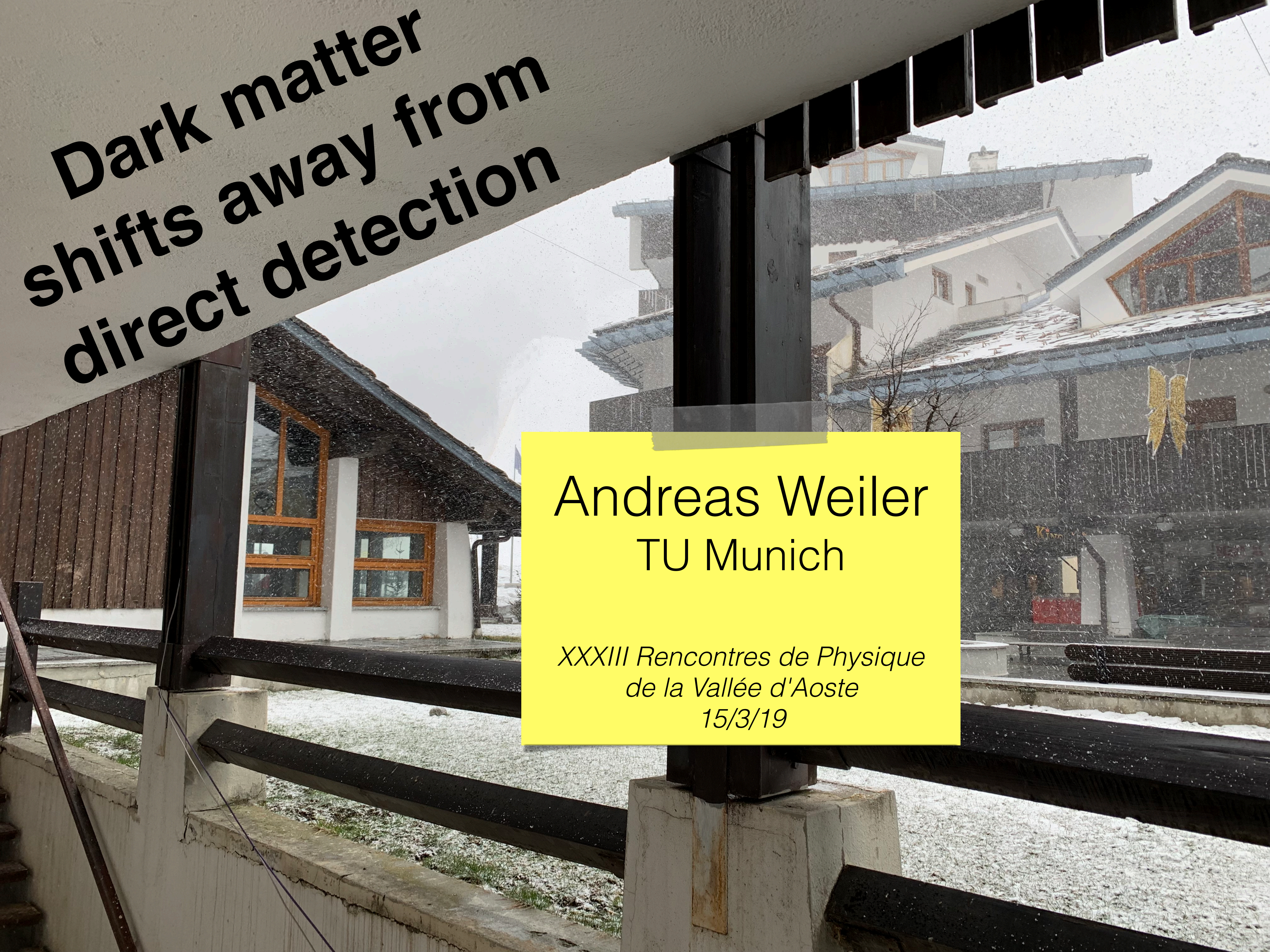


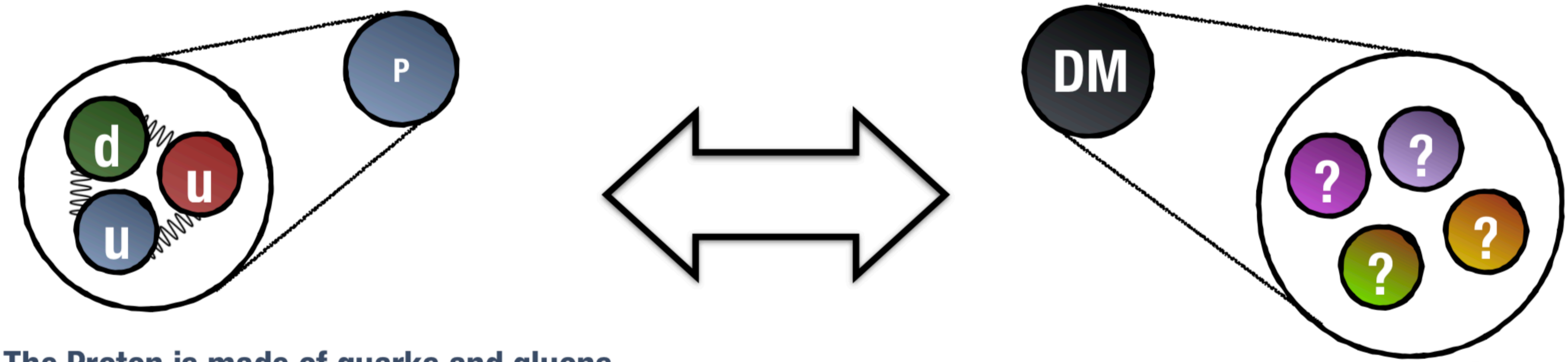
Dark matter shifts away from direct detection

Andreas Weiler

TU Munich

XXXIII Rencontres de Physique
de la Vallée d'Aoste
15/3/19

Could Dark Matter be a composite particle?



The Proton is made of quarks and gluons, held together by the strong force

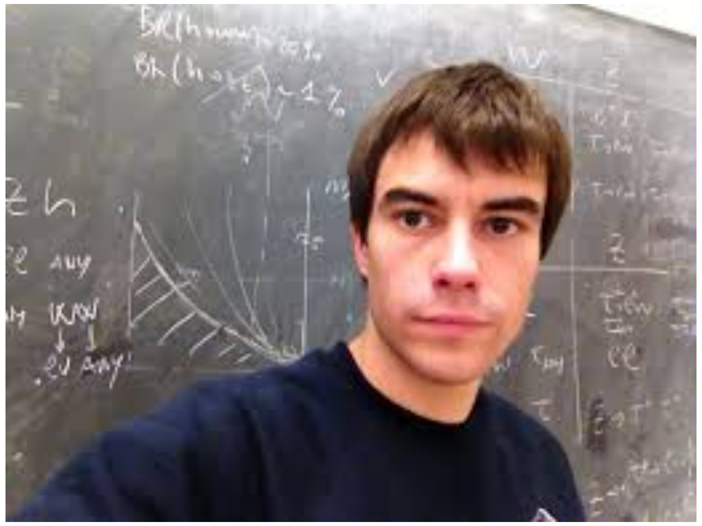
New particles, new forces

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:

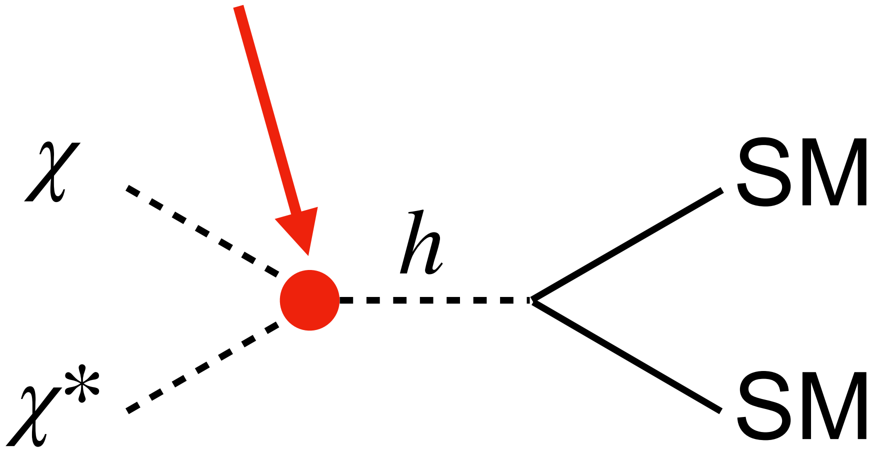
$$\frac{1}{f^2}\partial_\mu(h^2)\partial^\mu(\chi^*\chi) + \ldots$$

Higgs

DM

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.

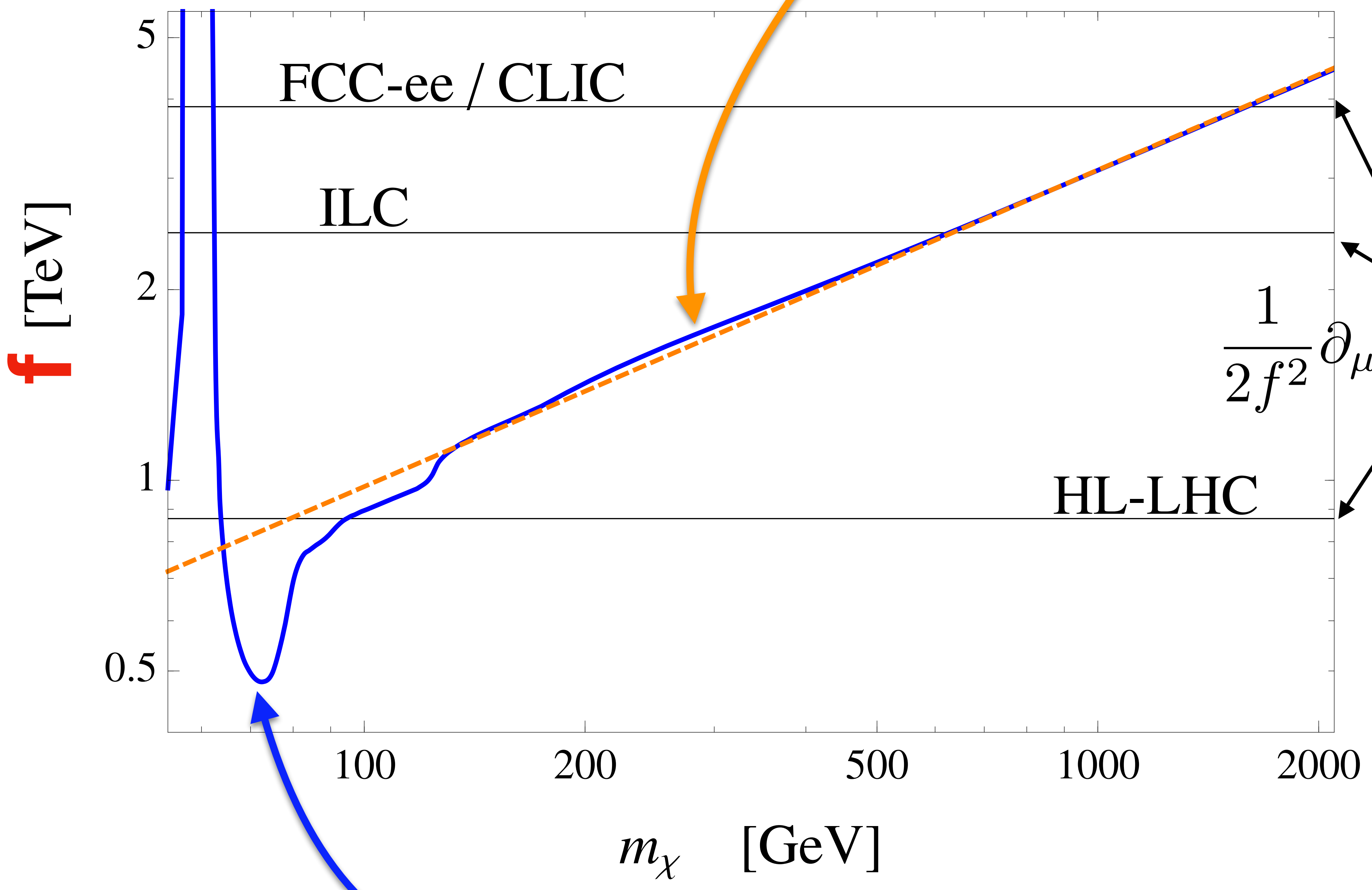
Correct DM thermal relic density requires:

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

Interesting !

This scale corresponds to expectation for a natural pGB — as in minimal composite Higgs models.

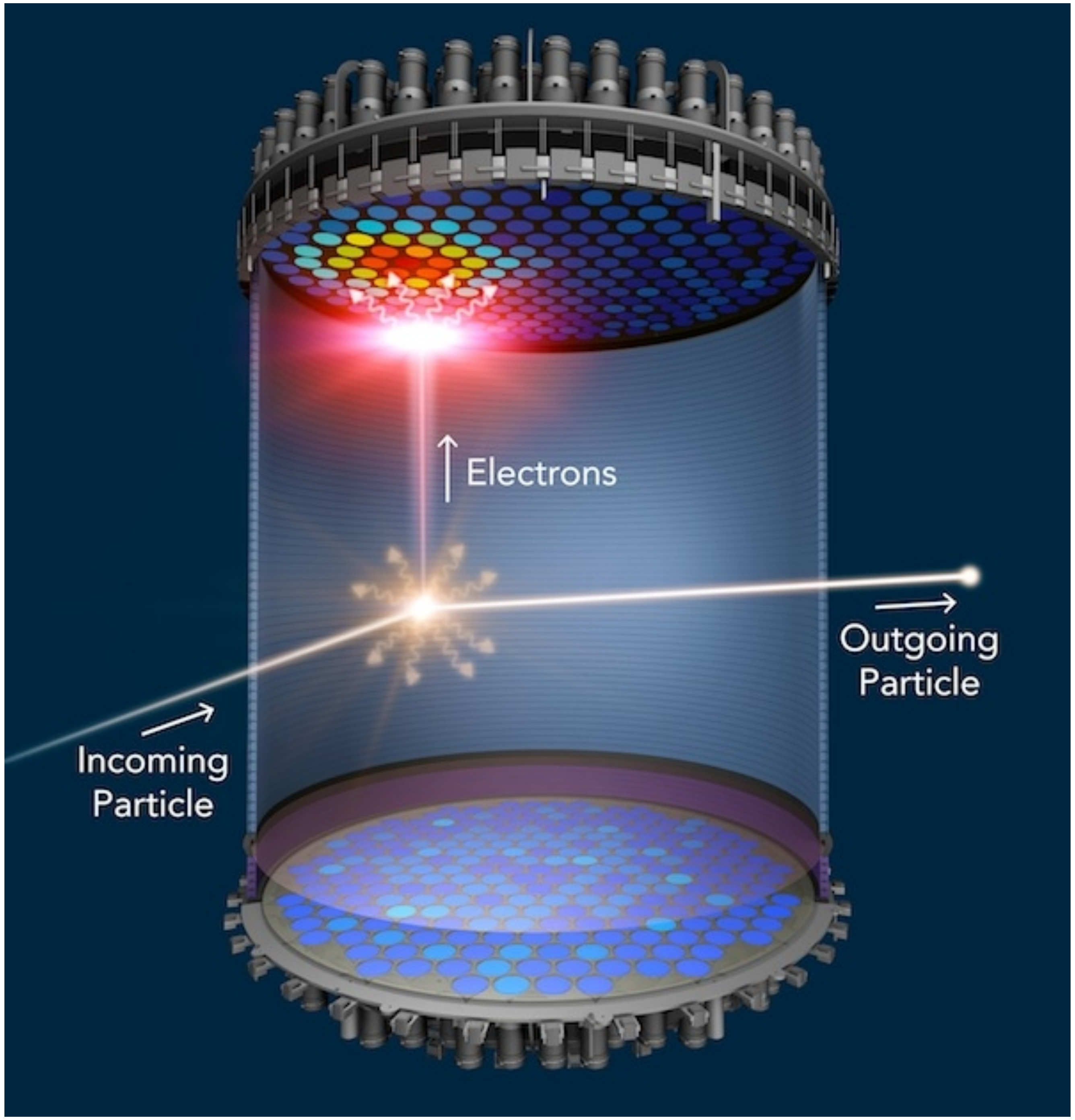
Estimation: $f \approx 1.1\,\mathrm{TeV}\,\left(\frac{m_\chi}{130\mathrm{GeV}}\right)^{1/2}$



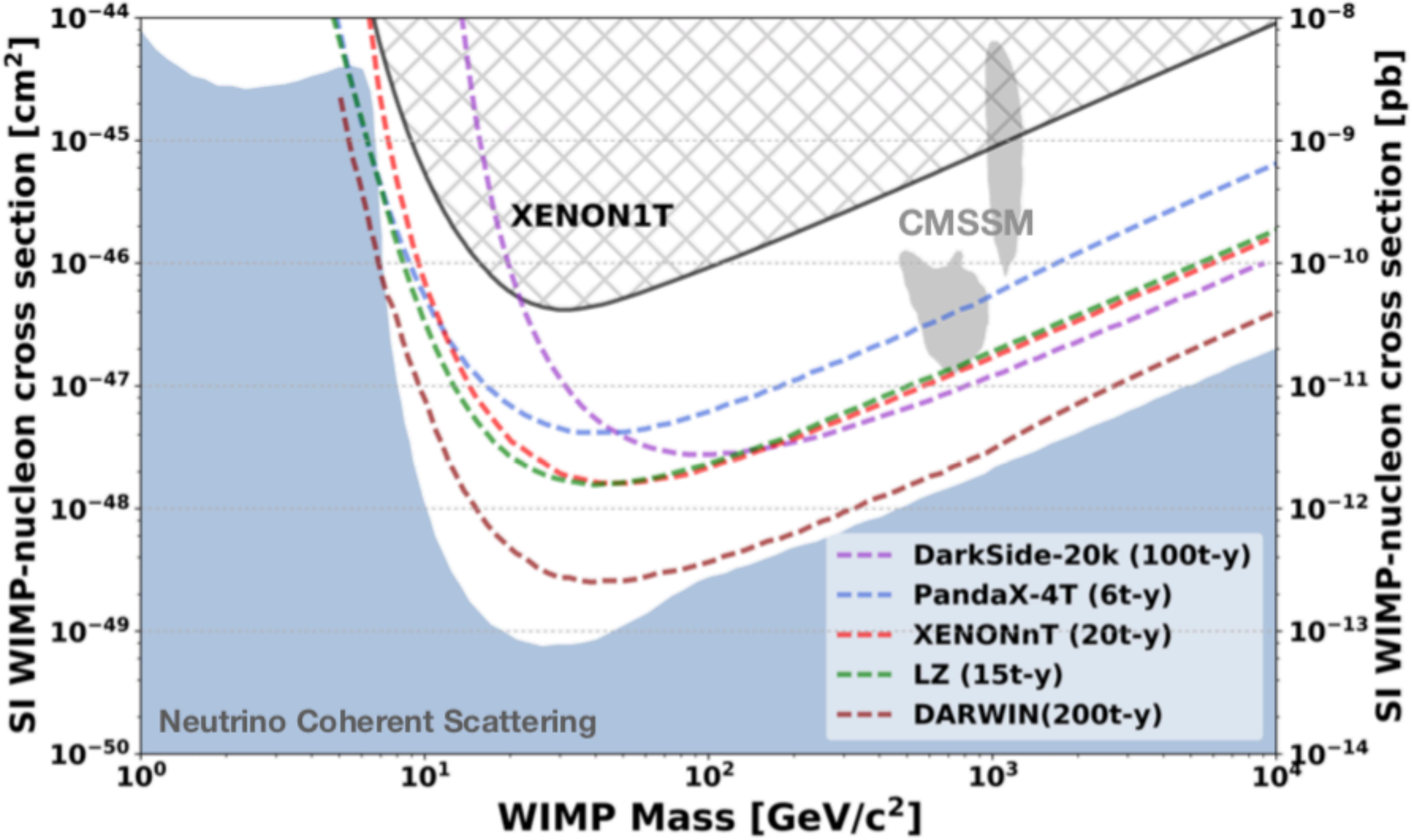
$$\frac{1}{2f^2}\partial_\mu |H|^2 \partial^\mu |H|^2$$

Full Boltzmann solution

Direct detection of DM ?

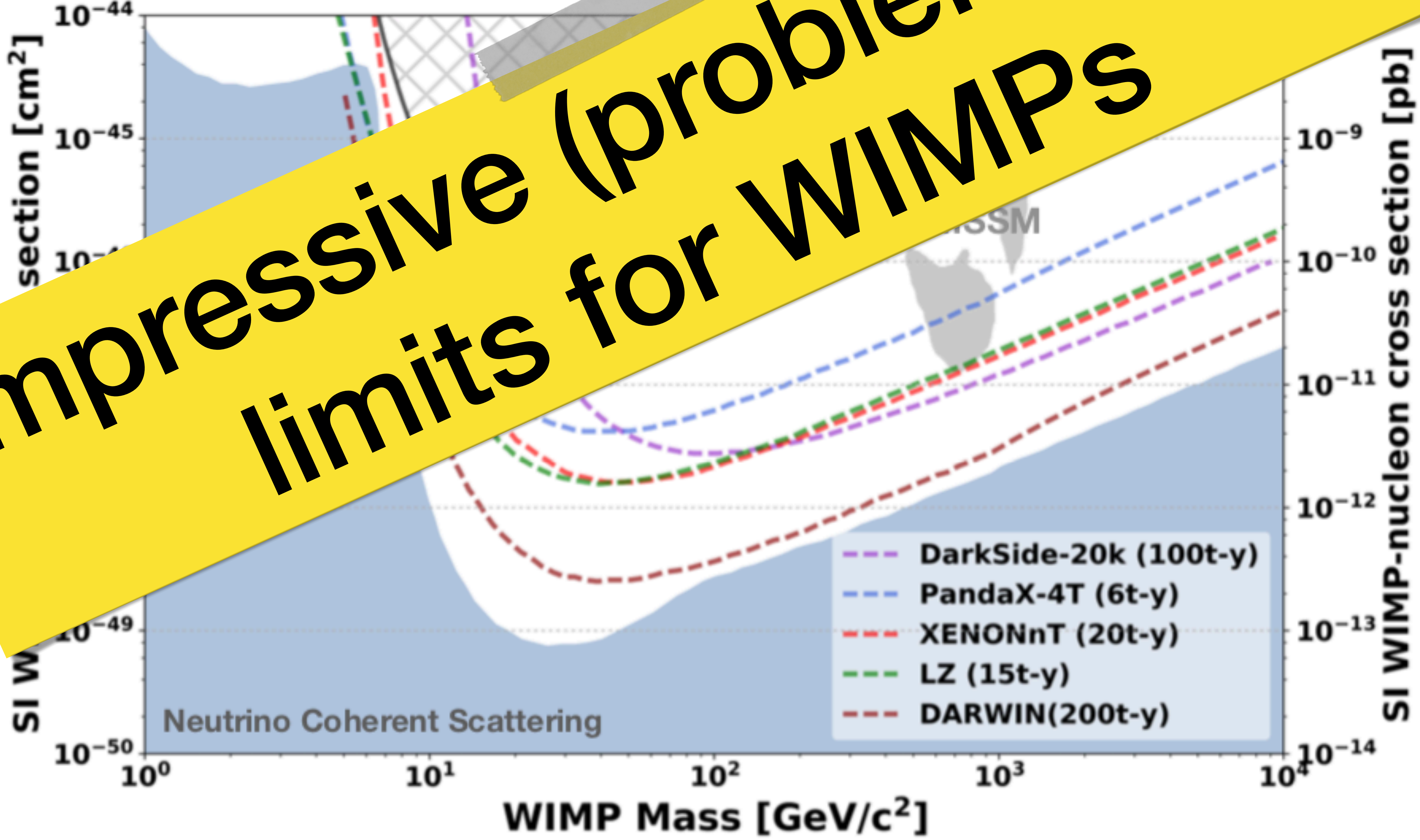


Direct detection



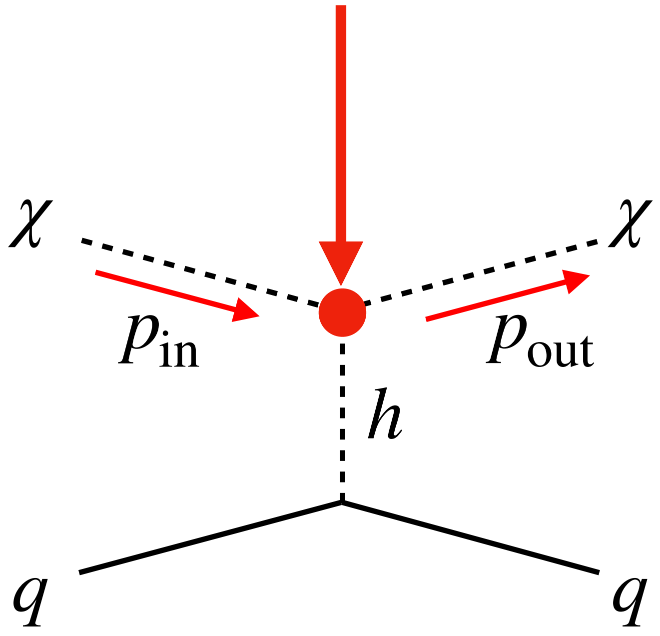
Direct detecti

Impressive (problematic?) limits for WIMPs



Direct detection of exact Goldstone DM

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



nuclear recoil energy

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

$f \approx 1\,\text{TeV}$

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

Wait …

- DM cannot be an exact Goldstone, because DM massive

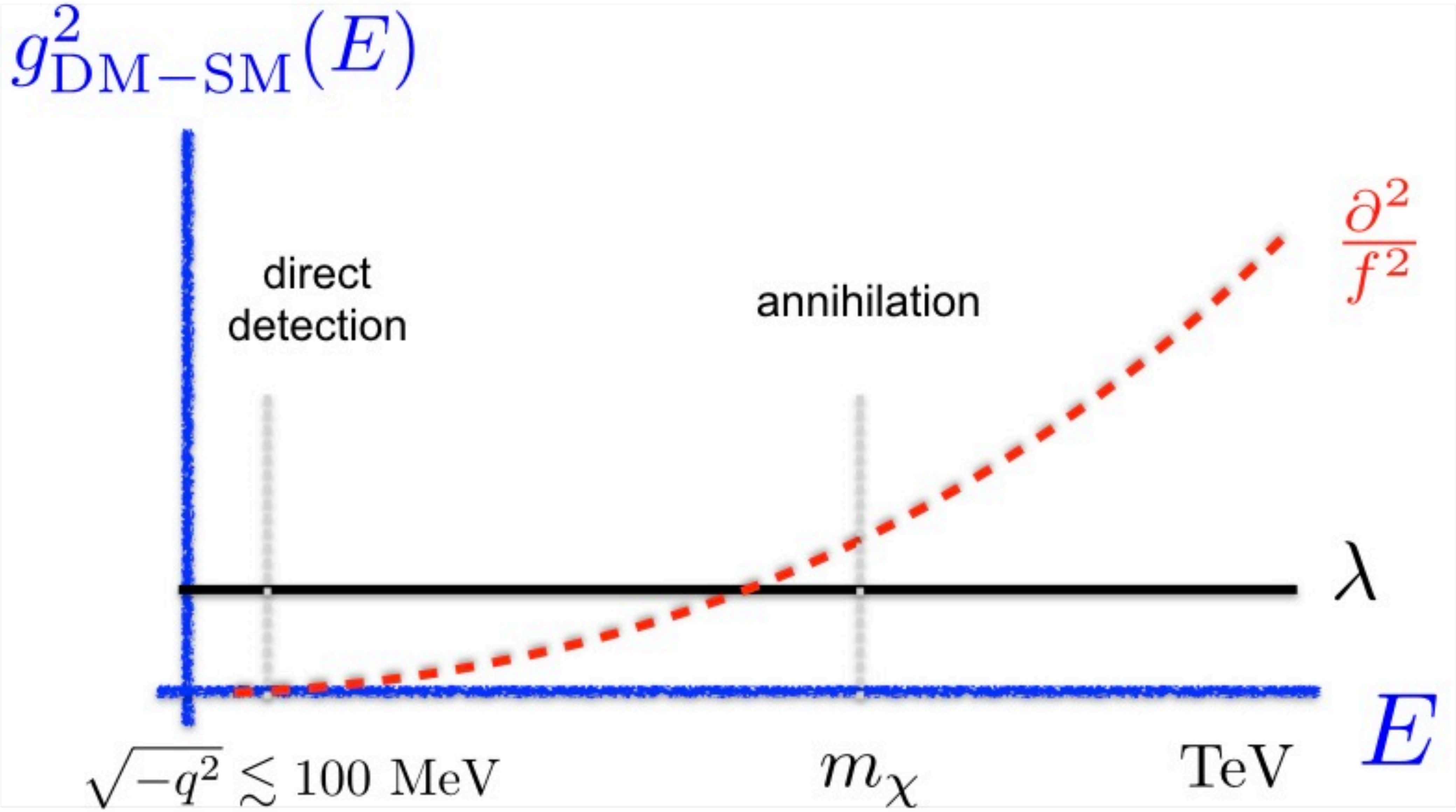
$$m_\chi^2|\chi|^2 + \dots \qquad \text{means} \qquad \cancel{\chi \to \chi + f}$$

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 to SM.

Direct detection is very sensitive to this λ .



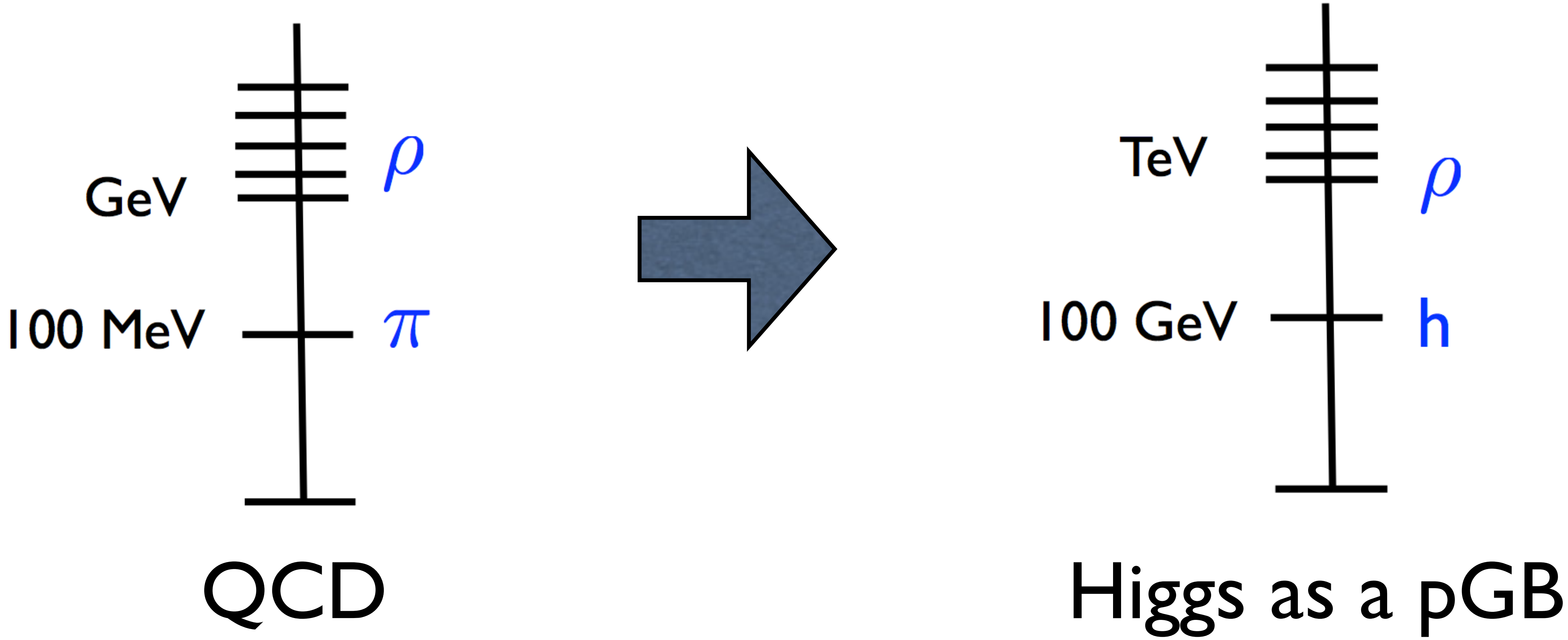
Want to stay close to Goldstone limit: $\lambda \ll 1$

Kaplan, Georgi ’84; Agashe, Contino, Pomarol ’04;
Giudice, Grojean, Pomarol, Rattazzi ‘07

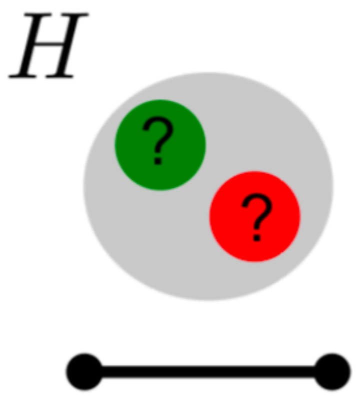
Composite Higgs

A solution to the hierarchy problem:

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



Description changes above confinement scale (~ TeV)



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

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

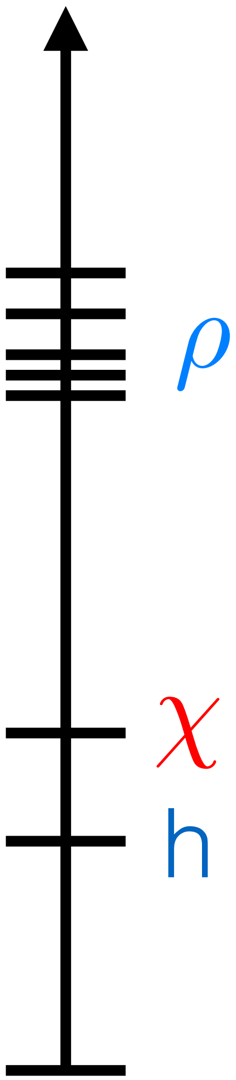
$\mathcal{G} \xrightarrow[H,\chi]{f} \mathcal{H}$ additional pNGB χ as WIMP

Compare to QCD:

2 flavors: $SU(2)_L x SU(2)_R / SU(2)_V$ -> 3 GBs $\pi^0,\ \pi^\pm$

3 flavors: $SU(3)_L x SU(3)_R / SU(3)_V$ -> 8 GBs $\pi^{0,\pm}, K^{0,\bar{0},\pm}, \eta$

Goldstone dark matter



Symmetry that protects the (Higgs mass)^2 also

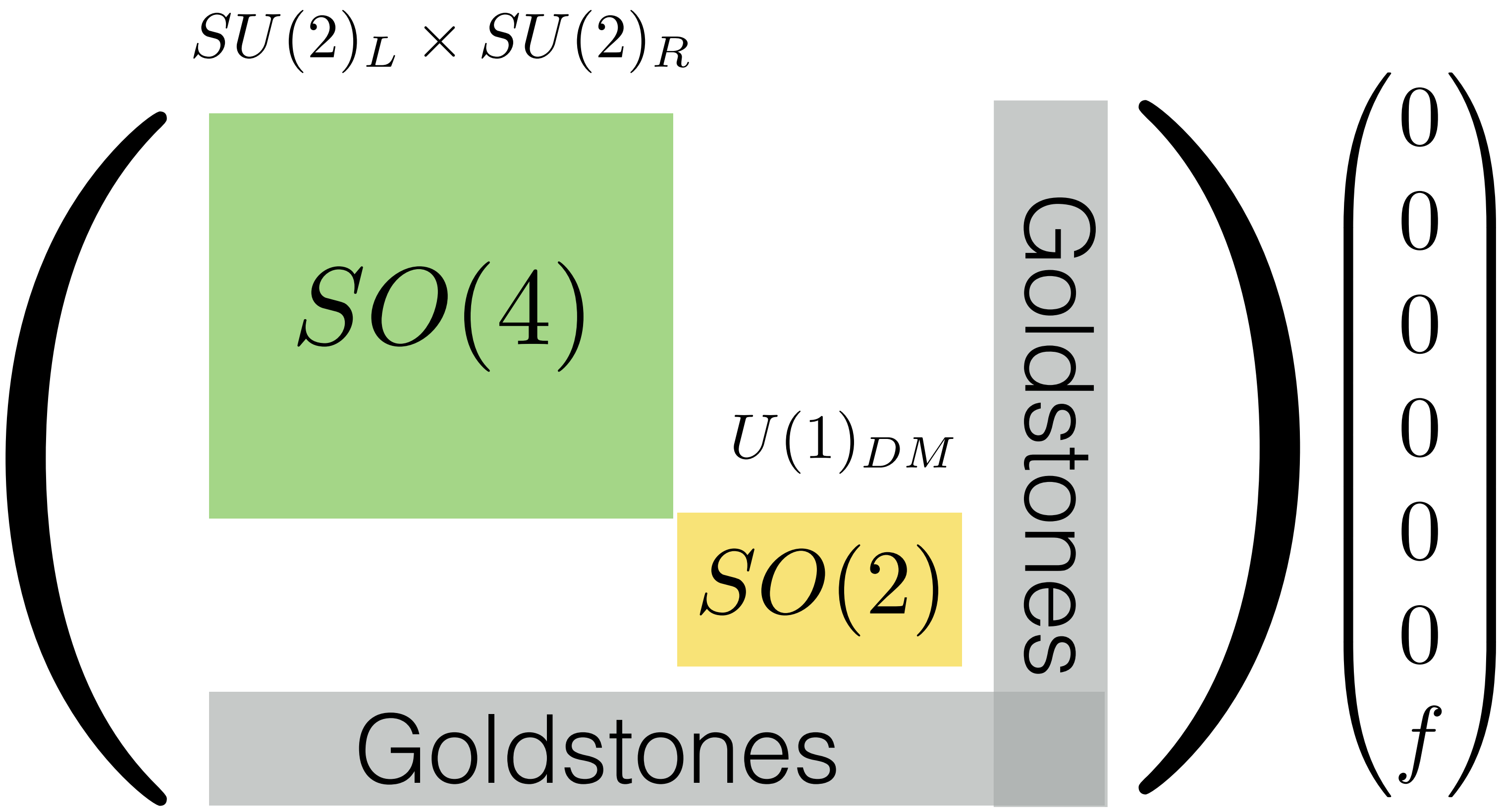
- keeps WIMP χ light: $\chi(x) \to \chi(x) + \alpha$
- renders χ stable: $\chi(x) \to -\chi(x)$ parity

or

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

will use here

SO(7)/SO(6)



Dm in composite Higgs, see also: Frigerio, Pomarol, Riva, Urbano ’12, Marzocca, Urbano ’14; Carmona, Chala ’15, M. Chala, G. Nardi
I. Sobolev ’16; Ballesteros, Carmona, Chala ’17, the discussion is away from Goldstone limit, large marginal contribution

Breaking the DM shift symmetry

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

Balkin, Ruhdorfer,
Salvioni,AW 1707.07685

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

Balkin, Ruhdorfer,
Salvioni,AW, 1809.09106

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

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

Breaking the DM shift symmetry

- Top quar

in tension with Xenon 1T

Ruhdorfer,
Salvioni,AW 1707.07685

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

Balkin, Ruhdorfer,
Salvioni,AW, 1809.09106

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

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Ruhdorfer,
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Goldstone symmetry U(1)DM : $\lambda \propto \text{higher-loop} \ll 1$

Focus on this

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

Balkin, Ruhdorfer,
Salvioni,AW, 1809.09106

DM shift symmetry broken by b-quark mass

b_R embedding

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

b$_{\mathbf{R}}$

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

...

$\mathbf{b}_R$ embedding

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

$\mathbf{b}_R$

$$\begin{aligned}
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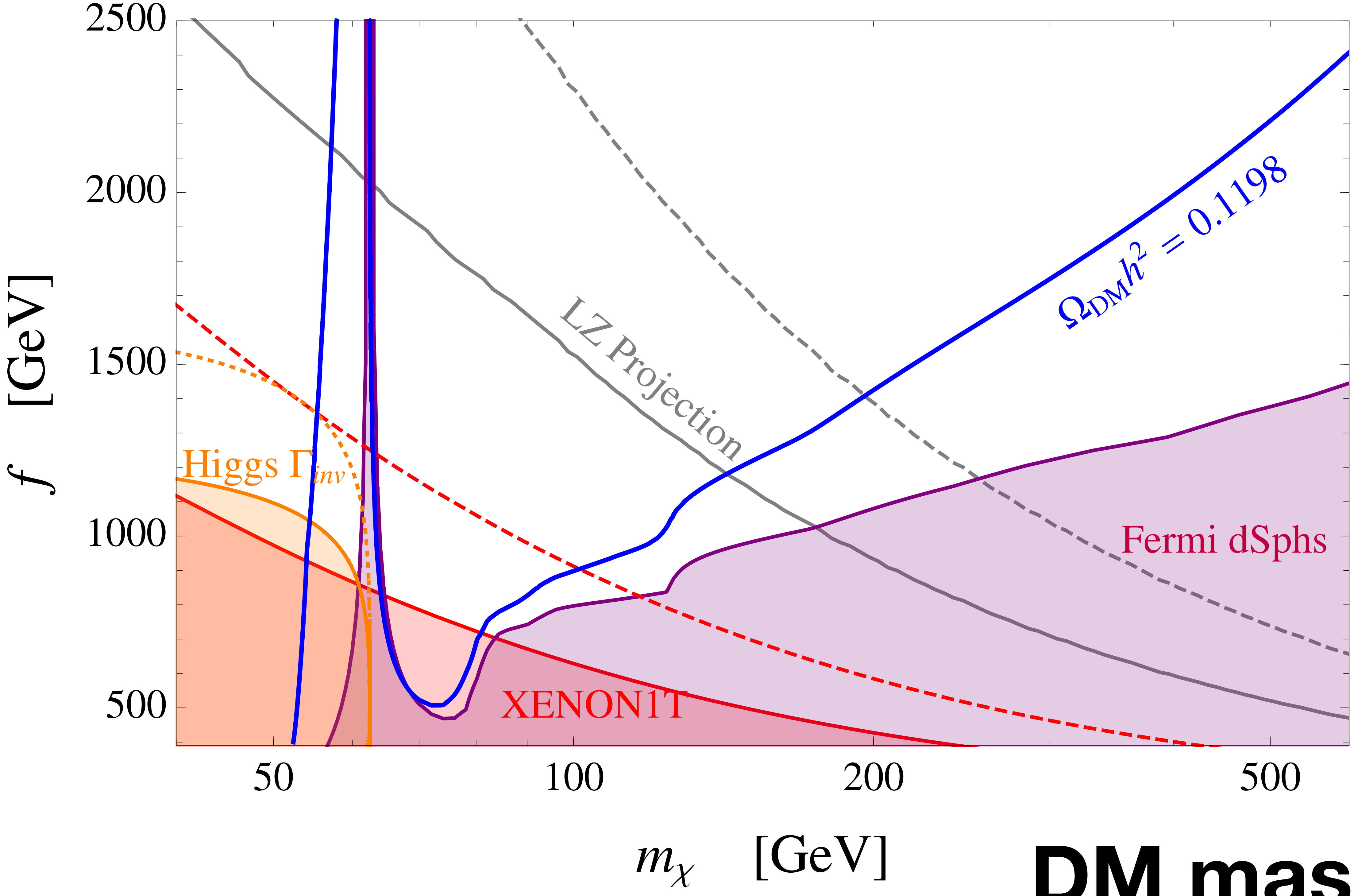
\end{aligned}$$

...

strong scale f

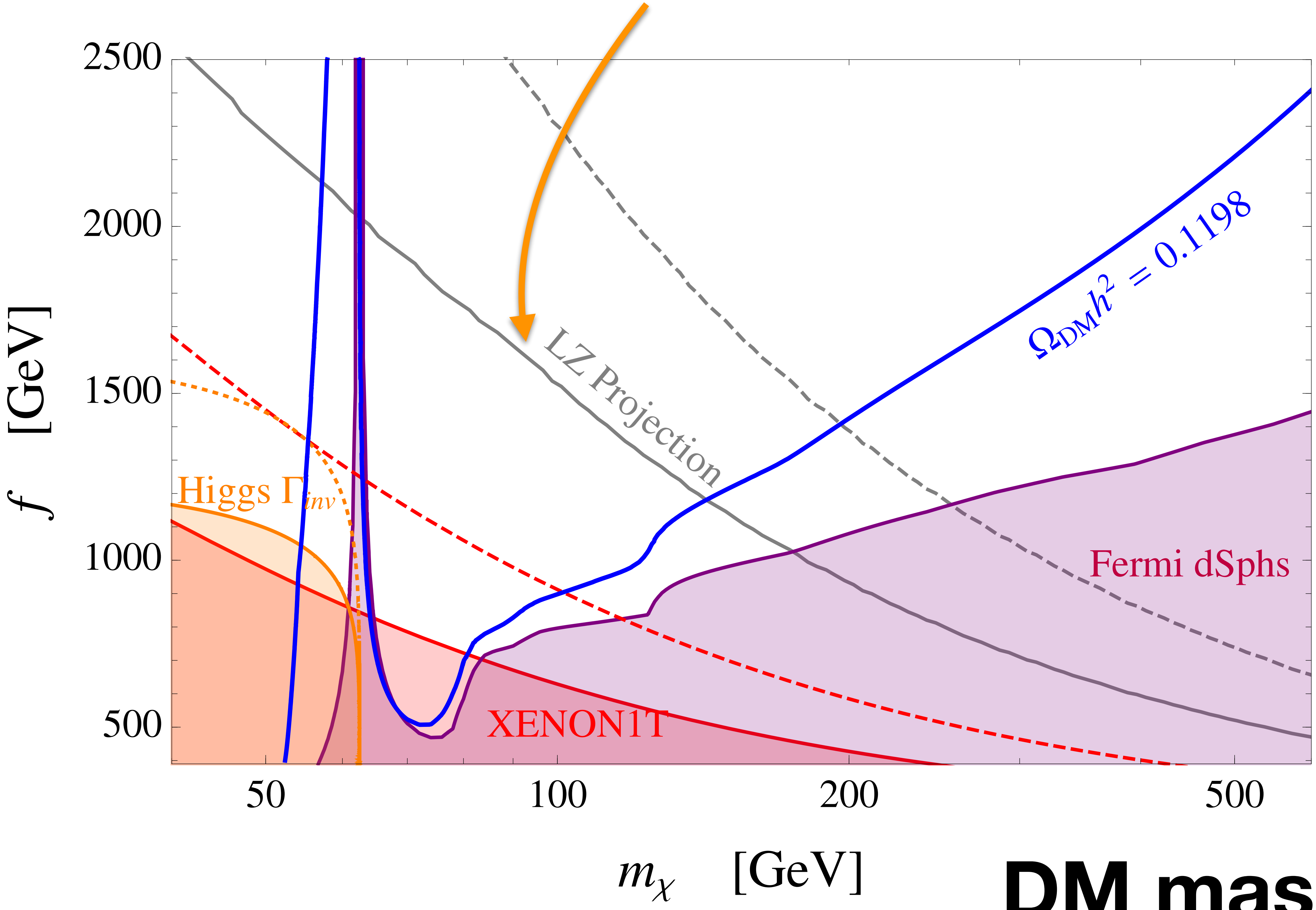


DM mass

Balkin, Ruhdorfer,
Salvioni,AW, 1809.09106

We will reach natural DM masses in the next generation of direct detection experiments

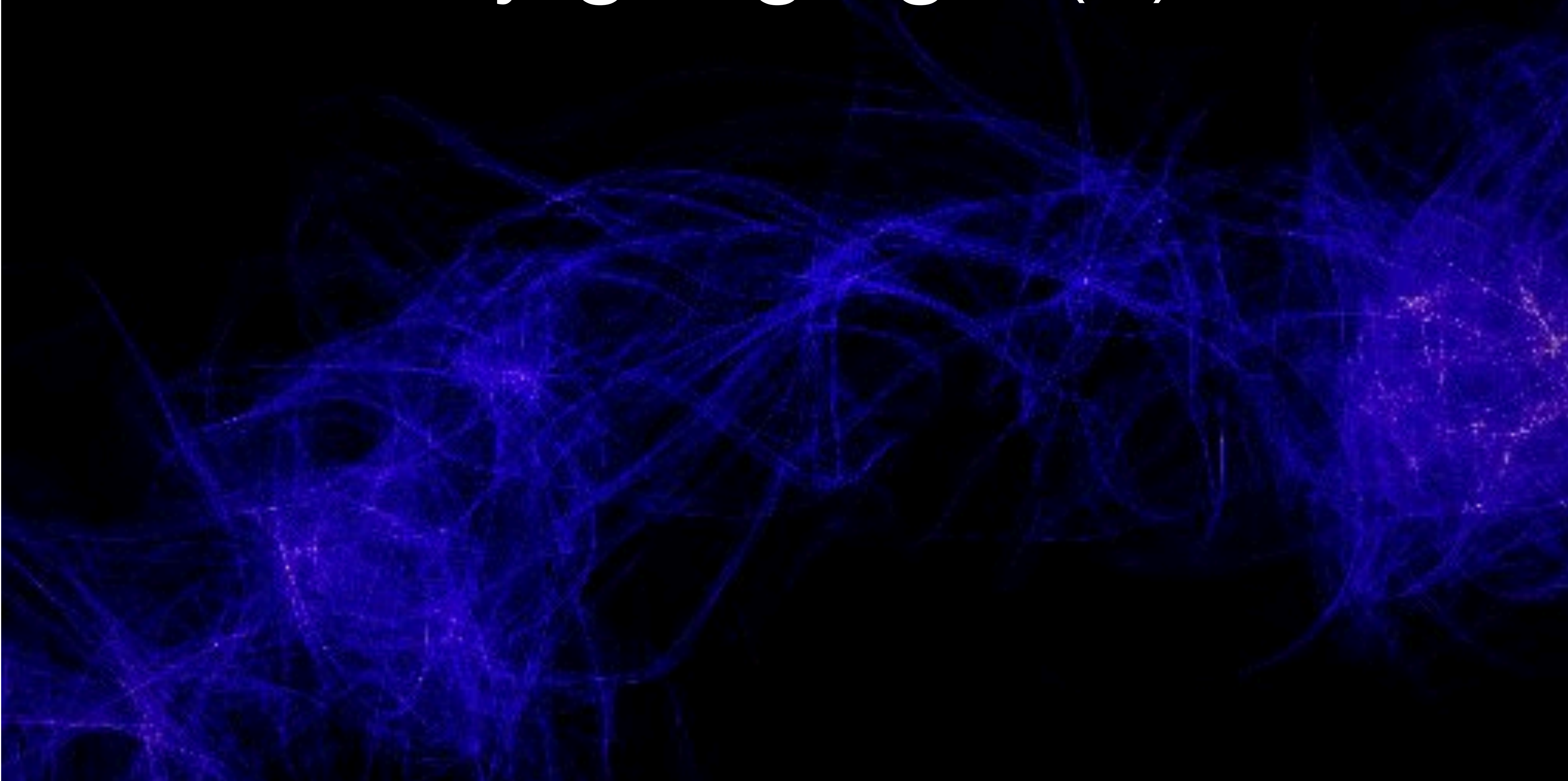
strong scale f



DM mass

Balkin, Ruhdorfer, Salvioni, AW, 1809.09106

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



global U(1)

local U(1)

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

global U(1)

local U(1)

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

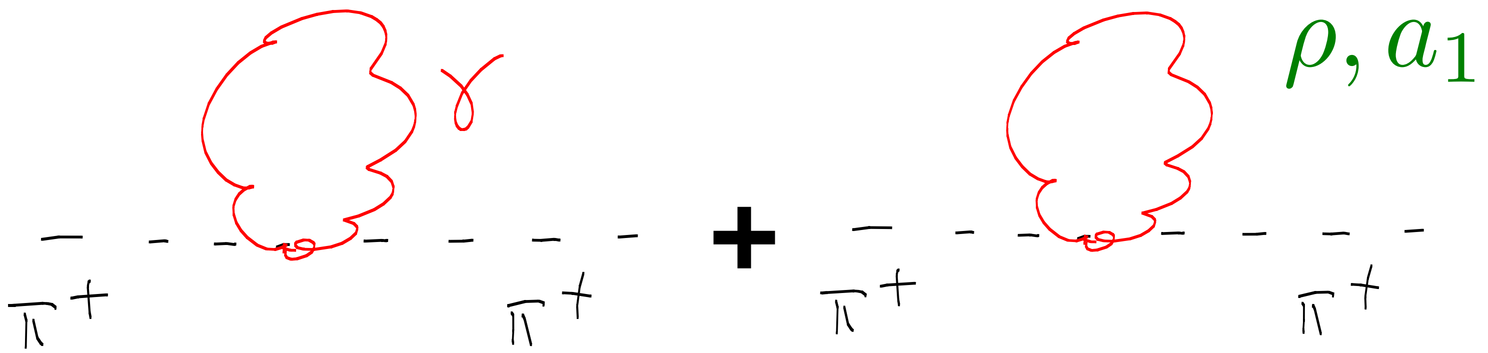
Unbroken symmetry

$$SO(6) \sim SO(4) \times SO(2)$$

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

EW custod' DM stabilisation

QCD analogy: radiative splitting of pion masses



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

Das et al ‘67

Dark photon 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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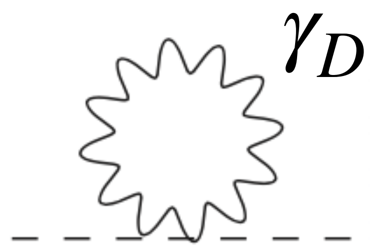


Radiative DM mass:

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

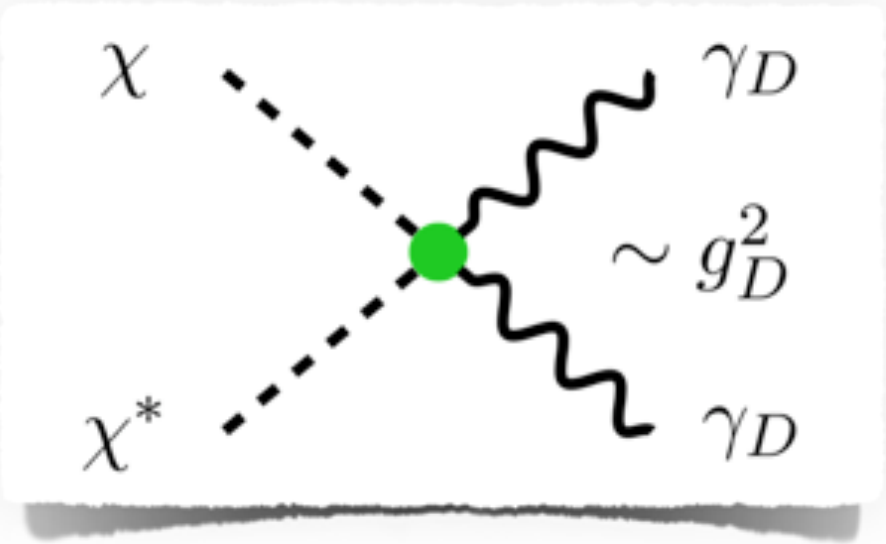
Not generated at
1-loop!

$$\lambda \ll 1$$

New annihilation channel to dark photons

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

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



$$m_{\gamma_D} = ?$$

1) Massless dark photon $m_{\gamma_D} = 0$

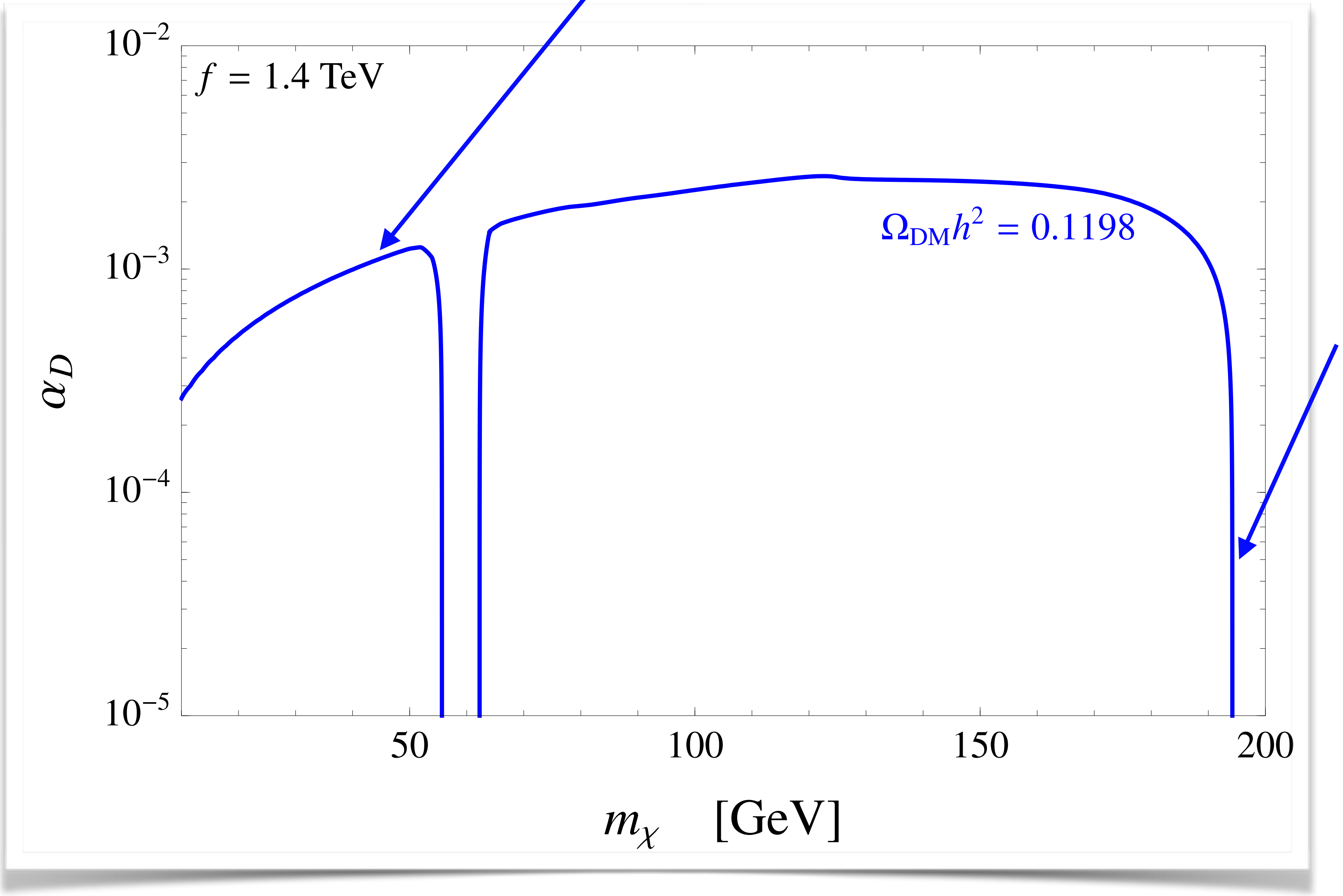
2) Massive dark photon $m_{\gamma_D} > 0$

1) 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

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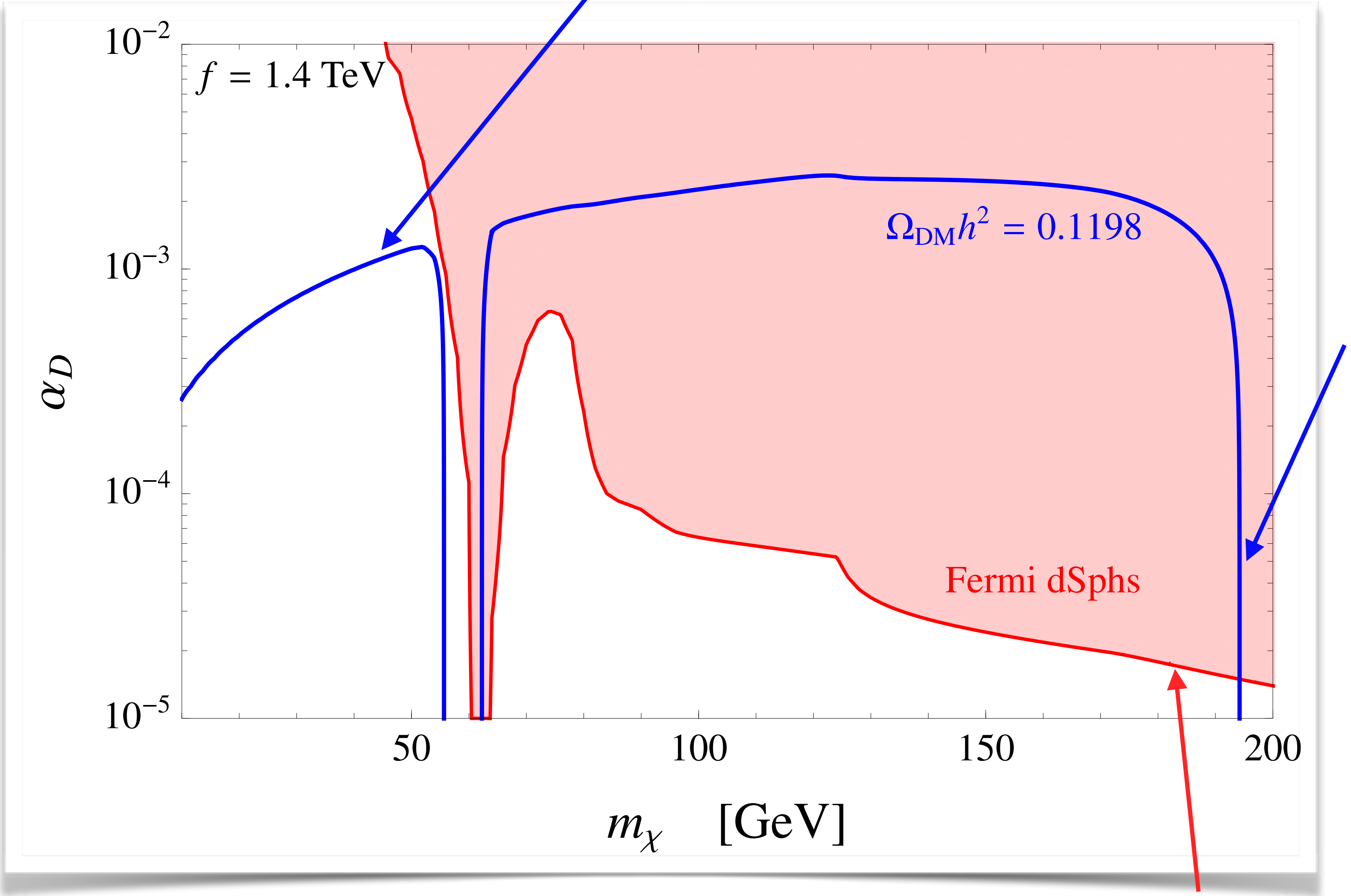


Annihilation purely to SM through

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

Annihilation is Sommerfeld Enhanced in dwarf galaxies today:

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

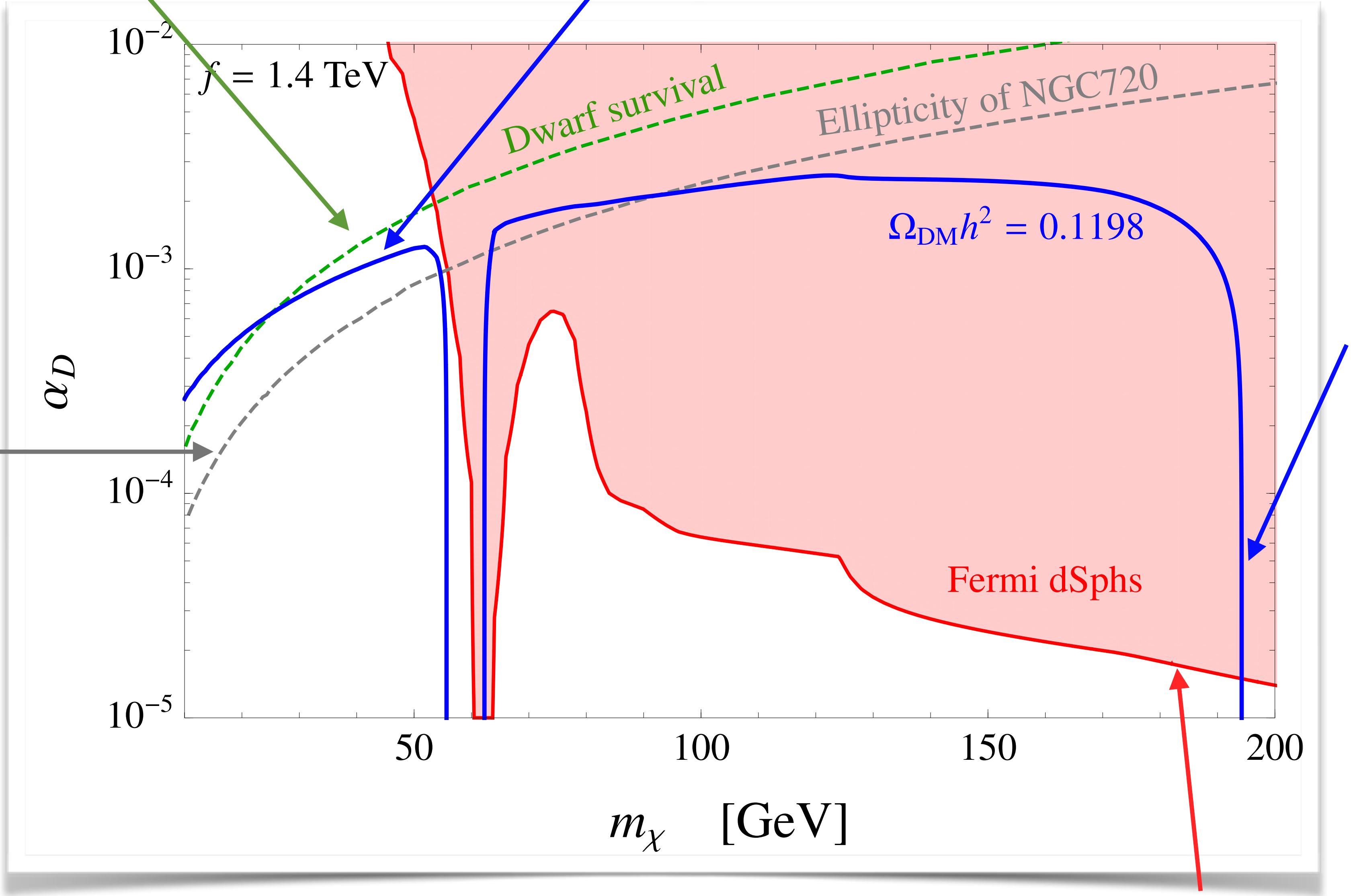
Massless γ_D

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

1308.3419

Annihilation mainly to dark photon

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



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

Agrawal et al. 1610.04611

Annihilation purely to SM through

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Massive dark photon

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

Massive dark photon

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$m_A < 2m_\chi$

↓

Dark photon is **stable**

Massive dark photon

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$m_A < 2m_\chi$

↓

Dark photon is **stable**

$m_A > 2m_\chi$

↓

Dark photon **unstable**

$A_D \to \chi^* \chi$

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

$m_A < 2m_\chi$

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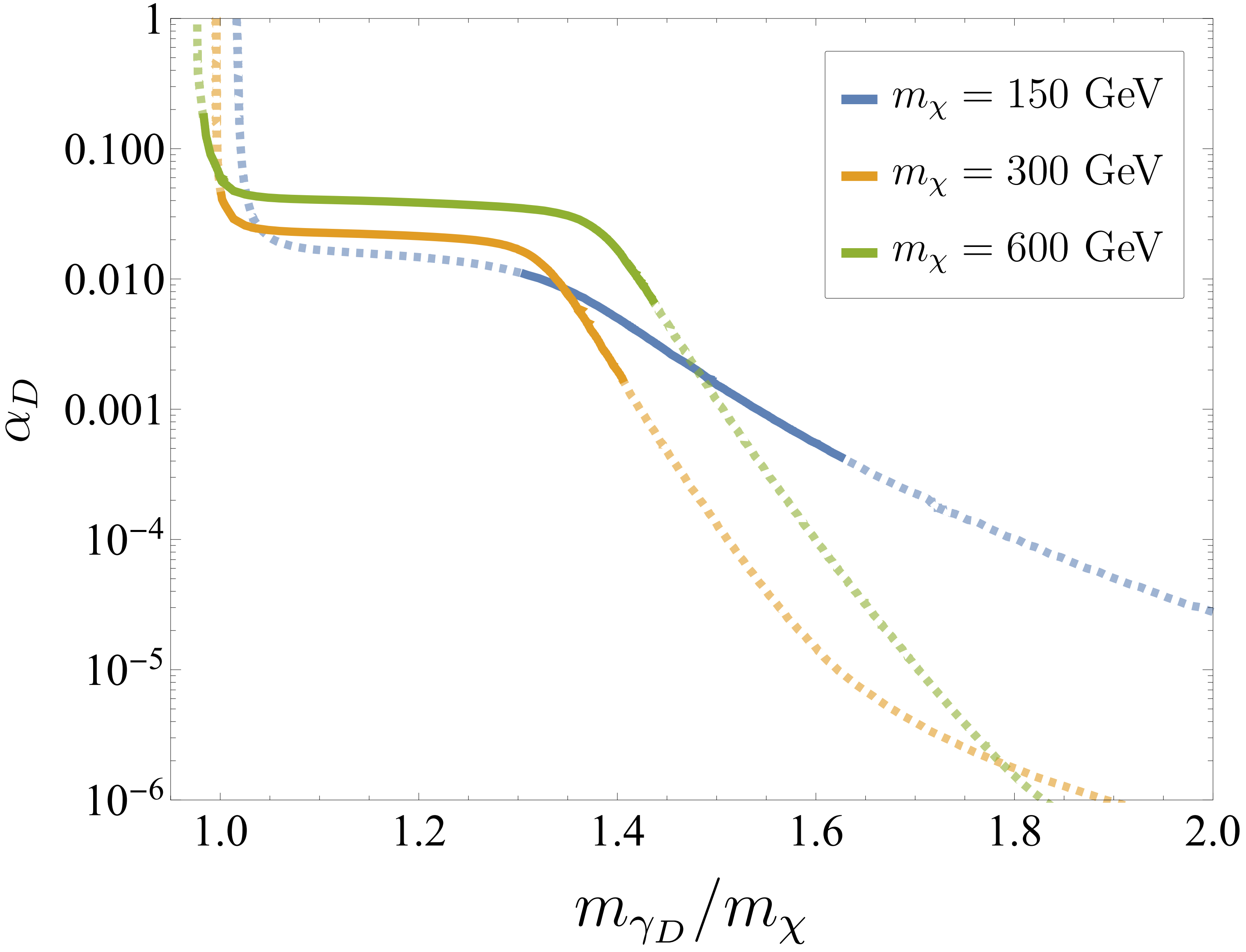
two component DM

Two-component DM

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

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

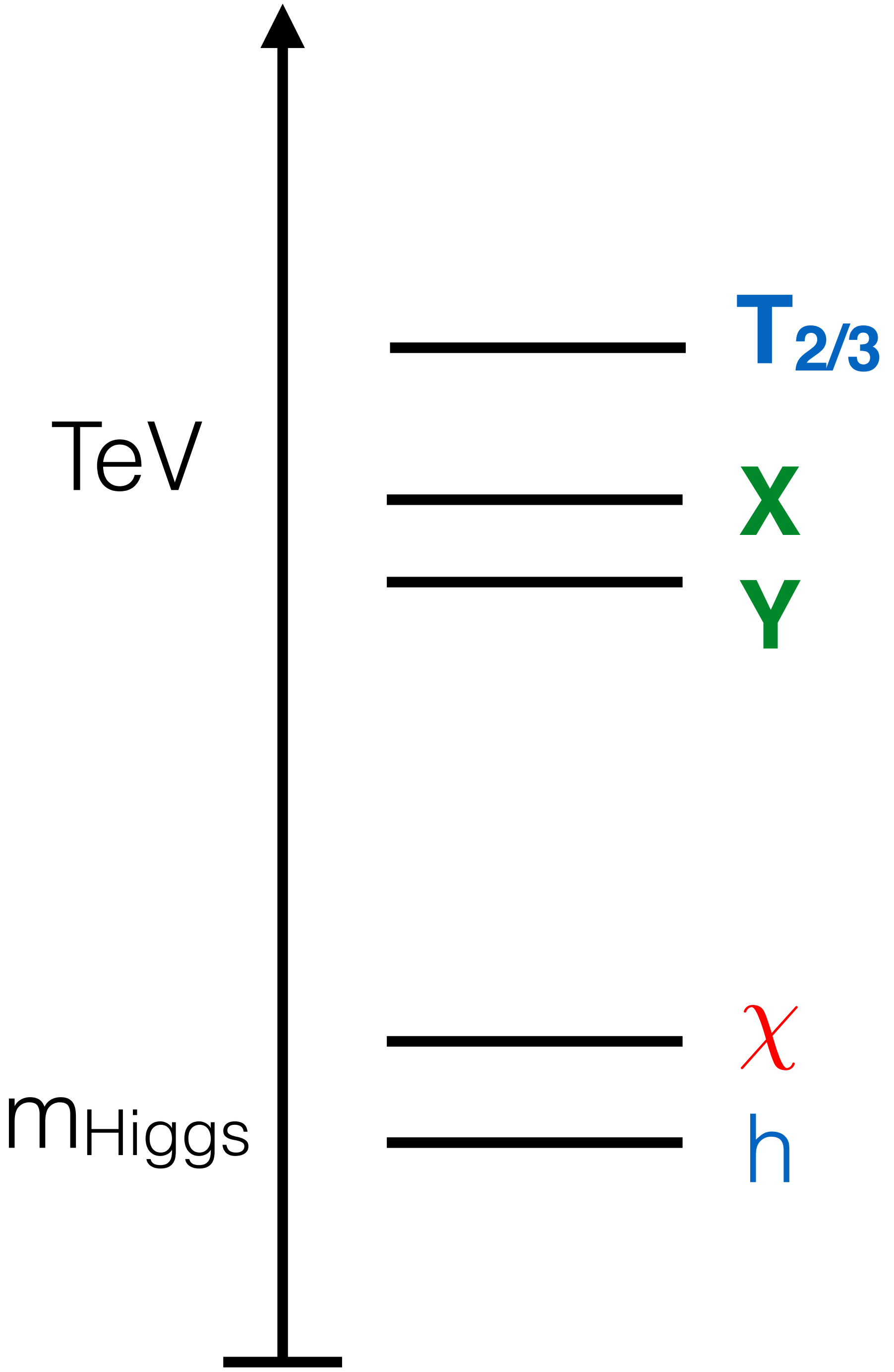


LHC signatures

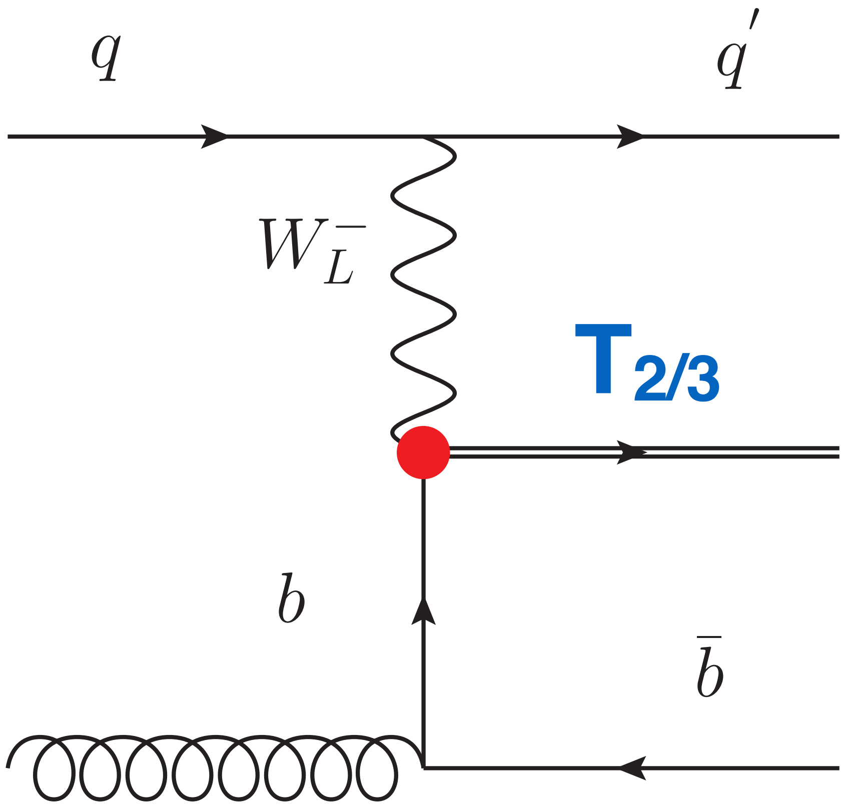
$$Q = \frac{1}{\sqrt{2}} \begin{pmatrix} iB - iX_{5/3} \\ B + X_{5/3} \\ iT + iX_{2/3} \\ -T + X_{2/3} \\ -iY + iZ \\ Y + Z \end{pmatrix}$$

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

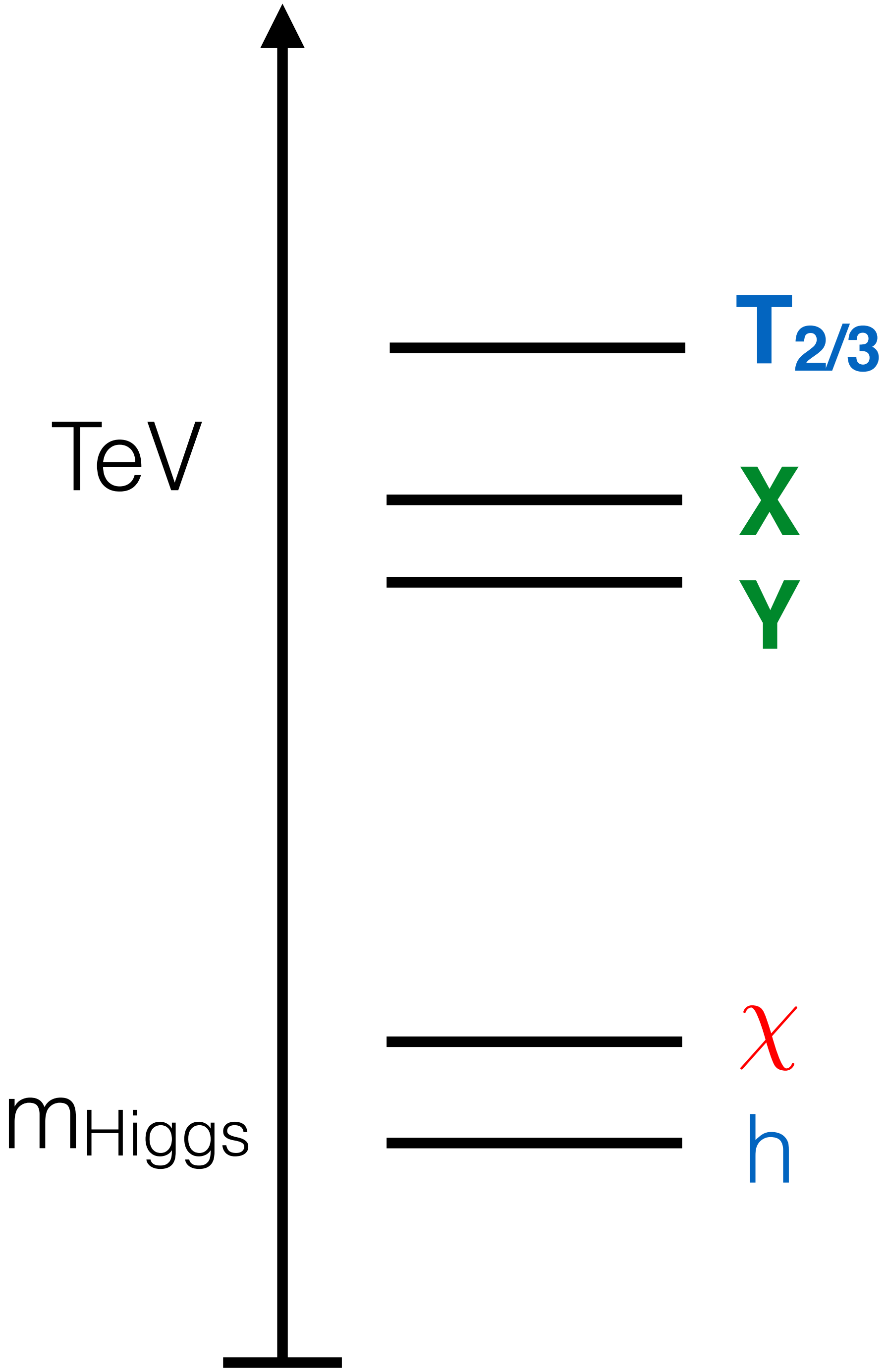
Single Production + MET



interesting new signatures



Single Production + MET



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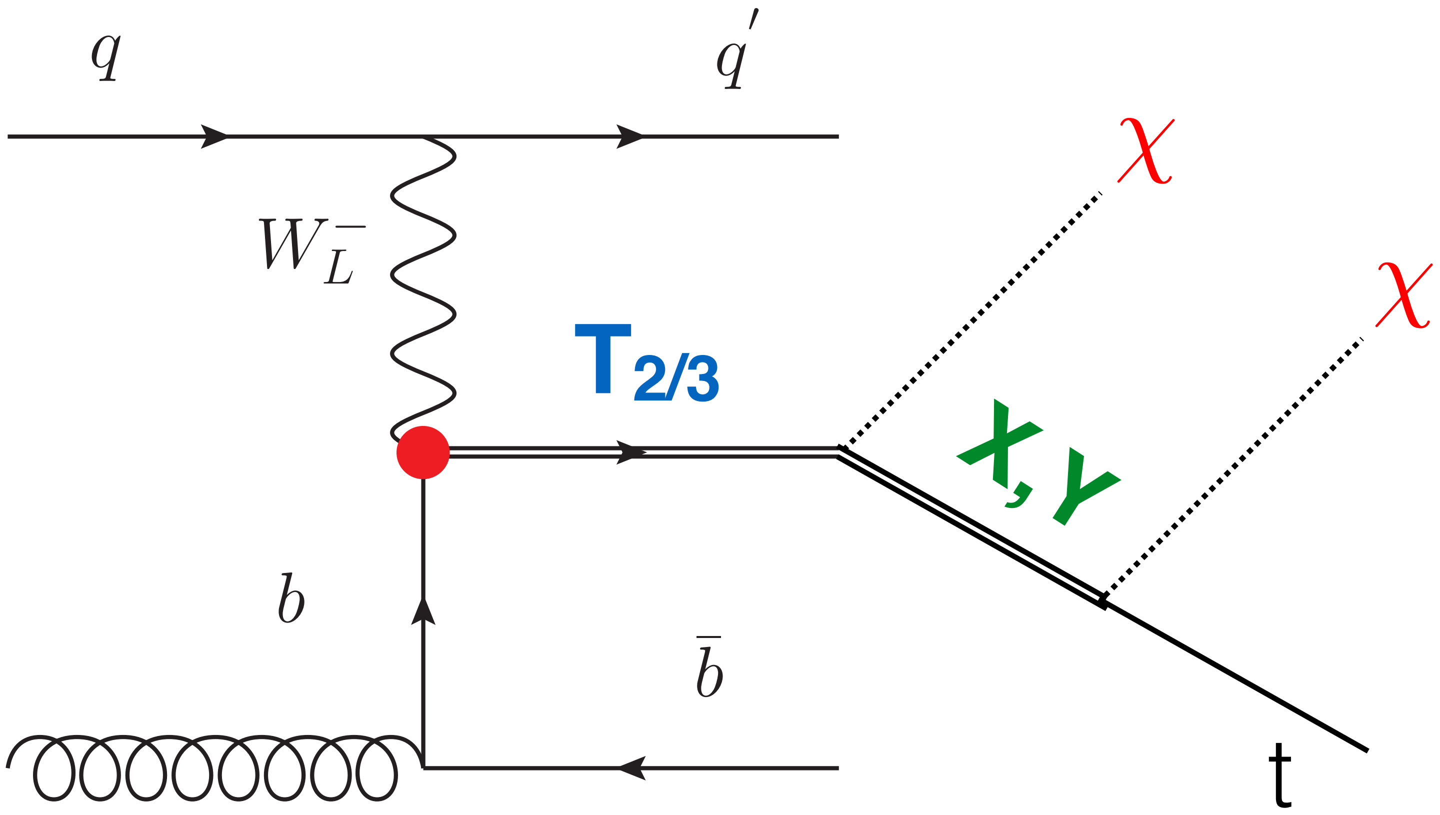

Conclusions

- Dark Matter as a Goldstone boson naturally arises, especially if Higgs is composite
- Direct detection is (strongly) suppressed
- Opportunities to discover pGB-DM in indirect detection and collider searches, and future direct detection experiments

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

→ **no WZW anomaly term**

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Unbroken symmetry

$$SO(6) \sim SO(4) \times SO(2)$$
$$\sim \underset{\text{EW}}{SU(2)_L} \times \underset{\text{custod'}}{SU(2)_R} \times \boxed{U(1)_{DM}}$$

EW custod' DM stabilisation

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

$$\mathcal{L}_{mix} \sim \varepsilon_q \bar{q}_L O_q + \varepsilon_t \bar{t}_R O_t$$

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

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

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

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

Dark charge conjugation $\mathbf{C}_{\mathrm{D}}$ forbids kinetic photon mixing

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

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

Linear mixing with operators in strong sector (partial compositness)

$$\mathcal{L}_{\rm mix}^{\rm UV} \sim \lambda_q f\, \bar{q}_L \mathcal{O}_q + \lambda_t f\, \bar{t}_R \mathcal{O}_t + \lambda_{q'} f\, \bar{q}_L \mathcal{O}_{q'} + \lambda_b f\, \bar{b}_R \mathcal{O}_b + \text{h.c.},$$

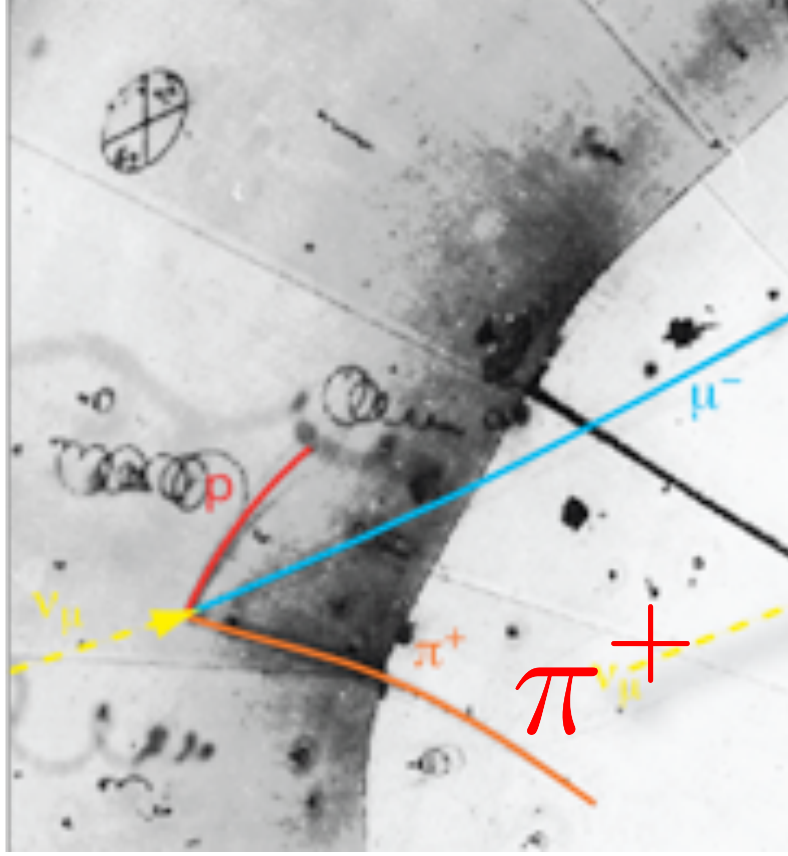
$$|SM\rangle = \cos\phi|elem.\rangle + \sin\phi|comp.\rangle$$

$$|heavy\rangle = -\sin\phi|elem.\rangle + \cos\phi|comp.\rangle$$

$$\mathbf{7}_{-1/3} \sim \xi_L^{(b)} = \frac{1}{\sqrt{2}}\left(-it_L,\ t_L,\ ib_L,\ b_L,\ \mathbf{0}_3^T\right)^T, \qquad \mathbf{7}_{-1/3} \sim \xi_R^{(b)} = b_R\left(\mathbf{0}_6^T,\ 1\right)^T.$$

in DM GB generator

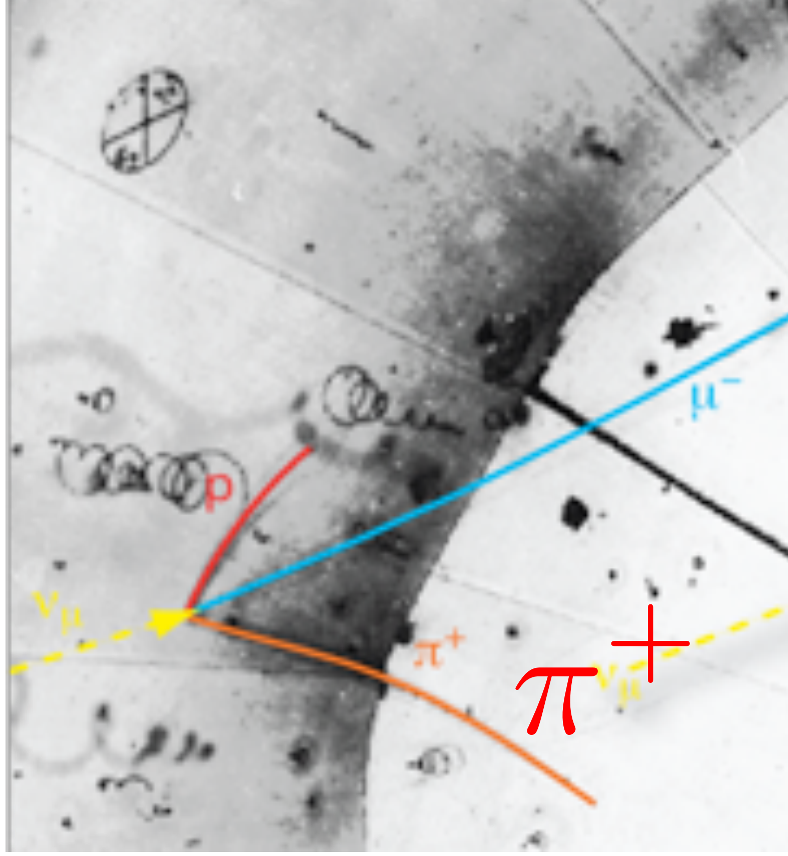
QCD-Pions as pNGBs



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

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

QCD-Pions as pNGBs



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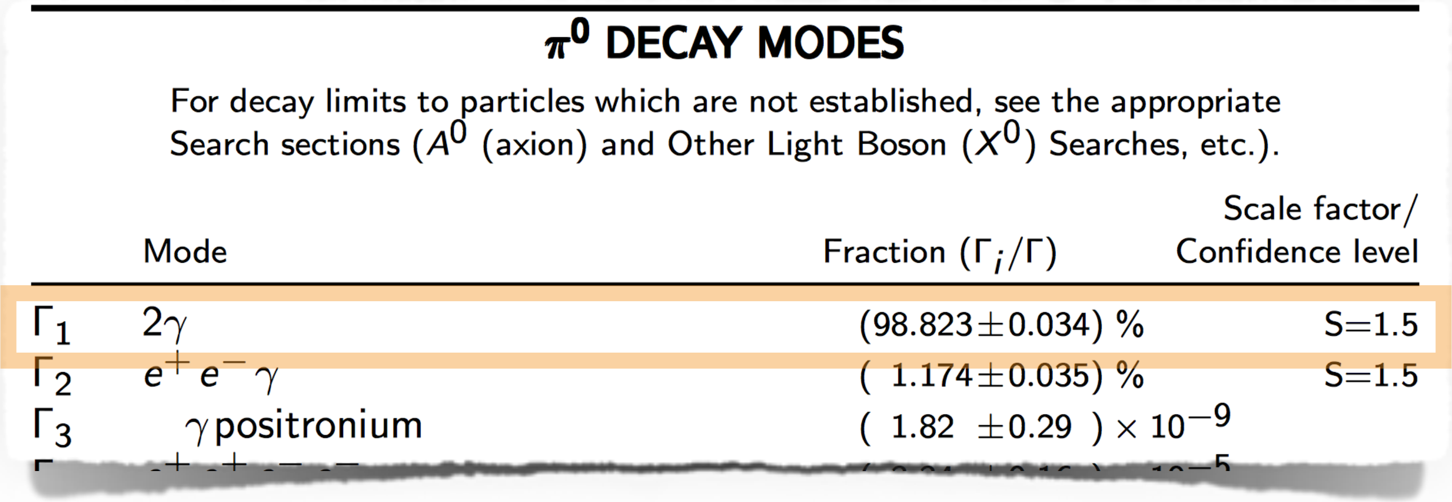
$$\boxed{\pi \to -\pi} \qquad (U \to U^\dagger)$$

Good symmetry? Depends on the UV…

IR probe of UV physics



π^0 DECAY MODES

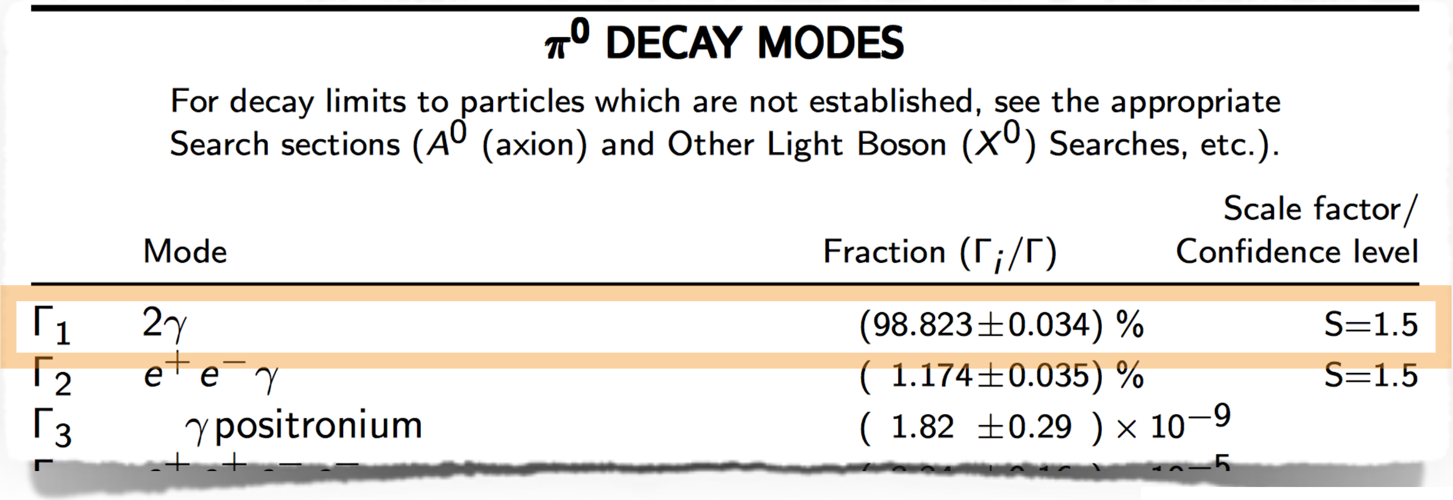
For decay limits to particles which are not established, see the appropriate Search sections (A^0 (axion) and Other Light Boson (X^0) Searches, etc.).

	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	$(1.82 \pm 0.29) \times 10^{-9}$	

pdg

. Wess, Zumino '71, Witten '83

IR probe of UV physics



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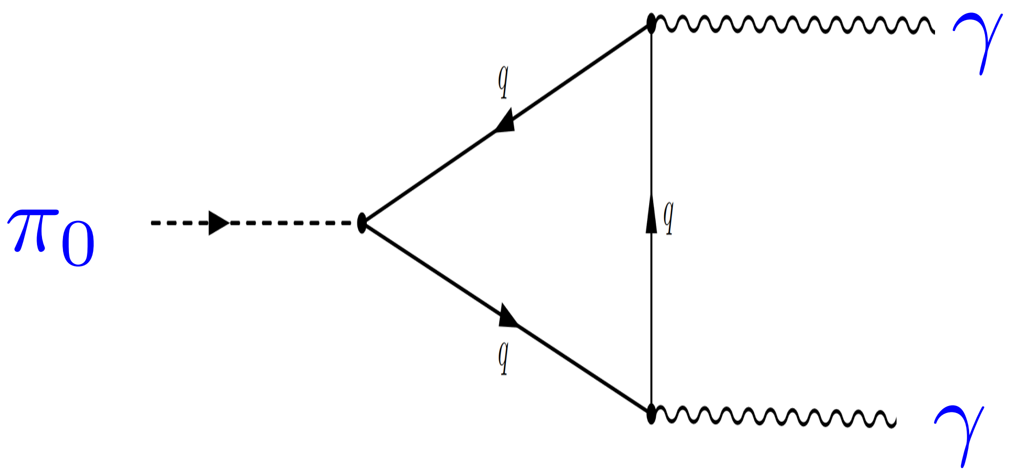
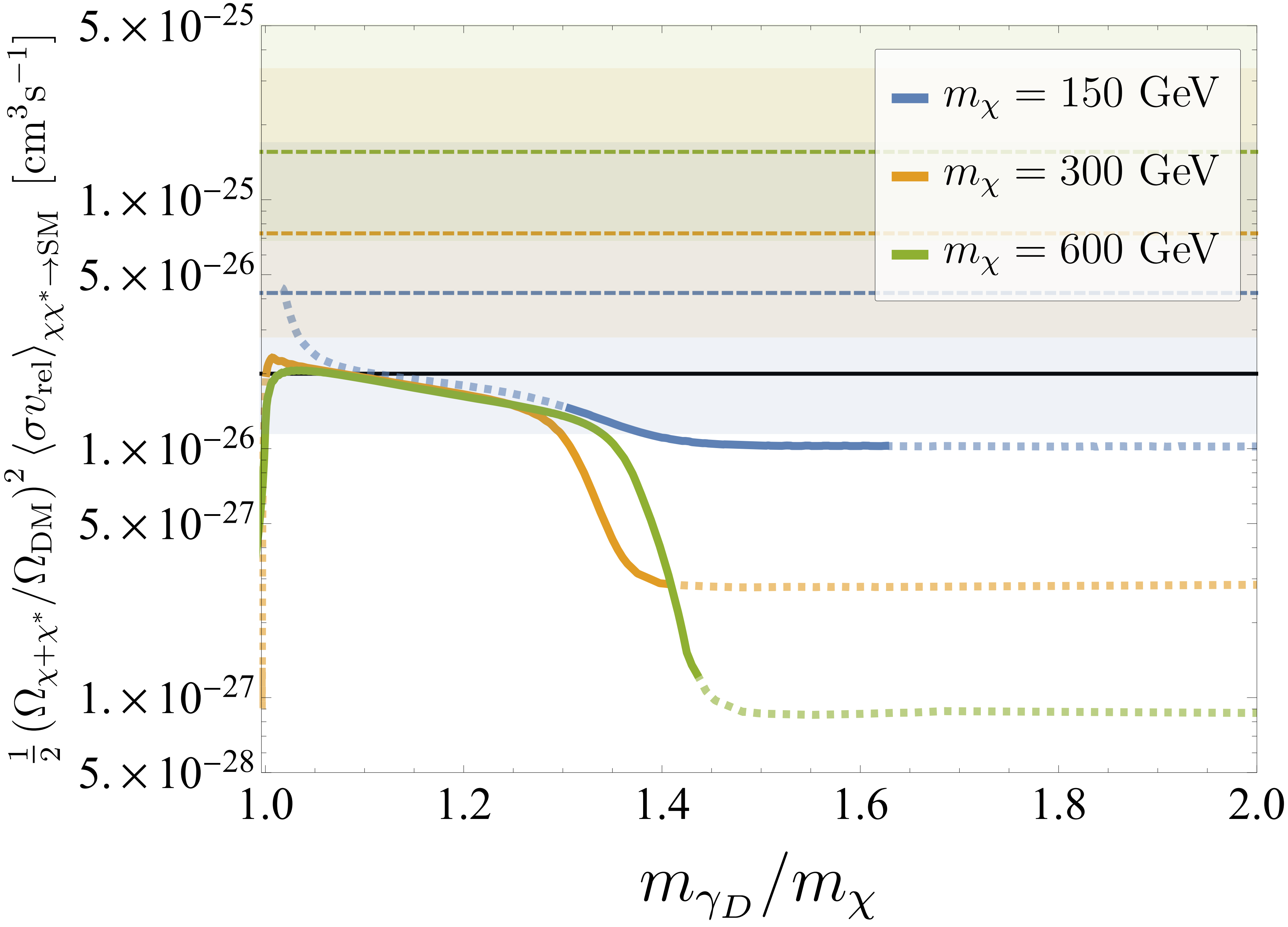
Anomaly: WZW term

Wess, Zumino ’71, Witten ‘83

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



$$\pi \cancel{\to} -\pi$$


$m_\chi = 150$ GeV
$m_\chi = 300$ GeV
$m_\chi = 600$ GeV
$5.\times10^{-25}$
$1.\times10^{-25}$
$5.\times10^{-26}$
$1.\times10^{-26}$
$5.\times10^{-27}$
$1.\times10^{-27}$
$5.\times10^{-28}$
1.0
1.2
1.4
1.6
1.8
2.0
m_{γ_D}/m_χ
$\frac{1}{2}\left(\Omega_{\chi+\chi^*}/\Omega_{\rm DM}\right)^2\langle\sigma v_{\rm rel}\rangle_{\chi\chi^*\to\rm SM}$ $[\rm cm^3 s^{-1}]$