Identifying the Theory of Dark Matter with Direct Detection

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arXiv:1506.04454 and ascl.net/1506.002

with Vera Gluscevic, Moira Gresham, Annika H. G. Peter, and Kathryn Zurek

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Motivation

- Dark matter exists
- Large ongoing experimental effort to discover its interactions with the Standard Model
- Imagine we detect dark matter: what information will we be able to extract?

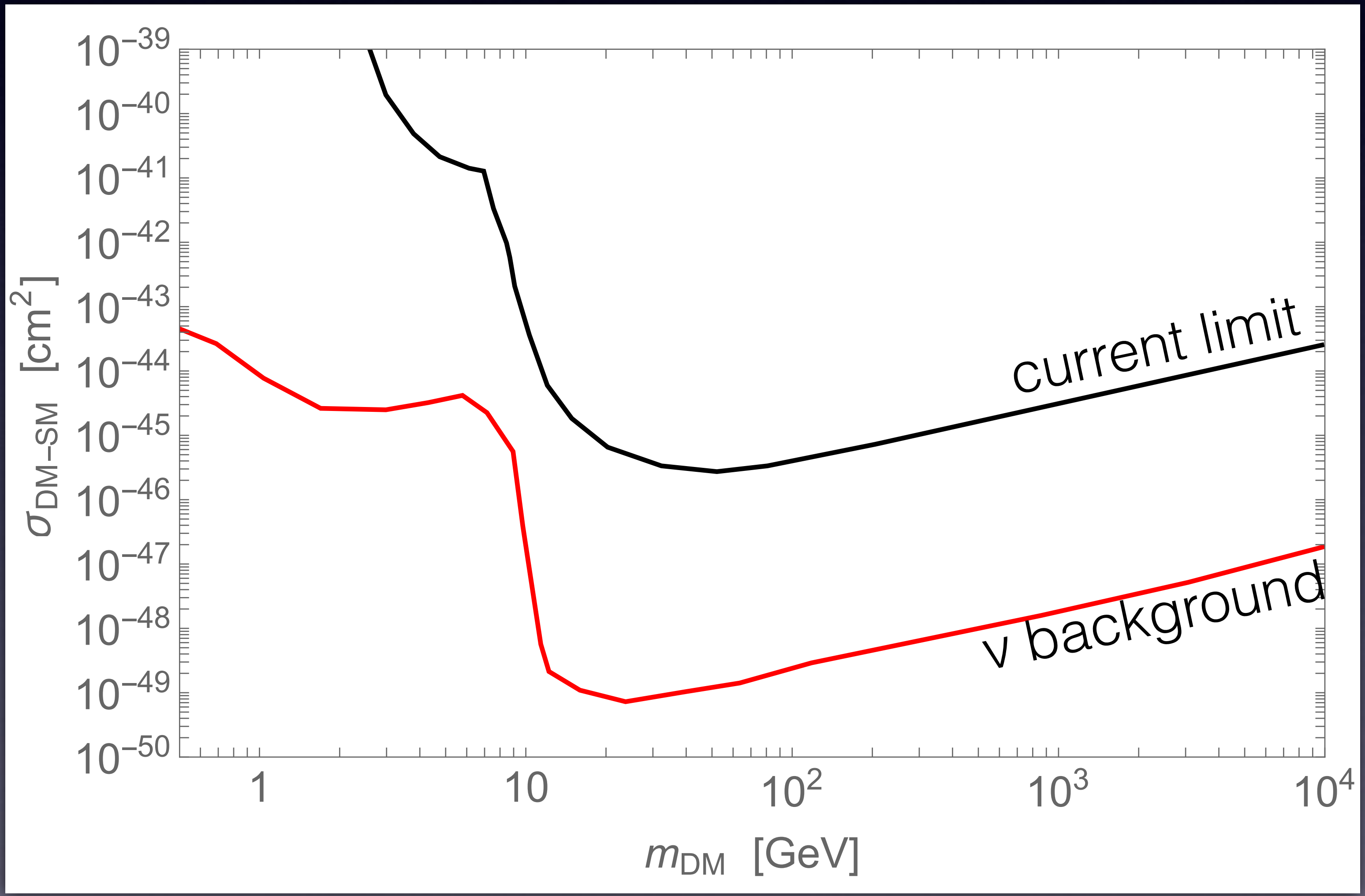
also, McDermott, Yu, Zurek 1110.4281,
Gluscevic, Peter 1406.7008,
Catena, 1406.0524, 1407.0127

Parameter Space

Direct detection experiments are probing several orders of magnitude in m_{DM}

Improving in σ_{DM} about x2/yr

Could make a discovery soon!



adapted from Snowmass document

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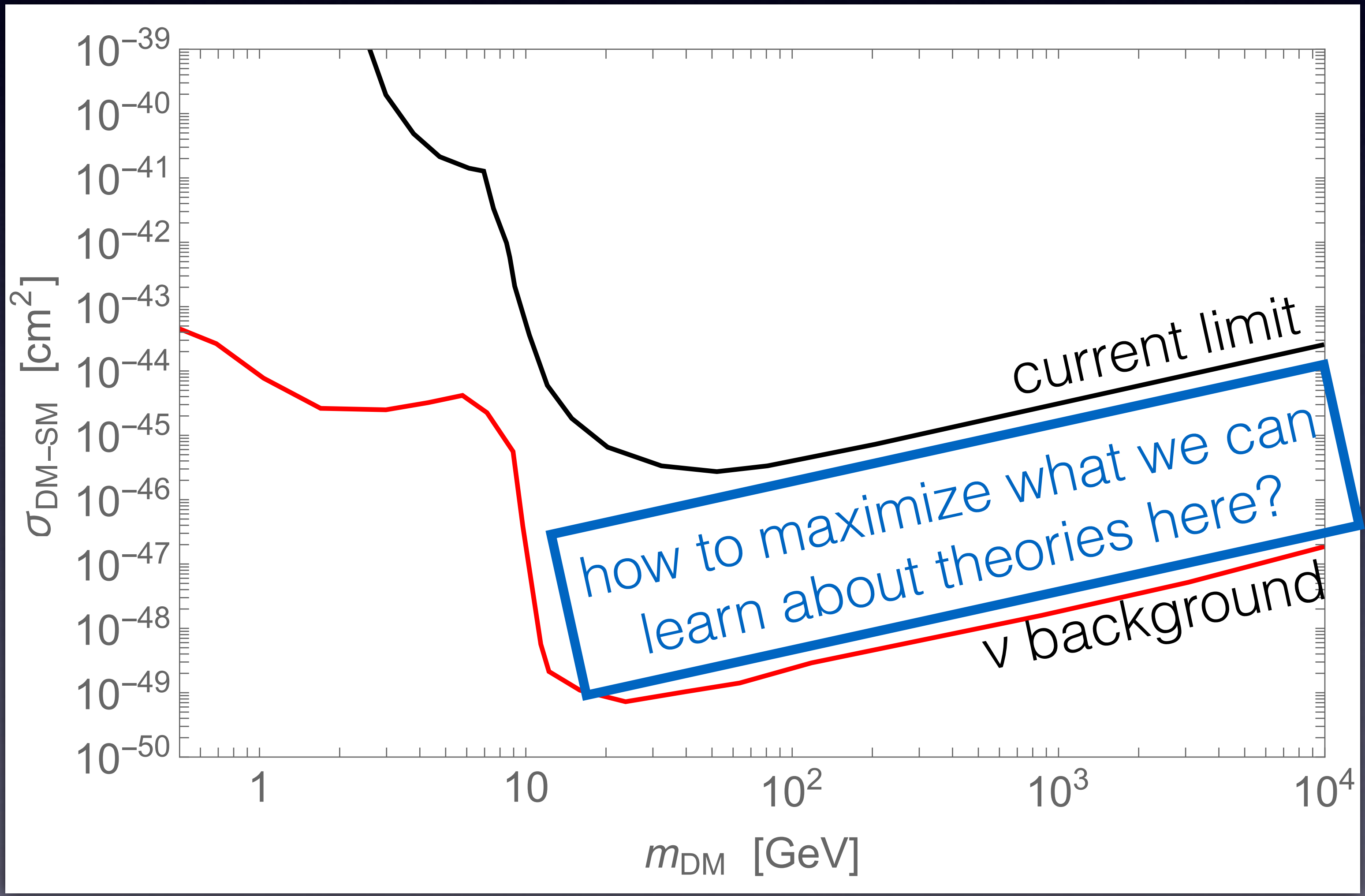

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Observables

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

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↓

recoil spectrum

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astrophysics

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recoil spectrum

nuclear / experimental physics

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particle physics

nuclear / experimental physics

Requirements

- A set of models (hypotheses) & corresponding phenomenology of scattering off nuclei
- A statistical representation of experiments
- An analysis framework for evaluating how well a given hypothesis fits a single data realization

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Bayesian model selection, cf. Gluscevic and Peter 1406.7008

EFT of DD

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

“particle physics”

given a Lorentz-invariant theory, calculate the low energy, non-relativistic cross section

nuclear form factors

given a Lorentz-invariant theory, nuclear physics measurements predict nuclear responses

$X = M, \Sigma', \Sigma'', \Phi'', \Delta, M\Phi'', \Delta\Sigma'$ (responses)

$y \equiv m_T E_R b^2/2, \quad (b/\mathrm{fm})^2 \equiv 41.467/(45A^{-1/3} - 25A^{-2/3})$

Particle Physics: R_X

lowest-dimension, least-suppressed Lorentz-invt. products of DM fermion bilinears with SM fields

- "standard" — SI ($\bar{\chi}\chi\bar{f}f$), SD ($\bar{\chi}\gamma^\mu\gamma_5\chi\ \bar{f}\gamma_\mu\gamma_5 f$)
- photon-mediated — millicharged ($\bar{\chi}\gamma^\mu\chi A_\mu$), anapole ($\bar{\chi}\gamma^\mu\gamma_5\chi\partial^\mu F_{\mu\nu}$), magnetic dipole ($\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$), electric dipole ($\bar{\chi}\sigma^{\mu\nu}\gamma_5\chi F_{\mu\nu}$)

UV theory ⇒ overall momentum and velocity dependence, triggered responses

“Nuclear Physics”: $\widetilde{W}_X$

- form factor = how rate falls off at higher energy
- depends on target, response, and energy

number of form factors =

= number of targets $\times$ number of responses

Statistical Methodology

likelihood

prior

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

observed (noisy) energy spectrum

given model

free parameters (σ_{DD} and m_{DM})

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

“What are the odds” of extracting the true underlying model from the data?

Statistical Methodology

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(Note: not maximizing a χ^2 statistic or finding a best fit)

Mock data

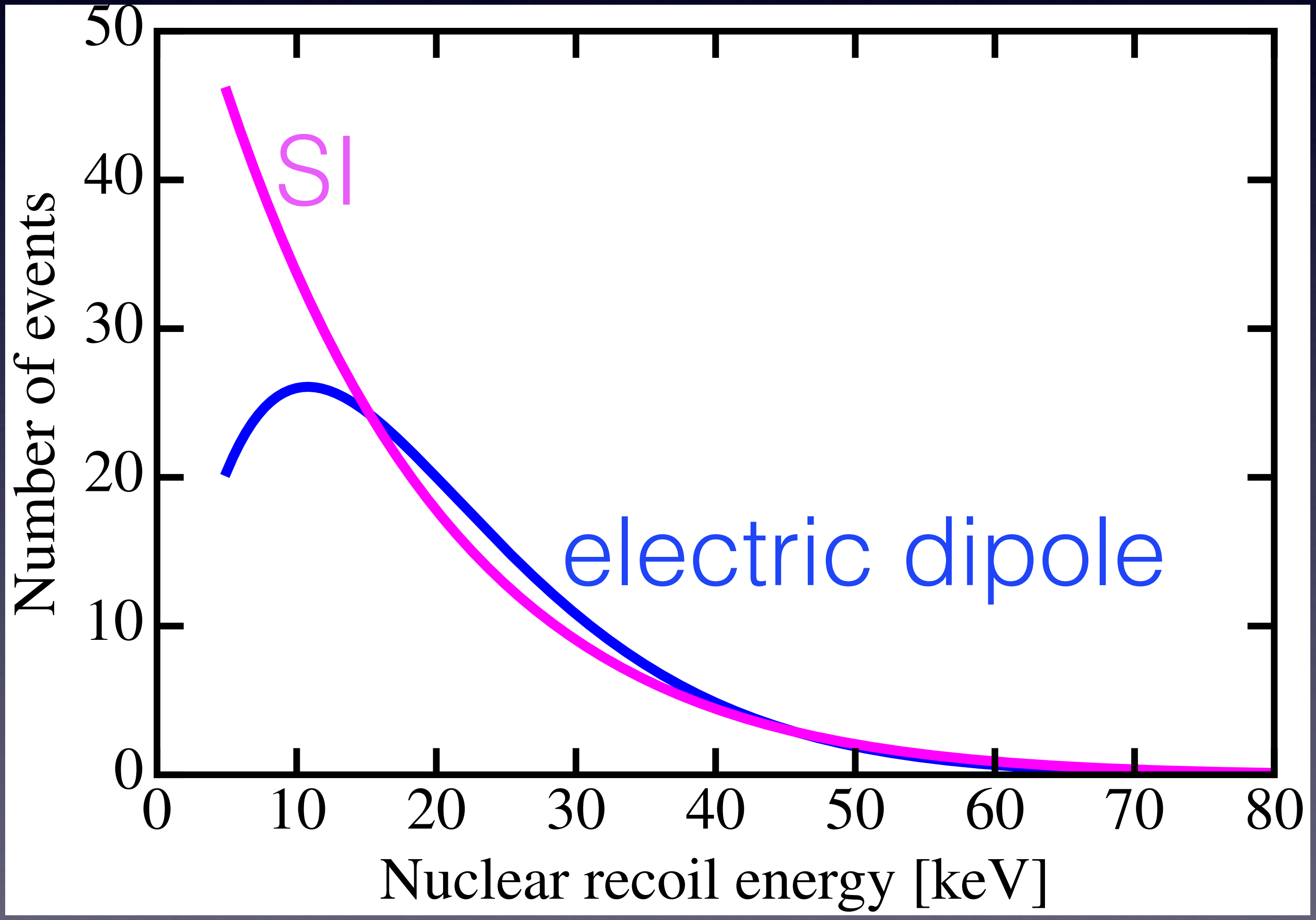
need to make mock data sets $\{E_R\}$

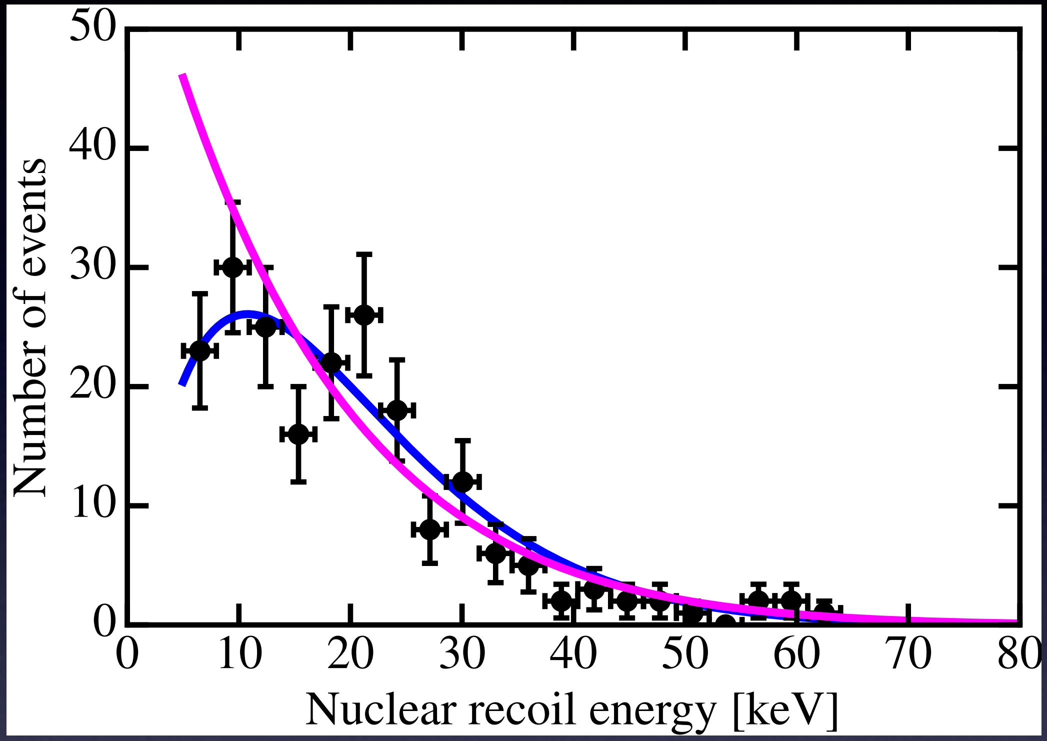
simulate G2-like experiments

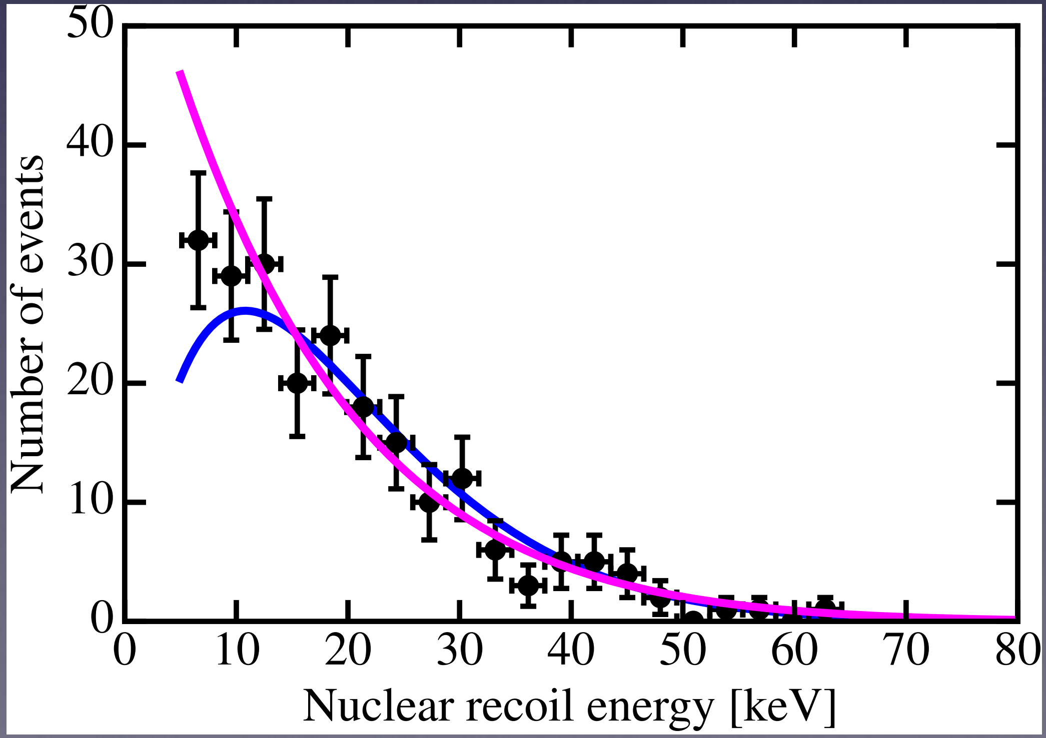
Label	A (Z)	Energy window [keVnr]	Exposure [kg-yr]
Xe	131 (54)	5-40	2000
Ge	73 (32)	0.3-100	100
I	127 (53)	22.2-600	212
F	19 (9)	3-100	606
Na	23 (11)	6.7-200	38

choose m_{DM}, set σ_{DD}
just below current limits

A Single Simulation







Criterion for Success

$$\Pr(\mathcal{M}_j) = \frac{\mathcal{E}(\{E_R\}|\mathcal{M}_j)}{\sum_i \mathcal{E}(\{E_R\}|\mathcal{M}_i)} > 90\%$$

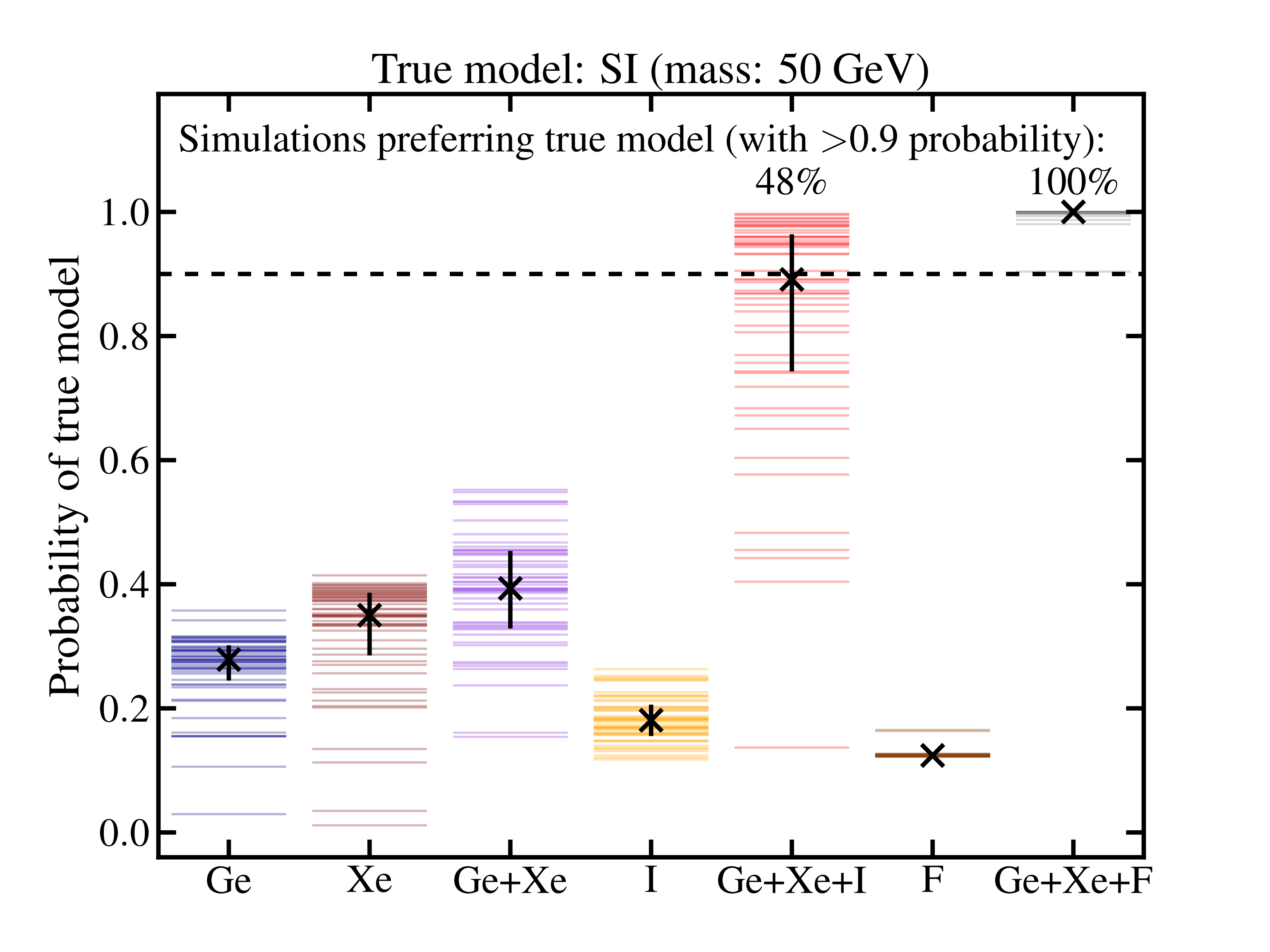
true underlying model is "confidently selected" if $\Pr(M_{true}) > 90\%$

↓

this depends on the Poisson realization

} create many Poisson realizations to test robustness

Results (example)



single elements not so good

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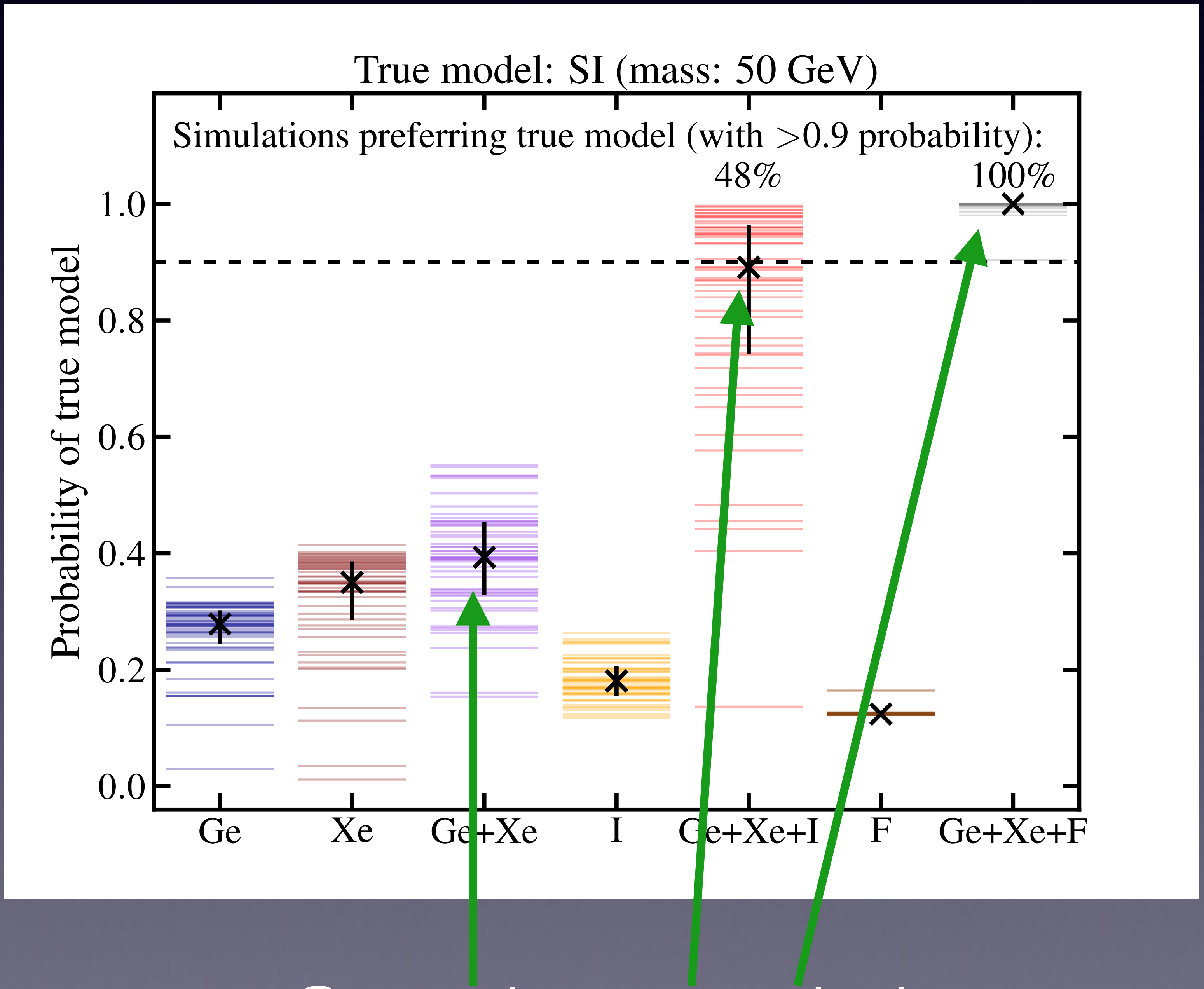

Complementarity!

Conclusions

- A conclusive direct observation of DM will just be the beginning of the work
- Target complementarity will be a critical requirement for learning about DM physics