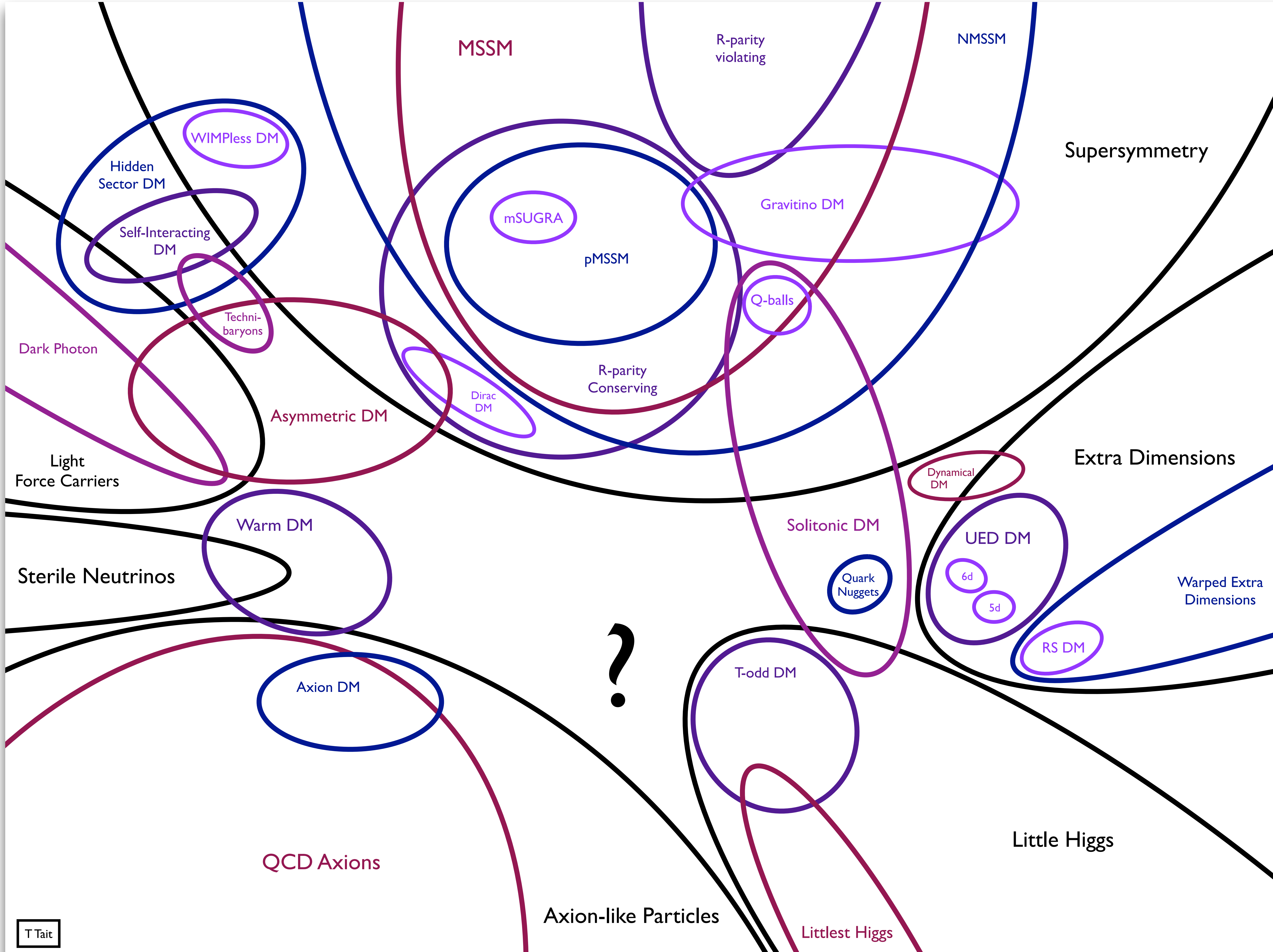
Dark Interactions and Supercomputers

Enrico Rinaldi

RIKEN BNL Research Center

What is Dark Matter?



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

Composite Dark Matter

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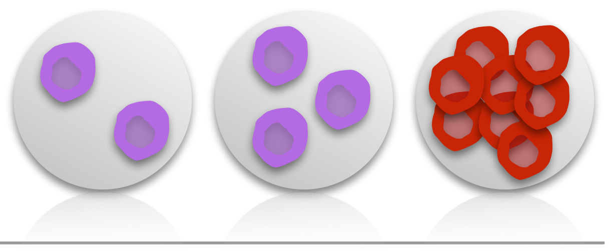

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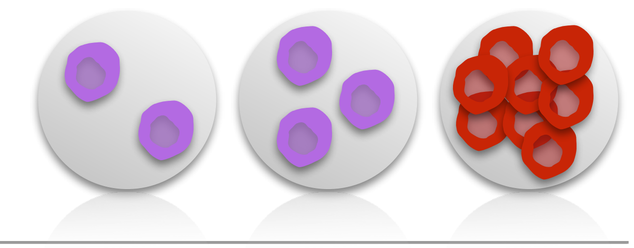

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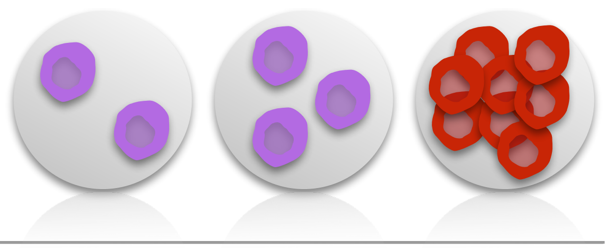

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- Properties dictated by strong dynamics
- Self-interactions are natural

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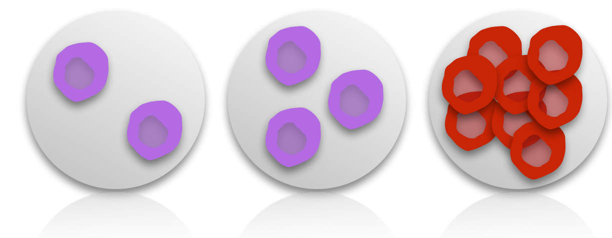

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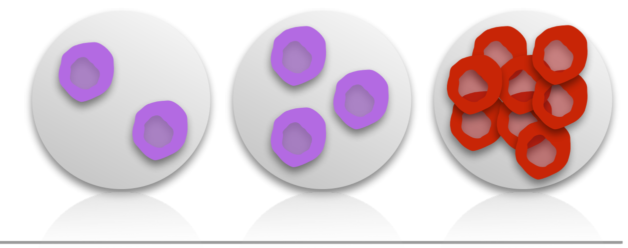

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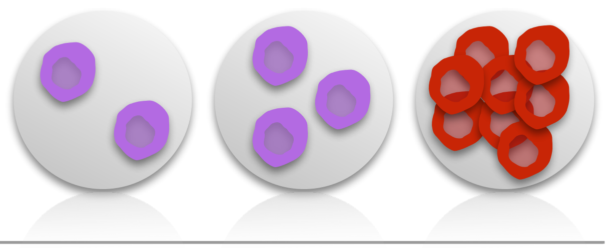

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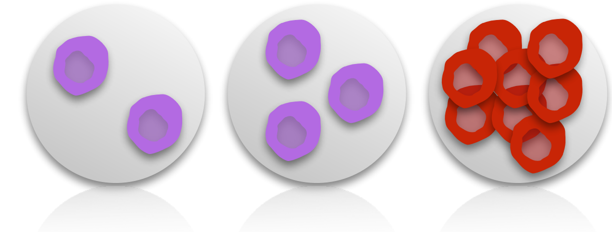

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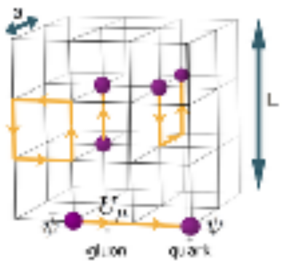
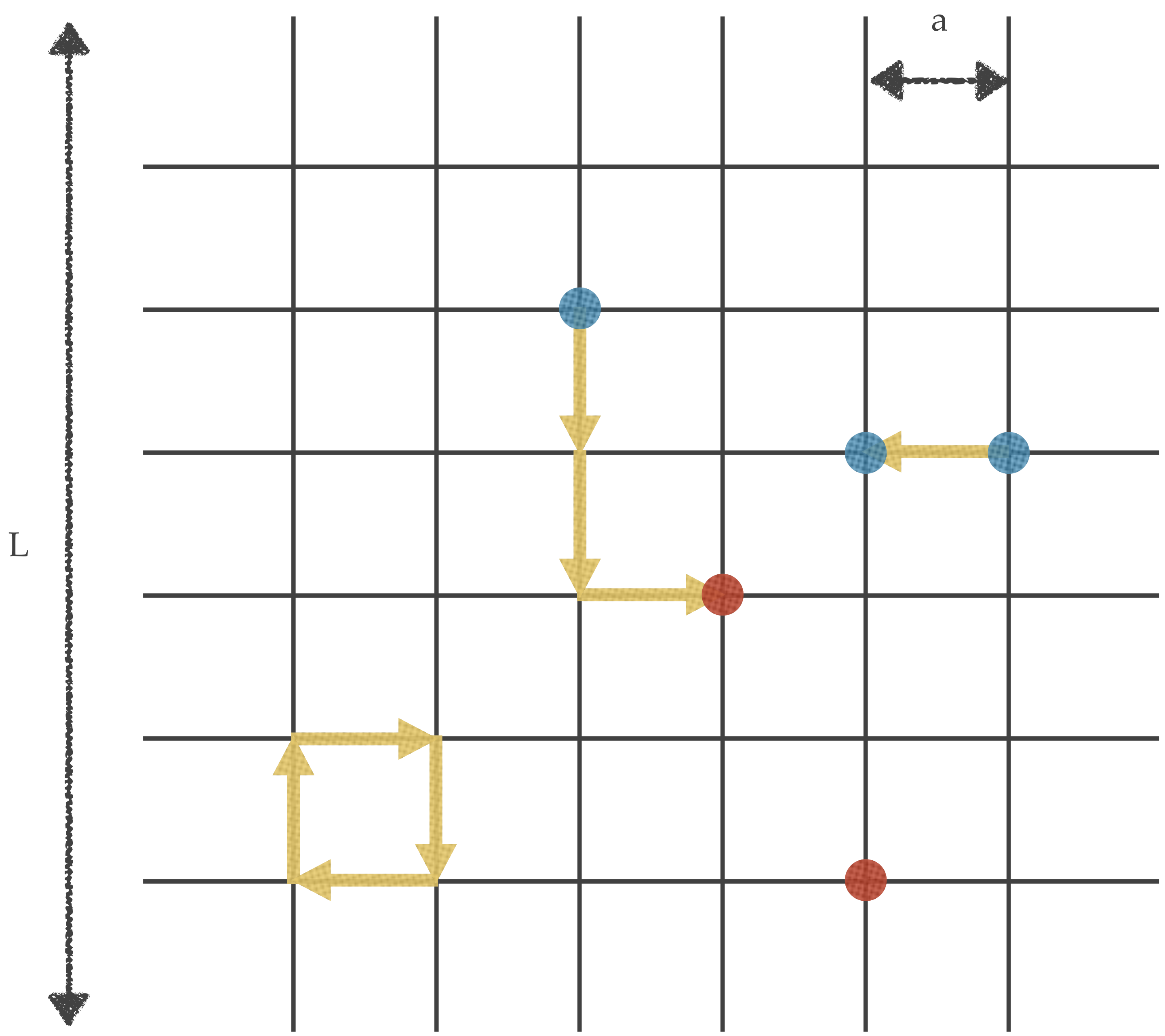
[KEK-Japan]



Gauge Theories on Supercomputers



- Discretize space and time
    - lattice spacing “a”
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- 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
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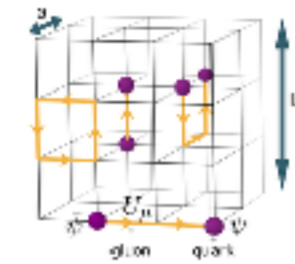

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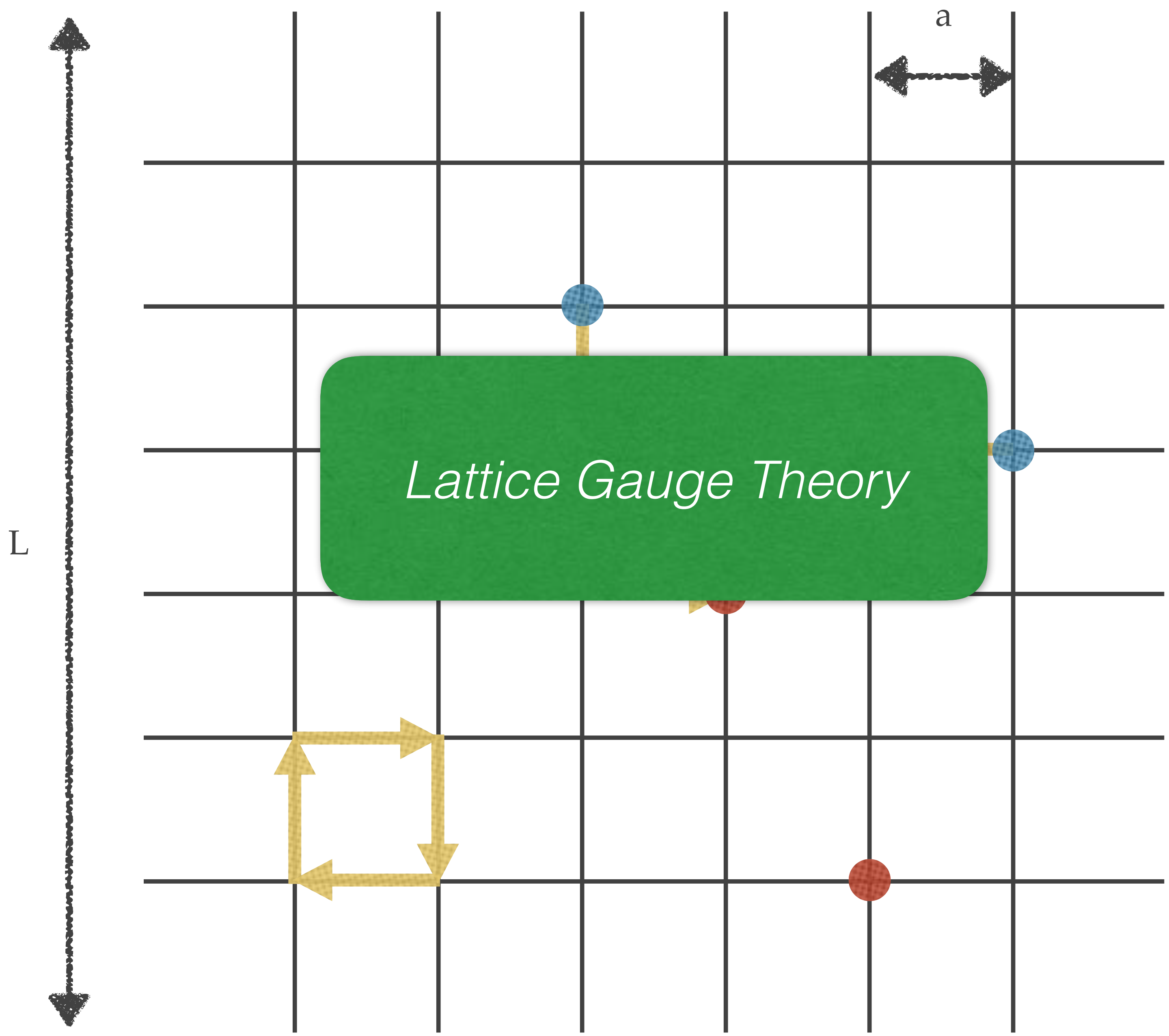

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"Stealth Dark Matter" - case study

- **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. DM is a *stable 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]

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

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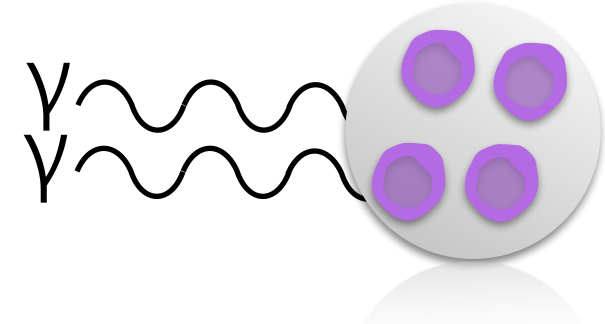
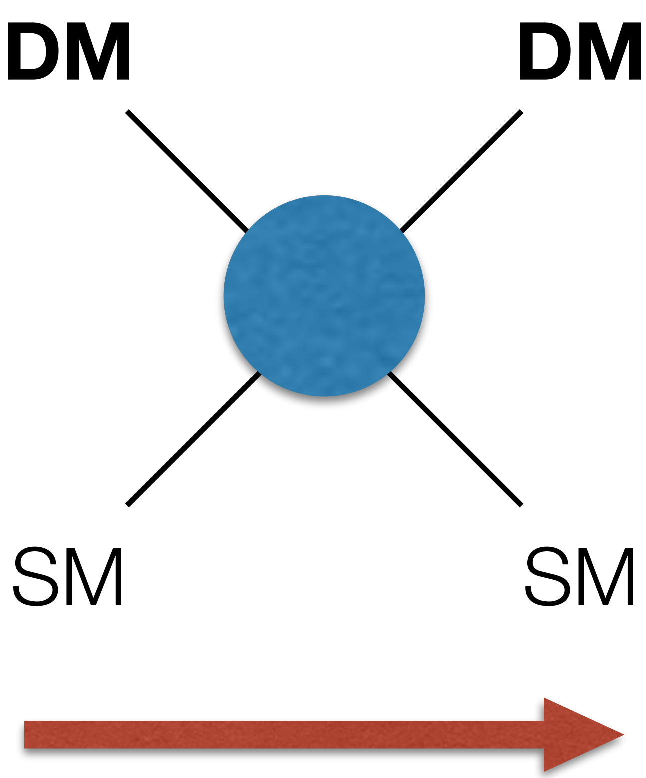
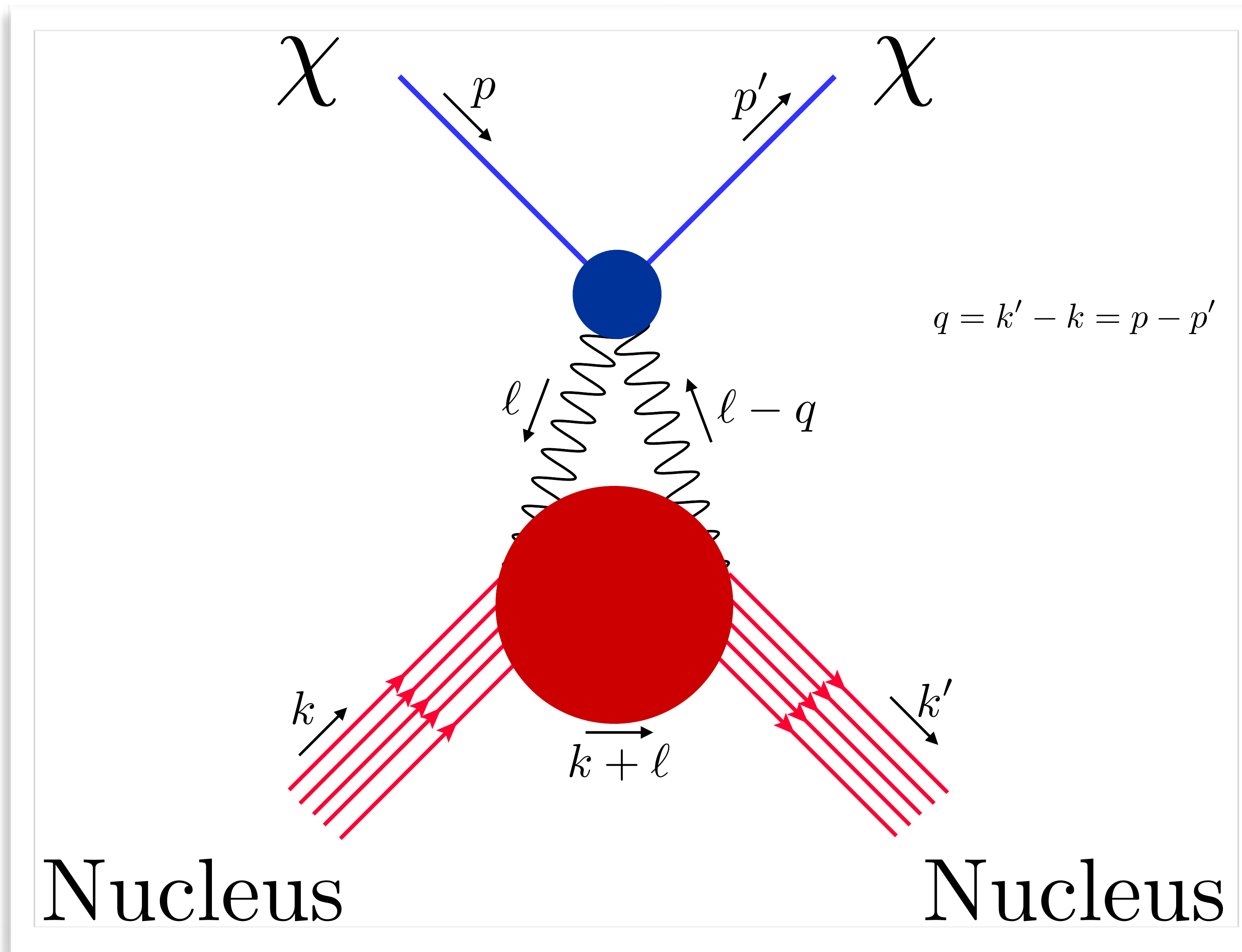


Detection: EM Polarizability

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





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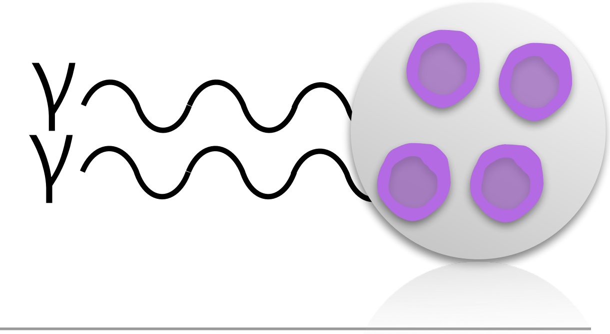

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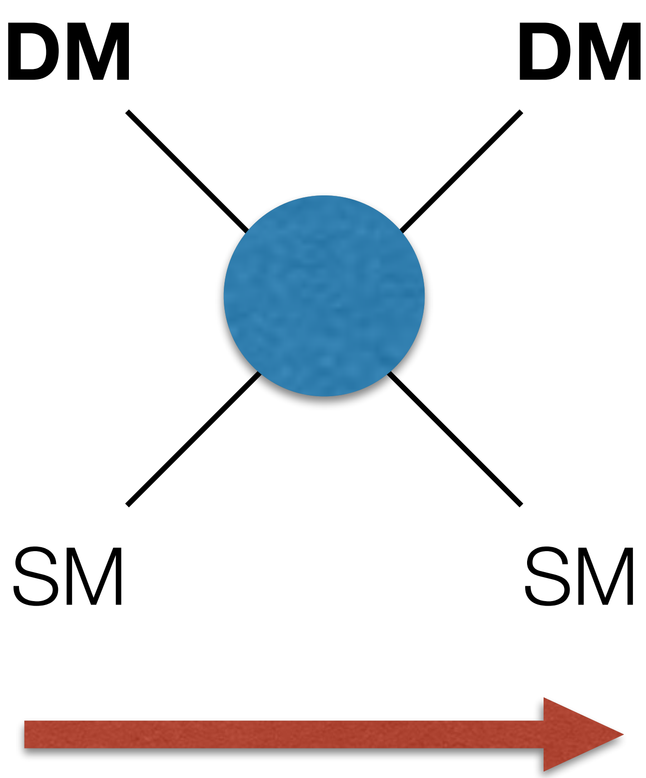

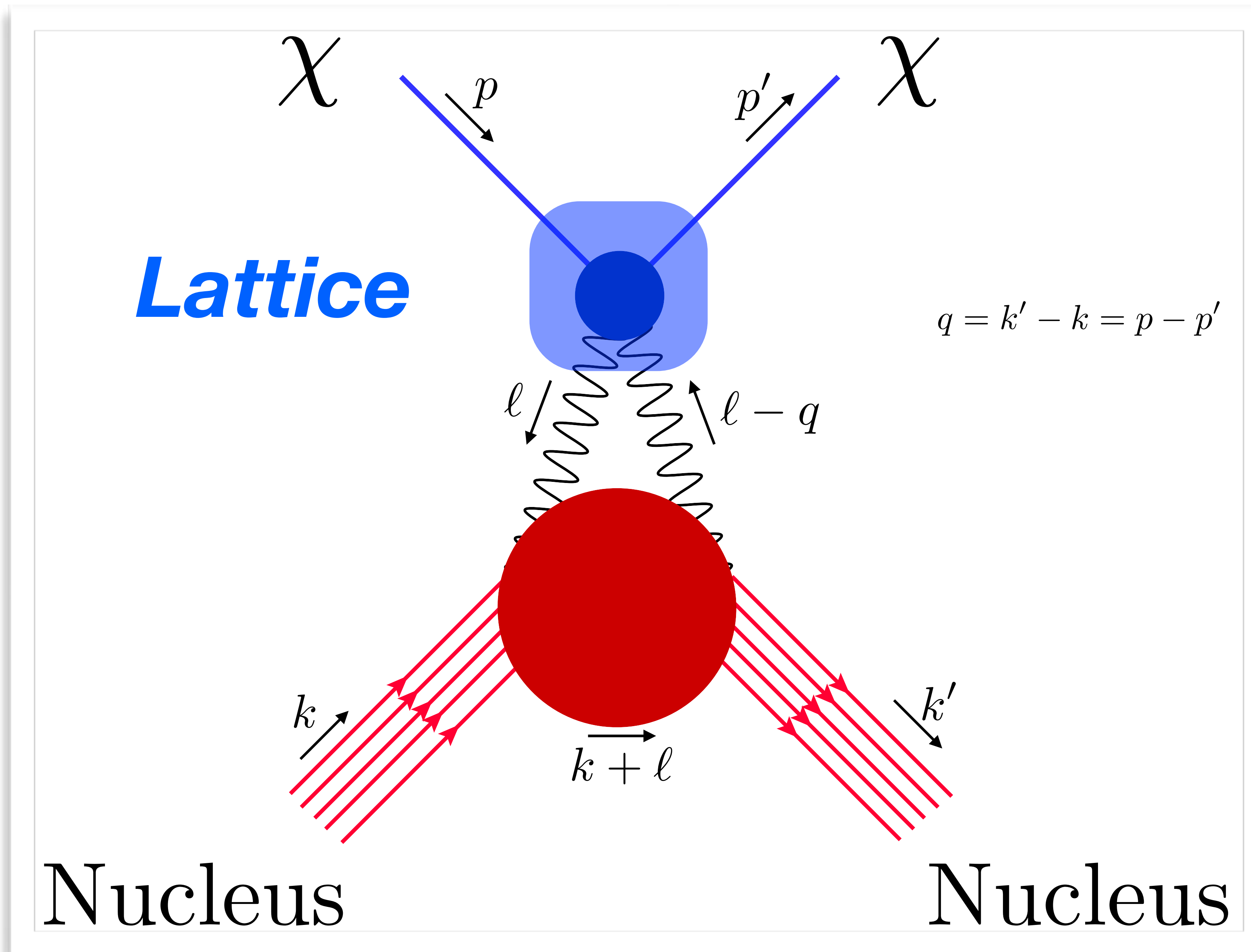

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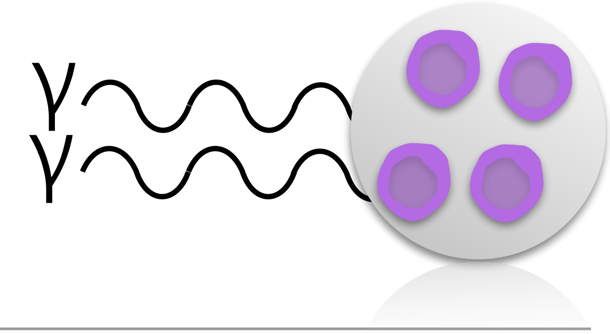

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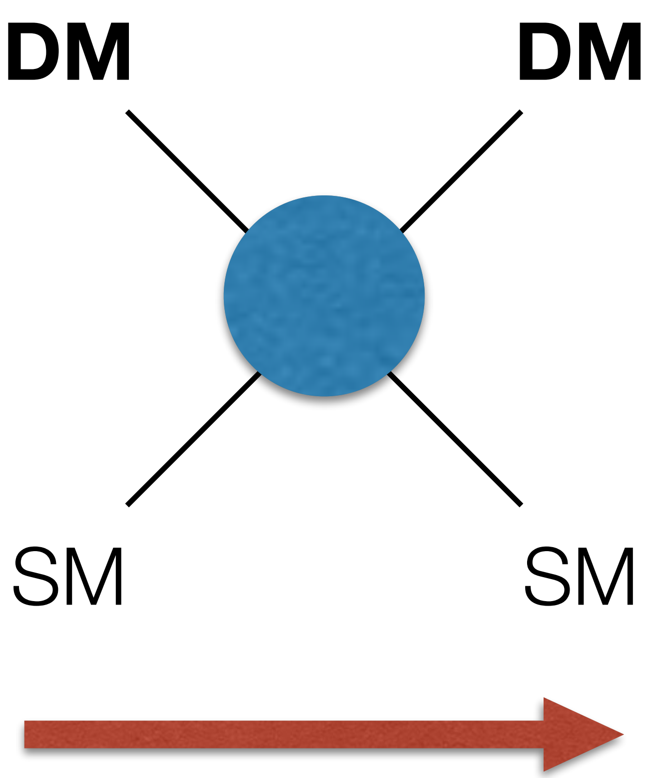

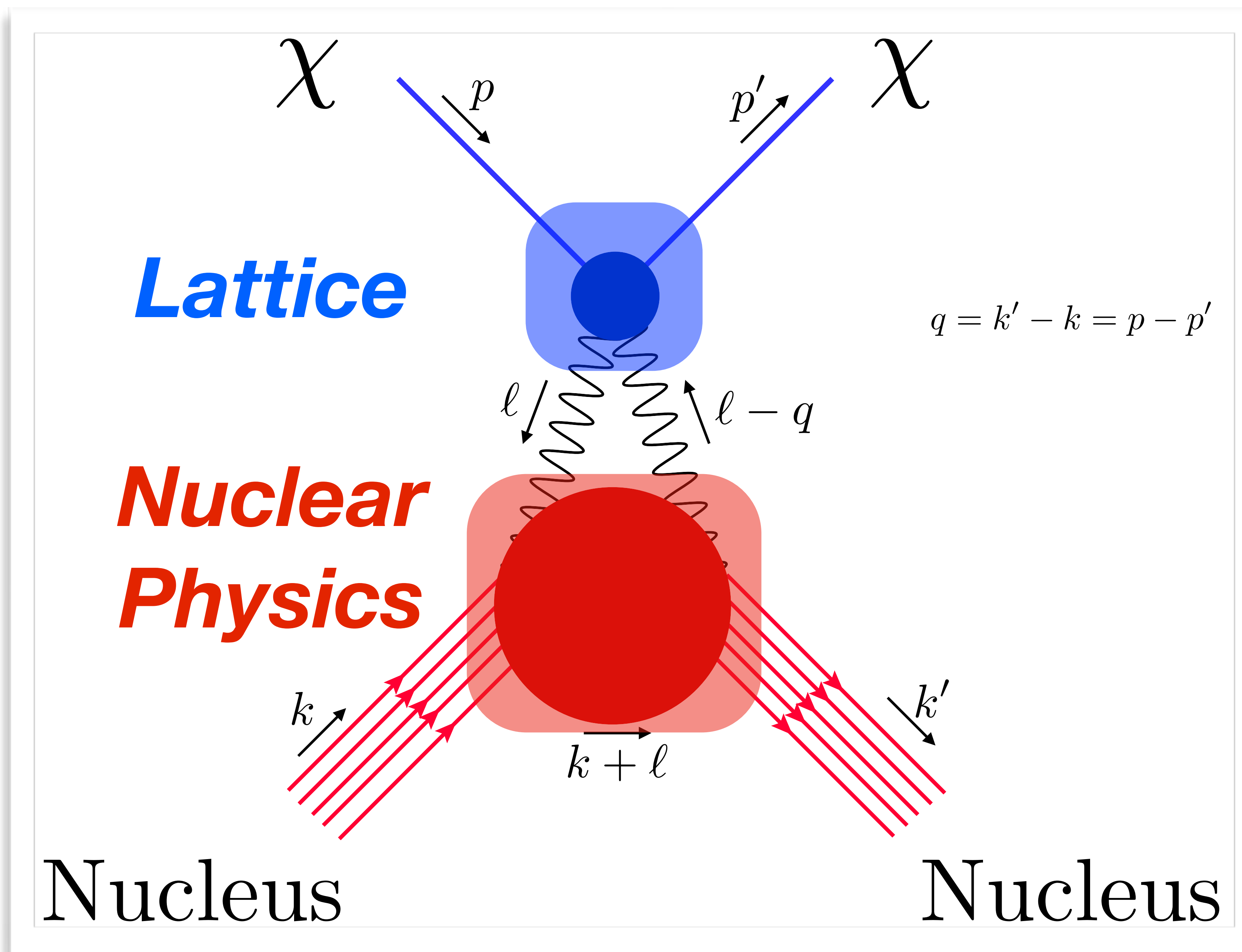

[NEW! PandaX-II, 1607.07400 and LUX-332d,1608.07648]

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

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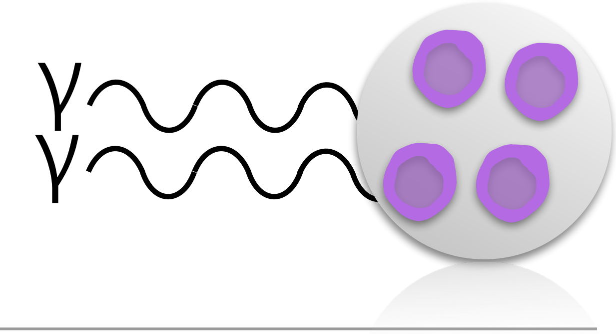
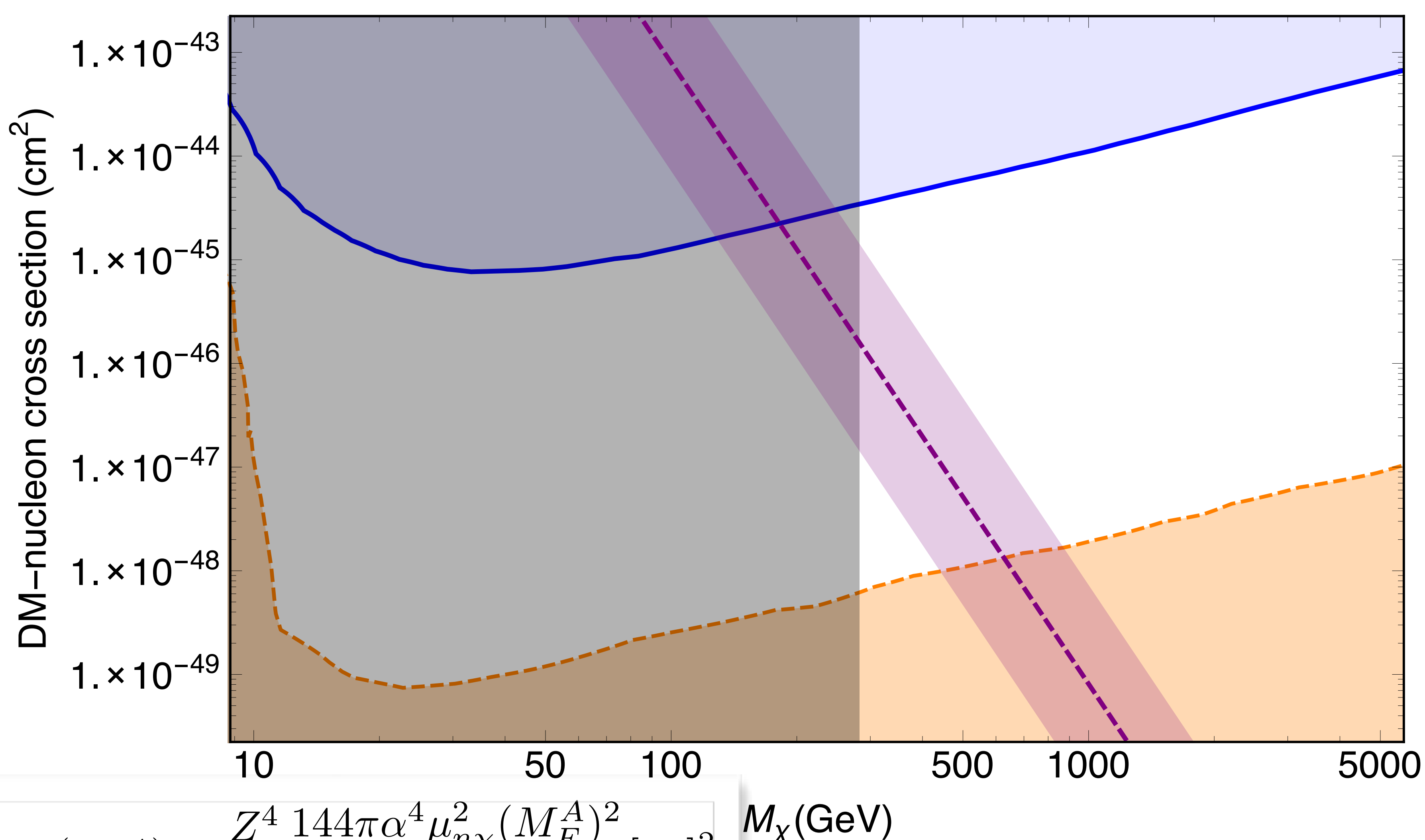


Electric polarizability from lattice simulations with background fields



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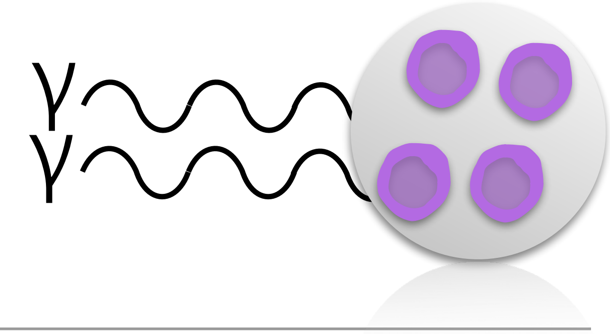

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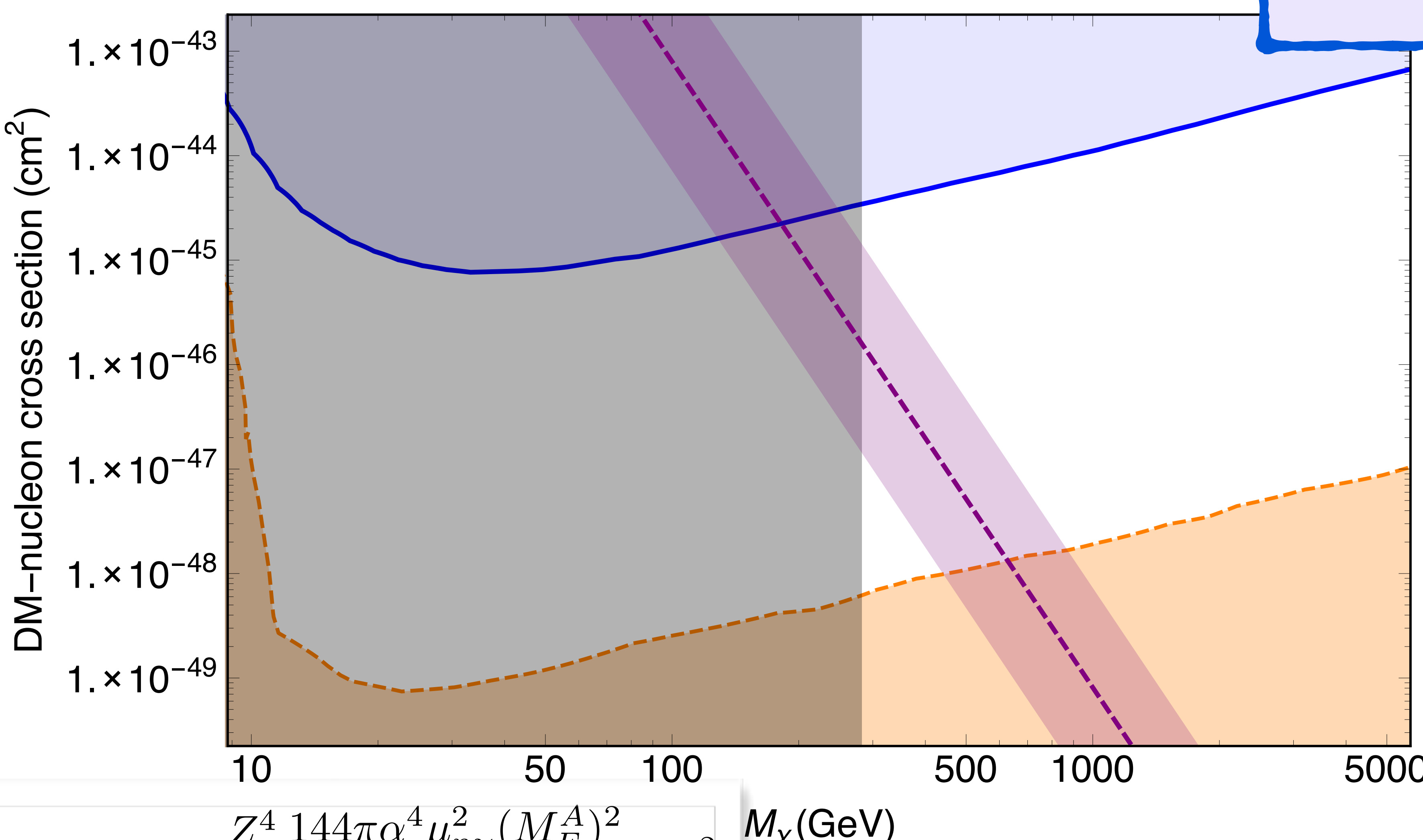
LUX exclusion bound for spin-independent cross section



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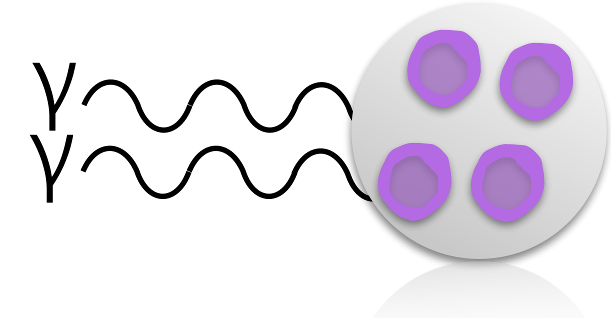

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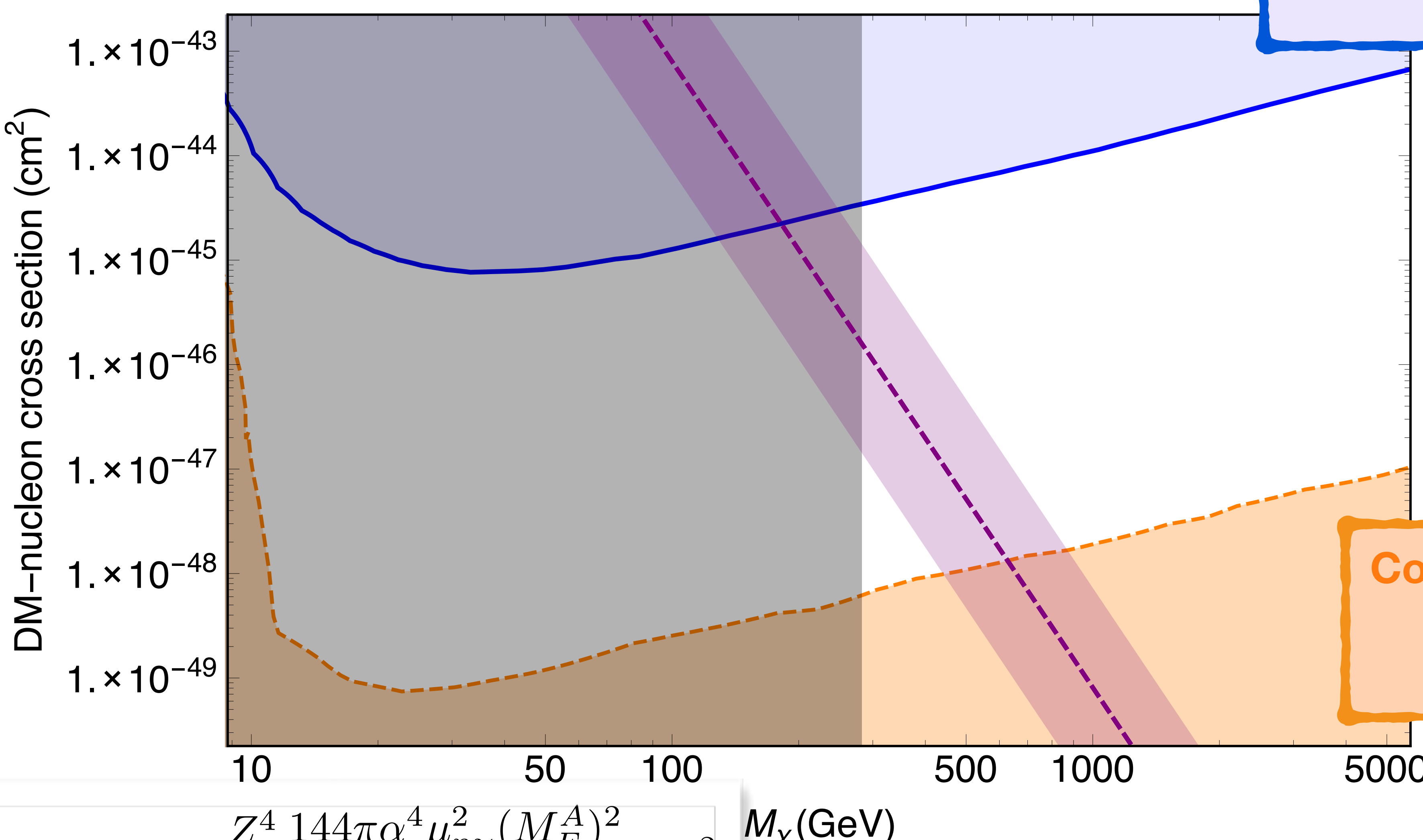

Coherent neutrino scattering background

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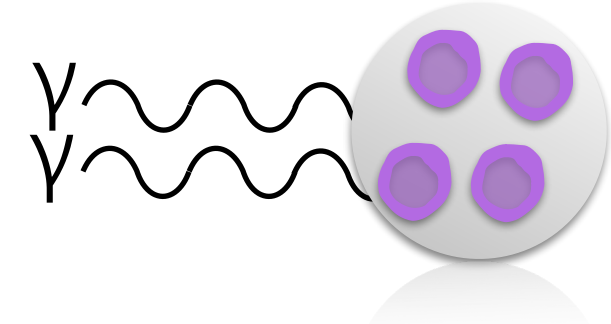

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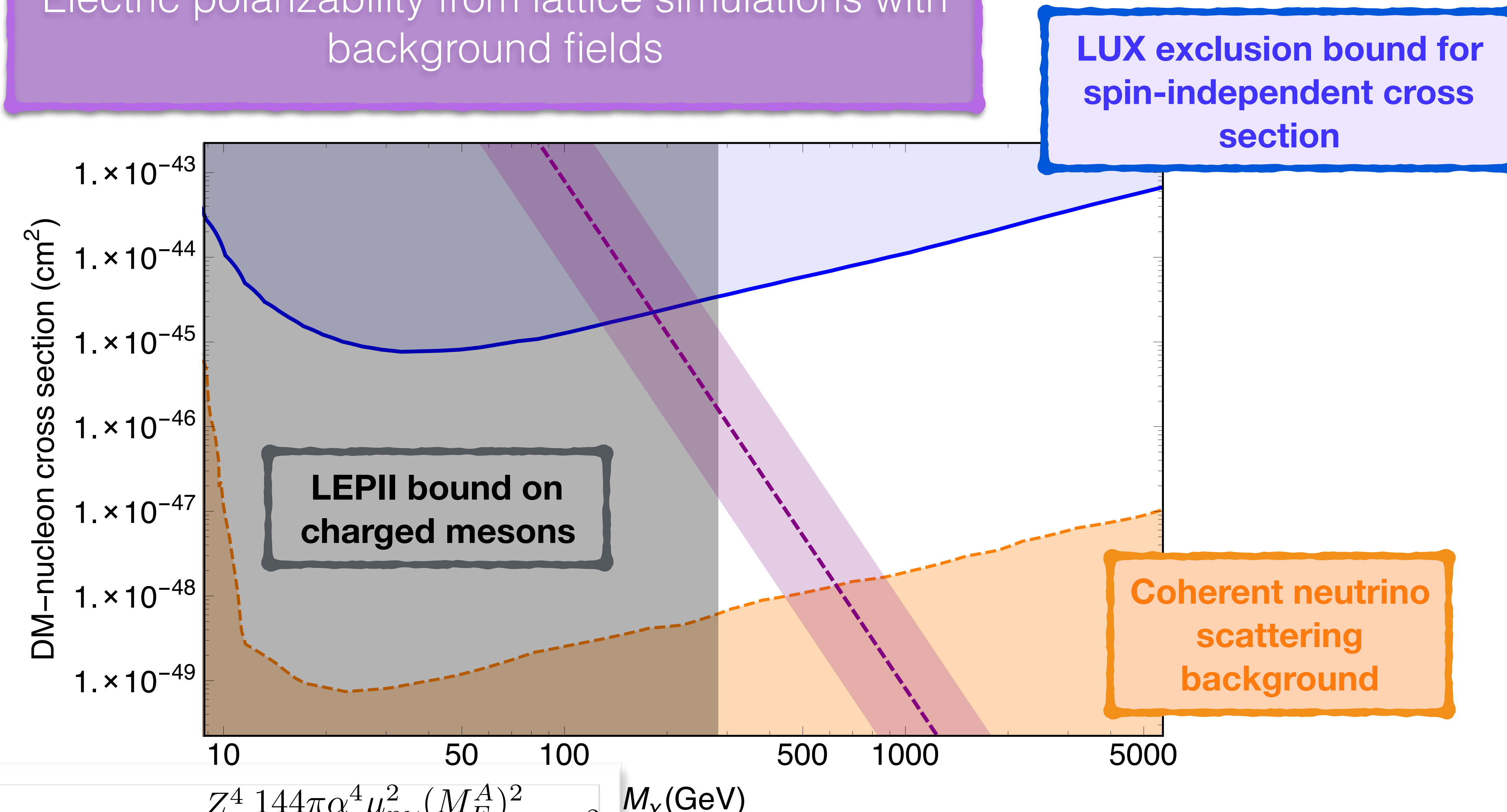

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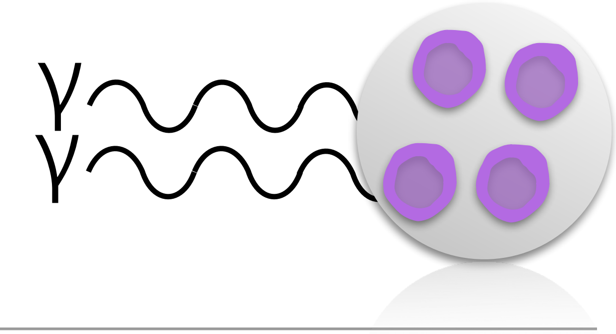

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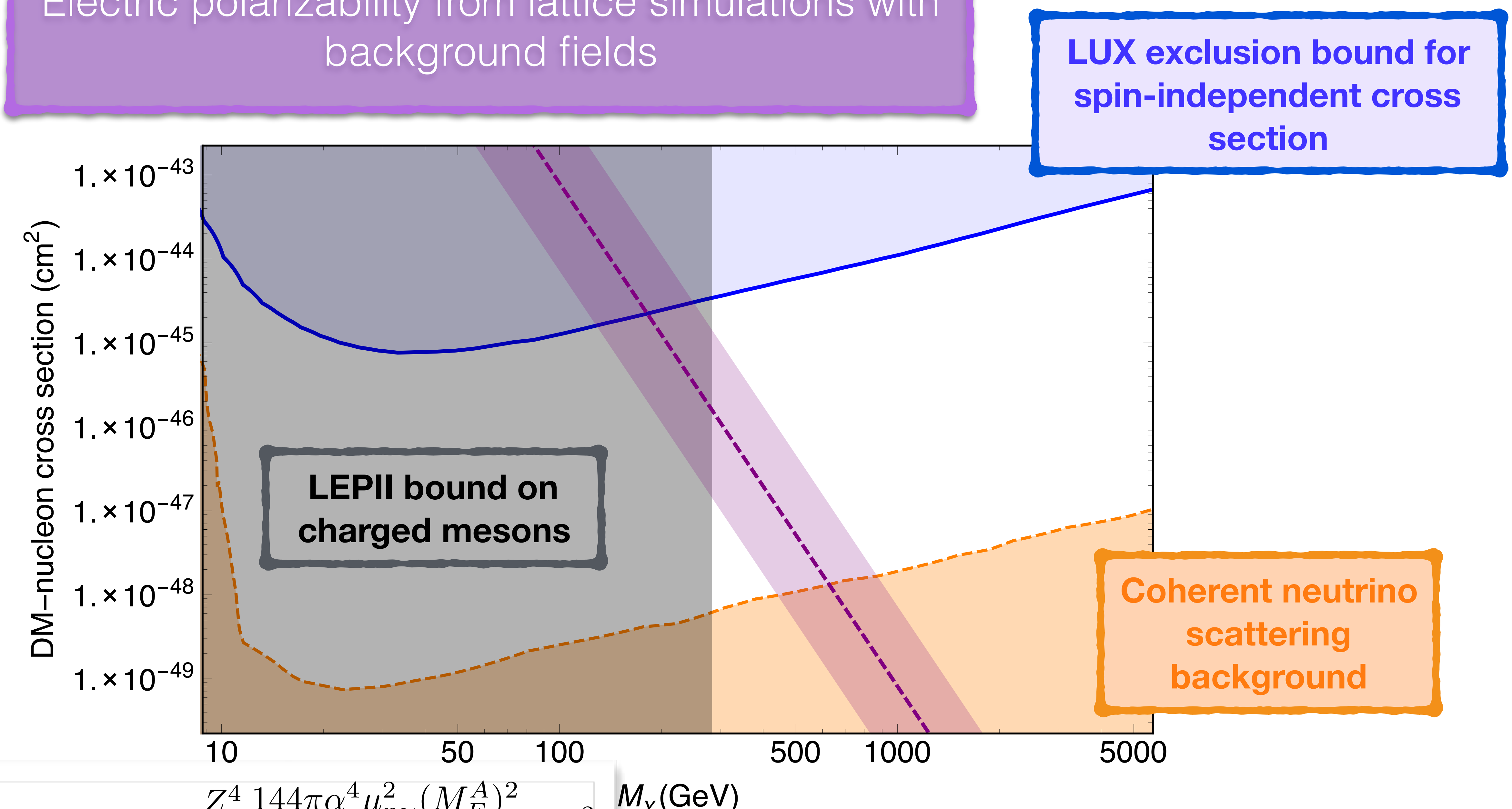

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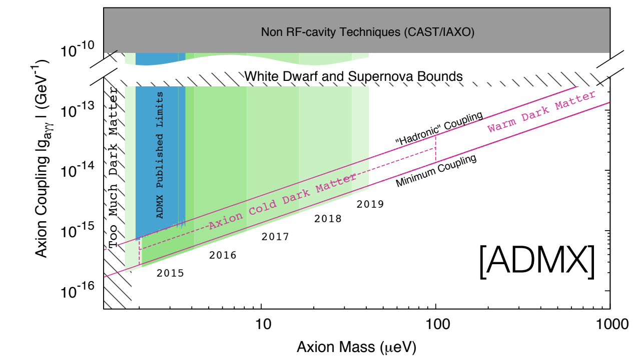
lowest allowed direct detection cross-section for composite dark matter theories with EW charged constituents

[Peccei & Quinn: PRL **38** (1977) 1440, PR **D16** (1977) 1791]
[Preskill, Wise & Wilczek, Phys. Lett. B **120** (1983) 127-132]



Axion Dark Matter

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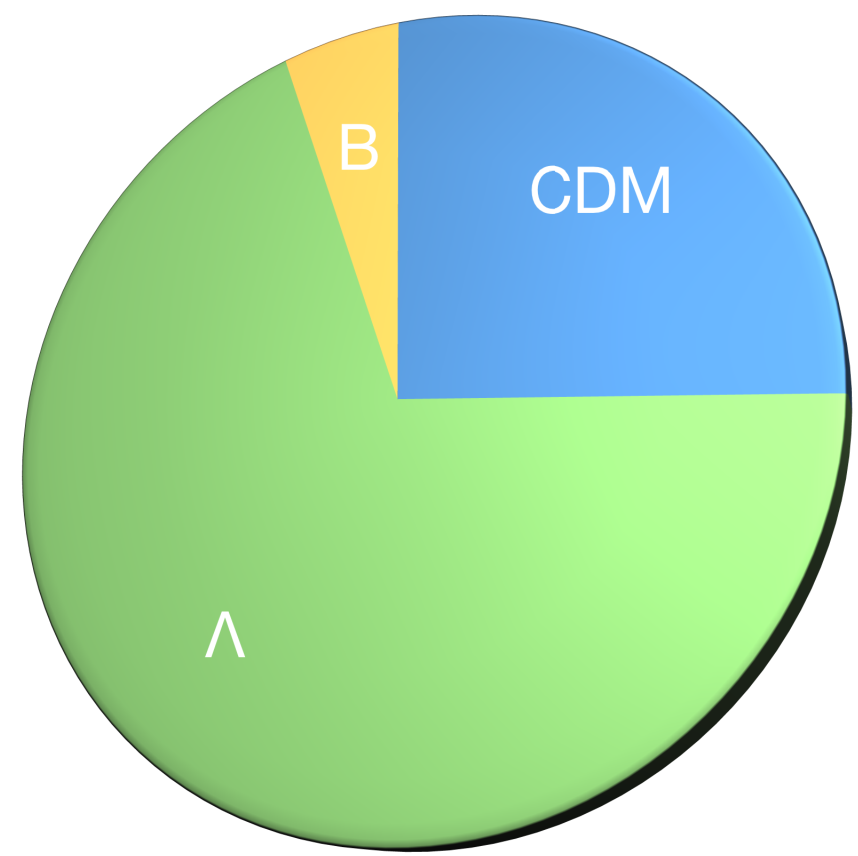

$\Omega_{tot} = 1.000(7)$
PDG 2014

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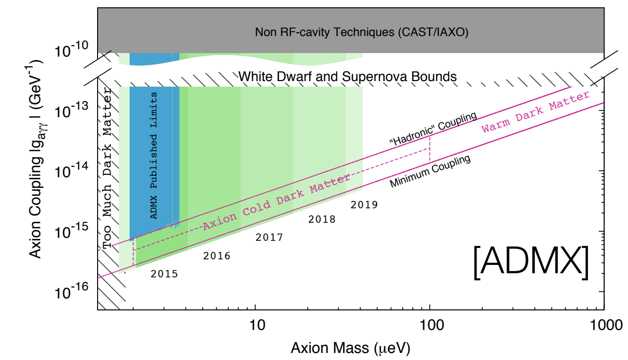

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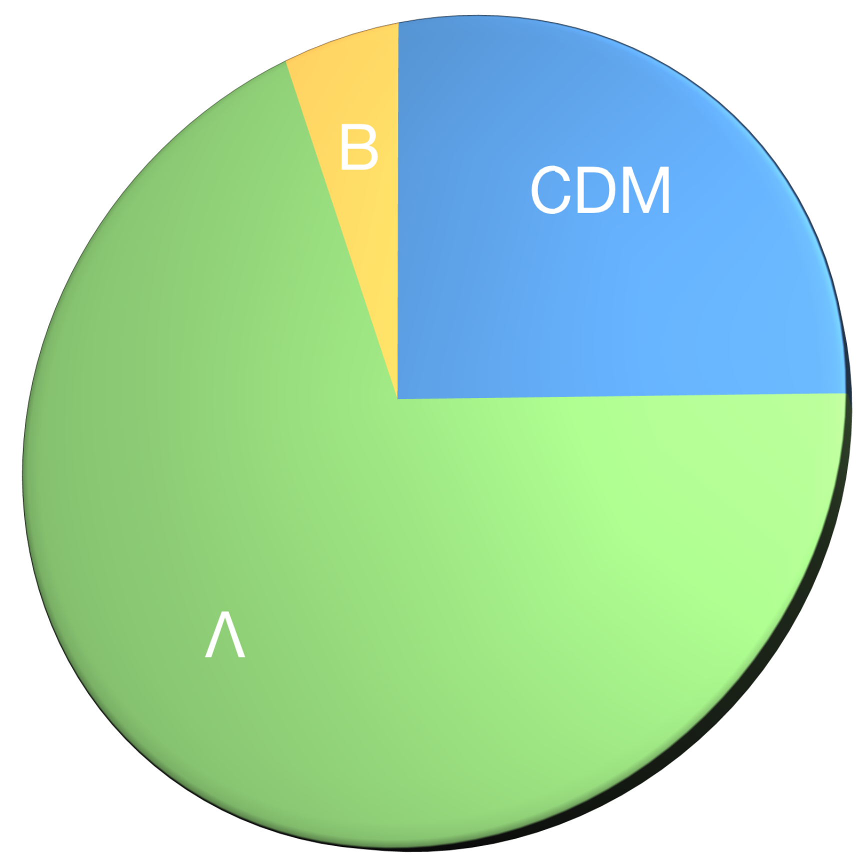

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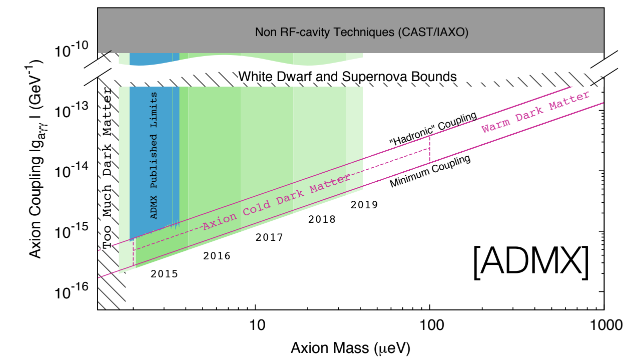

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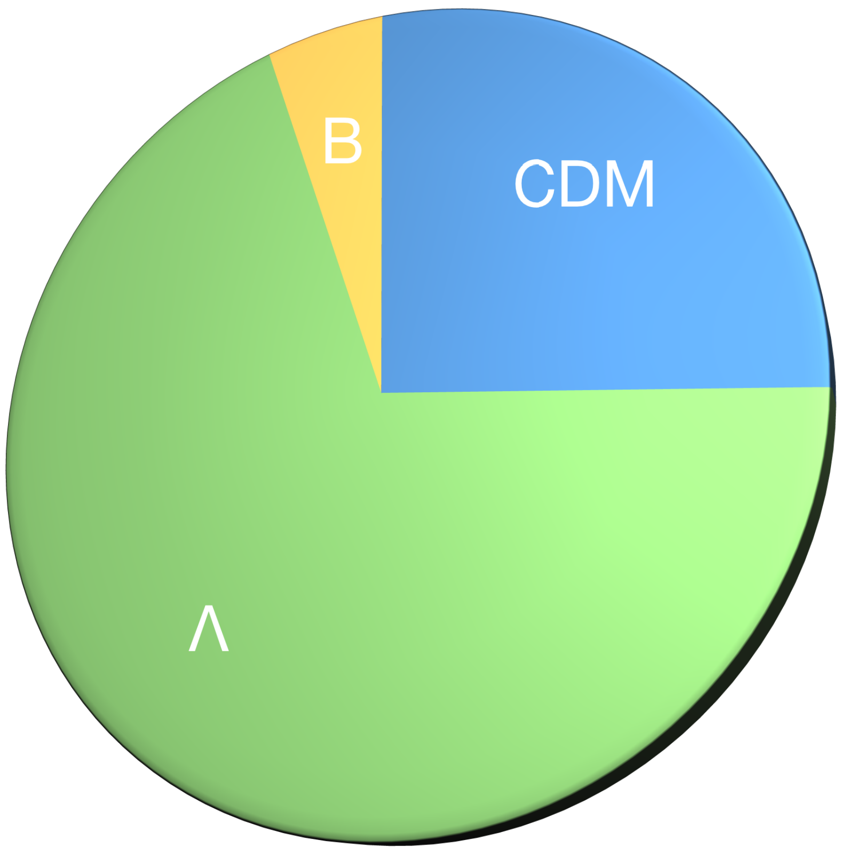

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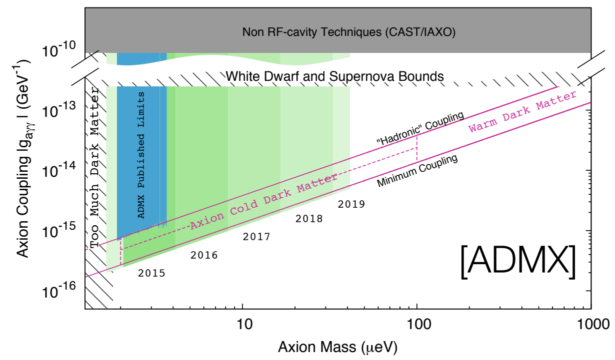

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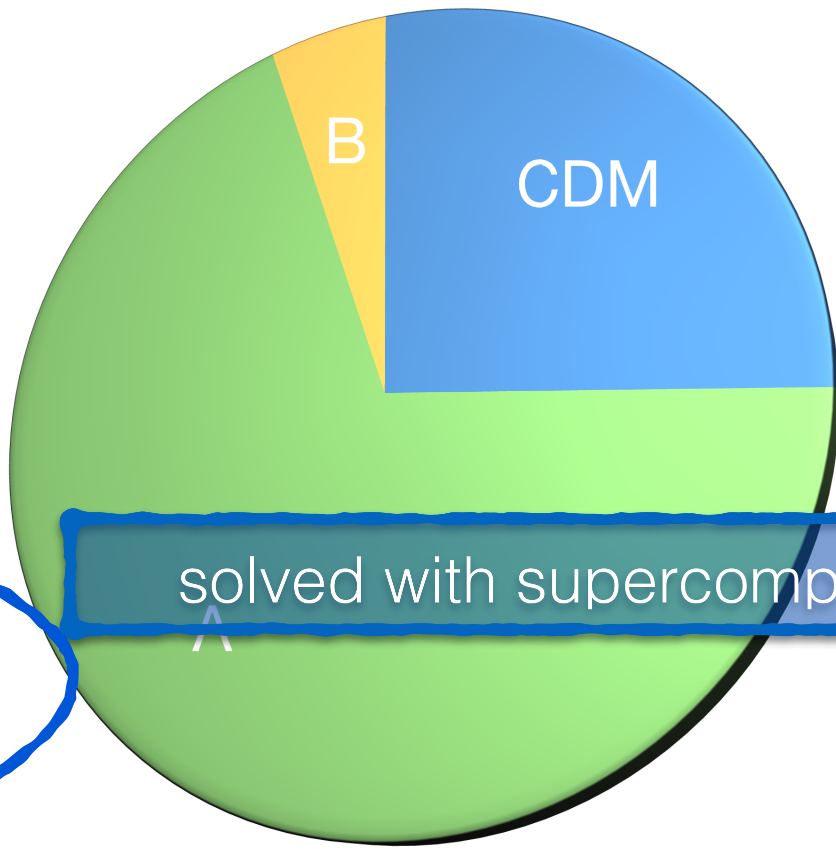

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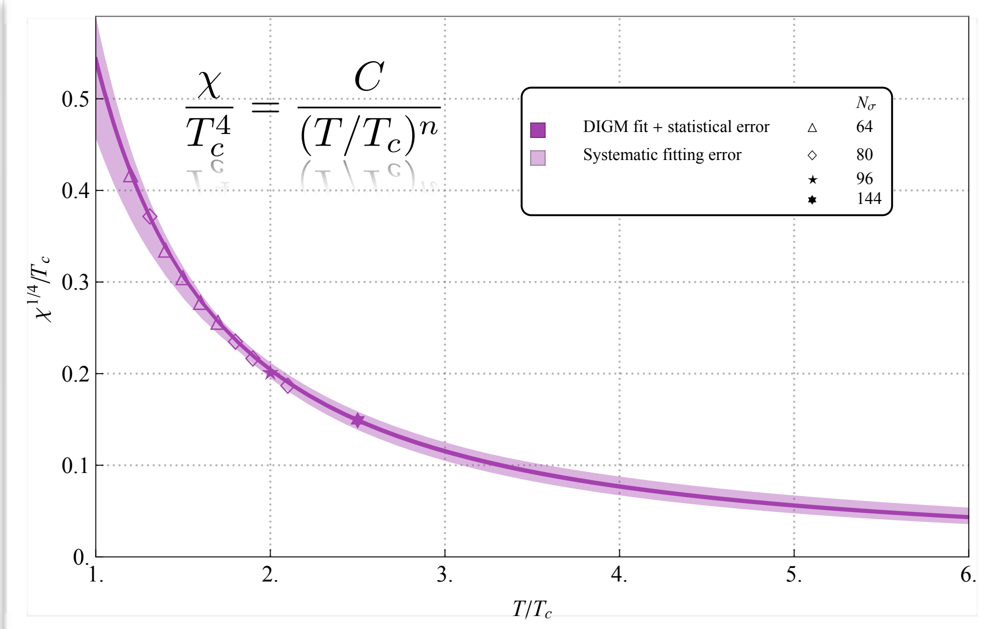
Axion mass from lattice simulations

Non-perturbative calculation of QCD topology at finite temperature



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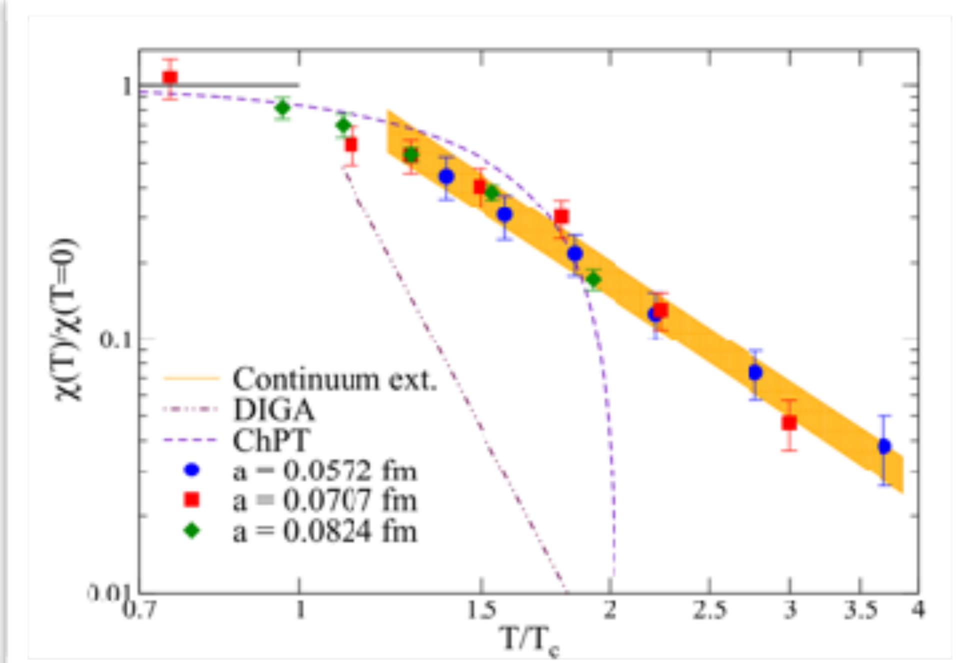

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Non-perturbative calculation of QCD topology at finite temperature

- Pure gauge SU(3) topological susceptibility ➥ compatible with model predictions (DIGM/IILM), but lattice identifies **important non-perturbative effects**

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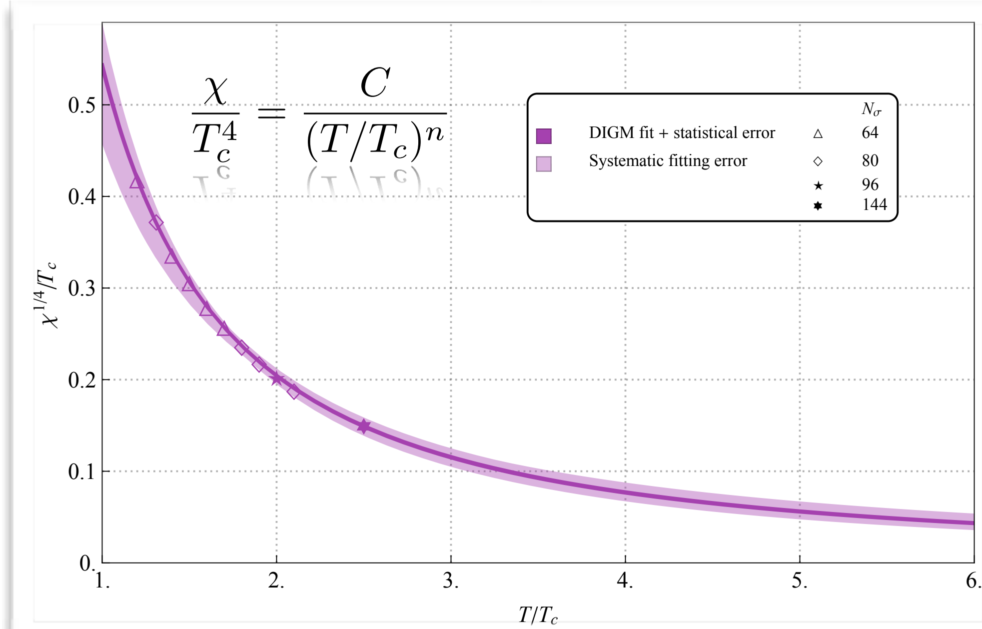

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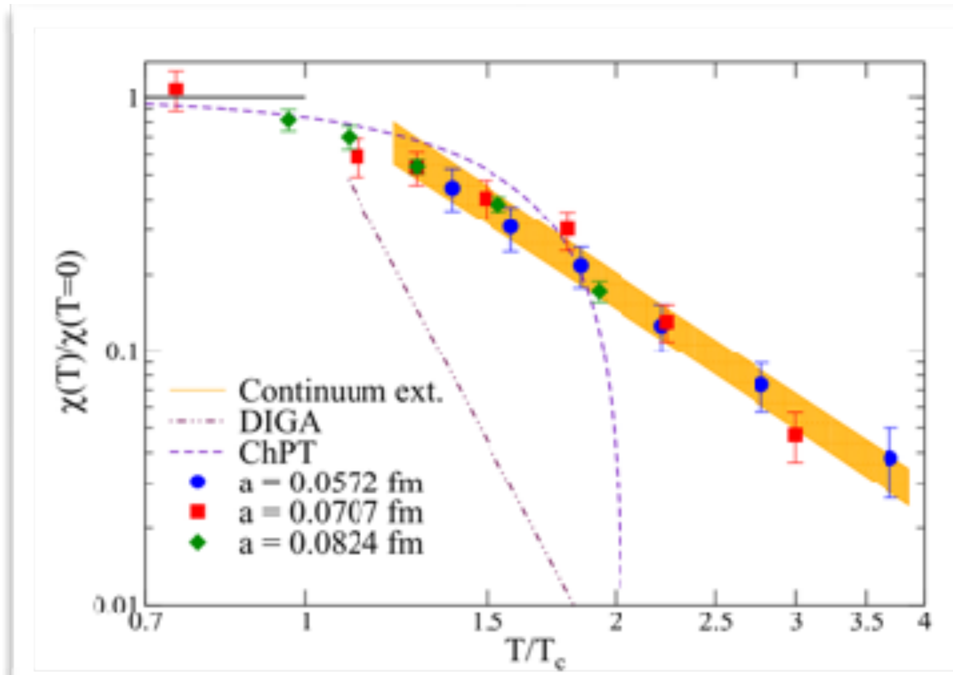

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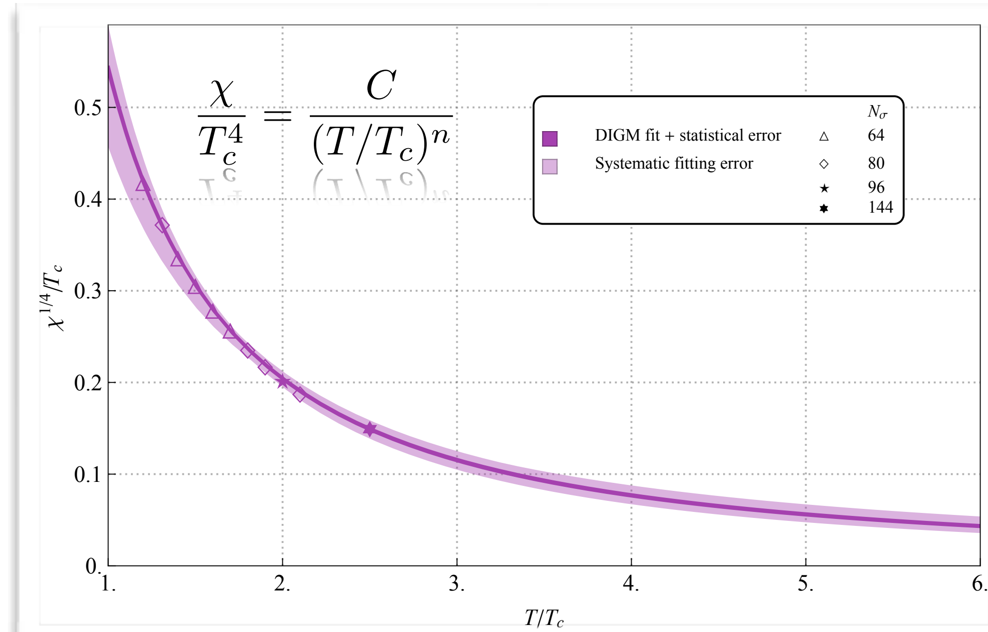
- is QCD topological susceptibility at high-T **well described by models?** ➥ light fermions importantly affect the vacuum

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



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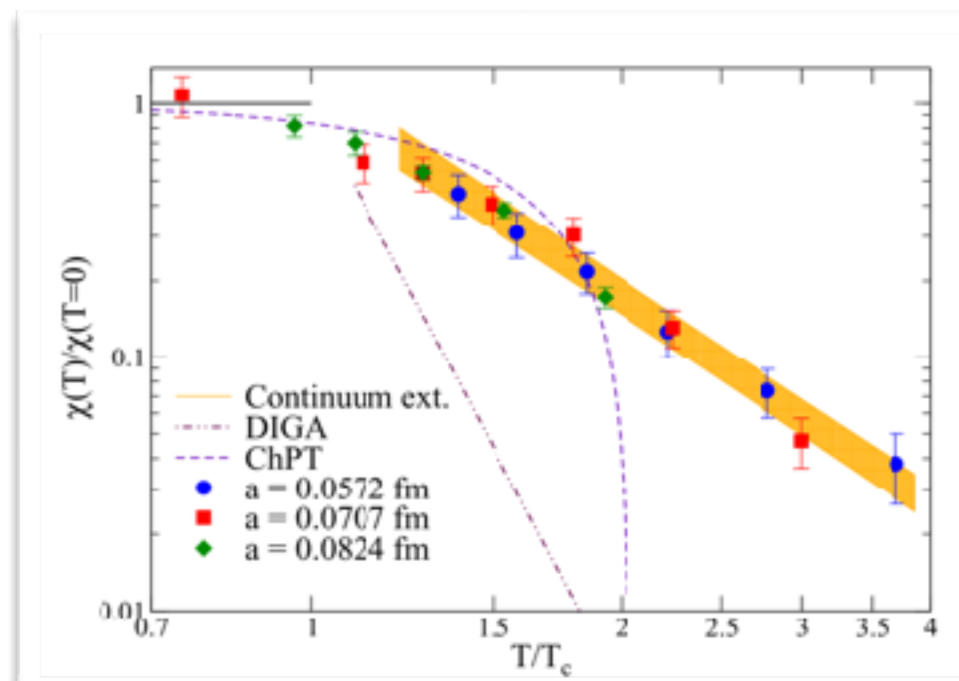

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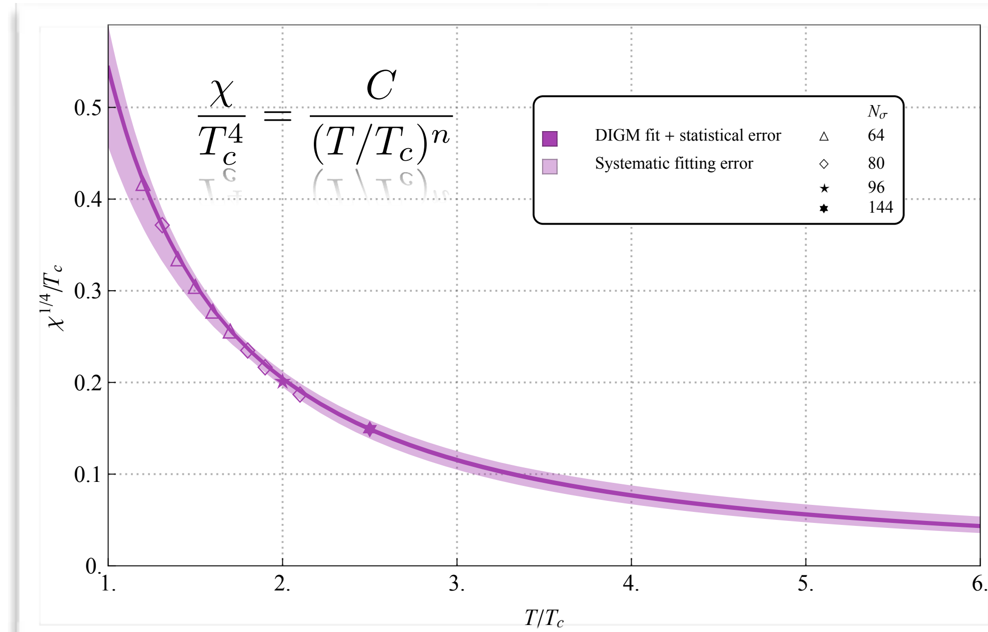

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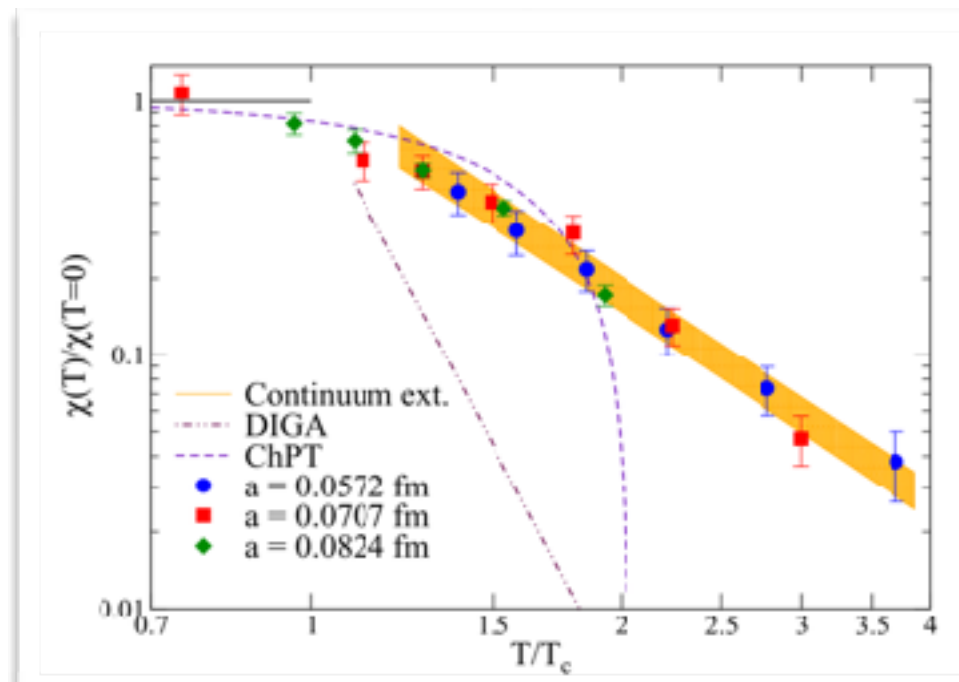
- is QCD topological susceptibility at high-T well described by models? ➥ light fermions importantly affect the vacuum

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

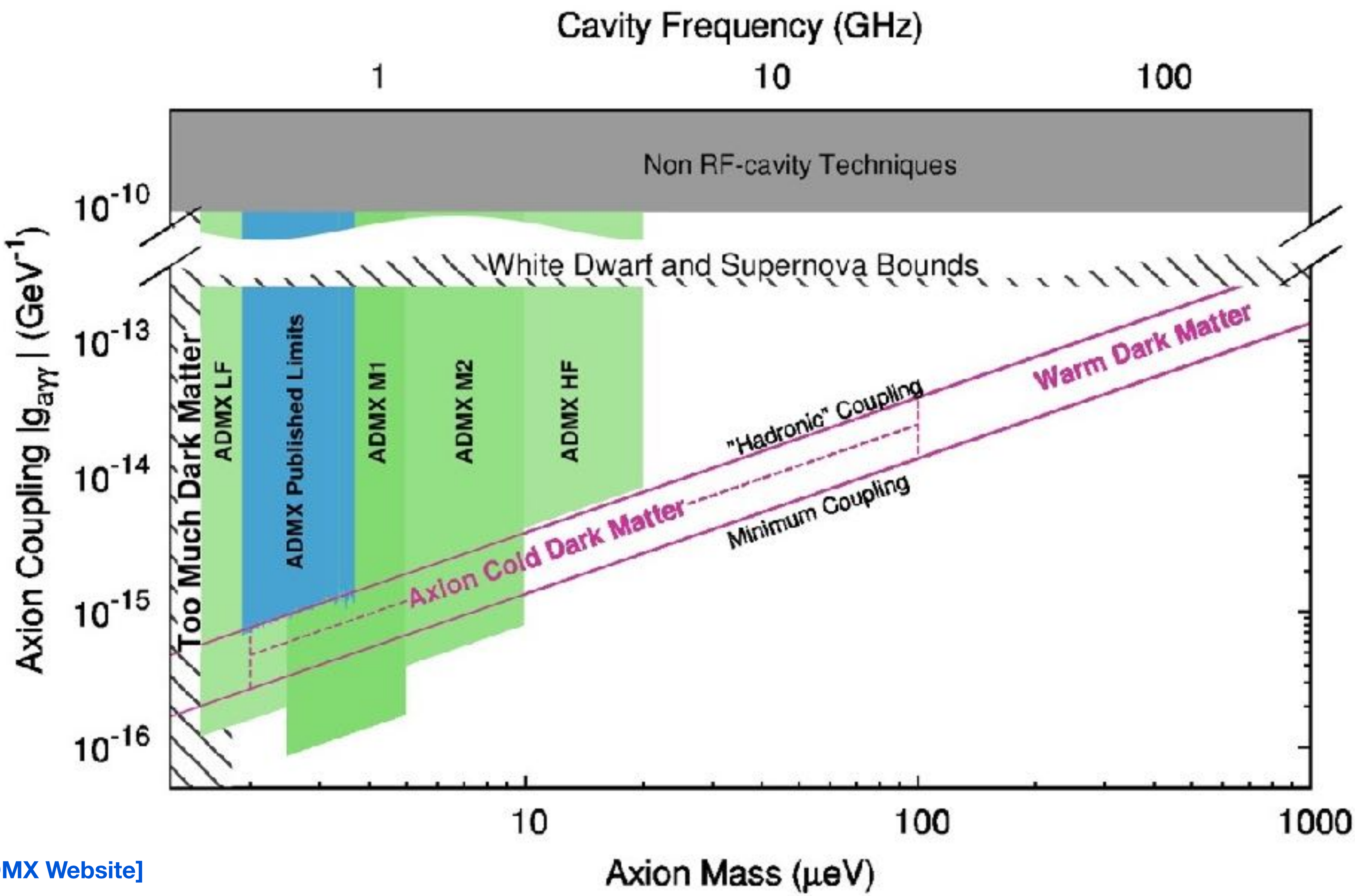


[Bonati et al., 1512.06746]

Great effort to control all systematic lattice effects in order to guide experiments. Challenging state-of-the art simulations.

[Berkowitz, Buchoff, ER, PRD 92 (2015) 034507]

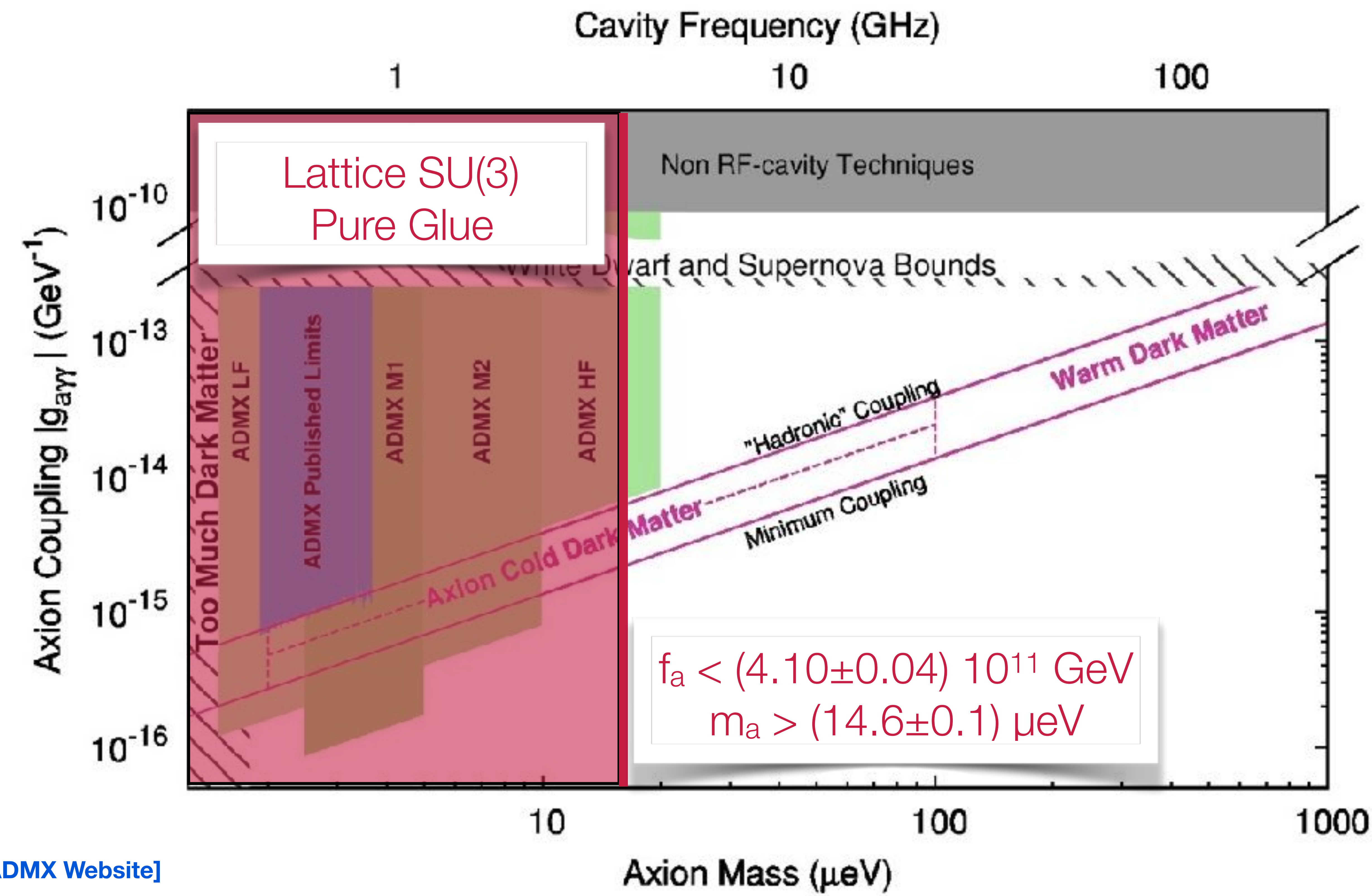
Axion mass lower bound



[ADMX Website]

[Berkowitz, Buchoff, ER, PRD 92 (2015) 034507]

Axion mass lower bound



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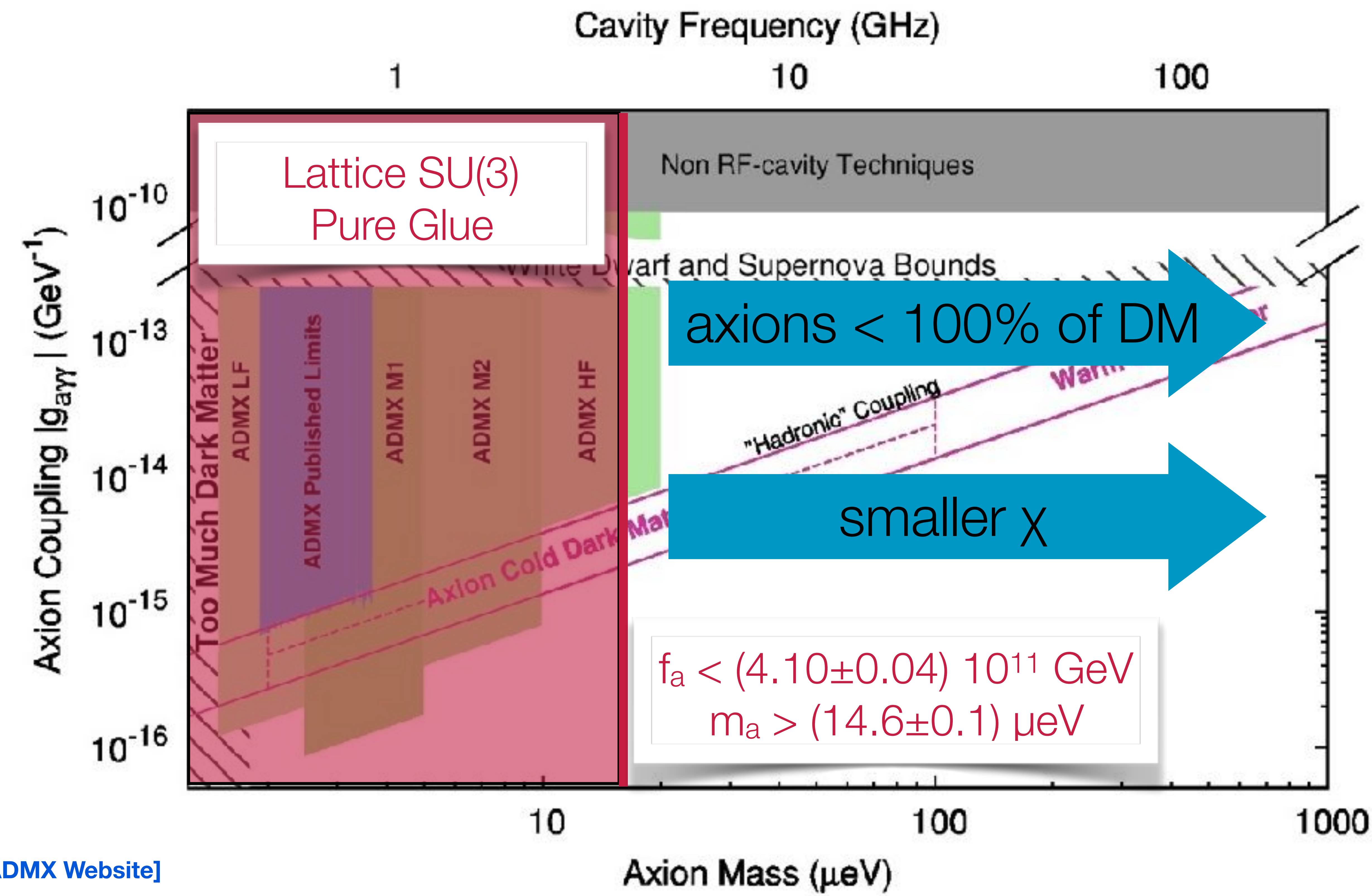
[Berkowitz, Buchoff, ER, PRD 92 (2015) 034507]

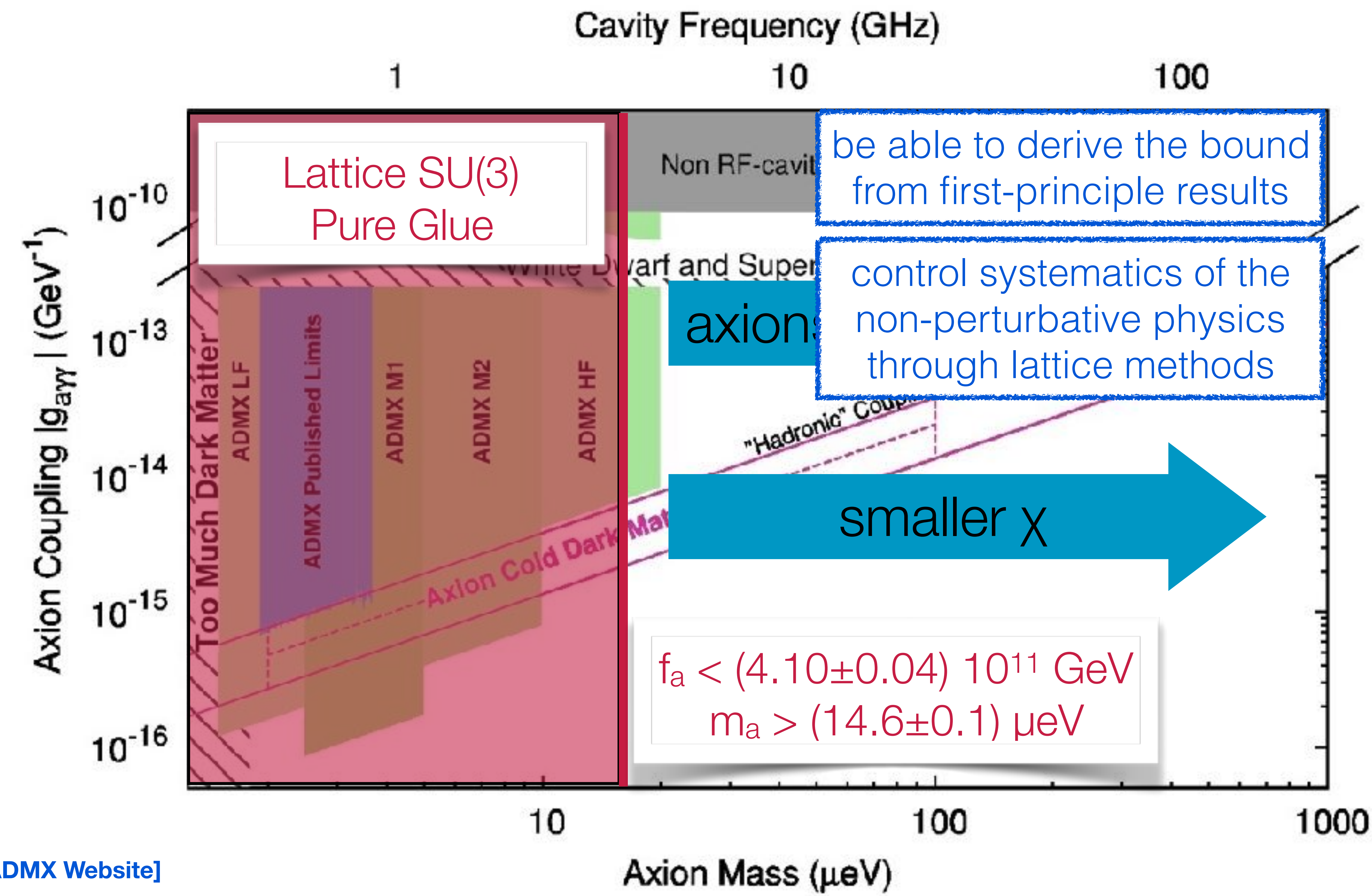
Axion mass lower bound



[ADMX Website]

[Berkowitz, Buchoff, ER, PRD 92 (2015) 034507]

Axion mass lower bound

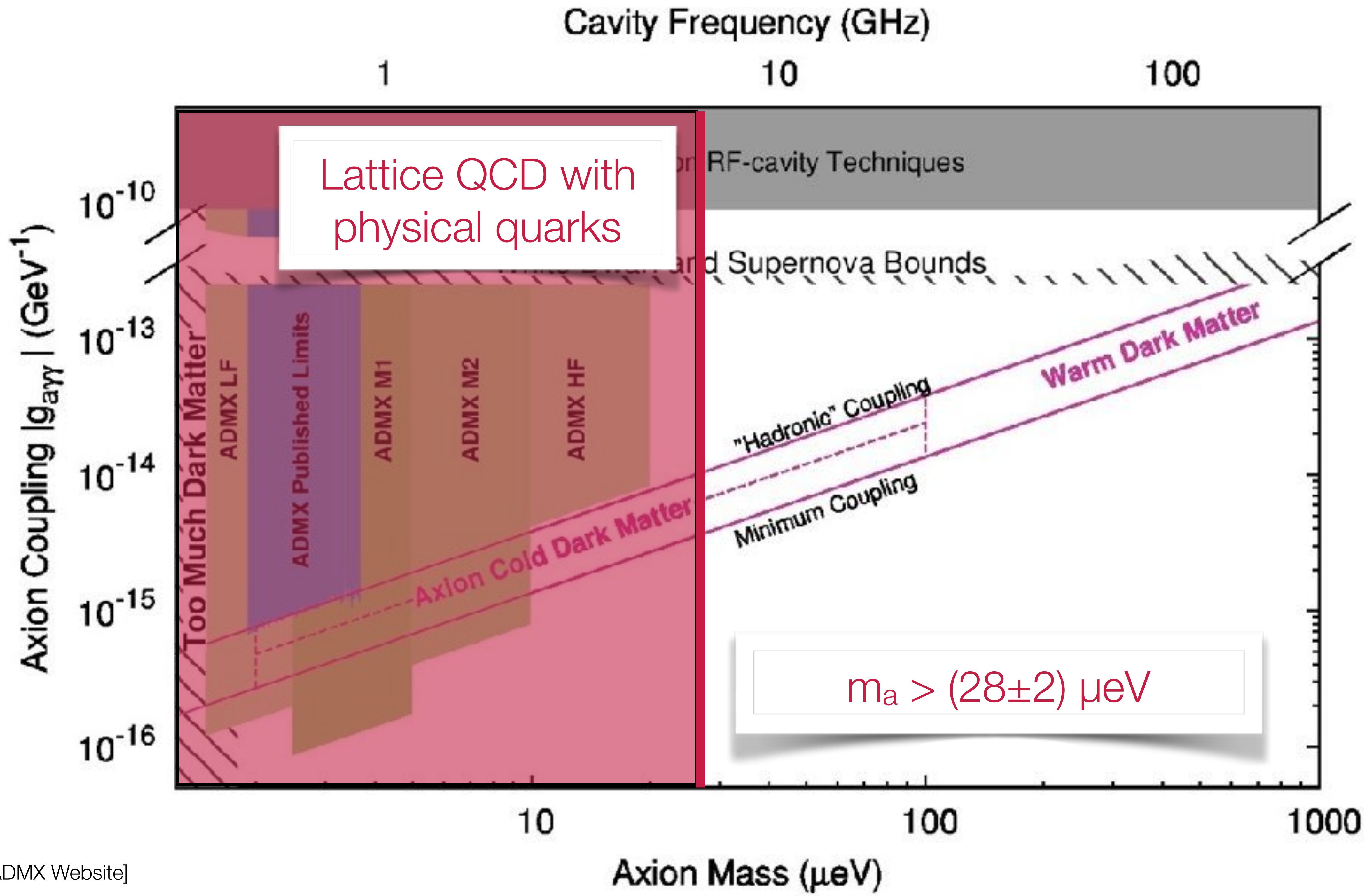


[ADMX Website]

[Borsanyi et al., 1606.07494, Nature 539]

Axion mass lower bound

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



[ADMX Website]

[Borsanyi et al., 1606.07494, Nature 539]

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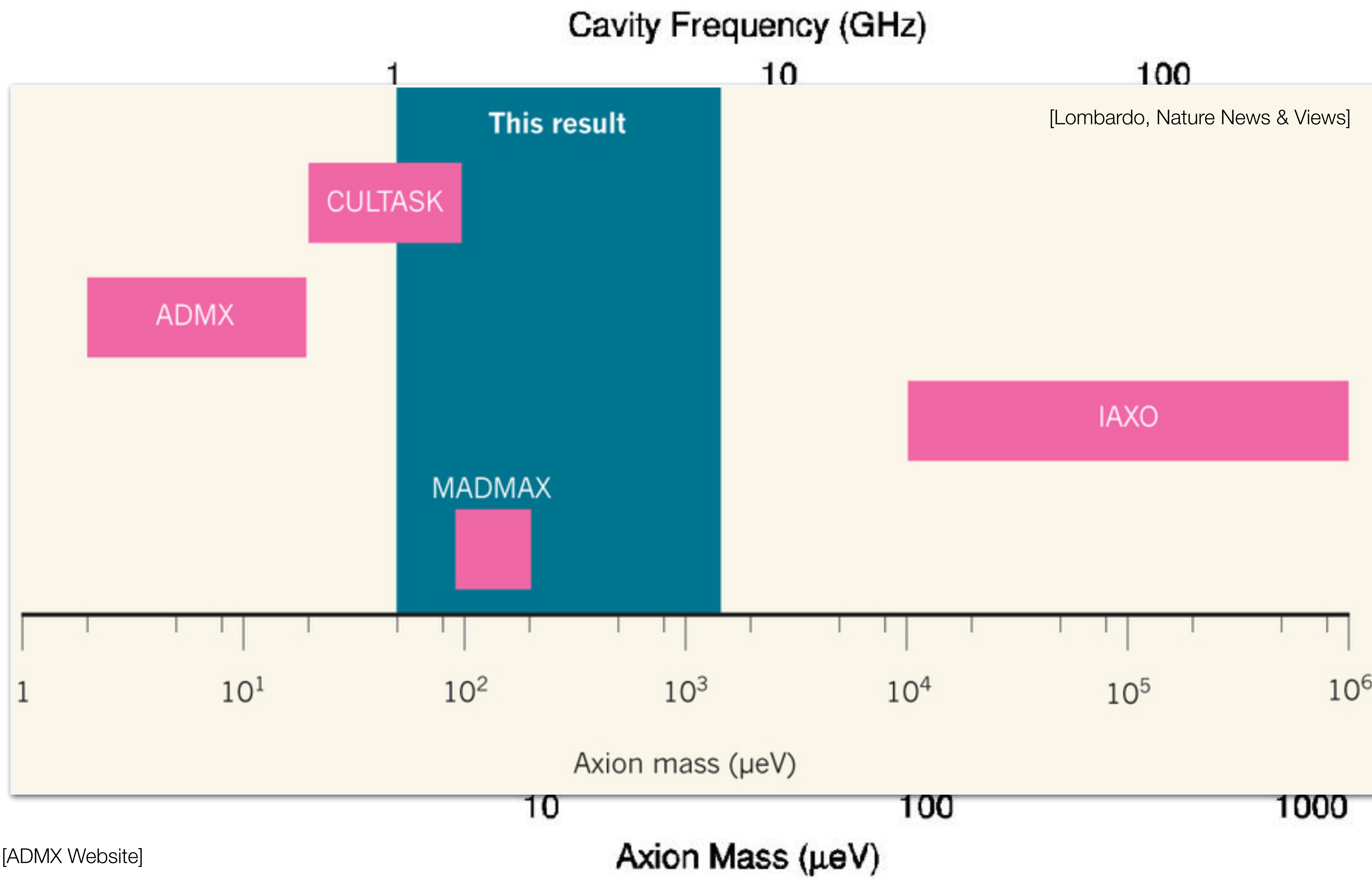
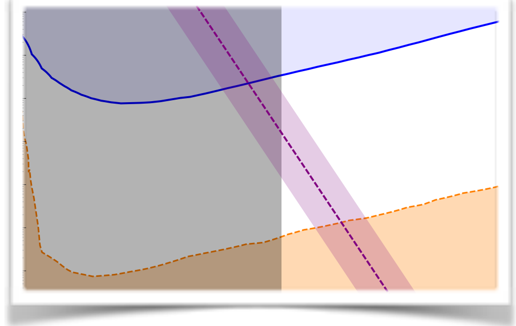
Axion mass lower bound



[ADMX Website]

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



Concluding remarks

- **Composite** dark matter and **Axion** dark matter are viable interesting possibility with rich phenomenology

- **Lattice** methods can help in calculating direct detection cross sections, production rates at colliders, self-interaction cross sections and the axion mass bound. Direct phenomenological relevance and guide to experimental searches.

- Dark matter constituents can carry electroweak charges and still the stable composites are currently undetectable. **Stealth** cross section.

- Lowest bound for **composite** dark matter models: ~300 GeV (colliders+direct detection+lattice)

- **Axions** from QCD dynamics have a lowest mass bound ~20-50 μeV (cosmology+lattice) extra

The darkness of Composite Dark Matter

[Wikipedia]

The darkness of Composite Dark Matter

[Wikipedia]

Lowest dimensional operators:

- ★ magnetic dipole (5)
- ★ charge radius (6)
- ★ polarizability (7)

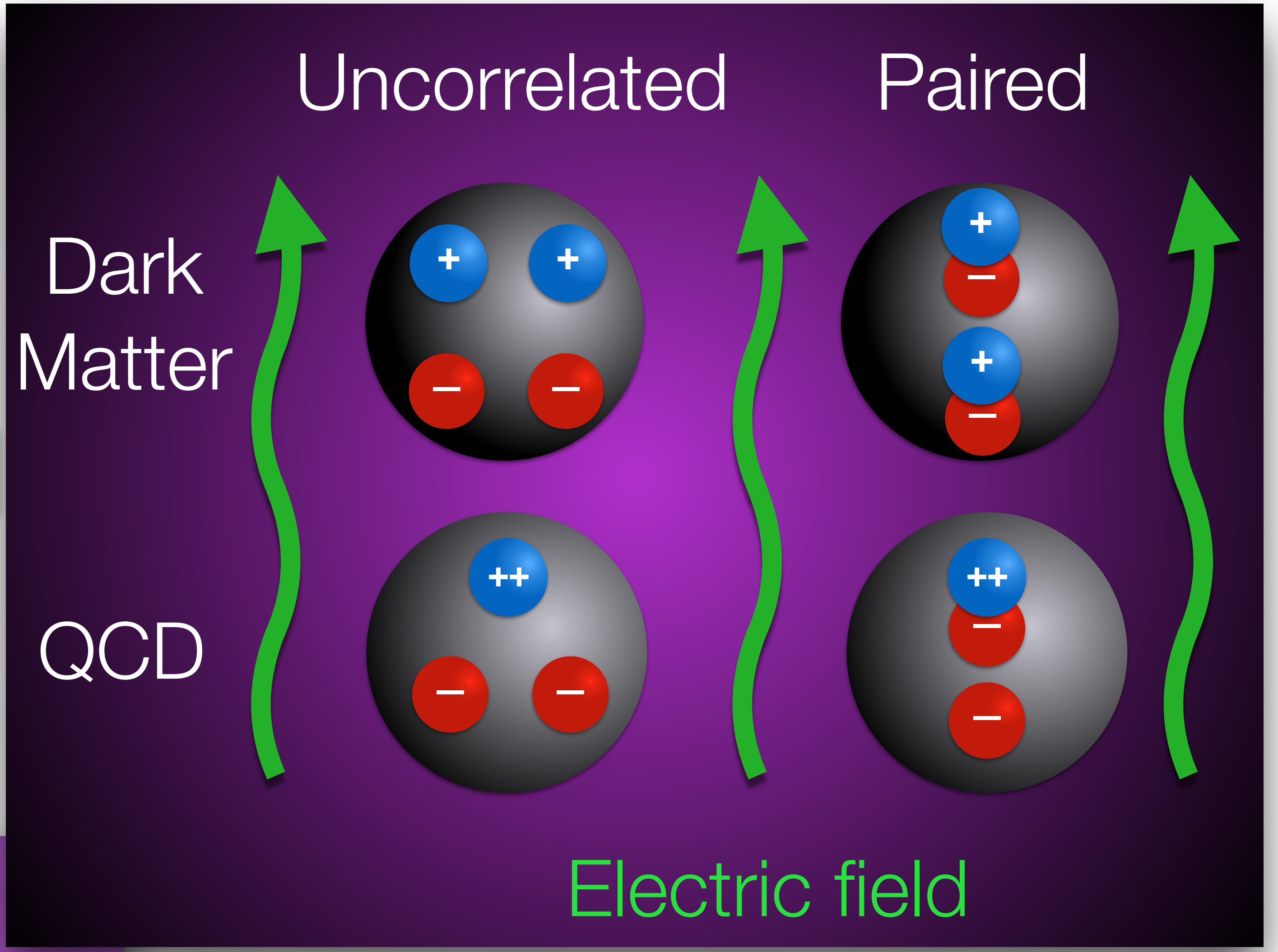
The darkness of Composite Dark Matter

[Wikipedia]

Lowest dimensional operators:

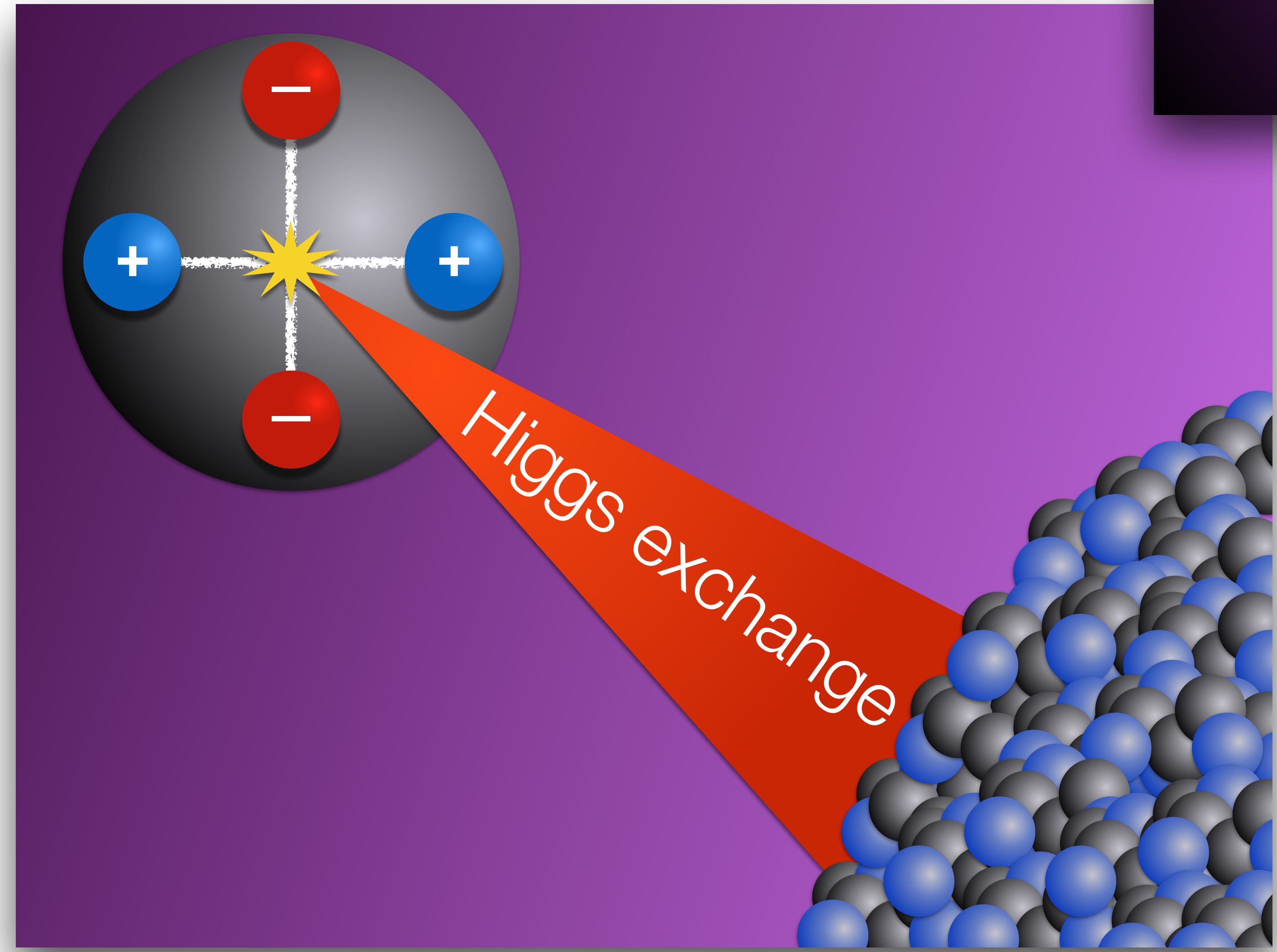
★ magnetic dipole (5)
★ charge radius (6)
★ polarizability (7)

Most relevant interaction if constituents have Yukawa couplings!



PRL Editors' Suggestion: Polarizability

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



PRD Editors' Suggestion: Higgs exchange

[LSD collab., Phys. Rev. D92 (2015) 075030] http://www.media.inaf.it/2015/09/25/materia-oscura-stealth/

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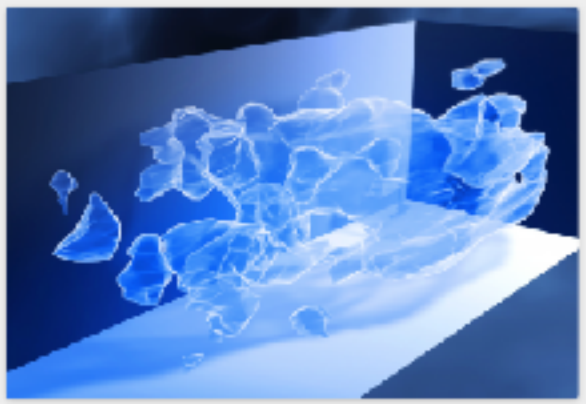
COME UN CACCIA INVISIBILE AI RADAR

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 — 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 al 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 del *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

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

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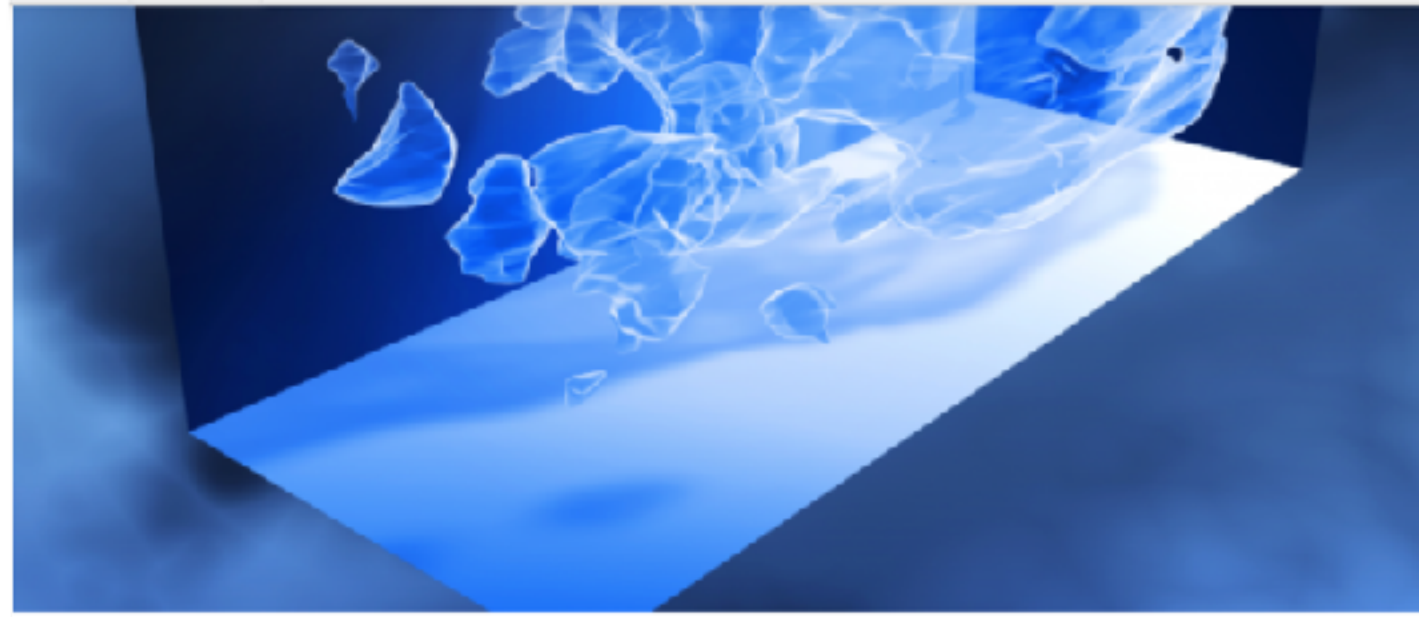

This 3D map illustrates the large-scale distribution of dark matter, reconstructed from measurements of weak gravitational lensing by using the Hubble Space Telescope. (Download Image)

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

Detecting Stealth Dark Matter Directly through Electromagnetic Polarizability.

Overview of attention for article published in Physical Review Letters, October 2015

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Title	Detecting Stealth Dark Matter Directly through Electromagnetic Polarizability.
Published in	Physical Review Letters, October 2015
DOI	10.1103/physrevlett.115.171803
Pubmed ID	26551103
Authors	T. Appelquist, E. Berkowitz, R.C. Brower, M.I. Buchoff, G.T. Fleming, X.-Y. Jin, J. Kiskis, G.D... [show]
Abstract	We calculate the spin-independent scattering cross section for direct detection that results from... [show]

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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)*

"Stealth Dark Matter" model

- 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*** ↔ ***d***

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	$\mathbf{N}$	$(\mathbf{1}, -1/2)$	$-1/2$
F_4^u	$\overline{\mathbf{N}}$	$(\mathbf{1}, +1/2)$	$+1/2$
F_4^d	$\overline{\mathbf{N}}$	$(\mathbf{1}, -1/2)$	$-1/2$

$$\mathcal{L} \supset + y_{14}^u \epsilon_{ij} F_1^i H^j F_4^d + y_{14}^d F_1 \cdot H^\dagger F_4^u - y_{23}^d \epsilon_{ij} F_2^i H^j F_3^d - y_{23}^u F_2 \cdot H^\dagger F_3^u + h.c.$$

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

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