Composite Dark Matter

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Sakata-Hirata Hall, Nagoya University
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Lattice Strong Dynamics Collaboration

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Tom Appelquist
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[LSD collab., Phys. Rev. D88 (2013) 014502]
[LSD collab., Phys. Rev. D89 (2014) 094508]
+ LSD collab., in preparation (x2)

Outline

- Motivations for searches of composite dark matter
- Features of strongly-coupled composite dark matter
- Searches for a class of models interesting for phenomenology
- Importance of lattice field theory simulations
- Lower bounds on composite dark matter models

BSM Is Out There

- Discovery of SM-like Higgs boson doesn’t mean BSM physics is dead:
  - ➡ What is the meaning of the hierarchy problem and naturalness?
  - ➡ What solves the strong CP problem?
  - ➡ What explains the matter-antimatter asymmetry?

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  - ➡ What solves the strong CP problem?
  - ➡ What explains the matter-antimatter asymmetry?
  - ➡ What is dark matter? Can it couple to the standard model? Is the mass scale related to the EW Higgs mechanism? Is it self-interacting?

The gravity of Dark Matter

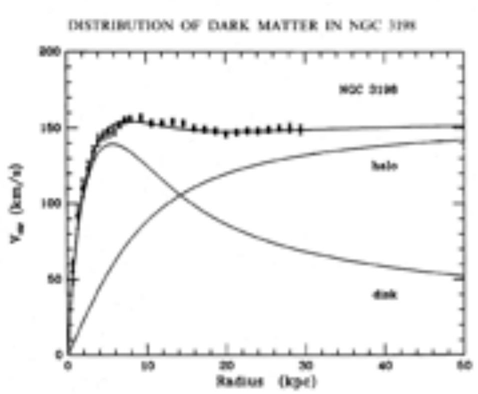
?????? →

New Physics!!

We Are Here

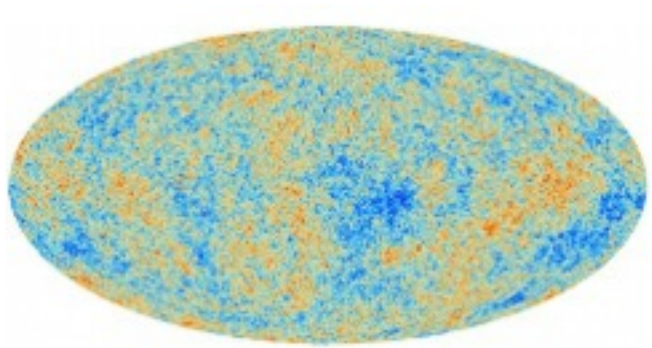
(QCD, EM, SM, etc.)

How do we know Dark Matter is there?



Rotational velocity Curves of Galaxies

Gravitational Lensing



Cosmological Backgrounds

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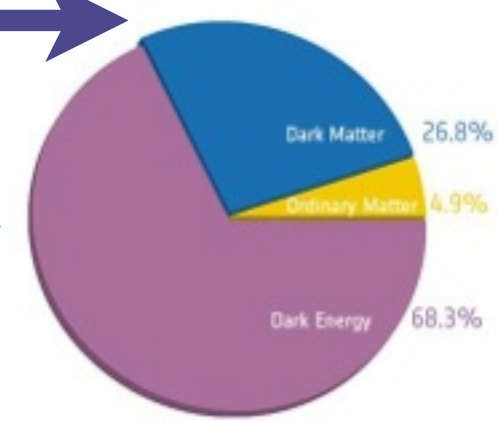

[Planck and ESA]

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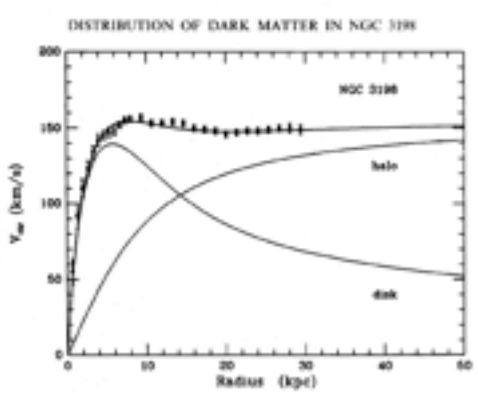

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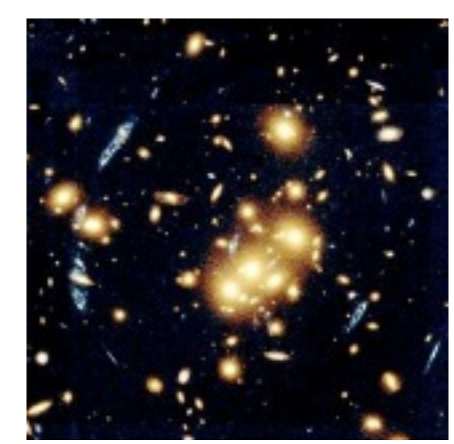

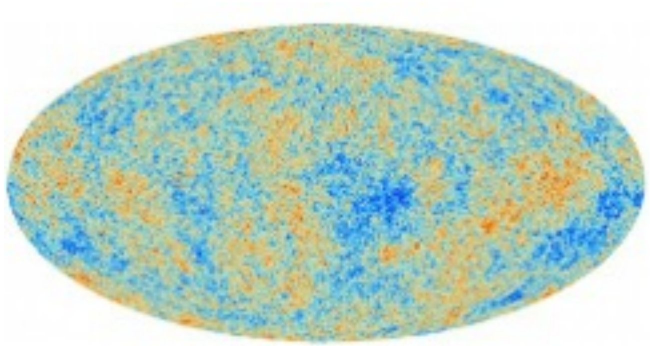

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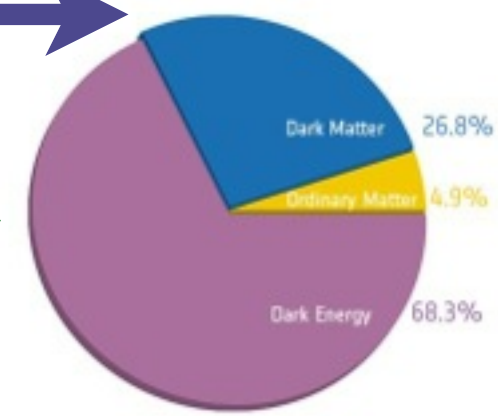

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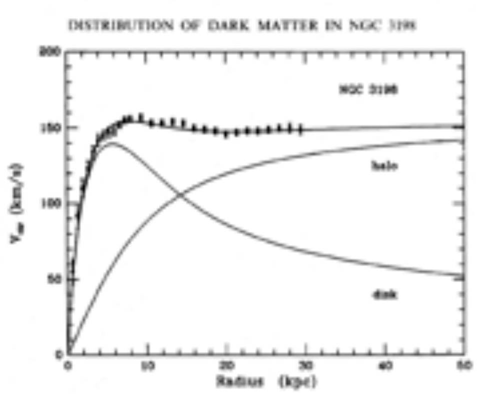

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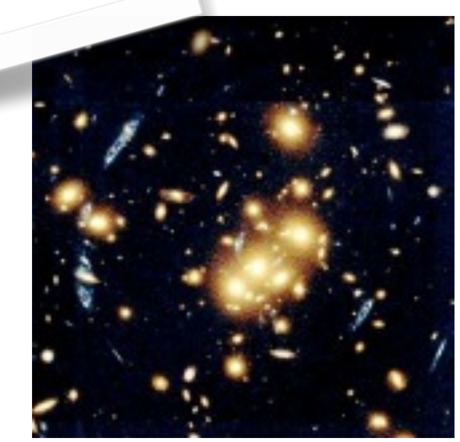

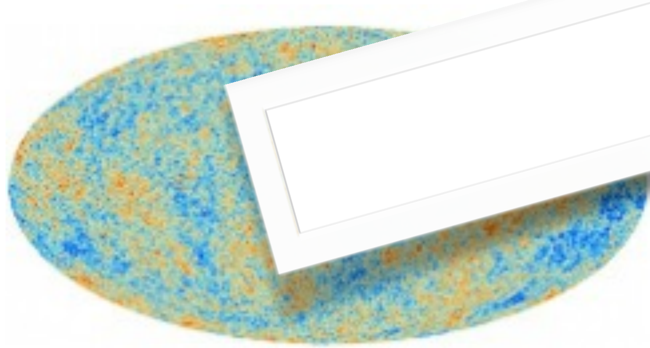

Cosmological Backgrounds

Gravitational Interactions

Problems?

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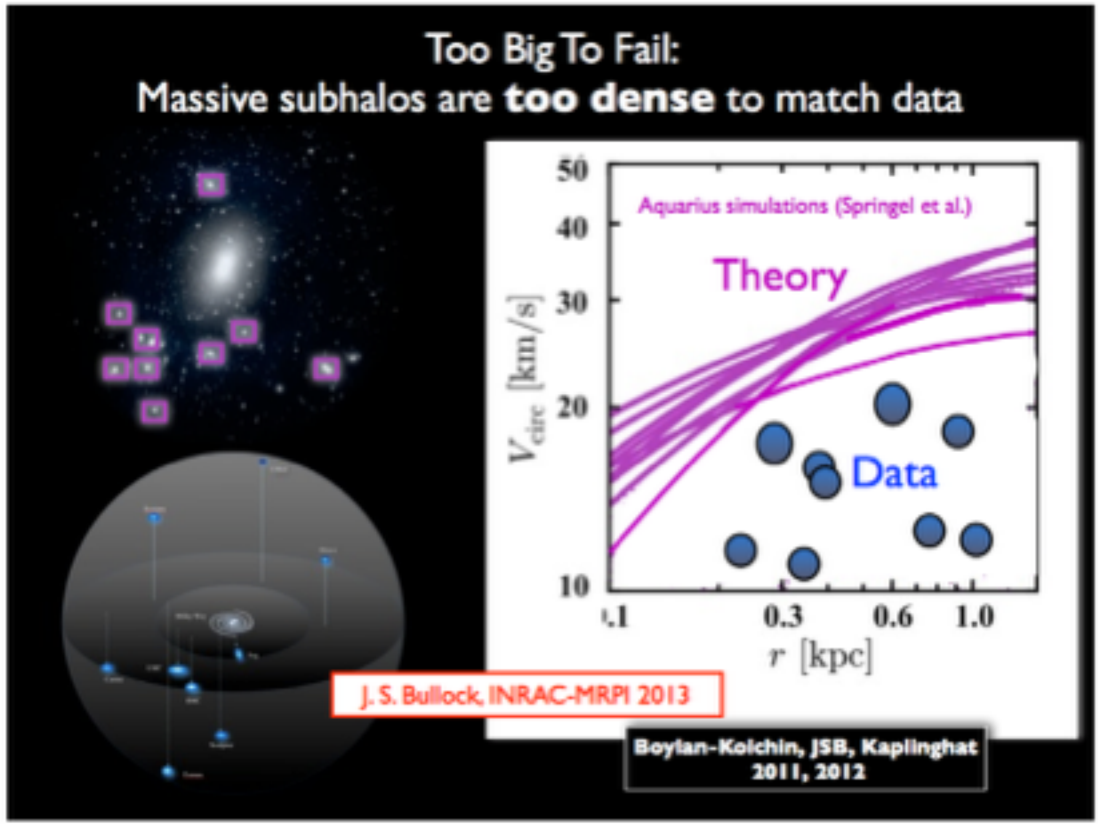
ameliorated by Self-Interacting Dark Matter

Self-Interacting Dark Matter

- In ΛCDM, galactic sub-halos have very dense, cuspy cores.
- Any dwarf galaxies residing in a cuspy sub-halo will be smaller and dimmer than in a sub-halo with more uniform density.
- Larger Milky Way and Andromeda dwarf galaxies are too bright for their expected sub-halos, if those sub-halos are made of non-interacting dark matter (ΛCDM).



Self-interacting dark matter (SIDM) will make sub-halo cores less dense, enabling larger dwarf galaxies.

$$\sigma(v_{\rm rms})/M \sim 0.5 - 50\ {\rm cm}^2\ {\rm g}^{-1}, \quad v_{\rm rms} \simeq 10 - 100\ {\rm km\ s}^{-1}$$

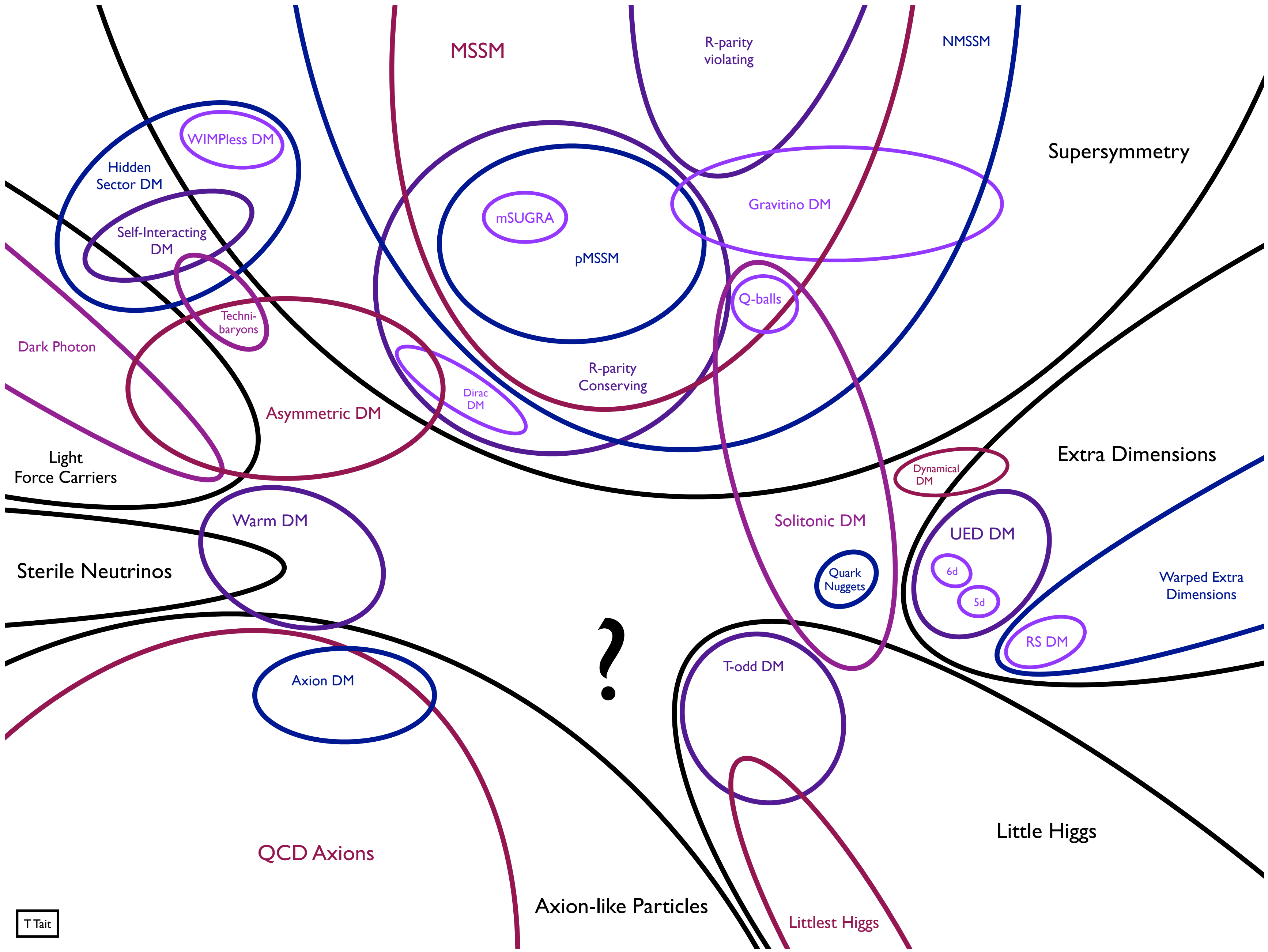
O. D. Elbert *et al.*, arXiv:1412.1477 [astro-ph.GA]

Self-Interacting Dark Matter

Strongly-Coupled Composite Dark Matter

interactions with SM particles that can evade current experimental constraints

View from Snowmass (I)



Snowmass 2013: The Cosmic Frontier **[arXiv:1401.6085]**

Where is composite dark matter?

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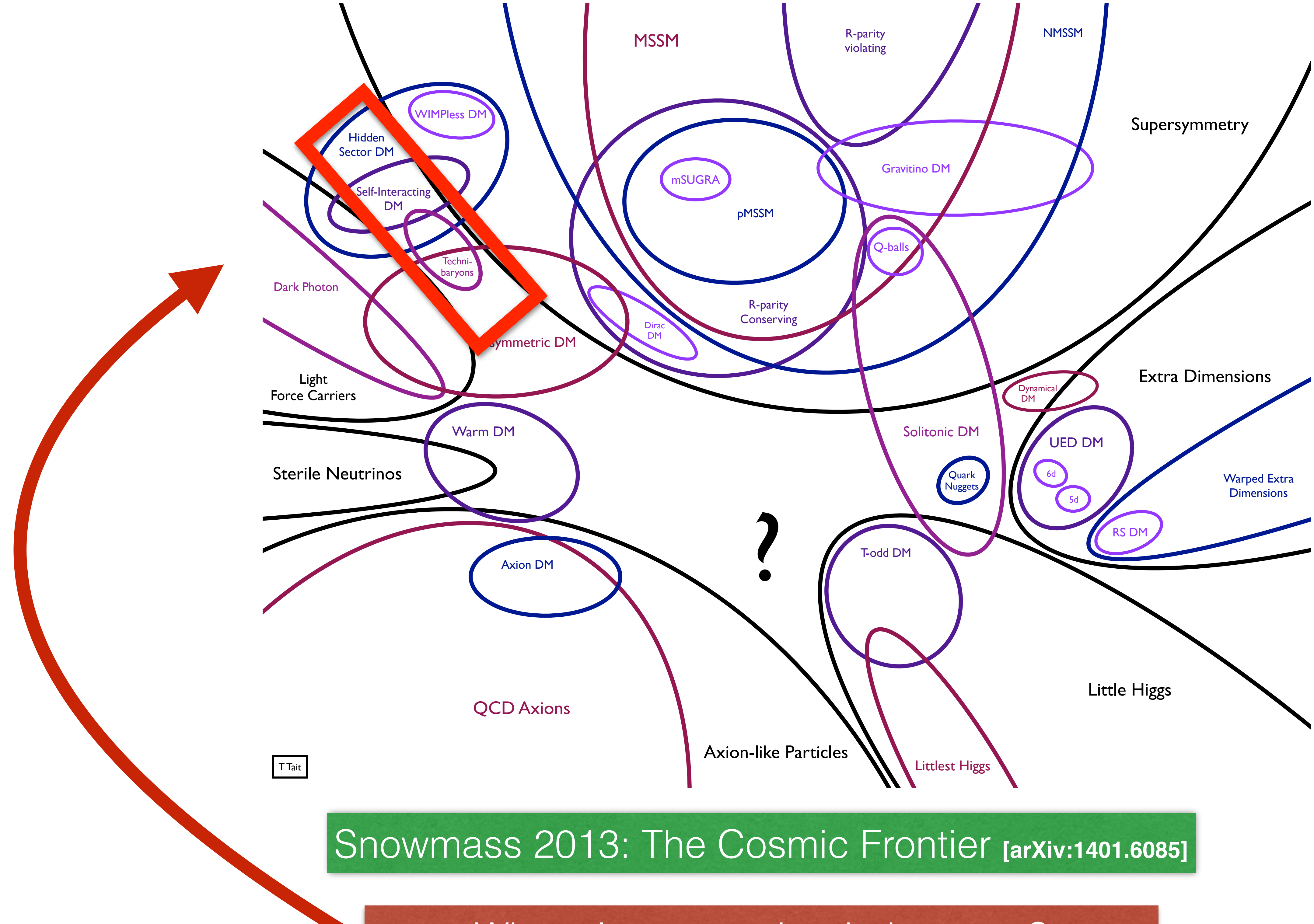

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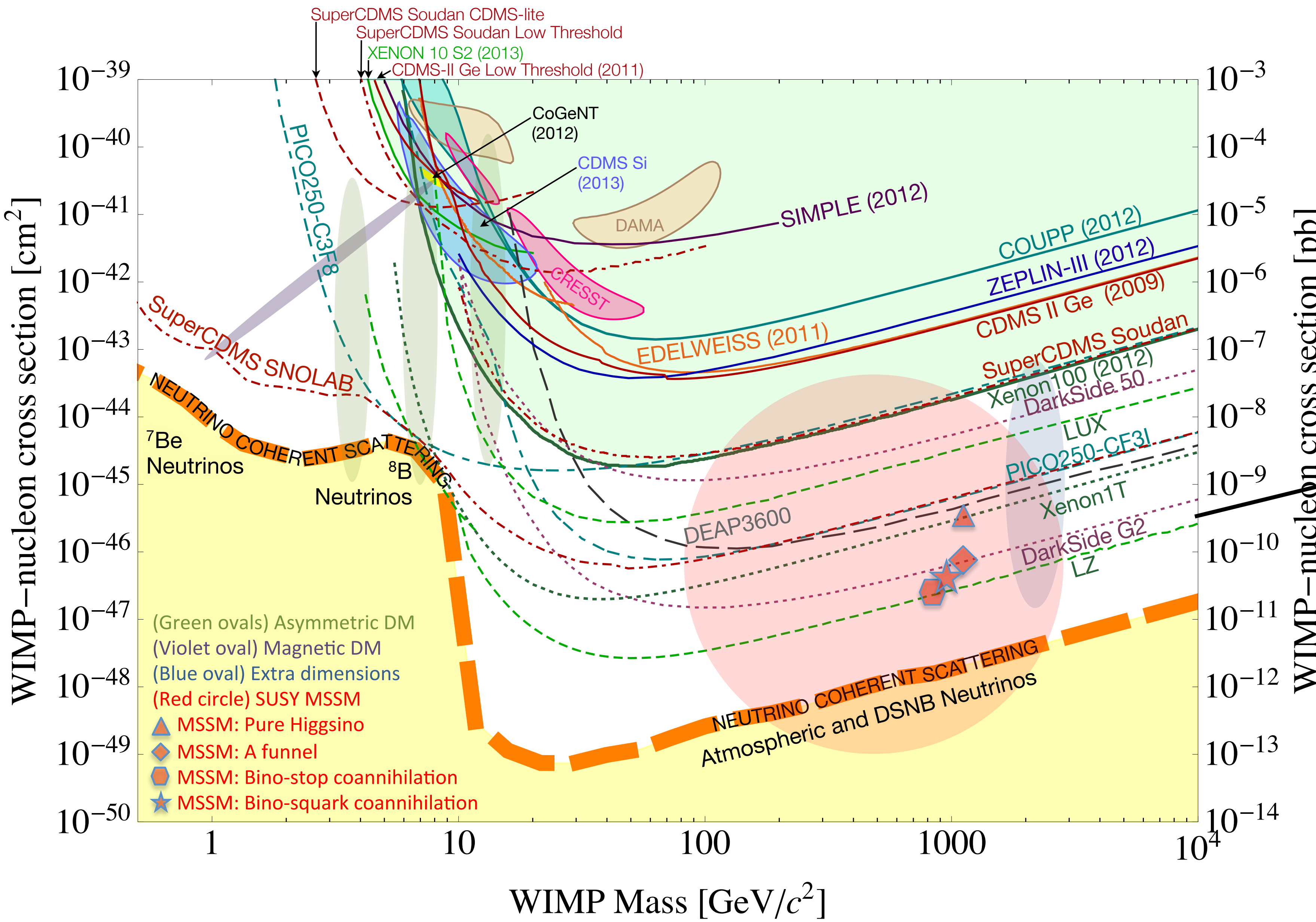
View from Snowmass (II)



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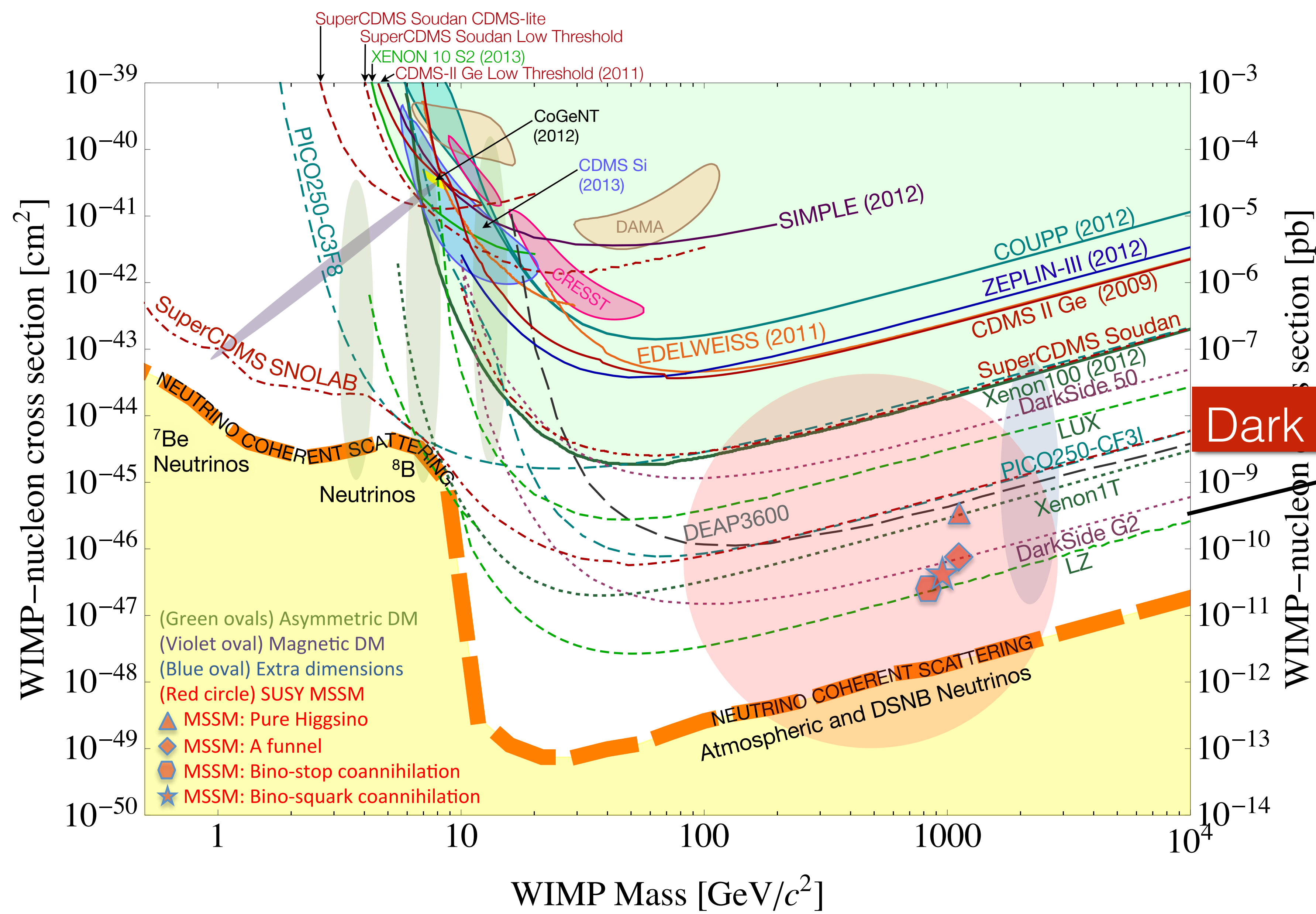

Dark SU(3) Baryon

Partial wave unitarity?

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Strongly-coupled composite dark matter

- Dark matter is a composite object
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What do we have in mind?

- In general we think about a new strongly-coupled gauge sector like QCD with a plethora of composite states in the spectrum
- Dark fermions have dark color and also have electroweak charges
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we construct a minimal model with these features

“How dark is Dark Matter?”

Interactions of neutral object with **photons + Higgs**

- dimension 4 ➥ Higgs exchange
- dimension 5 ➥ magnetic dipole $$\frac{(\bar{\chi}\sigma^{\mu\nu}\chi)F_{\mu\nu}}{\Lambda_{\rm dark}}$$
- dimension 6 ➥ charge radius $$\frac{(\bar{\chi}\chi)v_\mu\partial_\nu F^{\mu\nu}}{\Lambda^2_{\rm dark}}$$
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Coupling Dark Baryons to SM

	$\psi\ \sigma$ Mag. Moment dim. 5	$(\psi\psi)$ Charge Radius dim. 6	$(\psi\psi)\ F$ Polarizability dim. 7
Odd N No Flavor Sym.	✔	✔	✔
Odd N Flavor Sym			✔
Even N No Flavor Sym.		✔	✔
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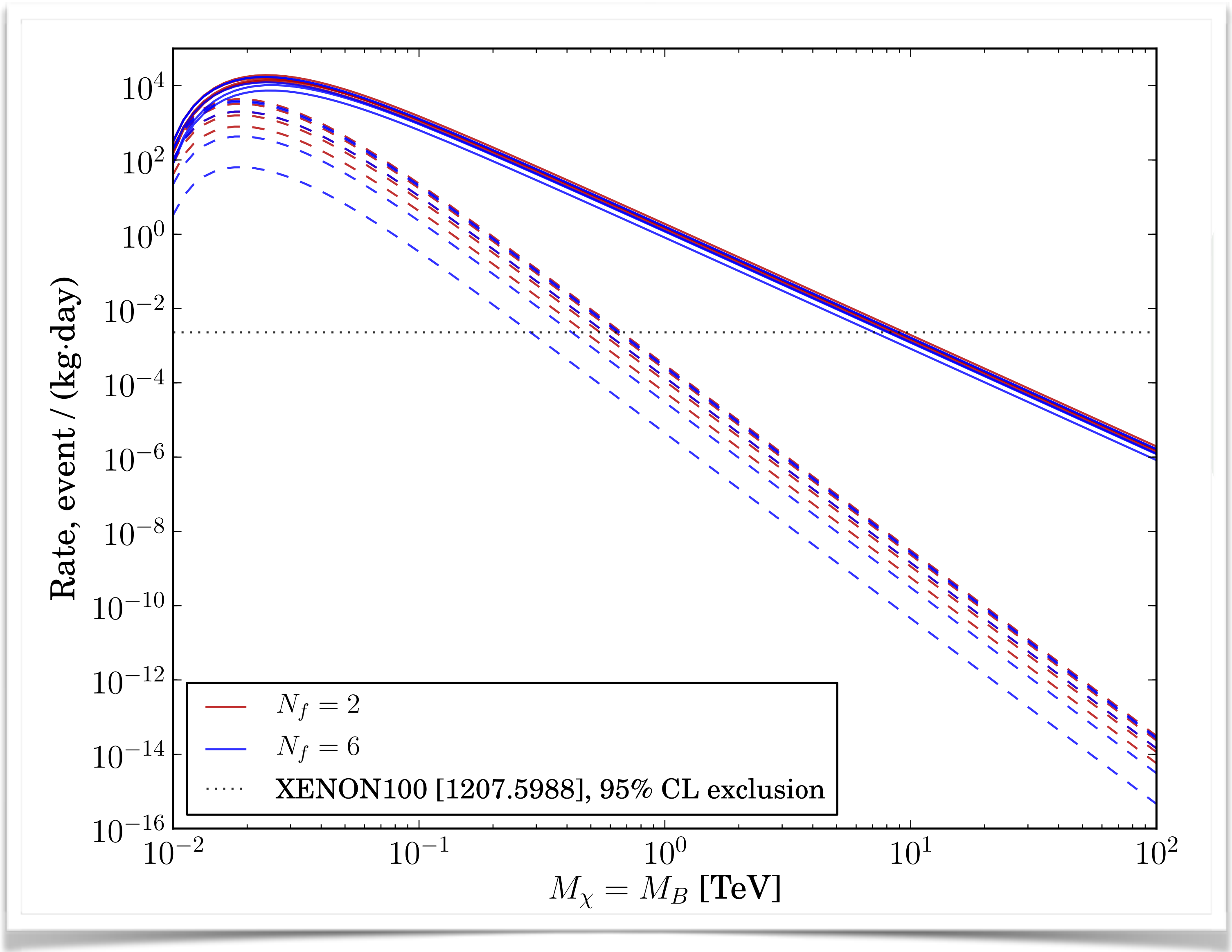
[LSD collab., Phys. Rev. D88 (2013) 014502]

Magnetic moment and charge radius of DM

SU(3) model: DM is neutral baryon with spin 1/2

- Need non-perturbative calculation of form-factors for DM composite object
- Negligible dependence on constituent mass and number of flavors
- Magnetic moment dominates for masses > 25GeV



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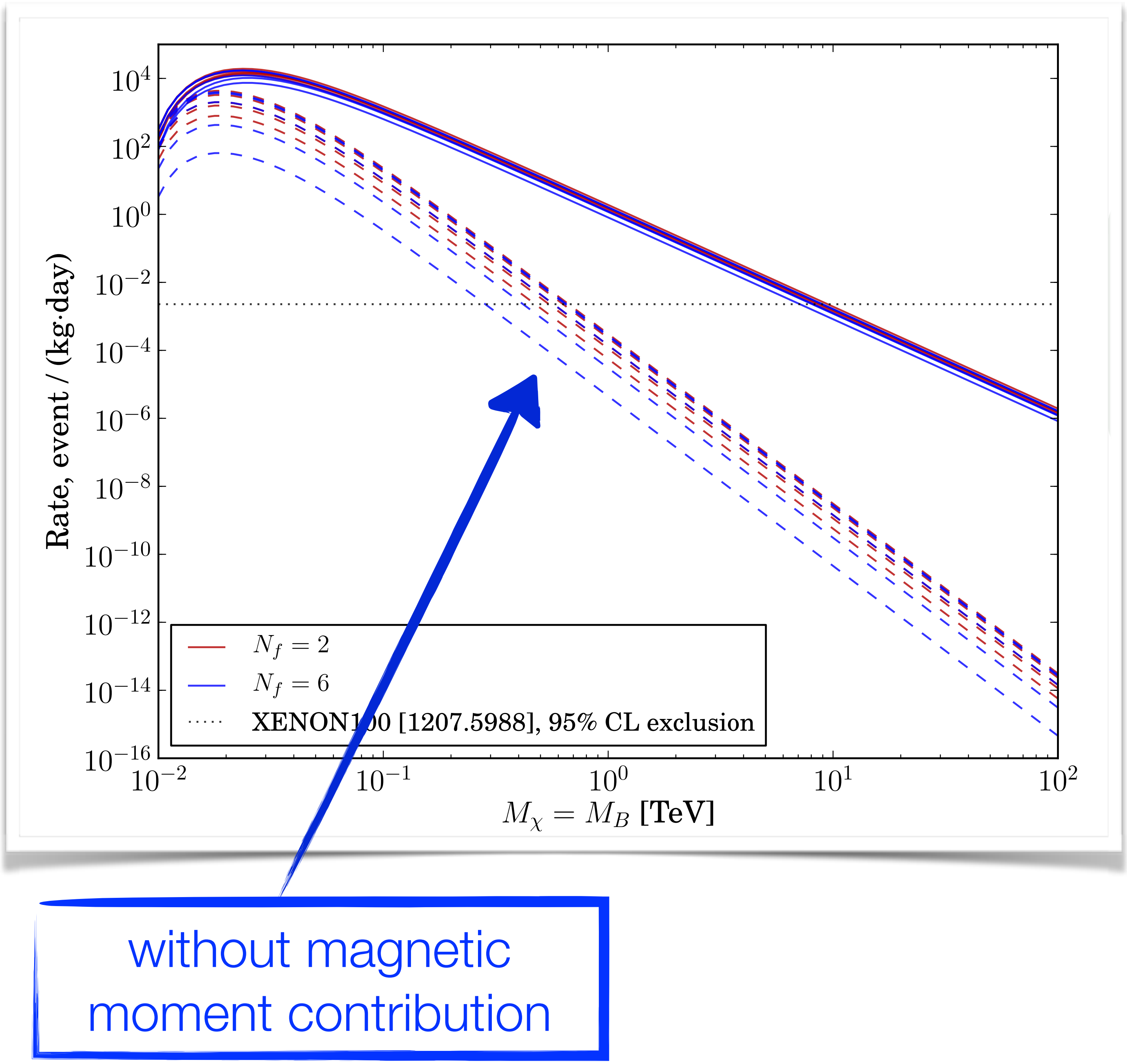

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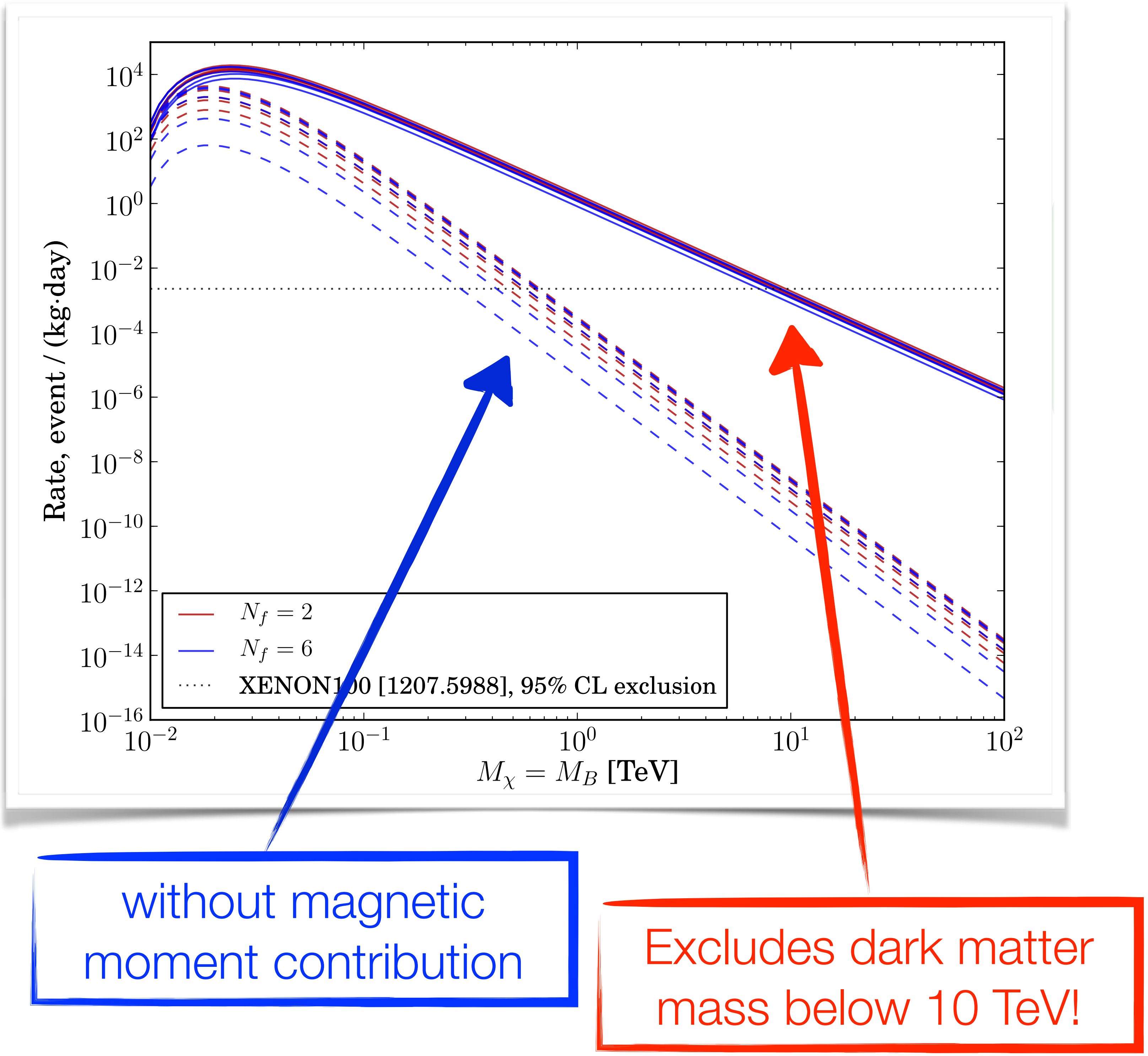

[LSD collab., in preparation]

"Stealth Dark Matter" model

- Let's focus on a SU(N) dark gauge sector with N=4
- Let dark fermions interact with the SM Higgs and obtain current/chiral masses
- Let's introduce vector-like masses for dark fermions that do not break EW symmetry

Field	$\mathrm{SU}(N)_D$	$(\mathrm{SU}(2)_L, Y)$	Q
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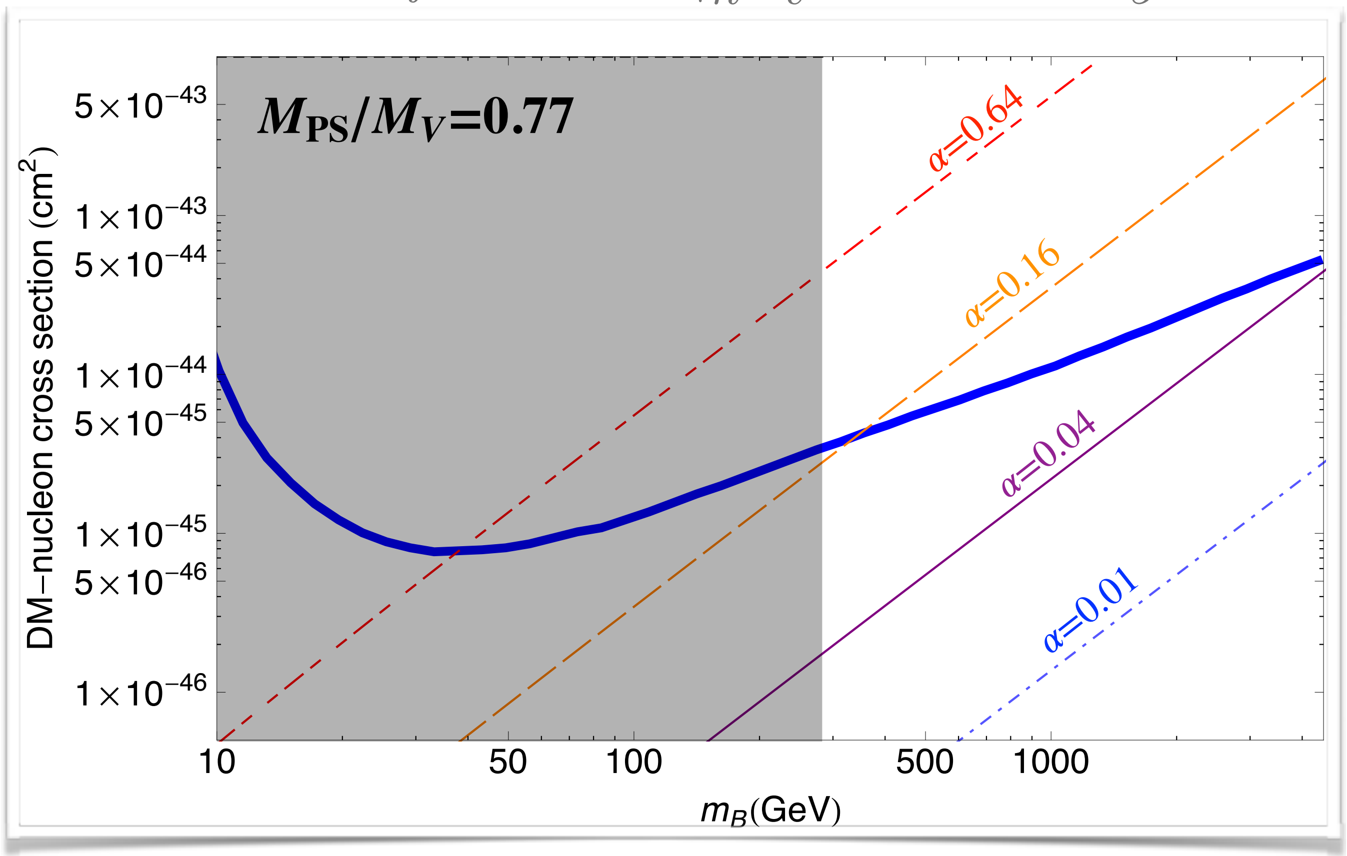
[LSD collab., Phys. Rev. D89 (2014) 094508]

Higgs exchange cross section in Stealth DM

- Need to non-perturbatively evaluate the σ-term of the dark baryon (scalar nuclear form factor)
- Effective Higgs coupling non-trivial with mixed chiral and vector-like masses
- *Model-dependent answer for the cross-section in this channels*
- A non-negligible vector mass is needed to evade direct detection bounds

$$m_f(h) = m + \frac{yh}{\sqrt{2}}$$

$$\alpha \equiv \frac{v}{m_f} \frac{\partial m_f(h)}{\partial h}\bigg|_{h=v} = \frac{yv}{\sqrt{2}m + yv} \leq 1$$



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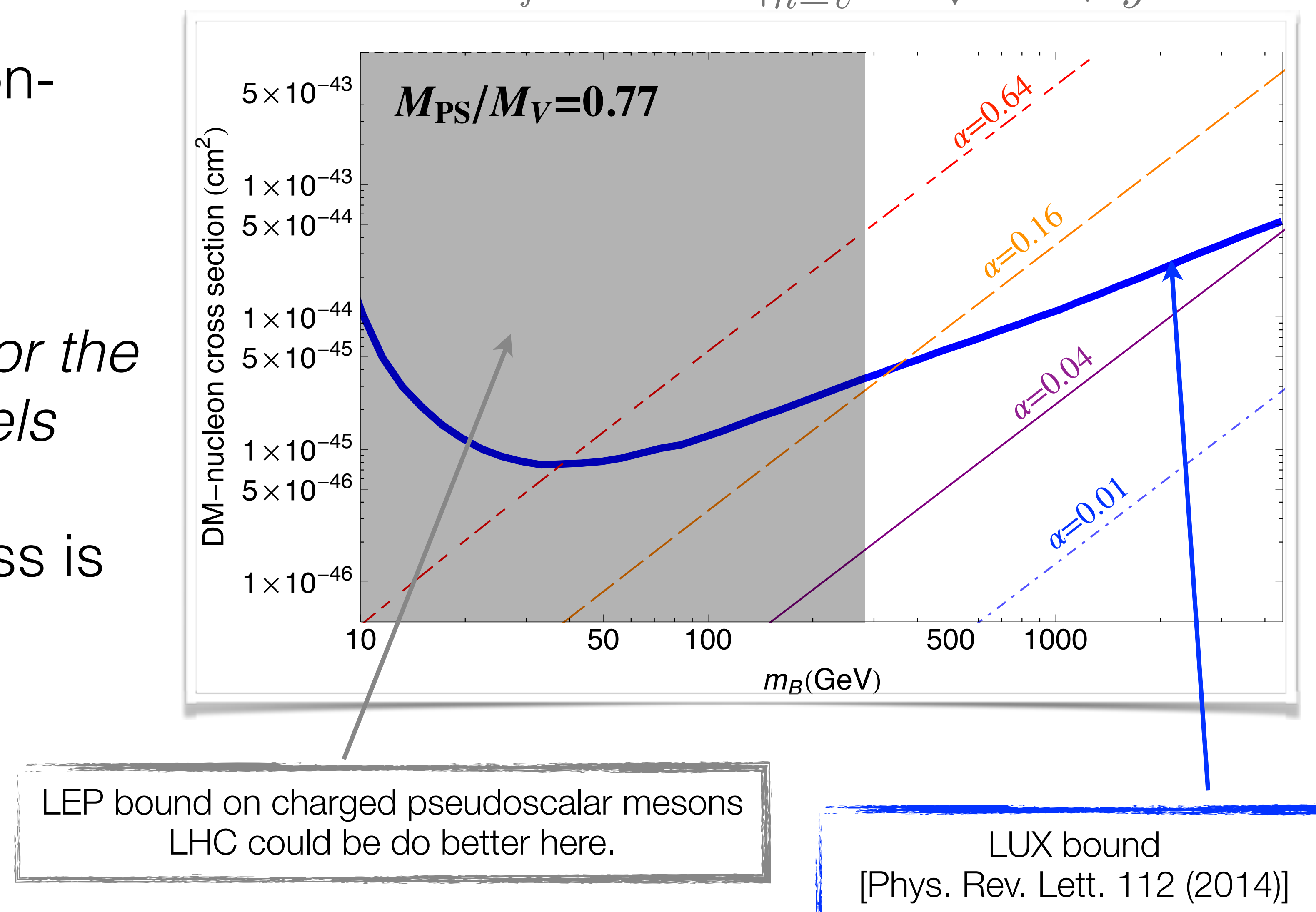
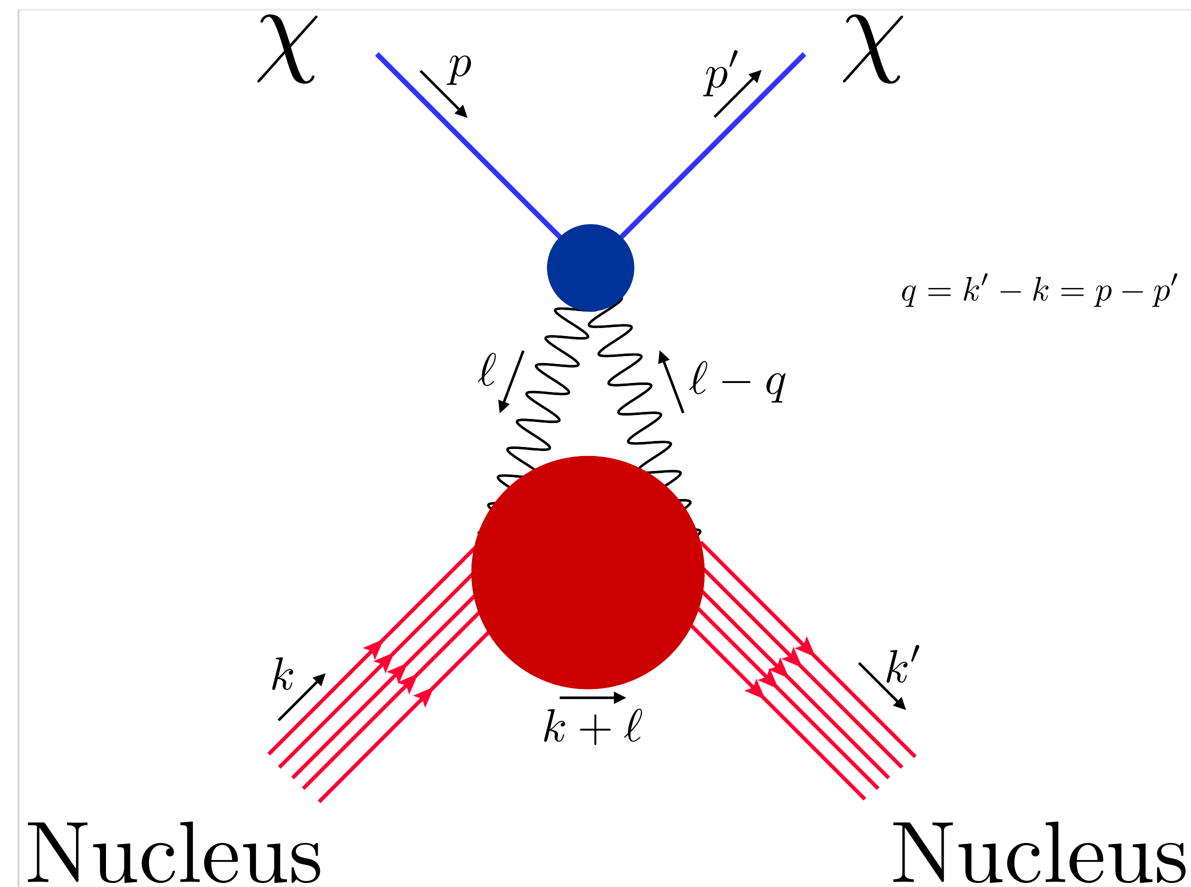


Electromagnetic polarizability

- remove magnetic dipole moment:
    - lightest stable baryon is a boson with S=0
- remove charge radius:
    - 2 flavors with degenerate masses $m_u = m_d$
- polarizability can not be removed



$$\mathcal{O}_F^\chi = \mathcal{C}_F^\chi \, \bar{\chi}\chi F^{\mu\nu} F_{\mu\nu}$$

Electromagnetic polarizability

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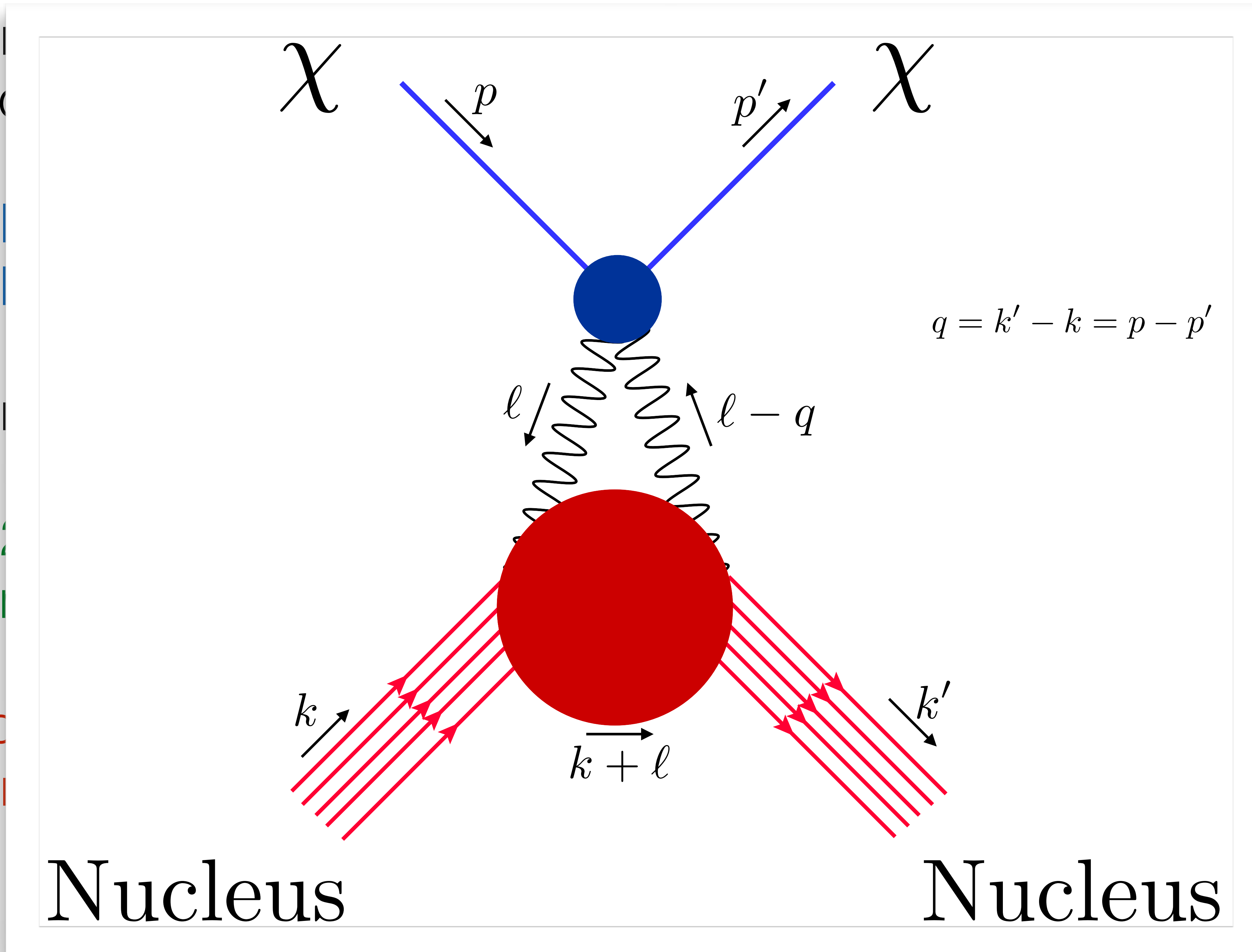

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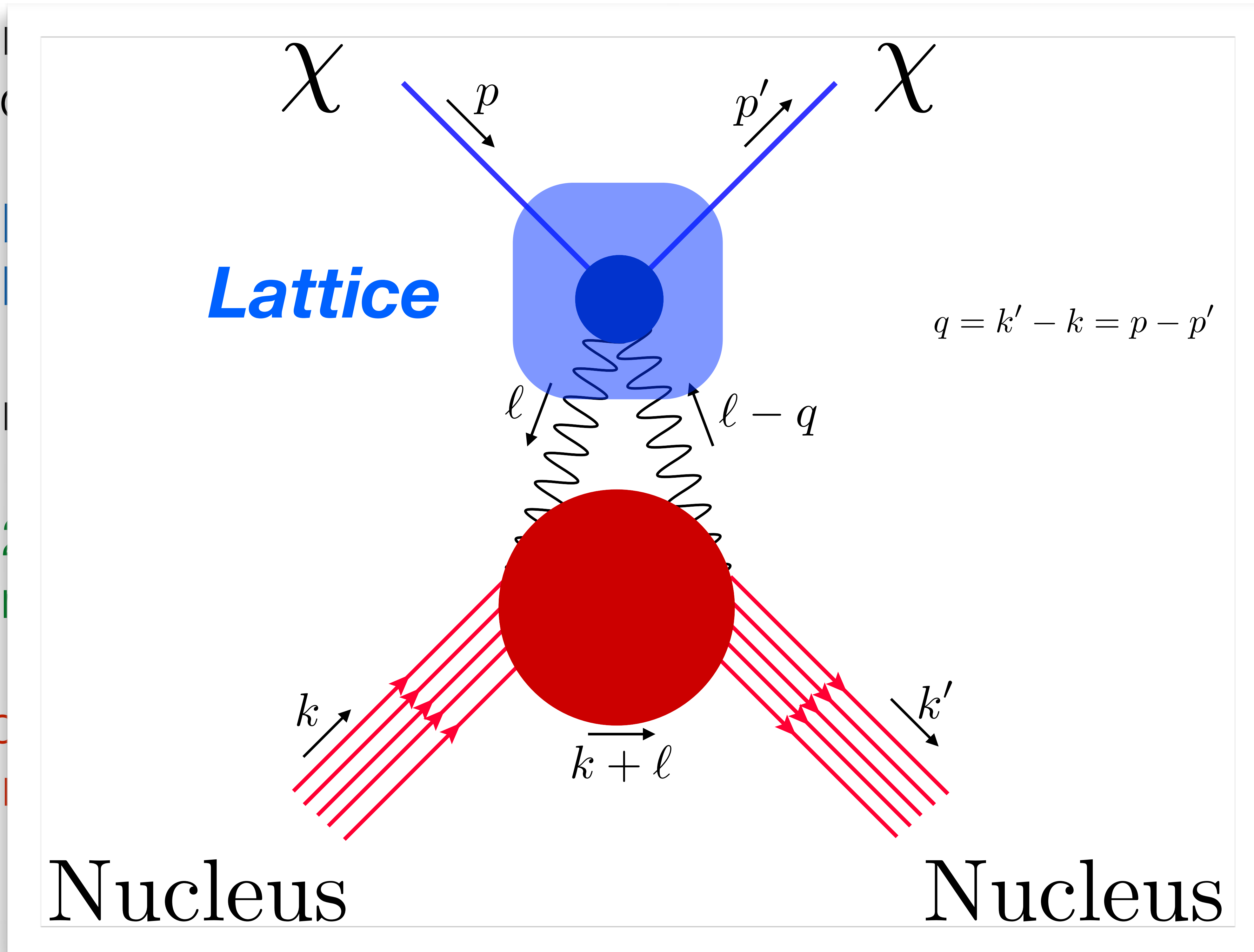

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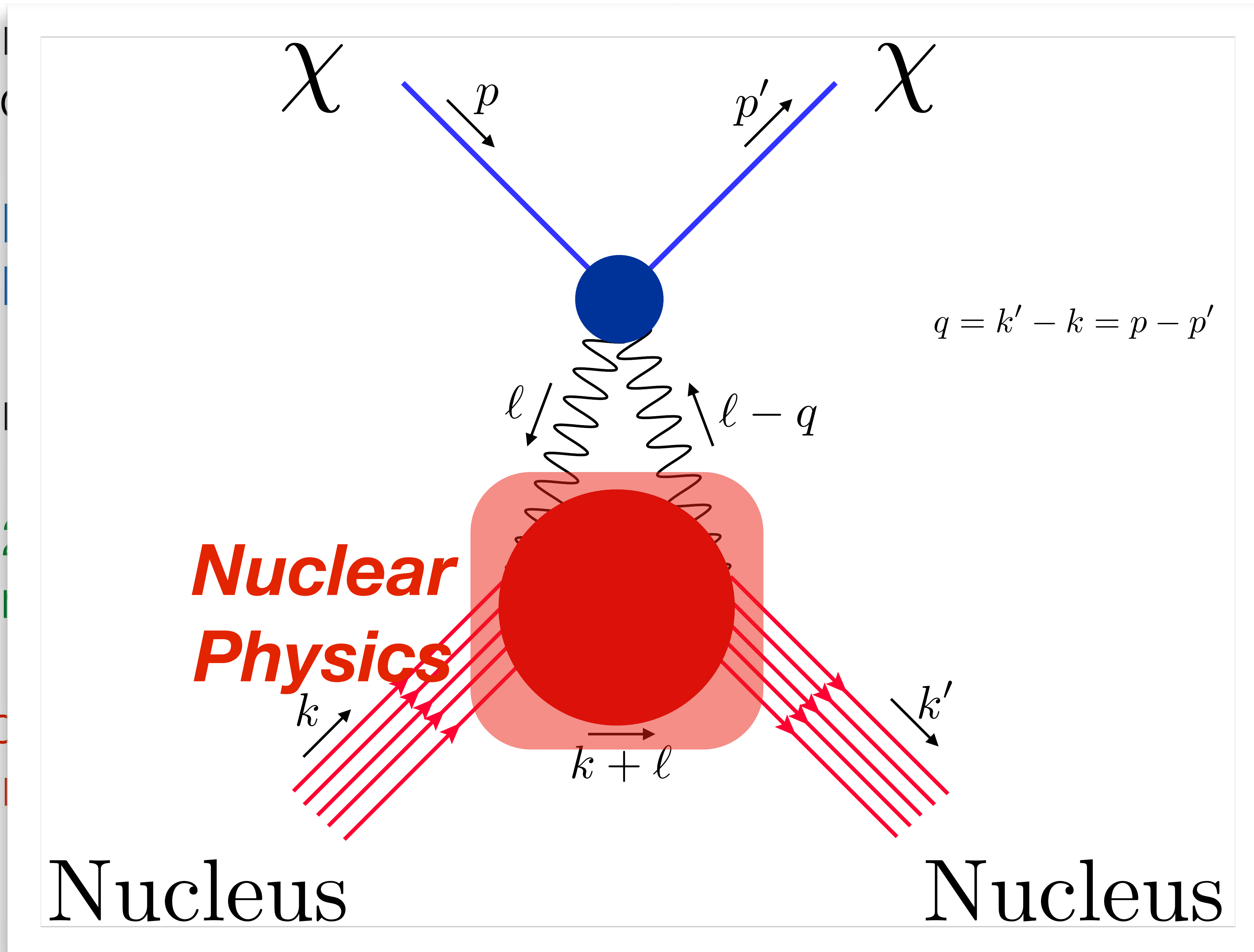

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- controlla… …provement

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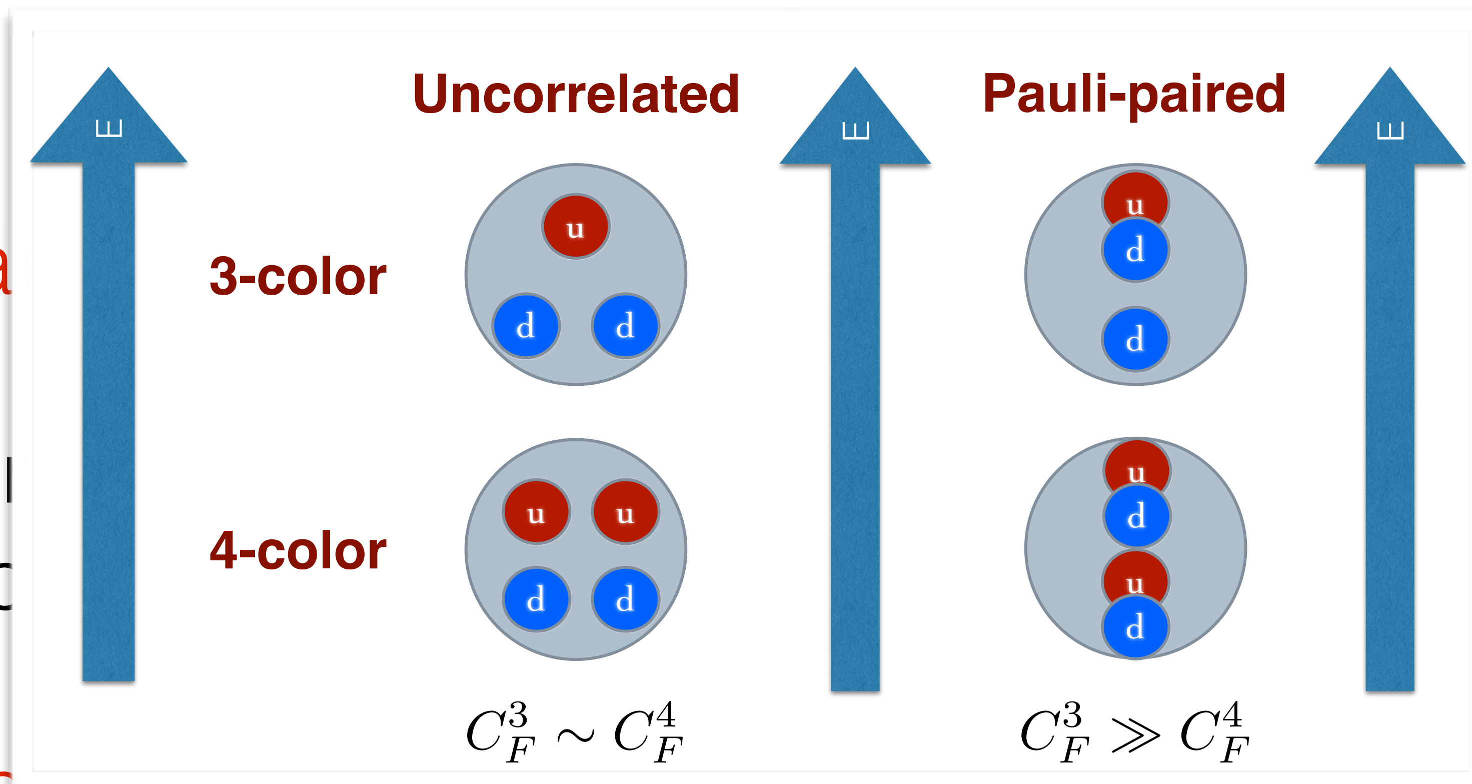

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[Detmold, Tiburzi & Walker-Loud, Phys. Rev. D79 (2009) 094505
and Phys. Rev. D81 (2010) 054502]
[LSD collab., in preparation]

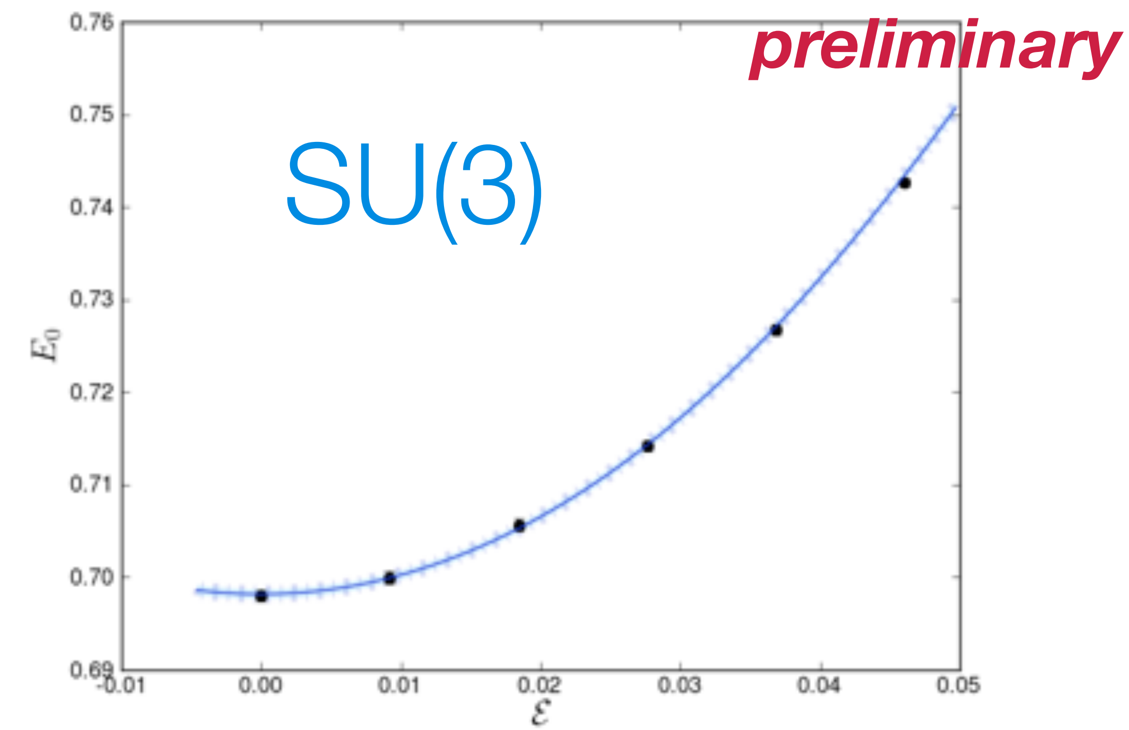
Lattice: Polarizability of DM

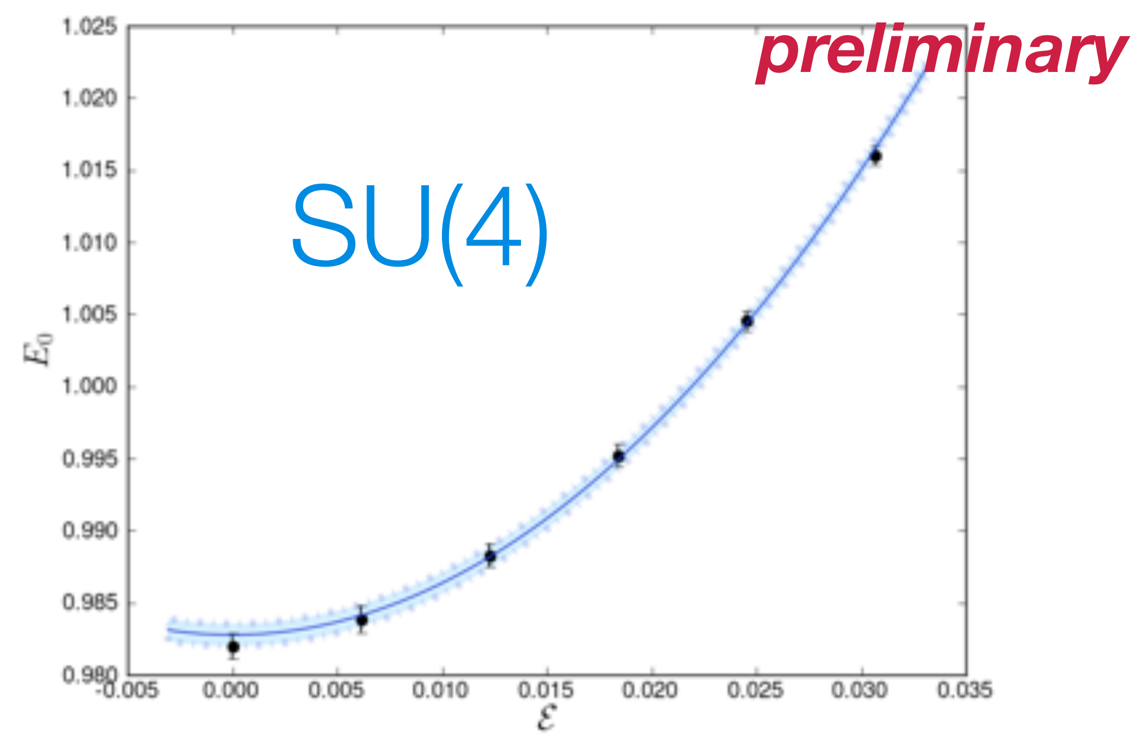
- Background field method: response of neutral baryon to external electric field $\mathcal{E}$
- Measure the shift of the baryon mass as a function of $\mathcal{E}$

$$E_{SU(3)} = M_\chi + \frac{1}{2}(\mathcal{C}_F^\chi + \frac{\mu^2}{4M_\chi^3})\mathcal{E}^2 + \text{h.o.}$$

$$E_{SU(4)} = M_\chi + \frac{1}{2}(\mathcal{C}_F^\chi)\mathcal{E}^2 + \text{h.o.}$$

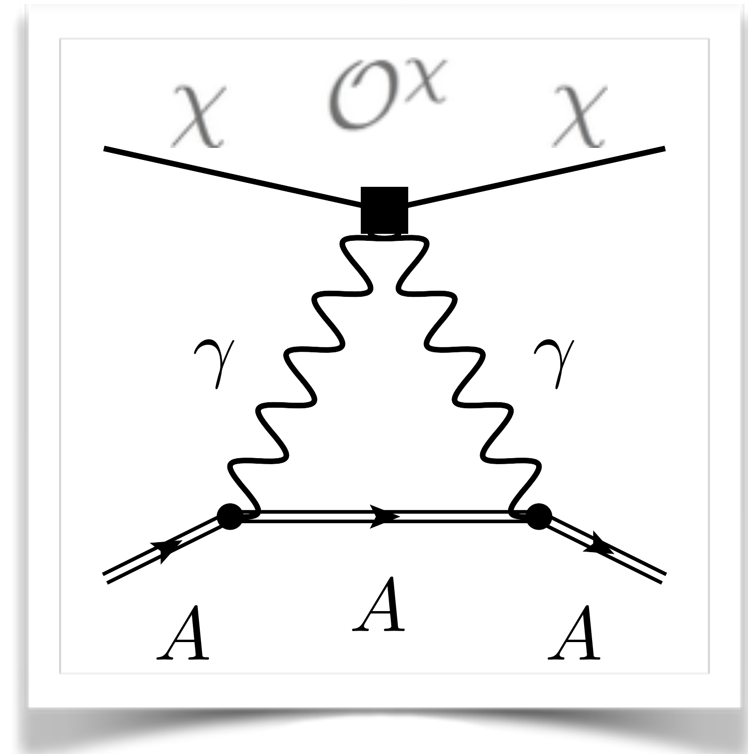
- Precise lattice results





Nuclear: Polarizability (Rayleigh scattering)

- several attempts to estimate this in the past, with increasing level of complexity in a perturbative setup
  [Pospelov & Veldhuis, Phys. Lett. B480 (2000) 181]
  [Weiner & Yavin, Phys. Rev. D86 (2012) 075021]
  [Frandsen et al., JCAP 1210 (2012) 033]
  [Ovanesyan & Vecchi, arxiv:1410.0601]



- multiple scales are probed by the momentum transfer in the virtual photons loop

- mixing operators and threshold corrections appear at leading order and interference is possible

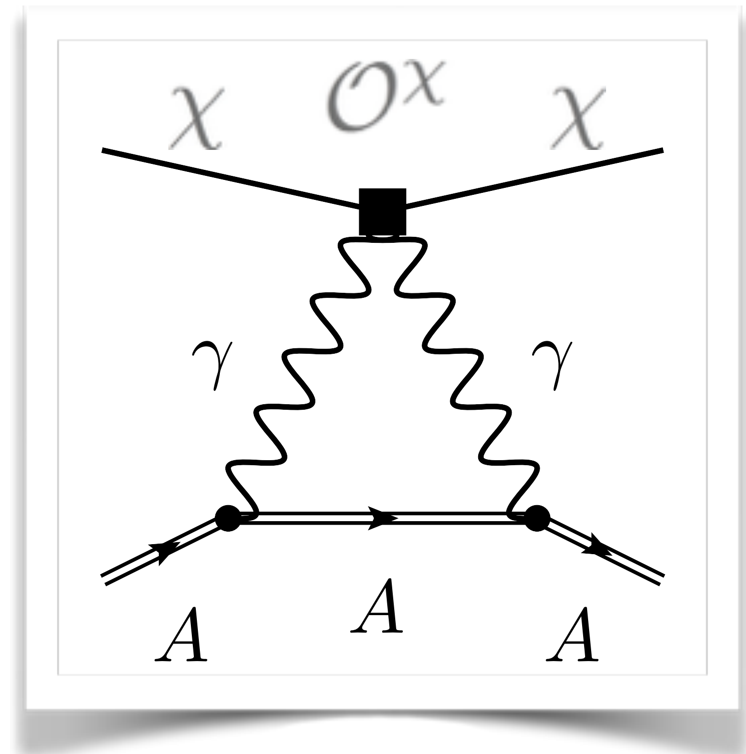
$$\langle A|\bar{\chi}\chi F^{\mu\nu}F_{\mu\nu}|A\rangle$$

- nuclear matrix element has non-trivial excited state structure that requires non-perturbative treatment

similar structure arising in double beta decay matrix elements

NDA for $\langle A|\bar{\chi}\chi F^{\mu\nu}F_{\mu\nu}|A\rangle$

- it is hard to extract the momentum dependence of this nuclear form factor
- similarities with the double-beta decay nuclear matrix element could suggest large uncertainties ~ $\mathcal{O}(5)$
- to asses the impact of uncertainties on the total cross section we start from naive dimensional analysis
- we allow a "magnitude" factor M_F^A to change from 0.3 to 3



$$f_F^A = \langle A|F^{\mu\nu}F_{\mu\nu}|A\rangle$$

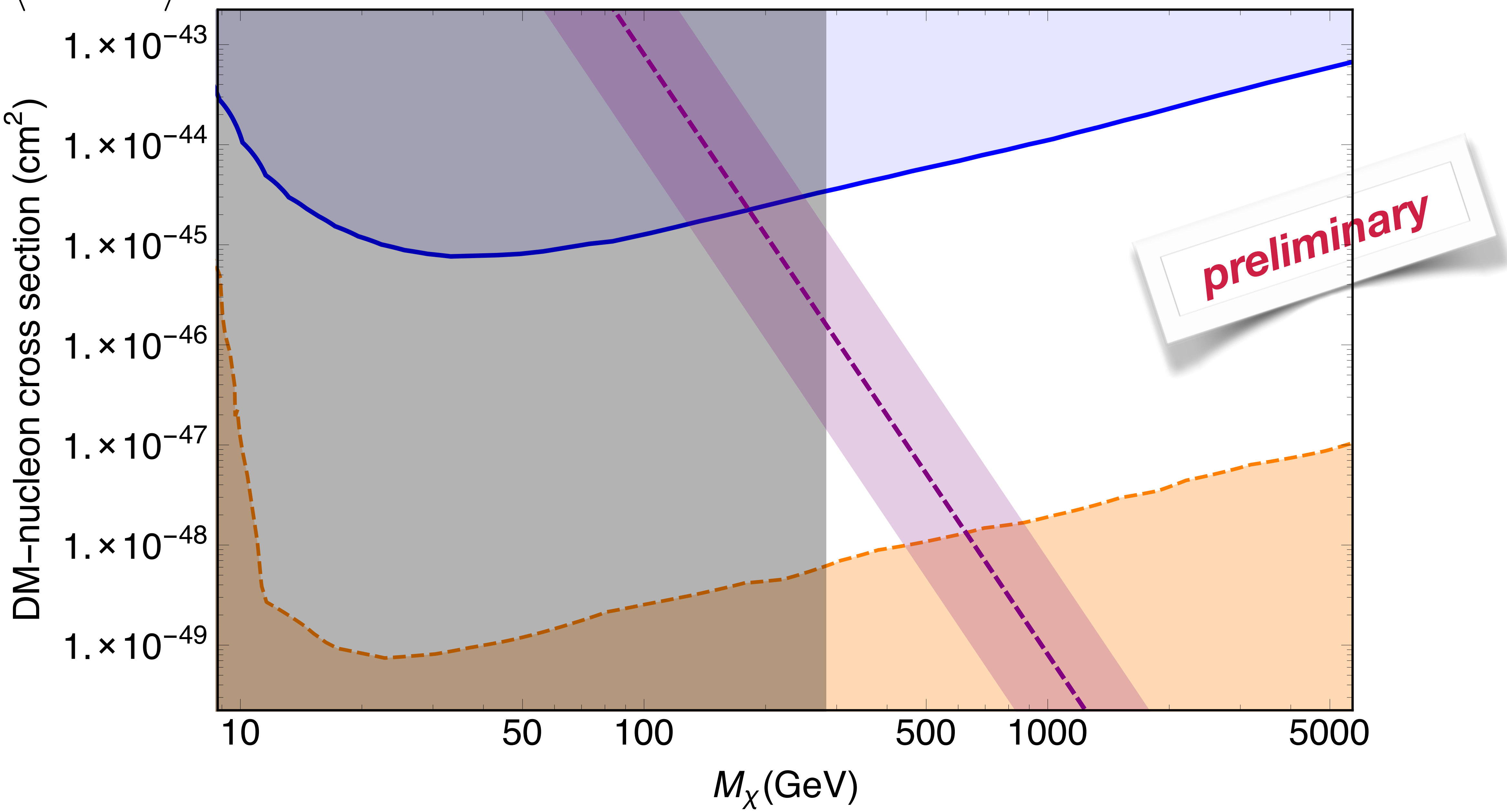
$$f_F^A \sim 3\,Z^2\,\alpha\,\frac{M_F^A}{R}$$

$$\sigma \simeq \frac{\mu_{n\chi}^2}{\pi A^2}\left\langle |C_F f_F^A|^2 \right\rangle$$

[LSD collab., in preparation]

Stealth DM Polarizability

$$\sigma \simeq \frac{\mu_{n\chi}^2}{\pi A^2}\left\langle |C_F f_F^A|^2 \right\rangle$$



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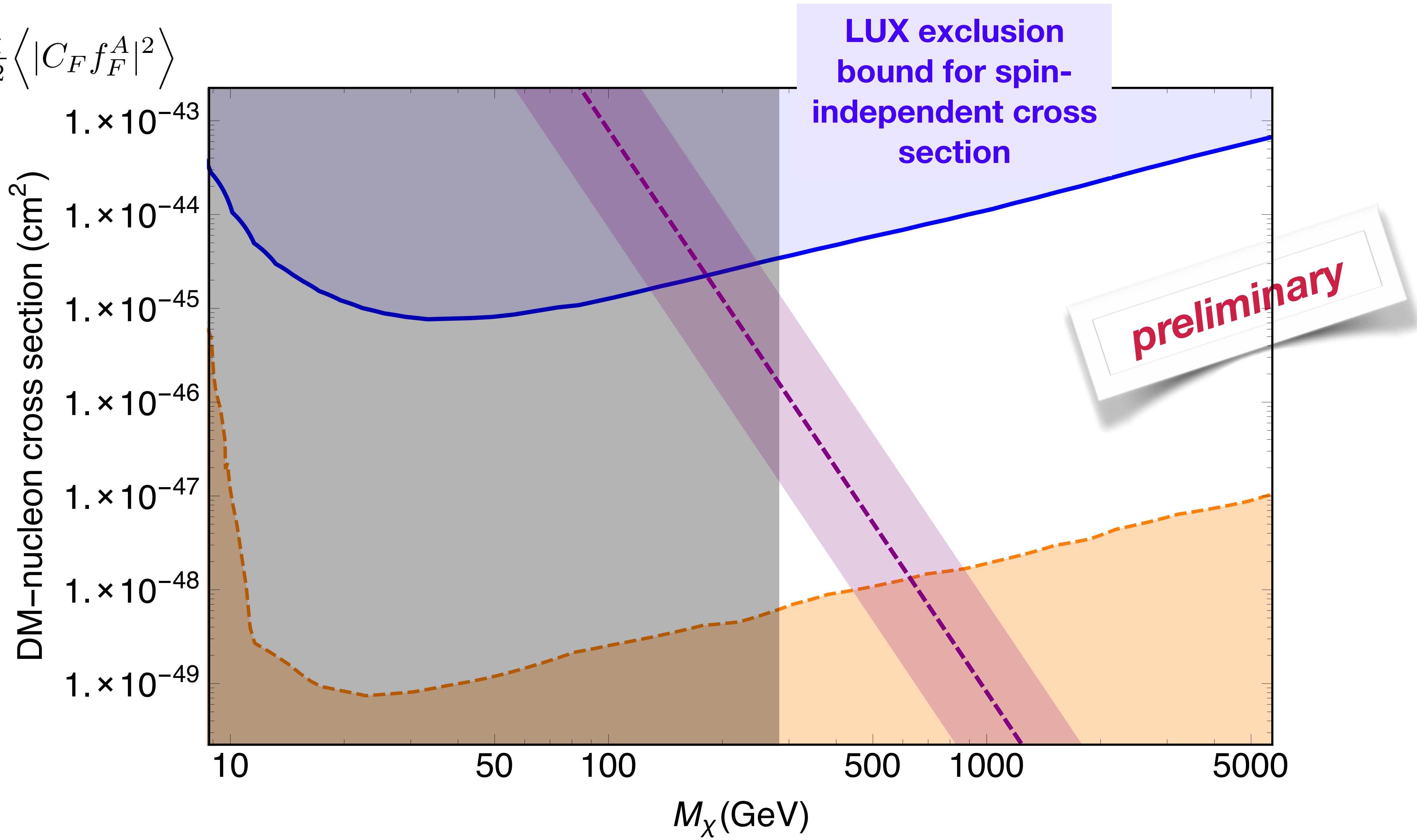

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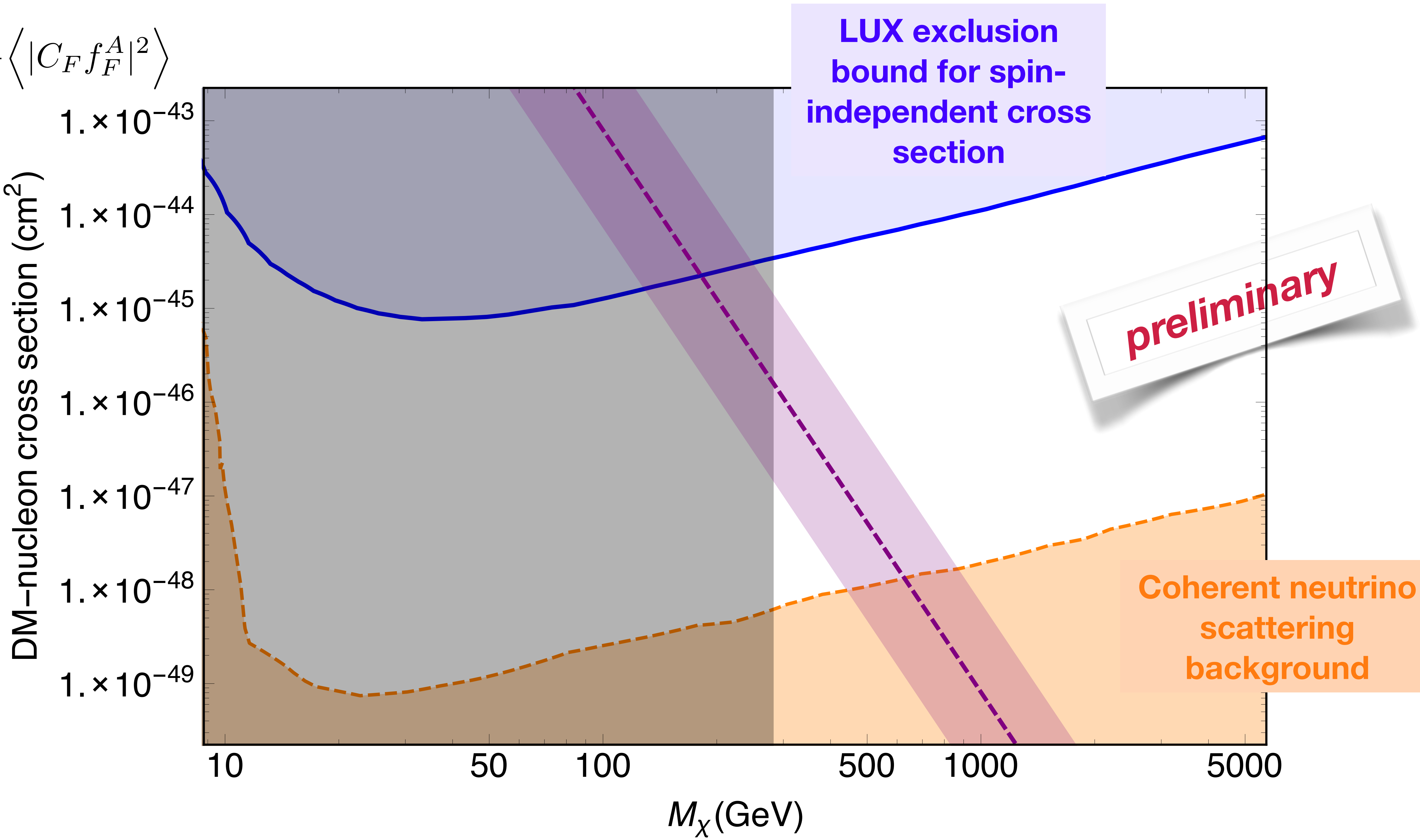

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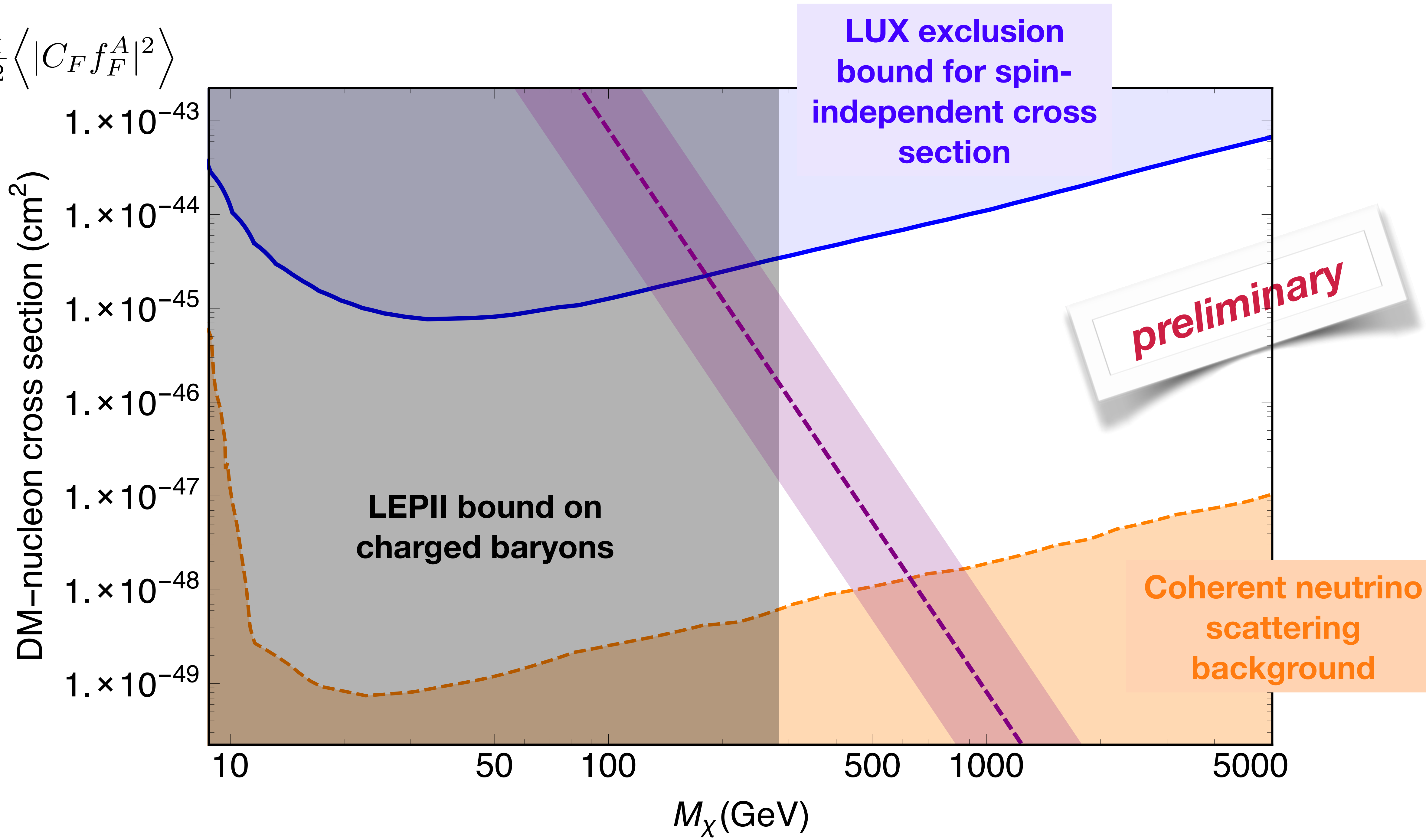

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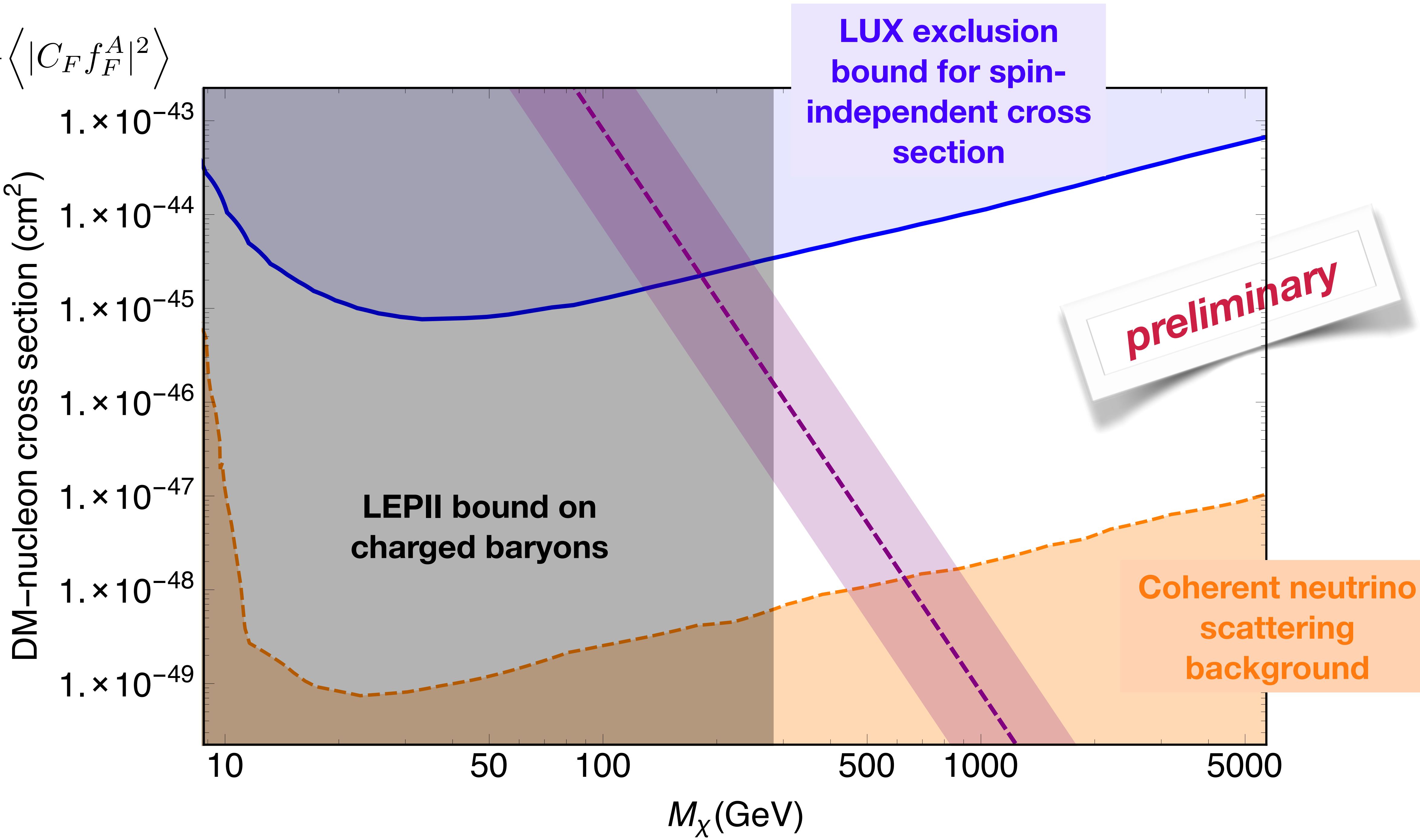
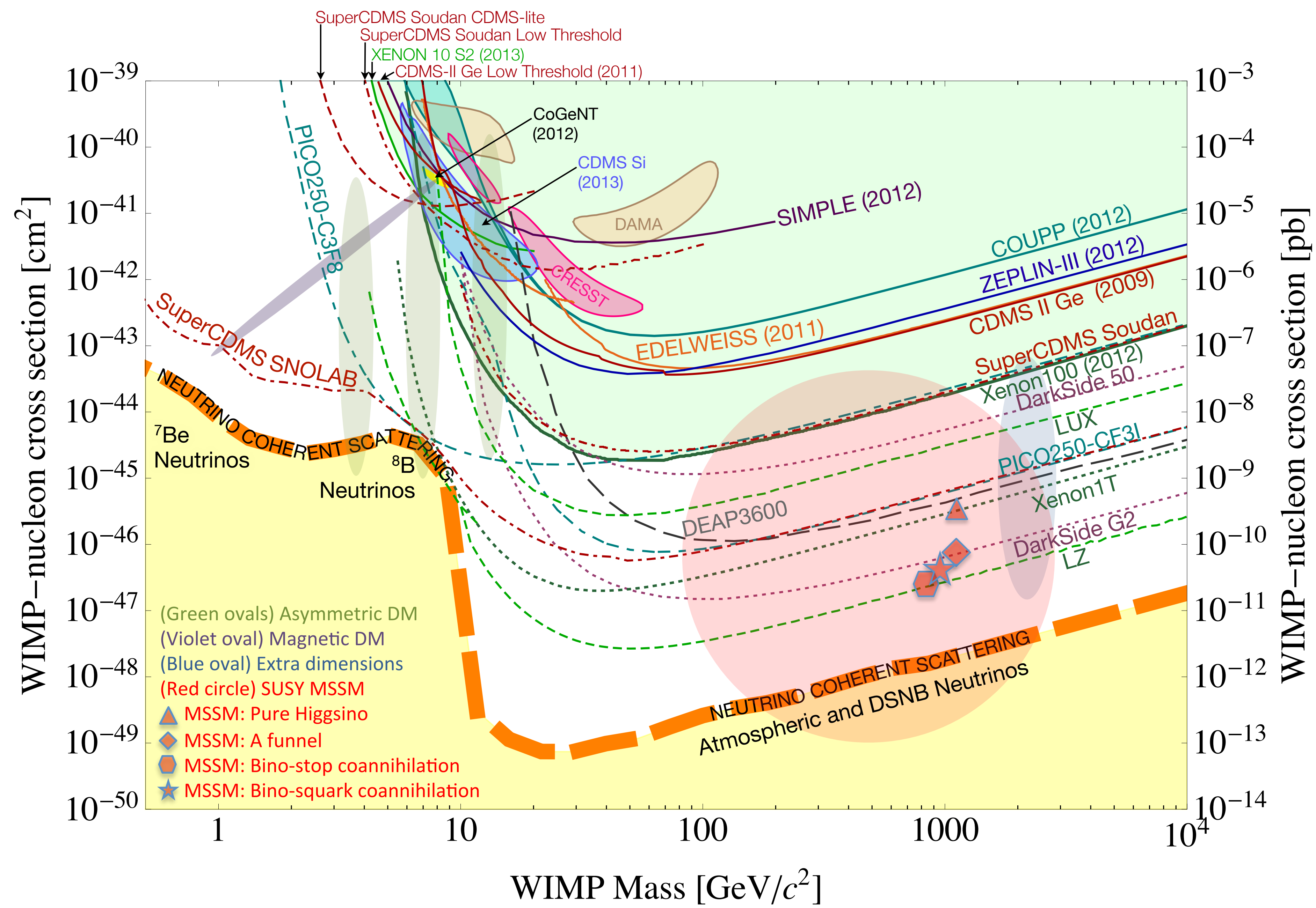


lowest allowed direct detection cross-section for composite dark matter theories with EW charged constituents

Stealth DM Polarizability



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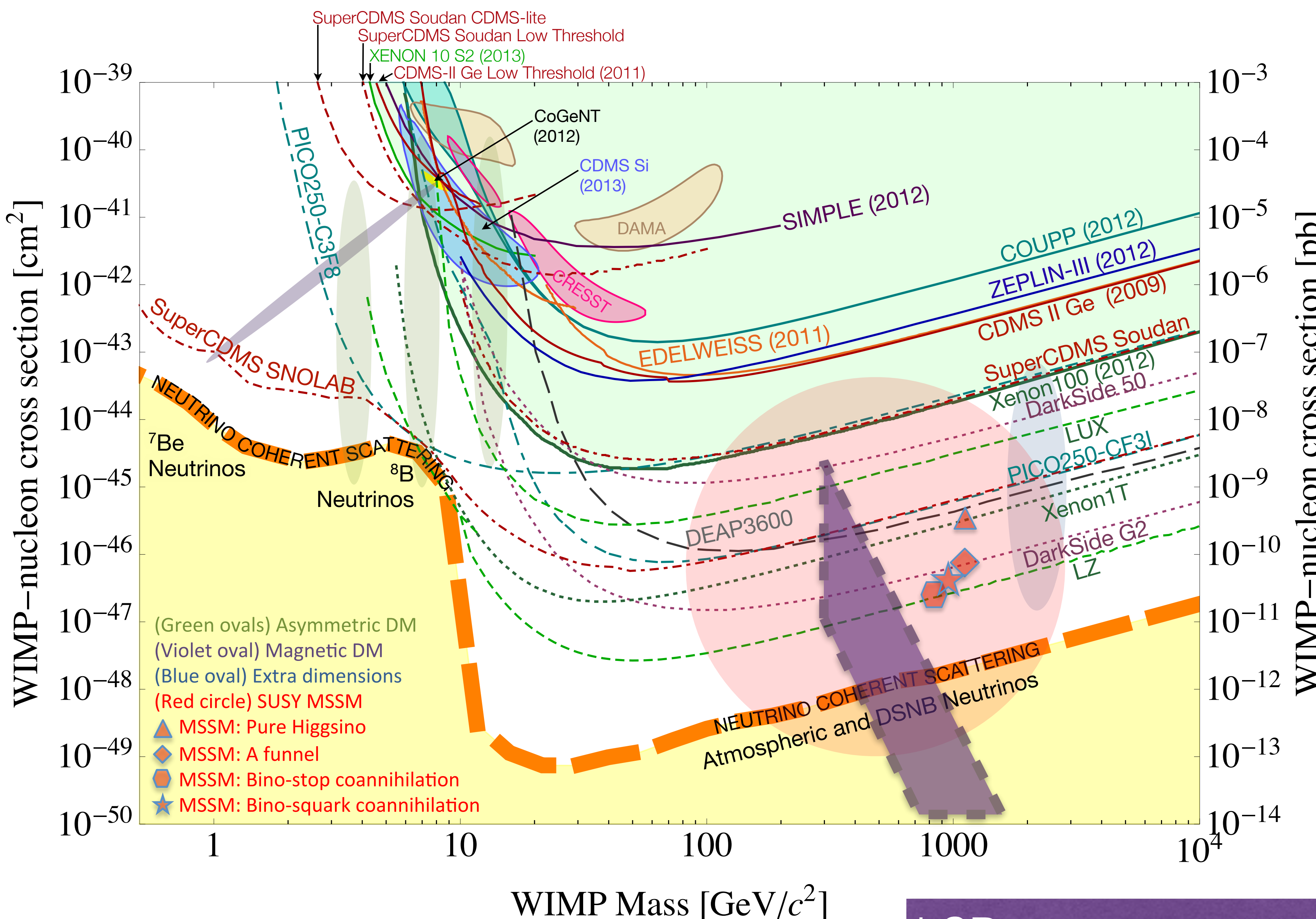
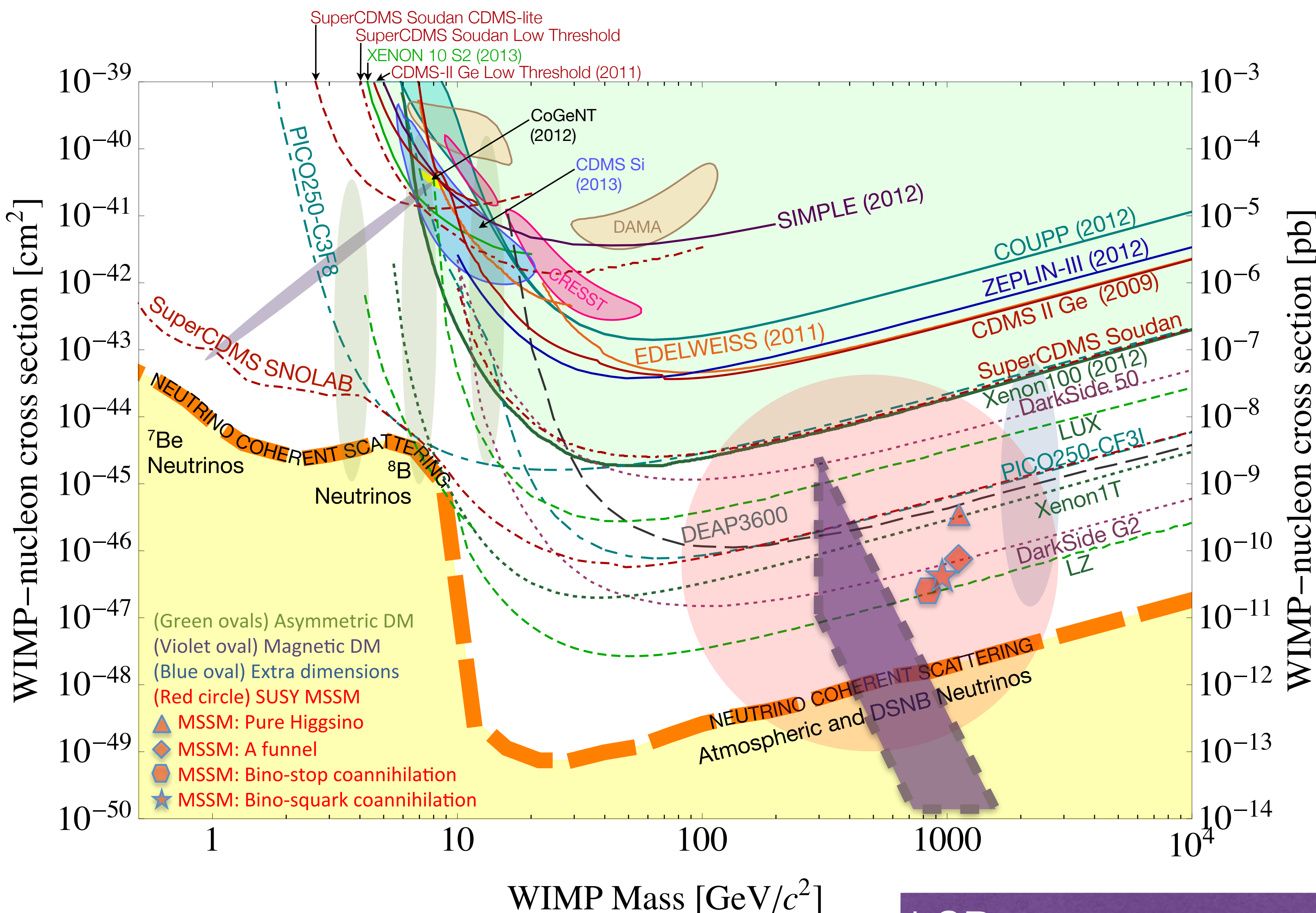


LSD paper to appear next week.

Stealth DM Polarizability



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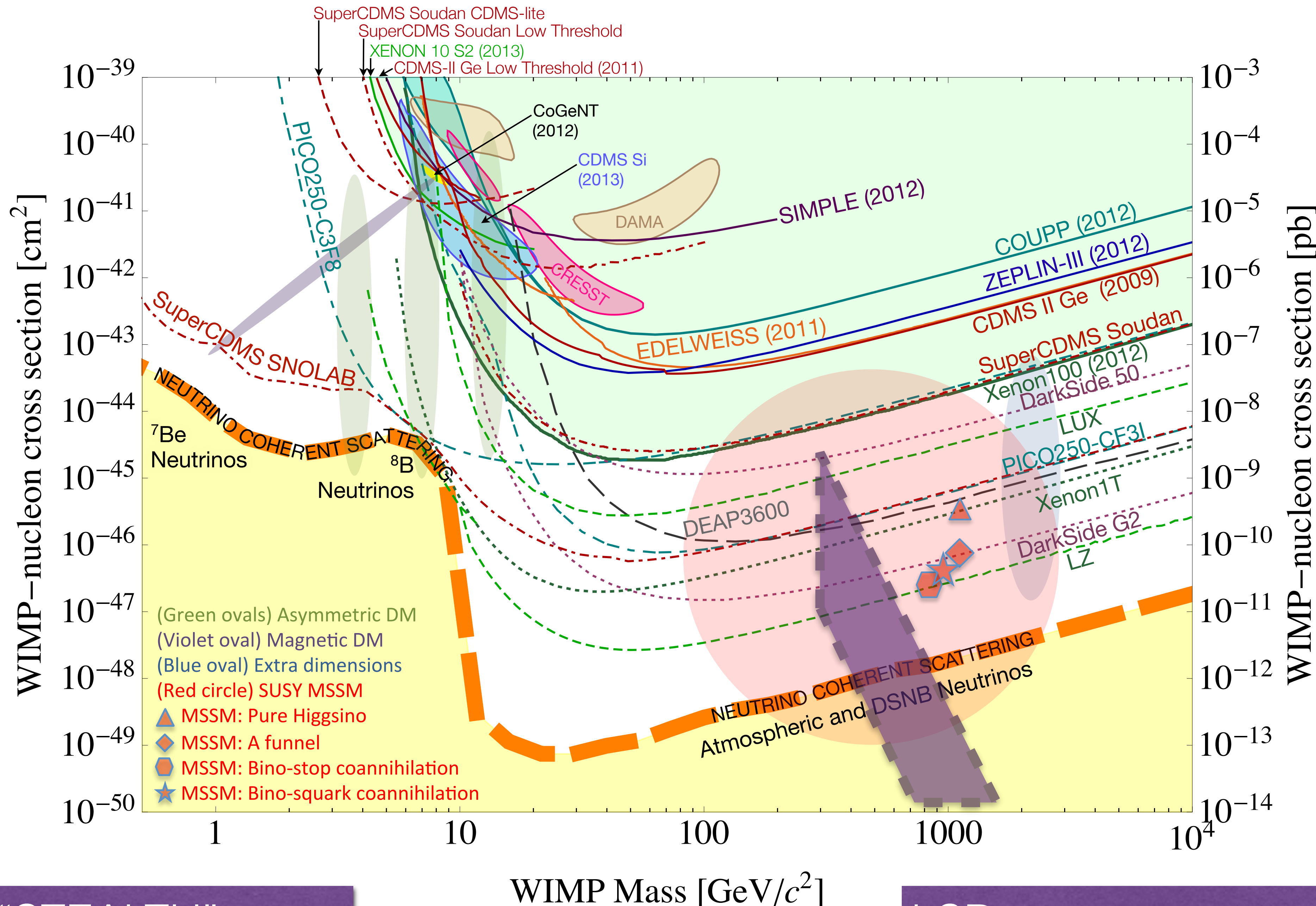
Direct detection signal is below the neutrino coherent scattering background for M_B>1TeV

Stealth DM Polarizability



Reason for "STEALTH" name

LSD paper to appear next week.

Direct detection signal is below the neutrino coherent scattering background for M_B>1TeV

Concluding remarks

- BSM physics has many opportunities for composite particles, *e.g.* dark matter.
- Dark matter constituents can carry electroweak charges and still the stable composites are currently undetectable. Stealth!
- No new forces required beyond SU(N) confining dark color force.
- Abundance can arise either by symmetric thermal freeze-out or by asymmetric baryogenesis.
- Future experiments could eventually rule out dark baryons with mag moments.
- Composite dark matter around 1 GeV is still a challenge due to LEP bounds.
- We need to work harder to inform the broader DM community about our exciting results!

"A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it."

- Max Planck

Backup slides

A Composite "Miracle"(I)

$$\Omega_{\rm dm} h^2 = 0.1199(27) \simeq 3 \times 10^{-27} {\rm cm}^3 {\rm s}^{-1} \langle \sigma_{\rm A} v \rangle^{-1}$$

$$\langle \sigma_{\rm A} v \rangle \sim \frac{\alpha^2}{M_{\rm dm}^2} \sim \alpha^2 \left(\frac{100\ {\rm GeV}}{M_{\rm dm}} \right)^2 10^{-21} {\rm cm}^3 {\rm s}^{-1}$$

- For **M_{dm} ~ 100 GeV** and α ~ 0.01 can be a thermal relic, but such WIMPs are being ruled out by XENON100/LUX.
- Current bounds on composite fermion dark matter are M_{dm}>20 TeV [LSD Collab., Phys. Rev. D 88, 014502 (2013)].
- Analogous to **$N\bar{N}$** annihilation, α ~ 16 which would mean M_{dm} ~ 320 TeV. Not ruled out but not likely to be observed soon.
- But, by dialing up the quark masses, we can bring down α to make a thermal relic M_{dm} ~ 20 TeV.
- Challenge: quark mass dependence of **$N\bar{N}$** annihilation, incl. heavy quarks.
- Strongly-interacting DM also helps with "Too Big To Fail" problem.

S. Nussinov, Phys. Lett. B165 (1985) 55
S. Barr, R. S. Chivukula, and E. Farhi, Phys. Lett. B241 (1990) 387
D. B. Kaplan, Phys. Rev. Lett. 68 (1992) 741

Asymmetric dark matter

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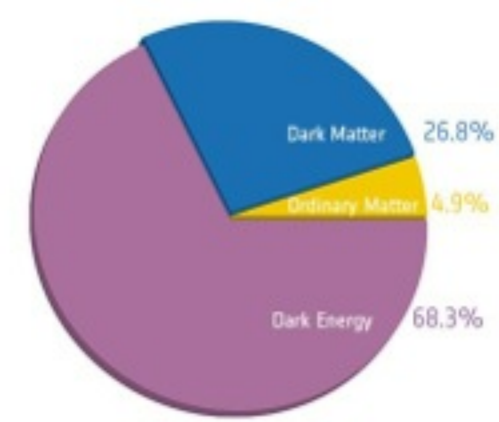
Asymmetric dark matter

- It is an observational fact that the number density for dark matter and baryonic matter are of the same order of magnitude

$$\Omega_{\rm DM} \approx 5\,\Omega_{\rm B}$$



[Planck and ESA]

S. Nussinov, Phys. Lett. B165 (1985) 55
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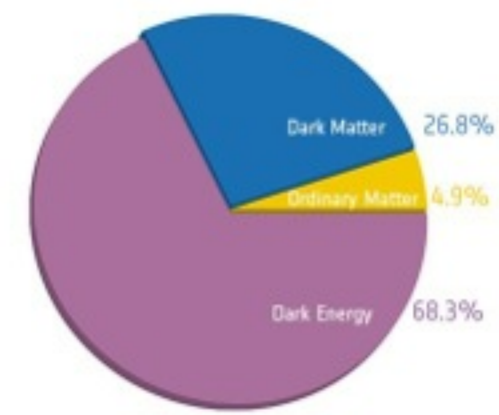

[Planck and ESA]

- This can be explained in Technicolor theories where dark matter is a baryon of a new strongly-coupled sector which shares an asymmetry with standard baryonic matter

$$n_{\mathrm{DM}} - \bar{n}_{\mathrm{DM}} \approx n_{\mathrm{B}} - \bar{n}_{\mathrm{B}}$$

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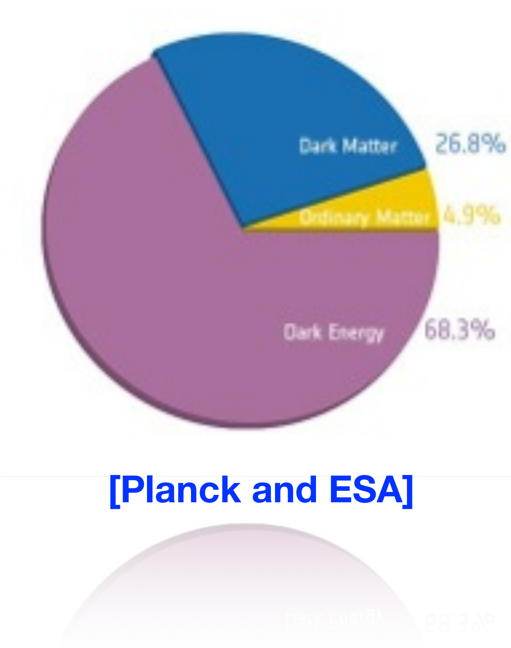

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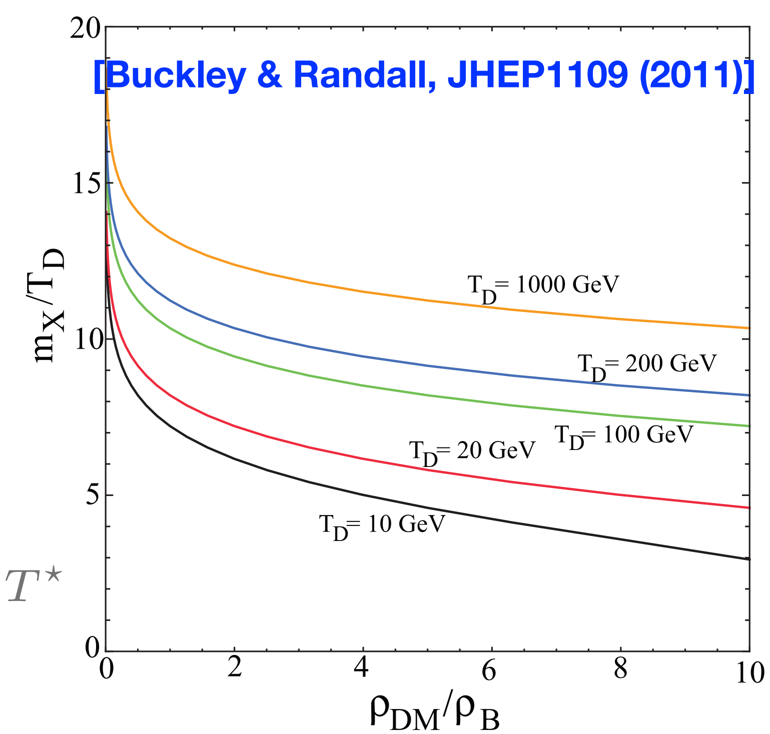
$$n_{\rm DM} - \bar{n}_{\rm DM} \approx n_{\rm B} - \bar{n}_{\rm B}$$

higher dimensional operators

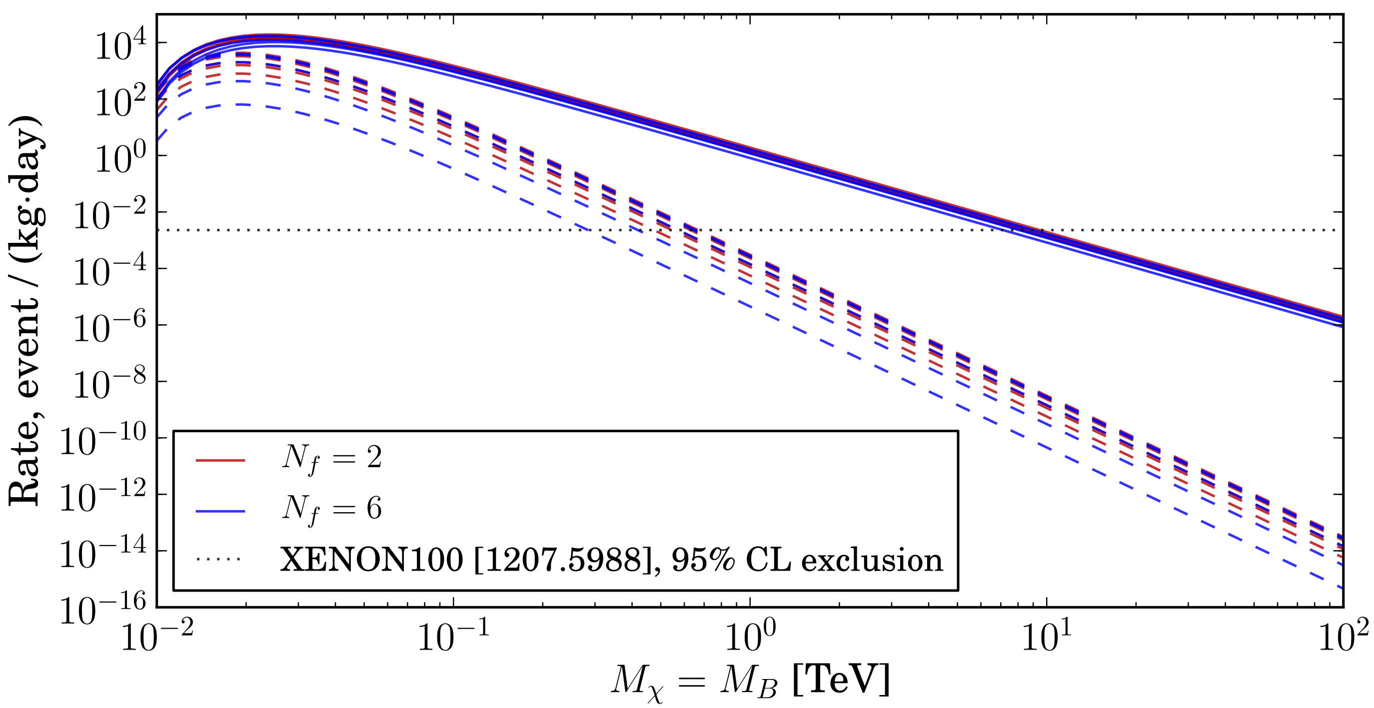
$$n_{\rm DM} \approx n_{\rm B} \rightarrow M_{\rm DM} \approx 5\ M_{\rm B}$$

sphaleron processes

$$M_{\rm DM} \gg M_{\rm B} \rightarrow n_{\rm B} \gg n_{\rm B} \approx e^{-M_{\rm DM}/T^\star}$$



A Composite "Miracle"(II)



	SU(3)	SU(2)	U(1)	SU(3)
Q	1	1	2/3	3
Q	1	1	-1/3	3
Q	1	1	0	3

- [LSD Collab., Phys. Rev. D 88, 014502 (2013)]
- Composite fermion dark matter from new vector-like SU(3) gauge theory with Dirac mass terms. Can be a thermal relic.
- Solid lines: magnetic moment. Dashed lines: charge radius.

Stealth Dark Matter (I)

- Composite dark matter can be lighter than 20 TeV if the leading low-energy interaction is dim. 7 polarizability.

- Requires even N_c so that baryons are scalars to eliminate magnetic moment interaction.

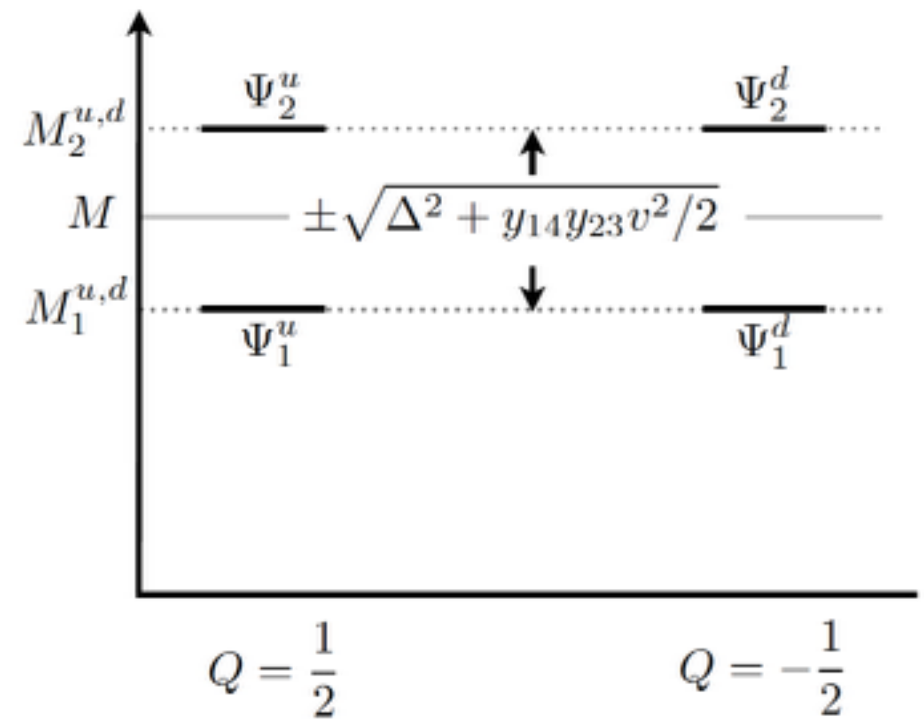
- Requires a global SU(2) custodial symmetry to eliminate charge radius interaction.

- Minimal coupling to weak SU(2) to enable dark pion decay. Now some coupling to Higgs boson.

- Also need vector-like masses so that dark sector doesn't impact Higgs vacuum alignment.

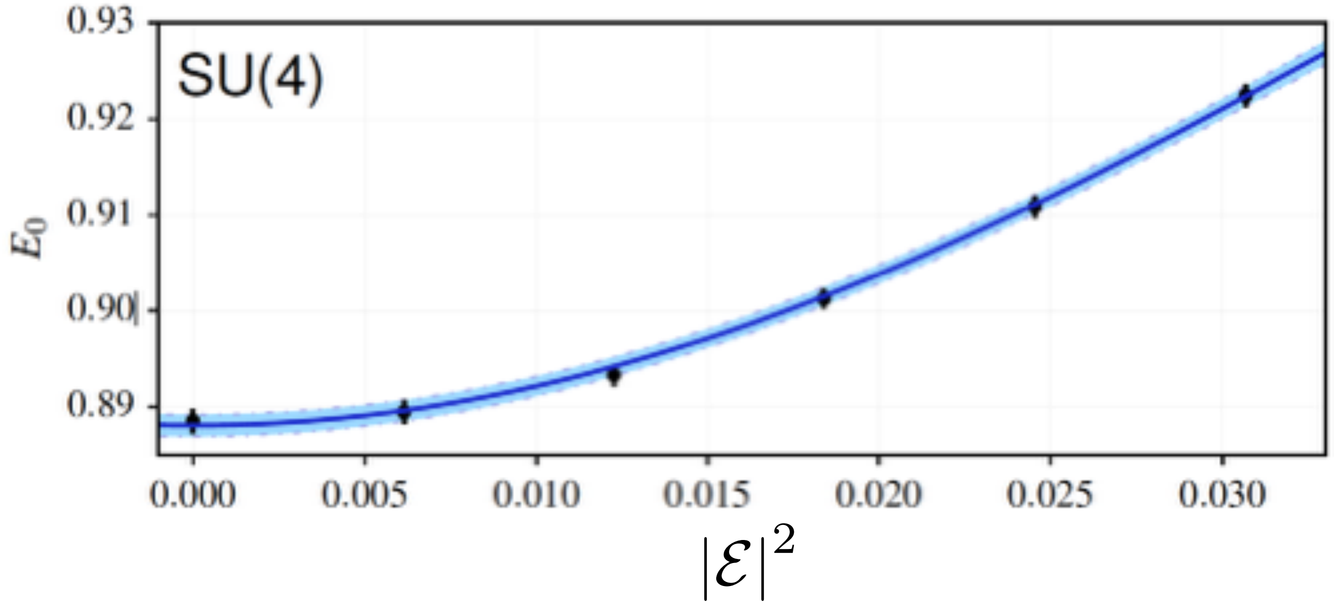
- Minimal model: Dark SU(4) color with N_f = 4 Dirac flavors.

Stealth Dark Matter (II)

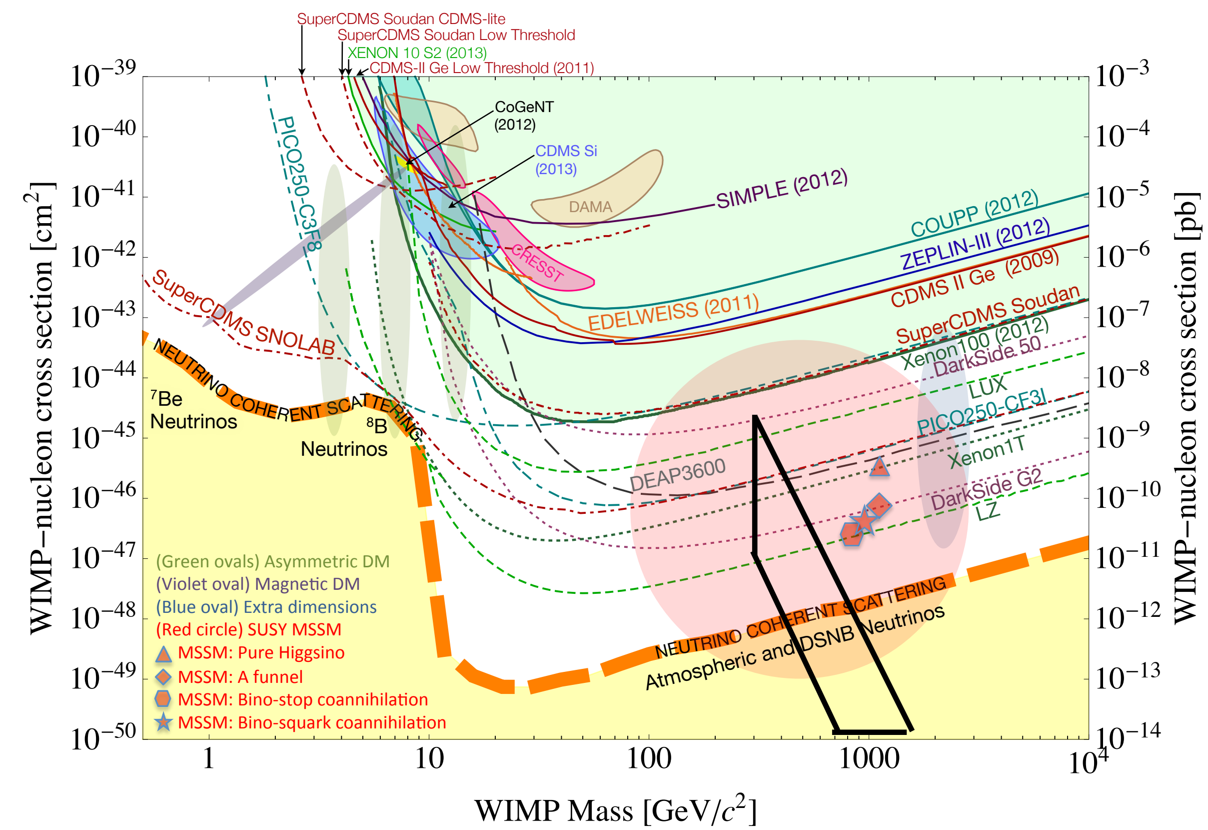


- Stable dark baryon is $(\psi_1^u \psi_1^u \psi_1^d \psi_1^d)$.
- Splitting between ψ_1 and ψ_2 Dirac doublets due either to vector mass splitting Δ or Yukawa couplings y.
- Coupling to Higgs can be made as small as needed (not a fine tuning) so that polarizability is dominant DM interaction, yet large enough to ensure no relic density of dark pions.
- Higgs VEV still dominates electroweak vacuum alignment and contributions to S and T parameters are small.

SU(4) Polarizability



$$E_0(\mathcal{E}) = M_B + 2C_F\,|\mathcal{E}|^2$$



$$\sigma \simeq \frac{\mu_{n\chi}^2}{\pi A}\left\langle \left|C_F f_F^A\right|^2 \right\rangle$$

$$f_F^A = \langle A\,|F^{\mu\nu}F_{\mu\nu}|\,A\rangle$$

- Coherent DM-nucleus cross section:
- Nuclear matrix element [O(3) uncertainty]:
- Direct detection signal below neutrino background for M_B > 1 TeV. Stealth!