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News from The Dark 2023
Bruxelles

Dark matter from the centre of SU(N)

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In collaboration with Michele Frigerio & Thomas Hambye

ArXiv:2212.11918

FÉDÉRATION WALLONIE-BRUXELLES

FREEDOM TO RESEARCH

Motivations

Observation today:

$\tau \geq \tau_{universe} \approx 10^{10}$ yr

Indirect detection, CMB, 21cm:

$\tau \geq 10^{17\text{-}19}$ yr

Stability of Dark Matter (DM)

Motivations

Origins of stability

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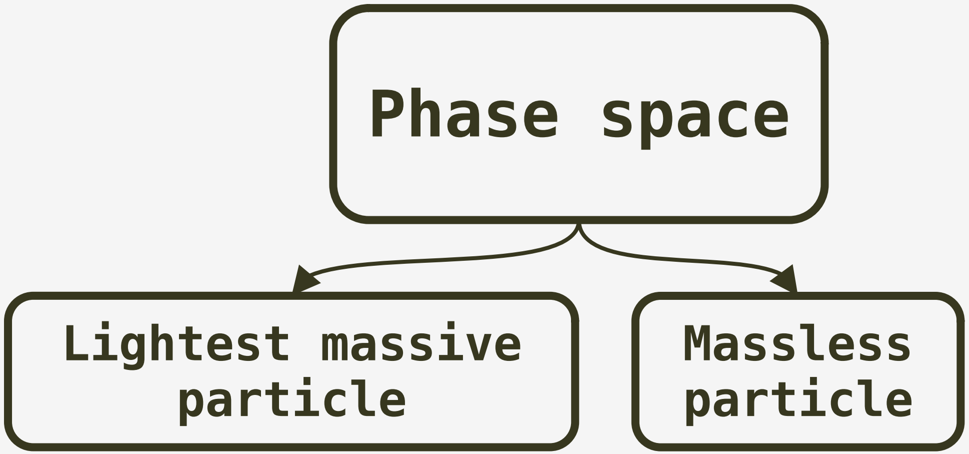
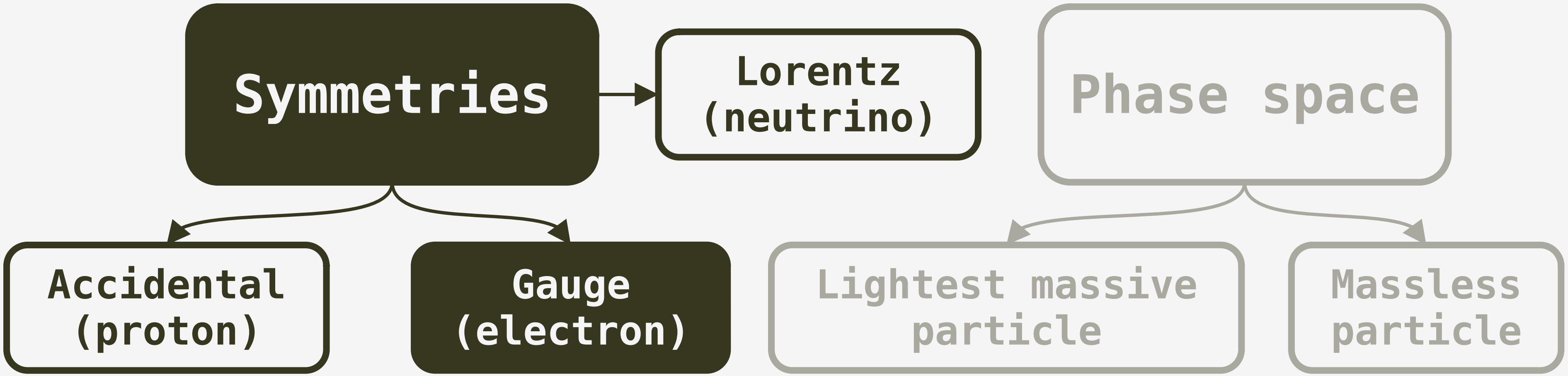
Origins of stability



Motivations

Origins of stability



Motivations

- ➔ DM **stability** from fundamental principles
- ➔ **Scalar** DM
- ➔ **Non-abelian** dark gauge symmetry
- ➔ Perturbative aspects (**SSB** to $U(1)_s$)
- ➔ **Minimal** particle content

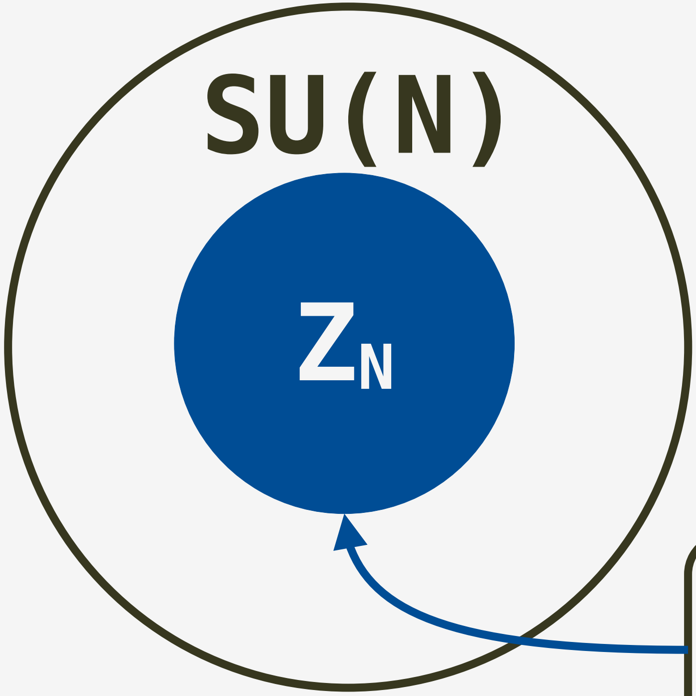
1. N-ality property and scalar DM models

2. Scalar potential and mass spectrum

3. DM phenomenology

1. N-ality property and scalar DM models

N-ality as a stabilisation mechanism:

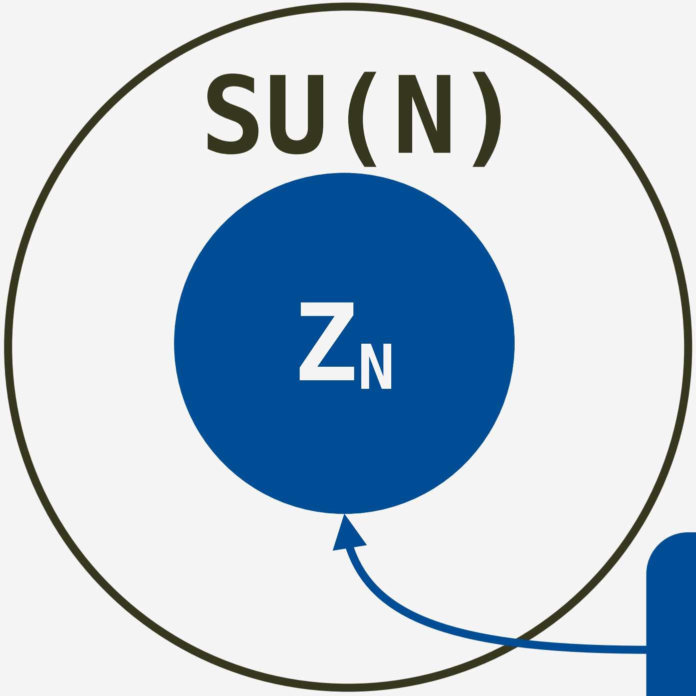


$$X^{i_1 i_2 i_3 \ldots i_k}_{j_1 j_2 j_3 \ldots j_l}$$

X has charge Q_X=k-n mod N under Z_N

Centre of SU(N) = set of elements that commute with all g∈SU(N)

N-ality as a stabilisation mechanism:

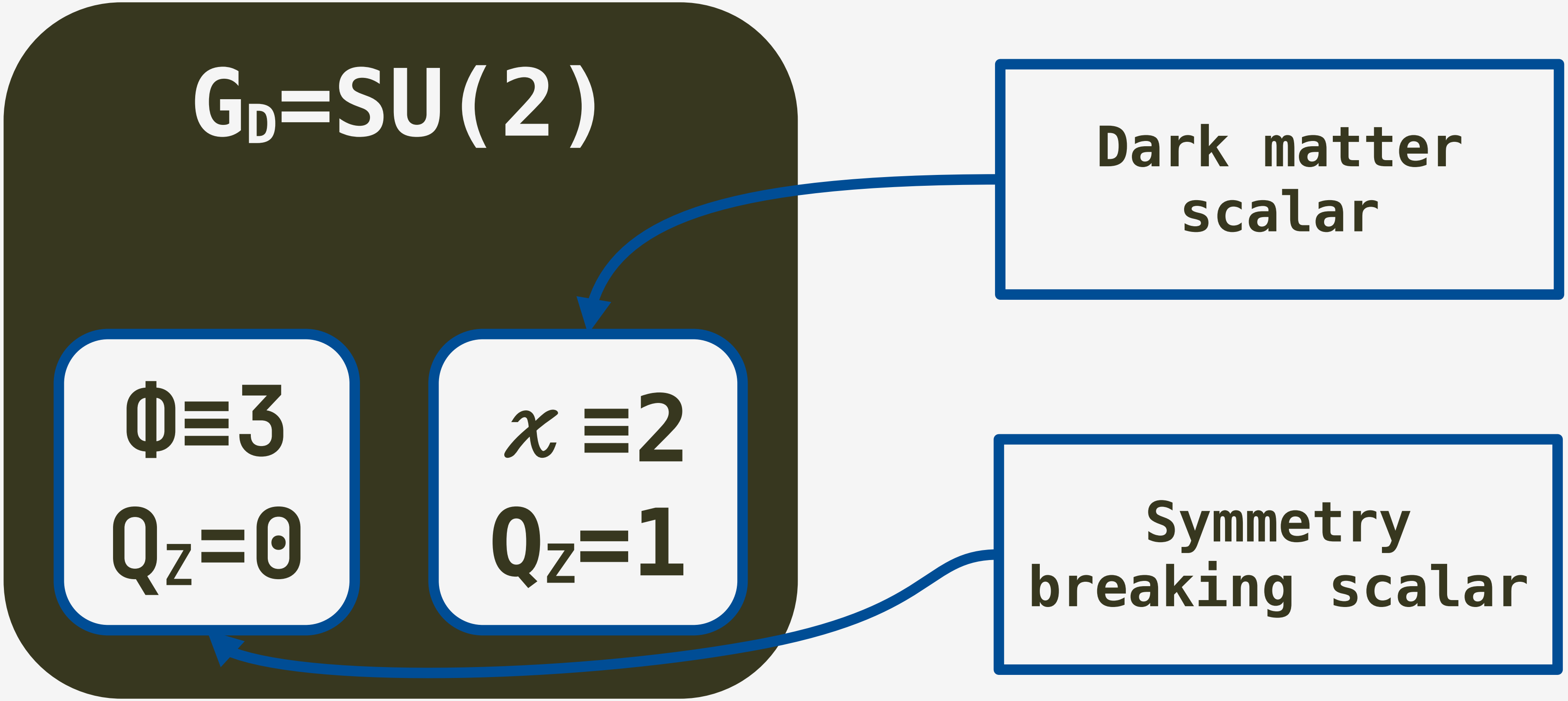


$$X^{i_1 i_2 i_3 \ldots i_k}_{j_1 j_2 j_3 \ldots j_l}$$

X has charge $Q_X = k - n \bmod N$ under Z_N

Z_N is preserved if SU(N) broken by X with $Q_X = 0$

Particle content:SU(2)



Particle content: SU(2)

$G_D = SU(2)$

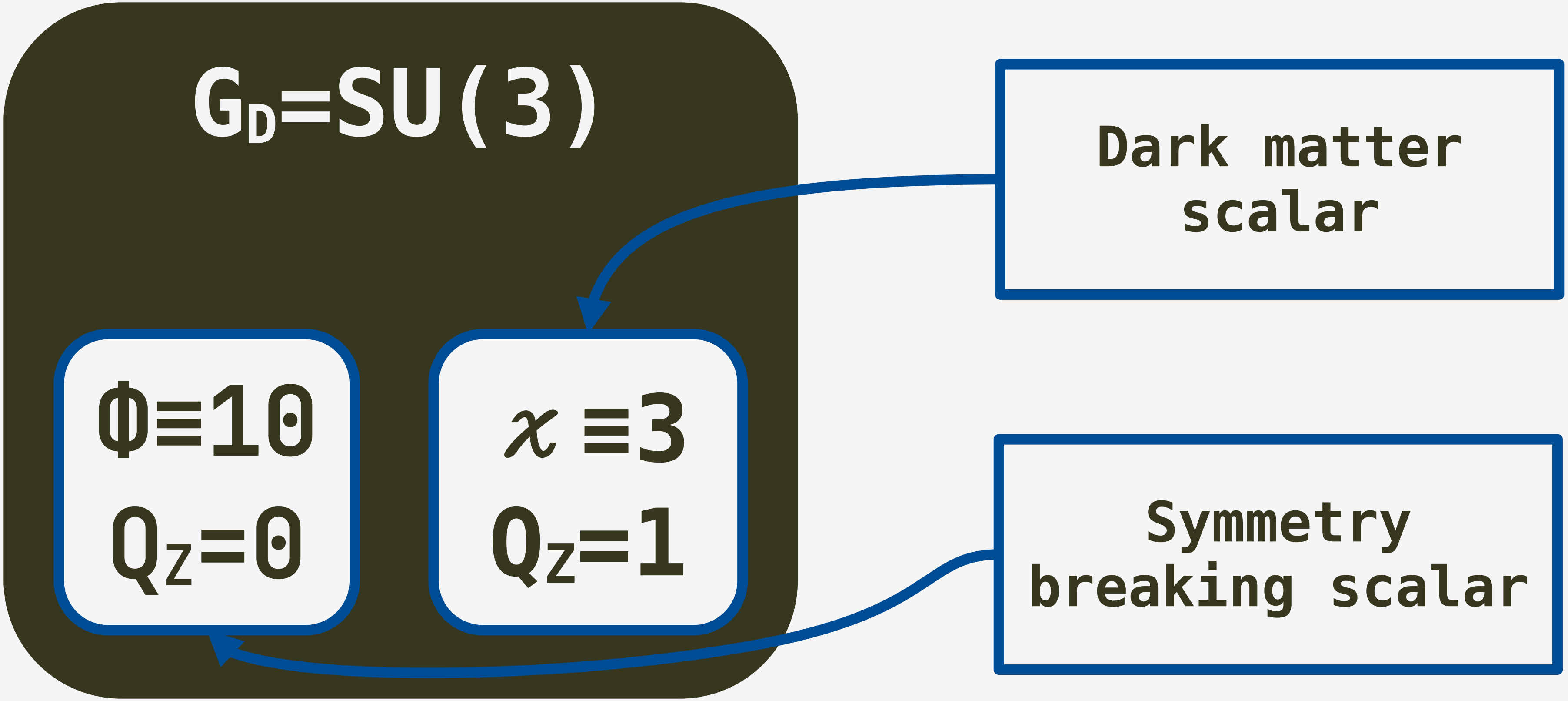
$\Phi \equiv 3$
$Q_Z = 0$

$\chi \equiv 2$
$Q_Z = 1$

Z_2 symmetry

$$V(\Phi, \chi) \supset \Phi_{ij} \chi^i \chi^j$$

Particle content: SU(3)



Particle content: SU(3)

$G_D = SU(3)$

$\Phi \equiv 10$	$\chi \equiv 3$
$Q_Z = 0$	$Q_Z = 1$

Z_3 symmetry

$$V(\Phi, \chi) \supset \Phi^*_{ijk}\chi^i\chi^j\chi^k$$

2. SSB: Scalar potential and mass spectrum

The SU(2) model

$$\mathcal{L}(\Phi) = \frac{1}{2} D_\mu \Phi^{ij} D^\mu \Phi_{ij} - V(\Phi)$$

$$V(\Phi) = -\frac{\mu^2}{2} \Phi^{ij} \Phi_{ji} + \frac{\lambda}{4} (\Phi^{ij} \Phi_{ji})^2$$

The S~~U~~(2) model → U(1)

$$\mathcal{L}(\Phi) = \frac{1}{2} D_\mu \Phi^{ij} D^\mu \Phi_{ij} - V(\Phi)$$

$$V(\Phi) = -\frac{\mu^2}{2} \Phi^{ij} \Phi_{ji} + \frac{\lambda}{4} (\Phi^{ij} \Phi_{ji})^2$$

SSB → $\langle \Phi^{ij} \Phi_{ji} \rangle = \mu^2 / \lambda \equiv v_D^2$

The SU(2) model

$$V(\chi) = \mu_\chi^2 \chi^i \tilde{\chi}_i + \lambda_\chi (\chi^i \tilde{\chi}_i)^2$$

$$\tilde{\chi}_i \equiv (\chi^i)^*$$

$$V(\Phi, \chi) = -\kappa\, \chi^i \Phi_{ij} \tilde{\chi}^j + \frac{1}{2} \lambda_{\chi\Phi} (\Phi^{ij} \Phi_{ji})(\chi^i \tilde{\chi}_i)$$

Induces mass splitting

The SU(2) model

$$V_{\text{portal}} = \left(\lambda_{H\chi} \chi^i \tilde{\chi}_i + \frac{1}{2} \lambda_{\Phi H} \Phi^{ij} \Phi_{ji} \right) H^\dagger H$$

Mixing between dark and SM higgs.

$$\sin \theta_m \simeq \lambda_{\Phi H} v_D v / [2(\lambda_H v^2 - \lambda v_D^2)]$$

Mass spectrum

- Gauge bosons:
  - ➔ 1 massless dark photon A_D
  - ➔ 1 complex charged boson $W^{\pm}_D$: $m_{W_D}^2 = g_D^2 v_D^2$

Mass spectrum

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- Real scalar triplet:
  - → 2 would-be NGBs
  - → 1 massive neutral mode ρ: $m^2_\rho \simeq 2\lambda v^2_D$

Mass spectrum

- Gauge bosons:
  - ➔ 1 massless dark photon A_D
  - ➔ 1 complex charged boson $W^{\pm}_D$: $m^2_{W_D} = g^2_D v^2_D$
- Real scalar triplet:
  - ➔ 2 would-be NGBs
  - ➔ 1 radial neutral mode ρ: $m^2_\rho \simeq 2\lambda v^2_D$
- **Complex scalar doublet (DM):**
  - ➔ **$\chi_\pm$ charged under A_D**
  - ➔ $m^2_{\chi_\pm} = \mu^2_\chi + \frac{1}{2}\lambda_{\chi\Phi} v^2_D + \frac{1}{2}\lambda_{\chi H} v^2 \pm \frac{1}{\sqrt{2}}\kappa v_D$

DM content

A) χ_- and χ_+ for $m_{\chi_+} + m_{\chi_-} < m_{W_D}$

B) χ_-, χ_+ and W_D for:

$$m_{\chi_+} - m_{\chi_-} \leq m_{W_D} \leq m_{\chi_+} + m_{\chi_-}$$

C) χ_- and W_D for $m_{W_D} < m_{\chi_+} - m_{\chi_-}$

3. DM phenomenology

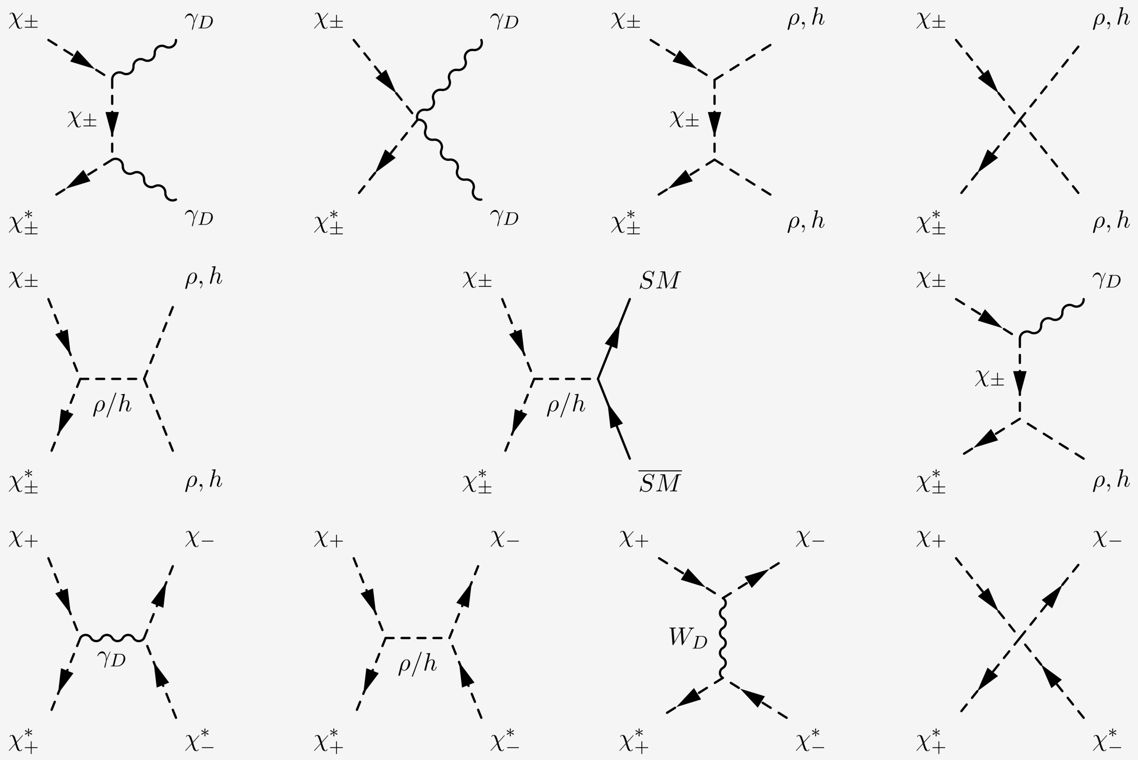
Annihilation processes

Case A: DM≡ $\chi_\pm$

$m_{\chi_+} + m_{\chi_-} < m_{W_D}$

Focus on 3 limiting cases dominated by a single coupling:

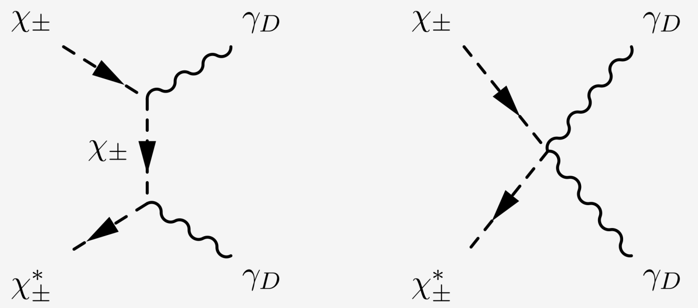
- α_D → Into dark photons
- $\lambda_{\chi\Phi}$ → Into ρ scalars
- $\lambda_{H\chi}$ → Into SM particles

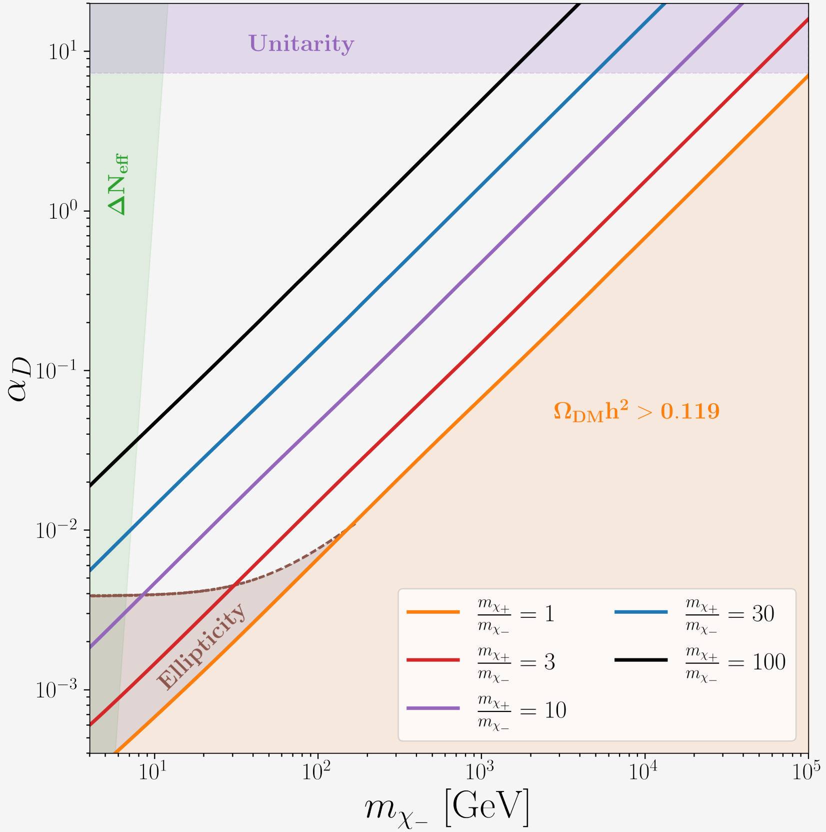


Freeze-out to dark photons

$$\langle \sigma v \rangle_\pm \equiv \langle \sigma_{\chi_\pm \chi_\pm^* \to \gamma_D \gamma_D} v \rangle = \frac{\pi \alpha_D^2}{4 m_{\chi_\pm}^2}$$

$$\Omega_{\chi_+} / \Omega_{\chi_-} \simeq m_{\chi_+}^2 / m_{\chi_-}^2$$





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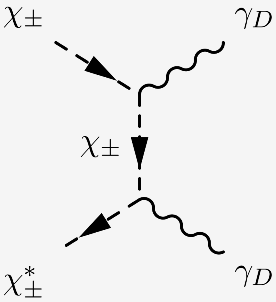
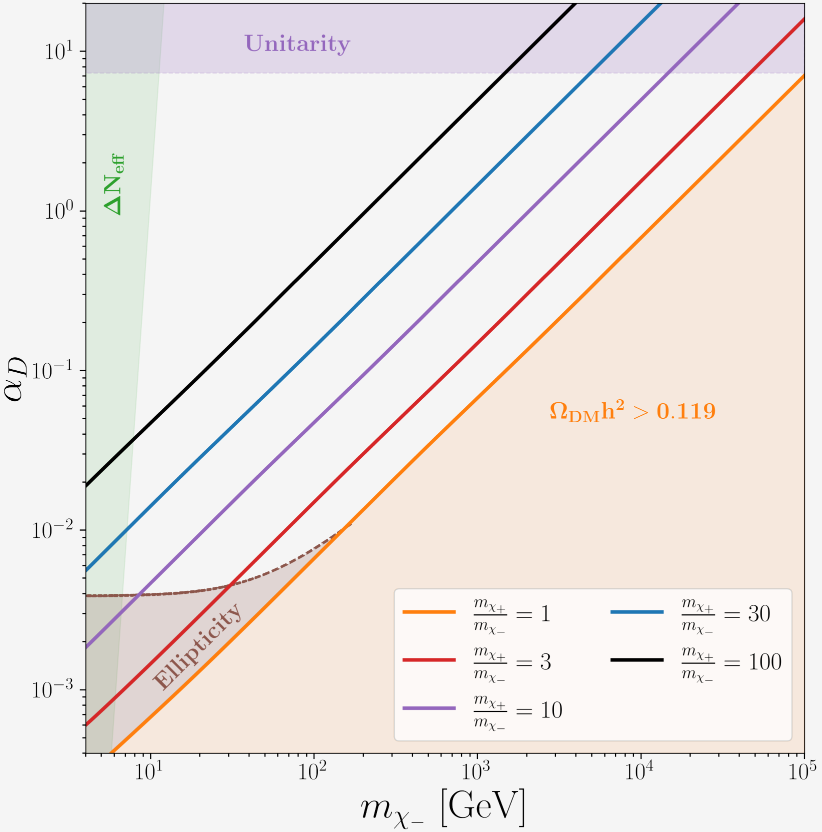


χ_+ dominates Ω_{DM}



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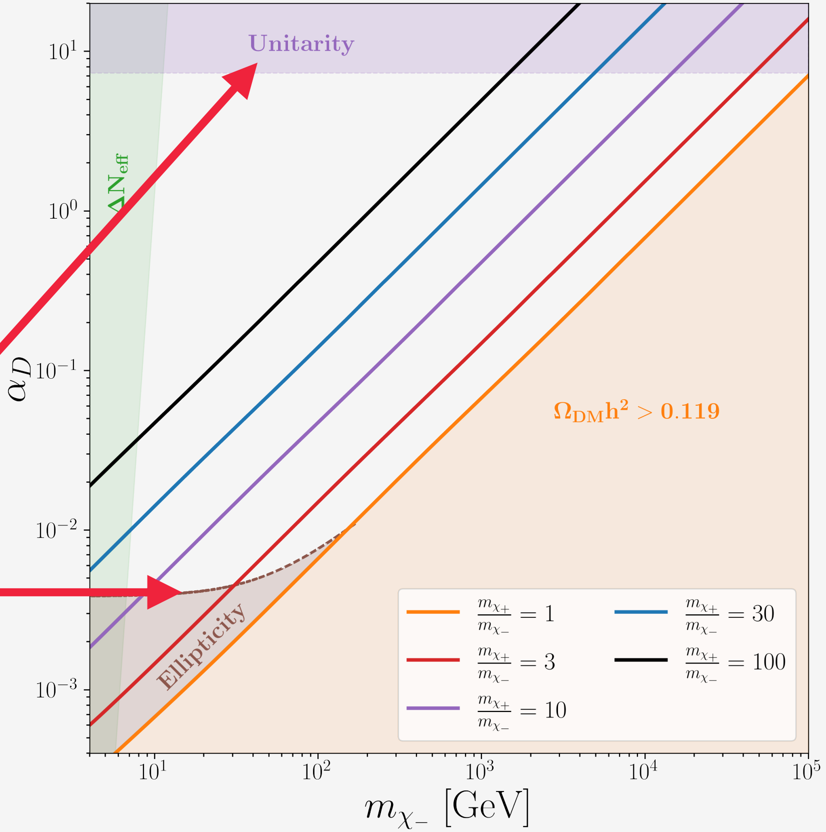
$$\langle \sigma v \rangle_J \lesssim 4\pi(2J+1)/(m_{DM}^2 v)$$

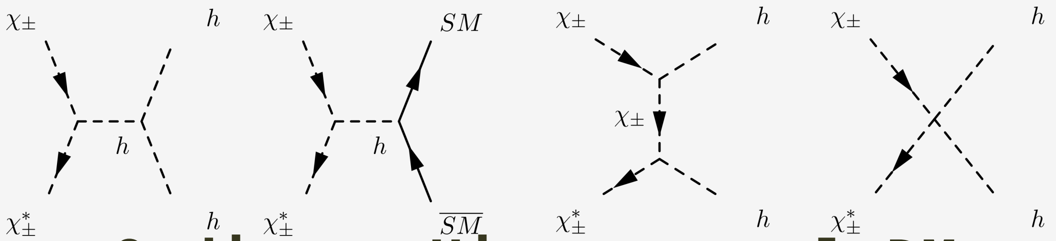
$$\alpha_D \lesssim 0.8\sqrt{10^{-11}(m_{DM}/\mathrm{GeV})^3}$$

See P. Agrawal, F. Cyr-Racine, L. Randall & J.Scholtz, 2016 (ArXiv :1610.04511)



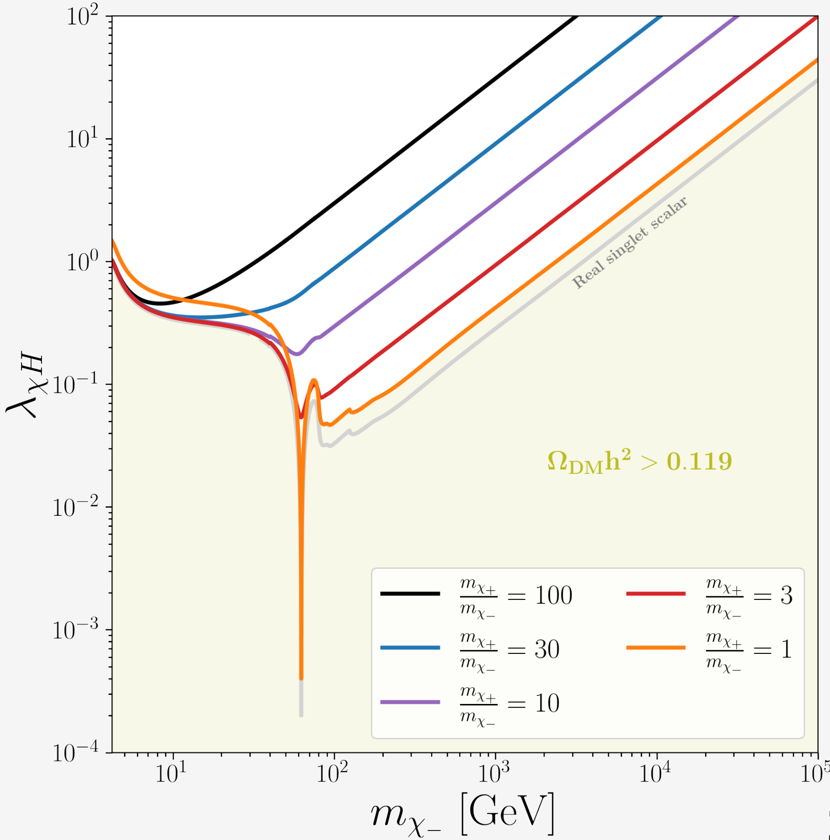
Freeze-out through Higgs portal

Usual Higgs portal cross sections



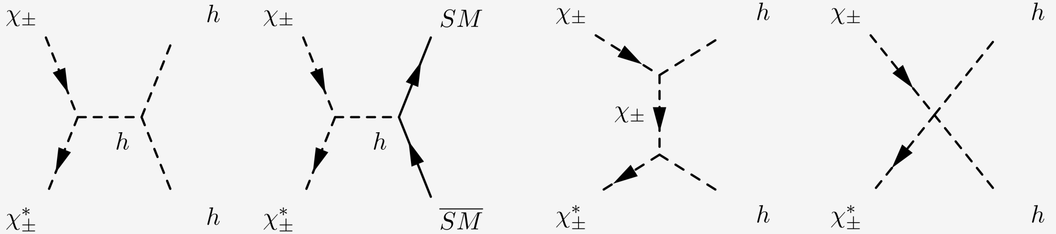
→ Ordinary Higgs portal DM setup (see G. Arcadi, A. Djouadi & M. Kado, ArXiv:2101.0257 for a review)

→ But **two DM components** contributing to the relic density



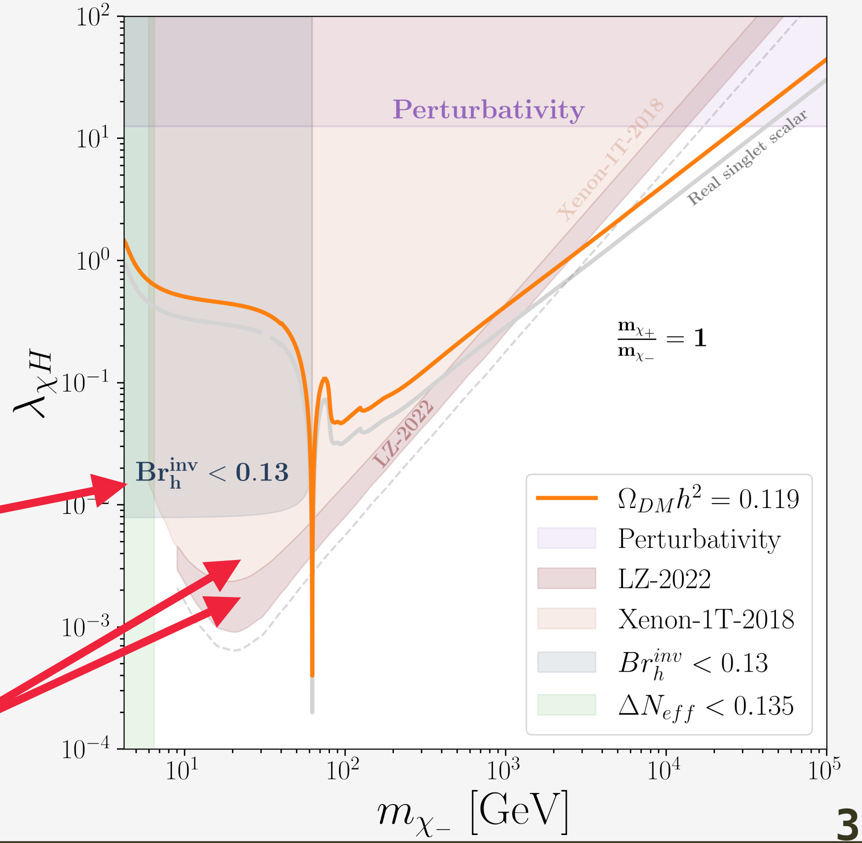
Freeze-out through Higgs portal

Usual Higgs portal cross sections (see e.g. 1204.2808)

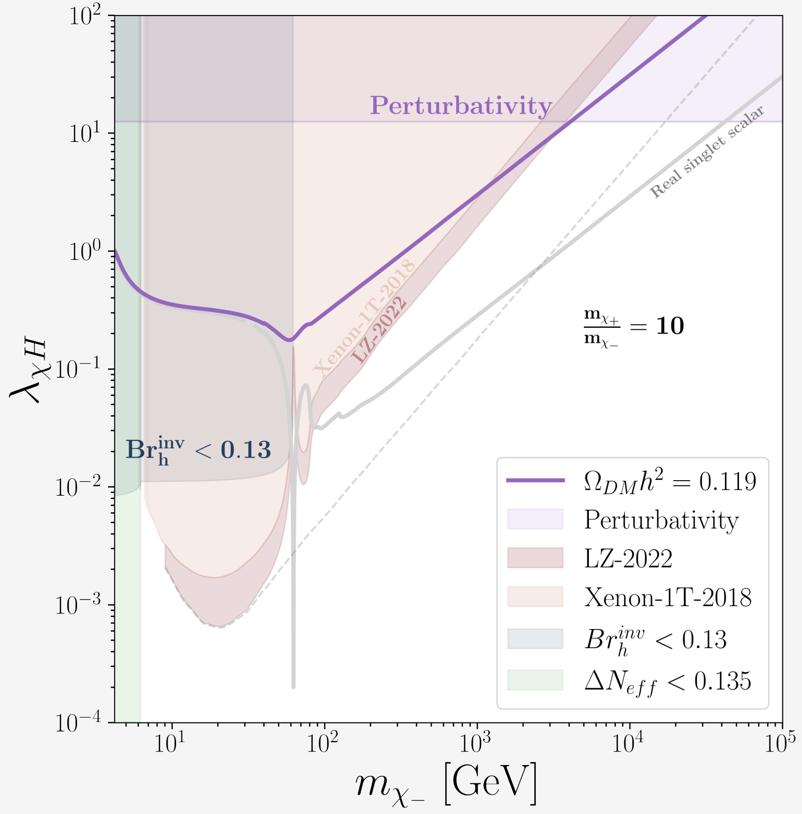


From Atlas latest analysis (2207.00092)

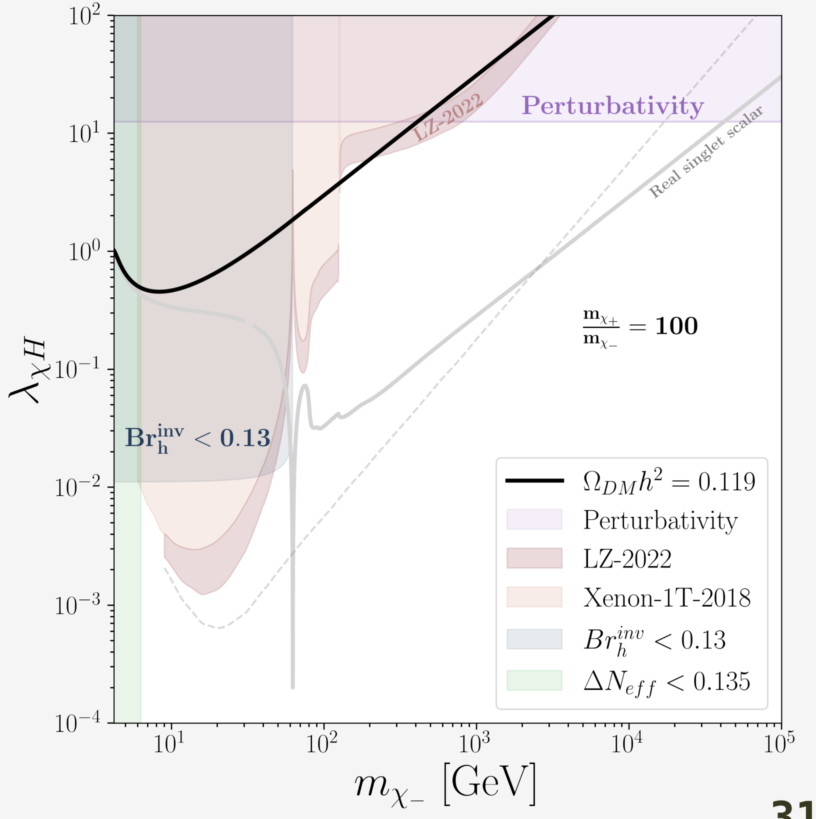
From Xenon1T and LZ (1805.12562 & 2207.03764)



Freeze-out through Higgs portal



DD constraints, driven by subleading χ_- component, relaxe.



Summary

- N-ality provides a simple way to **automatically stabilise** scalar DM with non-abelian gauge symmetries
- **Scalar potentials** of the SU(2) and SU(3) models are **rich** and have intriguing properties
- **Mass splitting** leads to non-trivial interplay between DM components in the SU(2) model
- **Semi-annihilation** processes in the SU(3) model stem from the stabilisation mechanism

More details can be found here: ArXiv:2212.11918

Thank you for your attention

The present work is supported by the Communauté française de Belgique through a FRIA PhD grant

Back-up slides

A few words on the SU(3) model

- Accidental flat directions if additional U(1) symmetry
- SSB pattern : SU(3)⟶U(1)xU(1)
- Additional unbroken discrete symmetries (S_3)
- Doublet of massless DP/triplet of massive gauge bosons
- Scalar tenplet decomposition : 3-3-3-1
- Triplet of scalar DM degenerate in mass

Symmetries of the SU(2) model

$SU(2)_{D\Phi}$

$\Phi \to U_{D\Phi}\Phi$

$\otimes$

$SU(2)_{Dx} \times SU(2)_{x}$

$X \to U_{Dx} X (U_{x})^{\dagger}$

κ-term → $SU(2)_{D} \times U(1)_{x}$

$X \equiv (\tilde{x}\ x)$

Symmetries of the SU(2) model

$SU(2)_{D\Phi}$

$\Phi \to U_{D\Phi}\Phi$

$\otimes$

$SU(2)_{D\chi} \times SU(2)_{\chi}$

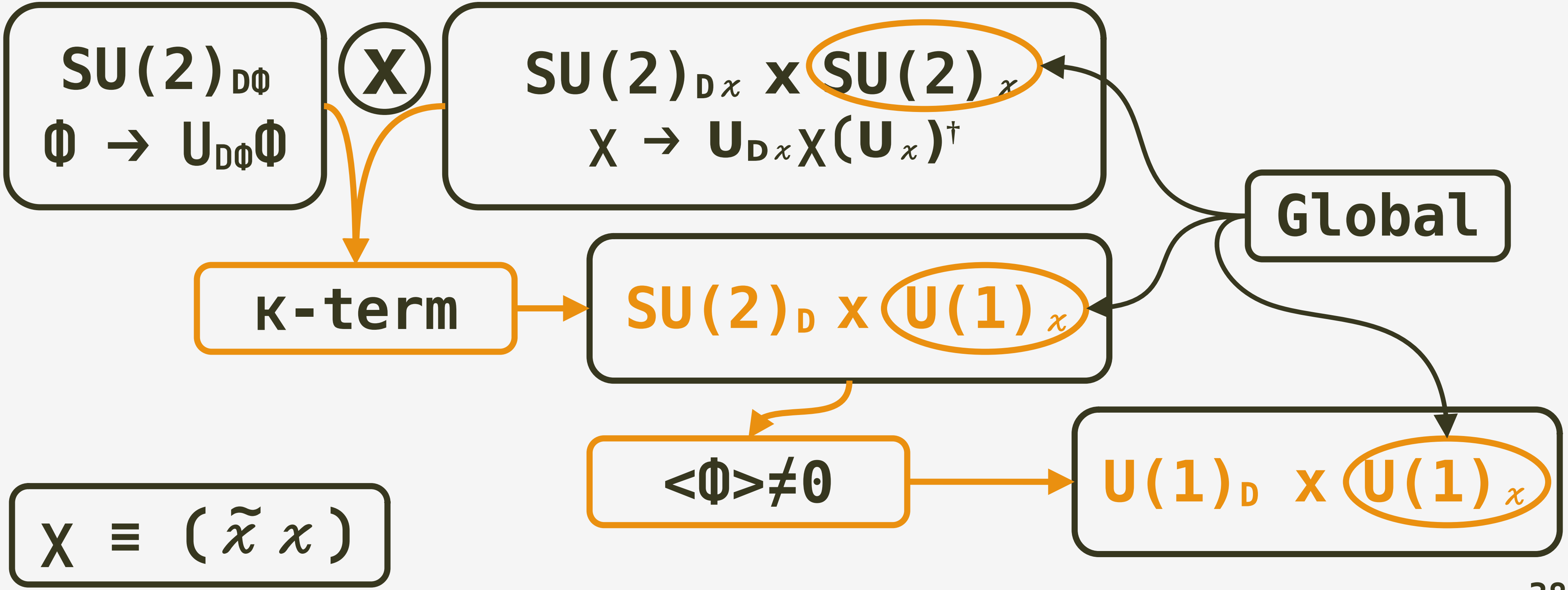
$X \to U_{D\chi} X (U_{\chi})^{\dagger}$

κ-term → $SU(2)_D \times U(1)_{\chi}$

$\langle\Phi\rangle \neq 0$ → $U(1)_D \times U(1)_{\chi}$

$X \equiv (\tilde{\chi}\ \chi)$

Symmetries of the SU(2) model



The SU(3) scalar potential

$$V(\Phi) = -\mu^2\, \Phi^*_{ijk}\Phi^{ijk} + \lambda\left(\Phi^*_{ijk}\Phi^{ijk}\right)^2 + \delta\, \Phi^{i_1 j_1 k_1}\Phi^*_{i_1 j_1 k_2}\Phi^{i_2 j_2 k_2}\Phi^*_{i_2 j_2 k_1}$$
$$+\left(\eta\, \epsilon_{i_1 i_2 i_3}\epsilon_{j_1 j_2 j_3}\Phi^{i_1 j_1 k_1}\Phi^{i_2 j_2 k_2}\Phi^{i_3 j_3 k_3}\Phi^*_{k_1 k_2 k_3} + h.c.\right)$$
$$+\left(\sigma\, \epsilon_{i_1 j_2 k_3}\epsilon_{i_4 j_1 k_2}\epsilon_{i_3 j_4 k_1}\epsilon_{i_2 j_3 k_4}\Phi^{i_1 j_1 k_1}\Phi^{i_2 j_2 k_2}\Phi^{i_3 j_3 k_3}\Phi^{i_4 j_4 k_4} + h.c.\right)$$

The SU(3) scalar potential

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$$+\left(\eta\,\epsilon_{i_1i_2i_3}\epsilon_{j_1j_2j_3}\Phi^{i_1j_1k_1}\Phi^{i_2j_2k_2}\Phi^{i_3j_3k_3}\Phi^*_{k_1k_2k_3} + h.c.\right)$$
$$+\left(\sigma\,\epsilon_{i_1j_2k_3}\epsilon_{i_4j_1k_2}\epsilon_{i_3j_4k_1}\epsilon_{i_2j_3k_4}\Phi^{i_1j_1k_1}\Phi^{i_2j_2k_2}\Phi^{i_3j_3k_3}\Phi^{i_4j_4k_4} + h.c.\right)$$

SU(3)xU(1)

1101.2417

The SU(3) scalar potential

$$V(\Phi) = -\mu^2\,\Phi^*_{ijk}\Phi^{ijk} + \lambda\left(\Phi^*_{ijk}\Phi^{ijk}\right)^2 + \delta\,\Phi^{i_1j_1k_1}\Phi^*_{i_1j_1k_2}\Phi^{i_2j_2k_2}\Phi^*_{i_2j_2k_1}$$

$$+\left(\eta\,\epsilon_{i_1i_2i_3}\epsilon_{j_1j_2j_3}\,\Phi^{i_1j_1k_1}\Phi^{i_2j_2k_2}\Phi^{i_3j_3k_3}\Phi^*_{k_1k_2k_3} + h.c.\right)$$

$$+\left(\sigma\,\epsilon_{i_1j_2k_3}\epsilon_{i_4j_1k_2}\epsilon_{i_3j_4k_1}\epsilon_{i_2j_3k_4}\,\Phi^{i_1j_1k_1}\Phi^{i_2j_2k_2}\Phi^{i_3j_3k_3}\Phi^{i_4j_4k_4} + h.c.\right)$$

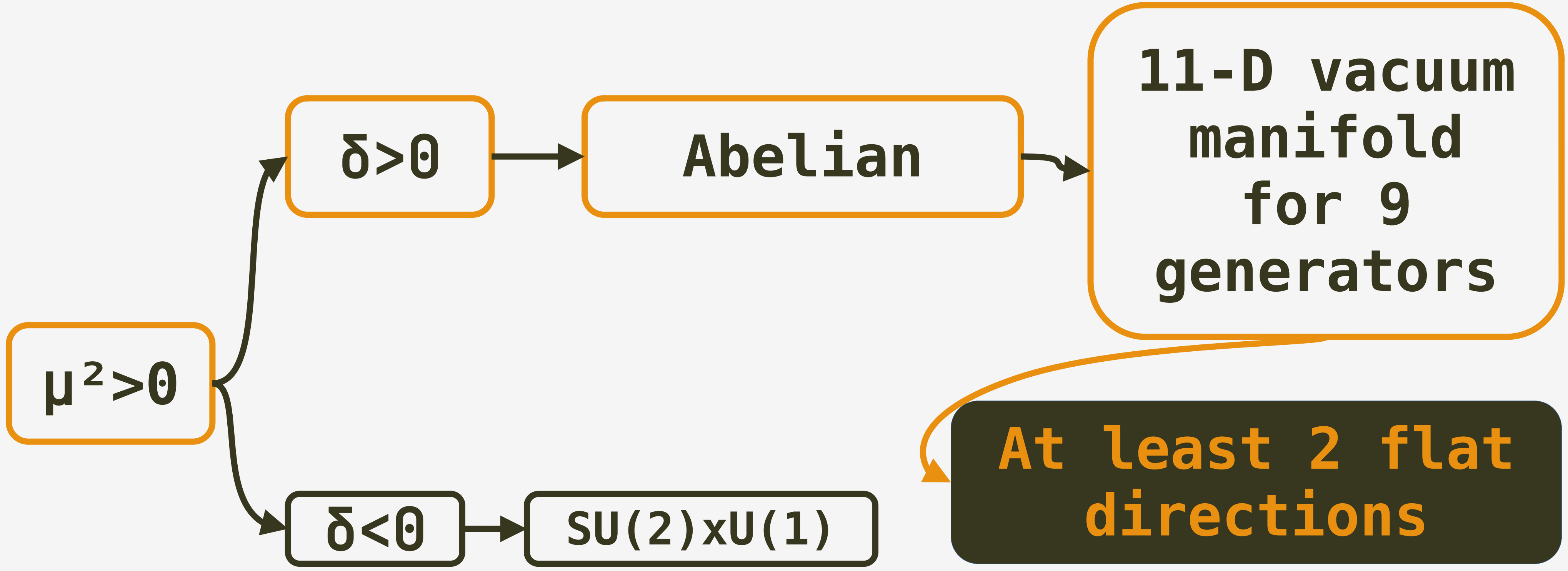
SU(3)xU(1)

$$V(\Phi) = -\mu^2\,A^i_i + \lambda\left(A^i_i\right)^2 + \delta\,A^i_jA^j_i$$

1101.2417

$$A^i_j \equiv \Phi^{ikl}\Phi^*_{jkl}$$

The SU(3) scalar potential



Decoupling temperature

$\Delta N_{eff} < 0.135$ at 2σ

From 1912.01132

1 dark photon

$g^*_{SM}(T_{dec}) \geq 53$

$T_{dec} \geq 300$ MeV

2 dark photons

$g^*_{SM}(T_{dec}) \geq 89$

$T_{dec} \geq 30$ GeV

Freeze-out to dark photons

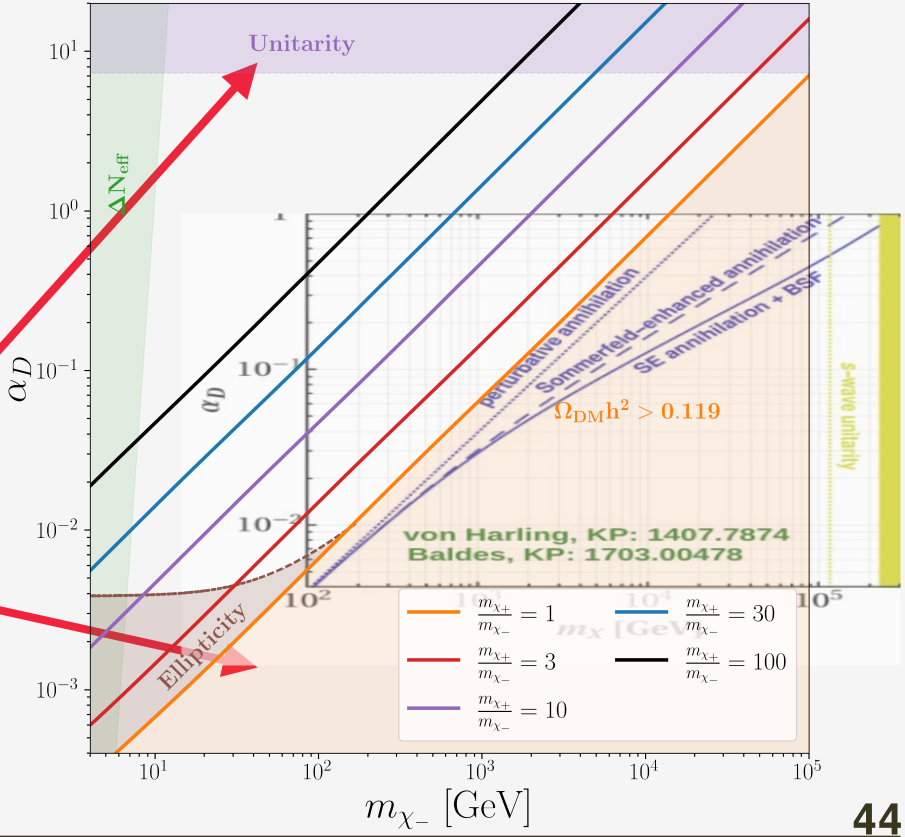
$$\langle\sigma v\rangle_\pm \equiv \langle\sigma_{\chi_\pm\chi_\pm^*\to\gamma_D\gamma_D} v\rangle = \frac{\pi\alpha_D^2}{4m_{\chi_\pm}^2}$$

$$\Omega_{\chi_+}/\Omega_{\chi_-} \simeq m_{\chi_+}^2/m_{\chi_-}^2$$

$$\langle\sigma v\rangle_J \lesssim 4\pi(2J+1)/(m_{DM}^2 v)$$

$$\alpha_D \lesssim 0.8\sqrt{10^{-11}(m_{DM}/\mathrm{GeV})^3}$$

See P. Agrawal, F. Cyr-Racine, L. Randall & J.Scholtz, 2016 (ArXiv :1610.04511)

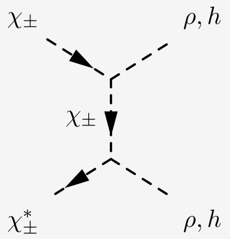


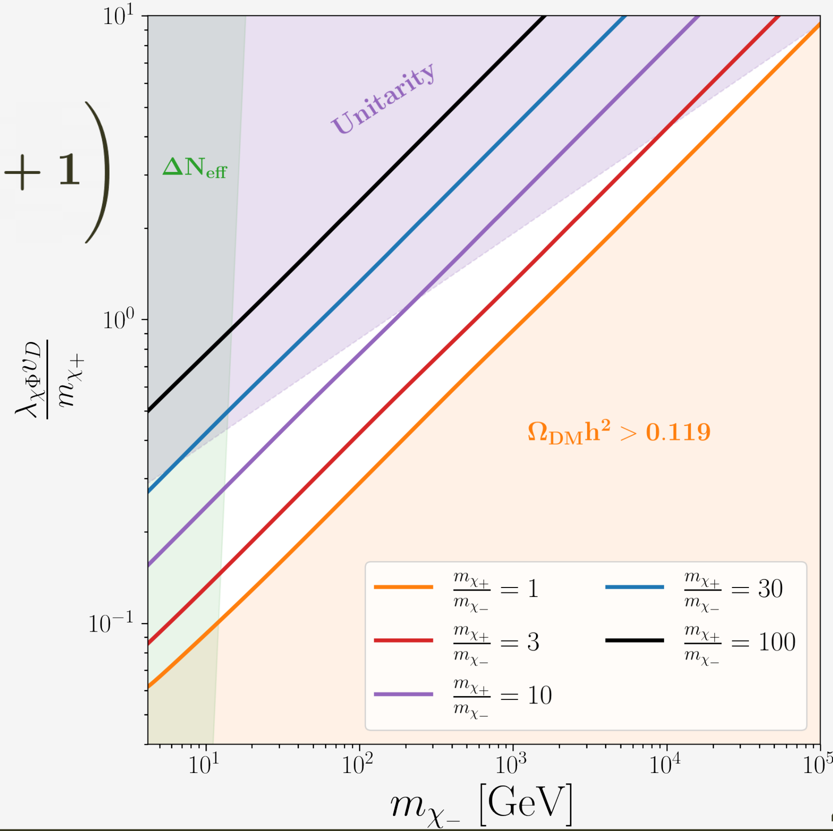
Freeze-out to dark scalars

$$\langle \sigma_{\chi_\pm \chi^*_\pm \to \rho\,\rho} v \rangle = \frac{\lambda^2_{\chi\Phi}}{64\pi m^2_{\chi_\pm}} \left(\lambda^2_{\chi\Phi} \frac{v_D^4}{m^4_{\chi_\pm}} - 2\lambda_{\chi\Phi} \frac{v_D^2}{m^2_{\chi_\pm}} + 1 \right)$$

Assuming that the first term dominates:

$$\Omega_{\chi_+}/\Omega_{\chi_-} \simeq m^6_{\chi_+}/m^6_{\chi_-}$$



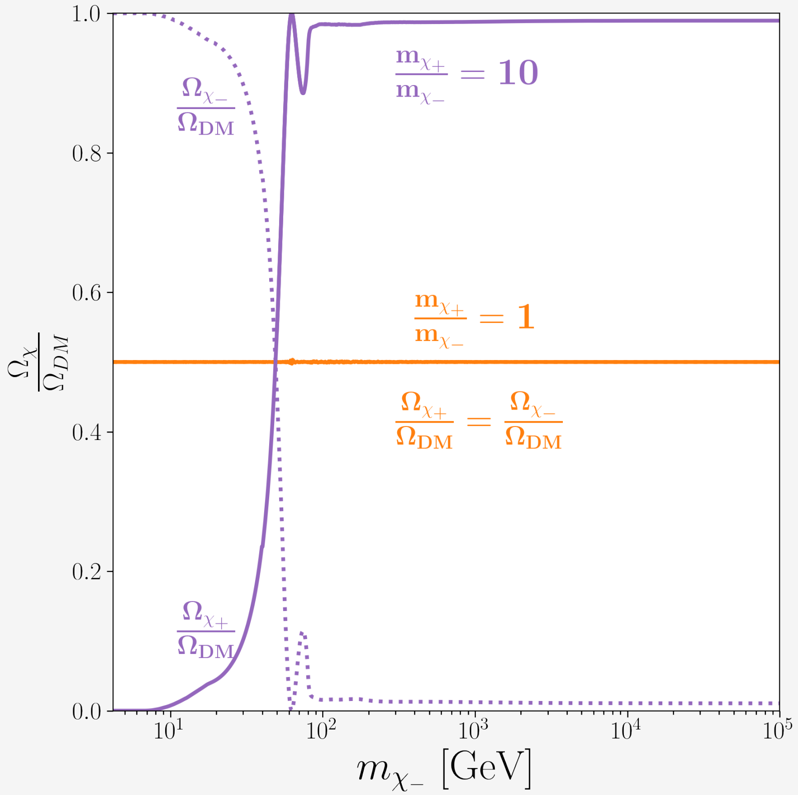


Higgs-portal DD constraints relaxation

$$m_{\chi\pm} \gg m_h \longrightarrow \sigma \sim 1/m_{\chi\pm}^2$$

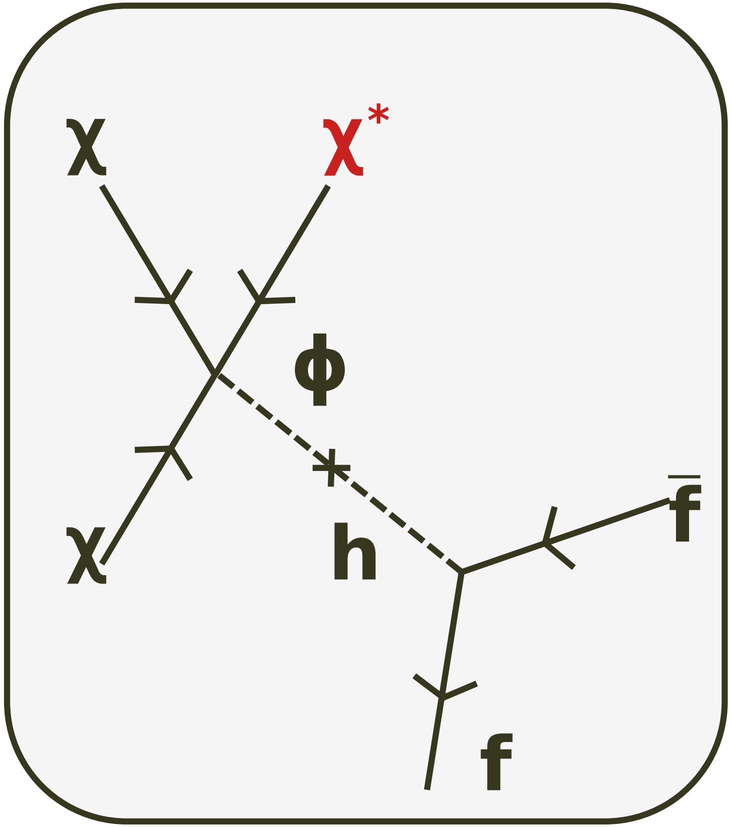
$$m_{\chi\pm} \ll m_h \longrightarrow \sigma \sim m_f^2/m_h^4$$

- For high masses and high mass ratios, the lightest component is suppressed
- DM-nuclei elastic cross-section scales as $1/m^2$
- DD upper limit relaxes at higher masses



Semi-annihilations

$$\mathcal{L} \supset \chi\chi\chi\phi^\dagger + h.c.$$



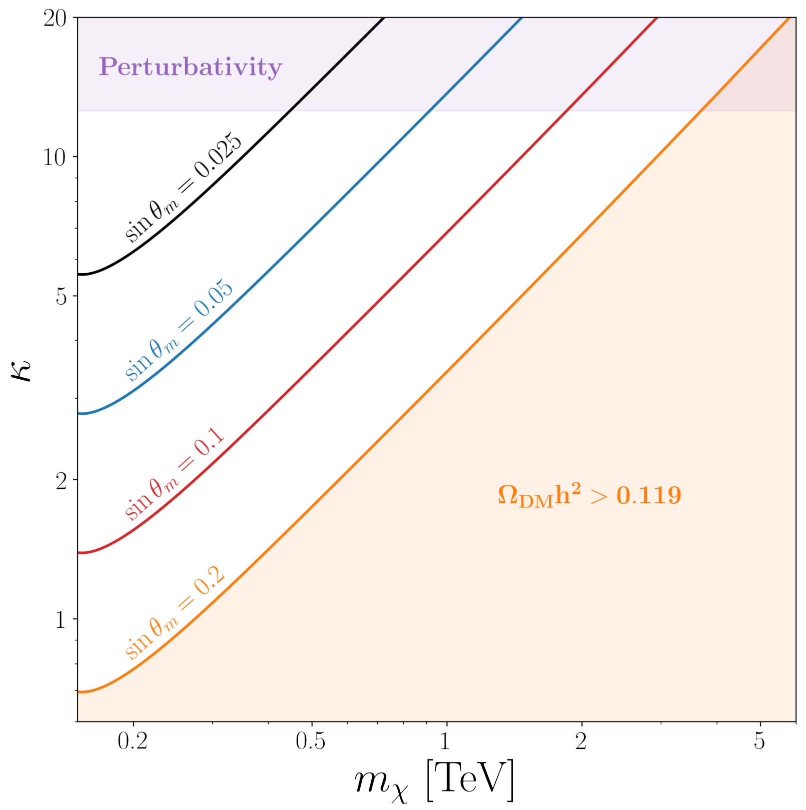
Direct detection of boosted DM in neutrino telescopes

(Berger & al., 2022 Snowmass)

$$\mathcal{L}_{eff} \supset \sqrt{3}\,\kappa \sin\theta_m (\chi^1\chi^2\chi^3 + \chi_1^*\chi_2^*\chi_3^*)h$$

Assuming **semi-annihilation to higgs boson** dominates the freeze-out process:

- All particles are heavier than DM triplet
- All coupling but trilinear and higgs-mixing coupling are small



Monochromatic flux of boosted DM particle:

$$E_\chi = (5m_\chi^2 - m_h^2)/(4m_\chi)$$