No Need for Speed: Halo-Independent Analysis of Dark-Matter-Electron Scattering

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based on

arXiv:2309.XXXXX with Patrick J. (Paddy) Fox, Benjamin Lillard, Anna-Maria Taki and Tien-Tien Yu

The big unknown in direct detection

- Direct detection with DM-electron scattering key tool for sub-GeV DM
- Ingredients entering the scattering rate:

$$\frac{dR}{d\ln E_e} = \frac{\rho_\chi}{m_\chi}\frac{\bar{\sigma}_e}{8\mu_{\chi e}^2}\int dq \left[q \left| F_{\rm DM}(q) \right|^2 \left| f_{\rm res}(E_e, q) \right|^2 \eta\left(v_{\rm min}\right) \right]$$

Material properties

DM-SM coupling

astrophysics: DM phase space distribution

- relies only on simulations
- large uncertainty in interpretation of results

Halo-independent analysis

The trouble with DM-electron scattering

- **Halo-independent analysis of DM-nucleon scattering is solved:**

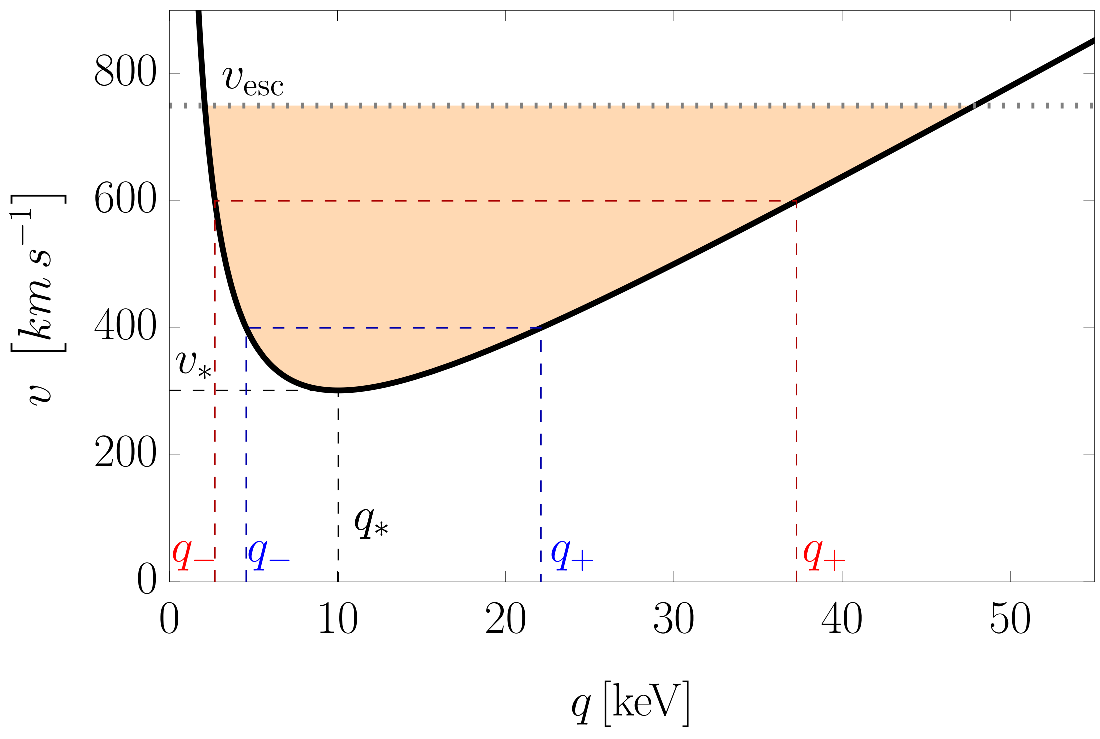
$$\frac{dR_n}{dE} \propto \int_{v_{\min}^{\text{nuc}}(E)}^{v_{\max}} d^3v \, \frac{f_\chi(\vec{v}+\vec{v}_E)}{v}$$

e.g. Fox, Kribs, Tait 1011.1910
Gondolo & Gelmini 1202.6359
Feldstein & Kahlhoefer 1403.4606
Gelmini, Huh, Witte, 1707.07019

Velocity-dependent part separates from everything else

- **NOT the case for DM-electron scattering**

Unknown initial momentum of electron leads to convoluted integral of velocity v and momentum transfer q Chen, Gelmini, Takhistov, 2105.08101



Integration region for fixed E_e lies between $v_{\rm esc}$ and

$$v_{\min}(q) = \frac{q}{2m_\chi} + \frac{E_e}{q}$$

Halo-independent formalism for e scattering

Re-formulate problem as fit with velocity distribution as nuisance parameter

$$\frac{dR}{dE}$$

Rate binned in energy

Fit

$$\tilde{\eta}(v_{\min}) = \frac{\rho_\chi \bar{\sigma}_e}{m_\chi} \int_{v_{\min}} d^3v \frac{f_\chi(\vec{v} + \vec{v}_E)}{v}$$

m_χ, F_{DM}, …

DM velocity distribution
and DM properties

Velocity distribution is infinite dimensional, high-dimensional approximation:

$$\tilde{\eta}(v_{\min}) = \sum_i \tilde{\eta}_i \Theta(v_i - v_{\min})$$

High-dimensional fit
analogous to ML training

use ADAM optimizer in
TensorFlow with log-likelihood
as loss function

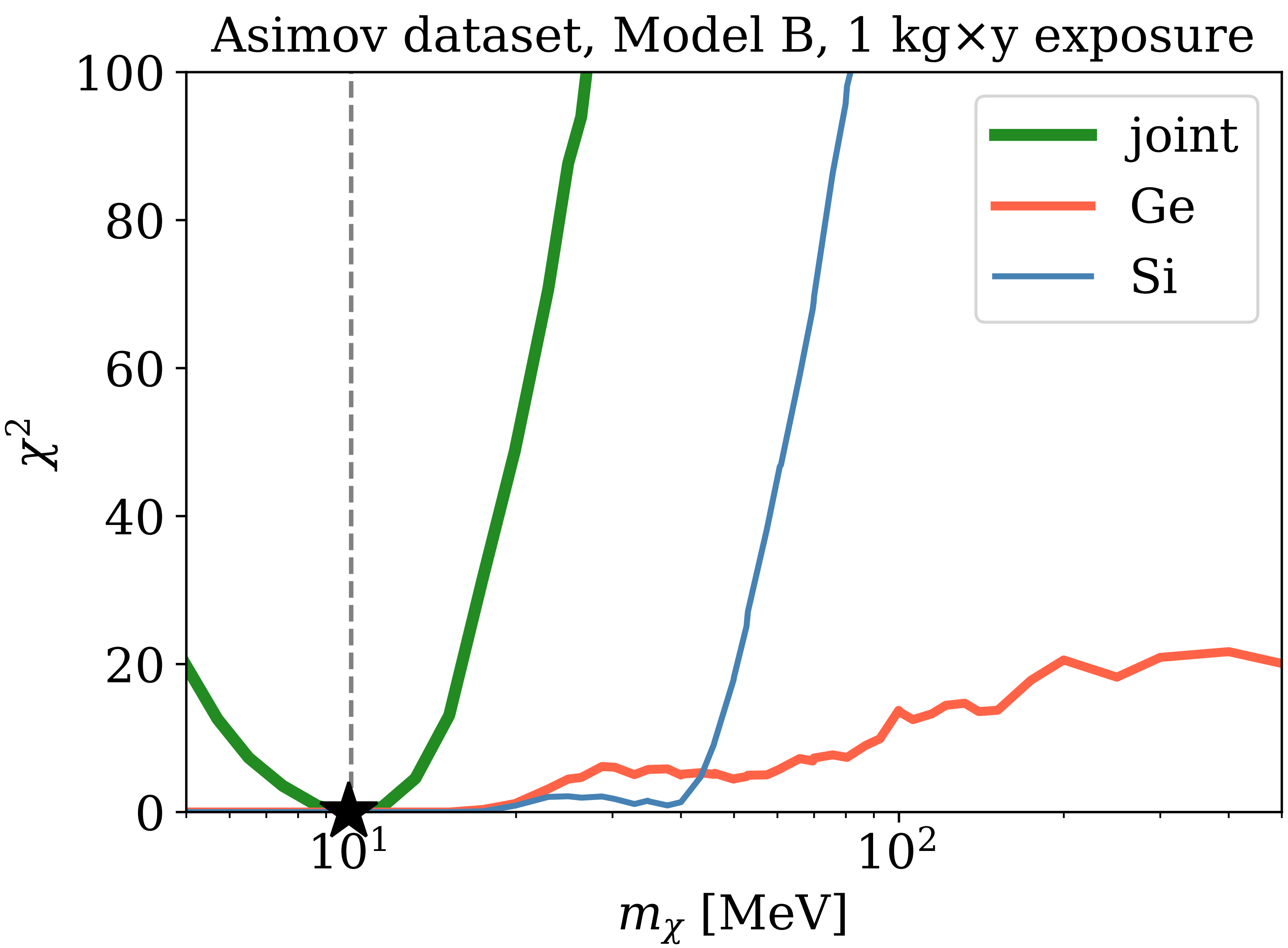
Test I: recovering the DM mass

Test of formalism with mock data generated with QEdark

Essig et al., 1509.01598

In this talk: One example, with $m_\chi = 10$ MeV, heavy mediator and SHM

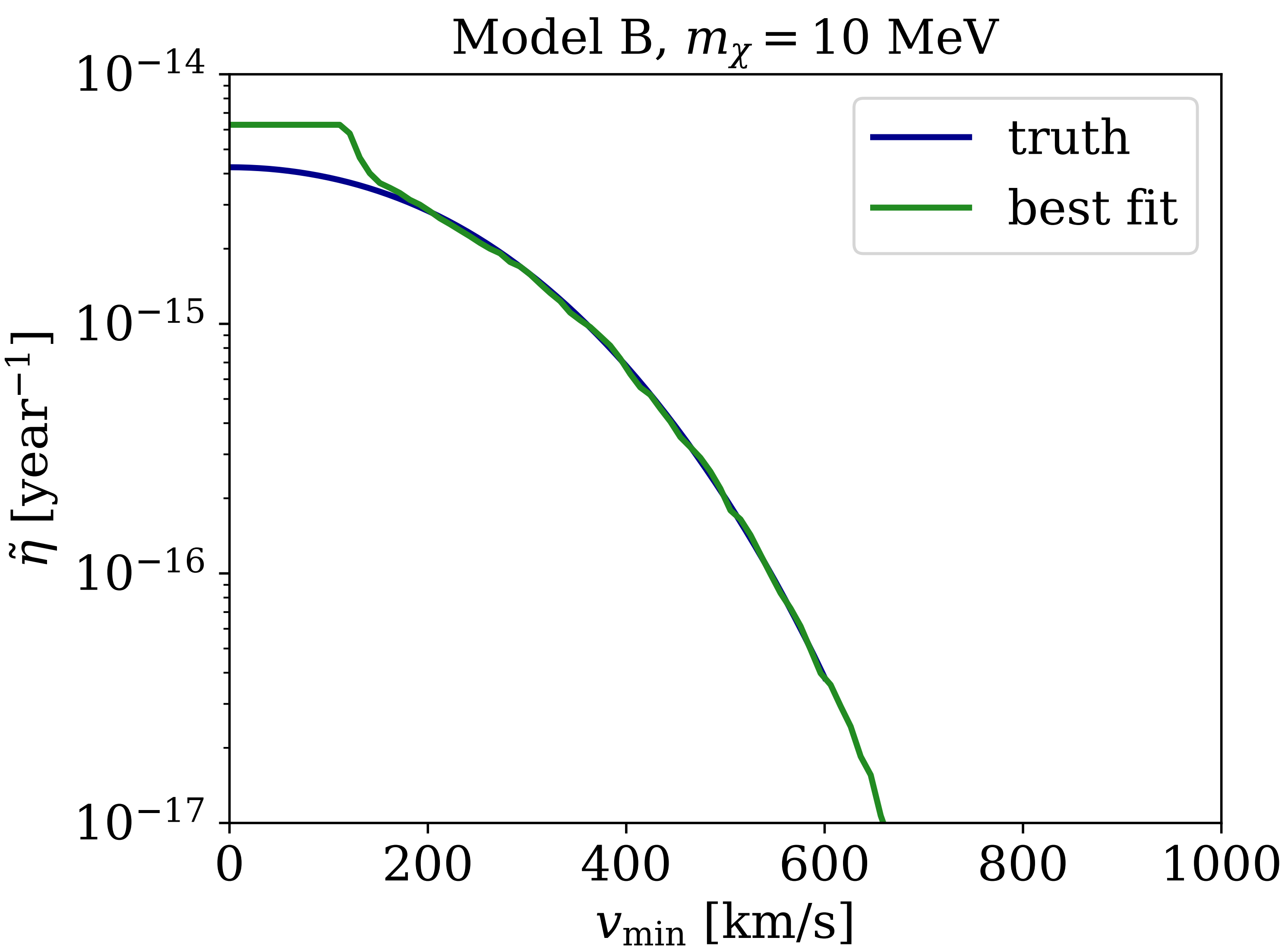
(other models in paper and backup)



- **Combining elements (here Si and Ge) is crucial**
- **Perfect joint fit only at correct mass for any velocity distribution**

Test II: recovering the DM velocity

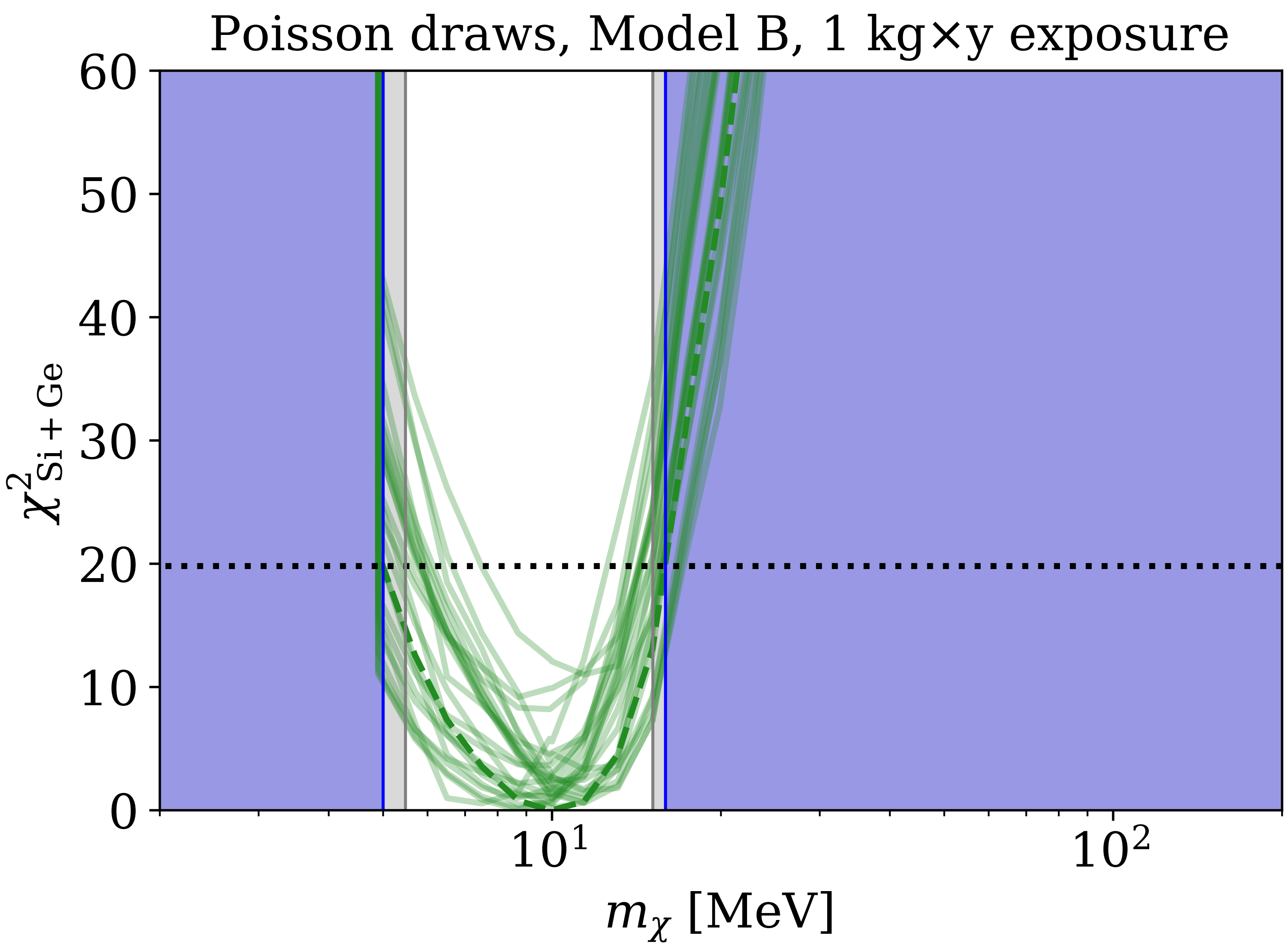
Best-fit velocity distribution



Flat directions are under control and yield envelope of equivalent solutions

Limits on the DM mass

Use profiled χ^2 quantitatively as a test statistic



Joint fit of Si and Ge excludes range of DM masses for any vel. distr.

Bounds are robust under Poisson fluctuations

Application to real data

We also have real event rates from SENSEI and EDELWEISS!

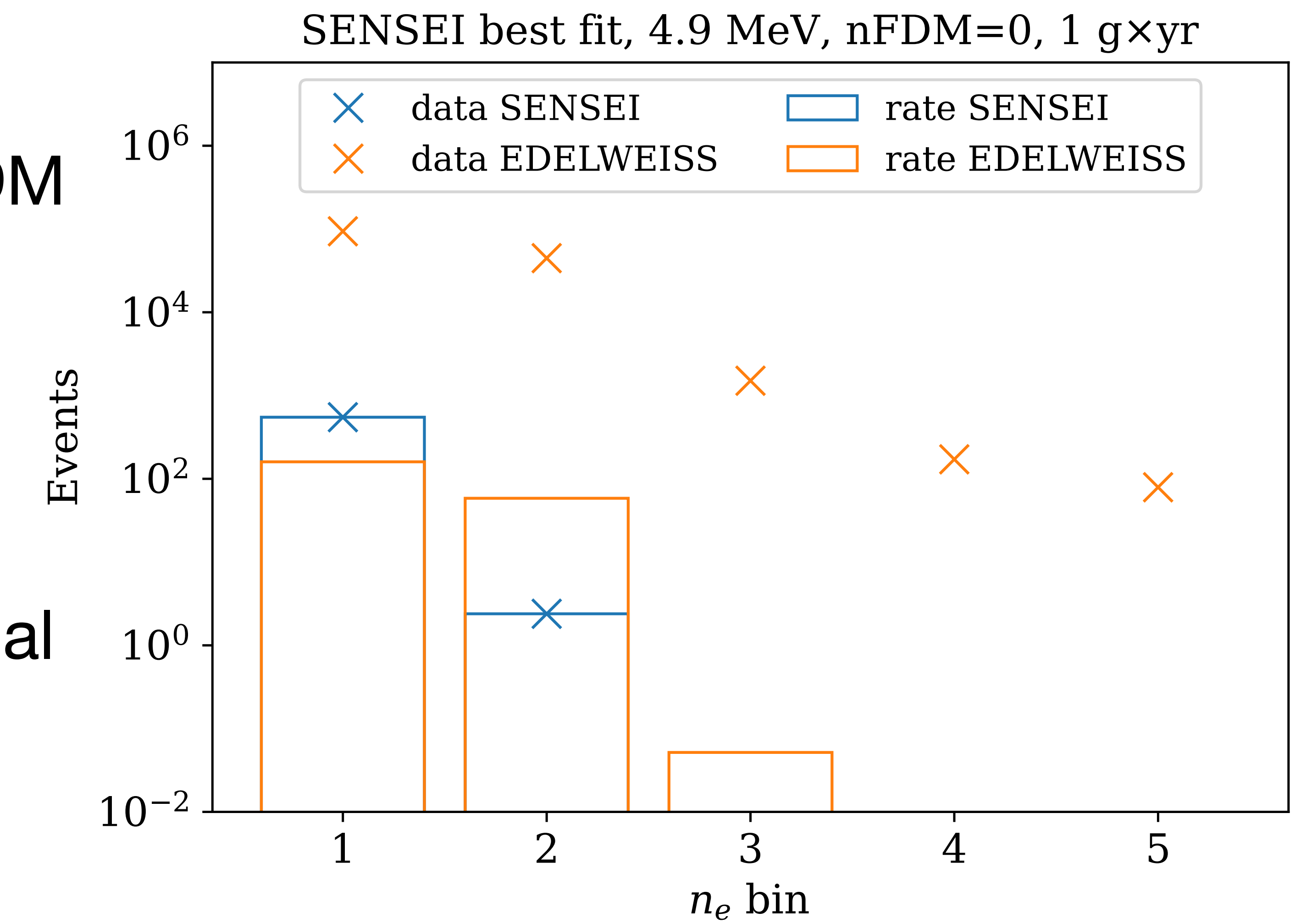
SENSEI Collaboration, 2004.11378, EDELWEISS Collaboration, 2003.01046

Joint fit yields $\chi^2 \sim 10^5$ → Rates cannot be explained by DM alone

But *assuming* SENSEI data is DM

↓

Prediction of EDELWEISS signal



Conclusions

- **Large uncertainty** in interpretation of DM direct detection experiments from **DM velocity distribution**

  ➡ **Halo-independent analysis**

- Established methods for nuclear scattering **not applicable to electron scattering**
- Can **formulate problem as fit** and use methods from ML
- Formalism can **constrain DM velocity distribution and DM properties** without using velocity distribution as input
- **First application to real data** in anticipation of much more data in the future

Backup

Mock data

Test of formalism with Mock data generated with QEdark:

model name	m_χ [MeV]	$F_{\rm DM}$	halo model
A	50	1	SHM
B	10	1	SHM
C	50	$(\alpha m_e/q)^2$	SHM
D	50	1	stream

Heavy mediator Light mediator

Standard Halo Model

$$f_\chi(\vec{v}_\chi) = \frac{1}{K_{SHM}} e^{-\frac{|\vec{v}_\chi + \vec{v}_E|^2}{v_0^2}} \Theta(v_{\rm esc} - |\vec{v}_\chi + \vec{v}_E|)$$

Stream

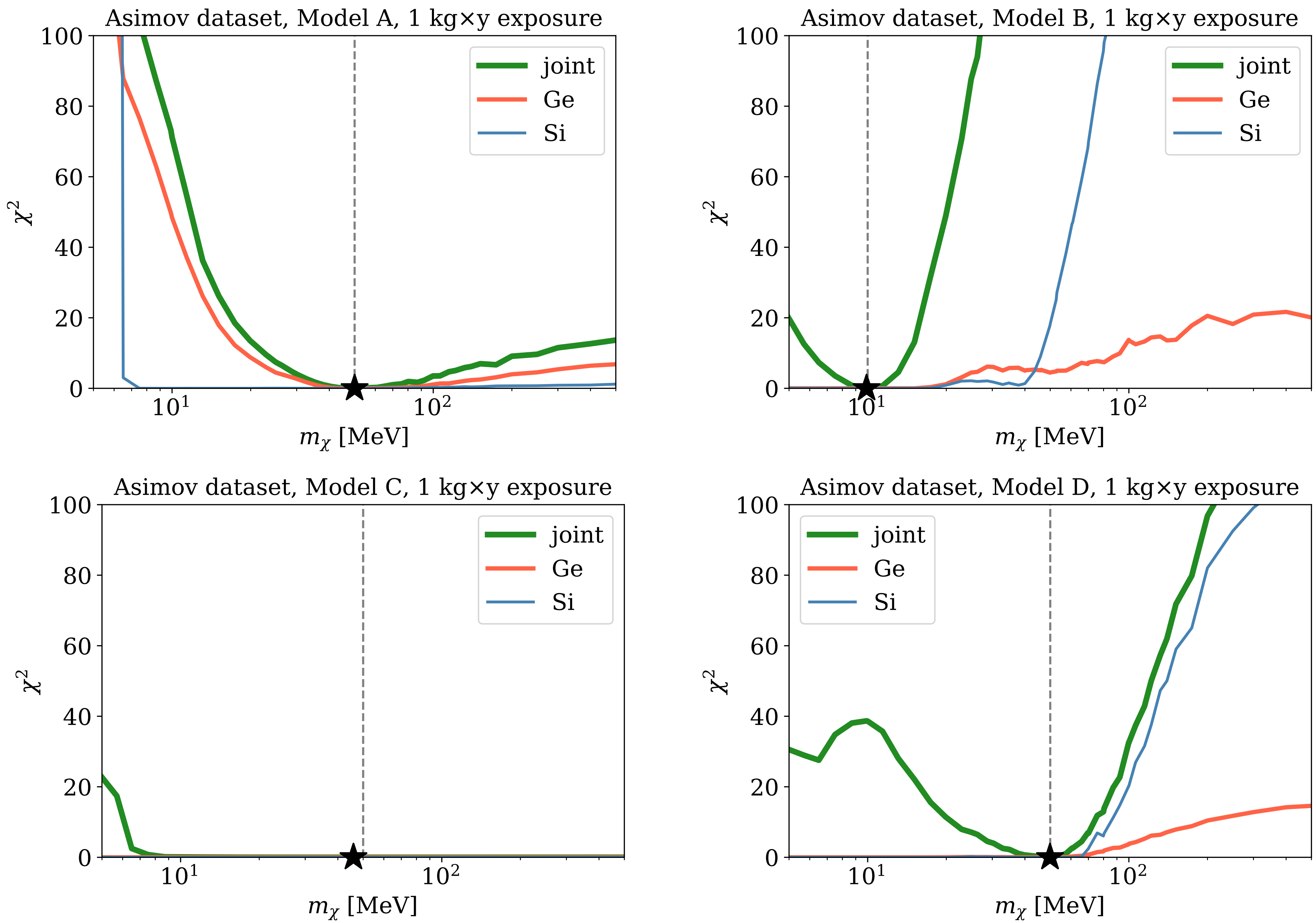
$$f_\chi(\vec{v}_\chi) = \frac{1}{K_{str}} \exp^{-\frac{(\vec{v}_\chi - \vec{v}_{\rm str})^2}{2\sigma^2}}$$

Test I: recovering the DM mass

χ^2 profiled over the DM velocity distribution

50 MeV
heavy mediator
SHM

10 MeV
heavy mediator
SHM



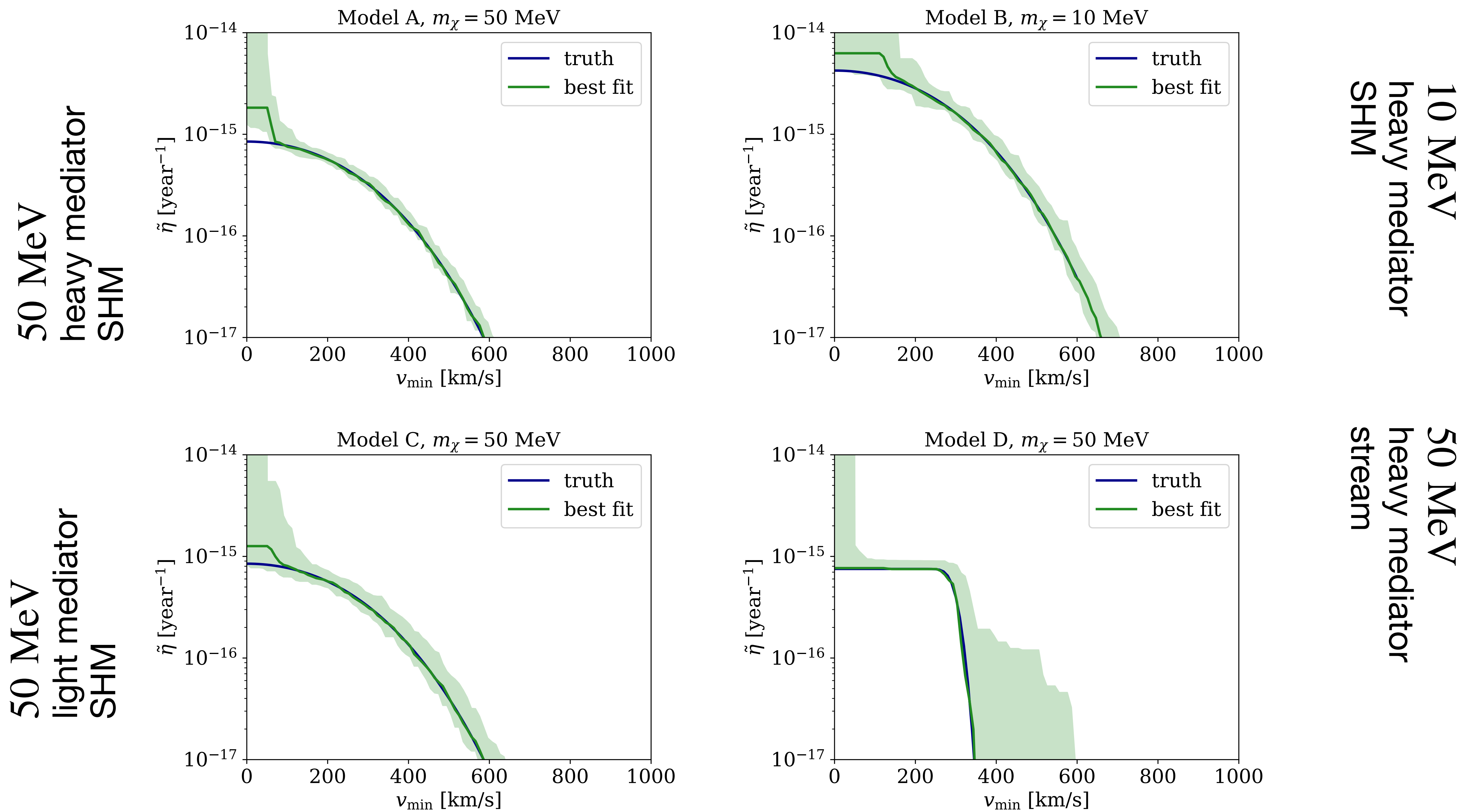
50 MeV
light mediator
SHM

50 MeV
heavy mediator
stream

➡ **Combining elements (here Si and Ge) is crucial**

Test II: recovering the DM velocity

Best-fit velocity distributions



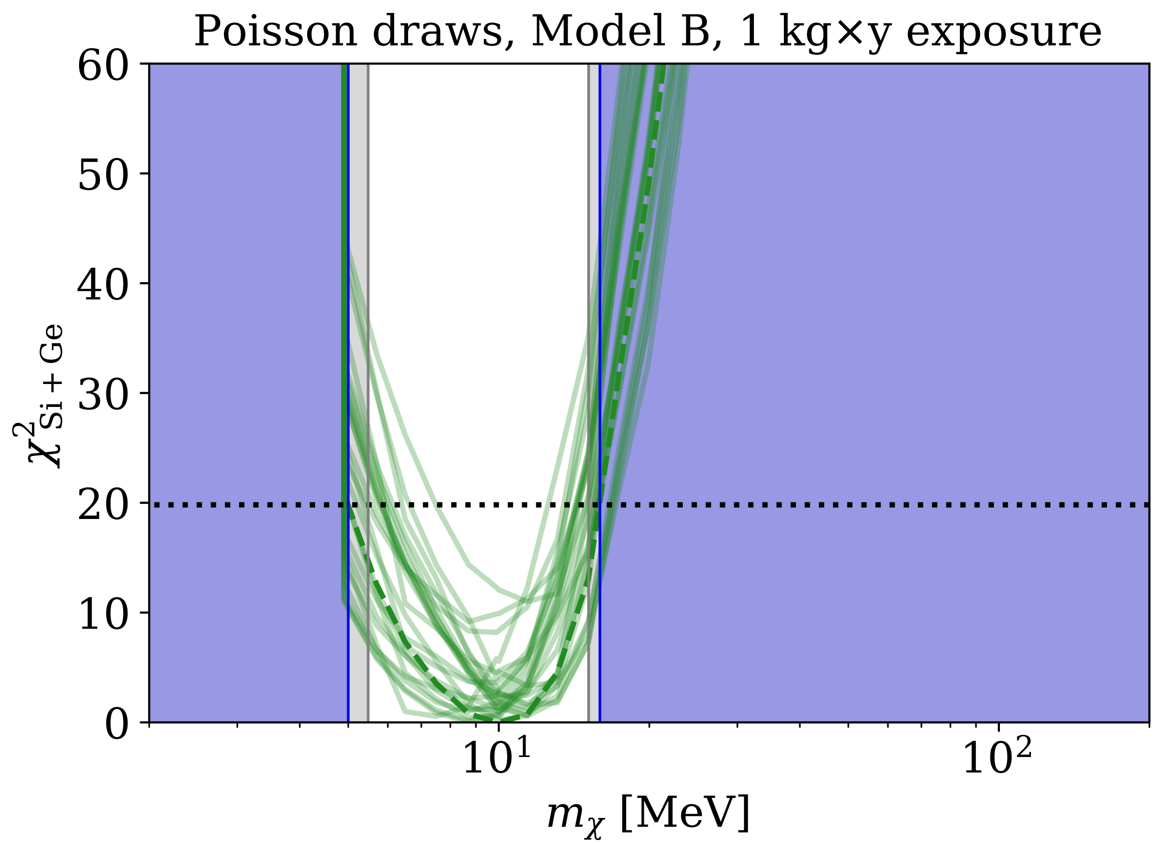
Flat directions are under control and yield envelope

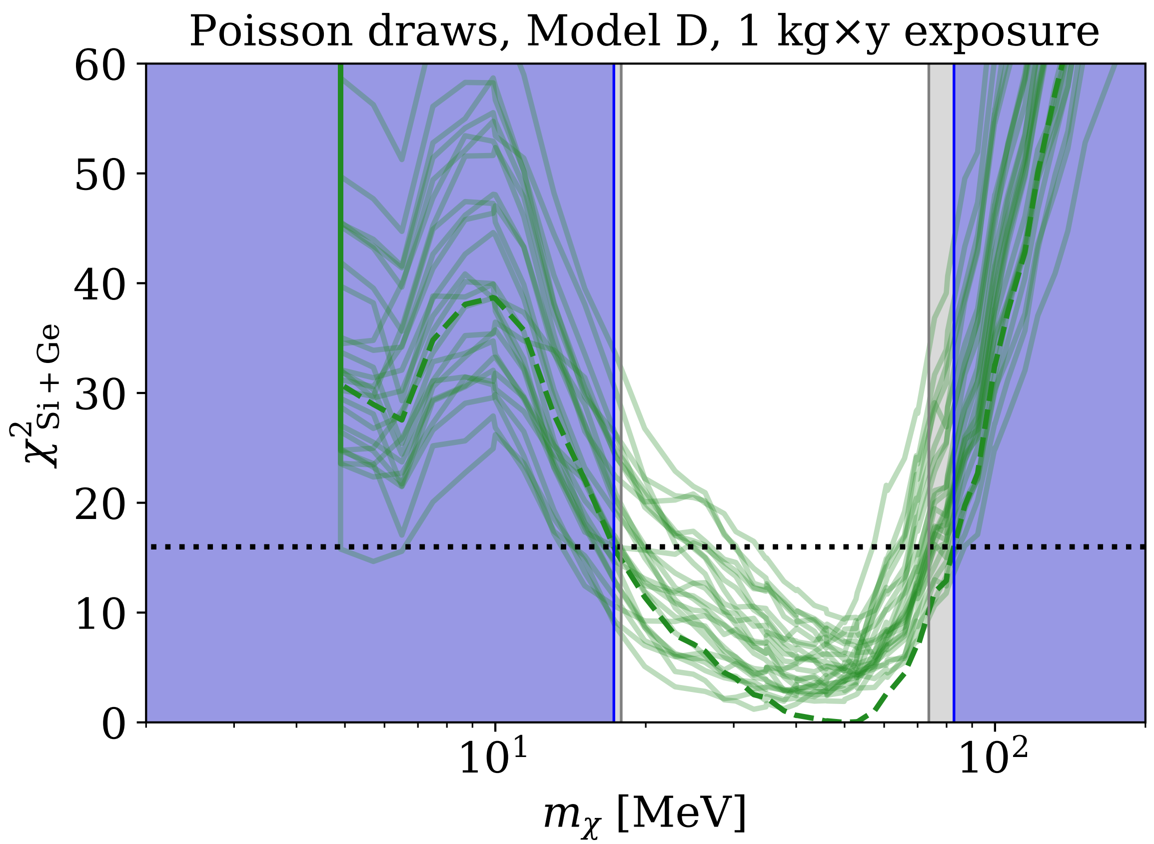
Limits on the DM mass

Use profiled χ^2 quantitatively as a test statistic

Standard Halo Model

Stream





- Joint fit of Si and Ge excludes range of DM masses for any vel. distr.
- Asimov dataset yields good projection
- Bounds improve with exposure