Forecasting DM searches at future DD experiments in light of astrophysical uncertainties: Result

J. Buch, J. Fan, and J. Leung, arXiv:1908.xxxxx

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Motivation

1. Recent Gaia-based analysis show debris flow[1] and stream[2]. Dark matter (DM) in solar neighborhood may deviate from the Standard Halo Model (SHM).

2. Different DM-nucleus interactions vary differently with DM velocity. How robust direct detection result is against astrophysics uncertainty? How can we improve them?

[1] L. Necib, M. Lisanti and V. Belokurov, 1807.02519
[2] C. A. J. O'Hare, C. McCabe, N. W. Evans, GC Myeong and V. Belokurov, 1807.09004v2

Overview

- ~~A very short review of dark matter direct detection~~
- ~~Dark matter astrophysics in the Gaia era~~
- ~~Statistical techniques: connecting theory to data~~

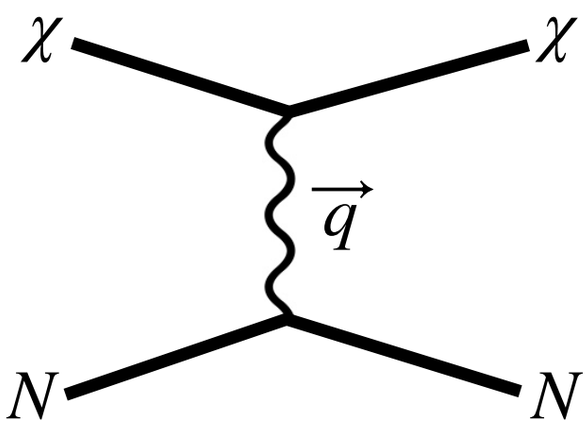
} Jatan's talk

- Non-relativistic EFT formalism (NREFT)
- From dark matter velocity to nuclear recoil response
- Results and outlook

} This presentation

Non-Relativistic Effective Field Theory (NREFT)

J. Fan, M. Reece and L. T. Wang, JCAP **1011**, 042 (2010). 1008.1591
A. L. Fitzpatrick, W. Haxton, E. Katz, N. Lubbers and Y. Xu, JCAP **1302**, 004 (2013). 1203.3542v3



In non-relativistic limit, scattering process depends on four 3-vector quantities:

- The DM and nuclear spin S_χ, S_N,
- The momentum transfer q,
- The transverse velocity $v^\perp = v + \dfrac{q}{2\mu_N}$ that satisfies

$$v^\perp \cdot q = 0,$$

where μ_N is the reduced mass of the system.

Operators	Form	Spin-Dependence
O_1	$\mathbb{1}$	✗
O_2	$(\vec{v}^{\perp})^2$	✗
O_3	$i\vec{S}_N \cdot (\vec{q} \times \vec{v}^{\perp})$	✓
O_4	$\vec{S}_\chi \cdot \vec{S}_N$	✓
O_5	$i\vec{S}_\chi \cdot (\vec{q} \times \vec{v}^{\perp})$	✗
O_6	$(\vec{S}_N \cdot \vec{q})(\vec{S}_\chi \cdot \vec{q})$	✓
O_7	$\vec{S}_N \cdot \vec{v}^{\perp}$	✓
O_8	$\vec{S}_\chi \cdot \vec{v}^{\perp}$	✗
O_9	$i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{q})$	✓
O_{10}	$i\vec{S}_N \cdot \vec{q}$	✓
O_{11}	$i\vec{S}_\chi \cdot \vec{q}$	✗

All 11 possible linear-independent non-relativistic operators.

Adequate to study these!

Question:

Which models are the most sensitive to astrophysics?

Common DM theories can be expressed in EFT operators:

Model	Relativistic Operator	EFT Operator	Mediator
scalar	$\bar{\chi}\chi\bar{q}q$	O_1	heavy
pseudoscalar	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	O_4	heavy
vector	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	O_5	heavy
axial-vector	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	O_8	heavy
millicharge	$\bar{\chi}\gamma^\mu\chi A_\mu$	$e\, m_\chi m_N \frac{1}{q^2} O_1$	light
DM magnetic dipole moment	$\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$	$e\, m_N (O_1 + 4\frac{m_\chi}{q^2} O_5) + 2 g_N m_\chi (O_4 - \frac{1}{q^2} O_6)$	light
DM electric dipole moment	$i\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu}$	$e\, m_\chi m_N \frac{1}{q^2} O_{11}$	light

Relation to astrophysics uncertainty?

The **scattering rate** (events per recoil energy bin) depends on the *squared matrix elements* of the EFT operators.

The EFT operators reside within the nuclear matrix element $\langle \cdot \rangle_N$.

DM velocity distribution from astrophysics

Matrix Element

Coupling strength

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} \propto \sum_{\text{spins}} \sum_{a,b} \int_{v_{\min}} \mathrm{d}^3 v \frac{f(v)}{v} \langle O_a O_b \rangle_N \frac{g_{a,b}^2}{q^2 + m_\phi^2}, \qquad a, b \in \{1,2,\cdots,11\} . \tag{1}$$

Mediator mass

Lower velocity cut off $v_{\min} = \sqrt{\frac{m_T E_R}{2\mu_T^2}}$

Label the the nuclear matrix element as the **nuclear form factor**, $\langle O_a O_b \rangle_N = F_{a,b}$.

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} \propto \sum_{\text{spins}} \sum_{a,b} \int_{v_{\min}} \mathrm{d}^3 v \underbrace{\frac{f(v)}{v} F_{a,b}(v,q)}_{} \frac{g_{a,b}^2}{q^2 + m_\phi^2} . \tag{2}$$

Probing the different part of the DM velocity distribution!

Decompose the nuclear form factor in powers of v, i.e. $F_{a,b}(v,q) = \sum_{n=0}^{\infty} v^{2n} f_{a,b}^{(n)}(q)$.

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} \propto \sum_{\text{spins}} \sum_{a,b} \int_{v_{\min}} \mathrm{d}^3 v\, f(v) \left(v^{-1} f_{a,b}^{(0)}(q) + v f_{a,b}^{(1)}(q) + \cdots \right) \frac{g_{a,b}^2}{q^2 + m_\phi^2} .$$

$$\propto \sum_{\text{spins}} \sum_{a,b} \left(g(v_{\min}) f_{a,b}^{(0)}(q) + h(v_{\min}) f_{a,b}^{(1)}(q) + \cdots \right) \frac{g_{a,b}^2}{q^2 + m_\phi^2} . \tag{3}$$

$g(v_{\min})$: (-1)-moment of $f(v)$

$h(v_{\min})$: 1-moment of $f(v)$

v dependence samples the (partial) moment of $f(v)$.

Factors of momentum transfer $q \longrightarrow$ factors of $v_{\min}$ multiplying the moments!

$$q^2 = 4\mu_T v_{\min} \tag{4}$$

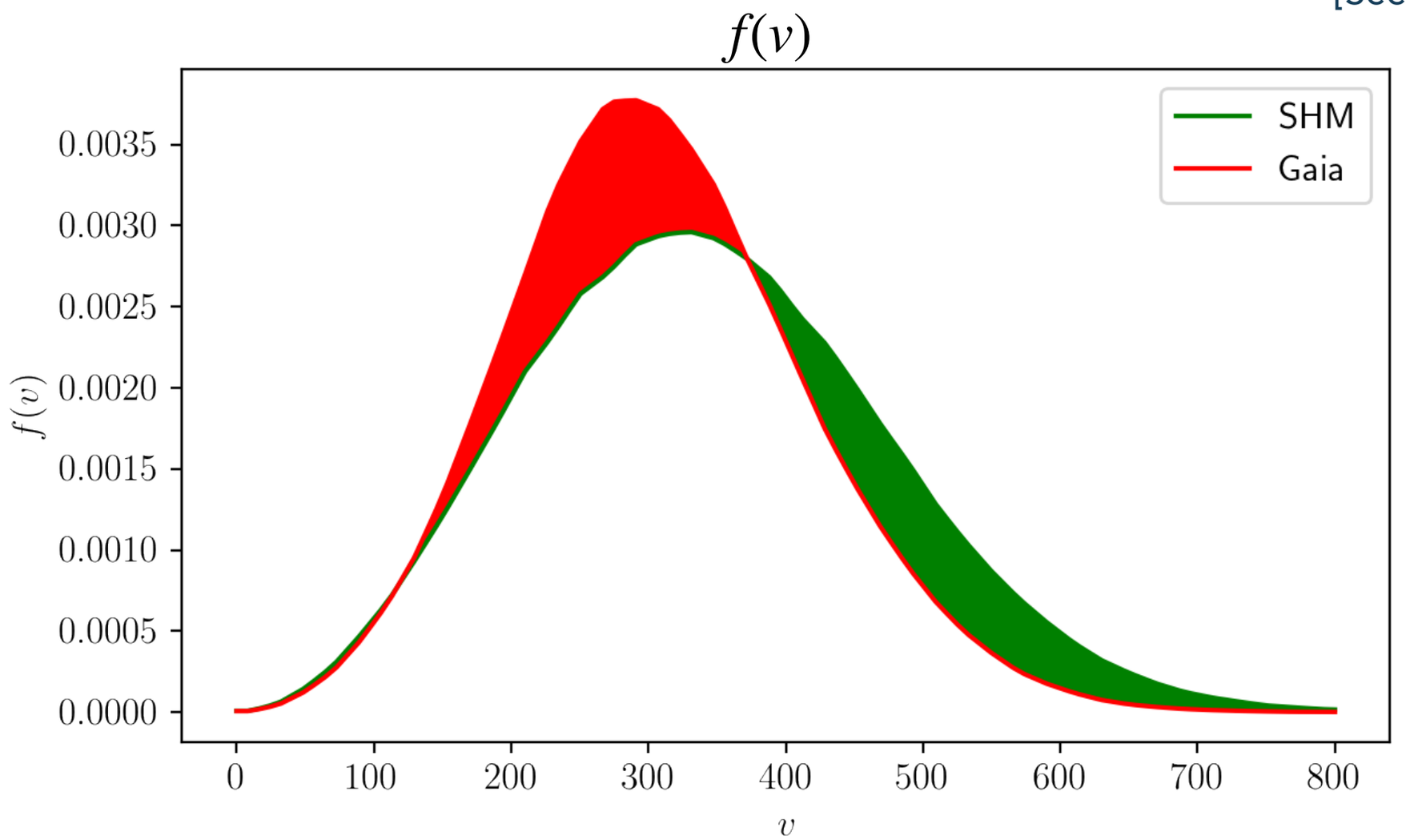
e.g. $f_{a,b}^{(0)} g(v_{\min}) = q^2 g(v_{\min}) \longrightarrow 4\mu_T v_{\min} g(v_{\min})$ (5)

Study of astrophysics effect on direct detection is study of DM velocity moments.

EFT operators in DM velocity distribution

DM velocity (Gaia vs SHM)

[See Jatan Buch's Talk!]

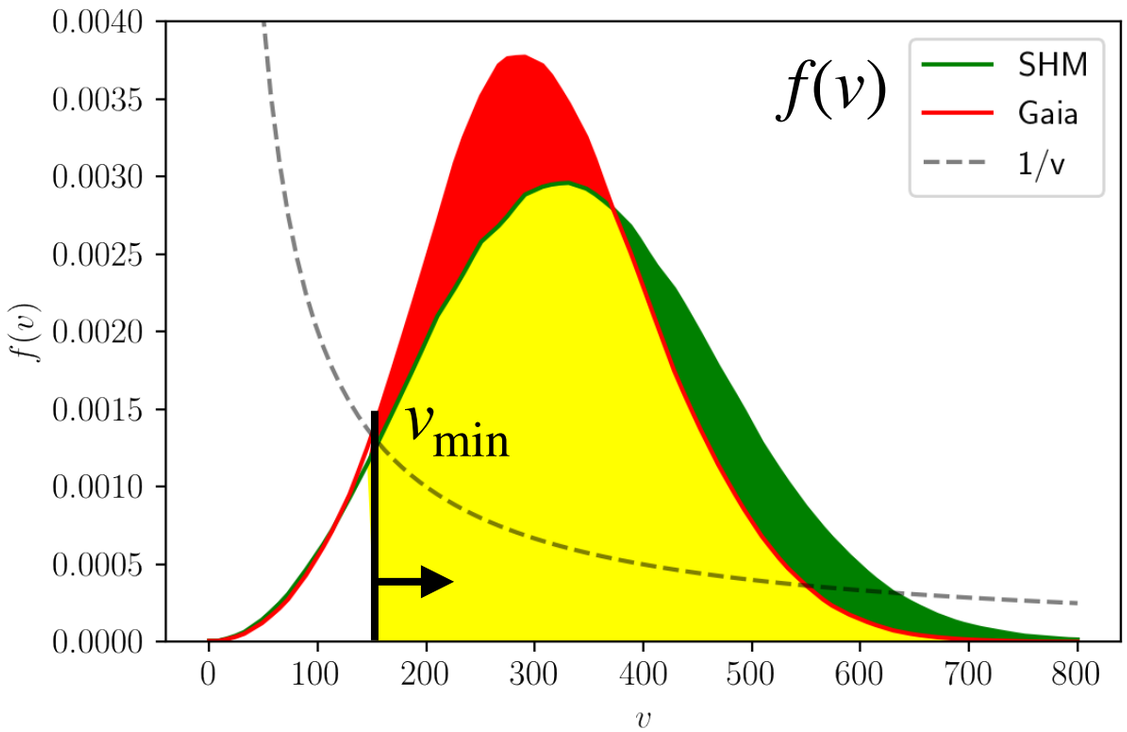


- The velocity distribution of Gaia model is a narrower velocity distribution peaking at a slower speed.

- The low velocity is phase space is more prominent for the Gaia distribution, and the higher velocity is more prominent for SHM.

L. Necib, M. Lisanti and V. Belokurov, APJ 874, 3 (2019). 1807.02519

$g(v_{min})$ dependent recoil

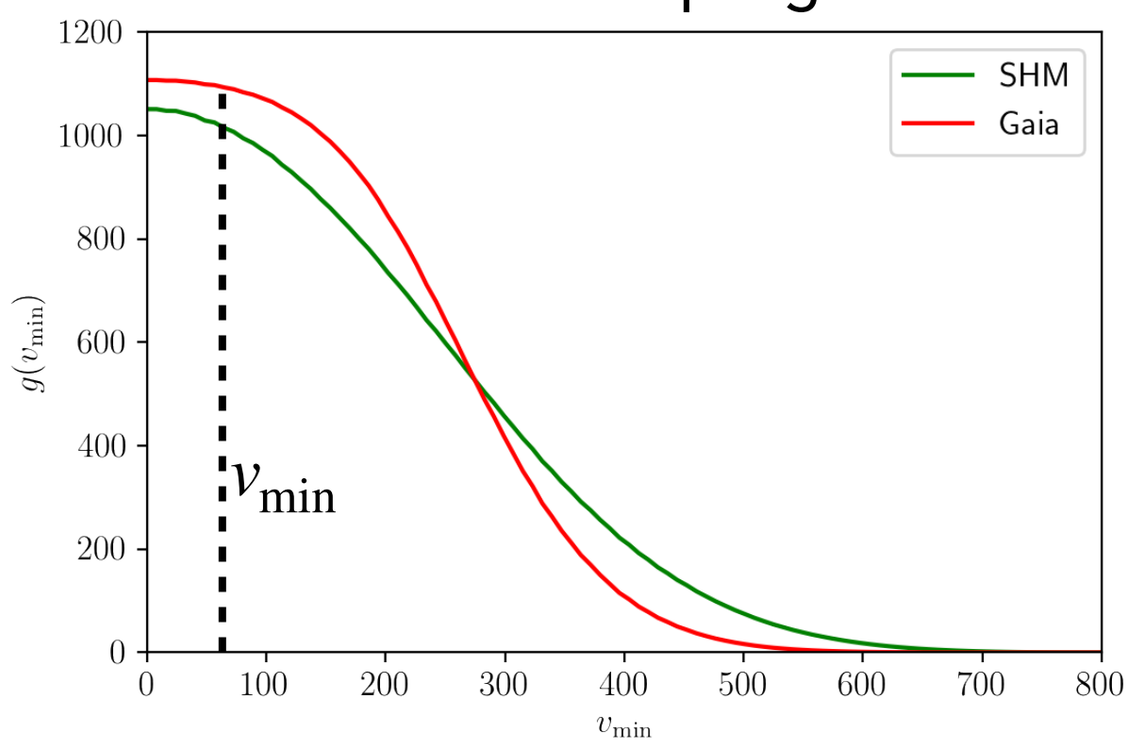


For velocity independent operator:

$$\text{Rate} \propto g(v_{min}) \tag{6}$$

Heavy dark matter - v_{min} covers the full velocity space.

⟶ Gaia more sensitive than SHM given the same coupling



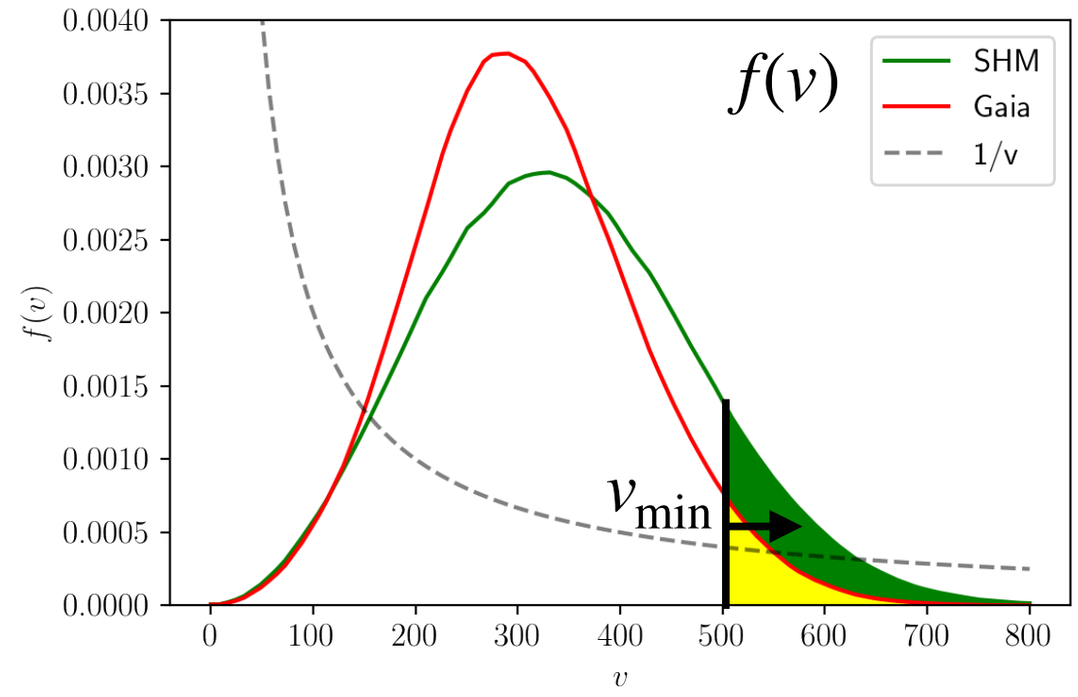
$$g(v_{min}) = \int_{v_{min}}^{\infty} \frac{f(v)}{v} d^3v$$

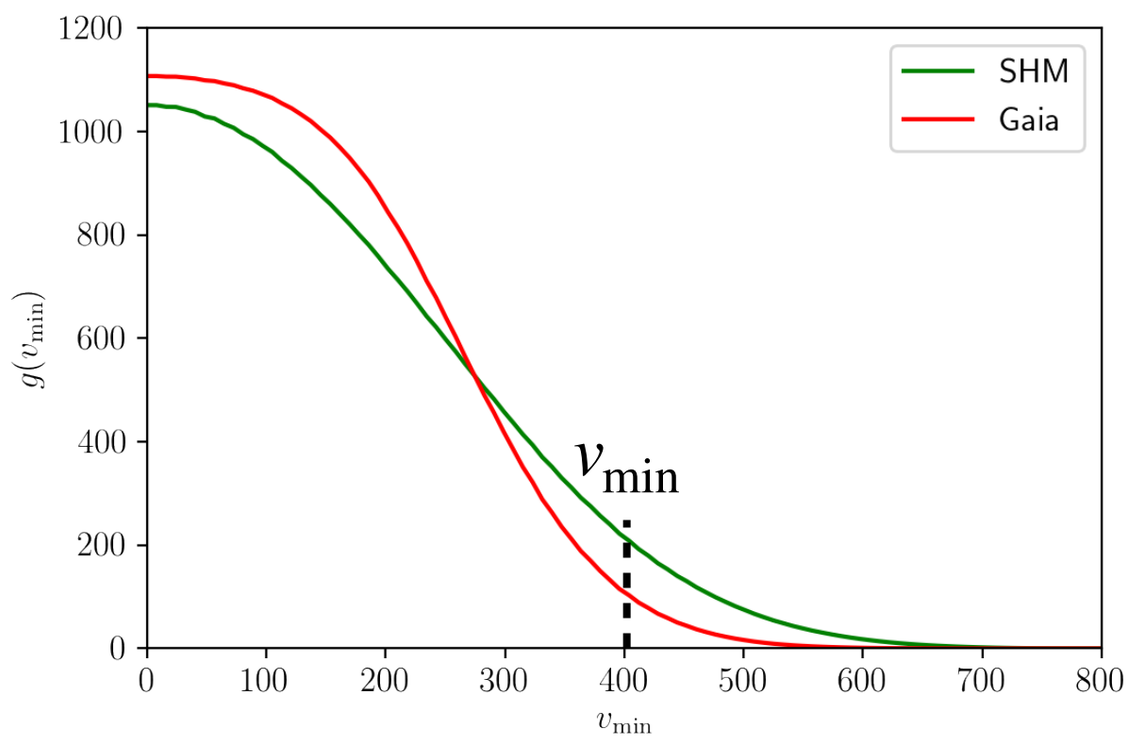
$g(v_{min})$ dependent recoil

Velocity independent operator

Light dark matter - incoming velocity space suppressed to high velocity tail.

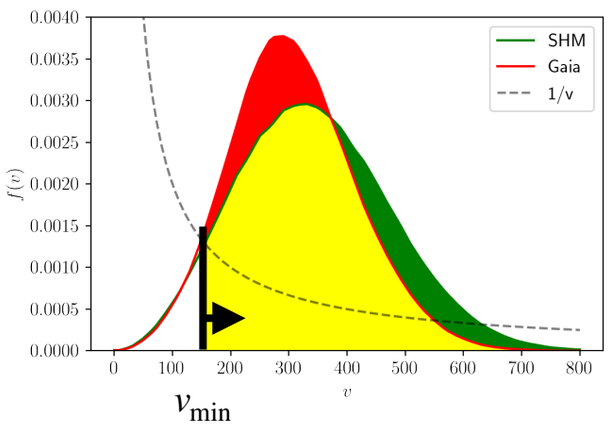
⟶ Gaia loses sensitive a lot faster.





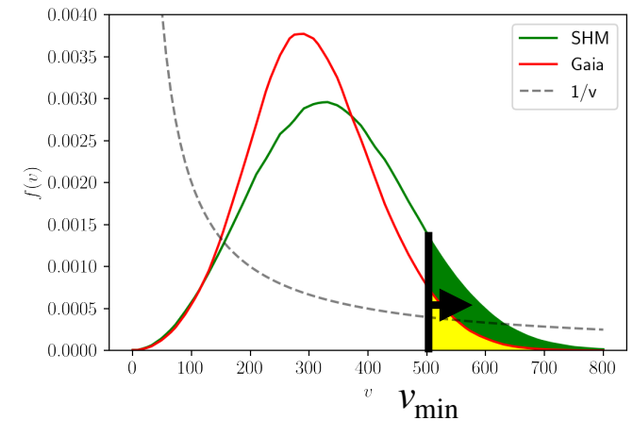
$$g(v_{min}) = \int_{v_{min}}^{\infty} \frac{f(v)}{v} d^3v$$

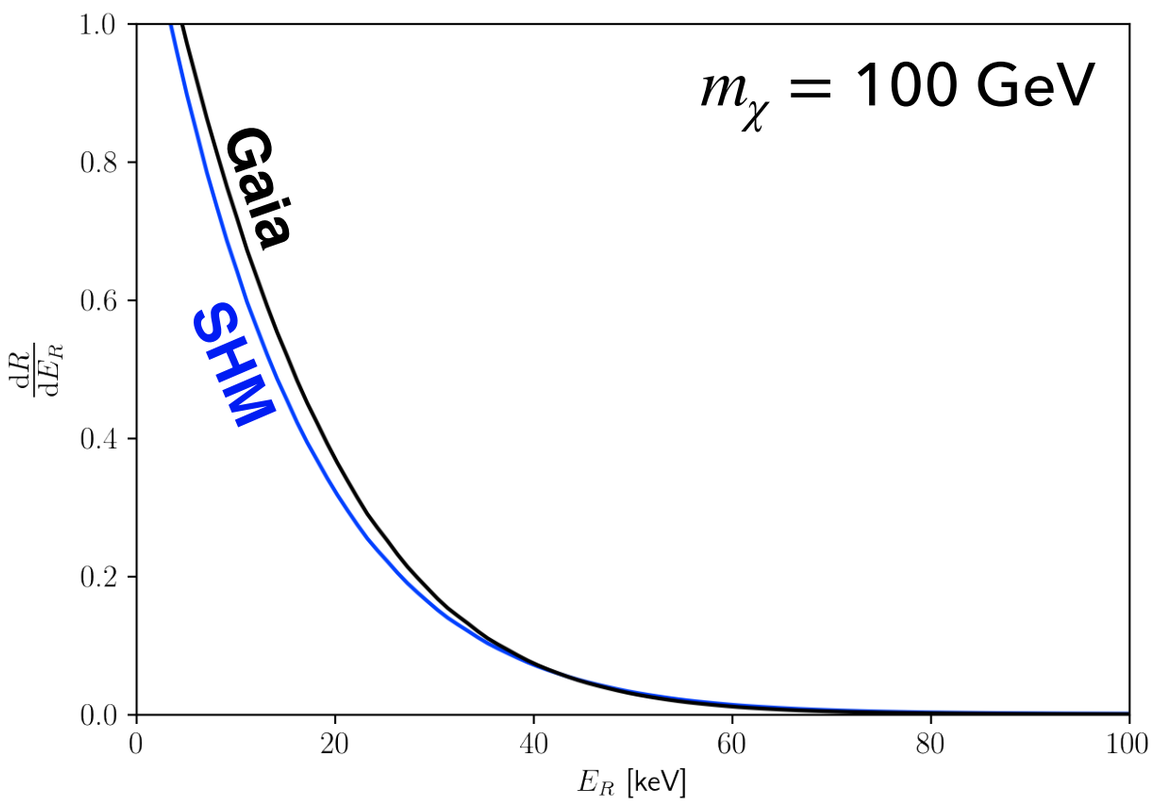
O_1 Recoil spectrum

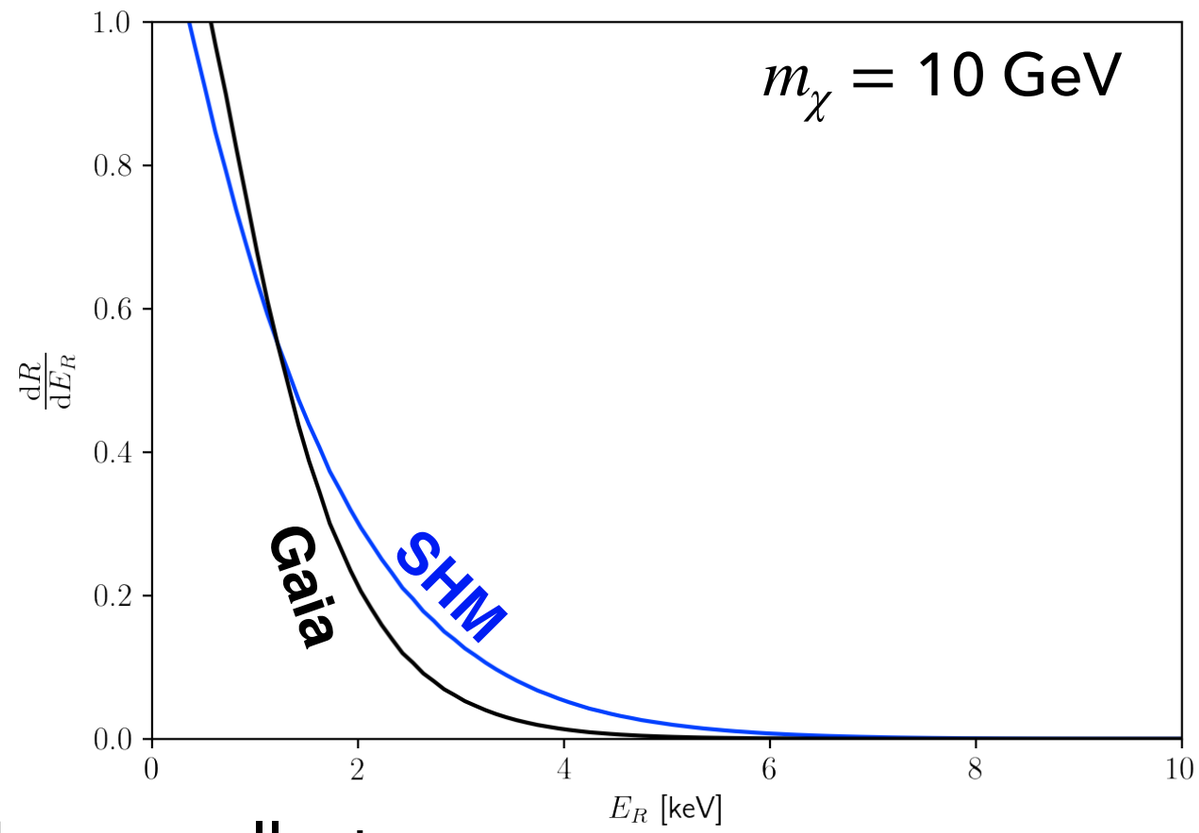


Lets look at the simplest operator…

As we have predicted…







Heavy DM in Gaia astrophysics reports higher overall rate.

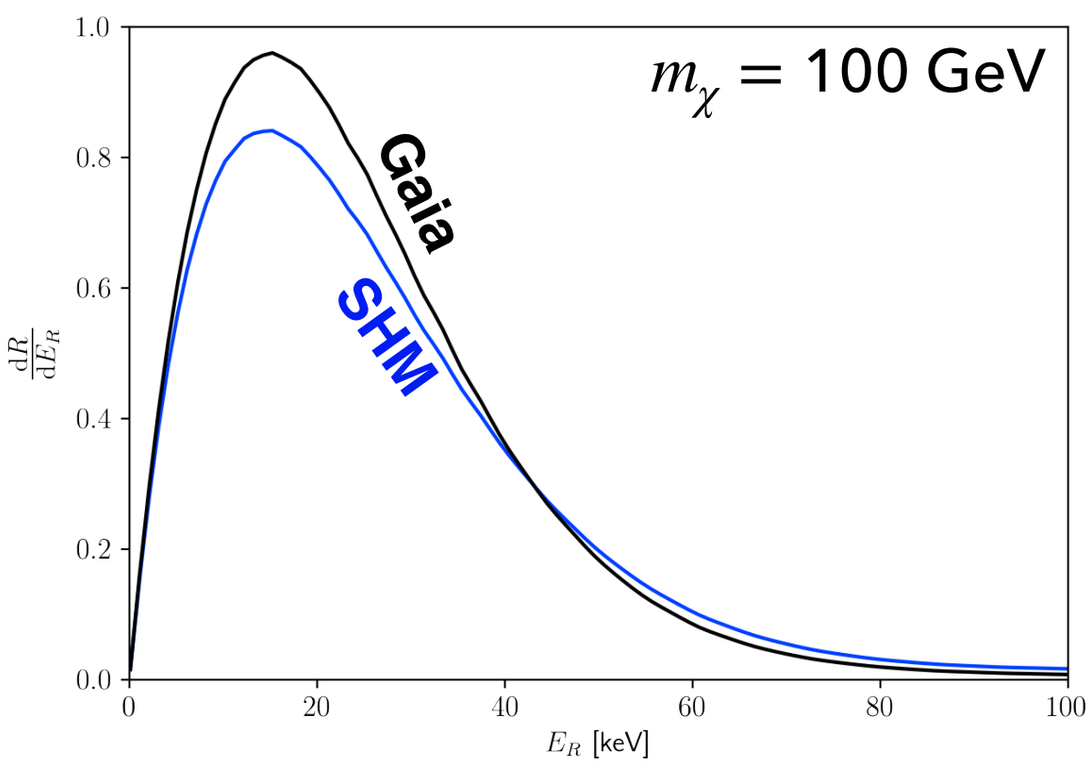
Light DM in Gaia reports a lot smaller rate. (for >1 keV E_R cut-off…)

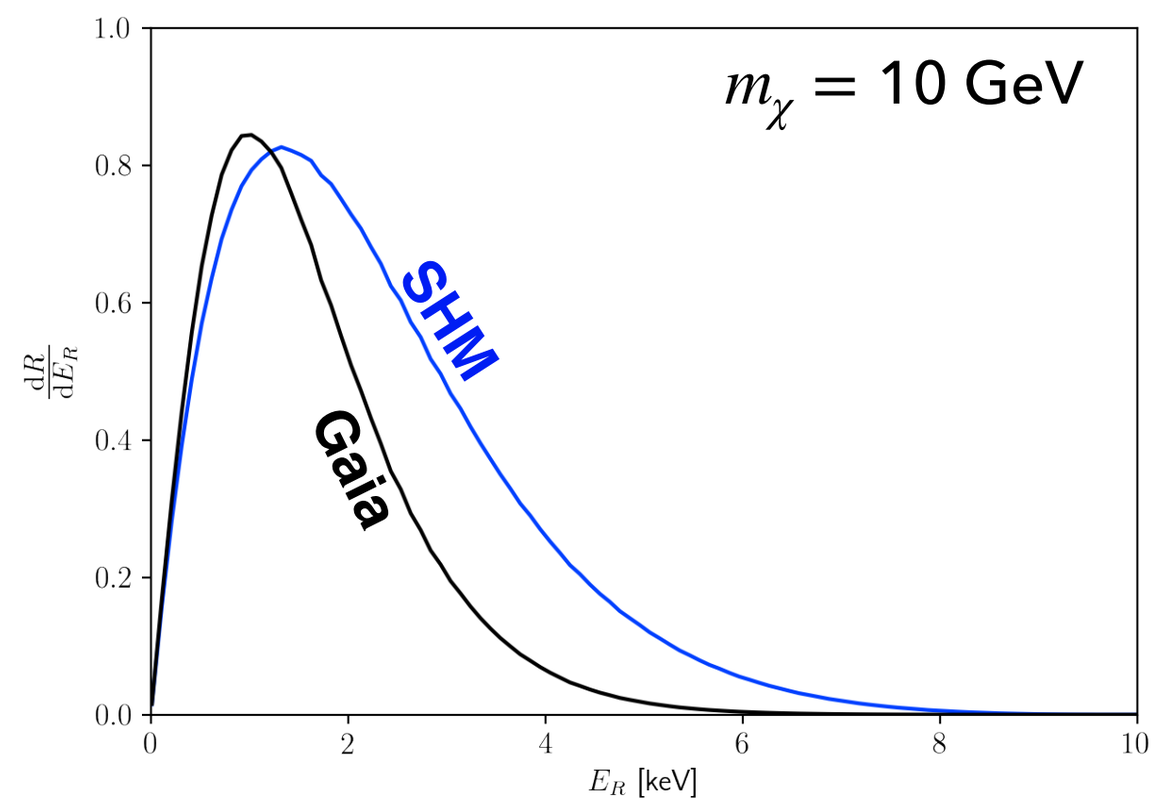
Note the spectra shape differences!

O_{11}

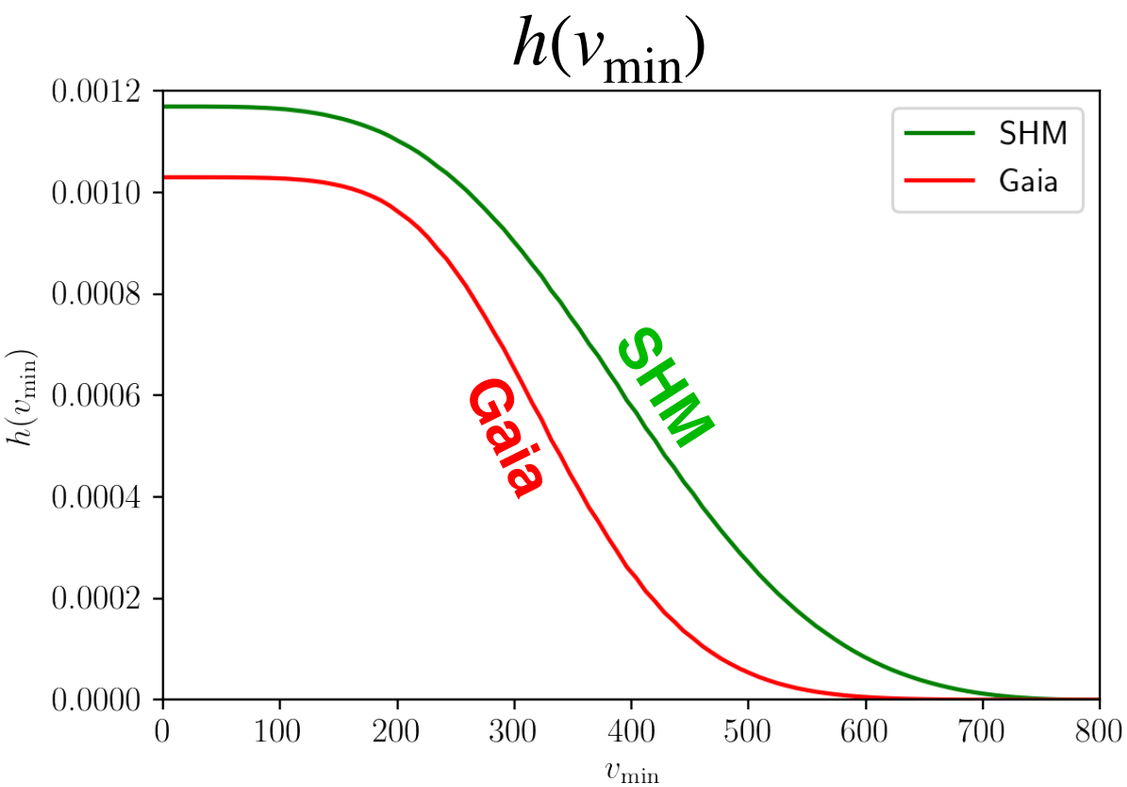
Let's look at another v-independent operator, $O_{11} = (q \cdot S_\chi)$.

- Similar to O_1, Gaia higher overall rate than SHM's for heavy DM. The opposite is true for light DM.
- Factor of q enhances the differences. (Note: $q^2 = 4\mu_T v_{\min}$)
- Spectrum shape difference for light DM…





Higer moment recoil: $h(v_{min})$



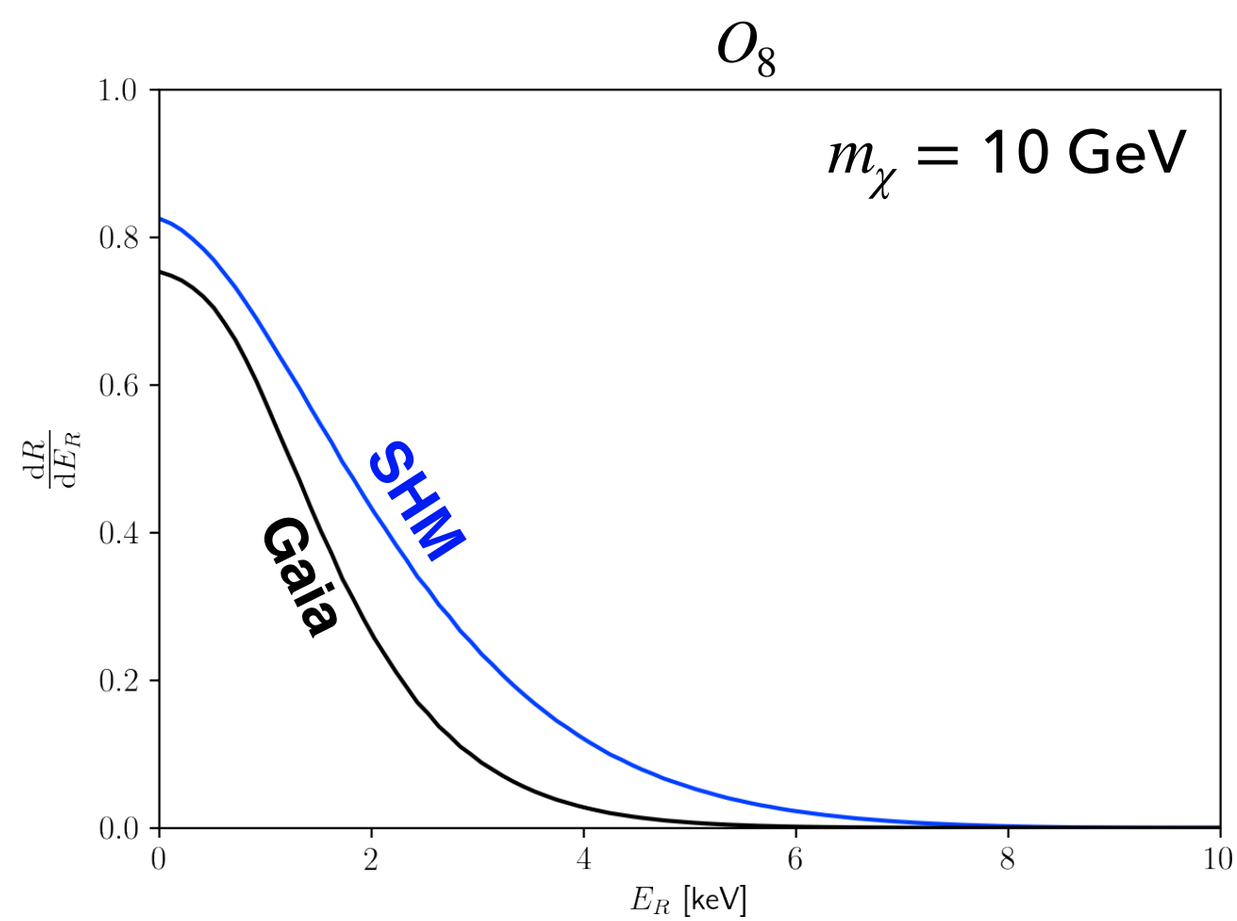
Operators can depend on velocity $v^{\perp}$.

i.e. rate $\propto h(v_{\rm min}) = \int_{v_{\rm min}}^{\infty} v f(v) \mathrm{d}^3 v.$ (7)

- Gaia's $h(v_{\rm min})$ always smaller than SHM!

- $v^{\perp}$ dependent operators always respond weaker under Gaia astrophysics than SHM!

e.g. $O_8 = v^{\perp} \cdot S_{\chi}$



lesson learnt:

Astrophysics affects different NREFT DM-Nucleus operator differently.

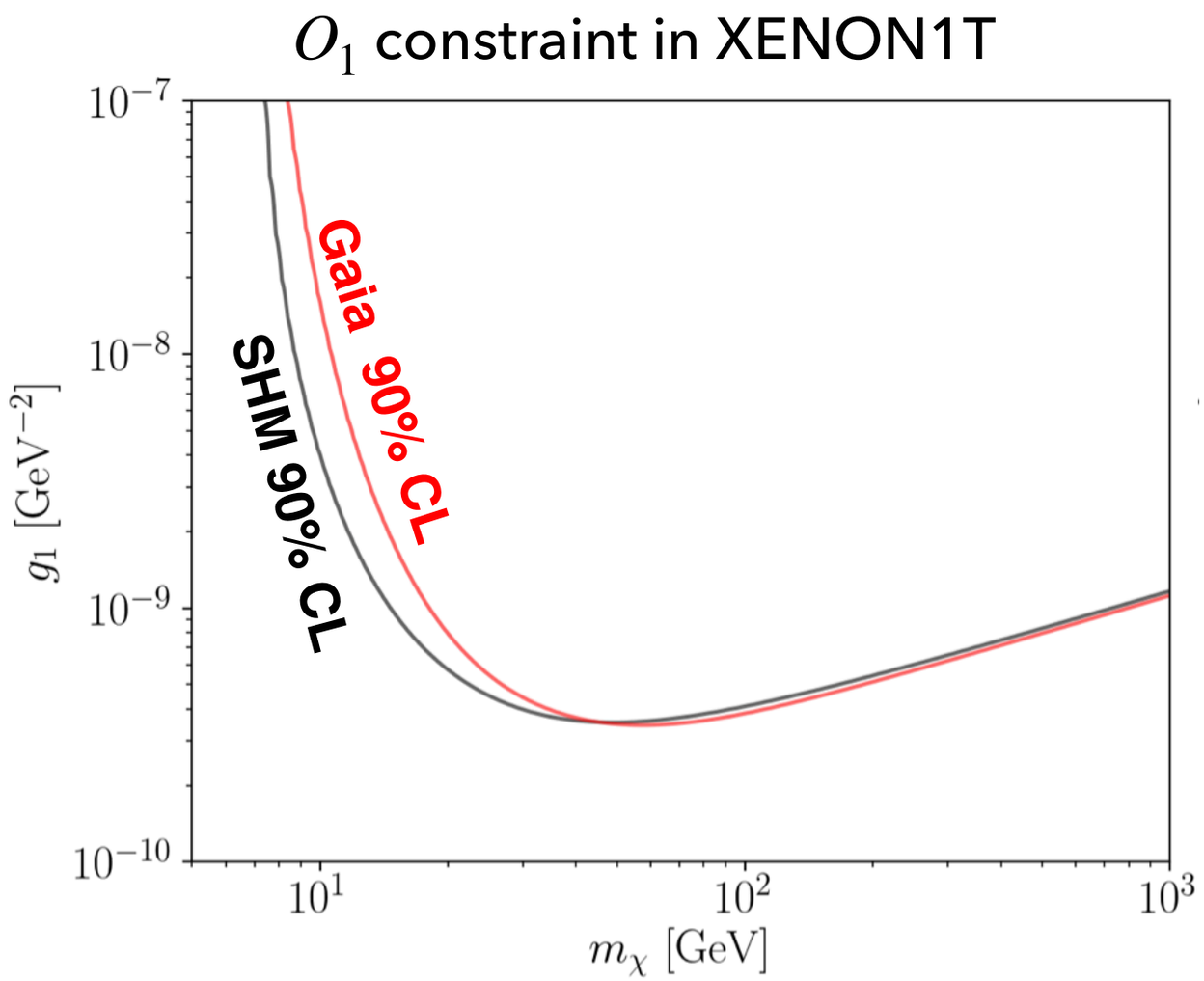
1. ***Look at the overall q and v-dependence of the scattering rate…***

2. ***Observe the correct velocity moments of DM's $f(v)$!***

Operators/Models with powers of q and v are more affected by astrophysics!

Astrophysical uncertainty in DM constraints

O_1 mass-coupling constraint



Inspected from E_R spectra:

- The light DM region: most highly affected region. The constraint with Gaia velocity distribution is significantly weakened!

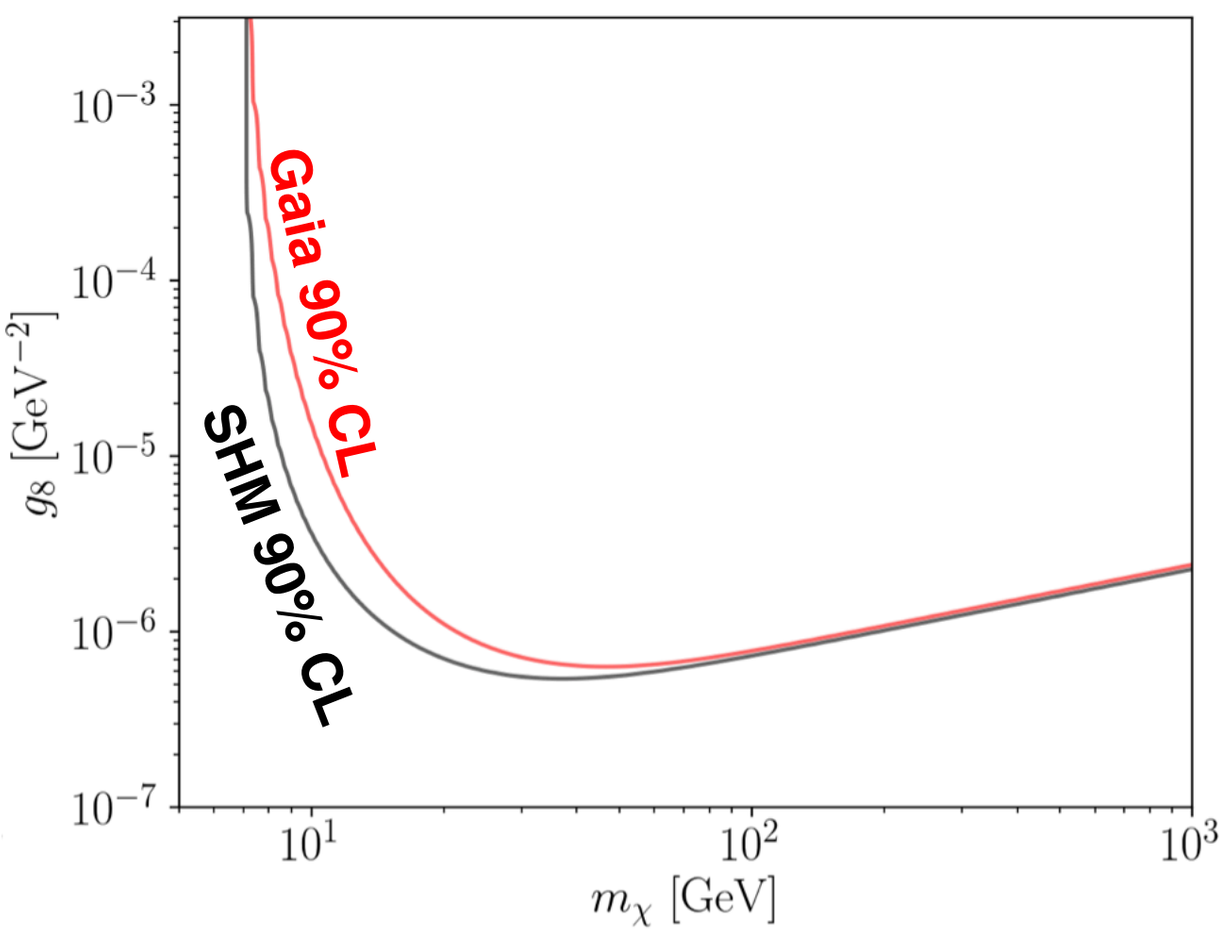
- The high mass region is weakly affected.

v,q- dependent operators

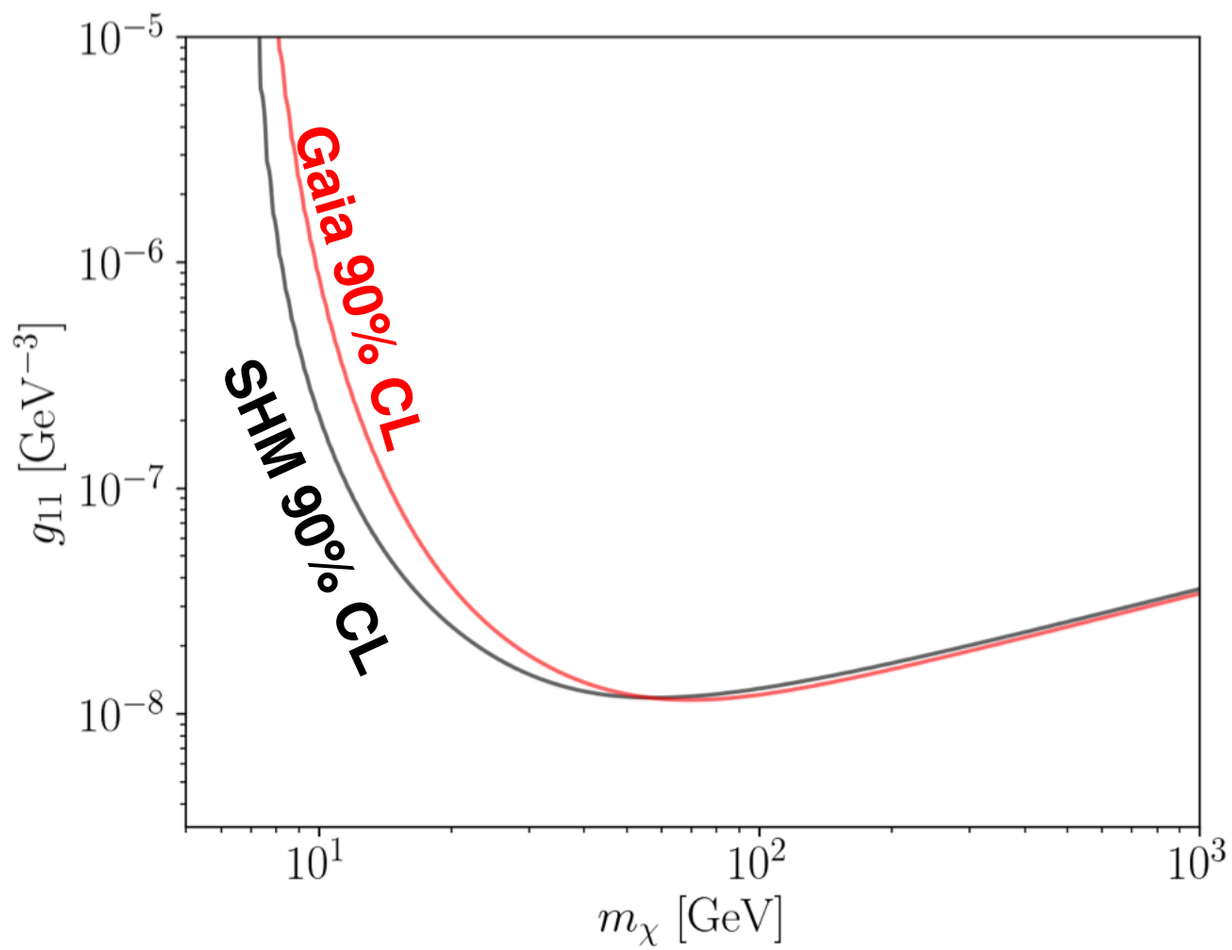
O_8 and O_{11} exclusion contour in Xenon1T roughly the same…

Except at high DM mass O_8, constraint also slightly worsen.

O_8 constraint



O_{11} constraint



Astrophysical uncertainty in *Future* DM Signals

Method: Euclideanized signal

[See Jatan Buch's Talk!]

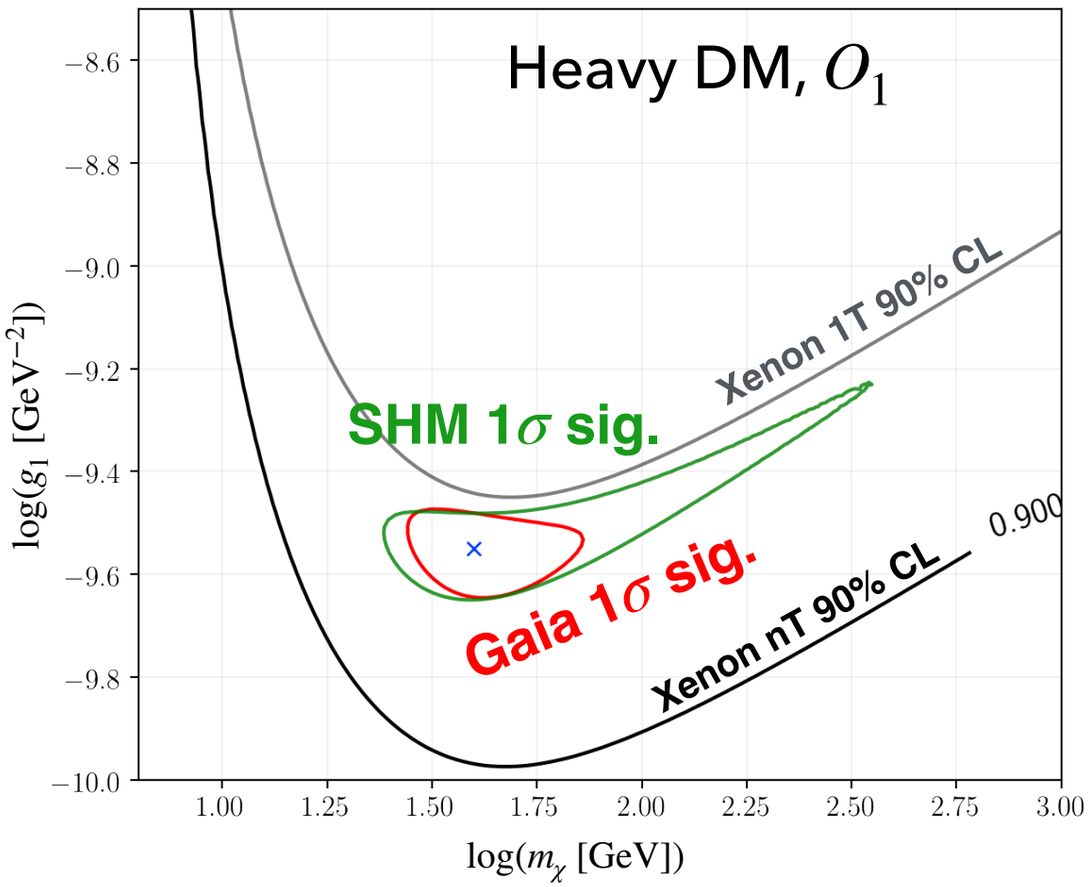
- Future experiment forecasting often requires Monte-Carlo simulations

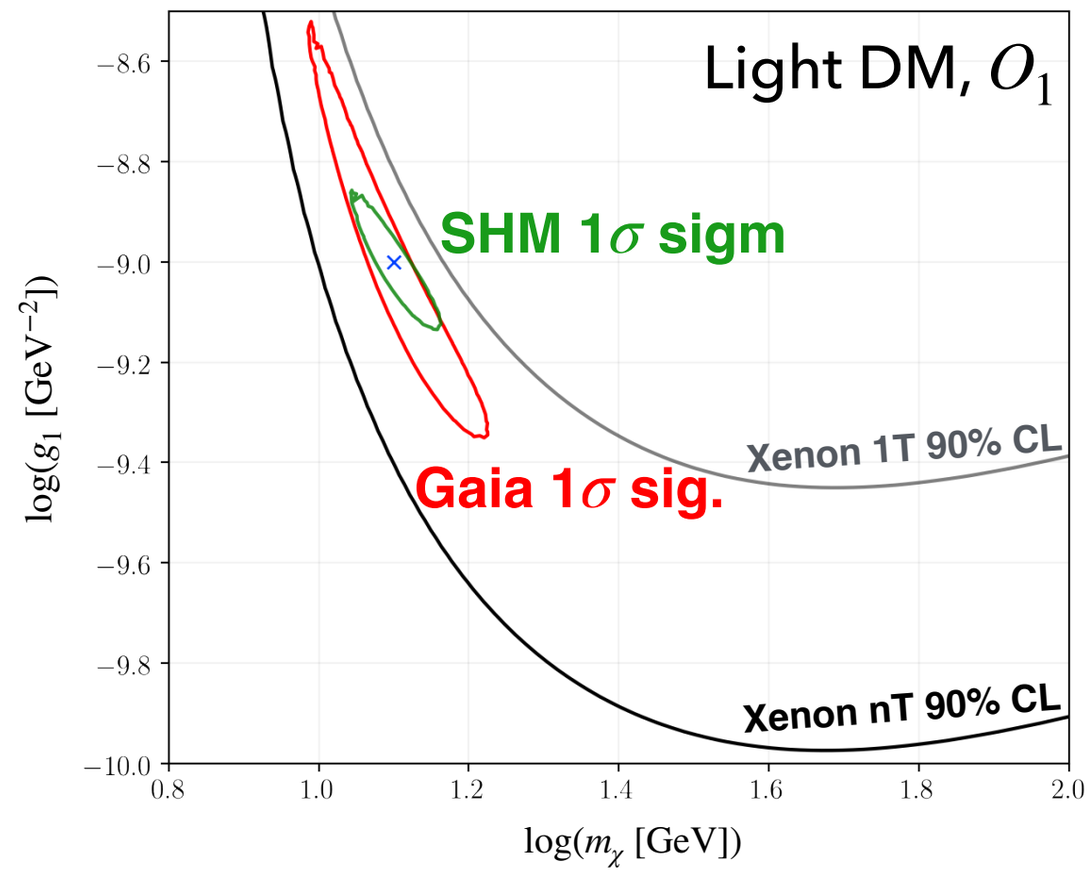
- Computationally expensive for $\underbrace{\text{high dimensional}}$ parameter space! (many data sets…)

Space of m_χ, m_ϕ, astrophysics parameters, couplings g_i for ith DM model

- Edwards and Weniger provides the **Swordfish**, a signal geometry method, an efficient tools for signal forecasting! (1704.05458 and 1712.05401).

O_1 mass-coupling space

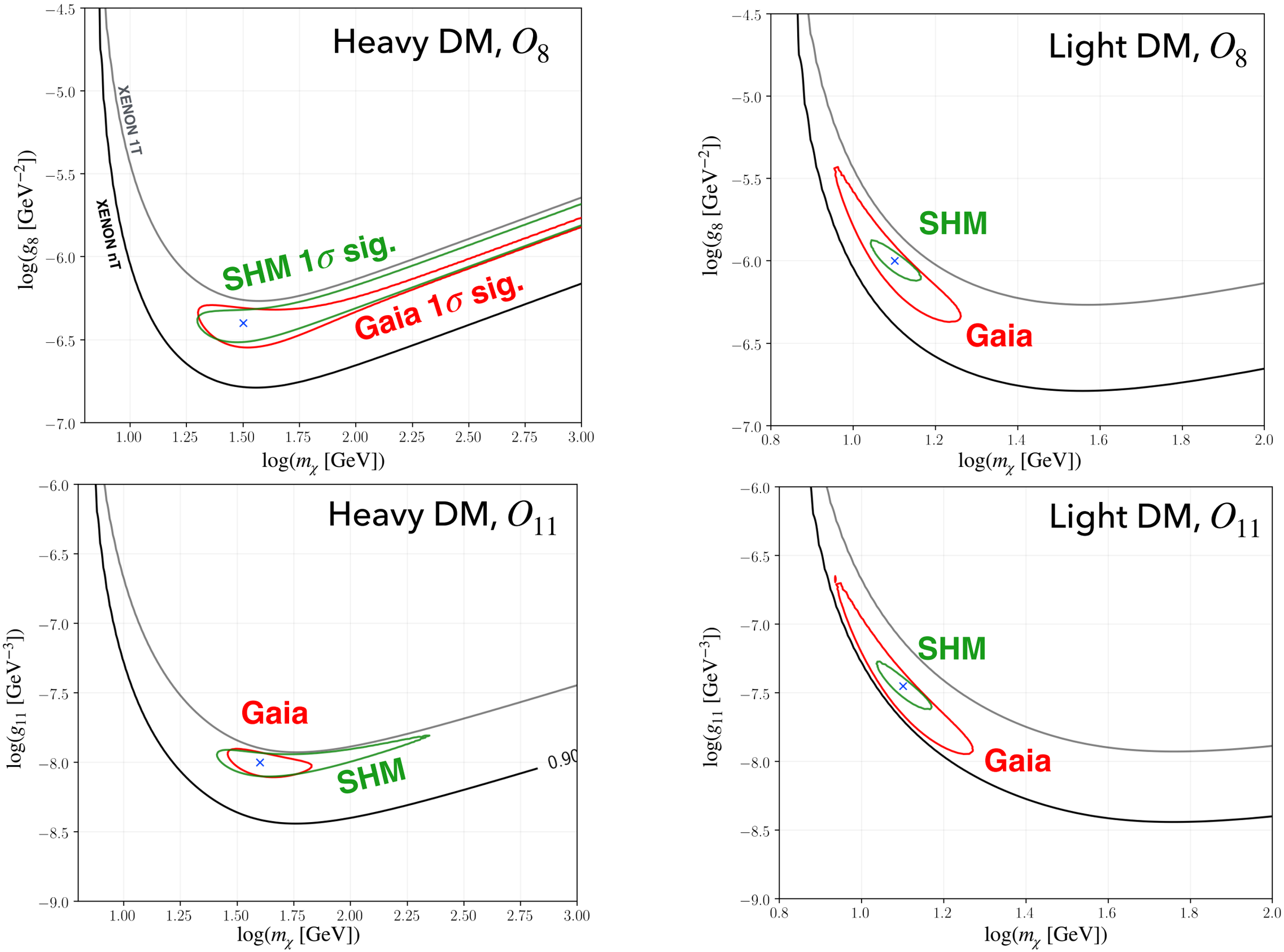




Astrophysical modeling effect goes very different directions…

- Heavy DM signal: Gaia slightly less parameter degeneracy.
- Light DM, signal: Gaia a lot more parameter degeneracy

v,q- dependent operators

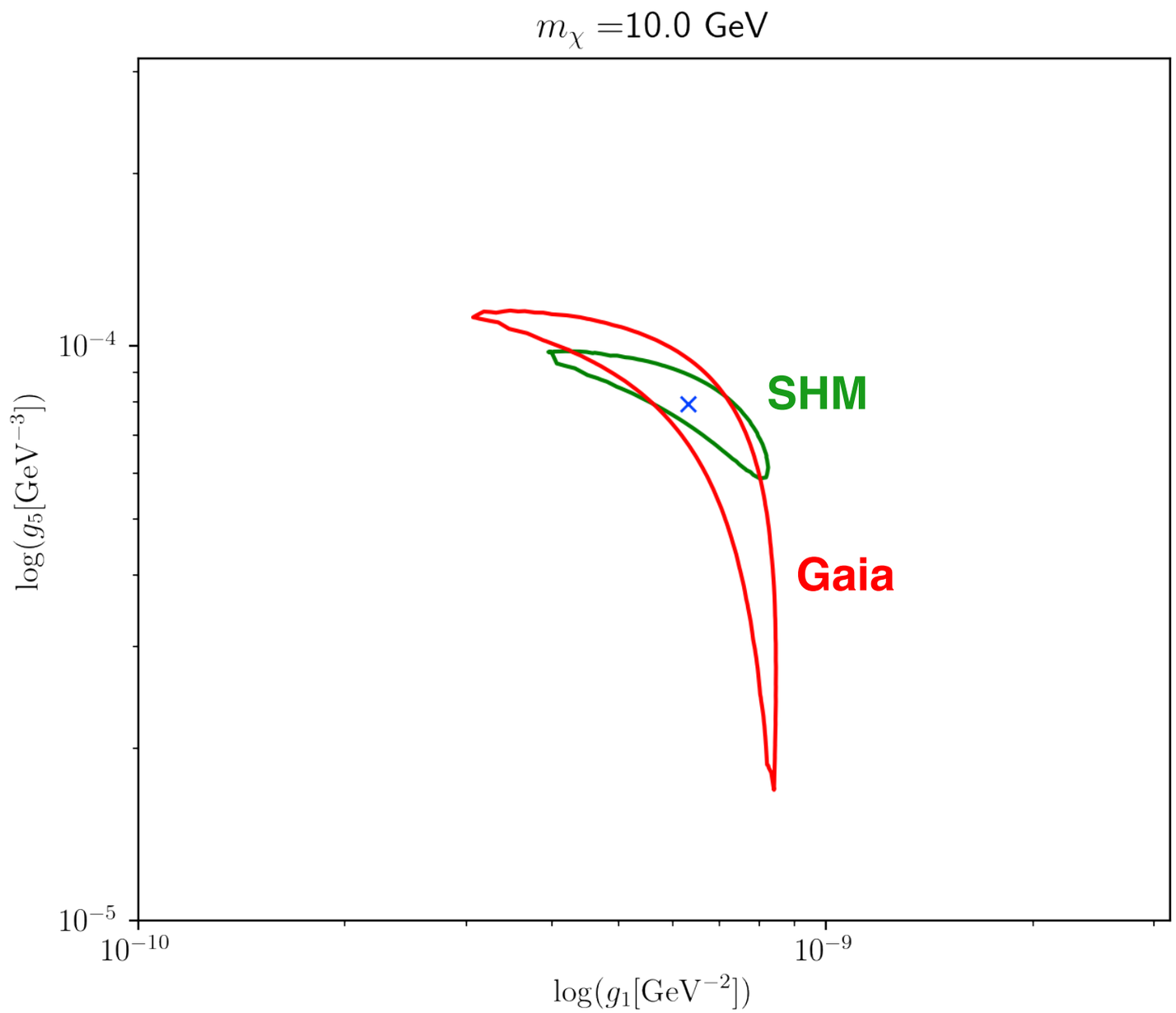


Model constraints

Constraining the possible models given the signal… (coupling-coupling space)

Scalar heavy mediator vs. Vector heavy mediator

Vector-vector:
$(\bar{\chi}\gamma^{\mu}\chi)(\bar{q}\gamma_{\mu}q)$



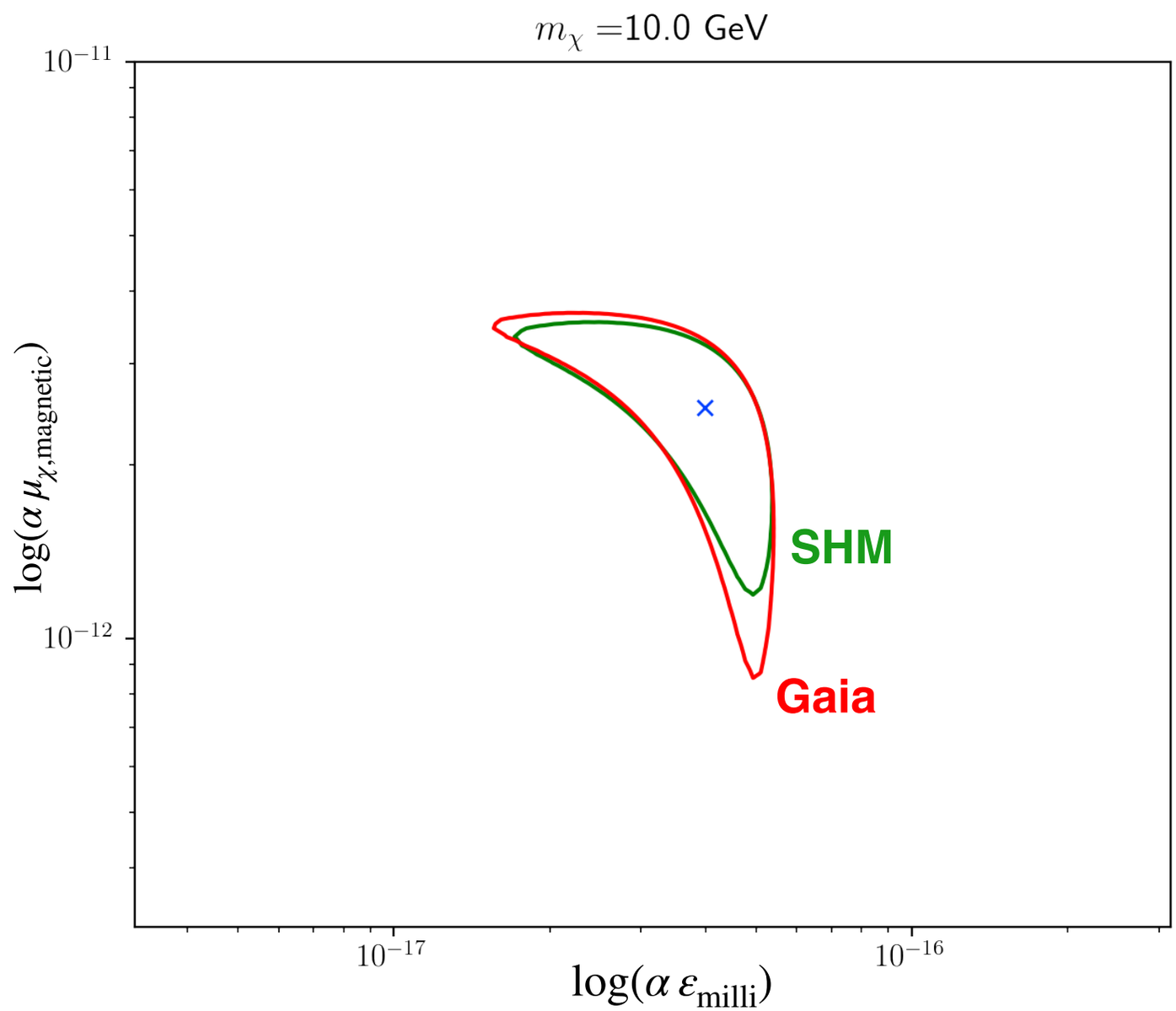
Scalar-scalar: $(\bar{\chi}\chi)(\bar{q}q)$

Model constraints

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} \propto \int_{v_{\min}} \frac{f(v)}{v}\left(\alpha\varepsilon_{\mathrm{milli}}\frac{4m_\chi m_T}{q^2}\right)^2 F_{11} \qquad \text{(millicharged DM } (\bar{\chi}\gamma^\mu\chi)A_\mu \text{)} \tag{8}$$

Light mediator!

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} \propto \int_{v_{\min}} \frac{f(v)}{v}\left(2\alpha\mu_{\chi,\mathrm{magnetic}}\frac{4m_\chi m_T}{q^2}\right)^2 \sum_{a,b=1,5,4,6} c_{a,b}F_{a,b} \qquad \text{(magnetic DM, } (\bar{\chi}\sigma^{\mu\nu}\chi)F_{\mu\nu} \text{)} \tag{9}$$



M. Cirelli, E. Del Nobile and P. Panci, JCAP **1310**, 019 (2013)

Take Away

1. Recent knowledge of stellar stream and debris flow changes our understanding on the dark matter velocity distributions.

2. **Different DM EFT models** are affected by **astrophysics very differently**. NREFT and recoil spectra are the systematic way to understand it.

3. The Swordfish method provides an easy to way for detector forecasting.

4. **Knowledge of (which) DM model comes together with knowledge of local astrophysics*. To interpret correctly direct detection, we must pin down the underlying astrophysical uncertainty.**

5. Information about direct detection recoil spectra helps theorists interpret DM result. (Much more than just the σ_p cross-section)

*Jatan Buch, S.C.L. (John) and Jiji Fan, JCAP **1904**, 026 (2019). 1808.05603