Pinning down the particle properties of Dark Matter with future direct detection experiments

Chalmers University of Technology
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GRAPPA
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As usual, the Dark Matter (DM) community stands on the brink of discovery. But there is still much we do not about Dark Matter and its interactions with the Standard Model. How does DM interact with nucleons? How strong is this interaction? Is DM its own antiparticle? I will discuss a number of ways to discriminate between different forms of DM-nucleon interaction in future 'Direct Detection' experiments: using directional detectors, using time-series data and using target complementary. Finally, I will discuss ongoing work (using the new statistical tool SWORDFISH) to explore prospects for model discrimination over the whole DM parameter space, not only at selected benchmark points. This work is crucial to inform future DM searches, guiding which experiments and techniques should be pursued in order to pin down the DM-nucleon interaction and probe the particle identity of Dark Matter.

Latest results from the Xenon1T experiment are expected soon…

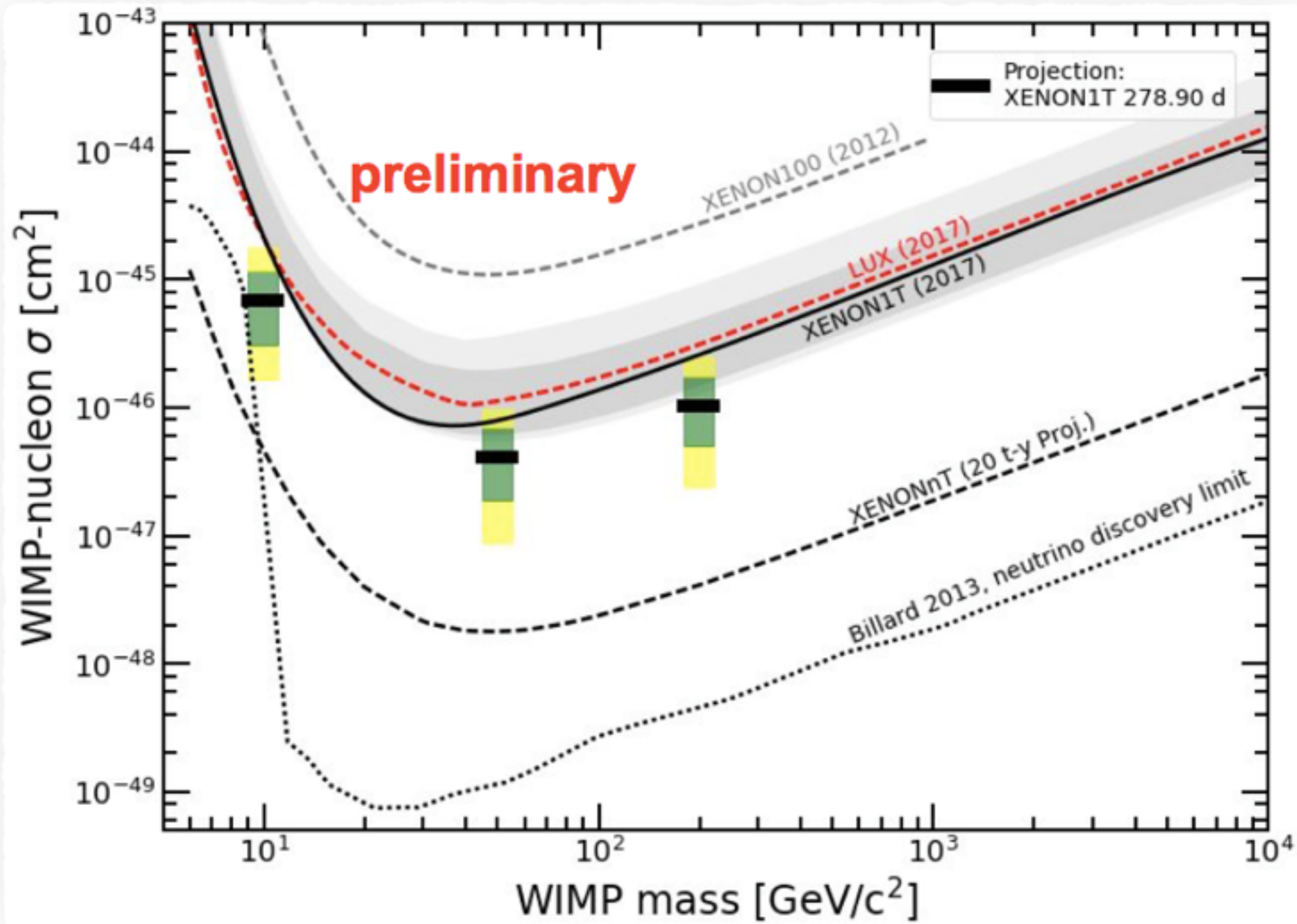
Summary

- XENON1T is the first LXeTPC dark matter at the multi-ton scale in operation.
- First result with 34 live days yielded the most stringent limit on SI WIMP cross section.
- Detector has continued to work incredibly well after the break forced by an earthquake.
- Demonstrated > 1 year operation with 3.2 t of LXe: a milestone for this technology.
- Achieved the lowest background ever measured in a DM detector: 0.2 events/ (t keV d)
- Collected ~ 1 ton x year dark matter data and large calibration statistics.
  - Data still blinded. Expect world-leading result in March 2018.
  - > 50% chance for a 3 sigma signal if WIMP cross-section at current limit!
- XENON1T continues to take data until we upgrade it to XENONnT. Installation of the new TPC (~6 t Xe target) before end of 2018. See Luca Grandi's talk.

Elena Aprile, Feb 2018 [https://tinyurl.com/Xe1T-Aprile]

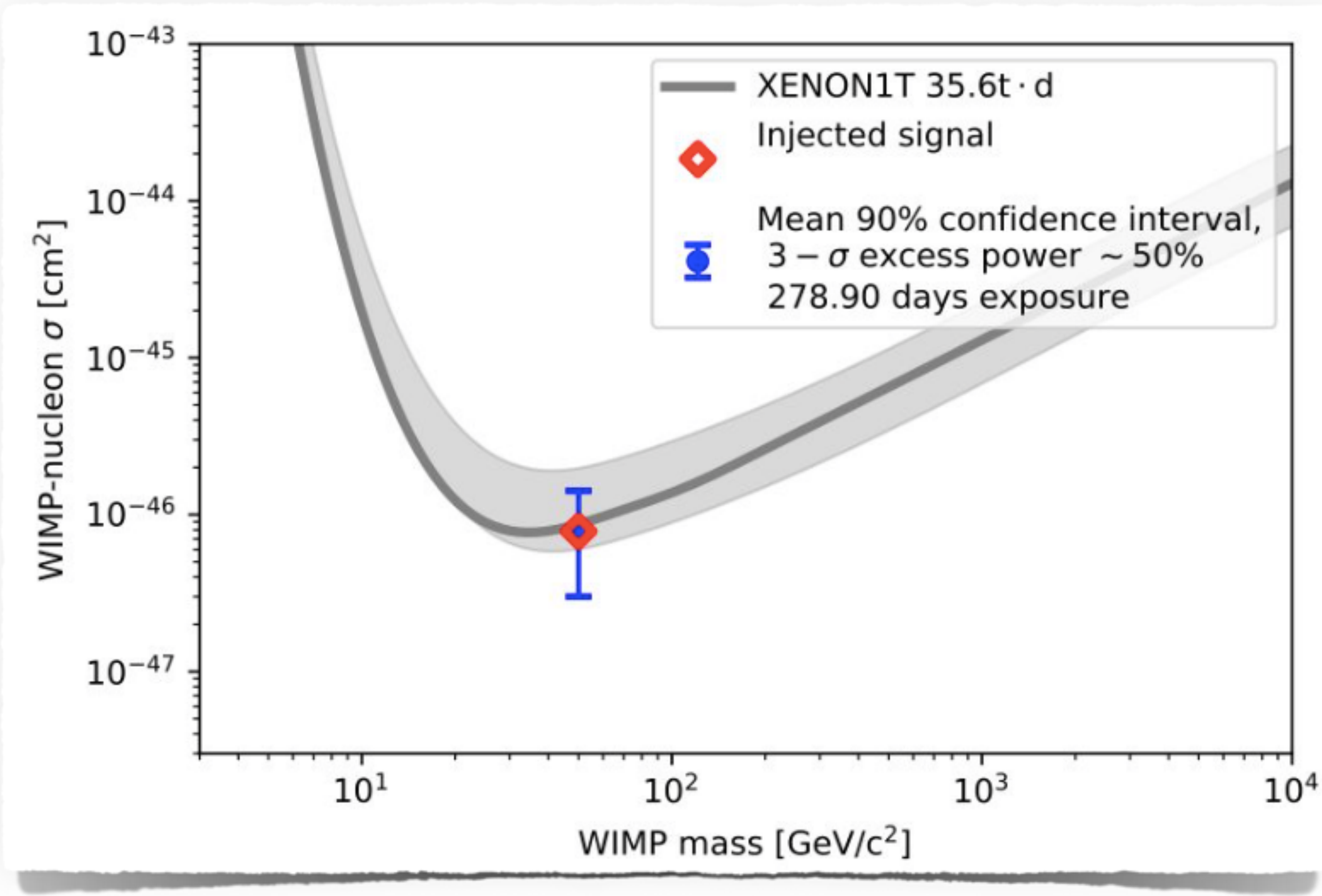
Bringing with them a factor of 2-3 improvement in sensitivity…

“Weakly Interacting Massive Particle”



Daniel Coderre, Mar 2018 [https://tinyurl.com/Xe1T-Coderre]

Or better yet, a discovery…



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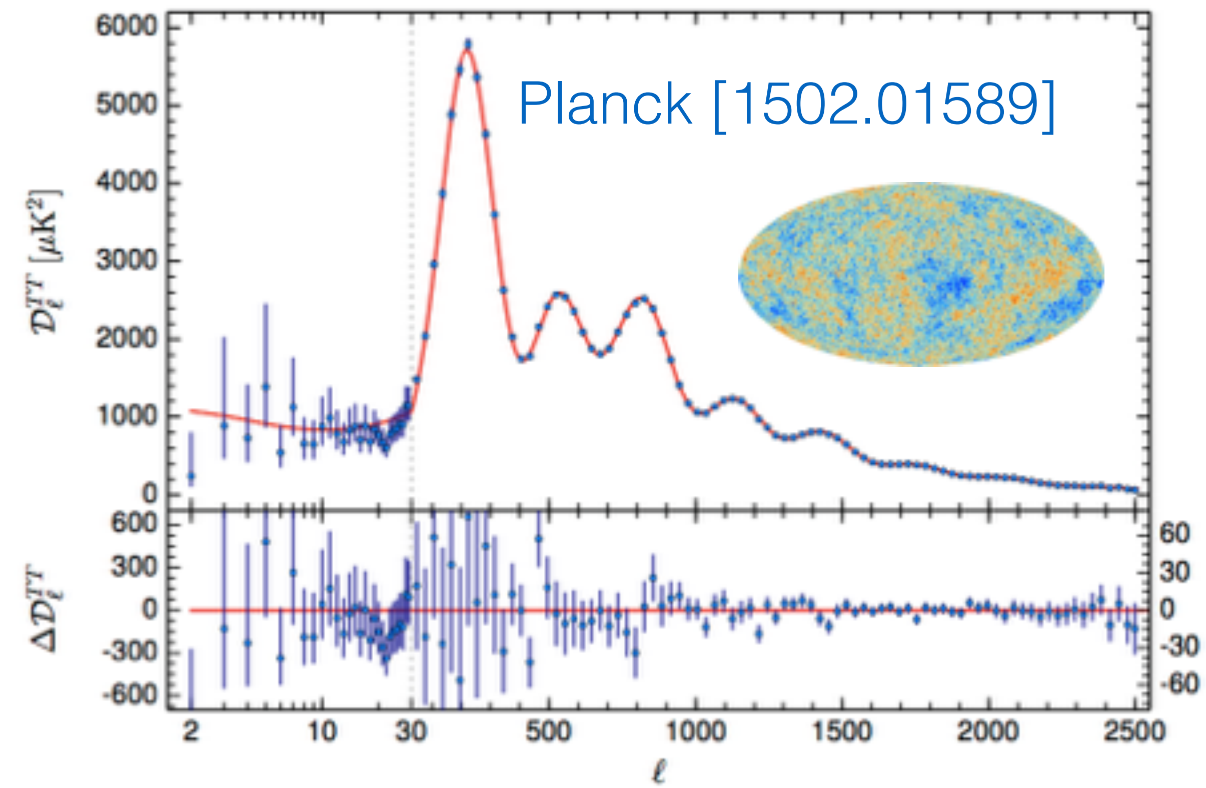
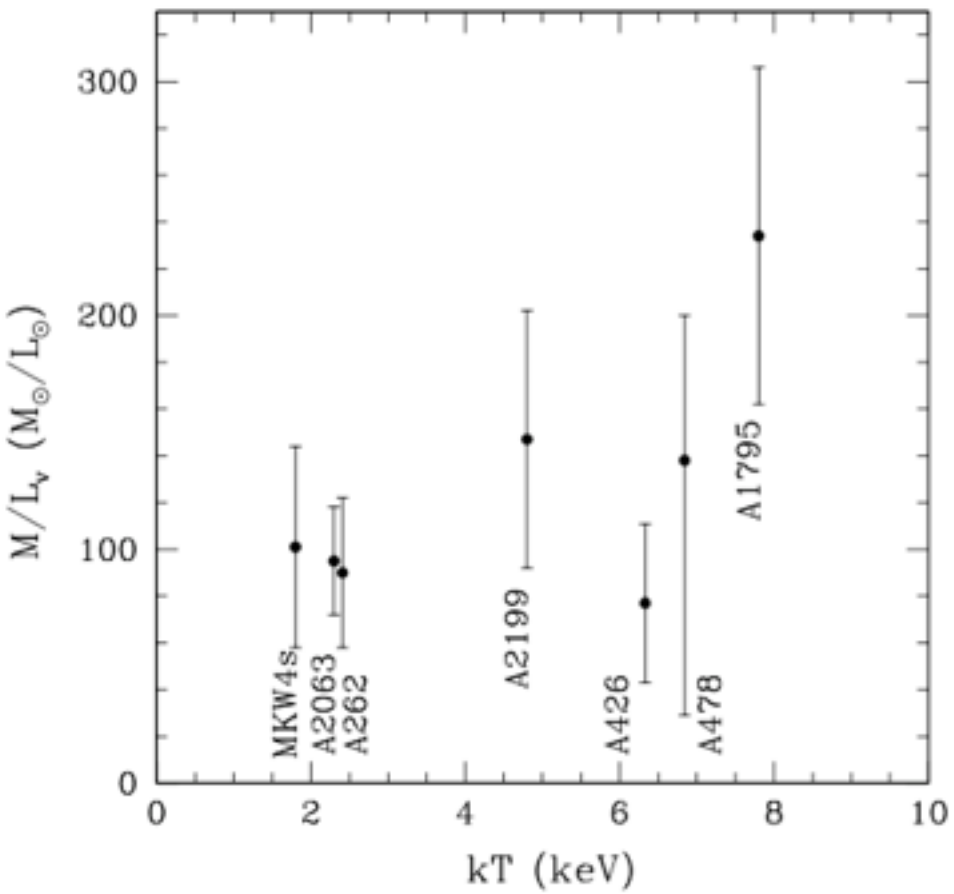
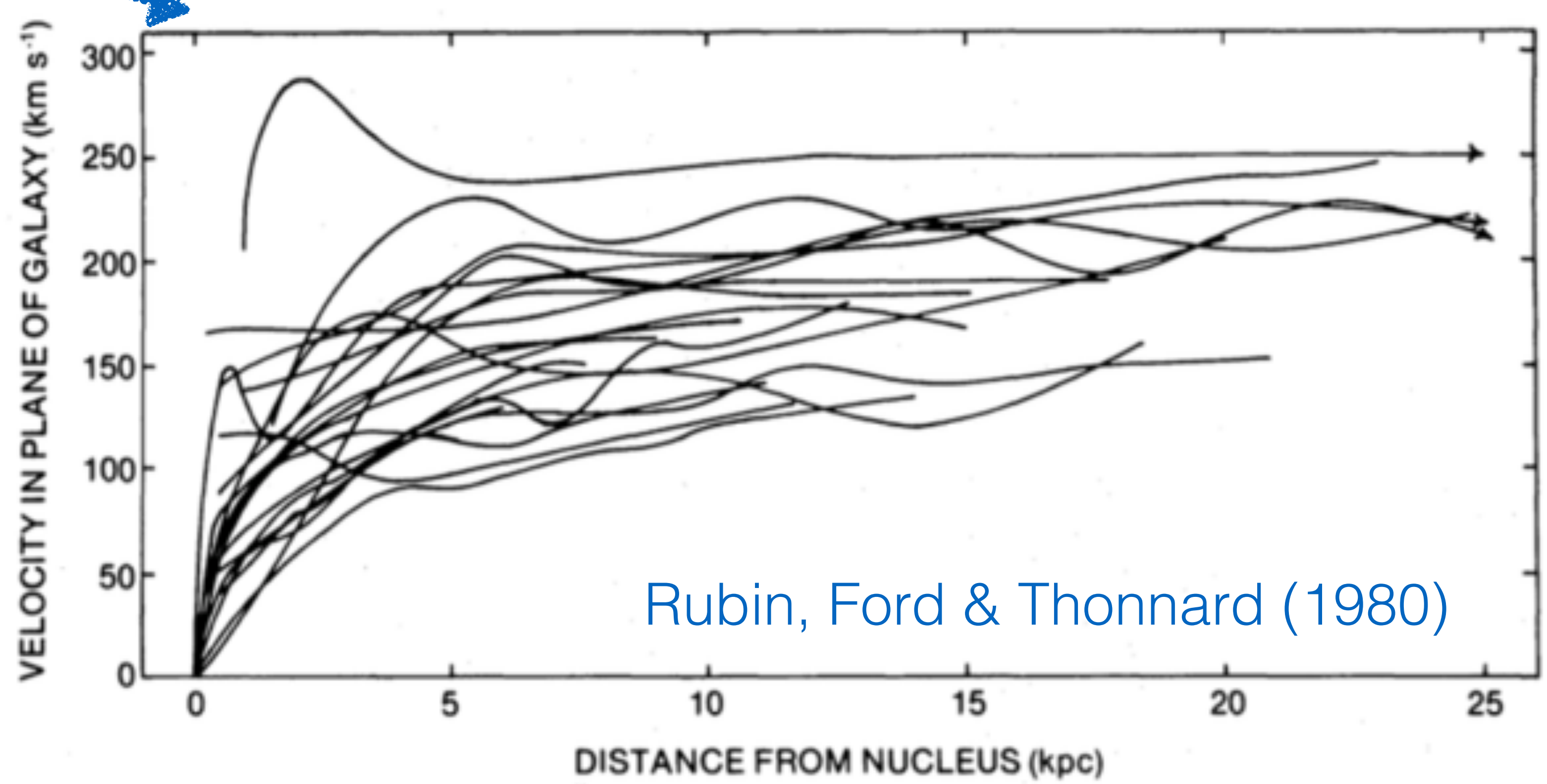
Dark Matter on all scales



Planck [1502.01589]



Hradecky et al. [astro-ph/0006397]



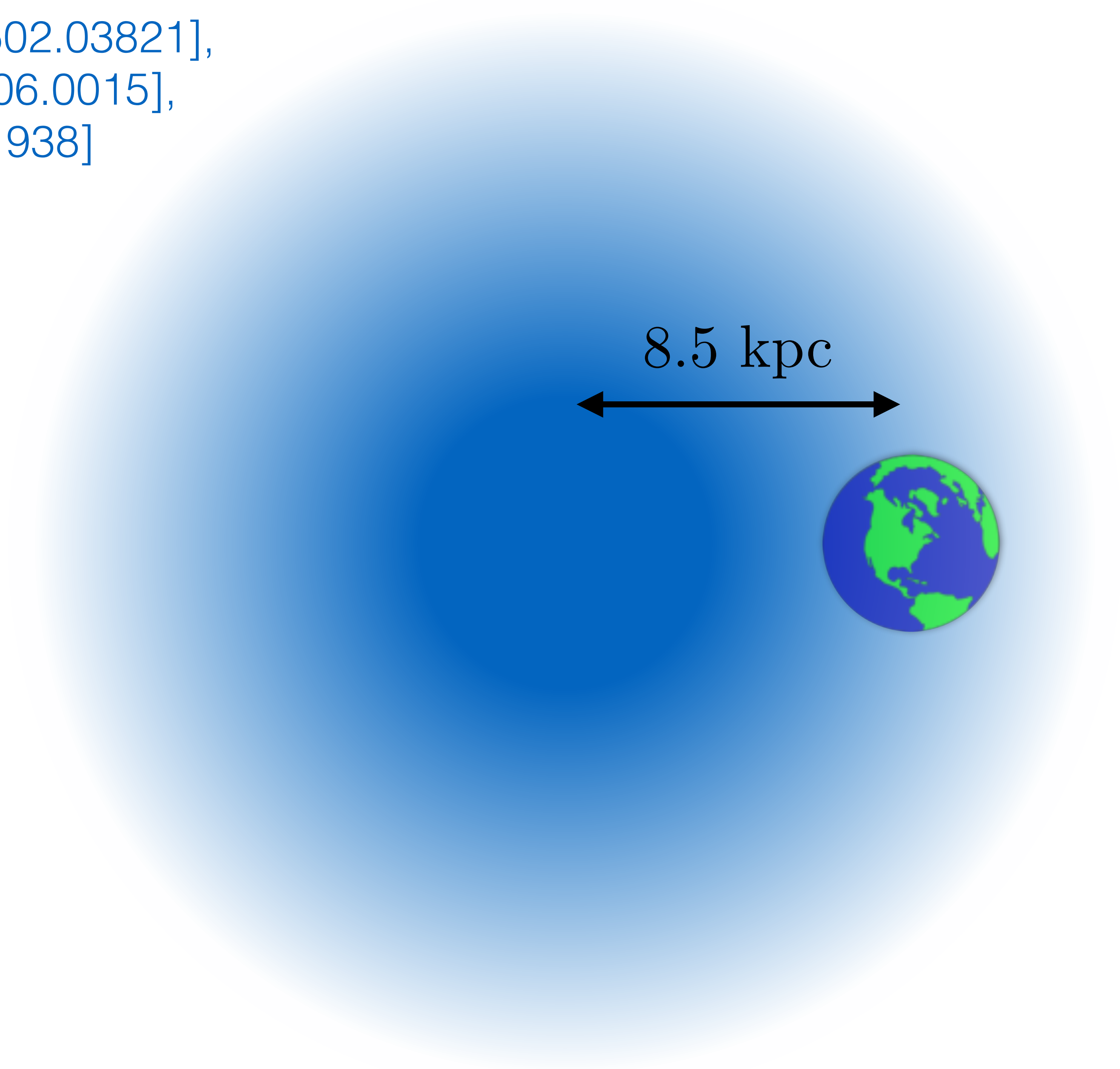
Rubin, Ford & Thonnard (1980)

Dark Matter at Earth

Global and local estimates of DM at Solar radius give:

$$\rho_\chi \sim 0.2\!-\!0.8\ \mathrm{GeV\ cm^{-3}}$$

E.g. Iocco et al. [1502.03821],
Garbari et al. [1206.0015],
Read [1404.1938]



NOT TO SCALE

Direct Detection of Dark Matter

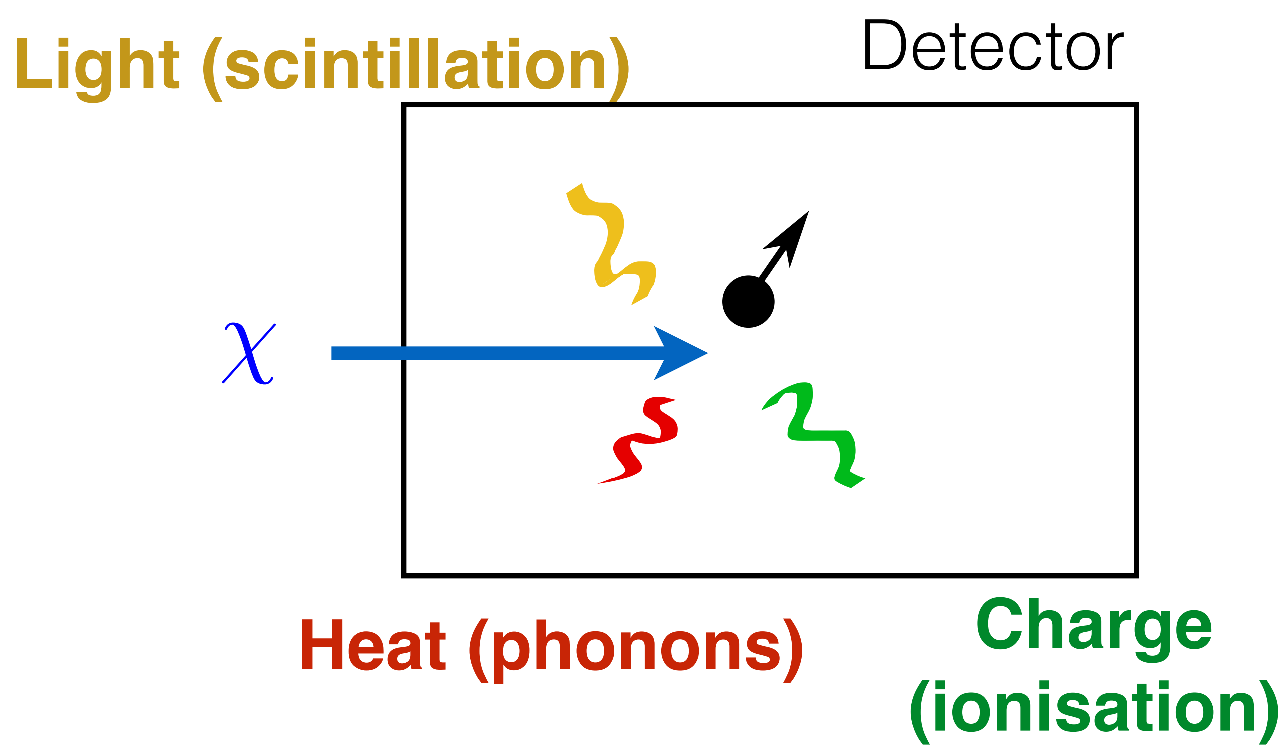
Aim to measure energy and possibly direction of nucleus recoiling after DM interaction

$$m_\chi \gtrsim 1\ \mathrm{GeV}$$

$$v \sim 10^{-3}$$

DM flux:

$$\Phi_\chi = \frac{\rho_\chi}{m_\chi} v f(\mathbf{v})$$



Convolve DM flux with DM-nucleus cross section to obtain expected nuclear recoil rate:

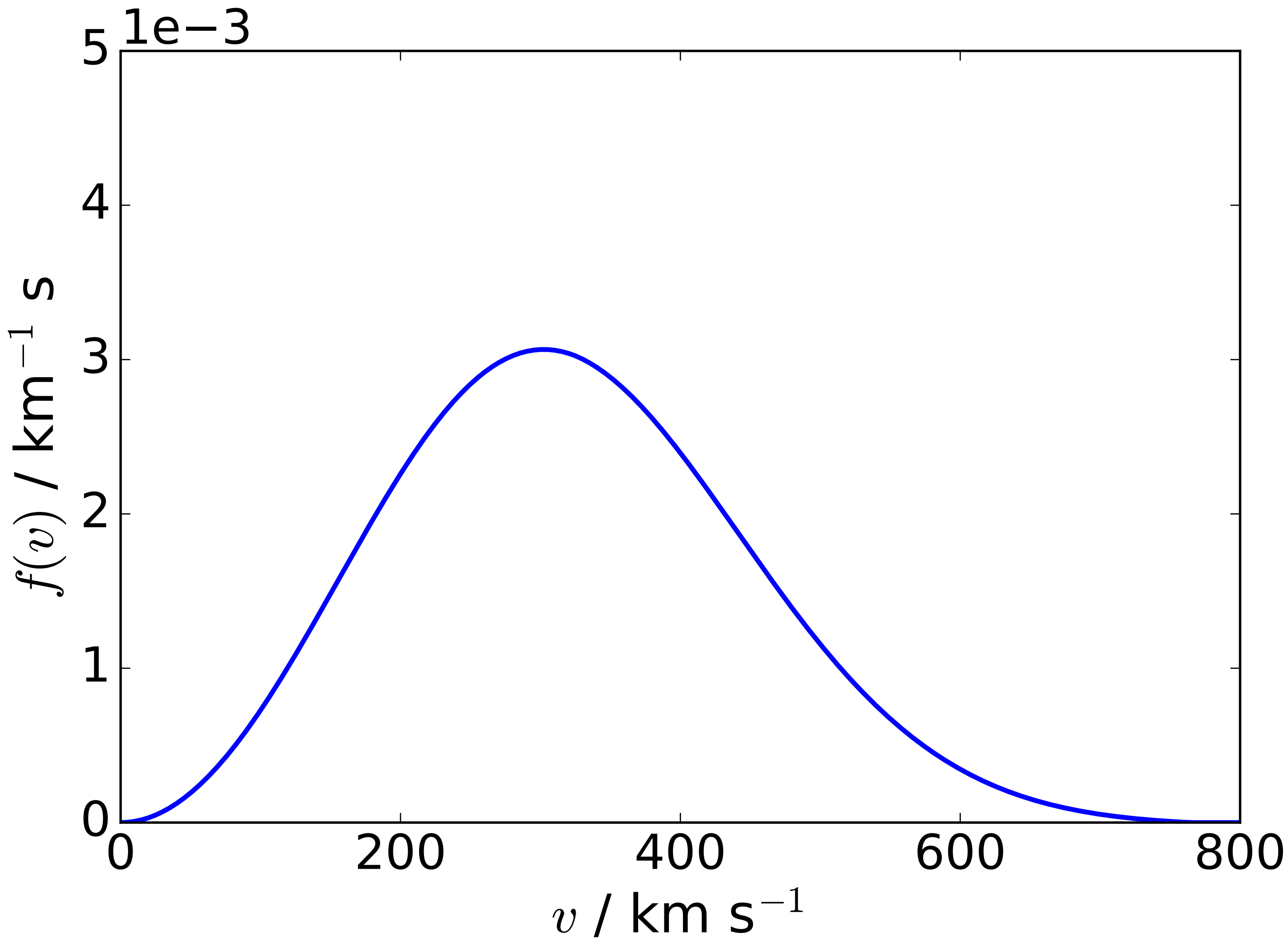
$$\frac{\mathrm{d}R}{\mathrm{d}E_R} \propto \frac{\rho_\chi}{m_\chi} \int_{v_{\mathrm{min}}}^{\infty} v f(v) \frac{\mathrm{d}\sigma}{\mathrm{d}E_R}\, \mathrm{d}v$$

Local astrophysics of DM (the simple picture)

Standard Halo Model (SHM) is typically assumed: isotropic, spherically symmetric distribution of particles with $\rho(r) \propto r^{-2}$.

Leads to a Maxwell-Boltzmann (MB) distribution (*in the lab frame*)

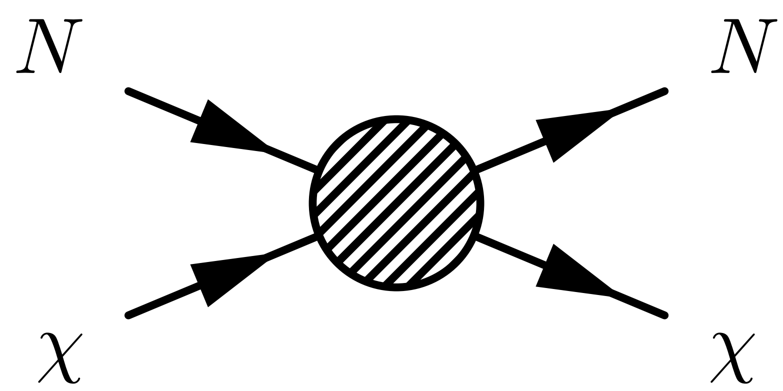
[But see e.g. 1705.05853]



Need to be careful of astrophysical uncertainties, but that's not the topic of this talk…

Fox, Liu, Weiner [1011.1915]
BJK, Green [1303.6868]
BJK, Fornasa, Green [1410.8051]
and others…

Particle Physics of DM (the simple picture)



Typically assume contact interactions (heavy mediators).
In the non-relativistic limit, obtain two main contributions.
Write in terms of DM-proton cross section σ^p:

$$\frac{\mathrm{d}\sigma^A}{\mathrm{d}E_R} \propto \frac{\sigma^p}{\mu_{\chi p}^2 v^2} \mathcal{C}_A F^2(E_R)$$

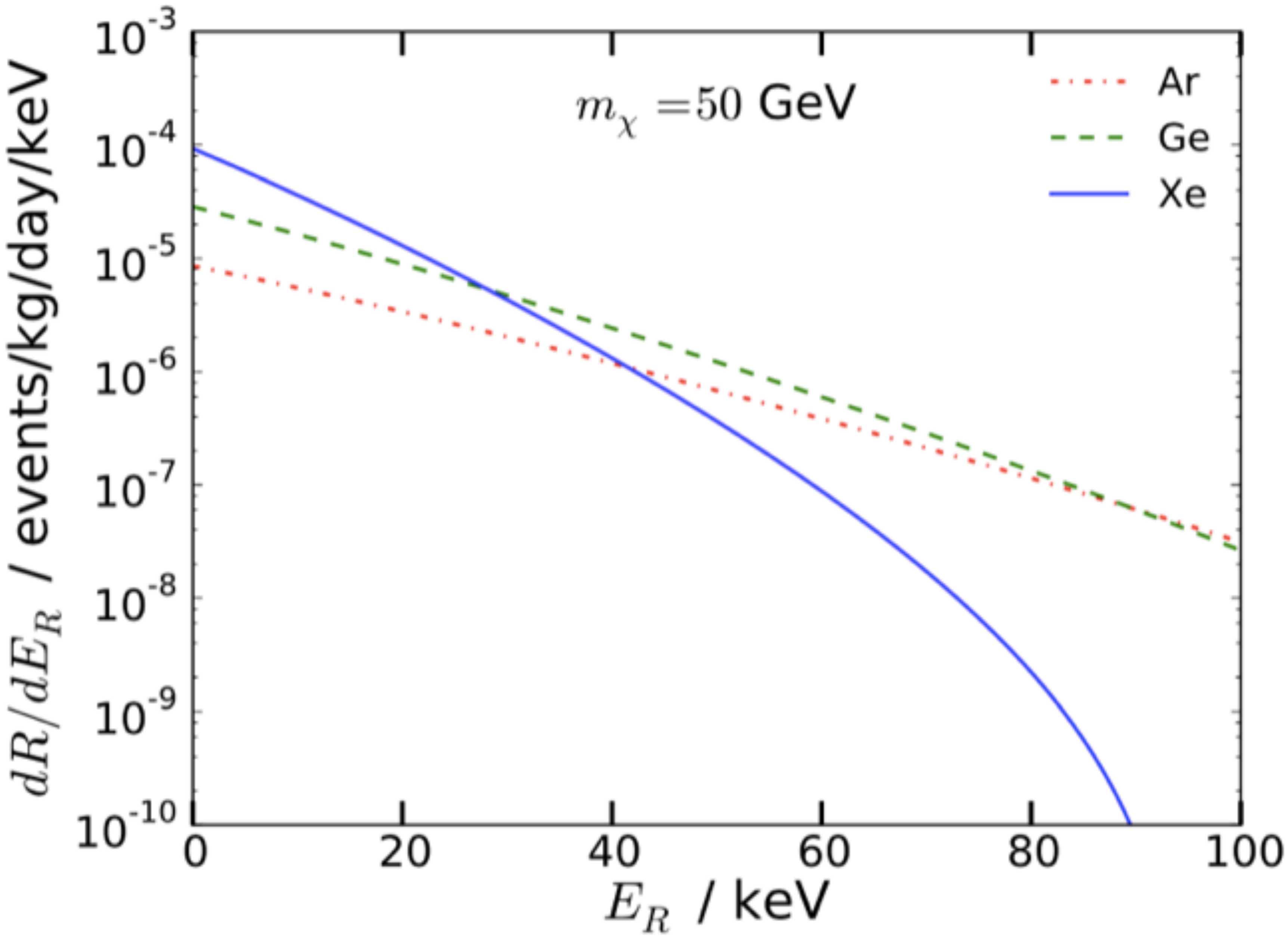
Form factor accounts for loss of coherence at high energy

Enhancement factor different for:

spin-independent (SI) interactions - $\mathcal{C}_A^{\mathrm{SI}} \sim A^2$

spin-dependent (SD) interactions - $\mathcal{C}_A^{\mathrm{SD}} \sim (J+1)/J$

Standard Direct Detection 'Signal'

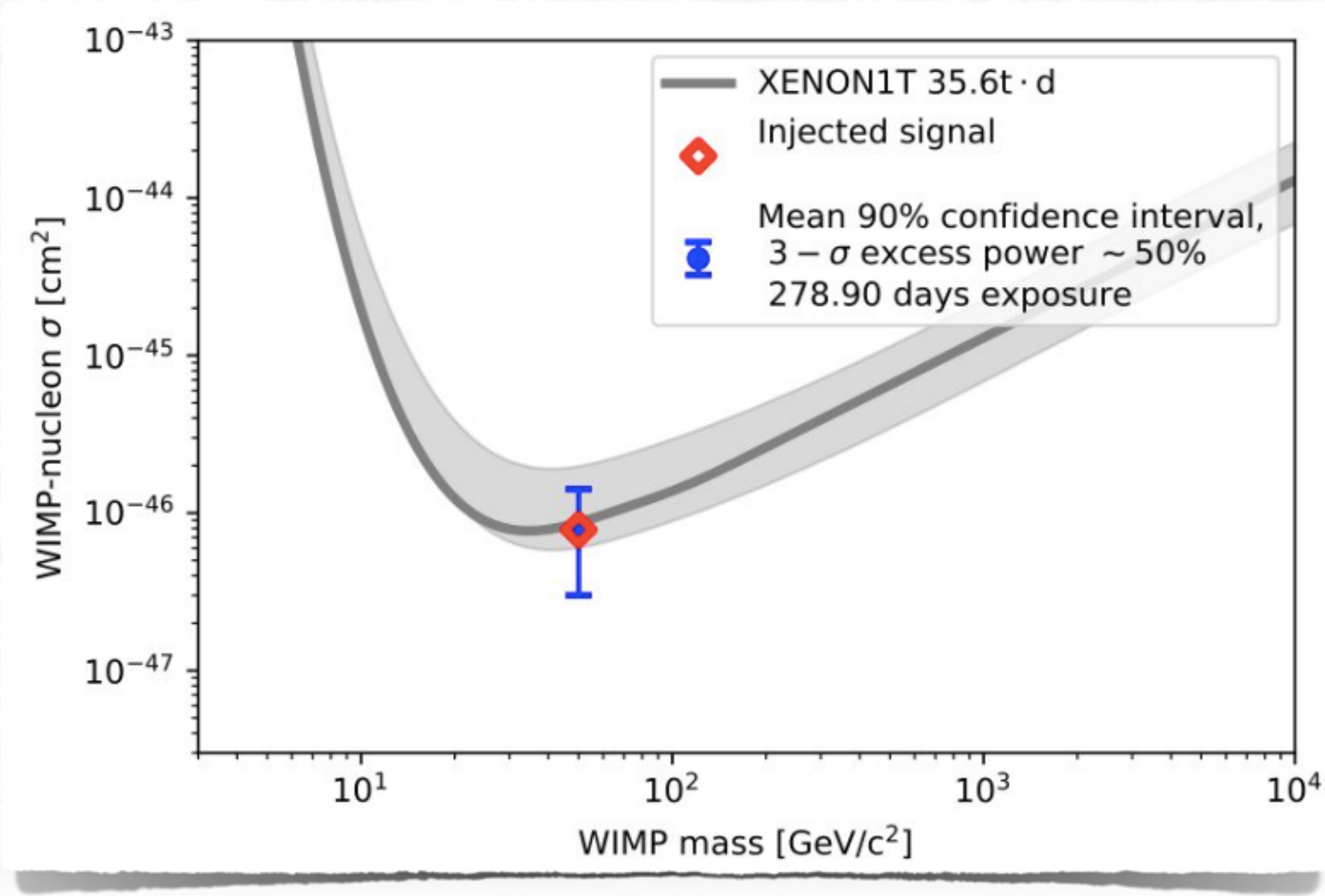


Hope to measure DM properties (mass, cross section, speed distribution, …)
from a measurement of the recoil spectrum

E.g. Green [0805.1704], Peter, Gluscevic, Green, **BJK**, Lee [1310.7039]

The future

What can we learn about the DM-nucleon interaction after a discovery?



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Direct Detection of Dark Matter
Overview and introduction ✓

Is the DM its own antiparticle?
Target Complementarity

Queiroz, Rodejohann, Yaguna [1610.06581]
BJK, Queiroz, Rodejohann, Yaguna [1706.07819]

What is the form of the DM-nucleon interaction?
Directionality and Time-dependence

BJK [1505.07406]
BJK, Catena, Kouvaris [1611.05453]

Where in the parameter space can we distinguish different models?
Mapping out the whole parameter space with SwordFish

Edwards & Weniger [1712.05401]
Edwards, **BJK** & Weniger [1804.XXXXX]

DM-nucleon contact interactions

Start thinking about how DM χ can interact with nucleons $N = (p, n)$:

$$\begin{aligned}\mathcal{L} \supset \lambda_{N,1}\,\overline{\chi}\chi\,\overline{N}N + \lambda_{N,2}\,\overline{\chi}\gamma^\mu\chi\,\overline{N}\gamma_\mu N \\ + \lambda_{N,3}\,\overline{\chi}\gamma^\mu\gamma^5\chi\,\overline{N}\gamma_\mu\gamma^5 N \\ + \lambda_{N,4}\,\overline{\chi}\gamma^5\chi\,\overline{N}N \\ + \lambda_{N,5}\,\overline{\chi}\gamma^\mu\chi\,\overline{N}\gamma_\mu\gamma^5 N \\ + \ldots\end{aligned}$$

Spin-dependent interaction

Velocity/momentum suppressed

DM-nucleon contact interactions

Start thinking about how DM χ can interact with nucleons $N = (p, n)$:

$$\mathcal{L} \supset \lambda_{N,e}\, \overline{\chi}\chi\, \overline{N}N + \lambda_{N,o}\, \overline{\chi}\gamma^\mu\chi\, \overline{N}\gamma_\mu N$$

Standard spin-independent DM-nucleon interactions couple to the number of nucleons in the target - expect a coherent enhancement of the cross section:

$$\sigma \sim \left[\lambda_p N_p + \lambda_n N_n\right]^2$$

But note that the scalar current operator is *even* under the exchange of particle and antiparticle $\chi \leftrightarrow \overline{\chi}$, while the vector current operator is *odd* under the particle-antiparticle exchange.

DM particles and antiparticles have different nucleon couplings!

Dirac DM

Start thinking about how DM χ can interact with nucleons $N = (p, n)$:

$$\mathcal{L} \supset \lambda_{N,e}\,\overline{\chi}\chi\,\overline{N}N + \lambda_{N,o}\,\overline{\chi}\gamma^{\mu}\chi\,\overline{N}\gamma_{\mu}N$$

Both interactions are allowed

Cross section for scattering with a nucleus A (in the zero-momentum transfer limit) is then:

$$\sigma^D = \frac{4\mu_{\chi A}^2}{\pi}\frac{1}{2}\left(\left[\lambda_p^D N_p + \lambda_n^D N_n\right]^2 + \left[\lambda_p^{\overline{D}} N_p + \lambda_n^{\overline{D}} N_n\right]^2\right)$$

Half of DM is particles, half is antiparticles

Cross section for DM particles

Cross section for DM antiparticles

$$\lambda_N^D = (\lambda_{N,e} + \lambda_{N,o})/2$$
$$\lambda_N^{\overline{D}} = (\lambda_{N,e} - \lambda_{N,o})/2$$

Majorana DM

Start thinking about how DM χ can interact with nucleons $N = (p, n)$:

$$\mathcal{L} \supset \lambda_{N,e}\,\overline{\chi}\chi\,\overline{N}N + \lambda_{N,o}\,\overline{\chi}\gamma^\mu\chi\,\overline{N}\gamma_\mu N$$

$$\equiv \lambda_N^M\,\overline{\chi}\chi\,\overline{N}N$$

Vanishes for Majorana DM

Cross section for scattering with a nucleus A (in the zero-momentum transfer limit) is then:

$$\sigma^M = \frac{4\mu_{\chi A}^2}{\pi}\left[\lambda_p^M N_p + \lambda_n^M N_n\right]^2$$

Comparing Dirac and Majorana

We can try to manipulate the Dirac cross section, to get it into the same form as the Majorana cross section:

$$\sigma^M = \frac{4\mu_{\chi A}^2}{\pi}\left[\lambda_p^M N_p + \lambda_n^M N_n\right]^2$$

After some high-school algebra:

$$\sigma^D = \frac{4\mu_{\chi A}^2}{\pi}\left(\left[\lambda_p N_p + \lambda_n N_n\right]^2 + 2\lambda_p \lambda_n (f-1) N_p N_n\right)$$

where $\lambda_N = \sqrt{\frac{1}{2}(\lambda_N^{D\,2} + \lambda_N^{\overline{D}\,2})}$

$$f = (\lambda_p^D \lambda_n^D + \lambda_p^{\overline{D}} \lambda_n^{\overline{D}})/(2\lambda_p \lambda_n)$$

$f \in [-1, 1]$

The DM-nucleus cross section scales differently with number of protons and neutrons for Dirac and Majorana DM!

Can be easily generalised to different DM spins…

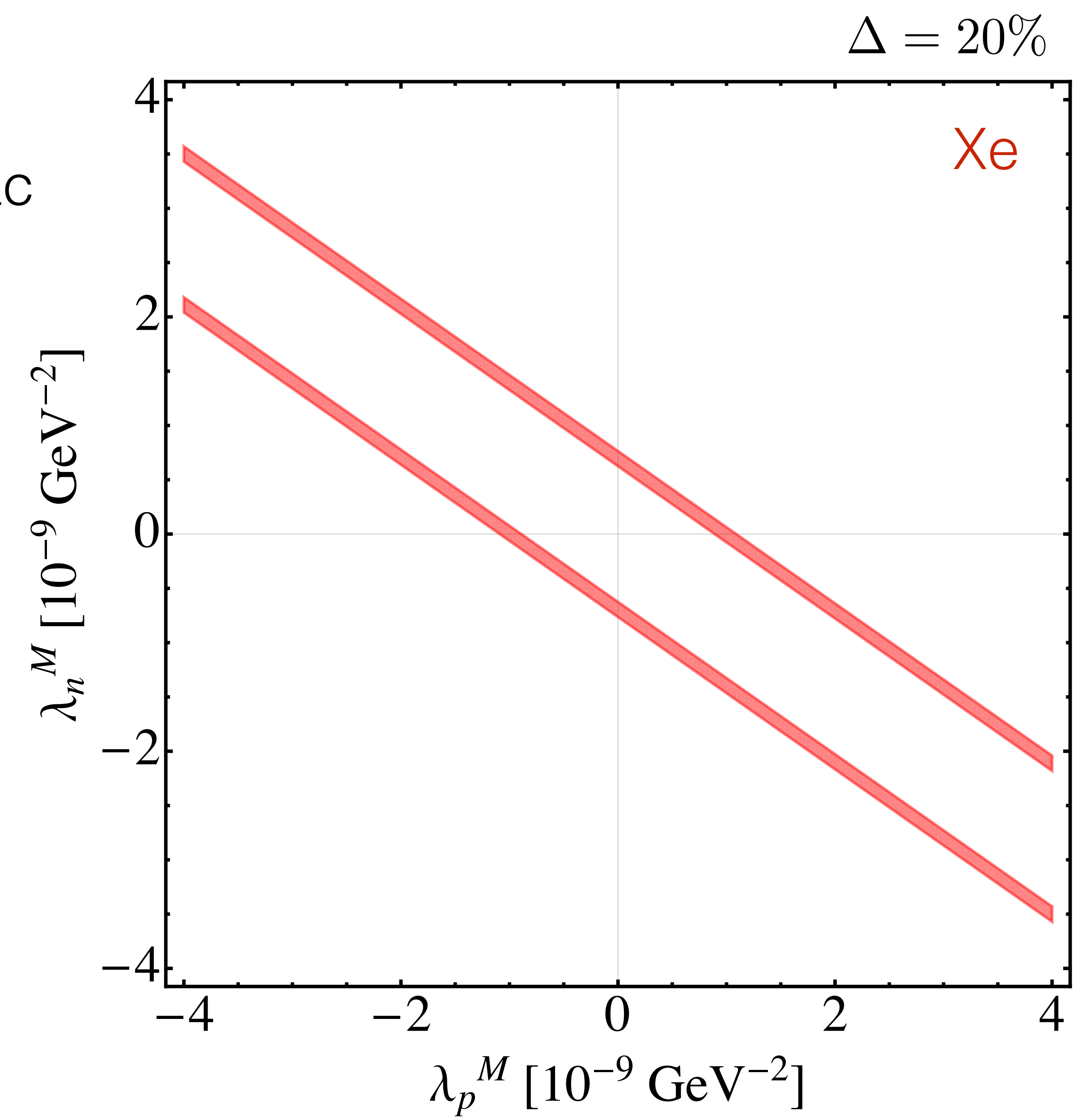
A visual example

Calculate DM-nucleus cross section for Dirac DM (for a particular set of couplings)

Assume DM-nucleus cross section is measured to 20% precision.

Attempt to fit assuming Majorana DM:

$$\sigma^M = \frac{4\mu_{\chi A}^2}{\pi}\left(\left[\lambda_p^M N_p + \lambda_n^M N_n\right]^2\right)$$



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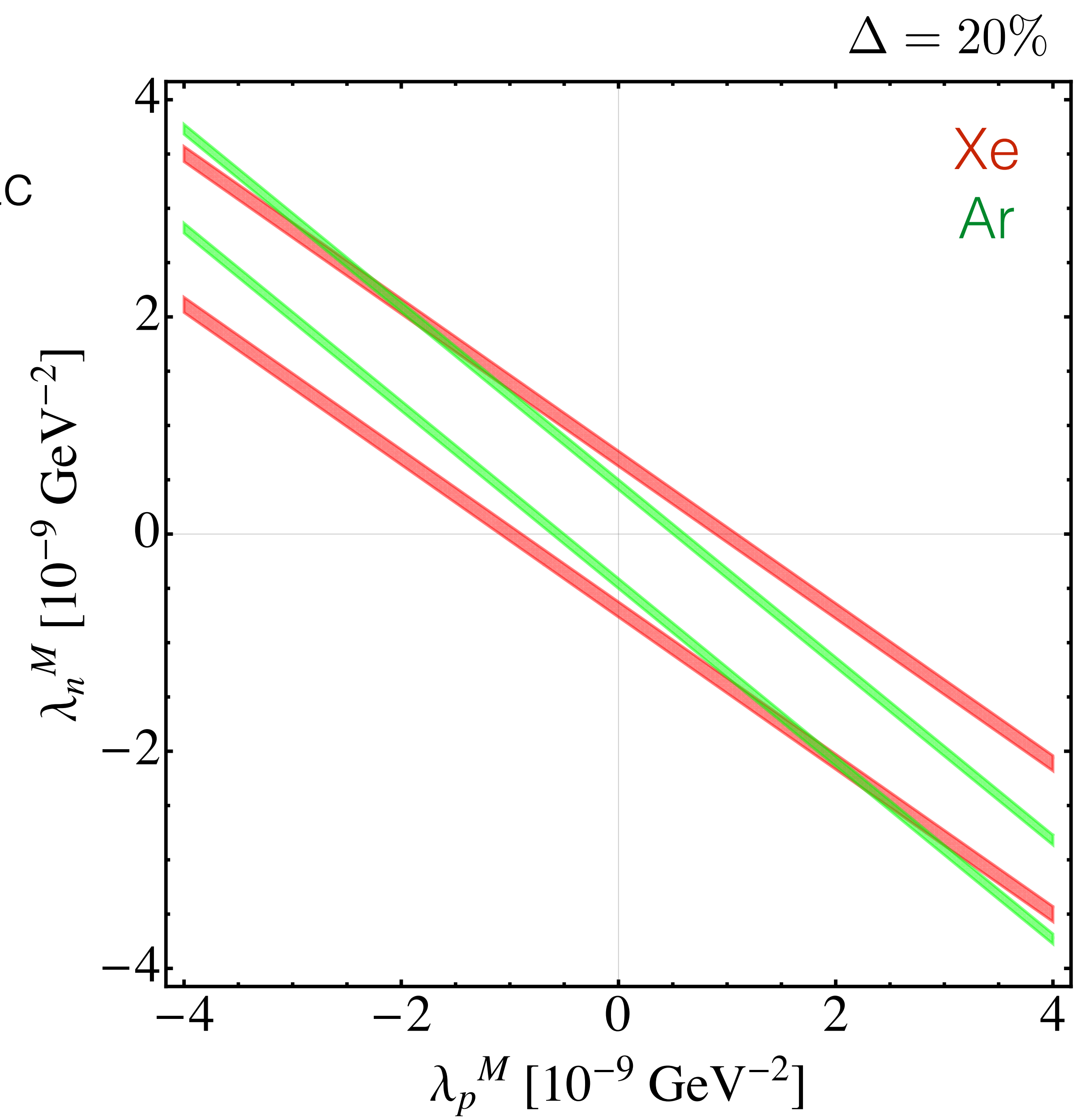

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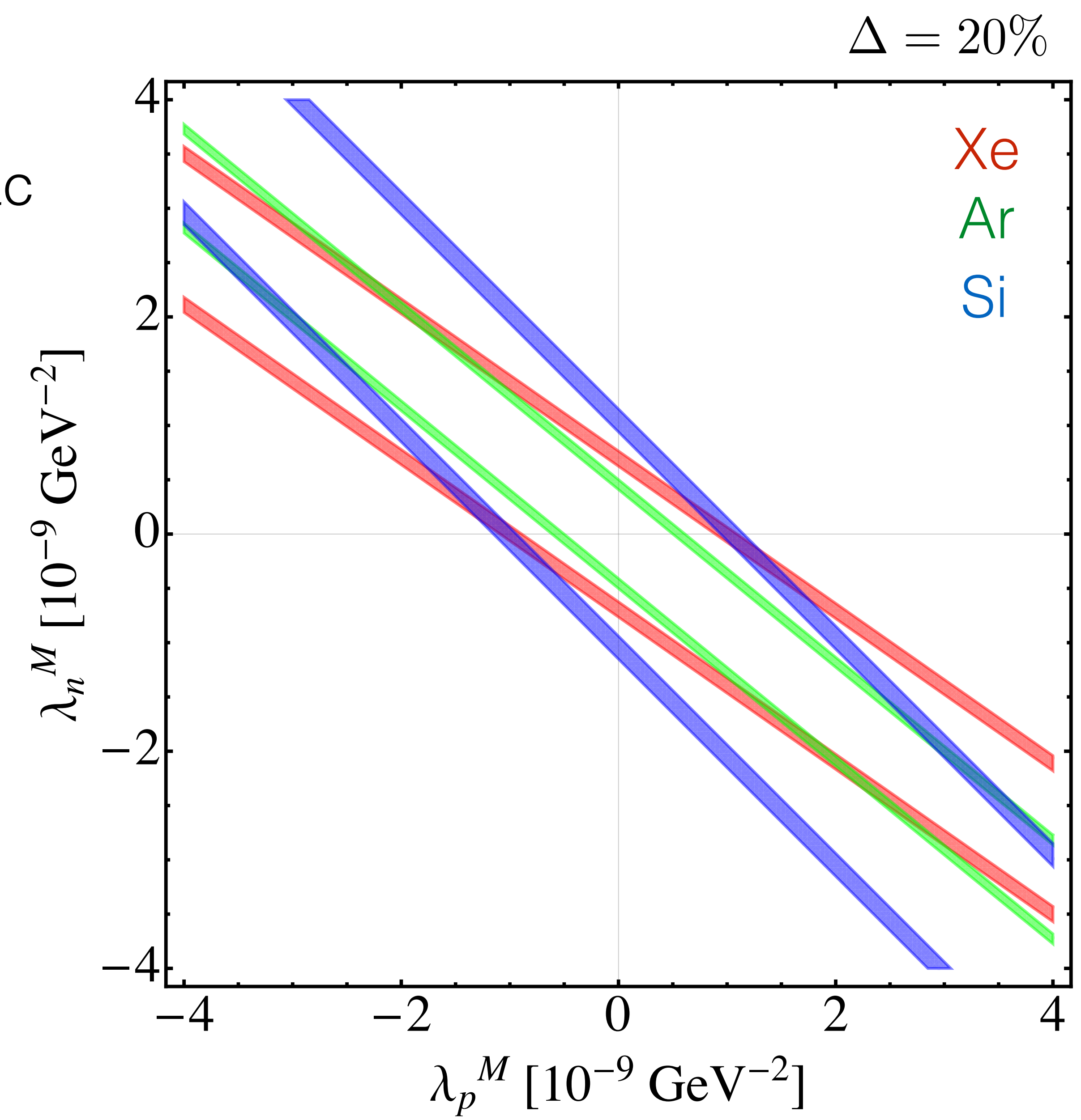


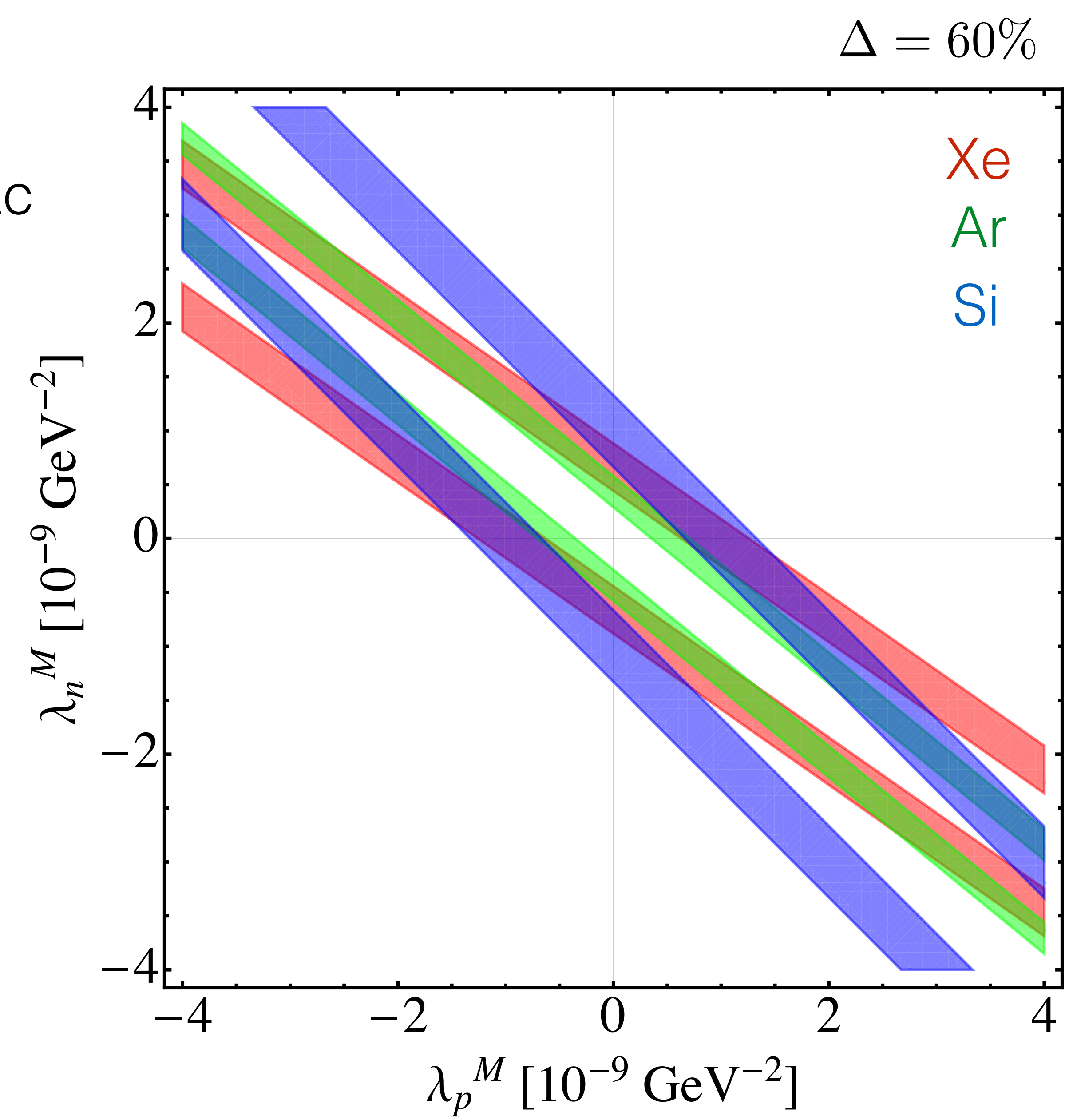
A visual example

Calculate DM-nucleus cross section for Dirac DM (for a particular set of couplings)

Assume DM-nucleus cross section is measured to 60% precision.

Attempt to fit assuming Majorana DM:

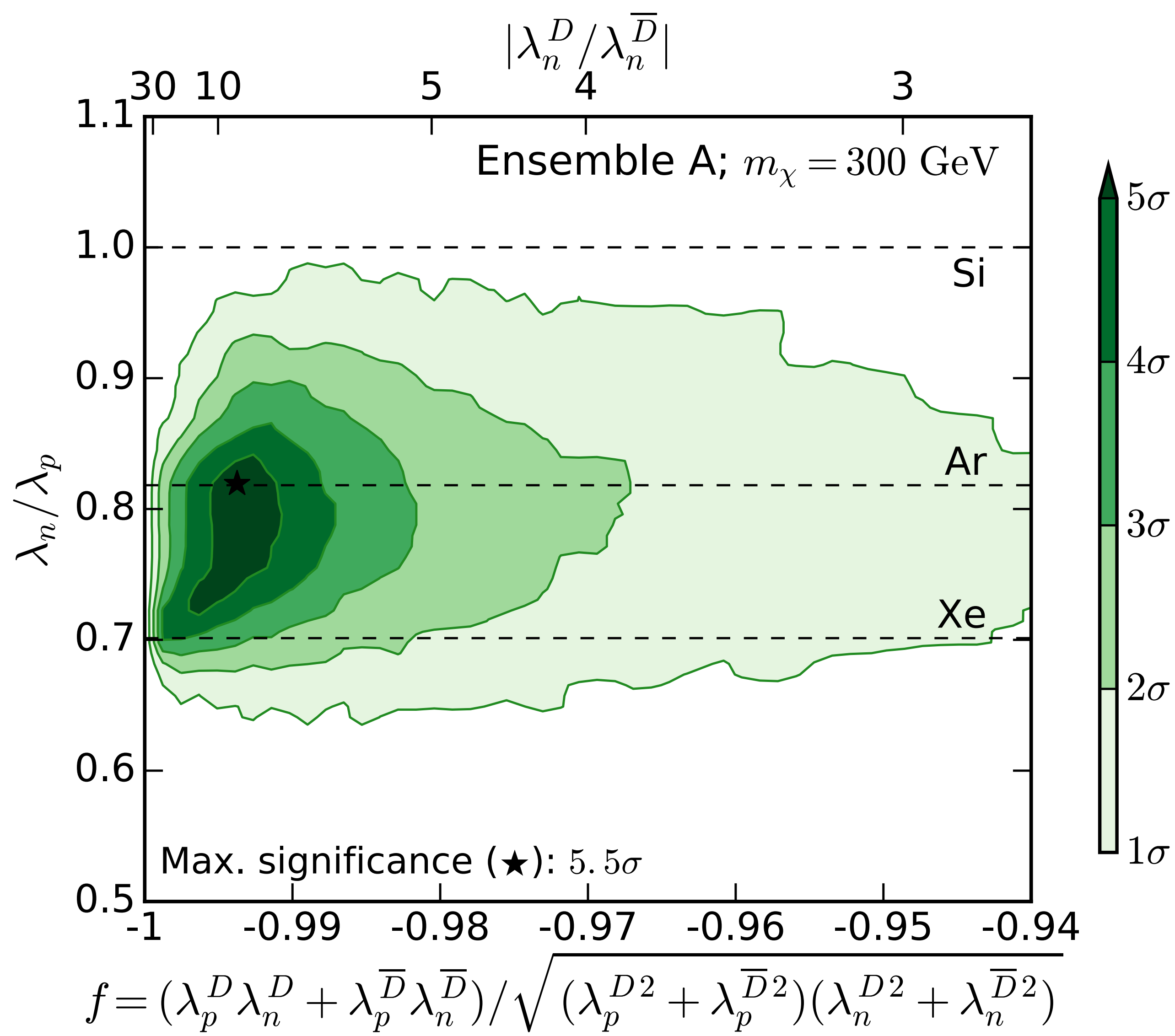
$$\sigma^M = \frac{4\mu_{\chi A}^2}{\pi}\left(\left[\lambda_p^M N_p + \lambda_n^M N_n\right]^2\right)$$



Discrimination Significance: Dirac vs. Majorana

Generate mock data, compare likelihood of Dirac and Majorana models…

Ensemble A: Xe + Ar + Si



Reminder: $\sigma^D = \frac{4\mu_{\chi A}^2}{\pi}\left([\lambda_p N_p + \lambda_n N_n]^2 + 2\lambda_p\lambda_n(f-1)N_pN_n\right)$

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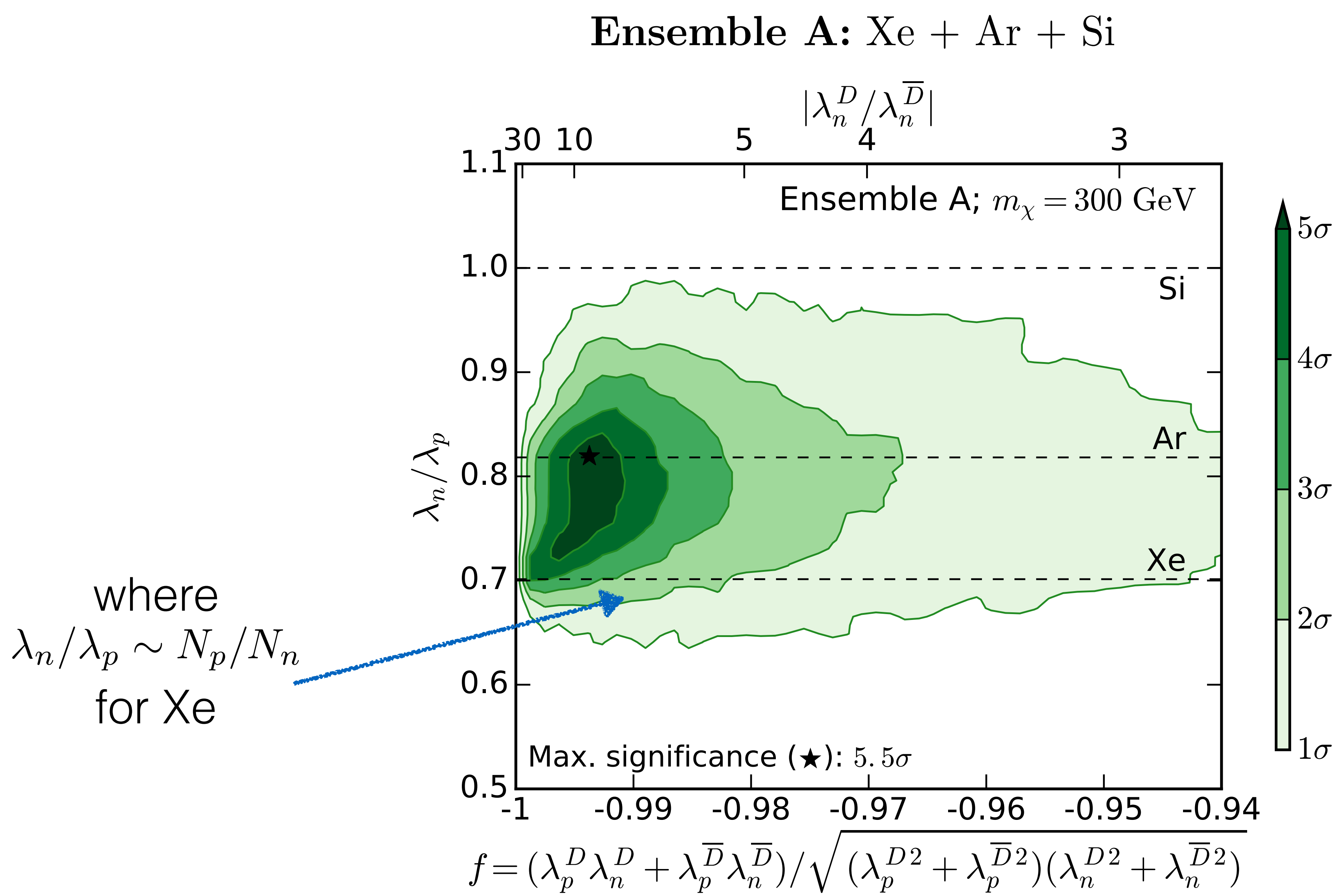

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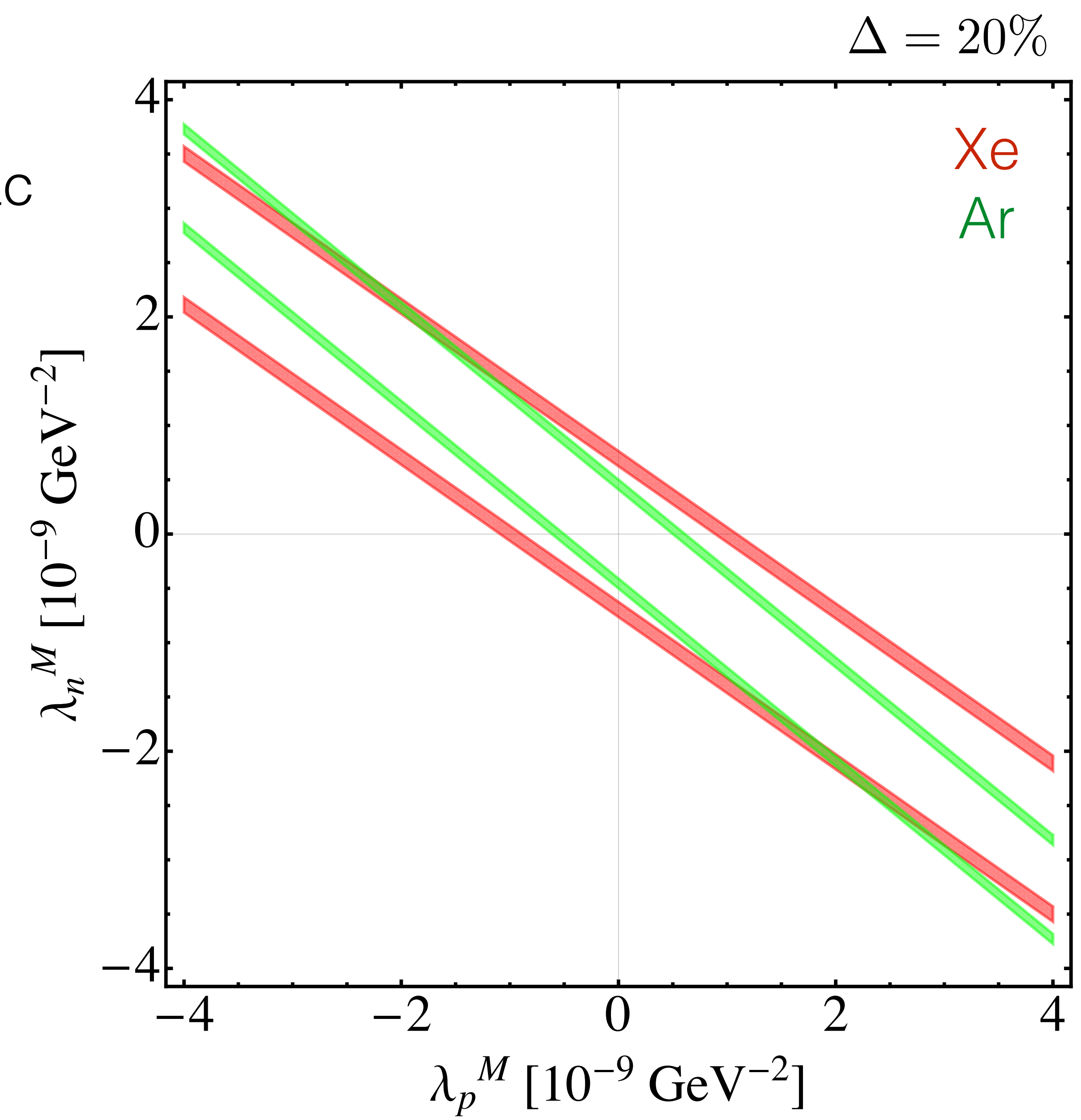

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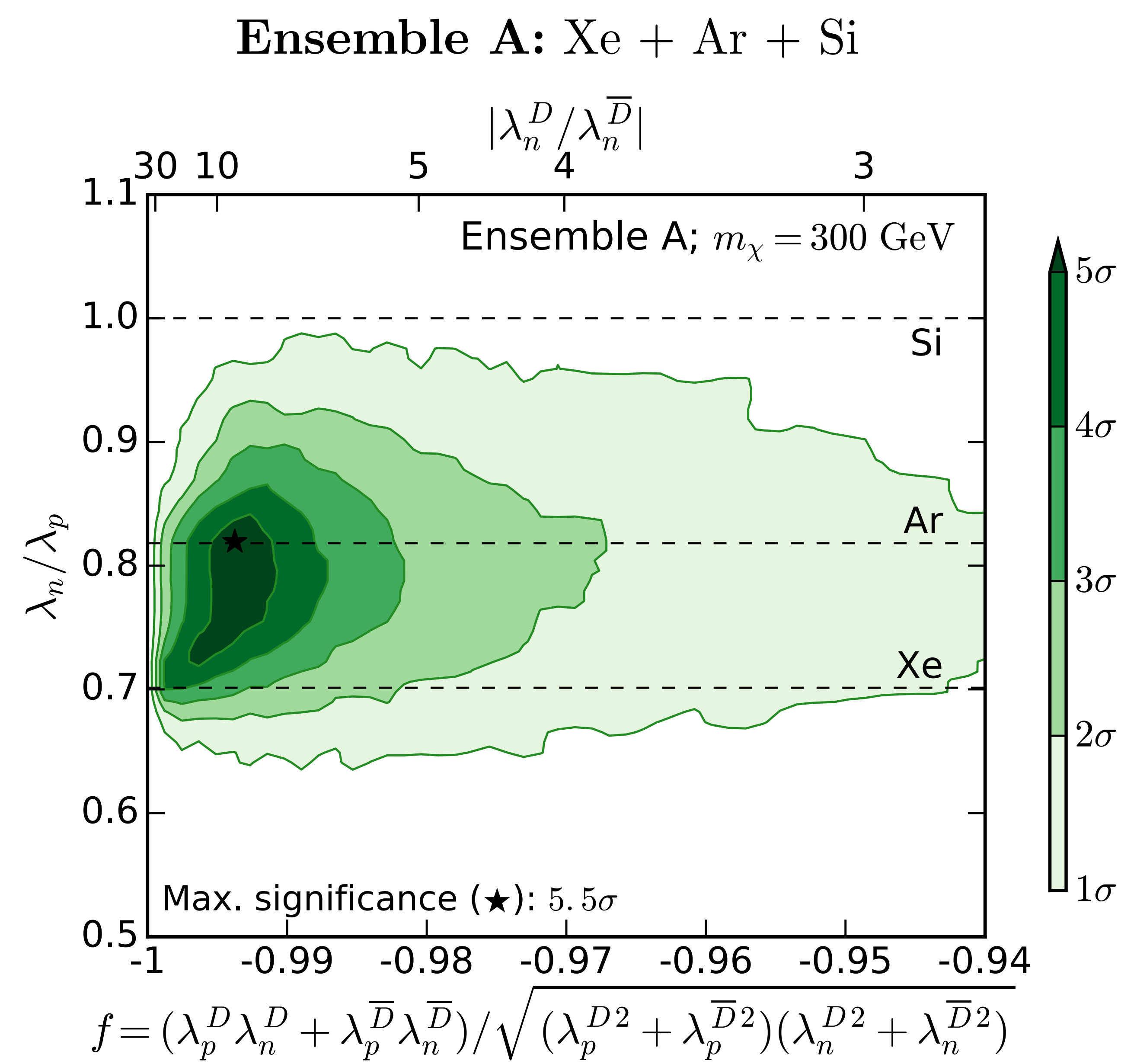

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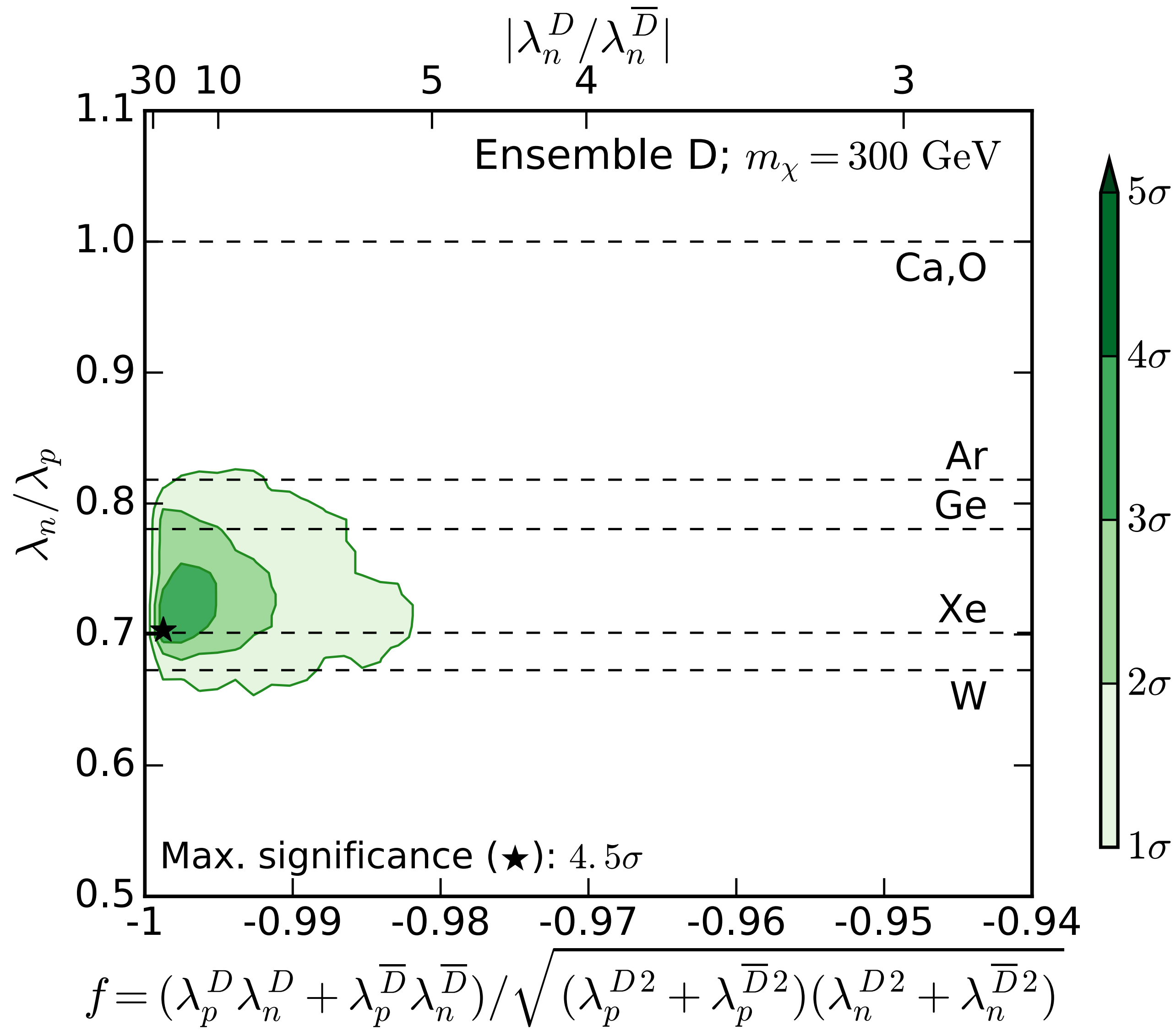
Discrimination Significance: Dirac vs. Majorana

Generate mock data, compare likelihood of Dirac and Majorana models…

Ensemble D: $\mathrm{Xe} + \mathrm{Ar} + 50\%\,\mathrm{Ge} + 50\%\,\mathrm{CaWO_4}$



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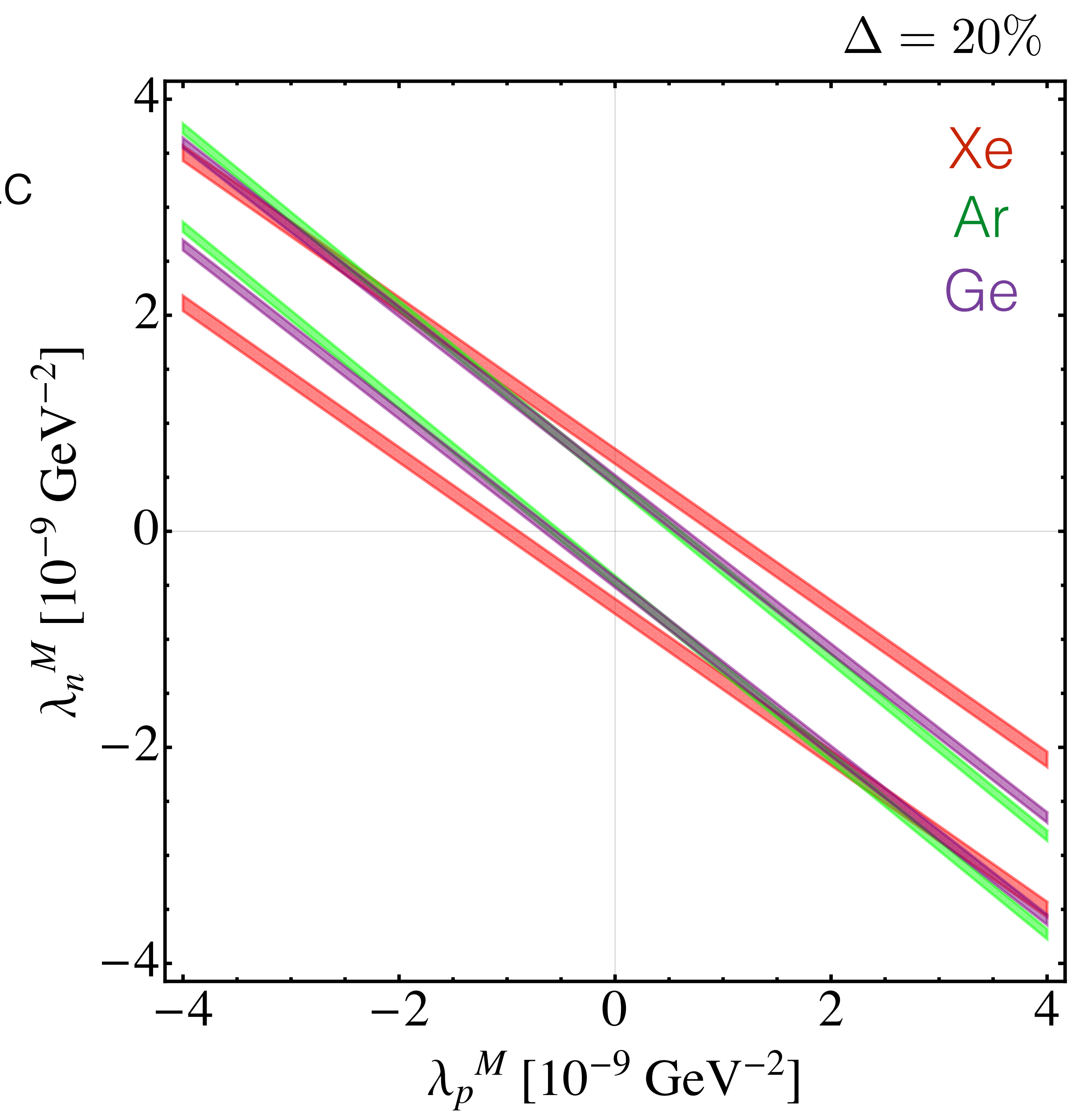
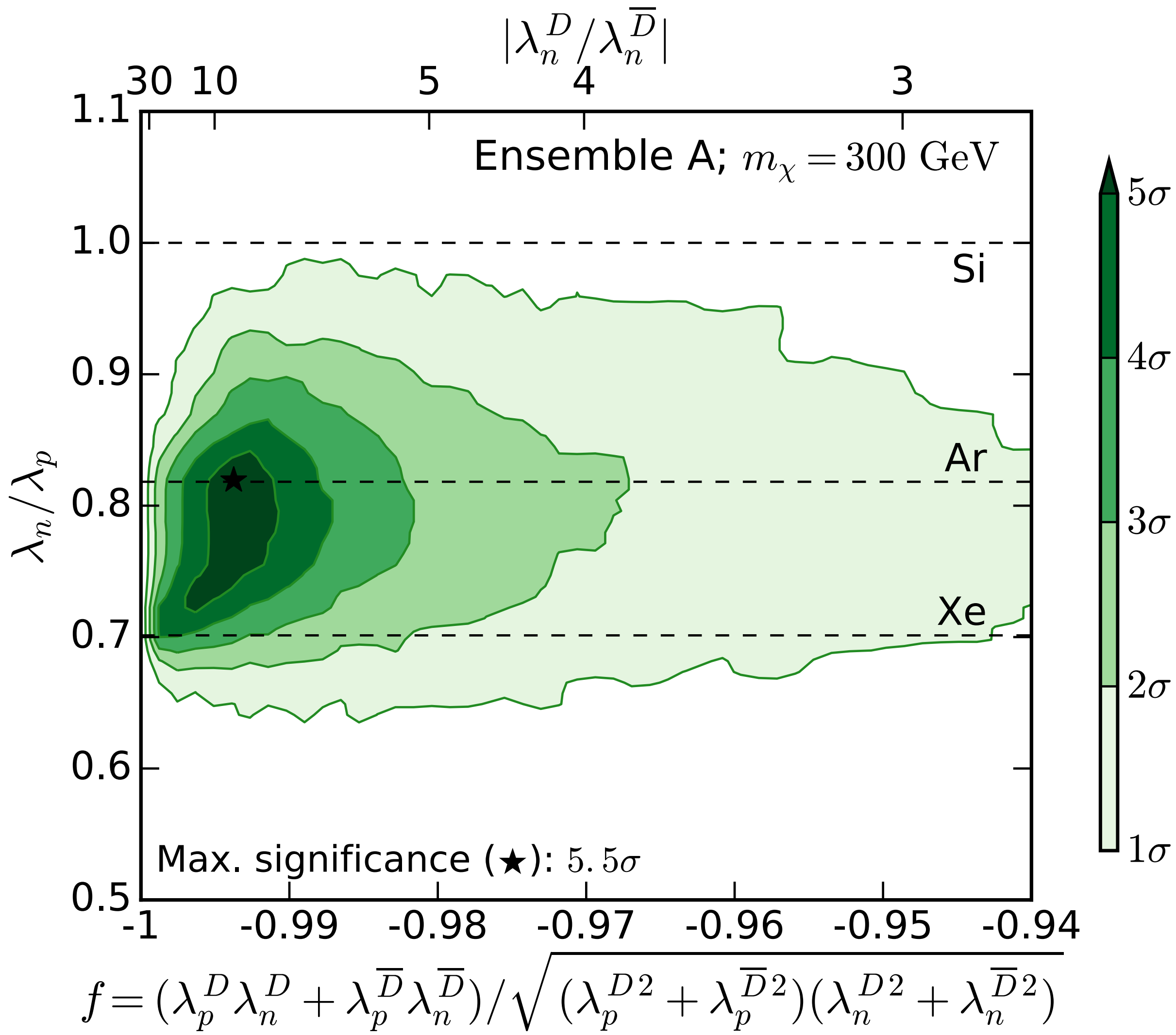
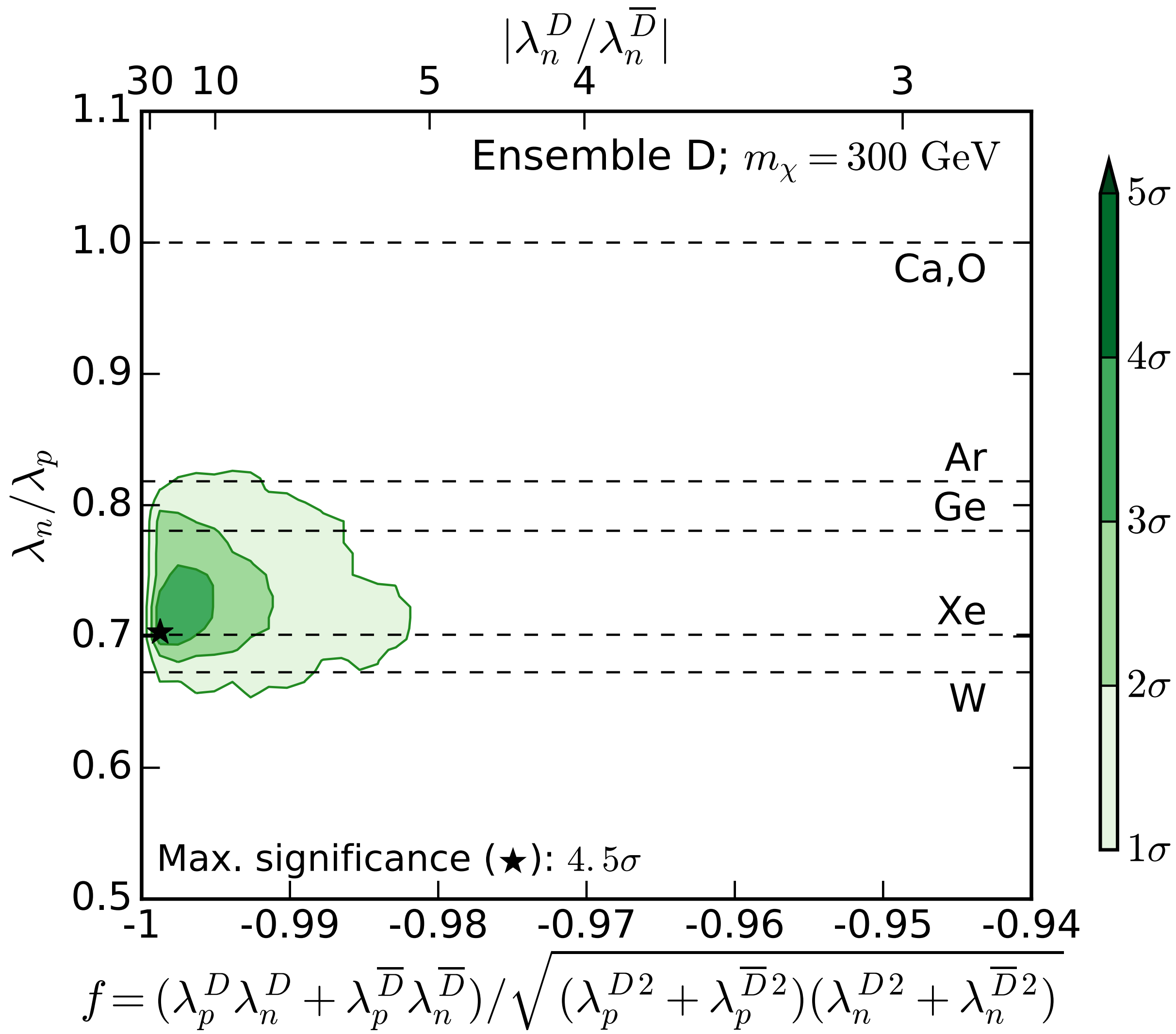


Comparing Ensembles

Ensemble A:
Xe + Ar + Si

Ensemble D:
Xe + Ar + 50% Ge + 50% $CaWO_4$





Silicon target helps determine particle/antiparticle nature of DM, but only in a small (fine-tuned?) region of parameter space…

Direct Detection of Dark Matter
Overview and introduction ✓

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Target Complementarity ✓

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Spin-dependent interaction

Velocity/momentum suppressed

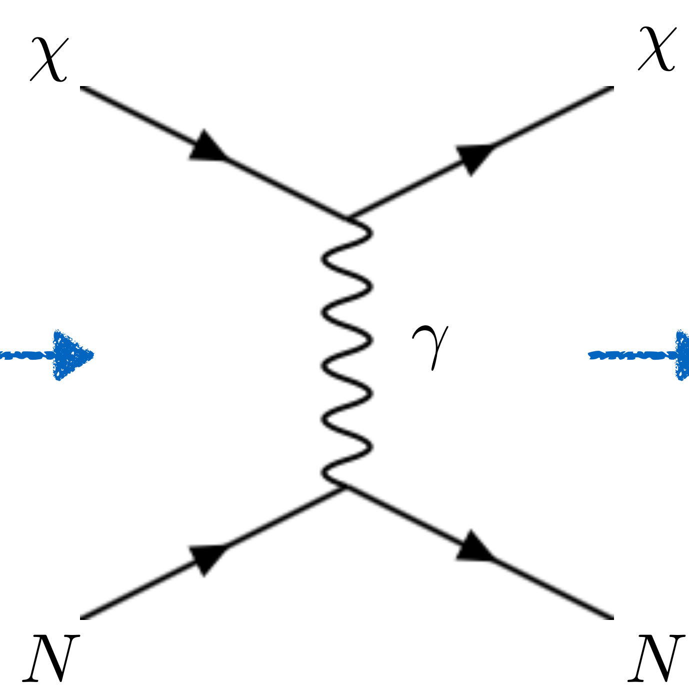
In some cases, we may be interested in these velocity/momentum suppressed interactions…

Example: Anapole Dark Matter

[1211.0503, 1401.4508, 1506.04454]

If DM has an 'anapole' moment
(lowest order EM moment possible for a Majorana fermion),
the interaction with nucleons is higher order in DM velocity, v.

$$\mathcal{O}_A = \bar{\chi}\gamma^\mu\gamma^5\chi\,\partial^\nu F_{\mu\nu}$$



$$\mathcal{O}_A^{(N)} = eQ_N\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{N}\gamma_\mu N$$

More general interactions

Can write non-relativistic (NR) DM-*nucleon* Lagrangian as an expansion in:

[Fan et al - 1008.1591, Fitzpatrick et al. - 1203.3542]

Recoil momentum - $\vec{q}$

DM velocity - $\vec{v}$

$$\mathcal{L} \supset \mathcal{L}_0 + \mathcal{L}_1(\vec{v}) + \mathcal{L}_2(\vec{q}) + \mathcal{L}_3(\vec{v}, \vec{q}) + \ldots$$

'Standard' interactions (zeroth order)

'Non-standard' interactions (higher order)

More general interactions

Can write non-relativistic (NR) DM-*nucleon* Lagrangian as an expansion in:

[Fan et al - 1008.1591, Fitzpatrick et al. - 1203.3542]

Recoil momentum - $\vec{q}$

Transverse DM velocity - $\vec{v}_\perp$

$$\mathcal{L} \supset \mathcal{L}_0 + \mathcal{L}_1(\vec{v}_\perp) + \mathcal{L}_2(\vec{q}) + \mathcal{L}_3(\vec{v}_\perp, \vec{q}) + ...$$

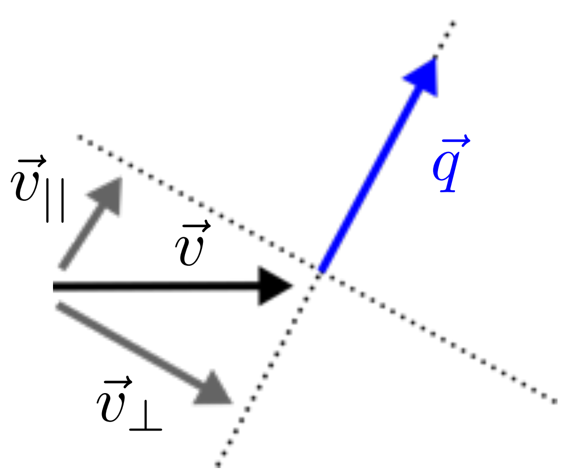
'Standard' interactions (zeroth order)

'Non-standard' interactions (higher order)

The DM velocity operator is not Hermitian, so it can appear only through the Hermitian *transverse velocity*:

Invariant under exchange of incoming and outgoing particles

$$\vec{v}_\perp = \vec{v} + \frac{\vec{q}}{2\mu_{\chi N}} \qquad \Rightarrow \vec{v}_\perp \cdot \vec{q} = 0$$



Non-Relativistic Effective Field Theory (NREFT)

Write down all operators which are Hermitian, Galilean invariant and time-translation invariant:

SI → $\mathcal{O}_1 = 1$

SD → $\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$

[1008.1591, 1203.3542, 1308.6288, 1505.03117]

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Write down all operators which are Hermitian, Galilean invariant and time-translation invariant:

SI → $\mathcal{O}_1 = 1$

$\mathcal{O}_3 = i\vec{S}_N \cdot (\vec{q} \times \vec{v}^\perp)/m_N$

SD → $\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$

$\mathcal{O}_5 = i\vec{S}_\chi \cdot (\vec{q} \times \vec{v}^\perp)/m_N$

$\mathcal{O}_6 = (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q})/m_N^2$

$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$

$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$

$\mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{q})/m_N$

$\mathcal{O}_{10} = i\vec{S}_N \cdot \vec{q}/m_N$

$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \vec{q}/m_N$

$\mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$

$\mathcal{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^\perp)(\vec{S}_N \cdot \vec{q})/m_N$

$\mathcal{O}_{14} = i(\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{v}^\perp)/m_N$

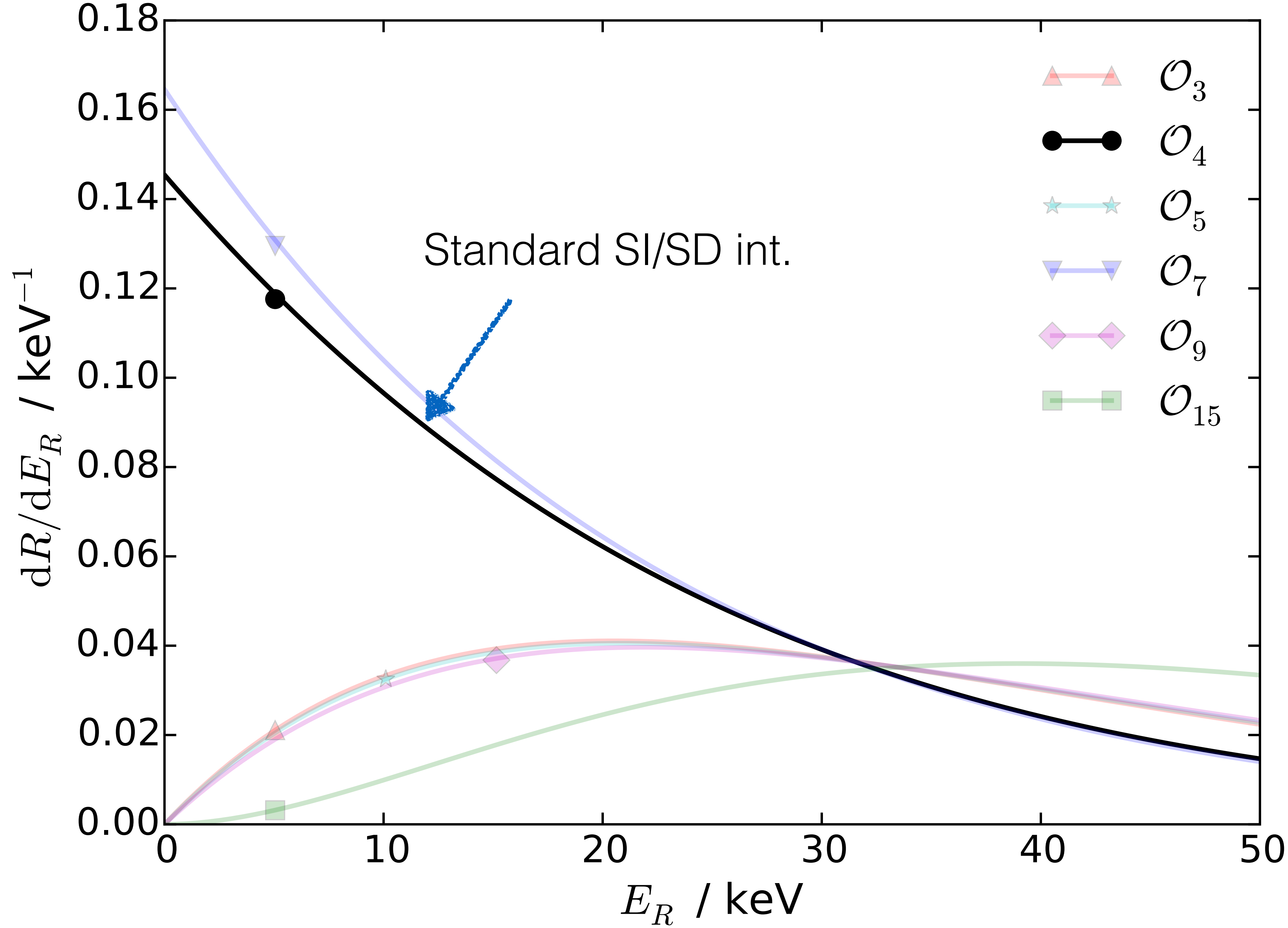
$\mathcal{O}_{15} = -(\vec{S}_\chi \cdot \vec{q})((\vec{S}_N \times \vec{v}^\perp) \cdot \vec{q}/m_N^2$

$\vdots$

Whole list of new operators, higher order in $\mathrm{v}_\perp$ and $E_R \sim q^2$

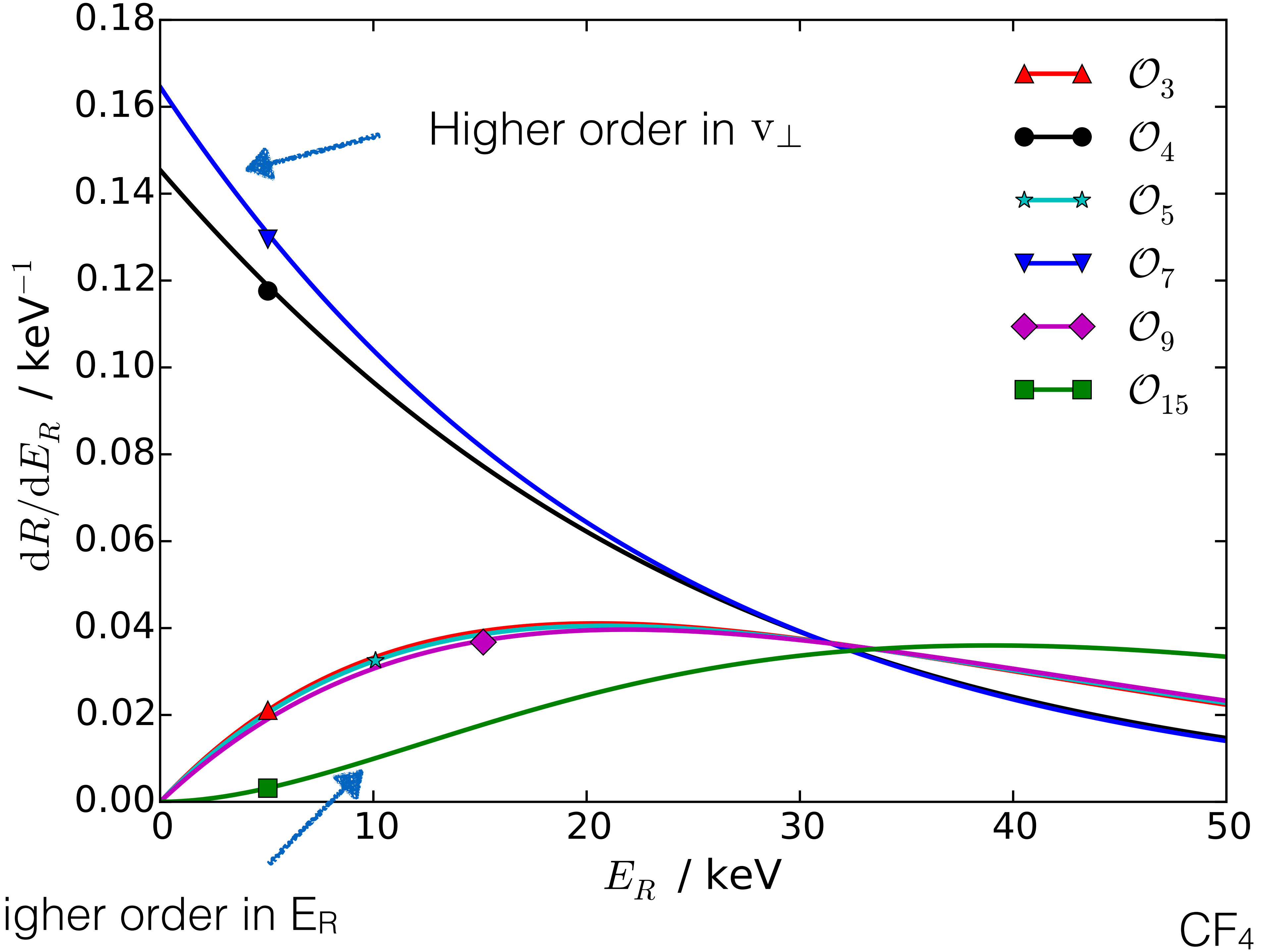
[1008.1591, 1203.3542, 1308.6288, 1505.03117]

Non-standard Interactions



CF_4 detector,
$m_\chi = 100$ GeV

Non-standard Interactions

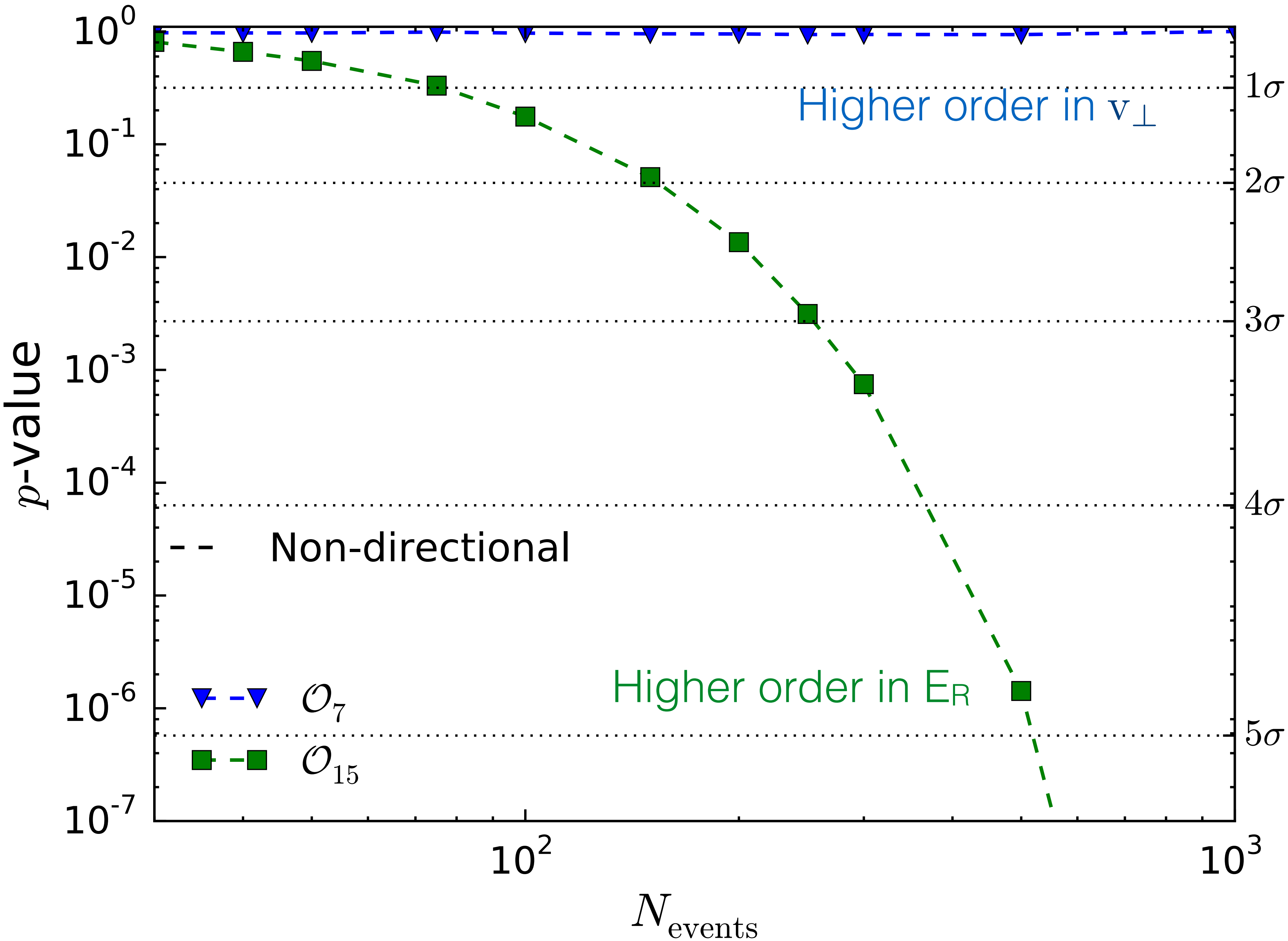


CF_4 detector,

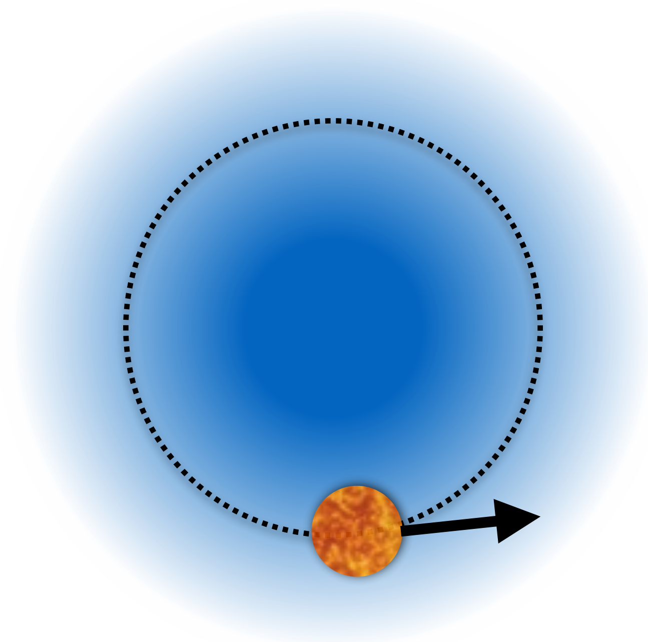
$m_\chi = 100$ GeV

Distinguishing Interactions - Energy only

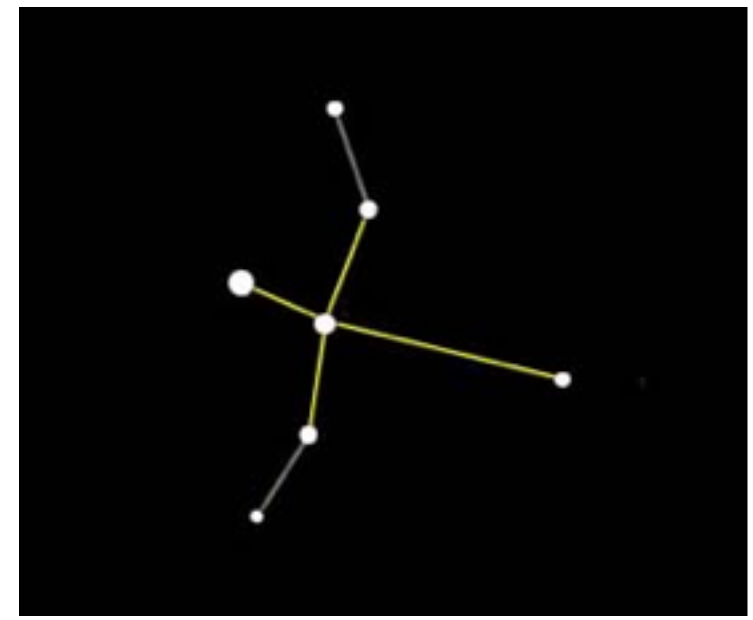
How many events are required to detect the effect of a 'non-standard' interaction?



Directional Detection of Dark Matter

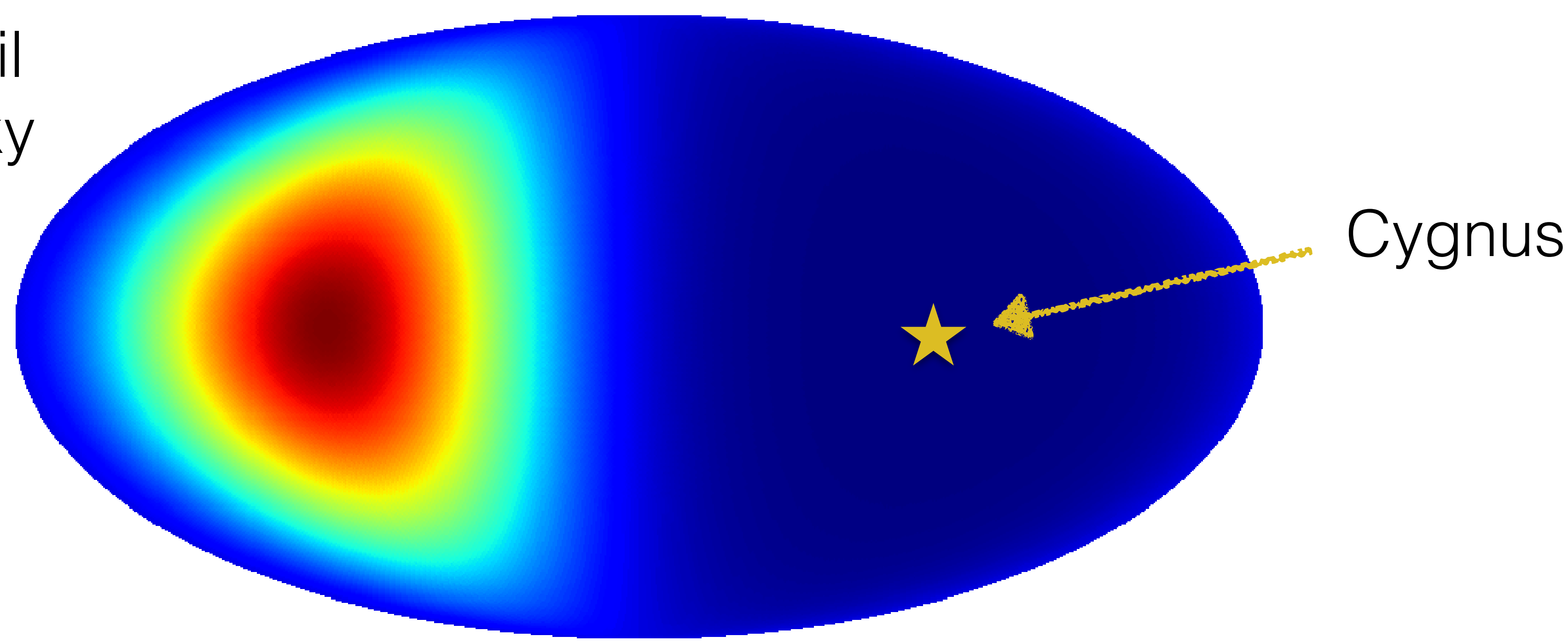


$v_{\rm sun} \sim 220\ {\rm km\,s^{-1}}$

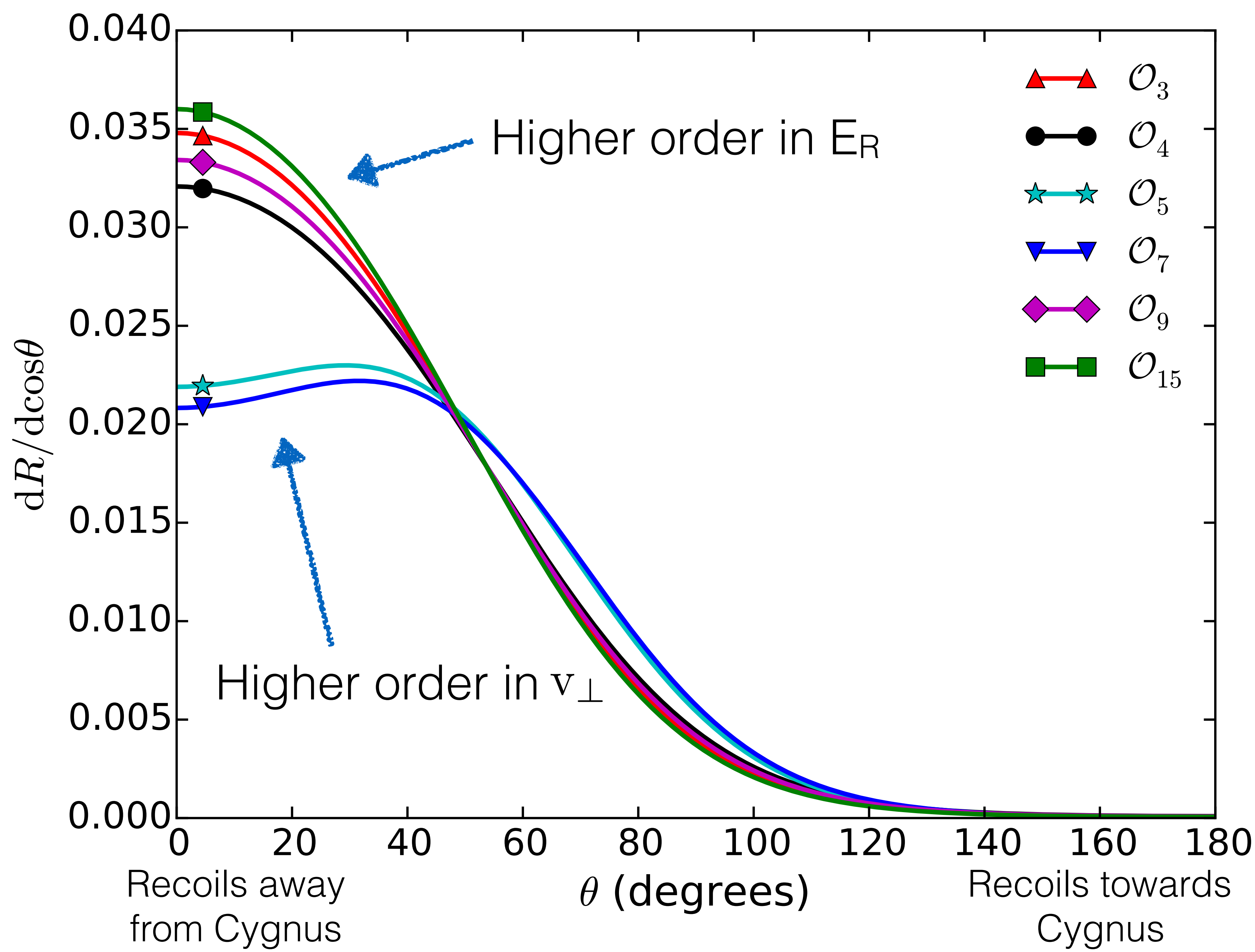


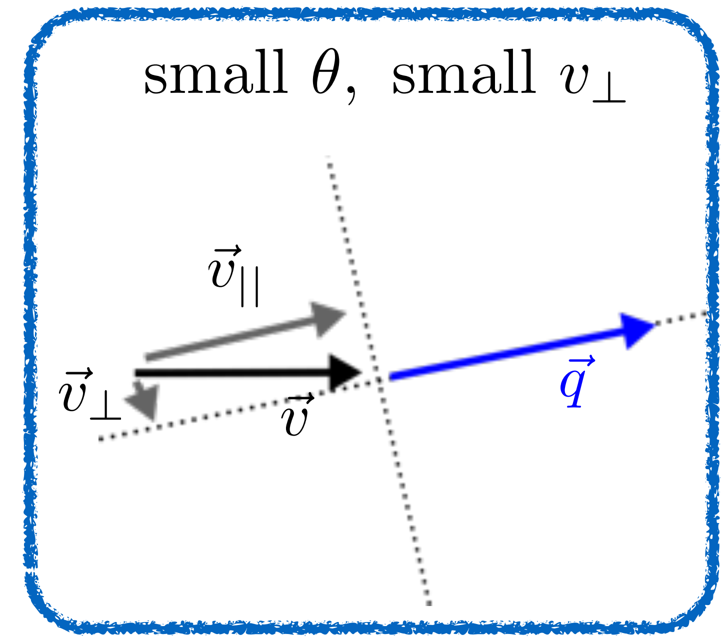
Cygnus constellation

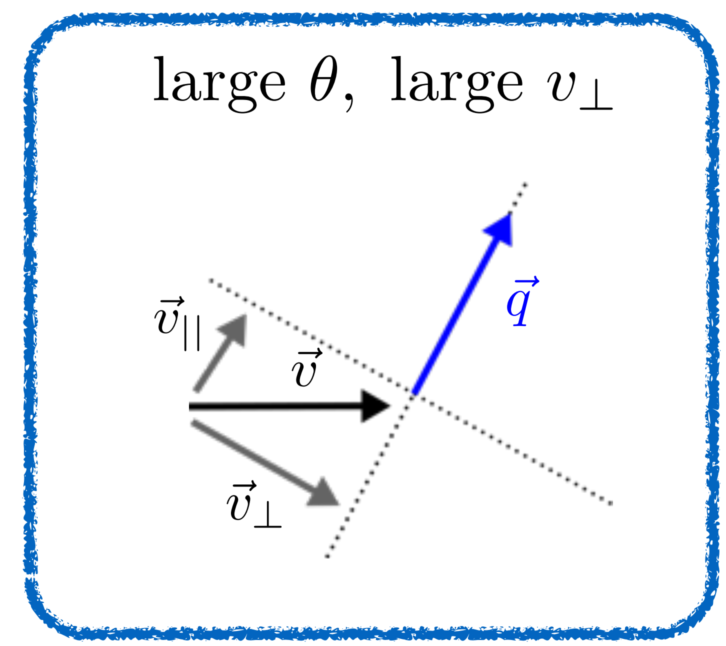
Distribution of recoil directions on the sky



Directional Spectrum





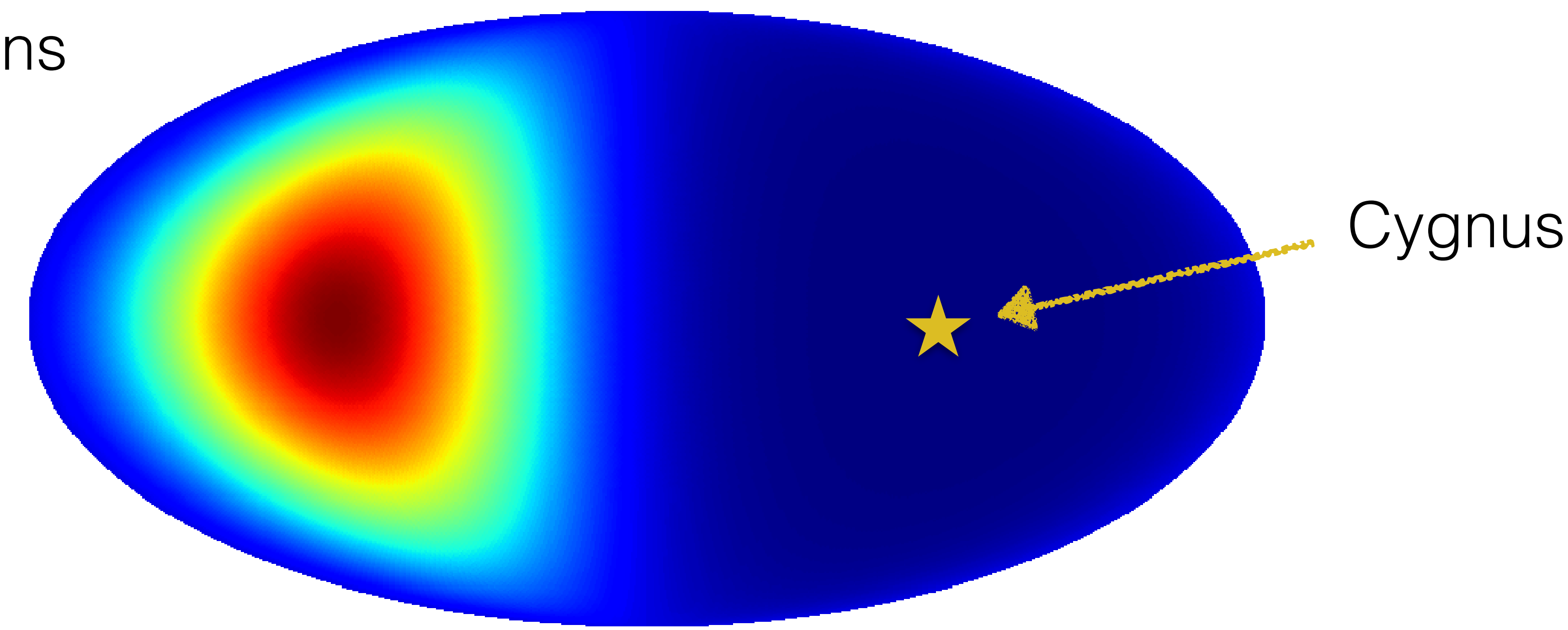


Also note: $q = 2\mu_{\chi N}\vec{v}\cdot\hat{q}$
$= 2\mu_{\chi N} v \cos\theta$

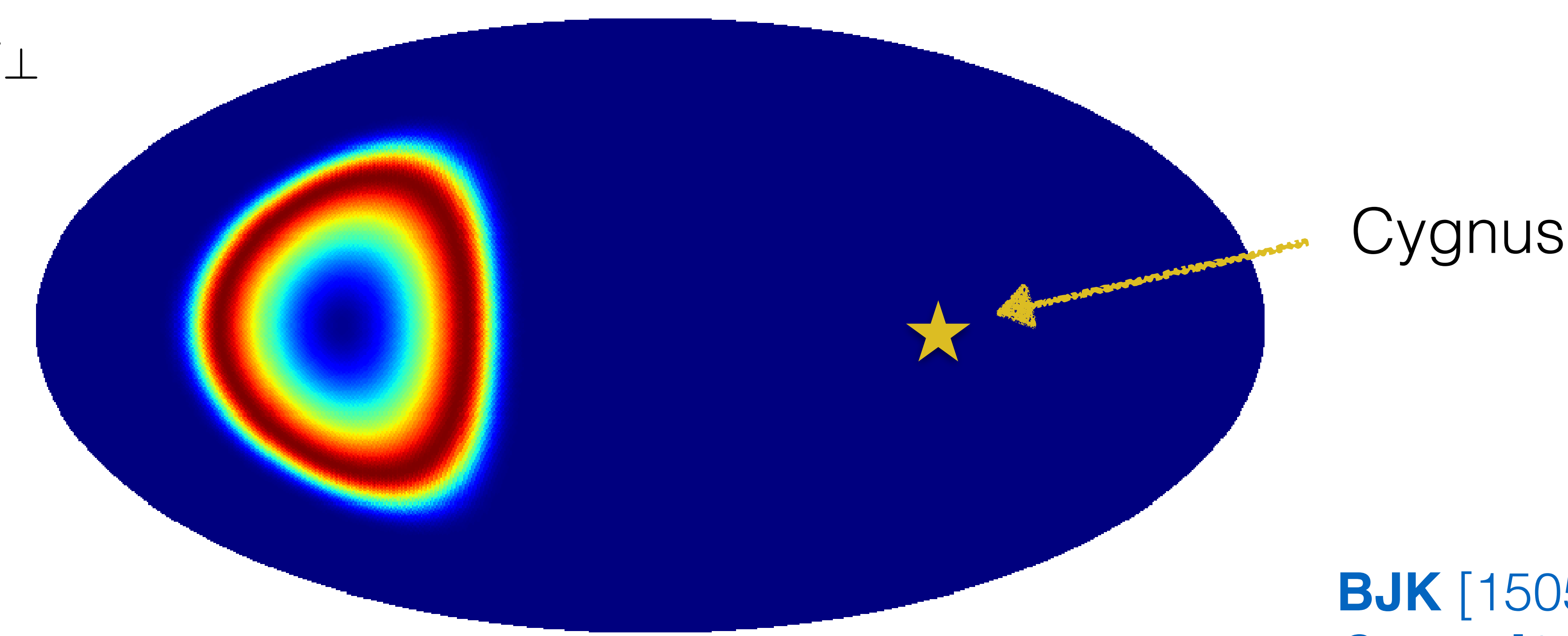
See also Catena [1505.06441]

Ring-like feature

Standard interactions



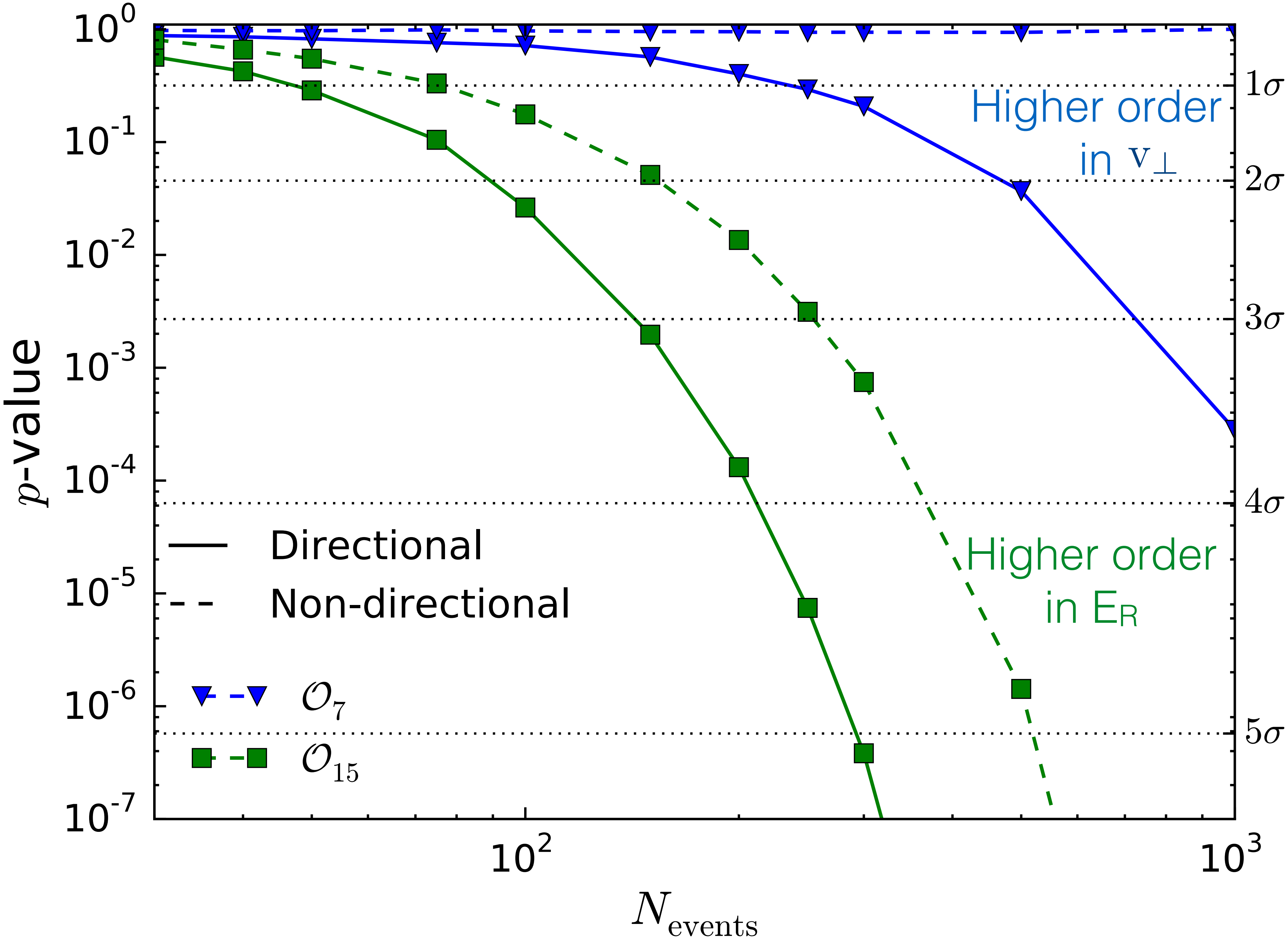
Higher order in $v_\perp$



BJK [1505.07406],
Catena [1505.06441]

Distinguishing Interactions - Directionality

How many events are required to detect the effect of a 'non-standard' interaction?

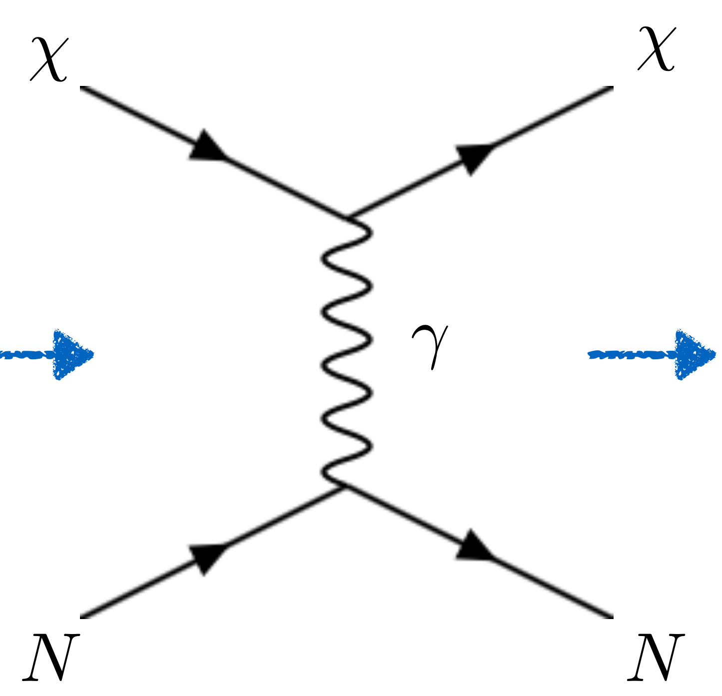


Example: Anapole Dark Matter

[1211.0503, 1401.4508, 1506.04454]

If DM has an 'anapole' moment
(lowest order EM moment possible for a Majorana fermion),
the interaction with nucleons is higher order in DM velocity, v.

$$\mathcal{O}_A = \bar{\chi}\gamma^\mu\gamma^5\chi\,\partial^\nu F_{\mu\nu}$$



$$\mathcal{O}_A^{(N)} = eQ_N\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{N}\gamma_\mu N$$

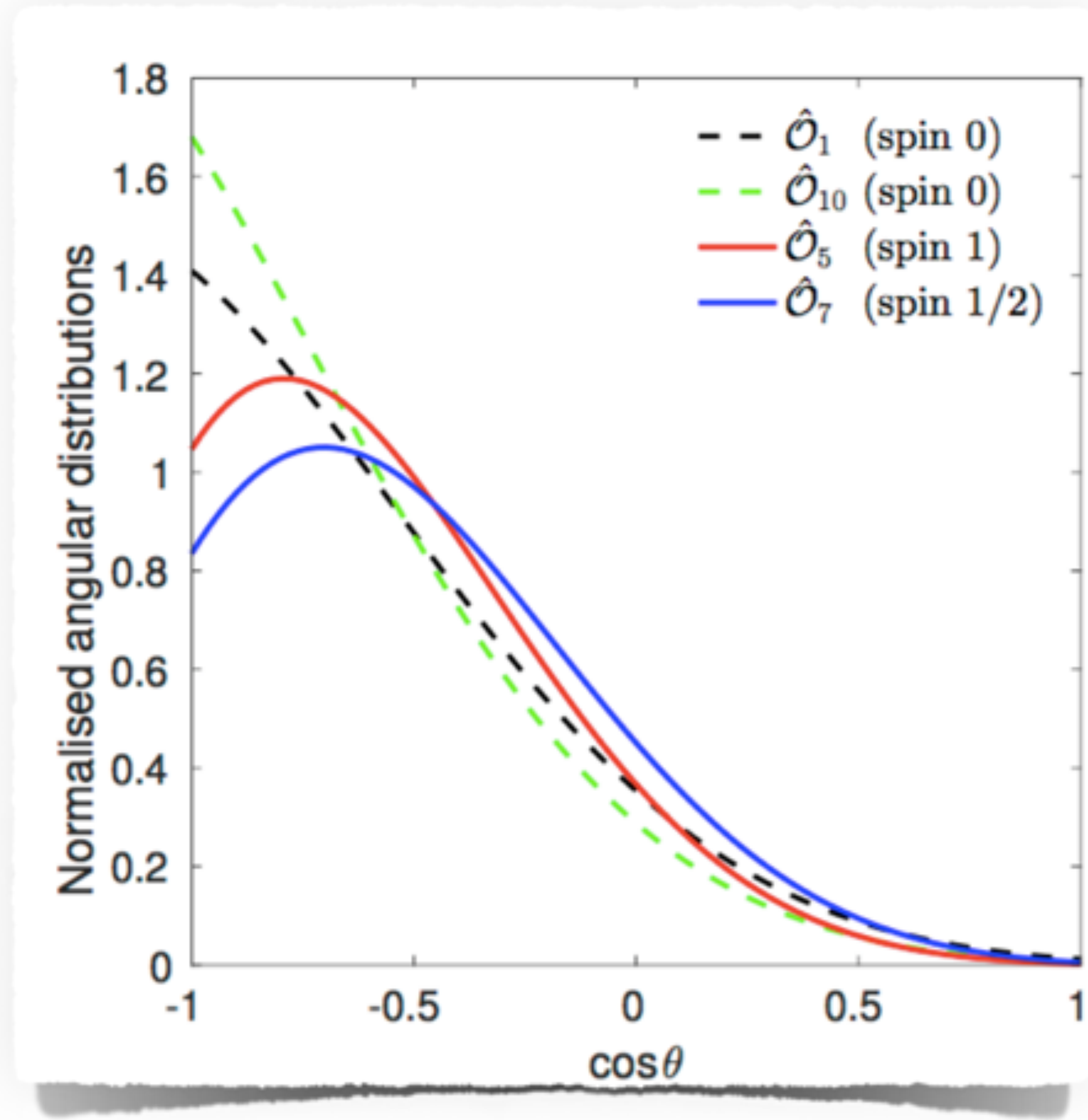
In a single experiment, this interaction can only be discriminated
from standard interactions using *directionality*!

Dark Matter spin from directional experiments?

Catena et al. [1706.09471]

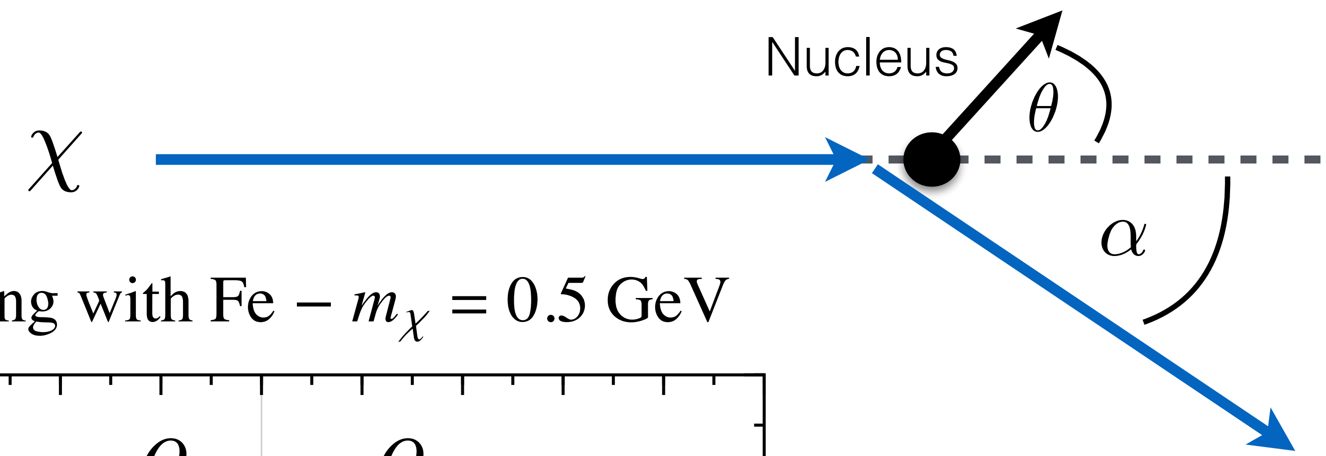
If Dark Matter is a spin-0 particle, it cannot have interactions which are higher order in $v_\perp$ ....

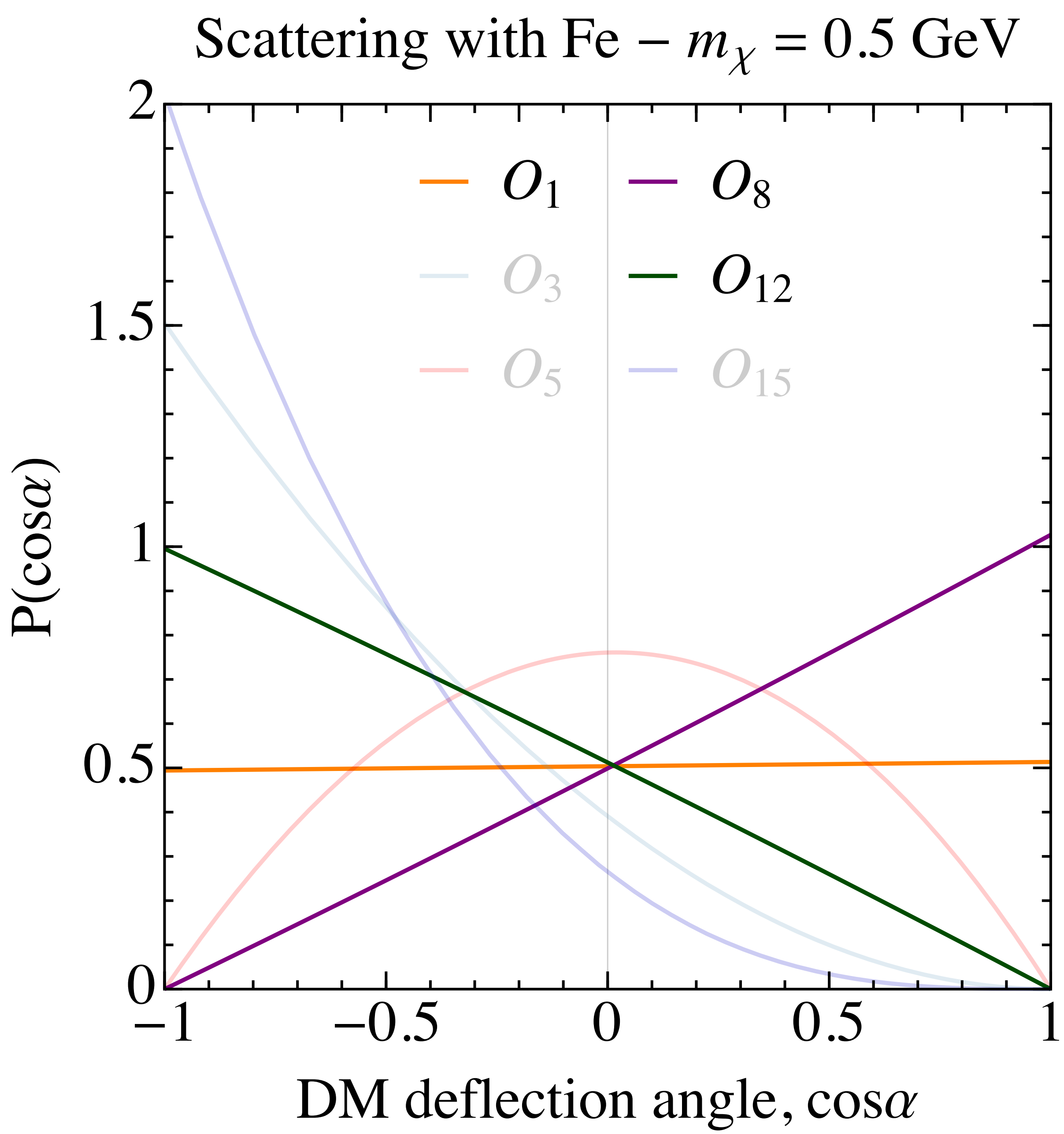
If observed, would rule out scalar DM!



But making a directionally-sensitive experiment is *hard*...

‘Deflection’ of Dark Matter





Backward Forward

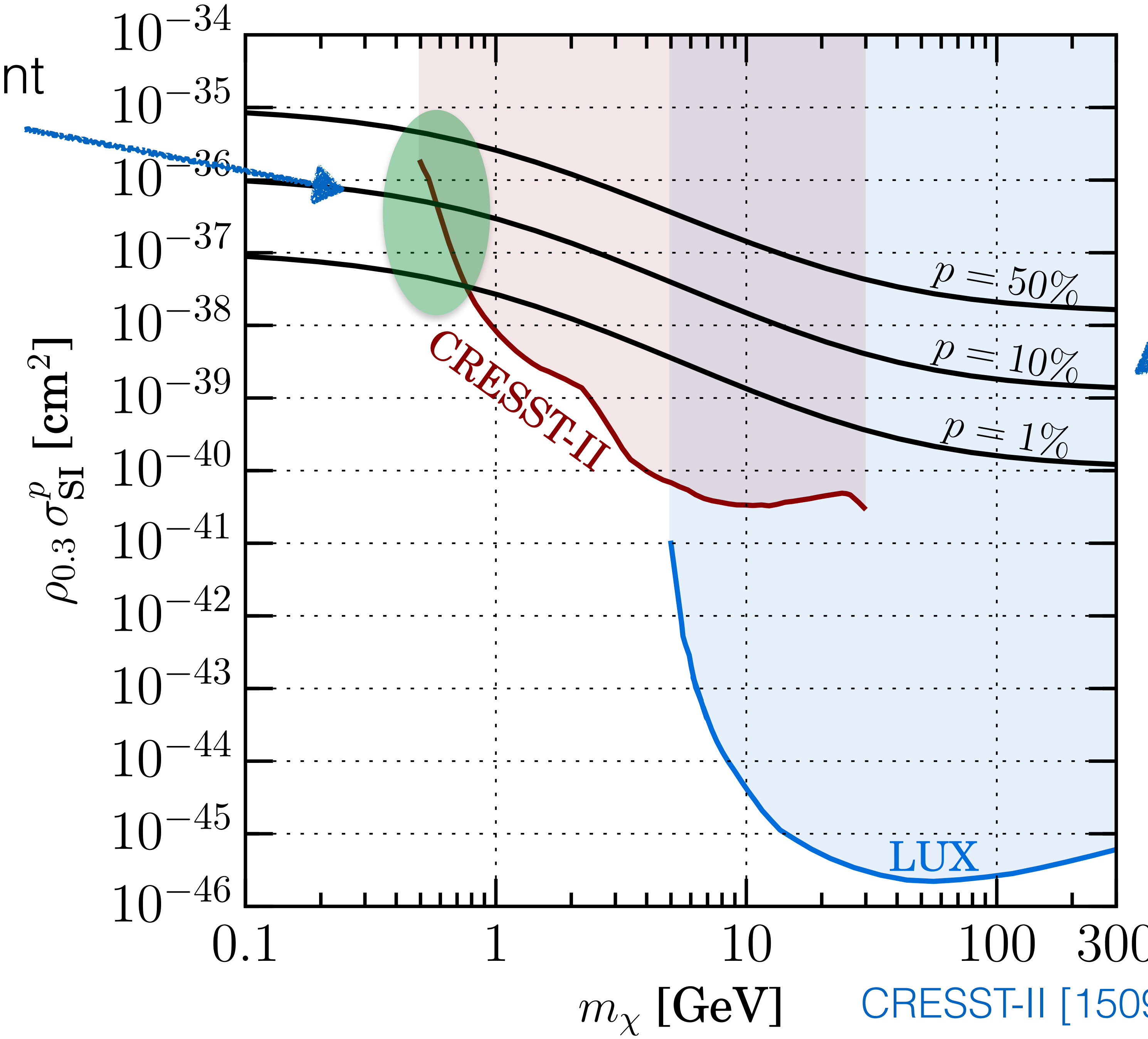
$\mathcal{O}_1$ - Standard SI

$\mathcal{O}_8$ - Higher order in $v_\perp$

$\mathcal{O}_{12}$ - Higher order in q^2

Sub-GeV DM

Could be relevant in this region!



Probability of scattering while passing through the Earth

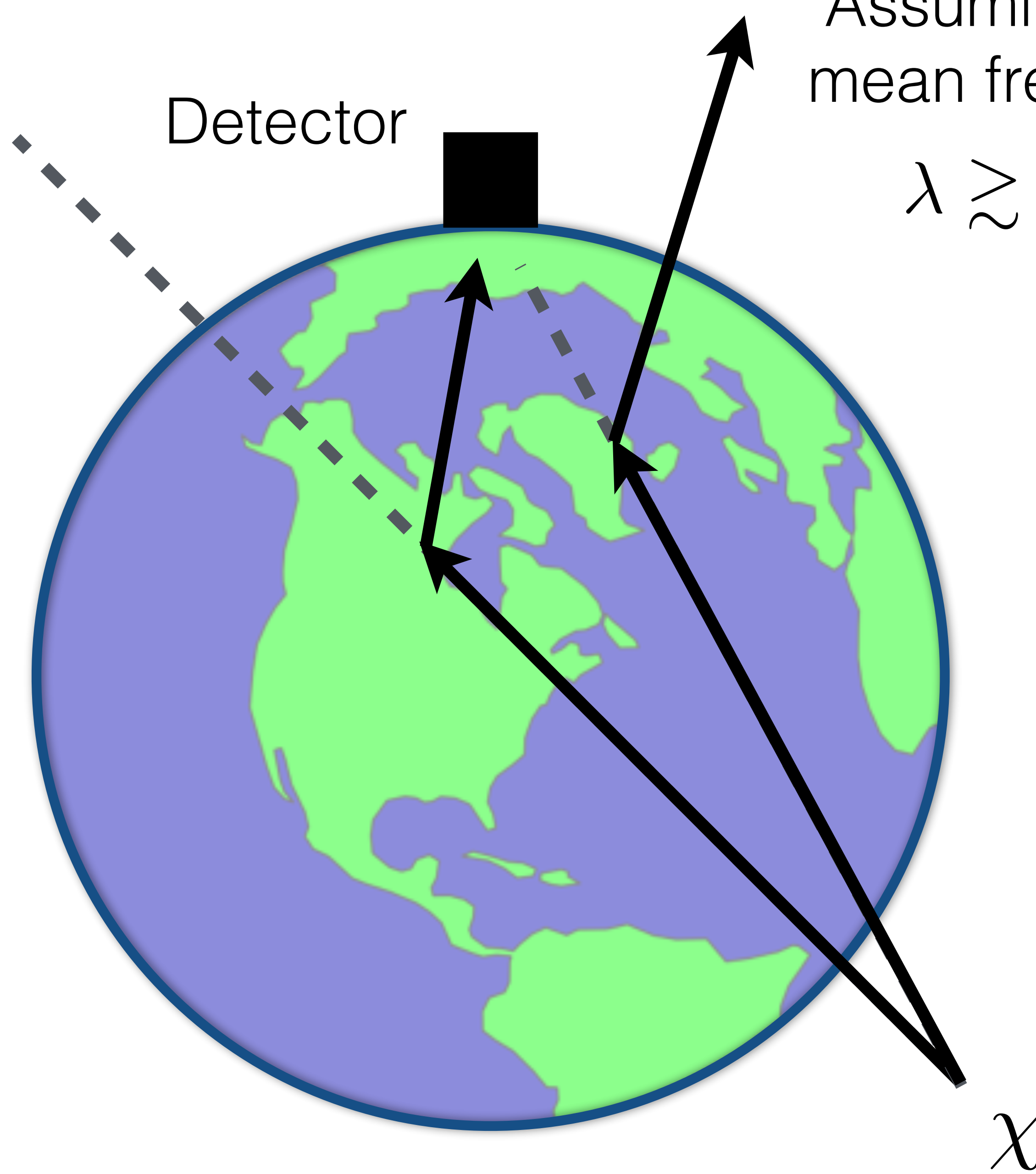
CRESST-II [1509.01515]

LUX [1608.07648]

+ many others…

Earth-Scattering

Calculate distribution of particles at the detector taking into account both attenuated and deflected DM particles



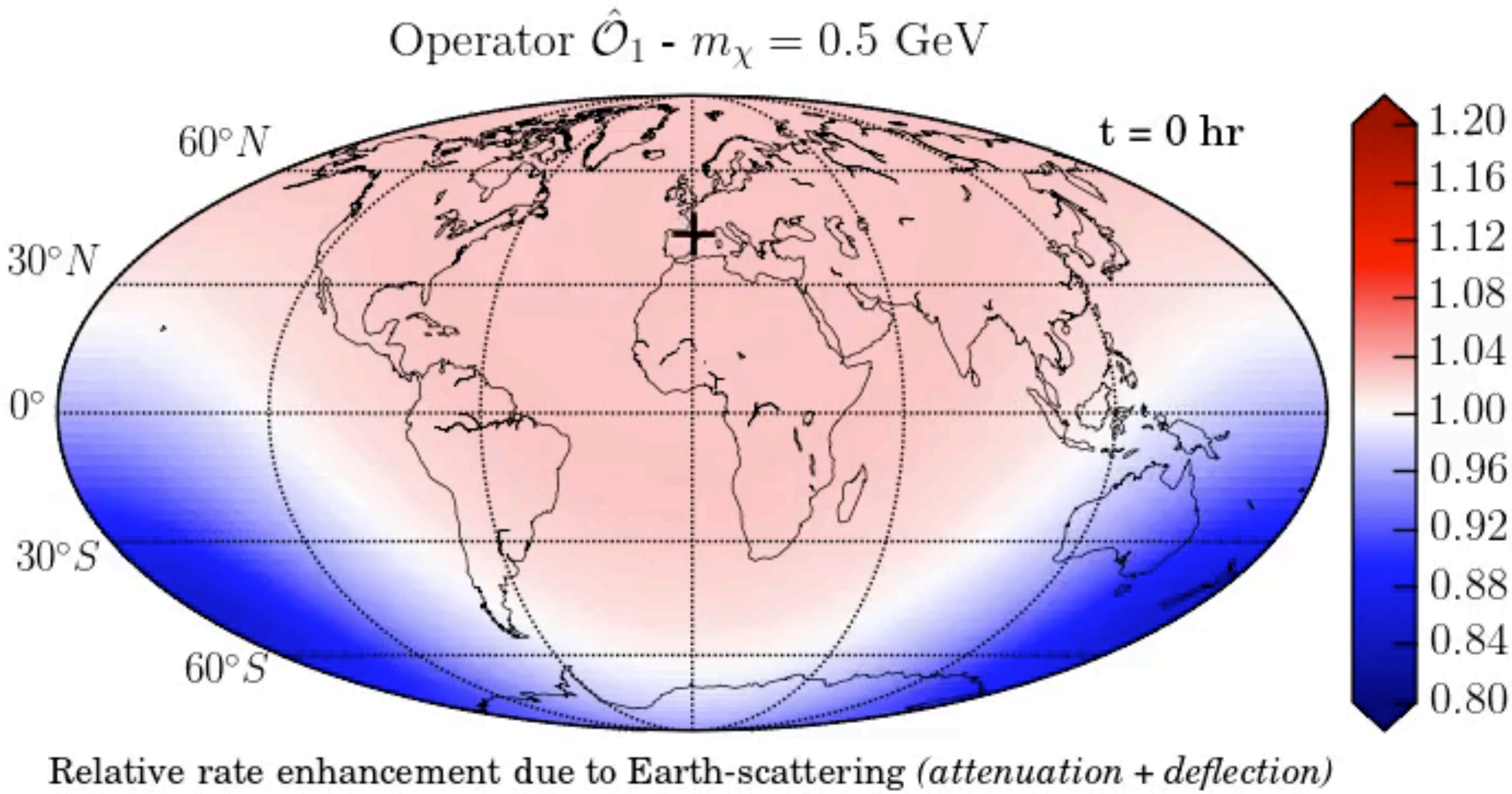
Detailed implementation in EARTHSHADOW code [https://github.com/bradkav/EarthShadow]

Perturbation in the velocity distribution due to scattering in the Earth lead to altered flux, directionality, daily modulation…

BJK, Catena, Kouvaris [1611.05453]

Mapping the Direct Detection Rate

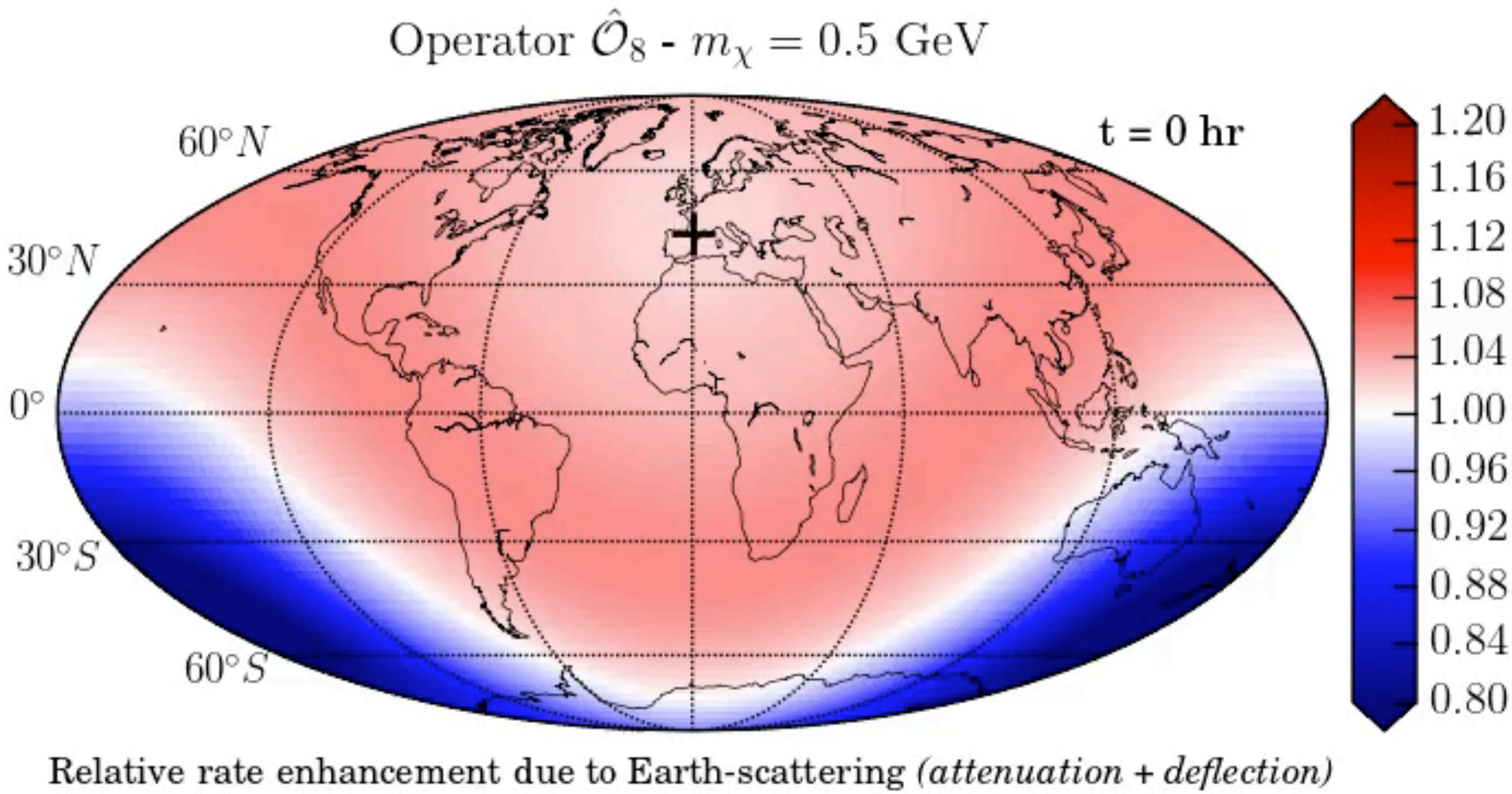
Operator 1 - isotropic deflection



Rate in CRESST-like experiment

Mapping the Direct Detection Rate

Operator 8 - forward deflection

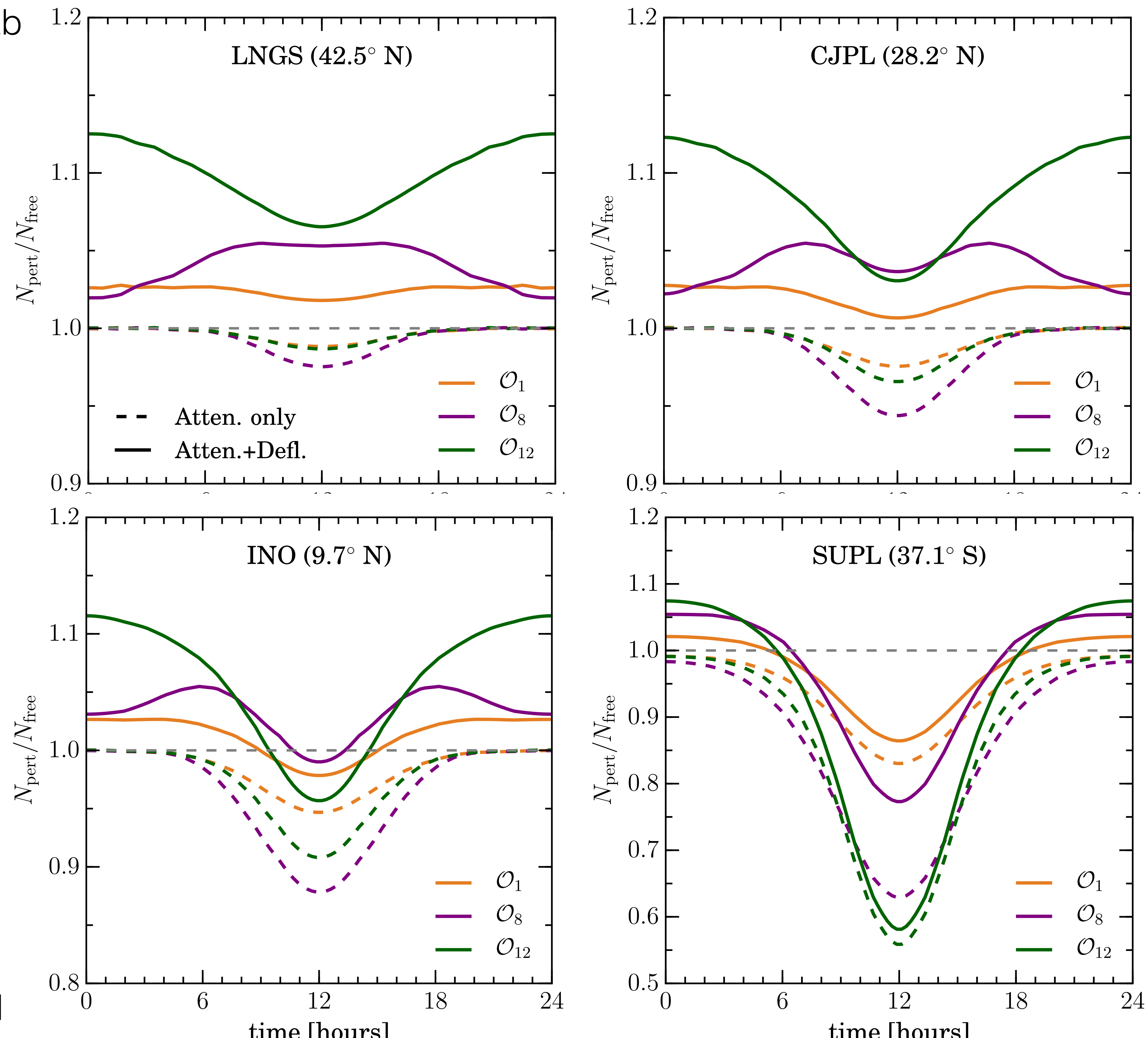


Rate in CRESST-like experiment

Around the world

Gran Sasso Lab

China Jinping Lab

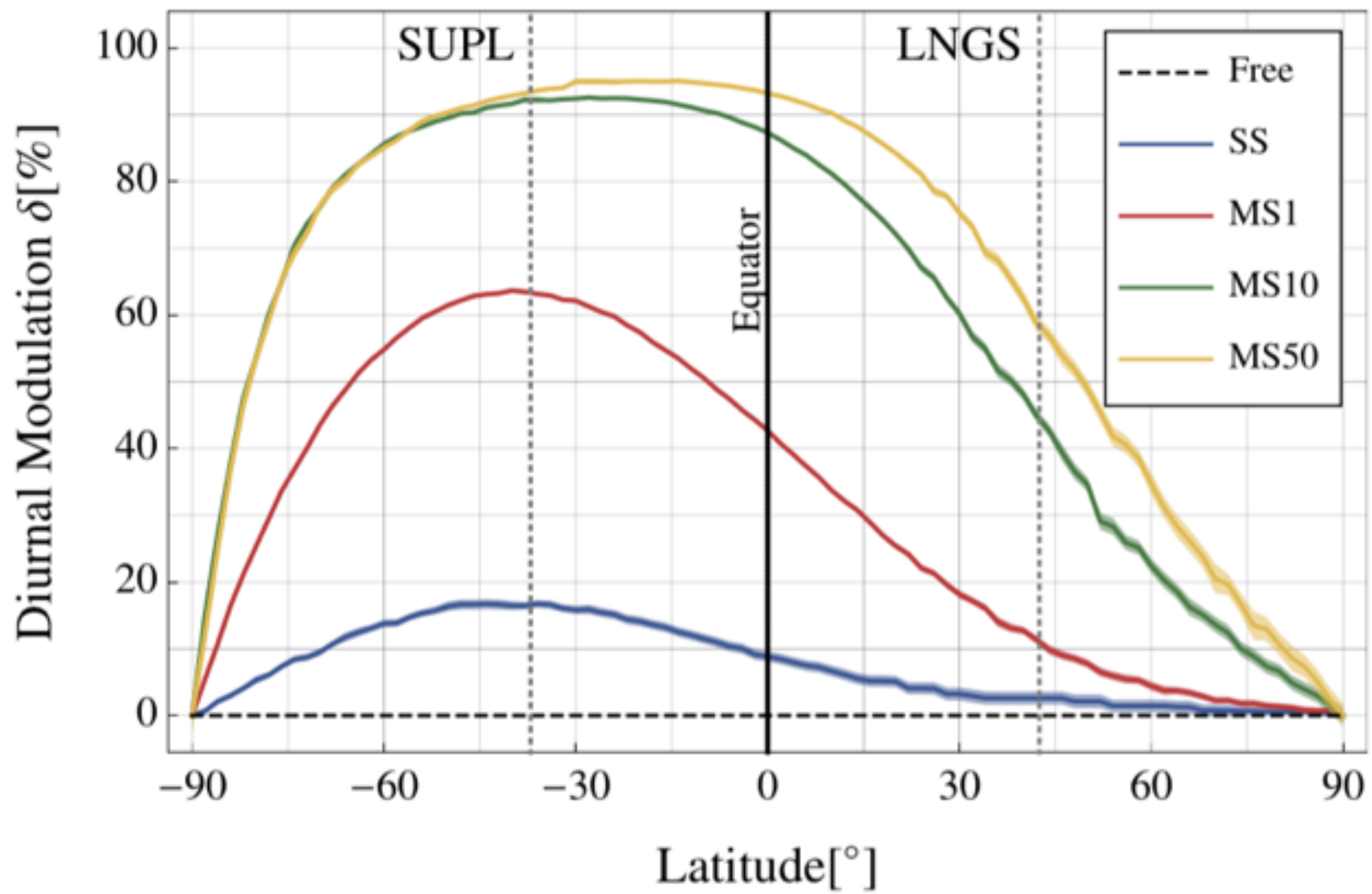


India-based Neutrino Observatory

Stawell Lab, Australia

Monte Carlo Results - DaMaSCUS

Going to large cross section with Monte Carlo codes:



Large O(1) daily modulation if DM scatters ~50 times during Earth crossing ("MS50")

Emken & Kouvaris [1706.02249]

DaMaSCUS: http://cp3-origins.dk/site/damascus

Direct Detection of Dark Matter
Overview and introduction

Is the DM its own antiparticle?
Target Complementarity

Queiroz, Rodejohann, Yaguna [1610.06581]
BJK, Queiroz, Rodejohann, Yaguna [1706.07819]

What is the form of the DM-nucleon interaction?
Directionality and Time-dependence

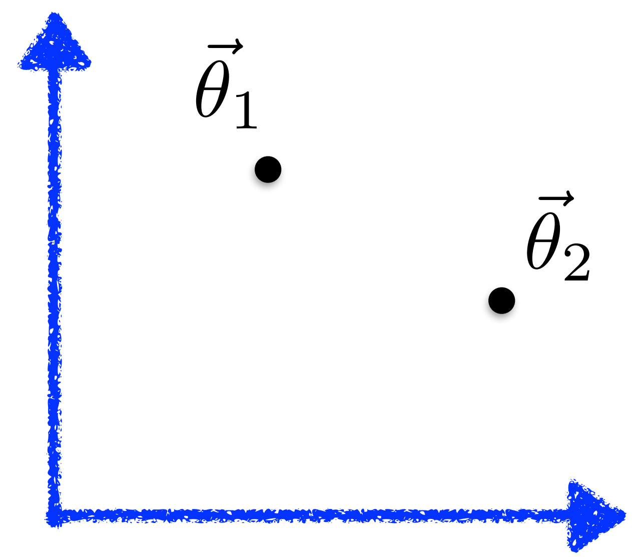
BJK [1505.07406]
BJK, Catena, Kouvaris [1611.05453]

Where in the parameter space can we distinguish different models?
Mapping out the whole parameter space with SwordFish

Edwards & Weniger [1712.05401]
Edwards, **BJK** & Weniger [1804.XXXXX]

Challenge of Model Comparison

Need to compare likelihood of data D_A for different parameter points



Likelihood ratio can be used to establish discriminability:

$$\mathrm{TS}(\vec{\theta}_1,\, \vec{\theta}_2) = -2\frac{\mathcal{L}(D_A(\vec{\theta}_1)|\vec{\theta}_2)}{\mathcal{L}(D_A(\vec{\theta}_1)|\vec{\theta}_1)}$$

But pair-wise comparison of points can be time-consuming
(for our 'Antiparticle' discrimination project, we needed to write a special optimiser…)

Typically rely on a (small?) number of benchmark points for comparison

E.g. Gluscevic et al. [1506.04454]

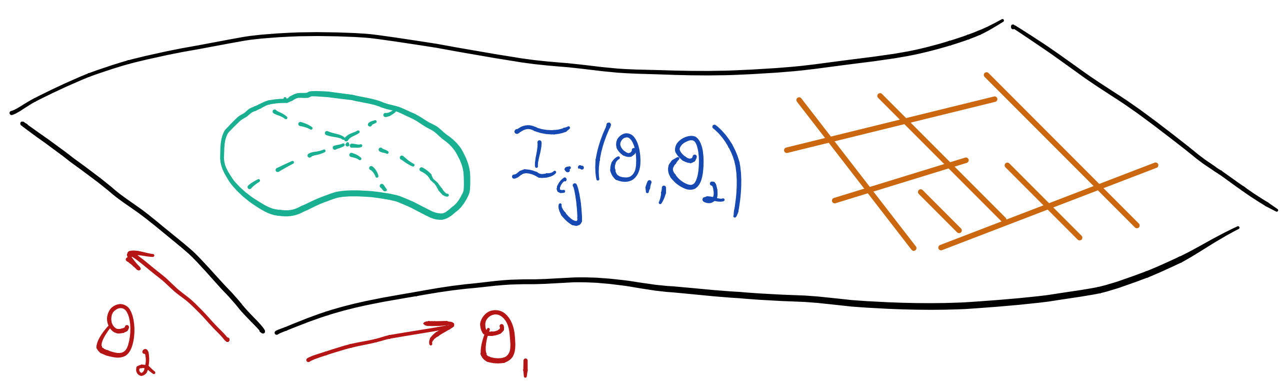
Fisher Information Matrix

Taylor expand the likelihood ratio:

$$\mathrm{TS}(\vec{\theta}_1,\, \vec{\theta}_2) = -2\frac{\mathcal{L}(D_A(\vec{\theta}_1)|\vec{\theta}_2)}{\mathcal{L}(D_A(\vec{\theta}_1)|\vec{\theta}_1)} \approx (\vec{\theta}_2 - \vec{\theta}_1)^T \mathcal{I}(\vec{\theta}_2 - \vec{\theta}_1)$$

where $\mathcal{I}_{kl} = -\left\langle \frac{\partial^2 \ln \mathcal{L}(D|\vec{\theta})}{\partial\theta_k \partial\theta_l} \right\rangle$ is the Fisher Information Matrix (FIM)

If we think of the likelihood ratio as a distance measure,
then the FIM is a metric on the parameter space…



Euclideanised Signals

Likelihood ratio can then be mapped (approximately) onto a Euclidean distance:

Parameter space → $$\mathrm{TS}(\vec{\theta}_1, \vec{\theta}_2) \approx \|\vec{x}_1 - \vec{x}_2\|^2$$ ← Signal space

Once we map from $\vec{\theta} \rightarrow \vec{x}$ we can now easily compare points in Euclidean space

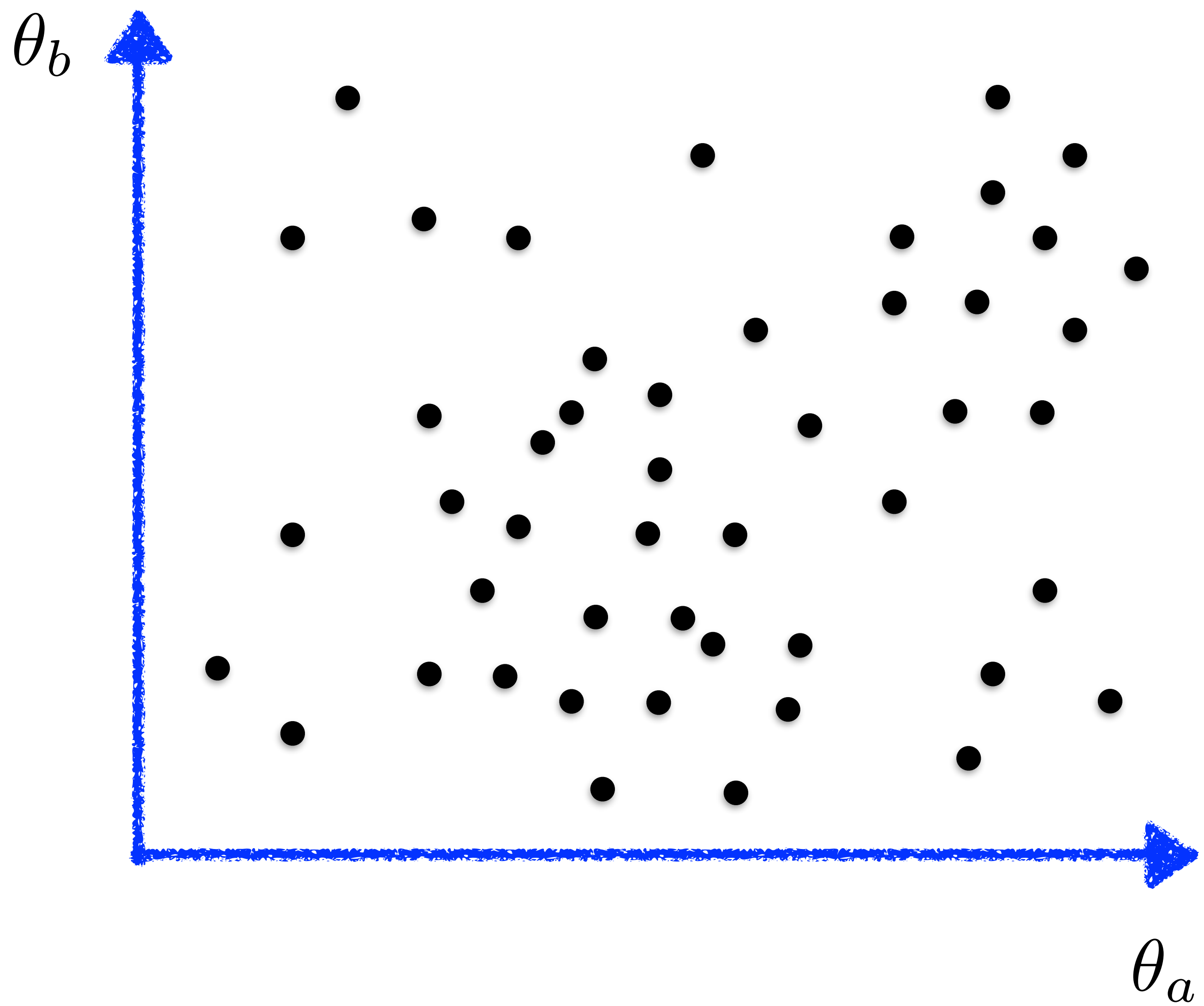
Use the publicly available SWORDFISH package to perform the analysis [1712.05401, https://github.com/cweniger/swordfish]

Advantages:

- Fast, approximate (but accurate) Fisher Information calculations
- Fisher Information is additive (simply add multiple experiments)
- Compare large numbers of points in Euclidean space using efficient algorithms (e.g. nearest neighbour search with 'ball-tree')

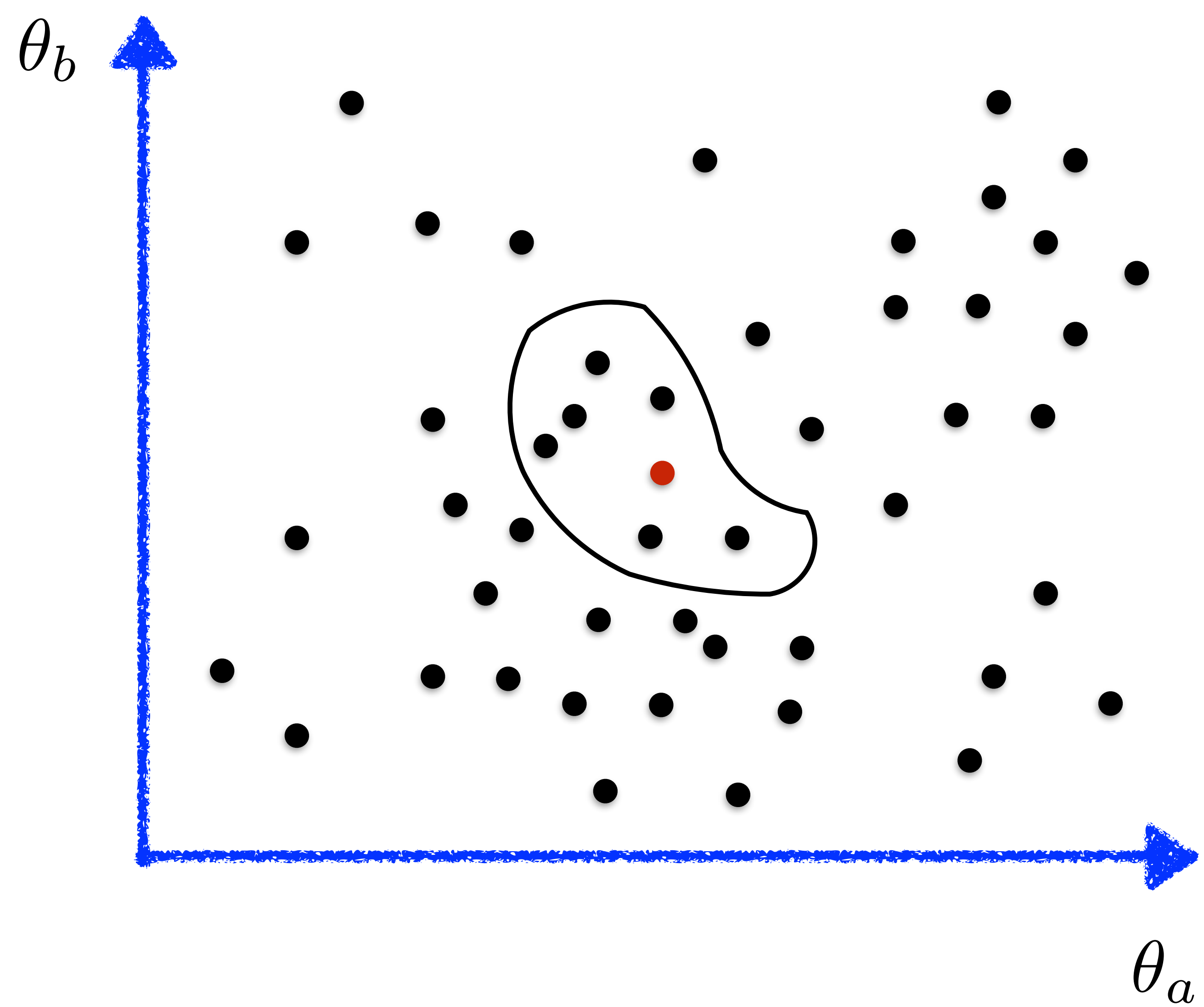
More details in backup slides

Euclideanised Signals



Euclideanised Signals

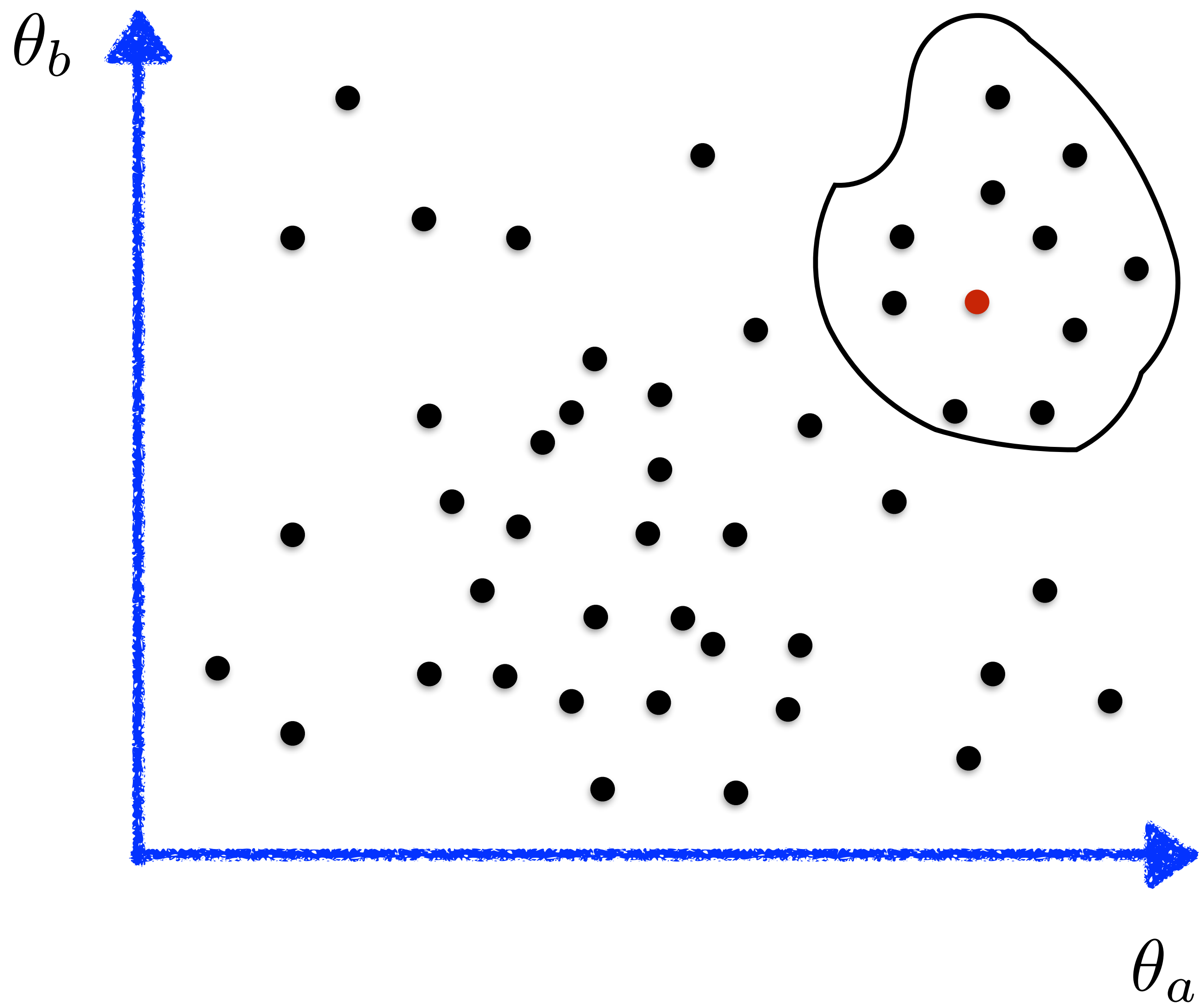
Can easily determine confidence regions around each point…



Which points to include is determined by their Euclidean distance…

Euclideanised Signals

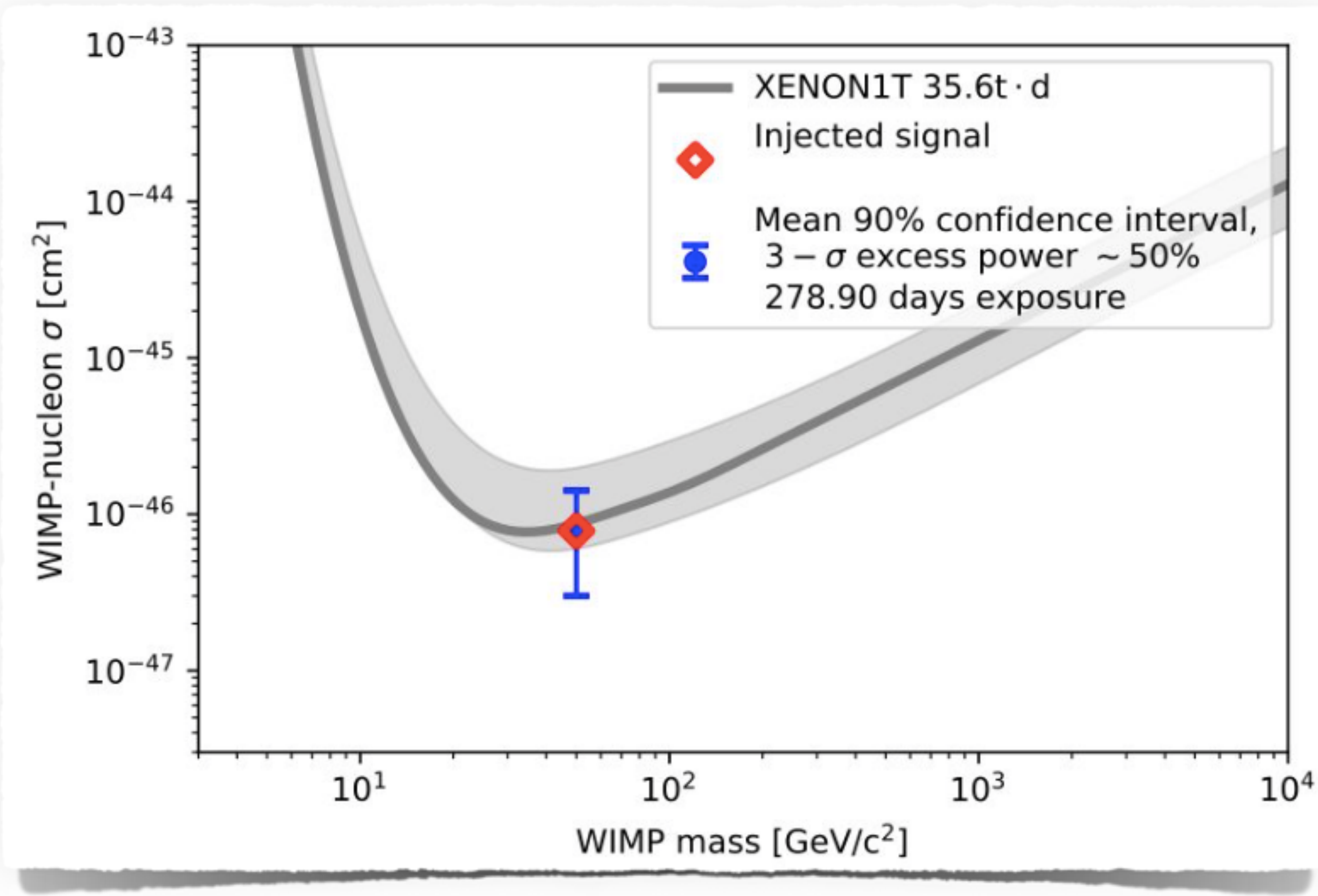
Can easily determine confidence regions around each point…



Which points to include is determined by their Euclidean distance…

Projections for DM Mass and Cross Section

Sample a large number of parameter points and map out the distinct 2-sigma regions



Projections for DM Mass and Cross Section

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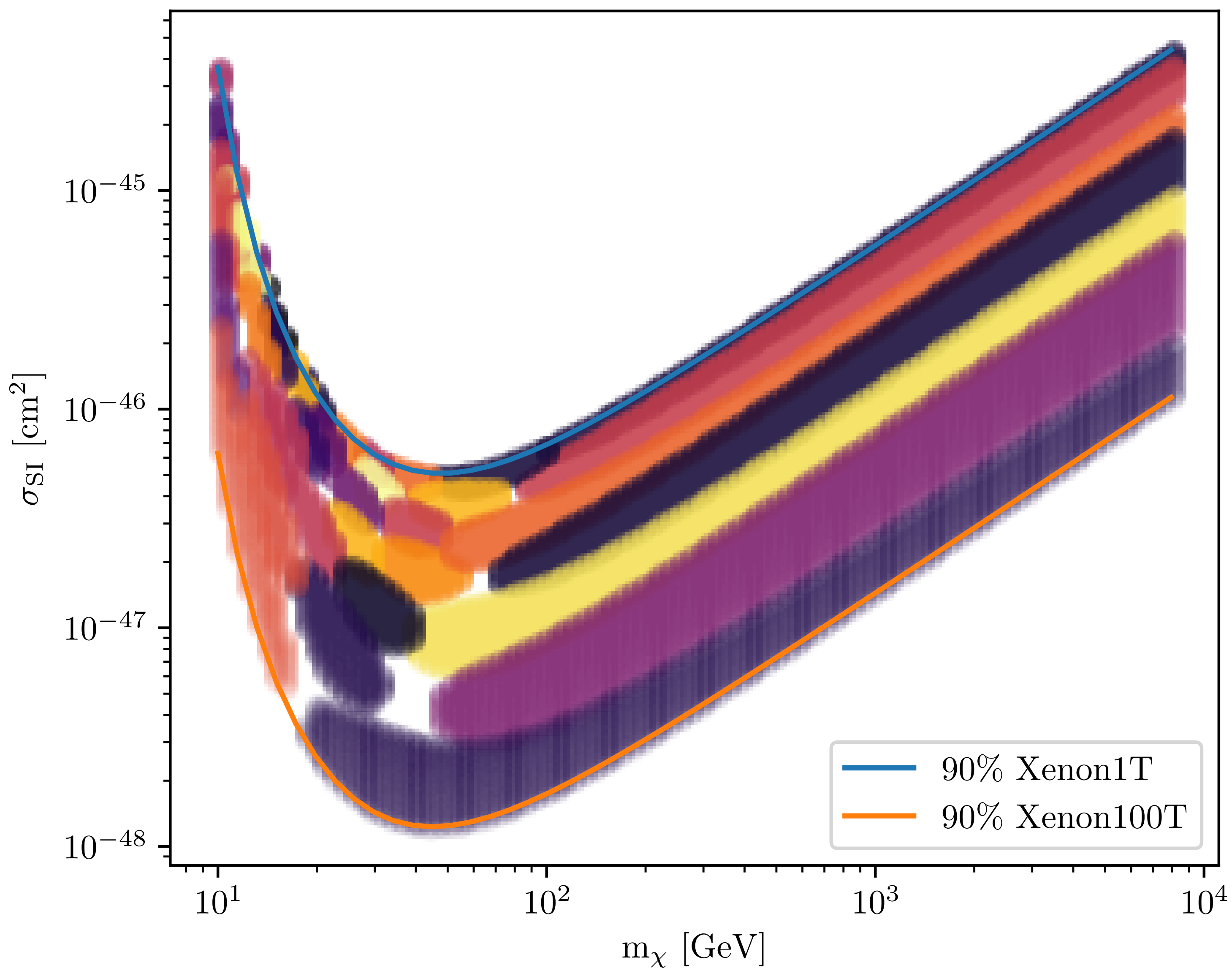
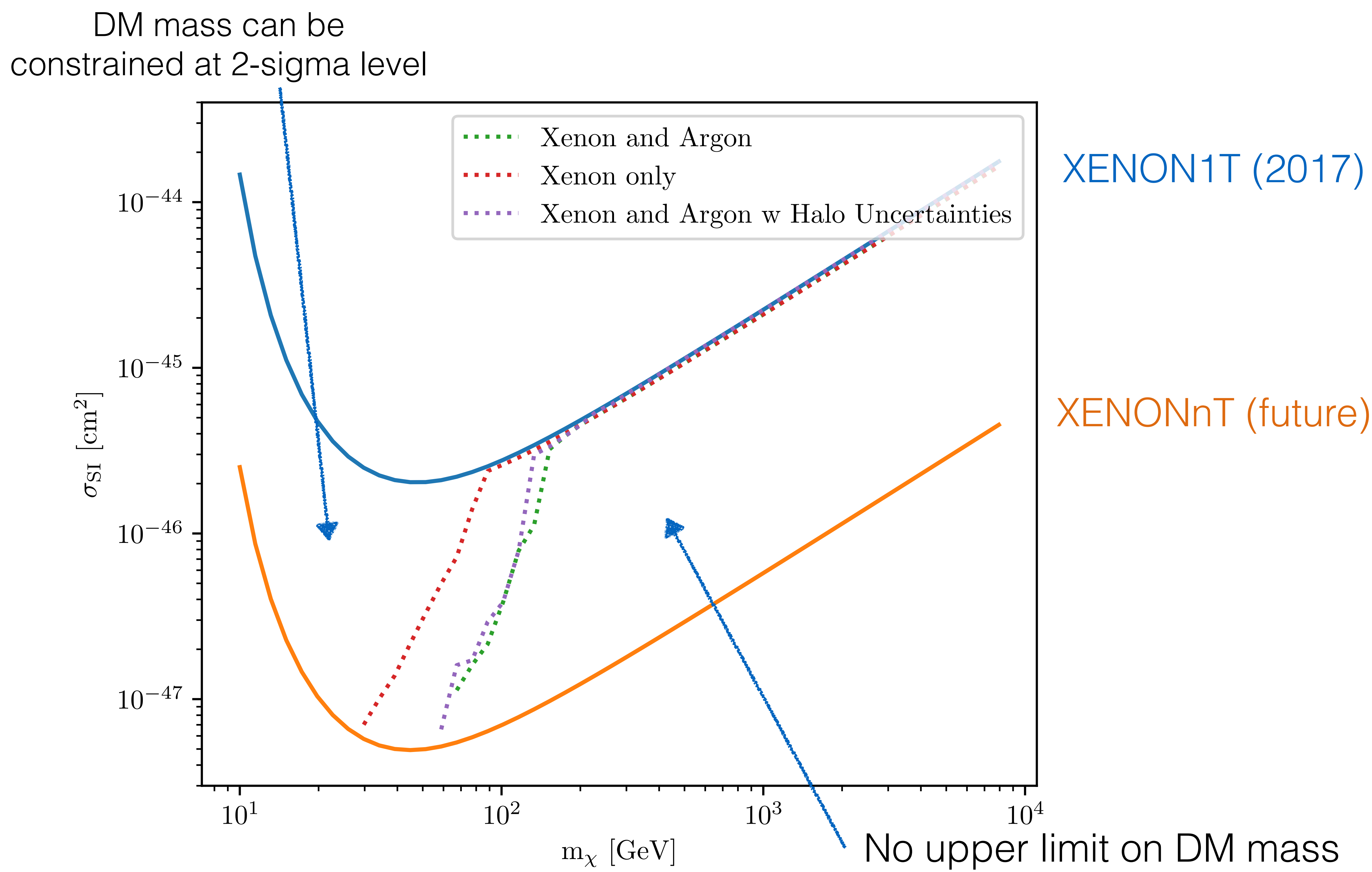
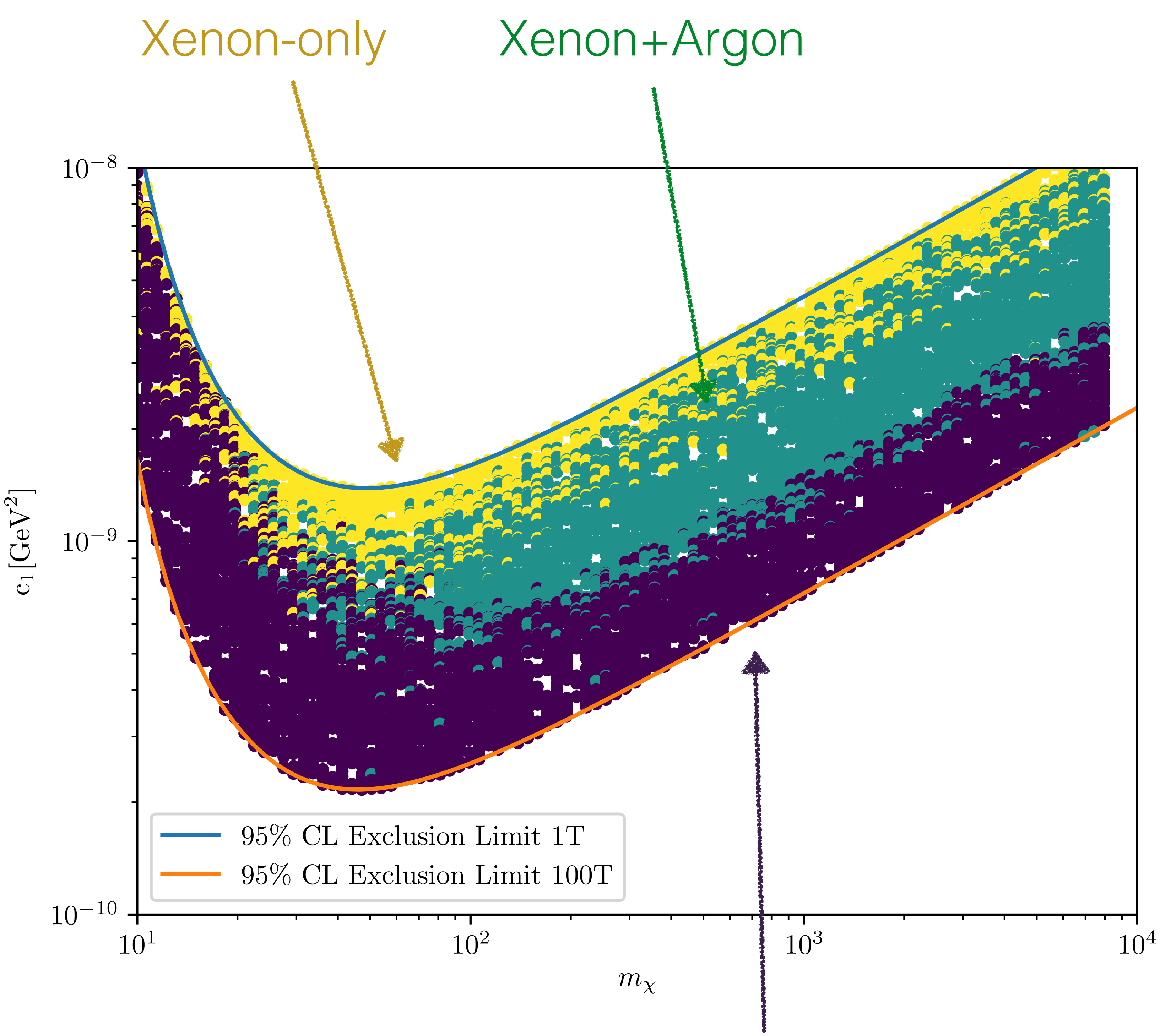
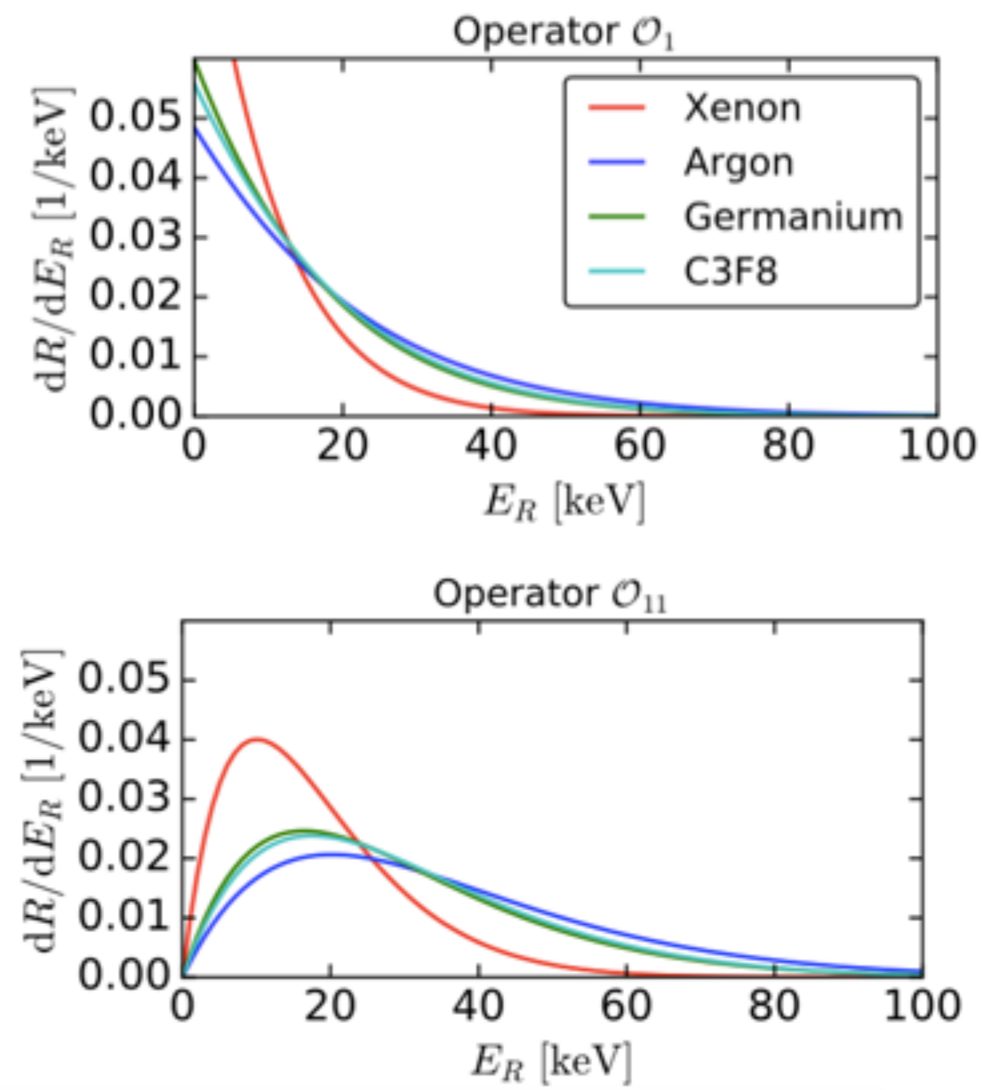


Mass Discrimination



Operator Discrimination





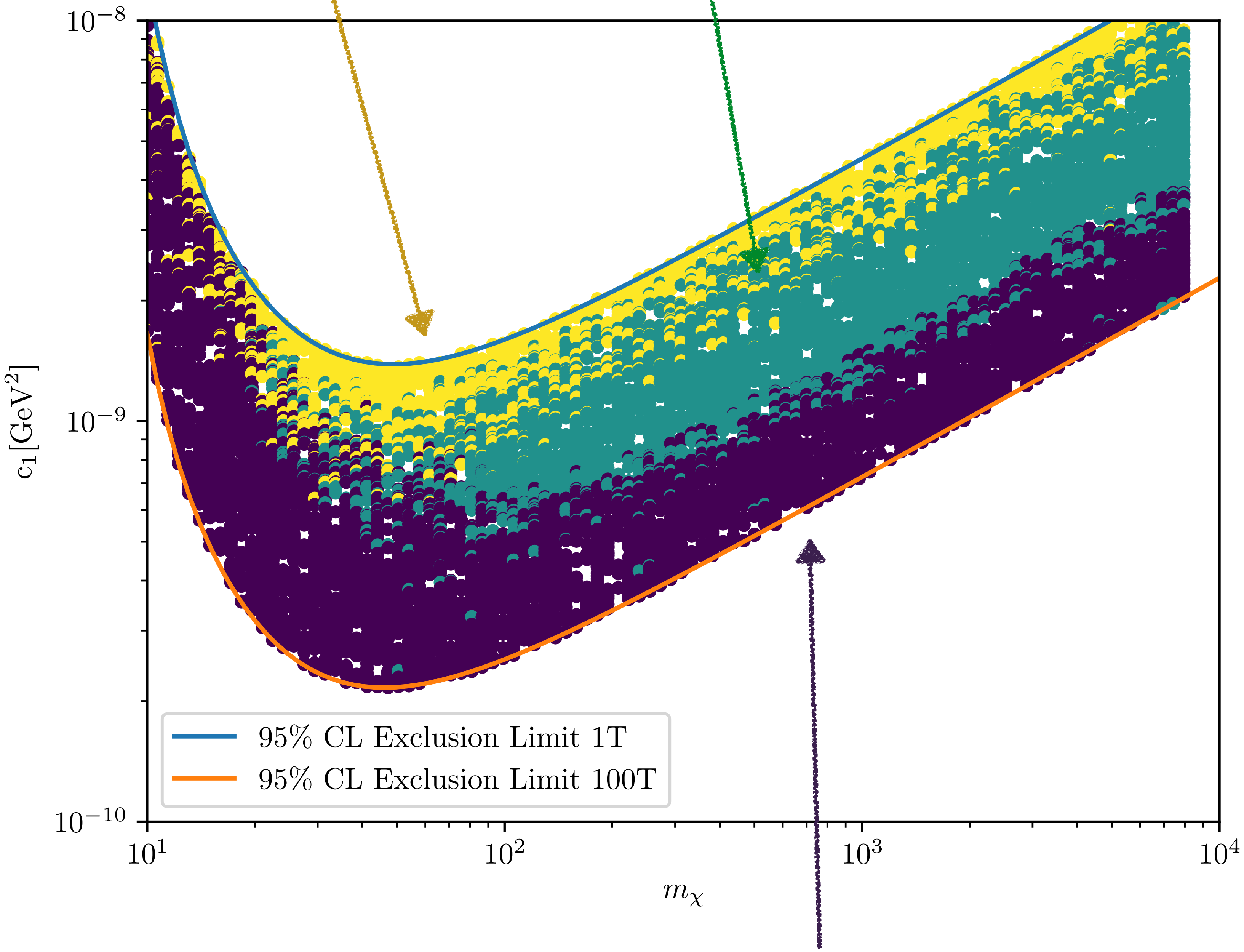
$m_\chi = 50\,\mathrm{GeV}$

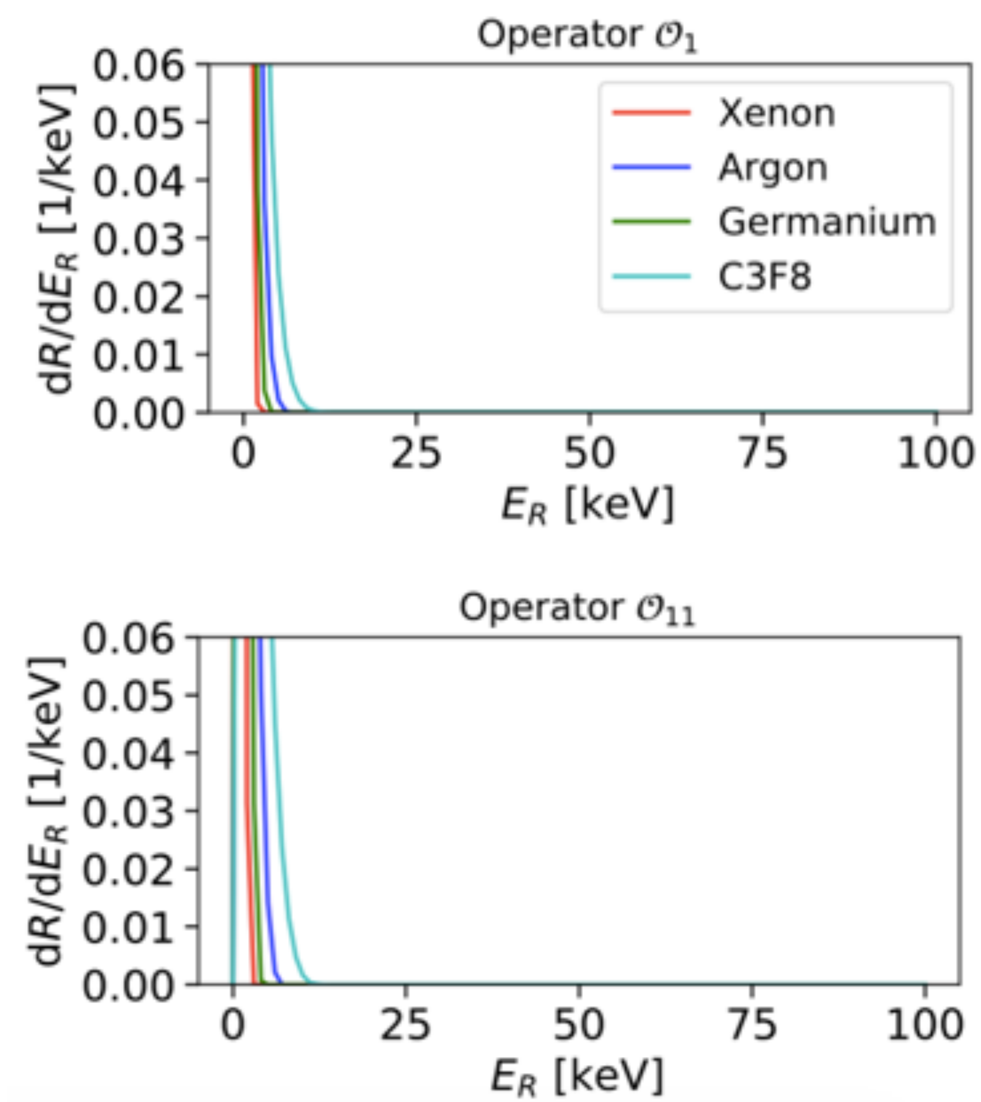
No discrimination in either case

Operator Discrimination

Xenon-only

Xenon+Argon



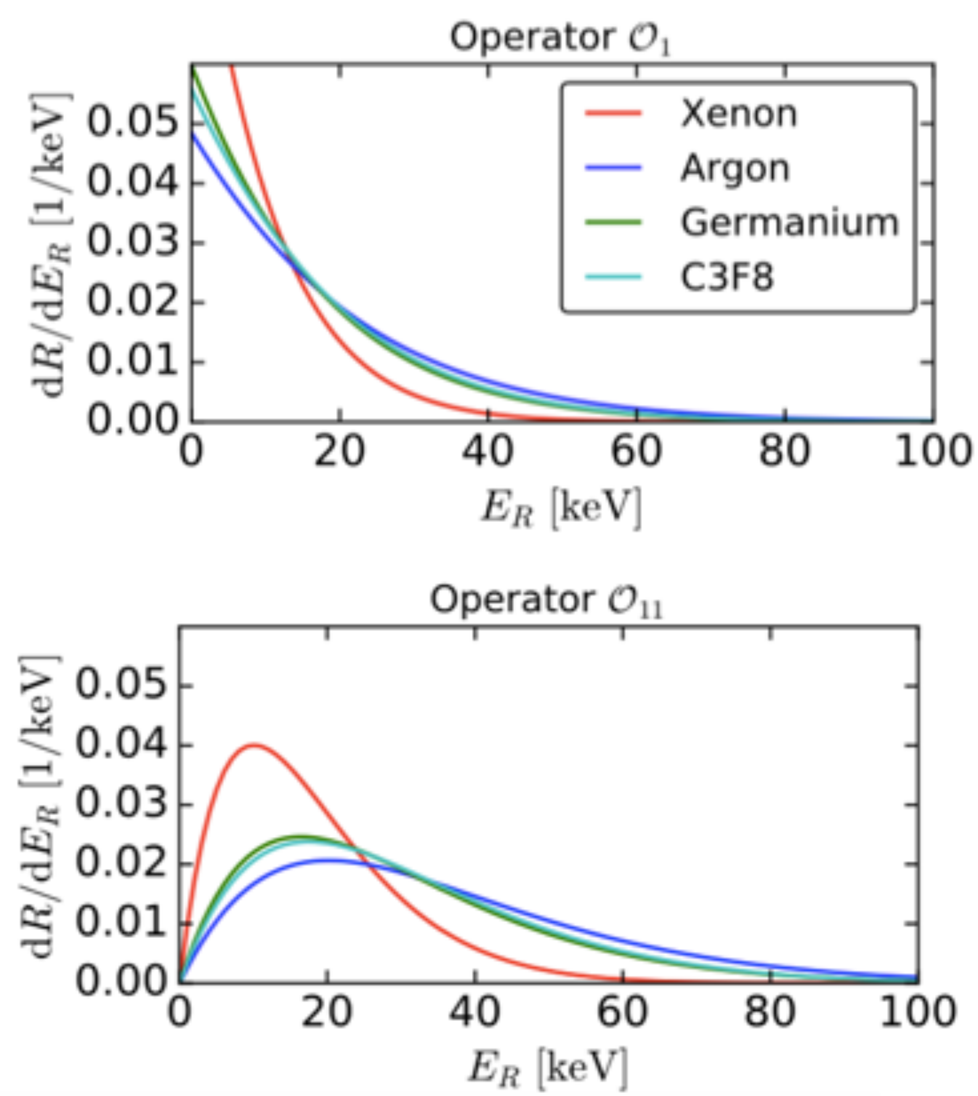


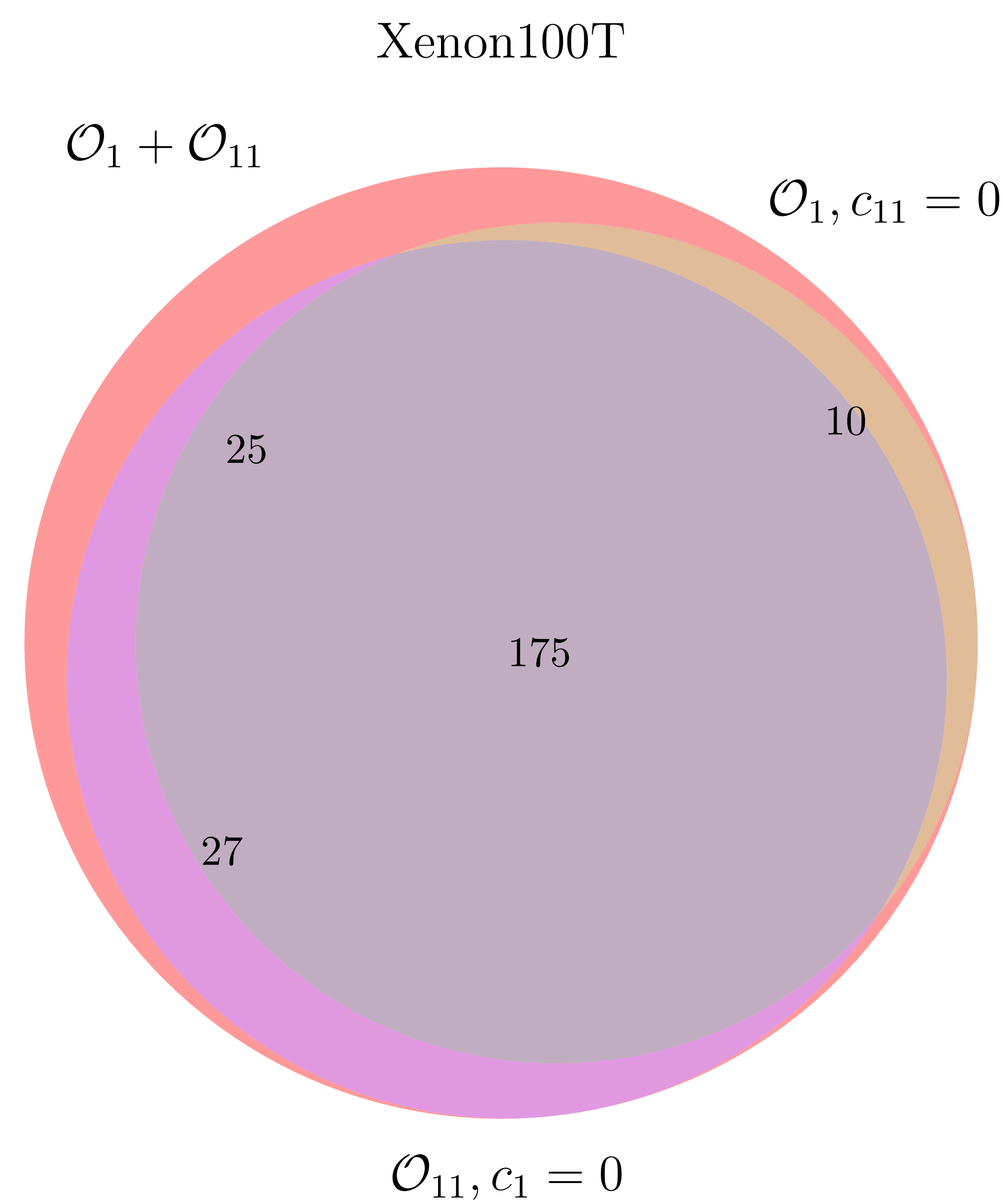
$m_\chi = 5\,\mathrm{GeV}$

No discrimination in either case

Number of discriminable signals

Can count number of distinct 2-sigma regions which will be covered by future experiments ("volume" of parameter space probed)





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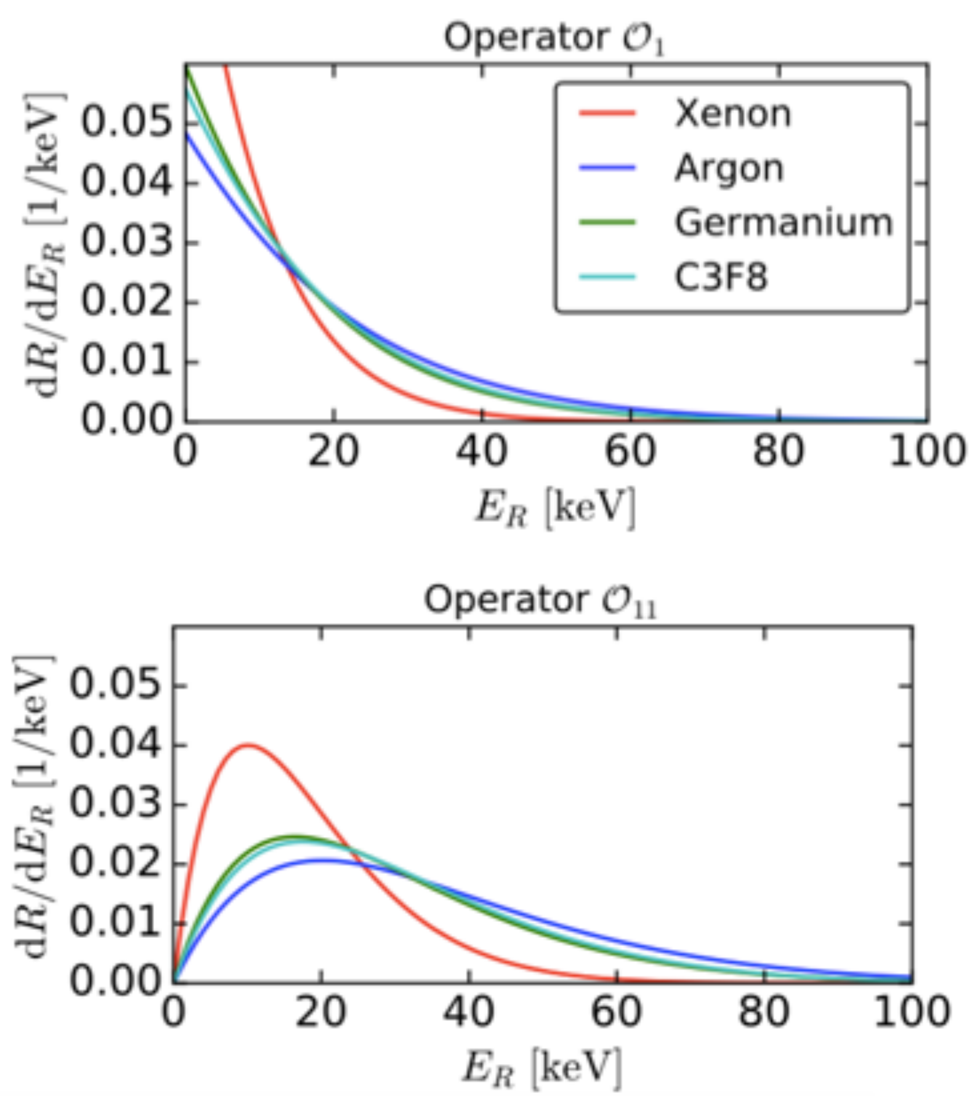

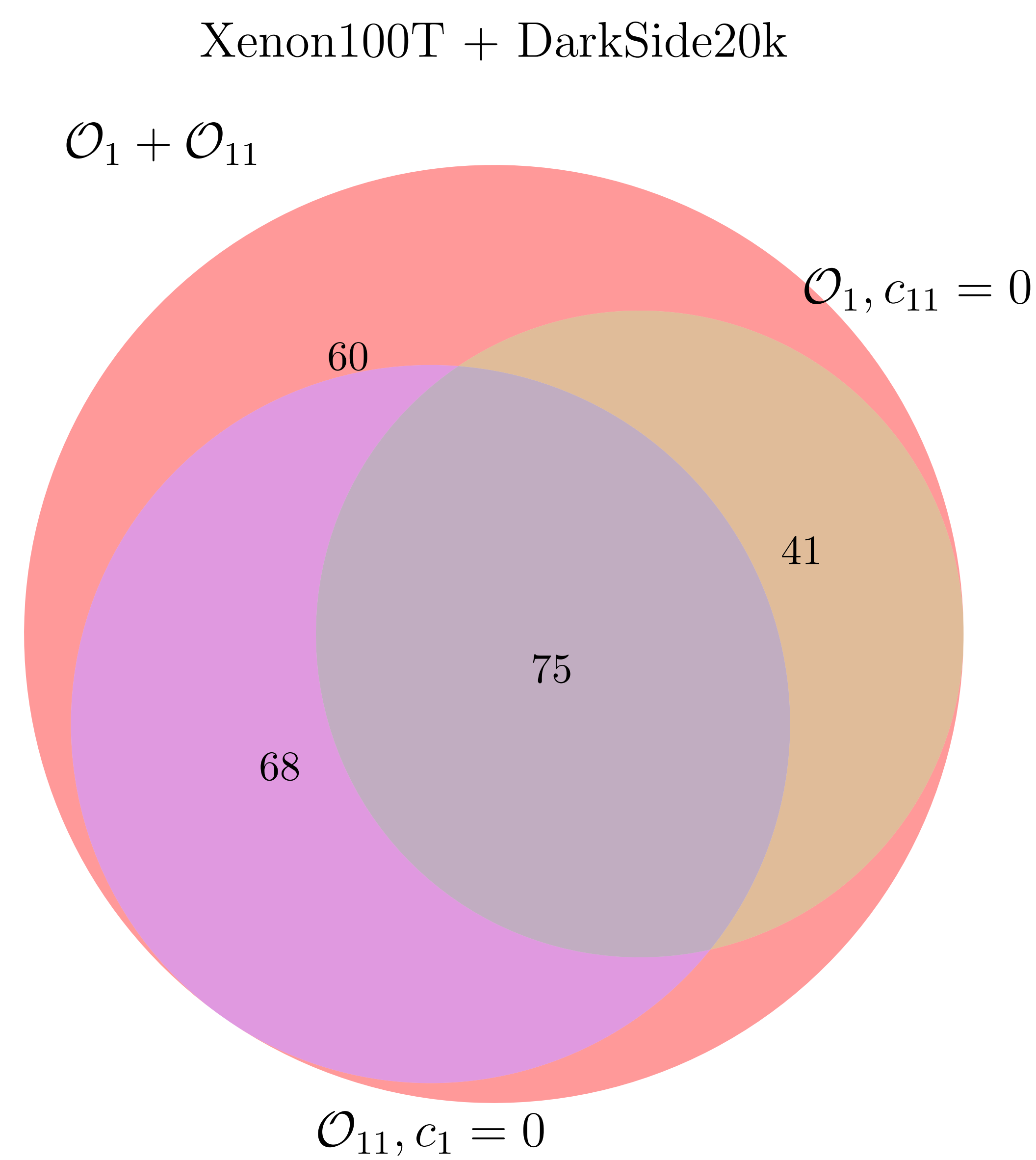

Can quantify discrimination power and complementarity!

Direct Detection of Dark Matter ✓
Overview and introduction

Is the DM its own antiparticle? ✓
Target Complementarity

Queiroz, Rodejohann, Yaguna [1610.06581]
BJK, Queiroz, Rodejohann, Yaguna [1706.07819]

What is the form of the DM-nucleon interaction? ✓
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Where in the parameter space can we distinguish different models? ✓
Mapping out the whole parameter space with SwordFish

Edwards & Weniger [1712.05401]
Edwards, **BJK** & Weniger [1804.XXXXX]

As usual, the Dark Matter (DM) community stands on the brink of discovery. But there is still much we do not about Dark Matter and its interactions with the Standard Model. How does DM interact with nucleons? How strong is this interaction? Is DM its own antiparticle? I will discuss a number of ways to discriminate between different forms of DM-nucleon interaction in future 'Direct Detection' experiments: using directional detectors, using time-series data and using target complementary. Finally, I will discuss ongoing work (using the new statistical tool SWORDFISH) to explore prospects for model discrimination over the whole DM parameter space, not only at selected benchmark points. This work is crucial to inform future DM searches, guiding which experiments and techniques should be pursued in order to pin down the DM-nucleon interaction and probe the particle identity of Dark Matter.

Future Questions

- Which experiments are best for disentangling the DM-proton and DM-nucleon couplings?
- Is a directional signal still useful if we have multiple direct detection experiments (or do we get all the information we need from target complementarity?)
- How well could we pin down the cross section (and local DM density) if we see a daily modulation from strongly-interacting DM?
- What is the minimal set of signal shapes which can be distinguished in a future (e.g. Xenon) experiment? This could act as a basis for a publicly-released likelihood…

Summary

Important to understand the power of future experiments, to know what questions we can answer and how best to answer them.

Target complementarity is powerful - e.g. for discriminating Dirac from Majorana DM, detectors like Silicon help a lot.

Directional detectors could help us pin down the DM-nucleon interaction (and therefore the DM spin).

New statistical tools are now available to explore the whole parameter space of DM.

Which models can be discriminated, and which experiments and techniques will allow us to do it?

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New statistical tools are now available to explore the whole parameter space of DM.

Which models can be discriminated, and which experiments and techniques will allow us to do it?

Thank you!

Backup Slides

Generalising to other spins

We have discussed only spin-1/2 DM particles.
However, similar logic applies
for DM candidates of other spins.

For example, in the case of scalar DM ϕ , the couplings leading to spin-independent scattering are:

$$\mathcal{L} \supset 2\lambda_{N,e} m_\phi \, \phi^\dagger \phi \, \overline{N} N + i\lambda_{N,o} \left[\phi^\dagger (\partial_\mu \phi) - (\partial_\mu \phi^\dagger)\phi\right] \, \overline{N}\gamma^\mu N$$

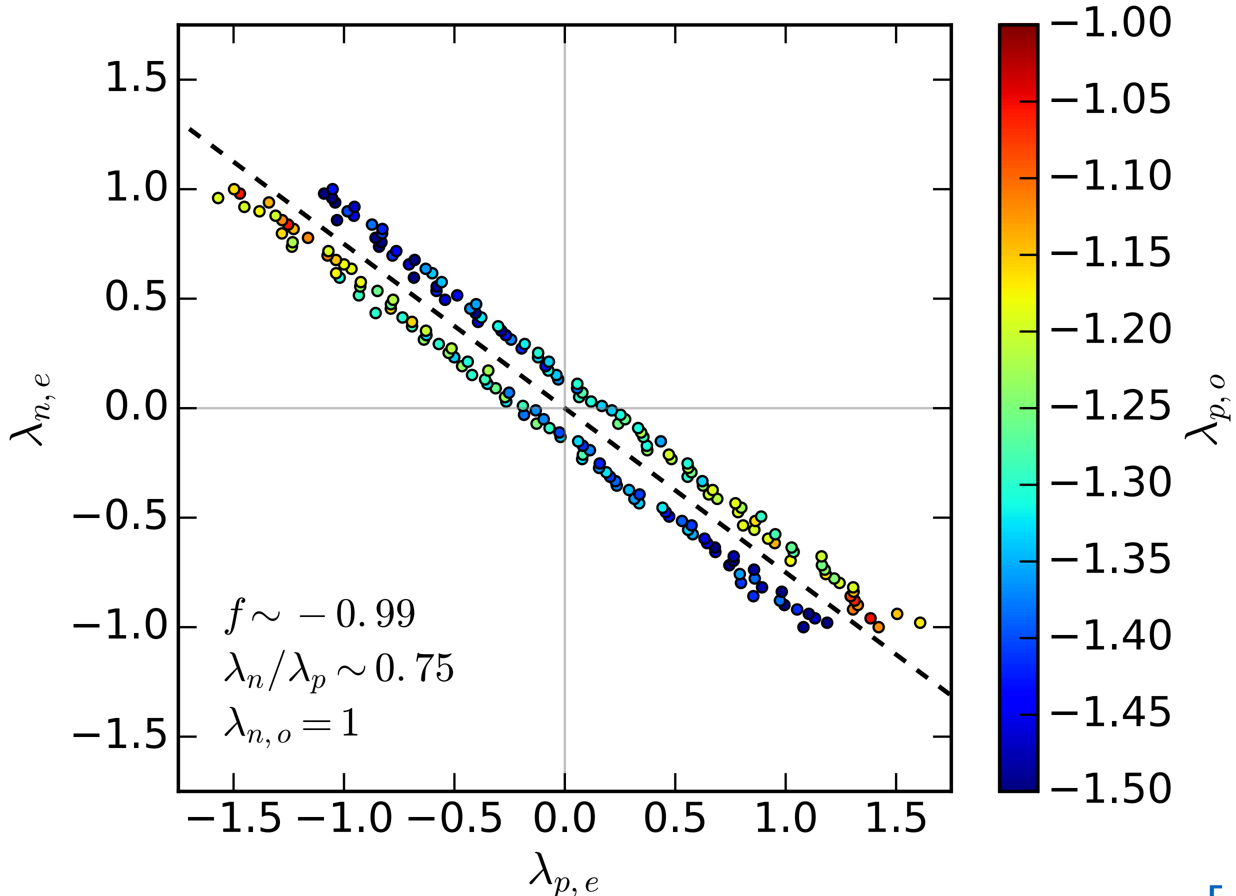
The second interaction is absent in the case of real scalar DM, so real and complex DM lead to different DM-nucleus cross sections!

For vector DM, see e.g. [arXiv:0803.2360].

Fundamental couplings

$$\mathcal{L} \supset \lambda_{N,e}\,\overline{\chi}\chi\,\overline{N}N + \lambda_{N,o}\,\overline{\chi}\gamma^{\mu}\chi\,\overline{N}\gamma_{\mu}N$$

Need to start off with some high-scale theory with couplings to quarks and determine the nucleon-level couplings



Good discrimination is possible without a substantial hierarchy between the nucleon-level couplings (although isospin violation *is* needed)

But isospin-violating Dirac DM is feasible (need, for example, new scalar and vector mediators) and has been studied

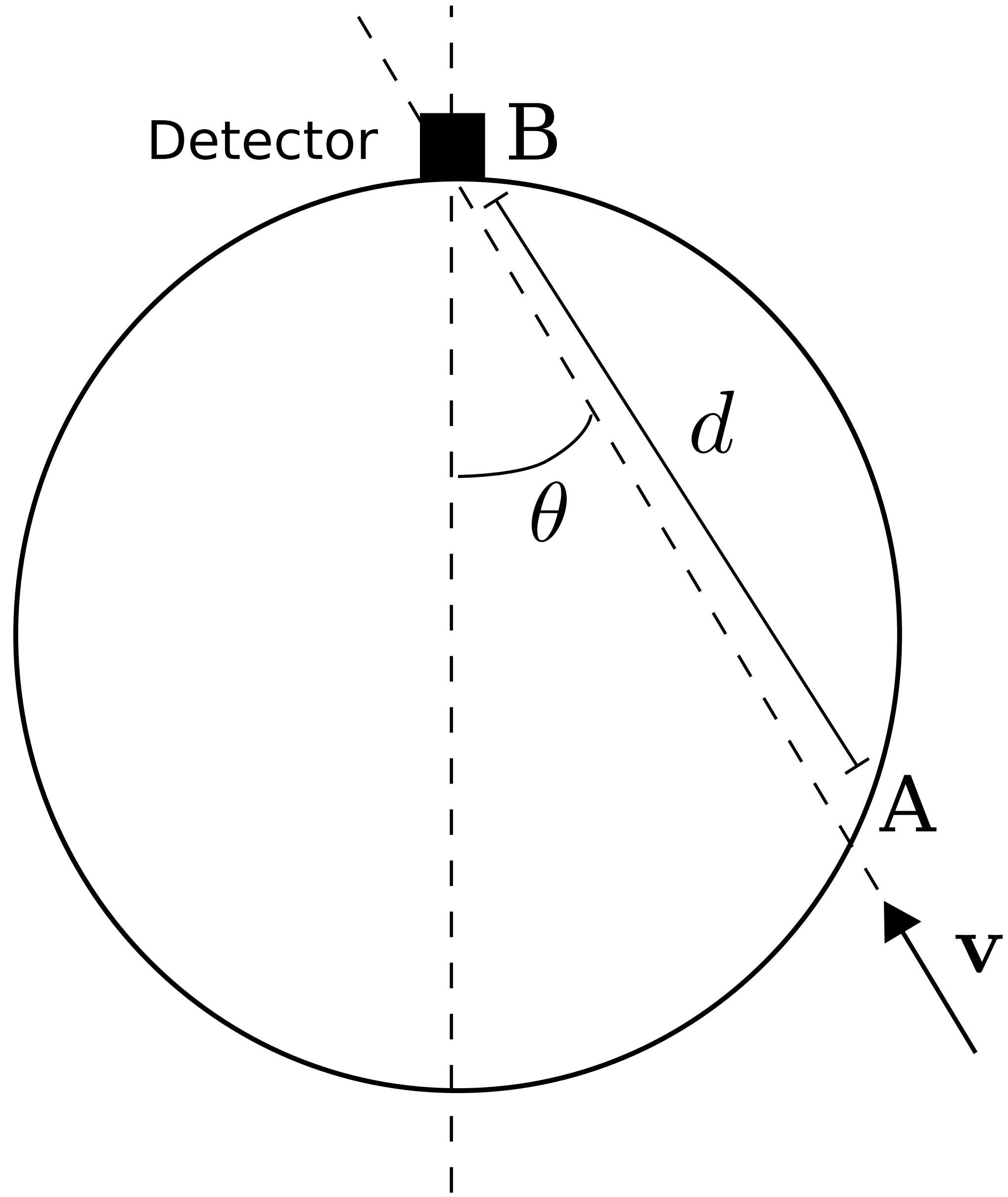
[1311.0022,1403.0324,1503.01780,1510.07053]

Need to map individual models onto $(\lambda_p,\,\lambda_n,\,f)$ to see whether Dirac nature can be determined

Attenuation

$$\mathbf{v} = (v, \cos\theta, \phi)$$

$$\bar{\lambda}_i(v)^{-1} = \bar{n}_i\,\sigma(v)$$



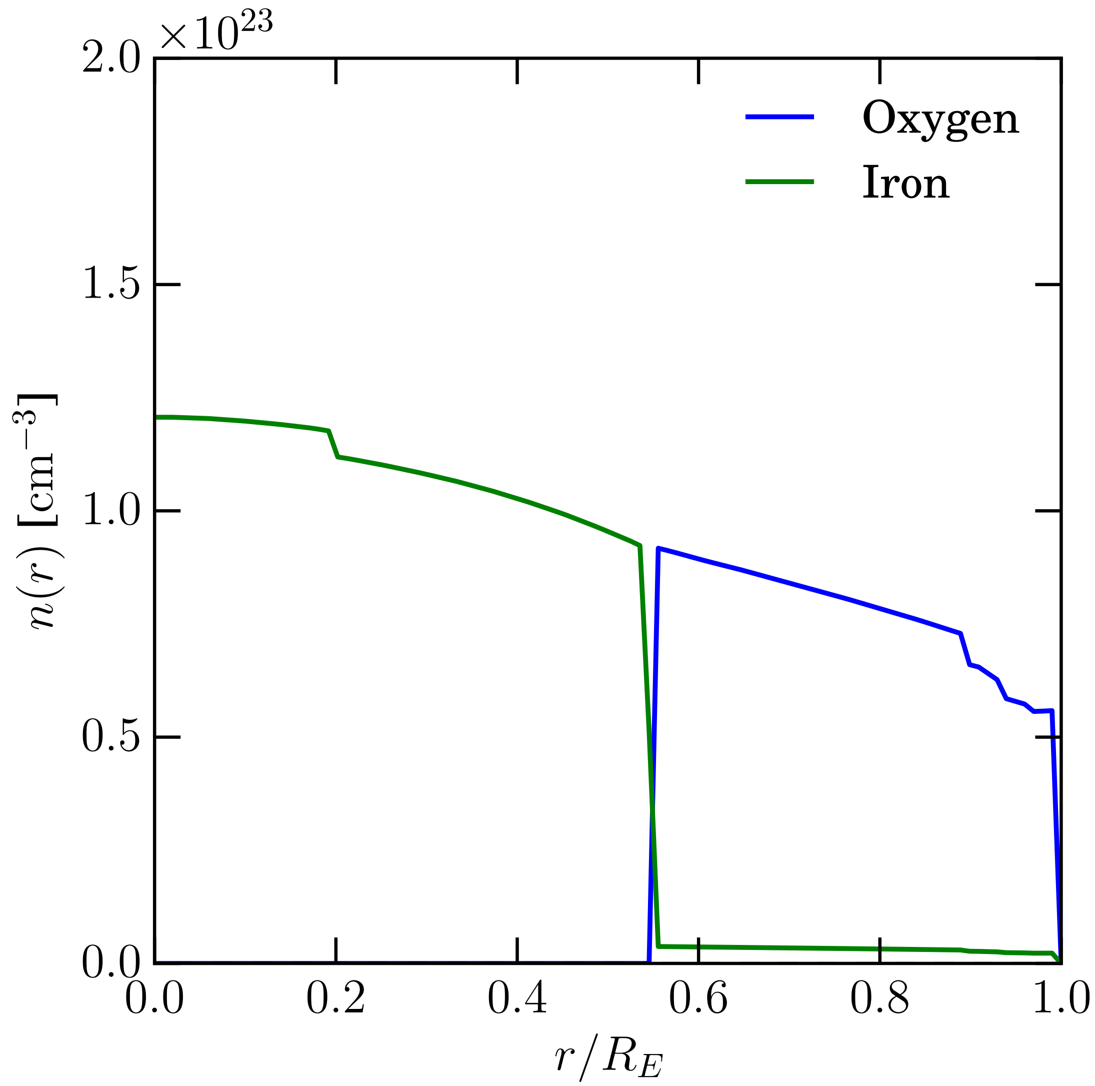
$$d_{\mathrm{eff},i} = \frac{1}{\bar{n}_i}\int_{\mathrm{AB}} n_i(\mathbf{r})\mathrm{d}l$$

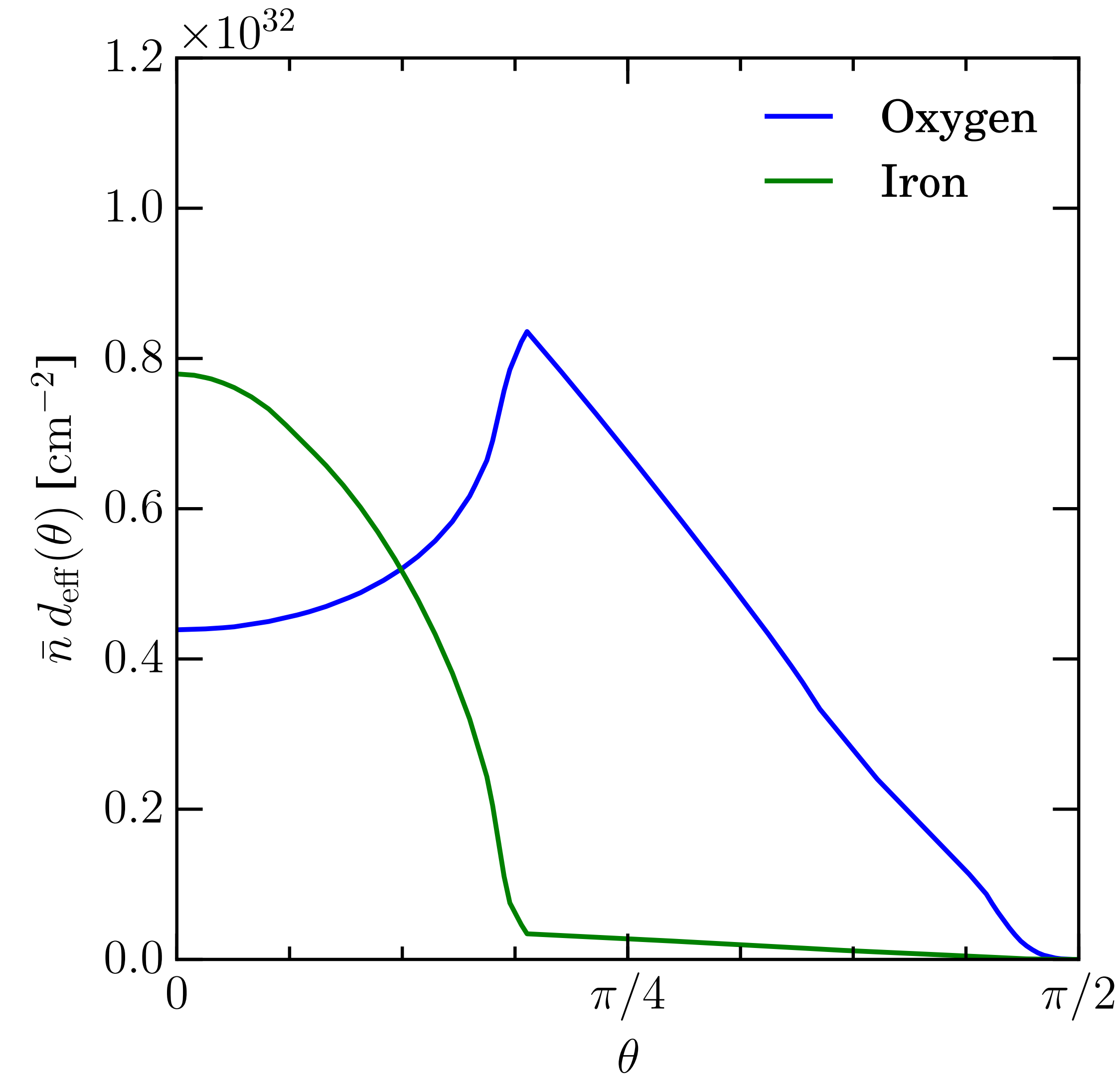
$$f_0(\mathbf{v}) - f_A(\mathbf{v}) = f_0(\mathbf{v})\exp\left[-\sum_i^{\mathrm{species}} \frac{d_{\mathrm{eff},i}(\cos\theta)}{\bar{\lambda}_i(v)}\right]$$

Sum over 8 most abundant elements in the Earth: O, Si, Mg, Fe, Ca, Na, S, Al

Effective Earth-crossing distance

Most scattering comes from Oxygen (in the mantle) and Iron (in the core)



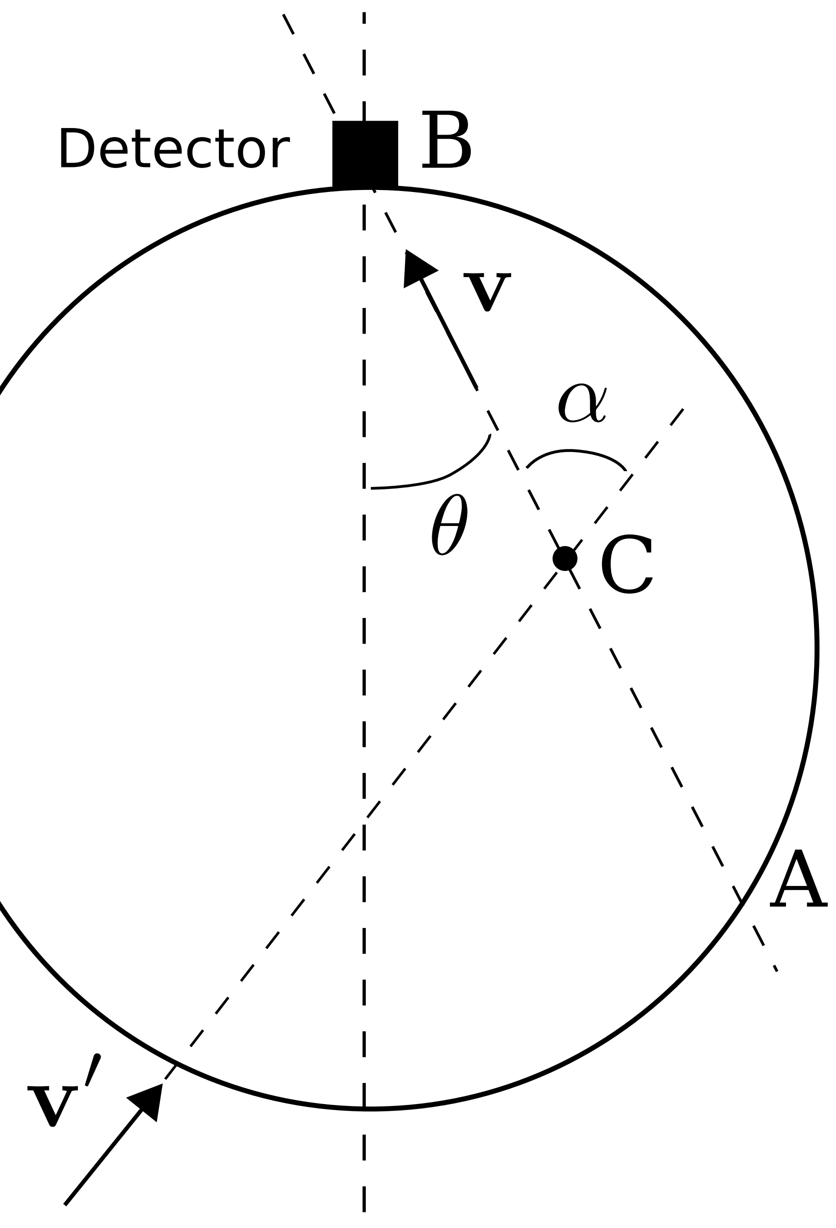


NB: little Earth-scattering for spin-dependent interactions

Deflection

$$\mathbf{v}' = (v', \cos\theta', \phi')$$
$$\mathbf{v} = (v, \cos\theta, \phi)$$

$$\bar{\lambda}_i(v)^{-1} = \bar{n}_i\,\sigma(v)$$



Deflection

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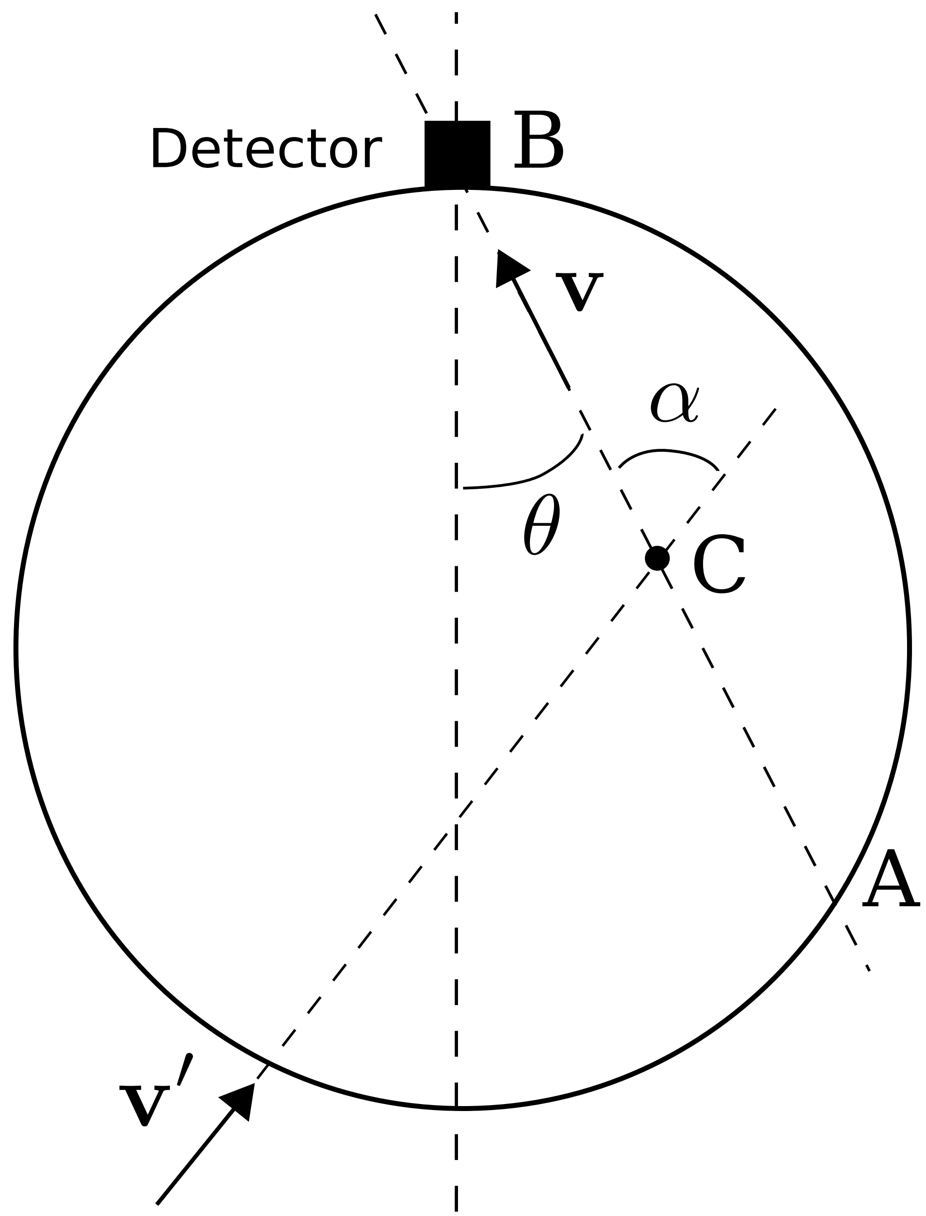


$$f_D(\mathbf{v}) = \sum_i^{\mathrm{species}} \int \mathrm{d}^2\hat{\mathbf{v}}' \,\frac{d_{\mathrm{eff},i}(\cos\theta)}{\bar{\lambda}_i(\kappa_i v)}\,\frac{(\kappa_i)^4}{2\pi} f_0(\kappa_i v, \hat{\mathbf{v}}')P_i(\cos\alpha)$$

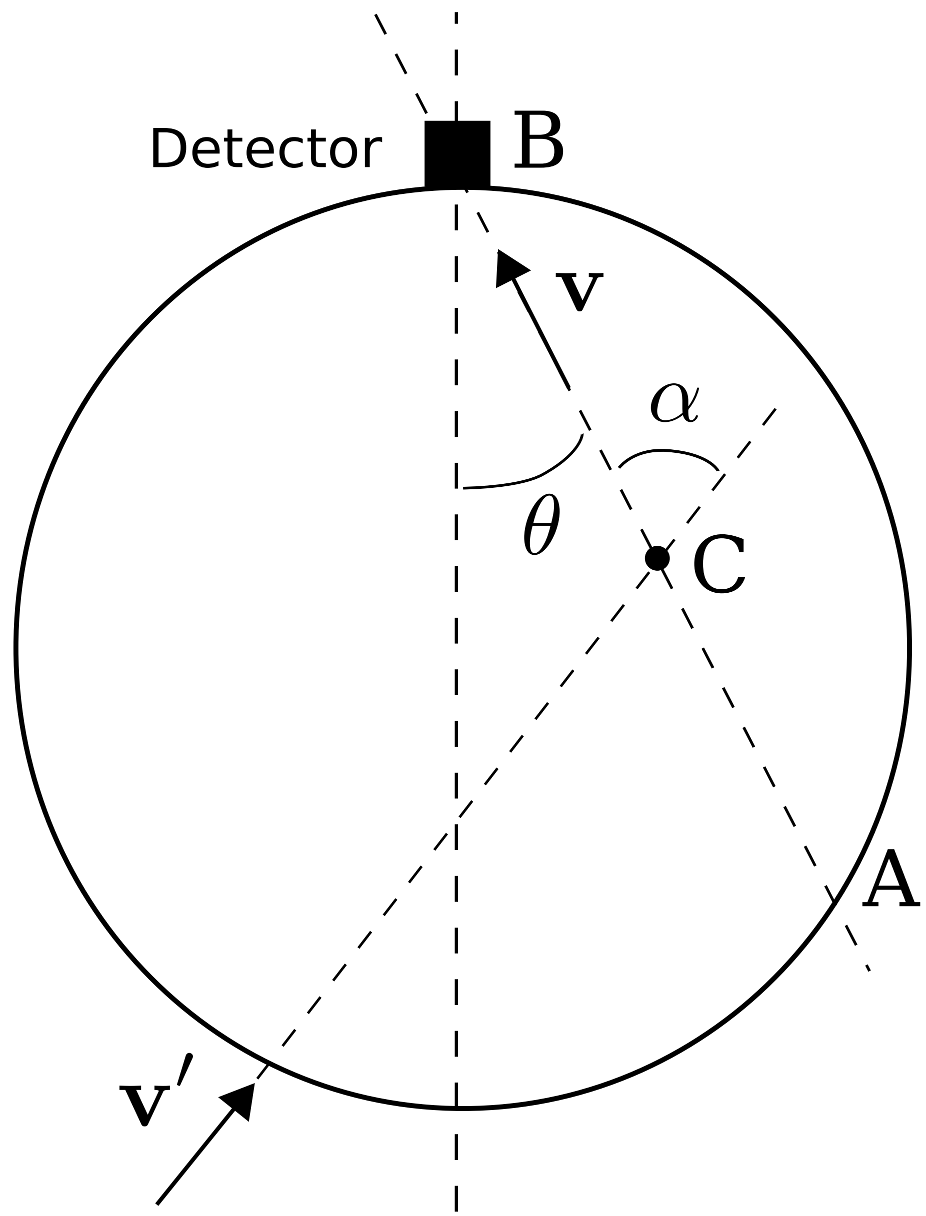
[Detailed calculation in 1611.05453]

$$\kappa_i = v'/v$$

Deflection

$$\mathbf{v}' = (v', \cos\theta', \phi')$$
$$\mathbf{v} = (v, \cos\theta, \phi)$$

$$\bar{\lambda}_i(v)^{-1} = \bar{n}_i\, \sigma(v)$$



Depends on differential cross section

$$f_D(\mathbf{v}) = \sum_i^{\text{species}} \int \mathrm{d}^2\hat{\mathbf{v}}' \, \frac{d_{\text{eff},i}(\cos\theta)}{\bar{\lambda}_i(\kappa_i v)} \frac{(\kappa_i)^4}{2\pi} f_0(\kappa_i v, \hat{\mathbf{v}}') P_i(\cos\alpha)$$

Depends on total cross section

$$\kappa_i = v'/v$$

Deflection

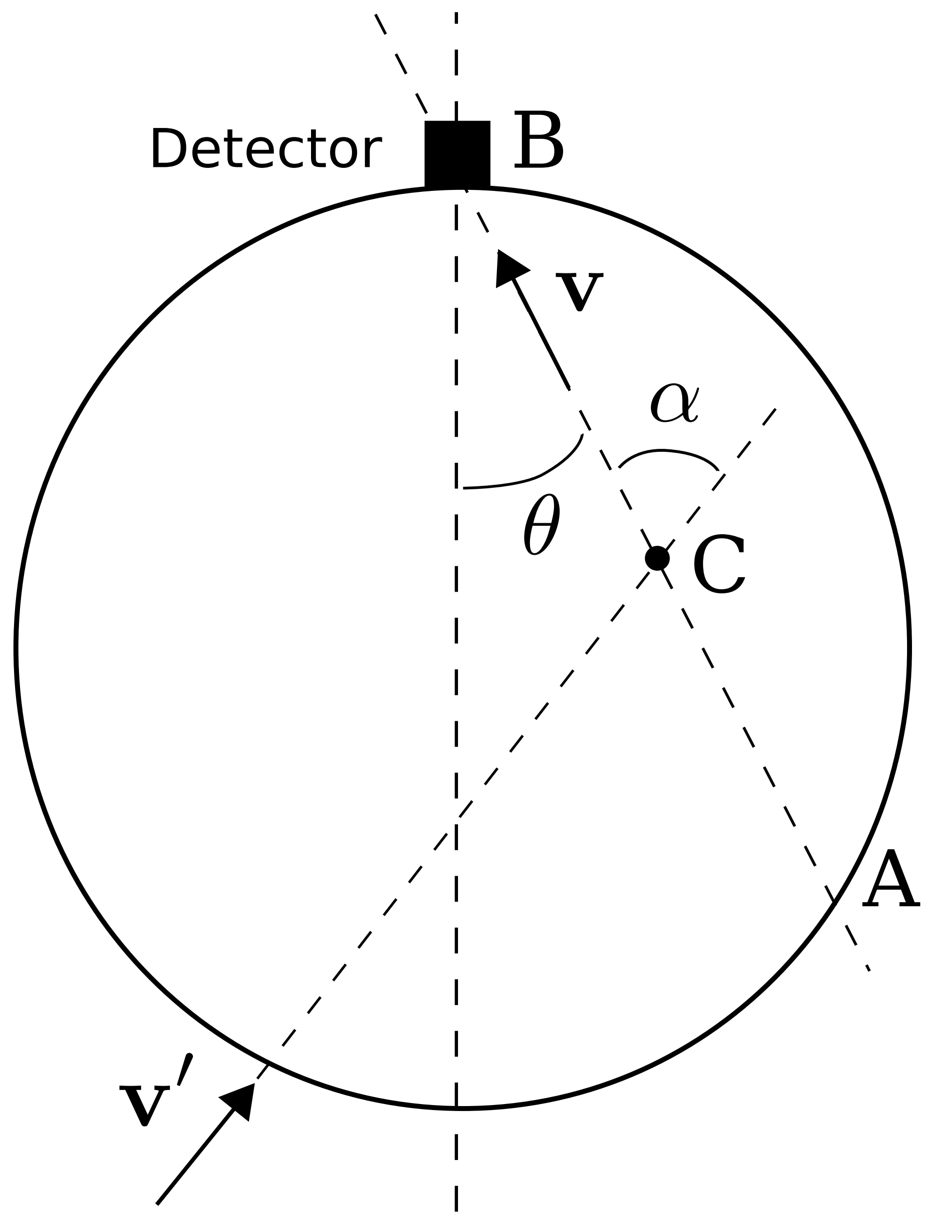
$$\mathbf{v}' = (v', \cos\theta', \phi')$$
$$\mathbf{v} = (v, \cos\theta, \phi)$$

$$\bar{\lambda}_i(v)^{-1} = \bar{n}_i\,\sigma(v)$$

Focus on low mass DM:

$$m_\chi = 0.5\ \mathrm{GeV}$$

Fix couplings to give 10% probability of scattering in the Earth



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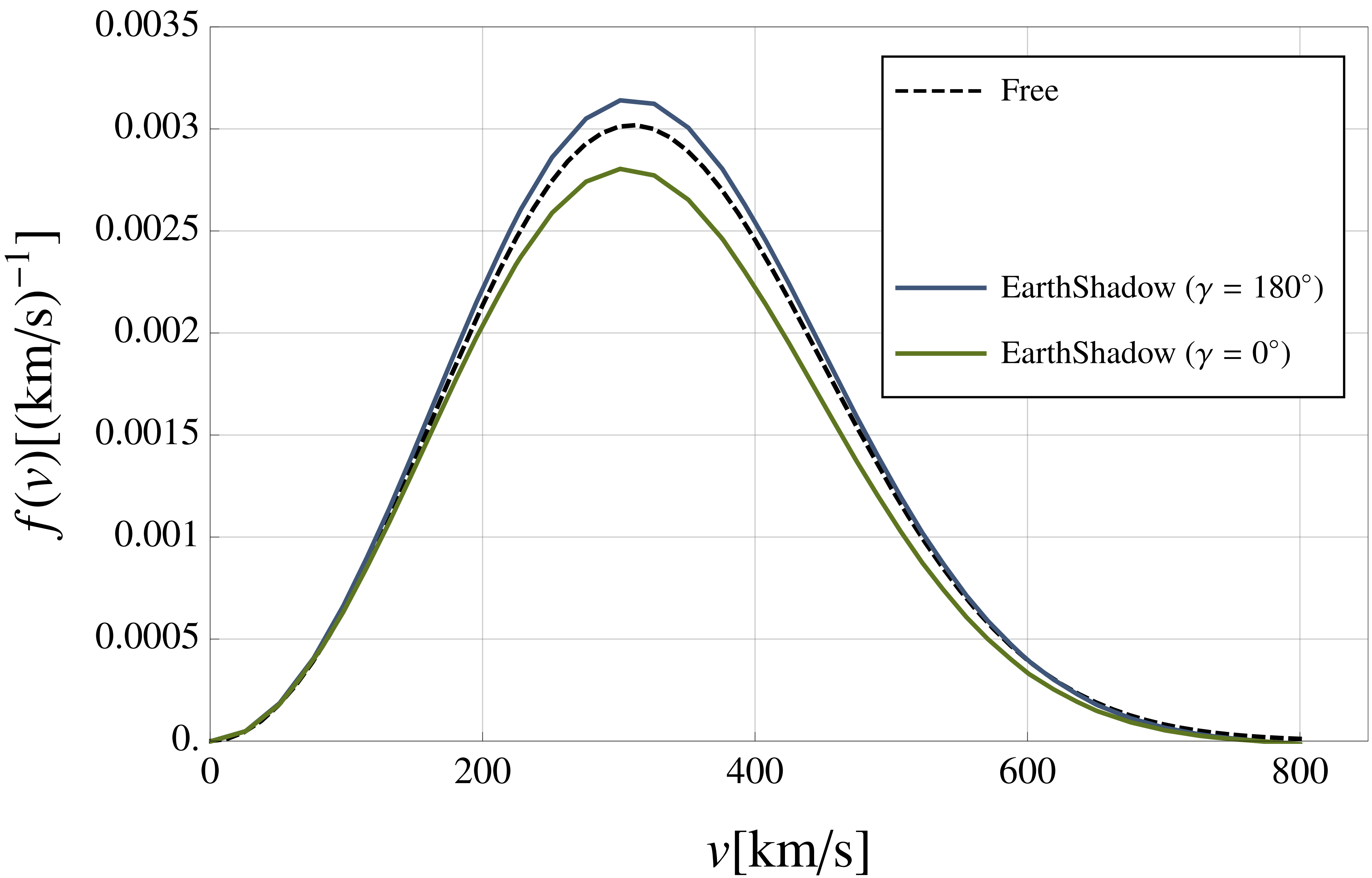
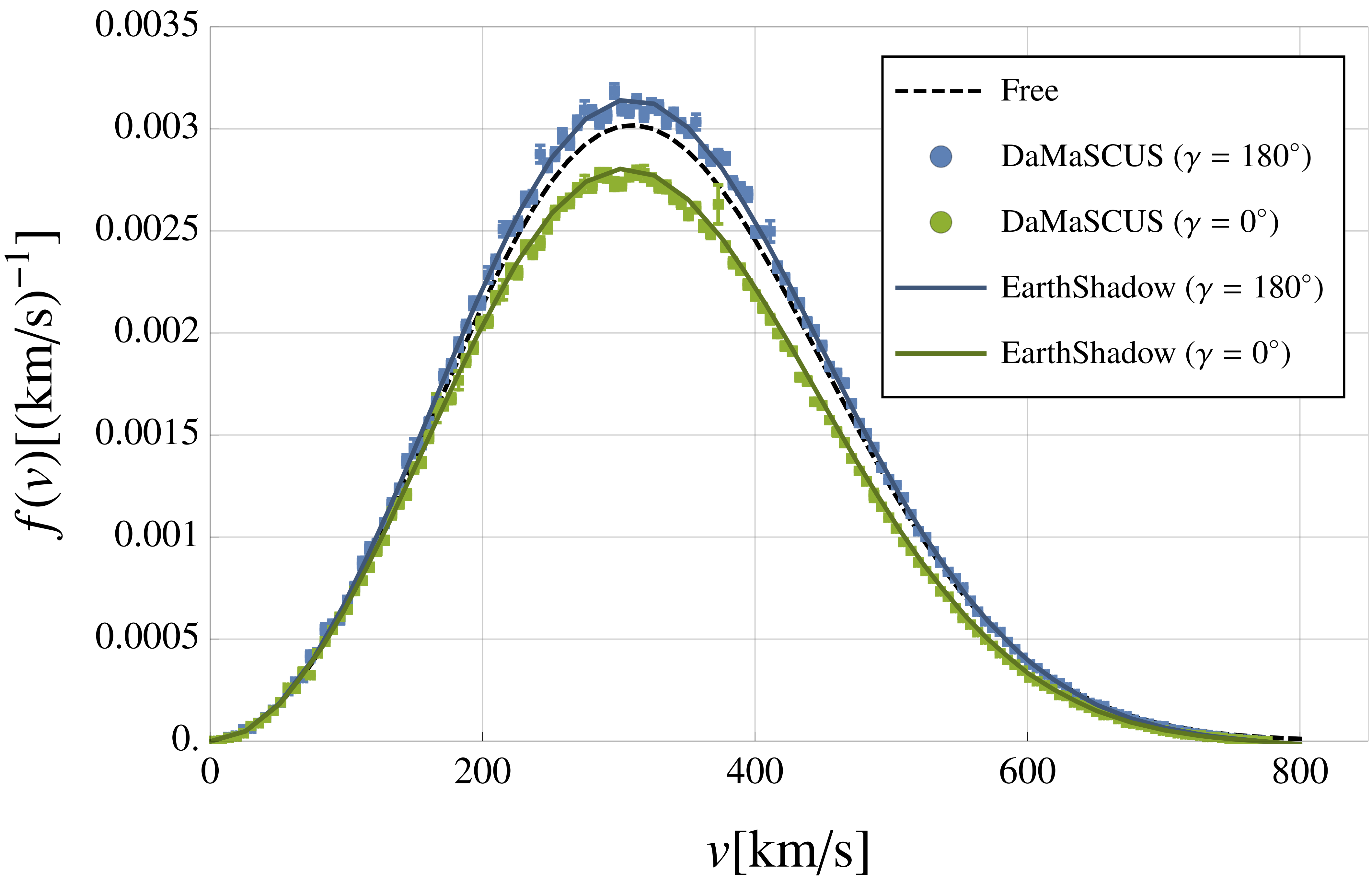
Comparison with Monte-Carlo



Monte-Carlo results from the DaMaSCUS code

[Emken & Kouvaris - 1706.02249]
http://cp3-origins.dk/site/damascus

Comparison with Monte-Carlo



Monte-Carlo results from the DaMaSCUS code

[Emken & Kouvaris - 1706.02249]
http://cp3-origins.dk/site/damascus

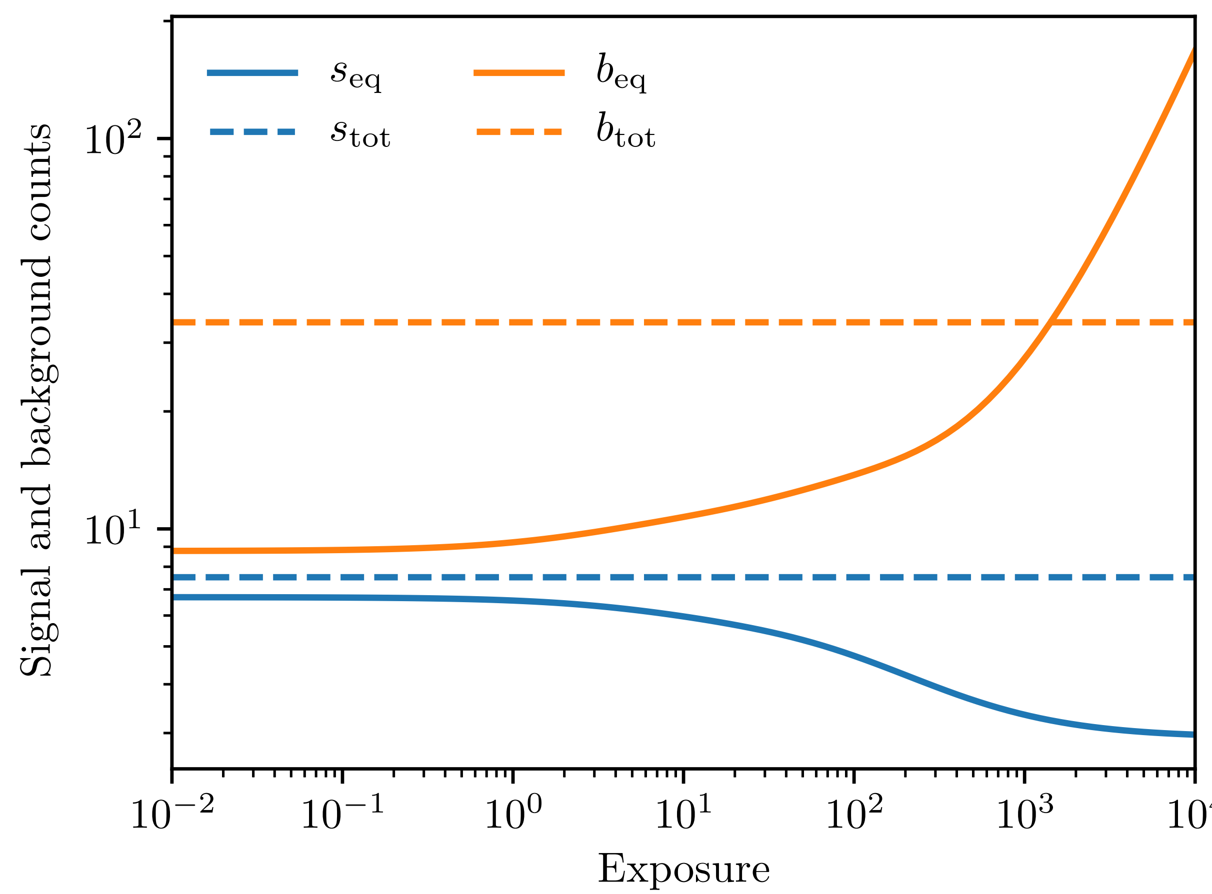
Equivalent Counts

Logic:

- **Signal to Noise of events in a single bin example tells us about the significance of the signal**
- **Extend same technique to multi-bin case**
- **Not all signal events statistically contribute if they are drowned out by large backgrounds**
- **Convenient to define significant signal and background events using the FIM**

$$s_{\mathrm{eq}}(\theta) \equiv \frac{\theta^2}{\sigma^2(\theta) - \sigma^2(\theta_0)}$$

$$b_{\mathrm{eq}}(\theta) \equiv \frac{\theta^2 \sigma^2(\theta_0)}{[\sigma^2(\theta) - \sigma^2(\theta_0)]^2}$$



Euclideanized Signals

$$x_i \equiv \left(\sum_j (D^{-1/2})_{ij} S_j E_j \right) \left(1 + \frac{R \cdot S_i}{R \cdot S_i + B_i + K_{ii} E_i} \right)$$

D_{ij} - Signal and background covariance matrix

S_i - Signal in the ith bin

E_i - Exposure in the ith bin

$R = 0.1$ - Fudge factor to deal with both signal dominated + signal limited regimes

Euclideanized Signals