Composite Dark Matter on the Lattice

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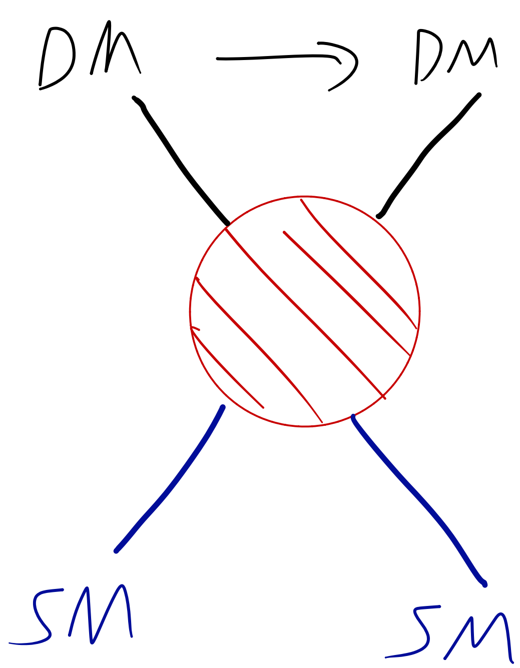
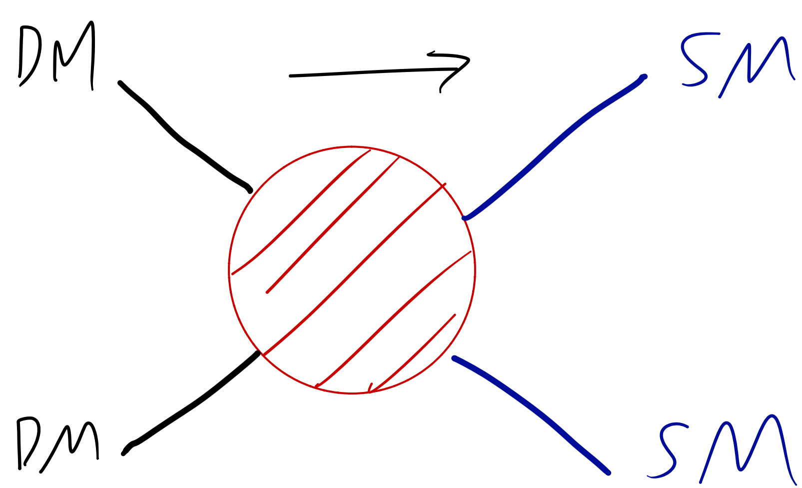
Particle dark matter: what do we know?

- Strongest evidence for dark matter - cosmology from CMB, lensing, large-scale structure - is all sensitive only to <u>gravitational</u> interactions

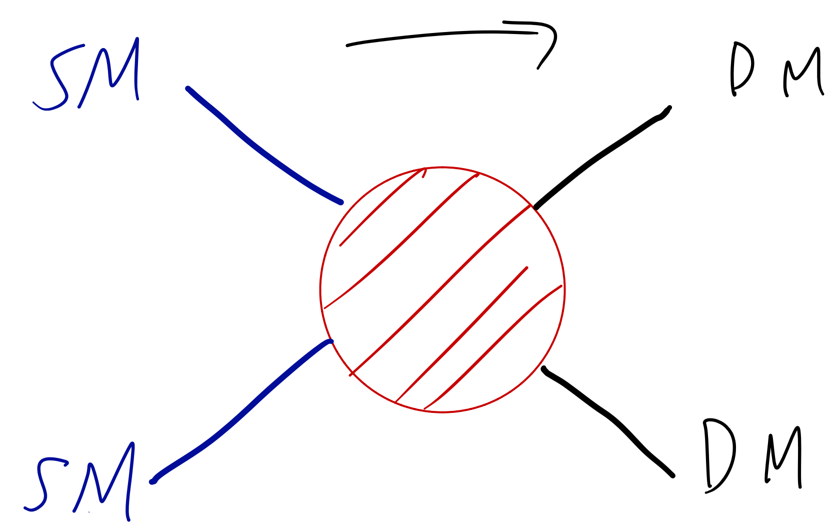
- However, interaction with ordinary matter is motivated by relic density coincidence (and by wanting to do experiments). Three ways to search in experiment, easy to picture through crossing symmetry:



“Direct detection”

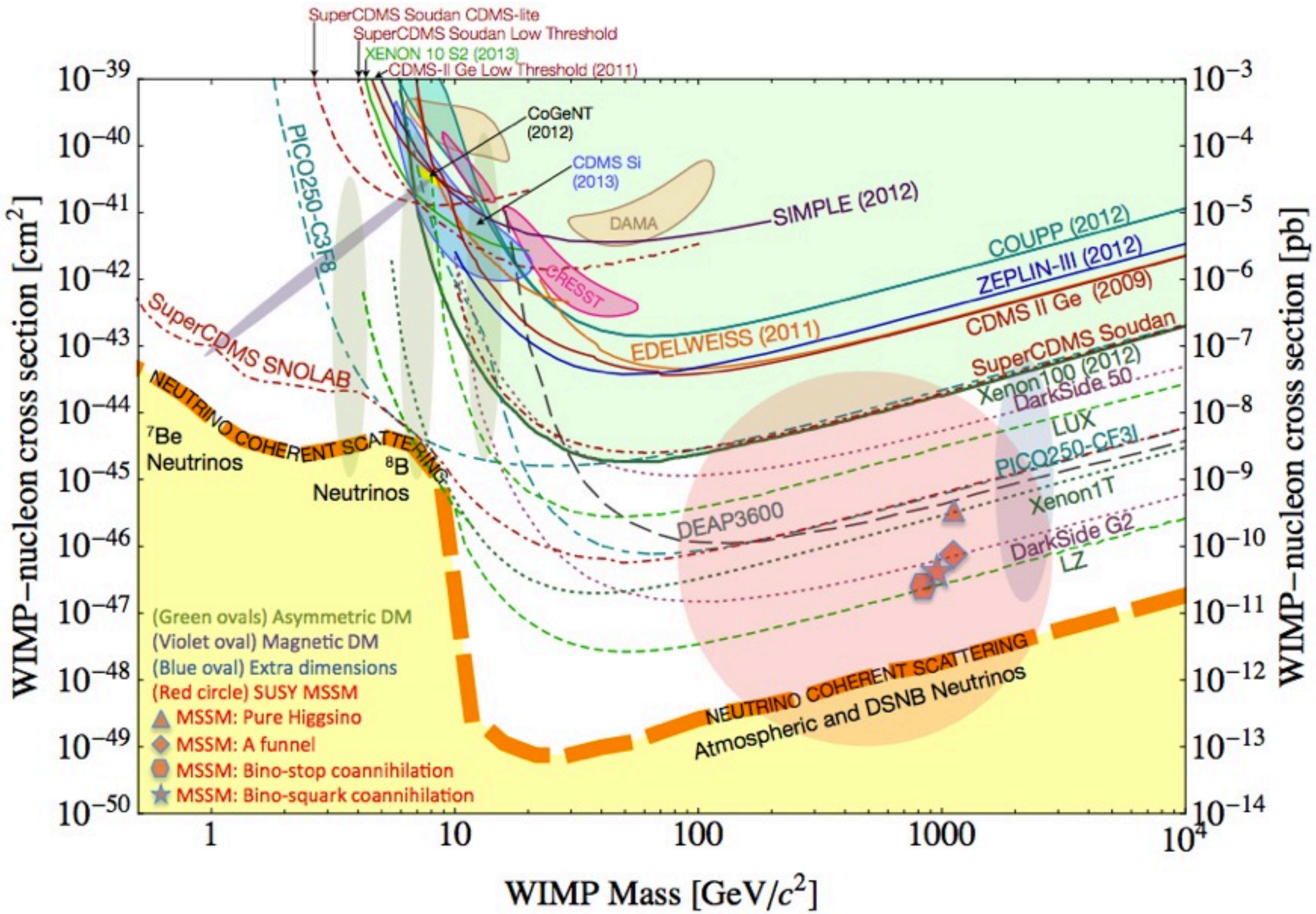


“Indirect detection”



“Collider”

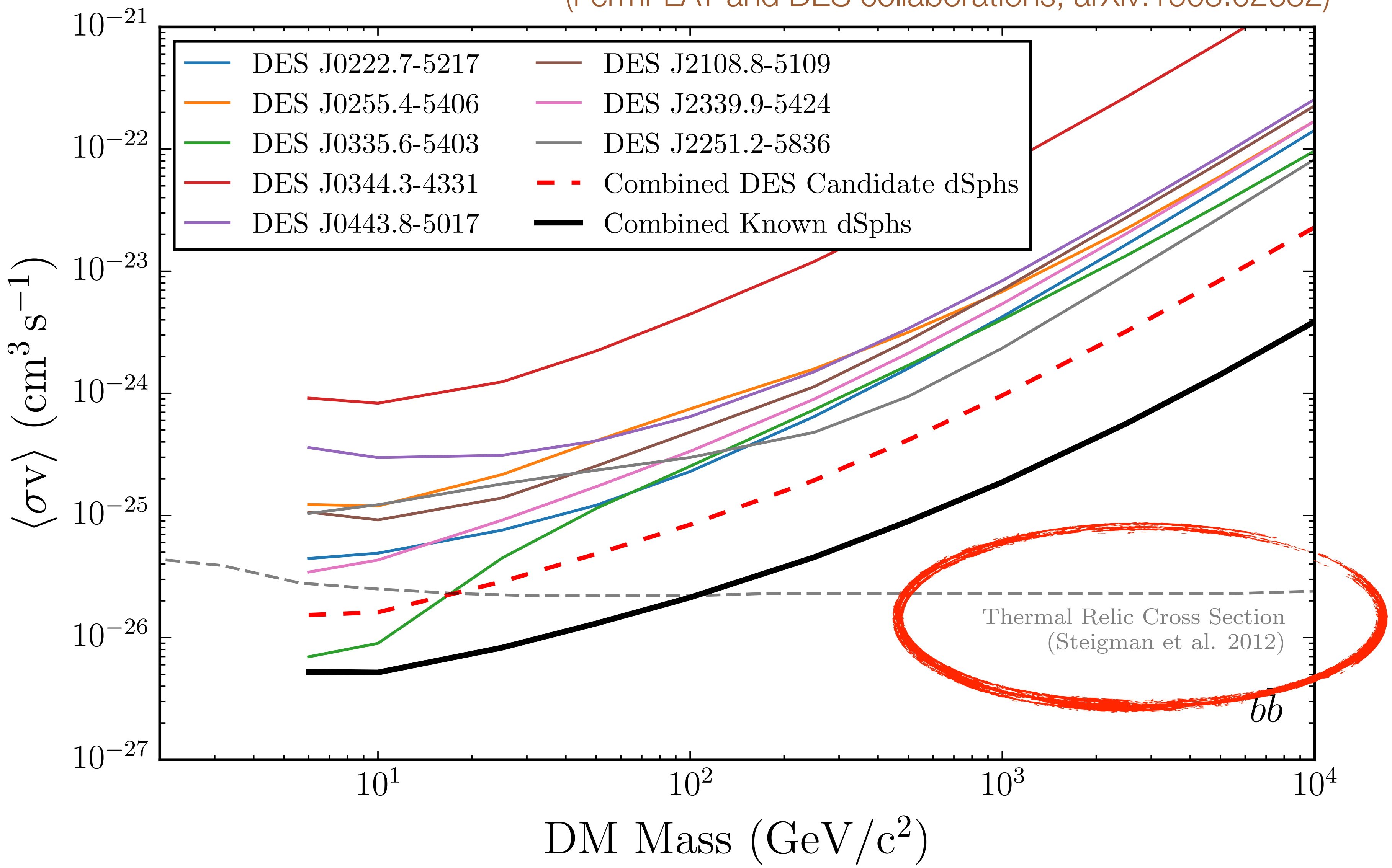
The picture* for direct detection



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

The picture* for indirect detection

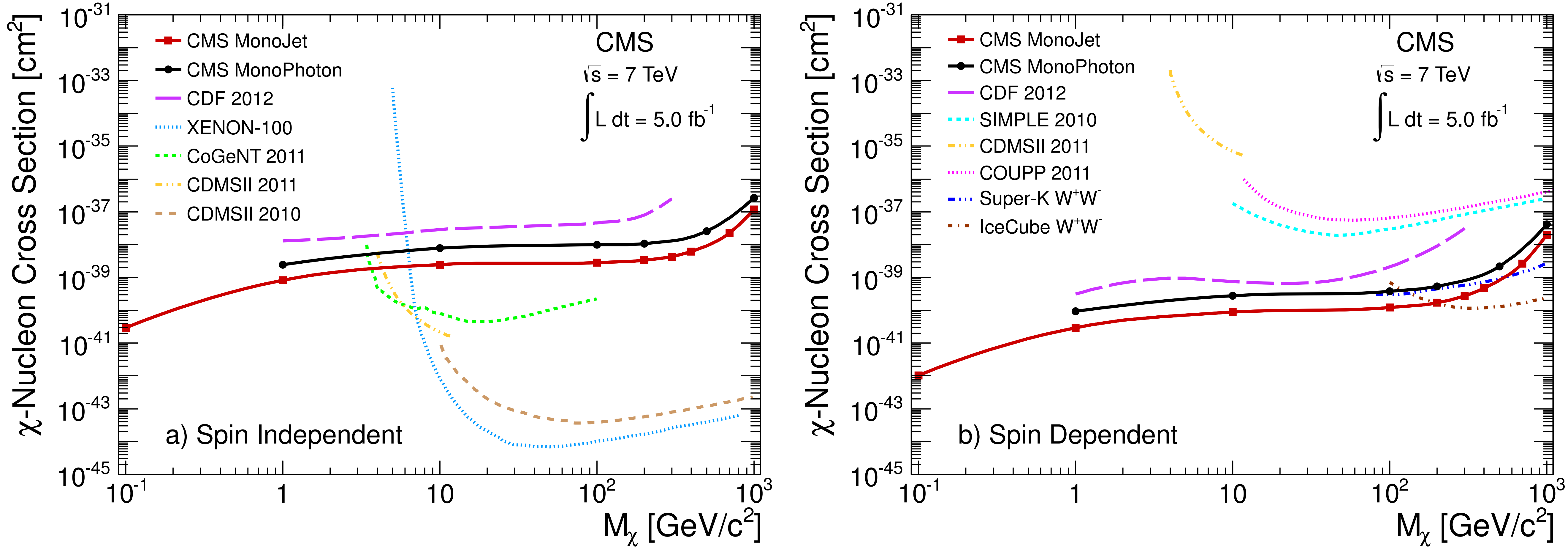
(Fermi-LAT and DES collaborations, arXiv:1503.02632)



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

The picture* for collider bounds

(arXiv:1206.5663)

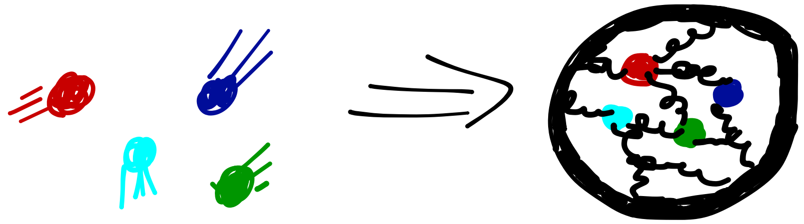


*assuming MET is the best way to probe the dark sector

Beyond the usual pictures

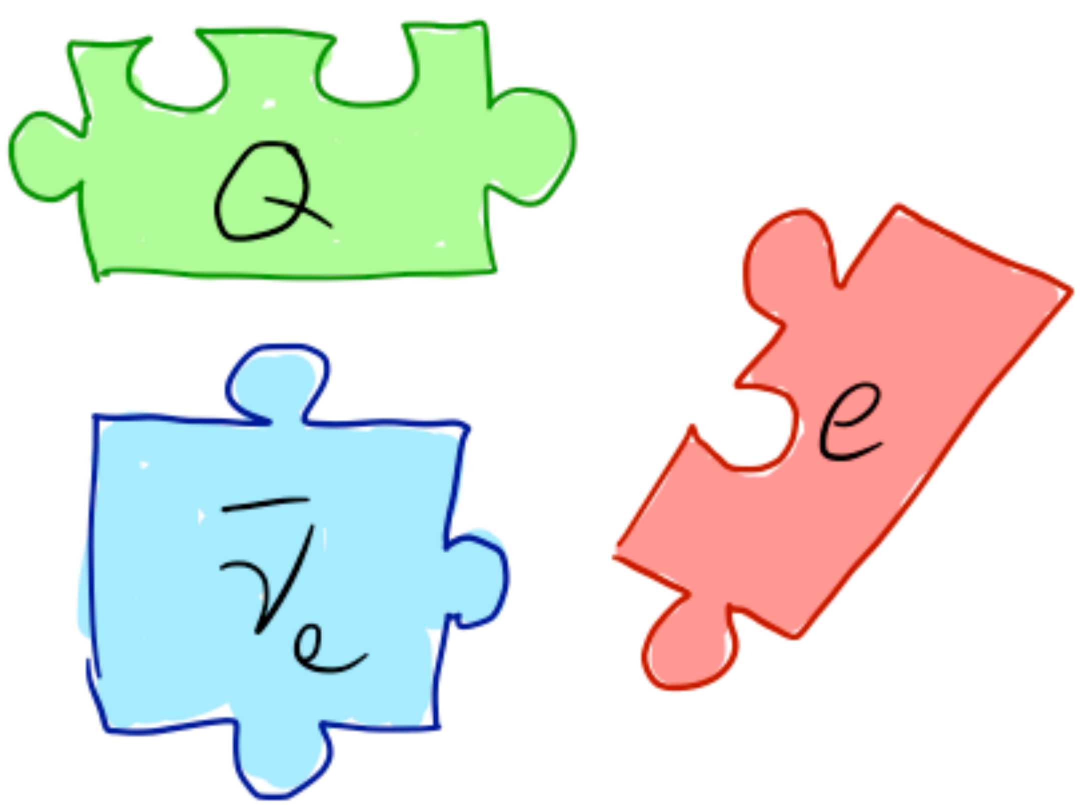
- There are a few particularly interesting properties that are worth looking for in the space of dark matter models:
  - Non-standard scaling of nuclear couplings *(reconcile direct-detection discrepancies, or suggest novel signatures)*
  - Direct coupling to SM for relic density, but suppressed today *(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!

*This talk: SU(**N**) "hidden" confining gauge sector, with some fermions in the *fundamental* representation



Accidental symmetry and stability

- Dark matter is stable (at least for the lifetime of the universe, and potentially many times longer from other constraints); symmetry explanation is desirable!
- Composite DM models very naturally lead to accidental symmetries, much like Standard Model baryon number, which stabilizes the proton



- "Accidental symmetry": other symmetries of the theory (gauge, Lorentz…) prevent construction of renormalizable interactions that would violate it

*T. Ryttov and F. Sannino, arXiv:0809.0713
*M. Buckley and EN, arXiv:1209.6054
*Y. Hochberg, E. Kuflik, H. Murayama, T. Volansky, J. Wacker, arXiv:1411.3727

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

***nice discussion and classification in arXiv:1503.08749

Stability of composite dark matter candidates

- Two kinds of color-singlet bound states:

$$\Pi \sim \bar{\Psi}\Psi \qquad\qquad B \sim \Psi\Psi\ldots\Psi \longleftarrow N_D \text{ constituents}$$

- 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, even with $\Lambda=M_{Pl}$.

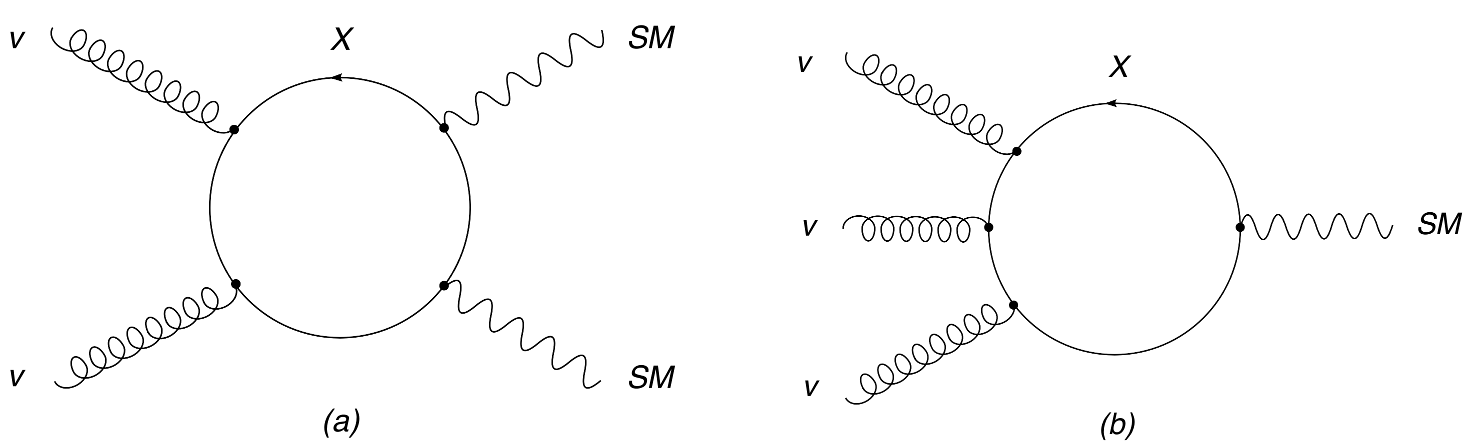
- Accidental dark baryon number*** symmetry provides automatic stability for B on very long timescales (as long as $N_D > 2$!) E.g. for N_D=4, decay through dimension-**8**

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

Stability continued: glueball dark matter

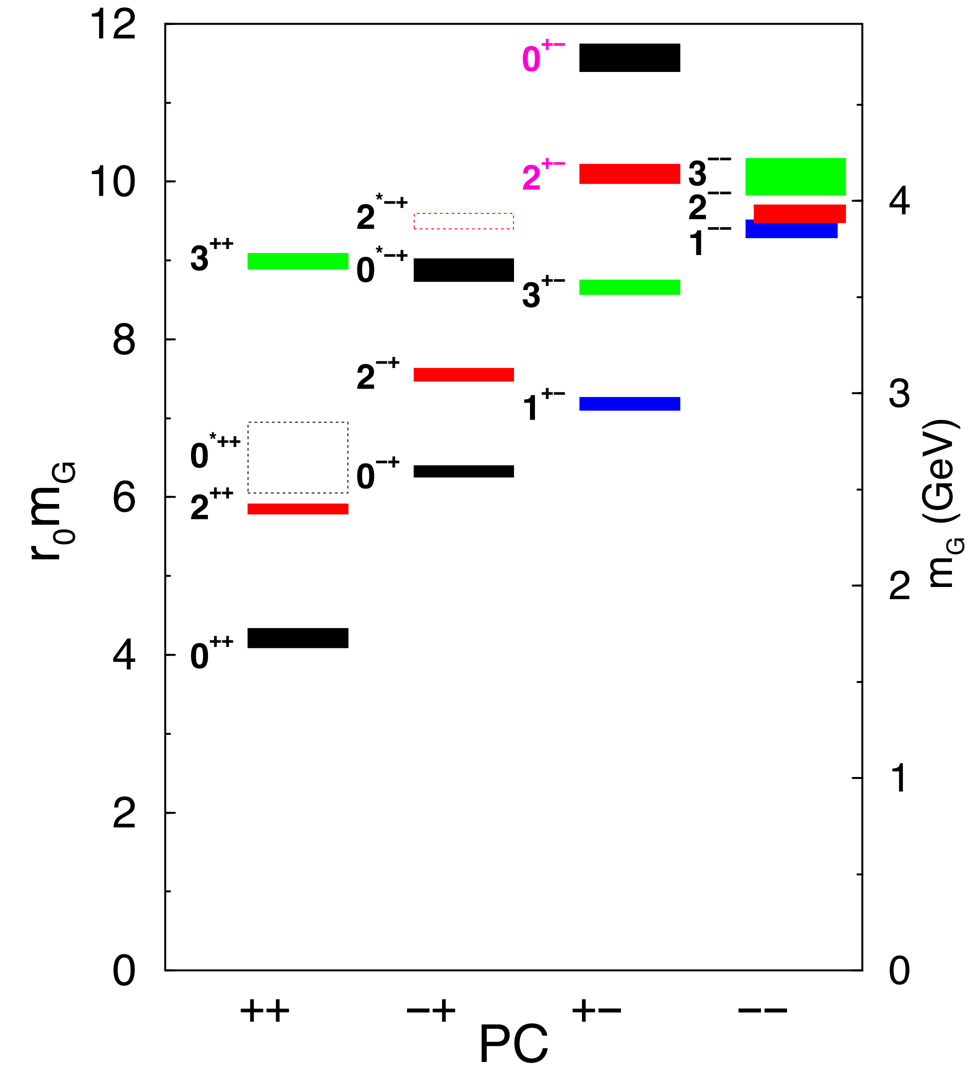
- For a gauge sector with all fermions much heavier than the confinement scale, glueballs are the lightest states in the spectrum

- In isolation, many glueballs are stable (e.g. SU(3) glueballs from lattice, right.) Heavy fermions with dark sector/SM charge can mediate decay:



(Juknevich, Melnikov, Strassler, arXiv:0903.0883)

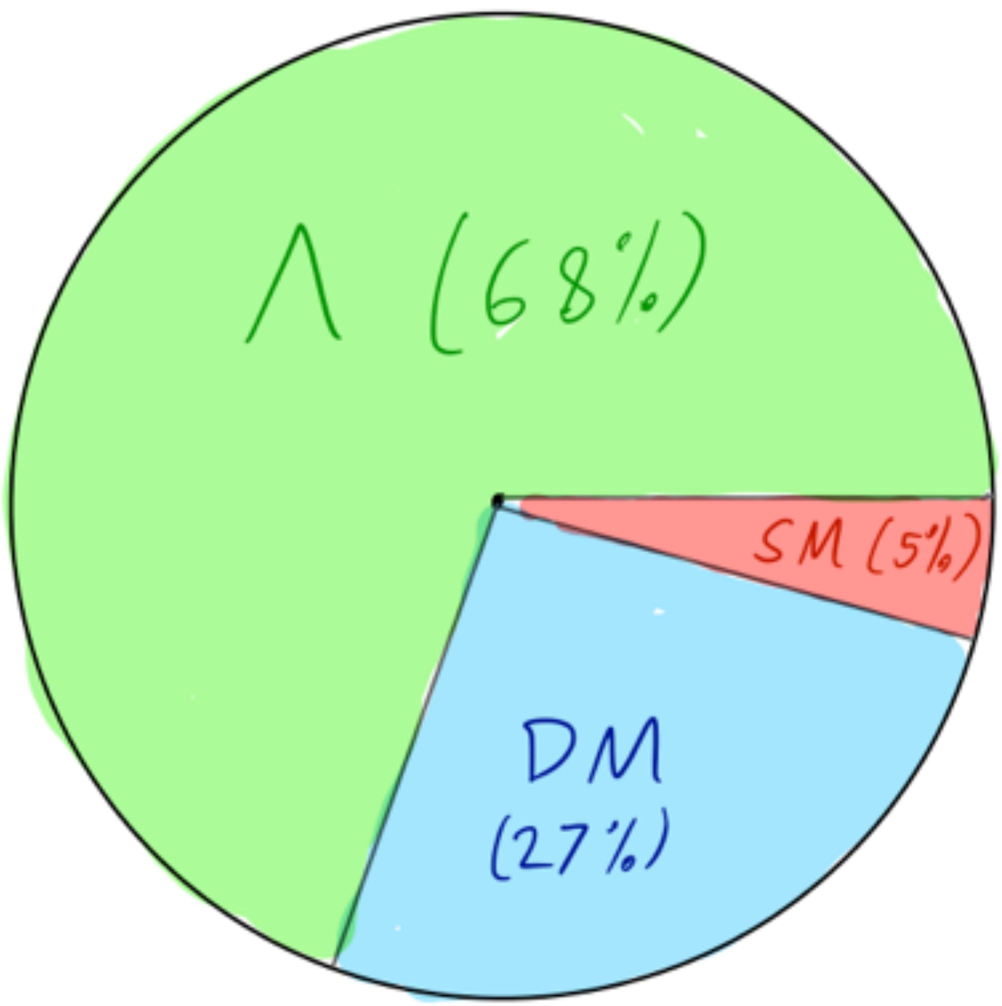
(Morningstar and Peardon, arXiv:hep-lat/9901004)



- Induced operators start here at dimension **8**, so decay width scales as $\mathbf{1/M_X^{\,8}}$ at least! Easy to stabilize on cosmological scales.

- See also: A. Faraggi and M. Pospelov, arXiv:hep-ph/0008223
K. Boddy, J. Feng, M. Kaplinghat, Y. Shadmi, T. Tait, arXiv:1408.6532 and arXiv:1402.3629
A. Soni and Y. Zhang, arXiv:1602.00714

Charging the dark sector

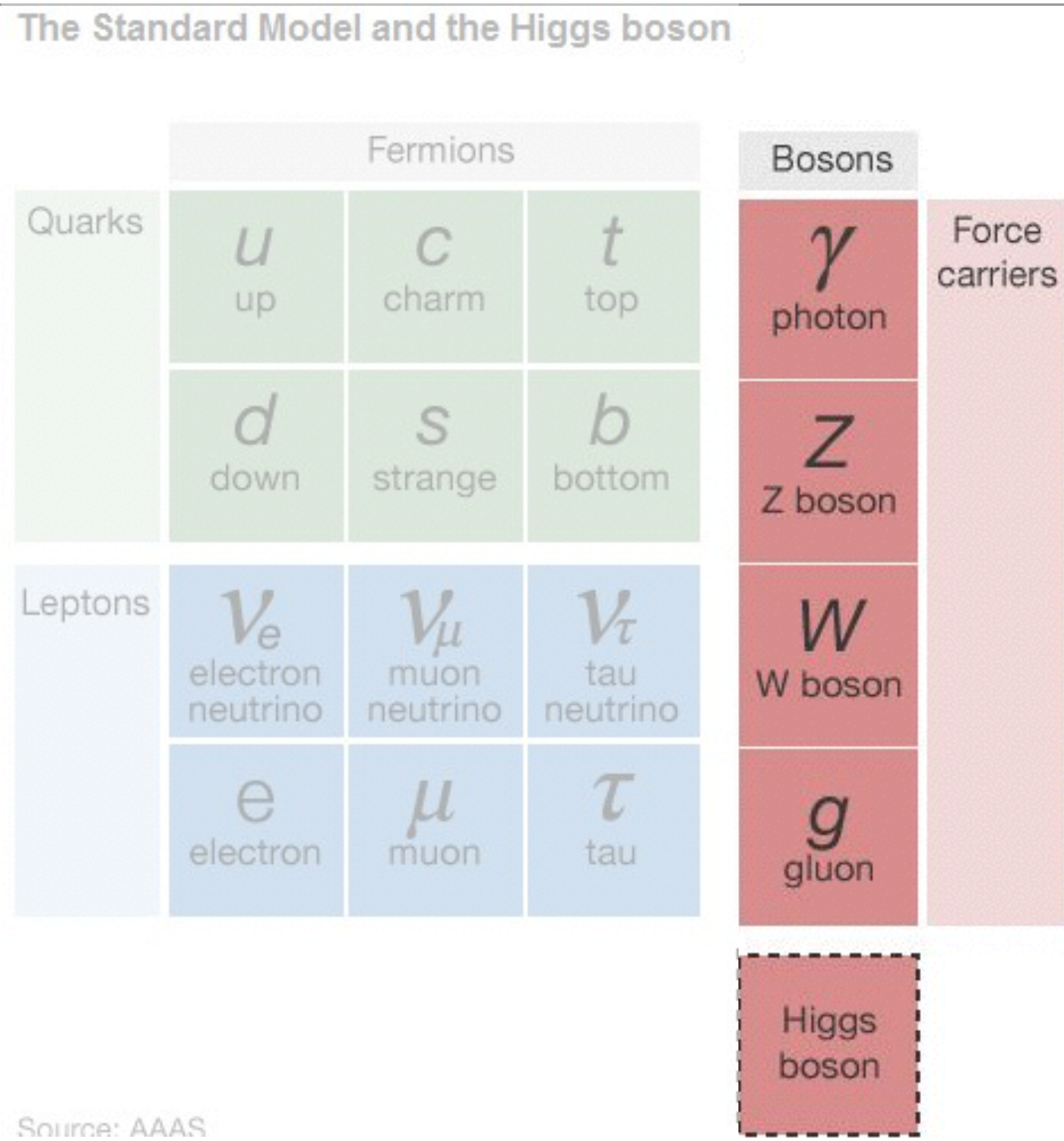


- Some DM/SM interaction is crucial for relic density (cosmic coincidence?)

- Other mediator forces are possible, but we assume dark sector fermions carry SM charge - because we can! (Neutral bound state; interactions suppressed by form factors.)

- Fairly natural for the lightest state to be the neutral one - for example, EM corrections lift the masses of π^+ over π^0, and would lift proton over neutron if m_u=m_d.

What kind of charge?



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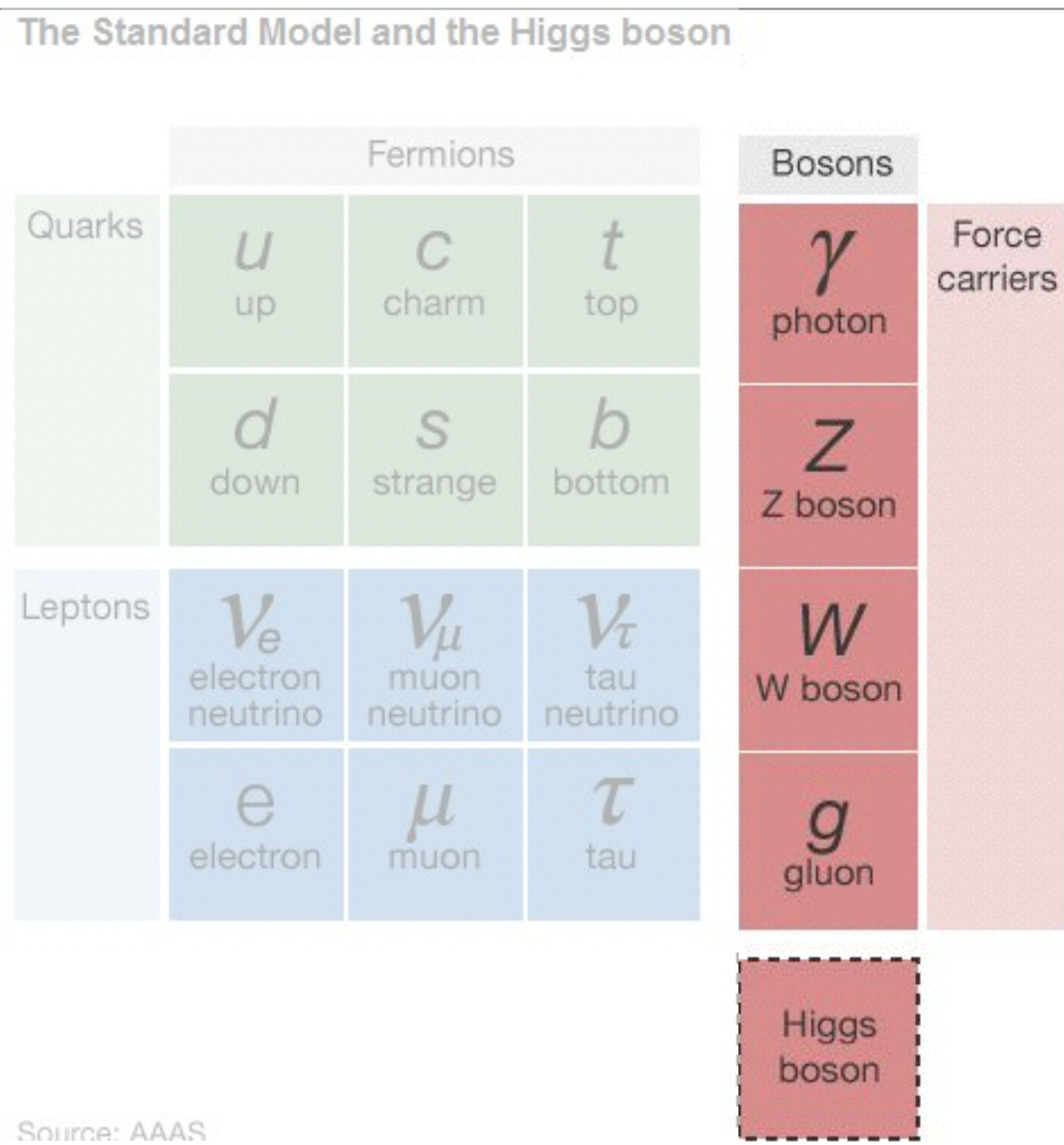

useful for meson decay

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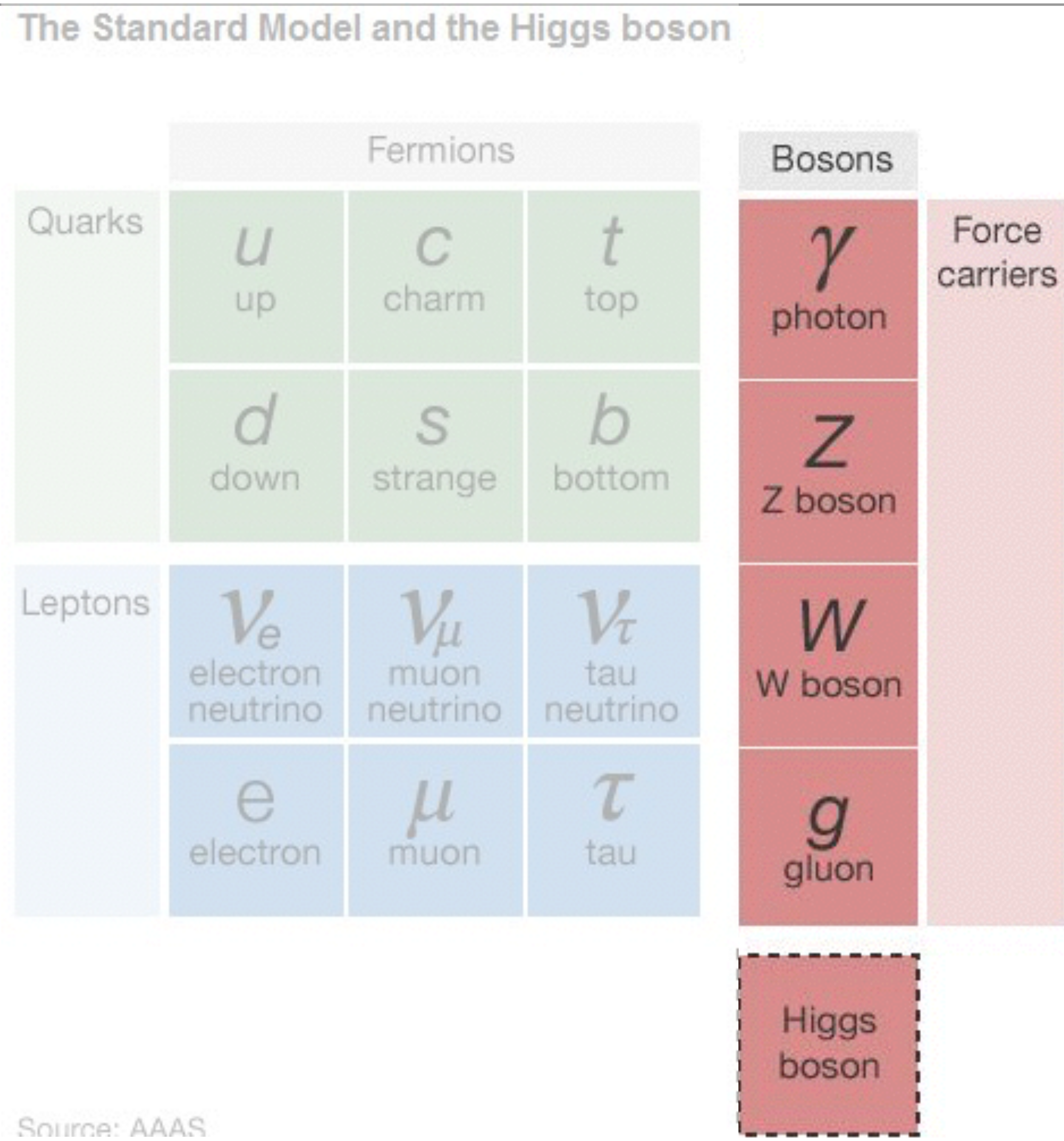

suppressed relative to γ

useful for meson decay

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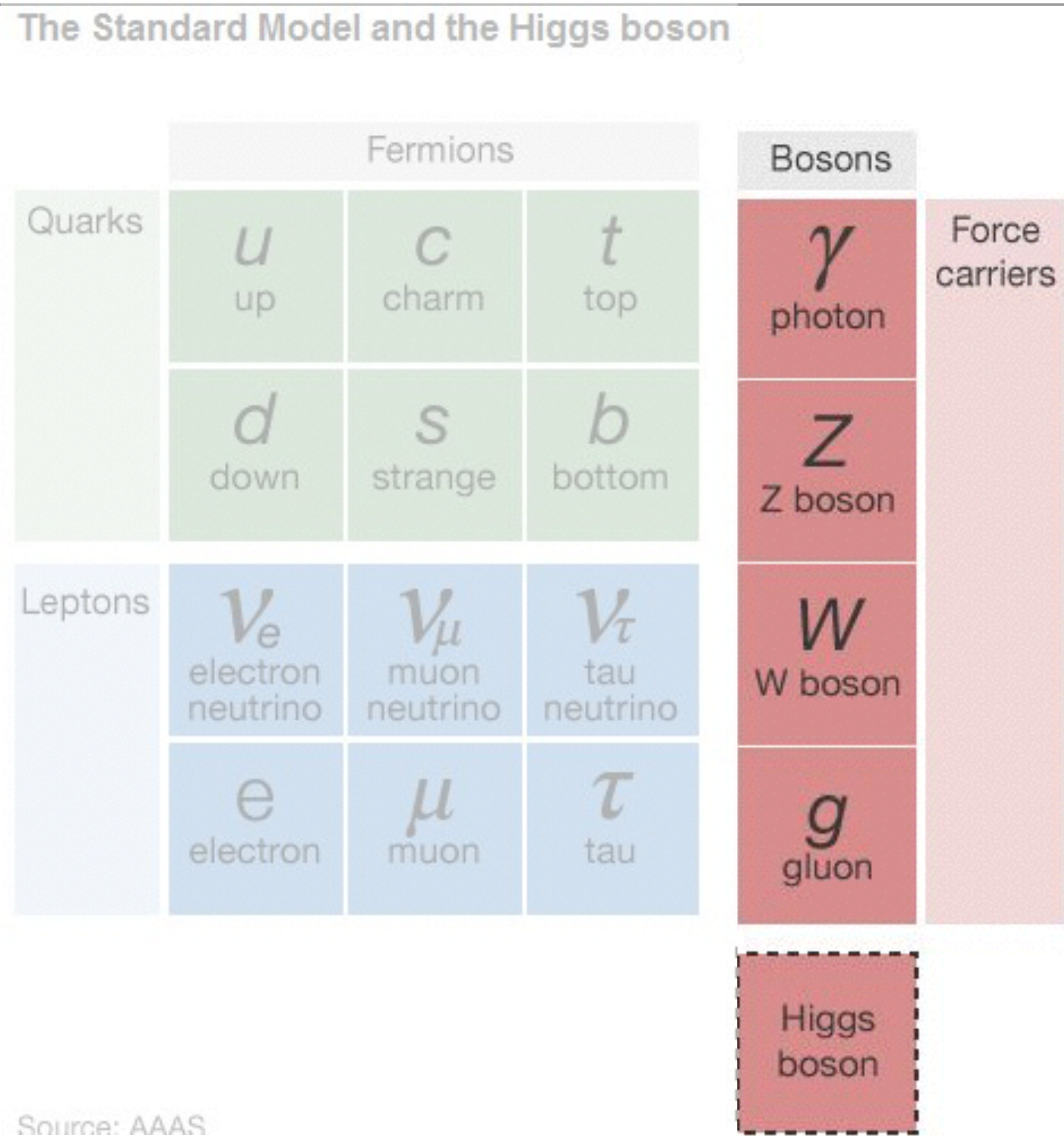

suppressed relative to γ

useful for meson decay

interesting…*

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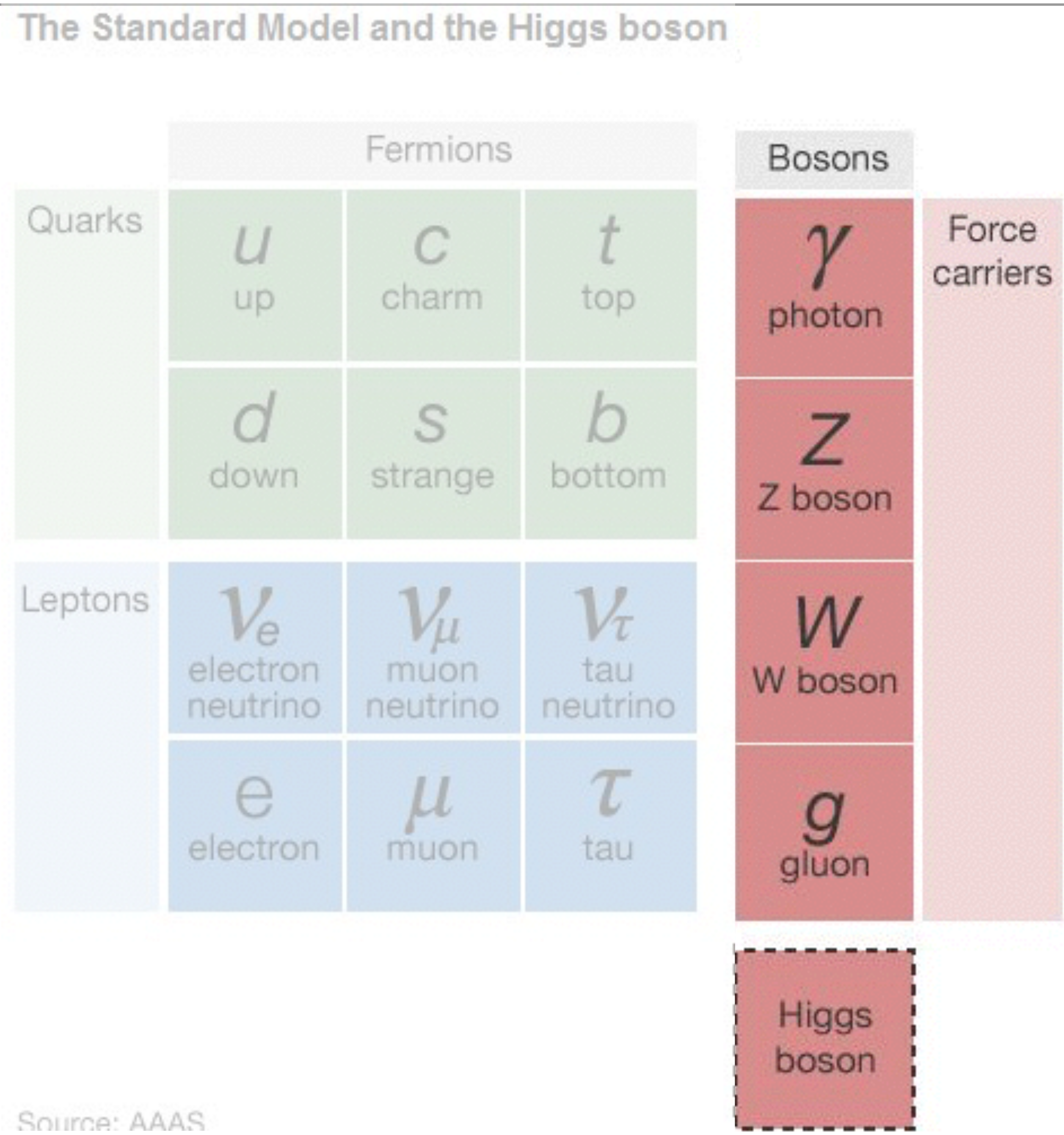

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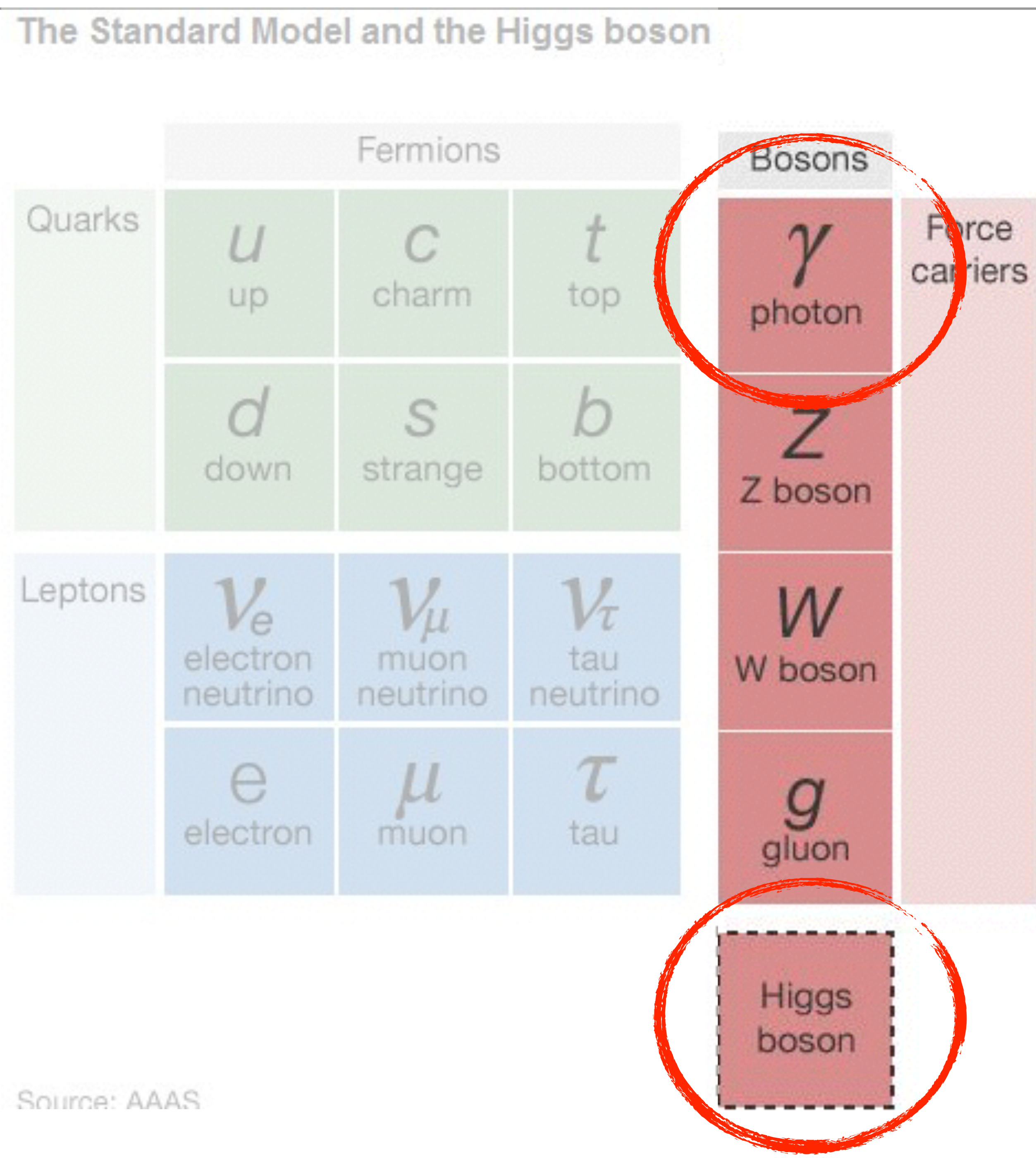
*Gluonic operators considered before in Bagnasco, Dine, Thomas **PLB 320 (1994) 99-104**. Similar to photon operators, but stronger bounds…could use an update! See also Godbole, Mendiratta, Tait (arXiv:**1506.01408**) for a simplified model.

What kind of charge?



<u>focus on these</u>

suppressed relative to γ

useful for meson decay

interesting…*

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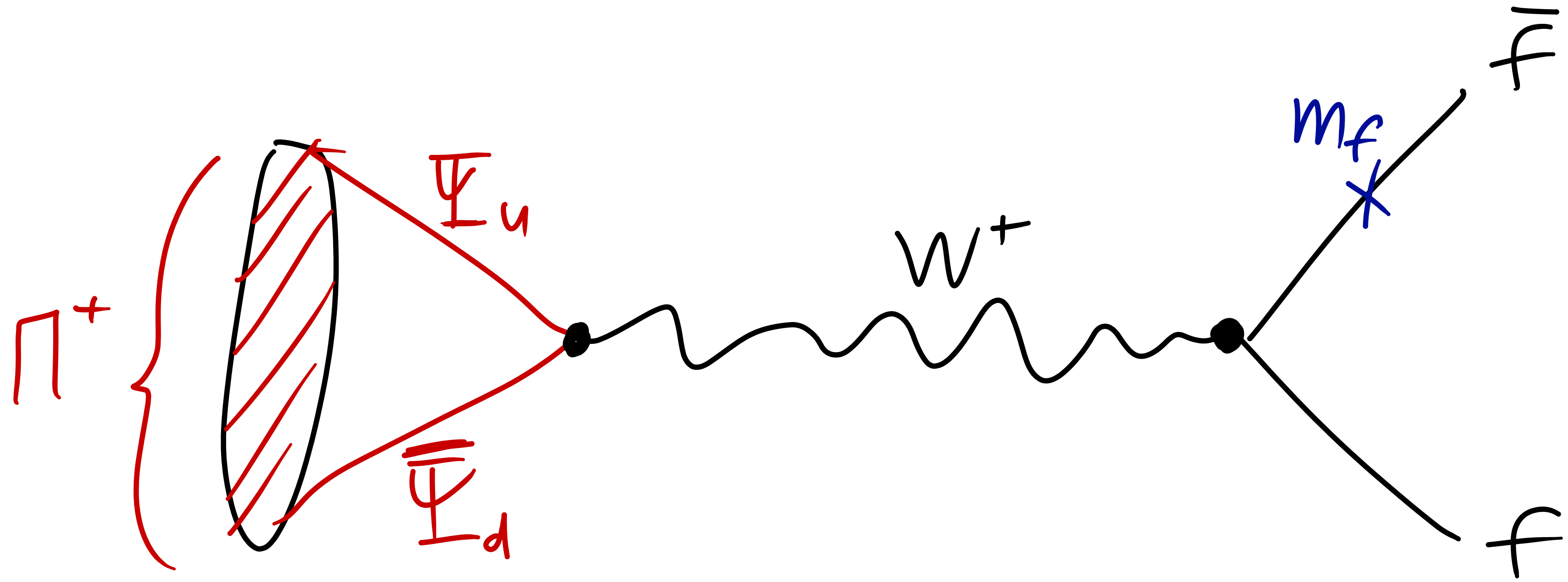
Brief aside: decays of charged mesons

- With SM charges in the dark sector, decay of many states to visible products is now allowed, e.g. for charged mesons:



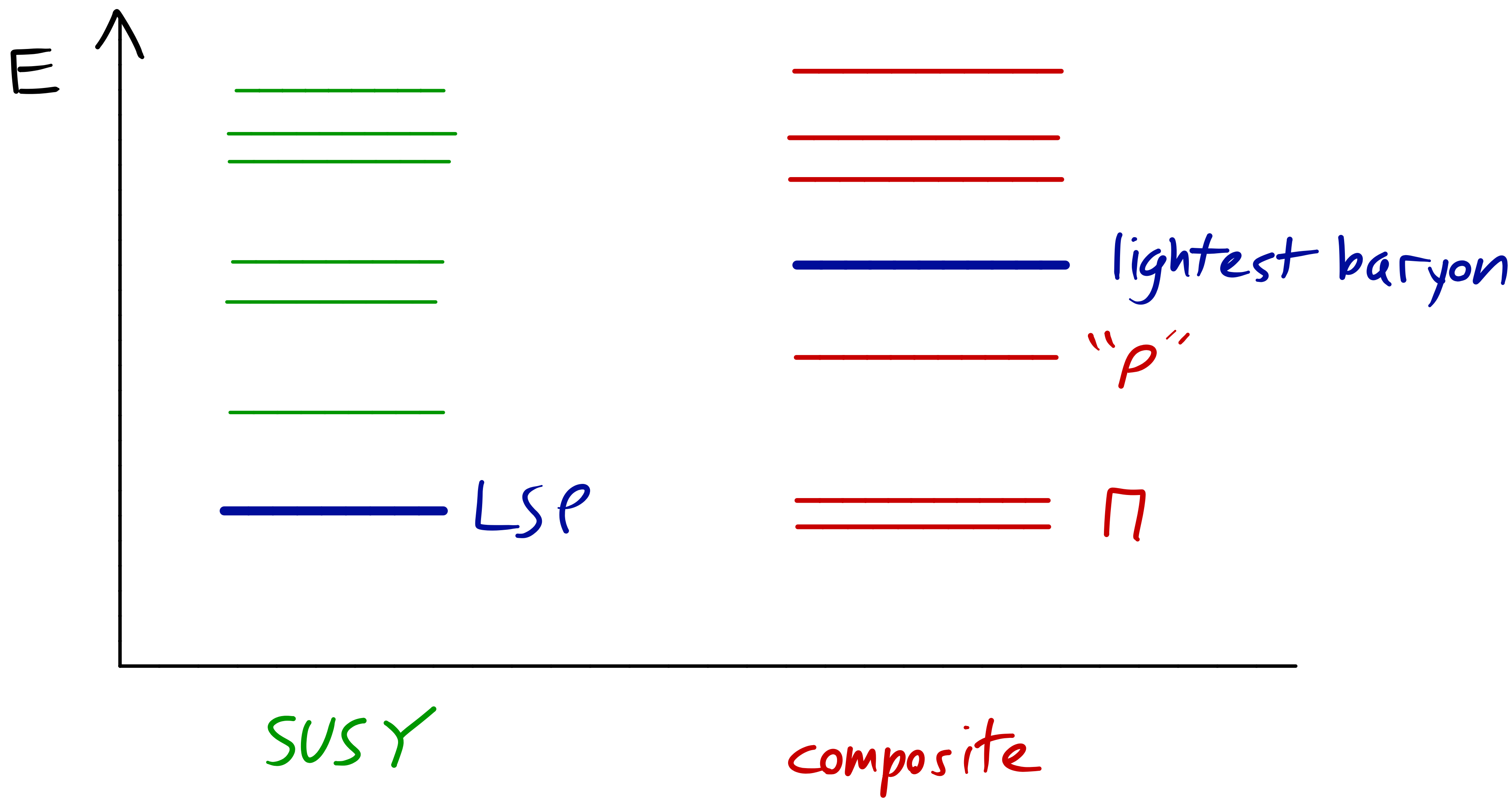
$$\langle 0 | j^{\mu}_{\text{axial}} | \Pi^{\pm} \rangle = i f_{\Pi} p^{\mu}$$

- 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:

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

- Robust bound from LEP stau searches, <u>$M_{\Pi} \gtrsim 90$ GeV</u>.

Comparison between typical SUSY DM and composite DM:



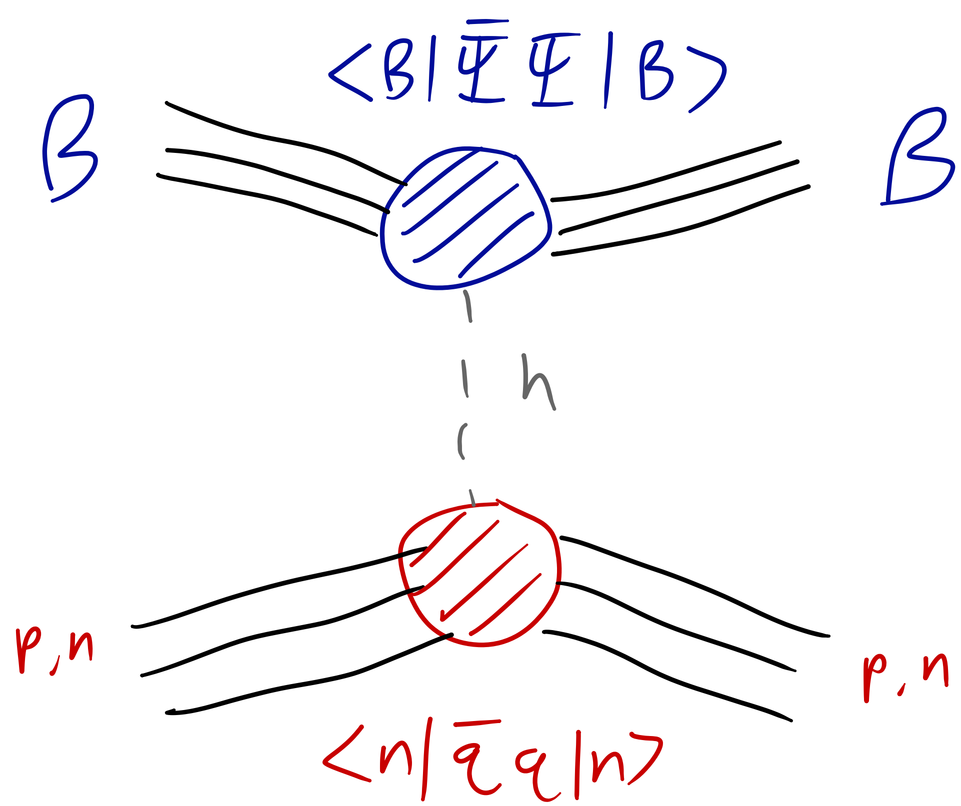
- DM is far from lightest particle in the new sector! Much harder to produce directly in colliders, so MET signals are greatly suppressed.
- On the other hand, presence of the much lighter and charged Π states gives strong bounds from complementary searches.

Direct detection: Higgs exchange

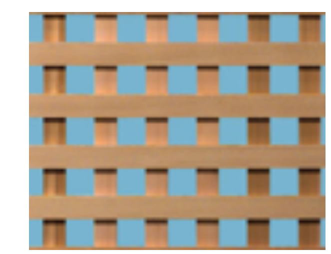
- If the dark-sector fermions couple to Higgs, then they will induce a dark baryon-Higgs coupling (sigma terms!)

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

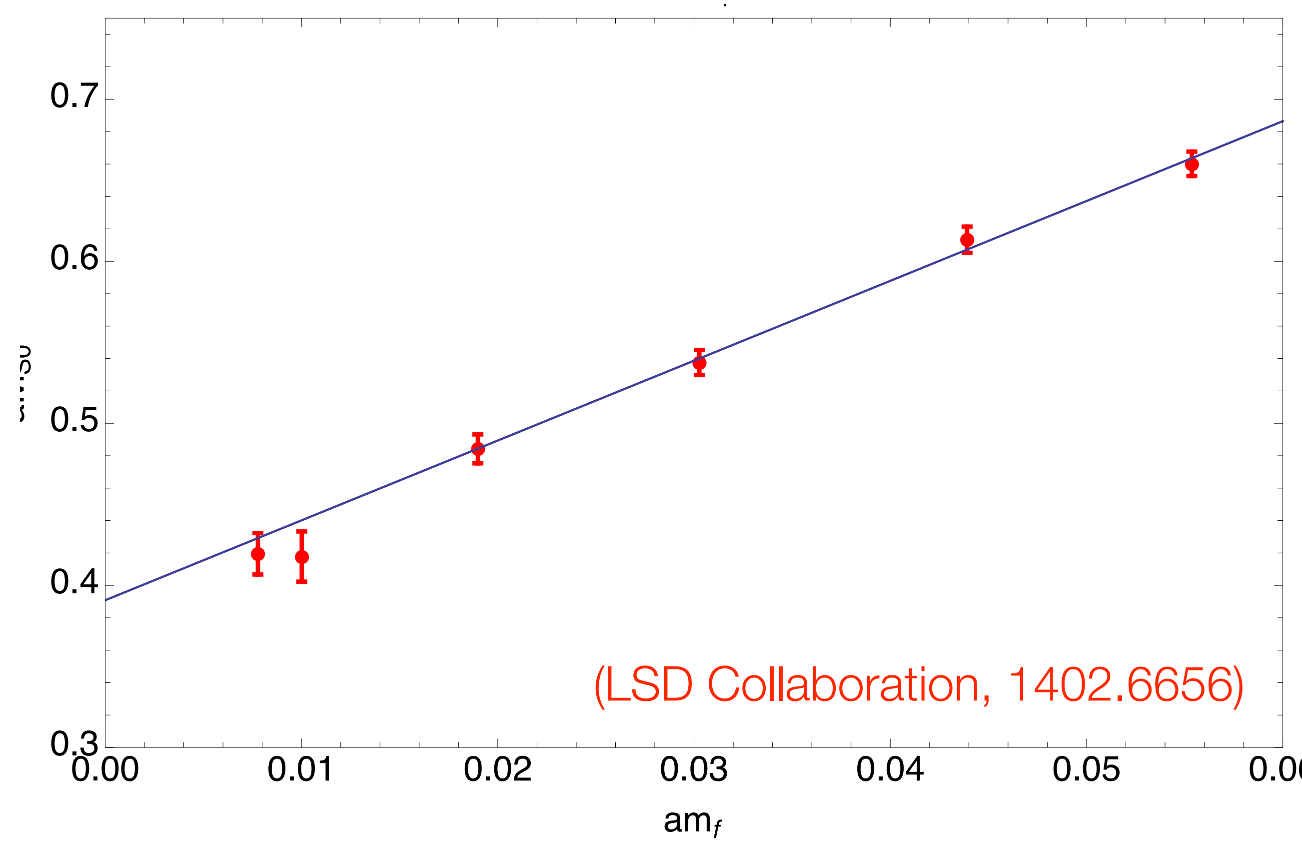
$$\langle B|m_f\bar{f}f|B\rangle = m_B f_f^B$$

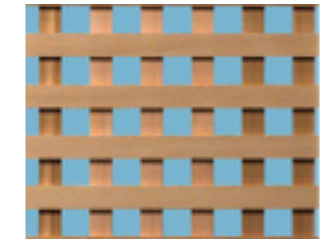


- Calculate on the lattice with Feynman-Hellman:



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





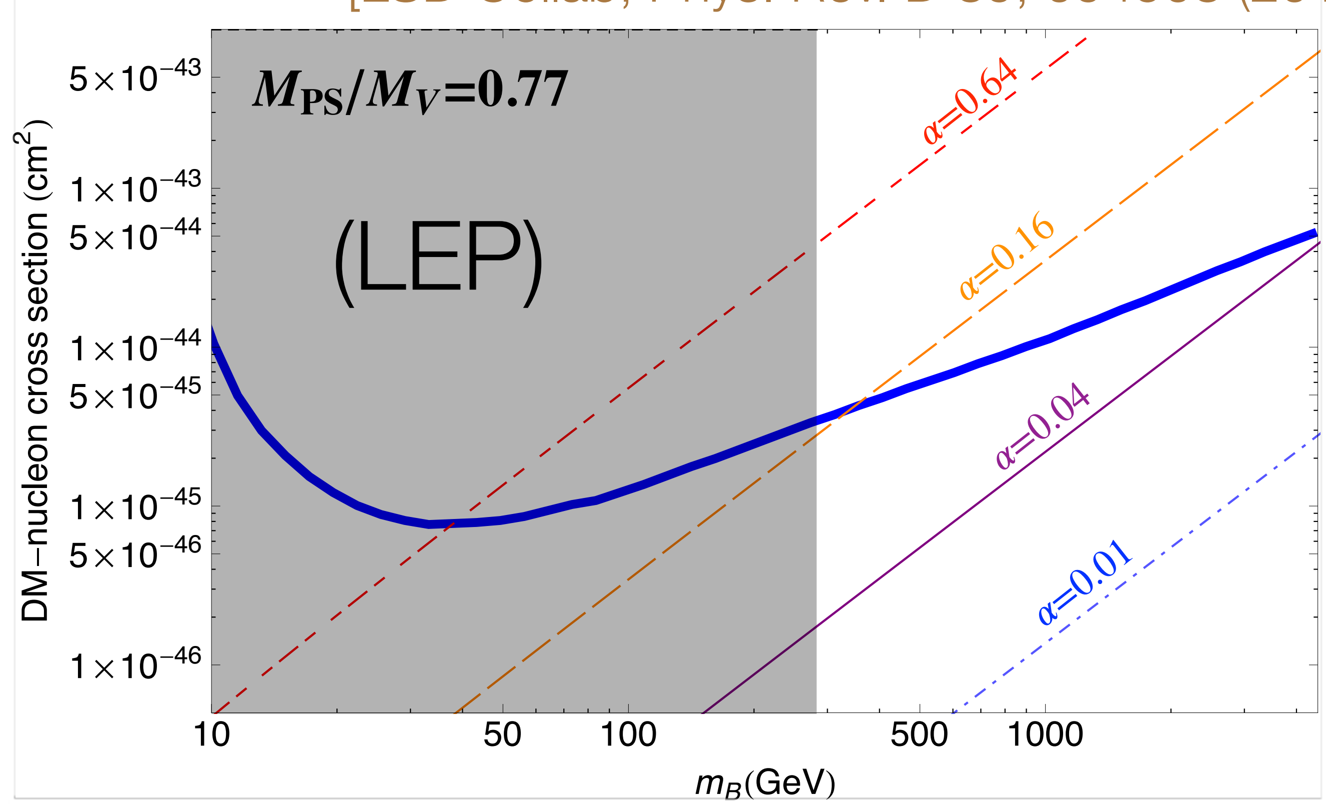
Experimental constraints on Higgs exchange

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

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

- 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)]



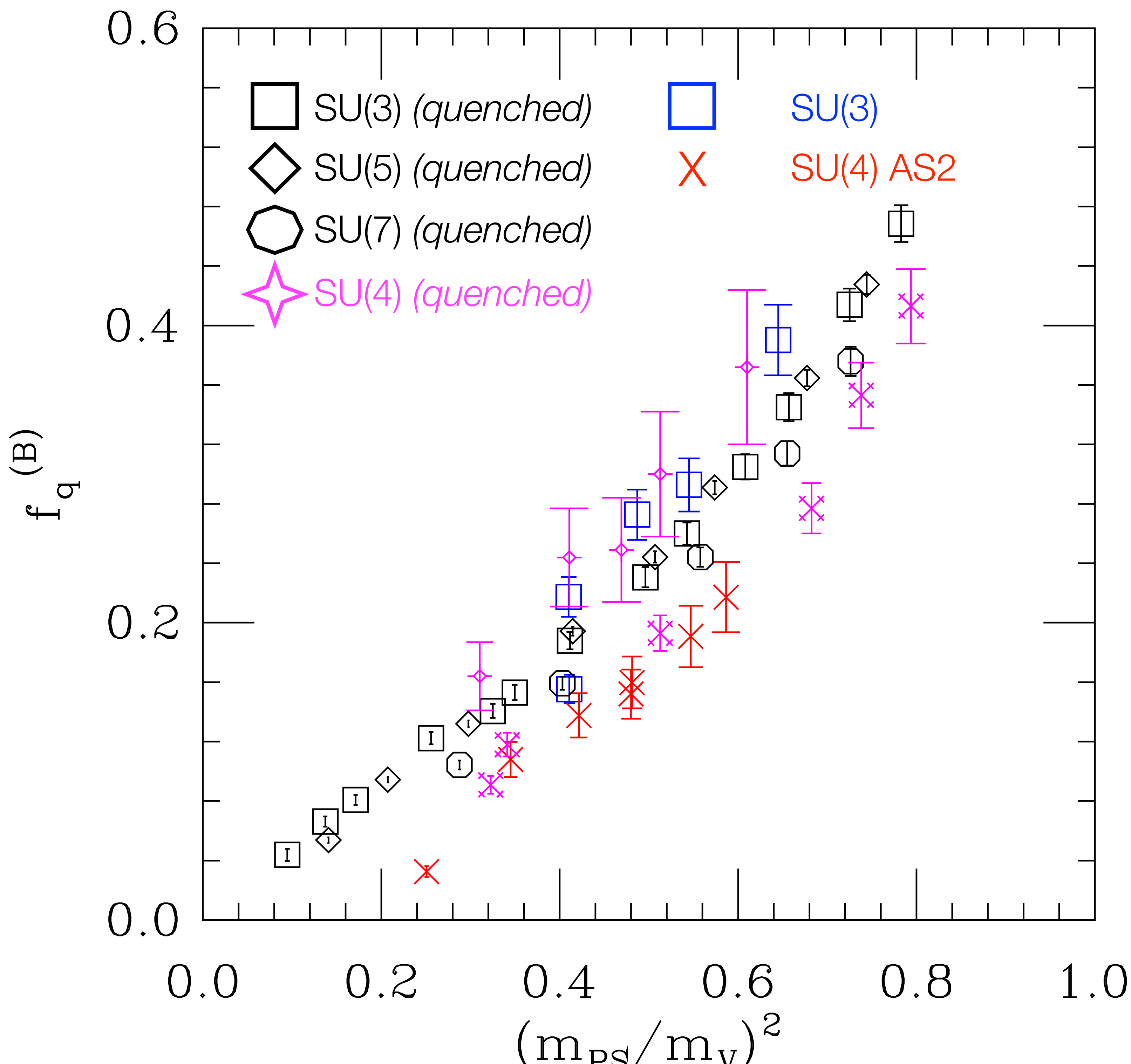
Experimental constraints on Higgs exchange

- 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 <u>may be fairly universal for different theories</u> in similar mass regimes (right)

- Statement that composite DM can't have mass generation purely from the Higgs mechanism 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 $\frac{1}{\Lambda_D^2}\bar{\chi}v_\mu\partial_\nu\chi F^{\mu\nu}$

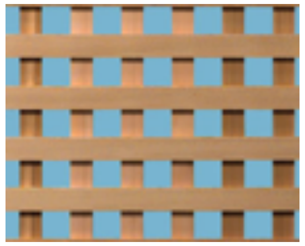
Dimension 7: polarizability $\frac{1}{\Lambda_D^3}\bar{\chi}\chi F_{\mu\nu}F^{\mu\nu}$

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

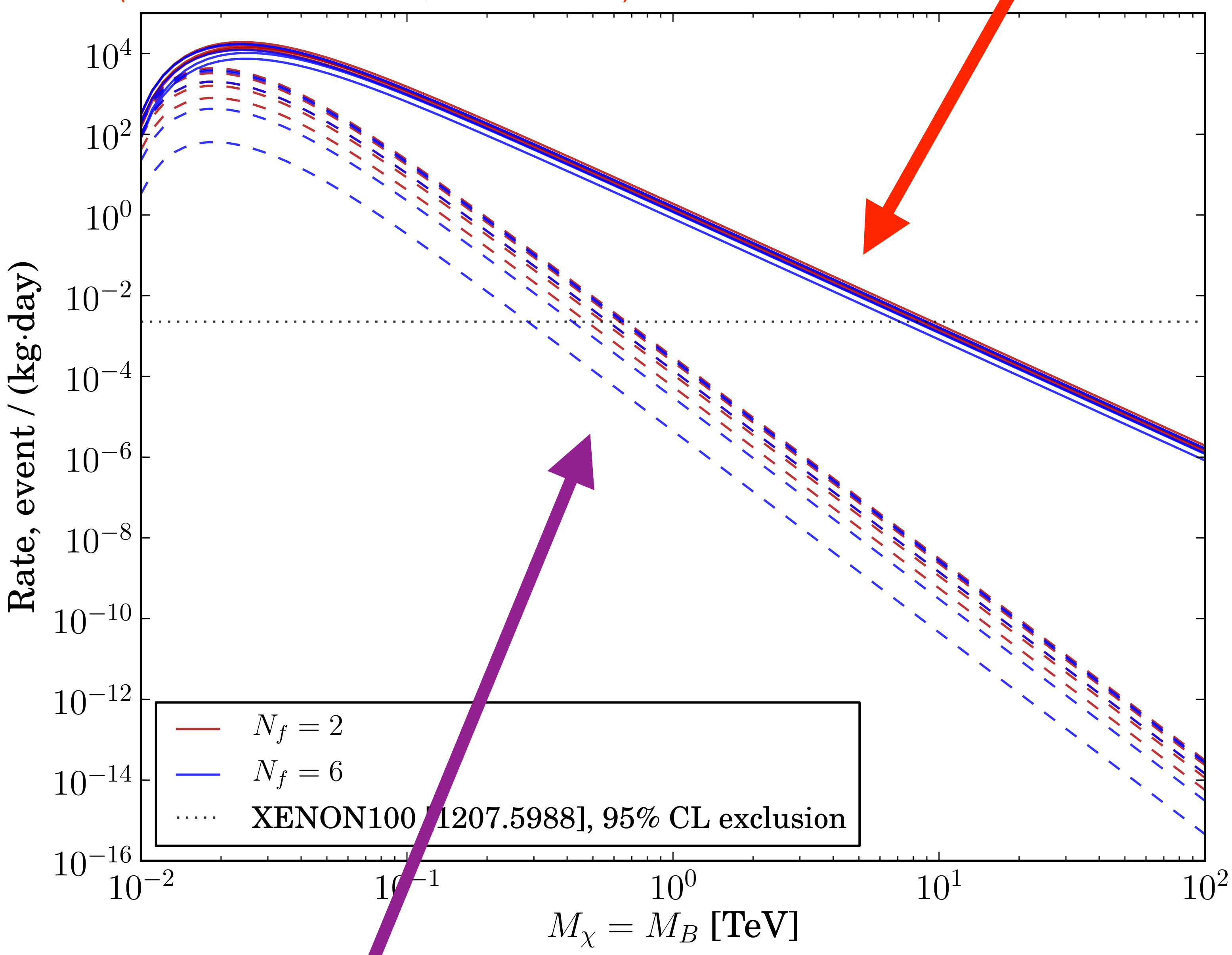
[Bagnasco, Dine and Thomas, PLB 320 (1994); Pospelov and ter Veldhuis, PLB 480 (2000)]

(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: exchange U,D

- Another model: "stealth dark matter", based on SU(4) gauge theory: LSD collaboration, arXiv:1503.04203

- Leading photon interaction is electromagnetic polarizability in these models

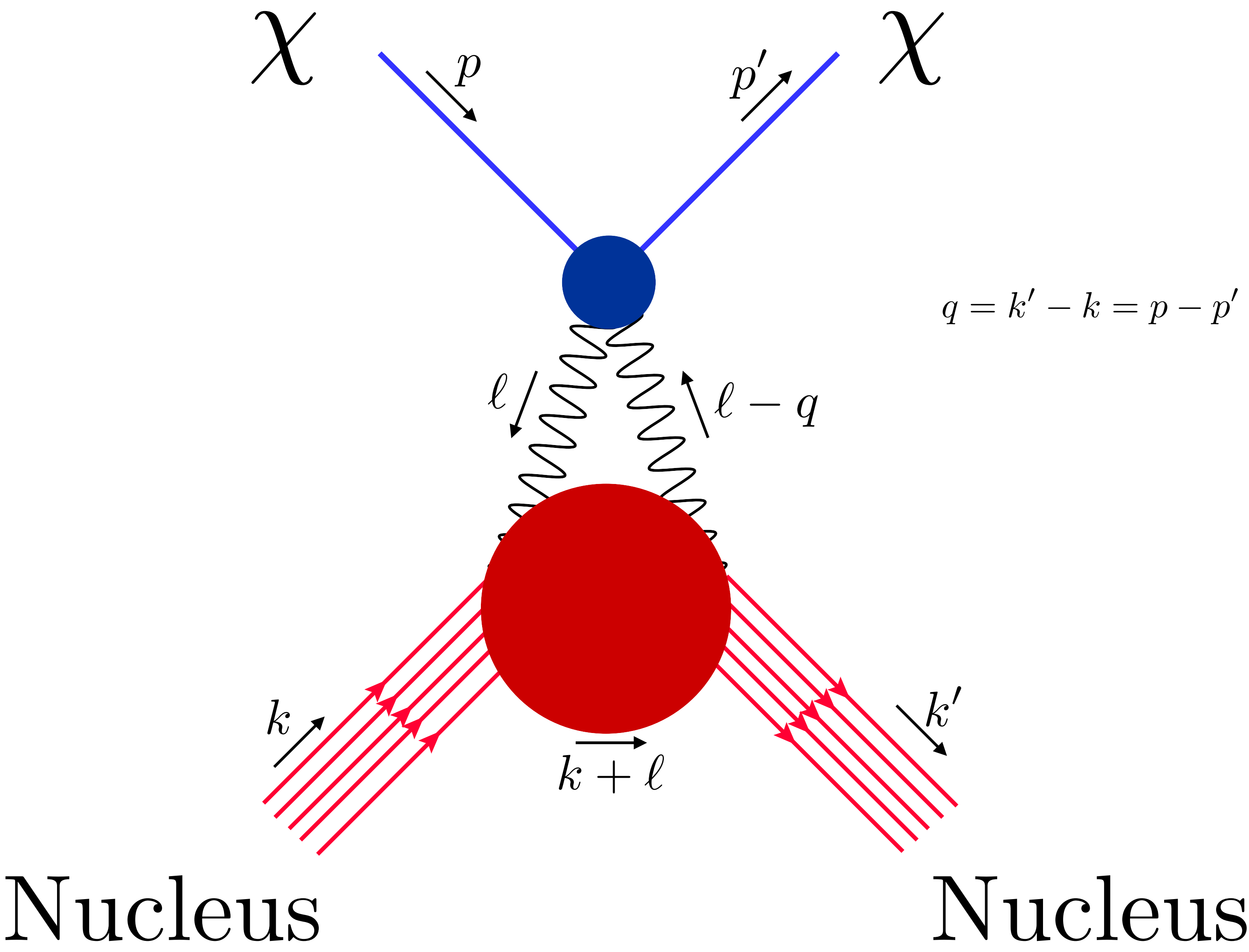
(see also: Weiner and Yavin, arXiv:1209.1093)

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 0vββ-decay nuclear MEs.)
- Enhancement due to excited nuclear states possible?

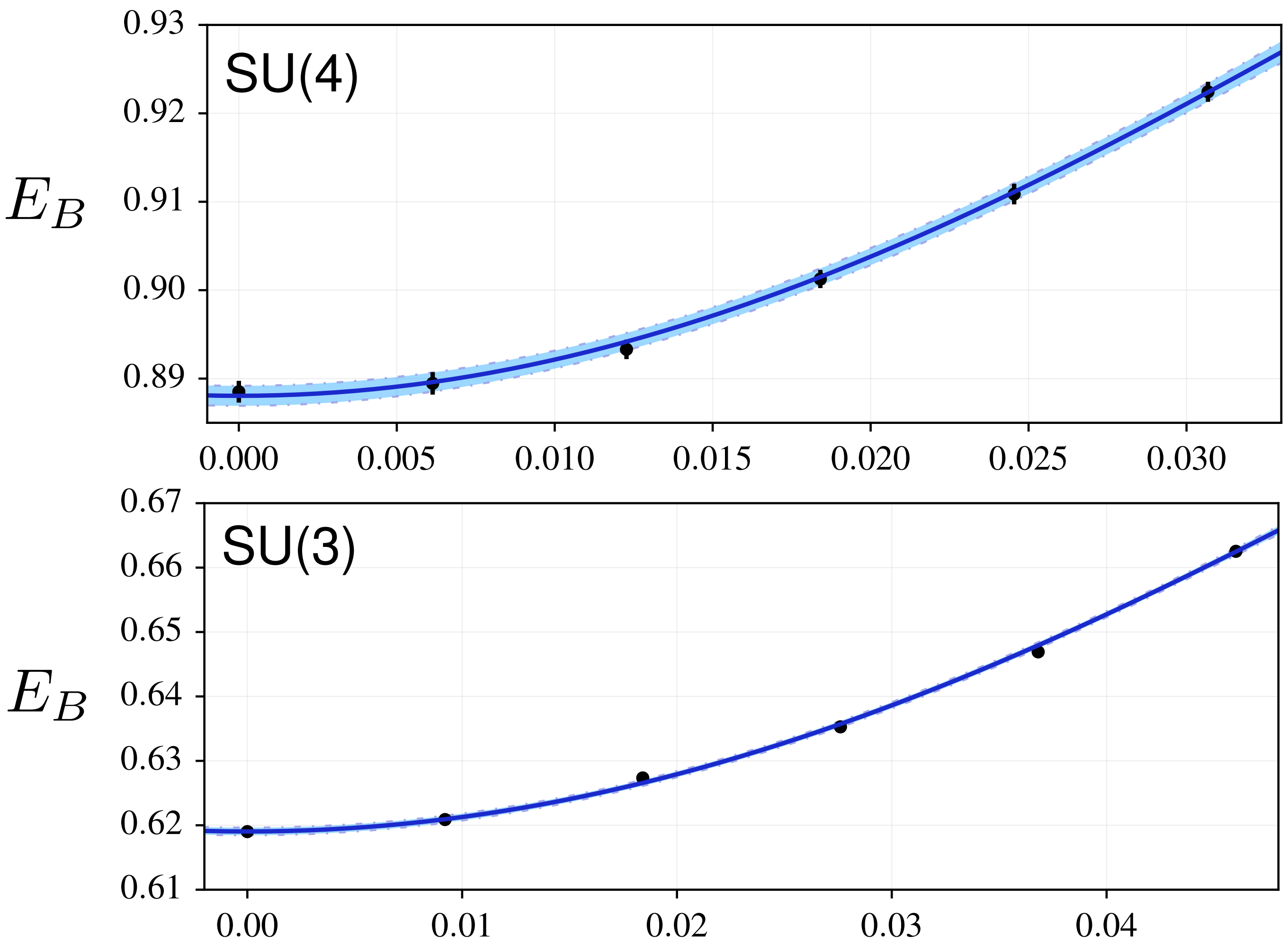


$q = k' - k = p - p'$

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

(see also: arXiv:1511.04370 for SU(2) polarizability calculation)

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

(LSD Collaboration, arXiv:1503.04205)

- Numerical study of polarizability in SU(4) gauge theory - "stealth dark matter" model. (LSD collab, arXiv:1503.04203)
- Technique pioneered by Detmold, Tiburzi, Walker-Loud (arXiv:1001.1131)
- Measure response to applied background field E (quadratic Stark shift)

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

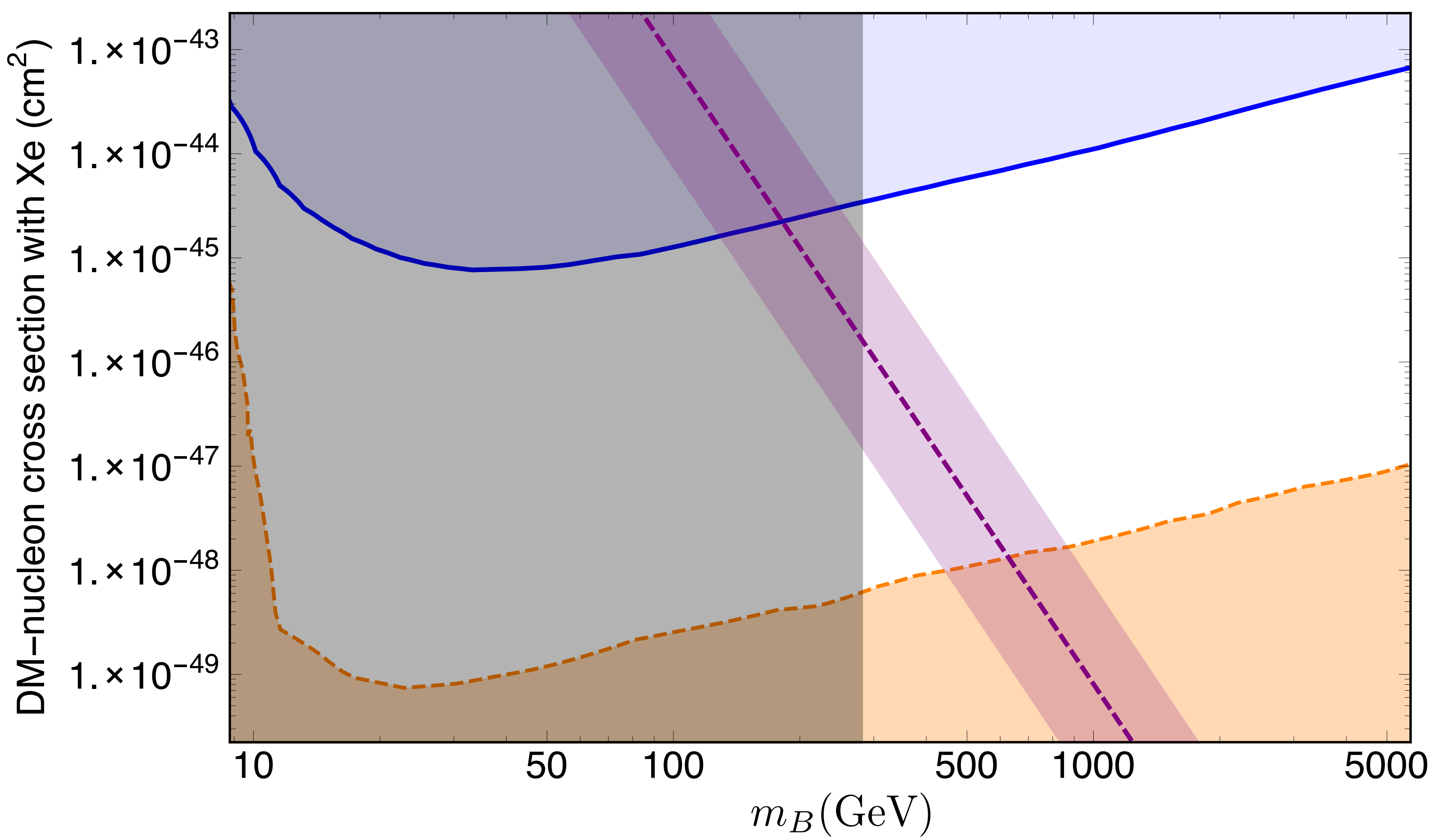
- Comparable results for SU(3) and SU(4), in units of m_B.

(LSD Collaboration, arXiv:1503.04205)

Direct-detection bound from polarizability

LUX direct-detection bound

LEP bound on charged stealth mesons



DM cross-section through polarizability*

expected cosmic neutrino background

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

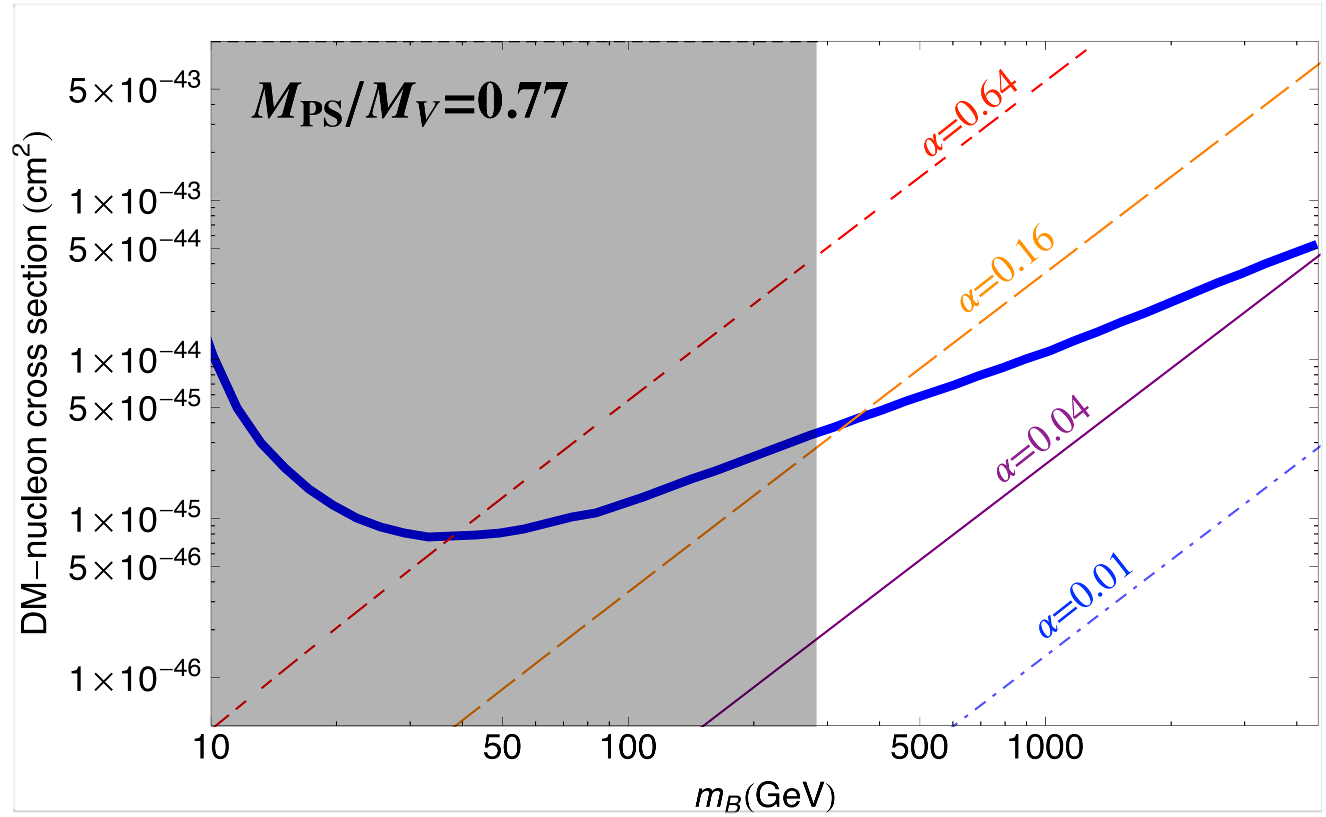
*Hardy, Lasenby, March-Russell, West, arXiv:1411.3739
Krnjaic and Sigurdson, arXiv:1406.1171
**Detmold, McCullough, Pochinsky, arXiv:1406.2276 and 1406.4116

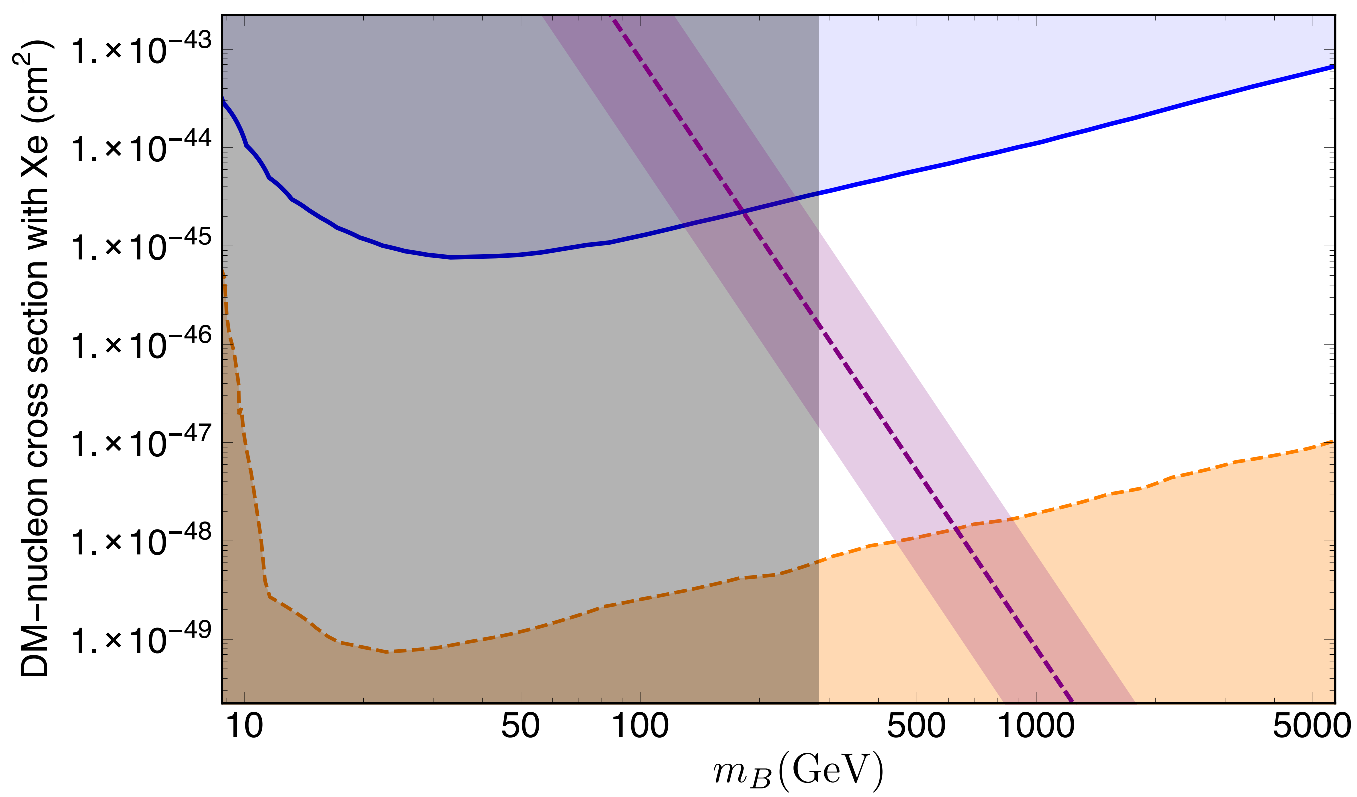
Open Questions for the lattice

- **How generic is formation of dark nuclei?*** If they form, does the spectrum terminate at low A, or do they become enormous? (Pioneering lattice study in SU(2)**)
- **Scattering cross-sections:** pi-pi, pi-N, N-N. What about multiplicity of final states?
- What are the order and temperature of the **dark-sector confinement phase transition?**
- What are the **meson form factors** for collider production? (at threshold, timelike!)
- **How do any of the above change** when the underlying strongly-coupled theory is different? (Matching to large-N_c, for example?)
- For glueballs, **how much of the pure-gauge theory can we solve?** Spectrum (mostly well-known), decay constants (a handful known), three-point interactions (unknown), scattering and annihilation (most interesting, but ???)

Conclusions

- Composite dark matter models are viable, interesting, but can be hard to study due to strong coupling - lattice is a great tool here.
- Lots of room to explore different theories and quantities on the lattice, no need for near-conformality!
- Interesting bounds are being placed on direct detection operators, but more work is needed, especially focused on DM-DM interactions (scattering and annihilation)





Backup slides

Relic density I: asymmetric origin

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

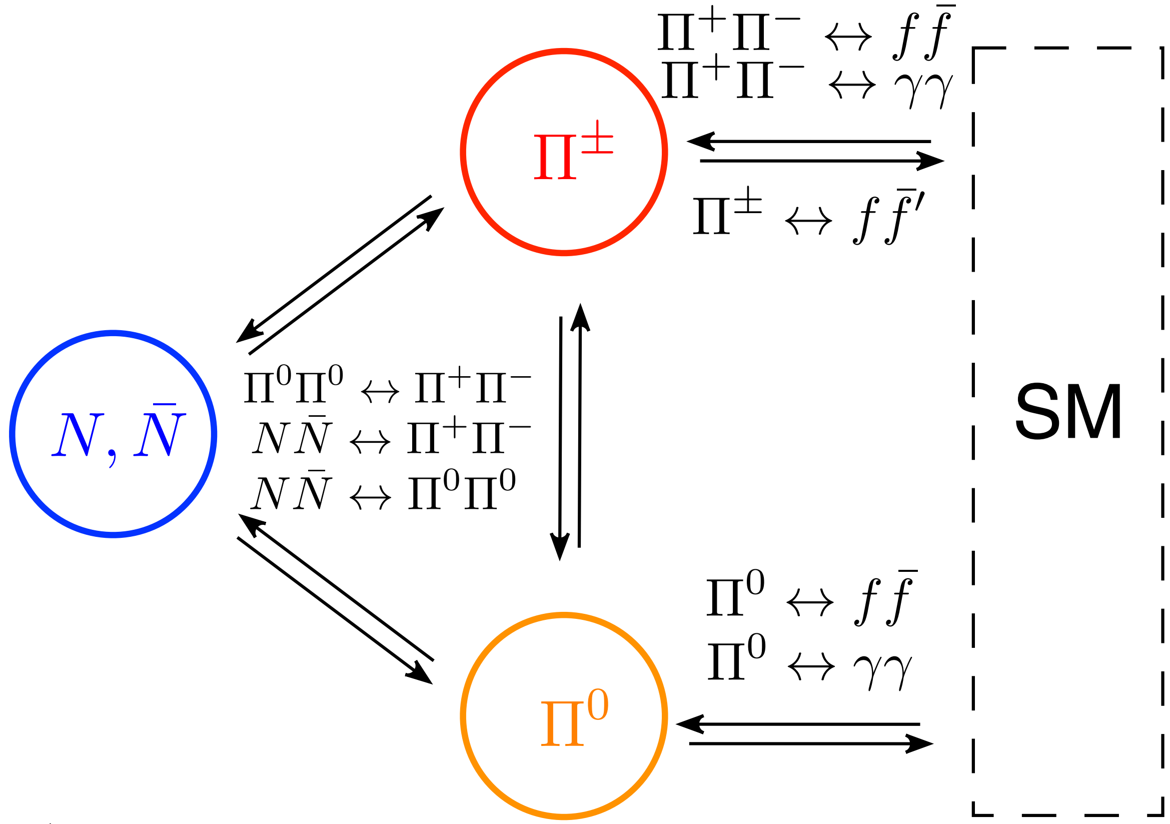
- Electroweak sphaleron equilibrates primordial asymmetries in baryon, lepton, and dark baryon number:

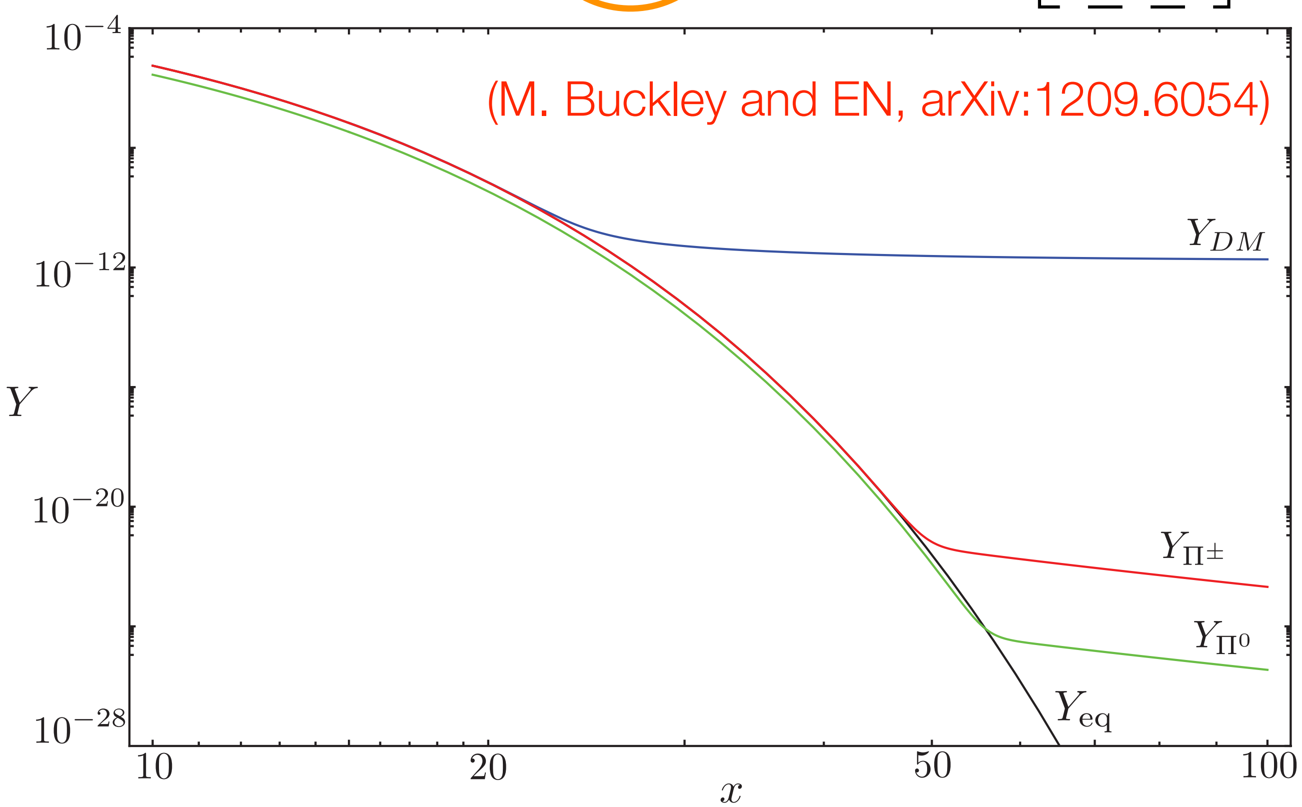
$$n_B - n_{\bar{B}} \simeq n_L - n_{\bar{L}} \simeq n_D - n_{\bar{D}}$$

- 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

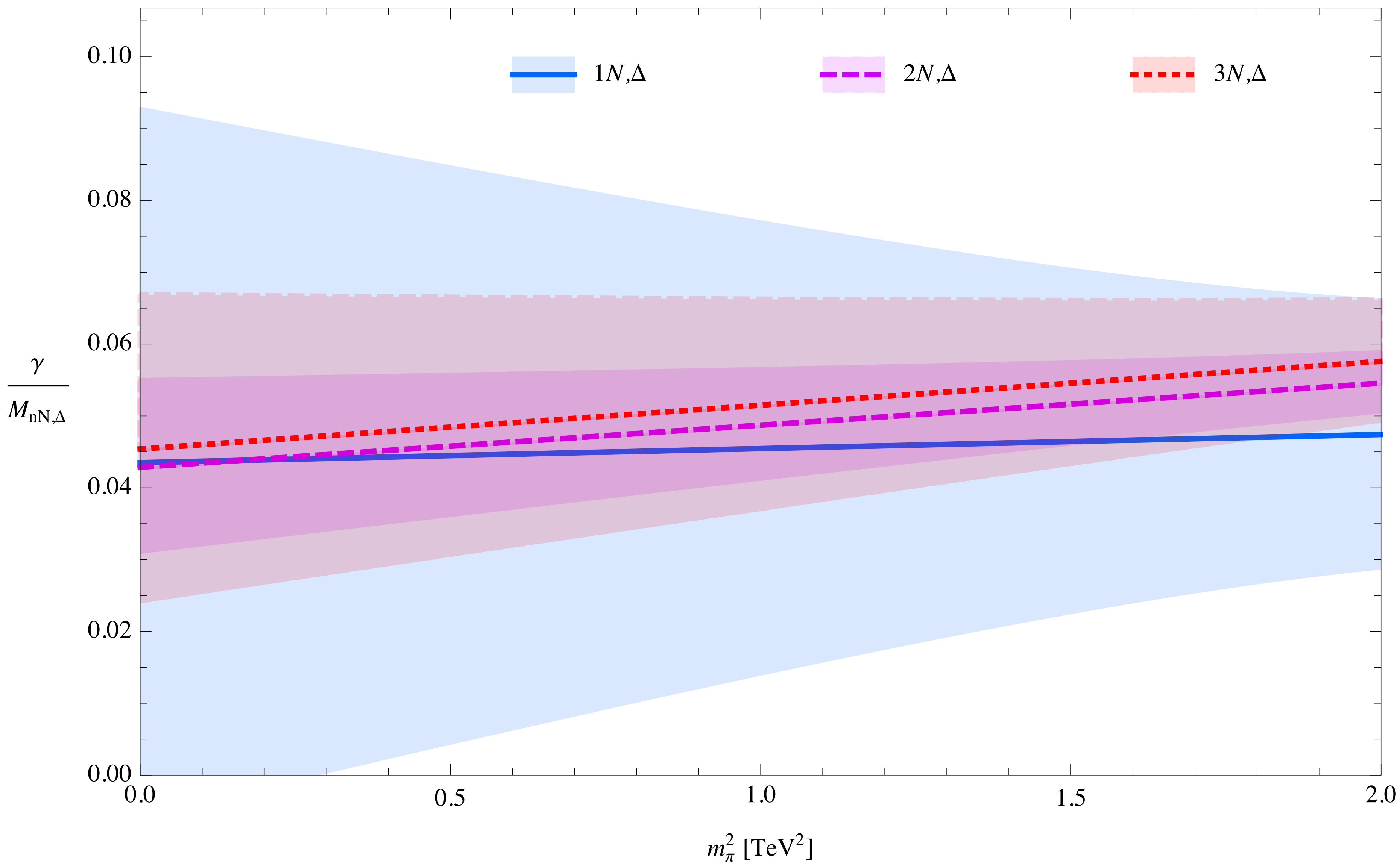




- Basic picture: charged states interact strongly with SM thermal bath, so dark matter freeze-out is set by DM annihilation cross-section
- If all states are PNGBs, then the resulting DM mass can be small (as in SU(2) example to the left).
- For dark baryons, dimensional analysis or partial-wave unitarity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

Dark nuclei?

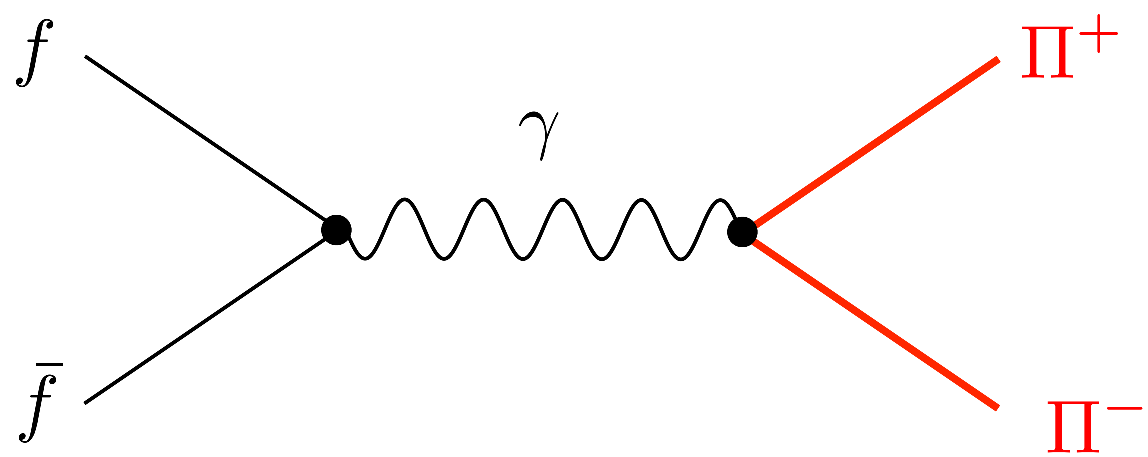
(Detmold, McCullough and Pochinsky, Phys.Rev. D90 (2014) 11, 114506 and 115013)

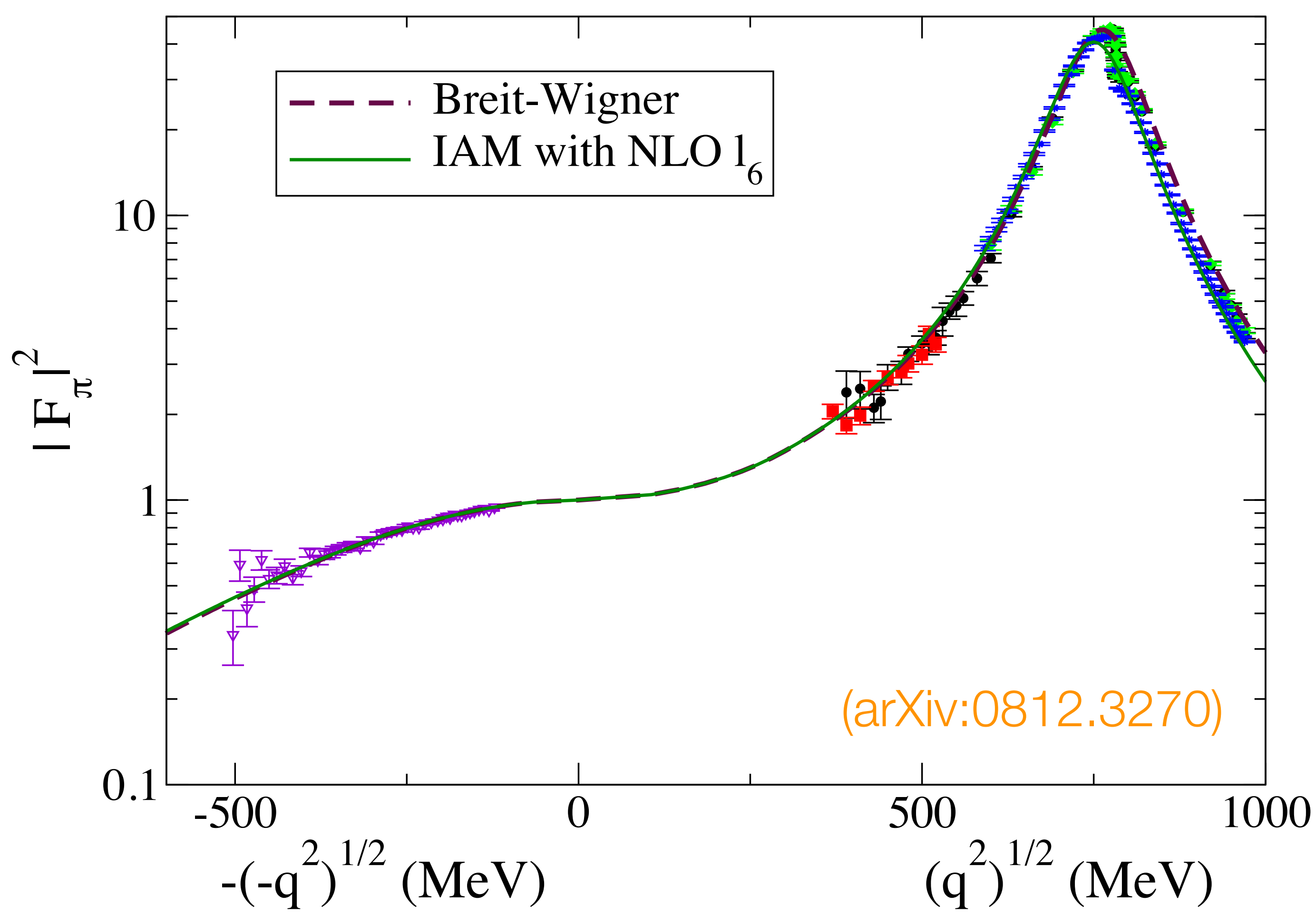


- Calculation of nuclear binding energies for **SU(2)** composite dark matter model reveals J=1 nuclear bound states!
- Points to ubiquity of nuclei in strongly-coupled gauge theories? Important consequences for dark matter models where nuclei can form!

- "Dark nuclear" processes can have rich phenomenology in early-universe cosmology, stellar physics, and more; binding energy of nuclei gives an additional physical scale
- See also: G. Krnjaic and K. Sigurdson, arXiv:1406.1171
  E. Hardy, R. Lasenby, J. March-Russell, S. West, arXiv:1411.3739 and 1504.05419

Meson production





- Distinctive collider signature: 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…calculations of “rho” properties can be used with vector-meson dominance as a start?

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

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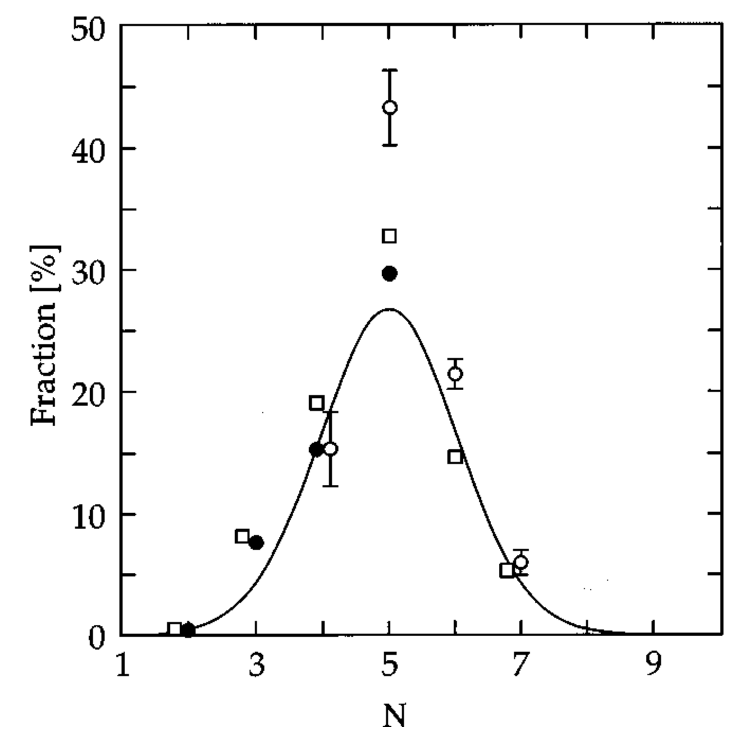

FIG. 1. Pion multiplicity distribution for $\bar{p}p$ annihilation at rest in liquid hydrogen: □, statistical distribution; ●, data; ○, estimates from Ghesquière (1974). The curve is a Gaussian fit assuming $\langle N \rangle = 5$.

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

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Results

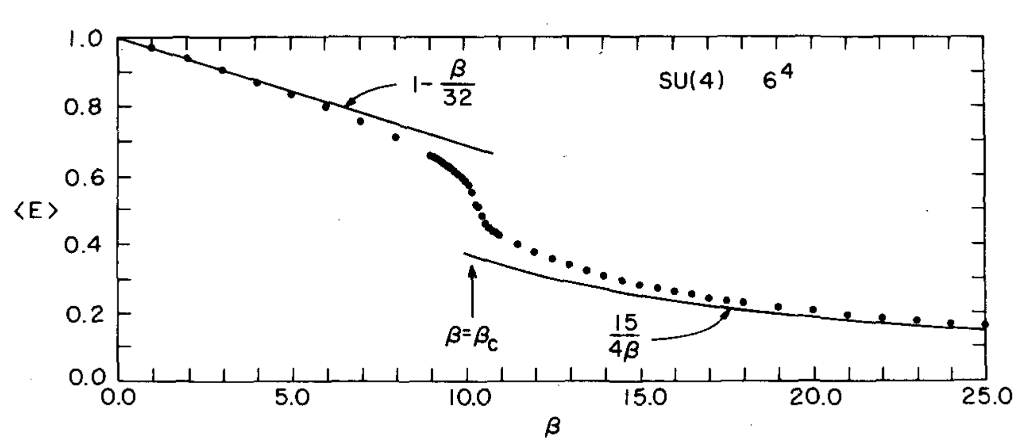
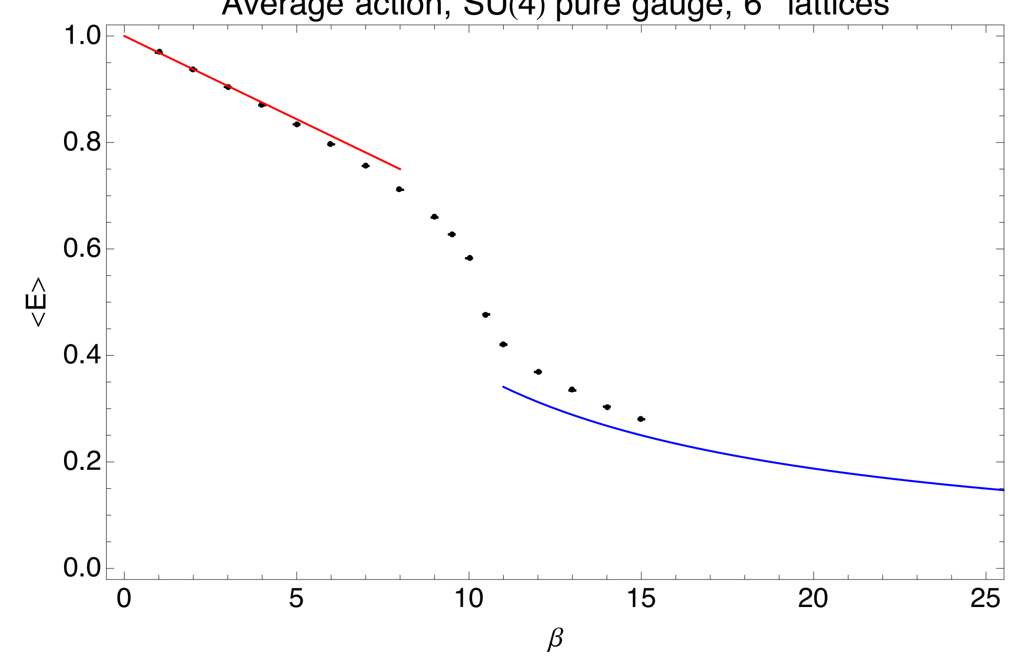
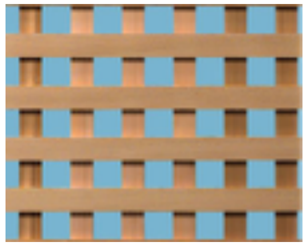


Fig. 10. The average action per plaquette $\langle E \rangle$ for pure SU(4) gauge theory on a 6^4 lattice as a function of the inverse temperature β. The curves represent the leading-order high- and low-temperature expansions of eqs. (1) and (3), respectively.

Our Code

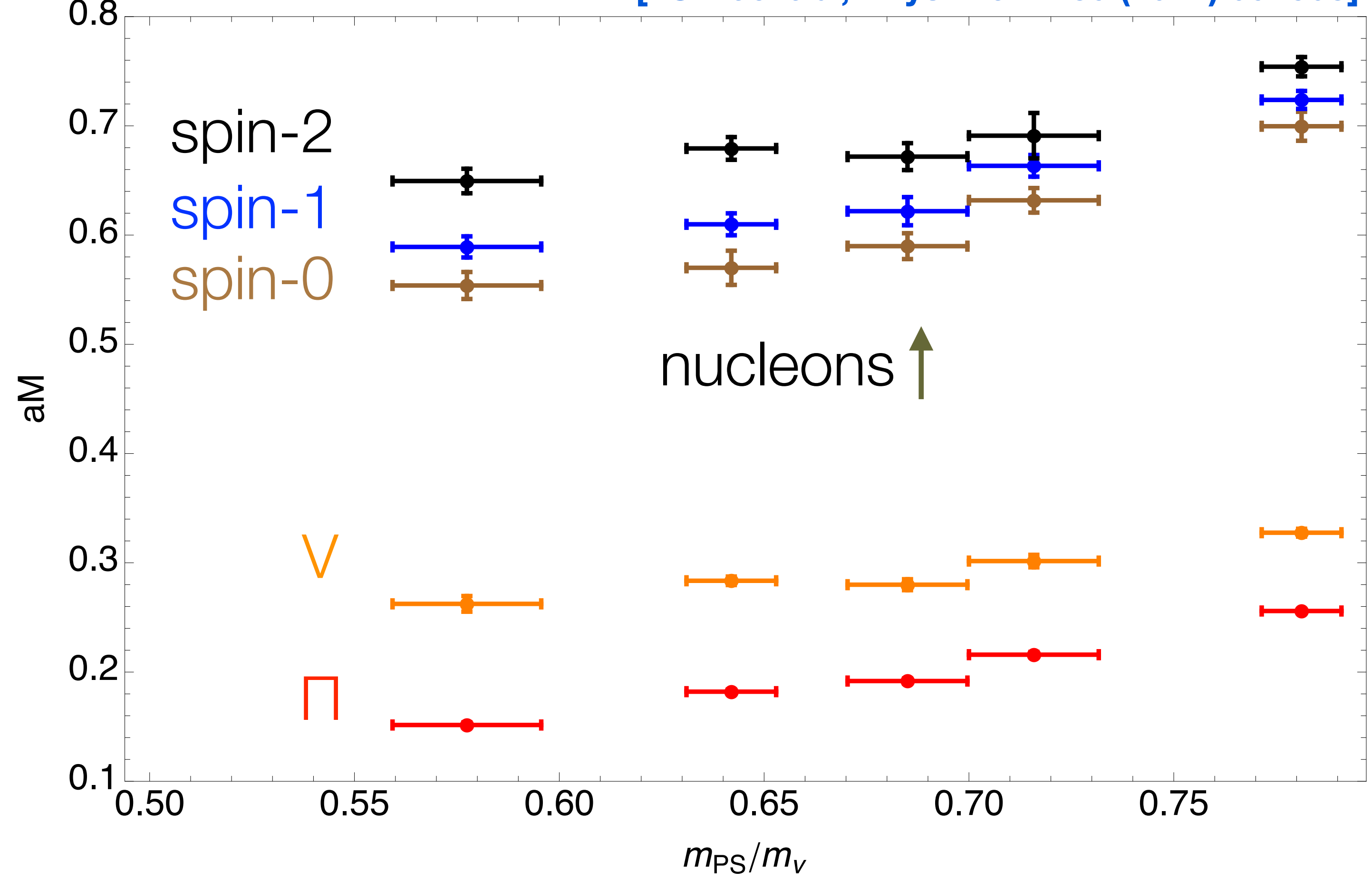


Spectrum



- 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]



SU(3) polarizability vs. the PDG

- Our polarizability differs from the PDG convention:

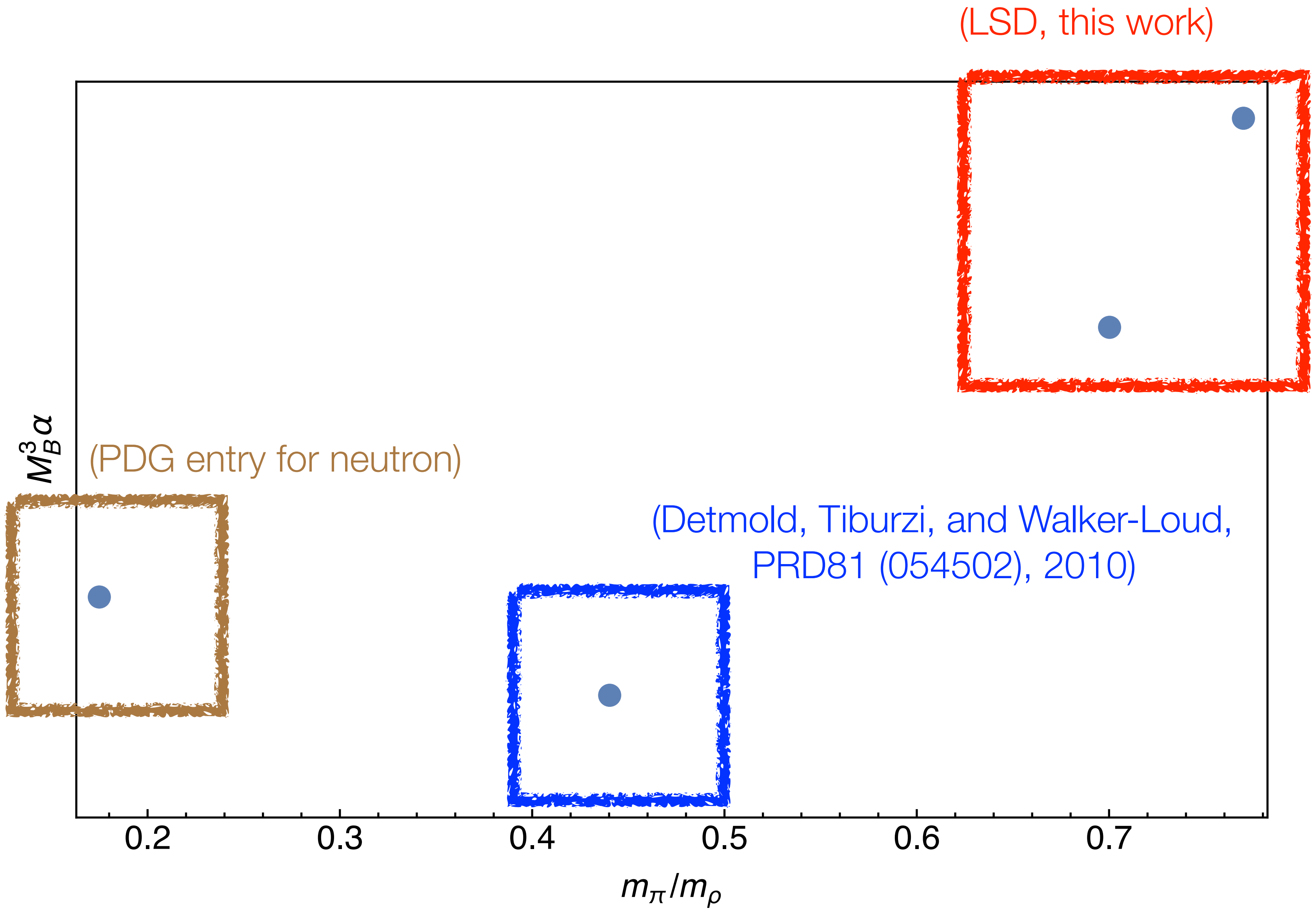
$$\alpha_E = C_F/\pi$$

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

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

$$m_B \sim C + D m_\pi^2$$

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

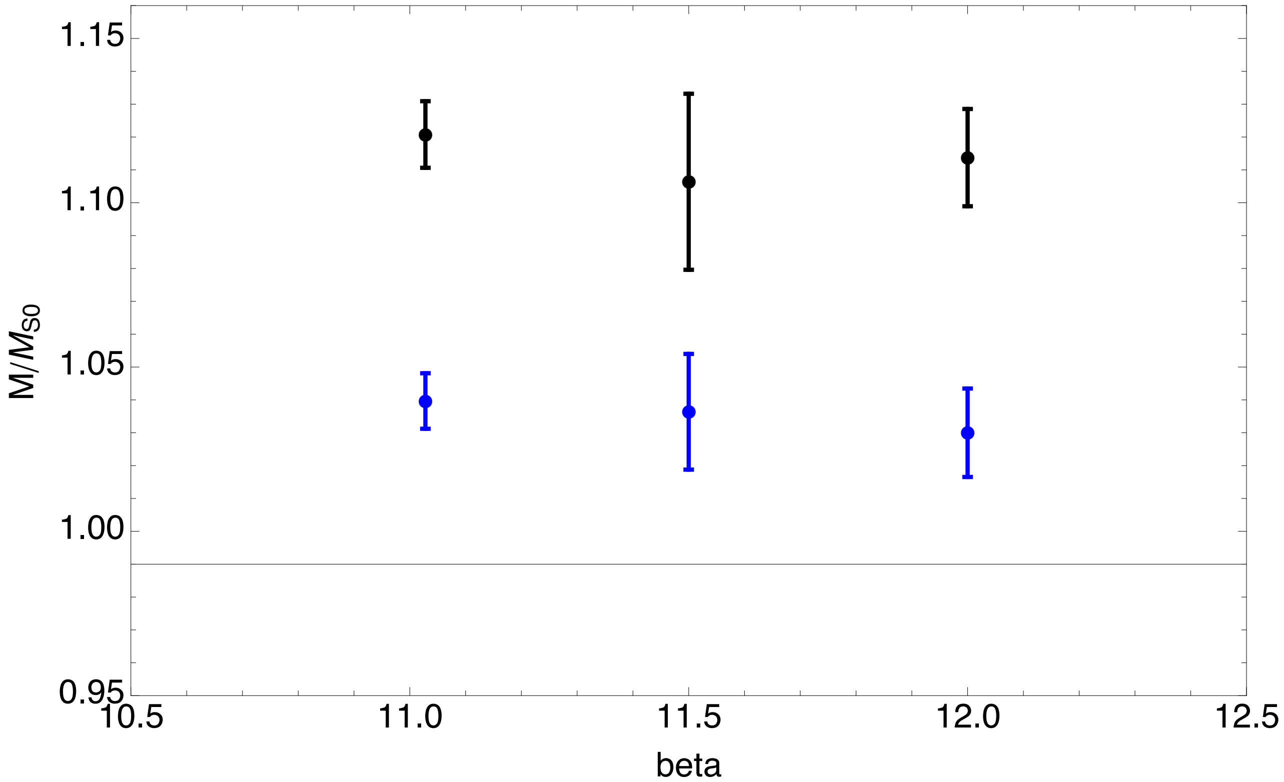


Set of ensembles

N_c	β	κ	$N_s^3 \times N_t$	# Meas.
4	11.028	0.1554	$16^3 \times 32$	4878
			$32^3 \times 64$	1126
		0.15625	$16^3 \times 32$	4765
			$32^3 \times 64$	1146
			$48^3 \times 96$	1091
		0.1572	$32^3 \times 64$	1075
	11.5	0.1515	$16^3 \times 32$	2975
			$32^3 \times 64$	1057
		0.1520	$16^3 \times 32$	2872
			$32^3 \times 64$	1052
		0.1523	$16^3 \times 32$	2976
			$32^3 \times 64$	914
			$48^3 \times 96$	637
			$64^3 \times 128$	489
		0.1524	$16^3 \times 32$	2970
			$32^3 \times 64$	863
		0.1527	$32^3 \times 64$	1011
	12.0	0.1475	$32^3 \times 64$	1125
		0.1480	$32^3 \times 64$	1189
		0.1486	$32^3 \times 64$	1055
		0.1491	$16^3 \times 32$	411
		0.1491	$32^3 \times 64$	1050
		0.1491	$48^3 \times 96$	1150
		0.1491	$64^3 \times 128$	928
		0.1495	$32^3 \times 64$	1043
		0.1496	$32^3 \times 64$	1009
3	6.0175	0.1537	$32^3 \times 64$	1000
		0.1547	$32^3 \times 64$	1000

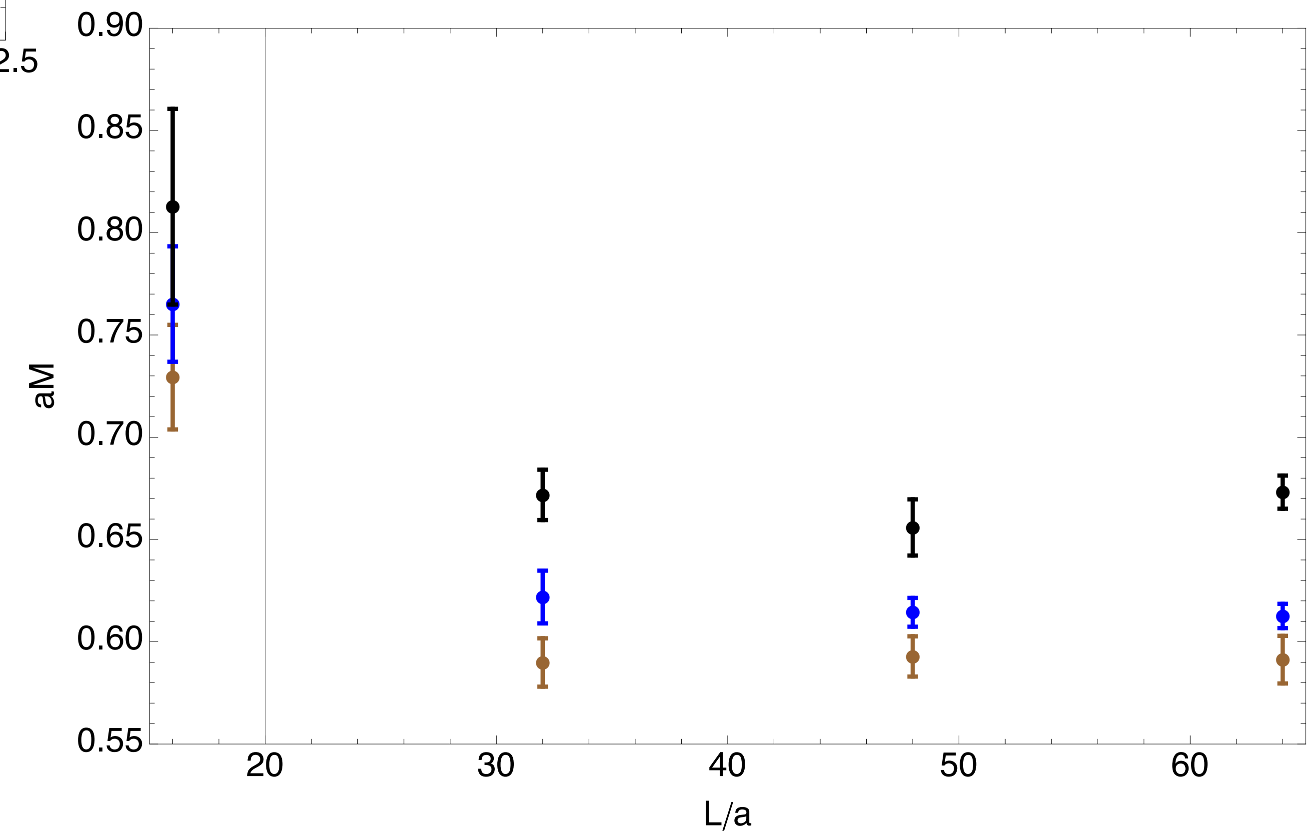
- Quenching allows huge volumes!
- 3-color lattices matched for comparison (string tension)
- All measurements with two valence fermions (we assume splitting between vector-like masses.)

Study of systematic effects



Cutoff effects

Finite-volume effects



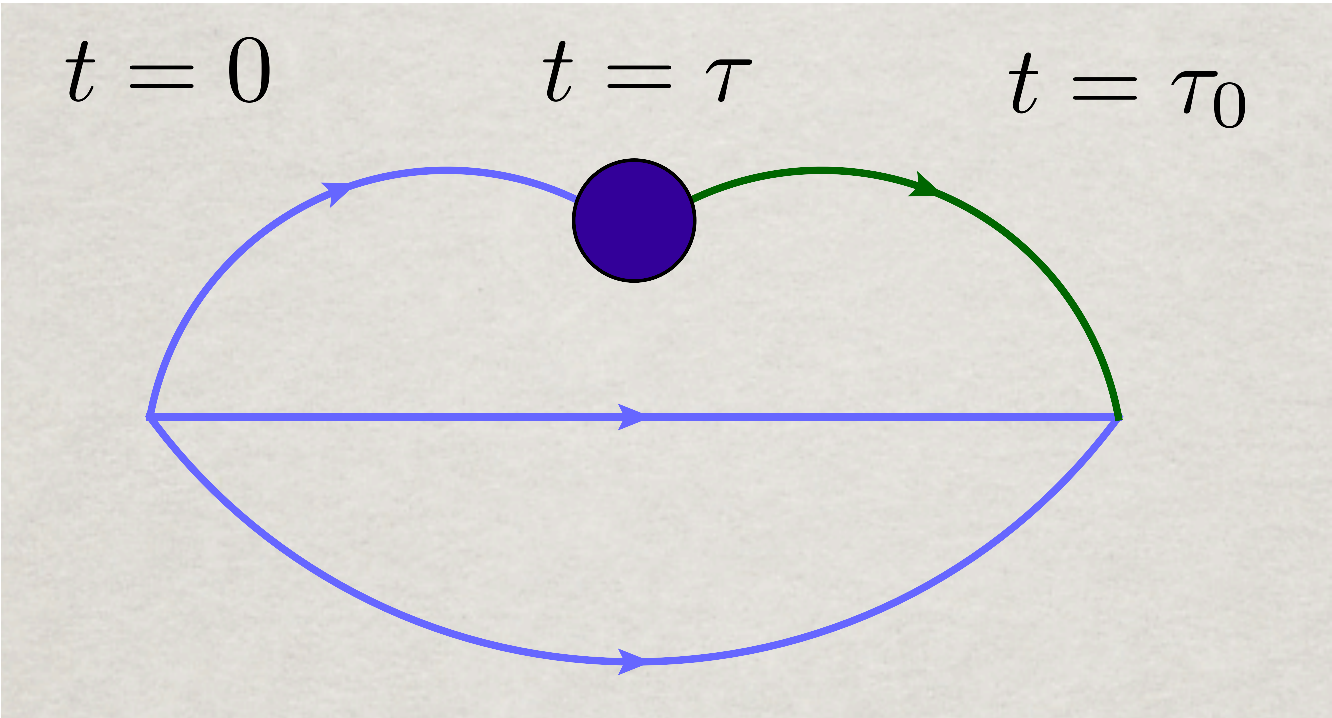
Constructing the form factors

- Calculation of three-point function: nucleon source/sink with EM current insertion.

$$C_{NN}(\tau, \mathbf{p}) = \sum_{\mathbf{x}} e^{-i\mathbf{p}\cdot\mathbf{x}} \langle N(\mathbf{x}, \tau)\bar{N}(0)\rangle$$

$$C_{N\mathcal{O}N}(\tau, T, \mathbf{p}, \mathbf{p}') = \sum_{\mathbf{x},\mathbf{y}} e^{-i\mathbf{p}'\cdot\mathbf{x}+i(\mathbf{p}'-\mathbf{p})\cdot\mathbf{y}} \times$$

$$\times \langle N(\mathbf{x}, T)\mathcal{O}(\mathbf{y}, \tau)\bar{N}(0)\rangle$$



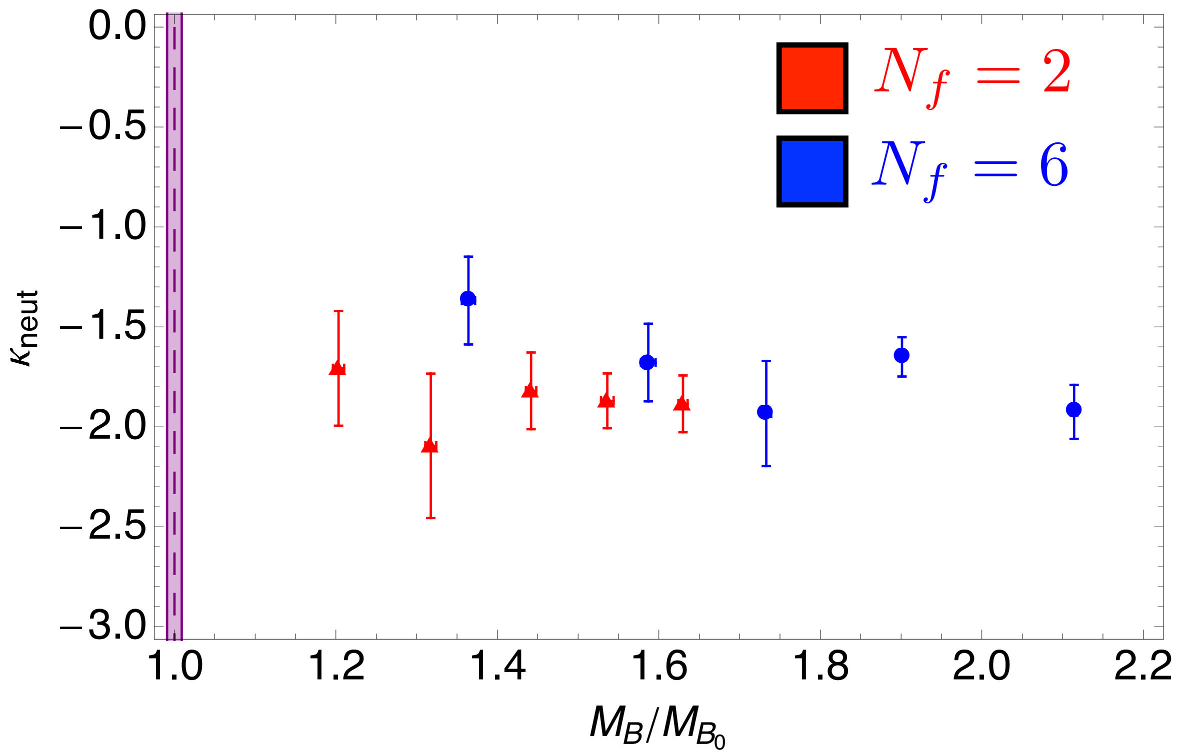
(caveat: no quark-disconnected diagrams!)

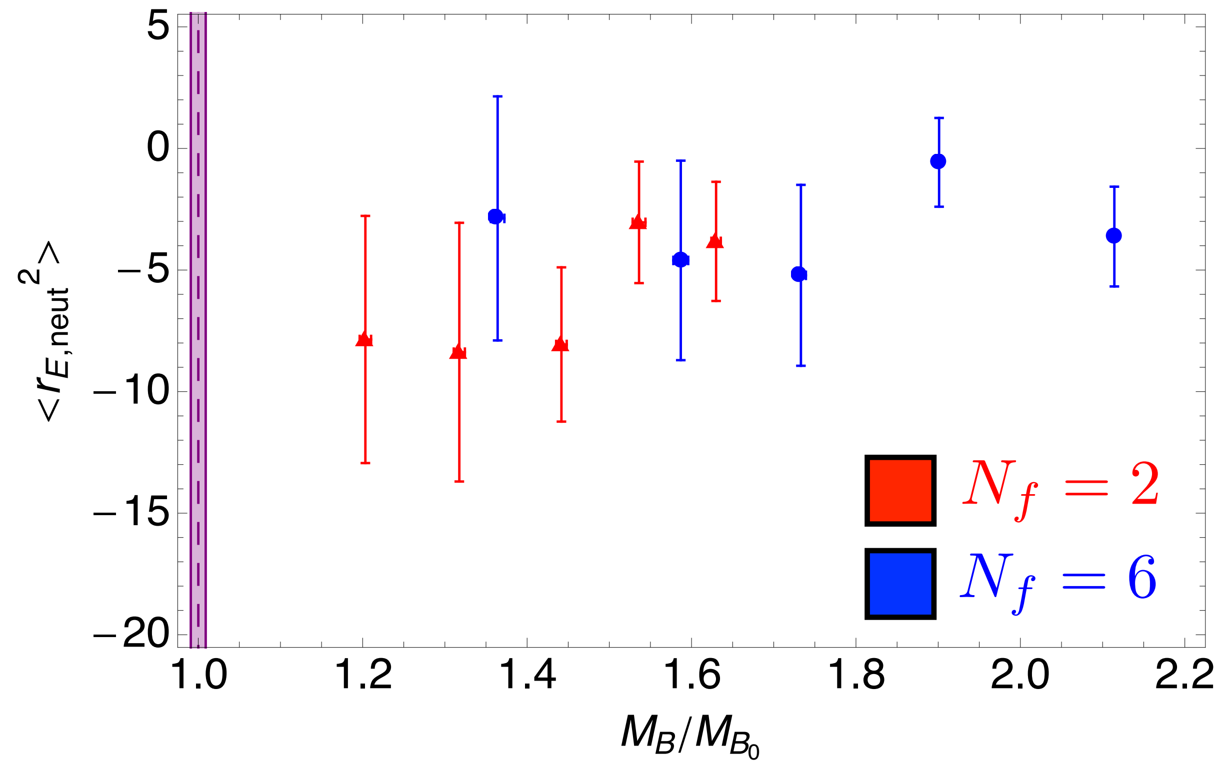
- Combine with two-point function in appropriate ratio in order to get the desired matrix element from large Euclidean time behavior:

$$R_{\mathcal{O}}(\tau, T, \mathbf{p}, \mathbf{p}') = \frac{C_{N\mathcal{O}N}(\tau, T, \mathbf{p}, \mathbf{p}')}{\sqrt{C_{NN}(T, \mathbf{p})C_{NN}(T, \mathbf{p}')}} \times \sqrt{\frac{C_{NN}(T-\tau, \mathbf{p})C_{NN}(\tau, \mathbf{p}')}{C_{NN}(T-\tau, \mathbf{p}')C_{NN}(\tau, \mathbf{p})}} \longrightarrow \boxed{\langle N(\mathbf{p}')|\mathcal{O}|N(\mathbf{p})\rangle}$$

$$+\mathcal{O}(e^{-\Delta\tau}) + \mathcal{O}(e^{-\Delta(T-\tau)}) + \mathcal{O}(e^{-\Delta T})$$

Form factor results





- Magnetic moment relatively flat, good agreement with neutron experimental value
- Charge radius too small for neutron, consistent with other lattice w/

$$F_{1;\text{neut}}(Q^2) = -\frac{1}{6}Q^2\langle r^2_{1;\text{neut}}\rangle + \mathcal{O}(Q^4)\,,$$

$$F_{2;\text{neut}}(Q^2) = \kappa_{\text{neut}} + \mathcal{O}(Q^2)\,,$$

Foldy term

$$\langle r^2_{E;\text{neut}}\rangle \stackrel{def}{=} -6\frac{dG_{E;\text{neut}}(Q^2)}{dQ^2}\bigg|_{Q^2=0} = \langle r^2_{1;\text{neut}}\rangle + \frac{3\kappa_{\text{neut}}}{2M_B^2}$$