Hunting for Hypercharge Anapole Dark Matter

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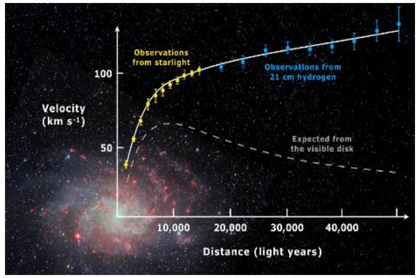
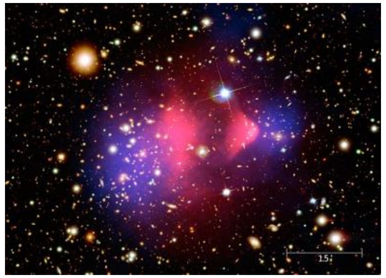
Dark Matter (DM)

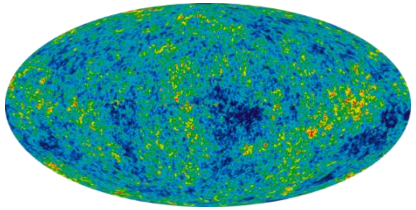
[Wikipedia. PDG]

Evidence
(several but only gravitational)

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







DM Candidate (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

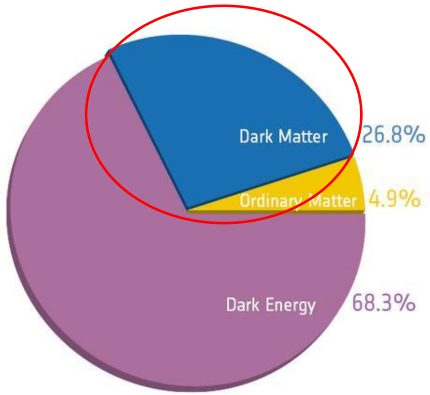
Strangelet
Superfluid vacuum theory
Dynamical dark matter

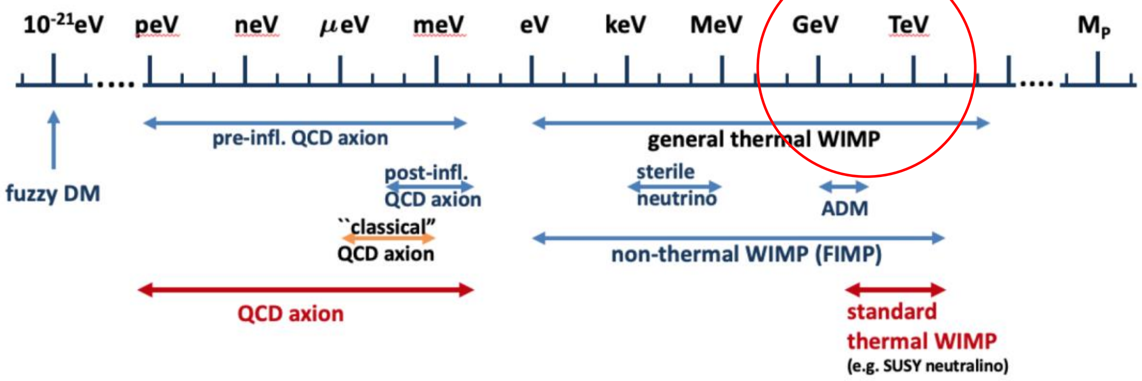
Modified Newtonian dynamics
Tensor-vector-scalar gravity
Entropic gravity
…

Dark!!

conceptually and
practically indeed

[NSF]





[Bilard ea, 2021]

$\oplus$

Standard Model (completed in 2012)

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

valid at least up to several TeV scales!

Our desperate guess and blind betting

A single (elementary or not) Majorana particle

⇓

GeV ~ a few TeV mass

Any allowed spin (1/2, 1, 3/2, 2, ...)

Colorless and electrically neutral

U(1) gauge symmetry

Weak due to higher-dim EFT operators

...

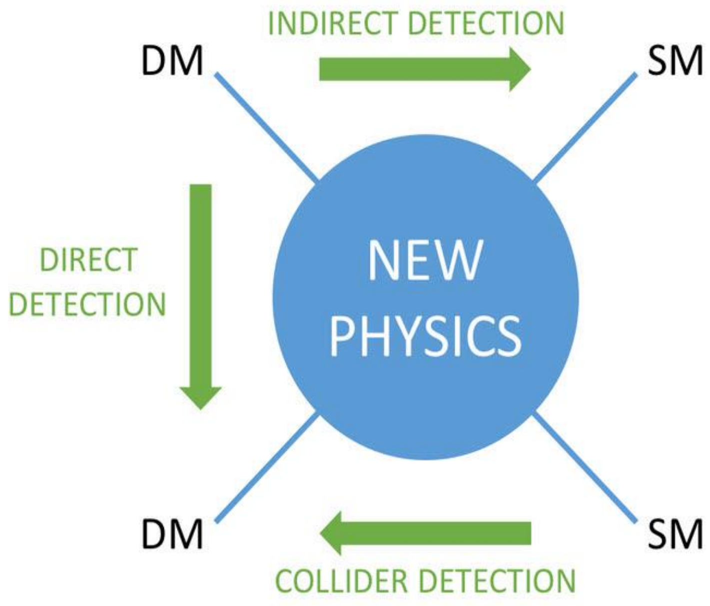
⇓

Anapole DM Particle

To be, or not to be?

Mass. Spin, couplings?

Complementary DM Hunting Strategies



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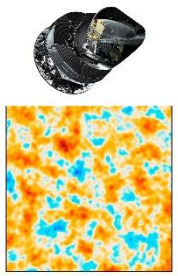
[A lot of ingenious probes]



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

$\oplus$

Conceptual constraints
unitarity, perturbativity

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

Previous Anapole DM Studies

A Majorana particle coupled to a U(1) gauge boson ⇒ Anapole interaction terms

Intrinsically higher-dimensional ⇔ EFT description

	Spin-1/2 EM	**Spin-1 EM**	**Spin-1/2 Hypercharge**
Relic abundance	Ho, Scherrer, PLB (2013), …		Arina, Cheek, Mimasu, Pagani, EPJC (2021)
Direct detection	Pospelov, ter Veldhuis, PLB (2000), …	Hisano, Ibarra, Nagai, JCAP (2020), …	
Collider (LHC)	Gao, Ho, Scherrer, PRD (2014), …		
(UV) models	Cabral-Rosetti, Mondragon, Reyes-Perez, NPB (2016)		

Hunting Target

A hypercharge anapole DM particle of any spin

Construct general 3-point hypercharge anapole $\chi\chi B$ 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 numerically for spin-1/2 and 1 Majorana particles

⇩

Combining the experimental results with a conceptual naïve perturbativity bound (NPD), we draw a unified picture for hunting for spin-1/2 and 1 hypercharge anapole DM.

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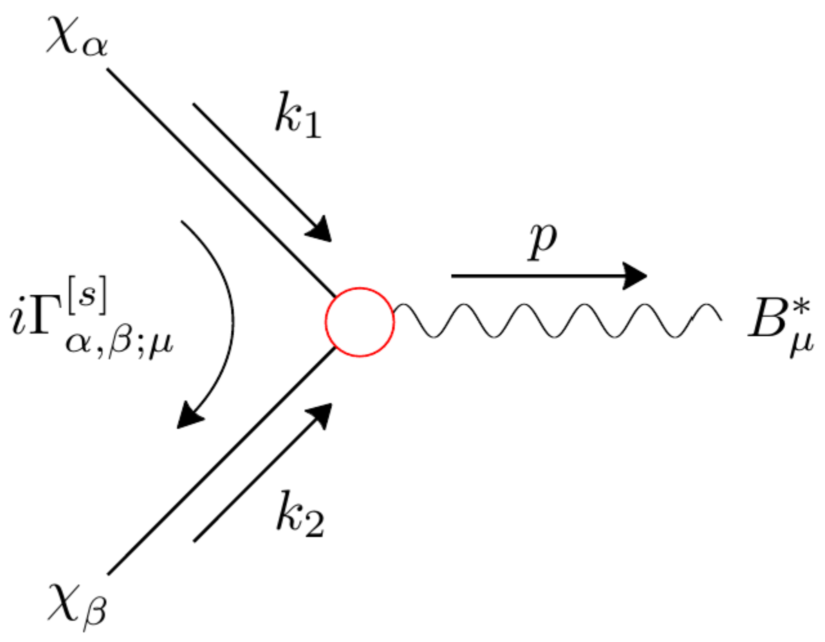
Based on the picture, we make a simple educated guess for higher-spin anapole DM particles.

Constructing general anapole vertices



$$p = k_1 + k_2 \qquad q = k_1 - k_2$$

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

$$\alpha \equiv \alpha_1 \cdots \alpha_n \qquad \beta \equiv \beta_1 \cdots \beta_n$$

U(1) gauge invariance

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

Identical-particle (IP) relation

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

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

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

Algorithm

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

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

⇨

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

⇨

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

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

$2s$ Independent terms

Half-integer $s = n + 1/2 = 1/2, \ldots$

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

⇨

Spin-1/2

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

Integer $s = n \neq 0 = 1, \ldots$

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

⇨

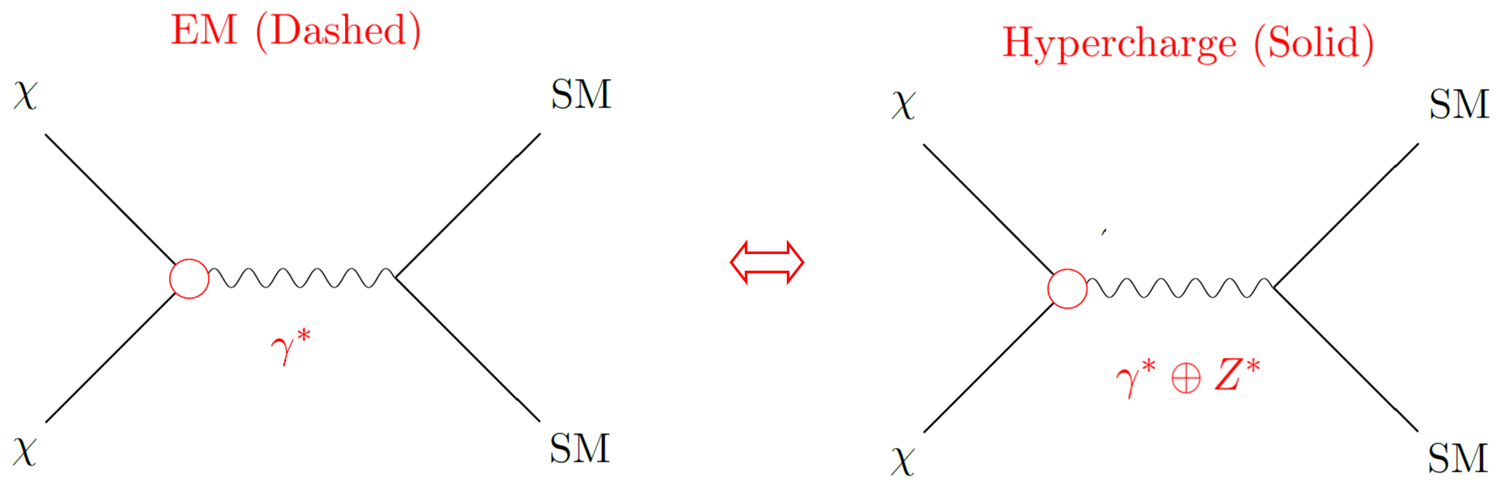
Spin-1

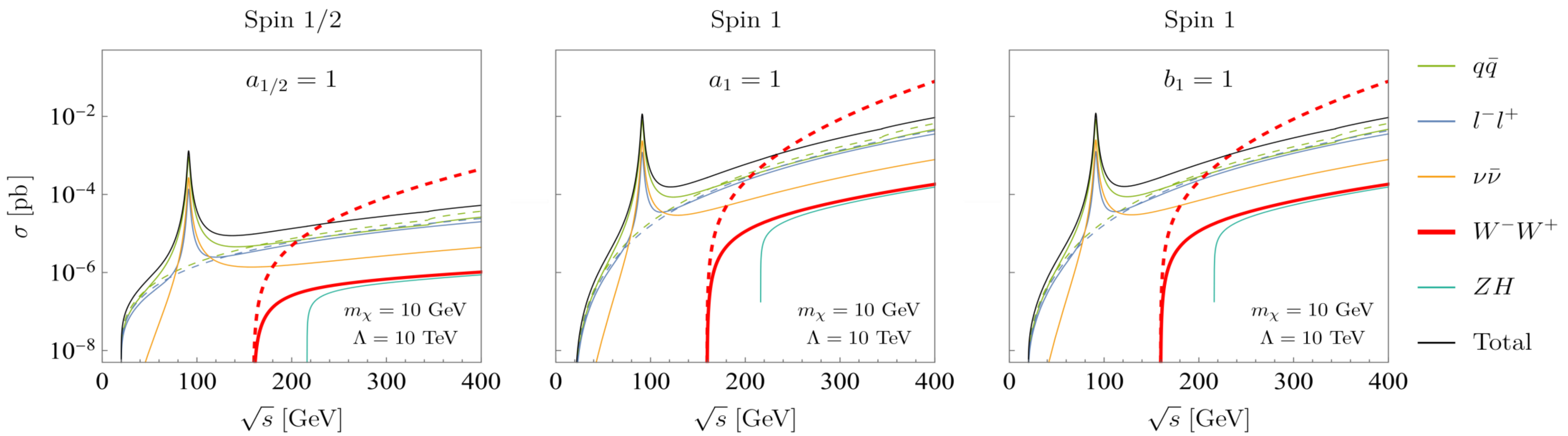
$$\Gamma^{[1]}_{\alpha,\beta;\mu} = \frac{ip^2}{\Lambda^2}[\,a_1\,\langle\alpha\beta\mu q\rangle_\perp - b_1\,(p_\alpha g_{\perp\beta\mu} + p_\beta g_{\perp\alpha\mu})]$$

A mass parameter Λ

Why hypercharge instead of EM?

[Arina, Cheek, Mimasu, Pagani, EPJC (2021)]





Improved high-E behavior!

$B \nsim W^3$ without EWSB

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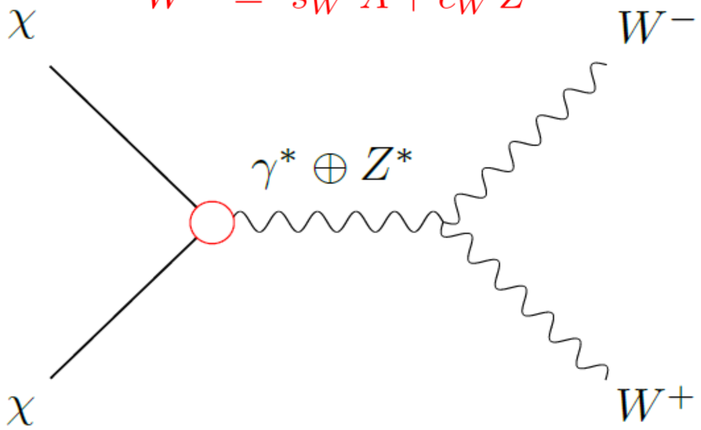
$\gamma \oplus Z$ cancellation in high-energy limit

$$B = c_W\, A - s_W\, Z$$
$$W^3 = s_W\, A + c_W\, Z$$



U(1) hypercharge gauge symmetry

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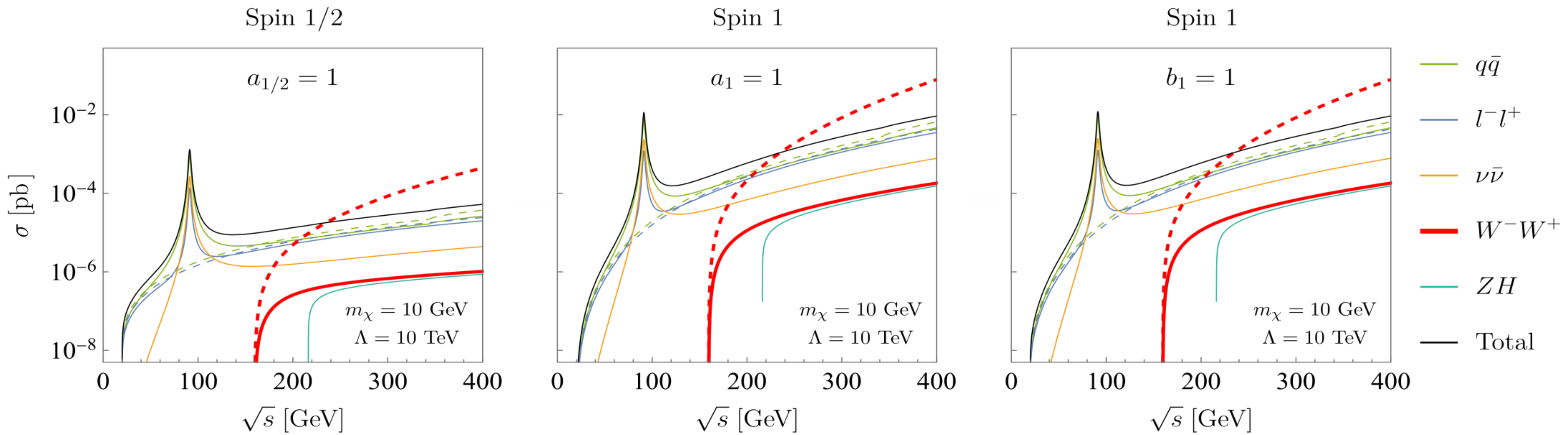
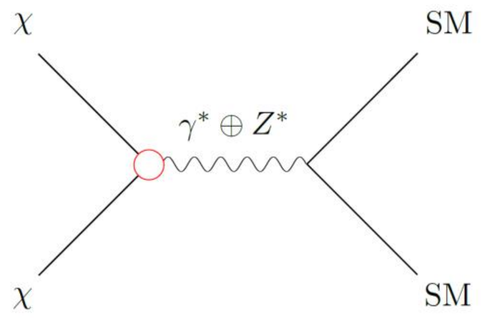
Significantly improved unitarity properties



Relic abundance constraints

[Gondolo, Gelmini, NPB (1991)]

Self-annihilation



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

p wave

$$\sigma_{1/2}^{[\chi\chi\to\mathrm{SMSM}]} = \frac{1}{4}\frac{|a_{1/2}|^2}{\Lambda^4}\beta_\chi \Sigma^{\mathrm{SM}} \quad \Leftrightarrow \quad \sigma_1^{[\chi\chi\to\mathrm{SMSM}]} = \frac{1}{9}\left[\frac{|a_1|^2\beta_\chi^2 + |b_1|^2}{\Lambda^4}\right]\left(\frac{s}{4m_\chi^2}\right)\beta_\chi\Sigma^{\mathrm{SM}}$$

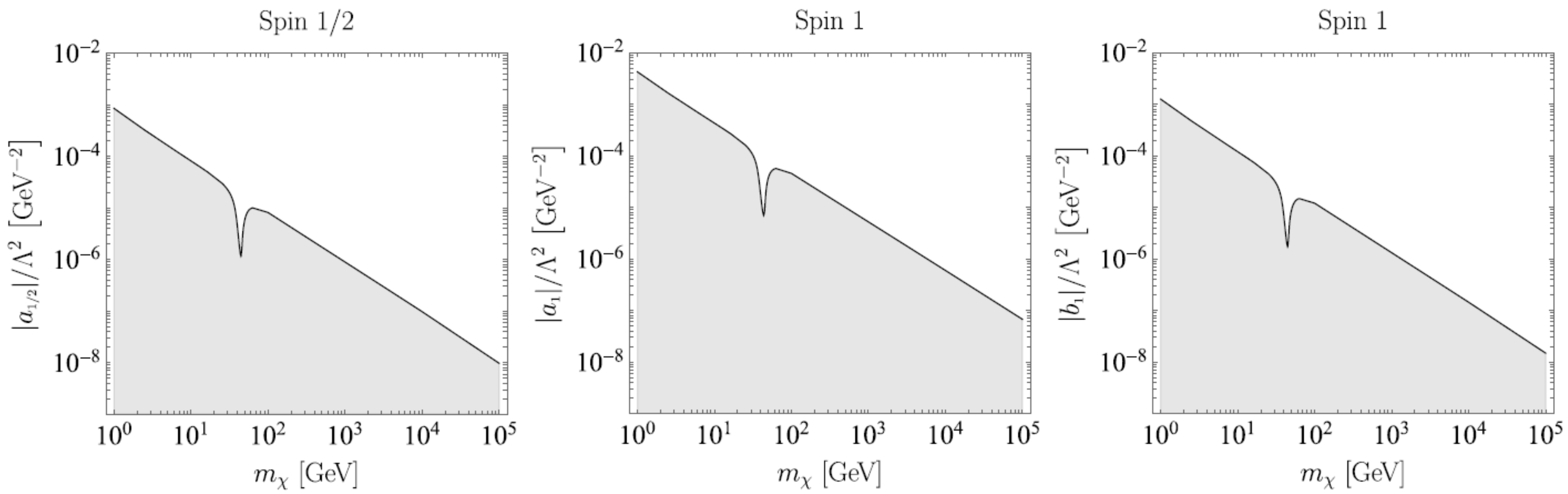
d wave $\quad p$ wave

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

$\Rightarrow$

$\frac{1}{4} \to \frac{1}{9}$ $\Rightarrow$ stronger constraints on the spin-1 case

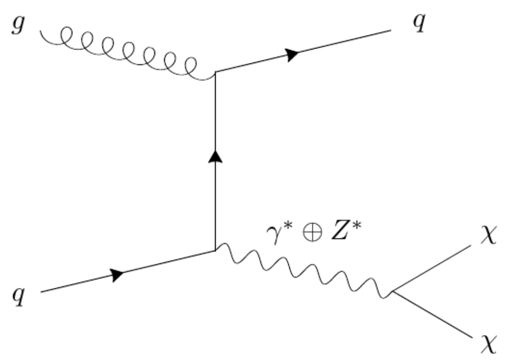
β_χ^2 $\Rightarrow$ much stronger constraints on $|a_1|$



LHC and HL-LHC mono-jet search constraints

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

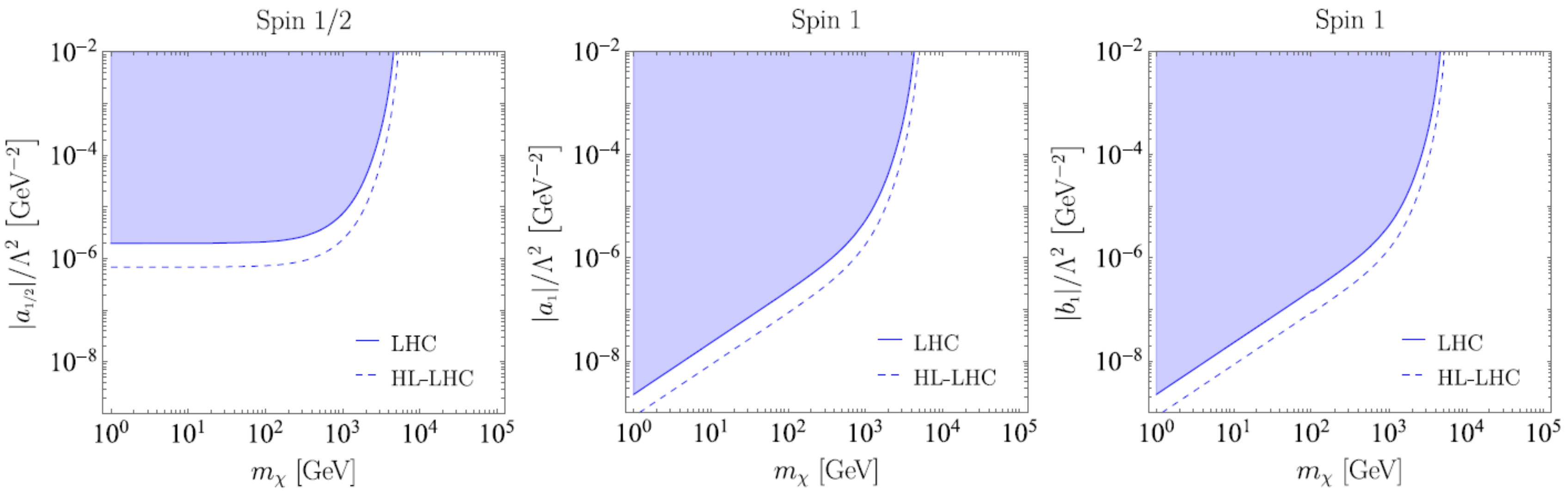
Dominant mono-jet processes
(suppressed WW fusion processes + ⋯)



invariant $\chi\chi$ mass Q^2

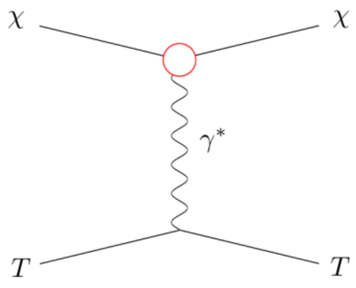
$$\sigma_{1/2}^{[gq\to q\chi\chi]} \propto \frac{|a_{1/2}|^2}{\Lambda^4} \quad \Longleftrightarrow \quad \sigma_{1}^{[gq\to q\chi\chi]} \propto \frac{|a_1|^2\,\beta_\chi^2 + |b_1|^2}{\Lambda^4}\left(\frac{Q^2}{4m_\chi^2}\right)$$

longitudinal ⇒ stronger (HL-)LHC constraints on the spin-1 case
$\beta_\chi \approx 1$ ⇒ similar constraints on the spin-1 couplings $|a_1|$ and $|b_1|$



Constraints from the DM direct detection XENONnT

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



NR scattering
(negligible Z-exchange)

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

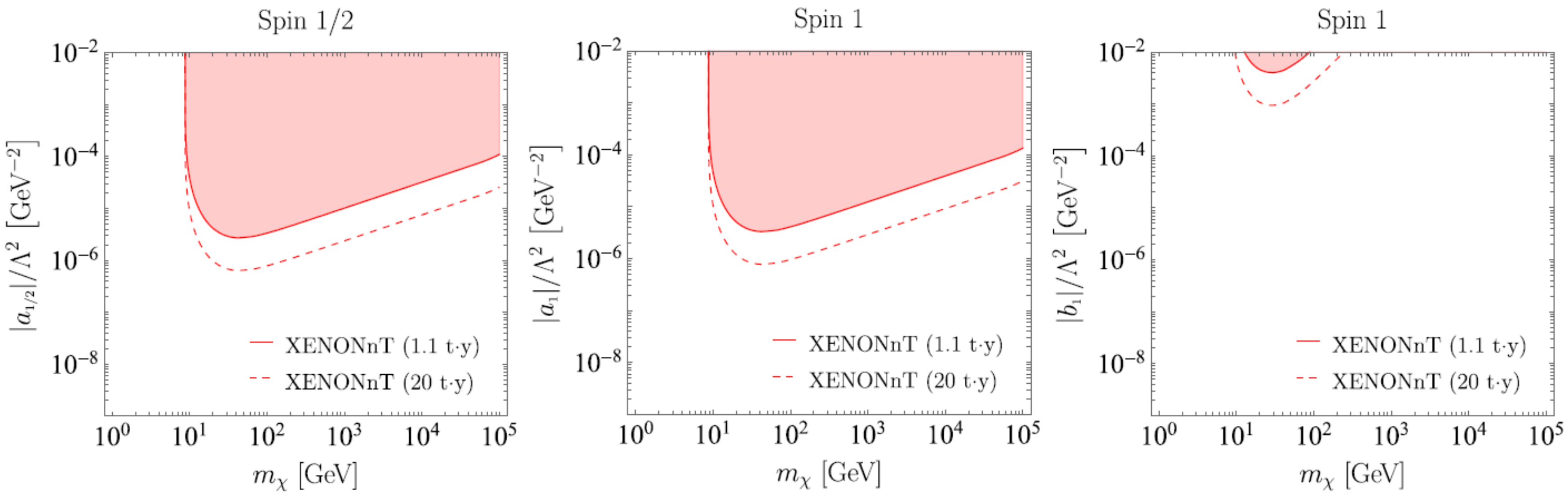
$$\frac{d\sigma_{1}^{[\chi T\to\chi T]}}{dE_R} \propto \frac{1}{3}\left[\frac{|a_1|^2}{\Lambda^4}\left(1+\frac{m_T E_R}{2m_\chi^2}\right)+\frac{|b_1|^2}{\Lambda^4}\frac{m_T E_R}{2m_\chi^2}\right]$$

Target nucleus T = Xe

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

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

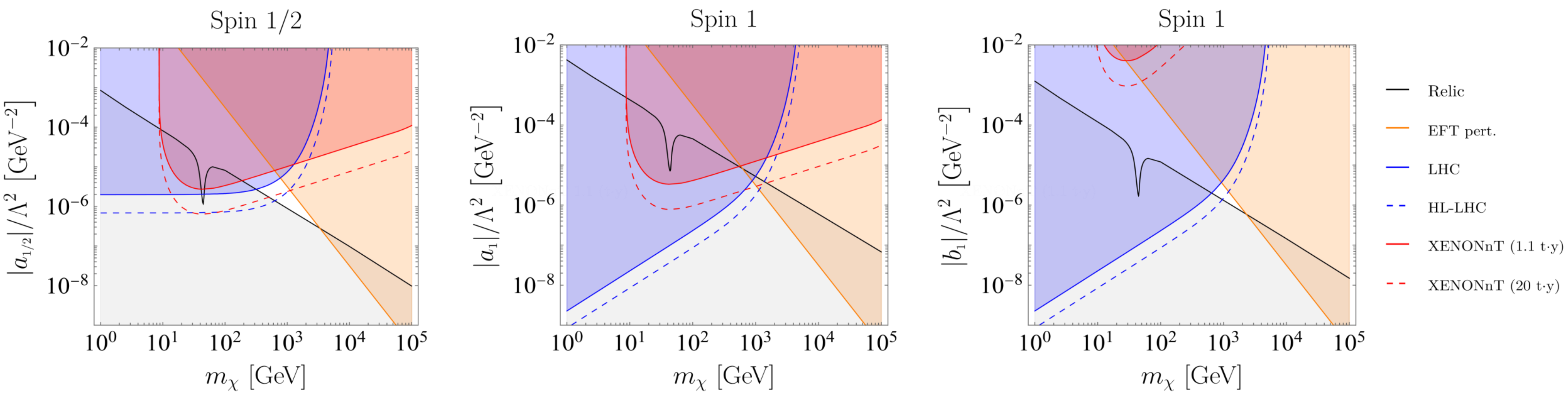
☞ extremely small $m_T E_R/2m_\chi^2 < 4\times 10^{-3}$ ⇒ very weak constraint on $|b_1|$



Combined constraints ⊕ naive perturbativity bound (NPD)

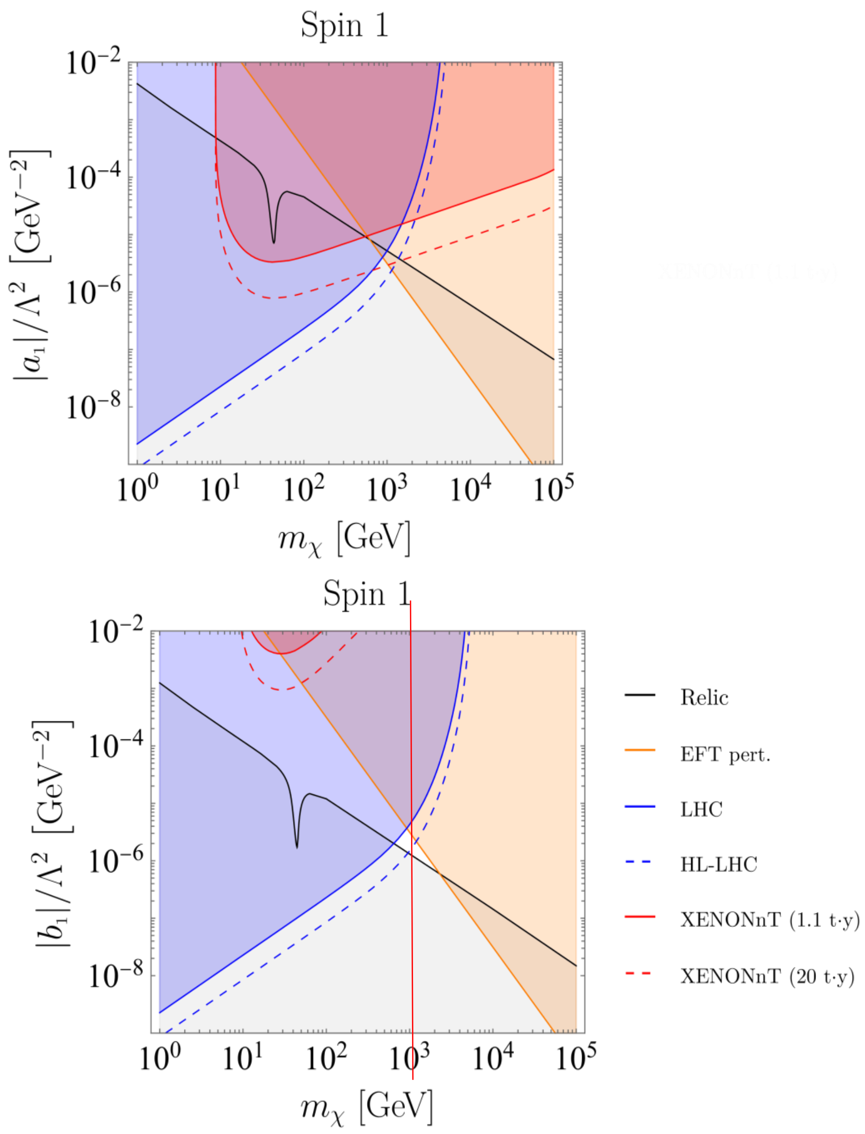
$$\frac{C}{\Lambda^2}\, s \leq 4\pi \;\Rightarrow\; \frac{C}{\Lambda^2}\, m_\chi^2 \leq \pi \;\text{ with }\; C = |a_{1/2}| \;\text{ or }\; \sqrt{|a_1|^2 + |b_1|^2}$$

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

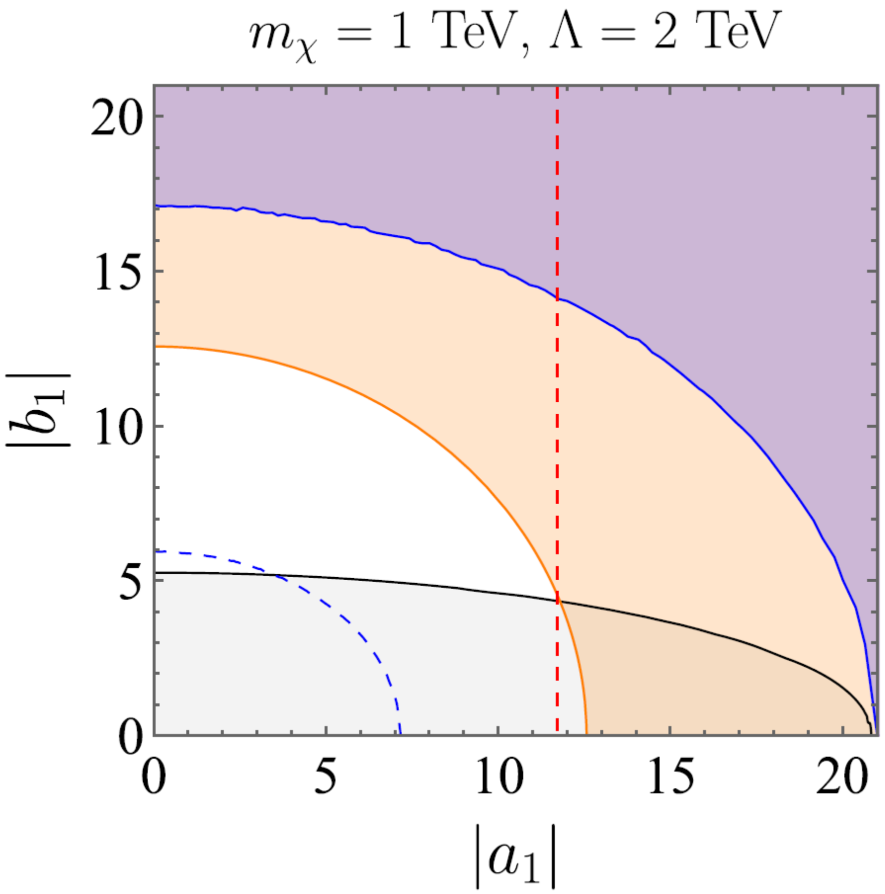


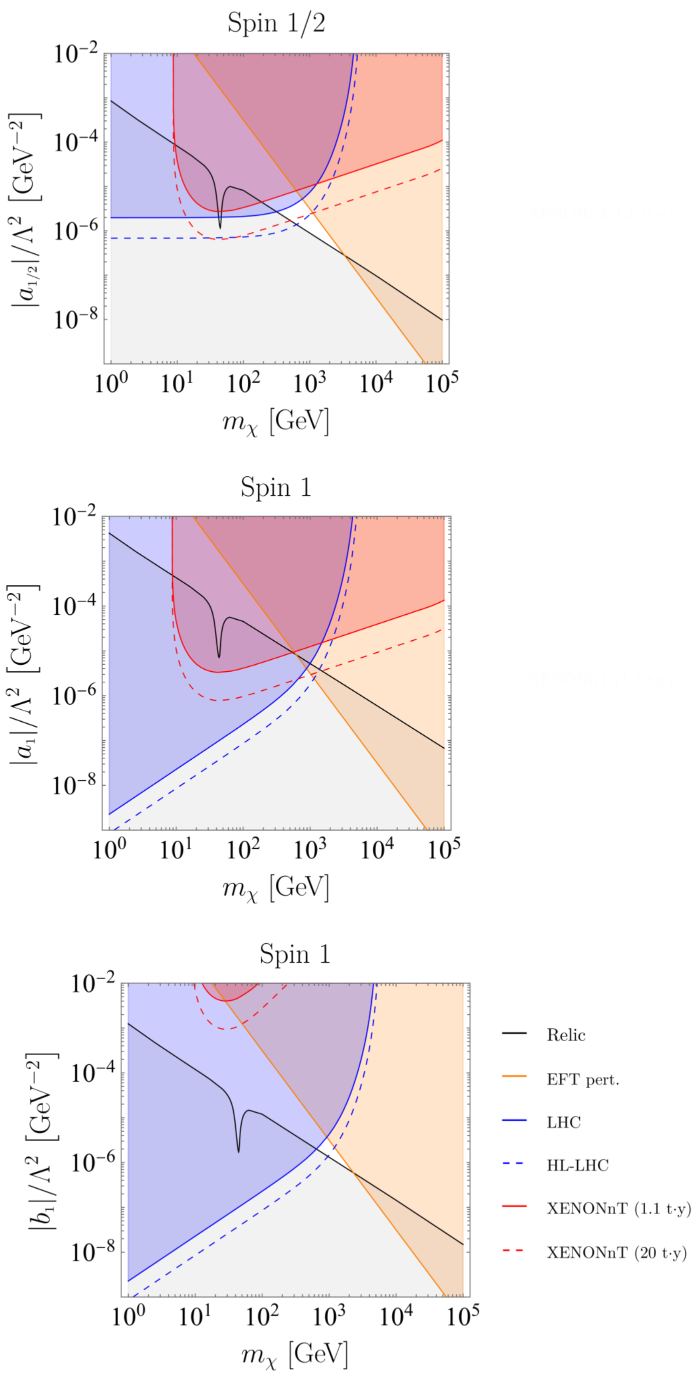
Stronger constraints for the spin-1 case than the spin-1/2 case
The spin-1 case with $|a_1|$ (middle) is already completely excluded
Promising XENONnt (20 t-y) and HL-LHC especially for the spin-1/2 case

Correlated a_1 and b_1 constraints



$$\sigma_1 \propto \frac{(|a_1|^2\,\beta_\chi^2 + |b_1|^2)}{\Lambda^4}\,\frac{s}{4m_\chi^2} \quad \Rightarrow \quad \text{ellipses}$$





Conclusion

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

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

Nearly half of the allowed region for the spin-1/2 case excluded by the future XENONnT experiments in 5 years at a faster pace than the HL-LHC

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

Stronger constraints on the spin-1 case than the spin-1/2 case

Complete exclusion of the higher-spin anapole DM?!!
(stronger relic-abundance ⊕ LHC constraints)

Finding UV scenarios of the hypercharge anapole DM