Stealth Composite Dark Matter

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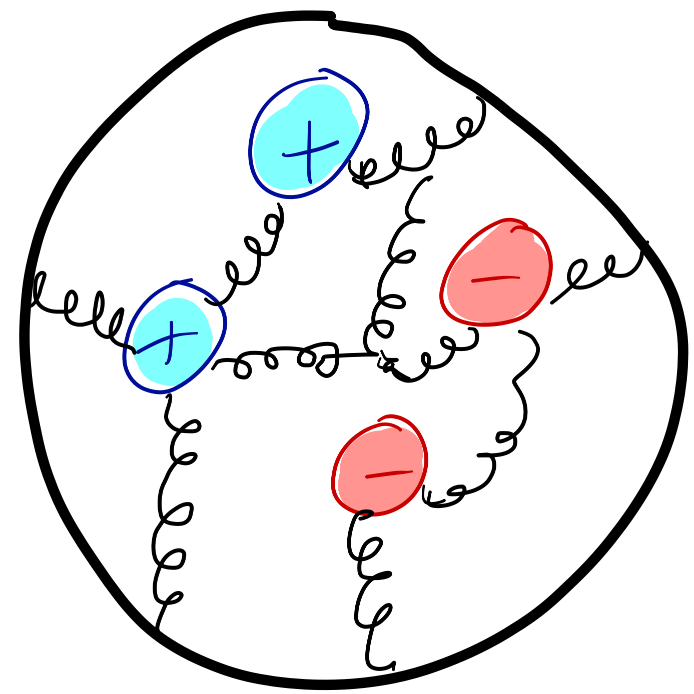
Stealth Dark Matter is a new model of DM

- Dark matter candidate is a “dark baryon” of an SU(4) gauge theory, with constituent fermions carrying electroweak charges

- Fermion mass is of order the confinement scale. No effective analytic methods - use lattice to fill in the gaps!



- Discrete exchange symmetry eliminates one-photon interactions with stealth DM; leading direct detection through dimension-7 EM polarizability or Higgs exchange

- Other signatures (collider especially) are worth exploring, we have some ideas

Outline

1. Motivation: the state of particle dark matter

2. Composite dark matter

3. A case study: stealth dark matter

4. Outlook

Lattice Strong Dynamics Collaboration

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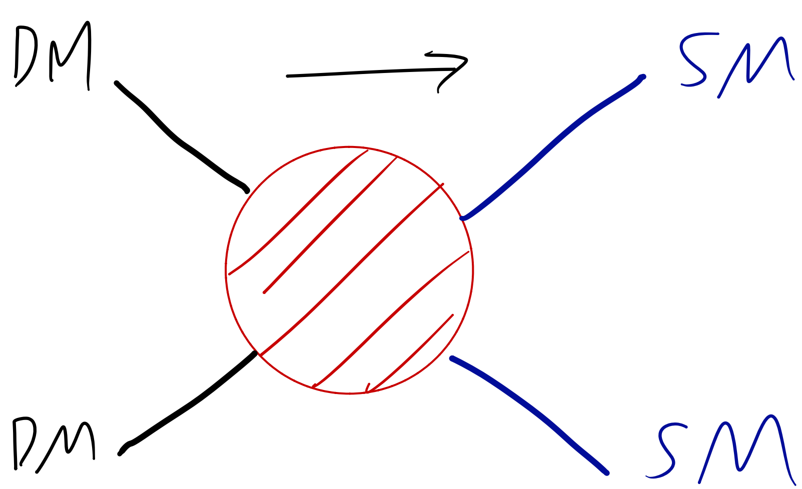
1. Motivation: particle dark matter

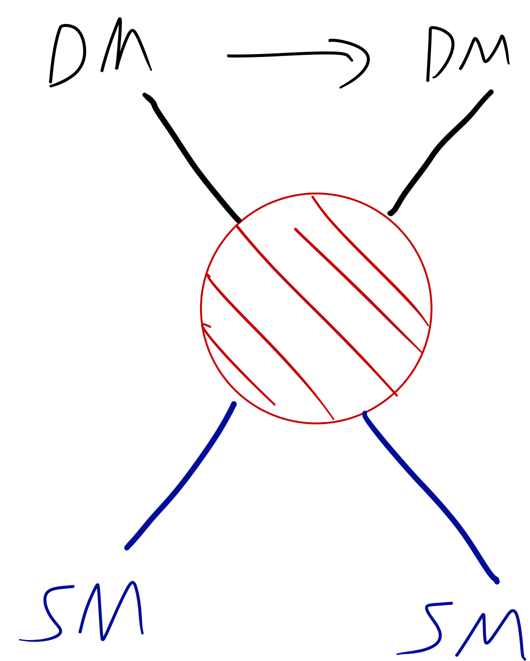
Particle dark matter: what do we know?

- Strongest evidence for dark matter (cosmology from CMB, lensing, large-scale structure) is all sensitive only to gravitational interactions

- However, interaction with ordinary matter is motivated by relic density coincidence (and by wanting to do experiments). Three ways to search in experiment, easy to picture through crossing symmetry:



"Indirect detection"



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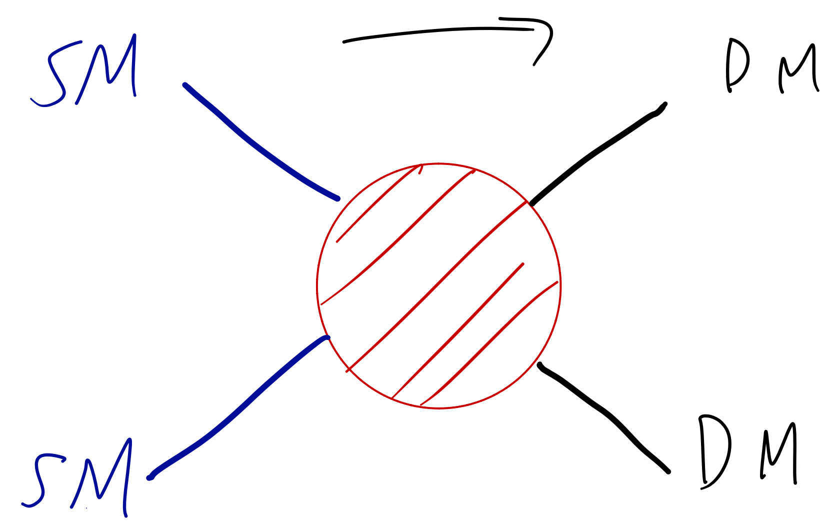
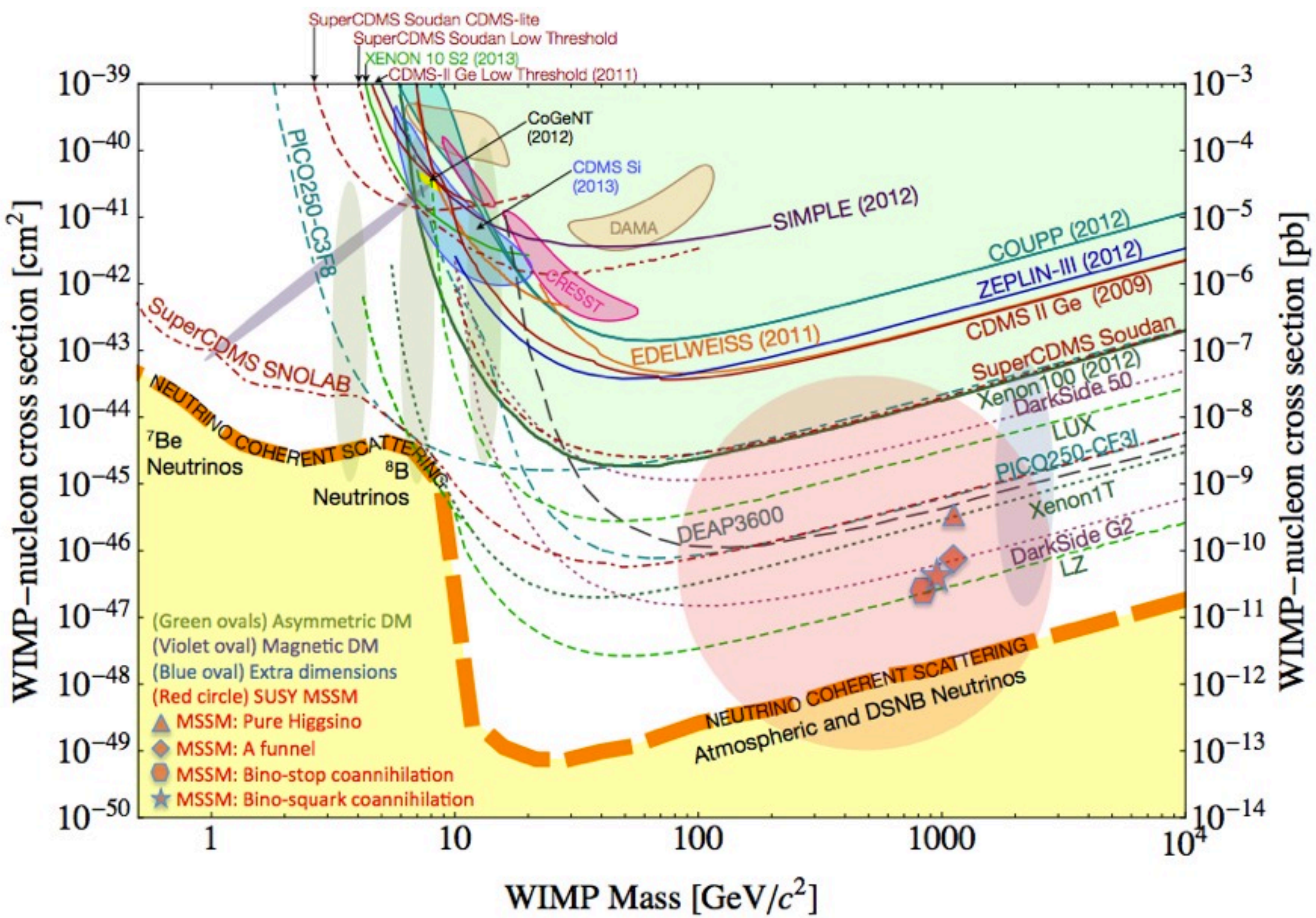


"Collider"

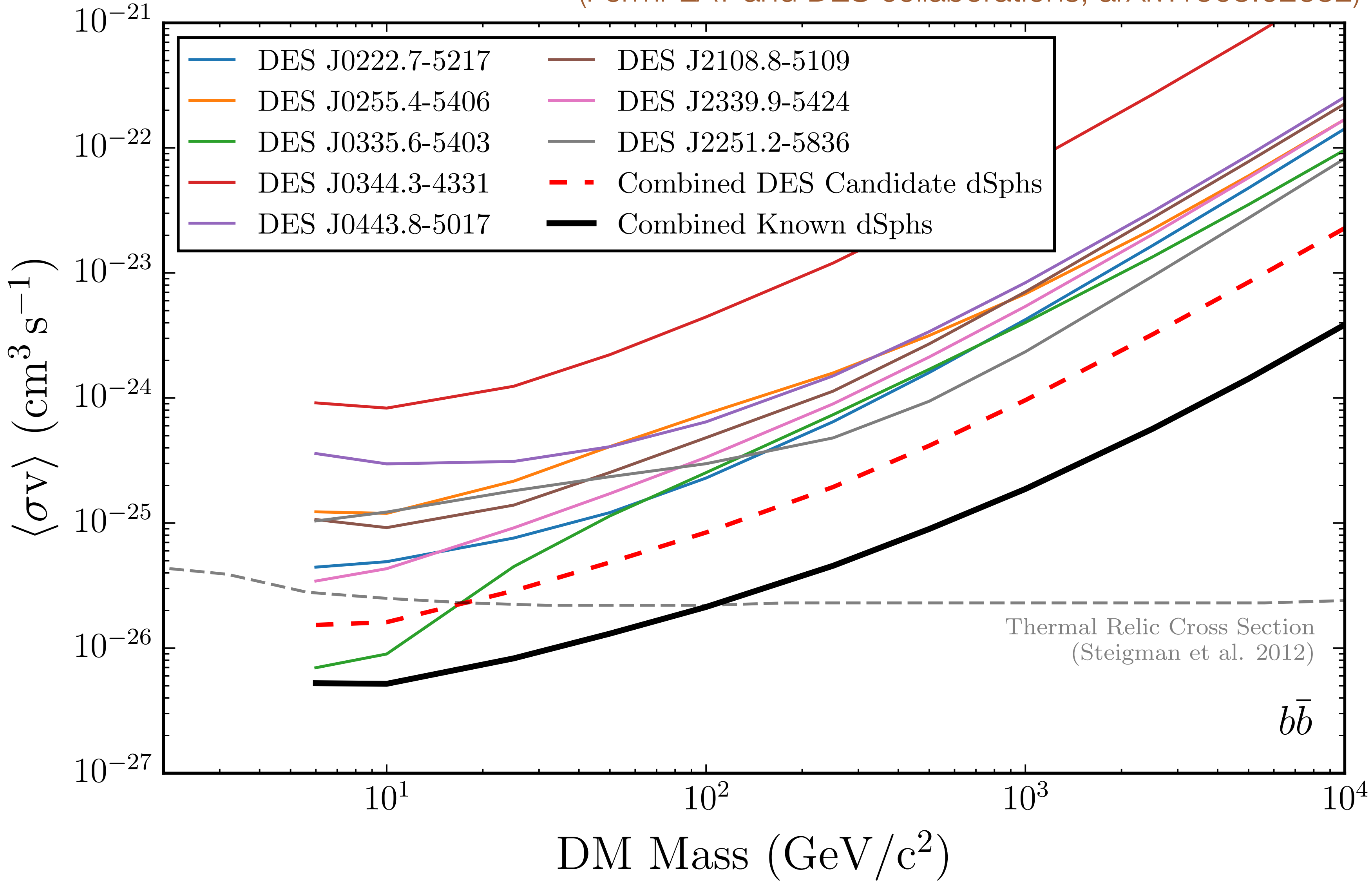
The picture* for direct detection



*assuming coherent, $f_p=f_n$ interaction (i.e. Higgs exchange)

The picture* for indirect detection

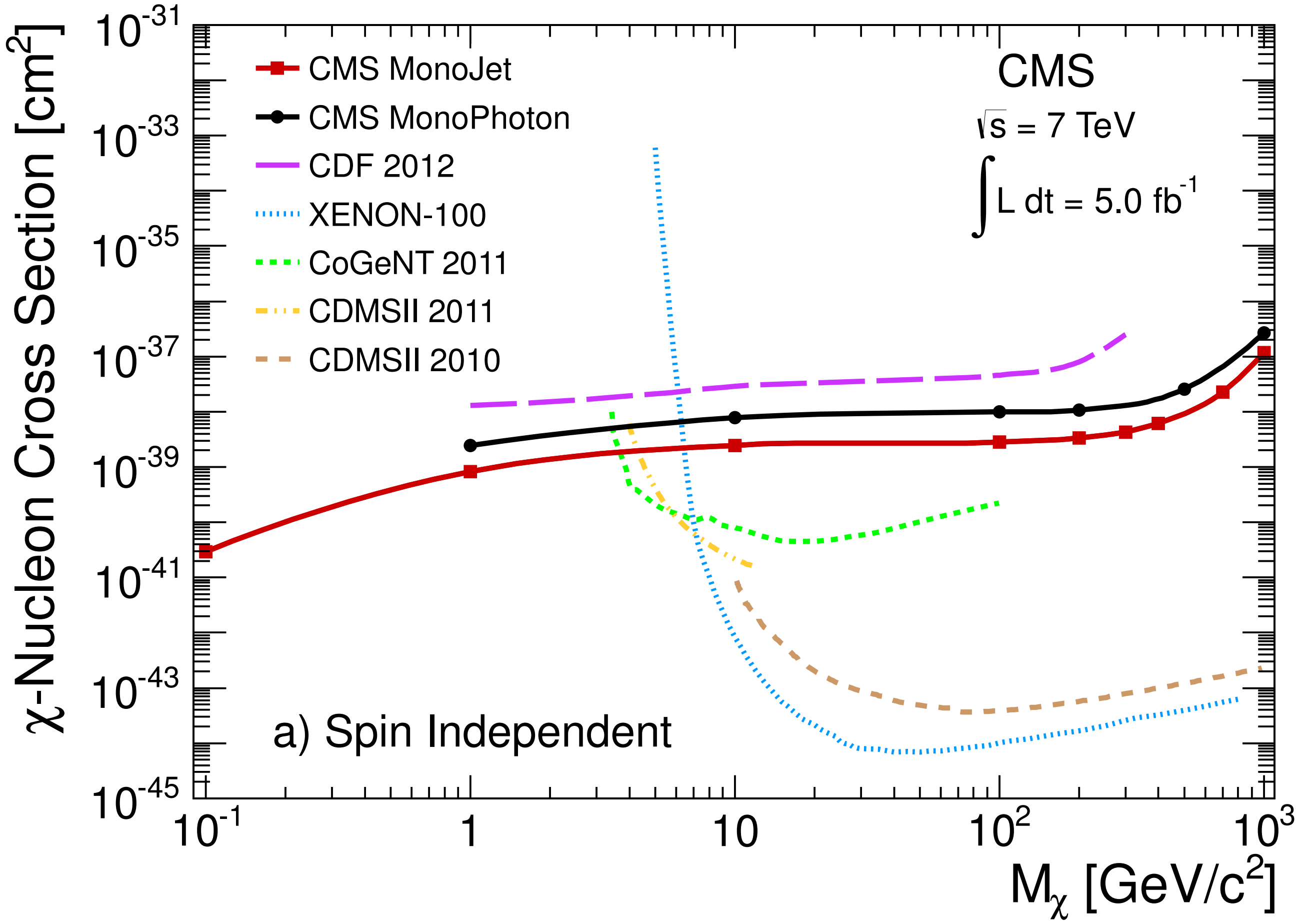
(Fermi-LAT and DES collaborations, arXiv:1503.02632)

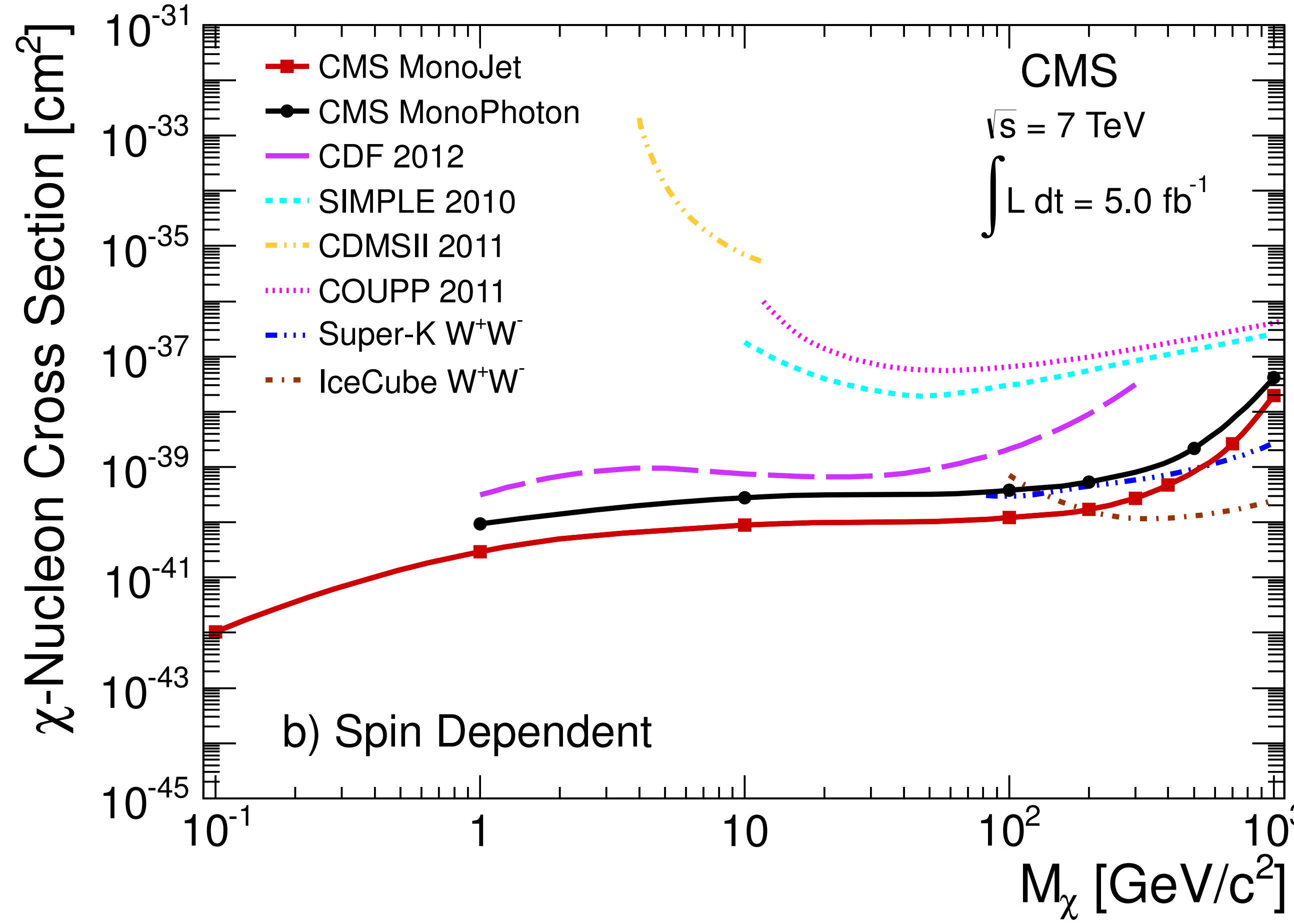


*assuming the same 2->2 process dominates both relic density and present-day DM annihilation

The picture* for collider bounds

(arXiv:1206.5663)





*assuming MET is the best way to probe the dark sector

Beyond the usual pictures

- There are a few particularly interesting properties that are worth looking for in the space of dark matter models:
  - Non-standard scaling of nuclear couplings *(reconcile direct-detection discrepancies, or suggest novel signatures)*
  - Direct coupling to SM for relic density, but suppressed today *(reconcile indirect-detection results with a thermal relic)*
  - Novel collider signatures *(are there interesting collider searches that we're overlooking?)*
  - Strongly self-interacting *(explain galactic structure anomalies?)*

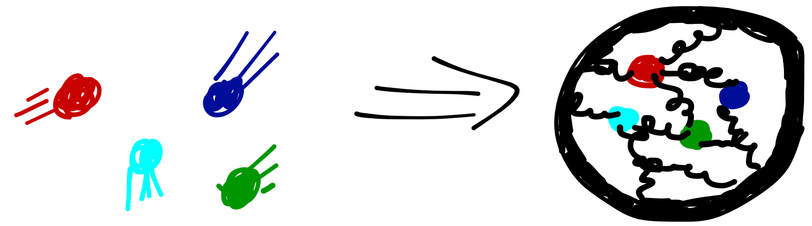
- Composite dark matter can exhibit all of these properties!

2. Composite dark matter

(a) Stability and relic density

Strongly-coupled composite dark matter

- Focus on composite DM as a strongly-bound state of some more fundamental objects (think of the neutron)

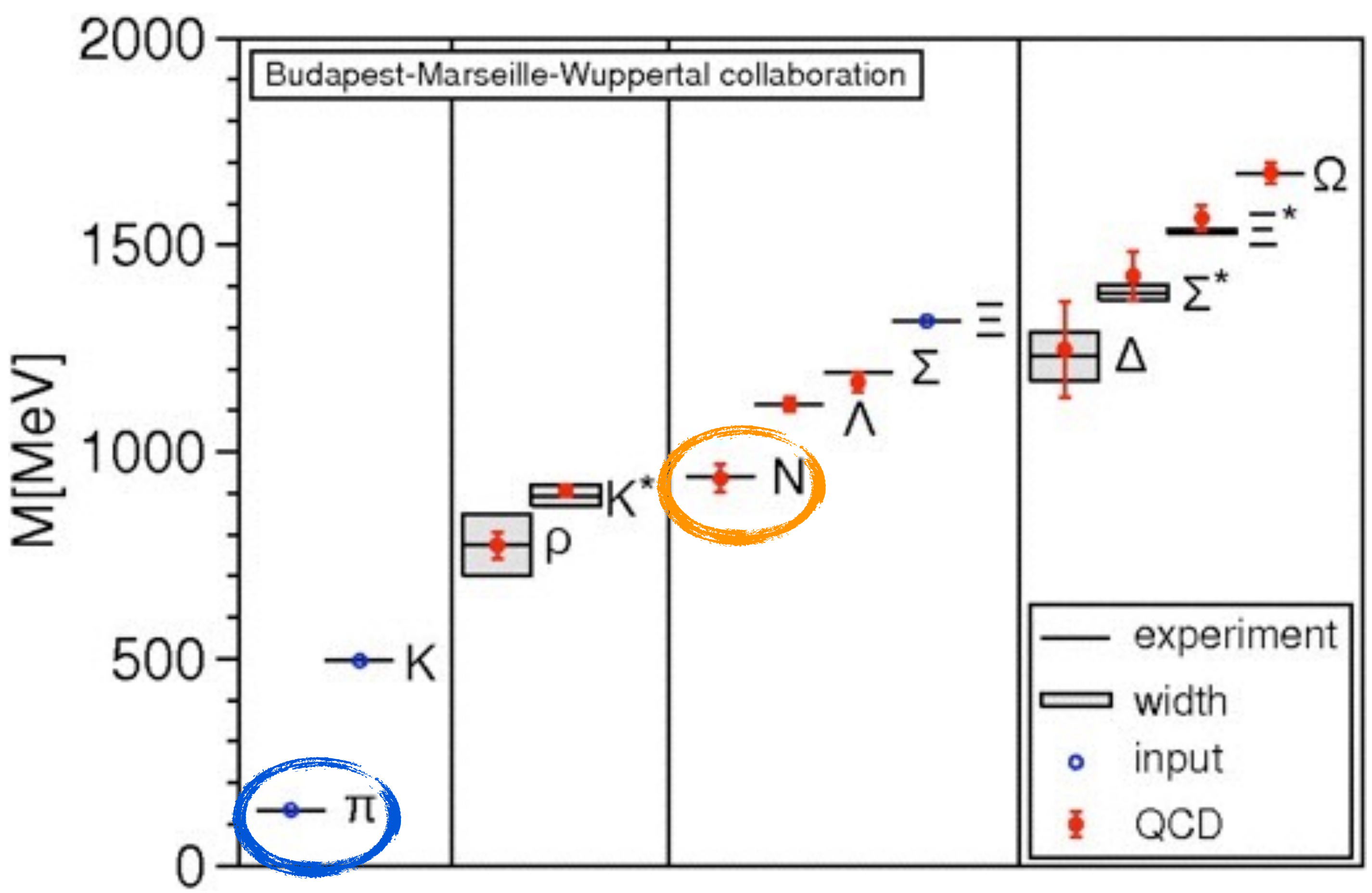


- Dark-sector fundamental fermions can carry SM charges, giving charged excited states active in early universe.

- Composite DM relic interacts via SM particles (**photon**, **Higgs**) but with form factor suppression!

- Here I take **SU(N)** gauge theory w/**fundamental** rep. fermions; not the most general possibility, but a well-motivated and familiar starting point

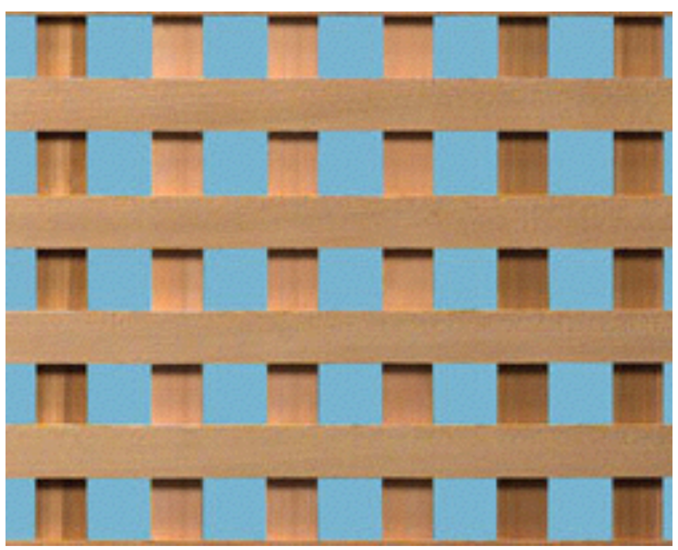
Composite dark sector spectrum



- QCD spectrum gives us a rough idea of what to expect: lightest mesons Π, baryons, lots of excited states
- DM candidate must be neutral, but many of these states can be charged under the SM! Many implications…
- Note: we know the QCD spectrum from experiment, but this plot is from lattice, which we can apply to more general theories! I'll frequently use lattice results from here on.

Lattice field theory, in one slide

$$\langle \mathcal{O} \rangle = \frac{1}{\mathcal{Z}} \int \mathcal{D}U \mathcal{D}\overline{\psi} \mathcal{D}\psi \; \mathcal{O}(U, \overline{\psi}, \psi) \exp\left(-S[U, \overline{\psi}, \psi]\right)$$



$$\langle \mathcal{O} \rangle = \frac{1}{N} \sum_{U \in \mathcal{U}} \langle \mathcal{O} \rangle_U$$

- Start with the path integral (formal, non-perturbative, generally intractable!)
- Discretize to make the integral finite-dimensional so we can evaluate numerically
- Importance sampling and Monte Carlo numerical evaluation to give us an ensemble of field configurations with weight exp(-S)
- Main advantages: non-perturbative and broad (can investigate many observables on one weighted ensemble)

(nice discussion here: arXiv:1503.08749)

*M. Buckley and EN, arXiv:1209.6054

**Y. Bai and R. Hill, arXiv:1005.0008

Stability of composite dark matter candidates

$$\Pi \sim \bar{\Psi}\Psi \qquad B \sim \Psi\Psi\ldots\Psi$$

$\longleftarrow$ N_D constituents

- Lightest mesons (Π) can be stabilized by flavor symmetries* or G-parity**, but then one has to argue against the presence of dimension-5 operators like

$$\frac{1}{\Lambda}\bar{\Psi}\Psi H^\dagger H \longrightarrow$$ instability over lifetime of the universe.

- Accidental dark baryon number symmetry provides automatic stability for B on very long timescales (as long as N_D > 2!) E.g. for N_D=4, decay through dimension-8(!)

$$\frac{1}{\Lambda^4}\Psi\Psi\Psi\Psi H^\dagger H$$

Relic density I: asymmetric origin

- Basic mechanism recognized in original technicolor DM papers (Nussinov ’85, Barr, Chivukula and Farhi ‘90)

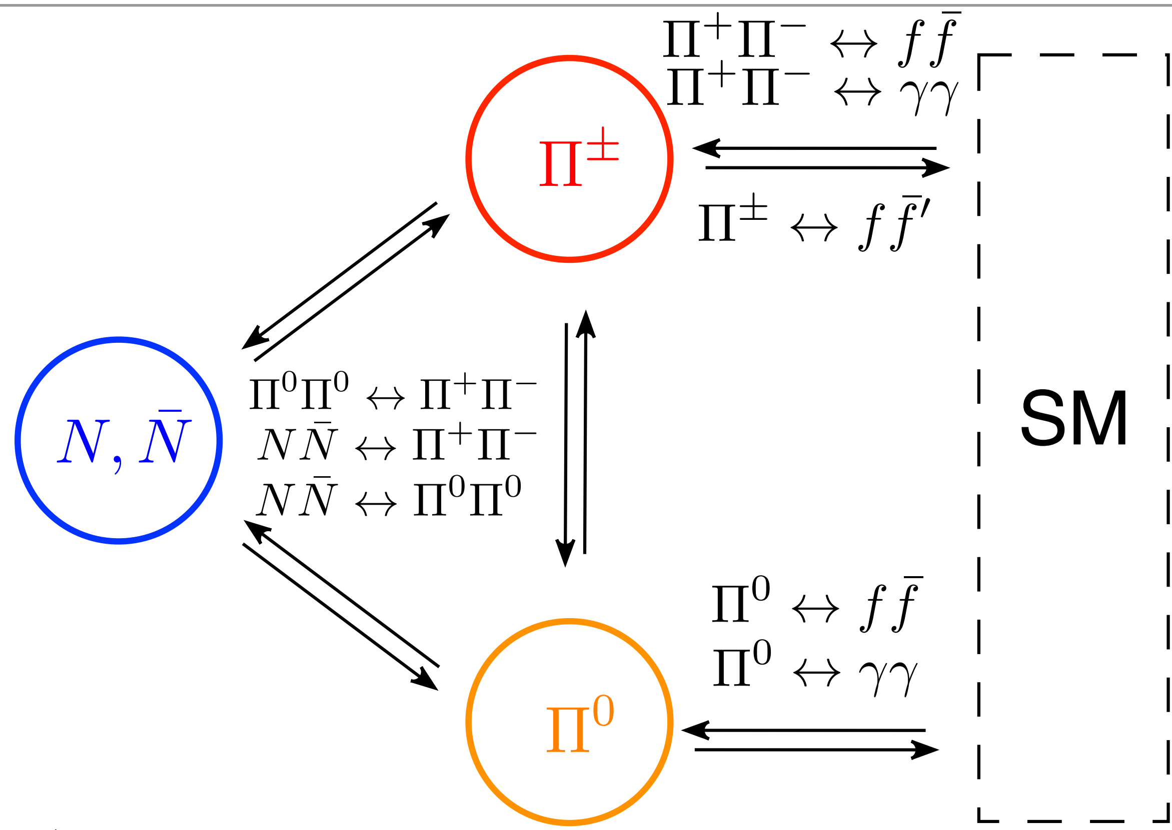
- Electroweak sphaleron equilibrates primordial asymmetries in baryon, lepton, and dark baryon number:

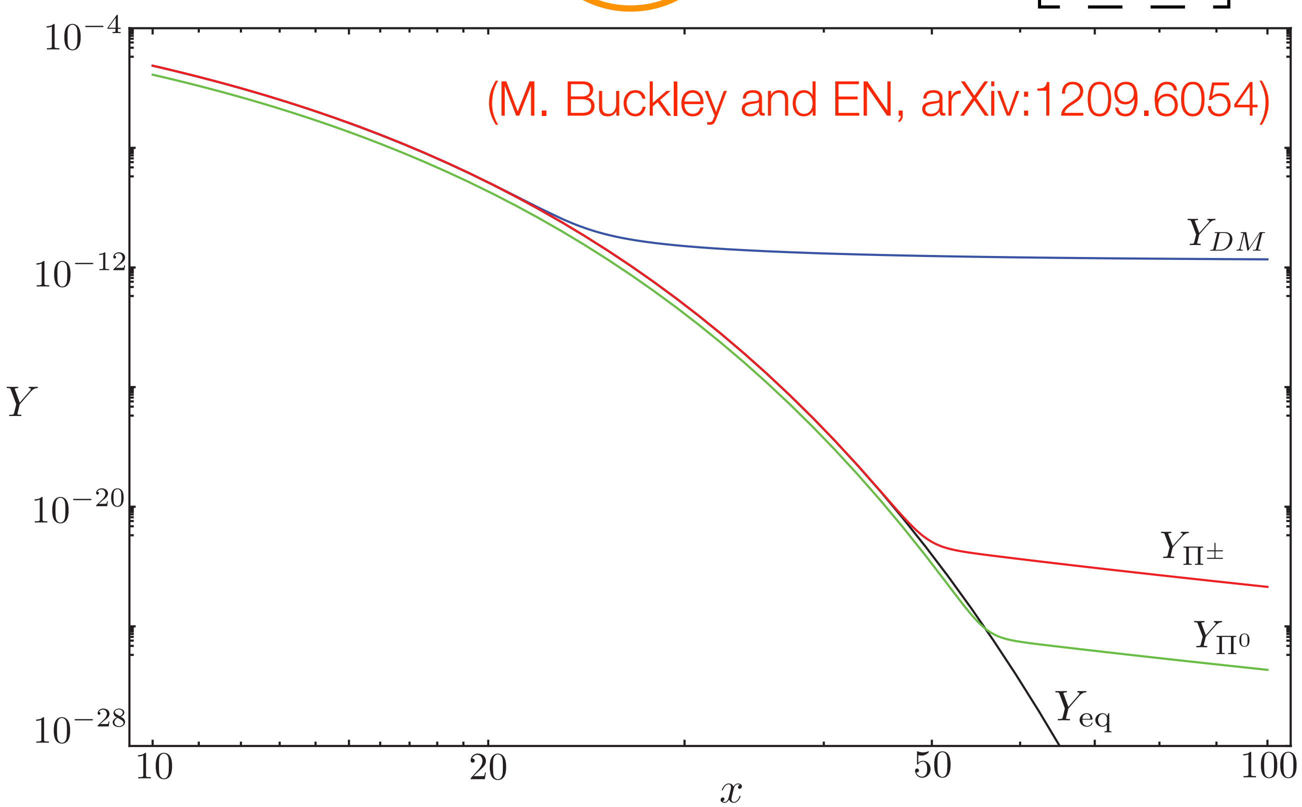
$$n_B - n_{\bar{B}} \simeq n_L - n_{\bar{L}} \simeq n_D - n_{\bar{D}}$$

- This condition would give us DM mass of O(GeV), but technibaryons are massive relative to T_{sph}, which exponentially depletes them; in early technicolor models, masses of O(TeV) give the correct abundance

- The story seems more complicated for composite DM models with vector-like mass terms, and/or extra EW-charged states which can alter the sphaleron temperature…

Relic density II: thermal origin



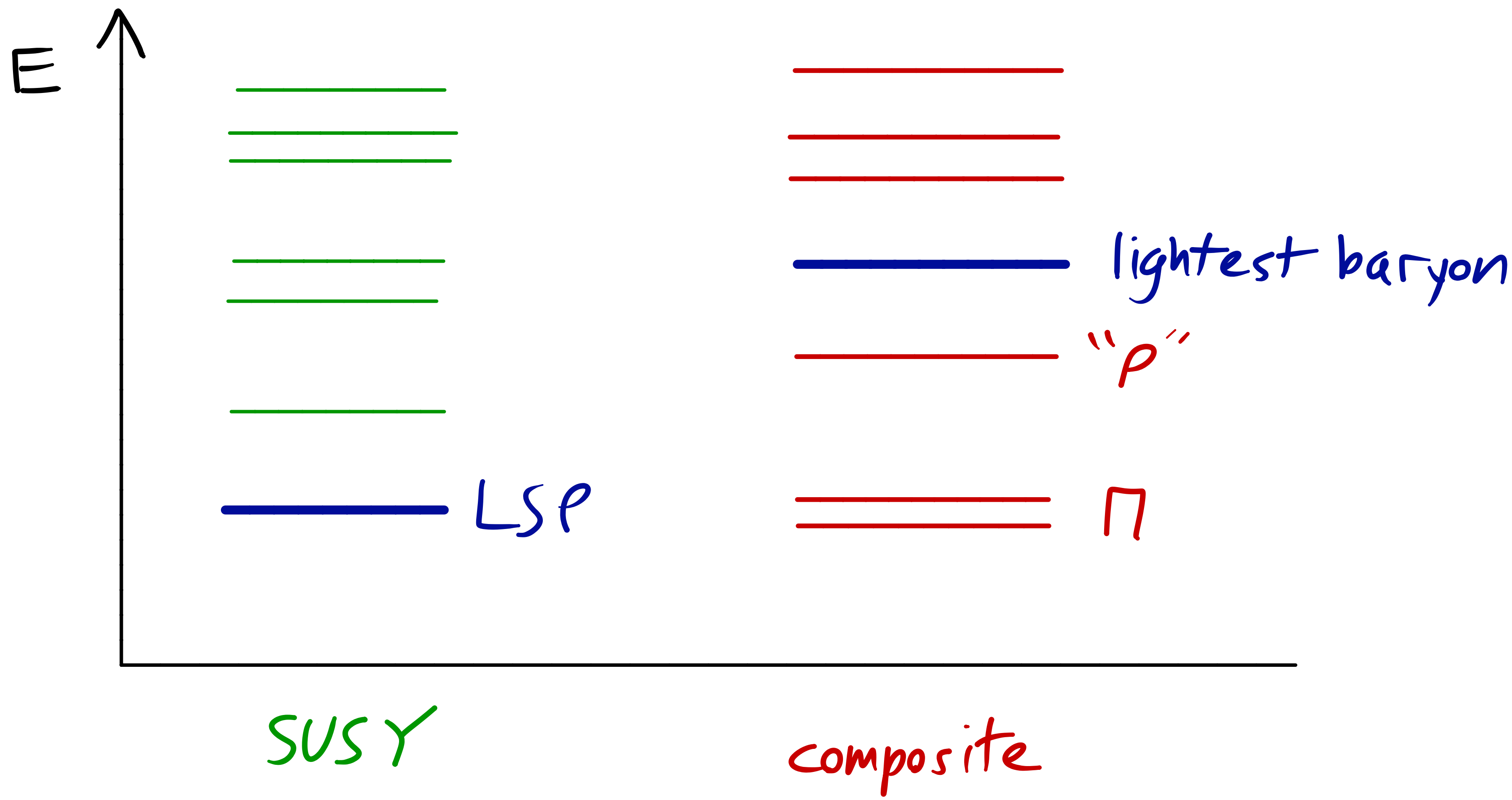


- Basic picture: charged states interact strongly with SM thermal bath, so dark matter freeze-out is set by DM annihilation cross-section
- If all states are PNGBs, then the resulting DM mass can be small (as in SU(2) example to the left).
- For dark baryons, dimensional analysis or partial-wave unitarity give M~100 TeV (assuming 2->2); however, 2—>N processes might dominate at low temperatures…

2. Composite dark matter

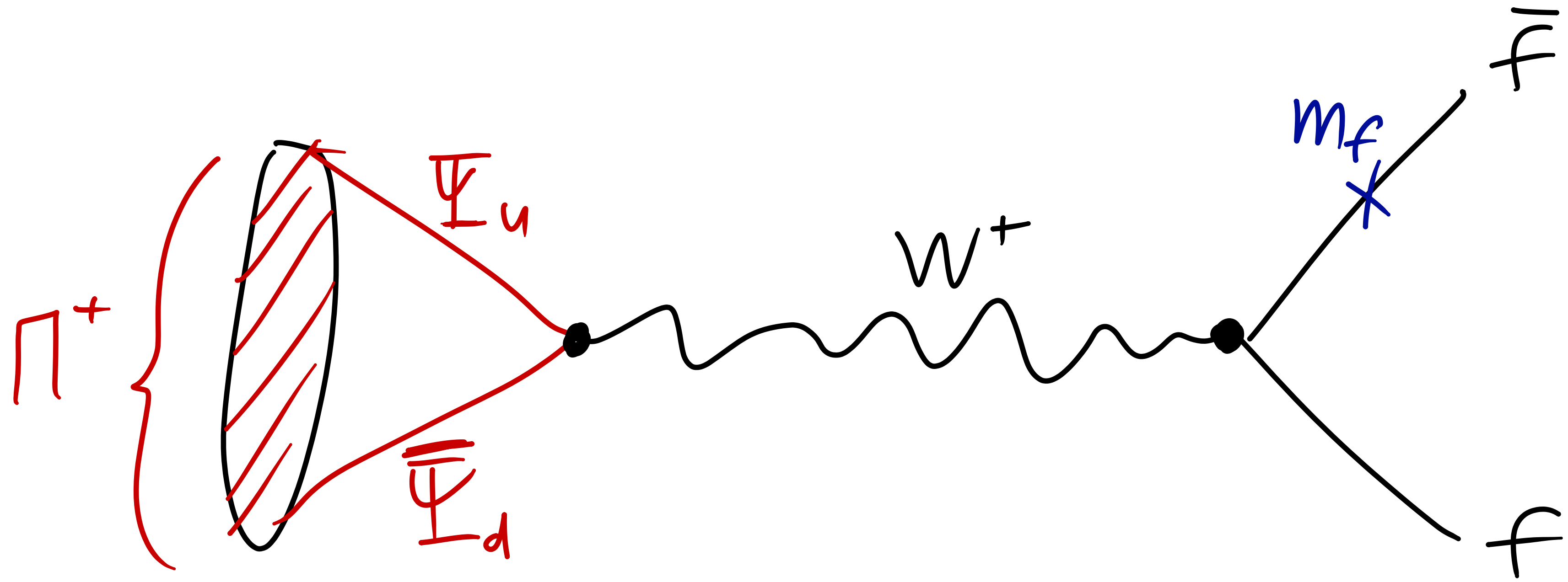
(b) Collider searches

Collider searches: SUSY DM vs. dark baryons



- The lightest neutral baryon (DM candidate) is **not** the lightest particle in the new sector! Much harder to produce directly in colliders, so MET signals are greatly suppressed. Search for light, charged mesons instead?

Fermionic decay of mesons



$$\langle 0 | j^{\mu}_{\mathrm{axial}} | \Pi^{\pm} \rangle = i f_{\Pi} p^{\mu}$$

- Mass flip in final state, due to decay of pseudoscalar bound state (same for QCD pions.) Gives preferred decay to <u>heaviest</u> SM states:

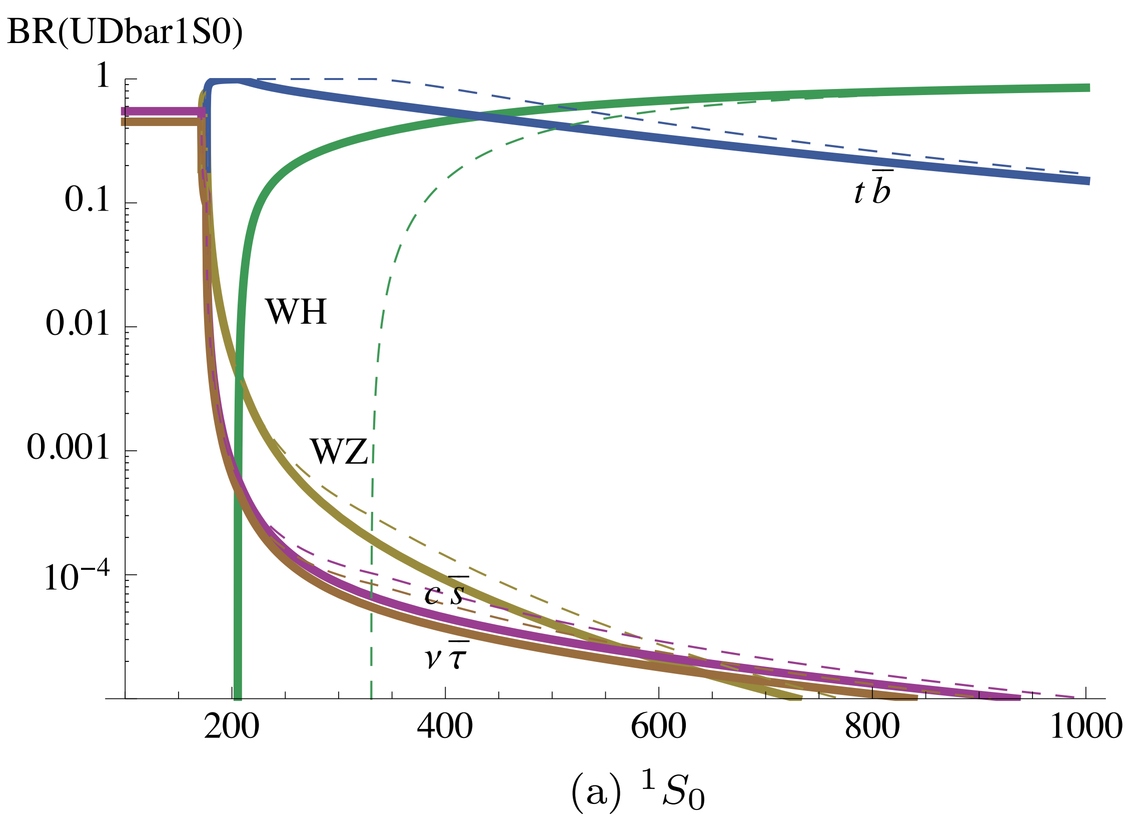
$$\Gamma(\Pi^+ \to f \overline{f}') = \frac{G_F^2}{4\pi} f_{\Pi}^2 m_f^2 m_{\Pi} c_{\mathrm{axial}}^2 \left(1 - \frac{m_f^2}{m_{\Pi}^2}\right)$$

- Robust bound from LEP stau searches, $M_{\Pi} \gtrsim 90$ GeV. At LHC, top-bottom resonance pair production may be a distinctive signature

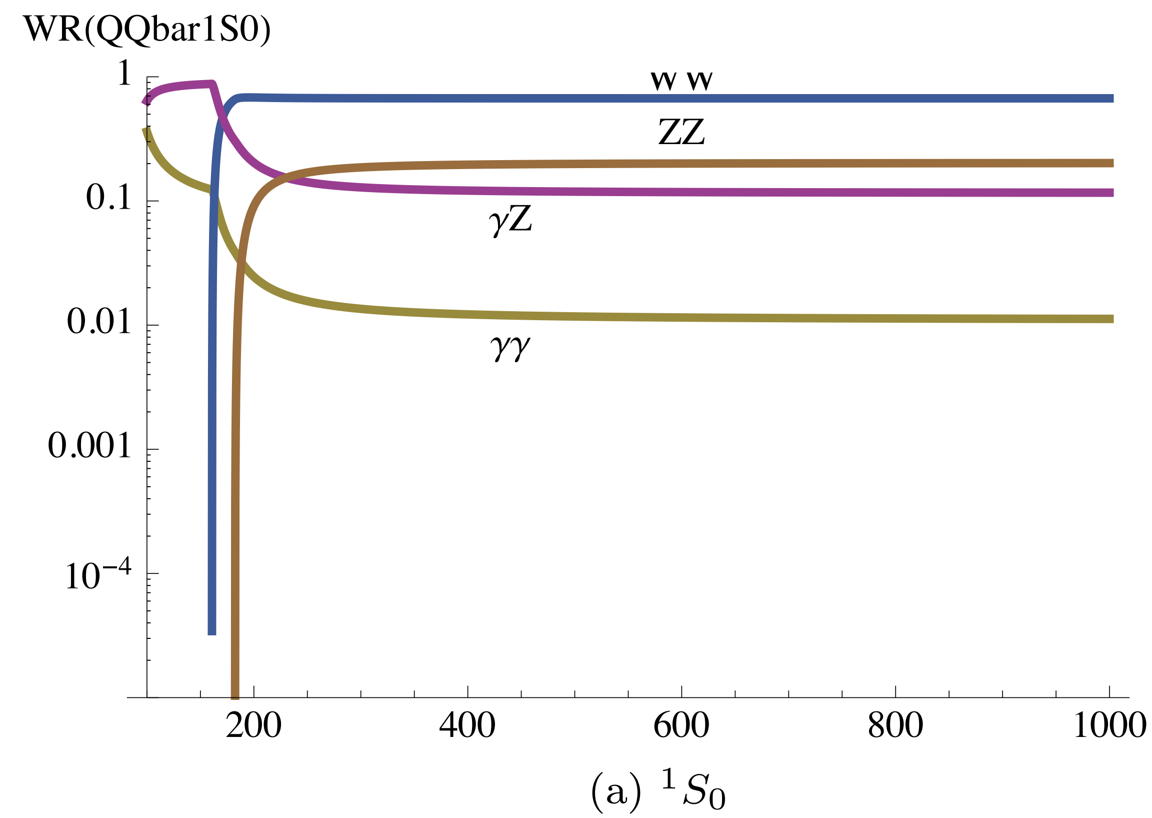
Meson Decay Rates

Fok, Kribs; 1106.3101

(Quirky) charged pion decay



(Vector-like) neutral meson decay



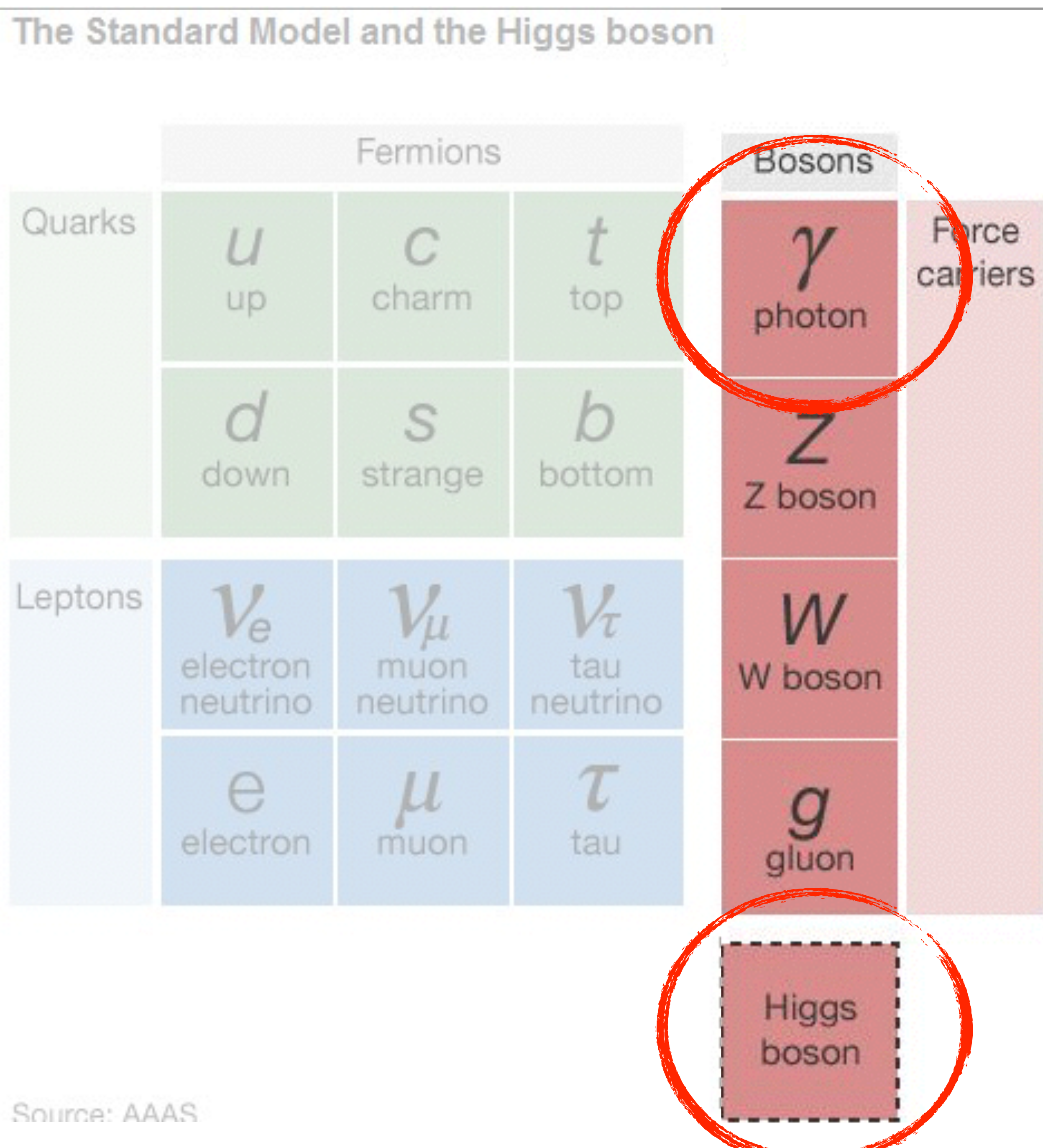
- Diboson decays generally occur too (may or may not be anomalous, depending on charge assignments)
- Whether diboson or fermionic decay modes dominate is likely model-dependent…

(slide from G. Kribs)

2. Composite dark matter

(c) Direct detection

Direct detection of composite DM



<u>focus on these</u>

suppressed relative to γ

probably not

interesting…*

<u>focus on these</u>

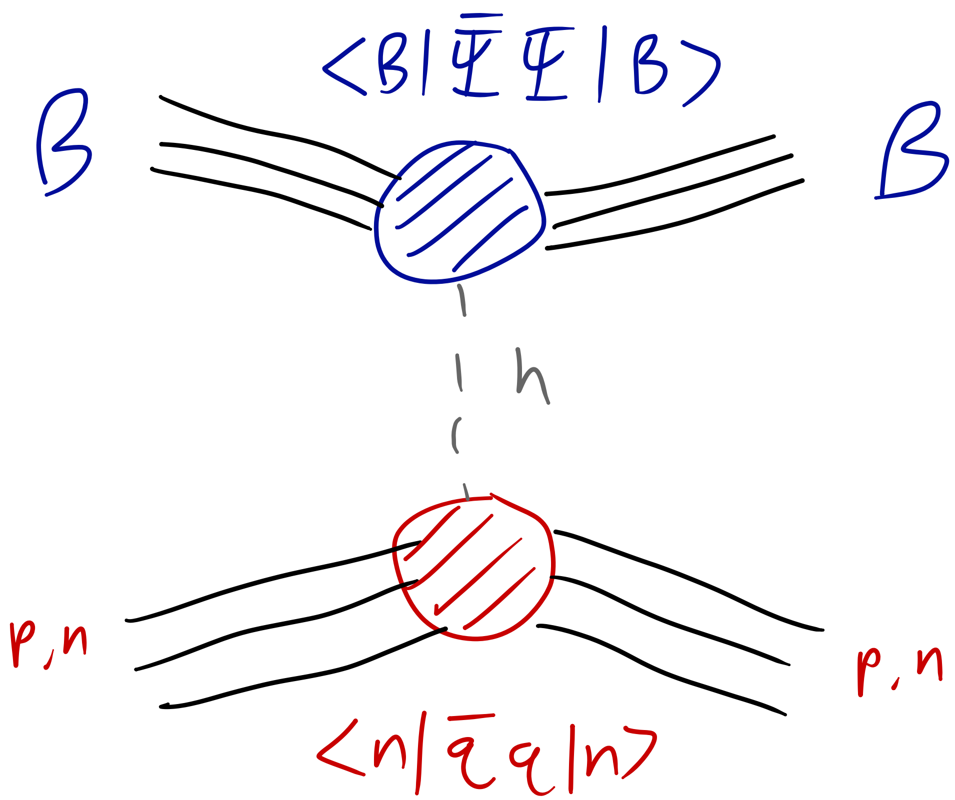
*Gluonic operators considered before in Bagnasco, Dine, Thomas **PLB 320 (1994) 99-104**. Similar to photon operators, but stronger bounds…could use an update! See also Godbole, Mendiratta, Tait (arXiv:**1506.01408**) for a simplified model.

Direct detection: Higgs exchange

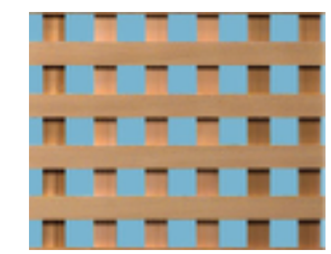
- If the dark-sector fermions couple to Higgs, then they will induce a dark baryon-Higgs coupling (sigma terms!)

$$\langle p,n|m_q\bar{q}q|p,n\rangle = m_{p,n}f_q^{p_n}$$

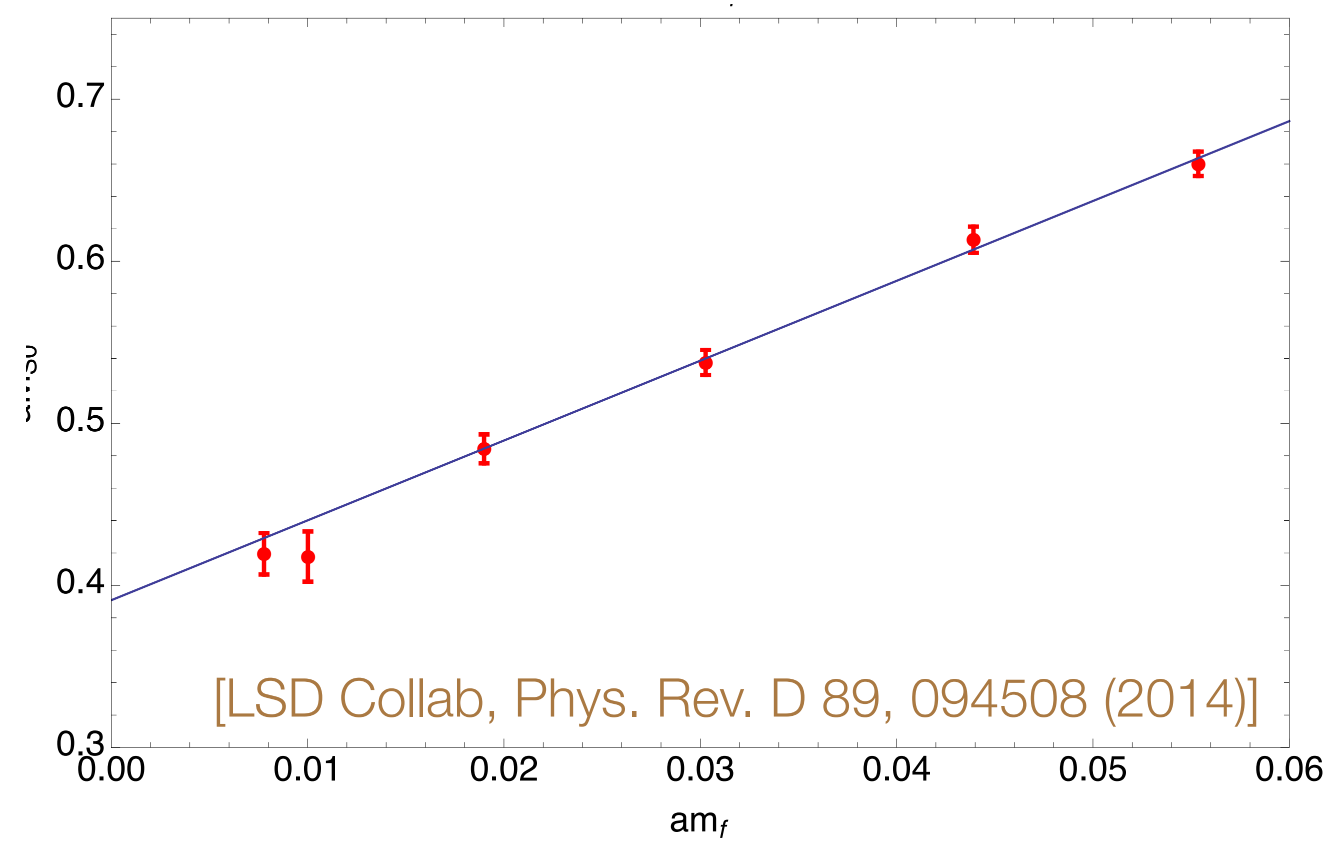
$$\langle B|m_f\bar{f}f|B\rangle = m_B f_f^B$$



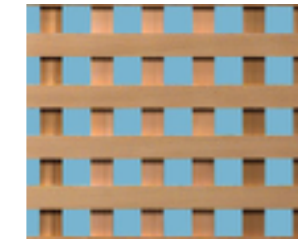
- Calculate on the lattice with Feynman-Hellman:



$$f_f^B = \frac{m_f}{M_B}\frac{\partial M_B}{\partial m_f}$$



Experimental constraints on Higgs exchange

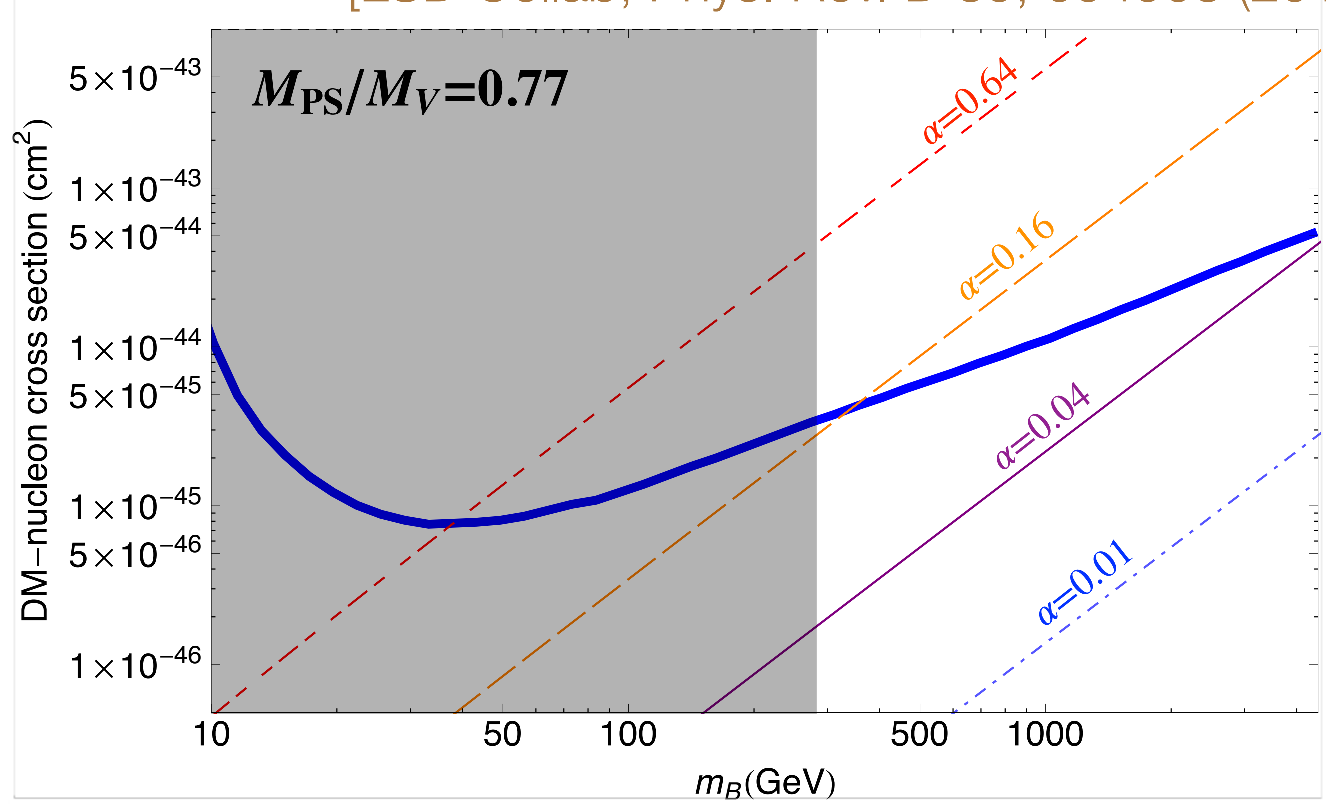


- Coupling on DM side is model-dependent. How much DM mass can come from Higgs?

$$m_f(h) = m + \frac{yh}{\sqrt{2}} \qquad \Bigg| \qquad \alpha \equiv \frac{v}{m_f} \frac{\partial m_f(h)}{\partial h}\bigg|_{h=v} = \frac{yv}{\sqrt{2}m + yv} \leq 1$$

- α=0 for no Higgs coupling, α=1 is pure Higgs mass generation.
- Non-perturbative calculation of scalar matrix element (sigma term) on DM side needed
- α=1 ruled out by experiment in this SU(4) theory!

[LSD Collab, Phys. Rev. D 89, 094508 (2014)]



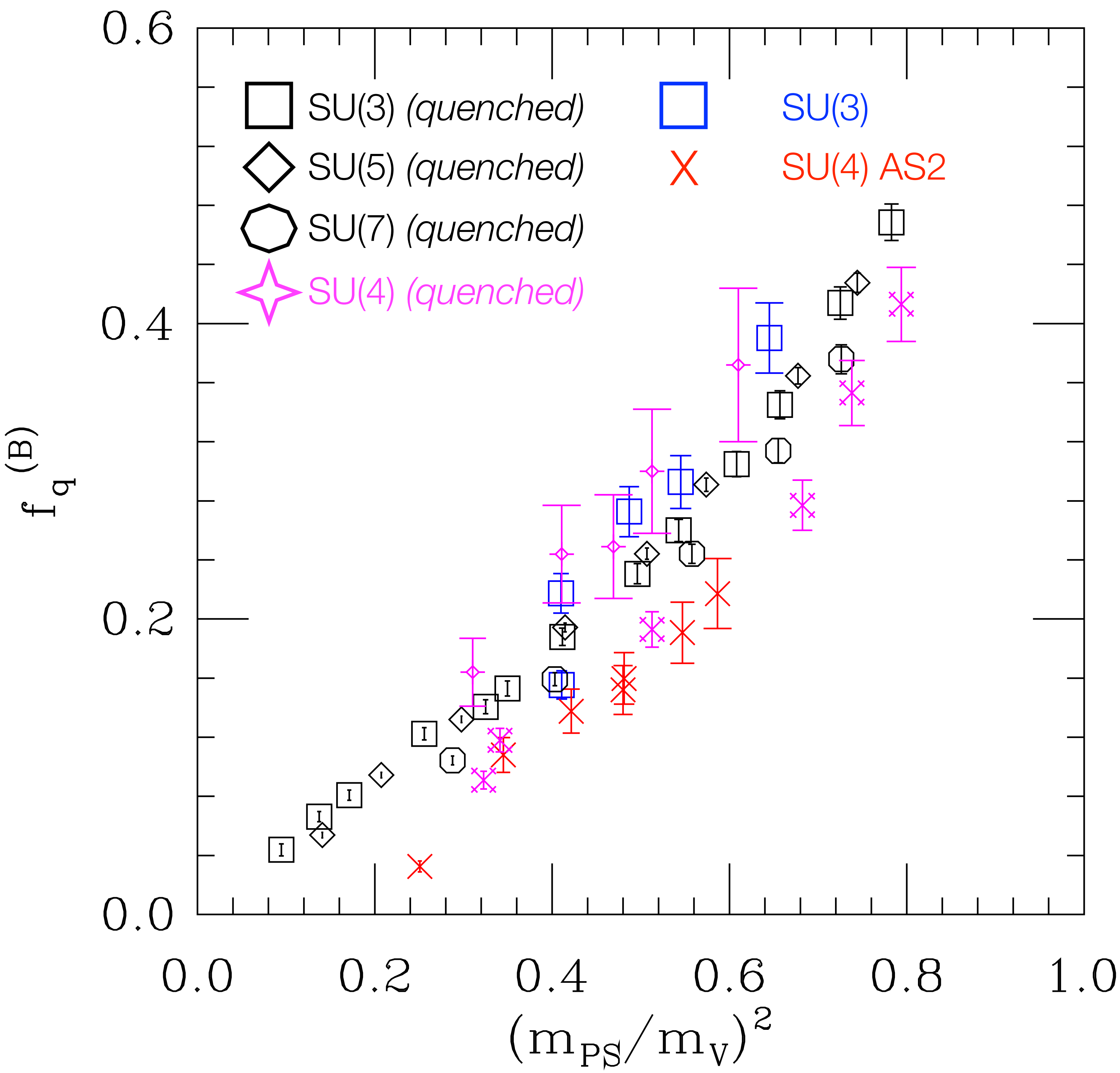
Experimental constraints on Higgs exchange (II)

- Results above are for a particular theory, relying on the scalar matrix element:

$$f_f^B = \frac{m_f}{M_B}\frac{\partial M_B}{\partial m_f}$$

- Lattice results hint that this matrix element may be fairly universal for different theories in similar mass regimes (right)

- Statement that <u>composite DM can't have mass generation purely from the Higgs mechanism</u> may be very general!



[T. DeGrand, Y. Liu, EN, B. Svetitsky, Y. Shamir, Phys. Rev. D 91, 114502 (2015)]

Photon effective interactions

- Interaction of composite DM with photon can also be written as a momentum-dependent matrix element:

$$\langle B(p')|j_V^\mu|B(p)\rangle \sim F(Q^2)$$

- Can also work with effective photon-DM interactions:

Dimension 5: magnetic moment $\frac{1}{\Lambda_D}\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$

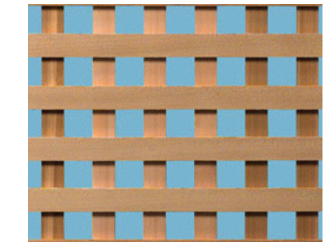
Dimension 6: charge radius $\frac{1}{\Lambda_D^2}\bar{\chi}v_\mu\partial_\nu\chi F^{\mu\nu}$

Dimension 7: polarizability $\frac{1}{\Lambda_D^3}\bar{\chi}\chi F_{\mu\nu}F^{\mu\nu}$

- Note that these all interact very differently with different nuclear targets compared to Higgs exchange!

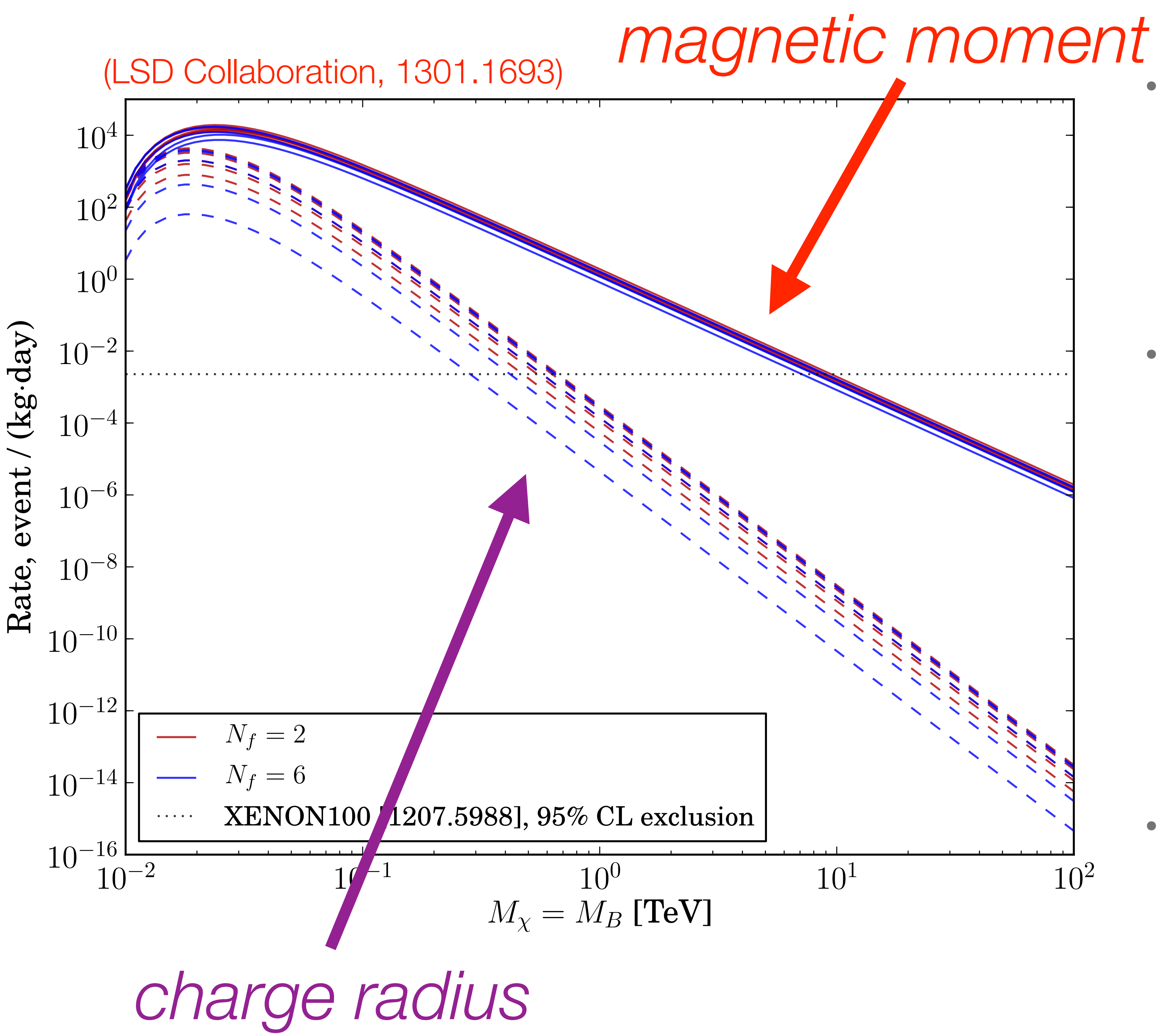
[Bagnasco, Dine and Thomas, PLB 320 (1994); Pospelov and ter Veldhuis, PLB 480 (2000)]

(lattice results in another model: A. Hietanen, R. Lewis, C. Pica and F. Sannino, arXiv:1308.4130)



Direct detection via leading EM operators

(LSD Collaboration, 1301.1693)



- Results using lattice for simple SU(3) “neutron-like” DM model
- Constraints from the leading interactions are quite strong - mass > 10 TeV from mag moment (even from XENON100!)
- Lattice calculation of form factors was crucial input for these plots

Photon effective interactions and symmetry

- No magnetic moment if spin-zero - requires even N_D.
- Charge radius vanishes if we identify a Z_2 symmetry under which the photon field is odd:

$$\frac{1}{\Lambda_D^2}\bar{\chi}v_\mu\partial_\nu\chi F^{\mu\nu}$$

zero if

$$\chi \to \chi$$
$$A^\mu \to -A^\mu$$

- Simplest example is SU(2) gauge theory with two fermions U,D carrying Q=±1/2 ("*quirky DM": 0909.2034*)

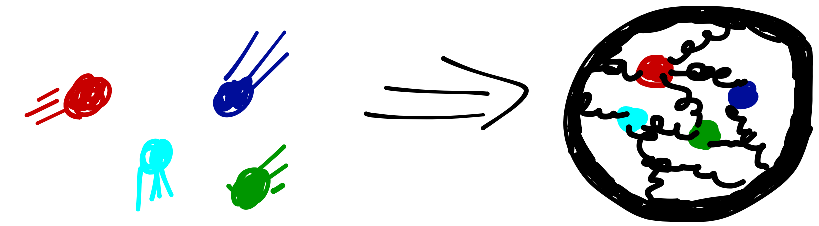
$$\chi \sim UD$$
$$Q_U = -Q_D = 1/2$$

symmetry is exchange of U,D labels

(…meticulously constructed, incredibly complicated, can completely fail to work if one screw is loose?)

3. A case study: stealth dark matter

Starting with symmetries



- Start with SU(N_D) gauge theory and N_F Dirac fermions, in the fundamental rep, and impose some conditions.

- First requirement: *baryons are bosons, no mag. moment.* - even N_D. N_D>=4 gives automatic DM stability from Planck-scale violations!

- Second requirement: *couplings to electroweak and Higgs* - one EW doublet and one singlet, N_F>=3. Ensures meson decay as well.

- Third requirement: *custodial SU(2) for electroweak precision* - N_F=4. As a bonus, charge radius is eliminated —> stealth DM!

Field content and mass terms

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	$\overline{\mathbf{N}}$	$(\mathbf{1}, -1/2)$	$-1/2$

EW-preserving mass:

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

EW-breaking mass:

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

- Field content of the model shown to the left
- Two sources of mass generation allowed: EW-breaking (Higgs mechanism) and EW-preserving (vector-like)
- With most general masses and EW symmetry breaking, we have U(4)xU(4) broken to a single U(1) [dark baryon number].
- Insist on SU(2) custodial: (u <-> d) symmetry.

Re-diagonalizing in the mass eigenbasis

- Two sources of mass, electroweak breaking and preserving.

$$M \equiv \frac{M_{12}+M_{34}}{2} \qquad \Delta \equiv \left|\frac{M_{12}-M_{34}}{2}\right| , \qquad y_{14} = y + \epsilon_y\,, \quad y_{23} = y - \epsilon_y\,, \quad |\epsilon_y| \ll |y|\,.$$

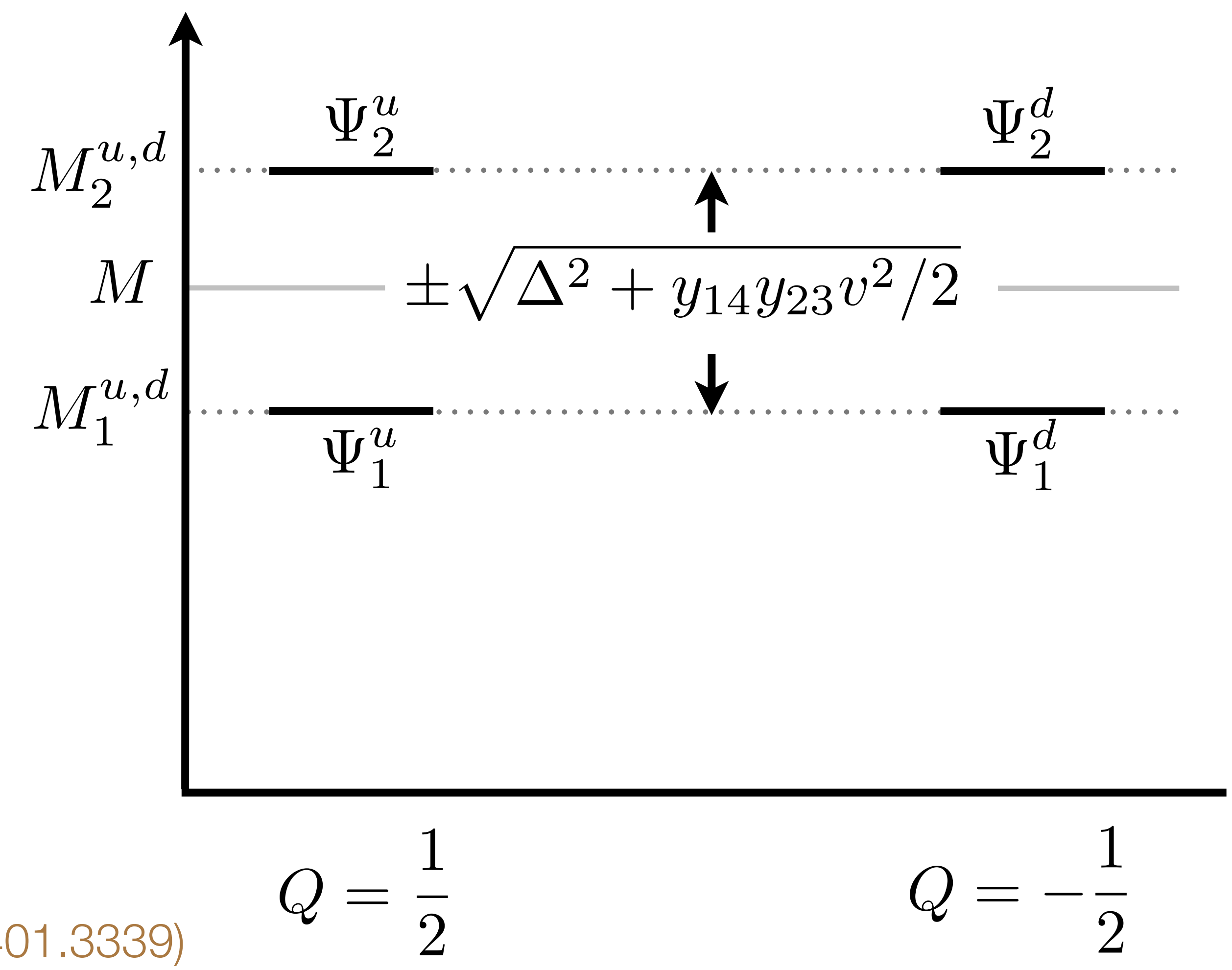
- Assume *yv<<M*, to avoid vacuum alignment issues w/EWSB. Then two regimes arise, depending on the origin of the mass splitting:

<u>Linear Case:</u> $yv \gg \Delta$

$$y_\Psi = \frac{y}{\sqrt{2}}$$

<u>Quadratic Case:</u> $yv \ll \Delta$

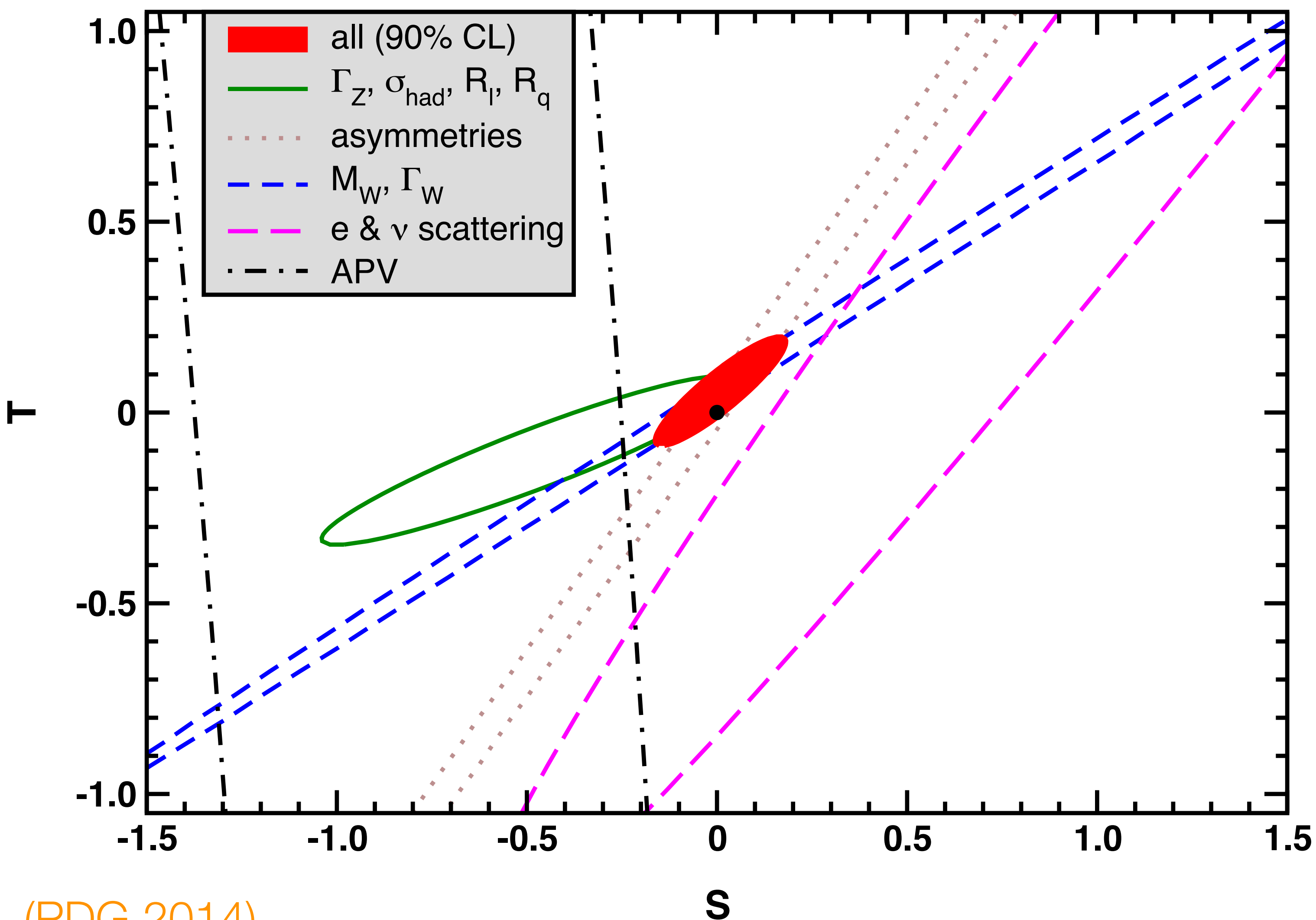
$$y_\Psi = \frac{y^2 v}{2\Delta}$$



(linear/quadratic effect observed before, see Hill and Solon 1401.3339)

Electroweak precision

- No T parameter by construction (custodial symm), but S parameter is an important constraint! Two asymptotic forms of S contribution:



(PDG 2014)

$$\boxed{M_2 \gg M_1}$$

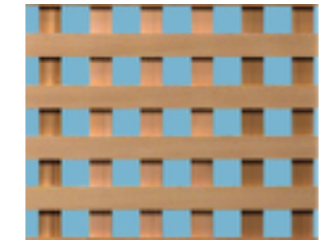
$$\Pi_{3Y}(q^2) = \frac{1}{8}\frac{y^2 v^2}{y^2 v^2 + 2\Delta^2}\Pi_{VV}(q^2)$$

$$\boxed{M_1 \approx M_2}$$

$$\Pi_{3Y}(q^2) \approx \frac{\epsilon_y^2 v^2}{4M^2}\Pi_{LR}(q^2)$$

- Calculation of strong-coupling part yields direct bounds on Yukawa couplings (important for asymmetric relic density)

Stealth Dark Matter on the lattice



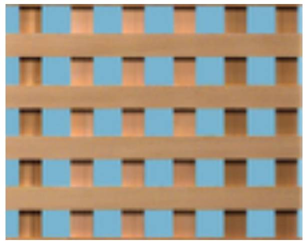
- Why use lattice for this? We’re not looking for precision, but controllable and improvable systematics!

- From LEP bound, we favor regime with heavier fermion masses near the confinement scale - ideally suited to lattice (no large scale separation to fit inside “the box”.)

- Specialize to N_D=4 - smallest group with the properties we want. (LEP bound also gets worse at large N_D as the baryon is made of more fermions!)

- Already showed one result from this series of calculations (nucleon sigma-term for Higgs-exchange direct detection)

Lattice simulation details



- Simplest approach to start: unimproved Wilson fermions, plaquette action
- All results so far are **quenched** (no fermion loops.) Studying heavy fermions and larger Nc, so should result in smaller errors than quenching QCD, which were typically O(10%).
- Implemented using the Chroma code base - merged back into public repository

Nucl.Phys. B225 (1983) 156
Results

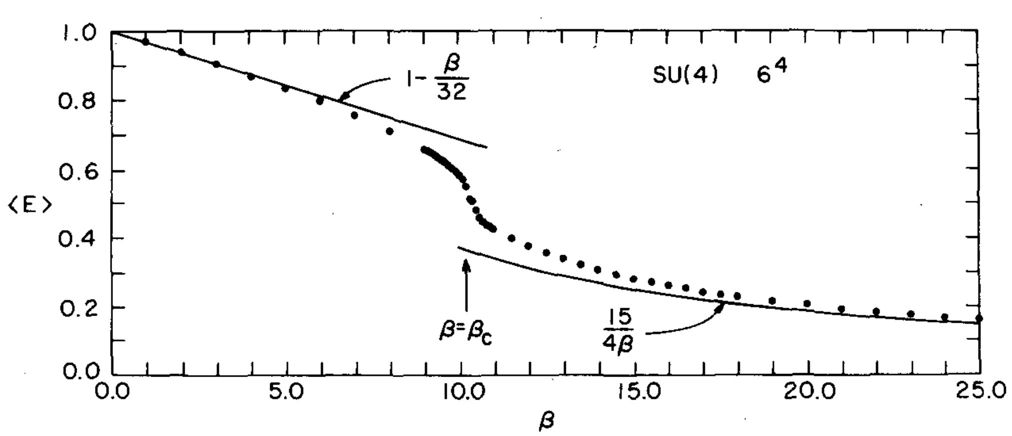
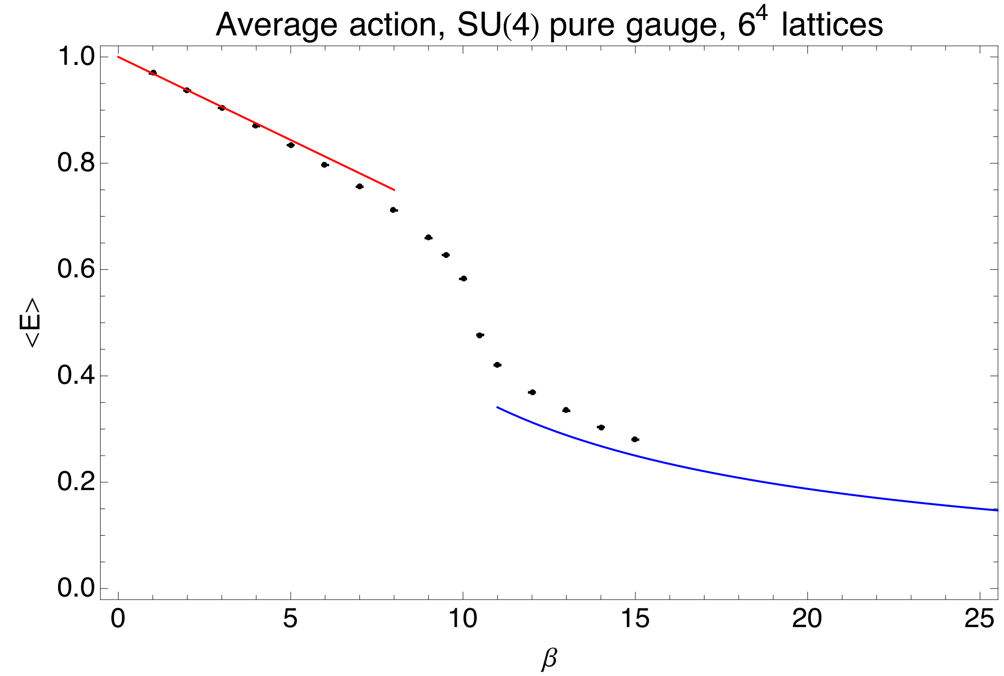
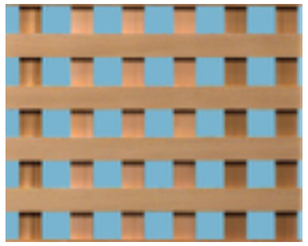


Fig. 10. The average action per plaquette $\langle E \rangle$ for pure SU(4) gauge theory on a 6^4 lattice as a function of the inverse temperature β. The curves represent the leading-order high- and low-temperature expansions of eqs. (1) and (3), respectively.

Our Code

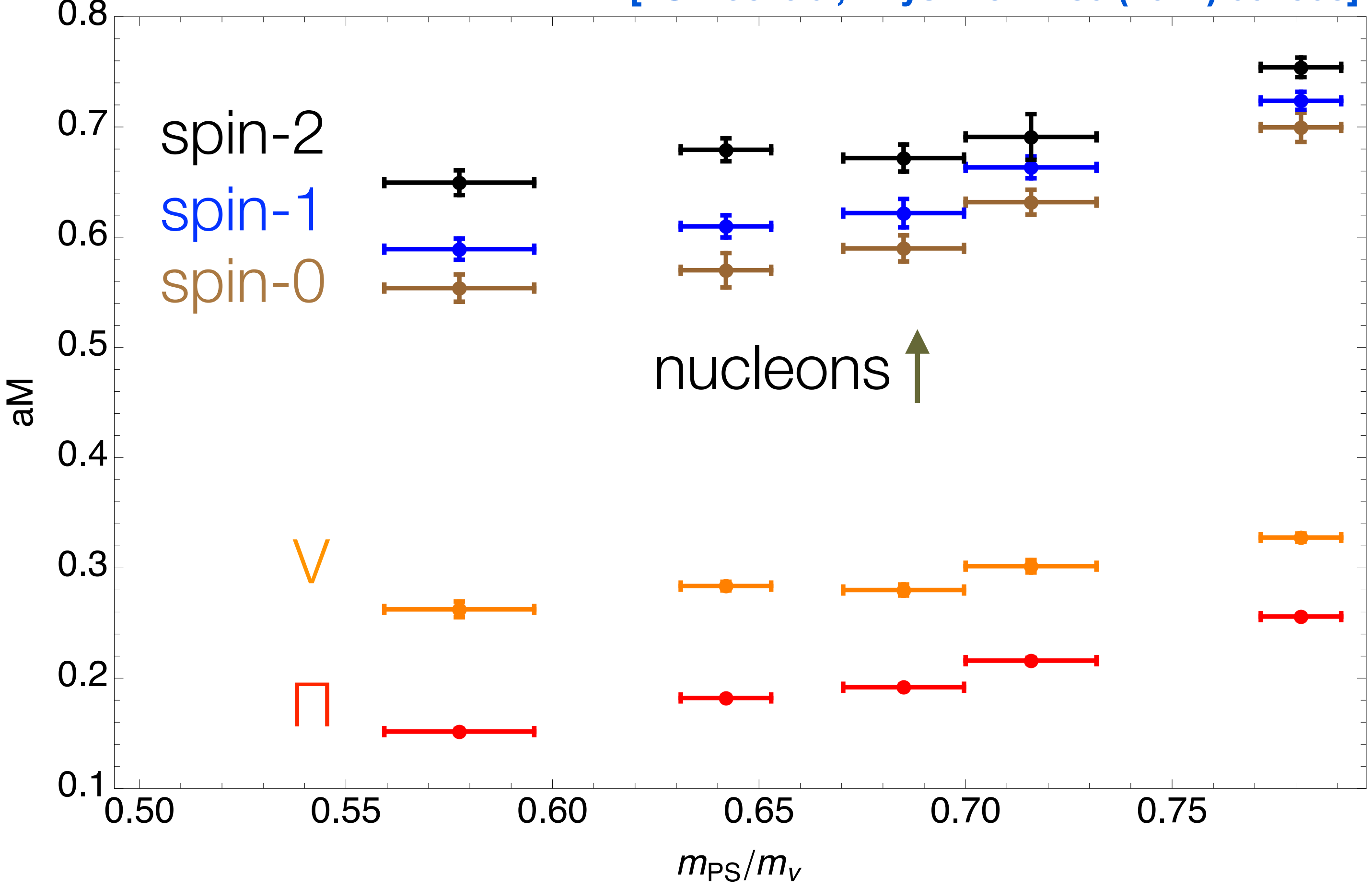


Spectrum



- Spectrum scaling with input mass shown right.
- Verifies that spin-0 is lightest here; ratio of Π to baryon mass fixes LEP bound
- Study of splitting masses in the future…is there a corner of the space where the spin-1 baryon is lightest?

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



(see also: Weiner and Yavin, arXiv:1209.1093)

Direct detection via polarizability

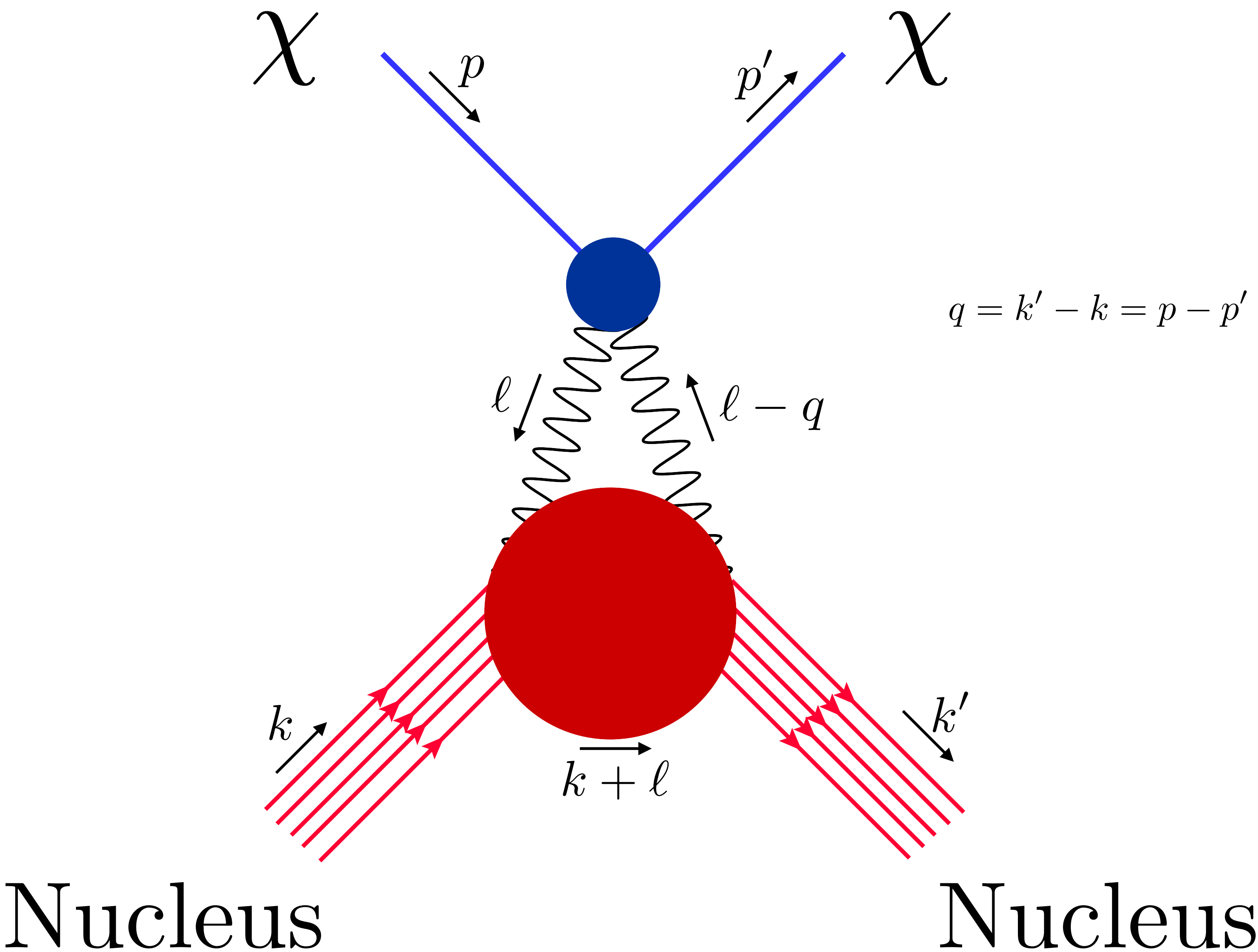
- Dark matter scatters by two-photon exchange (a loop!)

- Significant uncertainties on the *nuclear physics* side for this matrix element!

$$f_F^a \equiv \langle A | F_{\mu\nu} F^{\mu\nu} | A \rangle \sim 3Z^2 \alpha \frac{M_F^A}{R}$$

- Naive estimate - take M_F^A in the range [1/3,3] to be conservative… (similar to uncertainty claimed for 0νββ-decay nuclear MEs.)

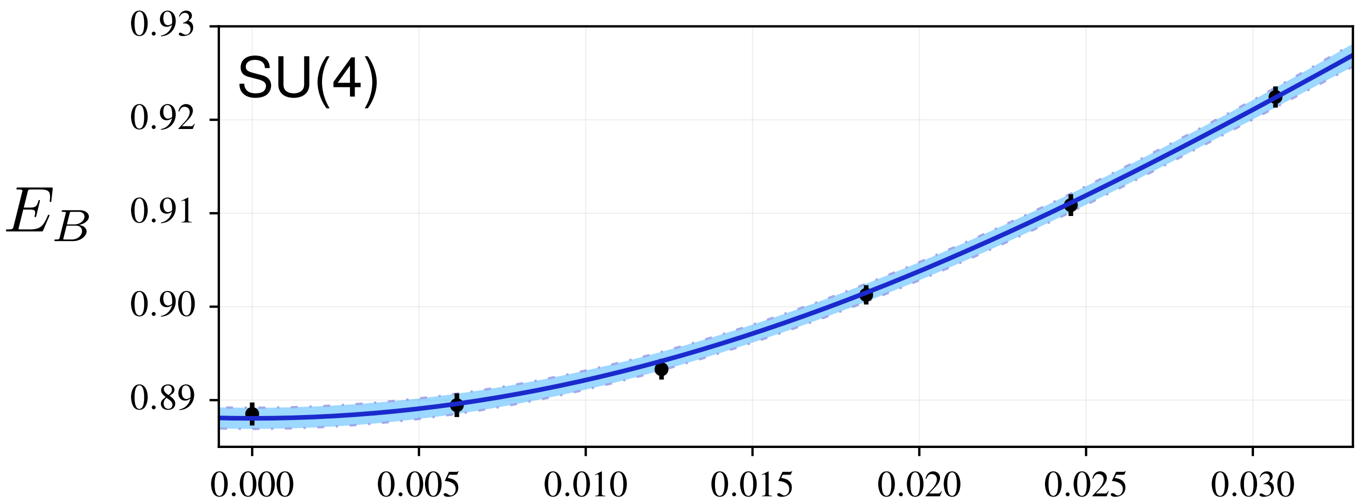
- Enhancement due to excited nuclear states possible?

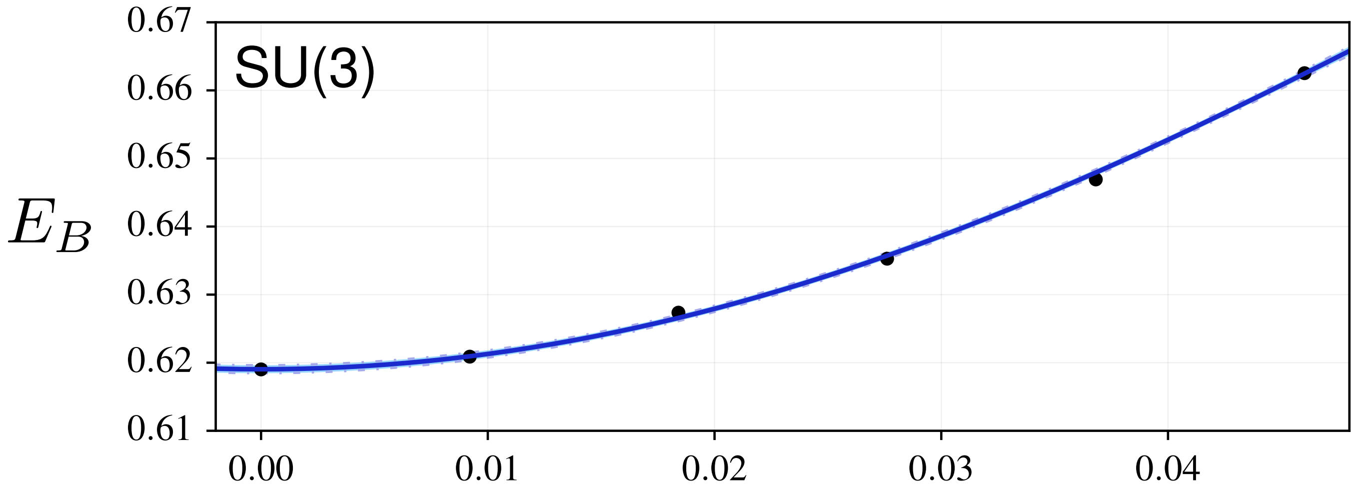


$q = k' - k = p - p'$

$$\sigma_{\text{nucleon}}(Z, A) = \frac{Z^4}{A^2} \frac{144\pi\alpha^2 \mu_{nB}^2 (M_F^A)^2}{m_B^6 R^2} [\alpha \tilde{m}_B^3 \tilde{C}_F]^2$$

Polarizability on the lattice





N_D	m_{PS}/m_V	$\tilde{m}_B$	$\alpha\tilde{C}_F$	$\alpha^2\tilde{C}'_F$	$\tilde{\mu}_B$	$\tilde{\mu}'_B$	χ^2/dof
4	0.77	0.98204(93)	0.1420(56)	-0.089(29)	—	—	0.7/3
	0.70	0.88805(113)	0.1514(106)	-0.142(68)	—	—	4.8/3
3	0.77	0.69812(51)	0.2829(127)	-0.177(45)	-6.87(26)	714(103)	3.0/7
	0.70	0.61904(59)	0.2829(81)	-0.165(24)	-5.55(18)	396(78)	13.4/7

- Technique pioneered by Detmold, Tiburzi, Walker-Loud (arXiv:1001.1131)
- Measure response to applied background field E (quadratic Stark shift)

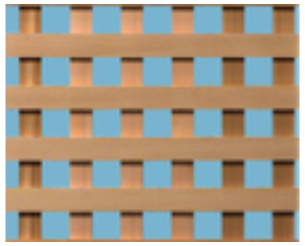
$$E_{B,4c} = m_B + 2C_F|\mathcal{E}|^2 + \mathcal{O}\left(\mathcal{E}^4\right)$$

- SU(3) case simulated for comparison; complicated by magnetic moment μ_B

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

- Comparable results for SU(3) and SU(4), in units of m_B.

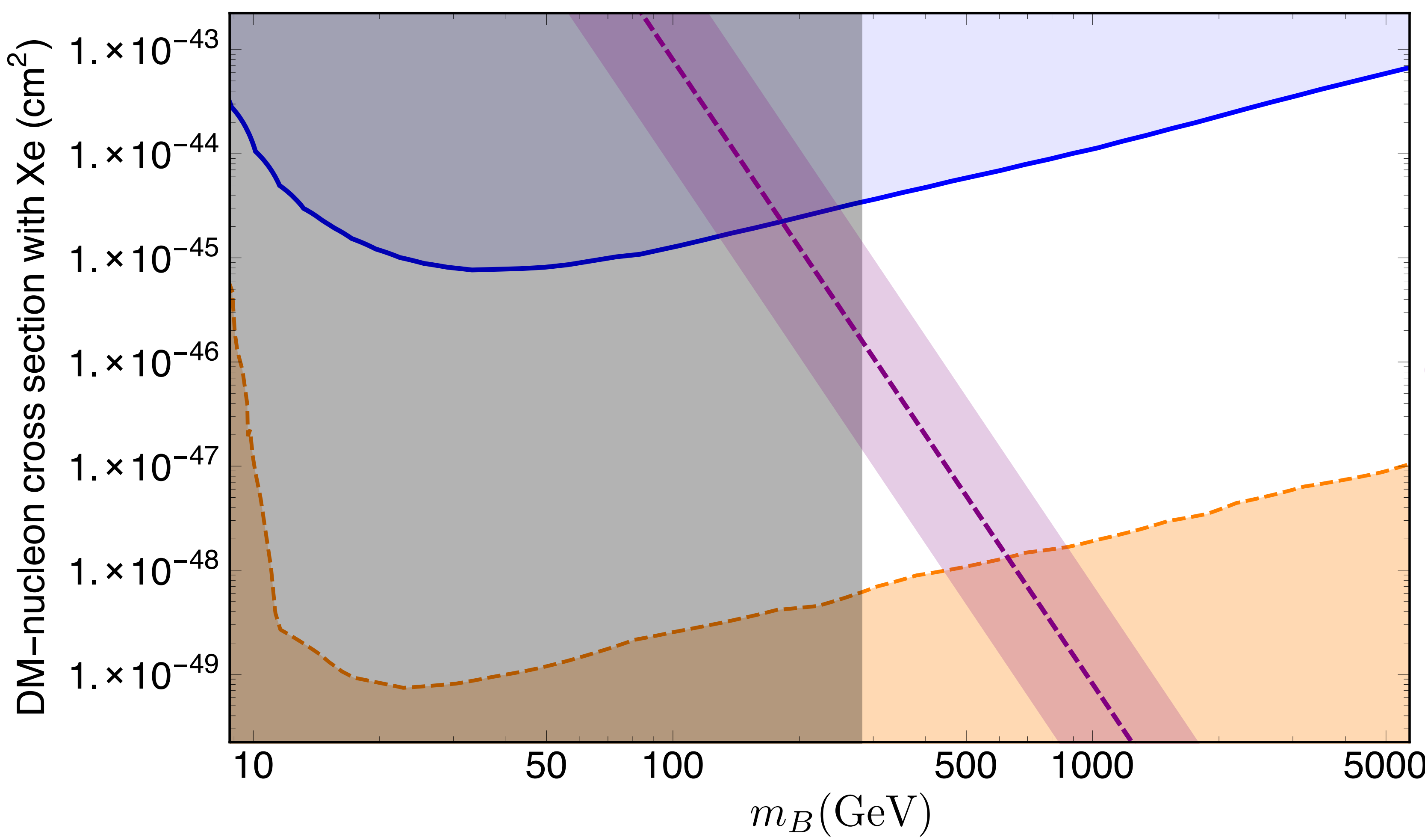
(LSD Collaboration, arXiv:1503.04205)



Direct-detection bound from polarizability

LUX direct-detection bound

LEP bound on charged stealth mesons



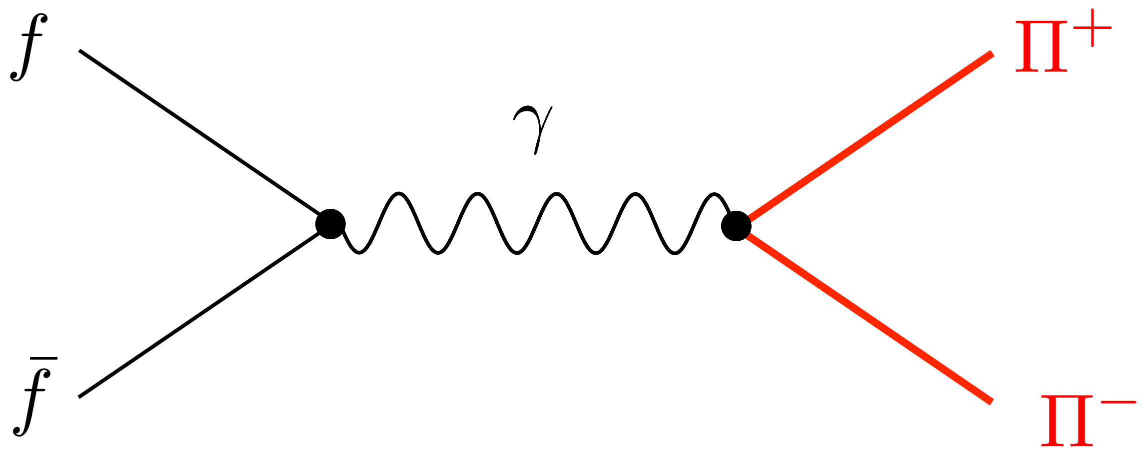
Our result for stealth DM cross-section through polarizability*

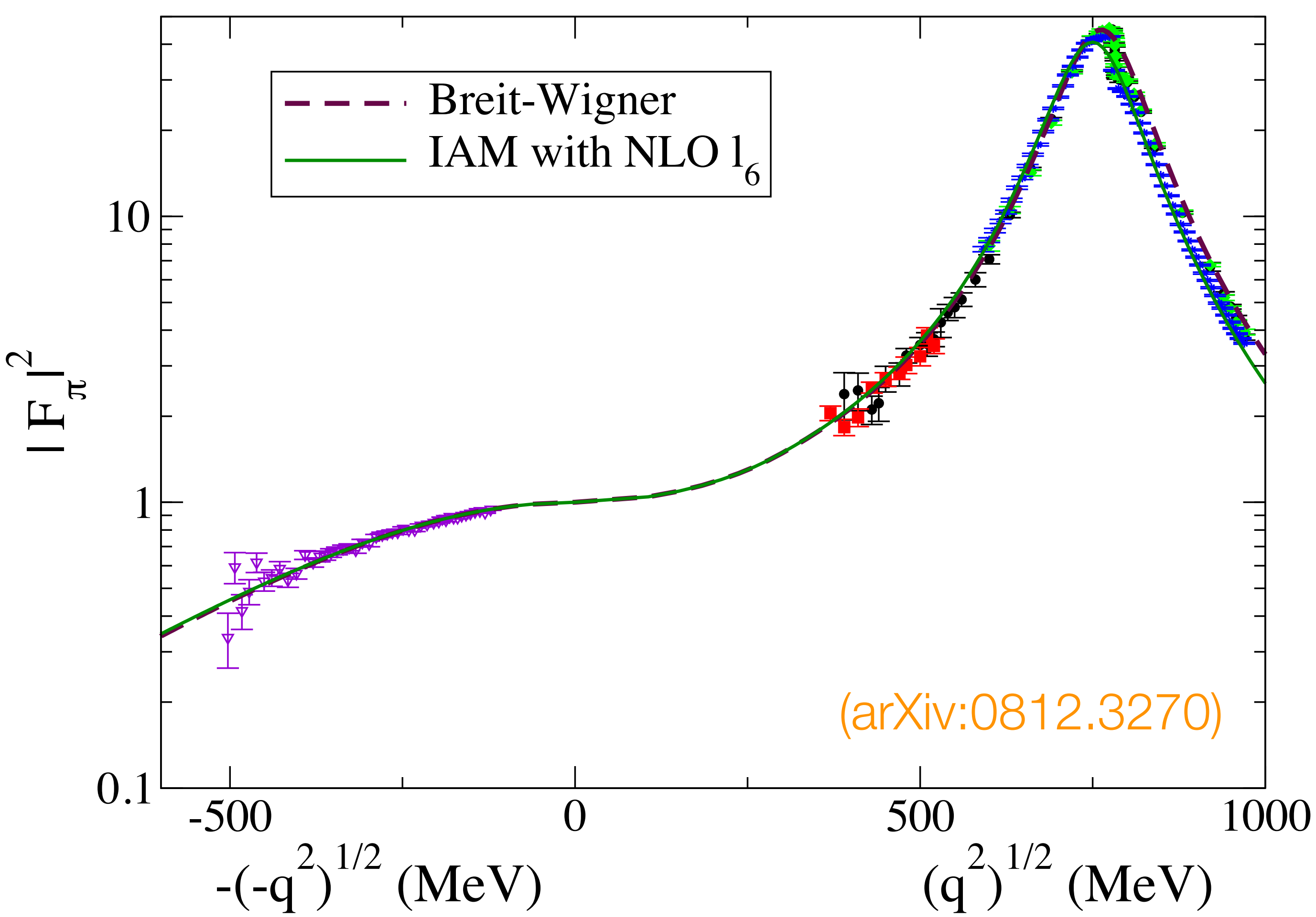
expected cosmic neutrino background

*Note: Xe target only! Scaling as $Z^4/A^{8/3}$ for other targets.

4. Outlook

Meson production





- First signature expected: Drell-Yan photon production of charged Π
- To calculate rate, pion form factor needed at threshold: $F_V(Q^2=4m_\Pi^2)$
- Hard to access at this momentum on lattice directly. Planning calculations of “rho” properties, to use with vector-meson dominance

Indirect detection: fireballs and gamma rays

- With thermal origin or dark nucleon oscillation, can have an indirect gamma-ray signal from DM annihilation!
- Expected to be quite complicated…e.g. QCD annihilation at low momentum gives many-pion final states.
- This may also change the story for thermal abundance!

Proton-antiproton annihilation and meson spectroscopy with the Crystal Barrel

Claude Amsler
Physik-Institut der Universität Zürich, CH-8057 Zürich, Switzerland

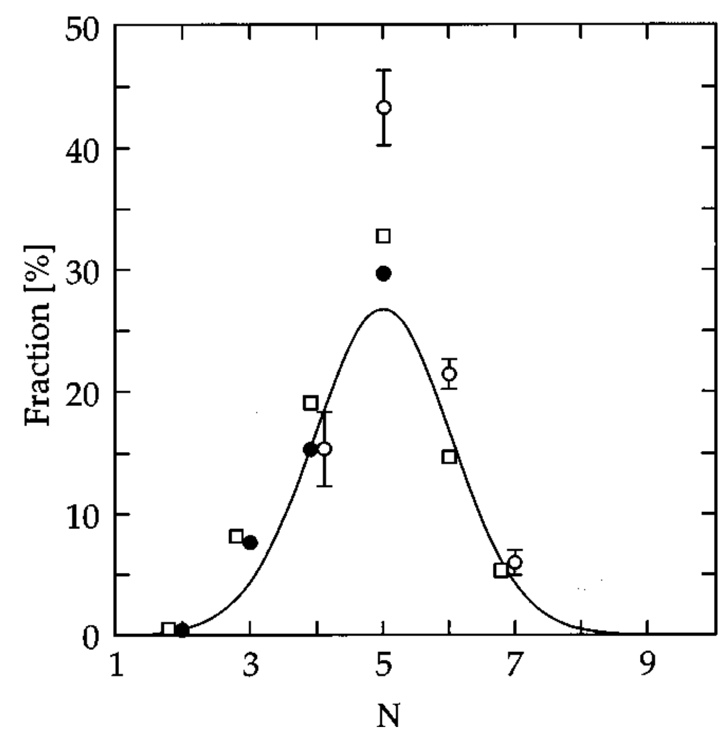


FIG. 1. Pion multiplicity distribution for $\bar{p}p$ annihilation at rest in liquid hydrogen: □, statistical distribution; ●, data; ○, estimates from Ghesquière (1974). The curve is a Gaussian fit assuming $\langle N \rangle = 5$.

Other Open Questions

- Can composite models account for self-interacting dark matter astronomical hints? (Back of the envelope says this is tough for stealth at allowed masses, but in general?)

- Model building: how well-motivated is M~Λ? How do these models fit into [your favorite UV completion]?

- Glueball dark matter? Formation of “dark nuclear” bound states? Here some lattice input is needed, but there has been some interesting work anyway…

K. Boddy, J. Feng, M. Kaplinghat, Y. Shadmi, T. Tait, arXiv:1408.6532 and arXiv:1402.3629

W. Detmold, M. McCullough, A. Pochinsky, arXiv:1406.2276 and 1406.4116

E. Hardy, R. Lasenby, J. March-Russell, S. West, arXiv:1411.3739 and 1504.05419

(and others!)

Conclusions

- Composite dark matter models are viable, interesting, but can be hard to study due to strong coupling - lattice is a great tool here.

- Stealth dark matter is a particular example - very hard to see in direct detection (but window below 1 TeV)!

- Next step is a detailed calculation of the relic abundance - we have some ideas for thermal and asymmetric, but work to do

- Lots of room for interesting pheno in composite DM, even before a lattice calculation comes in!