

Composite pNGB Dark Matter

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1707.07685 [JHEP], 1809.09106 [JCAP]

+ work in progress

with R.Balkin, M.Ruhdorfer and A.Weiler

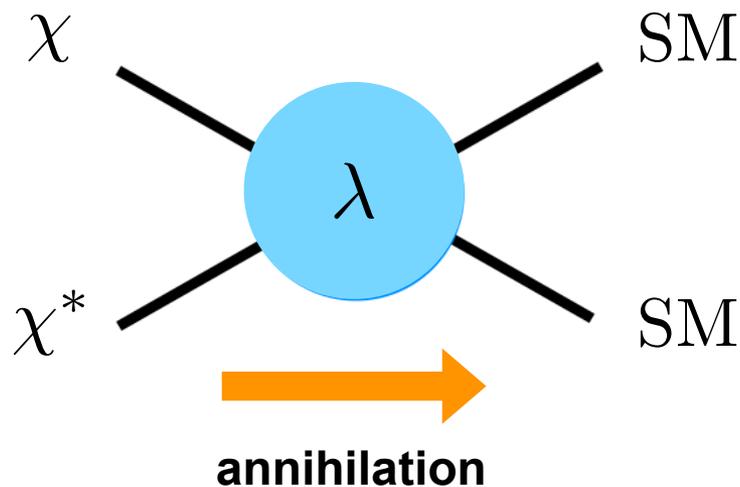


Istituto Nazionale di Fisica Nucleare

***7th Rome Joint Workshop
LNF, December 20, 2018***

Introduction: WIMP dark matter

- WIMPs have long been a favorite candidate for particle dark matter

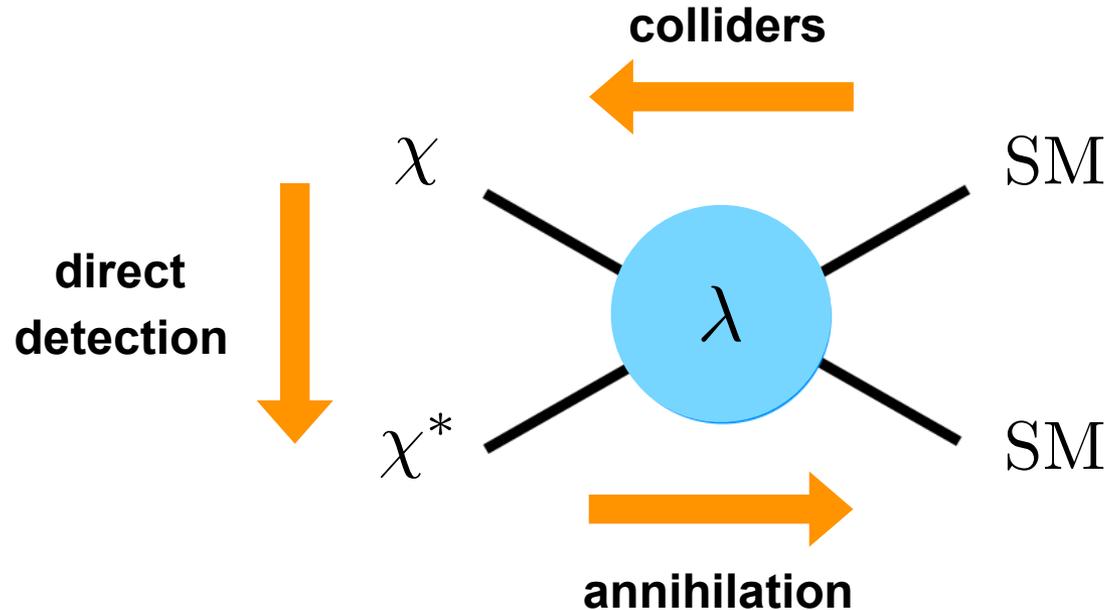


Thermal freeze-out:

$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{\pi m_\chi^2}{\lambda^2} \quad \rightarrow \quad \frac{\Omega_\chi h^2}{0.1} \sim \left(\frac{0.1}{\lambda} \right)^2 \left(\frac{m_\chi}{100 \text{ GeV}} \right)^2$$

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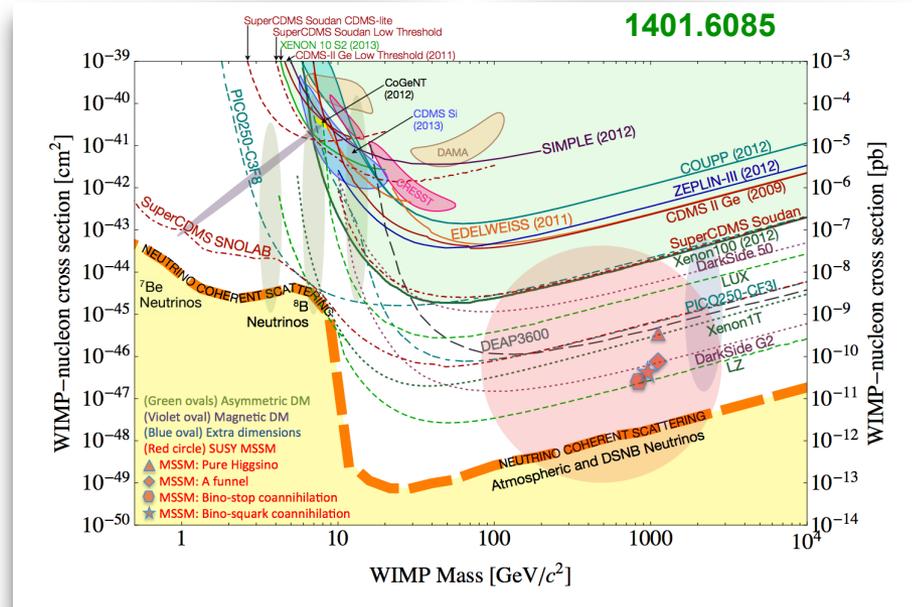
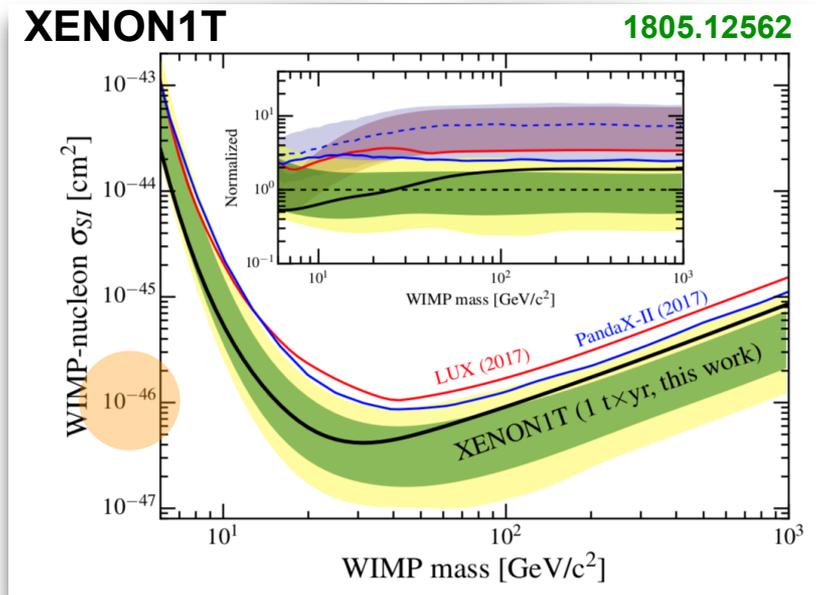
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- Relic density fixes $\lambda \propto m_{\chi}$, can be tested with **complementary probes**

Introduction: WIMP dark matter

- But so far, no signs of WIMPs at **direct detection** experiments

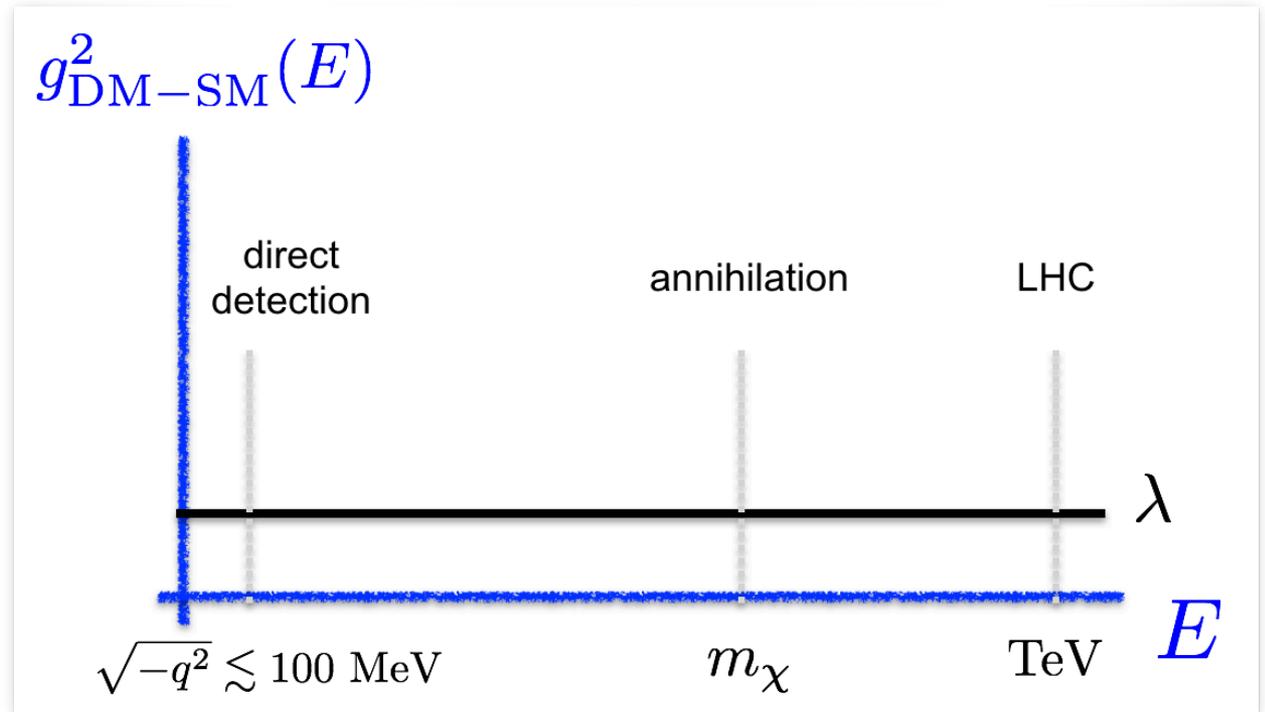


- For example: scalar DM with coupling $\mathcal{L} \ni \lambda |H|^2 |\chi|^2$

$$\sigma_{SI}^{\chi N} = \frac{f_N^2}{\pi} \frac{m_N^4}{m_\chi^2} \frac{\lambda^2}{m_h^4} \sim 10^{-44} \text{ cm}^2 \left(\frac{\lambda}{0.1} \right)^2 \left(\frac{100 \text{ GeV}}{m_\chi} \right)^2$$

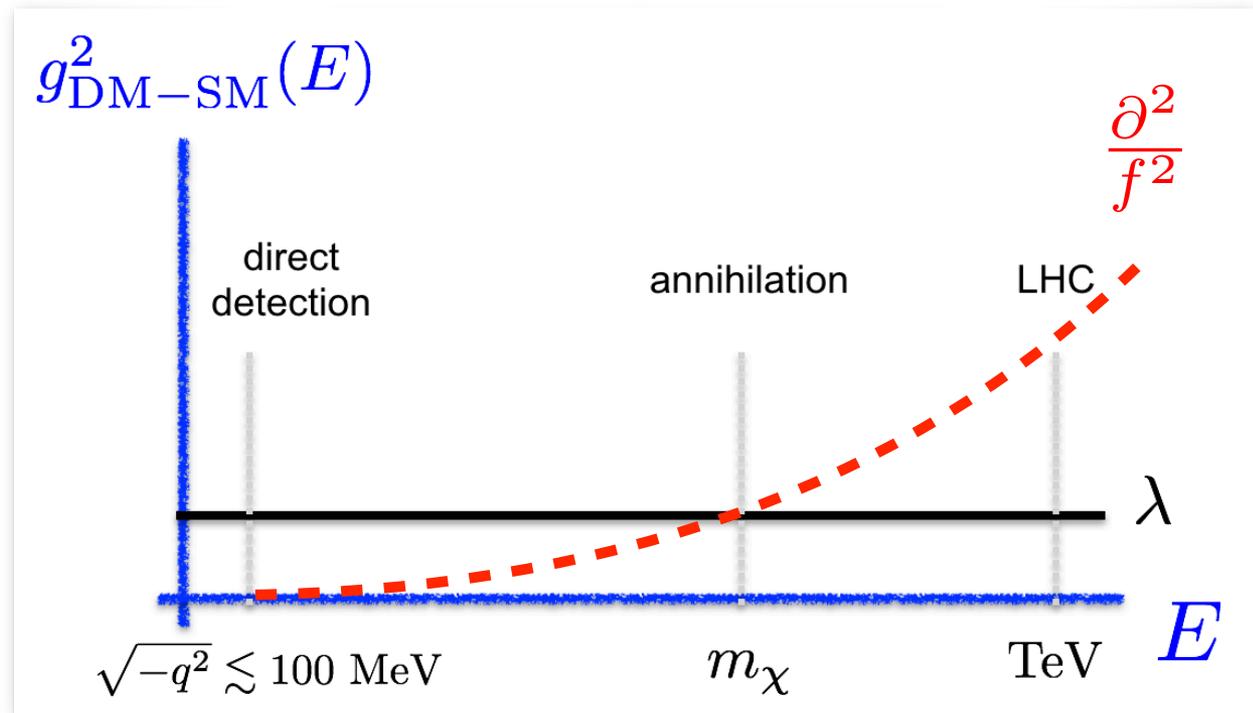
Pseudo-Goldstone dark matter

- The tension I just sketched:



Pseudo-Goldstone dark matter

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Frigerio, Pomarol,
Riva, Urbano 2012
Bruggisser, Urbano,
Riva 2016

- What about **this** instead? **Goldstone DM**:

$$\chi \rightarrow \chi + \epsilon$$



leading coupling

$$\mathcal{L} \ni \frac{1}{f^2} \partial_\mu |H|^2 \partial^\mu |\chi|^2$$

- Take scalar DM candidate χ

$$\mathcal{L}_{\text{BSM}} = |\partial_\mu \chi|^2 + \frac{1}{f^2} \partial_\mu |\chi|^2 \partial^\mu |H|^2 - m_\chi^2 |\chi|^2 - \lambda |\chi|^2 |H|^2 + \dots$$

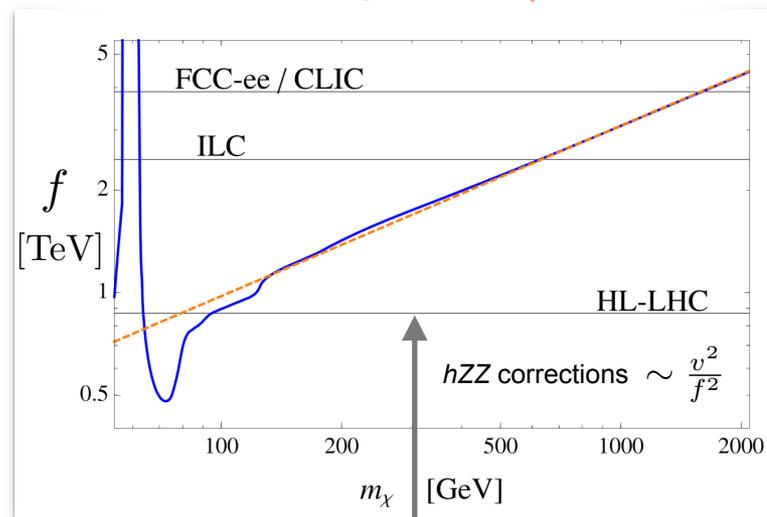

pNGB Dark Matter

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- Freeze-out reproduces relic density for $f \sim \text{TeV}$ and $m_\chi \sim m_h$

$$\langle \sigma v \rangle \simeq \frac{m_\chi^2}{\pi f^4} \quad \rightarrow \quad f \simeq 1.1 \text{ TeV} \left(\frac{m_\chi}{130 \text{ GeV}} \right)^{1/2}$$



$$\frac{1}{2f^2} \partial_\mu |H|^2 \partial^\mu |H|^2$$

pNGB Dark Matter

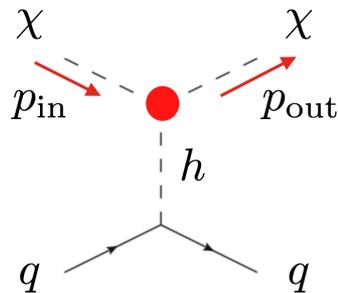
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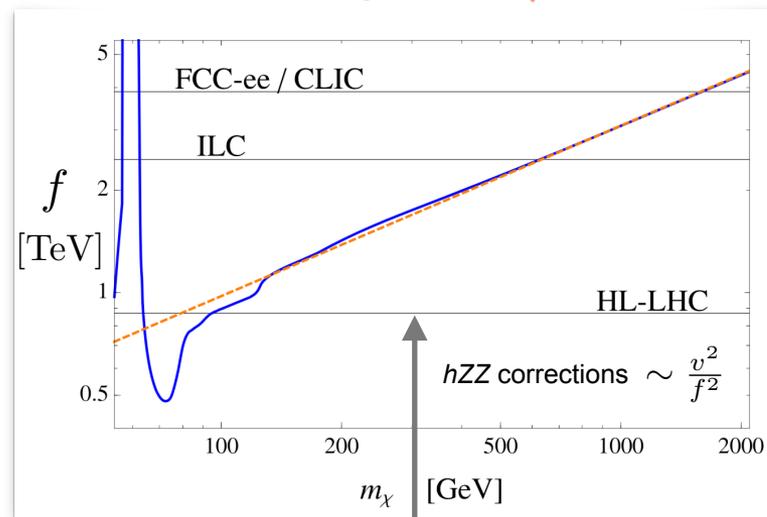
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- Direct detection extremely suppressed



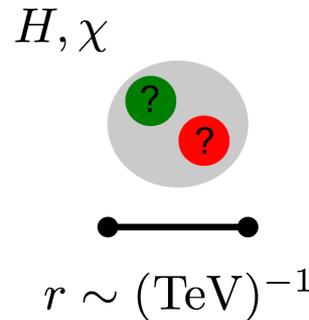
$$\propto \frac{(p_{\text{in}} - p_{\text{out}})^2}{f^2} = \frac{t}{f^2} \lesssim \frac{(100 \text{ MeV})^2}{\text{TeV}^2} \sim 10^{-8}$$



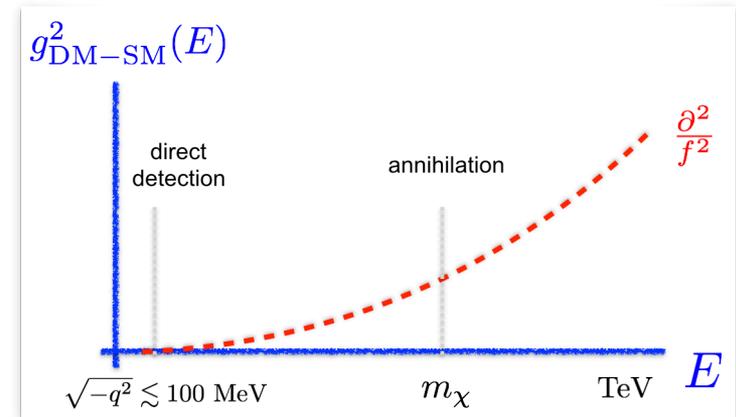
$$\frac{1}{2f^2} \partial_\mu |H|^2 \partial^\mu |H|^2$$

pNGB Dark Matter

- This picture can arise if **both Higgs and DM** are composite pseudo-Goldstones with decay constant $f \sim \text{TeV}$



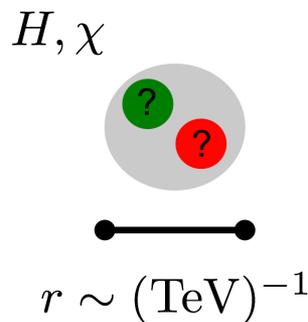
Frigerio, Pomarol,
Riva, Urbano 2012



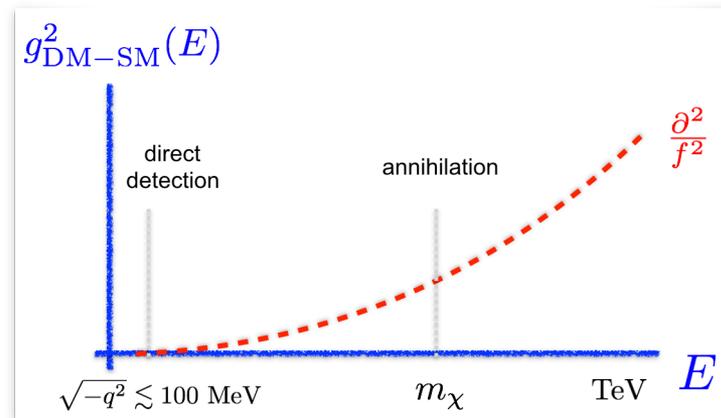
- Attractive solution to Higgs naturalness problem
- Extra pNGB stabilized by discrete or continuous symmetry
- Naturally light** and weakly coupled at low energies

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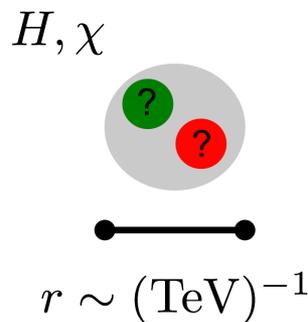


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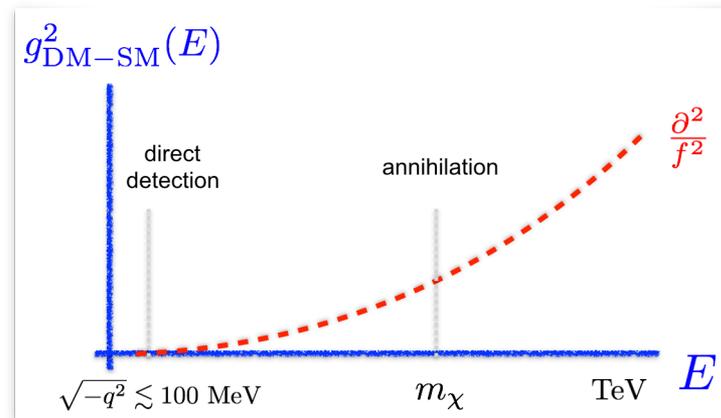
Hold up, wait a minute...



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Frigerio, Pomarol,
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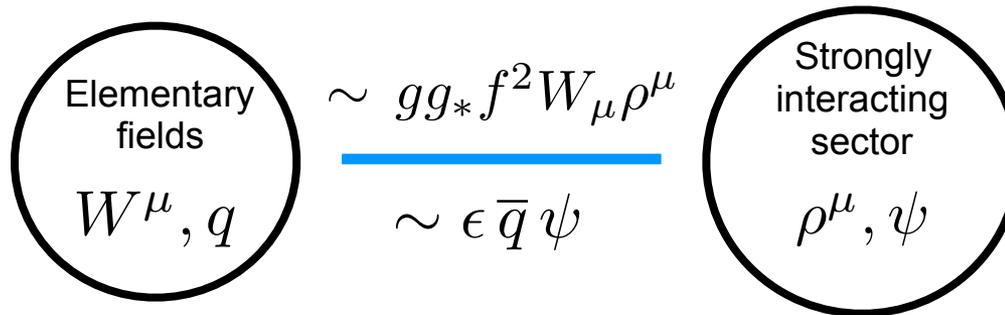


- Explicit symmetry breaking required to generate (radiatively) DM mass

➔ in general, $\lambda |\chi|^2 |H|^2$ appears too. **Dangerous even at 1-loop**

- Need to write down **concrete models** where $\lambda \approx 0$ while $m_{\chi,h} \sim O(100) \text{ GeV}$

- **Higgs and DM** as approximate Goldstone bosons, like SM pions



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

$$H, \chi, \dots$$

$$m_{\rho, \psi} \sim g_* f$$

Agashe, Contino,
Pomarol 2004

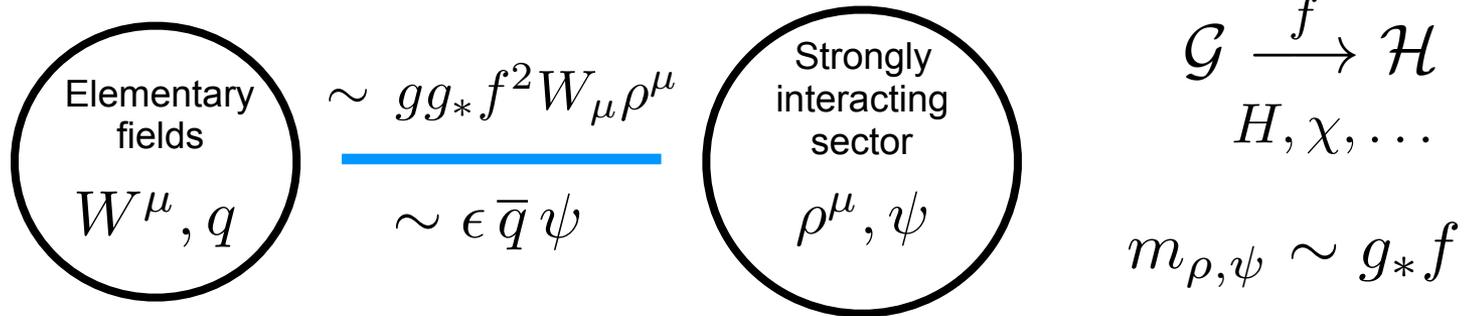
- SM vectors coupled by gauging $SU(2)_L \times U(1)_Y \subset \mathcal{H}$ (~ photon-rho mixing)
- Fermions also coupled linearly to fermionic resonances
- Except pNGBs, all states are **partially composite**:

Kaplan 1991

$$|q_{\text{physical}}\rangle = \frac{m_\psi}{\sqrt{m_\psi^2 + \epsilon^2}} |q_{\text{elementary}}\rangle + \frac{\epsilon}{\sqrt{m_\psi^2 + \epsilon^2}} |\psi\rangle$$

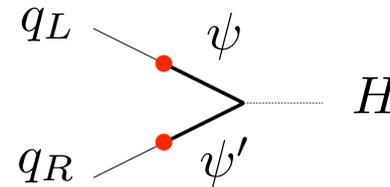
Framework: composite pNGB Higgs

- Higgs and DM as approximate Goldstone bosons, like SM pions

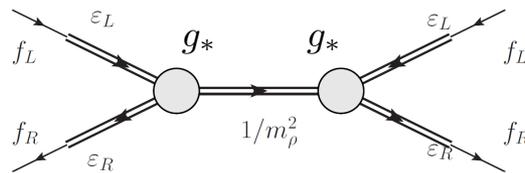


Agashe, Contino, Pomarol 2004

- Fermion masses $m_q \sim g_* \frac{\epsilon_L}{m_\psi} \frac{\epsilon_R}{m_{\psi'}} v$



- “RS-GIM” flavor protection: FCNCs suppressed by small mixings



$$\sim \theta_L^i \theta_R^j \theta_L^k \theta_R^l \frac{1}{f^2} \left(\bar{f}_L^i f_R^j \bar{f}_L^k f_R^l \right)$$

Frigerio, Nardecchia, Serra, Vecchi 2018

(some tension remains, Kaon mixing and neutron EDM)

Origin of DM stability?

- Minimal realistic model $SO(5)/SO(4)$, Higgs doublet as 4 GBs

Agashe, Contino,
Pomarol 2004

- Real scalar with parity, e.g.

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

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

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

Balkin, Ruhdorfer,
Salvioni, Weiler 2017

$$SO(7)/SO(6) \rightarrow (H, \chi) \sim \mathbf{4} + \mathbf{1}_\pm \quad \chi \rightarrow e^{i\alpha} \chi$$

can be weakly **gauged**  $U(1)_{\text{DM}} \subset SO(6)$

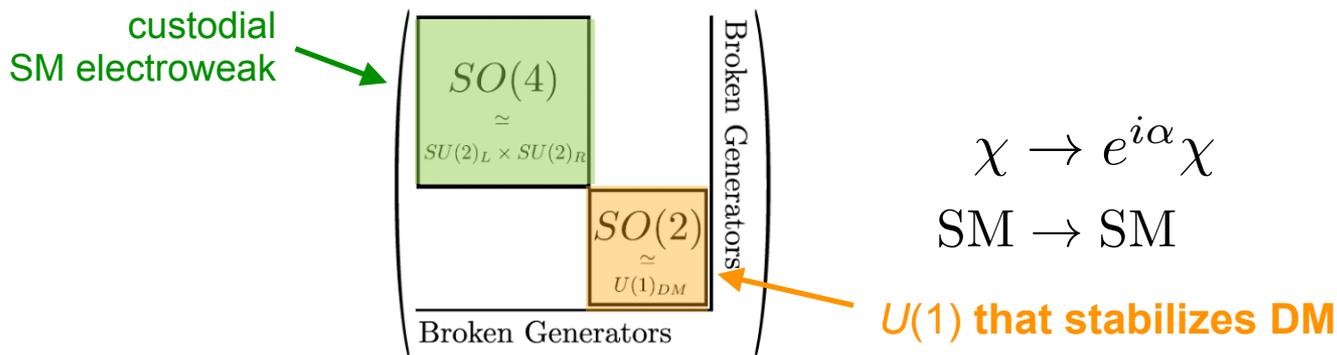
Composite Higgs + DM

- Minimal realistic model is $SO(5)/SO(4)$: Higgs doublet as 4 GBs

Agashe, Contino, Pomarol 2004

Composite Higgs + DM

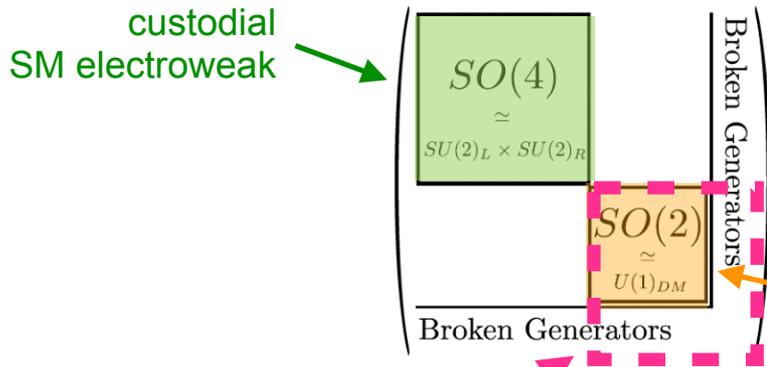
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**Balkin, Ruhdorfer,
Salvioni, Weiler
1707.07685**

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Balkin, Ruhdorfer,
Salvioni, Weiler
1707.07685

$$\chi \rightarrow e^{i\alpha} \chi$$

$$SM \rightarrow SM$$

$U(1)$ that stabilizes DM

$SO(3)$

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

DM shift symmetries

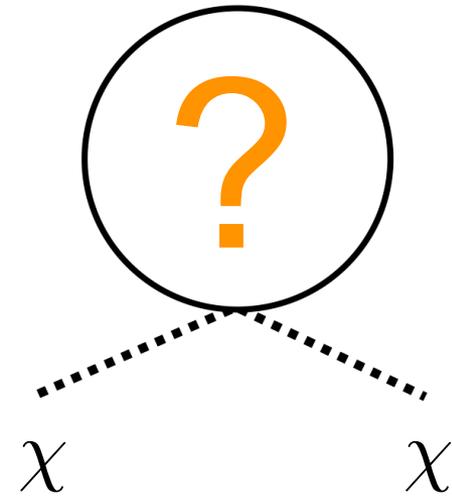
partial compositeness

$$\mathcal{L}_{mix}^{UV} \sim \epsilon_q \bar{q}_L \mathcal{O}_q + \epsilon_t \bar{t}_R \mathcal{O}_t + \epsilon_b \bar{b}_R \mathcal{O}_b$$

- Fix $SO(7)$ reps for \mathcal{O}_i \rightarrow explicit breaking of shift symmetries for GBs \rightarrow structure of non-derivative interactions

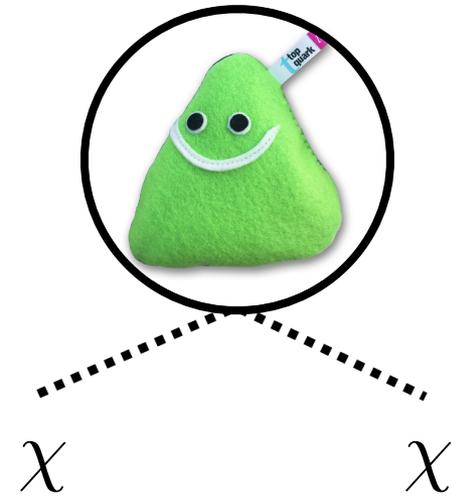
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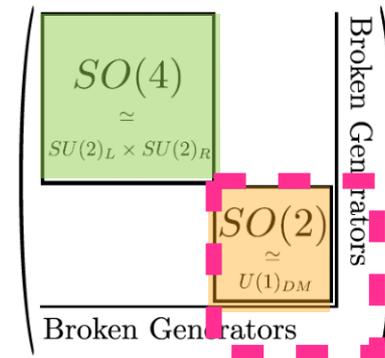
Coupling of LH quarks

$$\mathcal{L}_{\text{mix}}^{\text{UV}} \sim \epsilon_q \bar{q}_L \mathcal{O}_q + \epsilon_t \bar{t}_R \mathcal{O}_t + \epsilon_b \bar{b}_R \mathcal{O}_b$$

$$\{T^{\text{DM}}, X_{\text{Re}}, X_{\text{Im}}\} \quad \text{SO}(3)$$

$U(1)_{\text{DM}}$ DM shift symmetries

$SO(7)/SO(6)$



Agashe, Contino,
Da Rold 2006

q_L respects both $U(1)_{\text{DM}}$ and DM shift symmetries

$$\begin{aligned} \mathbf{1} &= (\mathbf{1}, \mathbf{1}, \mathbf{1}) \\ \mathbf{7} &= (\mathbf{2}, \mathbf{2}, \mathbf{1}) \oplus (\mathbf{1}, \mathbf{1}, \mathbf{3}) \\ \mathbf{21} &= (\mathbf{2}, \mathbf{2}, \mathbf{3}) \oplus (\mathbf{3}, \mathbf{1}, \mathbf{1}) \oplus (\mathbf{1}, \mathbf{3}, \mathbf{1}) \oplus (\mathbf{1}, \mathbf{1}, \mathbf{3}) \\ \mathbf{27} &= (\mathbf{3}, \mathbf{3}, \mathbf{1}) \oplus (\mathbf{2}, \mathbf{2}, \mathbf{3}) \oplus (\mathbf{1}, \mathbf{1}, \mathbf{5}) \oplus (\mathbf{1}, \mathbf{1}, \mathbf{1}) \end{aligned}$$

$$q_L \rightarrow \begin{pmatrix} ib_L \\ b_L \\ it_L \\ -t_L \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

q_L loops do **not** contribute to DM potential

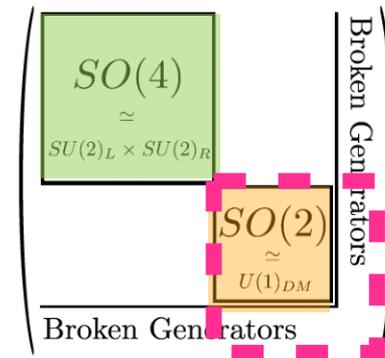
Coupling of RH top

$$\mathcal{L}_{\text{mix}}^{\text{UV}} \sim \epsilon_q \bar{q}_L \mathcal{O}_q + \epsilon_t \bar{t}_R \mathcal{O}_t + \epsilon_b \bar{b}_R \mathcal{O}_b$$

$$\{T^{\text{DM}}, X_{\text{Re}}, X_{\text{Im}}\} \quad \text{SO}(3)$$

$U(1)_{\text{DM}}$ DM shift symmetries

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



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 \mathbf{27} &= (\mathbf{3}, \mathbf{3}, \mathbf{1}) \oplus (\mathbf{2}, \mathbf{2}, \mathbf{3}) \oplus (\mathbf{1}, \mathbf{1}, \mathbf{5}) \oplus (\mathbf{1}, \mathbf{1}, \mathbf{1})
 \end{aligned}$$

t_R respects the $U(1)_{\text{DM}}$
but **breaks DM shift symmetries**

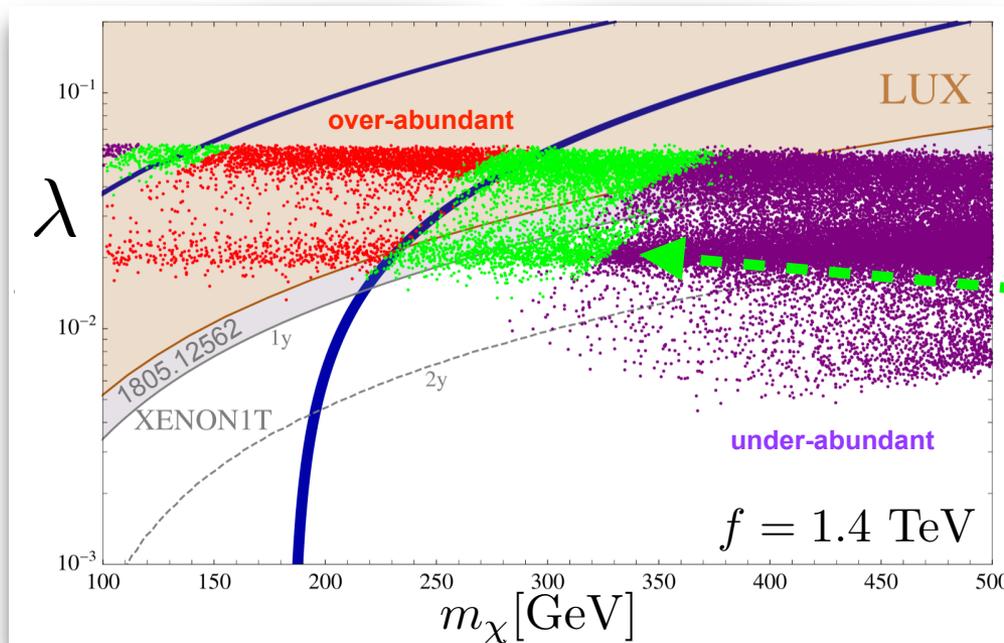
$$t_R \rightarrow \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ t_R \end{pmatrix}$$

t_R loops generate a potential for the DM, $m_\chi \gtrsim m_h$

DM mass from top loops

- If top quark mixings break DM shift symmetry,

$$V \ni \lambda |H|^2 |\chi|^2 + \lambda_h |H|^4 \quad \text{with} \quad \lambda \sim \frac{\lambda_h}{\text{few}} \sim 10^{-2}$$



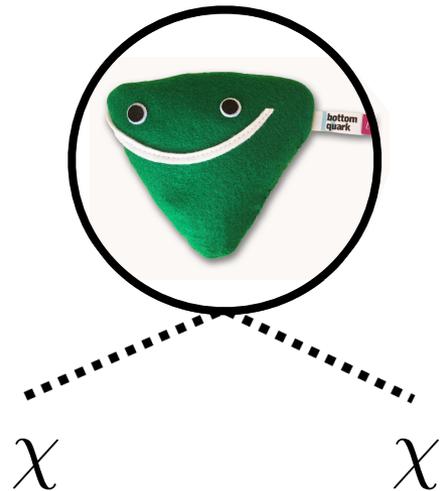
observed
relic density

also [Marzocca, Urbano 2014](#)

Tested at **XENON1T**

Origin of dark matter mass: what's in the loop?

- Top quarks?
- **Bottom quarks?**
- BSM physics?

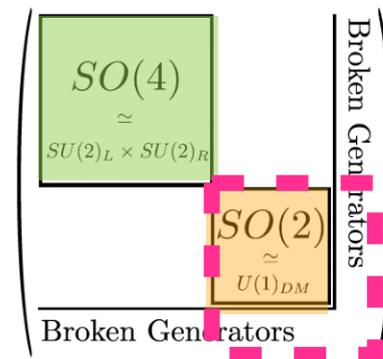


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$U(1)_{\text{DM}}$ DM shift symmetries

 $SO(7)/SO(6)$


t_R respects **both** $U(1)_{\text{DM}}$
and DM shift symmetries

$$1 = (1, 1, 1)$$

$$7 = (2, 2, 1) \oplus (1, 1, 3)$$

$$21 = (2, 2, 3) \oplus (3, 1, 1) \oplus (1, 3, 1) \oplus (1, 1, 3)$$

$$27 = (3, 3, 1) \oplus (2, 2, 3) \oplus (1, 1, 5) \oplus (1, 1, 1)$$

all top loops do not generate a DM potential

DM mass from bottom loops

- If mixing of b_R breaks DM shift symmetry, can obtain

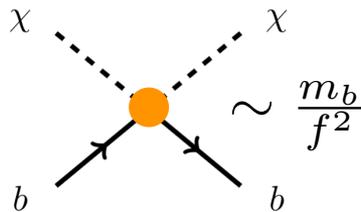
$$m_\chi \propto (y_b g_*)^{1/2} f$$

$$\lambda \propto y_b^2$$

“collective breaking”

$$\lambda \ll 10^{-3}$$

The breaking also mediates subleading direct detection,



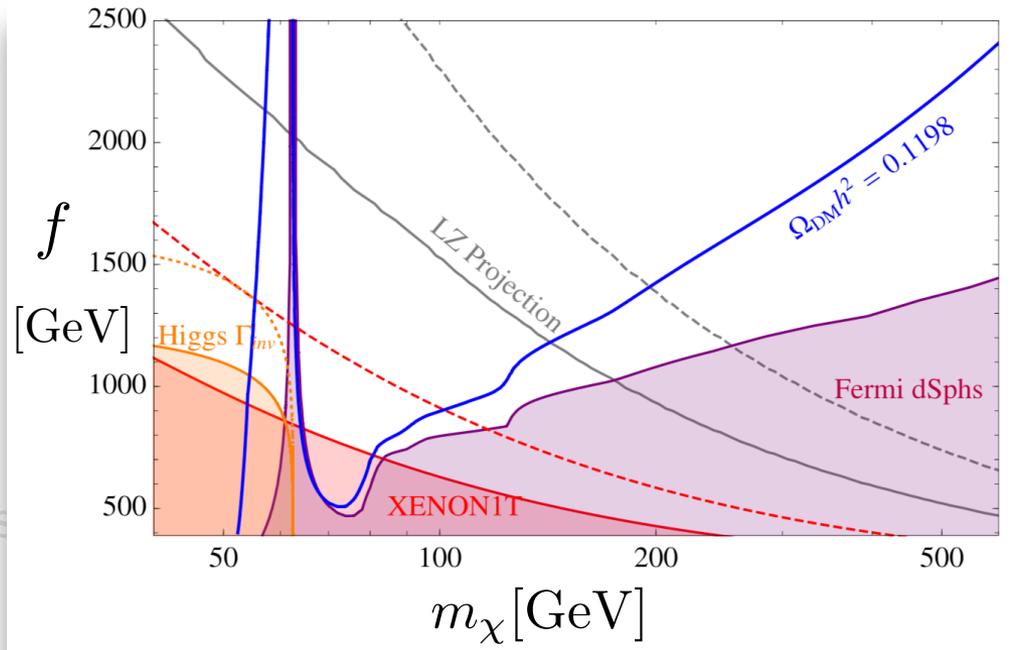
$$\begin{aligned} \sigma_{\text{SI}}^{\chi N} &\simeq \frac{\tilde{f}_N^2}{\pi} \frac{m_N^4}{4f^4 m_\chi^2} \\ &\approx 1.0 - 5.6 \times 10^{-47} \text{ cm}^2 \left(\frac{1 \text{ TeV}}{f} \right)^4 \left(\frac{100 \text{ GeV}}{m_\chi} \right)^2 \end{aligned}$$



Small, but probed at **next generation (LUX-ZEPLIN)**

DM mass from bottom loops

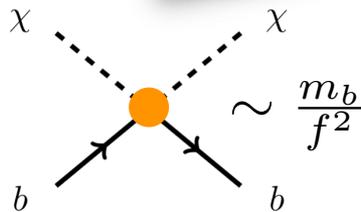
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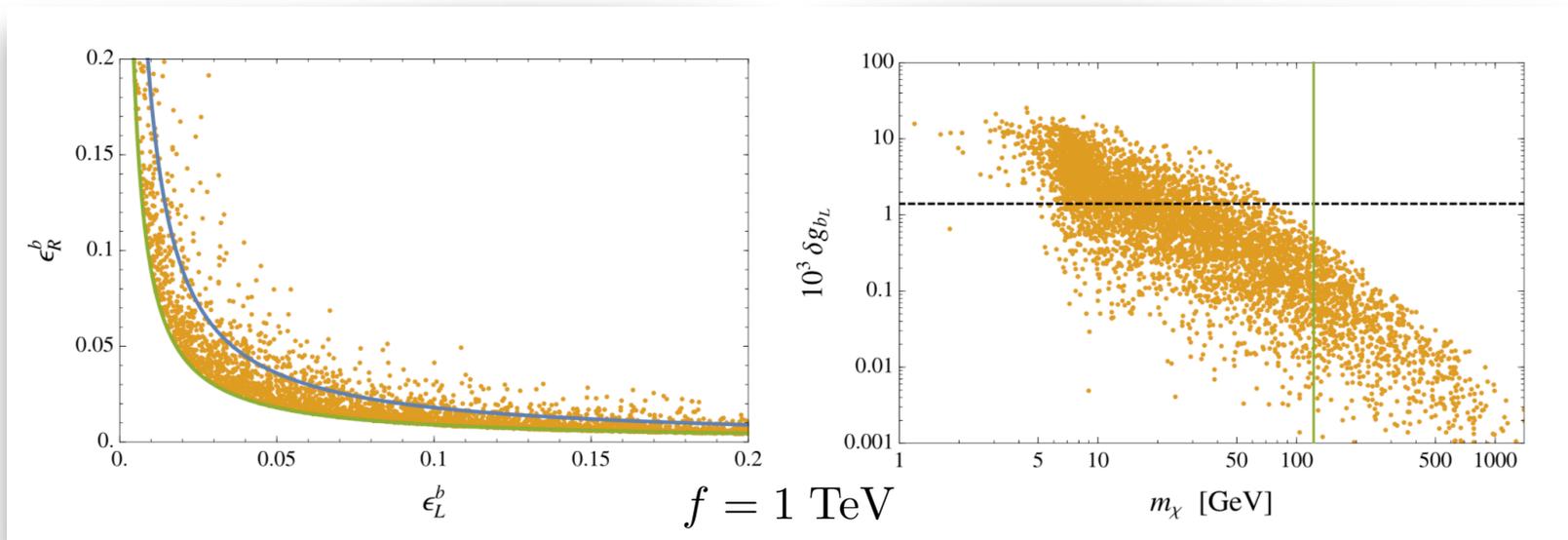
DM mass from bottom loops

$$SO(7) \times U(1)_X \quad \mathcal{O}_q \sim \mathbf{7}_{2/3}, \quad \mathcal{O}_t \sim \mathbf{21}_{2/3}, \quad \mathcal{O}_{q',b} \sim \mathbf{7}_{-1/3}$$

$$\epsilon_L^b \sim \epsilon_R^b \sim \sqrt{y_b f / M_{*b}}$$

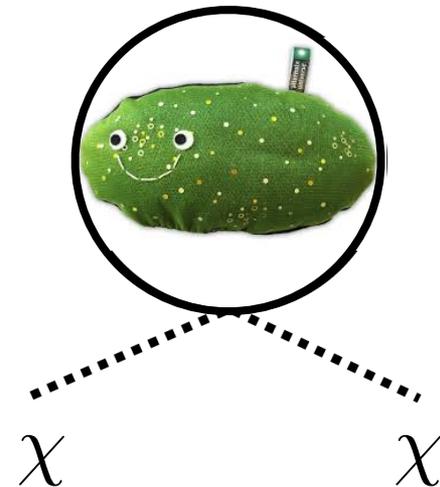
$$T_L^3 \neq T_R^3$$

tree-level corrections to Zbb



Origin of dark matter mass: what's in the loop?

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- Bottom quarks?
- **BSM physics?**

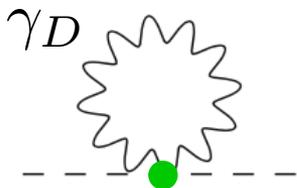


DM mass from beyond the Standard Model

- Scenario where SM fully preserves DM shift symmetry (but generates realistic potential for Higgs)
- *How does the DM get a mass?*

DM mass from dark photon loops

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- For **complex** pNGB, natural to **gauge the stabilizing $U(1)$**



(think of pion mass difference from EM)

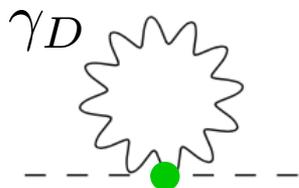


$$m_\chi \simeq \sqrt{\frac{3\alpha_D}{2\pi}} m_\rho \approx 100 \text{ GeV} \left(\frac{\alpha_D}{10^{-3}}\right)^{1/2} \left(\frac{m_\rho}{5 \text{ TeV}}\right)$$

while ~~$\lambda |H|^2 |\chi|^2$~~ **not generated at 1 loop**

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- Also makes DM stability more robust:

Kamionkowski, March-Russell 1992, Kallosh, Linde, Linde, Susskind 1995, Susskind 1995 + many others

- ➔ avoid issues with global symmetries **vs** quantum gravity
- ➔ subleading mixings of SM fermions automatically preserve $U(1)_{\text{DM}}$

Dark sector phenomenology

- Dark photon mass is free parameter of EFT (Stückelberg)
- **First** $m_{\gamma_D} = 0$, massive case if time allows
- Kinetic mixing with hypercharge forbidden by $U(1)_{\text{DM}}$ charge conjugation C_D

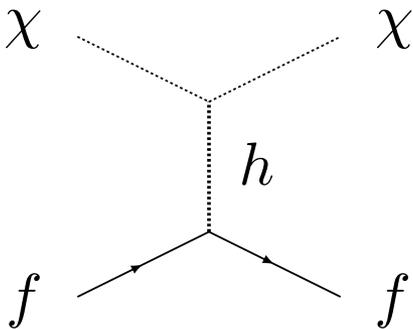
$$\varepsilon B_{\mu\nu} F_D^{\mu\nu} \xrightarrow{C_D} -\varepsilon B_{\mu\nu} F_D^{\mu\nu} \quad [\text{embedded in } O(6)]$$

Dark sector phenomenology

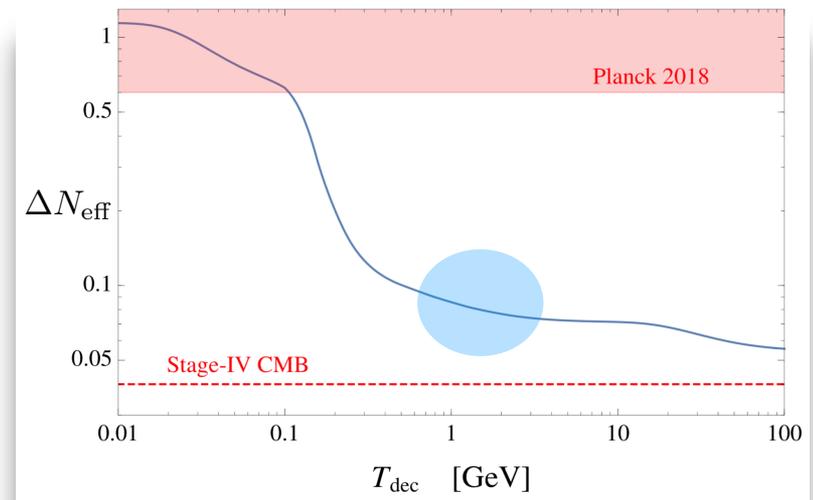
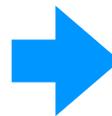
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- $\chi f \rightarrow \chi f$ scattering controls kinetic decoupling of SM and dark sector

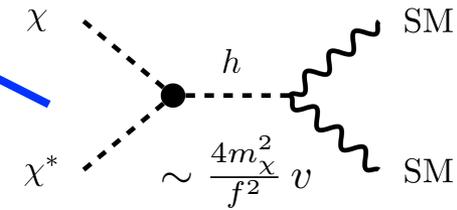
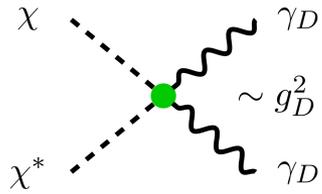
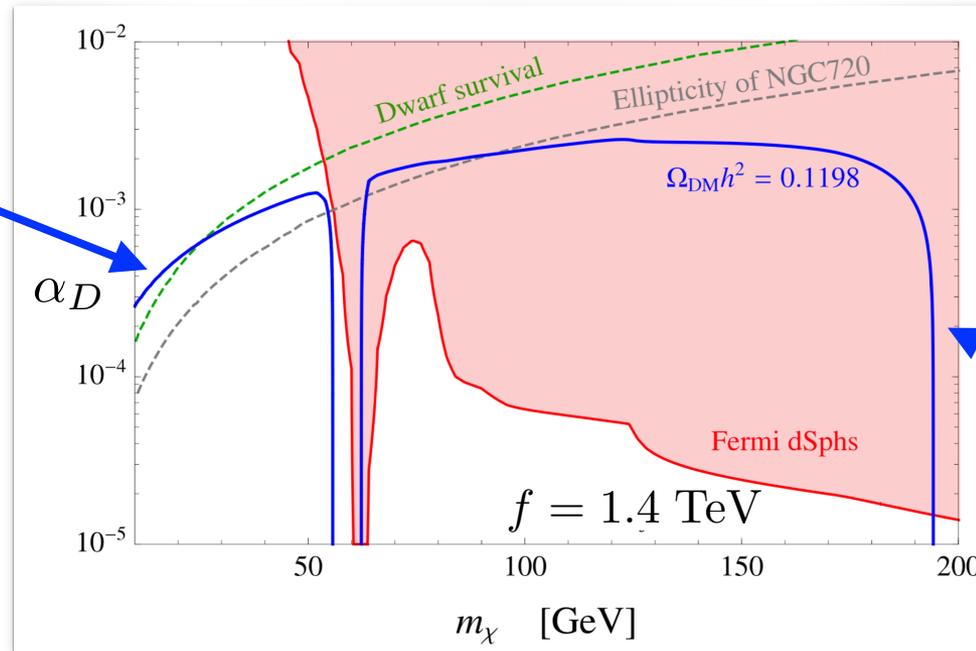


contribution of dark photon
to ΔN_{eff} @ CMB



Dark matter phenomenology

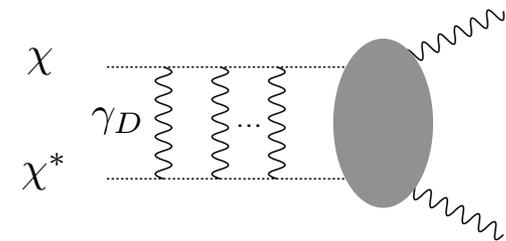
Balkin, Ruhdorfer,
Salvioni, Weiler
1809.09106



Sommerfeld

$$v_{\text{rel}} \sim 10^{-4}$$

in dwarf galaxies

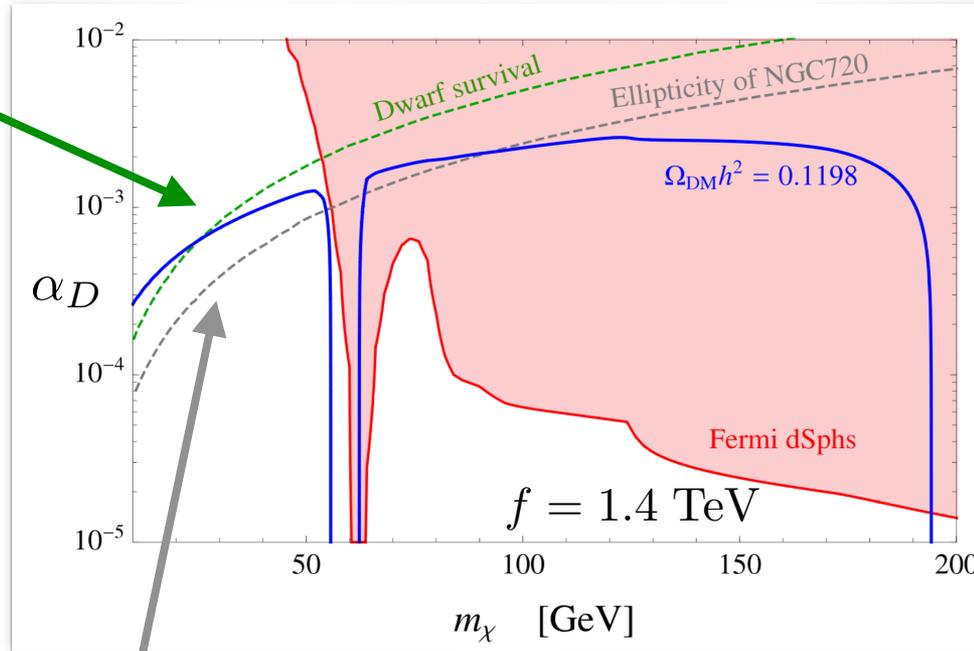


$$S = \frac{2\pi\alpha_D/v_{\text{rel}}}{1 - e^{-2\pi\alpha_D/v_{\text{rel}}}} \approx 2\pi \frac{\alpha_D}{v_{\text{rel}}}$$

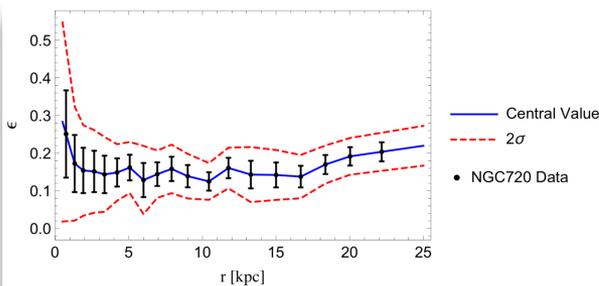
Dark matter self-interactions

Kahlhoefer, Schmidt-Hoberg, Frandsen, Sarkar 2013

dSphs not stripped as they travel through Milky Way halo



galaxy ellipticity

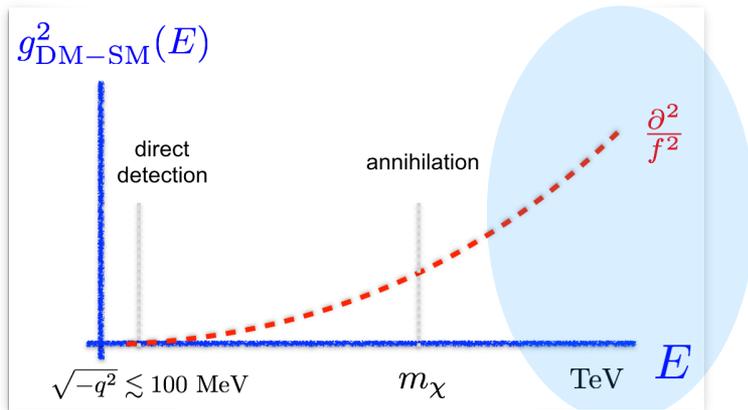


$$\frac{d\sigma}{d\Omega}(\chi\chi \rightarrow \chi\chi) \simeq \frac{\alpha_D^2}{4m_\chi^2 v_{\text{cm}}^4 (1 - \cos\theta_{\text{cm}})^2}$$

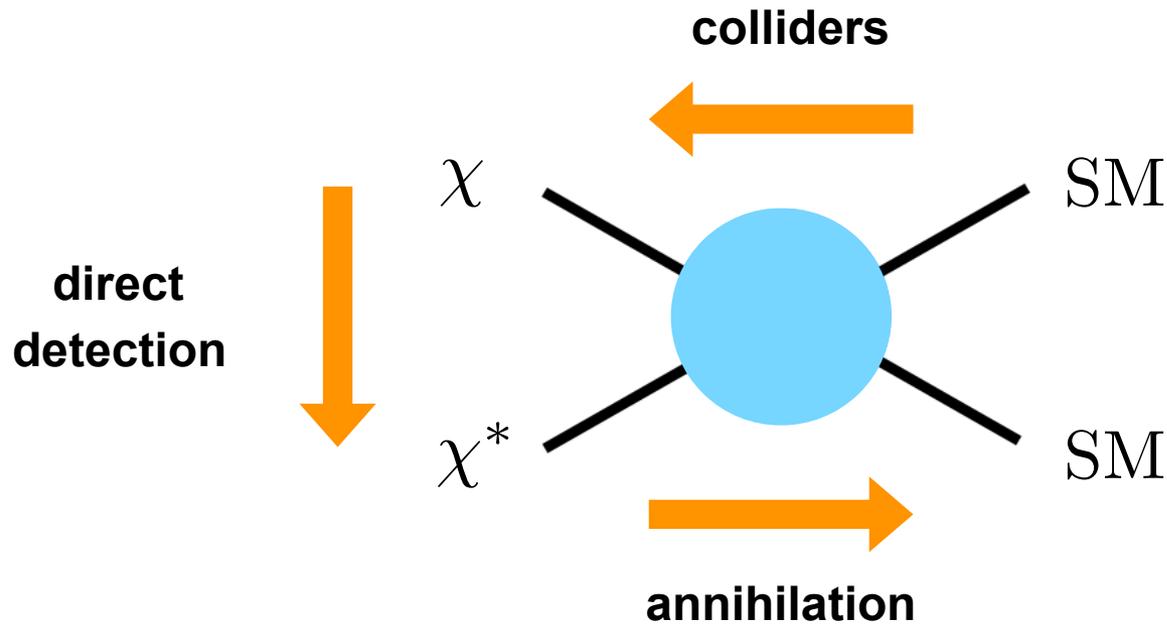
$$\tau_{\text{iso}} \equiv \langle E_k \rangle / \langle \dot{E}_k \rangle = \mathcal{N} m_\chi^3 v_0^3 (\log \Lambda)^{-1} / (\sqrt{\pi} \alpha_D^2 \rho_\chi) > 10^{10} \text{ years}$$

Feng, Kaplinghat, Tu, Yu 2009
Agrawal, Cyr-Racine, Randall, Scholtz 2016

pNGB dark matter at colliders?



$$\mathcal{L} \ni \frac{1}{f^2} \partial_\mu |H|^2 \partial^\mu |\chi|^2$$

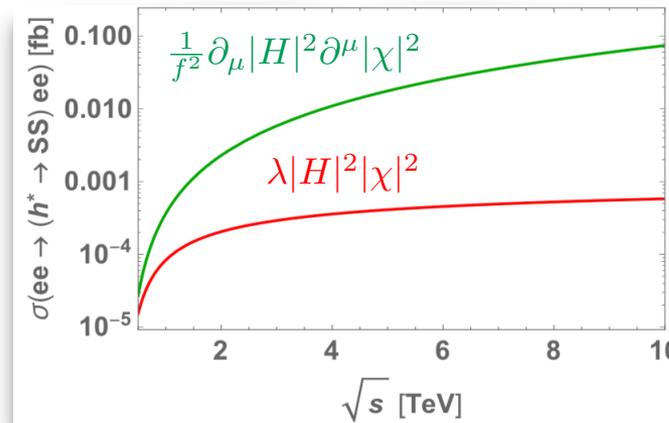
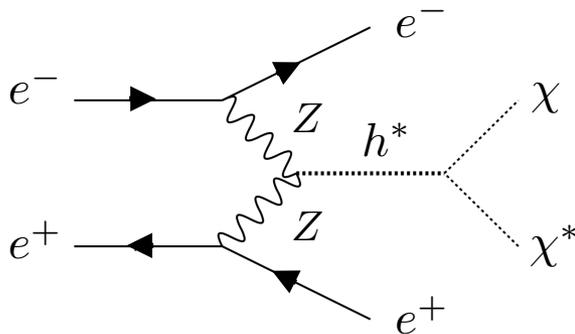


pNGB dark matter at colliders

- If $m_\chi < m_h/2$, invisible Higgs decays: $f > 1.6$ TeV at HL-LHC
- If DM is heavier, must go through “off-shell Higgs portal”

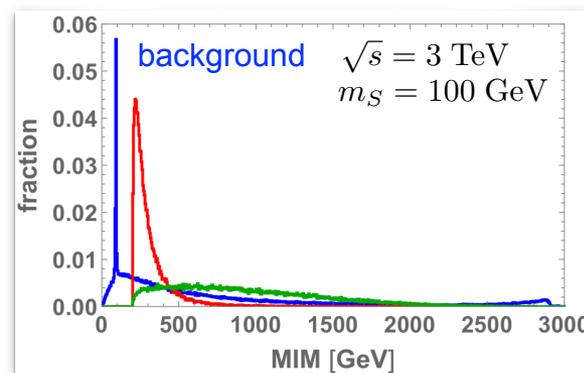
ATL-PHYS-
PUB-2013-014

High-energy lepton colliders



$$\sigma \propto \frac{s}{f^4}$$

$$\sigma \propto \frac{\lambda^2}{m_\chi^2} \log(s/m_\chi^2)$$



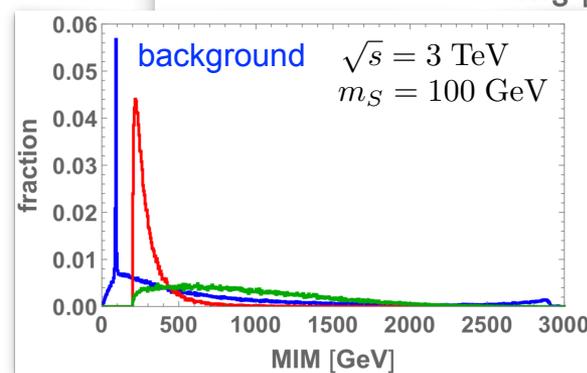
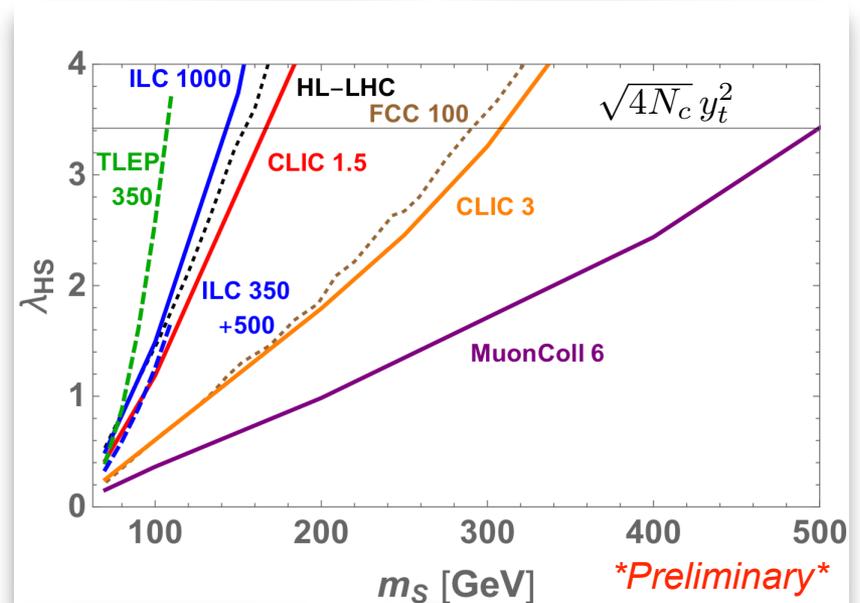
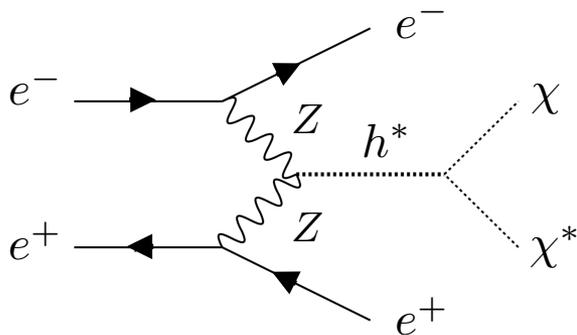
Ruhdorfer, Salvioni
in progress

pNGB dark matter at colliders

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PUB-2013-014

High-energy lepton colliders



analysis for derivative coupling
is ongoing...

Ruhdorfer, Salvioni
in progress

Summary

- Extra pNGB scalars in composite Higgs models as compelling WIMP DM
- Derivative Higgs portal suppressed at small momentum, naturally avoid conflict with direct detection
- DM pheno sensitive to origin of radiative DM mass (leading source of shift symmetry breaking)
 - * Standard Model quarks: indirect detection, direct detection @ next generation
 - * Dark sector: gauge the exact $U(1)$ that stabilizes DM
 Direct detection negligible, but **complementary observables:**
 - $m_\chi \gtrsim m_h/2$ excluded by Sommerfeld-enhanced indirect detection
 - $m_\chi \lesssim m_h/2$ testable in $h \rightarrow$ invisible , ΔN_{eff} , DM self-interactions

Massive dark photon

Stückelberg

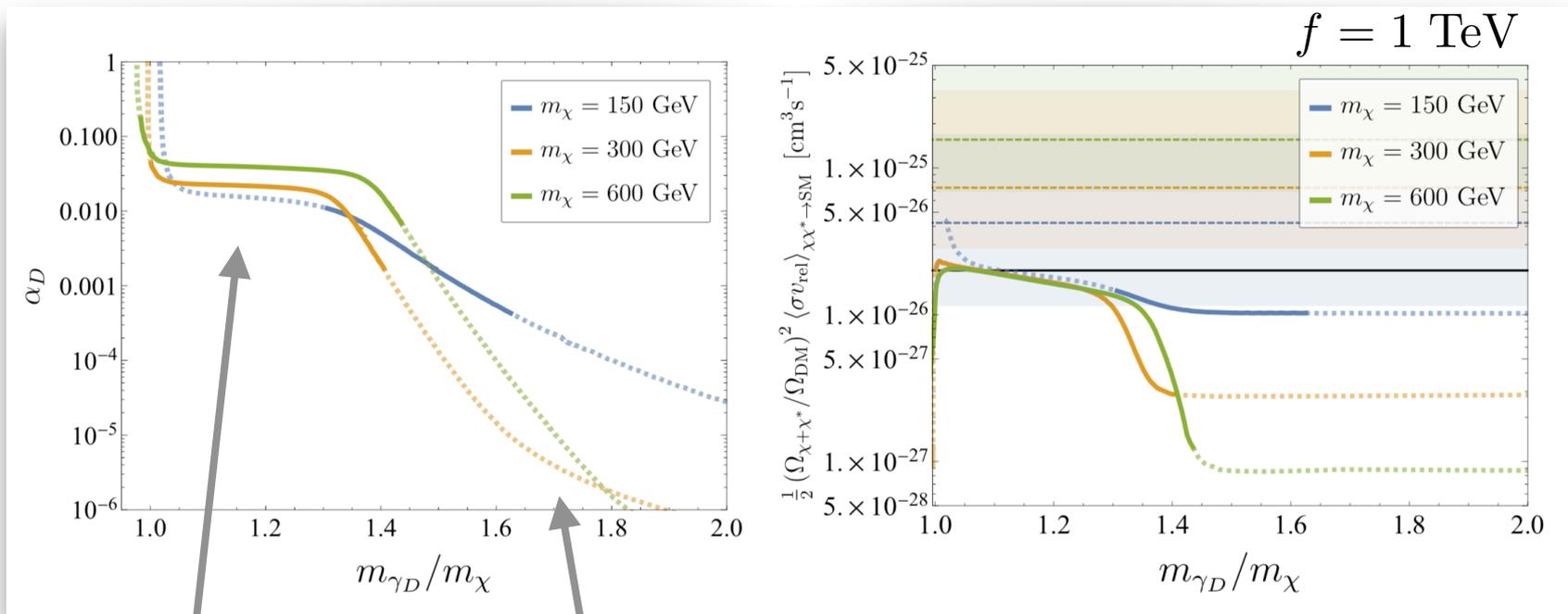
$$\mathcal{L}_{\text{eff}} \ni \frac{1}{2} m_{\gamma_D}^2 A_{D\mu} A_D^\mu$$

$$A_D \xrightarrow{C_D} -A_D \quad \text{dark photon **stable** if } m_{\gamma_D} < 2m_\chi$$

$m_{\gamma_D} < 6 \times 10^{-4} \text{ eV}$	✓ / X	γ_D is dark radiation today, strong constraints from SE of $\chi\chi^* \rightarrow \text{SM}$
$6 \times 10^{-4} \text{ eV} < m_{\gamma_D} \lesssim 3m_\chi/25$	X	γ_D is relativistic at freeze-out, ruled out by warm DM bounds/overabundant
$3m_\chi/25 < m_{\gamma_D} < m_\chi$	X	γ_D is non-relativistic at freeze-out, overabundant
$m_\chi \lesssim m_{\gamma_D} < 2m_\chi$	✓	both γ_D and χ are cold DM

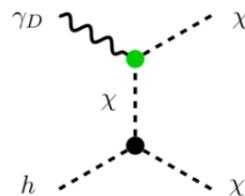


Two-component DM



$\gamma_D \gamma_D \rightarrow \chi \chi^*$
(coupled system)

$\gamma_D h \rightarrow \chi \chi^*$
(semi-annihilation)



dark photon freeze-out via