Can we identify the theory of dark matter with direct detection?

1506.04454v1 (accepted to JCAP)
1406.7008v2 (JCAP)

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UCLA, Feb 2016.

Broad scope:

What can we really learn about dark matter *parameters* ***and*** *interactions* from direct detection?

DM-nucleus scattering

$$\frac{dR}{dE_R}(E_R) = \frac{\rho_\chi}{m_T m_\chi} \int_{v_{\rm min}}^{v_{\rm esc,lab}} v f(\mathbf{v}) \frac{d\sigma_T}{dE_R}(E_R, v) d^3 v.$$

DM-nucleus scattering

Astrophysics

$$\frac{dR}{dE_R}(E_R) = \frac{\rho_\chi}{m_T m_\chi} \int_{v_{\rm min}}^{v_{\rm esc,lab}} v f(\mathbf{v}) \frac{d\sigma_T}{dE_R}(E_R, v) d^3 v.$$

"Observable"

DM particle + nuclear physics

DM-nucleus scattering

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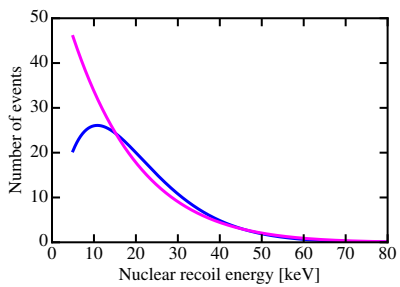
"Observable"

DM particle + nuclear physics

Traditionally assumed momentum and velocity independent SI or SD scattering

DM-nucleus scattering



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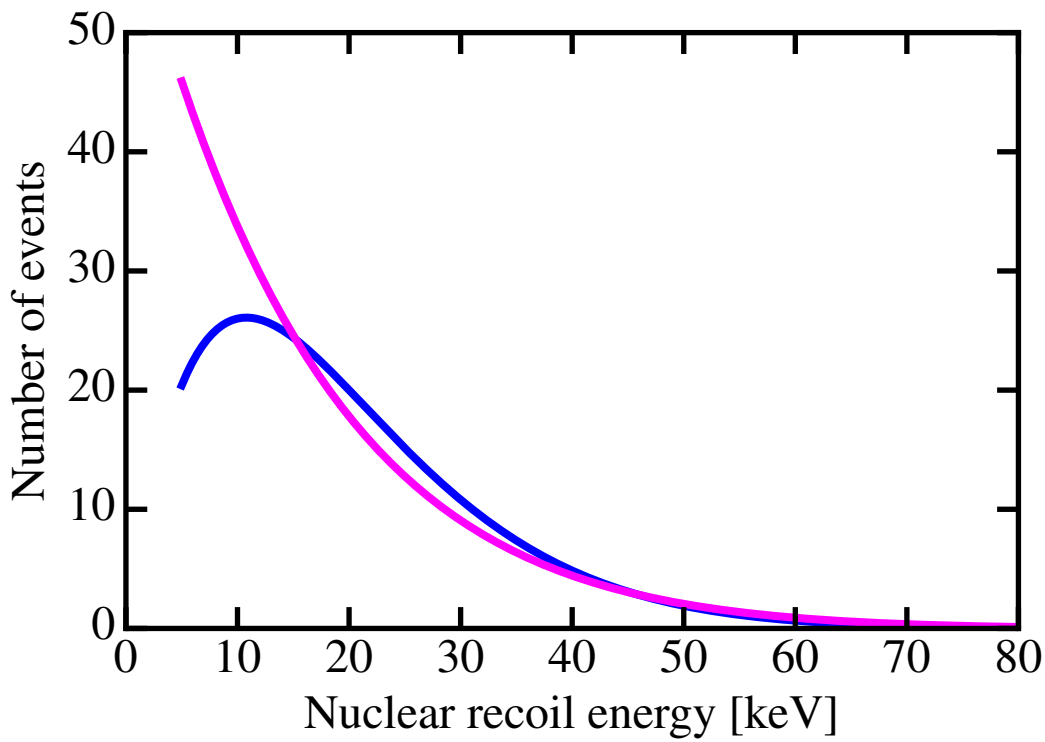
Context: noisy recoil-energy spectra



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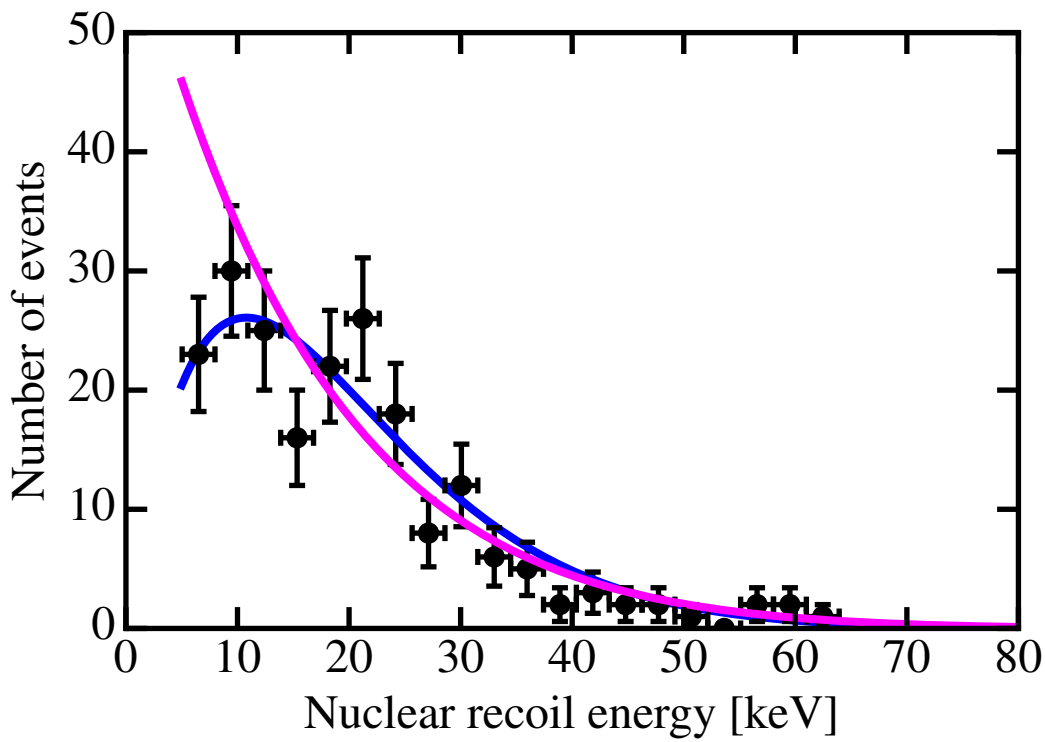

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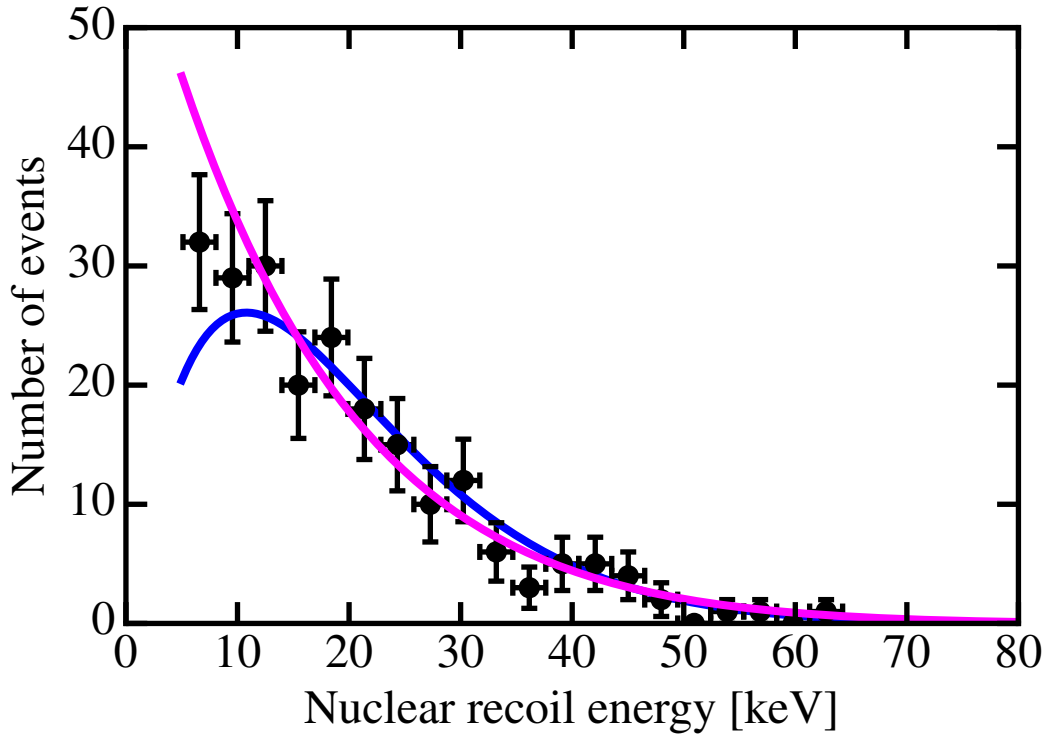


Main question:

How likely is direct detection to successfully identify the correct theory, and which experimental strategies maximize chances for success?

Theory ingredients:

Fan et al, 2010; Fitzpatrick et al, 2012; Anand et al, 2013; Gresham & Zurek, 2014; etc.

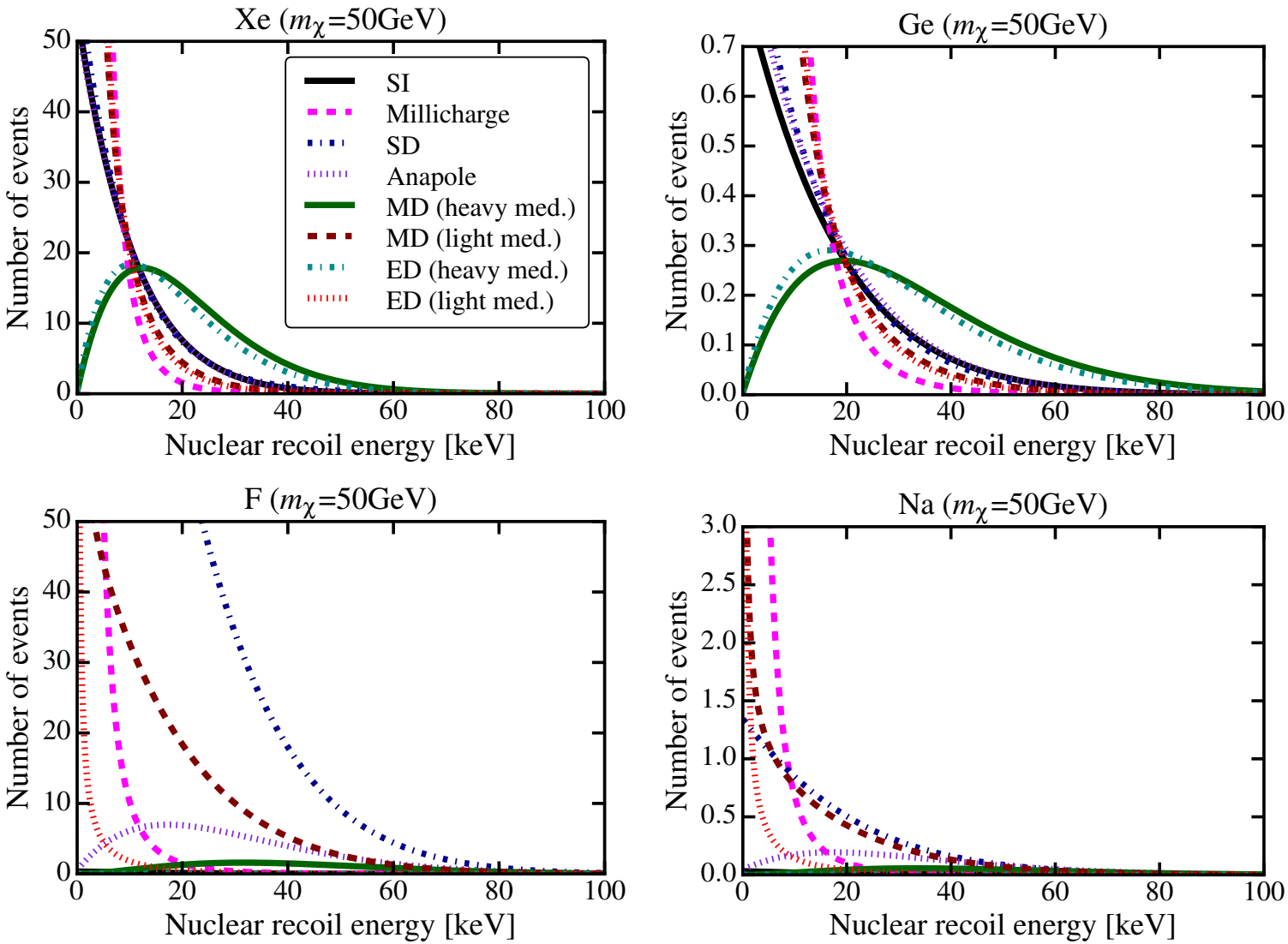
- Spin ½ DM, elastic scattering through scalar or vector mediators
- Broad range of (UV complete) theories
- Nuclear responses triggered by non-standard interactions $(M, \Sigma', \Sigma'', \Delta, \Phi'')$
- Variety of target elements with natural abundances of isotopes

14 models (hypotheses)

See also: Gresham & Zurek, 2014

Model name	Lagrangian	$\vec{q}$, v Dependence	Response	f_n/f_p
SI	$\bar{\chi}\chi\bar{N}N$	1	M	+1
SD	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{N}\gamma_\mu\gamma_5 N$	1	$\Sigma' + \Sigma''$	–1.1
Anapole	$\bar{\chi}\gamma^\mu\gamma_5\chi\partial^\nu F_{\mu\nu}$	$v^{\perp 2}$ $\vec{q}^2/m_N^2$	M $\Delta + \Sigma'$	photon–like
Millicharge	$\bar{\chi}\gamma^\mu\chi A_\mu$	$m_N^2 m_\chi^2/\vec{q}^4$	M	photon–like
MD (light med.)	$\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$	$1 + \frac{v^{\perp 2} m_N^2}{\vec{q}^2}$ 1	M $\Delta + \Sigma'$	photon–like
ED (light med.)	$\bar{\chi}\sigma^{\mu\nu}\gamma_5\chi F_{\mu\nu}$	$m_N^2/\vec{q}^2$	M	photon–like
MD (heavy med.)	$\bar{\chi}\sigma^{\mu\nu}\partial_\mu\chi\partial^\alpha F_{\alpha\nu}$	$\frac{\vec{q}^4}{\Lambda^4} + \frac{v^{\perp 2} m_N^2 \vec{q}^2}{\Lambda^4}$ $\vec{q}^4/\Lambda^4$	M $\Delta + \Sigma'$	photon–like
ED (heavy med.)	$\bar{\chi}\sigma^{\mu\nu}\gamma_5\partial_\mu\chi\partial^\alpha F_{\alpha\nu}$	$\vec{q}^2 m_N^2/\Lambda^4$	M	photon–like
SI_{q^2}	$i\bar{\chi}\gamma_5\chi\bar{N}N$	$\vec{q}^2/m_\chi^2$	M	+1
SD_{q^2} (Higgs-like/flavor–univ.)	$i\bar{\chi}\chi\bar{N}\gamma_5 N$	$\vec{q}^2/m_N^2$	Σ''	$+1/-0.05$
SD_{q^4} (Higgs-like/flavor–univ.)	$\bar{\chi}\gamma_5\chi\bar{N}\gamma_5 N$	$\vec{q}^4/m_\chi^2 m_N^2$	Σ''	$+1/-0.05$
$\vec{L}\cdot\vec{S}$-like	$\bar{\chi}\gamma_\mu\chi\frac{\partial^2\bar{N}\gamma^\mu N}{m_N^2} +$ $+\bar{\chi}\gamma_\mu\chi\frac{\partial_\nu\bar{N}\sigma^{\mu\nu}N}{2m_N}$	$\vec{q}^4/m_N^4$ $\vec{q}^4/m_N^4$ $\frac{\vec{q}^2 v^{\perp 2}}{m_N^2} + \frac{\vec{q}^4}{m_\chi^2 m_N^2}$	M Φ'' Σ'	+1

14 models (hypotheses)



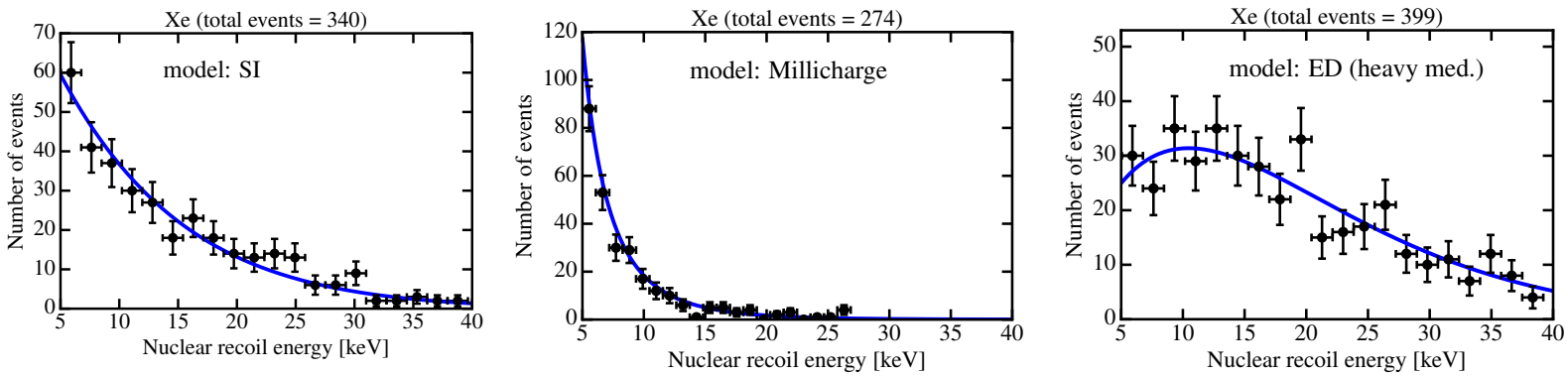
Experiments: G2+

Baseline analysis

Label	A (Z)	Energy window [keVnr]	Exposure [kg-yr]
Xe	131 (54)	5-40	2000
Ge	73 (32)	0.3-100	100
I	127 (53)	22.2-600	212
F	19 (9)	3-100	606
Na	23 (11)	6.7-200	38
Ar	40 (18)	25-200	3000
He	4 (2)	3-100	300
Xe(lo)	131 (54)	1-40	2000
Xe(hi)	131 (54)	5-100	2000
Xe(wide)	131 (54)	1-100	2000
I(lo)	127 (53)	1-600	212
XeG3	131 (54)	5-40	40 000
I+	127 (53)	1-600	424
F+	19 (9)	3-100	1200

Analysis

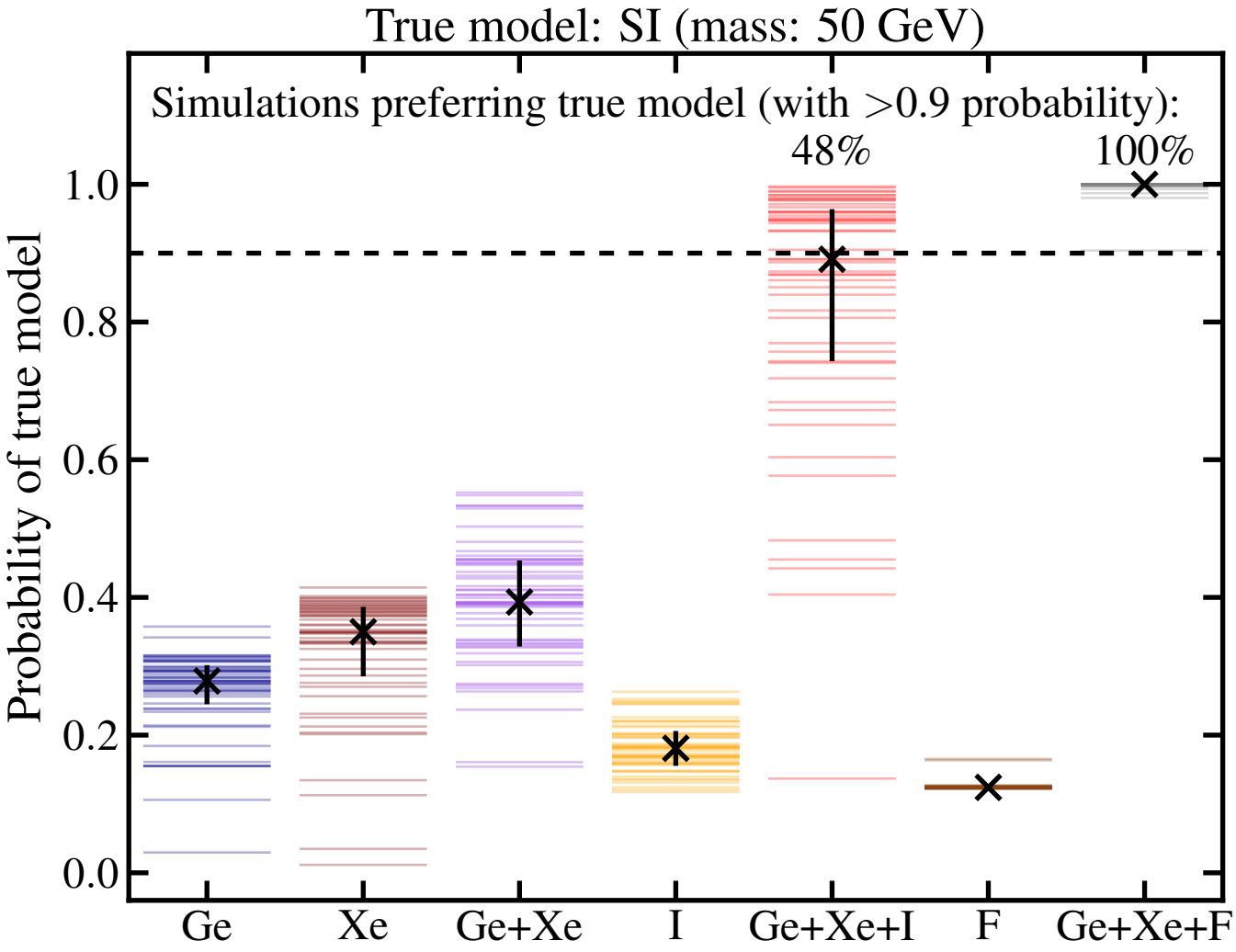
1. Simulate events under different hypotheses, for a signal **just below the current detection threshold**.



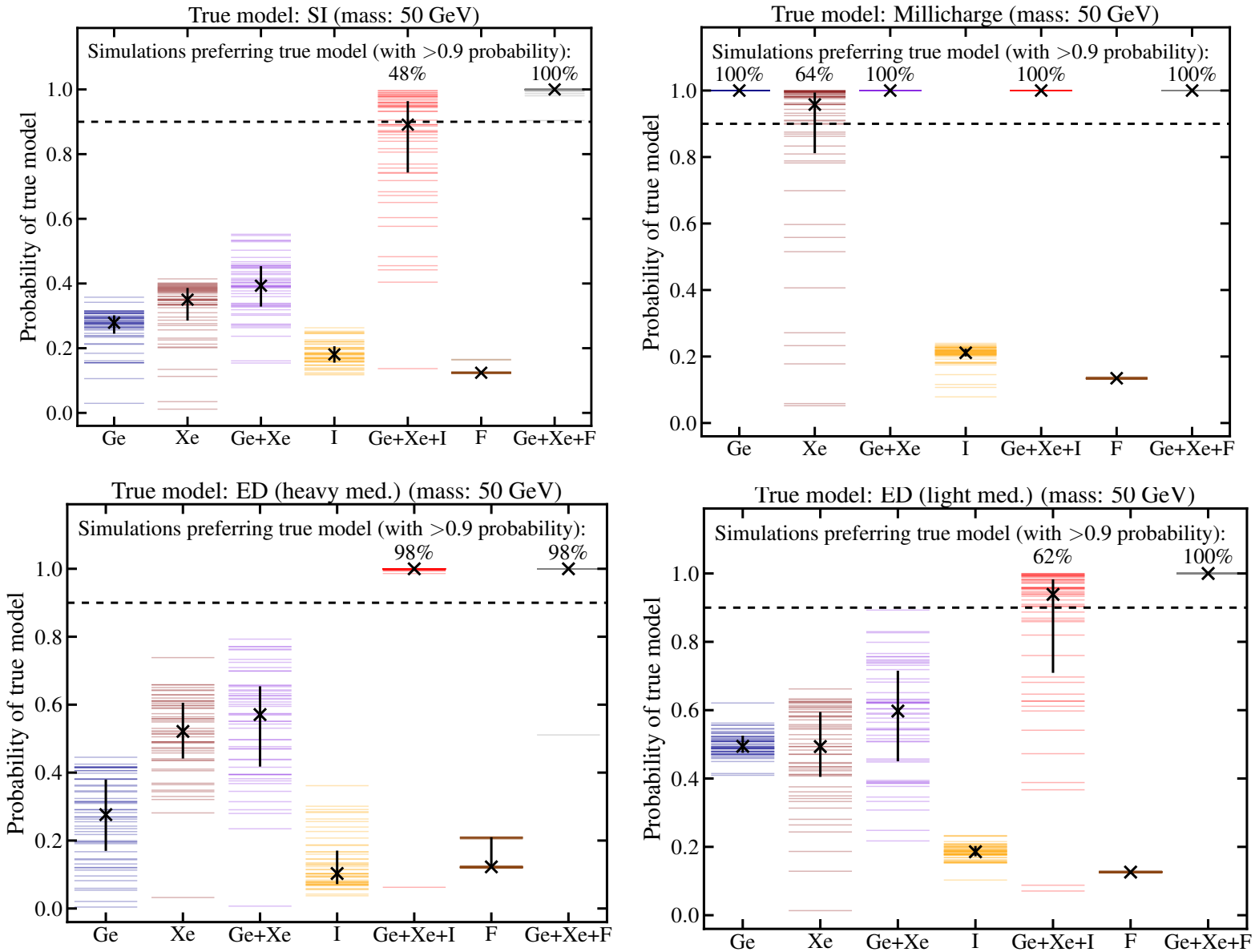
2. Reconstruct posteriors for one or more mock experiments jointly (fit for: **mass** and **cross-section**)

3. Compare models *a posteriori* (Bayesian model selection)

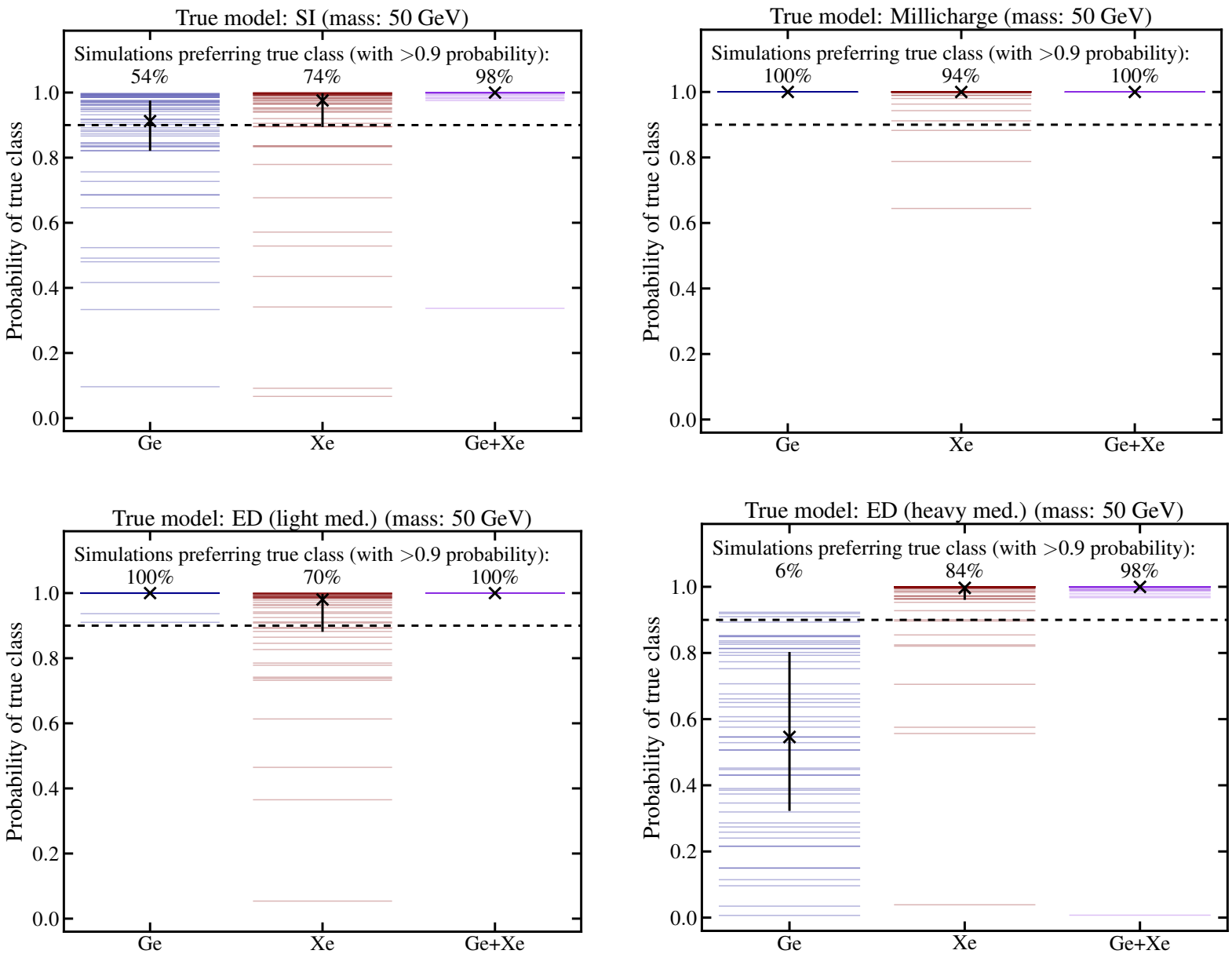
Results


True model: SI (mass: 50 GeV)
Simulations preferring true model (with >0.9 probability):
48%
100%
Probability of true model
1.0
0.8
0.6
0.4
0.2
0.0
Ge
Xe
Ge+Xe
I
Ge+Xe+I
F
Ge+Xe+F

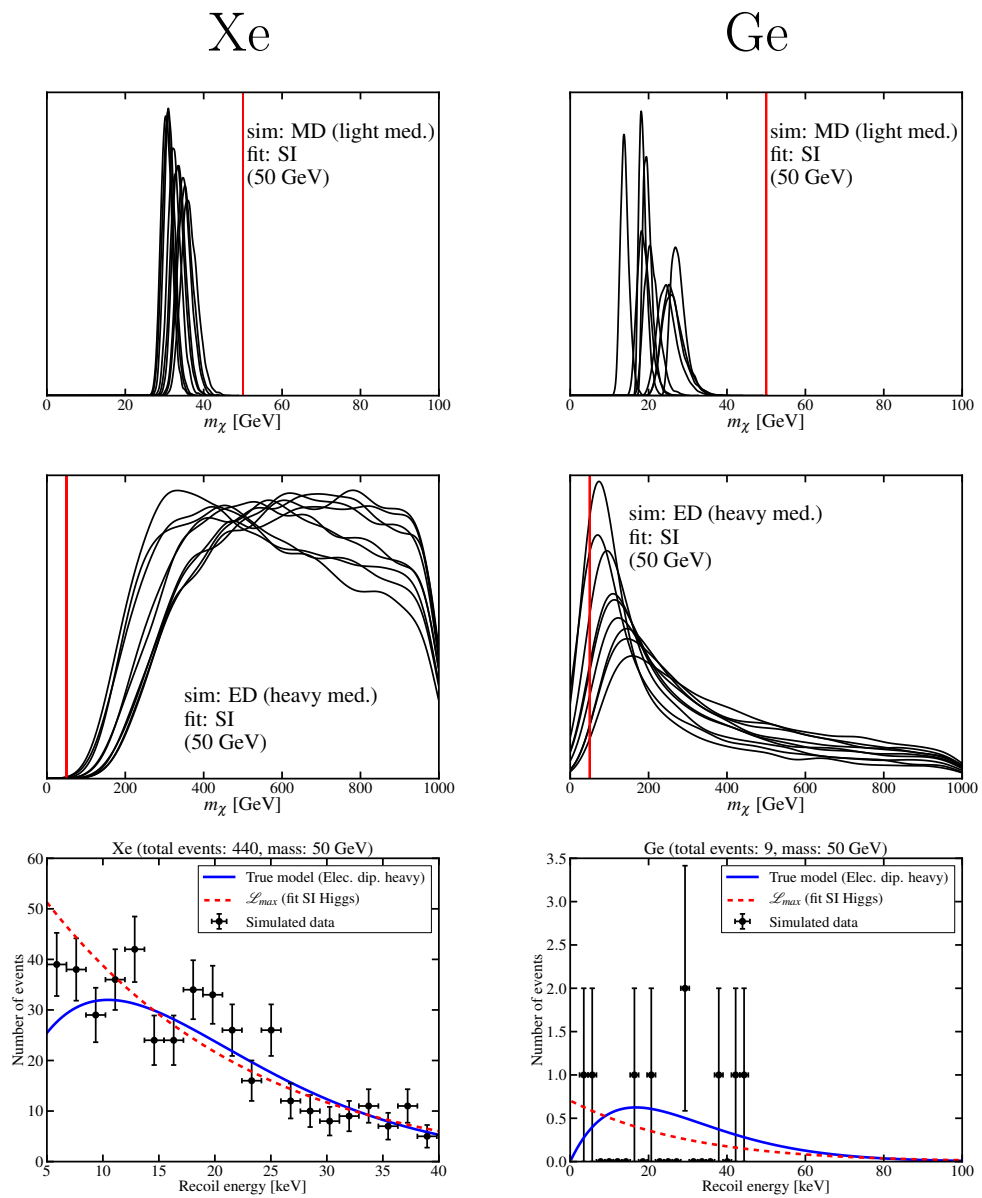
Complementarity of targets is essential



Momentum dependence is robust

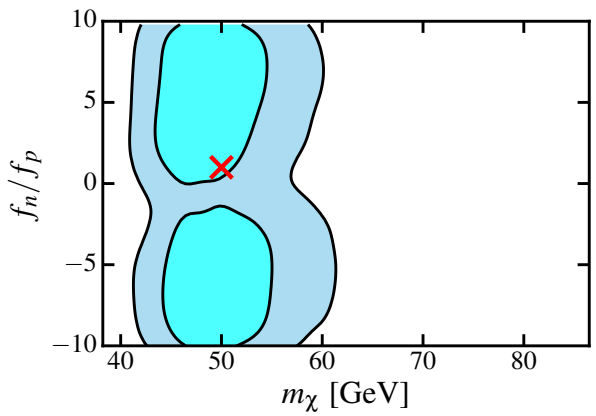


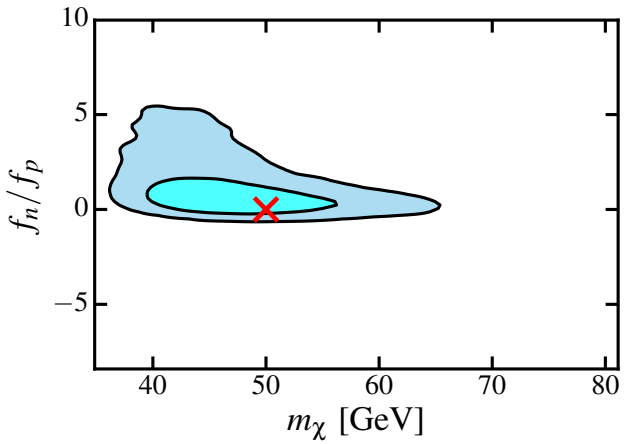
Wrong model fits lead to biased mass



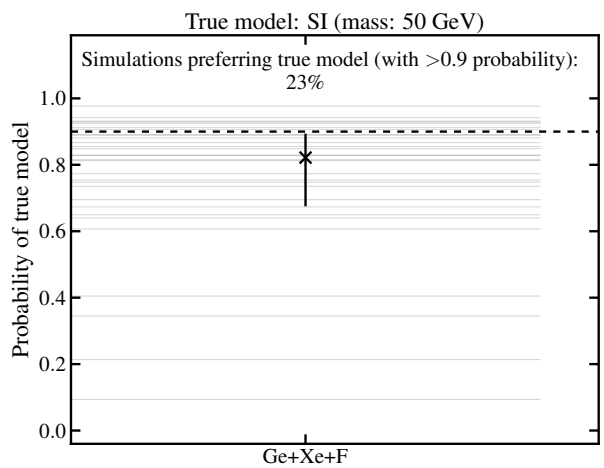
fn/fp uncertainty is *not* a show stopper

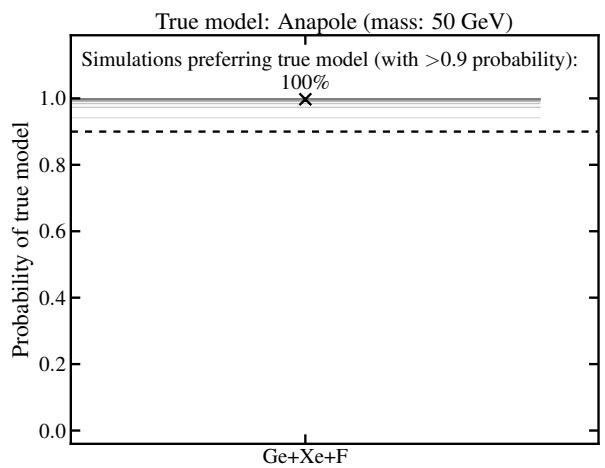
Parameter estimation:





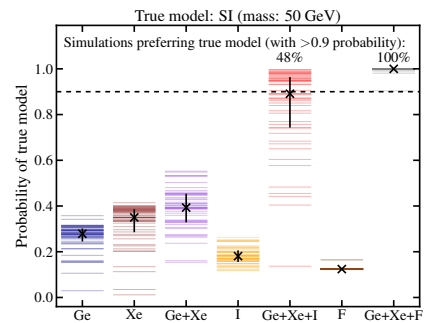
Model selection:





Conclusions

- ✓ Low thresholds, complementary targets, and a joint analysis of all available data are key to identifying DM theory in an agnostic approach.



arXiv: 1506.04454v1

- ✓ **`dmdd`** python code @ GitHub: **>> pip install dmdd**