Stealth Dark Matter on the lattice

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Lattice Strong Dynamics Collaboration

LLNL-PRES-669543

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

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

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

lightest baryon is a spin=0 boson

- Let dark fermions have current/chiral masses together with vector-like masses

avoid issues with charged dark mesons

- Let dark fermions masses to be at the dark confinement scale

lighter masses are more strongly constrained by collider bounds

- Assign electroweak charges to dark fermions

allow SM interactions necessary for DM production and detection

- The symmetry group is U(4)xU(4) and with generic masses it breaks down to U(1) (dark baryon number)

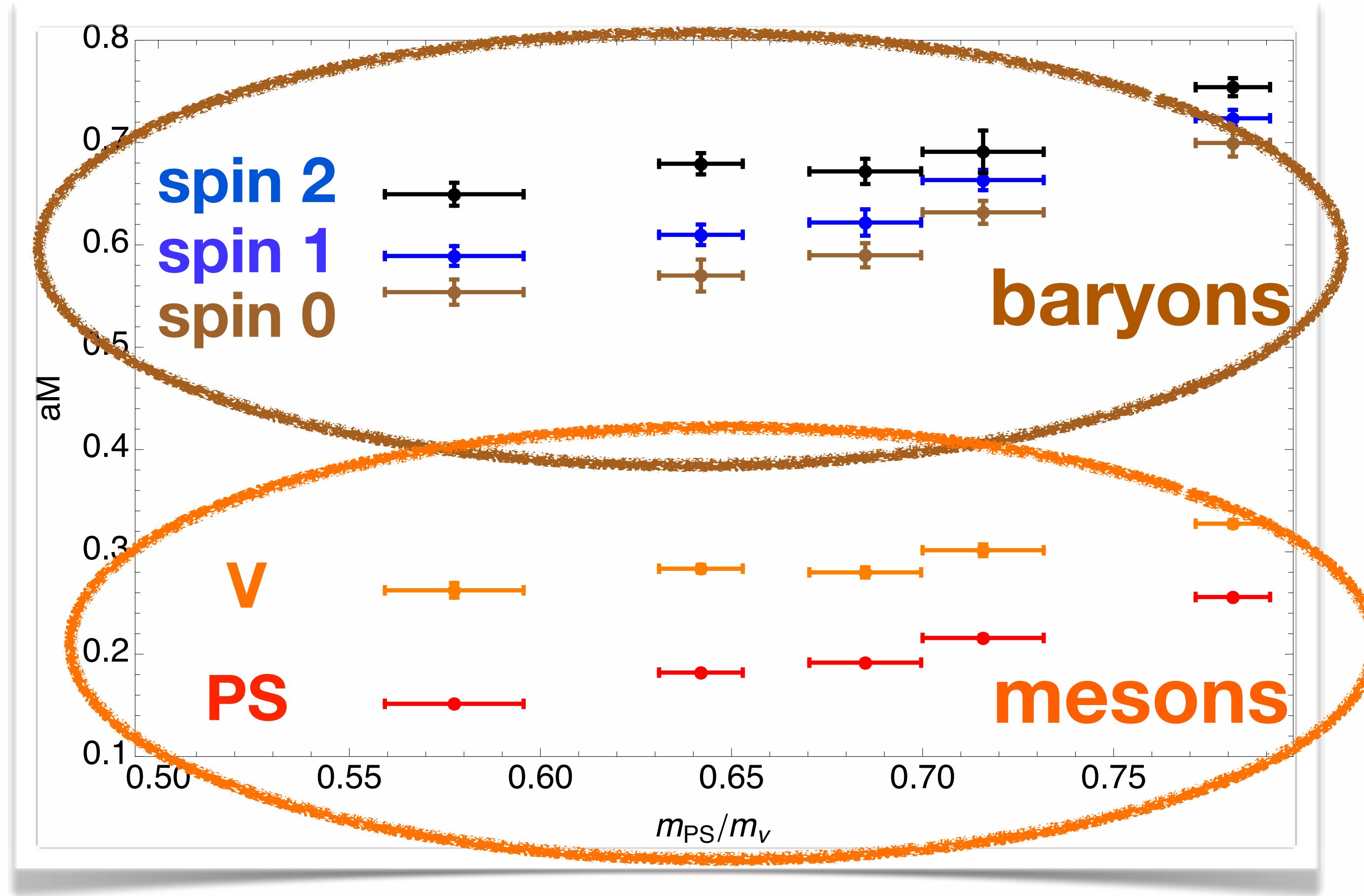
the only stable particle is the lightest baryon

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]

Lattice Stealth DM

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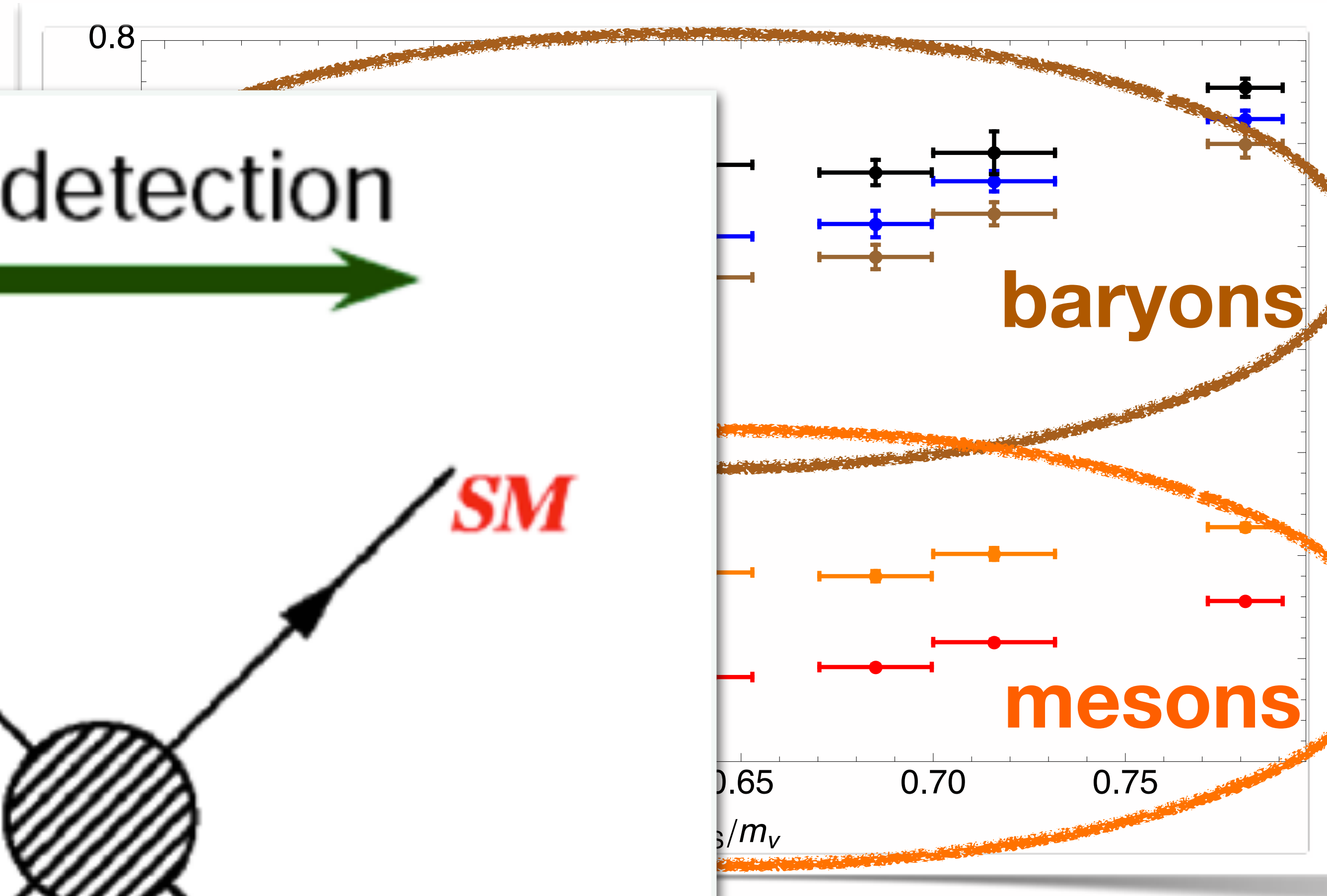

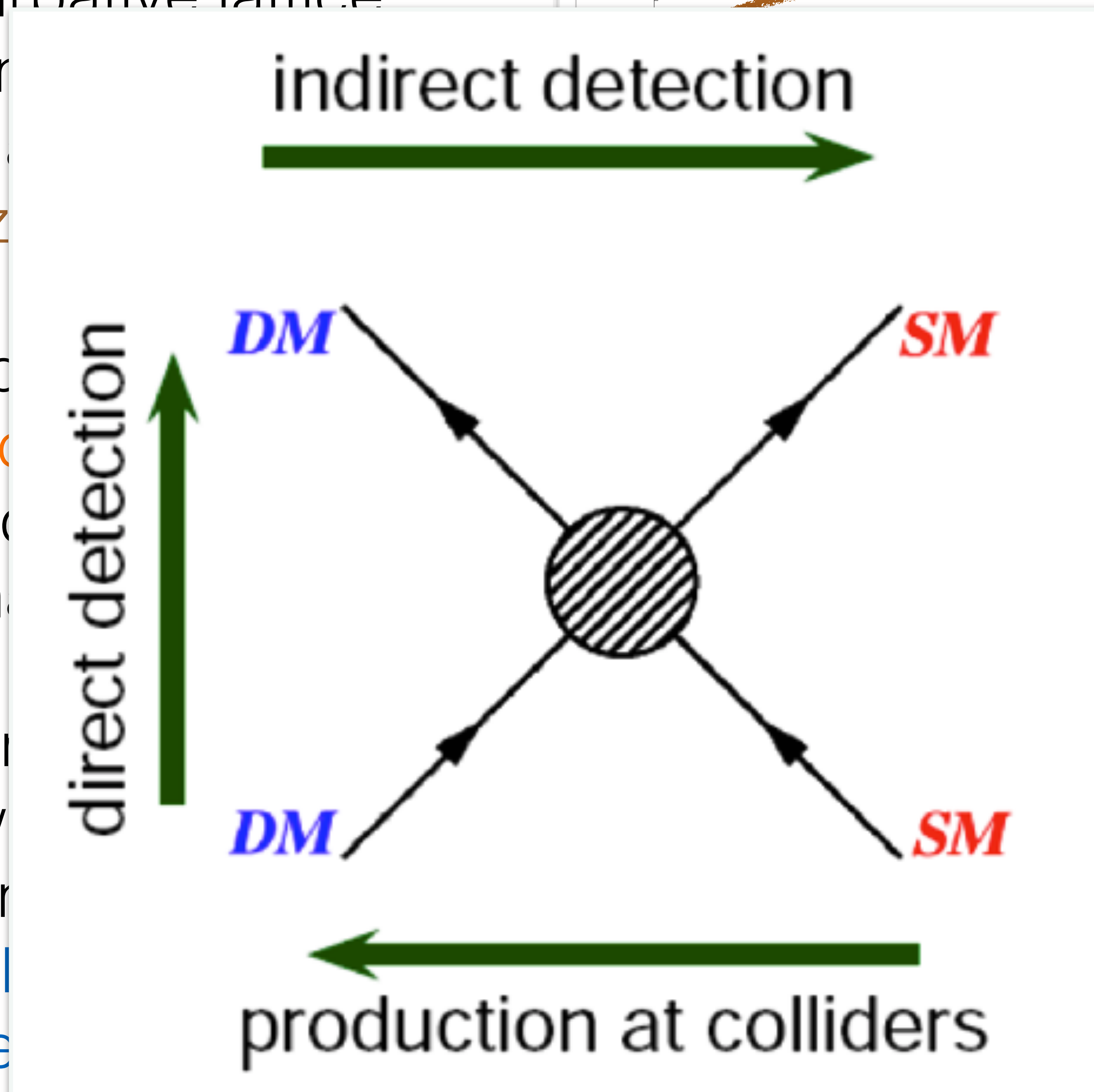

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[LSD collab., Phys. Rev. D89 (2014) 094508]

“How dark is Stealth DM?”

Interactions of dark fermions with Higgs

+

Interactions of dark baryon with photon through form factors

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

- ~~dimension 5 ➥ magı ple~~ spin 0 $\cancel{\frac{(\bar{\chi}\sigma^{\mu\nu}\chi)F_{\mu\nu}}{\Lambda_{\mathrm{dark}}}}$

- ~~dimension 6 ➥~~ custodial SU(2) $\cancel{\frac{(\bar{\chi}\chi)v_{\mu}\partial_{\nu}F^{\mu\nu}}{\Lambda_{\mathrm{dark}}^{2}}}$

- dimension 7 ➥ polarizability $\frac{(\bar{\chi}\chi)F_{\mu\nu}F^{\mu\nu}}{\Lambda_{\mathrm{dark}}^{3}}$

[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

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

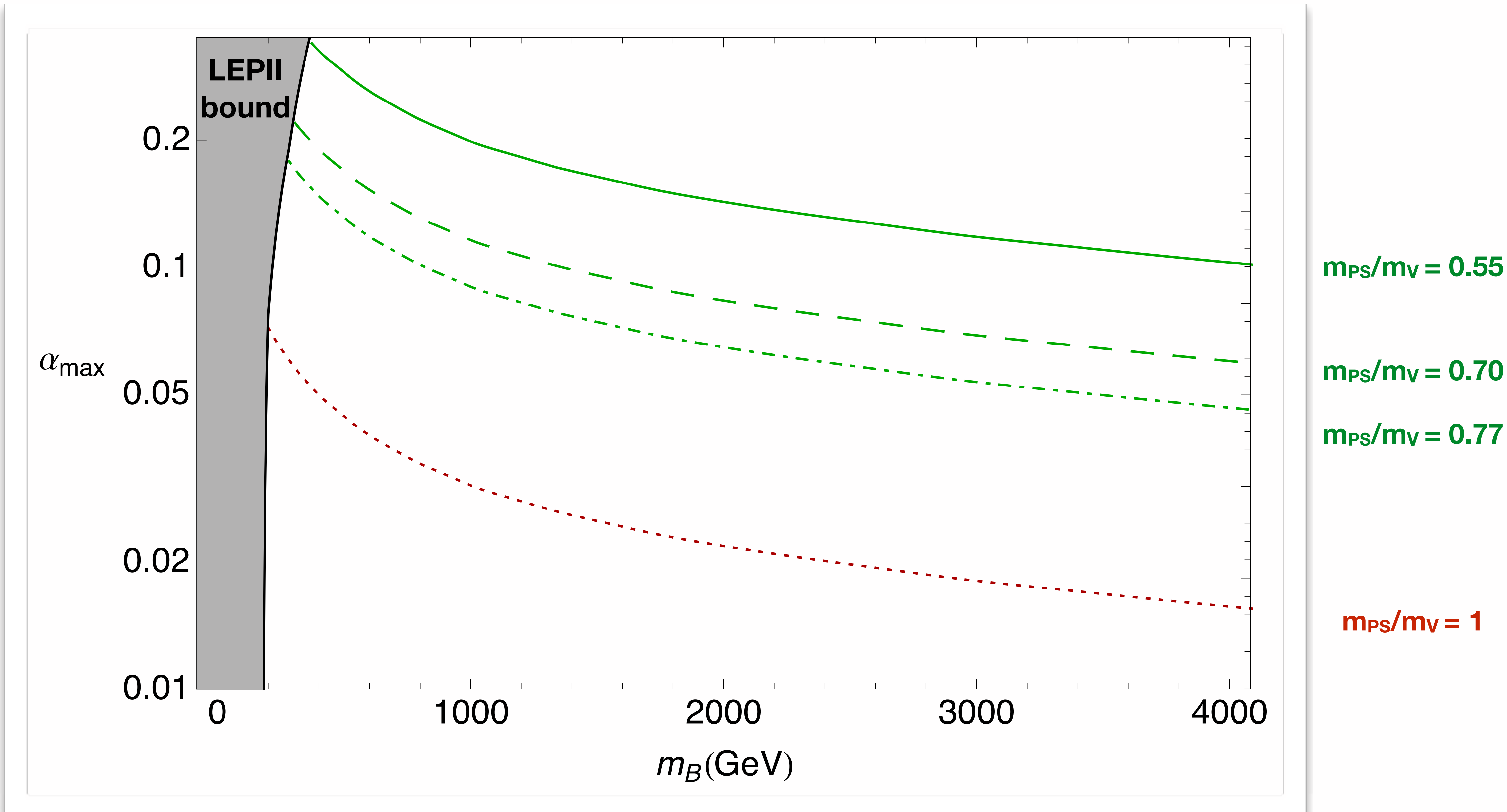
$$m_f(h) = m + \frac{y_f h}{\sqrt{2}}$$

Lattice!

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

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

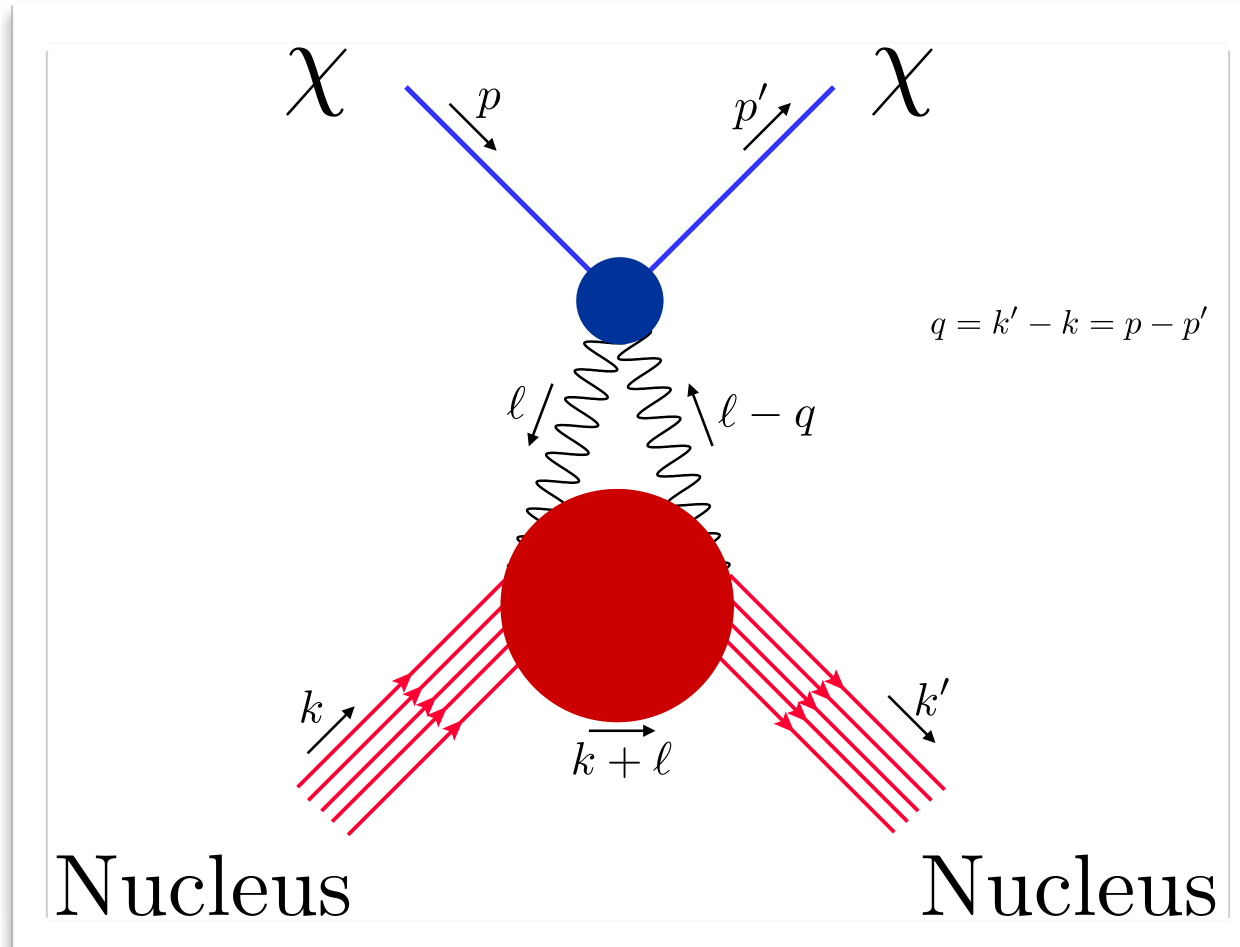
Bounds on the coupling



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

Electromagnetic polarizability

- **NO** magnetic dipole moment:
  - lightest stable baryon is a boson with S=0
- **NO** charge radius:
  - 2 flavors with degenerate masses $m_u = m_d$
- **Polarizability** can not be removed



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

Electromagnetic polarizability

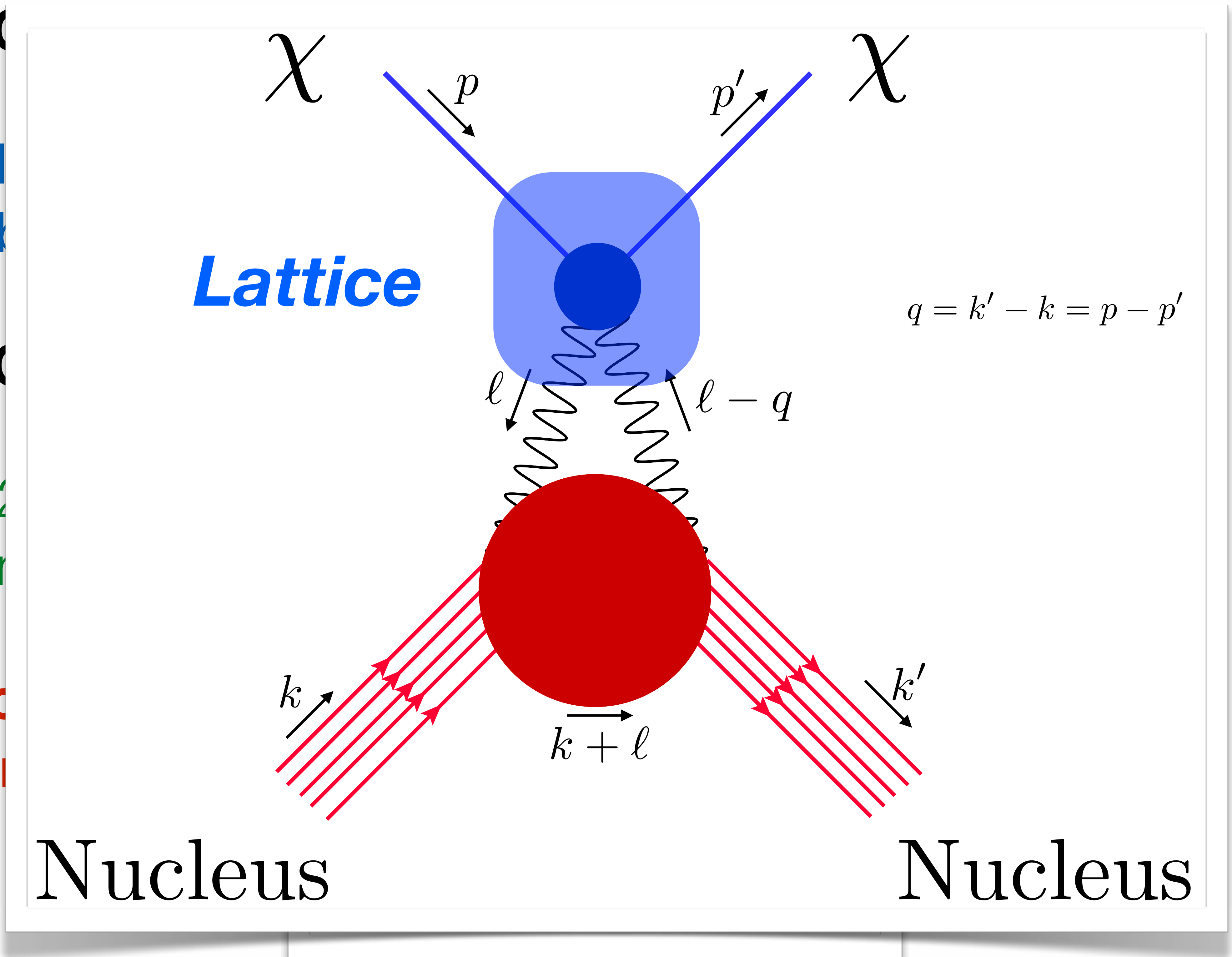
- **N**

  - I
    k

- **N**

  - 2
    r

- **Po**
  re



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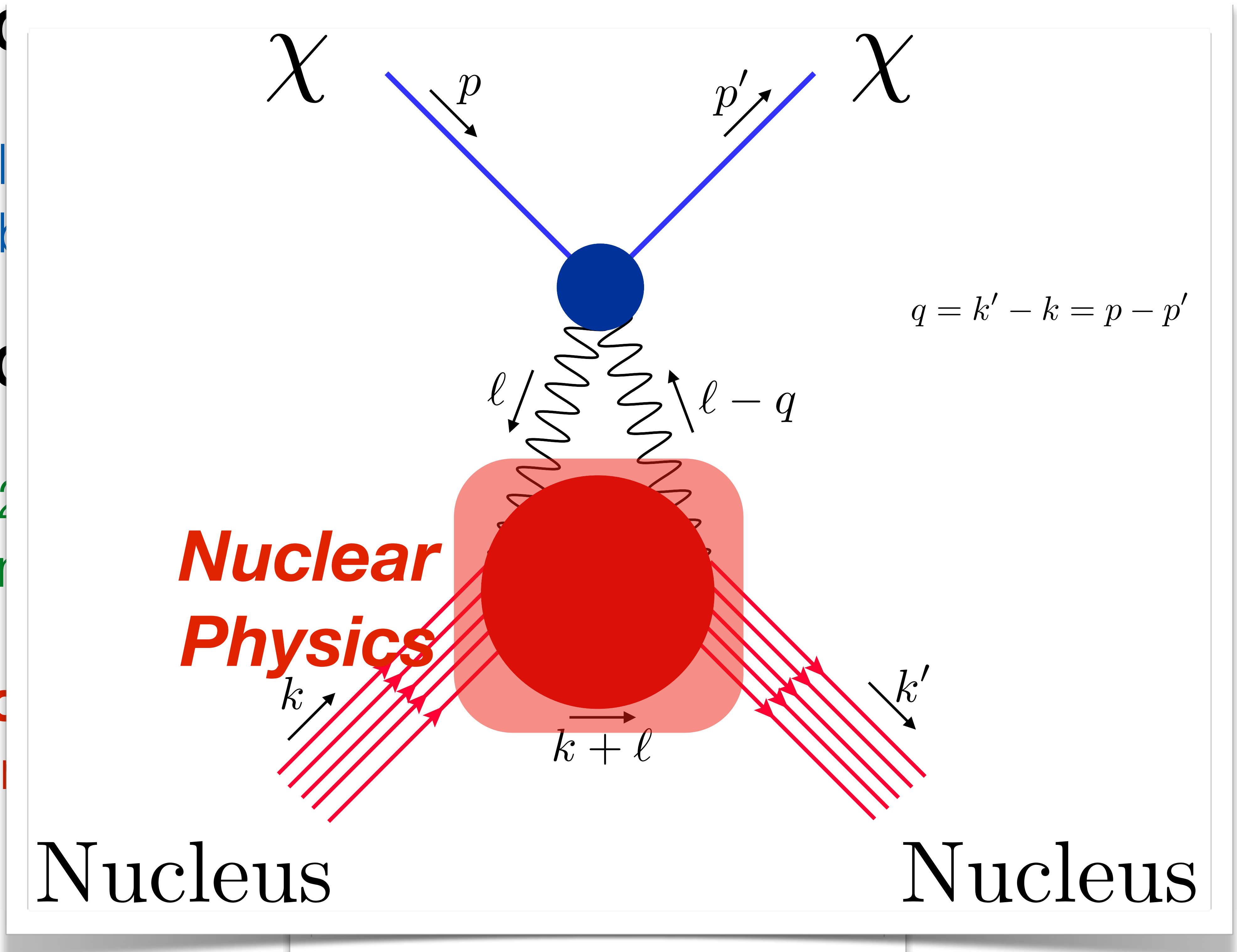


[LSD collab., arxiv:1503.04203]

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

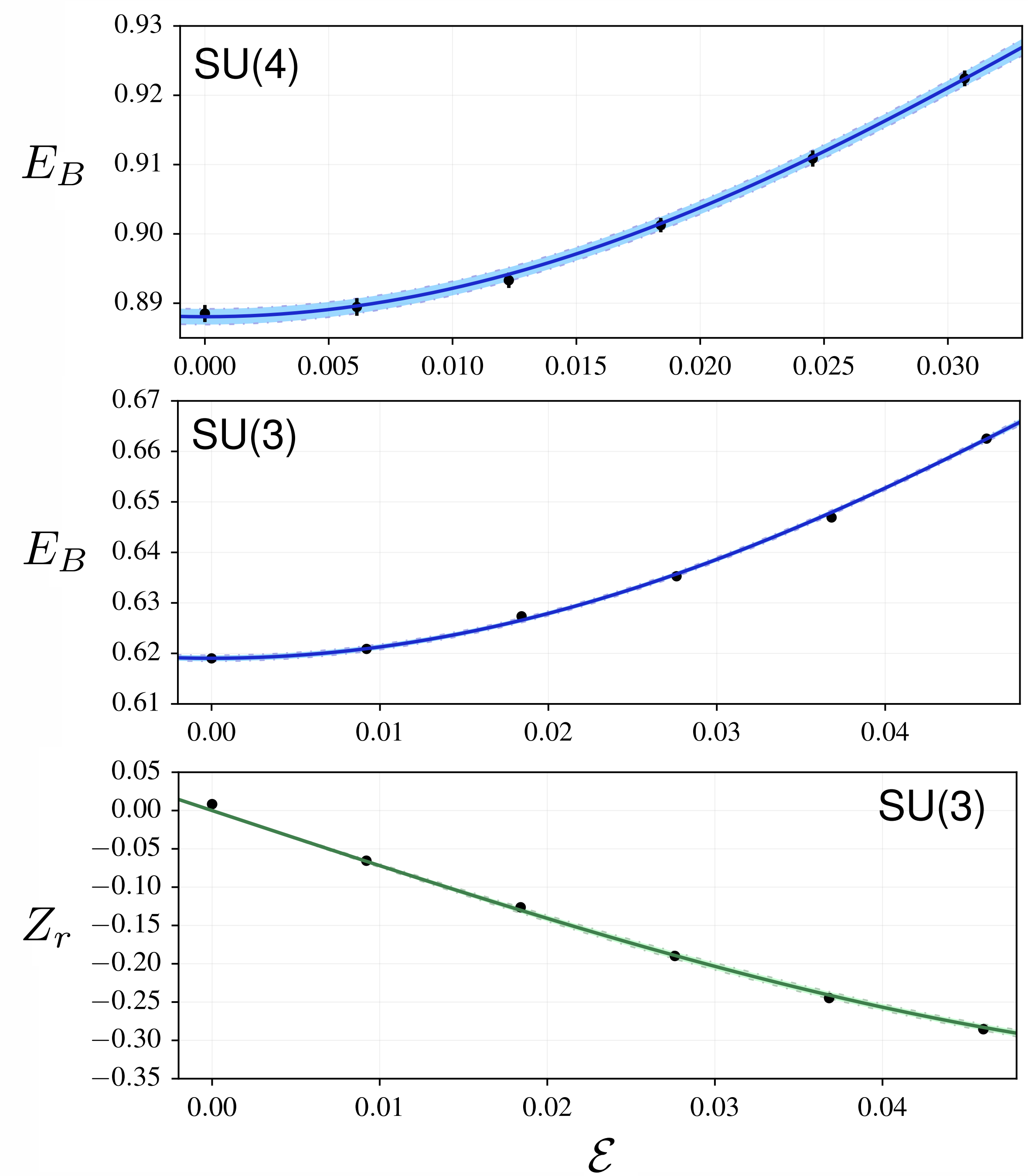
Lattice: Polarizability of DM

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

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

$$E_{B,3c} = m_B + \left(2C_F - \frac{{\mu_B}^2}{8m_B^3}\right)|\mathcal{E}|^2 + \mathcal{O}\left(\mathcal{E}^4\right)$$

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

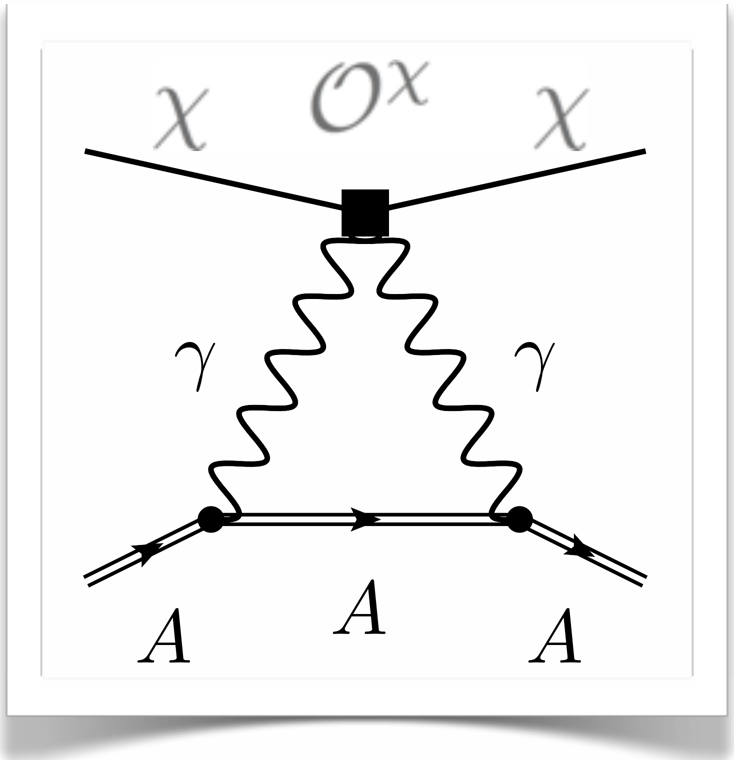


precise lattice results

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

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

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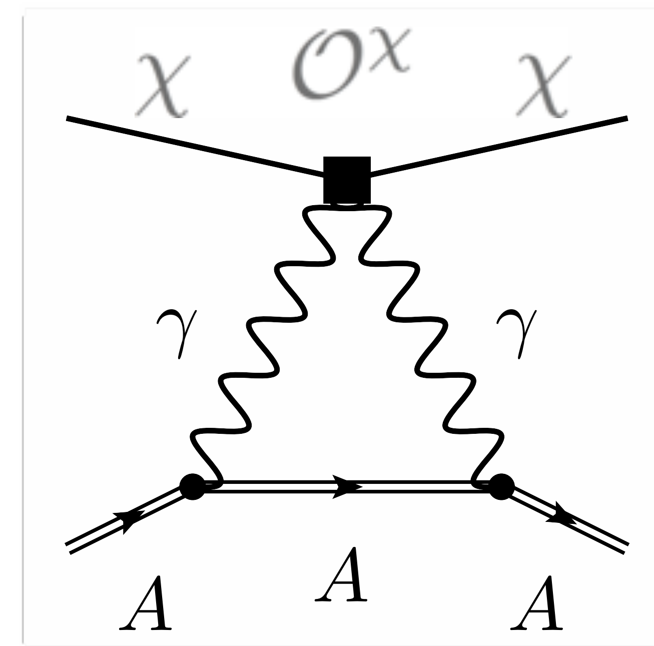

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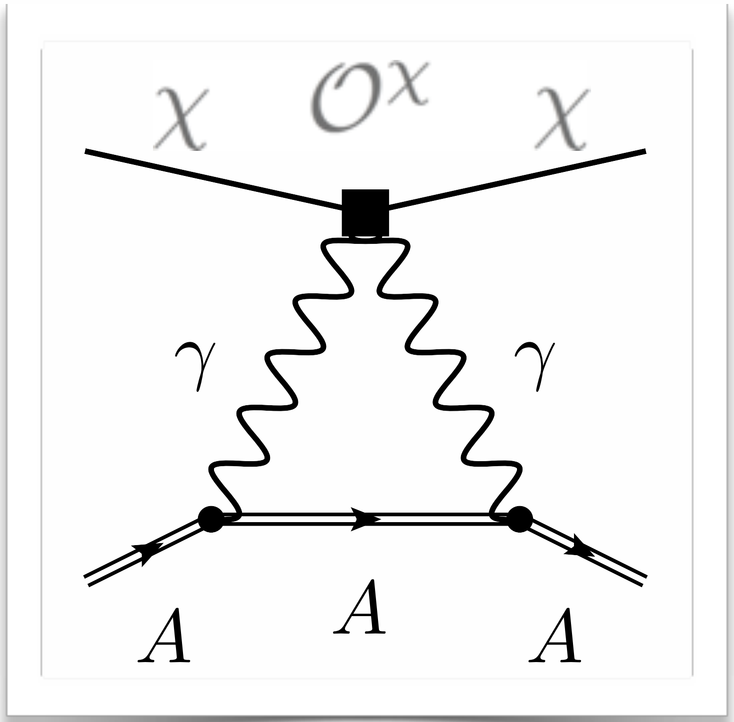
similar structure arising in double beta decay matrix elements.

Interesting nuclear physics problem!

Estimate for $\langle A|F^{\mu\nu}F_{\mu\nu}|A\rangle$

- 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 ~ orders of magnitude



- to asses the impact of uncertainties on the total cross section we start from naive dimensional analysis

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

- we allow a "magnitude" factor M_F^A to change from 0.3 to 3

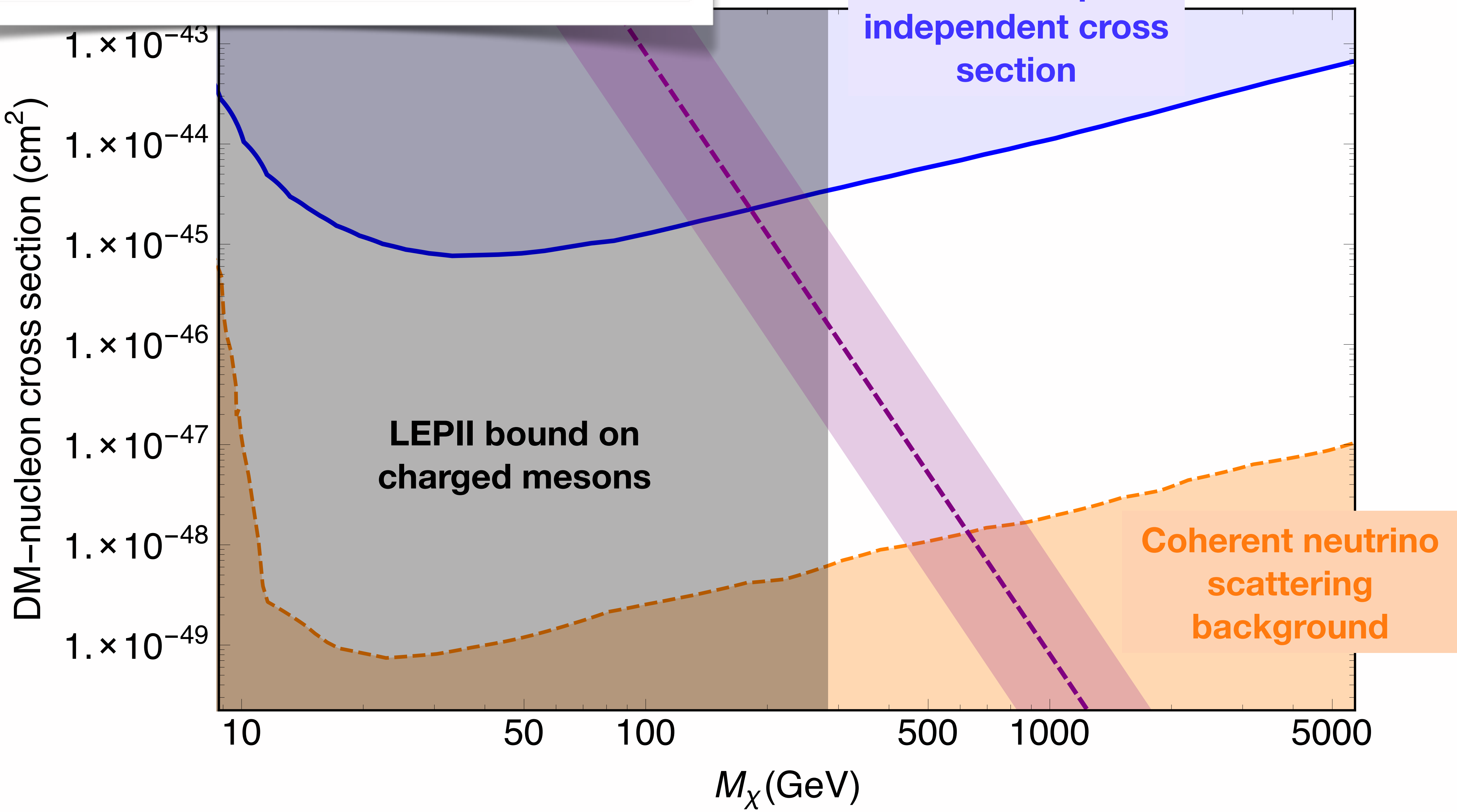
$$f_F^A \sim 3\,Z^2\,\alpha\,\frac{M_F^A}{R}$$

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

[LSD collab., arxiv:1503.04203]

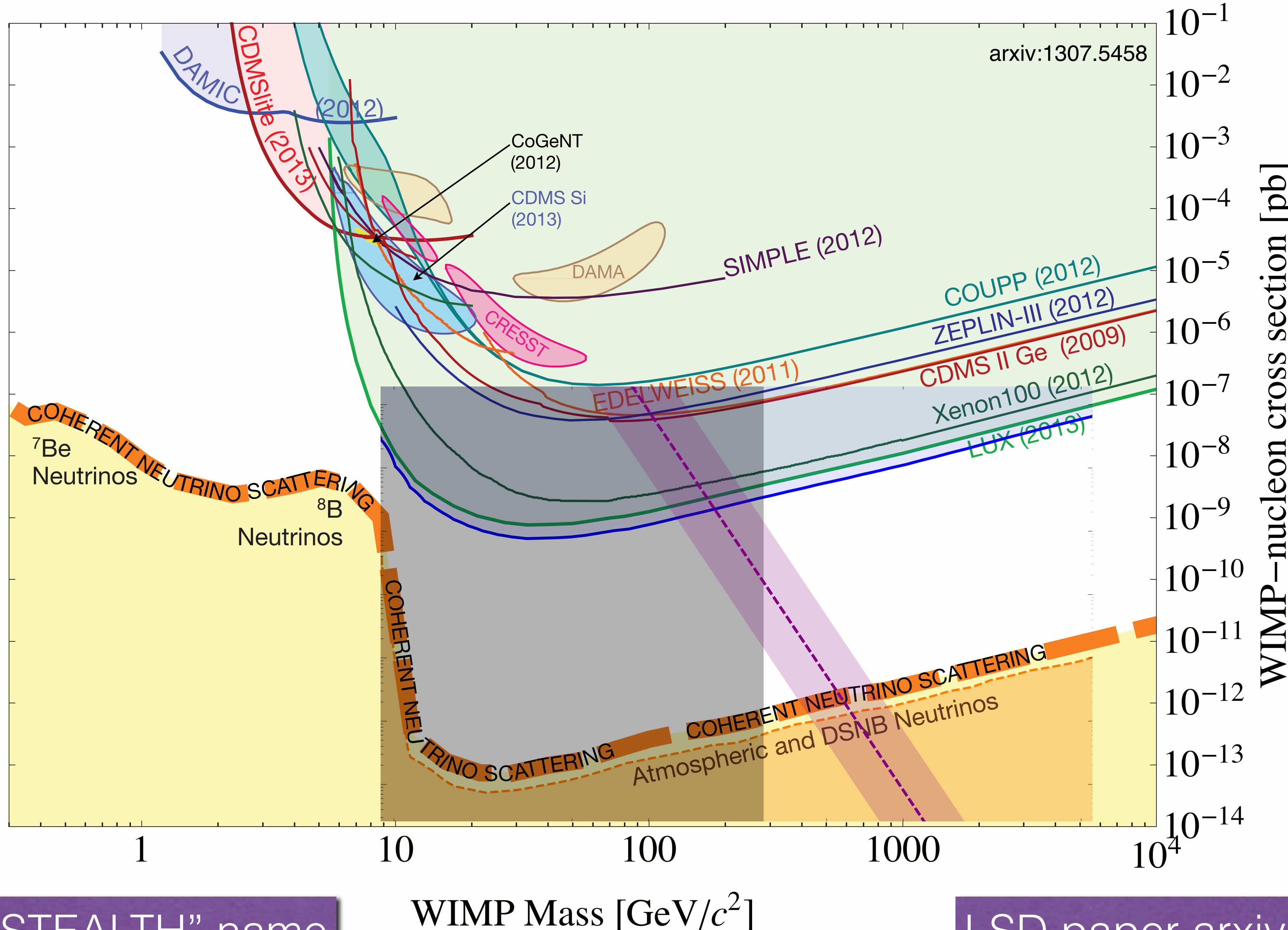
Stealth DM Polarizability

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



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

Stealth DM Polarizability



Reason for “STEALTH” name

LSD paper arxiv:1503.04205

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!
- Abundance can arise either by symmetric thermal freeze-out or by asymmetric baryogenesis.
- Composite dark matter is a viable interesting possibility, but needs non-perturbative lattice input due to strong coupling