SIGNALS OF COMPOSITE DARK MATTER

Enrico Rinaldi

RIKEN BNL Research Center
RIKEN Nishina Center

LFC19

ECT*, Trento, 09/12/2019

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http://lsd.physics.yale.edu

Lattice Strong Dynamics collaboration

Argonne: Jin, Osborn

Bern:Gasbarro

Boston: Brower, Rebbi, Howarth

Nvidia: Weinberg

Colorado: Neil, Witzel

Liverpool: Schaich

LLNL: Vranas

UC Davis: Kiskis

Yale: Appelquist, Fleming, Cushman

Oregon: Kribs

RIKEN: ER

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Liverpool: Schaich

Bern:Ga

Lattice for BSM workshops

- University of Colorado Boulder, April 2018
- Boston University, April 2017
- Argonne National Lab, April 2016
- Lawrence Livermore National Lab, April 2015
- Brookhaven National Lab, December 2013
- University of Colorado Boulder, October 2012
- Fermilab, October 2011
- Boston University, November 2009
- Lawrence Livermore National Lab, May 2008

Boston:

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Witzel

RIKEN: ER

NEW STRONG DYNAMICS

Composite Higgs

Composite Dark Matter

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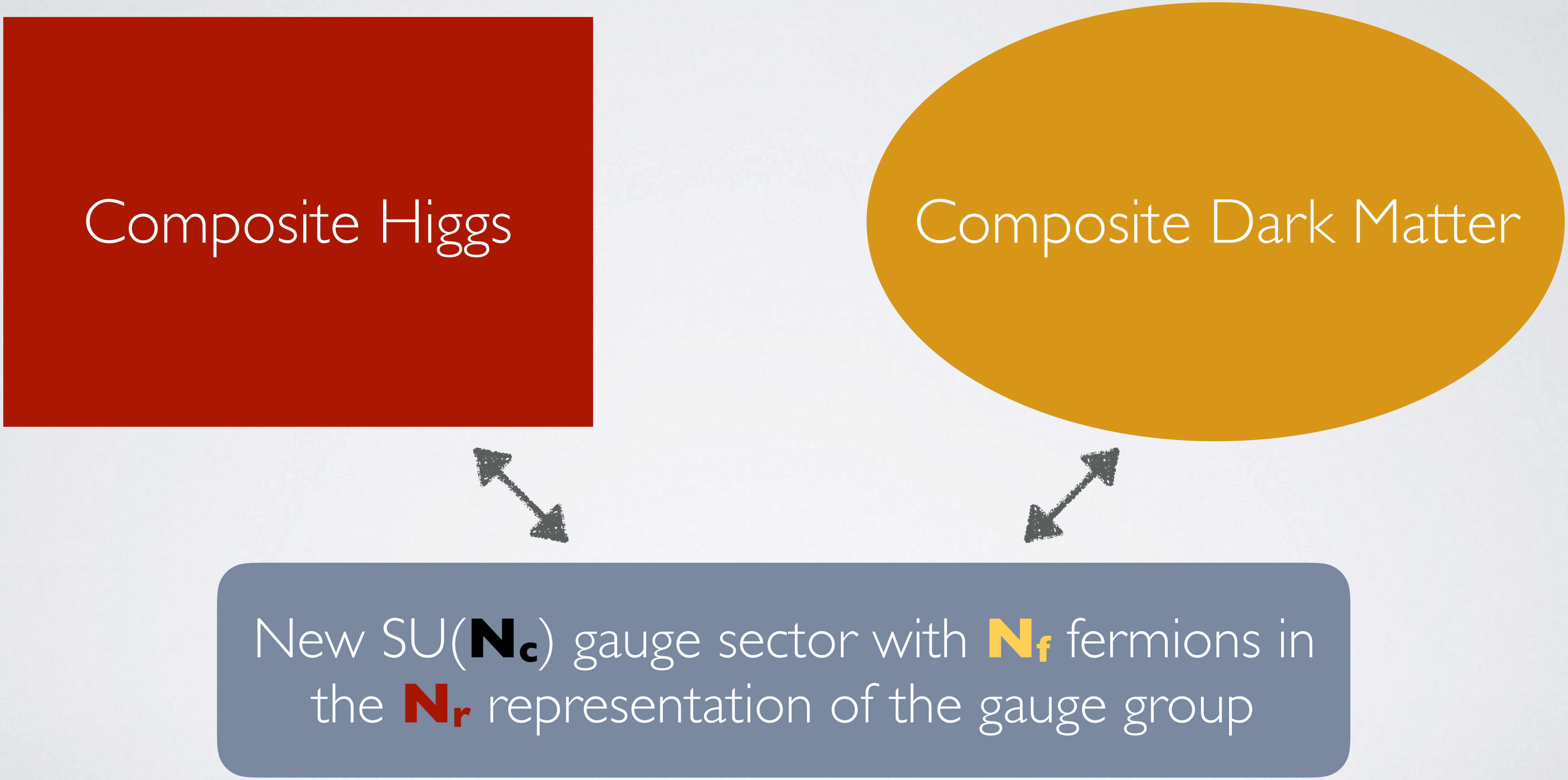

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Composite Dark Matter

New SU($\mathbf{N_c}$) gauge sector with $\mathbf{N_f}$ fermions in the $\mathbf{N_r}$ representation of the gauge group

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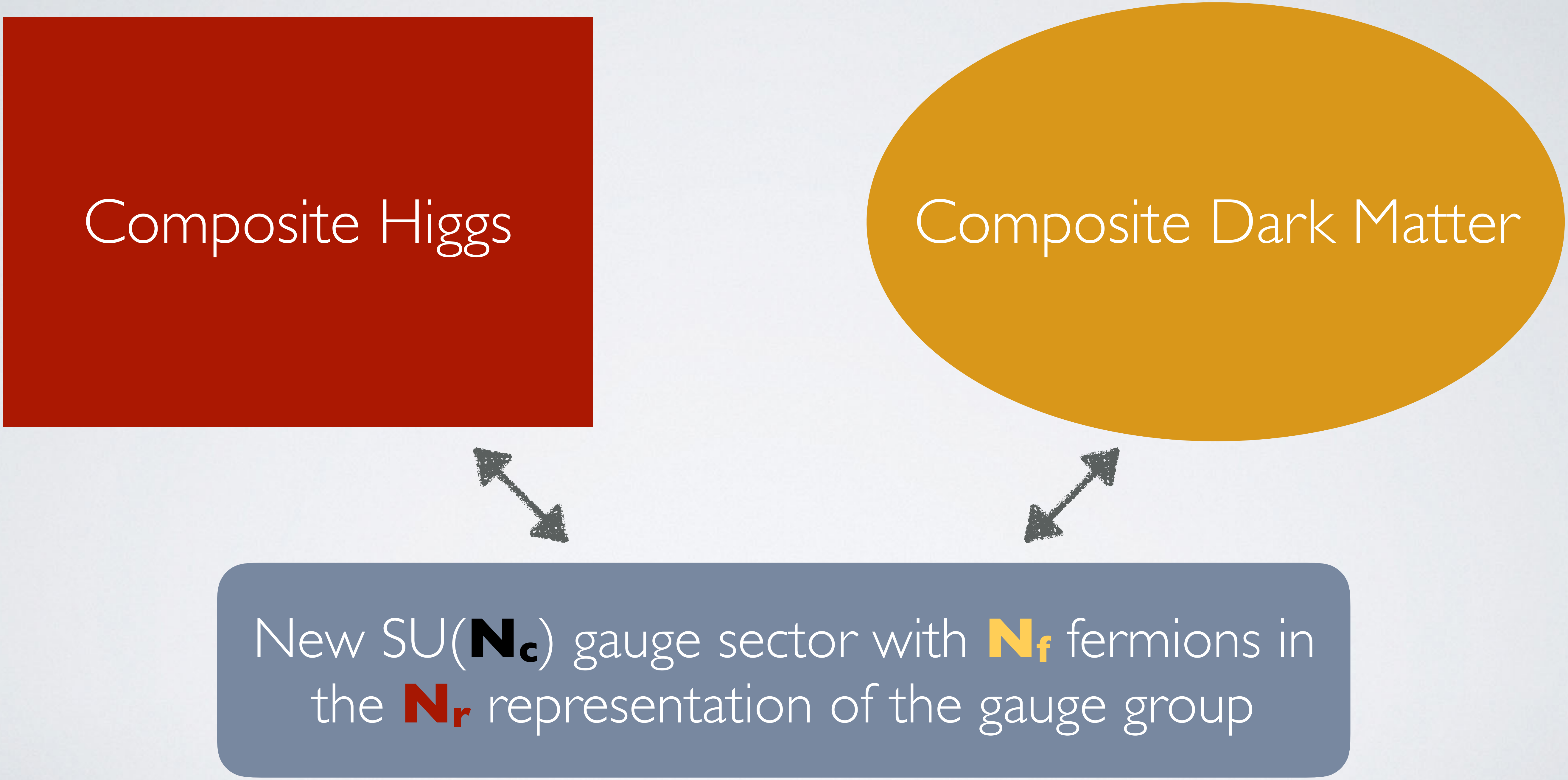

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Most of the theory work is done using EFTs at the SM scale, but we want to use UV complete models

What is composite dark matter?

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- Dark Matter is a composite object

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e.g. hidden sector baryon or glueball

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

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- Constituents may interact with Standard Model particles

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Lattice Field Theory methods

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[review by Kribs & Neil, 1604.04627]

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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

[list of references focused on lattice results when possible]

[review by Kribs & Neil, 1604.04627]

COMPOSITE DARK MATTER

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- ★ 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]*
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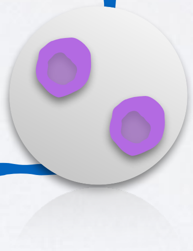
  - ✦ Minimal SU(2) *[Francis et al.,1610.10068]*



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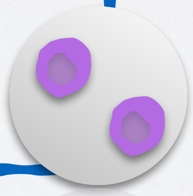
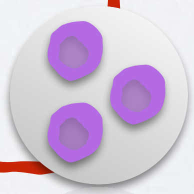


★ Baryon-like (multiple quarks)

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



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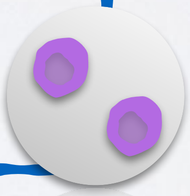

- ★ Glueball-like (only gluons)
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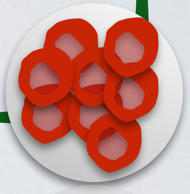

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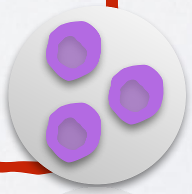

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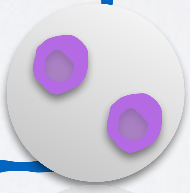

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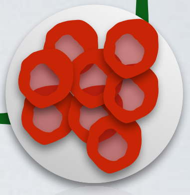

★ Dark Nuclei *[Detmold et al., 1406.2276-1406.4116]*

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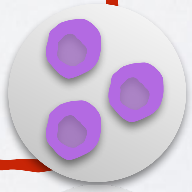
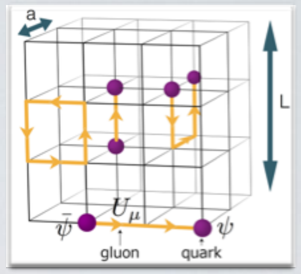


Importance of lattice simulations



[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

★EFTs inspired by QCD might not work when the dynamics is different

★Lattice studies can reliably point out similarities or differences as the parameter space (N_c,N_f,N_r) is scanned

"Stealth Dark Matter" model

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

- **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]

"Stealth Dark Matter" model

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- The field content of the model consists in *8 Weyl fermions*
- Dark fermions interact with the SM Higgs and obtain current/chiral masses
- Introduce vector-like masses for dark fermions that do not break EW symmetry
- Diagonalizing in the mass eigenbasis gives *4 Dirac fermions*
- Assume custodial SU(2) symmetry arising when ***u*** ↔ ***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	$\mathbf{N}$	$(\mathbf{1}, +1/2)$	$+1/2$
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$$\begin{aligned}\mathcal{L} \supset\ & + \boxed{y_{14}^u} \epsilon_{ij} F_1^i H^j F_4^d + y_{14}^d F_1 \cdot H^\dagger F_4^u \\ & - y_{23}^d \epsilon_{ij} F_2^i H^j F_3^d - y_{23}^u F_2 \cdot H^\dagger F_3^u + h.c.\end{aligned}$$

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

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

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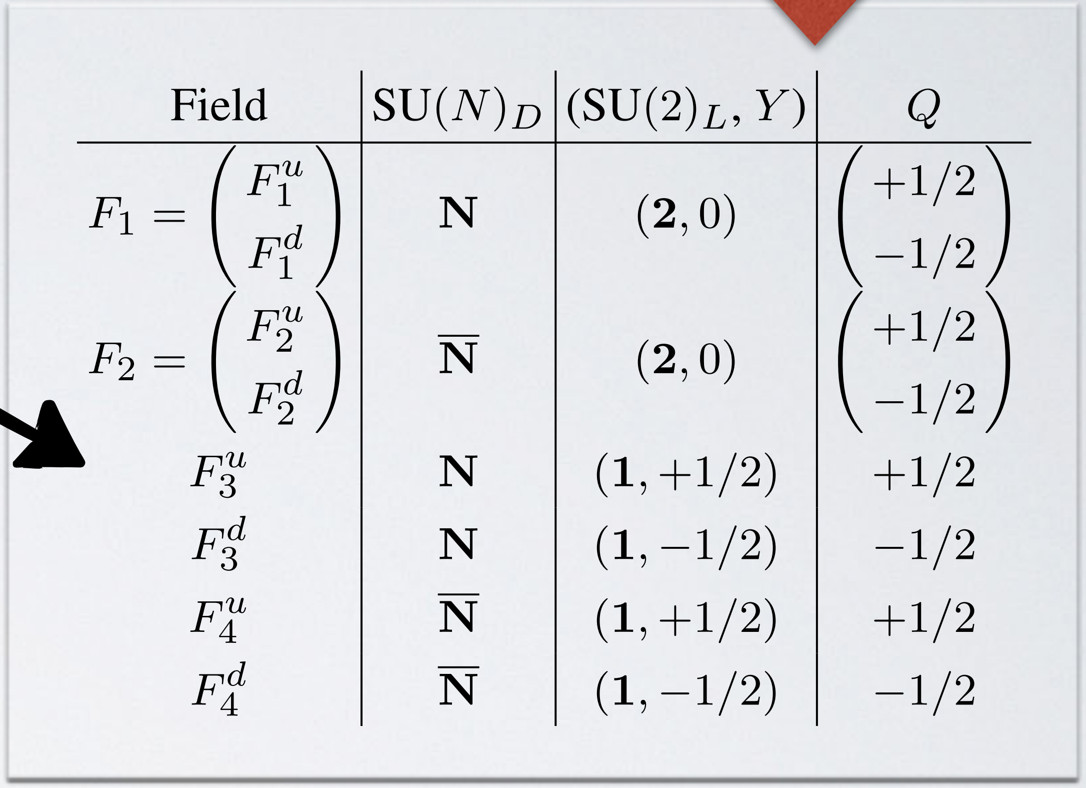
EW interactions



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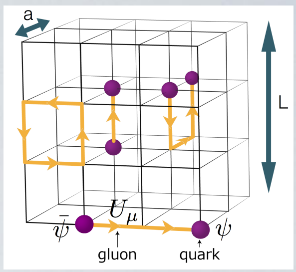
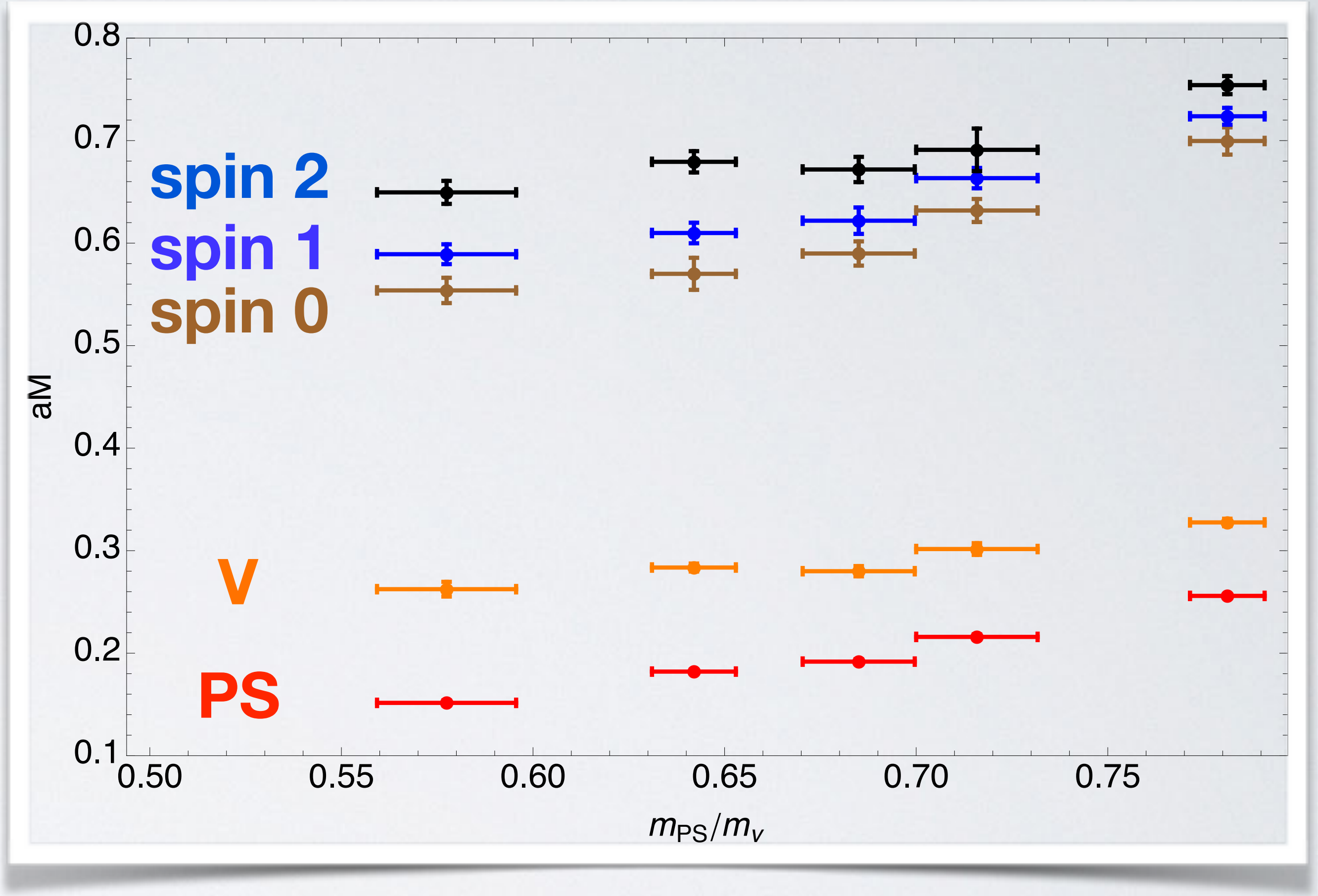
Lattice Stealth DM



[KEK-Japan]

- Non-perturbative lattice calculations of the spectrum confirm that lightest baryon has spin zero
- The ratio of pseudoscalar (PS, pion) to vector (V, rho) 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)

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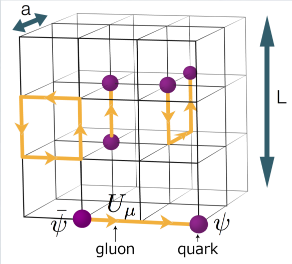

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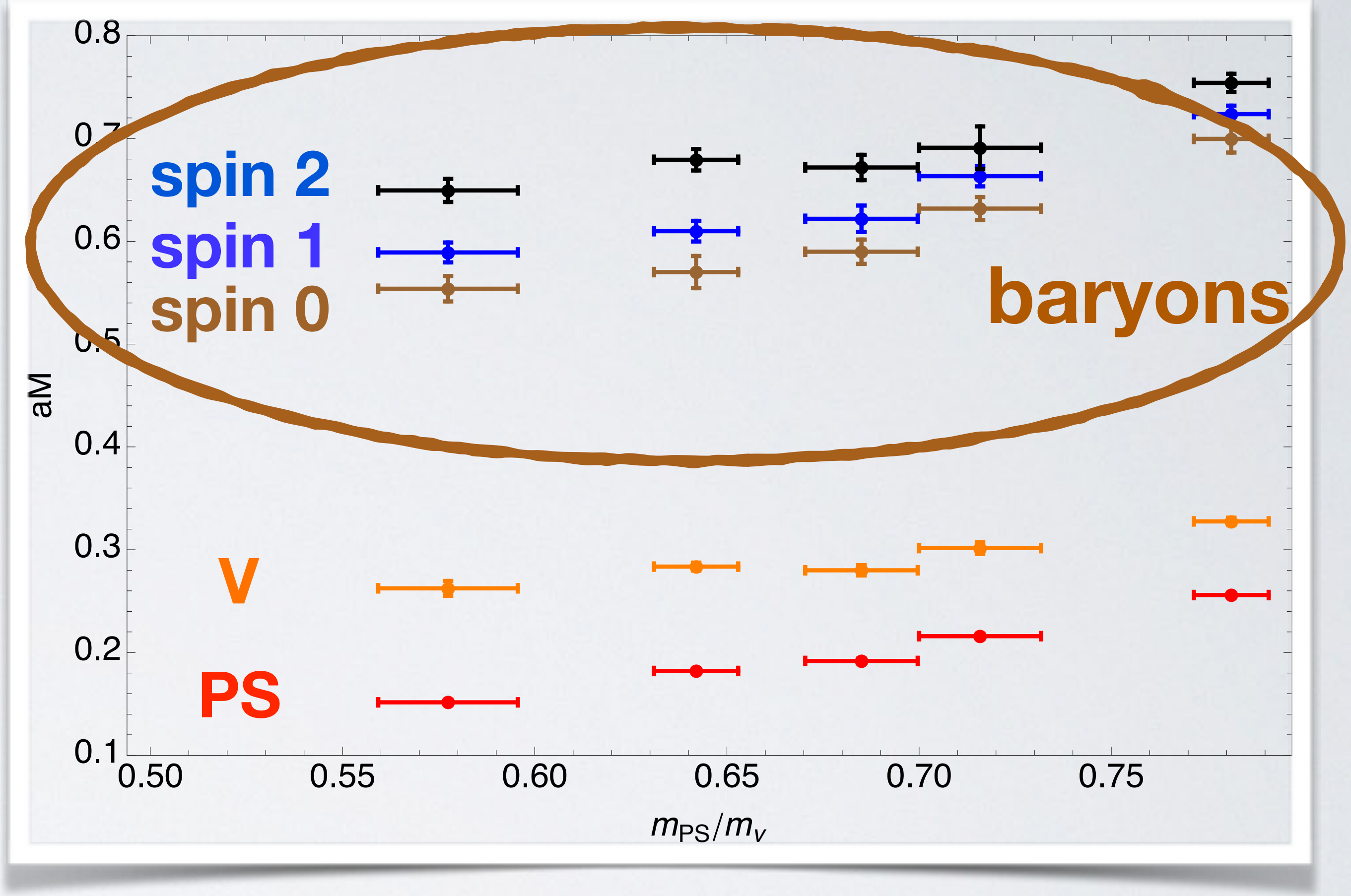

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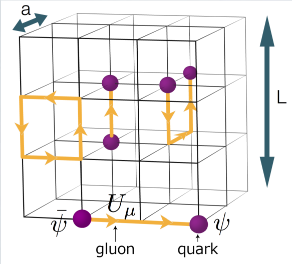

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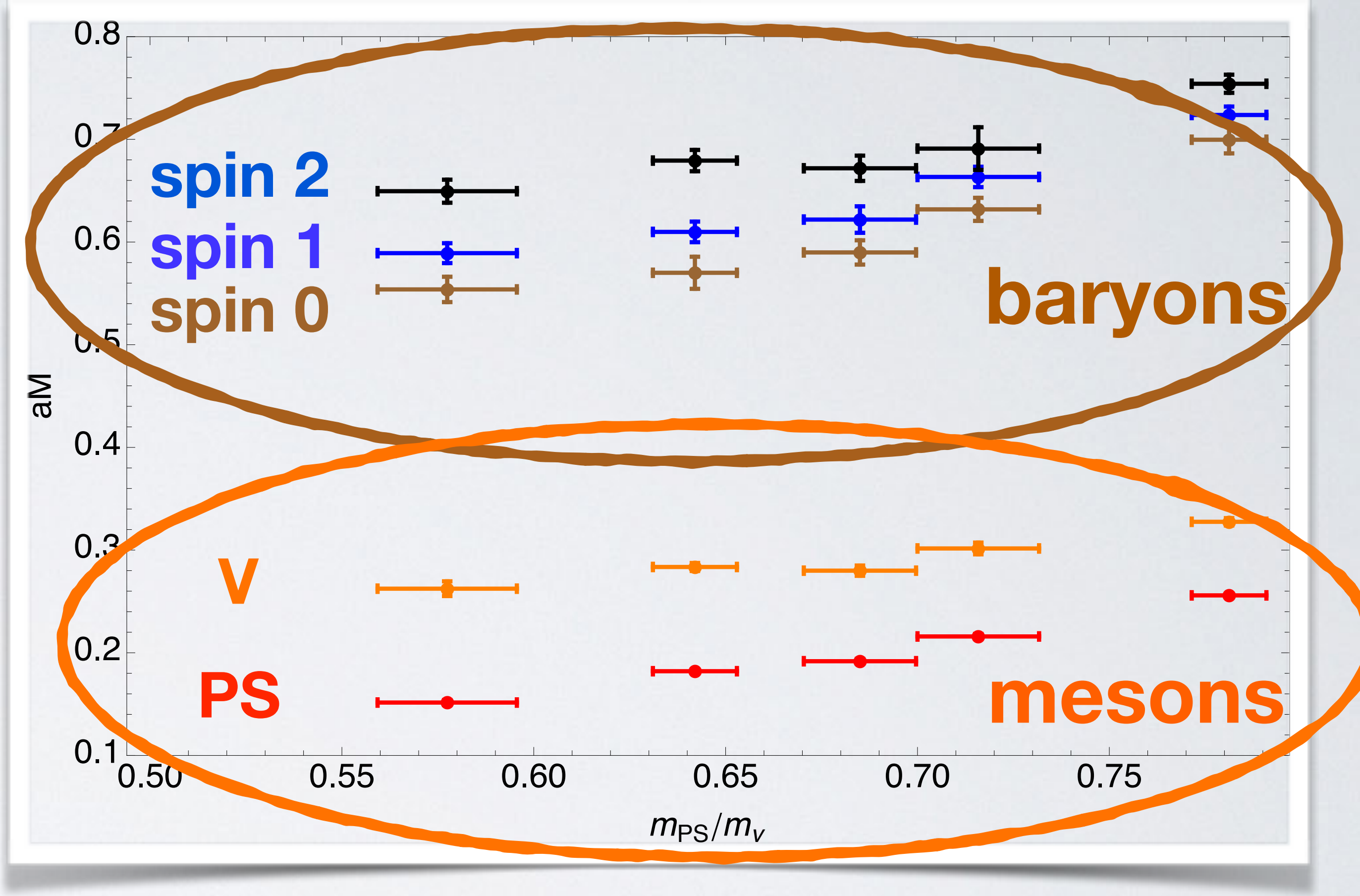

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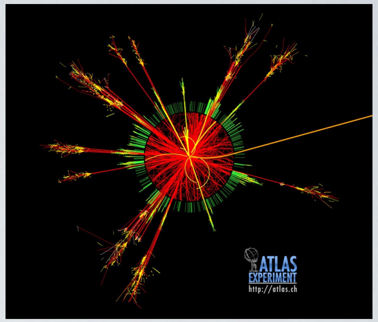
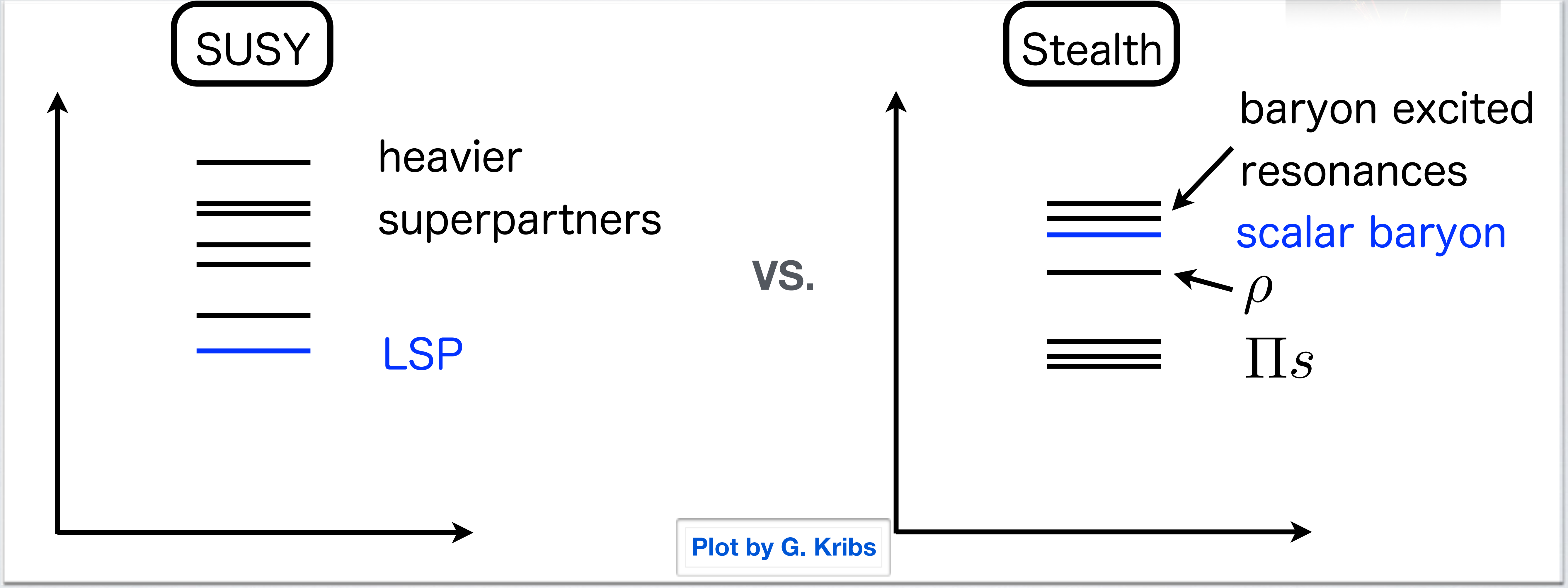
Stealth Dark Matter at colliders



[ATLAS]



Plot by G. Kribs

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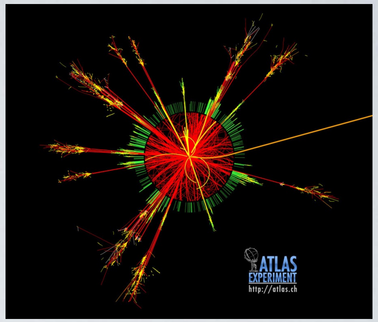

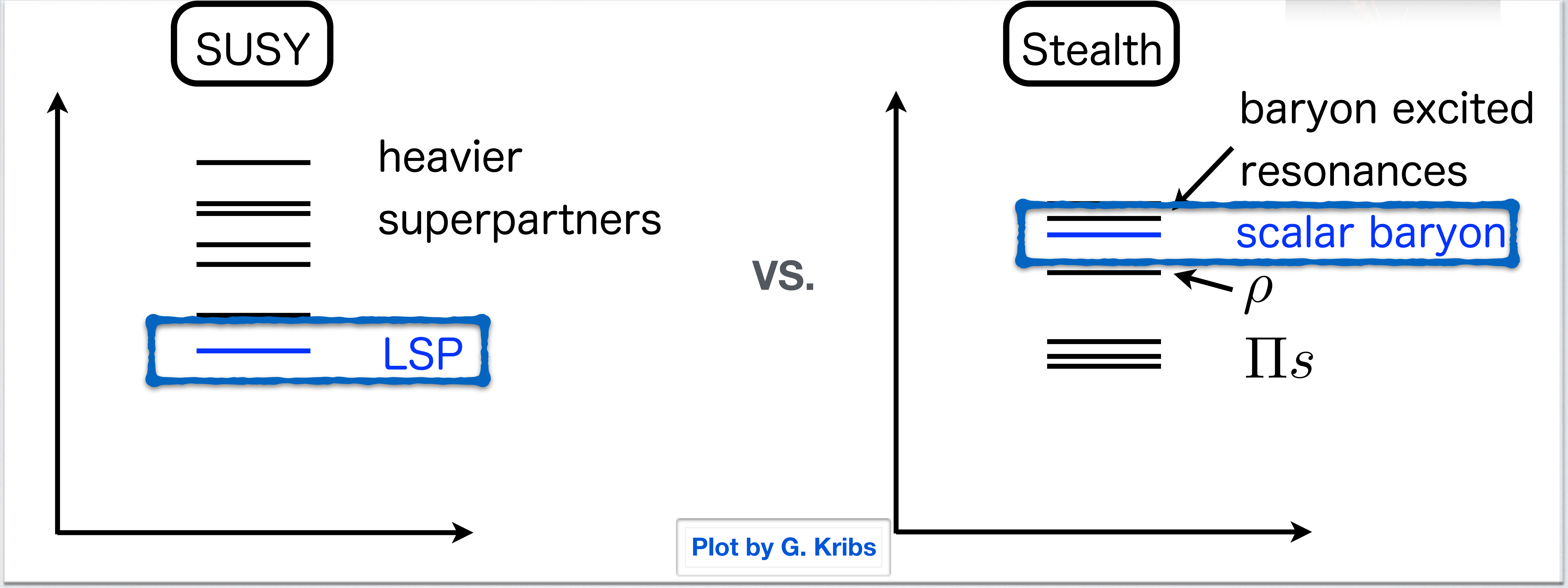

SUSY

heavier superpartners

LSP

vs.

Stealth

baryon excited resonances

scalar baryon

ρ

Πs

Plot by G. Kribs

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

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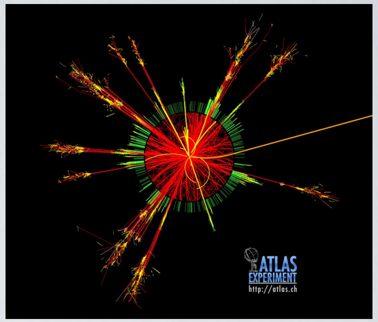

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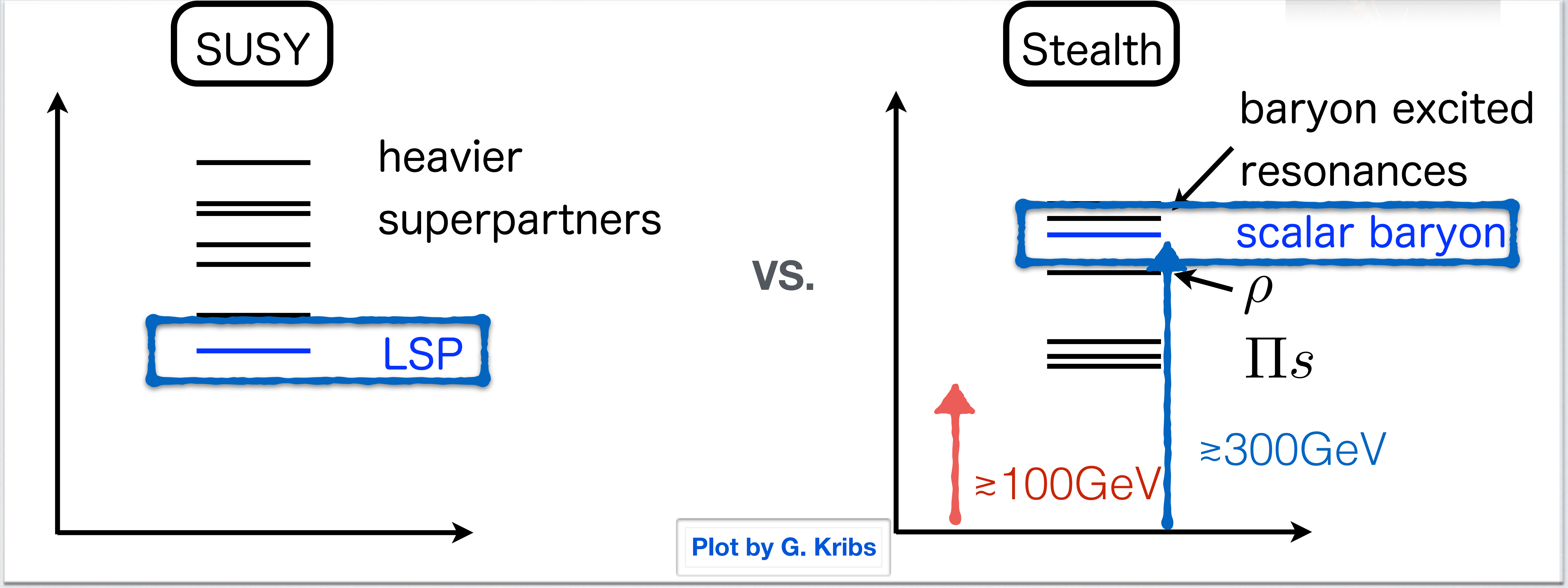

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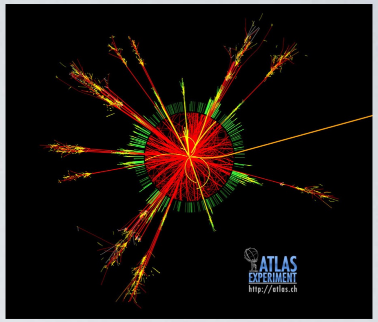
- Signatures are not dominated by missing energy: **DM is not the lightest particle!** The interactions are suppressed (form factors)
- Light dark meson production and decay give interesting signatures: **the model can be constrained by LHC/LEP data!** $\Pi \gtrsim$ 100GeV

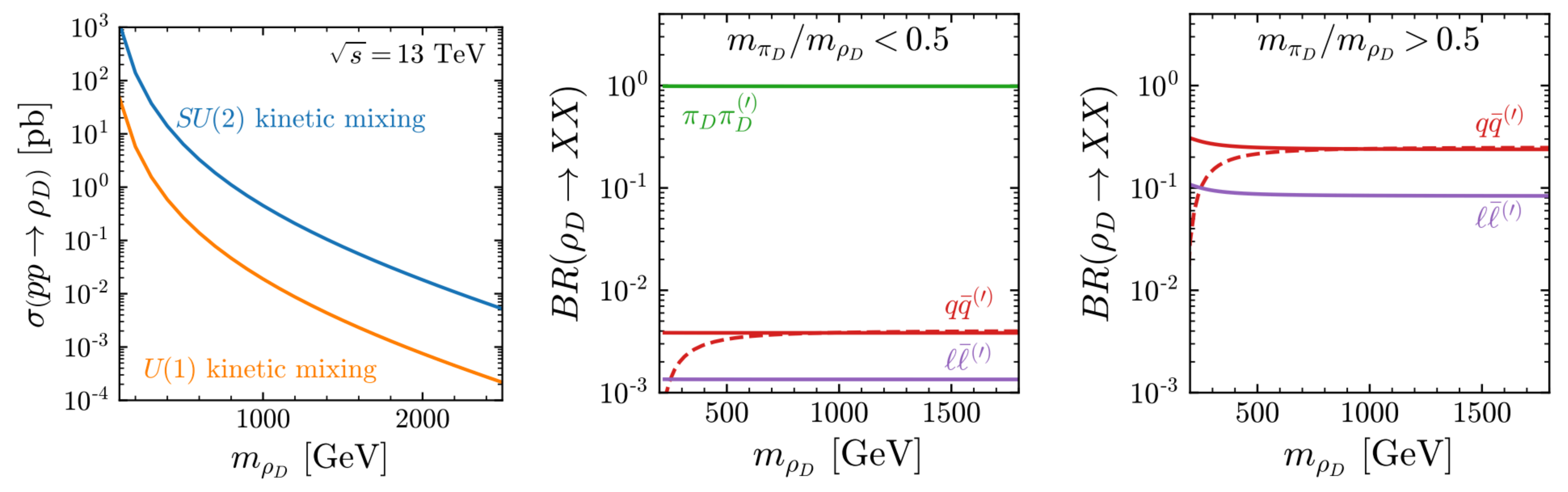
More general bounds on “dark” mesons

[Kribs, Martin, Ostdiek, Tong 1809.10184]

[ATLAS]



- Dark mesons can be created through Drell-Yan or vector kinetic mixing
- Dark vector meson can decay to dark “pions” depending on mass ratio
- Re-cast existing SUSY searches (not optimal)
- Bounds can be strong depending on model parameters (a few benchmarks)



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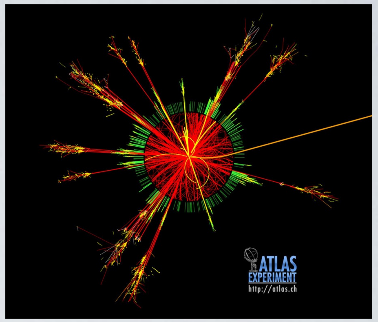

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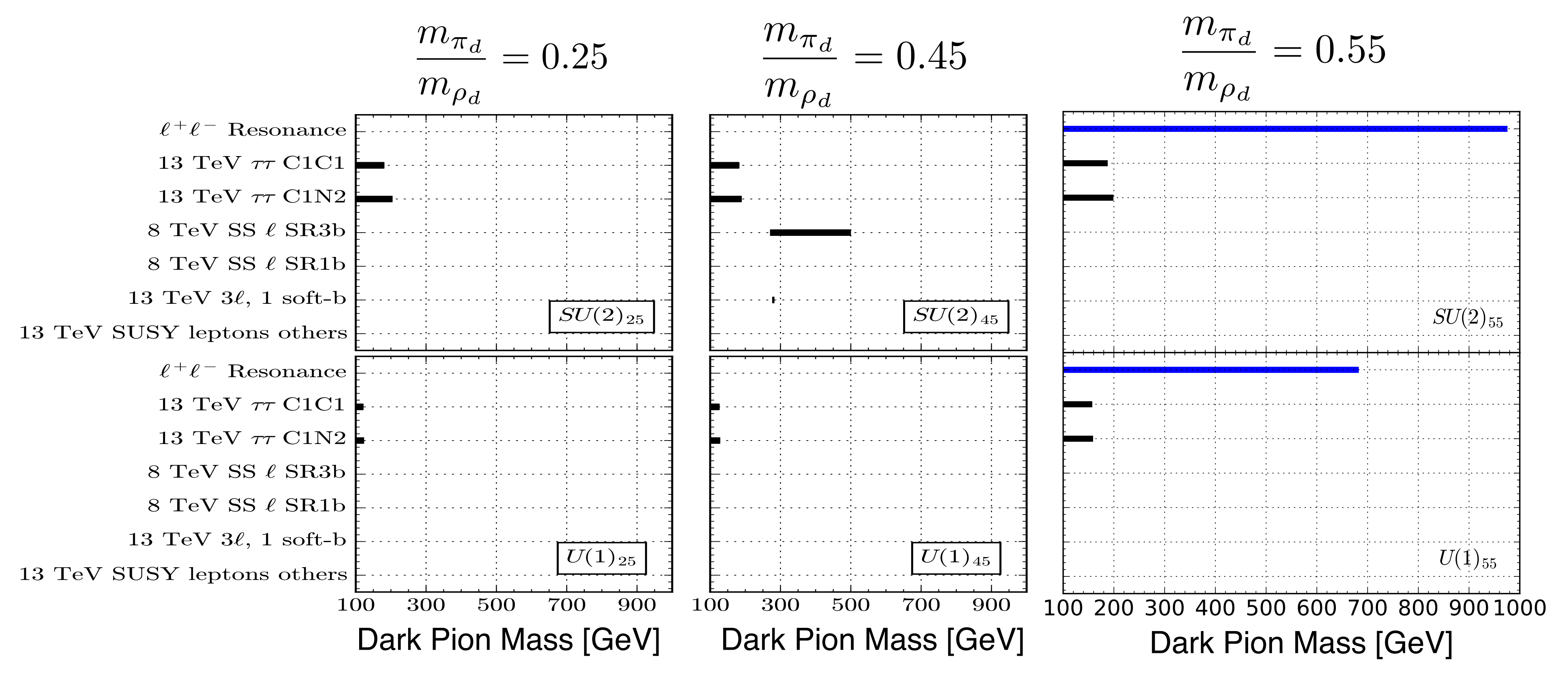
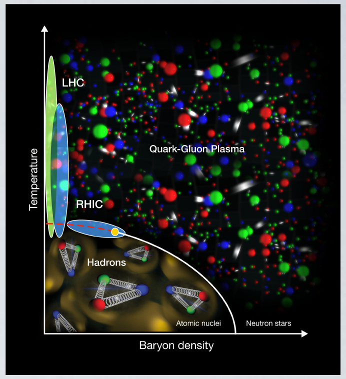


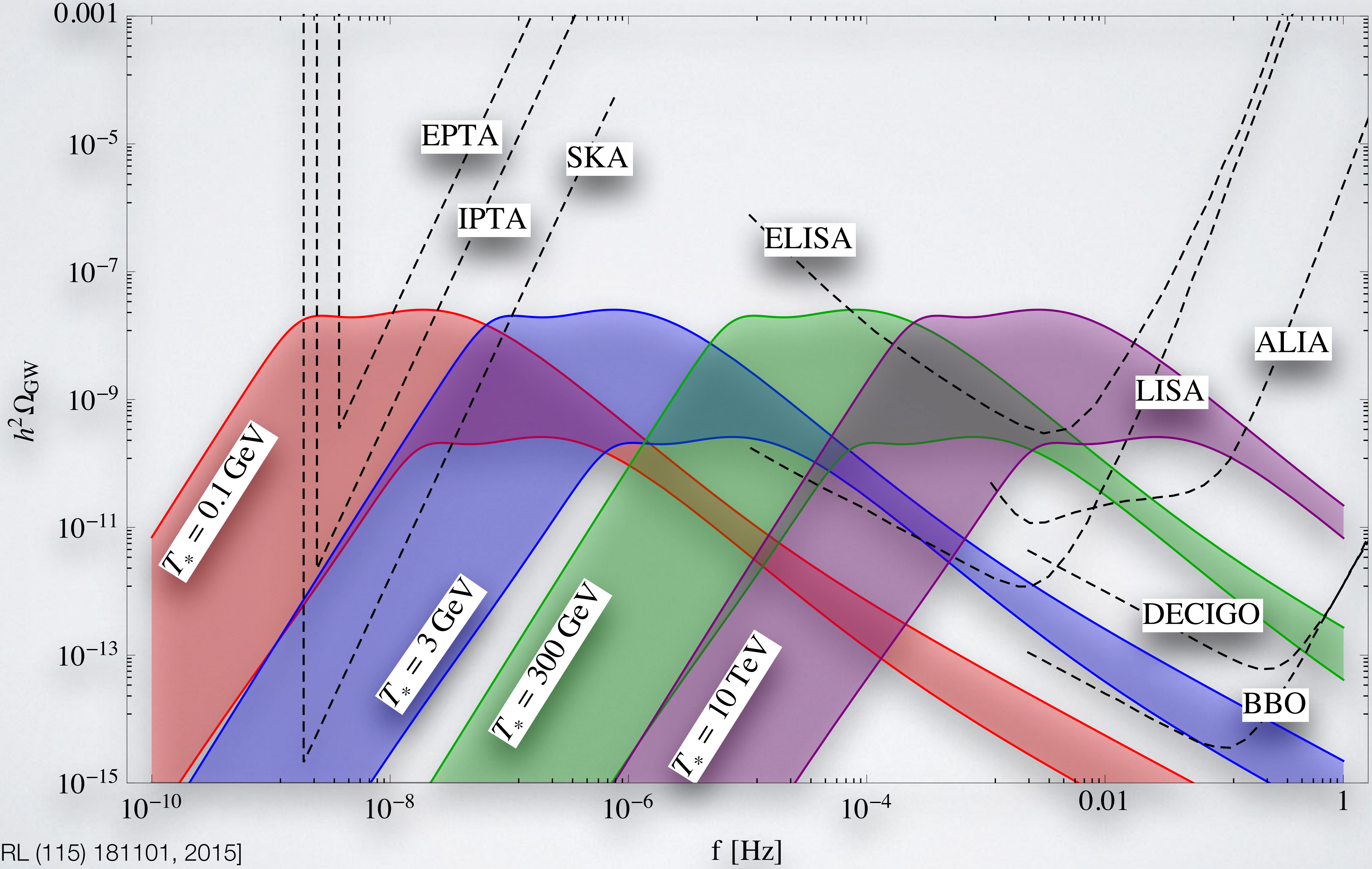
Plots from G. Kribs @ Lattice for BSM physics, University of Colorado Boulder, 4/2018

Stealth DM: gravitational wave signatures



[RHIC]

- ✦Spectrum of GW from a deconfinement first order phase transition in the dark sector, as a function of the <u>dark transition temperature</u>



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

[Laermann, Philipsen, Ann, Rev, Nucl. Part. Sci. 53 (2003) 163-198]

Phase Transitions in Strongly-coupled Theories

- We know that QCD has a weak cross-over transition between a confined phase and a plasma phase
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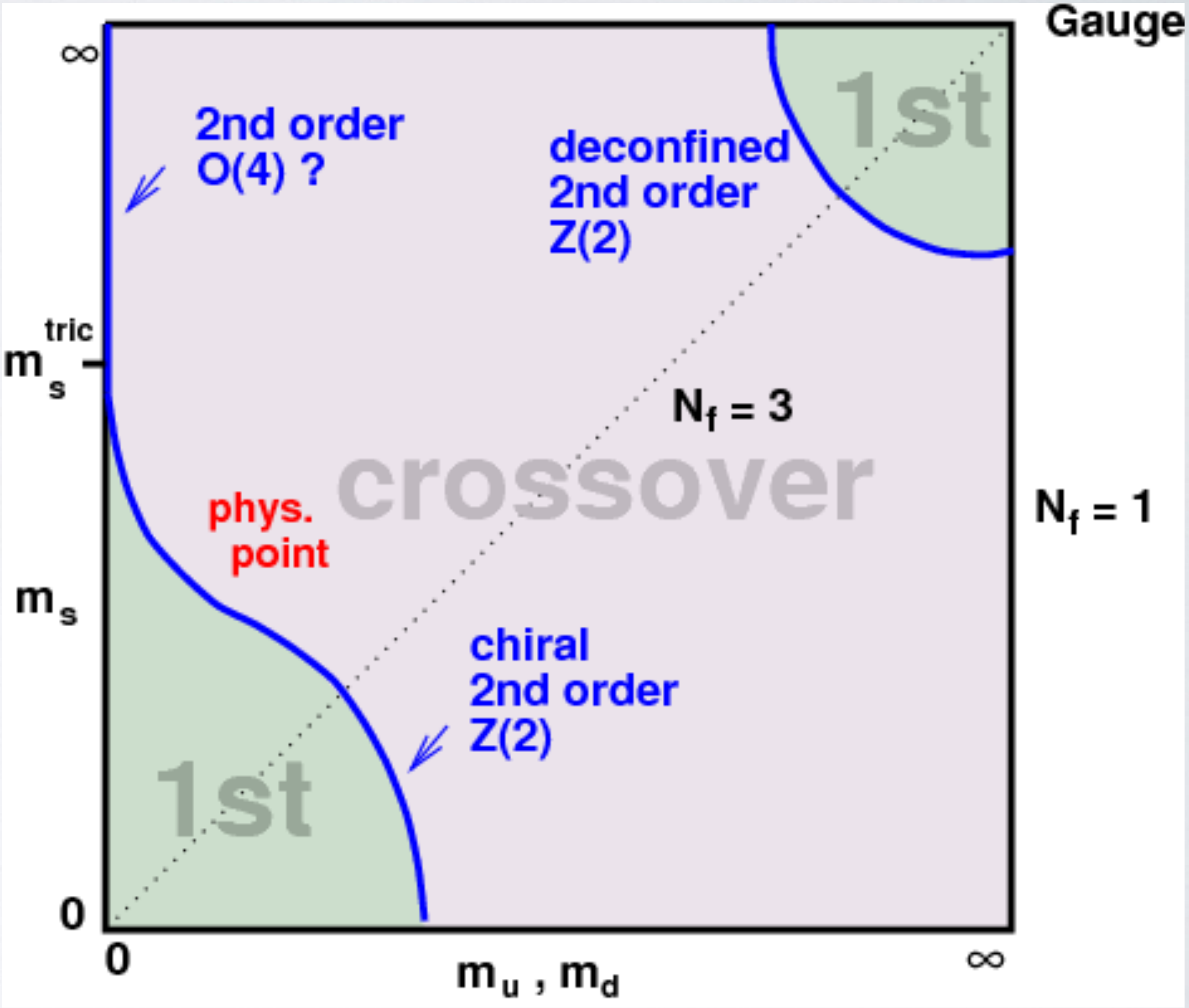

“Columbia” plot

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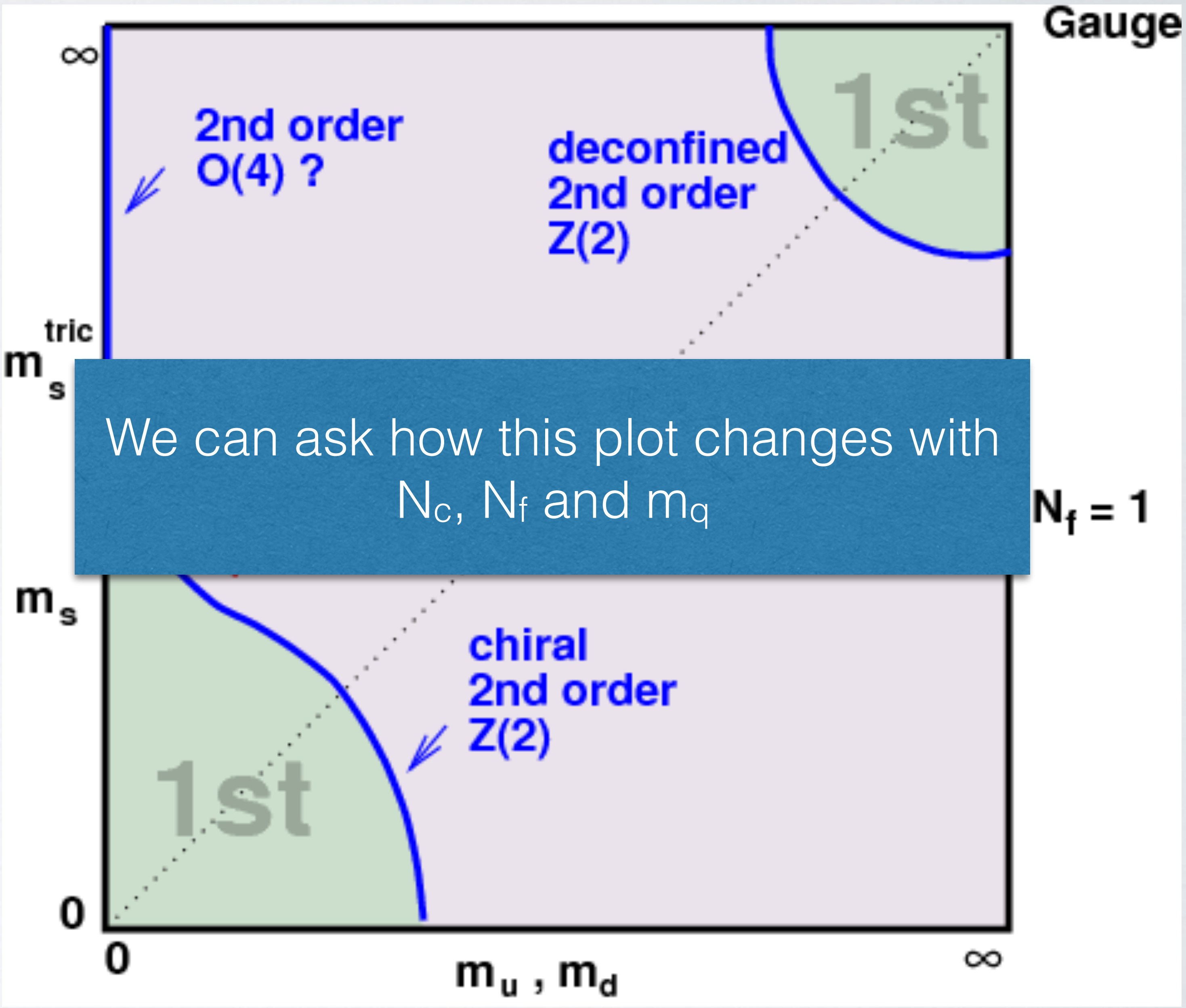

We can ask how this plot changes with N_c, N_f and m_q

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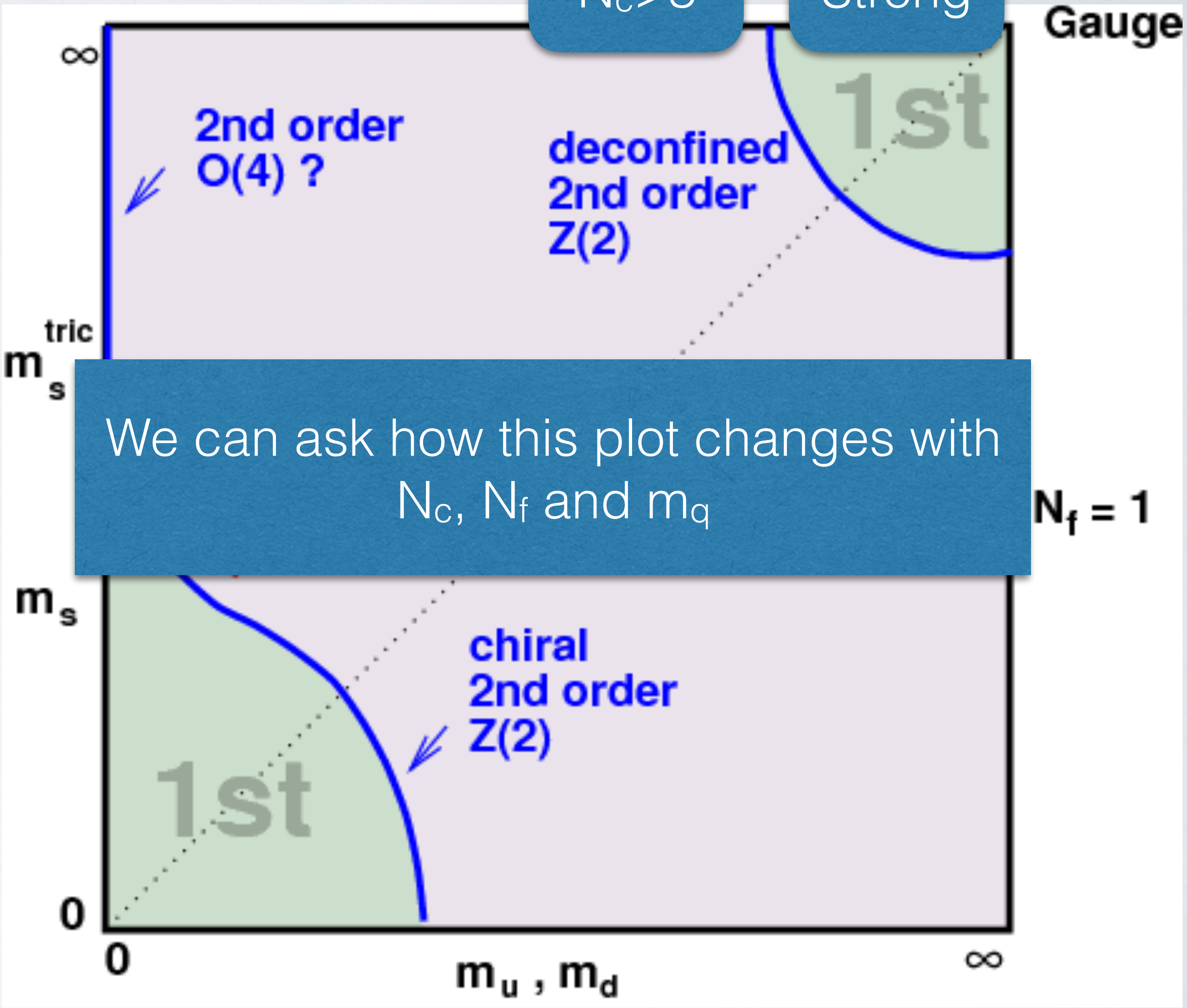

N_c>3

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Phase Transitions in Strongly-coupled Theories

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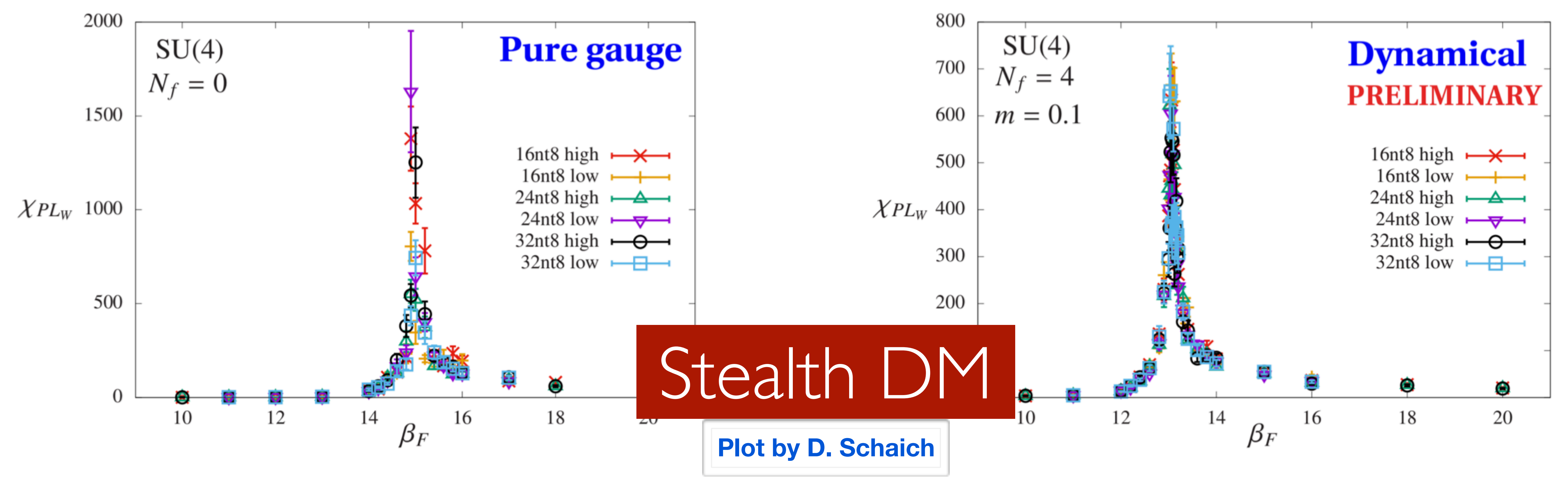
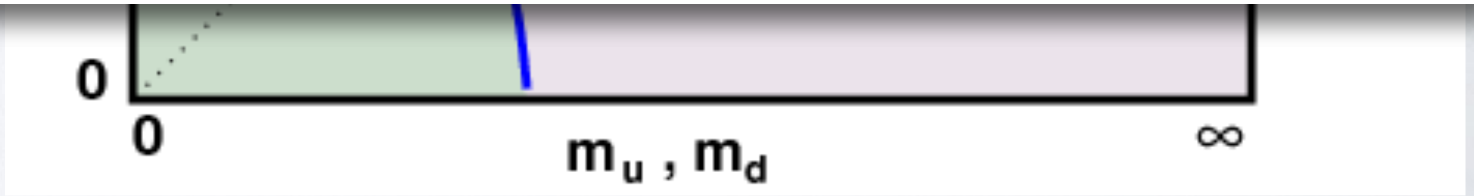


Stealth DM

Plot by D. Schaich

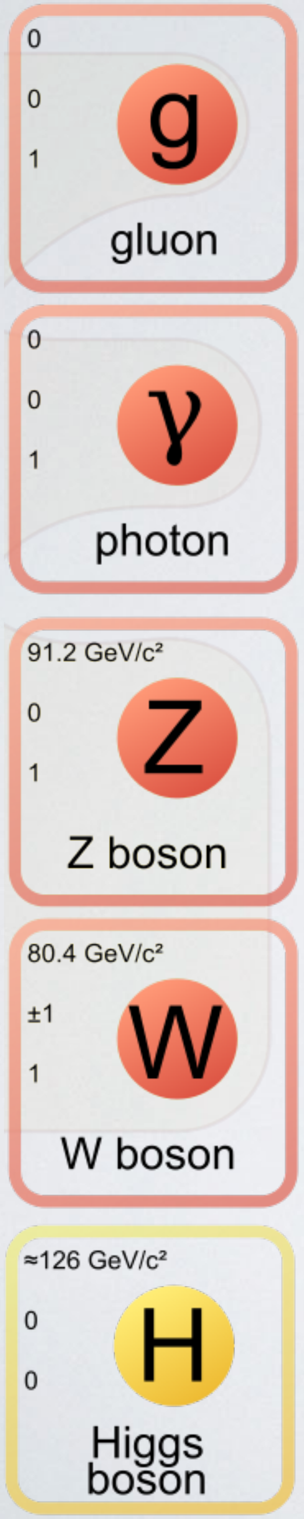
phase diagram is heavily based on lattice simulations at finite temperature



“Columbia” plot

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

The darkness of Composite Dark Matter



[Wikipedia]

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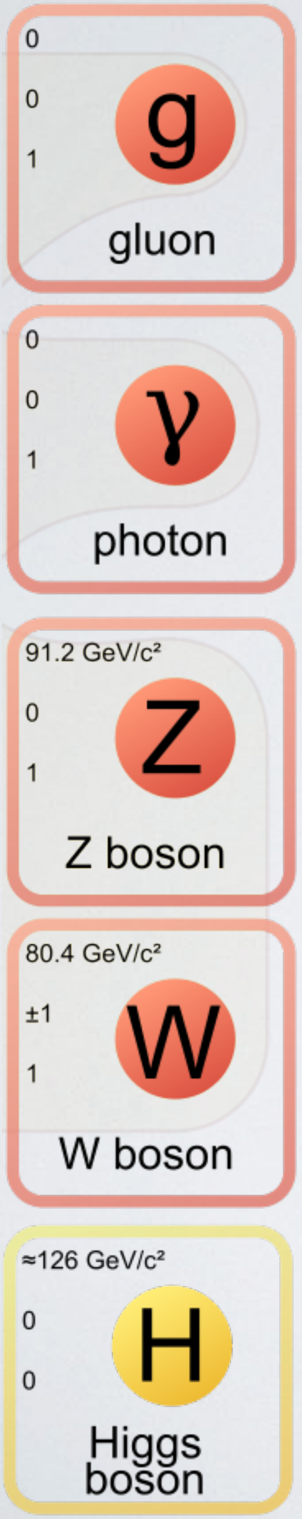

[Wikipedia]

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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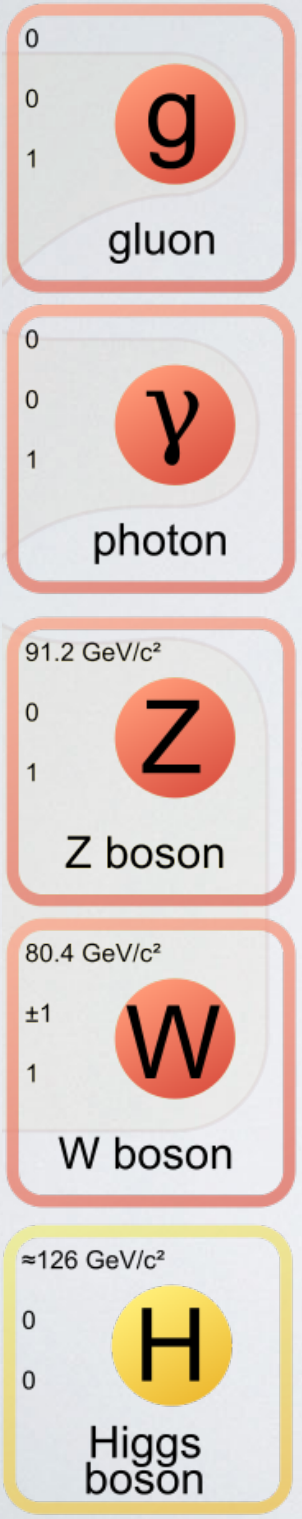

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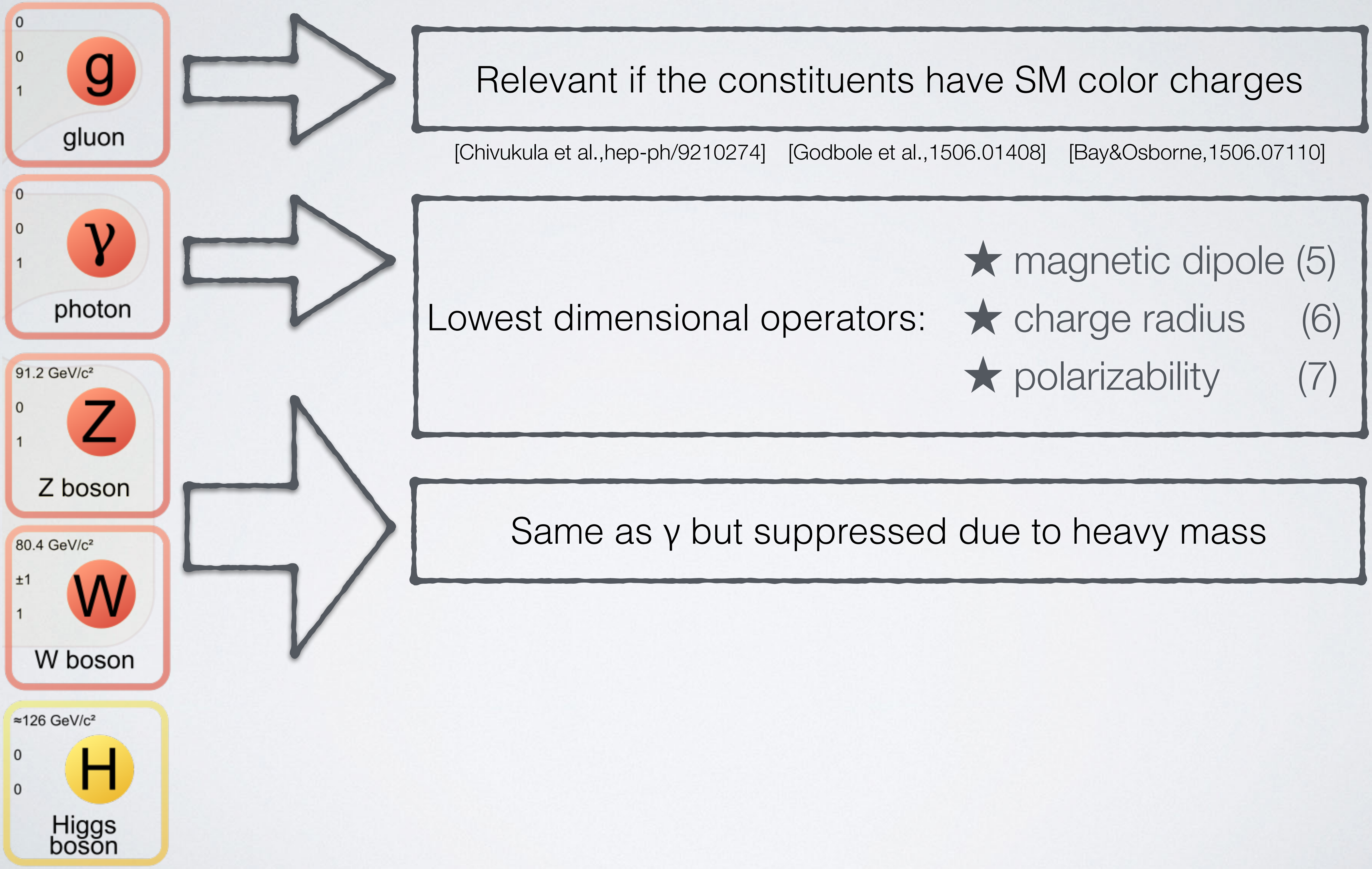

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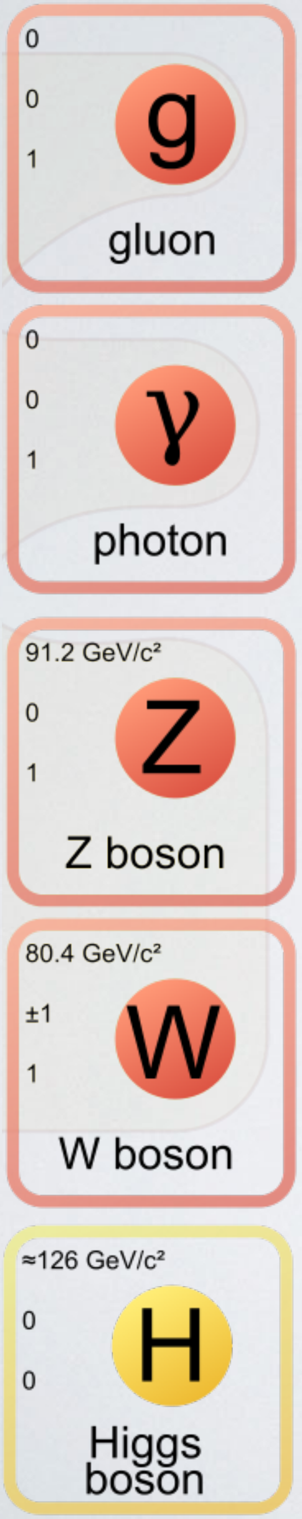

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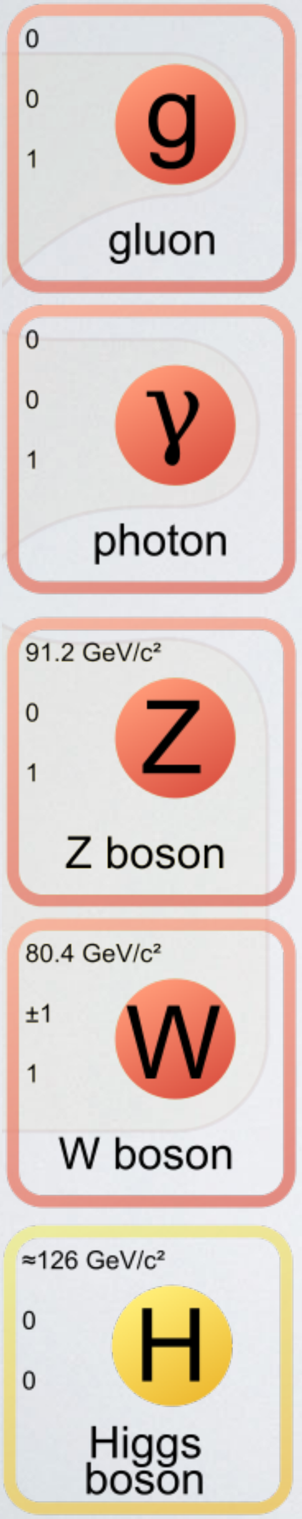

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[references in Kribs & Neil, 1604.04627]

★ lattice
☆ estimate
🟥 forbidden

LATTICE RESULTS

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	★				

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SU(4) N_f=4	★	★	🟥	🟥	★
SO(4) N_f=2 (V)	★				
SU(N) N_f=0	★	🟥	🟥	🟥	🟥

forbidden in pNGB DM

forbidden in Stealth DM

forbidden in SUNonia

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

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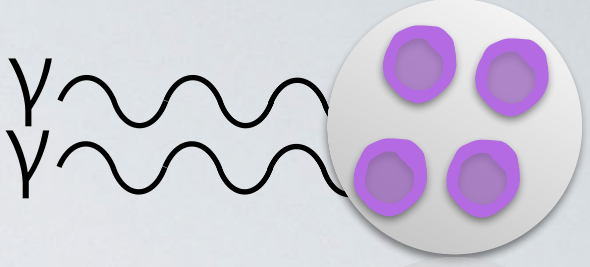
Computing polarizability



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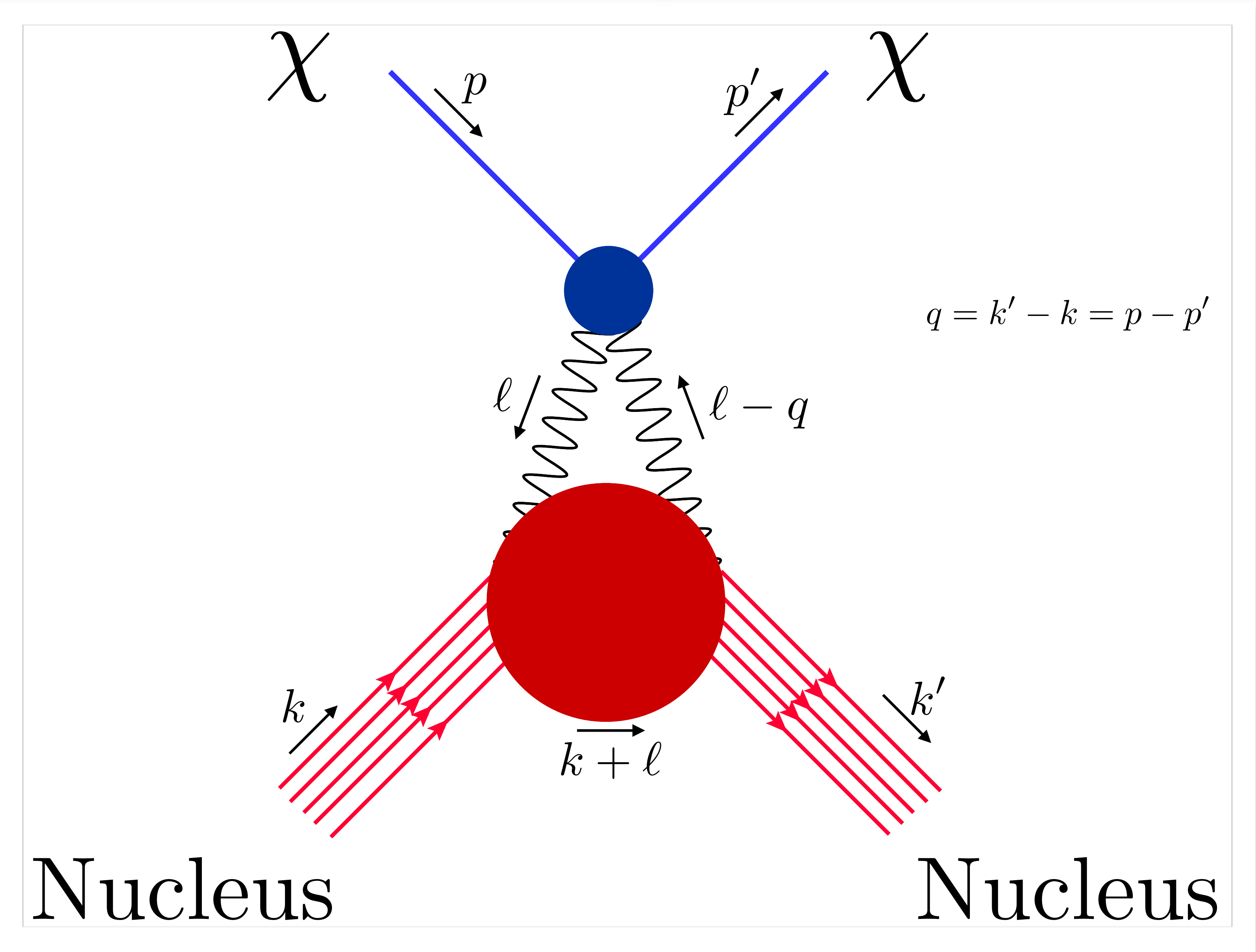

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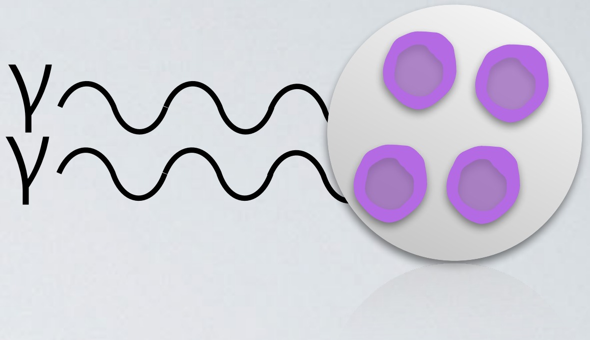

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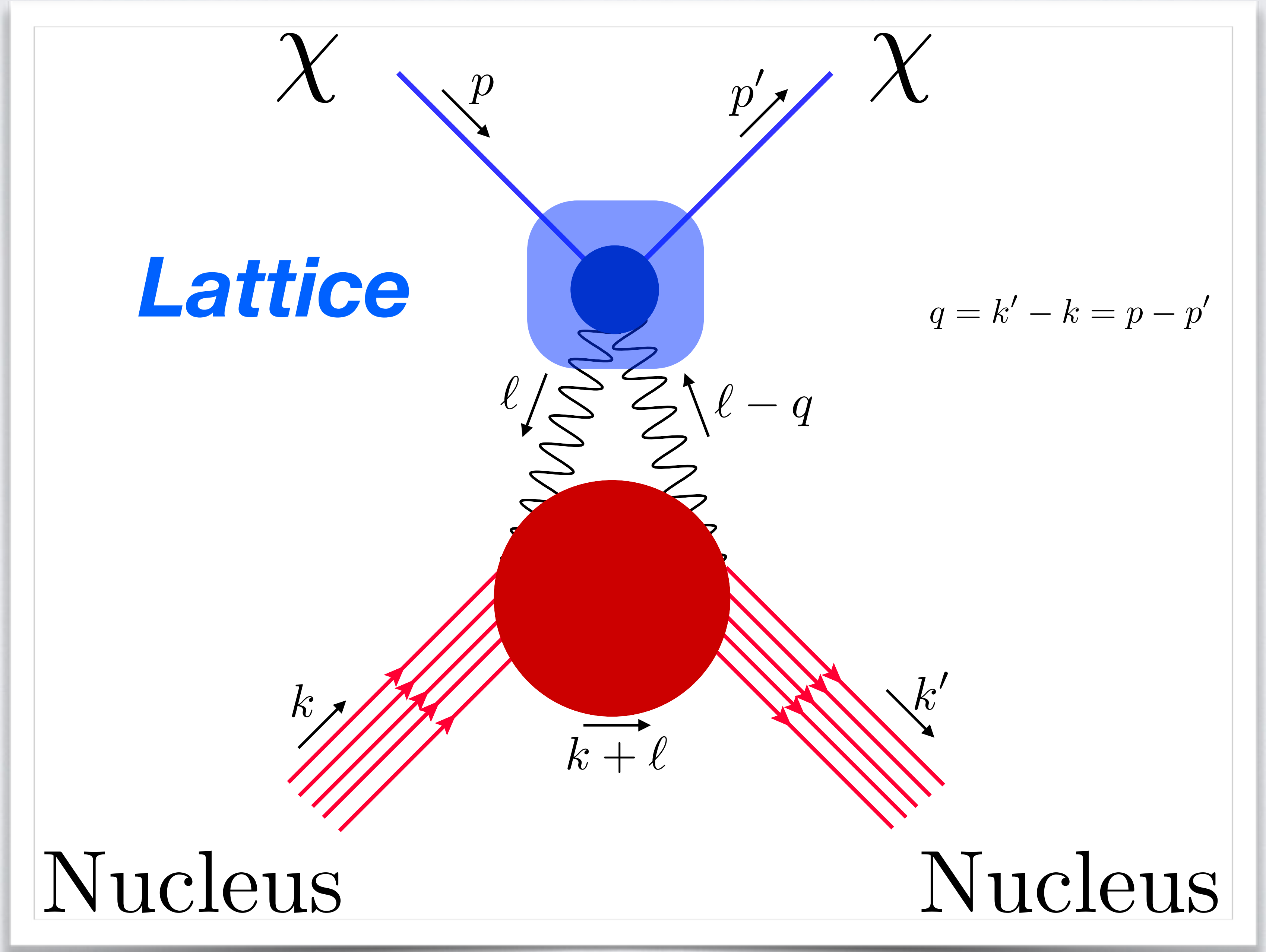

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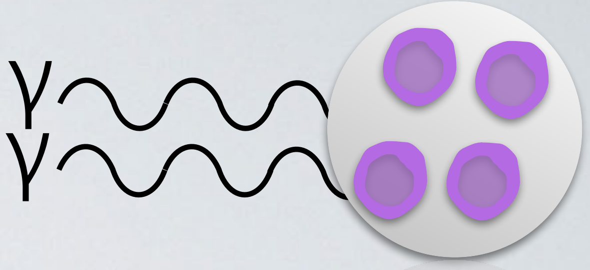

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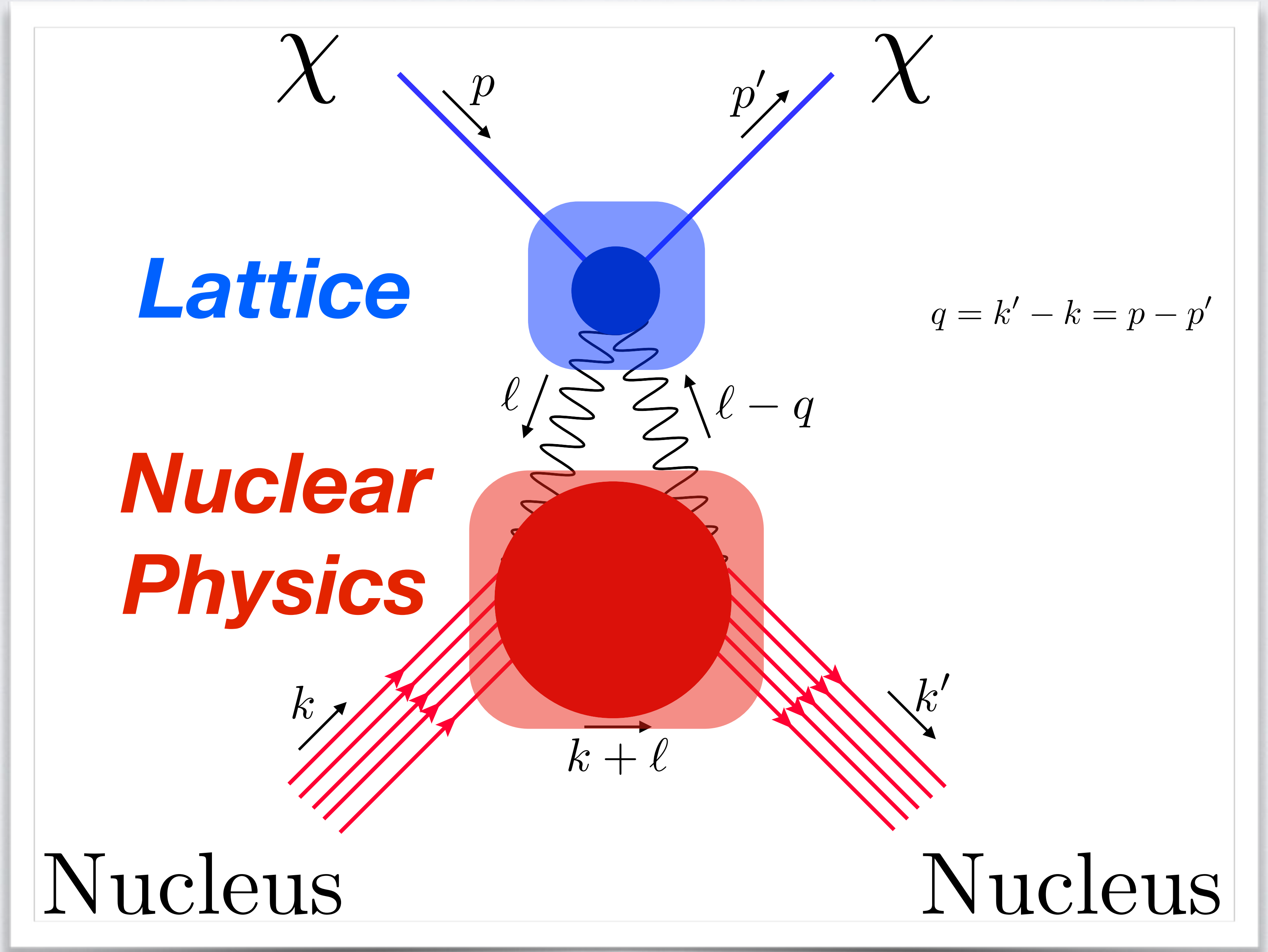
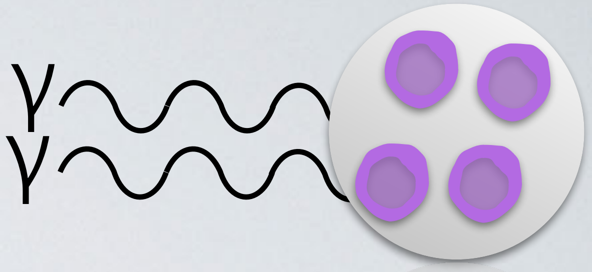


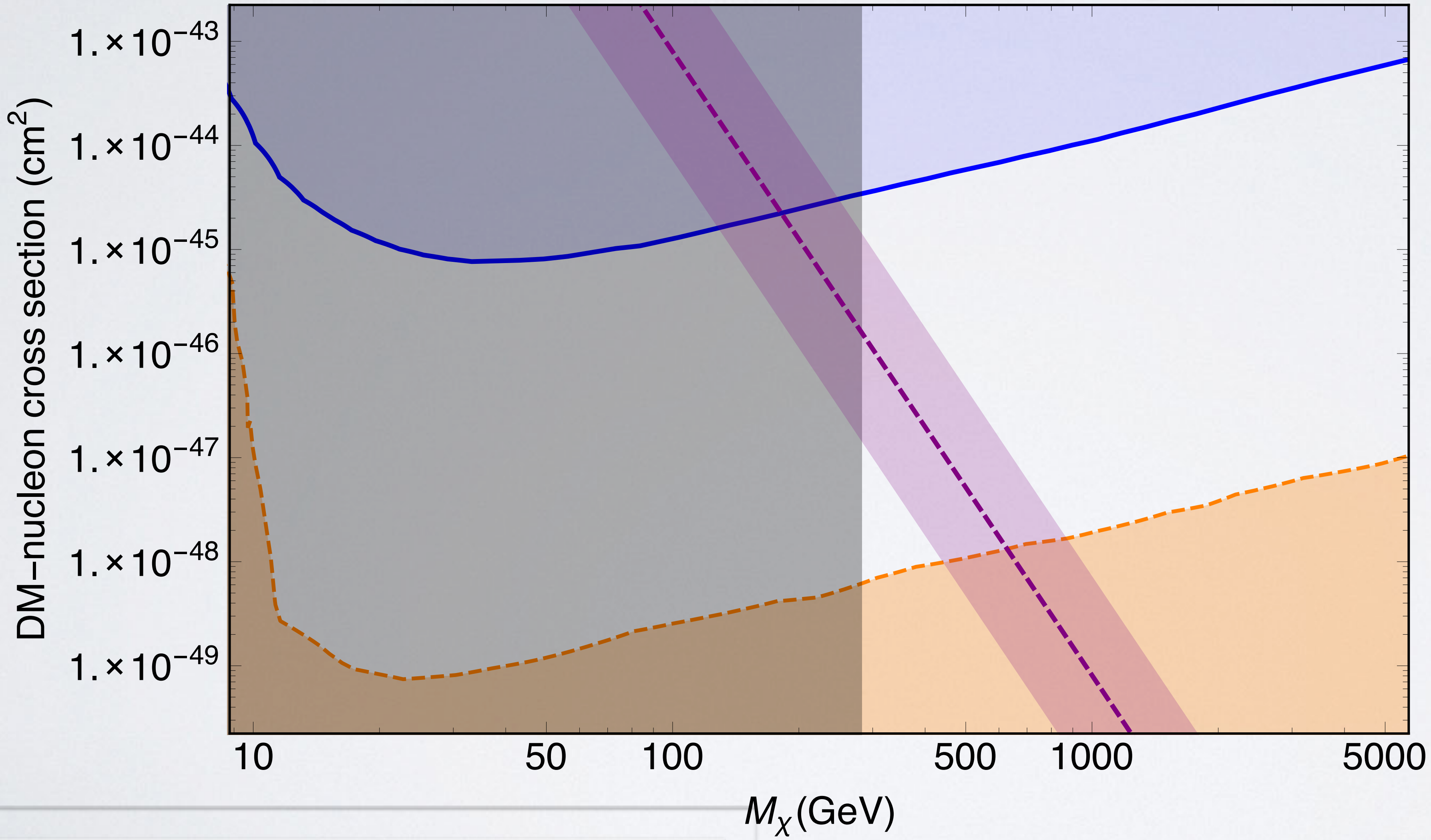
[Newer bounds: PandaX-II 1607.07400, LUX-332d 1608.07648, XENON1T-34d 1705.06655]

[see also Drach et al.,1511.04370 for SU(2) N_f=2]

Lowest bound from EM polarizability



Electric polarizability from lattice simulations



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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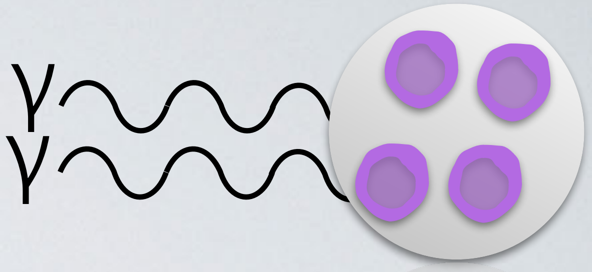

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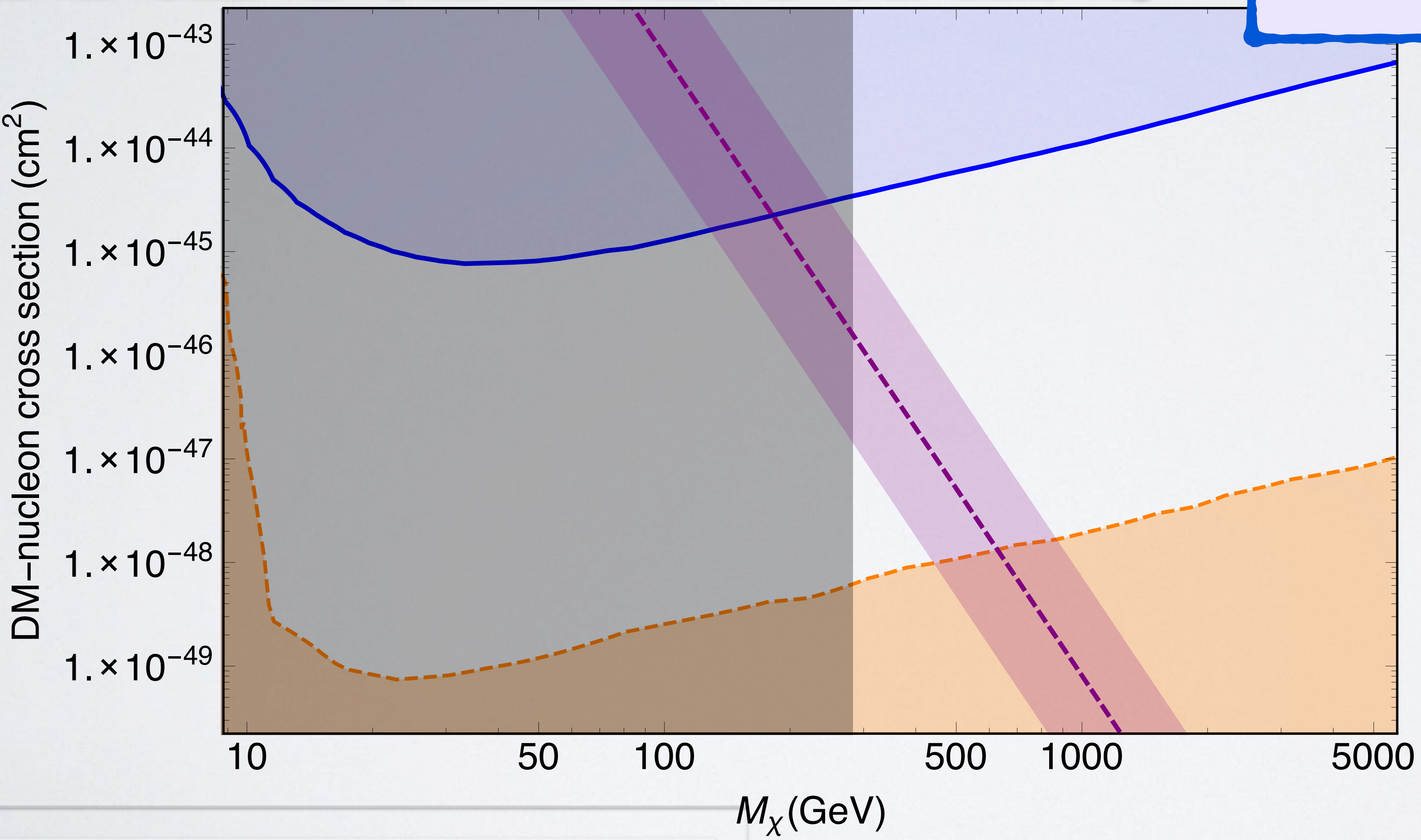
LUX exclusion bound for spin-independent cross section



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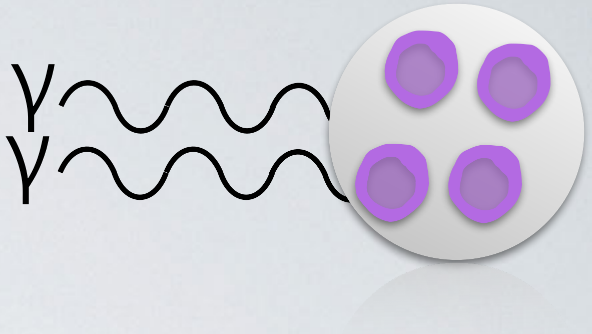

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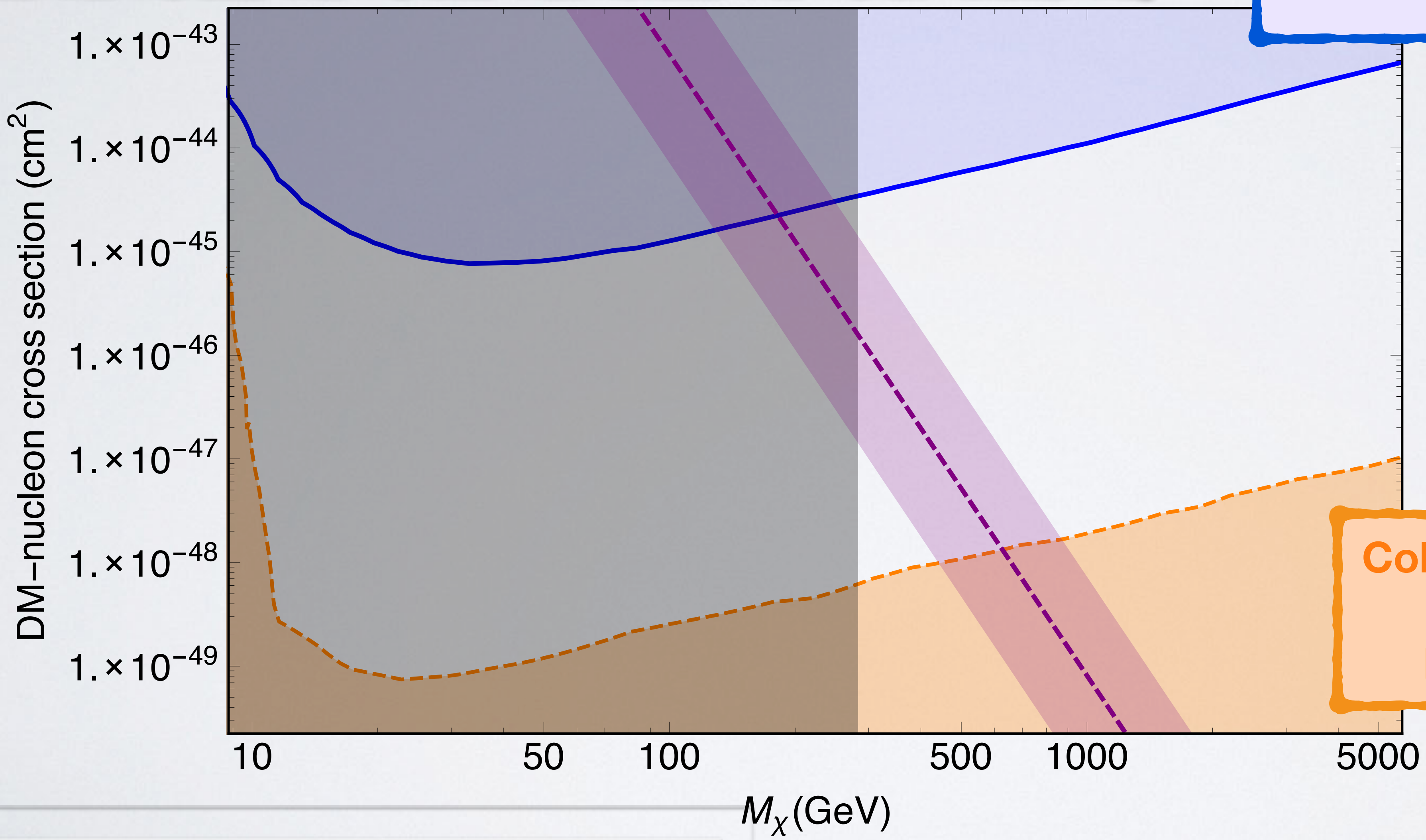

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Coherent neutrino scattering background

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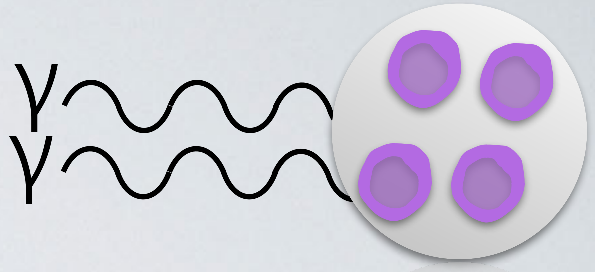

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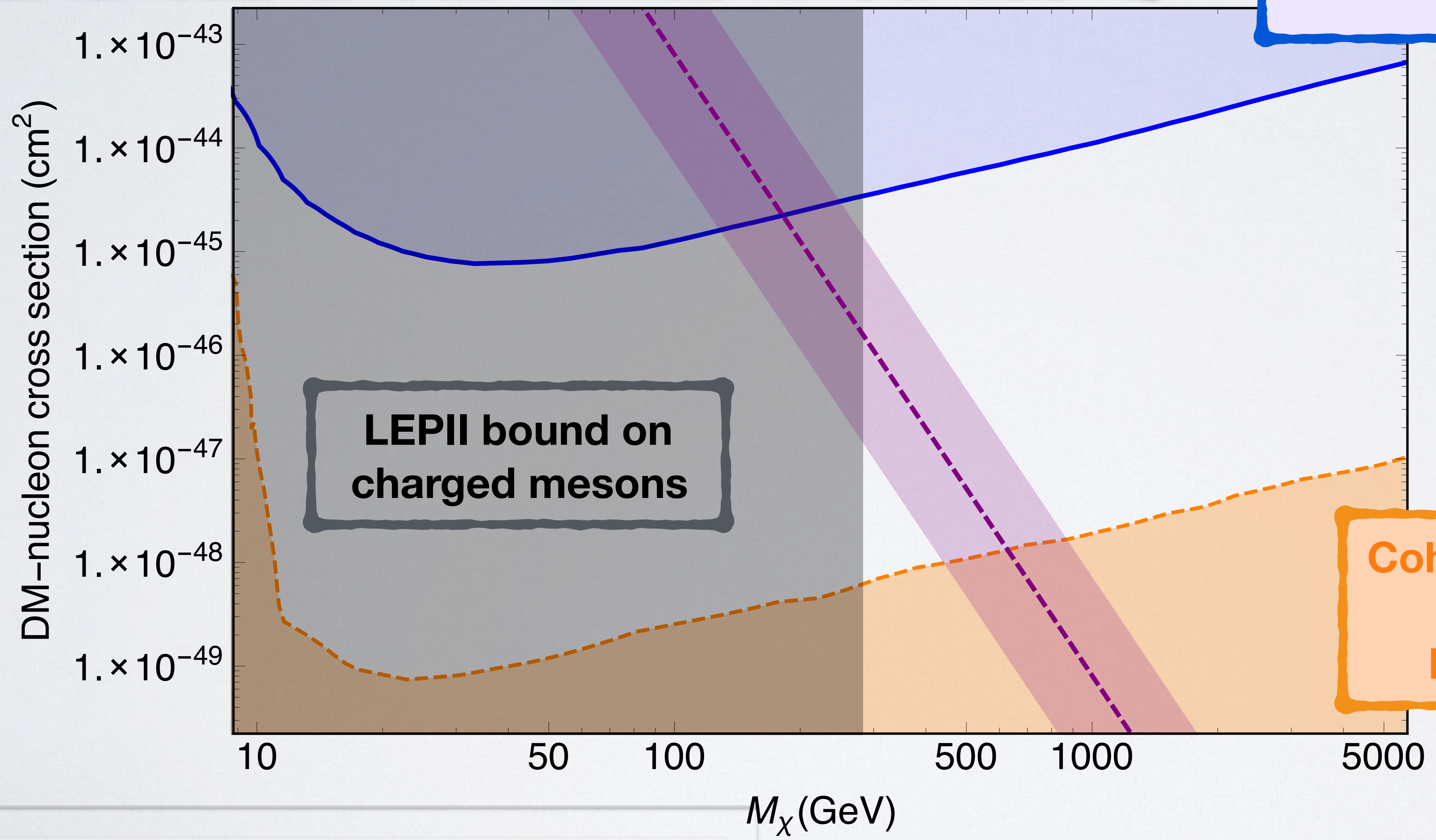

LEPII bound on charged mesons

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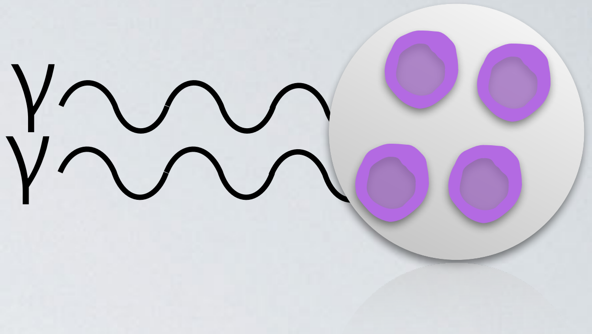

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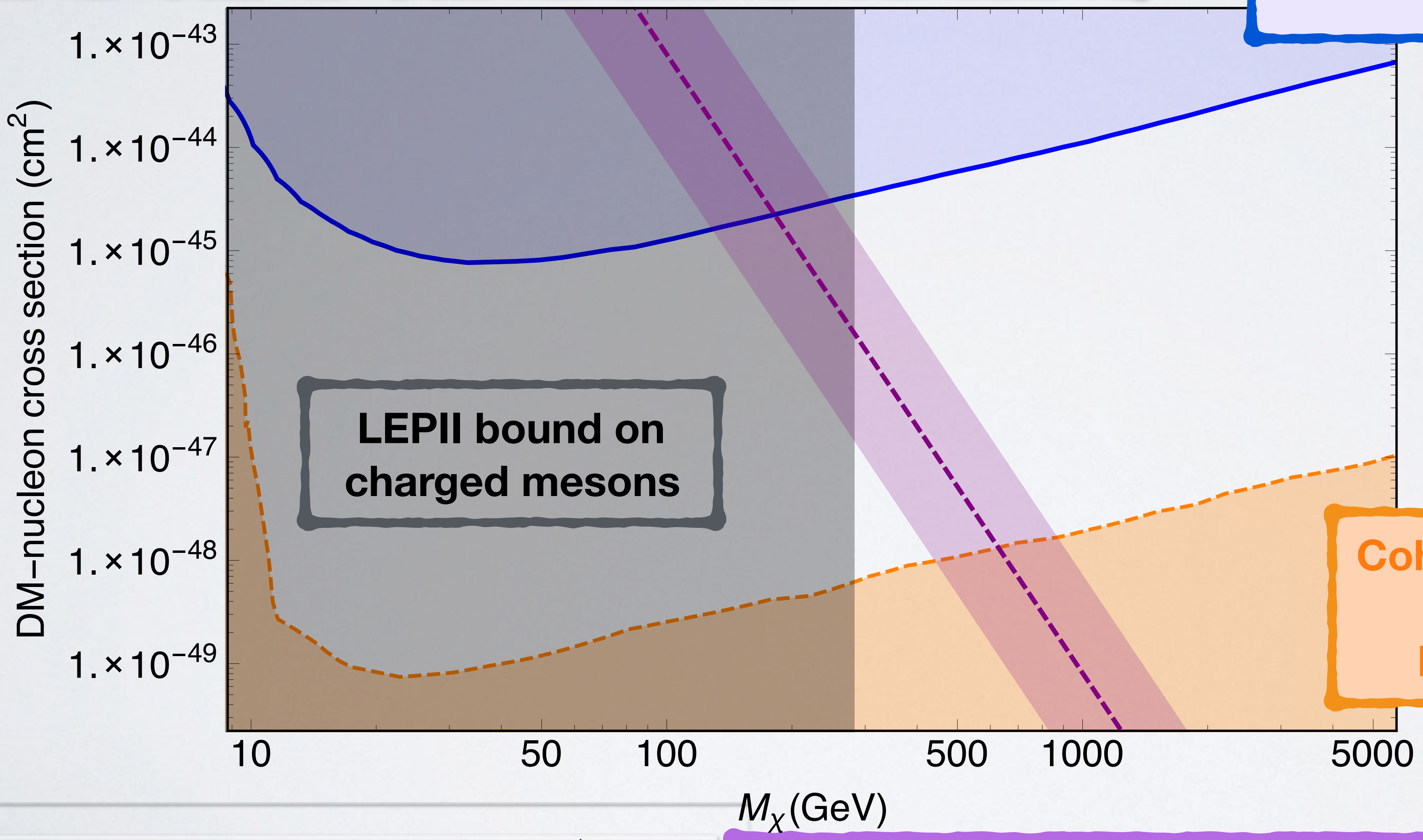

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lowest allowed direct detection cross-section for composite dark matter theories with EW charged constituents

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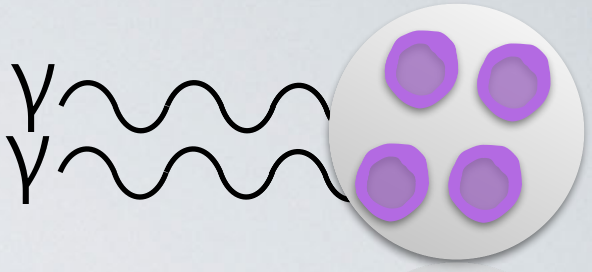

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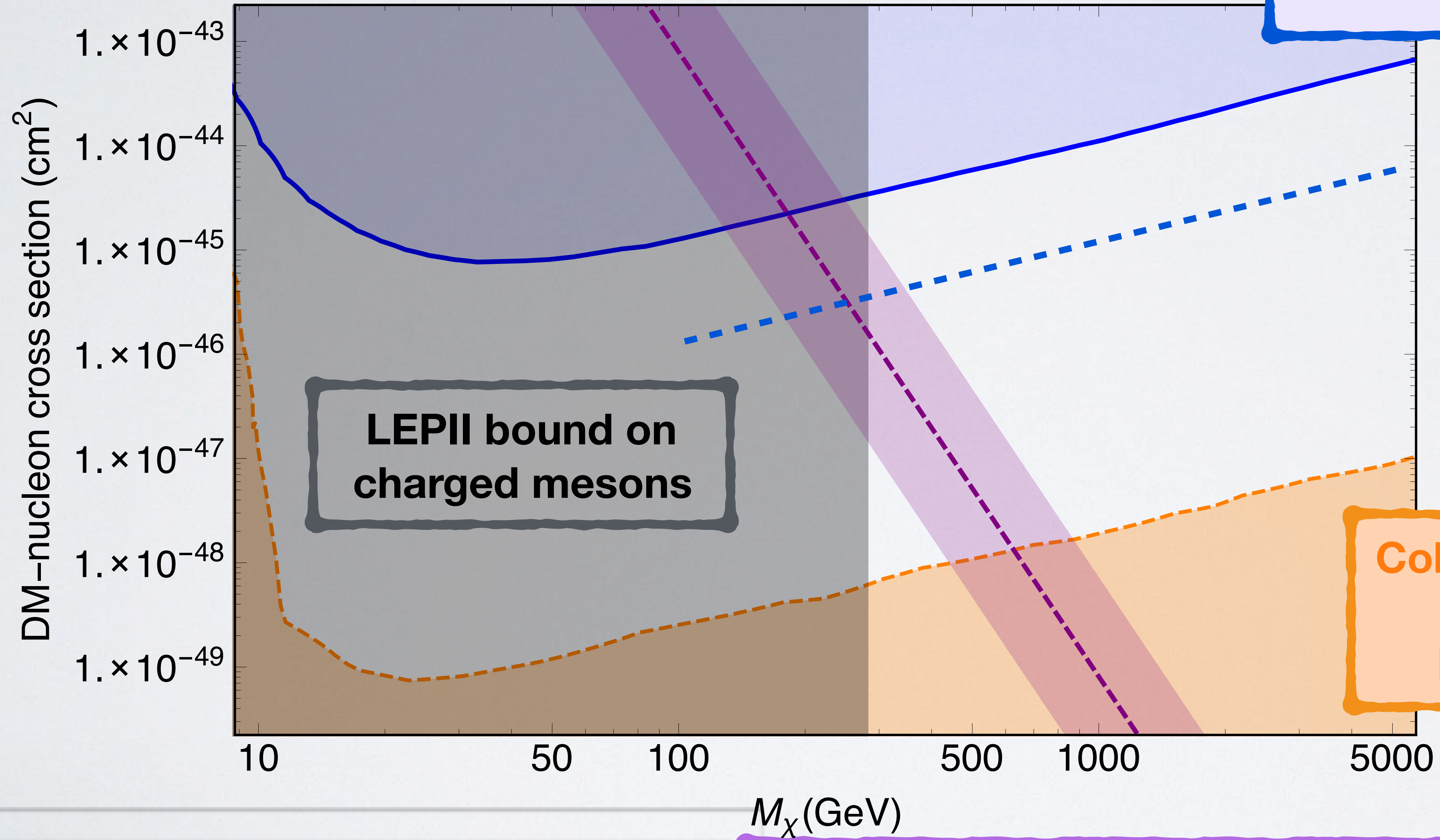

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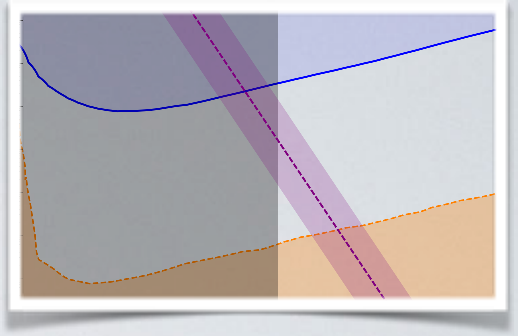
[LSD collab., Phys. Rev. Lett. 115 (2015) 171803]



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) (can be improved!)

DEEP LEARNING AND PHYSICS

ECT* workshop (3/2020): Machine Learning for High Energy Physics, on and off the Lattice

Deep Learning
And Physics
DLAP2019

http://kabuto.phys.sci.osaka-u.ac.jp/~koji/workshop/DLAP2019/

\> Yukawa Institute for Theoretical Physics
\> Kyoto, Japan
\> 31 Oct - 2 Nov 2019

\> Invited speakers include:
\> Shun-Ichi Amari (RIKEN)
\> *James Halverson (Northeastern U)
\> Hong-Ye Hu (UC San Diego)
\> Gurtej Kanwar (MIT)
\> Sven Krippendorf (Sommerfeld Center)
\> Junwei Liu (HKUST)
\> Zi Yang Meng (CAS)
\> Youichiro Miyake (Square Enix)
\> Masayuki Ohzeki (Tohoku U)
\> Fabian Ruhle (CERN)
\> Rak-Kyeong Seong (Samsung SDS)
\> Gary Shiu (U Wisconsin)
\> Lei Wang (CAS)
\> Youhei Yamaji (Tokyo U)
\> Greg Yang (Microsoft Research)
\> Hajime Yoshino (Osaka U)
\> *special lecture at Osaka U on 30 Oct

\> Organizers:
\> Koji Hashimoto (Osaka U)
\> Masatoshi Imada (Toyota RIKEN / Waseda U)
\> Kouji Kashiwa (Fukuoka Institute of Technology)
\> Yuki Nagai (JAEA CCSE)
\> Masayuki Ohzeki (Tohoku U)
\> Enrico Rinaldi (RIKEN & Arithmer Inc.)
\> Akinori Tanaka (RIKEN AIP)
\> Akio Tomiya (RIKEN BNL)

This conference is supported by: Yukawa Institute, JSPS/MEXT KAKENHI No.2902, 17H06462, 18K13548, Post-K CDSMI
本研究会は以下の研究費にサポートを受けて開催されます：新学術領域科研費「次世代物質探索のための離散幾何学」、
科研費17H06462、科研費18K13548、ポスト「京」プロジェクト「世代の産業を支える新機能デバイス・高性能材料の創成」

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 ai 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

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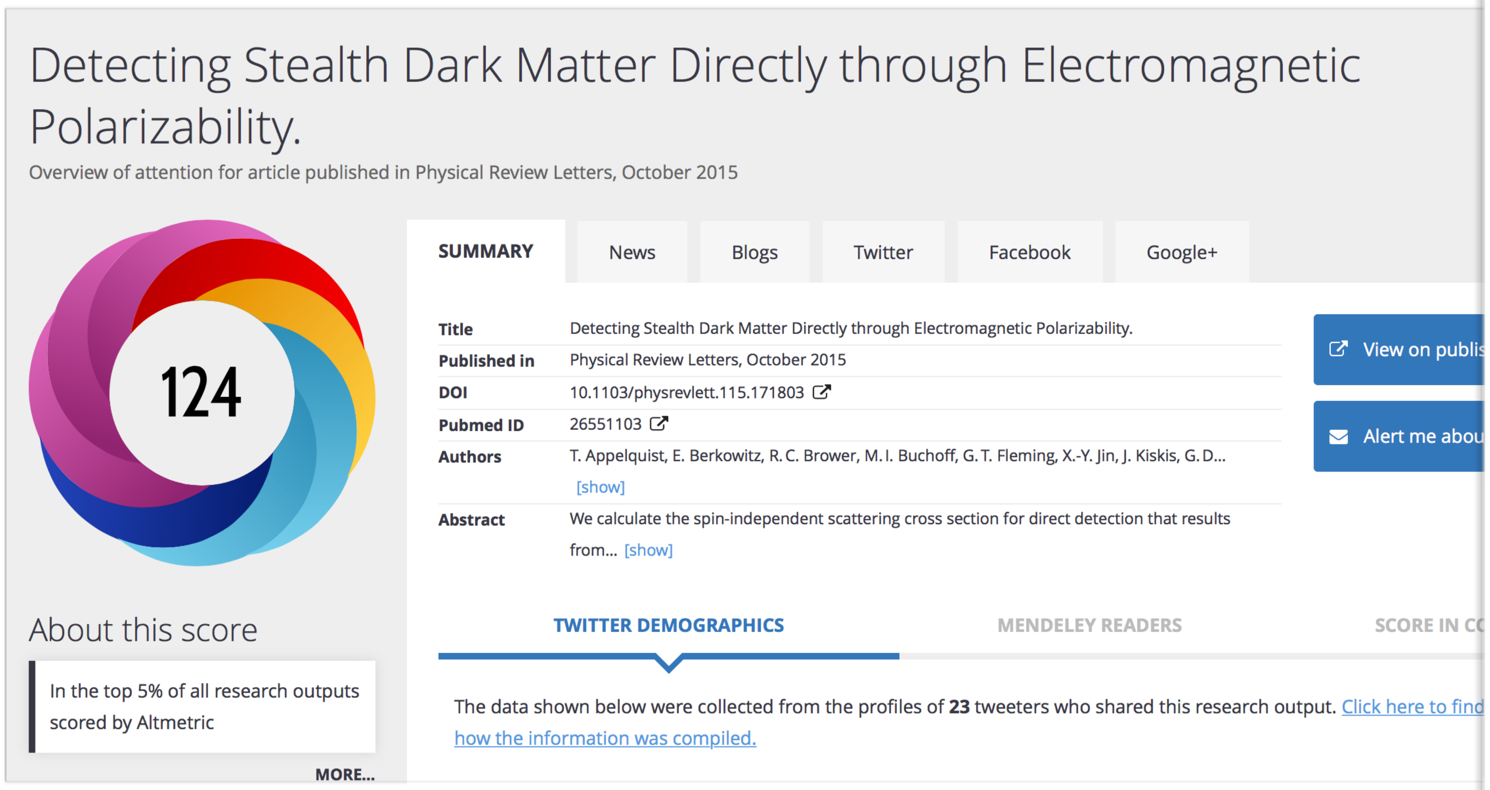
https://www.llnl.gov/news/new-stealth-dark-matter-theory-may-explain-mystery-universes-missing-mass

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

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Materia osc
Nuove ipotesi su
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In edicola dal 1

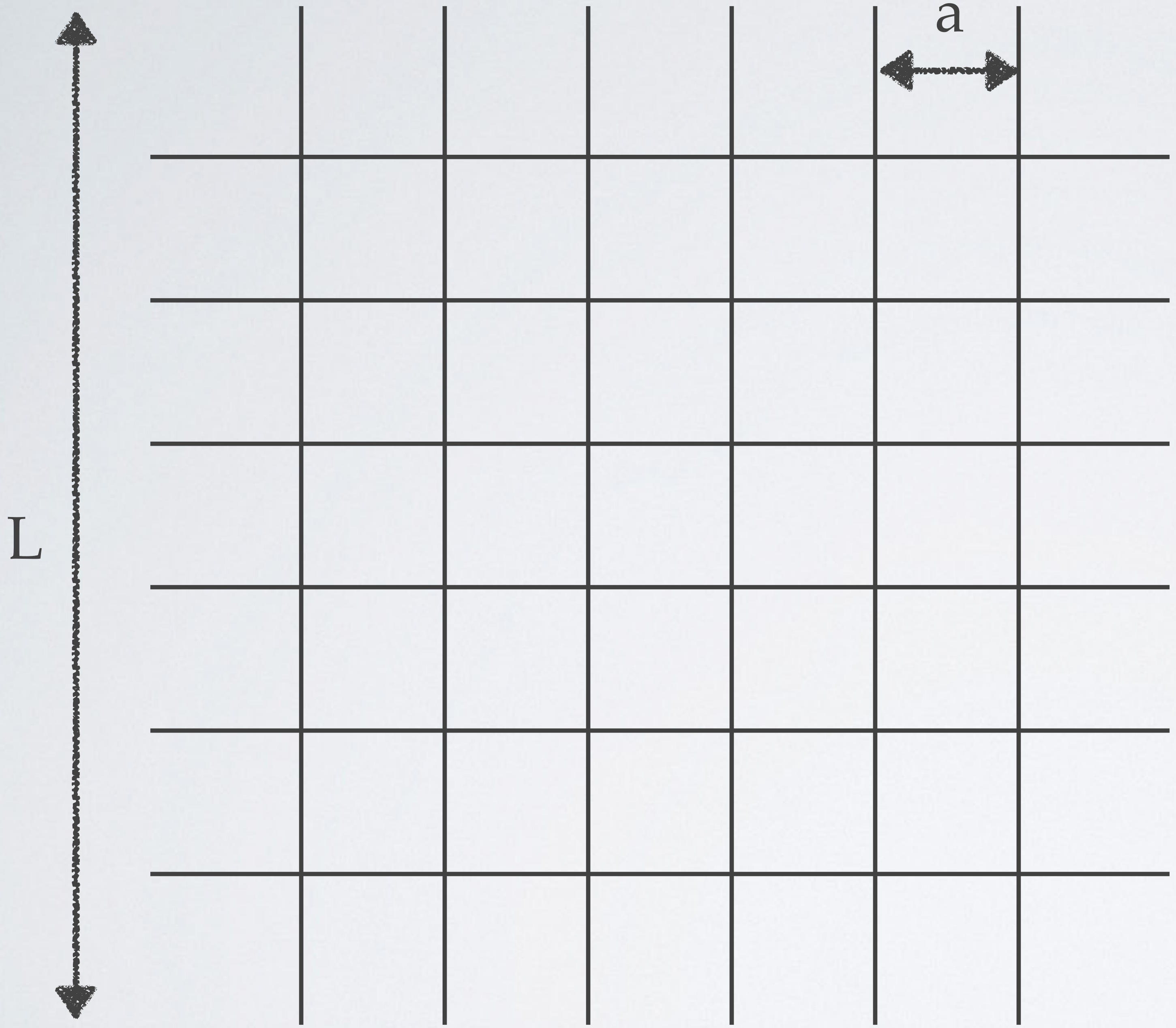
28 settembre 2015

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)*

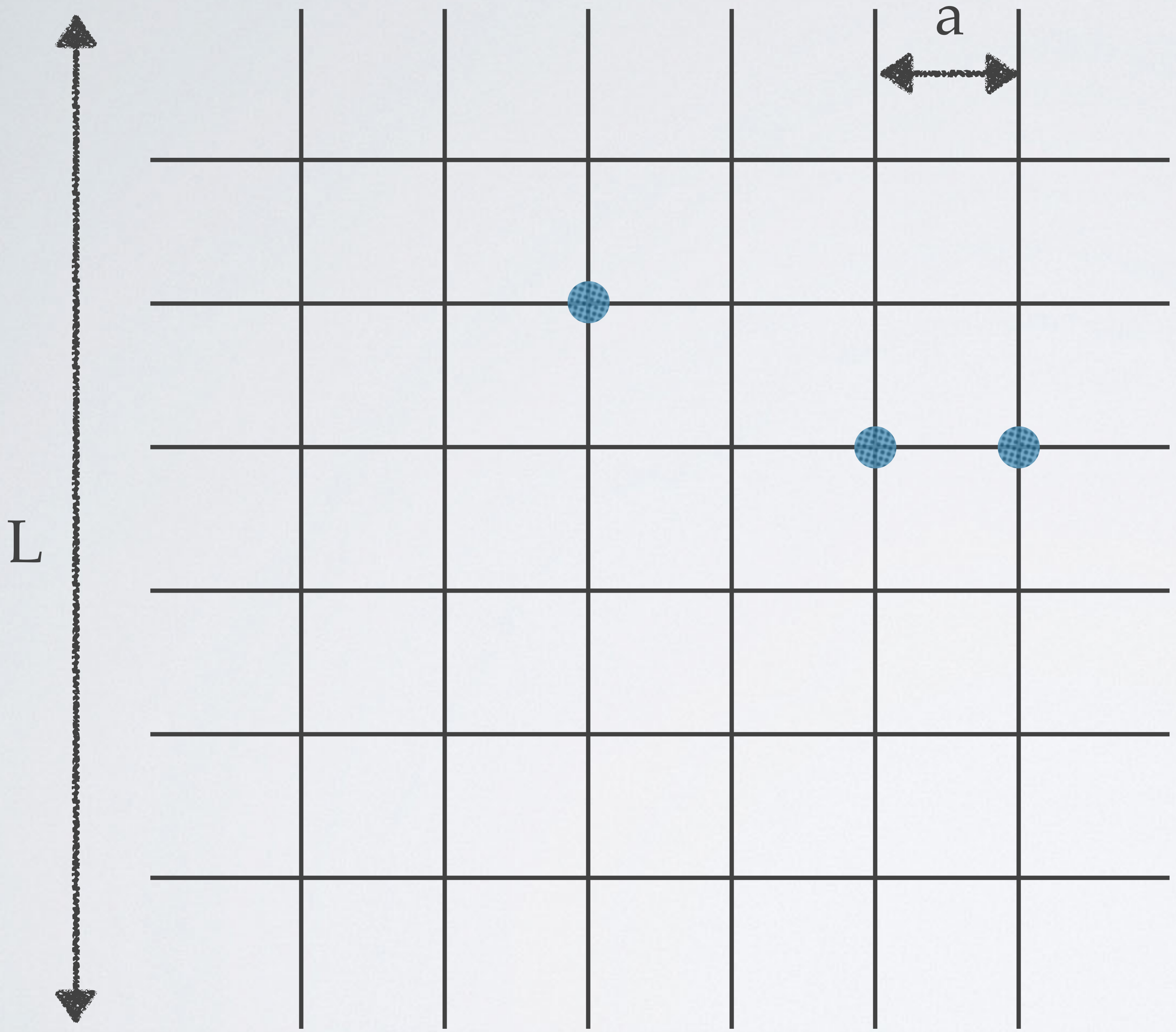
Cortesia Lawrence Livermore National Laboratory

Lattice primer



- 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

Lattice primer



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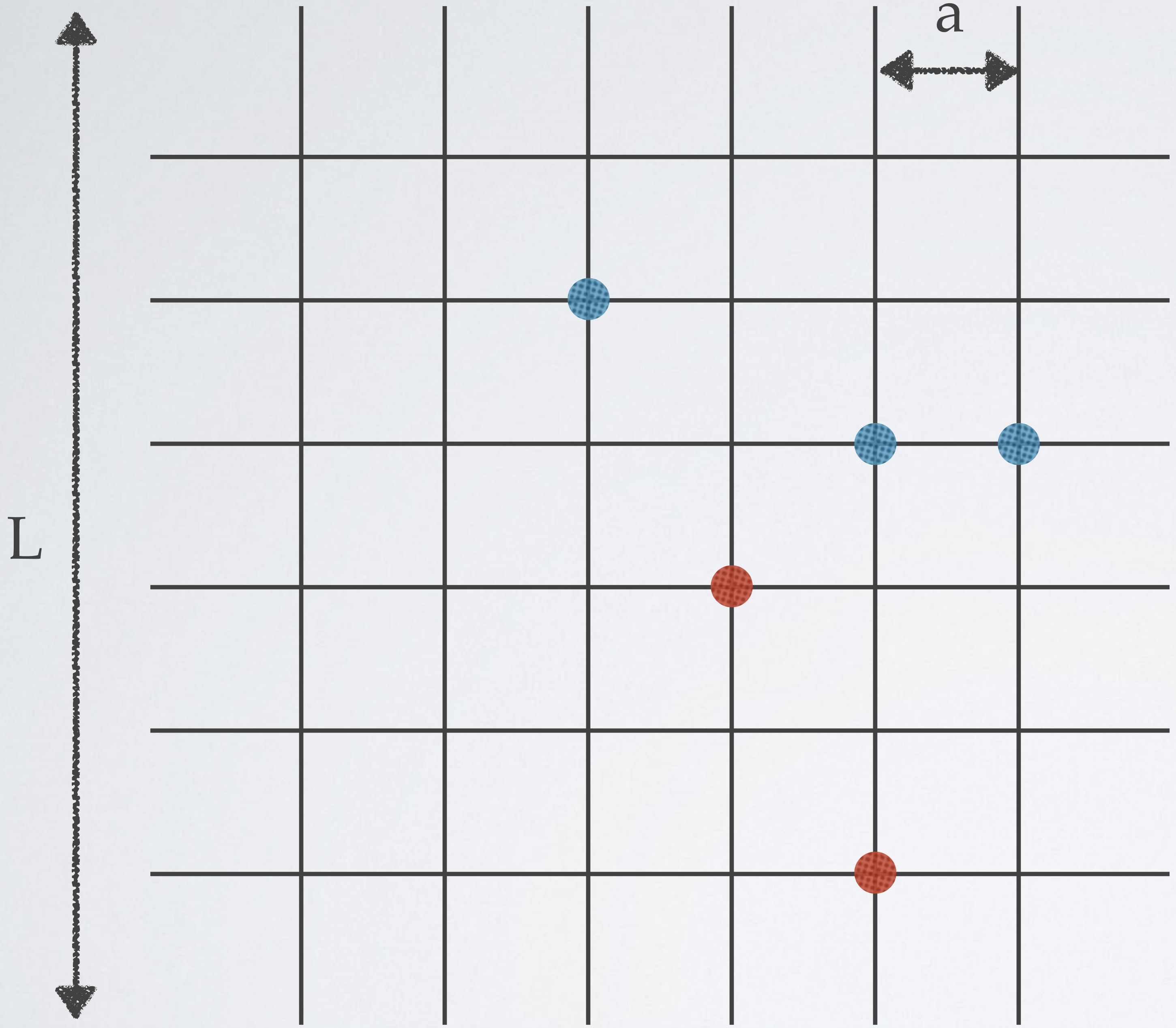

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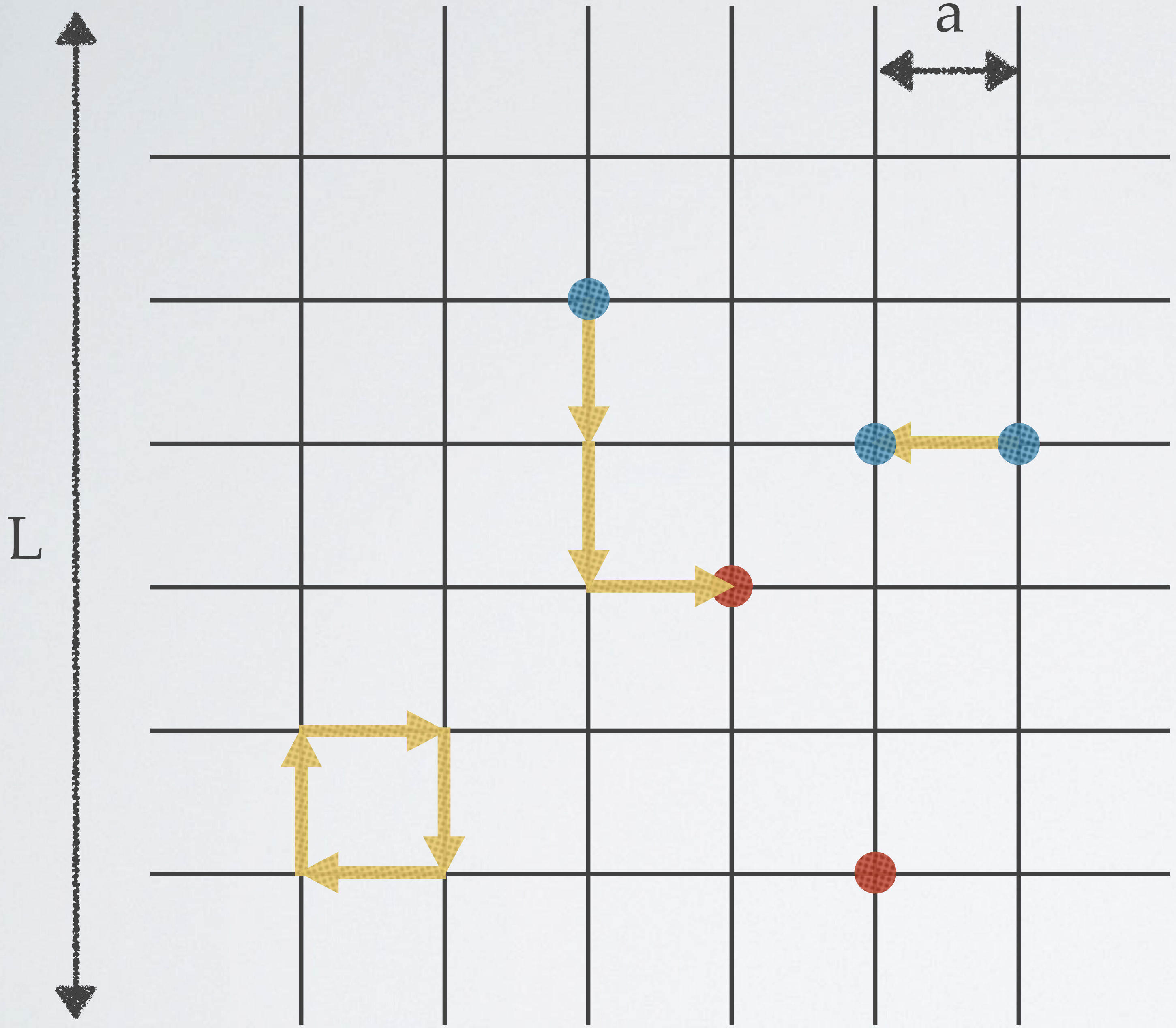

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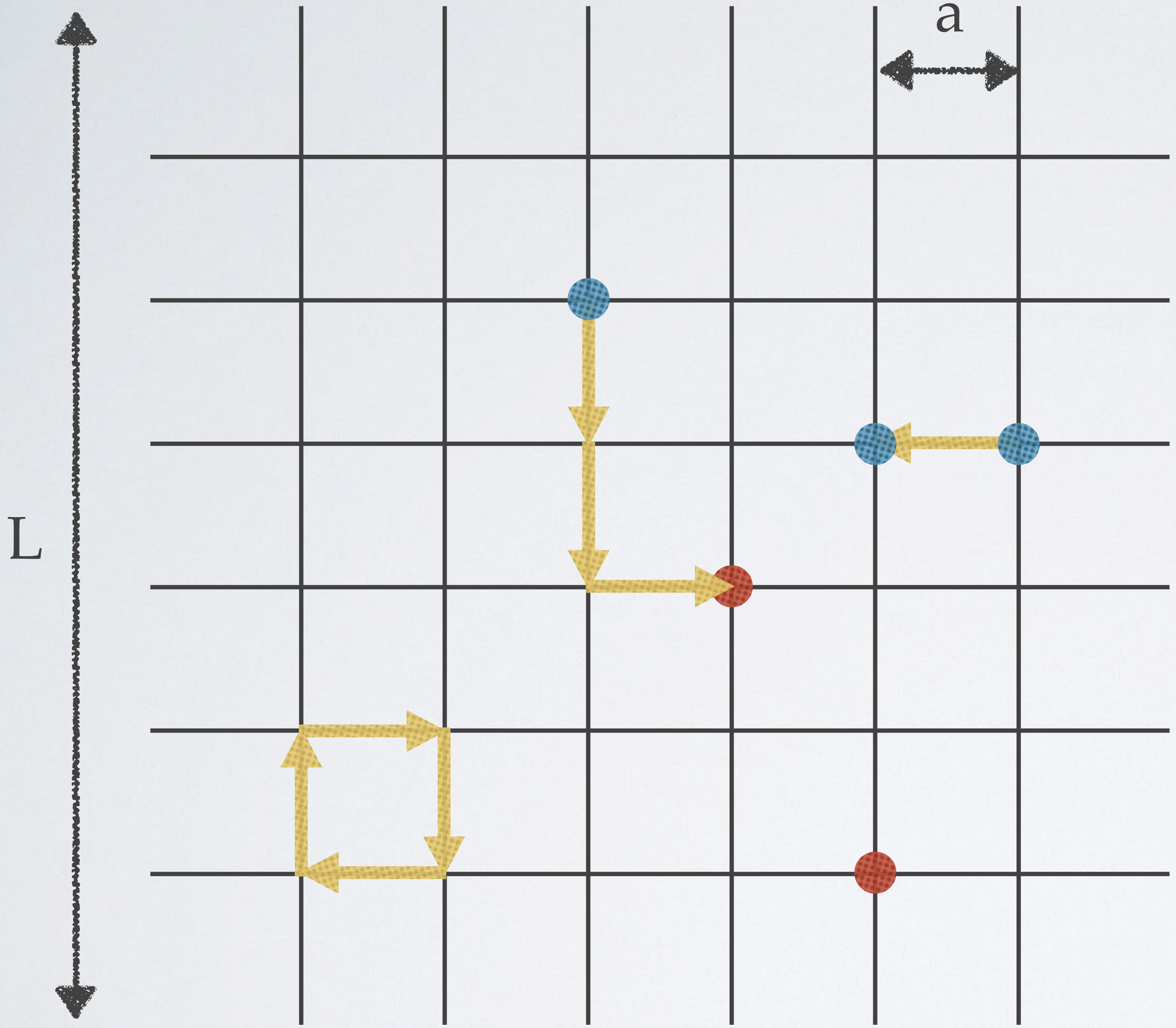

N_c **N_f** **N_r** parameters that can be easily changed

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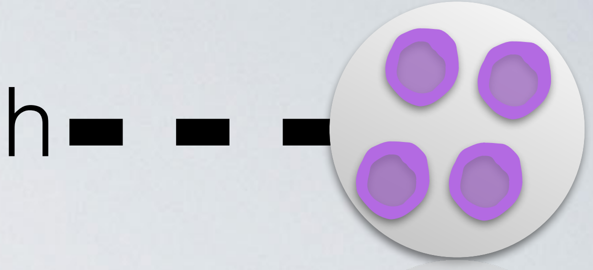
Bounds from Higgs exchange

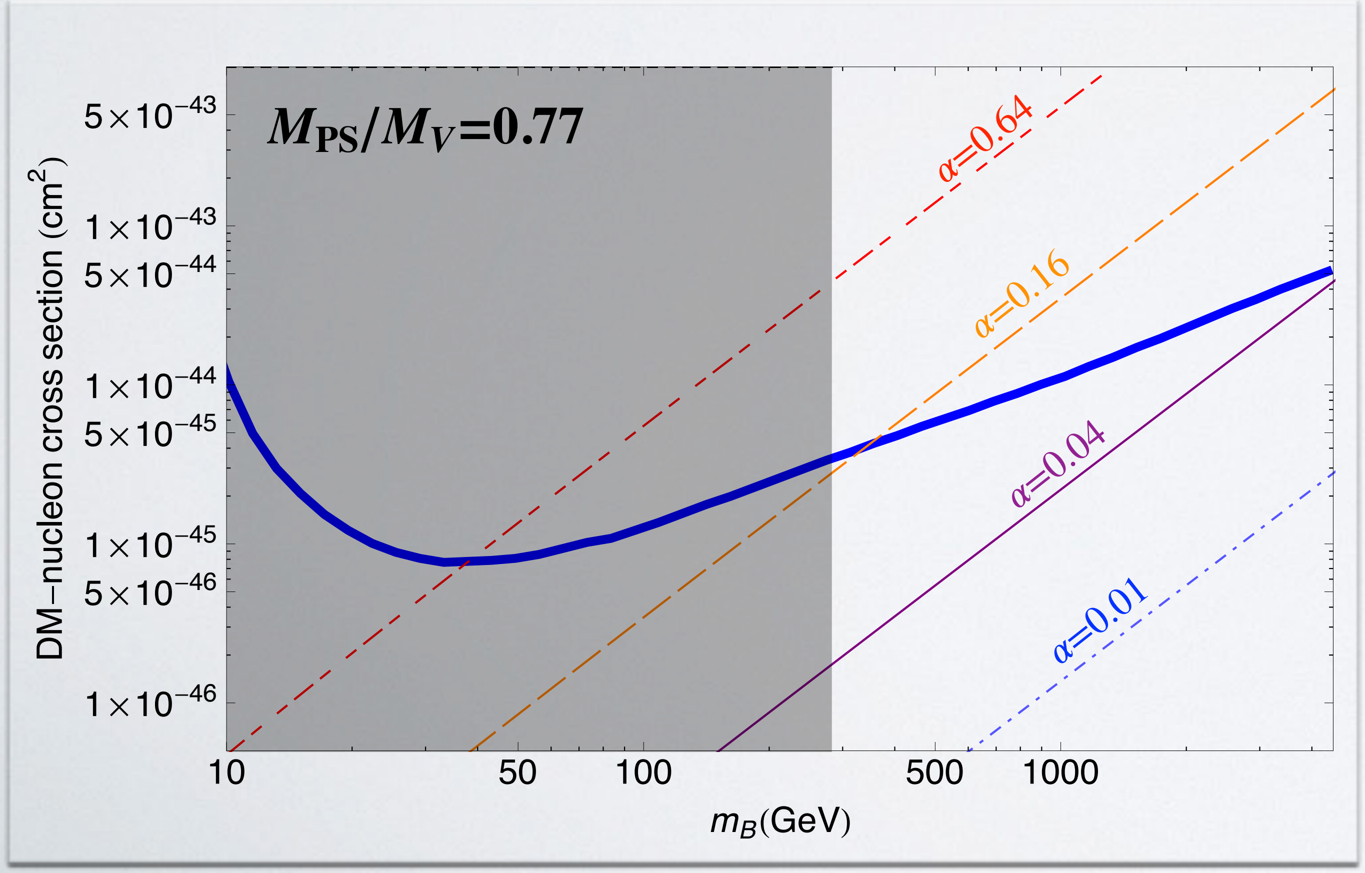


✦Lattice results for the cross-section are compared to **experimental** bounds

✦Coupling space in specific models can be vastly constrained

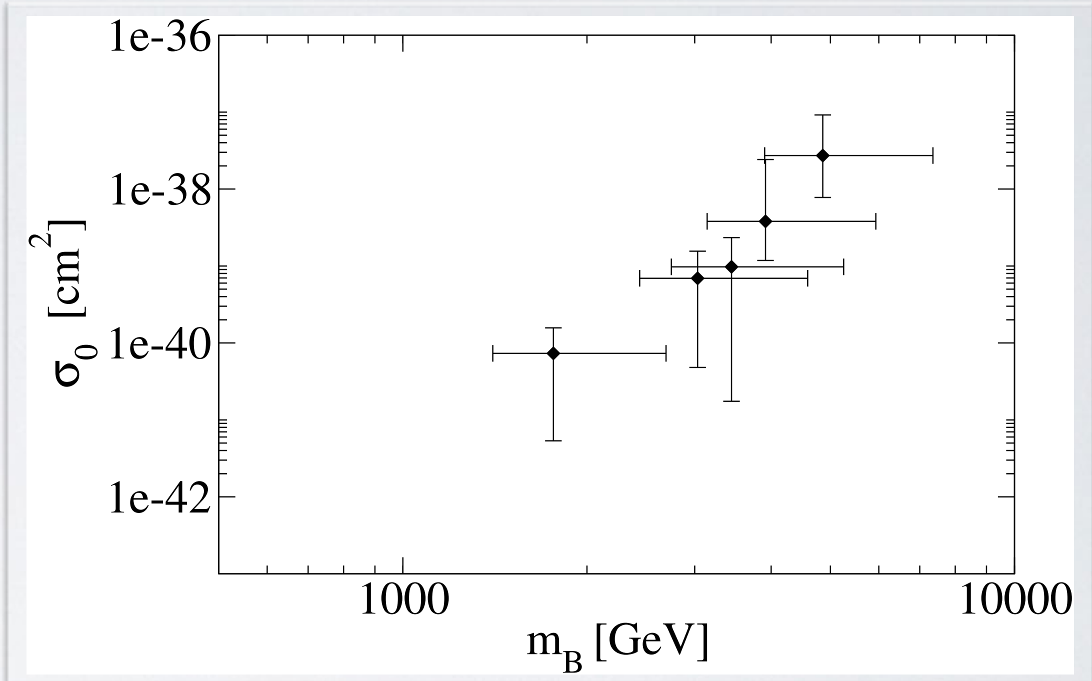
SU(4) N_f=4 Stealth DM

[LSD, 1402.6656-1503.04203]



SU(3) N_f=8 “technibaryon”

[LatKMI, 1510.07373]

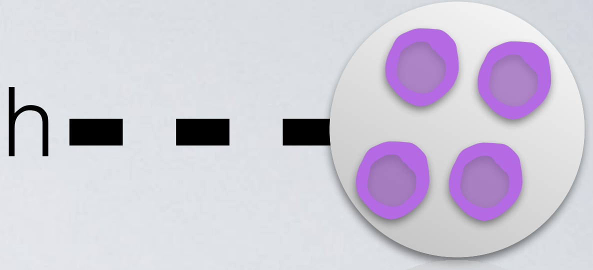


✦Some candidates can be excluded as dominant sources of dark matter

✦There is lattice evidence for universality of dark scalar form factors

[DeGrand et al., 1501.05665]

Bounds from Higgs exchange



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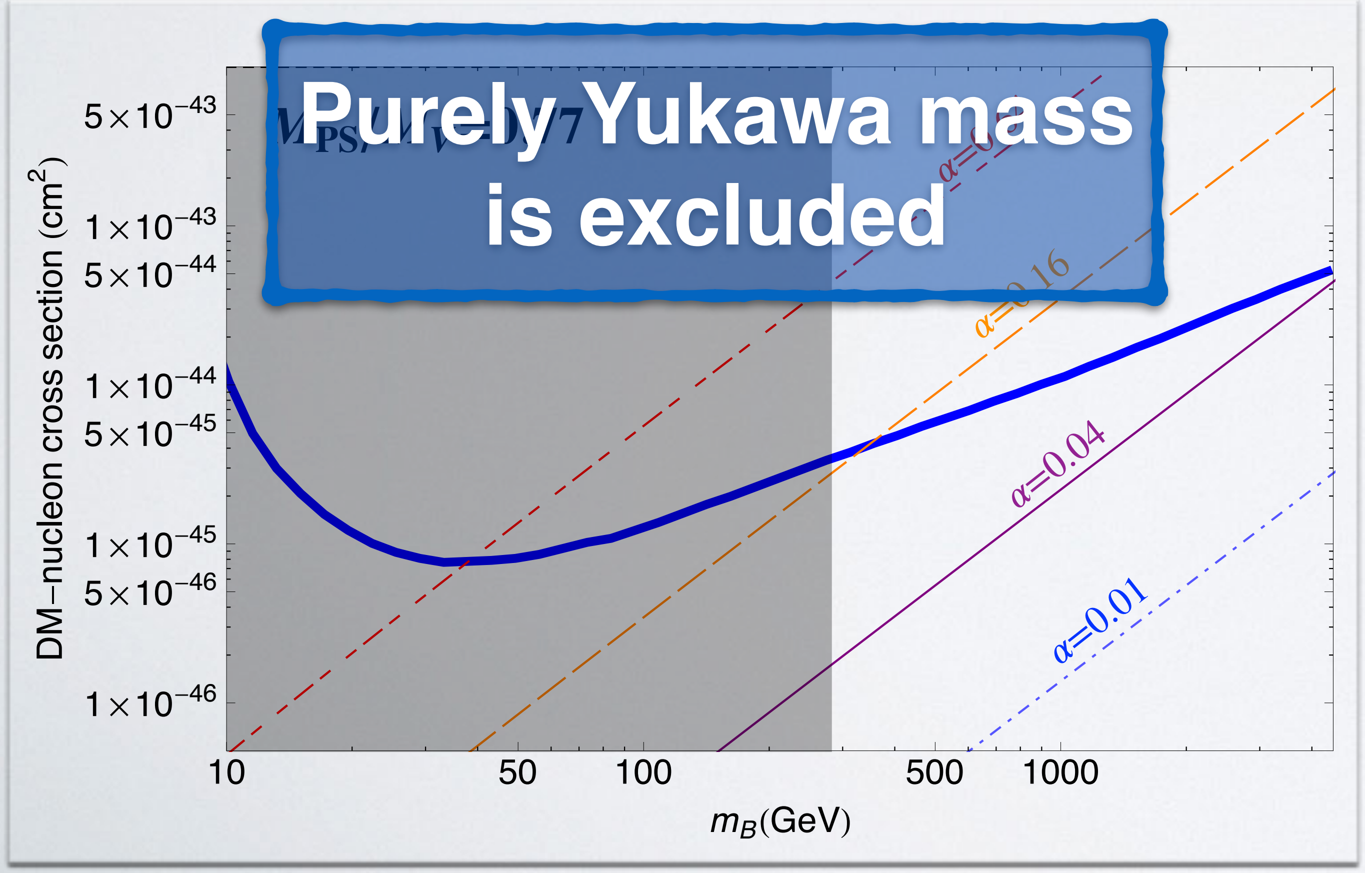

Purely Yukawa mass is excluded

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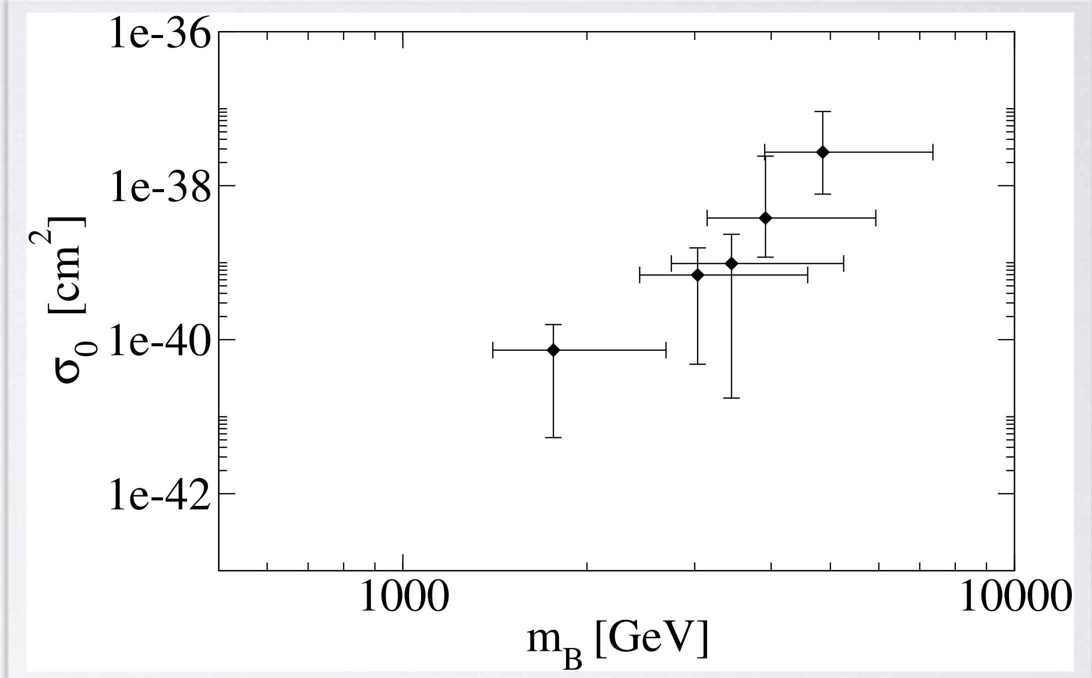

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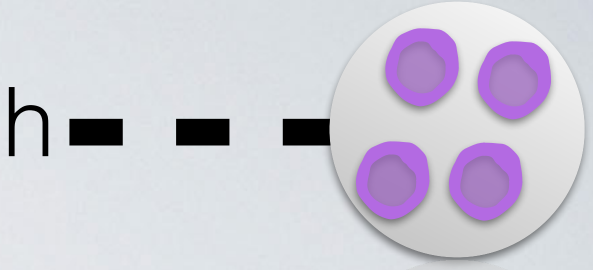

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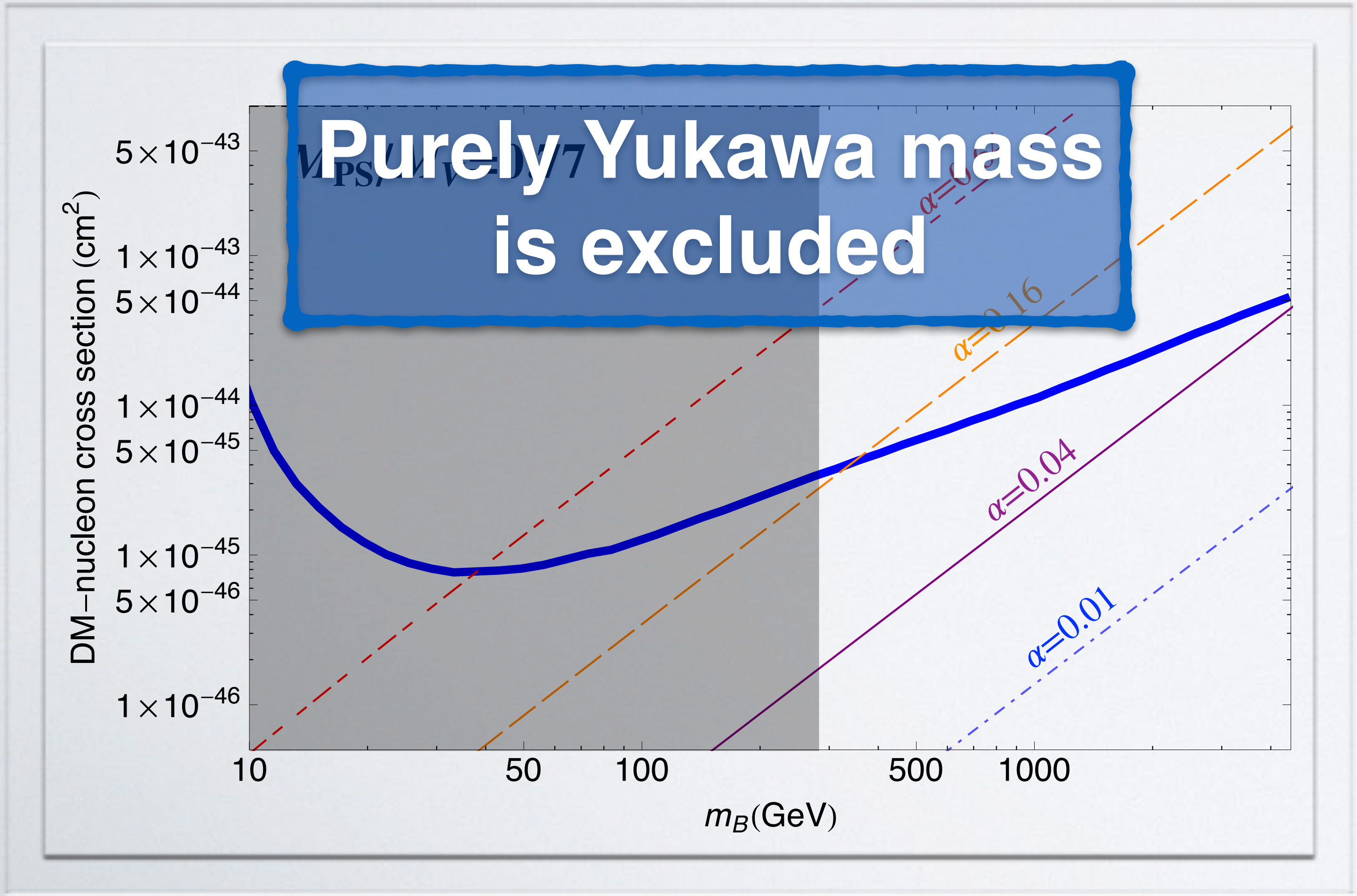

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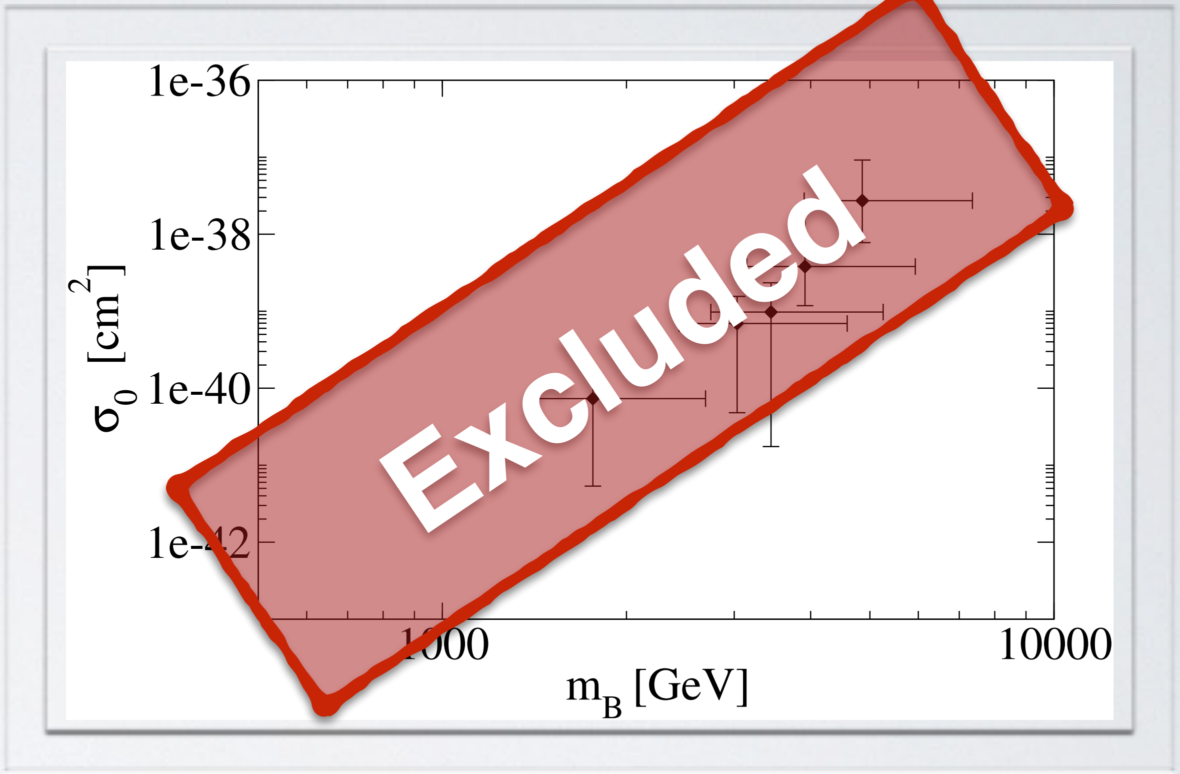

Excluded

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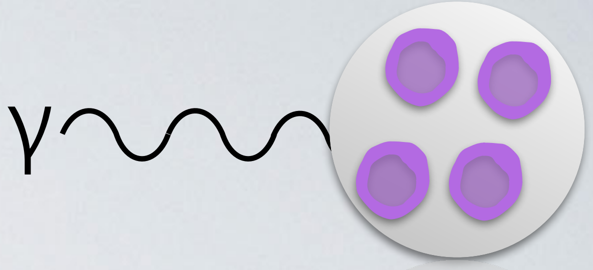
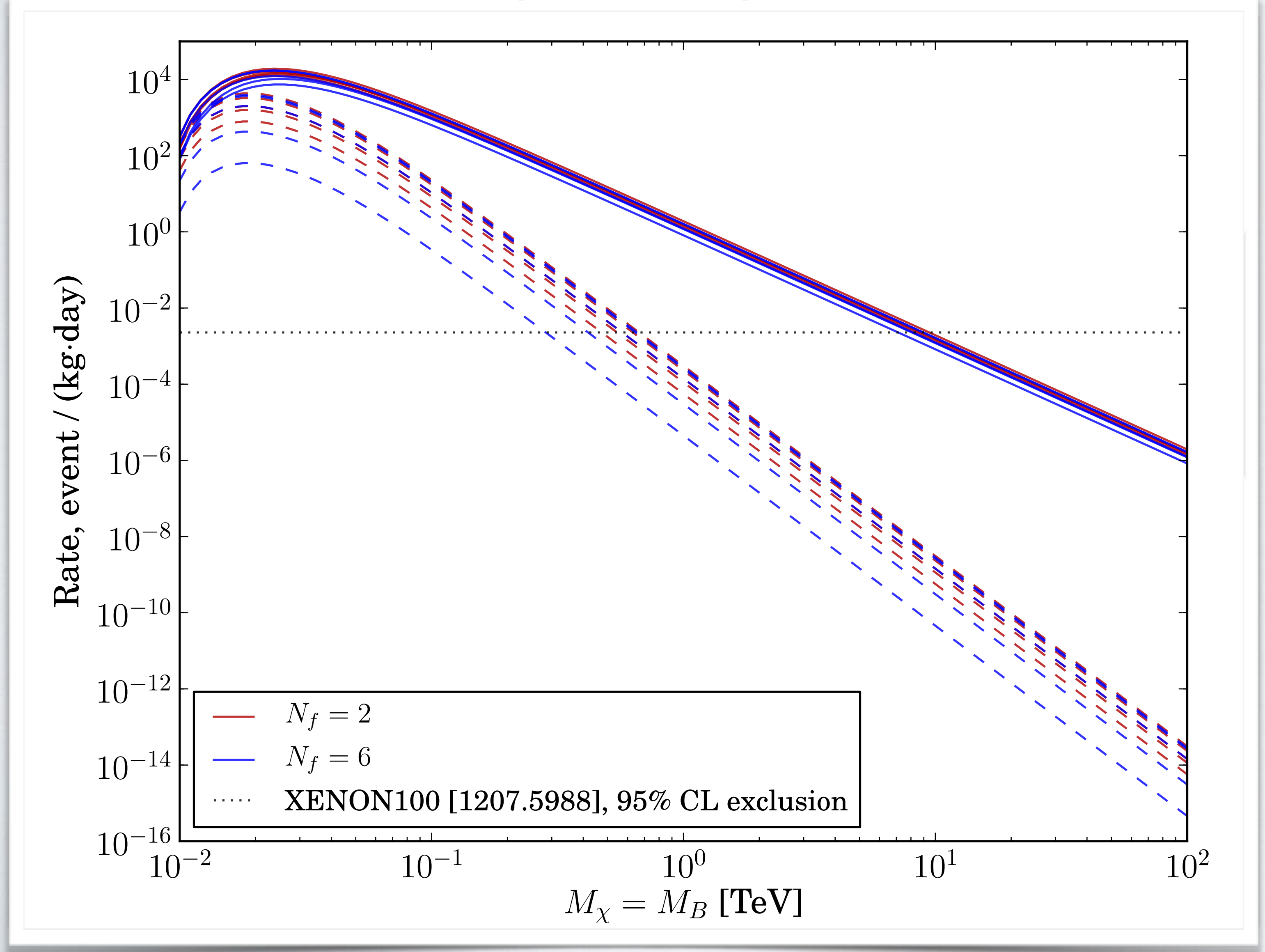
Bounds from EM moments



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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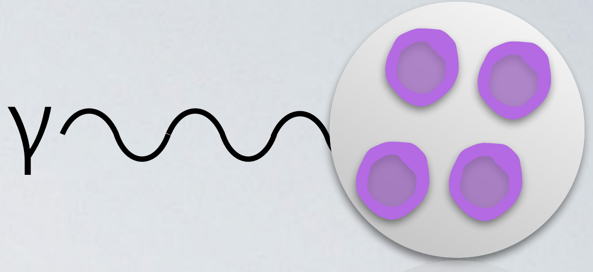

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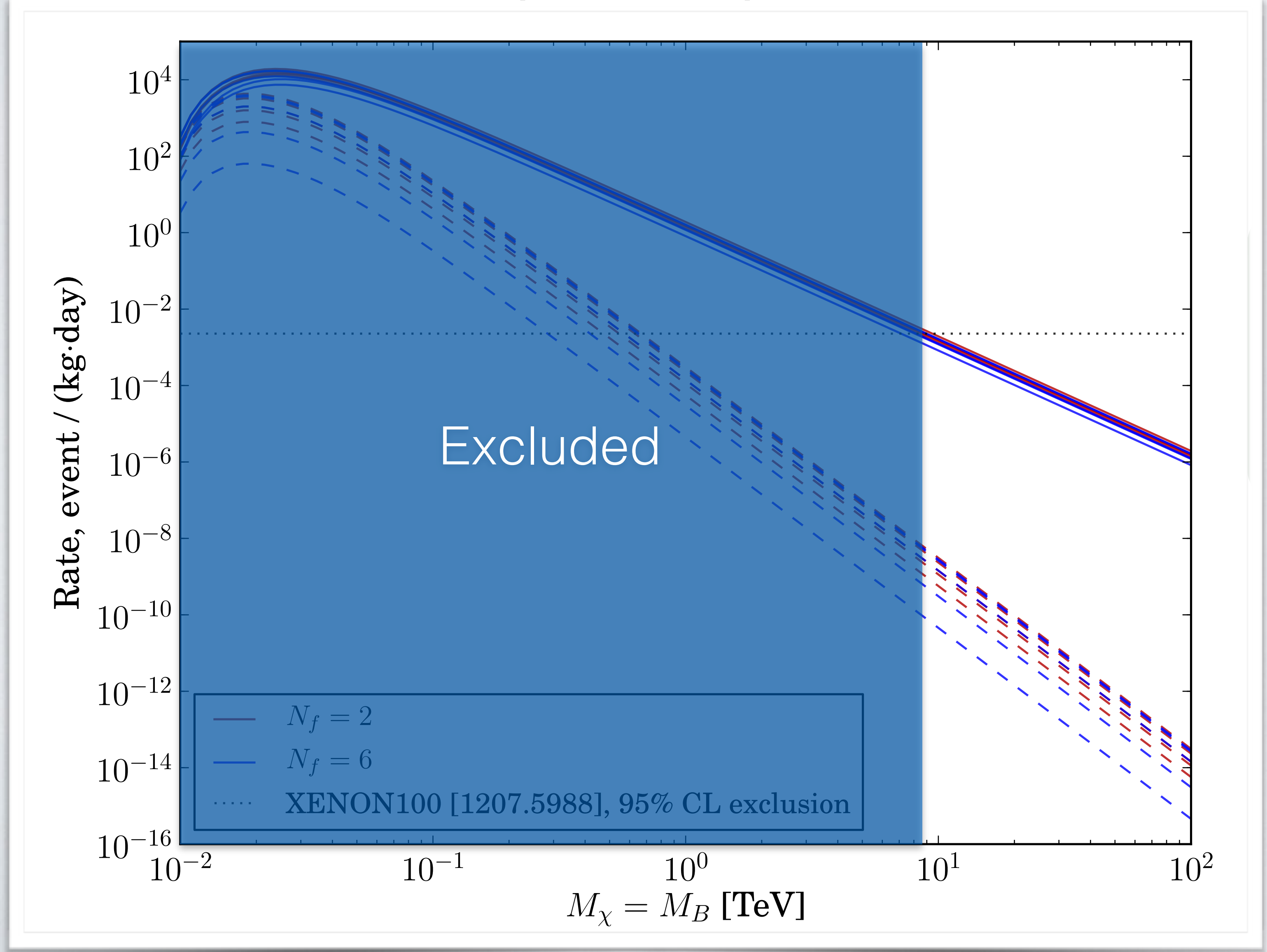

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M_B > 10 TeV

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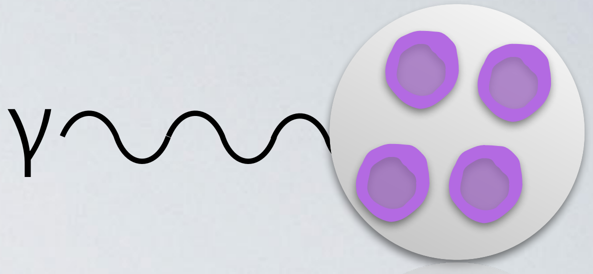

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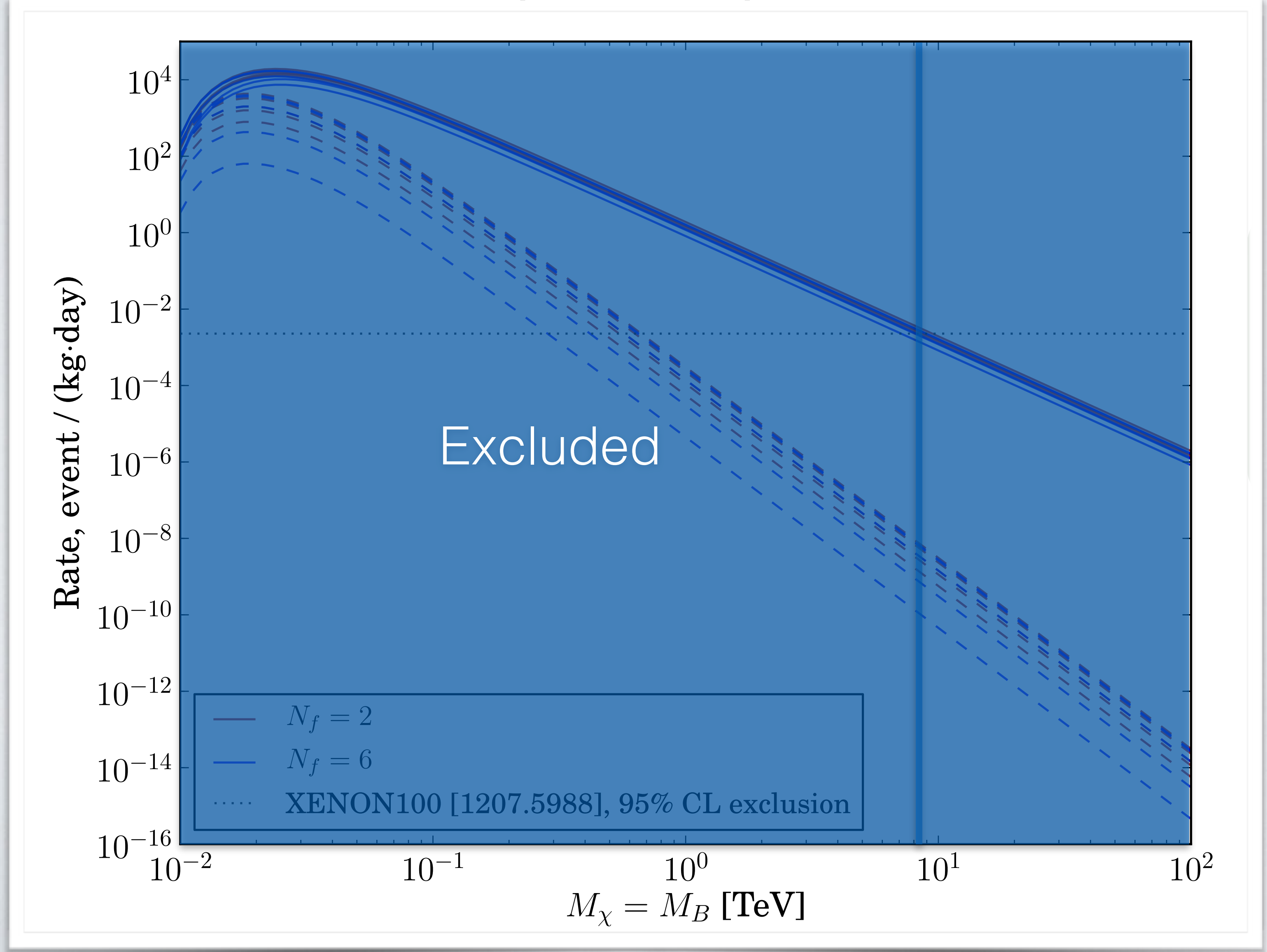

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pushed to >100 TeV with new LUX