A Model of Stealth Dark Matter

Graham Kribs

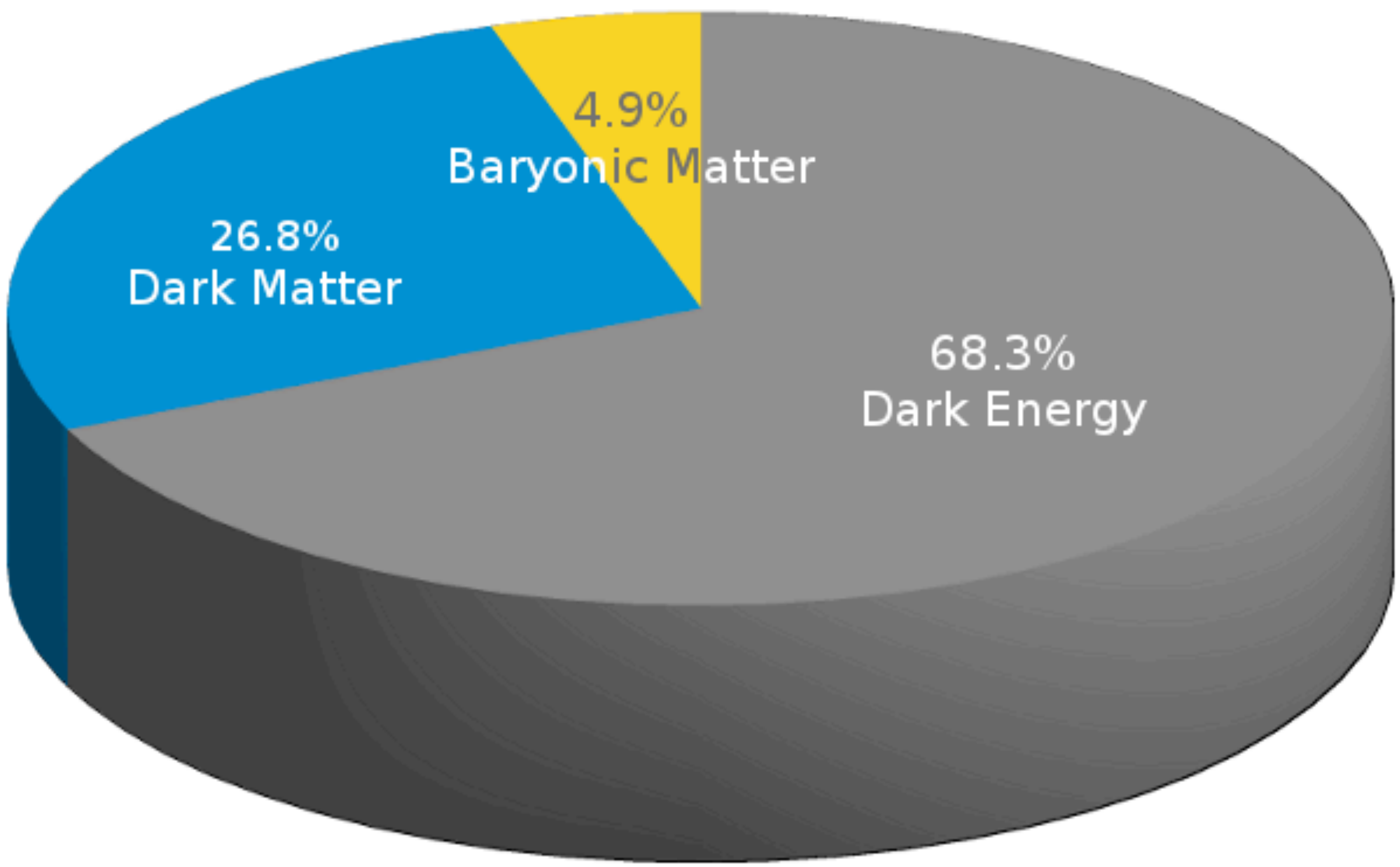
Based on 1402.6656, 1503.04203, 1503.04205
with LSD Collaboration

LLNL | Lattice for BSM Workshop | April 2015

Lattice Strong Dynamics Collaboration

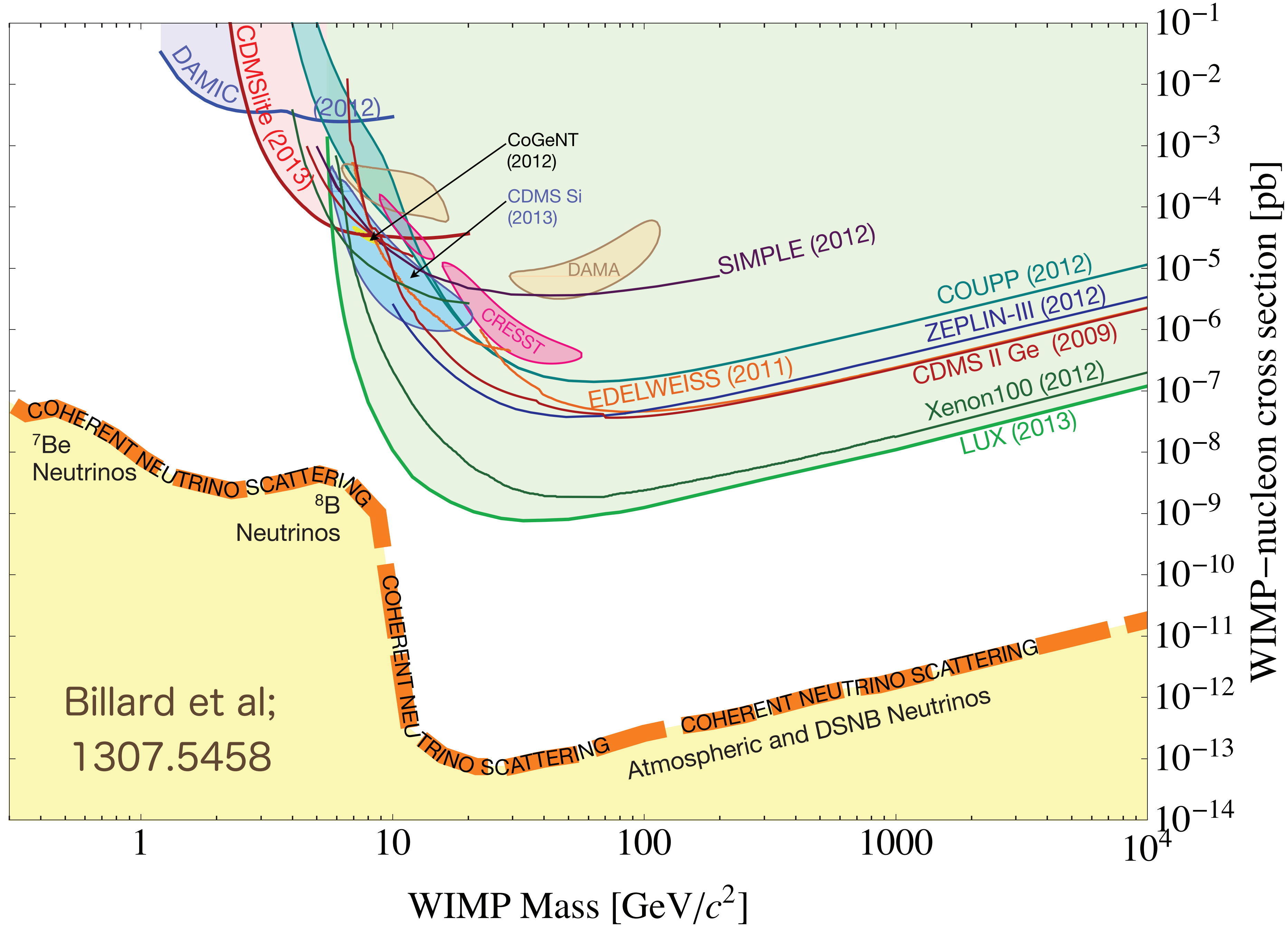
T. Appelquist, G. Fleming (Yale)
E. Berkowitz, E. Rinaldi, C. Schroeder, P. Vranas (Livermore)
R. Brower, C. Rebbi, E. Weinberg (Boston U)
M. Buchoff (Washington)
X. Jin, J. Osborn (Argonne)
J. Kiskis (UC Davis)
G. Kribs (Oregon)
E. Neil (Colorado & Brookhaven)
S. Sryitsyn (Brookhaven)
D. Schaich (Syracuse)
O. Witzel (Boston U & Edinburgh)

Dark Matter

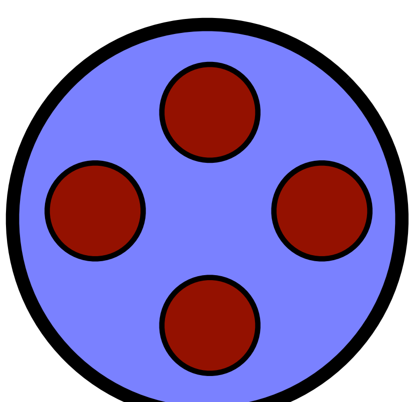


Overwhelming evidence from CMB; galaxies; clusters; BAO; ...

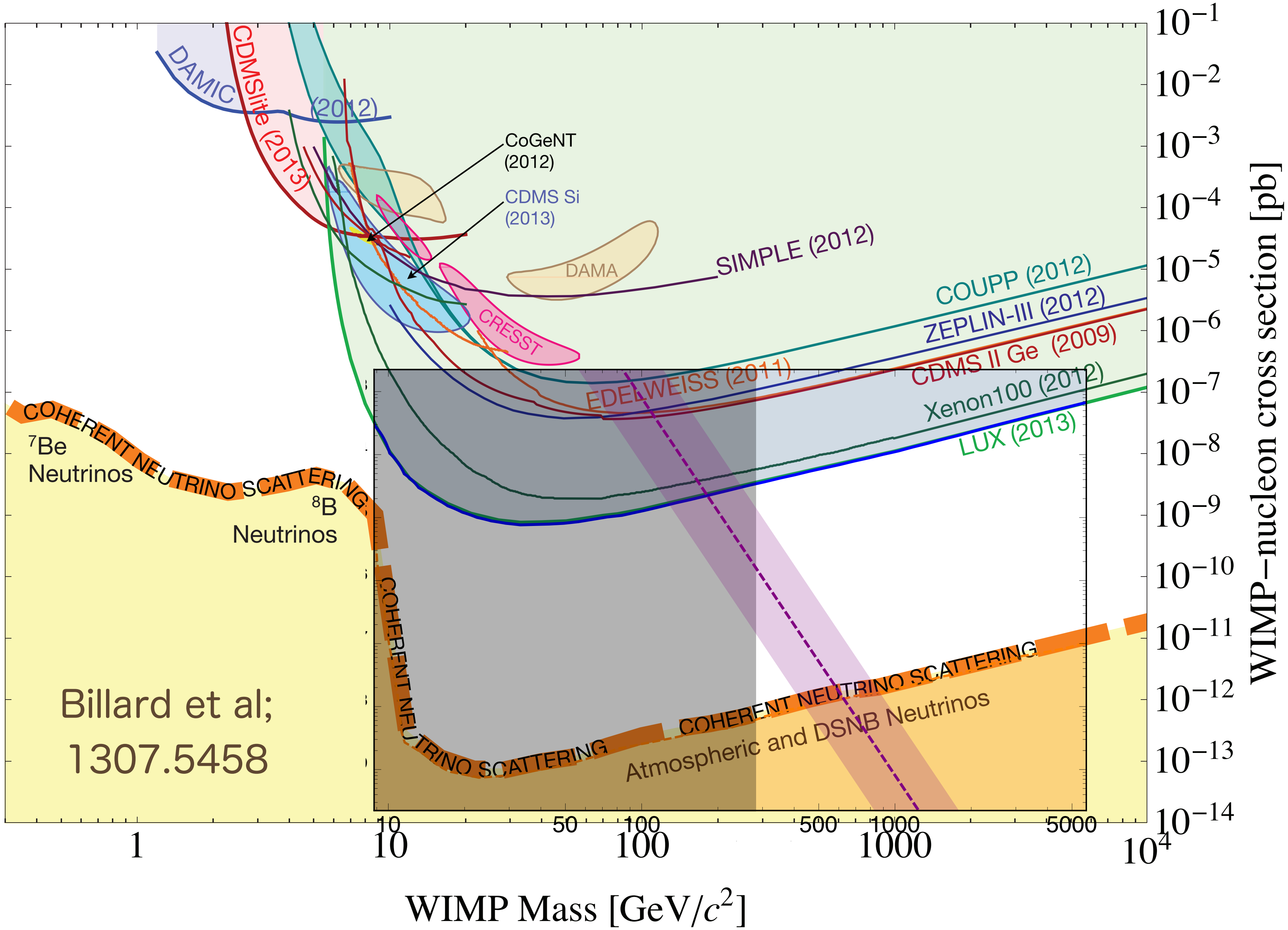
Direct Detection Cross Section



Suppressed Cross Sections

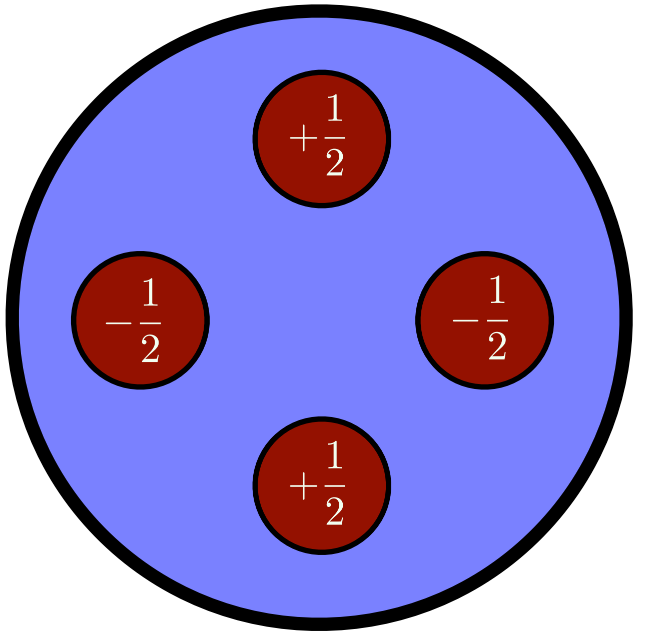
	σ_{nucleon}		σ_{RADAR}
4th Dirac neutrino 	$\sim 10^{-38}\ \text{cm}^2$	B-52 	$\sim 100\ \text{m}^2$
Quirky DM	$\sim 10^{-43}\ \text{cm}^2$	Falcon 	$\sim 10^{-2}\ \text{m}^2$
Stealth DM 	$\sim \left(\frac{200\ \text{GeV}}{m_B}\right)^6 \times 10^{-45}\ \text{cm}^2$	Stealth B-2 	even smaller

Direct Detection Cross Section



Effective lower bound on composite DM with electrically charged constituents.

Stealth Dark Matter



- Scalar baryon of strongly-coupled SU(N_D), with N_D even [focus on SU(4)] and dark fermions transforming under EW group
- All mass scales are technically natural; very roughly $100 \text{ GeV} \lesssim M_f \sim \Lambda_D \lesssim 100 \text{ TeV}$
- We use lattice simulations to calculate several non-perturbative observables (mass spectrum; interactions of DM with SM)
- Naturally "stealthy" with respect to direct detection; we determine the "ultimate" lower bound on composite DM with charged constituents
- LHC phenomenology completely different from weakly-coupled DM models

Lattice Gauge Theory Simulations

Ideal tool to calculate properties of theories with

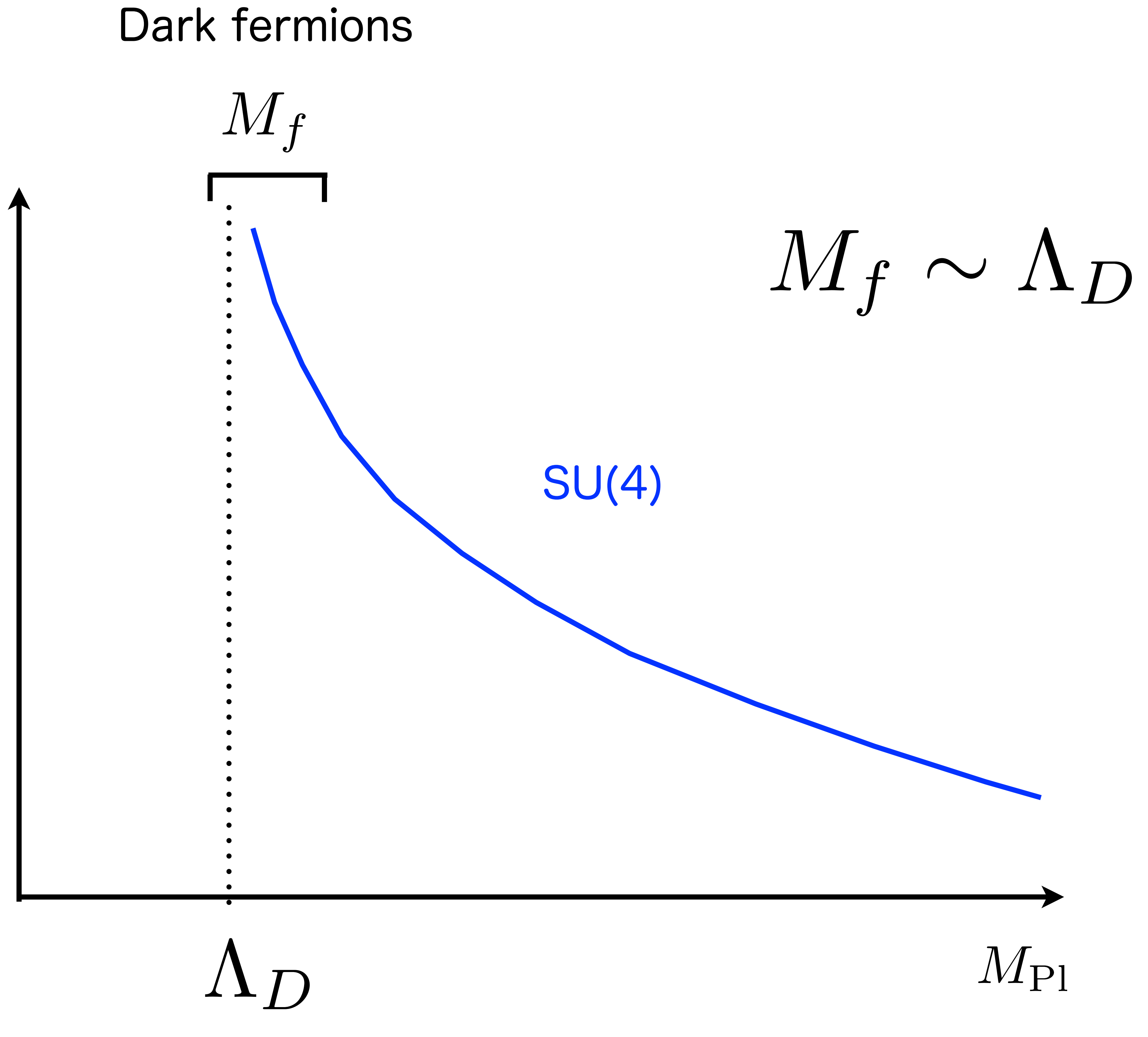
$$M_f \sim \Lambda_D$$

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

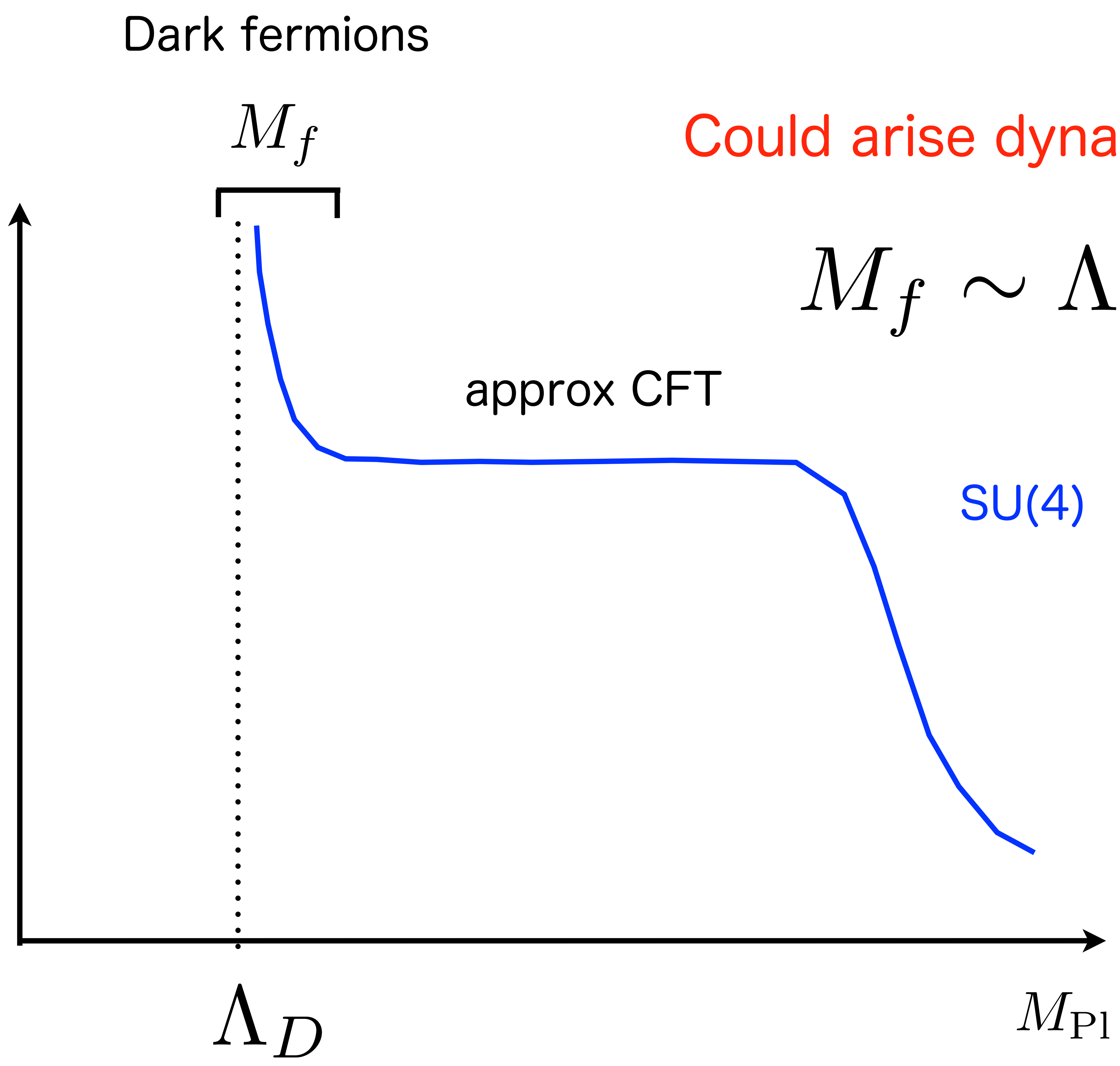
Relevant to DM: Thus far, we have accurate estimates of the spectrum, the "sigma term", and polarizability. Future work will nail down additional correlators (for S parameter), meson form factor, ...

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

Dynamics



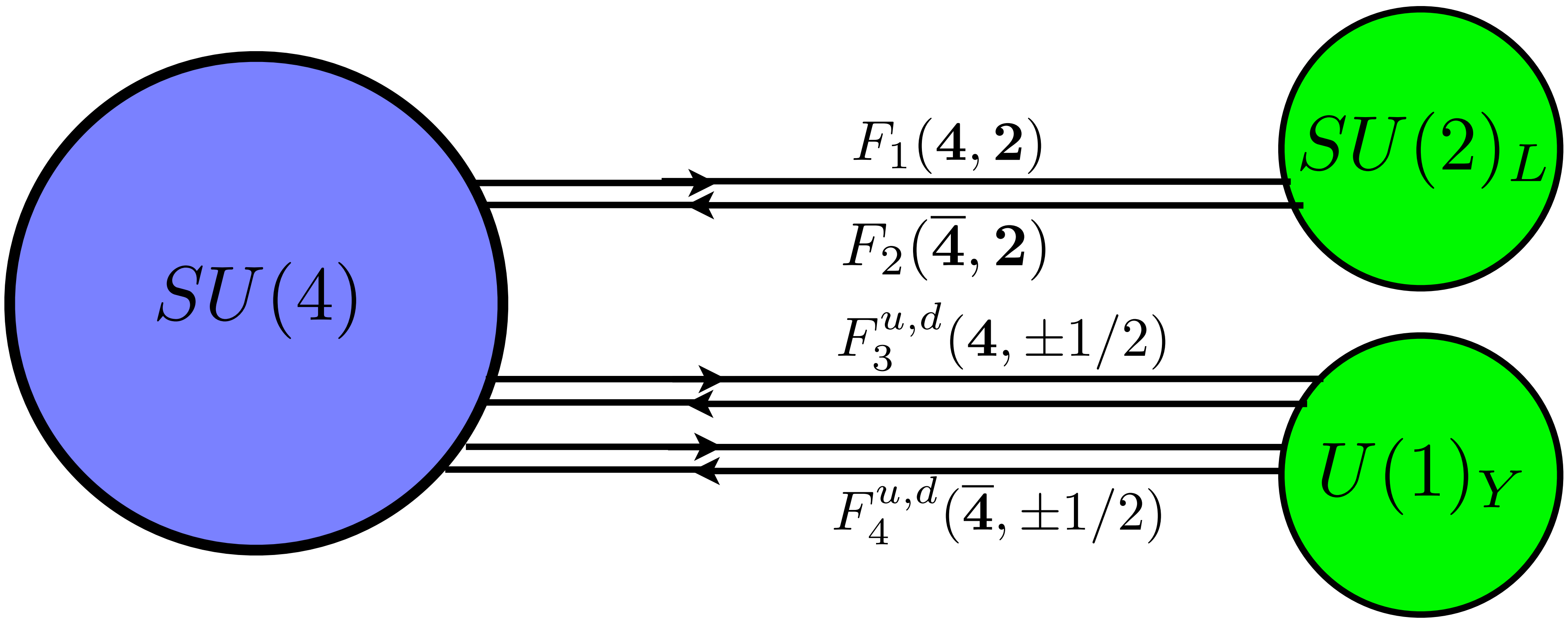
Dynamics



Could arise dynamically

$$M_f \sim \Lambda_D$$

Dark Fermions



Vector-like masses

$$M_{12}\epsilon_{ij}F_1^iF_2^j - M_{34}^u F_3^u F_4^d + M_{34}^d F_3^d F_4^u + h.c.,$$

EW breaking masses

$$\begin{aligned} &y_{14}^u\epsilon_{ij}F_1^iH^jF_4^d + y_{14}^d F_1\cdot H^\dagger F_4^u \\ &-y_{23}^d\epsilon_{ij}F_2^iH^jF_3^d - y_{23}^u F_2\cdot H^\dagger F_3^u \end{aligned} \quad +h.c.$$

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: $U(1)_B$

Dark baryon number automatic.

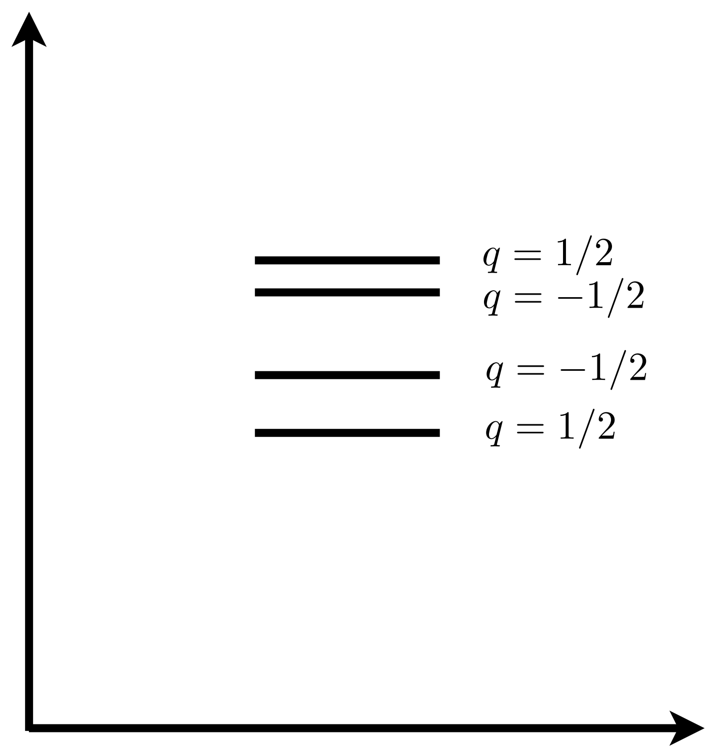
and very safe against cutoff scale violations of global symmetries
e.g.

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

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

Dark Fermion Mass Spectrum

General

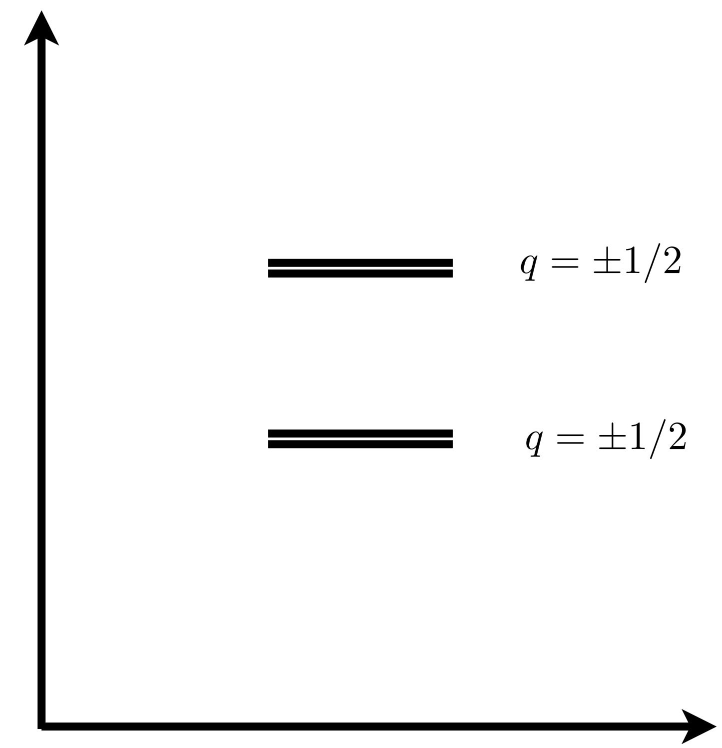


$$M_{12},\ M_{34}^{u},\ M_{34}^{d}$$

$$y_{14}^{u},\ y_{14}^{d}$$

$$y_{23}^{u},\ y_{23}^{d}$$

Custodial SU(2)

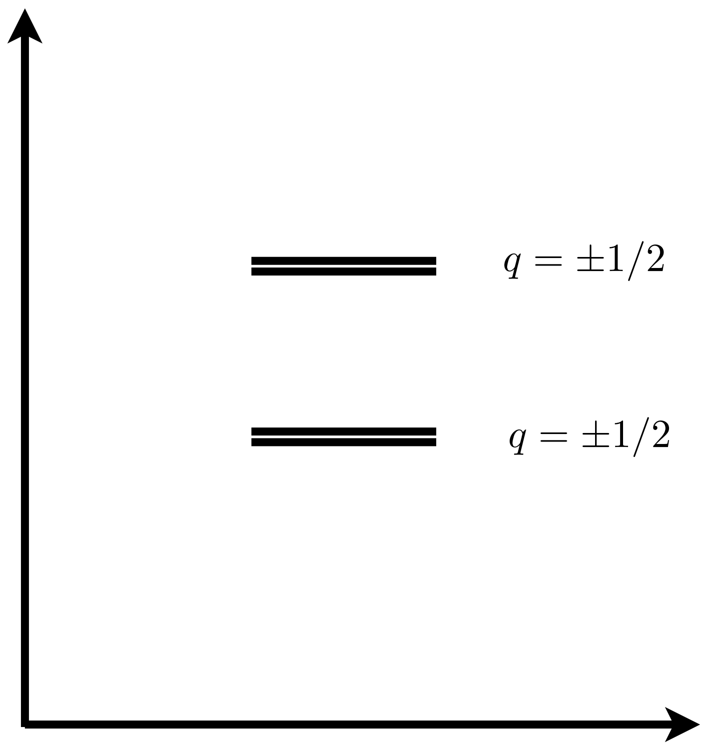


$$M_{34}^{u} = M_{34}^{d}$$

$$y_{14}^{u} = y_{14}^{d}$$

$$y_{23}^{u} = y_{23}^{d}$$

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

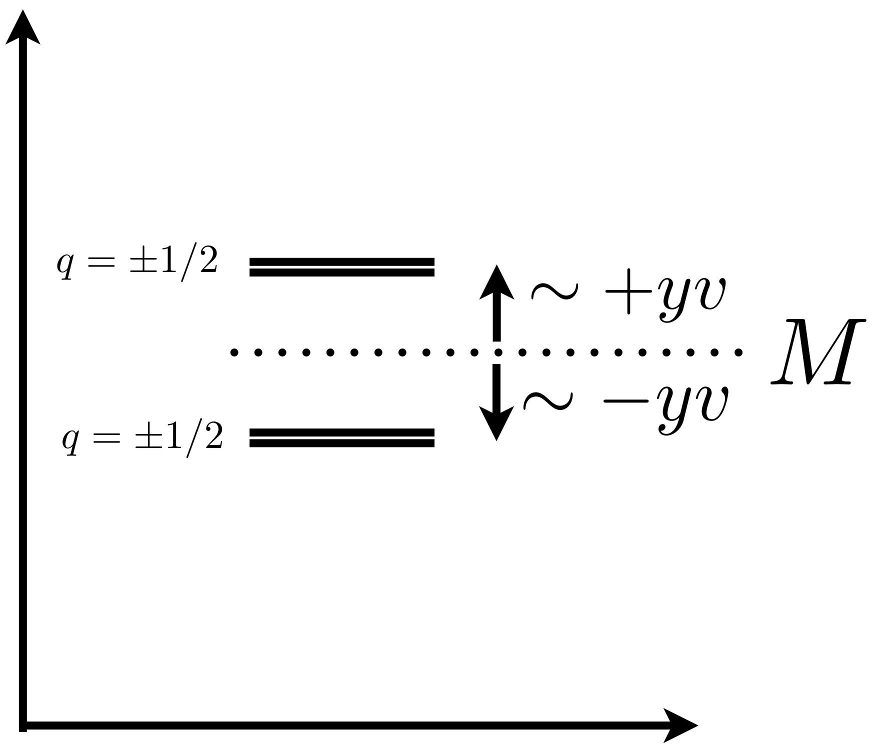
  (no Z coupling to dark matter; otherwise significant constraints)

- Dim-6 charge radius vanishes

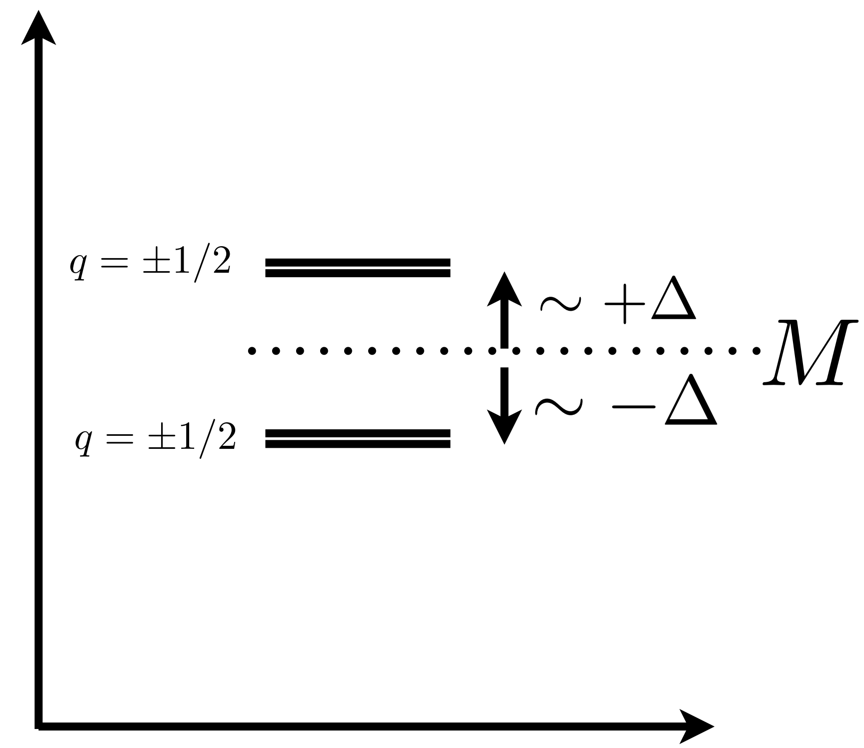
  (more stealthy w.r.t. direct detection;
  one less thing to calculate on lattice)

Two Distinct "Cases"

"Linear Case"



"Quadratic Case"



As we'll see, 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

Fermion mass matrices with custodial SU(2)

$$M^u = M^d = \begin{pmatrix} M \pm \Delta & y_{14} v/\sqrt{2} \\ y_{23} v/\sqrt{2} & M \mp \Delta \end{pmatrix}$$

Convenient to expand around the symmetric matrix limit

$$y_{14} = y + \epsilon_y$$
$$y_{23} = y - \epsilon_y$$

Then the axial current

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

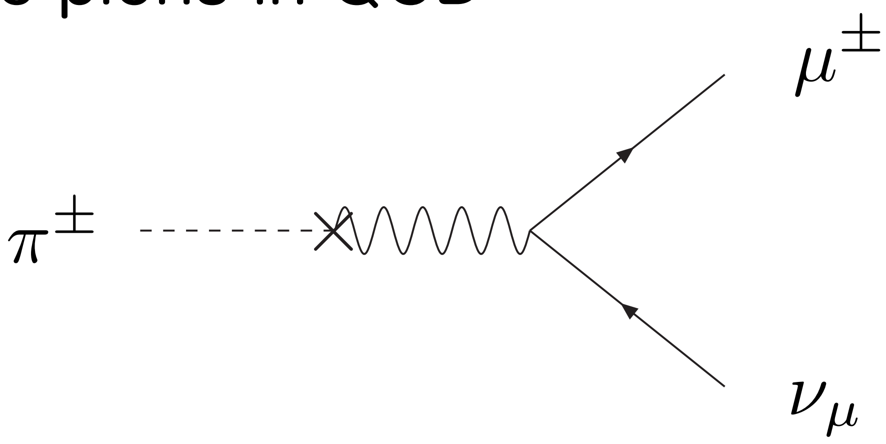
becomes

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

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

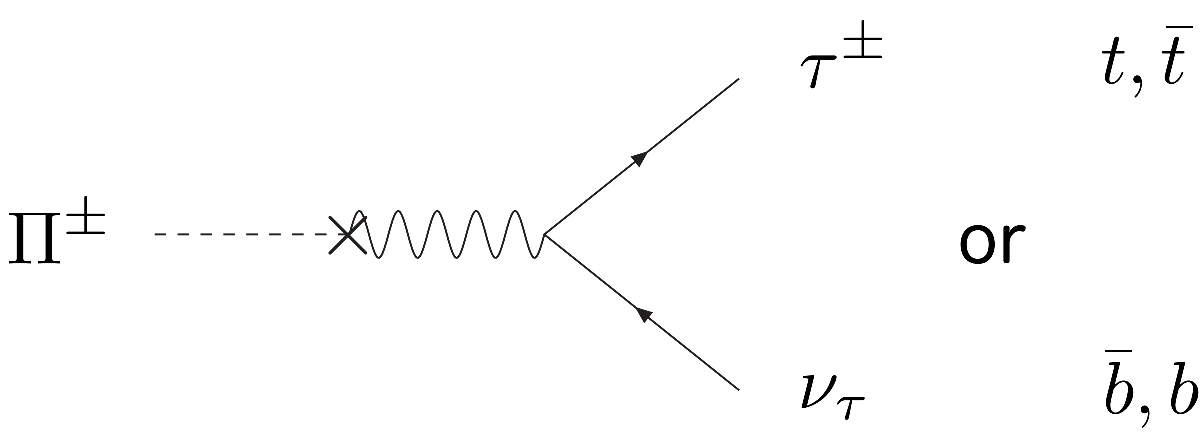
Charged Meson Decay

Like pions in QCD



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

Lightest dark mesons decay through



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

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

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

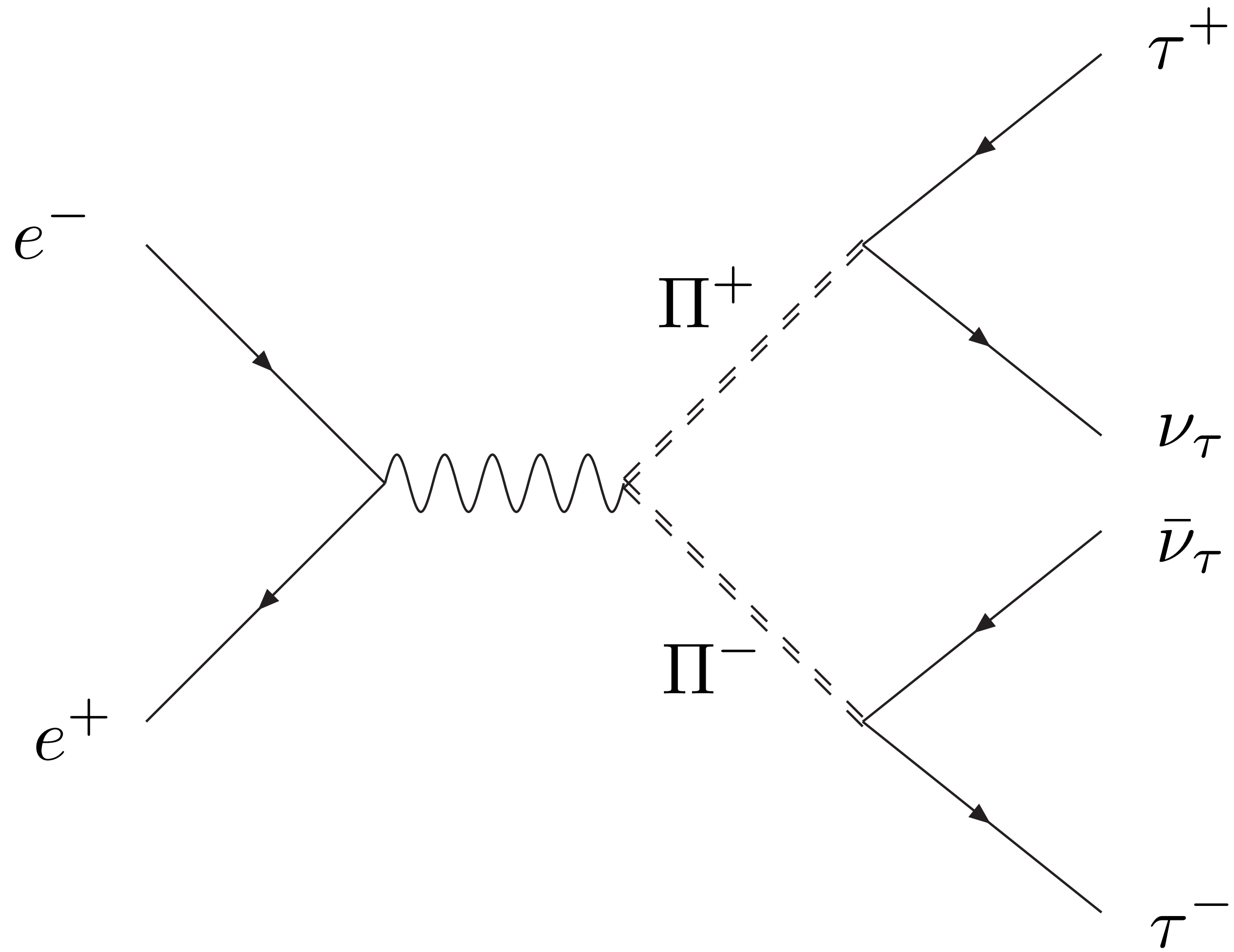
(unlike “Vector-like Confinement”)

Kilic, Okui, Sundrum; 0906.0577

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

Lower bound on meson mass ...

Charged pion production at LEP II

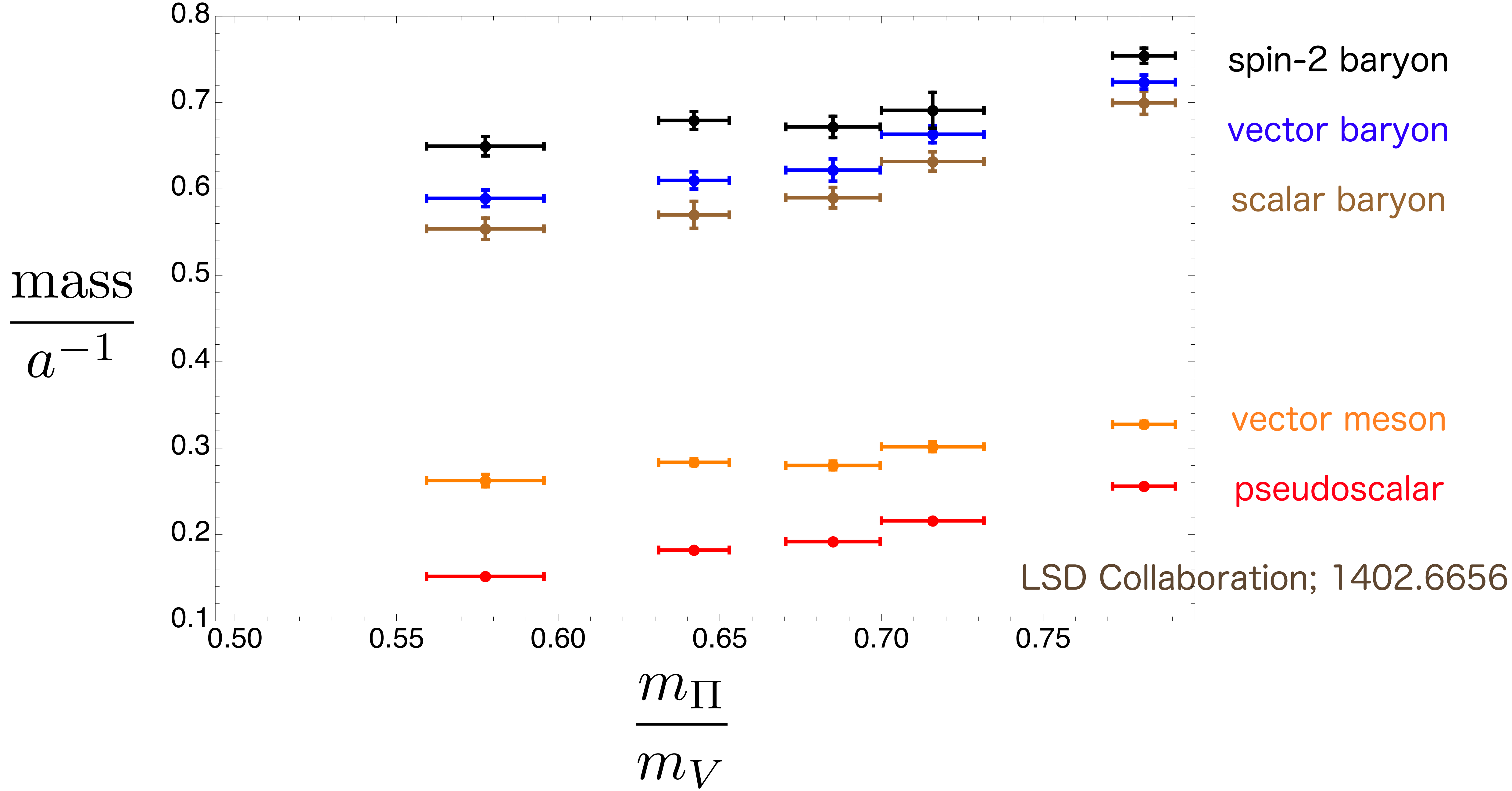


Using a crude recasting of bounds on staus, we find

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

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

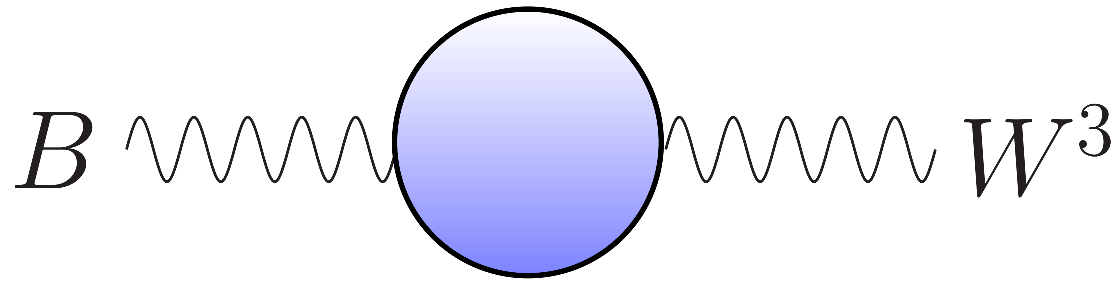
… becomes lower bound on the baryon mass



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

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

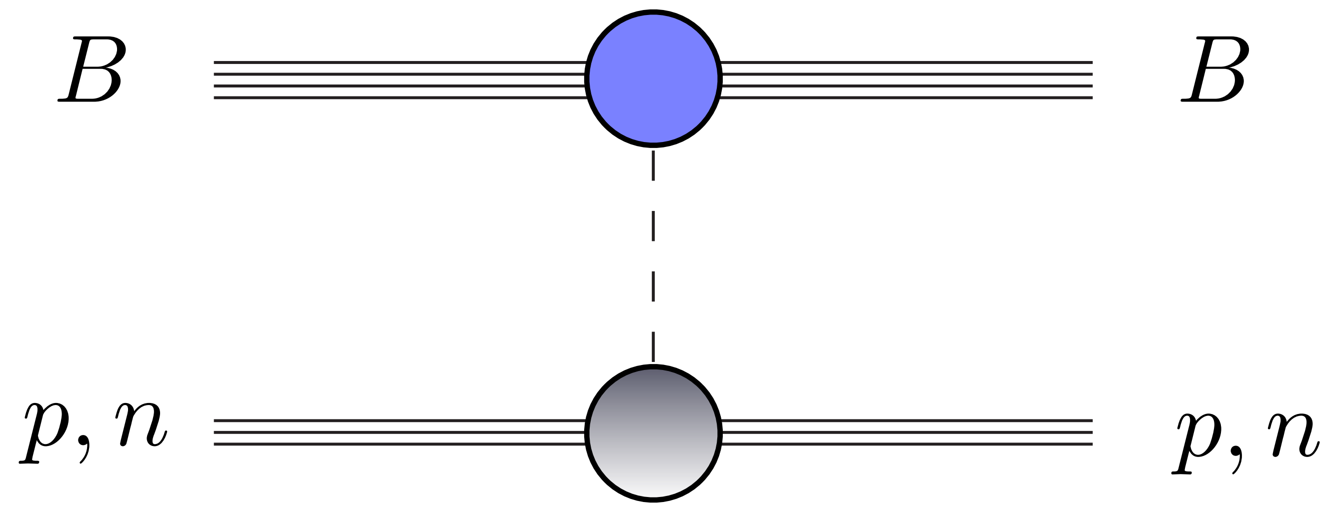
$$y_{\text{eff}} \equiv \begin{cases} y \frac{m_B}{\sqrt{2} M_1} & \text{Linear Case} \\ y \frac{m_B}{\sqrt{2\Delta M_1}} & \text{Quadratic Case.} \end{cases}$$

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

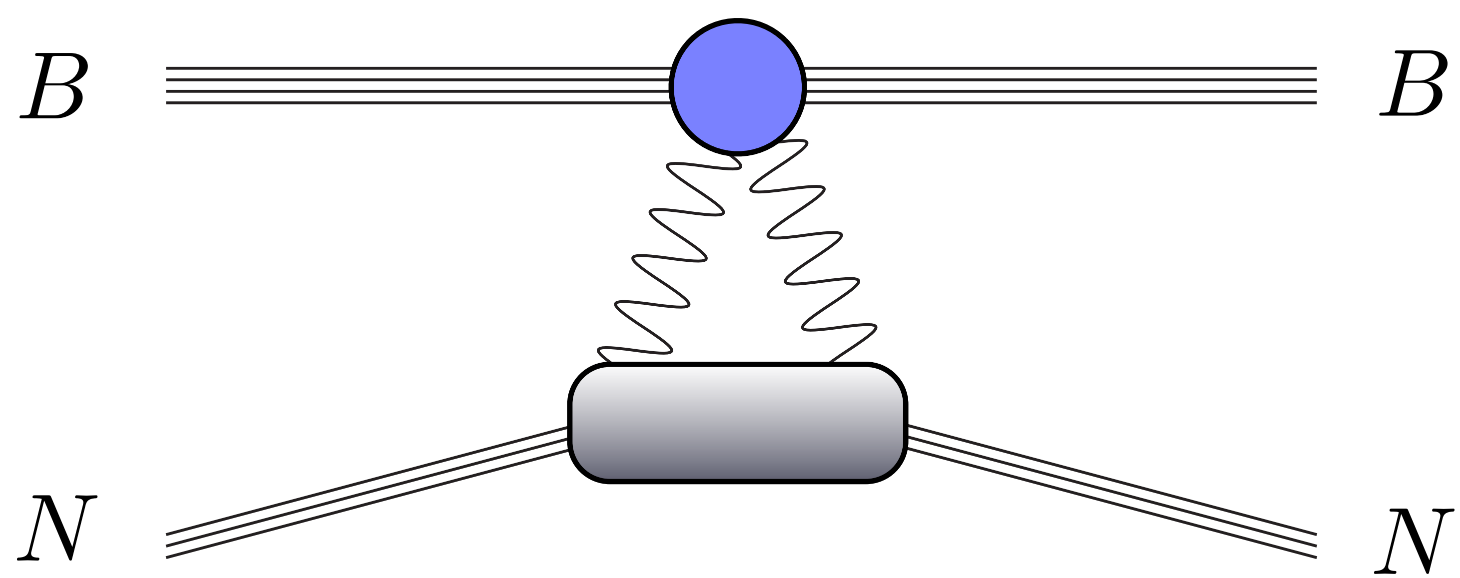
Extracted from lattice!

Direct Detection

Higgs exchange



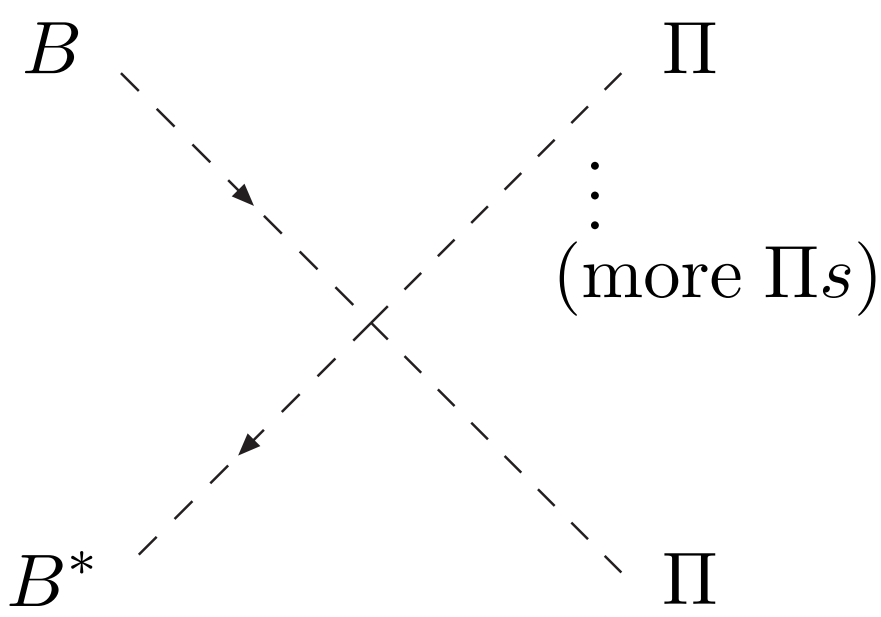
EM polarizability



Stay tuned for Enrico's talk!

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

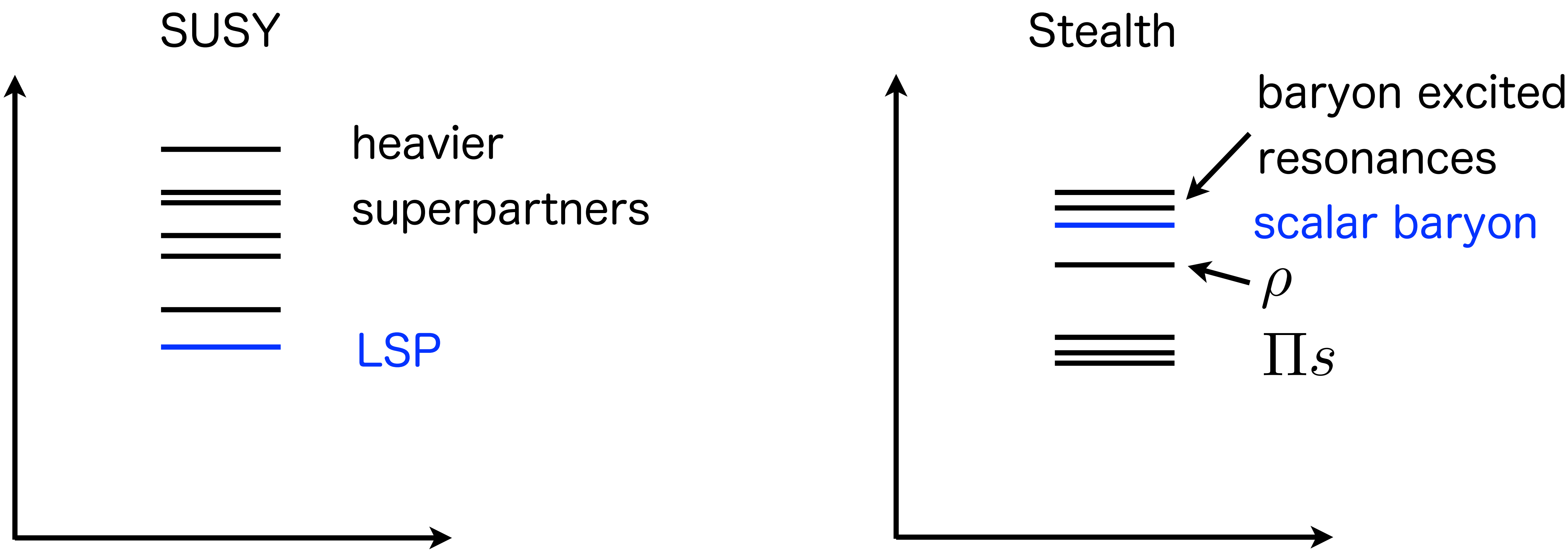
$$n_D \sim n_B \left(\frac{yv}{m_B}\right)^2 \exp\left[-\frac{m_B}{T_{\rm sph}}\right]$$

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...

Colliders

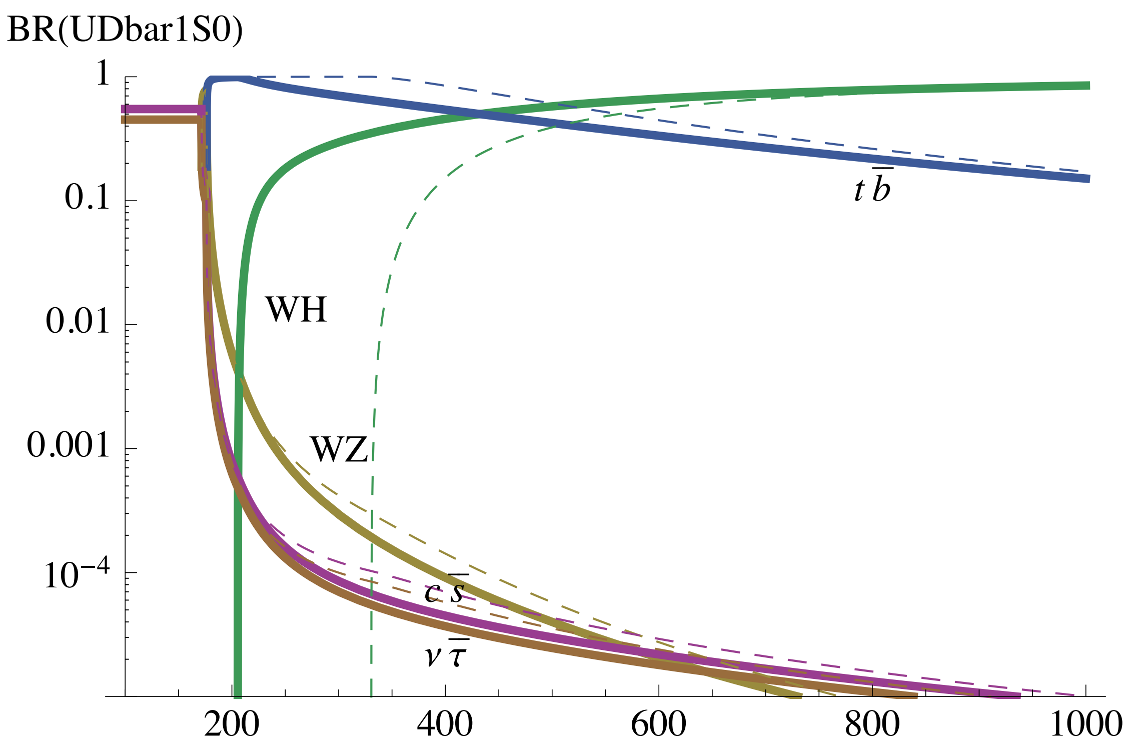


Collider searches dominated by light meson production and decay.

Missing energy signals largely absent!

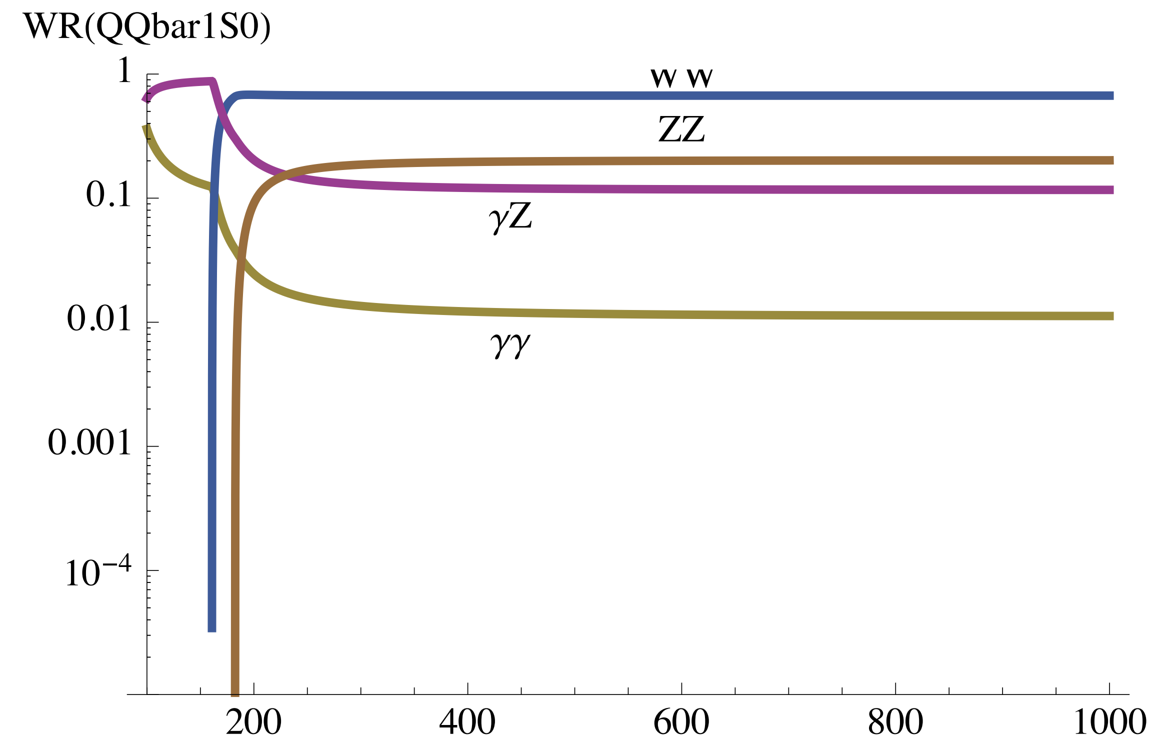
Meson Decay Rates - A First Look

(Quirky) charged pion decay



(a) $^1S_0$

(Vector-like) neutral meson decay



(a) $^1S_0$

Fok, Kribs; 1106.3101

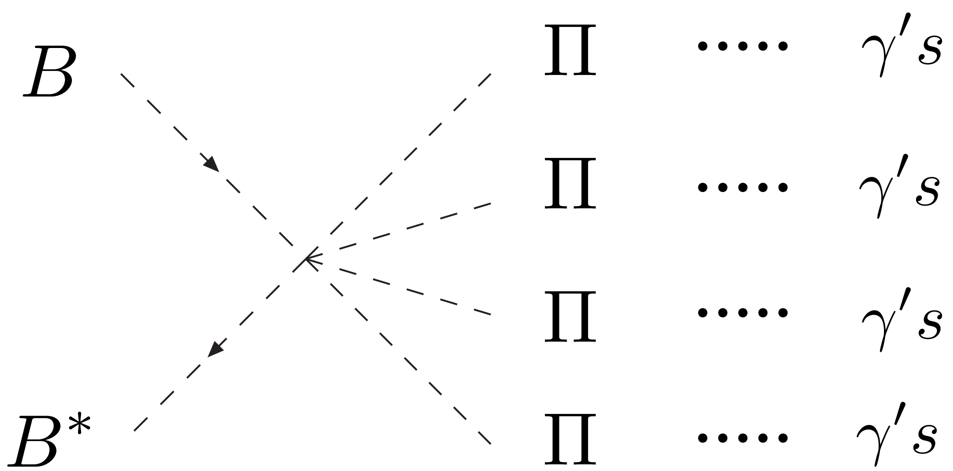
Astrophysical Signals - A First Look

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 γs) are extremely interesting. It could be that multibody final states are generic, e.g.



Cascade annilihition begun to be explored!

Elor, Rodd, Slatyer; 1503.01773

Summary and Future

- Stealth Dark Matter is a viable composite dark matter candidate composed of electrically charged constituents

- Qualitatively different direct, indirect, and collider signals are expected, illustrating the importance of "thinking outside the box"

- Meson production and decay is an extremely interesting LHC signal
  - calculating meson form factor f_{Π} from lattice is a high priority needed to make quantitative predictions for LHC

- S parameter from lattice would lead to bounds on EW breaking parameters (important!)

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

- Further investigation of abundance remains interesting (esp. asymmetric)