Composite Dark Matter

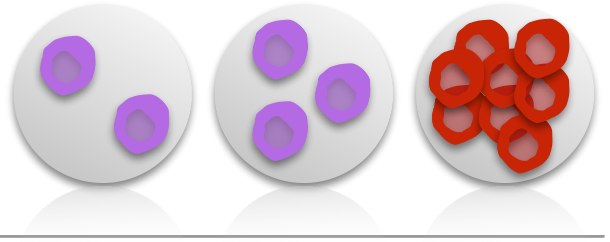
Enrico Rinaldi

RIKEN BNL Research Center

work with the Lattice Strong Dynamics Collaboration

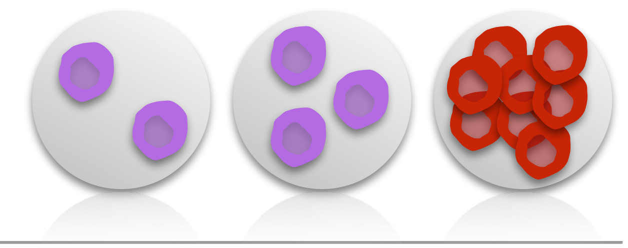
Composite Dark Matter

Composite Dark Matter



- Dark Matter is a composite object

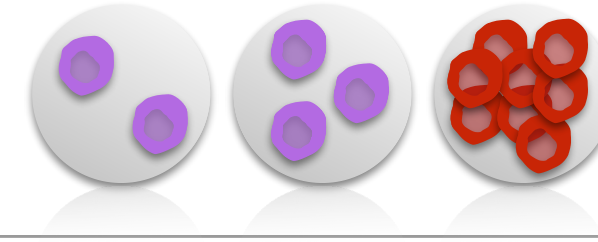
Composite Dark Matter



- Dark Matter is a composite object

e.g. hidden sector baryon or glueball

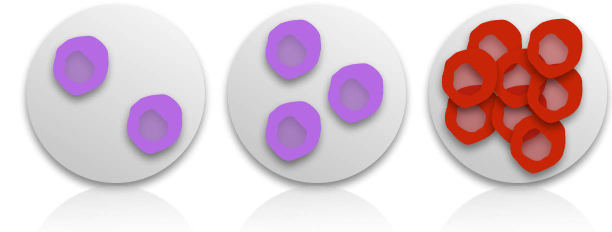
Composite Dark Matter



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

e.g. hidden sector baryon or glueball

Composite Dark Matter



- Dark Matter is a composite object

e.g. hidden sector baryon or glueball

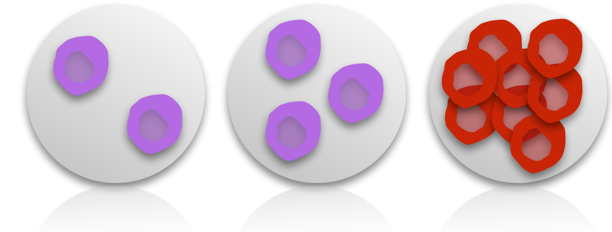
- Interesting and complicated internal structure

- Properties dictated by strong dynamics

Similar to QCD

- Self-interactions are natural

Composite Dark Matter

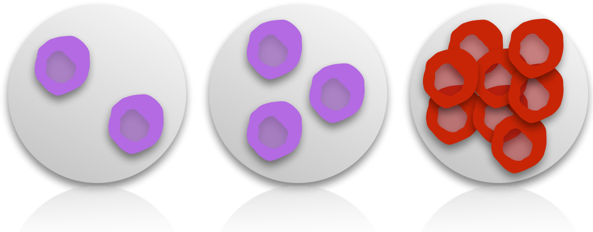


- Dark Matter is a composite object
- Interesting and complicated internal structure
- Properties dictated by strong dynamics
- Self-interactions are natural
- Composite object is neutral
- Constituents may interact with Standard Model particles

e.g. hidden sector baryon or glueball

Similar to QCD

Composite Dark Matter



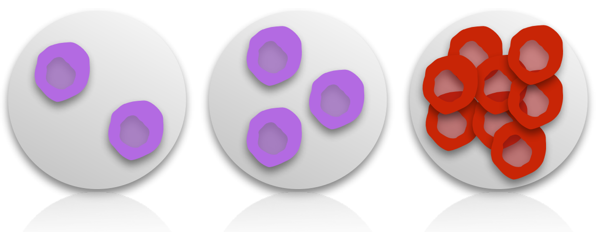
- Dark Matter is a composite object
- Interesting and complicated internal structure
- Properties dictated by strong dynamics
- Self-interactions are natural
- Composite object is neutral
- Constituents may interact with Standard Model particles

e.g. hidden sector baryon or glueball

Similar to QCD

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

Composite Dark Matter



- Dark Matter is a composite object
- Interesting and complicated internal structure
- Properties dictated by strong dynamics
- Self-interactions are natural
- Composite object is neutral
- Constituents may interact with Standard Model particles

e.g. hidden sector baryon or glueball

Lattice Field Theory methods

Similar to QCD

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

[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**

[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

[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)

[review by Kribs & Neil, 1604.04627]

Natural features of Composite Dark Matter

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

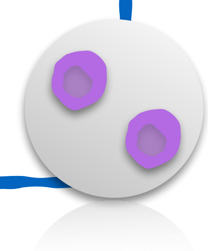
Neutrality follows naturally from **confinement** into singlet objects wrt. SM charges

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

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

Models for Composite Dark Matter

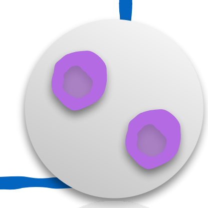
- ★ Pion-like (dark quark-antiquark)
  - ✦ pNGB DM *[Hietanen et al.,1308.4130]*
  - ✦ Quirky DM *[Kribs et al.,0909.2034]*
  - ✦ Ectocolor DM *[Buckley&Neil,1209.6054]*
  - ✦ SIMP *[Hochberg et al.,1411.3727]*
  - ✦ Minimal SU(2) *[Lewis,1610.10068]*



Models for Composite Dark Matter

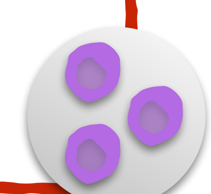
★ Pion-like (dark quark-antiquark)

- ✦ 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]*



★ Baryon-like (multiple quarks)

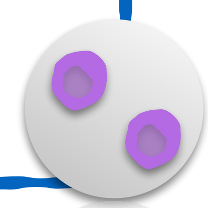
- ✦ "Technibaryons" *[LSD, 1301.1693]*
- ✦ Stealth DM *[LSD, 1503.04203-1503.04205]*
- ✦ One-family WTC *[LatKMI, 1510.07373]*
- ✦ Sextet CH *[LatHC, 1601.03302]*



Models for Composite Dark Matter

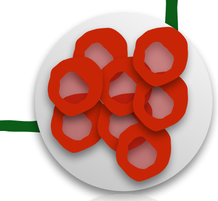
★ Pion-like (dark quark-antiquark)

- ✦ 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]*



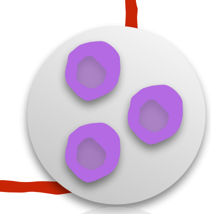
★ Glueball-like (only gluons)

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



★ 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]*



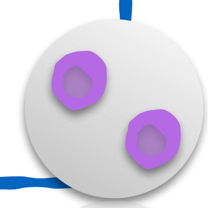
[list of references focused on lattice results when possible]

[for more details see review by Kribs & Neil, 1604.04627]

Models for Composite Dark Matter

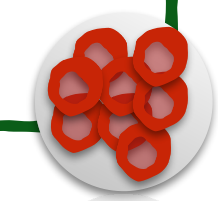
★ Pion-like (dark quark-antiquark)

- ✦ 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]*

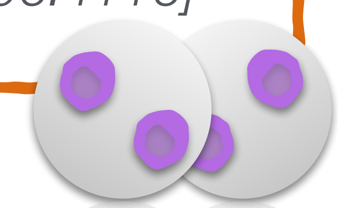


★ Glueball-like (only gluons)

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

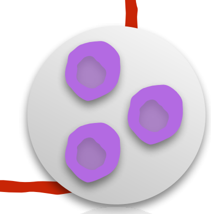


★ Dark Nuclei *[Detmold et al.,1406.2276-1406.4116]*



★ 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]*



[list of references focused on lattice results when possible]

[for more details see 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]*

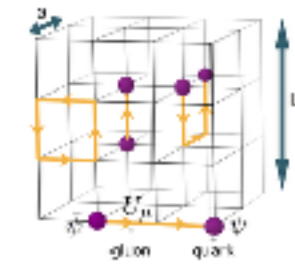
★ Dark Nuclei *[Detmold et al.,1406.2276-1406.4116]*

★ 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]*

[KEK-Japan]



Importance of lattice field theory simulations

- *need to solve the strong dynamics: lattice gauge theory*
- simulations are naturally suited for models where dark fermion masses are around 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 always work: there are uncontrolled theoretical errors which are usually neglected

“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

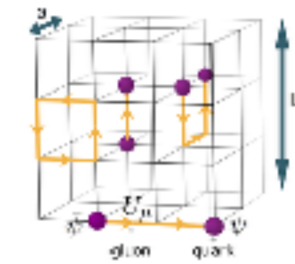
- New **Dark fermions**: have dark color and also have **electroweak charges** (W/Z,γ)

- Dark fermions have electroweak breaking masses (Yukawa couplings) and electroweak preserving masses (from confinement)

- A global symmetry naturally stabilizes the dark lightest baryonic composite states (e.g. dark U(1) “baryon number”) which is a singlet of 4 dark fermions: spin 0 (!!)

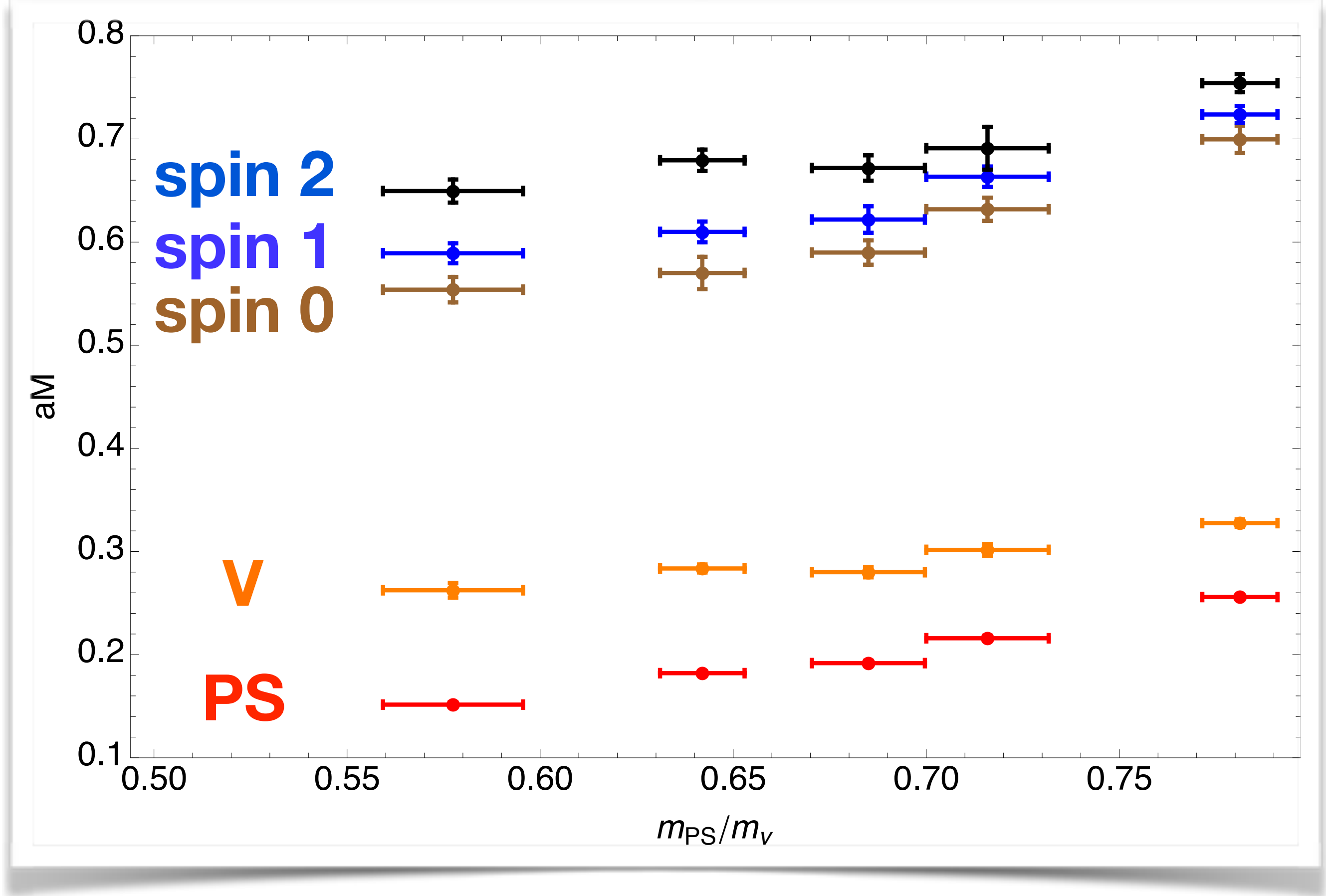
[LSD collab., Phys. Rev. D88 (2013) 014502]
[LSD collab., Phys. Rev. D89 (2014) 094508]
[LSD collab., Phys. Rev. D92 (2015) 075030]
[LSD collab., Phys. Rev. Lett. 115 (2015) 171803]

[KEK-Japan]



Lattice Stealth DM

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



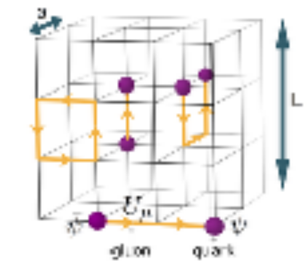
[LSD collab., Phys. Rev. D89 (2014) 094508]

- The ratio of pseudoscalar (PS) to vector (V) is used as probe for different dark fermion masses

- The meson-to-baryon mass ratio is a non-perturbative number which can only be extracted from lattice simulations

- Lattice discretization and finite volume effects are studied using multiple simulations (similar to what is done in QCD)

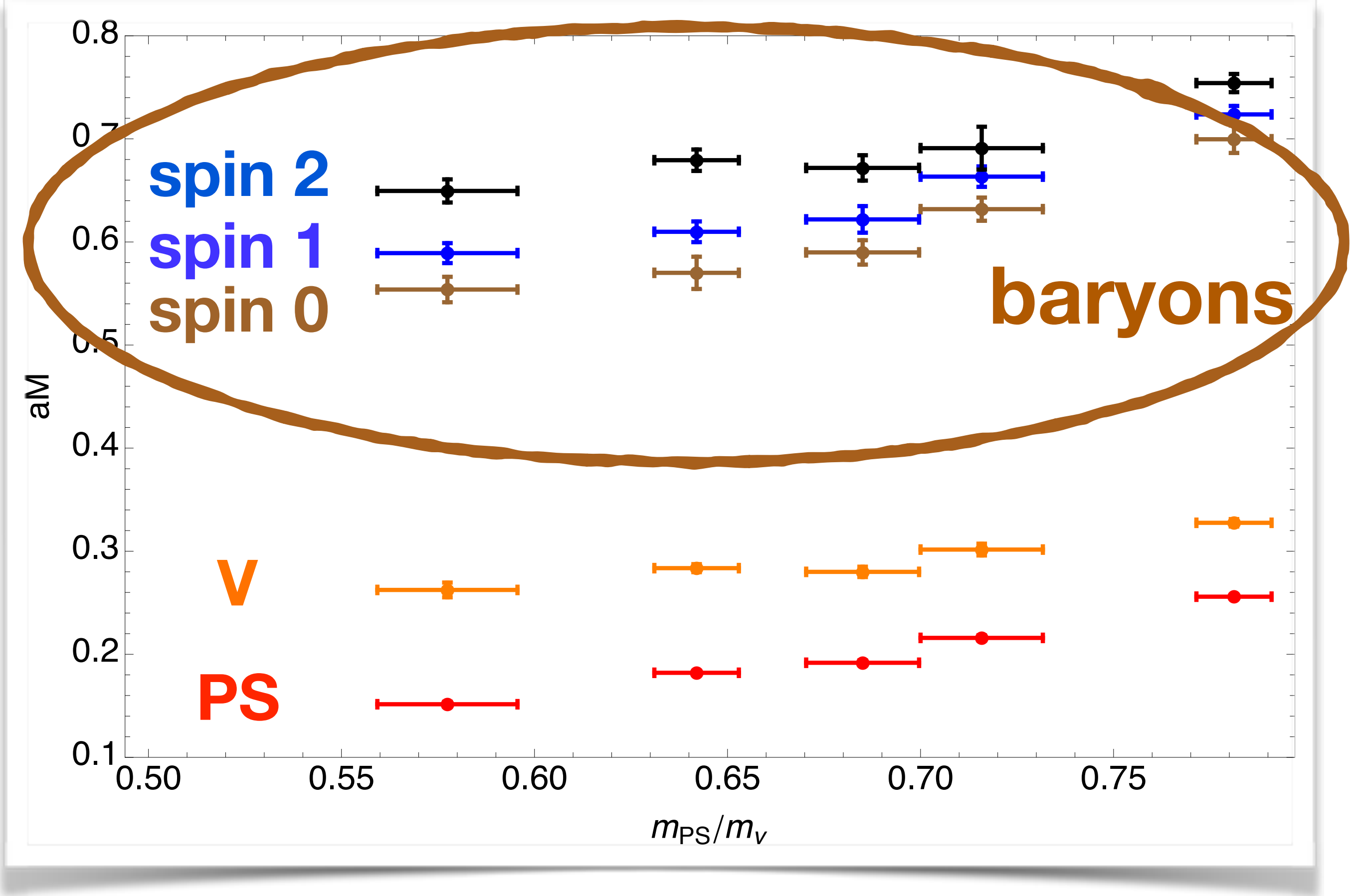
[KEK-Japan]



Lattice Stealth DM

- 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



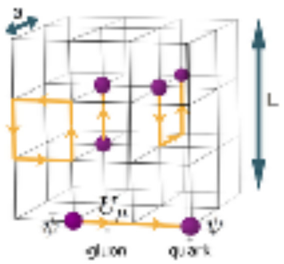
[LSD collab., Phys. Rev. D89 (2014) 094508]

- The meson-to-baryon mass ratio is a non-perturbative number which can only be extracted from lattice simulations

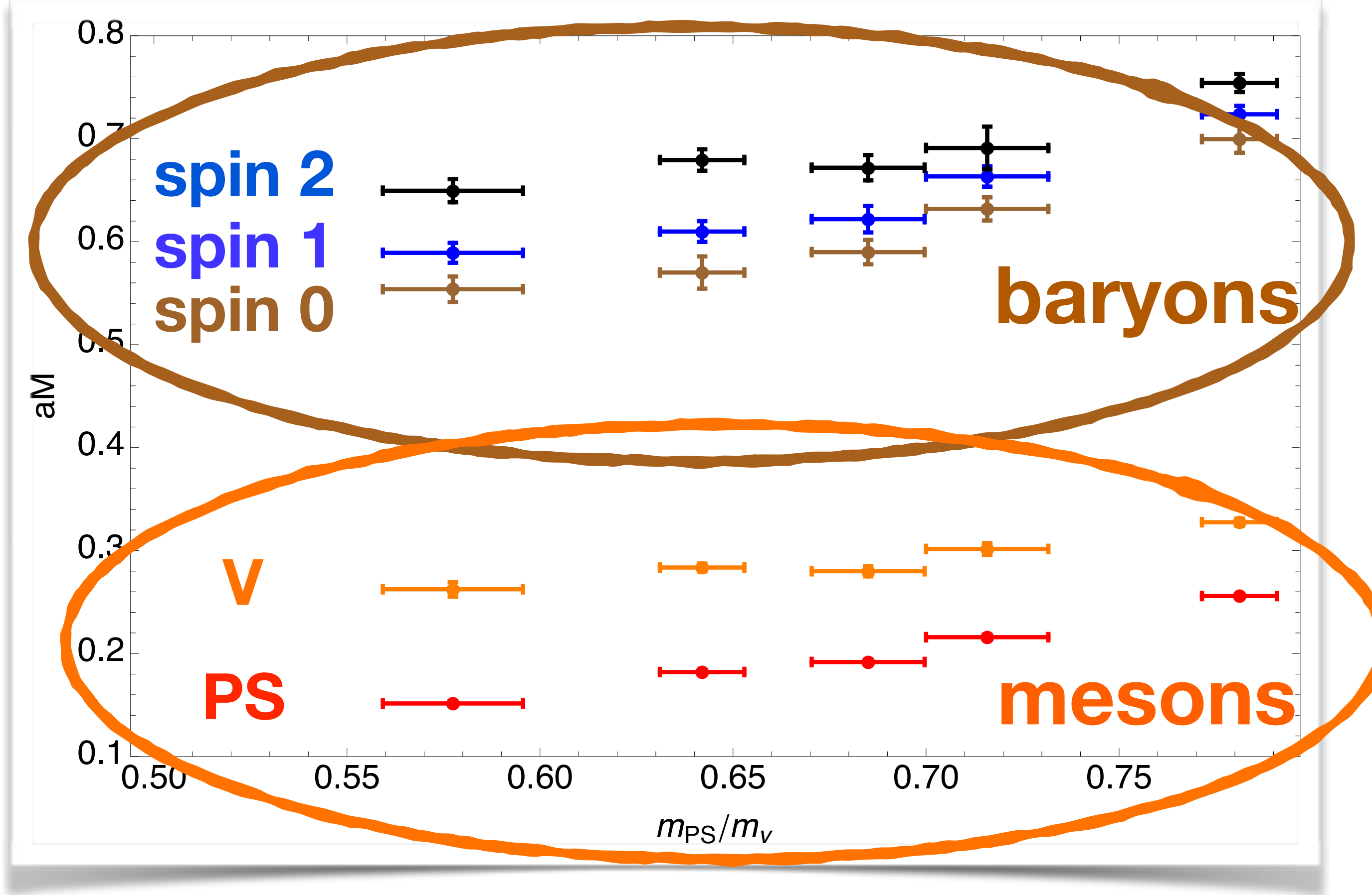
- Lattice discretization and finite volume effects are studied using multiple simulations (similar to what is done in QCD)

Lattice Stealth DM

[KEK-Japan]



- 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 is a non-perturbative number which can only be extracted from lattice simulations

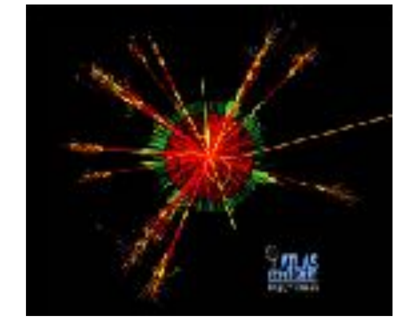


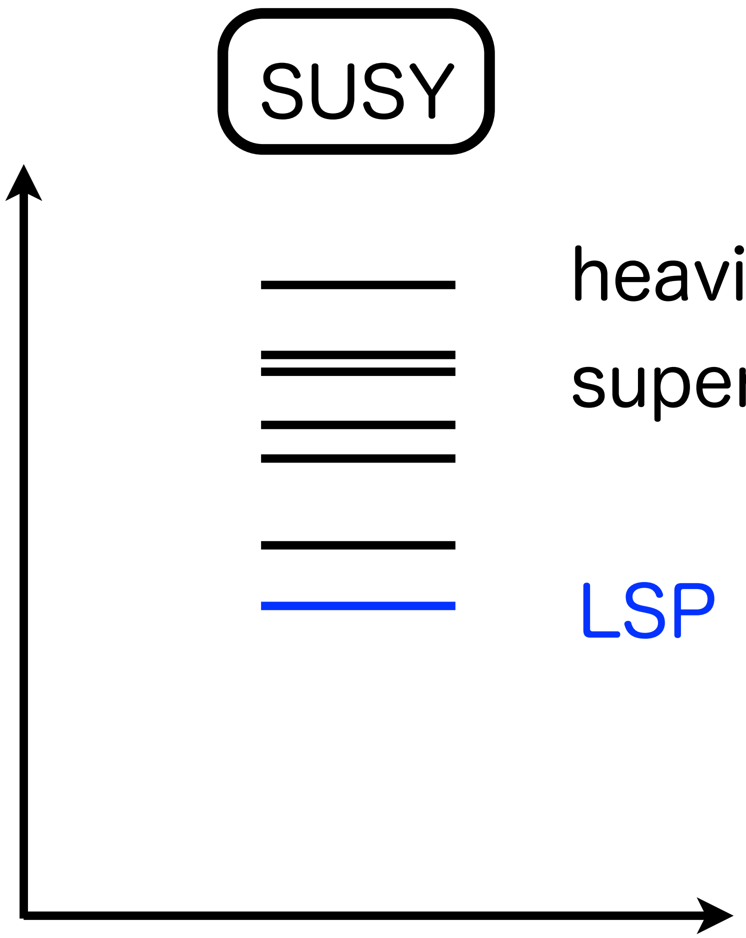
[LSD collab., Phys. Rev. D89 (2014) 094508]

- Lattice discretization and finite volume effects are studied using multiple simulations (similar to what is done in QCD)

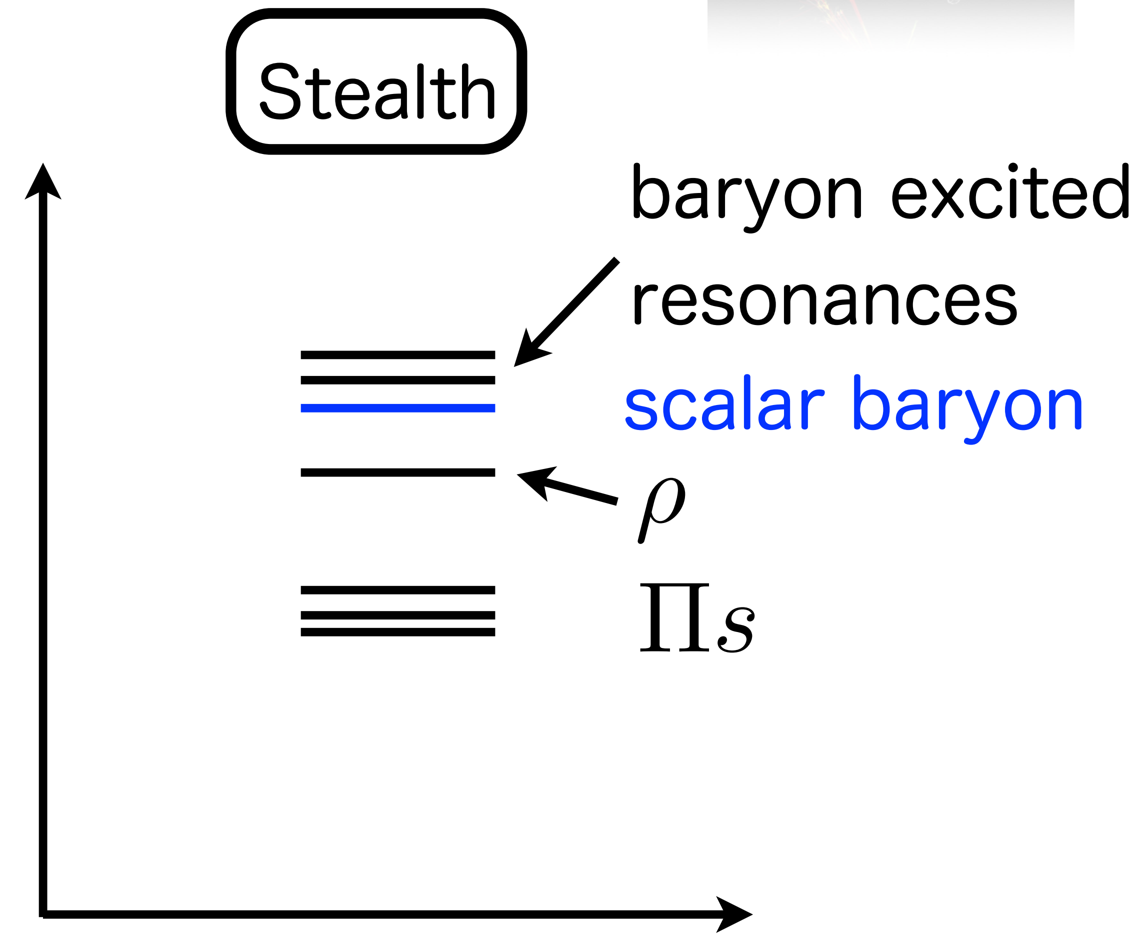
Stealth DM at colliders

[ATLAS]





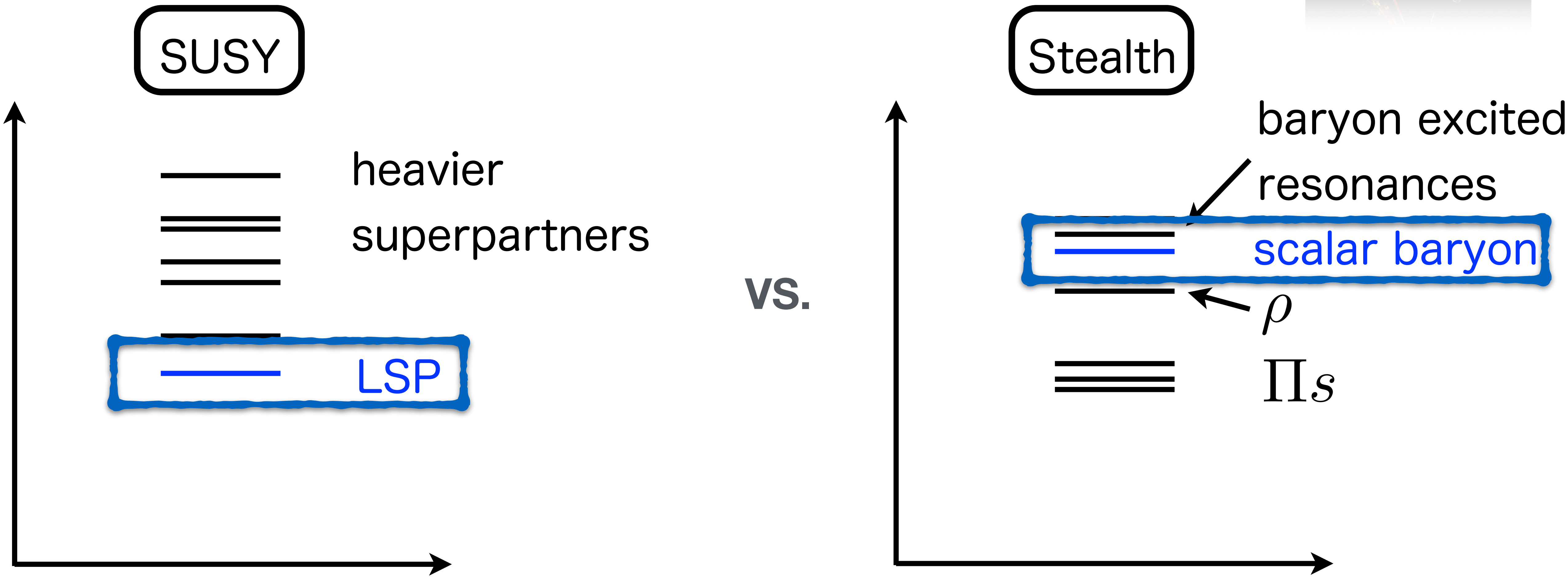
vs.



Plot by G. Kribs

[ATLAS]

Stealth DM at colliders

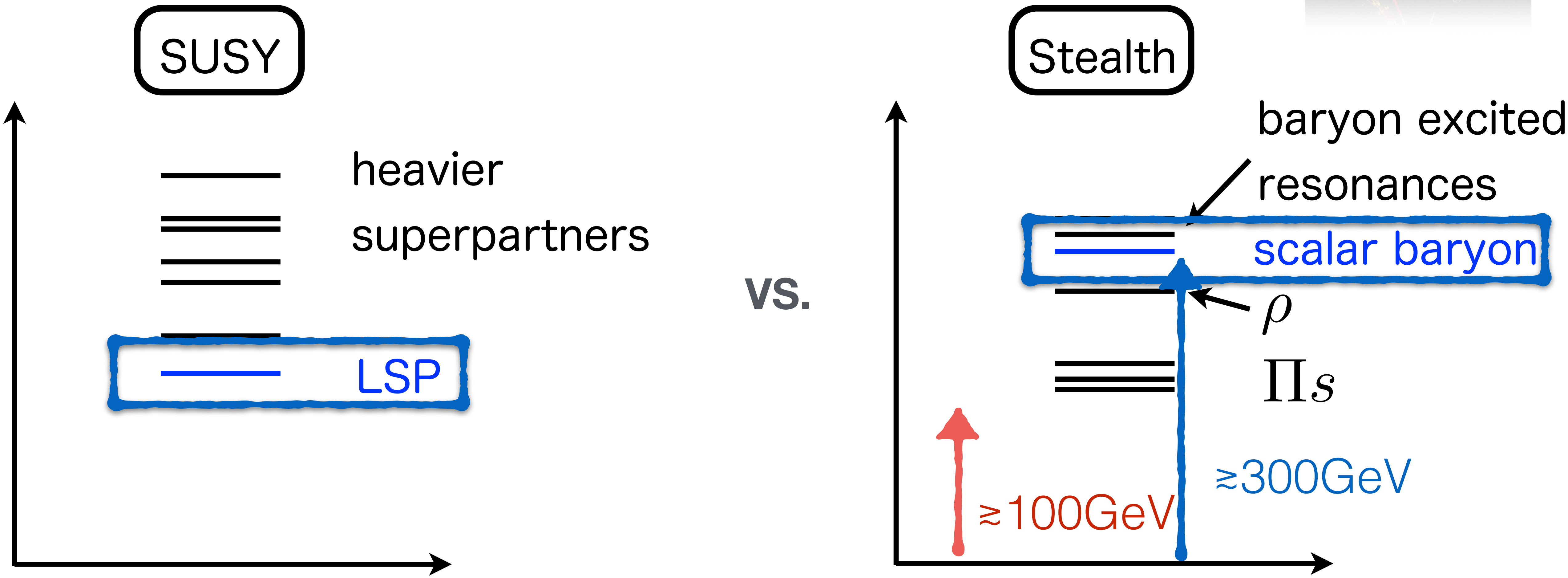


Plot by G. Kribs

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

Stealth DM at colliders

[ATLAS]

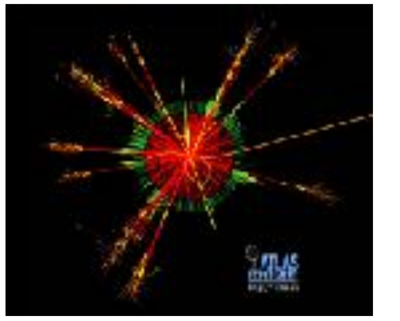


Plot by G. Kribs

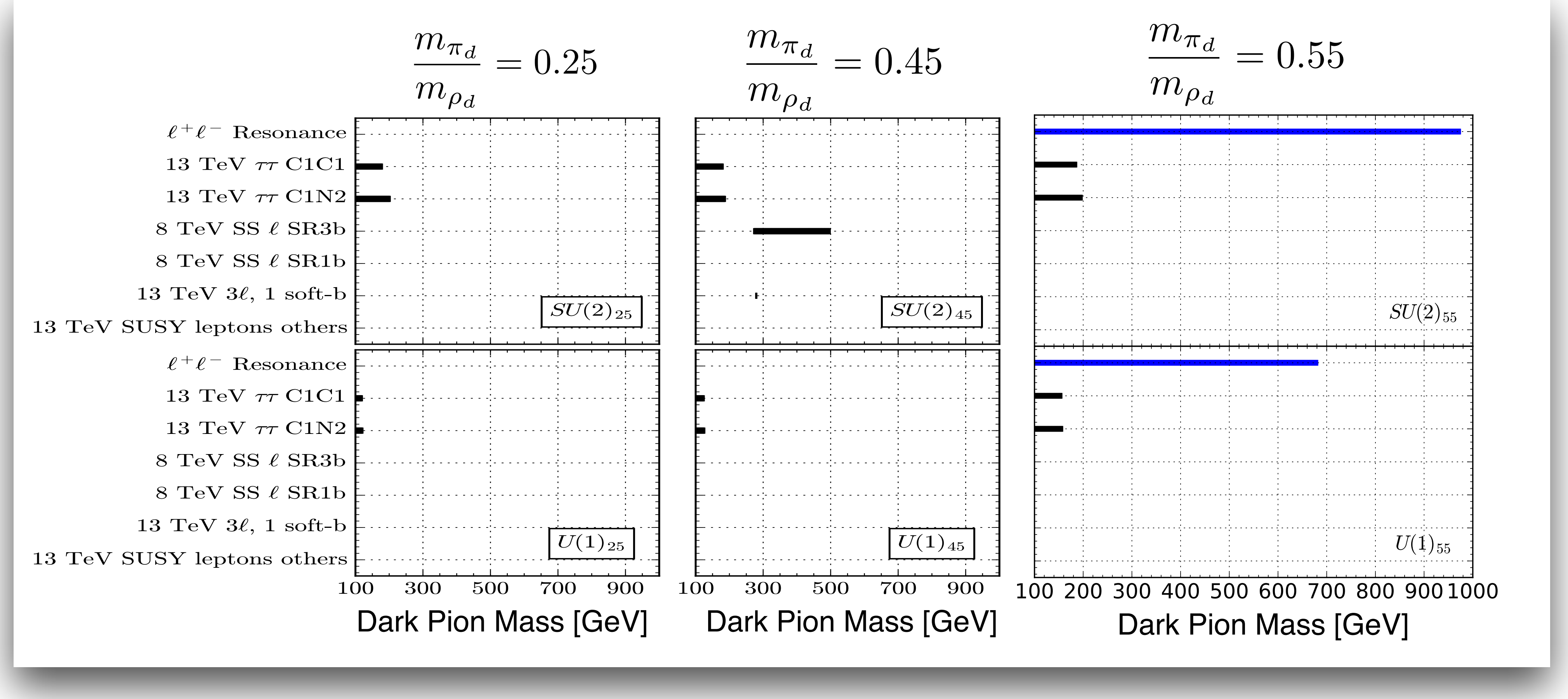
- Signatures are not dominated by missing energy: **DM is not the lightest particle!** The interactions are suppressed (form factors)
- Light dark meson production and decay give interesting signatures: **the model can be constrained by LHC/LEP data!** $\Pi \gtrsim 100\mathrm{GeV}$

More general bounds on “dark” mesons

[ATLAS]

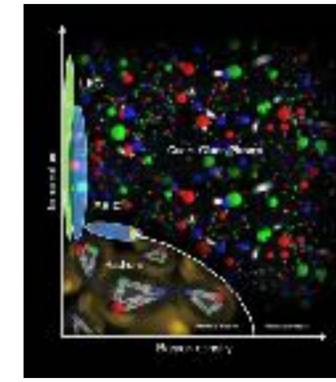


- Dark mesons can be created through Drell-Yan or vector kinetic mixing
- Dark vector meson decays to dark “pions”
- Re-cast existing SUSY searches (not optimal) [Kribs, Martin, Ostdiek, Tong (in preparation)]



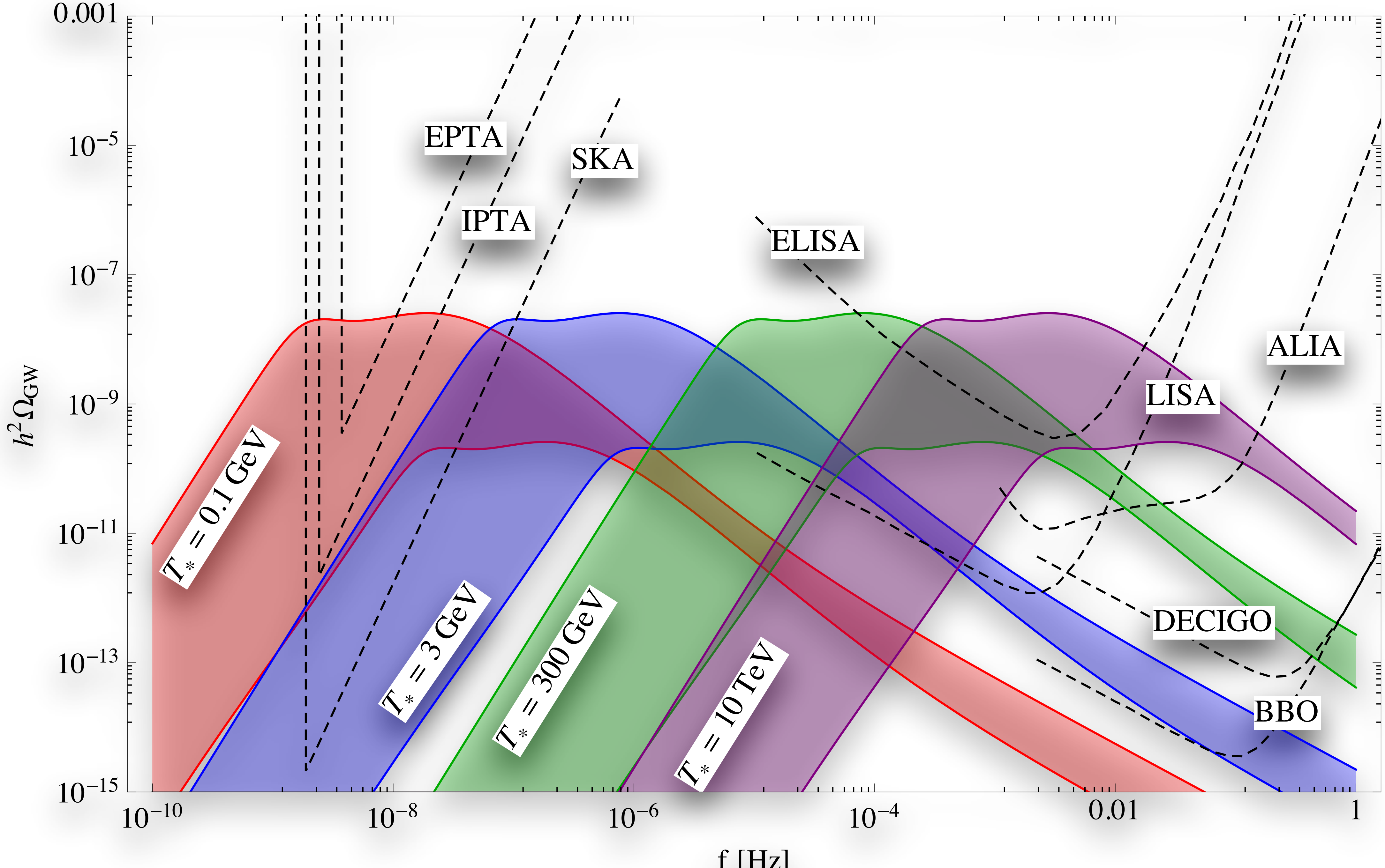
Plots from G. Kribs @ Lattice for BSM physics, University of Colorado Boulder, 4/2018

[RHIC]



Gravitational wave signatures from PT

- ✦Spectrum of GW from a deconfinement first order phase transition in the dark sector



[P. Schwaller, PRL (115) 181101, 2015]

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

The darkness of Composite Dark Matter

[Wikipedia]

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

The darkness of Composite Dark Matter

[Wikipedia]

Lowest dimensional operators:

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

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

The darkness of Composite Dark Matter

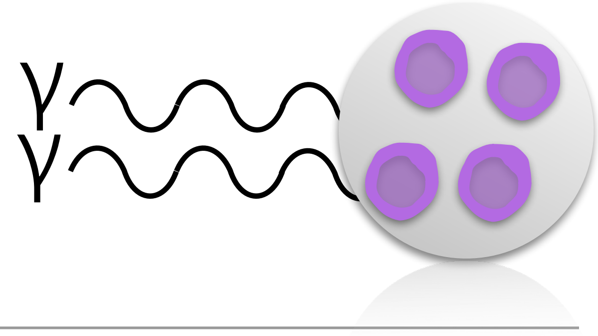
[Wikipedia]

Lowest dimensional operators:

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

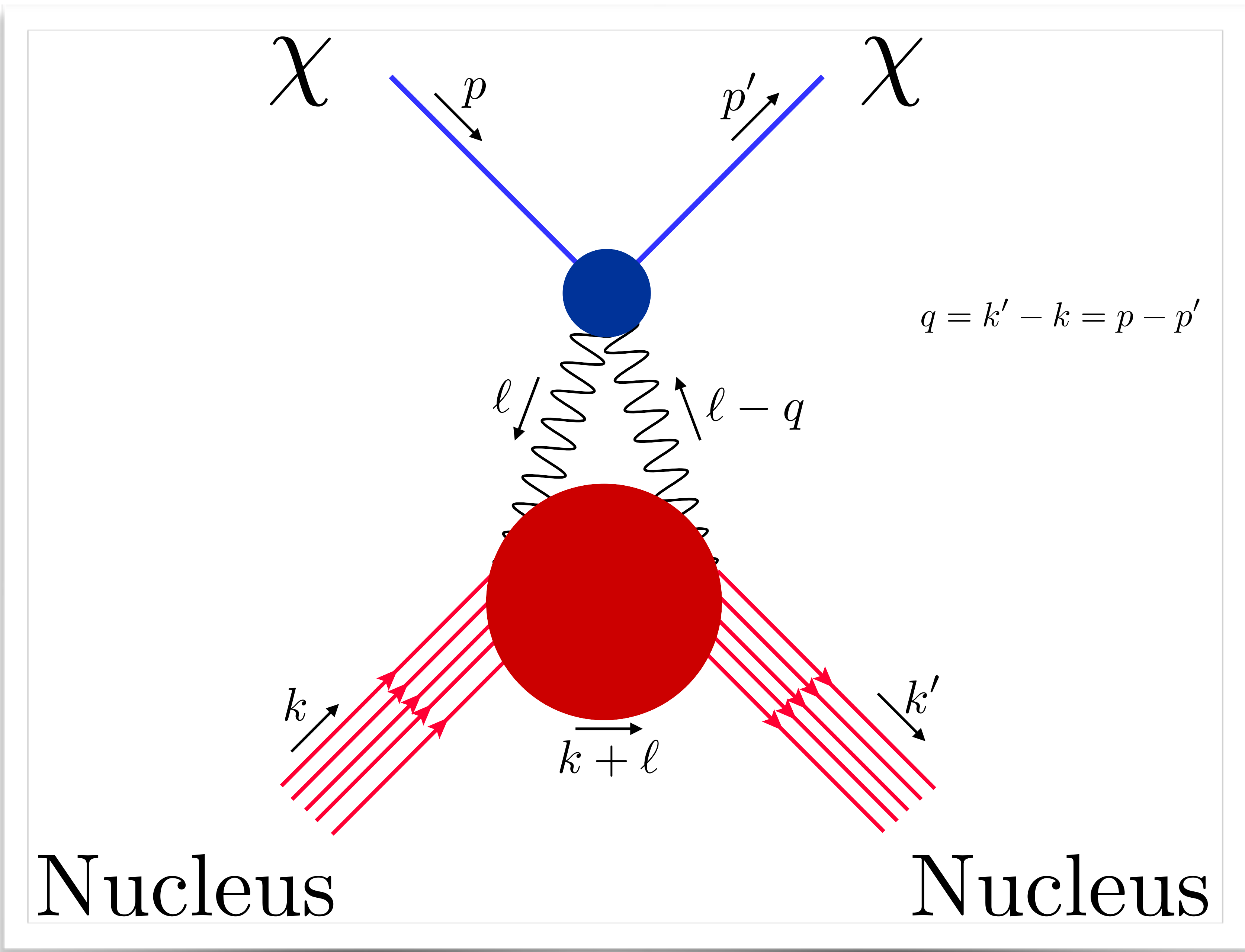
Most relevant interaction if constituents have Yukawa couplings!

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



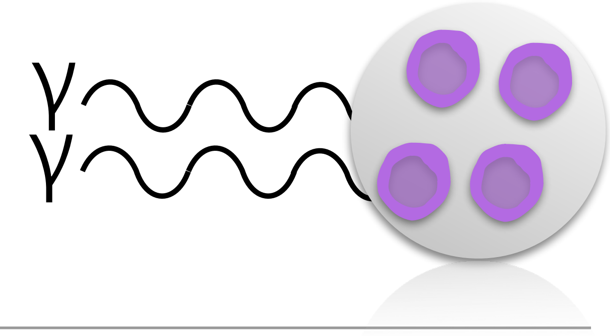
Computing polarizability

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



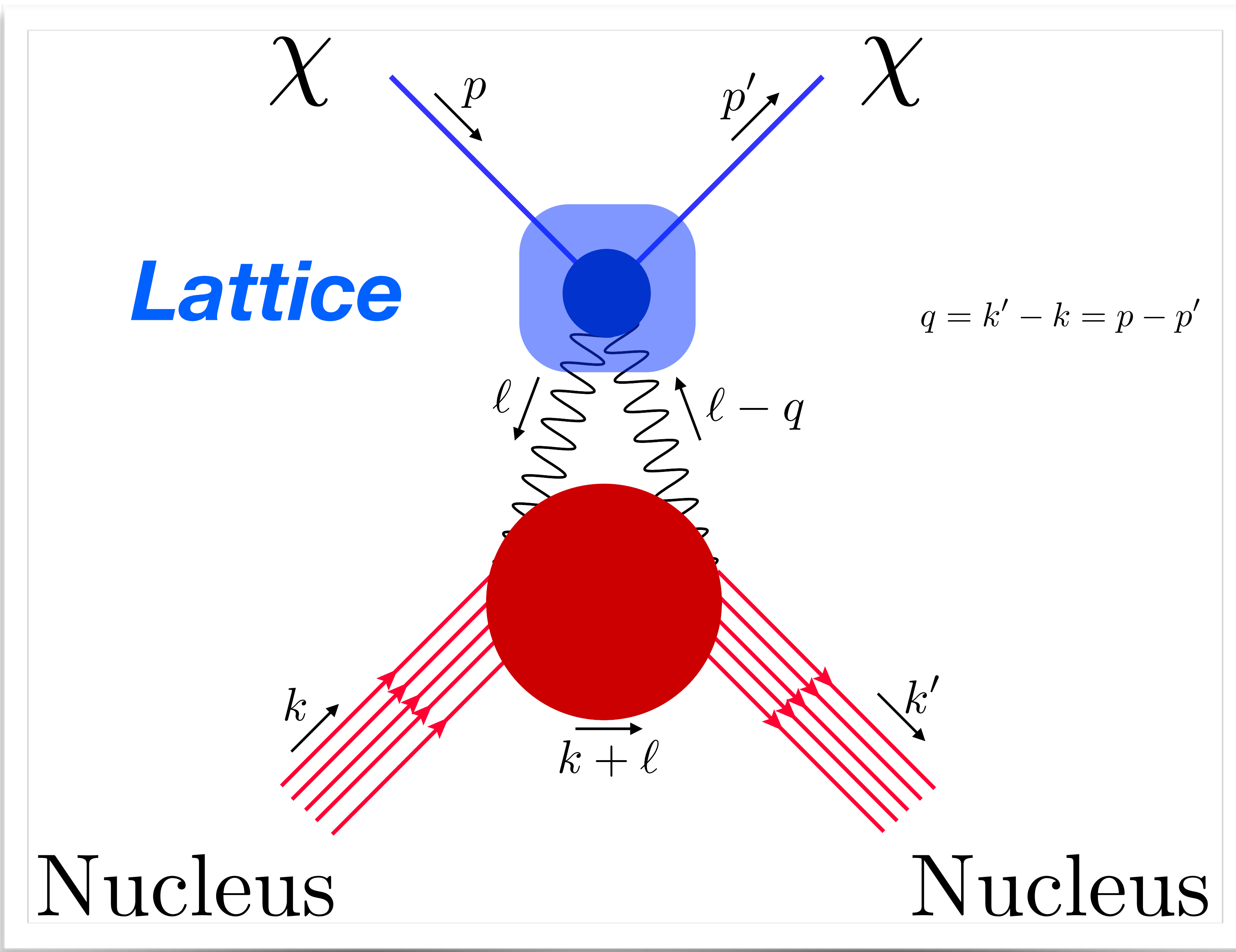
[Pospelov & Veldhuis, hep-ph/0003010] [Ovanesyan & Vecchi, 1410.0601] [Weiner & Yavin,1206.2910] [Frandsen et al., 1207.3971]

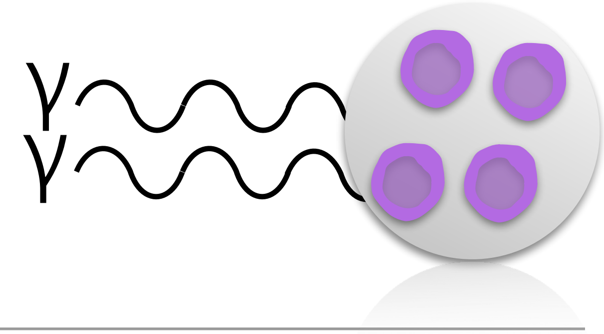
[Detmold et al., 0904.1586-1001.1131]



Computing polarizability

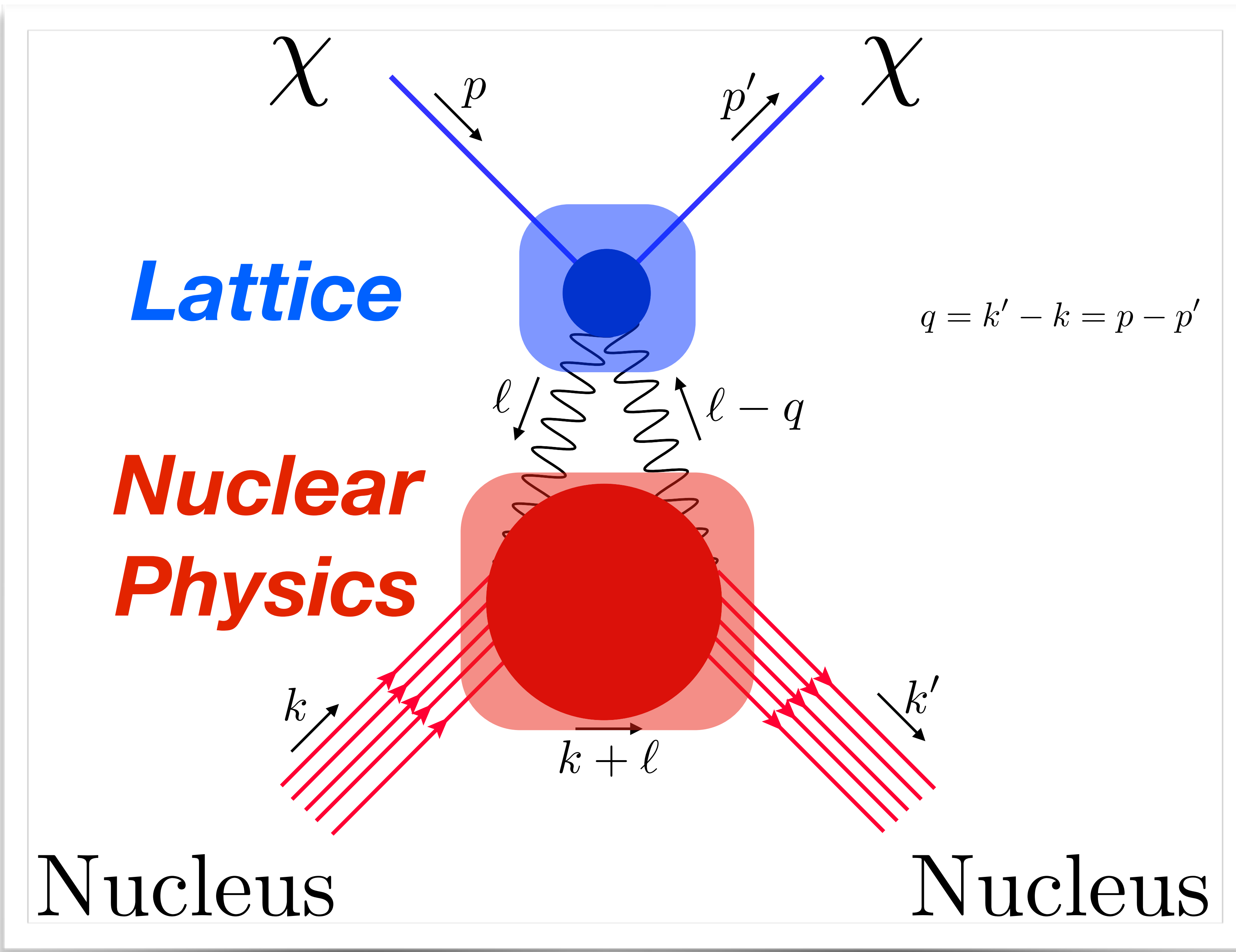
$$\frac{c_F e^2}{m_\chi^3} \chi^\star \chi F^{\mu\alpha} F^\nu_\alpha v_\mu v_\nu$$





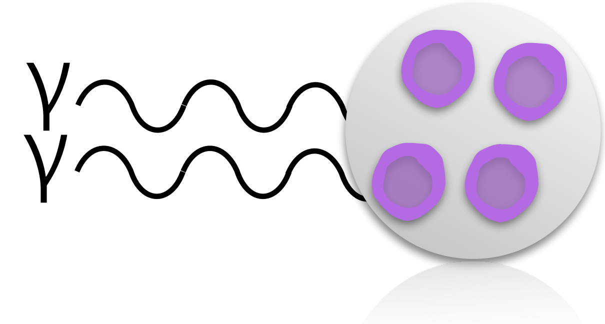
Computing polarizability

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

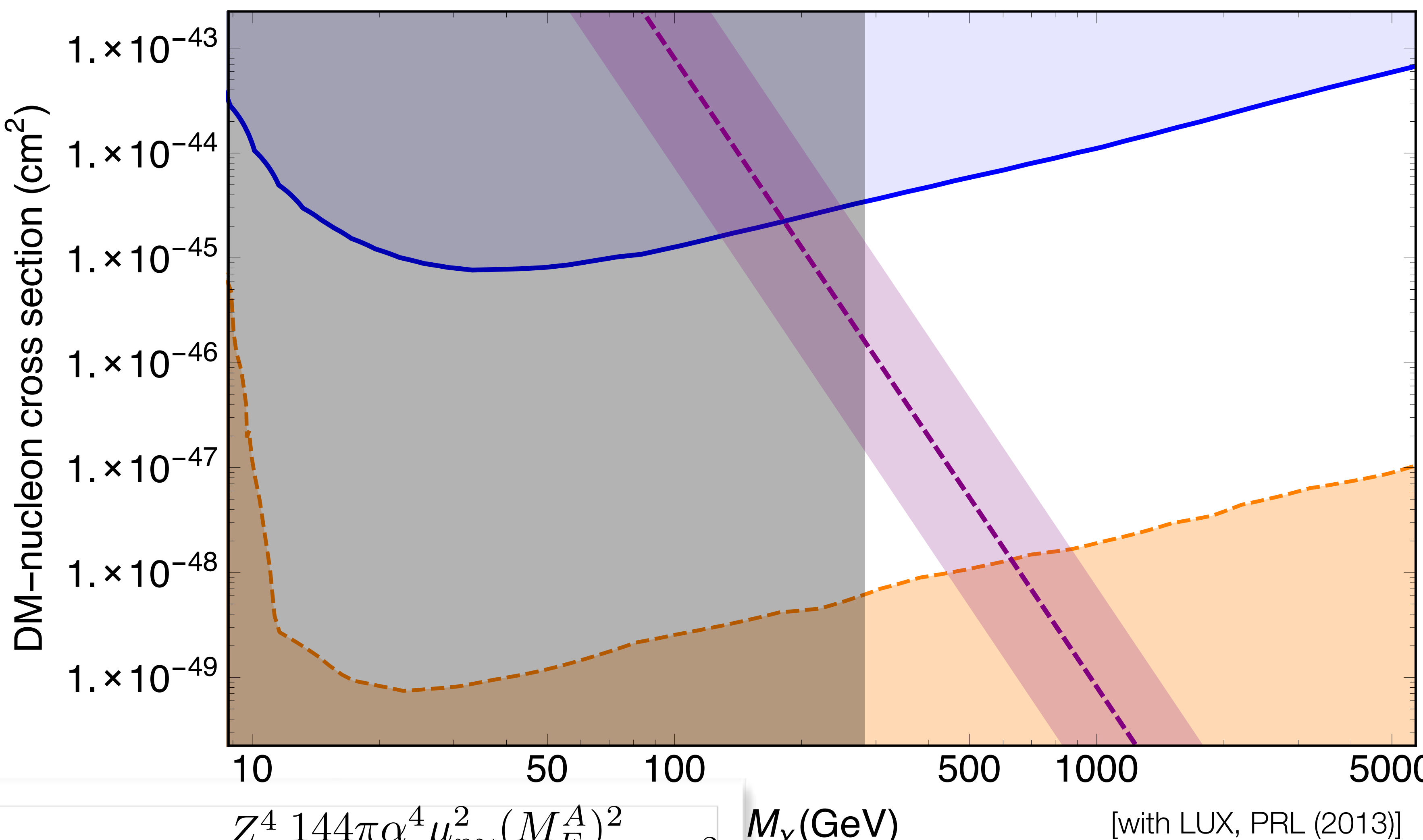


[Newer bounds: PandaX-II 1607.07400, LUX-332d 1608.07648, XENON1T-34d 1705.06655]

Lowest bound from EM polarizability



Electric polarizability from lattice simulations with background fields



SU(4) N_f=4 Stealth DM

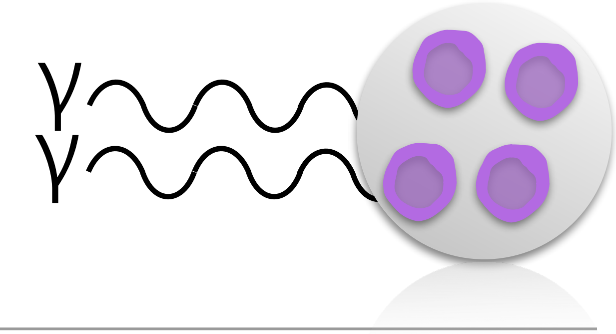
[LSD collab., Phys. Rev. Lett. 115 (2015) 171803]

[with LUX, PRL (2013)]

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

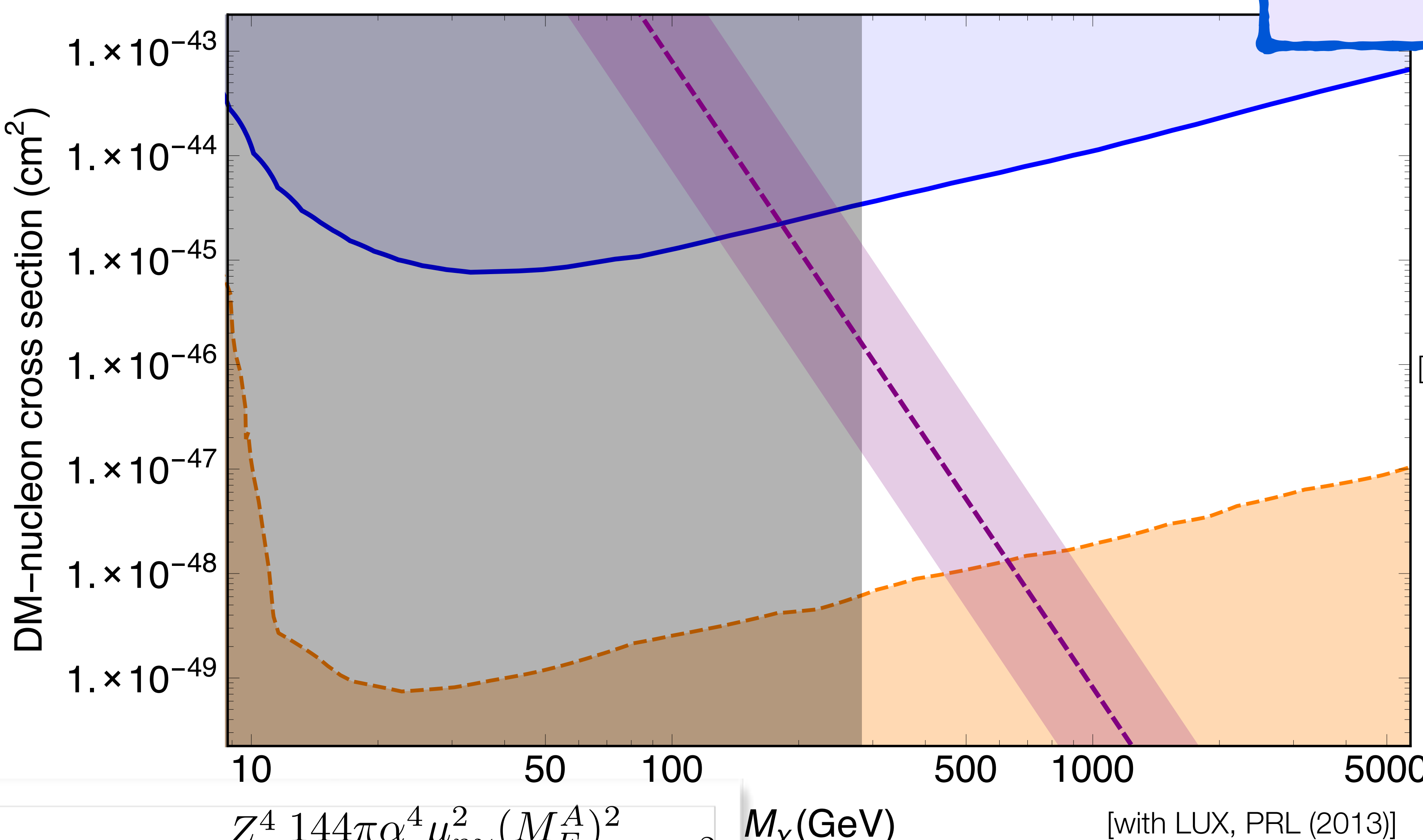
[Newer bounds: PandaX-II 1607.07400, LUX-332d 1608.07648, XENON1T-34d 1705.06655]

Lowest bound from EM polarizability



Electric polarizability from lattice simulations with background fields

LUX exclusion bound for spin-independent cross section



SU(4) N_f=4 Stealth DM

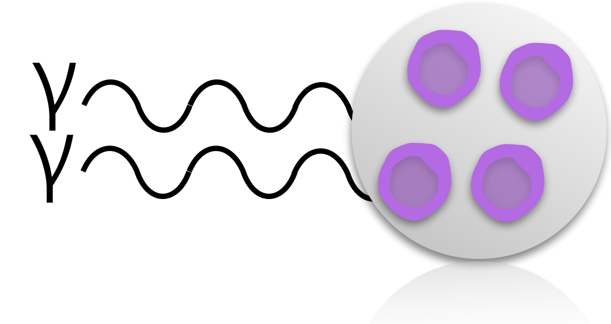
[LSD collab., Phys. Rev. Lett. 115 (2015) 171803]

[with LUX, PRL (2013)]

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

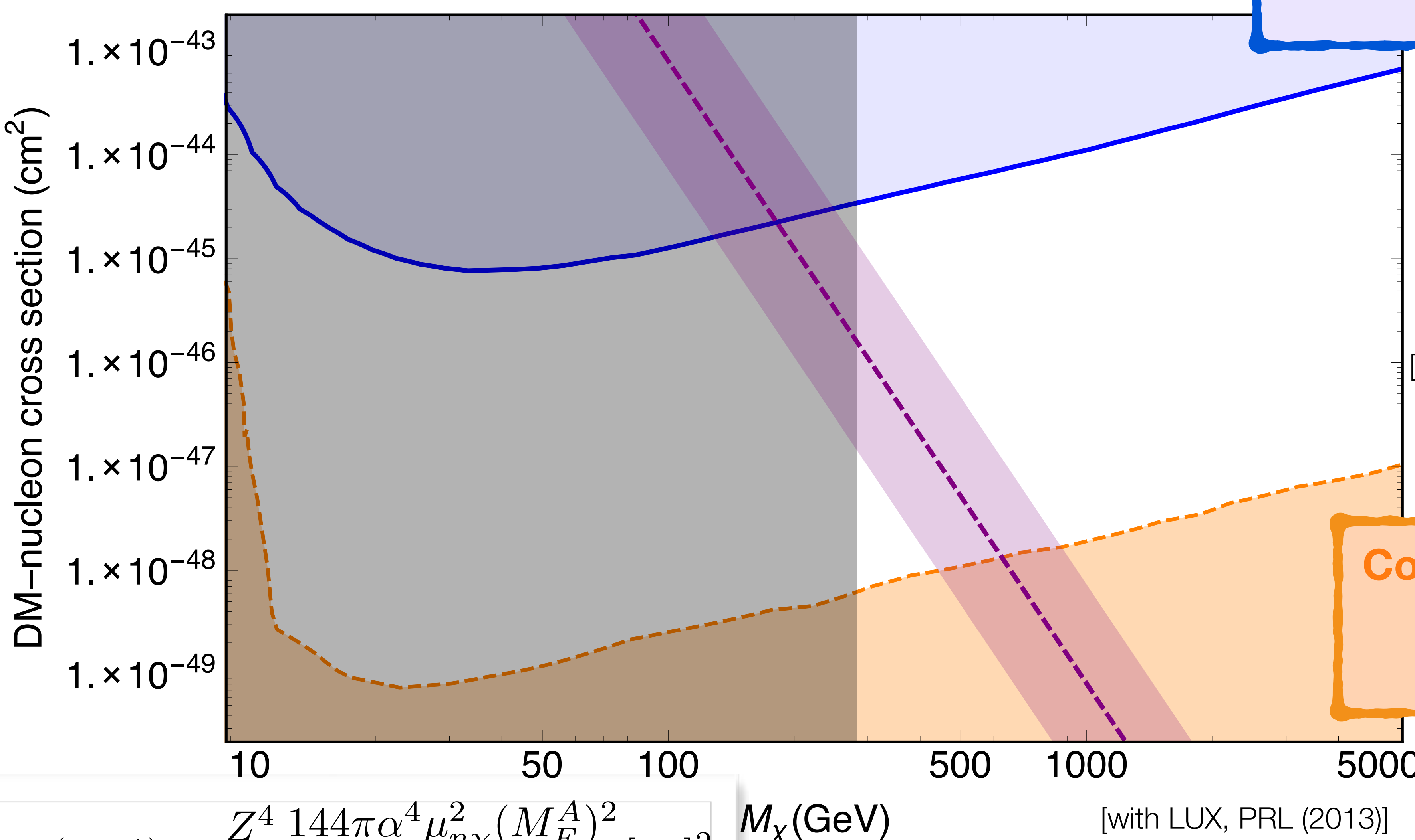
[Newer bounds: PandaX-II 1607.07400, LUX-332d 1608.07648, XENON1T-34d 1705.06655]

Lowest bound from EM polarizability



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

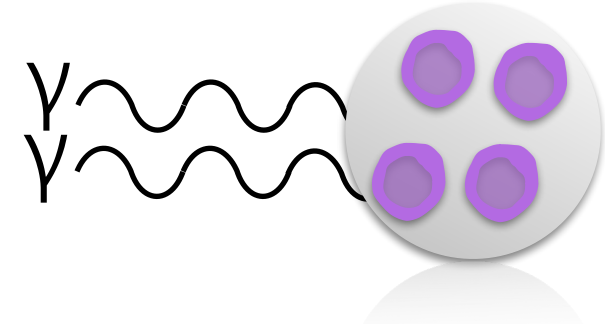
[LSD collab., Phys. Rev. Lett. 115 (2015) 171803]

Coherent neutrino scattering background

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

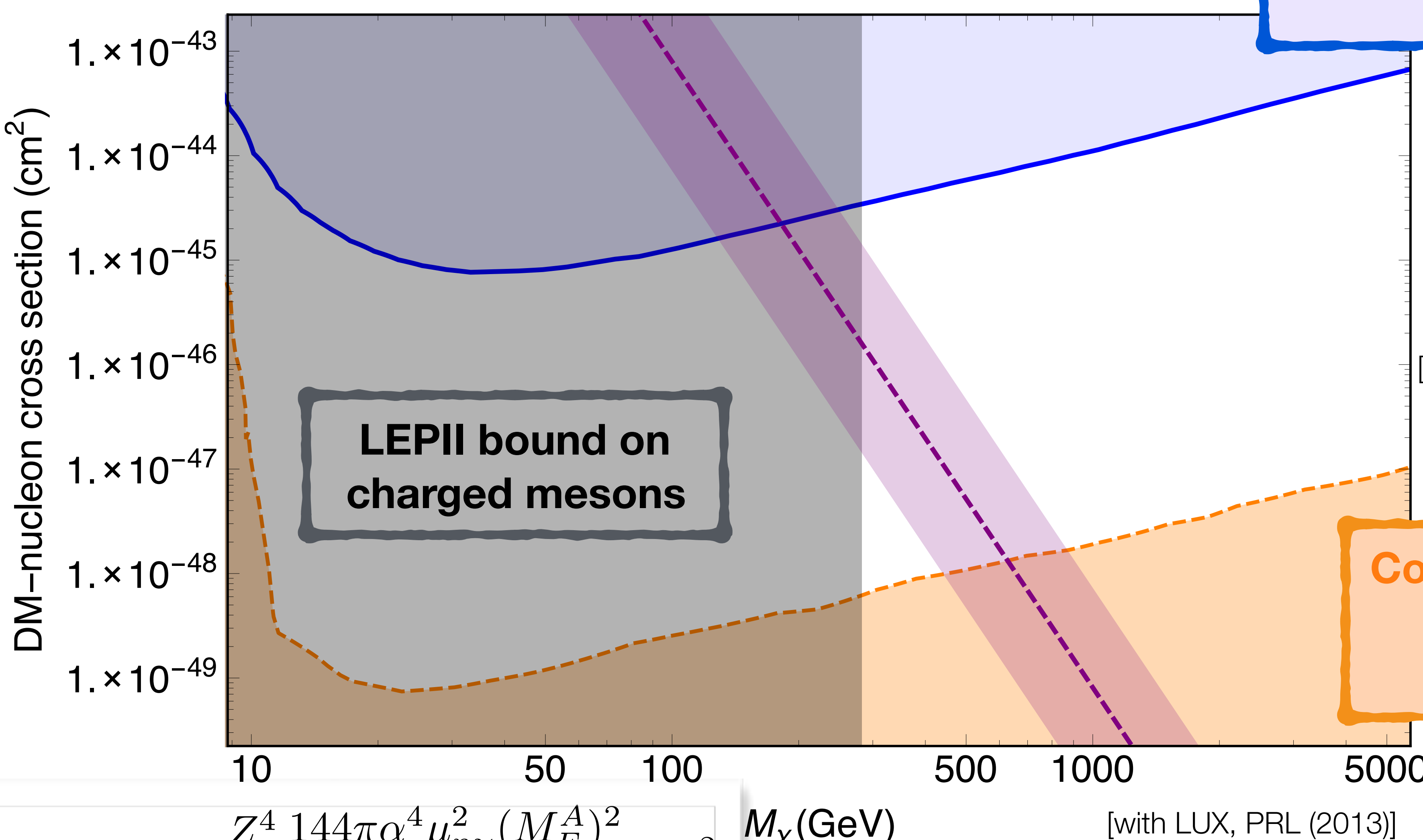
[Newer bounds: PandaX-II 1607.07400, LUX-332d 1608.07648, XENON1T-34d 1705.06655]

Lowest bound from EM polarizability



Electric polarizability from lattice simulations with background fields

LUX exclusion bound for spin-independent cross section



SU(4) N_f=4 Stealth DM

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

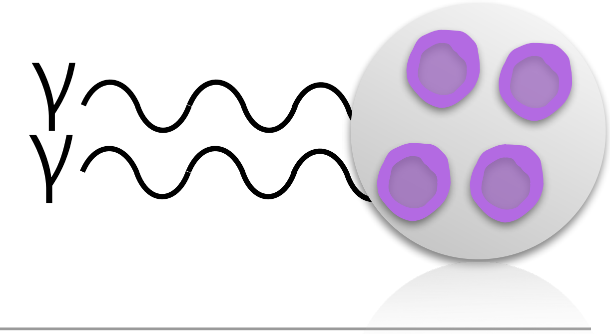
Coherent neutrino scattering background

[with LUX, PRL (2013)]

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

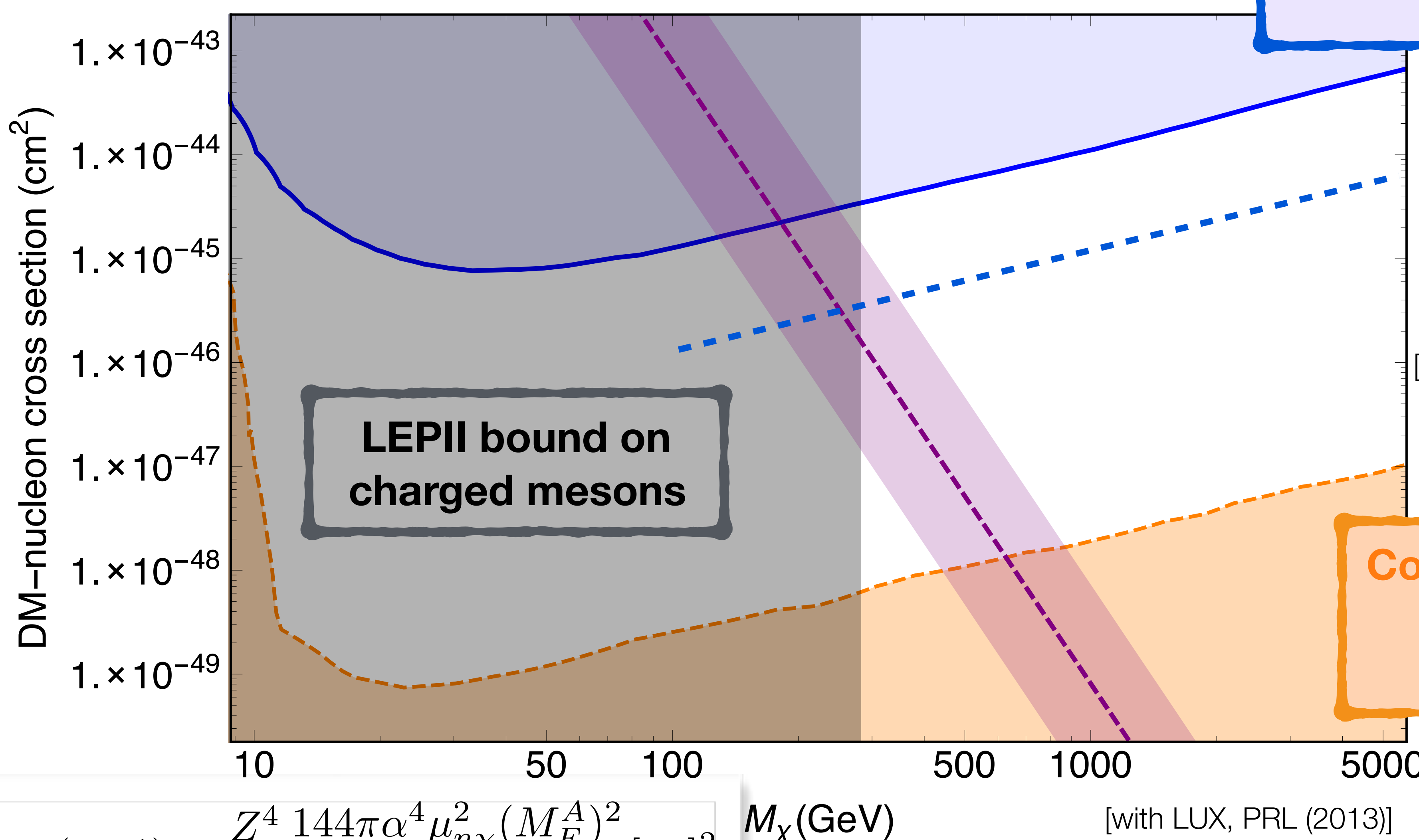
[Newer bounds: PandaX-II 1607.07400, LUX-332d 1608.07648, XENON1T-34d 1705.06655]

Lowest bound from EM polarizability



Electric polarizability from lattice simulations with background fields

LUX exclusion bound for spin-independent cross section



[XENON1T 34.2days 1705.06655]

SU(4) N_f=4 Stealth DM

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

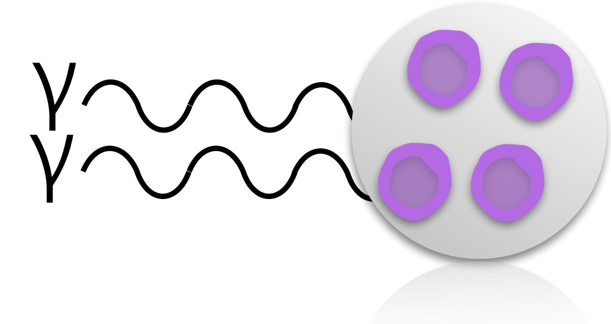
Coherent neutrino scattering background

[with LUX, PRL (2013)]

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

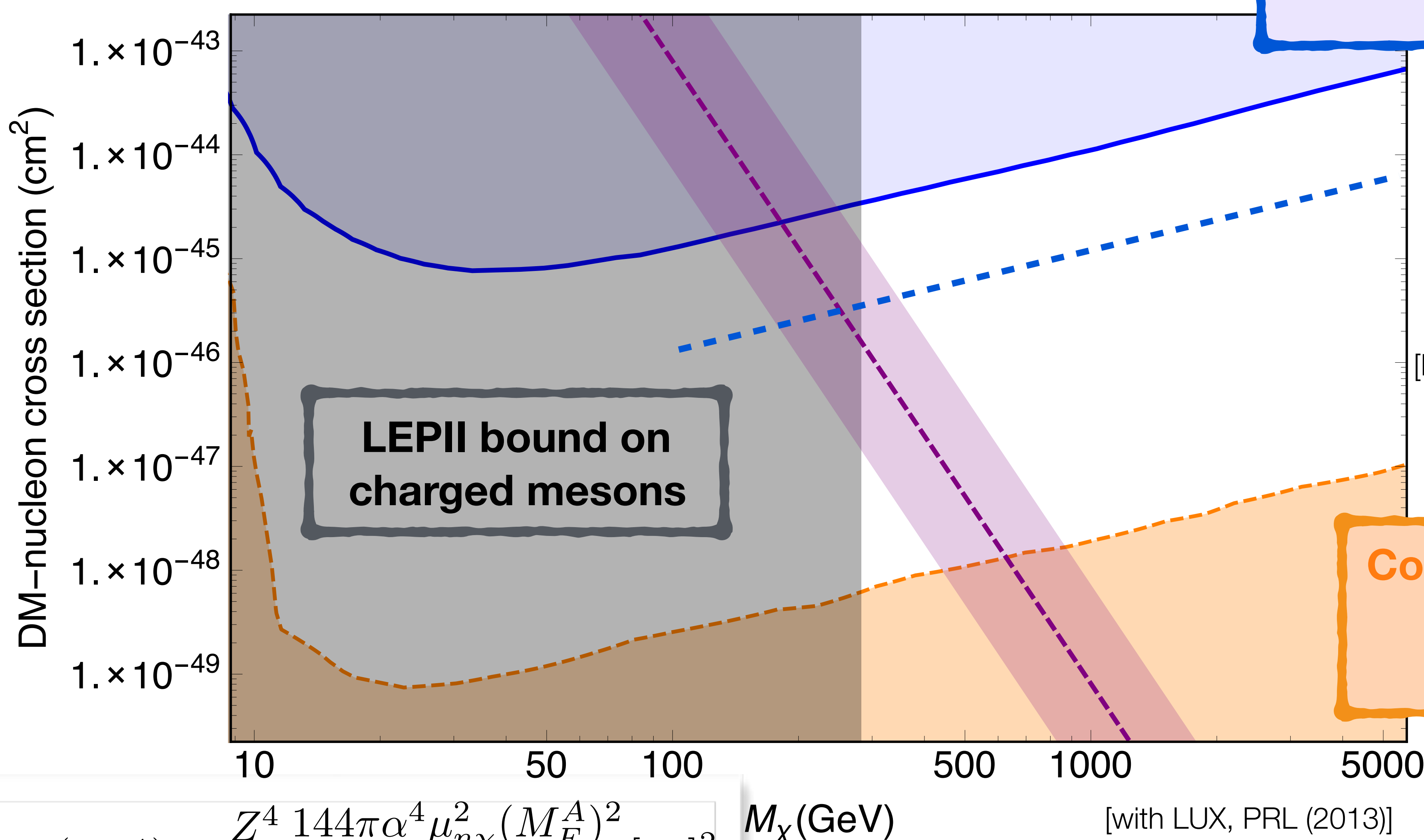
[Newer bounds: PandaX-II 1607.07400, LUX-332d 1608.07648, XENON1T-34d 1705.06655]

Lowest bound from EM polarizability



Electric polarizability from lattice simulations with background fields

LUX exclusion bound for spin-independent cross section



[XENON1T 34.2days 1705.06655]

SU(4) N_f=4 Stealth DM

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

LEPII bound on charged mesons

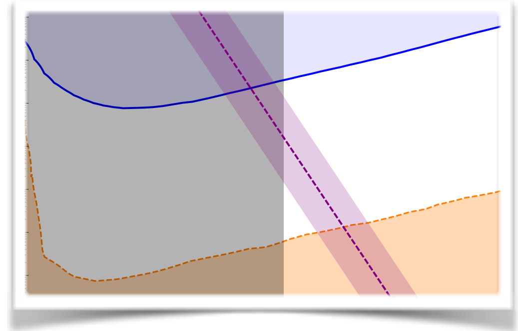
Coherent neutrino scattering background

[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

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



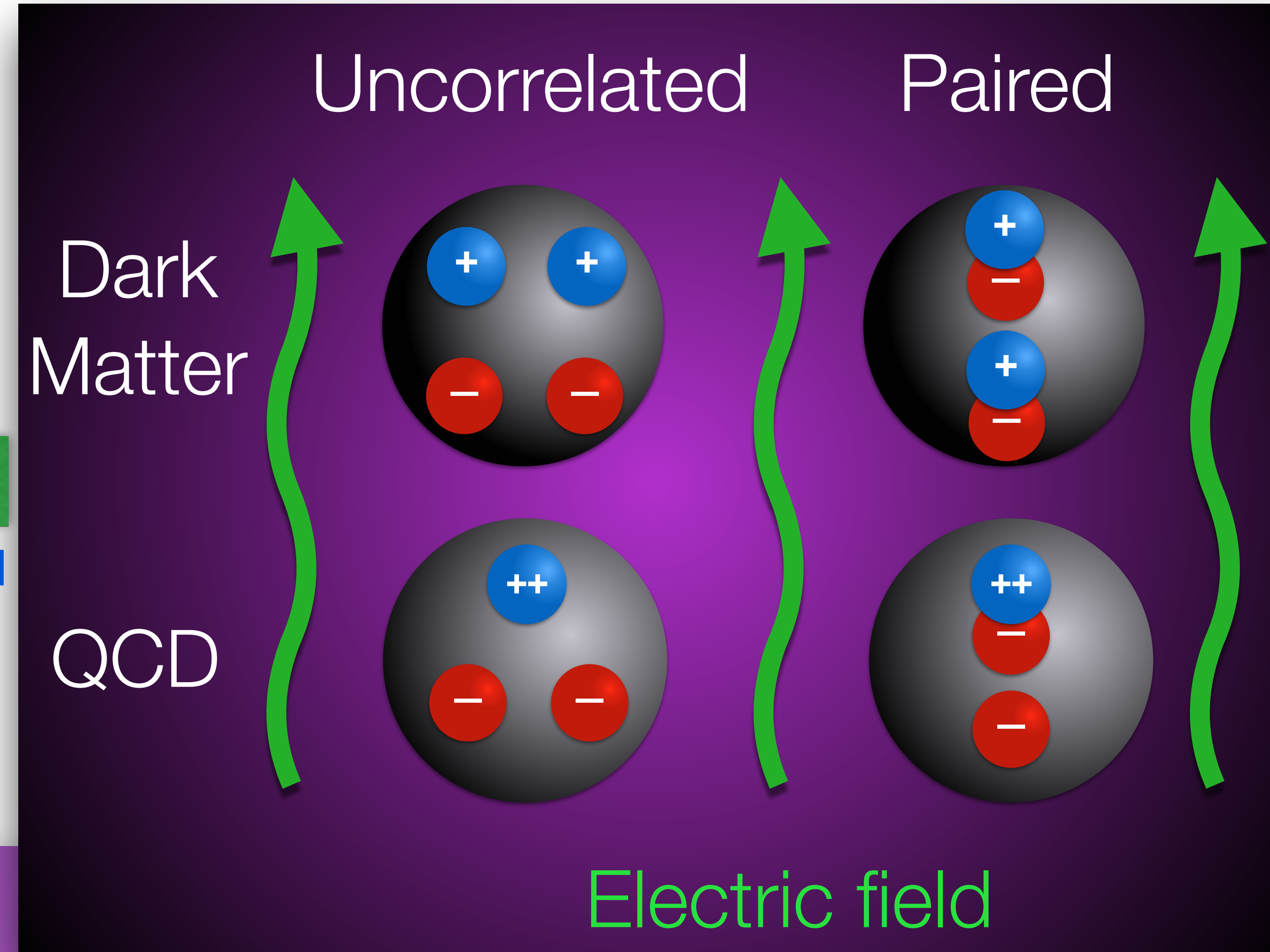
Concluding remarks

✦ **Composite** dark matter is a viable interesting possibility with rich phenomenology: all scales are natural

✦ **Lattice** methods can help in calculating direct detection cross sections, production rates at colliders, self-interaction cross sections and the spectrum of gravitational waves. Direct phenomenological relevance.

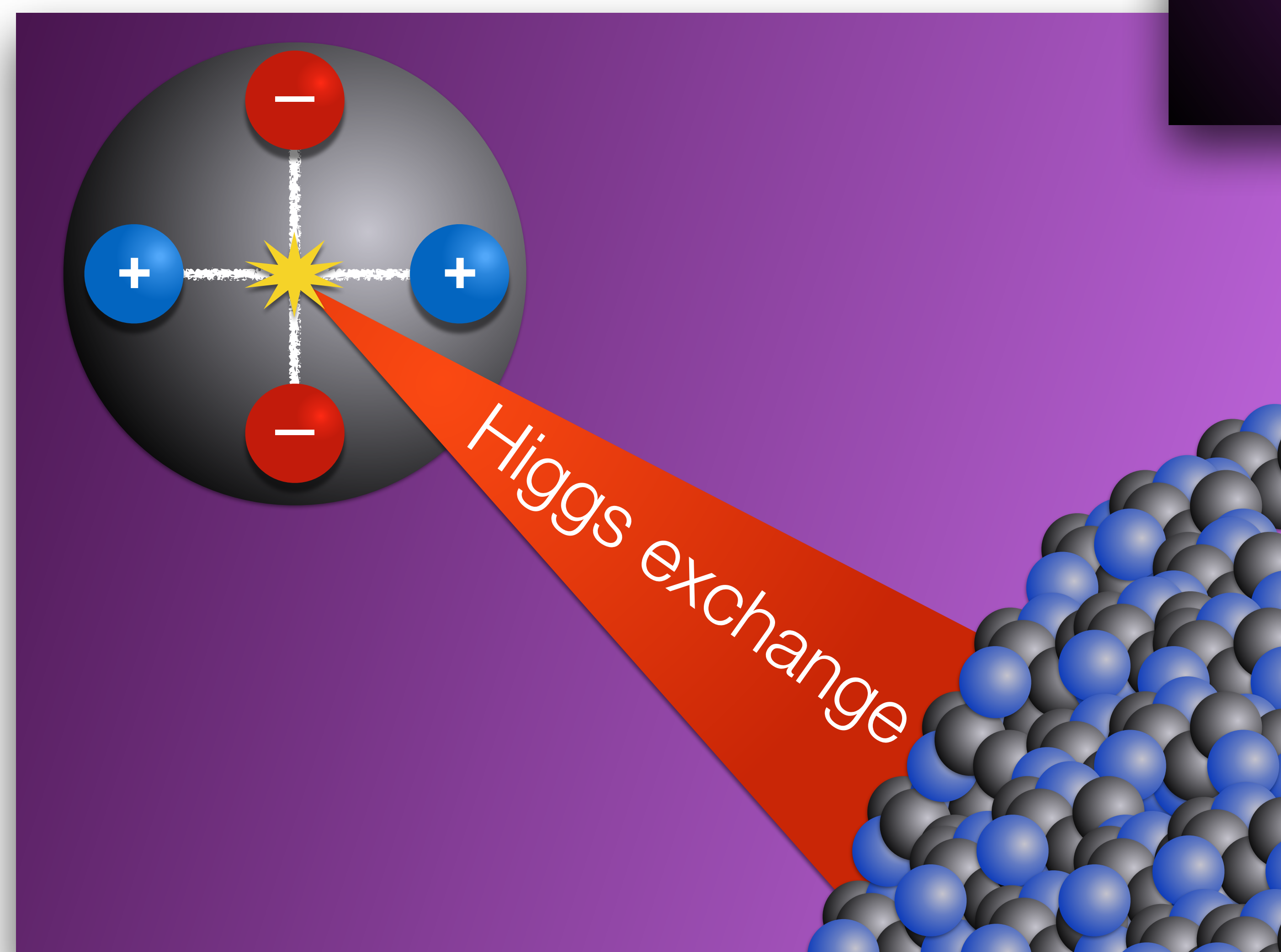
✦ Dark matter constituents can carry electroweak charges and still the stable composites are currently undetectable. **Stealth** cross section.

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



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/

MEDIA INAF

NOTIZIARIO ON-LINE DELL'ISTITUTO NAZIONALE DI ASTROFISICA

Universo INAF | App | Sedi | Astrochannel | Progetti da Terra | Progetti spaziali | Agenda | Lavoro | Seminari

HOME | ASTRONOMIA | SPAZIO | FISICA | TECH | EVENTI | ARCHIVIO | GALLERY

COME UN CACCIA INVISIBILE AI RADAR

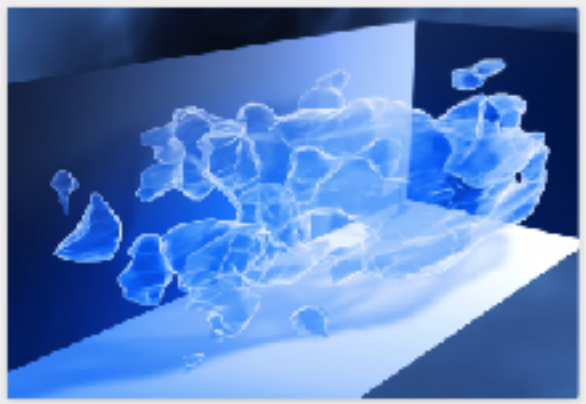
G+1 1 Tweet 7 Share 215

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 | Segui @malamine | venerdì 25 settembre 2015 @ 16:15

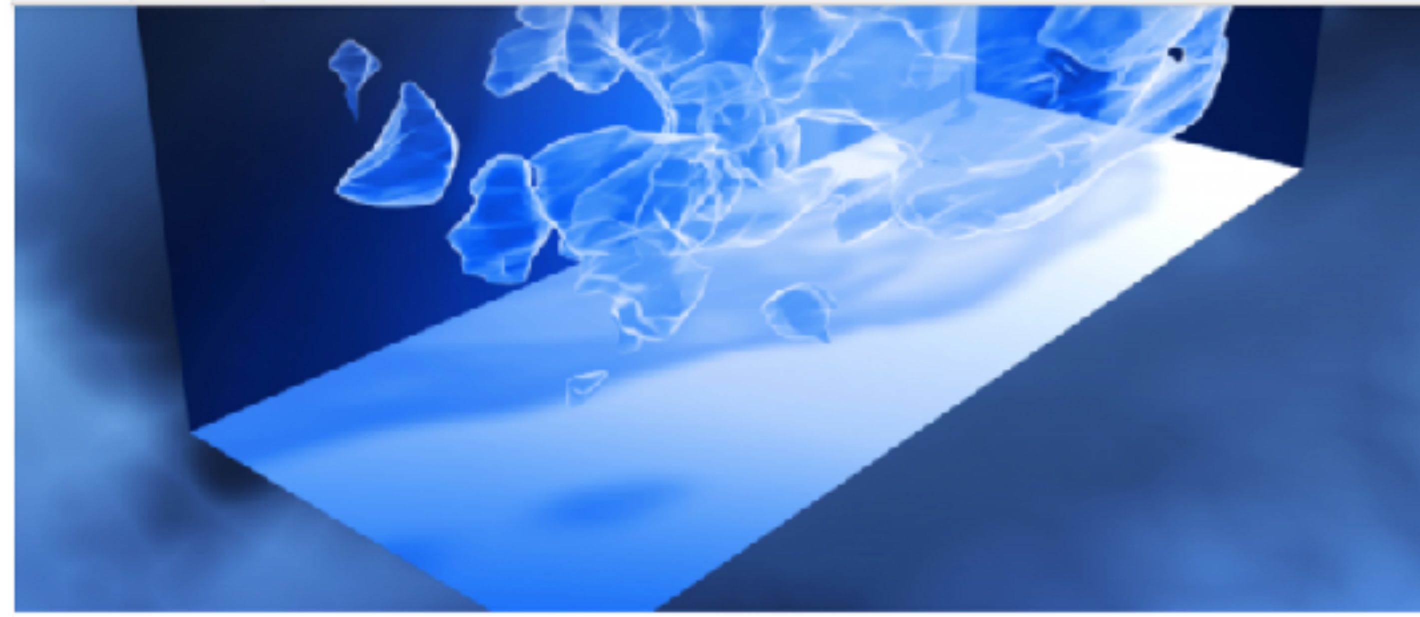
Stealth come furtiva. *Stealth* come imprendibile. *Stealth* come quei minacciosi aerei da guerra dal profilo sagomato così da essere invisibili al radar. Da quanto emerge dai calcoli dei fisici dell'LLNL, il Lawrence Livermore National Laboratory californiano, e dai modelli dati in pasto a Vulcan (un 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

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

usiness | News | About | Careers | Community



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

SUMMARY | News | Blogs | Twitter | Facebook | Google+

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]

View on publi... | Alert me abou...

About this score

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

MORE...

TWITTER DEMOGRAPHICS | MENDELEY READERS | SCORE IN C...

The data shown below were collected from the profiles of 23 tweeters who shared this research output. Click here to find... how the information was compiled.

Le Scienze

EDIZIONE ITALIANA DI SCIENTIFIC AMERICAN

LA RIVISTA IN ED...
Materia osc...
Nuove ipotesi su... misteriosa comp... ancora più bizza...
In edicola dal 1...
ABBONAMENTI E...

ZOOM SU | comportamento | cosmologia | neuroscienze | alimentazione

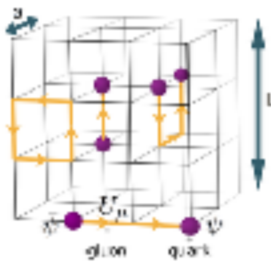
28 settembre 2015

Un nuovo modello per la materia oscura

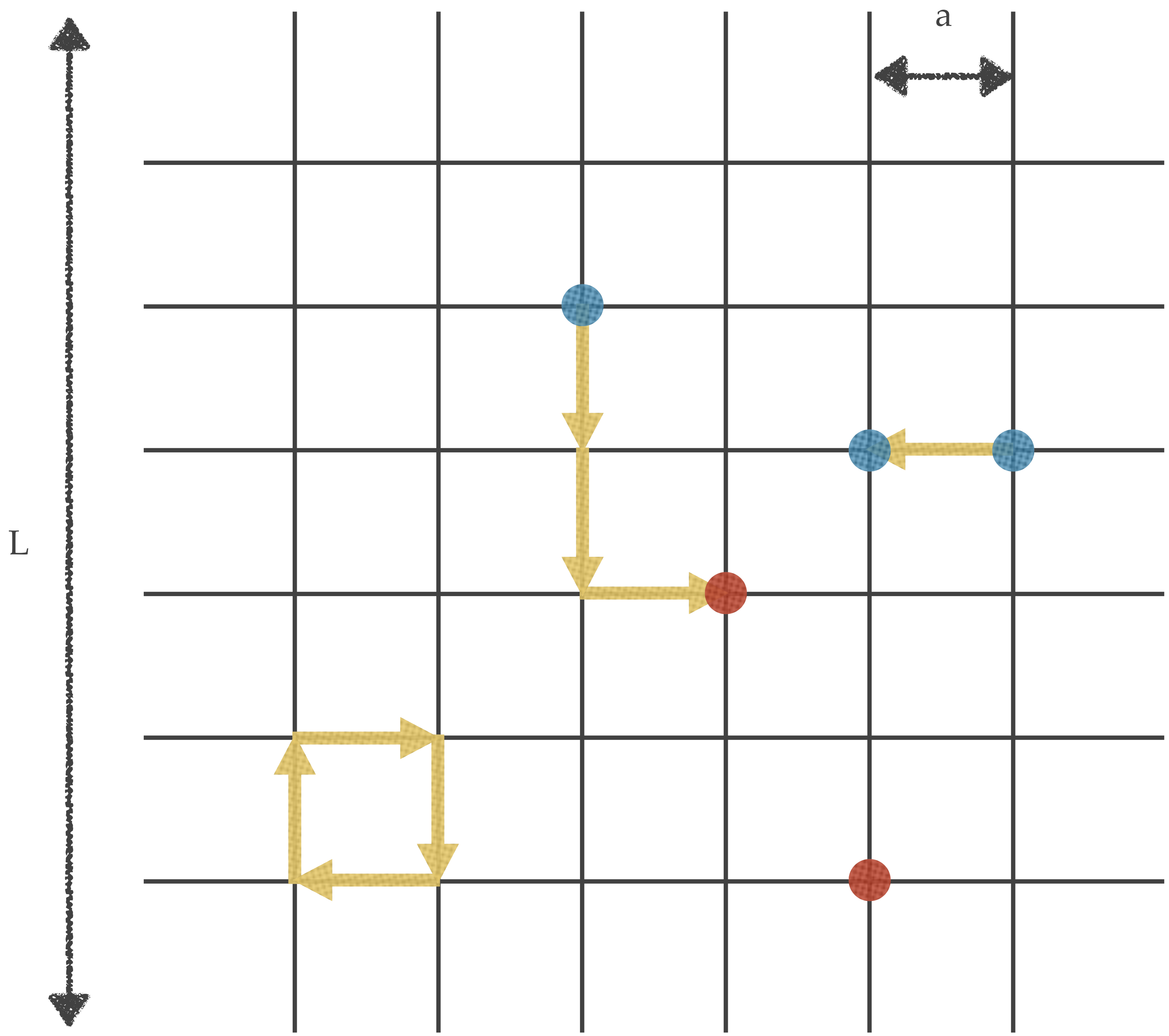
Cortesia Lawrence Livermore National Laboratory

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)*

[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

[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***

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

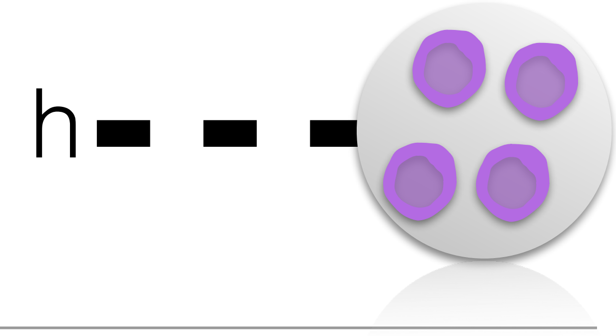
$$\mathcal{L} \supset + y^u_{14} \epsilon_{ij} F_1^i H^j F_4^d + y^d_{14} F_1 \cdot H^\dagger F_4^u - y^d_{23} \epsilon_{ij} F_2^i H^j F_3^d - y^u_{23} F_2 \cdot H^\dagger F_3^u + h.c.$$

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

$$y^u_{14} = y^d_{14} \qquad y^u_{23} = y^d_{23} \qquad M^u_{34} = M^d_{34}$$

[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
- Effective Higgs coupling non-trivial with mixed chiral and vector-like masses
- Model-dependent answer for the cross-section
- **Lattice input** is necessary: compute mass and form factor

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

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 [Plenary talk by Collins, Tue@10:15]

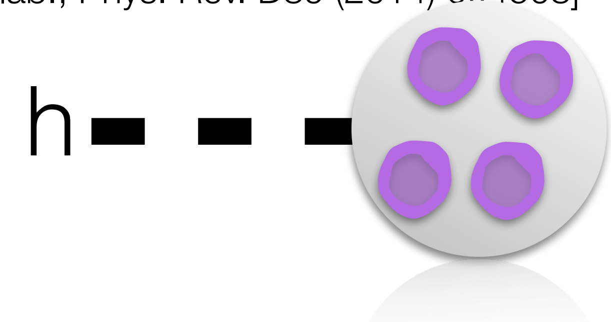
$$y_f\langle B|\bar{f}f|B\rangle = \frac{m_B}{v}\sum_f \frac{v}{m_f}\frac{\partial m_f(h)}{\partial h}\bigg|_{h=v} f_f^{(B)}$$

Lattice!

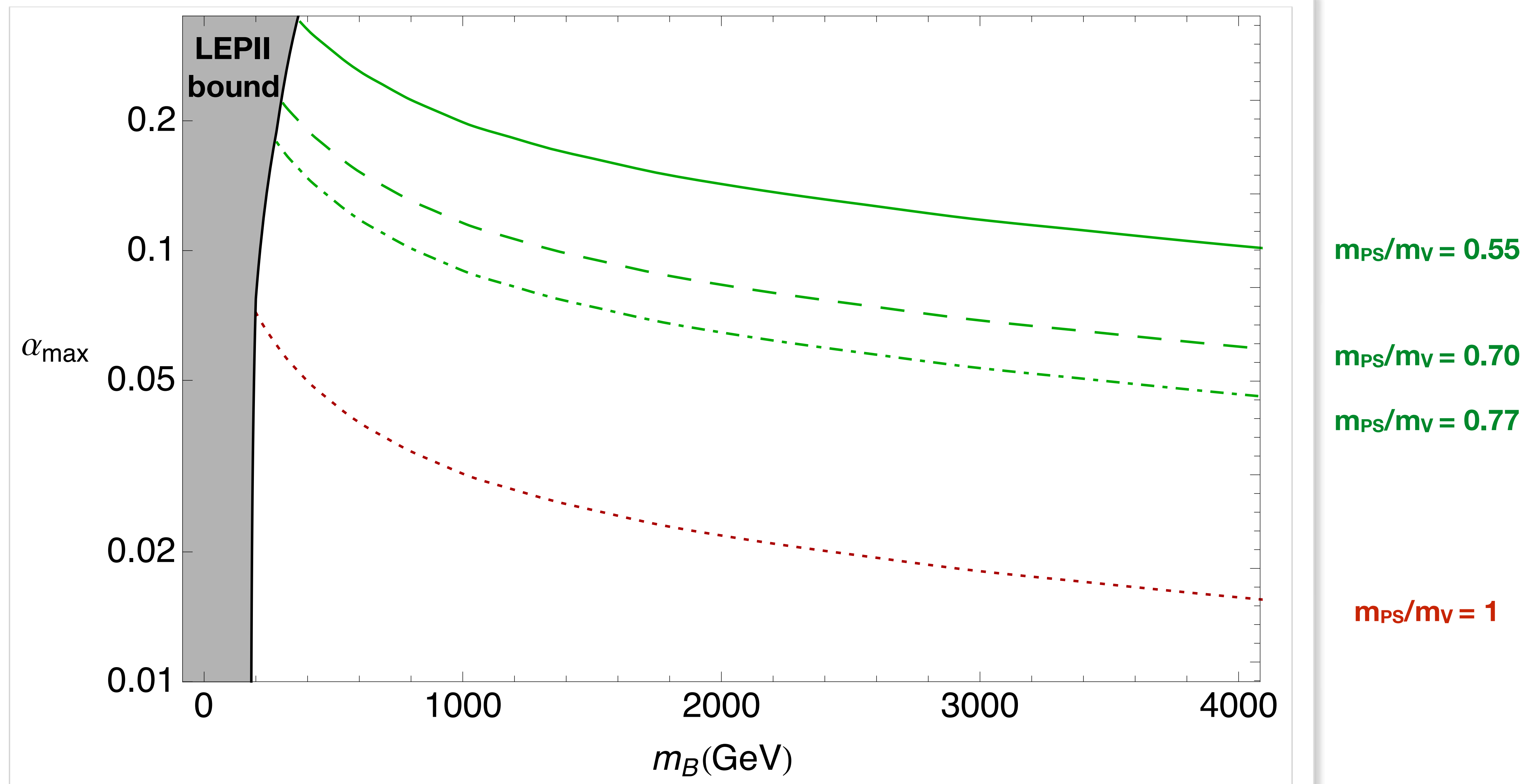
$$m_f(h) = m + \frac{y_f h}{\sqrt{2}}$$

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

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

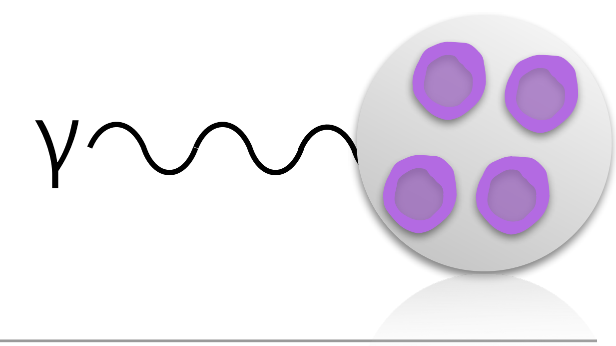


Bounds on the Yukawa coupling



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

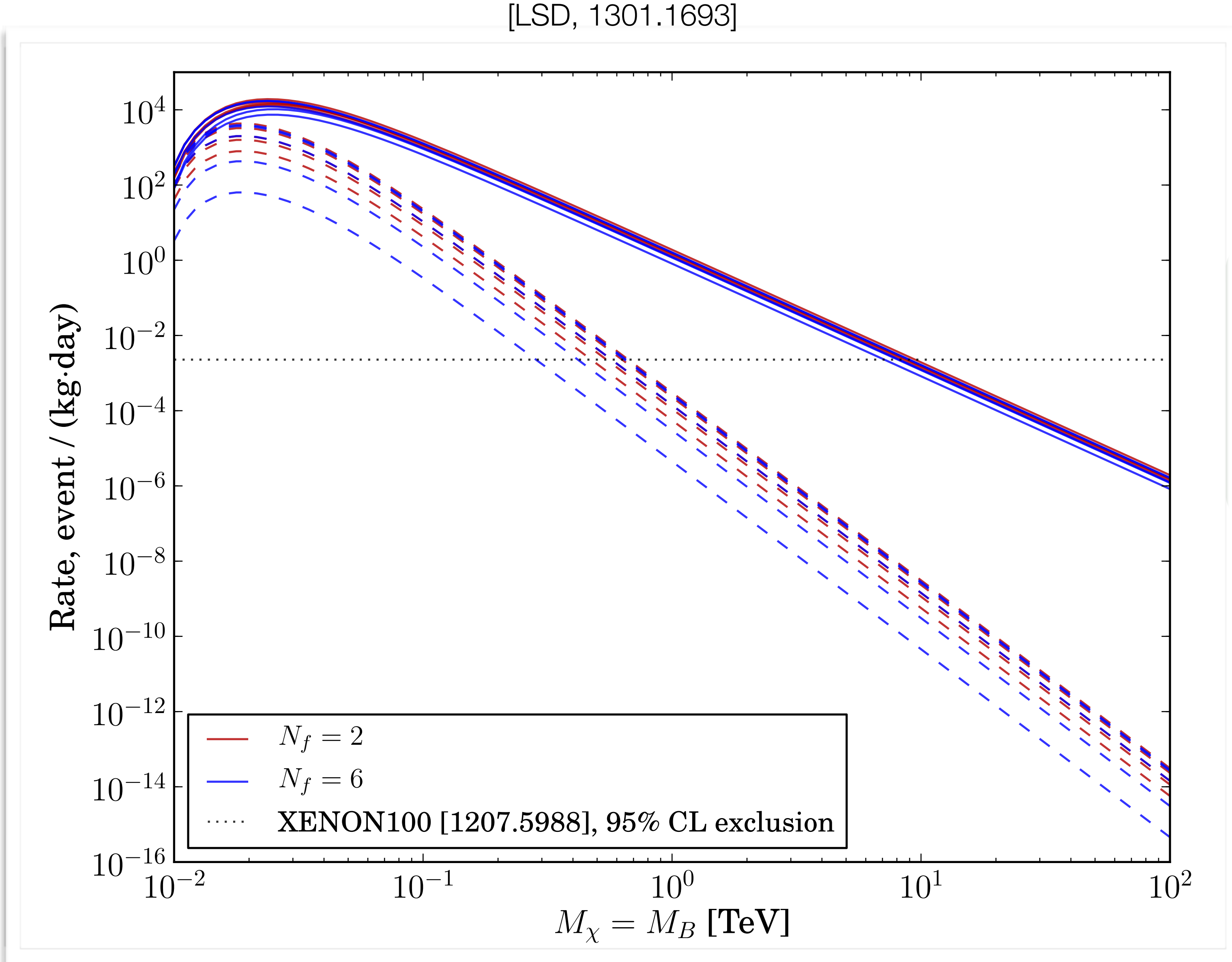
Bounds from EM moments



Mesonic and Baryonic EM form factors directly from lattice simulations

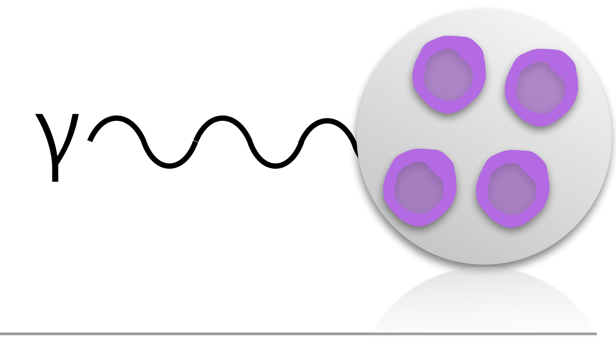
SU(3) N_f=2,6 dark fermionic baryon

[LSD, 1301.1693]



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

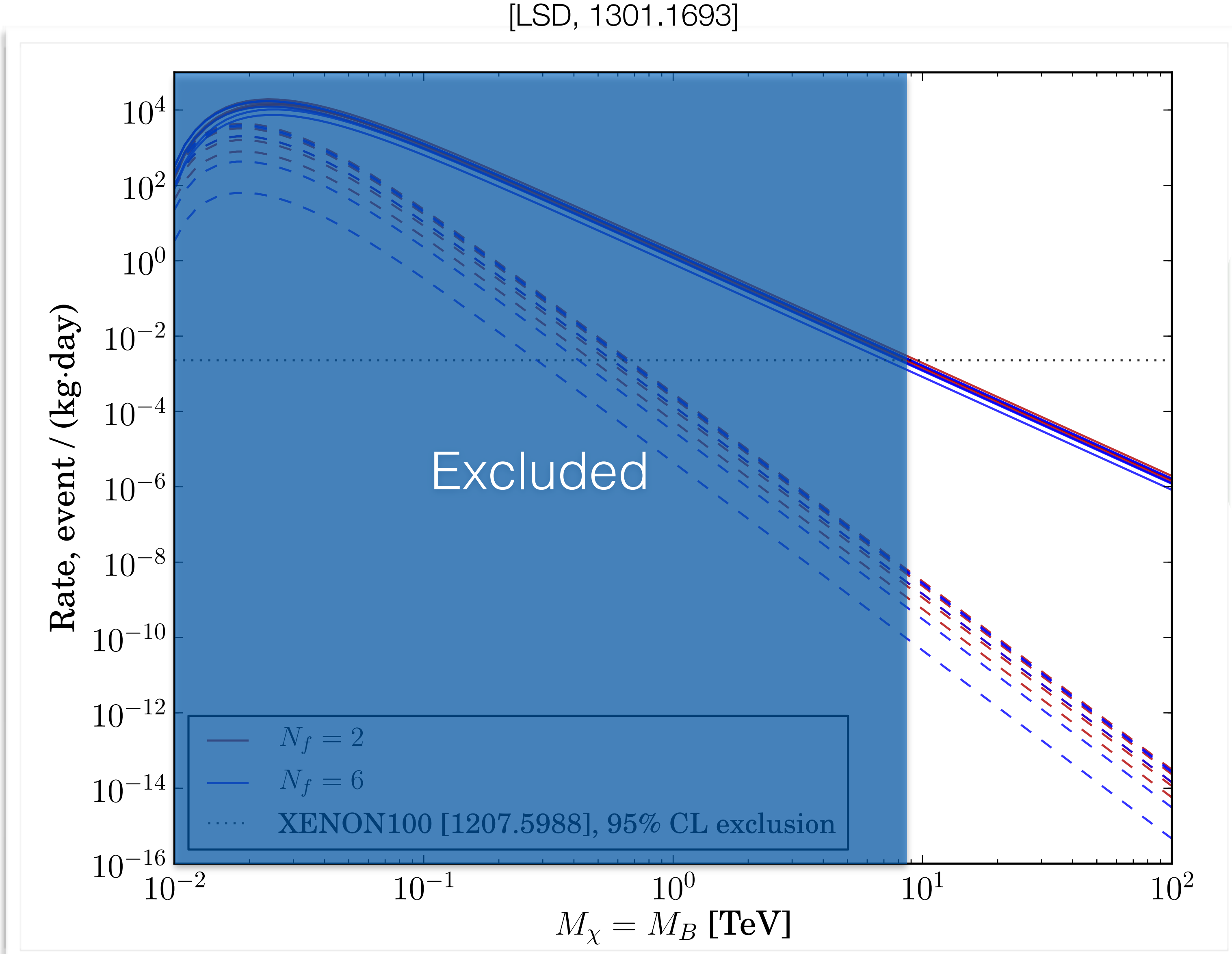
Bounds from EM moments



Mesonic and Baryonic EM form factors directly from lattice simulations

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

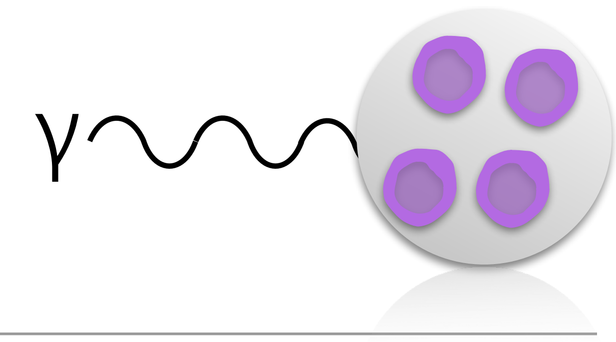
[LSD, 1301.1693]



- ★ 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

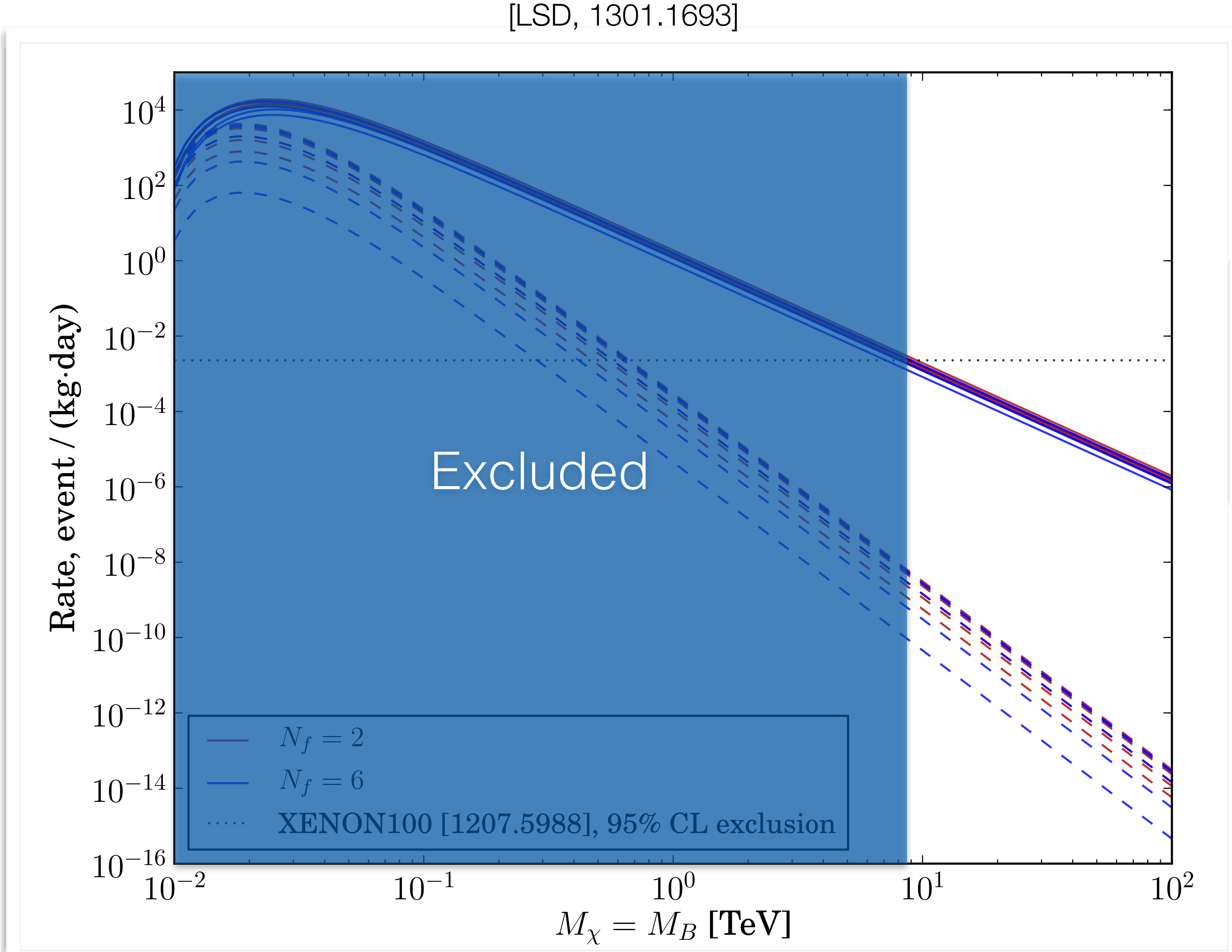
Bounds from EM moments



Mesonic and Baryonic EM form factors directly from lattice simulations

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

[LSD, 1301.1693]



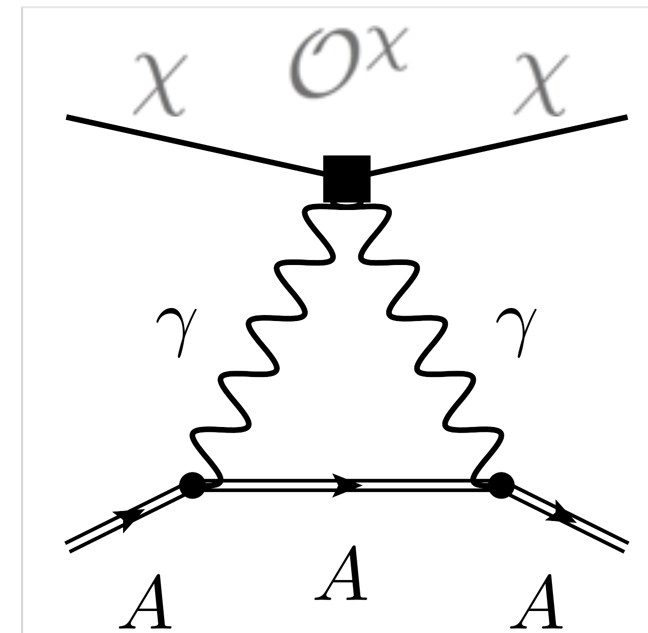
- ★ baryon similar to QCD neutron
- ★ dark quarks with Q=Y
- ★ calculate connected 3pt
- ★ scale set by DM mass
- ★ magnetic moment dominates
- ★ results independent of N_f

M_B >~ 10 TeV

pushed to ~100 TeV with new LUX

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



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

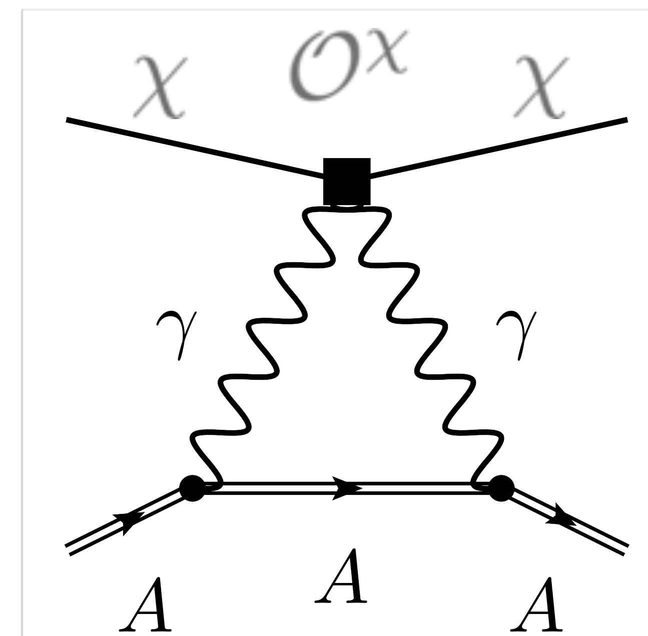
$$f_F^A \sim 3\, Z^2\, \alpha\, \frac{M_F^A}{R}$$

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

[Pospelov & Veldhuis, Phys. Lett. B480 (2000) 181]
[Weiner & Yavin, Phys. Rev. D86 (2012) 075021]
[Frandsen et al., JCAP 1210 (2012) 033]
[Ovanesyan & Vecchi, arxiv:1410.0601]

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



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

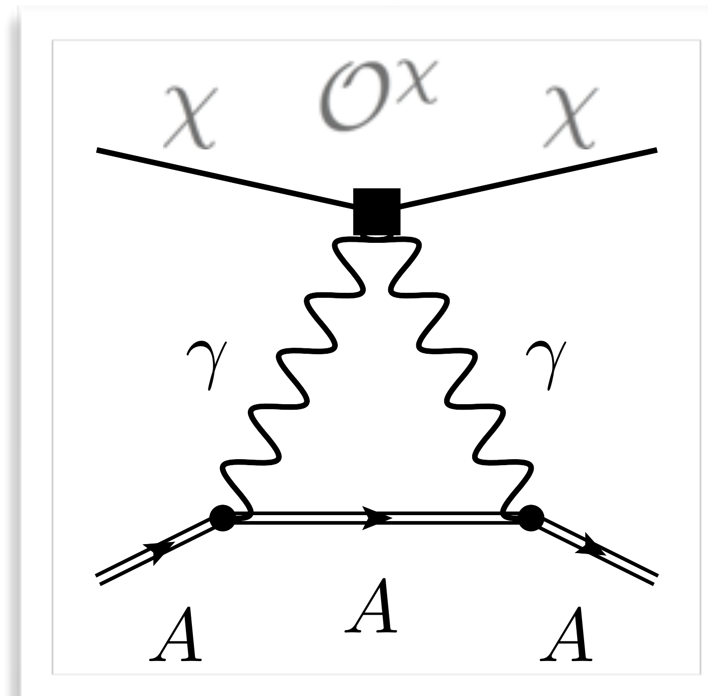
$$f_F^A \sim 3\, Z^2\, \alpha \, \frac{M_F^A}{R}$$

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

[Pospelov & Veldhuis, Phys. Lett. B480 (2000) 181]
[Weiner & Yavin, Phys. Rev. D86 (2012) 075021]
[Frandsen et al., JCAP 1210 (2012) 033]
[Ovanesyan & Vecchi, arxiv:1410.0601]

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



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

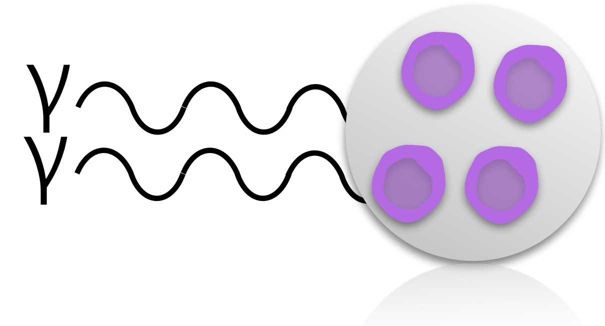
$$f_F^A \sim 3\, Z^2\, \alpha\, \frac{M_F^A}{R}$$

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

[Pospelov & Veldhuis, Phys. Lett. B480 (2000) 181]
[Weiner & Yavin, Phys. Rev. D86 (2012) 075021]
[Frandsen et al., JCAP 1210 (2012) 033]
[Ovanesyan & Vecchi, arxiv:1410.0601]

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

Lattice: Polarizability of DM



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

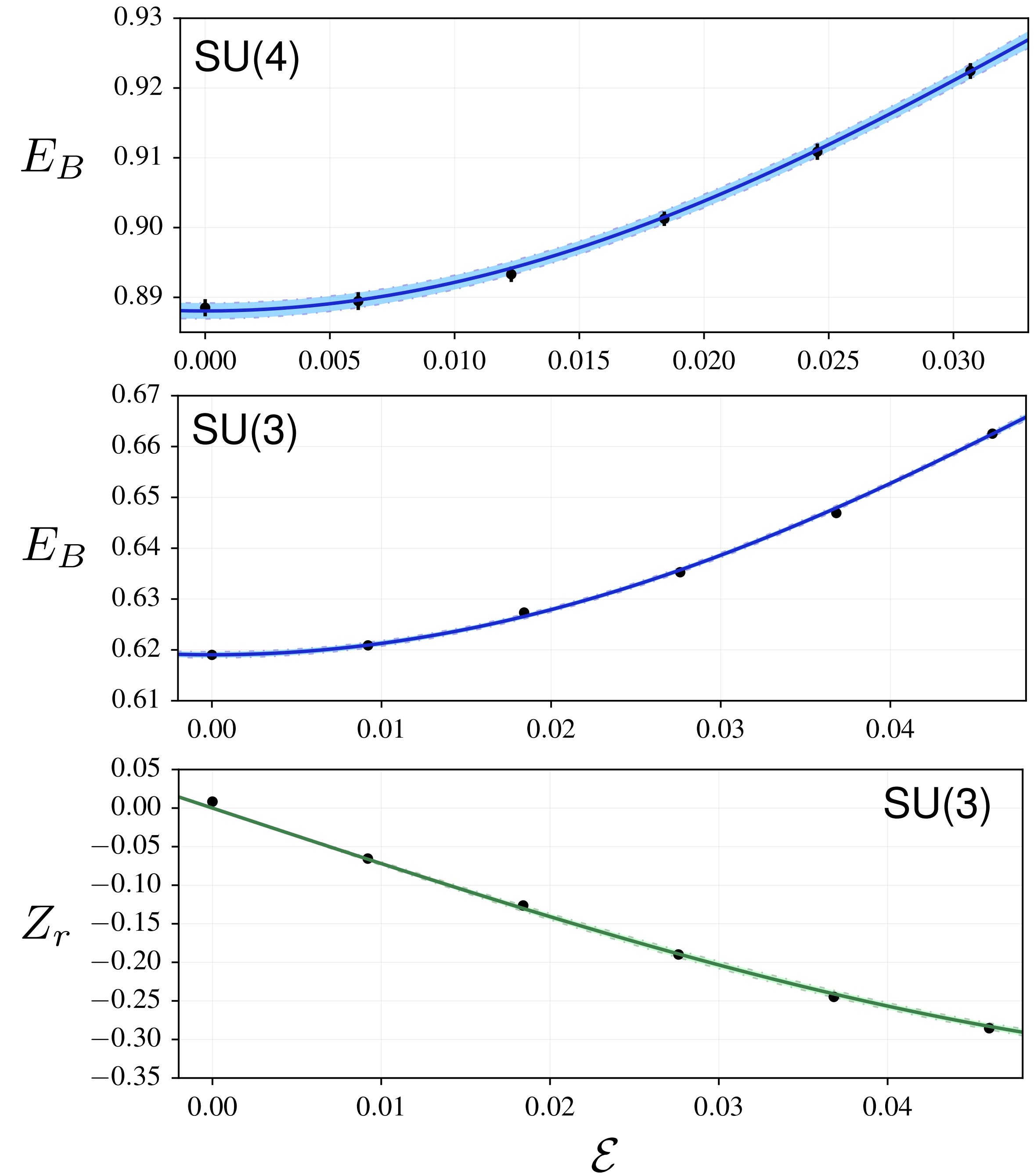
- Measure the shift of the baryon mass as a function of $\mathcal{E}$

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

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

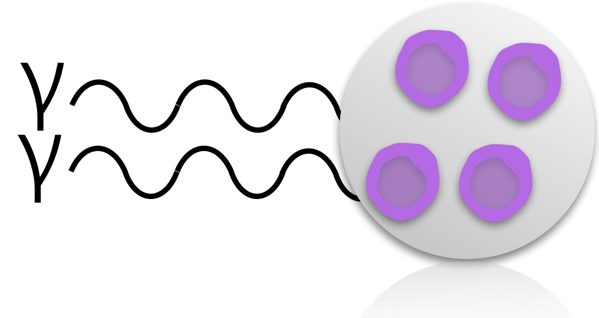
$$Z_r = \frac{\mathcal{E}\mu_B(\mathcal{E})}{2m_B^2}$$

32³x64 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



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

Lattice: Polarizability of DM



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

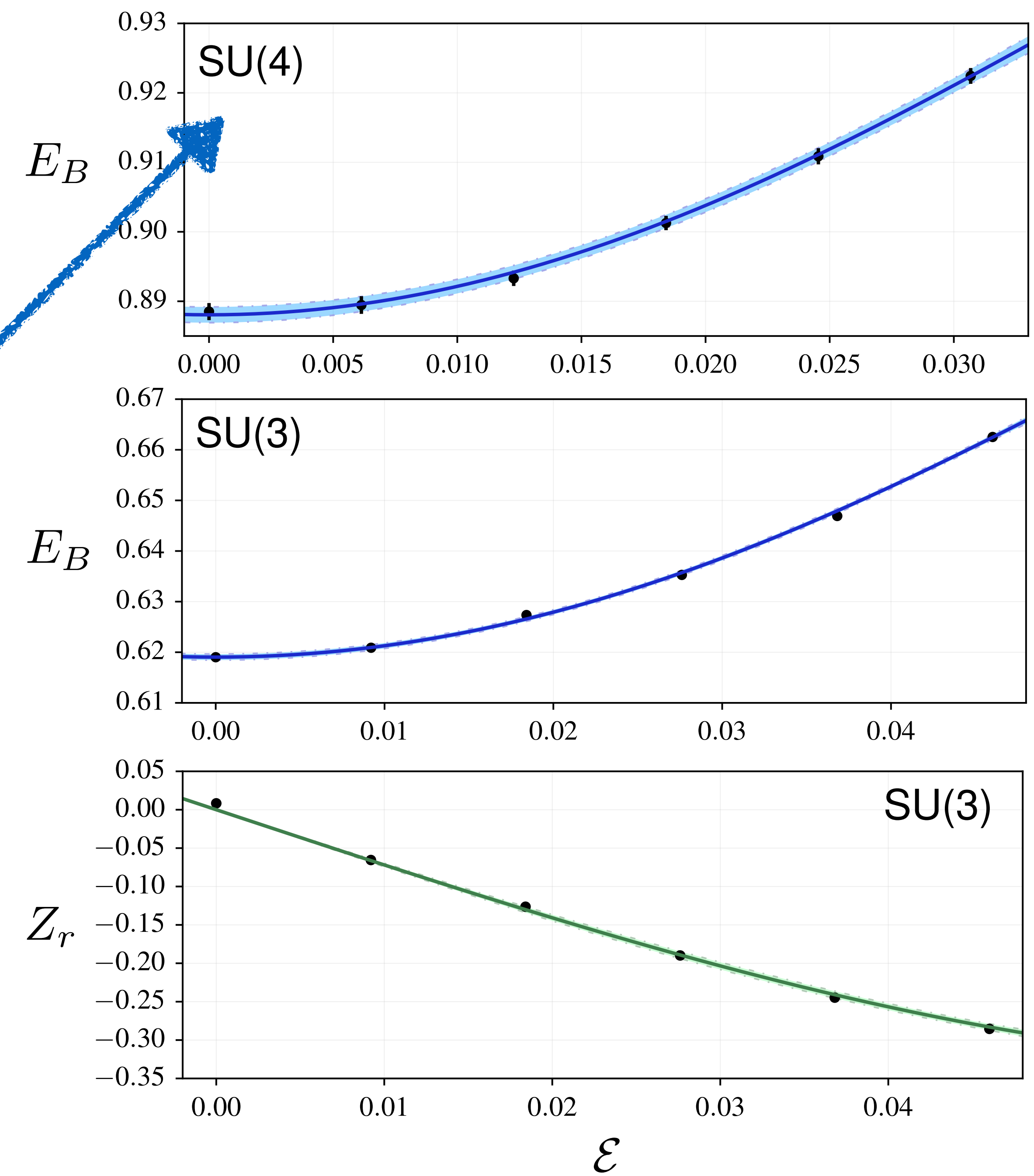
- Measure the shift of the baryon mass as a function of $\mathcal{E}$

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

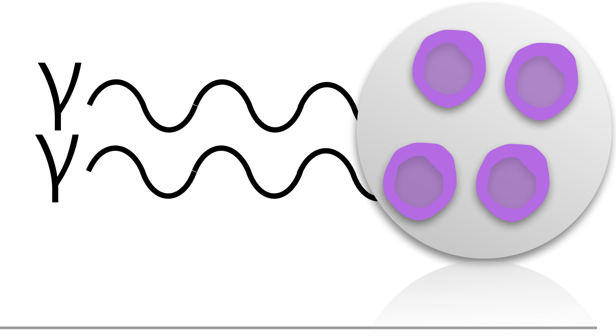
$$E_{B,3c} = m_B + \left(2C_F - \frac{{\mu_B}^2}{8m_B^3}\right)|\mathcal{E}|^2 + \mathcal{O}\left(\mathcal{E}^4\right)$$

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

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



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



Lattice: Polarizability of DM

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

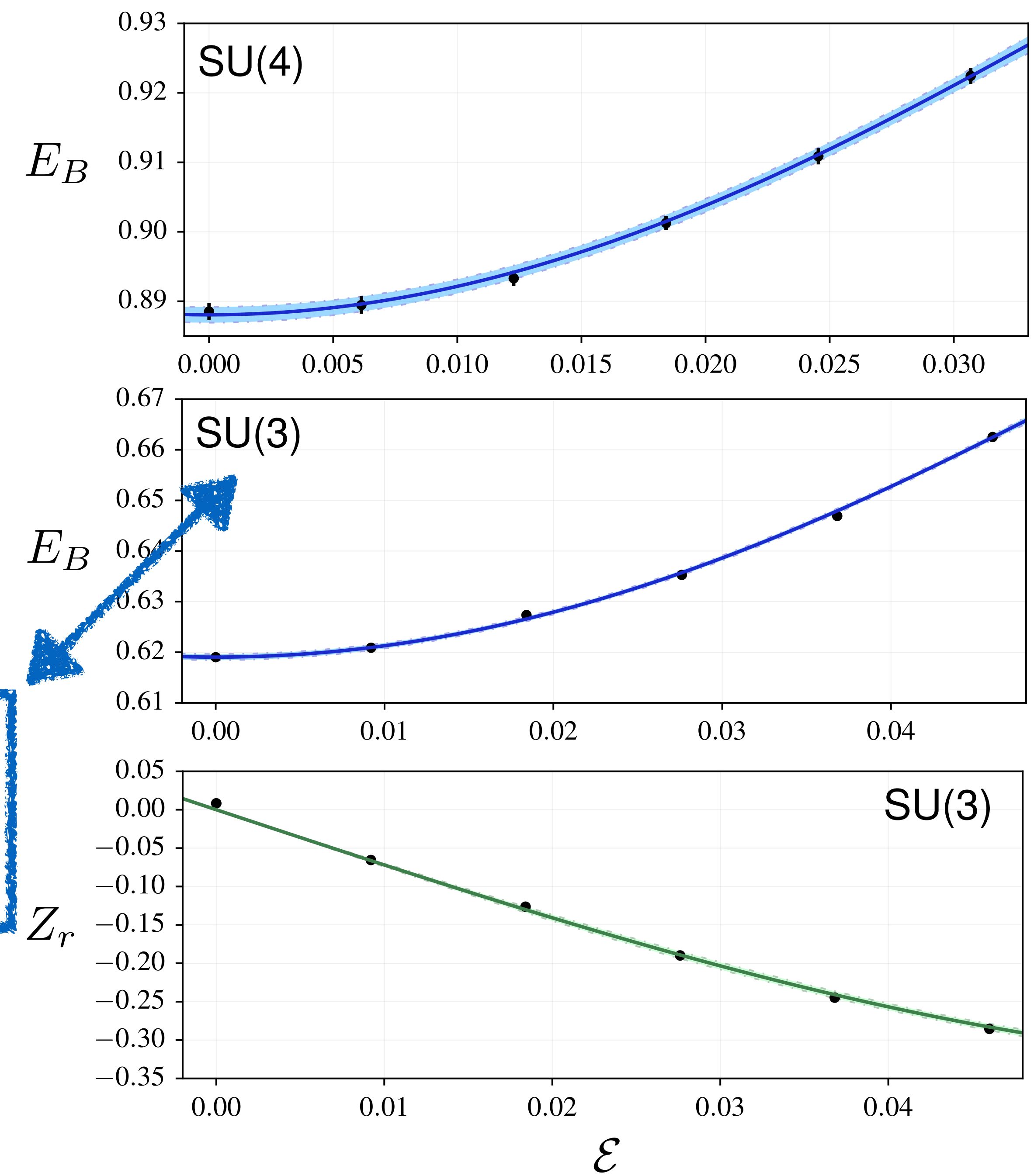
- Measure the shift of the baryon mass as a function of $\mathcal{E}$

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

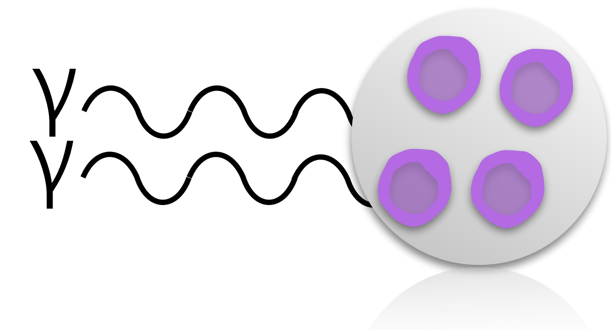
$$E_{B,3c} = m_B + \left(2C_F - \frac{{\mu_B}^2}{8m_B^3}\right)|\mathcal{E}|^2 + \mathcal{O}\left(\mathcal{E}^4\right)$$

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

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



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



Lattice: Polarizability of DM

- 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[3]x64 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