Can we determine the particle/antiparticle nature of Dark Matter?

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LAW Physics - 17th January 2018

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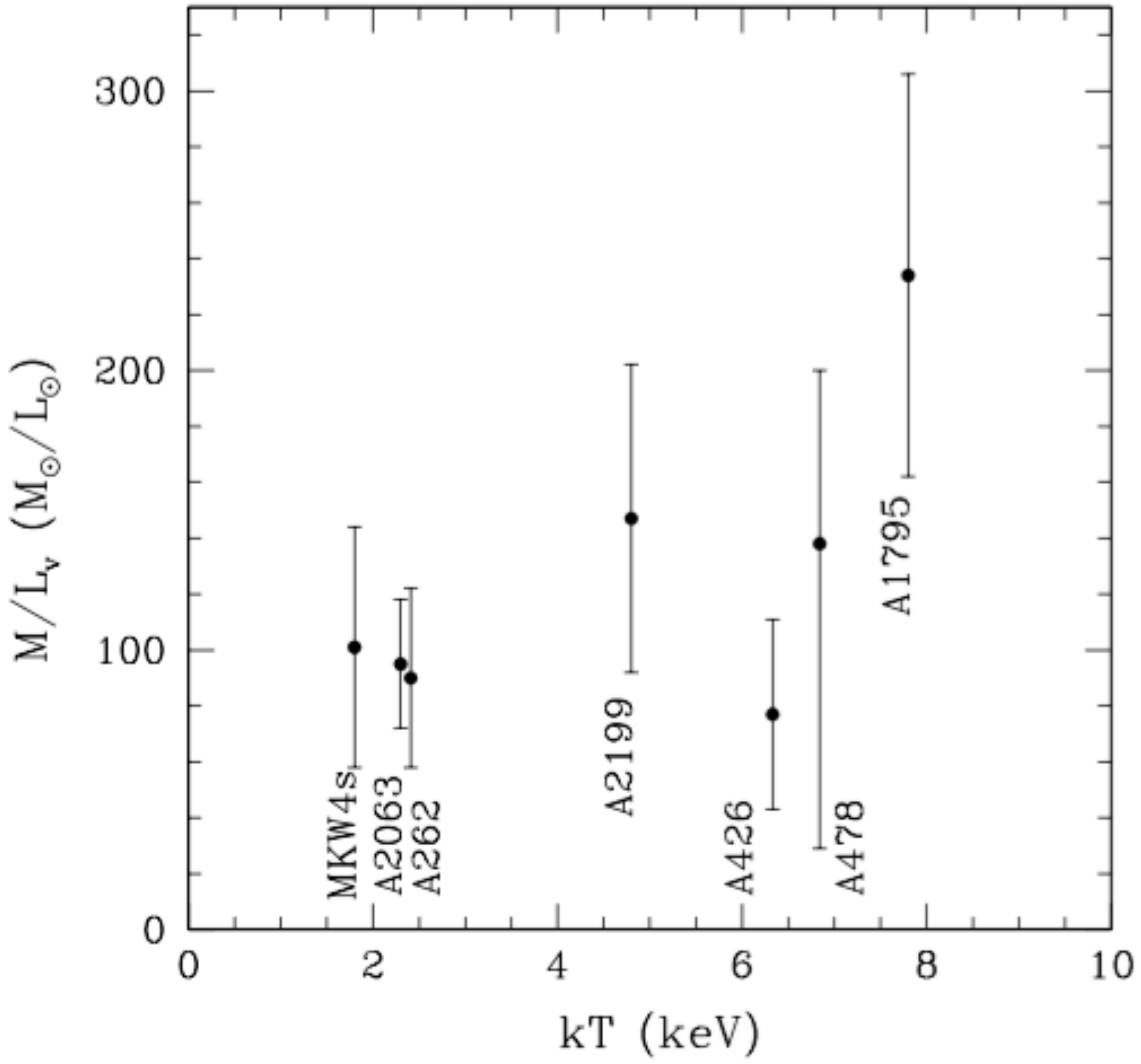
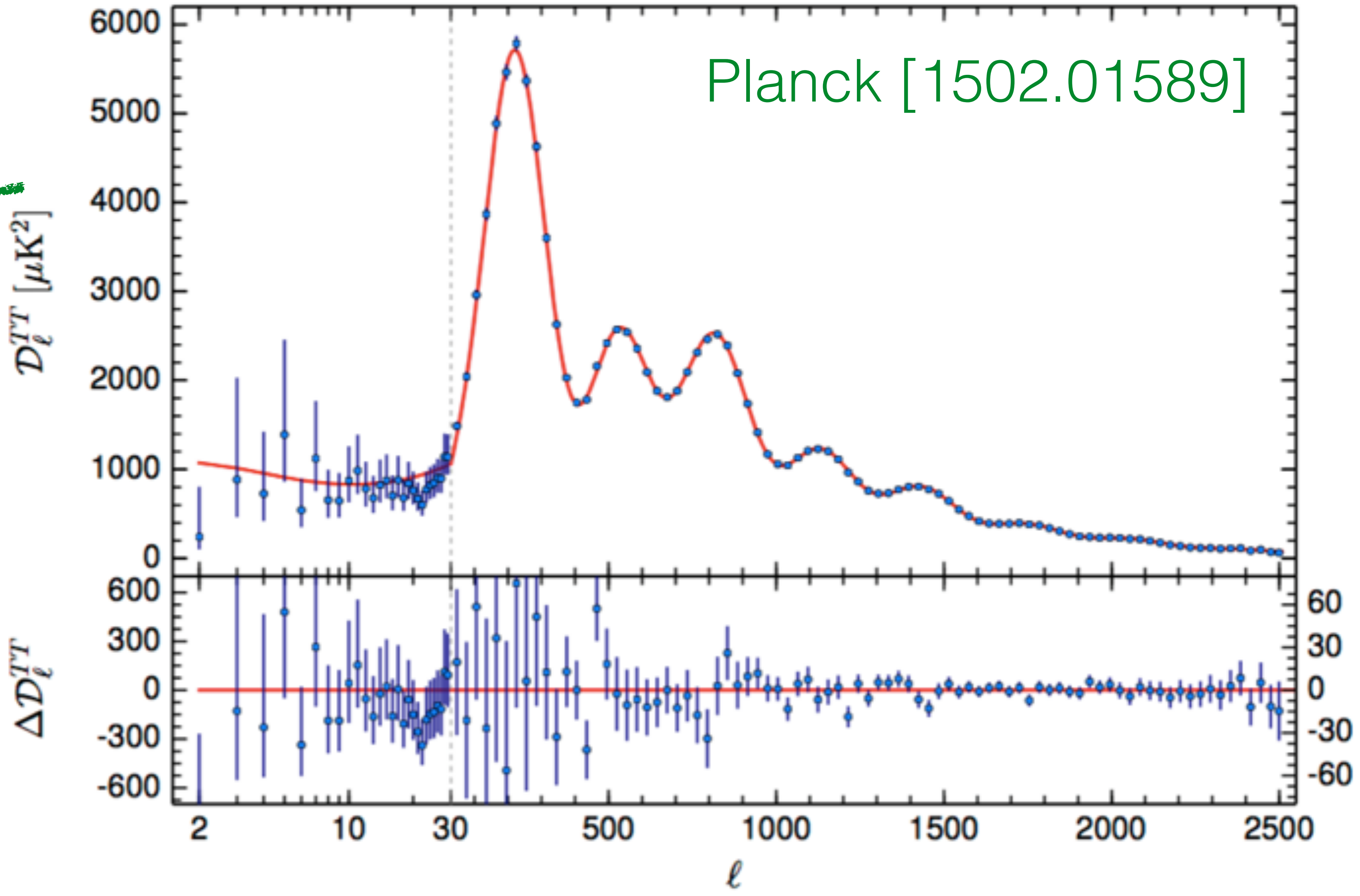
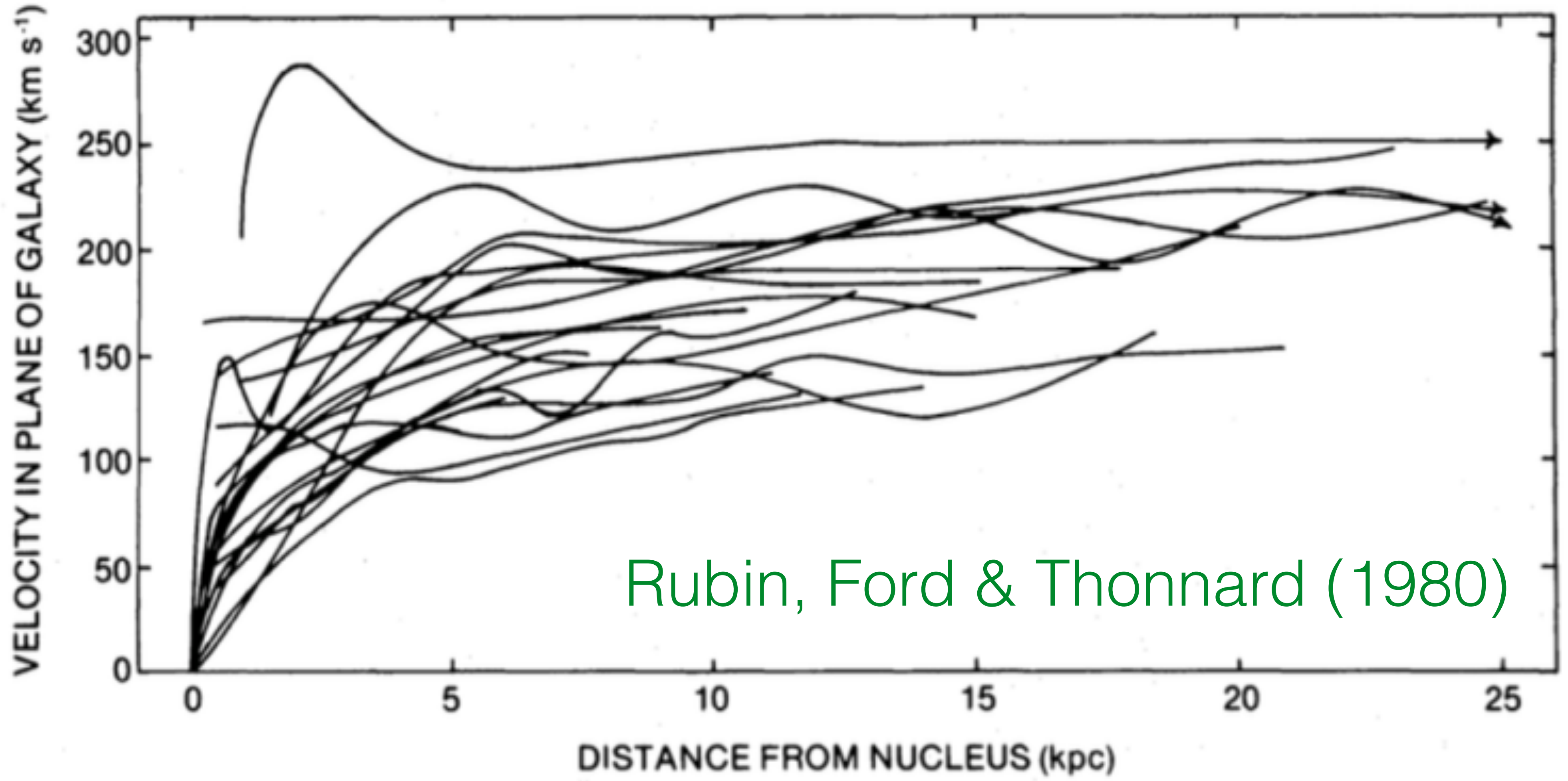
Dark Matter on all scales

Hradecky et al. [astro-ph/0006397]




Planck [1502.01589]

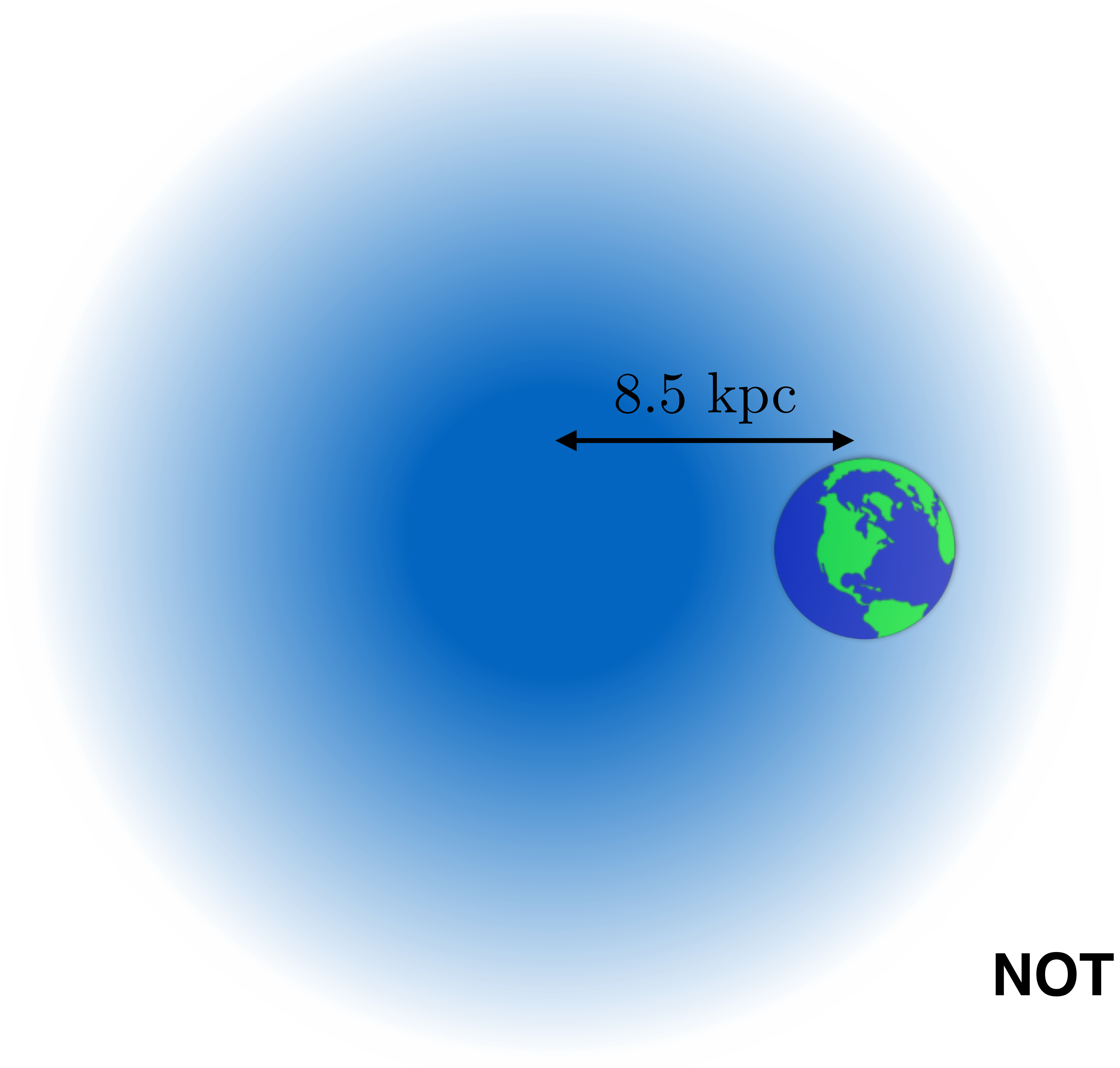

Rubin, Ford & Thonnard (1980)

Dark Matter near the 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]

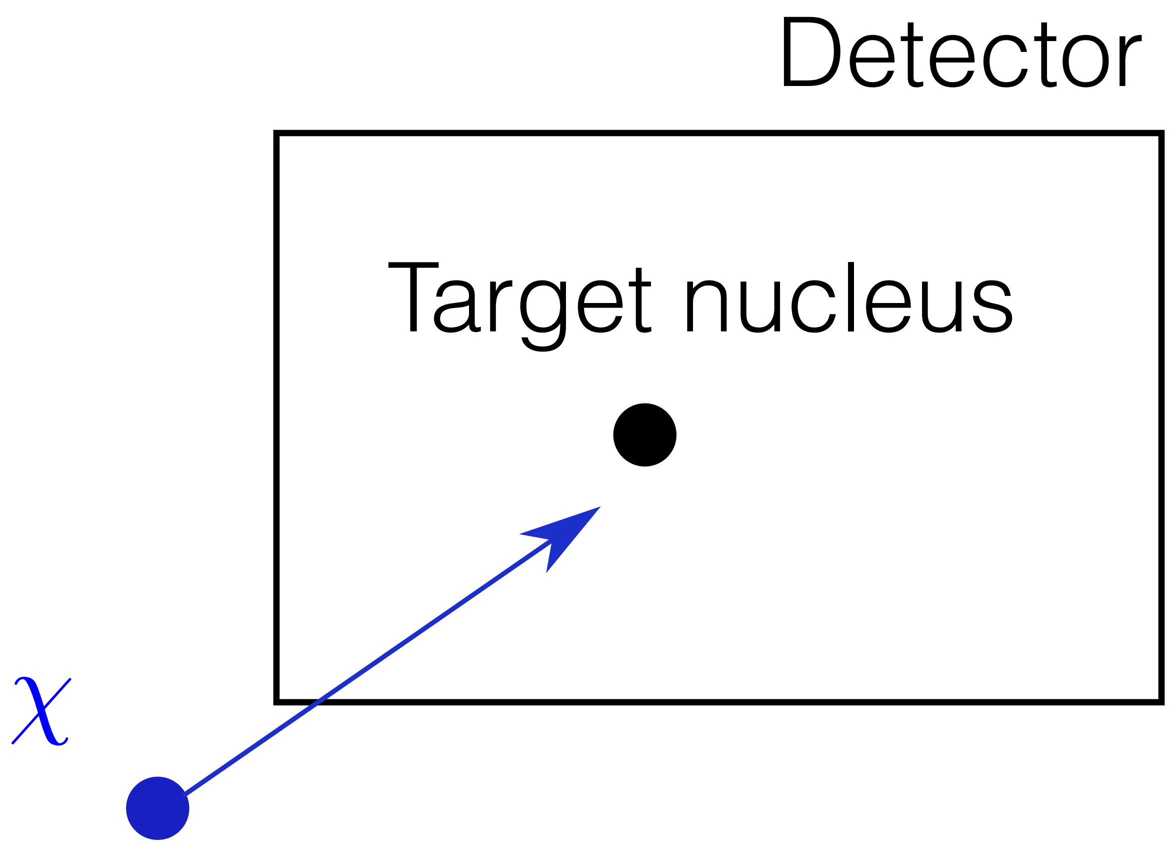


NOT TO SCALE

Direct detection of Dark Matter

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

$$v \sim 10^{-3}\,\mathrm{c}$$



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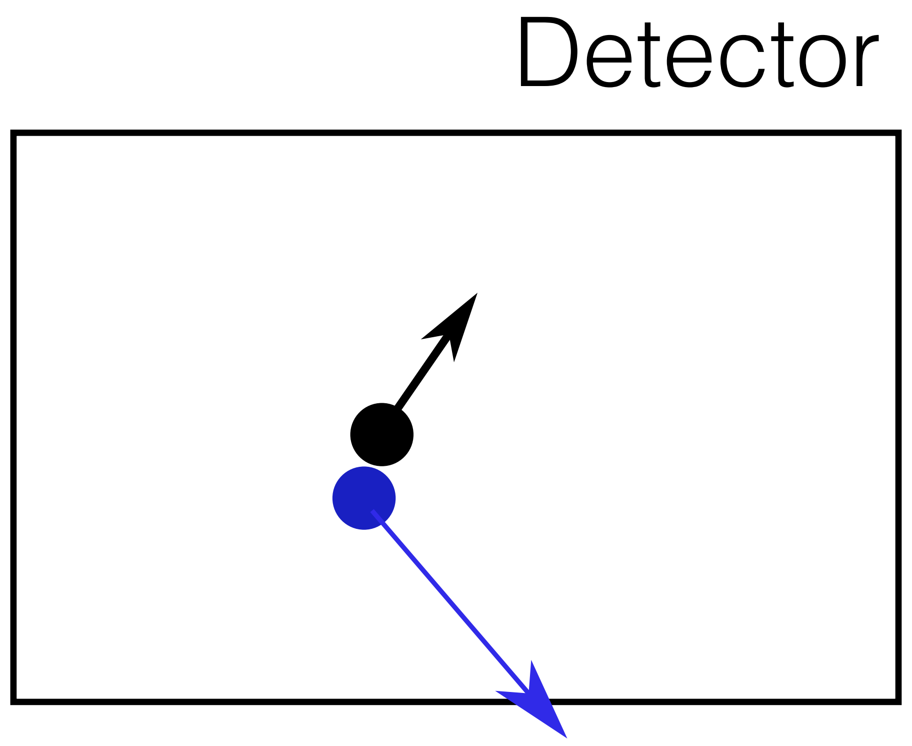

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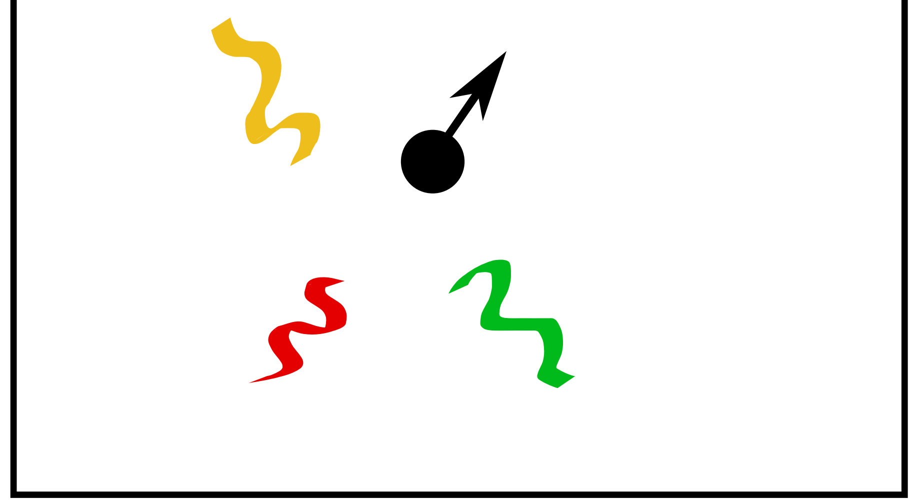

Light (scintillation)

Detector

Heat (phonons)

Charge (ionisation)

Measure rate of recoils and energy of recoiling nuclei

↓

Reconstruct the properties of DM (mass, cross section, etc.)

Direct detection of Dark Matter

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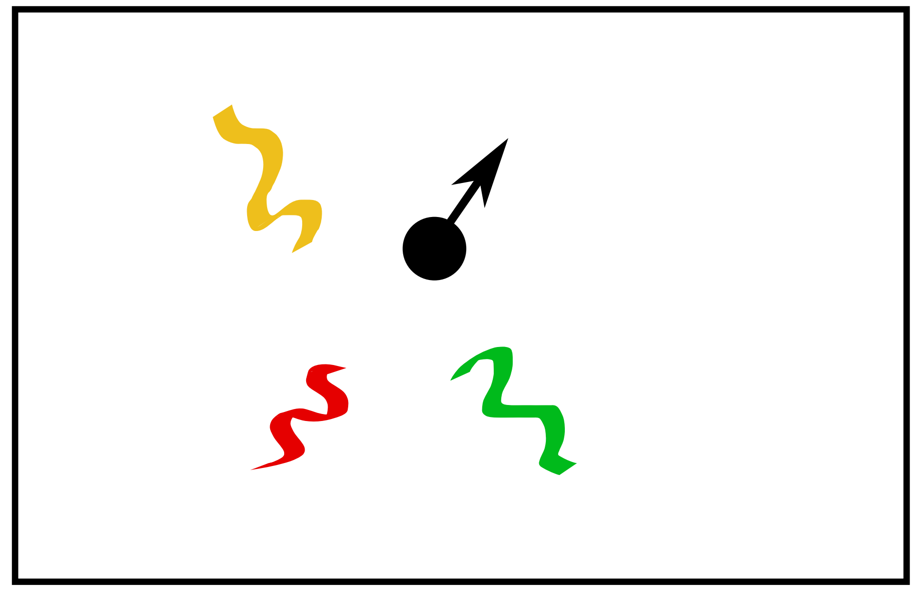


Light (scintillation)

Detector

Heat (phonons)

Charge (ionisation)

In practise, need to worry about backgrounds, background rejection, detection efficiencies, energy resolutions, validation across multiple detectors, …

Measure rate of recoils and energy of recoiling nuclei

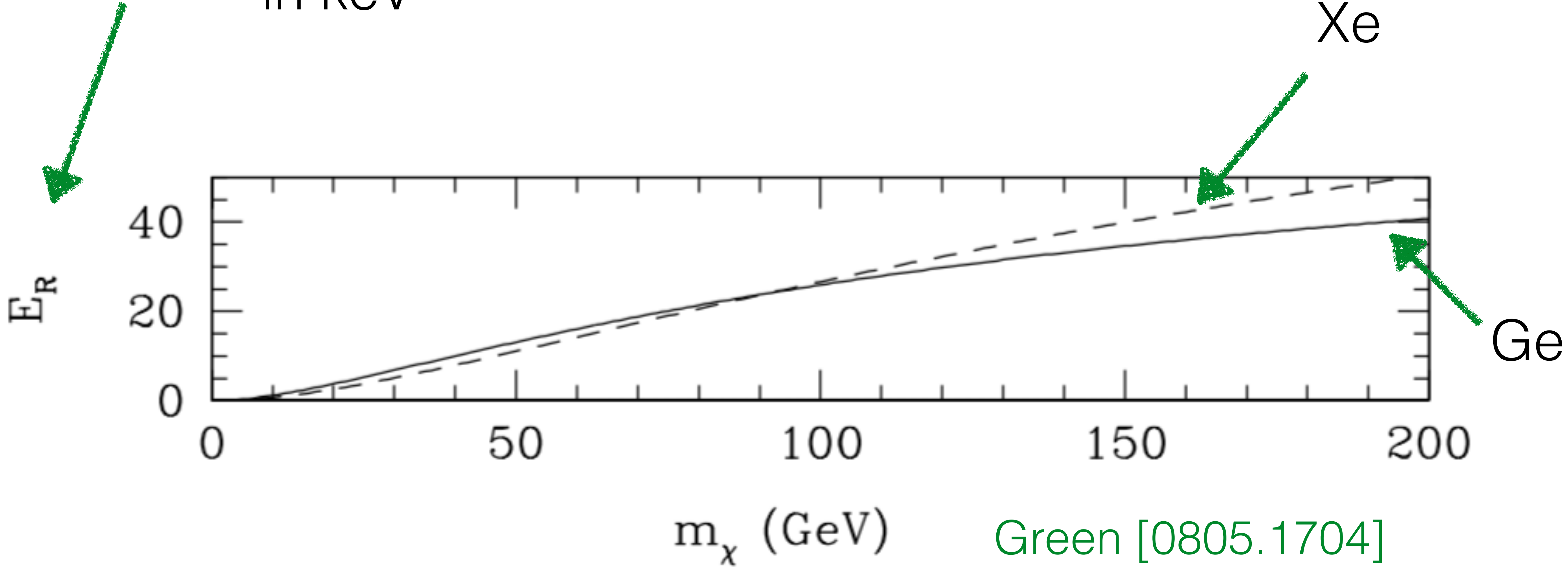
↓

Reconstruct the properties of DM (mass, cross section, etc.)

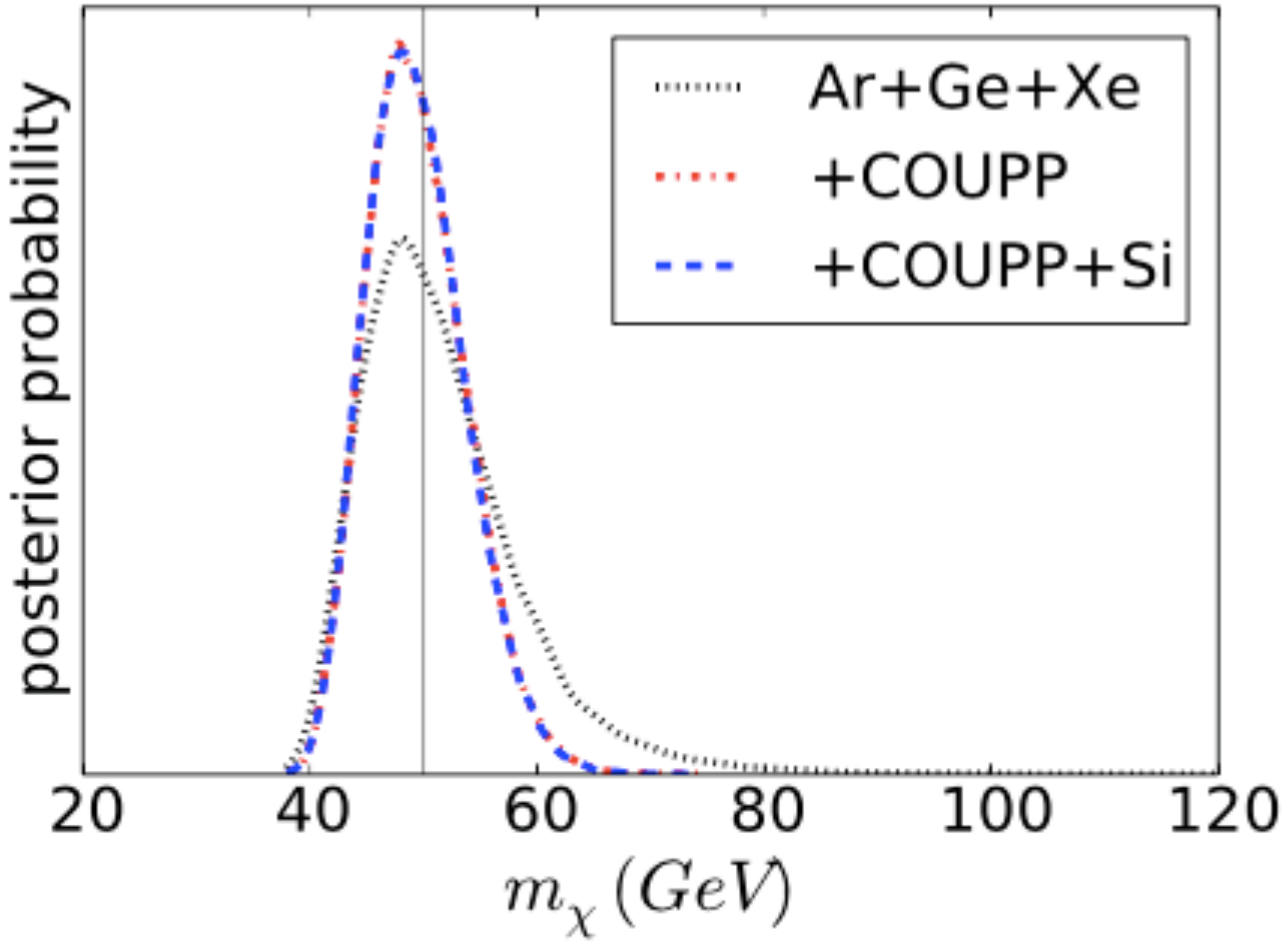
Measuring the DM mass

DM mass can be extracted from the slope of the recoil spectrum

Characteristic recoil energy
in keV



Green [0805.1704]

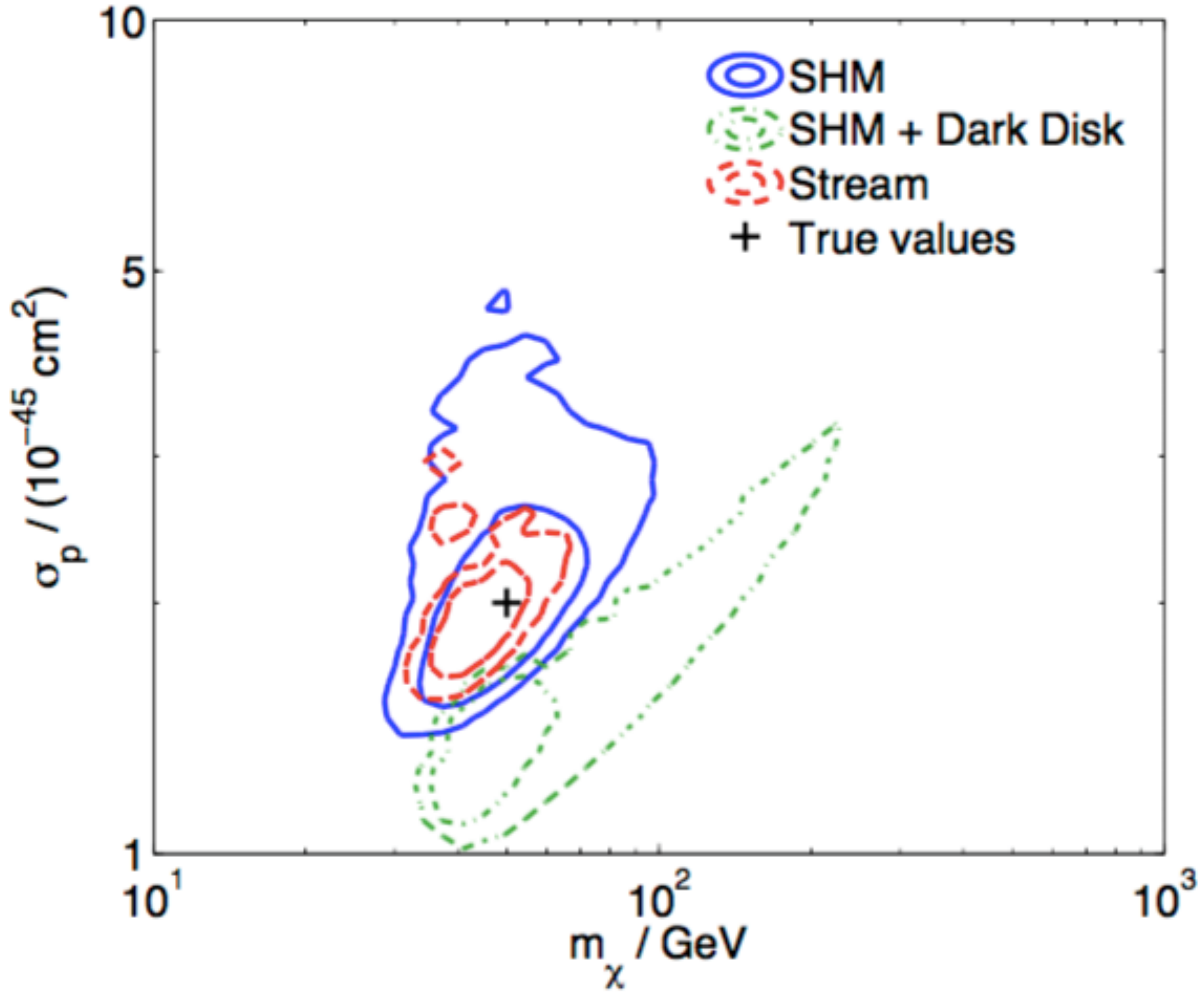


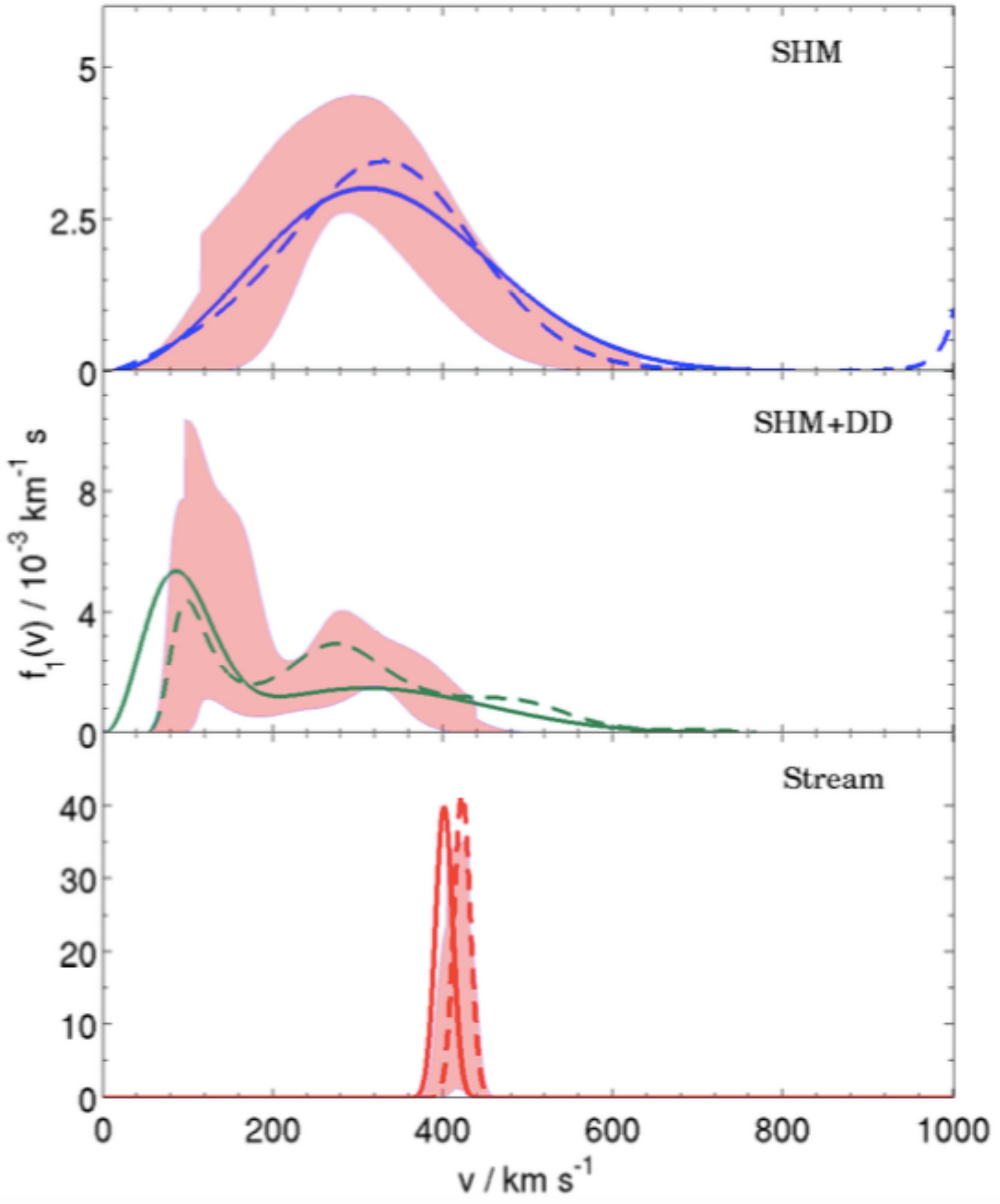
Peter, Gluscevic, Green, **BJK**, Lee [1310.7039]

Measuring the local DM speed distribution

With multiple experiments and more precise data, you could extract the DM mass and DM speed distribution simultaneously

Using Xe, Ar and Ge targets:





BJK, Green [1303.6868], but see also **BJK,** Fornasa,Green [1410.8051] and others

Distinguishing Dirac from Majorana Dark Matter

Cross sections for Dirac and Majorana DM should scale differently with number of protons and neutrons

Queiroz, Rodejohann & Yaguna [arXiv:1610.06581]

What are the prospects for distinguishing Dirac vs. Majorana DM in upcoming experiments

BJK, Queiroz, Rodejohann & Yaguna [arXiv:1706.07819]

Which experiments should we build to get the most out of a DM discovery?

3 highlights of this work

1) It may be possible to determine whether DM is its own antiparticle: using multiple ton-scale direct detection experiments!

2) To maximise our chances, we have to use particular combinations of detectors: should pursue Silicon detectors!

3) This work is 100% reproducible: check it, make fun of it, reuse it, whatever!

Dirac vs. Majorana DM

DM-nucleon contact interactions

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

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

DM-nucleon contact interactions

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

Spin-dependent interaction

DM-nucleon contact interactions

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Spin-dependent interaction

Velocity 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 couplings typically dominate. These operators 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.

Majorana DM

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

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

Vanishes for Majorana DM

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

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

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

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

Same as Majorana case, with $\lambda_{N,e} \rightarrow \lambda_{N,e} \pm \lambda_{N,o}\,.$

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

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

Dirac DM (continued)

We can try to manipulate the Dirac cross section, to get it into the same form as the Majorana cross section, $\sigma^M \sim \left[\lambda_p^M N_p + \lambda_n^M N_n\right]^2$.

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

$$= \frac{2\mu_{\chi N}^2}{\pi}\left((\lambda_p^{D\,2} + \lambda_p^{\overline{D}\,2})N_p^2 + (\lambda_n^{D\,2} + \lambda_n^{\overline{D}\,2})N_n^2 + 2(\lambda_p^D \lambda_n^D + \lambda_p^{\overline{D}} \lambda_n^{\overline{D}})N_p N_n\right)$$

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

where $\lambda_N = \sqrt{\frac{1}{2}(\lambda_N^{D\,2} + \lambda_N^{\overline{D}\,2})}$ and $f = (\lambda_p^D \lambda_n^D + \lambda_p^{\overline{D}} \lambda_n^{\overline{D}})/(2\lambda_p\lambda_n)$

$f \in [-1, 1]$

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

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].

A visual example

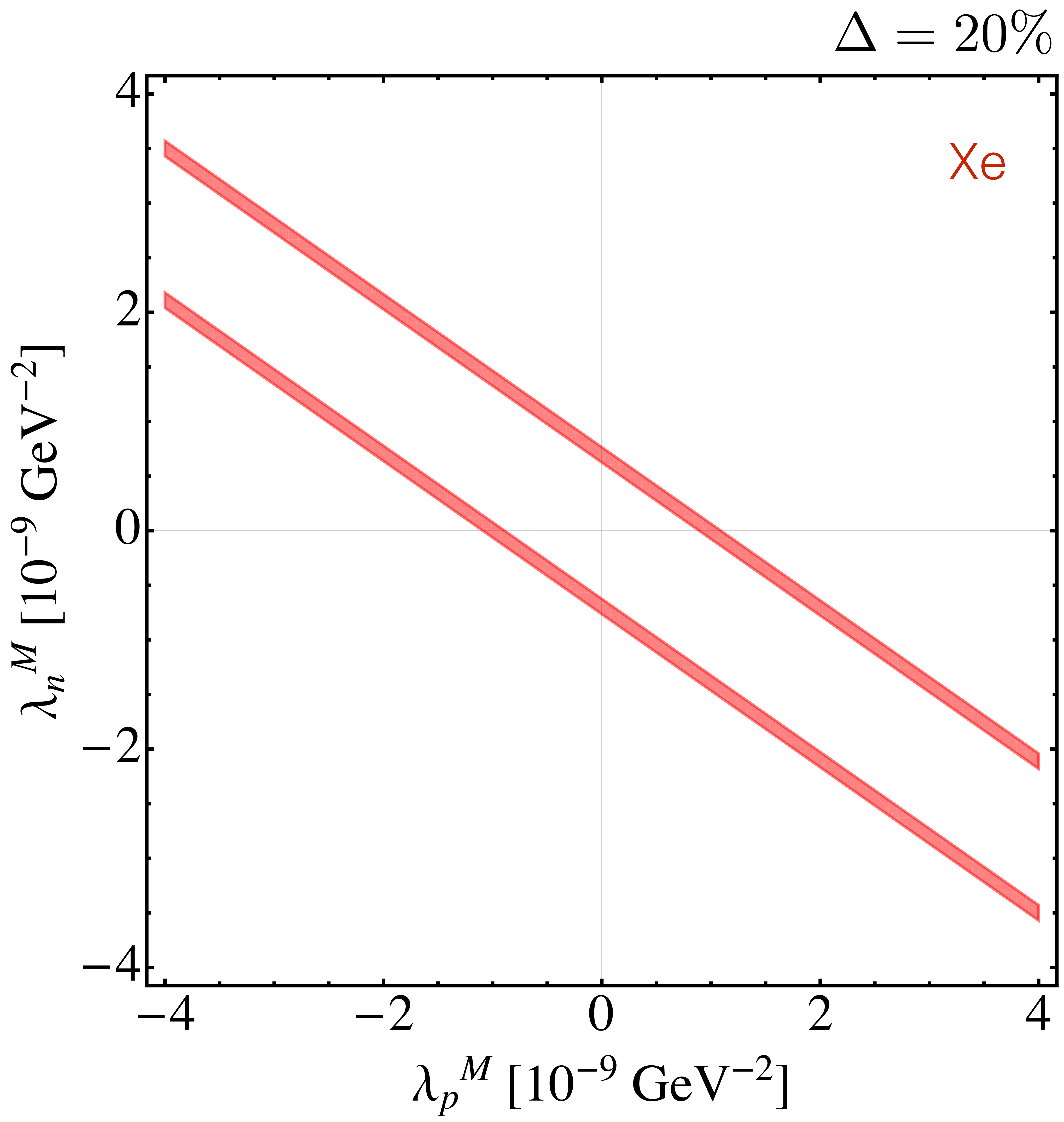
Calculate DM-nucleus cross section for Dirac DM.
Here, assume the following couplings:

$$(\lambda_p^D,\, \lambda_p^{\overline{D}},\, \lambda_n^D,\, \lambda_n^{\overline{D}}) = (6.7,\, 2.0,\, -5.6,\, -1.0) \times 10^{-9}\ \mathrm{GeV}^{-2}$$

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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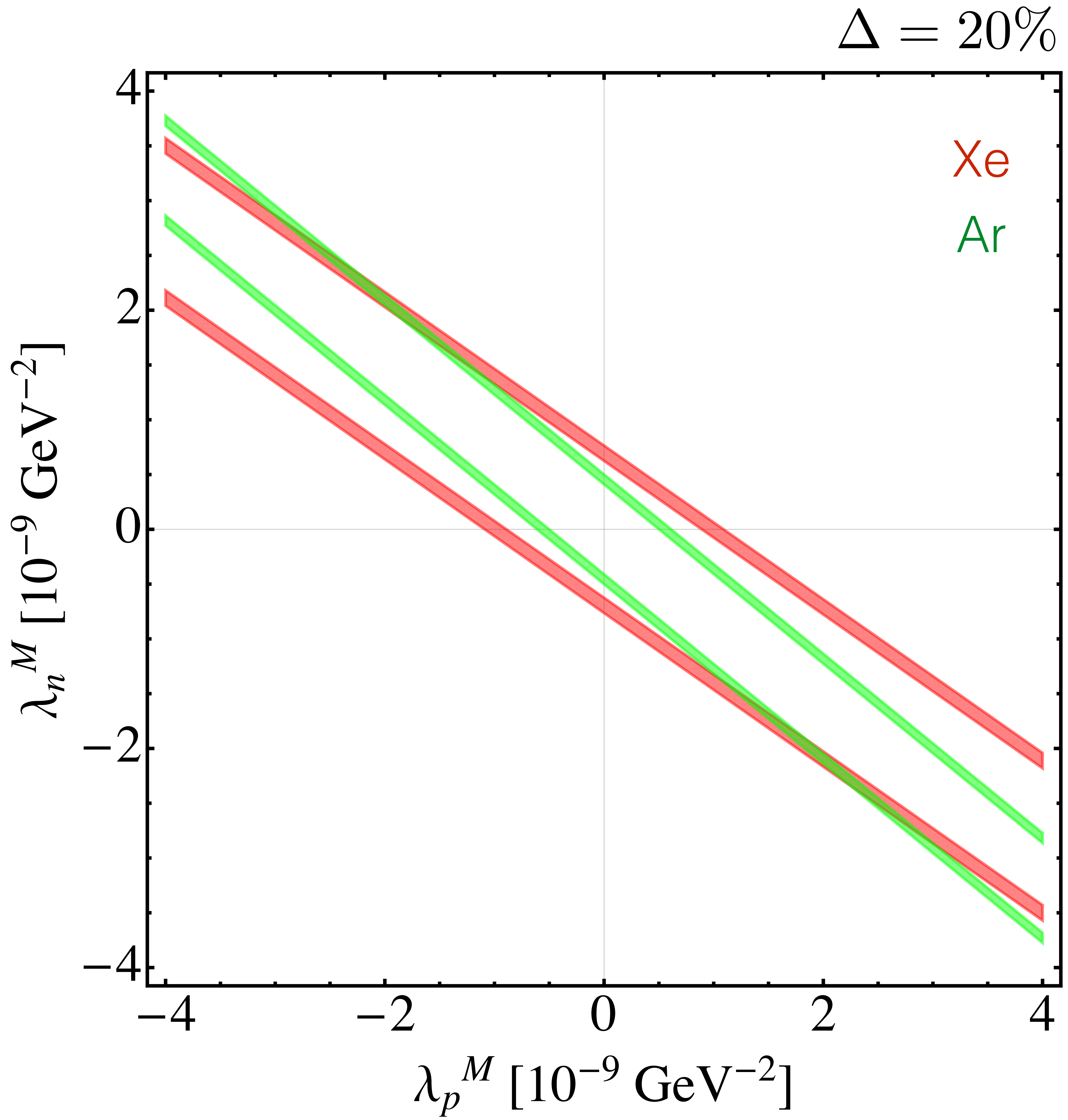

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Assume DM-nucleus cross section is measured to 20% precision.

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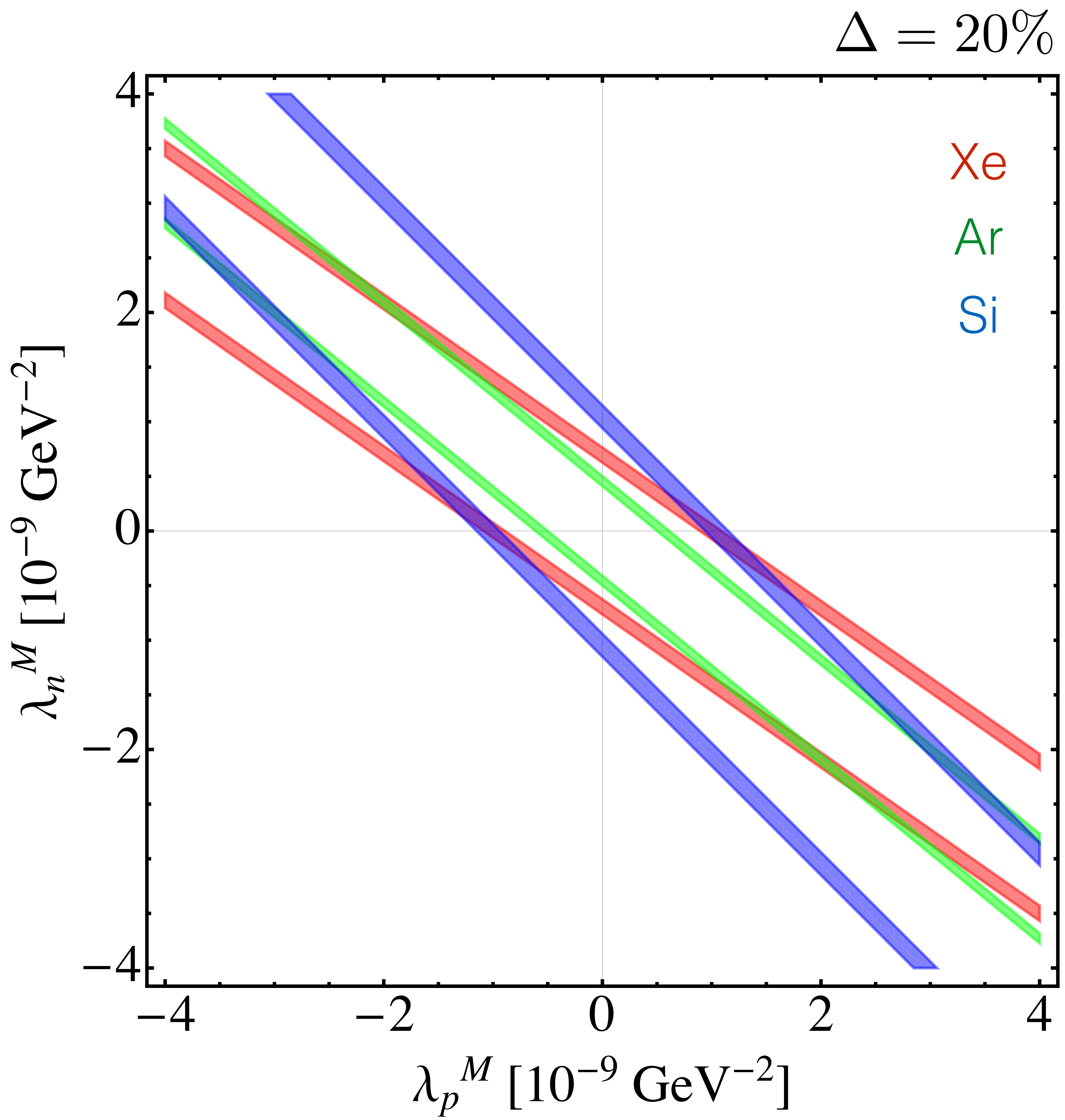

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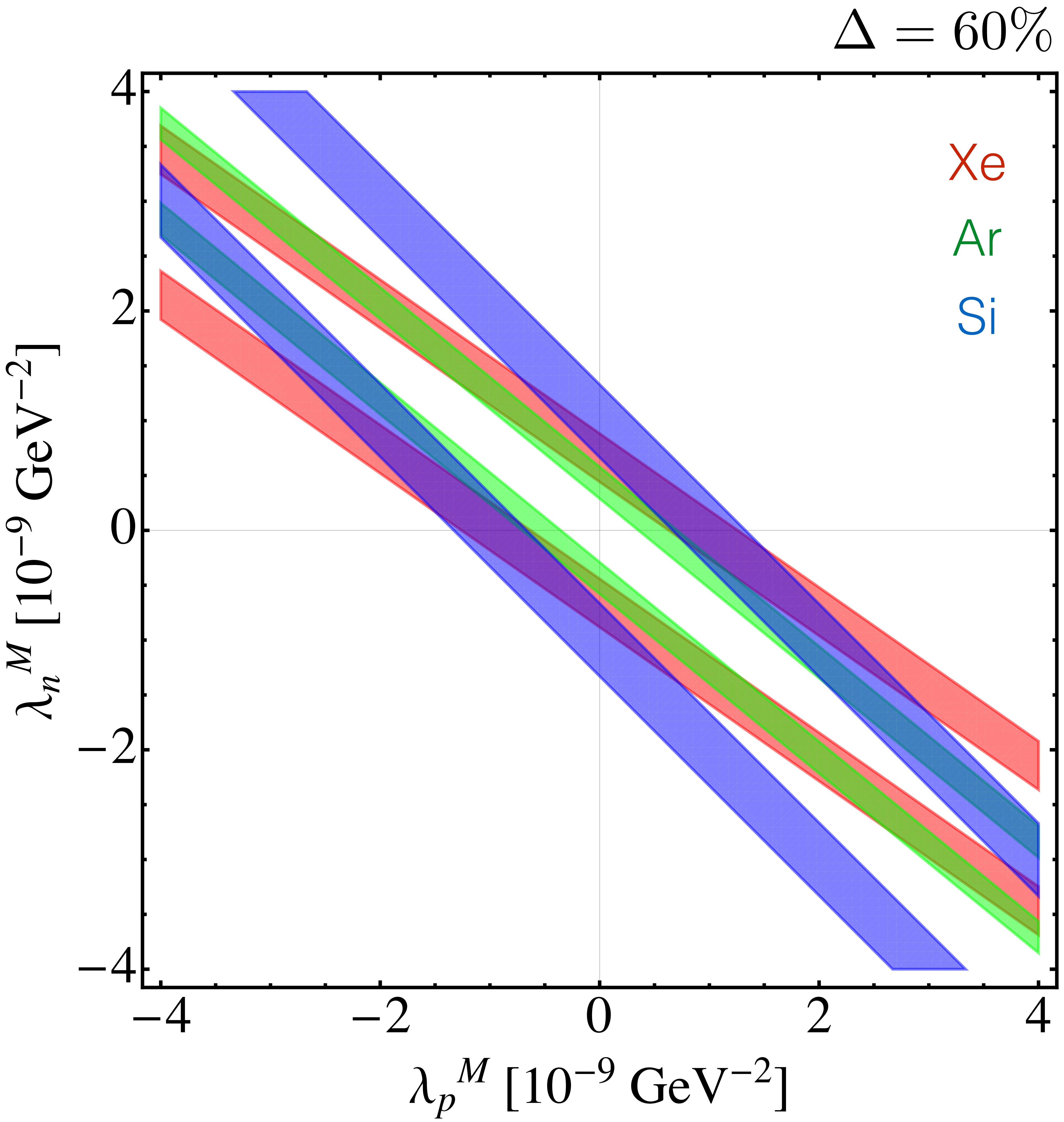
Assume DM-nucleus cross section is measured to 60% precision.

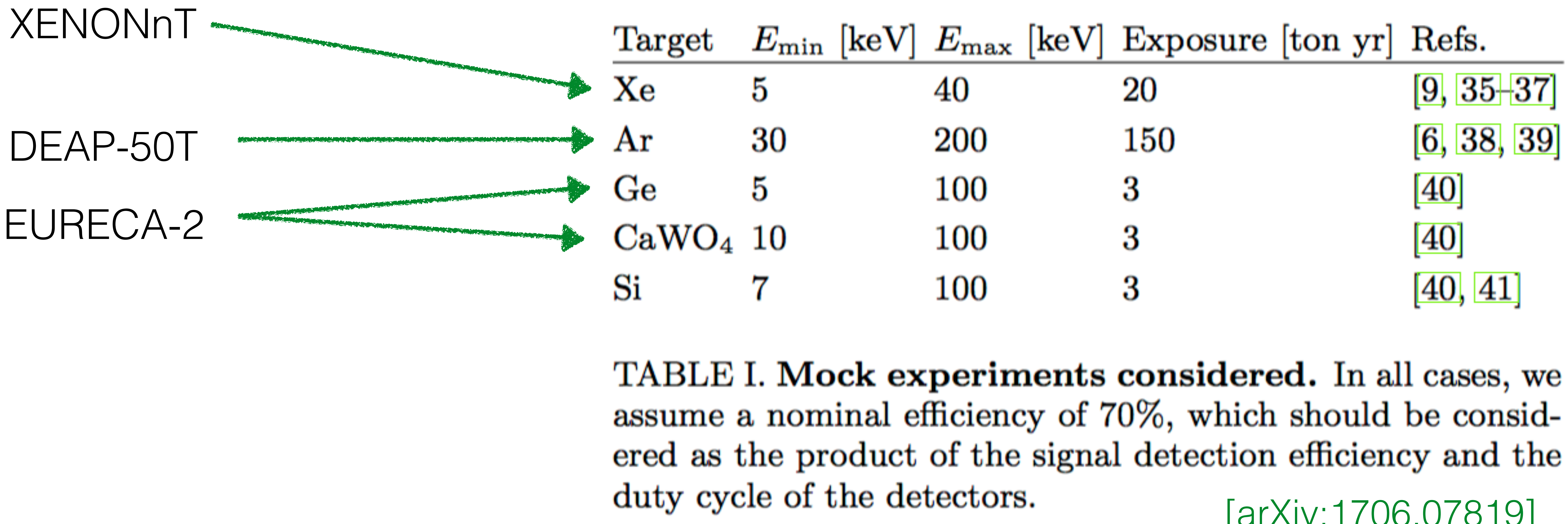
Attempt to fit assuming Majorana DM:

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



Prospects for future experiments

Future Experiments (2020-2025)



XENONnT

DEAP-50T

EURECA-2

Target	$E_{\rm min}$ [keV]	$E_{\rm max}$ [keV]	Exposure [ton yr]	Refs.
Xe	5	40	20	[9, 35–37]
Ar	30	200	150	[6, 38, 39]
Ge	5	100	3	[40]
$CaWO_4$	10	100	3	[40]
Si	7	100	3	[40, 41]

TABLE I. **Mock experiments considered.** In all cases, we assume a nominal efficiency of 70%, which should be considered as the product of the signal detection efficiency and the duty cycle of the detectors.

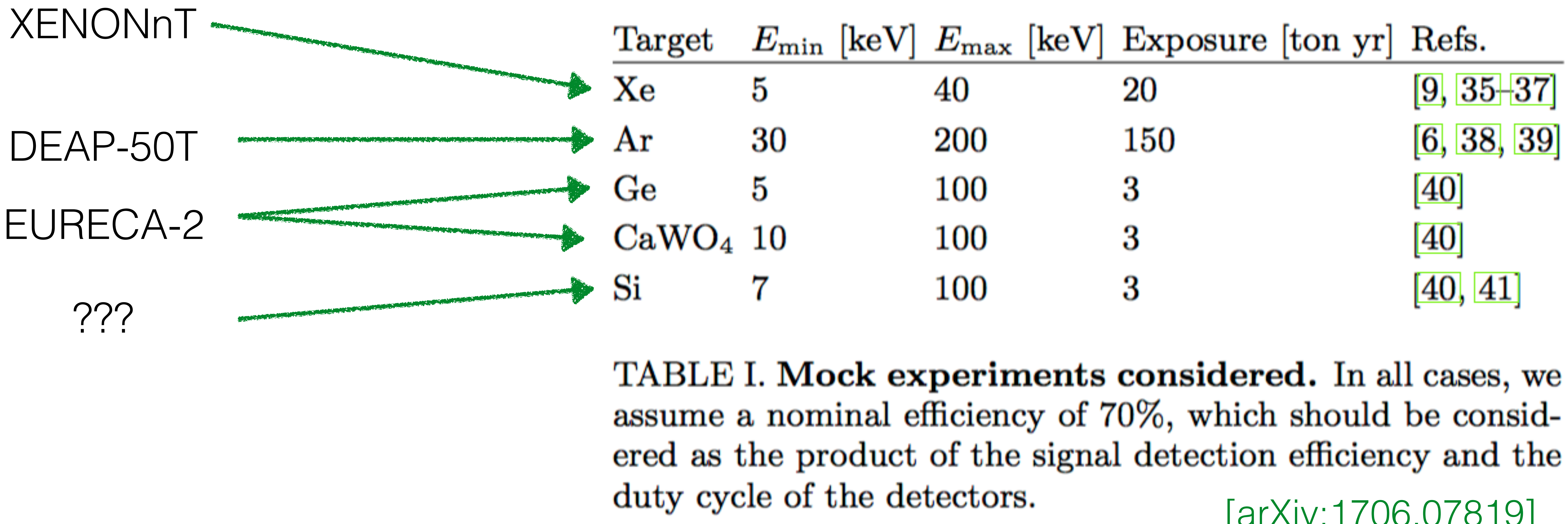
[arXiv:1706.07819]

Assume constant efficiency for nuclear recoils in range $E_R \in [E_{\rm min}, E_{\rm max}]$

No backgrounds, perfect energy resolution

“Best-case scenario”

Future Experiments (2020-2025)



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"Best-case scenario"

Ensembles

Nucleus	A	Z	N_p/N_n
Silicon (Si)	28	14	1.0
Oxygen (O)	16	8	1.0
Calcium (Ca)	40	20	1.0
Argon (Ar)	40	18	0.82
Germanium (Ge)	73	32	0.78
Xenon (Xe)	131	54	0.70
Tungsten (W)	184	74	0.67

Ensemble A: Xe + Ar + Si,

Ensemble B: Xe + Ar + Ge,

Ensemble C: Xe + Ar + $CaWO_4$,

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

NB: Fix the overall cross section normalisation to give ~300 Xenon events (just below current bounds from LUX/Xenon1T)

Statistical procedure

Recall that in the Dirac case, the DM-nucleus cross section can be written as:

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

For a given set of couplings and a given experimental ensemble:

1. Generate mock data for the experiments
2. Calculate the maximum likelihood under two hypotheses:

$\mathbf{H}_M$ - the DM is Majorana-like, with free parameters: $(m_\chi, \lambda_p, \lambda_n, f = \pm 1)$

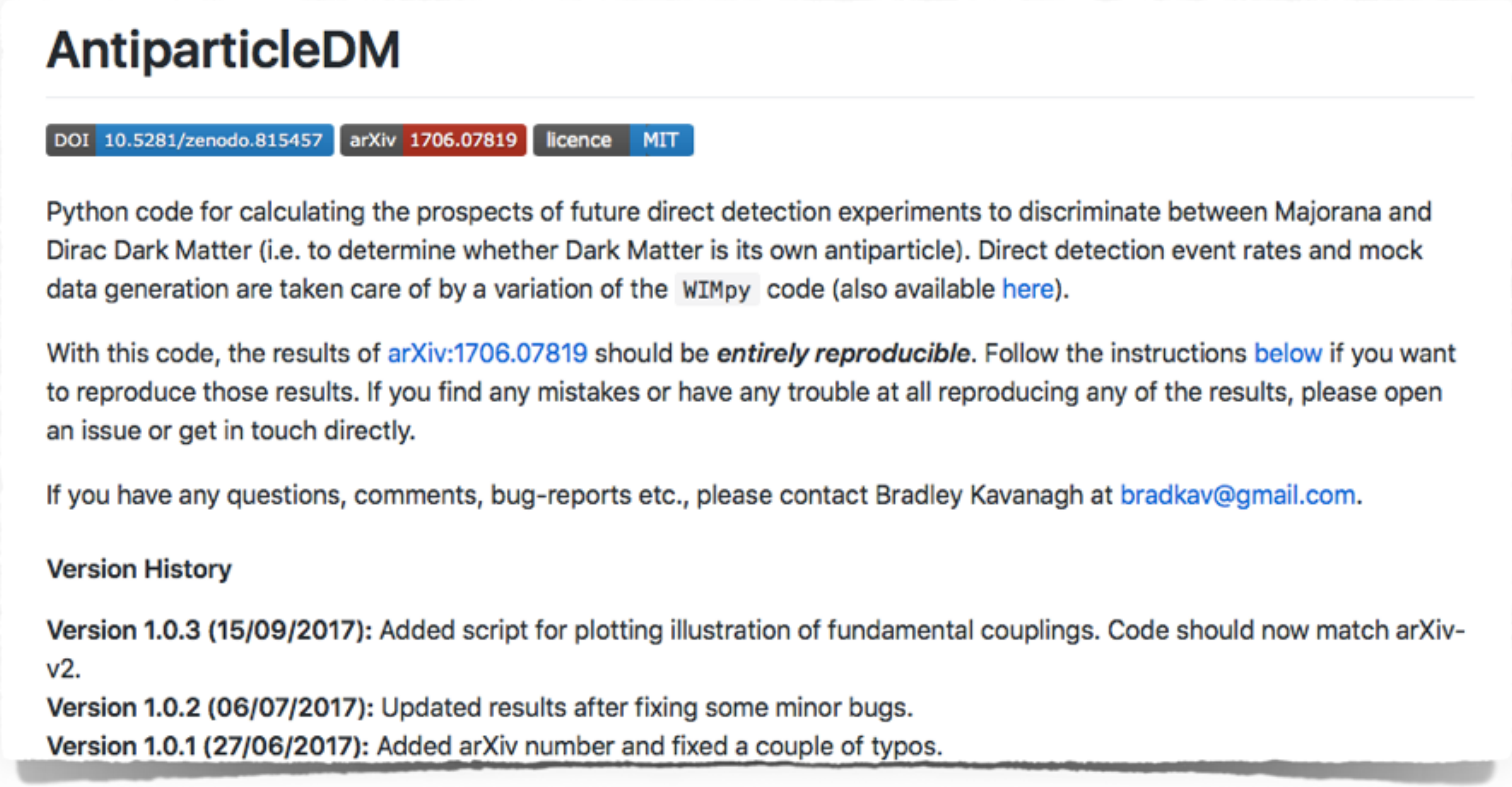
$\mathbf{H}_D$ - the DM is Dirac-like, with free parameters: $(m_\chi, \lambda_p, \lambda_n, f \in [-1, 1])$

3. Calculate the discrimination significance from the log-likelihood ratio

Repeat 100 times to estimate the *median* significance with which Dirac DM can be distinguished from Majorana.

Code

All code for generating mock data, calculating likelihoods and producing plots is available online (and archived on Zenodo)



AntiparticleDM

DOI 10.5281/zenodo.815457 arXiv 1706.07819 licence MIT

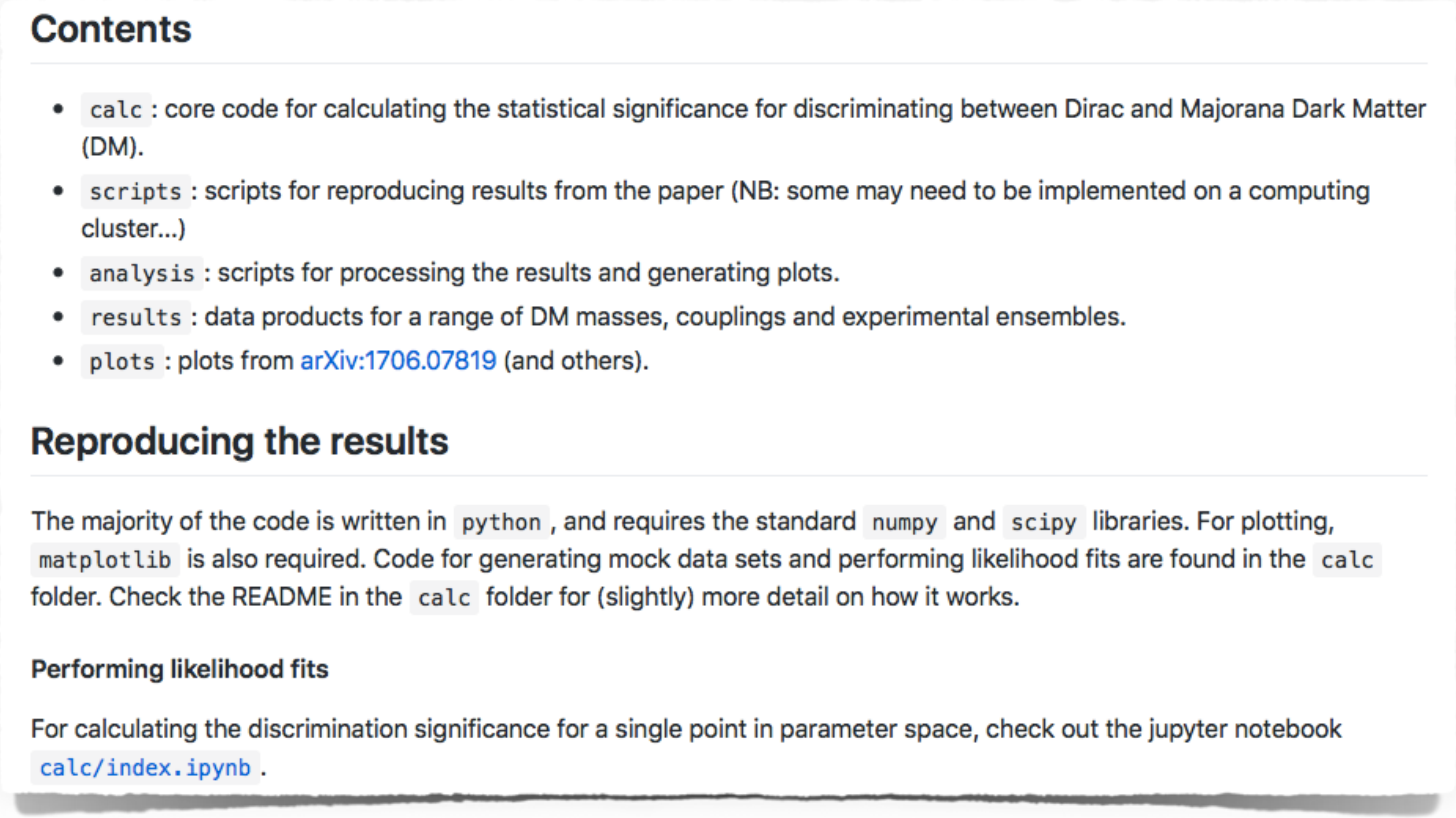
Python code for calculating the prospects of future direct detection experiments to discriminate between Majorana and Dirac Dark Matter (i.e. to determine whether Dark Matter is its own antiparticle). Direct detection event rates and mock data generation are taken care of by a variation of the `WIMpy` code (also available here).

With this code, the results of arXiv:1706.07819 should be ***entirely reproducible***. Follow the instructions below if you want to reproduce those results. If you find any mistakes or have any trouble at all reproducing any of the results, please open an issue or get in touch directly.

If you have any questions, comments, bug-reports etc., please contact Bradley Kavanagh at bradkav@gmail.com.

Version History

Version 1.0.3 (15/09/2017): Added script for plotting illustration of fundamental couplings. Code should now match arXiv-v2.
Version 1.0.2 (06/07/2017): Updated results after fixing some minor bugs.
Version 1.0.1 (27/06/2017): Added arXiv number and fixed a couple of typos.



Contents

- `calc` : core code for calculating the statistical significance for discriminating between Dirac and Majorana Dark Matter (DM).
- `scripts` : scripts for reproducing results from the paper (NB: some may need to be implemented on a computing cluster...)
- `analysis` : scripts for processing the results and generating plots.
- `results` : data products for a range of DM masses, couplings and experimental ensembles.
- `plots` : plots from arXiv:1706.07819 (and others).

Reproducing the results

The majority of the code is written in `python`, and requires the standard `numpy` and `scipy` libraries. For plotting, `matplotlib` is also required. Code for generating mock data sets and performing likelihood fits are found in the `calc` folder. Check the README in the `calc` folder for (slightly) more detail on how it works.

Performing likelihood fits

For calculating the discrimination significance for a single point in parameter space, check out the jupyter notebook `calc/index.ipynb`.

https://github.com/bradkav/AntiparticleDM

http://doi.org/10.5281/zenodo.815457

Code

All code for generating mock data, calculating likelihoods and producing plots is available online (and archived on Zenodo)

- Finding the maximum likelihood needed to be fast and the method we used couldn’t be described in enough detail in the paper. Luckily, the code is an explanation of itself!
- If people want to use this method to test their favourite model, now they can, without having to re-do any of the work we did!
- While making the code public, we found several mistakes. In explaining and checking the code, we made it better!

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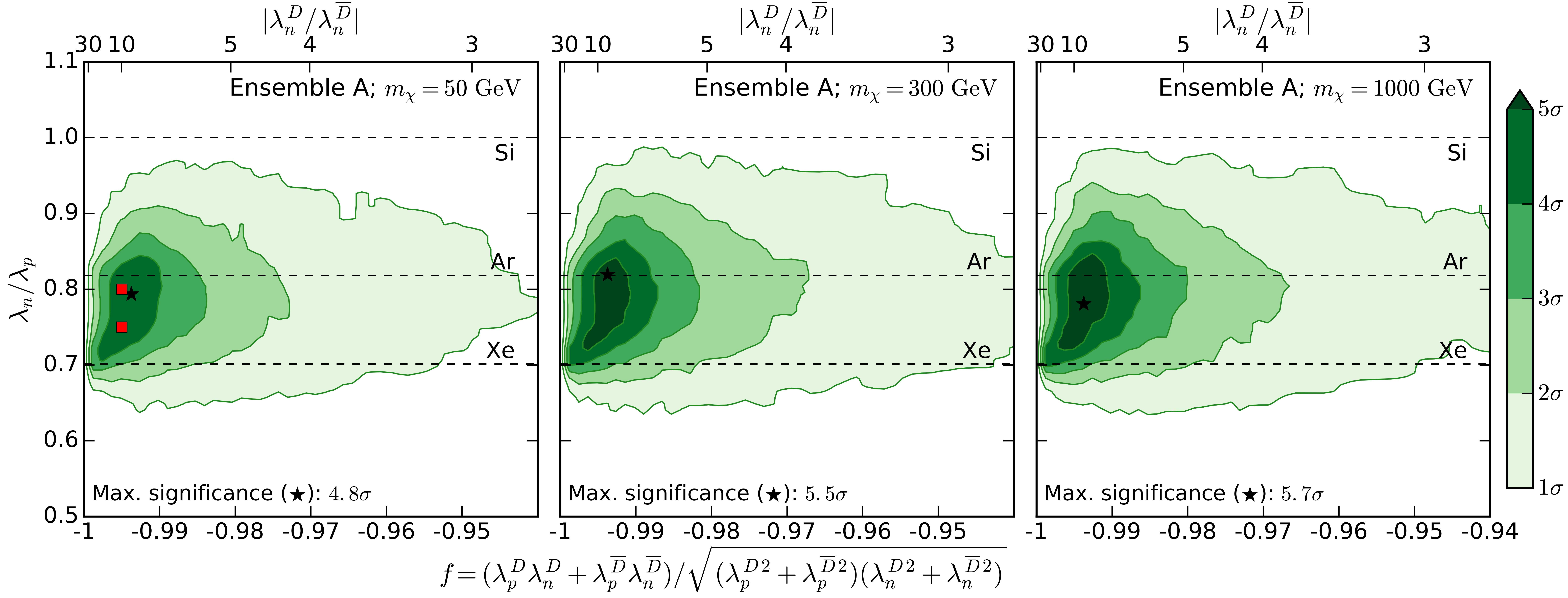
Discrimination significance: Dirac vs Majorana

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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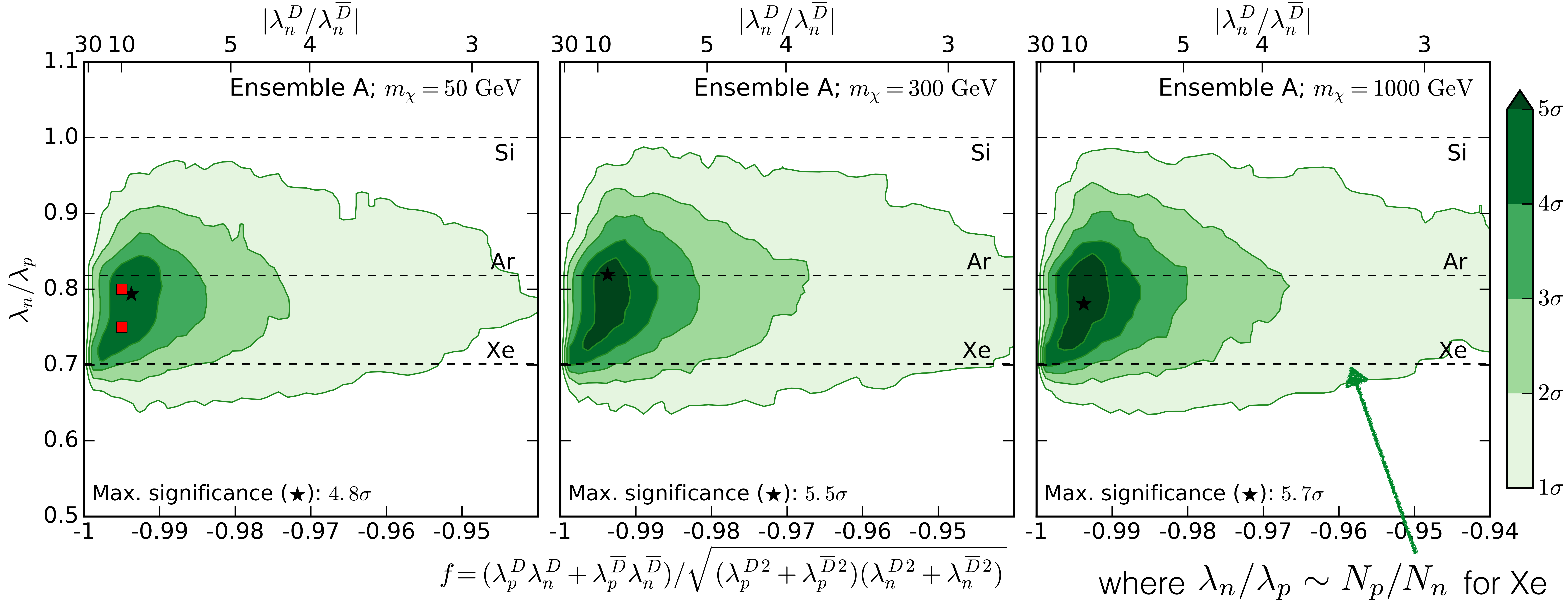

where $\lambda_n/\lambda_p \sim N_p/N_n$ for Xe

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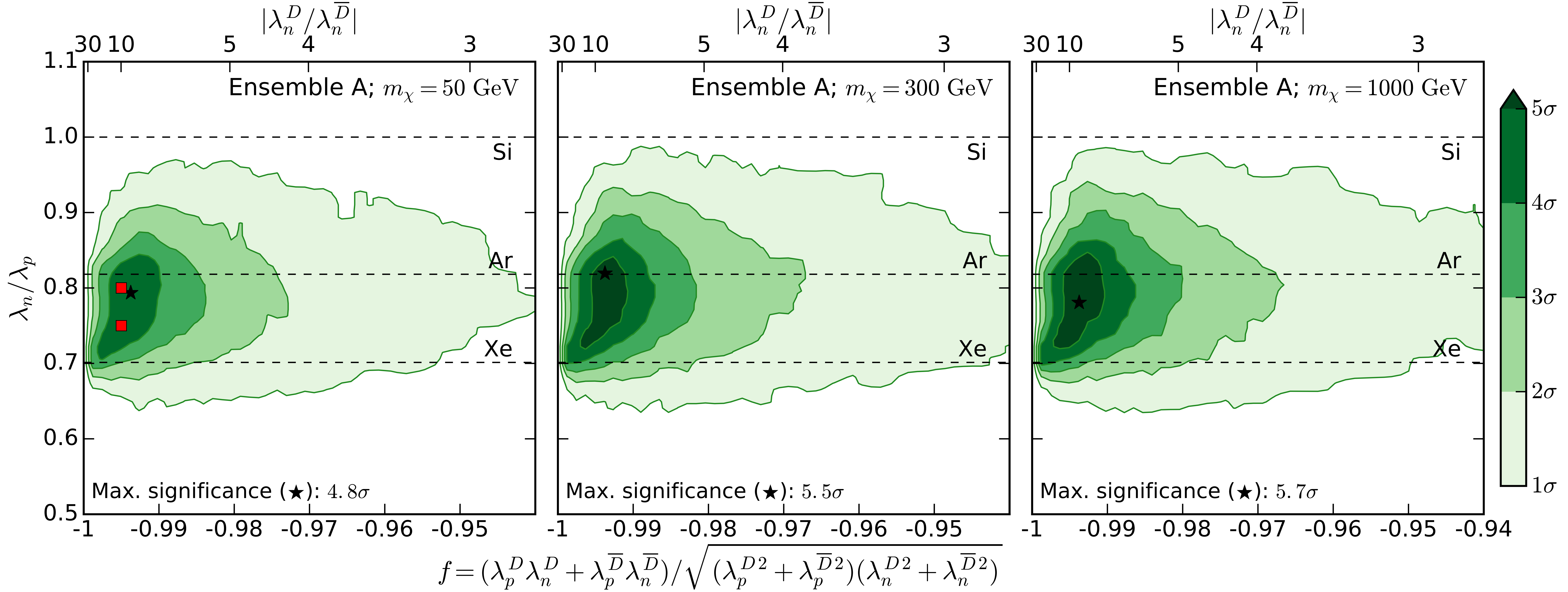

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Assume DM-nucleus cross section is measured
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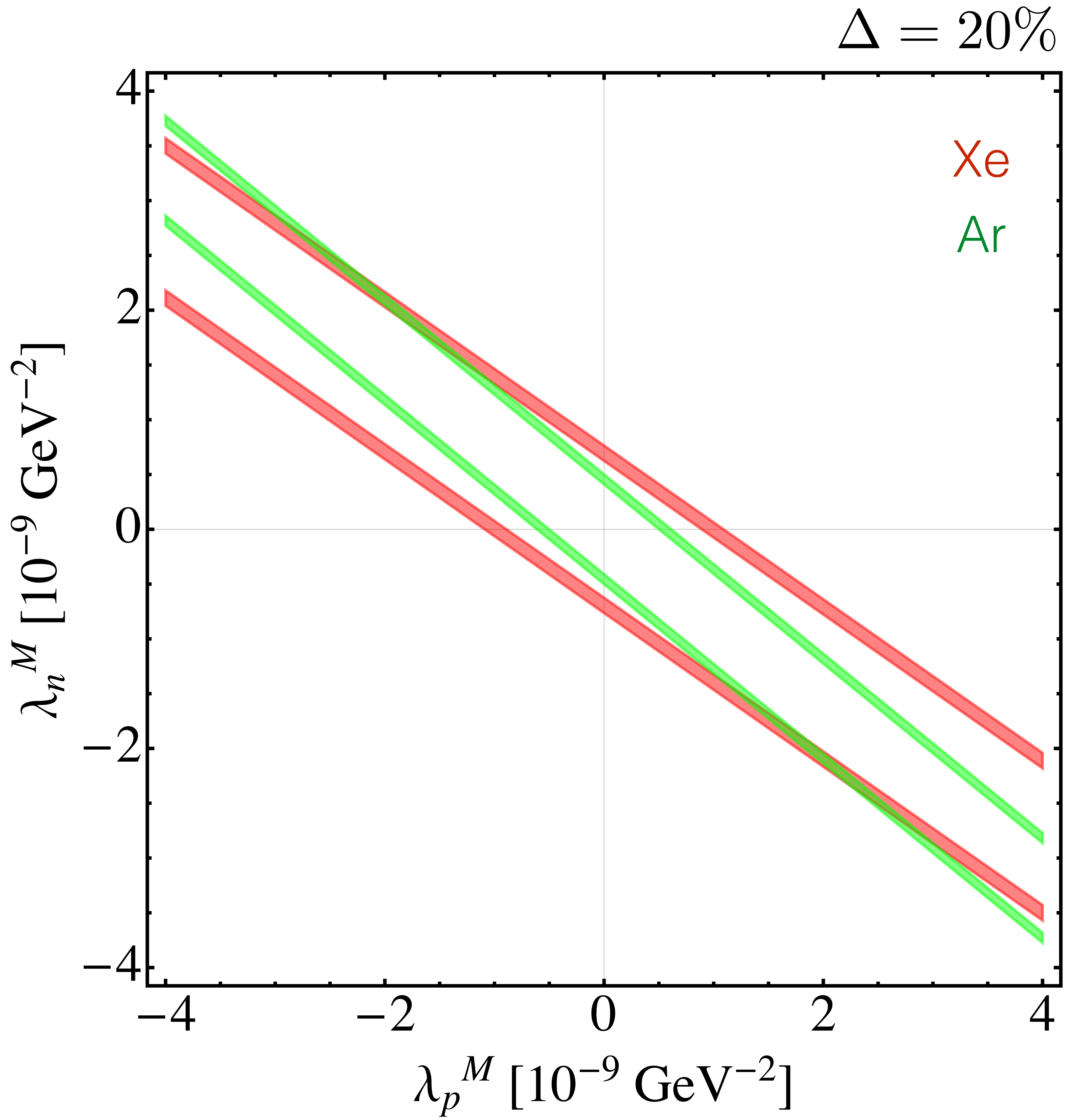
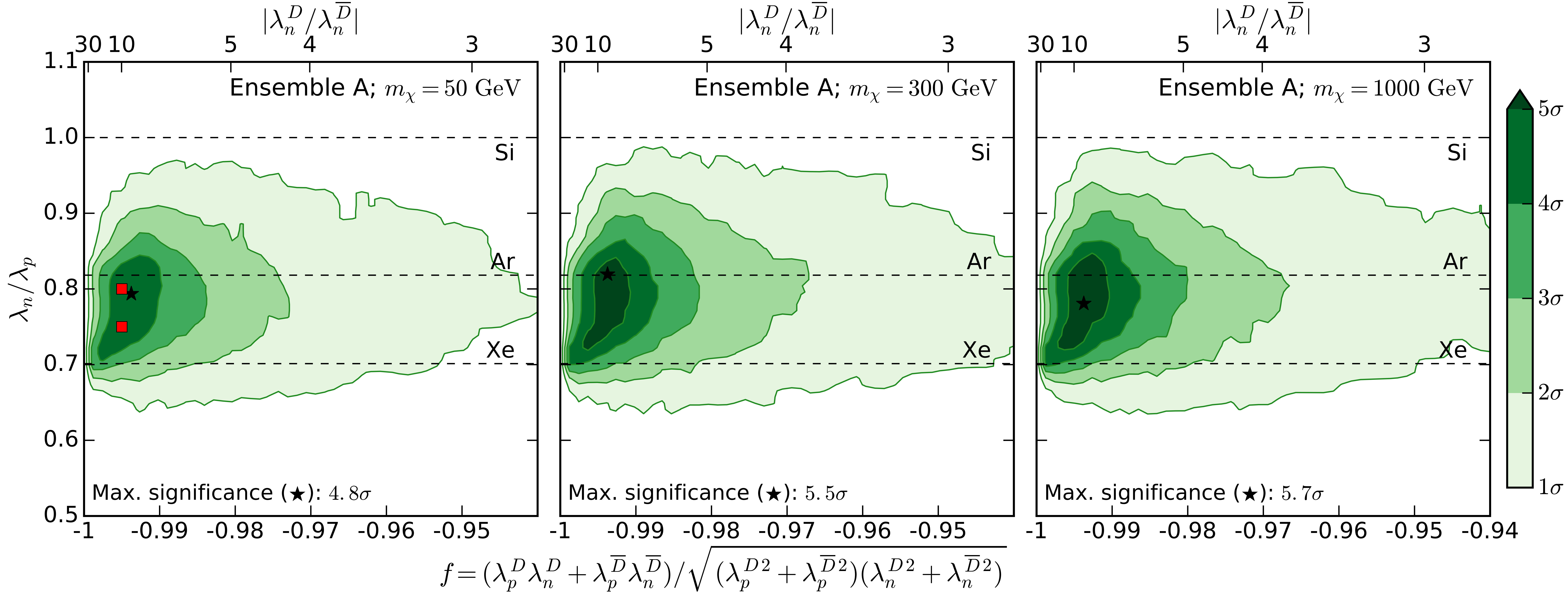
Attempt to fit assuming Majorana DM:

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



Discrimination significance: Dirac vs Majorana

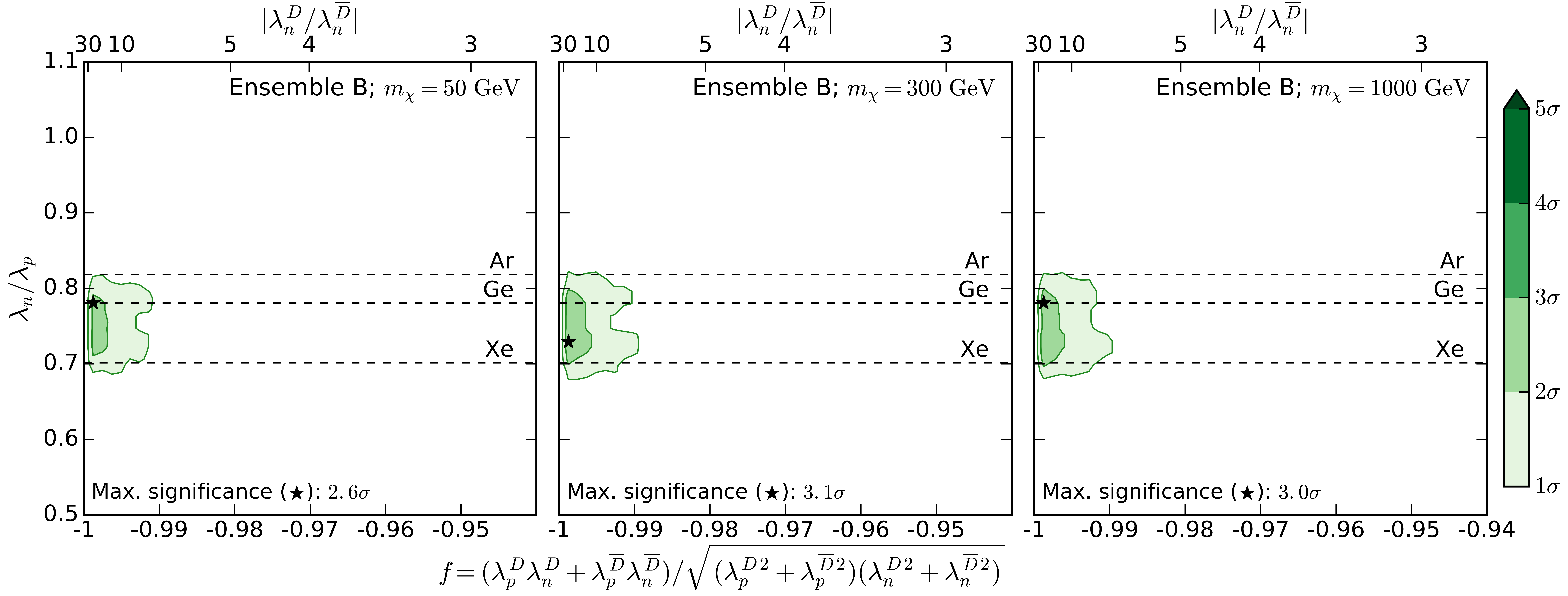
Ensemble A: Xe + Ar + Si



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

Discrimination significance: Dirac vs Majorana

Ensemble B: Xe + Ar + Ge



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

A visual example

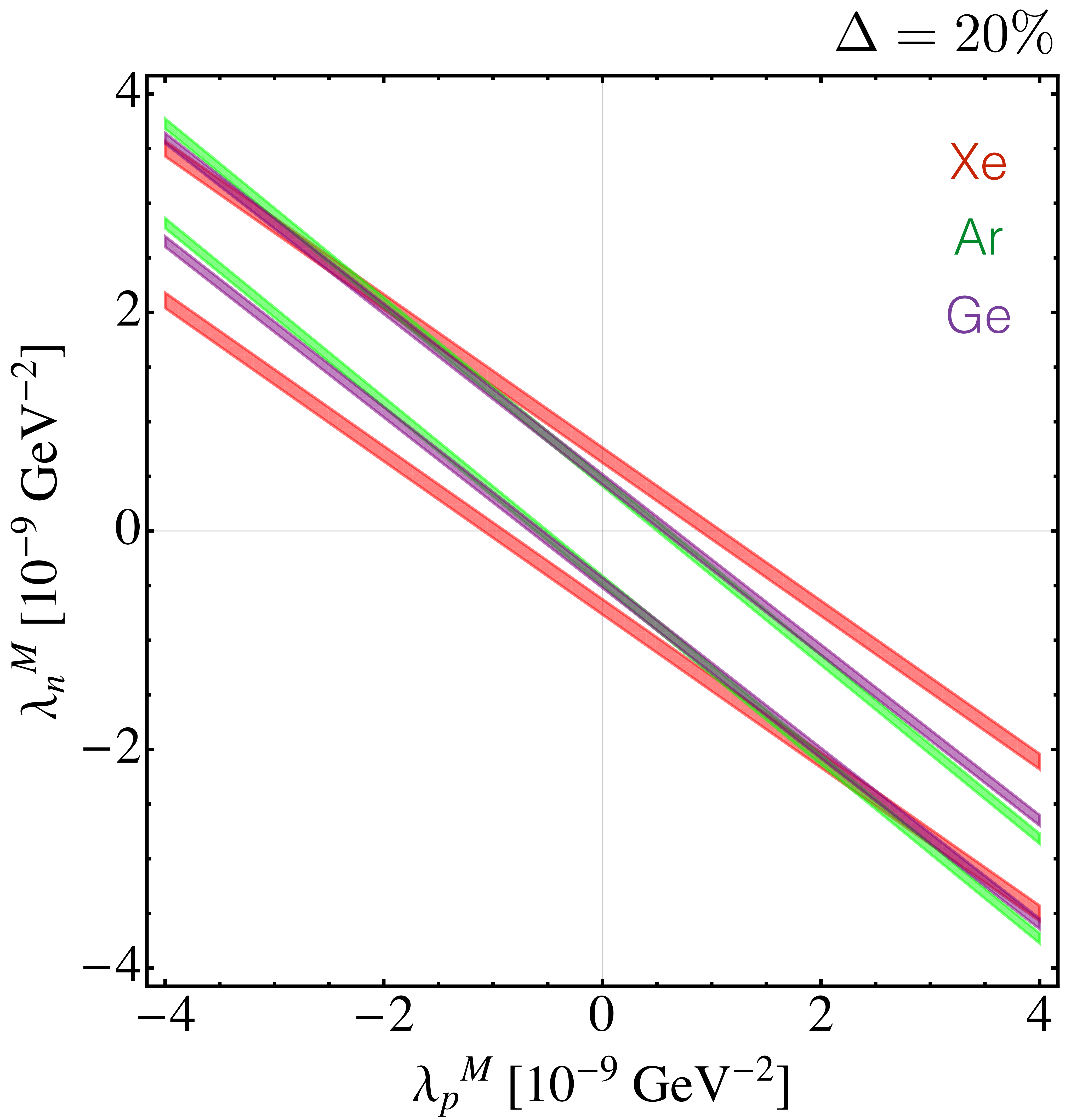
Calculate DM-nucleus cross section for Dirac DM.
Here, assume the following couplings:

$$(\lambda_p^D,\, \lambda_p^{\overline{D}},\, \lambda_n^D,\, \lambda_n^{\overline{D}}) = (6.7,\, 2.0,\, -5.6,\, -1.0) \times 10^{-9}\ \mathrm{GeV}^{-2}$$

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

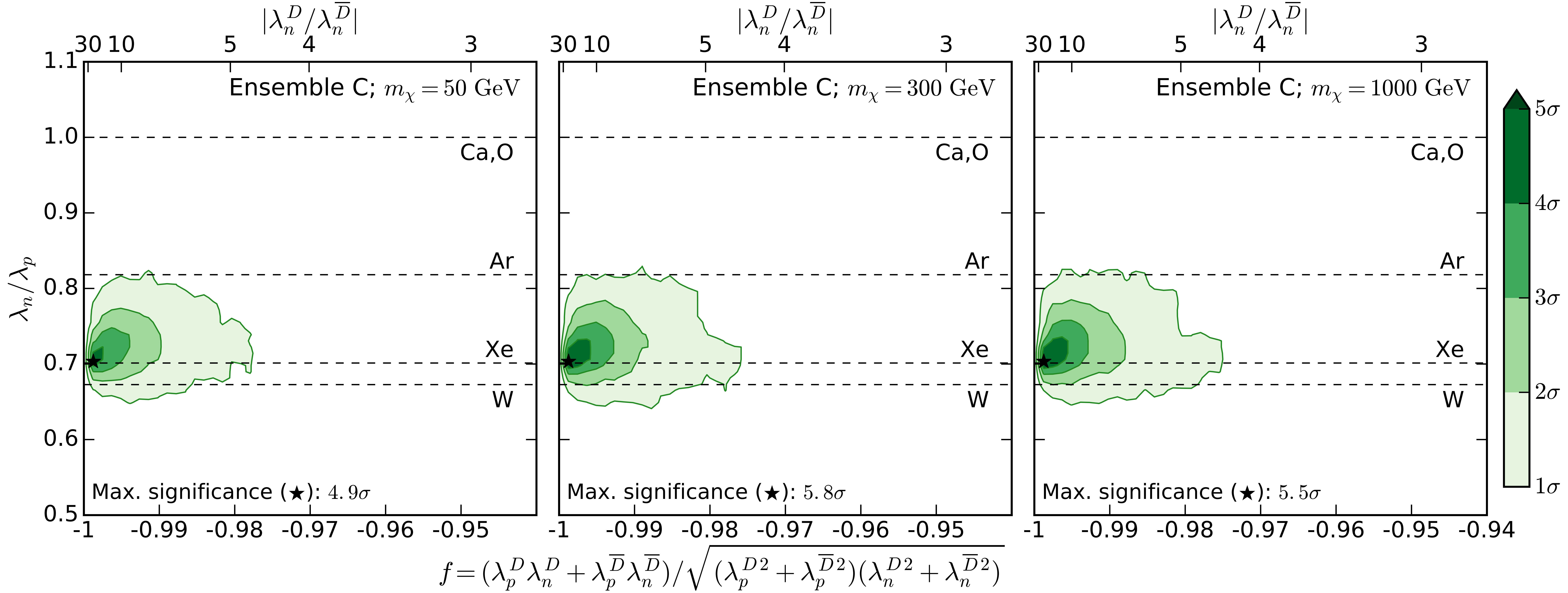
Attempt to fit assuming Majorana DM:

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



Discrimination significance: Dirac vs Majorana

Ensemble C: Xe + Ar + $CaWO_4$



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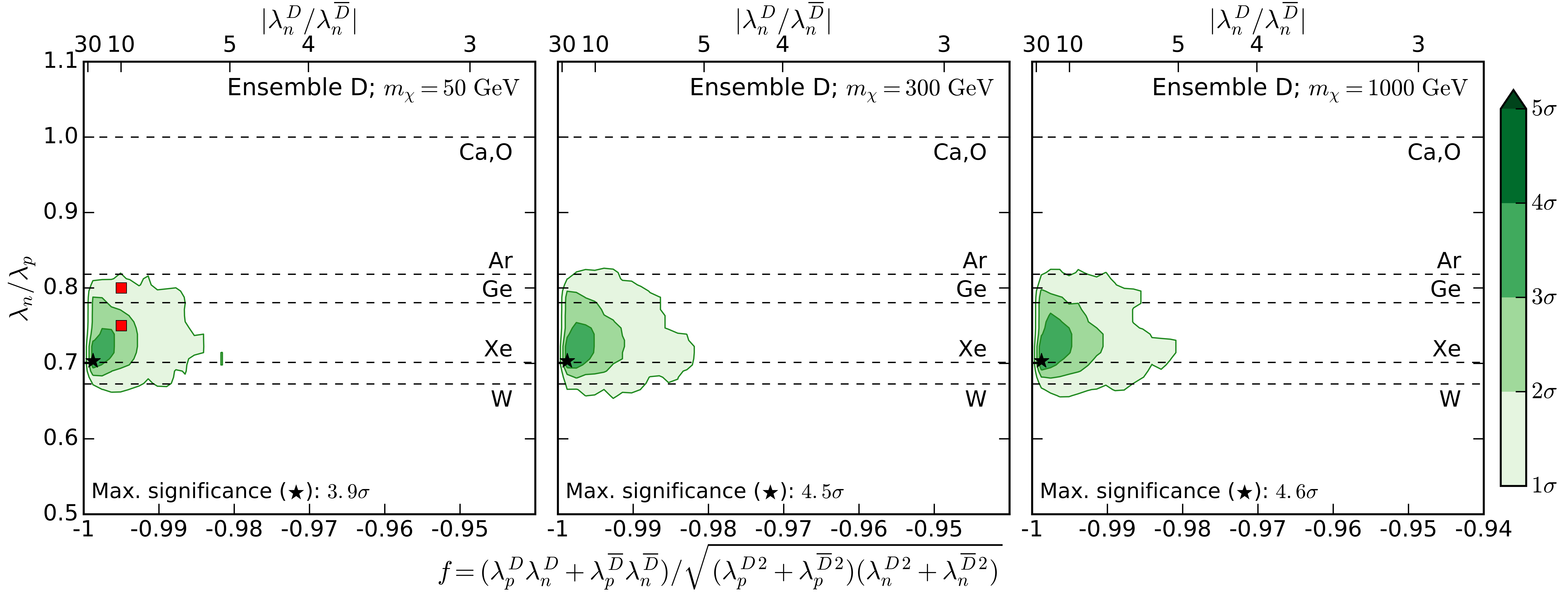
Discrimination significance: Dirac vs Majorana

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



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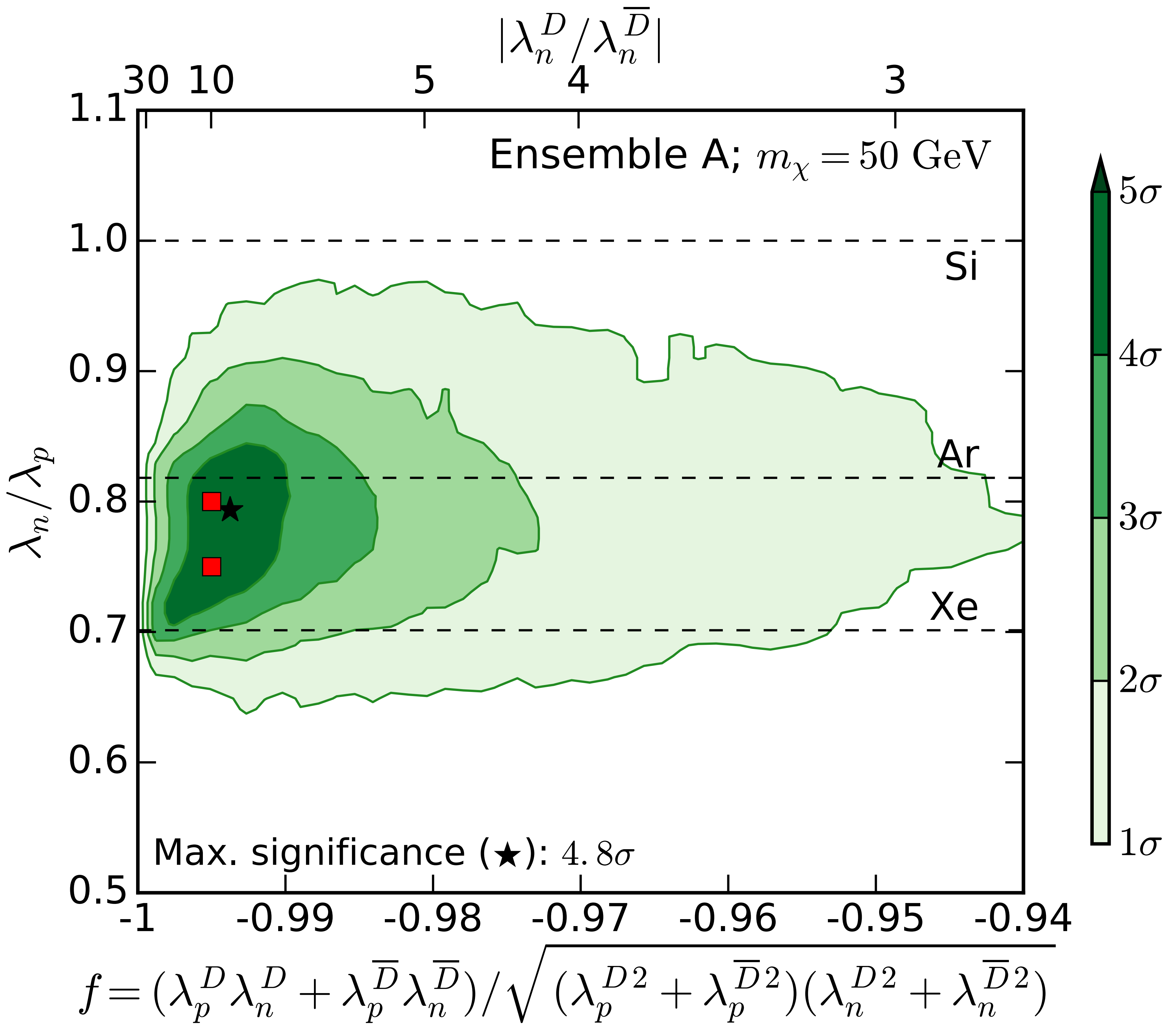
Comparing Ensembles

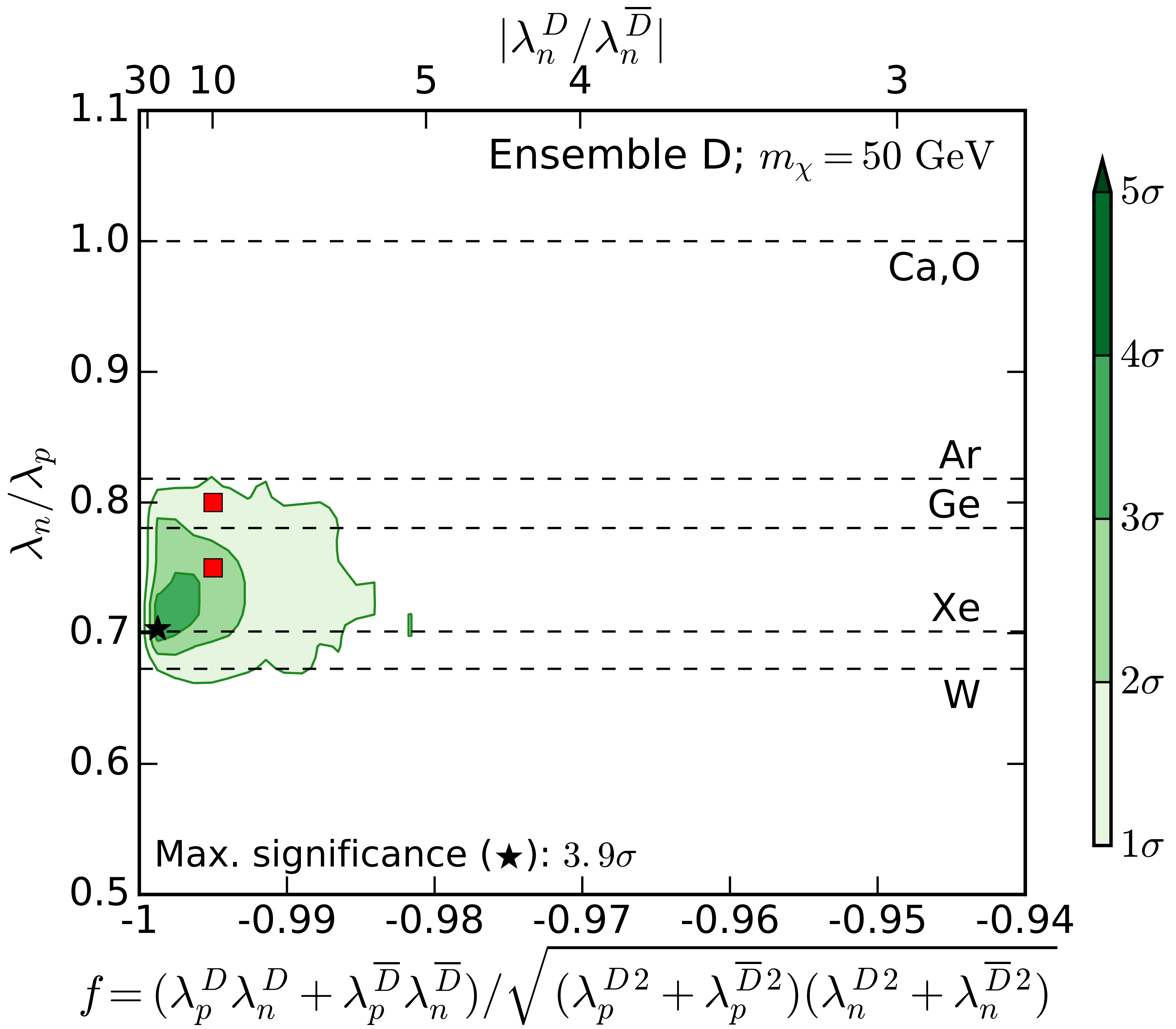
Ensemble A:

Xe + Ar + Si



Ensemble D:

Xe + Ar + 50% Ge + 50% $CaWO_4$



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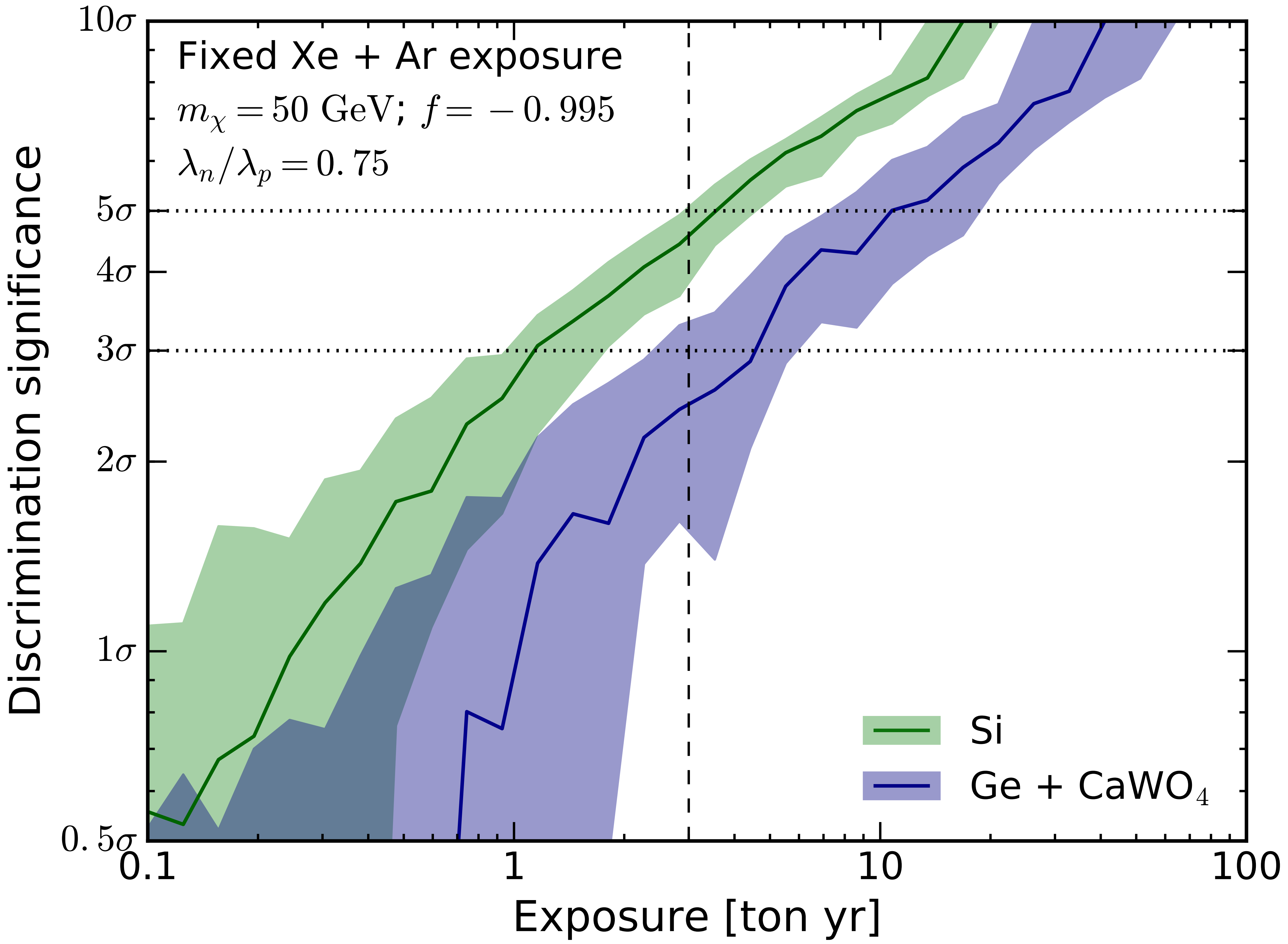
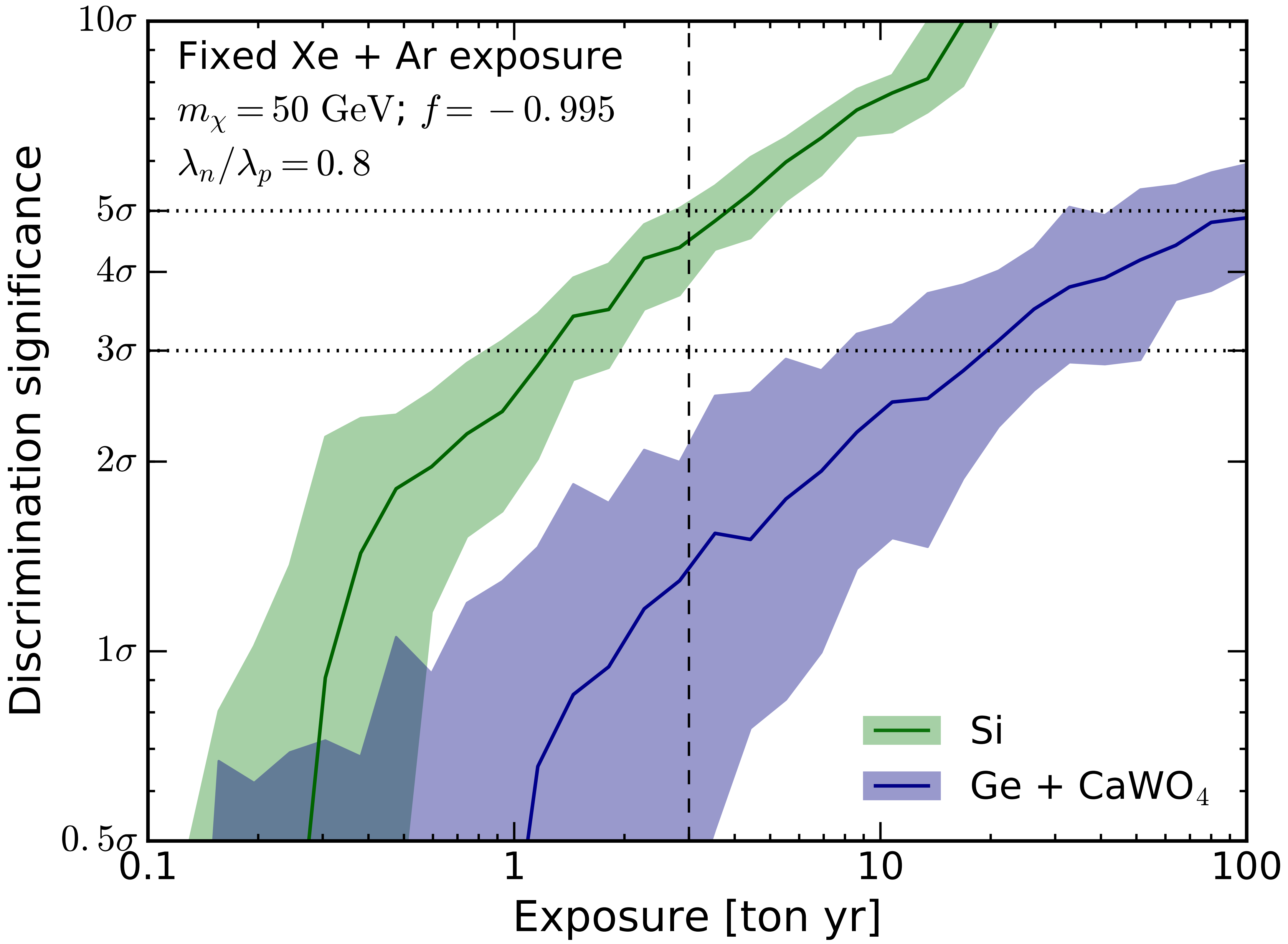
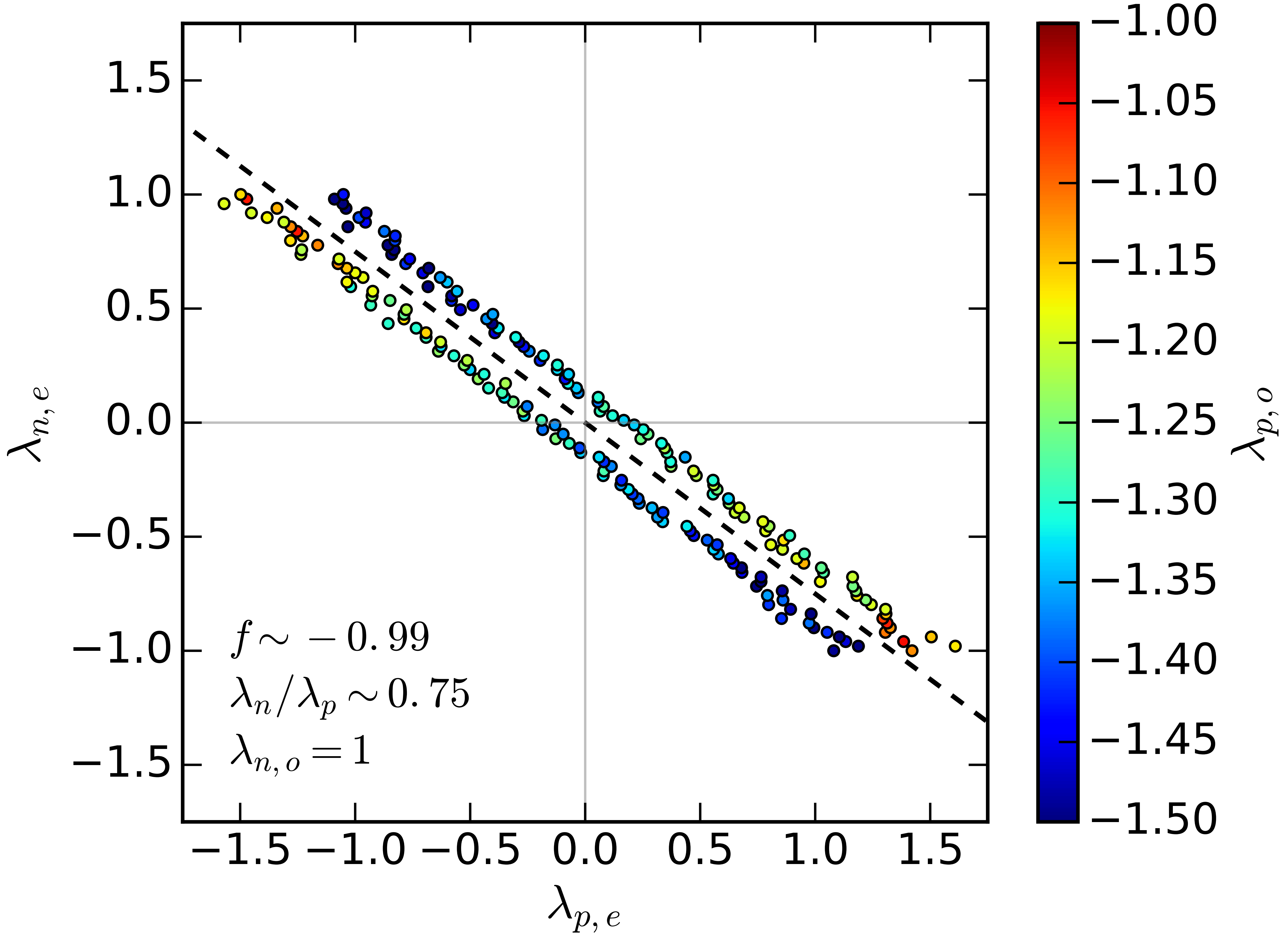




In some cases, you need more than 10x the exposure to achieve the same significance, when using Ge + CaWO$_4$ vs. using Si

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

Understanding Dark Matter

What are the best detectors to use to learn the most about Dark Matter?

DM particle/antiparticle nature?
[This Work]

Understanding Dark Matter

What are the best detectors to use to learn the most about Dark Matter?

Mediator mass?
[1707.08571]

Dark Matter mass?
[0805.1704, 1310.7039]

DM-nucleon interactions?
[1505.07406, 1506.04454]

DM particle/antiparticle nature?
[This Work]

Dark Matter distribution?
[1303.6868, 1410.8051]

Number of DM species?
[1709.01945]

Dark Matter relic density?
[1712.04793,1712.07969]

Conclusions

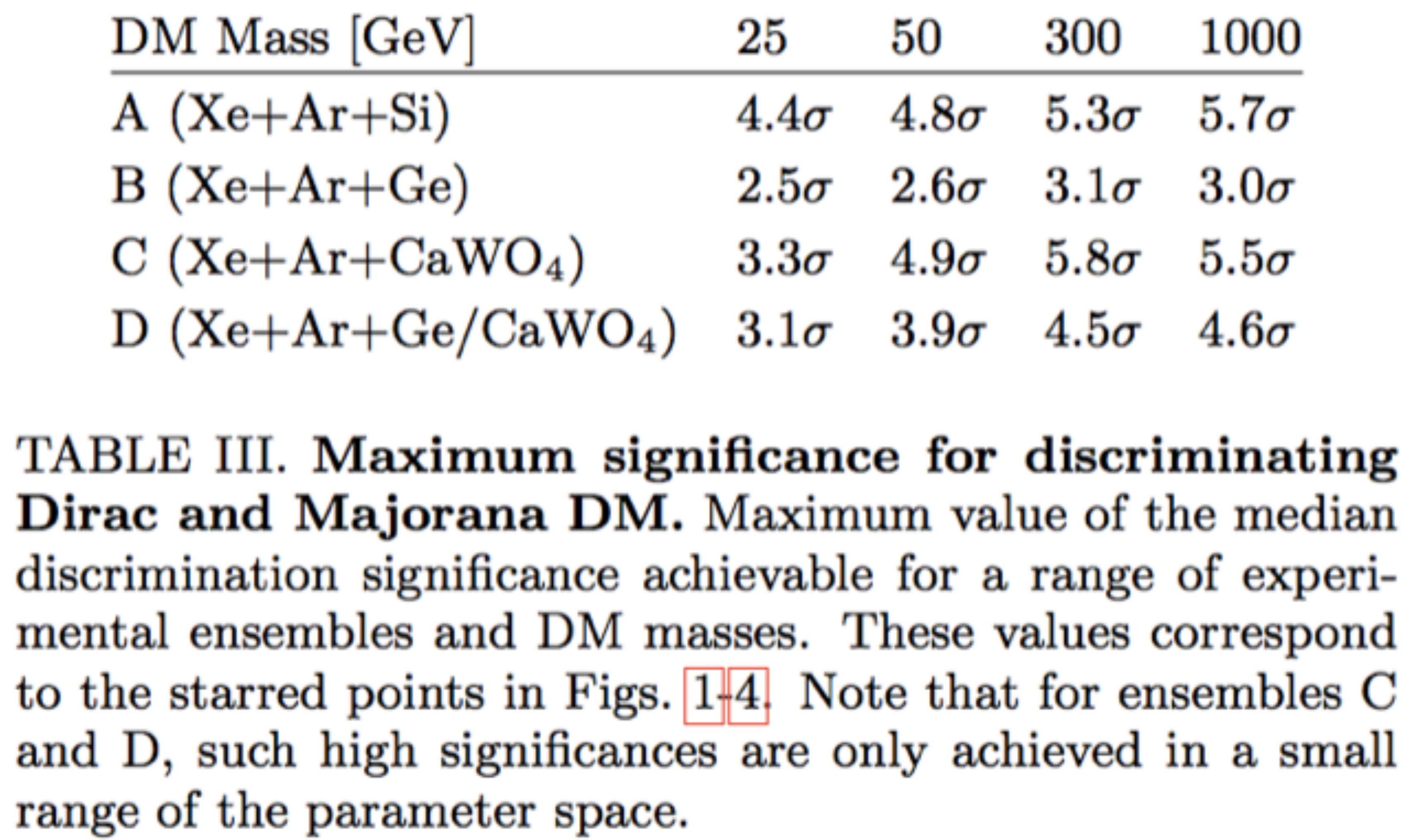
Dirac and Majorana DM-nucleus cross sections should scale differently across different detectors

Depending on the model/couplings, 2020-2025 era detectors could determine the Dirac nature of DM at the 3-5σ level

Models with isospin-violation lead to cancellations in the DM-nucleus cross section and are easiest to discriminate

There are no current plans for a Silicon detector, but this would greatly improve prospects for Dirac/Majorana discrimination (in general, more variety is better!)

The entire analysis is 100% reproducible, so you can see what we did, check it or apply it on your own favourite model!



DM Mass [GeV]	25	50	300	1000
A (Xe+Ar+Si)	4.4σ	4.8σ	5.3σ	5.7σ
B (Xe+Ar+Ge)	2.5σ	2.6σ	3.1σ	3.0σ
C (Xe+Ar+CaWO$_4$)	3.3σ	4.9σ	5.8σ	5.5σ
D (Xe+Ar+Ge/CaWO$_4$)	3.1σ	3.9σ	4.5σ	4.6σ

TABLE III. **Maximum significance for discriminating Dirac and Majorana DM.** Maximum value of the median discrimination significance achievable for a range of experimental ensembles and DM masses. These values correspond to the starred points in Figs. 1-4. Note that for ensembles C and D, such high significances are only achieved in a small range of the parameter space.

[arXiv:1706.07819]

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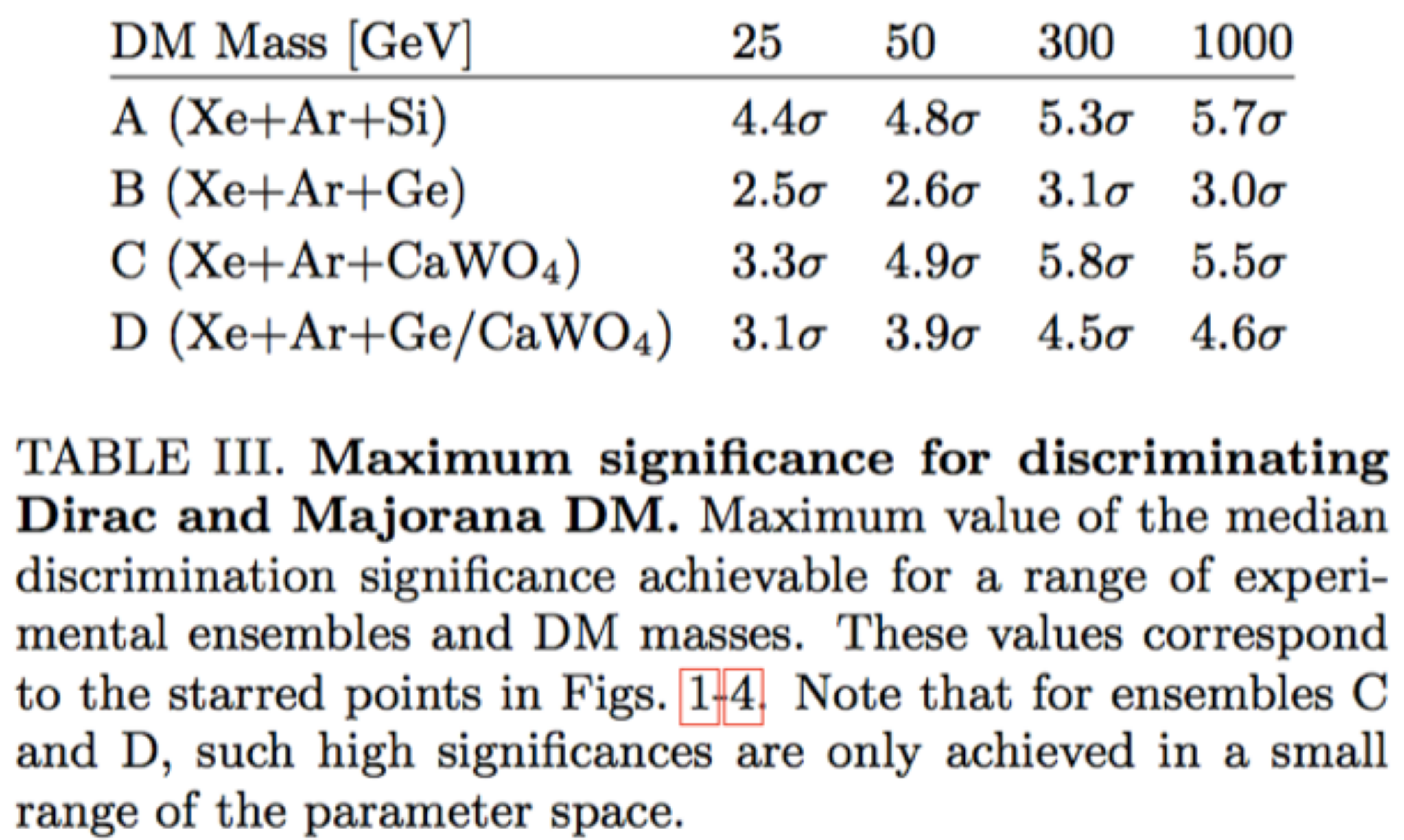

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Thank you!