FRONTIERS IN NUCLEAR PHYSICS

11/03/2016 - KITP

Dark Interactions and the Lattice

Enrico Rinaldi

RIKEN BNL Research Center

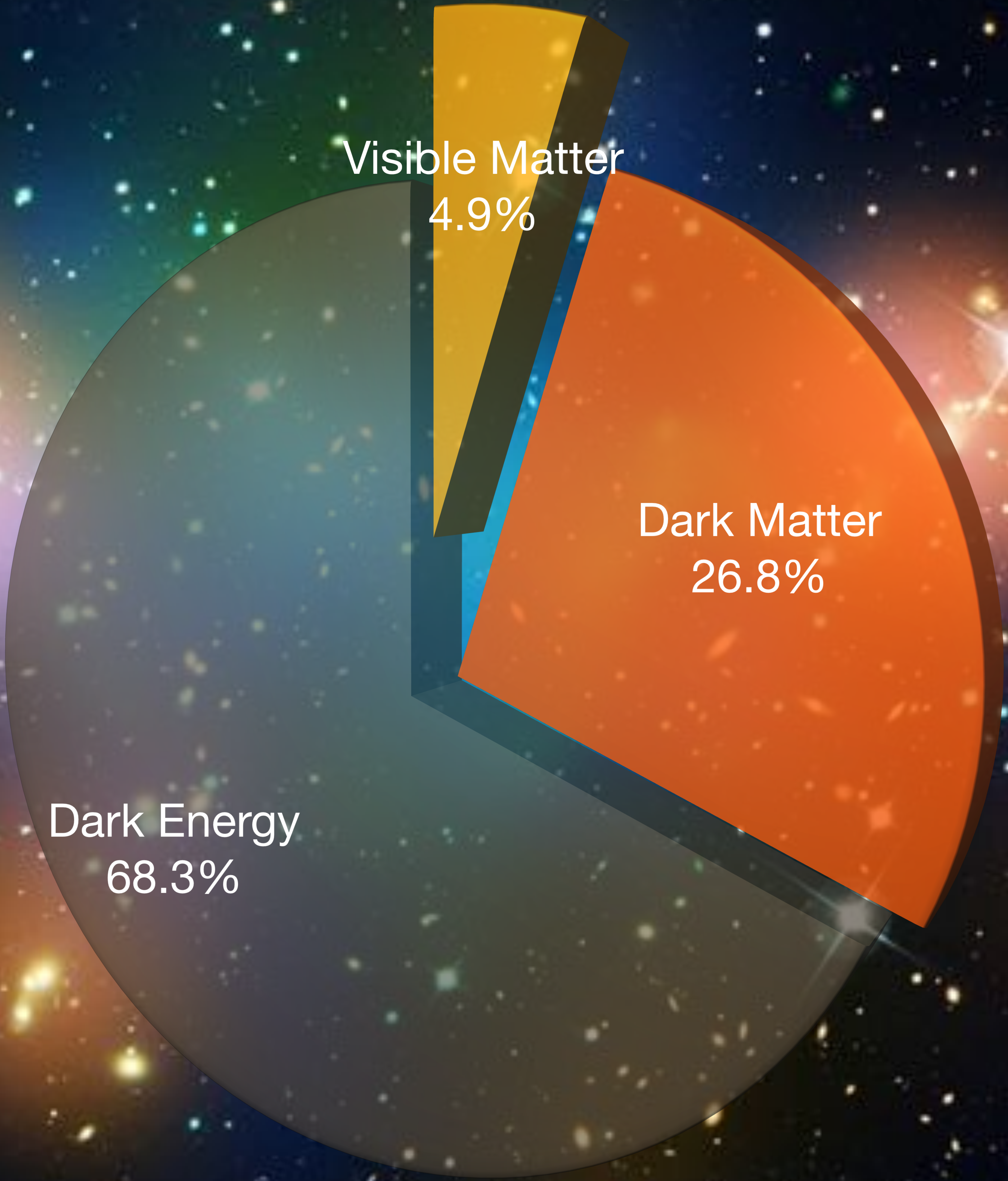
This research was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and supported by the LLNL LDRD "Illuminating the Dark Universe with PetaFlops Supercomputing" 13-ERD-023.

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

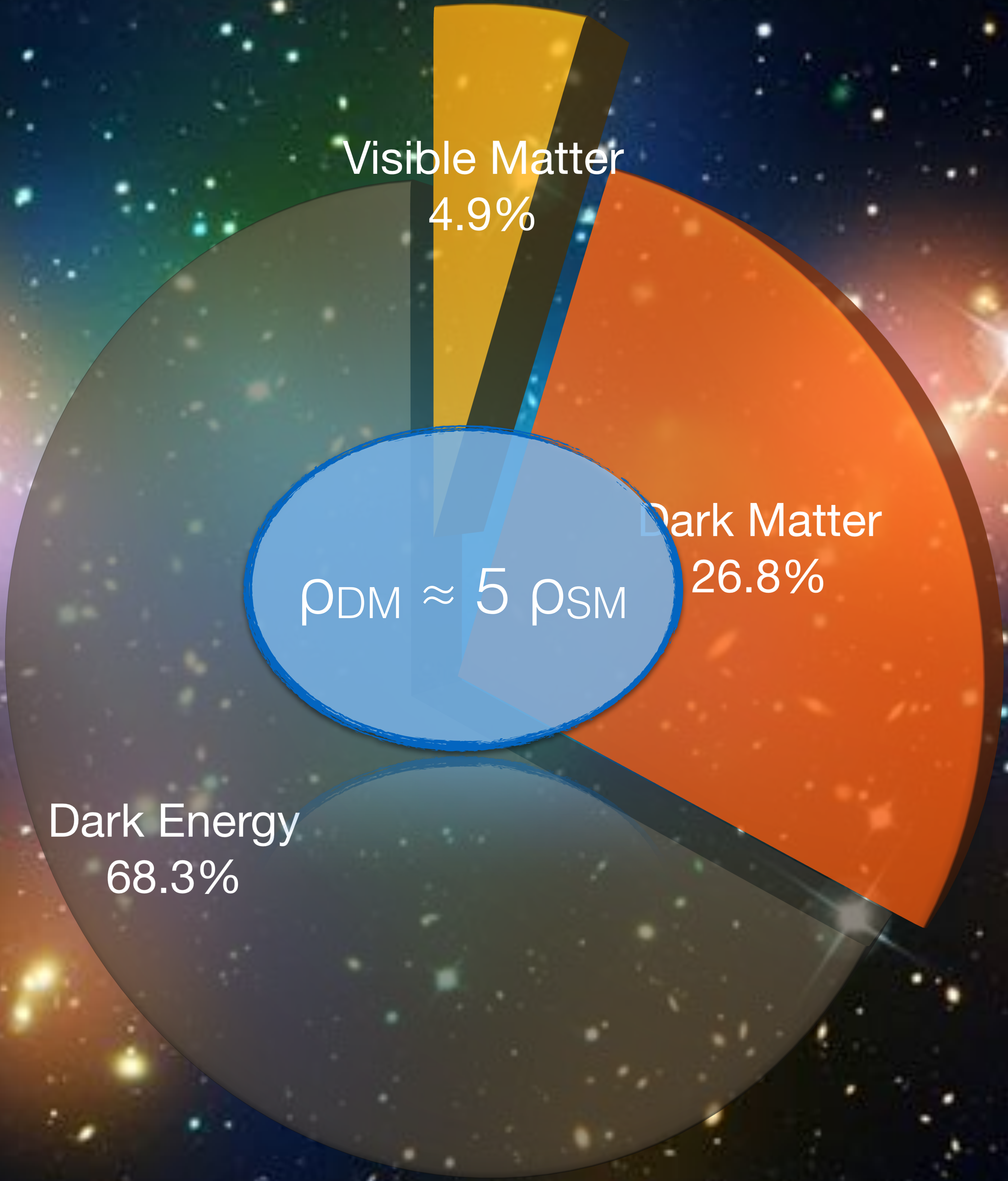
[Hubble + Plank/ESA]

Visible Matter
4.9%

[Hubble + Plank/ESA]

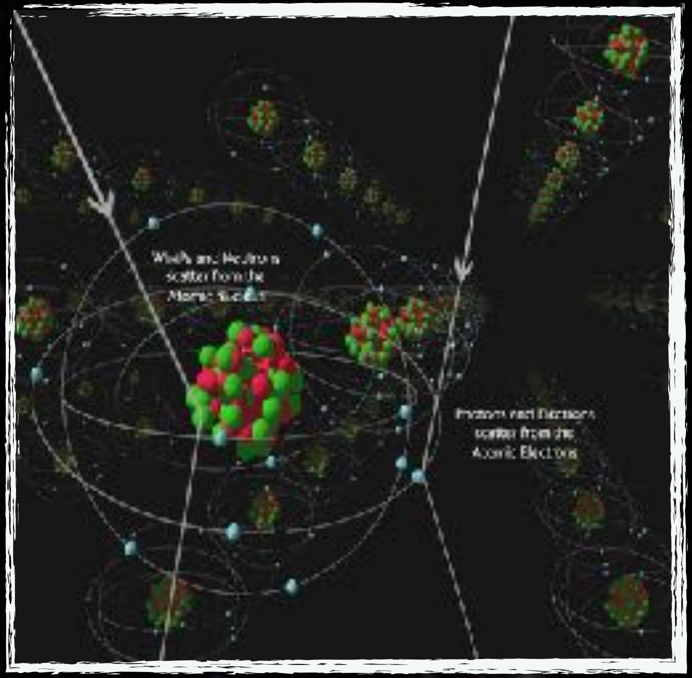


[Hubble + Plank/ESA]

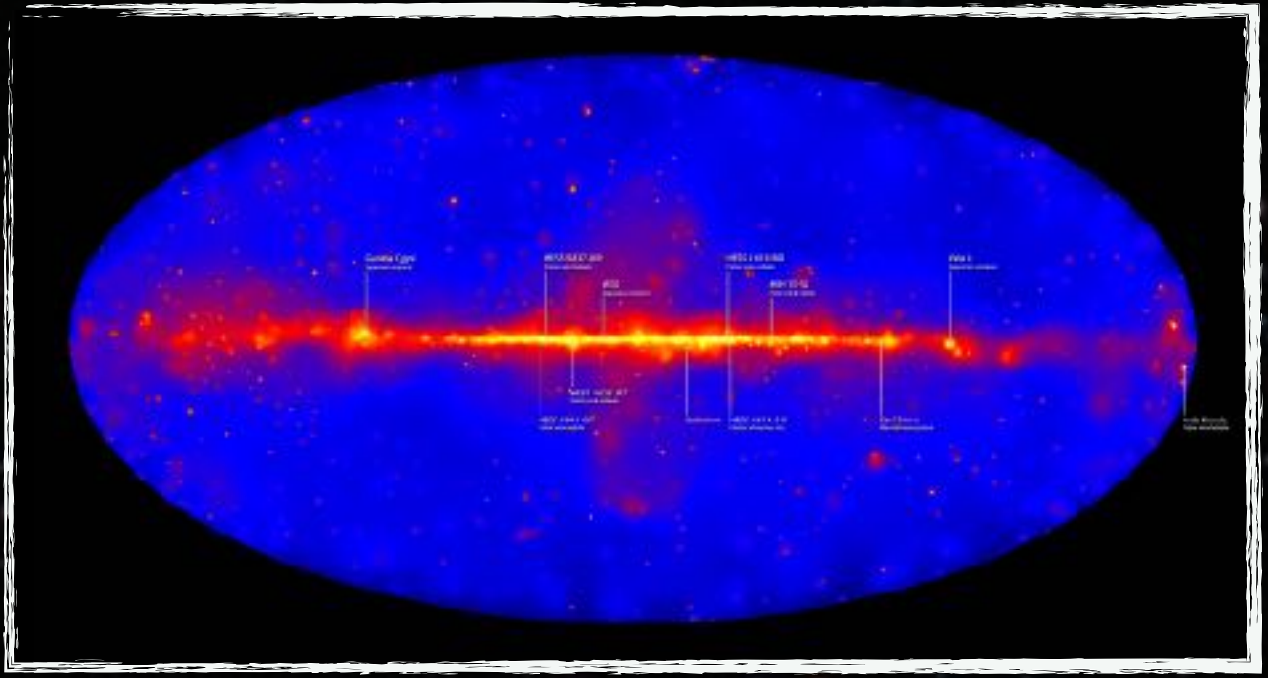


$\rho_{DM} \approx 5\ \rho_{SM}$

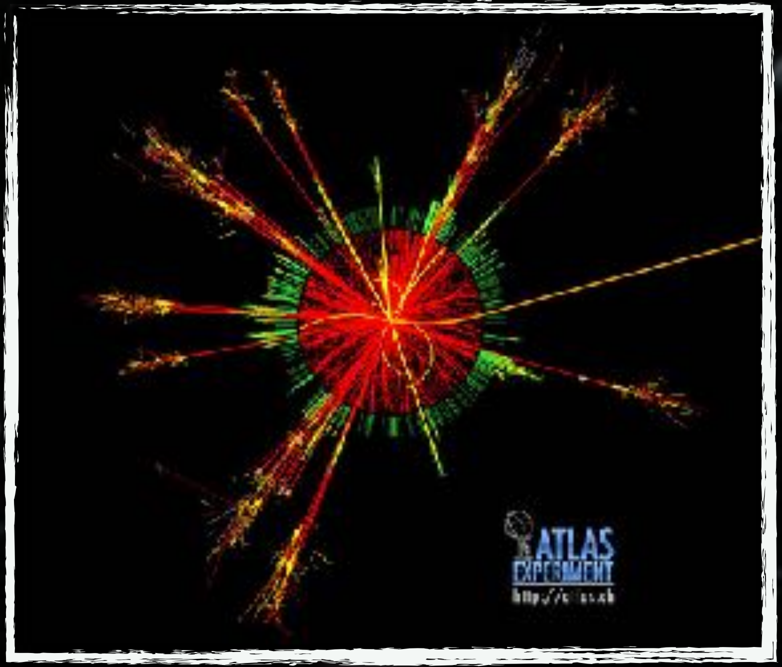
[Hubble + Plank/ESA]



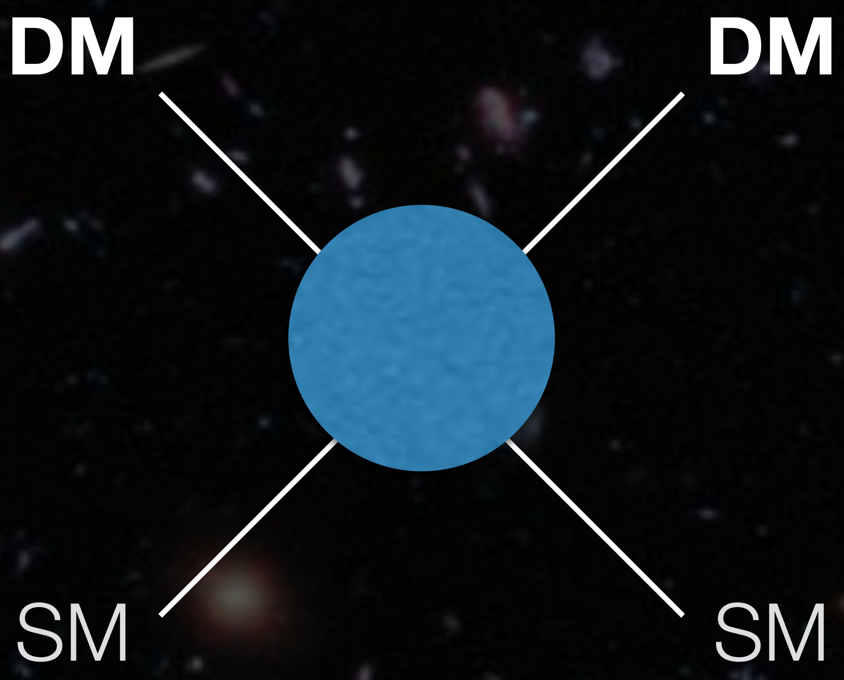
Direct Detection



Indirect Detection

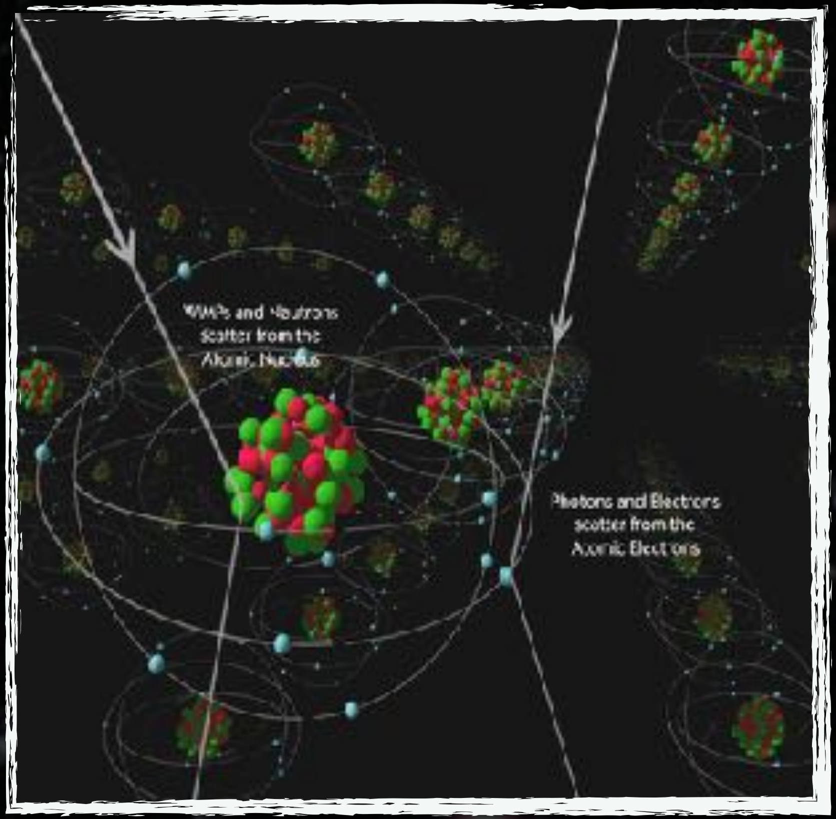


Production at Colliders



DM **DM**

SM SM



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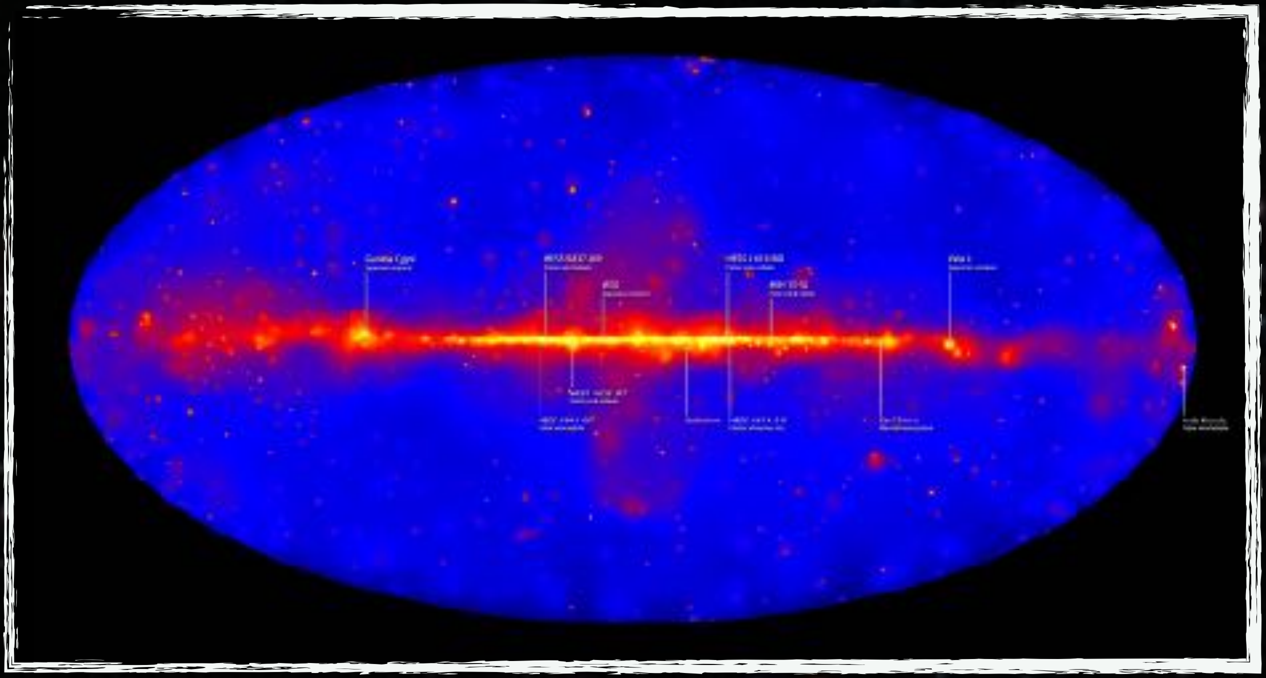

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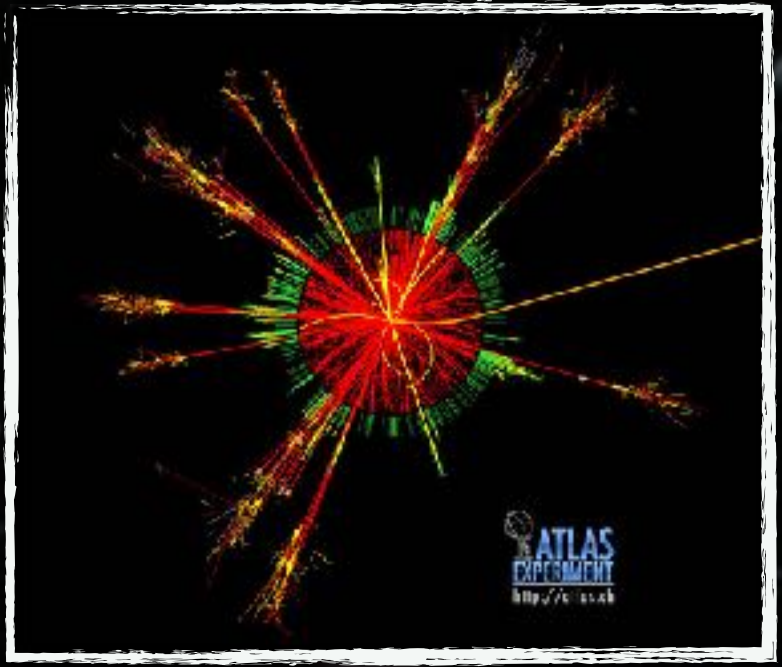

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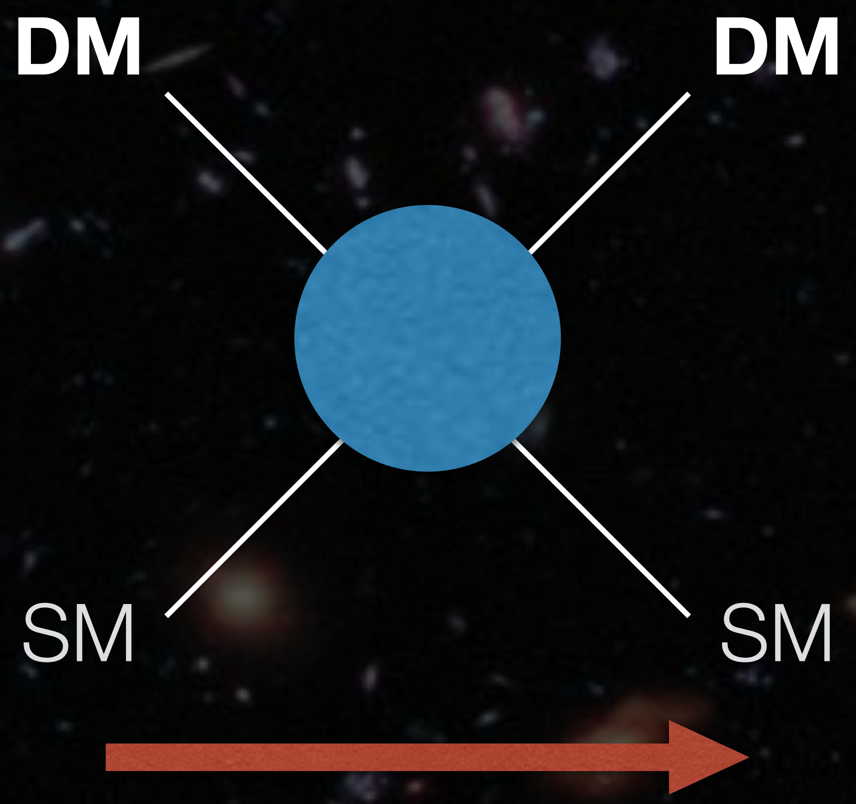

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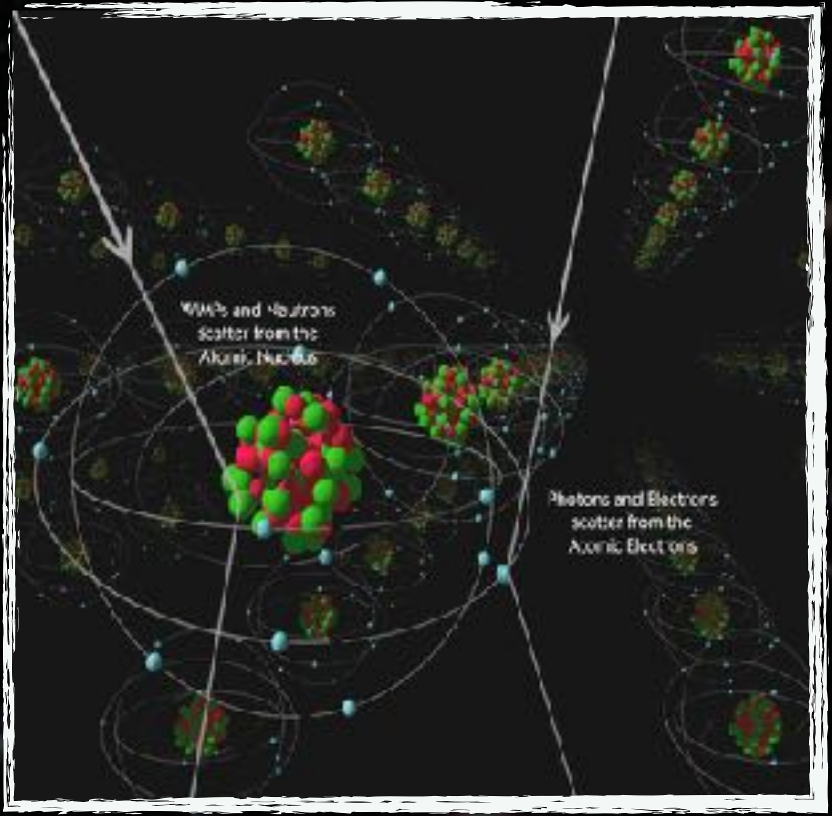

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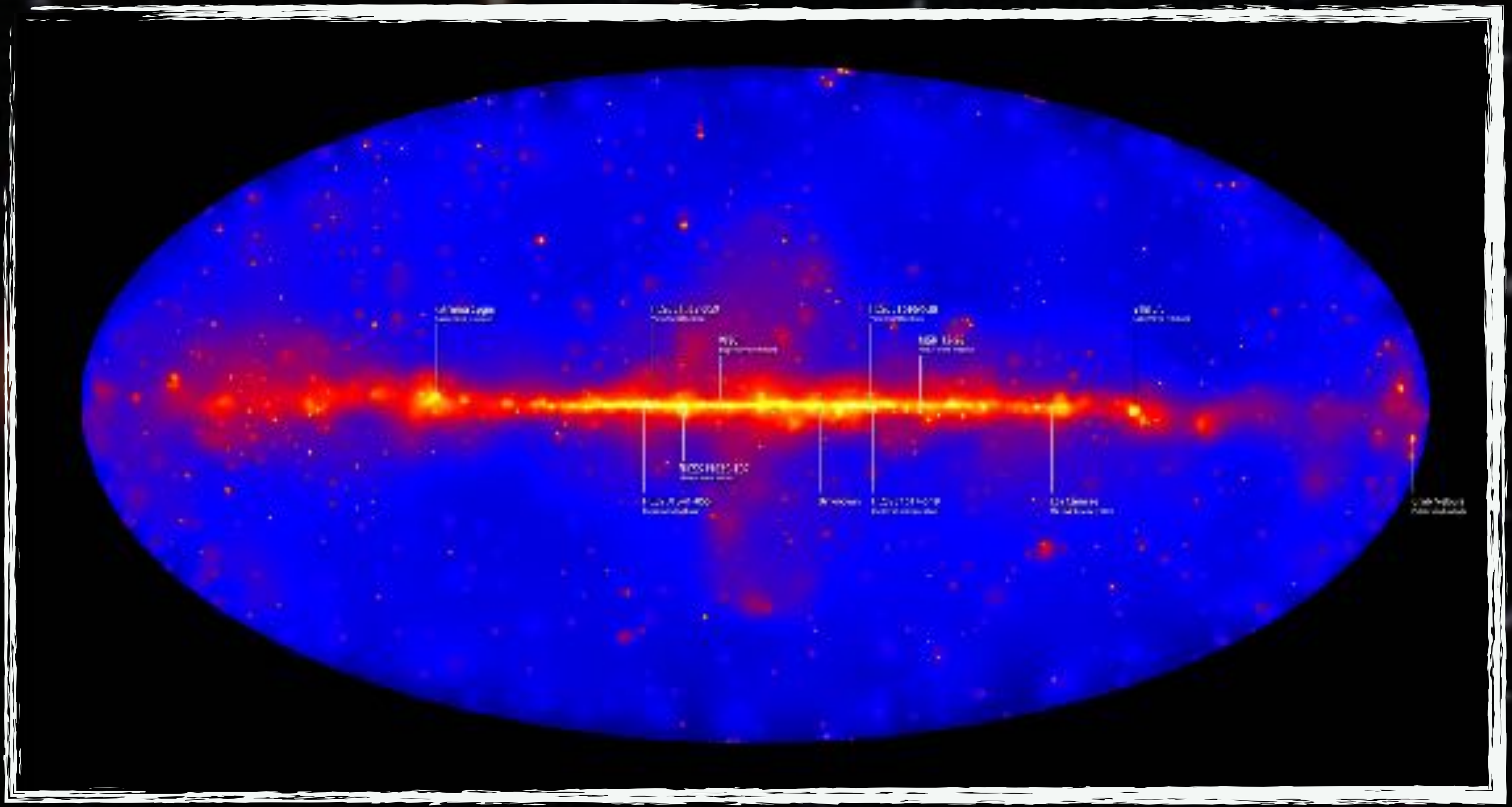

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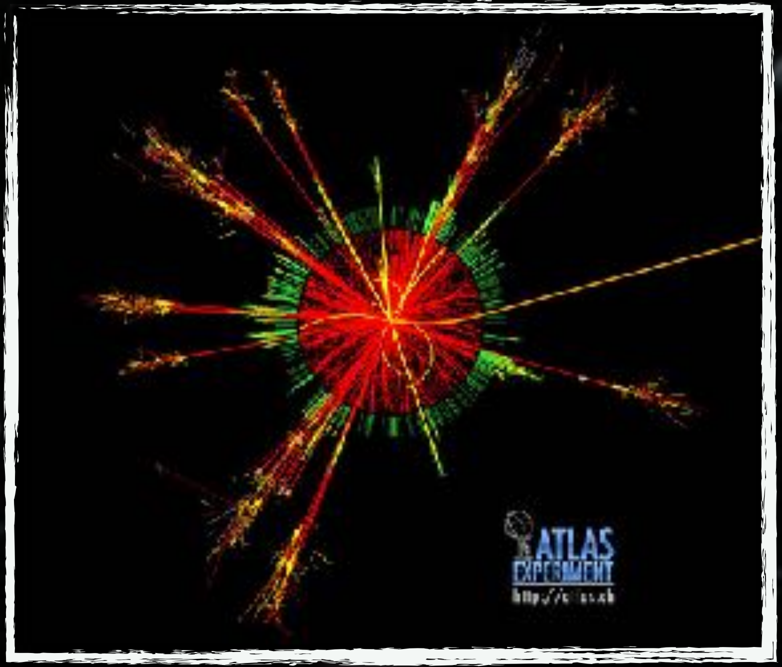

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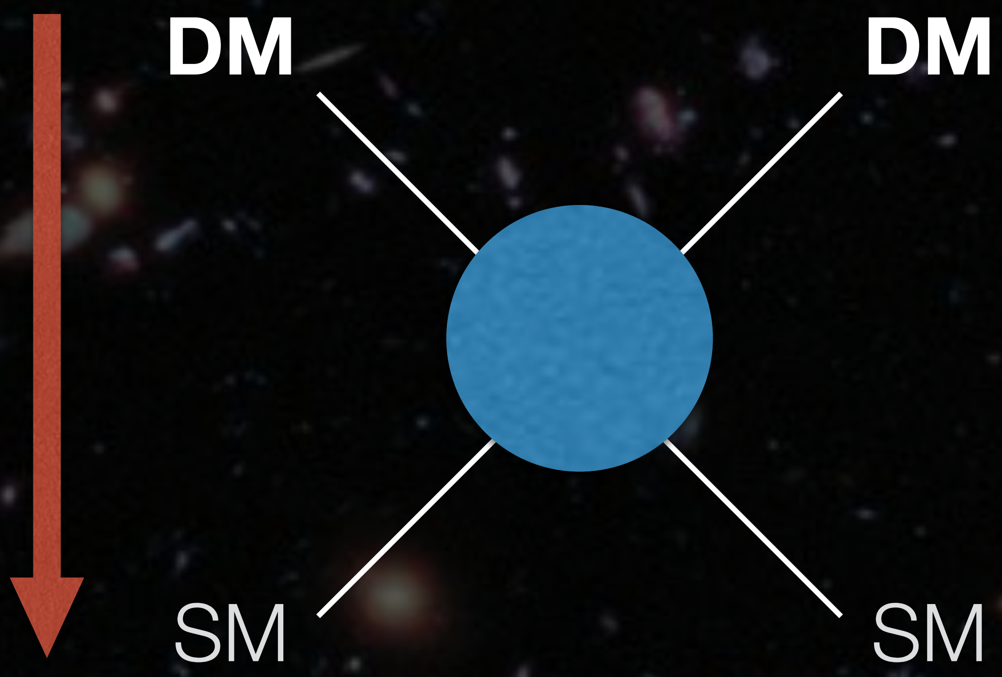

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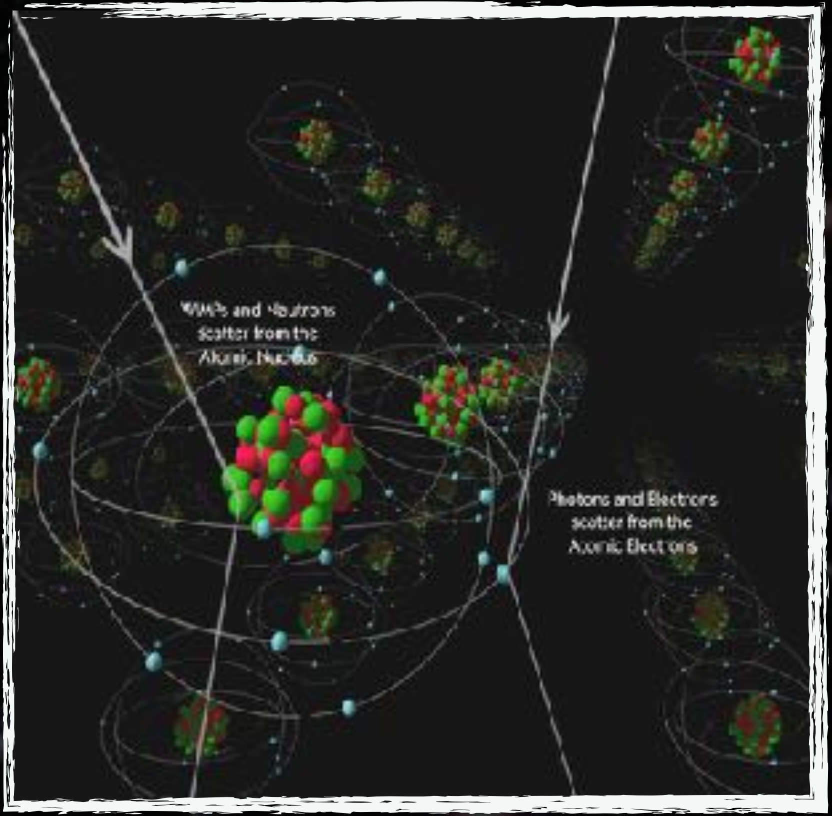

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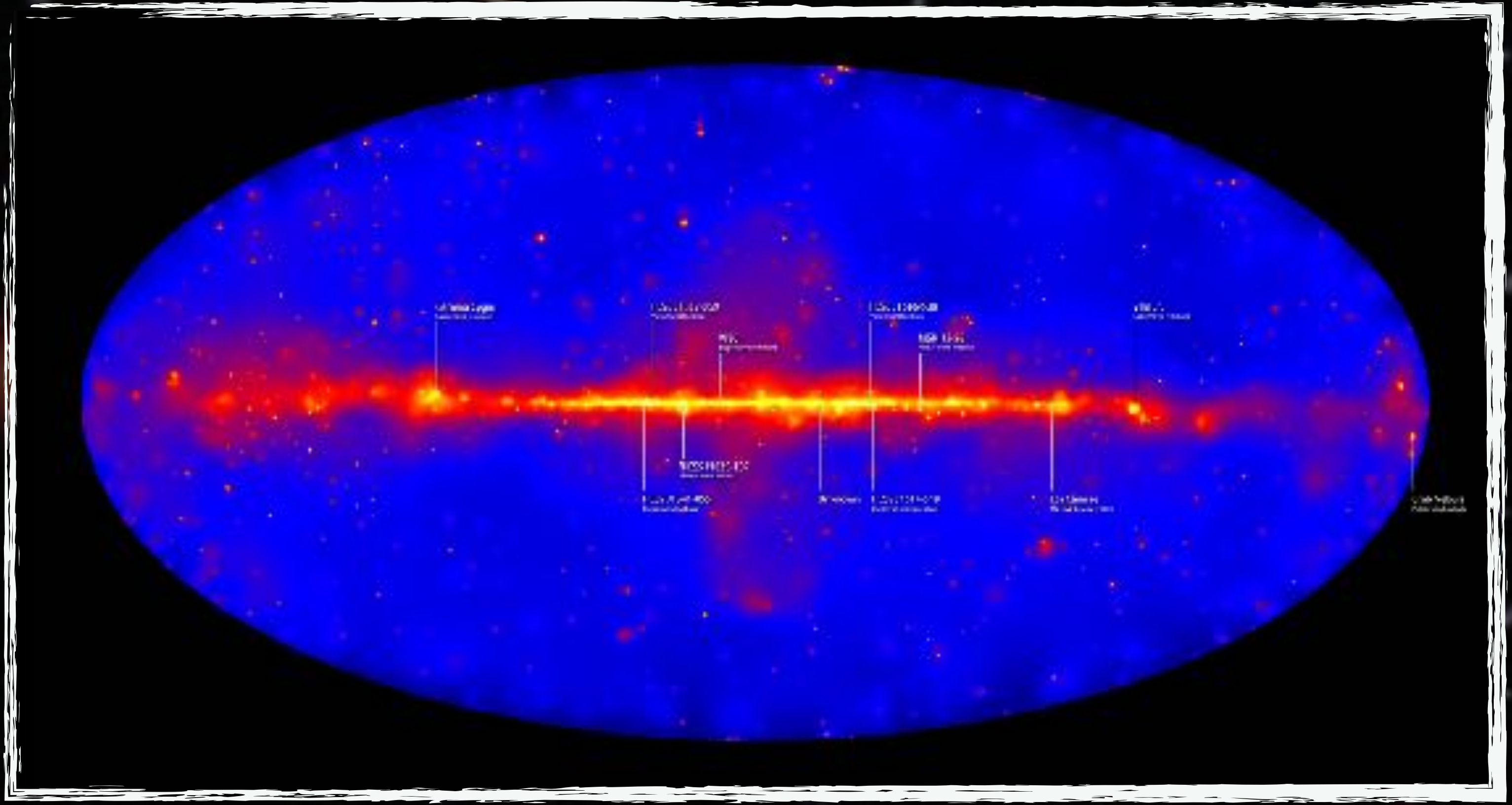

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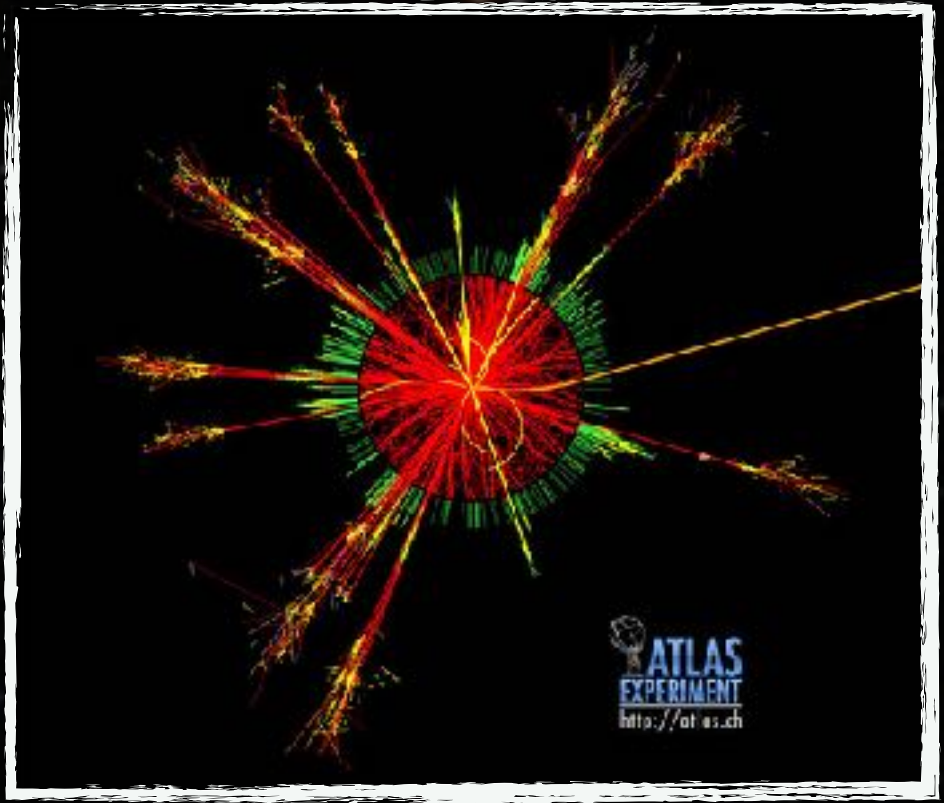

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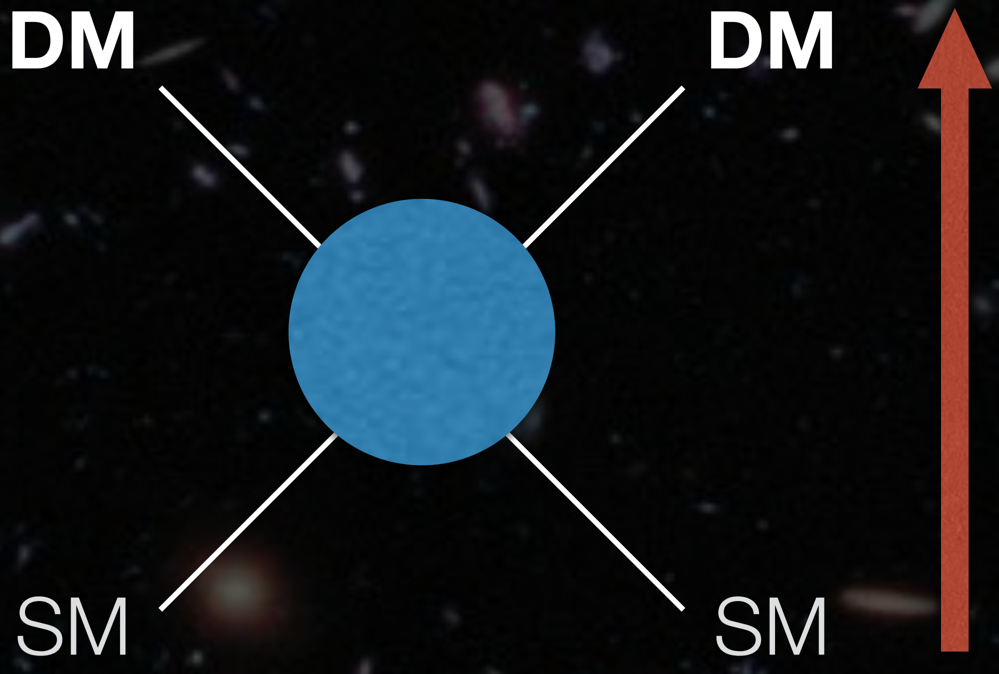
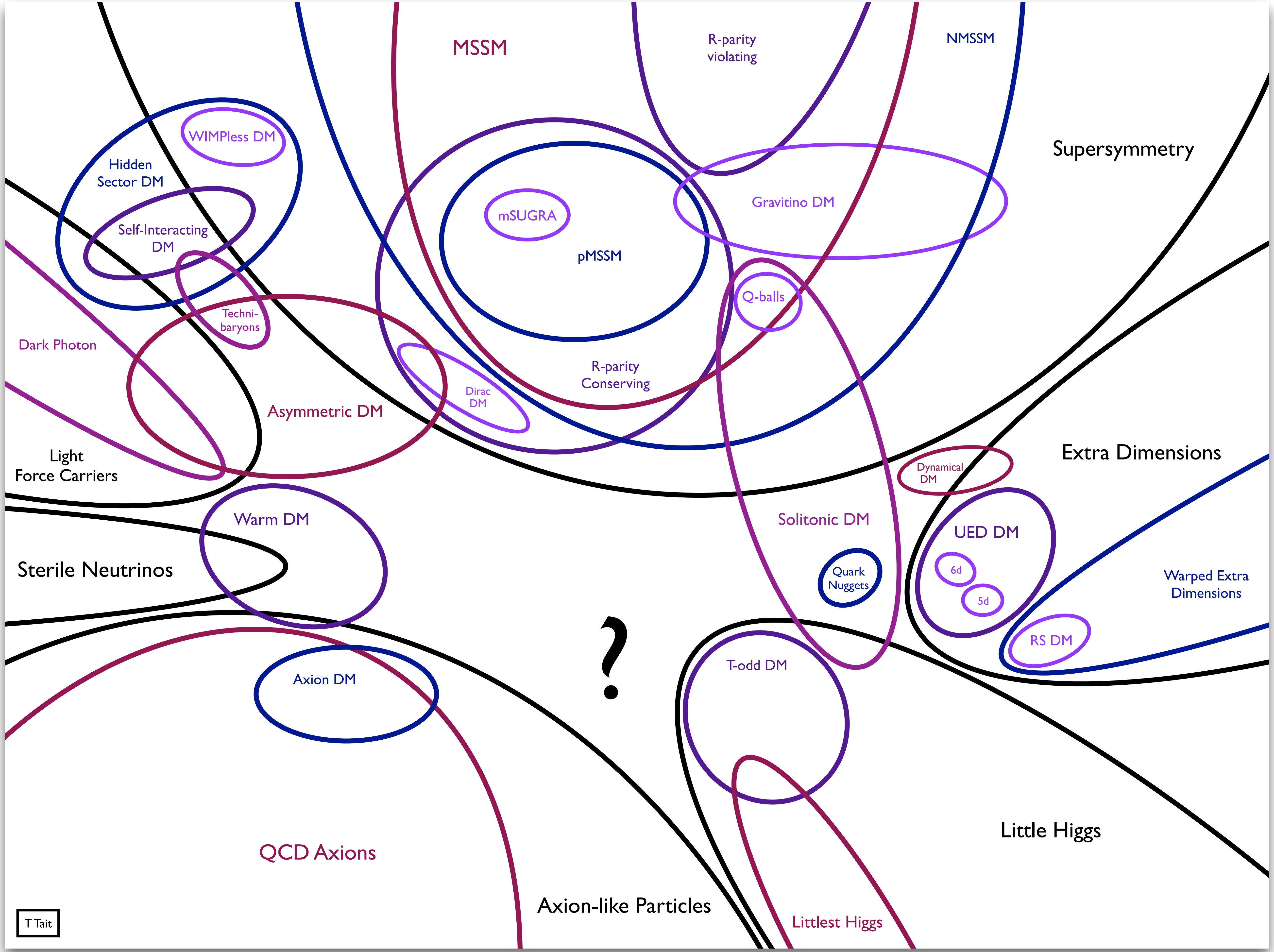


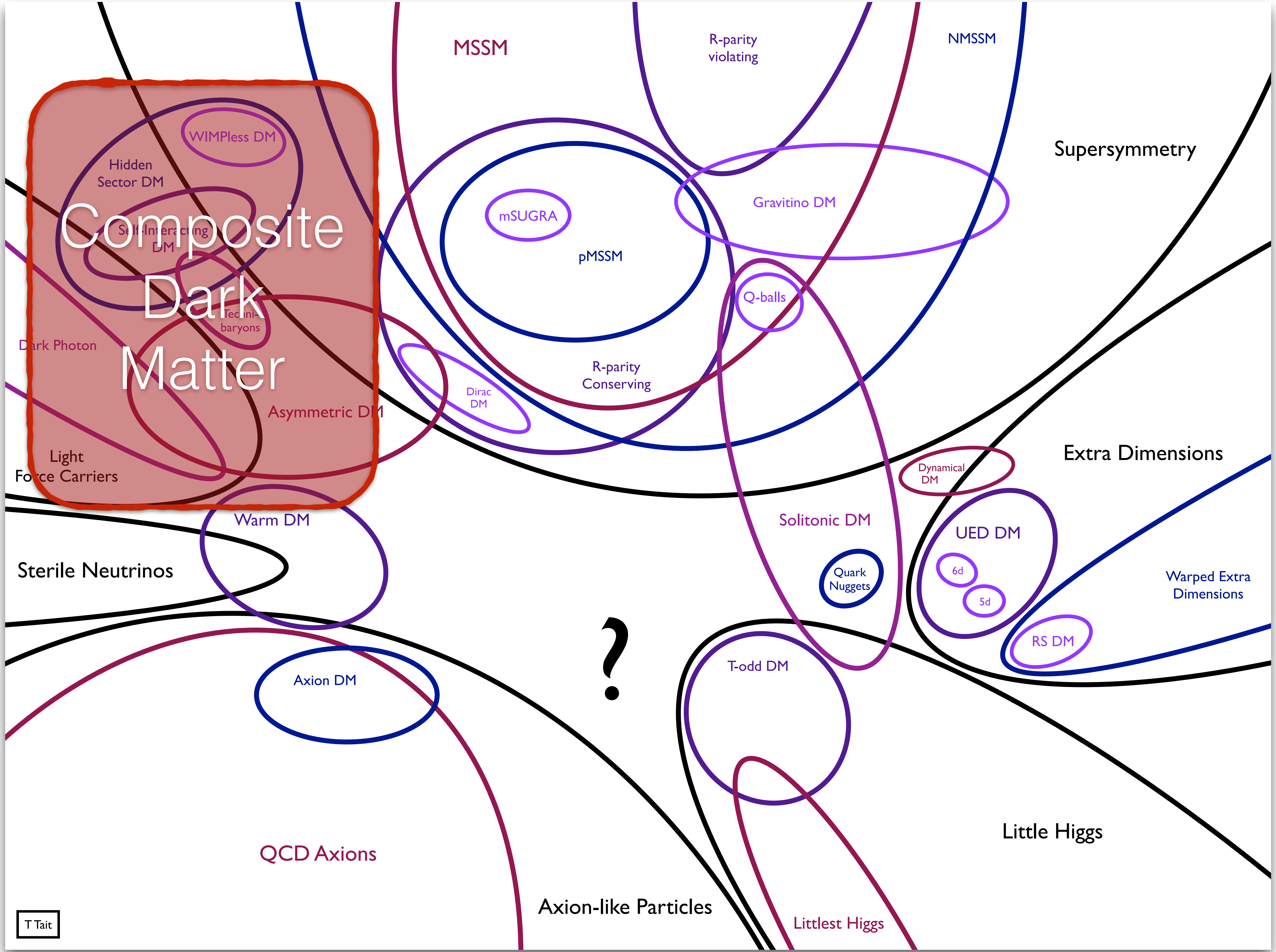
DM **DM**

SM SM

What is Dark Matter?



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



Composite Dark Matter

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

Lattice Strong Dynamics

✓**LLNL** P. Vranas (M. Buchoff, C. Schroeder, E. Berkowitz [Jülich])

✓**ANL** X.-Y. Jin, J. Osborn

✓**BNL** M. Lin, E.R.

✓**RBRC** E. Neil, S. Syritsyn, E.R.

✓**Colorado** A. Hasenfratz, (E. Neil)

✓**Edinburgh** O. Witzel

✓**Bern** D. Schaich

✓**UC Davis** J. Kiskis

✓**Yale** T. Appelquist, G. Fleming, A. Gasbarro

✓**Boston** R. Brower, C. Rebbi, E. Weinberg

✓**Oregon** G. Kribs

Lattice Strong Dynamics

✓**LLNL** P. Vranas (M. Buchoff, C. Schroeder, E. Berkowitz [Jülich])

Strongly-interacting systems for BSM physics

✓**A**

✓**B**

✓**R**

✓**C**

✓**E**

✓**B**

✓**U**

✓**Y**

✓**Boston** R. Brower, C. Rebbi, E. Weinberg

✓**Oregon** G. Kribs

Lattice Strong Dynamics

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- ✓**U**
- ✓**Ya**
- ✓**Boston** R. Brower, C. Rebbi, E. Weinberg
- ✓**Oregon** G. Kribs

Strongly-interacting systems for BSM physics

★ Strongly-coupled Composite Dark Matter

Lattice Strong Dynamics

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Strongly-interacting systems for BSM physics

★ Strongly-coupled Composite Dark Matter

★ Electroweak Symmetry Breaking from strong dynamics

Lattice Strong Dynamics

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Strongly-interacting systems for BSM physics

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Strongly-interacting systems for BSM physics

★ Strongly-coupled Composite Dark Matter

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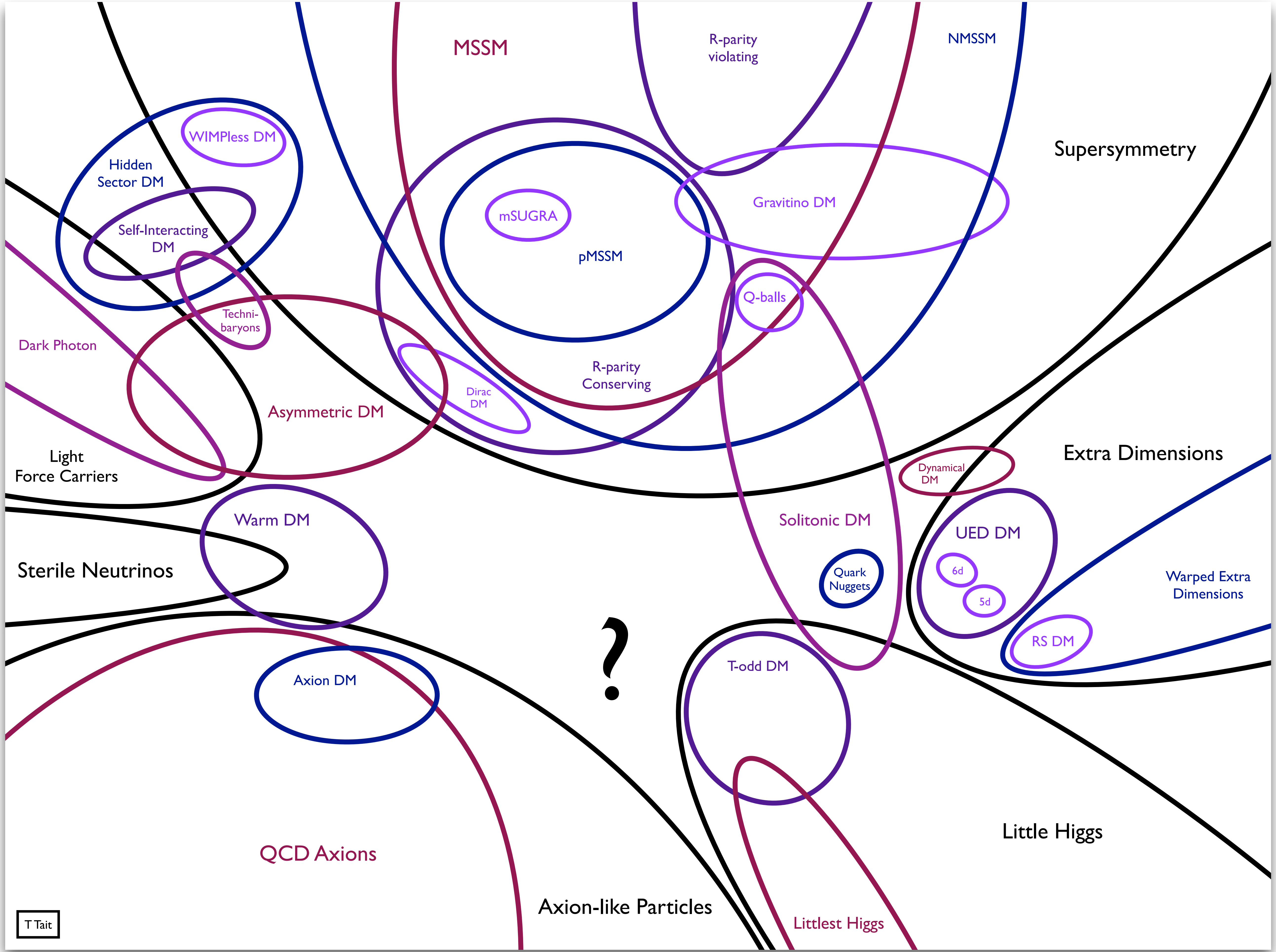
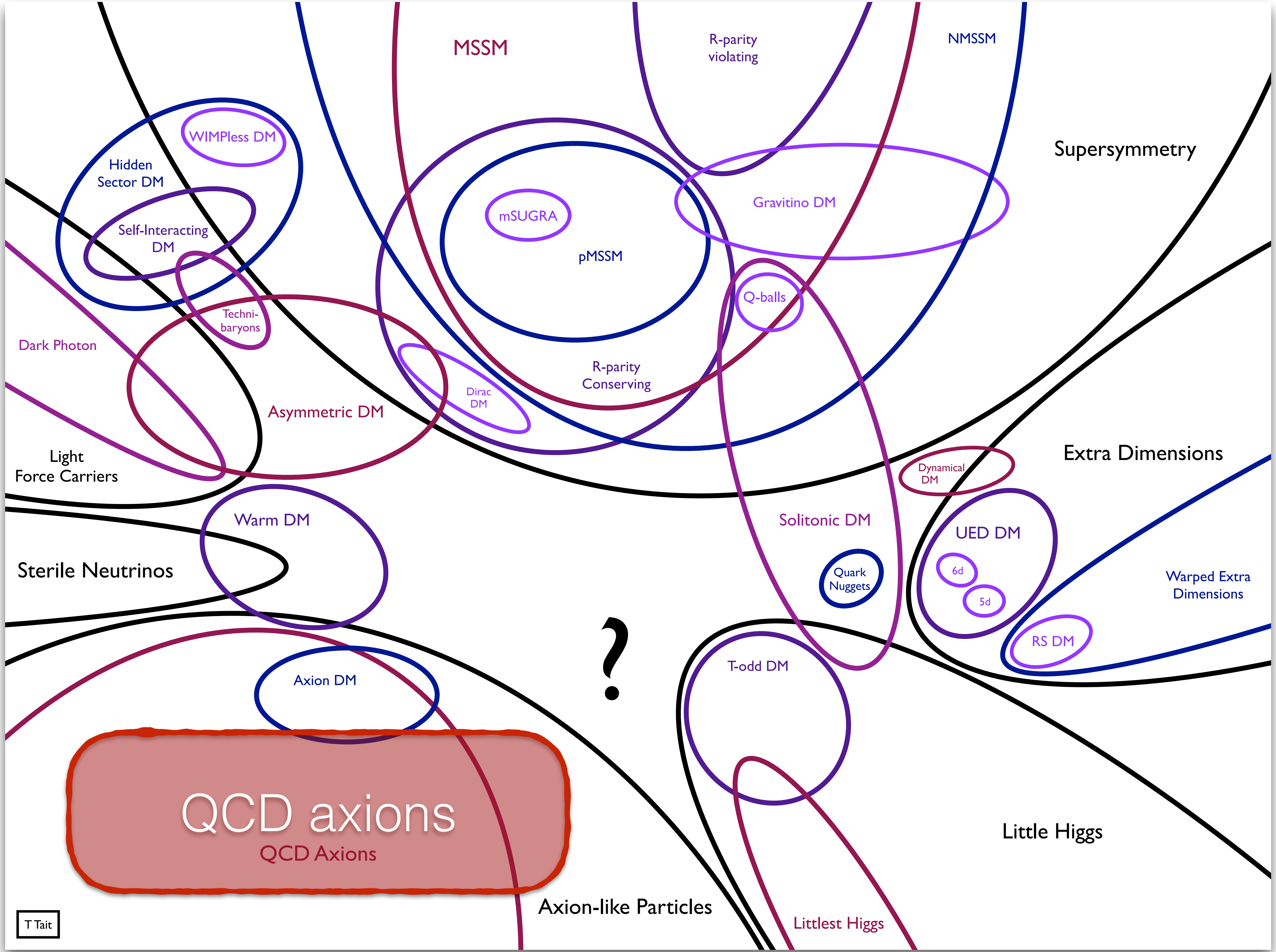
★ Axion cosmology (Buchoff, Berkowitz, ER **PRD 92 (2015) 034507**)

★ Gauge-gravity duality (MCSMC - Berkowitz, ER et al. **PRD (2016)**)

★ Holographic cosmology (LatticeHC - Southamp/Edinb/LLNL)



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



MSSM

R-parity
violating

NMSSM

WIMPless DM

Hidden
Sector DM

Supersymmetry

Self-Interacting
DM

mSUGRA

Gravitino DM

pMSSM

Q-balls

Techni-
baryons

Dark Photon

R-parity
Conserving

Dirac
DM

Asymmetric DM

Light
Force Carriers

Extra Dimensions

Dynamical
DM

Warm DM

Solitonic DM

UED DM

Sterile Neutrinos

Quark
Nuggets

6d

5d

Warped Extra
Dimensions

?

RS DM

Axion DM

T-odd DM

QCD axions

QCD Axions

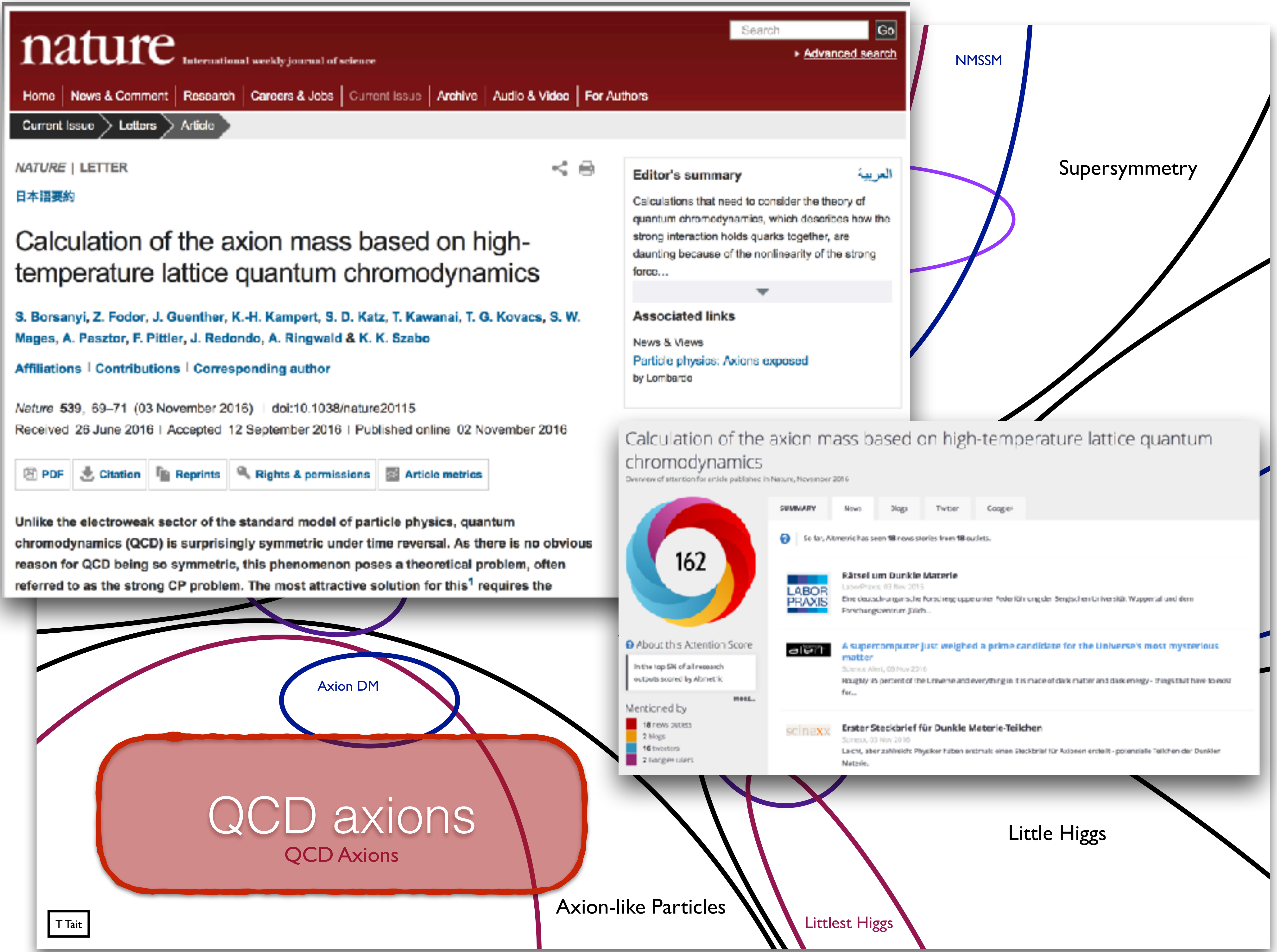
Little Higgs

Axion-like Particles

Littlest Higgs

T Tait

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



NATURE | LETTER

日本語要約

Calculation of the axion mass based on high-temperature lattice quantum chromodynamics

S. Borsanyi, Z. Fodor, J. Guenther, K.-H. Kampert, S. D. Katz, T. Kawanai, T. G. Kovacs, S. W. Mages, A. Pasztor, F. Pittler, J. Redondo, A. Ringwald & K. K. Szabo

Affiliations | Contributions | Corresponding author

Nature **539**, 69–71 (03 November 2016) | doi:10.1038/nature20115
Received 26 June 2016 | Accepted 12 September 2016 | Published online 02 November 2016

Unlike the electroweak sector of the standard model of particle physics, quantum chromodynamics (QCD) is surprisingly symmetric under time reversal. As there is no obvious reason for QCD being so symmetric, this phenomenon poses a theoretical problem, often referred to as the strong CP problem. The most attractive solution for this[1] requires the

Editor's summary العربية

Calculations that need to consider the theory of quantum chromodynamics, which describes how the strong interaction holds quarks together, are daunting because of the nonlinearity of the strong force…

Associated links

News & Views

Particle physics: Axions exposed

by Lombardo

Calculation of the axion mass based on high-temperature lattice quantum chromodynamics

Overview of attention for article published in Nature, November 2016

So far, Altmetric has seen **18** news stories from **18** outlets.

Rätsel um Dunkle Materie

A supercomputer just weighed a prime candidate for the Universe's most mysterious matter

Science Alert, 03 Nov 2016

Erster Steckbrief für Dunkle Materie-Teilchen

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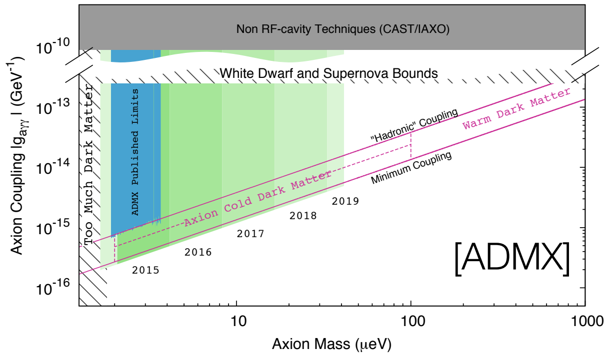
🟧 2 blogs
🟦 16 tweeters
🟪 2 Google+ users

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

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

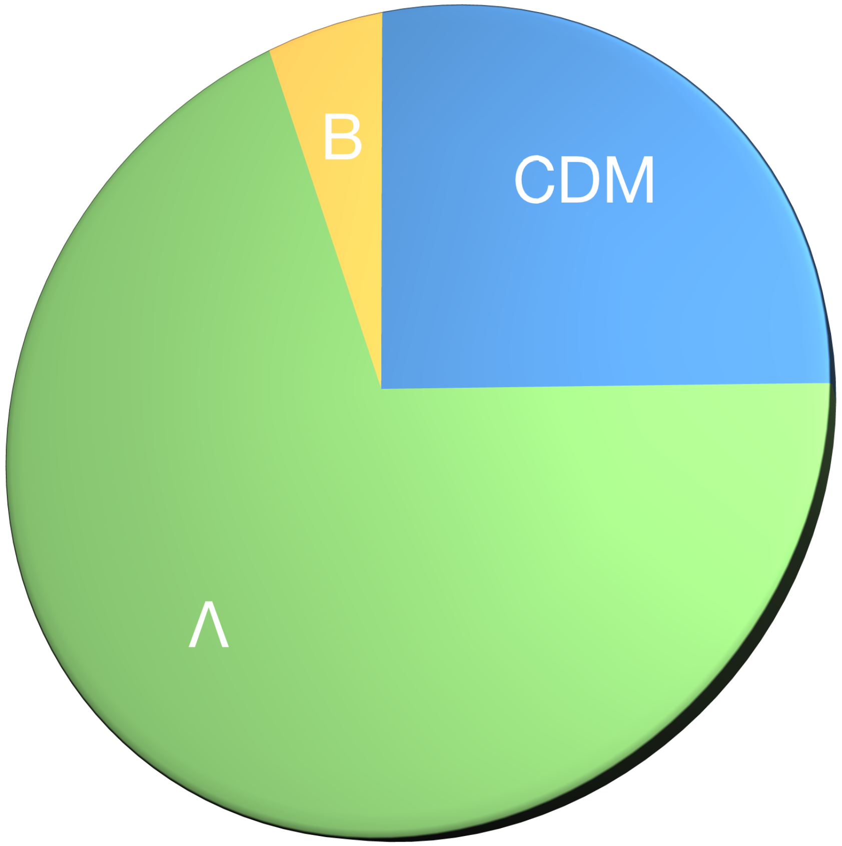
[Preskill, Wise & Wilczek, Phys. Lett. B **120** (1983) 127-132]

Axion Dark Matter



[ADMX]

- 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

[ER, talk at KITP-LatticeQCD15: http://online.kitp.ucsb.edu/online/latticeqcd15/rinaldi/]

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

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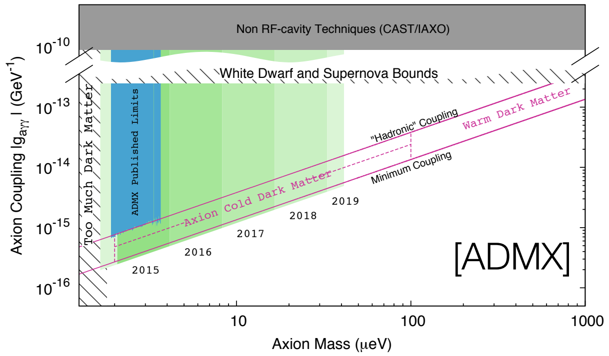

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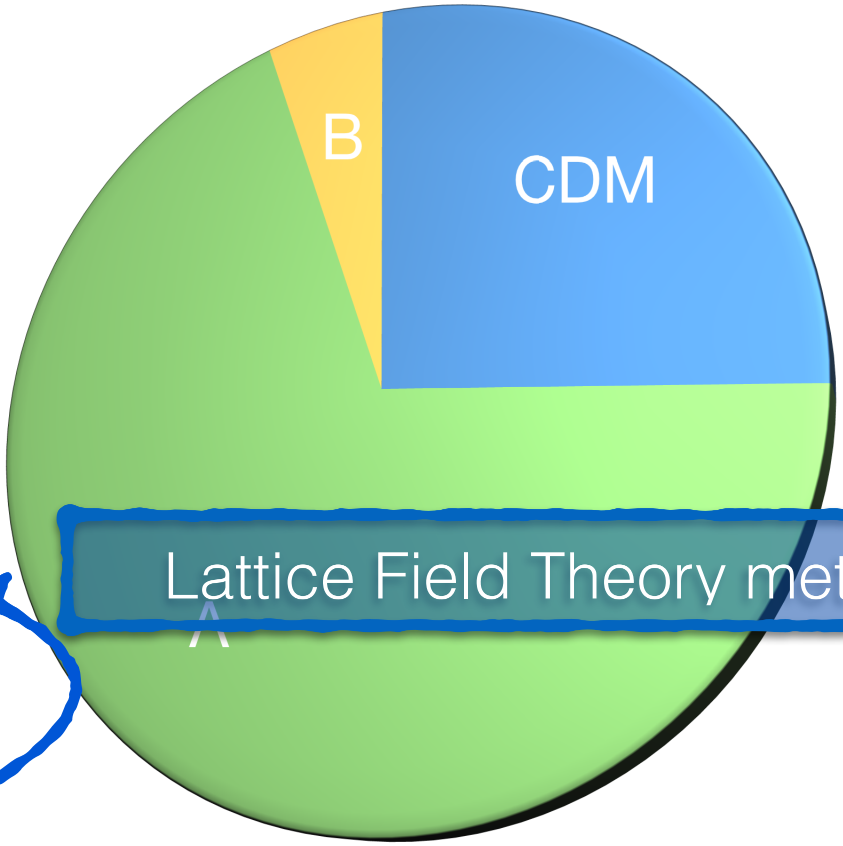


Lattice Field Theory methods

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

[ER, talk at KITP-LatticeQCD15: http://online.kitp.ucsb.edu/online/latticeqcd15/rinaldi/]

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

Constraints from lattice simulations

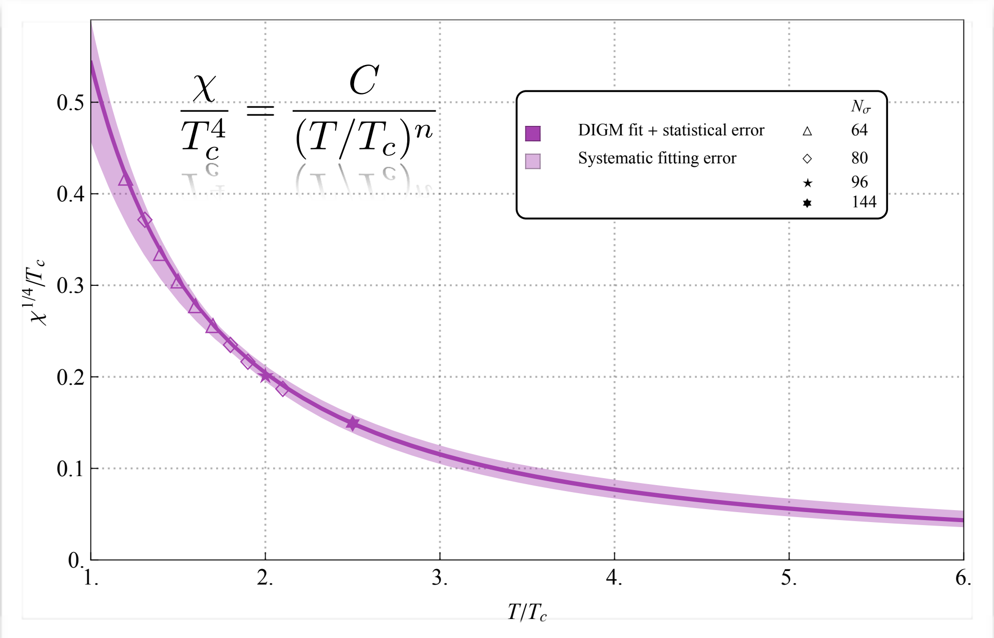
Non-perturbative calculation of QCD topology at finite temperature

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

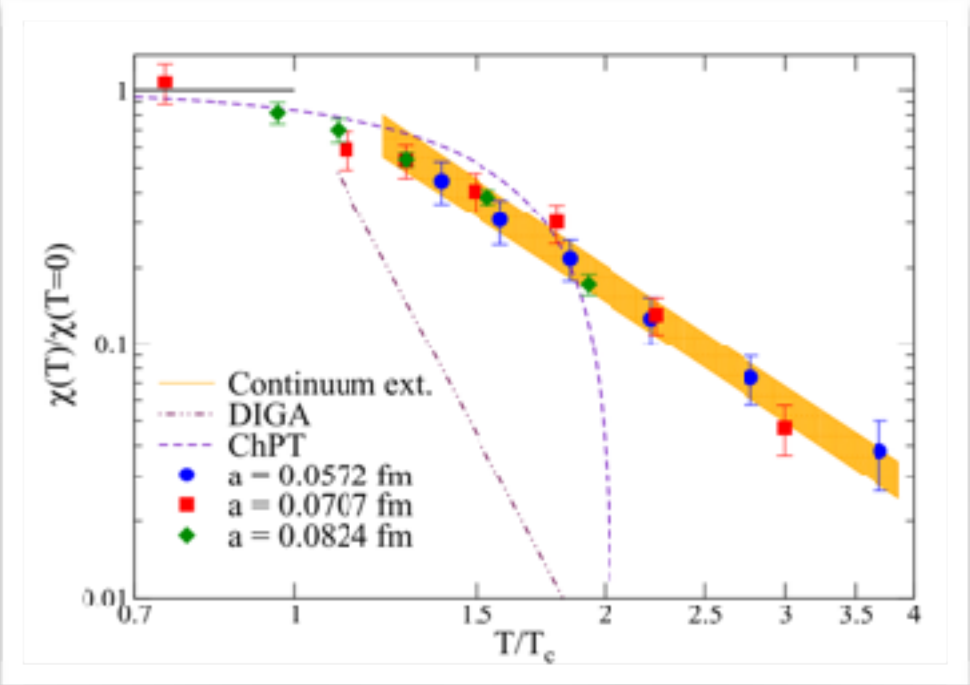
[Kitano&Yamada, 1506.00370][Borsanyi et al., 1508.06917][Frison et al.,1606.07175]

- 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]



[Berkowitz, Buchoff, ER., 1505.07455]



[Bonati et al., 1512.06746]

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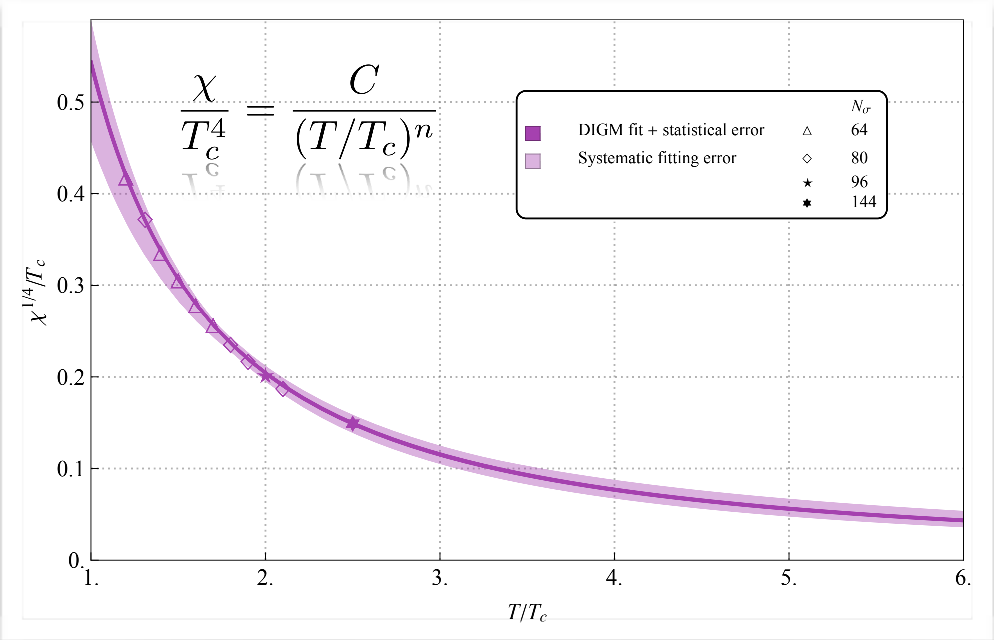
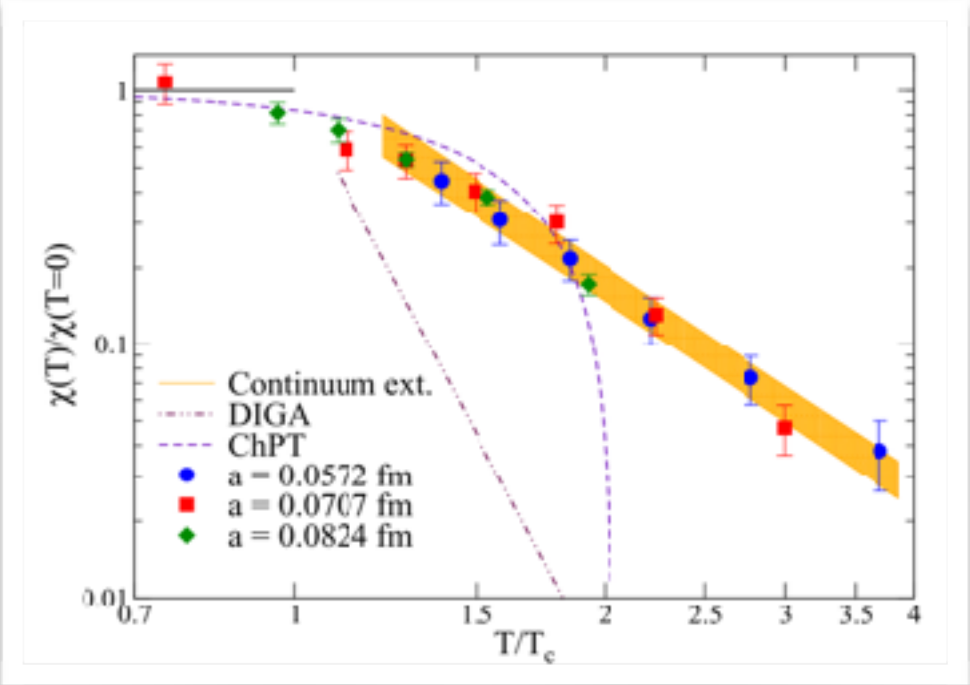
Great effort to control all systematic lattice effects in order to impact experiments.
This direction has started only 1 year ago!



[Berkowitz, Buchoff, ER., 1505.07455]



[Bonati et al., 1512.06746]

[Berkowitz, Buchoff, ER., 1505.07455]

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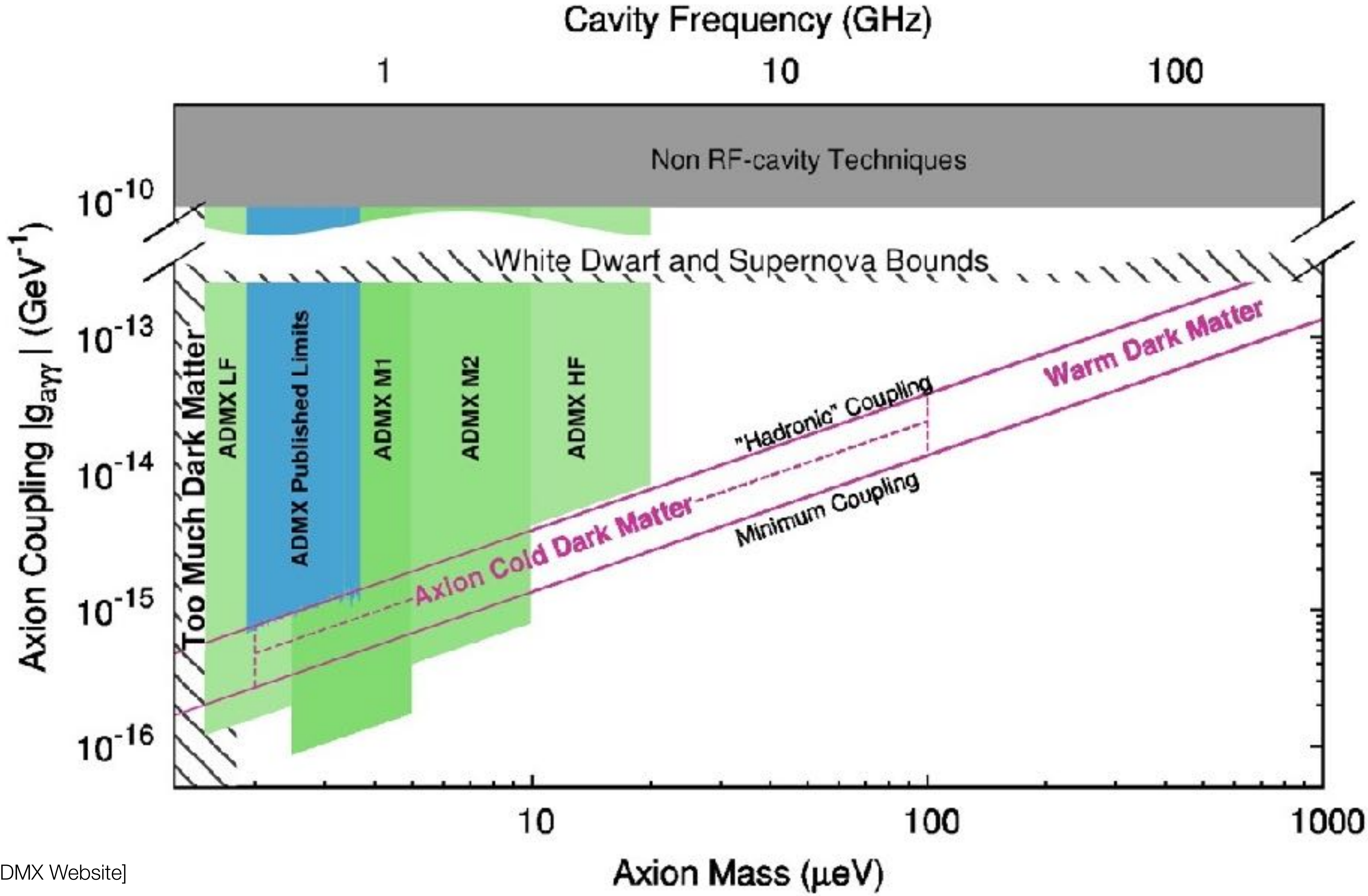
Axion mass lower bound



[ADMX Website]

[Berkowitz, Buchoff, ER., 1505.07455]

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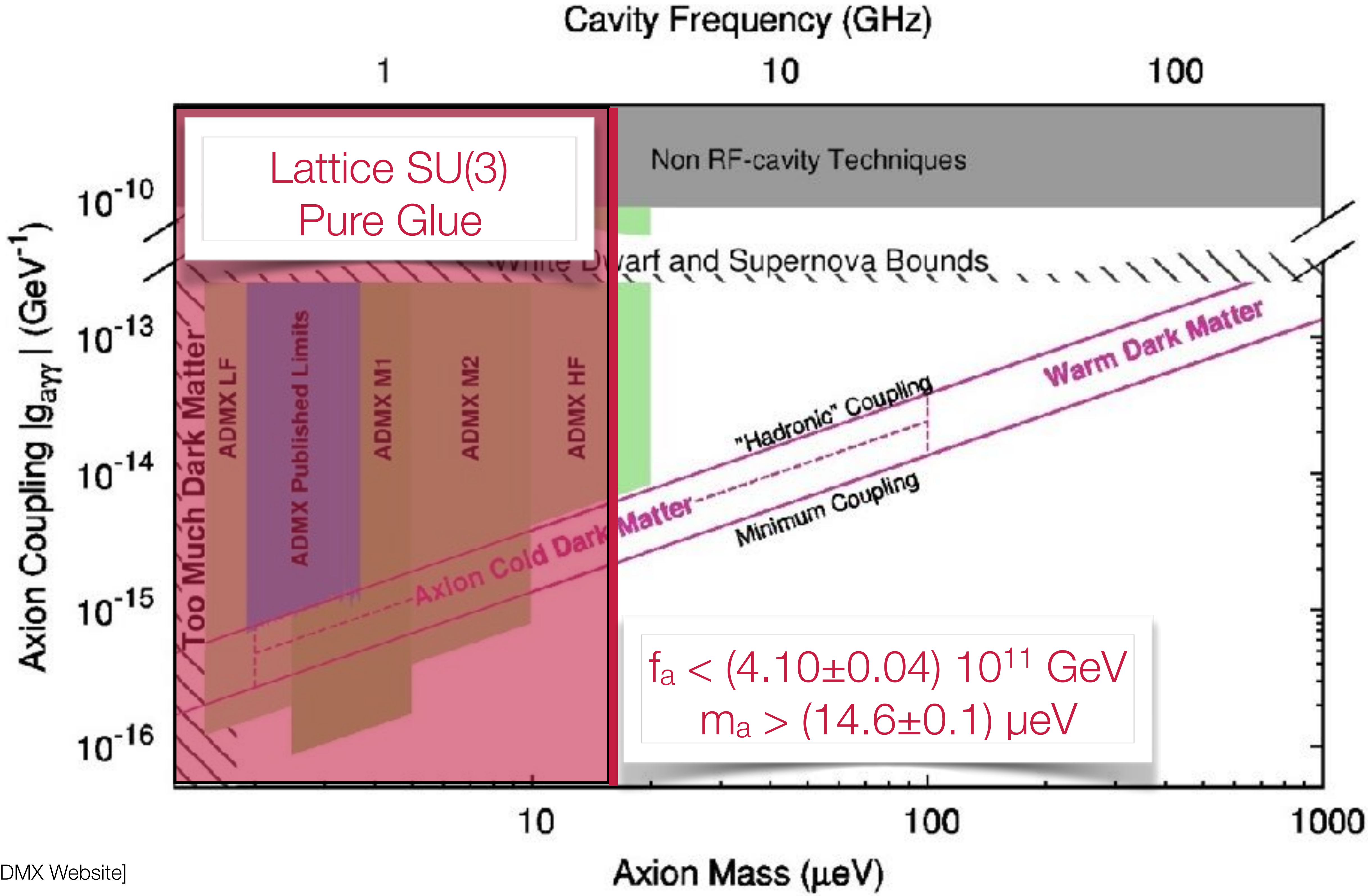


Lattice SU(3)
Pure Glue

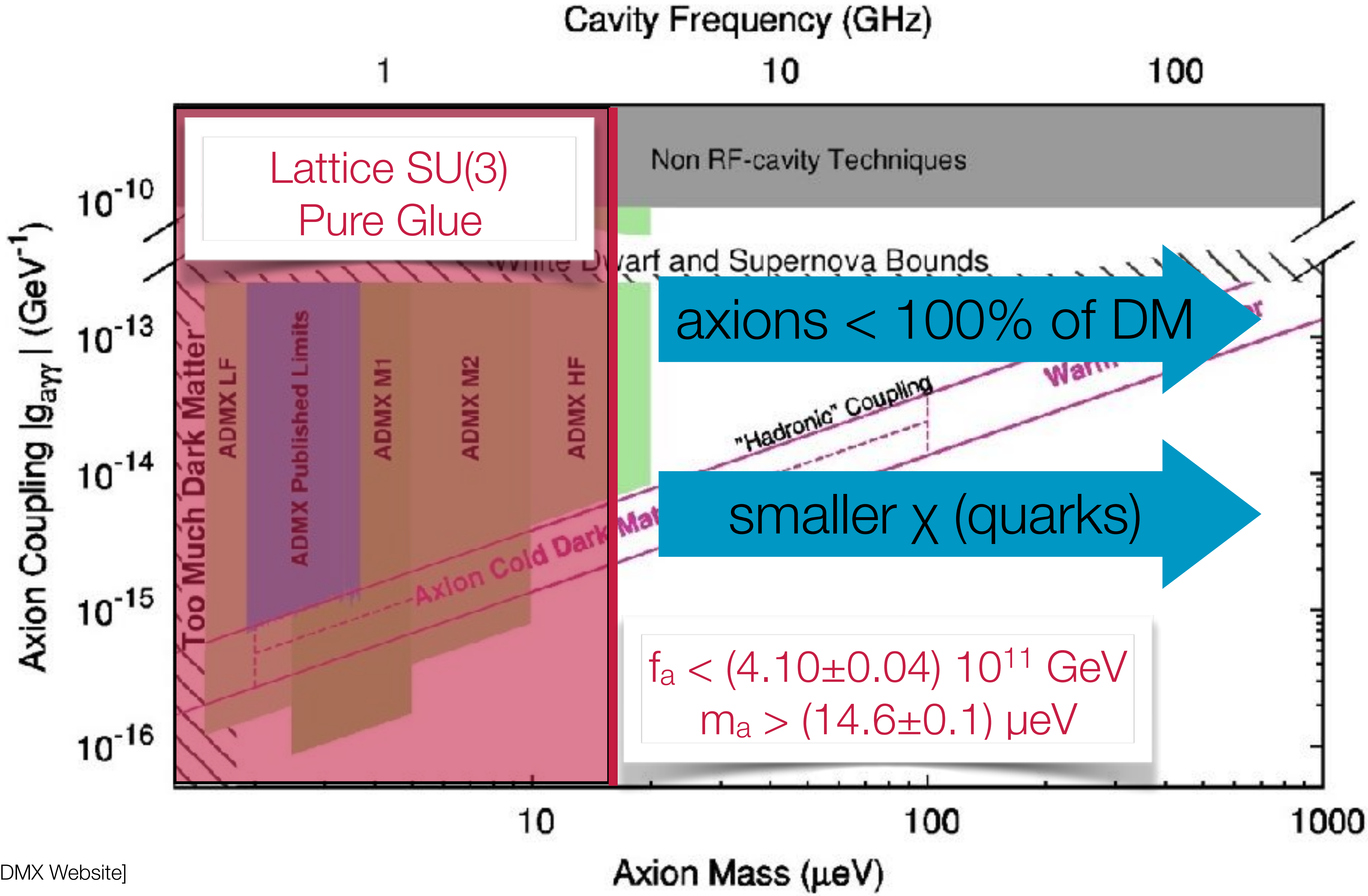
$f_a < (4.10 \pm 0.04)\ 10^{11}$ GeV
$m_a > (14.6 \pm 0.1)\ \mu$eV

[ADMX Website]

[Berkowitz, Buchoff, ER., 1505.07455]

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

Axion mass lower bound



Lattice SU(3)
Pure Glue

axions < 100% of DM

smaller χ (quarks)

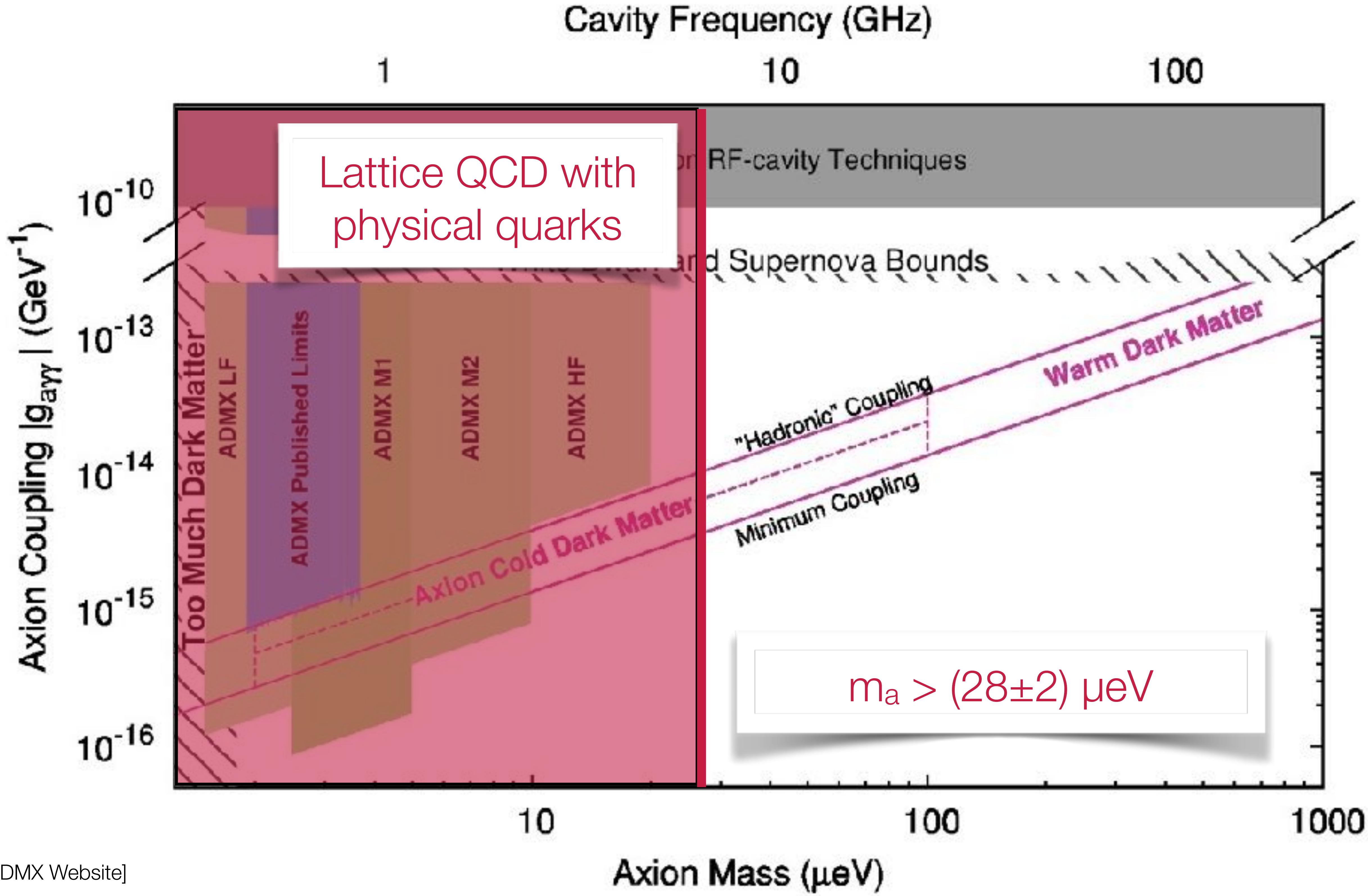
$f_a < (4.10 \pm 0.04)\ 10^{11}$ GeV
$m_a > (14.6 \pm 0.1)$ μeV

[ADMX Website]

[Borsanyi et al., 1606.07494, Nature]

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

Axion mass lower bound



Lattice QCD with physical quarks

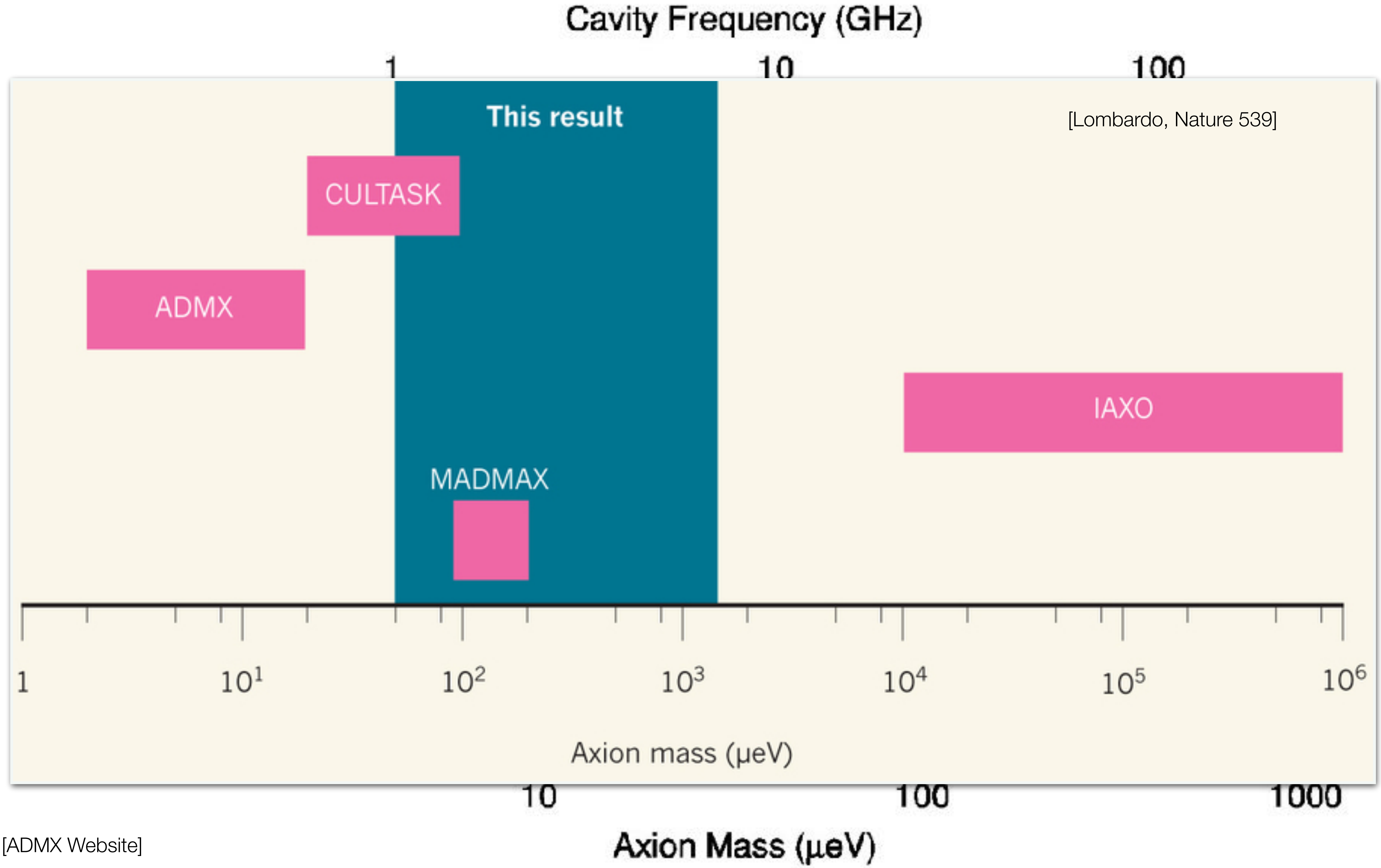
$m_a > (28\pm2)$ μeV

[ADMX Website]

[Borsanyi et al., 1606.07494, Nature]

Axion mass lower bound

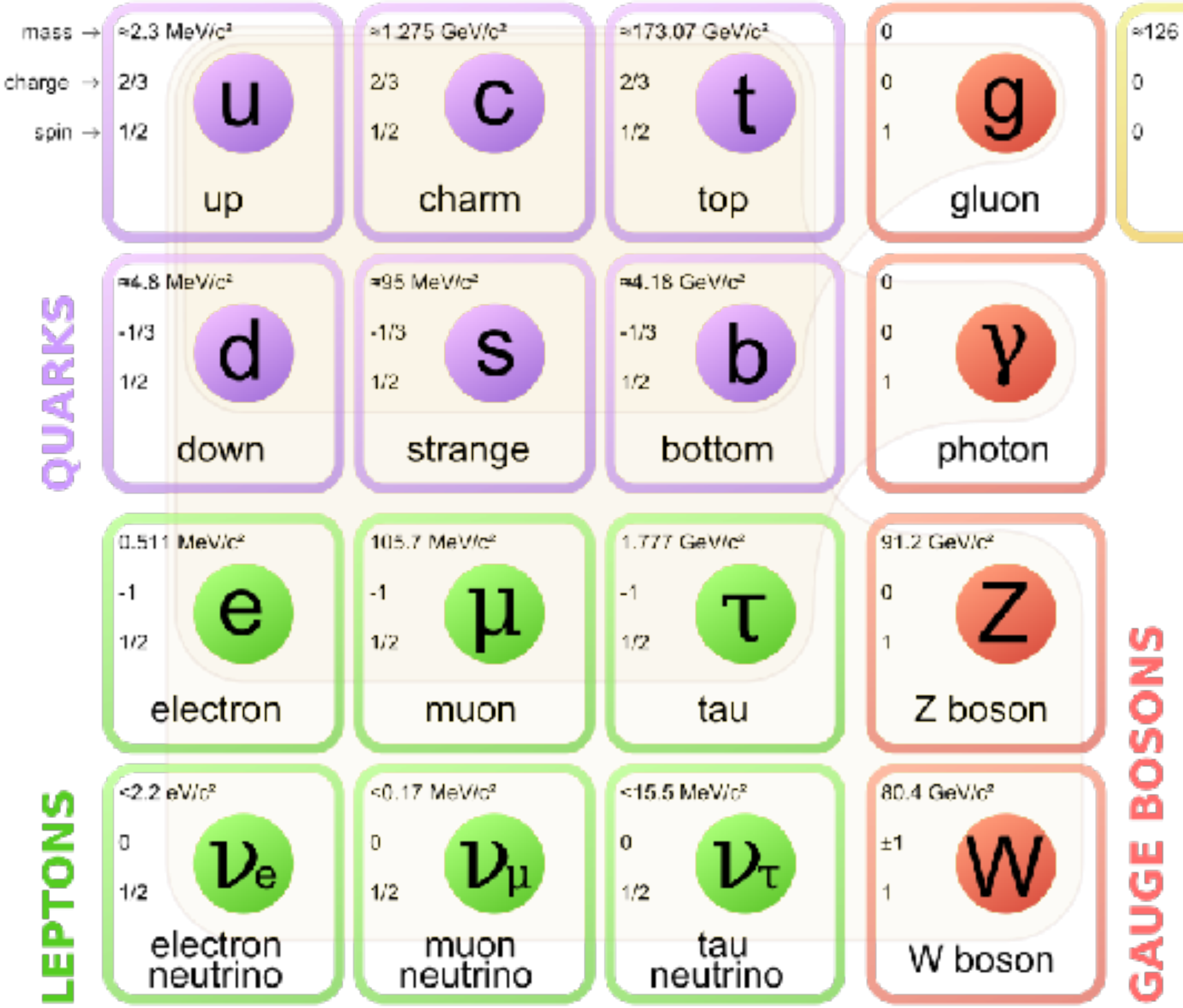
$$m_a^2 f_a^2 = \left.\frac{\partial^2 F}{\partial \theta^2}\right|_{\theta=0}$$



[ADMX Website]

A very familiar picture

The Standard Model of particles



[Wikipedia]

A very familiar picture

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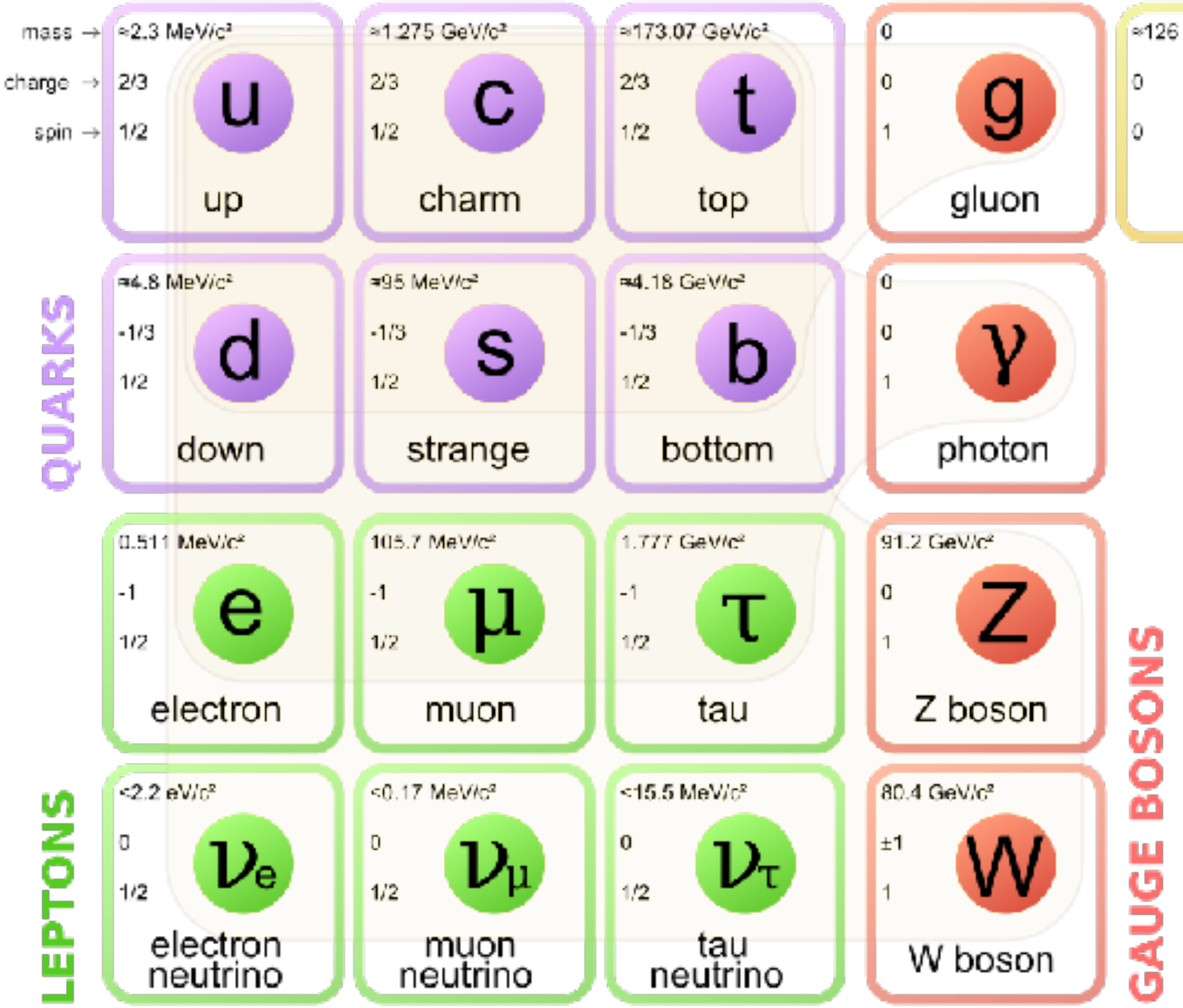
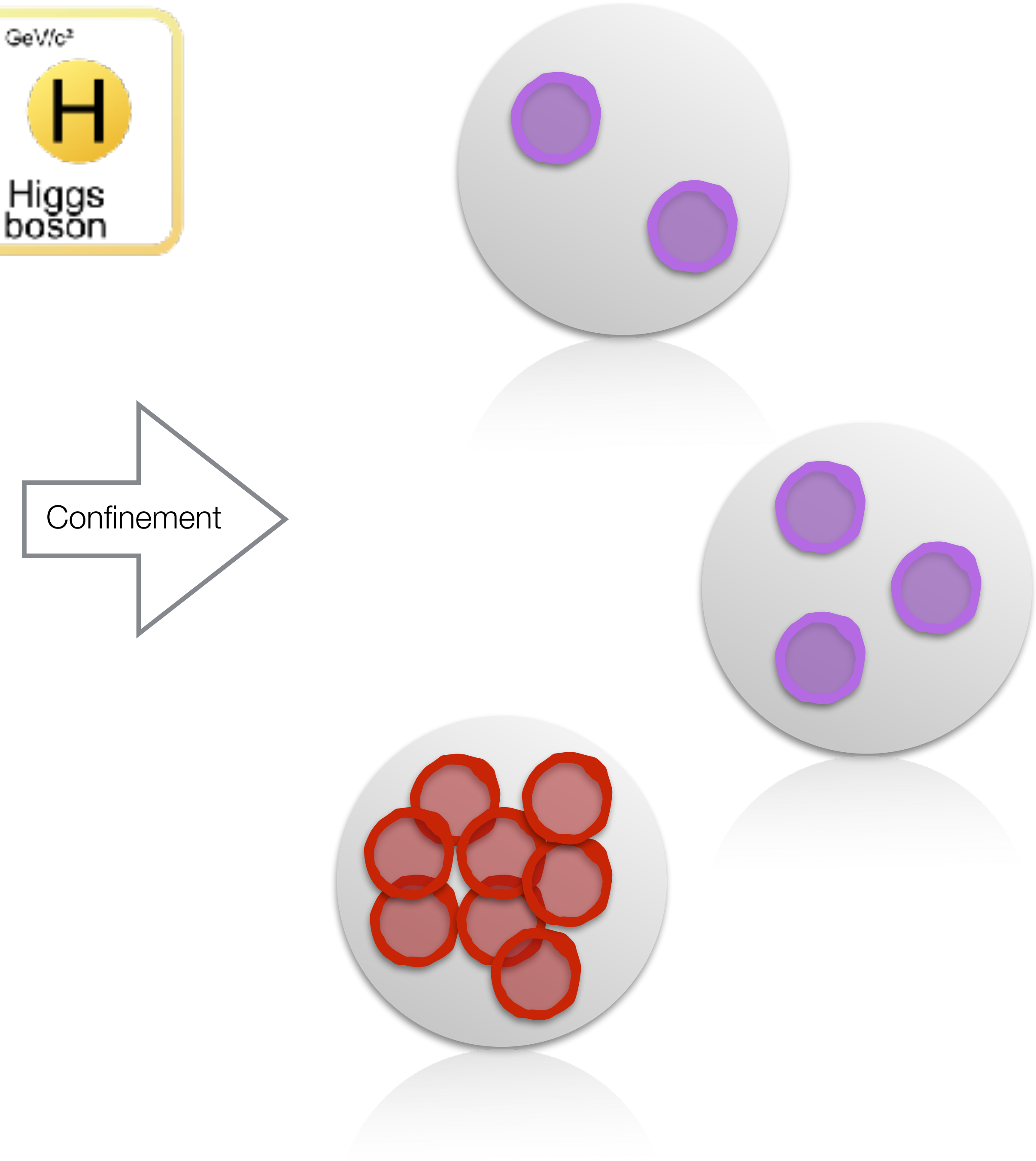


mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson	GAUGE BOSONS
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson	

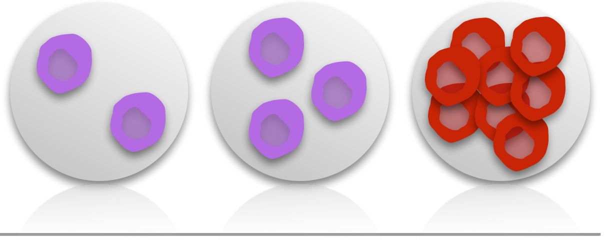
[Wikipedia]

Mesons, Baryons and Glueballs



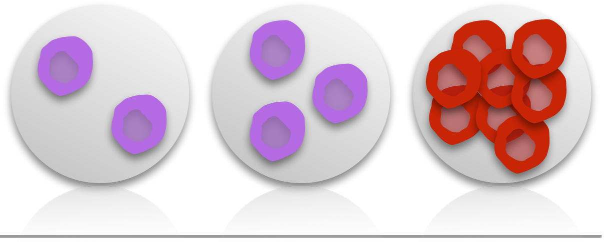
Composite Dark Matter

Composite Dark Matter



- Dark Matter is a composite object

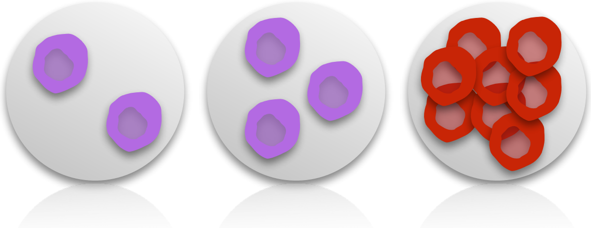
Composite Dark Matter



- Dark Matter is a composite object

e.g. technibaryon or
hidden glueball

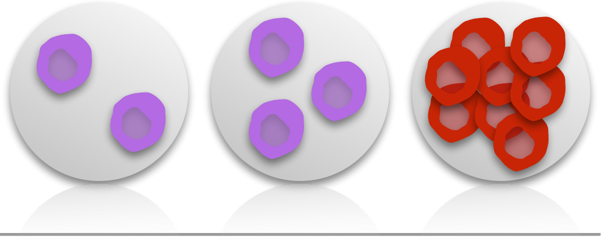
Composite Dark Matter



e.g. technibaryon or hidden glueball

- Dark Matter is a composite object
- Interesting and complicated internal structure
- Properties dictated by strong dynamics
- Self-interactions are natural

Composite Dark Matter



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Similar to QCD

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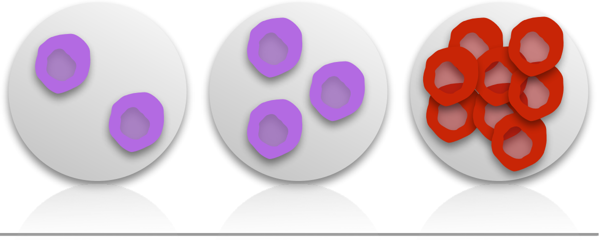

- Dark Matter is a composite object

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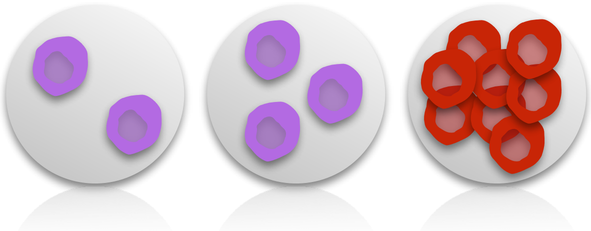
- Composite object is neutral
- Constituents may interact with Standard Model particles

Composite Dark Matter



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Similar to QCD

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Chance to observe them in experiments and give the correct relic abundance

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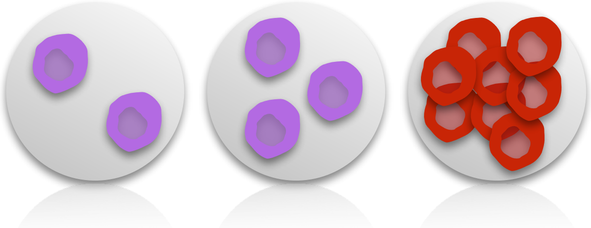
Composite Dark Matter



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e.g. technibaryon or hidden glueball

- ✦ Interesting and complicated internal structure

Lattice Field Theory methods

- ✦ Properties dictated by strong dynamics

Similar to QCD

- ✦ Self-interactions are natural

Chance to observe them in experiments and give the correct relic abundance

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[review by Kribs & Neil, 1604.04627]

Natural features of Composite Dark Matter

[review by Kribs & Neil, 1604.04627]

Natural features of Composite Dark Matter

Stability is a direct consequence of accidental **symmetries**

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Neutrality follows naturally from **confinement** into singlet objects wrt. SM charges

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Small **interactions** with SM particles arise from form factor **suppression** (higher dim. operators)

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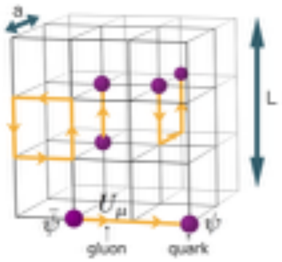
Neutrality follows naturally from **confinement** into singlet objects wrt. SM charges

Small **interactions** with SM particles arise from form factor **suppression** (higher dim. operators)

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

Importance of lattice field theory simulations



[KEK-Japan]

- *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]

[review by Kribs & Neil, 1604.04627]

Models for Composite Dark Matter

- ★ Pion-like (dark quark-antiquark)
  - ✦ pNGB DM *[Hietanen et al., 1308.4130]*
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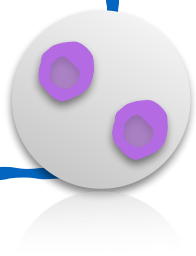

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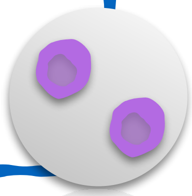

- Baryon-like (multiple quarks)
  - “Technibaryons” *[LSD,1301.1693]*
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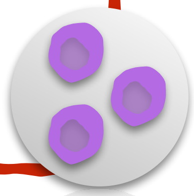

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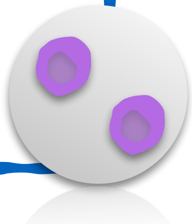
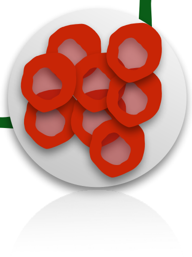


★ Glueball-like (only gluons)

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



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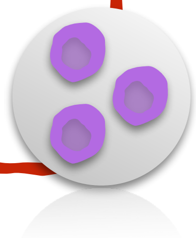

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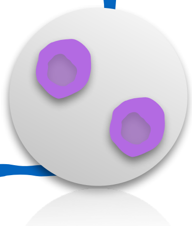

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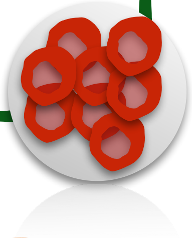
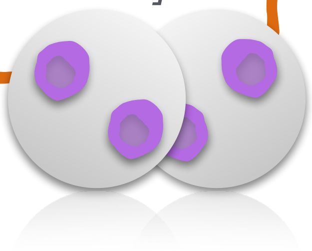


★ Dark Nuclei *[Detmold et al., 1406.2276-1406.4116]*



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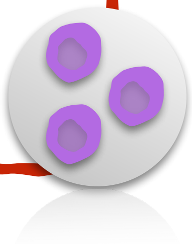

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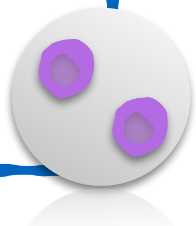

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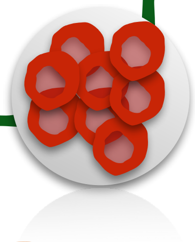

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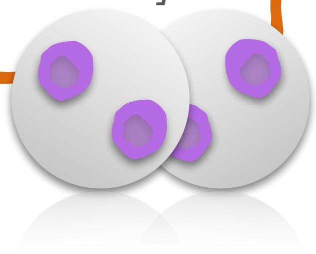

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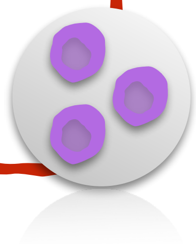

★ Atoms, Molecules *[Cline et al.,1312.3325]*

[Bagnasco et al., hep-ph/9310290]
[Antipin et al., 1503.08749]

The darkness of Composite Dark Matter

[Wikipedia]

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Relevant if the constituents have SM color charges

[Chivukula et al.,hep-ph/9210274] [Godbole et al.,1506.01408] [Bay&Osborne,1506.07110]

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★ magnetic dipole (5)
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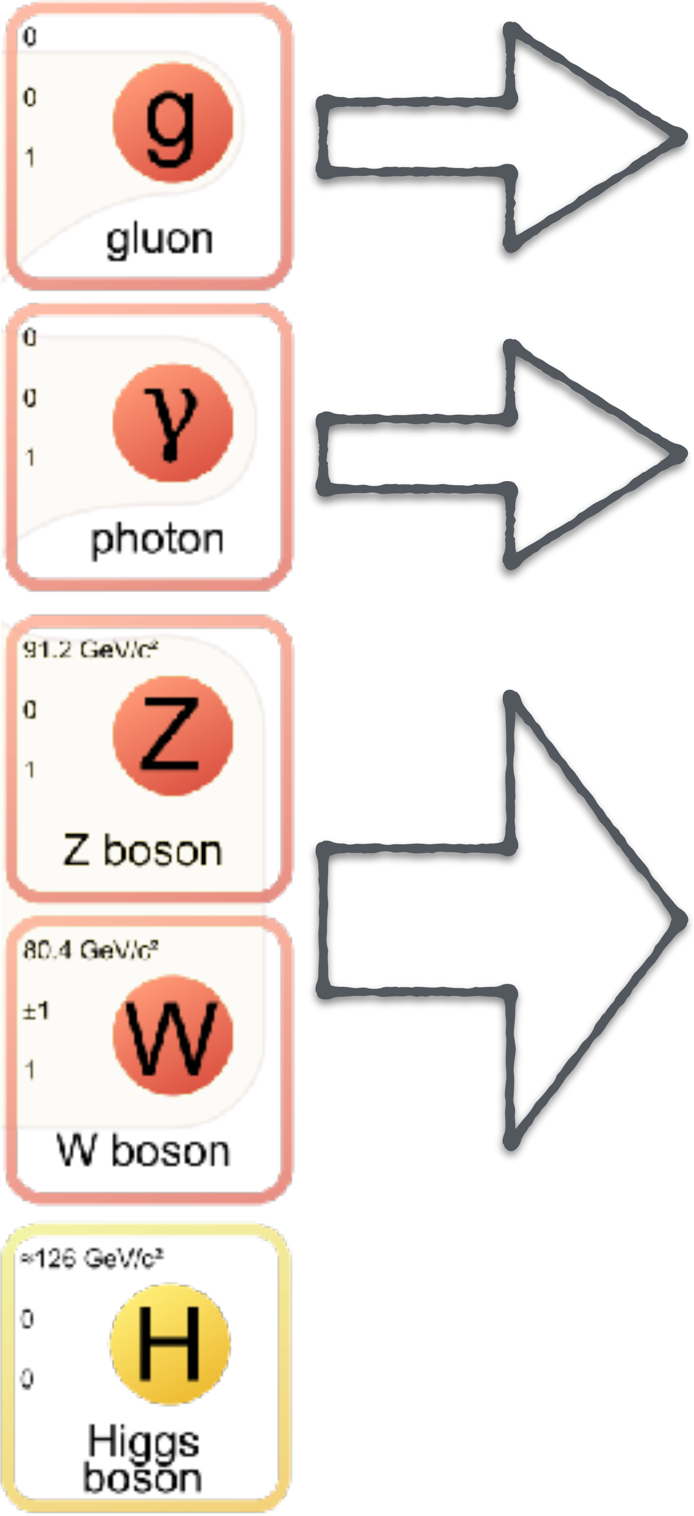

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[references in Kribs & Neil, 1604.04627]

★ lattice
☆ estimate
🟥 forbidden

Lattice results for Composite Dark Matter

Template Models	Spectrum	Higgs	Mag. Dip.	Charge r.	Polariz.
SU(2) N_f=1	★				
SU(2) N_f=2	★	☆		☆	★
SU(3) N_f=2,6	★		★	★	
SU(3) N_f=8	★	☆			
SU(3) N_f=2 (S)	★				
SU(4) N_f=4	★	★			★
SO(4) N_f=2 (V)	★				
SU(N) N_f=0	★				

[references in Kribs & Neil, 1604.04627]

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☆ estimate

🟥 forbidden

Lattice results for Composite Dark Matter

Template Models	Spectrum	Higgs	Mag. Dip.	Charge r.	Polariz.
SU(2) N_f=1	★				
SU(2) N_f=2	★	☆	🟥 forbidden in pNGB DM	☆	★
SU(3) N_f=2,6	★		★	★	
SU(3) N_f=8	★	☆			
SU(3) N_f=2 (S)	★				
SU(4) N_f=4	★	★	🟥	🟥	★
SO(4) N_f=2 (V)	★				
SU(N) N_f=0	★	🟥	🟥	🟥	🟥

forbidden in Stealth DM

forbidden in SUNonia

[references in Kribs & Neil, 1604.04627]

★ lattice
⭐ estimate
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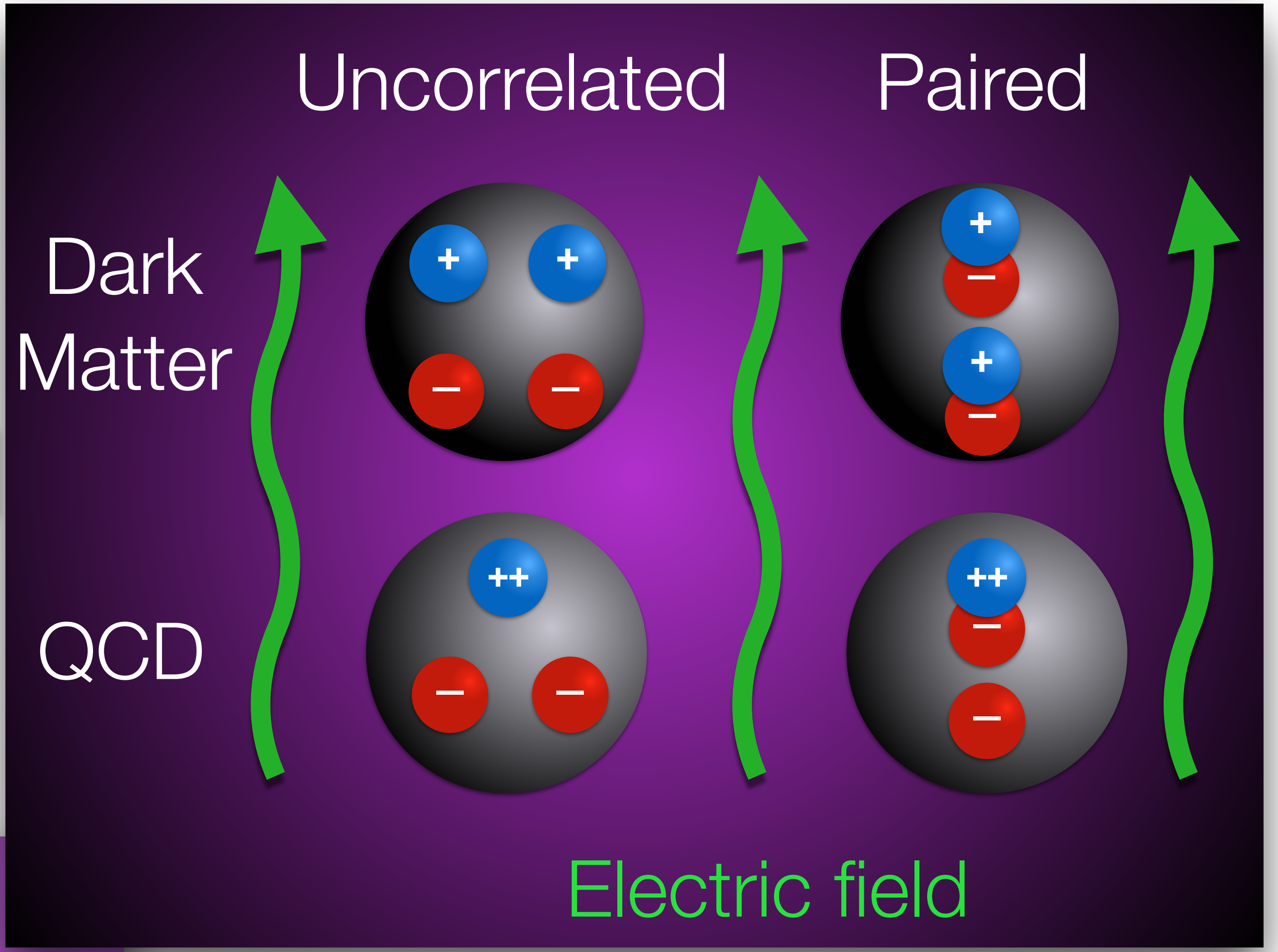
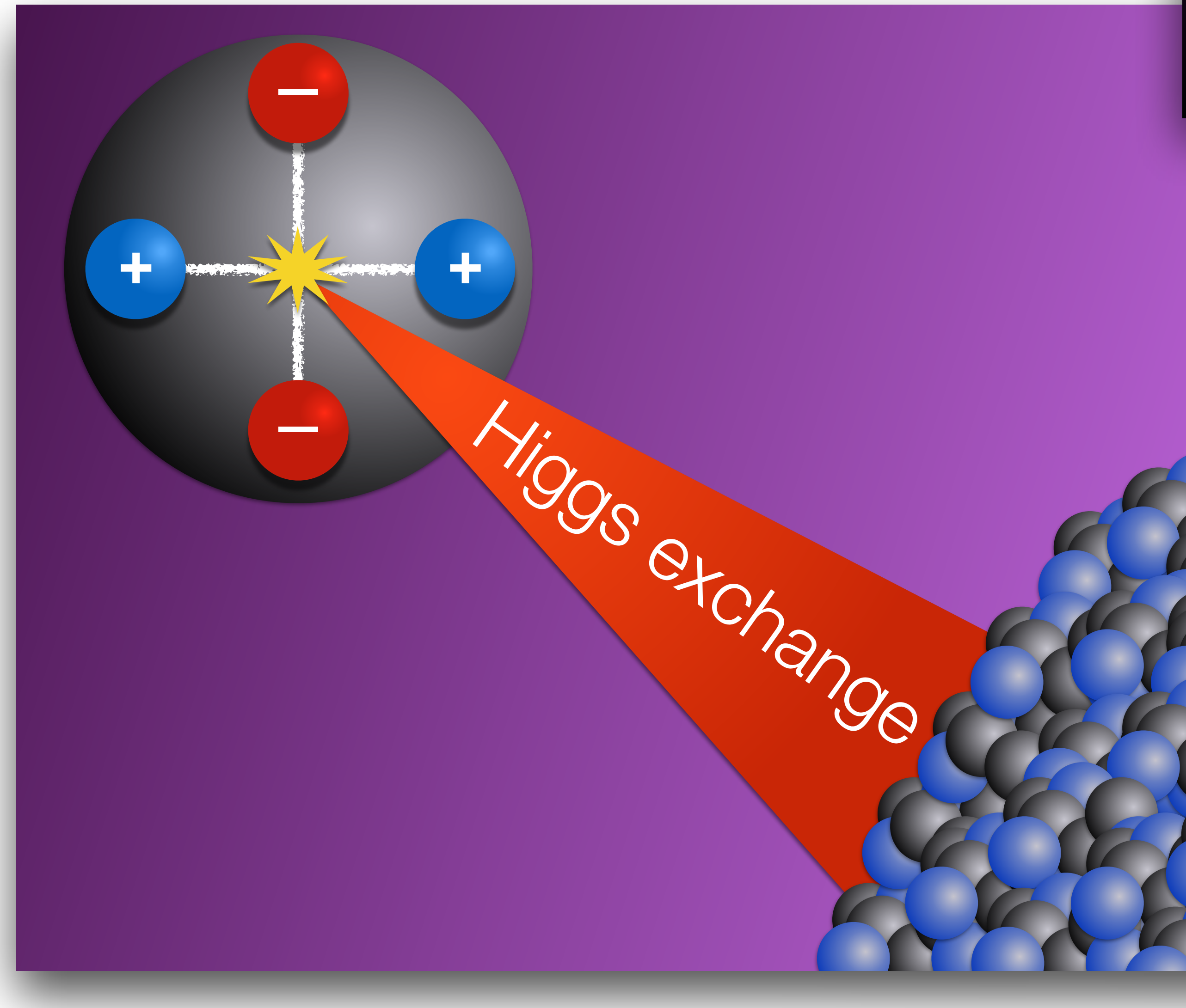
Lattice results for Composite Dark Matter

Template Models	Spectrum	Higgs	Mag. Dip.	Charge r.	Polariz.
SU(2) $N_f=1$	★				
SU(2) $N_f=2$	★	⭐	🟥 **forbidden in pNGB DM**	⭐	★
SU(3) $N_f=2,6$	★		★	★	
SU(3) $N_f=8$	★	⭐			
SU(3) $N_f=2$ (S)	★				
SU(4) $N_f=4$	★	★	🟥 **forbidden in Stealth DM**	🟥	★
SO(4) $N_f=2$ (V)	★				
SU(N) $N_f=0$	★	🟥	🟥 **forbidden in SUNonia**	🟥	🟥

PRL Editors’ Suggestion: Polarizability

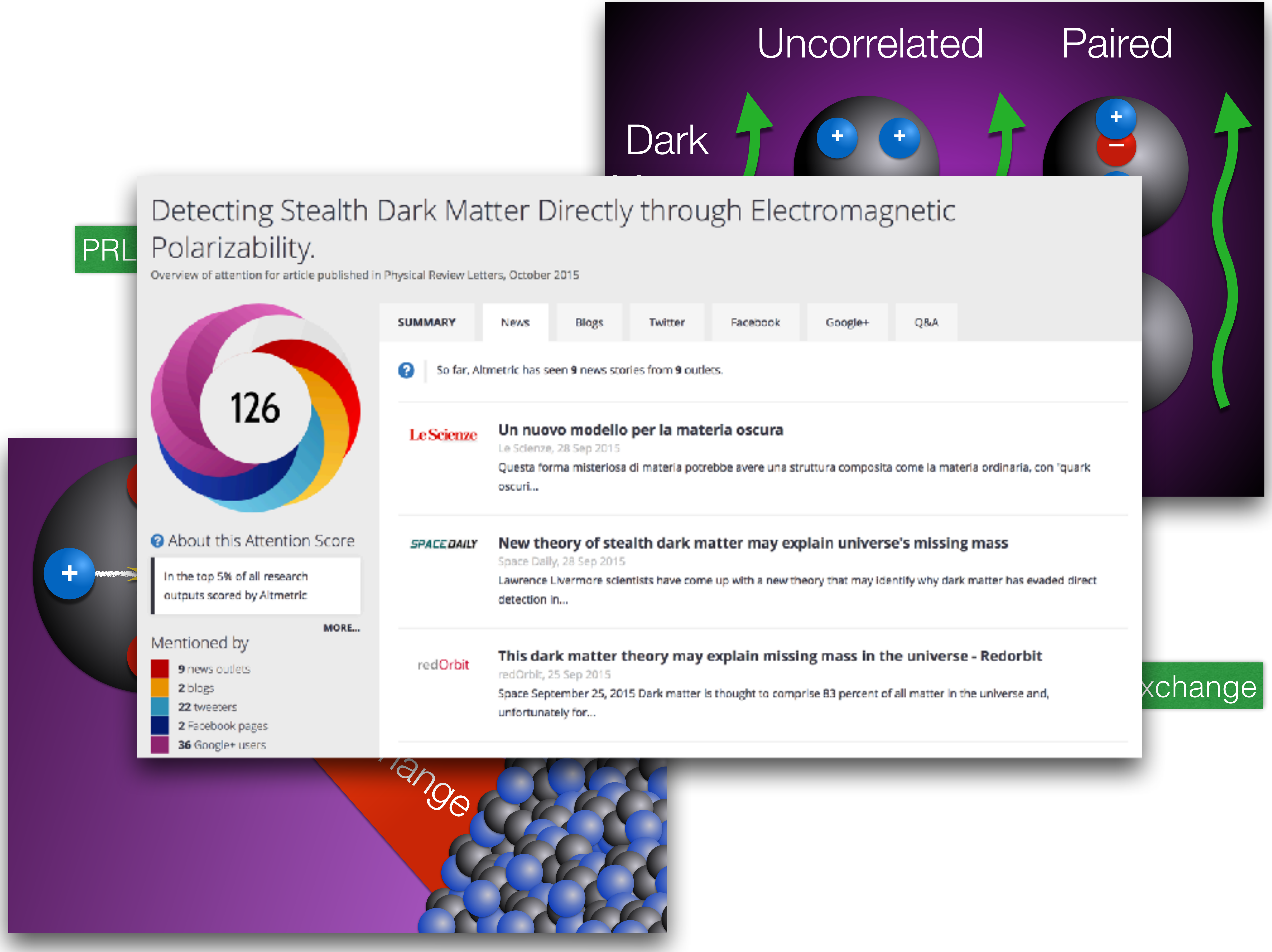
[LSD collab., Phys. Rev. Lett. 115 (2015) 171803]





PRD Editors’ Suggestion: Higgs exchange

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



Detecting Stealth Dark Matter Directly through Electromagnetic Polarizability.

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

126

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So far, Altmetric has seen 9 news stories from 9 outlets.

Le Scienze

Un nuovo modello per la materia oscura

Le Scienze, 28 Sep 2015

Questa forma misteriosa di materia potrebbe avere una struttura composita come la materia ordinaria, con "quark oscuri...

SPACE DAILY

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

Space Daily, 28 Sep 2015

Lawrence Livermore scientists have come up with a new theory that may identify why dark matter has evaded direct detection in...

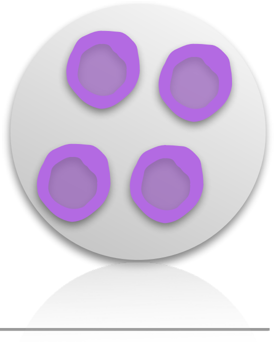
redOrbit

This dark matter theory may explain missing mass in the universe - Redorbit

redOrbit, 25 Sep 2015

Space September 25, 2015 Dark matter is thought to comprise 83 percent of all matter in the universe and, unfortunately for...

“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]

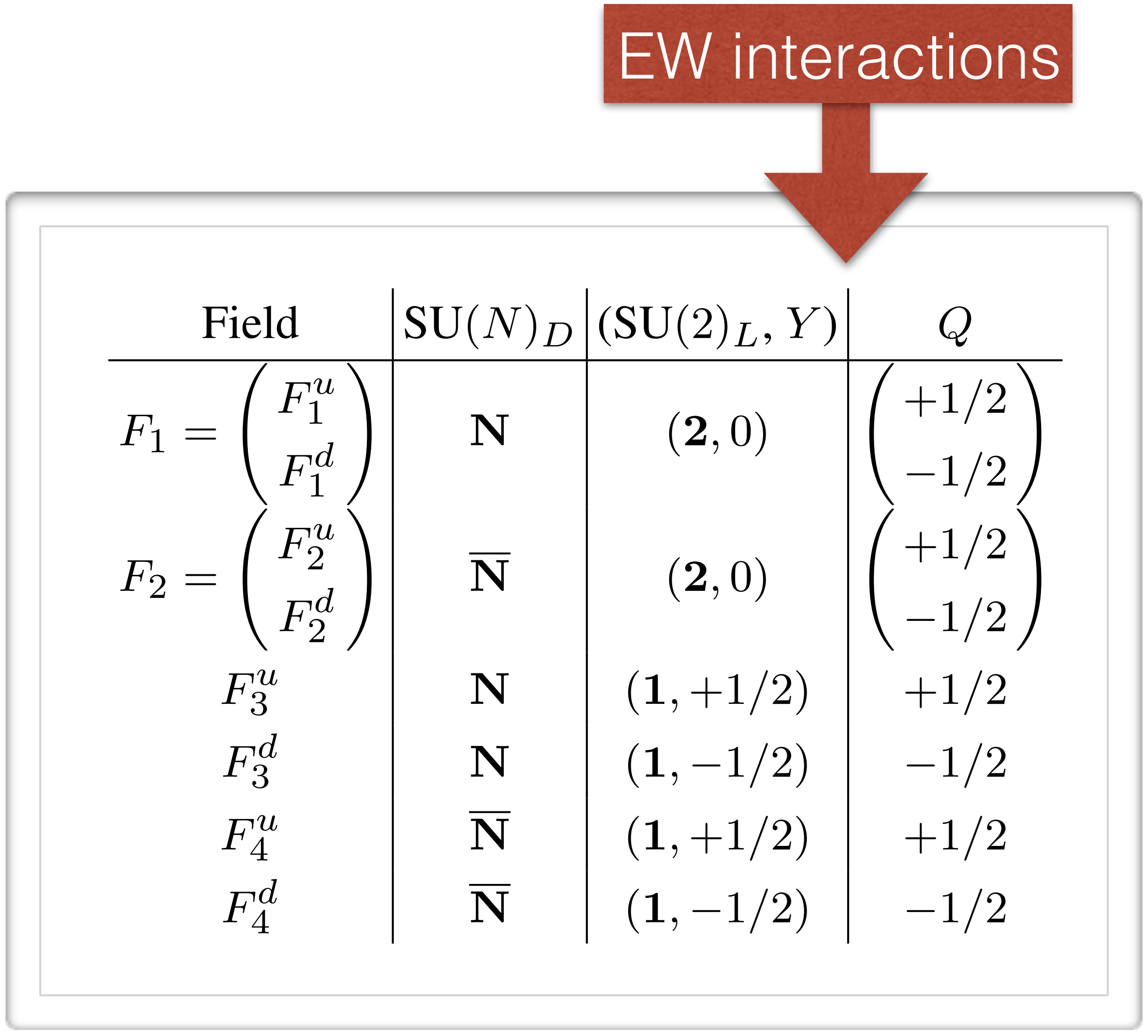
[LSD collab., Phys. Rev. D92 (2015) 075030]

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

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

“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***



EW interactions

Field	$\mathrm{SU}(N)_D$	$(\mathrm{SU}(2)_L, Y)$	Q
$F_1 = \begin{pmatrix} F_1^u \\ F_1^d \end{pmatrix}$	$\mathbf{N}$	$(\mathbf{2}, 0)$	$\begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$
$F_2 = \begin{pmatrix} F_2^u \\ F_2^d \end{pmatrix}$	$\overline{\mathbf{N}}$	$(\mathbf{2}, 0)$	$\begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$
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	$\overline{\mathbf{N}}$	$(\mathbf{1}, +1/2)$	$+1/2$
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[LSD collab., Phys. Rev. D92 (2015) 075030]

“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
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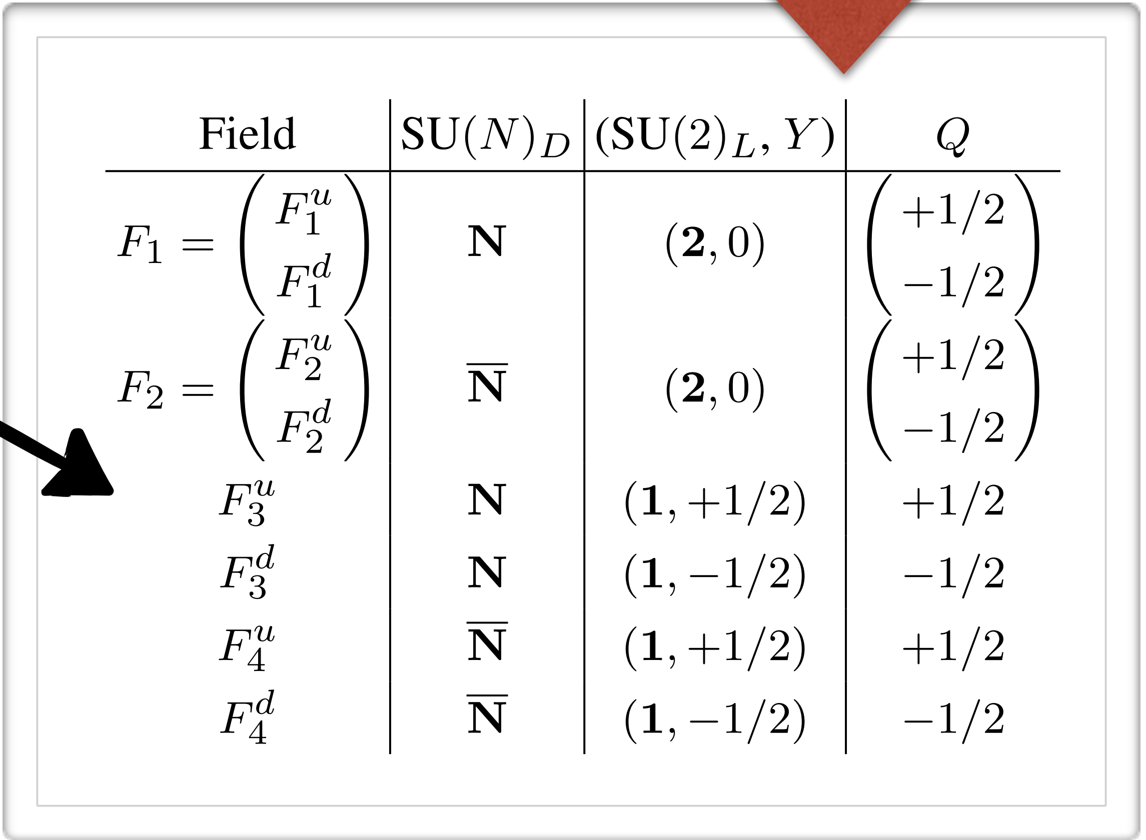
EW interactions



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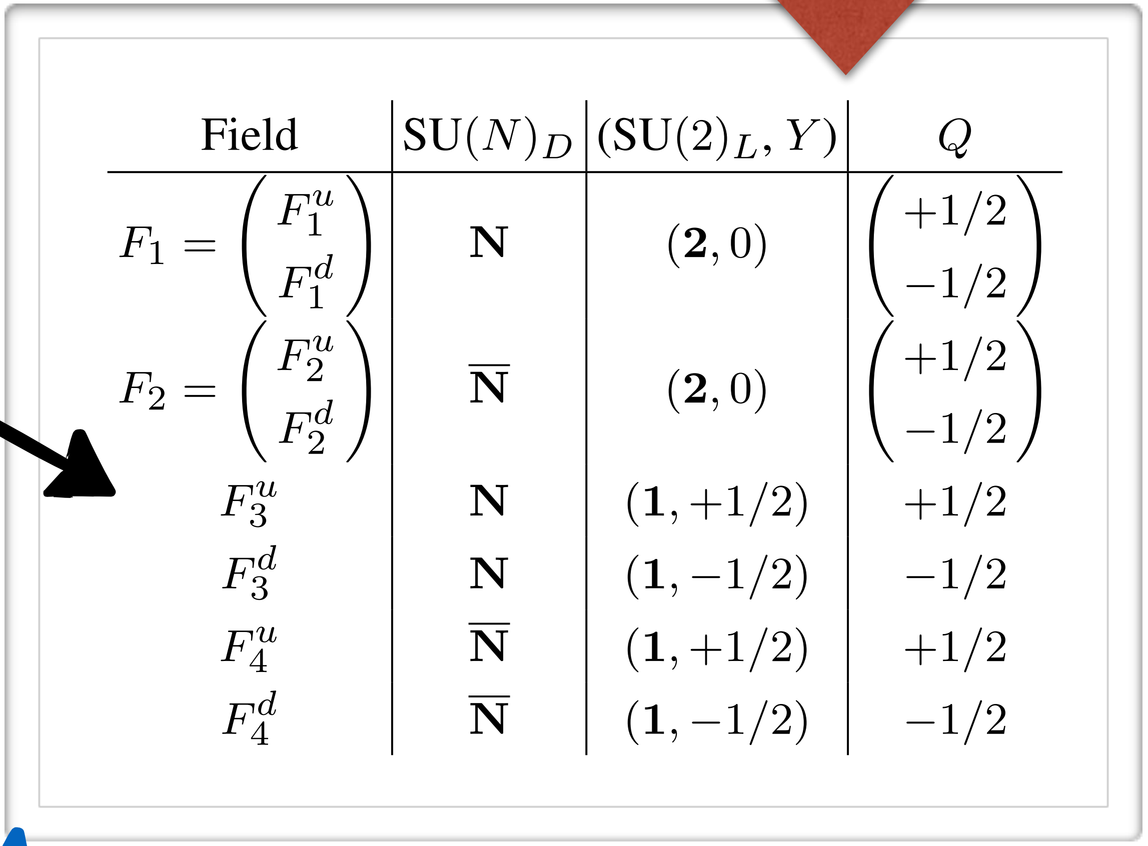

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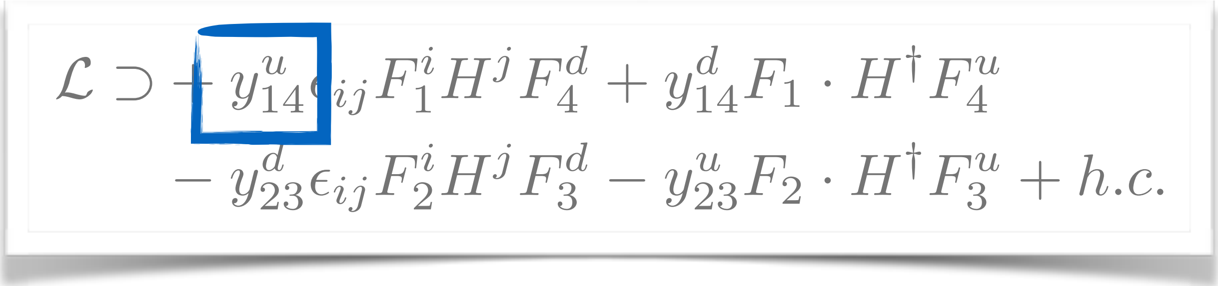

$$\mathcal{L} \supset \boxed{+ y_{14}^u} \epsilon_{ij} F_1^i H^j F_4^d + y_{14}^d F_1 \cdot H^\dagger F_4^u - y_{23}^d \epsilon_{ij} F_2^i H^j F_3^d - y_{23}^u F_2 \cdot H^\dagger F_3^u + h.c.$$

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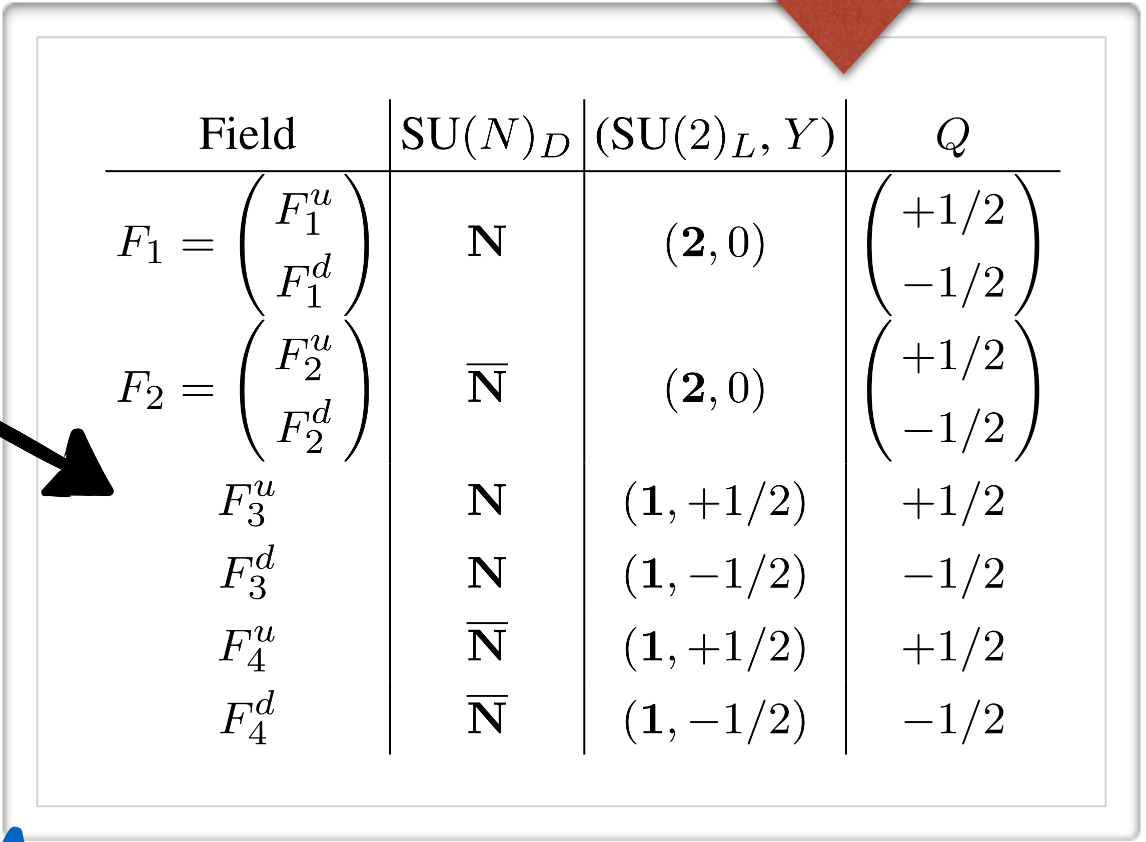

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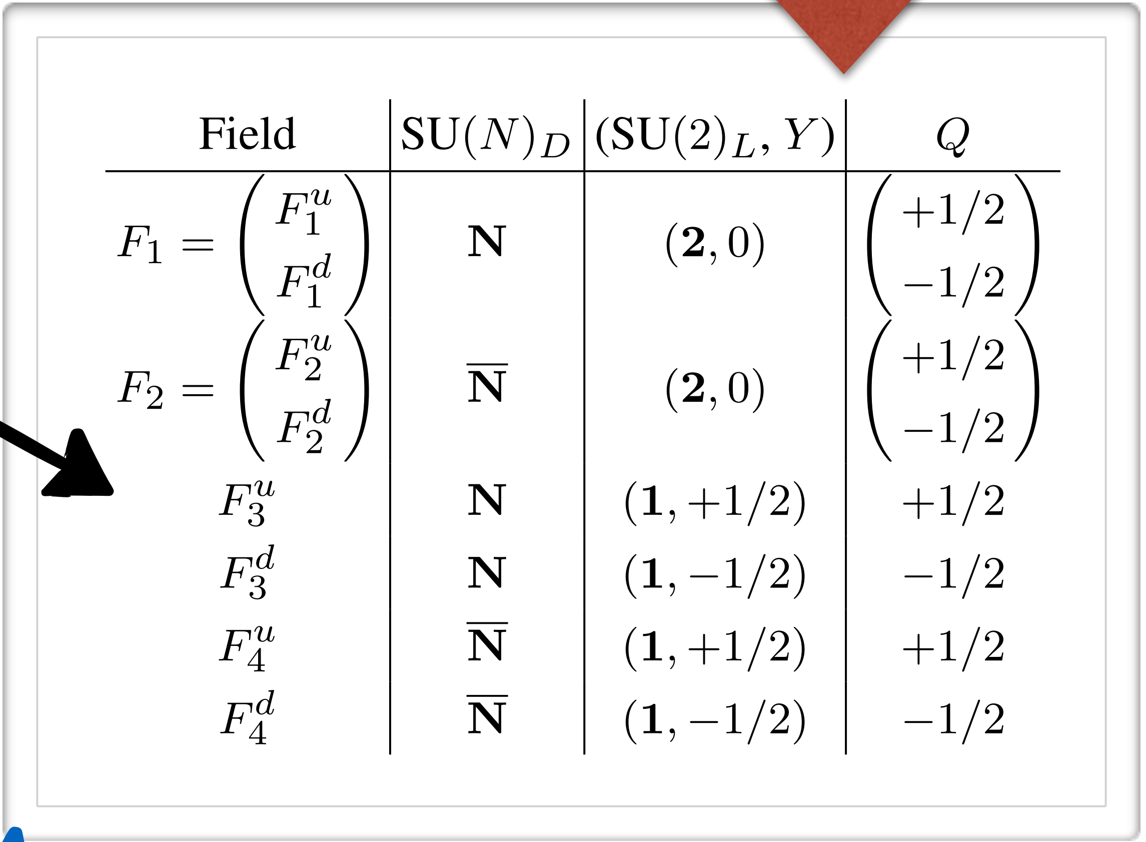

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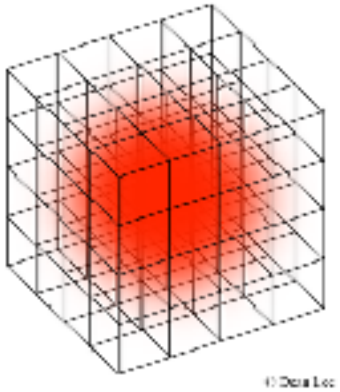
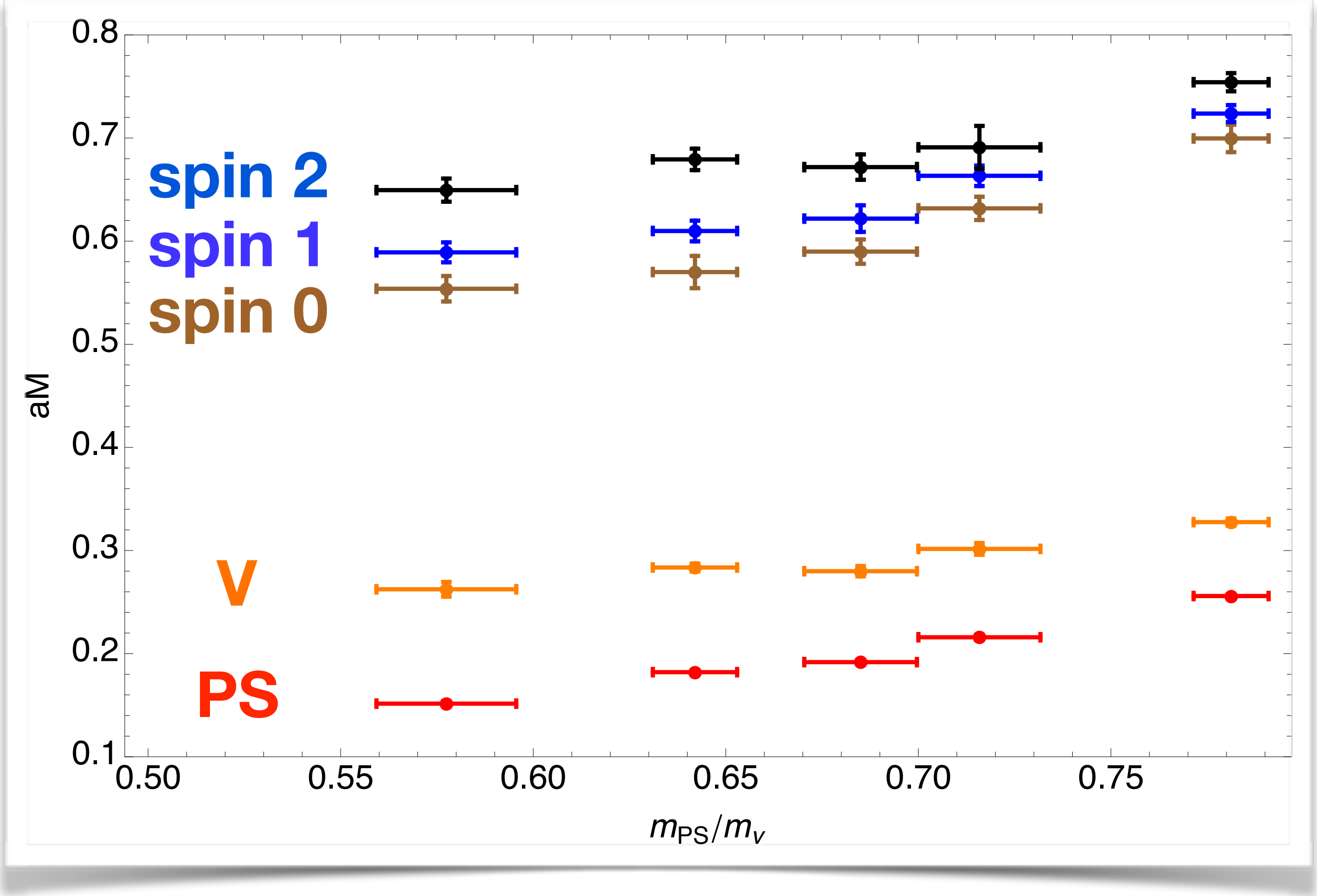
[LSD collab., Phys. Rev. D89 (2014) 094508]

Lattice Stealth Dark Matter



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



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- The meson to baryon mass ratio allows us to translate LEPII bounds on charged meson to LEPII 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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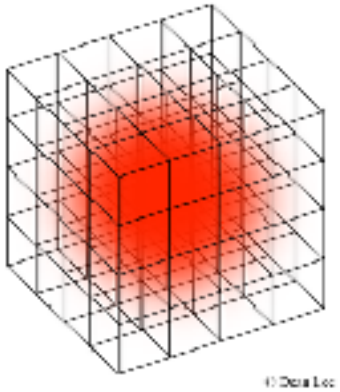

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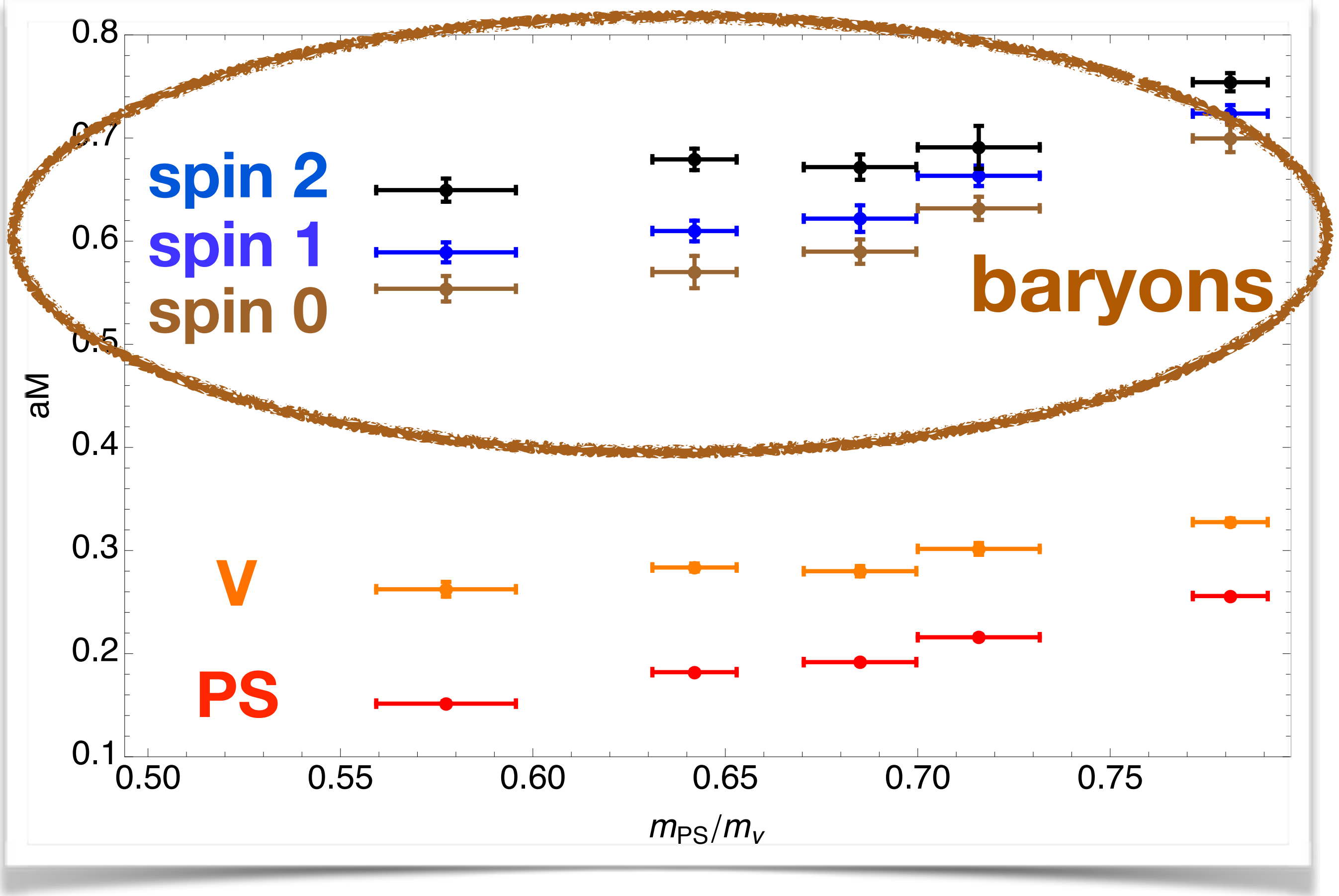

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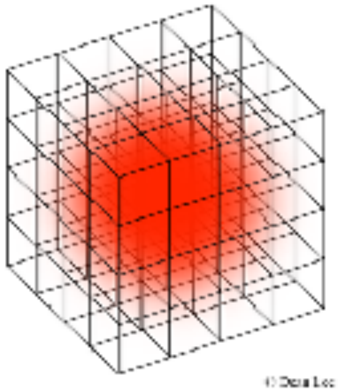

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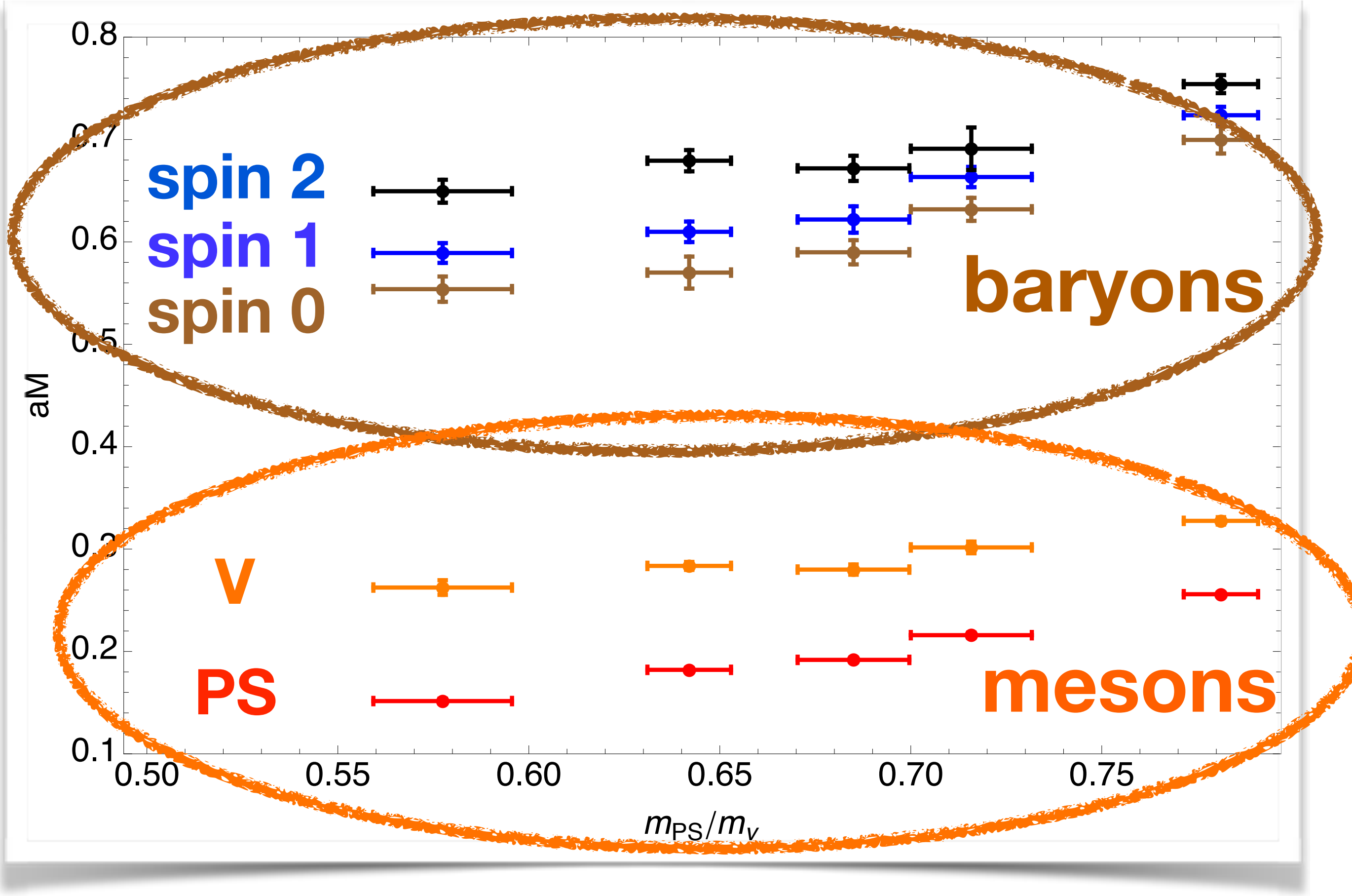

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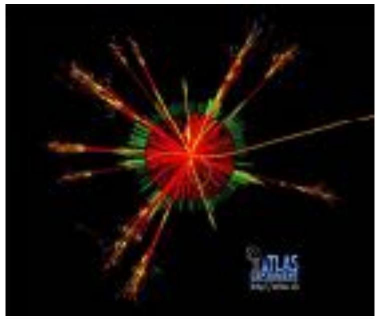
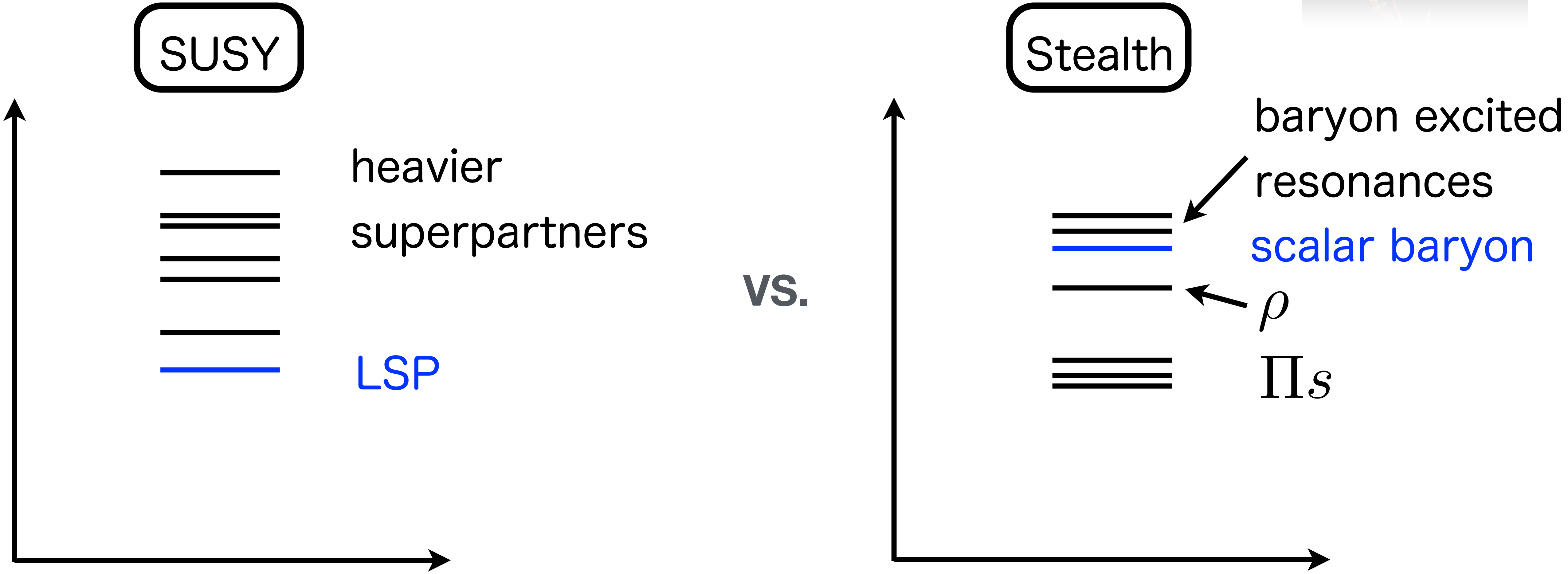


Stealth Dark Matter at colliders



SUSY

heavier superpartners

LSP

vs.

Stealth

baryon excited resonances

scalar baryon

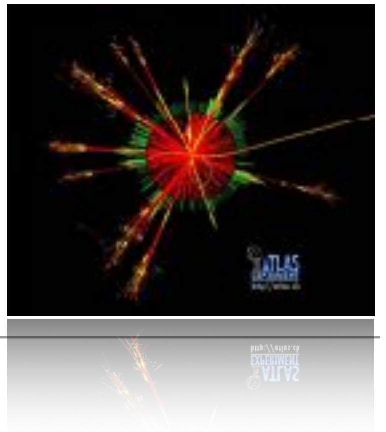
ρ

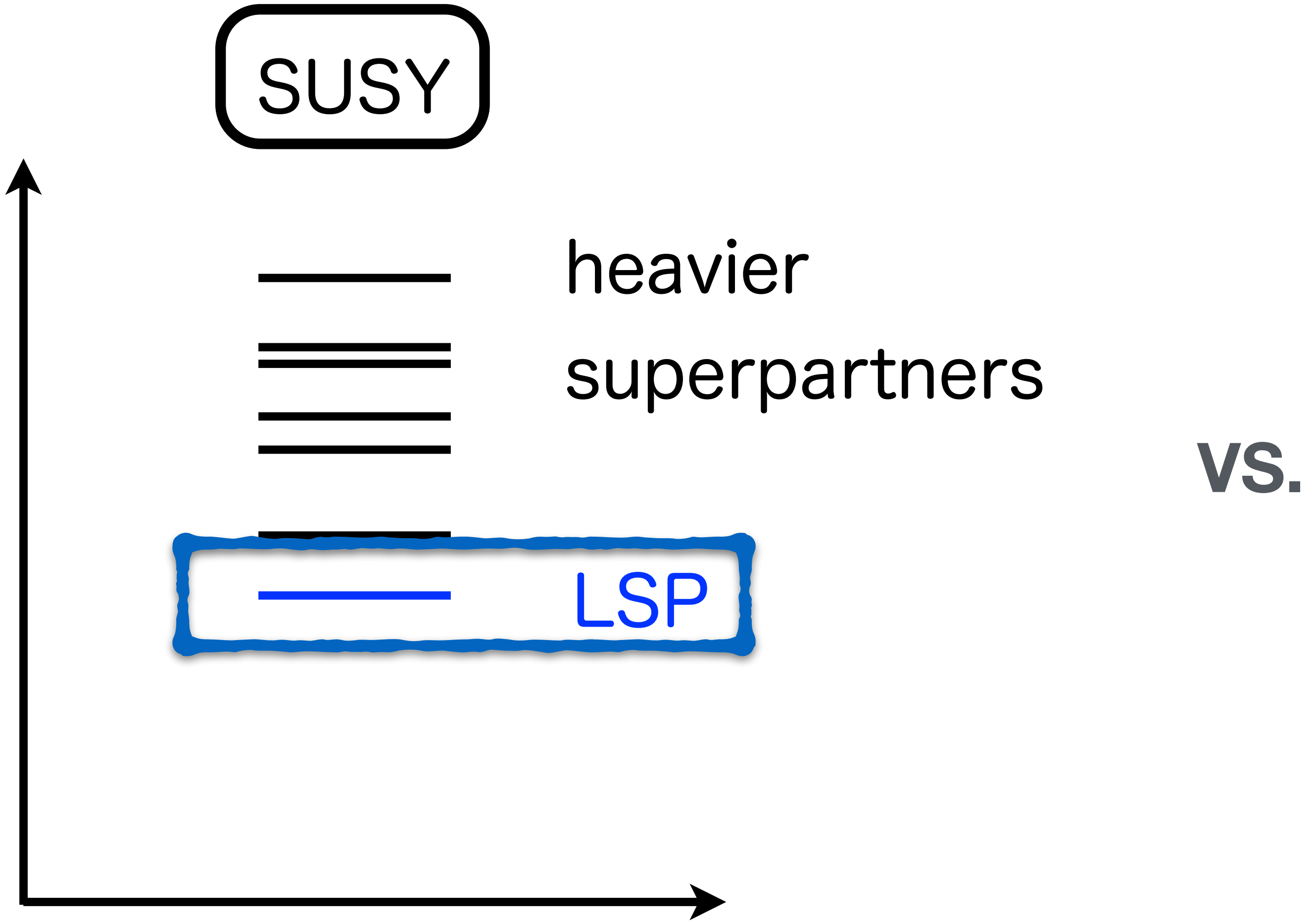
Πs

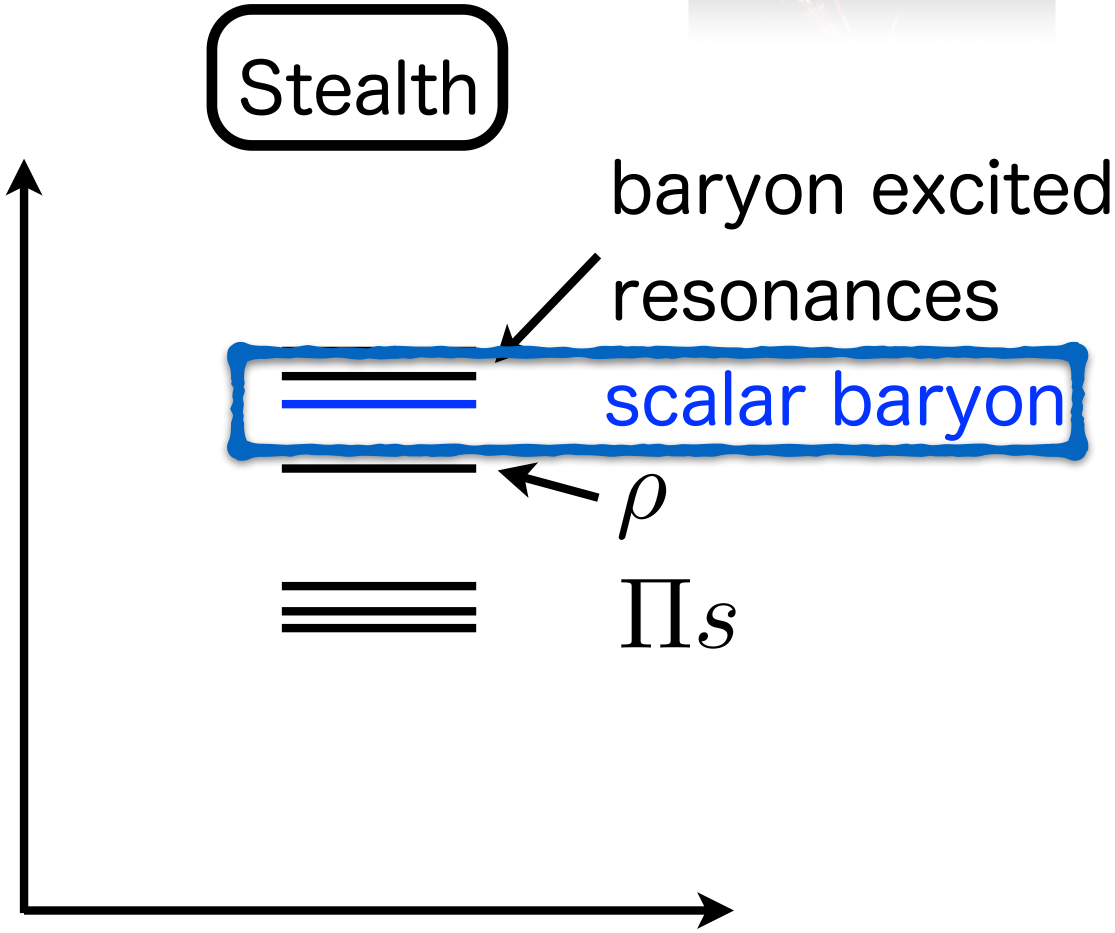
Plot by G. Kribs

Stealth Dark Matter at colliders

[ATLAS]







Plot by G. Kribs

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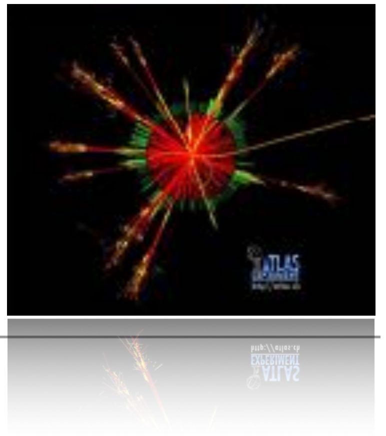
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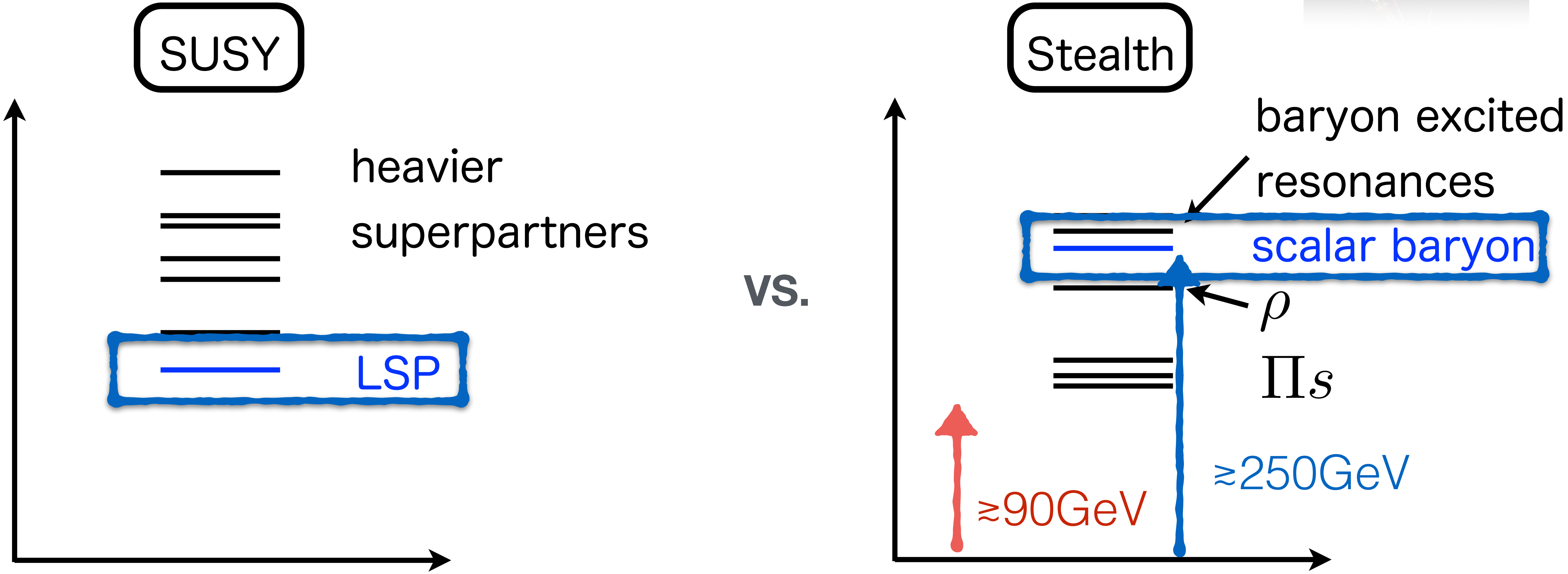

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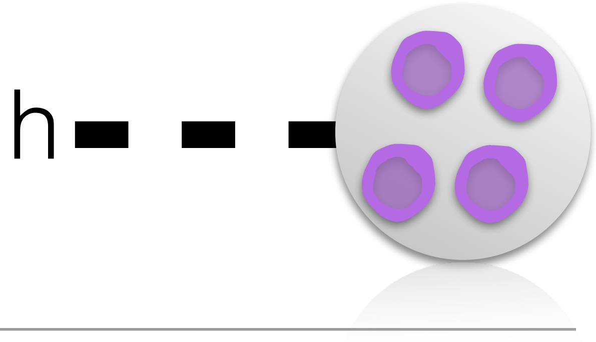
- Signatures are not dominated by missing energy: **DM is not the lightest particle!** The interactions are suppressed (form factors)
- Dark mesons production and decay give interesting signatures: **the model can be constrained by collider limits!**

[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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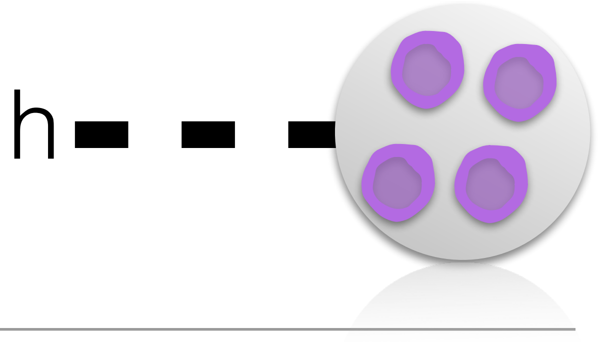

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1. effective Higgs coupling with dark fermions and quark Yukawa coupling
2. dark baryon scalar form factor: need lattice input for generic DM models!
3. nucleon scalar form factor: ChPT and lattice input

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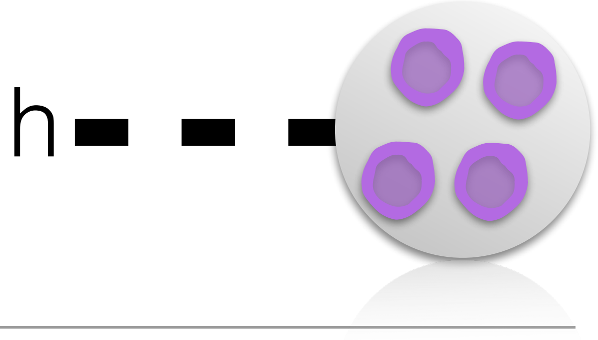

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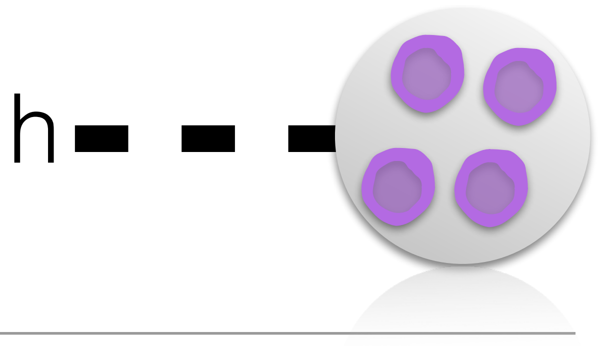

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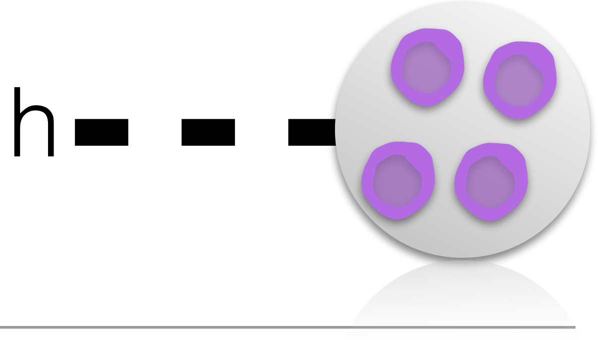

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- Model-dependent answer for the cross-section
- **Lattice input** is necessary: compute mass and form factor (using Feynman-Hellmann)

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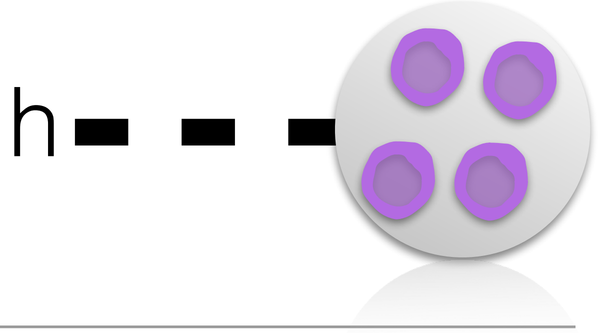
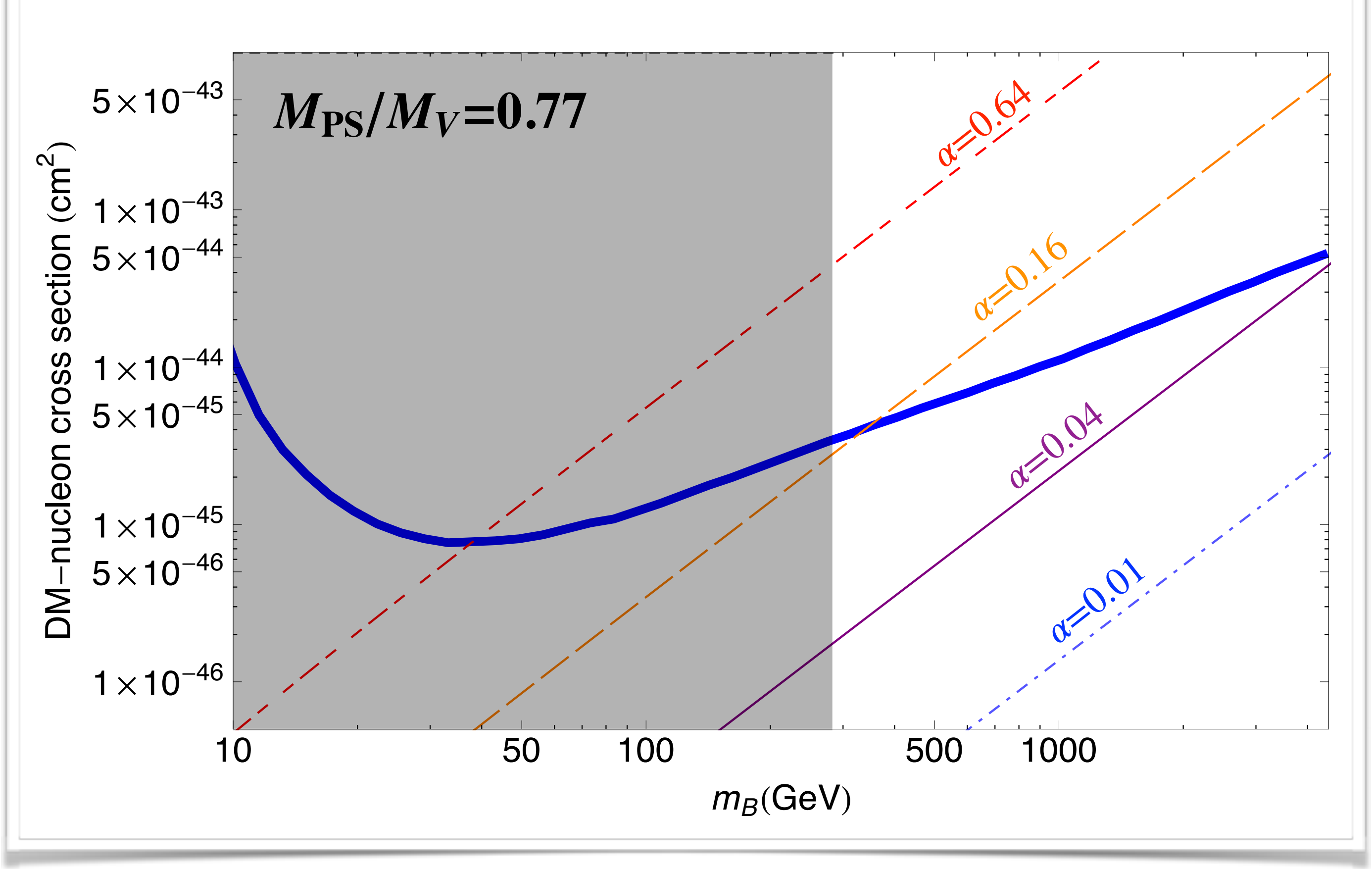
Bounds from Higgs exchange



- ✦Lattice results for the cross-section are compared to **experimental** bounds
- ✦Coupling space in specific models can be vastly constrained

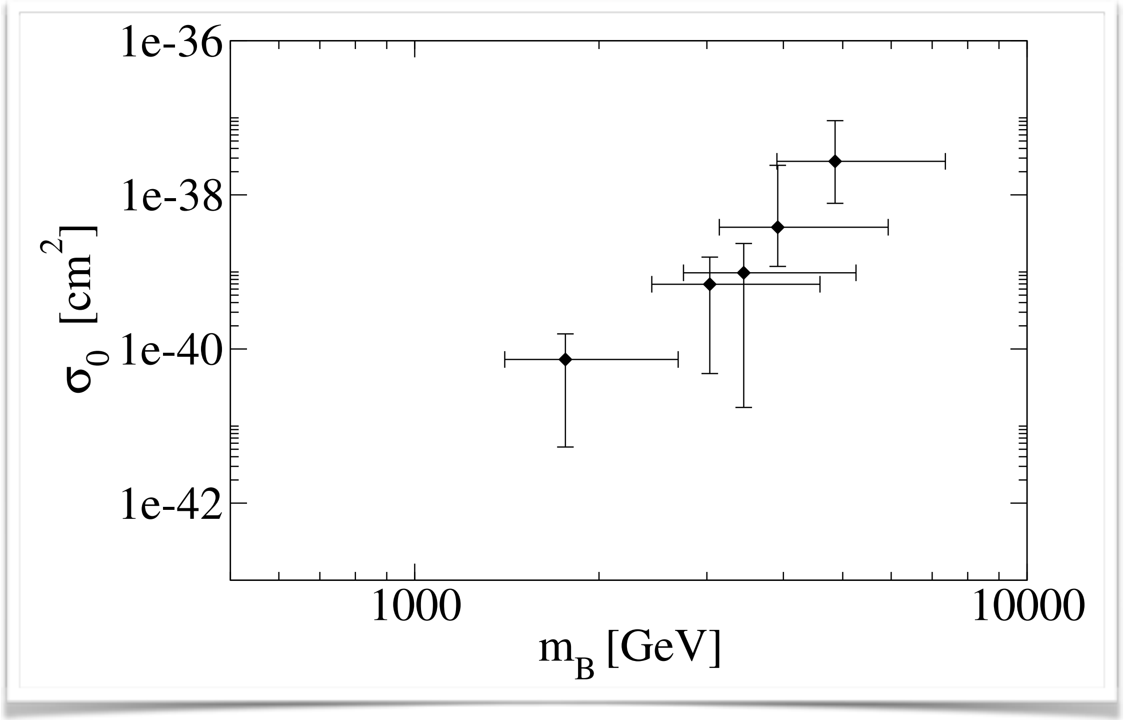
SU(4) N_f=4 Stealth DM

[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
- ✦There is **lattice evidence** for universality of dark scalar form factors: includes N_c=2,3,4,5,7

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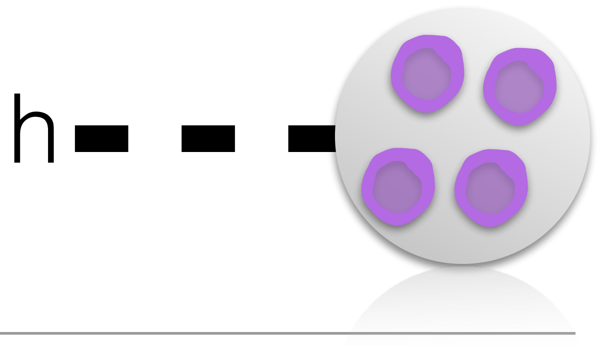

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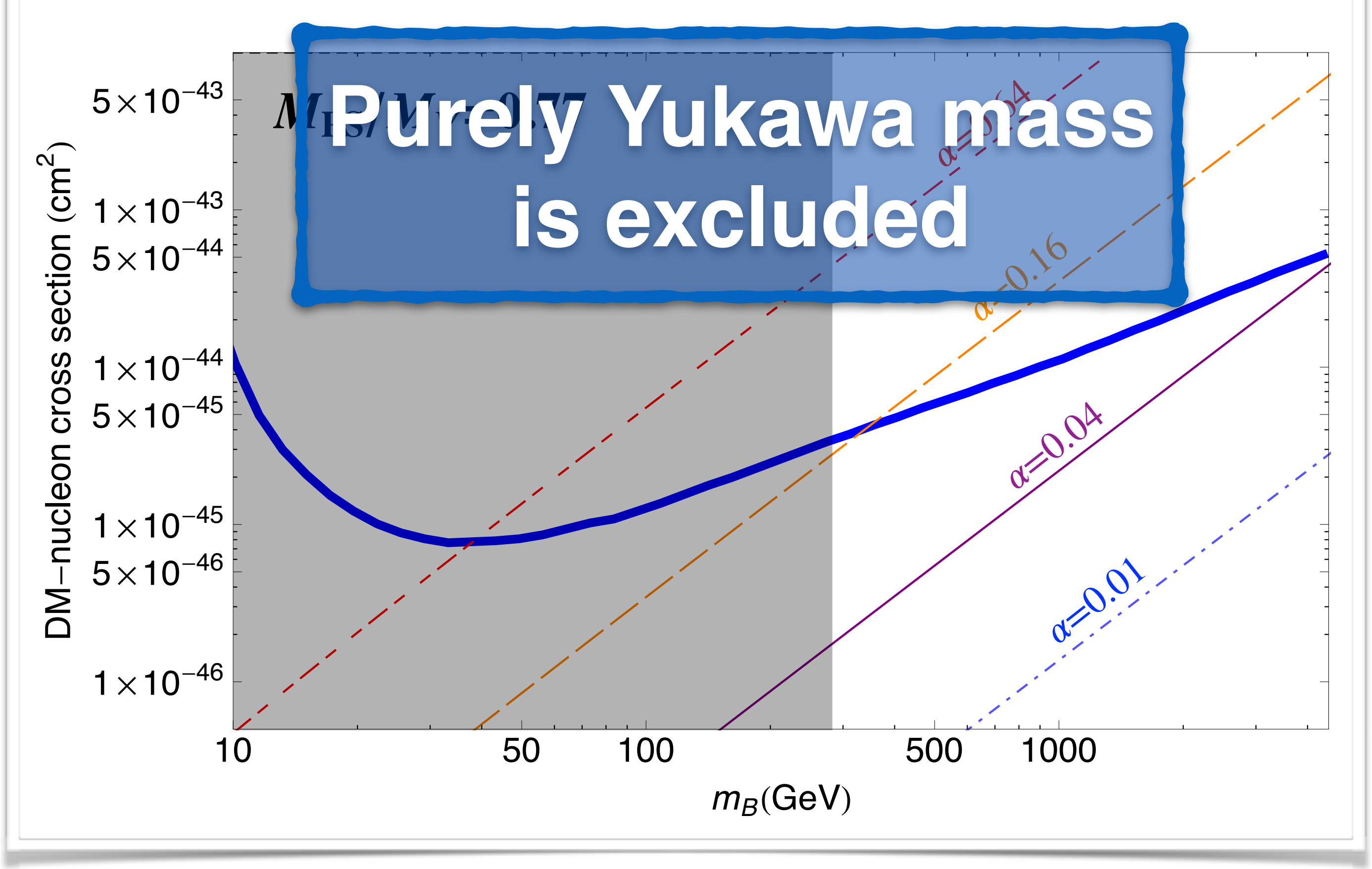

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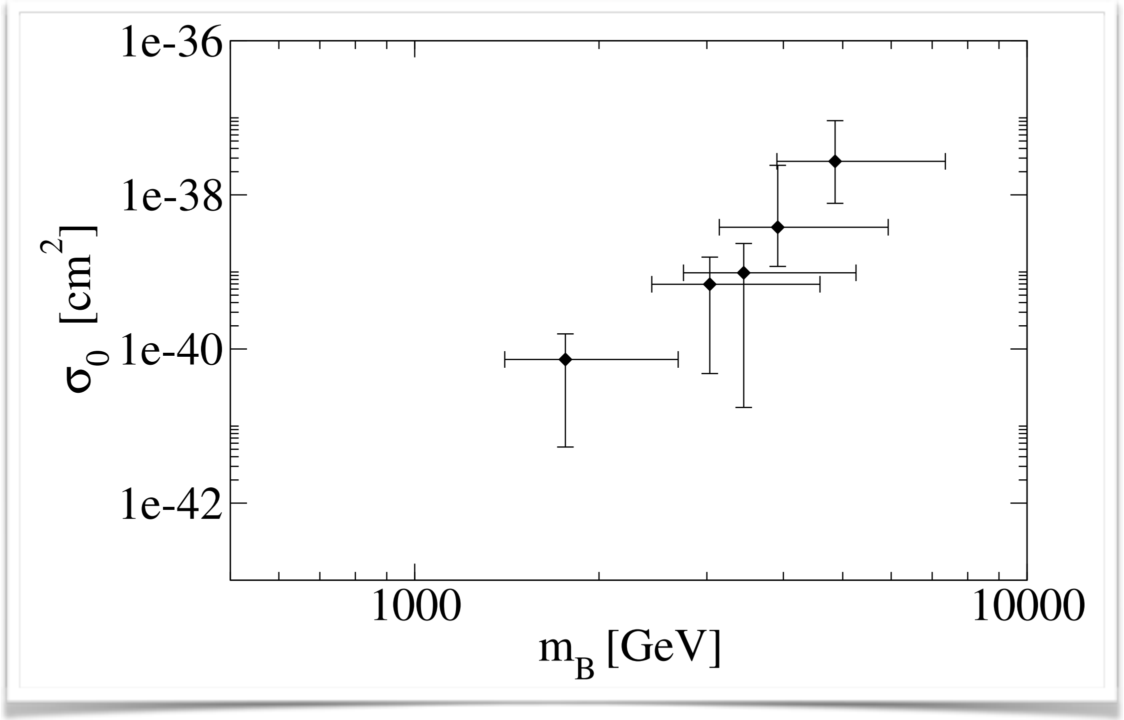

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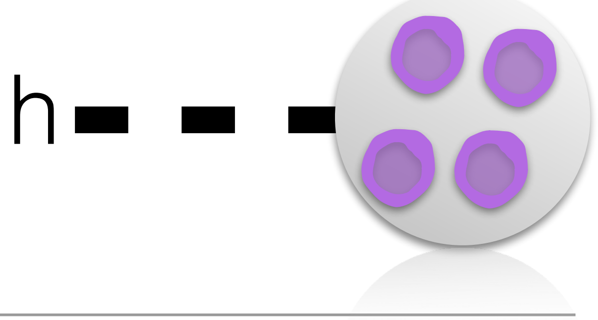

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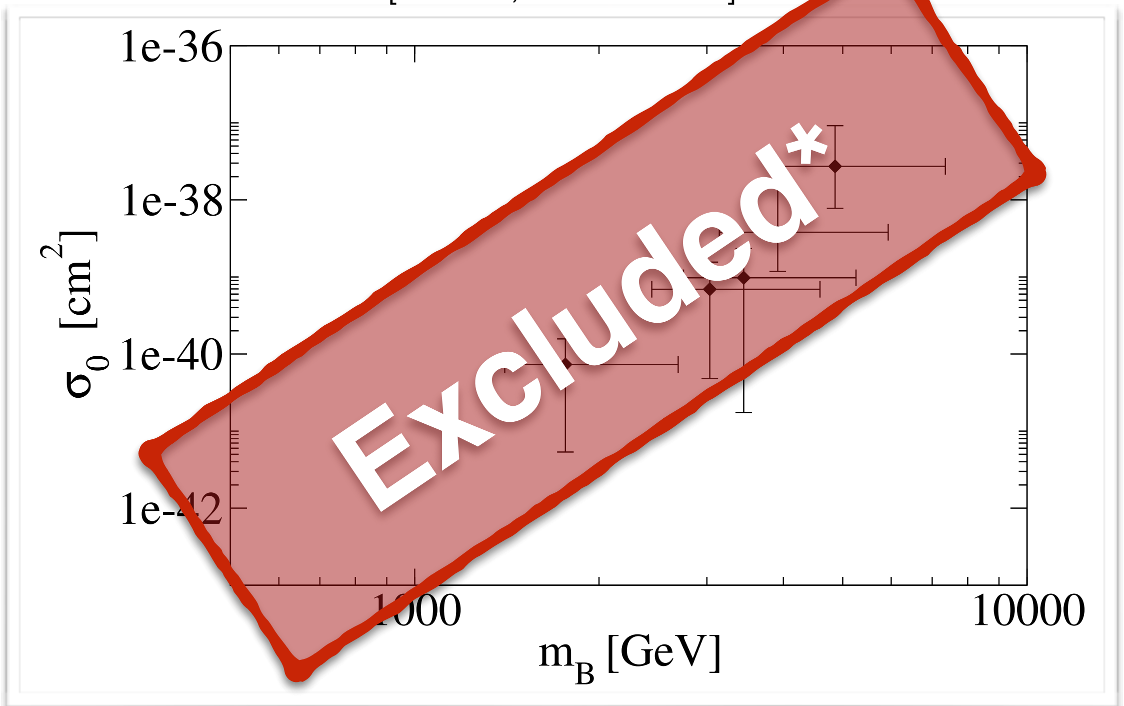

Excluded*

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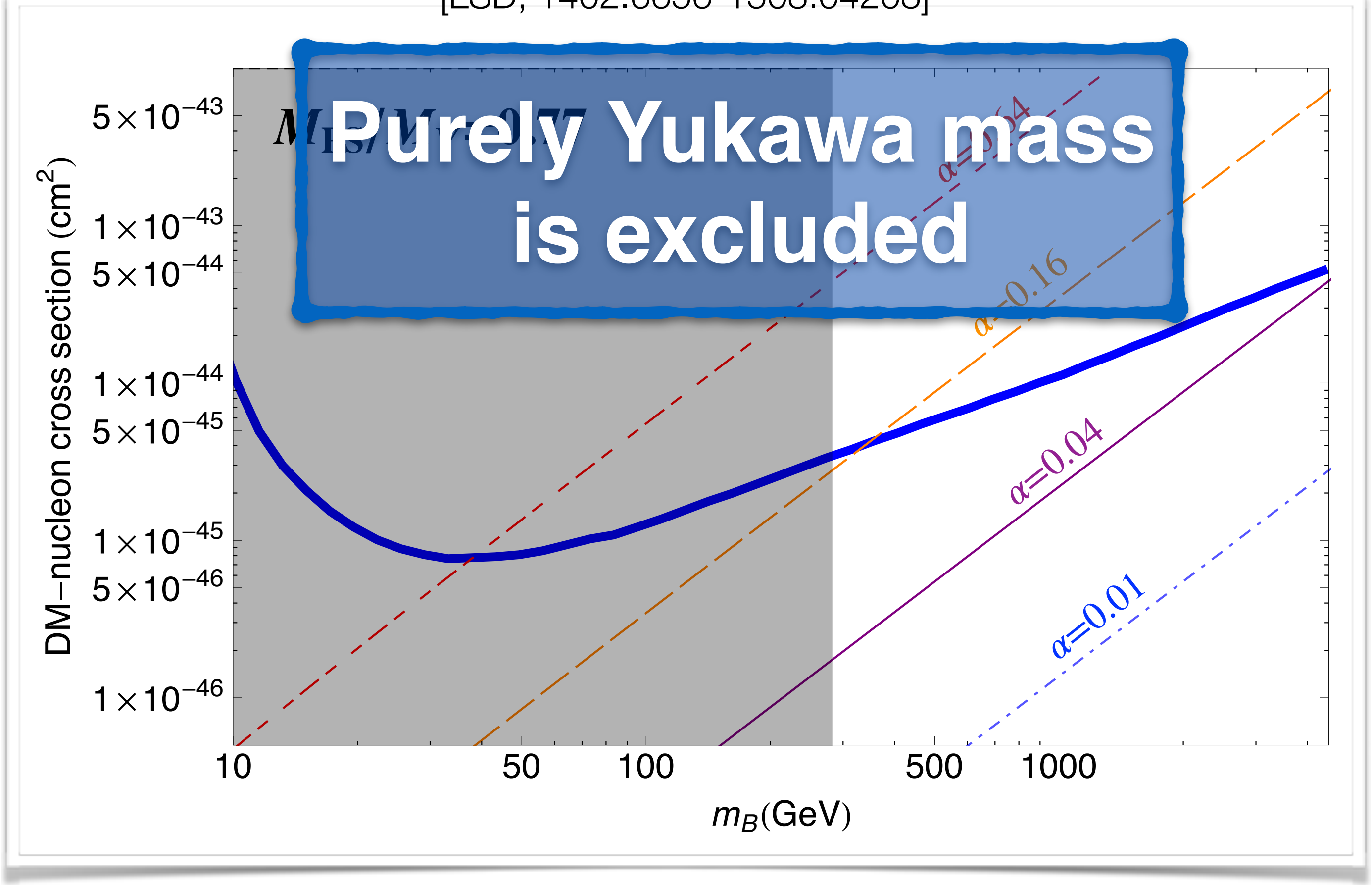
[LSD, 1402.6656-1503.04203]



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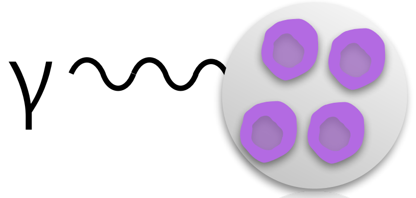
- ✦There is **lattice evidence** for universality of dark scalar form factors: includes N_c=2,3,4,5,7

[DeGrand et al., 1501.05665]

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

Photon interactions



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

Expansion at low momentum through effective operators

✦dimension 5 ➥ magnetic dipole

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

✦dimension 6 ➥ charge radius

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

✦dimension 7 ➥ polarizability

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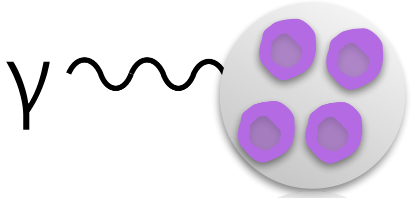

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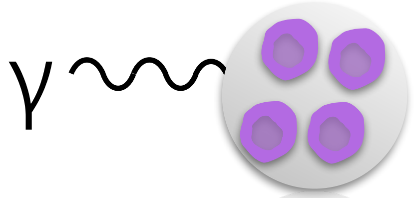

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$$\cancel{\frac{(\bar{\chi}\sigma^{\mu\nu}\chi)F_{\mu\nu}}{\Lambda_{\mathrm{dark}}}}$$

✦dimension 6 ➥ ~~c~~ *custodial SU(2)*

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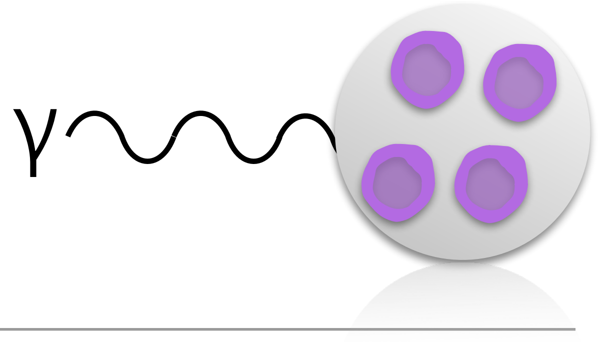
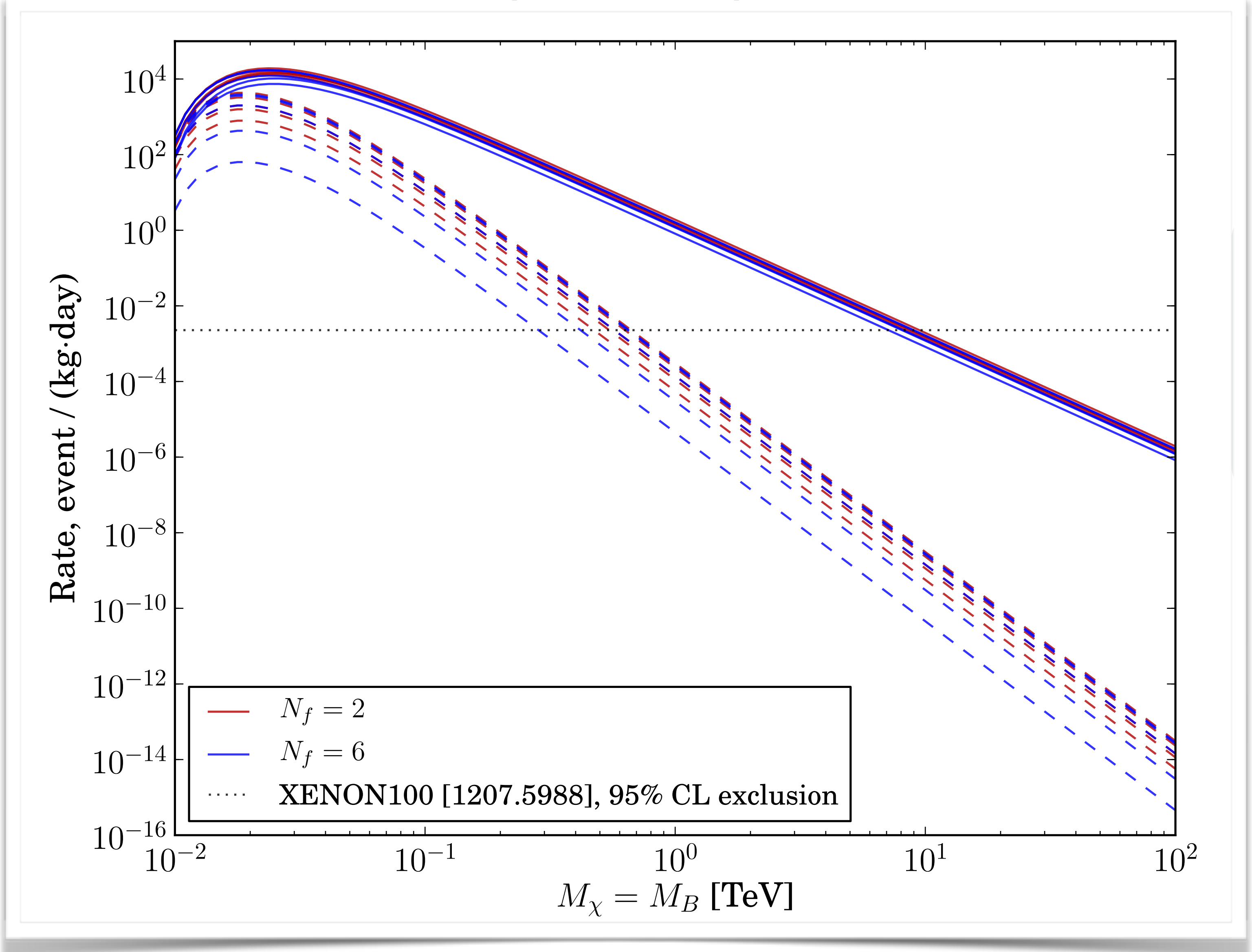
Bounds from EM moments



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

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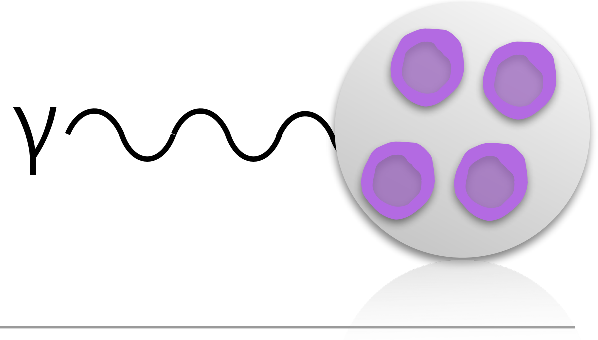

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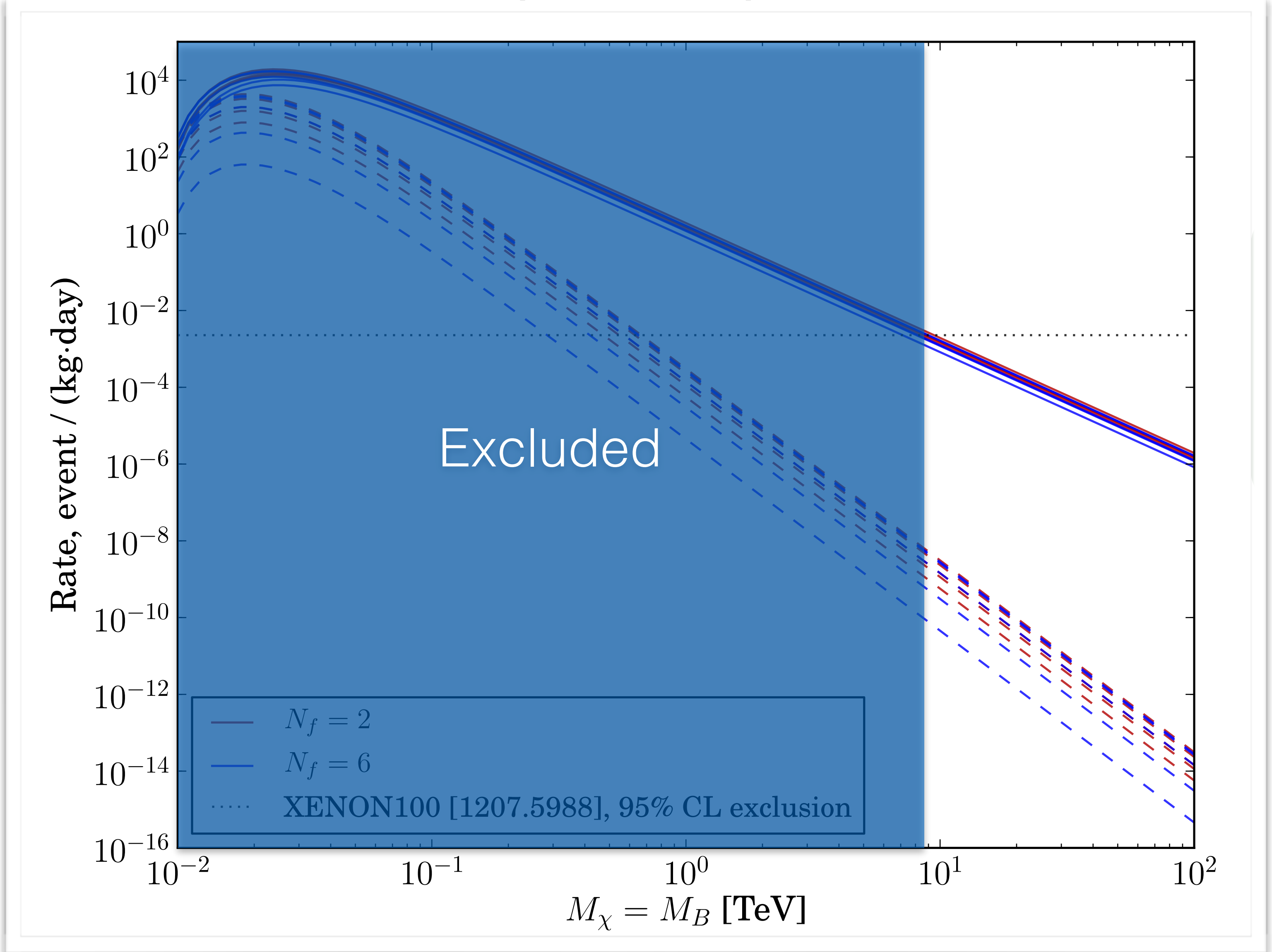

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M_B >~ 10 TeV

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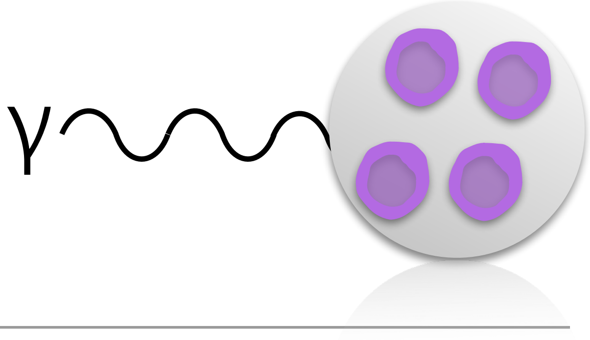

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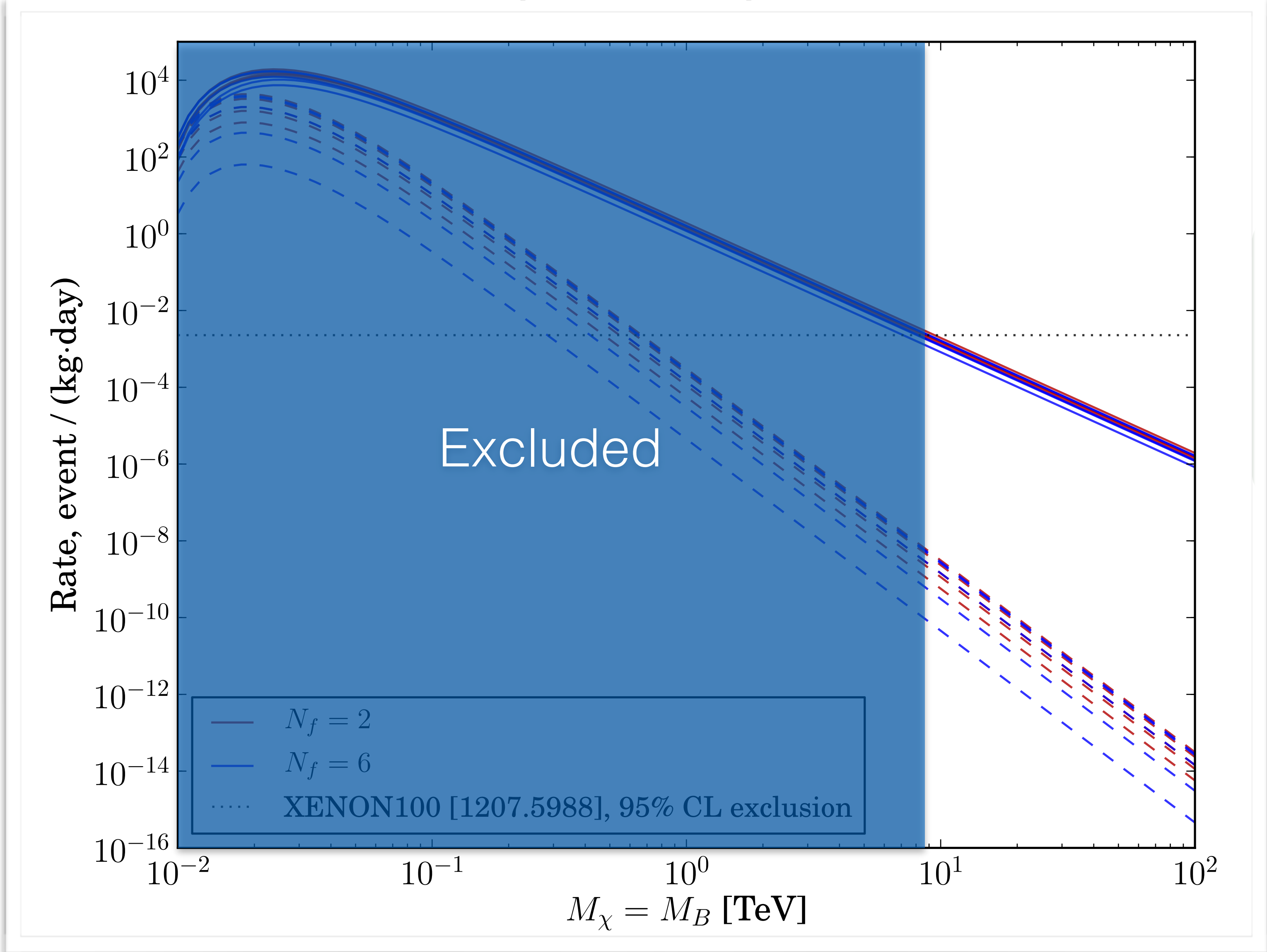

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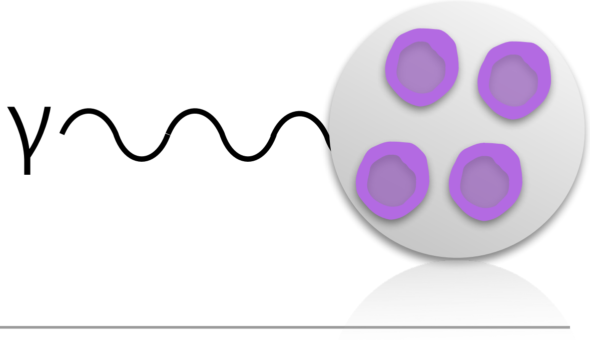
M_B >~ 10 TeV

pushed to ~100 TeV with new LUX

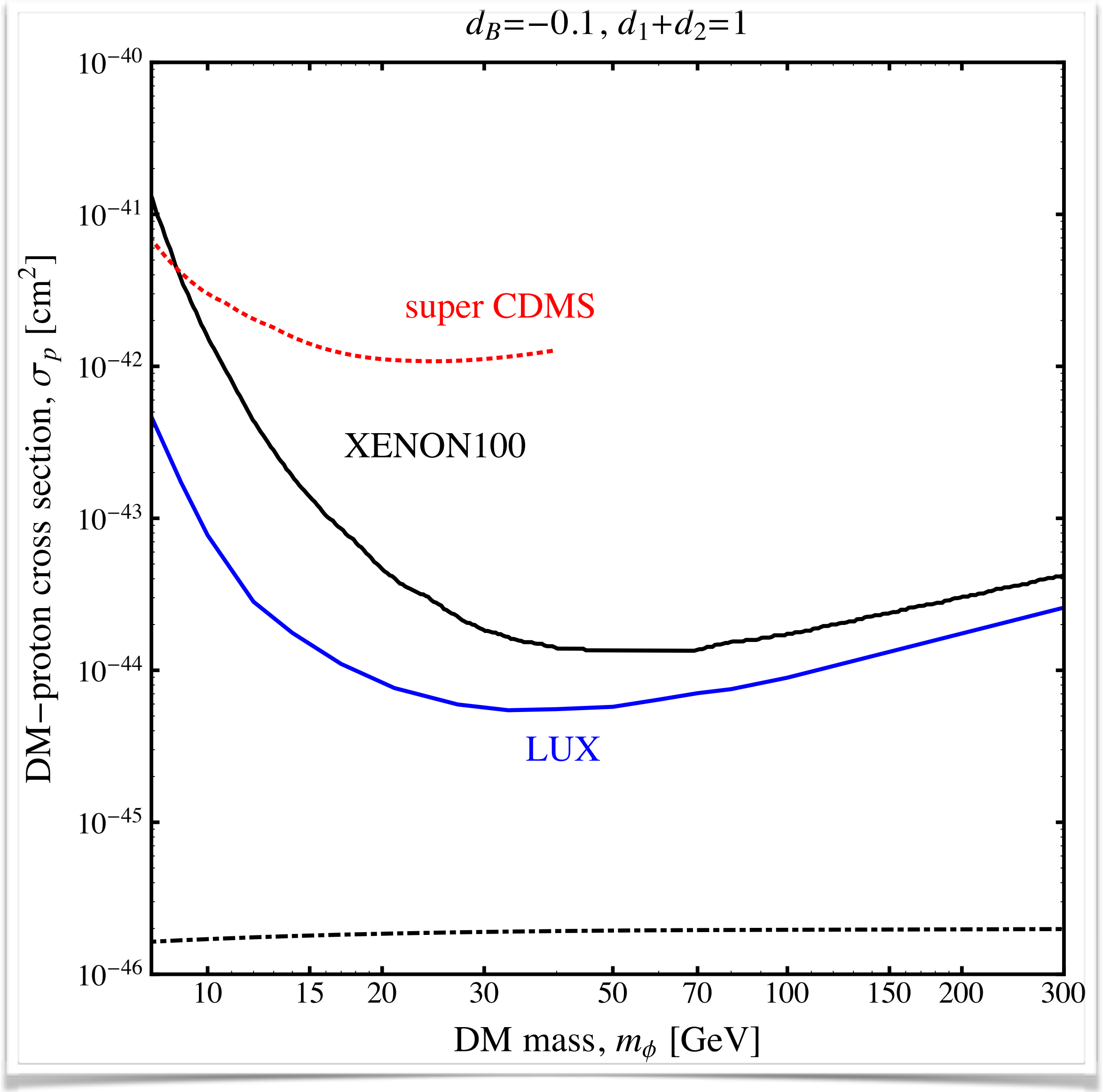
Bounds from EM moments



Mesonic and Baryonic EM form factors directly from lattice simulations

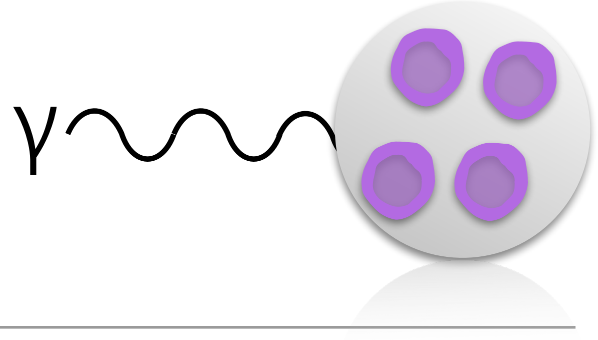
SU(2) N_f=2 pNGB DM

[Hietanen et al., 1308.4130]


$d_B=-0.1,\ d_1+d_2=1$

- ★ 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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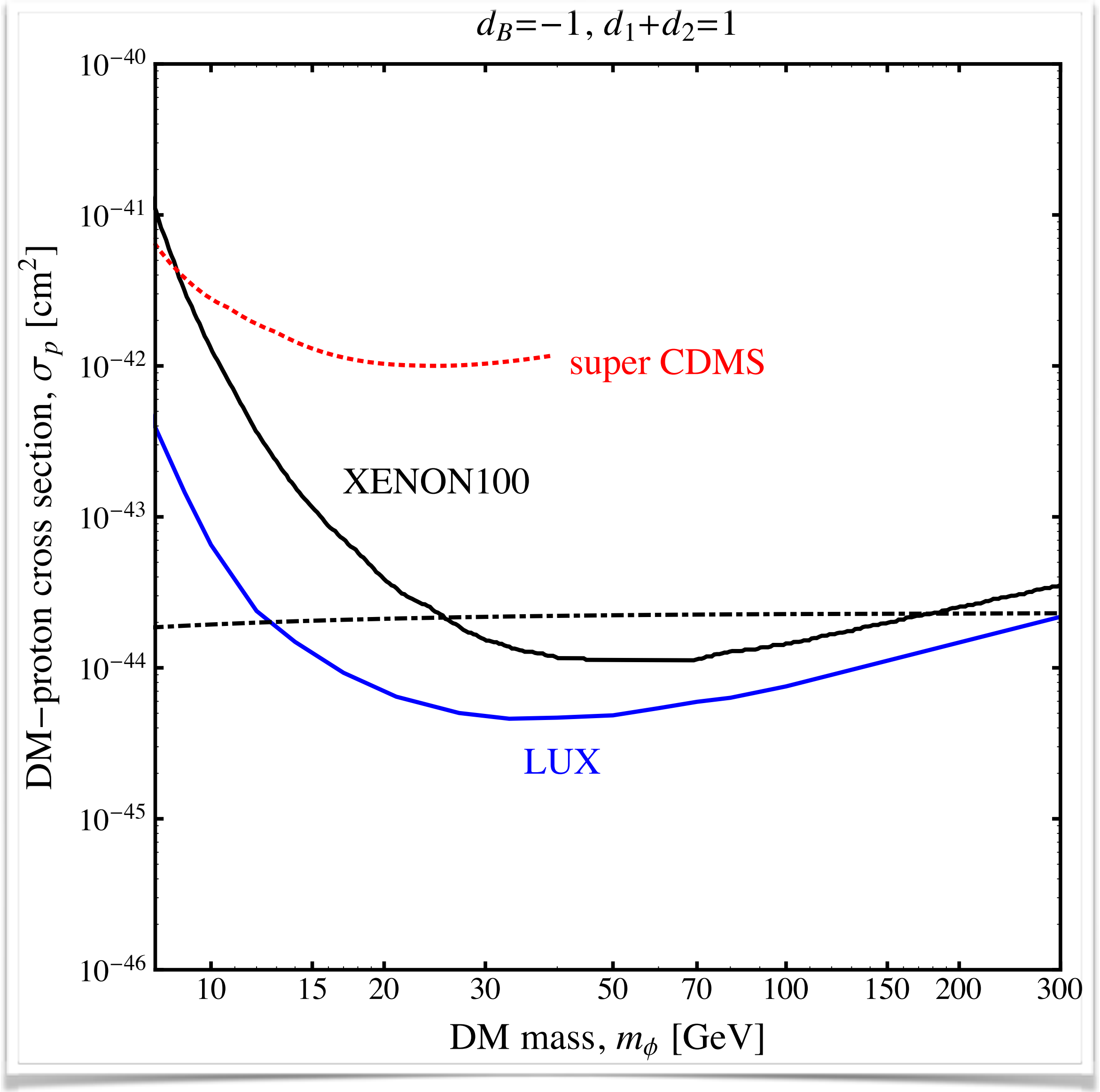

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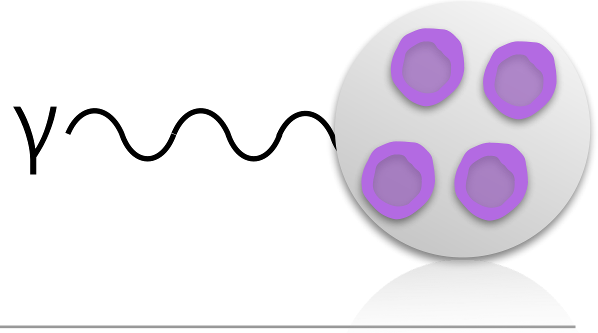

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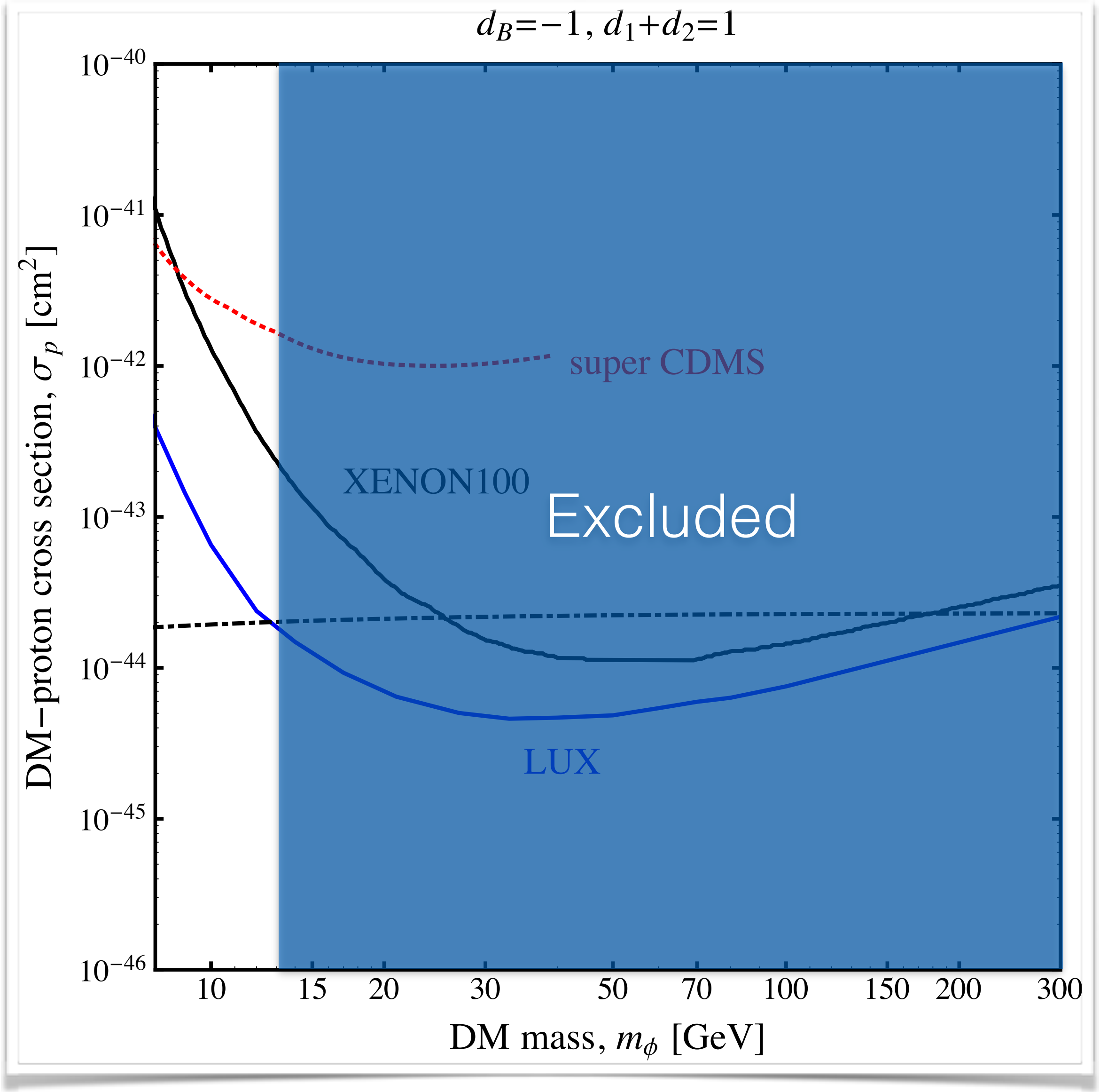

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- ★ also couples to Higgs (d_1+d_2)

M_B ~< 13 GeV
depends on d_B

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

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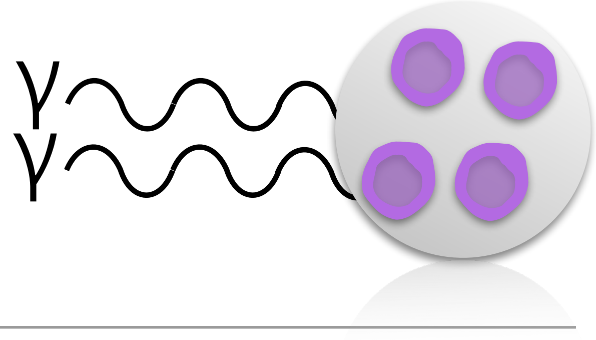
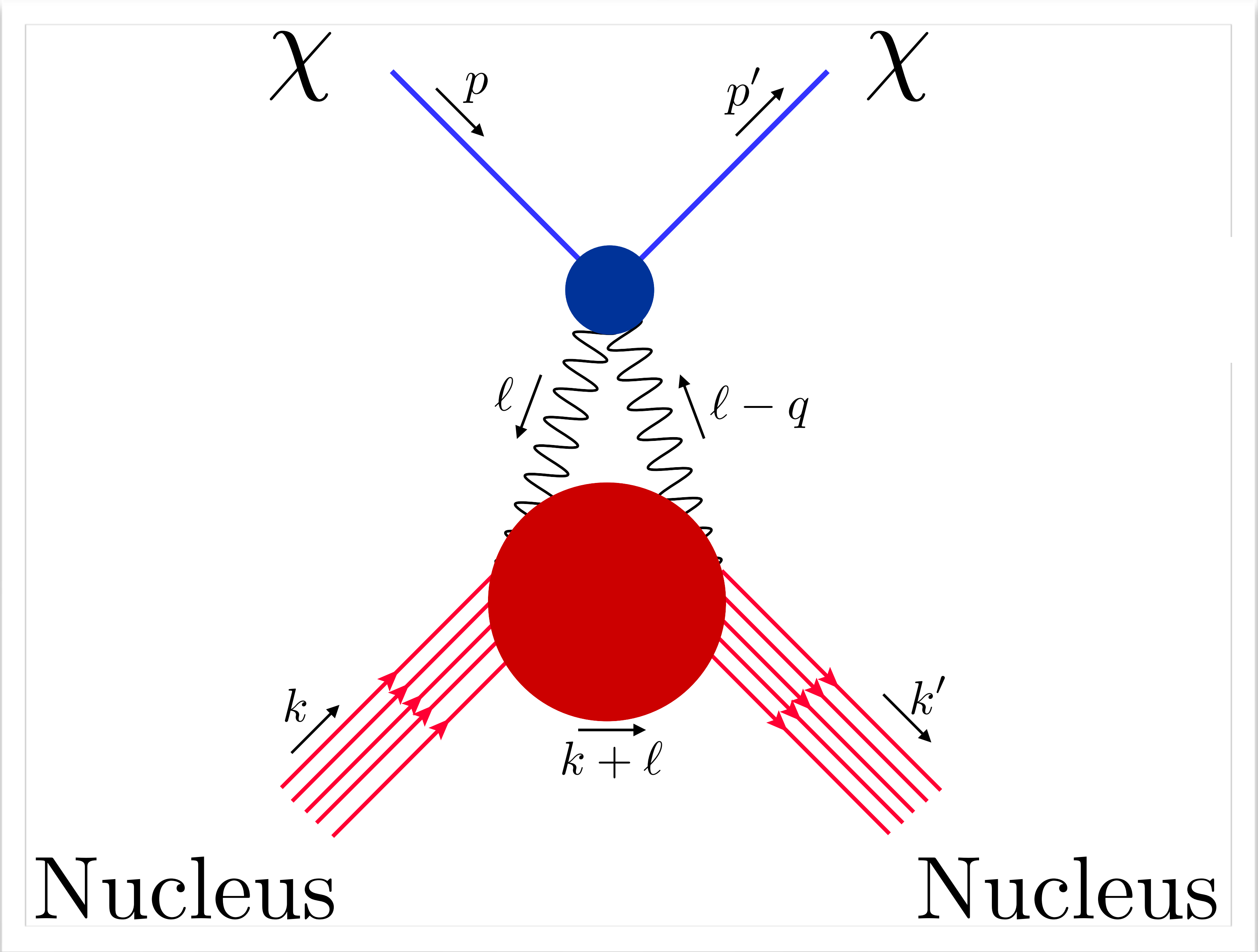


Computing polarizability

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



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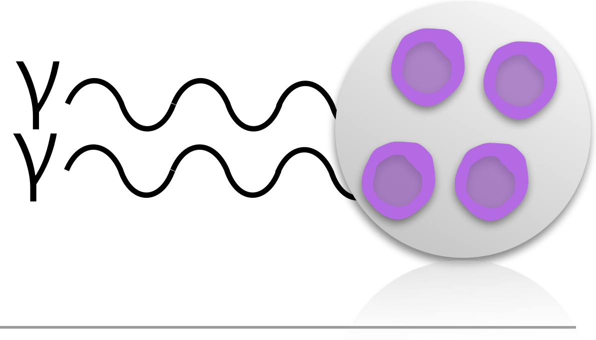

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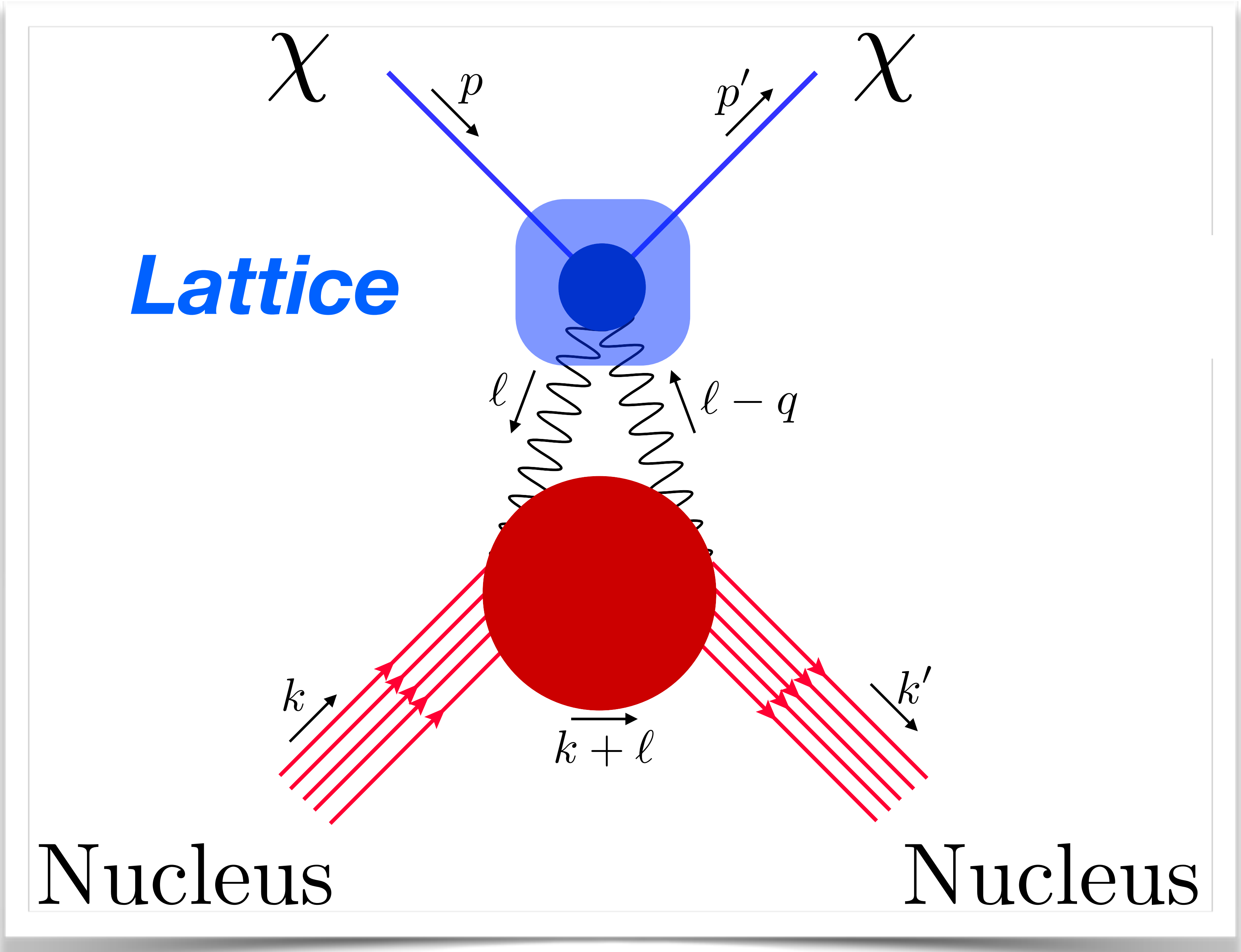

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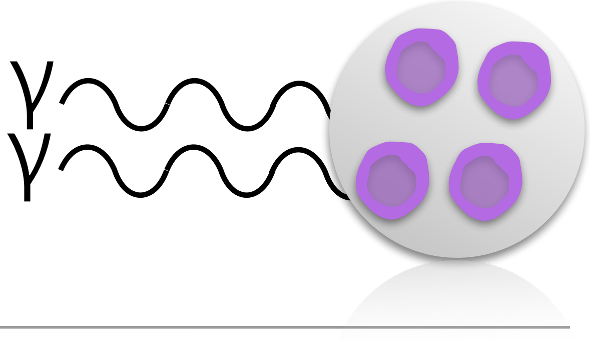

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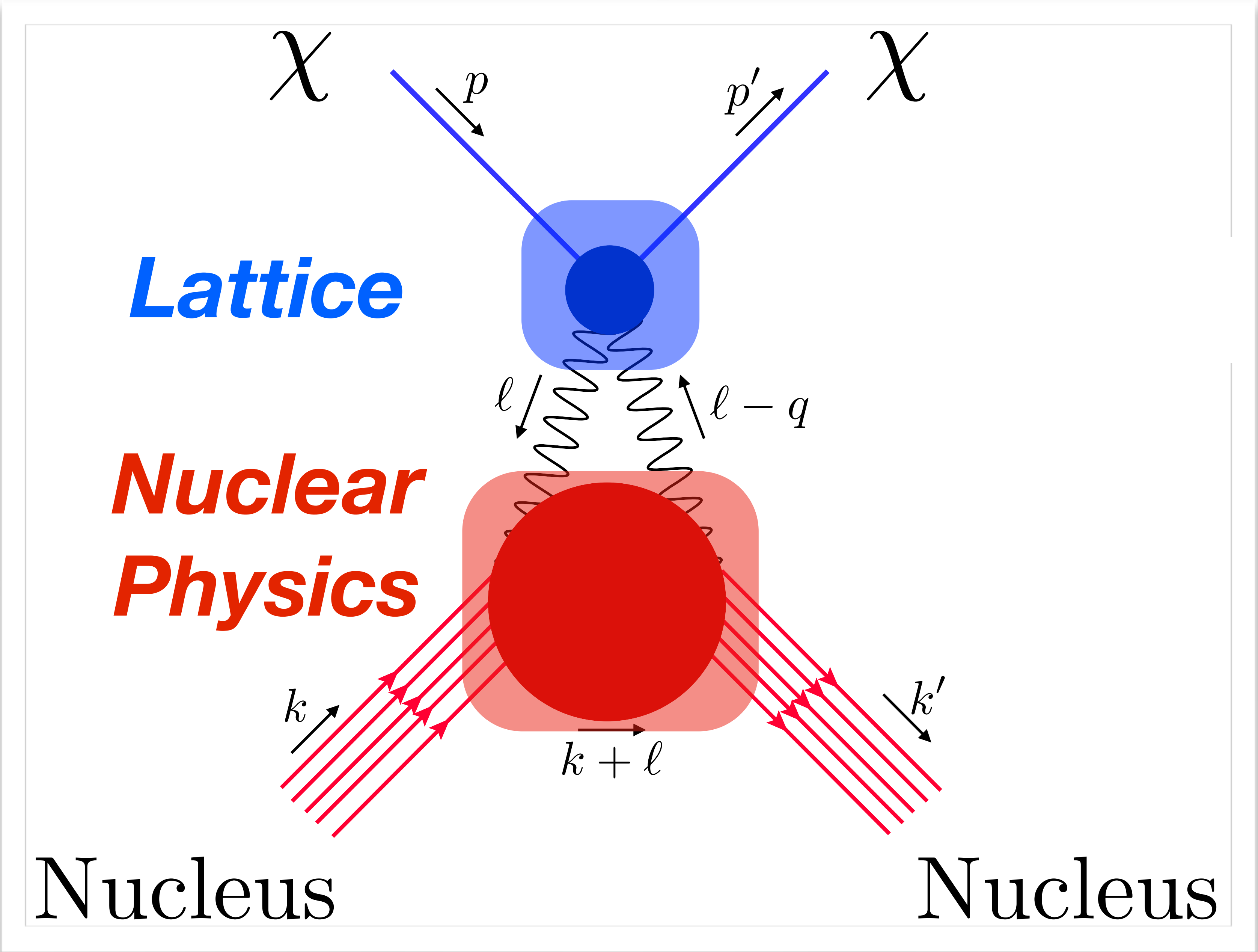


[LSD collab., Phys. Rev. Lett. 115 (2015) 171803]

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

Lattice: Polarizability of Dark Matter

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

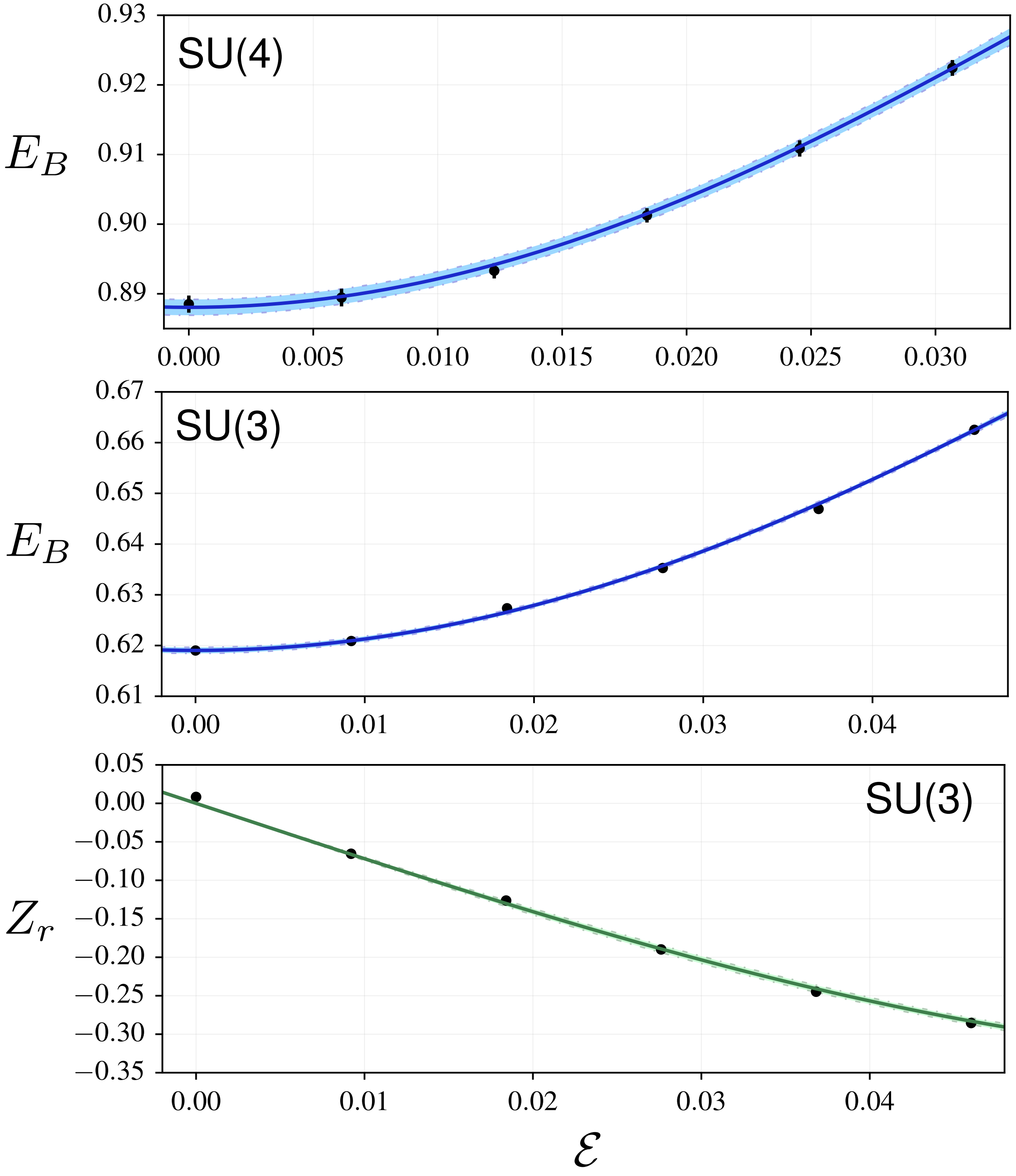
- Measure the shift of the baryon mass as a function of $\mathcal{E}$

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

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

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

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



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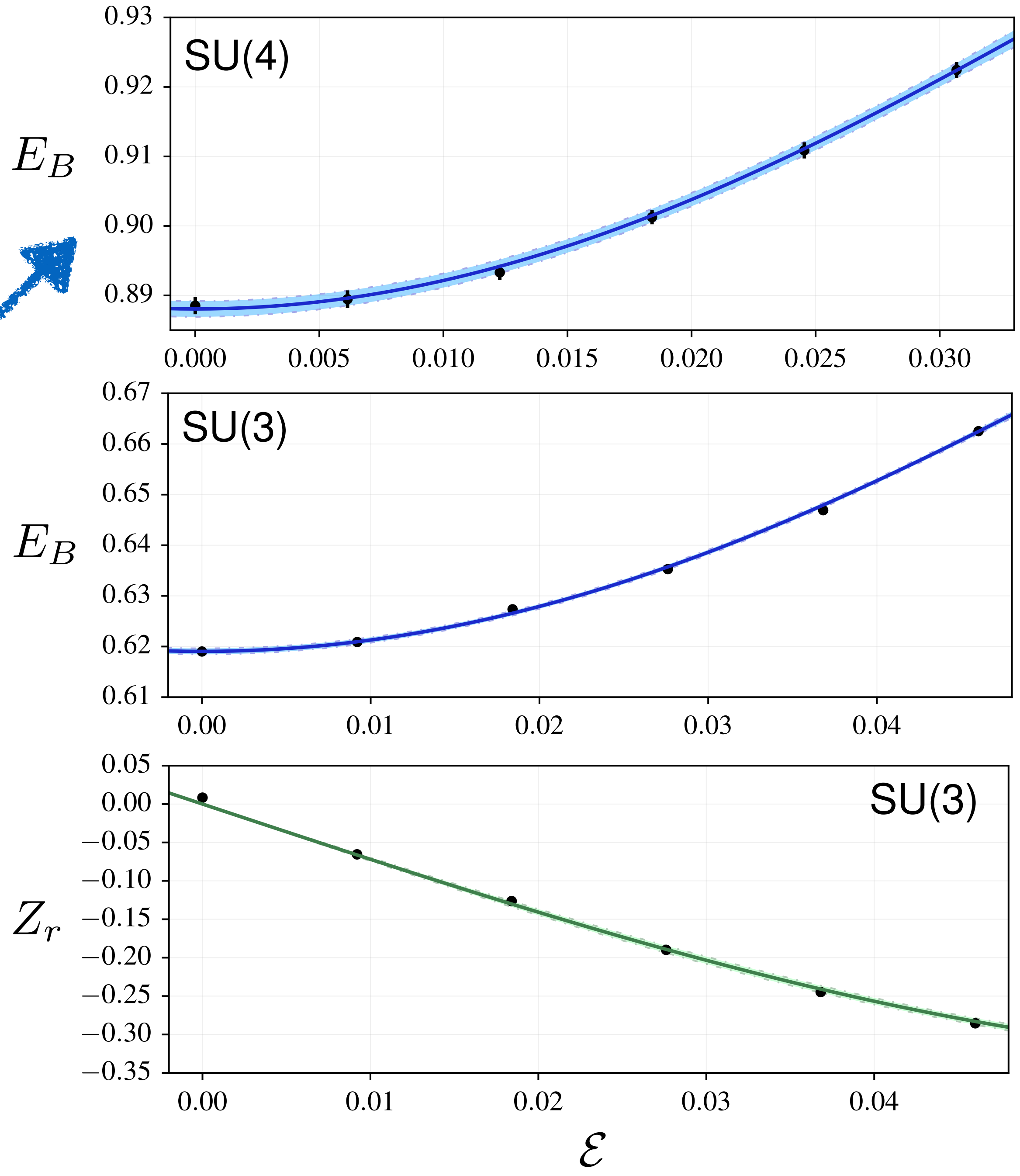

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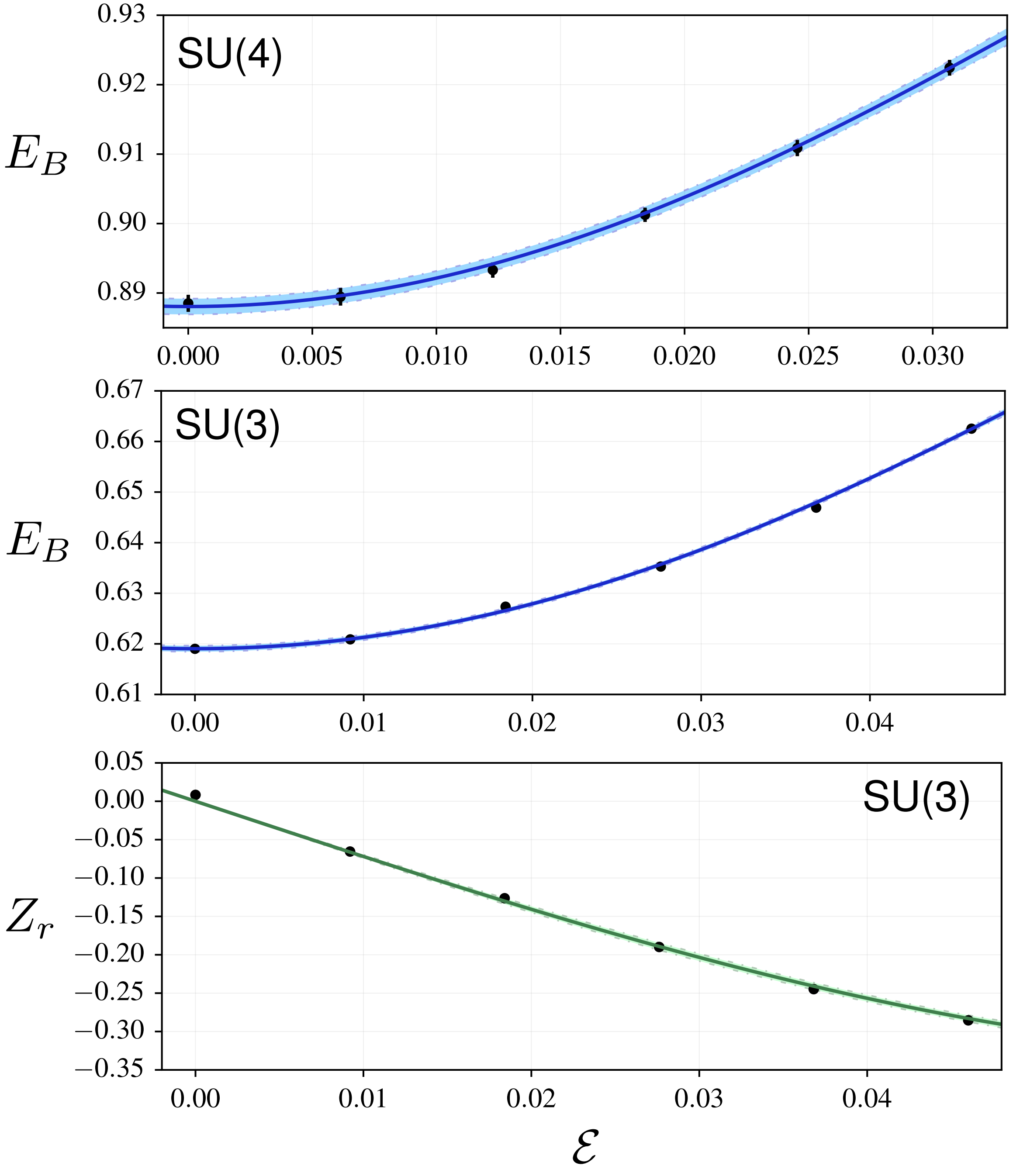

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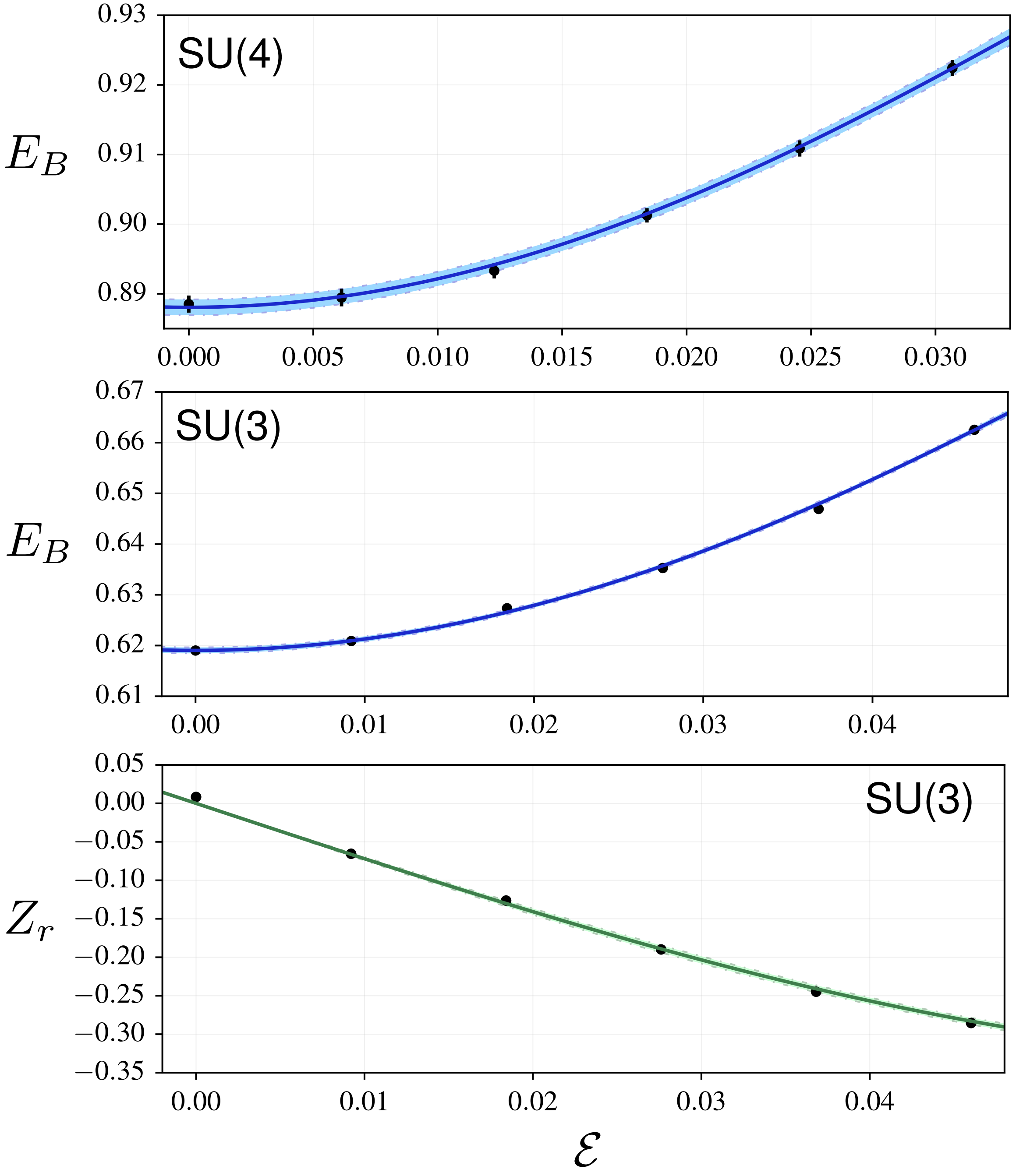

[Pospelov & Veldhuis, Phys. Lett. B480 (2000) 181]
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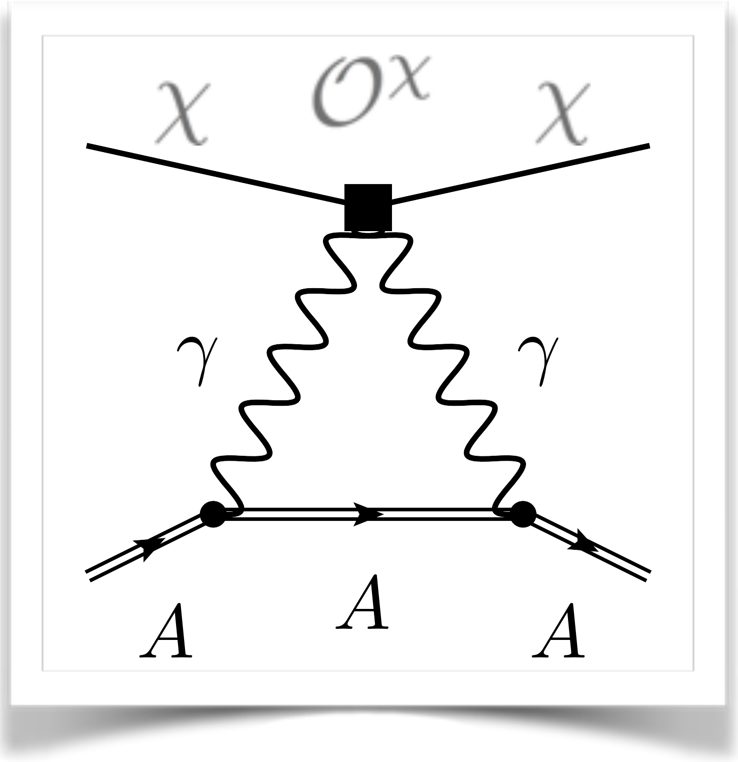
Nuclear: Rayleigh scattering



- 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

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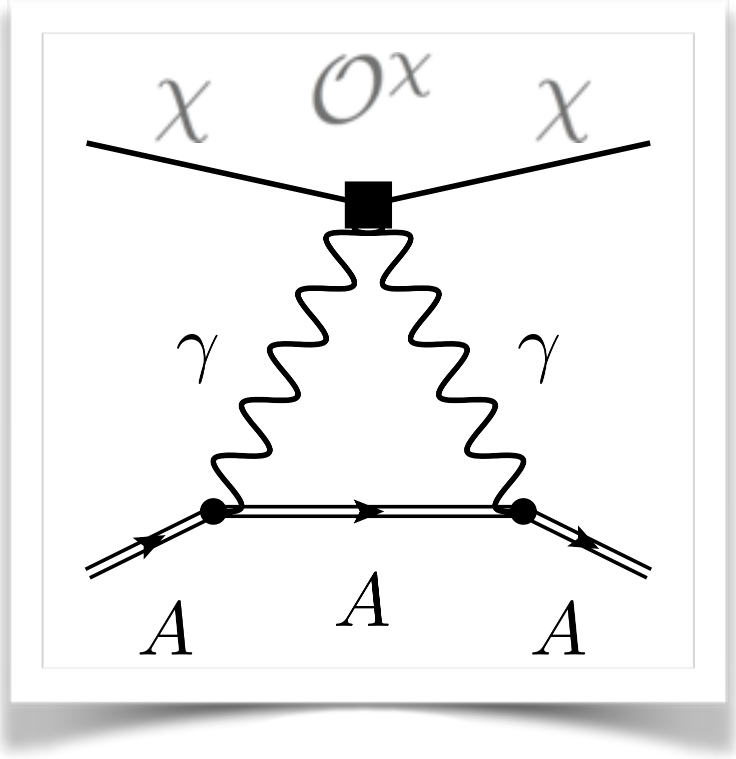

similar structure arising in double beta decay matrix elements: *two-nucleon effects*

Interesting nuclear physics problem!

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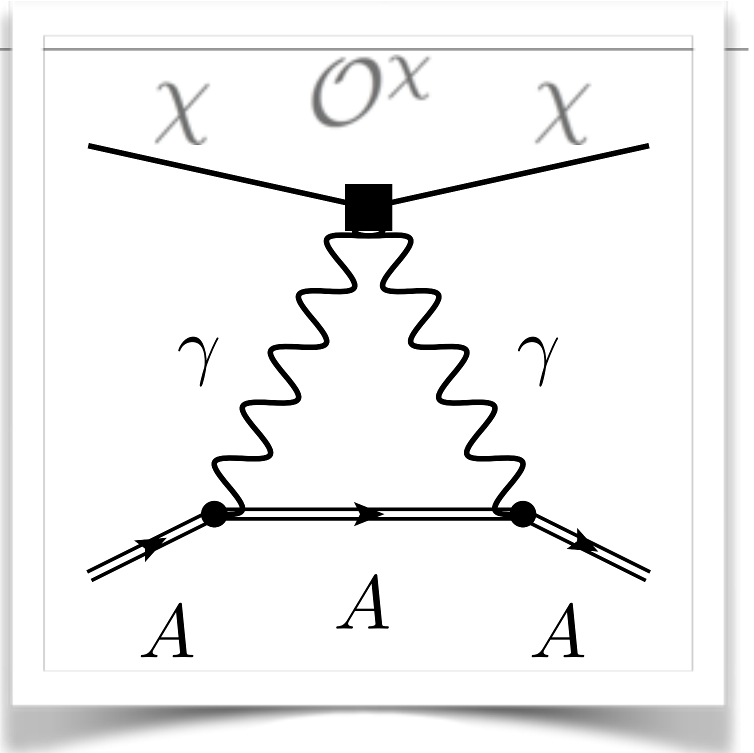

- it is hard to extract the momentum dependence of this nuclear form factor

- 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

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

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

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

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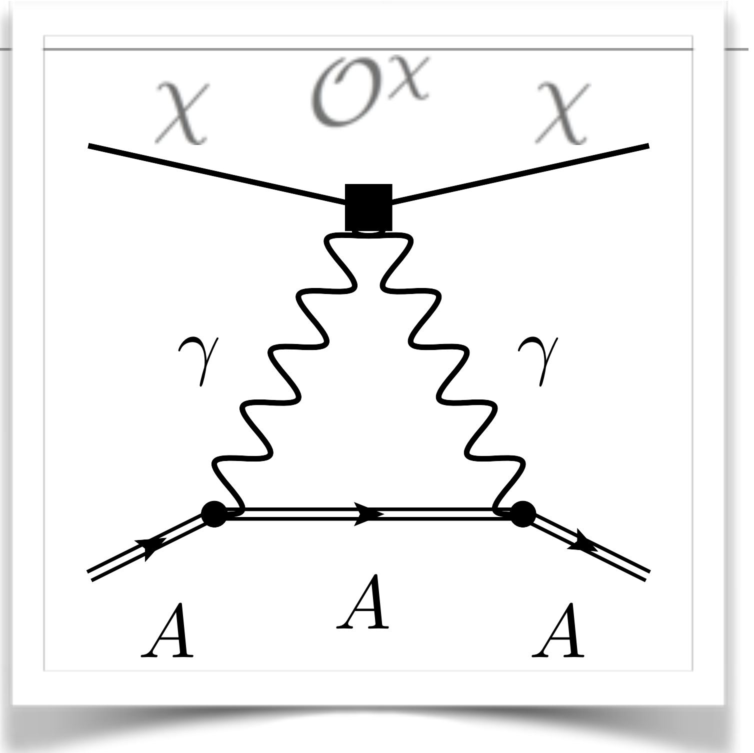

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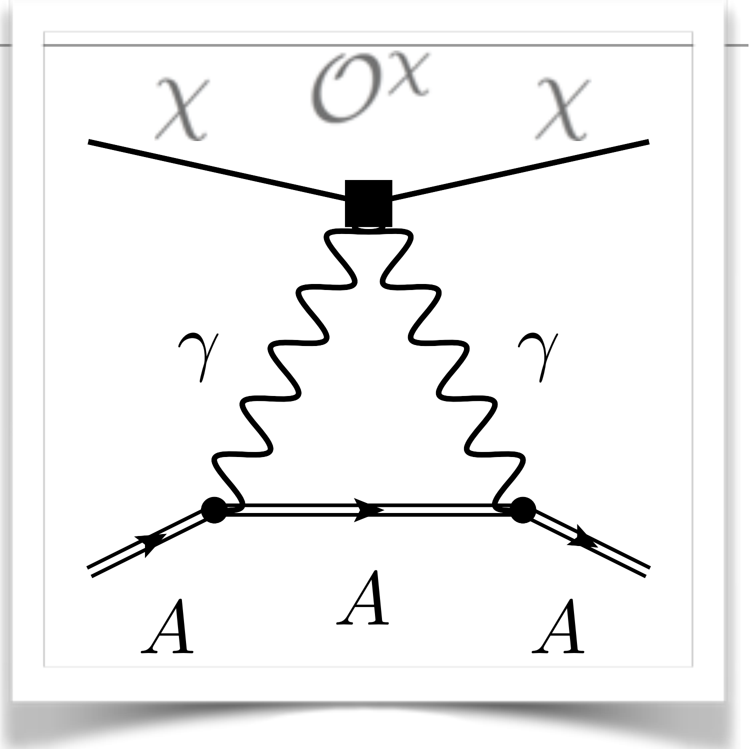

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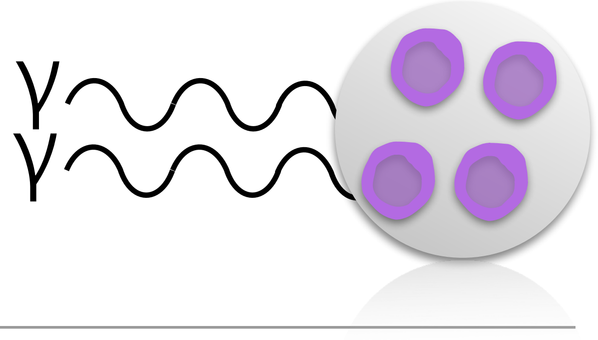
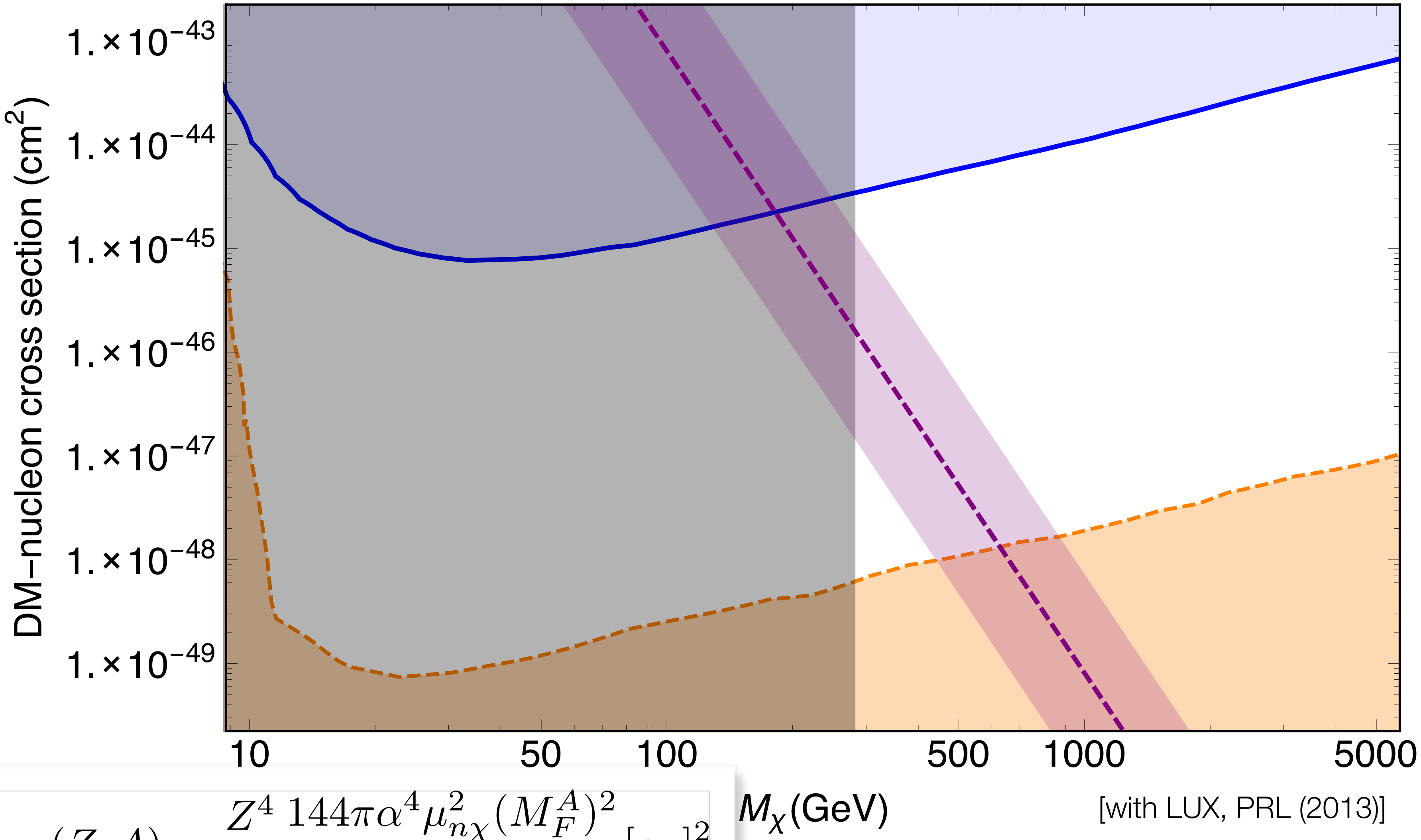
[NEW! PandaX-II, 1607.07400 and LUX-332d,1608.07648]

Lowest bound from EM polarizability



Electric polarizability from lattice simulations with background fields



[with LUX, PRL (2013)]

SU(4) N_f=4 Stealth DM

[LSD, 1503.04205]

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

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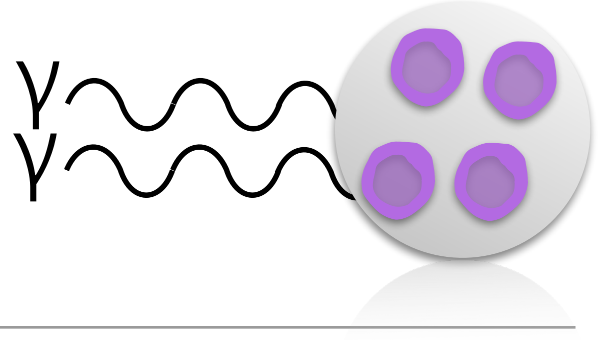
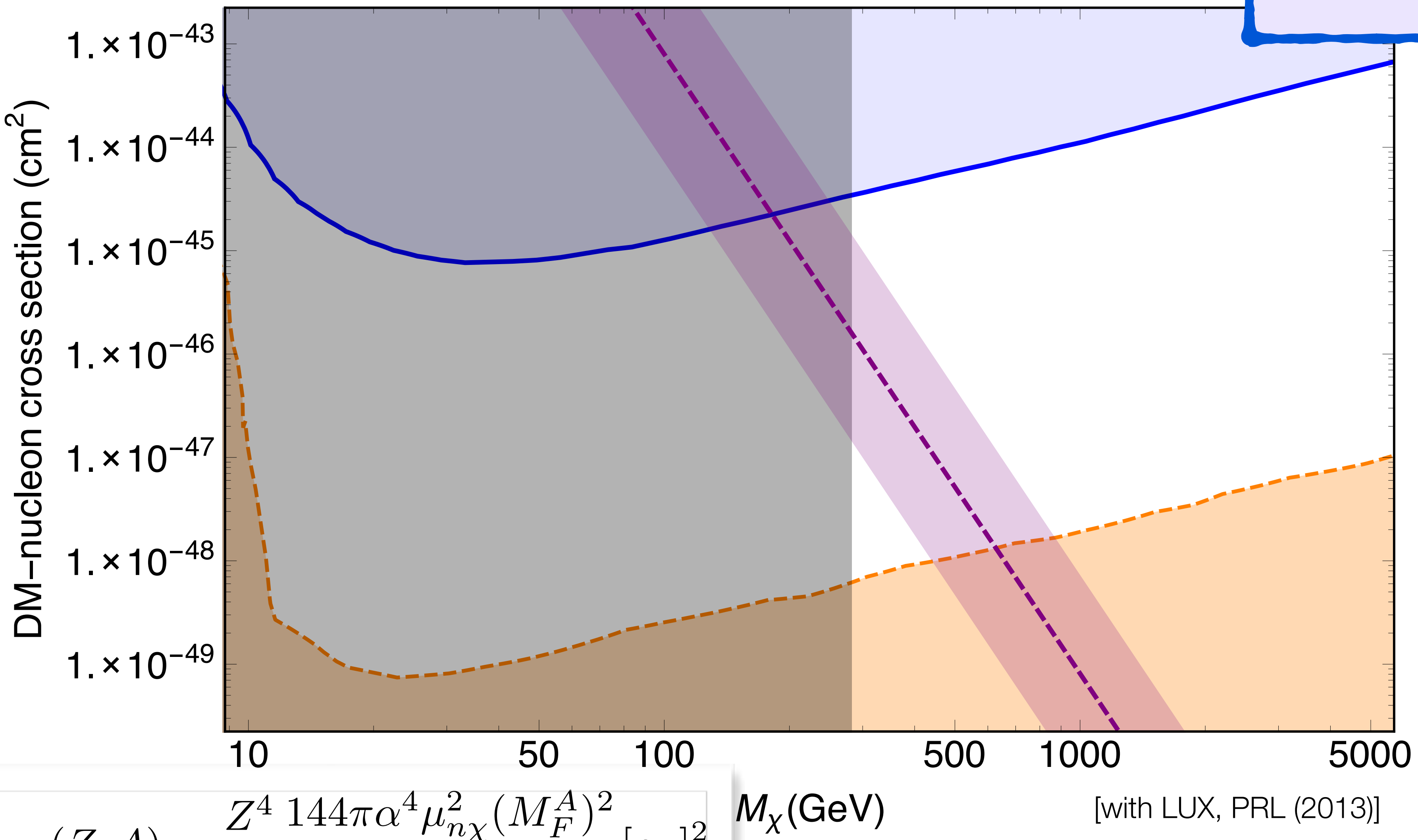


Electric polarizability from lattice simulations with background fields

LUX exclusion bound for spin-independent cross section



[with LUX, PRL (2013)]

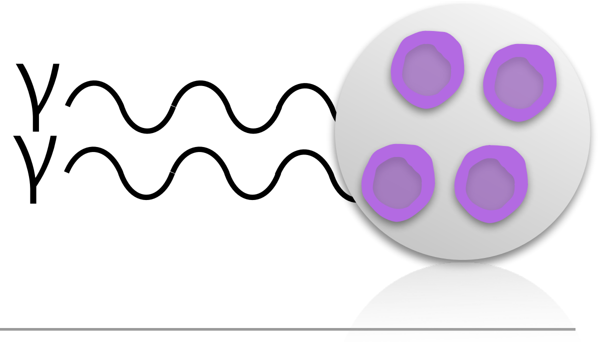
SU(4) N$_f$=4 Stealth DM

[LSD, 1503.04205]

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

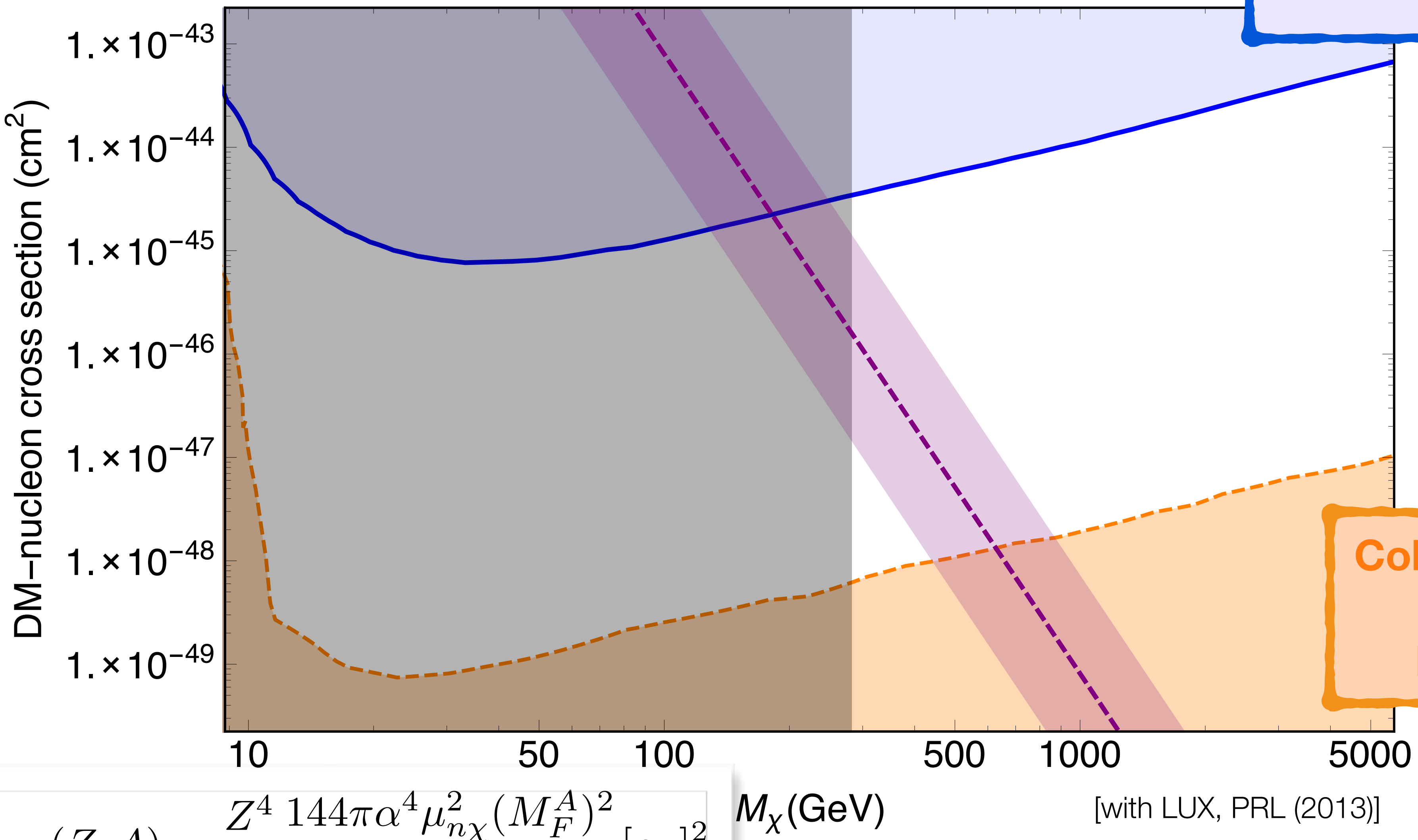
[NEW! PandaX-II, 1607.07400 and LUX-332d,1608.07648]

Lowest bound from EM polarizability



Electric polarizability from lattice simulations with background fields

LUX exclusion bound for spin-independent cross section



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Coherent neutrino scattering background

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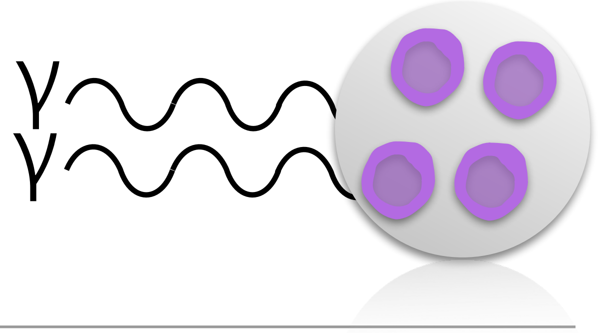

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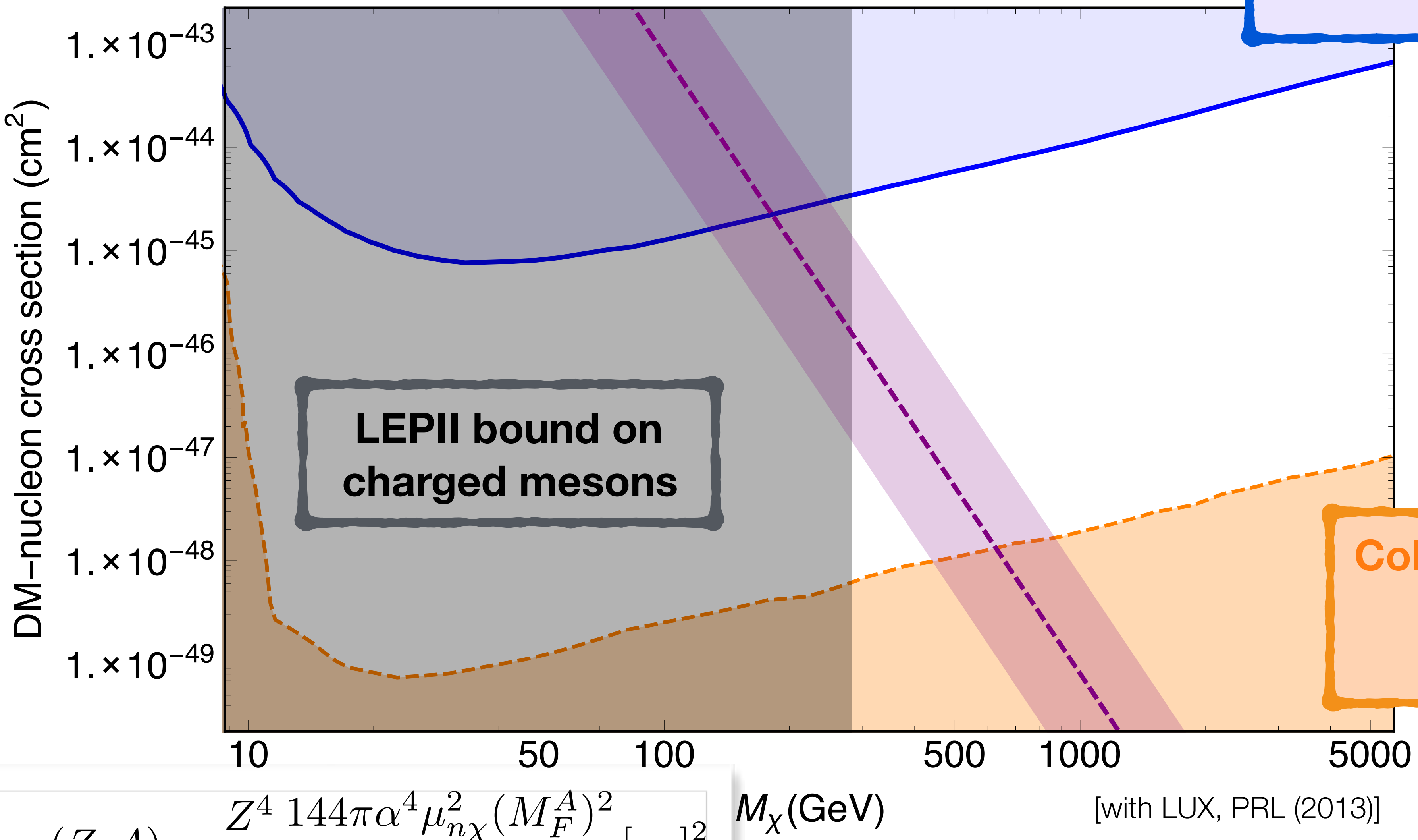

LEPII bound on charged mesons

SU(4) N_f=4 Stealth DM

[LSD, 1503.04205]

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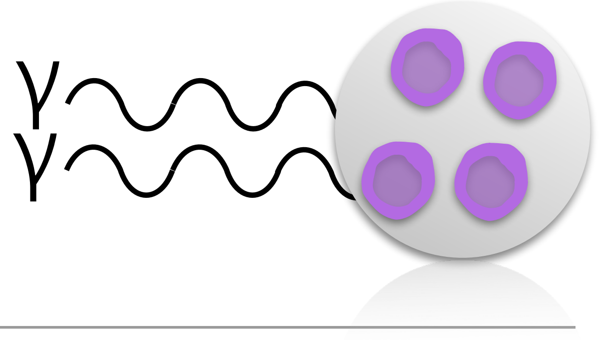

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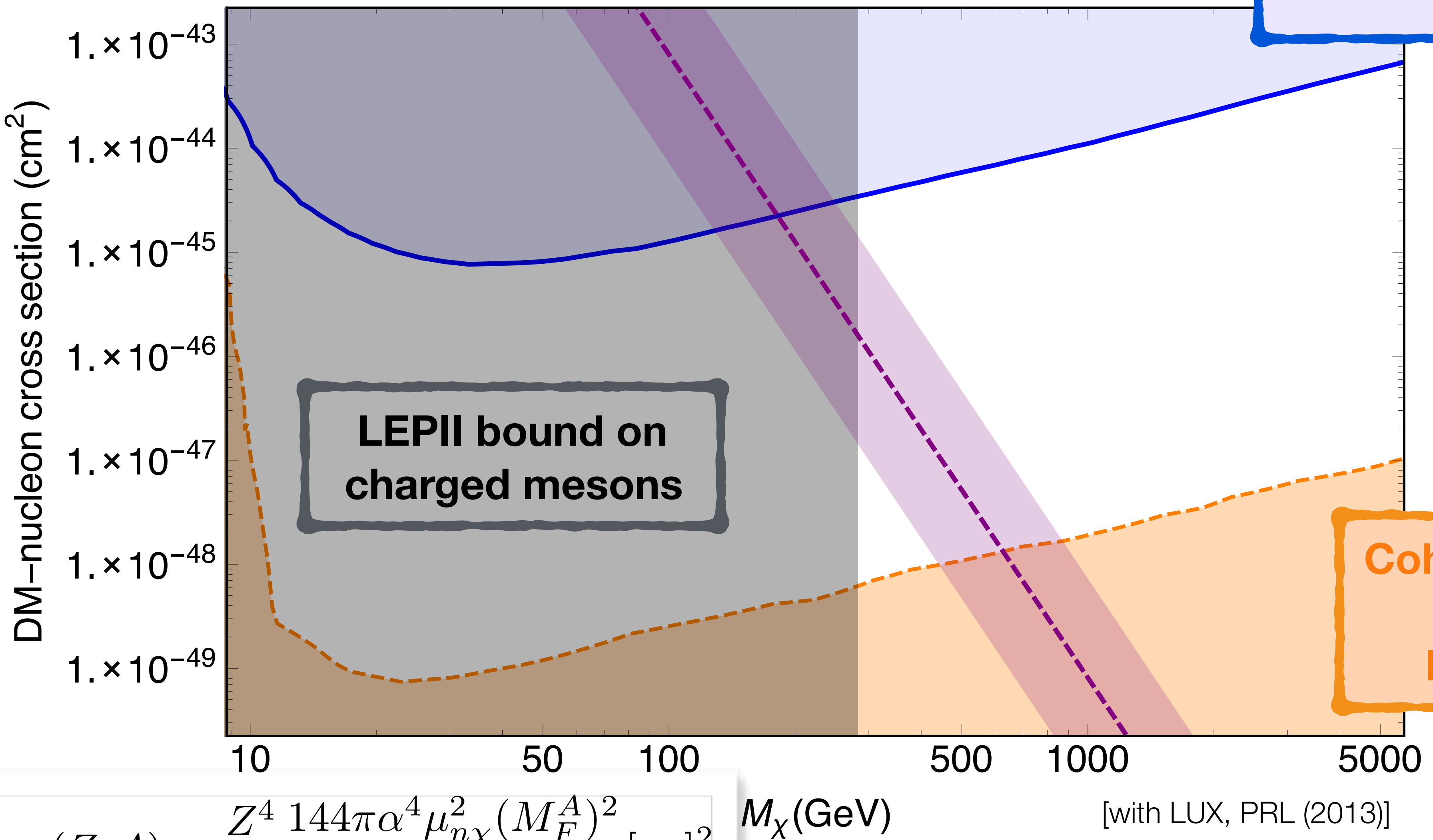

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Coherent neutrino scattering background

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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.

Open questions and future projects

- Structure formation in galaxies ➜ influenced by DM scattering cross-section: hadron-hadron interactions are hard to model, but can be studied directly with lattice methods. *Discussion: Can we use large-N methods?*

- Colliders could produce the (lightest) dark mesons, but need to know their form factors: lattice methods can be used

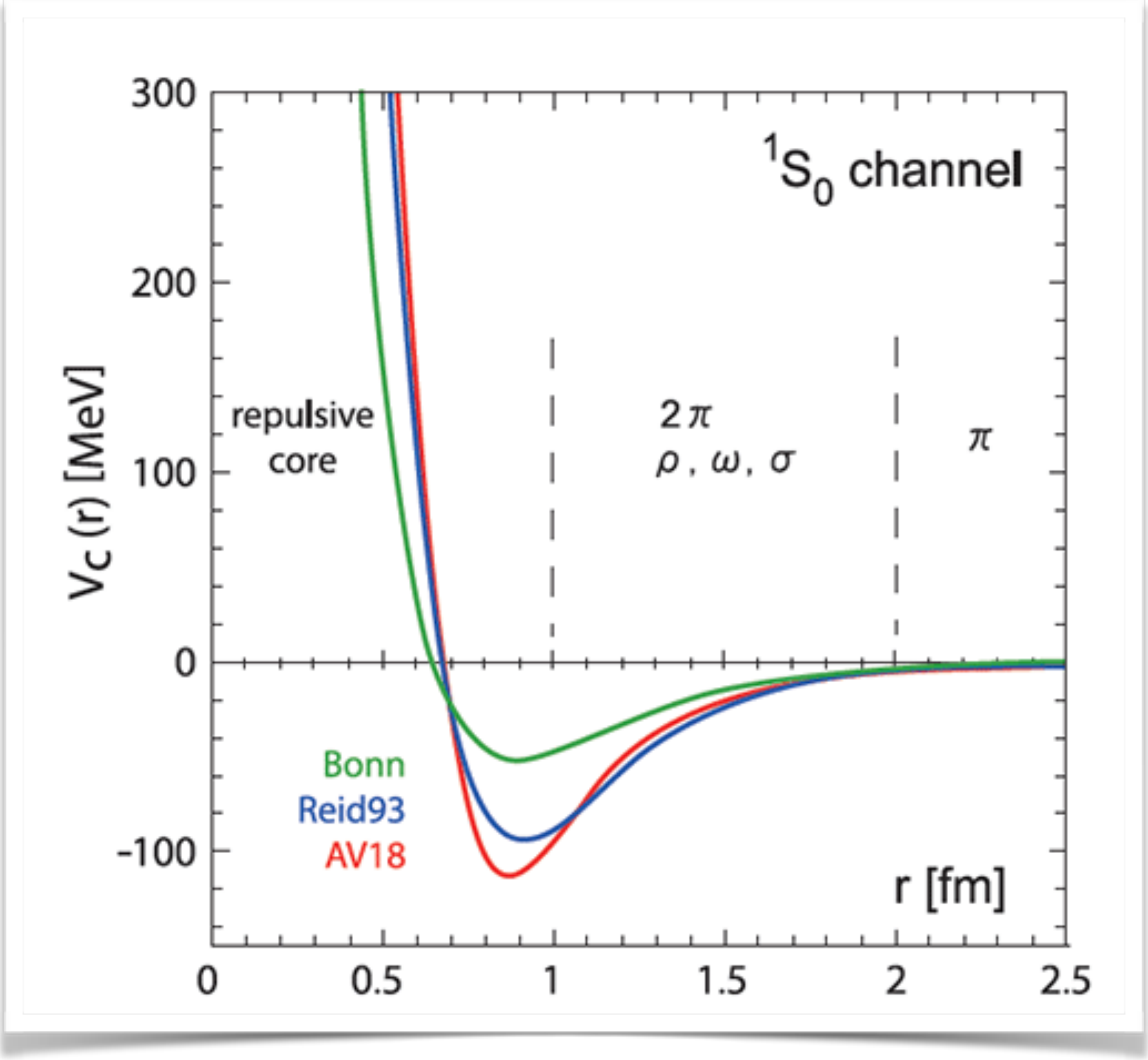
- New dark sector ➜ deconfinement phase transition: if first order, gravitational wave signals could be soon observed
  [Schwaller, 1504.07263]

[Gross, KITP-nuclear16: http://online.kitp.ucsb.edu/online/nuclear16/gross/]
[Savage, KITP-nuclear16: http://online.kitp.ucsb.edu/online/nuclear16/qcdanthrop/]

[E. Witten, Nucl.Phys. B160, 57 (1979)]
[D. B. Kaplan and M. J. Savage, Phys.Lett. B365, 244 (1996)]
[D. B. Kaplan and A. V. Manohar, Phys.Rev. C56, 76 (1997)]
[T. D. Cohen, Phys.Rev. C66, 064003 (2002)]
[S. R. Beane, hep-ph/0204107]
[L. Bonanno and F. Giacosa, 1102.3367]

Discussion: nuclear matter at large N_c

- Interesting to change the number of colors in a non-abelian SU(N) theory: AdS/CFT, Anthropic, Dark Matter
- *Lattice simulations* give us a way to test large-N_c predictions: already true for glueball masses, meson masses, baryon masses, baryon structure
- Situation much more uncertain for scattering properties: what is the potential between two large-N_c baryons or glueballs?



[Ishii et al. 2007]

[Gross, KITP-nuclear16: http://online.kitp.ucsb.edu/online/nuclear16/gross/]
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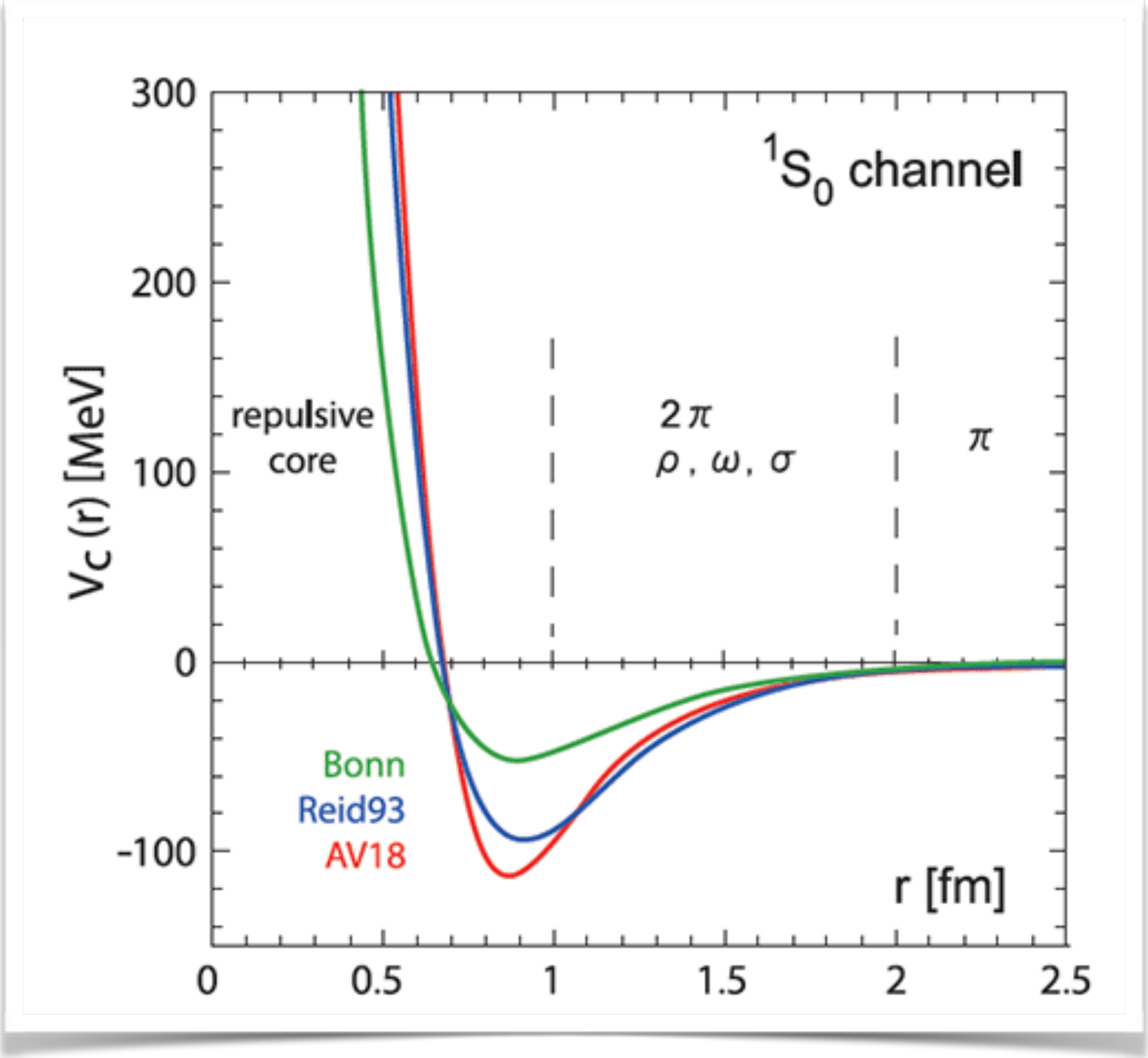
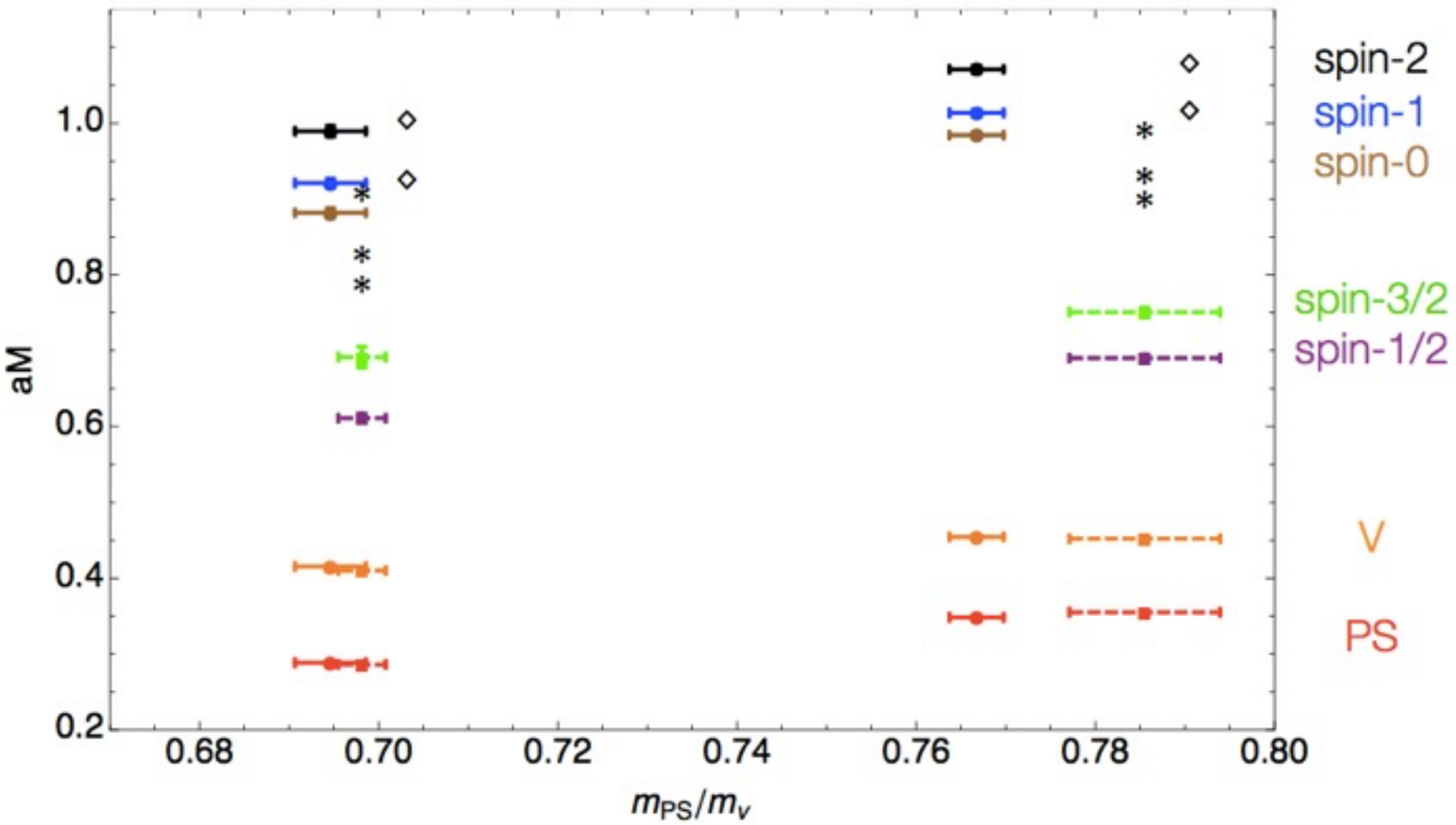


[Ishii et al. 2007]

is nuclear matter universal?

extra

Rotor spectrum at large N



$$* : \ M(N_c, J) = N_c m_0 + \frac{J(J+1)}{N_c} B + \mathcal{O}(1/N_c^2)$$

$$\diamond : \ M(N_c, J) = N_c m_0^{(0)} + C + \frac{J(J+1)}{N_c} B + \mathcal{O}(1/N_c^2)$$

Slide courtesy of
E. Neil

SU(3) polarizability vs. the PDG

- Our polarizability differs from the PDG convention:

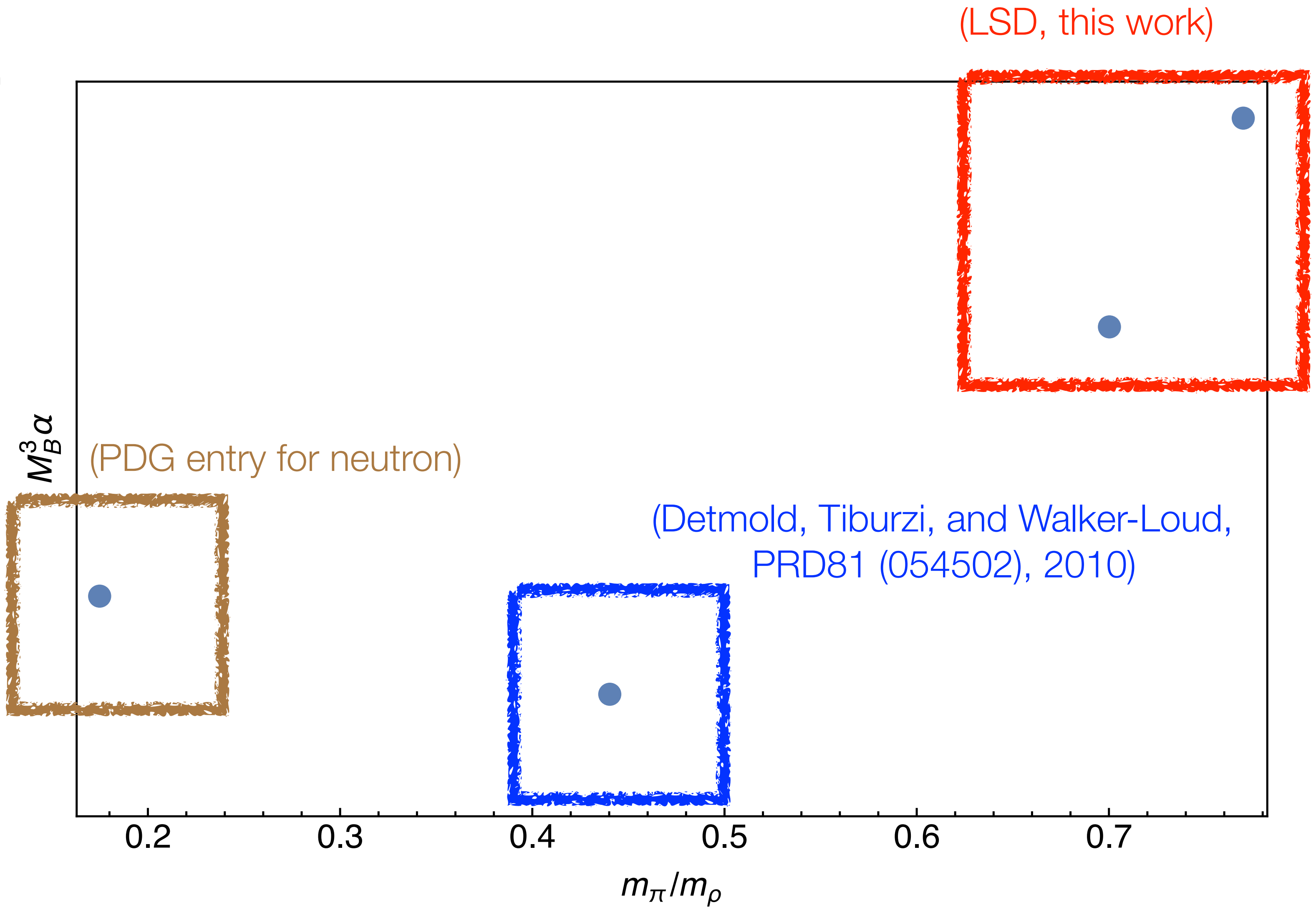
$$\alpha_E = C_F/\pi$$

- Have to compare at very different masses! Expected scaling is

$$\alpha_E \sim \frac{A}{m_\pi} + B$$

$$m_B \sim C + Dm_\pi^2$$

- Qualitative agreement with expected trend! (Can't fit well - mass range too large.)



[Grießhammer et al., 1511.01952]

Slide courtesy of E. Neil