Composite pNGB Dark Matter

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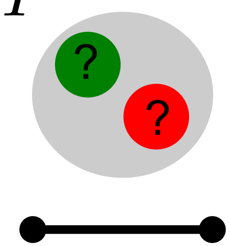
1807.xxxxx + 1707.07685 [JHEP]

***with* R. Balkin, M. Ruhdorfer and A. Weiler (TUM)**

Motivation: composite Higgs

- A light elementary scalar particle is fine-tuned: the **Higgs naturalness problem**

H



- Plausible resolution: the Higgs is bound state of new degrees of freedom

The description of the theory changes above ~ TeV, Higgs mass is naturally "screened"

$$r_H \sim (\mathrm{TeV})^{-1}$$

- In viable **composite Higgs** models, Higgs doublet arises as set of (pseudo) Nambu-Goldstone bosons

$$\mathcal{G} \xrightarrow{f} \mathcal{H}$$
$$H, \ldots$$

- Minimal model: $$SO(5) \xrightarrow{f} SO(4)$$
$$H$$

Agashe, Contino, Pomarol 2004

Motivation: Goldstone scalar dark matter

- In viable **composite Higgs** models, Higgs doublet arises as set of (approximate) Goldstone bosons

$$SO(5) \xrightarrow{f} SO(4)$$
$$H$$

- But from bottom-up perspective, no reason for H to go alone:

$$\mathcal{G} \xrightarrow{f} \mathcal{H}$$
$$H, \chi, \ldots \quad ?$$

- If stable, extra pNGB scalars make attractive WIMP candidates
- **Naturally light** and weakly coupled at low energies

Frigerio, Pomarol, Riva, Urbano 2012

- DM mass and interactions dictated by

  global symmetry + some amount of explicit breaking

pNGB dark matter

- Higgs portal to the Standard Model:

radiative,
$\propto$ explicit breaking

$$\frac{1}{f^2}\partial_\mu(h^2)\partial^\mu(\chi^*\chi) + \lambda h^2\chi^*\chi$$

leading, derivative interaction

$$f \sim 1 \text{ TeV}$$

pNGB dark matter

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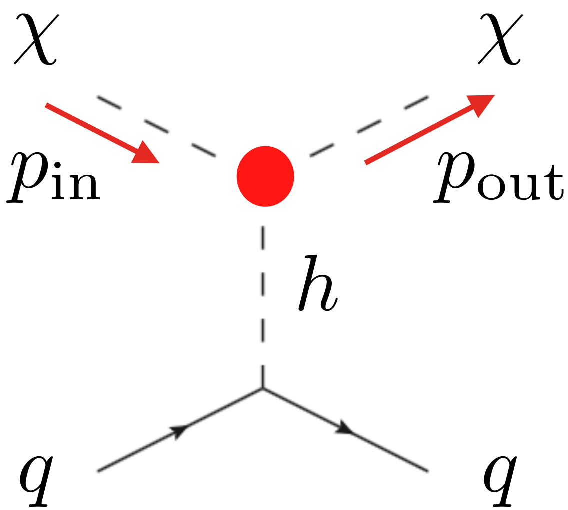

direct detection:

$$\propto \frac{(p_{\rm in} - p_{\rm out})^2}{f^2} = \frac{t}{f^2}$$

annihilation:

$$t \quad \to \quad s \simeq 4m_\chi^2$$

pNGB dark matter

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∝ explicit breaking

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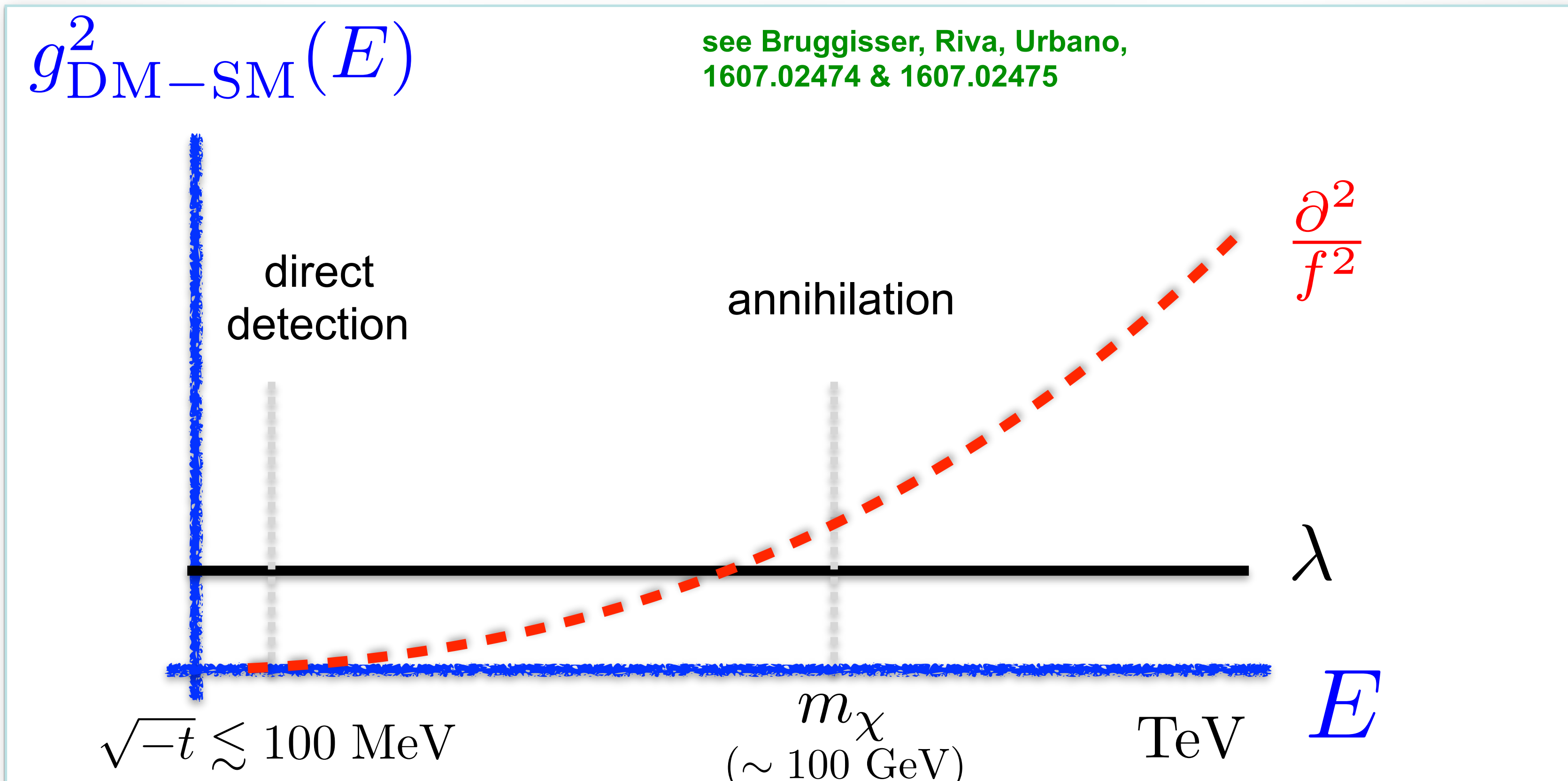
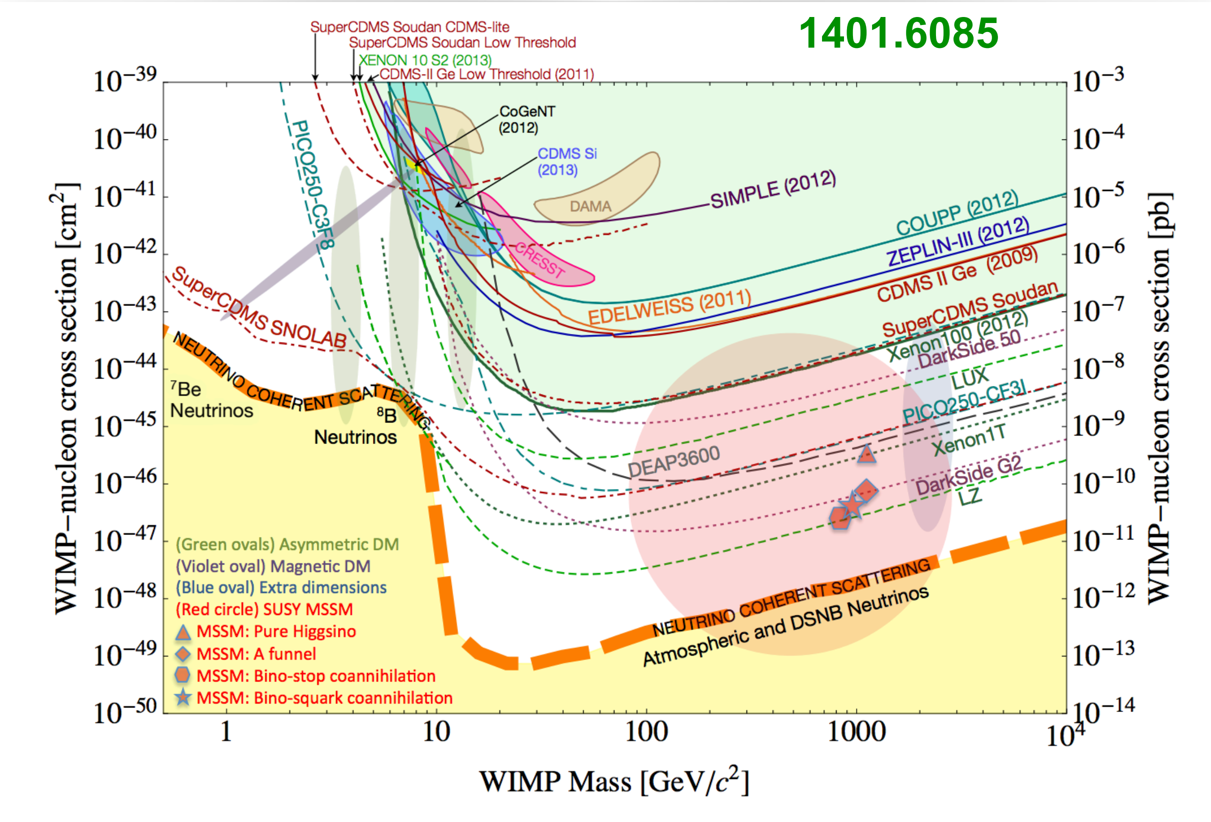


pNGB scalar is attractive WIMP

$$\frac{1}{f^2}\partial_\mu(h^2)\partial^\mu(\chi^*\chi)$$

derivative Higgs portal can easily satisfy strong constraints from **direct detection**



see **excellent overview by K. Palladino,** Tuesday morning

Origin of DM stability?

Gripaios et al. 2009,
Frigerio et al. 2012
Marzocca et al. 2014

- Real scalar with parity symmetry,

$$SO(6)/SO(5) \quad \rightarrow \quad (H,\eta) \sim \mathbf{4}+\mathbf{1} \qquad\qquad \eta \xrightarrow{P_\eta} -\eta$$

In this case, some **assumptions** needed on UV completion:

WZW term $$\frac{n_W}{16\pi^2}\,\eta\,(g^2 W^a_{\mu\nu}\tilde{W}^{a\,\mu\nu} - g'^{\,2} B_{\mu\nu}\tilde{B}^{\mu\nu})$$

Balkin, Ruhdorfer, Salvioni, Weiler, 1707.07685

- Complex scalar charged under unbroken *U*(1), e.g.

$$SO(7)/SO(6) \quad \rightarrow \quad (H,\chi) \sim \mathbf{4}+\mathbf{1}_\pm \qquad\qquad U(1)_{\rm DM} \subset SO(6)$$

Can be weakly **gauged, robust DM stabilization**
+ consequences on phenomenology

Couplings of elementary fermions

- Non-derivative interactions of DM are subleading, **but** important for pheno:

direct detection

$$\frac{1}{f^2}\partial_\mu(h^2)\partial^\mu(\chi^*\chi) + \lambda h^2\chi^*\chi$$

Strength is model-dependent: Yukawas from partial compositeness

$$\mathcal{L}_{\rm UV} \sim \epsilon_q \bar{q}_L \mathcal{O}_q + \epsilon_u \overline{u}_R \mathcal{O}_u + \epsilon_d \overline{d}_R \mathcal{O}_d$$

- Pick reprs. for the $\mathcal{O}_i$ ➡ fix size of breaking of DM shift symmetry

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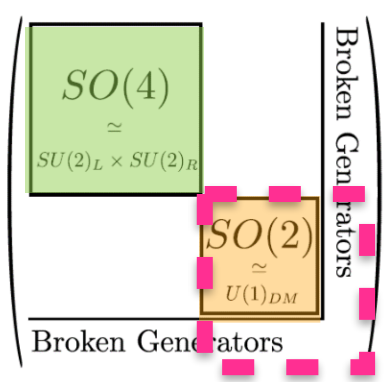
Example:

$$SO(7)/SO(6)$$



$$SO(4)_{\rm SM} \times SO(3)'$$

$$\{T^{\rm DM}, X_{\rm Re}, X_{\rm Im}\}$$

$$U(1)_{\rm DM}$$

DM shift symmetries

Three scenarios

DM shift symmetry is…

1. Broken by top quark couplings

2. Broken by bottom quark couplings

3. Respected by all SM fermions

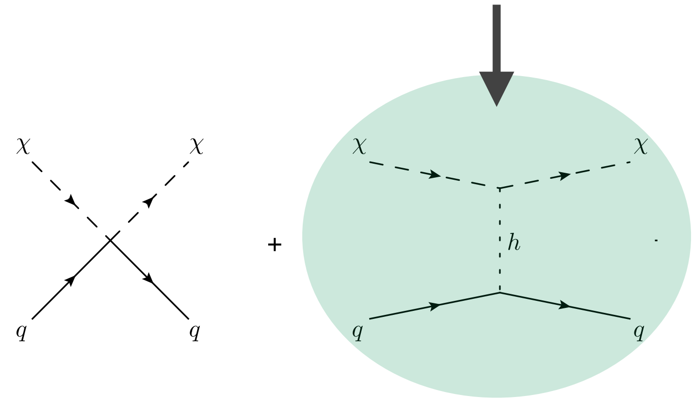
1. Top quark breaks DM shift symmetry

- Top quark loops give $m_\chi^2 \chi^* \chi + \lambda h^2 \chi^* \chi + \ldots$

  with

$$m_\chi \gtrsim m_h \qquad \lambda \lesssim \frac{\lambda_h}{2} \sim \text{few}\,\%$$

- Direct detection

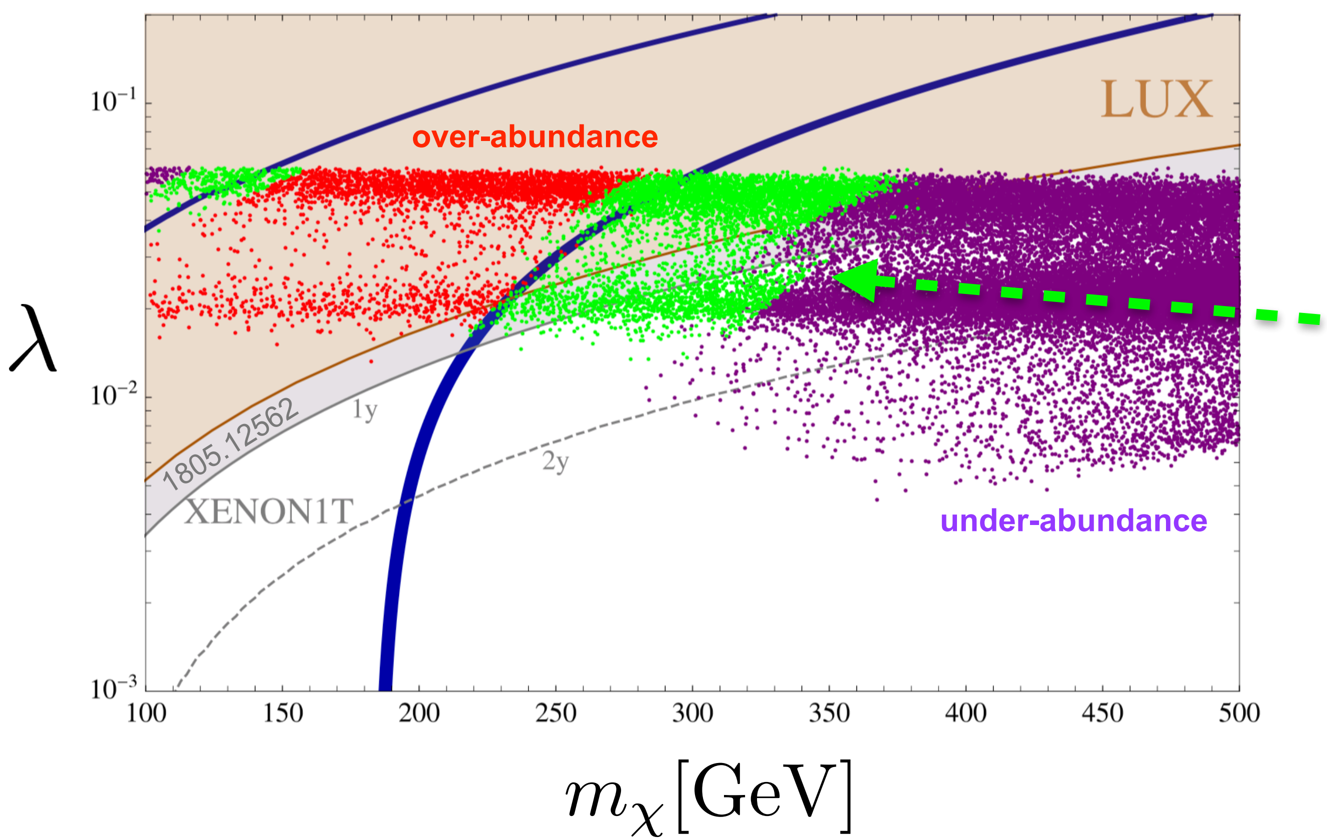


$$\frac{1}{2f^2} \ll \frac{\lambda}{m_h^2}$$

$$\rightarrow \quad \sigma_{\rm SI}^{\chi N} \simeq \frac{f_N^2}{\pi} \frac{m_N^4 \lambda^2}{m_\chi^2 m_h^4} \sim 4 \times 10^{-46}\,\text{cm}^2 \left(\frac{\lambda}{0.03}\right)^2 \left(\frac{300\ \text{GeV}}{m_\chi}\right)^2$$

$(f_N \simeq 0.30)$

1. Top quark breaks DM shift symmetry



Balkin, Ruhdorfer, Salvioni, Weiler 1707.07685

correct relic density

annihilation via derivative + marginal Higgs portals

$$\rightarrow \quad \sigma_{\rm SI}^{\chi N} \simeq \frac{f_N^2}{\pi}\frac{m_N^4 \lambda^2}{m_\chi^2 m_h^4} \sim 4\times 10^{-46}\,{\rm cm}^2 \left(\frac{\lambda}{0.03}\right)^2 \left(\frac{300\ {\rm GeV}}{m_\chi}\right)^2$$

2. Bottom quark breaks DM shift symmetry

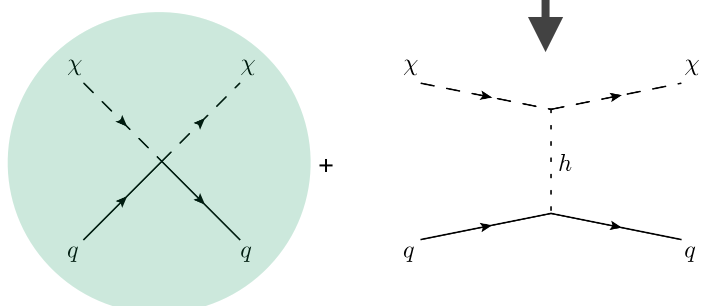
- Bottom quark loops give $m_\chi^2 \chi^* \chi + \lambda h^2 \chi^* \chi + \ldots$

  with

$$m_\chi \lesssim m_h \qquad \lambda \sim \frac{N_c y_b^2}{8\pi^2}\frac{m_*^2}{f^2} \lesssim 10^{-3}$$

very suppressed

- Direct detection



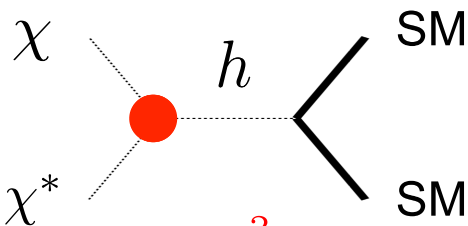
$$\frac{1}{2f^2} \qquad \gg \qquad \frac{\lambda}{m_h^2}$$

$$\rightarrow \qquad \sigma_{\rm SI}^{\chi N} \simeq \frac{\tilde{f}_N^2}{4\pi}\frac{m_N^4}{m_\chi^2 f^4} \sim 10^{-47}\,{\rm cm}^2 \left(\frac{1\ {\rm TeV}}{f}\right)^4 \left(\frac{100\ {\rm GeV}}{m_\chi}\right)^2$$

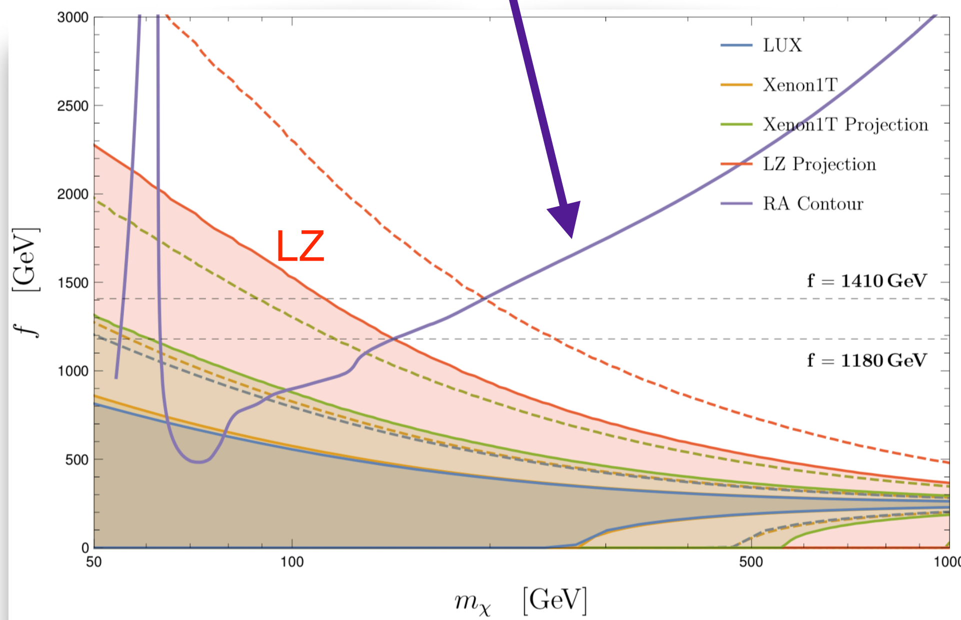
$(\tilde{f}_N \simeq 0.07)$

2. Bottom quark breaks DM shift symmetry

Annihilation dominated by derivative portal: **one-to one correspondence** between f and m_χ



$$\sim \frac{4m_\chi^2}{f^2}$$



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3. All SM fermions respect DM shift symmetry

- We can construct a model where all fermions exactly preserve the DM shift symmetry. For example in $SO(7)/SO(6)$:

$$q_L \sim \mathbf{7}$$
$$u_R, d_R \sim \mathbf{21}$$

- Coupling between DM and SM is $\sim \frac{1}{f^2}\partial(h^2)\partial(\chi^*\chi)$
- **Direct detection cross section negligible**

- But also, DM has no potential…

Balkin, Ruhdorfer, Salvioni, Weiler, 1807.xxxxx

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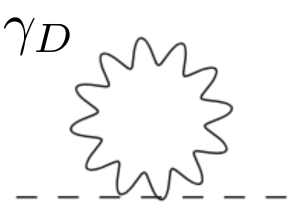
- **Gauging of** $U(1)_{\mathrm{DM}}$



$$m_\chi^2 \approx \frac{3g_D^2}{8\pi^2} m_\rho^2$$

(think of pion mass difference from EM)

$\lambda h^2 \chi^* \chi$ **not** generated at 1 loop

Gauged $U(1)_{DM}$

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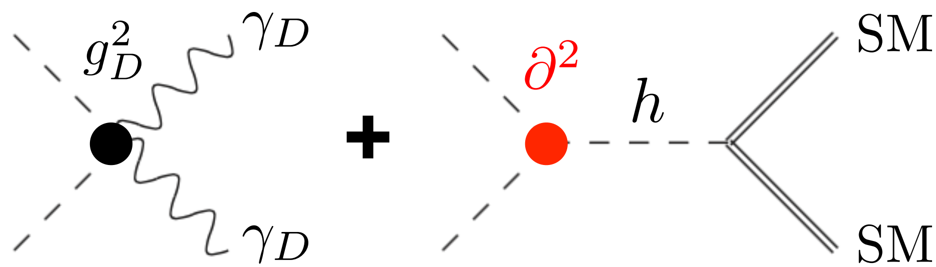
- Gauging has **important effects on pheno**

- Take $U(1)_{DM}$ and $U(1)_Y$ **unmixed kinetically** (motivated by explicit model), DM-SM interactions:

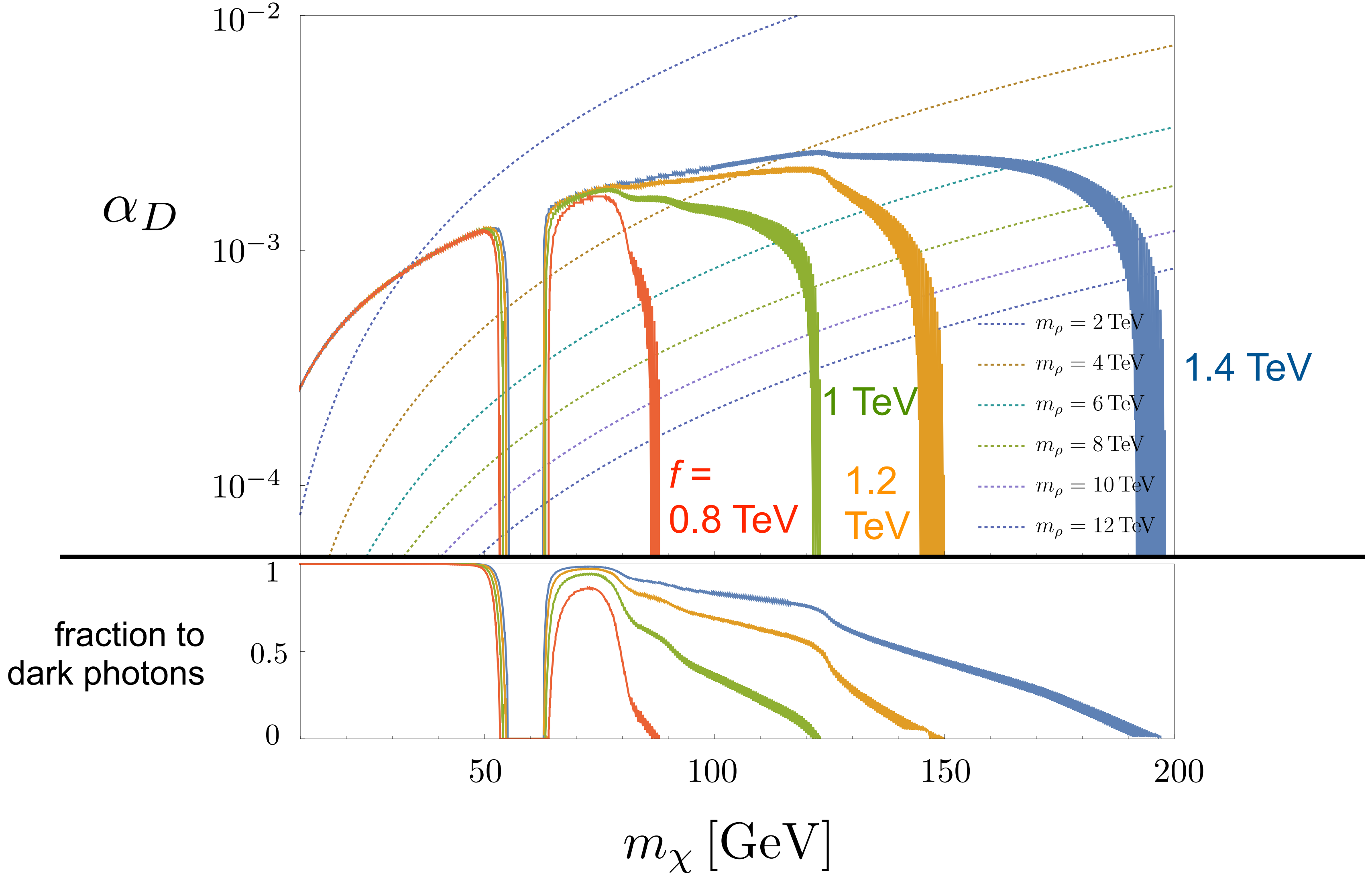


- Dark photon can get a Stückelberg mass. If very light (or massless), it mediates long-range DM self-interactions

- If $m_\chi > m_{\gamma_D}$, new annihilation channel for the DM

$$\chi\chi^* \to \gamma_D\gamma_D \qquad \langle \sigma v \rangle \approx \frac{2\pi\alpha_D^2}{m_\chi^2}$$

DM relic abundance



colored bands: correct DM relic density

Constraints?

- Take **massless** dark photon

Constraints: $N_{\rm eff}$

- Take **massless** dark photon
- Bounds on extra radiation from BBN and CMB?

- At early times, the dark sector (DM + dark radiation) remains in kinetic equilibrium with the Standard model via $\chi f \to \chi f$ scattering mediated by (derivative) Higgs exchange

- Below $T_{\rm dec}$ where the two sectors decouple, entropies are separately conserved. At BBN:

$$\frac{g_{A_D}\xi(T_{\rm BBN})^3}{g_{*{\rm s,vis}}(T_{\rm BBN})} = \frac{(g_{A_D}+\cancel{g_\chi})\xi(T_{\rm dec})^3}{g_{*{\rm s,vis}}(T_{\rm dec})} \qquad \xi \equiv \frac{T_D}{T_{\rm vis}}\,, \qquad \xi(T_{\rm dec}) = 1$$

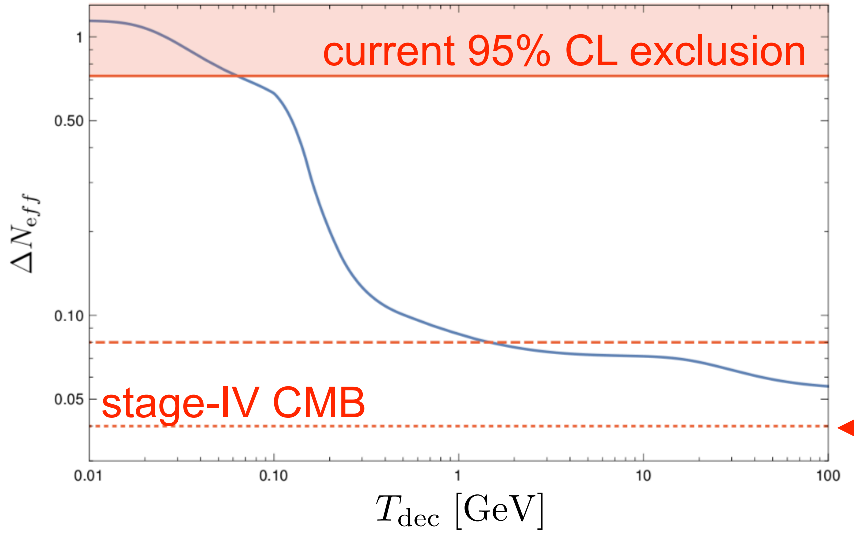
$$g_{A_D}\xi(T_{\rm BBN})^4 \leq \frac{7}{8}\,2\,(N_{\rm eff}-3)$$

Feng et al. 2008
Ackerman et al. 2008
Feng et al. 2009

$$N_{\rm eff} \leq 3.90 \ \ @ \ \ 95\% \ {\rm CL} \quad \to \quad g_{*s,vis}(T_{\rm dec}) \geq 12.8$$

$$\Rightarrow \qquad T_{\rm dec} \gtrsim 100 \ {\rm MeV}$$

CMB bounds and decoupling temperature



$\sigma(N_{\rm eff}) = 0.02$

1309.5383 (Snowmass)

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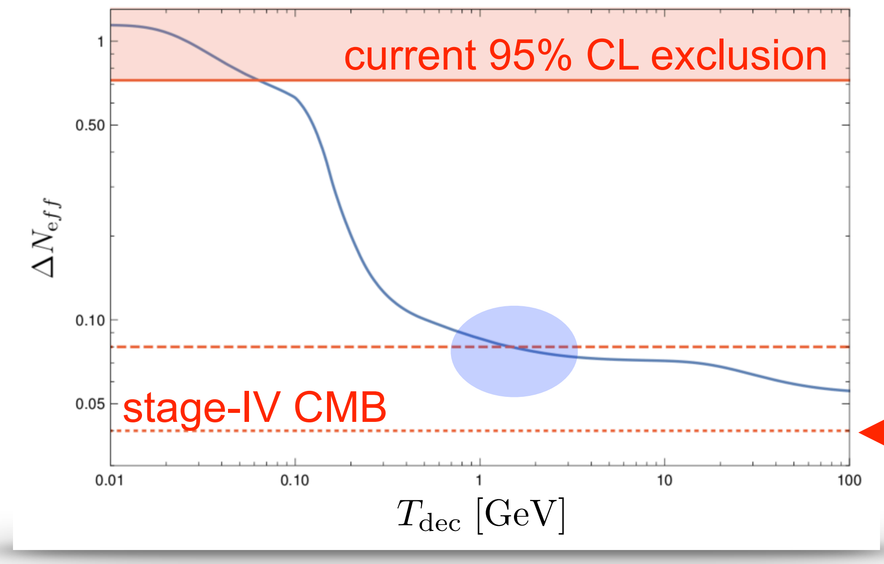

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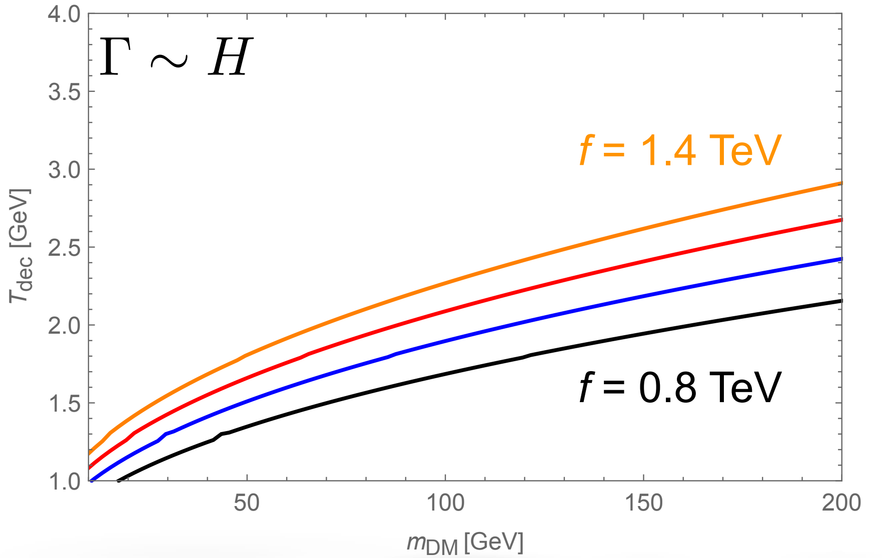
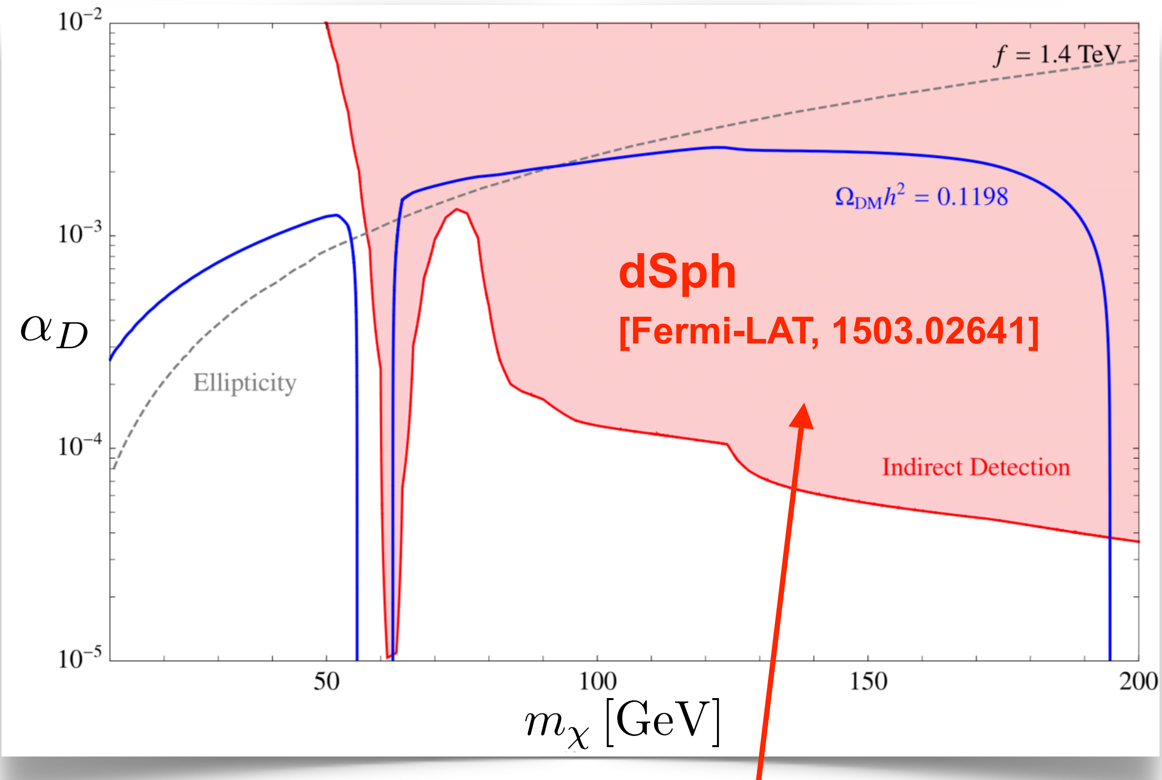


$$\Gamma(T) \approx \sum_f \frac{g_i}{6 m_\chi T} \int \frac{d^3p}{(2\pi)^3} e^{-\sqrt{m_i^2+p^2}} \frac{p}{\sqrt{m_i^2+p^2}} \int_{-4p^2}^{0} dt(-t) \frac{d\sigma_{\chi f_i \to \chi f_i}}{dt}$$

Gondolo et al. 2012

Constraints: DM

- Take **massless** dark photon (it is dark radiation today)



Sommerfeld-enhanced annihilation **to SM**

$$S = \frac{2\pi\alpha_D/v_{\rm rel}}{1-e^{-2\pi\alpha_D/v_{\rm rel}}} \qquad (v_{\rm rel}^{\rm dSph} \sim 10^{-4})$$

Constraints: DM

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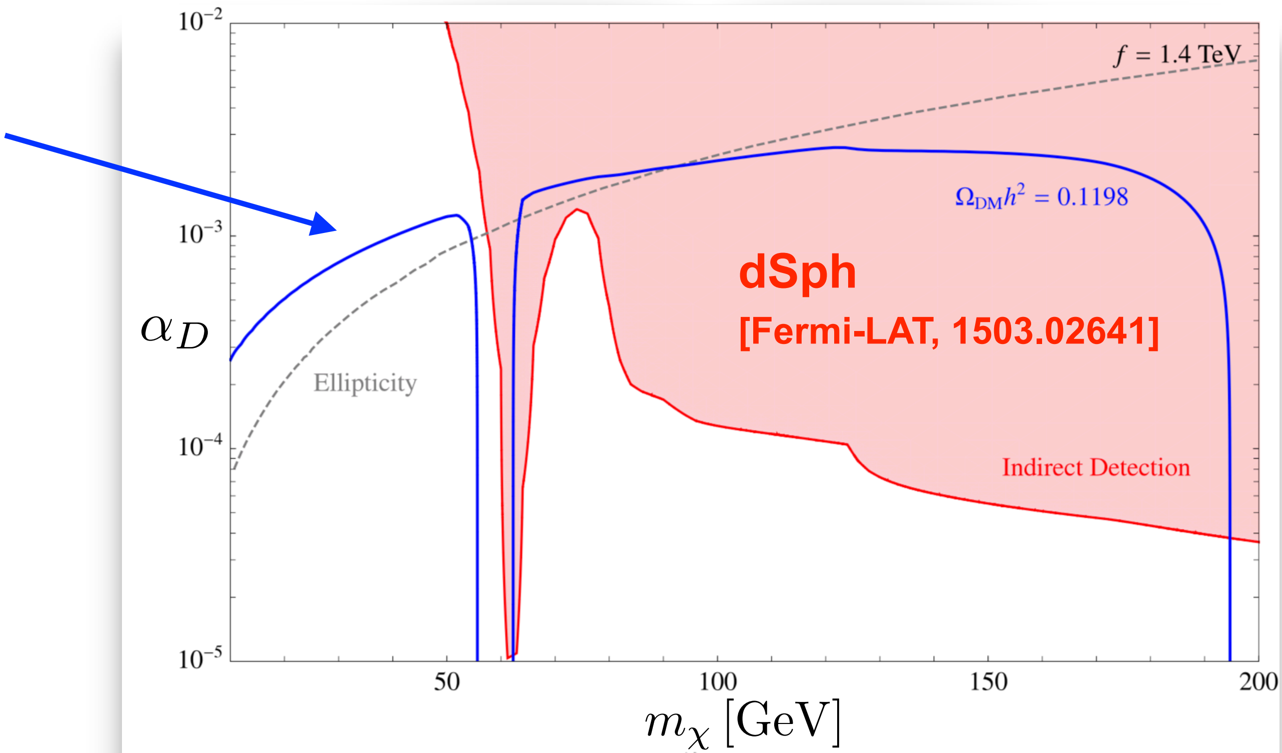
annihilation to $\gamma_D \gamma_D$

($b\bar{b}$ very suppressed)



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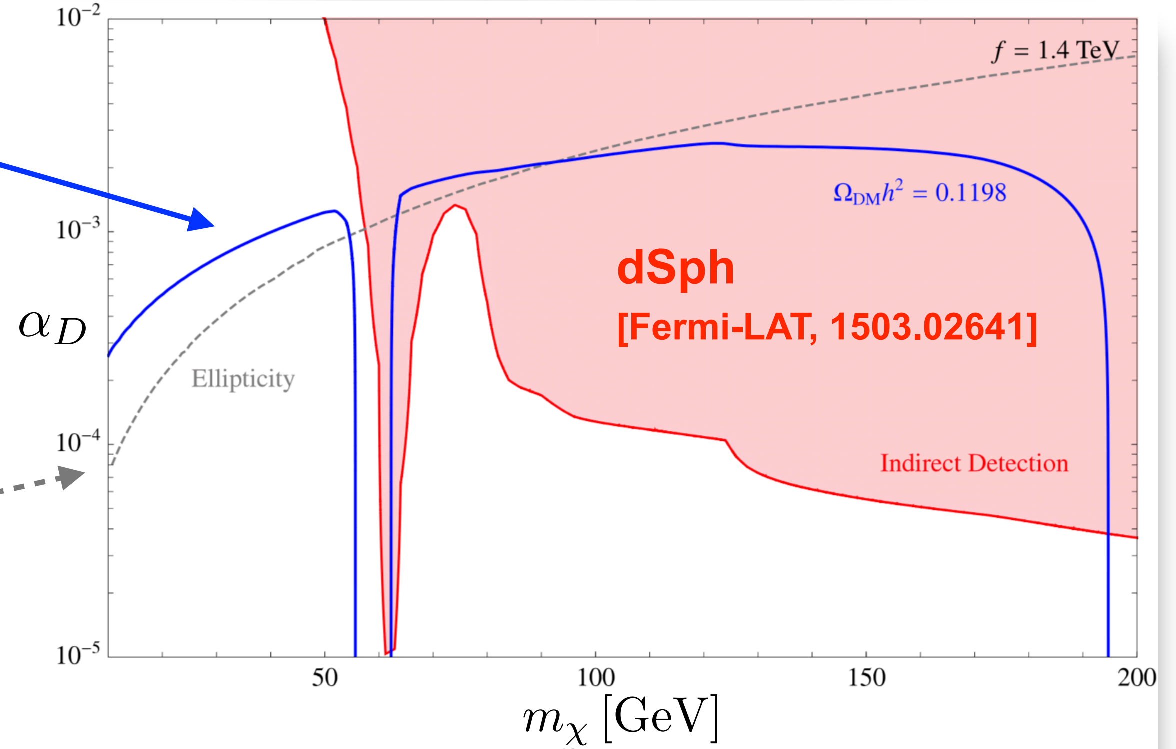
limit on long-range DM self-interaction (ellipticity of grav. potential of NGC720) according to **Agrawal et al. 1610.04611**



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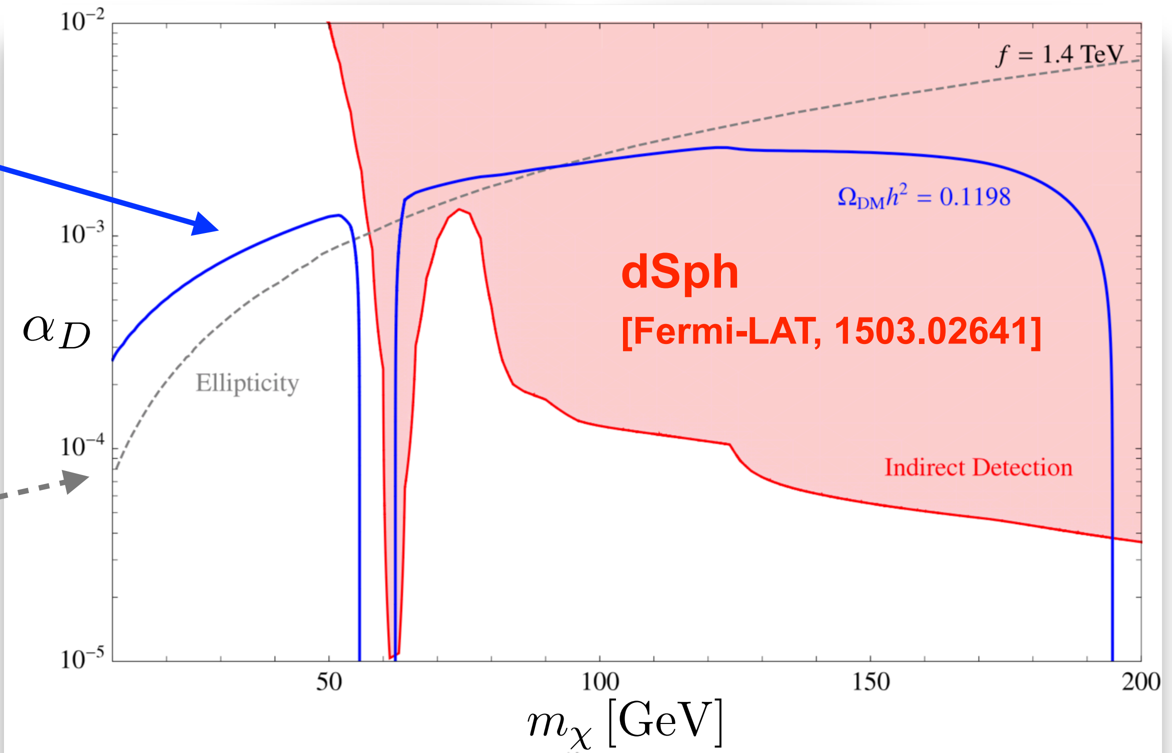

limit on long-range DM self-interaction (ellipticity of grav. potential of NGC720) according to **Agrawal et al. 1610.04611**

invisible Higgs width @LHC:

$$\Gamma(h \to \chi\chi^*) \simeq \frac{m_h^3 v^2}{16\pi f^4}\sqrt{1 - \frac{4m_\chi^2}{m_h^2}}$$

$BR_{inv} < 0.24$

CMS 1610.09218

$$f \gtrsim 1.2 \text{ TeV}$$

Summary & the way ahead

- A composite pNGB scalar that accompanies the Higgs can make compelling WIMP DM candidate
- "UV-robust" stabilization by dark $U(1)_{\rm DM}$ symmetry of strong sector
- **Derivative Higgs portal** to SM, **direct detection xsec naturally very suppressed**

- Pheno strongly depends on the **"quality" of the DM shift symmetries** (model dependence):

    - Broken by top quark couplings: tested now @ XENON1T
    - Broken by bottom quark: @ next generation experiments
    - Fully respected by SM fermions:
      Leading breaking from gauging of $U(1)_{\rm DM}$
      Out of reach for direct detection, but signatures
      in cosmo, astrophysics, and at colliders

Backup

Coupling of the RH bottom

- The coupling of b_R may break the DM shift symmetry, for ex. $b_R \sim \mathbf{7}_{-1/3}$
- Contributes to DM mass as

$$\mu^2_{\rm DM} \simeq \frac{N_c}{4\pi^2 f^2} \int_0^\infty dp^2 p^2 \left(\sum_{j=1}^{N_S} \frac{|\epsilon^j_{bS}|^2}{p^2+m^2_{S^{(b)}{}_j}} - \sum_{i=1}^{N_Q} \frac{|\epsilon^i_{bQ}|^2}{p^2+m^2_{Q^{(b)}{}_i}} \right)$$

UV-finite if $\sim \frac{1}{p^6}$ or faster

obtain calculability through
generalized **Weinberg Sum Rules**,
which give relations between parameters

Marzocca et al. 2012
Pomarol, Riva 2012

Marzocca, Urbano 2014

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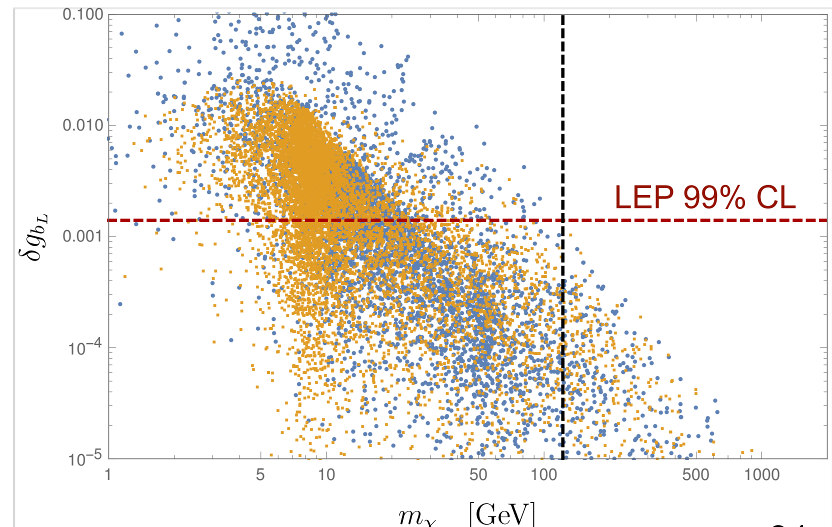
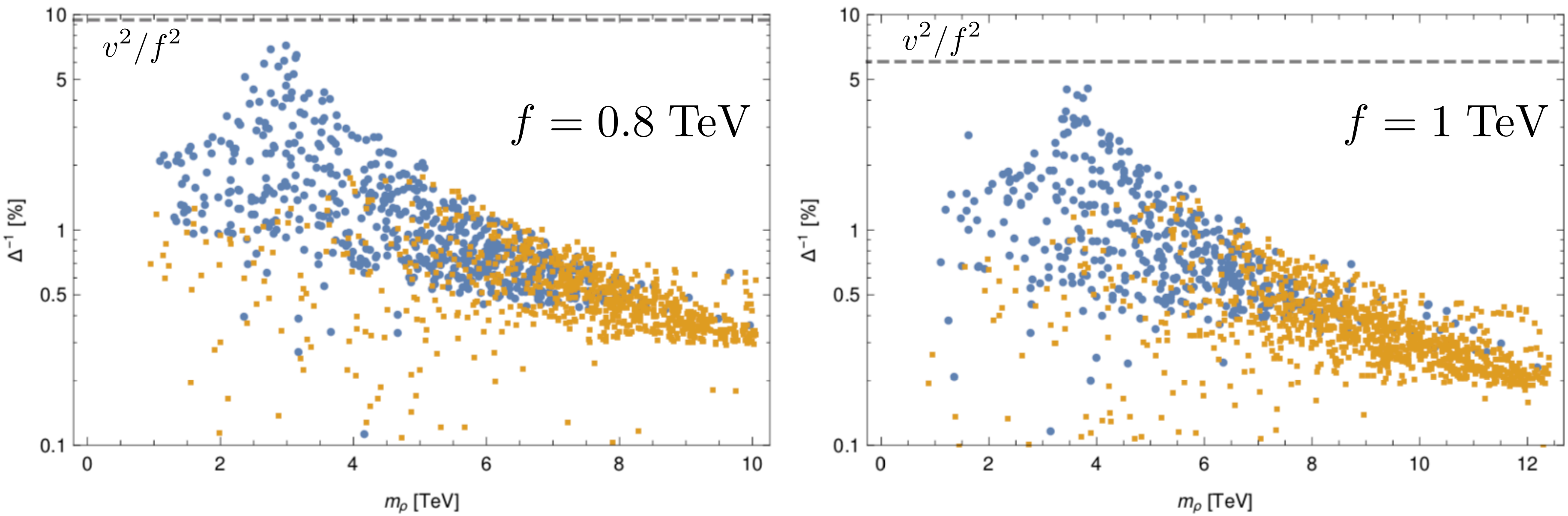
Marzocca, Urbano 2014

- In this model, tree-level corrections to Z-b_L-b_L are generated



Fine-tuning, 7 + 21 model

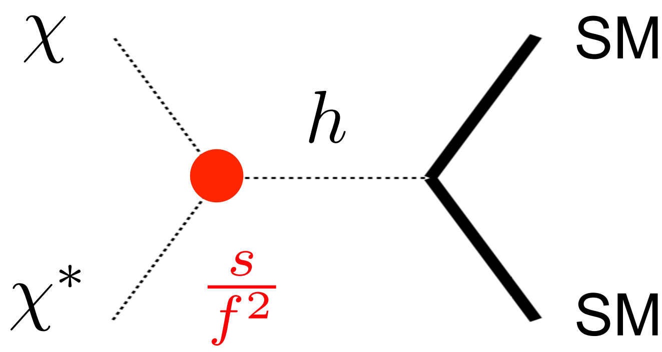


orange: all top partners above 1 TeV

"doubly-tuned" model: $$\Delta^{-1} \sim \frac{v^2}{f^2}\frac{\epsilon^2}{m_*^2} \sim \frac{v^2}{f^2}\frac{y_t}{g_*} < \frac{v^2}{f^2}$$

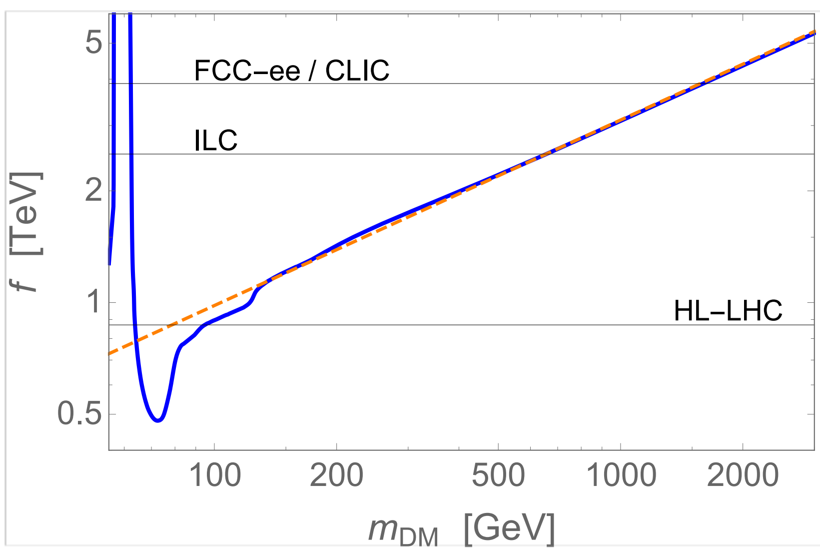
see e.g. Panico, Redi, Tesi, Wulzer, 1210.7114

Constraint from DM relic density



reproducing relic density fixes **one-to-one relation** between

$m_{\rm DM}$ and f



blue: full Boltzmann solution

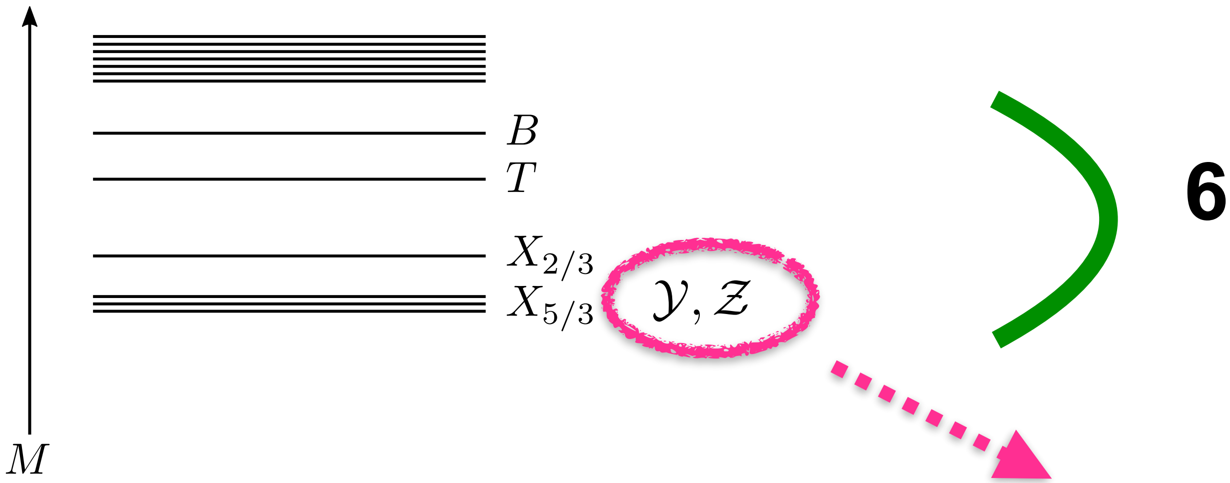
orange:

$$\frac{1}{2}\,\sigma v_{\rm rel} \sim 3\cdot 10^{-26}\,{\rm cm}^3\,{\rm s}^{-1}$$

$$\sigma \sim \frac{9}{4\pi}\,\frac{m_{\rm DM}^2}{f^4}$$

Collider pheno, sketch

$SO(7)/SO(6)$



typical spectrum

top partners charged under

$$U(1)_{\rm DM}$$

$$\mathcal{Y}, \mathcal{Z} \to t + \chi^{(*)}$$

current LHC bounds:

$$M_X > 1.2 \text{ TeV} \qquad M_{\mathcal{Y},\mathcal{Z}} > 1.4 \text{ TeV}$$

same-sign leptons

$t\bar{t} + \text{MET}$

CMS 1705.04650