Title: Can We Identify the Theory of Dark Matter with Direct Detection?

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Abstract: <p>In light of the upcoming Generation 2 (G2) direct-detection experiments attempting to record dark matter scattering with nuclei in underground detectors, it is timely to inquire about their ability to single out the correct theory of dark-matter-baryon interactions, in case a signal is observed. I will present a recent study in which we perform statistical analysis of a large set of direct-detection simulations, covering a wide variety of operators that describe scattering of fermionic dark matter with nuclei. I will show that a strong signal on G2 xenon and germanium targets has enough discrimination power to reconstruct the momentum dependence of the interaction, ruling out entire classes of models. However, zeroing in on a correct UV completion will critically depend on the availability of measurements from a wide variety of nuclear targets (including iodine and fluorine) and on the availability of low energy thresholds. This study quantifies complementarity amongst different experimental designs and targets, and provides a roadmap for future data analyses. It also highlights the critical need for bringing in information from all available probes in dark matter studies.</p>

Identifying the theory of dark matter with direct detection

1506.04454v1 (accepted to JCAP)
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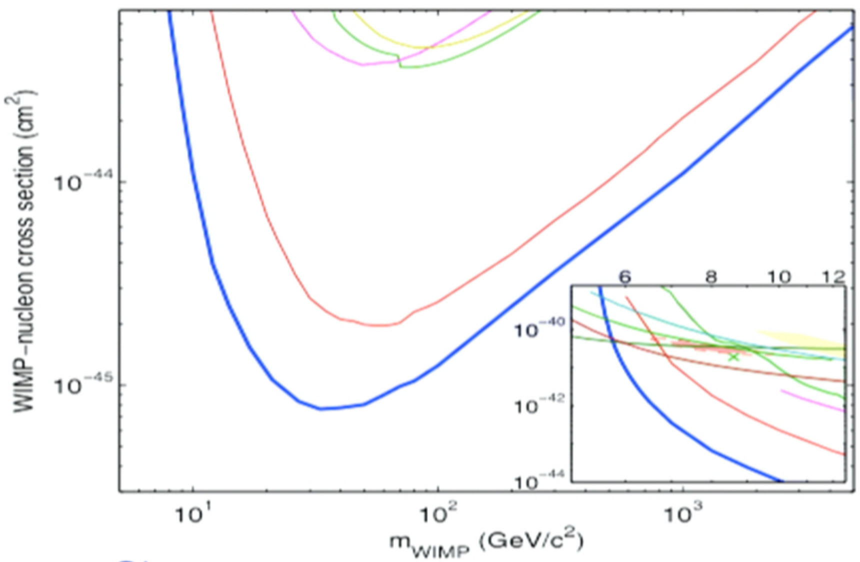
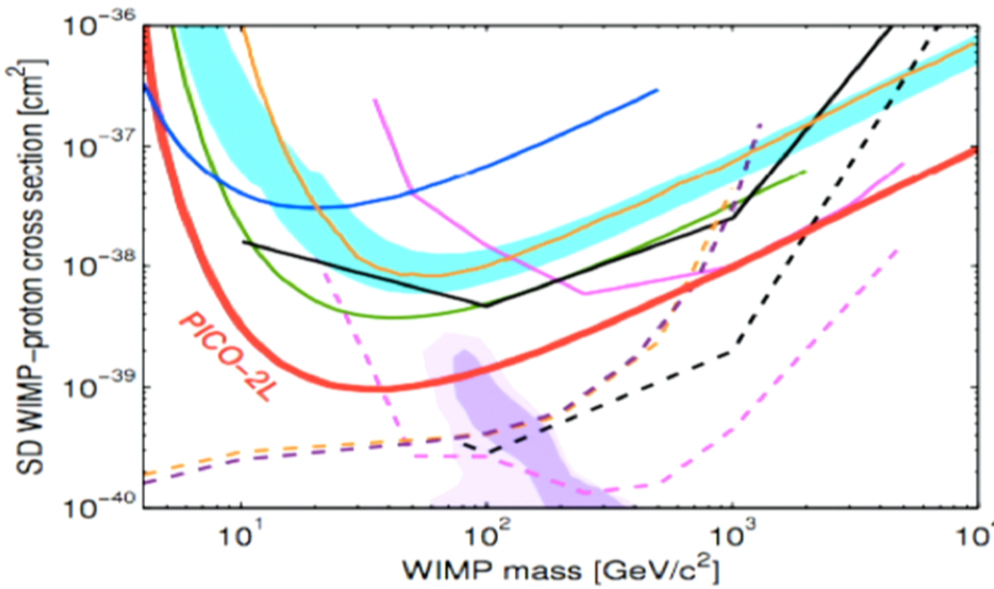
Perimeter Institute Cosmology Seminar, 2015.

Status

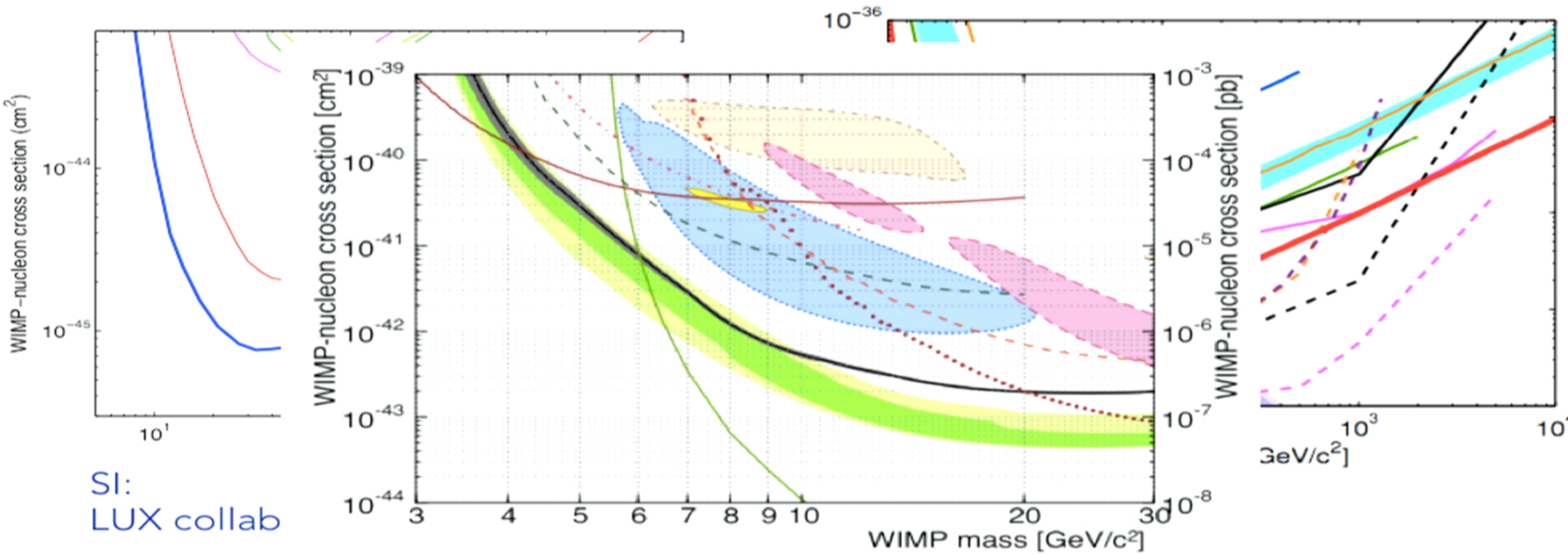


SI:
LUX collaboration, PRL 2014



SD:
PICO 2L, PRL 2015

Status

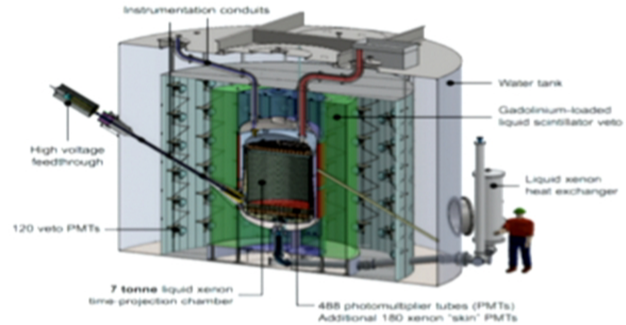


SI:
LUX collab

SI:
SuperCDMS & CDMSlite 2014

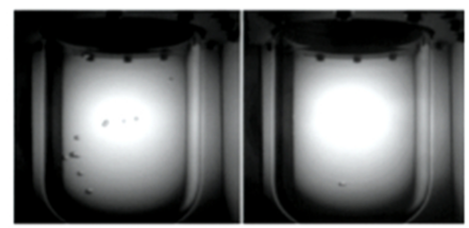
Going forth…

- ✓ Time-projection chambers with liquid noble gases (LZ, Xenon: Xe)



- ✓ Cryogenic semiconductors with solid-state targets (SuperCDMS: Ge+Si)

- ✓ Scintilating crystals (ANAIS, SABRE, KIMS: NaI)



- ✓ Bubble chambers (PICO: CF3I)

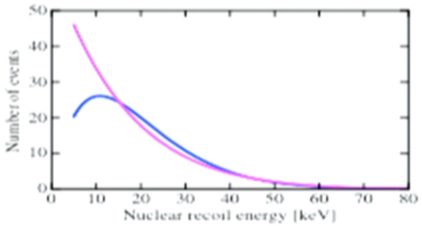
Broad scope:

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

DM-nucleus elastic scattering

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

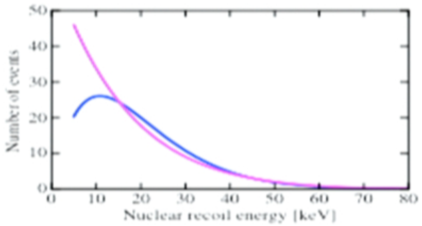
DM-nucleus elastic scattering



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

"Observable"

DM-nucleus elastic scattering



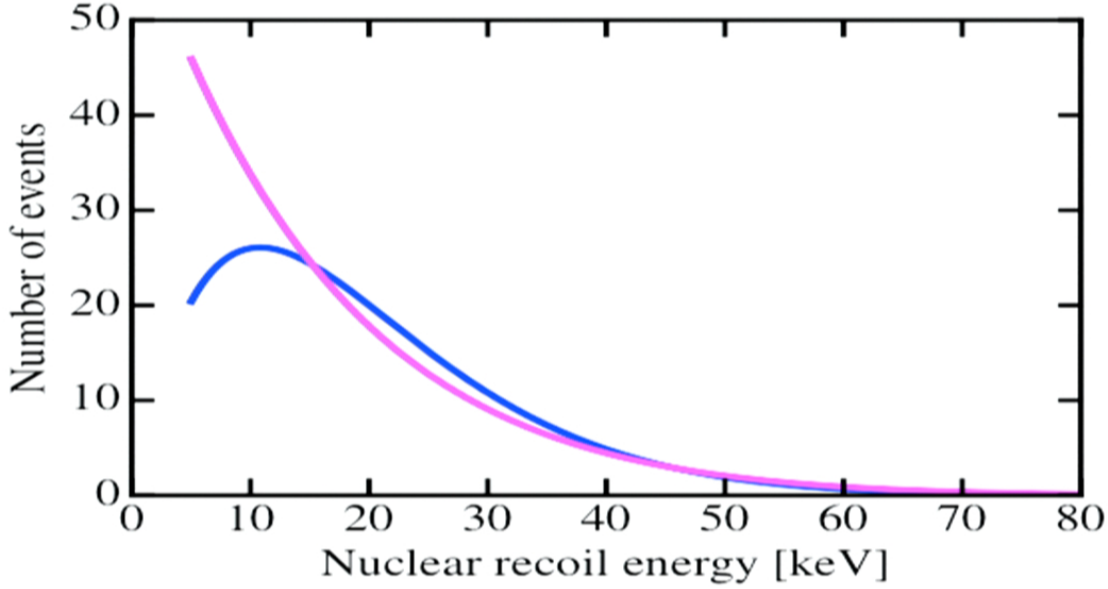
Astrophysics

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

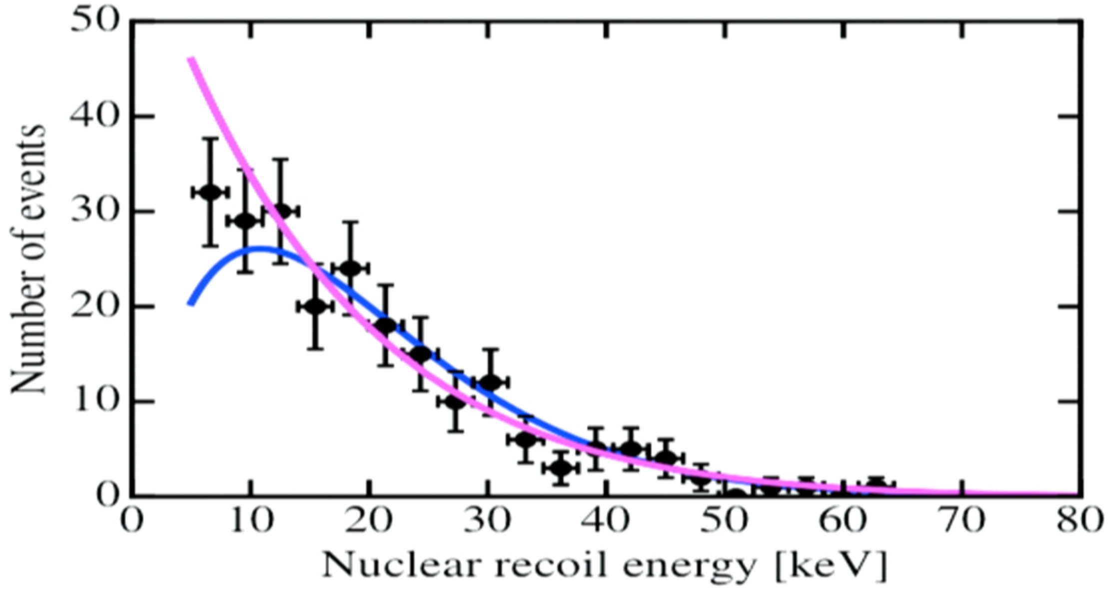
"Observable"

DM particle + nuclear physics

Context: noisy recoil-energy spectra



Context: noisy recoil-energy spectra



Main question:

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

Ingredients

1. List of scattering models (hypotheses)
2. Statistical representation of possible experimental outcomes (simulations)
3. Analysis framework to compare models (Bayesian model selection)

The theory of DM…

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

Goal: Write down the most general form of DM-nucleon interaction, and embed it into the nucleus.

- Complete *list of non-relativistic operators* and mapping onto relativistic scattering operators
- Nuclear responses triggered by non-standard interactions $(M, \Sigma', \Sigma'', \Delta, \Phi'')$

The theory of DM...

$$\frac{d\sigma_T}{dE_R}(E_R, v) = \frac{m_T}{2\pi v^2} \sum_{(N,N')} \sum_X R_X \left(E_R, v, c_i^N, c_j^{N'}\right) \widetilde{W}_X^{(N,N')}(y)$$

Anand et al, 2013

DM response

Nuclear response

$$X \in \{M, \Sigma', \Sigma'', \Phi'', \Delta, M\Phi'', \Delta\Sigma'\}$$

$$(N, N') \in \{(p,p), (n,n), (p,n), (n,p)\}$$

$$y \equiv m_T E_R b^2/2$$

$$b \equiv \sqrt{41.467/(45A^{-1/3} - 25A^{-2/3})}\ \text{fm}$$

14 models

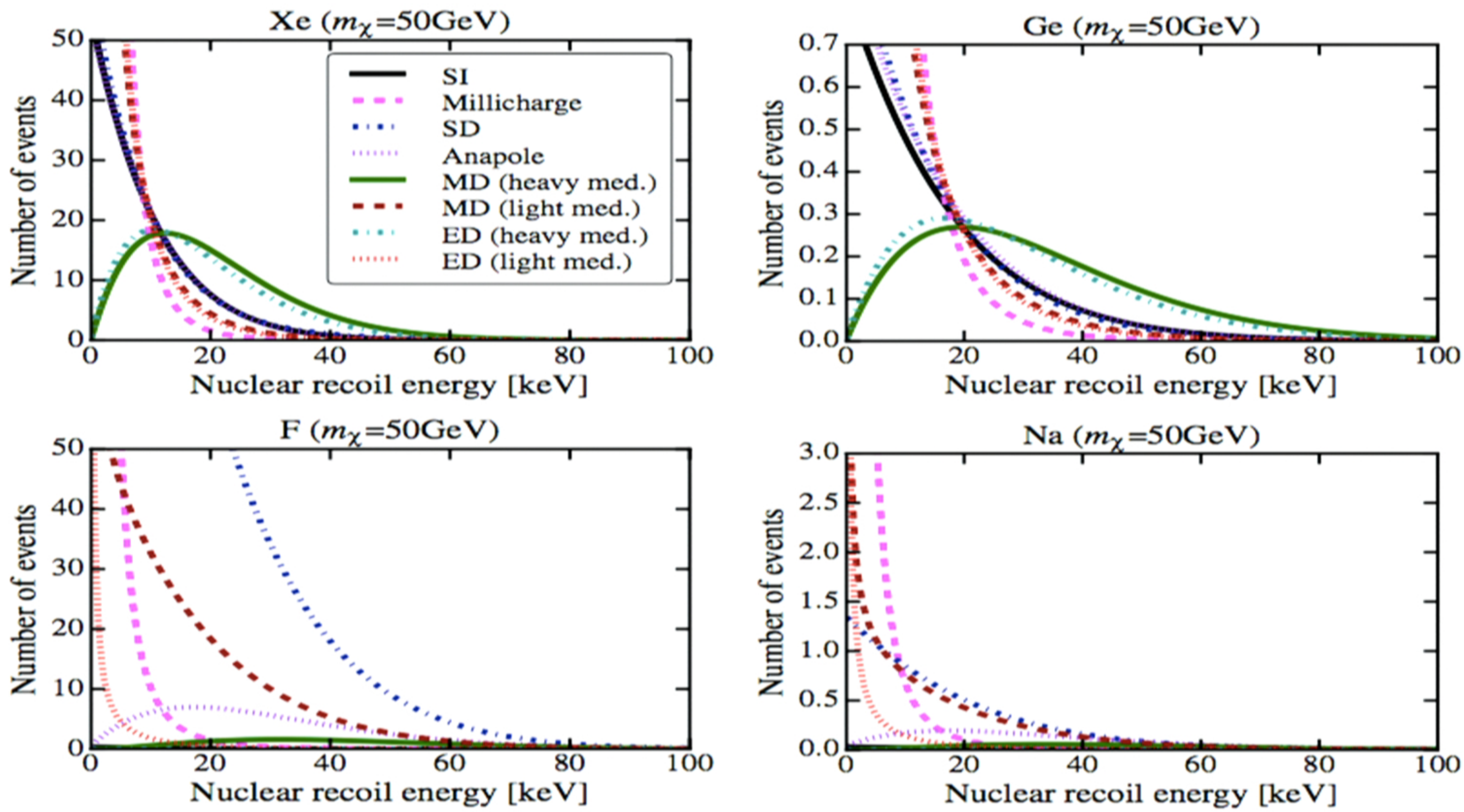
See also:
Gresham &
Zurek, 2014

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'	$+1$

Experiments: G2+

	Label	A (Z)	Energy window [keVnr]	Exposure [kg-yr]
Baseline analysis	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

Hypotheses:



Xe (m_χ=50GeV)
Ge (m_χ=50GeV)
F (m_χ=50GeV)
Na (m_χ=50GeV)
Number of events
Nuclear recoil energy [keV]
SI
Millicharge
SD
Anapole
MD (heavy med.)
MD (light med.)
ED (heavy med.)
ED (light med.)

Method: Bayesian inference

Posterior probability: $$\mathcal{P}(\Theta|\{E_R\},\mathcal{M}) = \frac{\mathcal{L}(\{E_R\}|\Theta,\mathcal{M})p(\Theta|\mathcal{M})}{\mathcal{E}(\{E_R\}|\mathcal{M})}$$

Likelihood: $$\mathcal{L}(\{E_R\}|\Theta,\mathcal{M}) = P(N|\Theta,\mathcal{M})\prod_{i=1}^{N} P_1(E_R^i|\Theta,\mathcal{M})$$

Evidence: $$\mathcal{E}(\{E_R\}|\mathcal{M}) = \int d\Theta\mathcal{L}(\{E_R\}|\Theta,\mathcal{M})p(\Theta|\mathcal{M})$$

Method: Bayesian inference

$$\Pr(\mathcal{M}_j) = \frac{\mathcal{E}(\{E_R\}|\mathcal{M}_j)}{\sum_i \mathcal{E}(\{E_R\}|\mathcal{M}_i)}$$

→ Model probability (given data)

Method: Bayesian inference

$$\Pr(\mathcal{M}_j) = \frac{\mathcal{E}(\{E_R\}|\mathcal{M}_j)}{\sum_i \mathcal{E}(\{E_R\}|\mathcal{M}_i)}$$

→ Model probability (given data)

Success probability = percent of simulations in which the right model was selected with >90% probability.

Method: Bayesian inference

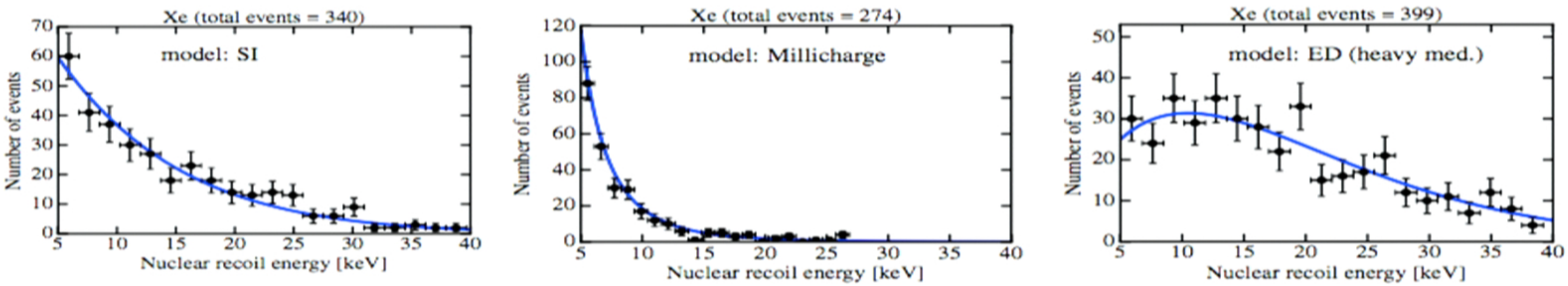
$$\Pr(\mathcal{M}_j) = \frac{\mathcal{E}(\{E_R\}|\mathcal{M}_j)}{\sum_i \mathcal{E}(\{E_R\}|\mathcal{M}_i)}$$

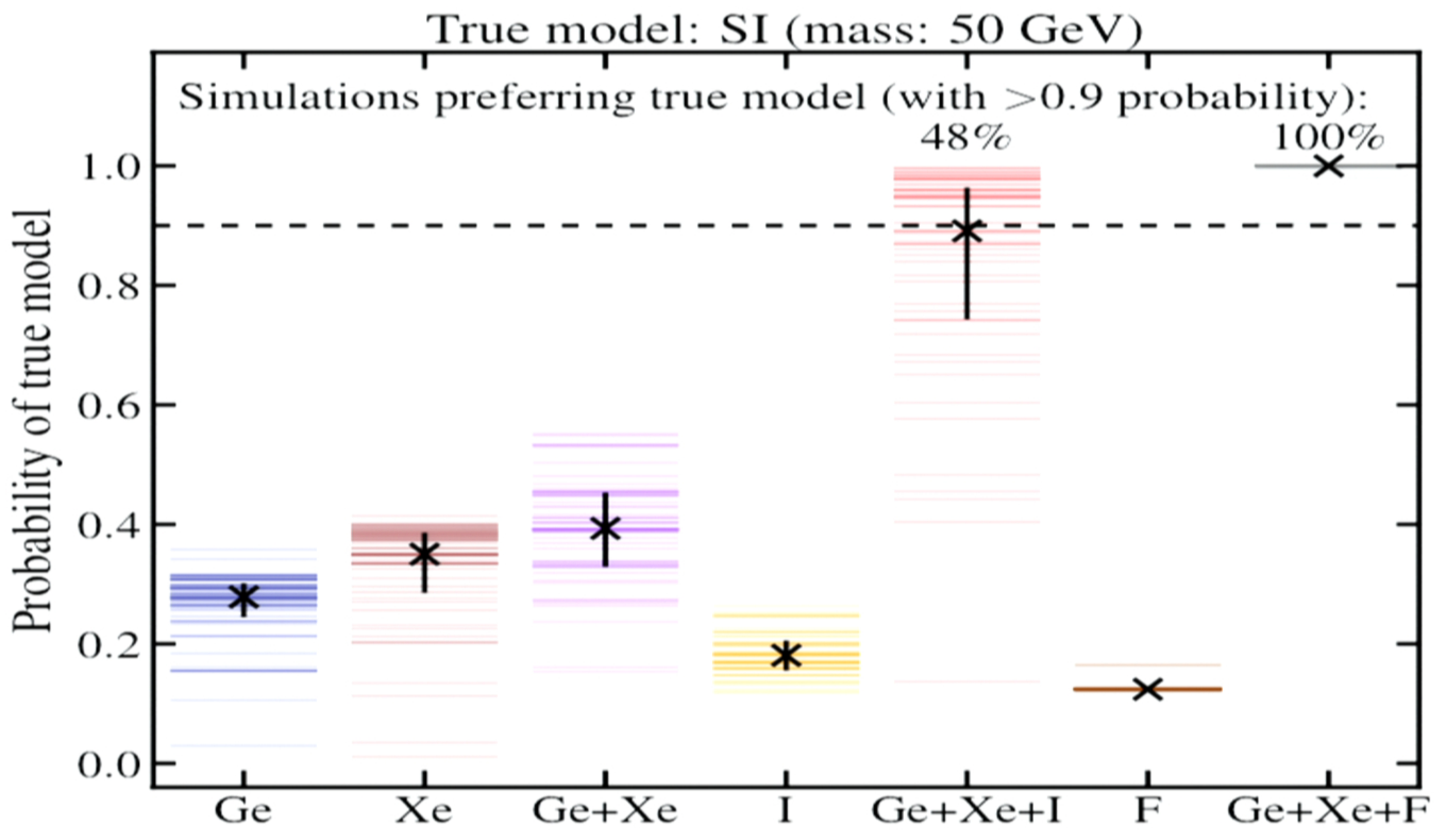
→ Model probability (given data)

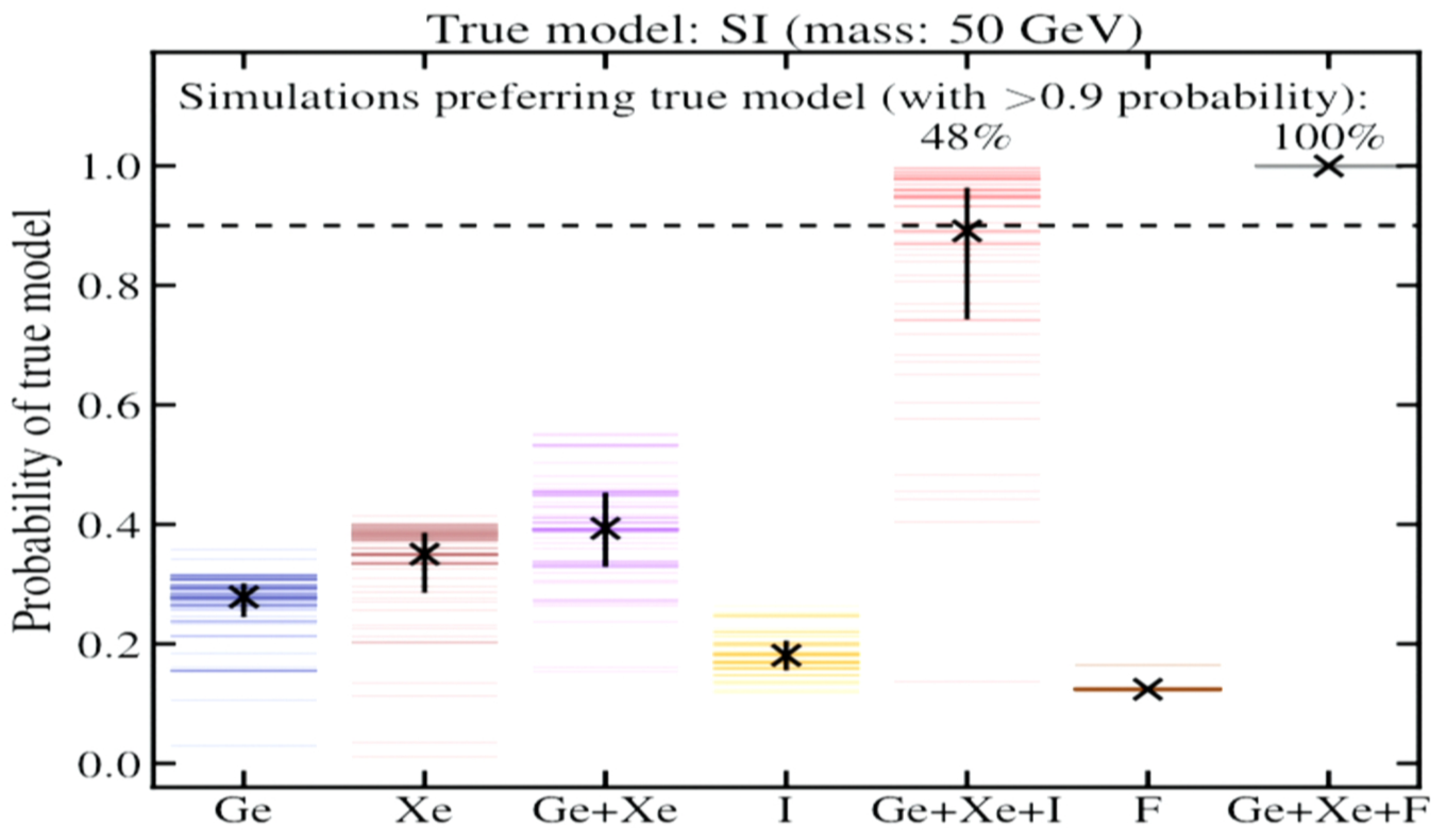
Success probability = percent of simulations in which the right model was selected with >90% probability.

Analysis:

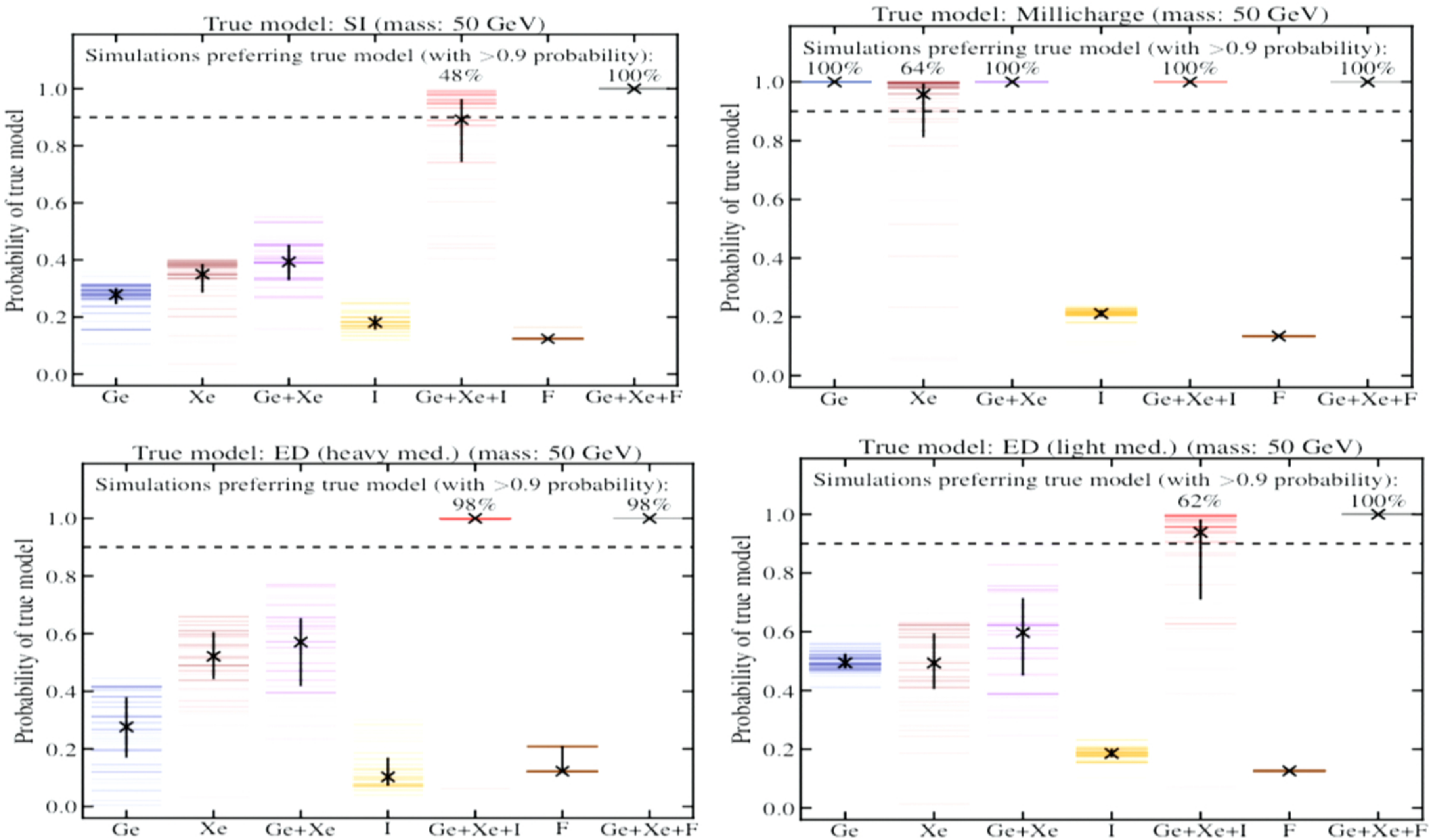
1. Simulate events under different hypotheses, for a signal **just below the current detection threshold**.

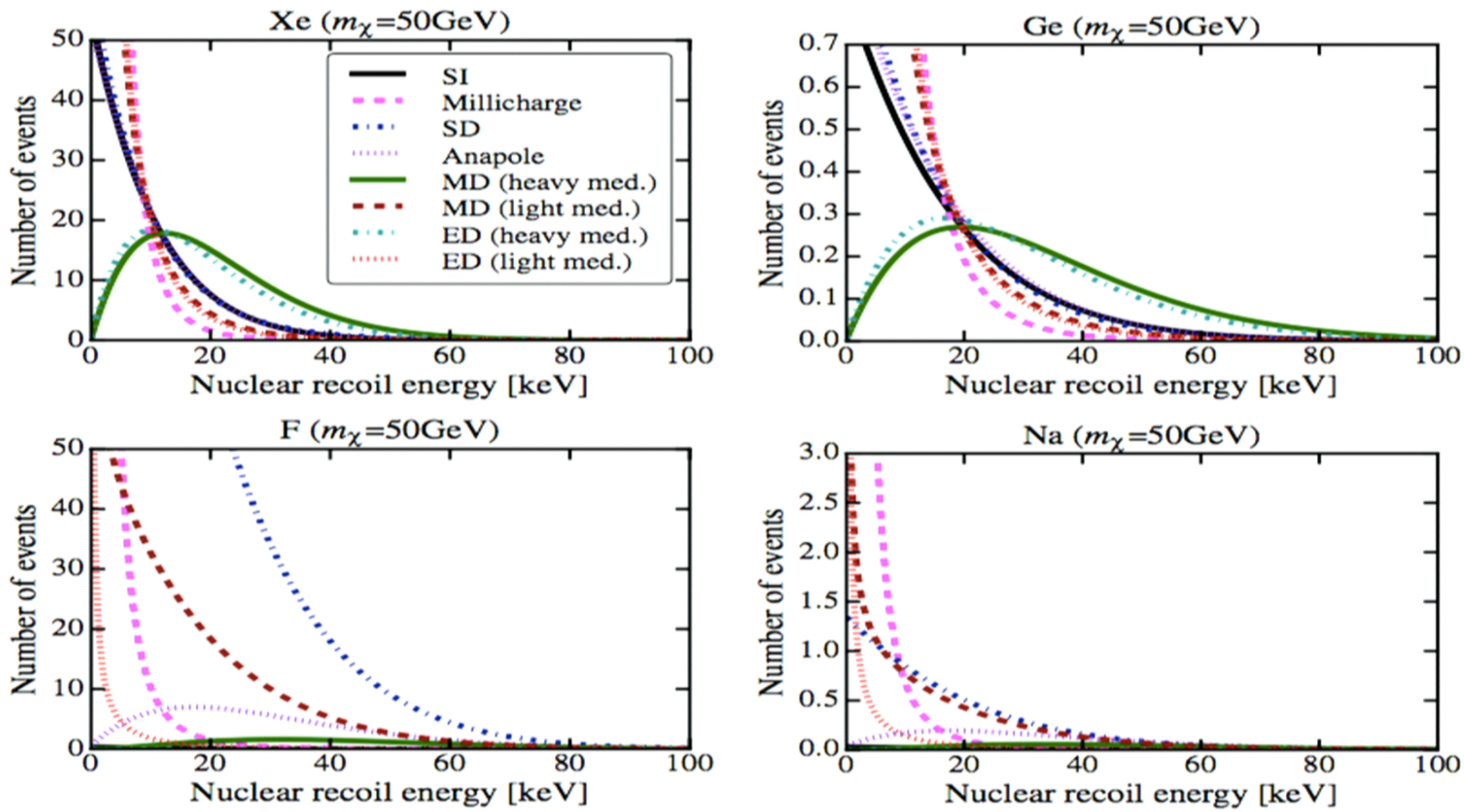



True model: SI (mass: 50 GeV)
Simulations preferring true model (with >0.9 probability):
48%
100%
Probability of true model
1.0
0.8
0.6
0.4
0.2
0.0
Ge
Xe
Ge+Xe
I
Ge+Xe+I
F
Ge+Xe+F



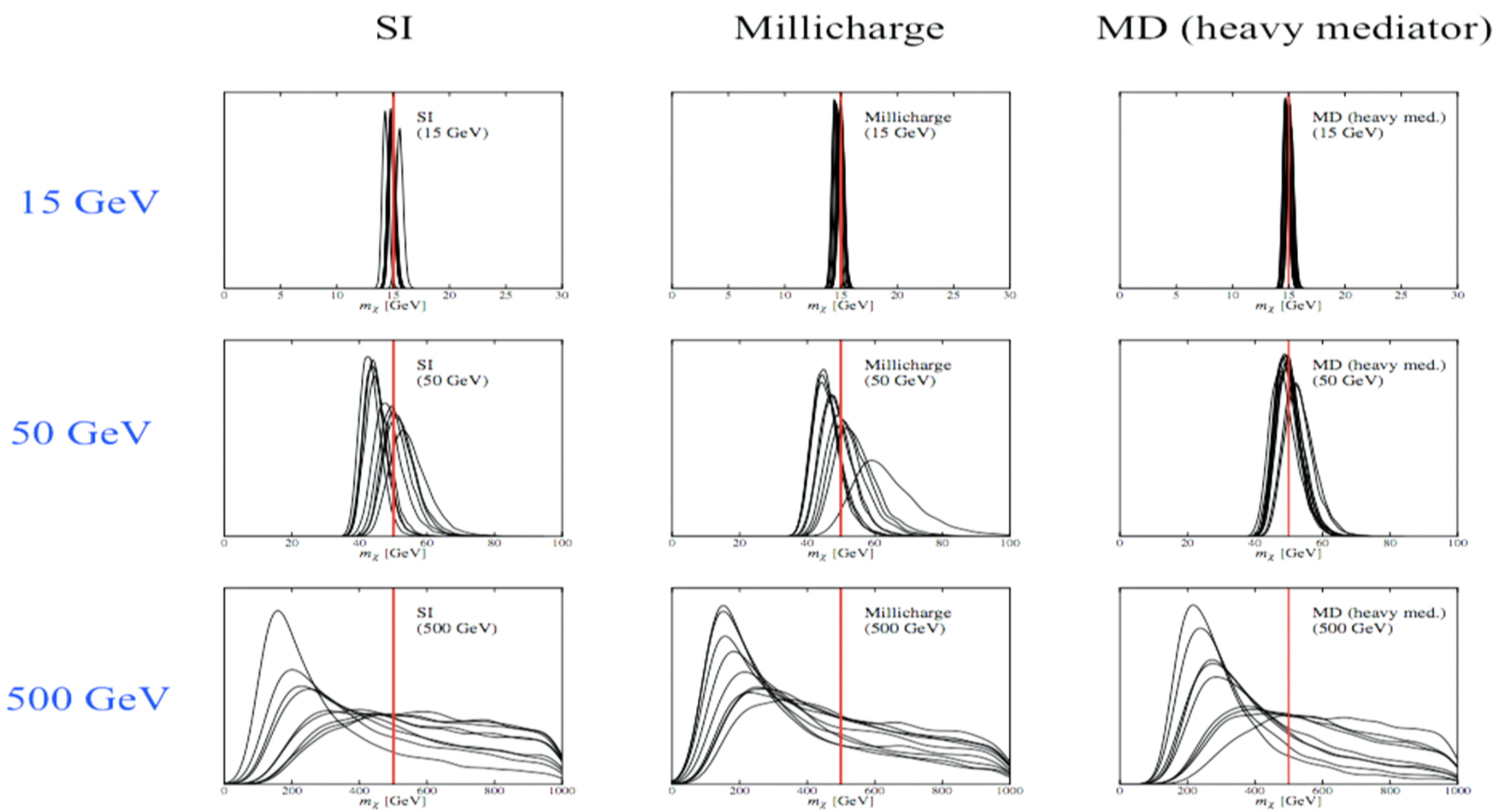
True model: SI (mass: 50 GeV)
Simulations preferring true model (with >0.9 probability):
48%
100%
Probability of true model
1.0
0.8
0.6
0.4
0.2
0.0
Ge
Xe
Ge+Xe
I
Ge+Xe+I
F
Ge+Xe+F

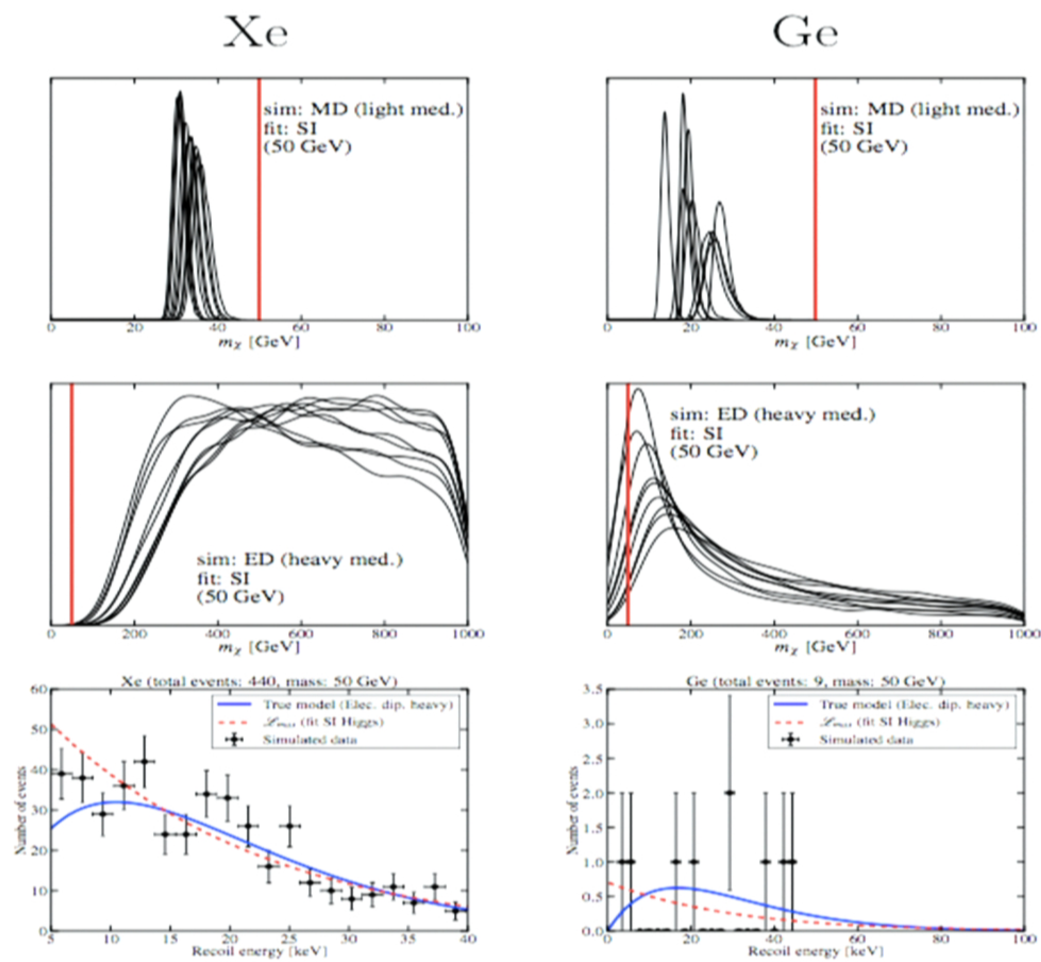

True model: SI (mass: 50 GeV)
Simulations preferring true model (with >0.9 probability):
48%
100%
Probability of true model
Ge
Xe
Ge+Xe
I
Ge+Xe+I
F
Ge+Xe+F
True model: Millicharge (mass: 50 GeV)
Simulations preferring true model (with >0.9 probability):
100%
64%
100%
100%
100%
True model: ED (heavy med.) (mass: 50 GeV)
Simulations preferring true model (with >0.9 probability):
98%
98%
True model: ED (light med.) (mass: 50 GeV)
Simulations preferring true model (with >0.9 probability):
62%
100%



Xe (m_χ=50GeV)
Ge (m_χ=50GeV)
F (m_χ=50GeV)
Na (m_χ=50GeV)
Number of events
Nuclear recoil energy [keV]
SI
Millicharge
SD
Anapole
MD (heavy med.)
MD (light med.)
ED (heavy med.)
ED (light med.)

Mass reconstruction

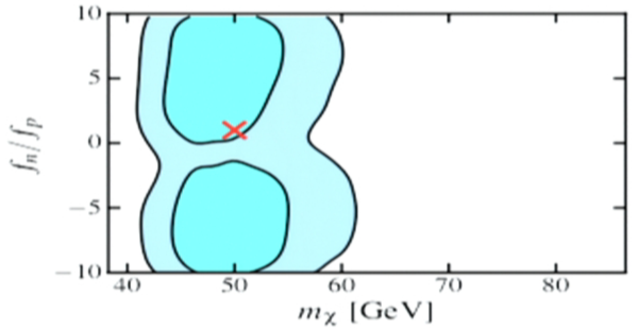

SI
Millicharge
MD (heavy mediator)
15 GeV
50 GeV
500 GeV
SI (15 GeV)
Millicharge (15 GeV)
MD (heavy med.) (15 GeV)
SI (50 GeV)
Millicharge (50 GeV)
MD (heavy med.) (50 GeV)
SI (500 GeV)
Millicharge (500 GeV)
MD (heavy med.) (500 GeV)
m_χ [GeV]

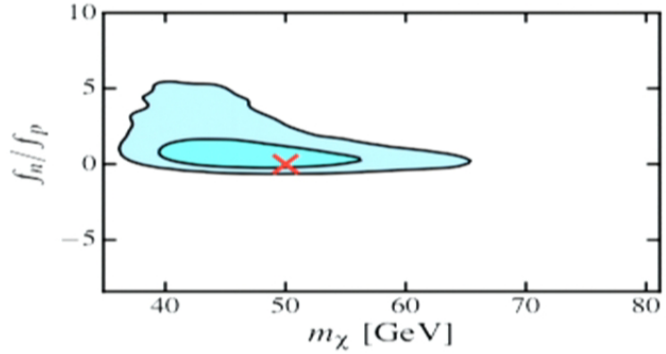

Xe
Ge
sim: MD (light med.)
fit: SI
(50 GeV)
sim: ED (heavy med.)
fit: SI
(50 GeV)
m_χ [GeV]
Xe (total events: 440, mass: 50 GeV)
Ge (total events: 9, mass: 50 GeV)
True model (Elec. dip. heavy)
Simulated data
Number of events
Recoil energy [keV]

fn/fp uncertainty

fn/fp as a free fitting parameter (for Xe+Ge+F only):

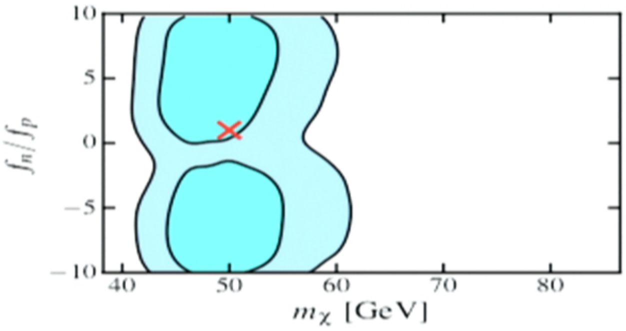
Parameter estimation:

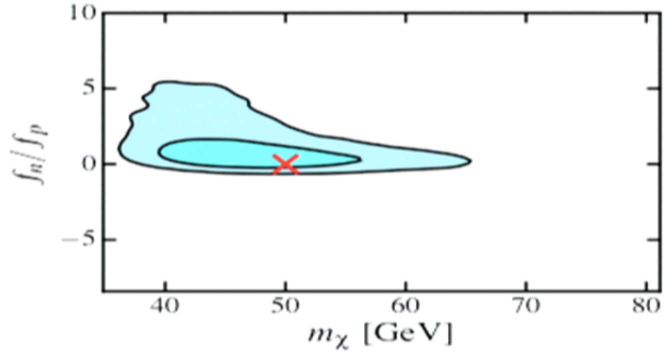




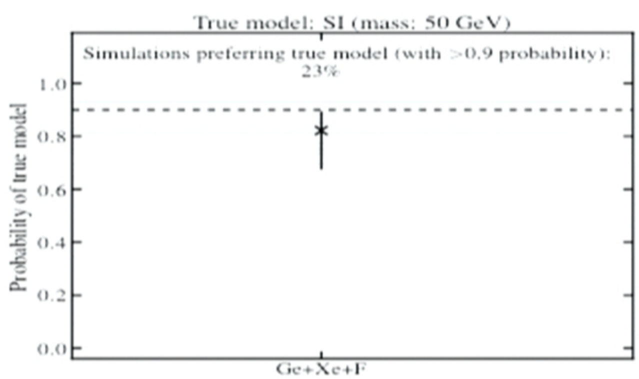
fn/fp as a free fitting parameter (for Xe+Ge+F only):

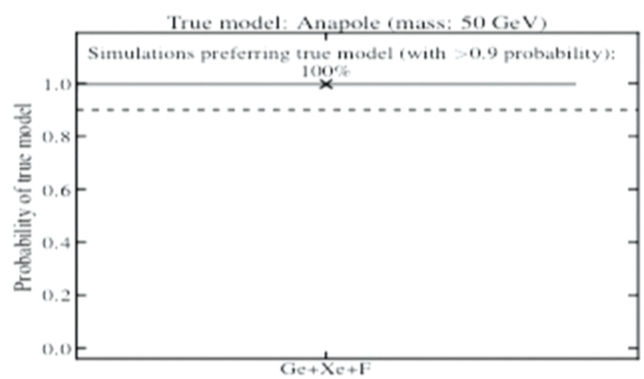
Parameter estimation:





Model selection:

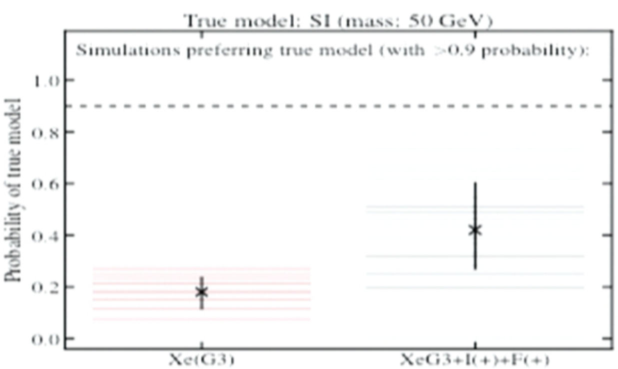


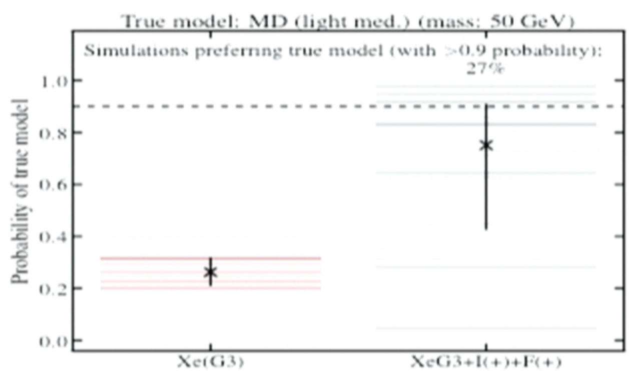


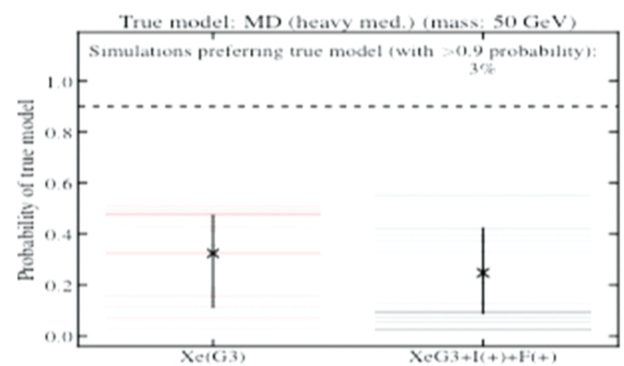
What next?

Signal at the projected G2 upper limit, on neutrino-floor experiments:

Label	A (Z)	Energy window [keVnr]	Exposure [kg-yr]
XeG3	131 (54)	5-40	40 000
I+	127 (53)	1-600	424
F+	19 (9)	3-100	1200





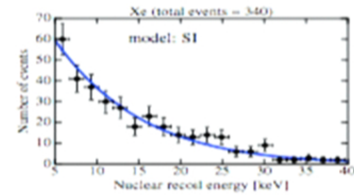


Conclusion 4:

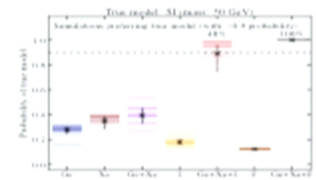
If G2 reports NO strong DM signal, prospects for identifying the right interaction from an agnostic analysis are slim; proceed with larger F or NaI experiments?

Summary

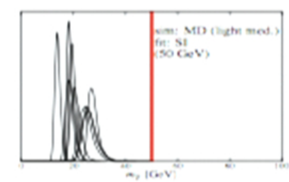
- ✓ Xenon + germanium can determine momentum dependence (mediator-mass regime), but we likely need other targets (F, I, Na) to distinguish richer phenomenology.



- ✓ Success is <u>not</u> a simple function of the number of events (i.e. exposure): low energy thresholds + multiple targets contribute.

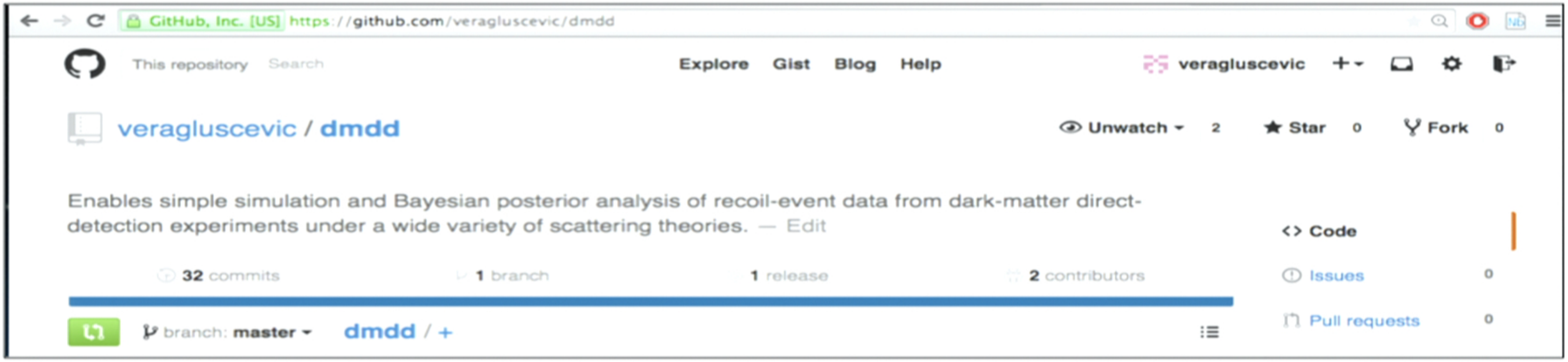


- ✓ If a wrong scattering model is assumed, inferred DM mass can be biased.



- ✓ If G2 makes a strong detection, prospects are good, but not otherwise: we **need to consider all available information in DM studies** (complementarity of direct detection with cosmology, LHC,...)

dmdd @ GitHub!



Basic Usage

Here is a quick example of basic usage:

```
from dmdd import UV_Model, Experiment, MultinestRun

model1 = UV_Model('SI_Higgs', ['mass', 'sigma_si'], fixed_params={'fnfp_si': 1})
model2 = UV_Model('SD_fu', ['mass','sigma_sd'], fixed_params={'fnfp_sd': -1.1})

xe = Experiment('Xe', 'xenon', 5, 40, 1000, eff.efficiency_Xe)

run = MultinestRun('sim', [xe,ge], model1,{'mass':50.,'sigma_si':70.},
                   model2, prior_ranges={'mass':(1,1000), 'sigma_sd':(0.001,1000)})

run.fit()
run.visualize()
```