Strongly-coupled composite dark matter and lattice field theory

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Lattice **S**trong **D**ynamics collaboration

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Outline

- Features of strongly-coupled composite dark matter
- Searching for a class of models: guidelines
- Importance of lattice field theory simulations
- Polarizability of composite dark matter

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in the end it's a nuclear physics problem!

Strongly-coupled composite dark matter

- Dark matter is a composite object
- Composite object is electroweak neutral
- Constituents can have electroweak charges
- Dark matter is stable thanks to a global symmetry (like baryon number)

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- 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
- 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. neutron)

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we construct a minimal model with these features

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today focus on the general features

[Pospelov & Veldhuis, Phys. Lett. B480 (2000) 181]
[Weiner & Yavin, Phys. Rev. D86 (2012) 075021]

"How dark is dark matter?"

Interactions of neutral object with **photons**

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

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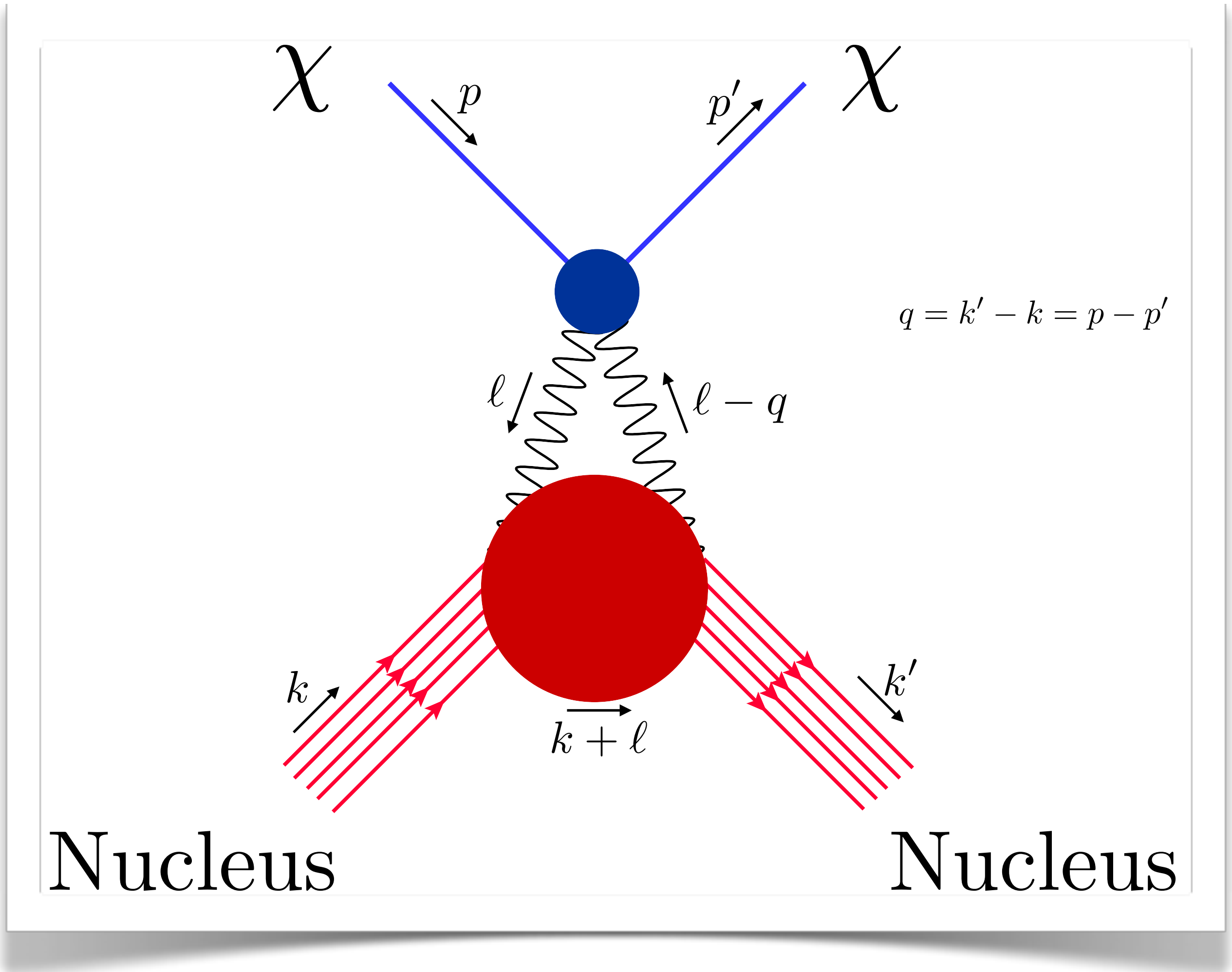
our guy for today

Electromagnetic polarizability

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

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



Electromagnetic polarizability

- remov
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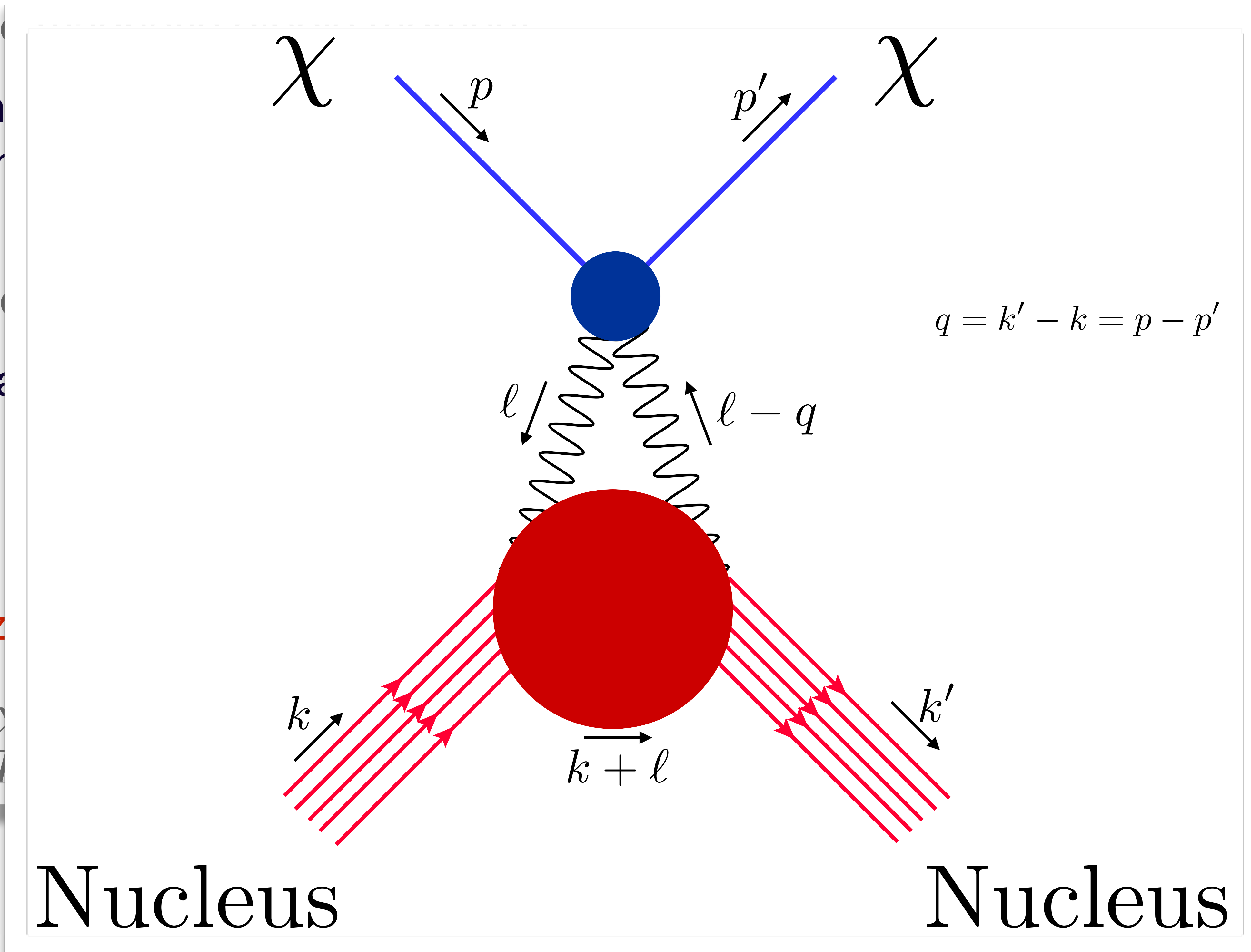

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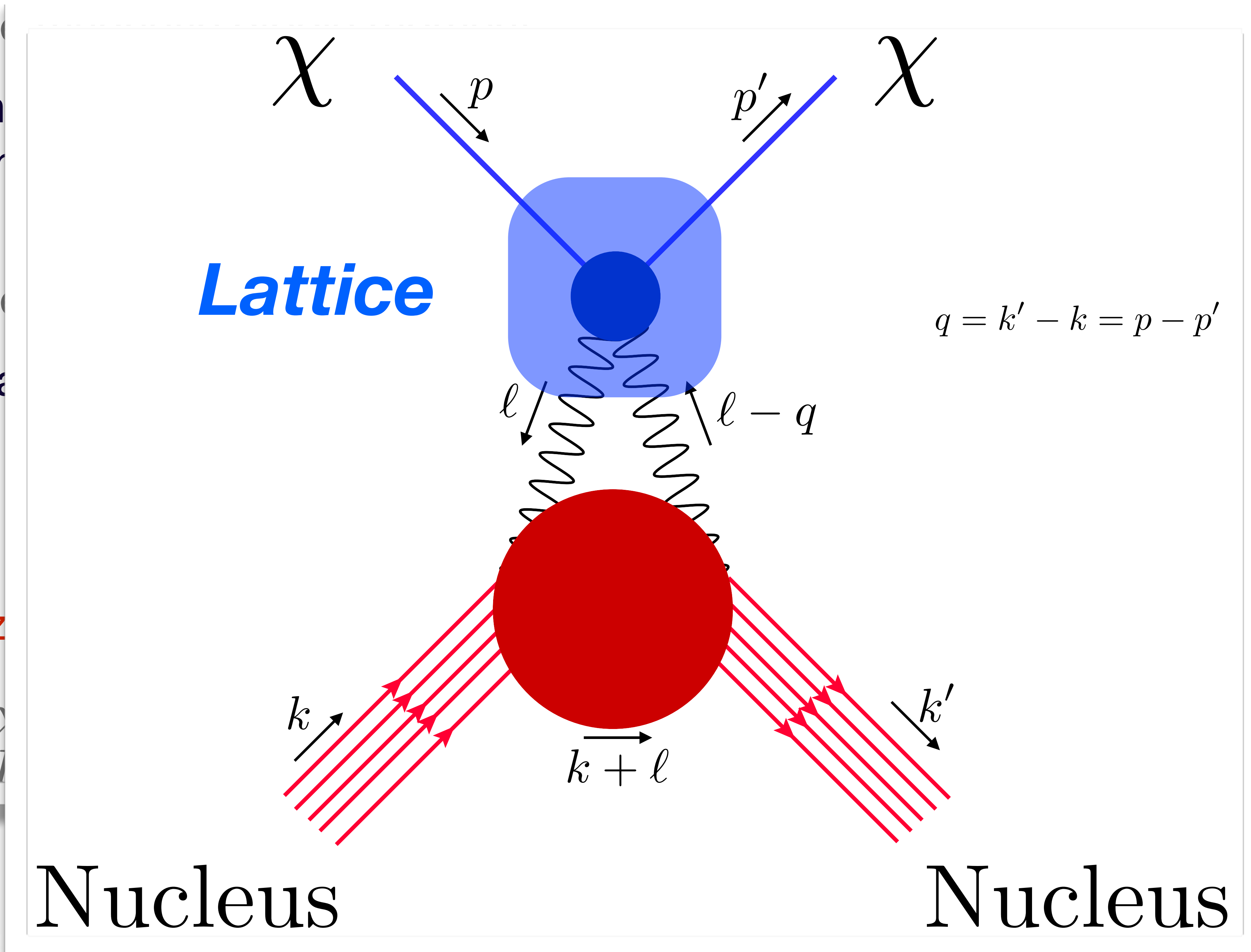

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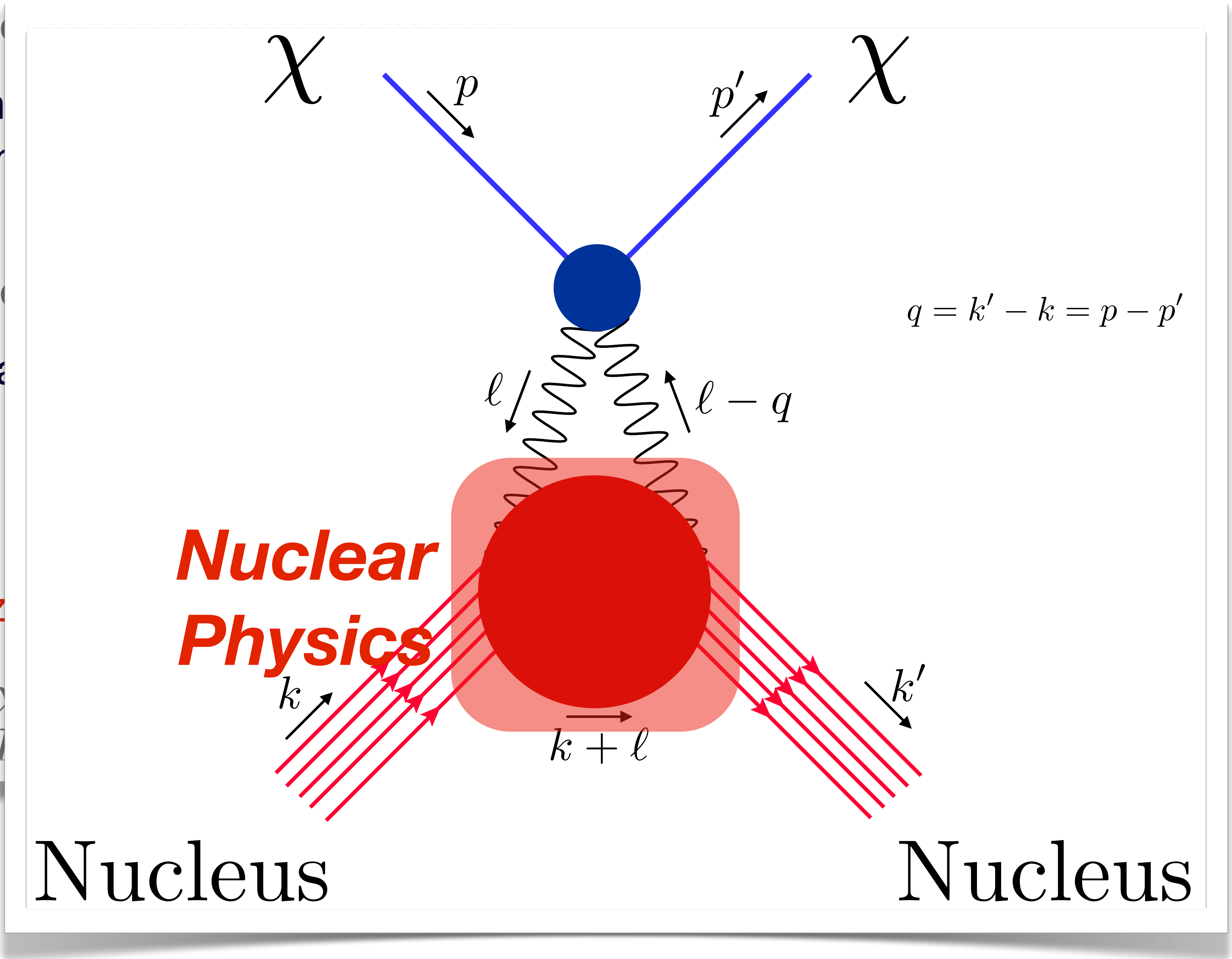

Importance of lattice field theory techniques

- 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

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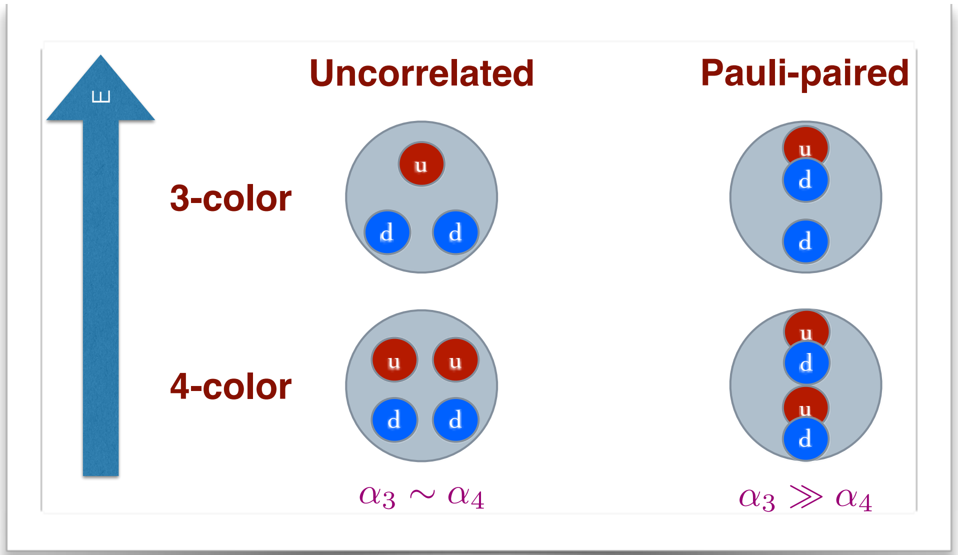
e.g. polarizability of a SU(4) neutral baryon



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

Polarizability of DM from lattice simulations

- Background field method: response of neutral baryon to external electric field $\mathcal{E}$

- Measure the shift of the baryon mass as a function of $\mathcal{E}$

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

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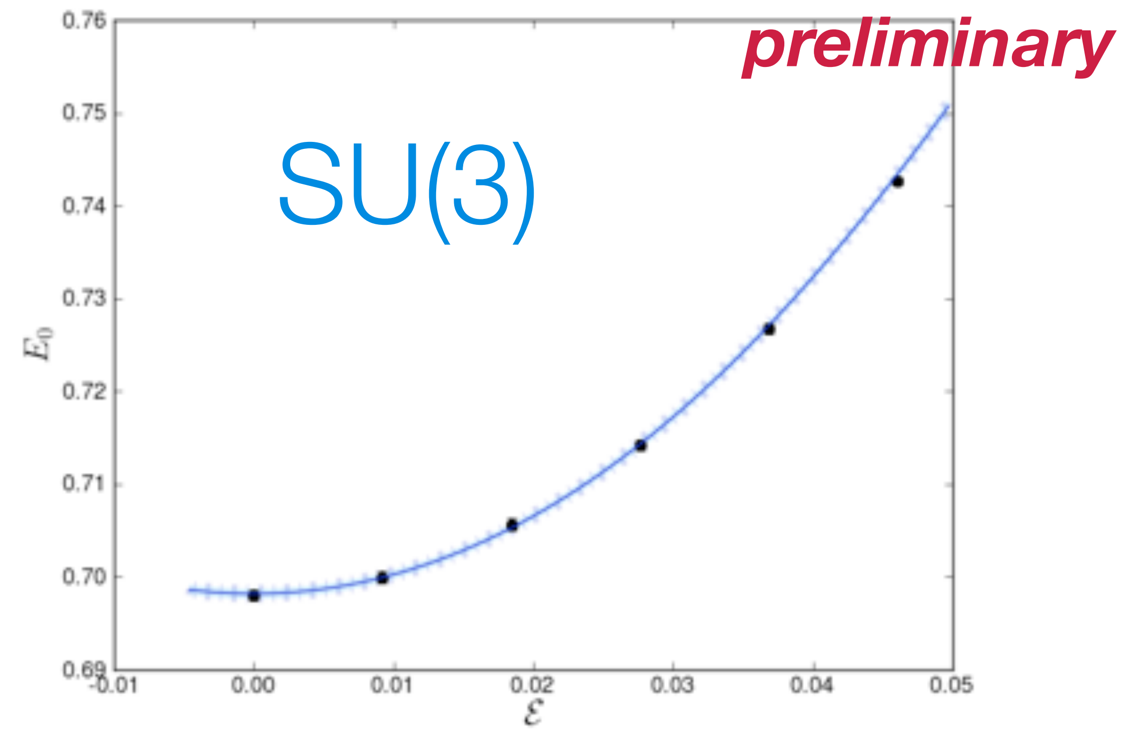
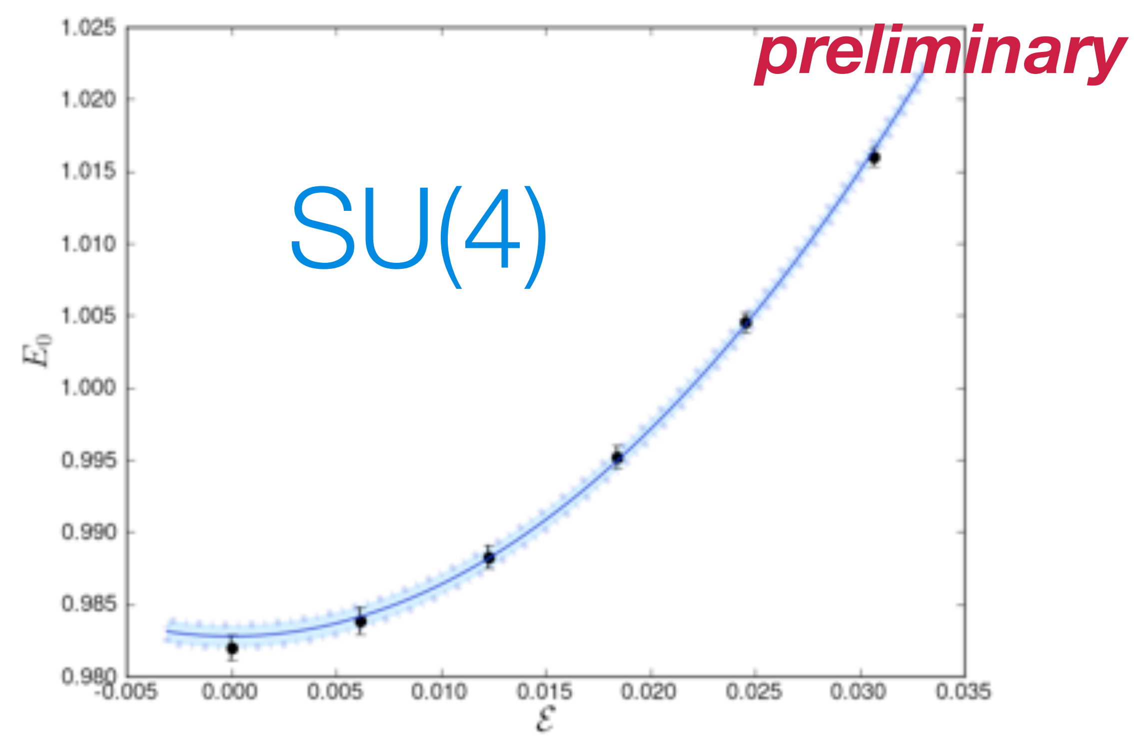
- Precise lattice results





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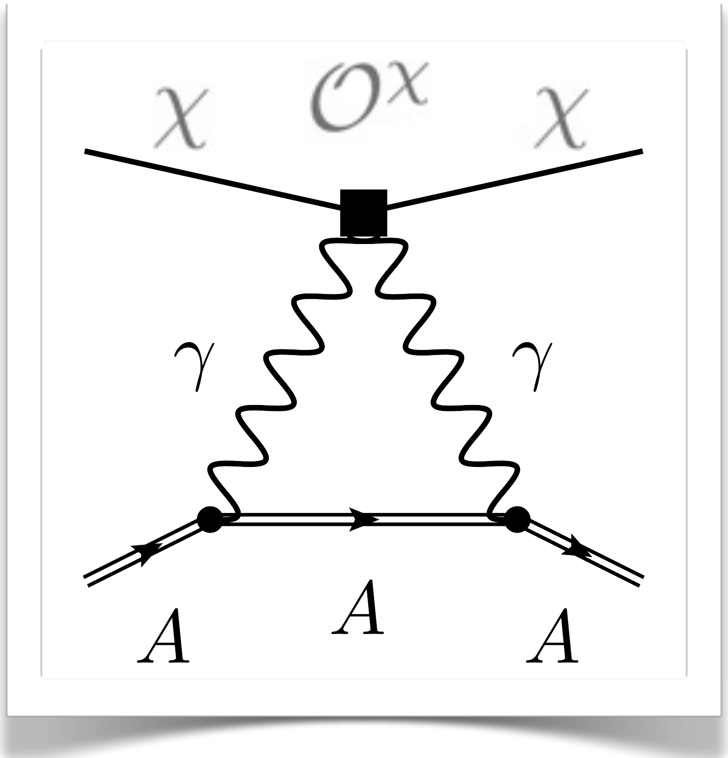
[Ovanesyan & Vecchi, arxiv:1410.0601]

Nuclear polarizability (Rayleigh scattering)



- several attempts to estimate this in the past, with increasing level of complexity in a perturbative setup
- 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

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

- similar structure arising in double beta decay matrix elements

[Frandsen et al., JCAP 1210 (2012) 033]
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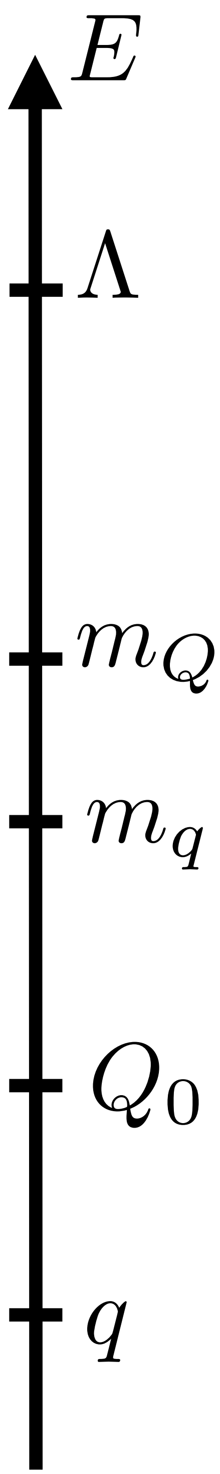
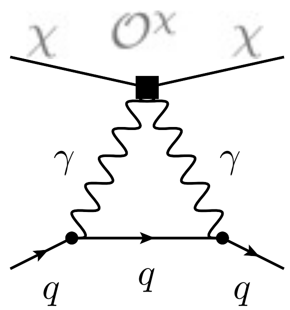
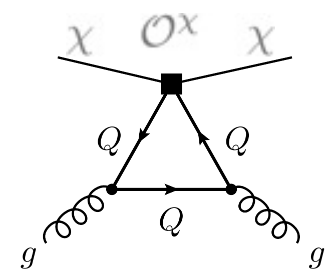
EFT treatment for the polarizability operator







$$\mathcal{O}_q^\chi = \mathcal{C}_q^\chi \, m_q \, \bar{\chi}\chi\bar{q}q$$

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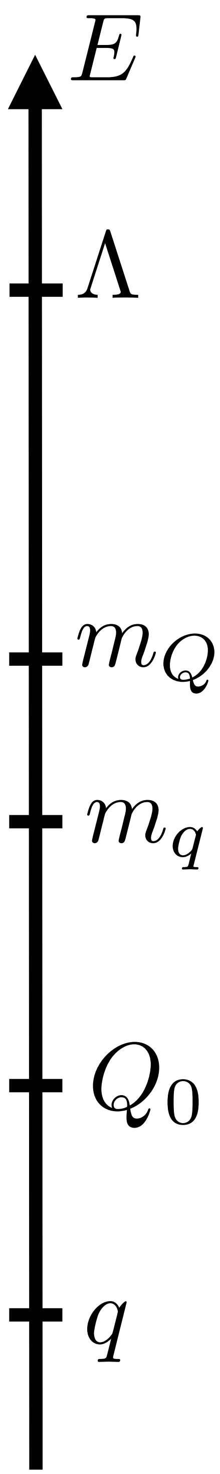

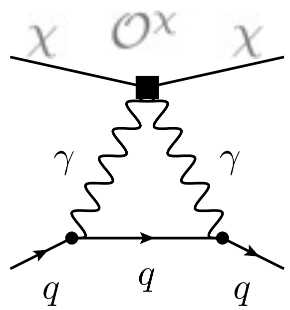

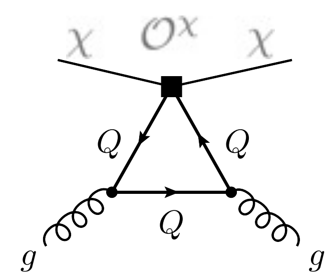

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$$\mathcal{C}_q^\chi \sim \alpha \mathcal{C}_F^\chi \qquad \mathcal{C}_G^\chi \sim \alpha\alpha_s \mathcal{C}_F^\chi \qquad \mathcal{C}_F^\chi$$

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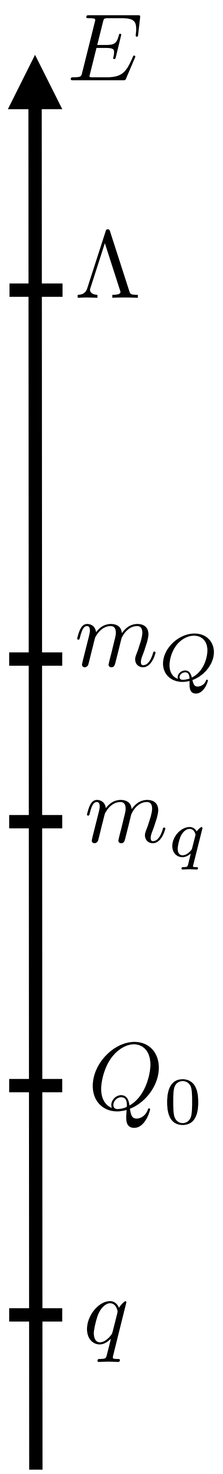

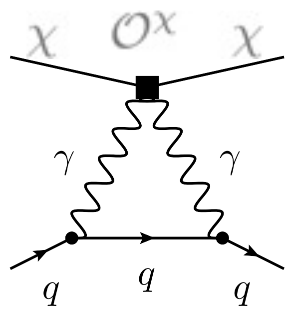

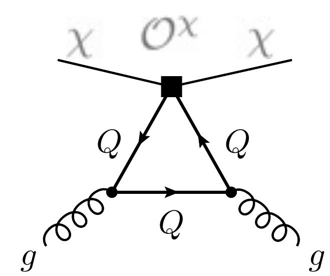

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Known from Higgs exchange physics

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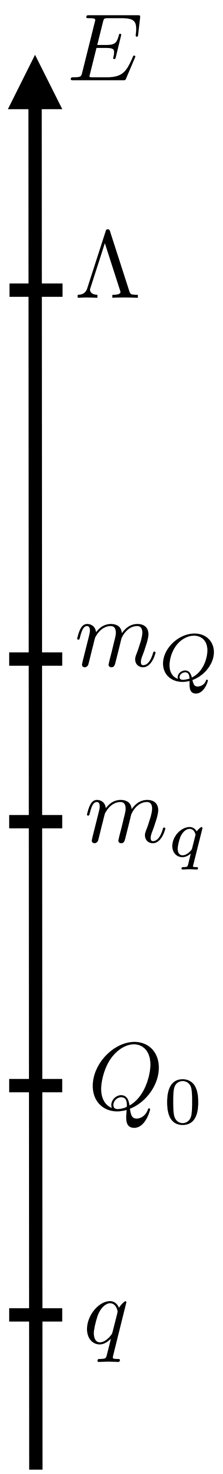

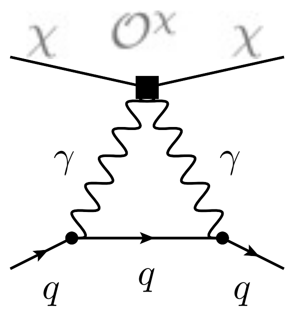

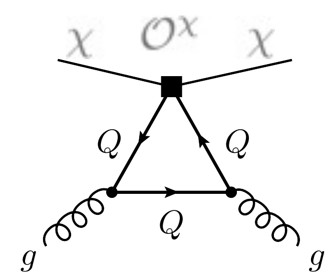

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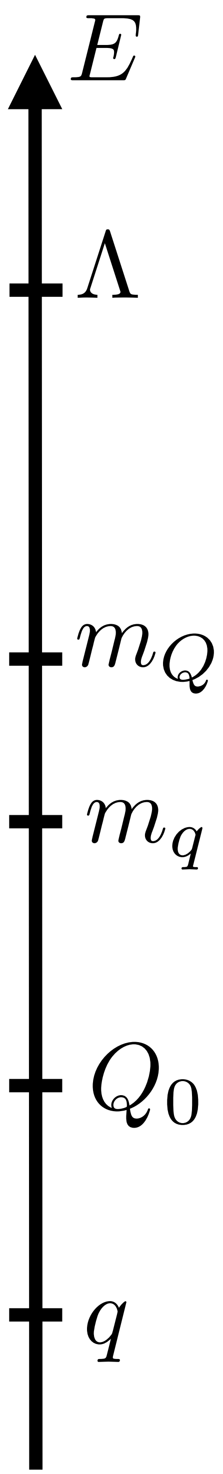

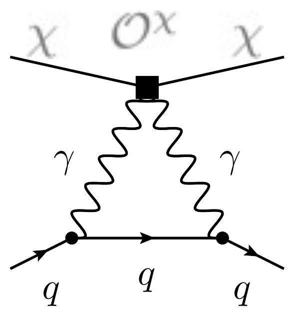

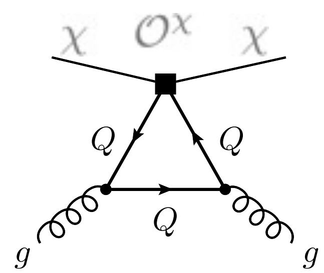

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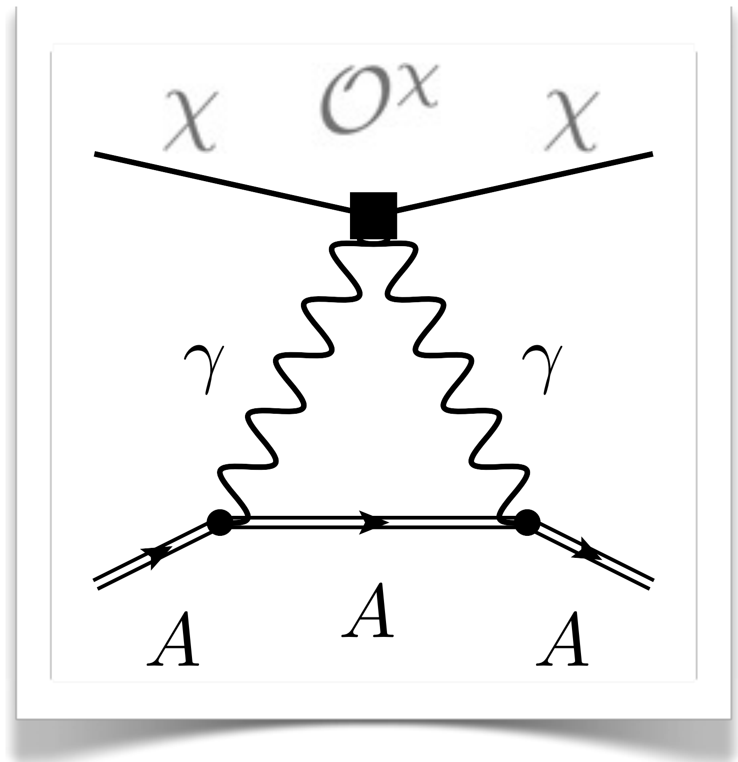
Naive dimensional analysis of $\langle A|\bar{\chi}\chi F^{\mu\nu}F_{\mu\nu}|A\rangle$

- 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 1 to 25



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

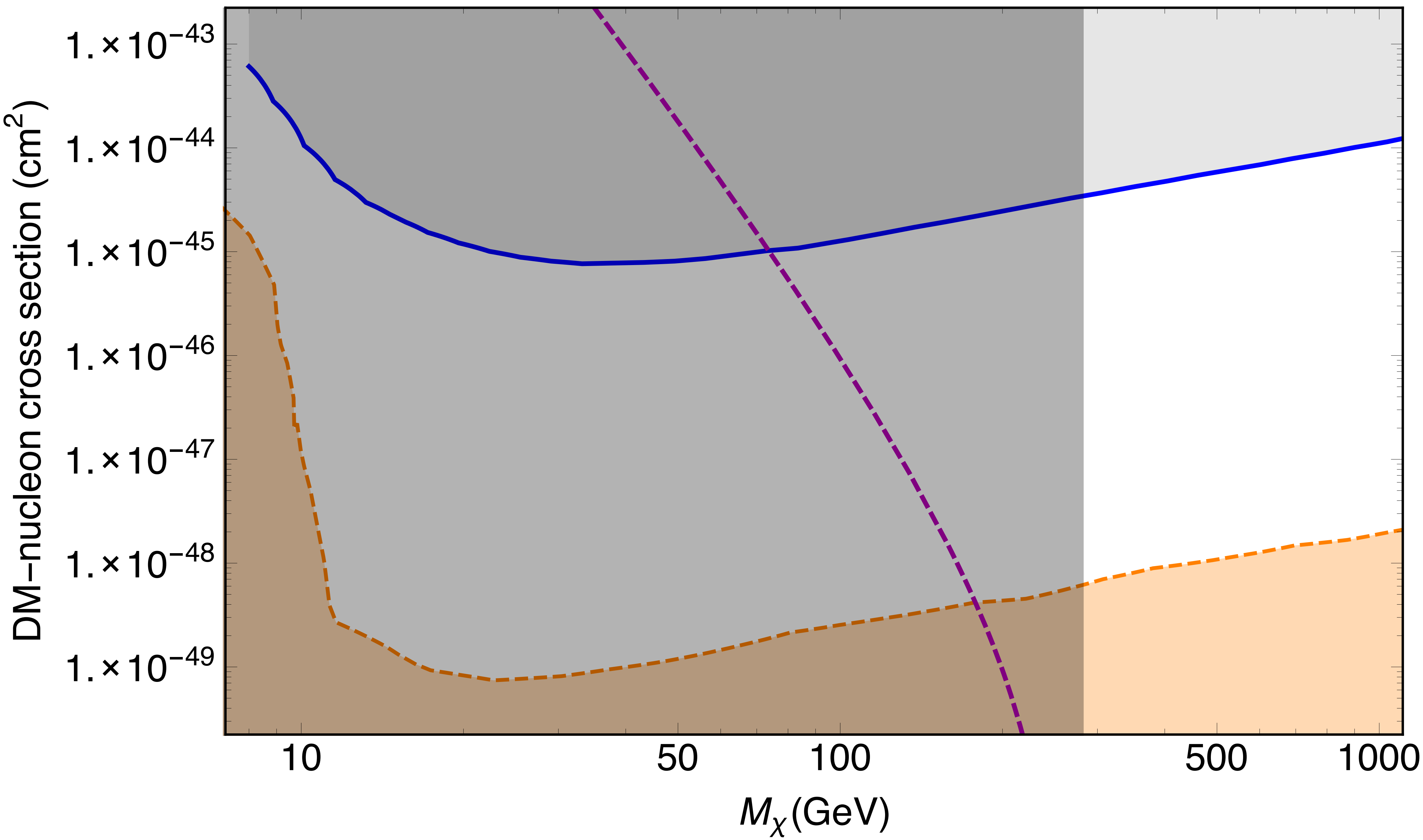
↓

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

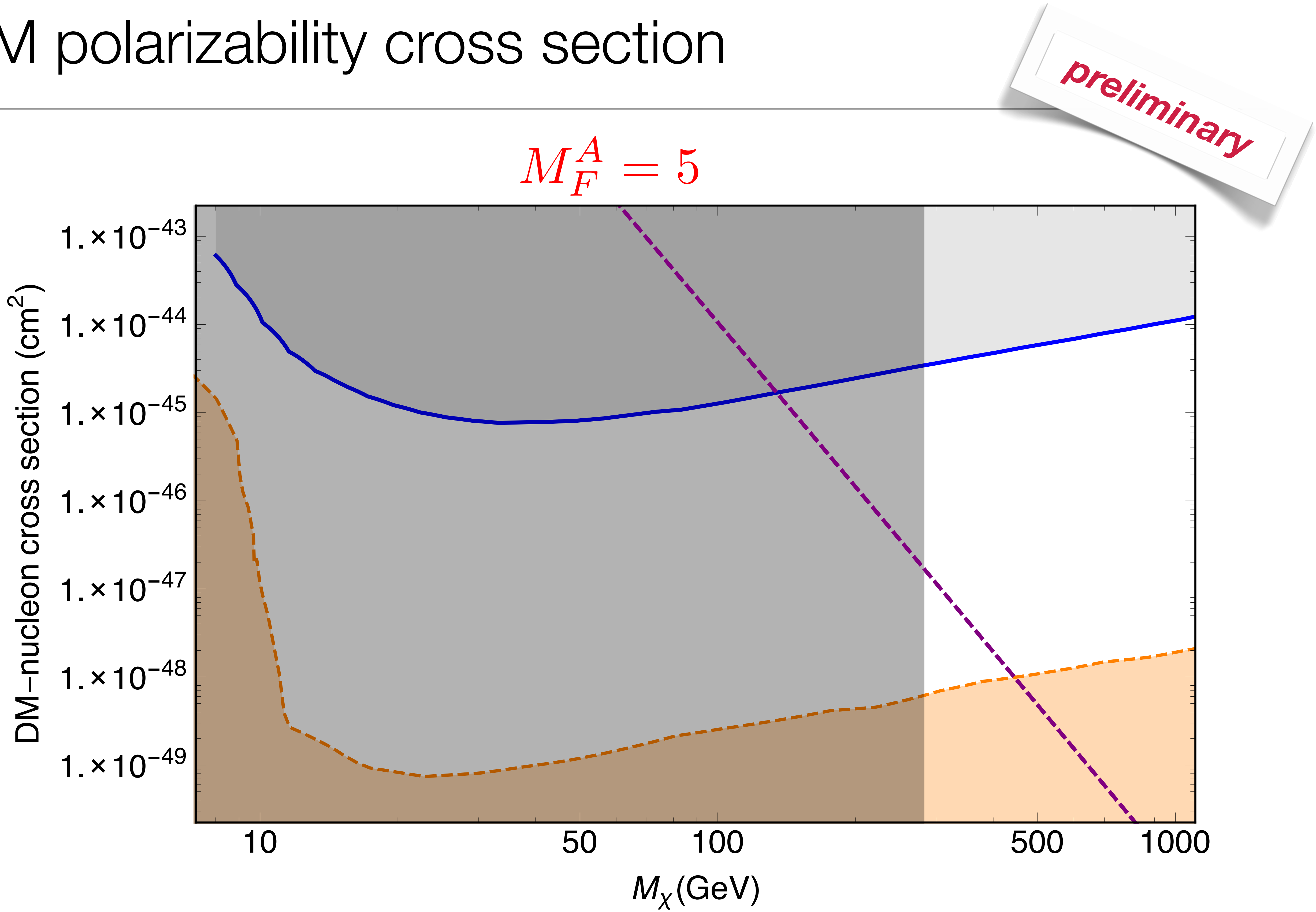
DM polarizability cross section

preliminary

$$M_F^A = 1$$



DM polarizability cross section



[LSD collab., in preparation]

DM polarizability cross section

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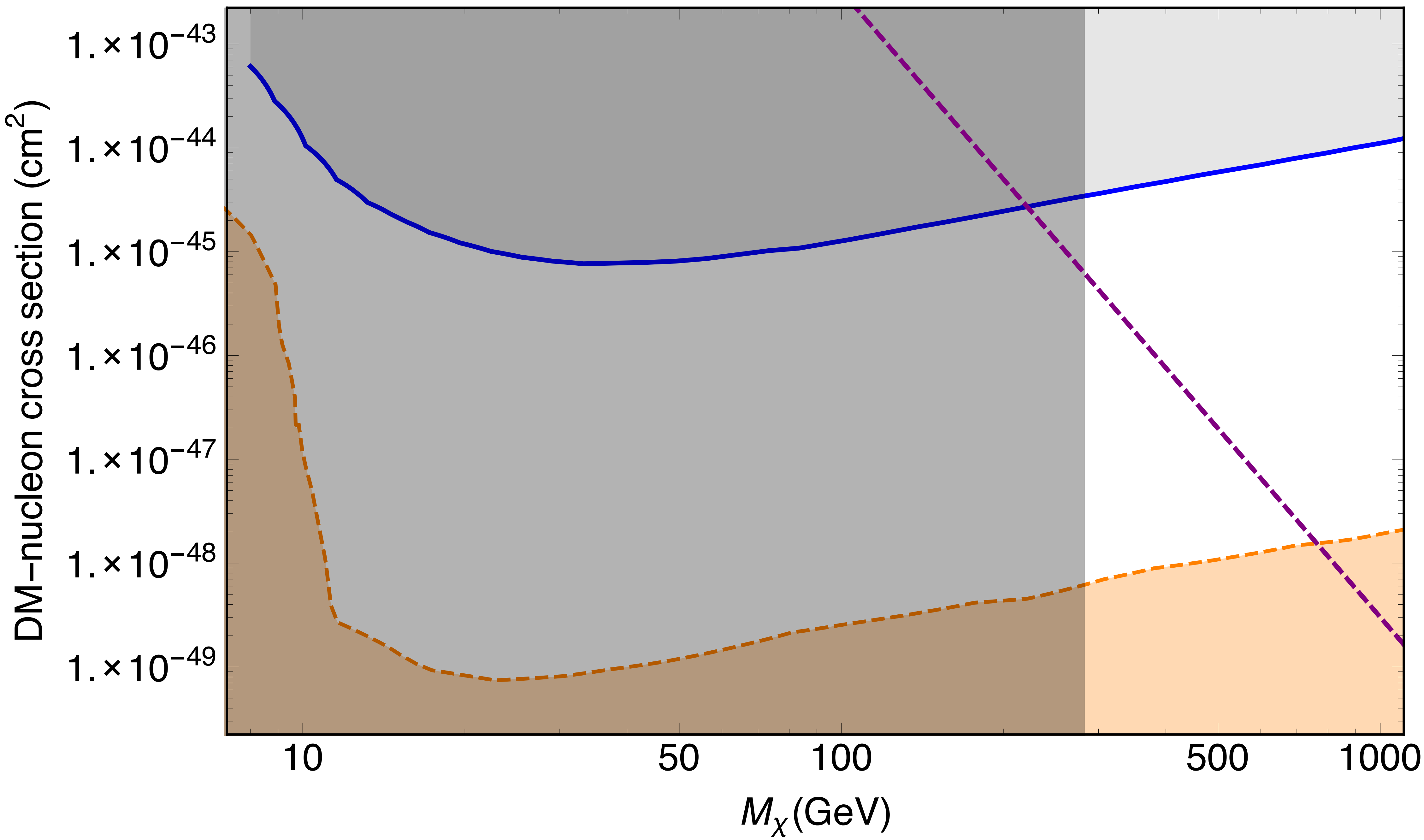
$M_F^A = 25$



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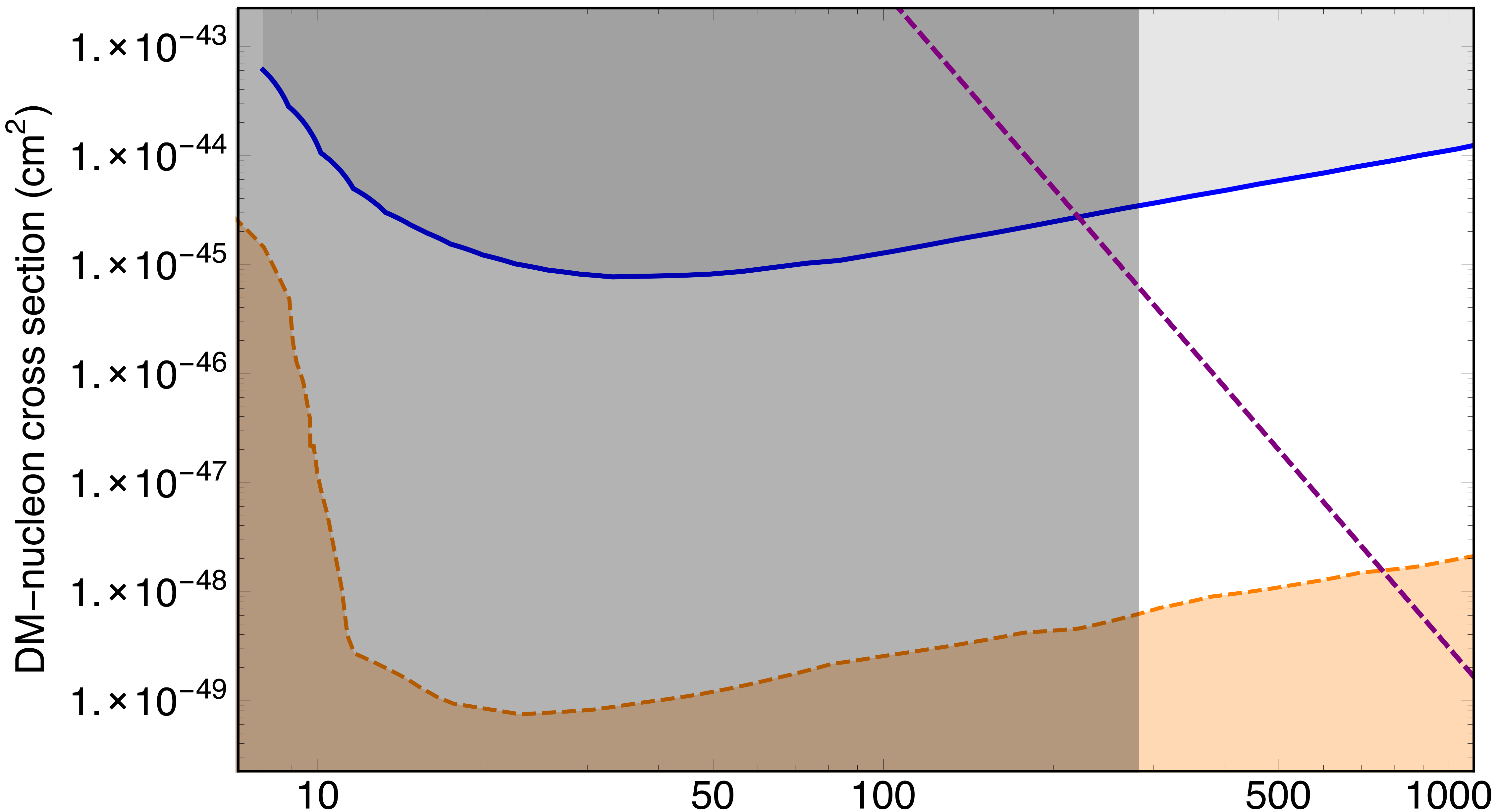

lowest allowed direct detection cross-section for composite dark matter theories with EW charged constituents

Summary and future directions

- strongly-coupled composite dark matter is an interesting scenario that should not be overlooked
- within this space of theories it is not hard to find regions where all interactions with SM are suppressed up to dimension-7 operators
- dimension-7 EM polarizability can not be eliminated in any case
- lattice simulations can calculate the EM form factors of the composite object with controllable errors (using mature LQCD techniques)
- nuclear physics input is needed and nuclear matrix elements have the largest uncertainties that should be assessed

Questions

?

Questions

?

YES.

- Q: How much does the nuclear matrix element influence the conclusions?
    - *we tried to estimate this and it seems a O(25) change could affect results*
- Q: What methods can be used to evaluate the nuclear matrix element?
    - *can we learn something from double-beta decays? or electron-nuclei scattering?*
- Q: Are there experimental limits that can bound the matrix element?
    - *not sure at the moment.*

Backup slides

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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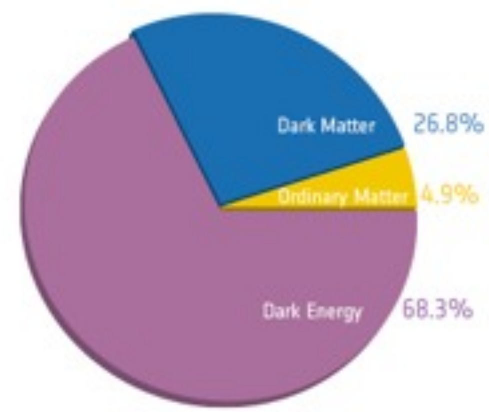
Asymmetric dark matter

- 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]

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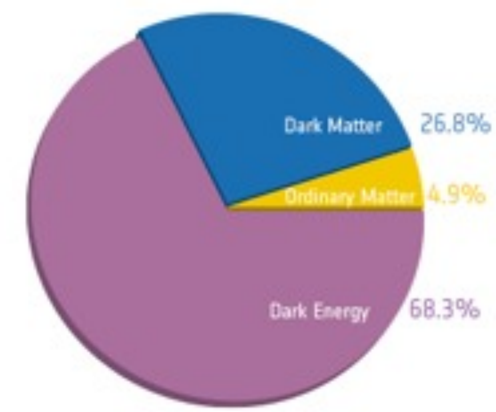

[Planck and ESA]

- 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

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

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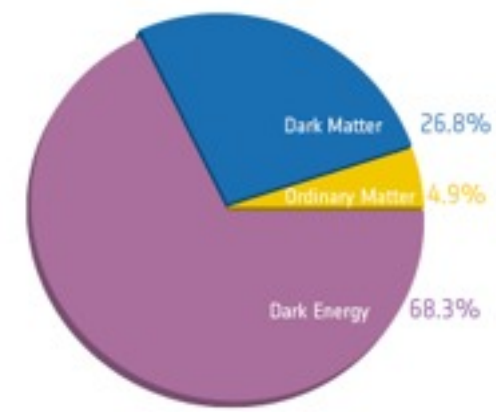

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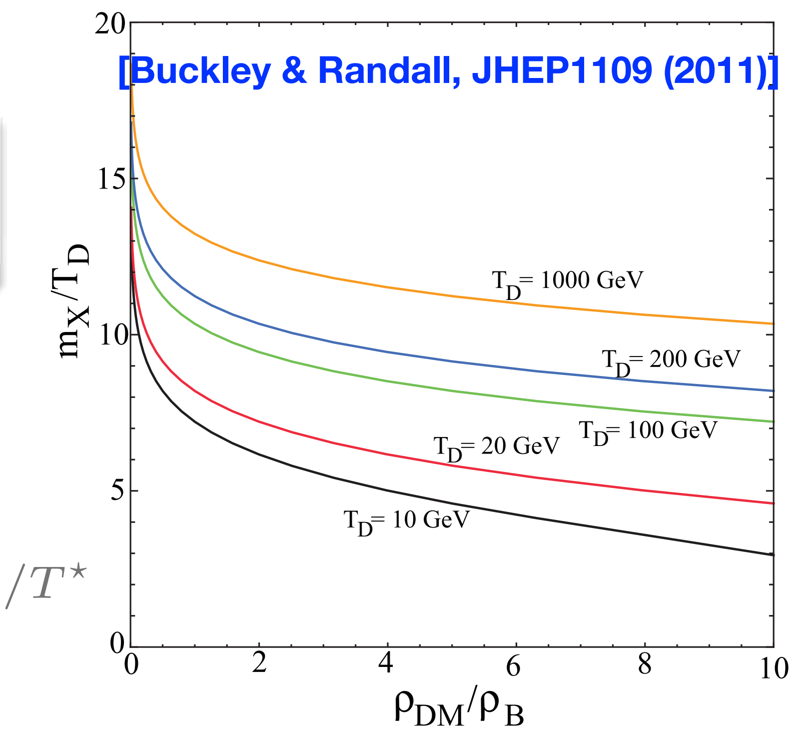
higher dimensional operators	sphaleron processes
$n_{\rm DM} \approx n_{\rm B} \to M_{\rm DM} \approx 5\ M_{\rm B}$	$M_{\rm DM} \gg M_{\rm B} \to n_{\rm B} \gg n_{\rm B} \approx e^{-M_{\rm DM}/T^\star}$



A composite 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	$SU(N)_D$	$(SU(2)_L, Y)$	Q
$F_1 = \begin{pmatrix} F_1^u \\ F_1^d \end{pmatrix}$	$\mathbf{N}$	$(\mathbf{2}, 0)$	$\begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$
$F_2 = \begin{pmatrix} F_2^u \\ F_2^d \end{pmatrix}$	$\overline{\mathbf{N}}$	$(\mathbf{2}, 0)$	$\begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$
F_3^u	$\mathbf{N}$	$(\mathbf{1}, +1/2)$	$+1/2$
F_3^d	$\mathbf{N}$	$(\mathbf{1}, -1/2)$	$-1/2$
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A composite 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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$$\mathcal{L} \supset + y_{14}^u \epsilon_{ij} F_1^i H^j F_4^d + y_{14}^d F_1 \cdot H^\dagger F_4^u - y_{23}^d \epsilon_{ij} F_2^i H^j F_3^d - y_{23}^u F_2 \cdot H^\dagger F_3^u + h.c.$$

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$$\mathcal{L} \supset M_{12} \epsilon_{ij} F_1^i F_2^j - M_{34}^u F_3^u F_4^d + M_{34}^d F_3^d F_4^u + h.c.$$

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

Higgs exchange cross section

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

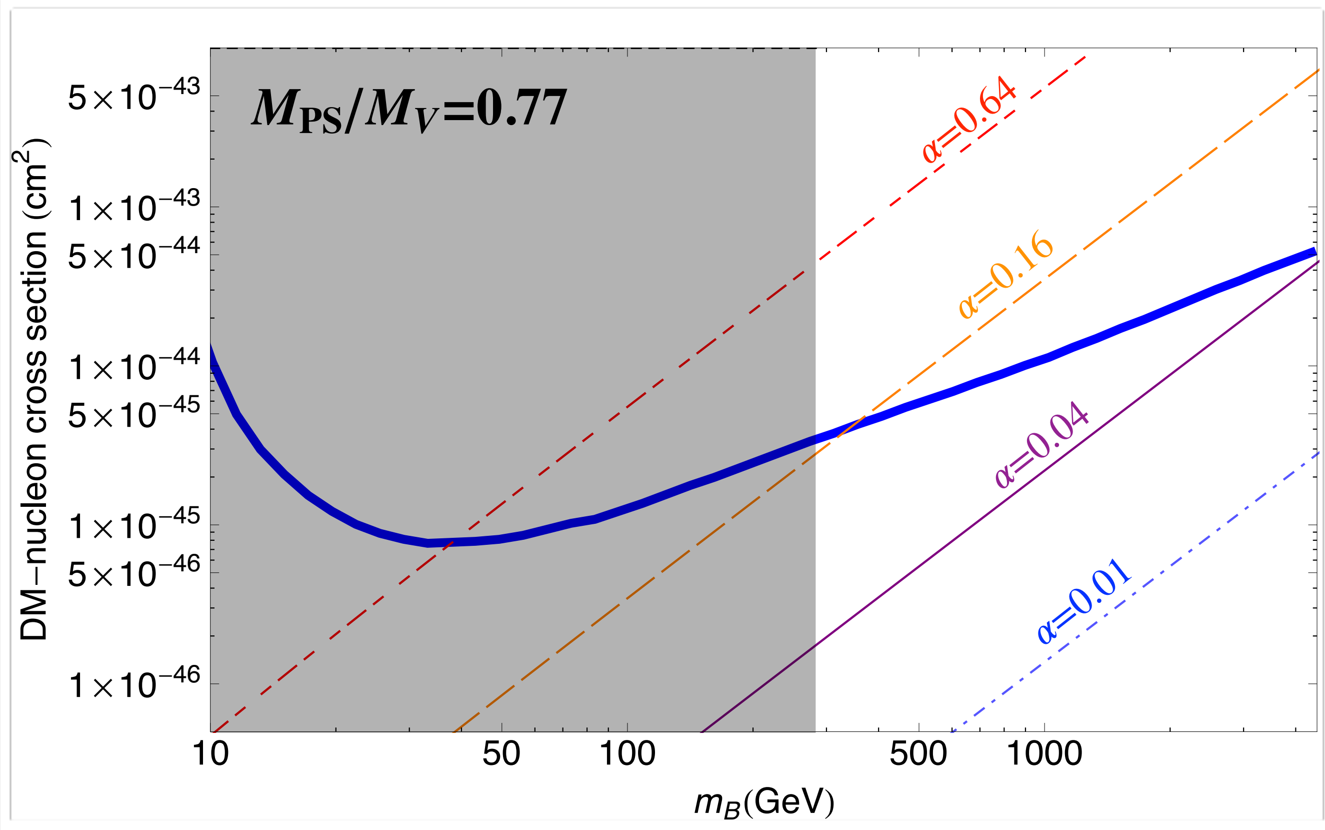
$$m_f(h) = m + \frac{yh}{\sqrt{2}}$$

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

- 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



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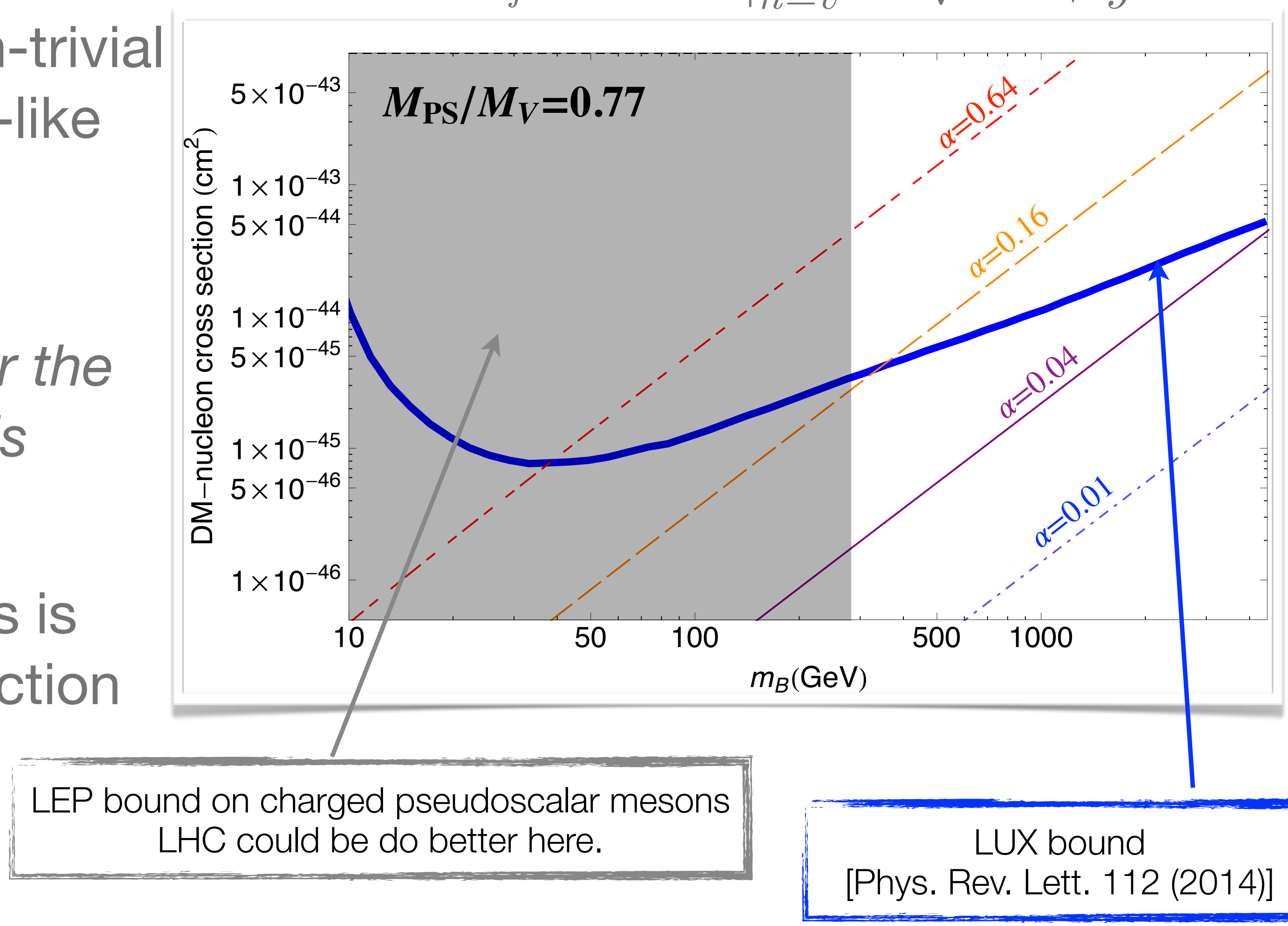
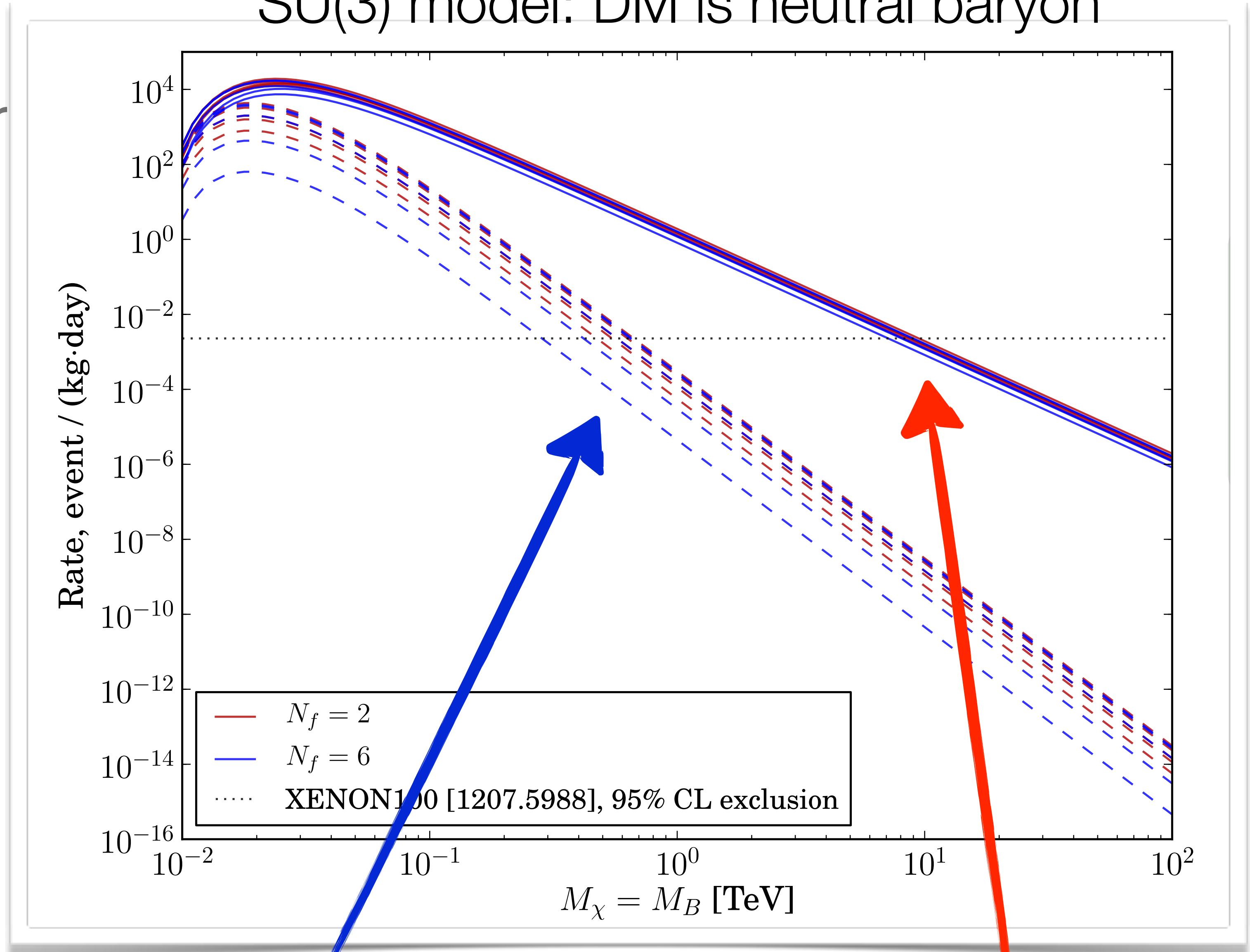


[LSD collab., Phys. Rev. D88 (2013) 014502]

Magnetic moment and charge radius of DM

- 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

SU(3) model: DM is neutral baryon



without magnetic moment contribution

Excludes dark matter mass below 10 TeV!

[Frandsen et al., JCAP 1210 (2012) 033]

EFT operator treatment for polarizability

$$\sigma \simeq \frac{\mu_{n\chi}^2}{\pi A^2} \left\langle \left| \sum_q \mathcal{C}_q^\chi f_q^A + \mathcal{C}_G^\chi f_G^A + \mathcal{C}_F^\chi f_F^A \right|^2 \right\rangle$$

[Frandsen et al., JCAP 1210 (2012) 033]

EFT operator treatment for polarizability

$$\mathcal{O}_q^\chi = \mathcal{C}_q^\chi \, m_q \, \bar{\chi}\chi\bar{q}q$$

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[Frandsen et al., JCAP 1210 (2012) 033]

EFT operator treatment for polarizability

$$
\begin{aligned}
f_q^A &= \langle A | m_q \bar{q} q | A \rangle \\
f_G^A &= \langle A | G^{\mu\nu} G_{\mu\nu} | A \rangle \\
f_F^A &= \langle A | F^{\mu\nu} F_{\mu\nu} | A \rangle
\end{aligned}
$$

$$
\begin{aligned}
f_q^A &\sim 2 A m_n f_{Tq}^n \\
f_G^A &\sim -2 \frac{8\pi}{9\alpha_s(\mu)} A m_n \left(1 - \sum_q f_{Tq}^n \right) \\
f_F^A &\sim Z^2 \alpha \frac{M_F^A}{R}
\end{aligned}
$$

$$
\sigma \simeq \frac{\mu_{n\chi}^2}{\pi A^2} \left\langle \left| \sum_q c_q^\chi f_q^A + c_G^\chi f_G^A + c_F^\chi f_F^A \right|^2 \right\rangle
$$