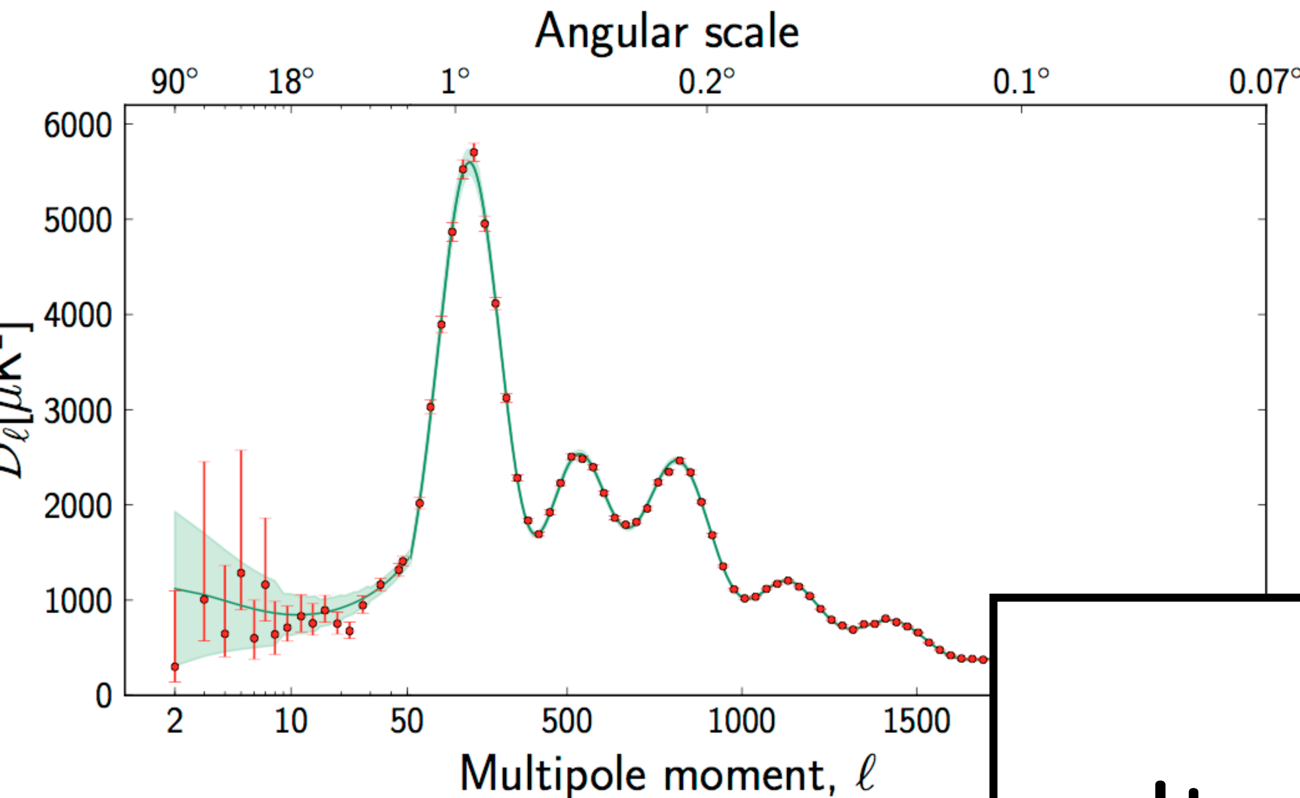
Stealth Dark Matter

Graham Kribs
University of Oregon

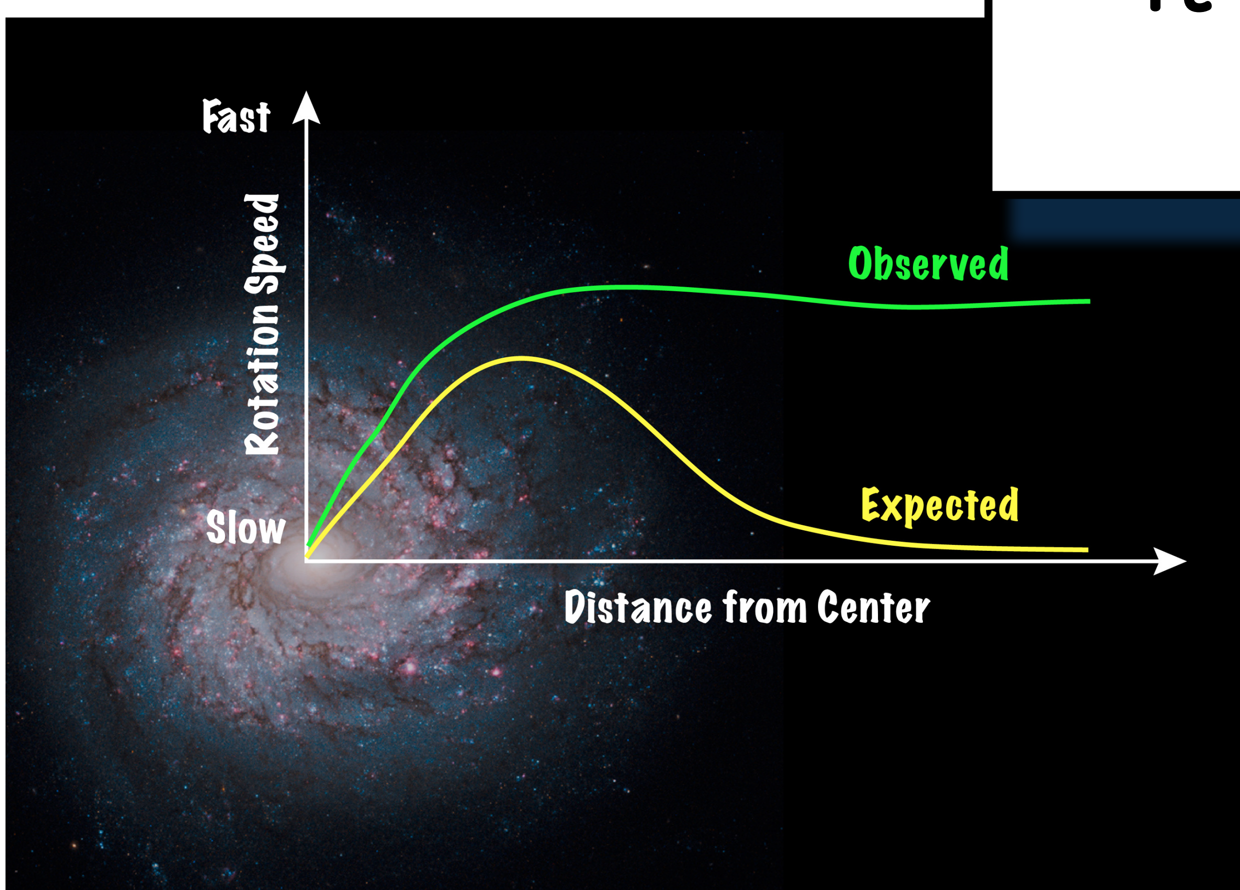
Based on 1402.6656 (PRD), 1503.04203 (PRD), 1503.04205 (PRL)
with Lattice Strong Dynamics (LSD) Collaboration
(and work in progress)

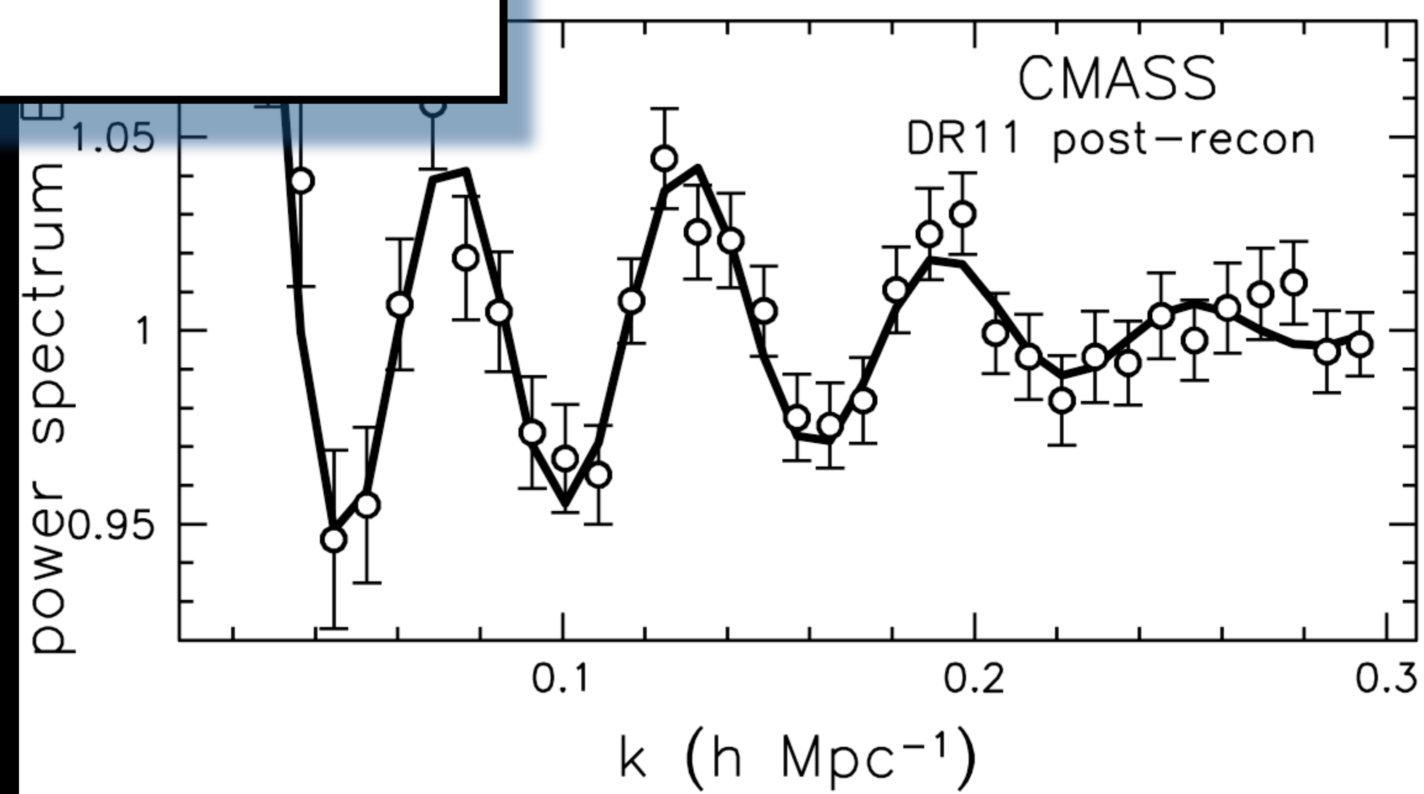
Kavli-IPMU-Durham-KIAS workshop | September 2015

Dark Matter



It exists.

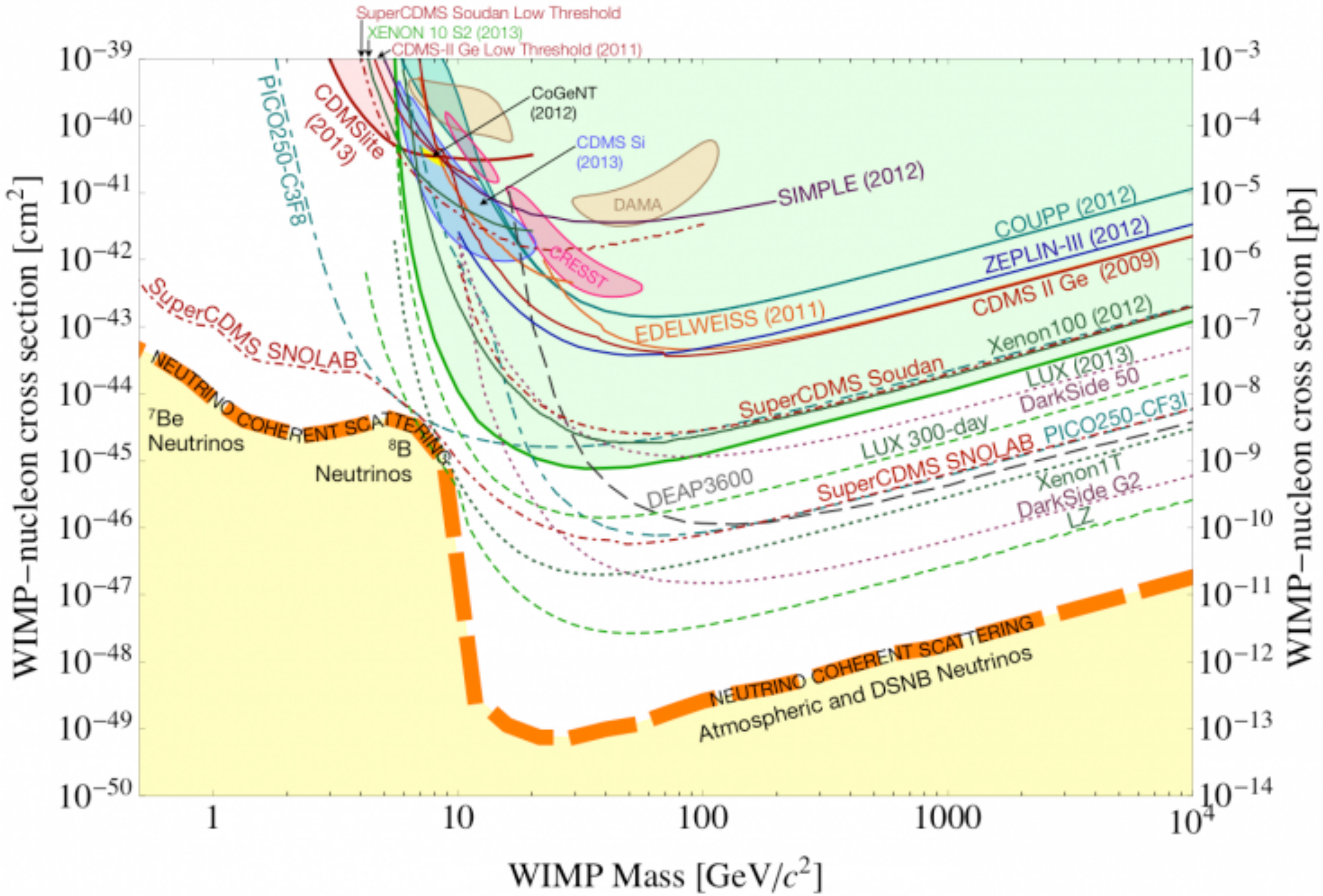




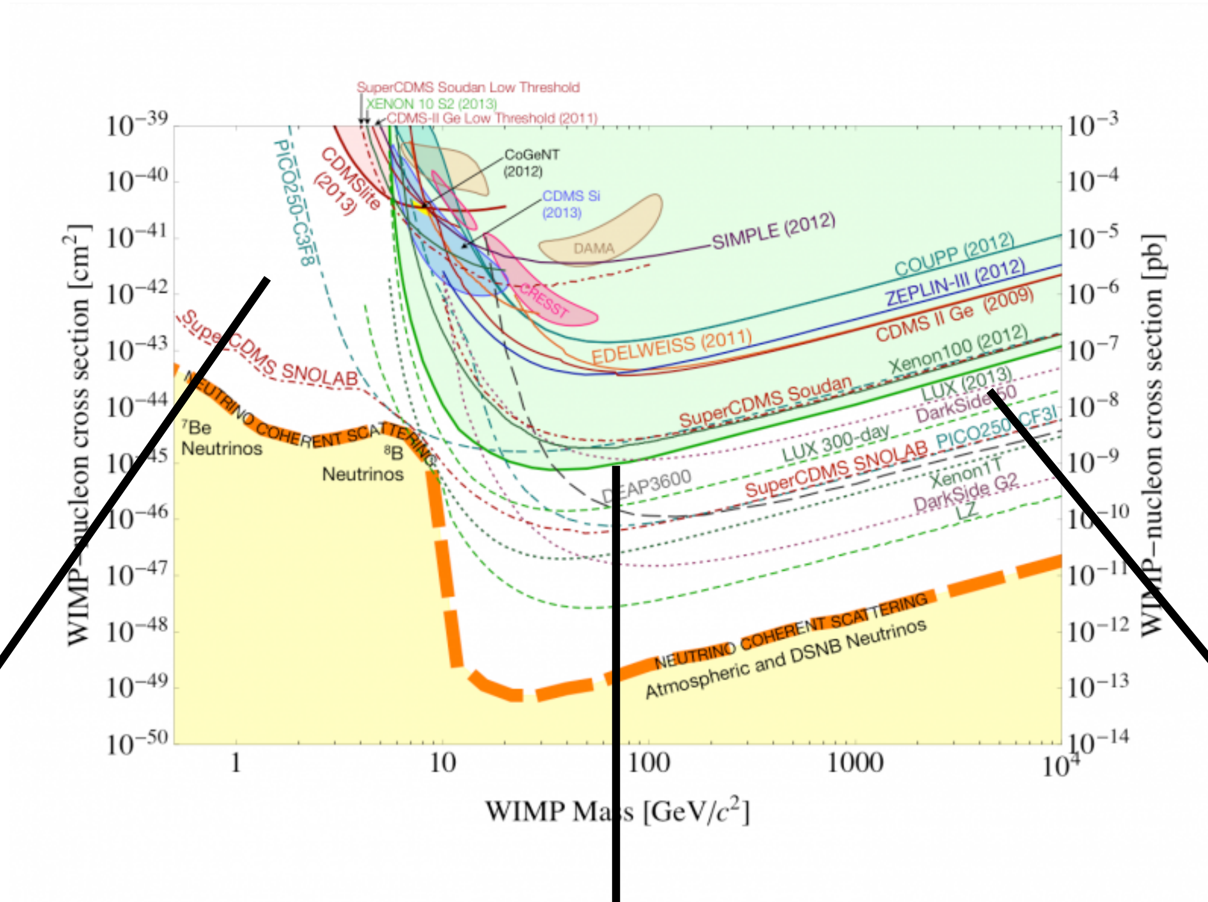
Dark Matter

No unambiguous evidence for non-gravitational interactions.

Direct Detection



Interpretation with a Broad Brush



$$m_{\rm DM} \lesssim \text{few GeV}$$

(no nuclear recoil above detection threshold)

$$\frac{y_{\rm eff}\, v}{m_{\rm DM}} \lesssim 0.1$$

effective coupling of DM to Higgs must be suppressed

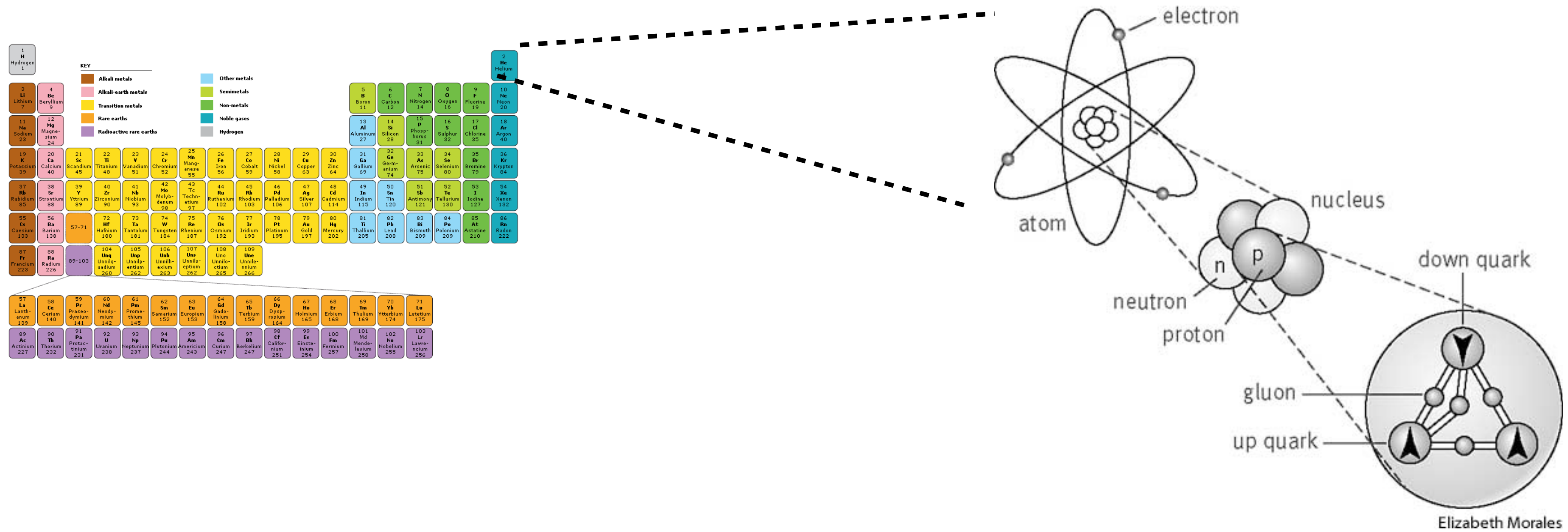
$$m_{\rm DM} \gtrsim \text{TeV}$$

(suppression of Higgs coupling by at least

$$\left(\frac{v}{m_{\rm DM}}\right)^2$$

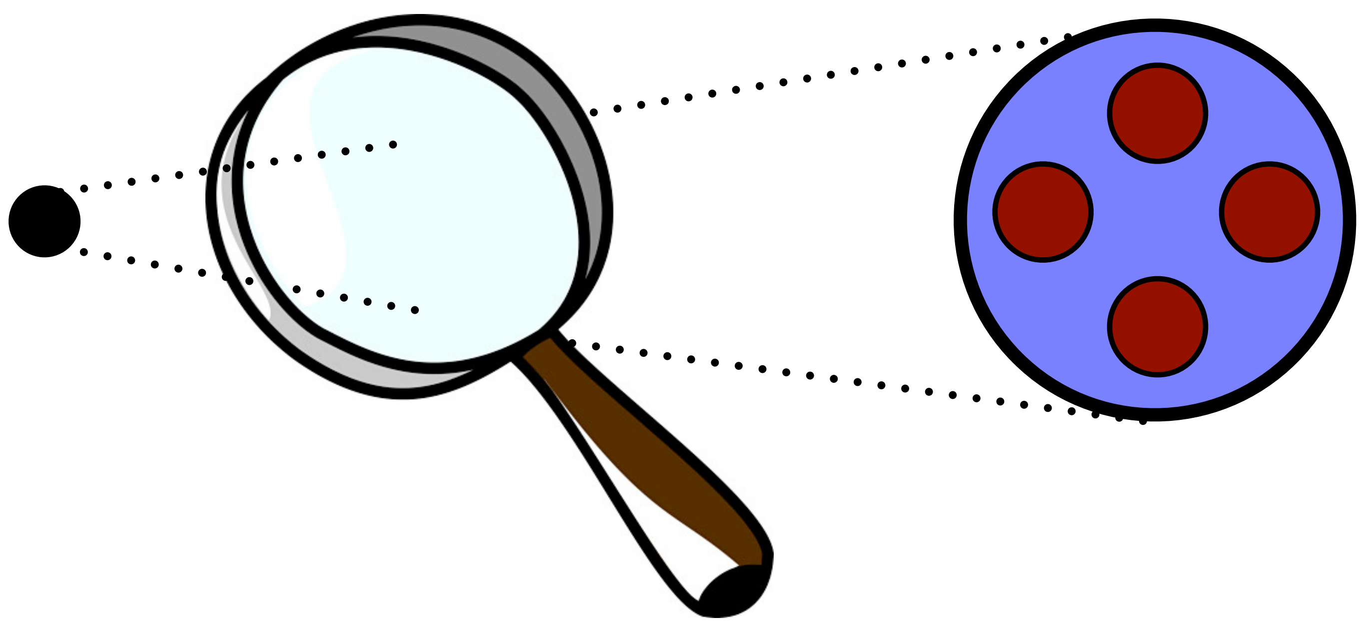
Compositeness in Nature

Illustrious history of fundamental physics has involved the discovery of the compositeness of apparently fundamental particles.



Several good reasons to consider that dark matter itself could be composite.

Composite Dark Matter?



—> new mass scales can be technically natural (Λ_{dark}, M_f)

—> DM stability automatic (e.g., baryon number)

—> interactions with SM matter can be suppressed by powers of the compositeness scale

—> self-interactions can be naturally strongly-coupled

—> has a rich spectrum of states (e.g., baryons and mesons), leading to qualitative changes to experimental signals

Composite DM models

- Technibaryon dark matter (too bad, so sad)
  Nussinov (1985); Chivukula, Walker (1990)
  Barr Chivukula, Farhi (1990)
- Quirky dark matter
  GDK, Roy, Terning, Zurek 0909.2034
- Atomic dark matter
  Kaplan, Krnjaic, Rehermann, Wells 0909.0753
- Composite Inelastic
  Alves, Behbahani, Schuster, Wacker 0903.3945
- Weakly Interacting Stable Pions
  Bai, Hill 1005.0008
- Dark SU(2) with $m_f \ll \Lambda_{dark}$
  Buckley, Neil 1209.6054
- Dark SU(3) with magnetic moment
  LSD Collaboration 1301.1693
- SIMPlest Miracle
  Hochberg, Kuflik, Murayama, Volansky, Wacker 1411.3727
- Dark Nuclei [with SU(2)]
  Detmold, McCullough, Pochinsky 1406.2276
- Glueball / glueballino ($\Lambda \ll M_{gluino}$)
  Boddy, Feng, Kaplinghat, Shadmi, Tait 1408.6532

How does strong coupling mitigate direct detection constraints?

Effective interactions with the Standard Model arise in the expansion

such as $$\frac{1}{(\Lambda_{\mathrm{dark}})^n}$$

magnetic moment: $$\frac{\overline{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu}}{\Lambda_{\mathrm{dark}}}$$

charge radius: $$\frac{(\overline{\psi}\psi)v_\mu\partial_\nu F^{\mu\nu}}{(\Lambda_{\mathrm{dark}})^2}$$

polarizability: $$\frac{(\overline{\psi}\psi)F_{\mu\nu}F^{\mu\nu}}{(\Lambda_{\mathrm{dark}})^3}$$

How does SU(N) even N mitigate direct detection constraints?

Effective interactions with the Standard Model arise in the expansion

$$\frac{1}{(\Lambda_{\mathrm{dark}})^n}$$

such as

magnetic moment: $$\cancel{\frac{\bar{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu}}{\Lambda_{\mathrm{dark}}}}$$ (DM is scalar baryon)

charge radius: $$\cancel{\frac{(\bar{\psi}\psi)v_\mu\partial_\nu F^{\mu\nu}}{(\Lambda_{\mathrm{dark}})^2}}$$ (dark custodial SU(2))

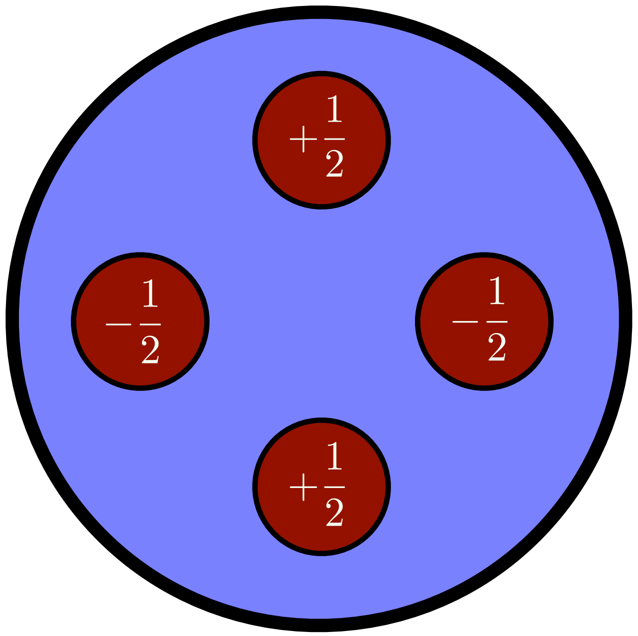
polarizability: $$\frac{\phi\phi^* F_{\mu\nu}F^{\mu\nu}}{(\Lambda_{\mathrm{dark}})^3}$$ (dimension-7 in non-relativistic EFT)

Naturally “stealthy” with respect to direct detection!

Stealth Dark Matter

"Stealth Dark Matter": a neutral composite scalar baryon of a strongly-coupled SU(N) (even N) confining theory made of electroweak-charged "dark fermions" in vector-like reps

Generally consider SU(4) with a range of scales that, as we will see, broadly extends from



$$100\ \mathrm{GeV} \lesssim \Lambda_{\mathrm{dark}} \sim M_f \lesssim 100\ \mathrm{TeV}$$

Stealth Dark Matter Scales

$M_f \ll \Lambda_{\rm dark}$

chiral limit

bounds from LEP II
on light electrically
charged mesons
imply hierarchy

$m(B) \gtrsim \Lambda_{\rm dark}$

$m(\Pi^{\pm})$

$\Lambda_{\rm dark} \sim M_f$

$M_f \gg \Lambda_{\rm dark}$

quarkonia limit

bounds from light
glueballs becoming
too-long-lived

$m(B) \simeq N_c M_f$

$m(\Pi) \simeq 2M_f$

$m(\text{glueball})$

Stealth Dark Matter Scales

$M_f \ll \Lambda_{\rm dark}$

chiral limit

bounds from LEP II
on light electrically
charged mesons
imply hierarchy

$m(B) \gtrsim \Lambda_{\rm dark}$

$m(\Pi^{\pm})$

$\Lambda_{\rm dark} \sim M_f$

all scales coincident

maximize discovery potential!

$M_f \gg \Lambda_{\rm dark}$

quarkonia limit

bounds from light
glueballs becoming
too-long-lived

$m(B) \simeq N_c M_f$

$m(\Pi) \simeq 2M_f$

$m(\text{glueball})$

Lattice Gauge Theory Simulations

Ideal tool to calculate properties of theories with

$$M_f \sim \Lambda_D$$

in the fully non-perturbative regime. Joy of these calculations is that what we simulate is interesting "out of the box" without chiral extrapolations.

What we have done: Accurate estimates of the spectrum, "sigma term", and polarizability. Future work will nail down additional correlators (more precise S parameter), f_π, f_ρ...

Simulated with modified Chroma mainly on LLNL computers. Quenched, unmodified Wilson fermions. Several volumes and lattice spacings.

Lattice Strong Dynamics Collaboration

T. Appelquist, G. Fleming (Yale)

E. Berkowitz, E. Rinaldi, C. Schroeder, P. Vranas (Livermore)

R. Brower, C. Rebbi, E. Weinberg (Boston U)

M. Buchoff (Washington)

X. Jin, J. Osborn (Argonne)

J. Kiskis (UC Davis)

G. Kribs (Oregon)

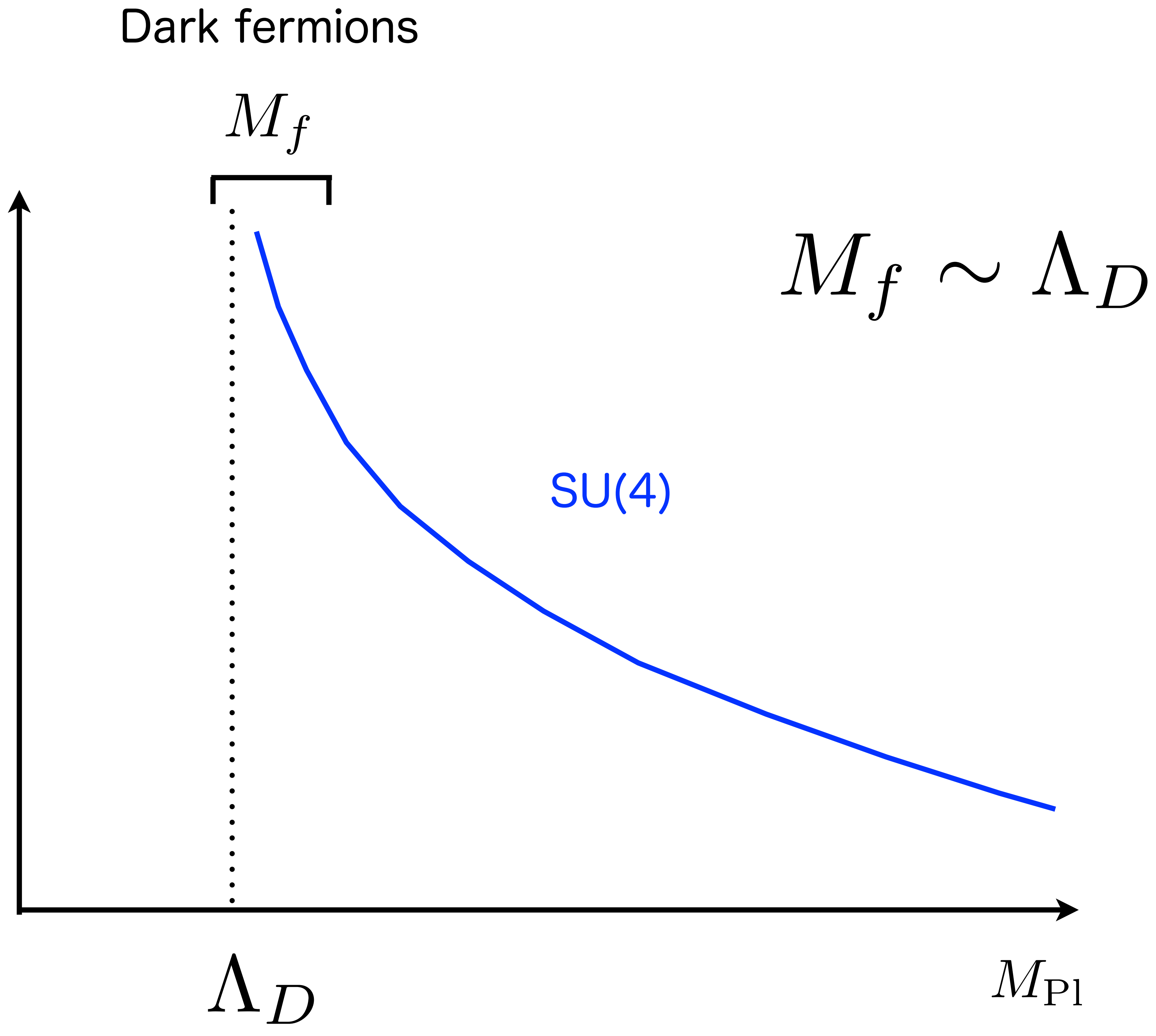
E. Neil (Colorado & Brookhaven)

S. Sryitsyn (Brookhaven)

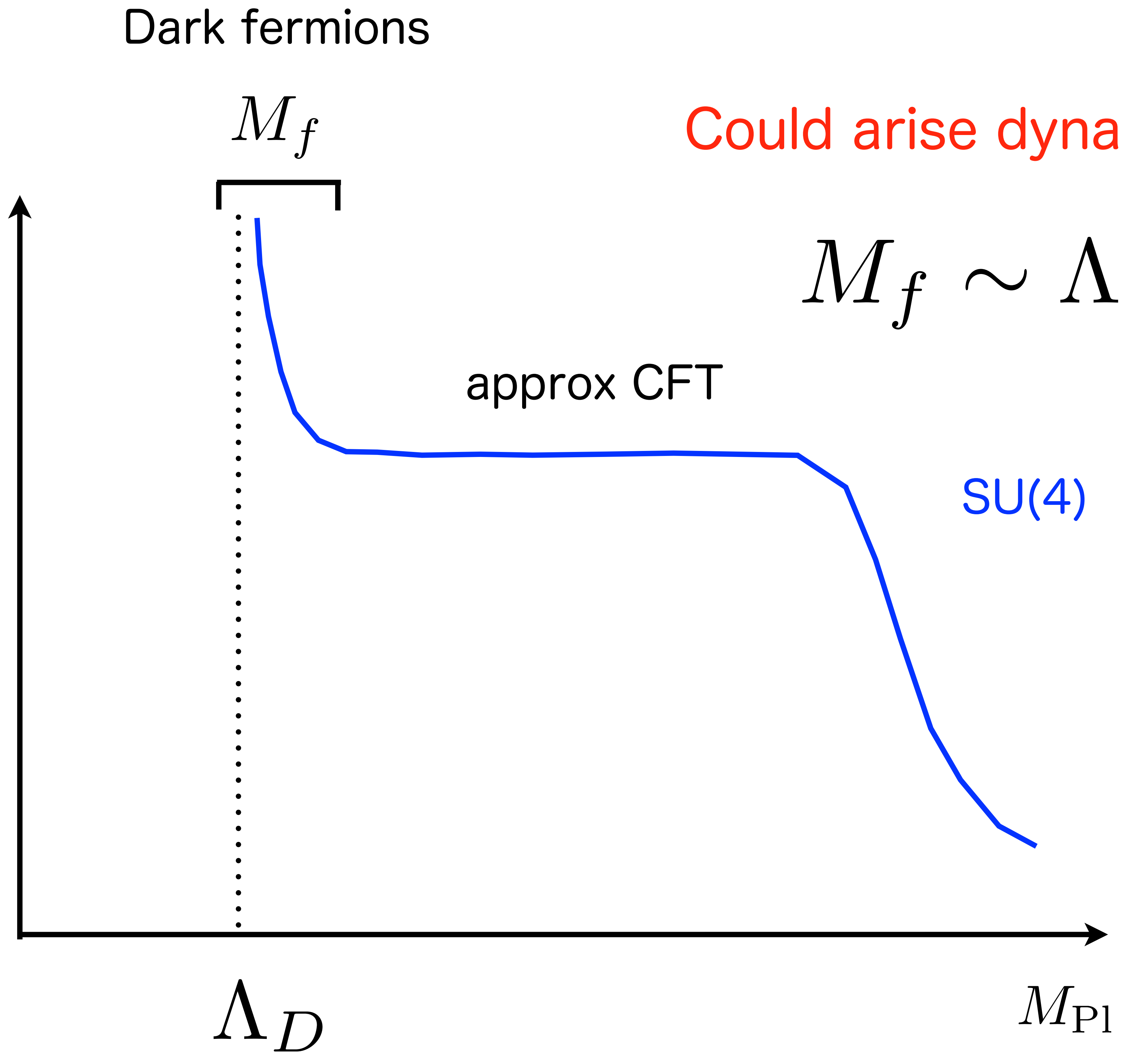
D. Schaich (Syracuse)

O. Witzel (Boston U & Edinburgh)

Dark Sector Dynamics



Dark Sector Dynamics

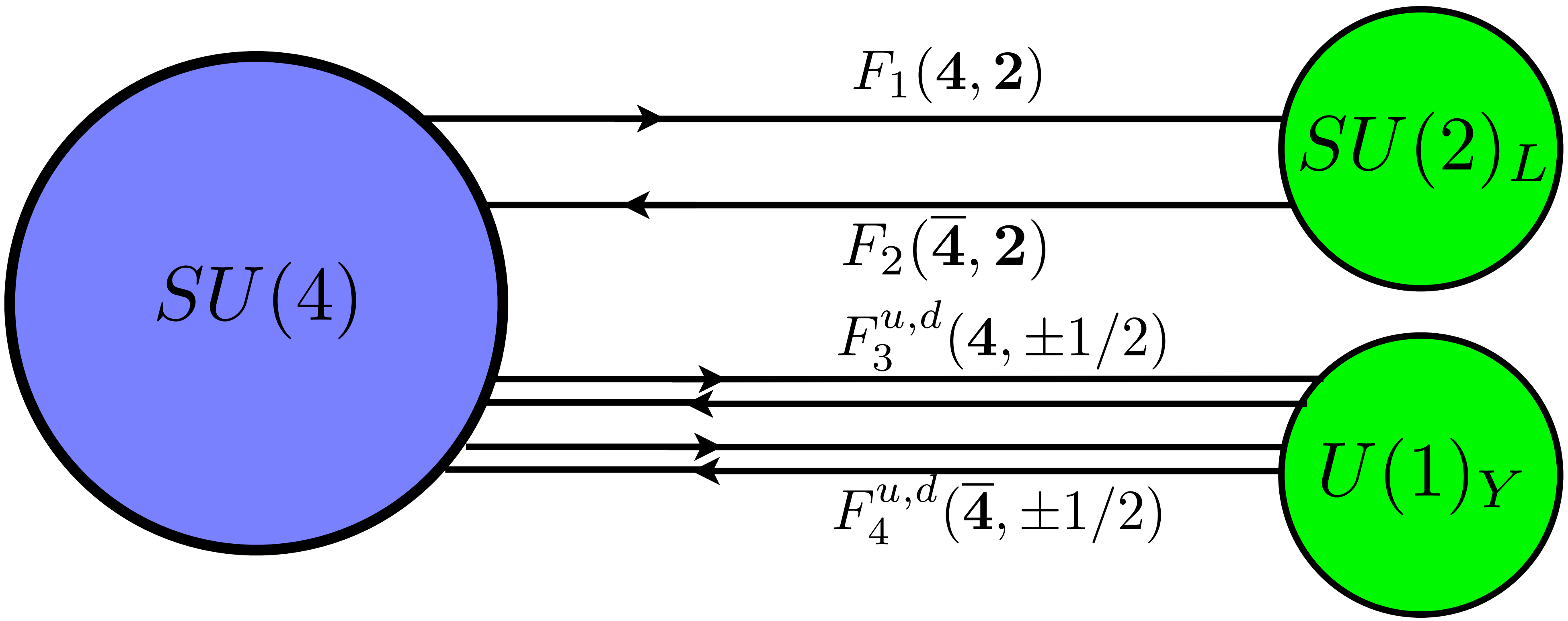


Could arise dynamically

$$M_f \sim \Lambda_D$$

Dark Fermions

Dark fermions transform in vector-like representations:



Vector-like masses are permitted for dark fermions

$$\begin{pmatrix} M_{12} & \\ & M_{34}^u \end{pmatrix}_{+\frac{1}{2}}$$

$$\begin{pmatrix} M_{12} & \\ & M_{34}^d \end{pmatrix}_{-\frac{1}{2}}$$

as well as contributions from EWSB

$$\begin{pmatrix} M_{12} & y_{14}^u v/\sqrt{2} \\ y_{23}^u v/\sqrt{2} & M_{34}^u \end{pmatrix}_{+\frac{1}{2}}$$

$$\begin{pmatrix} M_{12} & y_{14}^d v/\sqrt{2} \\ y_{23}^d v/\sqrt{2} & M_{34}^d \end{pmatrix}_{-\frac{1}{2}}$$

Dark Flavor Symmetries

Under SU(4):	$U(4) \times U(4)$
Weak gauging:	$[SU(2) \times U(1)]^4$ (that contains $SU(2)_L \times U(1)_Y$)
Vector-like masses:	$SU(2)_L \times U(1)_Y \times U(1) \times U(1)$
Yukawas with Higgs:	$U(1)_B$

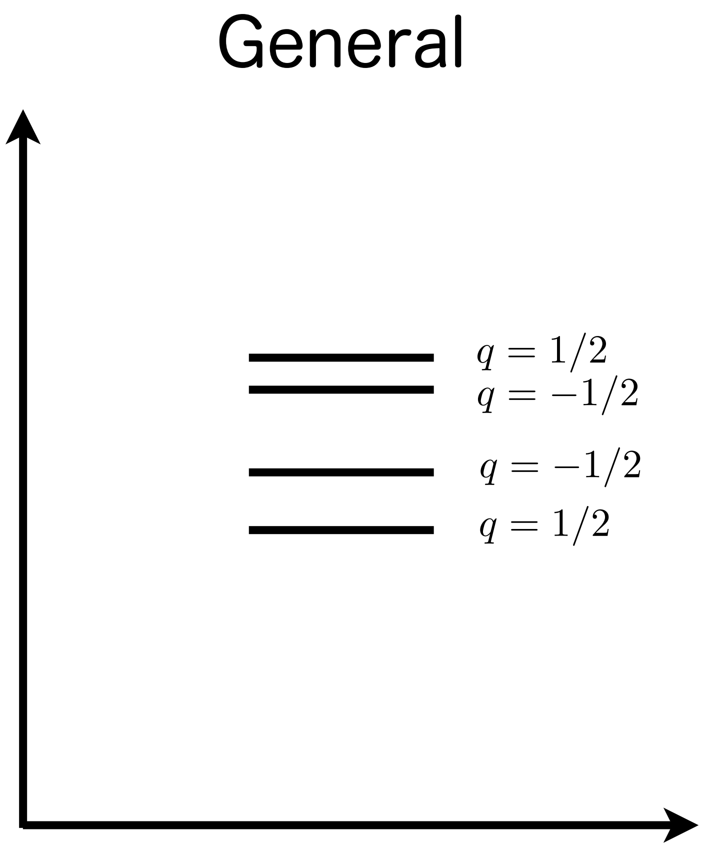
$\boxed{\text{Dark baryon number automatic.}}$

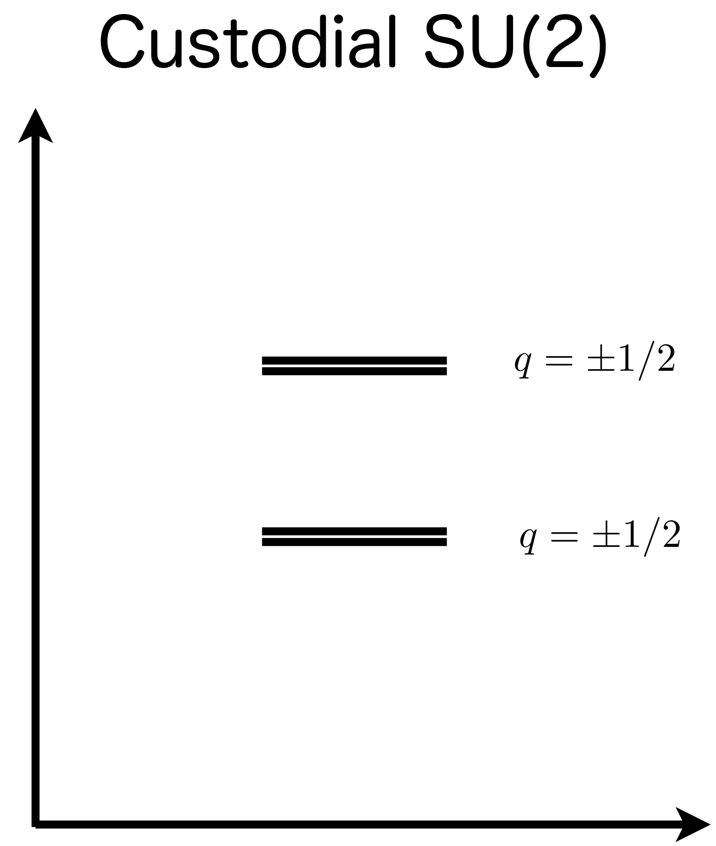
and very safe against cutoff scale violations of global symmetries e.g.

$$\frac{qqqq\, H^\dagger H}{\Lambda^4_{\rm cutoff}}$$

[This is one reason to prefer SU(4) over SU(2).]

Dark Fermion Mass Spectrum



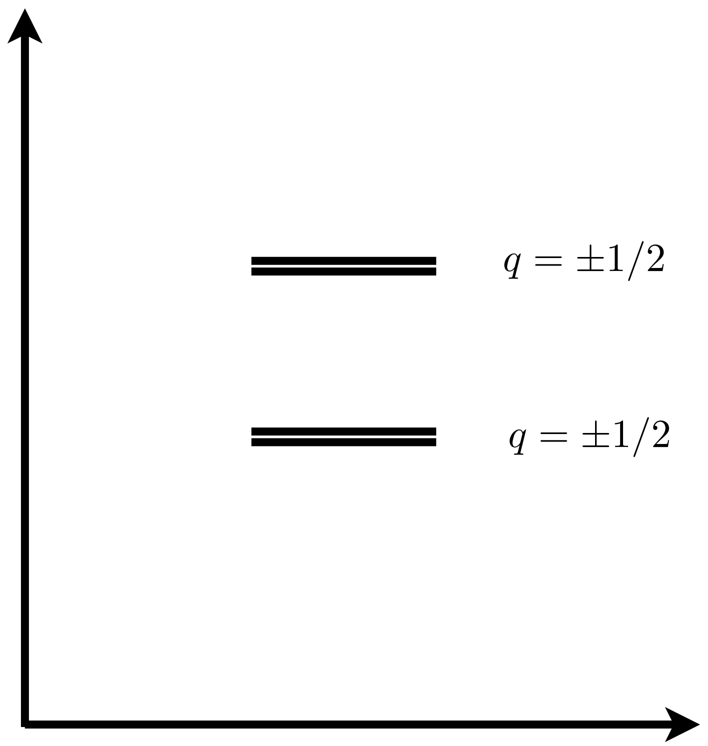


$$\begin{pmatrix} M_{12} & y^u_{14} v/\sqrt{2} \\ y^u_{23} v/\sqrt{2} & M^u_{34} \end{pmatrix}_{+\frac{1}{2}}$$

$$\begin{pmatrix} M_{12} & y^d_{14} v/\sqrt{2} \\ y^d_{23} v/\sqrt{2} & M^d_{34} \end{pmatrix}_{-\frac{1}{2}}$$

$$\longrightarrow \begin{pmatrix} M_{12} & y_{14} v/\sqrt{2} \\ y_{23} v/\sqrt{2} & M_{34} \end{pmatrix}_{\pm\frac{1}{2}}$$

Custodial SU(2)



- Lightest baryon is a neutral complex scalar

  (eliminates operators dependent on spin,
  e.g., dim-5 magnetic moment)

- Contributions to T parameter vanish

  (no need to make life more complicated)

- Weak isospin exactly zero

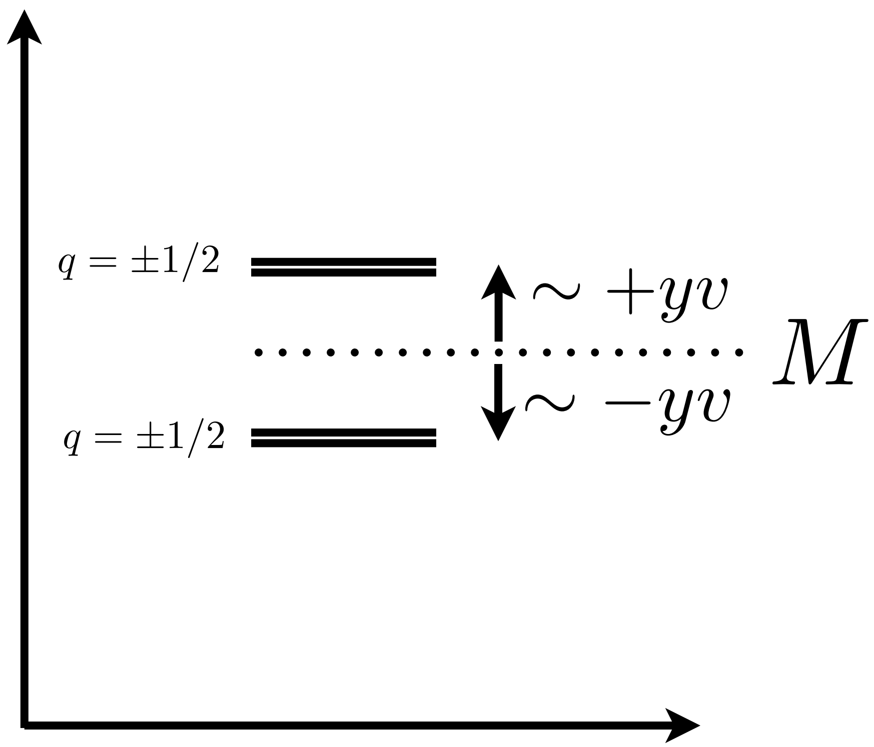
  (no Z coupling to dark matter; otherwise significant constraints)

- Dim-6 charge radius vanishes

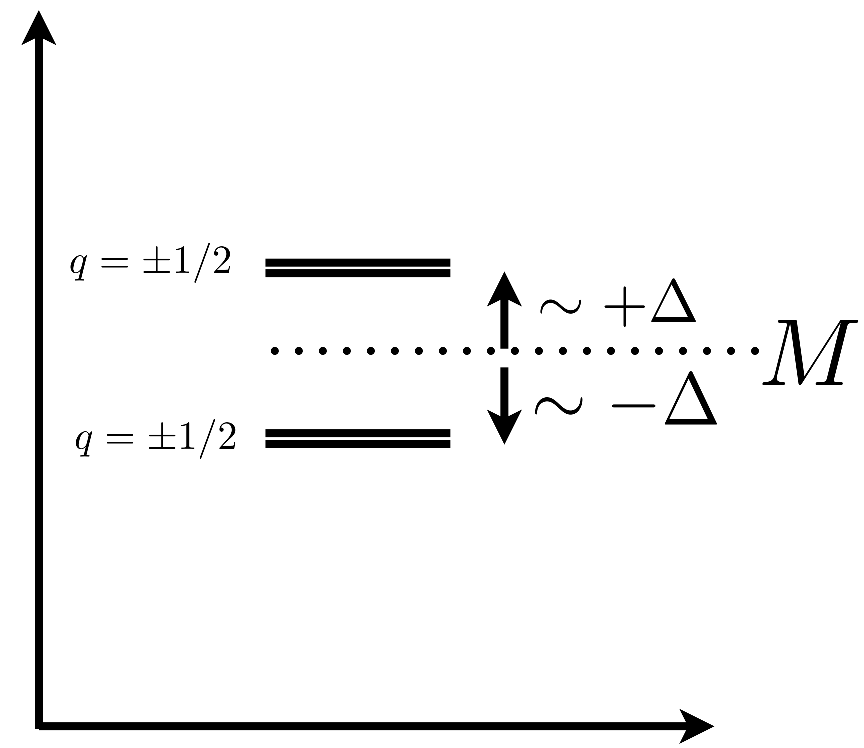
  (more stealthy w.r.t. direct detection;
  one less thing to calculate on lattice)

Two Distinct "Cases"

"Linear Case"



"Quadratic Case"



Higgs boson coupling to lightest dark fermions is proportional to

y	Linear Case
y^2	Quadratic Case

A similar observation of linear/quadratic effect also in Hill, Solon; 1401.3339

Approximately Symmetric / Vector-Like

Convenient to expand around the symmetric matrix limit

$$\begin{pmatrix} M_{12} & y_{14}v/\sqrt{2} \\ y_{23}v/\sqrt{2} & M_{34} \end{pmatrix} = \begin{pmatrix} M_{12} & yv/\sqrt{2} \\ yv/\sqrt{2} & M_{34} \end{pmatrix} + \frac{\epsilon_y v}{\sqrt{2}} \begin{pmatrix} & 1 \\ -1 & \end{pmatrix}$$

$$|\epsilon_y| \ll |y|$$

Then the axial current

$$j^{\mu}_{+,\mathrm{axial}} \supset c_{\mathrm{axial}} \overline{\Psi^u_1} \gamma^\mu \gamma_5 \Psi^d_1$$

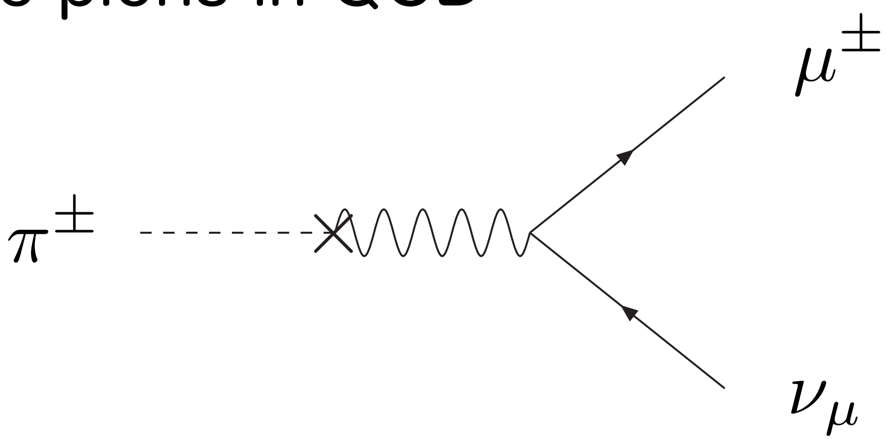
becomes

$$c_{\mathrm{axial}} = \frac{\epsilon_y y v^2}{2M\sqrt{2\Delta^2 + y^2 v^2}}$$

$$\simeq \frac{\epsilon_y v}{2M} \times \begin{cases} 1 & \text{Linear Case} \\ yv/(\sqrt{2}\Delta) & \text{Quadratic Case.} \end{cases}$$

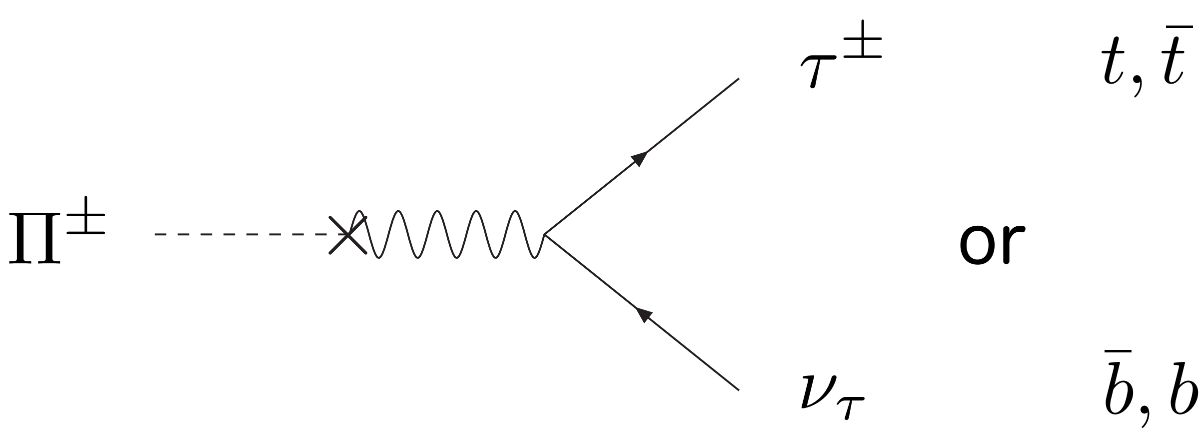
Charged Meson Decay

Like pions in QCD



$$\langle 0 | j^\mu_{\pm,\text{axial}} | \pi^\pm \rangle = i f_\pi p^\mu$$

Lightest dark mesons decay through



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

The non-zero Yukawa couplings with $\epsilon_y \neq 0$ cause $j^\mu_{\pm,\text{axial}} \neq 0$

$$\frac{\Gamma(\Pi^+ \to f\overline{f}')}{\Gamma(\pi \to \mu^+ \nu_\mu)} \simeq \frac{c^2_{\text{axial}}}{|V_{ud}|^2} \left(\frac{f_\Pi}{f_\pi}\right)^2 \left(\frac{m_f}{m_\mu}\right)^2 \left(\frac{m_\Pi}{m_\pi}\right)$$

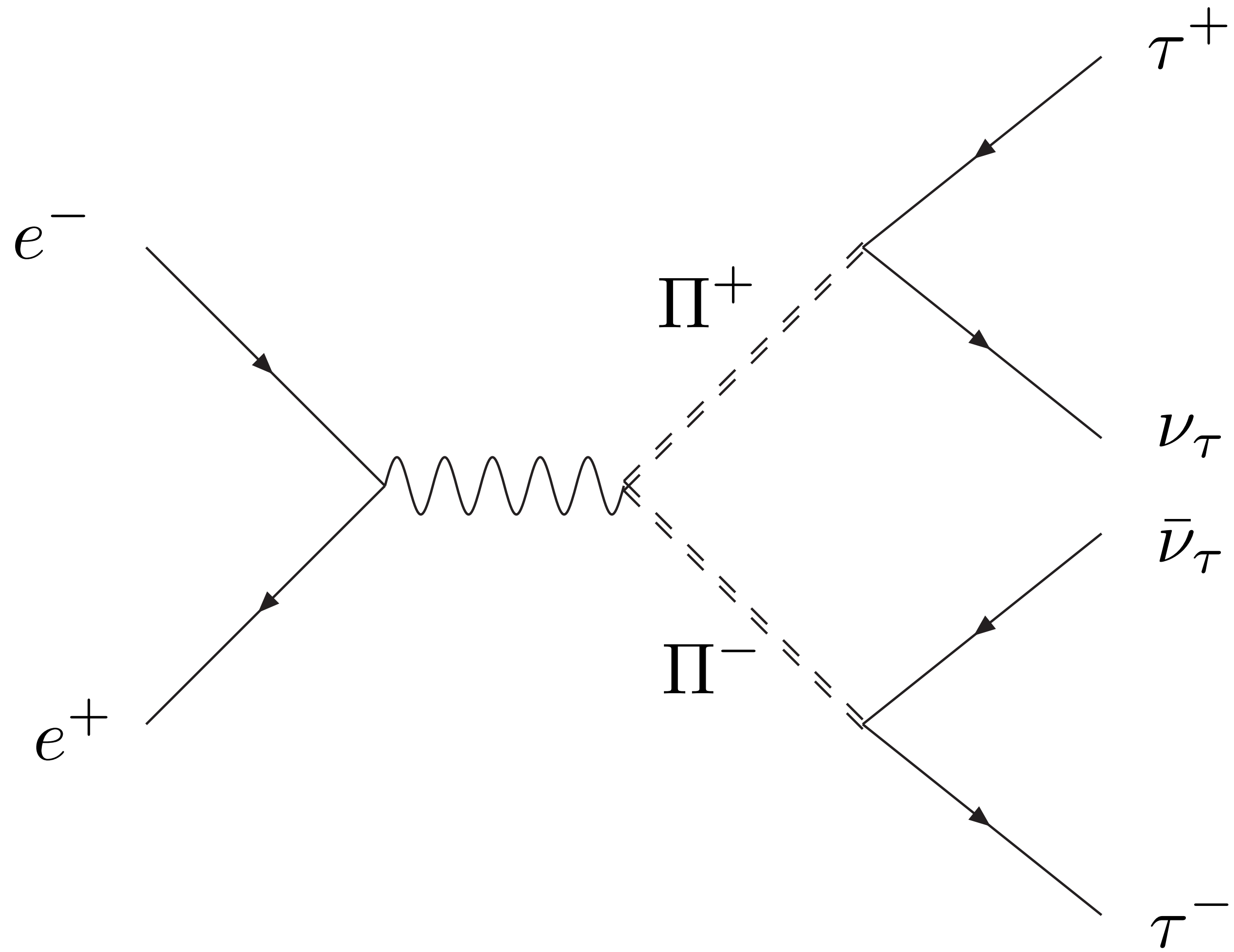
(unlike “Vector-like Confinement”)

Kilic, Okui, Sundrum; 0906.0577

and so dark mesons decay much faster than QCD pions even with $c_{\text{axial}} \ll 1$

Lower bound on meson mass ...

Charged pion production at LEP II

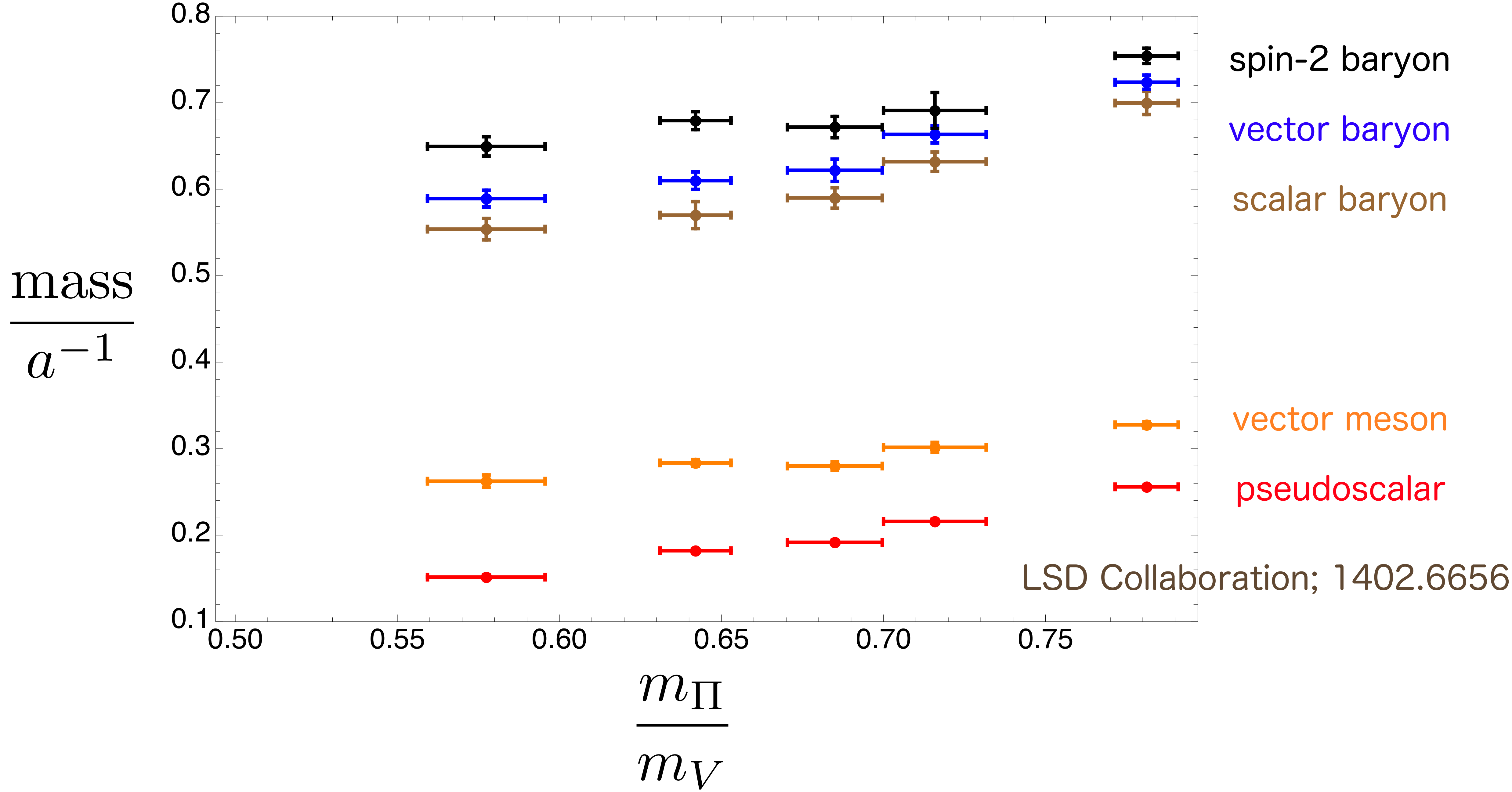


Assuming just Drell-Yan production, a crude recasting of bounds on staus gives

$$m_{\Pi^\pm} > 86 \text{ GeV}$$

This is fairly robust to promptness/non-promptness of dark meson decay.

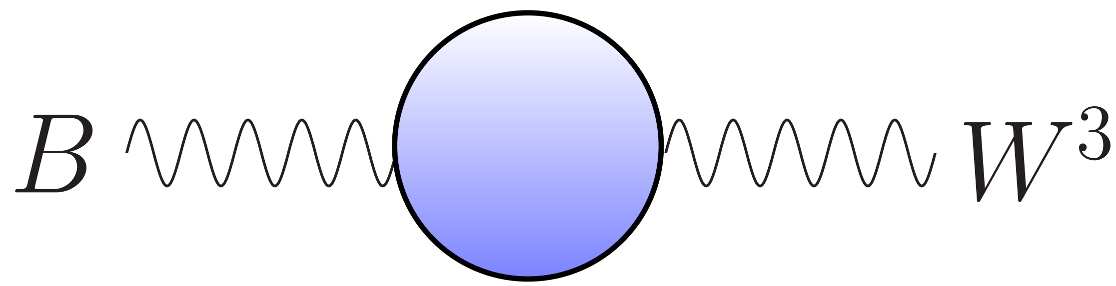
… becomes lower bound on the baryon mass



Within the range simulated on our lattices, we obtain

$$2.5 \lesssim \frac{m_B}{m_\Pi} \lesssim 3.8$$

S parameter



Peskin, Takeuchi (1990, 92)

Obviously ΔS -> 0 as (yv) -> 0.

With custodial SU(2), approximate symmetric, and M_1 close to M_2

$$S \;\propto\; \int d^4x\, e^{-i\mathbf{q}\cdot\mathbf{x}} \langle j_3^\mu(x) j_Y^\nu(0)\rangle \;\simeq\; \frac{\epsilon_y^2 v^2}{4M^2} G_{LR}^{\mu\nu},$$

$$G_{LR}^{\mu\nu} \equiv \langle \bar{\psi}^u \gamma^\mu P_L \psi^u \bar{\psi}^u \gamma^\nu P_R \psi^u \rangle\big|_{\text{connected}}$$

and thus can be easily suppressed below experimental limits.

[Vector-like masses for dark fermions crucial.]

Effective Higgs Coupling

The Higgs coupling to the lightest dark fermions

$$\mathcal{L} \supset y_\Psi h \overline{\Psi}_1 \Psi_1$$

$$y_\Psi = \frac{y^2 v}{M_2 - M_1} + O(\epsilon_y) \simeq \begin{cases} \frac{y}{\sqrt{2}} & \text{Linear Case} \\ \frac{y^2 v}{2\Delta} & \text{Quadratic Case.} \end{cases}$$

This leads to an effective Higgs coupling to the dark scalar baryon

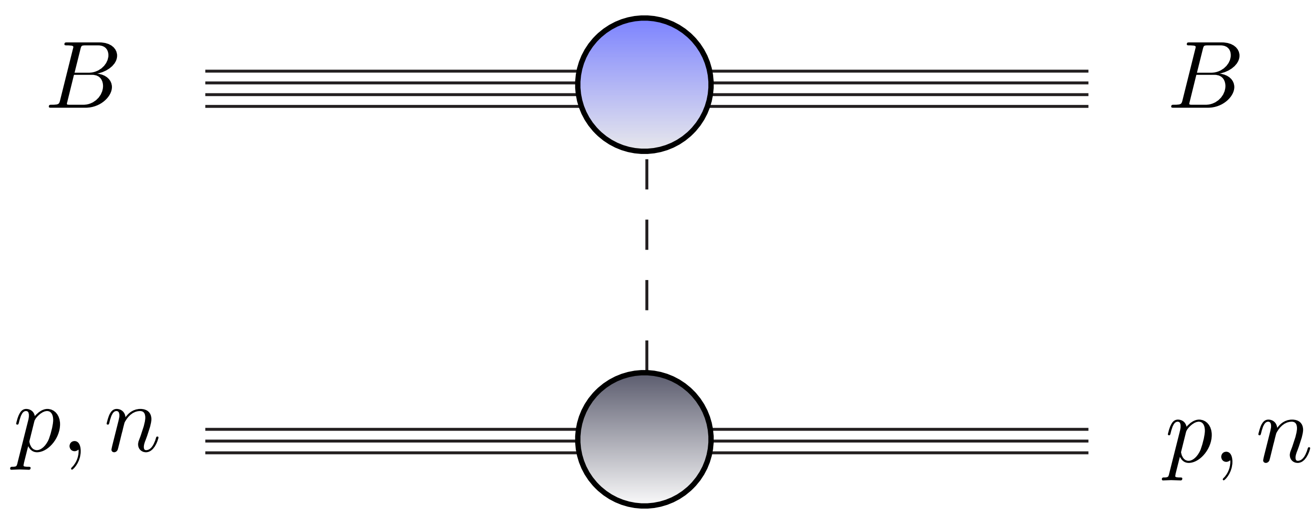
$$g_B \simeq f_f^B \times \begin{cases} y_{\text{eff}} & \text{Linear Case} \\ y_{\text{eff}}^2 \frac{v}{m_B} & \text{Quadratic Case} \end{cases}$$

$$y_{\text{eff}} \equiv \begin{cases} y \frac{m_B}{\sqrt{2} M_1} & \text{Linear Case} \\ y \frac{m_B}{\sqrt{2 \Delta M_1}} & \text{Quadratic Case.} \end{cases}$$

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

Extracted from lattice!

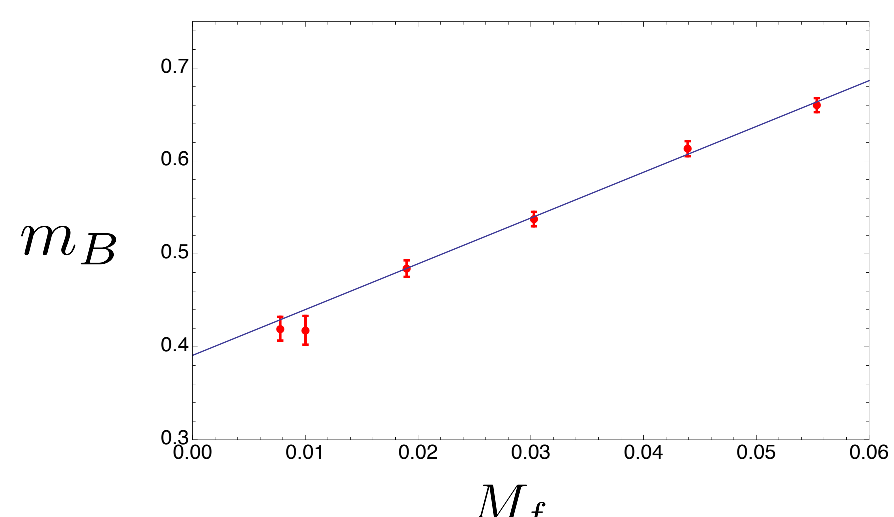
Direct Detection 1: Higgs exchange



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

We have $\langle B|\, m_f \bar{f} f\, |B\rangle \;=\; m_B f_f^B$

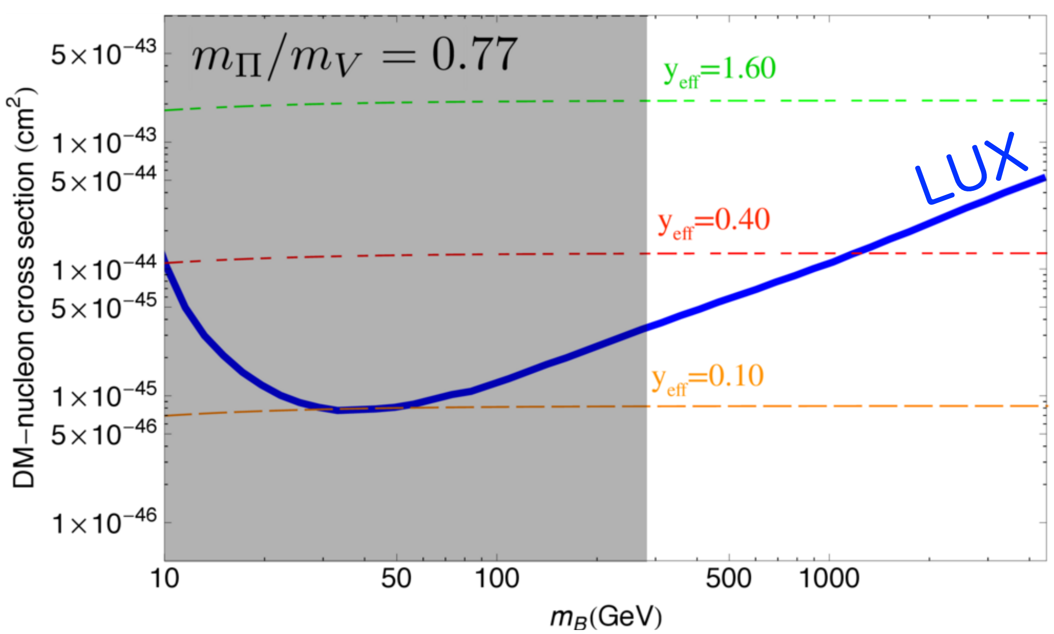
We can extract from lattice using Feynman-Hellman $f_f^B = \dfrac{M_f}{m_B}\dfrac{\partial m_B}{\partial M_f}$



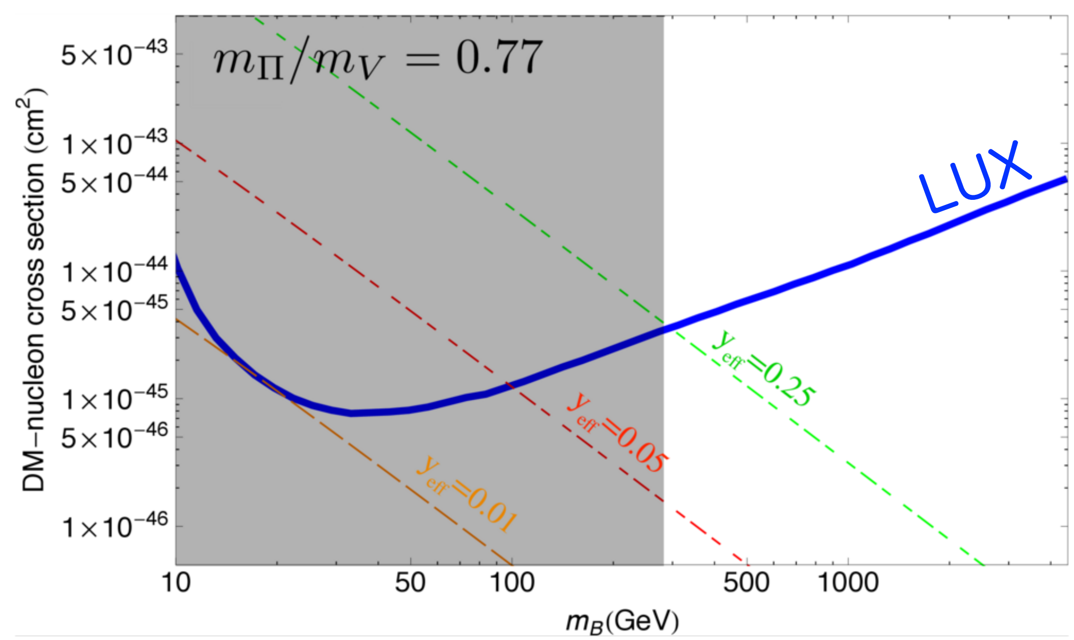
LSD Collaboration; 1402.6656

Higgs exchange results

Linear case



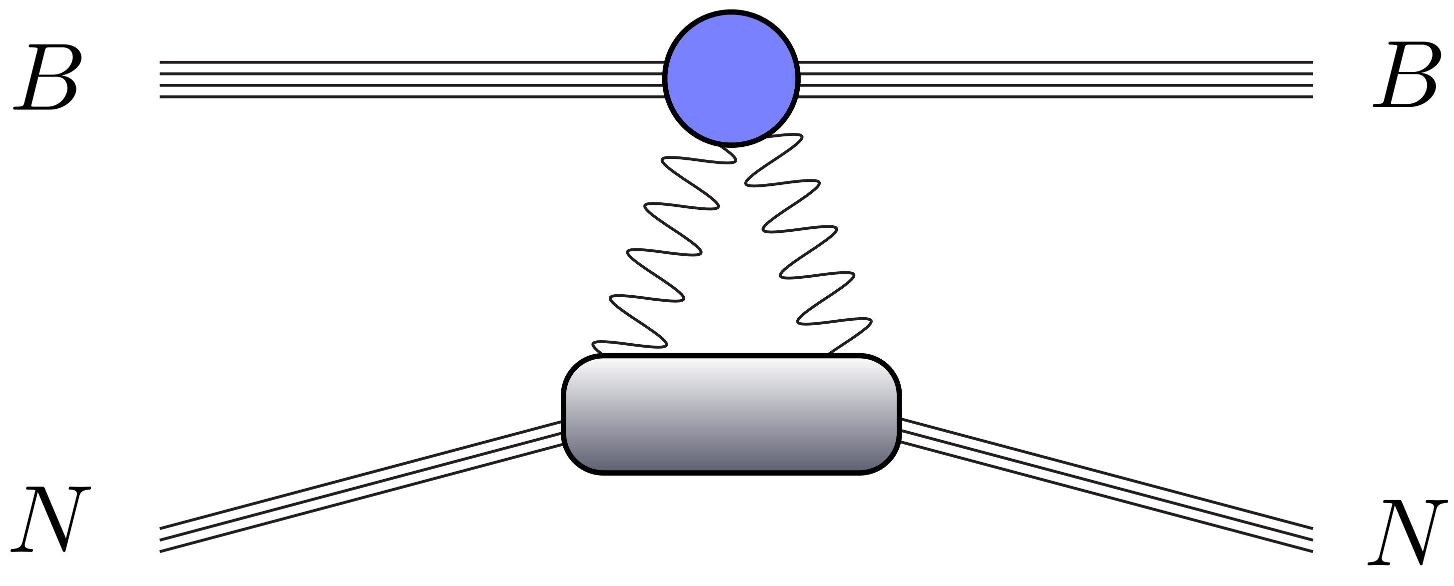
Quadratic case



LSD Collaboration; 1503.04203

Roughly, yeff < 0.25 for lightest baryon mass, with constraints that become looser proportional to m_B for linear or $(m_B)^2$ for quadratic case.

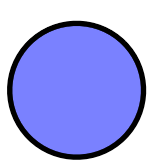
Direct Detection 2: Polarizability



Wonderful formalism for extracting the electric polarizability from lattice using background field methodology.

Detmold, Tiburzi, Walker-Loud; 0904.1586, 1001.1113

In the NR limit, the scalar baryon operator is dimension-7



$$\frac{c_F e^2}{m_B^3} B^* B F^{\mu\alpha} F^{\nu}_{\alpha} v_\mu v_\nu$$

$v_\mu = (1,0,0,0)$

extracted from our lattice simulations

Polarizability

The per nucleon cross section

$$\sigma_{\text{nucleon}} = \frac{\mu_{nB}^2}{\pi A^2}\left|\frac{c_F e^2}{m_B^3} f_F^A\right|^2$$

has large uncertainties on the nuclear side (momenta-dependent structure factors, operator mixing, nuclear resonances)

Weiner, Yavin; 1206.2910
Frandsen et al; 1207.3971
Ovanesyan, Vecchi; 1410.0601

We parametrize simply as

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

$1/3 < M_F^A < 3$

$R = 1.2\ A^{1/3}$ fm

To obtain

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

Where the nuclear structure factor remains the largest uncertainty.

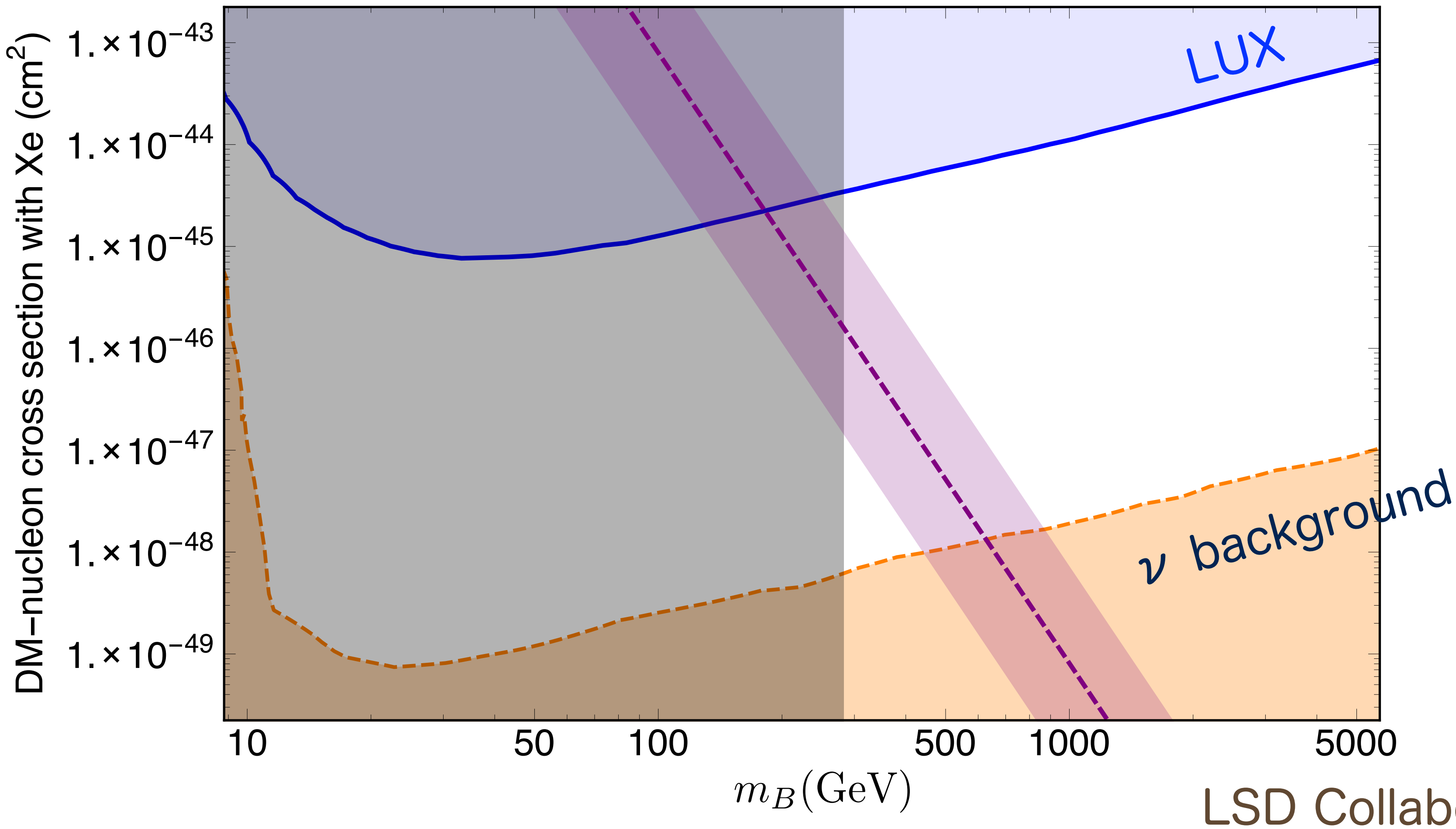
Polarizability

Note!

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

Depends on (Z,A), since it doesn't have A^2-like (Higgs-like) scaling.

For Zenon, we obtain:



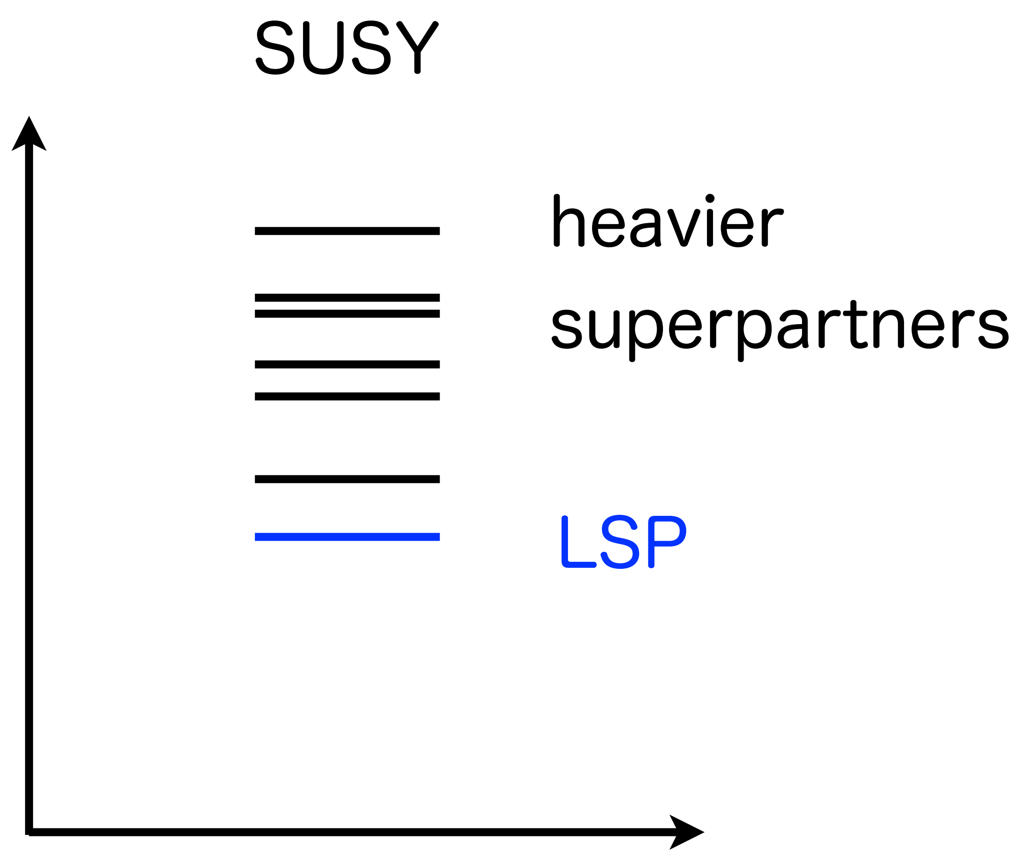
LSD Collaboration; 1503.04205

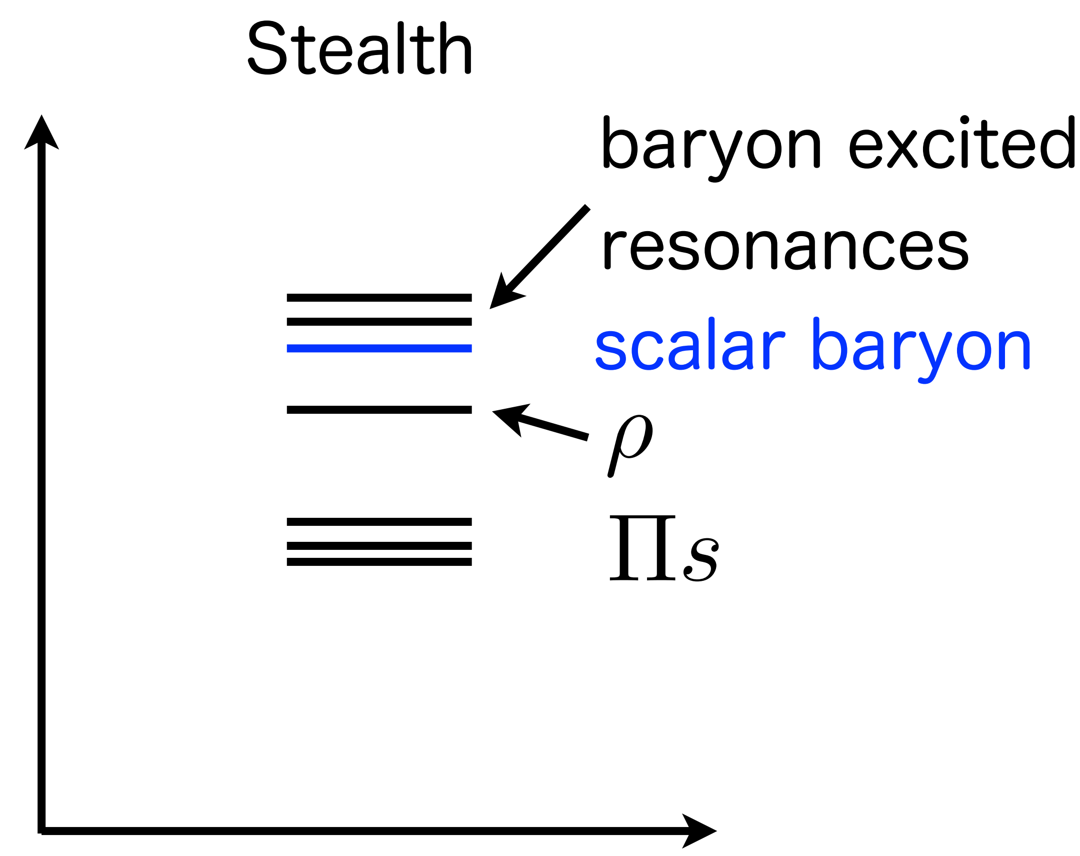
Confluence of collider and direct detection bounds, but for reasons completely different than ordinary (elementary) WIMPs.

Polarizabilities in SU(3) and SU(4)

	m_Π / m_V	c_F	
$SU(4)_{dark}$	0.77	13.3	LSD Collaboration; 1503.04205
$SU(4)_{dark}$	0.70	10.5	
$SU(3)_{dark}$	0.77	9.5	
$SU(3)_{dark}$	0.70	6.7	
neutron - $SU(3)_c$	0.18	2.8	(expt from PDG)

Colliders

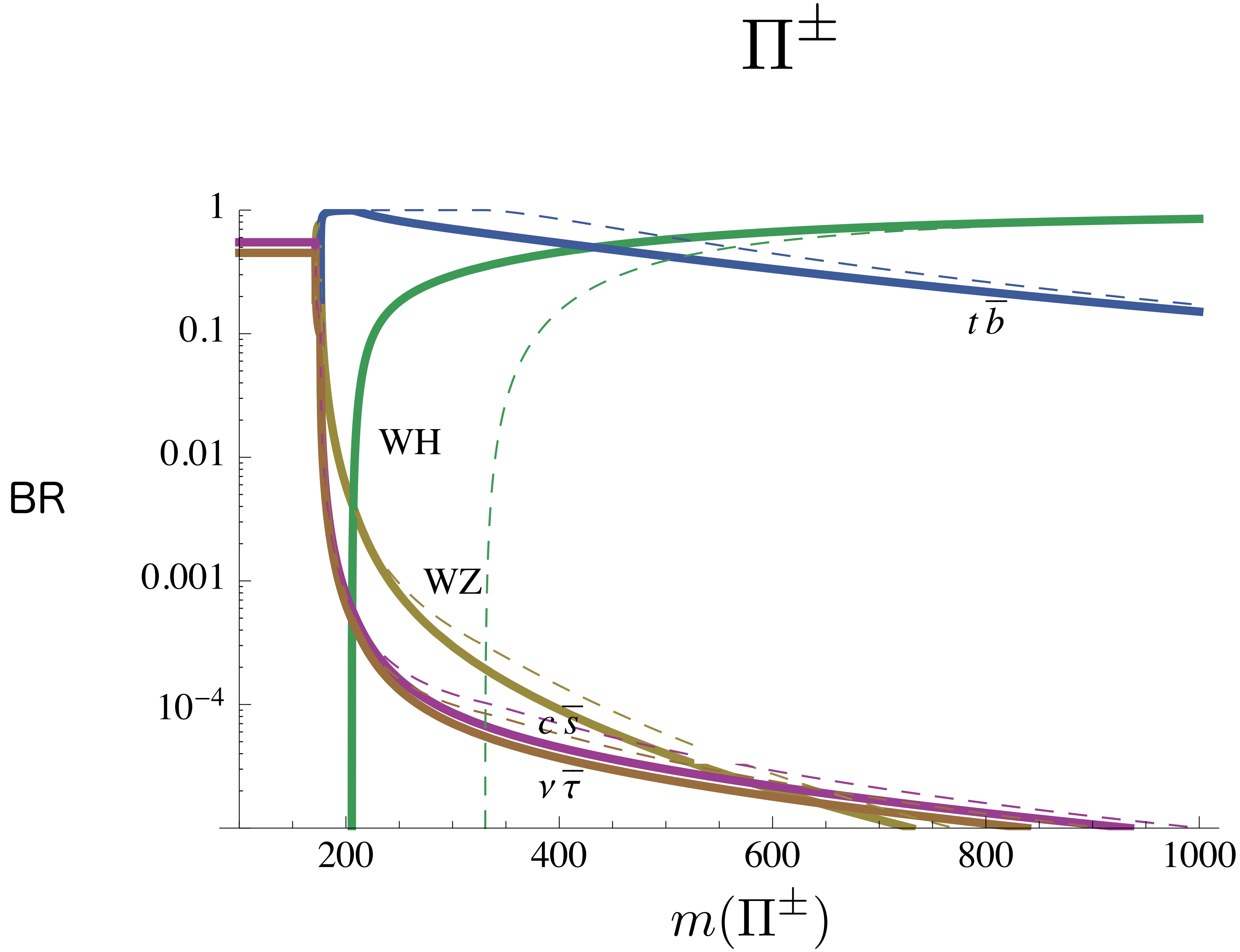




Collider searches dominated by light meson production and decay.

Missing energy signals largely absent!

Lightest Meson Decay Rates - A First Look



Fok, Kribs; 1106.3101

Also, vector meson (ρ) phenomenology interesting (and constrained); depends sensitively on f_ρ/m_ρ

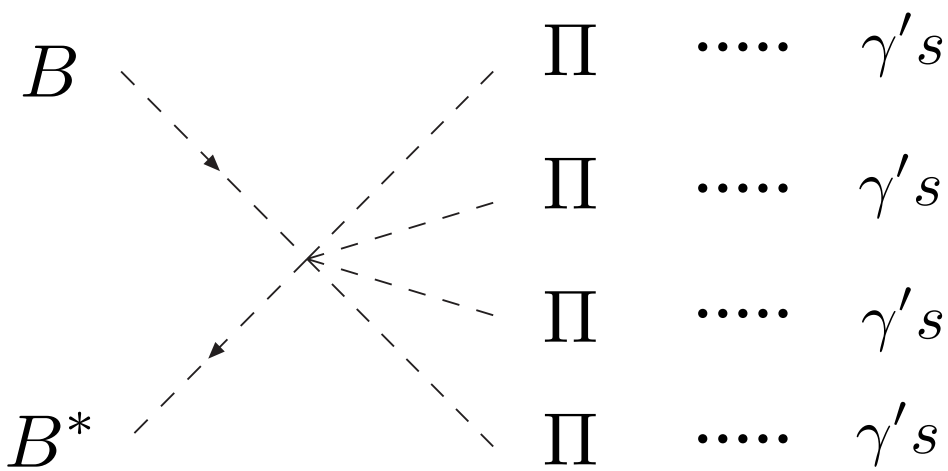
Astrophysical Signals - A First Look

Excited states of dark baryon that are nearby in mass

- fine structure
- hyperfine structure

could be visible through γ-ray emission/absorption lines.

If some symmetric component, annihilation signals (into γ s) are extremely interesting. It could be that multibody final states are generic, e.g.



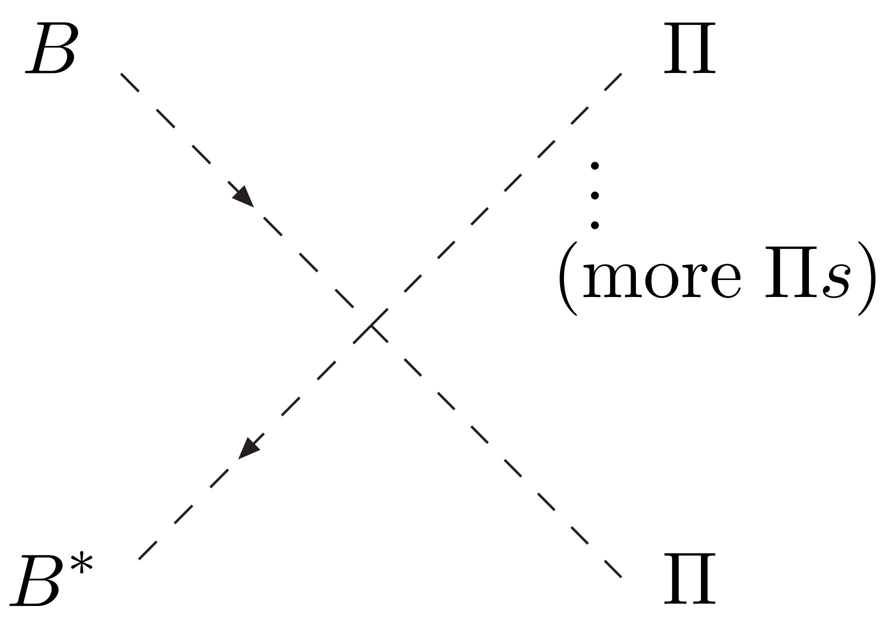
2->4->8-> etc cascade annihilation explored in

Elor, Rodd, Slatyer; 1503.01773

BUT! Expect 2->n gives qualitatively different distribution

Abundance

Symmetric



If 2 -> 2 dominates the thermal annihilation rate and saturates unitarity, expect

Griest, Kamionkowski; 1990

$$m_B \sim 100 \text{ TeV}$$

Unfortunately, this is a hard calculation to do using lattice...

Asymmetric

e.g., through EW sphalerons

Barr, Chivukula, Farhi; 1990

$$n_D \sim n_B \left(\frac{yv}{m_B}\right)^2 \exp\left[-\frac{m_B}{T_{\rm sph}}\right]$$

IF EW breaking comparable to EW preserving masses, expect roughly

$$m_B \lesssim m_{\rm techni-B} \sim 1 \text{ TeV}$$

How much less depends on several factors...

Summary and Future

- Stealth Dark Matter is a viable composite dark matter composed of electrically charged constituents
  --> all new mass scales technically natural
  --> stability of DM is automatic and very safe from higher-dim operators
  --> EW interaction allows thermal/asymmetric mechanisms
  --> Higgs couplings ensure charged mesons decay without new physics; contributions to S parameter controlable (lattice input)

- Direct detection through polarizability possible for dark baryons roughly between 200-800 GeV

- Dark meson production and decay is an extremely interesting LHC signal
  --> meson form factors important to determine rates (lattice input)

- Indirect astrophysical signals (γ-rays) possible between excited states as well as annihilation of a symmetric component