZW/WW$.

LHC Phenomenology

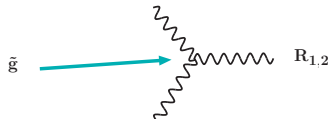
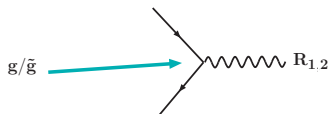
- Basic phenomenology controlled by $\tilde{g}$, M_A , M_H .



- Different decay channels probe R_1 , R_2 and H .
 - Di-lepton: $R_{1,2}^0 \rightarrow \ell^+ \ell^-$. Single top: $R_{1,2}^\pm \rightarrow tb$
 - Di-boson: $R_2 \rightarrow ZW/WW$.
 - Higgs-Strahlung: $R_1 \rightarrow HZ/HW$.

LHC Phenomenology

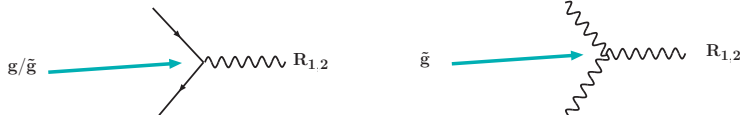
- Basic phenomenology controlled by $\tilde{g}$, M_A , M_H .



- Different decay channels probe R_1 , R_2 and H .
 - Di-lepton: $R_{1,2}^0 \rightarrow \ell^+ \ell^-$. Single top: $R_{1,2}^\pm \rightarrow tb$
 - Di-boson: $R_2 \rightarrow ZW/WW$.
 - Higgs-Strahlung: $R_1 \rightarrow HZ/HW$.
 - Higgs-Decays: $H \rightarrow ZZ/WW (b\bar{b}?)$.

LHC Phenomenology

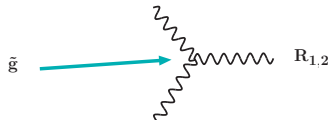
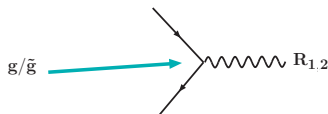
- Basic phenomenology controlled by $\tilde{g}$, M_A , M_H .



- Different decay channels probe R_1 , R_2 and H .
 - Di-lepton: $R_{1,2}^0 \rightarrow \ell^+ \ell^-$. Single top: $R_{1,2}^\pm \rightarrow tb$
 - Di-boson: $R_2 \rightarrow ZW/WW$.
 - Higgs-Strahlung: $R_1 \rightarrow HZ/HW$.
 - Higgs-Decays: $H \rightarrow ZZ/WW (b\bar{b}?)$.
 - boosted tops, W, Z and H**

LHC Phenomenology

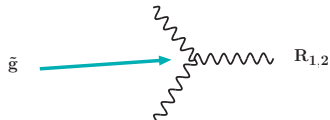
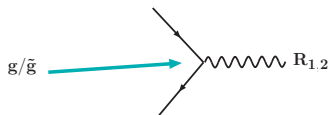
- Basic phenomenology controlled by $\tilde{g}$, M_A , M_H .



- Different decay channels probe R_1 , R_2 and H .
 - Di-lepton: $R_{1,2}^0 \rightarrow \ell^+ \ell^-$. Single top: $R_{1,2}^\pm \rightarrow tb$
 - Di-boson: $R_2 \rightarrow ZW/WW$.
 - Higgs-Strahlung: $R_1 \rightarrow HZ/HW$.
 - Higgs-Decays: $H \rightarrow ZZ/WW (b\bar{b}?)$.
 - boosted tops, W, Z and H**
- Lattice can (in principle) narrow down parameter space for each model

LHC Phenomenology

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



- Different decay channels probe R_1 , R_2 and H .
 - Di-lepton: $R_{1,2}^0 \rightarrow \ell^+ \ell^-$. Single top: $R_{1,2}^\pm \rightarrow tb$
 - Di-boson: $R_2 \rightarrow ZW/WW$.
 - Higgs-Strahlung: $R_1 \rightarrow HZ/HW$.
 - Higgs-Decays: $H \rightarrow ZZ/WW (b\bar{b}?)$.
 - boosted tops, W, Z and H**
- Lattice can (in principle) narrow down parameter space for each model
 - MWT/OMT**, **NMWT**, **UMT** etc...

Vector Production

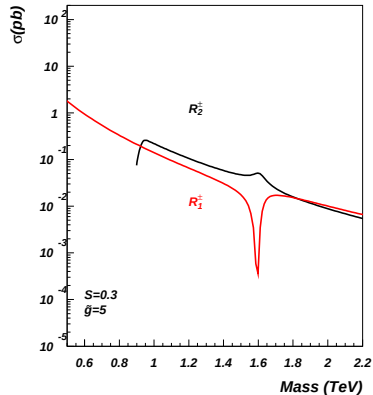
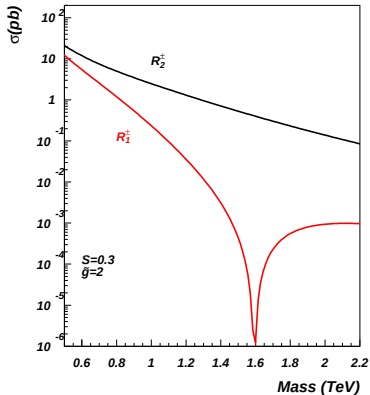


Figure: DY production of $R_{1,2}$.

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

Vector BRs

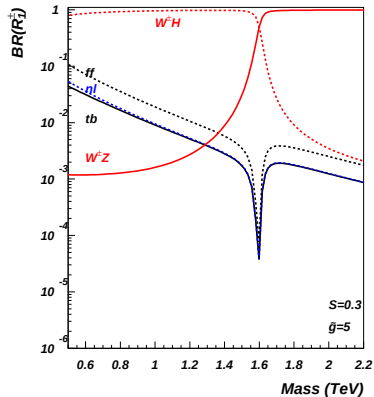
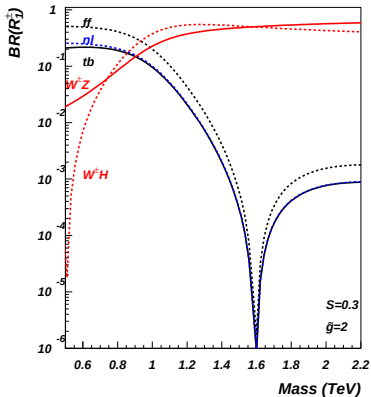


Figure: BR's of R_1 .

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

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

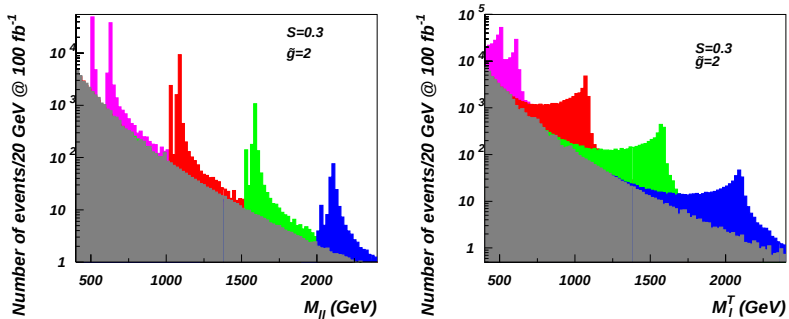


Figure: Left: Dilepton invariant mass distributions $M_{\ell\ell}$ for
 $pp \rightarrow R_{1,2}^0 \rightarrow \ell^+\ell^-$

Right: Single lepton transverse mass distributions M_{ℓ}^T for $pp \rightarrow R_{1,2}^{\pm} \rightarrow \ell^{\pm}$

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

Results for tb

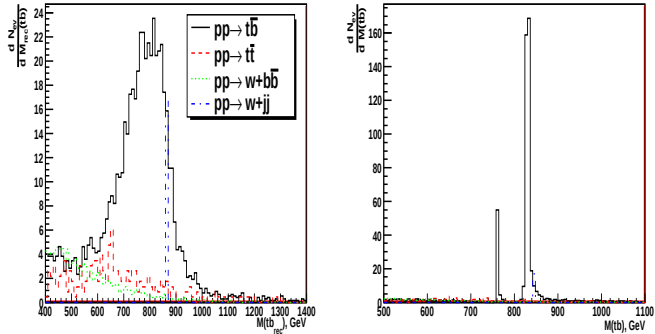
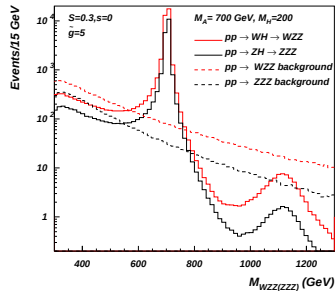
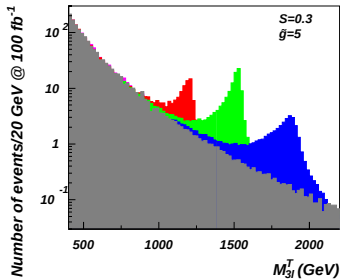
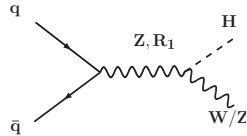
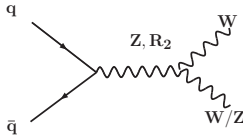


Figure: Reconstructed (left plot) and partonic (right plot) invariant mass of top and b-quarks after final cuts. Distributions normalized to 30 fb^{-1} .

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

Di-boson vs Higgs-strahlung



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

Symmetric vs Asymmetric TIMPs

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

Can pNGB TIMPs have
a symmetric relic density?

$$\phi \sim \lambda \lambda, \quad T^0 \sim U_L D_L$$

Φ complex composite scalar with
uncharged components $\sim$

λ s motivated by achieving
Minimality & Walking

(Dynamical realization of scalar
singlet DM models)

Specific model example:
'Ultra Minimal TC'

UMT model

- $G_{TC} = SU(2)$
- $\mathcal{R} = F, Adj$

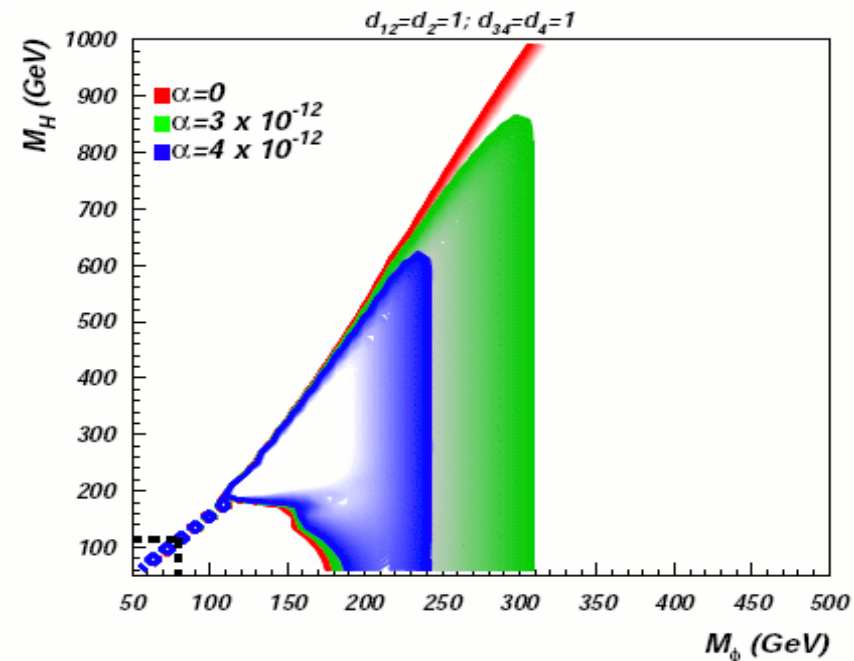
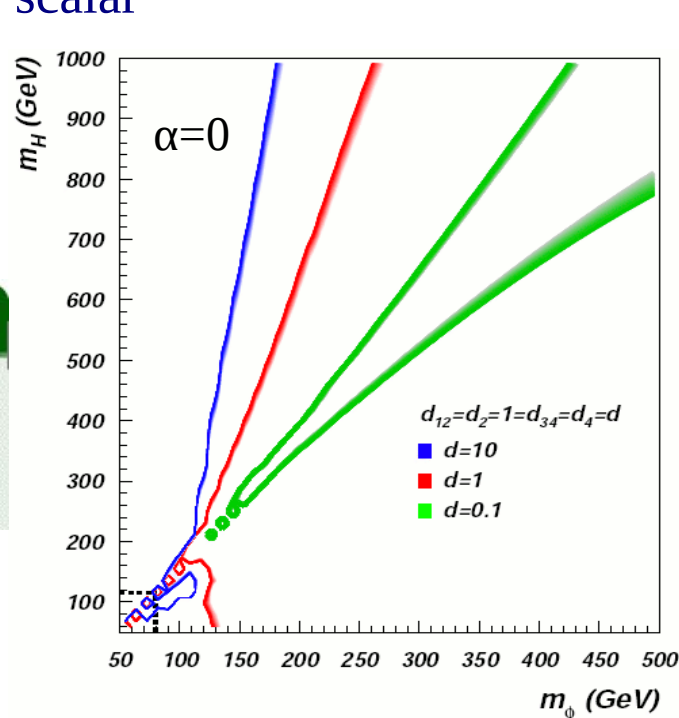
(Ryttov & Sannino 09)

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

Yield and relic density in the presence of asymmetry:

$$\frac{dY_-}{dx} = \lambda x^{-2} [Y_-^{\text{eq}}(Y_-^{\text{eq}} + 2\alpha) - Y_-(Y_- + 2\alpha)] \quad \Omega_\phi h^2 = 5.5 \times 10^8 (Y_{-\infty} + \alpha) \frac{m_\phi}{\text{GeV}}$$

(Griest & Seckel 85)



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

Symmetric vs Asymmetric TIMPs

TIMPs with charged constituents

$$T^0 \sim U_L D_L$$

Symmetric relic density of T^0

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

Higgs interactions of T^0 identical to those of ϕ

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

T may also have charge radius interaction :

$$\mathcal{L}_B = ie \frac{d_B}{\Lambda^2} T^* \overleftrightarrow{\partial}_\mu T \partial_\nu F^{\mu\nu}$$

In addition T^0 has contact interactions with SM gauge bosons, due to EW charges of U, D :

$$L_{WW,ZZ} = -\frac{T^* T}{2} \text{Tr} [d_W W_\mu W^\mu + d_Z Z_\mu Z^\mu] , \quad (12)$$

with $d_W = g^2$ and $d_Z = (g^2 + g'^2)/2$ for the TIMPs T of both the UMT and the OMT models.

(Preskill 81; Chadha and Peskin 81)

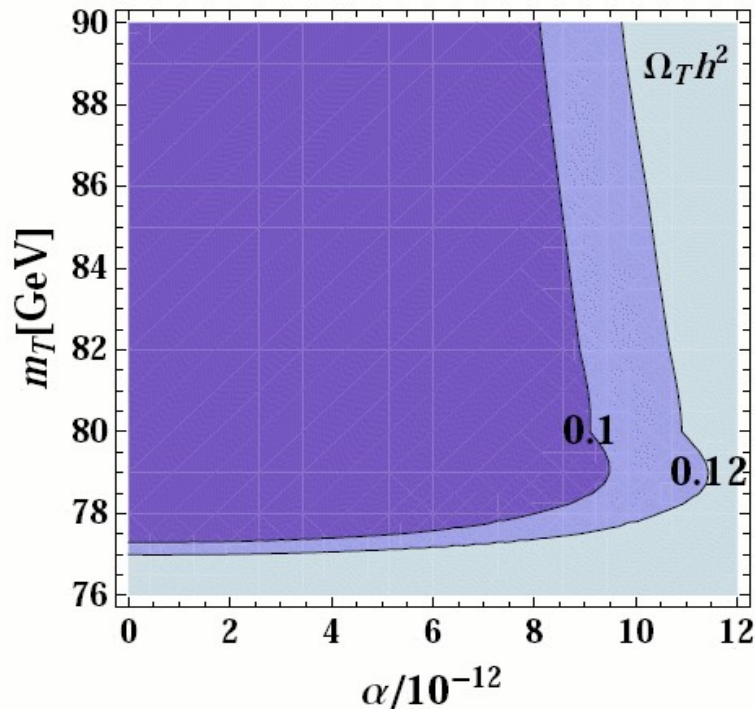
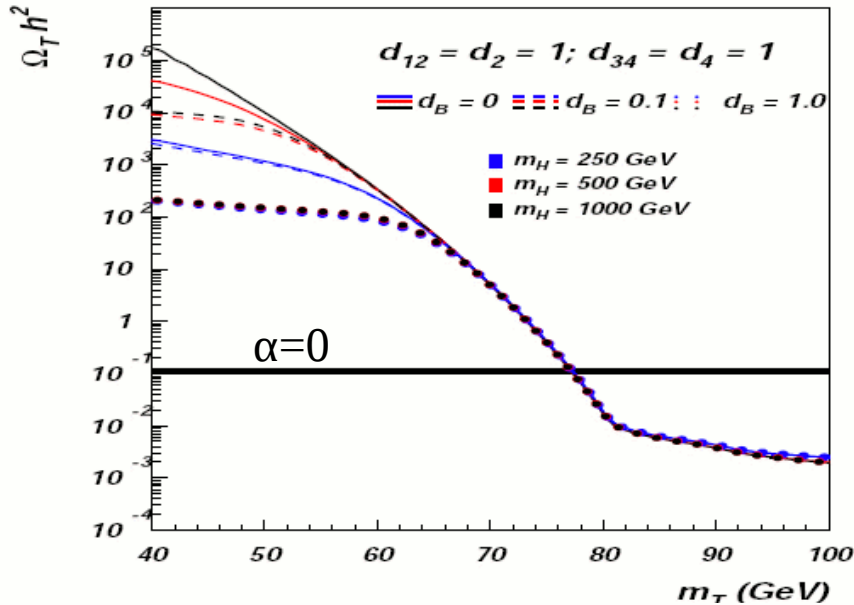
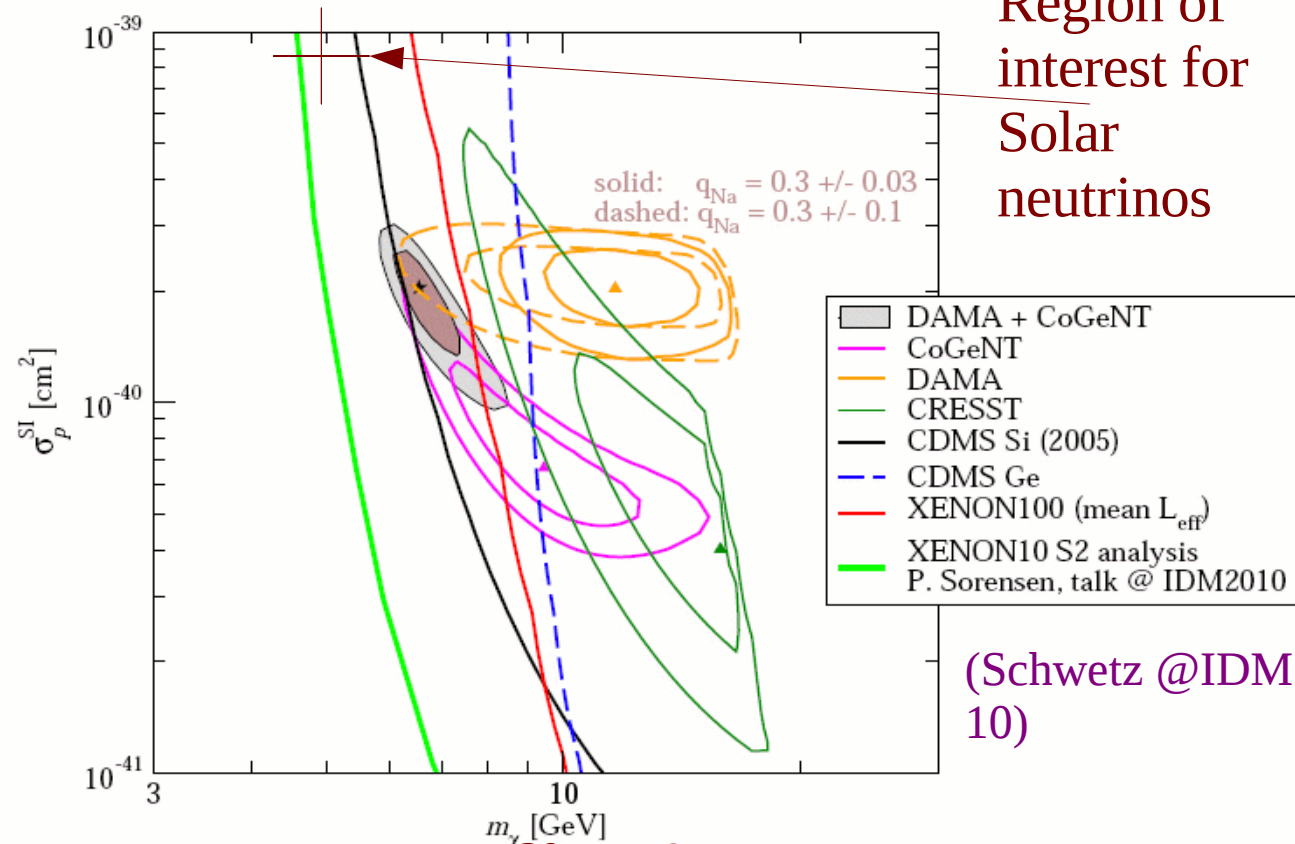
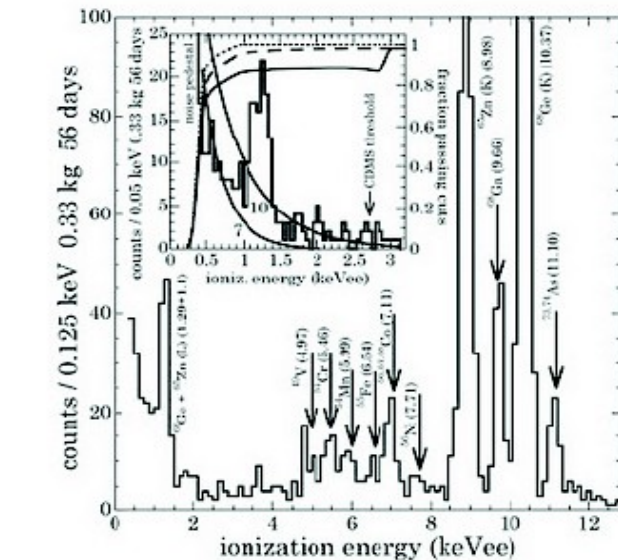


Diagram illustrating the SM-dark sector system. The SM (Standard Model) and dark sector are connected via a horizontal line with a cross in the middle, labeled H and H' above it. A curved line with a cross in the middle connects the SM and dark sector at the bottom, labeled $B_{\mu\nu}$ and $B'_{\mu\nu}$ below it. A neutrino N^c is shown at the top, connected to the SM by a line labeled ν and to the dark sector by a line labeled ν' .

Recently several experiments have reported events close to threshold



Region of interest for Solar neutrinos

(Schwetz @IDM
10)

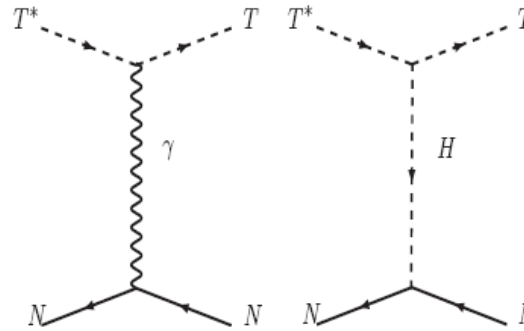
Spin-dependent cross-sections up to 10^{-36} cm²

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 $\sim 10^{-41}$ cm²

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

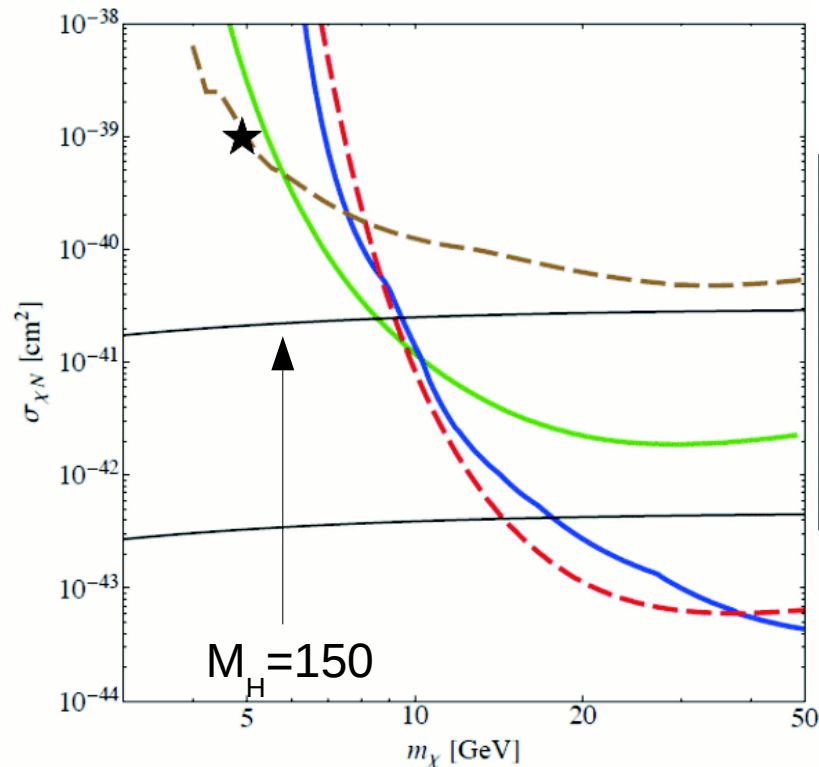


Charge radius can provide $\sim 10^{-39}$ cm² SI cross-sections

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

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

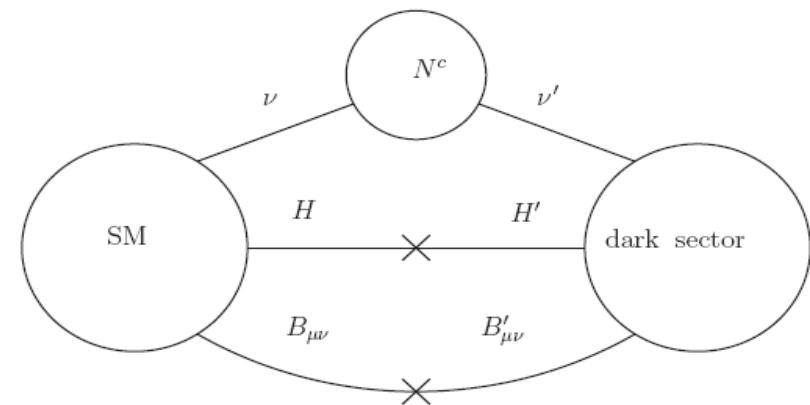
(Sigurdson et al 2006, Gardner 08, Heo 09, Masso et al 09, An et al 10, Banks et al 10, Barger et al 10...)



(Fit Courtesy of McCabe, McCabe 10)

Interesting LHC signatures like for TIMPs incl 'monojets'

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



Astrophysical aspects of light ADM

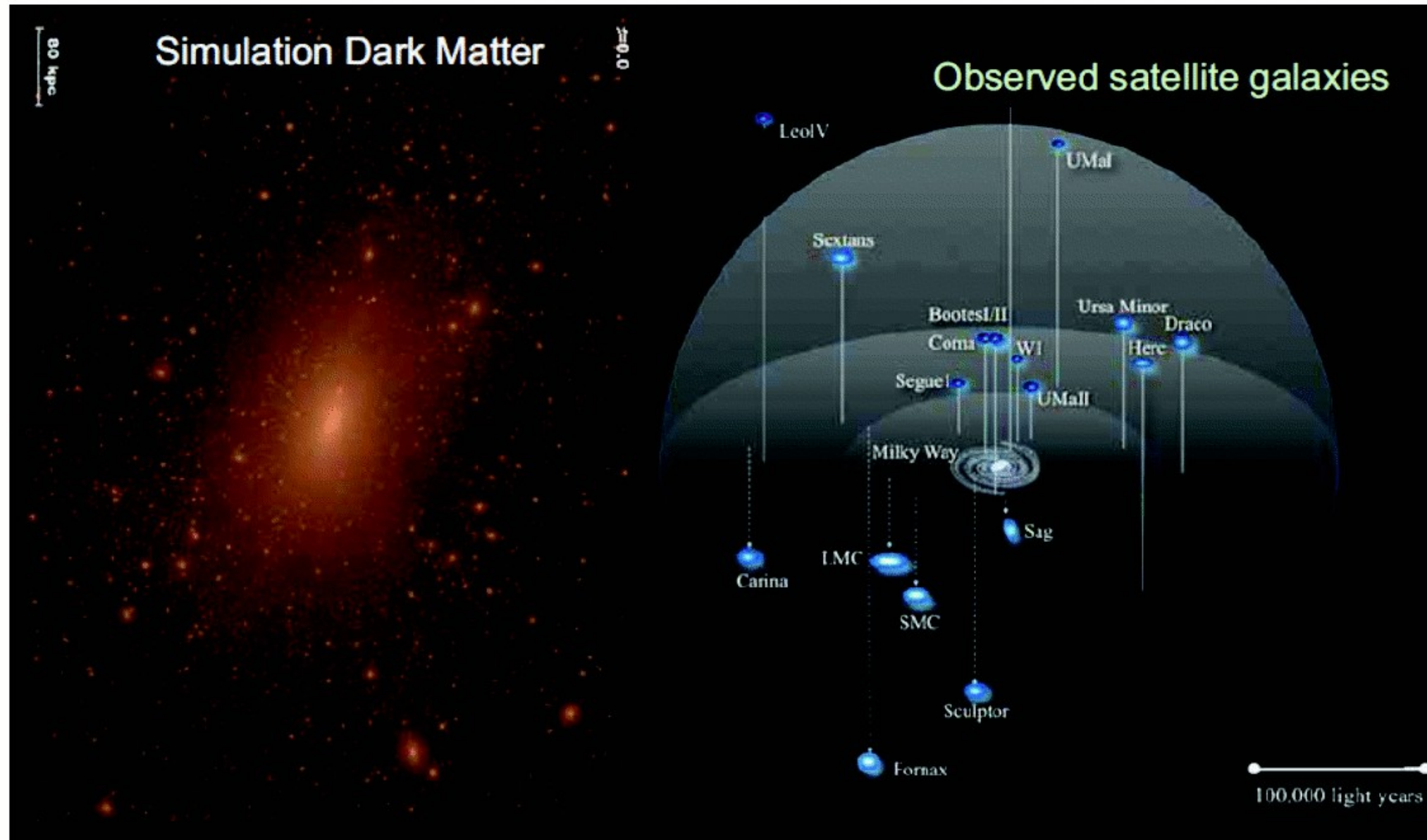
Such particles would also be naturally **self-interacting** with a typical cross-section: $\sigma_{\chi\chi} \sim \sigma_{nn} (m_n/m_\chi)^2$, where $\sigma_{nn} \sim 10^{-23} \text{ cm}^2$



... well below the bound of $2 \times 10^{-24} \text{ cm}^2/\text{GeV}$ from the 'Bullet cluster'
Long range self-interactions are more tightly constrained by the 'Bullet cluster'

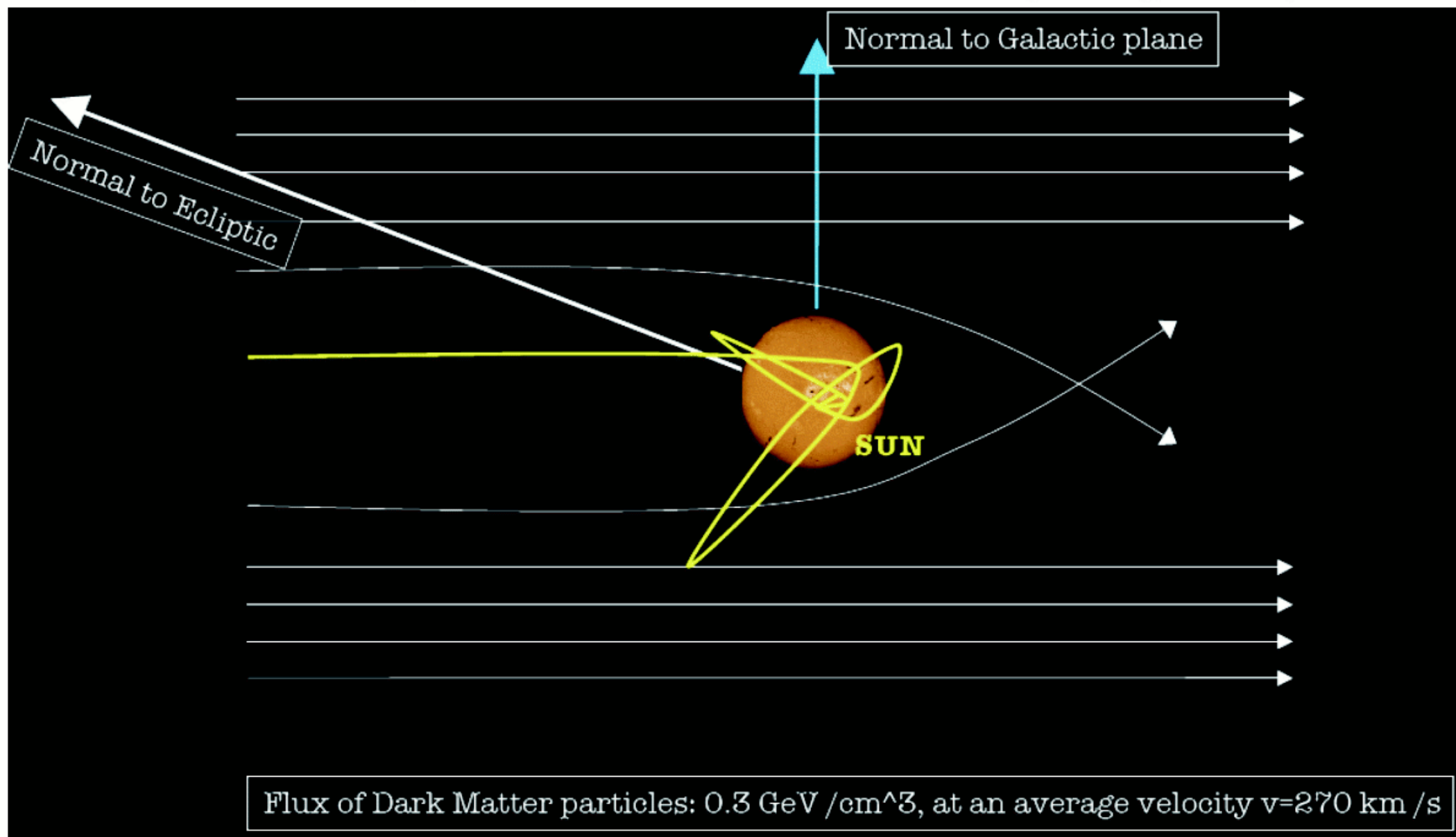
(Feng, Kaplinghat and Yu 10)

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 $\sim 10^5$ are expected

The Sun has been accreting dark matter particles for $\sim 4.6 \times 10^9$ yr as it orbits around the Galaxy ... these will orbit *inside* affecting energy transport



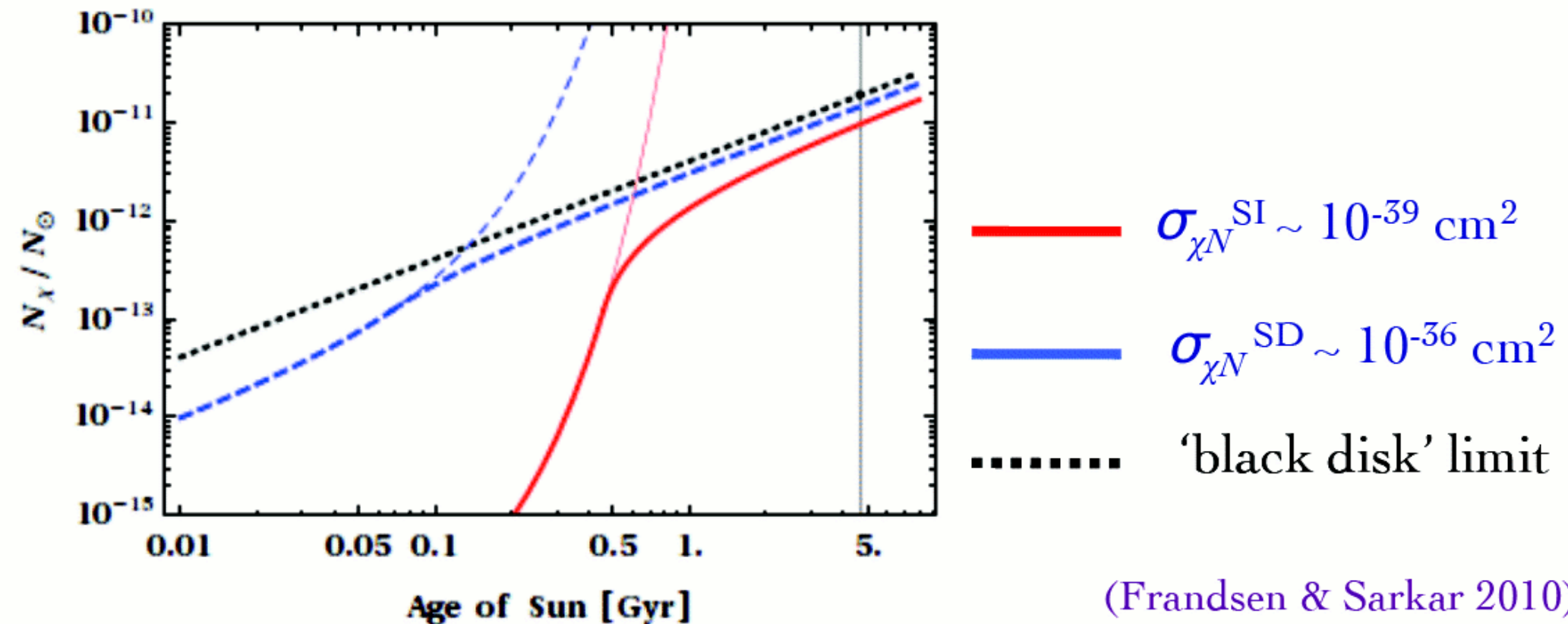
The flux of Solar neutrinos is *very* sensitive to the core temperature and can thus be *reduced* (Steigman *et al* 1978, Faulkner *et al* 1985, Press & Spergel 1985, Gould 1987)

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)

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

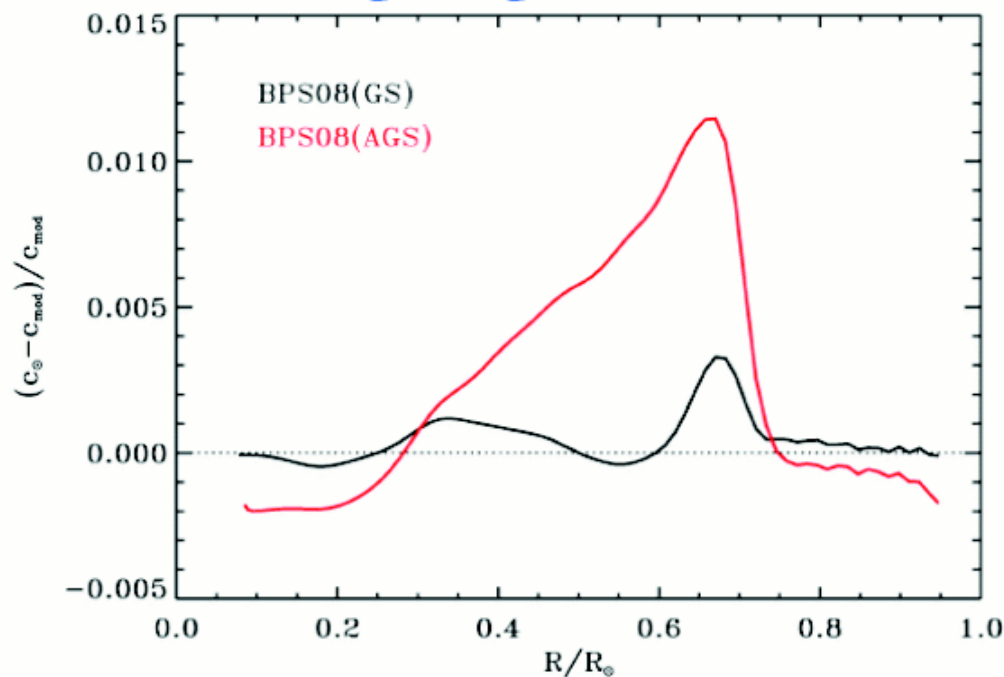
Self-capture rate:
$$C_{\chi\chi} = \sqrt{\frac{3}{2}} \rho_{\text{local}} s_\chi \frac{v_{\text{esc}}^2(R_\odot)}{\bar{v}} \langle \phi \rangle \frac{\text{erf}(\eta)}{\eta}$$



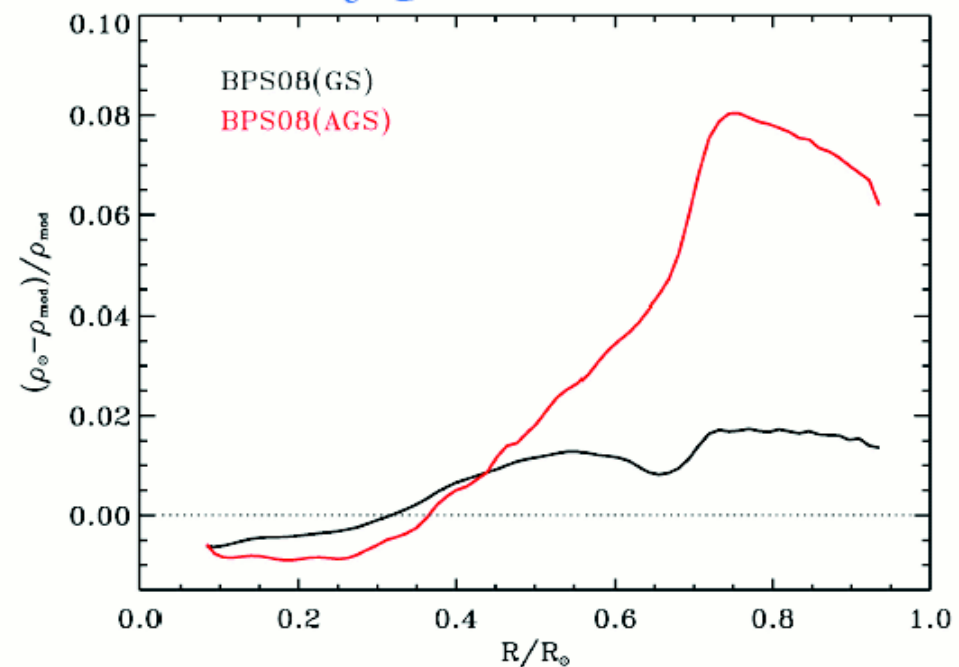
A problem with the standard Solar model

- 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

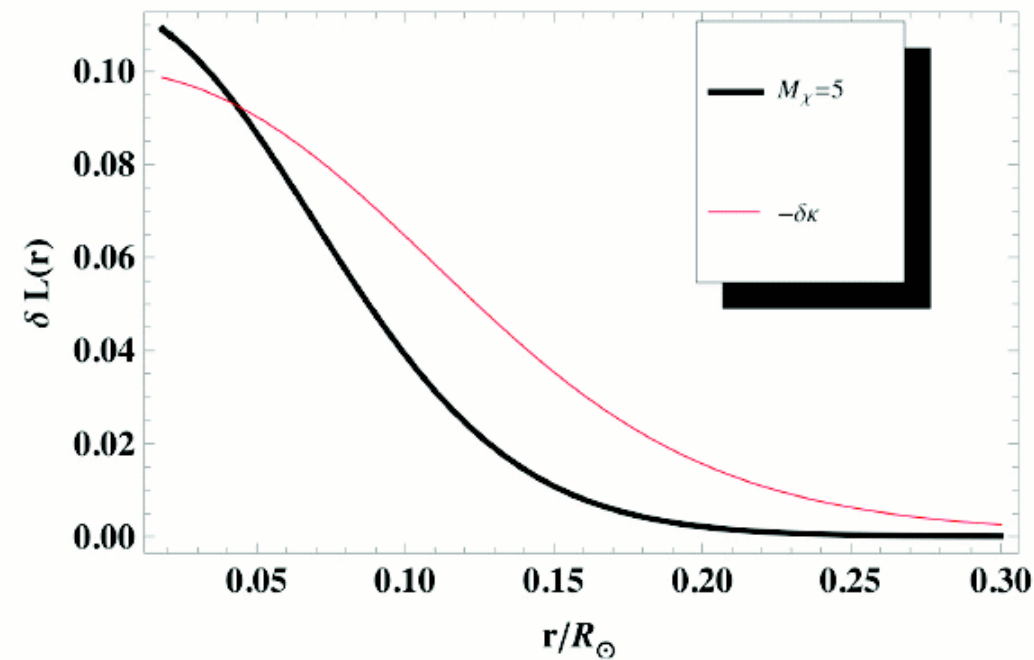


Could light dark matter particles accreted by the Sun solve this problem?
(Villante, talk@TAUP'09, Frandsen & Sarkar 2010)

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 $\sim 10\%$ reduction of the opacity in the core lowers the convective boundary by $\sim 0.7\%$ so will (largely) *restore* agreement with helioseismology

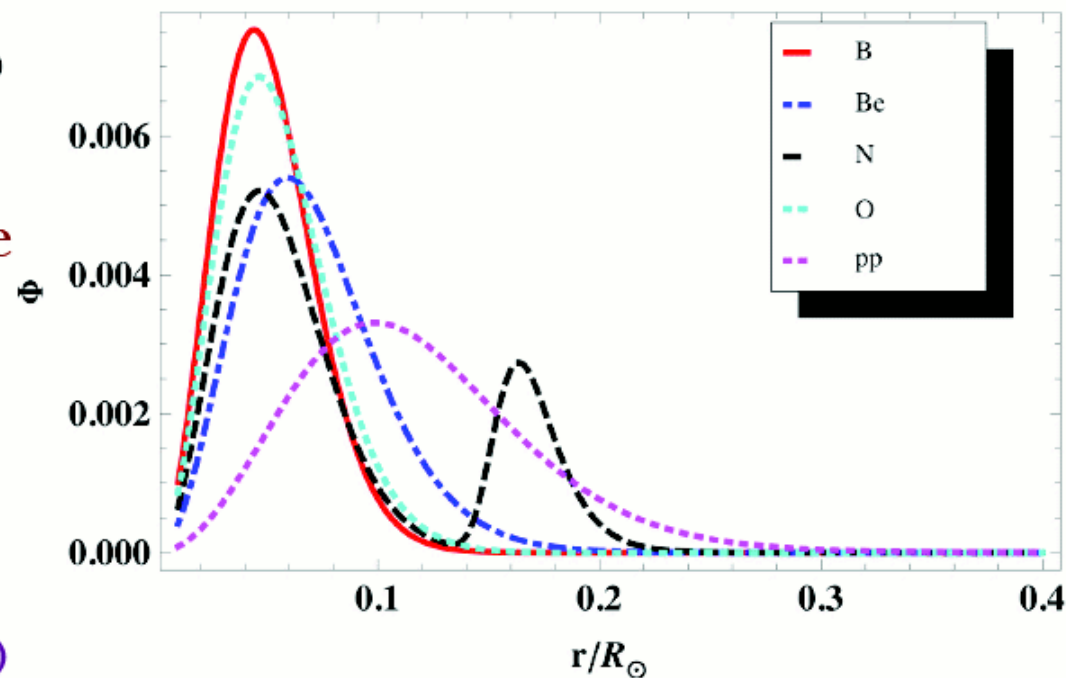
Modification of the luminosity profile will also reduce neutrino fluxes:

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

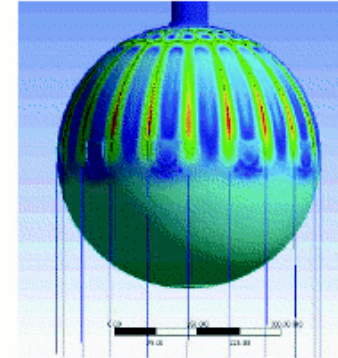
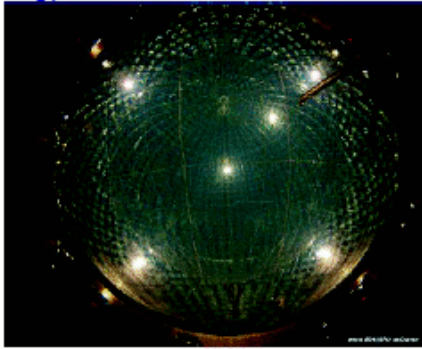
$$\delta \Phi_N = -10\%, \quad \delta \Phi_O = -14\%$$

... testable by Borexino & SNO⁺

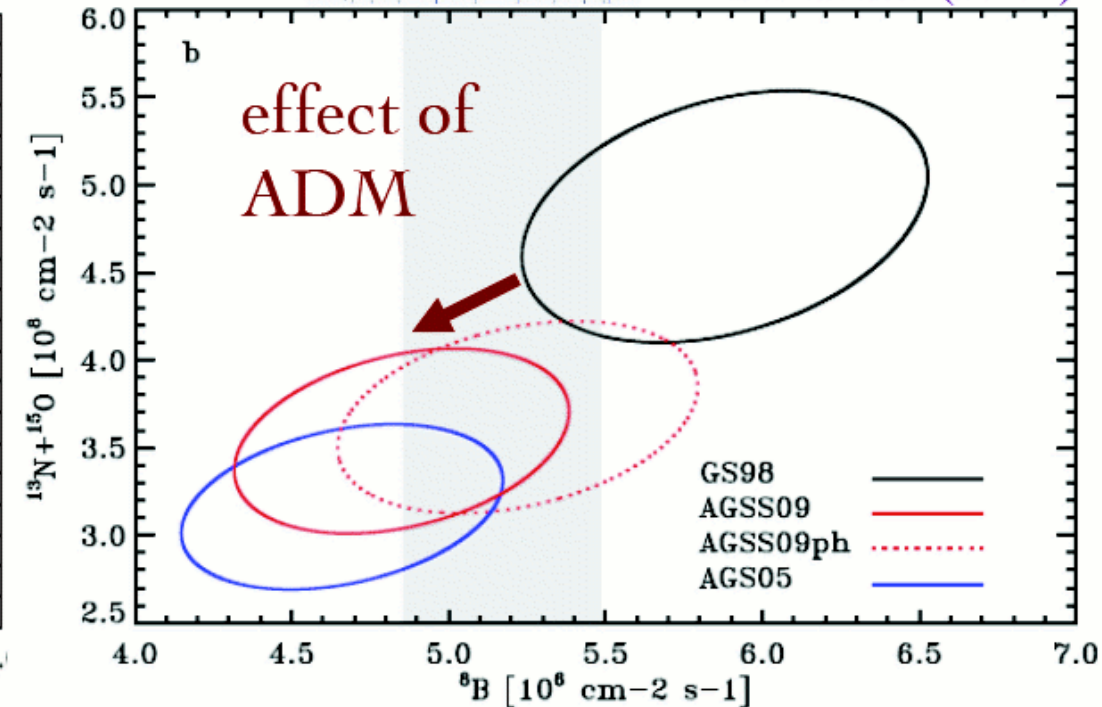
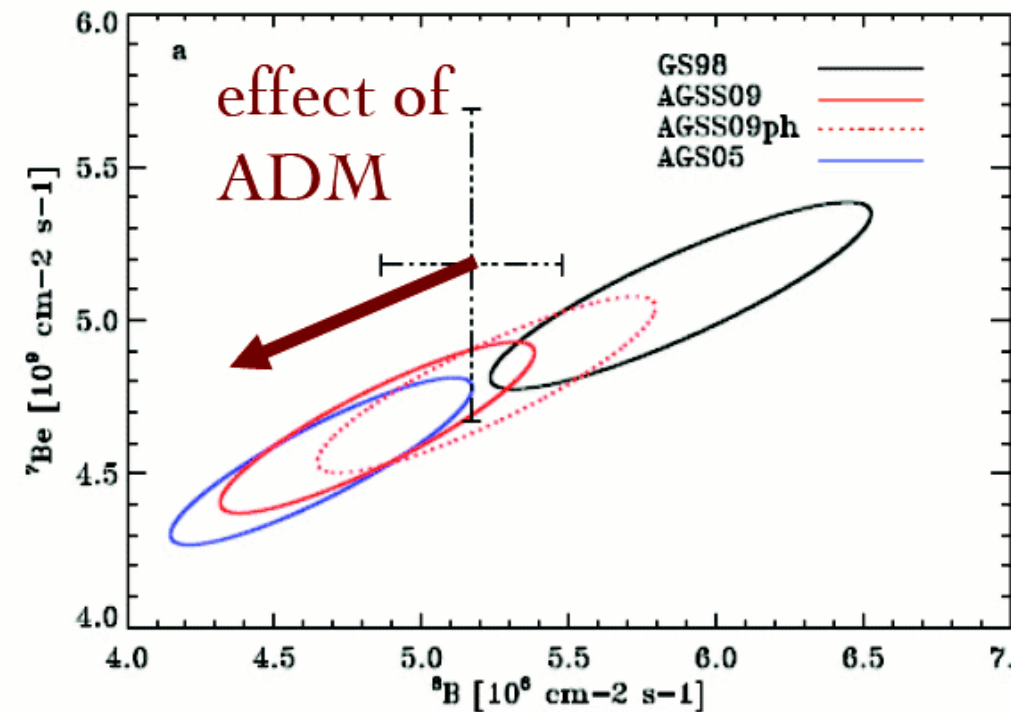
(Frandsen & Sarkar 2010)



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

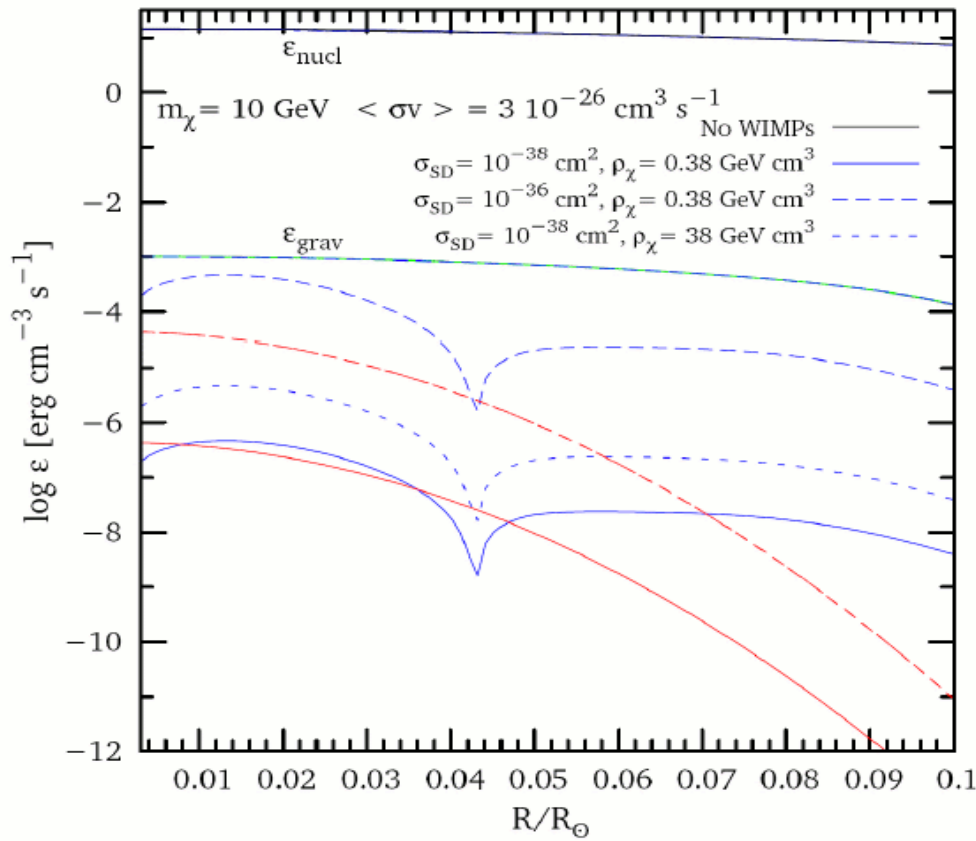


Serenelli (2010)



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

Measurement of ${}^{13}\text{N}$ and ${}^{15}\text{O}$ fluxes by SNO+ will provide additional constraint ..
but it may be hard to distinguish between effects of metallicity and dark matter

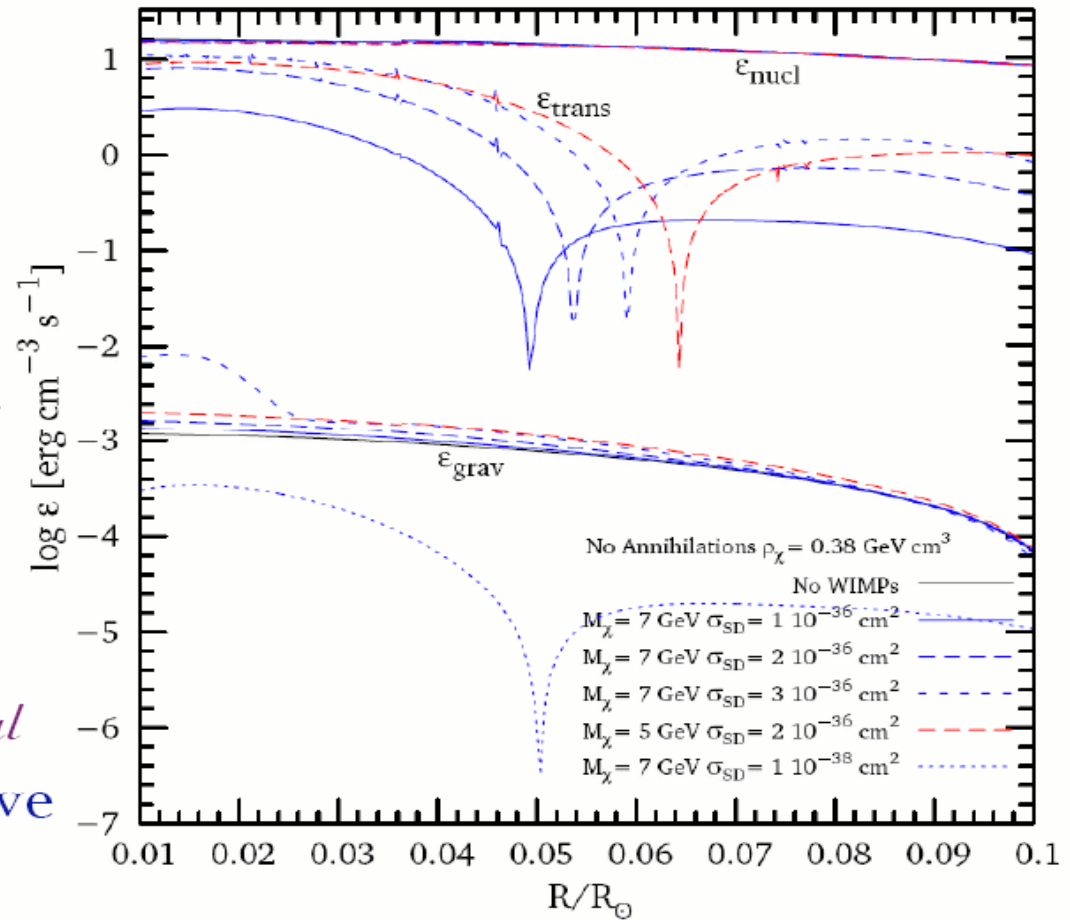


... but can be significant for *asymmetric* dark matter!

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.

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



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

Symmetric vs. asymmetric relics

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

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

(Griest & Seckel 85)

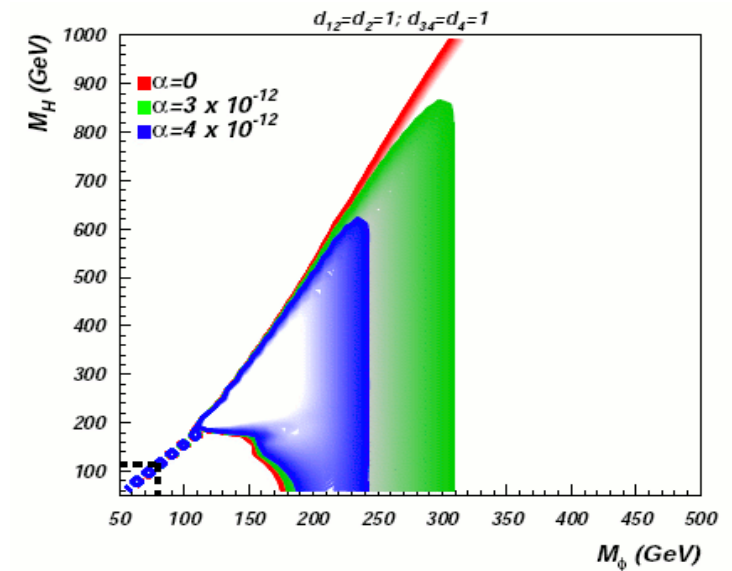
Freeze out vs. freeze-in

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

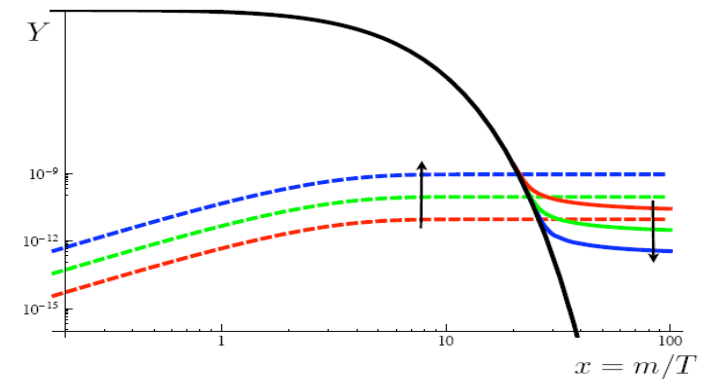
$$\dot{n}_{\tilde{\nu}_R} + 3Hn_{\tilde{\nu}_R} = C_{\text{decay}}$$

(Asaka, Ishiwata & Moroi 05)

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



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



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