# Prospects for understanding dark matter-baryon interactions with direct detection

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# Main question:

Could we discern details of underlying DM physics, such as the type of scattering interaction, with Generation 2 of direct detection?

# EFT of DM-nucleon interactions

EFT = experiment-driven way of parameterizing underlying theories.

$$V_{\text{eff}} = h_1 \delta^3(\vec{r}) - h_2 \vec{s}_\chi \cdot \vec{\nabla} \delta^3(\vec{r}) + \ell_1 \frac{1}{4\pi r} + \ell_2 \frac{\vec{s}_\chi \cdot \vec{r}}{4\pi r^3}$$

heavy mediator

light mediator

Fan et al, 2010

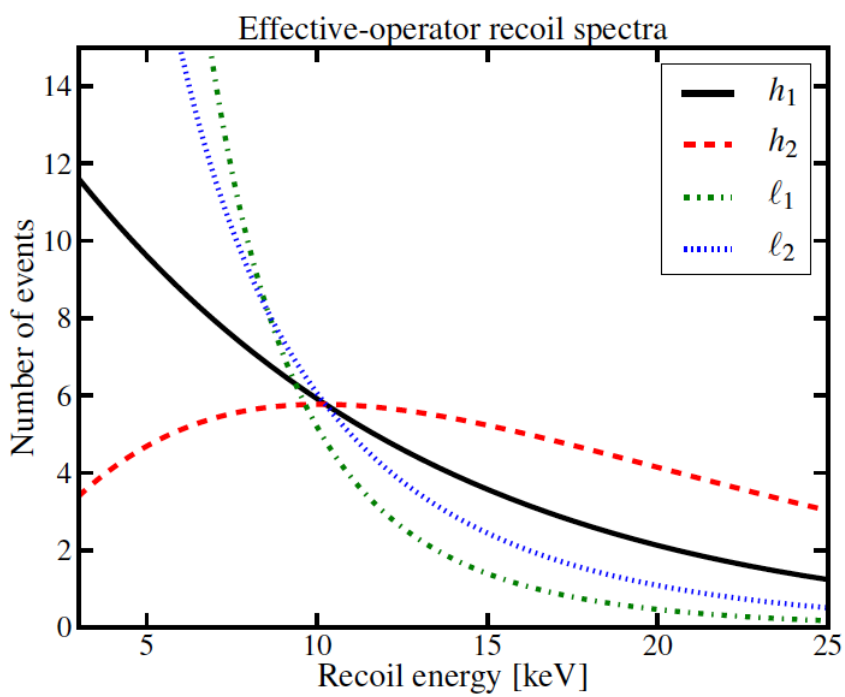
(also, McDermott et al, 2012; Feldstein et al, 2012; Chang et al, 2010; Fitzpatrick et al 2013, etc.)

# EFT of DM-nucleon interactions

$$\frac{d\sigma}{dE_R} = \frac{A^2 F^2(E_R) m_N}{2\pi v^2}\left(\left|h_1 + \frac{\ell_1}{2m_N E_R}\right|^2 + \frac{1}{4}\left|h_2\sqrt{2m_N E_R} + \frac{\ell_2}{\sqrt{2m_N E_R}}\right|^2\right)$$

Fan et al, 2010

$$(\sigma_{SI} = \frac{\mu_p^2}{\pi} h_1^2)$$



# Experimental context: Generation 2

| Experiment label | Target | Nuclear mass [AMU] | Energy window [keV] | Exposure [kg-yr] |
|---|---|---|---|---|
| Xe | Xe | 131 | 5-40 | 2000 |
| Ar | Ar | 40 | 30-100 | 1000 |
| Ge | Ge | 73 | 8-100 | 100 |
| SiLT | Si | 28 | 0.1-100 | 0.2 |
| GeLT | Ge | 73 | 0.3-100 | 4 |
| Xe ultimate | Xe | 131 | 3-40 | 10 000 |

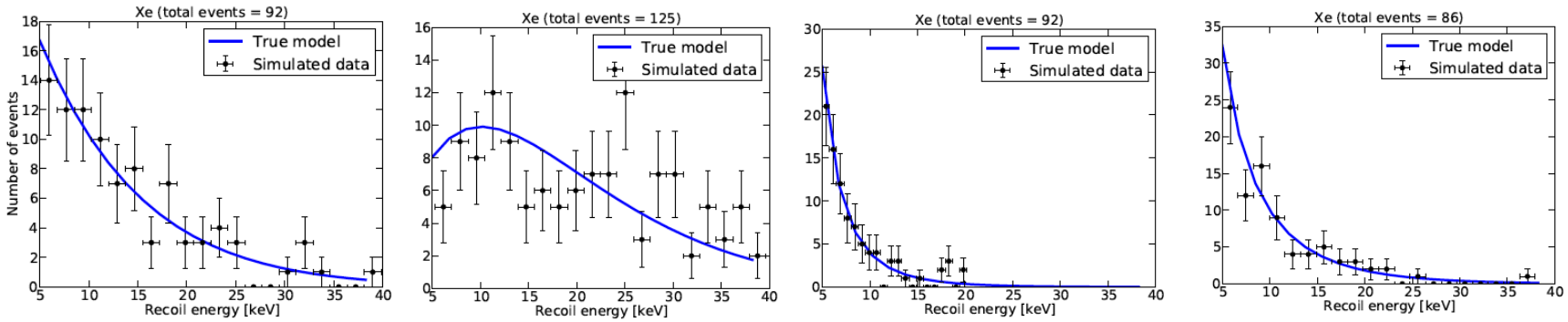
"Neutrino floor" experiment

LUX
Xenon1T
Panda-X

Dark Side

SuperCDMS(lite)
Edelweiss

# Method




Step 1: Simulate data ({$E_R$} spectrum) + Poisson noise for a single operator with max coupling.

Step 2: Analyze each simulation by fitting each of the 4 operator models.

Step 3: Evaluate probability of the right model compared to other models.

Step 4: Repeat 1-3 for each of the 5 mock experiments, many times.

Step 5: Jointly analyze different experiments.

# Framework: Bayesian model selection

coupling + mass

Posterior probability:

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

Likelihood:

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

Evidence:

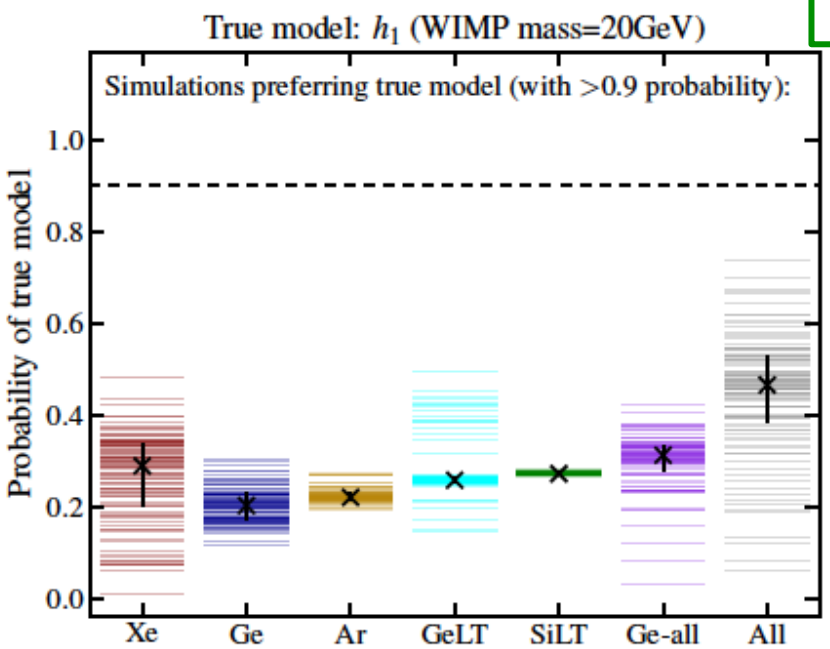
$$\mathcal{E}(M) = \int d\Theta \mathcal{L}(\{E_R\}|\Theta, M)p(\Theta|M)$$

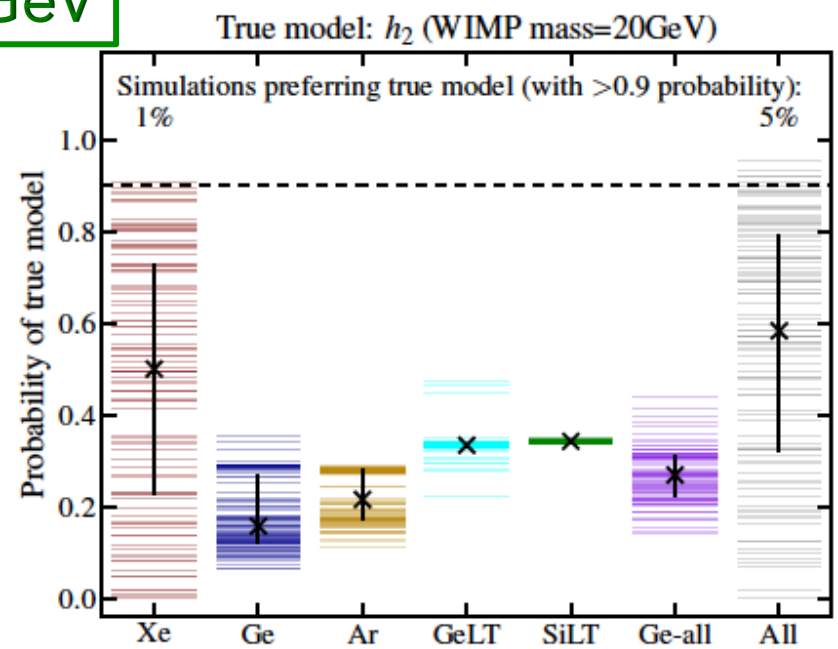
$$\boxed{p(M_j) = \frac{\mathcal{E}(M_j)}{\sum_i \mathcal{E}(M_i)}}$$

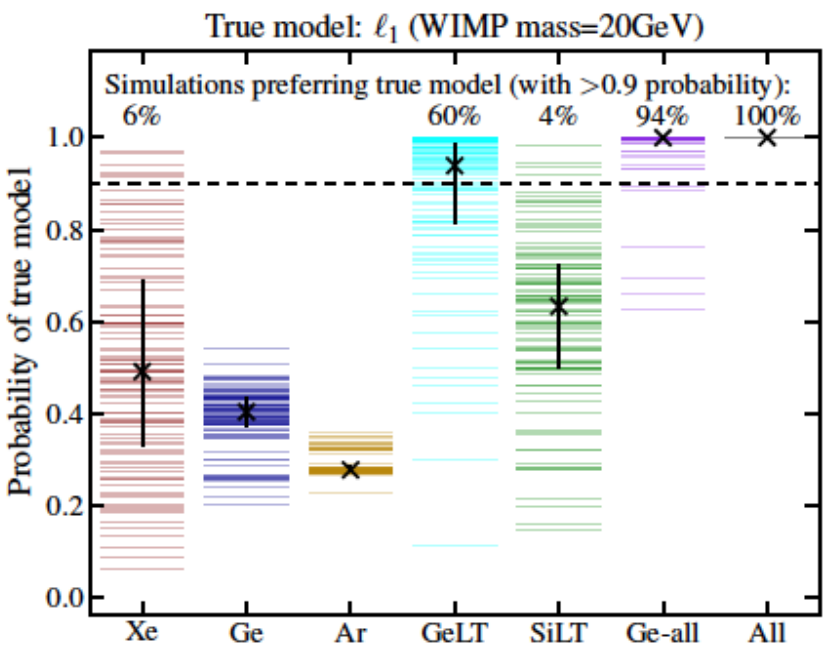
Model probability (given data)

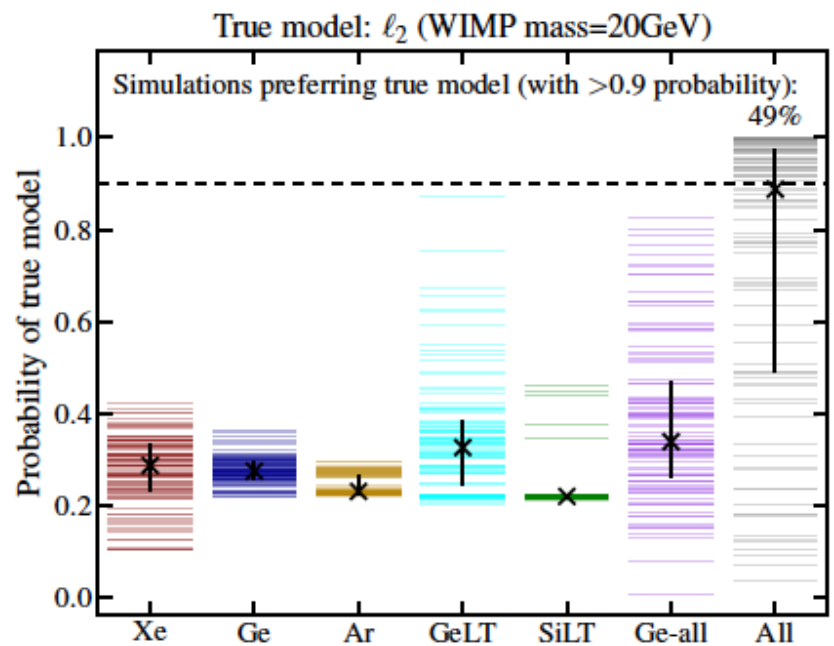
**Success probability = percent of simulations in which the right operator was selected with >90% probability.**

20 GeV

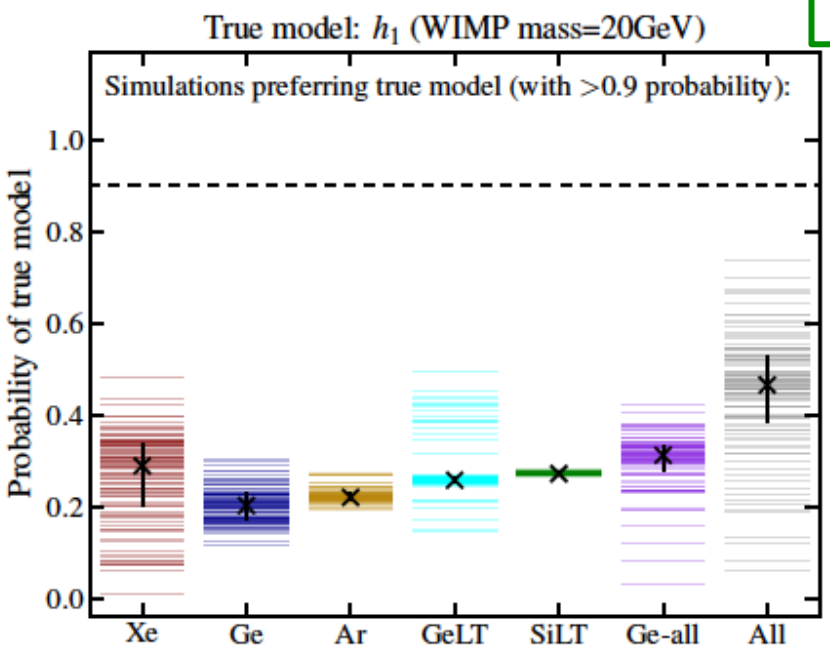

True model: $h_1$ (WIMP mass=20GeV)
Simulations preferring true model (with >0.9 probability):
Probability of true model
1.0
0.8
0.6
0.4
0.2
0.0
Xe
Ge
Ar
GeLT
SiLT
Ge-all
All

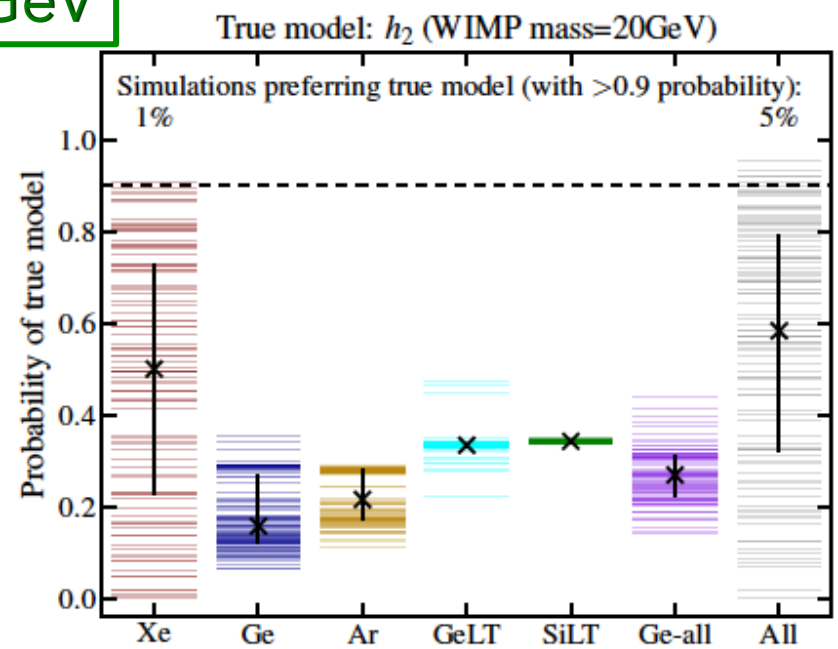

True model: $h_2$ (WIMP mass=20GeV)
Simulations preferring true model (with >0.9 probability):
1%
5%
Probability of true model
1.0
0.8
0.6
0.4
0.2
0.0
Xe
Ge
Ar
GeLT
SiLT
Ge-all
All

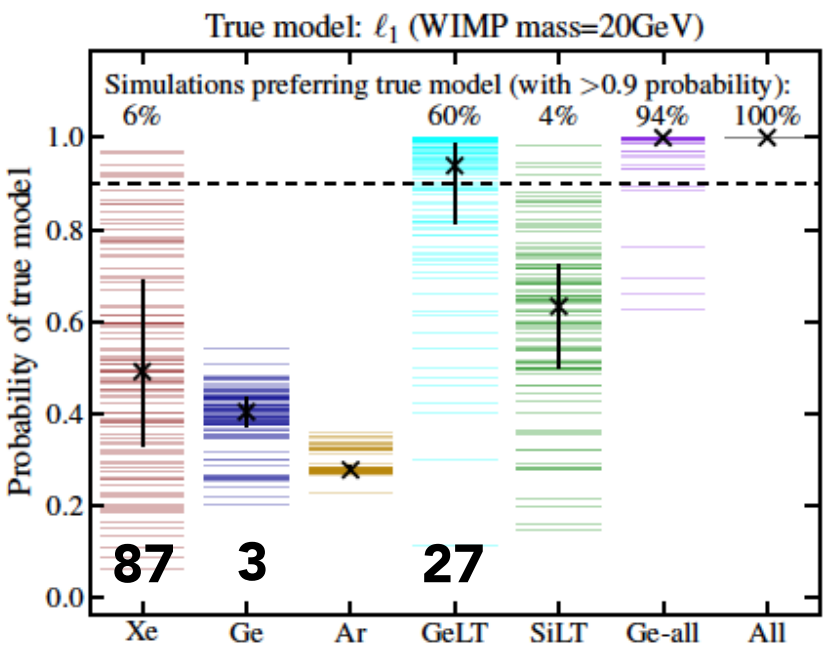

True model: $\ell_1$ (WIMP mass=20GeV)
Simulations preferring true model (with >0.9 probability):
6%
60%
4%
94%
100%
Probability of true model
1.0
0.8
0.6
0.4
0.2
0.0
Xe
Ge
Ar
GeLT
SiLT
Ge-all
All

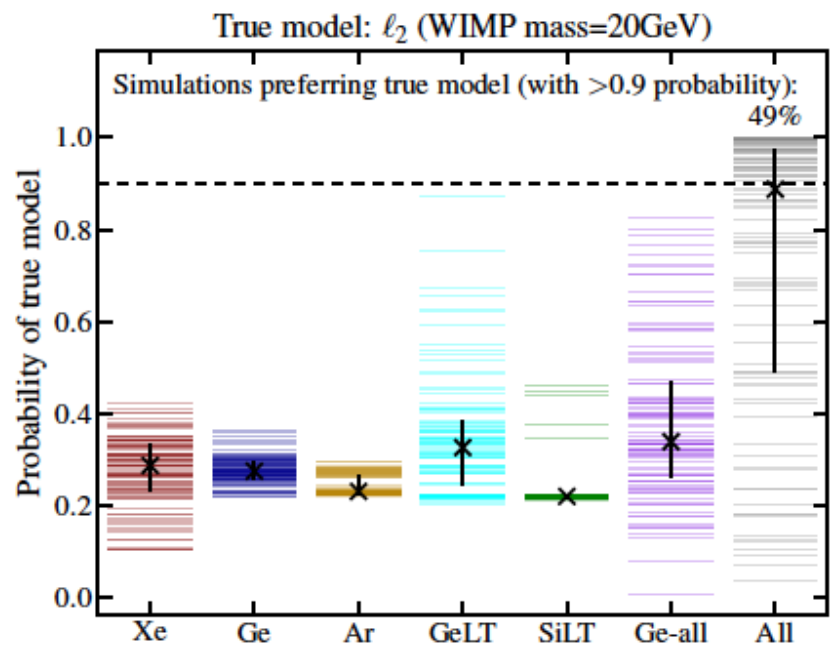

True model: $\ell_2$ (WIMP mass=20GeV)
Simulations preferring true model (with >0.9 probability):
49%
Probability of true model
1.0
0.8
0.6
0.4
0.2
0.0
Xe
Ge
Ar
GeLT
SiLT
Ge-all
All

20 GeV

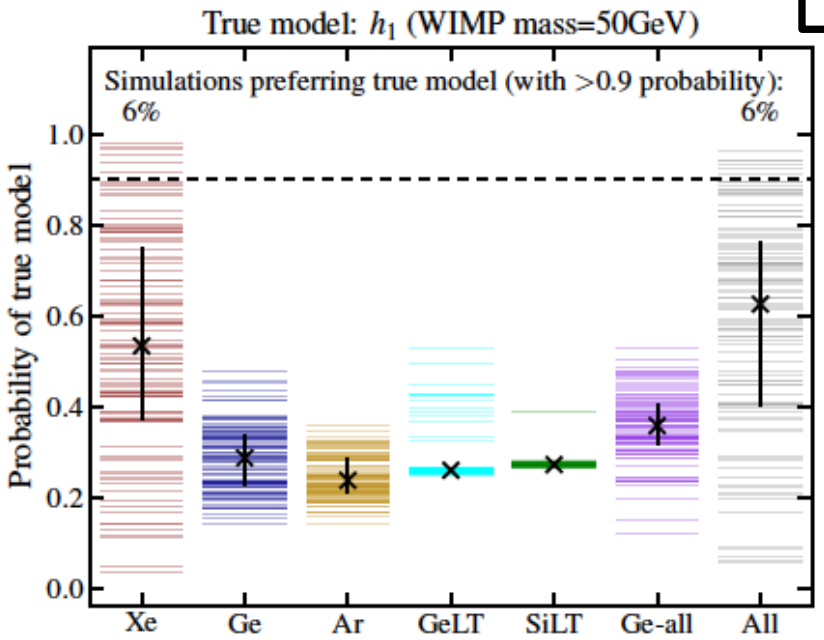

True model: $h_1$ (WIMP mass=20GeV)
Simulations preferring true model (with >0.9 probability):
Probability of true model
1.0
0.8
0.6
0.4
0.2
0.0
Xe
Ge
Ar
GeLT
SiLT
Ge-all
All

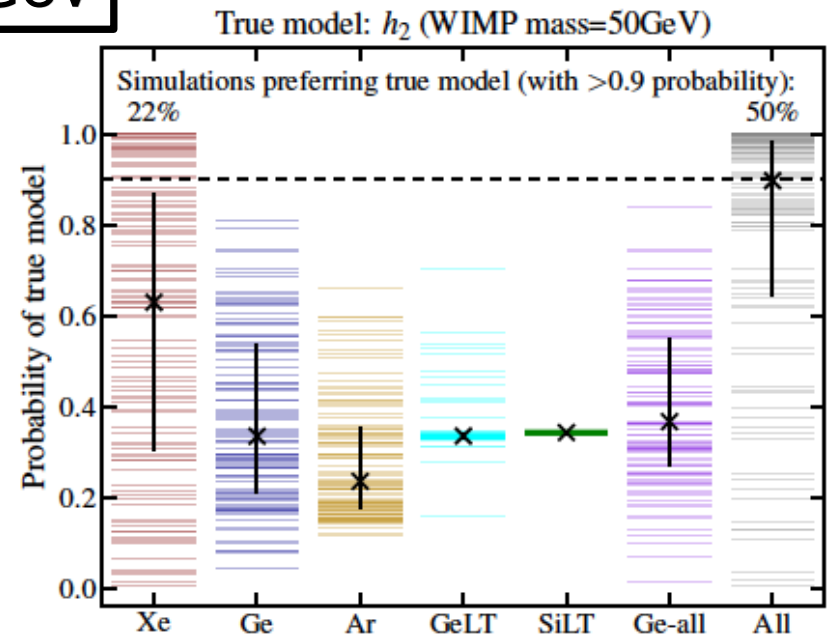

True model: $h_2$ (WIMP mass=20GeV)
Simulations preferring true model (with >0.9 probability):
1%
5%
Probability of true model
1.0
0.8
0.6
0.4
0.2
0.0
Xe
Ge
Ar
GeLT
SiLT
Ge-all
All

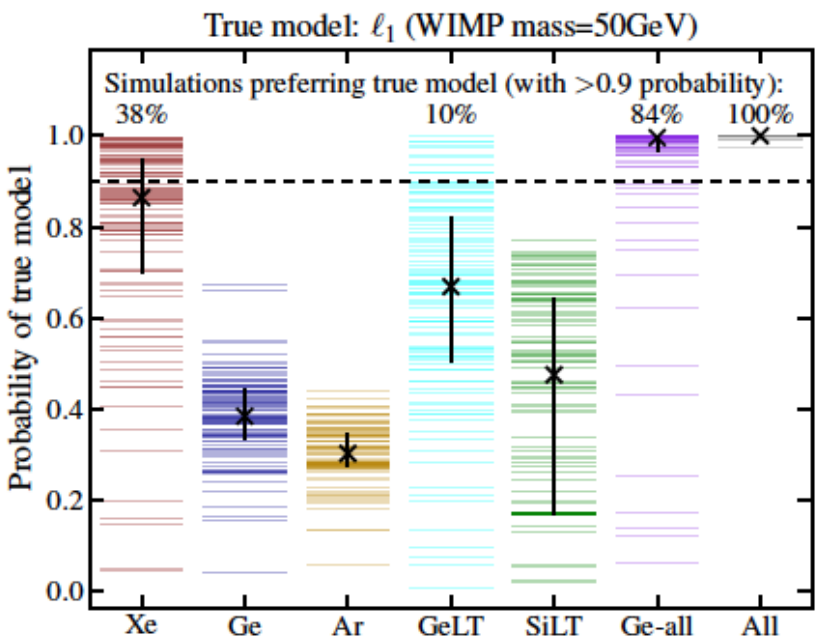

True model: $\ell_1$ (WIMP mass=20GeV)
Simulations preferring true model (with >0.9 probability):
6%
60%
4%
94%
100%
87
3
27
Probability of true model
1.0
0.8
0.6
0.4
0.2
0.0
Xe
Ge
Ar
GeLT
SiLT
Ge-all
All

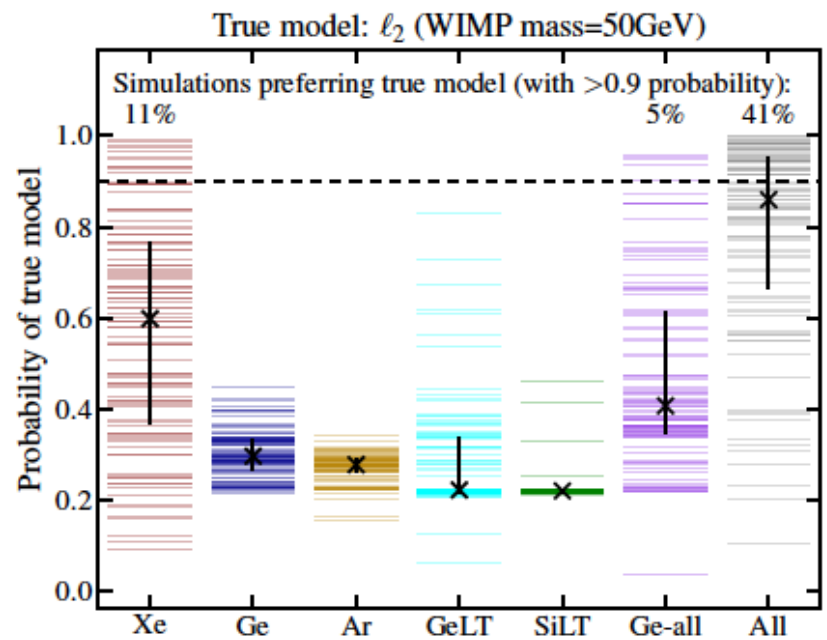

True model: $\ell_2$ (WIMP mass=20GeV)
Simulations preferring true model (with >0.9 probability):
49%
Probability of true model
1.0
0.8
0.6
0.4
0.2
0.0
Xe
Ge
Ar
GeLT
SiLT
Ge-all
All

50 GeV

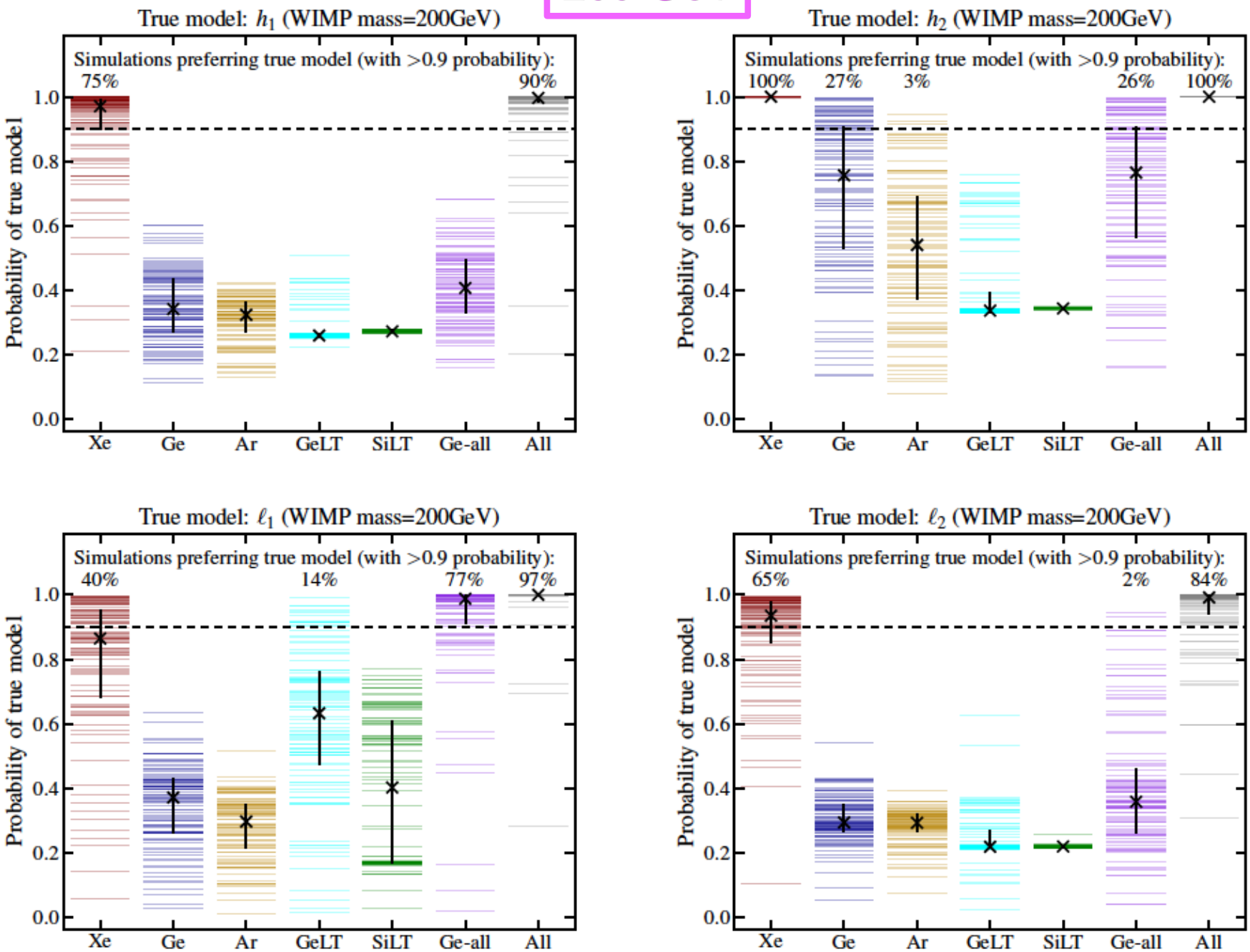

True model: $h_1$ (WIMP mass=50GeV)
Simulations preferring true model (with >0.9 probability):
6%
6%
Probability of true model
1.0
0.8
0.6
0.4
0.2
0.0
Xe
Ge
Ar
GeLT
SiLT
Ge-all
All


True model: $h_2$ (WIMP mass=50GeV)
Simulations preferring true model (with >0.9 probability):
22%
50%
Probability of true model
1.0
0.8
0.6
0.4
0.2
0.0
Xe
Ge
Ar
GeLT
SiLT
Ge-all
All


True model: $\ell_1$ (WIMP mass=50GeV)
Simulations preferring true model (with >0.9 probability):
38%
10%
84%
100%
Probability of true model
1.0
0.8
0.6
0.4
0.2
0.0
Xe
Ge
Ar
GeLT
SiLT
Ge-all
All

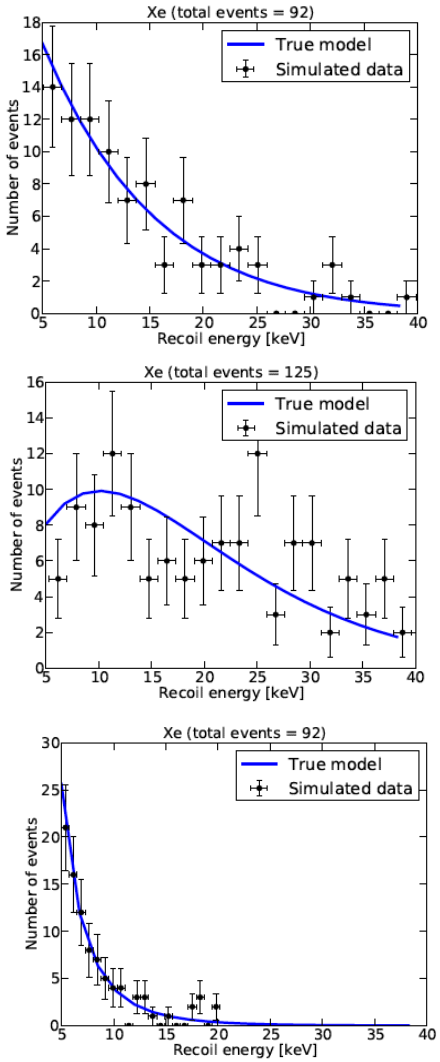

True model: $\ell_2$ (WIMP mass=50GeV)
Simulations preferring true model (with >0.9 probability):
11%
5%
41%
Probability of true model
1.0
0.8
0.6
0.4
0.2
0.0
Xe
Ge
Ar
GeLT
SiLT
Ge-all
All

200 GeV

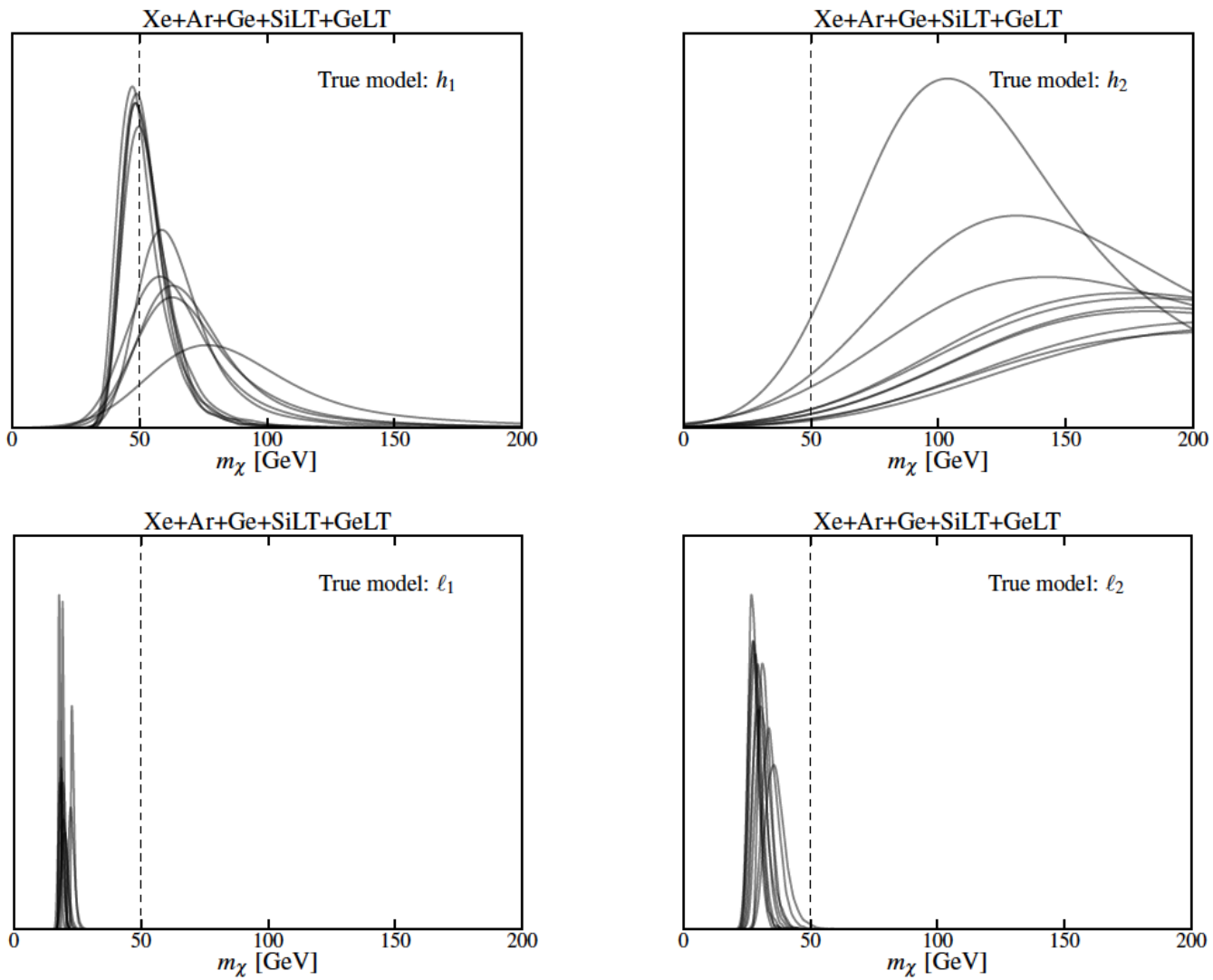

True model: $h_1$ (WIMP mass=200GeV)
Simulations preferring true model (with >0.9 probability):
75%
90%
True model: $h_2$ (WIMP mass=200GeV)
Simulations preferring true model (with >0.9 probability):
100%
27%
3%
26%
100%
True model: $\ell_1$ (WIMP mass=200GeV)
Simulations preferring true model (with >0.9 probability):
40%
14%
77%
97%
True model: $\ell_2$ (WIMP mass=200GeV)
Simulations preferring true model (with >0.9 probability):
65%
2%
84%
Probability of true model
0.0
0.2
0.4
0.6
0.8
1.0
Xe
Ge
Ar
GeLT
SiLT
Ge-all
All

# For successful model selection

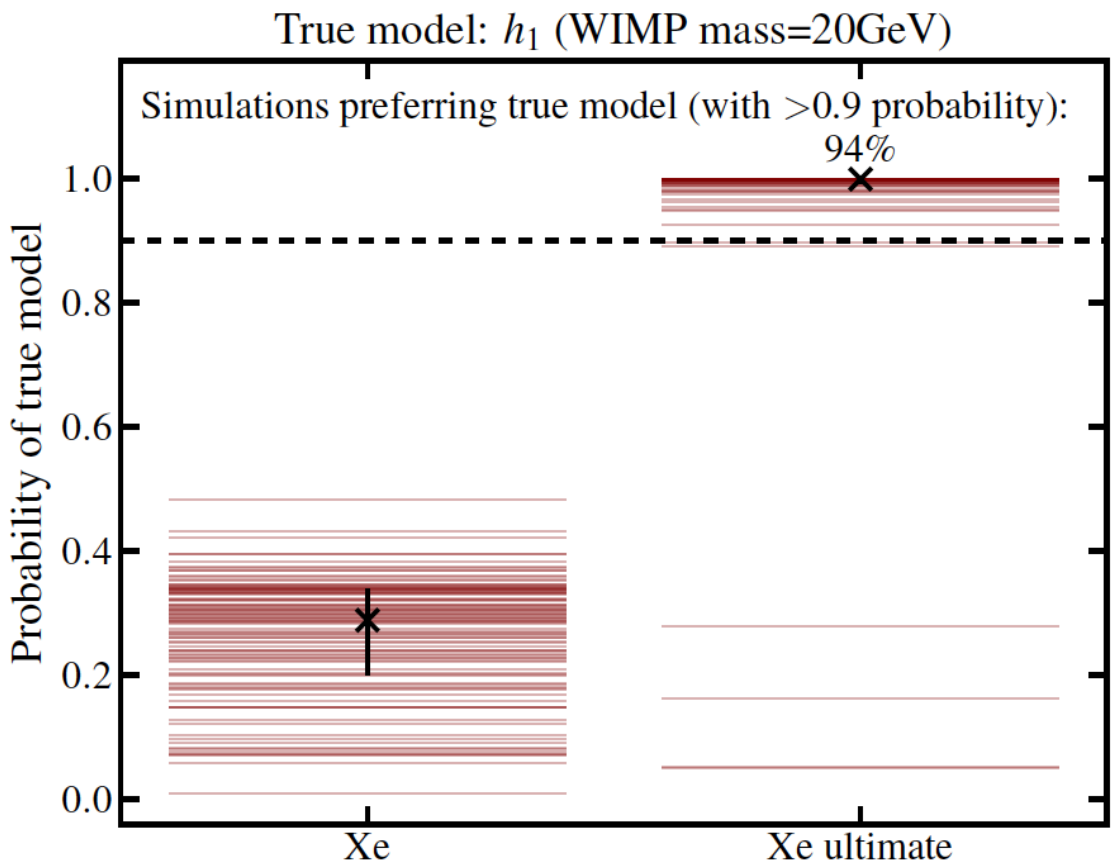
- Wide energy coverage
- Low threshold
- Large exposure
- Multiple targets



# WIMP mass reconstruction: beware of bias



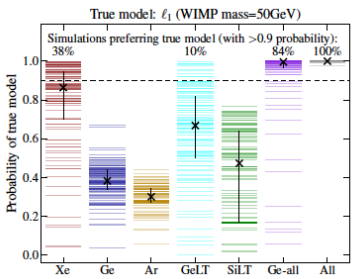
# How far can model selection go for a signal at the current limit?

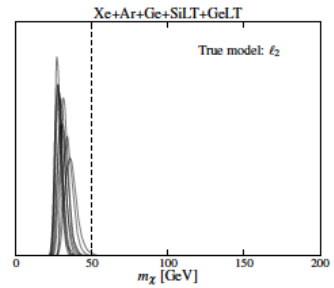


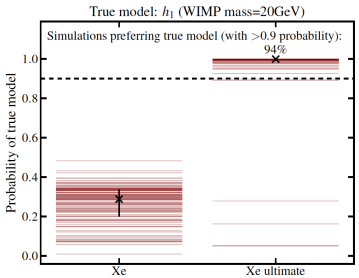

Example case: 20 GeV WIMP with the standard interaction on Xe target, and maximal interaction cross-section.

# Conclusions

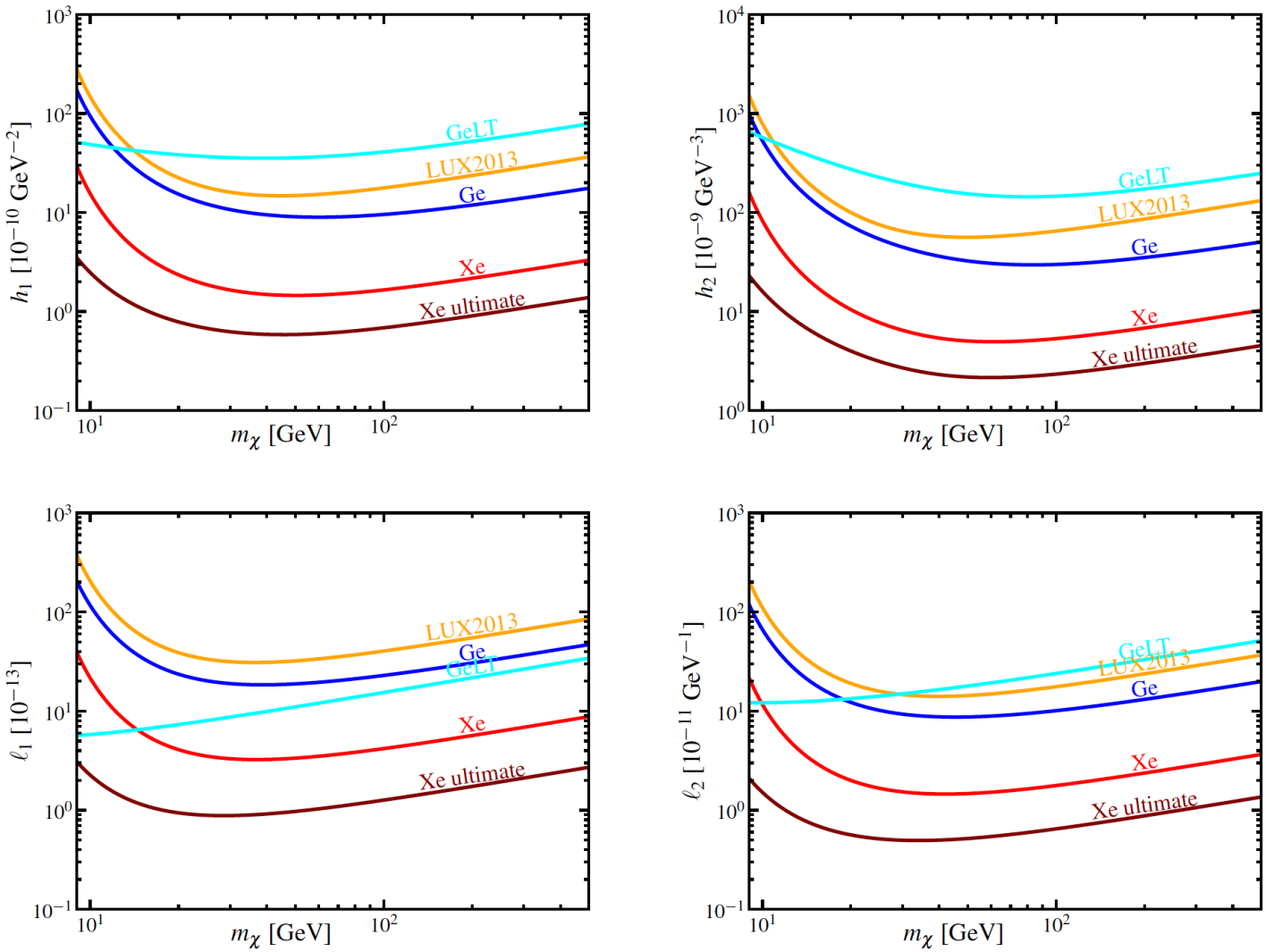
- ✓ A variety of effective operators can describe DM-baryon scattering. We study how distinguishable they are with incoming data.
- ✓ Prospects for model-selection in the context of DM EFT depend on WIMP mass, type of interaction, and experimental capabilities. Low energy thresholds, wide energy window, and large exposures are good.
- ✓ Mass estimates can be biased if data is analyzed assuming a wrong scattering operator. Solution: model selection prior to parameter estimation, or agnostic analysis.
- ✓ Prospects for correctly distinguishing the right operator before reaching the neutrino floor are excellent if signal is just below the current limit, but slim if G2 does not see a signal.



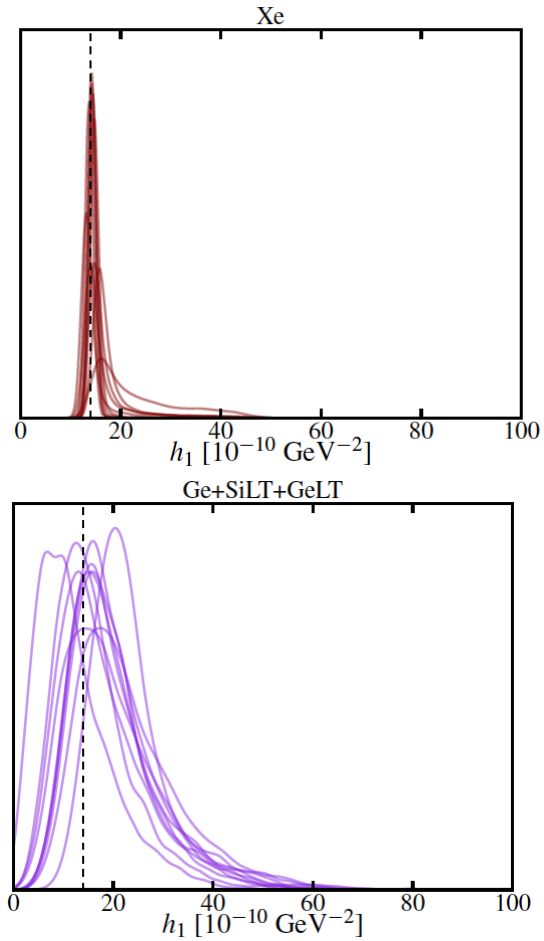



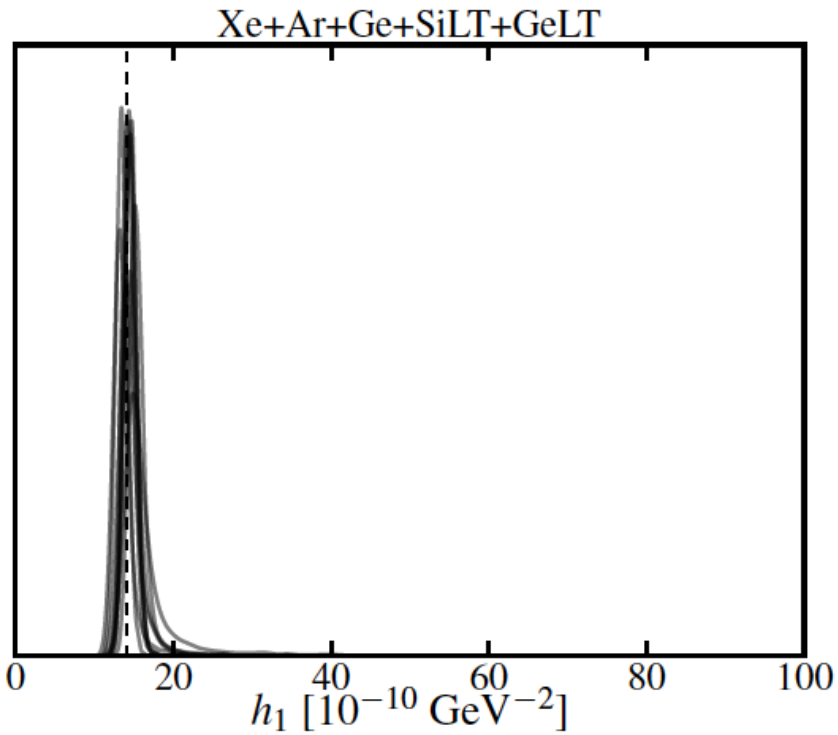



# Projected exclusions

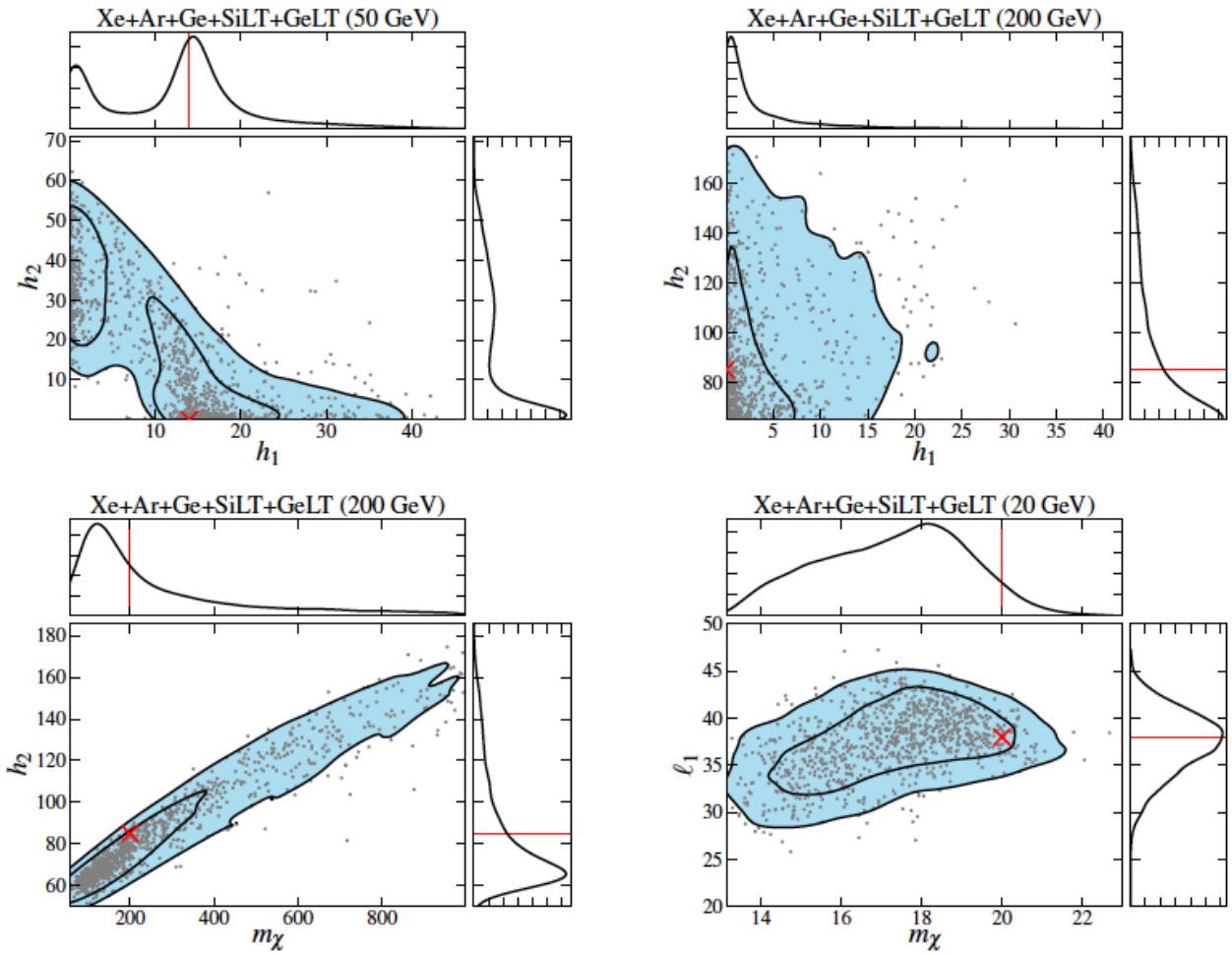


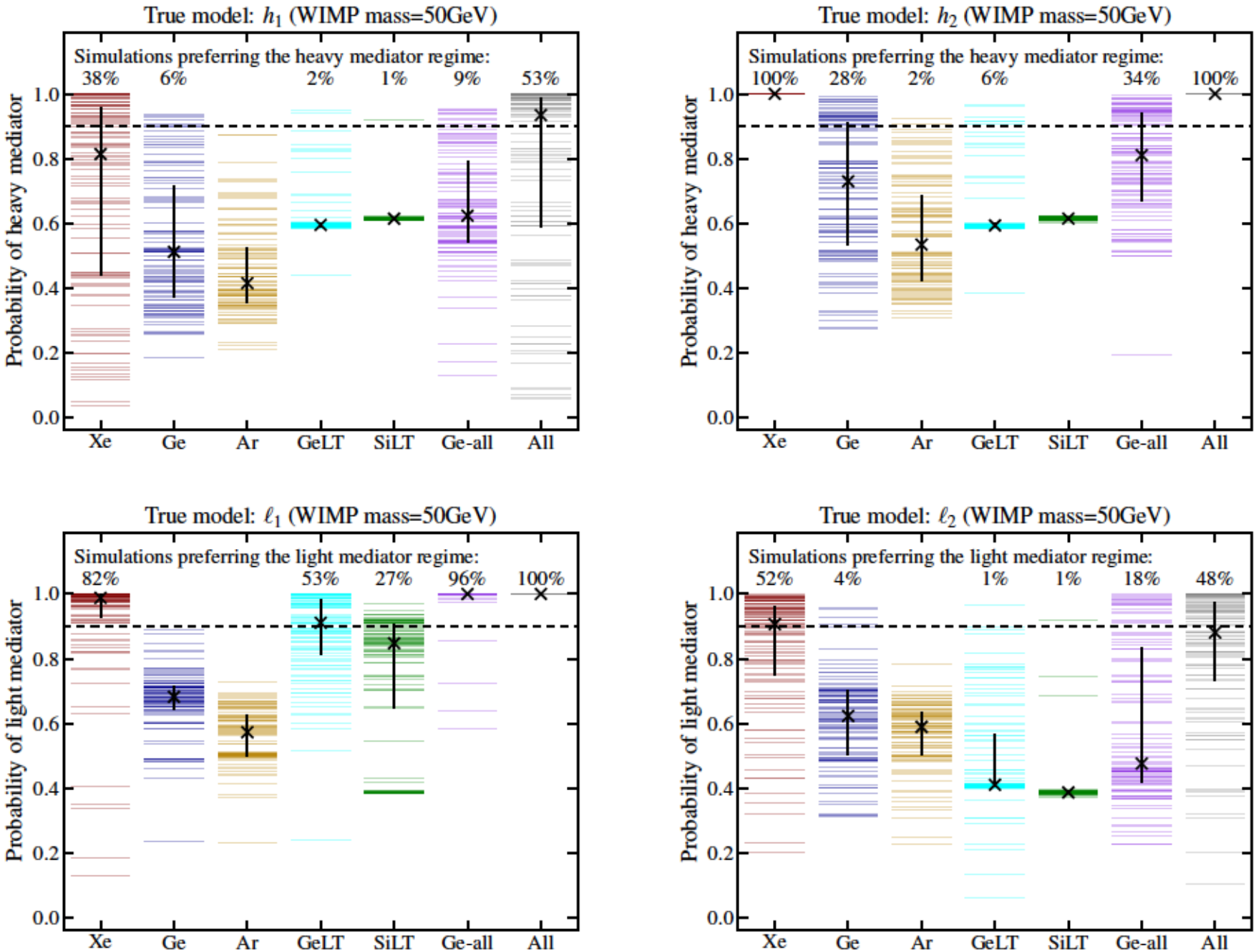
# Parameter estimation when true model is known: need large exposure



# Multimodal posteriors and large degeneracies




True model: $h_1$ (WIMP mass=50GeV)
Simulations preferring the heavy mediator regime:
38% 6% 2% 1% 9% 53%
Probability of heavy mediator
Xe Ge Ar GeLT SiLT Ge-all All
True model: $h_2$ (WIMP mass=50GeV)
Simulations preferring the heavy mediator regime:
100% 28% 2% 6% 34% 100%
Probability of heavy mediator
Xe Ge Ar GeLT SiLT Ge-all All
True model: $\ell_1$ (WIMP mass=50GeV)
Simulations preferring the light mediator regime:
82% 53% 27% 96% 100%
Probability of light mediator
Xe Ge Ar GeLT SiLT Ge-all All
True model: $\ell_2$ (WIMP mass=50GeV)
Simulations preferring the light mediator regime:
52% 4% 1% 1% 18% 48%
Probability of light mediator
Xe Ge Ar GeLT SiLT Ge-all All

| $m_\chi$ | $h_1$ [$10^{-10}$ GeV$^{-2}$] | $h_2$ [$10^{-9}$ GeV$^{-3}$] | $\ell_1$ [$10^{-13}$] | $\ell_2$ [$10^{-11}$ GeV$^{-1}$] |
|---|---|---|---|---|
| 20 GeV | 22 | 100 | 38 | 19 |
| 50 GeV | 14 | 56 | 32 | 14 |
| 200 GeV | 23 | 85 | 54 | 23 |

| Parameter name | Prior range |
|---|---|
| $m_\chi$ [GeV] | 1-1000 |
| $h_1$ [$10^{-10}$ GeV$^{-2}$] | 0.1-10 000 |
| $h_2$ [$10^{-9}$ GeV$^{-3}$] | 0.1-10 000 |
| $\ell_1$ [$10^{-13}$] | 0.1-10 000 |
| $\ell_2$ [$10^{-11}$ GeV$^{-1}$] | 0.1-10 000 |

| WIMP mass | 20 GeV | 50 GeV | 200 GeV |
|---|---|---|---|
| Xe | (88, 91, 87, 90) | (93, 123, 91, 91) | (113, 155, 91, 94) |
| Ar | (0, 1, 0, 0) | (3, 4, 2, 2) | (7, 10, 3, 5) |
| Ge | (2, 2, 3, 2) | (2, 3, 3, 3) | (4, 6, 3, 3) |
| SiLT | (0, 0, 5, 0) | (0, 0, 2, 0) | (0, 0, 1, 0) |
| GeLT | (0, 0, 27, 2) | (0, 0, 8, 1) | (0, 0, 6, 0) |