DM shifts away from direct detection

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Ikaho, Hotel Tenbo
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SFB 1258 Neutrinos Dark Matter Messengers

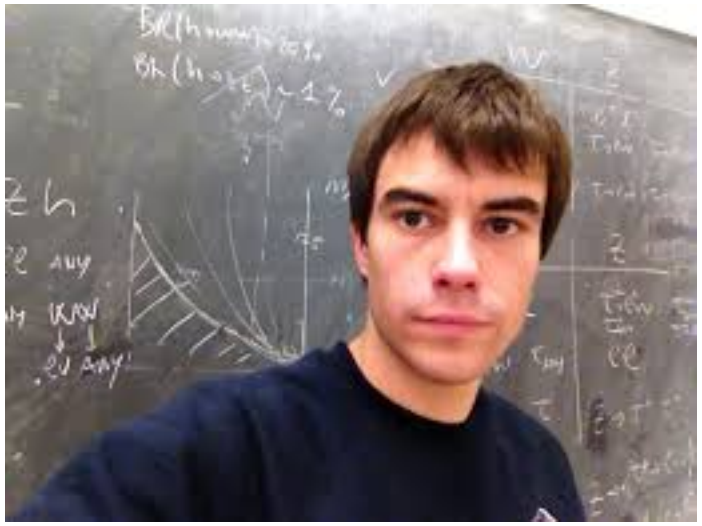
Excellence Cluster Universe

In collaboration with

arXiv:1707.07685 , arXiv:1809.09106

Reuven Balkin (PhD student)

Ennio Salvioni (Post-doc)



Max Ruhdorfer (PhD student)

Goldstone DM

$$\chi \to \chi + f$$

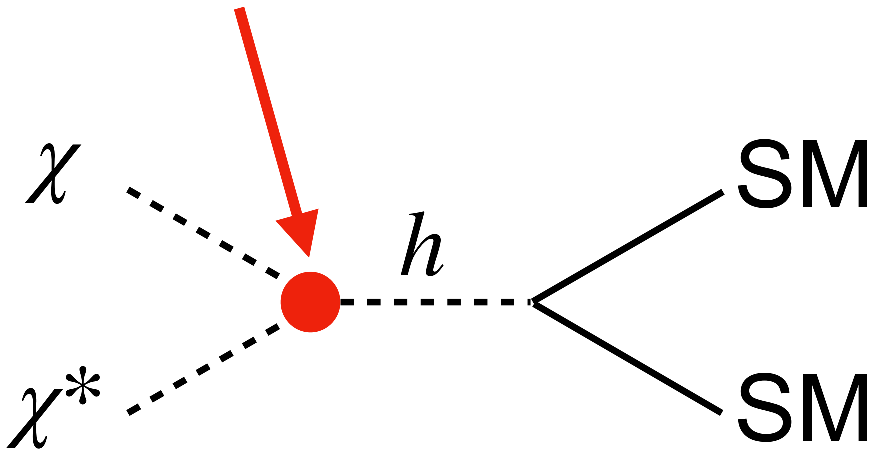
GB shift symmetry

Leading coupling between DM and SM involves derivative:

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

Annihilation

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



$$\propto \frac{s}{f^2} \simeq \frac{4m_\chi^2}{f^2}$$

Relic density: $$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma v \rangle}$$

This fixes a one-to-one relation between m_χ and f

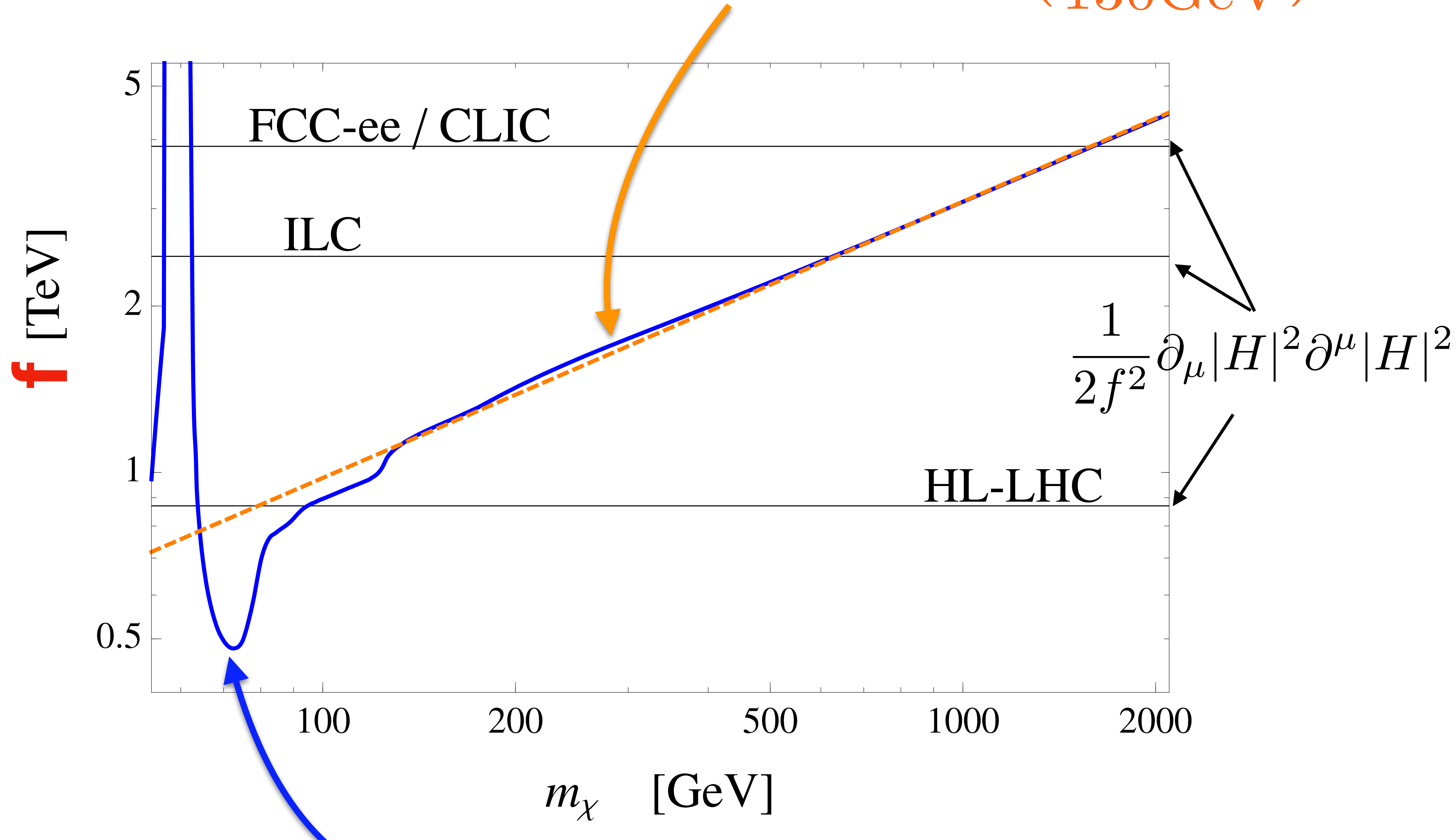
Correct relic density requires:

$$f \approx 1.1\,\mathrm{TeV}\,\left(\frac{m_\chi}{130\mathrm{GeV}}\right)^{1/2}$$

Interesting !

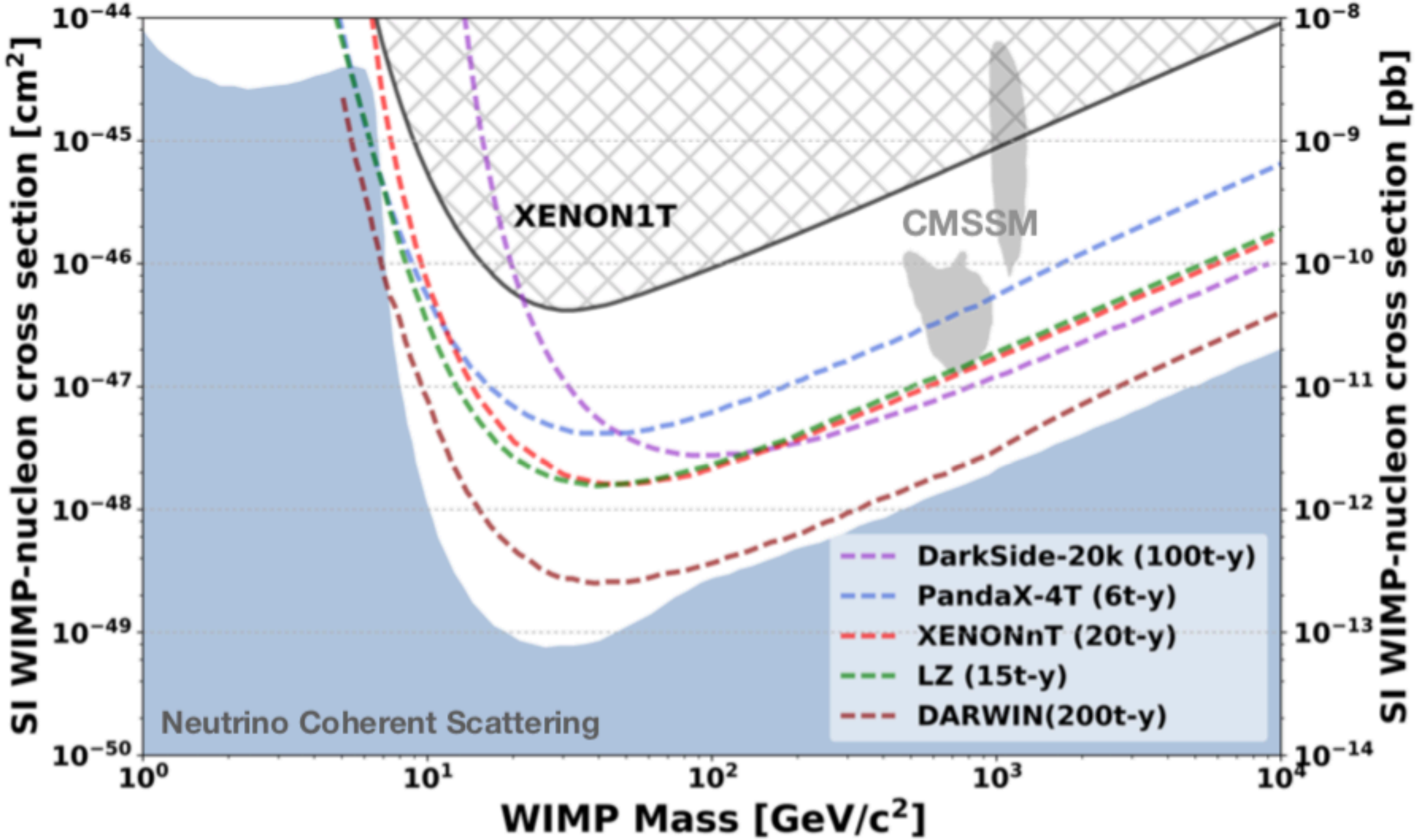
This corresponds to expectation for a natural pGB (compare to minimal composite Higgs models).

Estimation: $f \approx 1.1\,\mathrm{TeV}\left(\frac{m_\chi}{130\mathrm{GeV}}\right)^{1/2}$



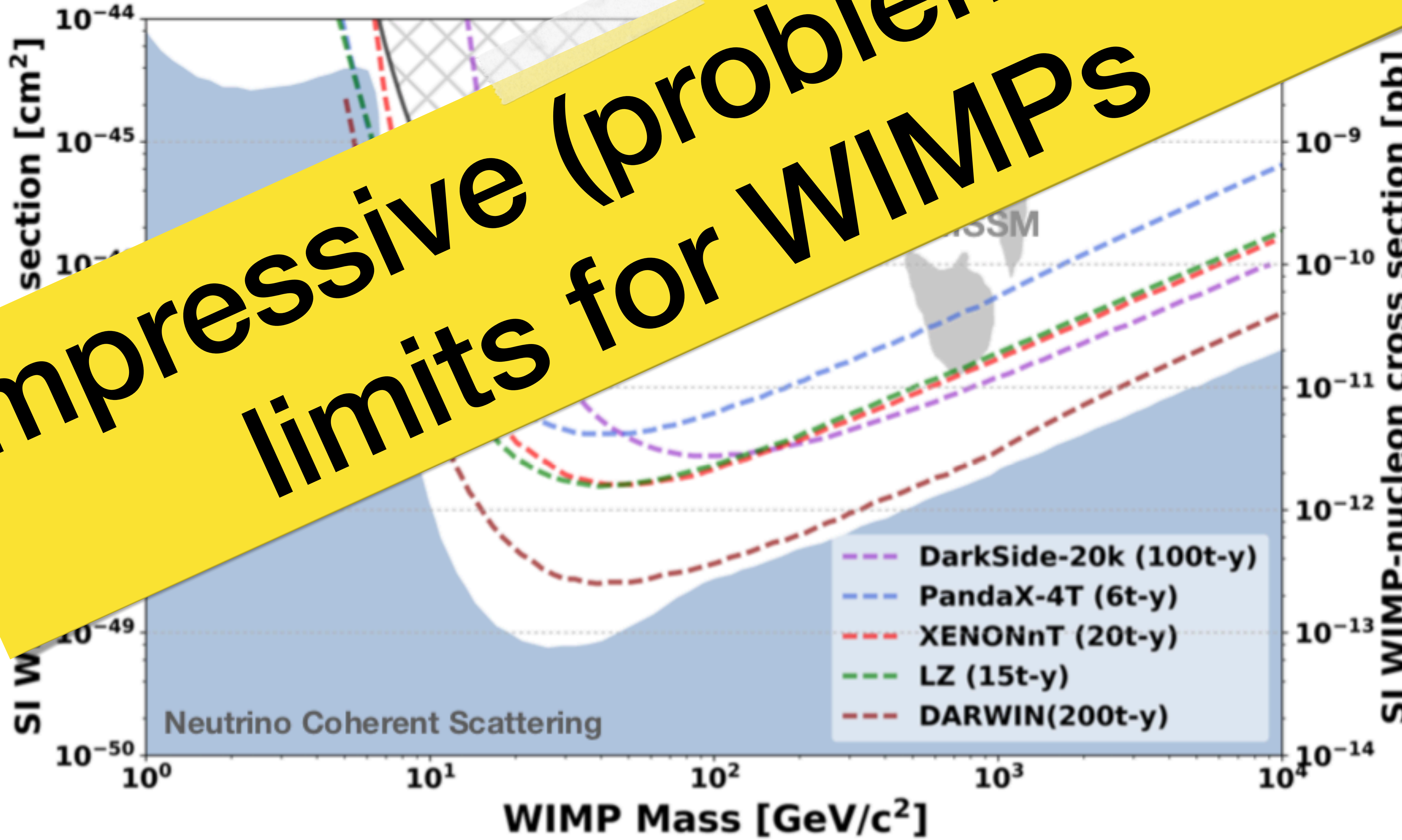
Full Boltzmann solution

Direct detection



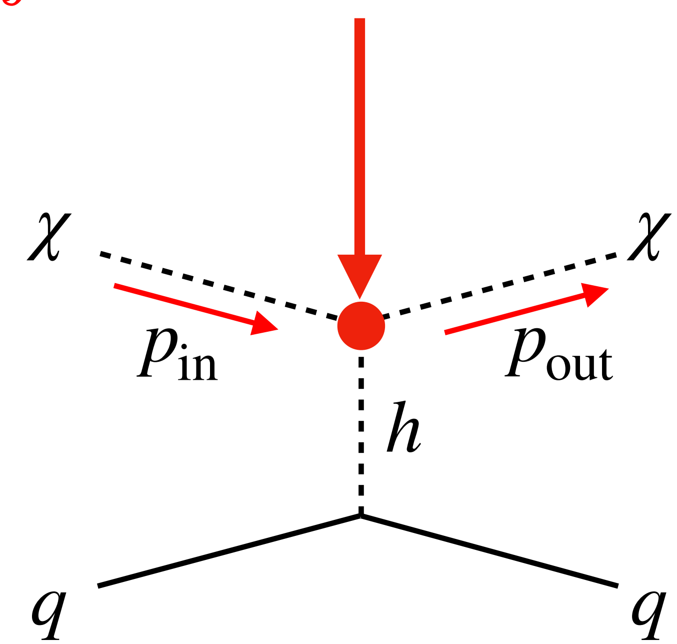
Direct detecti

impressive (problematic?) limits for WIMPs



Direct detection of pure Goldstone DM

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



$$\propto \frac{(p_{\text{in}} - p_{\text{out}})^2}{f^2} \lesssim \frac{(1\,\text{MeV})^2}{(1\,\text{TeV})^2}$$

Explains absence of current (and future) direct detection signals.

Wait …

- DM cannot be an exact Goldstone b/c of DM mass:

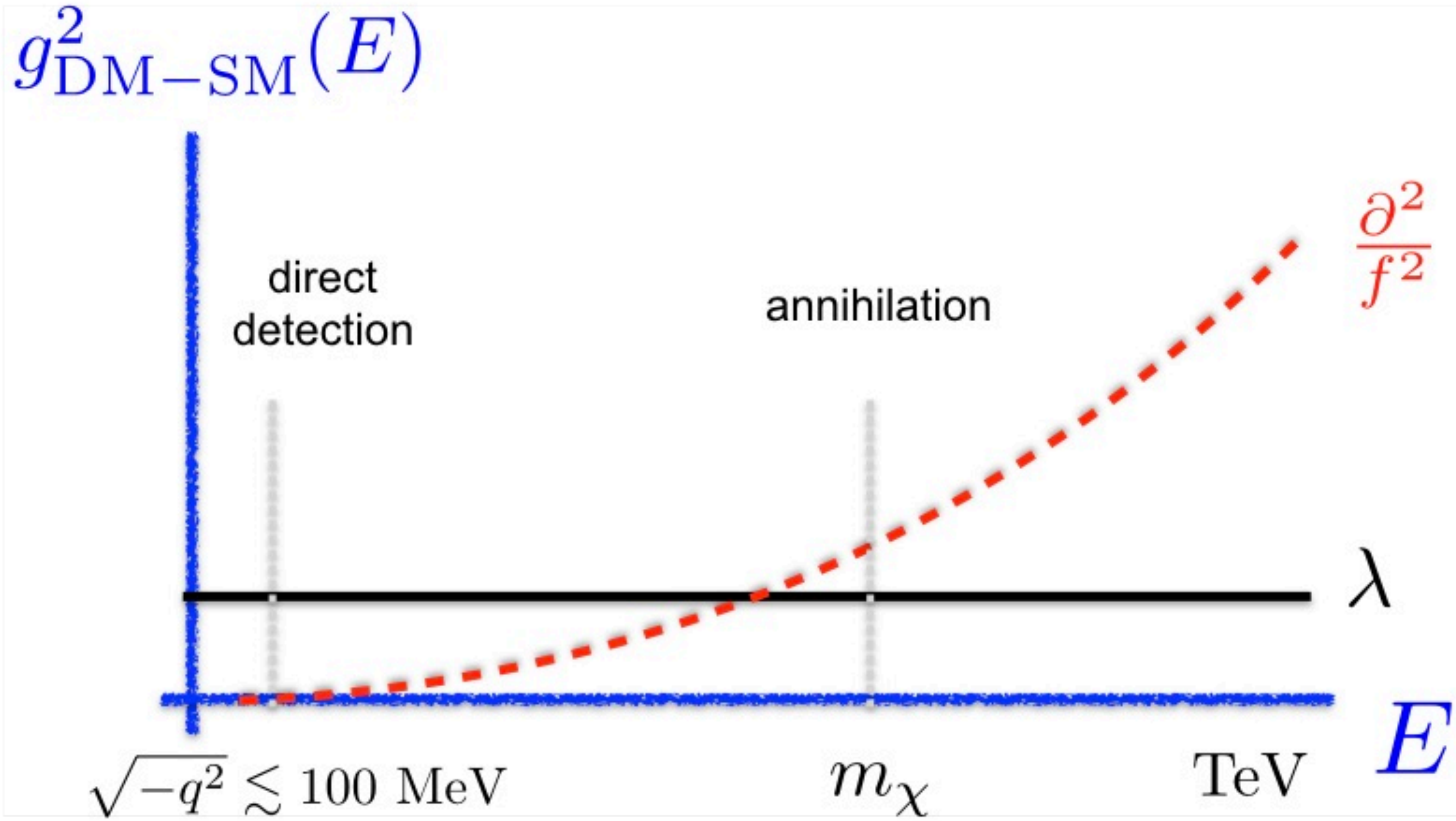
$$m_\chi^2|\chi|^2 + \ldots \quad \text{means} \quad \cancel{\chi \to \chi + f}$$

Controlled breaking of DM shift symmetry

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

induces mass but also marginal portal.

Direct detection is very sensitive to λ.

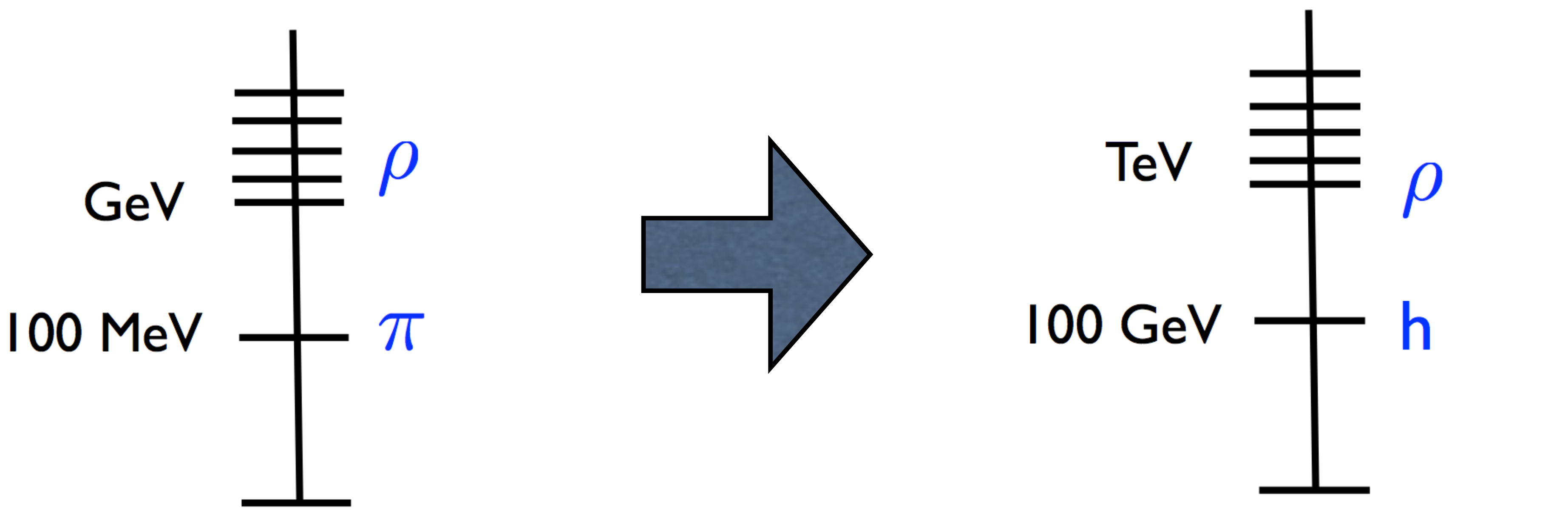


Want to be close to Goldstone limit: $\lambda \ll 1$

Framework

A solution to the hierarchy problem:

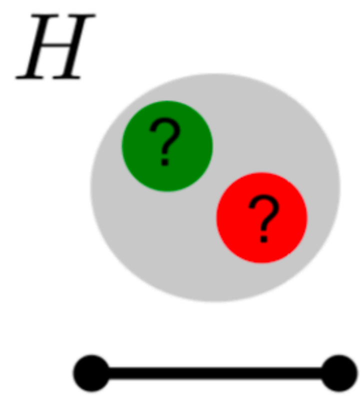
the Higgs as a pGB bound state of a new strong force.



QCD

Higgs as a pGB

Description changes above confinement scale (~ TeV)



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

Higgs mass is naturally "screened".

Spontaneous breaking of a global symmetry $\mathcal{G}$

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

Minimal Model: $SO(5) \xrightarrow[H]{f} SO(4)$

Agashe, Contino, Pomarol 2004

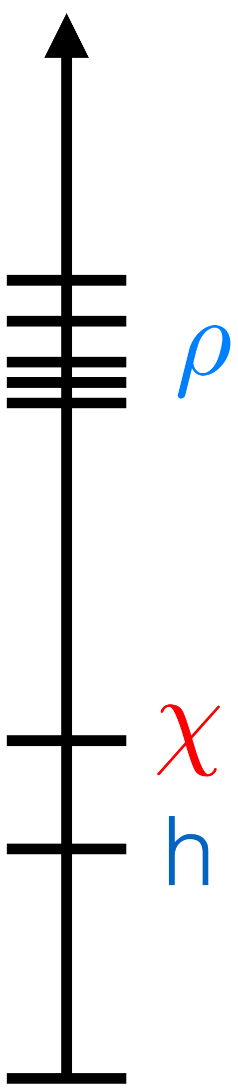
Enlarge global symmetry group: non-minimal pNGB

$$\mathcal{G} \xrightarrow[H,\chi]{f} \mathcal{H}$$

additional pNGB χ as WIMP

E.g. SO(6)/SO(5) or SO(7)/SO(6), etc.

Goldstone dark matter



Symmetry that protects the (Higgs mass)^2 also

- keeps WIMP χ light: $\chi(x) \to \chi(x) + \alpha$
- renders χ stable: $\chi(x) \to -\chi(x)$ parity

or

$\chi(x) \to e^{i\beta}\chi(x)$ U(1)$_{DM}$

will use here

A pNGB Model

Balkin, Ruhdorfer, Salvioni,AW 1707.07685

$SO(7)/SO(6)$ (H, χ) Higgs + complex scalar

SO(7) has only real rep’s: automatically UV safe

$\rightsquigarrow$ no WZW anomaly term

A pNGB Model

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$SO(7)/SO(6)$ (H,χ) Higgs + complex scalar

SO(7) has only real rep's: automatically UV safe

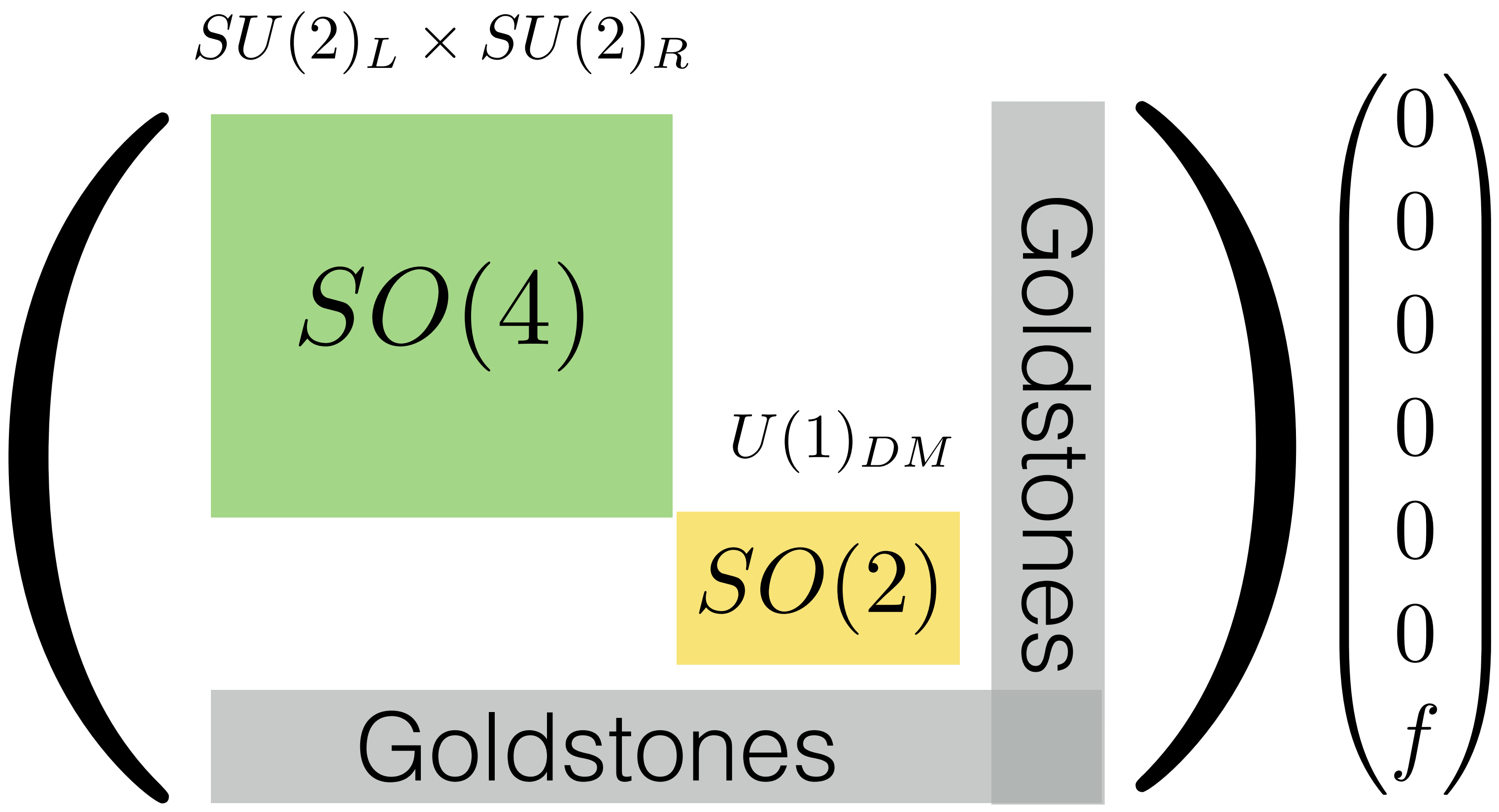
→ **no WZW anomaly term**

Unbroken symmetry

$$SO(6) \sim SO(4) \times SO(2)$$
$$\sim SU(2)_L \times SU(2)_R \times U(1)_{DM}$$

EW custod' DM stabilisation

SO(7)/SO(6)


$SU(2)_L \times SU(2)_R$
$SO(4)$
$U(1)_{DM}$
$SO(2)$
Goldstones
Goldstones
0
0
0
0
0
0
f

Breaking the DM shift symmetry

arXiv:1707.07685

- Top quark mass: $\lambda \sim \frac{\lambda_h}{2}$

- Bottom quark mass: $\lambda \propto y_b^2 \ll 1$ arXiv:1809.09106

- Partial gauging of DM Goldstone symmetry $U(1)_{DM}$: $\lambda \propto \text{higher-loop} \ll 1$

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

Breaking the DM shift symmetry

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- Top quar

in tension with Xenon 1T

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DM shift symmetry broken
by b-quark embedding

NGB -> **p**NGB

Shift symmetry $\chi(x) \to \chi(x) + \alpha$ broken by

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

- SM fermions in incomplete **G=SO(7)** multiplets, couple linearly to strong sector

$$\mathcal{L}_{mix} \sim \varepsilon_q \bar{q}_L \mathcal{O}_q + \varepsilon_t \bar{t}_R \mathcal{O}_t$$

partial compositeness

Partial compositeness

D. B. Kaplan '91

$$\mathcal{L} = \lambda_L\, \bar{q}_L O_R + \lambda_R\, \bar{u}_R O_L + h.c.$$

(linear couplings)

elementary composite

$$|SM\rangle = \cos\alpha\, |t > + \sin\alpha\, |T\rangle$$

$$\frac{m_t}{v} \approx \sin\alpha_L \cdot Y \cdot \sin\alpha_R$$

SM matter embedding

- Useful to classify according to

$$SO(7) \supset SO(4) \times SO(3) = SU(2)_L \times SU(2)_R \times SU(2)_{DM}$$

where the SU(2)$_{DM}$ is generated by

$$\{T^{\pm}, T_{DM}\}$$

broken generators -> charged DM pNGB

U(1)$_{DM}$: stability of DM

Example: t_R embedding

$$SO(7) \supset SU(2)_L \times SU(2)_R \times SU(2)_{DM}$$

$$t_R$$

$$\begin{aligned}
\mathbf{7} &= (\mathbf{2},\mathbf{2},\mathbf{1}) \oplus (\mathbf{1},\mathbf{1},\mathbf{3}), \\
\mathbf{8} &= (\mathbf{2},\mathbf{1},\mathbf{2}) \oplus (\mathbf{1},\mathbf{2},\mathbf{2}), \\
\mathbf{21} &= (\mathbf{2},\mathbf{2},\mathbf{3}) \oplus (\mathbf{3},\mathbf{1},\mathbf{1}) \oplus (\mathbf{1},\mathbf{3},\mathbf{1}) \oplus (\mathbf{1},\mathbf{1},\mathbf{3}), \\
\mathbf{27} &= (\mathbf{3},\mathbf{3},\mathbf{1}) \oplus (\mathbf{2},\mathbf{2},\mathbf{3}) \oplus (\mathbf{1},\mathbf{1},\mathbf{5}) \oplus (\mathbf{1},\mathbf{1},\mathbf{1}).
\end{aligned}$$

...

Example: t_R embedding

$$SO(7) \supset SU(2)_L \times SU(2)_R \times SU(2)_{DM}$$

t_R

1)

$$\mathbf{7} = (\mathbf{2},\mathbf{2},\mathbf{1}) \oplus (\mathbf{1},\mathbf{1},\mathbf{3}),$$

$$\mathbf{8} = (\mathbf{2},\mathbf{1},\mathbf{2}) \oplus (\mathbf{1},\mathbf{2},\mathbf{2}),$$

2)

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$$\mathbf{27} = (\mathbf{3},\mathbf{3},\mathbf{1}) \oplus (\mathbf{2},\mathbf{2},\mathbf{3}) \oplus (\mathbf{1},\mathbf{1},\mathbf{5}) \oplus (\mathbf{1},\mathbf{1},\mathbf{1}).$$

...

2)

Higgs & DM mass

Integrate out heavy composite resonances

$$\mathcal{L}_{eff} = \Pi_L \bar{t}_L \not{p} t_L + \Pi_R \bar{t}_R \not{p} t_R - (\Pi_{LR} \bar{t}_L t_R + h.c.)$$

with

$$\begin{cases} \Pi_L = \Pi_{L_0} + \frac{h^2}{f^2}\Pi_{L_1} \\ \Pi_R = \Pi_{R_0} + \left(\frac{h^2}{f^2} + \frac{2\chi^\dagger\chi}{f^2}\right)\Pi_{R_1} \\ \Pi_{LR} = i\frac{h}{f}\sqrt{1 - \frac{h^2}{f^2} - \frac{2\chi^\dagger\chi}{f^2}}\Pi_1 . \end{cases}$$

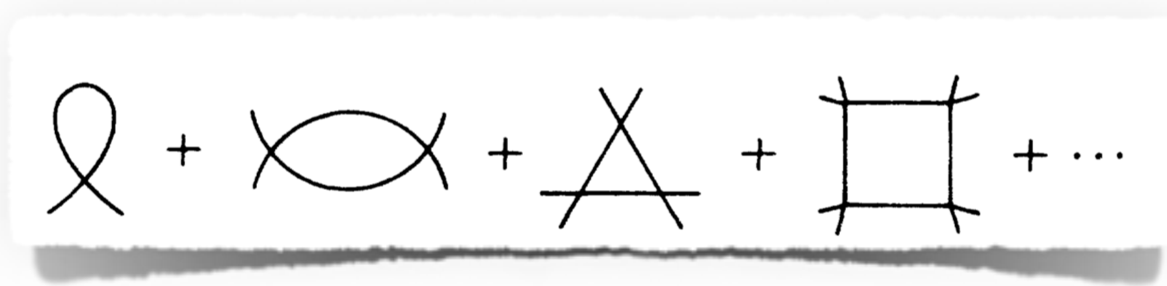
w/ eg. $\Pi_{R_0} = 1 - \sum_{j=1}^{N_S} \frac{|\epsilon_{tS}^j|^2}{p^2 - m_{S_j}^2}$

etc

Higgs & DM mass 2

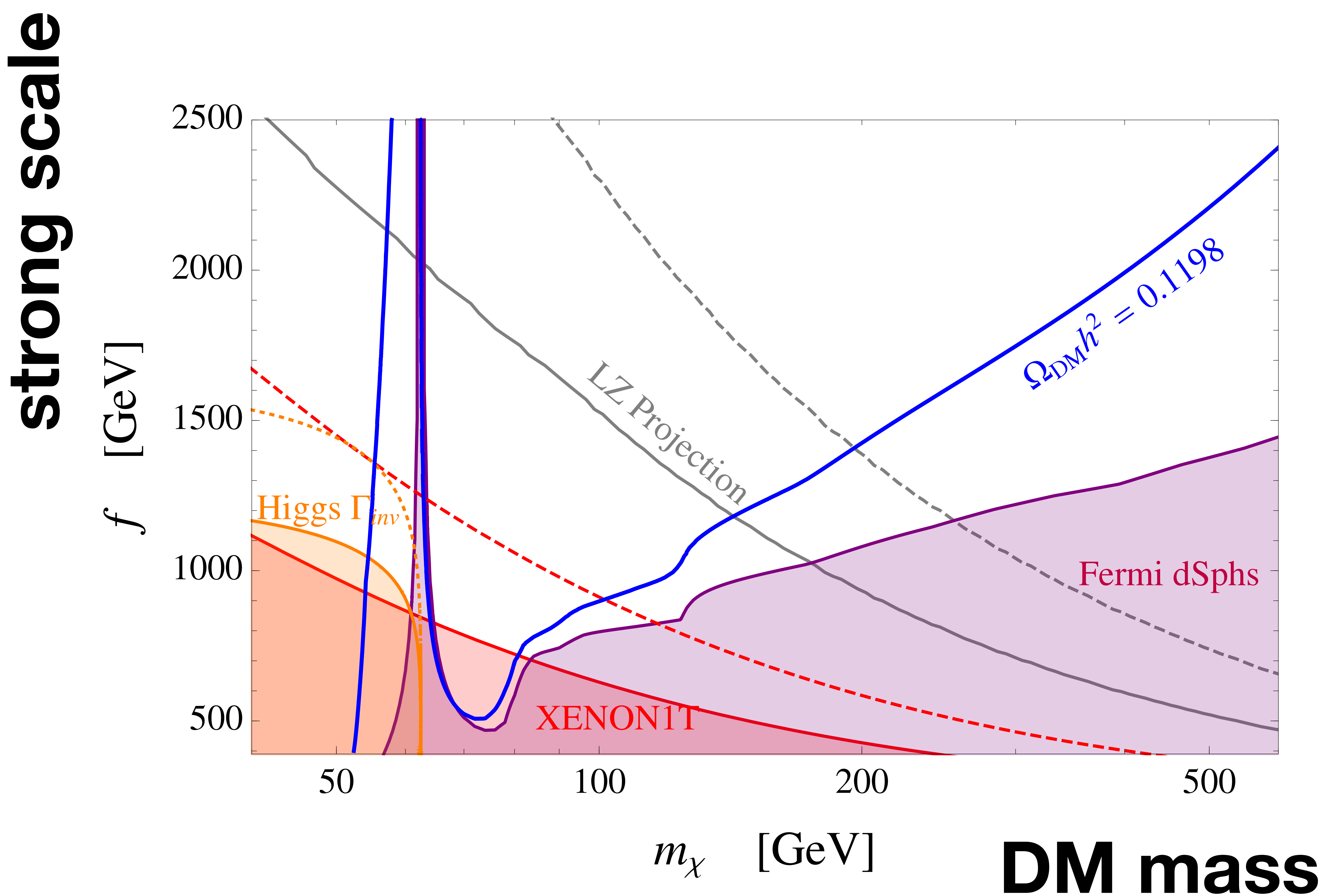
Coleman-Weinberg

$$V_{eff}(h,\chi) = \frac{-2N_c}{(4\pi)^2}\int_0^\infty dk_E^2 k_E^2 \log\left[1 + \frac{h^2}{f^2}f_1(k_E^2) + \frac{h^2}{f^2}\left(\frac{h^2}{f^2} + \frac{2\chi^\dagger\chi}{f^2}\right)f_2(k_E^2) + \frac{2\chi^\dagger\chi}{f^2}f_3(k_E^2)\right]$$



DM shift symmetry broken by b-quark embedding:

DM phenomenology



strong scale
f [GeV]
2500
2000
1500
1000
500
50
100
200
500
m_χ [GeV]
DM mass
LZ Projection
Ω_DM h^2 = 0.1198
Higgs Γ_inv
Fermi dSphs
XENON1T

DM shift symmetry broken by gauging of $U(1)_{DM}$

$$|\partial^\mu \chi|^2 \quad \to \quad |(\partial^\mu - i g_D A_D^\mu)\chi|^2 - \frac{1}{4} F_D^{\mu\nu} F_{D\mu\nu} + \frac{1}{2}\, m_{\gamma_D}^2 A_{D\mu} A_D^\mu$$

DM shift symmetry broken by gauging of U(1)$_{\text{DM}}$

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Unbroken symmetry

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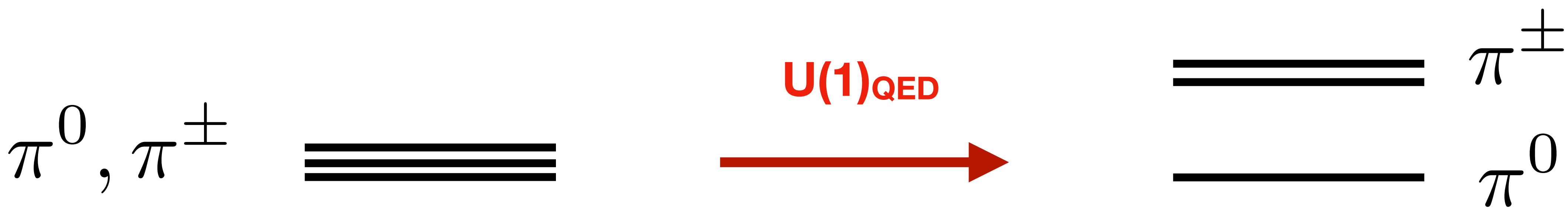
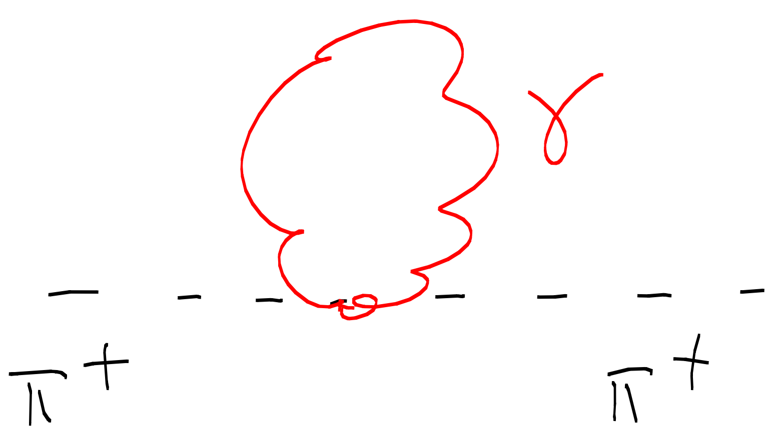
EW custod' DM stabilisation

Gauging $U(1)_{DM}$ generates DM mass

QCD Analogy

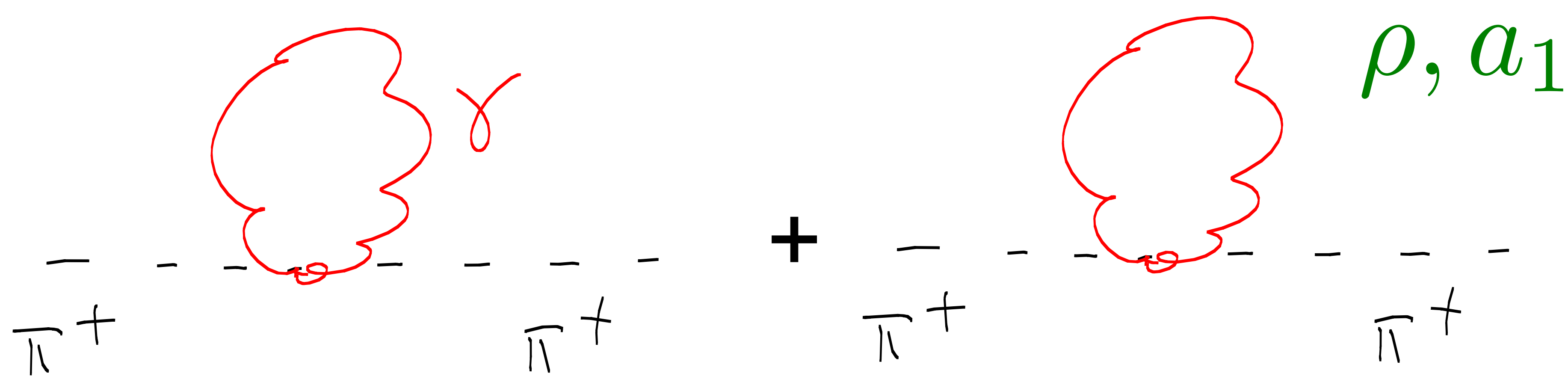




Das et al '67

$$m^2_{\pi^\pm} - m^2_{\pi_0} \simeq \frac{3\,\alpha_{em}}{4\pi}\,\frac{m^2_\rho m^2_{a_1}}{m^2_{a_1} - m^2_\rho}\,\log\left(\frac{m^2_{a_1}}{m^2_\rho}\right)$$

QCD Analogy



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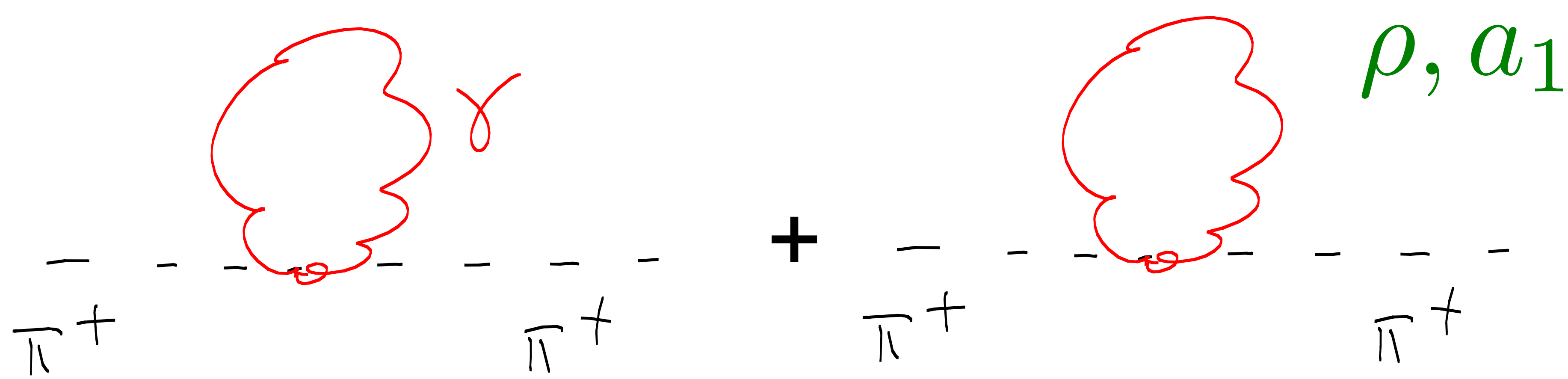

Das et al '67

$$m_{\pi^\pm}^2 - m_{\pi_0}^2 \simeq \frac{3\,\alpha_{em}}{4\pi}\,\frac{m_\rho^2 m_{a_1}^2}{m_{a_1}^2 - m_\rho^2}\,\log\left(\frac{m_{a_1}^2}{m_\rho^2}\right)$$

Dark gauge interaction $U(1)_{DM}$ breaks shift symmetry.

Radiatively generates non-derivative terms:

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

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Not generated at 1-loop!

$$\lambda \ll 1$$

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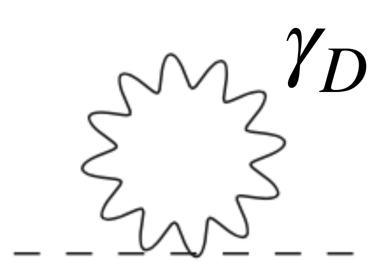


Radiative DM mass:

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

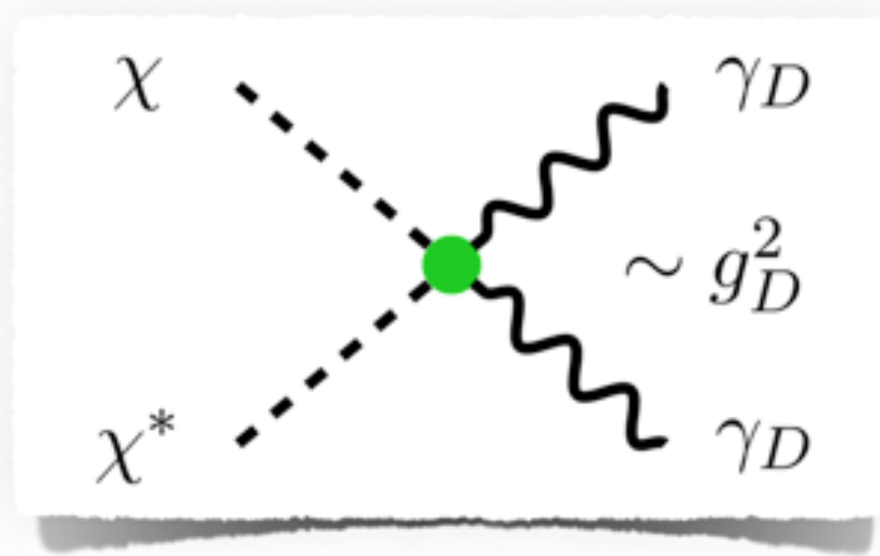
Not generated at 1-loop!

$$\lambda \ll 1$$

New annihilation channel to dark photons

$$\chi^*\chi \to A_D A_D$$

$$\langle \sigma v \rangle \simeq \frac{2\pi\alpha_D^2}{m_\chi^2}$$



$U(1)_{\rm DM}$ and $U(1)_Y$ do not mix kinetically (in $SO(7)/SO(6)$)

Accidental parity: $P_6 = \mathrm{diag}\,(1,1,1,1,1,-1,1) \in O(7)$

C$_{\rm D}$: $A_D^\mu \to -A_D^\mu$ and $\chi \to -\chi^*$

Dark charge conjugation **C**$_{\rm D}$ forbids kinetic photon mixing

$$\epsilon B_{\mu\nu} F_D^{\mu\nu}$$

Respected by fermion embedding (since $Q_{\rm DM}$ = 0 for SM).

1) Massless dark photon

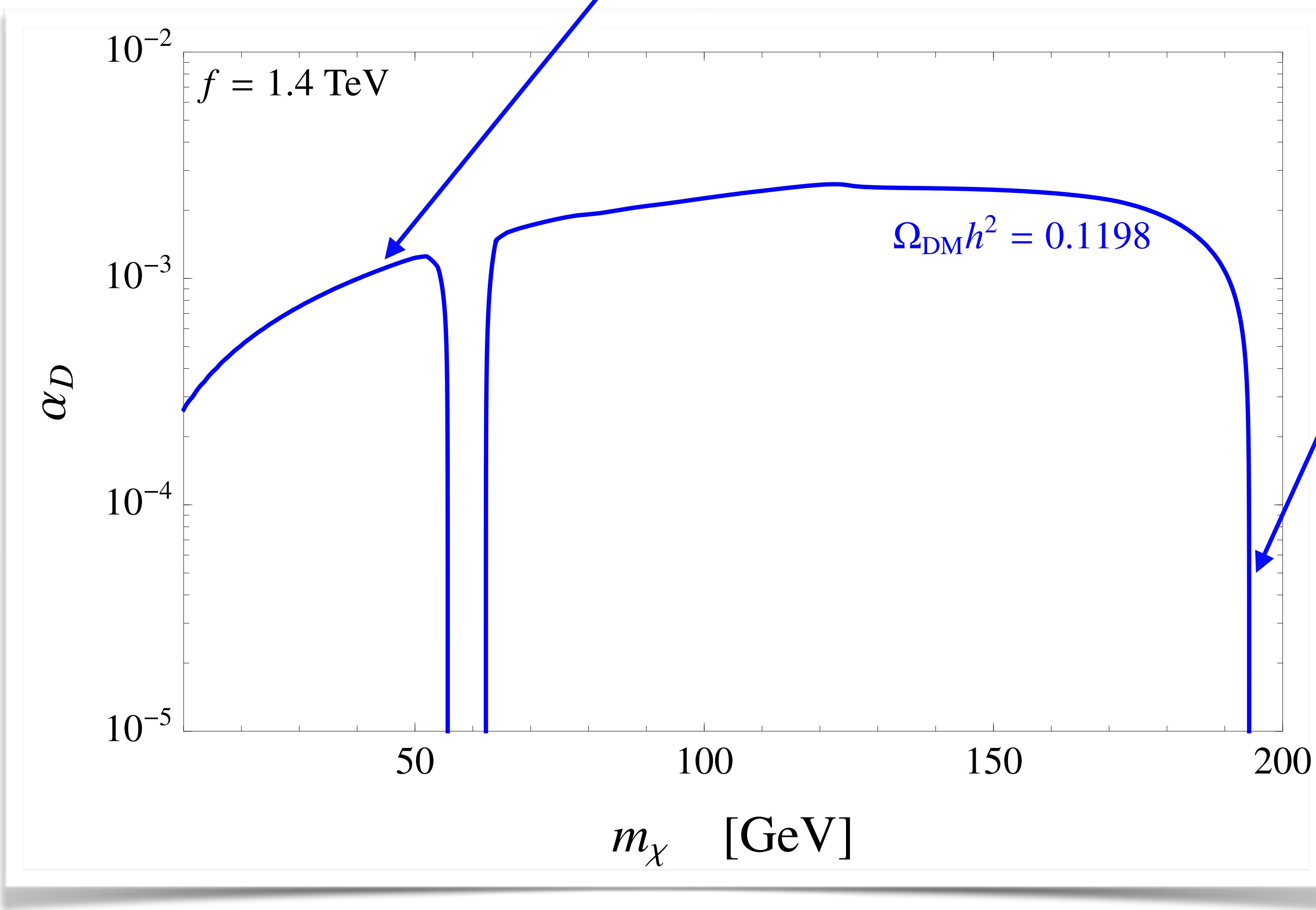
2) Massive dark photon

Massless γ_D

DM gauge coupling

Annihilation mainly to dark photon

$$\chi^*\chi \to A_D A_D$$



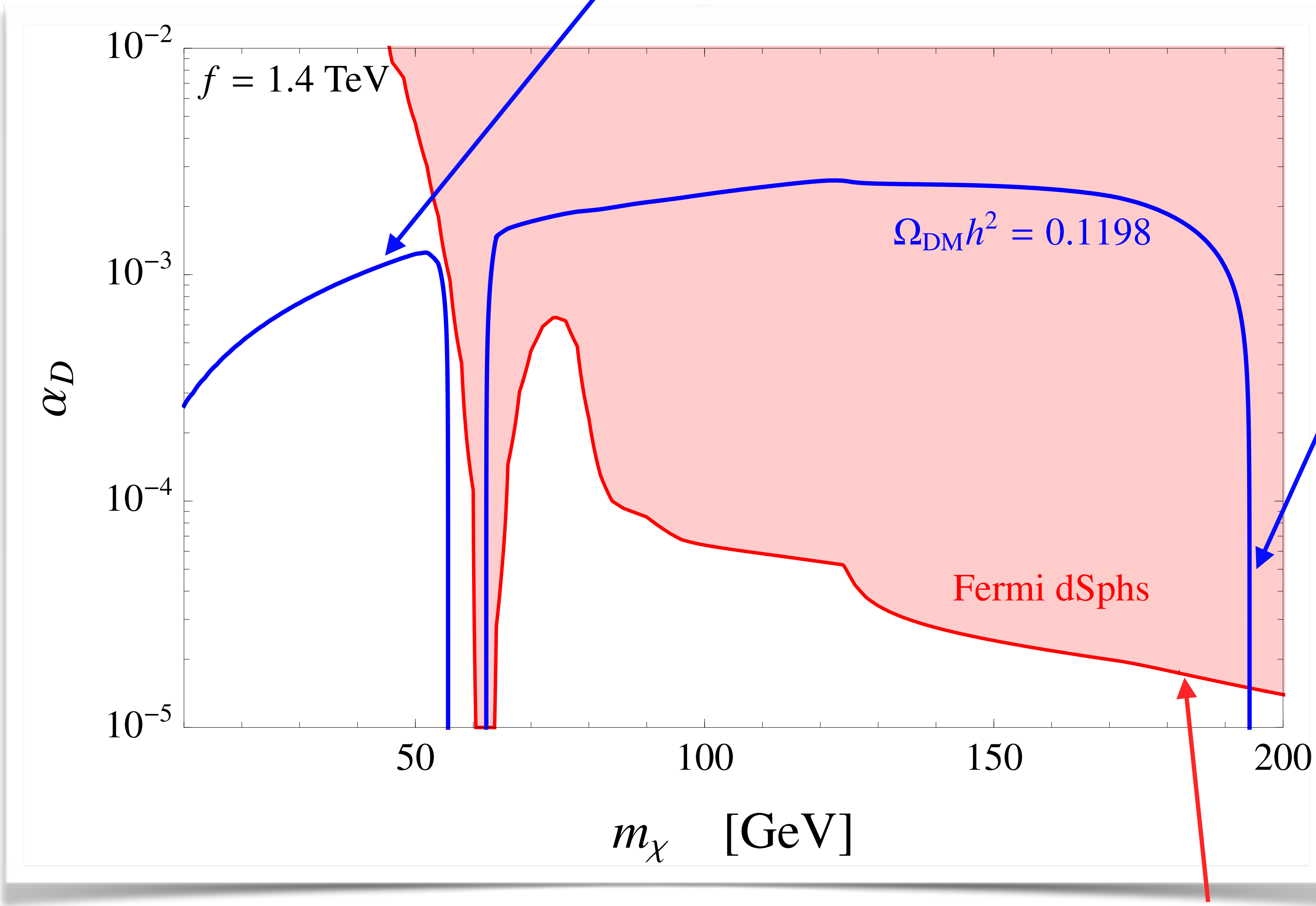
Annihilation purely to SM through

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

DM mass

Massless γ_D

Annihilation mainly to dark photon
$\chi^*\chi \to A_D A_D$



Annihilation purely to SM through

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

Annihilation is Sommerfeld Enhanced in dwarf galaxies today:

$$\frac{\alpha_D}{v_{\rm rel}} \gtrsim \frac{10^{-3}}{10^{-4}} \gg 1$$

Massless γ_D

Non-evaporation of dwarf galaxies until today while traveling through DM halo of MW

1308.3419

Annihilation mainly to dark photon

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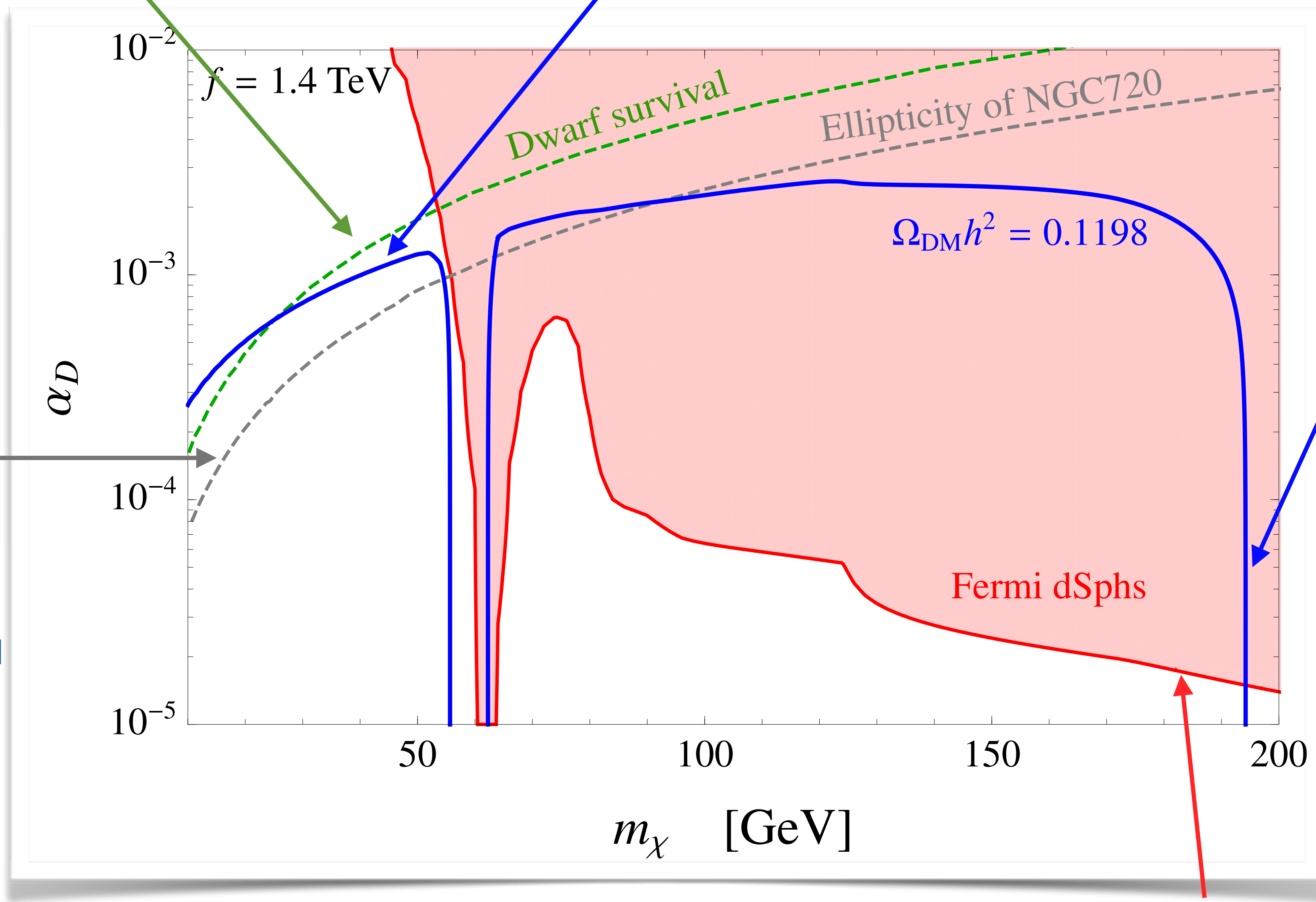

Ellipticity of the halo of NGC720: Self-interactions erase anisotropy of DM velocity distribution

Agrawal et al. 1610.04611

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Massive dark photon

Can add a **Stückelberg mass** $\frac{m_A^2}{2} A_{D\,\mu} A_D^{\mu}$

$m_A < 2m_\chi$

↓

Dark photon is **stable**

$m_A > 2m_\chi$

↓

Dark photon **unstable**

$A_D \rightarrow \chi^* \chi$

Negligible impact on pheno

$$m_A < 2m_\chi$$

Constraints

$m_{\gamma_D} < 6 \times 10^{-4}$ eV	✓/ X	γ_D is dark radiation today, strong constraints from SE of $\chi\chi^* \to$ SM
6×10^{-4} 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

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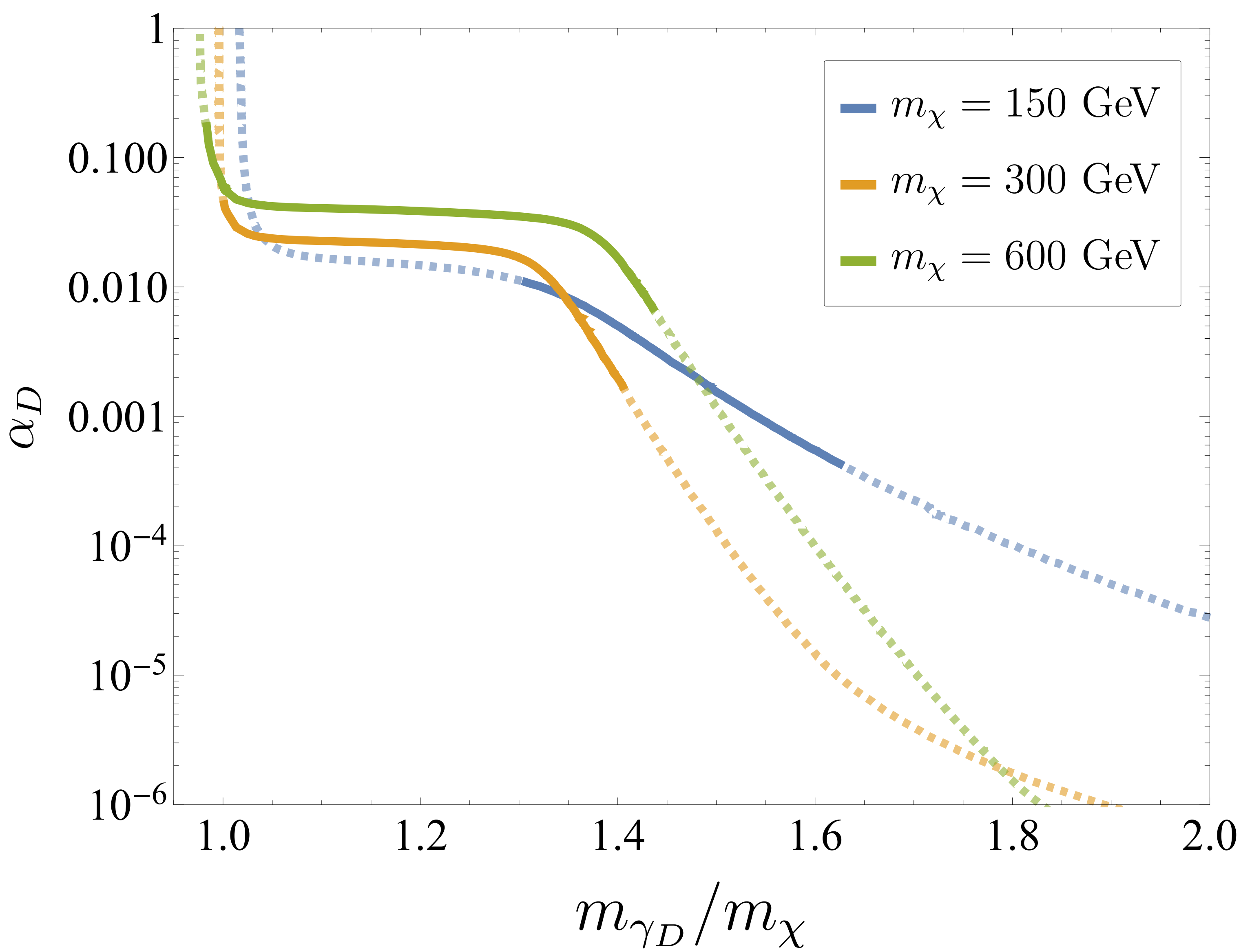
two component DM

Two-component DM

$$\widehat{\lambda}^{-1} x^2 \frac{dY_\chi}{dx} = -\langle \sigma v_{\rm rel} \rangle_{\rm SM} Y_\chi^2 + \tfrac{1}{2} \langle \sigma v_{\rm rel} \rangle_{\gamma_D \gamma_D} Y_{\gamma_D}^2$$

$$\widehat{\lambda}^{-1} x^2 \frac{dY_{\gamma_D}}{dx} = -\langle \sigma v_{\rm rel} \rangle_{\gamma_D \gamma_D} Y_{\gamma_D}^2$$

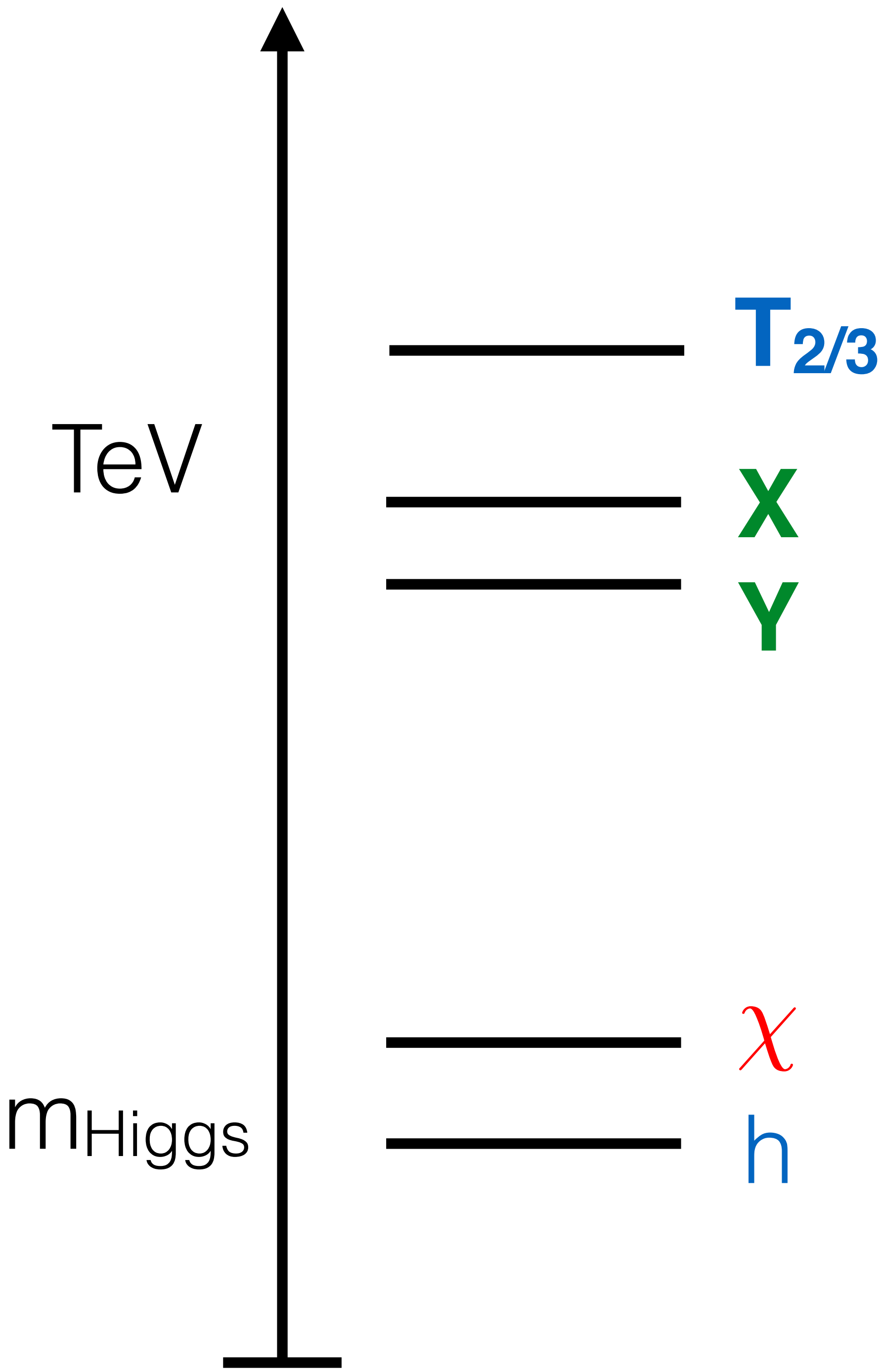


LHC signatures

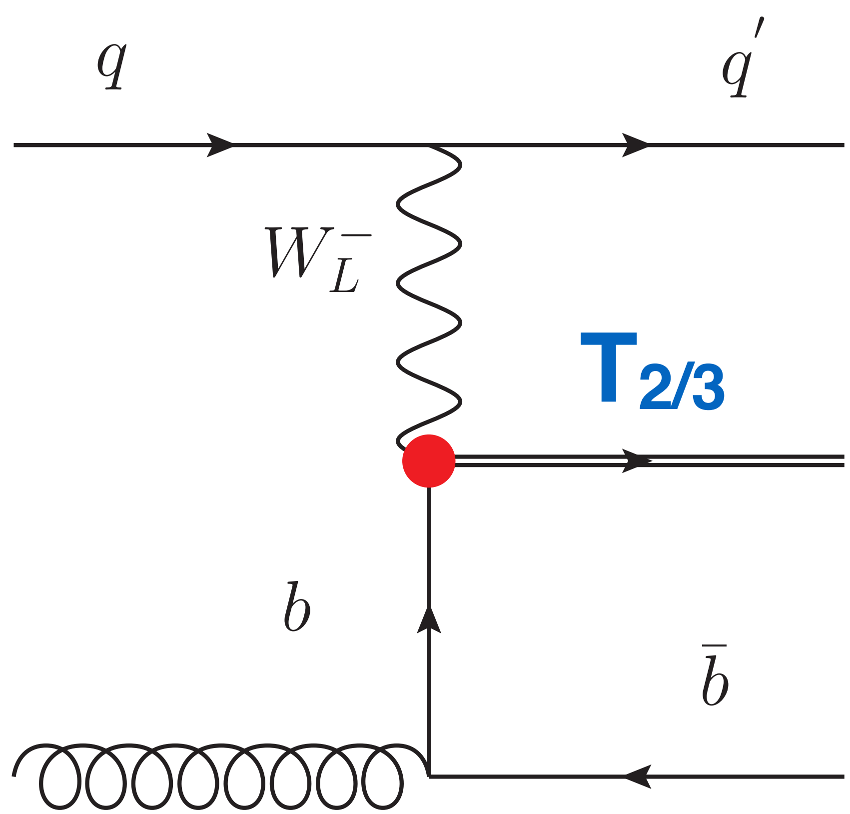
$$Q = \frac{1}{\sqrt{2}} \begin{pmatrix} iB - iX_{5/3} \\ B + X_{5/3} \\ iT + iX_{2/3} \\ -T + X_{2/3} \\ -iY + iZ \\ Y + Z \end{pmatrix}$$

- Composite Top partners, Higgs/DM mass light
  -> at least one top partner ~ 1 TeV
- Additional $U(1)_{DM}$ charged particles -> MET
- Interesting new signatures

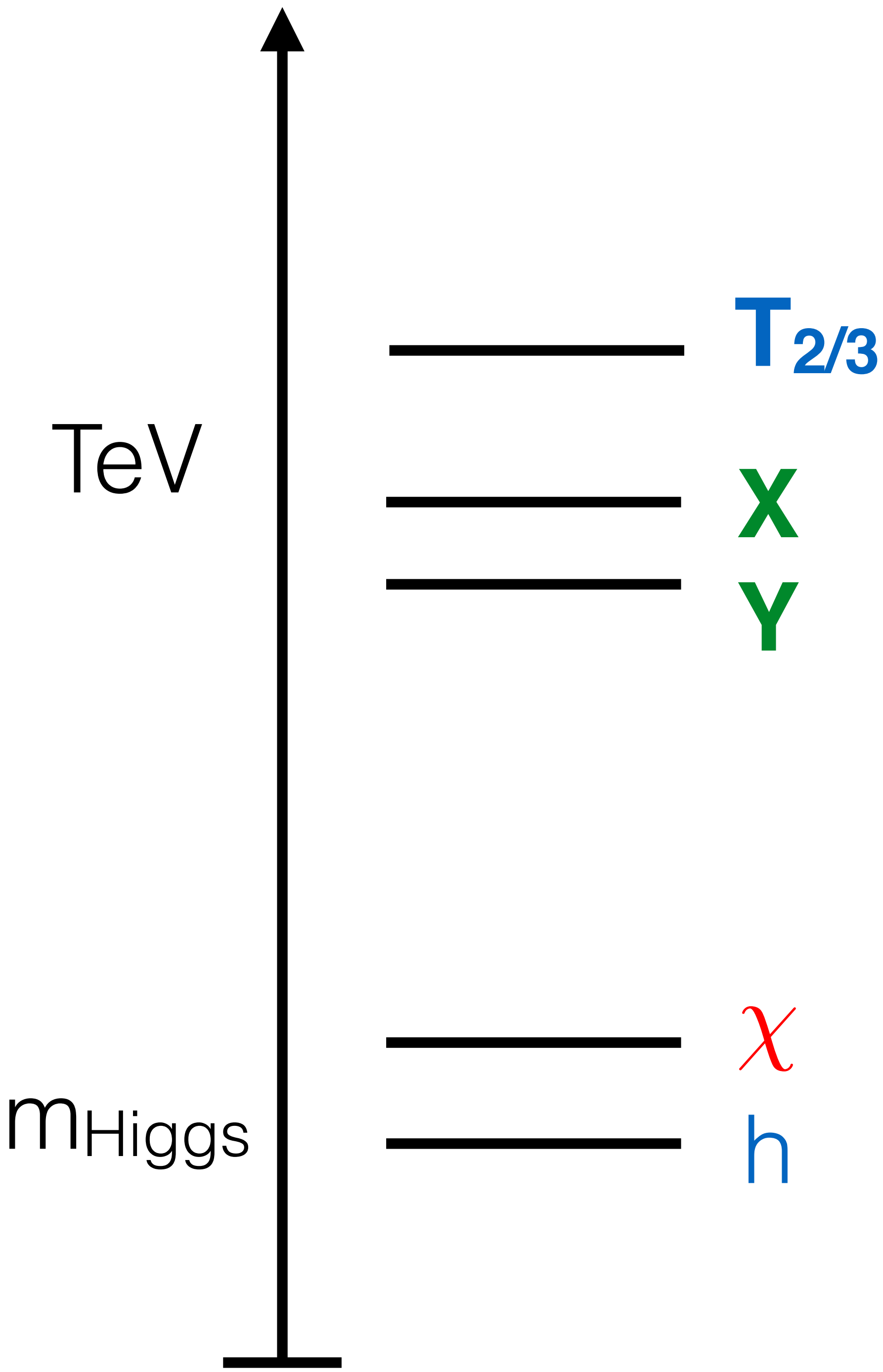
Single Production + MET



interesting new signatures



Single Production + MET



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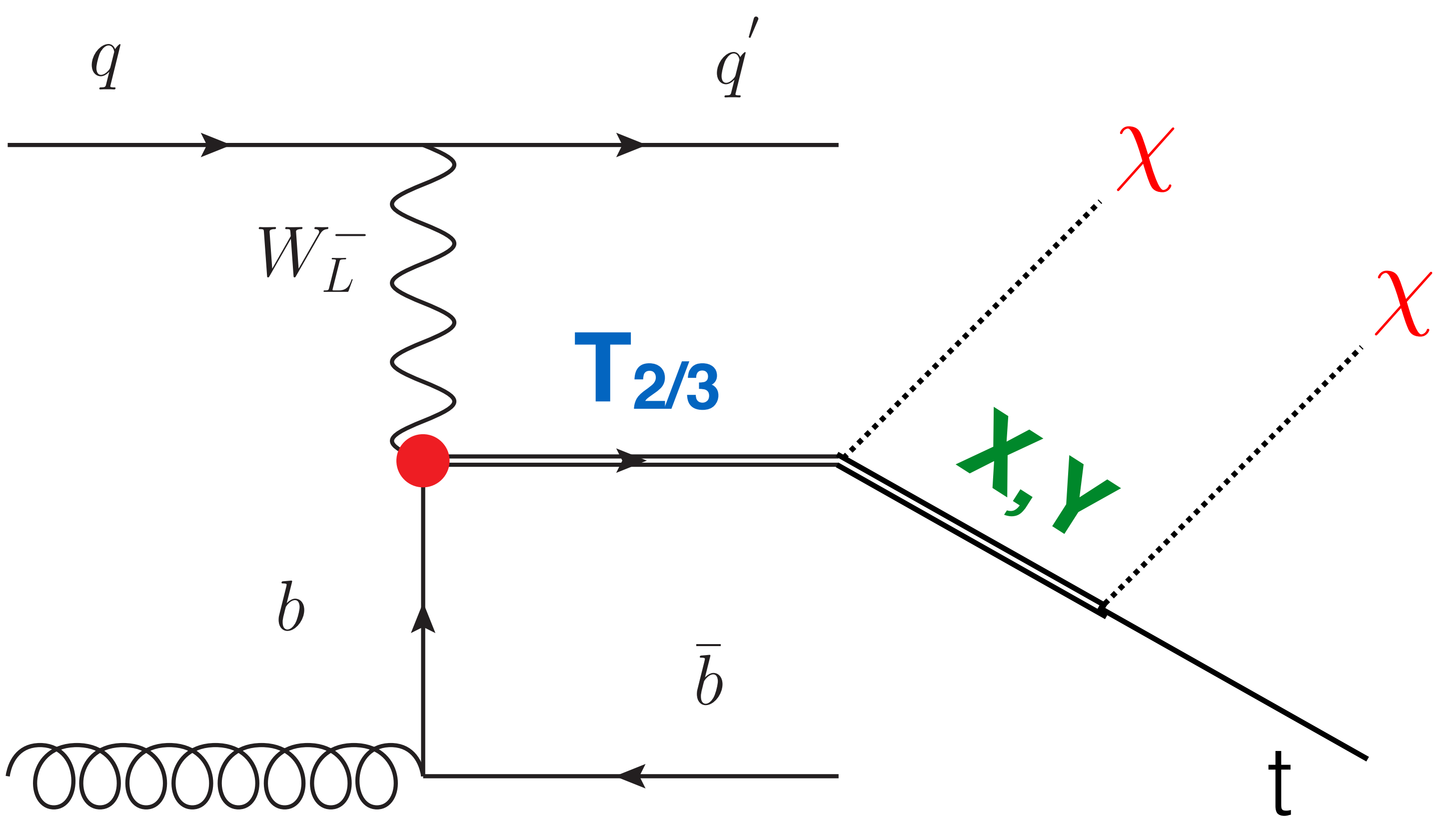


Conclusions

- Additional pNGB scalars in Composite Higgs models can be attractive WIMP candidates
- Robust **UV-safe** stabilisation of DM by exact $U(1)_{\rm DM}$
- Stabilizing $U(1)_{\rm DM}$ can be **weakly gauged**:

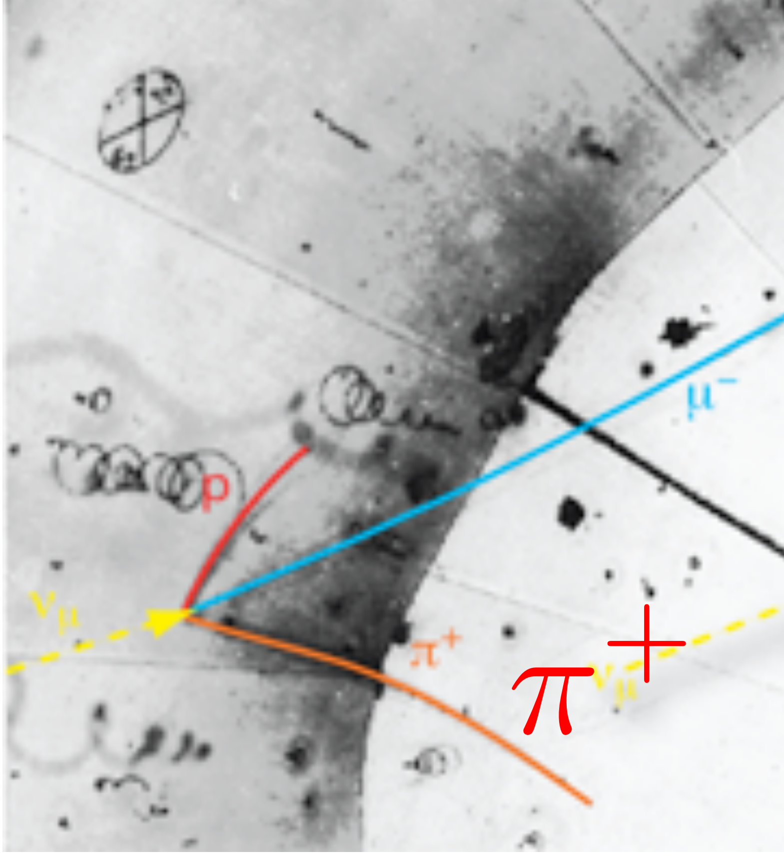
A. Gauging of $U(1)_{\rm DM}$ generates DM mass

B. Negligible direct detection cross-section

C. Massless dark photon model is in tension with Fermi-LAT gamma-ray data for $m_\chi > m_h/2$

D. Massive dark photon with $m_A > m_\chi$ satisfies constraints from astro-ph and features rich DM phenomenology

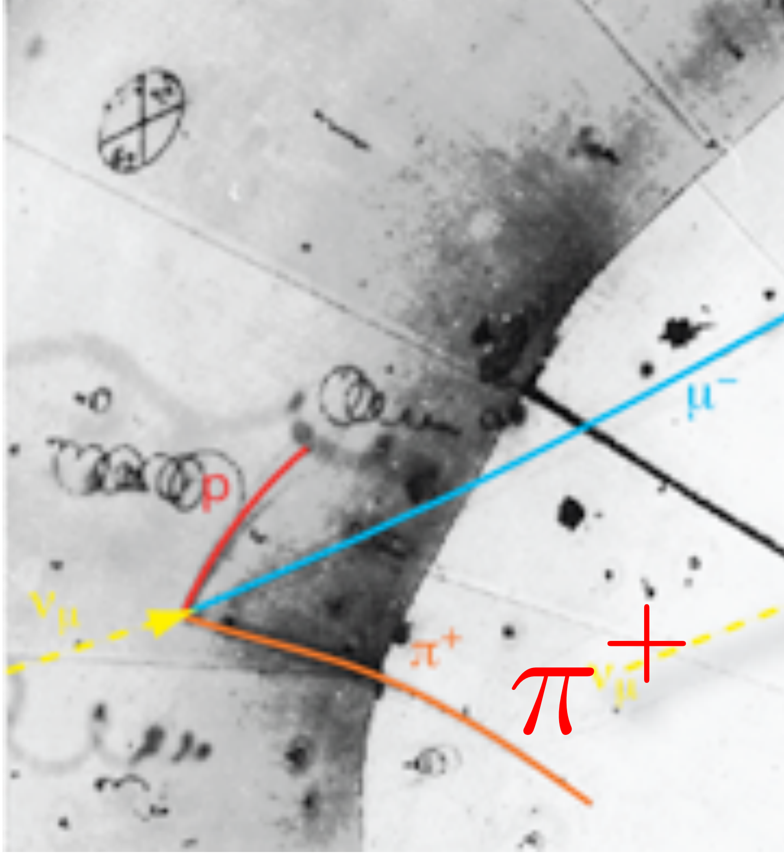
QCD-Pions as pNGBs



$$SU(2)_L \times SU(2)_R / SU(2)_{L+R}$$

$$U = e^{i\pi/f} \langle \phi \rangle \qquad \mathcal{L}_{\rm eff} = \frac{f^2}{4} \, {\rm tr}(\partial_\mu U^\dagger \partial^\mu U) + \ldots$$

QCD-Pions as pNGBs



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$$\boxed{\pi \longrightarrow -\pi} \qquad (U \to U^\dagger)$$

Good symmetry? Depends on the UV…

IR probe of UV physics

π^0 DECAY MODES

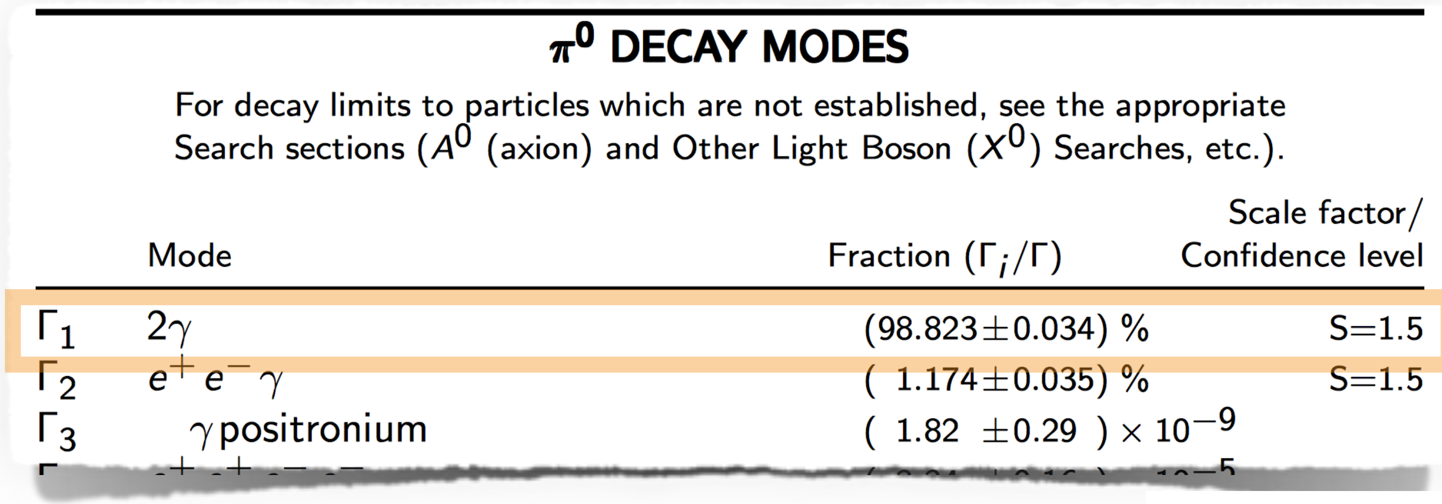
For decay limits to particles which are not established, see the appropriate Search sections (A^0 (axion) and Other Light Boson (X^0) Searches, etc.).

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	2γ	(98.823 ± 0.034) %	S=1.5
Γ_2	$e^+e^-\gamma$	(1.174 ± 0.035) %	S=1.5
Γ_3	γ positronium	$(1.82\pm0.29)\times10^{-9}$	

pdg

. Wess, Zumino '71, Witten '83

IR probe of UV physics



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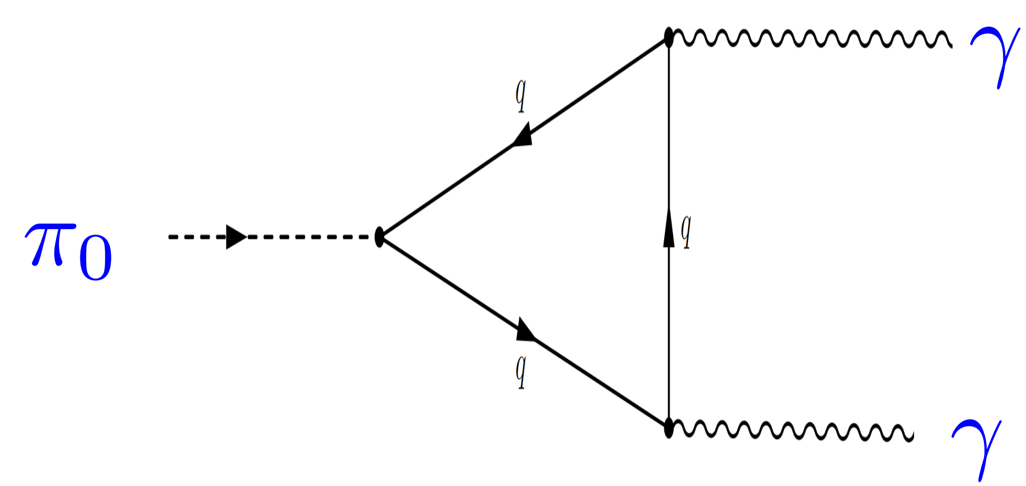
pdg

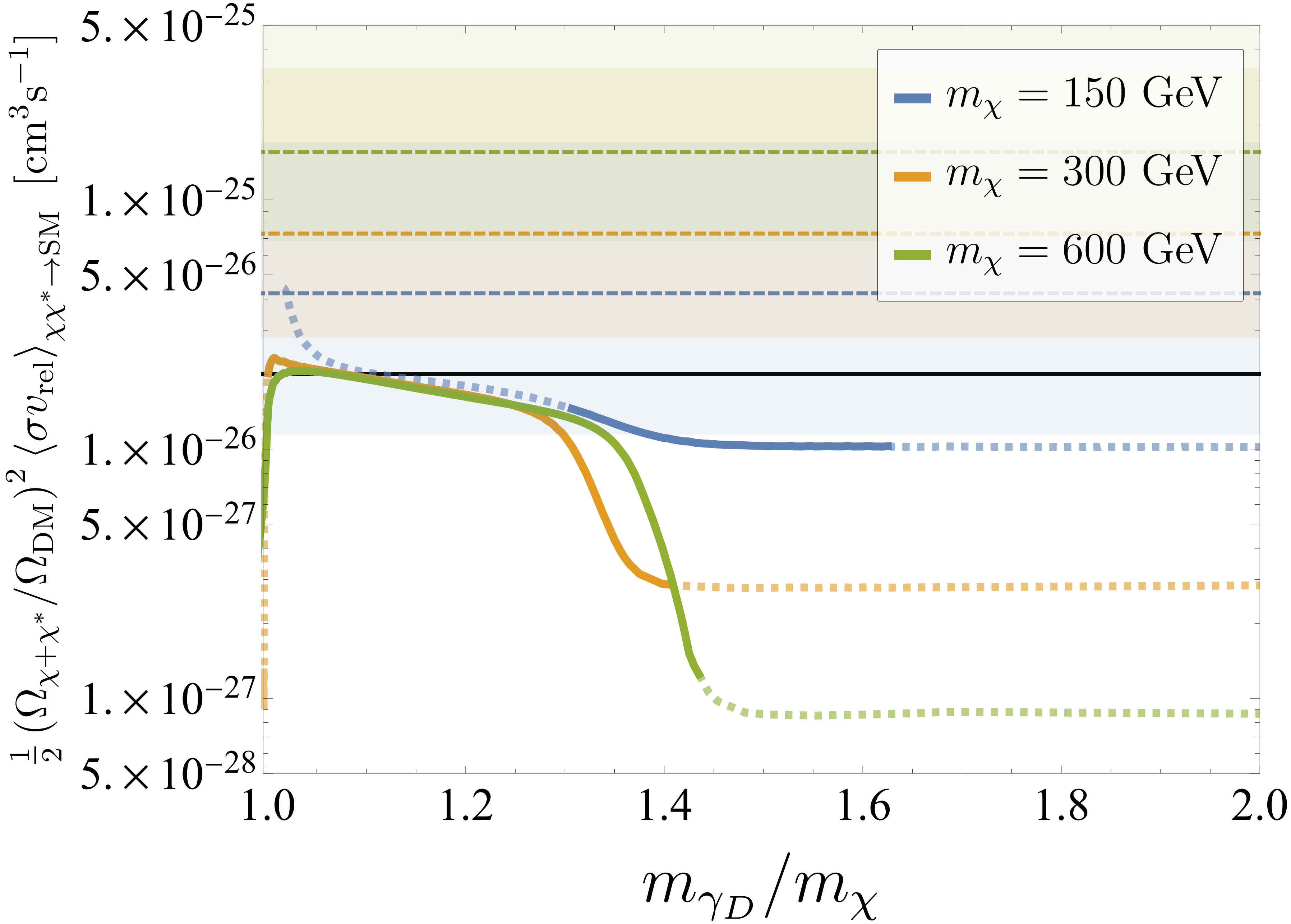
Wess, Zumino '71, Witten '83

Anomaly: WZW term

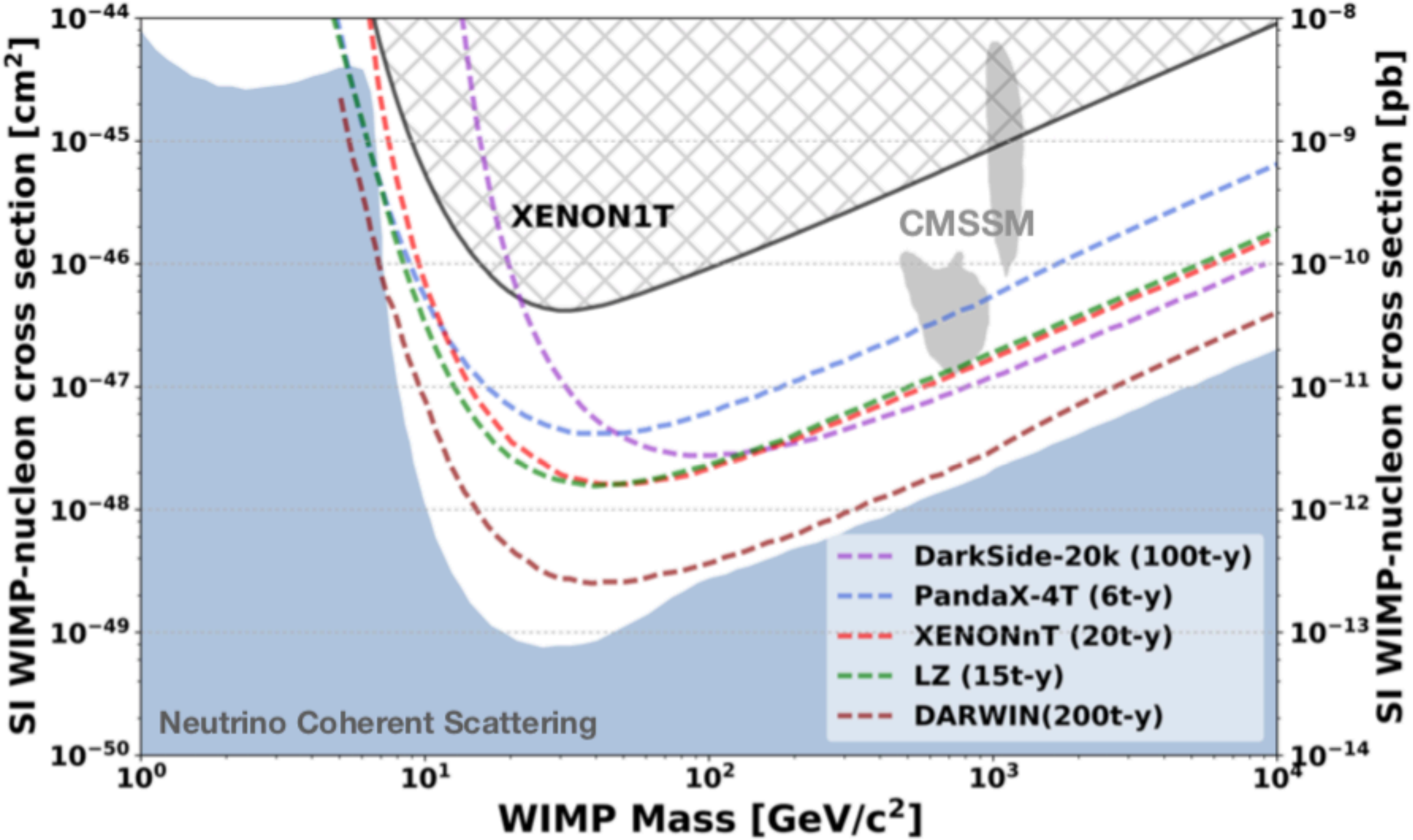
$$\mathcal{L}_A = \frac{e^2 N_c}{48\pi^2 F_\pi} 3\,\mathrm{Tr}\,(Q^2 \tau_3)\, \epsilon^{\mu\nu\alpha\beta} F_{\mu\nu} A_\alpha \partial_\beta \pi^0$$



$$\pi \not\rightarrow -\pi$$

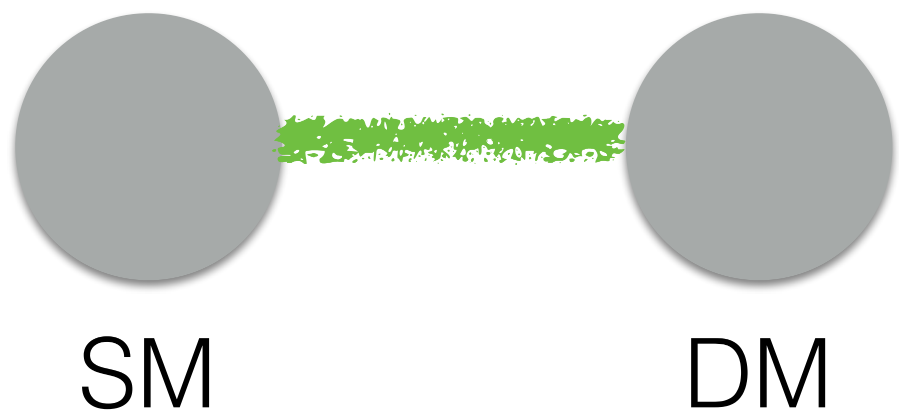


$5.\times 10^{-25}$
$1.\times 10^{-25}$
$5.\times 10^{-26}$
$1.\times 10^{-26}$
$5.\times 10^{-27}$
$1.\times 10^{-27}$
$5.\times 10^{-28}$
1.0
1.2
1.4
1.6
1.8
2.0
$\frac{1}{2}(\Omega_{\chi+\chi^*}/\Omega_{\rm DM})^2\langle\sigma v_{\rm rel}\rangle_{\chi\chi^*\to{\rm SM}}$ $[{\rm cm}^3{\rm s}^{-1}]$
m_{γ_D}/m_χ
$m_\chi = 150$ GeV
$m_\chi = 300$ GeV
$m_\chi = 600$ GeV



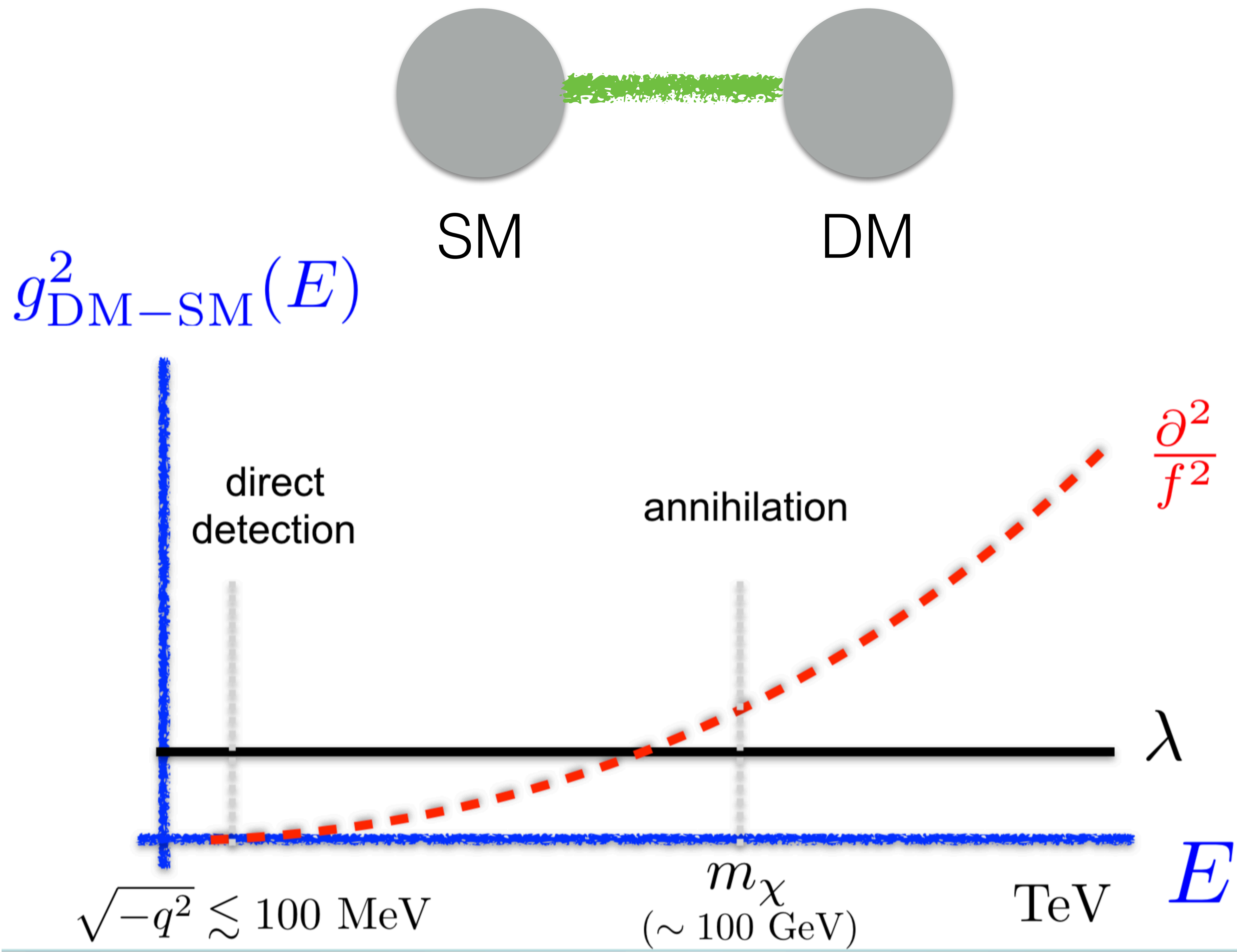
SI WIMP-nucleon cross section [cm²]
SI WIMP-nucleon cross section [pb]
WIMP Mass [GeV/c²]
XENON1T
CMSSM
Neutrino Coherent Scattering
DarkSide-20k (100t-y)
PandaX-4T (6t-y)
XENONnT (20t-y)
LZ (15t-y)
DARWIN(200t-y)

$$\mathcal{L}_{SM}(h) + \mathcal{L}_{DM}(\chi) + \lambda h^2 \chi^* \chi + \frac{1}{f^2}\partial_\mu(h^2)\partial^\mu(\chi^*\chi) + \ldots$$



see e.g.1607.02474

$$\mathcal{L}_{SM}(h) + \mathcal{L}_{DM}(\chi) + \lambda h^2 \chi^* \chi + \frac{1}{f^2} \partial_\mu (h^2) \partial^\mu (\chi^* \chi) + \ldots$$



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