Intersections of BSM phenomenology and QCD for New Physics Searches

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Lattice QCD techniques for Dark Matter Searches

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[LSD collab., Phys. Rev. D88 (2013) 014502]
[LSD collab., Phys. Rev. D89 (2014) 094508]
[LSD collab., arxiv:1503.04203, Phys. Rev. D]
[LSD collab., arxiv:1503.04205, Phys. Rev. Lett.]

Outline

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

Dark Matter

- Gravitational effects of DM show up in CMB, lensing and other large scale phenomena
- direct Standard Model interactions are needed for production in the early Universe
- Direct detection and Collider experiments rely on SM interactions, but they are suppressed
- Strong exclusion bounds push theorists to explore a wider landscape of models for DM
- Problems with cosmological models can hint at strongly self-interacting dark matter

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Strongly-coupled
Composite
Dark Matter

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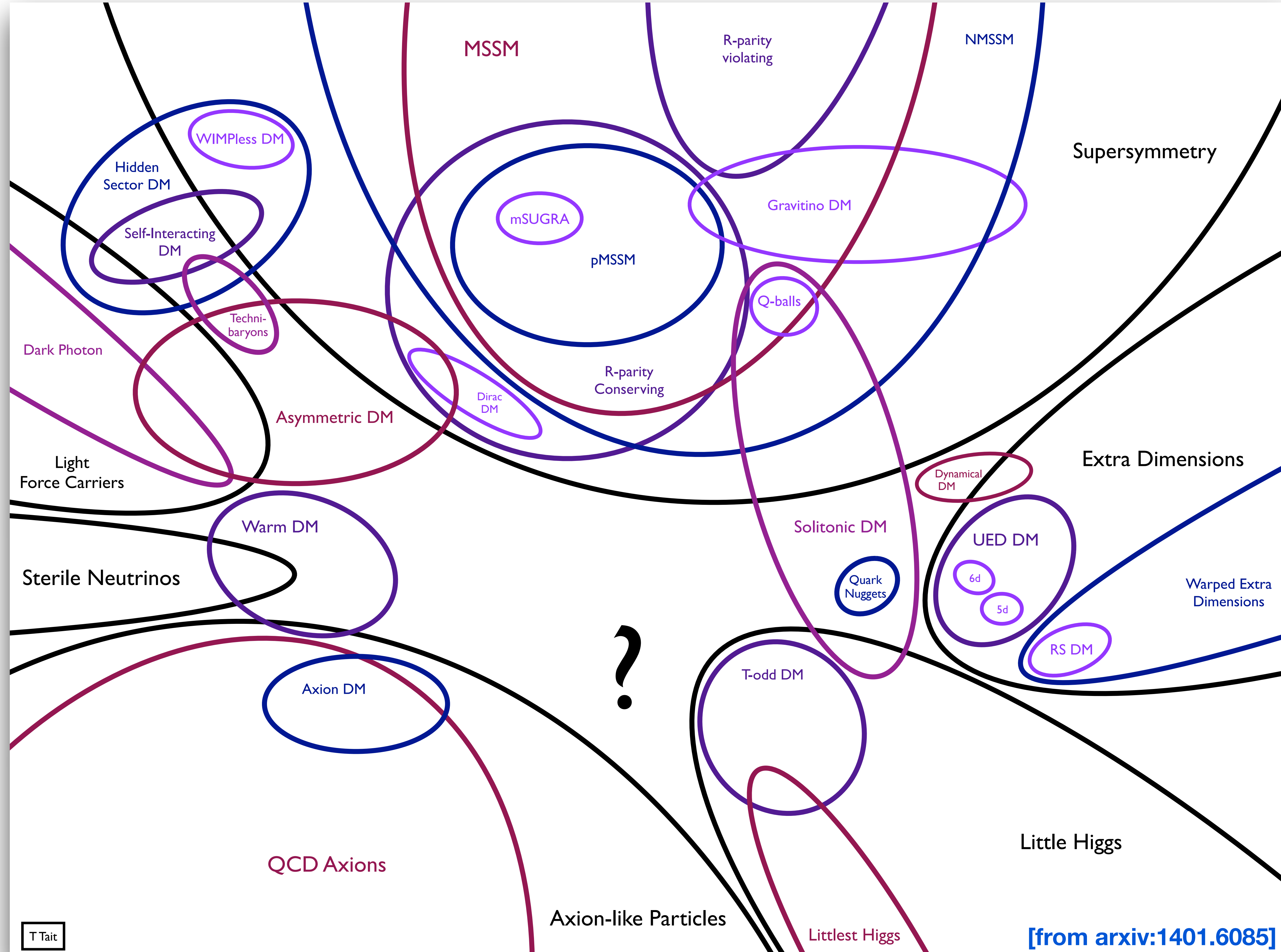
The DM landscape



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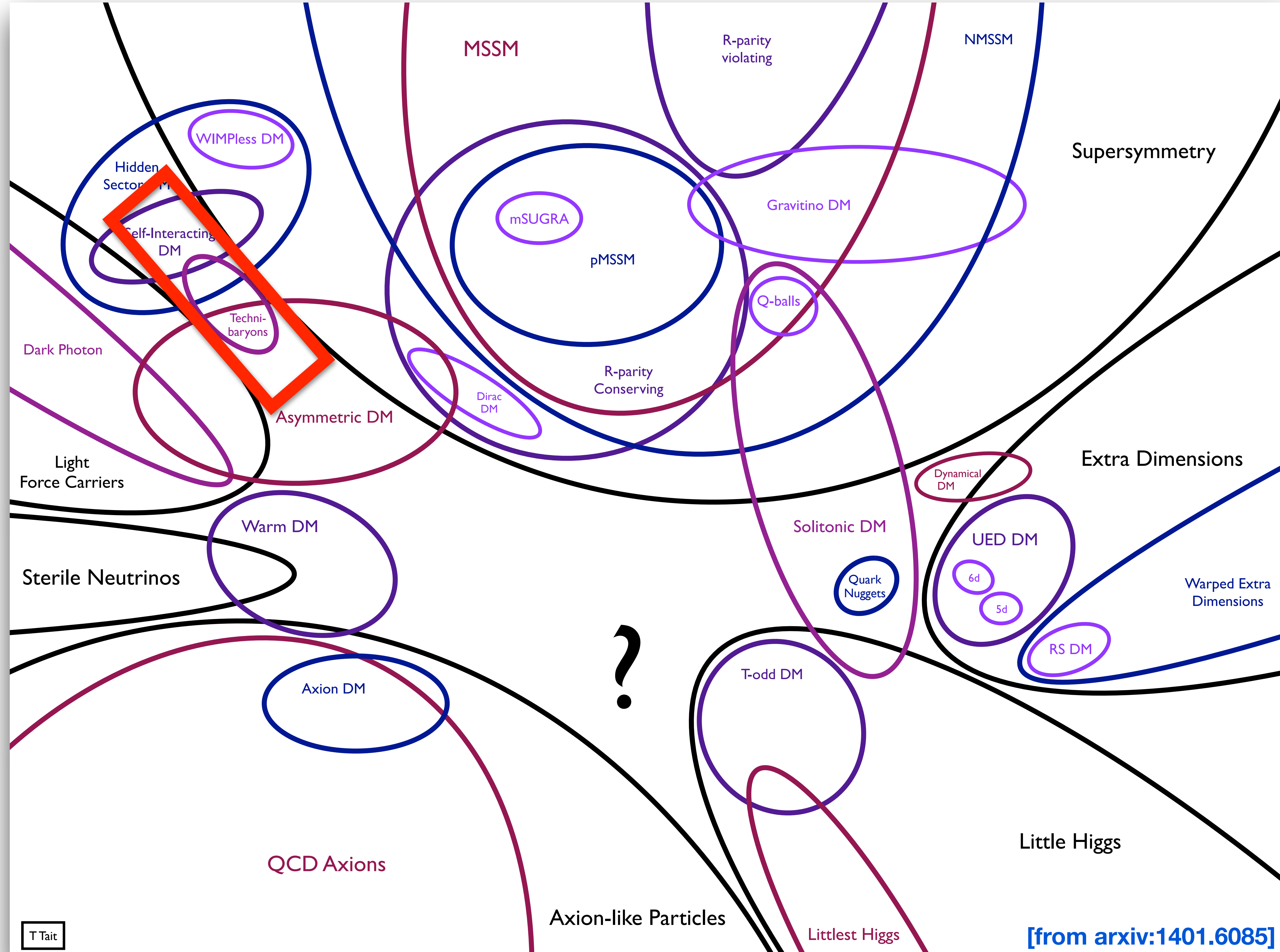

Lattice Strong Dynamics Collaboration

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Strongly-coupled composite dark matter

- Dark matter is a <u>composite object</u> of a new sector
- Composite object is <u>electroweak neutral</u>
- Constituents can have *electroweak charges*
- Dark matter is **stable** thanks to a global symmetry (like baryon number)

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Mechanisms to provide observed relic abundance

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- Composite object is electroweak neutral → **Suppressed interactions with SM**
- Constituents can have *electroweak charges* → **Mechanisms to provide observed relic abundance**
- Dark matter is **stable** thanks to a global symmetry (like baryon number) → **Guaranteed in many models**

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: all mass scales are technically natural

- Dark fermions have dark color and also have electroweak charges

- Depending on the model, dark fermions have electroweak breaking masses (chiral), electroweak preserving masses (vector) or a mixture

- A global symmetry of the theory naturally stabilizes the dark baryonic composite states (e.g. dark neutron)

“Stealth Dark Matter” model

[LSD collab., arxiv:1503.04203]

- Let’s focus on a SU(N) dark gauge sector with N=4
- Let dark fermions have current/chiral masses together with vector-like masses
- Let dark fermions masses to be at the dark confinement scale
- Assign electroweak charges to dark fermions
- The symmetry group is U(4)xU(4) and with generic masses it breaks down to U(1) (dark baryon number)

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the only stable particle is the lightest baryon

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- Dark fermions interact with the SM Higgs and obtain current/chiral masses
- Introduce vector-like masses for dark fermions that do not break EW symmetry
- Diagonalizing in the mass eigenbasis gives *4 Dirac fermions*
- Assume custodial SU(2) symmetry arising when ***u*** $\leftrightarrow$ ***d***

Field	$\mathrm{SU}(N)_D$	$(\mathrm{SU}(2)_L, Y)$	Q
$F_1 = \begin{pmatrix} F_1^u \\ F_1^d \end{pmatrix}$	$\mathbf{N}$	$(\mathbf{2}, 0)$	$\begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$
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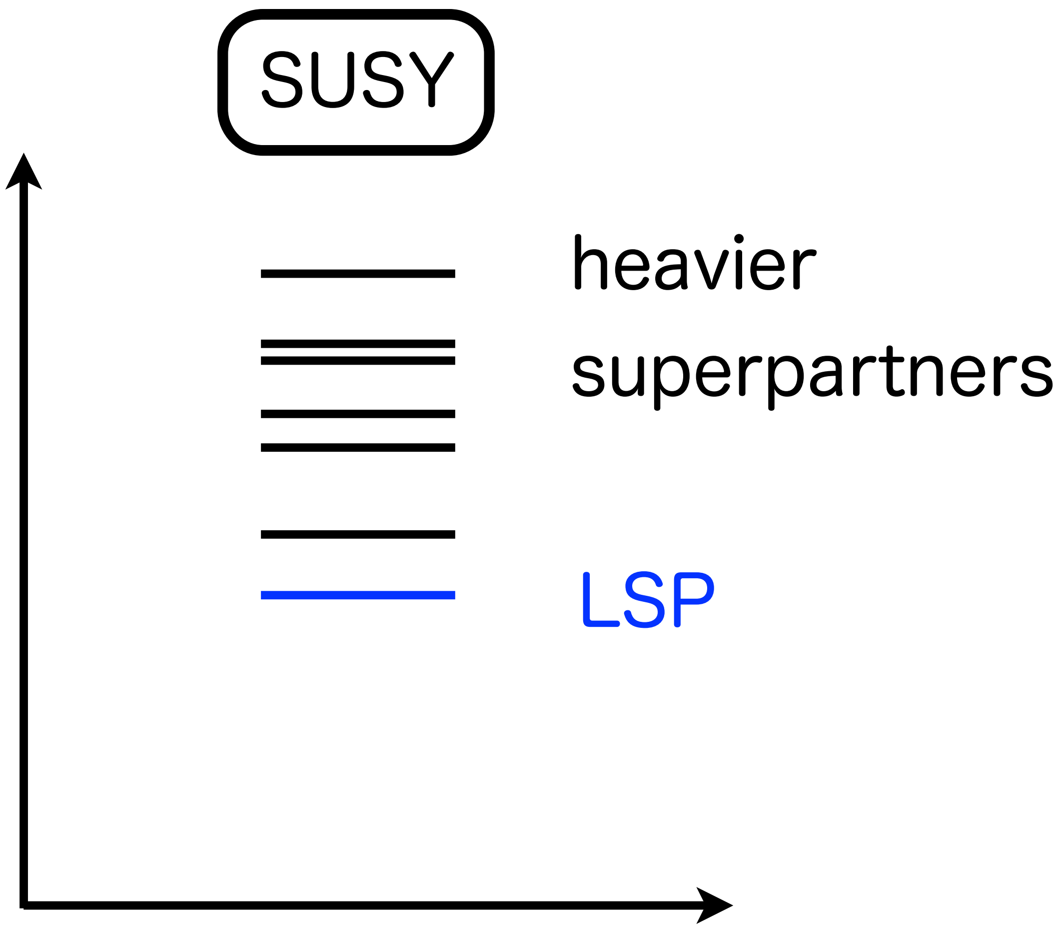
Stealth DM at colliders



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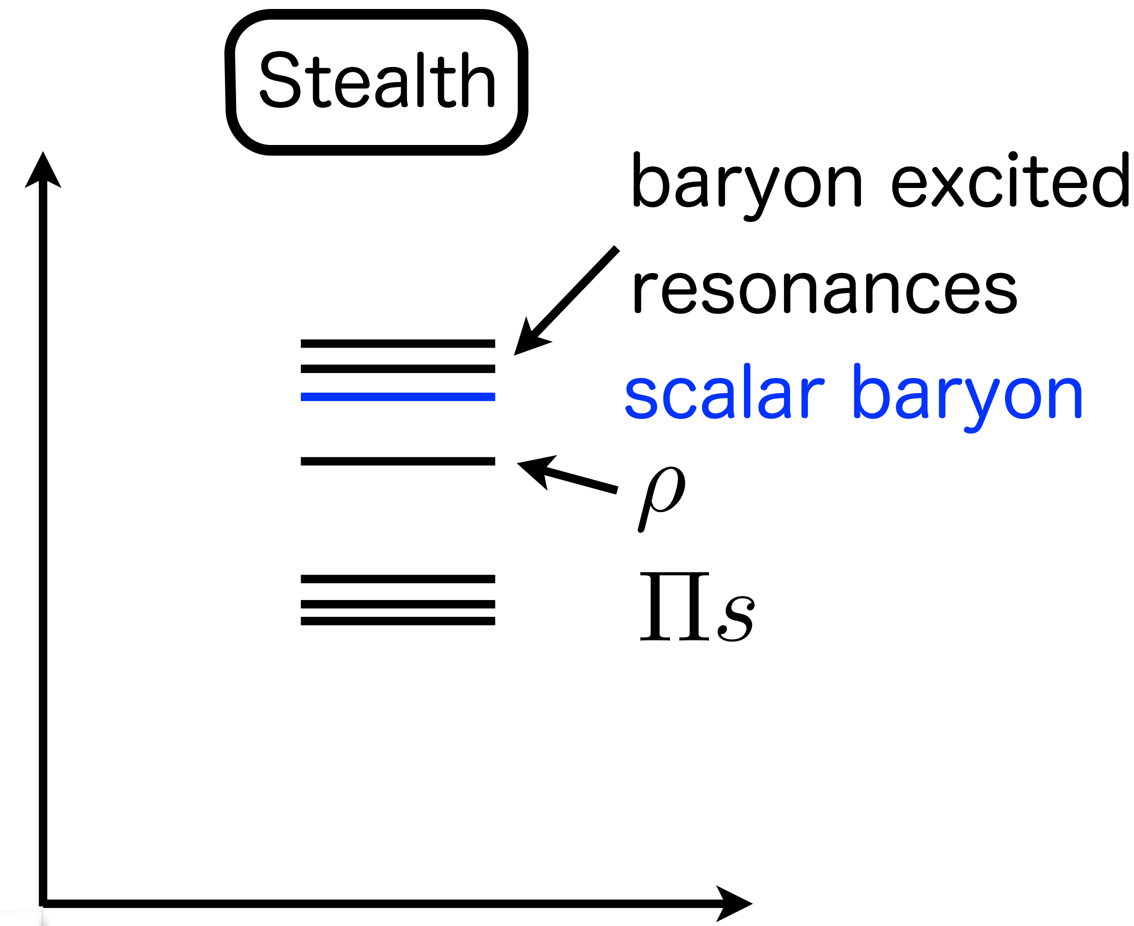

Plot by G. Kribs

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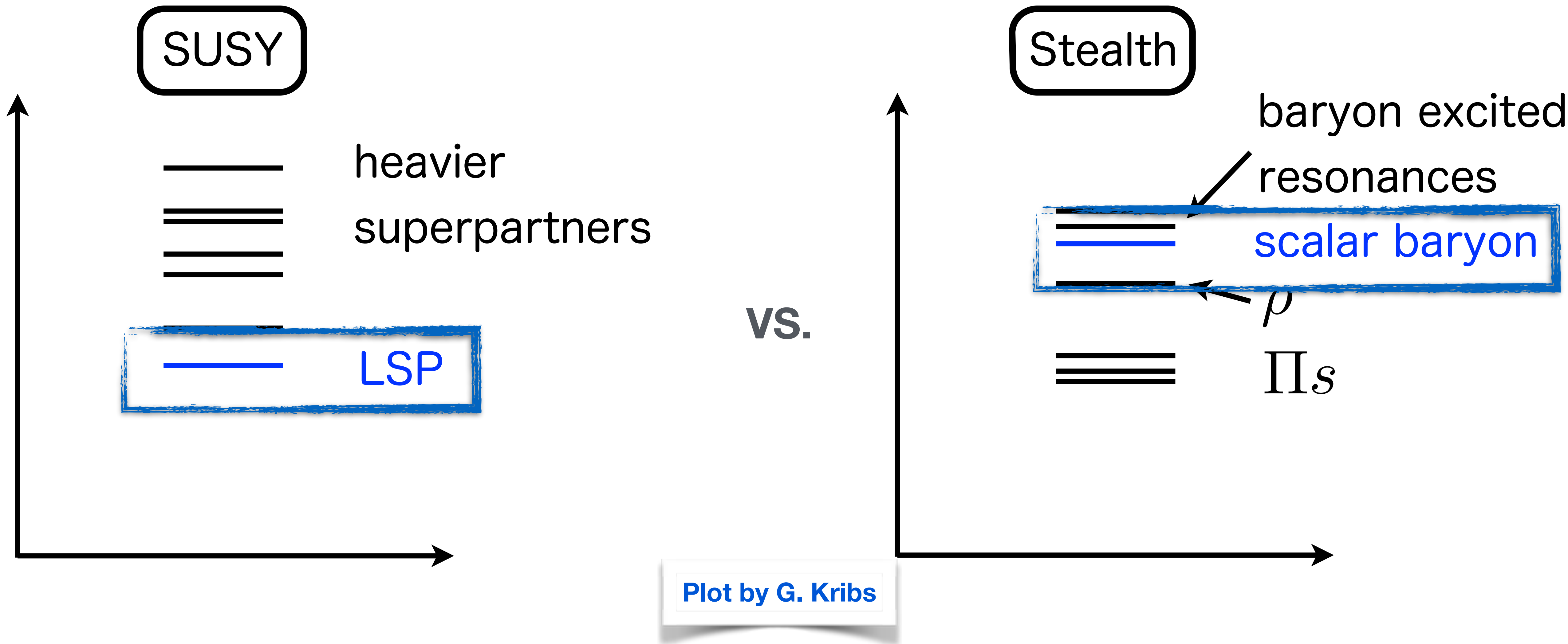

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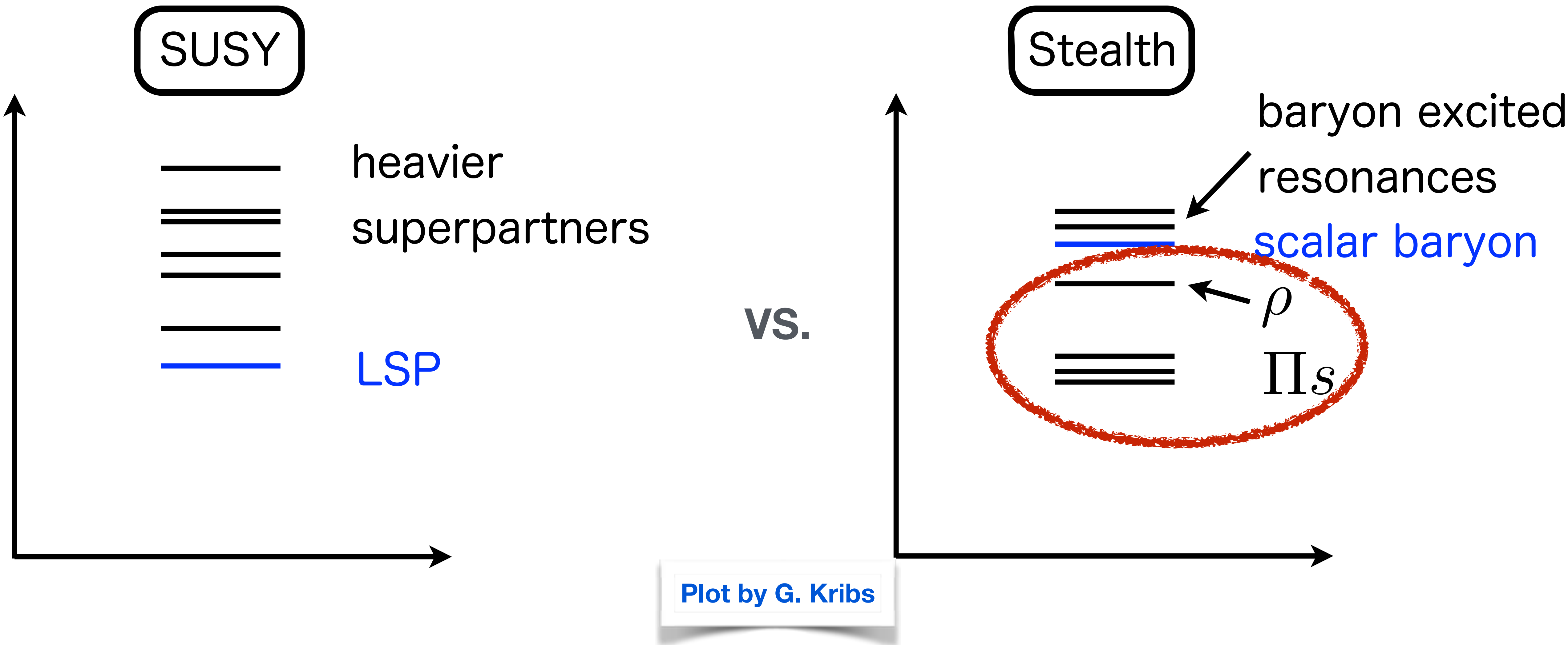

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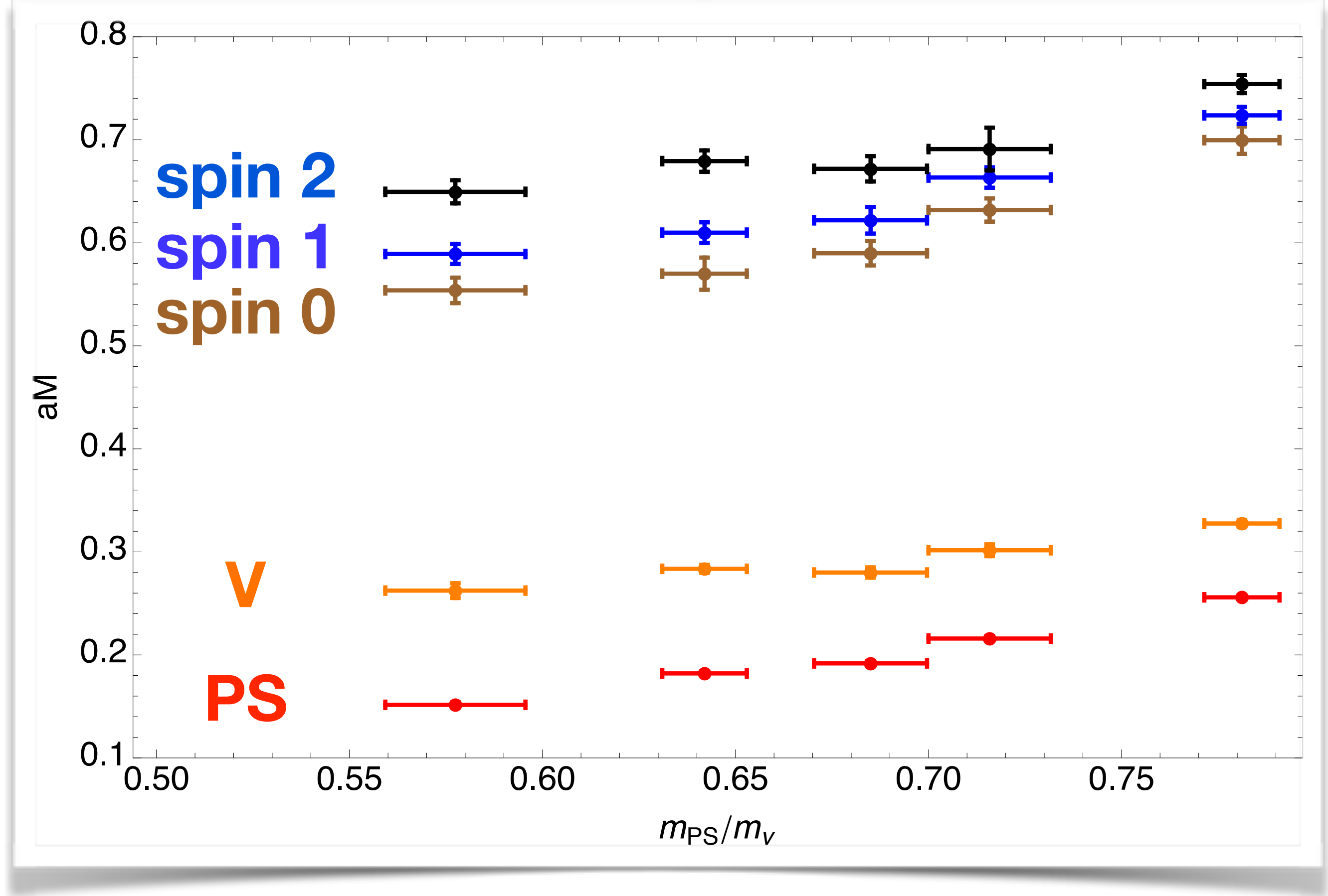
- Light meson production and decay give interesting signatures: **the model can be constrained by collider limits**

Lattice Stealth DM

- Non-perturbative lattice calculations of the spectrum confirm that lightest baryon has spin zero



- The ratio of pseudoscalar (PS) to vector (V) is used as probe for different dark fermion masses

- The meson to baryon mass ratio allows us to translate LEPII bounds on charged meson to LEP bounds on composite bosonic dark matter

- Study systematic effects due to lattice discretization and finite volume due to the relative unfamiliar nature of the system

[LSD collab., Phys. Rev. D89 (2014) 094508]

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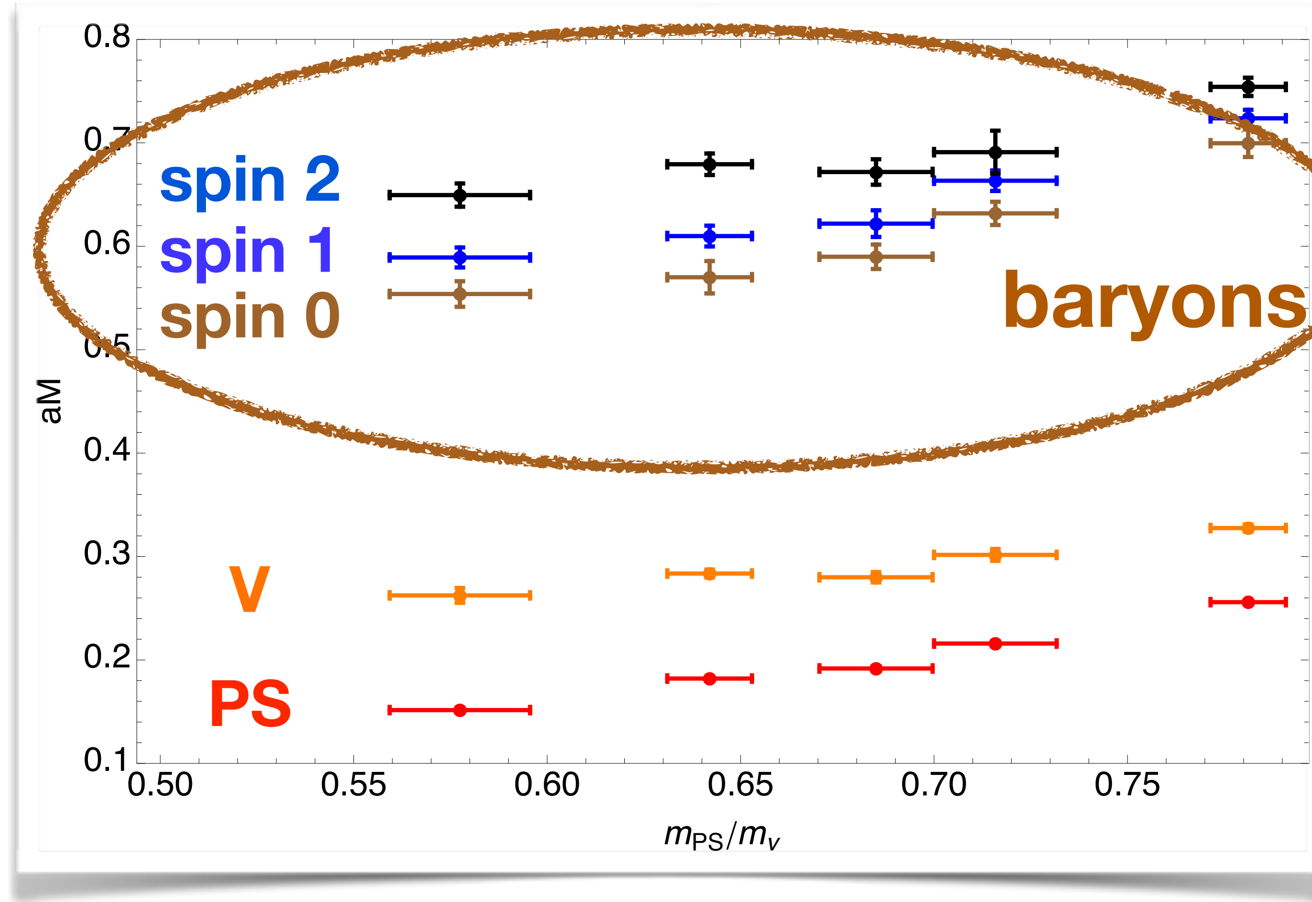

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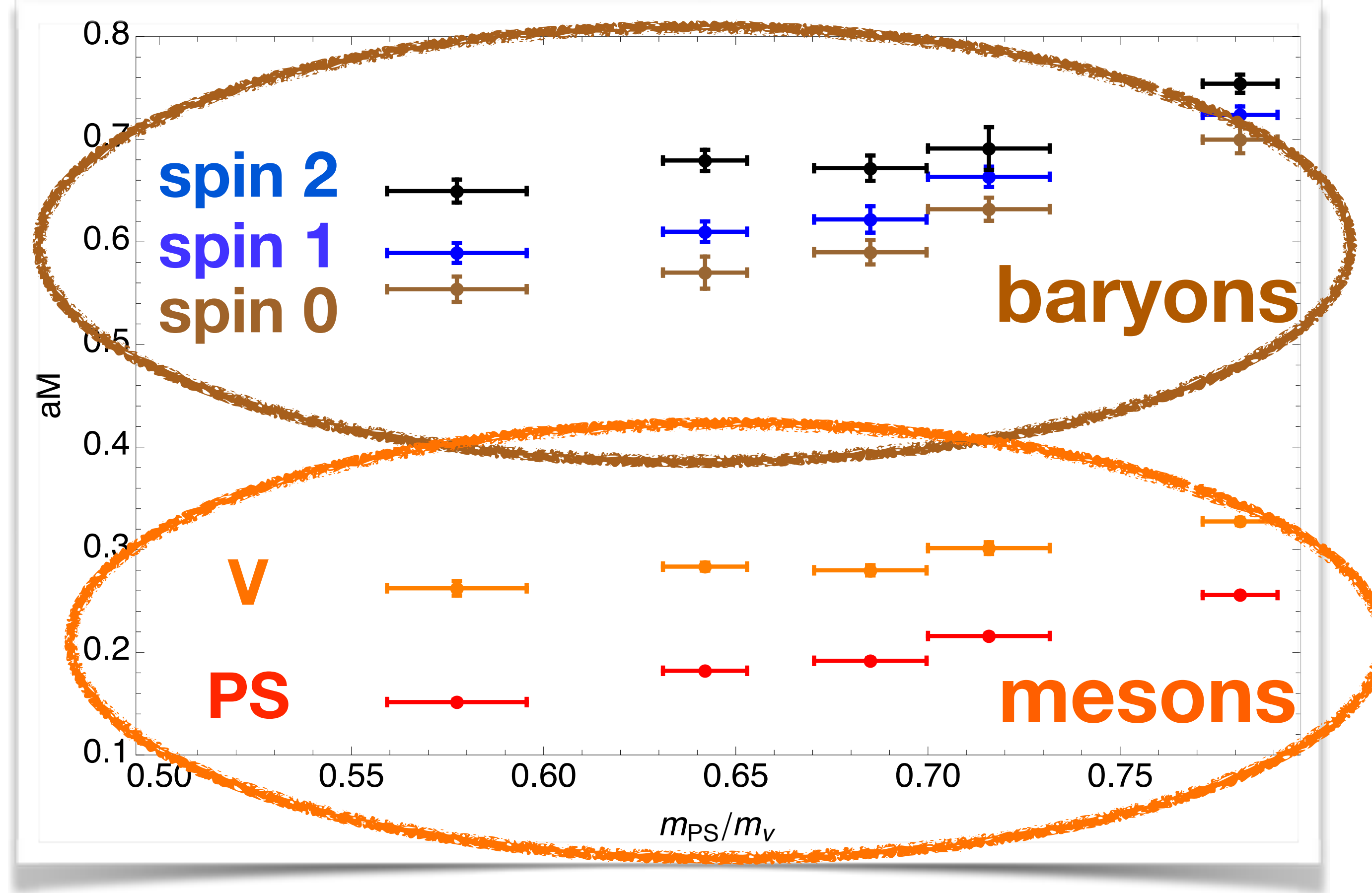

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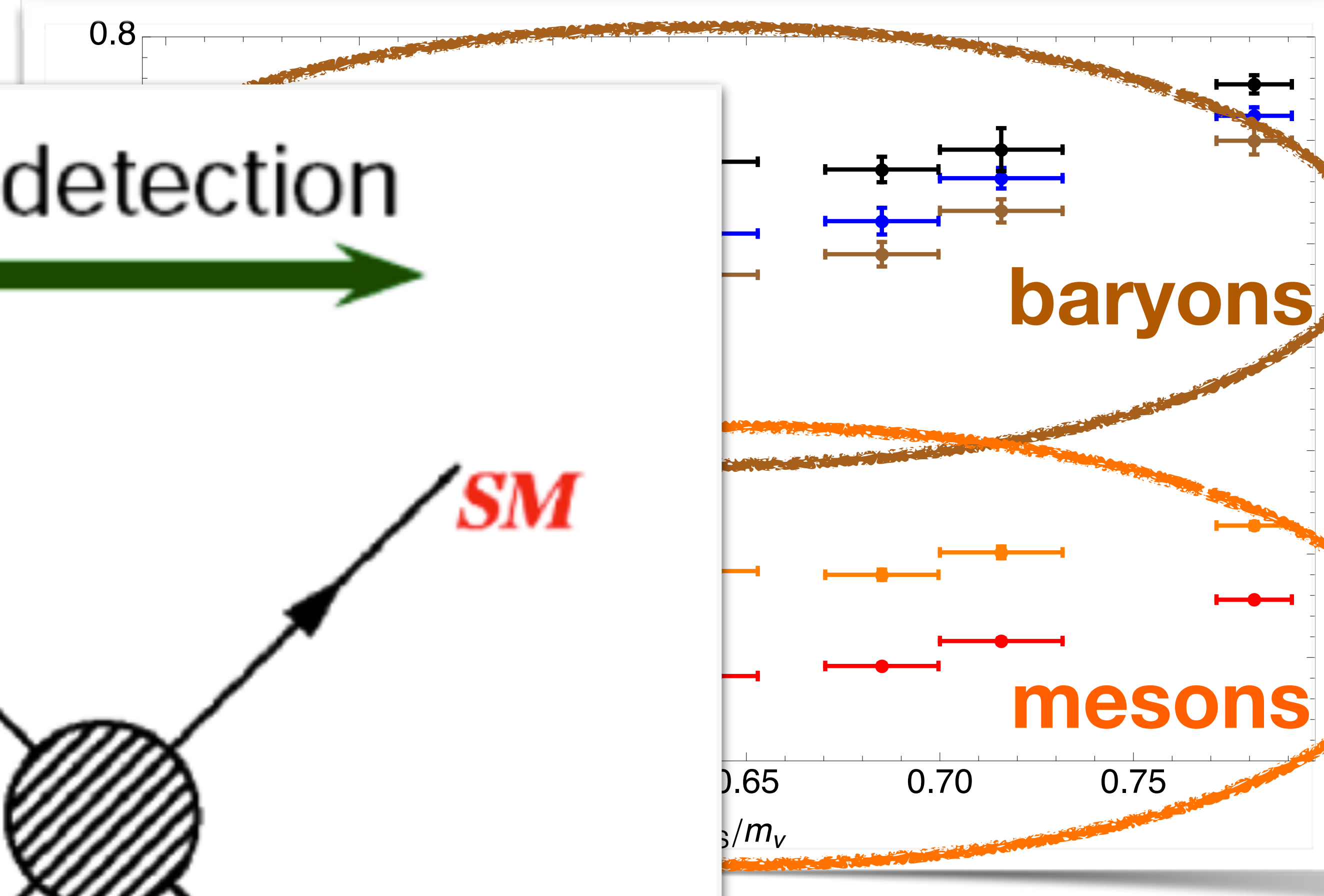

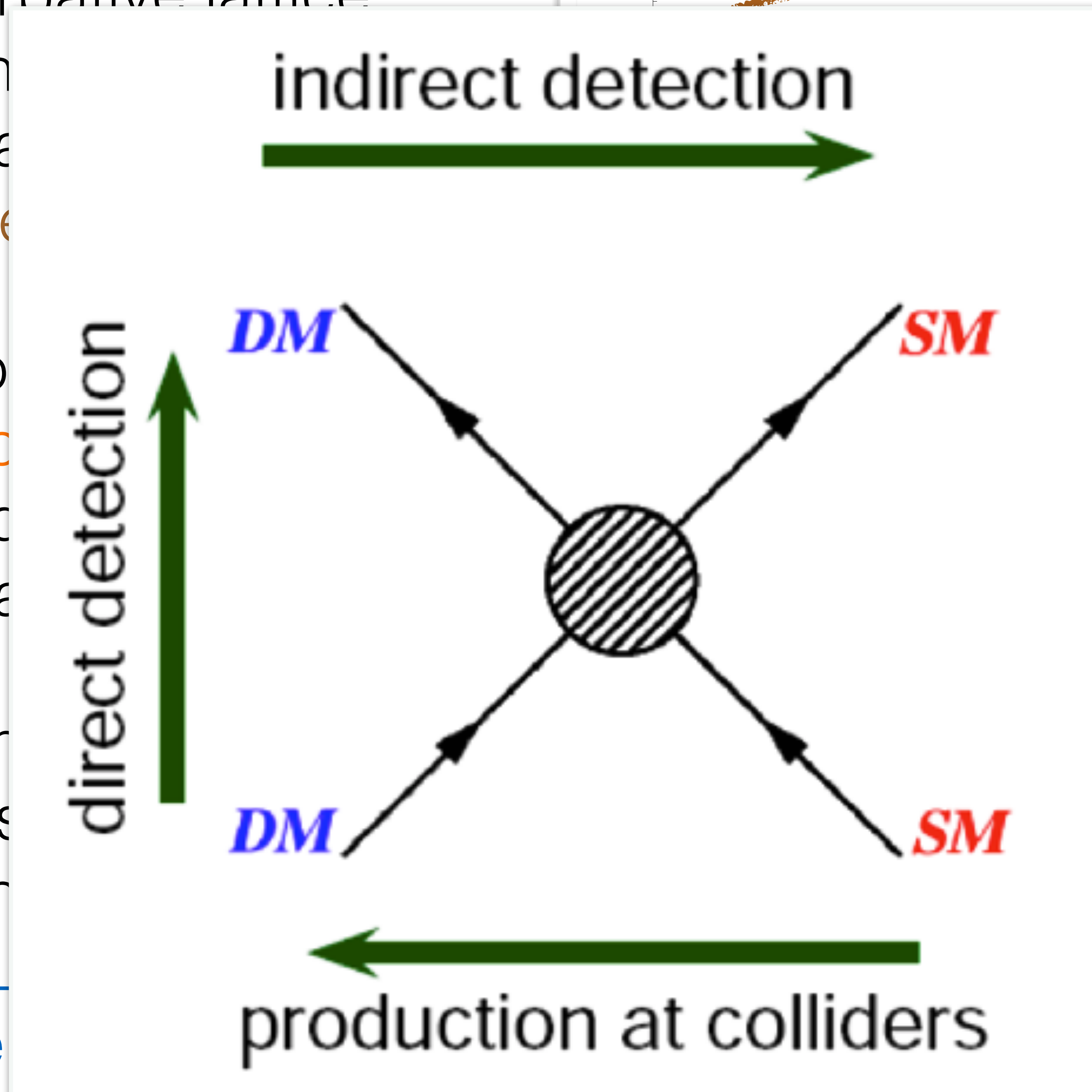

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“How dark is Stealth DM?”

Interactions of dark fermions with Higgs
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Interactions of dark baryon with photon through form factors

- dimension 4 ➥ Higgs exchange $\quad h f \bar{f}$

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- dimension 5 ➥ magnetic dipole $\quad \frac{(\bar{\chi}\sigma^{\mu\nu}\chi)F_{\mu\nu}}{\Lambda_{\text{dark}}}$
- dimension 6 ➥ charge radius $\quad \frac{(\bar{\chi}\chi)v_\mu\partial_\nu F^{\mu\nu}}{\Lambda^2_{\text{dark}}}$
- dimension 7 ➥ polarizability $\quad \frac{(\bar{\chi}\chi)F_{\mu\nu}F^{\mu\nu}}{\Lambda^3_{\text{dark}}}$

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Higgs exchange cross section in Stealth DM

- Need to non-perturbatively evaluate the σ-term of the dark bosonic baryon (scalar nuclear form factor)

$$\mathcal{M}_a = \frac{y_f y_q}{2m_h^2} \sum_f \langle B|\bar{f}f|B\rangle \sum_q \langle a|\bar{q}q|a\rangle$$

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2. dark baryon scalar form factor: need lattice input!
3. nucleon scalar form factor: ChPT and lattice input

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$$\boxed{y_f}\boxed{\langle B|\bar{f}f|B\rangle} = \frac{m_B}{v}\sum_f \frac{v}{m_f}\frac{\partial m_f(h)}{\partial h}\bigg|_{h=v} f_f^{(B)}$$

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

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

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- *Model-dependent answer for the cross-section in this channels*

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

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

[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 bosonic 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*
- <u>Lattice input is necessary: compute the baryon mass and form factor</u>

$$\mathcal{M}_a = \frac{y_f y_q}{2m_h^2} \sum_f \langle B|\bar{f} f|B\rangle \sum_q \langle a|\bar{q} q|a\rangle$$

1. effective Higgs coupling with dark fermions and quark Yukawa coupling
2. dark baryon scalar form factor: need lattice input!
3. nucleon scalar form factor: ChPT and lattice input

$$y_f \langle B|\bar{f} f|B\rangle = \frac{m_B}{v} \sum_f \frac{v}{m_f} \frac{\partial m_f(h)}{\partial h}\Big|_{h=} f_f^{(B)}$$

Lattice!

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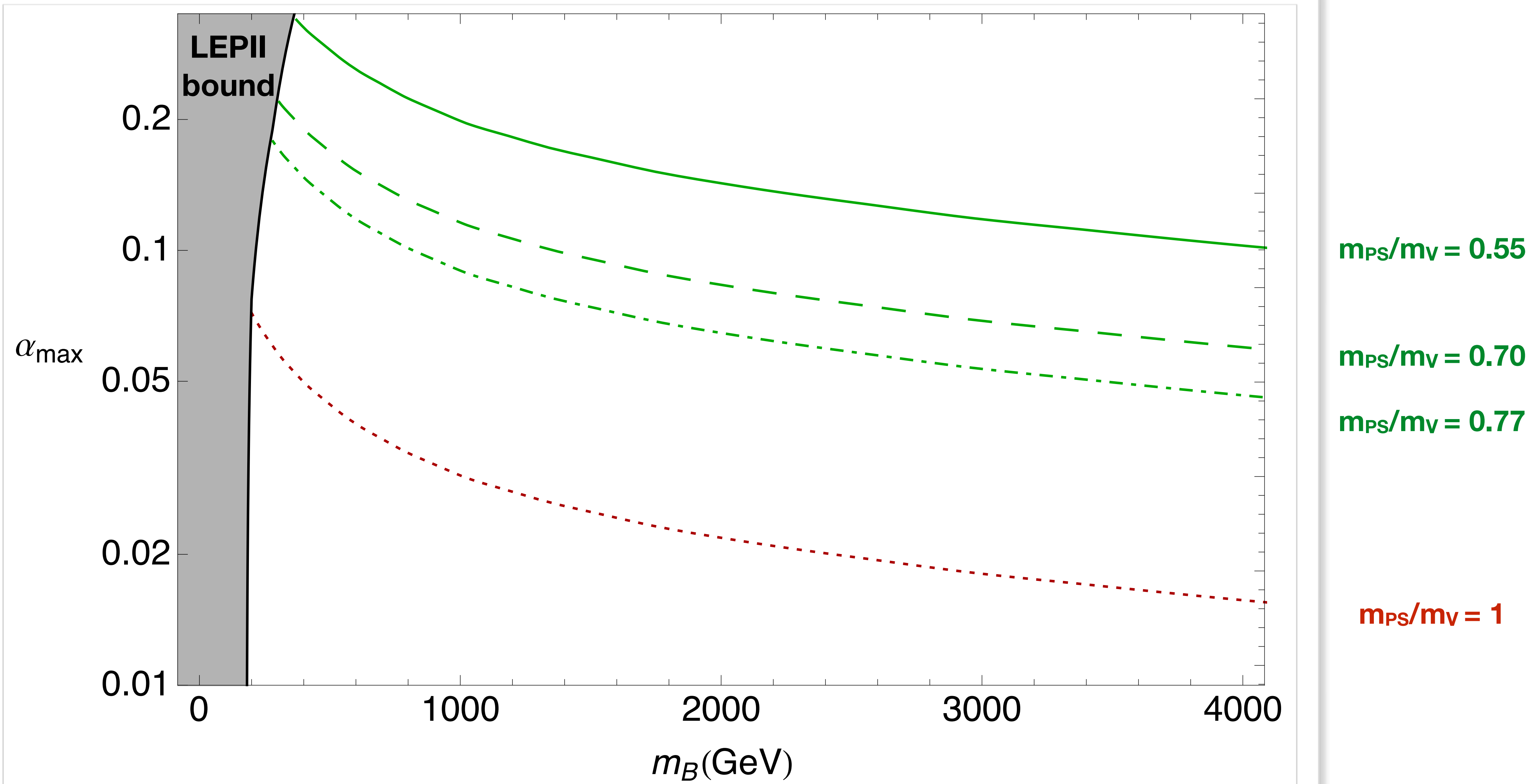
Bounds on the coupling



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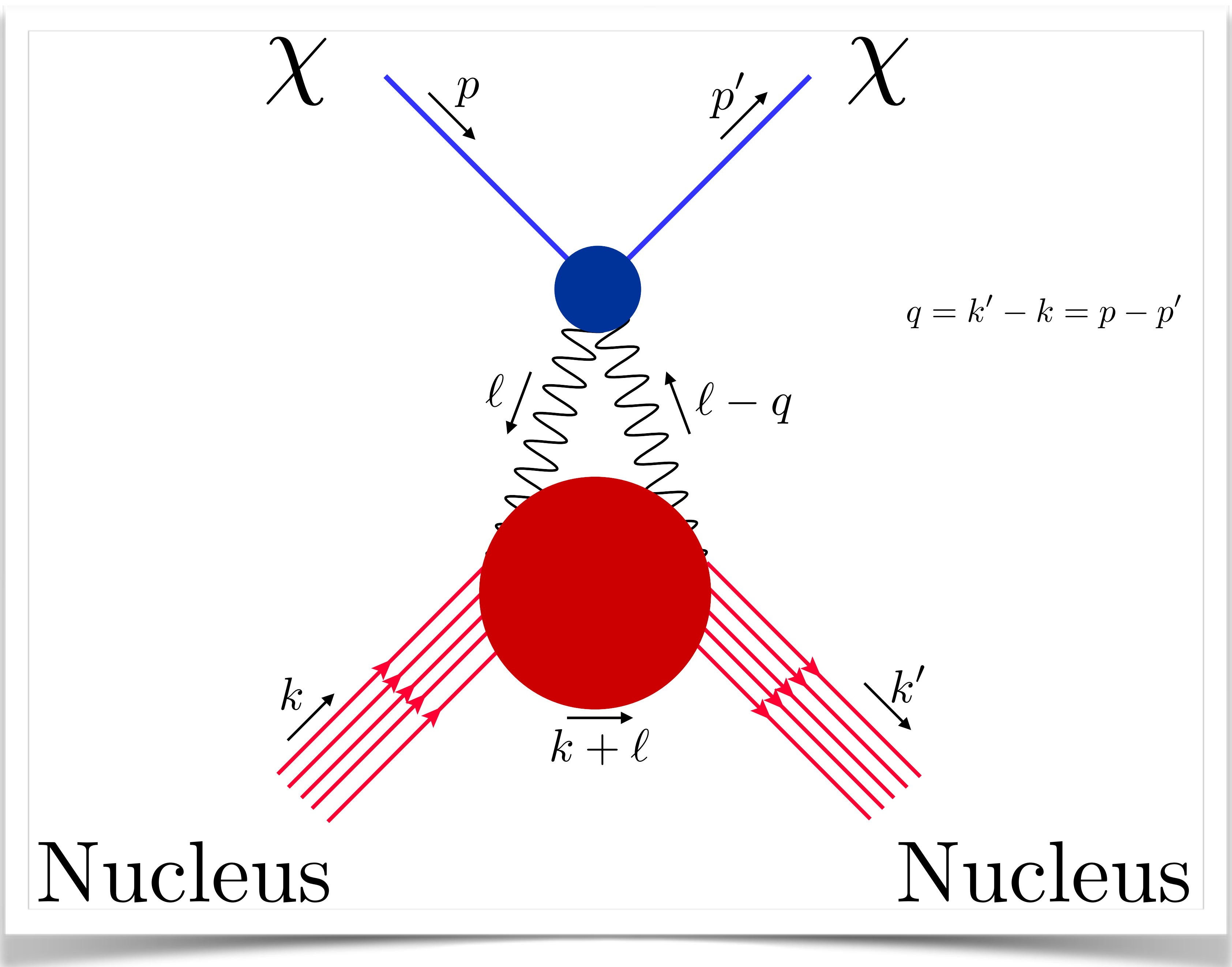
Computing polarizability

$$\boxed{\frac{c_F e^2}{m_\chi^3}\,\chi^\star \chi F^{\mu\alpha} F^{\nu}_{\alpha} v_\mu v_\nu}$$



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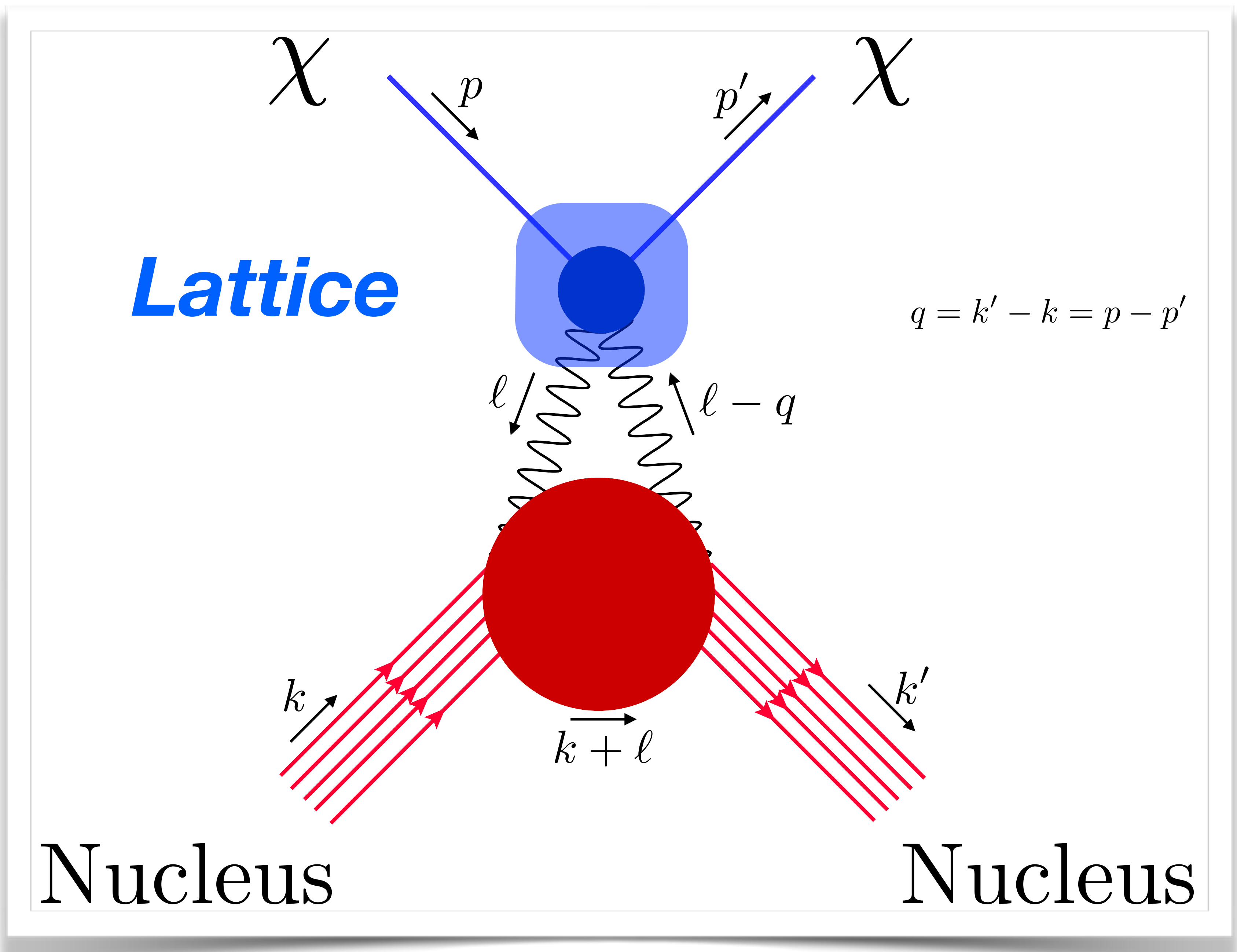

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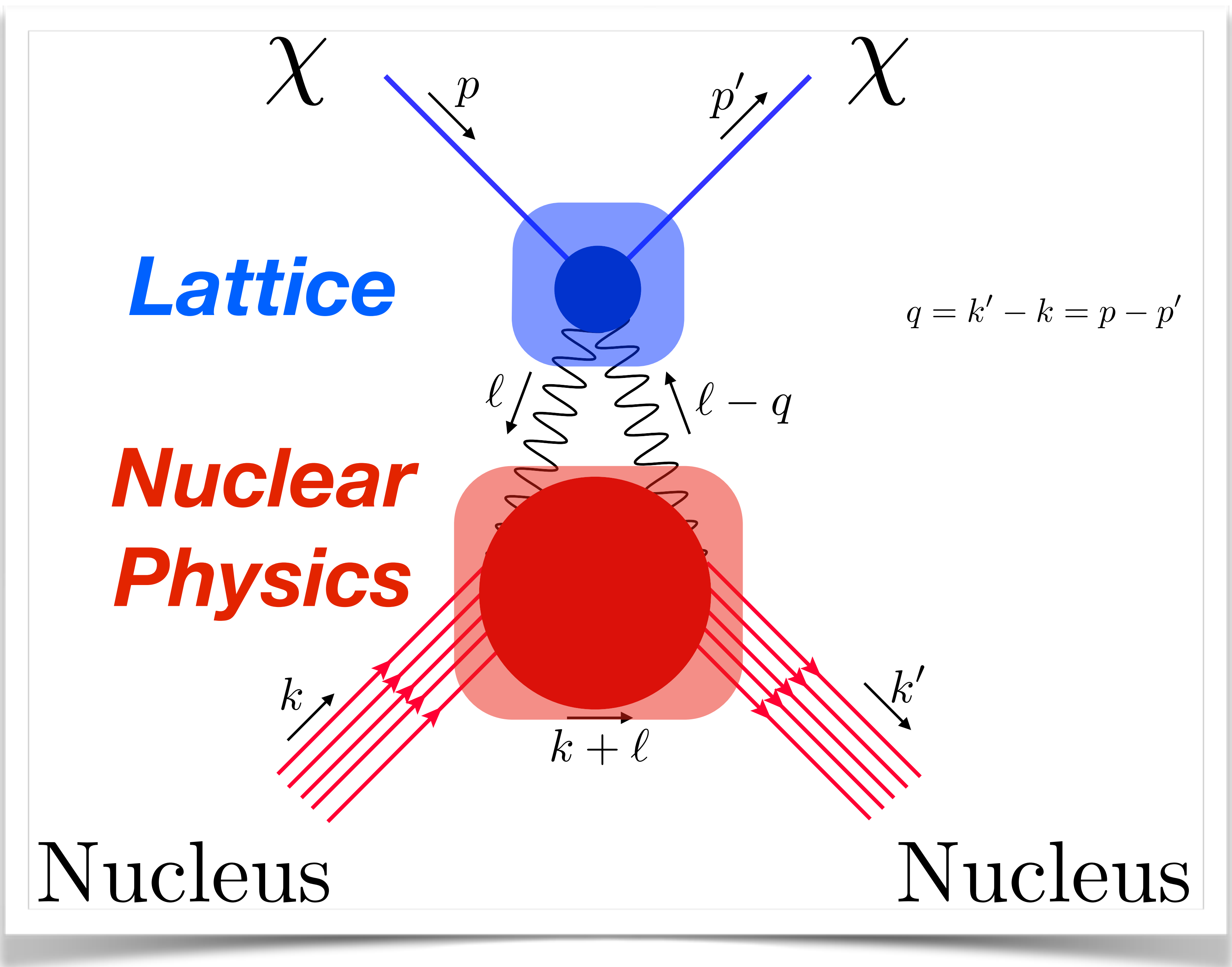

Importance of lattice field theory techniques

- lattice simulations are naturally suited for models where dark fermion masses are comparable to the confinement scale

- controllable systematic errors and room for improvement

- Naive dimensional analysis and EFT approaches can miss important non-perturbative contributions

- NDA is not precise enough when confronting experimental results and might not work for certain situations: there are uncontrolled theoretical errors

[LSD collab., arxiv:1503.04203, Phys. Rev. Lett.]

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

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 $\mathcal{E}$

$$E_{B,4c} = m_B + 2C_F|\mathcal{E}|^2 + \mathcal{O}\left(\mathcal{E}^4\right)$$

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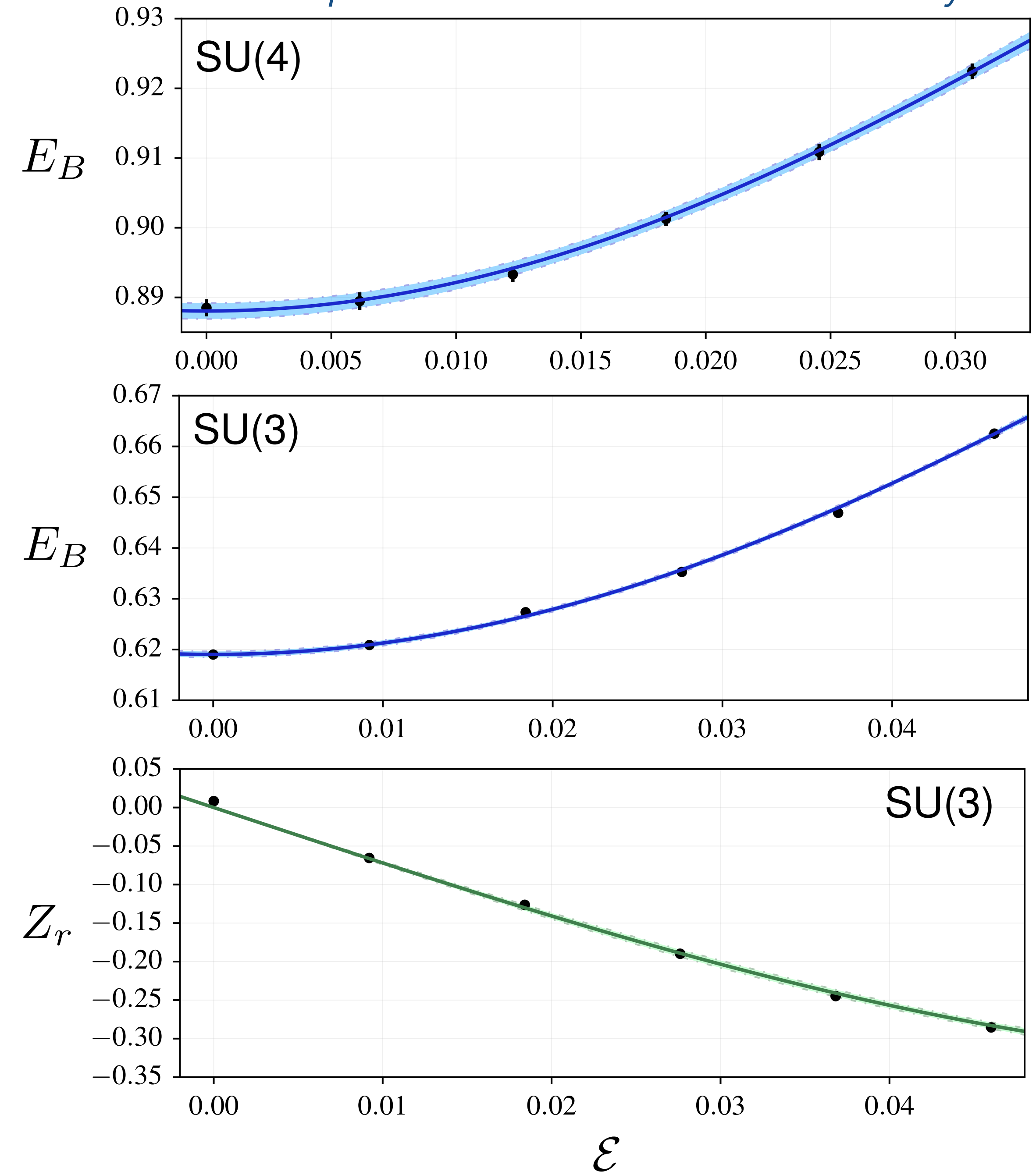
$$Z_r = \frac{\mathcal{E}\mu_B(\mathcal{E})}{2m_B^2}$$

32^3x64 quenched lattices (large volume)
one lattice spacing and two masses (matched)
40 sources on 200 independent configurations
multi-exponential fits with 3 states for the baryon



precise lattice results

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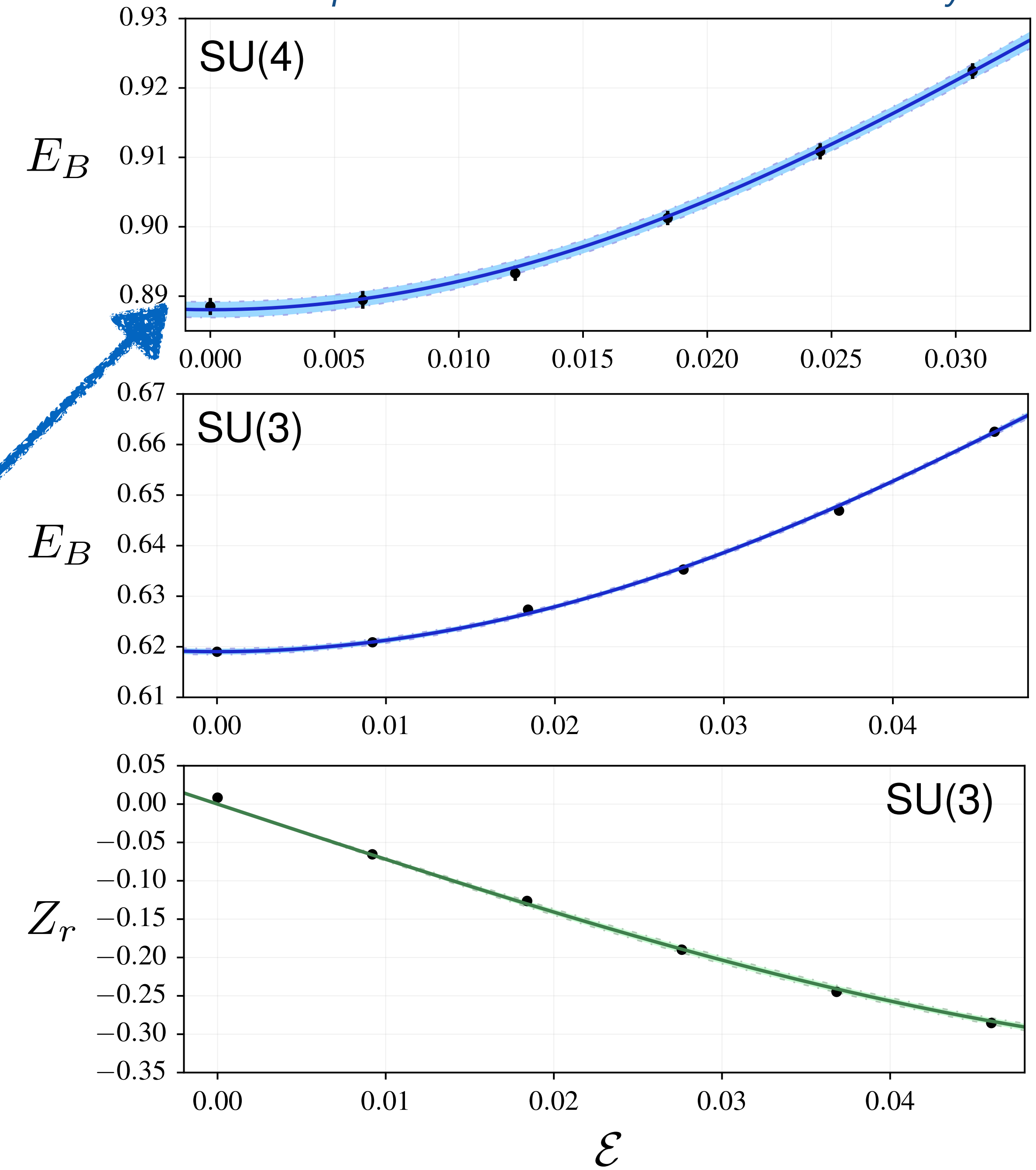

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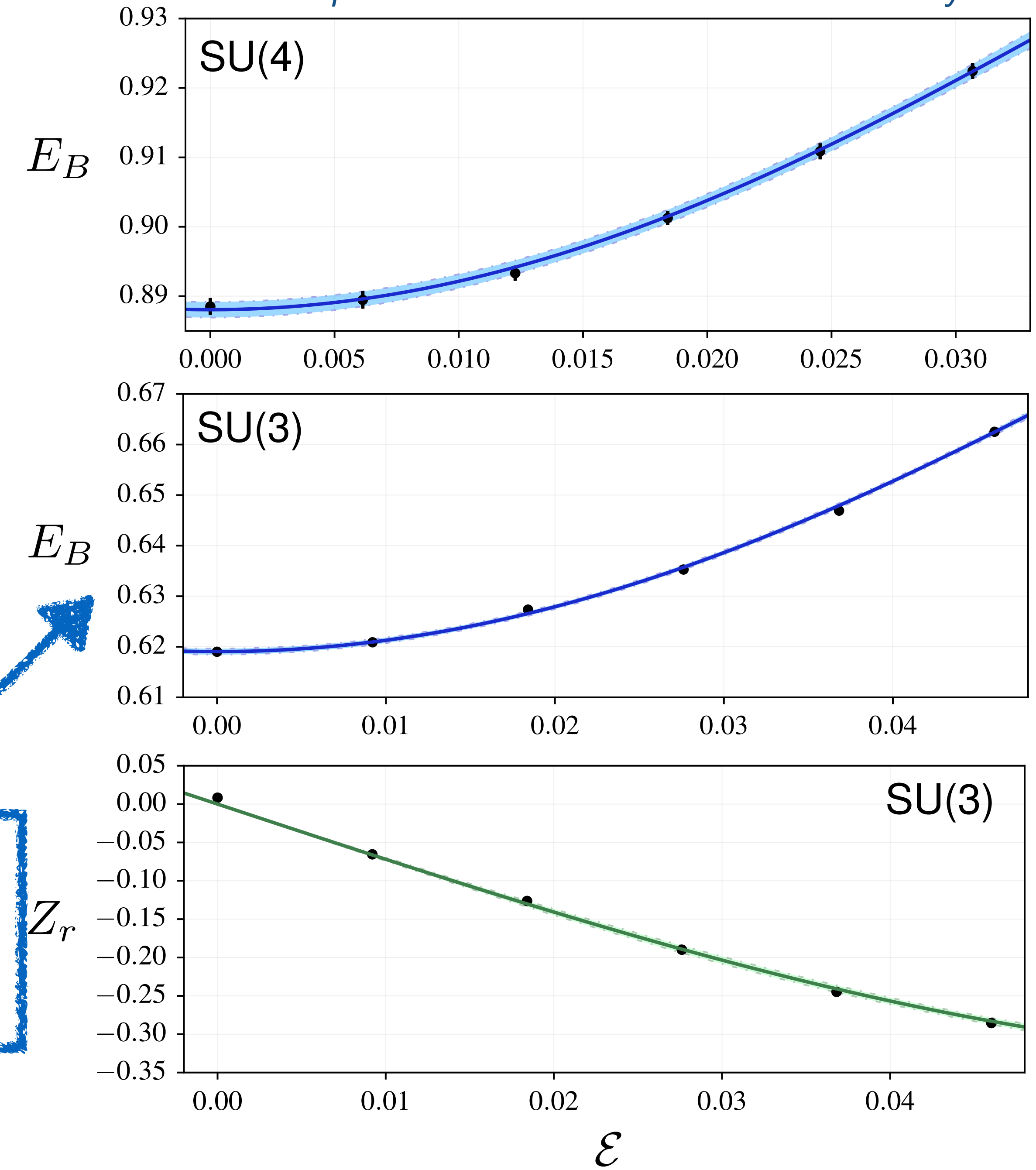

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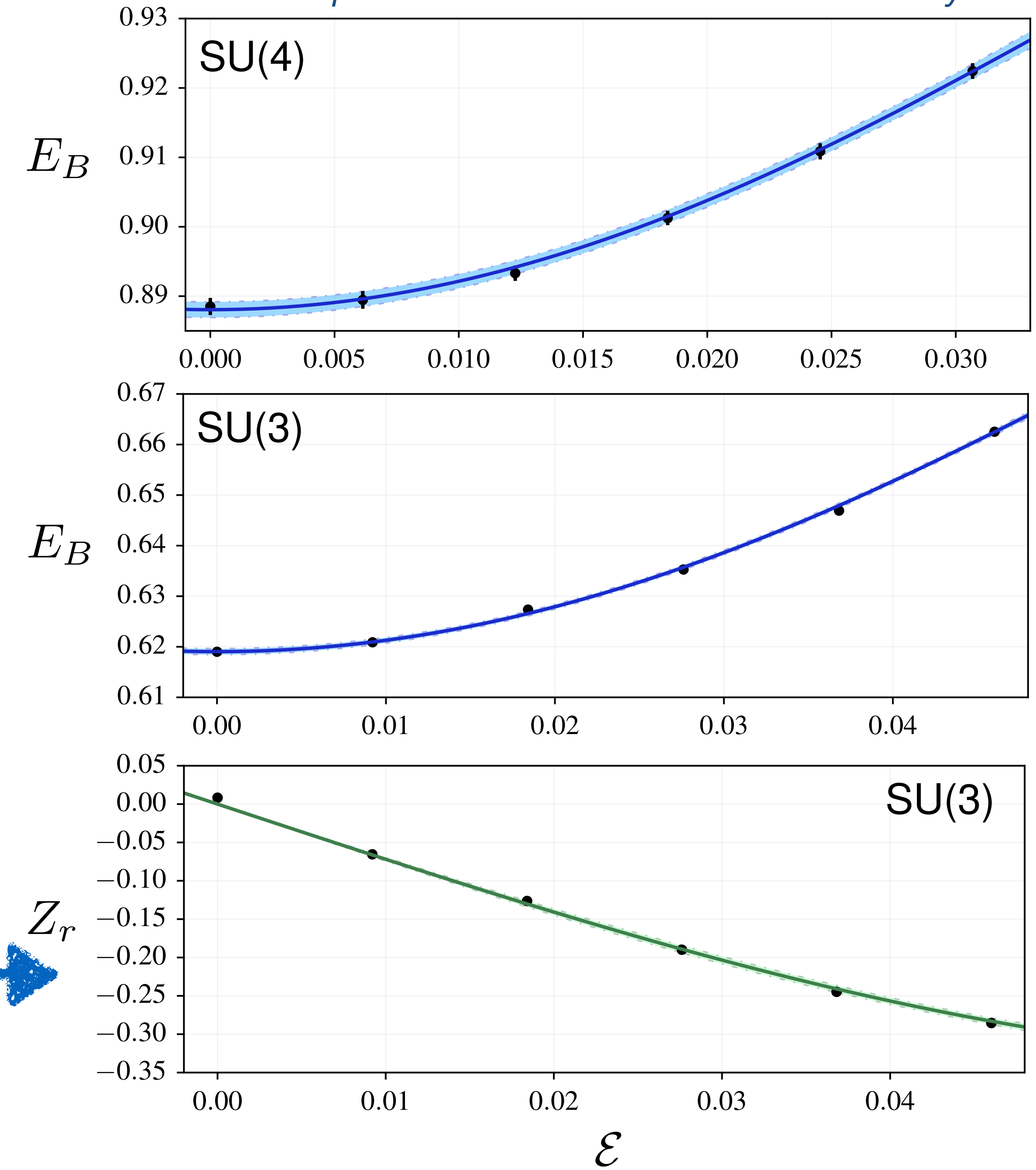
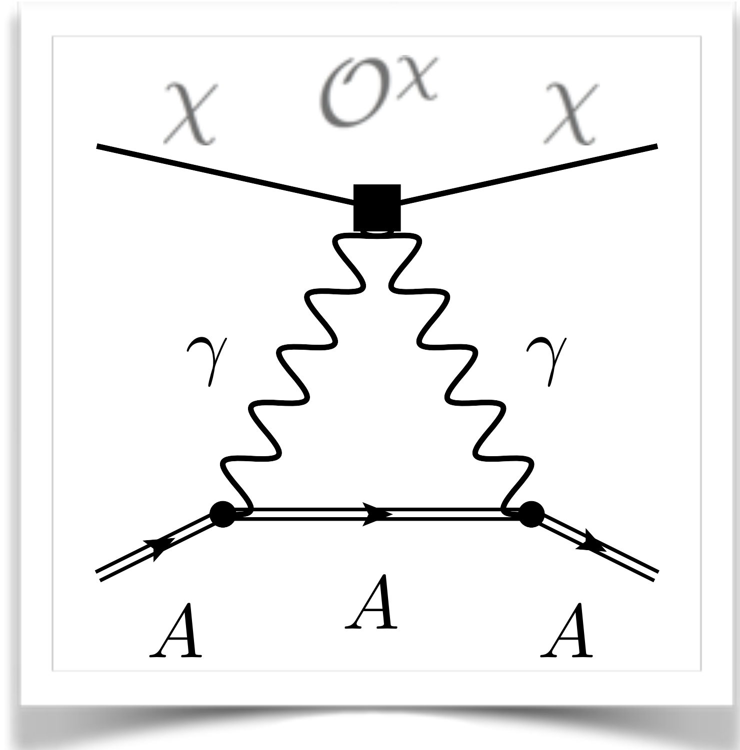


precise lattice results

Nuclear: Rayleigh scattering

- 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 ~ orders of magnitude
- 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



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

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

$$\sigma \simeq \frac{\mu_{n\chi}^2}{\pi A^2} \left\langle \left| \frac{c_F e^2}{m_\chi^3} f_F^A \right|^2 \right\rangle$$

[Pospelov & Veldhuis, Phys. Lett. B480 (2000) 181]
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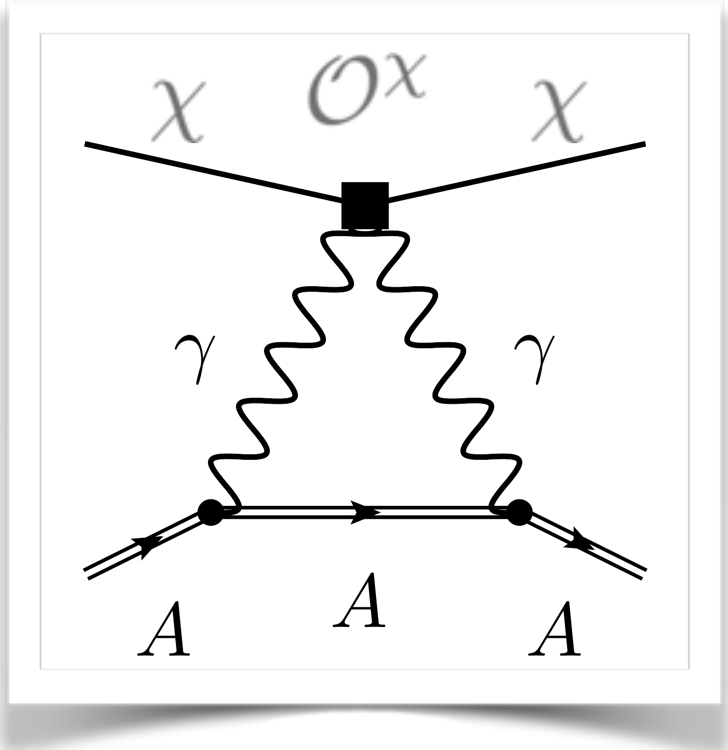

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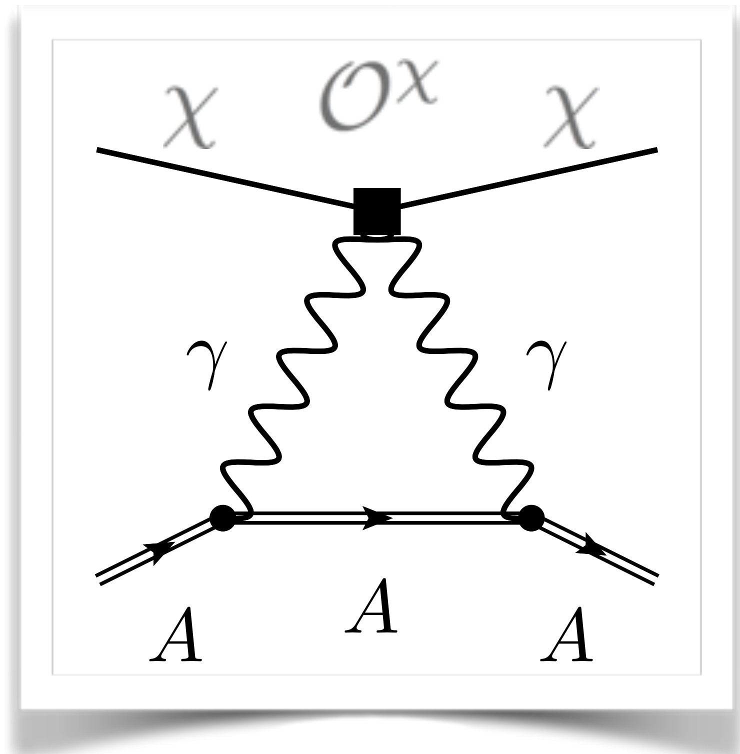

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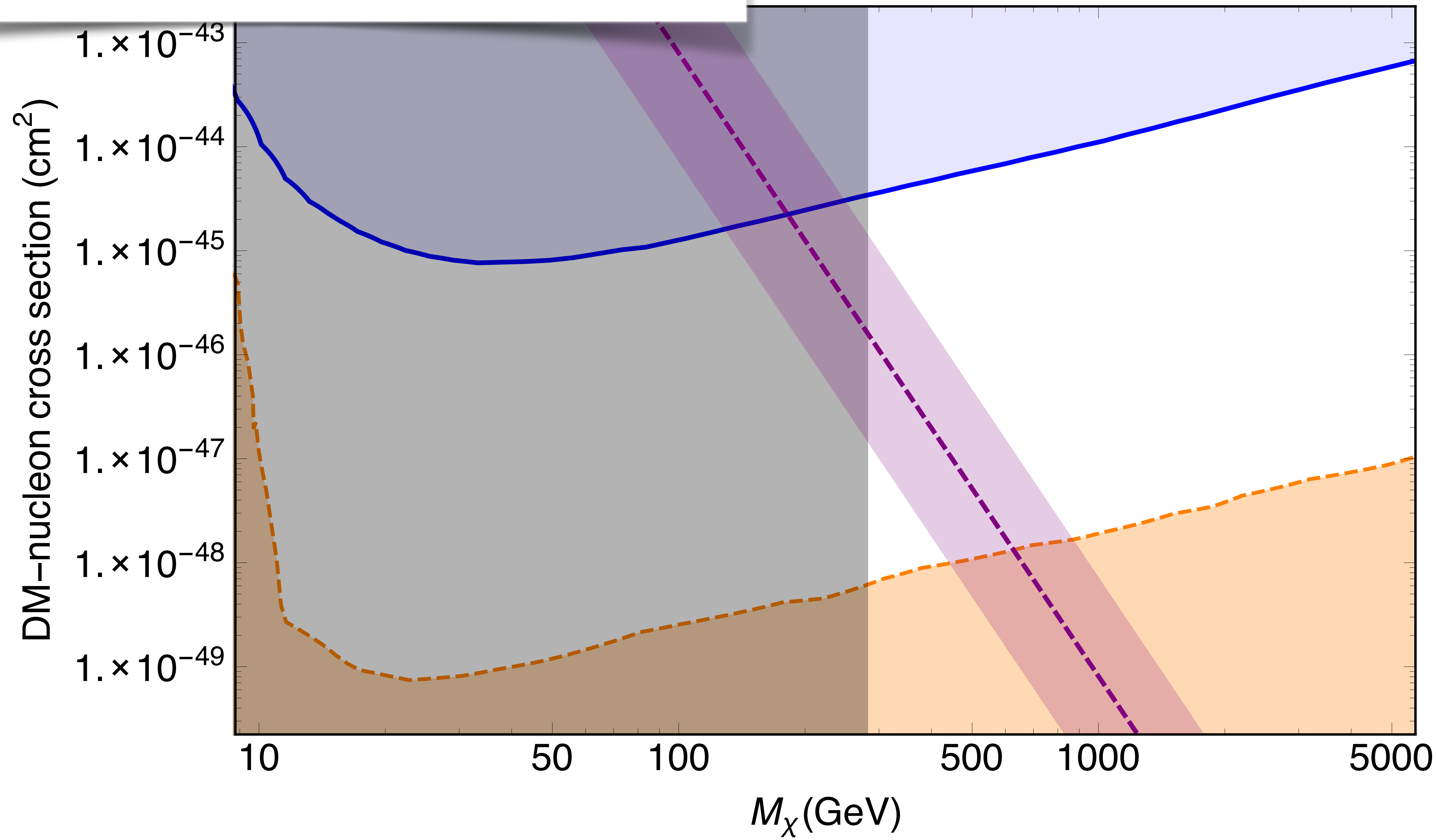
Stealth DM polarizability

$$\sigma_{\text{nucleon}}(Z,A) = \frac{Z^4}{A^2}\frac{144\pi\alpha^4\mu_{n\chi}^2(M_F^A)^2}{m_\chi^6 R^2}[c_F]^2$$



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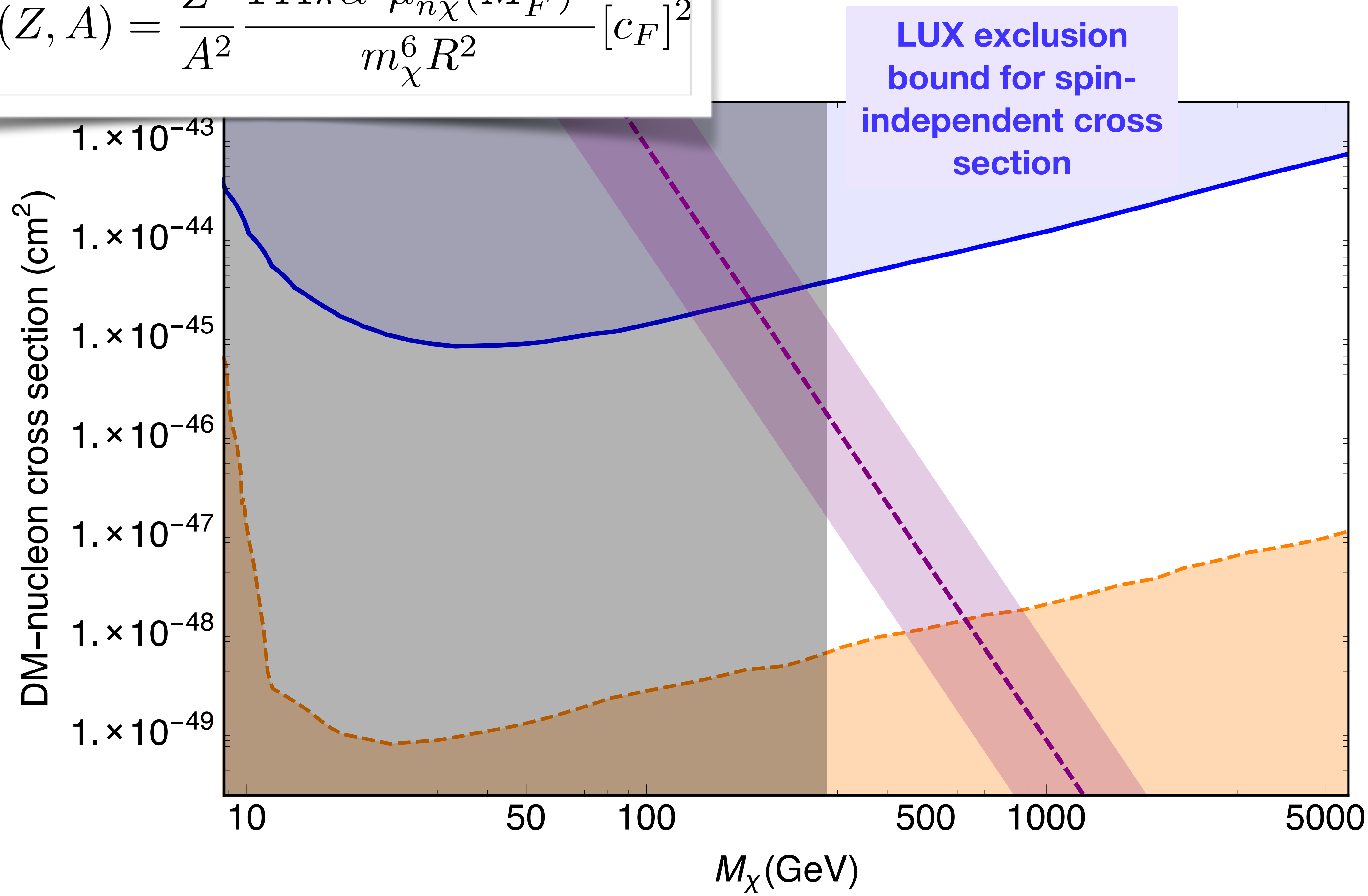

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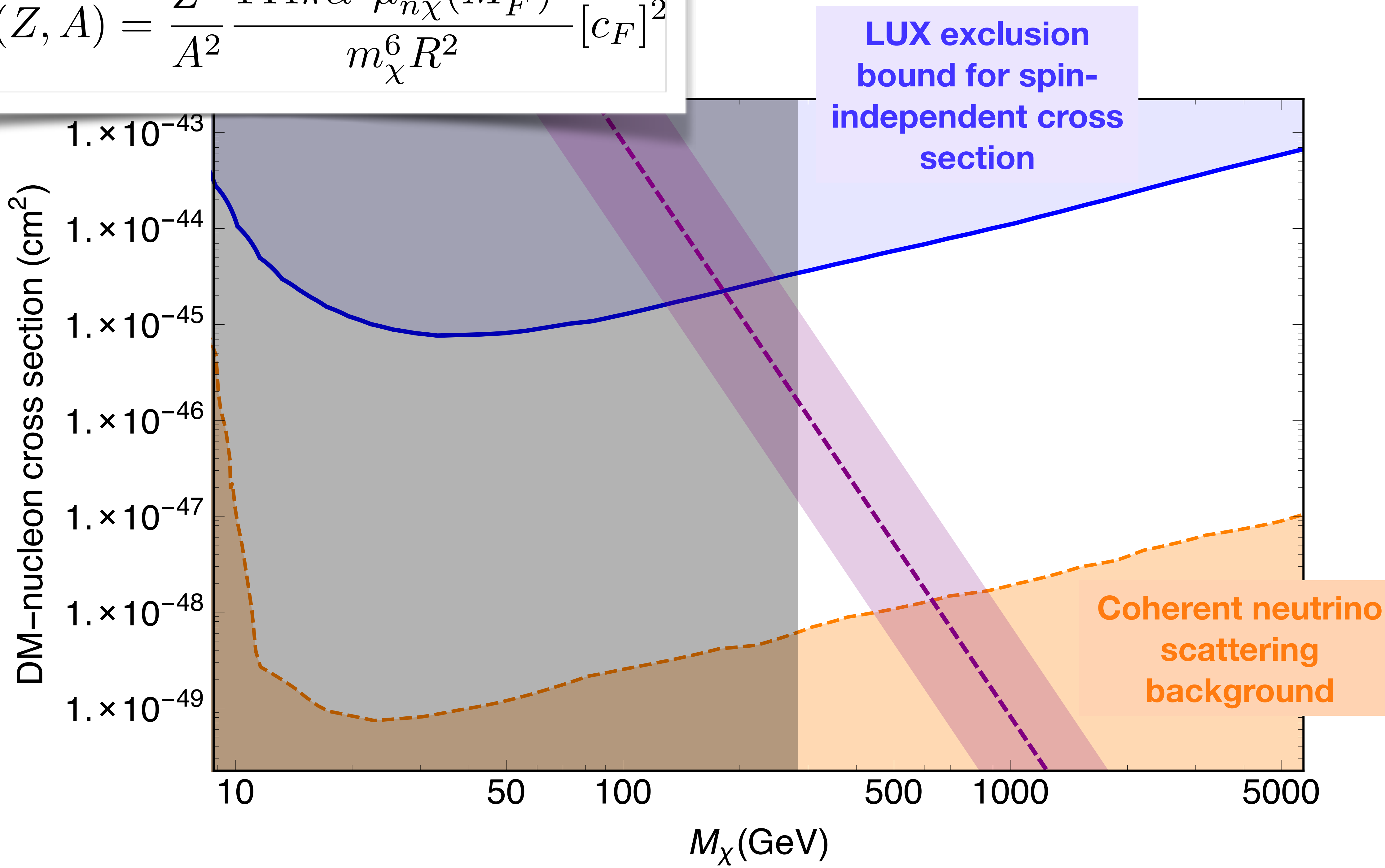

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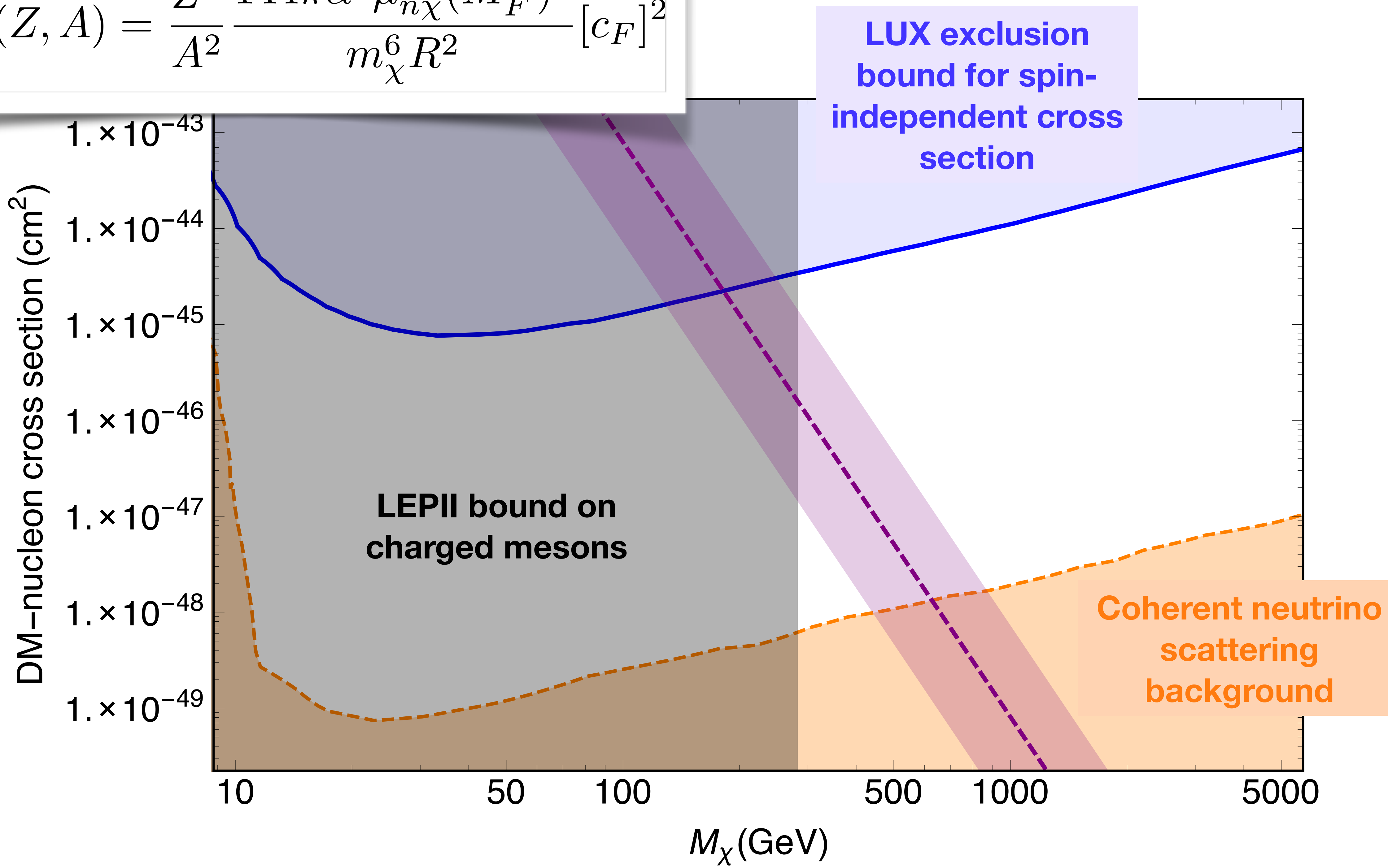

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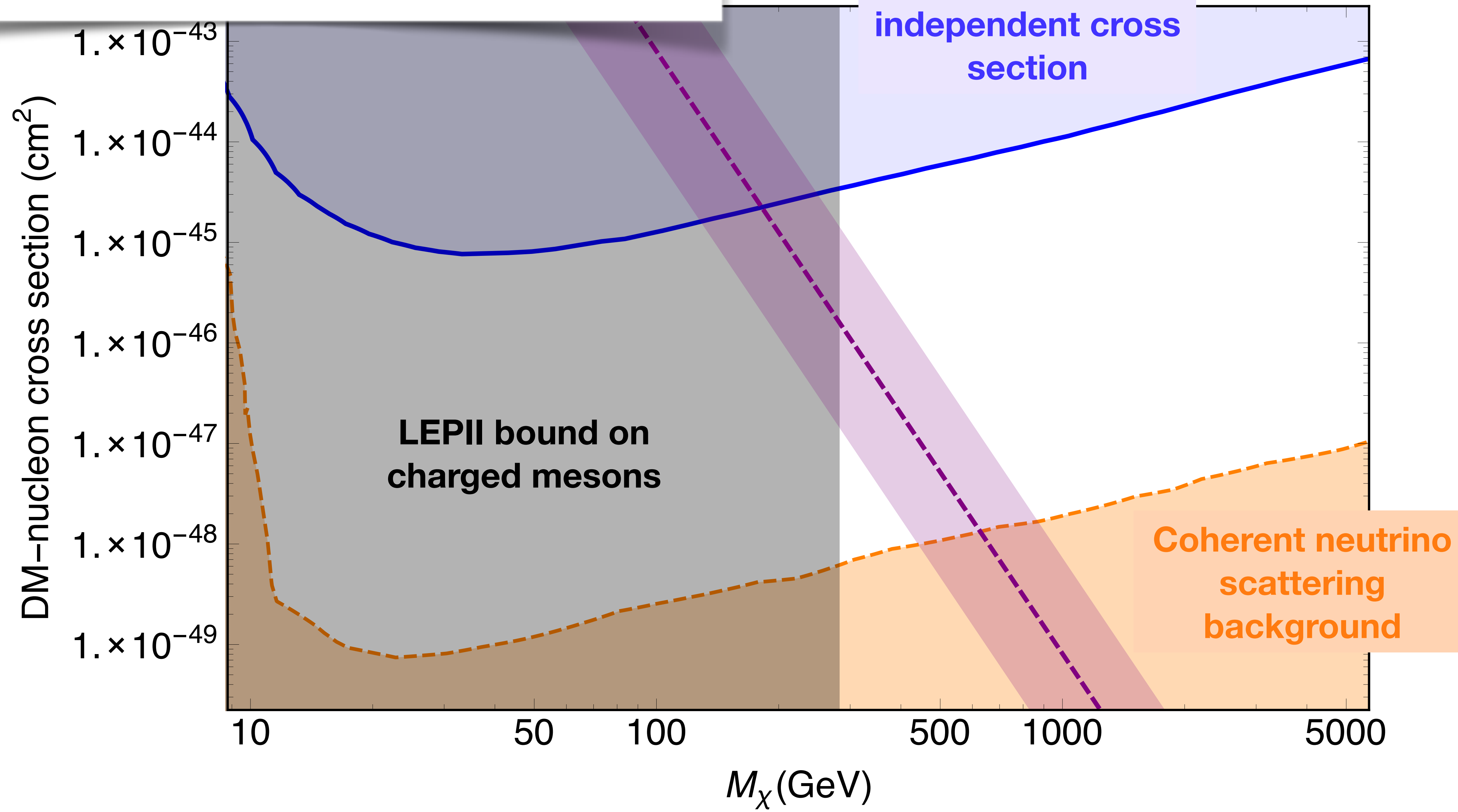
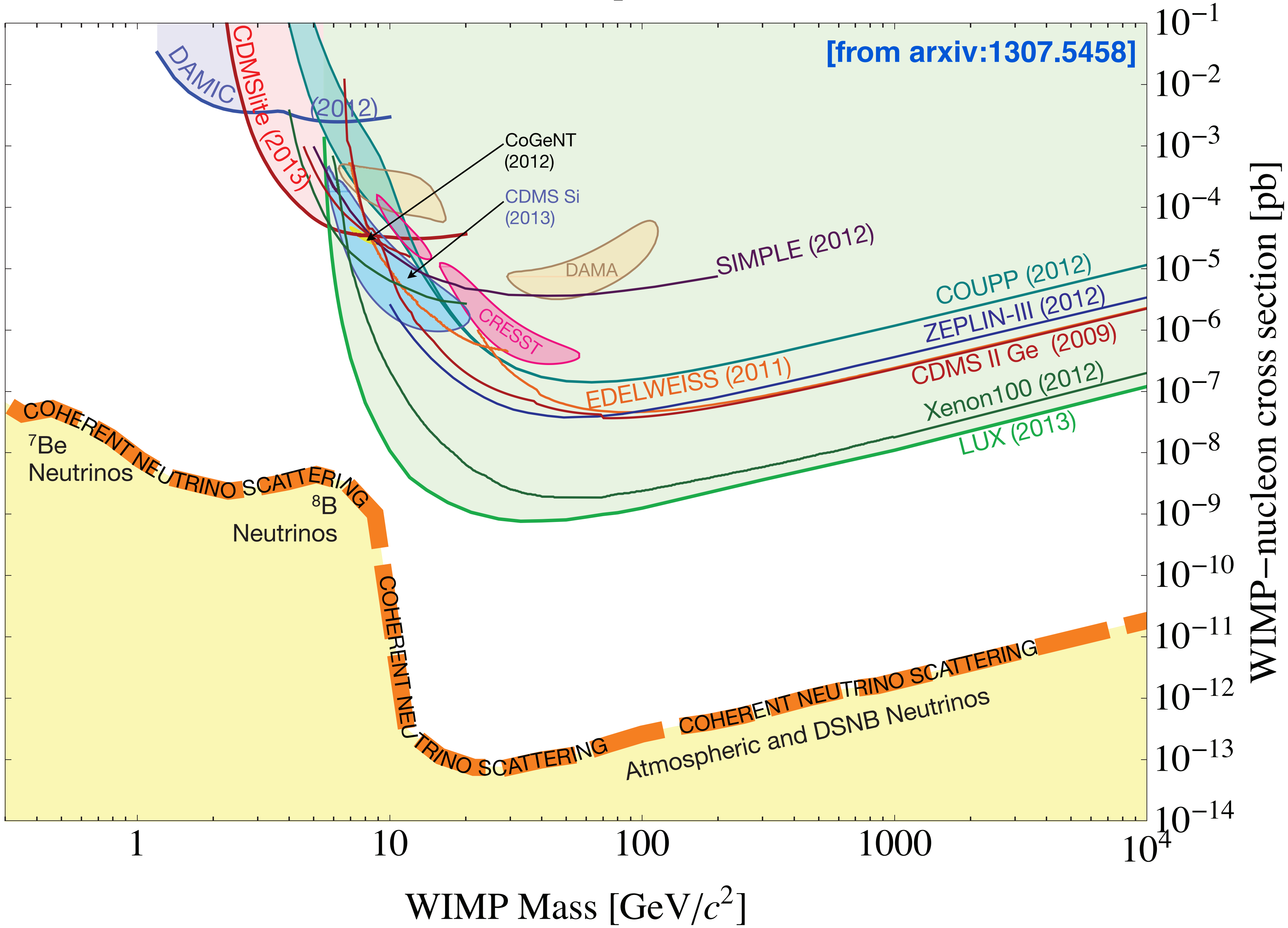


lowest allowed direct detection cross-section for composite dark matter theories with EW charged constituents

Stealth DM polarizability



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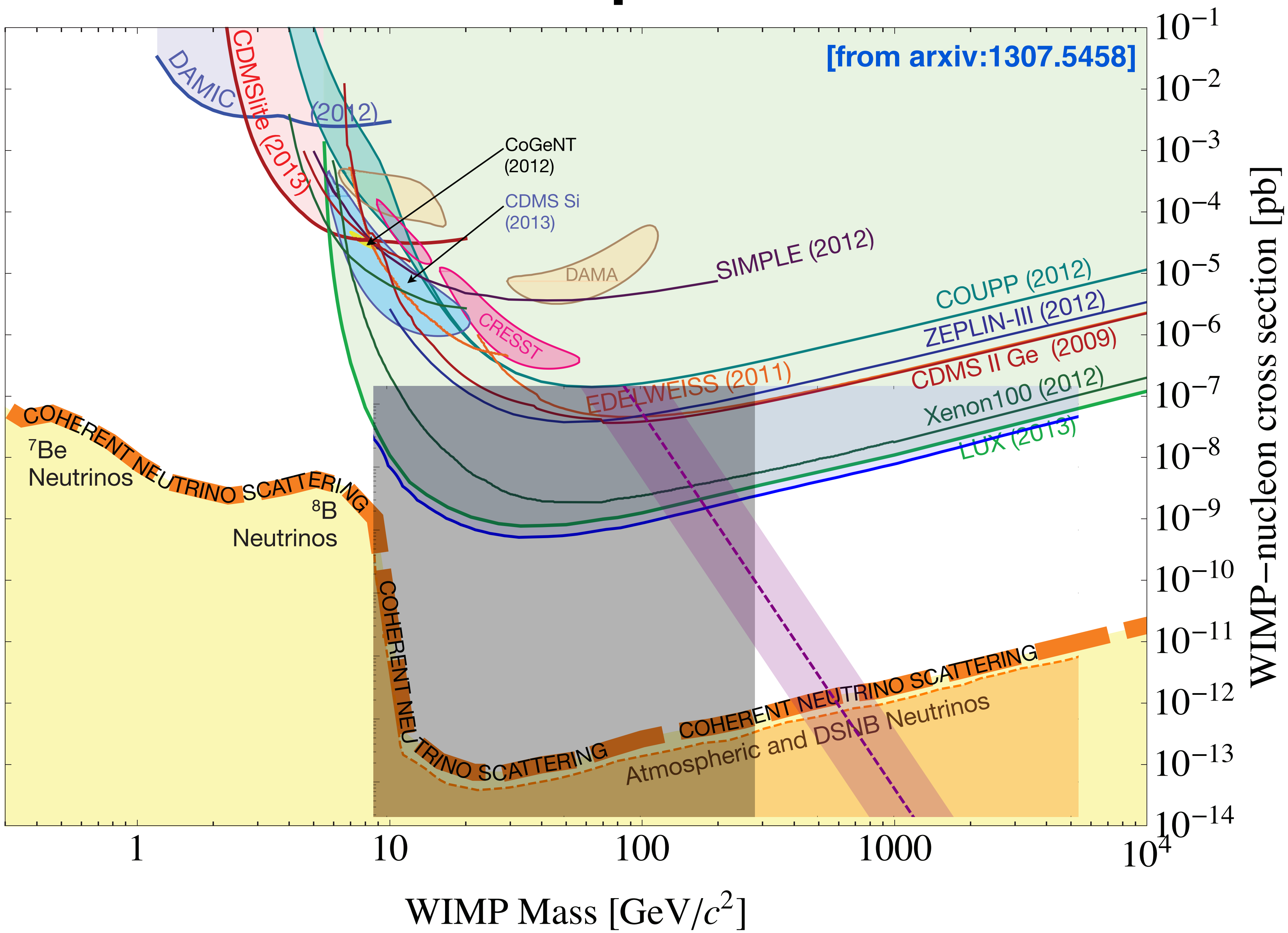


Direct detection signal is below the neutrino coherent scattering background for M_B>1TeV

Concluding remarks

- QCD ideas and lattice QCD techniques can be borrowed when exploring the DM landscape (BSM)
- Composite dark matter is a viable interesting possibility with rich phenomenology
- Lattice methods can help in calculating direct detection cross sections and production rates at colliders. Direct phenomenological relevance.
- Dark matter constituents can carry electroweak charges and still the stable composites are currently undetectable. Stealth cross section.

http://www.media.inaf.it/2015/09/25/materia-oscura-stealth/

MEDIA INAF
NOTIZIARIO ON-LINE DELL'ISTITUTO NAZIONALE DI ASTROFISICA

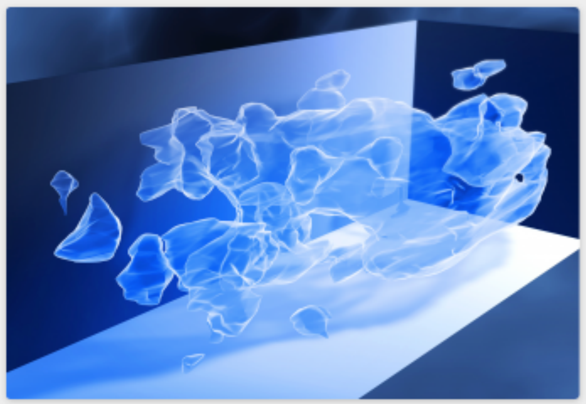
COME UN CACCIA INVISIBILE AI RADAR

Materia oscura "stealth"

Quark oscuri tenuti insieme da un'interazione forte a sua volta oscura. Ecco come la dark matter riuscirebbe a eludere a ogni tentativo d'incastrarla. Enrico Rinaldi (LLNL): «Esiste la possibilità che questo "mondo oscuro", con le sue nuove particelle, possa essere rivelato dagli esperimenti in corso al Large Hadron Collider al CERN di Ginevra»

di Marco Malaspina | Segui @malamiao | venerdì 25 settembre 2015 @ 16:15

Stealth come furtiva. *Stealth* come imprendibile. *Stealth* come quei minacciosi aerei da guerra dal profilo sagomato così da essere invisibili ai radar. Da quanto emerge dai calcoli dei fisici dell'LLNL, il Lawrence Livermore National Laboratory californiano, e dai modelli dati in pasto a Vulcan (un supercomputer per il calcolo parallelo in grado masticare numeri al ritmo dei *petaflop*), sarebbe questa la natura della materia oscura: *stealthy*, appunto. Per forza non c'è ancora esperimento che sia riuscito a incastrarla.



Mappa 3D della distribuzione su larga scala della materia oscura ricostruita da misure di lente gravitazionale debole utilizzando il telescopio spaziale Hubble

Di cos'è dunque fatta, questa materia della cui presenza abbiamo sentore grazie soltanto alla sua attrazione gravitazionale? Secondo la nuova teoria, avrebbe natura *composita* e *confinata*. Come un neutrone o un protone, quindi. Solo che a comporla sarebbero dei fermioni *dark*. Una sorta di "quark oscuri" confinati in nuclei di *stealth matter* da una forza anch'essa *dark* e sconosciuta: l'equivalente oscuro dell'interazione forte descritta dalla QCD, la cromodinamica quantistica.

«È davvero singolare che una candidata particella di materia oscura, centinaia di volte più pesante d'un protone, possa essere costituita da componenti elettricamente cariche e, nonostante questo, possa esser riuscita a eludere, fino a oggi, il rilevamento diretto», dice uno dei coautori dell'articolo, **Pavlos Vranas**, dell'LLNL.

Ma non è sempre stato così. Nell'epoca immediatamente successiva al big bang, per esempio, la temperatura era talmente elevata da presentare le condizioni giuste affinché materia ordinaria e materia *stealth* riuscissero a interagire senza difficoltà. Condizioni che, sostengono gli autori dello studio, disponendo di acceleratori sufficientemente potenti potrebbero essere ricreate anche oggi. Permettendo così una rilevazione diretta della *dark matter*. Questo perché, sebbene i nuclei di materia oscura *stealth* – proprio come i protoni – siano estremamente stabili anche su scale cosmiche, quando si creano (come avveniva nell'universo primordiale) dovrebbero produrre una cascata di altre particelle nucleari a decadimento rapido. Particelle che potrebbero dar luogo a interazioni.

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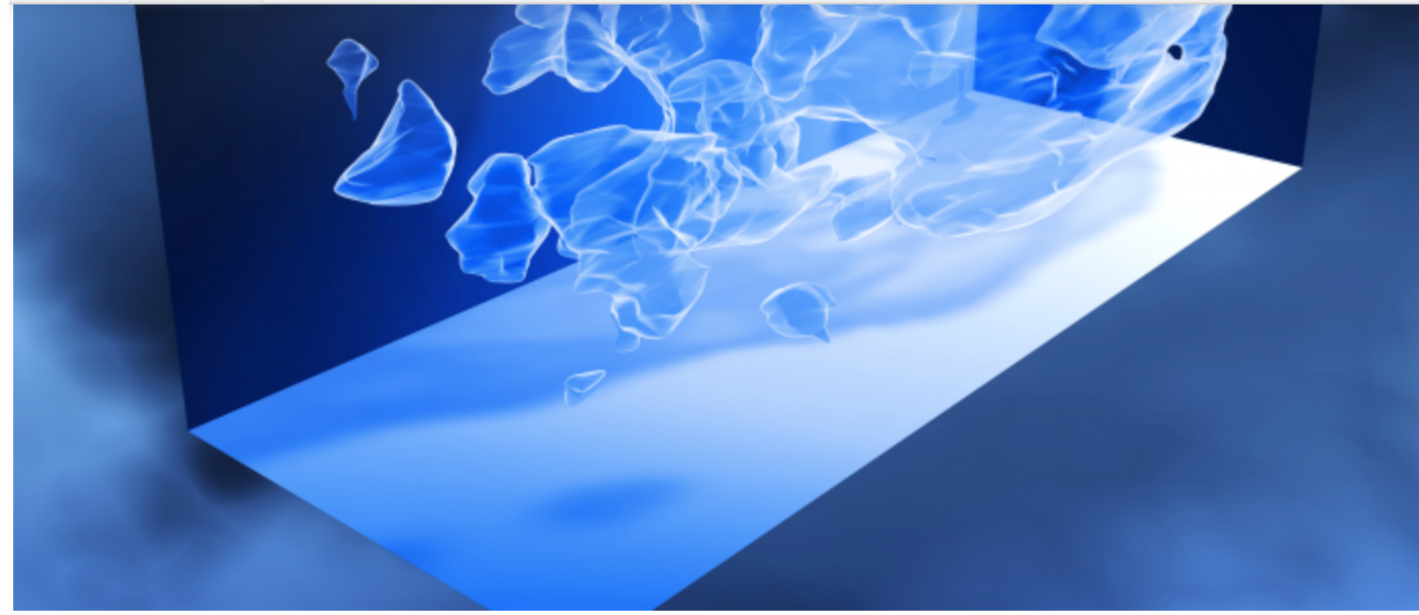
https://www.llnl.gov/news/new-stealth-dark-matter-theory-may-explain-mystery-universes-missing-mass



This 3D map illustrates the large-scale distribution of dark matter, reconstructed from measurements of weak gravitational lensing by using the Hubble Space Telescope. (Download Image)

New 'stealth dark matter' theory may explain mystery of the universe's missing mass

Lawrence Livermore National Laboratory (LLNL) scientists have come up with a new theory that may identify why dark matter has evaded direct detection in Earth-based experiments.

Anne M Stark
stark8@llnl.gov
925-422-9799

LINKS

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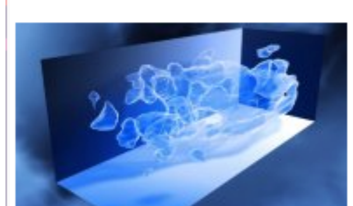
Le Scienze
EDIZIONE ITALIANA DI SCIENTIFIC AMERICAN

http://www.lescienze.it/news/2015/09/28/news/materia_oscura_stealth_matter_lhc-2779983

28 settembre 2015

Un nuovo modello per la materia oscura



Cortesia Lawrence Livermore National Laboratory

Questa forma misteriosa di materia potrebbe avere una struttura composita come la materia ordinaria, con "quark oscuri" aggregati e tenuti insieme da un analogo della forza che permette ai normali nuclei di rimanere stabili. I componenti di questo tipo di materia oscura, definita stealth matter, potrebbero essere studiati in modo indiretto dal collisore Large Hadron Collider del CERN di Ginevra *(red)*