Lattice Gauge Theory insights on Dark Matter

Enrico Rinaldi

RIKEN BNL Research Center

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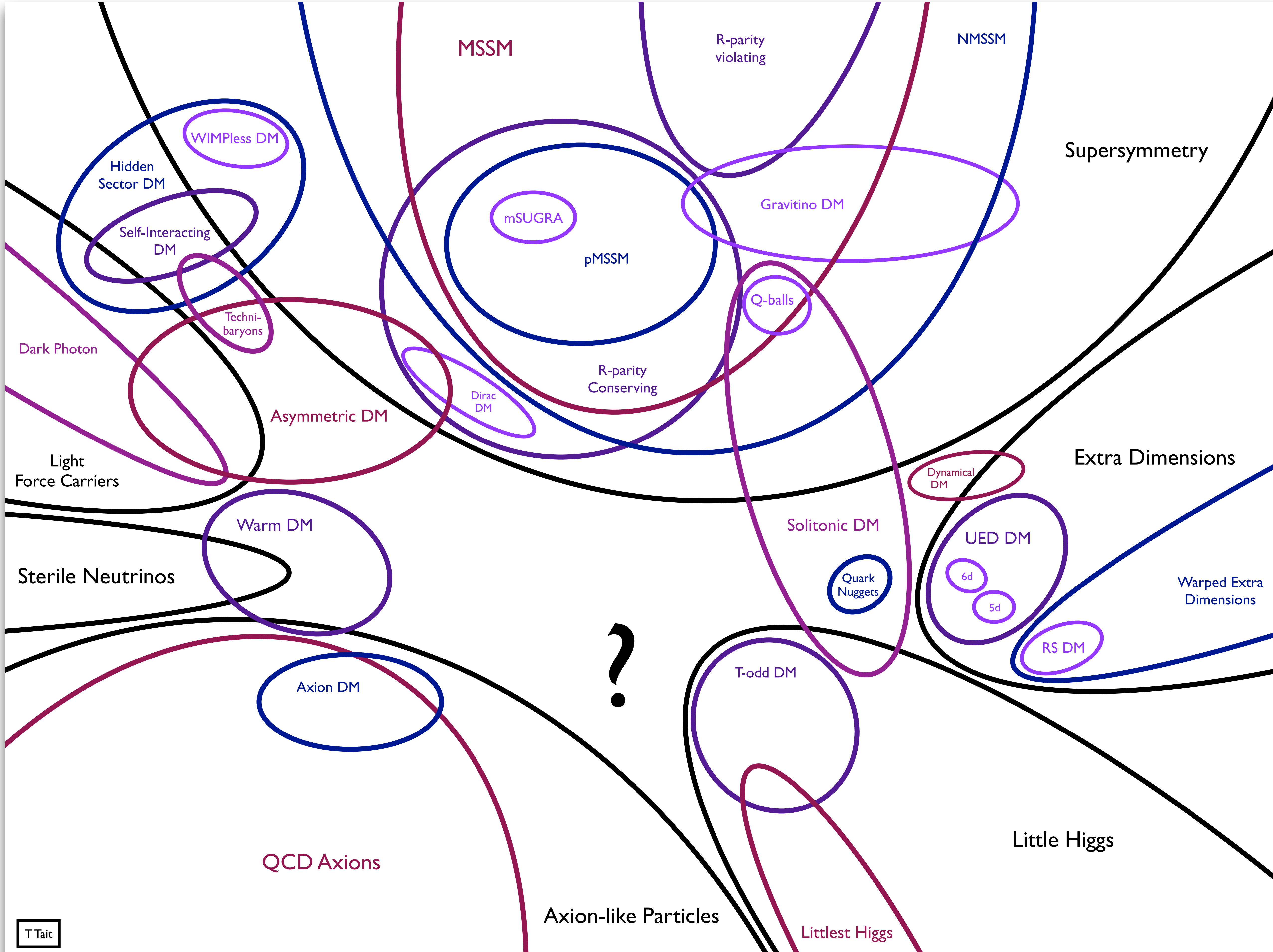
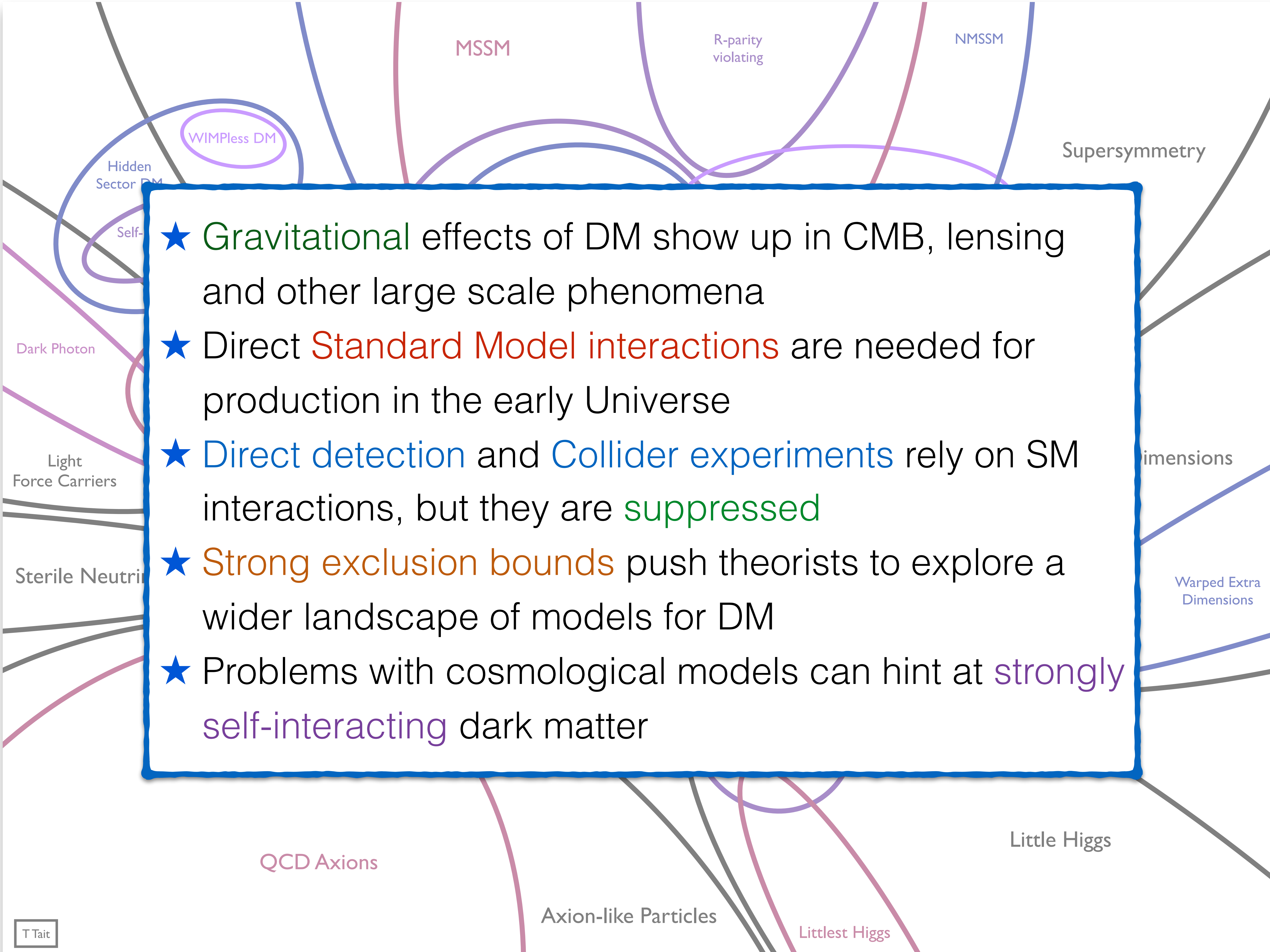
Computing support comes from the LLNL Institutional Computing Grand Challenge program.

What is Dark Matter?



[Planning the Future of U.S. Particle Physics (Snowmass 2013), 1401.6085]



★ 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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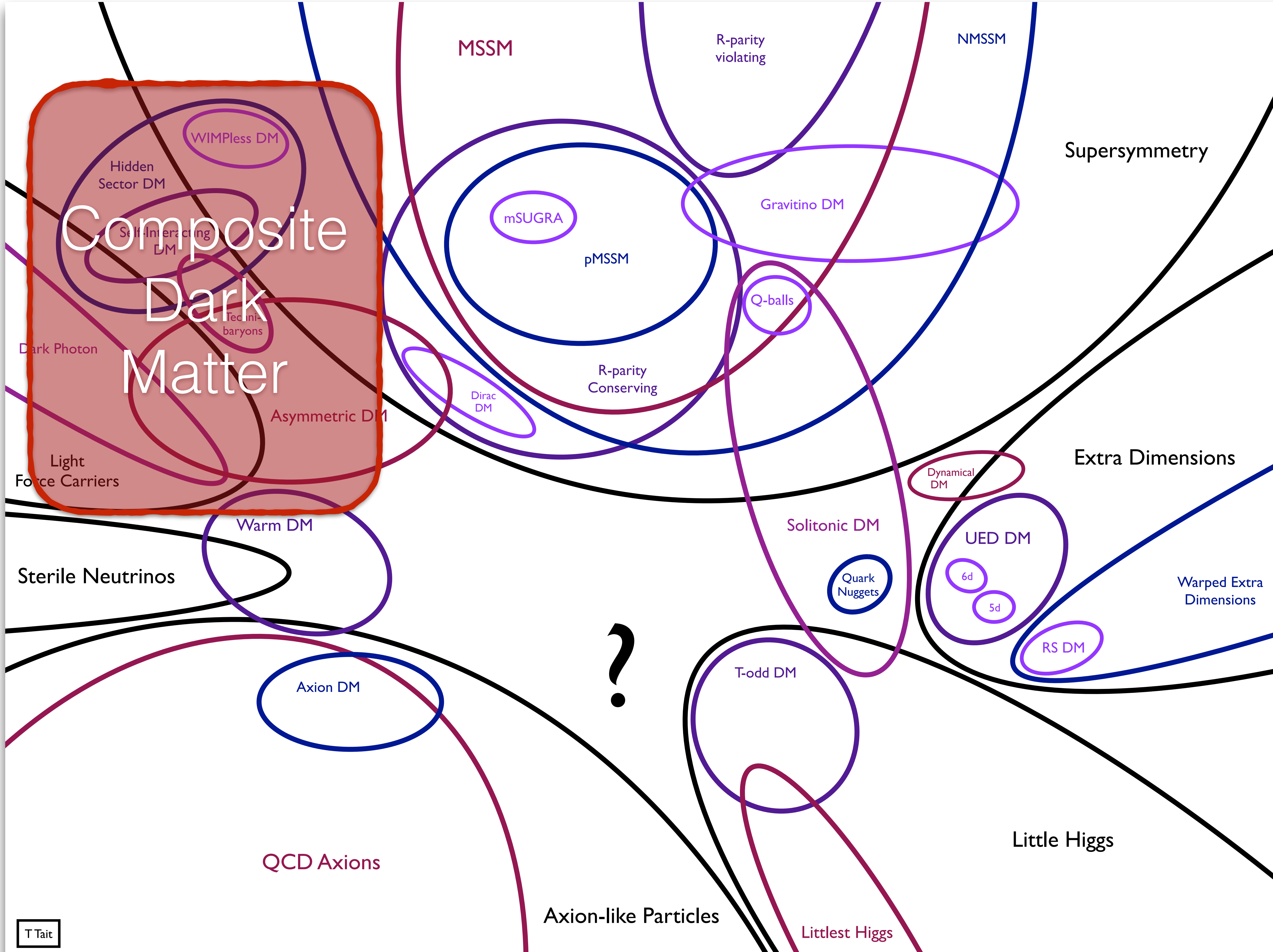

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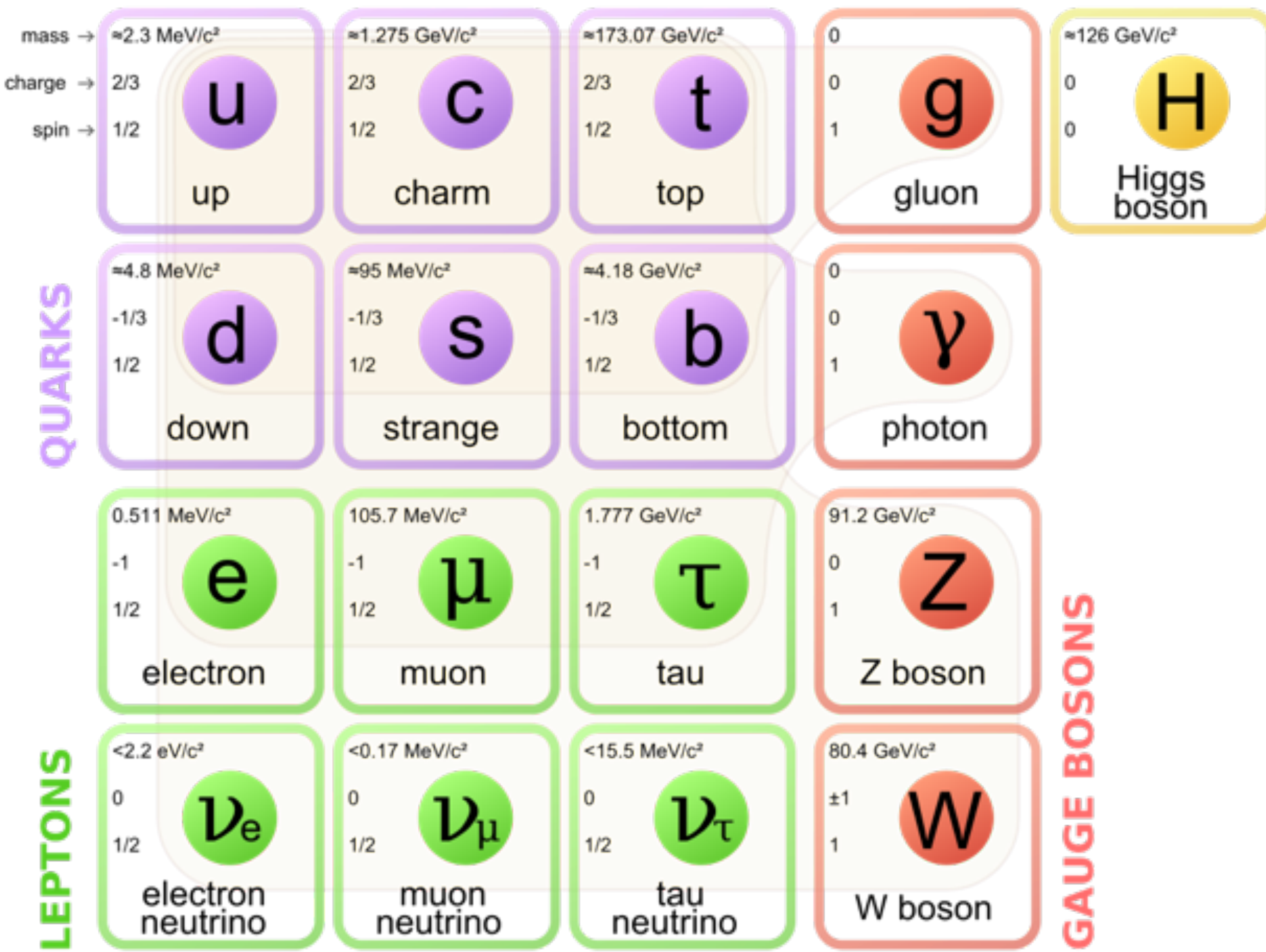
A very familiar picture

The Standard Model of particles



[Wikipedia]

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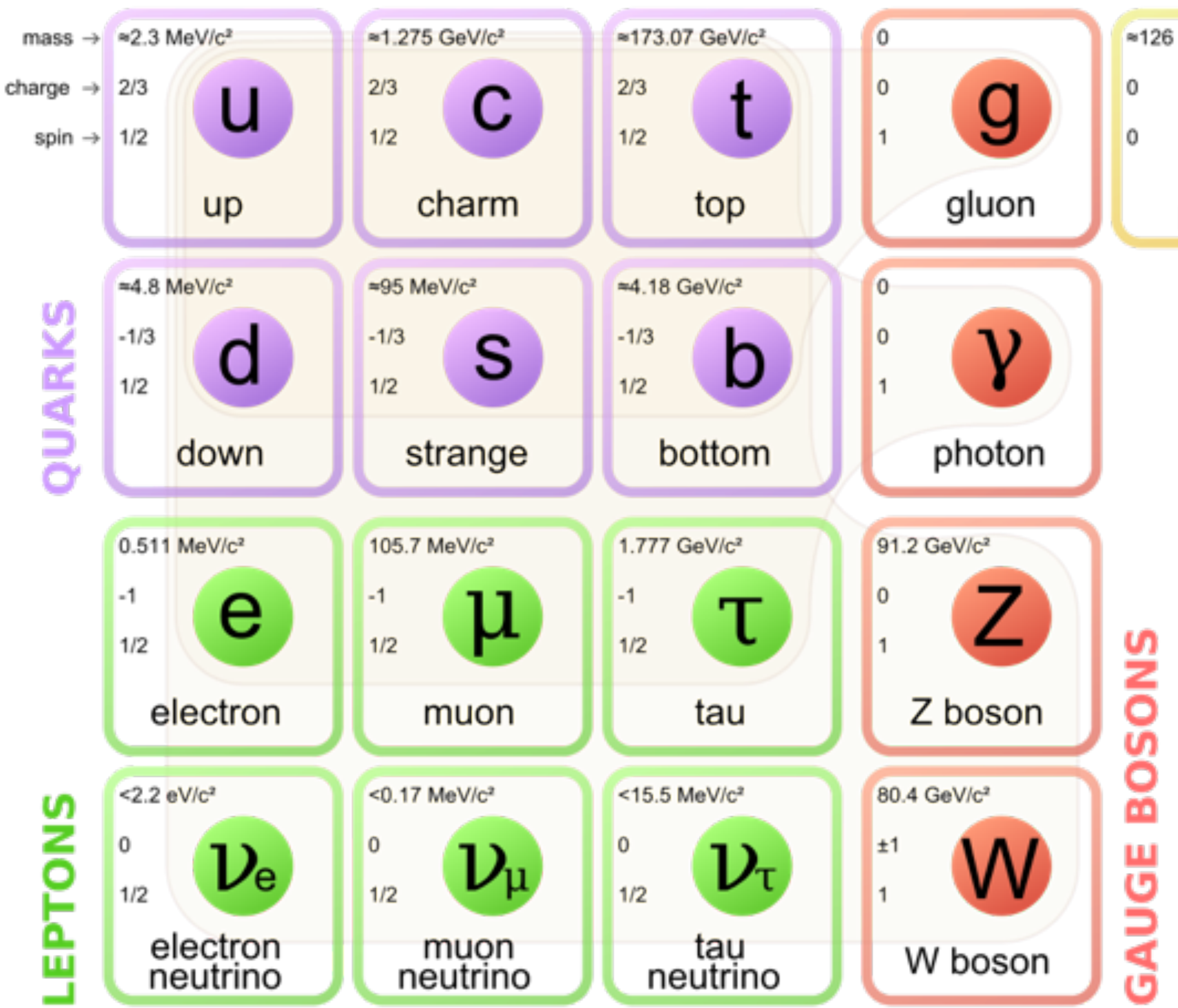
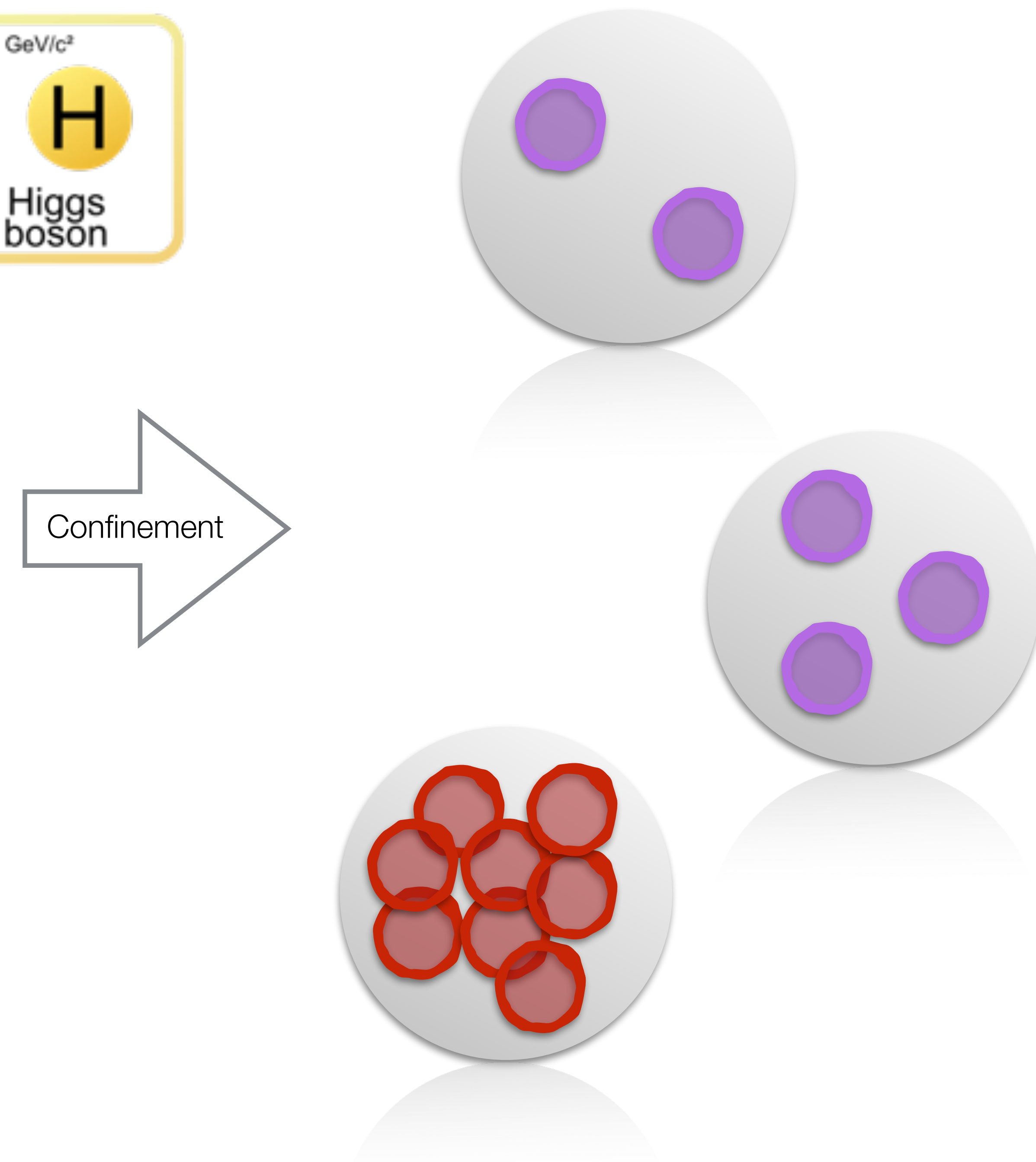


Mesons, Baryons and Glueballs



[Wikipedia]

Composite Dark Matter

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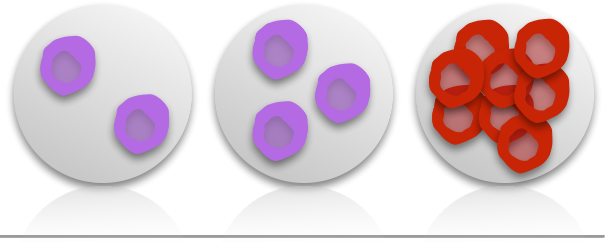

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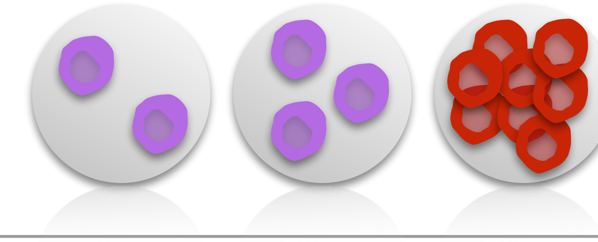

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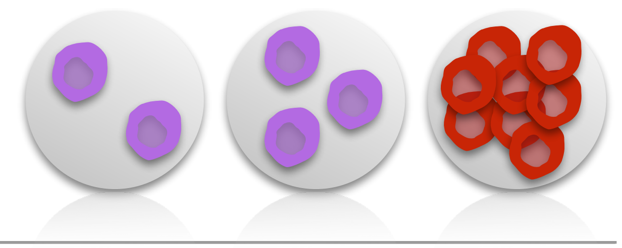

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- Interesting and complicated internal structure
- Properties dictated by strong dynamics
- Self-interactions are natural

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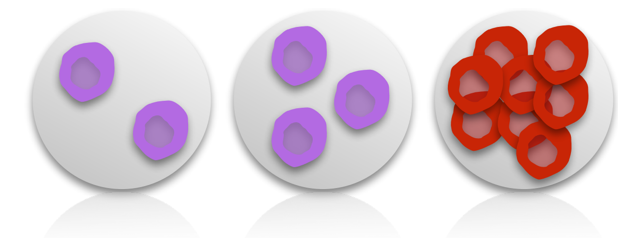

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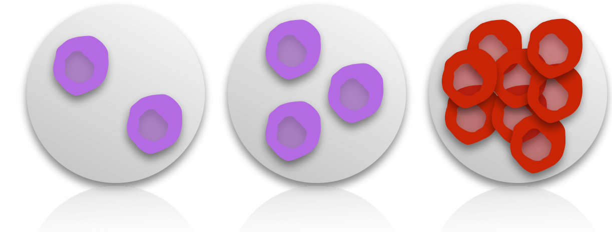

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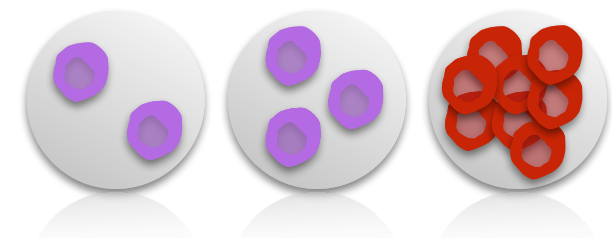

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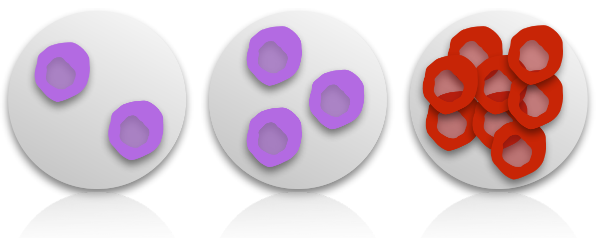

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Lattice Field Theory methods

Similar to QCD

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[review by Kribs & Neil, 1604.04627]

Natural features of Composite Dark Matter

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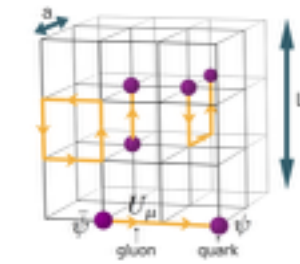
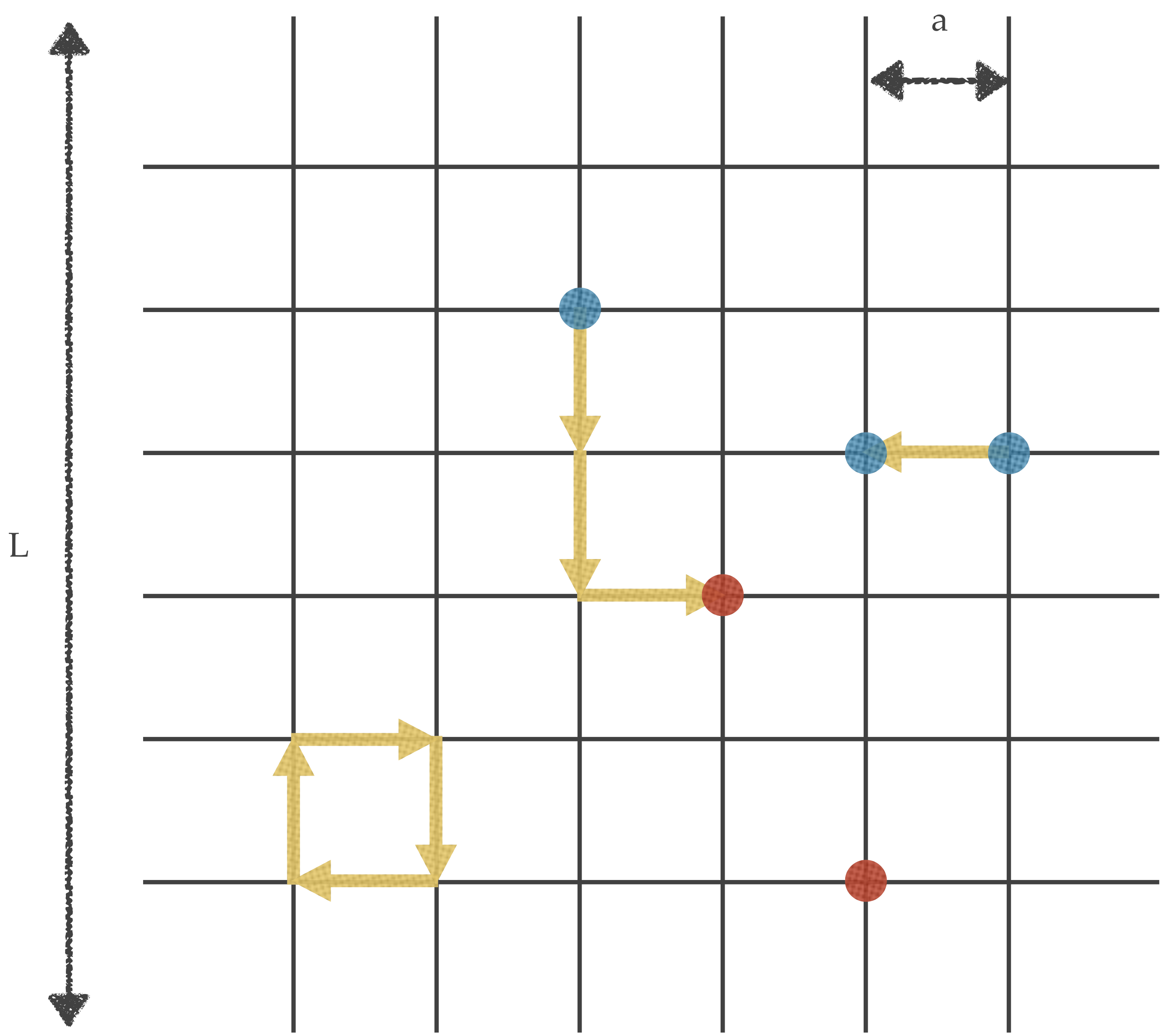
Self-interactions are included due to **strongly coupled** dynamics

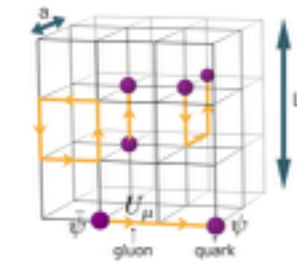

[KEK-Japan]

Lattice Gauge Theory - basics



- Discretize space and time
  - lattice spacing “a”
  - lattice size “L”
- Keep all d.o.f. of the theory
  - not a model!
  - no simplifications
- Amenable to numerical methods
  - Monte Carlo sampling
  - use supercomputers
- Precisely quantifiable and improvable errors
  - Systematic
  - Statistical

[KEK-Japan]



Importance of lattice field theory simulations

- *lattice simulations are needed to solve the strong dynamics*

- 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

[list of references focused on lattice results when possible]

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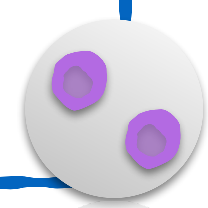
Models for Composite Dark Matter

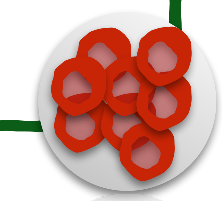
★ Pion-like (dark quark-antiquark)

- ✦ pNGB DM *[Hietanen et al.,1308.4130]*
- ✦ Quirky DM *[Kribs et al.,0909.2034]*
- ✦ Ectocolor DM *[Buckley&Neil,1209.6054]*
- ✦ SIMP *[Hochberg et al.,1411.3727]*
- ✦ Minimal SU(2)



★ Glueball-like (only gluons)

- ✦ SUNonia *[Boddy et al.,1402.3629]* *[Soni,1602.00714]*



★ Dark Nuclei *[Detmold et al.,1406.2276-1406.4116]*

★ Baryon-like (multiple quarks)

- ✦ “Technibaryons” *[LSD,1301.1693]*
- ✦ *Stealth* DM *[LSD,1503.04203-1503.04205]*
- ✦ One-family TC *[LatKMI,1510.07373]*
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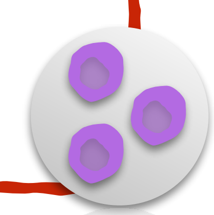

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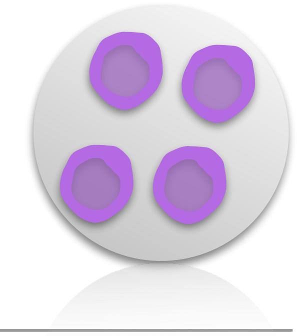
“Stealth Dark Matter” Model



- **New strongly-coupled SU(4) gauge sector** “like” QCD with a plethora of composite states in the spectrum: all mass scales are technically natural for hadrons

- New **Dark fermions**: have dark color and also have **electroweak charges** (W/Z,γ)

- Dark fermions have electroweak breaking masses (Higgs) and electroweak preserving masses (not-Higgs)

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

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

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

[LSD collab., Phys. Rev. D92 (2015) 075030]

[LSD collab., Phys. Rev. Lett. 115 (2015) 171803]

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- The field content of the model consists in *8 Weyl fermions*

- 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***

EW interactions

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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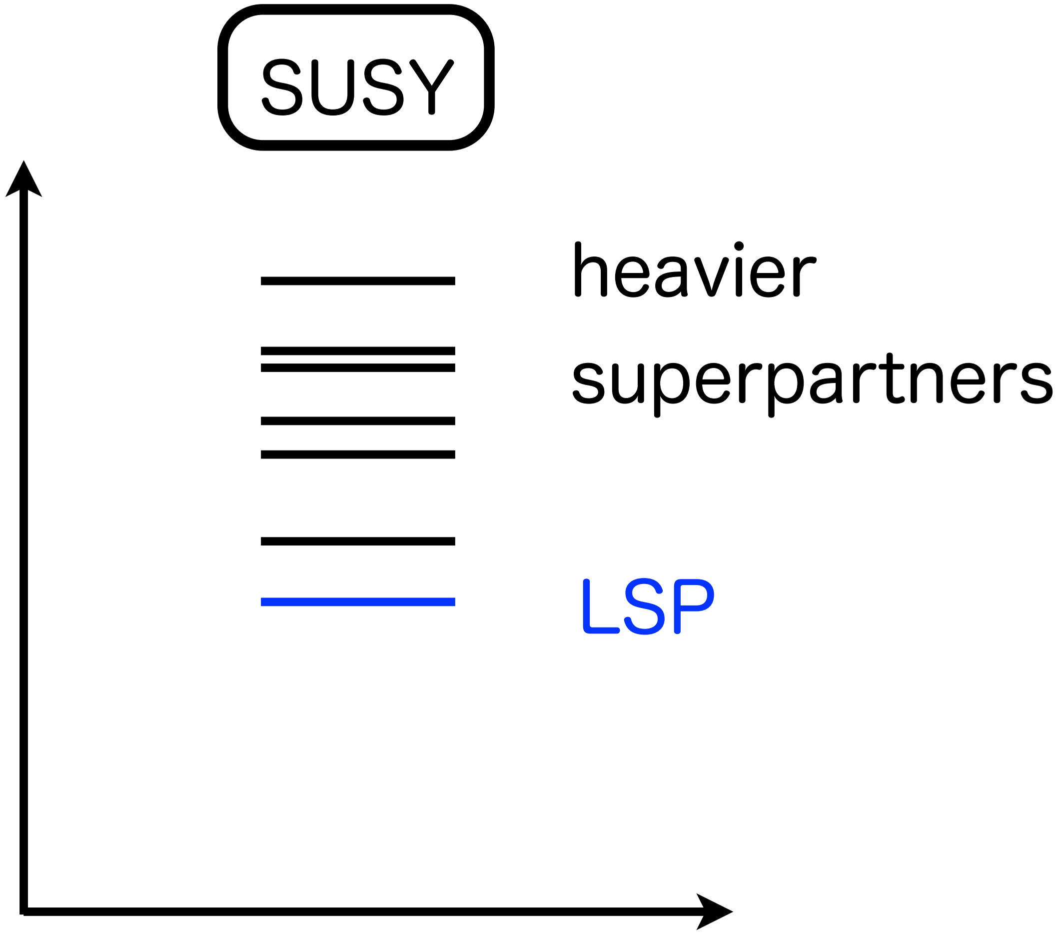
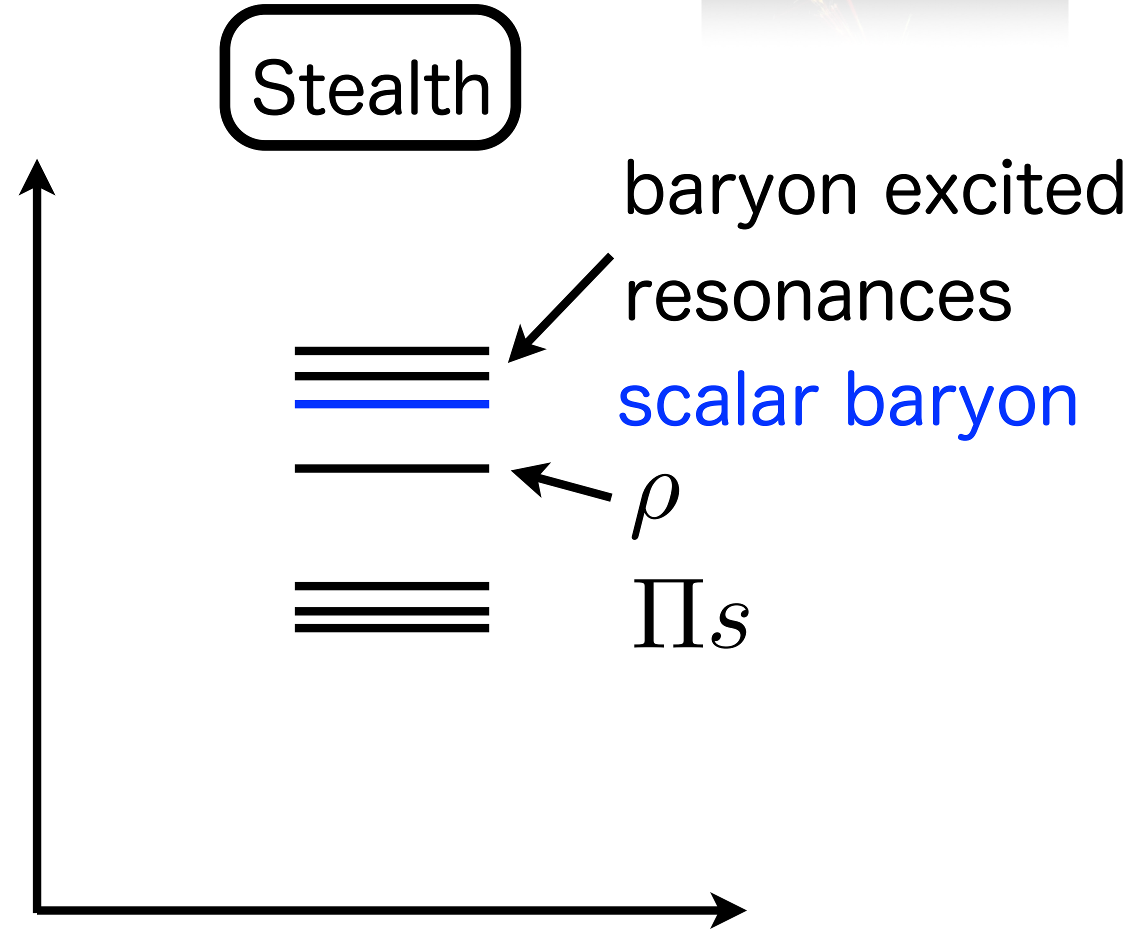
$$y_{14}^u = y_{14}^d \qquad y_{23}^u = y_{23}^d \qquad M_{34}^u = M_{34}^d$$

[ATLAS]

Stealth DM at colliders



vs.



Plot by G. Kribs

[ATLAS]

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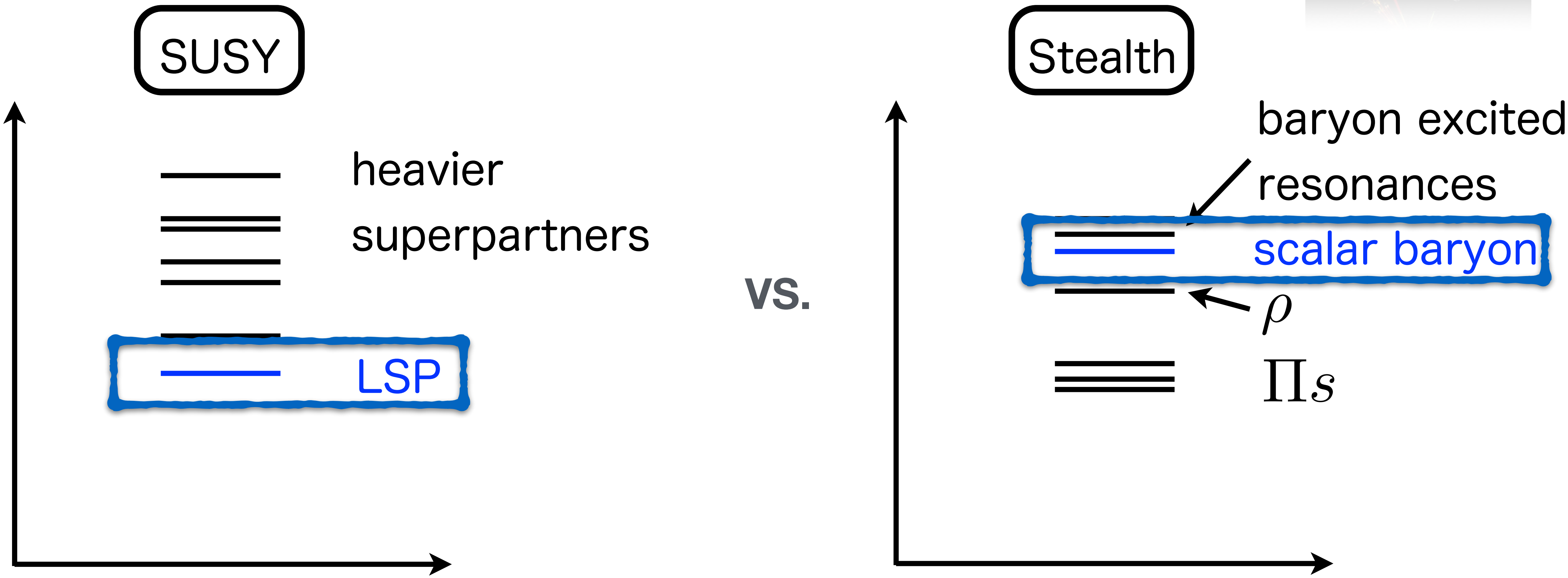

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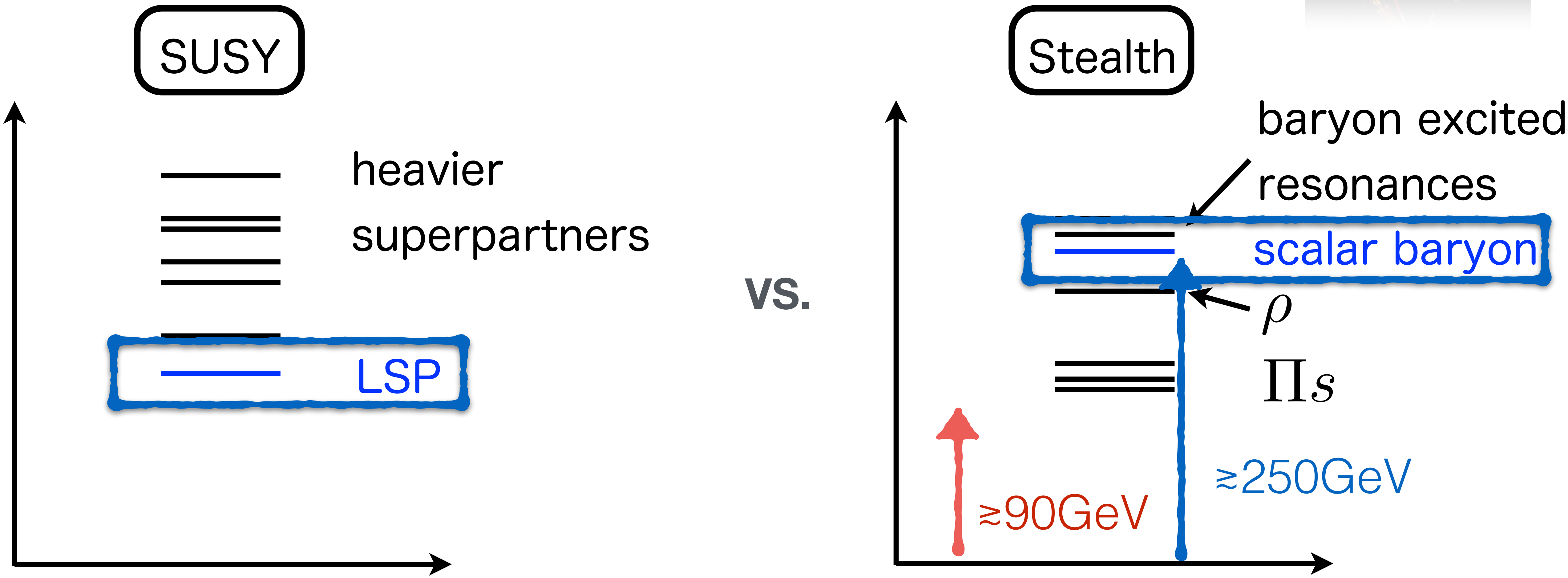

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- Dark mesons production and decay give interesting signatures: **the model can be constrained by collider limits!**

[Bagnasco et al.,hep-ph/9310290]

Photon interactions

$$\langle \chi(p')|j^\mu_{\rm EM}|\chi(p)\rangle = F(q^2)q^\mu$$

Expansion at low momentum through effective operators

✦dimension 5 ➥ magnetic dipole

$$\frac{(\bar\chi\sigma^{\mu\nu}\chi)F_{\mu\nu}}{\Lambda_{\rm dark}}$$

✦dimension 6 ➥ charge radius

$$\frac{(\bar\chi\chi)v_\mu\partial_\nu F^{\mu\nu}}{\Lambda^2_{\rm dark}}$$

✦dimension 7 ➥ polarizability

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custodial SU(2)

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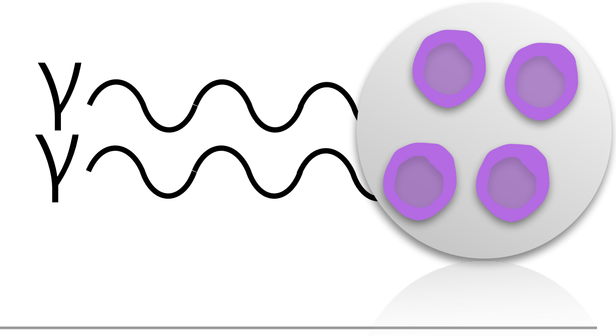
[Pospelov & Veldhuis, hep-ph/0003010] [Ovanesyan & Vecchi, 1410.0601] [Detmold et al., 0904.1586-1001.1131]
[Weiner & Yavin,1206.2910] [Frandsen et al., 1207.3971]



Computing polarizability

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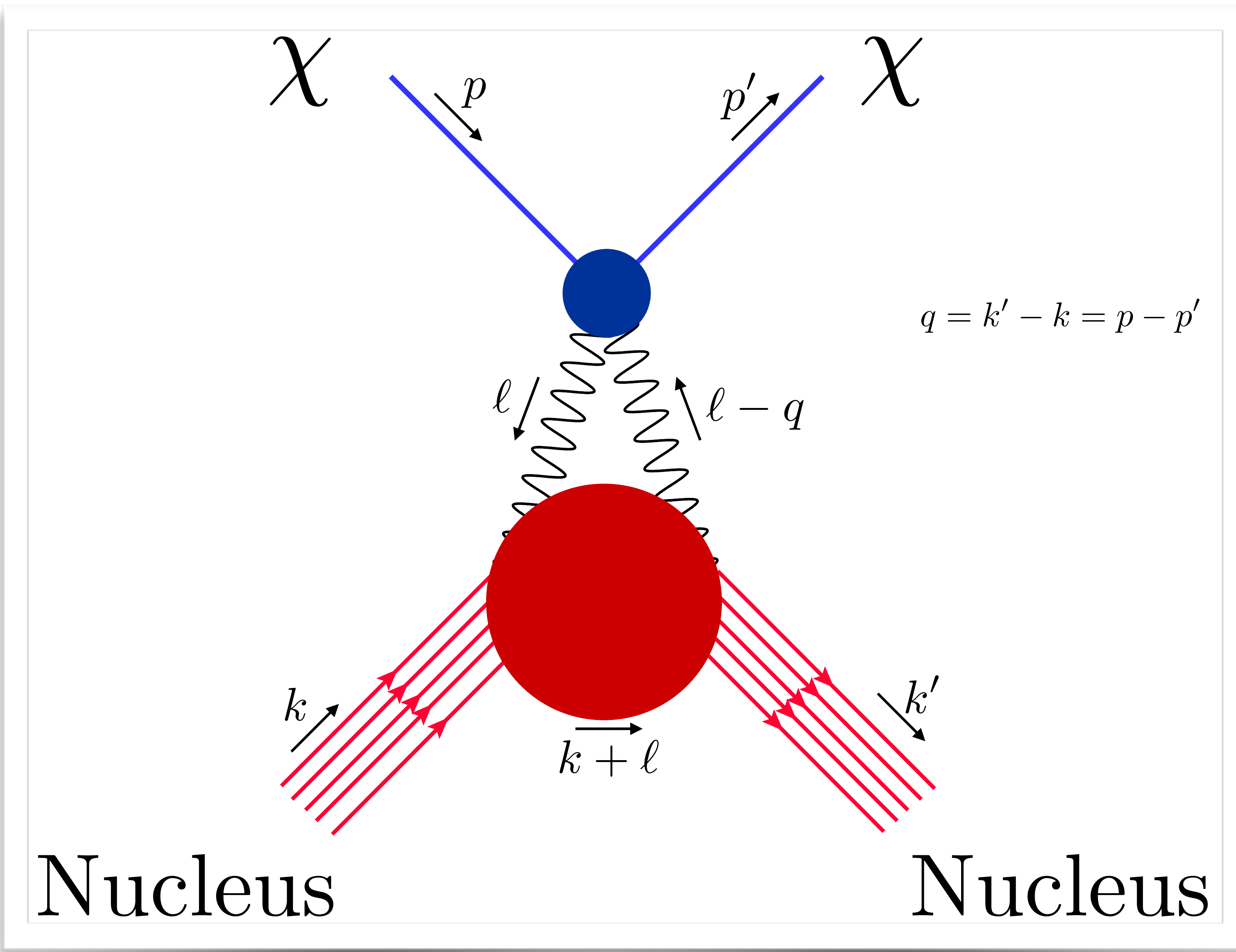

[Pospelov & Veldhuis, hep-ph/0003010] [Ovanesyan & Vecchi, 1410.0601] [Weiner & Yavin,1206.2910] [Frandsen et al., 1207.3971]

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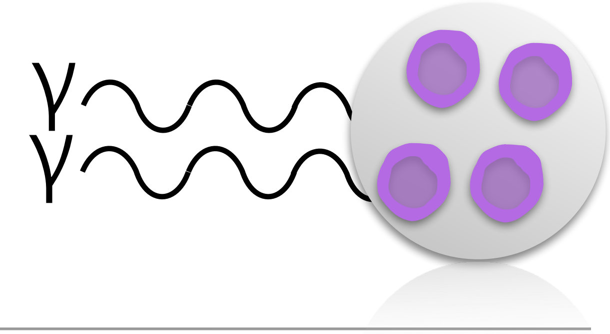

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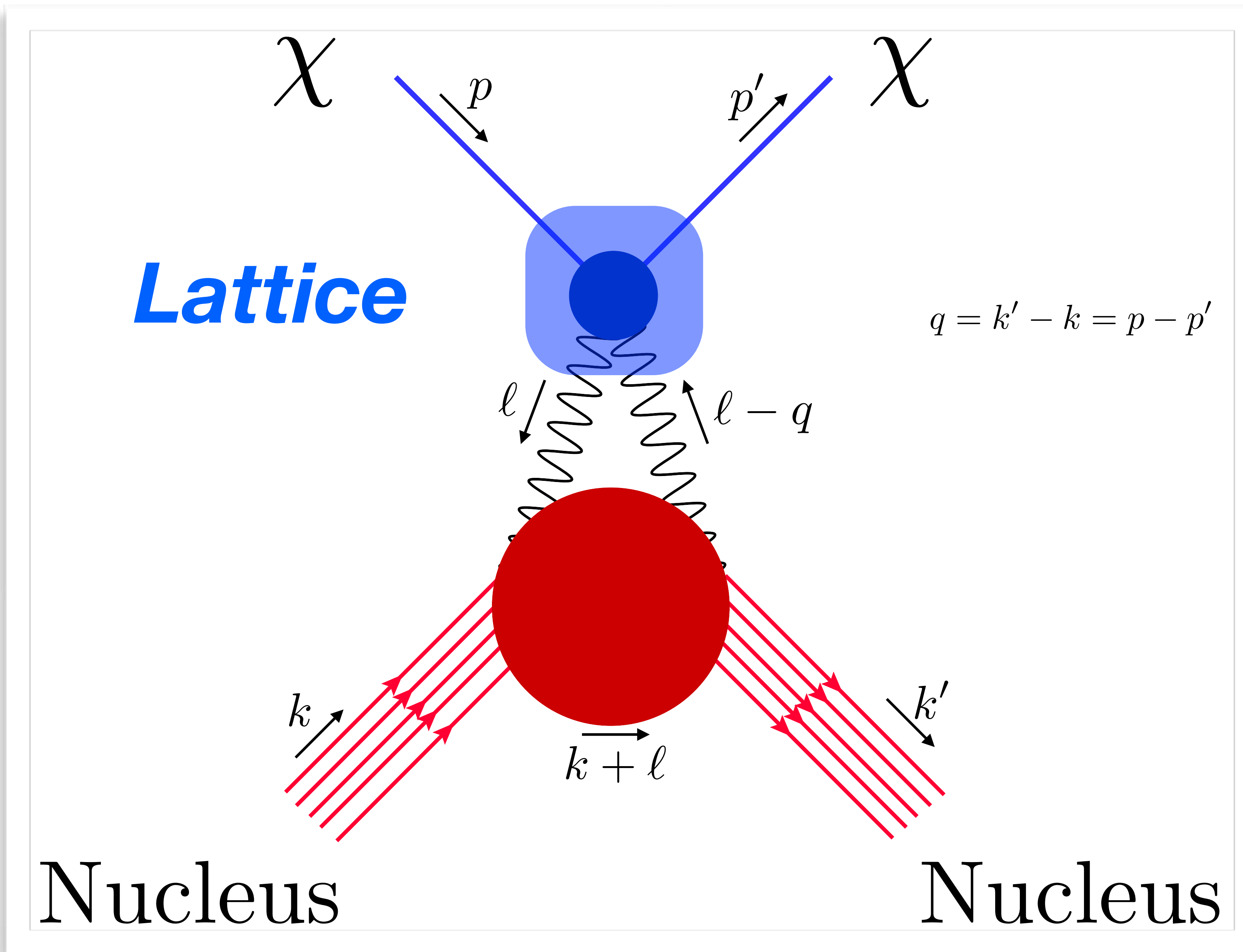

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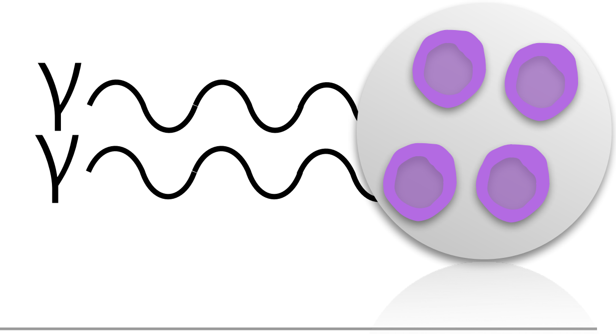

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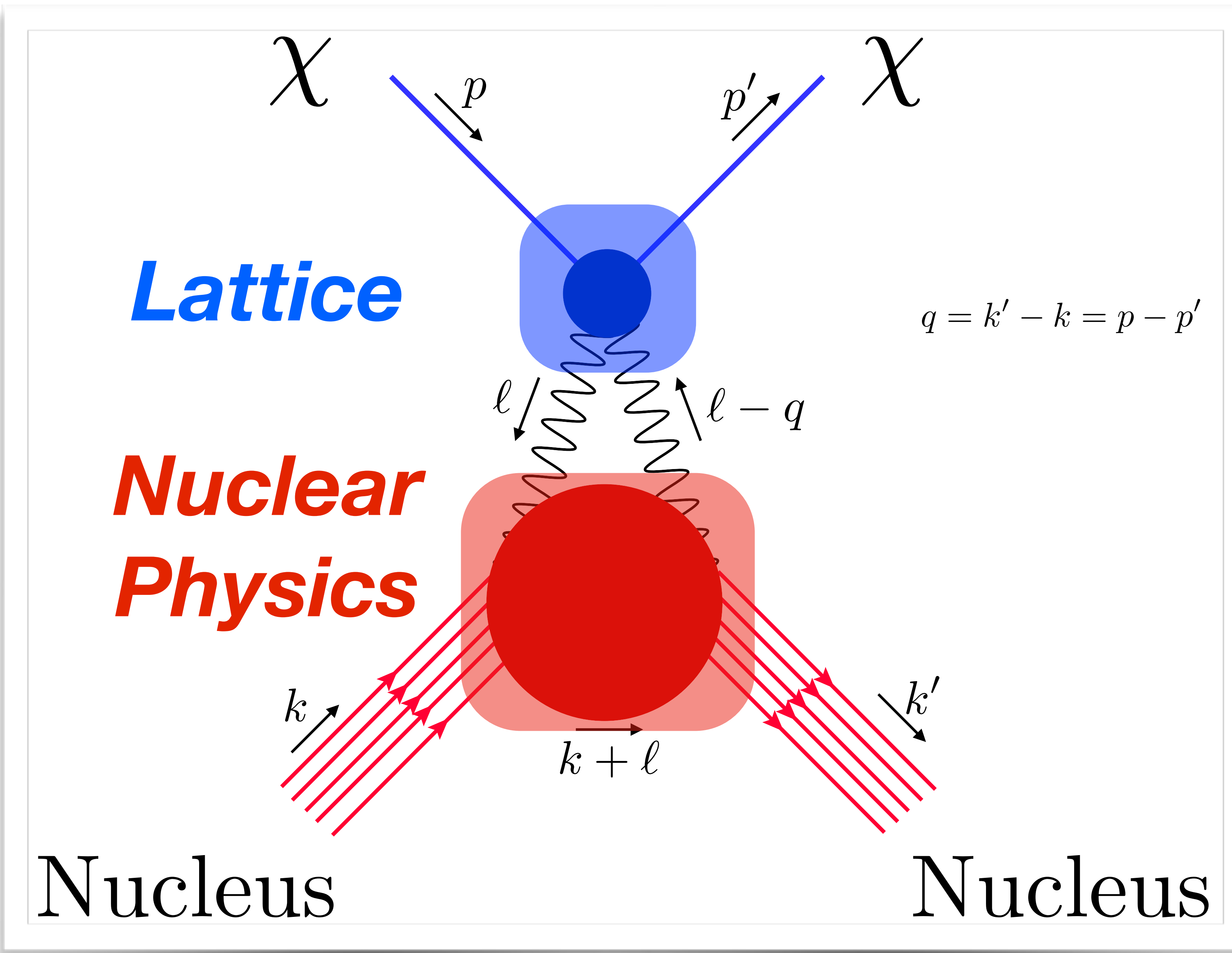
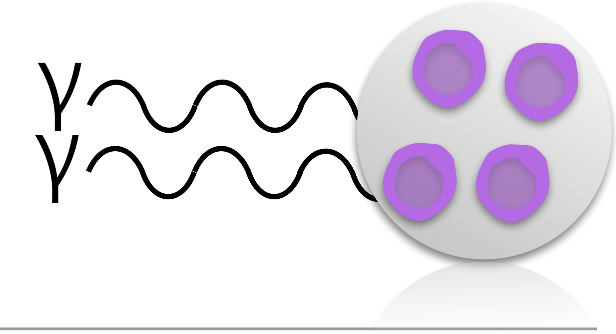
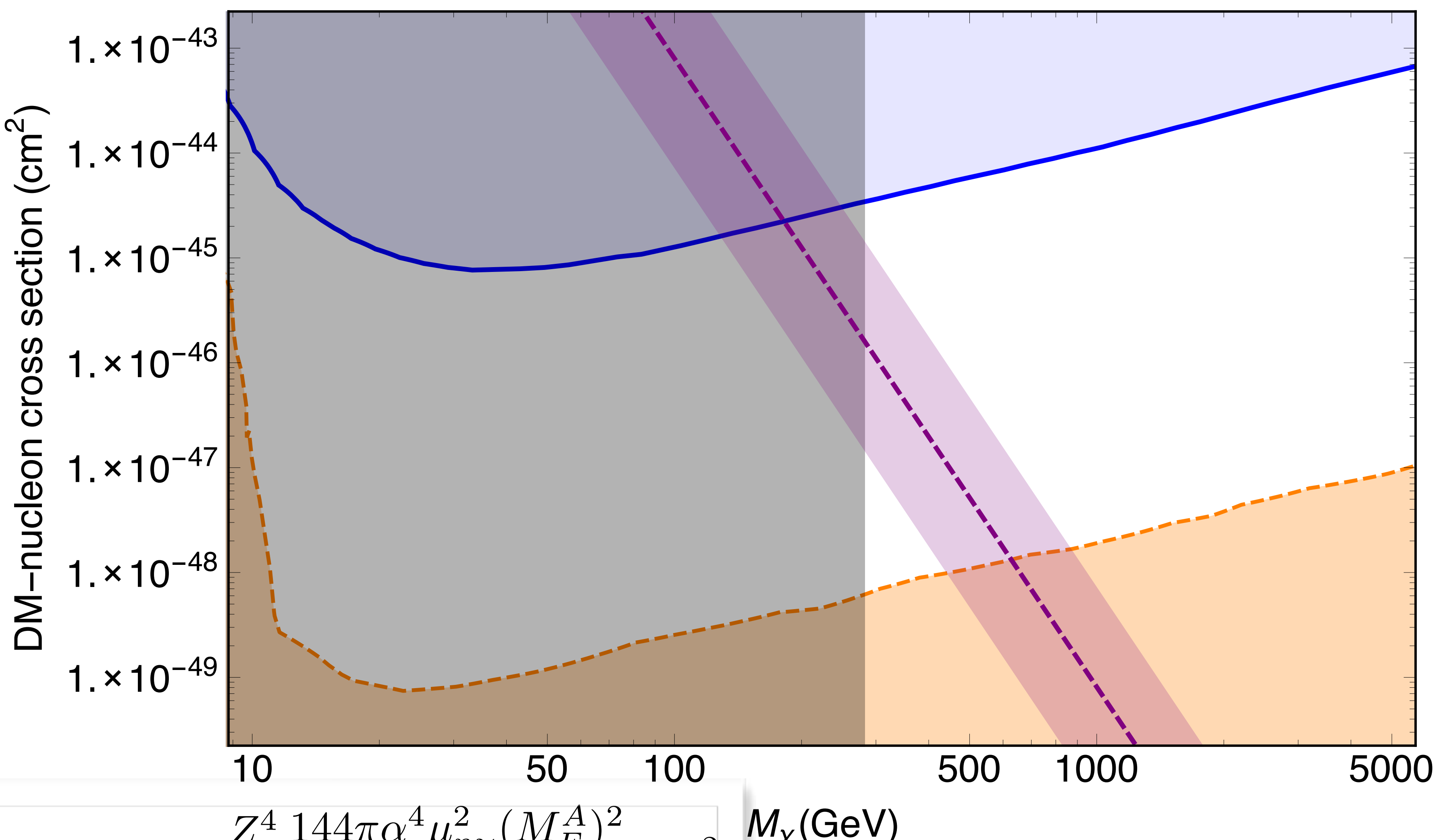


Lowest bound from EM polarizability



Electric polarizability from lattice simulations with background fields



SU(4) N_f=4 Stealth DM

[LSD, 1503.04205]

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

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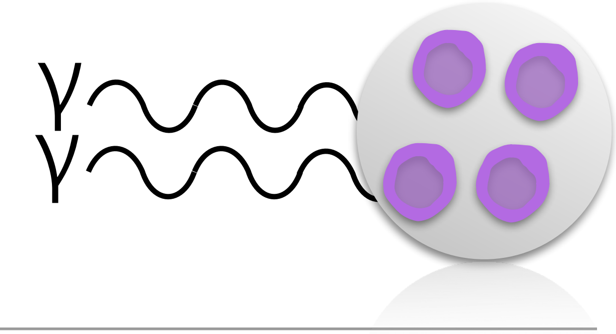

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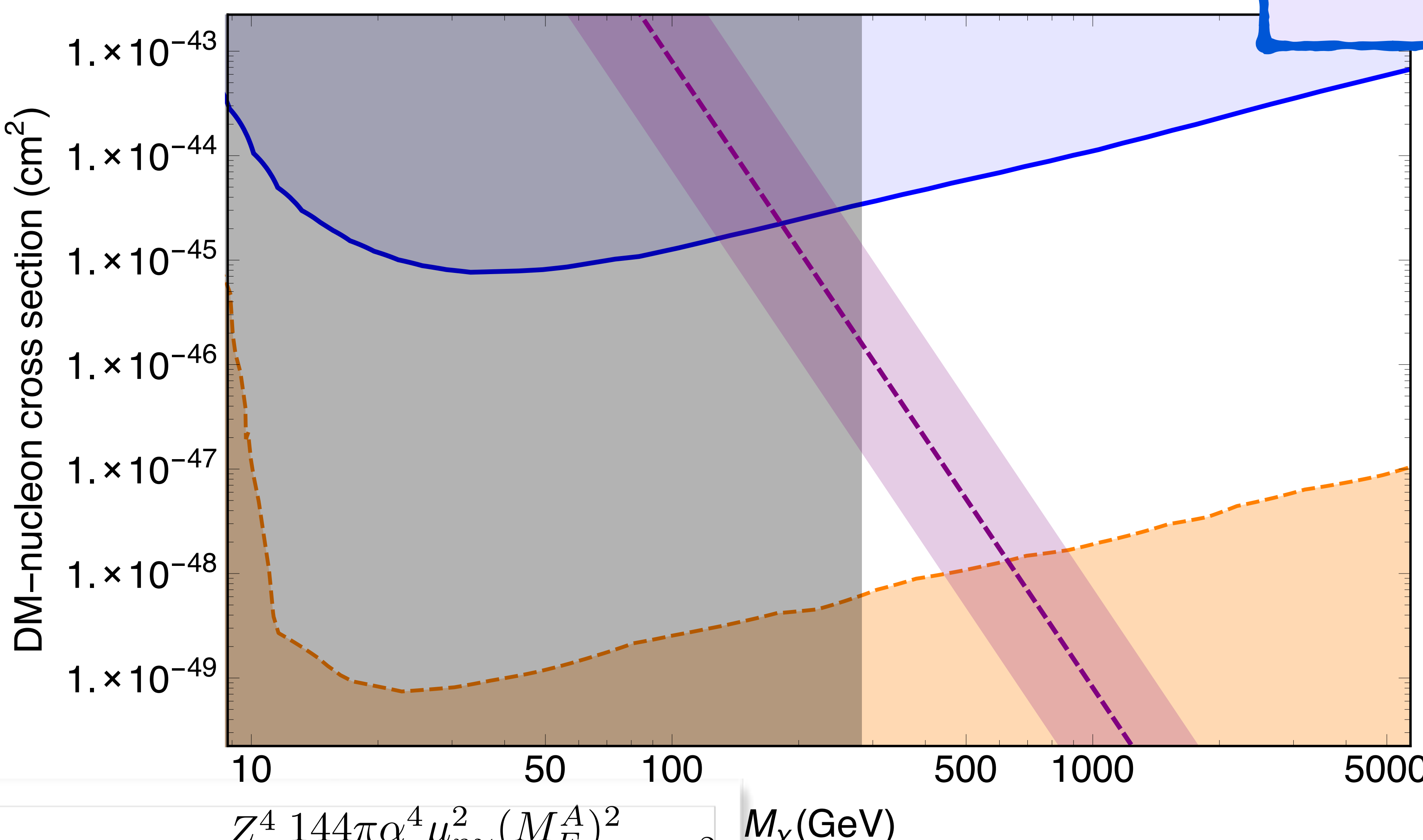
LUX exclusion bound for spin-independent cross section



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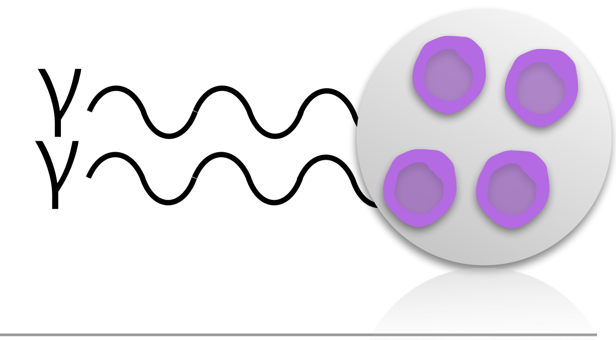

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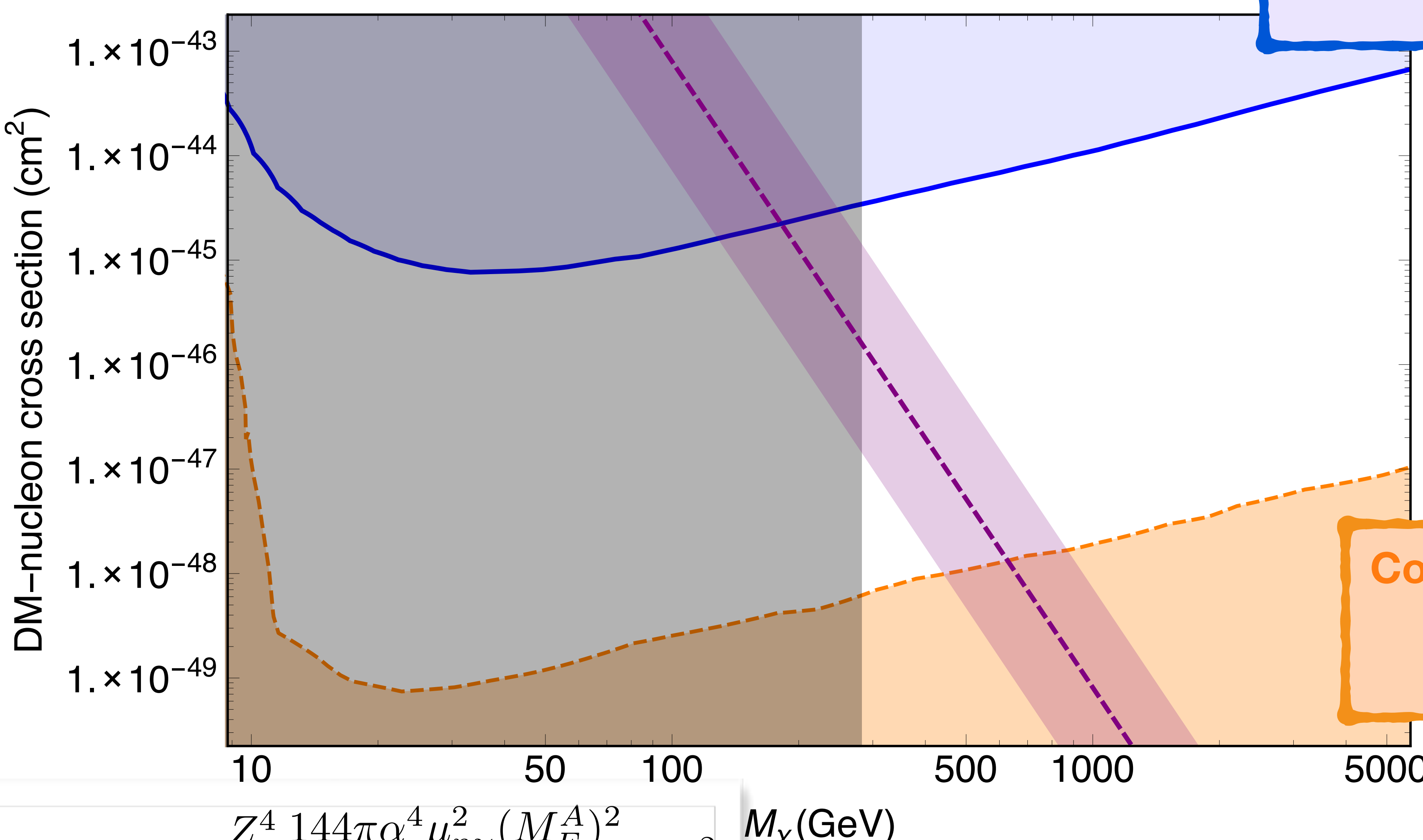

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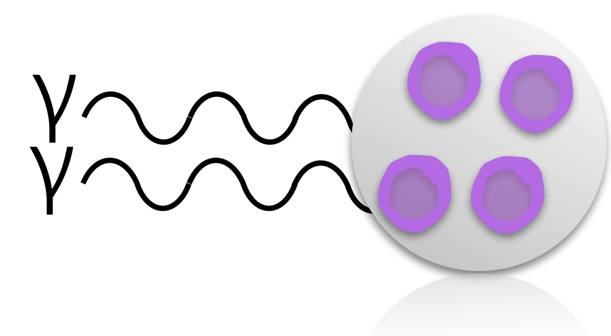

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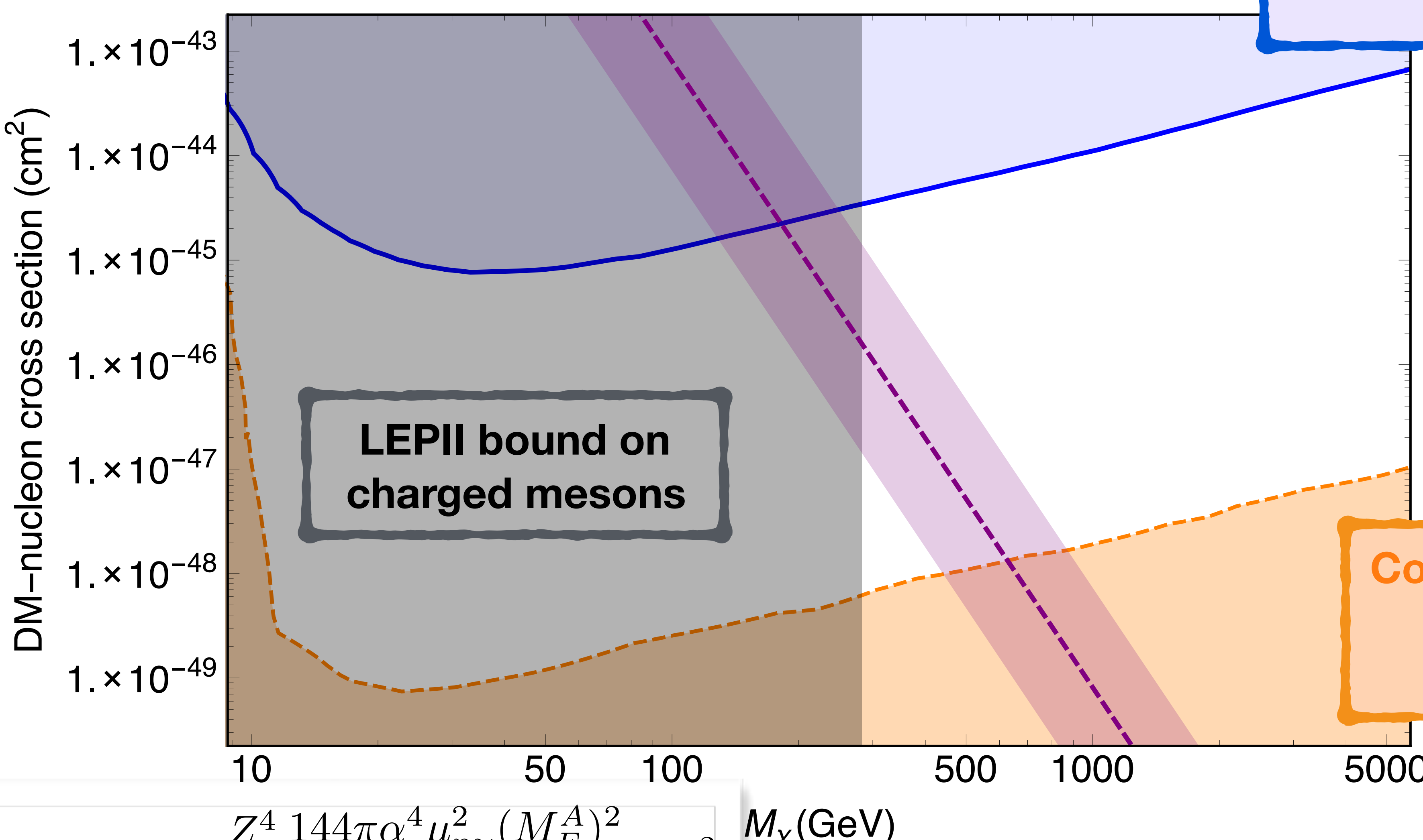

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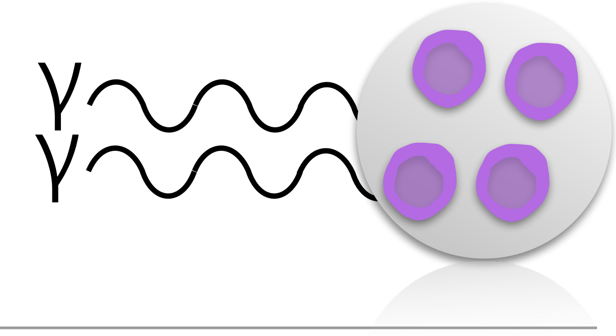

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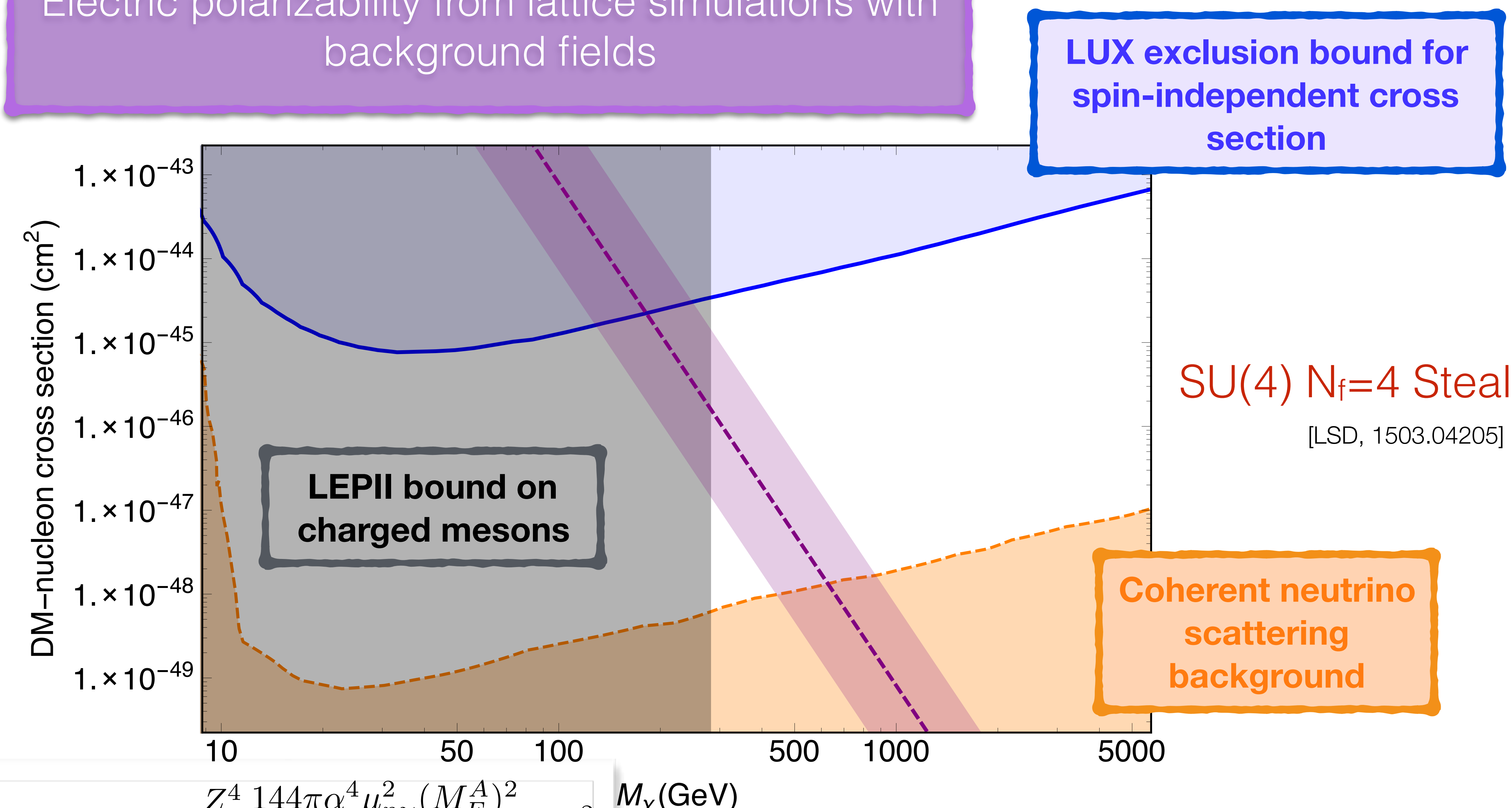

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lowest allowed direct detection cross-section for composite dark matter theories with EW charged constituents

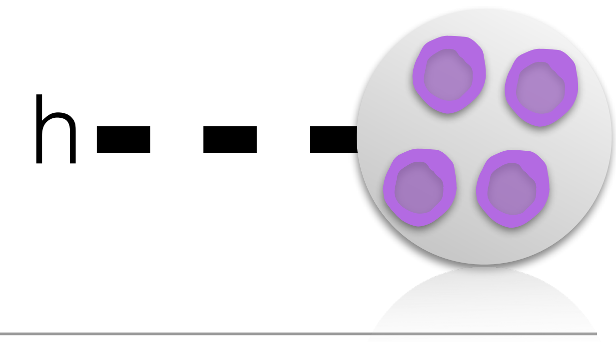
Concluding remarks

- ★ 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, production rates at colliders, and self-interaction cross sections of phenomenological relevance.
- ★ Dark matter constituents can carry electroweak charges and still the stable composites are currently undetectable. Stealth cross section.

extra

[LSD, 1402.6656-1503.04203]
[LatKMI, 1510.07373]
[DeGrand et al., 1501.05665]

Computing Higgs exchange



- Need to non-perturbatively evaluate the dark σ-term

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

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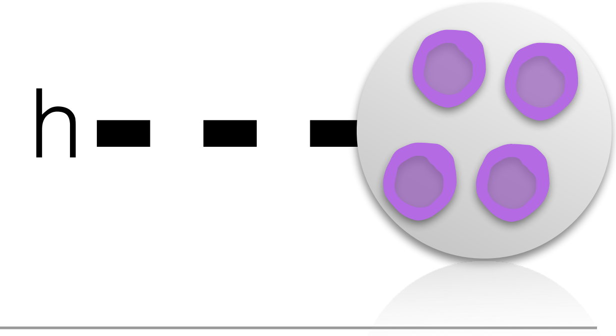

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2. dark baryon scalar form factor: need lattice input for generic DM models!
3. nucleon scalar form factor: ChPT and lattice input

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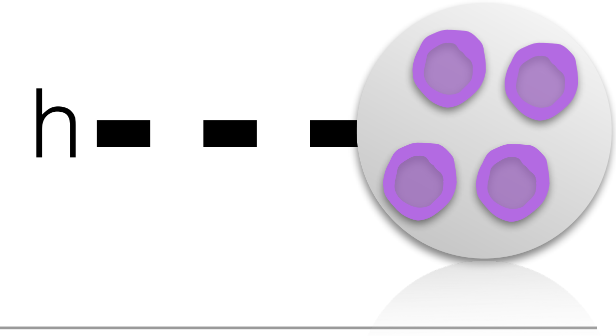

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$$m_f(h) = m + \frac{y_f h}{\sqrt{2}}$$

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

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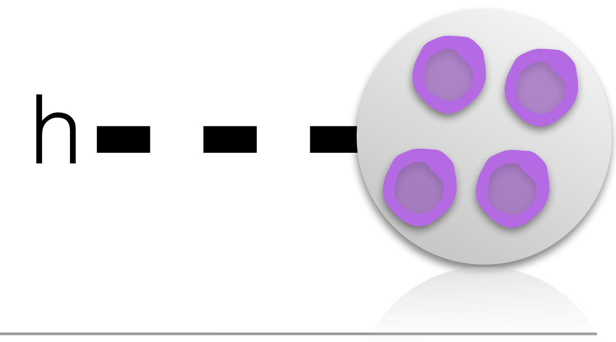

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- Model-dependent answer for the cross-section

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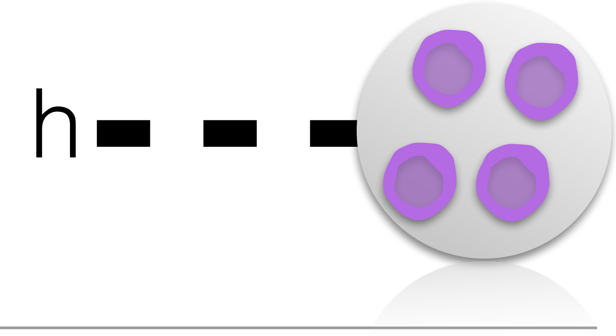

- Need to non-perturbatively evaluate the dark σ-term
- Effective Higgs coupling non-trivial with mixed chiral and vector-like masses
- Model-dependent answer for the cross-section
- **Lattice input** is necessary: compute mass and form factor

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

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Lattice!

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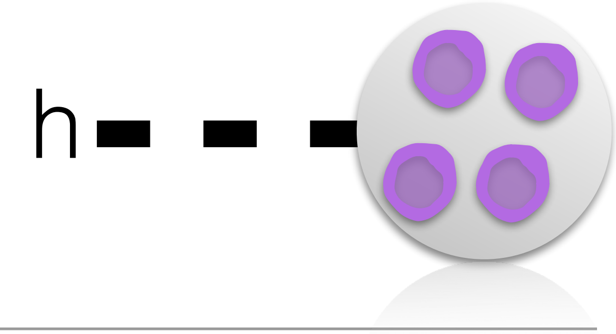
Bounds from Higgs exchange

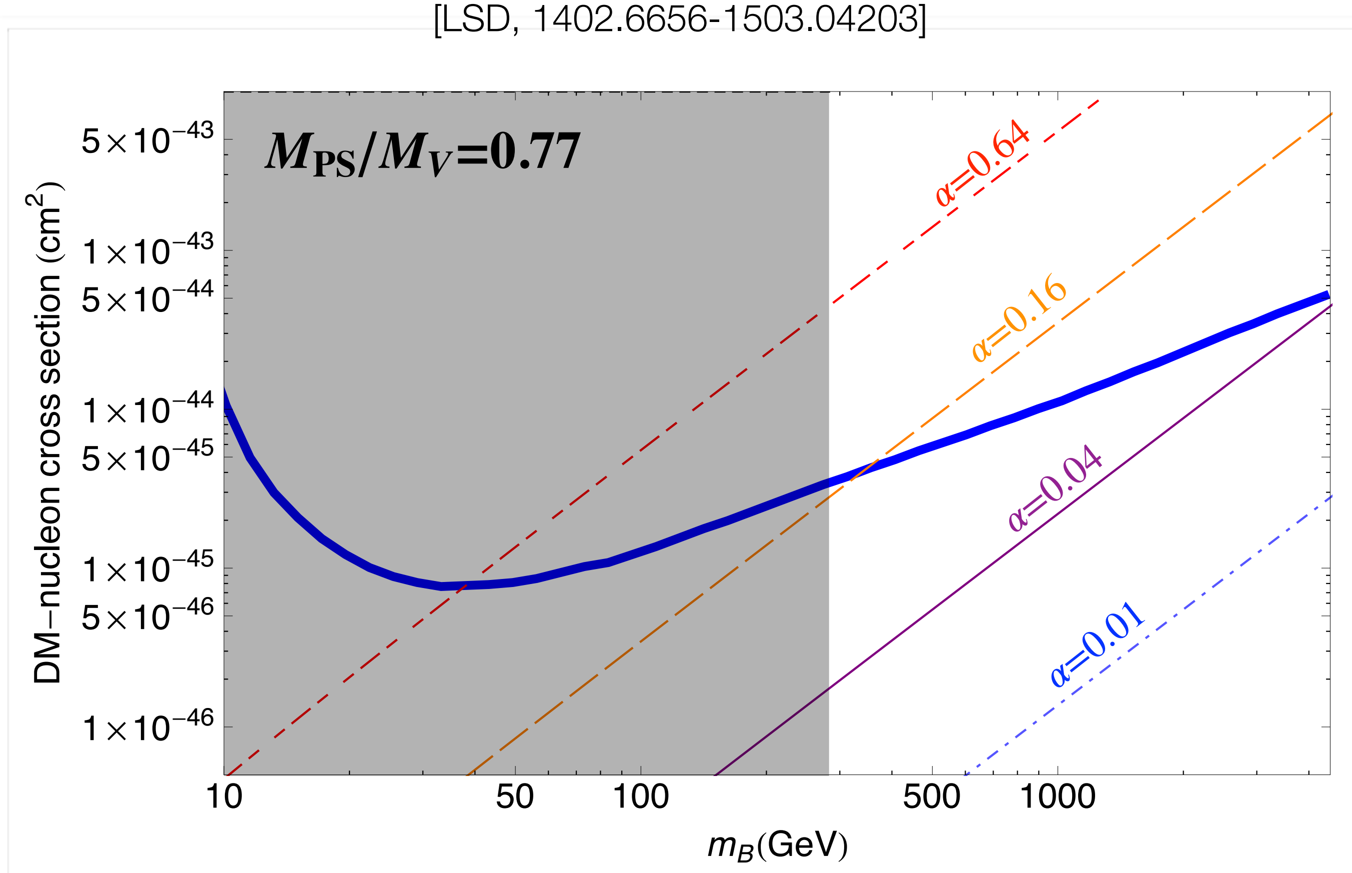


✦Lattice results for the cross-section are compared to **experimental** bounds

✦Coupling space in specific models can be vastly constrained

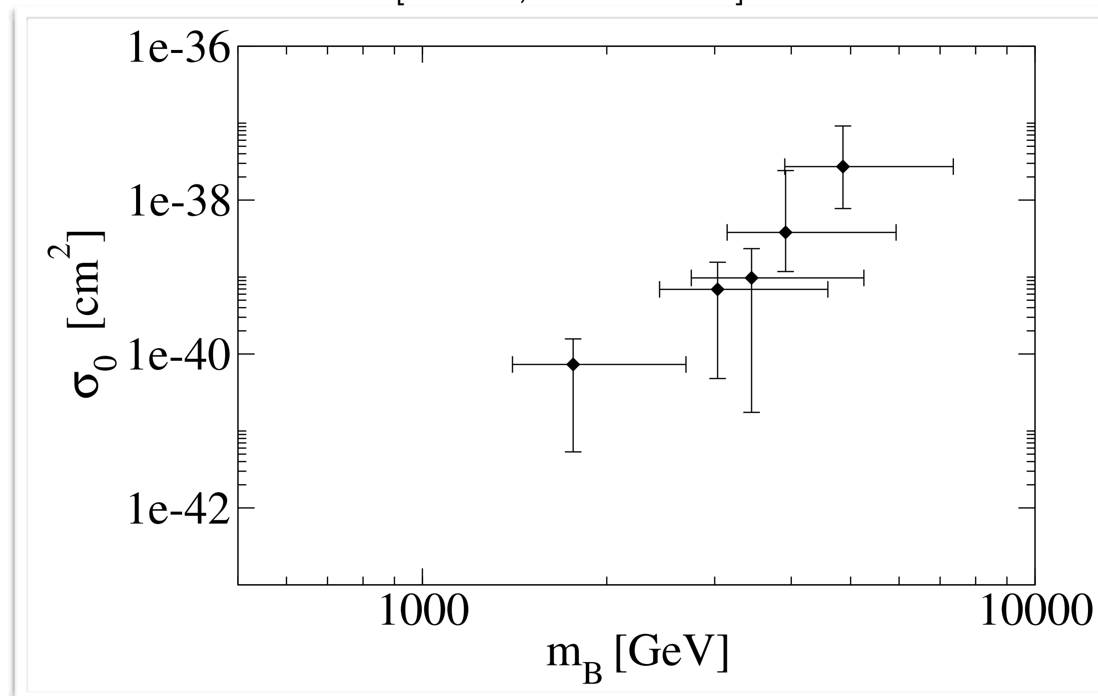
SU(4) N_f=4 Stealth DM

[LSD, 1402.6656-1503.04203]



SU(3) N_f=8 “technibaryon”

[LatKMI, 1510.07373]



✦Some candidates can be excluded as *dominant sources of dark matter

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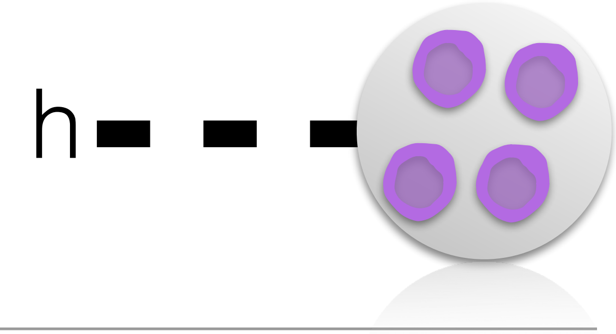

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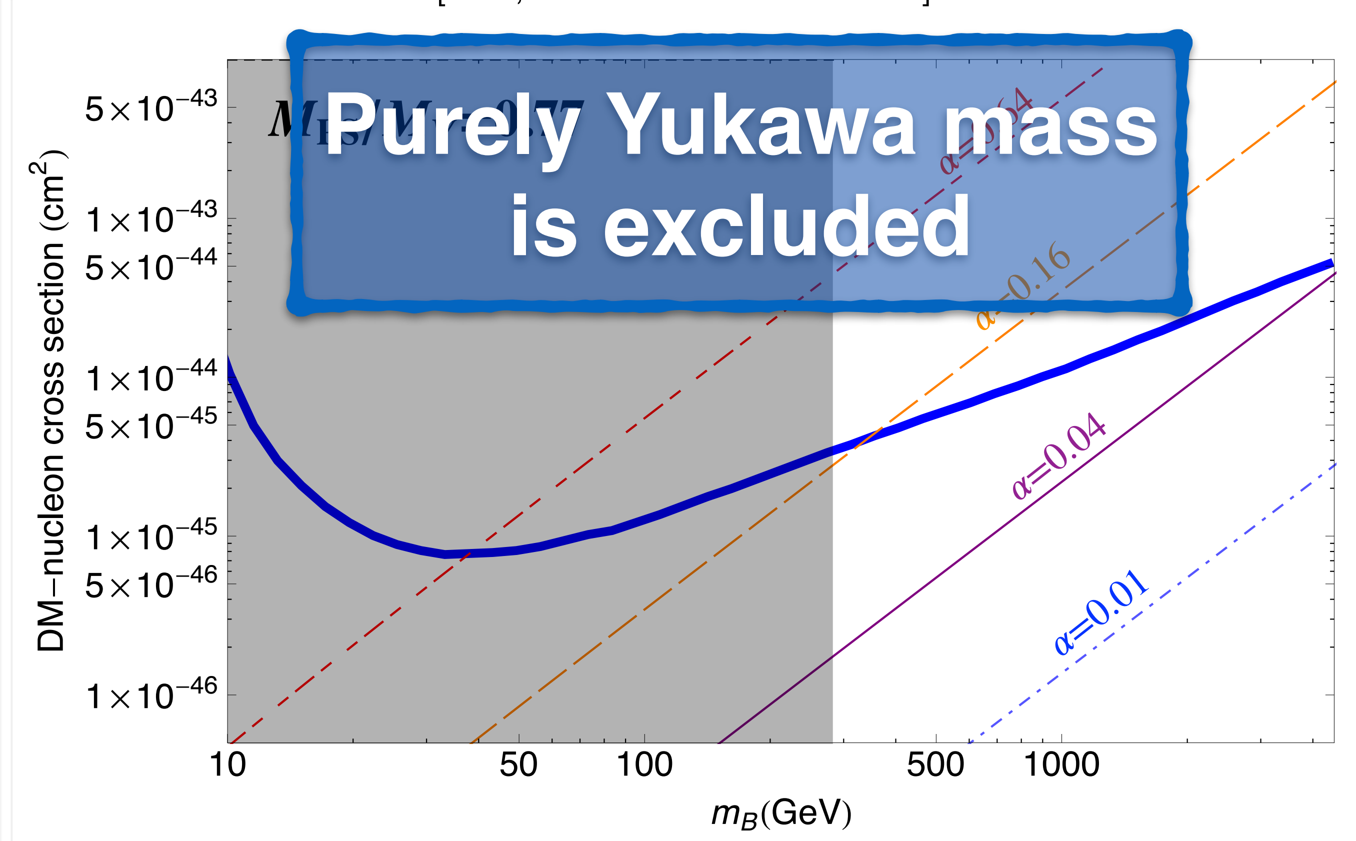

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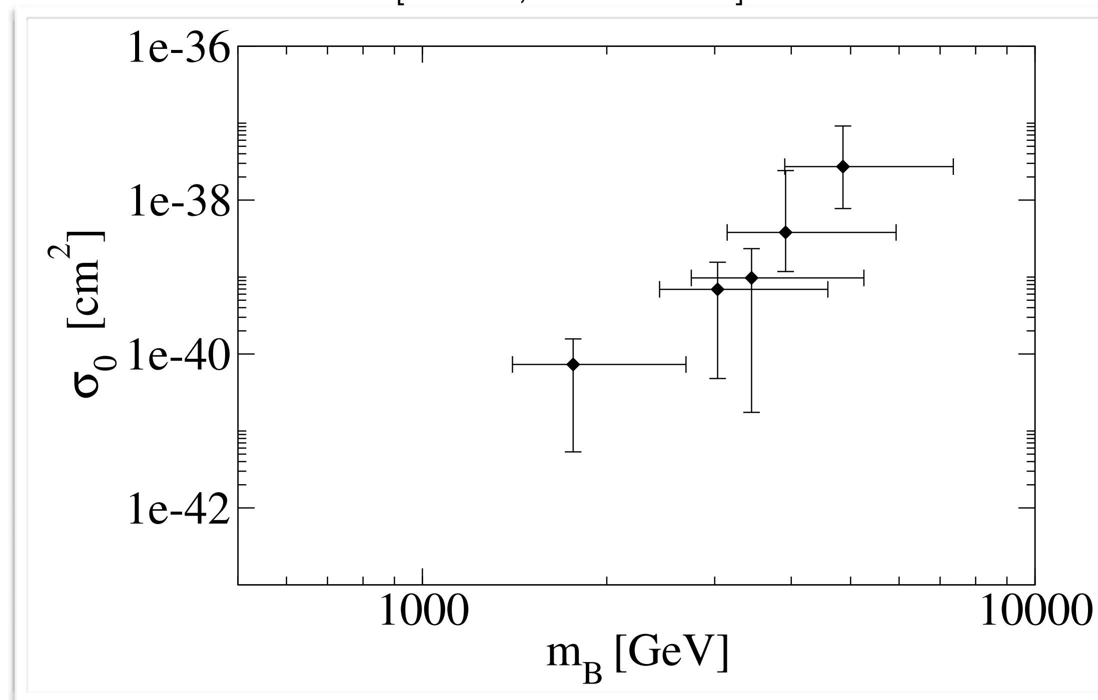

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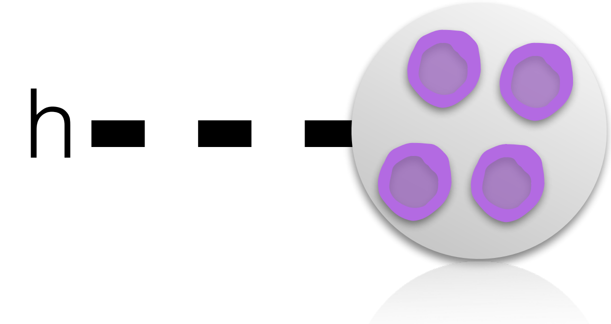

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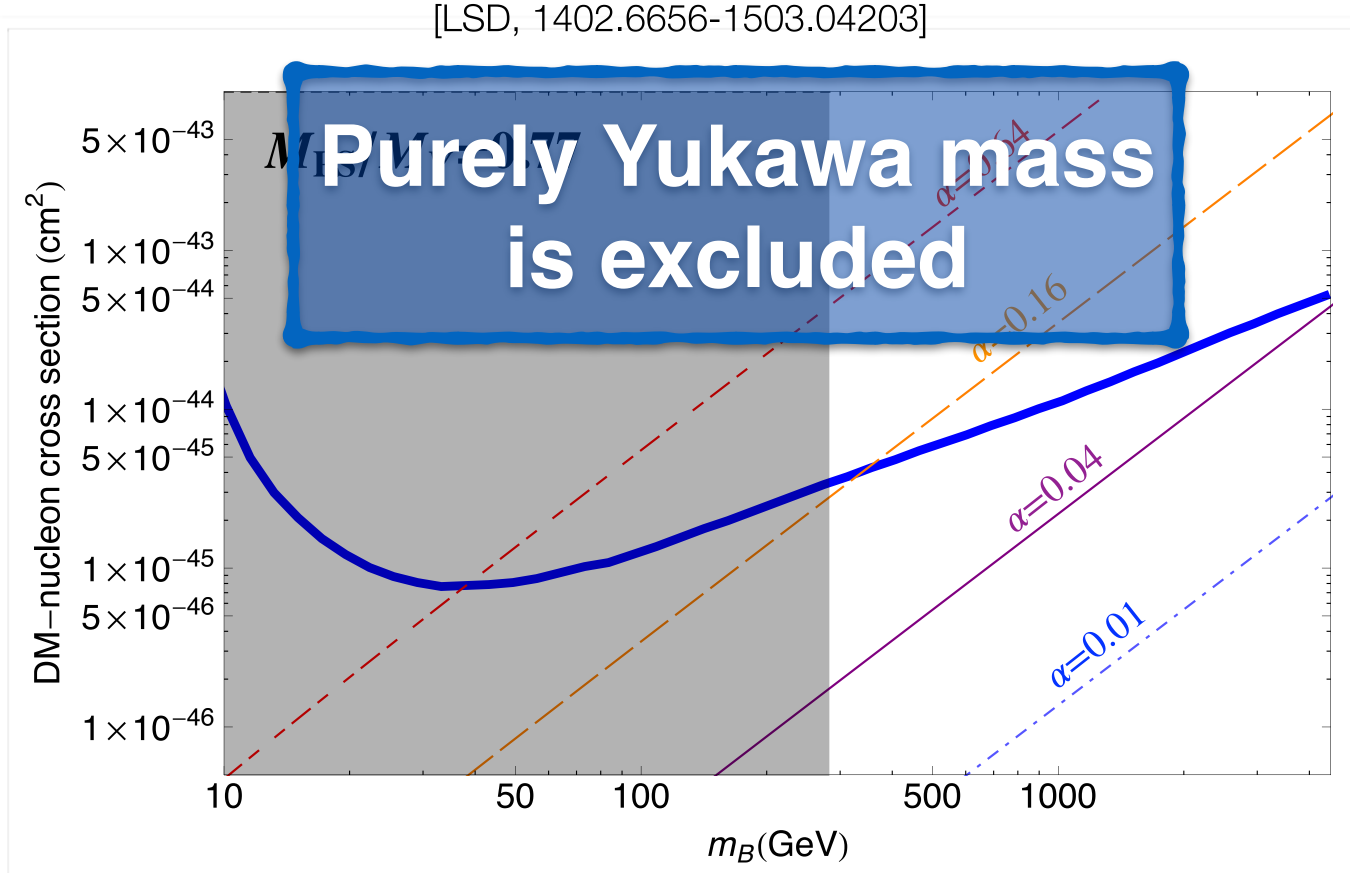

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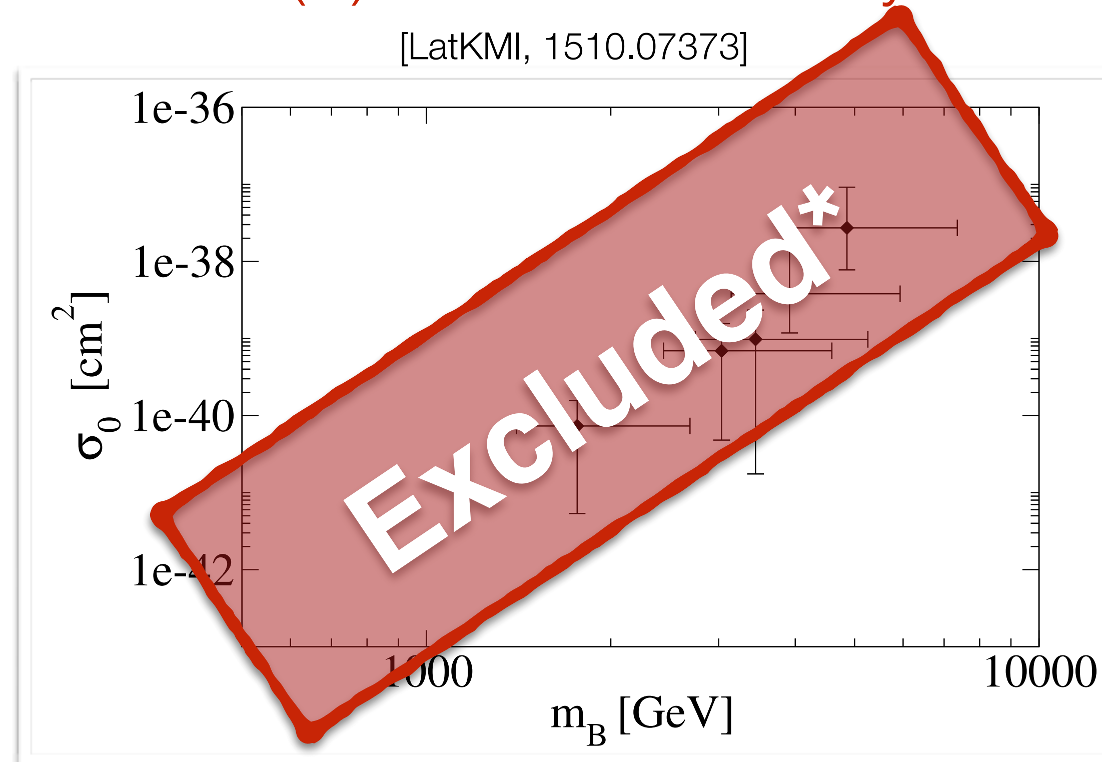

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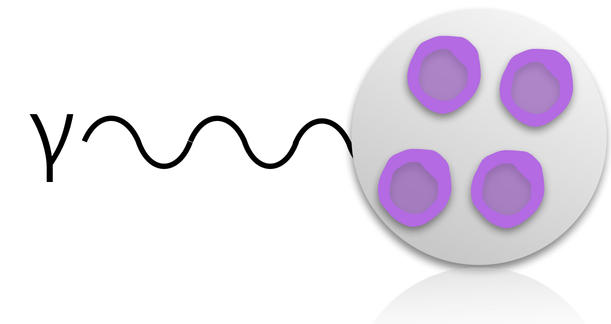
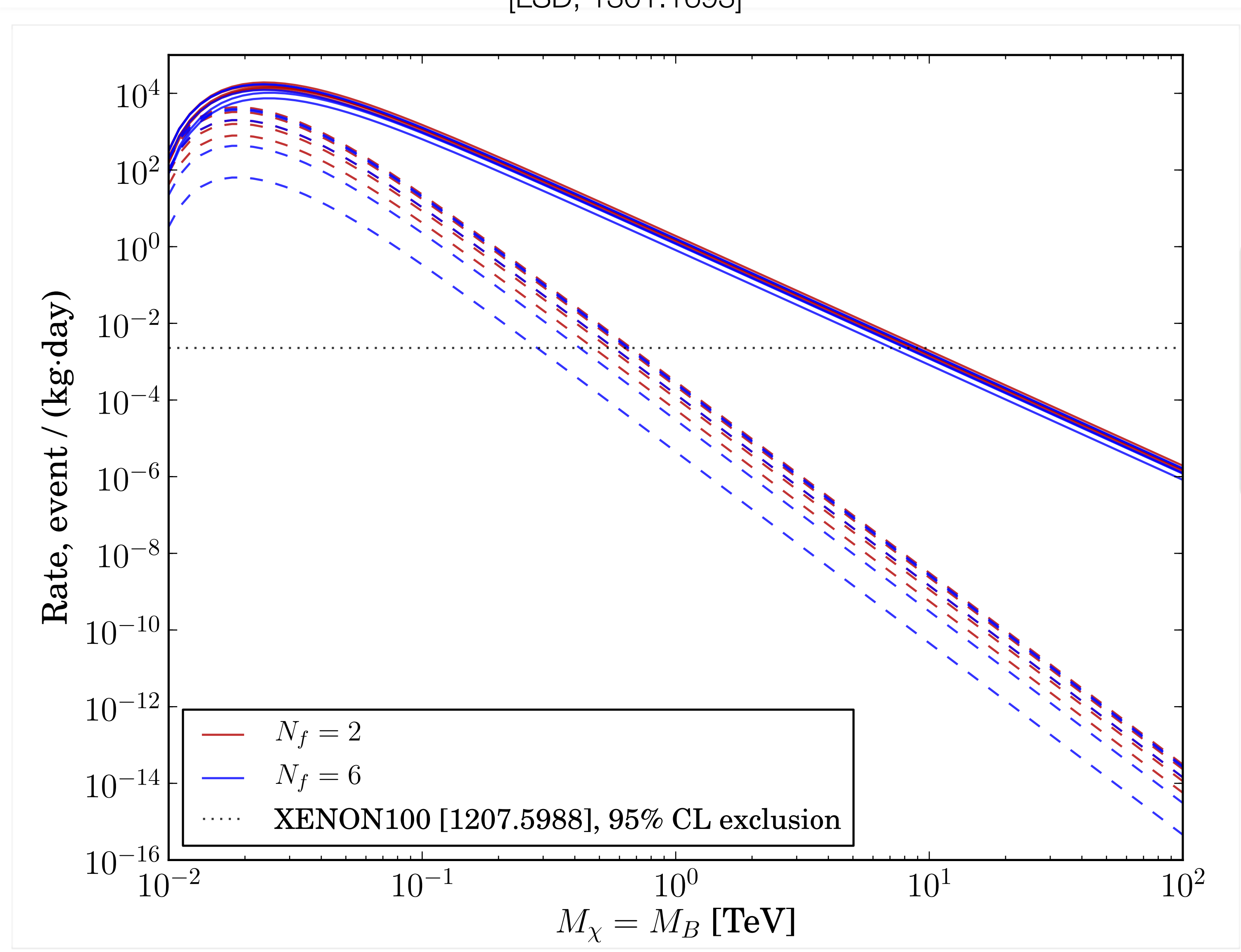
Bounds from EM moments



Mesonic and Baryonic EM form factors directly from lattice simulations

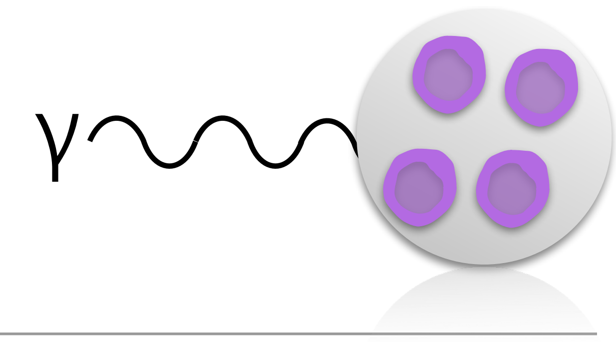
SU(3) N_f=2,6 dark fermionic baryon

[LSD, 1301.1693]



- ★ baryon similar to QCD neutron
- ★ dark quarks with Q=Y
- ★ calculate connected 3pt
- ★ scale set by DM mass
- ★ magnetic moment dominates
- ★ results independent of N_f

Bounds from EM moments



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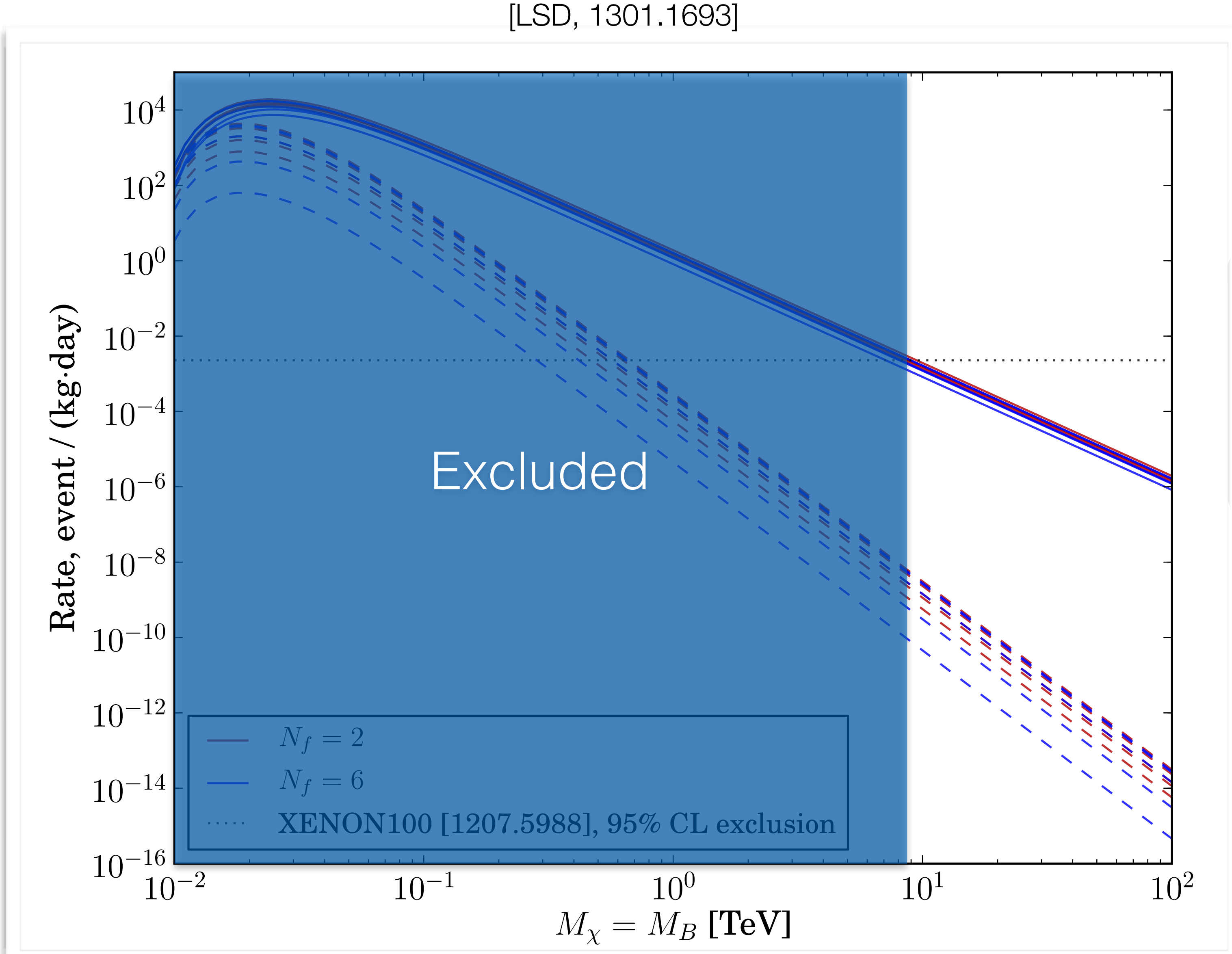

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M_B >~ 10 TeV

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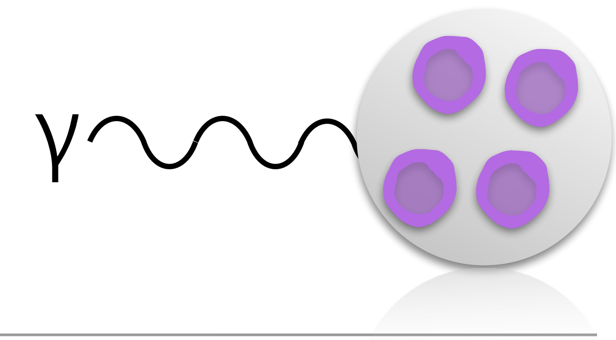

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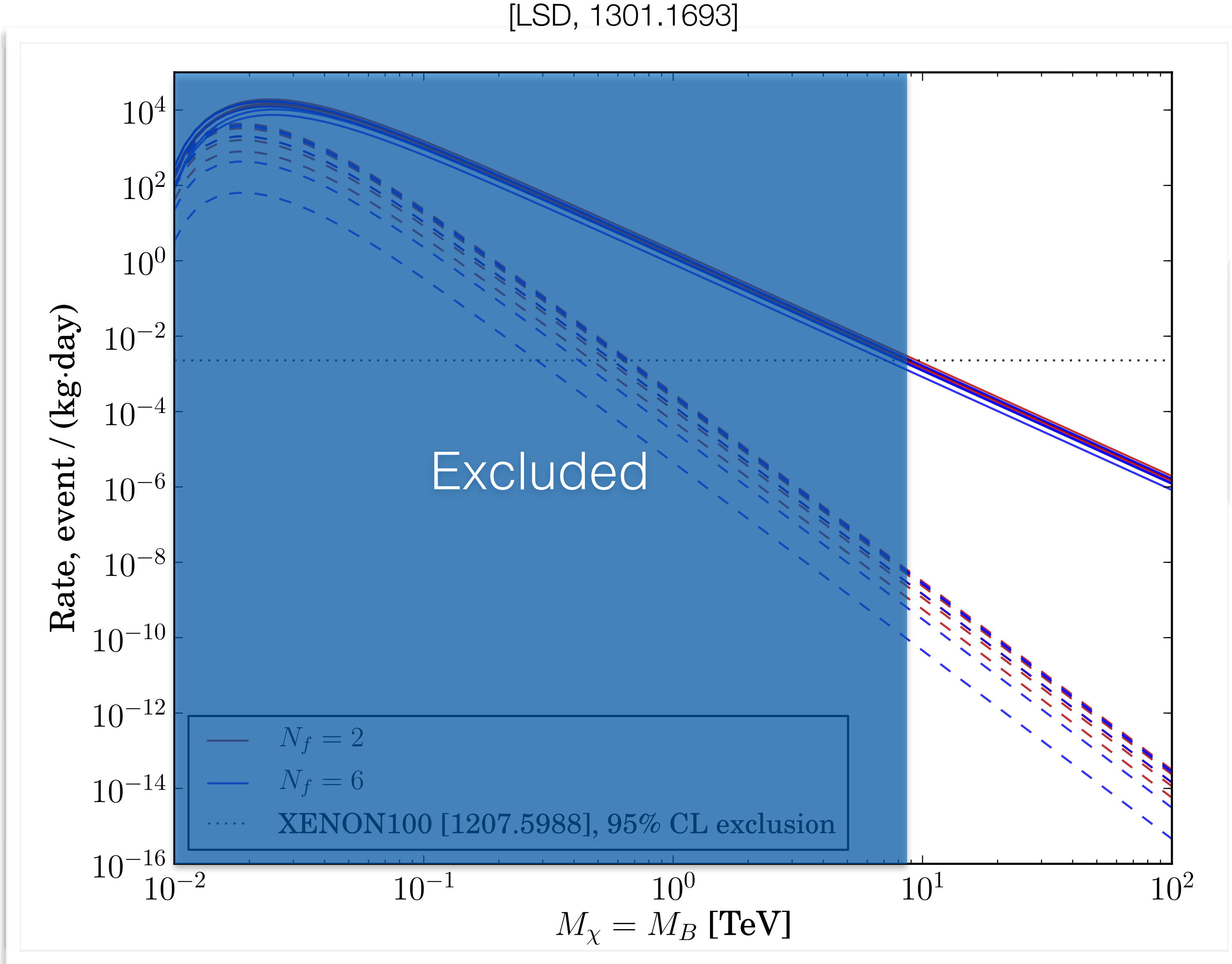

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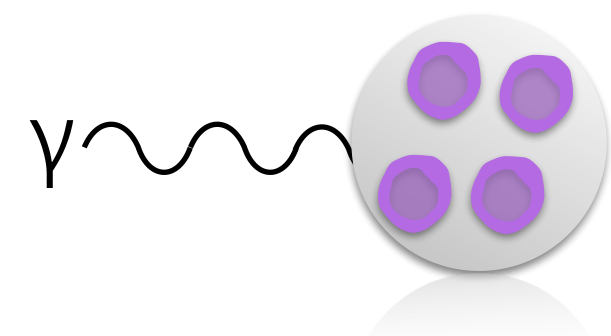
pushed to ~100 TeV with new LUX

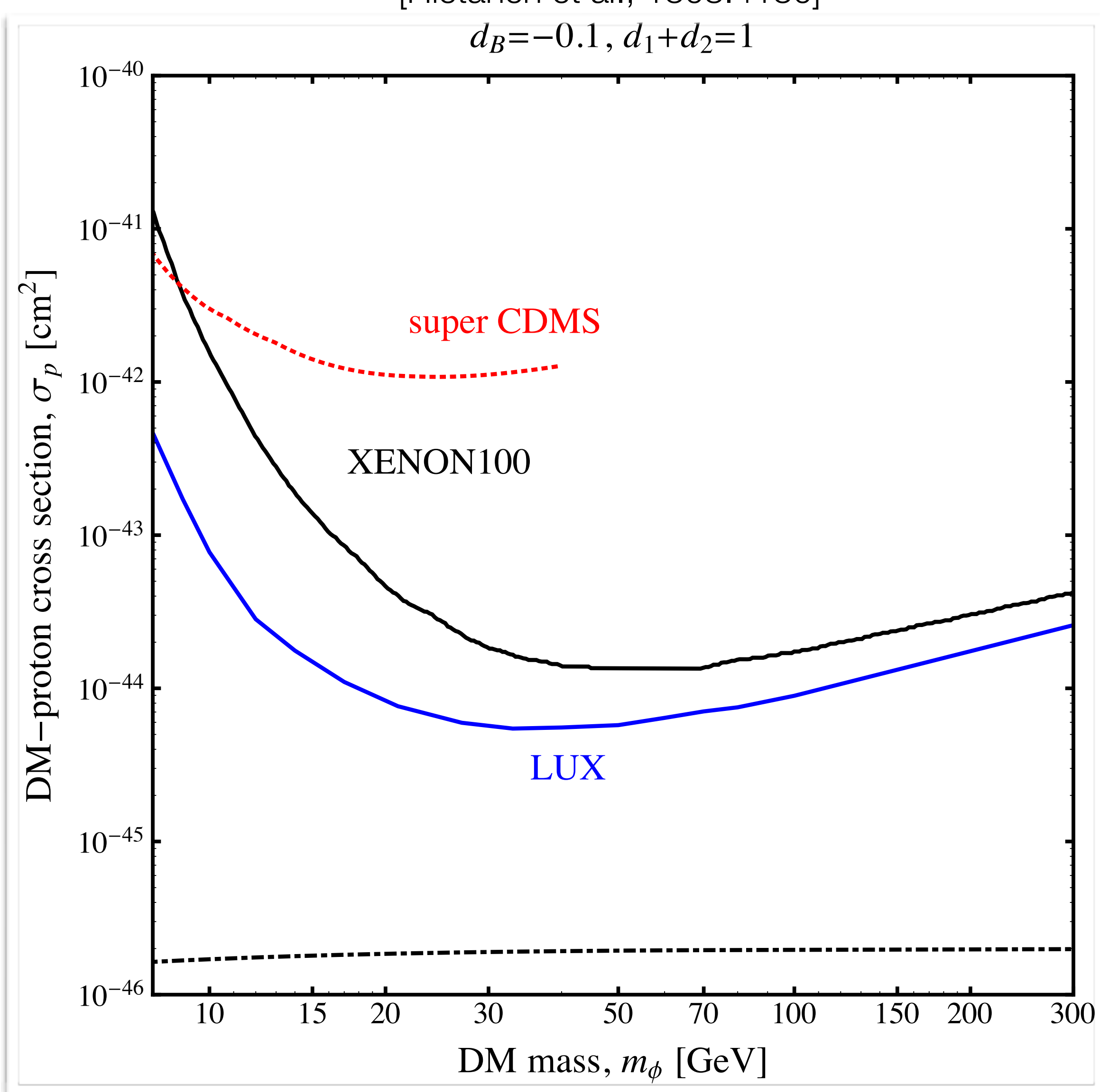
Bounds from EM moments



Mesonic and Baryonic EM form factors directly from lattice simulations

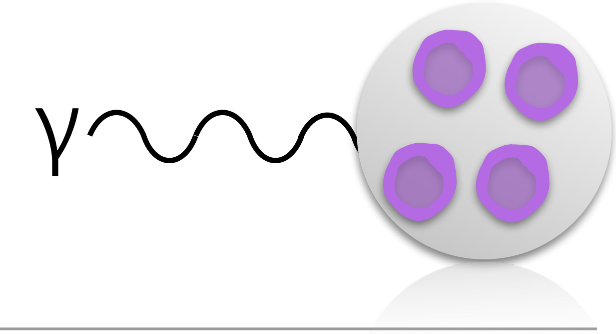
SU(2) N_f=2 pNGB DM

[Hietanen et al., 1308.4130]



- ★ dm is “mesonic” pNGB
- ★ calculate connected 3pt
- ★ use VMD with lattice ρ mass
- ★ scale set by F_π=256 GeV
- ★ depends on isospin breaking d_B
- ★ also couples to Higgs (d_1+d_2)

Bounds from EM moments



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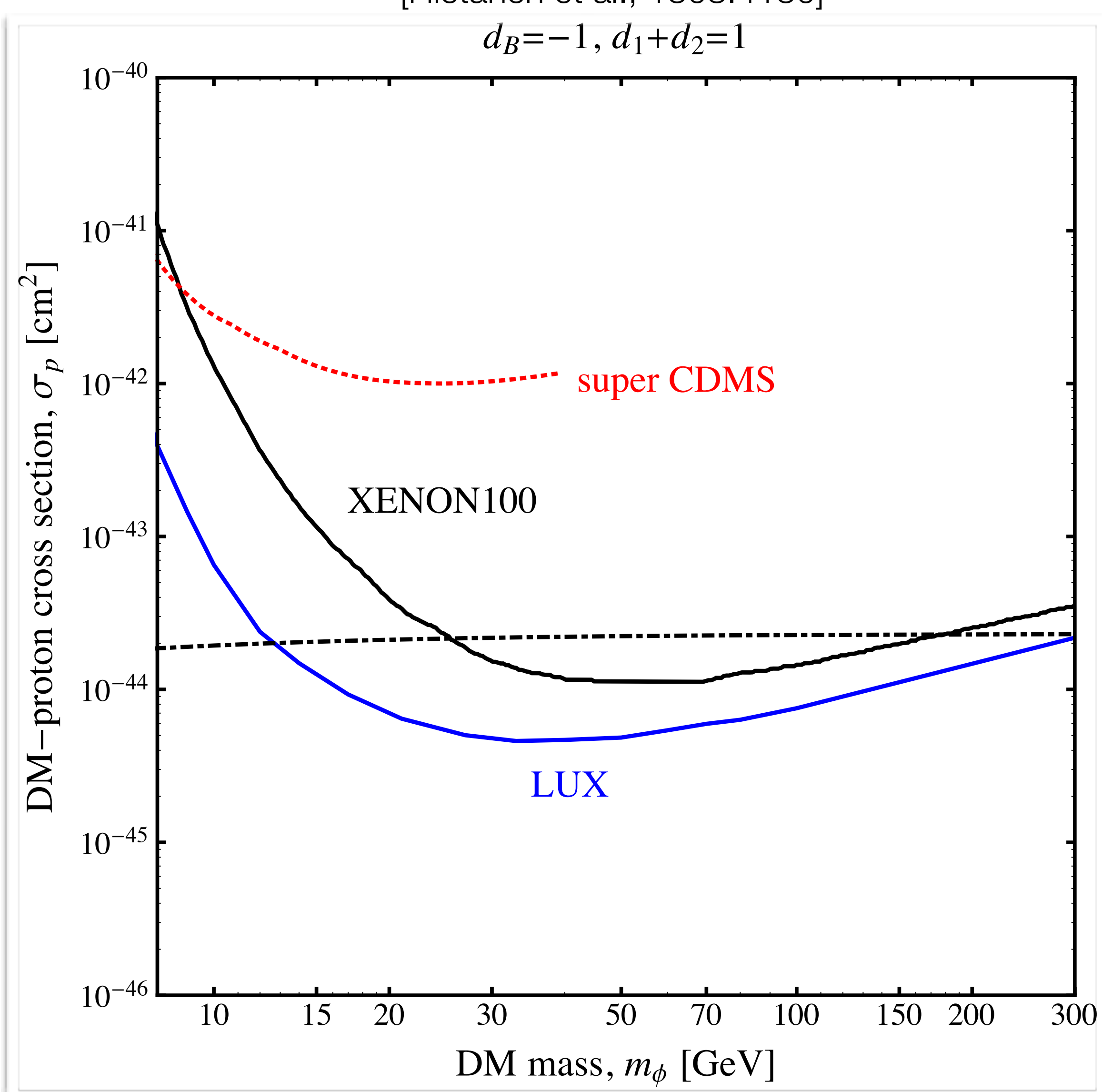

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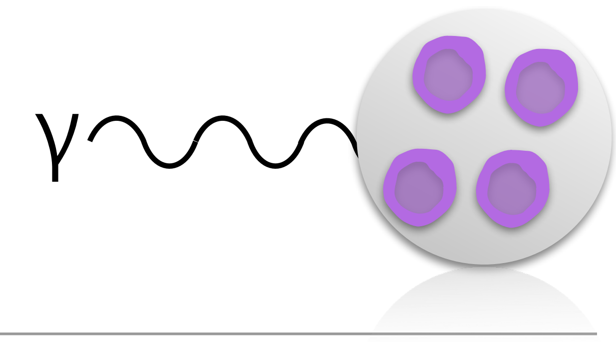

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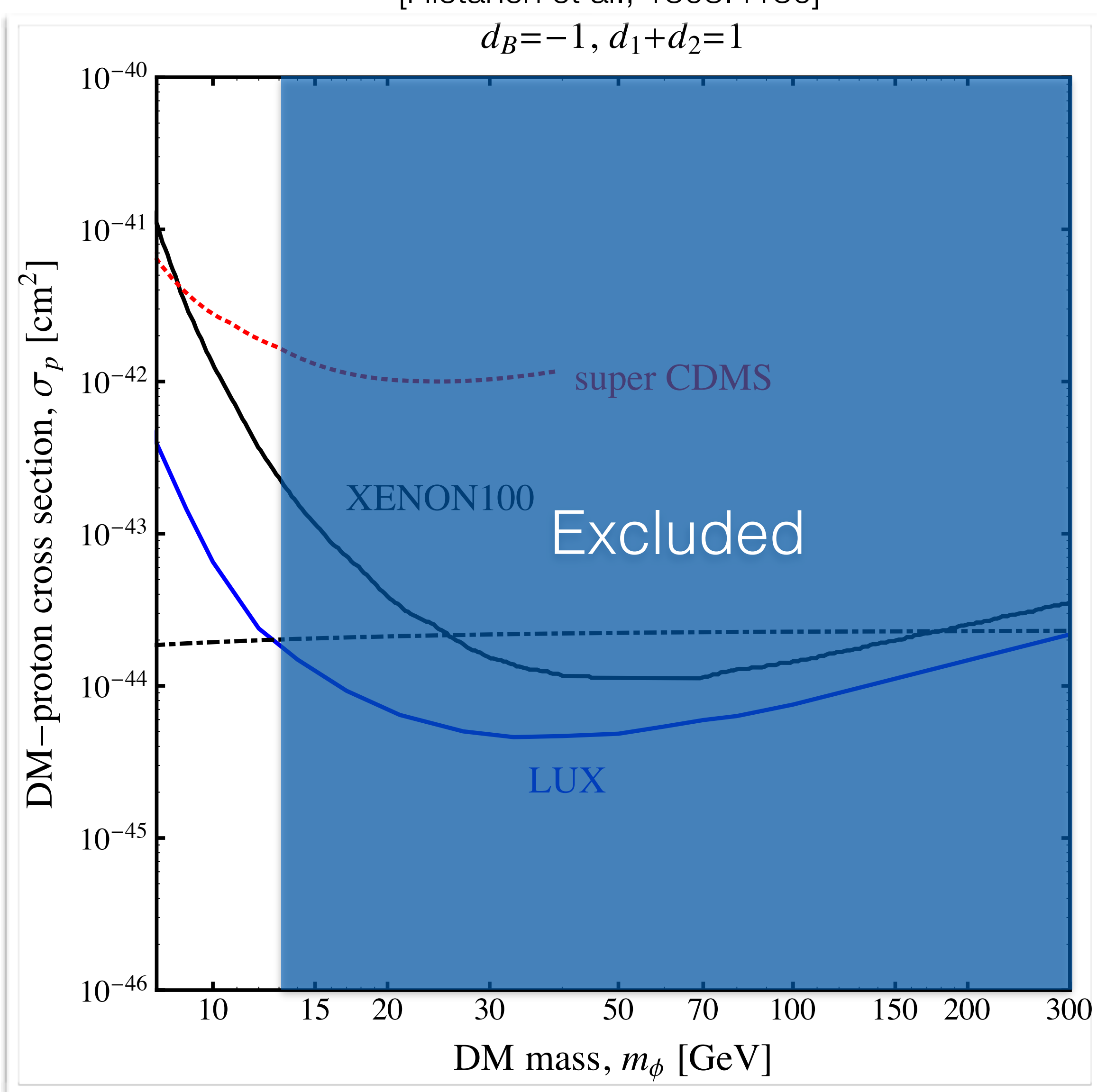
[Hietanen et al., 1308.4130]



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★ scale set by F_π=256 GeV

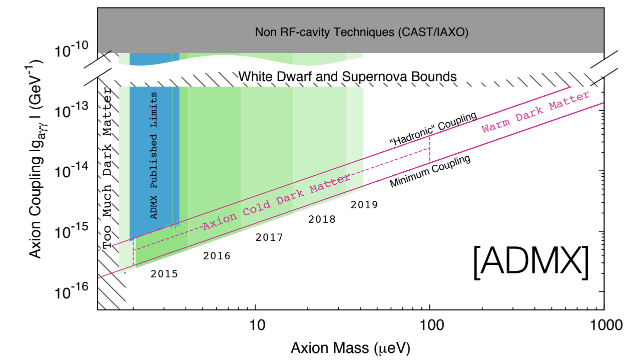
★ depends on isospin breaking d_B

★ also couples to Higgs (d_1+d_2)

M_B ~< 13 GeV
depends on d_B

[Peccei & Quinn: PRL **38** (1977) 1440, PR **D16** (1977) 1791]

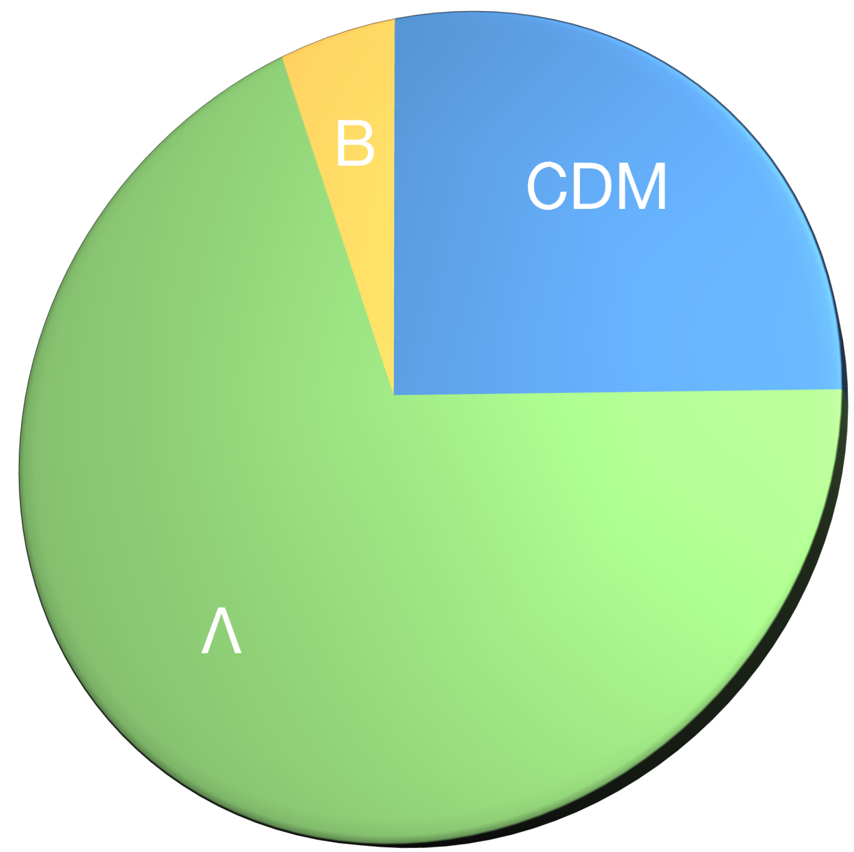
[Preskill, Wise & Wilczek, Phys. Lett. B **120** (1983) 127-132]



[ADMX]

Axion dark matter

- Axions were originally proposed to deal with the Strong-CP problem
    - They also form a plausible DM candidate
    - The axion energy density requires non-perturbative QCD input
- Being sought in ADMX (LLNL, UW) & CAST-IAXO (CERN) with large discovery potential in the next few years
- Requiring $\Omega_a \leq \Omega_{CDM}$ yields a lower bound on the axion mass today



$\Omega_{tot} = 1.000(7)$
PDG 2014

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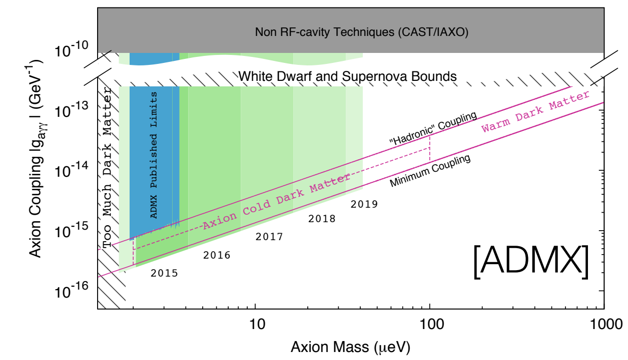

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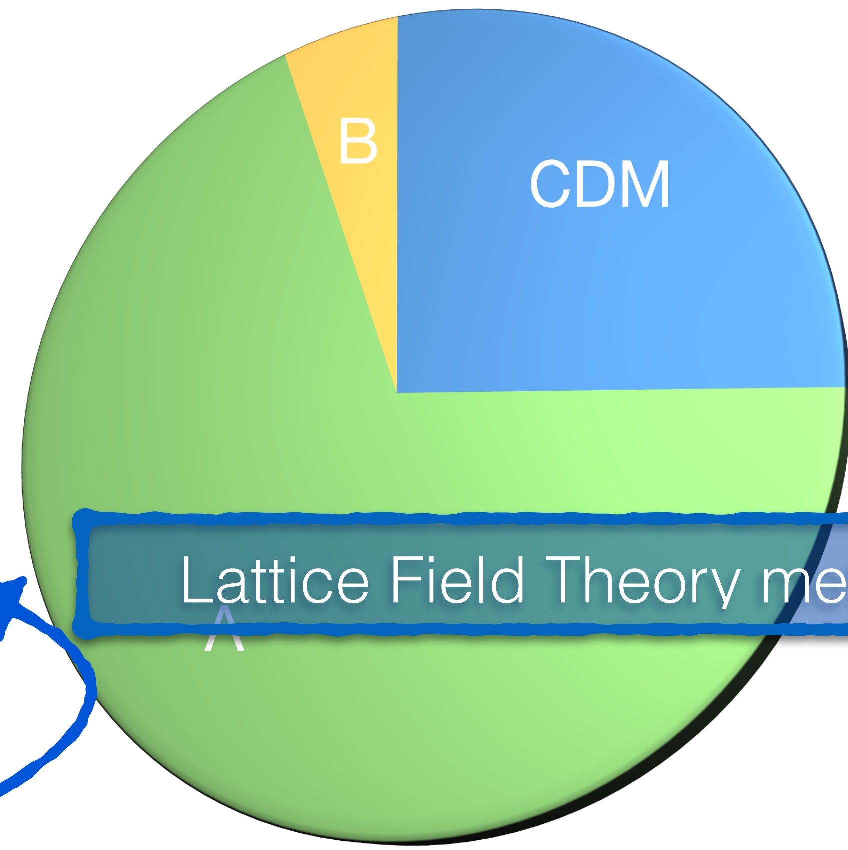


Lattice Field Theory methods

$\Omega_{tot} = 1.000(7)$
PDG 2014

$$m_a^2 f_a^2 = \left.\frac{\partial^2 F}{\partial \theta^2}\right|_{\theta=0}$$

Constraints from lattice simulations

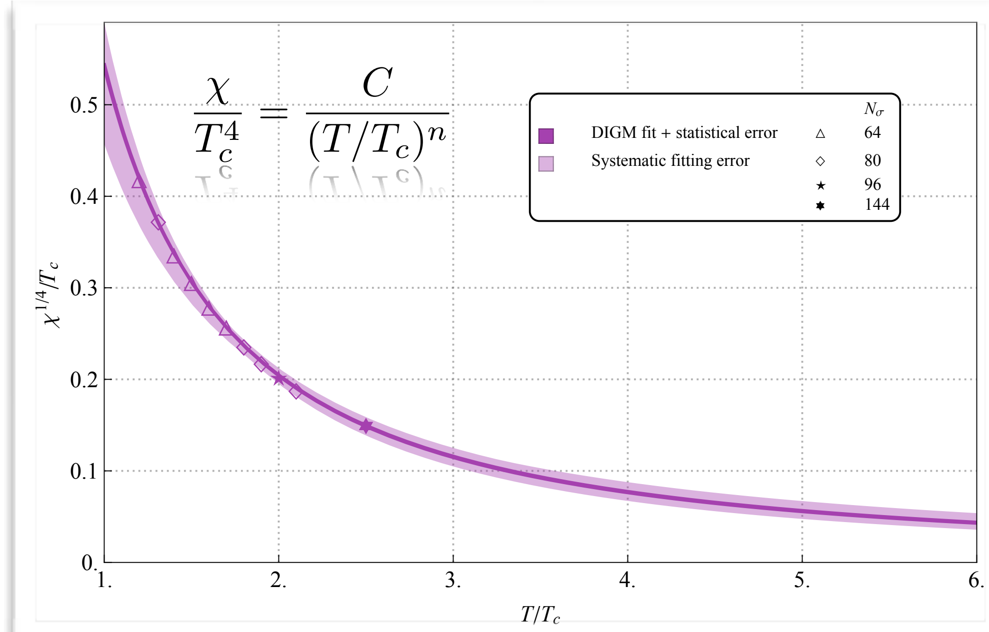
Non-perturbative calculation of QCD topology at finite temperature

- Pure gauge SU(3) topological susceptibility ➥ compatible with model predictions, but large non-perturbative effects

[Kitano&Yamada, 1506.00370][Borsanyi et al., 1508.06917][Frison et al.,1606.07175]

- is QCD topological susceptibility at high-T well described by models? ➥ light fermions importantly affect the vacuum

[Trunin et al., 1510.02265][Petreczky et al., 1606.03145][Borsanyi et al., 1606.07494]



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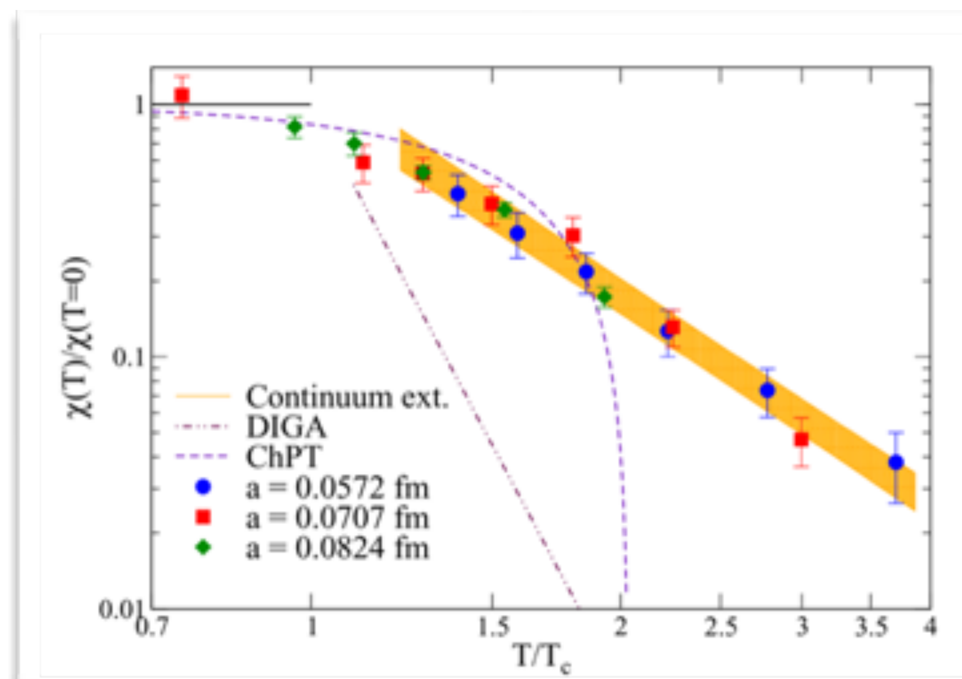

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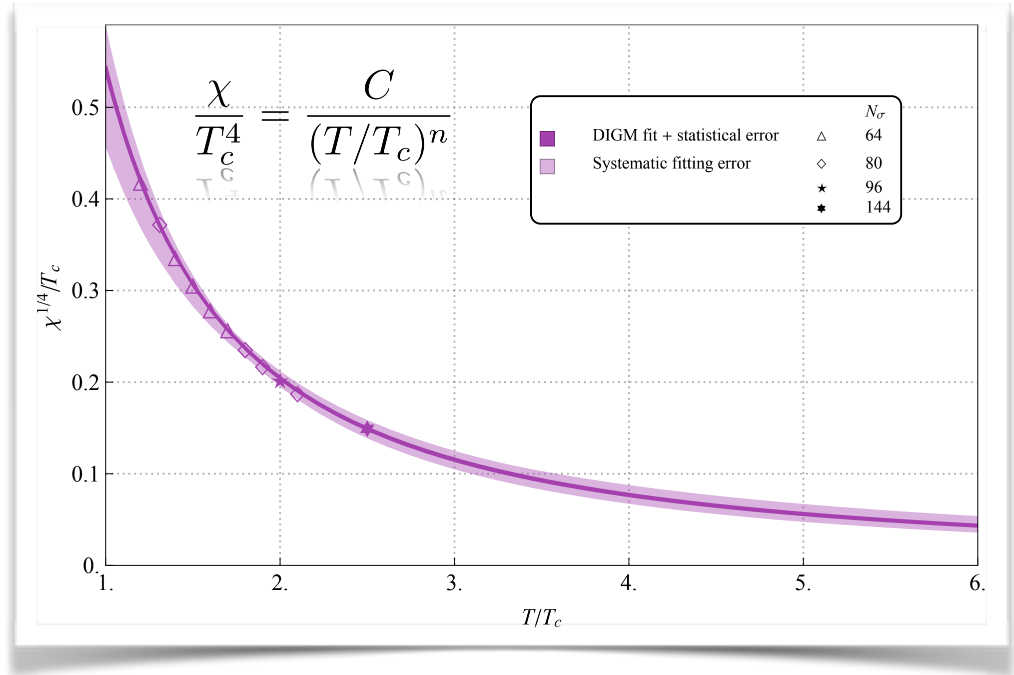
Great effort to control all systematic lattice effects in order to impact experiments.
This research has started only 1 year ago!



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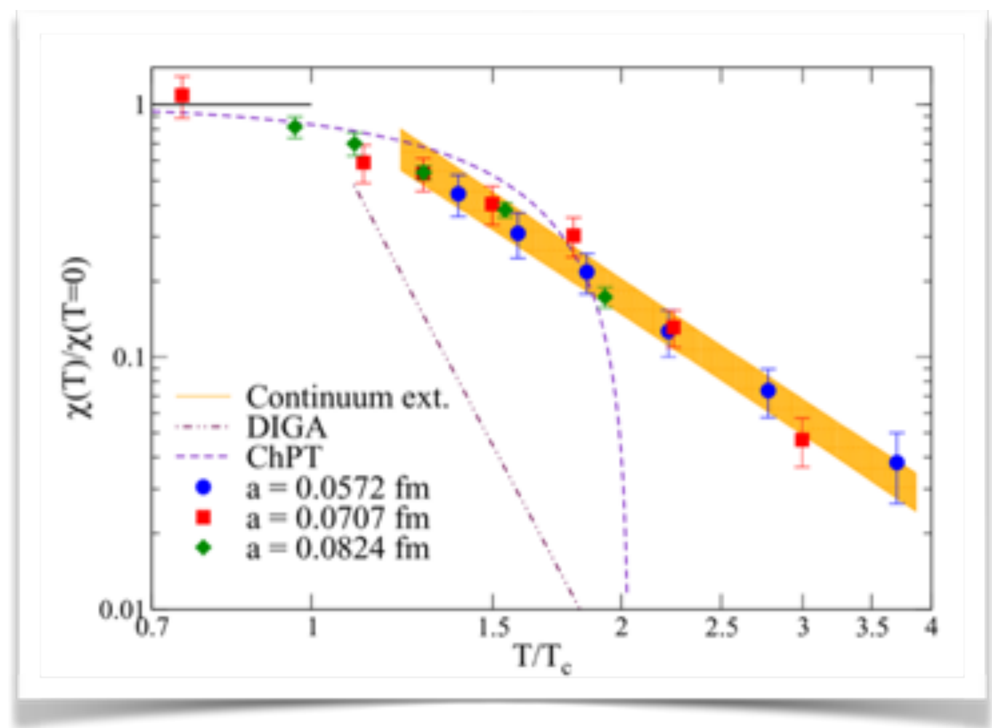

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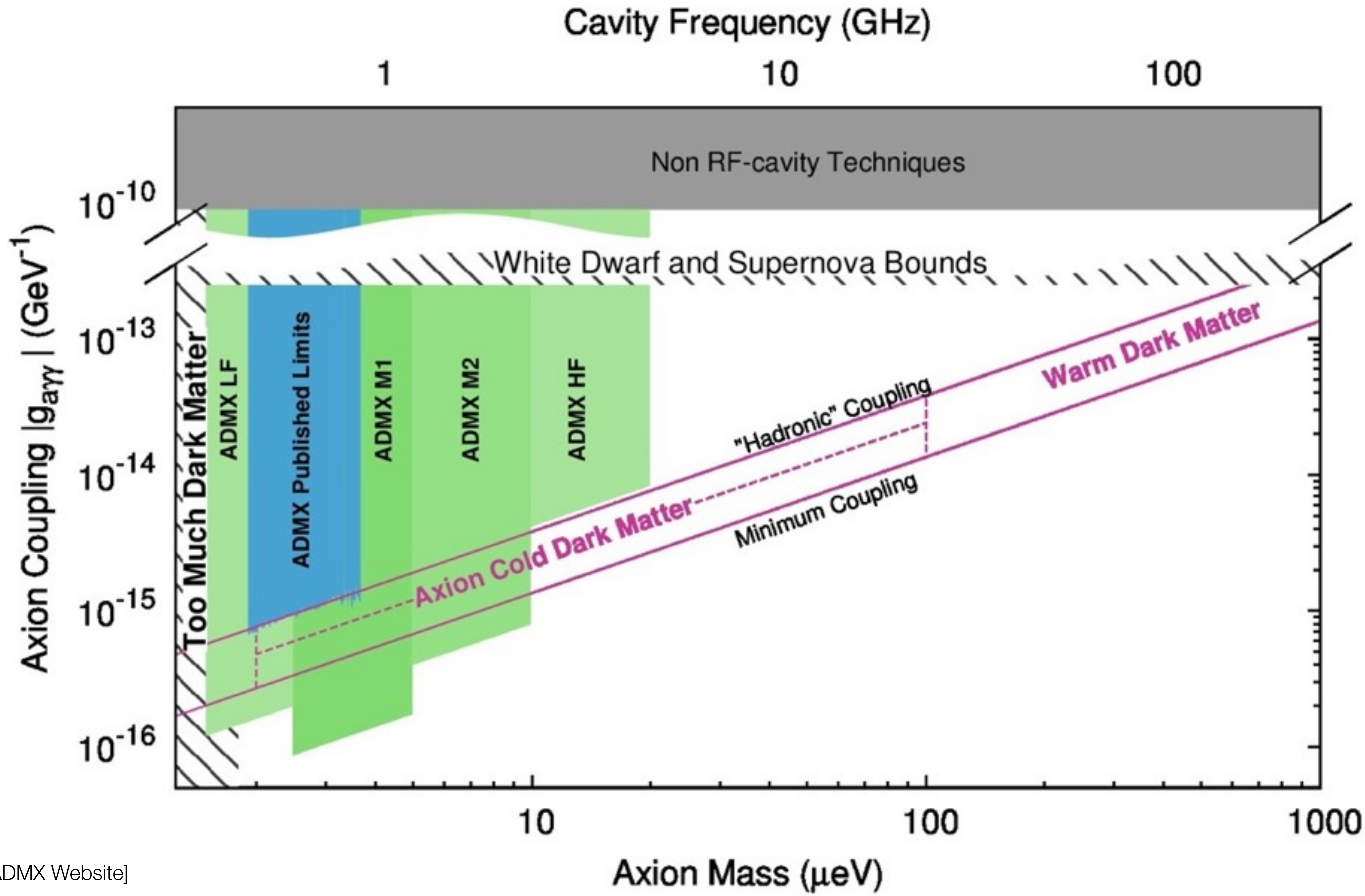
Axion mass lower bound



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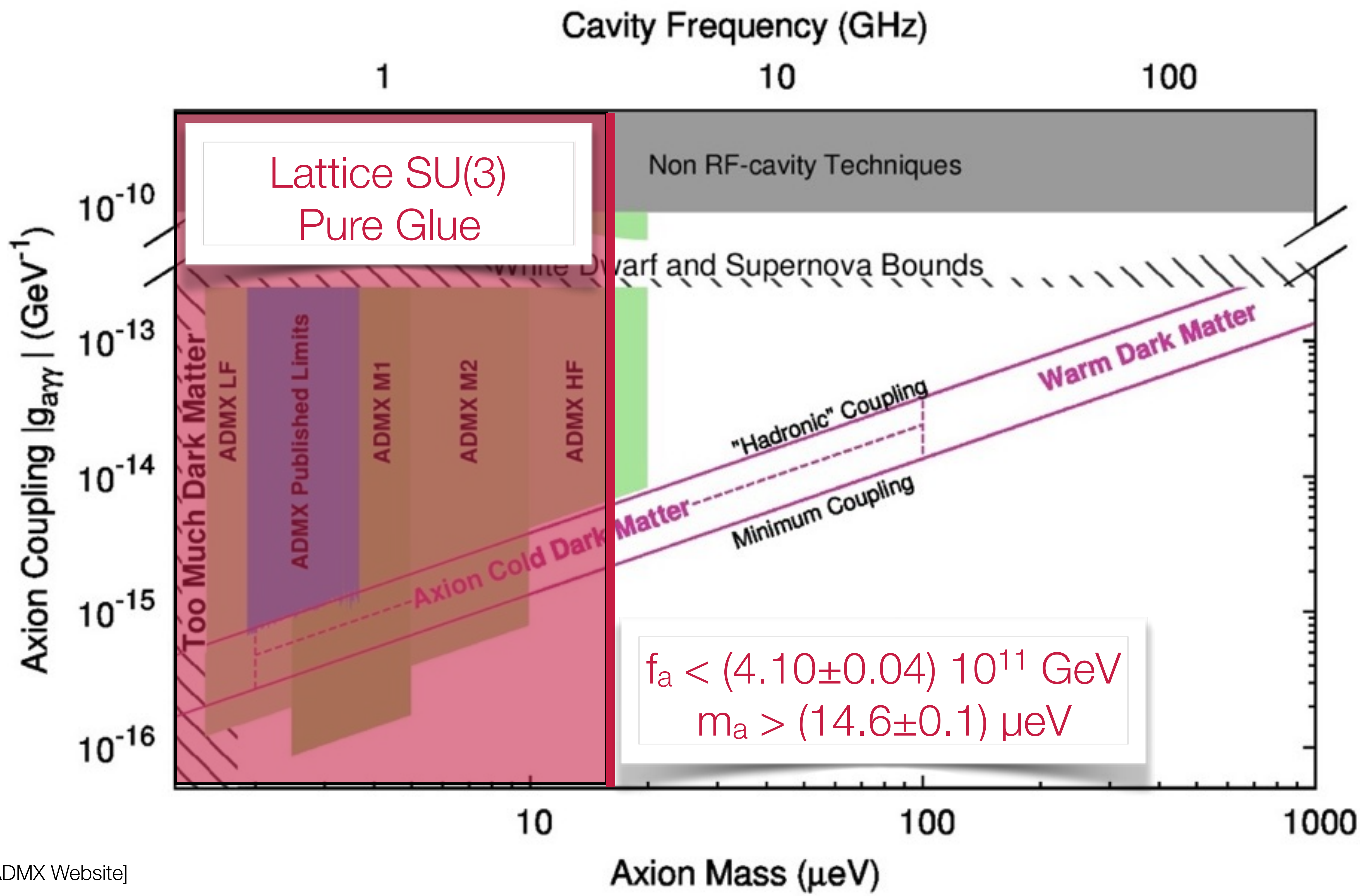

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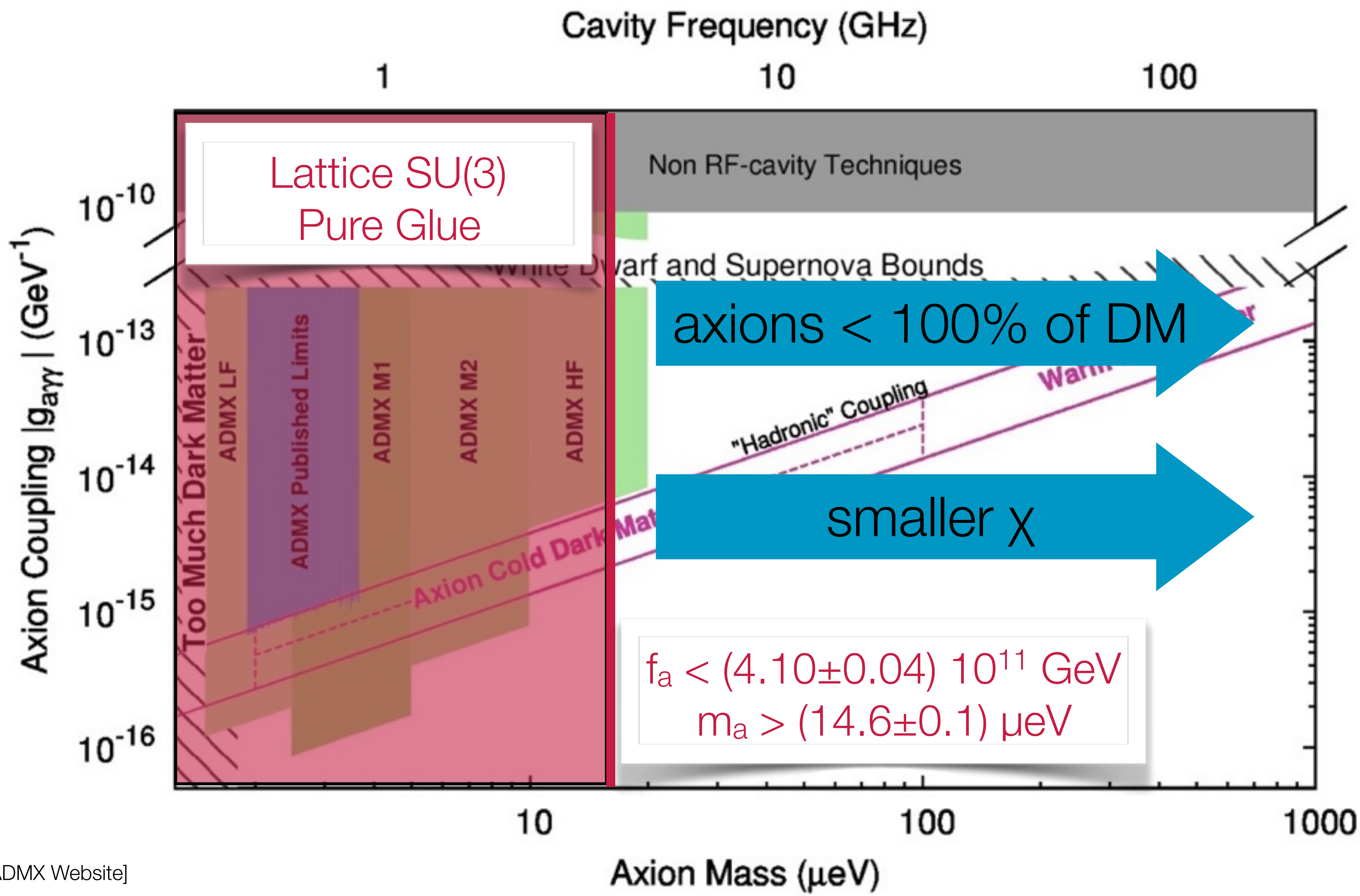

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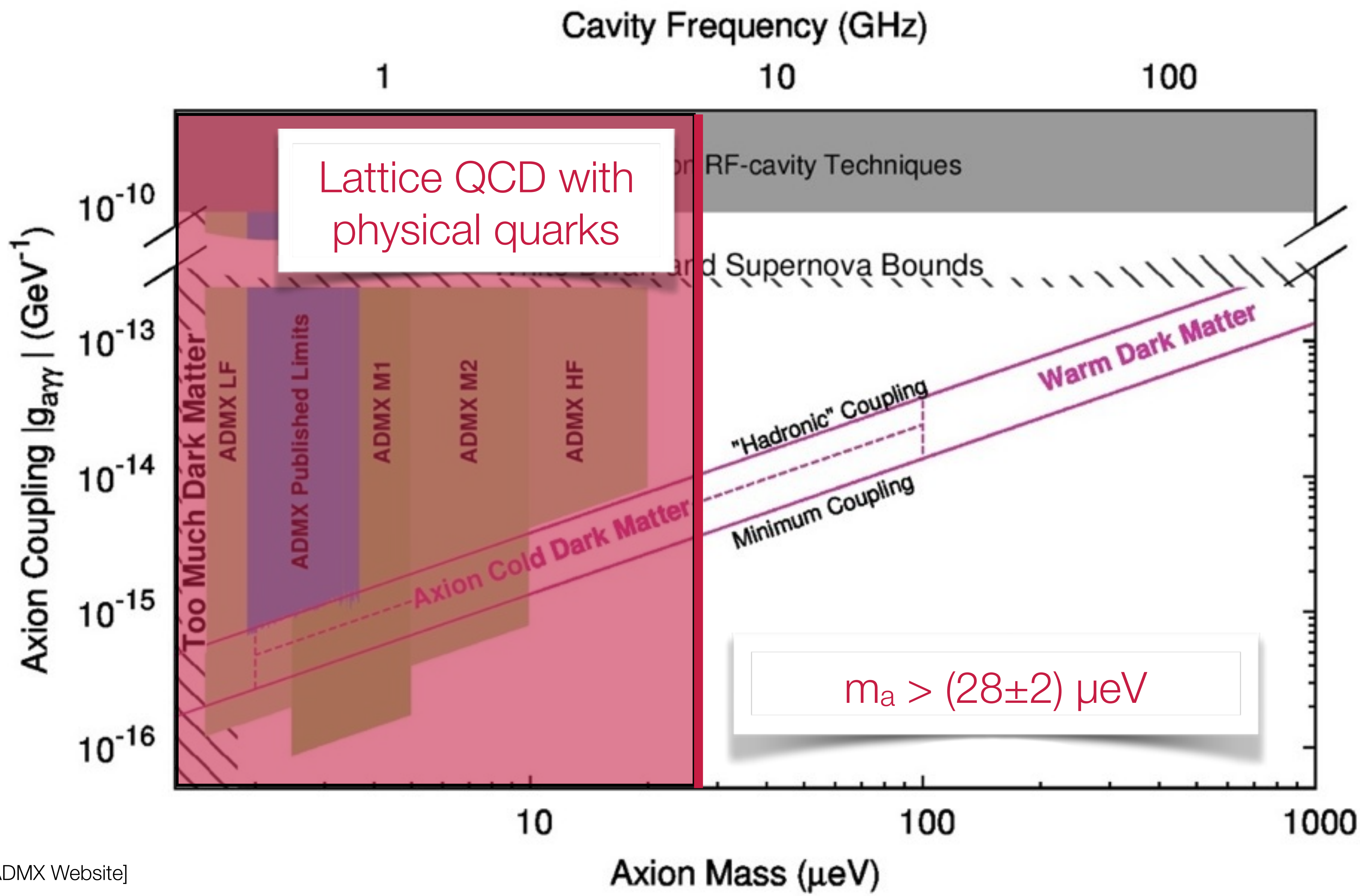

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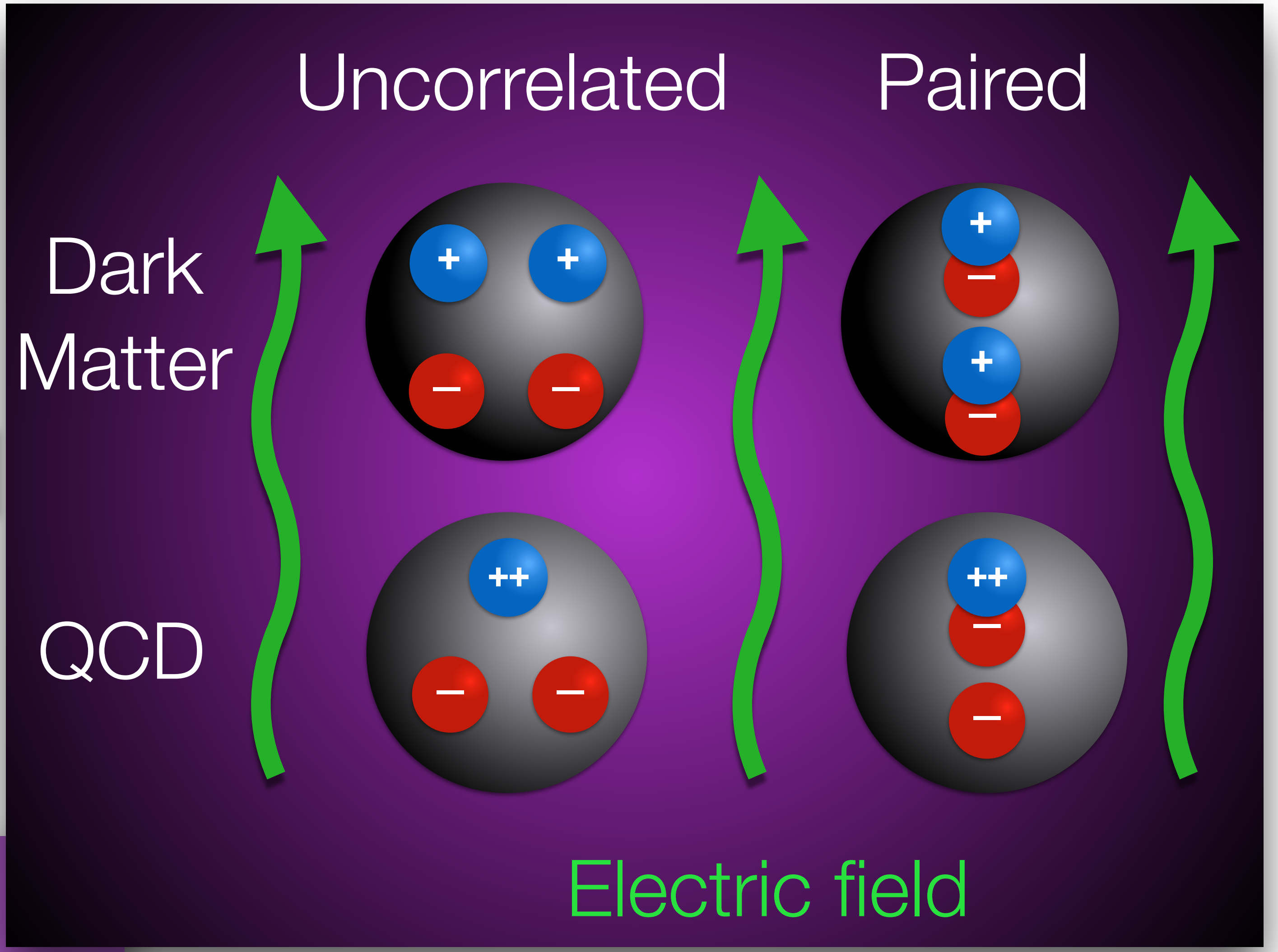
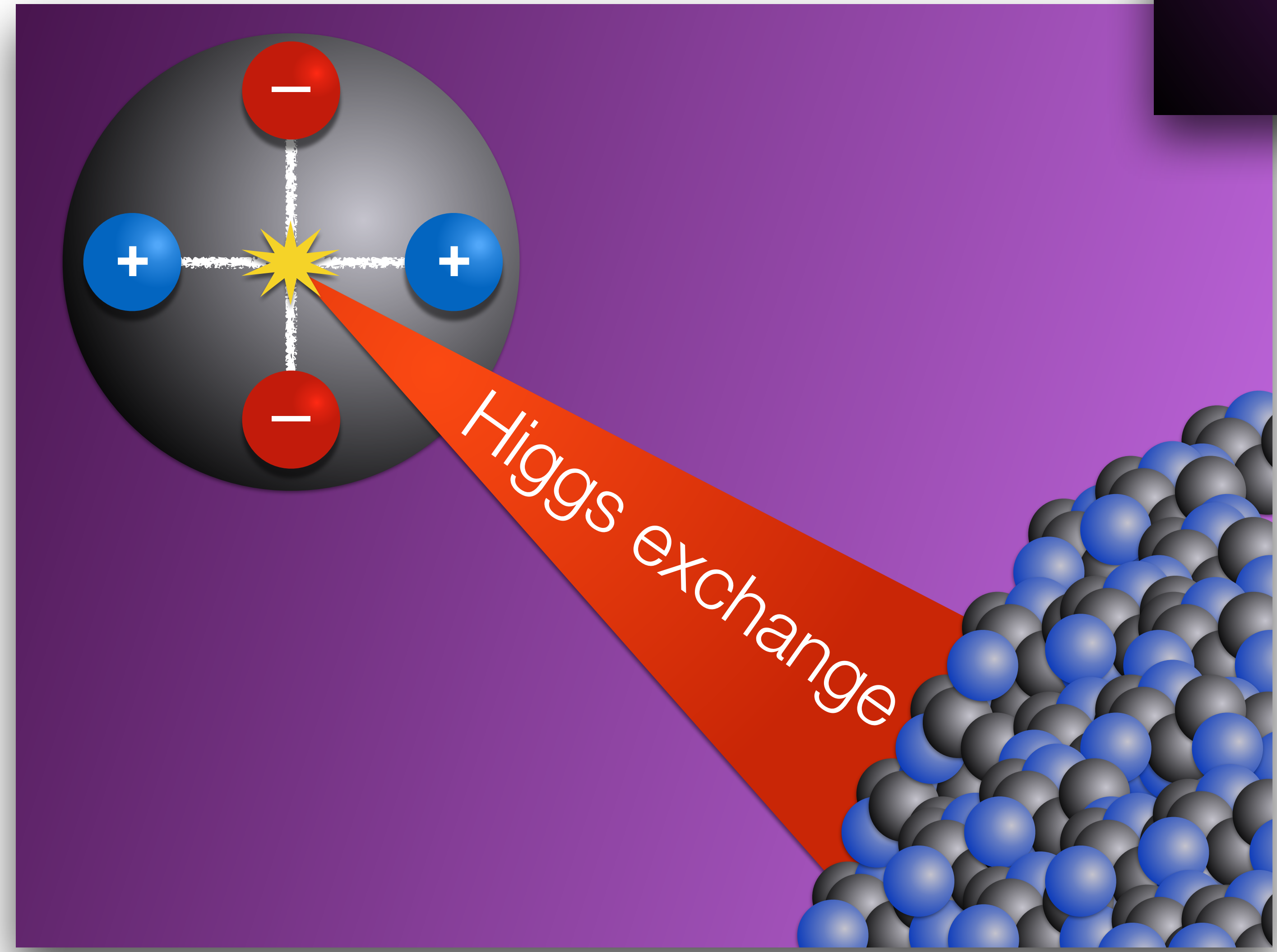


PRL Editors' Suggestion: Polarizability

[LSD collab., Phys. Rev. Lett. 115 (2015) 171803]



PRD Editors' Suggestion: Higgs exchange

[LSD collab., Phys. Rev. D92 (2015) 075030]