New Strong Dynamics for EWSB and DM

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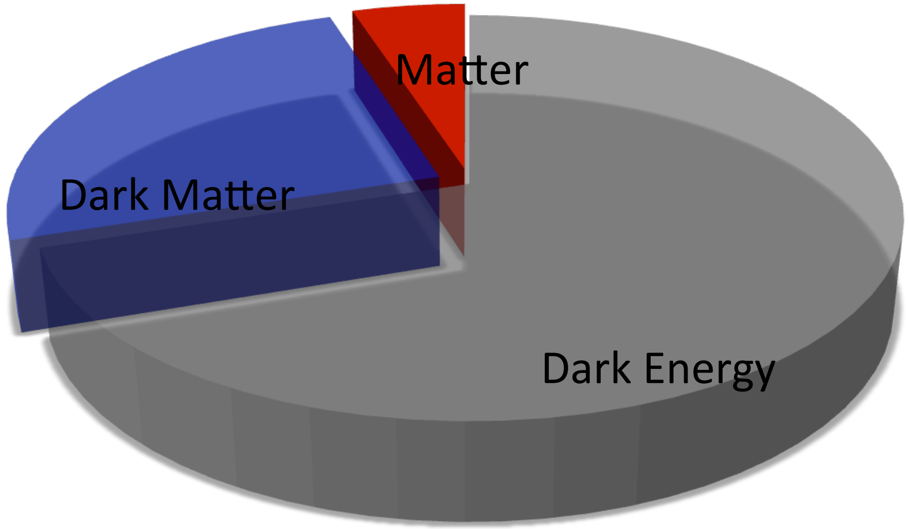
Outline

- Introduction to Technicolor
  - Minimal Walking Technicolor models
  - Constraints on Technicolor
- Technicolor phenomenology and collider signatures

- Introduction to Asymmetric Dark Matter
- ADM from Technicolor or New Strong Dynamics
- DM vs ADM signatures – direct (incl. recent 'hints')/ indirect/collider detection

What should the world made of?

$\Omega_{\rm DM}/\Omega_B \sim 5$



$\Omega_B \sim 0.05$

Baryons, but no antibaryons

Baryonic matter is asymmetric - mass and stability arises from strong dynamics

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
Λ_{QCD} Dynamical	**Baryons** No antibaryons	U(1) Baryon number	$\tau > 10^{33}$ yr (dim-6 OK)	'freeze-out' from thermal equilibrium Asymmetry	$\Omega_B \sim 10^{-10}$ *cf.* observed $\Omega_B \sim 0.05$

The mass density of dark matter is of the same order as baryonic matter!

Is the origin of mass dynamical?

Is DM asymmetric?

$$\Omega_\chi/\Omega_B = m_\chi/m_B \times \mathcal{N}_\chi/\mathcal{N}_B$$

$$\mathcal{N}_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

Is the origin of DM due to NSD?

technicolor

Higgs everywhere short for Brout-Englert-Higgs

Technicolor

EWSB from Technicolor: (Weinberg 78, Susskind 78)

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

   (Farhi & Susskind 81)

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

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

Left-handed technifermions in weak doublets, right-handed in weak singlets

$$Q^a_L = \begin{pmatrix} U^a \\ D^a \end{pmatrix}_L , \; Q^a_R = (U^a_R, D^a_R),$$
$$a = 1, \ldots d(\mathcal{R}_{TC})$$

At the weak scale, the technifermions condense and break the weak symmetries correctly to EM:

$$\langle \bar{U}_L U_R + \bar{D}_L D_R \rangle \neq 0$$

Technicolor

EWSB from Technicolor: (Weinberg 78, Susskind 78)

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Example: Scaled-up QCD !

New Strong Sector

1. The SM gauge group is augmented:

$$G_{SM} \rightarrow SU(3)_{\mathrm{c}} \times SU(2)_{\mathrm{W}} \times U(1)_{\mathrm{Y}} \times G_{\mathrm{SD}} \ .$$

(SD=Strong Dynamics/Technicolor)

2. The Higgs sector of the SM is replaced:

$$\mathcal{L}_{Higgs} \rightarrow -\frac{1}{4} F^{a}_{\mu\nu} F^{a\mu\nu} + i\bar{Q}_{\mathrm{L}} \gamma_{\mu} D^{\mu} Q_{\mathrm{L}} + i\bar{Q}_{\mathrm{R}} \gamma_{\mu} D^{\mu} Q_{\mathrm{R}} + \ldots$$

$$\langle \bar{U}_L U_R + \bar{D}_L D_R \rangle \sim F_{\Pi}^3 \rightarrow M_W = \frac{g F_{\pi}}{2}$$

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

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

Minimal fermion content:
2 Dirac technifermions in a weak doublet,
TC charge but no QCD charges

$$Q^a_{\mathrm{L}} = \begin{pmatrix} U^a \\ D^a \end{pmatrix}_{\mathrm{L}}, \quad Q^a_{\mathrm{R}} = (U^a_{\mathrm{R}}, D^a_{\mathrm{R}}),$$

$$a = 1, \ldots d(\mathcal{R}_{\mathrm{TC}})$$

Minimal Walking

technicolor

Minimal Technicolor Theory Space

Minimal Technicolor: 2 EW charged Dirac Flavors

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

Can group minimal models by representation $\mathcal{R}$ of technifermions under TC gauge group $\mathcal{G}_{TC}$

'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 $SU(N)$
- $SU(2)$
- 3_Π

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

'Symplectic TC'

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

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

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

3 pions absorbed by W/Z Additional pNGB's T carry TB number – T (light) DM candidate

All 3 breaking patterns contain
The minimal one:

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

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

Minimal Models of Walking Technicolor

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)

- Other TC Models (non-minimal/including ETC):

  Farhi and Susskind 79; Eichten and Lane 89; Appelquist and Terning 94; Appelquist, Christensen, Pia and Shrock 04; Lane and Martin 06; Ryttov and Shrock 10 M.T.F, Sarkar and Scmidt-Hoberg 11)

Constraints on models of

technicolor

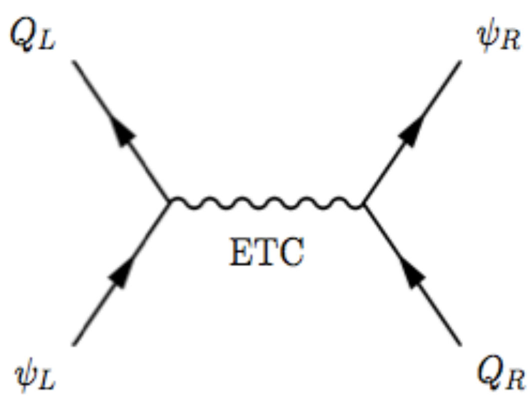
Why minimality and near conformality/walking?

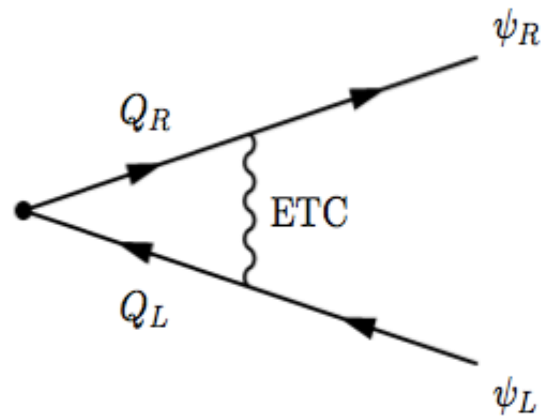
Fermion masses

Need new interactions to generate SM fermion masses

Low energy four-fermion operators:

$$\alpha_{ab}\frac{\bar{Q}\gamma_\mu T^a Q\bar{\psi}\gamma^\mu T^b\psi}{\Lambda^2_{\rm ETC}} + \beta_{ab}\frac{\bar{Q}\gamma_\mu T^a Q\bar{Q}\gamma^\mu T^b Q}{\Lambda^2_{\rm ETC}} + \gamma_{ab}\frac{\bar{\psi}\gamma_\mu T^a\psi\bar{\psi}\gamma^\mu T^b\psi}{\Lambda^2_{\rm ETC}}$$



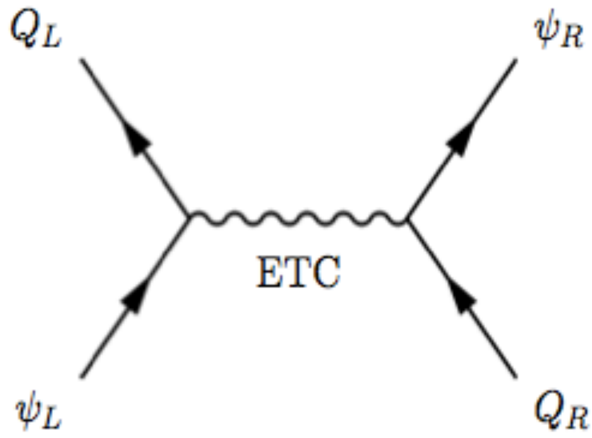


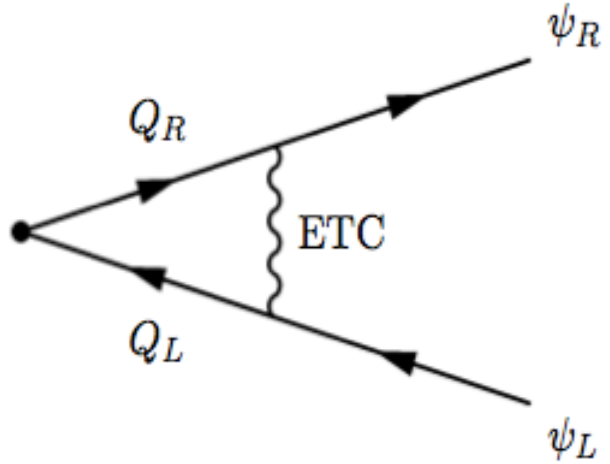
Classical example is Extended Technicolor (ETC):
TC gauge group embedded in Larger ETC group,
SM fermions also charged under ETC, ETC breaks to TC at : $\Lambda_{\rm ETC}$

Fermion masses

After Fierz rearrangement:

$$\alpha_{ab}\frac{\bar{Q}T^aQ\bar{\psi}T^b\psi}{\Lambda^2_{\rm ETC}}+\beta_{ab}\frac{\bar{Q}T^aQ\bar{Q}T^bQ}{\Lambda^2_{\rm ETC}}+\gamma_{ab}\frac{\bar{\psi}T^a\psi\bar{\psi}T^b\psi}{\Lambda^2_{\rm ETC}}+\dots$$





$$m_\psi \sim \frac{\langle\bar{Q}Q\rangle_{\rm ETC}}{\Lambda^2_{\rm ETC}}$$

Problem: FCNC

The four-fermion interactions with only SM fermions are dangerous:

$$\alpha_{ab}\frac{\bar{Q}T^aQ\bar{\psi}T^b\psi}{\Lambda^2_{\rm ETC}} + \beta_{ab}\frac{\bar{Q}T^aQ\bar{Q}T^bQ}{\Lambda^2_{\rm ETC}} + \boldsymbol{\gamma_{ab}}\frac{\boldsymbol{\bar{\psi}T^a\psi\bar{\psi}T^b\psi}}{\boldsymbol{\Lambda^2_{\rm ETC}}} + \dots$$

Example:

$$\frac{1}{\Lambda^2_{\rm ETC}}(\bar{s}\gamma^5 d)(\bar{s}\gamma^5 d) + \frac{1}{\Lambda^2_{\rm ETC}}(\bar{\mu}\gamma^5 e)(\bar{e}\gamma^5 e) + \dots$$

- The first term is a $\Delta S = 2$ FCNC interaction affecting the $K_L - K_S$ mass difference which is measured accurately.
- The second term induces FCNC in the leptonic sector such as $\mu \to e\bar{e}e, e\gamma$ which are not observed.

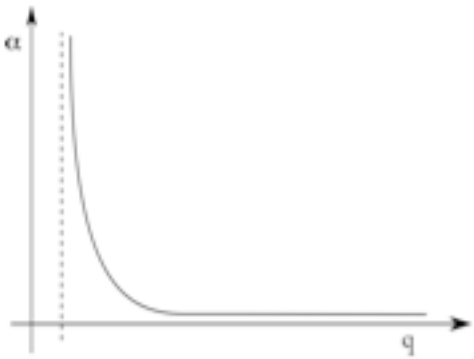
Note this is *not* a problem of the Technicolor sector per se

Walking alleviates tension between FCNC's and fermion mass generation in ETC

- $\langle \bar{Q}Q \rangle_{\rm ETC}$ can be related to $\langle \bar{Q}Q \rangle_{\rm TC}$ by the renormalization group equations:

$$\langle \bar{Q}Q \rangle_{\rm ETC} = \exp\left(\int_{\Lambda_{\rm TC}}^{\Lambda_{\rm ETC}} d(\ln \mu) \gamma(\alpha(\mu)) \right) \langle \bar{Q}Q \rangle_{\rm TC}$$

Running



$$\alpha(q) \sim 1/\mathrm{Log(q)}$$

$$\langle \bar{Q}Q \rangle_{\rm ETC} \sim \mathrm{Log}\left(\frac{\Lambda_{\rm ETC}}{\Lambda_{\rm TC}}\right)^{\gamma} \langle \bar{\mathrm{Q}}\mathrm{Q} \rangle_{\rm TC}$$

Walking

$$\alpha(q) \sim \alpha^*$$

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

Walking – near conformal gauge dynamics

Example

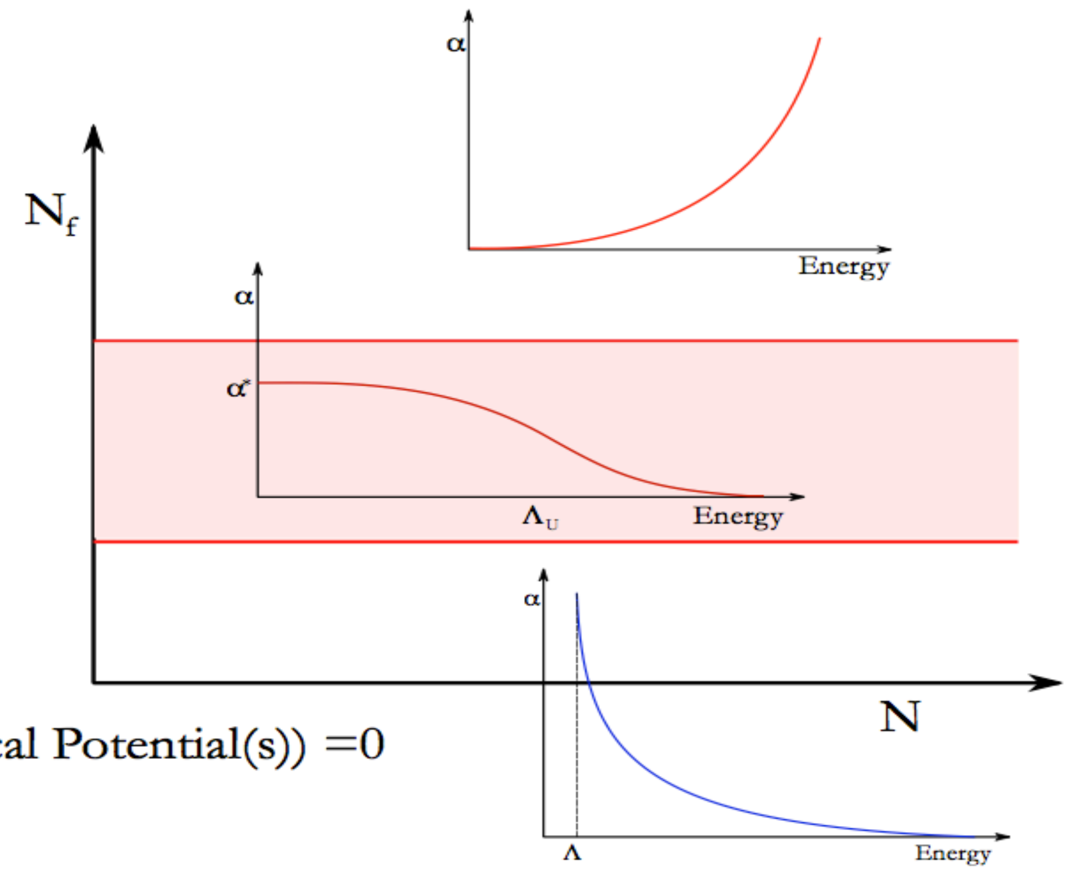
SU(N)

Adjoint Dirac Matter

Nf

Temperature = 0

Matter Density (i.e. Chemical Potential(s)) =0



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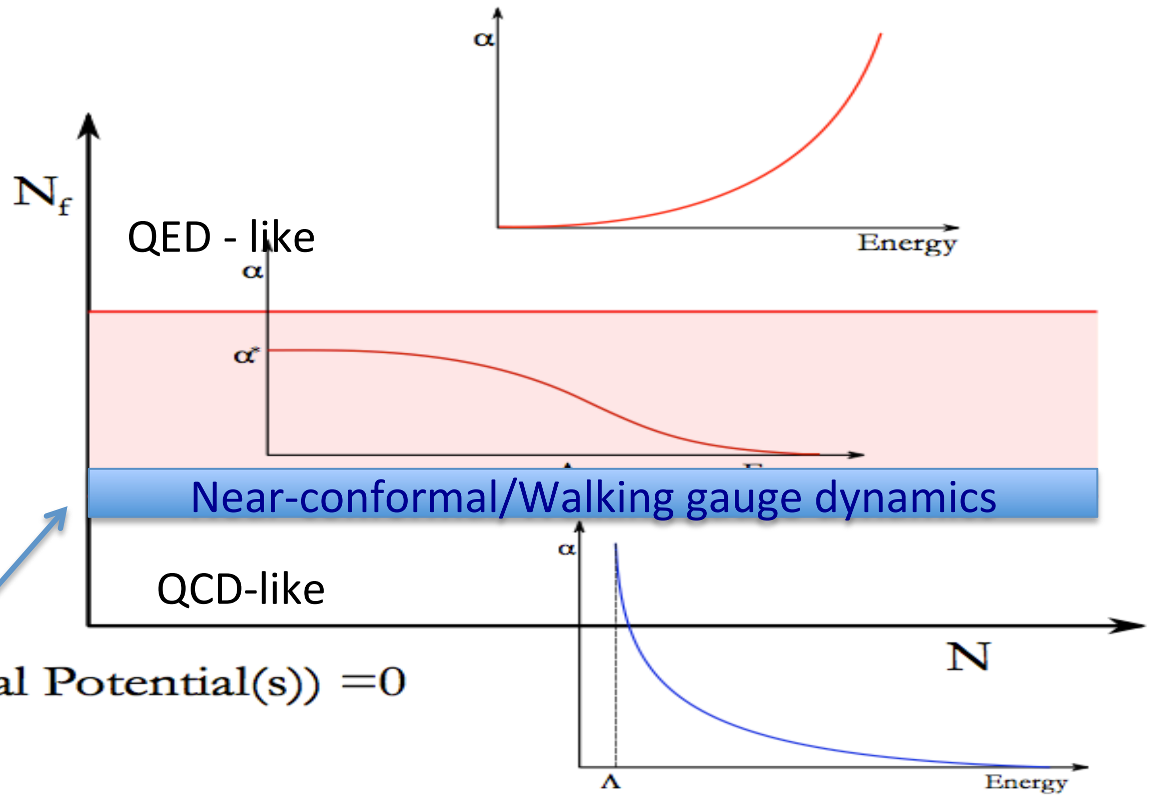
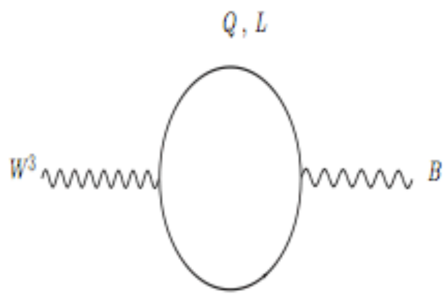


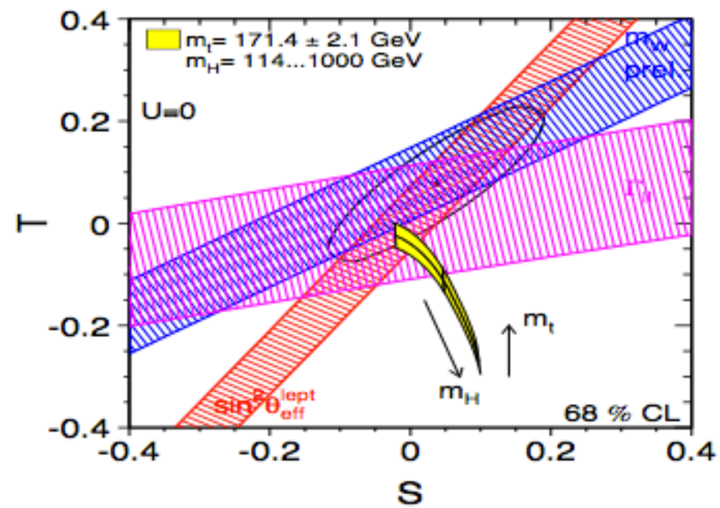
Constraints from LEP

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

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



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



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

But: technifermions are *strongly interacting* at LEP energies, would large corrections to one-loop estimate: $S = S_{\rm naive}(1+\delta)$

In QCD
$\delta \sim O(1)$

Walking potentially reduces the S parameter

Example

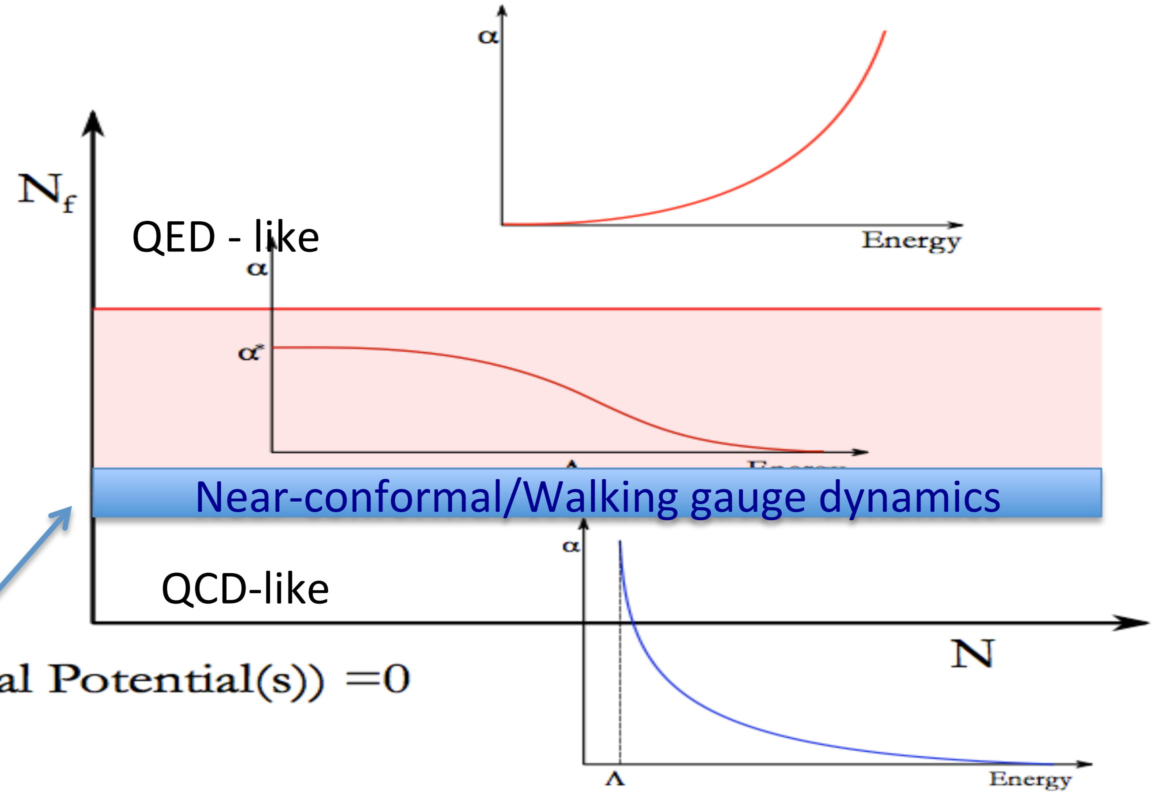
SU(N)

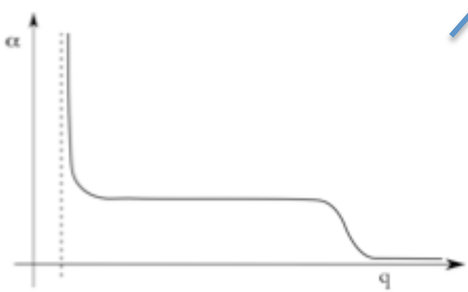
Adjoint Dirac Matter

Nf

Temperature = 0

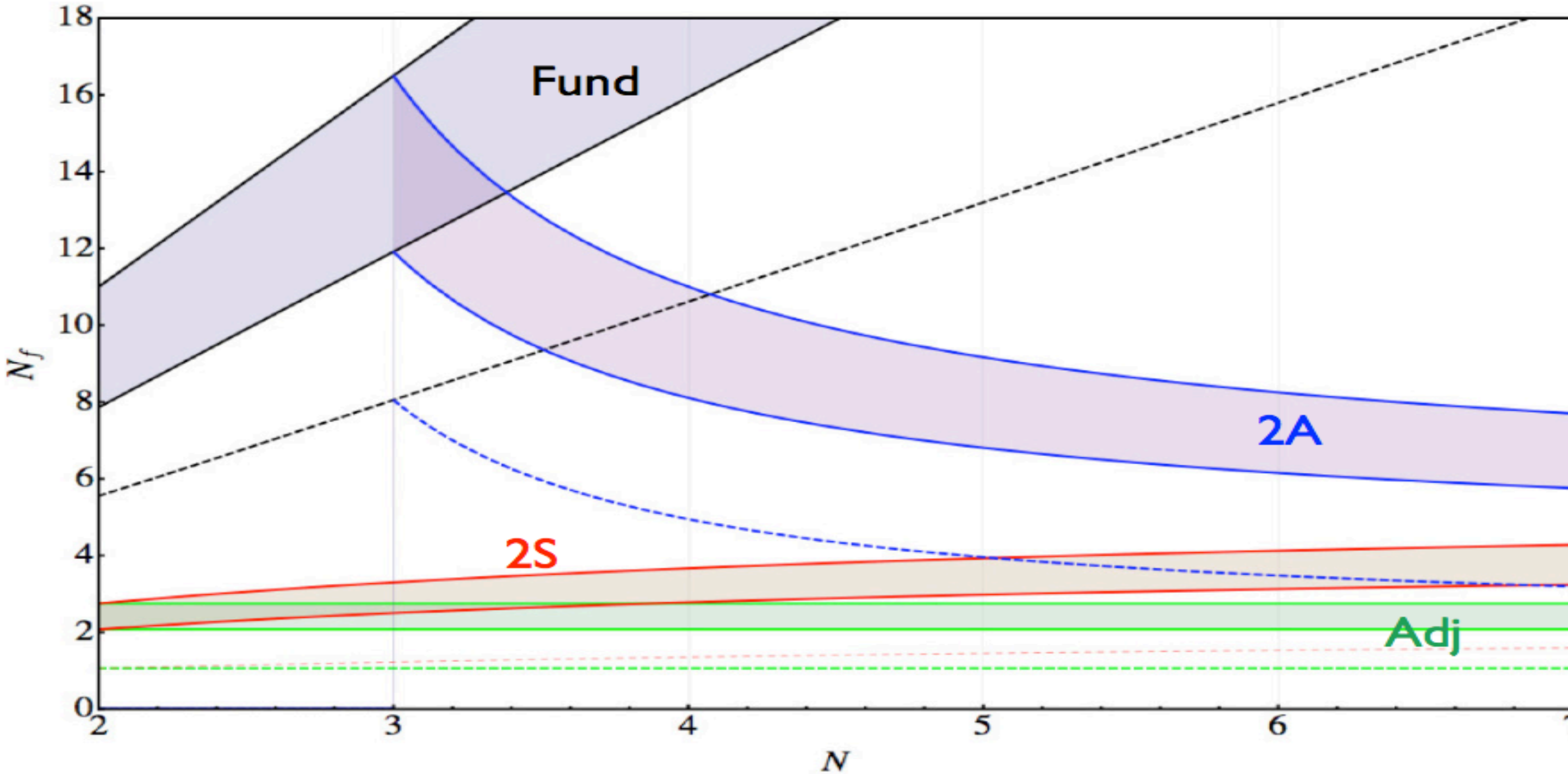
Matter Density (i.e. Chemical Potential(s)) =0





Walking potentially reduces the S parameter

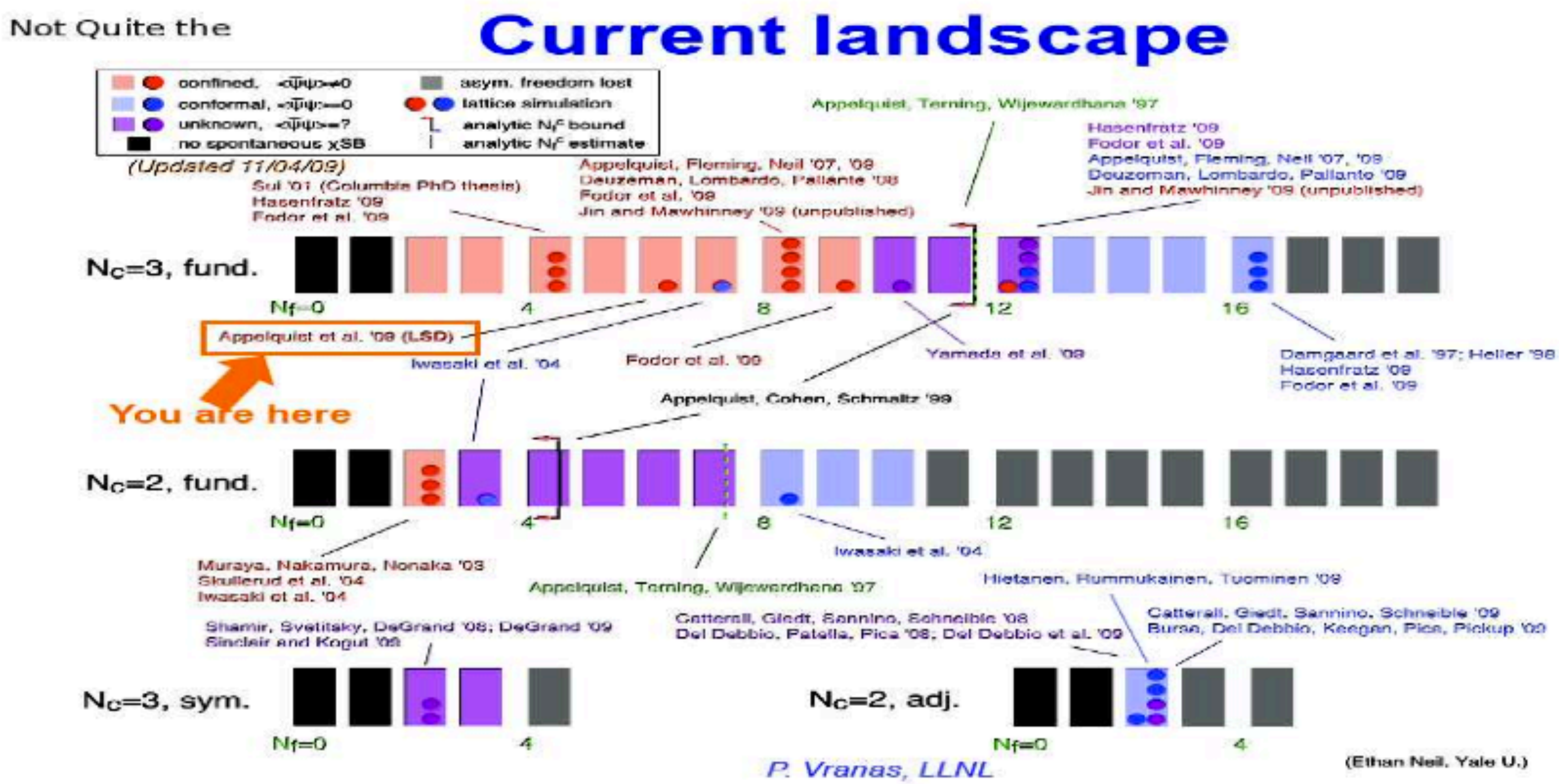
Conformal phase diagram – Model computations & lattice



If Technifermions are in the fund representation of the TC gauge group a large number of Techni-flavors required to be near-conformal -> large S at one-loop level

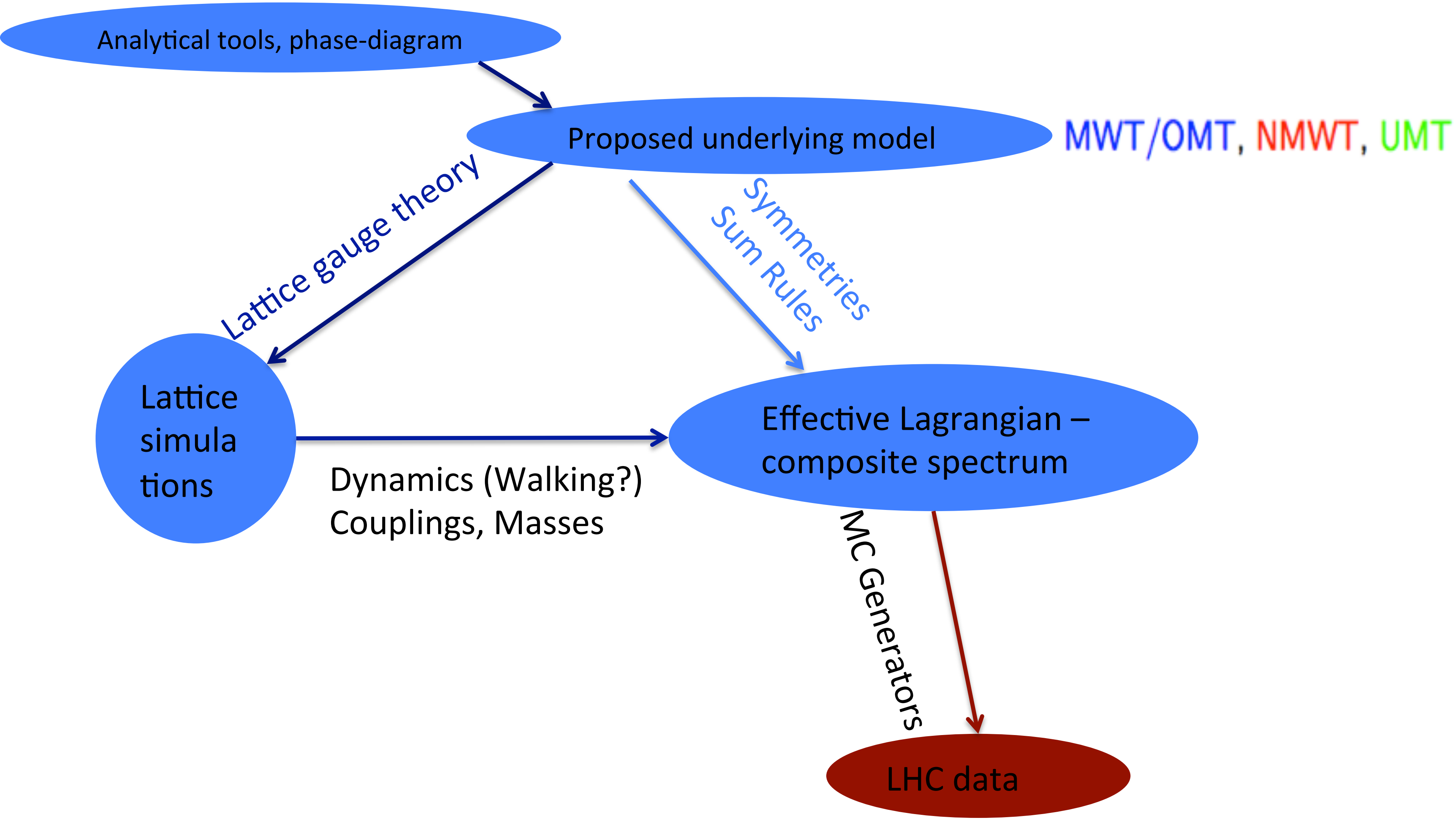
With different reps like the adjoint much less matter is needed to be near-conformal

Ongoing lattice simulations of MWT and other models

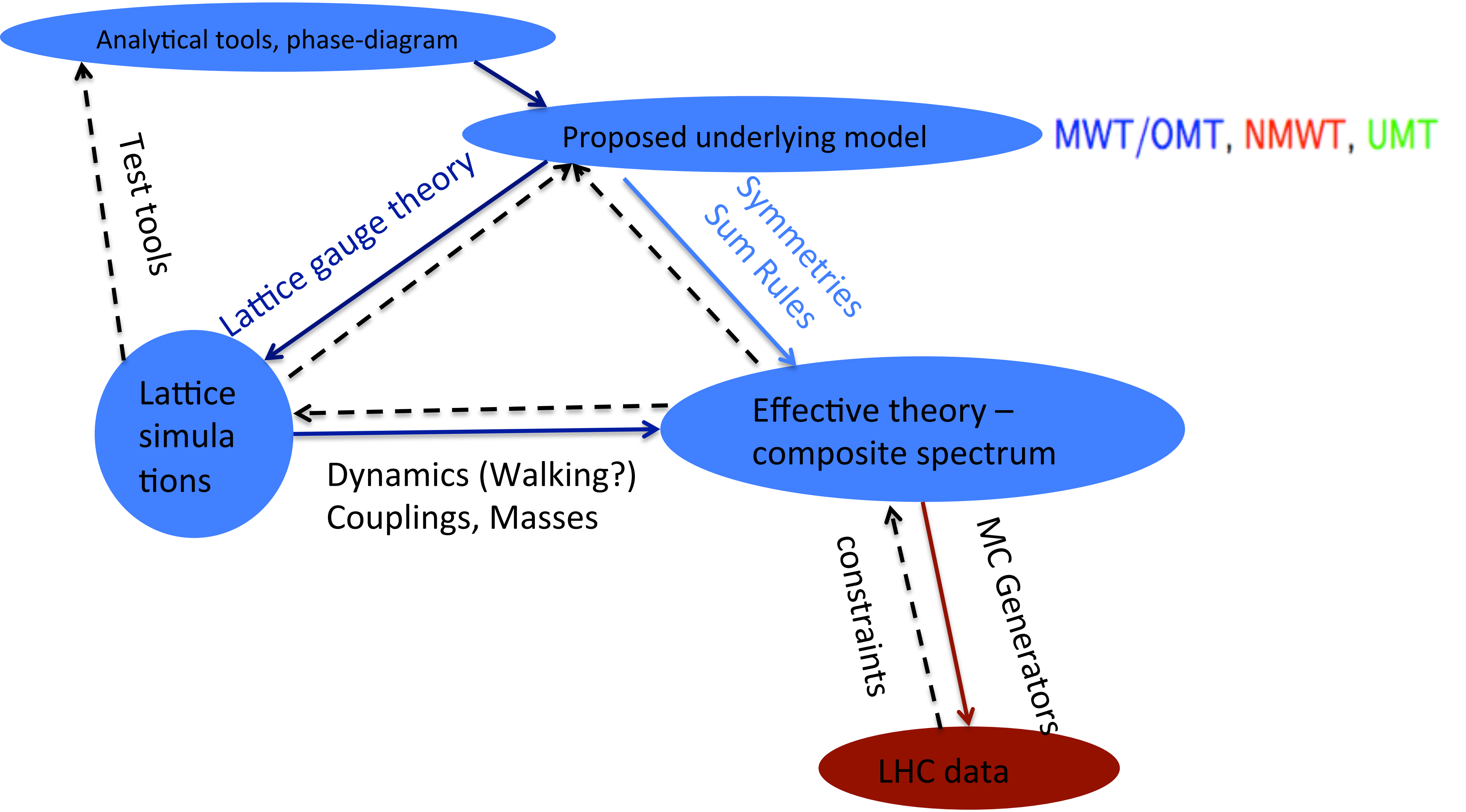


Dedicated international collaborations include the
LSD collaboration (US) & StrongBSM collaboration (Europe)

From Strong Dynamics to LHC



From Strong Dynamics to LHC



Summary - II

Minimal Walking Technicolor

- *Minimality* (few technifermions) reduces the S parameter at the perturbative level
- *Walking* potentially reduces the full S parameter reduced non-perturbative contributions)
- Walking reduces tension with FCNC's when constructing complete ETC models
- Lattice simulations of MWT models are ongoing to determine if candidate models are near-conformal/walking

LHC phenomenology of Minimal Walking

(A. Belyaev, R. Foadi, MTF, M. Jarvinen,
F. Sannino & A. Pukhov 08; Work in progress)

EFT for strong dynamics @ LHC

common sector:

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

Classify composite states according to the **unbroken chiral symmetries**
Organize in effective Lagrangian

Triplets and singlets of vector mesons, compared to QCD:

$$R_{1,2} \sim \rho, a_1 \qquad R_\omega \sim \omega \qquad M_{R_2} > M_{R_1}$$

Scalar mesons:

$$H \sim \sigma(600) \qquad \Pi \sim K, \ldots$$

Note that pions in MWT models can carry techni-baryon number and be DM candidates

Compare with experimental 'benchmark' states:

$$R^0_{1,2} \sim Z'_{1,2}, R^{\pm}_{1,2} \sim W'^{\pm}_{1,2} \qquad H \sim h$$

EFT for strong dynamics @ LHC

common sector:

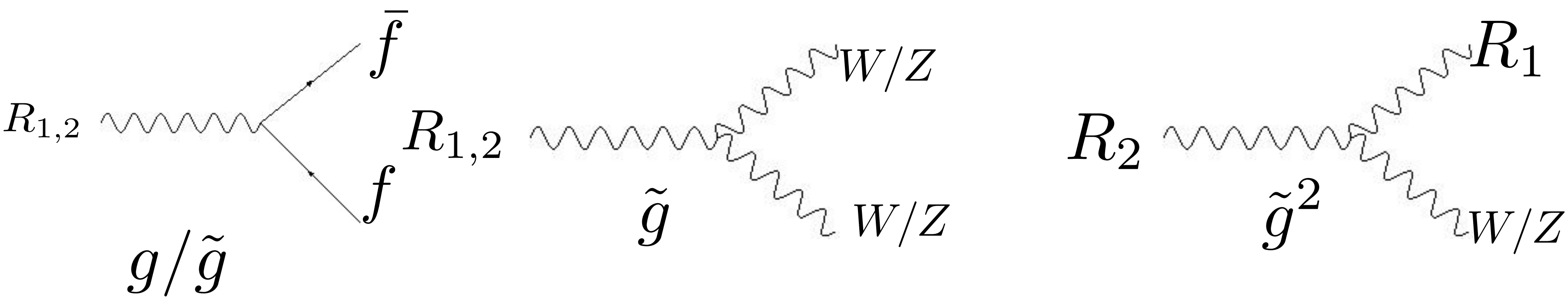
$$SU_L(2) \times SU_R(2) \times U_{TB}(1) \to SU_V(2) \times U_{TB}(1) \ .$$

Effective coupling and masses of composite states:

$$\tilde{g} \sim g_{\rho\pi\pi} \qquad M_{R_{1,2}} \sim M_{A,V} \qquad M_{R_\omega} \sim M_V$$

($M_{A,V}$ Are the vector meson masses before including the EW corrections)

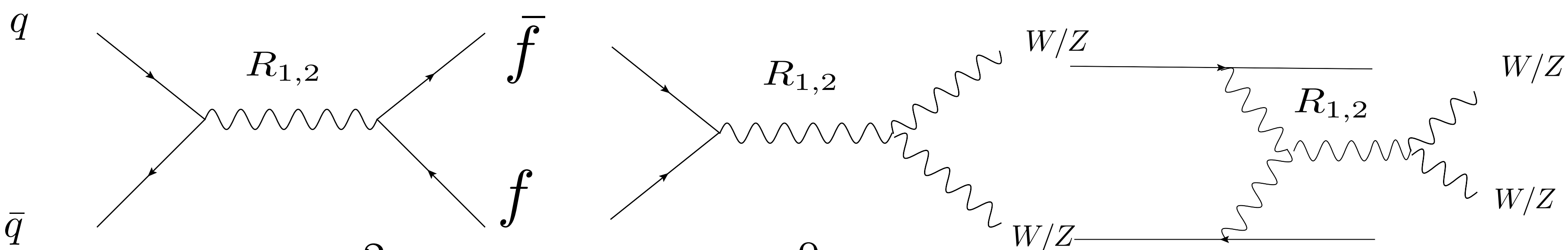
Coupling structure to SM fields :



(Assuming couplings to SM fermions only from vector meson mass mixing –
Can have additional contribution from ETC

LHC Phenomenology

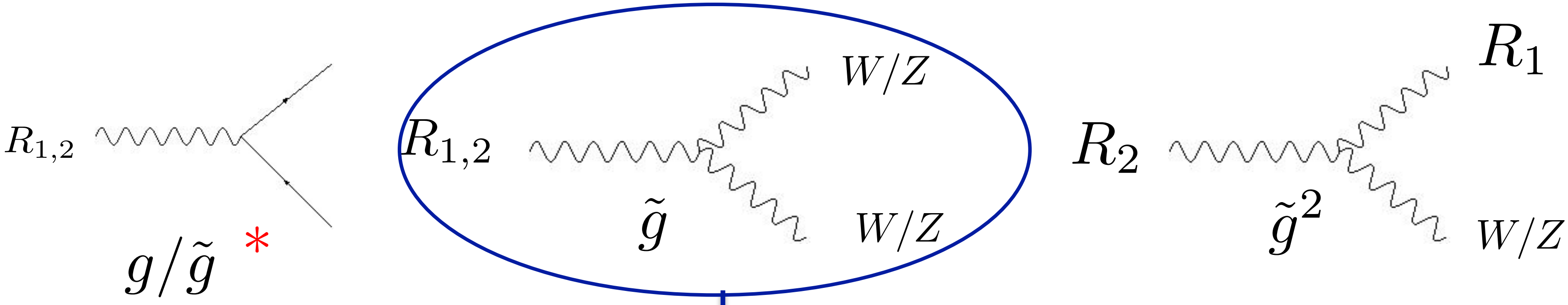
Example production and decay amplitudes:

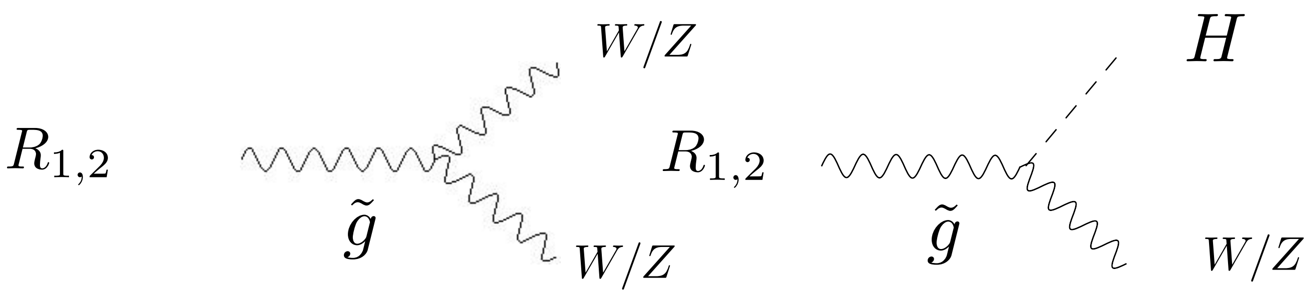


$\mathcal{A} \sim$: $(g/\tilde{g})^2$ $\tilde{g}^0$ $\tilde{g}^2$

Different production modes and decay channels probe different regions in the parameter space $\tilde{g}, M_A(M_V)$

LHC Phenomenology





The axial-vector R mainly couples mainly via H while the vector state couples to 2 vectors

Note that symmetries of the strong dynamics alone, determine important aspects of phenomenology

(A. Belyaev, R. Foadi, M.T.F, M. Jarvinen, F. Sannino & A. Pukhov 08)

Model implementation

NMWT Lagrangian model files for CalcHEP & MadGraph available at:

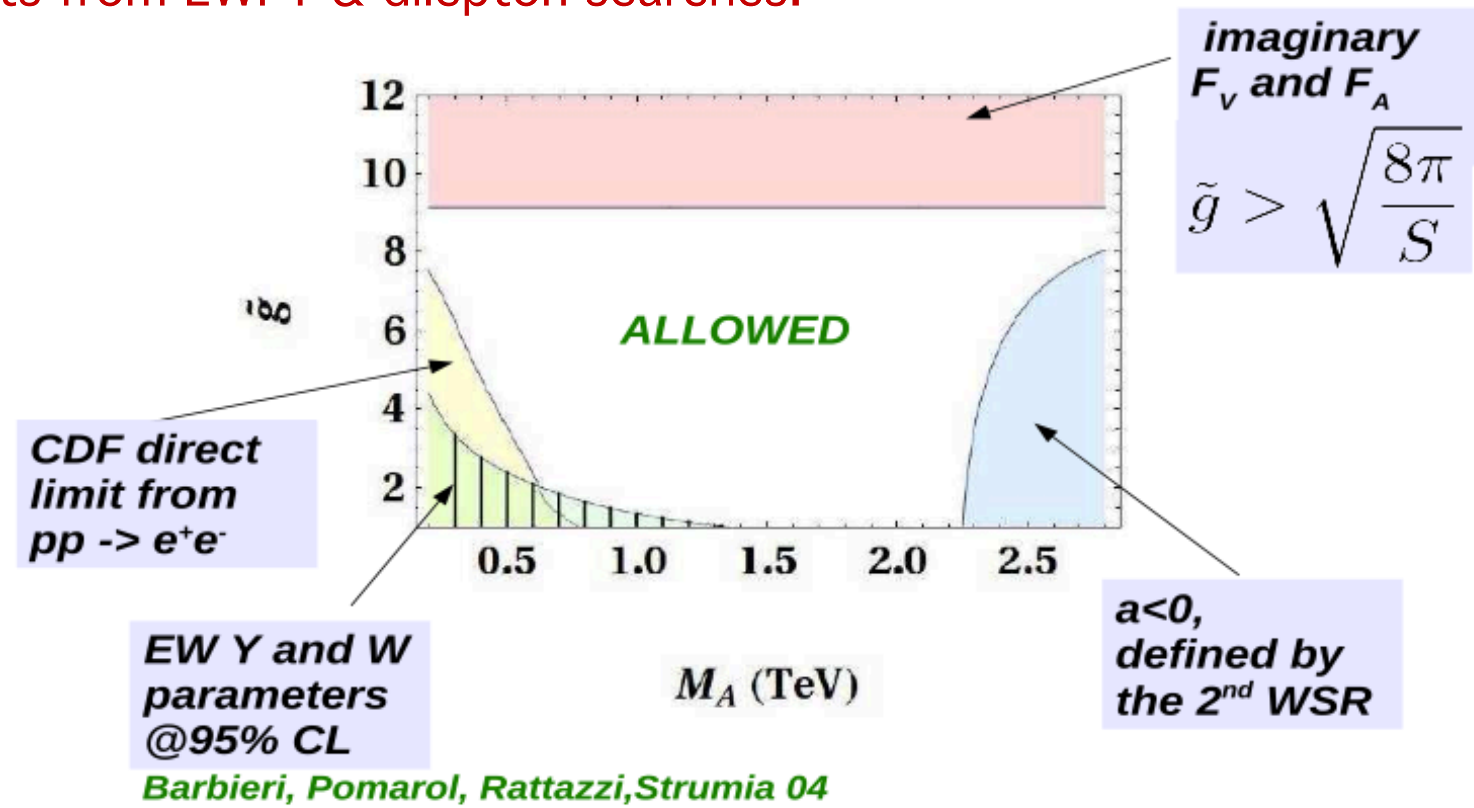
(A. Belyaev, R. Foadi, M.T.F, M. Jarvinen, F. Sannino & A. Pukhov 08)

http://cp3-origins.dk/research/tc-tools

Both LanHEP and FeynRules models have been implemented to generate model files.

Parameter space

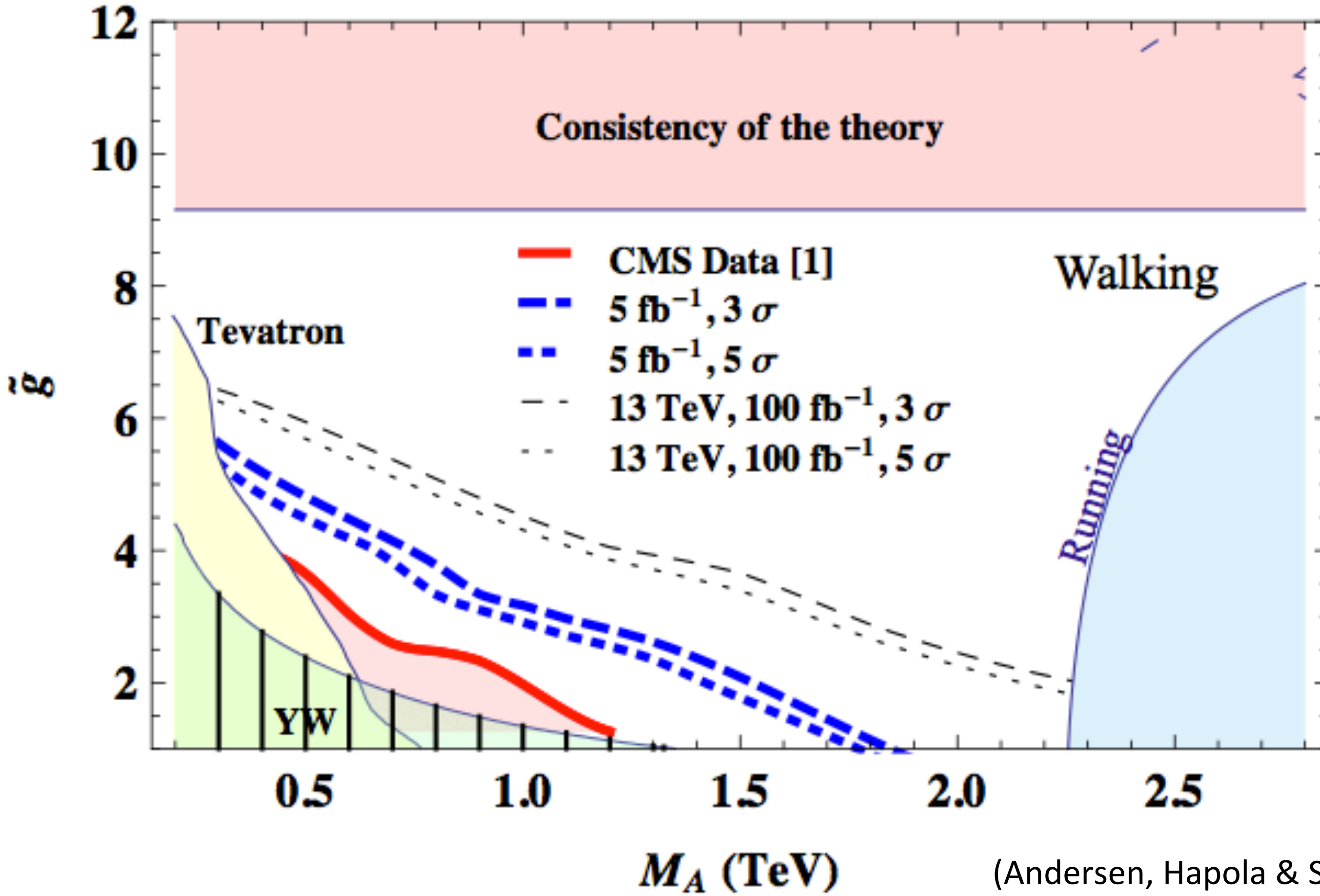
Limits from EWPT & dilepton searches:



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

Composite Higgs mass and S parameter fixed: $M_H = 0.2\,\mathrm{TeV}, S = 0.3$

Update and projections for di-lepton channel:

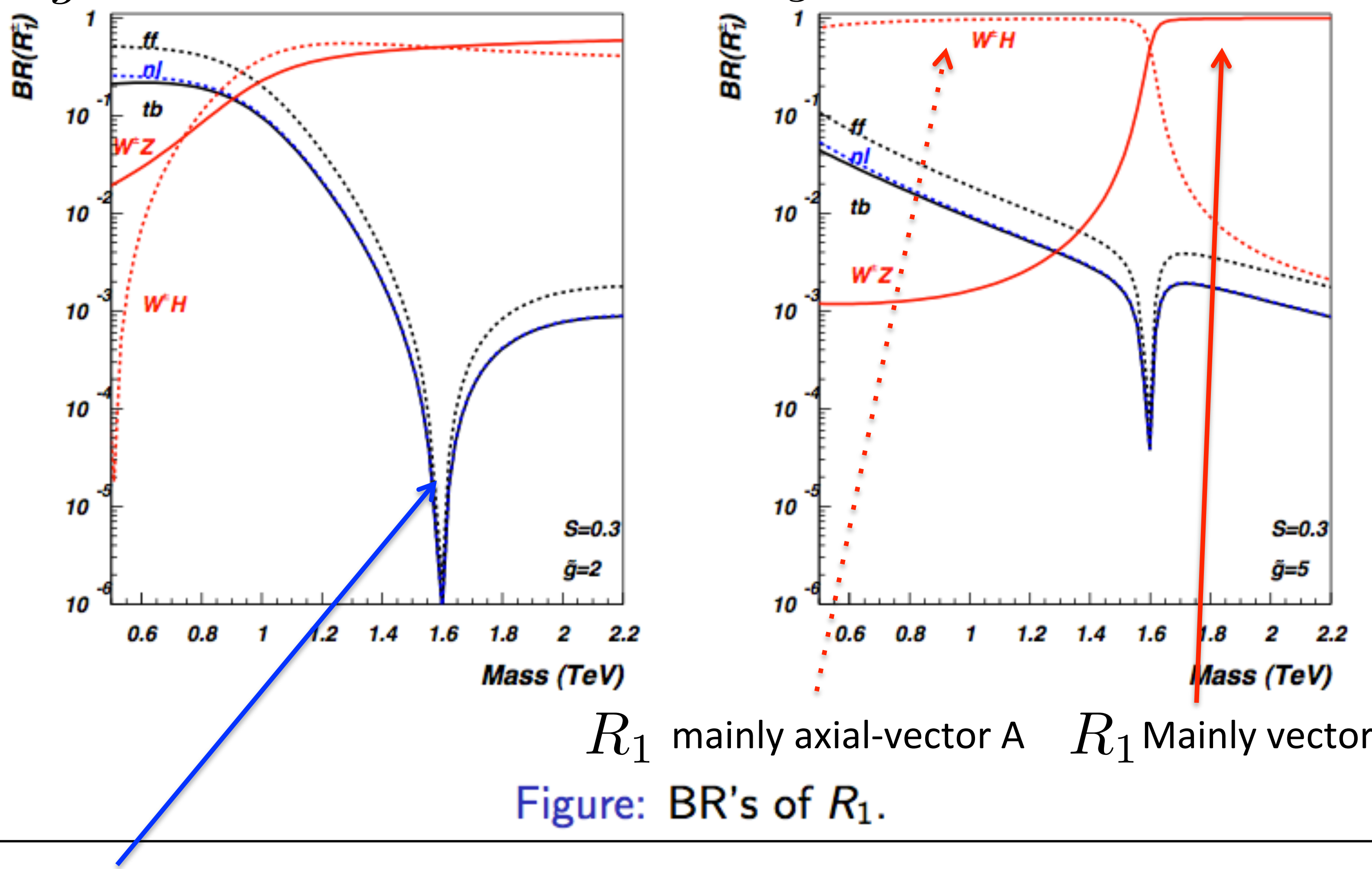


(Andersen, Hapola & Sannino 11
Belyaev, Jarvinen, MTF in progress)

Vector BRs

$\tilde{g}$ small: main coupling to fermions

$\tilde{g}$ large: main coupling to WH/WZ



R_1 mainly axial-vector A

R_1 Mainly vector V

Figure: BR's of R_1.

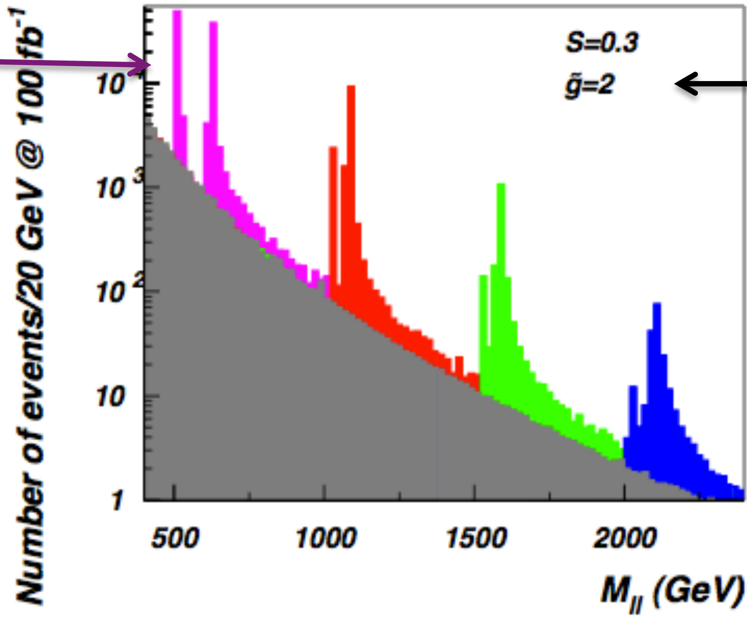
A-V inversion point – 'accidental A-V symmetry', compare with D-BESS or 'Custodial TC'

(R. Foadi, M.T.F & F. Sannino 07)

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

4 Different colors corresponds to 4 different choices of mass parameter M_A

$R_{1,2}$ Peaks both visible
Narrow and mixed
'Standard' Z' like
regime

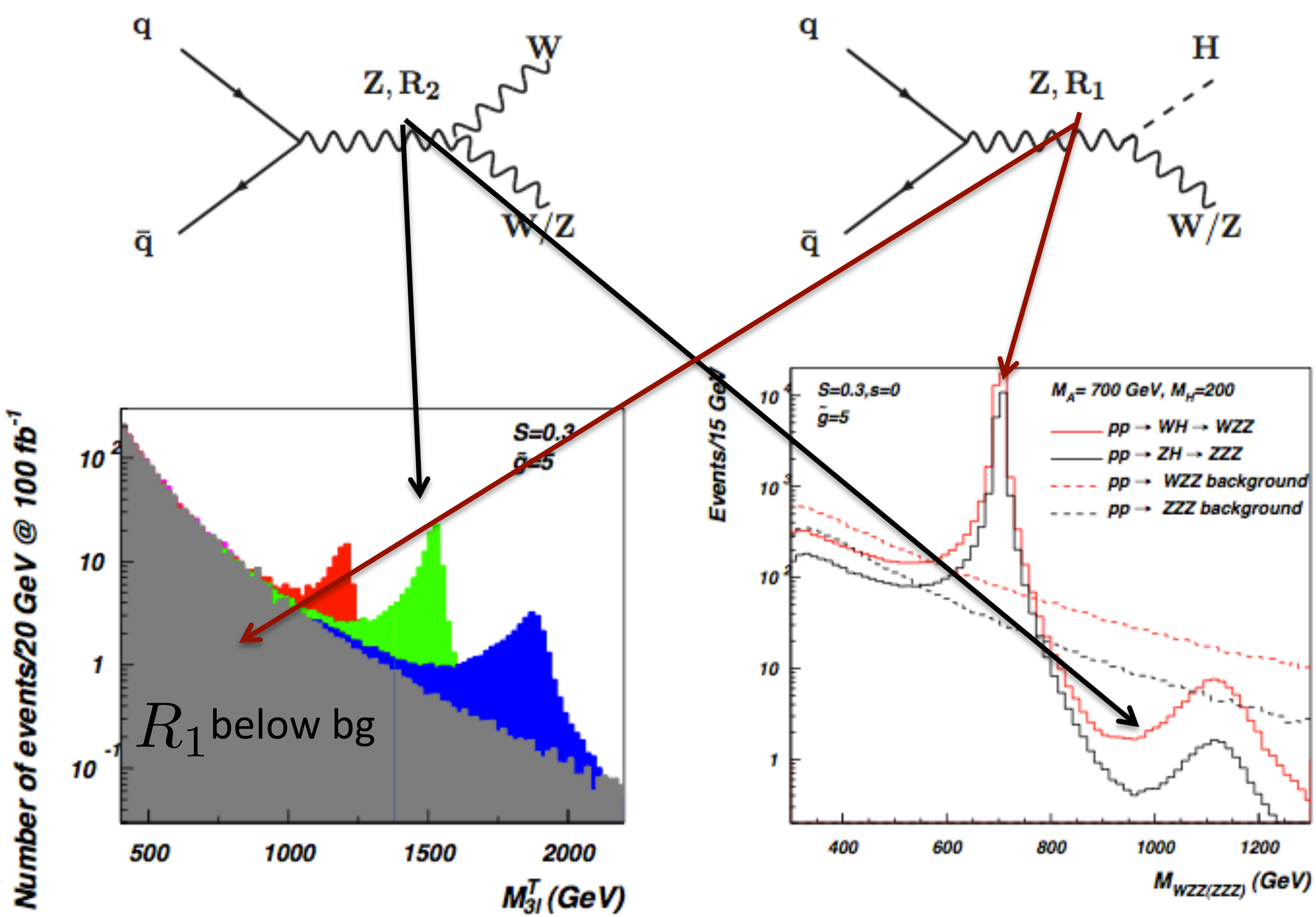


For larger coupling the
height of resonance bumps
Is quickly reduced

Figure: Dilepton invariant mass distribution $M_{\ell\ell}$ for $pp \to R^0_{1,2} \to \ell^+\ell^-$

$M_A(GeV) =:$ 500 1000 1500 2000

Di-boson vs Higgs-strahlung



$M_A(GeV) =:$ 500 1000 1500 2000

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

Summary I

- Technicolor provides a natural origin of EWSB and of asymmetric dark matter.
- Candidate MWT models: MWT/OMT, NMWT, UMT

  - constructed to be viable (pass EWPT, and FCNCs in complete ETC model)
  - and in some cases provide DM .

- Simple phenomenological Lagrangians implemented to study the basic LHC signals

  - a lot of interesting collider phenomenology to consider
  - Experimental groups interested in setting model specific limits

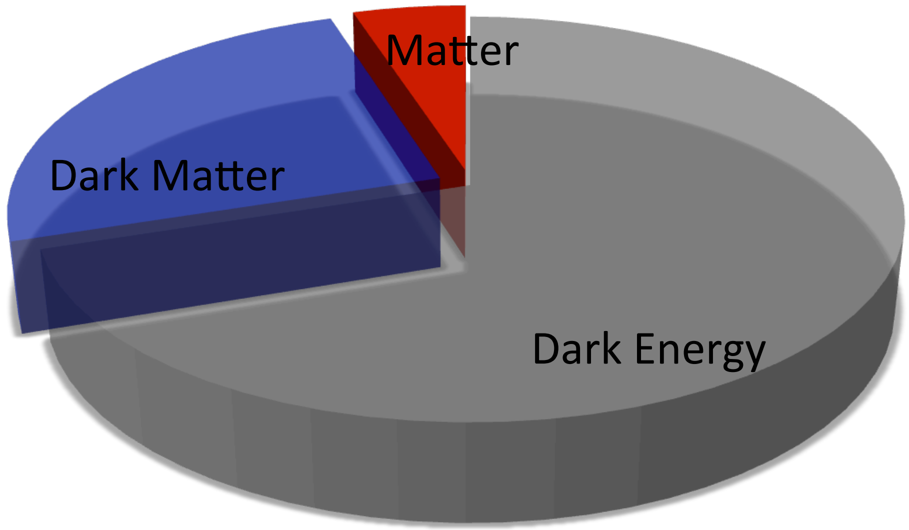
- Extensive on-going lattice simulations to investigate underlying gauge theories and map it to LHC physics

ASYMMETRIC DARK MATTER

ASYMMETRIC DARK MATTER

$\Omega_B \sim 0.05$

Baryons, but no antibaryons



$\Omega_{DM}/\Omega_B \sim 5$

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
Λ_{QCD} **Dynamical**	**Baryons** **No antibaryons**	U(1) Baryon number	$\tau > 10^{33}$ yr (dim-6 OK)	'freeze-out' from thermal equilibrium Asymmetry	$\Omega_B \sim 10^{-10}$ *cf.* observed $\Omega_B \sim 0.05$

Baryon disaster (WIMP miracle)

Chemical and thermal equilibrium when annihilation rate exceeds the Hubble expansion rate:

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

'Freeze-out' occurs when annihilation rate:

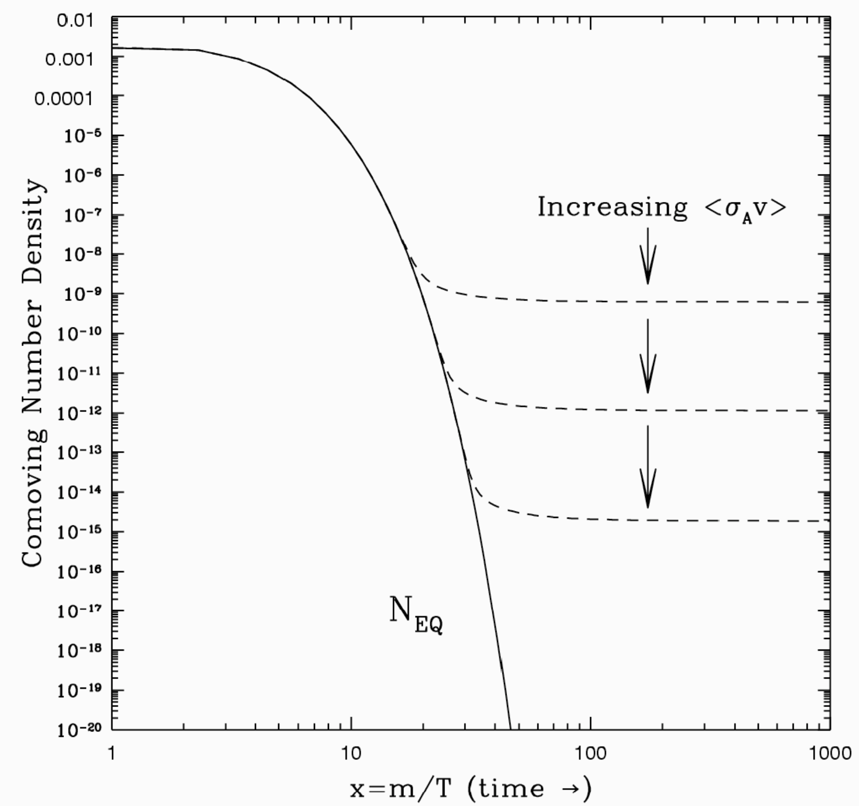
$$\Gamma = n\sigma v \sim m_N^{3/2} T^{3/2} \mathrm{e}^{-m_N/T} \frac{1}{m_\pi^2}$$

becomes comparable to the expansion rate

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

i.e. freeze-out occurs at T ~ m_B/45, with:

$$\frac{n_B}{n_\gamma} = \frac{n_{\bar{B}}}{n_\gamma} \sim 10^{-19}$$



The observed ratio is 10^9 times bigger for baryons, so we must invoke an initial *asymmetry*:

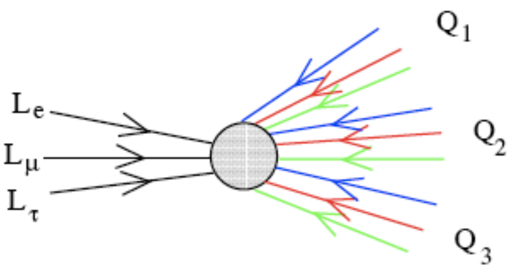
$$\mathcal{N}_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-9}$$

Sakharov conditions for baryogenesis:

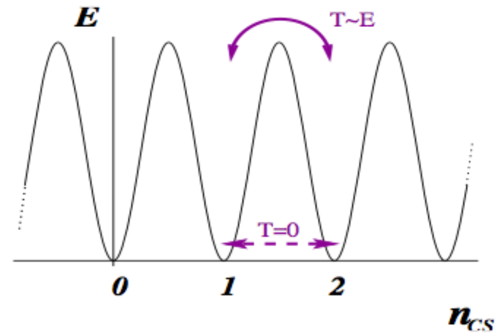
1. Baryon number violation
2. C and CP violation
3. Departure from thermal equilibrium

Classically baryon number can be violated by dim-6 operators in SM

When $T > M_W$ baryon number is also violated in the SM via sphaleron processes that preserve B – L, but violate B + L …



$$\partial_\mu j_i^\mu = \partial_\mu(\bar{\psi}^i \gamma^\mu \psi^i) = \frac{g^2}{8\pi} W^{a\mu\nu} \tilde{W}^a_{\mu\nu}$$

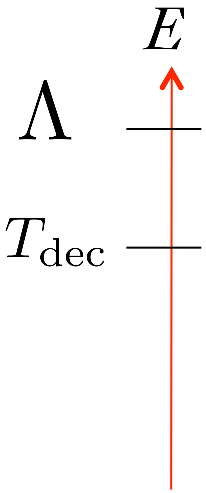


…CP-violation is too weak, electroweak phase transition is a 'cross-over'

The observed matter-antimatter asymmetry requires BSM physics

The same or similar mechanism could generate ADM density

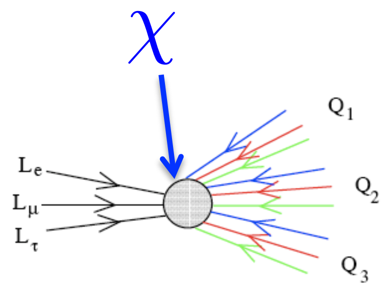
ADM model frameworks



Asymmetry transfer/sharing:

- B or L asymmetry generated at a high scale, e.g. Leptogenesis.
- Asymmetry transferred to DM
- Transfer operator decouples, asymmetry fixed
- Symmetric component is annihilated away

Transfer operator could be the sphalerons of the SM:



(e.g. Barr, Chivukula & Farhi 90)

Or transfer via effective operators inducing L or B number for DM:

$$\mathcal{O}_{B-L}\mathcal{O}_X$$

(e.g. Farrar & Zaharijas '05; Cosme, Lopez Honorez & Tytgat 05; March-Russell & West 05; Kaplan, Luty & Zurek '09)

Asymmetry co-generation:

- B and DM asymmetries generated from the same microphysics

(e.g Kaplan 92; Enqvist & McDonald '98; Hall, March-Russell & West 10; Hook 11; Cheung & Zurek 11; March-Russell & McCullough '11;Graesser, Shoemaker & Vecchi '11)

ADM from

technicolor

...and NSD

ADM from Technicolor

(Nussinov 85)

1. The SM gauge group is augmented:

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

2. The Higgs sector of the SM is replaced:

$$\mathcal{L}_{Higgs} \rightarrow -\frac{1}{4} F^{a}_{\mu\nu} F^{a\mu\nu} + i\bar{Q}_{\mathrm{L}}\gamma_{\mu}D^{\mu}Q_{\mathrm{L}} + i\bar{Q}_{\mathrm{R}}\gamma_{\mu}D^{\mu}Q_{\mathrm{R}} + \dots$$

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

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

The Lightest Technibaryon, stable due to global symmetry $U_{TB}(1)$
(eg $TB \sim QQQ$ in a QCD-like or a pNGB state from MWT models $T \sim QQ$)

ADM from Technicolor - Technibaryon

(Nussinov 85)

The asymmetric part of DM relic density is simply related to the baryon relic density

$$\Omega_\chi = (m_\chi \mathcal{N}_\chi / m_{\rm B} \mathcal{N}_{\rm B}) \Omega_B$$

Nussinov assumed asymmetries of same order $\mathcal{N}_\chi \sim \mathcal{N}_{\rm B}$

And a TeV mass TB state, as from scaled up QCD-TC $m_\chi \sim O(\text{TeV})$

The predicted ratio of relic densities would then be $\Omega_\chi / \Omega_B \sim O(1000)$

The symmetric relic density effectively annihilated away by the TC dynamics – In general this is a constraint on ADM models but automatic in many models with NSD. See however (Belyaev, Frandsen, Sannino & Sarkar 10)

To get the observed relic density, asymmetries of same order today implies:

$$m_\chi \sim 5 \text{ GeV}$$

This is close to the mass region seemingly favoured by DM detection `hints' and has generated a lot of recent model building activity

ADM from Technicolor - sphalerons

(Barr, Chivukula and Farhi 90)

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

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

With technifermions in $SU_W(2)$ doublets:

$$Q_{\rm L}^a = \begin{pmatrix} U^a \\ D^a \end{pmatrix}_{\rm L}, \quad Q_R^a = (U_{\rm R}^a, D_{\rm R}^a),$$
$$a = 1, \ldots d(\mathcal{R}_{\rm TC})$$

The global $U_{TB}(1)$ is violated via the electroweak anomaly just as the baryon number:

$$\partial_\mu J^\mu_{TB} = \frac{1}{2\sqrt{2}} \frac{g^2}{32\pi^2} \epsilon_{\mu\nu\rho\sigma} W^{\mu\nu} W^{\rho\sigma} \ , \quad \text{and} \quad J^\mu_{TB} = \frac{1}{2\sqrt{2}} \left(\bar{U}\gamma^\mu U + \bar{D}\gamma^\mu D \right)$$

ADM and sphalerons

(Barr, Chivukula and Farhi 90)

This means there are 2 distinct 'mass solutions' for the correct relic density of ADM:

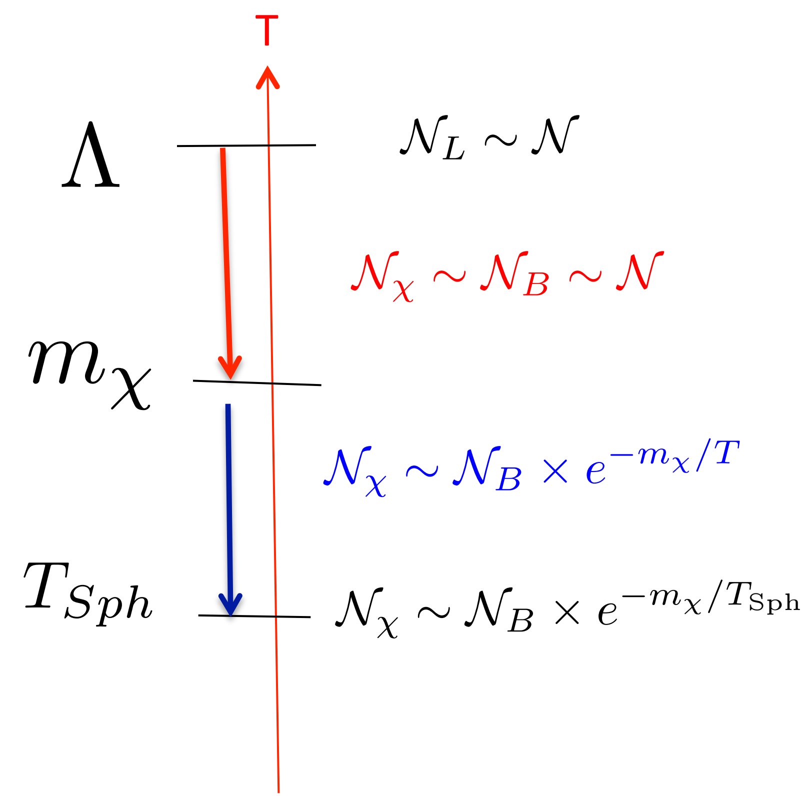
At a high scale, lepton number violation e.g. via Leptogenesis

Asymmetry transferred to DM via sphalerons

The final asymmetry Boltzmann suppressed below the DM if Sphalerons are still active:

$$T_{\rm Sph} > T > m_\chi$$

So the TeV mass ADM envisaged by Nussinov remains an interesting possibility!



ADM and sphalerons

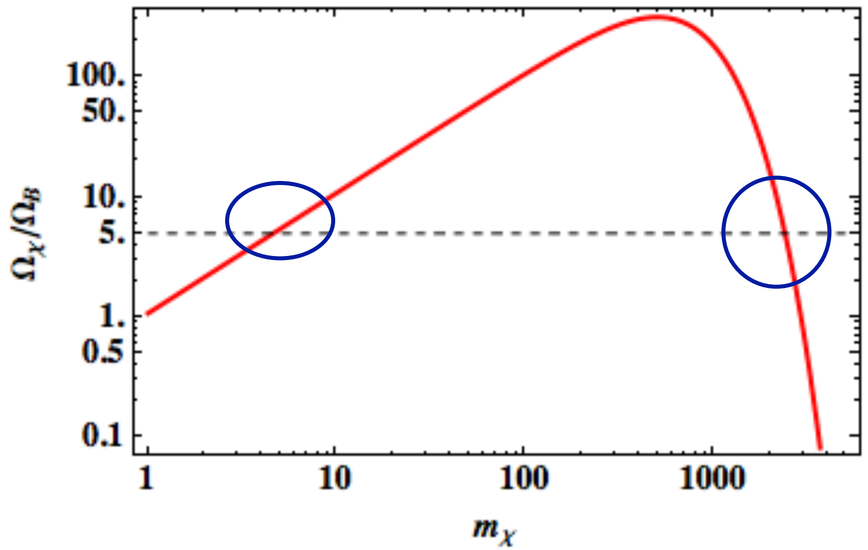


Figure schematic: Ω_χ/Ω_B depends on L/B & other new quantum numbers!
The line is really a (wide) band

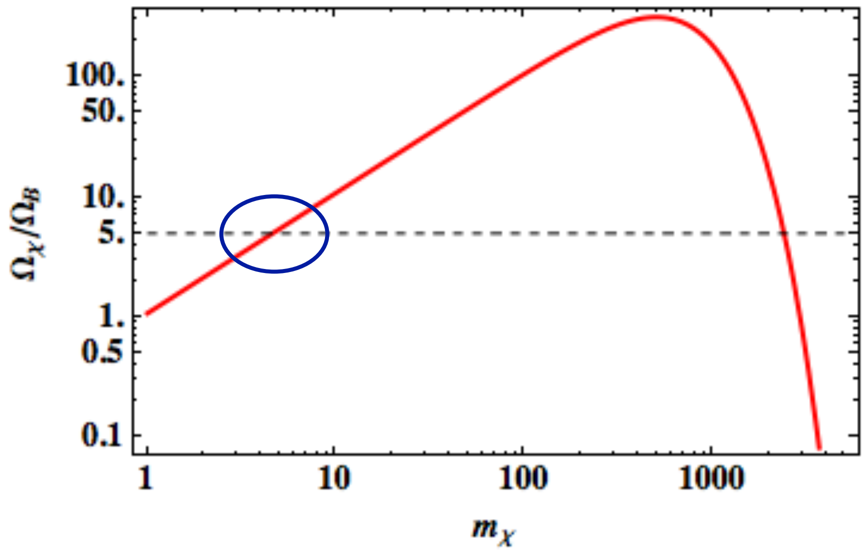
(Barr, Chivukula and Farhi 90; Gudnason, Kouvaris & Sannino '05)

Framework generalizes: Asymmetry transfer/sharing mechanism

- Asymmetry generated at a high scale
- Asymmetry transferred to DM
- Transfer operator decouples and asymmetry is fixed
- Symmetric component is annihilated away

Light ADM from strong dynamics

Additionally motivated by current direct detection `hints'.
In principle testable also via production at colliders, capture in stars, …



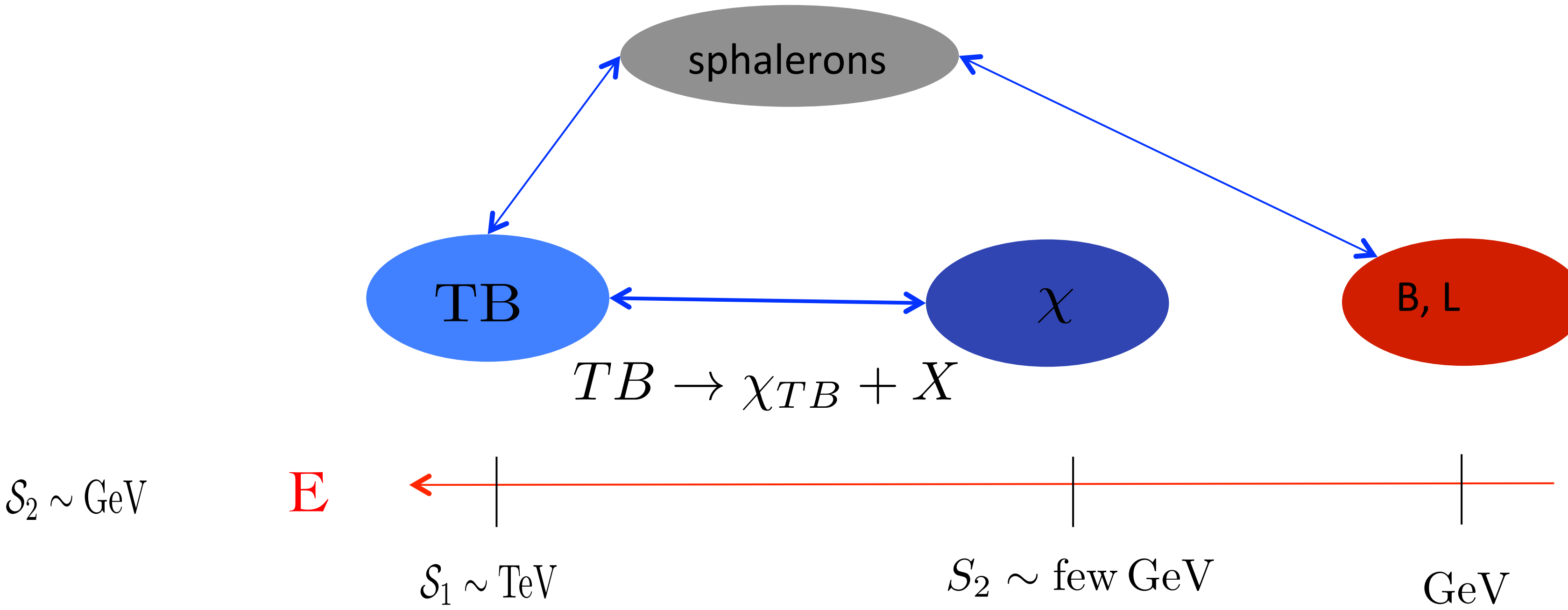
DM is a pNGB from high (weak) scale strong interactions

(Gudnason, Kouvaris & Sannino '05; Foadi, MTF & Sannino 08; Ryttov & Sannino 08; Belyaev, MTF, Sarkar & Sannino 10; Del Nobile, Kouvars & Sannino '11)

Low scale strong interactions

(MTF, Sarkar and Schmidt-Hoberg 11)

Light ADM from strong dynamics



S_1 States (constituents) carry weak charges and are connected to sphalerons

S_2 States are SM singlets (Could be a Hidden sector/Hidden Valleys (Cline, Zurek,..) but could be directly connected to an S_1 sector with scale separation)

$TB \to \chi_{TB} + X$ Preserves 'TB number' and is in equilibrium until $T \lesssim T_{\rm sph}$

Decay mode could be from strong dynamics itself (MTF, Sarkar and Schmidt-Hoberg 11)

pNGB ADM from Technicolor

(Sannino & collaborators 05;...)

'Minimal Dark Matter' scenarios for ADM

'iTIMP'

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

(Gudnason, Kouvaris & Sannino 05; MTF & Sannino 09)

'TIMP'

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

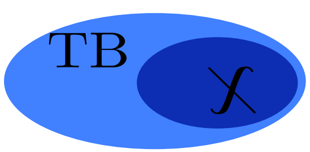
(Barr, chivukula & Farhi 90)

'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 09)

A candidate is the pNGB $T^0 \sim \chi_{TB}$ in models with pseudo-real representation



Or models with two intrinsic scales

(MTF, Sarkar and Schmidt-Hoberg 11)

General analysis of signals and the annihilation cross-section:

(Foadi, MTF & Sannino 08; Belyaev, MTF, Sarkar & Sannino 10, Del Nobile, Kouvars & Sannino '11)

Minimal Technicolor Theory Space

Minimal Technicolor: 2 EW charged Dirac Flavors

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

Can group minimal models by representation $\mathcal{R}$ of technifermions under TC gauge group $\mathcal{G}_{TC}$

'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 $SU(N)$
- $SU(2)$
- 3_Π

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

'Symplectic TC'

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

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

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

3 pions absorbed by W/Z   Additional pNGB's T carry TB number – T (light) DM candidate

All 3 breaking patterns contain
The minimal one:

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

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

ADM signatures

- Direct detection – no generic difference between ADM and symmetric DM

- Collider signatures – not generic but
  -for ADM from NSD expect resonance patterns in met signals.
  –ADM with baryon number, B-violating processes at LHC

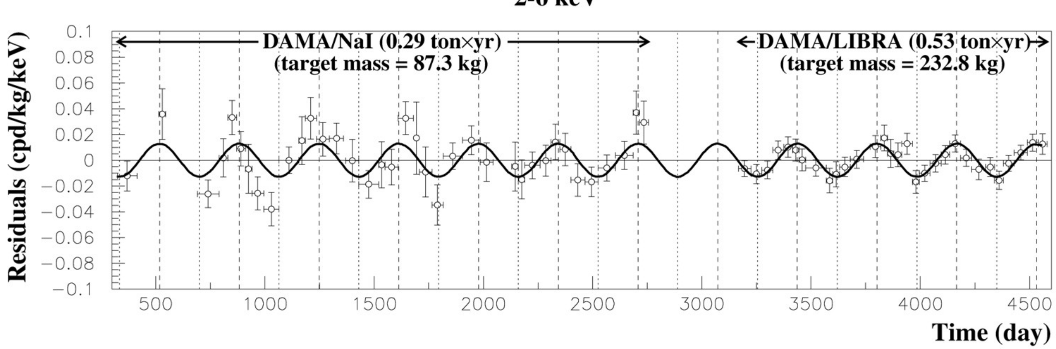
- Indirect detection – generic difference:

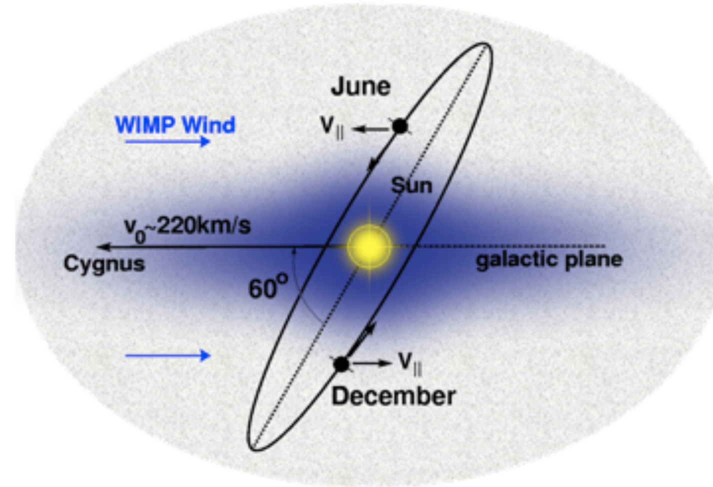
  -No annihilation signals in Galaxy, possibly decays
  -No annihilation signals from stars,
  -larger DM build-up and different effects on e.g. heat transport in stars.

...but indirect signals very challenging

Direct detection

DAMA sees annual modulation signal





$$\frac{dR}{dE_R} = \frac{\rho\,\sigma_n}{2m_\chi\mu_{n\chi}^2} C_T^2(A,Z)F^2(E_R)g(v_{\min}) \qquad g(v_{\min},t) \equiv \int_{v_{\min}}^{\infty} \frac{f(\boldsymbol{v}+\boldsymbol{v}_E(t))}{v}\, d^3v \qquad v_{\min}(E_R) = \sqrt{\frac{m_N E_R}{2\mu^2}}$$

Cogent sees more events than expected at low energies and hints of annual modulation

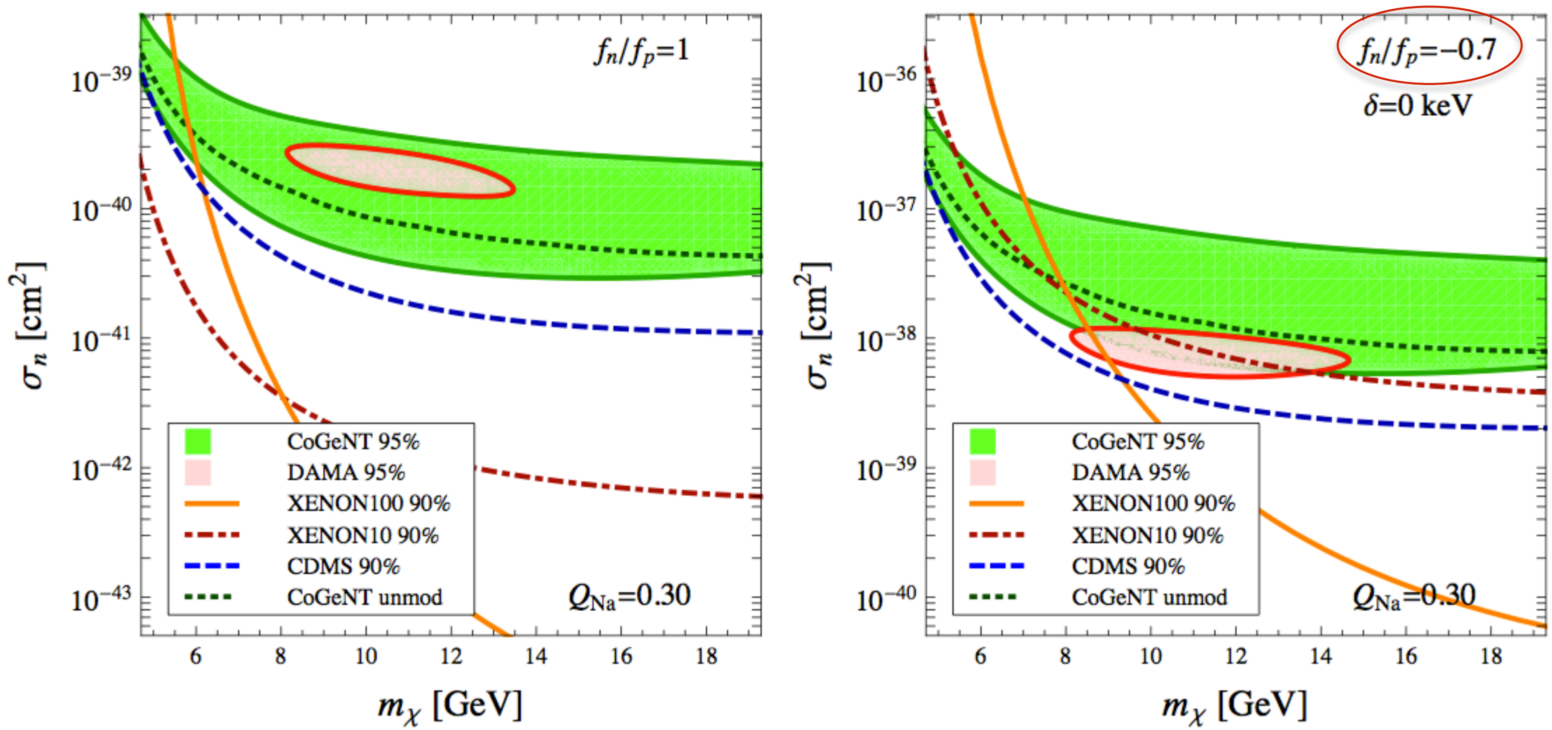
CRESST-II sees more events than expected at low energies

Hints of light DM from direct detection

(MTF et al 11; Farina et al 11; Fox et al 11; Schwetz & Zupan 11; Fornengo et al 11; talks by Kolb and Schnee this conference)

Possible to reduce constraints from a specific target, e.g. XENON, by choosing appropriate value of the DM-nucleon couplings f_n/f_p

(Kurylov and Kamionkowski 04; Giuliani 05; Chang et al 10, Feng et al 11, MTF et al 11, Cline and Frey 11)

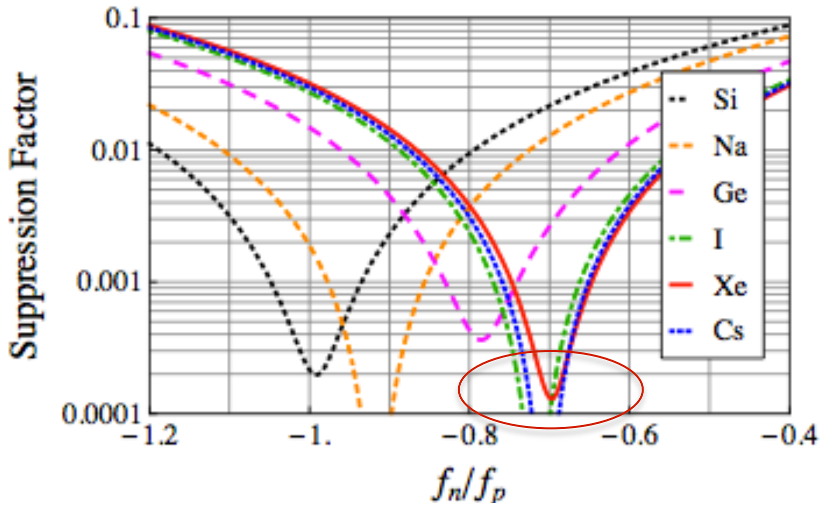


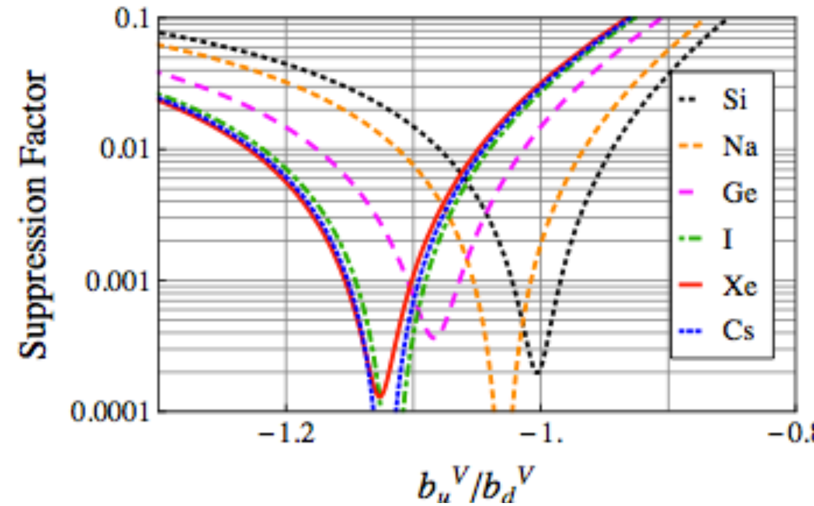
(MTF, Kahlhoefer, March-Russell, McCabe, McCullough & Schmidt-Hoberg 11)

DM-nucleus interactions from general vector mediator R

Possible to suppress scattering on a specific target
By choosing $f_{n,p}$ appropriately!

$$\sigma_N = \frac{\mu_{\chi N}^2}{\mu_{\chi n}^2}\left(Z\frac{f_p}{f_n} + A - Z\right)^2 \sigma_n$$





$$\mathcal{L}_R^{\rm NC} = R_\mu \bar{\chi}\gamma^\mu(g_\chi^{\rm V} - g_\chi^{\rm A}\gamma^5)\chi + R_\mu \bar{f}\gamma^\mu(g_f^{\rm V} - g_f^{\rm A}\gamma^5)f$$

Proton/neutron couplings and quark couplings after integrating out R:

$$f_p = 2b_u^{\rm V} + b_d^{\rm V}\ , \quad f_n = 2b_d^{\rm V} + b_u^{\rm V}\ . \qquad b_f^{\rm A,V} = b_{fR}^{\rm A,V} + b_{fZ}^{\rm A,V} = \frac{g_{\chi R}^{\rm A,V}\, g_{fR}^{\rm A,V}}{m_R^2} + \frac{g_{\chi Z}^{\rm A,V}\, g_{fZ}^{\rm A,V}}{m_Z^2}\ .$$

If vector mediator couples to isospin as e.g. QCD rho-meson, then $f_n/f_p = -1$

(MTF, Kahlhoefer, Schmidt-Hoberg & Sarkar 11)

DM-nucleus couplings from vector mediator model

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}\hat{X}^{\mu\nu}\hat{X}_{\mu\nu} + \frac{1}{2}m^2_{\hat{X}}\hat{X}_\mu\hat{X}^\mu - m_\chi\bar{\chi}\chi$$

(Babu, Kolda, March-Russell 96, …)

$$- \frac{1}{2}\sin\epsilon\,\hat{B}_{\mu\nu}\hat{X}^{\mu\nu} + \delta m^2\hat{Z}_\mu\hat{X}^\mu - \sum_f f_f^{\rm V}\hat{X}^\mu\bar{f}\gamma_\mu f - f_\chi^{\rm V}\hat{X}^\mu\bar{\chi}\gamma_\mu\chi\,,$$

$\hat{X}, \hat{Z}$ Interaction eigenstats

$\hat{X}, \hat{Z} \rightarrow R, Z$ After mass diagonalization

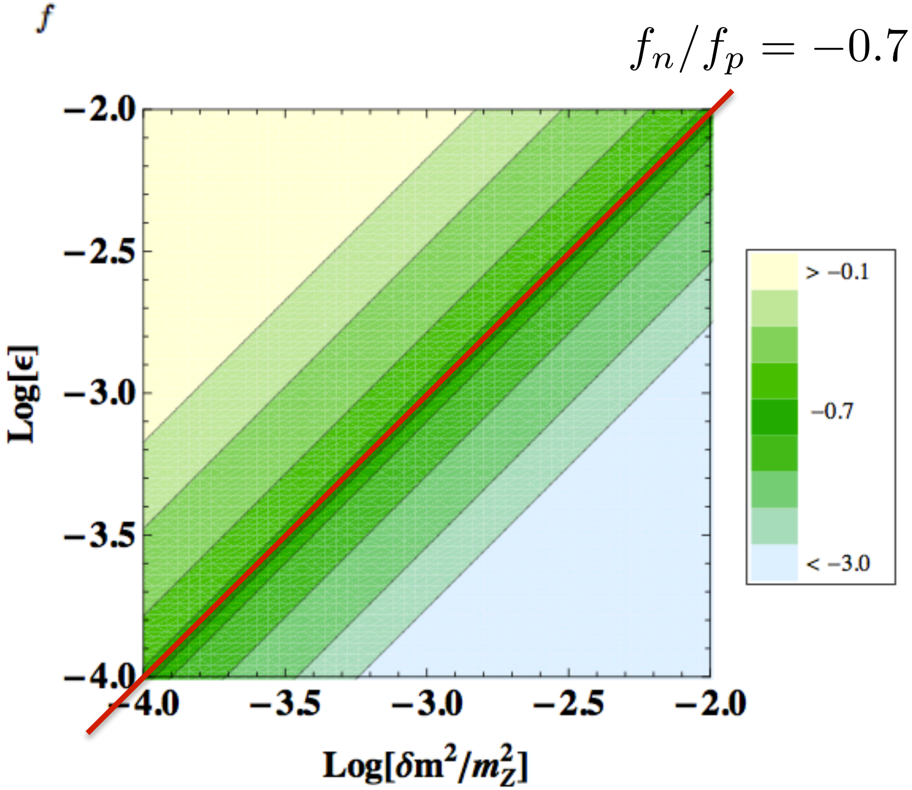
Simple relation: $\epsilon \sim \delta m^2/m_Z^2$

required for: $f_n/f_p = -0.7$

Vector could be a Z’ or
a `techni-omega’ in NSD models

(MTF, Schmidt-Hoberg & S. Sarkar 11)

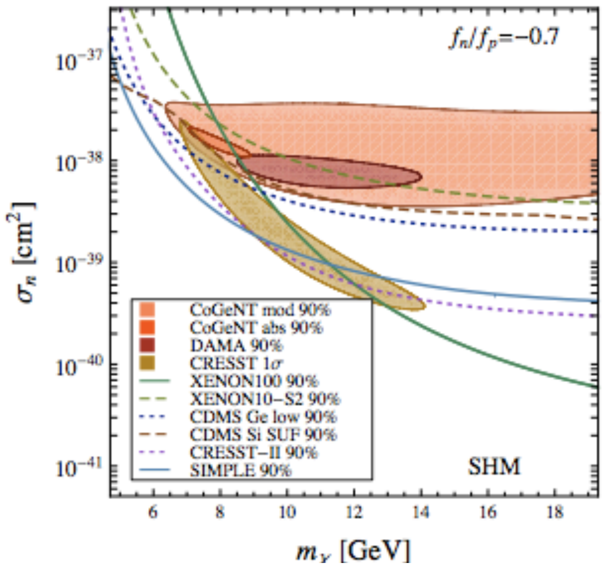
Cannot suppress CDMS constraints on CoGeNT this way! Have to assume large modulation fraction e.g. due to inelasticity

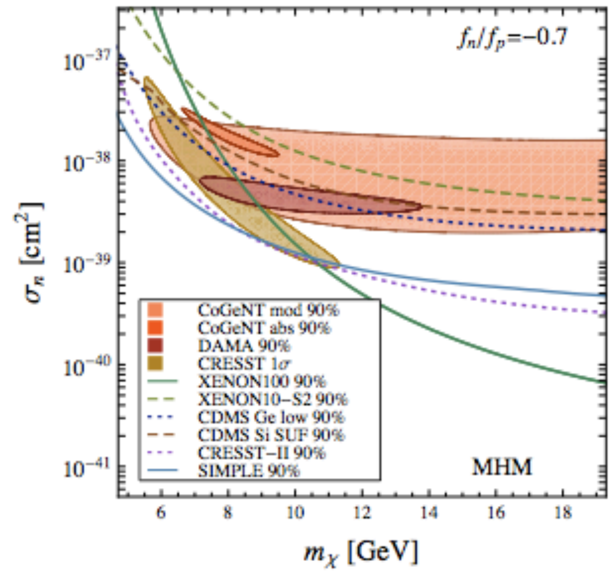


(MTF, Kahlhoefer, Schmidt-Hoberg & Sarkar 11)

Hints from direct detection – CRESST-II update

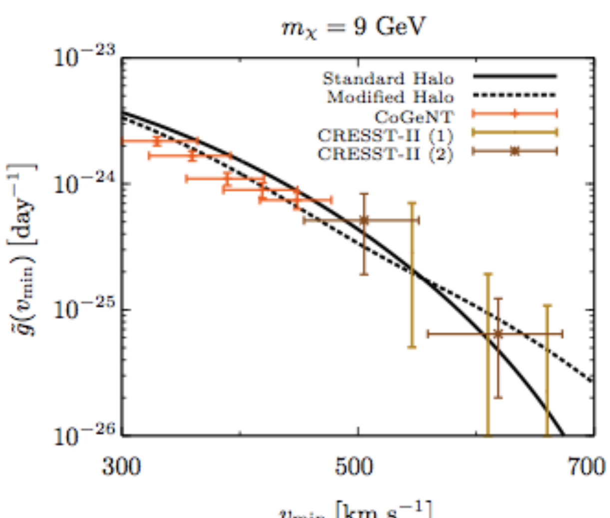
(Kopp, Schwetz & Zupan 11; Kelso, Hooper & Buckley 11;
MTF, Kahlhoefer, McCabe, Schmidt-Hoberg & Sarkar to appear)

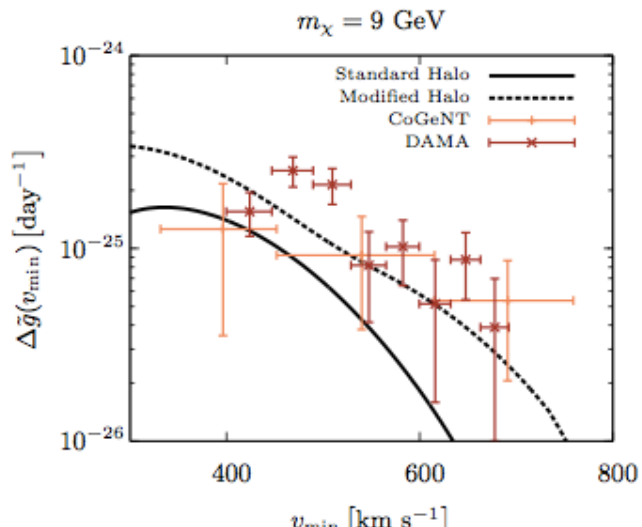




To reconcile data

1) isospin-dependent Couplings to avoid XENON constraints
2) non-standard halo, with anisotropy to Fit (modulation) data



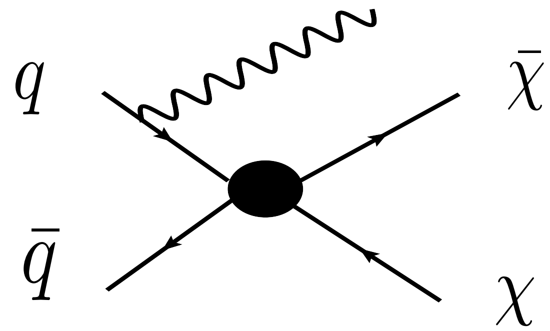


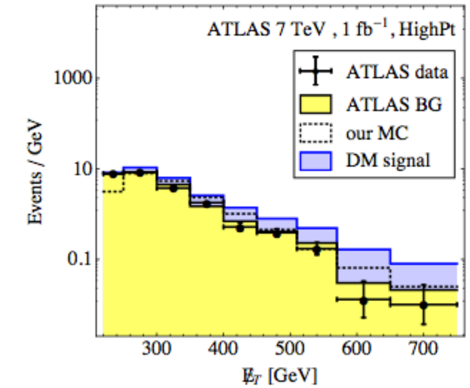
DM at colliders vs direct detection

(Goodman et al 10; Fox et al 10; Fortin et al 11; Rajaraman et al 11)

If mediator mass M is heavy, can integrate it out and study mono-photon/mono-jet signals

$$\sigma_{1j} \sim \begin{cases} \alpha_s \, g_\chi^2 \, g_q^2 \, \frac{1}{p_T^2} & M \lesssim p_T \\ \alpha_s \, g_\chi^2 \, g_q^2 \, \frac{p_T^2}{M^4} & M \gtrsim p_T \end{cases}$$





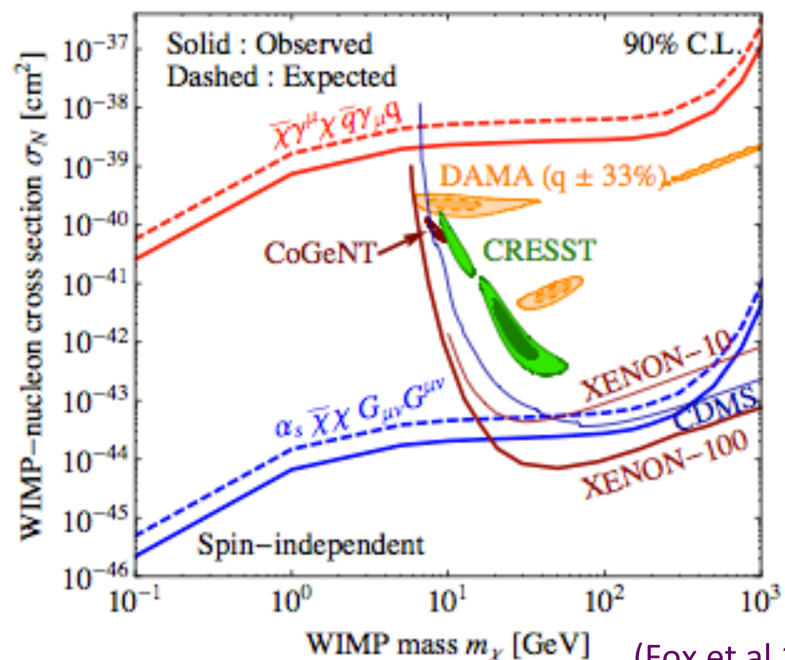
ATLAS 7TeV, 1fb^{-1} VeryHighPt

ATLAS limits for vector interactions do not rule out `best fit regions'

However in principle they do for

$f_n/f_p = -0.7 \qquad \sigma_N \sim 10^{-38}$

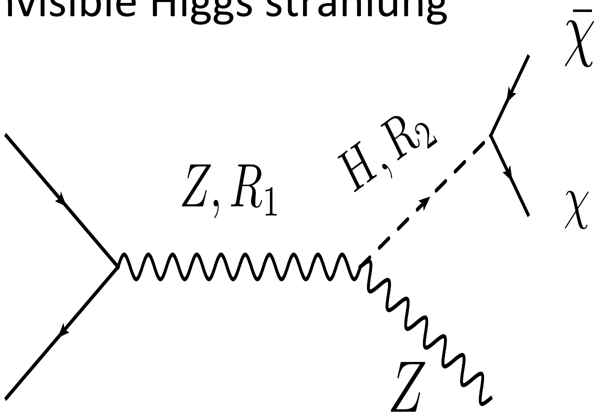
Constraints from colliders much weaker if mediator is light! (Fox et al 10)

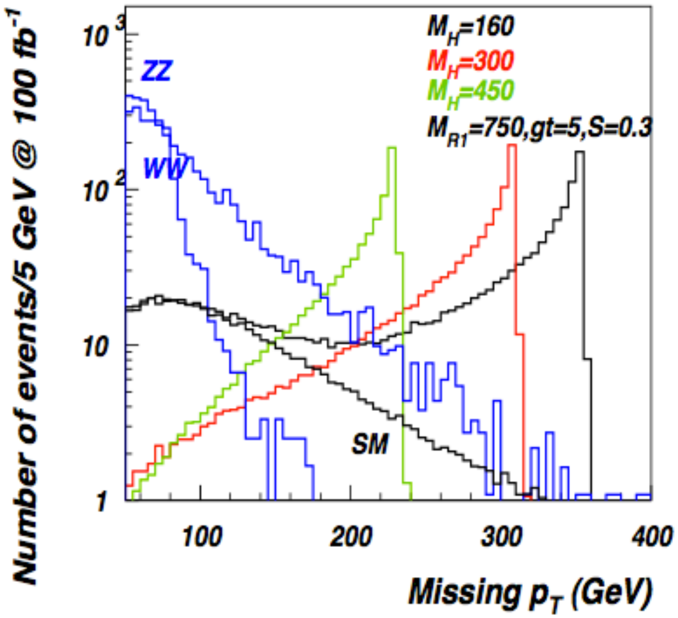


(Fox et al 11)

DM from NSD at colliders

The mediator of DM-nucleus scattering might couple dominantly to other states, e.g. Invisible Higgs strahlung





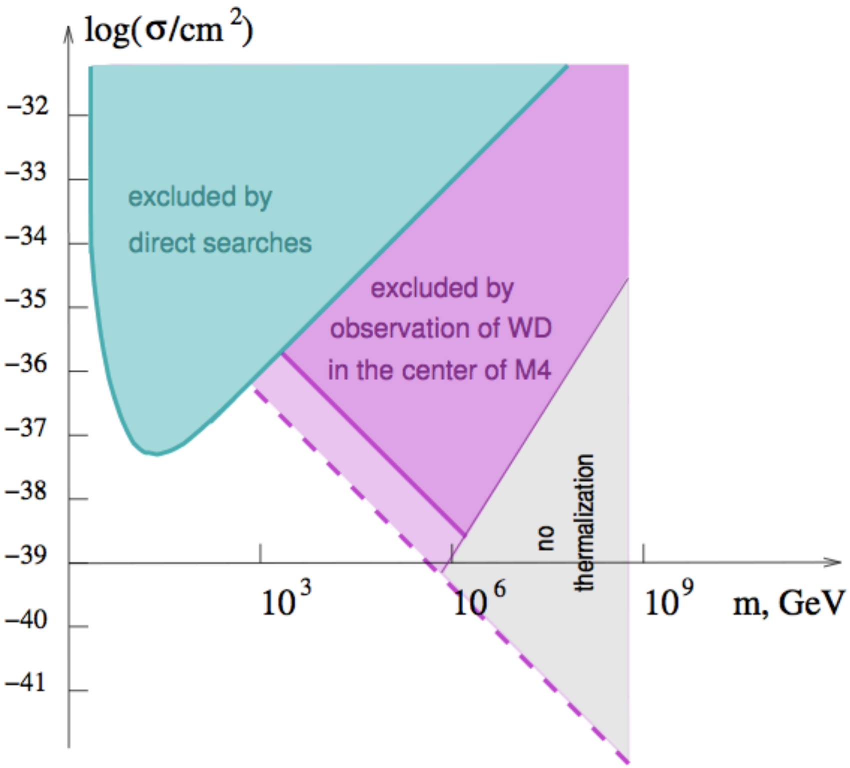
(Foadi, MTF & Sannino 08)

The resonance structure can discriminate against background (which dominate this process in SM)

Channels more model-dependent, but also more realistic in NSD models

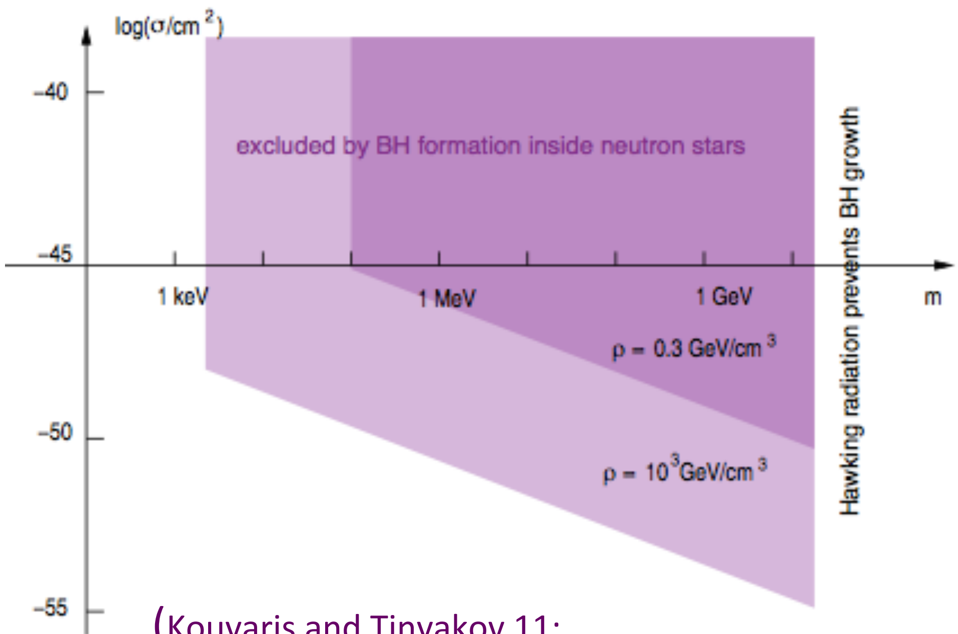
ADM limits from compact stars

Limits from White Dwarves



(Kouvaris and Tinyakov 10)

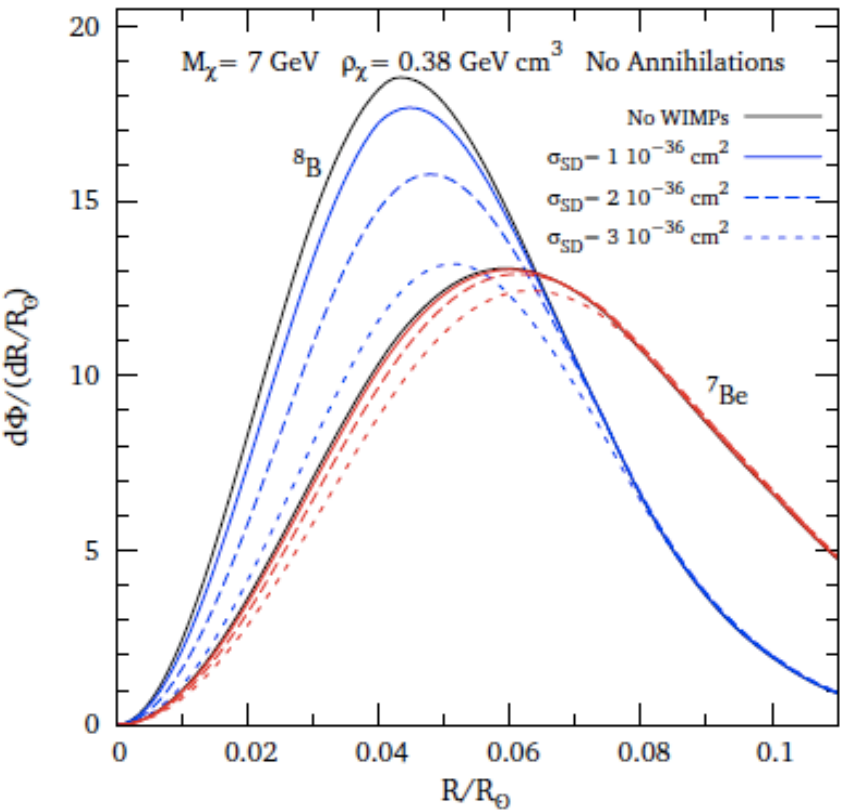
Limits on fundamental bosonic ADM from neutron stars

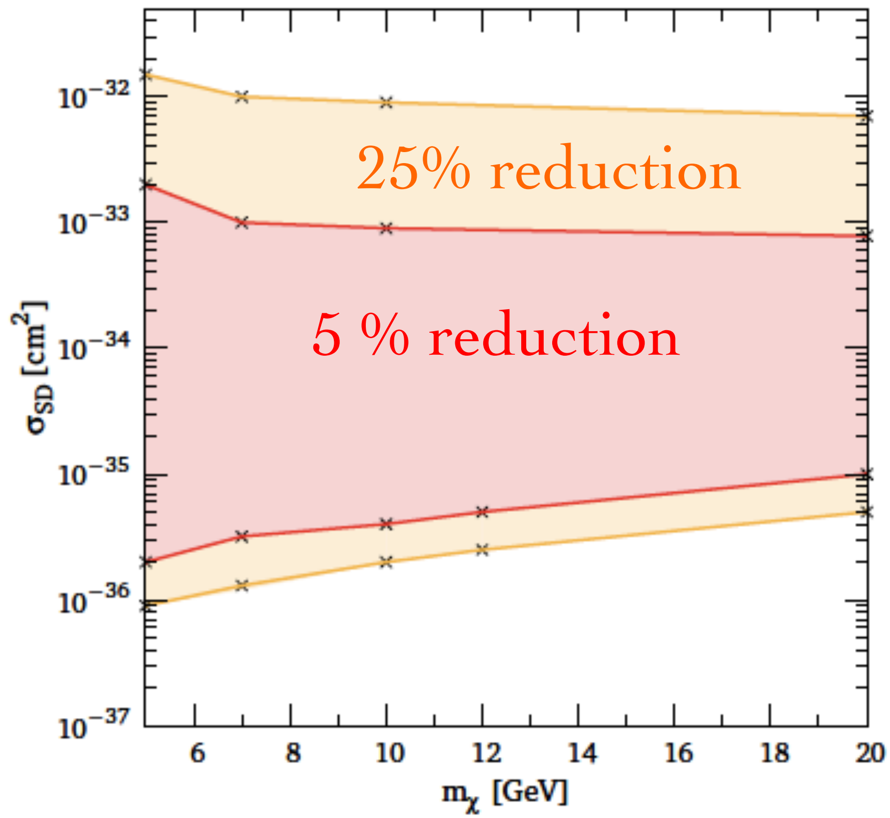


(Kouvaris and Tinyakov 11; McDermott, Yu & Zurek 11)

ADM reduction of solar neutrino fluxes – `Neutrino spectroscopy'

(Spergel & Press 85; Faulkner & Gililand 85; MTF & Sarkar 10, Taoso et al 10, Cumberbatch et at 10, Silk & Lopes 10)





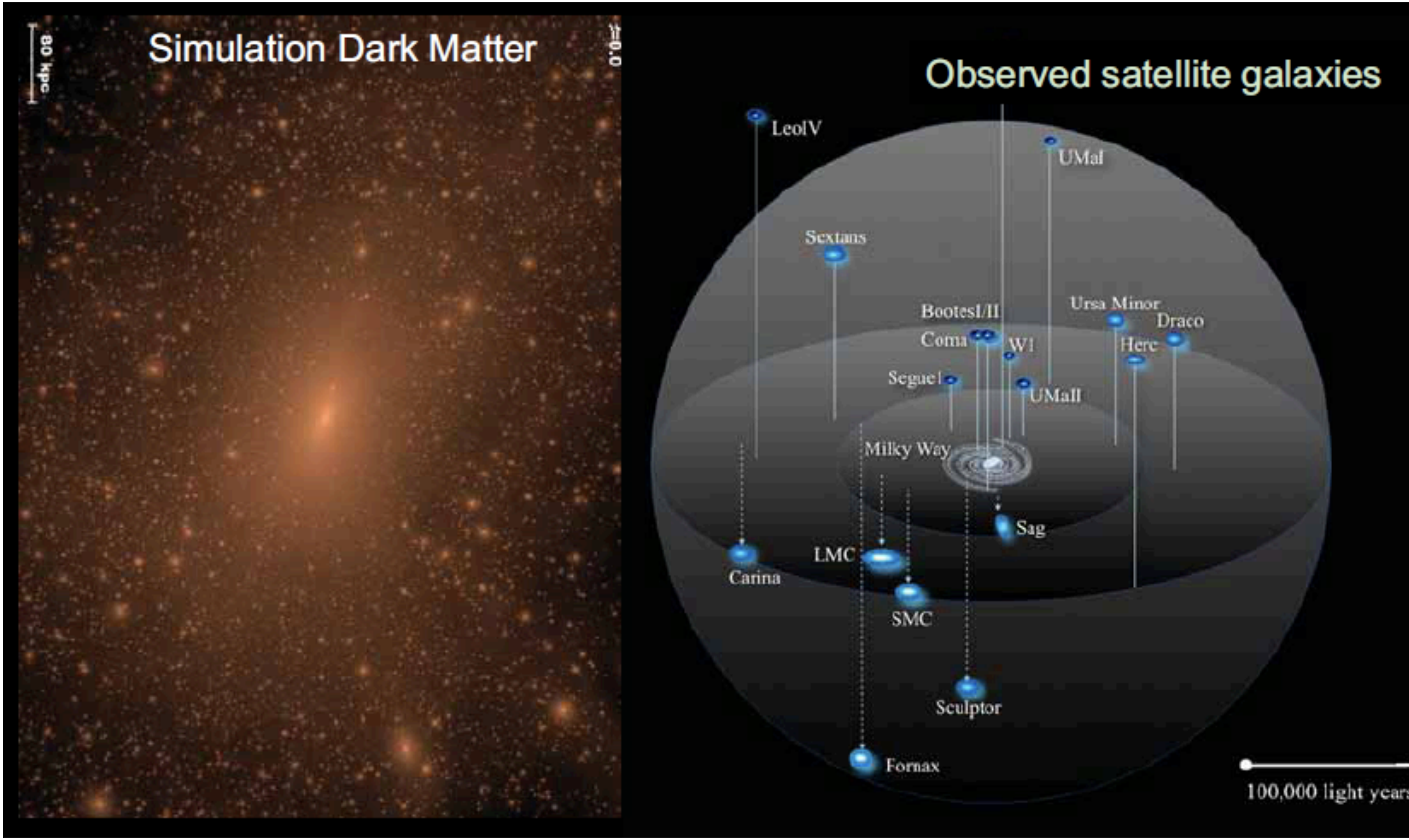
(Taoso et al 10)

The particle mass must be ~4-10 GeV to have an effect on energy transport

(too light and they 'evaporate', too heavy and their orbits do not extend out far enough)

Same range as natural for light ADM scenario and hinted at by direct detection results!

Self-interacting dark matter has been invoked to reduce excessive substructure in simulations of collisionless dark matter (Spergel & Steinhardt '99)



This may or may not still be a relevant problem to address with DM properties

Summary II

- ADM motivated by the asymmetry of baryonic matter and the desire to explain $\Omega_{\rm DM}/\Omega_{\rm B} \approx 5$
- New Strong Dynamics, e.g. Technicolor, natural framework for ADM
- Recent hints in direct detection experiments point to an interesting mass range for some classes of ADM models
- ADM from NSD has implications for collider searches, capture in stars, structure formation…
- ADM scenario much less investigated than standard WIMP paradigm – much to do!