La Sapienza, Roma

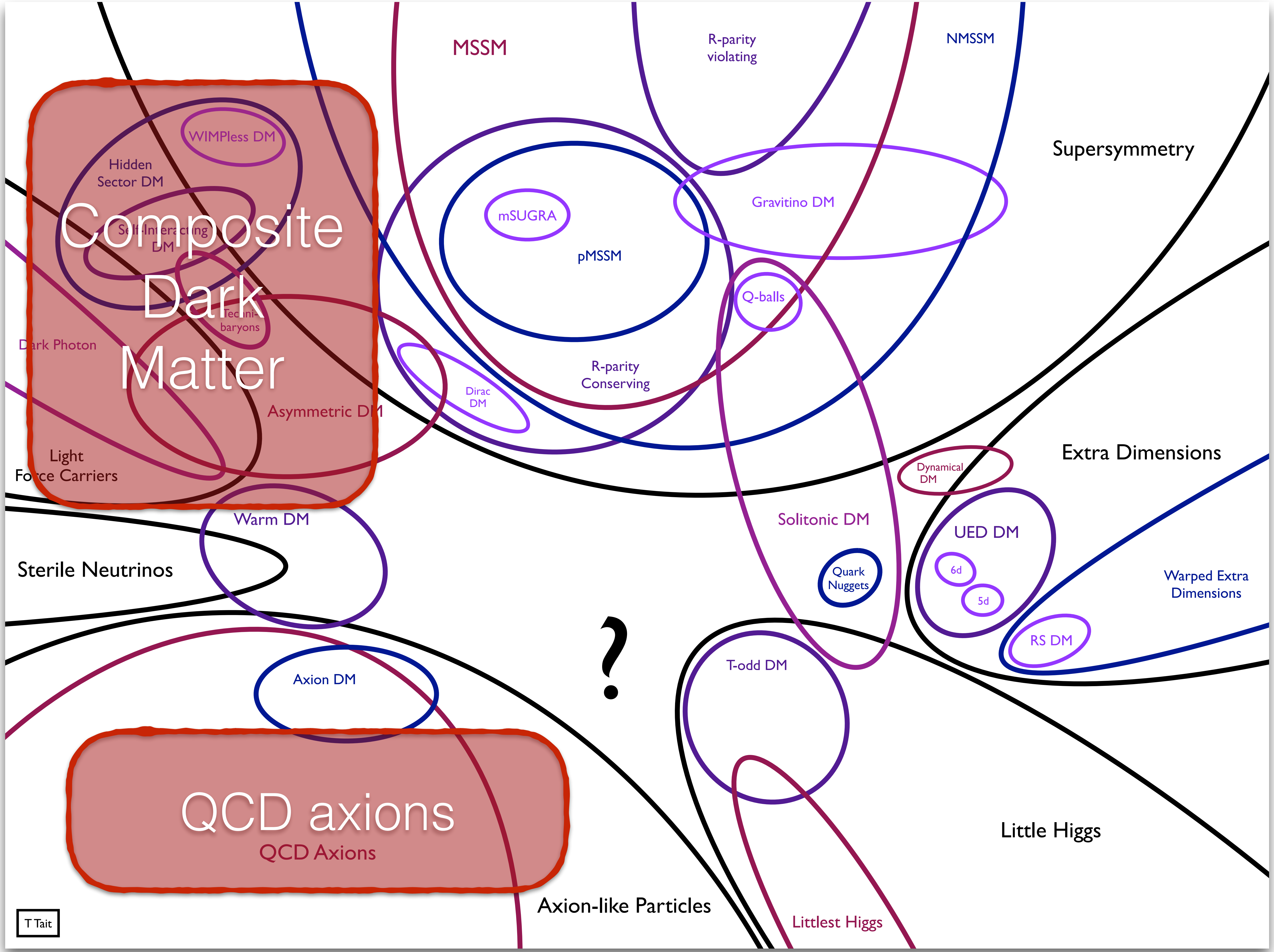
23 Febbraio 2017

BROOKHAVEN
NATIONAL LABORATORY

What lattice gauge theories can do for Dark Matter searches

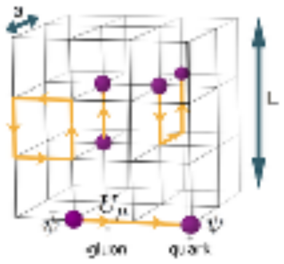
Enrico Rinaldi

RIKEN BNL Research Center

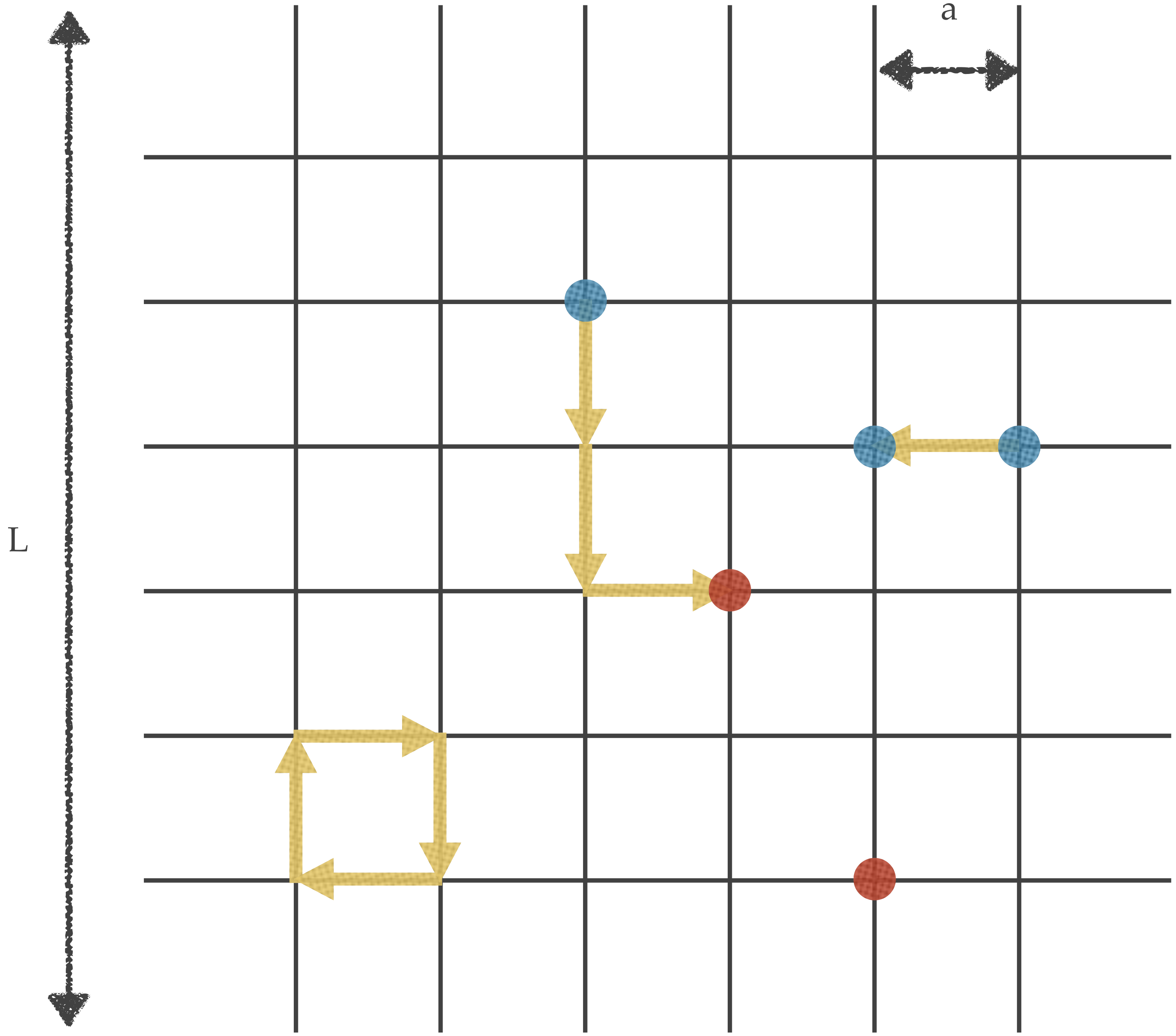


[Planning the Future of U.S. Particle Physics (Snowmass 2013), 1401.6085]

[KEK-Japan]

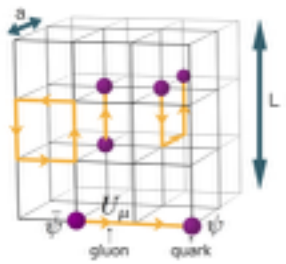


Lattice Gauge Theory - basics

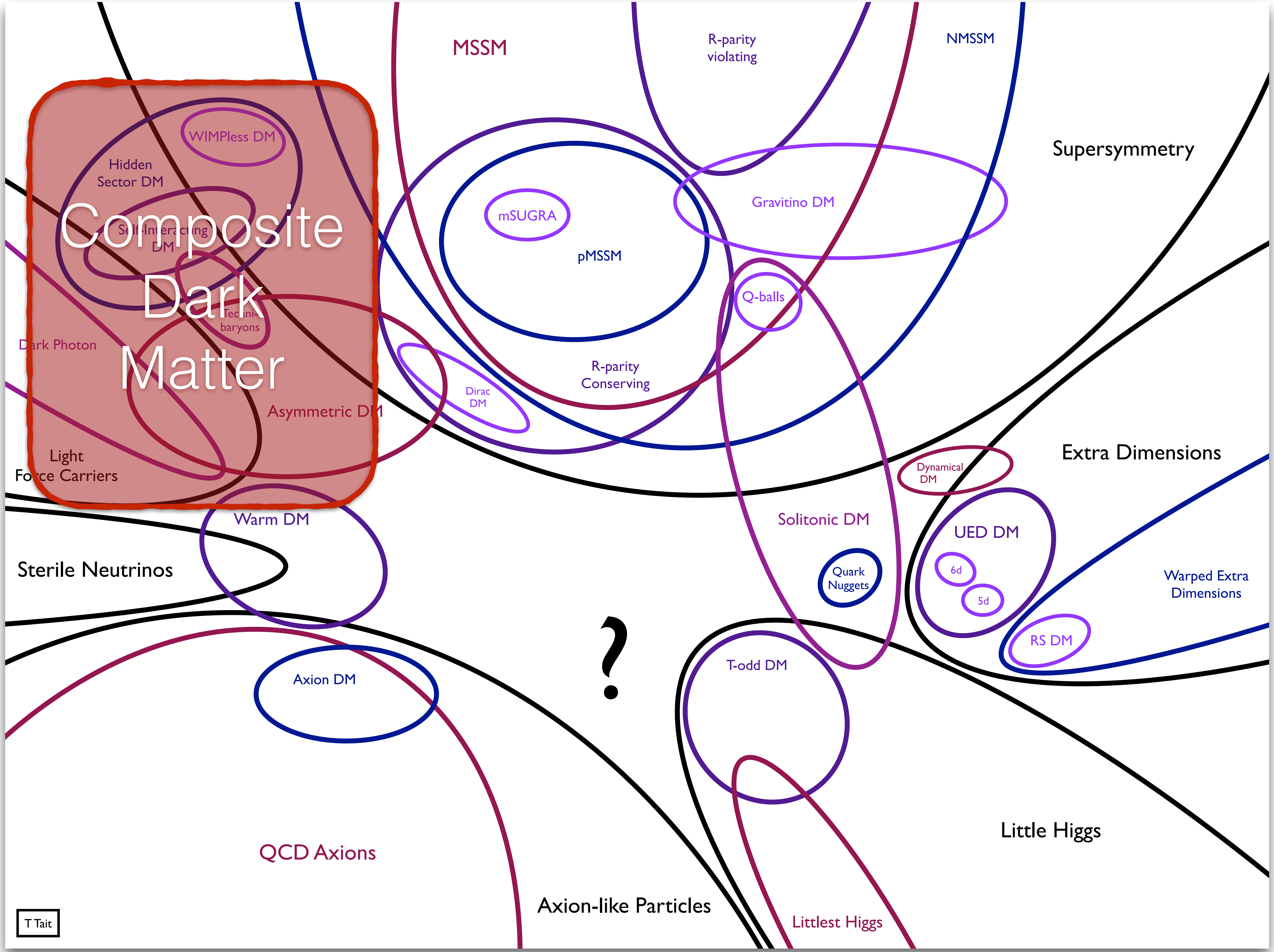


- Discretize space and time
  - lattice spacing “a”
  - lattice size “L”
- Keep all d.o.f. of the theory
  - not a model!
  - no simplifications
- Amenable to numerical methods
  - Monte Carlo sampling
  - use supercomputers
- Precisely quantifiable and improvable errors
  - Systematic
  - Statistical

Importance of lattice field theory simulations


[KEK-Japan]

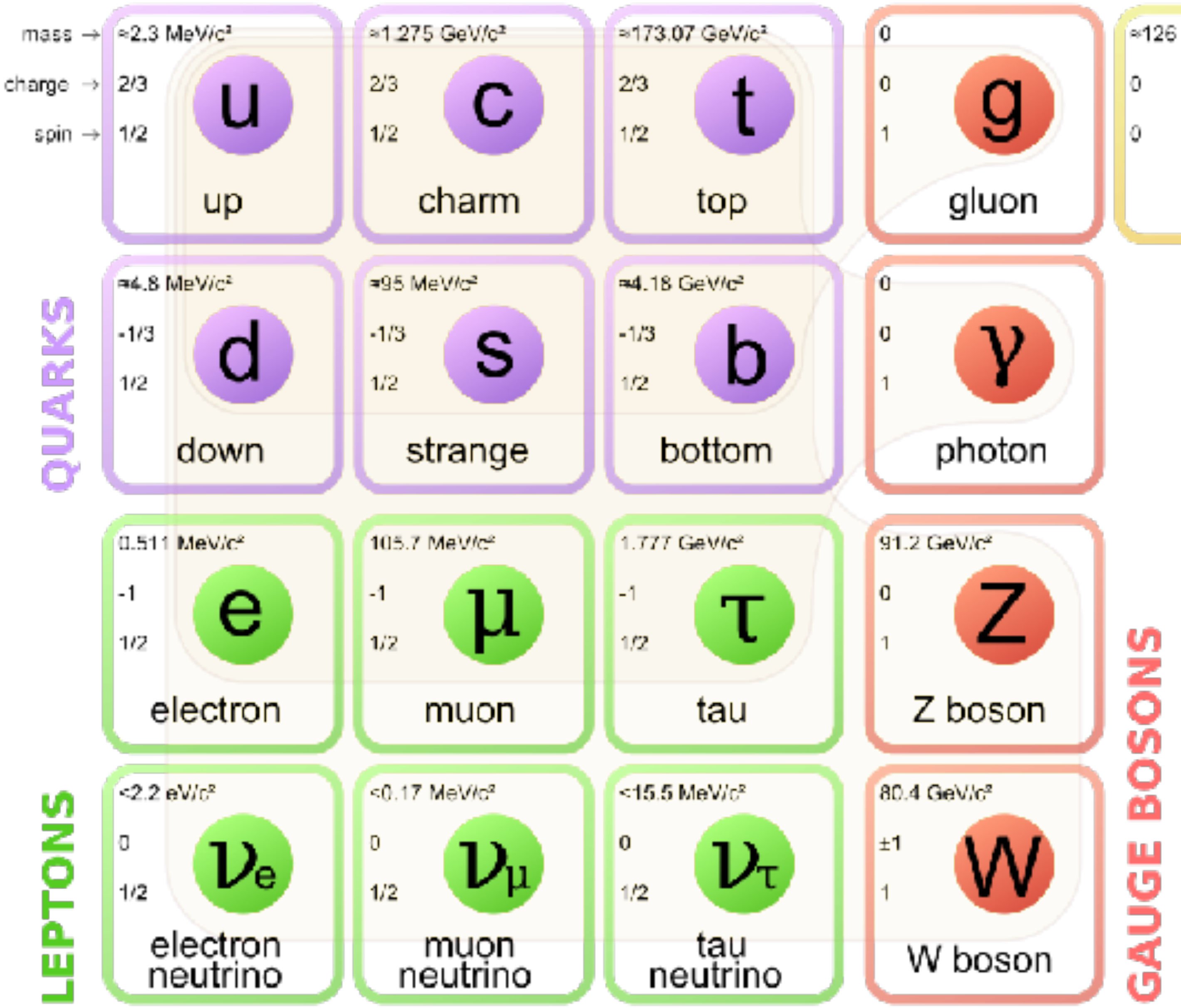
- *lattice simulations are needed to numerically solve strong dynamics*
- controllable systematic errors and room for improvement
- Naive dimensional analysis and EFT approaches can miss important non-perturbative contributions
- NDA is not precise enough when confronting experimental results and might not work for certain situations: there are uncontrolled theoretical errors



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

A very familiar picture

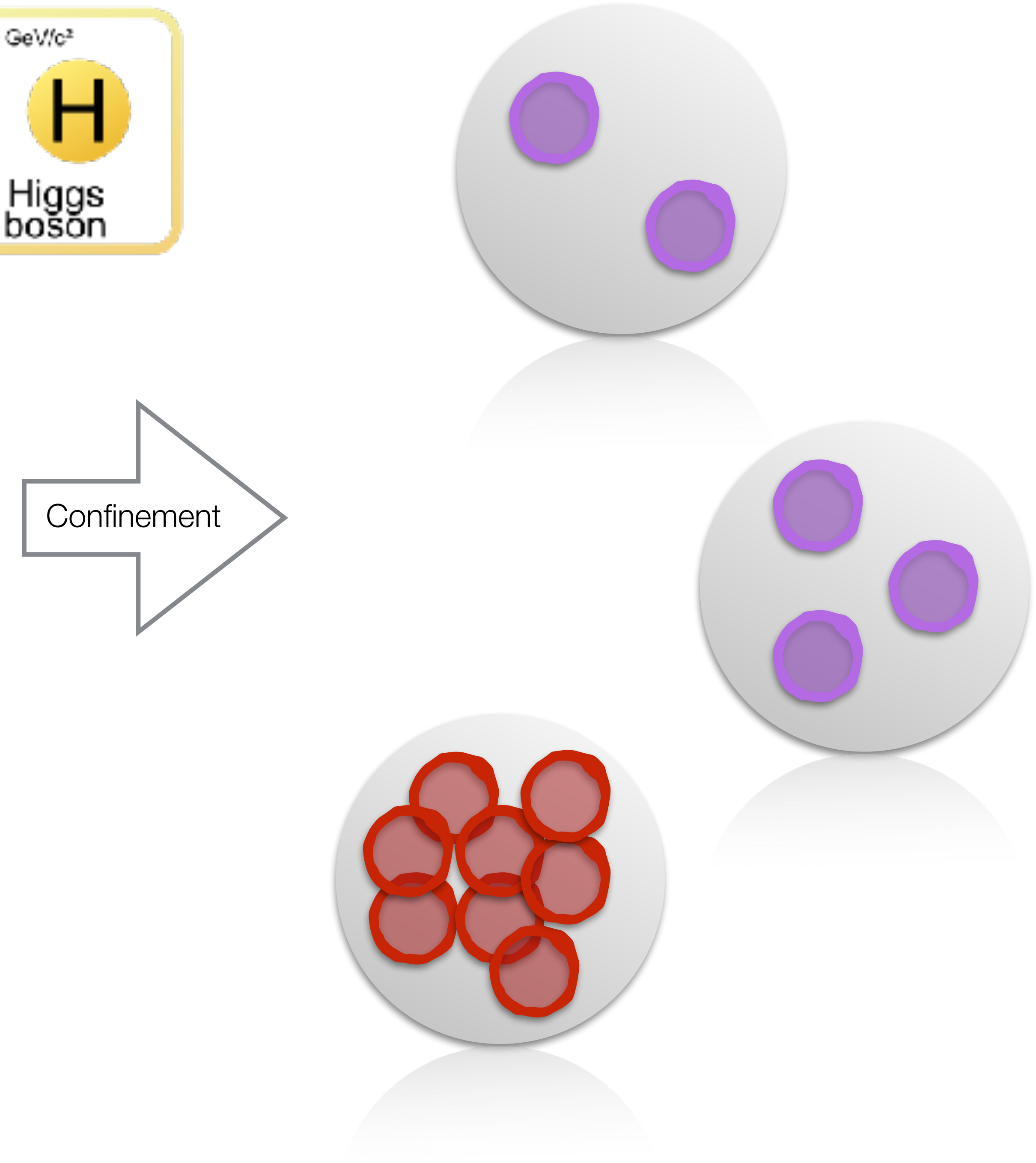
The Standard Model of particles



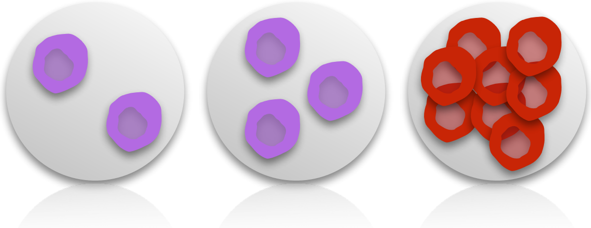
mass → charge → spin →	≈ 2.3 MeV/c^2 2/3 1/2 u up	≈ 1.275 GeV/c^2 2/3 1/2 c charm	≈ 173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈ 126 GeV/c^2 0 0 H Higgs boson
QUARKS	≈ 4.8 MeV/c^2 -1/3 1/2 d down	≈ 95 MeV/c^2 -1/3 1/2 s strange	≈ 4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
	0.511 MeV/c^2 -1 1/2 e 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



- Dark Matter is a composite object

e.g. techni-baryon or hidden glueball

- Interesting and complicated internal structure

Lattice Field Theory methods

- Properties dictated by strong dynamics

Similar to QCD

- Self-interactions are natural
- Composite object is neutral

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

- Constituents interact with Standard Model particles

[review by Kribs & Neil, 1604.04627]

Natural features of Composite Dark Matter

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

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

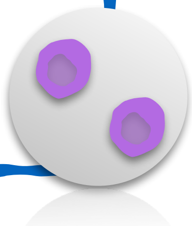
[list of references focused on lattice results when possible]

[review by Kribs & Neil, 1604.04627]

Models for Composite Dark Matter

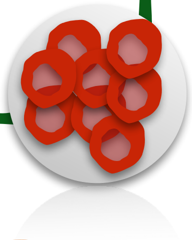
★ Pion-like (dark quark-antiquark)

- ✦ pNGB DM *[Hietanen et al.,1308.4130]*
- ✦ Quirky DM *[Kribs et al.,0909.2034]*
- ✦ Ectocolor DM *[Buckley&Neil,1209.6054]*
- ✦ SIMP *[Hochberg et al.,1411.3727]*
- ✦ Minimal SU(2) *[Lewis,1610.10068]*

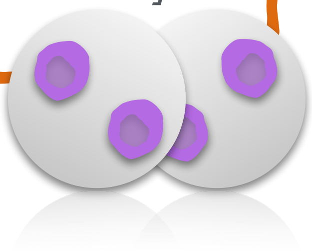


★ Glueball-like (only gluons)

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

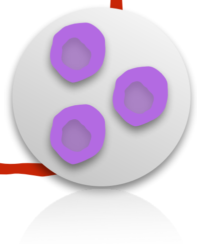


★ Dark Nuclei *[Detmold et al.,1406.2276-1406.4116]*



★ Baryon-like (multiple quarks)

- ✦ "Technibaryons" *[LSD,1301.1693]*
- ✦ Stealth DM *[LSD,1503.04203-1503.04205]*
- ✦ One-family WTC *[LatKMI,1510.07373]*
- ✦ Sextet CH *[LatHC,1601.03302]*



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

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

[Antipin et al., 1503.08749]

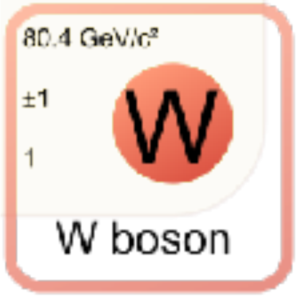
The darkness of Composite Dark Matter

Relevant if the constituents have SM color charges

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

Lowest dimensional operators:

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



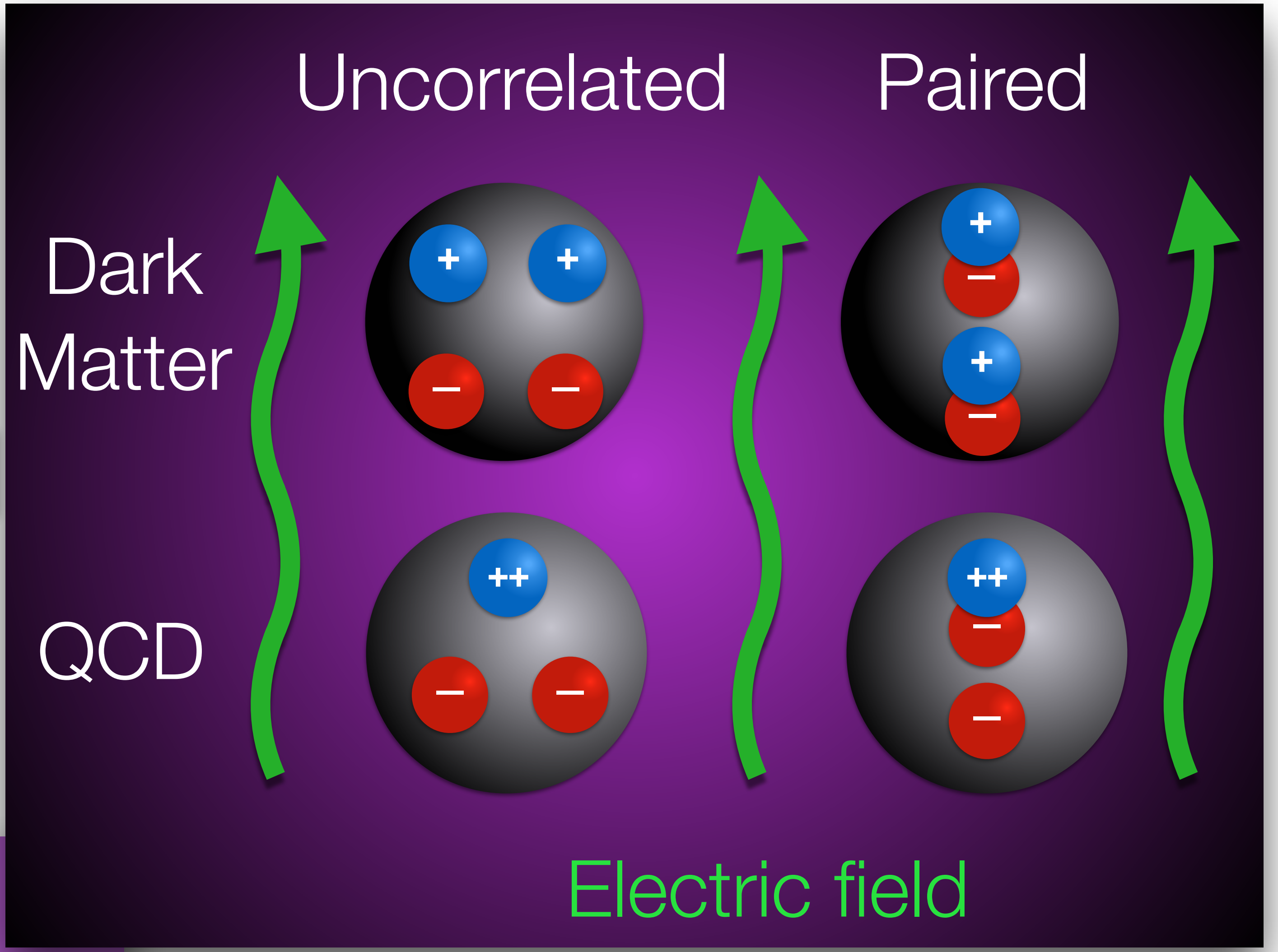
Same as γ but suppressed due to heavy mass

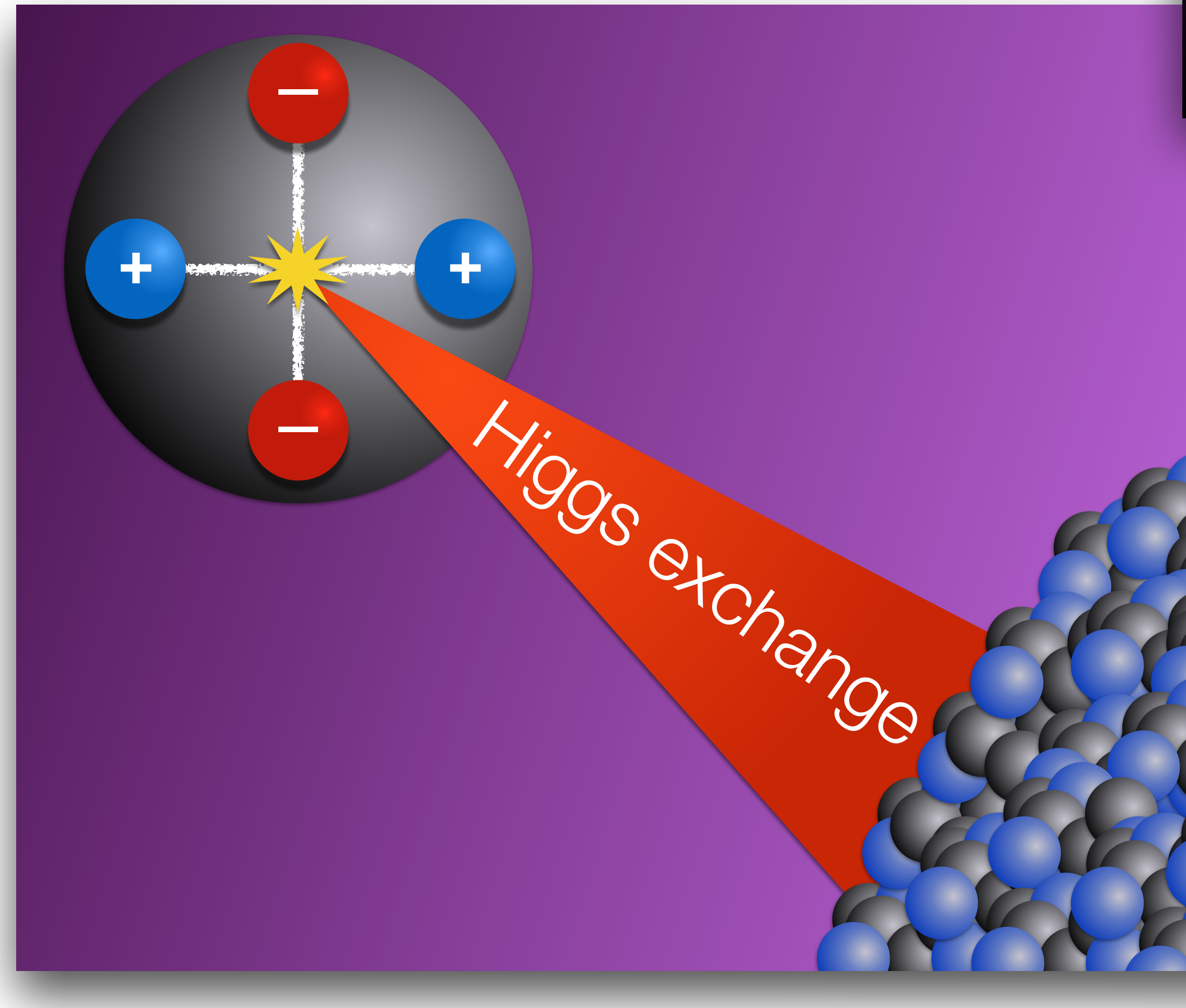
Most relevant interaction if constituents have Yukawa couplings!

[Wikipedia]

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/

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 dei *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

---

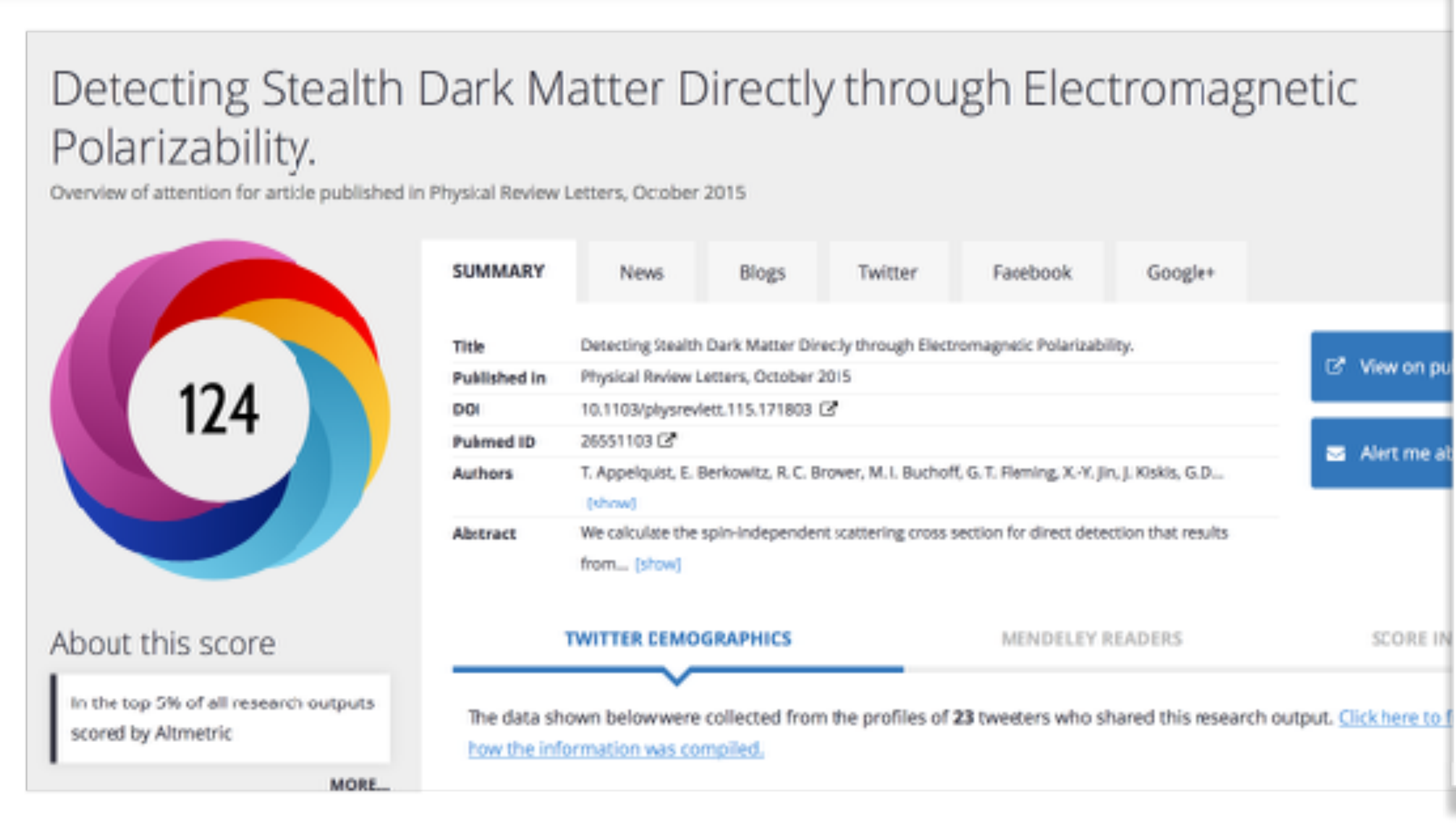
https://www.llnl.gov/news/new-stealth-dark-matter-theory-may-explain-mystery-universes-missing-mass

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

Title	Detecting Stealth Dark Matter Direcly 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]

About this score

In the top 5% of all research outputs scored by Altmetric

TWITTER DEMOGRAPHICS

The data shown belowwere collected from the profiles of **23** tweeters who shared this research output. Click here to f how the information was compiled.

---

http://www.lescienze.it/news/2015/09/28/news/materia_oscura_stealth_matter_lhc-2779983

28 settembre 2015

Un nuovo modello per la materia oscura

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)*

Cortesia Lawrence Livermore National Laboratory

“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 neutral proton*)

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

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

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

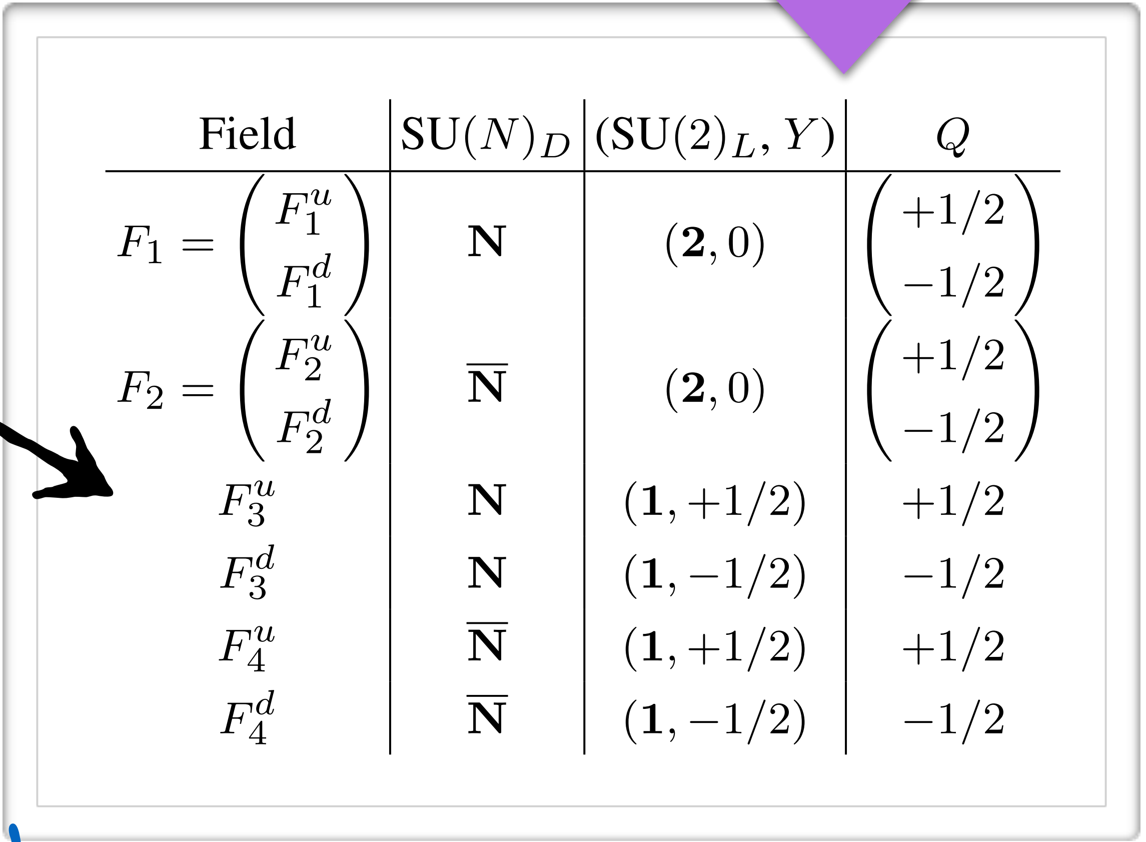
[LSD collab., Phys. Rev. Lett. 115 (2015) 171803]

[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 <u>do not break EW symmetry</u>
- Diagonalizing in the mass eigenbasis gives *4 Dirac fermions*
- Assume custodial SU(2) symmetry arising when ***u*** ↔ ***d***

EW interactions



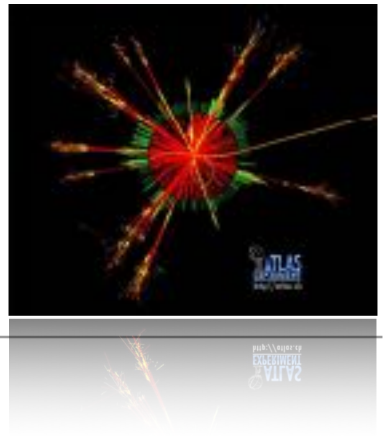
Field	$SU(N)_D$	$(SU(2)_L, Y)$	Q
$F_1 = \begin{pmatrix} F_1^u \\ F_1^d \end{pmatrix}$	$\mathbf{N}$	$(\mathbf{2}, 0)$	$\begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$
$F_2 = \begin{pmatrix} F_2^u \\ F_2^d \end{pmatrix}$	$\overline{\mathbf{N}}$	$(\mathbf{2}, 0)$	$\begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$
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	$\overline{\mathbf{N}}$	$(\mathbf{1}, -1/2)$	$-1/2$

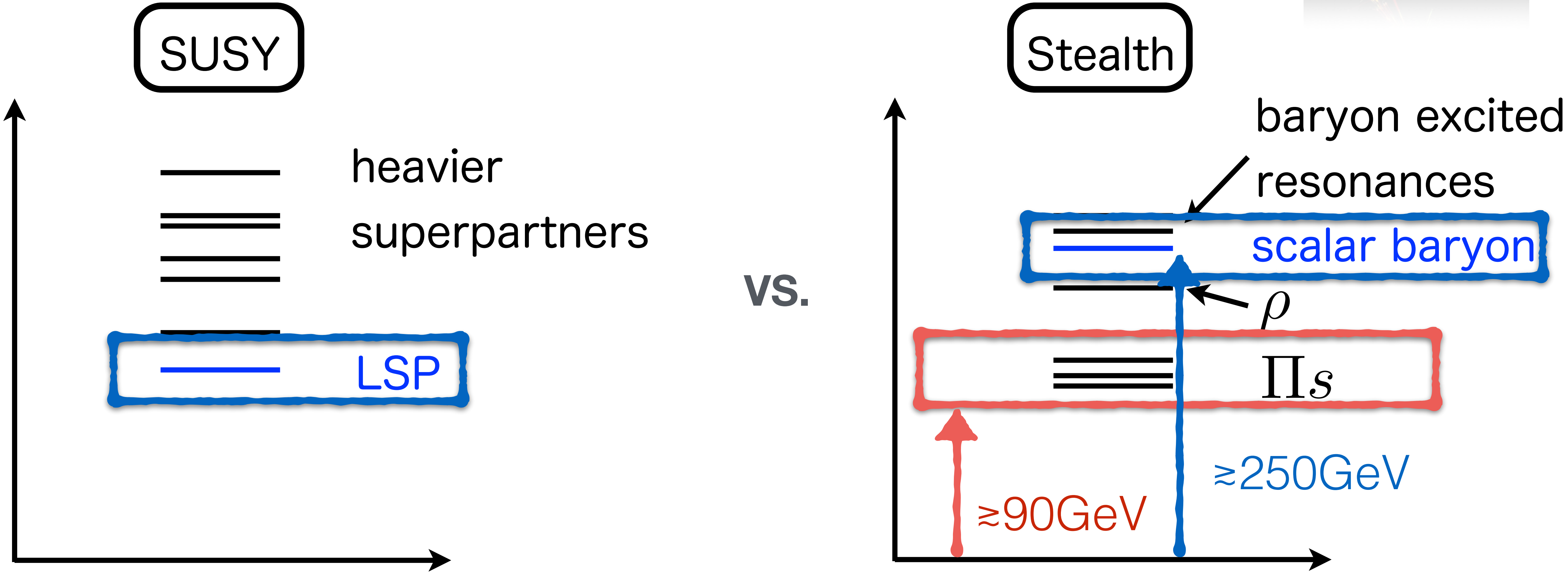
$$\mathcal{L} \supset -\boxed{y_{14}^u}\epsilon_{ij} F_1^i H^j F_4^d + y_{14}^d F_1 \cdot H^\dagger F_4^u - y_{23}^d \epsilon_{ij} F_2^i H^j F_3^d - y_{23}^u F_2 \cdot H^\dagger F_3^u + h.c.$$

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

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

Stealth Dark Matter at colliders


[ATLAS]



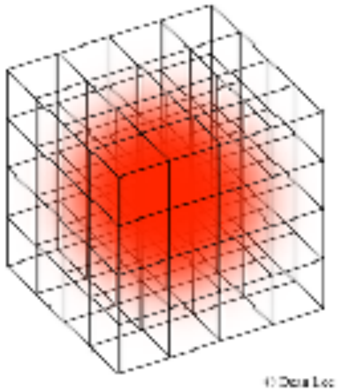
Plot by G. Kribs

- Signatures are not dominated by missing energy: **DM is not the lightest particle!** The interactions are suppressed (form factors)

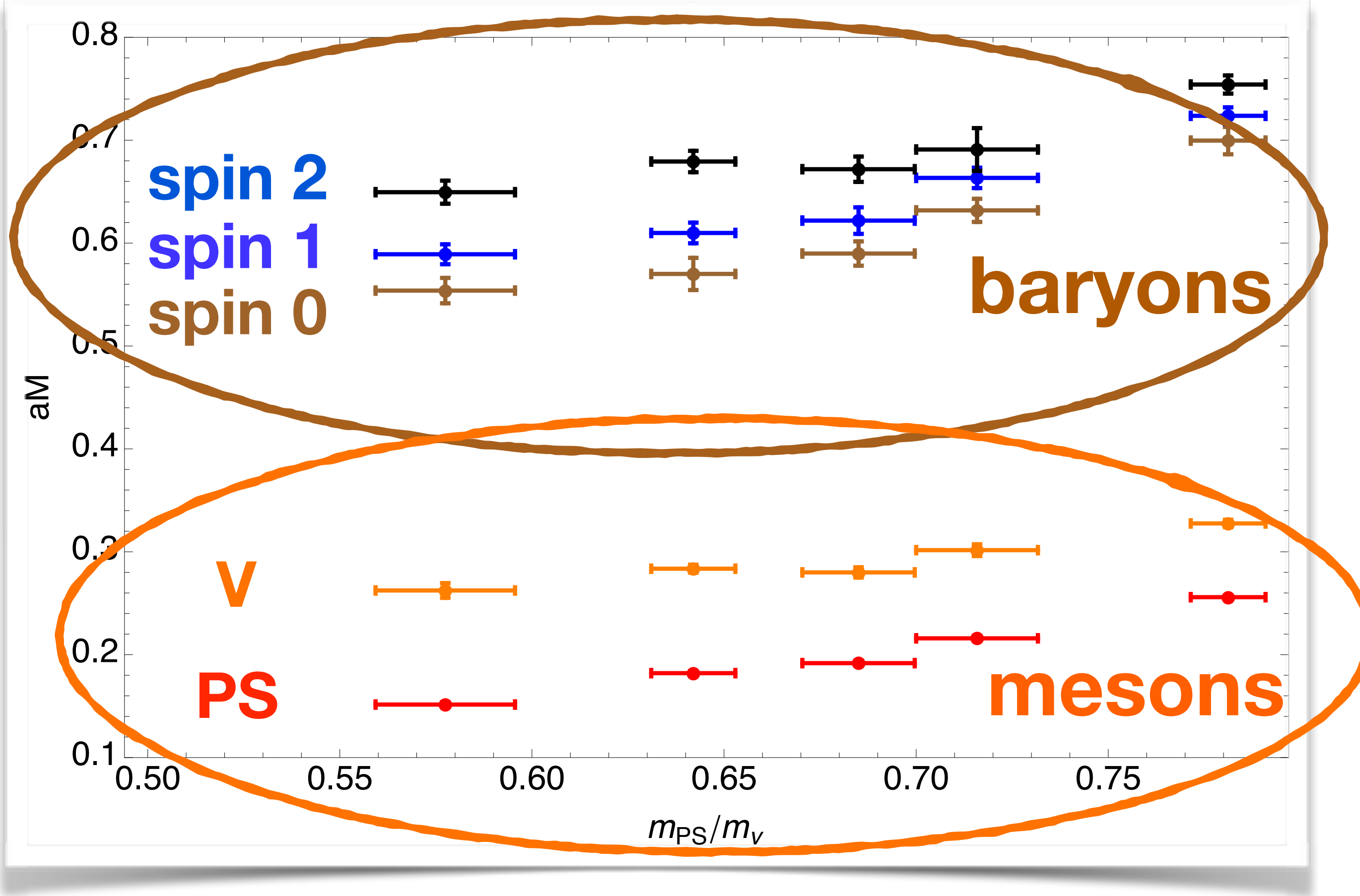
- Dark mesons production and decay give interesting signatures: **the model can be constrained by collider limits!**

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

Lattice Stealth Dark Matter



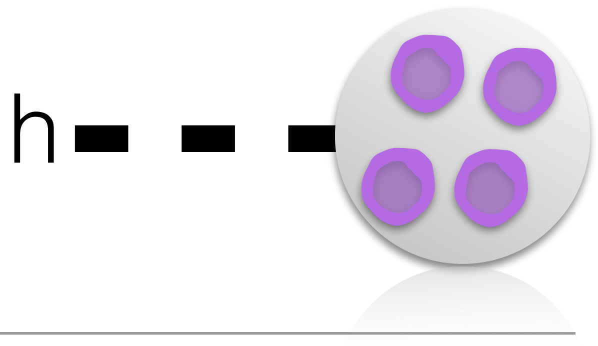
- Non-perturbative lattice calculations of the spectrum confirm that lightest baryon has spin zero
- The ratio of pseudoscalar (PS) to vector (V) is used as probe for different dark fermion masses



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

Computing Higgs exchange



- Need to evaluate the dark σ-term (non-perturbative)
- 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 (using Feynman-Hellmann)

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

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

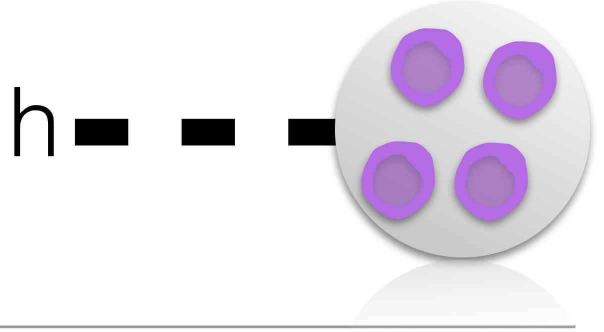
$$\boxed{y_f}\boxed{\langle B|\bar{f}f|B\rangle} = \boxed{\frac{m_B}{v}} \sum_f \boxed{\frac{v}{m_f}\frac{\partial m_f(h)}{\partial h}\Big|_{h=v}} \boxed{f_f^{(B)}}$$

Lattice!

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

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

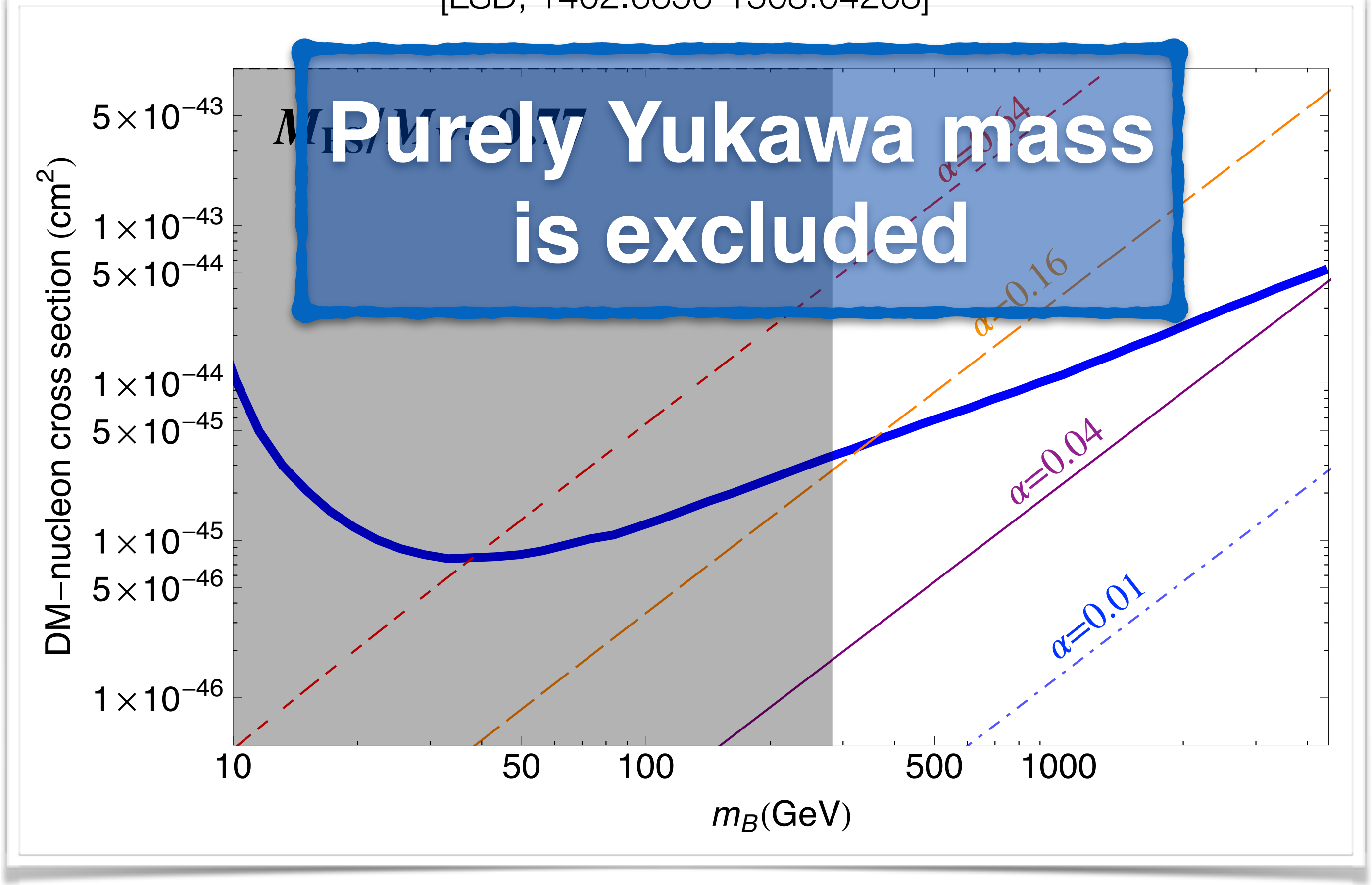
Bounds from Higgs exchange



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

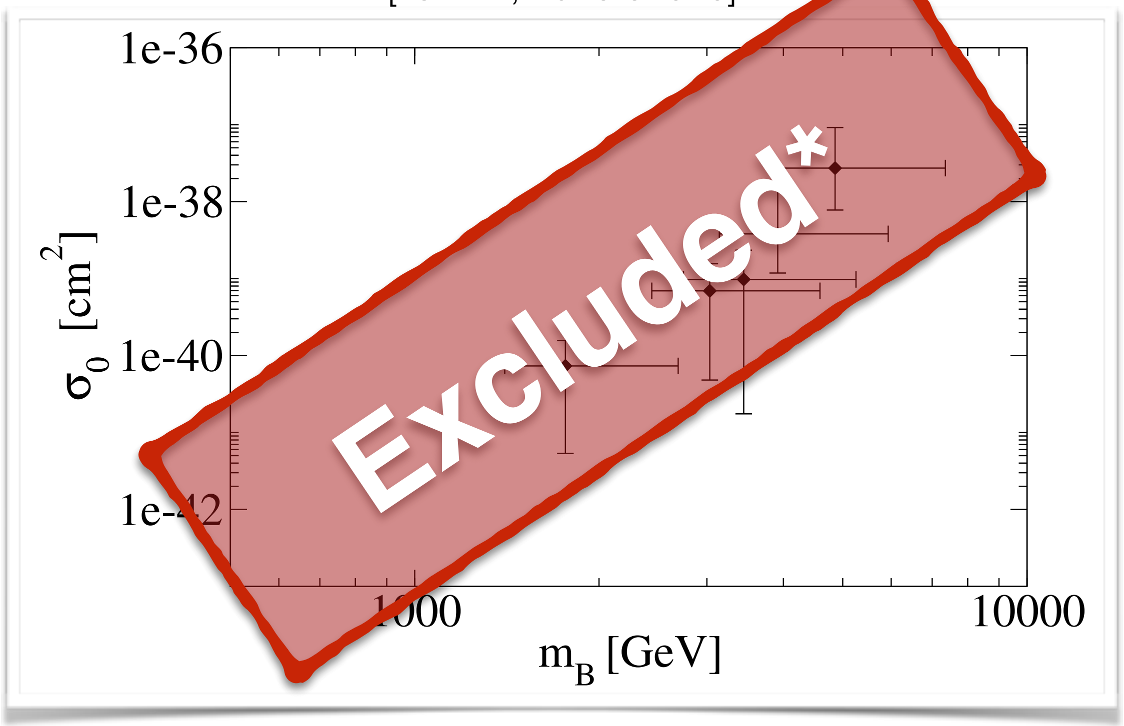
SU(4) N_f=4 Stealth DM

[LSD, 1402.6656-1503.04203]


Purely Yukawa mass is excluded

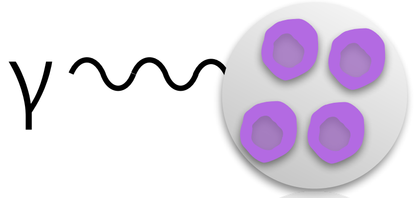
SU(3) N_f=8 "technibaryon"

[LatKMI, 1510.07373]


Excluded*

- ✦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

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



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

Photon interactions

Expansion at low momentum through effective operators

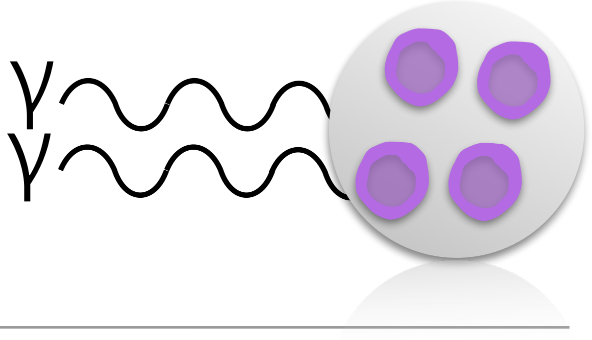
✦~~dimension 5 ➥ magne~~ spin 0 ~~$\dfrac{(\bar{\chi}\sigma^{\mu\nu}\chi)F_{\mu\nu}}{\Lambda_{\mathrm{dark}}}$~~

✦~~dimension 6 ➥ c~~ custodial SU(2) ~~$\dfrac{(\bar{\chi}\chi)v_{\mu}\partial_{\nu}F^{\mu\nu}}{\Lambda^2_{\mathrm{dark}}}$~~

✦dimension 7 ➥ polarizability $\dfrac{(\bar{\chi}\chi)F_{\mu\nu}F^{\mu\nu}}{\Lambda^3_{\mathrm{dark}}}$

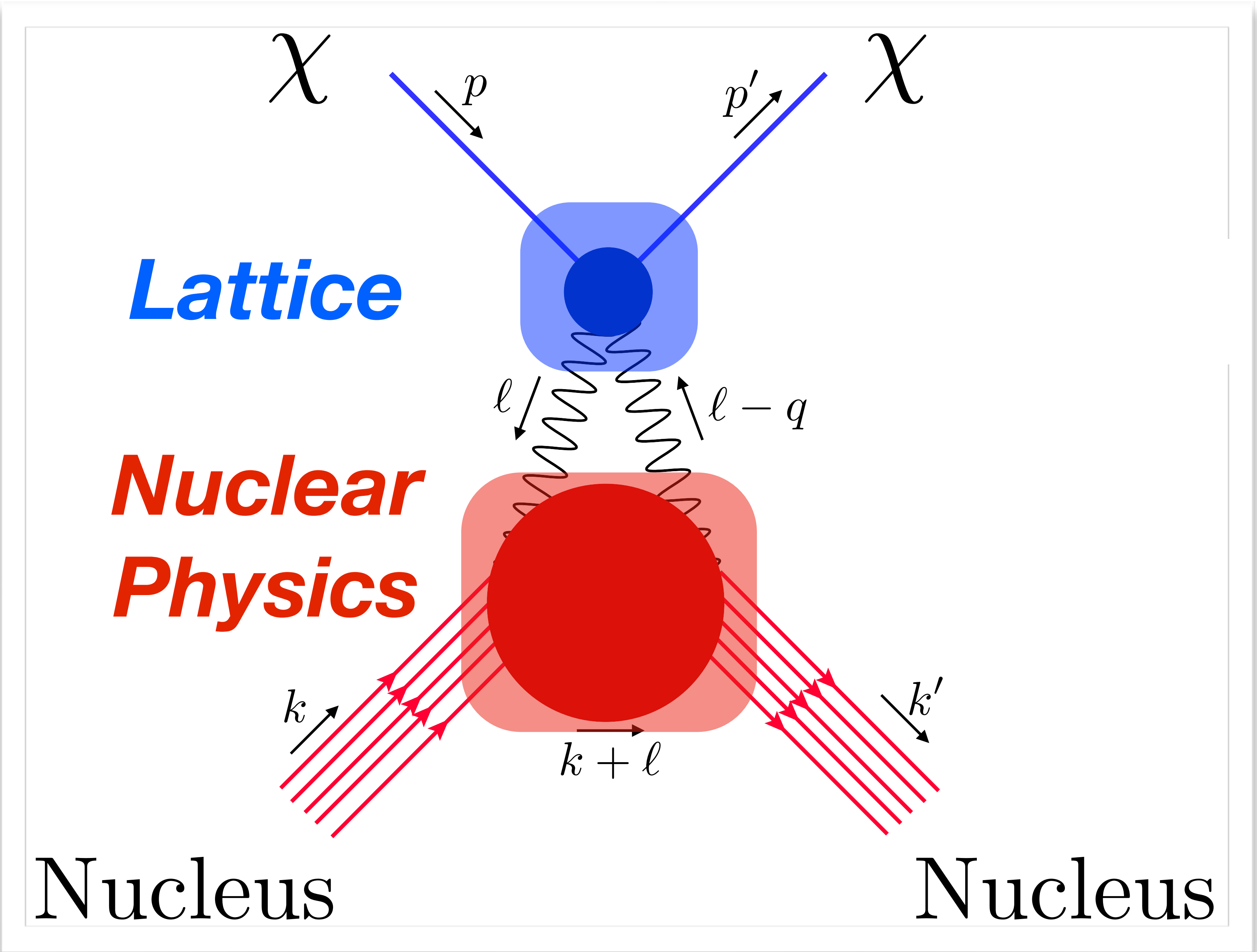
[Pospelov & Veldhuis, hep-ph/0003010] [Ovanesyan & Vecchi, 1410.0601]
[Weiner & Yavin,1206.2910] [Frandsen et al., 1207.3971]

[Detmold et al., 0904.1586-1001.1131]



Computing polarizability

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



[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

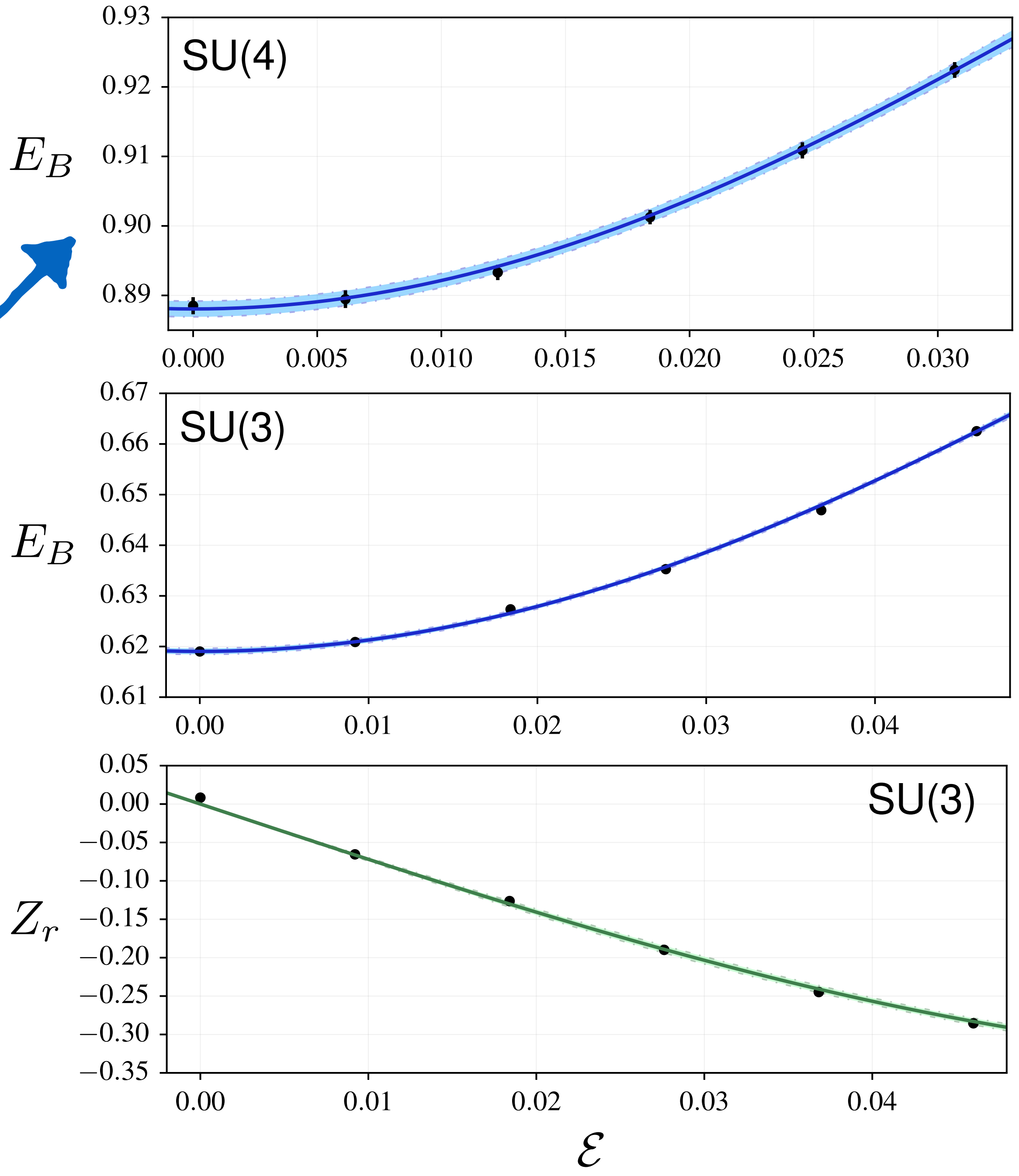
- Background field method: response of neutral baryon to external electric field $\mathcal{E}$
- Measure the shift of the baryon mass as a function of $\mathcal{E}$

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

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

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

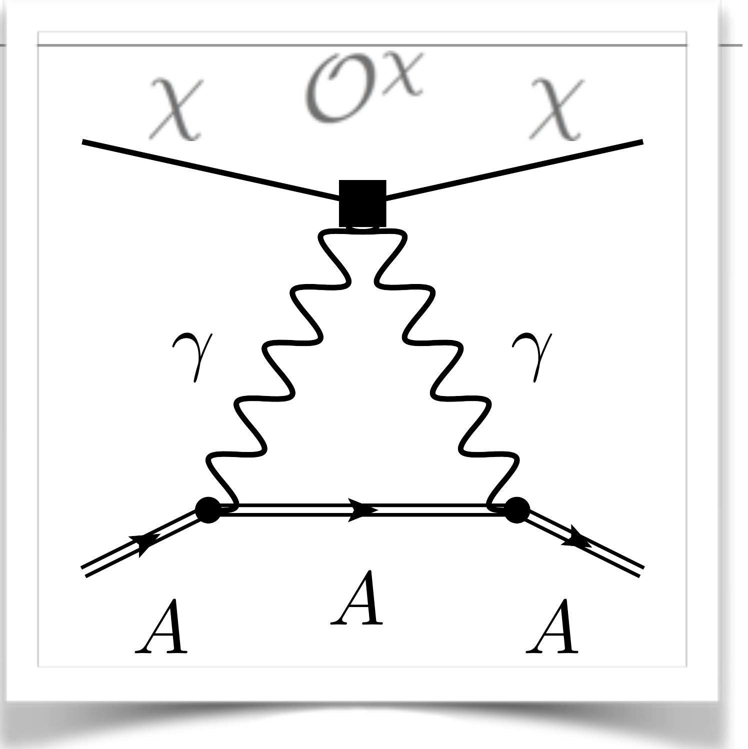
32^3x64 quenched lattices (large volume)
one lattice spacing and two masses (matched)
40 sources on 200 independent configurations
multi-exponential fits with 3 states for the baryon



[Pospelov & Veldhuis, Phys. Lett. B480 (2000) 181]
[Weiner & Yavin, Phys. Rev. D86 (2012) 075021]
[Frandsen et al., JCAP 1210 (2012) 033]
[Ovanesyan & Vecchi, JHEP 07 (2015) 128]

Nuclear: Rayleigh scattering

- 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



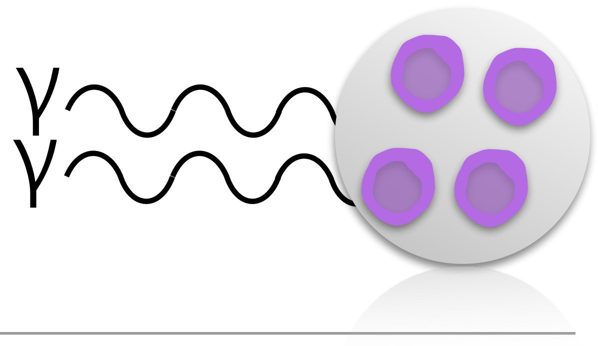
$$f_F^A = \langle A | F^{\mu\nu} F_{\mu\nu} | A \rangle$$

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

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

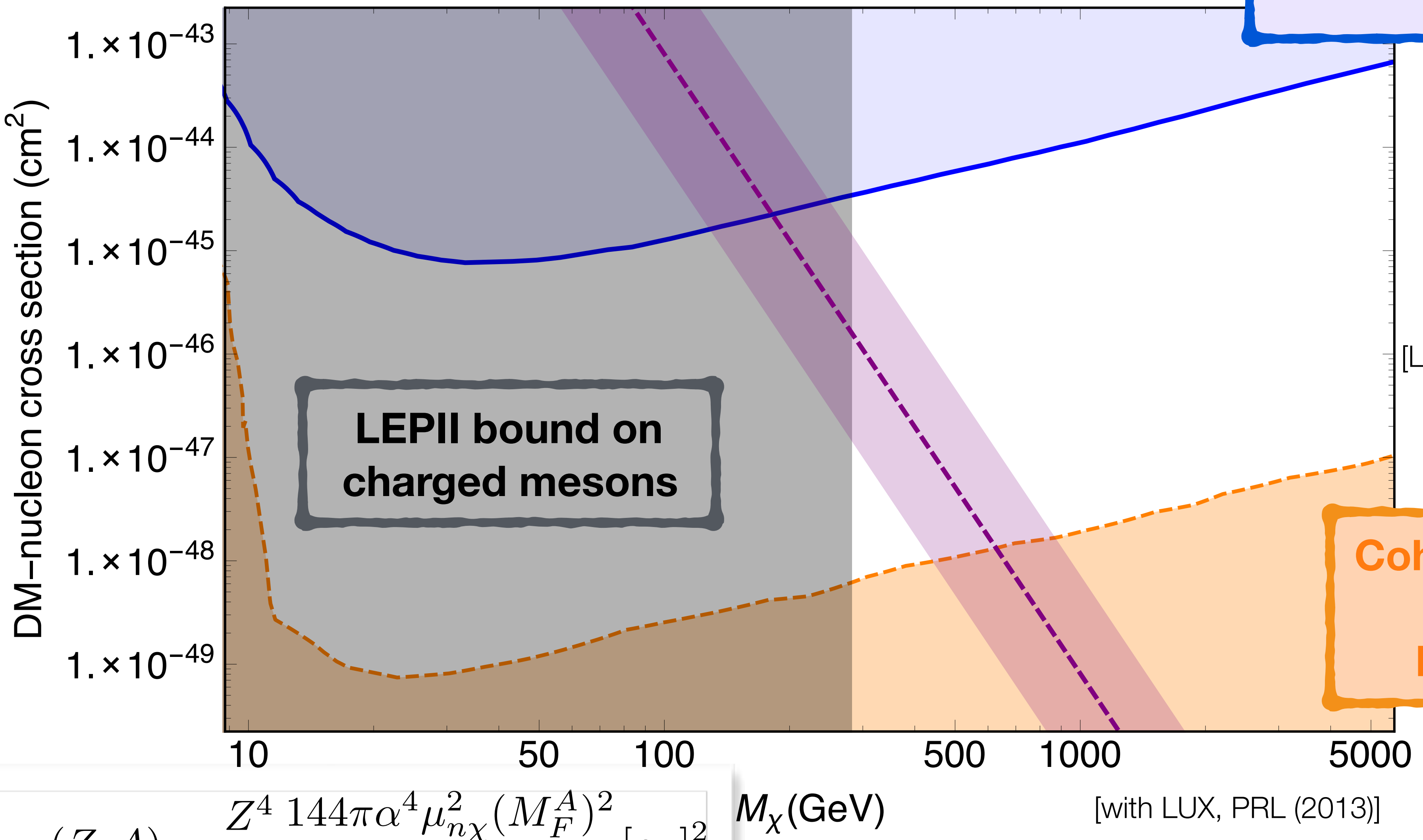
[NEW! PandaX-II, 1607.07400 and LUX-332d,1608.07648]

Lowest bound from EM polarizability



Electric polarizability from lattice simulations with background fields

LUX exclusion bound for spin-independent cross section



LEPII bound on charged mesons

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

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

Coherent neutrino scattering background

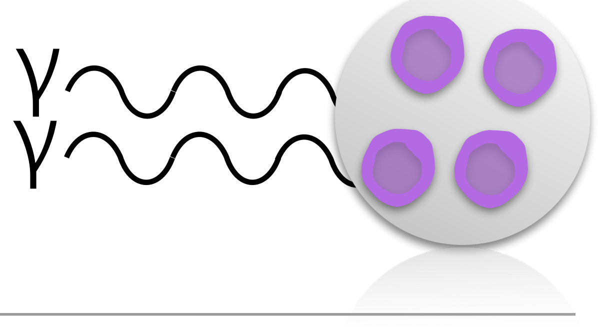
[with LUX, PRL (2013)]

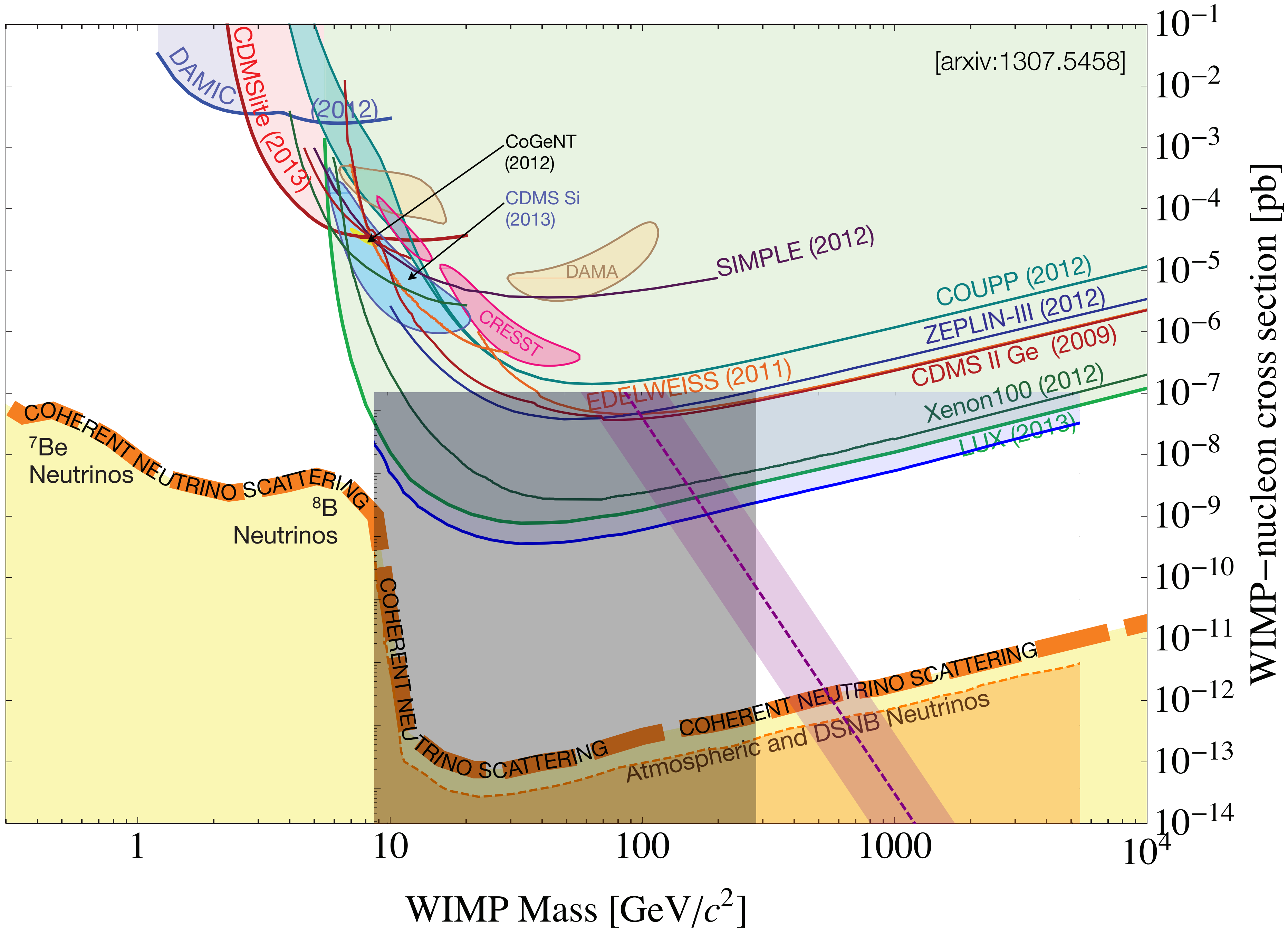
$$\sigma_{\text{nucleon}}(Z,A) = \frac{Z^4}{A^2}\frac{144\pi\alpha^4\mu_{n\chi}^2(M_F^A)^2}{m_\chi^6 R^2}[c_F]^2$$

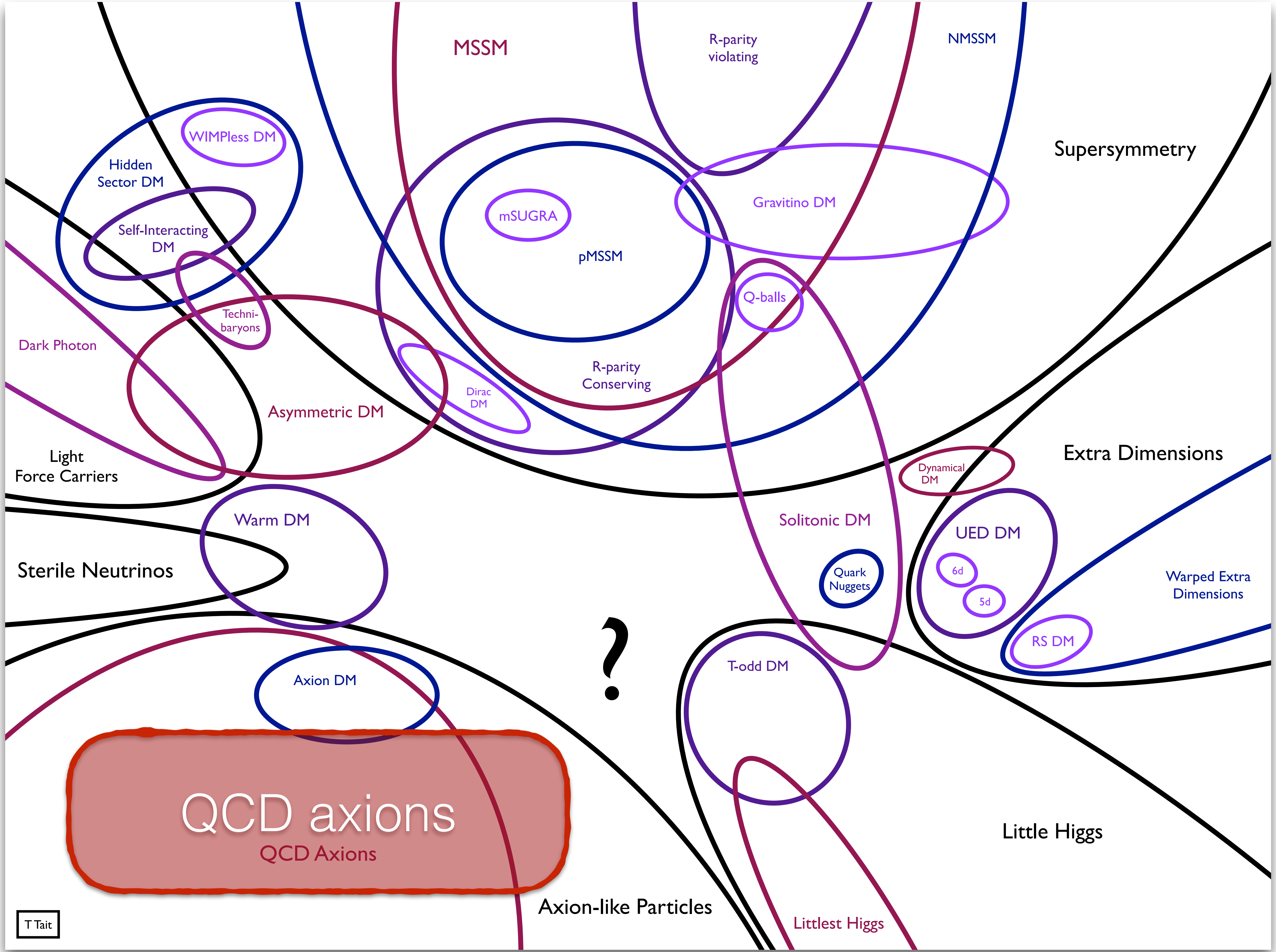
lowest allowed direct detection cross-section for composite dark matter theories with EW charged constituents

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

Bound from EM polarizability





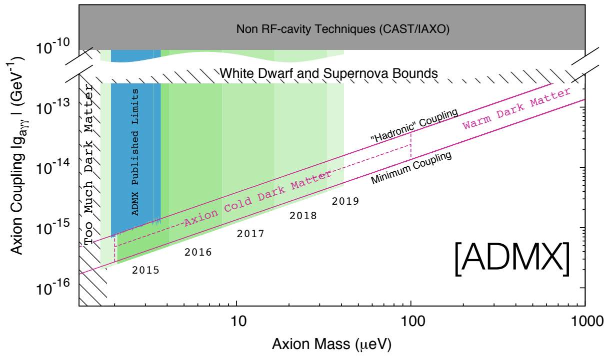


QCD axions

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

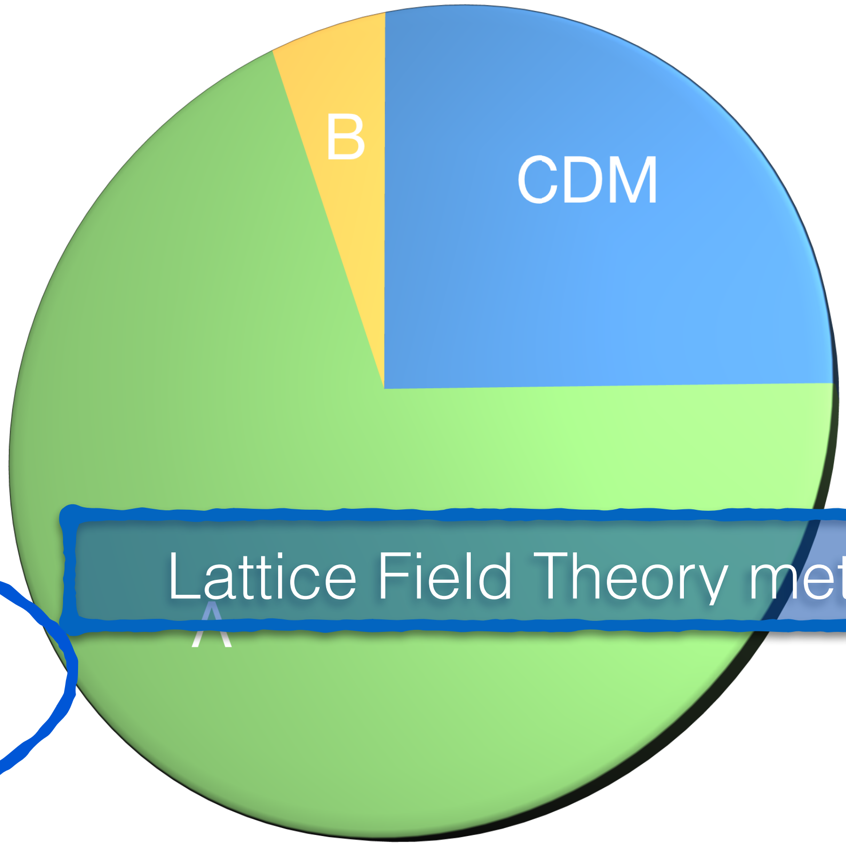
[Peccei & Quinn: PRL **38** (1977) 1440, PR **D16** (1977) 1791]
[Preskill, Wise & Wilczek, Phys. Lett. B **120** (1983) 127-132]

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 $\Omega_{\mathrm{axion}} \leq \Omega_{\mathrm{CDM}}$ yields a lower bound on the axion mass today

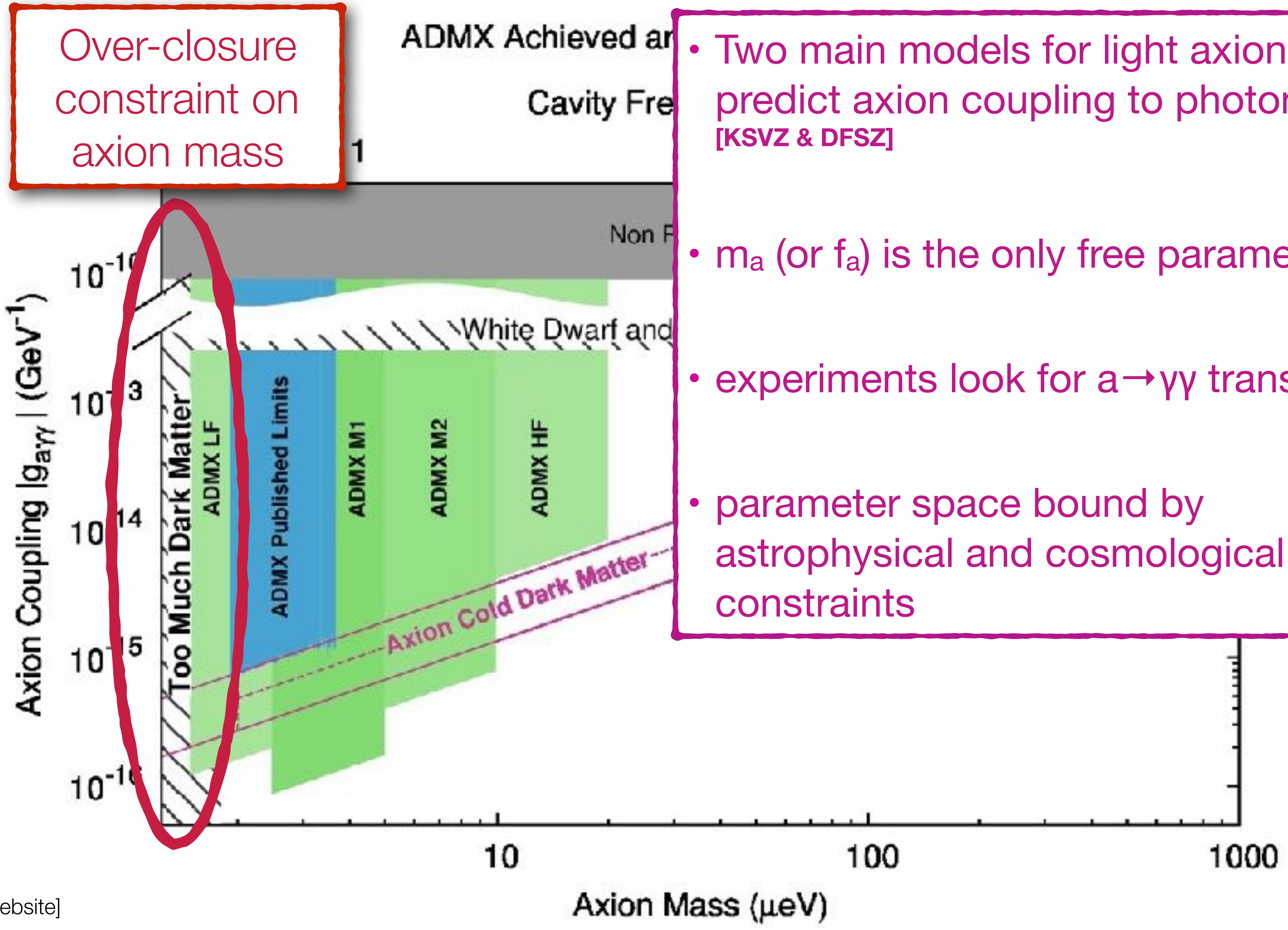


Lattice Field Theory methods

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

Current axion constraints

Over-closure constraint on axion mass



- Two main models for light axions predict axion coupling to photons **[KSVZ & DFSZ]**
- m_a (or f_a) is the only free parameter
- experiments look for $a \rightarrow \gamma\gamma$ transitions
- parameter space bound by astrophysical and cosmological constraints

[ADMX Website]

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

Axion energy density

$$\rho(T_\gamma) = \rho(T_1)\frac{m_a(T_\gamma)}{m_a(T_1)}\left(\frac{R(T_1)}{R(T_\gamma)}\right)^3$$

$$\frac{\rho(t)R^3}{m_a(t)} = \#\text{ axions in a fixed comoving volume}$$

$$T_\gamma = 2.73\mathrm{K}$$

$$T_1 = T_1(f_a) \qquad m_a(T_1) = \frac{\sqrt{\chi}}{f_a}$$

$$m_a(T_\gamma) = \frac{1}{f_a}\frac{\sqrt{m_u m_d}}{m_u + m_d} f_\pi m_\pi$$ from χPT

Rely on controllable lattice calculations

$R(T)$ from cosmology

$$\rho(T_1) = \frac{1}{2} m_a^2 f_a^2 \theta_1^2$$

θ_1 is the initial misalignment angle: effectively another free parameter, but can be averaged over in the post-inflationary PQsb scenario

Axion mass from lattice simulations

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

Non-perturbative calculation of QCD topology at finite temperature

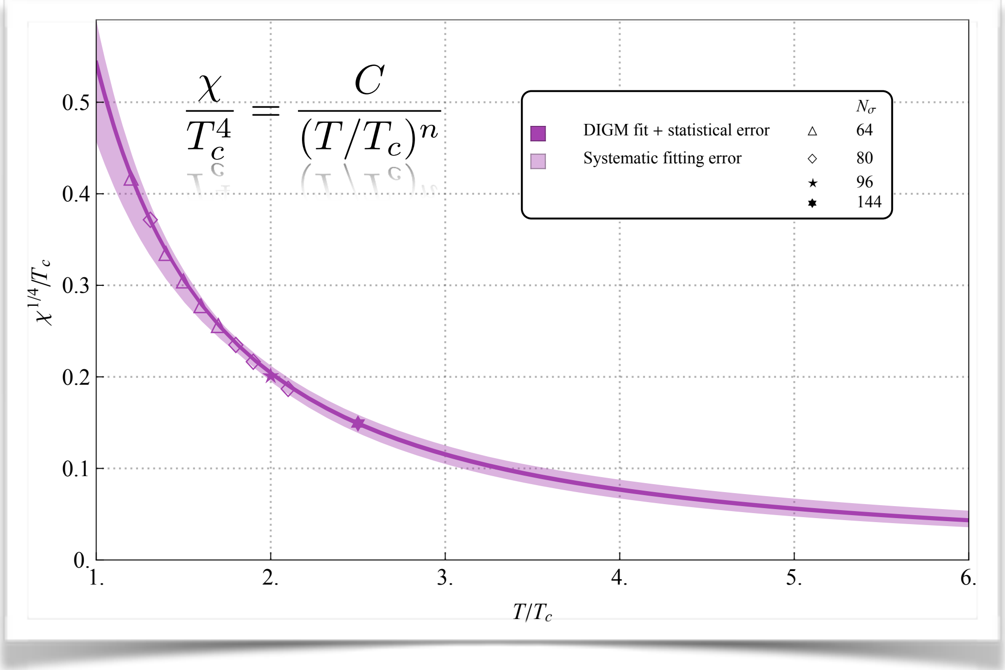
- Pure gauge SU(3) topological susceptibility ➥ compatible with model predictions (DIGM/IILM), but important non-perturbative effects

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

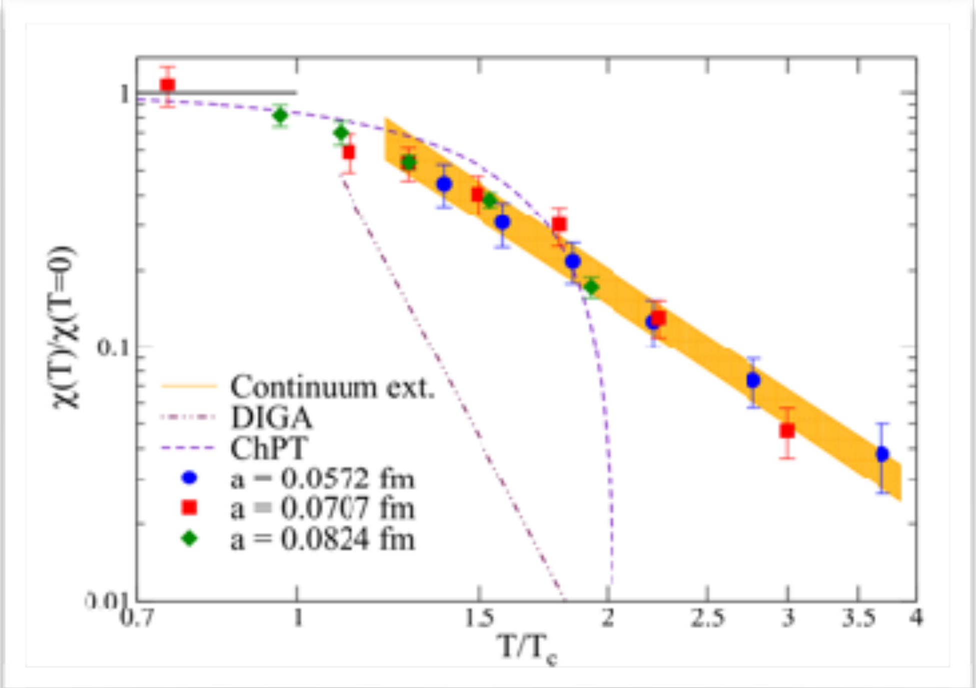
- is QCD topological susceptibility at high-T well described by models? ➥ light fermions importantly affect the vacuum

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

Great effort to control all systematic lattice effects in order to impact experiments. Near-final results reached in about a year!



[Berkowitz, Buchoff, ER., 1505.07455]

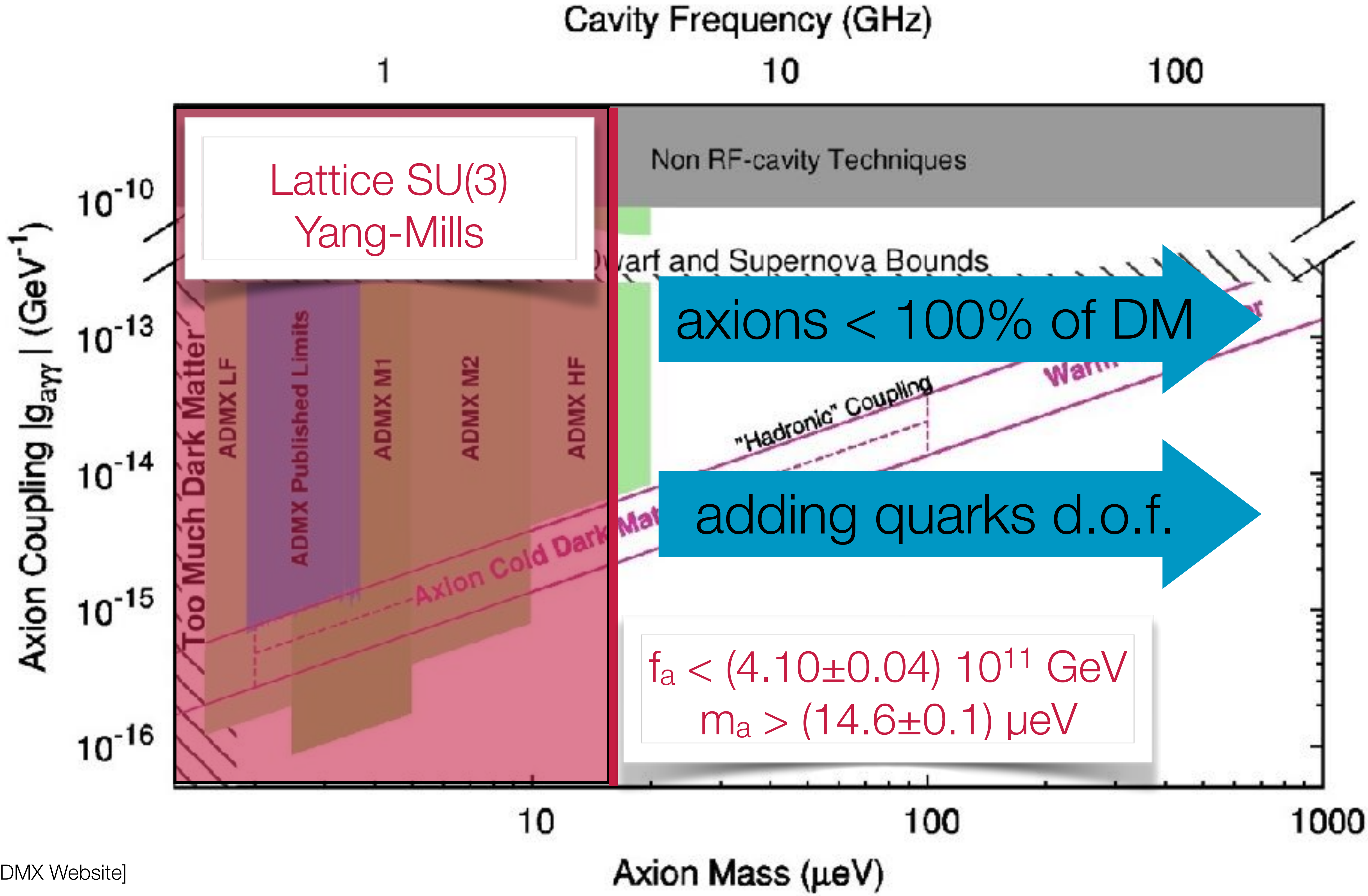


[Bonati et al., 1512.06746]

[Berkowitz, Buchoff, ER., 1505.07455, PRD]

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

Axion mass lower bound



Lattice SU(3)
Yang-Mills

axions < 100% of DM

adding quarks d.o.f.

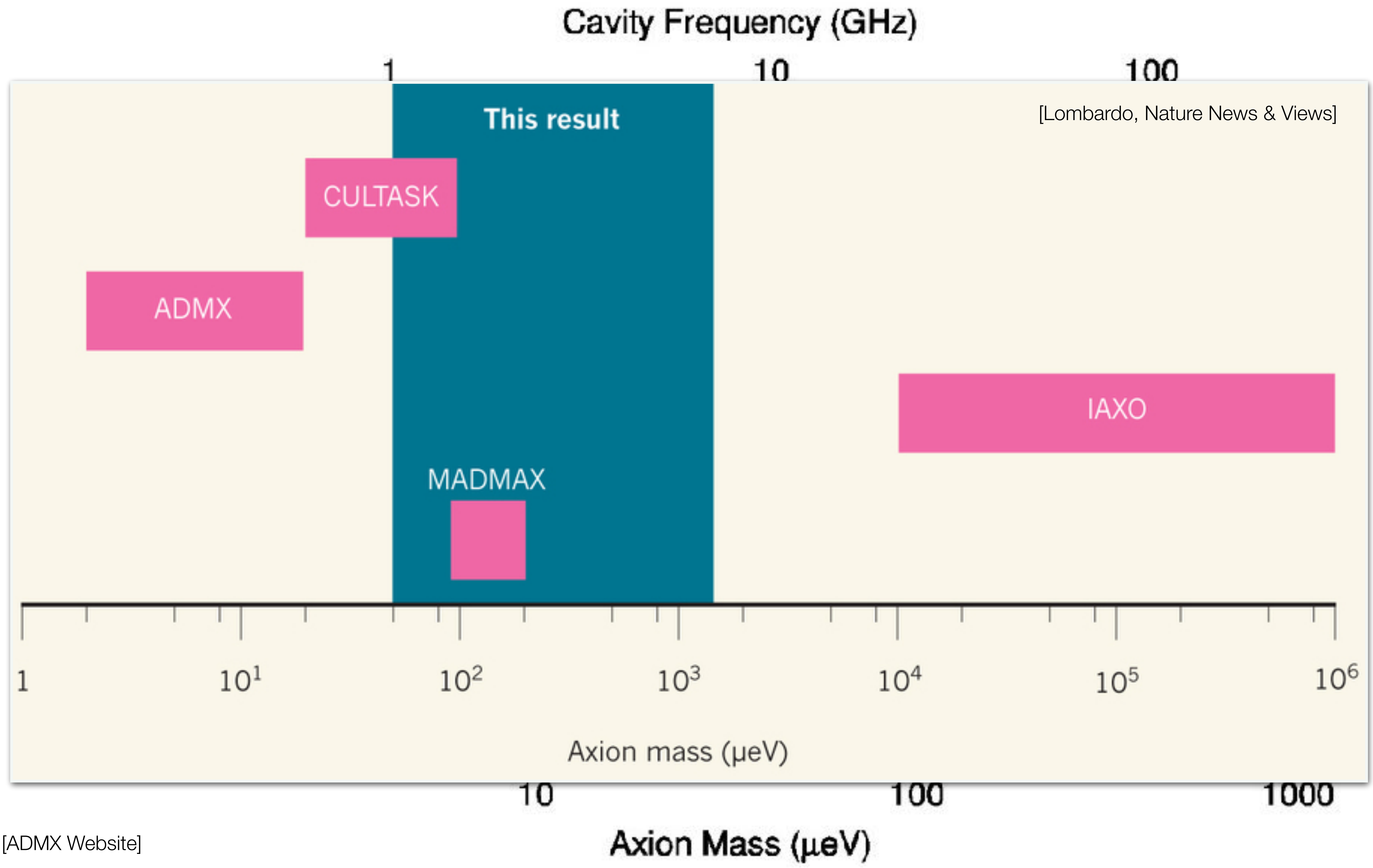
$f_a < (4.10 \pm 0.04)\ 10^{11}$ GeV
$m_a > (14.6 \pm 0.1)$ μeV

[ADMX Website]

[Borsanyi et al., 1606.07494, Nature 539]

Axion mass lower bound

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



[Lombardo, Nature News & Views]

[ADMX Website]

Concluding remarks

★QCD ideas and lattice QCD techniques can be borrowed when exploring the DM landscape (BSM physics)

★Composite dark matter is a viable interesting possibility with rich phenomenology.

★Axion-like dark matter has a strong discovery potential

★Lattice methods can help in calculating direct detection cross sections, production rates at colliders, and self-interaction cross sections for composite dark matter

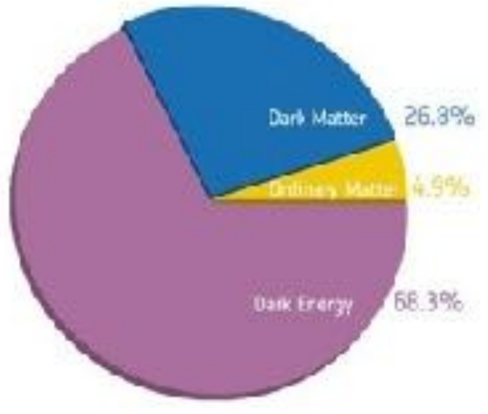
★Lattice methods are now the preferred tool to study the evolution of the axion mass density in the early universe extra

S. Nussinov, Phys. Lett. B165 (1985) 55
S. Barr, R. S. Chivukula, and E. Farhi, Phys. Lett. B241 (1990) 387
D. B. Kaplan, Phys. Rev. Lett. 68 (1992) 741

Asymmetric dark matter

- It is an observational fact that the number density for dark matter and baryonic matter are of the same order of magnitude

$$\Omega_{\mathrm{DM}} \approx 5\ \Omega_{\mathrm{B}}$$



[Planck and ESA]

- This can be explained in Technicolor theories where dark matter is a baryon of a new strongly-coupled sector which shares an asymmetry with standard baryonic matter

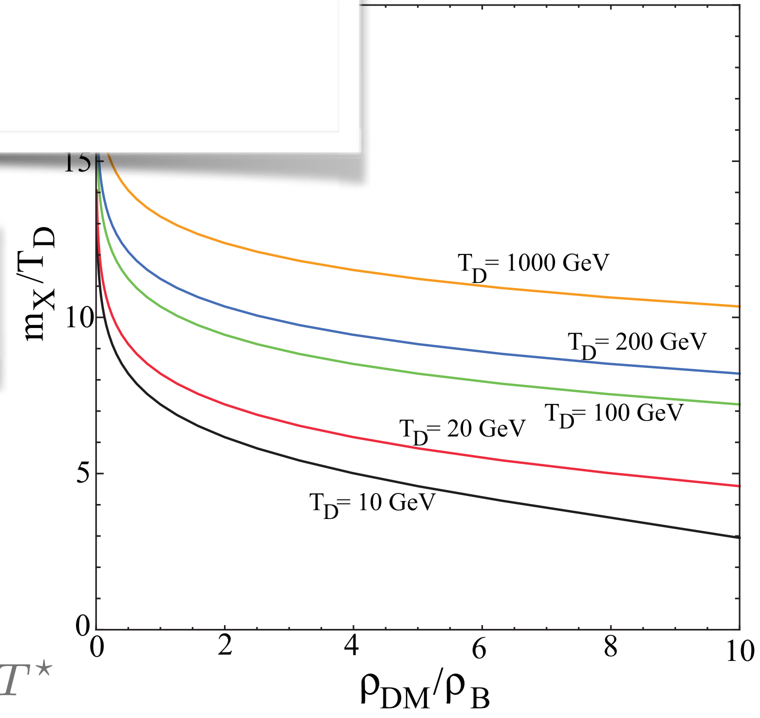
requires coupling of DM to SM particles!

higher dimensional operators

$$n_{\mathrm{DM}} \approx n_{\mathrm{B}} \rightarrow M_{\mathrm{DM}} \approx 5\ M_{\mathrm{B}}$$

sphaleron processes

$$M_{\mathrm{DM}} \gg M_{\mathrm{B}} \rightarrow n_{\mathrm{B}} \gg n_{\mathrm{B}} \approx e^{-M_{\mathrm{DM}}/T^{\star}}$$

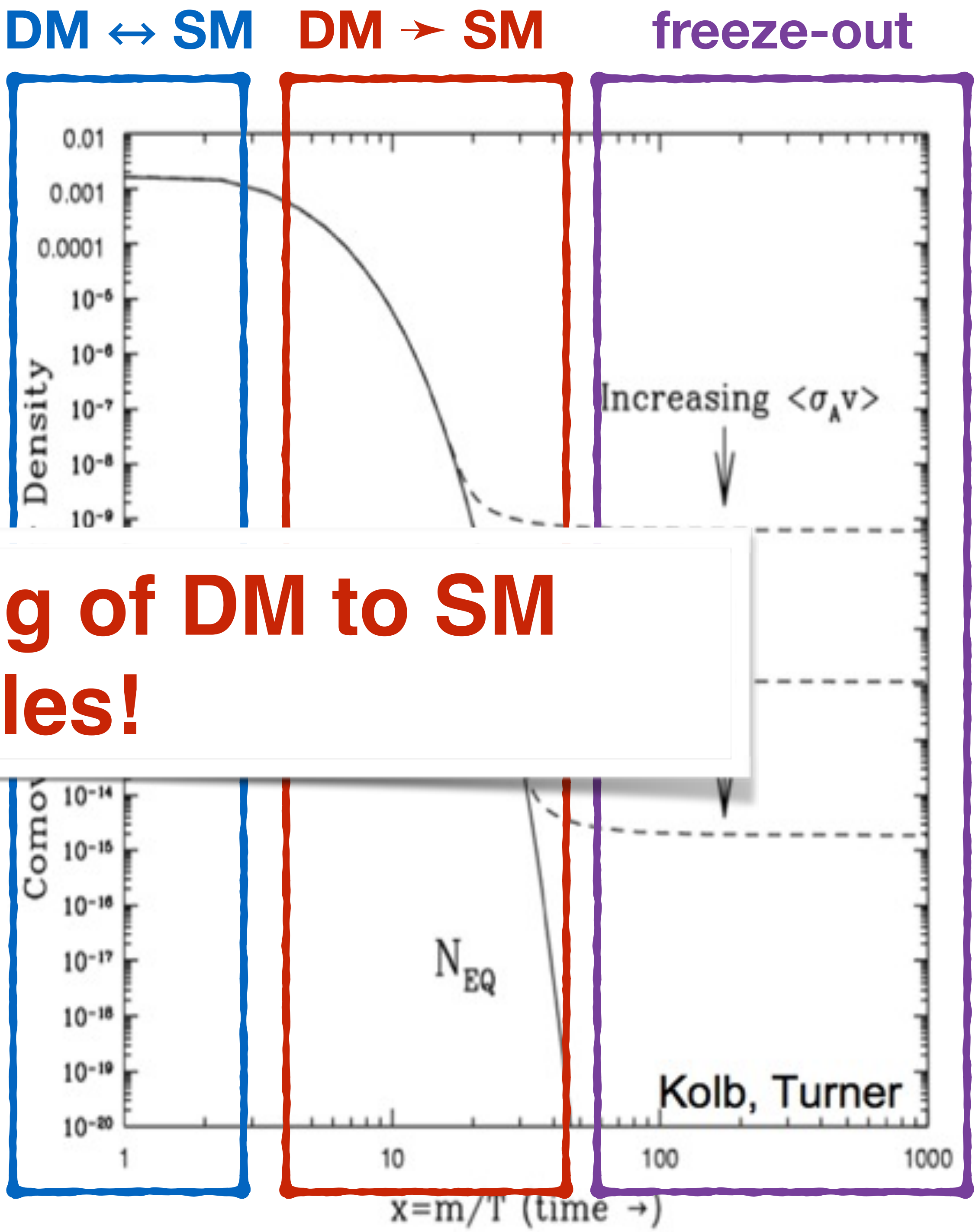


[Buckley & Randall, JHEP1109 (2011)]

Thermal Dark Matter

- Dark matter starts in thermal equilibrium with ordinary matter
- Dark matter cannot be created in equilibrium when the temperature drops below m$_\chi$
- Incre
  cres
  relic density
- Observed relic density:

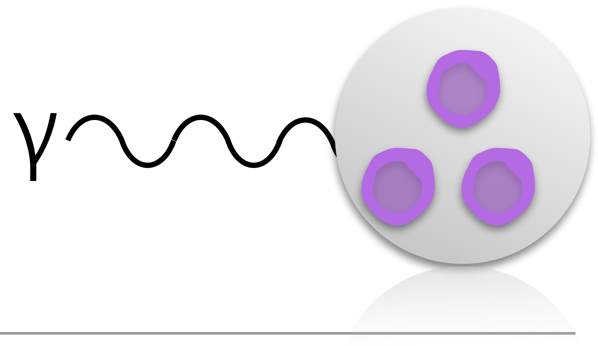
$$\Omega_\chi \approx \frac{1}{\langle\sigma_a v\rangle} \approx \frac{m_\chi^2}{g_\chi^4}$$



requires coupling of DM to SM particles!

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

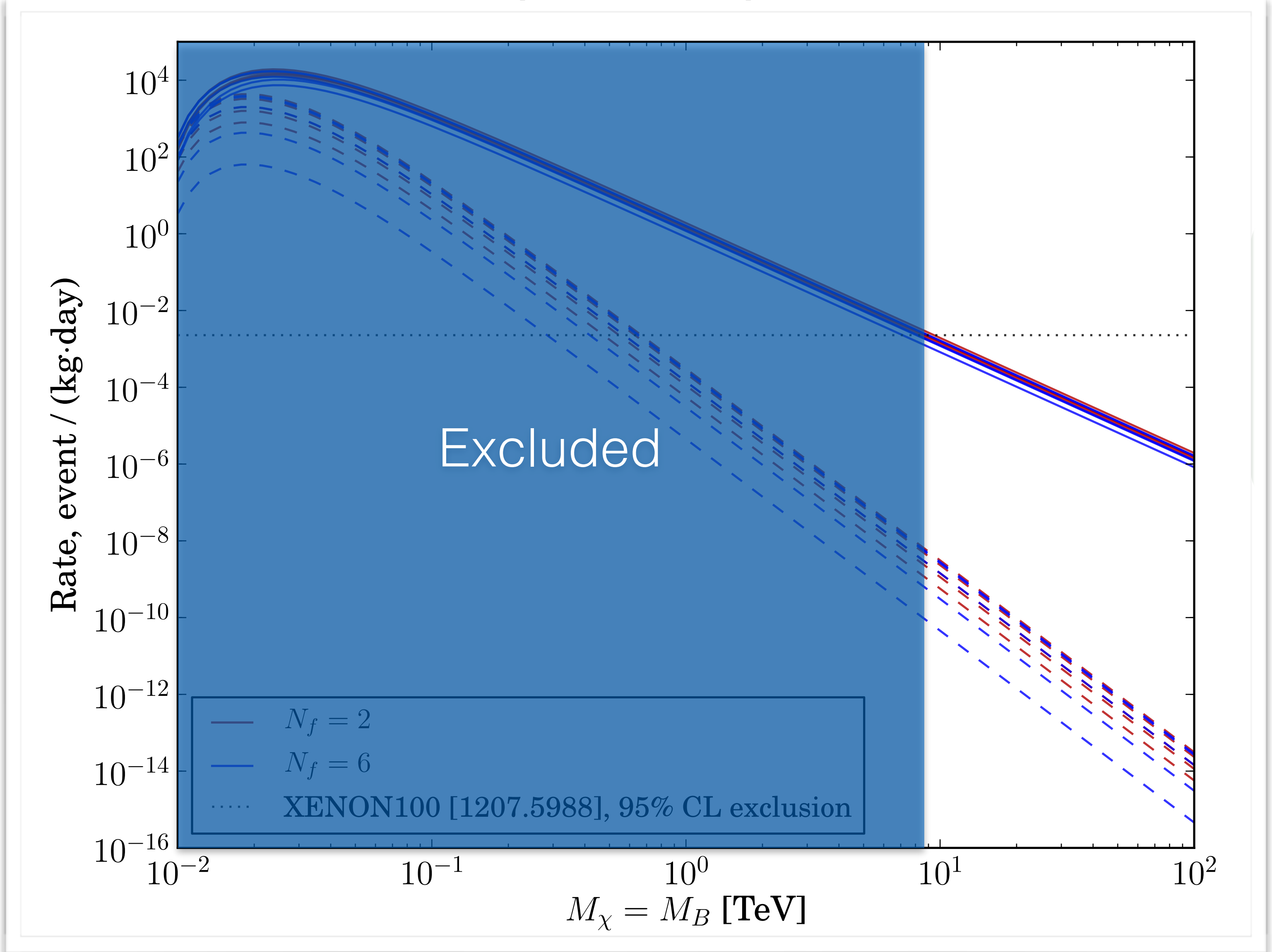
Bounds from EM moments



Mesonic and Baryonic EM form factors directly from lattice simulations

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

[LSD, 1301.1693]



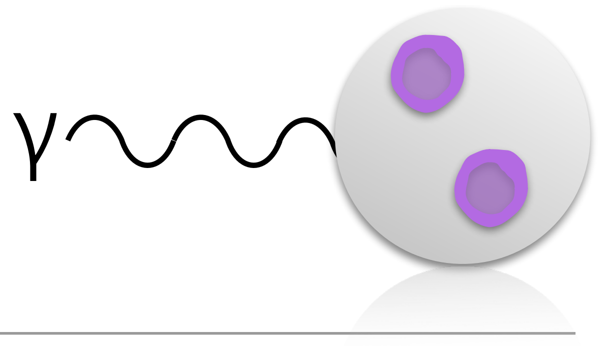
- ★ baryon similar to QCD neutron
- ★ dark quarks with Q=Y
- ★ calculate connected 3pt
- ★ scale set by DM mass
- ★ magnetic moment dominates
- ★ results independent of N_f

M_B >~ 10 TeV

pushed to ~100 TeV with new LUX

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

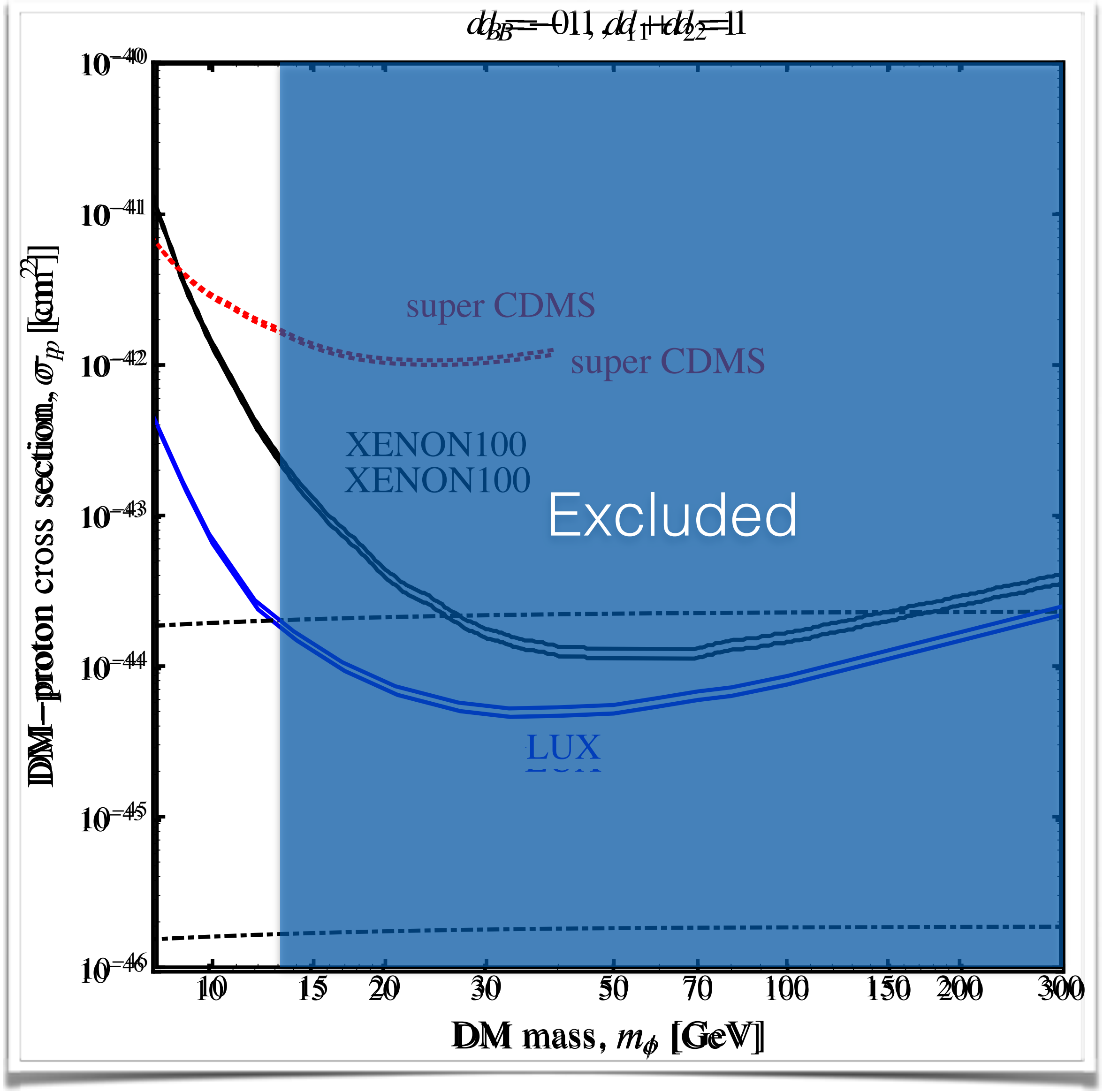
Bounds from EM moments



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)

M_B ~< 13 GeV
depends on d_B