Vectorlike Dark Confinement at Direct Detection Experiments

Pouya Asadi

pasadi@uoregon.edu

Institute for Fundamental Science
University of Oregon

Advertising : 2409.XXXXX
With : Graham Kribs, Chester Mantel

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The Coincidence Problem and Confining Dark Sectors

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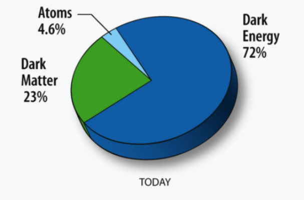

Image Credit: WMAP

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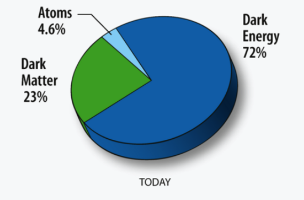

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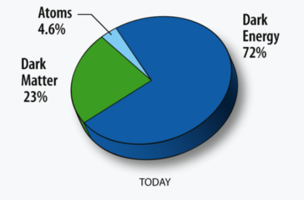

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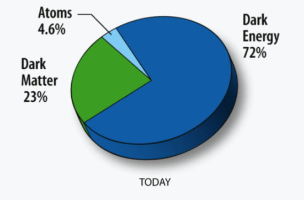

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- Search the parameter space of models that explain this.
- The only existing full solution to the energy density coincidence problem: A confining dark sector.

The Minimal Confining Dark Sector: WIMP's Next of Kin

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Dark quarks charged under electromagnetism.

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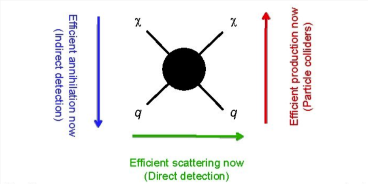

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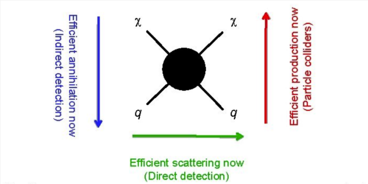

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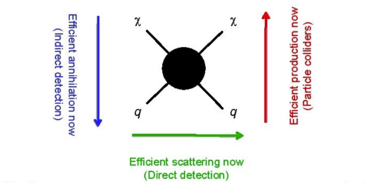

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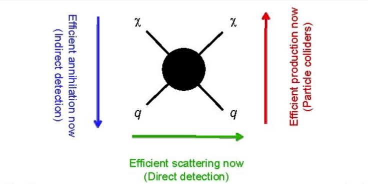

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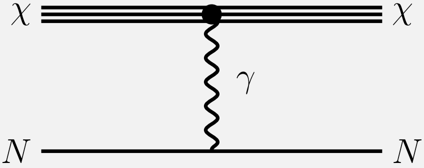

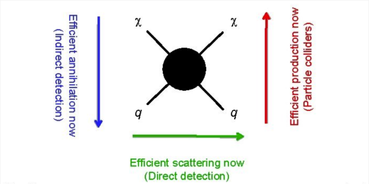

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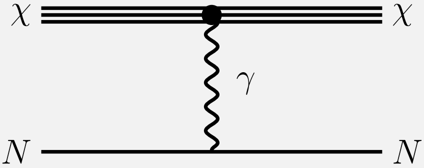

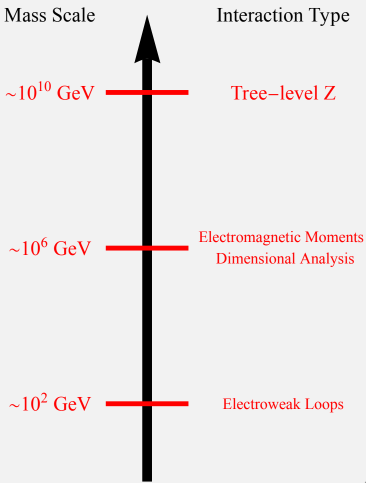

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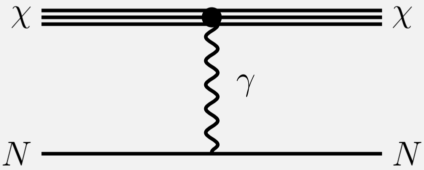
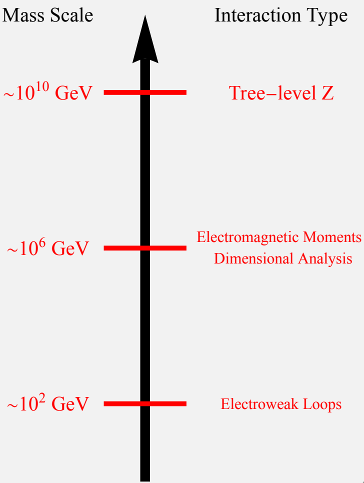


- Model presumed dead!



$\mathcal{H}$-Parity: A Deep Dive

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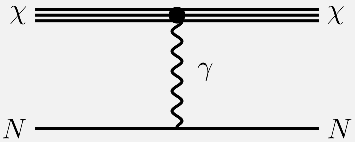

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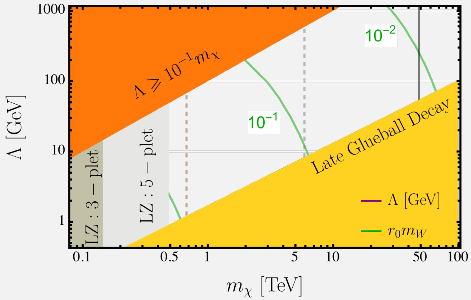

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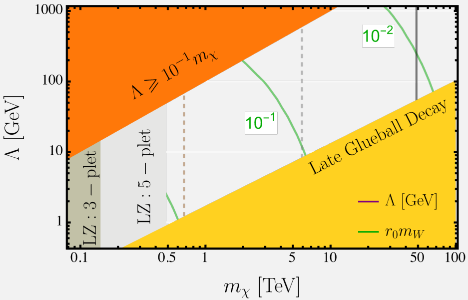

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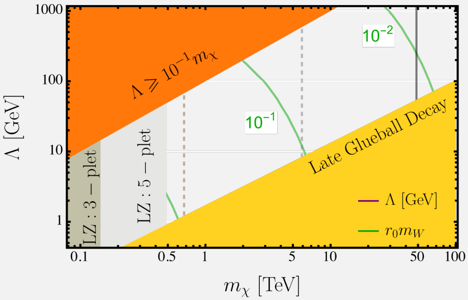

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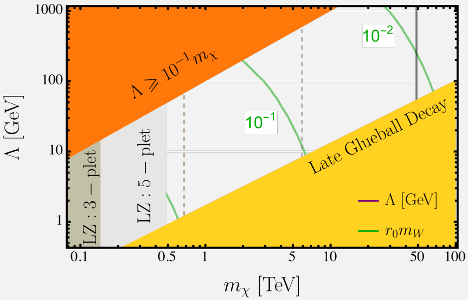
- This result applies to models with any values of N_f, N_c, Reps., DM masses, ...



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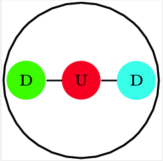

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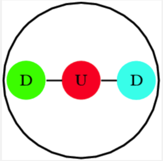

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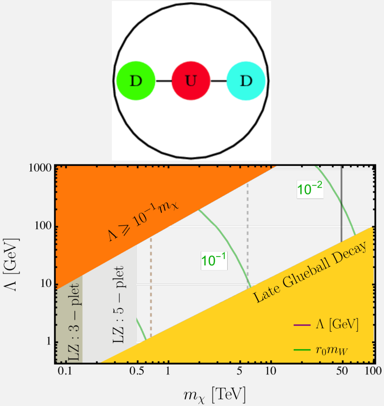

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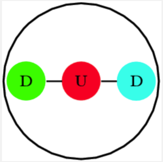

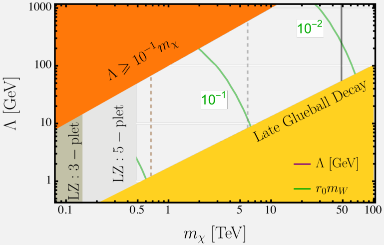

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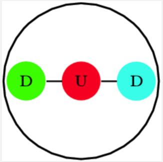

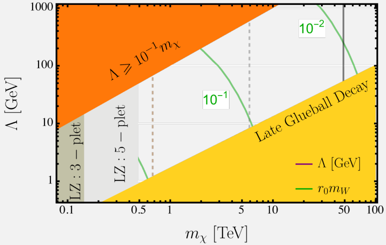

THANK YOU!

Back up

- Evidence for Dark Matter
- More Motivations for Dark Confinement
- All EM Moments
- Polarizability
- Baryon Masses
- Baryons for different $(N_c,\ N_f)$
- Symmetry to a Theorist
- Hödor Parity
- $\mathcal{H}$-Parity Violation
- Direct Detection from EW Loops
- Indirect Detection
- Searching for WIMP's Next of Kin

Evidence for Dark Matter

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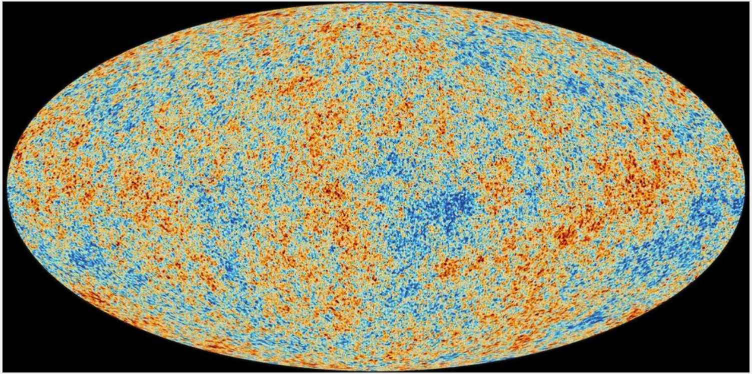

Image Credit: Planck Telescope

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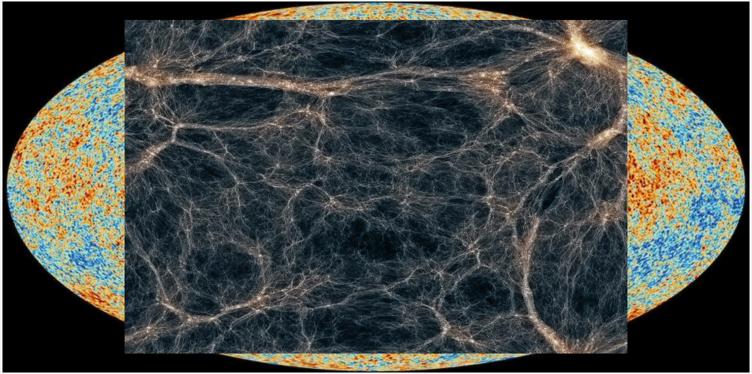

Image Credit: UW N-Body Shop

Evidence for Dark Matter

Image Credit: Chanda X-ray Observatory

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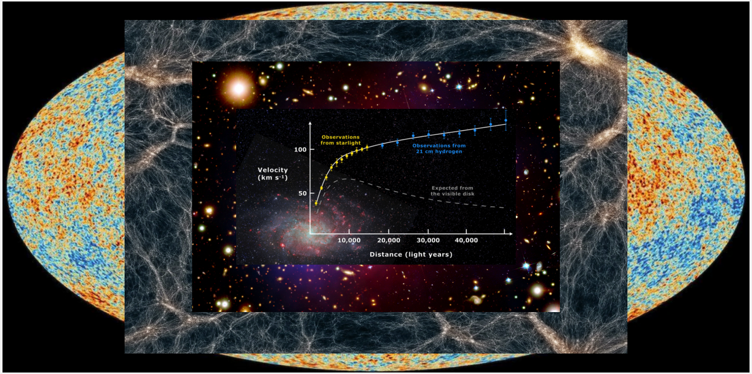


Image Credit: Wikipedia

Why Confining Dark Sectors?

- SM has confinement; why not the dark side of the universe?
- Stabilizing DM à la SM.
- New viable dark matter masses, with rich phenomenology.
- Avenue for studying confinement.
- Possible new CP violation and out-of-equilibrium dynamics.
- The coincidence problem motivates studying confining dark sections - even beyond the abundance calculation.

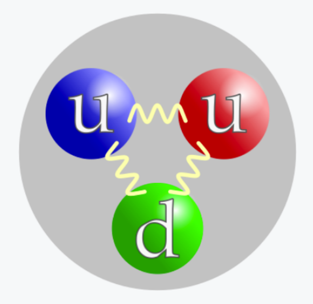
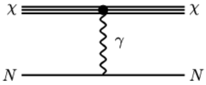
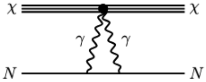
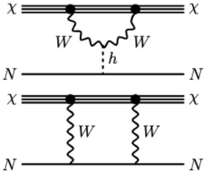


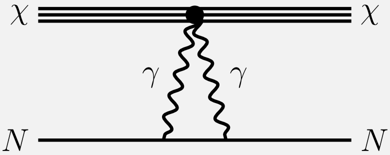
Table of All EM Moment Operators

$\mathcal{H}$ Transformation	Diagram	Operators	Direct Detection Constraints (Naive Estimates)
$\mathcal{H}$-odd		magnetic dipole moment electric dipole moment charge radius anapole moment	(*e.g.* magnetic dipole moment) $m_\chi \gtrsim 50$ TeV
$\mathcal{H}$-even		polarizability	$m_\chi \gtrsim \mathcal{O}(200)$ GeV
		electroweak loops	(*i.e.* DM in $SU(2)_L$ Triplet) $m_\chi \gtrsim 200$ GeV

Polarizability

Operator	Dim.	WC and Name
$\bar{\chi}\chi F^{\mu\nu}F_{\mu\nu}$	7	Polarizability
$\phi^\dagger\phi F^{\mu\nu}F_{\mu\nu}$	6	Polarizability

$$\mathcal{H}: \ \bar{\chi}\chi F^{\mu\nu}F_{\mu\nu} \to \bar{\chi}\chi F^{\mu\nu}F_{\mu\nu}, \quad \mathcal{H}: \ \phi^\dagger\phi F^{\mu\nu}F_{\mu\nu} \to \phi^\dagger\phi F^{\mu\nu}F_{\mu\nu}$$



- Two-nucleon form factor undetermined.
- Estimated bounds: $\mathcal{O}(100)$ GeV

Baryon Masses

$$M = \Delta M_Q + \bar{M} + \sum_{i>j} \Big[-\tfrac{N_c+1}{2N_c}\alpha_\chi (b - \tfrac{c+2d}{m_0^2}) + \alpha_{em}(b - \tfrac{c+2d}{m_0^2})\langle Q_i Q_j\rangle - \tfrac{16\alpha_{em}}{3m_0^2} d\langle Q_i Q_j \vec{S}_i \cdot \vec{S}_j\rangle + \tfrac{32\alpha_\chi}{9m_0^2} d\langle \vec{S}_i \cdot \vec{S}_j\rangle \Big],$$

$$\begin{aligned} a &= \frac{1}{2}\langle\Psi_0|\, p_1^2 \,|\Psi_0\rangle\,, \\ b &= \langle\Psi_0|\, \frac{1}{|\vec{r}_{12}|} \,|\Psi_0\rangle\,, \\ c &= \frac{1}{2}\langle\Psi_0|\, \frac{|\vec{r}_{12}|^2 \vec{p}_1 \cdot \vec{p}_2 + \vec{r}_{12}\cdot(\vec{r}_{12}\cdot\vec{p}_1)\cdot\vec{p}_2}{|\vec{r}_{12}|^3} \,|\Psi_0\rangle\,, \\ d &= \frac{\pi}{2}\langle\Psi_0|\, \delta^{(3)}(\vec{r}_{12}) \,|\Psi_0\rangle\,. \end{aligned}$$

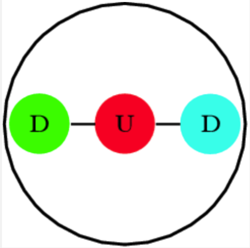
Baryon's Rep. under SU(2)$_L$ - Different $(N_c,\ N_f)$

Lowest-spin spectra:

(N_c, N_f)	$SU(2)_L$ multiplets	baryons	neutral baryons
(5,5)	17 ⊕ 15 ⊕ 13 ⊕ 13 ⊕ 11 ⊕ 11 ⊕ 11 ⊕ 11 ⊕ 9 ⊕ 9 ⊕ 9 ⊕ 9 ⊕ 7 ⊕ 7 ⊕ 7 ⊕ 5 ⊕ 5 ⊕ 5 ⊕ 5 ⊕ 3 ⊕ 3 ⊕ 1	175	21
(5 3)	7 ⊕ 5 ⊕ 3	15	3
(4,5)	13 ⊕ 9 ⊕ 9 ⊕ 7 ⊕ 5 ⊕ 5 ⊕ 1 ⊕ 1	50	8
(4,4)	9 ⊕ 5 ⊕ 5 ⊕ 1	20	4
(4,3)	5 ⊕ 1	6	2
(4,2)	1	1	1
(3,5)	11 ⊕ 9 ⊕ 7 ⊕ 5 ⊕ 5 ⊕ 3	40	6
(3,3)	5 ⊕ 3	8	2
(2,5)	7 ⊕ 3	10	2
(2,4)	5 ⊕ 1	6	2
(2,3)	3	3	1
(2,2)	1	1	1

Symmetry to a Theorist

- Is the naive dim. analysis reliable?
- Partons randomly-distributed? Or there is some order?
- The right language: symmetry!
- Symmetry helps us see cancellations that are not conspicuously manifest.



$\mathcal{H}$-Parity: A Deep Dive

Field	SU(N_c)	SU(2)$_L$	SU(N_f)	U(1)$_B$
$\mathfrak{q}$	$\square$	N_f	$\square$	$1/N_c$
$\bar{\mathfrak{q}}$	$\bar{\square}$	$\bar{N}_f$	$\bar{\square}$	-$1/N_c$

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Field	SU(N_c)	SU(2)$_L$	SU(N_f)	U(1)$_B$
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We will show a symmetry forbids the electromagnetic moments.

$\mathcal{H}$-Parity: A Deep Dive

Field	SU(N_c)	SU(2)$_L$	SU(N_f)	U(1)$_B$
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We will show a symmetry forbids the electromagnetic moments.

$$\mathcal{H} : \mathfrak{q}_i \to S_{ij}\mathfrak{q}_j, \text{ with } S = \exp(i\pi J_2) = (-1)^{Q_i+\mathtt{j}}\delta_{Q_i,-Q_j},$$

$\mathcal{H}$ swaps dark quarks of opposite charges.

$\mathcal{H}$-Parity: A Deep Dive

Field	SU(N_c)	SU(2)$_L$	SU(N_f)	U(1)$_B$
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$\mathcal{H}$ swaps dark quarks of opposite charges.

$$\mathcal{H} : X_{\rm SM} \to \mathcal{C}X_{\rm SM}\mathcal{C}, \text{ with } X_{\rm SM} : \text{ any electroweak gauge field}$$

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Field	$\mathrm{SU}(N_c)$	$\mathrm{SU}(2)_L$	$\mathrm{SU}(N_f)$	$\mathrm{U}(1)_B$
$\mathfrak{q}$	$\square$	N_f	$\square$	$1/N_c$
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$\mathcal{H}$ swaps dark quarks of opposite charges.

$$\mathcal{H} : X_{\mathrm{SM}} \to \mathcal{C}X_{\mathrm{SM}}\mathcal{C}, \text{ with } X_{\mathrm{SM}} : \text{ any electroweak gauge field}$$

(Insensitive to $\mathcal{H}$'s action on the rest of SM.)

$\mathcal{H}$-Parity: A Deep Dive

Field	$SU(N_c)$	$SU(2)_L$	$SU(N_f)$	$U(1)_B$
$\mathfrak{q}$	$\square$	N_f	$\square$	$1/N_c$
$\bar{\mathfrak{q}}$	$\bar{\square}$	$\bar{N}_f$	$\bar{\square}$	$-1/N_c$

We will show a symmetry forbids the electromagnetic moments.

$$N_f = 3. \quad \mathcal{H} : \begin{pmatrix} \mathfrak{q}_1 \\ \mathfrak{q}_0 \\ \mathfrak{q}_{-1} \end{pmatrix} \to \begin{pmatrix} 0 & 0 & 1 \\ 0 & -1 & 0 \\ 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} \mathfrak{q}_1 \\ \mathfrak{q}_0 \\ \mathfrak{q}_{-1} \end{pmatrix} = \begin{pmatrix} \mathfrak{q}_{-1} \\ -\mathfrak{q}_0 \\ \mathfrak{q}_1 \end{pmatrix},$$

$\mathcal{H}$-Parity: A Deep Dive

Field	$SU(N_c)$	$SU(2)_L$	$SU(N_f)$	$U(1)_B$
$\mathfrak{q}$	$\Box$	N_f	$\Box$	$1/N_c$
$\bar{\mathfrak{q}}$	$\bar{\Box}$	$\bar{N}_f$	$\bar{\Box}$	$-1/N_c$

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$$N_f = 4. \quad \mathcal{H} : \begin{pmatrix} \mathfrak{q}_{3/2} \\ \mathfrak{q}_{1/2} \\ \mathfrak{q}_{-1/2} \\ \mathfrak{q}_{-3/2} \end{pmatrix} \to \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \mathfrak{q}_{3/2} \\ \mathfrak{q}_{1/2} \\ \mathfrak{q}_{-1/2} \\ \mathfrak{q}_{-3/2} \end{pmatrix} = \begin{pmatrix} \mathfrak{q}_{-3/2} \\ -\mathfrak{q}_{-1/2} \\ \mathfrak{q}_{1/2} \\ -\mathfrak{q}_{3/2} \end{pmatrix},$$

$\mathcal{H}$-Parity: A Deep Dive

Field	$SU(N_c)$	$SU(2)_L$	$SU(N_f)$	$U(1)_B$
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$\mathcal{H}$ is a symmetry of the UV theory.

$\mathcal{H}$-Parity: A Deep Dive

Field	SU(N_c)	SU(2)$_L$	SU(N_f)	U(1)$_B$
$\mathfrak{q}$	$\square$	N_f	$\square$	$1/N_c$
$\bar{\mathfrak{q}}$	$\bar{\square}$	$\bar{N}_f$	$\bar{\square}$	-$1/N_c$

We will show a symmetry forbids the electromagnetic moments.

If $\theta_\chi = 0 \implies$ parity unbroken in IR

$\mathcal{H}$-Parity: A Deep Dive

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$$\mathcal{H} : \chi_{B_0}, \phi_{B_0} \rightarrow \pm\chi_{B_0}, \phi_{B_0}, \;\; \mathcal{H} : F^{\mu\nu} \rightarrow -F^{\mu\nu}$$

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Field	$SU(N_c)$	$SU(2)_L$	$SU(N_f)$	$U(1)_B$
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$$\mathcal{H} : \bar{\chi}_{B_0}\sigma^{\mu\nu}(\gamma^5)\chi_{B_0}F_{\mu\nu}$$

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Field	$SU(N_c)$	$SU(2)_L$	$SU(N_f)$	$U(1)_B$
$\mathfrak{q}$	$\square$	N_f	$\square$	$1/N_c$
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$$\mathcal{H} : \bar{\chi}_{B_0}\gamma^{\mu}(\gamma^5)\chi_{B_0}\partial^\nu F_{\mu\nu} \ \to \ -\bar{\chi}_{B_0}\gamma^{\mu}(\gamma^5)\chi_{B_0}\partial^\nu F_{\mu\nu},$$

$$\mathcal{H} : \phi^\dagger_{B_0}\overleftrightarrow{\partial^\mu}\phi_{B_0}\partial^\nu F_{\mu\nu} \ \to \ -\phi^\dagger_{B_0}\overleftrightarrow{\partial^\mu}\phi_{B_0}\partial^\nu F_{\mu\nu},$$

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Field	$SU(N_c)$	$SU(2)_L$	$SU(N_f)$	$U(1)_B$
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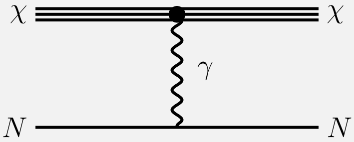

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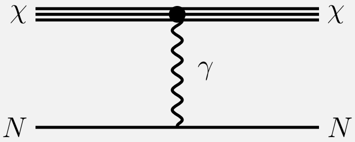

The relevant operators don't respect the $\mathcal{H}$-parity.

$\mathcal{H}$-Parity: A Deep Dive

Field	$SU(N_c)$	$SU(2)_L$	$SU(N_f)$	$U(1)_B$
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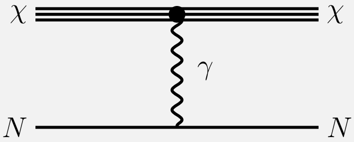


The relevant operators don't respect the $\mathcal{H}$-parity.

The diagram does not exist!
They don't give rise to a signal in direct detection searches.

$\mathcal{H}$ in the UV Theory

$$\mathcal{S}: \begin{cases} \mathfrak{q}_a & \to & S_{ab}\mathfrak{q}_b \\ \bar{\mathfrak{q}}_a & \to & S^\dagger_{ab}\bar{\mathfrak{q}}_b \end{cases} \quad \text{with } S = \exp(i\pi J_2) = (-1)^{Q_a+\mathtt{k}}\delta_{Q_a,-Q_b}$$

$$S^\dagger J^i S \;=\; \begin{cases} J^i & i=2 \\ -J^i & i=1,3\,, \end{cases}$$

$$W^c_{\mu,i} \equiv \mathcal{C} W_{\mu,i}\mathcal{C} \;=\; \begin{cases} W_{\mu,i} & i=2 \\ -W_{\mu,i} & i=1,3\,. \end{cases}$$

$$\begin{aligned} \Longrightarrow \mathcal{H}(\bar{\mathbf{Q}}\gamma^\mu J^a \mathbf{Q} W_{\mu,a}) &= (\bar{\mathbf{Q}}S^\dagger)\gamma^\mu J^a (S\mathbf{Q})\mathcal{C}W_{\mu,a}\mathcal{C} \\ &= \bar{\mathbf{Q}}\gamma^\mu S^\dagger J^a S \mathbf{Q} W^c_{\mu,a} \\ &= \bar{\mathbf{Q}}\gamma^\mu J^a \mathbf{Q} W_{\mu,a}\,, \end{aligned}$$

$\mathcal{H}$ vs. $\mathcal{G}$

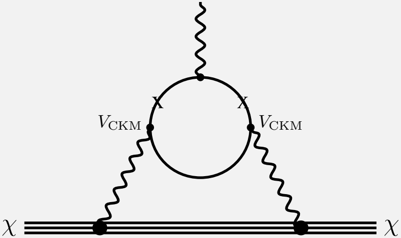
$$\mathcal{H} = \mathcal{C}_{\rm SM} \otimes S_\chi, \;\; S = e^{i\pi J_2}$$

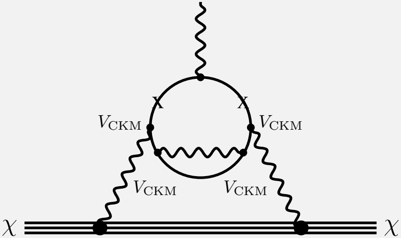
- $\mathfrak{q}_i \to \pm\mathfrak{q}_{-i}$
- Mesons $\to$ Mesons
- Baryons $\to$ Baryons
- Utility: Zero Baryon EM Moments
- Broken by: SM EW Interactions

$$\mathcal{G} = 1_{\rm SM} \otimes \mathcal{C}_\chi S_\chi$$

- $\mathfrak{q}_i \to \mathfrak{q}_i^{\mathfrak{c}}$
- Mesons $\to$ Mesons
- Baryons $\to$ Anti-baryons
- Utility: Mesons Stable
- Broken by: Dim. 5 Operators

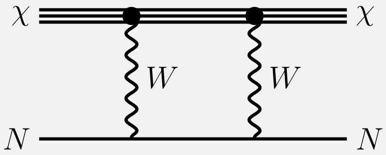
$\mathcal{H}$-Parity Violation



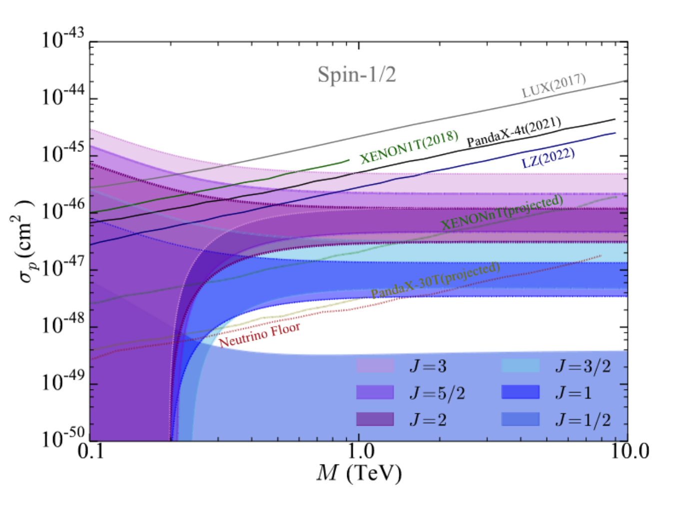


Mass Spectrum and Model-Dependent Nuances

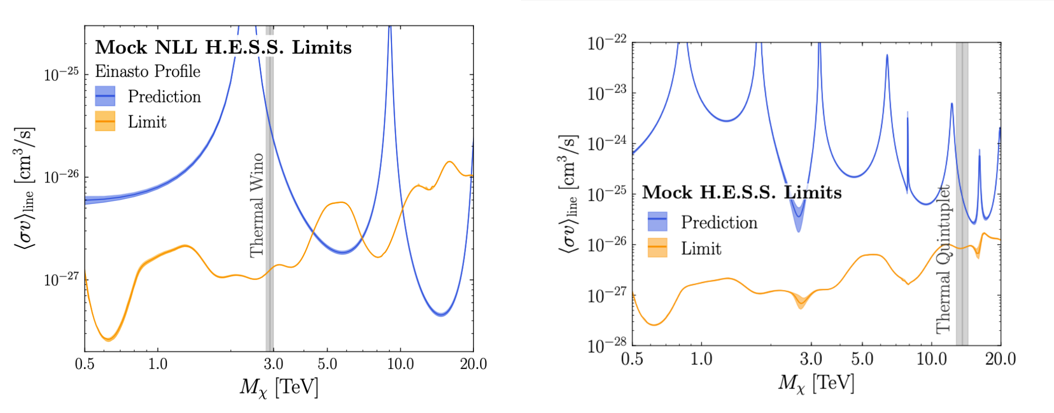
- Further nuances in connecting to direct detection signals.
- Transition moments possible: inelastic scattering.
- Lightest baryon is not guaranteed to be neutral!
- $SU(2)_L$ representation relevant for direct detection.



Direct Detection



Indirect Detection



Indirect detection signal can be reduced in asymmetric models.

Searching for WIMP's Next of Kin

- Quark are charged under SM electroweak group.
- Ubiquitously produced at a future MuC.
- (Future of the energy frontier?)
- Potential LLP signals.
- Upcoming paper!