Stealth Dark Matter

Graham Kribs

Based on 1402.6656, 1503.04203, 1503.04205
with LSD Collaboration

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Lattice Strong Dynamics Collaboration

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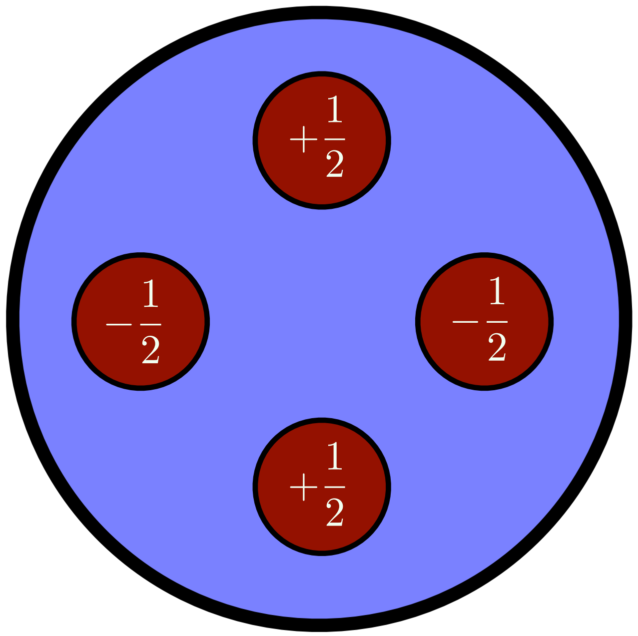
(Radar) Cross Sections

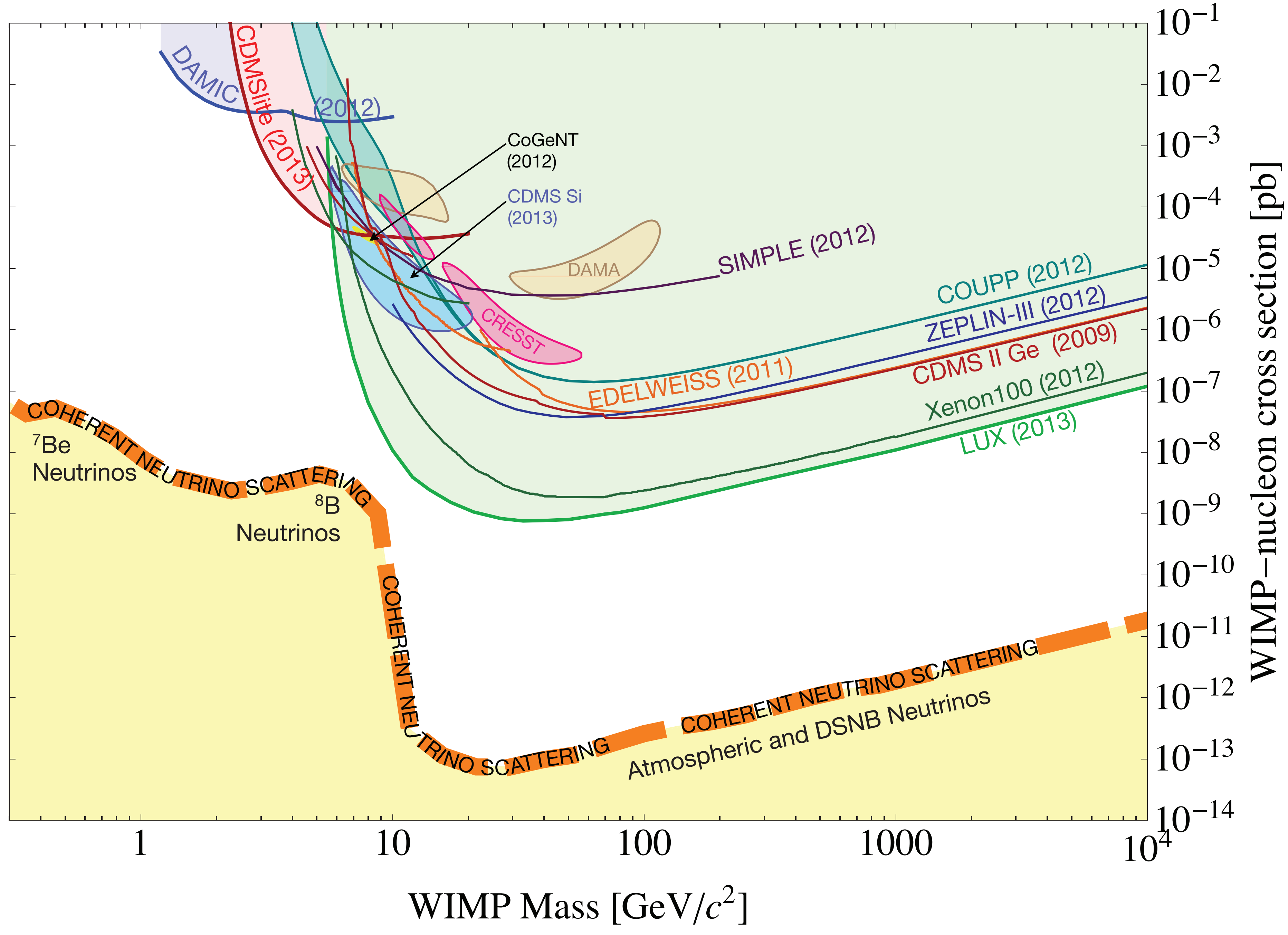
B-52	Falcon	Stealth B-2
		
$\approx 100\ m^2$	$\approx 0.01\ m^2$	$\approx 0.001\ m^2$

Stealth DM is a new model of DM

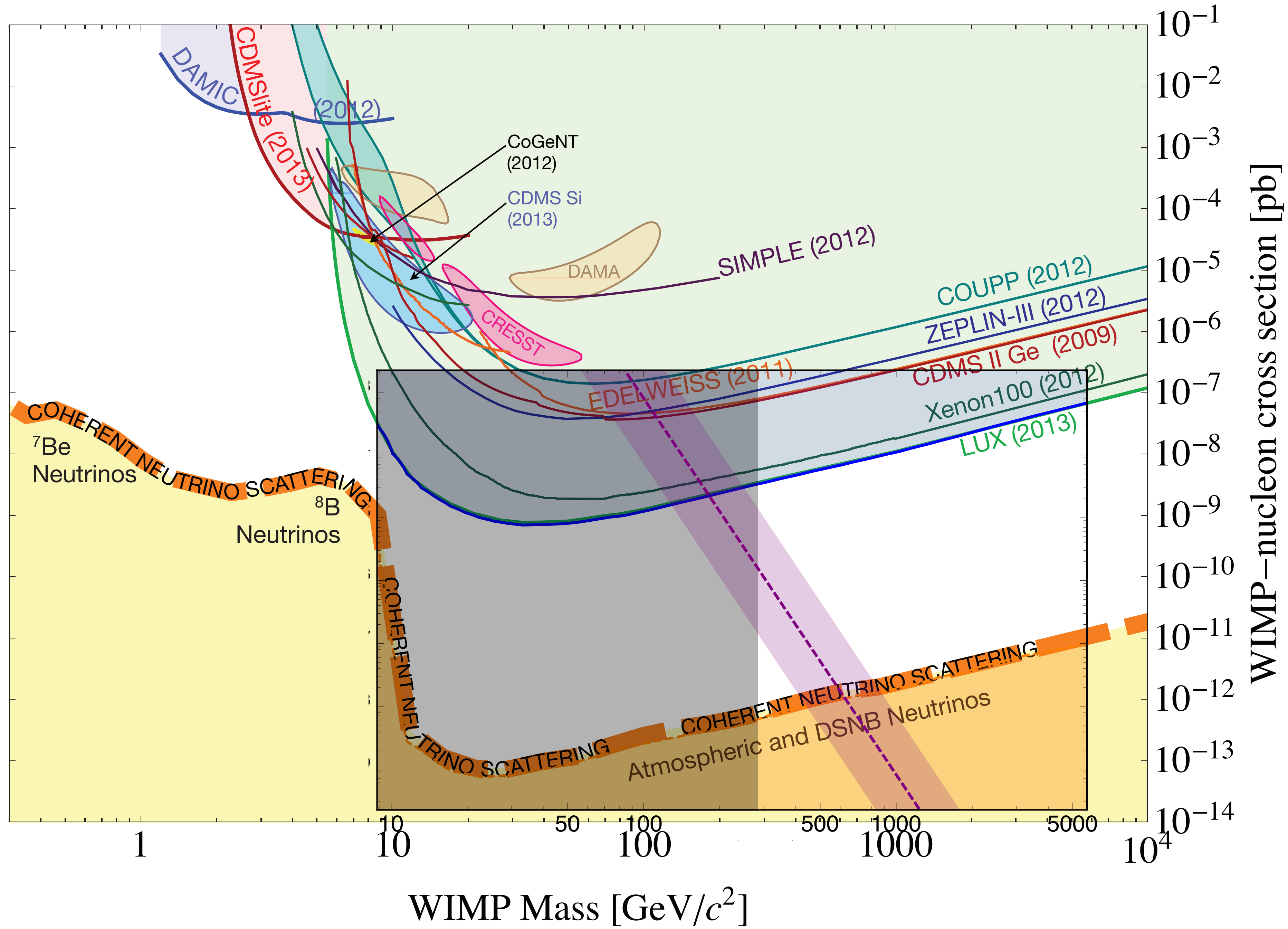


- Scalar baryon of strongly-coupled SU(N_D), with N_D even [focus on SU(4)] and dark fermions transforming under EW group
- All mass scales are technically natural; very roughly $100\ \mathrm{GeV} \lesssim M_f \sim \Lambda_D \lesssim 100\ \mathrm{TeV}$
- We use lattice simulations to calculate several non-perturbative observables (mass spectrum; interactions of DM with SM)
- Naturally “stealthly” 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

Direct Detection Cross Section



Direct Detection Cross Section



Effective lower bound on composite DM with electrically charged constituents.

Lattice Gauge Theory Simulations

Ideal tool to calculate properties of theories with

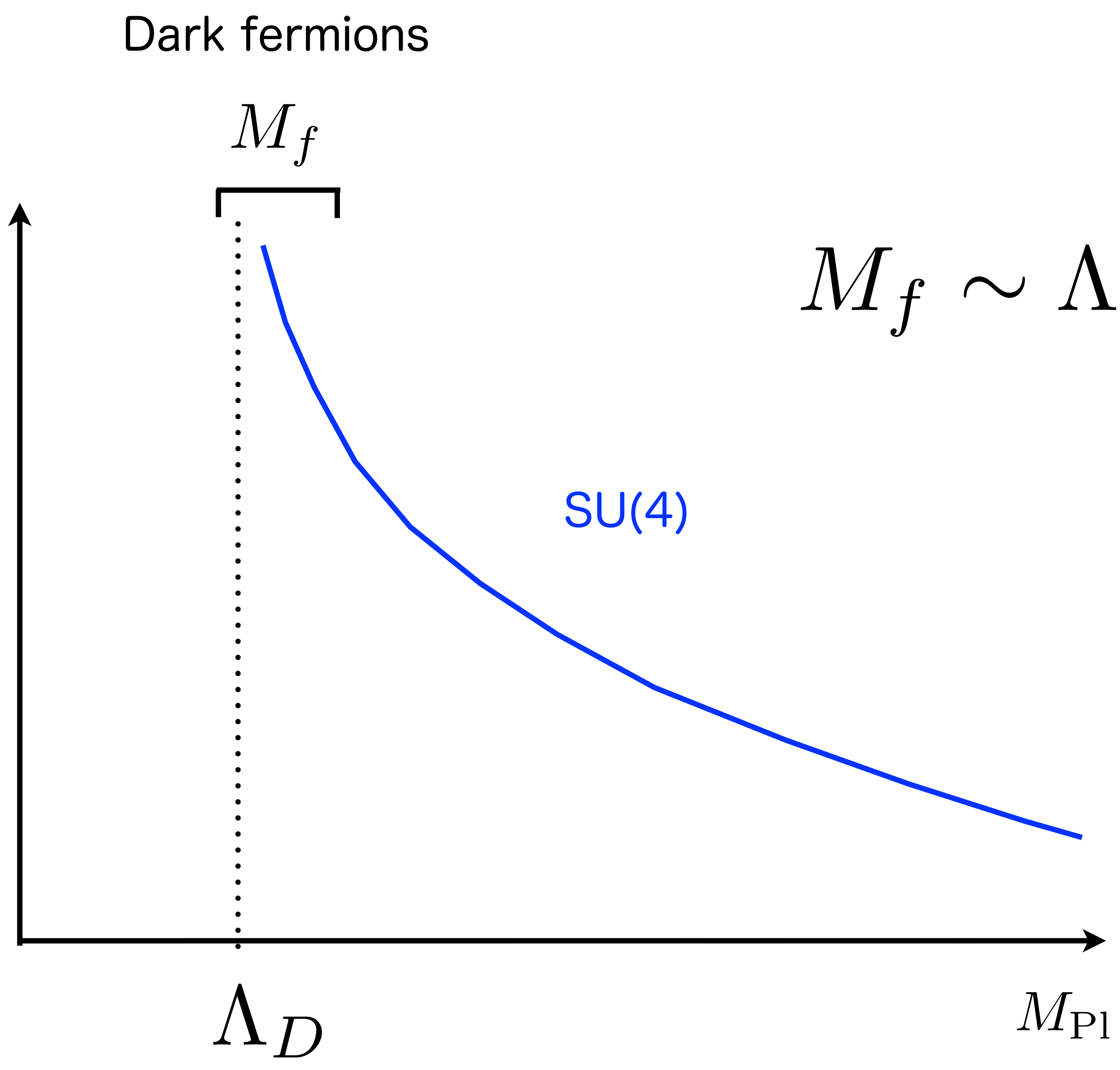
$$M_f \sim \Lambda_D$$

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, ...

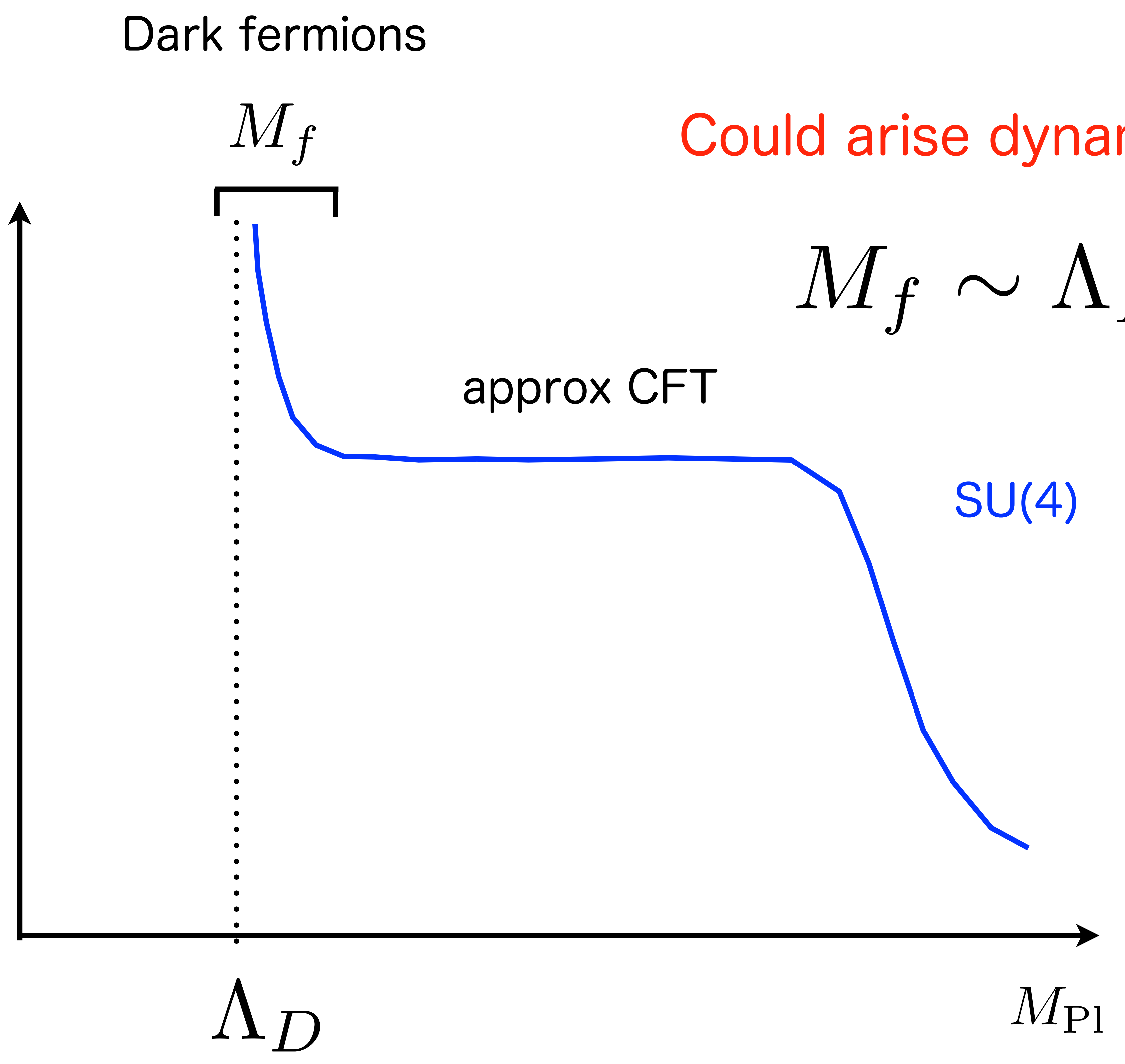
Simulated with modified Chroma mainly on LLNL sequoia/vulcan. Quenched, unmodified Wilson fermions. Several volumes and lattice spacings.

Dynamics



$$M_f \sim \Lambda_D$$

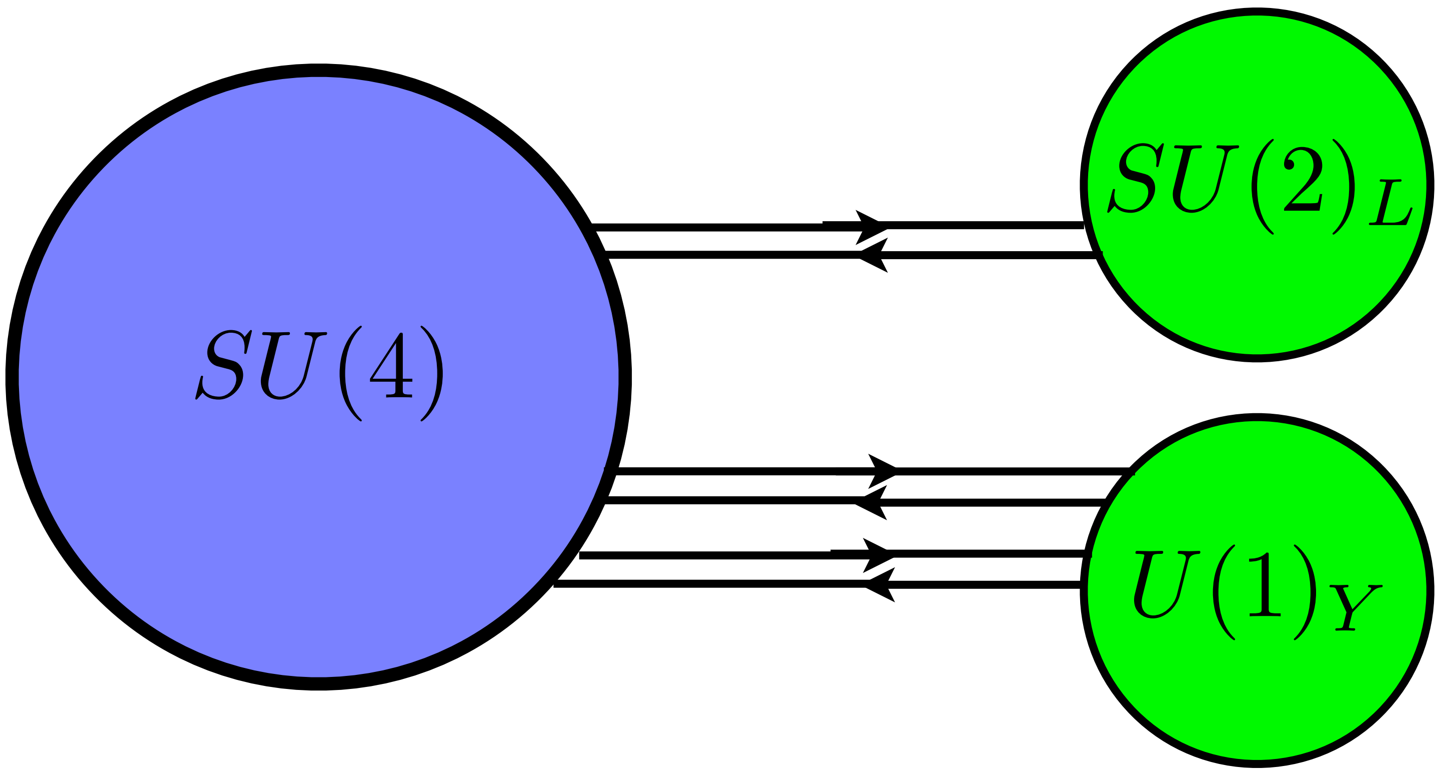
Dynamics



Could arise dynamically

$$M_f \sim \Lambda_D$$

Dark Fermions



$F_1(\mathbf{4},\mathbf{2})$
$F_2(\overline{\mathbf{4}},\mathbf{2})$

$F_3^{u,d}(\mathbf{4},\pm 1/2)$
$F_4^{u,d}(\overline{\mathbf{4}},\pm 1/2)$

Vector-like masses

$$M_{12}\epsilon_{ij}F_1^iF_2^j - M_{34}^uF_3^uF_4^d + M_{34}^dF_3^dF_4^u + h.c.,$$

EW breaking masses

$$\begin{aligned} &y_{14}^u\epsilon_{ij}F_1^iH^jF_4^d + y_{14}^dF_1\cdot H^\dagger F_4^u \\ &-y_{23}^d\epsilon_{ij}F_2^iH^jF_3^d - y_{23}^uF_2\cdot H^\dagger F_3^u \end{aligned} \quad +h.c.$$

Dark Flavor Symmetries

Under SU(4): U(4) x 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.

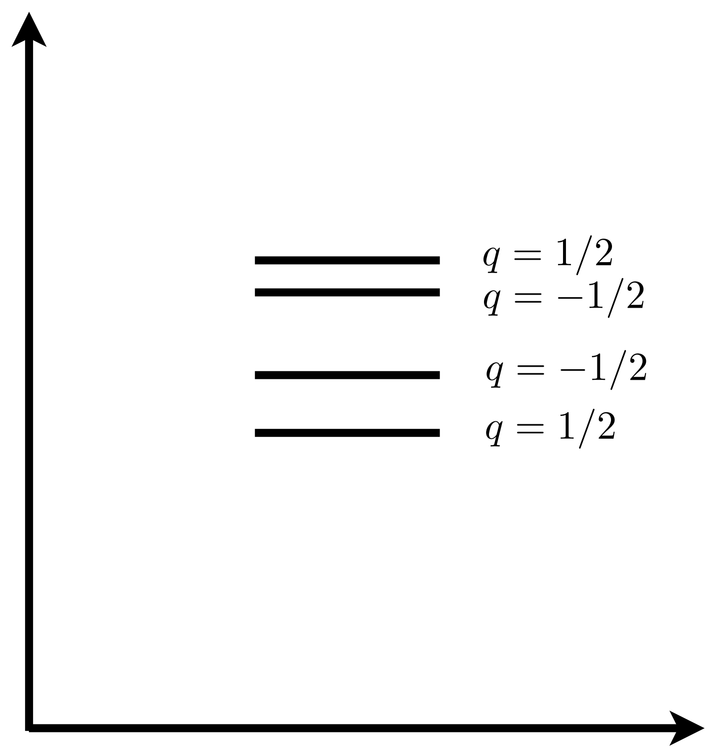
and very safe against cutoff scale violations of global symmetries e.g.

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

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

Dark Fermion Mass Spectrum

General

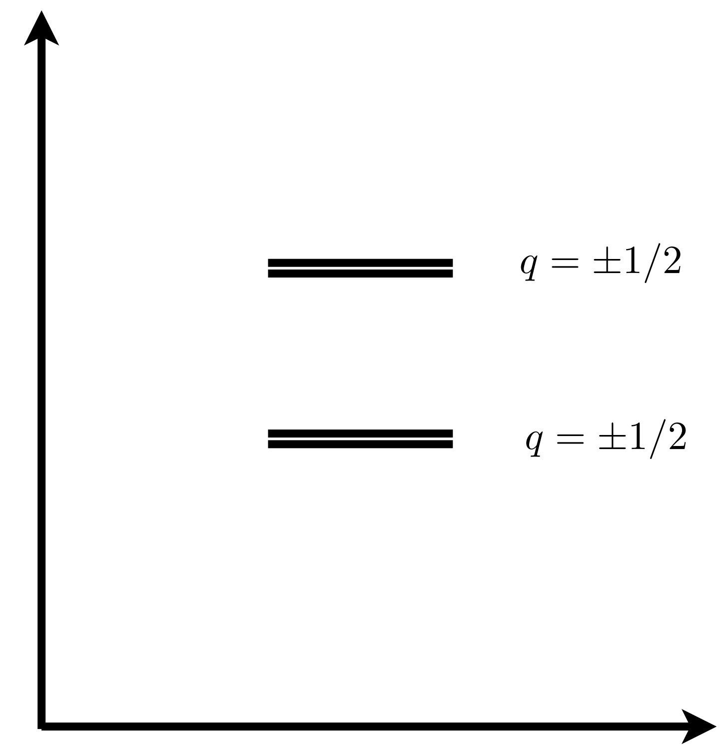


$$M_{12},\ M_{34}^u,\ M_{34}^d$$

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

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

Custodial SU(2)

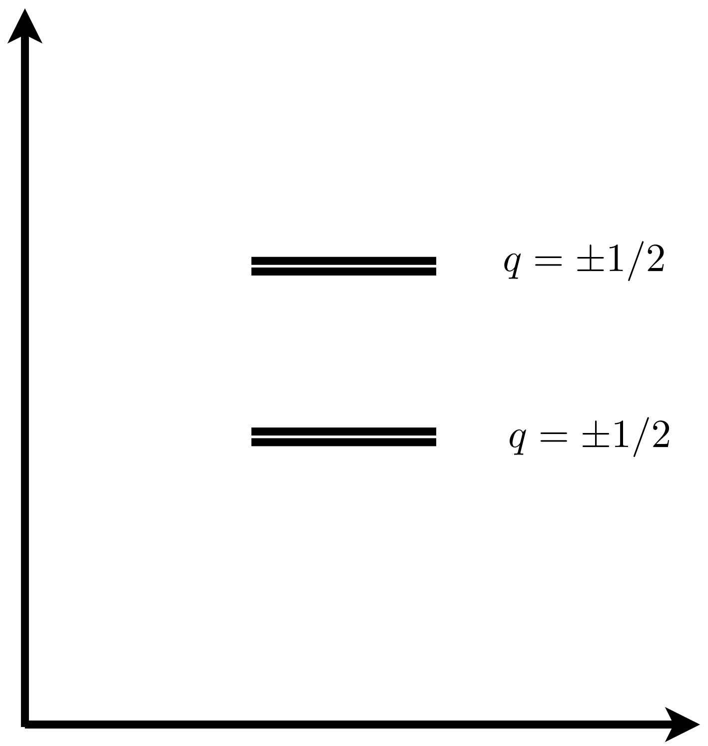


$$M_{34}^u = M_{34}^d$$

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

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

Custodial SU(2)



- Lightest baryon is a neutral complex scalar

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

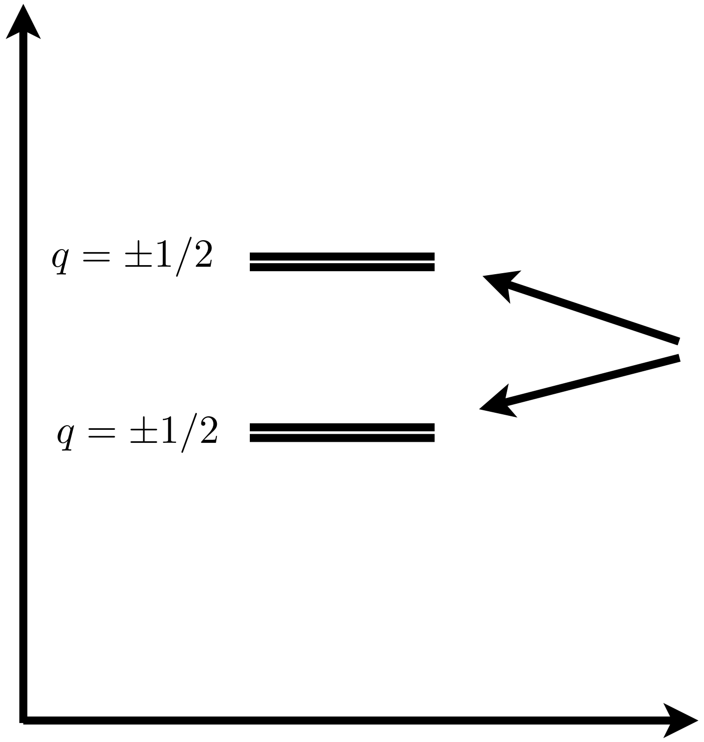
- Contributions to T parameter vanish

  (no need to make life more complicated)

- Dim-6 charge radius vanishes

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

Notation

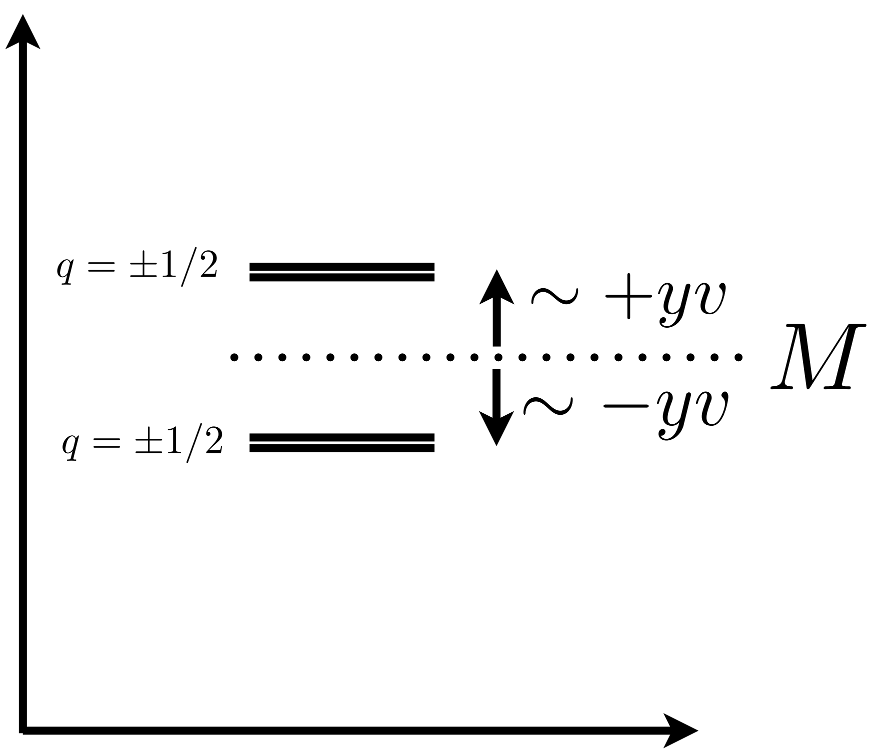


$$M_{1,2} = M \mp \sqrt{\Delta^2 + \frac{y_{14} y_{23} v^2}{2}}$$

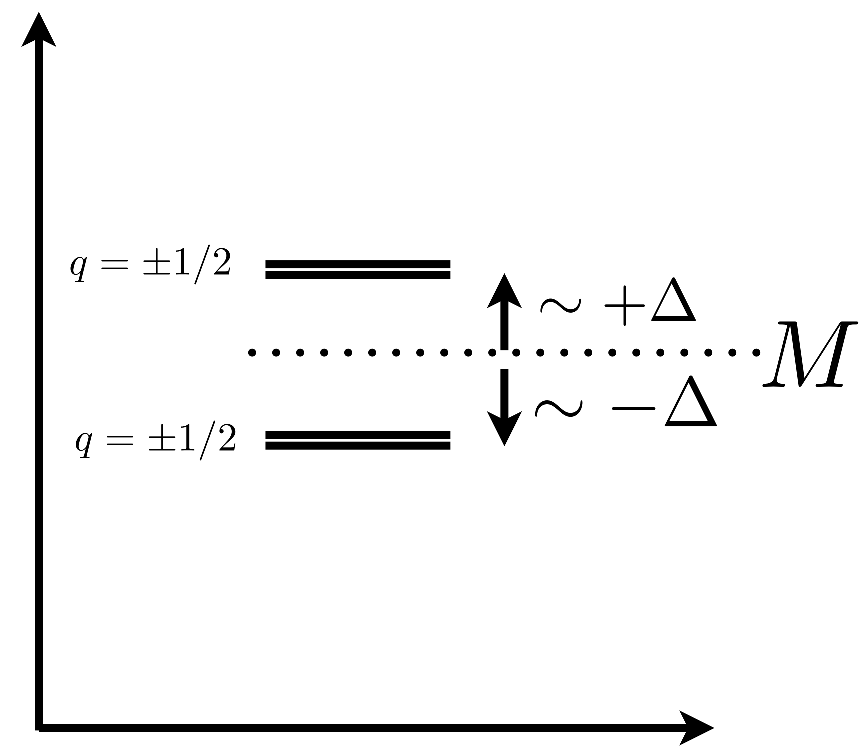
$$\Delta \equiv \left| \frac{M_{12} - M_{34}}{2} \right|$$

$$M \equiv \frac{M_{12} + M_{34}}{2}$$

“Linear Case”



“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

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

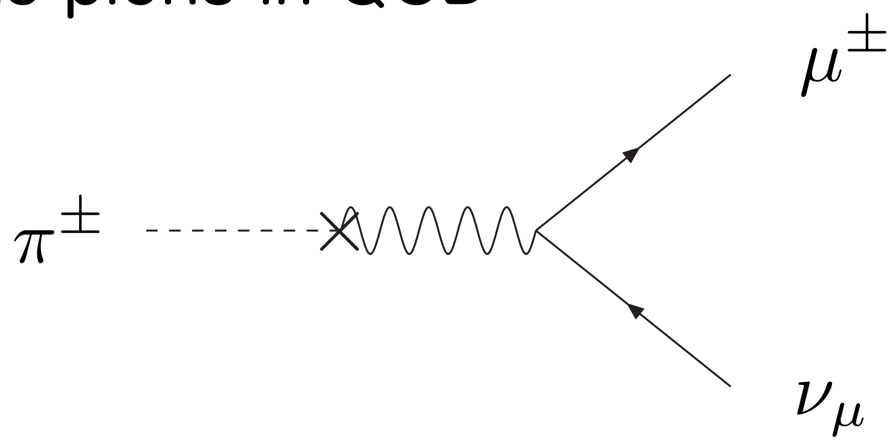
becomes

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

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

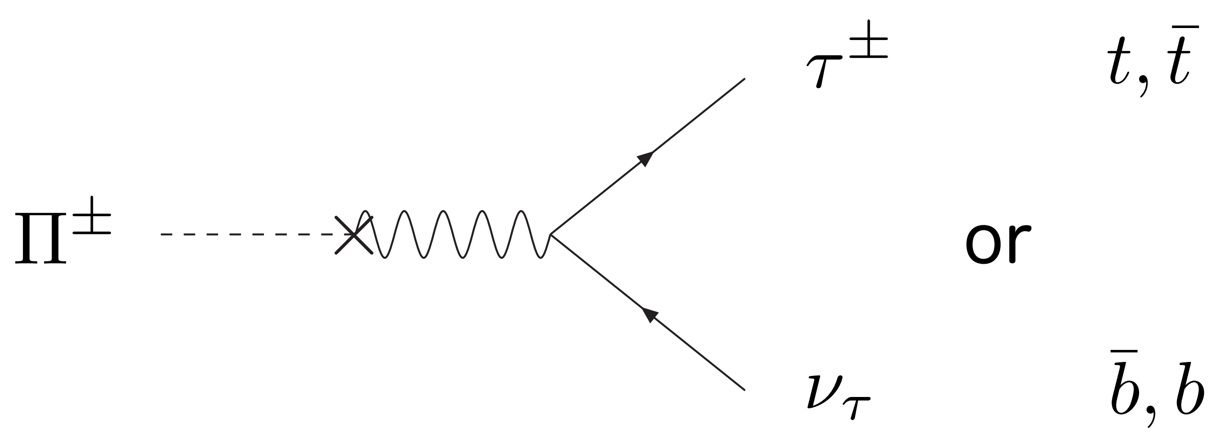
Charged Meson Decay

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 $j^{\mu}_{\pm,\mathrm{axial}} \neq 0$

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

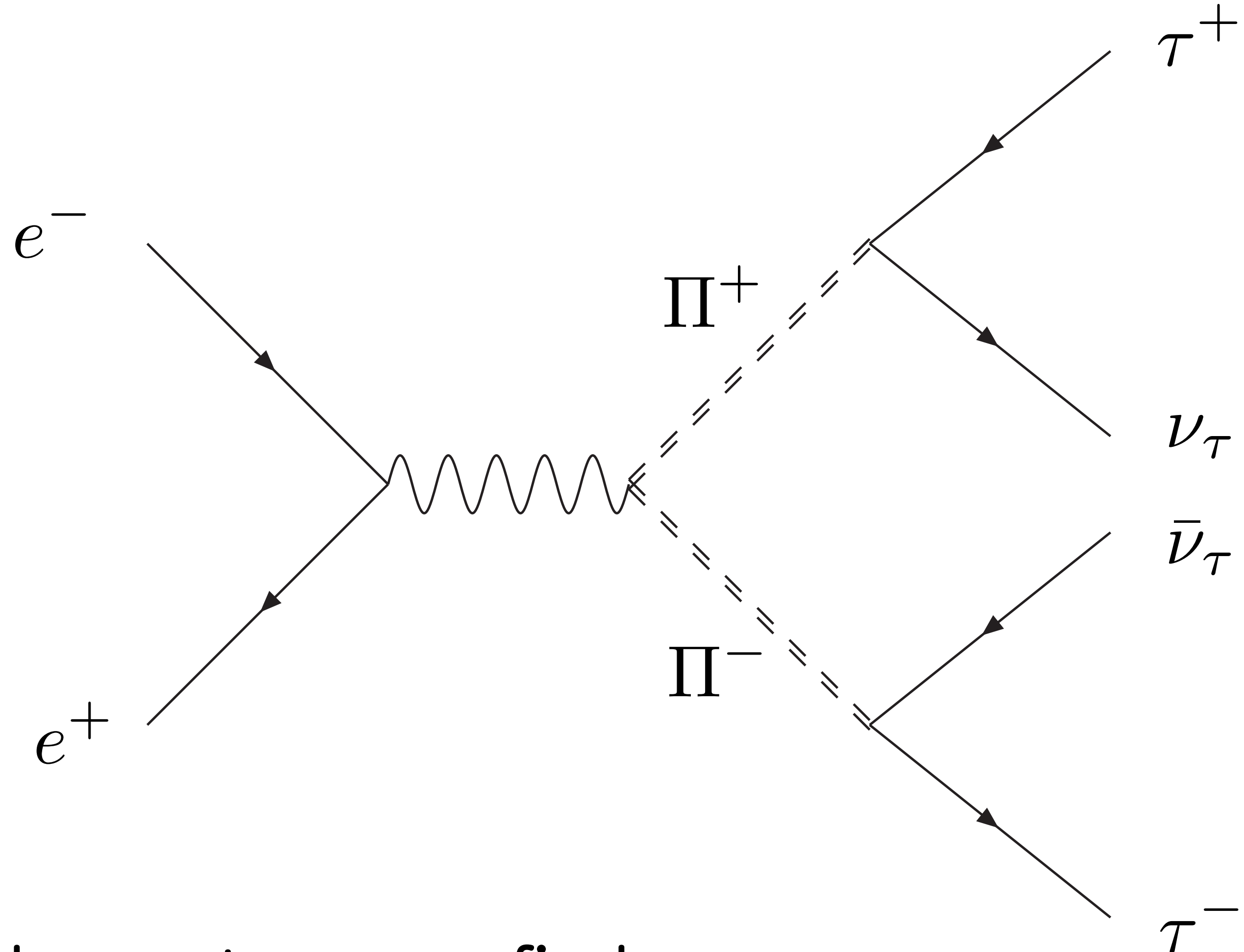
(unlike "Vector-like Confinement")

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

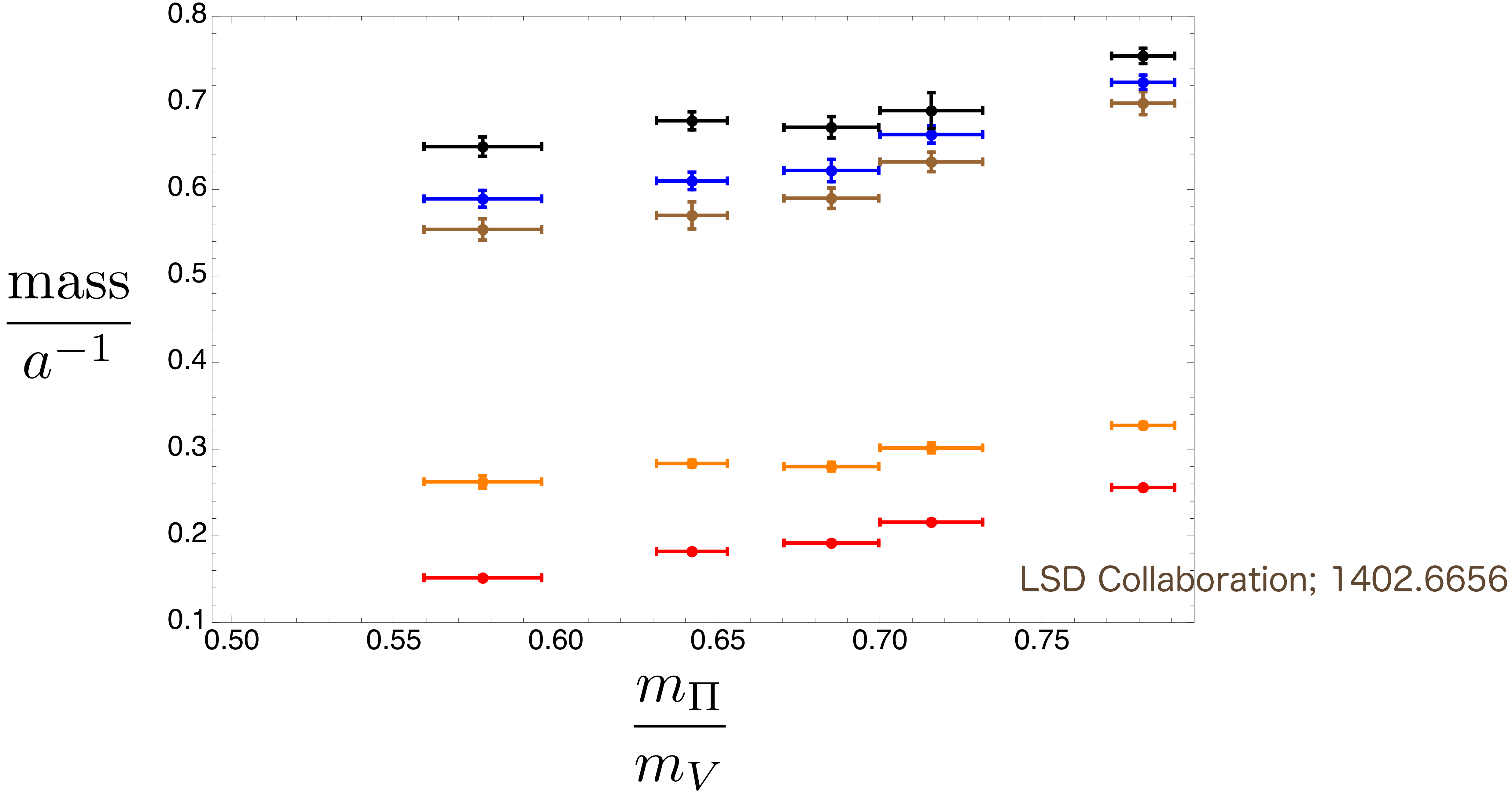


Using bounds on staus, we find

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

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

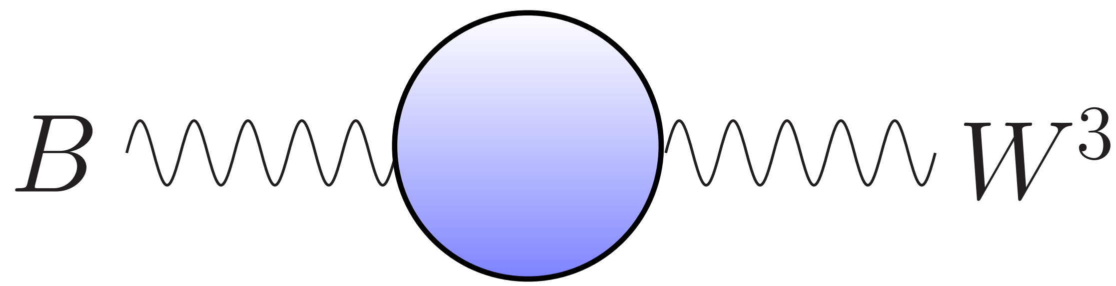
... becomes lower bound on the baryon mass



Within the range simulated on the lattice, we obtain

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

S parameter



Obviously ΔS -> 0 as (yv) -> 0.

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

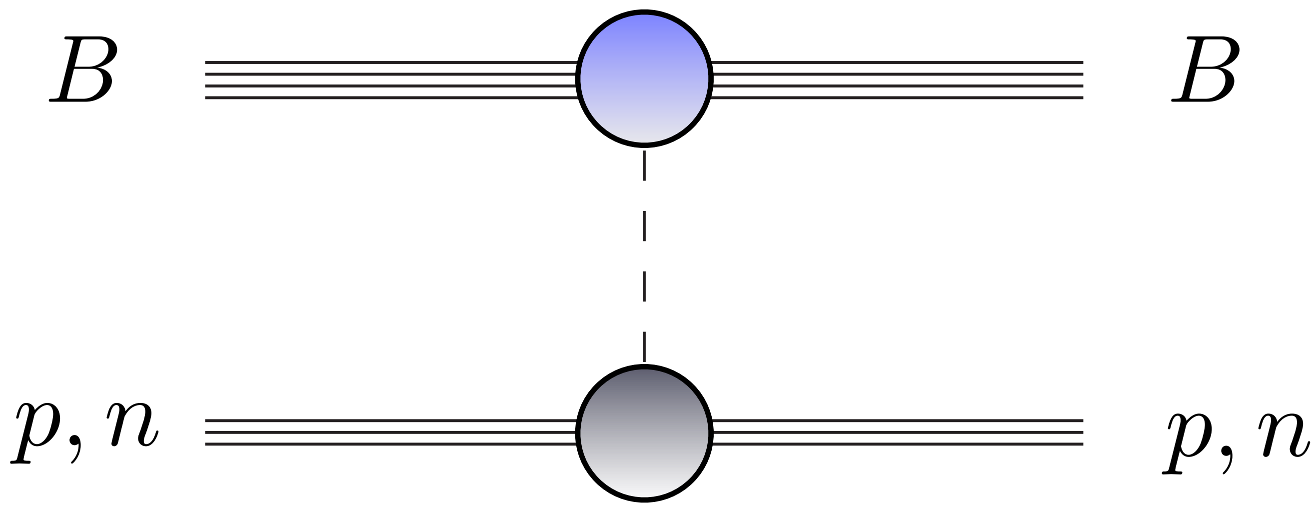
$$S \;\propto\; \int d^4x\, e^{-i\mathbf{q}\cdot\mathbf{x}} \langle j_3^{\mu}(x) j_Y^{\nu}(0)\rangle \;\simeq\; \frac{\epsilon_y^2 v^2}{4M^2} G_{LR}^{\mu\nu},$$

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

and thus can be easily suppressed to below experimental limits.

[Vector-like masses for dark fermions crucial.]

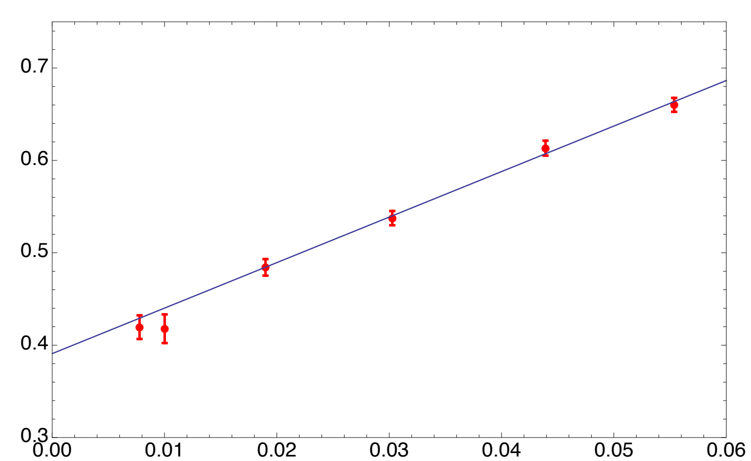
Direct Detection 1: Higgs exchange



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 $f_f^B \;=\; \dfrac{M_1}{m_B}\dfrac{\partial M_B}{\partial M_1}$



LSD Collaboration; 1402.6656

Effective Higgs Coupling

The Higgs coupling to the lightest dark fermions

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

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

Gives an effective coupling to the dark scalar baryon

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

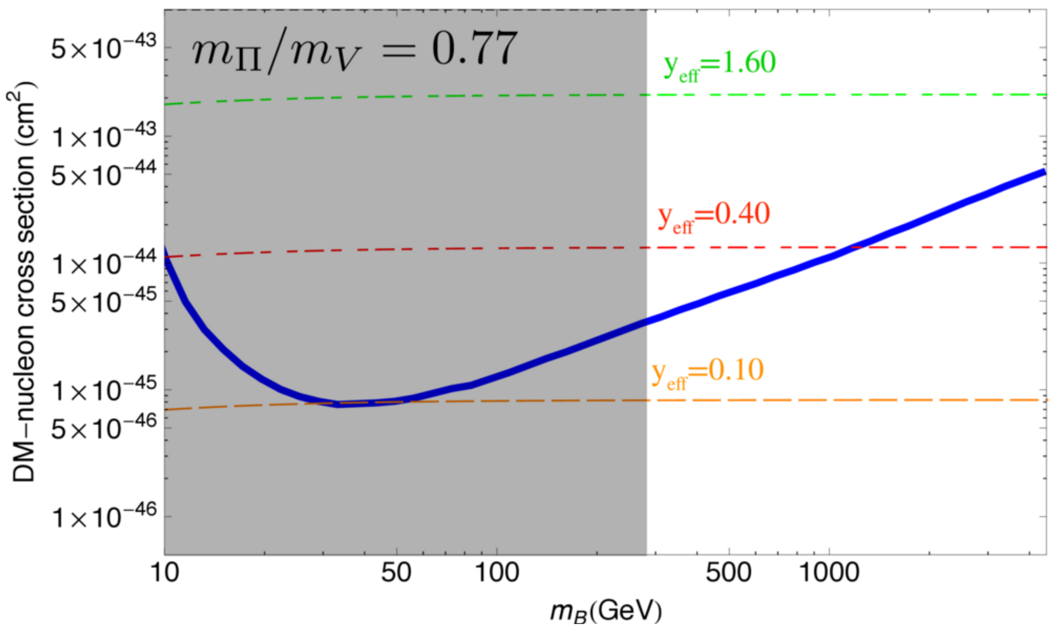
where

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

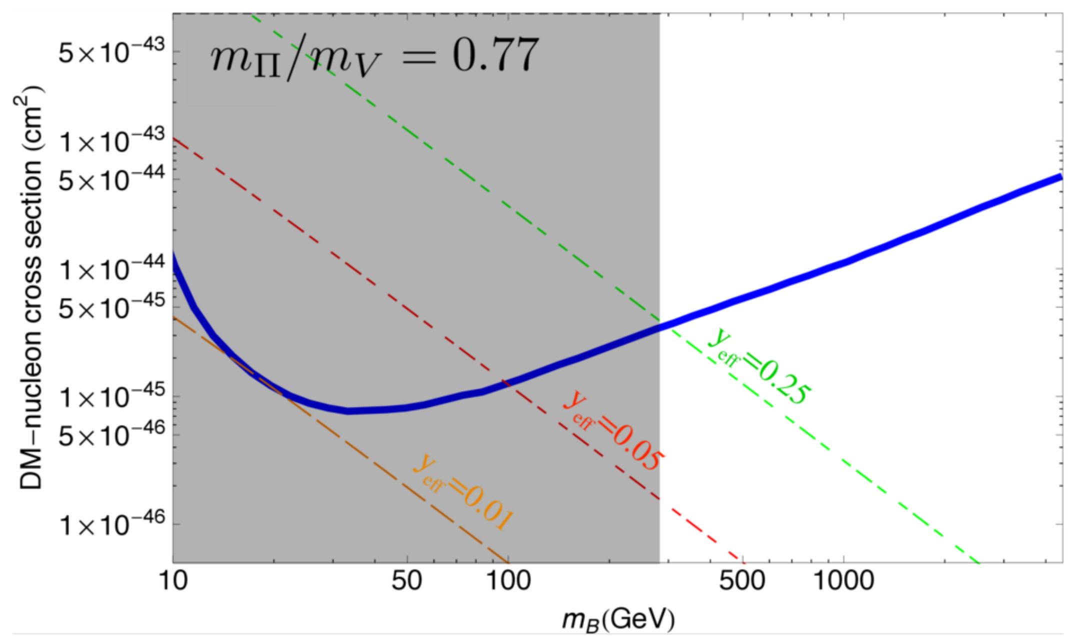
[We cannot extract bound on Yukawa directly, due to difficulty of getting dark fermion mass out of lattice regularization.]

Higgs exchange results

Linear case



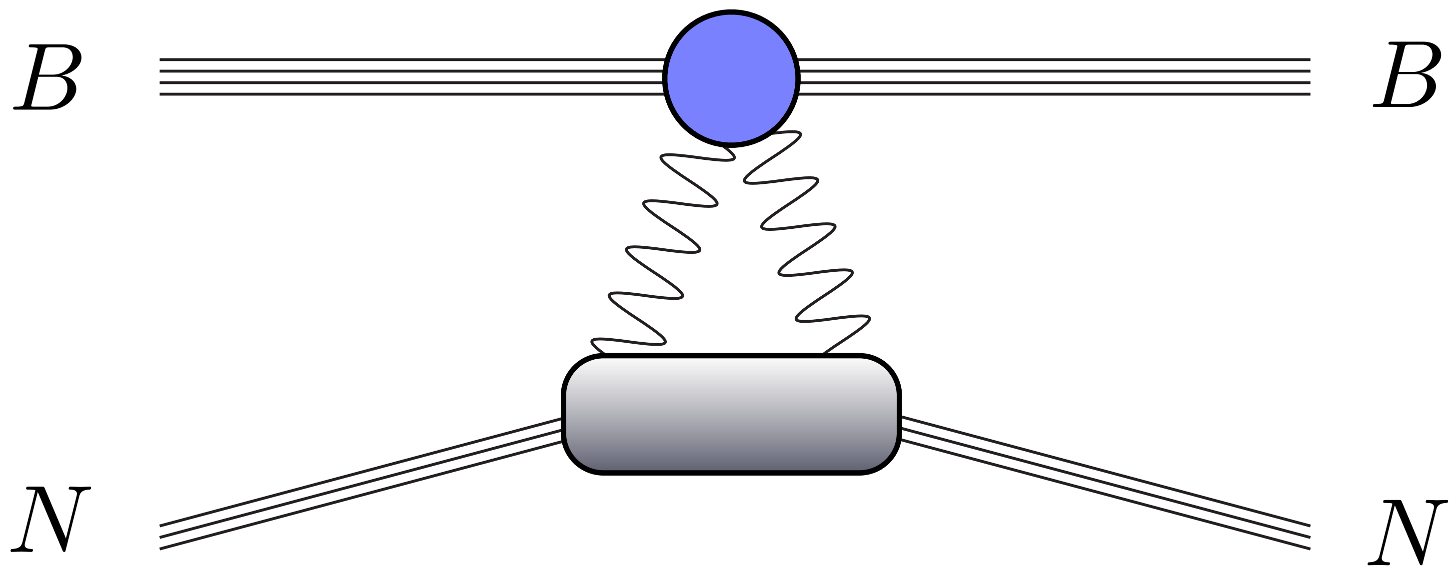
Quadratic case



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.

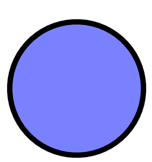
Direct Detection 2: Polarizability



Wonderful formalism for extracting the 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



$$\frac{c_f e^2}{m_B^3} B^* B F_{\mu\nu} F^{\mu\nu}$$

extracted from our lattice simulations

Polarizability

The per nucleon cross section

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

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

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

$1/3 < M_F^A < 3$

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

To obtain

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

Where the nuclear structure factor remains the largest uncertainty.

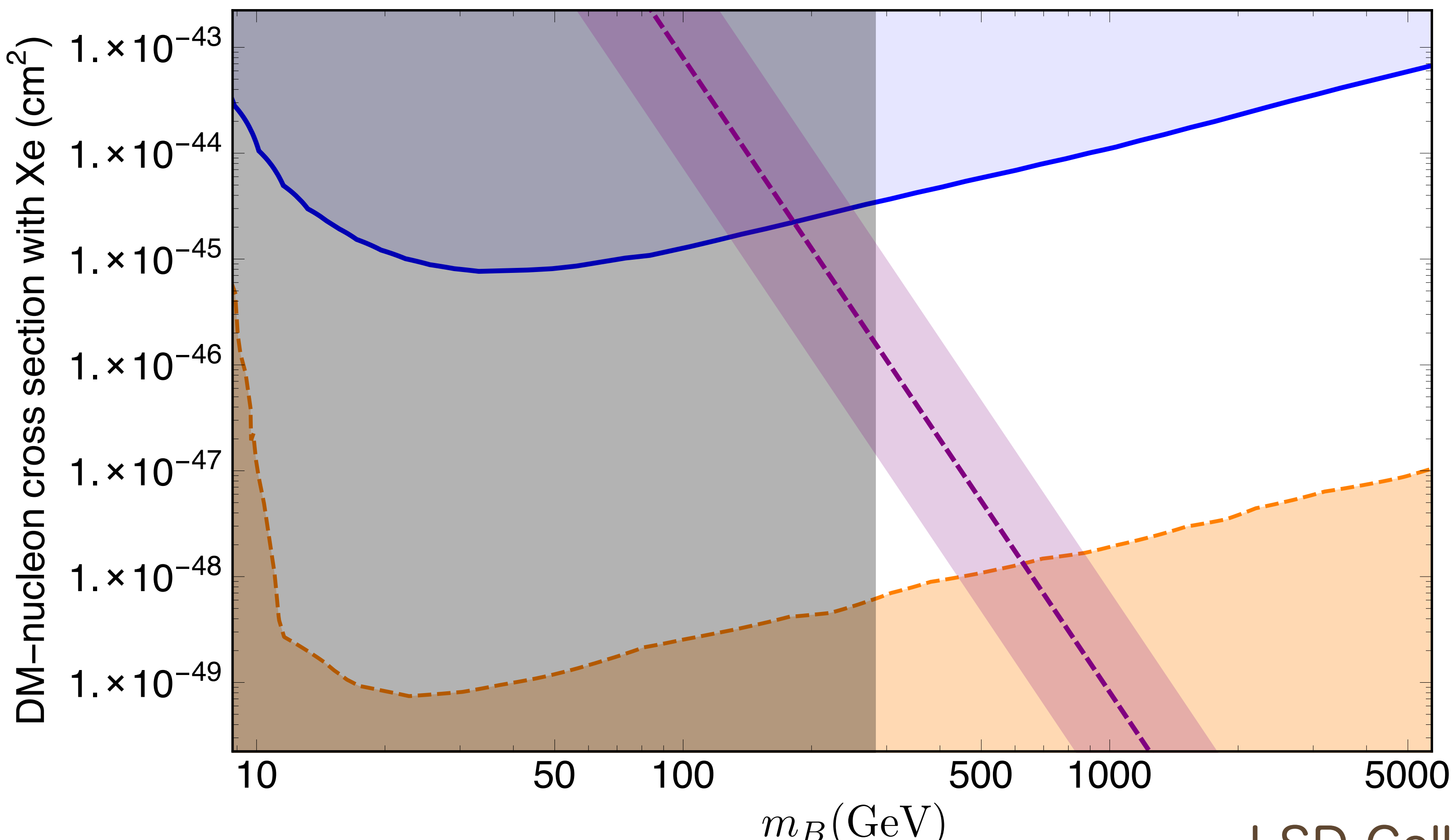
Polarizability

Note!

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

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

For Zenon, we obtain:

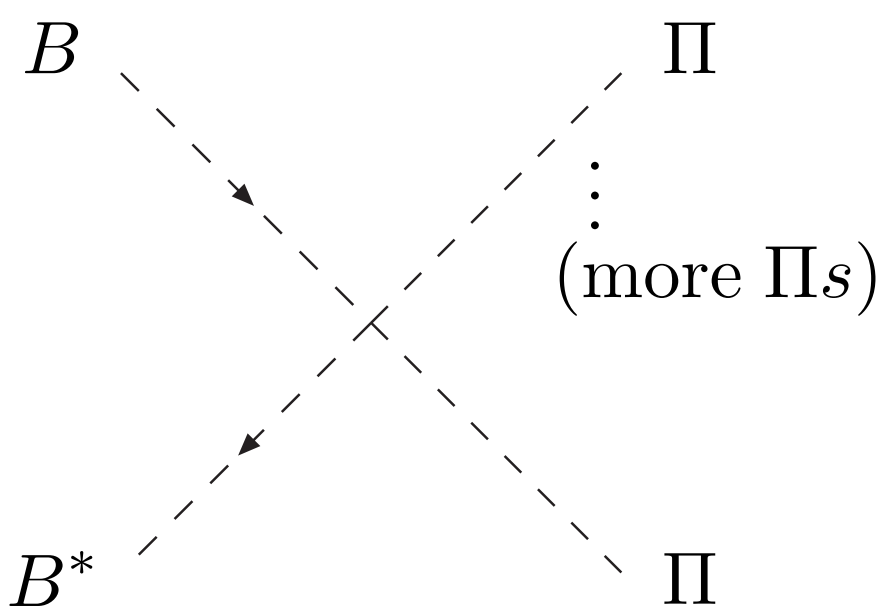


LSD Collaboration; 1503.04205

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

Abundance

Symmetric



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

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

Griest, Kamionkowski; 1990

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

Asymmetric

e.g., through EW sphalerons

Chivukula, Farhi, Barr; 1990

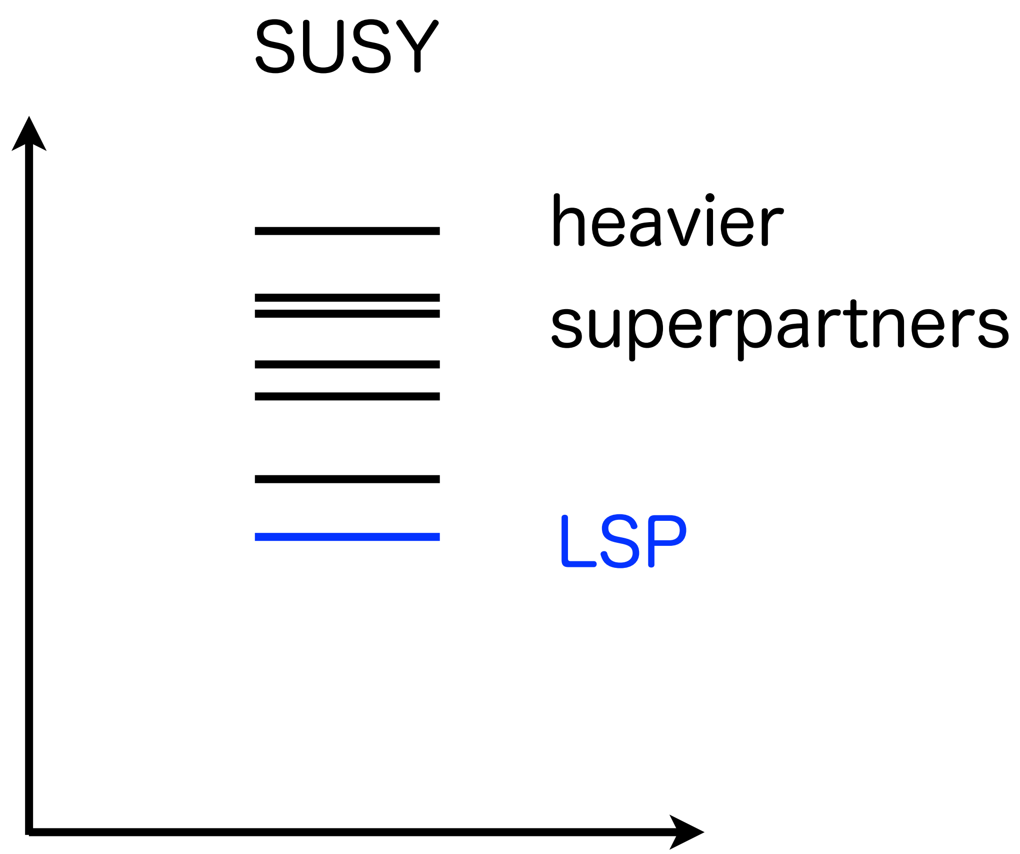
$$n_D \sim n_B \left(\frac{yv}{m_B}\right)^2 \exp\left[-\frac{m_B}{T_{\rm sph}}\right]$$

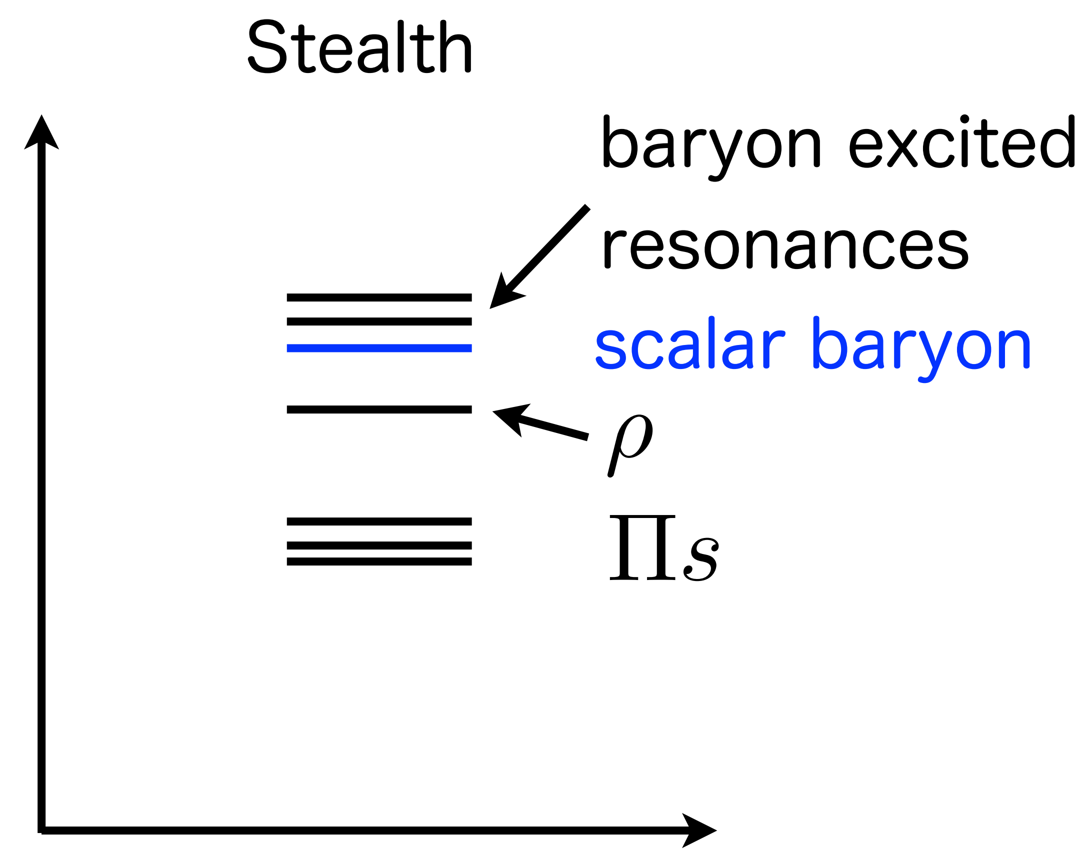
IF EW breaking comparable to EW preserving masses, expect roughly

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

How much less depends on several factors...

Colliders



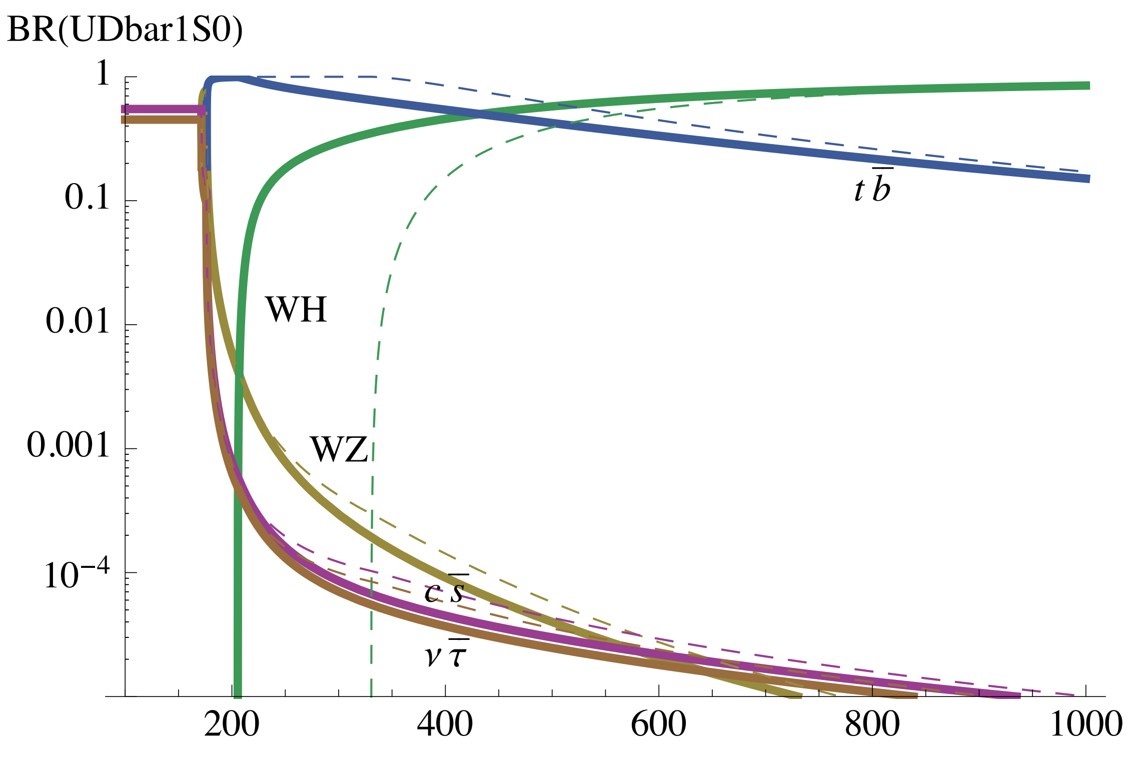


Collider searches dominated by light meson production and decay.

Missing energy signals largely absent!

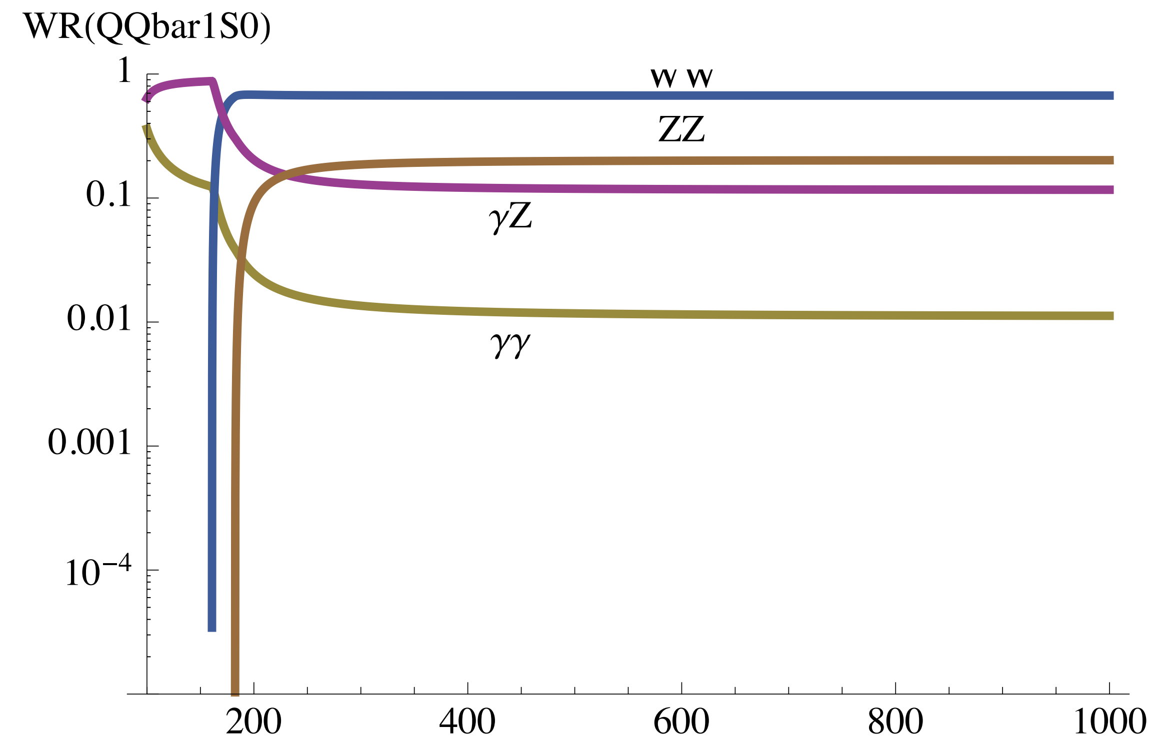
Meson Decay Rates

(Quirky) charged pion decay



(a) $^1S_0$

(Vector-like) neutral meson decay

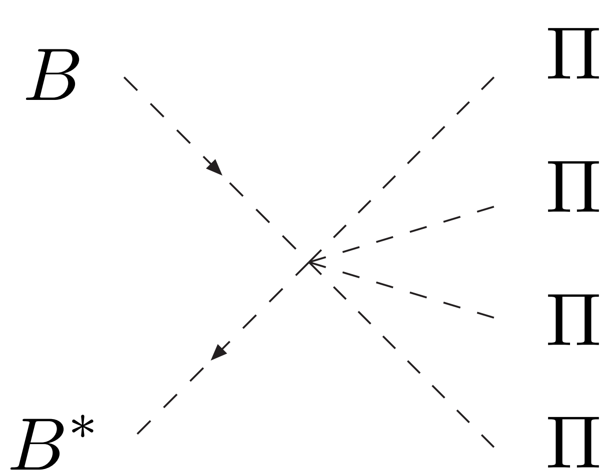


(a) $^1S_0$

Fok, Kribs; 1106.3101

Future

- Calculate the correlators on lattice to compute S parameter (get bounds on EW breaking parameters)
- Calculate meson form factor f_Π , needed to understand meson production and decay at LHC.
- Detailed investigation of abundance remains important and (especially in the case of asymmetric) interesting.
- If some symmetric component, annihilation signals (into γ s) extremely interesting. It could be that multibody states are generic, e.g.



Epilogue: Stealth DM versus SUSY DM

Need vector-like masses. --> Dark fermion flavor brekaing

SUSY needs Majorana masses --> SUSY breaking

Need (approx) custodial SU(2) --> (neutrality, T, charge radius)

SUSY needs parameter choices to get neutral LSP, and needs serious care with flavor sector to avoid FCNC.

Need $M_f \sim \Lambda_D$ --> Expt constaints + lattice simulation constraints

SUSY needs $\mu \sim M_{\text{SUSY breaking}}$

Danke Sehr