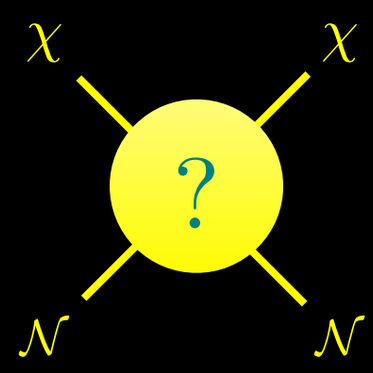
Hadronic Uncertainties and Isospin Violation in Supersymmetric Dark Matter Models

$$\left\{ \begin{array}{c} \chi\mathrm{PT}_{2,3} \\ + \\ \text{lattice QCD} \end{array} \right\} \Longleftrightarrow \left\{ \begin{array}{c} \\ \\ \end{array} \right.$$



$$\left. \begin{array}{c} \\ \\ \end{array} \right\}$$

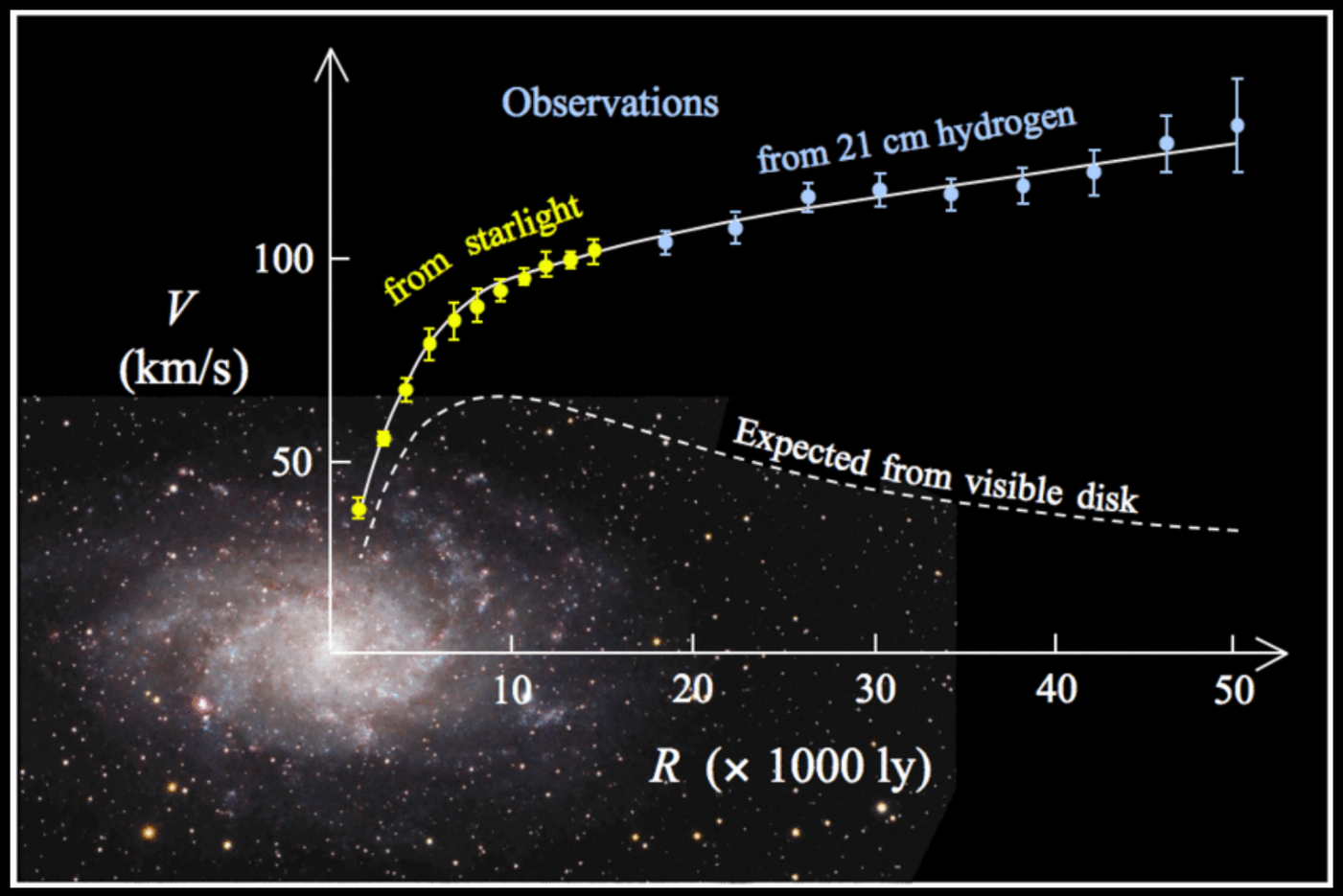
In collaboration with A. Crivellin, M. Hoferichter & M. Procura [arXiv:1503.03478]

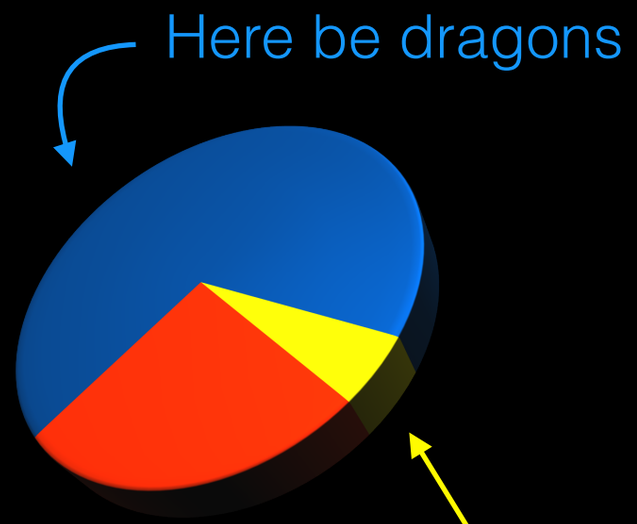
Lewis Tunstall
Albert Einstein Centre for Fundamental Physics
Universität Bern

The 8th International Workshop on Chiral Dynamics, Pisa, June 29 - July 3, 2015

The Dark Matter Puzzle

We know dark matter exists but we
understand very little about its composition





$$\Omega_{\rm DM} \simeq 0.2 - 0.3$$
$$\approx 5 \times \Omega_{\rm baryonic}$$

Key properties:

- Interacts weakly with ordinary matter
- Electromagnetically neutral
- Massive
- Stable

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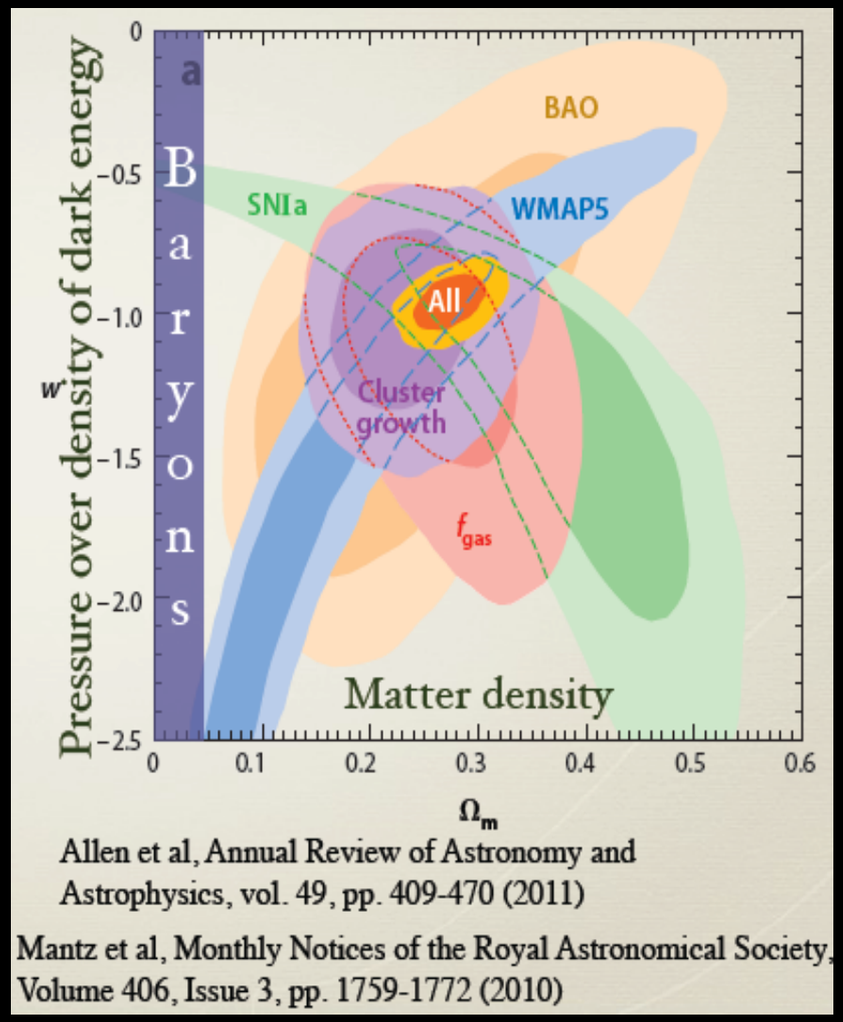

Allen et al, Annual Review of Astronomy and Astrophysics, vol. 49, pp. 409-470 (2011)

Mantz et al, Monthly Notices of the Royal Astronomical Society, Volume 406, Issue 3, pp. 1759-1772 (2010)

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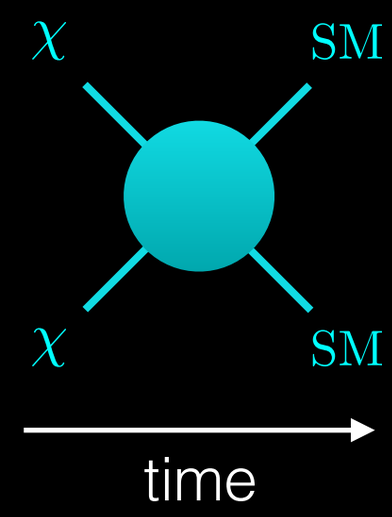
Candidates?

- ★ Requires physics beyond the SM
- ★ WIMPs, axions (strong CP), sterile neutrinos, …

$$\Omega_{\rm DM} \approx 10^{-26}\ {\rm cm}^3\ {\rm s}^{-1} / \langle \sigma_{\rm ann.} v \rangle$$



- ★ Right ballpark if

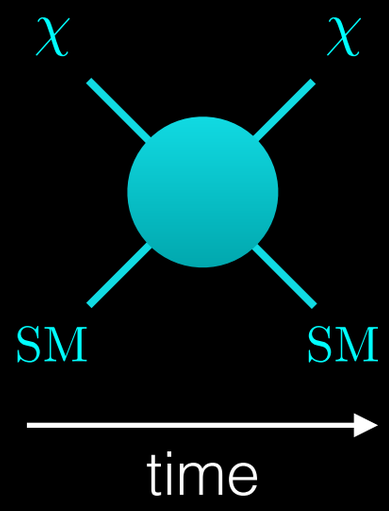
$$\langle \sigma_{\rm ann.} v \rangle \approx \alpha^2\ (100\ {\rm GeV})^{-2}$$
$$\approx 10^{-25}\ {\rm cm}^3\ {\rm s}^{-1}\,, \qquad \alpha \approx 10^{-2}$$

⇒ “WIMP miracle”:

If ∃ stable particle at weak scale, then forms DM (or part of it)

Direct Detection

Key observable: χ-nuclei elastic cross section



Theory involves 3 main steps:

⋆ calculate interaction of WIMPs with quark and gluons

$$\mathcal{L}_{\rm eff}^{\rm SI} = C_q m_q \chi\chi\bar{q}q + C_g \alpha_s \chi\chi G^a_{\mu\nu} G^{a\mu\nu}$$

⋆ translate $\chi - \{q, A_\mu\}$ interaction into χ-nucleon interaction

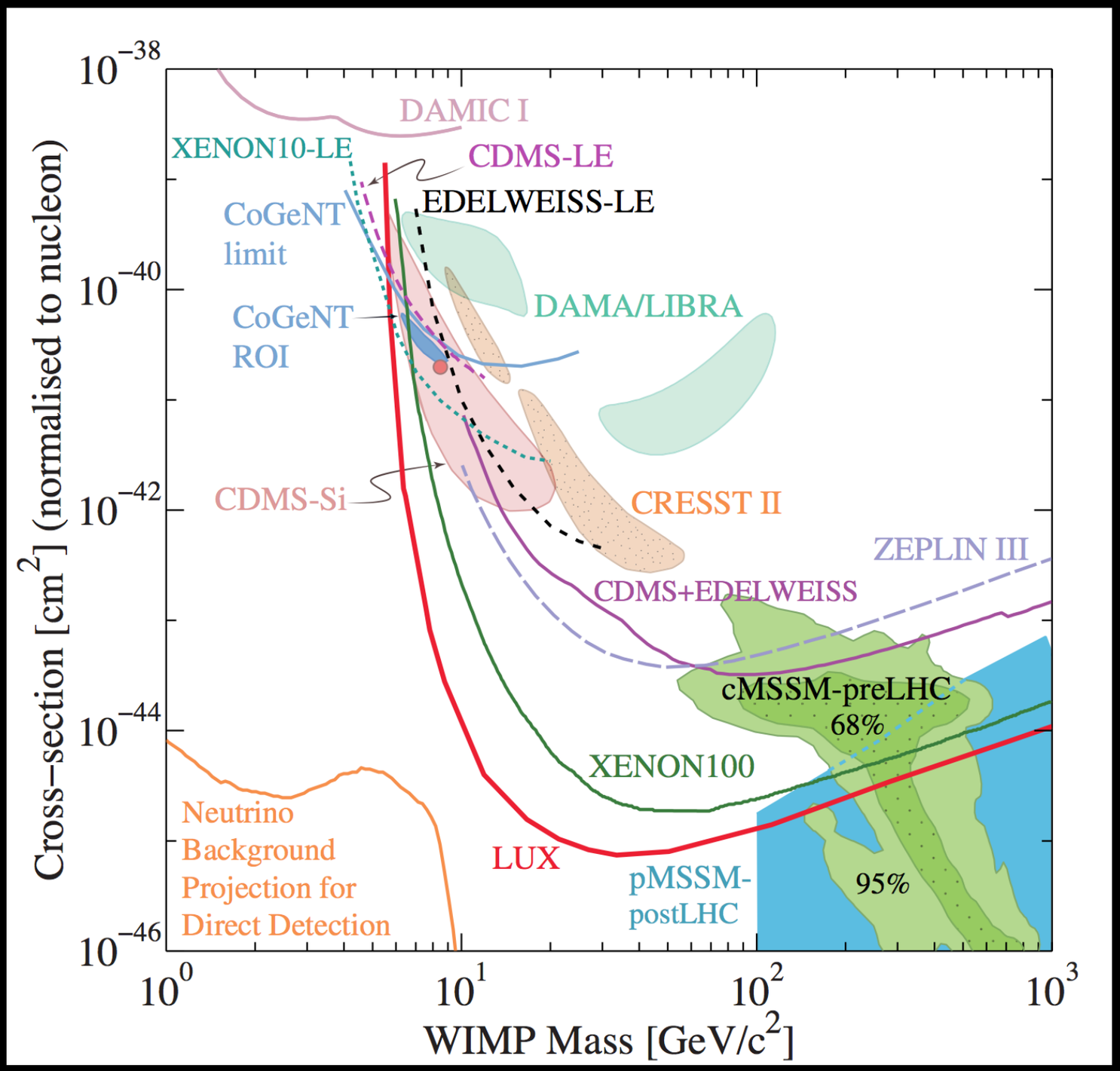
$\Rightarrow$ non-pert. matrix elements $\langle N|\bar{q}q|N\rangle$ & $\langle N|G^2|N\rangle$

⋆ nuclear form factors to add spin-spin/scalar components

$$\frac{d\sigma_{\rm SI}}{d|\vec{q}|^2} \propto [Z f_p + (A - Z) f_n]^2 F(Q^2)$$

Direct Detection

Current status



Future prospects

XENON1T

$\sigma_{\mathrm{SI}} \sim 2 \times 10^{-47}\ \mathrm{cm}^2$

LUX-ZEPLIN (LZ)

$\sigma_{\mathrm{SI}} \sim 5 \times 10^{-49}\ \mathrm{cm}^2$

Hadronic Input for Direct Detection

★ focus on WIMP-nucleon interactions

New physics

$$\sigma_{\rm SI}^N \propto \left| \sum_{q=u,d,s} C_q f_q^N - 12\pi C_g f_Q^N \right|^2$$

$\langle N|m_q \bar{q} q|N\rangle / m_N$

$\frac{2}{27}(1 - f_u^N - f_d^N - f_s^N)$

[Shifman et al. (1978)]

★ traditionally, f_q^N determined from $\chi\mathrm{PT}_3$ [Ellis, Olive & Savage (2008)]

$$f_u^N \propto \frac{\sigma_{\pi N}}{1+x} \qquad f_d^N \propto \frac{\sigma_{\pi N}}{1+x^{-1}} \qquad f_s^N \propto \sigma_{\pi N} y$$

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$$\frac{2 + y(z-1)}{2z - y(z-1)}\ , z \approx 1.5 \quad \text{(God given)}$$

Problems with $\chi\mathrm{PT}_3$ Method?

- ★ $f^N_{u,d}$ depend on 3-flavour quantities y and z
- ★ sensitive to input from $\sigma_{\pi N} \Rightarrow f^N_s\Big|_{\mathrm{pheno}} \approx 0.3$
- ★ incompatible with lattice results

$$f^N_s\Big|_{\mathrm{lattice}} = 0.043 \pm 0.011$$ [Junnarkar & Walker-Loud (2013)]

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CMSSM limits weakened by factors ~ 5-10!

[Giedt, Young & Thomas (2009)]

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$$f^N_s\Big|_{\text{lattice}} = 0.043 \pm 0.011$$

Solution $\left\{ \right.$ use $\chi\mathrm{PT}_2$ for $f^N_{u,d}$

[Crivellin, Hoferichter & Procura (2014)]

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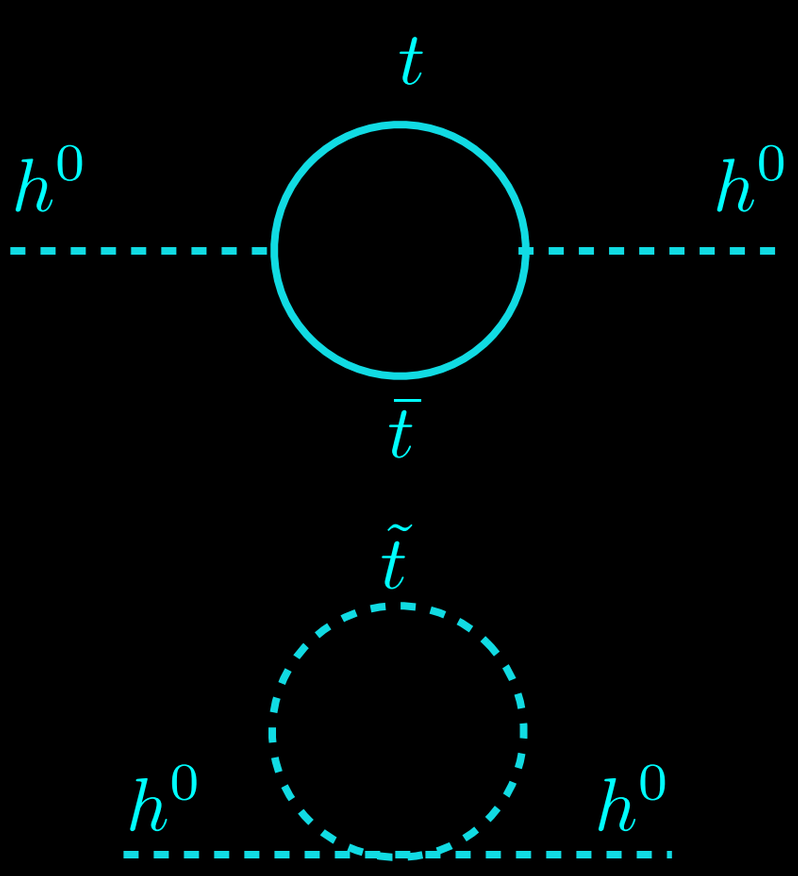
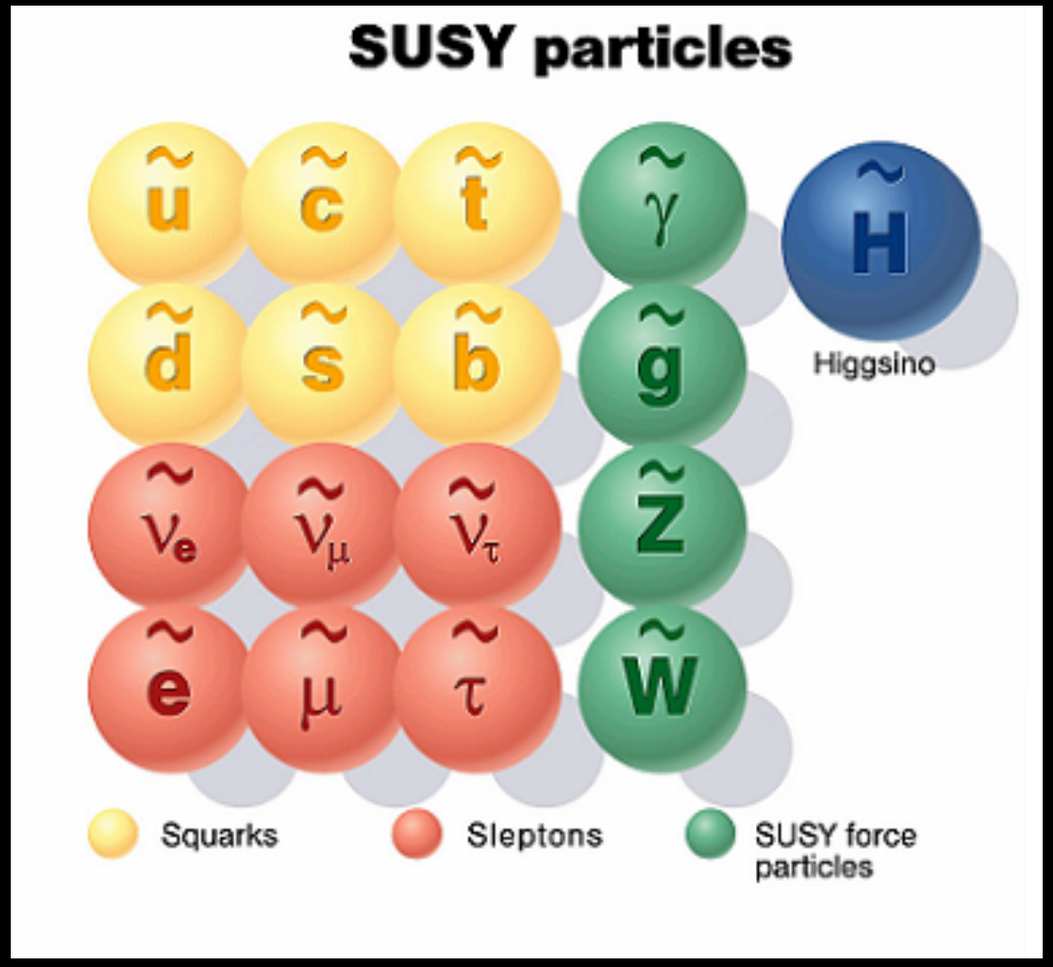
Bonus: can systematically include effects due to $m_u \neq m_d$

Are isospin violating effects important in e.g. MSSM?

Supersymmetric Dark Matter

- ⋆ postulated space-time symmetry between fermions and bosons
- ⋆ primarily motivated by hierarchy problem: why $v_{\rm weak} \ll M_{\rm Planck}$?
- ⋆ SM field content + SUSY ⇒ Minimal Supersymmetric SM (MSSM)





Supersymmetric Dark Matter

- ⋆ MSSM comes with discrete R-parity (matter parity)

$$P_R = (-1)^{3(B-L)+2s} = \begin{cases} +1 & \text{SM + Higgs} \\ -1 & \text{sparticles} \end{cases}$$

- ⋆ lightest superpartner (LSP) with $P_R = -1 \Rightarrow$ stable

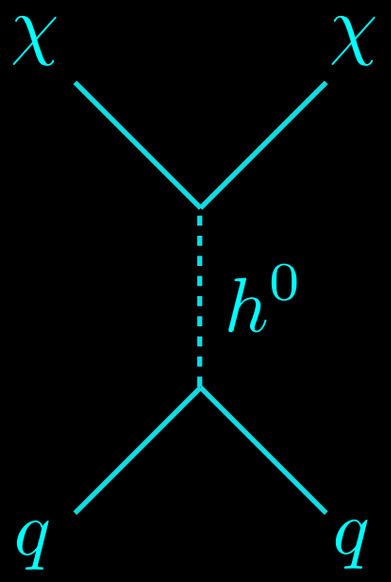
- ⋆ if EM neutral ⇒ WIMP candidate!

- ⋆ in most cases LSP is neutralino $\chi =$ mixture of $\widetilde{B}$, $\widetilde{W}$, $\widetilde{H}_u$, $\widetilde{H}_d$

$$M_\chi = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g_1 v_d & \frac{1}{2}g_1 v_u \\ 0 & M_2 & \frac{1}{2}g_2 v_d & -\frac{1}{2}g_2 v_u \\ -\frac{1}{2}g_1 v_d & \frac{1}{2}g_2 v_d & 0 & -\mu \\ \frac{1}{2}g_1 v_u & -\frac{1}{2}g_2 v_u & -\mu & 0 \end{pmatrix}$$

Light Higgs Exchange

- ★ SUSY-breaking ⇒ large theory parameter space
- ★ focus on signals of interest: "simplified models"
- ★ for DM, minimal model involves h^0 & χ

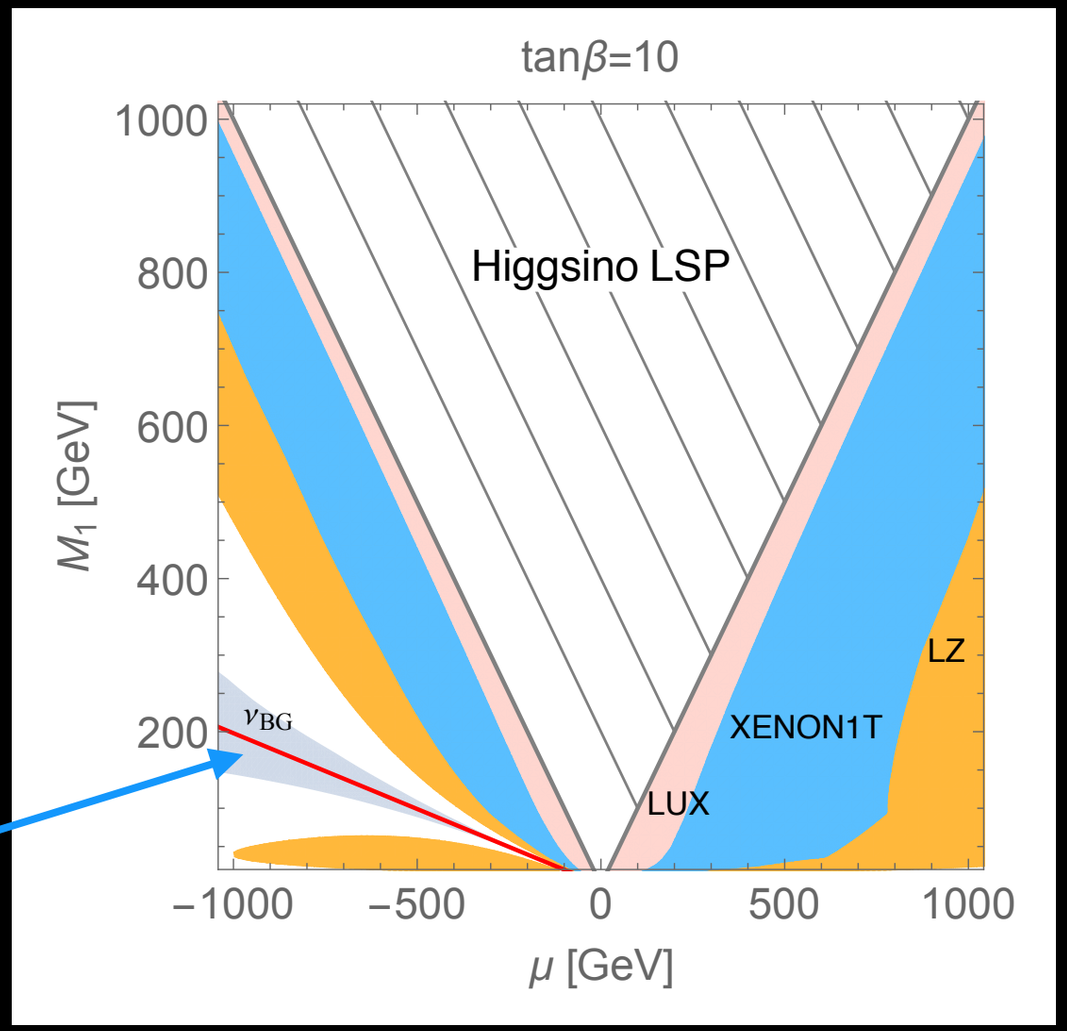


$$\mathcal{L}_{\rm eff}^{\rm SI} = C_q m_q \chi\chi\bar{q}q$$

$$C_q \propto (M_1 + \mu \sin 2\beta)$$

Blind spot: $M_1 + \mu \sin 2\beta = 0$

[Cheung, Hall, Pinner & Ruderman (2013)]



Light Higgs Exchange

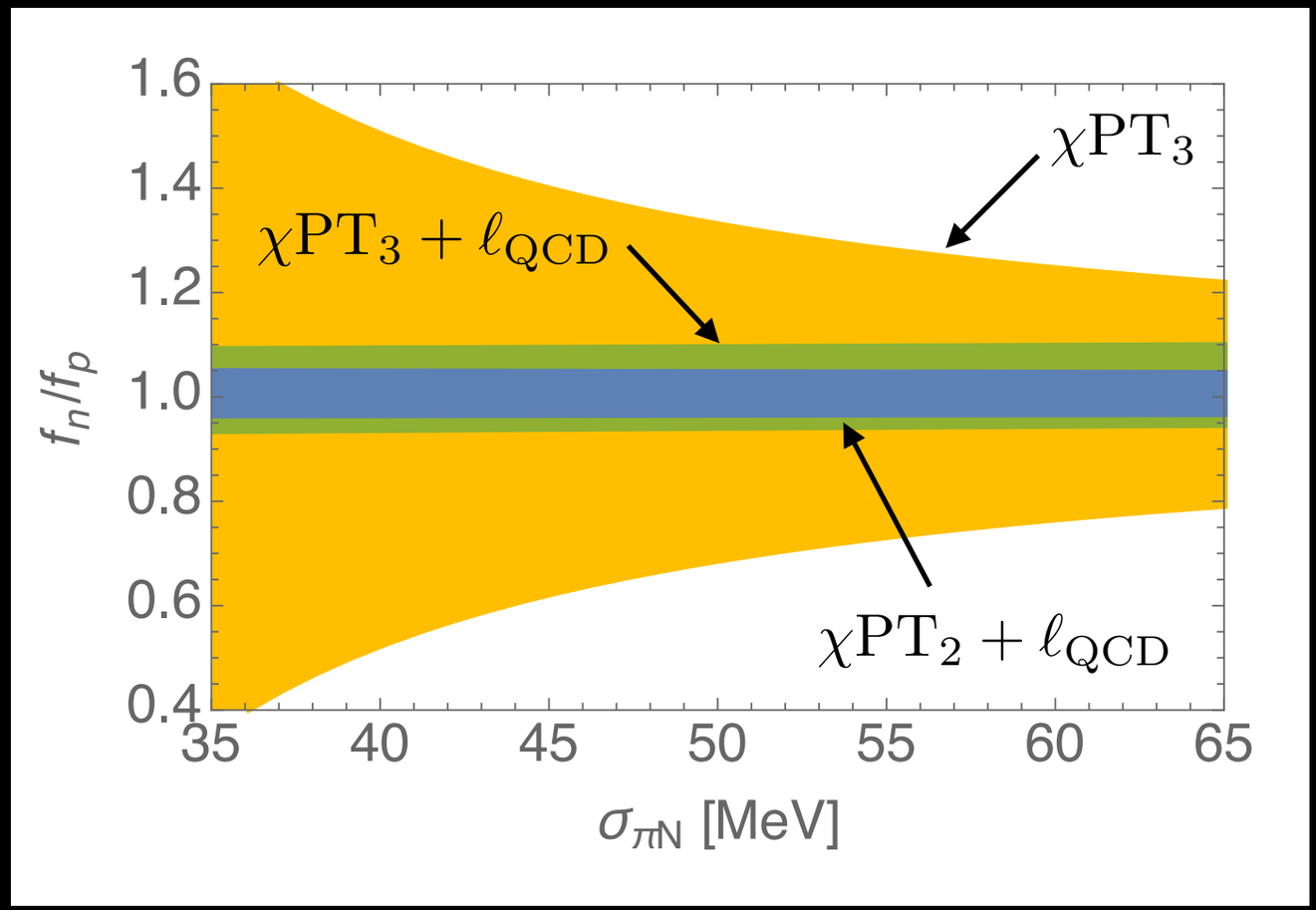
★ Hadronic uncertainties? Compare 3 methods which determine f_q^N

sensitive to f_s^N

$$f_N \propto \left(2 + 7 \sum_{u,d,s} f_q^N\right)$$

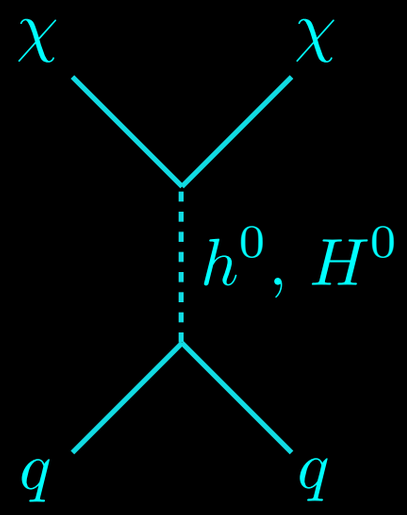
★ IV fully determined by QCD:

$$\frac{f_n}{f_p} = \left(\frac{m_n}{m_p}\right) \frac{2 + 7\sum f_q^n}{2 + 7\sum f_q^p}$$



Light & Heavy Higgs Exchange

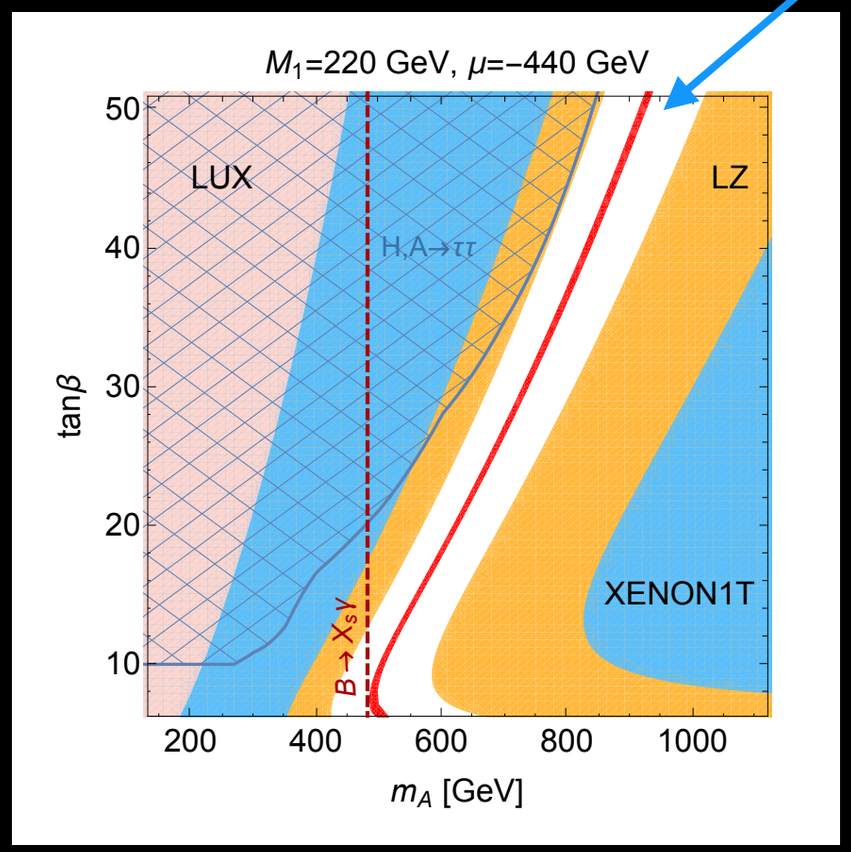
- In MSSM have extended Higgs sector $\{h^0,\, H^0,\, A^0,\, H^\pm\}$

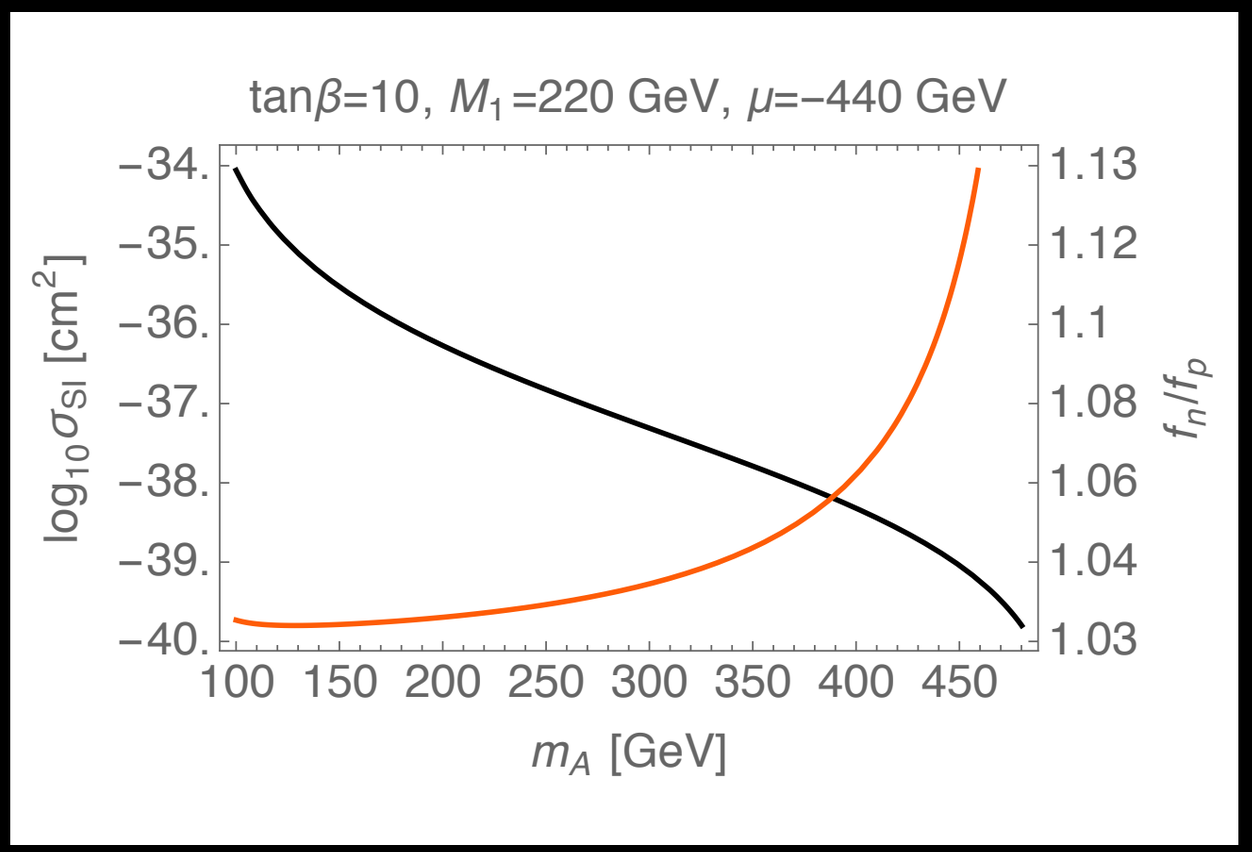


Blind spot

$$\frac{2}{m_h^2}(M_1 + \mu \sin 2\beta) + \mu \tan\beta \frac{1}{m_H^2} \simeq 0$$

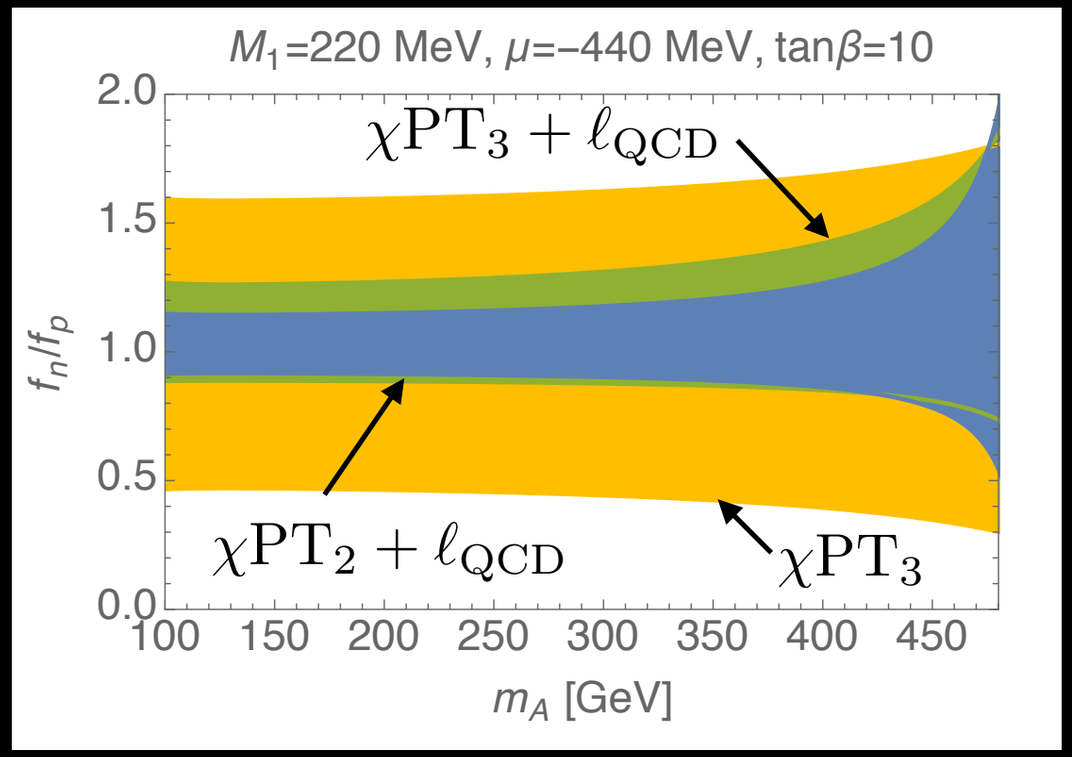
[Huang & Wagner (2014)]

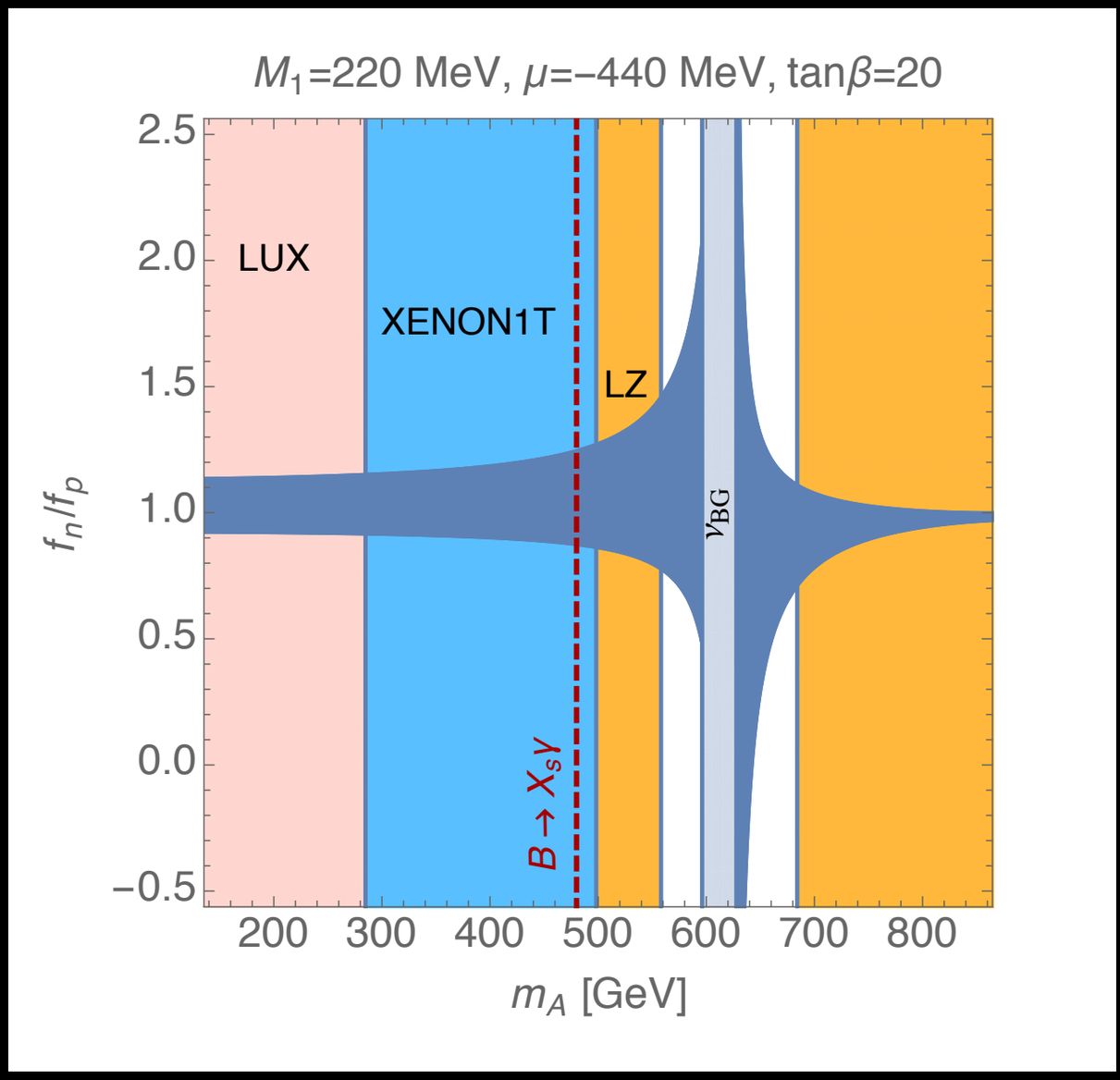




Light & Heavy Higgs Exchange

- ★ Hadronic uncertainties?
- ★ large uncertainty on IV near blind spots
- ★ need complementary constraints from e.g. flavour observables





Summary

- ⋆ Determination of scalar couplings

$$m_N f_q^N = \langle N | m_q \bar{q} q | N \rangle$$

crucial to interpretation of DM limits

- ⋆ Beware the pitfalls of $\chi\mathrm{PT}_3$: avoid by splitting 2- and 3-flavour sectors

- ⋆ Regions of MSSM parameter space produce blind spots in DM amp.

- ⋆ Can constrain these regions via complementary observables from flavour and collider experiments

- ⋆ The uncertainty on isospin violation is large near blind spots