Hunting for Hypercharge Anapole Dark Matter in All Spin Scenarios

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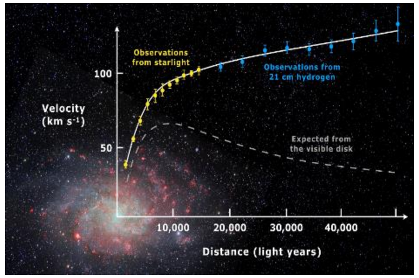
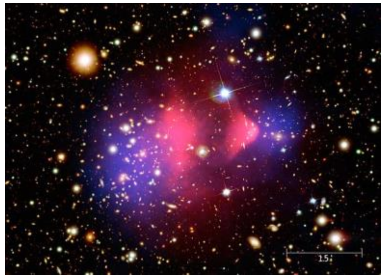
Dark Matter (DM)

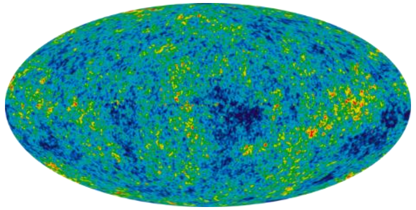
[Wikipedia. PDG]

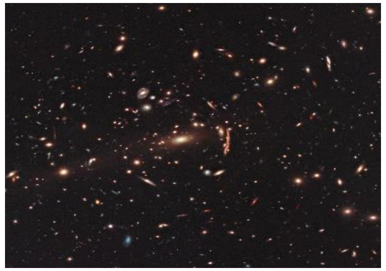
Empirical Evidences
(several but only gravitational)

Galaxy rotation curves
Velocity dispersions
Galaxy clusters
Gravitational lensing
Cosmic microwave background
Structure formation
Bullet cluster
…









DM Candidates (too many?!)

QCD axions
Axion-like particles
Fuzzy CDM

SM neutrinos
Sterlile neutrinos

Supersymmtry
Extra dimensions
Little Higgs
Simplified models
Effective field theories

Primordial black holes
MACHOs
Macros

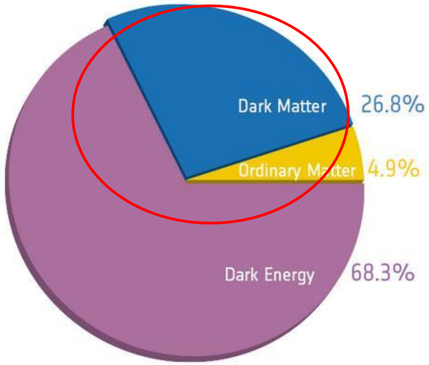
Strangelet
Superfluid vacuum theory
Dynamical dark matter

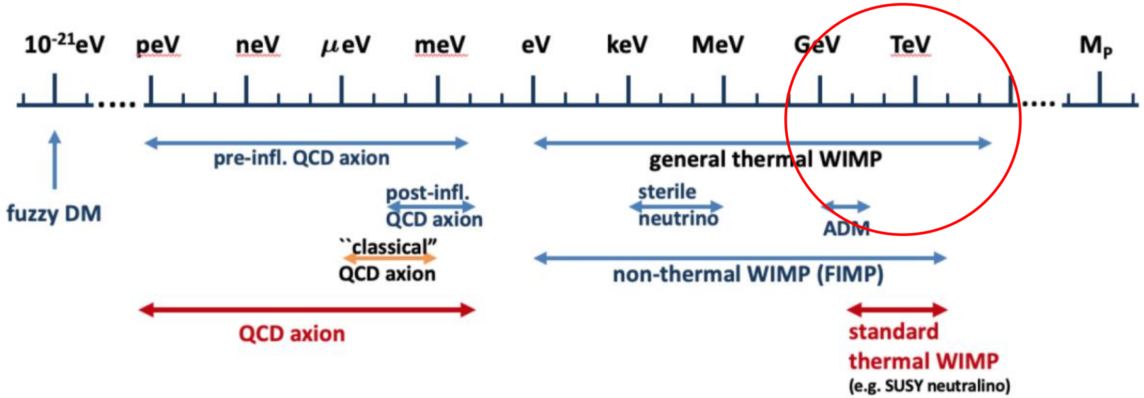
Modified Newtonian dynamics
Tensor-vector-scalar gravity
Entropic gravity
…

Dark!

conceptually and practically

[NSF]





[Bilard ea, 2021]

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Standard Model
(completed with H discovery in 2012)

$$\mathbf{SU(3)}_C \times \mathbf{SU(2)}_L \times \mathbf{U(1)}_Y \;\Rightarrow\; \mathbf{SU(3)}_C \times \mathbf{U(1)}_{\mathbf{EM}}$$

valid at least up to from zero to several TeV scales!

Our desperate guess and blind betting
A single (elementary or not) Majorana particle

⇩

GeV ~ a few TeV mass
Any spin (1/2, 1, 3/2, 2, …)
Colorless and electrically neutral
Hypercharge U(1) gauge symmetry
Weak due to higher-dim EFT operators
…

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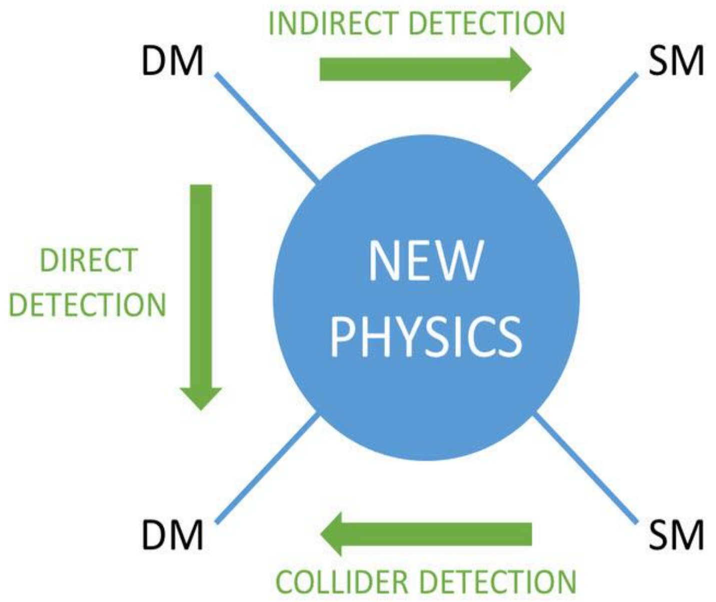
Anapole DM Particle

To be, or not to be?
Mass. Spin, couplings?

Complementary DM Hunting Strategies



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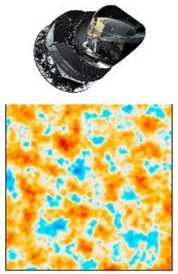
[A lot of ingenious probes]



Planck

$\Omega_\chi h^2 \simeq 0.12$

XENONnT
(1.1 t-y and 20 t-y)

Indirect detection (relic abundance)

DM + DM ⇒ SM + SM

Direct detection

DM + SM ⇒ DM + SM

Collider detection

SM + SM ⇒ DM + DM

LHC and HL-LHC
(139 fb^{-1} and 3 ab^{-1})

$\oplus$

Conceptual constraints
unitarity, perturbativity

History of Anapole DM Studies

	EM anapole DM		Hypercharge anapole DM				
Scenario (Spin)	1/2	1	1/2	1	3/2	2	
Relic abundance	C.M. Ho and R. J. Scherrer, PLB (2013)...	✗	C. Arina, at el. EPJC (2021)...				
LHC search	Y. Gao, C.M. Ho, and R. J. Scherrer (2014)...	✗	↓		This work ✓		…
Direct detection	C.M. Ho and R. J. Scherrer, PLB (2013)...	J. Hisano, A. Ibarra, and R. Nagai JCAP (2020)...					

A generic analytic & numerical (phenomenological) analysis for a hypercharge anapole DM particle of any spin (1/2, 1, 3/2, 2, …)

Hunting Target

A hypercharge anapole DM particle of any spin

Construct general 3-point $\chi\chi B$ vertices by imposing U(1) hypercharge symmetry and identical particle (Majorana) conditions for any spin

⇩

Evaluate the relic abundance, production cross sections at the (HL-)LHC and direct detection rate at the XENONnt for spin-1/2, 1, 3/2, 2, …

⇩

Combining the experimental results with a naïve perturbativity bound (NPD), we draw a unified picture for hunting for the hypercharge anapole DM.

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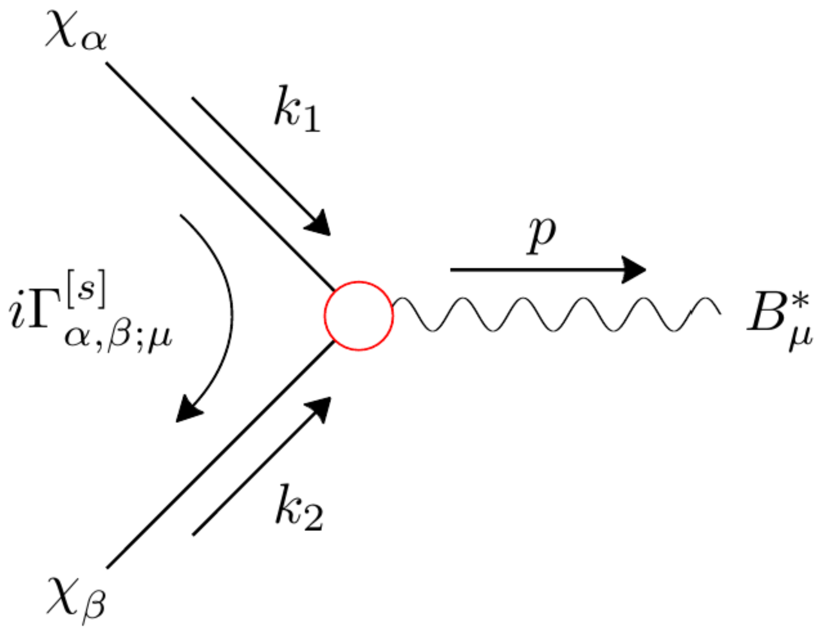
Grasp the implications for higher-spin anapole DM particles.

Constructing Anapole Vertices



$$p = k_1 + k_2 \qquad \alpha \equiv \alpha_1 \cdots \alpha_n$$
$$q = k_1 - k_2 \qquad \beta \equiv \beta_1 \cdots \beta_n$$

$$\text{with } n = \begin{cases} s & \text{for bosons} \\ s - \frac{1}{2} & \text{for fermions} \end{cases}$$

Hypercharge U(1) gauge invariance

$(B = \gamma \oplus Z)$

$$p^\mu \Gamma^{[s]}_{\alpha,\beta;\mu} = 0$$

Identical-particle (IP) relation

$$C\Gamma^{[s]}_{\beta,\alpha;\mu}(p,-q)C^{-1} = \Gamma^{[s]}_{\alpha,\beta;\mu}(p,q) \quad \text{for fermions}$$

$$\Gamma^{[s]}_{\beta,\alpha;\mu}(p,-q) = \Gamma^{[s]}_{\alpha,\beta;\mu}(p,q) \quad \text{for bosons}$$

$$(C = i\gamma^2\gamma^0)$$

General Algorithm [SY Choi, JH Jeong, PRD (2022)]

$$\hat{p} = p/\sqrt{p^2}$$
$$\hat{q} = q/\sqrt{-q^2}$$

⇨

$$g_{\perp\mu\nu} = g_{\mu\nu} - \hat{p}_\mu \hat{p}_\nu + \hat{q}_\mu \hat{q}_\nu$$
$$\gamma_{\perp\mu} = g_{\perp\mu\nu}\gamma^\nu$$
$$\langle \alpha\beta\hat{p}\hat{q}\rangle = \varepsilon_{\alpha\beta\rho\sigma}\,\hat{p}^\rho \hat{q}^\sigma$$

⇨

$$S^0_{\alpha\beta} = \hat{p}_\alpha \hat{p}_\beta$$
$$S^\pm_{\alpha\beta} = \frac{1}{2}[g_{\perp\alpha\beta} \pm i\langle\alpha\beta\hat{p}\hat{q}\rangle]$$
$$V^\pm_{\alpha\beta;\mu} = \hat{p}_\beta S^\pm_{\alpha\mu} + \hat{p}_\alpha S^\mp_{\beta\mu}$$
$$A_\mu = \gamma_{\perp\mu}\gamma_5$$
$$V_{\alpha\beta;\mu} = \hat{p}_\beta g_{\perp\alpha\mu} + \hat{p}_\alpha g_{\perp\beta\mu}$$

⇨

$$[g]^n \to g_{\alpha_1\beta_1}\cdots g_{\alpha_n\beta_n}$$
$$[S^0]^n \to S^0_{\alpha_1\beta_1}\cdots S^0_{\alpha_n\beta_n}$$
$$[S^\pm]^n \to S^\pm_{\alpha_1\beta_1}\cdots S^\pm_{\alpha_n\beta_n}$$
$$[V^\pm]^n \to V^\pm_{\alpha_1\beta_1;\mu_1}\cdots V^\pm_{\alpha_n\beta_n;\mu_n}$$
$$[A] \to A_\mu$$
$$[V] \to V_{\alpha\beta;\mu}$$

Half-integer $s = n + 1/2$

$$[\Gamma^{[s]}_F] = \left(\frac{p^2}{\Lambda^2}\right)[A]\sum_{\tau=0}^{n}\left(\frac{p^2}{\Lambda^2}\right)^\tau f^-_\tau\,[g]^{n-\tau}[S^0]^\tau + \left(\frac{p^2\sqrt{p^2}}{\Lambda^3}\right)[V]\sum_{\tau=1}^{n}\left(\frac{p^2}{\Lambda^2}\right)^{\tau-1} f^+_\tau\,[g]^{n-\tau}[S^0]^{\tau-1}$$

Integer $s = n \neq 0$ [Boudjema and Hamzaoui, PRD (1991)]

$$[\Gamma^{[s]}_B] = \sqrt{p^2}\left(\frac{p^2}{\Lambda^2}\right)\sum_{\tau=1}^{n}\left(\frac{p^2}{\Lambda^2}\right)^{\tau-1}\left(b^-_\tau[V^-] + b^+_\tau[V^+]\right)[g]^{n-\tau}[S^0]^{\tau-1}$$

2s terms ⇒ 1 (fermionic) vs 2 (bosonic) leading dim-6 terms

Leading $1/\Lambda^2$-order Anapole Terms

Half-integer $s = n + 1/2$

$$\Gamma_{\mu}^{[1/2]} = \frac{p^2}{\Lambda^2} a_{1/2} \gamma_{\perp\mu}\gamma_5$$

$$\Gamma_{\alpha,\beta;\mu}^{[3/2]} = \frac{p^2}{\Lambda^2} a_{3/2} \gamma_{\perp\mu}\gamma_5\, g_{\alpha\beta}$$

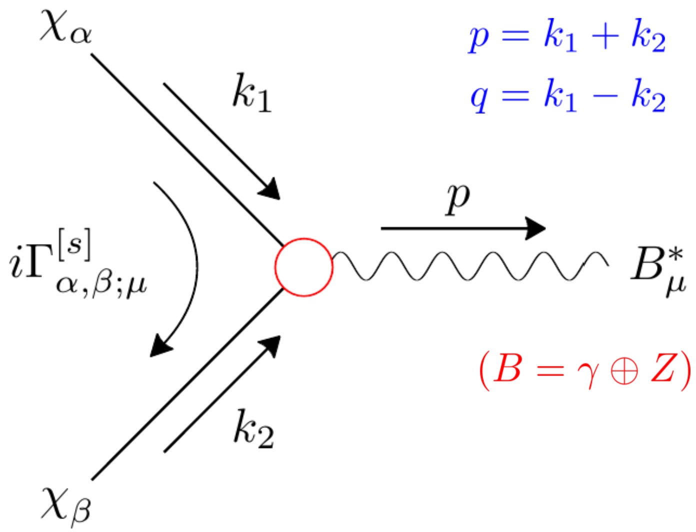
$$\cdots$$

Integer $s = n \neq 0$

$$\Gamma_{\alpha,\beta;\mu}^{[1]} = \frac{ip^2}{\Lambda^2} \left[a_1 \langle \alpha\beta\mu q\rangle_\perp - b_1 (p_\alpha g_{\perp\beta\mu} + p_\beta g_{\perp\alpha\mu})\right]$$

$$\Gamma_{\alpha_1,\alpha_2,\beta_1,\beta_2;\mu}^{[2]} = \frac{ip^2}{\Lambda^2} \left[a_2 \langle \alpha_1\beta_1\mu q\rangle_\perp - b_2 (p_{\alpha_1} g_{\perp\beta_1\mu} + p_{\beta_1} g_{\perp\alpha_1\mu})\right] g_{\alpha_2\beta_2}$$

$$\cdots$$



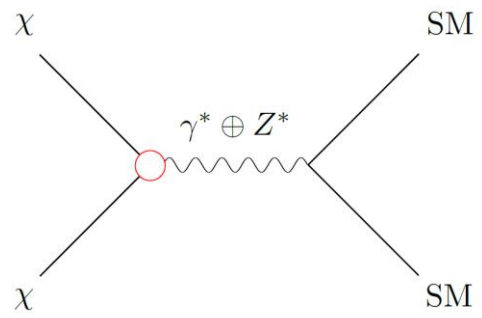
$p = k_1 + k_2$

$q = k_1 - k_2$

$(B = \gamma \oplus Z)$

Relic Abundance Constraints

Self-annihilation



$$\Omega_\chi h^2 \propto \frac{1}{\langle v\sigma_{\chi\chi}\rangle}$$

$$\beta_\chi = \chi \text{ CM speed}$$
$$\sqrt{s} = \text{CM energy}$$

$$\sigma_{1/2}^{[\chi\chi\to\mathrm{SMSM}]} = \frac{1}{4}\,\frac{|a_{1/2}|^2}{\Lambda^4}\,\beta_\chi\Sigma^{\mathrm{SM}}$$

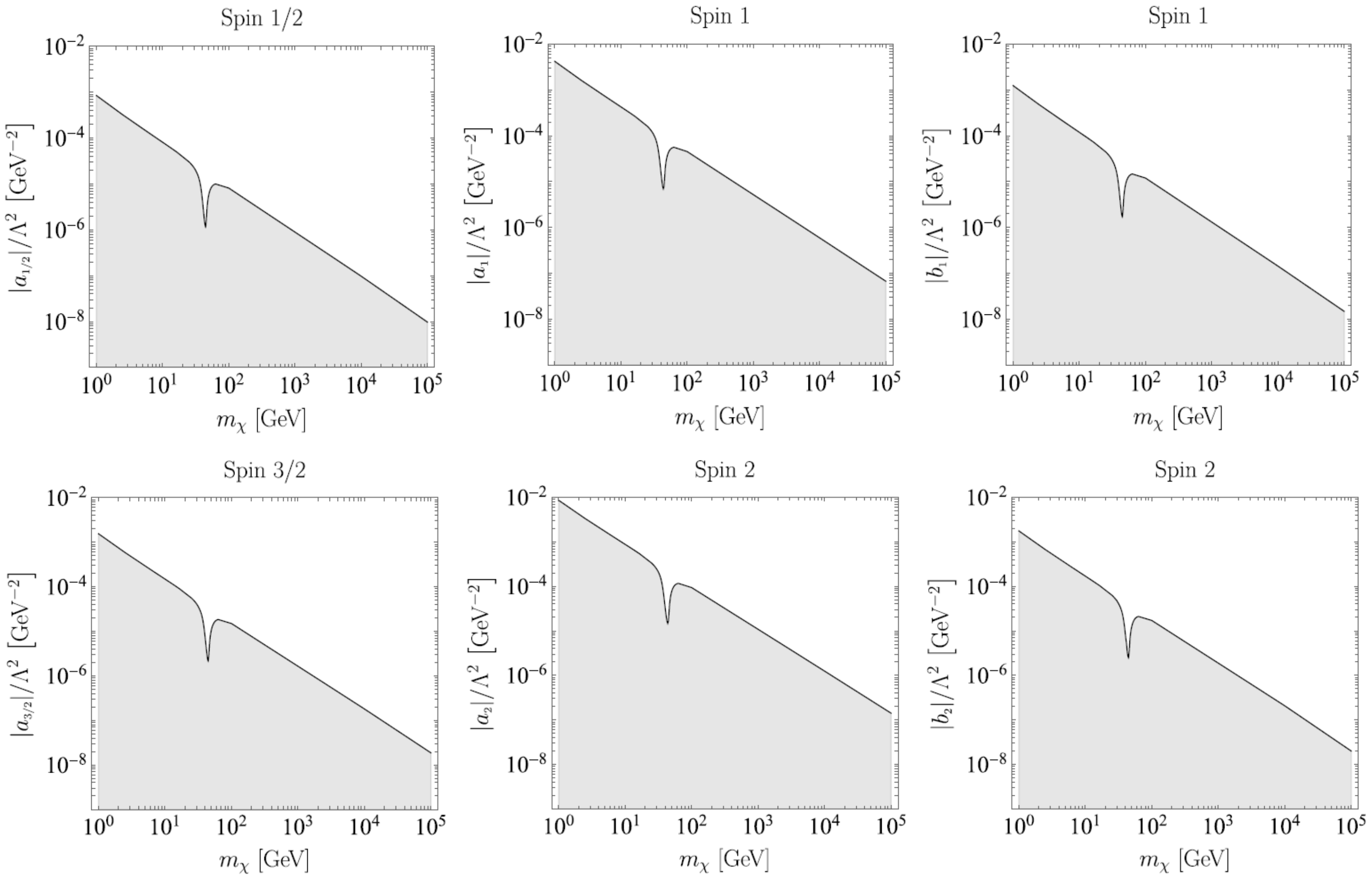
$$\sigma_{1}^{[\chi\chi\to\mathrm{SMSM}]} = \frac{1}{9}\left[\frac{|a_1|^2\,\beta_\chi^2 + |b_1|^2}{\Lambda^4}\right]\left(\frac{s}{4m_\chi^2}\right)\beta_\chi\Sigma^{\mathrm{SM}}$$

$$\sigma_{3/2}^{[\chi\chi\to\mathrm{SMSM}]} = \frac{5}{72}\,\frac{|a_{3/2}|^2}{\Lambda^4}\,\beta_\chi\Sigma^{\mathrm{SM}}$$

$$\sigma_{2}^{[\chi\chi\to\mathrm{SMSM}]} = \frac{1}{300}\left[\frac{7|a_2|^2\,\beta_\chi^2 + 15|b_2|^2}{\Lambda^4}\right]\left(\frac{s}{4m_\chi^2}\right)\beta_\chi\Sigma^{\mathrm{SM}}$$

small β_χ

Z-pole enhancement

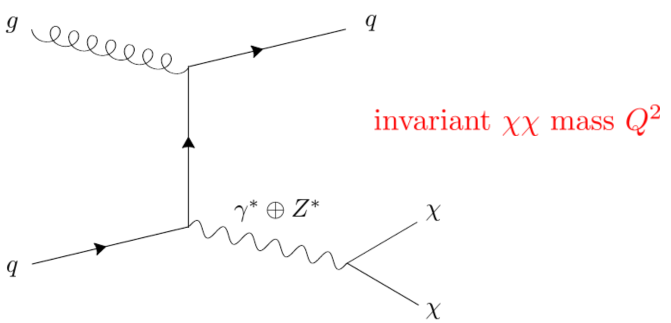


Smaller factors ⇒ smaller cross sections
⇒ Stronger relic-abundance constraints

(HL-)LHC Mono-jet Searches

[Aad ea [ATLAS], PRD (2021)]

Dominant mono-jet processes

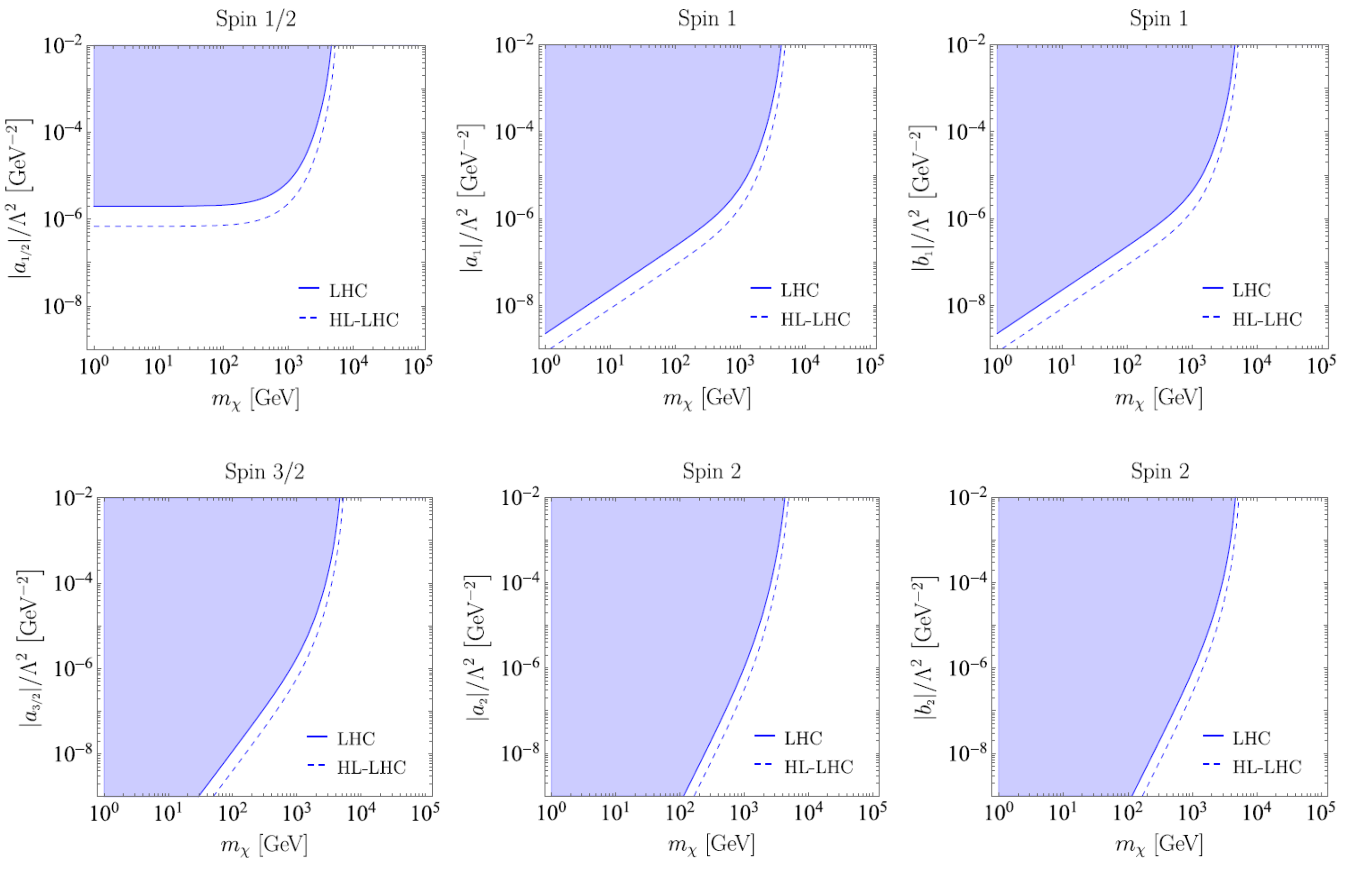


$$\sigma_{1/2}^{[gq\to q\chi\chi]} \propto \frac{|a_{1/2}|^2}{\Lambda^4}$$

$$\sigma_{1}^{[gq\to q\chi\chi]} \propto \left[\frac{|a_1|^2\,\beta_\chi^2 + |b_1|^2}{\Lambda^4}\right]\left(\frac{Q^2}{4m_\chi^2}\right)$$

$$\sigma_{3/2}^{[gq\to q\chi\chi]} \propto \frac{16|a_{3/2}|^2}{9\Lambda^4}\left(\frac{Q^2}{4m_\chi^2}\right)^2$$

$$\sigma_{2}^{[gq\to q\chi\chi]} \propto \left[\frac{8|a_2|^2\,\beta_\chi^2 + 7|b_2|^2}{6\Lambda^4}\right]\left(\frac{Q^2}{4m_\chi^2}\right)^3$$

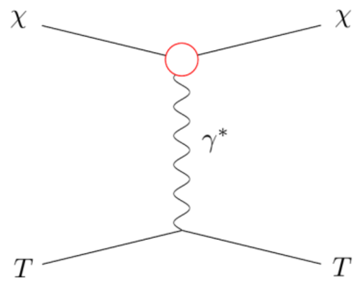


More longitudinal (L) modes ⇒ Stronger (HL-)LHC constraints

DM Direct Detection XENONnT

[Hisano, Ibarra, Nagai, JCAP (2020)]

NR scattering
(negligible Z-exchange)



Target nucleus T = Xe

Recoil energy E_R
$(E_R \ll m_\chi)$

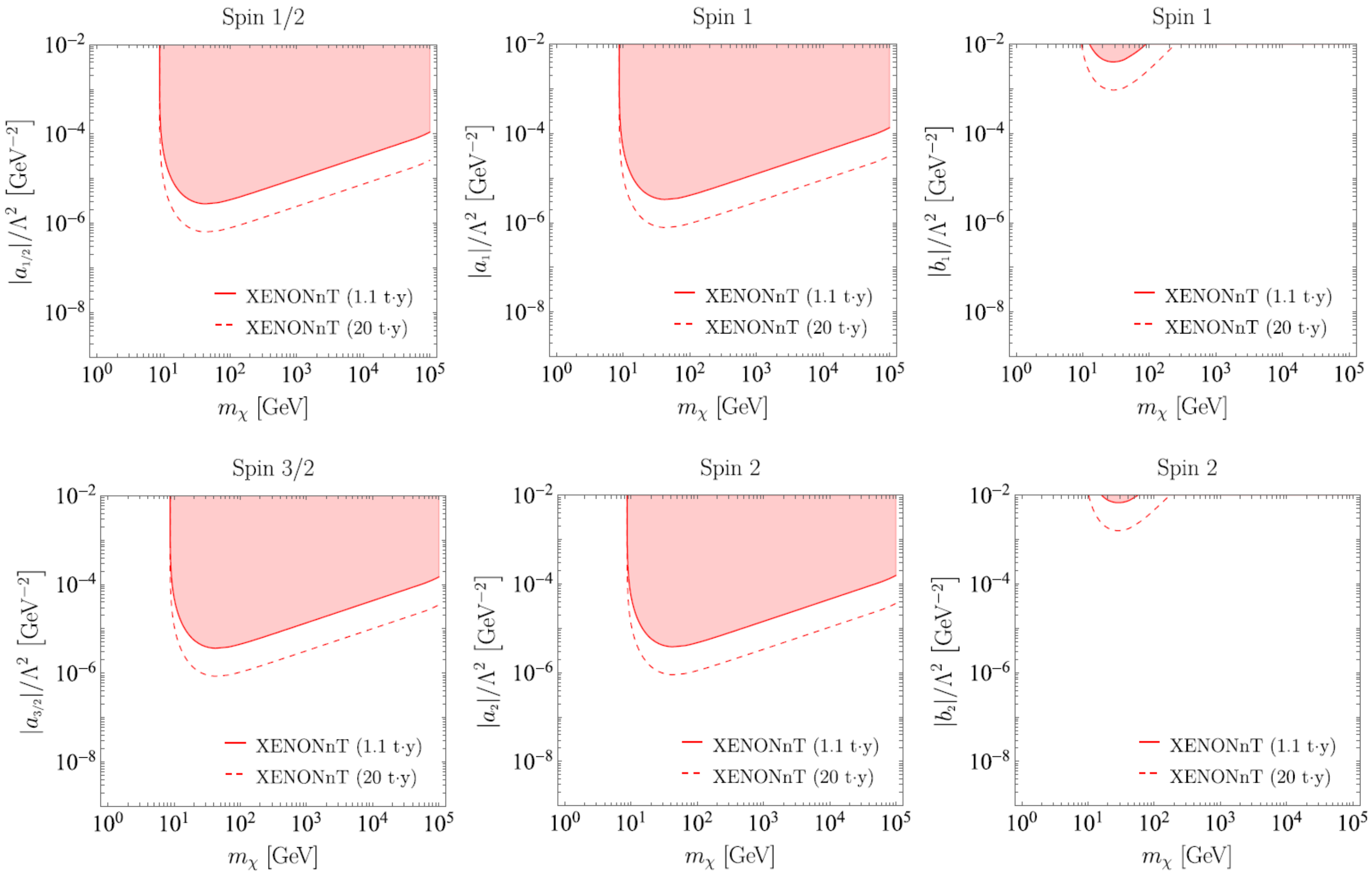
$3.3\,\mathrm{keV} \leq E_R \leq 60.5\,\mathrm{keV}$

$$\frac{d\sigma_{1/2}^{[\chi T\to\chi T]}}{dE_R} \propto \frac{1}{2}\,\frac{|a_{1/2}|^2}{\Lambda^4}$$

$$\frac{d\sigma_{1}^{[\chi T\to\chi T]}}{dE_R} \propto \frac{1}{3}\left[|a_1|^2\left(1+\frac{m_T E_R}{2m_\chi^2}\right)+|b_1|^2\frac{m_T E_R}{2m_\chi^2}\right]$$

$$\frac{d\sigma_{3/2}^{[\chi T\to\chi T]}}{dE_R} \propto \frac{5}{18}\,\frac{|a_{3/2}|^2}{\Lambda^4}$$

$$\frac{d\sigma_{2}^{[\chi T\to\chi T]}}{dE_R} \propto \frac{1}{60}\left[15|a_2|^2\left(1+\frac{13 m_T E_R}{10m_\chi^2}\right)+7|b_2|^2\frac{m_T E_R}{2m_\chi^2}\right]$$



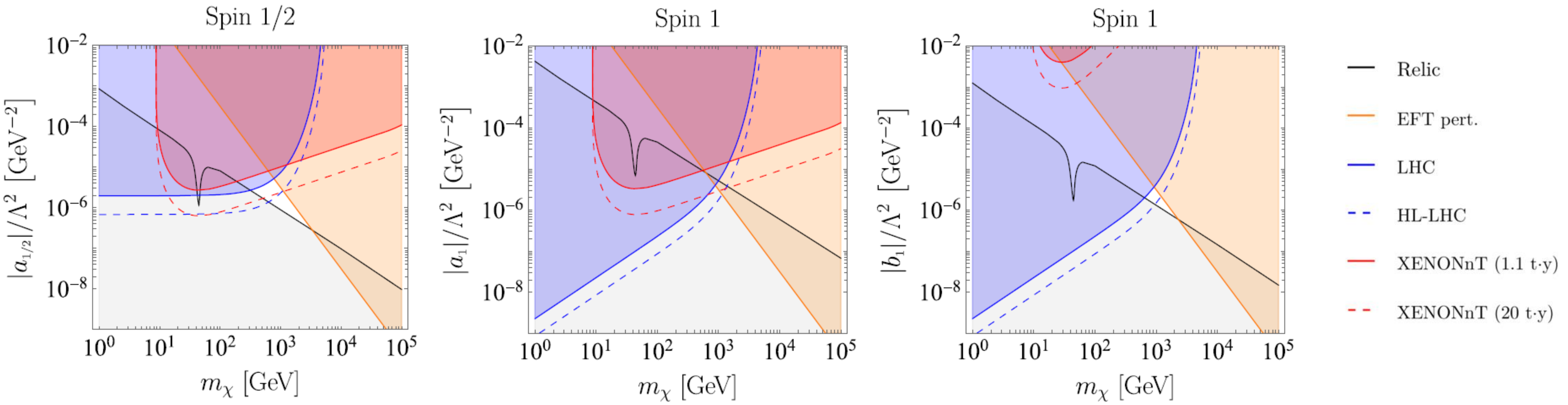
extremely small $m_T E_R/2m_\chi^2 < 4\times 10^{-3}$ ⇒ very weak constraints on $|b_{1,2}|$

Combined Constraints ⊕ Naive Perturbativity Bound

$$\frac{C}{\Lambda^2} s \leq 4\pi \quad \Rightarrow \quad \frac{C}{\Lambda^2} m_\chi^2 \leq \pi \quad \text{with} \quad C = |a_{1/2,3/2}| \quad \text{or} \quad \sqrt{|a_{1,2}|^2 + |b_{1,2}|^2}$$

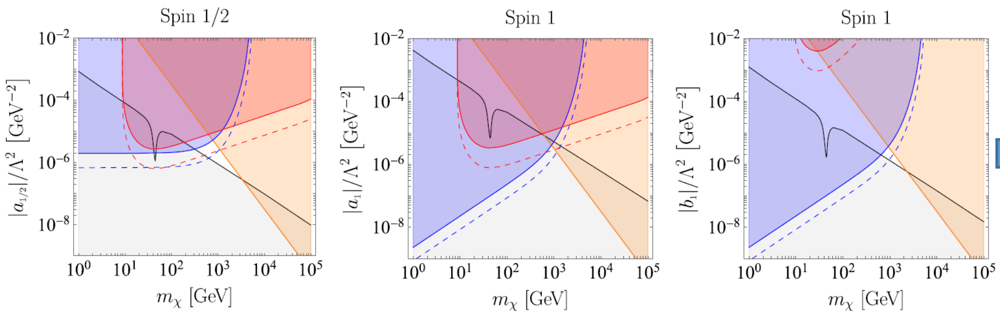
[Bruning, Zerlauth, JACoW (2023), TUYG1]
[Aalbersetal ea, J.Phys (2023)]

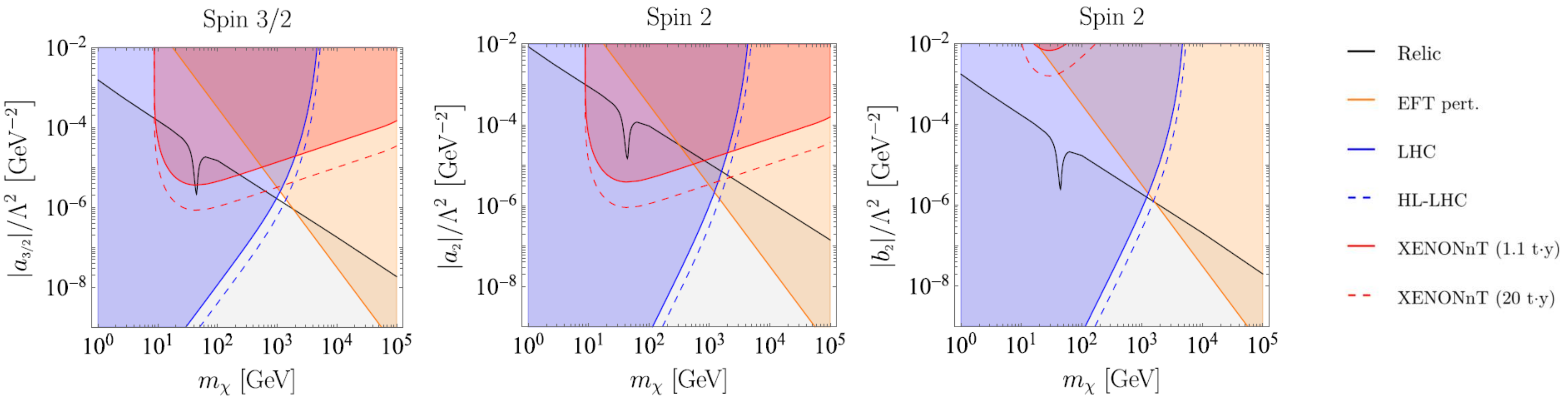
(yellow exclusion regions)



Stronger constraints for the spin-1 case than the spin-1/2 case
The spin-1 case with $|a_1|$ (middle) is already completely excluded
Promising XENONnt (20 t-y) and HL-LHC especially for the spin-1/2 case

Combined constraints





Stronger constraints for the higher-spin 3/2 and 2 cases
Nearly full exclusion or discovery is expected in the near future!

Conclusions

General 3-point anapole vertices for any spin were constructed
in a compact form for systematic analytic analyses and other projects

Detailed analytic and phenomenological analyses were performed
for the spin-1/2, 1, 3/2 and 2 hypercharge anapole DM particles

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Nearly half of the allowed region for the spin-1/2 case is
excluded by the future XENONnT experiments in 5 years

Nearly half of the allowed region for the spin-1 case is
excluded by the full running of the HL-LHC

Constraints are stronger from relic abundance and (HL-)LHC
but weaker from XENONnT for the higher-spin cases,
leading to complete exclusion or discovery of the anapole DM?!!

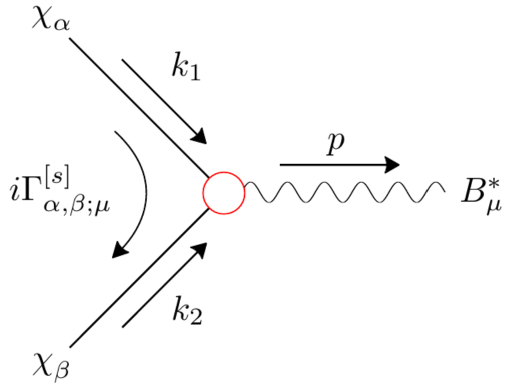
⇩

Finding UV scenarios of the hypercharge anapole DM

Back-up Slides

(Leading-order) Effective Lagrangian

$$
\begin{aligned}
\mathcal{L}_{1/2} &= \frac{a_{1/2}}{2\Lambda^2}\,\bar{\chi}_{\frac{1}{2}}\gamma^\mu\gamma_5\chi_{\frac{1}{2}}\,\partial_\nu B^{\mu\nu} \\
\mathcal{L}_1 &= \left[\frac{a_1}{2\Lambda^2}\epsilon_{\alpha\beta\mu\rho}\left[\chi_1^\alpha(\partial^\rho\chi_1^\beta) - (\partial^\rho\chi_1^\alpha)\chi_1^\beta\right] + \frac{b_1}{2\Lambda^2}\partial^\rho(\chi_{1\rho}\chi_{1\mu} + \chi_{1\mu}\chi_{1\rho})\right]\partial_\nu B^{\mu\nu} \\
\mathcal{L}_{3/2} &= \frac{a_{3/2}}{2\Lambda^2}\,\bar{\chi}_{\frac{3}{2}\rho}\gamma^\mu\gamma_5\chi^\rho_{\frac{3}{2}}\,\partial_\nu B^{\mu\nu}, \\
\mathcal{L}_2 &= \left[\frac{a_2}{2\Lambda^2}\epsilon_{\alpha\beta\mu\rho}\left[\chi_2^{\alpha\sigma}(\partial^\rho\chi^\beta_{2\,\sigma}) - (\partial^\rho\chi_2^{\alpha\sigma})\chi^\beta_{2\,\sigma}\right] + \frac{b_2}{2\Lambda^2}\partial^\rho(\chi_{2\rho}{}^\sigma\chi_{2\mu\sigma} + \chi_{2\mu}{}^\sigma\chi_{2\rho\sigma})\right]\partial_\nu B^{\mu\nu}
\end{aligned}
$$



Non-relativistic limit

$$a_i \;\to\; H \propto -\frac{\vec{\mathbf{S}}}{S}\cdot\vec{j}_{\text{ext}} \quad \text{(odd-parity dipole)}$$

$$b_i \;\to\; H \propto \frac{3}{2S(2S-1)}\left[\mathbf{S}^l\mathbf{S}^m + \mathbf{S}^l\mathbf{S}^m - \frac{2}{3}\delta^{ij}S(S+1)\right]\nabla^l j^m_{\text{ext}} \quad \text{(even-parity quadrupole)}$$

Elliptically-correlated $a_{1,2}$ & $b_{1,2}$ Constraints