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

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

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Motivation

1. Recent analyses using Gaia's second data release (DR2) and SDSS data provide compelling evidence that the dark matter (DM) in the solar neighborhood is in disequilibrium. Using a novel information geometry technique, we investigate the impact of an empirical DM velocity distribution and its associated uncertainties on reconstructing DM model parameters at future direct detection (DD) experiments.

2. Moreover, the most general description of DM-nuclear recoil includes Galilean invariant effective operators containing various combinations of spin, transverse velocity, and recoil momenta. These can enhance or suppress the effect of DM velocity distribution on the recoil spectra, leading to interesting phenomenology that merits closer attention.

Overview

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

This talk

(or lack thereof!)

- Implications for particle physics
- Results and outlook

John's presentation

Elements of Direct Detection (DD)

[Lewin & Smith, Astropart.Phys. 6 (1996) 87-112]
[KJG review, hep-ph/9506380]

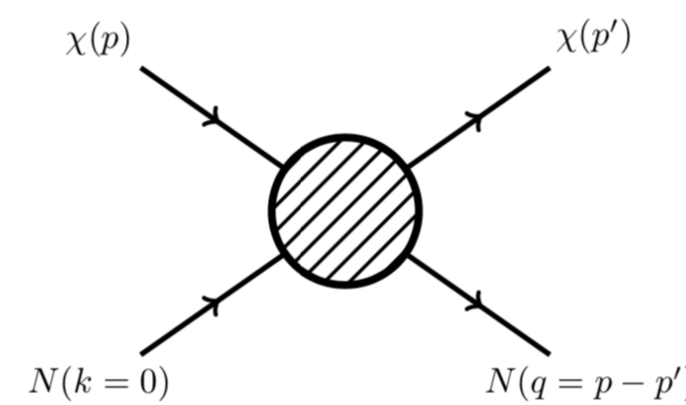
- The recoil energy E_R of a nucleus T moving at a relative velocity $\overrightarrow{v}$ w.r.t. the DM is,

$$2\, m_T E_R = q^2 = 2\, \mu_T^2\, v^2\, (1 - \cos\theta)$$

for typical DM velocities in the solar neighborhood, $v \sim 10^{-3}\, c$,

$$m_\chi \sim [1, 100]\ \mathrm{GeV} \ \Rightarrow\ E_R \sim [1, 50]\ \mathrm{keV}$$

NR kinematics!



[T. Lin, 1904.07915]

- Since the DM scattering rate per unit time is $R \sim < n\sigma v >$, the differential recoil rate can simply be written as,

See 1808.05603 for a recent determination with Gaia data

$$\frac{dR}{dE_R} = \underbrace{\frac{N_T\, m_T}{\mu_T^2}}_{\text{detector}} \times \underbrace{\frac{\rho_\chi}{m_\chi} \int_{v_{\min}}^{v_{\mathrm{esc}}} d^3v\, \frac{f(v)}{v}}_{\text{astrophysics}} \times \boxed{\underbrace{\frac{d\sigma}{d\cos\theta}}_{\text{particle physics}}}$$

Also includes nuclear form factor. More details in next talk!

where,

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{32\pi}\, \frac{1}{2j_\chi + 1}\, \frac{1}{2j_\psi + 1} \sum_{\text{spins}} \frac{|\mathscr{M}|^2}{(m_\chi + m_T)^2}\,, \qquad v_{\min} = \sqrt{\frac{m_T E_R}{2\mu_T^2}}$$

Non-relativistic Effective Field Theory

[J. Fan, M. Reece, L.T. Wang, 1008.1591]
[A.L. Fitzpatrick et al., 1203.3542]

- In the rest of this talk, I will consider two effective spin-independent (SI) interactions:

$$\left.\begin{aligned} \mathcal{O}^N_{s,s} &\sim (\bar{\chi}\chi)(\overline{N}N) \\ \mathcal{O}^N_{v,v} &\sim (\bar{\chi}\gamma^\mu\chi)(\overline{N}\gamma_\mu N) \end{aligned}\right\} \quad \mathcal{O}_{1,h} \sim \mathbf{1} \qquad ; \qquad \mathcal{O}^N_{ps,s} \sim (\bar{\chi}\gamma_5\chi)(\overline{N}N) \;\rightarrow\; \mathcal{O}_{11,h} \sim \vec{s}_\chi \cdot \vec{q}$$

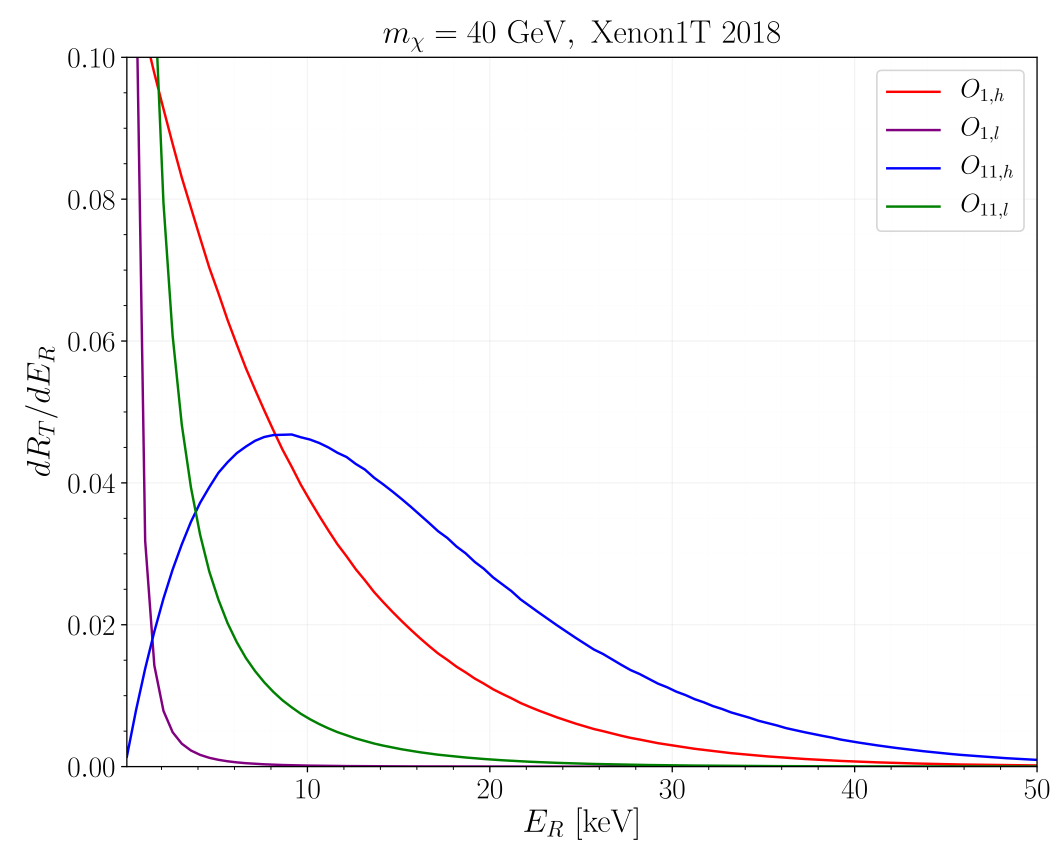
where h implies a heavy, $(m_\phi \gg q)$, mediator. In case of light mediators where we can no longer use our EFT framework, we approximate the interaction as:

$$\mathcal{O}_{i,l} \sim \frac{\mathcal{O}_{i,h}}{(q^2 + m_\phi^2)} \quad , \quad i \in \{1,11\}$$

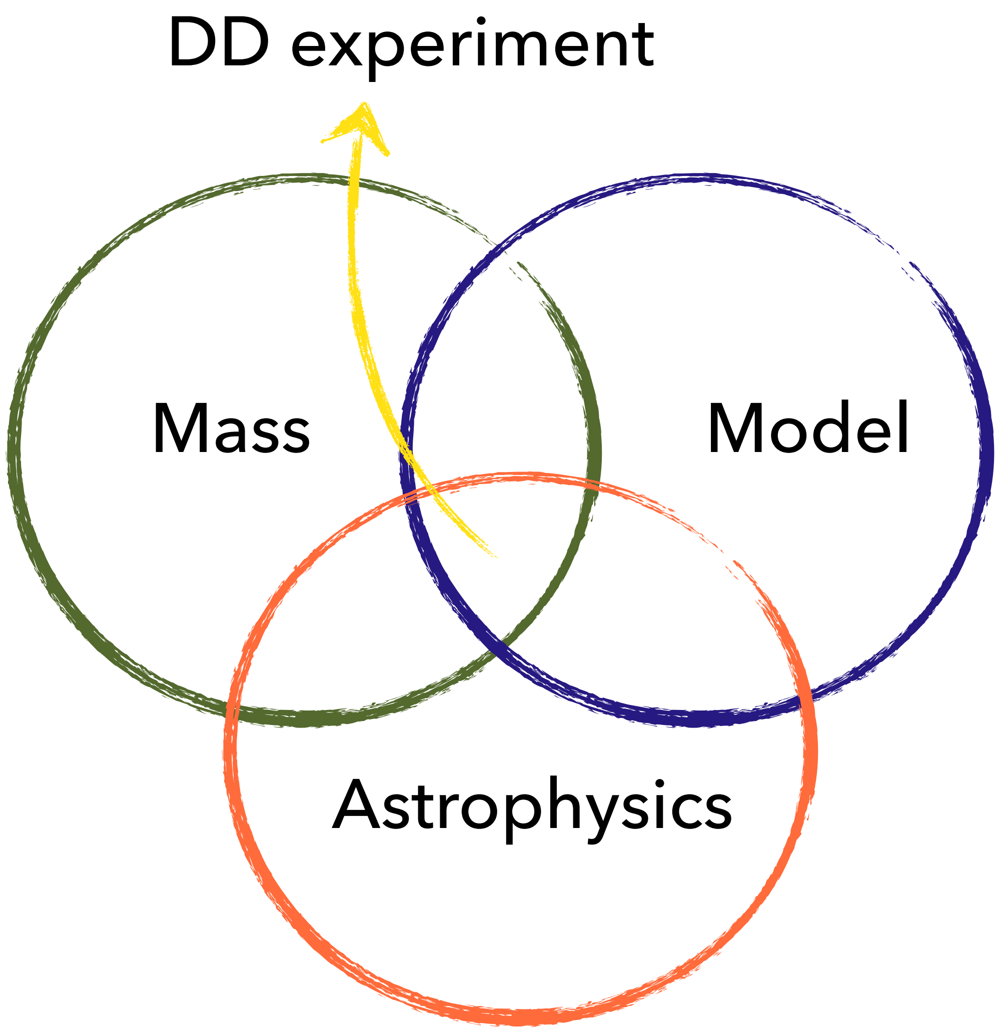
JB, J. Fan, J. Leung, (in prep)

- The resulting q dependence of the differential cross-section for the above operators is:

Operator	Cross-section scaling
$\mathcal{O}_{1,h}$	1
$\mathcal{O}_{11,h}$	E_R
$\mathcal{O}_{1,l}$	E_R^{-2}
$\mathcal{O}_{11,l}$	E_R^{-1}



Elements of Direct Detection (DD)



- The only observables, phenomenologically, in DD experiments are the normalization and shape of the recoil spectra.

- These are, as the table below illustrates, sensitive to different DM and detector parameters simultaneously.

- Broadly, there is a 3-fold degeneracy in inferring DM signal parameters using DD data.

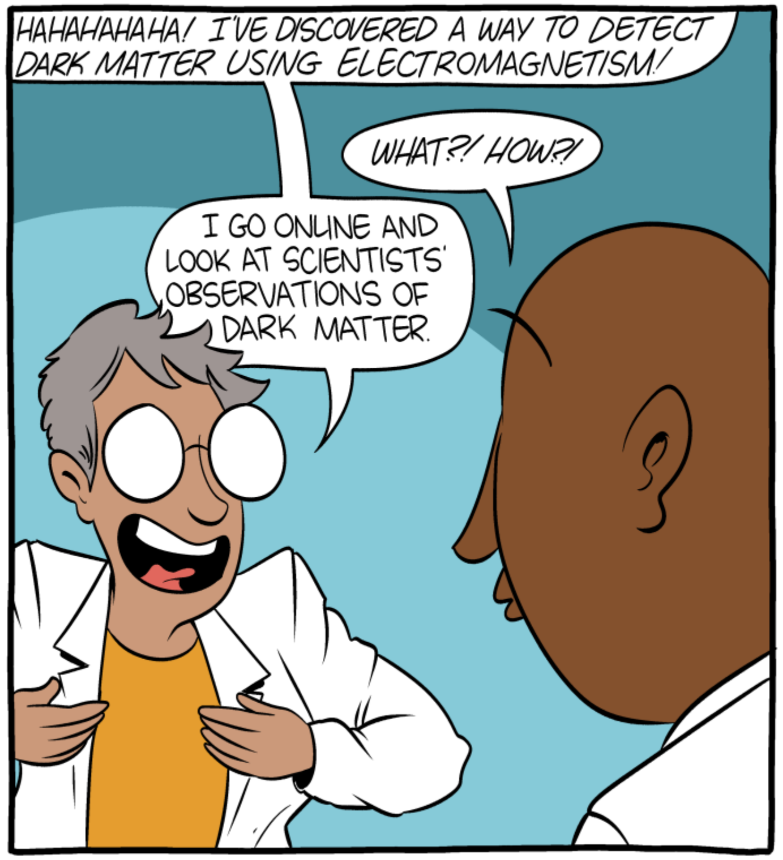
- Uncertainty in the estimation of one class of parameters (astrophysics, in our case) will affect the reconstruction of those in the other two classes (mass and model).

Type	Signal parameters \ Observables		Normalization	Shape
Particle physics	DM mass $[m_\chi]$		✓	✓
	Mediator mass $[m_\phi]$	model	✓	✓*
	Couplings $[c_\chi, c_N]$		✓	✗
Astrophysics	Local DM density $[\rho_\chi]$		✓	✗
	DM velocity distribution $[f(v)]$		✓	✓

* Applicable only for light mediators, *i.e* when $m_\phi/q \lesssim 1$.

Next-generation DD experiments

- Xenon-nT (LXe; 10t x year exposure) [talk by R. Lang]
- LZ (LXe) [talks by M. Szydagis, C. Levy, and G. Rischbieter]
- LBECA (LXe) [talk by M.T. Clark]
- Darkside-20k (Ar) [talk by Y. Wang]
- SuperCDMS (Si/Ge) [talk by J. Orrell]
- DAMIC (Si) [talks by A. Piers, K. Ramanathan]
- HeRALD (He) [talk by H. Pinckney]
- Snowball Chamber [talk by J. Martin]

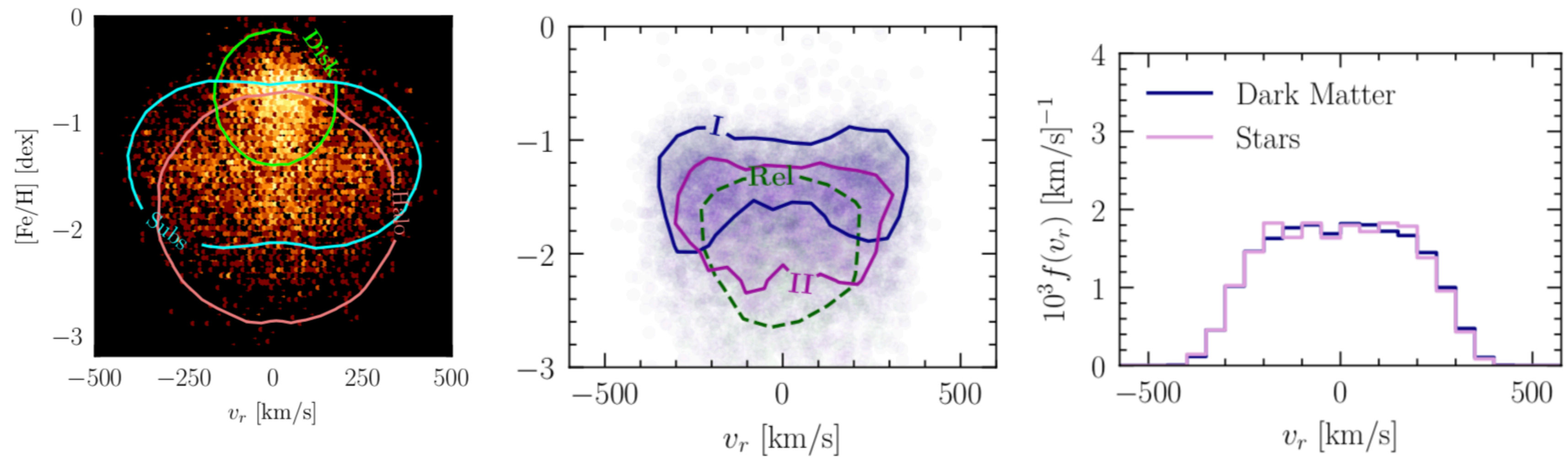


So far, the Nobel Committee has not returned my calls.

DM in disequilibrium

[L. Necib et al., 1807.02519, 1810.12301]
[G.C. Myeong et al., 1904.03185]

- Cross-matching DR2 with a spectroscopic survey such as SDSS gives a 7-D phase space distribution for MW inner halo stars in the solar neighborhood.

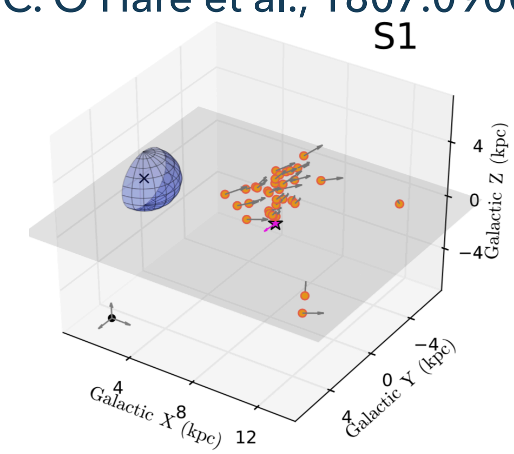


- Mixture model analyses of this data set have identified kinematic substructure with characteristic abundances. These are posited to be debris from recent mergers of dwarf galaxies, namely the Sausage and Sequoia, with the primary MW halo.

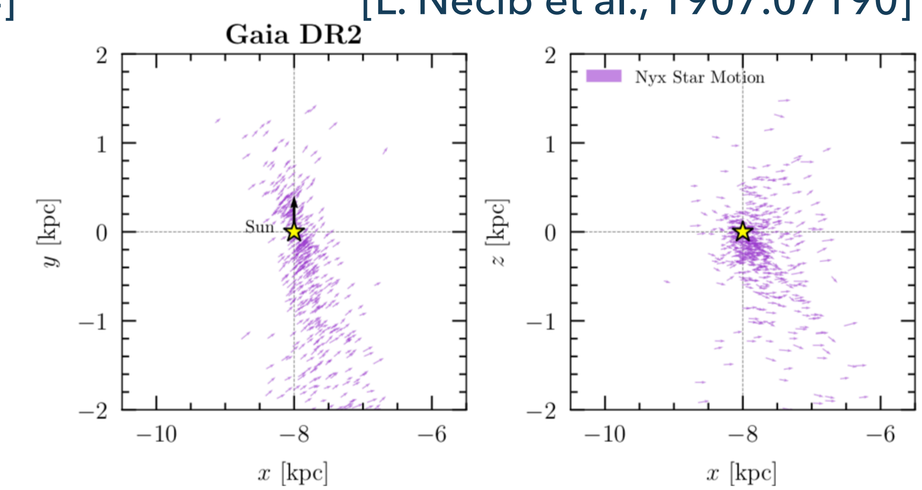
- The mergers also contribute DM to the solar neighborhood, and depending on the redshift of accretion, halo stars can be good tracers of the DM velocity distribution.

- Detailed N-body simulations are required, however, to estimate the accreted DM fraction that constitutes local substructure.

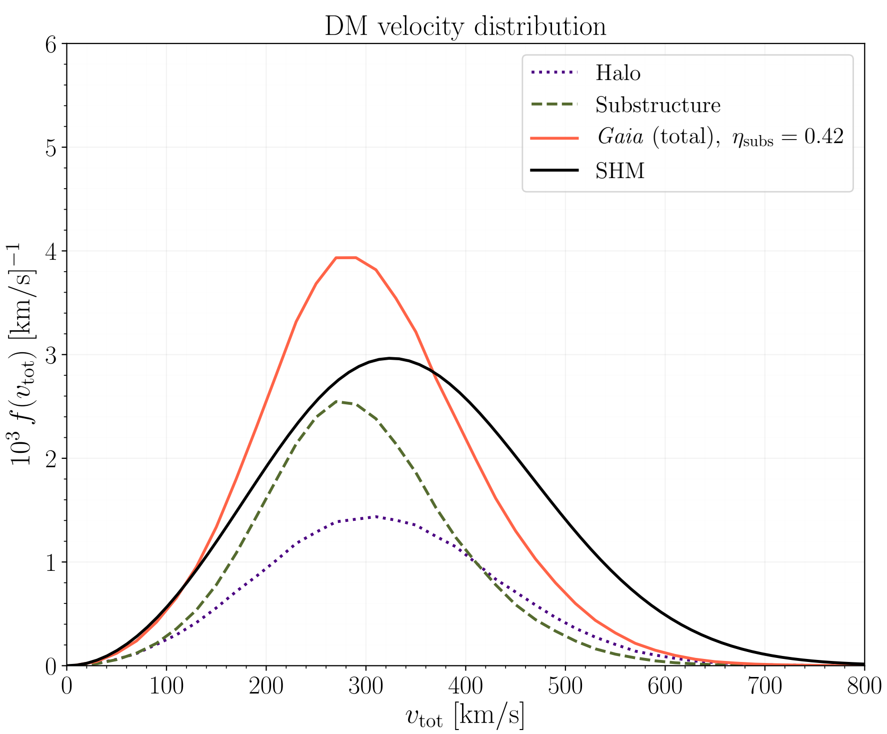
[C. O'Hare et al., 1807.09004]

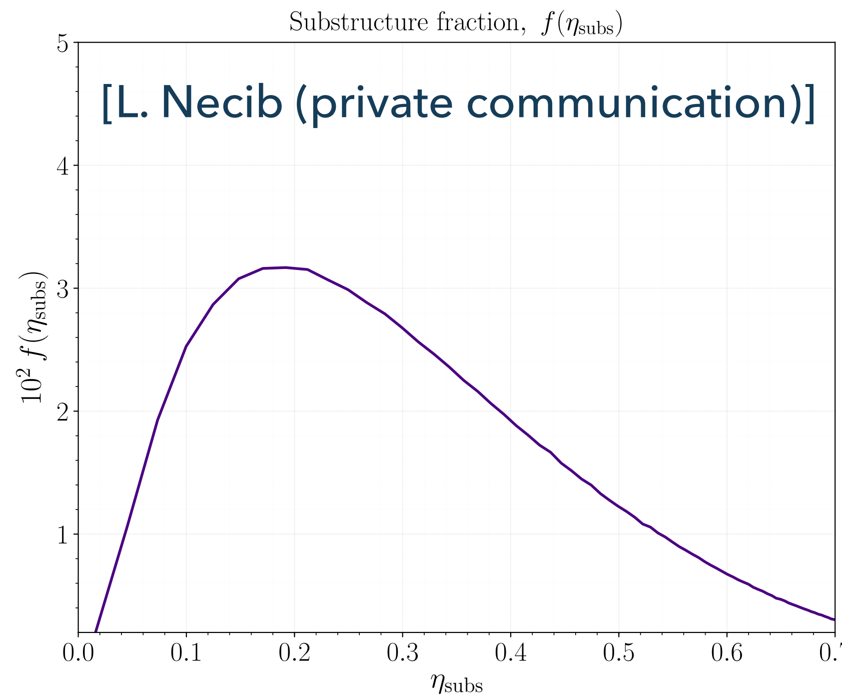


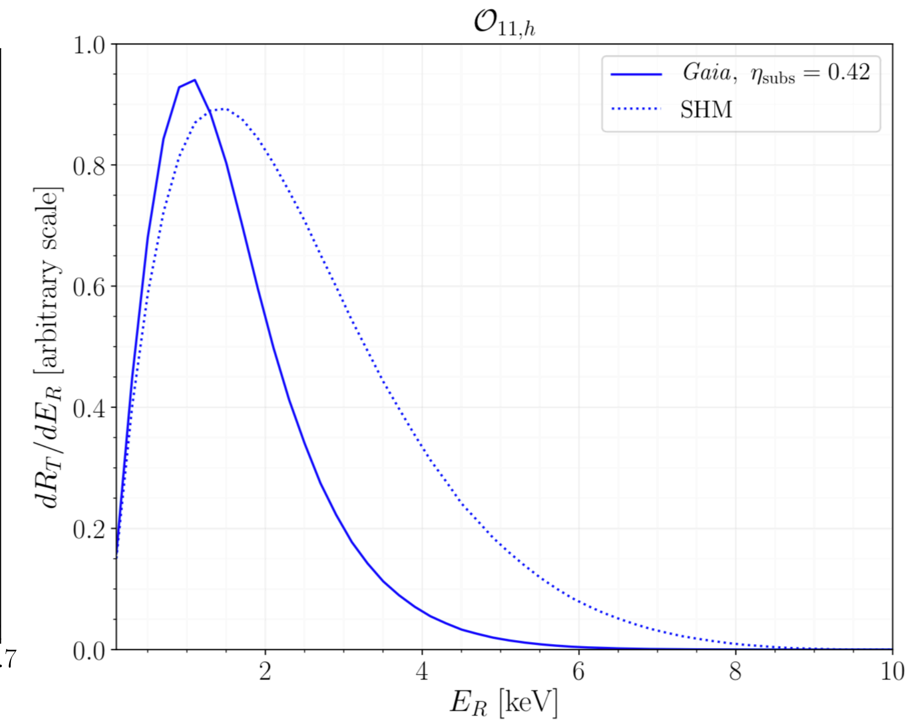
[L. Necib et al., 1907.07190]



DM velocity distribution: SHM and Gaia







- In our analysis, we define the Standard Halo Model (SHM) as the velocity distribution of DM in a virialized, isotropic halo,

$$\tilde{f}(v) \sim \left(\frac{1}{\pi v_0^2}\right)^{3/2} e^{-\mathbf{v}^2/v_0^2}\, \Theta(\mathbf{v} - v_{\rm esc}) \quad ; \quad \{v_0, v_{\rm esc}\} = \{232, 544\}\,\mathrm{km/s}$$

whereas the DM velocity distribution estimated using Gaia-SDSS data is given by,

$$\tilde{f}(\mathbf{v}) = \left(1 - \eta_{\rm subs,1} - \ldots\right) \tilde{f}_{\rm halo}(\mathbf{v}) + \eta_{\rm subs,1}\, \tilde{f}_{\rm subs,1}(\mathbf{v}) + \ldots$$

- We ignore the effect of streams for the moment, but depending on their velocity vector they could have an interesting annual modulation signature. [M. Buckley et al., 1905.05189]

Statistical techniques

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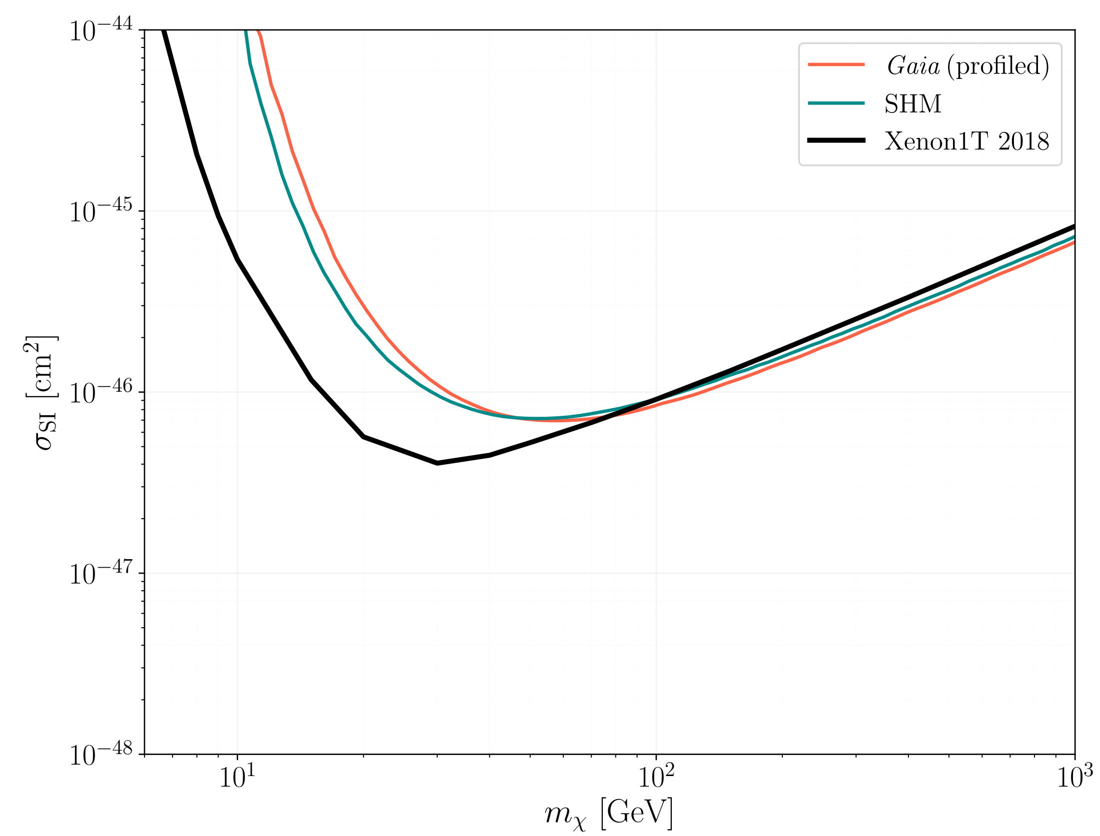


- For theorists, the name of the game while setting upper limits is to use some variant of the cut-'n-count method. These methods, however, only utilize the total number of signal events and don't take into account any spectral information.

- Meanwhile, forecasting sensitivity of future DD experiments typically involves using Monte-Carlo (MC) simulations.

  Unfortunately, these are restricted to benchmark DM models, and a scan of the parameter space can be quite (computationally) expensive.

- Our goal is two-fold: a) to *self-consistently* study the effect of astrophysical uncertainties in DM signal reconstruction, and b) doing so for future experiments using a technique that saturates their *information theoretic* bound.

Euclideanized signal method - I

[T. Edwards, C. Weniger: 1704.05458 and 1712.05401]

- Since DD experiments are essentially counting experiments, we consider the following likelihood function,

$$\ln \mathscr{L}(\mathscr{D}\,|\,\psi) = \sum_{i}^{n_b} \left(d_i \cdot \ln\, \mu_i(\mathbf{S}, \delta\mathbf{B}) - \mu_i(\mathbf{S}, \delta\mathbf{B})\right) - \underbrace{\frac{1}{2}\sum_{i,j}^{n_b} \delta B_i\,(K^{-1})_{ij}\,\delta B_j}_{\text{background systematics}}$$

where the expected number of events in a bin i are given by,

$$\mu_i(\mathbf{S}, \delta\mathbf{B}) = (S_i(\theta, \lambda) + B_i + \delta B_i) \cdot E_i$$

DM signal

Exposure

- Next, we define the Fisher information, which, through the Cramer-Rao bound, quantifies the maximum precision we can achieve while inferring our model parameters,

$$I_{ij}(\psi) = -\int d\mathscr{D}\,\mathscr{L}(\mathscr{D}\,|\,\psi)\,\frac{\partial^2 \ln \mathscr{L}(\mathscr{D}\,|\,\psi)}{\partial\psi_i\,\partial\psi_j} \quad ; \quad I_{\psi\psi} = \begin{pmatrix} I_{\theta\theta} & I_{\theta\delta\mathbf{B}} \\ I_{\delta\mathbf{B}\,\theta} & I_{\delta\mathbf{B}\,\delta\mathbf{B}} \end{pmatrix}$$

- Unlike a traditional analysis, where data (recoil spectrum) from a DD experiment is used for inferring the DM signal parameters, we constrain parameters by counting the number of *distinct signals* using the Fisher information.

Euclideanized signal method - II

[T. Edwards & C. Weniger: 1704.05458, 1712.05401]

- Concretely, we consider a d-dimensional parameter space, $\vec{\theta} \in \Omega_{\mathscr{M}} \in \mathbb{R}^d$, and a likelihood function $\mathscr{L}_X(\mathscr{D}_A | \vec{\theta})$ that represents the Asimov* data for X future experiments. Given two model parameter points $\vec{\theta}_{1,2} \in \Omega_{\mathscr{M}}$, we can construct a likelihood ratio test statistic (TS),

'local' distance metric

$$\mathrm{TS}(\vec{\theta}_1) = -2\ln\frac{\mathscr{L}_X(\mathscr{D}_A(\vec{\theta}_2) | \vec{\theta}_1)}{\mathscr{L}_X(\mathscr{D}_A(\vec{\theta}_2) | \vec{\theta}_2)} \approx (\vec{\theta}_1 - \vec{\theta}_2)^T \tilde{I}(\vec{\theta}_1 - \vec{\theta}_2) \sim \chi^2_d$$

where $\tilde{I}$ is the profiled Fisher information matrix, which for our likelihood function is,

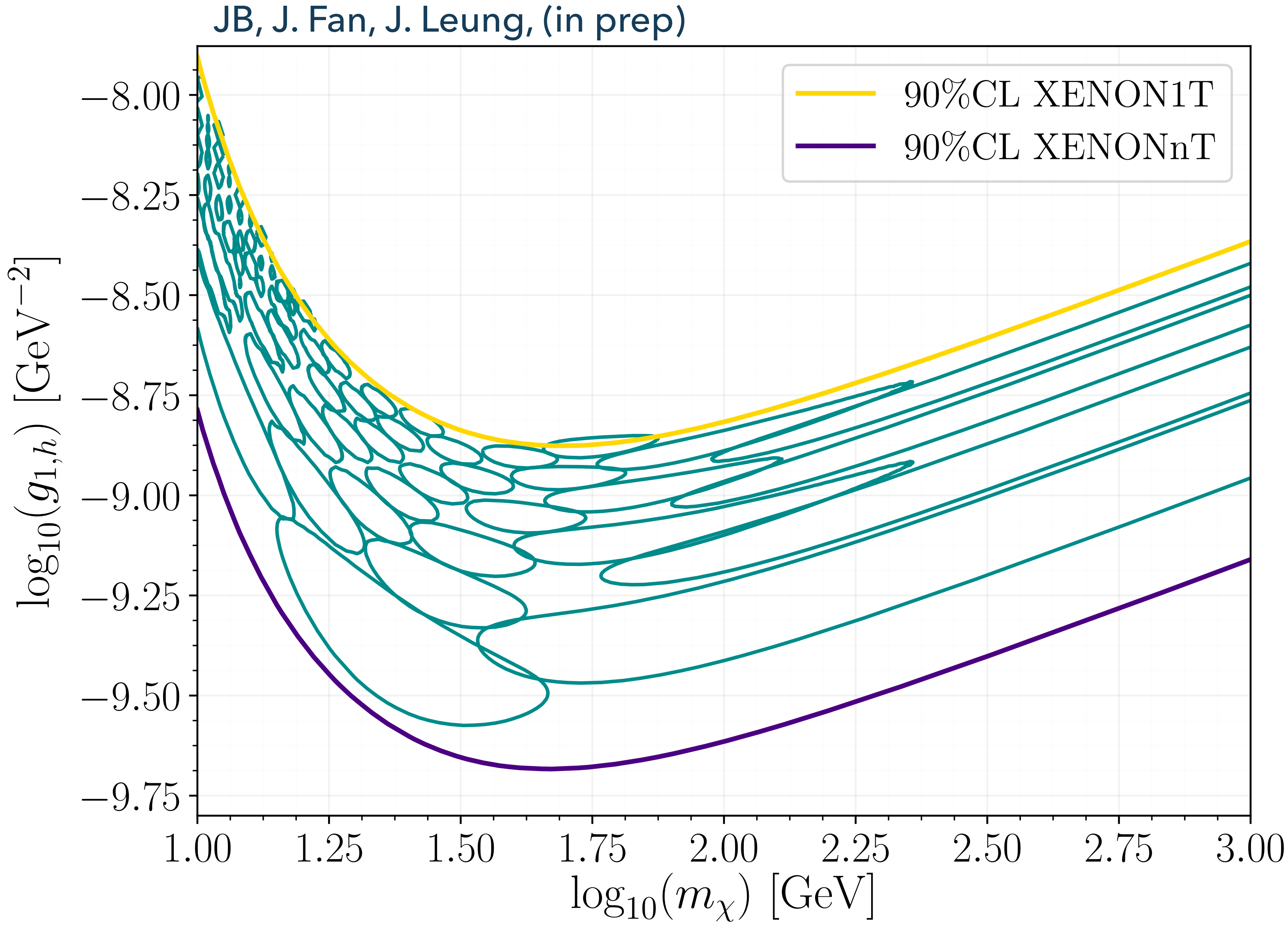
$$\tilde{I}_{ij}(\theta) = \sum_{k,l}^{n_b} \frac{\partial S_k}{\partial \theta_i}(D^{-1})_{kl}\frac{\partial S_k}{\partial \theta_j} \quad ; \quad D_{ij} = K_{ij} + \delta_{ij}\frac{S_i(\theta,\lambda) + B_i}{E_i}$$

- We can simply the calculation of the TS further by introducing a map $\vec{\theta} \mapsto x(\vec{\theta})$ between the parameter space and signal space,

$$x(\vec{\theta}) = \sum_{i,j}\left(D^{-1/2}\right)_{ij} S(\vec{\theta})_j E_j \quad \Rightarrow \quad TS(\vec{\theta}_1) \approx \sum_{i,j}\Delta\vec{\theta}_i D^{-1}_{ij}\Delta\vec{\theta}_j \approx |x(\vec{\theta}_1) - x(\vec{\theta}_2)|^2$$

*[G. Cowan et al., 1007.1727]

Results



- The radius of each of these contours in Euclidean space is given by $r_\alpha(\mathscr{M})^2 \leq F^{-1}_{\chi^2_d}(1-\alpha)$. For $d = 2$ dimensions and $68\,\%$ C.L. (1σ), this translates to $r_{1\sigma} \approx 1.52$.

Results

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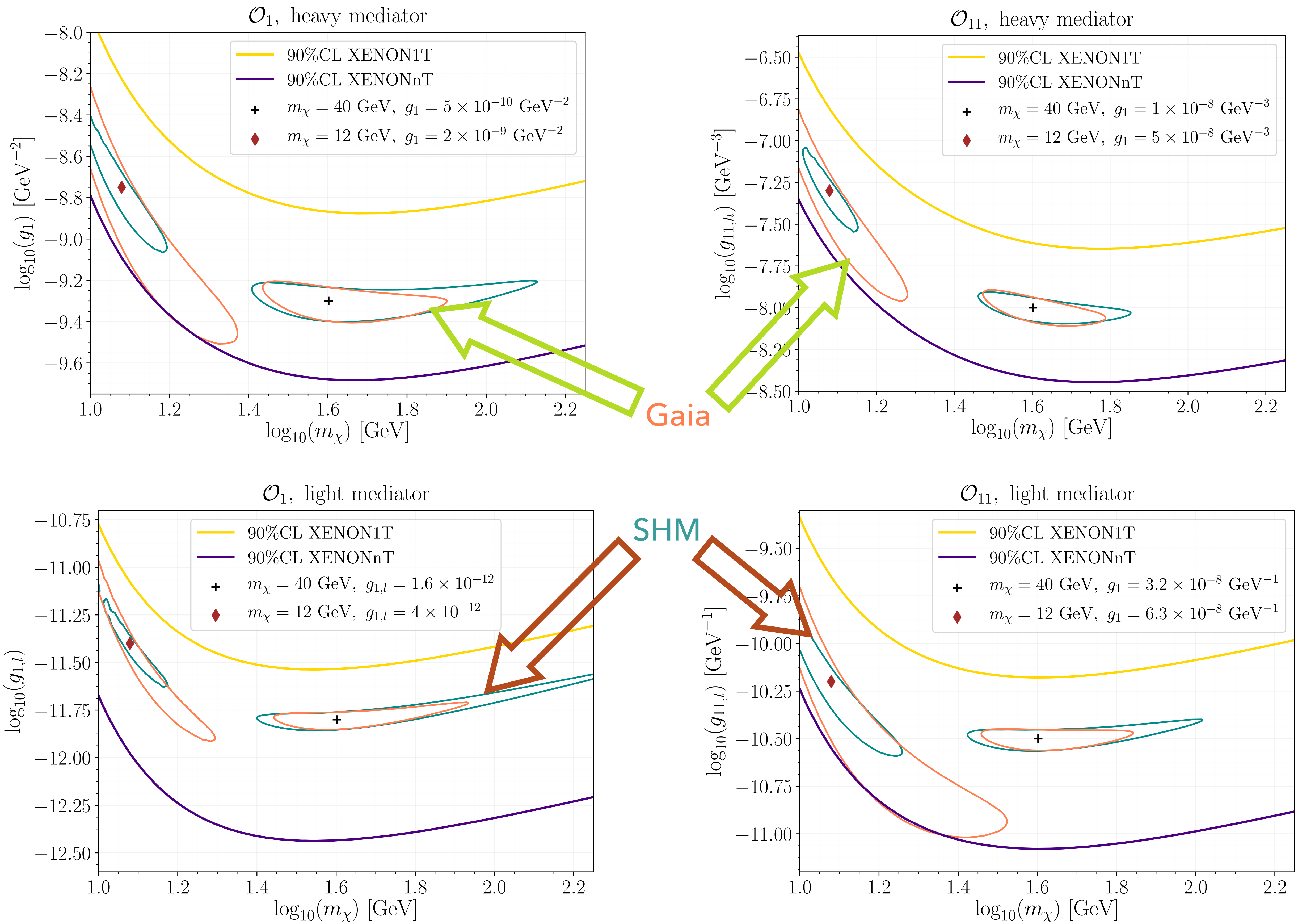
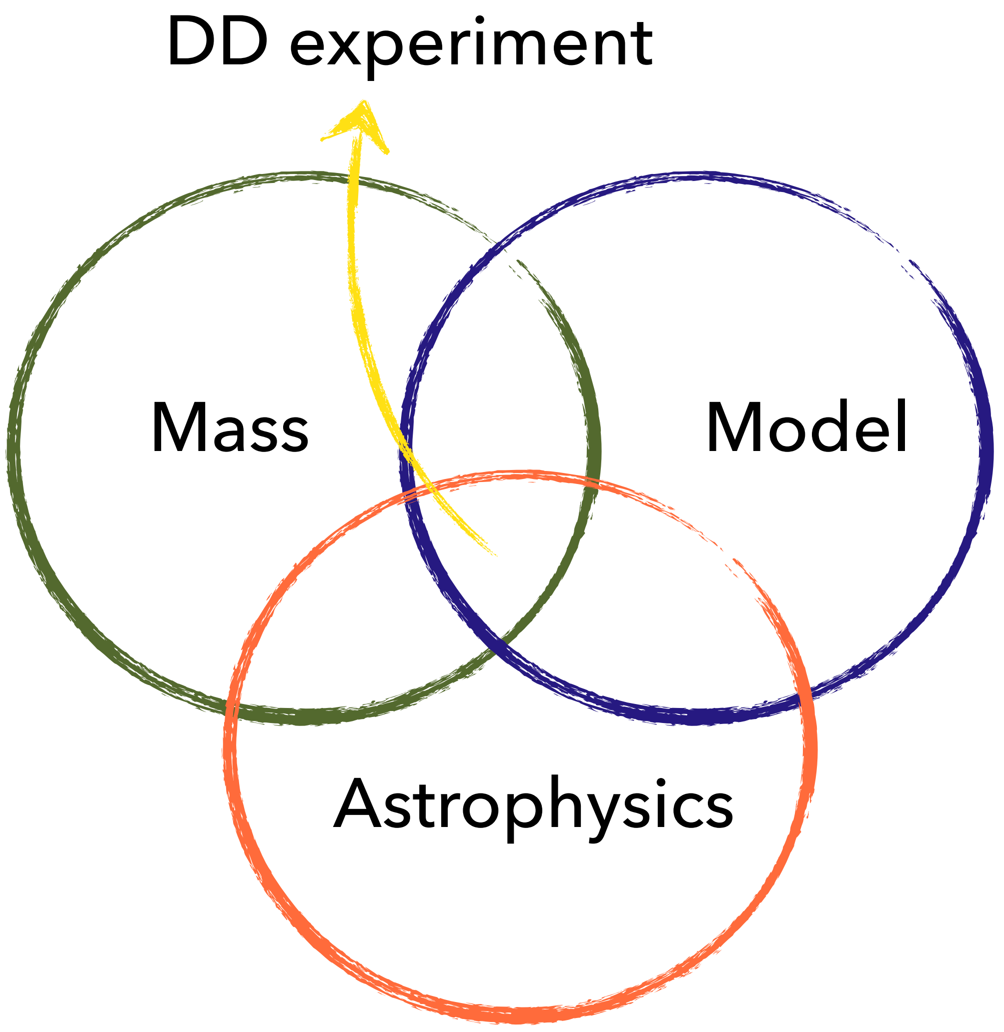


Results



Modus operandi: Fix/marginalize parameters of any one class, and estimate its effect on the degeneracy between parameters of the other two classes.

Results

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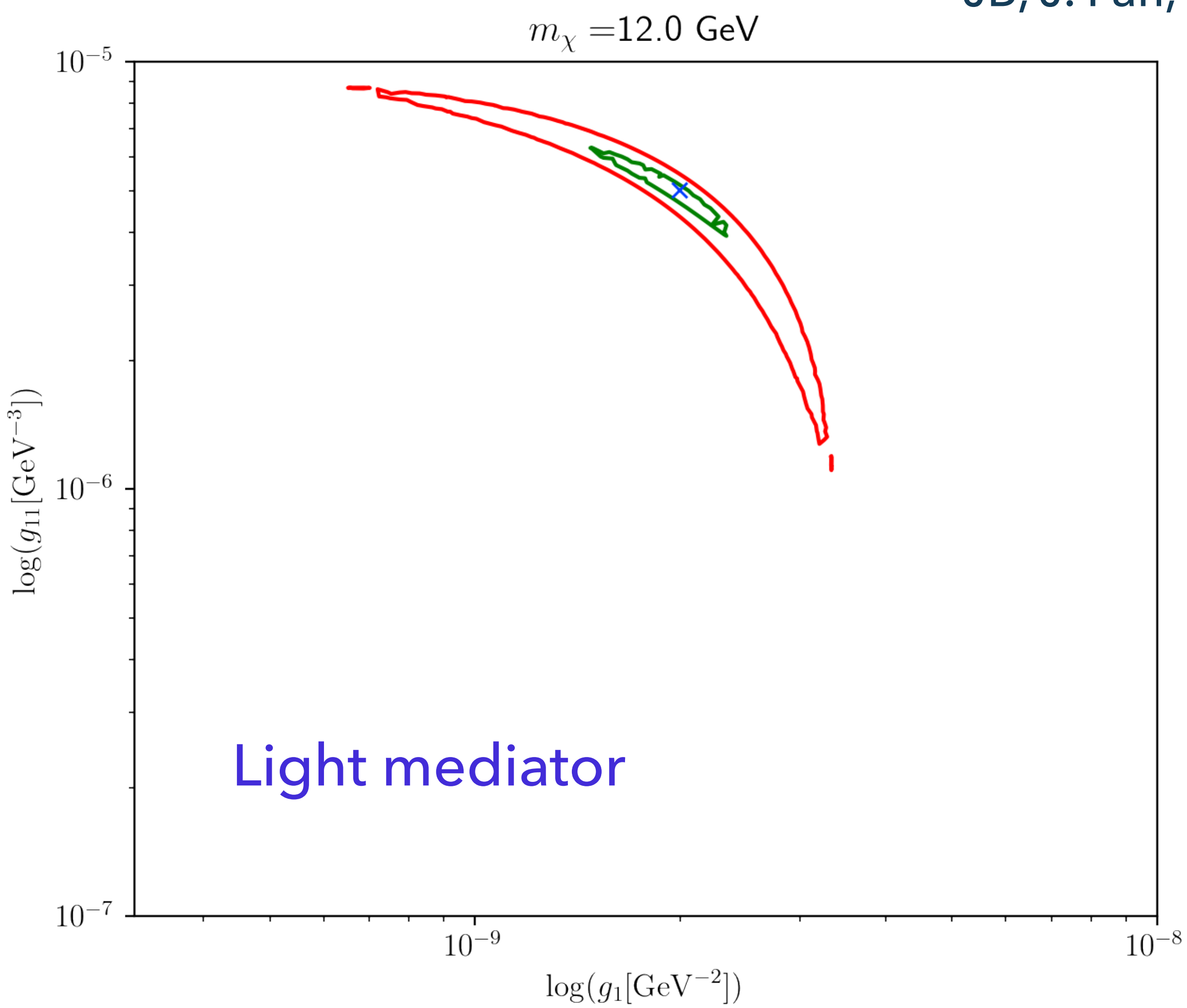

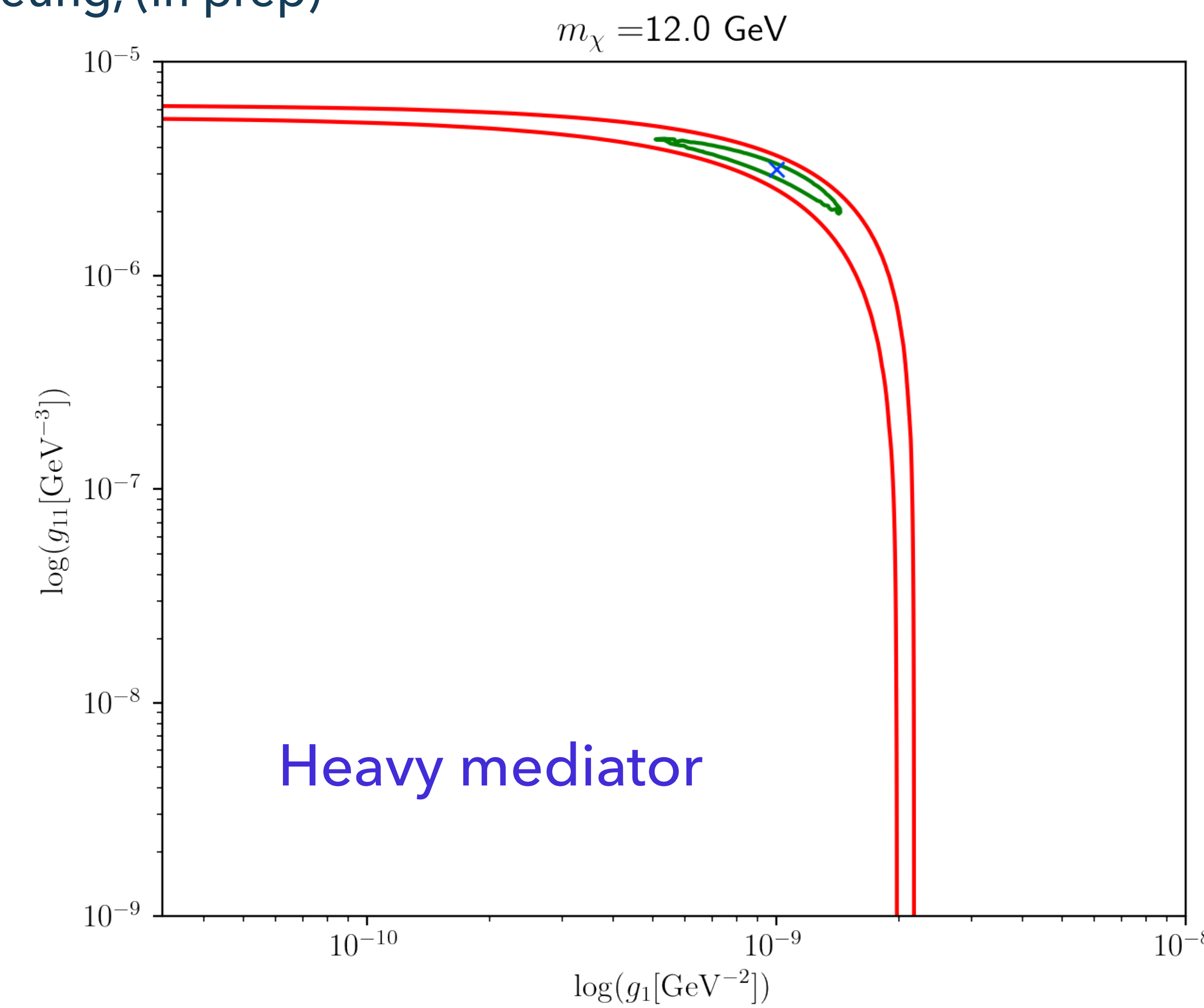

Conclusions

- Surveys like Gaia and LSST will not only provide insights into the local distribution of DM in the Milky Way, but also help understand the nature of DM.

- Direct detection experiments are a unique tool to explore the astroparticle phenomenology of DM; next-generation experiments will be an important complementary probe for a wide range of DM models and masses.

- As a proof-of-concept, we showed that using an empirical DM velocity distribution doesn't just weaken the constraints in the light DM region, it also boosts the sensitivity of an experiment relative to the SHM at higher DM masses.

- Although we have only discussed Xe as a target in our talks; results for other targets are currently under preparation.

- We're also looking for feedback from the experimental community regarding potential research directions or collaborations!

A new field perhaps?

Credit: Scott Adams

Thank you!