Studying generalised DM interactions with extended halo-independent methods

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mostly based on
1607.04418 (Felix Kahlhoefer, SW)

MIAPP Topical Workshop on Direct DM Detection
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Outline

Halo-independent methods for (in)direct detection
$\longleftrightarrow$ non-standard DM-nucleon interactions

Fitting future DD data in a halo-independent way:
(1) General idea
(2) Statistical framework & results

Conclusions

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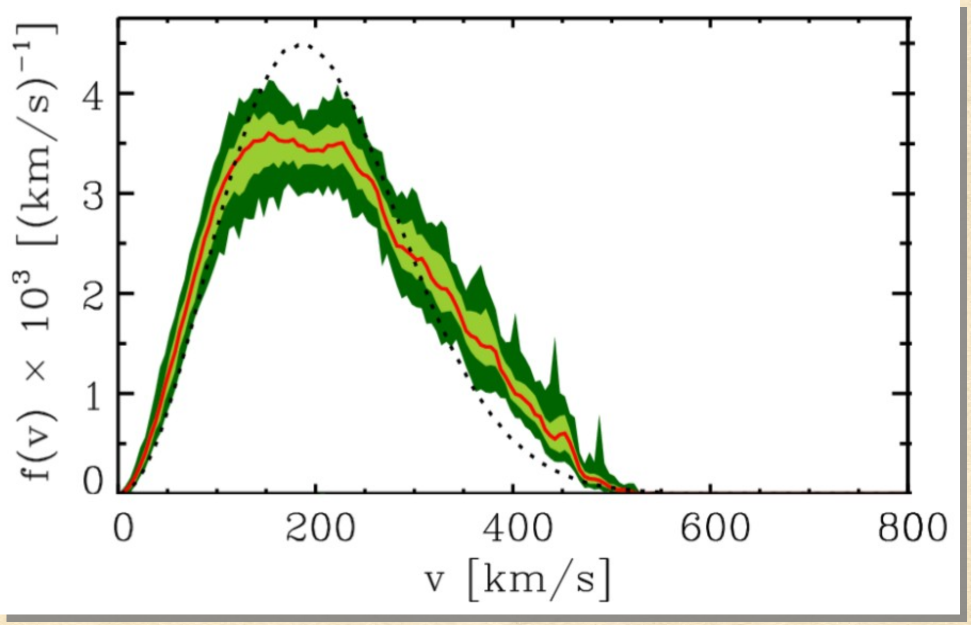
Direct detection and its complications

Astrophysical input

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\rho_{\mathrm{loc}}}{m_T m_{\mathrm{DM}}} \int_{v_{\min}(E_R)}^{\infty} \mathrm{d}v\, v f(v)\, \frac{\mathrm{d}\sigma}{\mathrm{d}E_R}$$



See the talk by Nassim Bozorgnia!

→ Halo-independent methods: fully agnostic, bottom-up approach to the problem

Direct detection and its complications

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Particle physics input

There is much more than standard SI and SD scattering!

(a) **spin-independent** $\mathcal{L} = f_N^{(\mathrm{SI})} \, \bar{\chi}\chi\bar{N}N$

(b) **spin-dependent** $\mathcal{L} = f_N^{(\mathrm{SD})} \, \bar{\chi}\gamma^\mu\gamma^5\chi\bar{N}\gamma_\mu\gamma^5 N$

(c) **anapole moment** $\mathcal{L} = \mathcal{A} \, \bar{\chi}\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu}$

(d) **magn. dipole mom.** $\mathcal{L} = \mathcal{D}_{\mathrm{magn}} \, \bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$

(e) **"dark" magnetic dipole moment** $\mathcal{L} = \mathcal{D}_{\mathrm{magn}} \, \bar{\chi}\sigma^{\mu\nu}\chi F'_{\mu\nu}$

(c)–(e): $\mathrm{d}\sigma/\mathrm{d}E_R$ has non-trivial dependence on E_R and v

Halo-independent methods: mini-overview

(1) Investigating (apparently) conflicting experiments:

DAMA, CDMS-Si, CoGeNT $\longleftrightarrow$ LUX, SuperCDMS, CRESST, ...

Fox/Liu/Weiner, McCabe, Frandsen/Kahlhoefer/McCabe/Sarkar/Schmidt-Hoberg, Gondolo/Gelmini, Herrero-Garcia/Bozorgnia/Schwetz, DelNobile/Gelmini/Gondolo/Huh, Feldstein/Kahlhoefer, ...

- Basic idea: interpret DD data in terms of measurements and upper limits of the **halo-integral** $\eta(v_{\rm min})$
  [see the talk by Paolo Gondolo]

- Extension to non-standard interactions possible (requires "regularisation procedure")
  [see e.g. DelNobile& 2013]

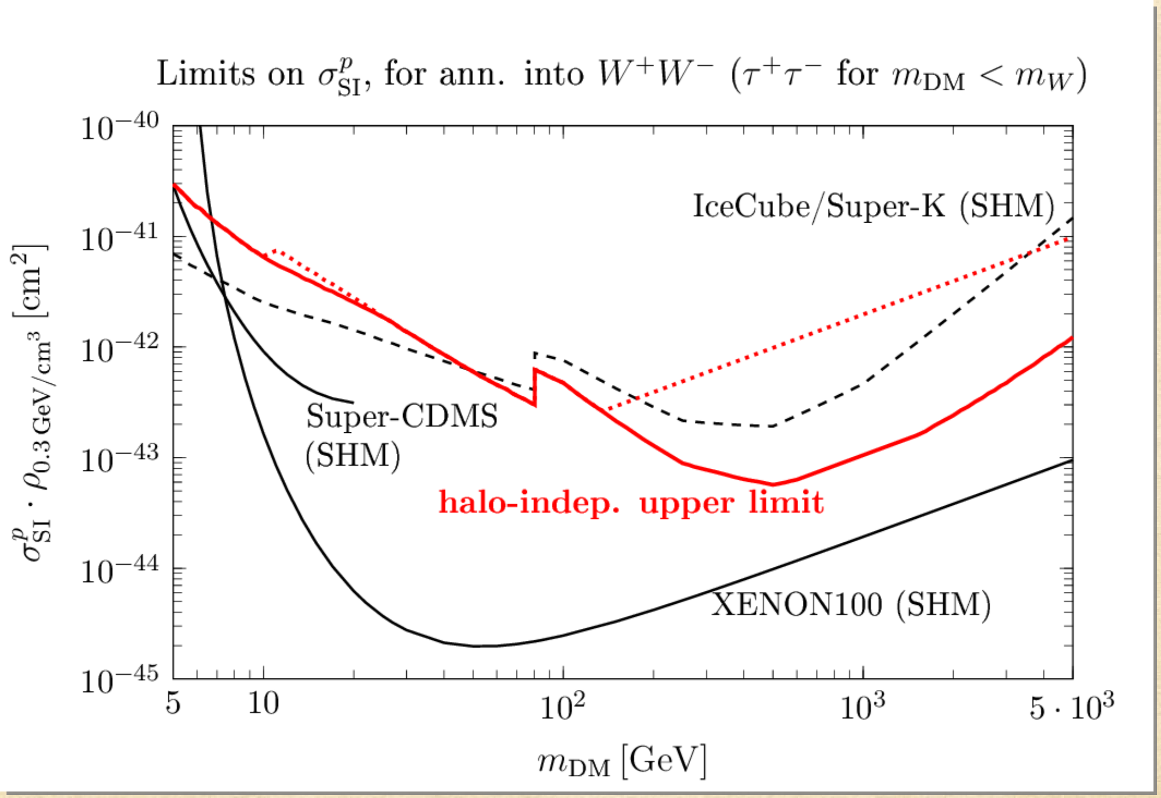
- Work in progress on halo-independent methods for non-standard interactions
  Ibarra, Catena, SW

Halo-independent methods: mini-overview

(2) Halo-independent upper limit on σ_p from null searches

Ferrer/Ibarra/Wild, c.f. also talk by Andreas Rappelt

- This necessarily requires the info from **neutrino telescopes**, in order to have access to the full velocity space



Ferrer, Ibarra, SW [1506.03386]

- first upper limit which is fully robust against changes of $f(v)$
  → it depends, however, on the ann. channel of DM in the Sun

Halo-independent methods: mini-overview

This talk!

(3) Determining DM particle physics from (future) signals

Kavanagh/Green, Fox/Gribs/Tait, Blennow/Herrero/Schwetz/Vogl,
Kahlhoefer/SW [1607.04418]

- What can we learn about the **particle physics properties** of DM from a future discovery?

(a) **spin-independent**

(b) **spin-dependent**

(c) **anapole moment**

(d) **magn. dipole mom.**

(e) **"dark" magnetic dipole moment**

Assume an unambiguous signal with O(100) events

Can we distinguish these models from data alone, in a fully halo-independent way?

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Rewriting the differential event rate

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\rho_{\mathrm{loc}}}{m_T m_{\mathrm{DM}}} \int_{v_{\min}(E_R)}^{\infty} \mathrm{d}v \, v f(v) \, \frac{\mathrm{d}\sigma}{\mathrm{d}E_R}$$

$$= \sqrt{m_T E_R / 2\mu_T^2}$$

- For (almost) all interaction types of DM, we have

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_R}(v, E_R) \equiv \frac{\mathrm{d}\sigma_1}{\mathrm{d}E_R}(E_R) \cdot \frac{1}{v^2} + \frac{\mathrm{d}\sigma_2}{\mathrm{d}E_R}(E_R)$$

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- We define the usual **velocity integrals**

$$g(v_{\min}) := \int_{v_{\min}}^{\infty} \mathrm{d}v\, \frac{f(v)}{v} \qquad\qquad h(v_{\min}) := \int_{v_{\min}}^{\infty} \mathrm{d}v\, v f(v)$$

$$\longrightarrow \boxed{\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\rho_{\mathrm{loc}}}{m_T m_{\mathrm{DM}}} \left(\frac{\mathrm{d}\sigma_1}{\mathrm{d}E_R} g(v_{\min}(E_R)) + \frac{\mathrm{d}\sigma_2}{\mathrm{d}E_R} h(v_{\min}(E_R)) \right)}$$

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- By partial integration, $h(v_{\min})$ can be expressed in terms of $g(v_{\min})$:

$$h(v_{\min}) = \left[-g(v) v^2\right]_{v_{\min}}^{\infty} + \int_{v_{\min}}^{\infty} \mathrm{d}v\, 2v\, g(v)$$

Reinterpreting direct detection data

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = [\text{particle physics}] \times g(v_{\min})$$

observable quantity

- captures all the astrophysical input
- same function for all experiments!
- has to be monotonically decreasing

For a given observed recoil spectrum $\mathrm{d}R/\mathrm{d}E_R$, we can confirm/exclude a given particle physics model as follows:

1) Translate the measurement of $\mathrm{d}R/\mathrm{d}E_R$ into a measurement of $g(v_{\min})$, **assuming** the given particle physics model

2) Check whether there is **any** monotonically decreasing function $g(v_{\min})$ providing a good fit to the data

→ if not, the model is excluded in a **halo-independent way!**

Reinterpreting direct detection data

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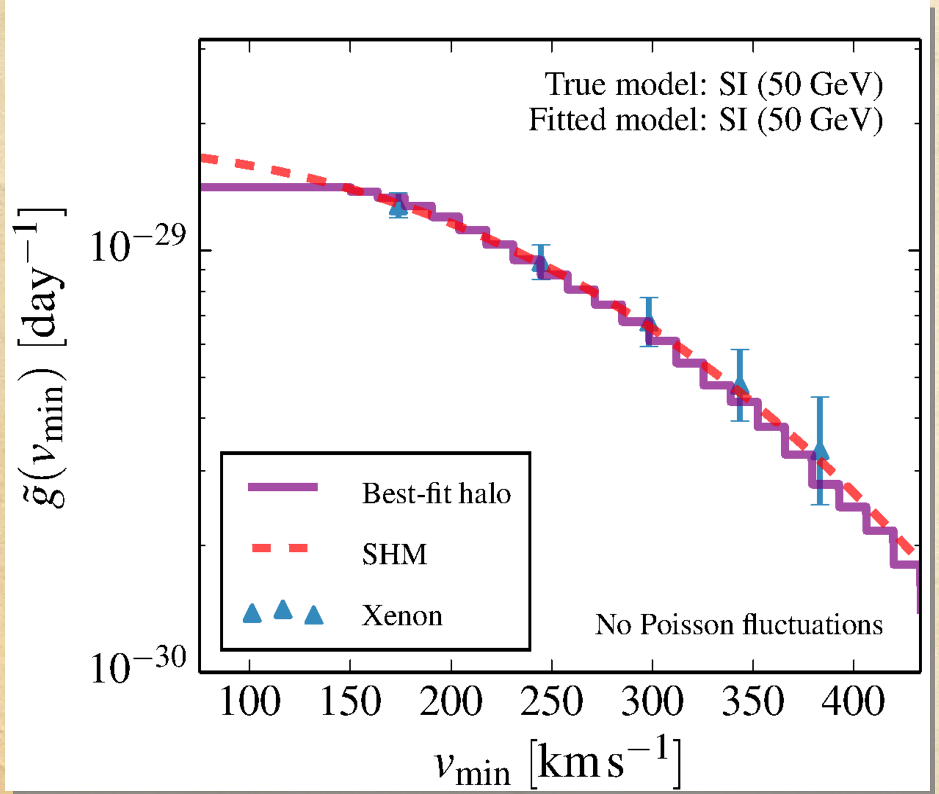
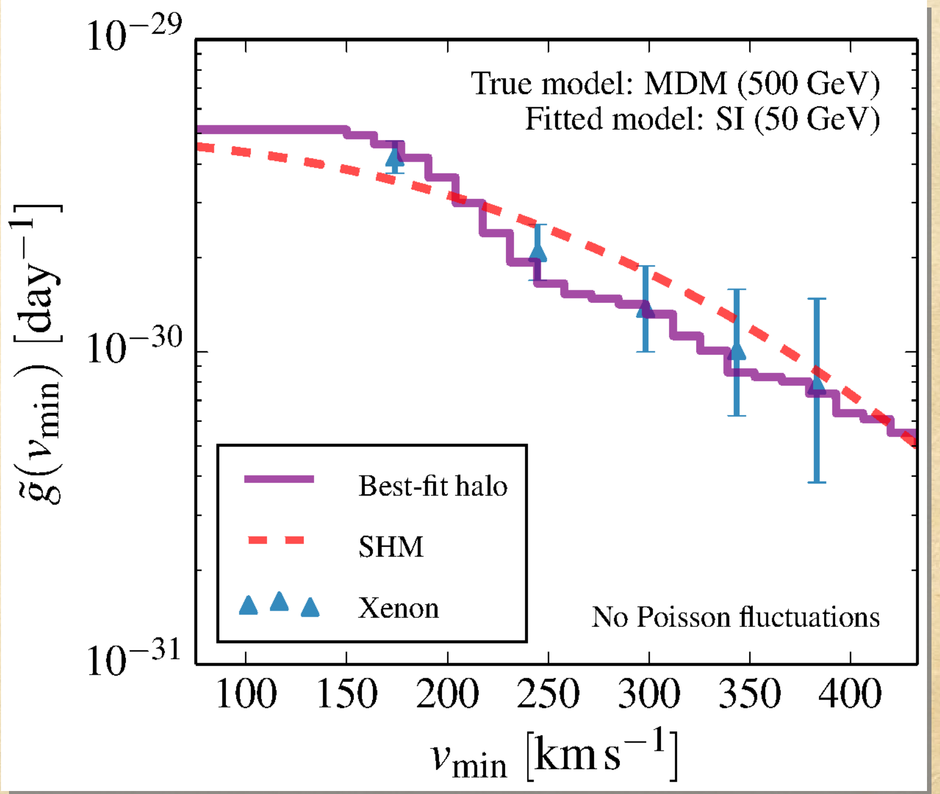
true model: SI interaction
fitted model: SI interaction



true model: MDM interaction
fitted model: SI interactions



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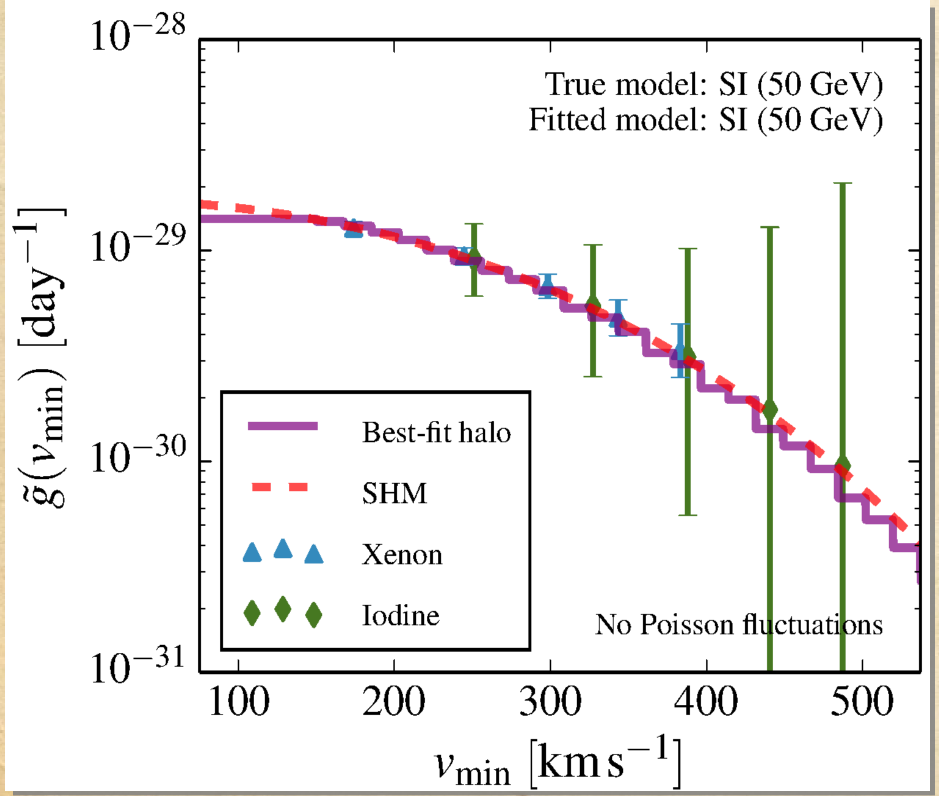
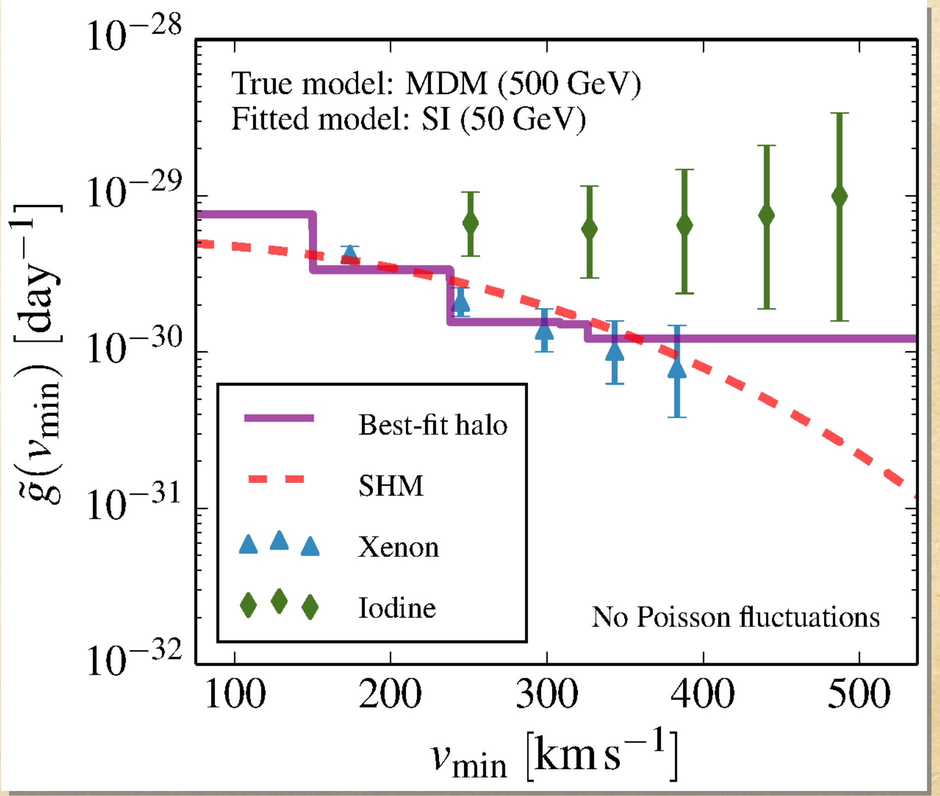
… adding an iodine-based experiment to the xenon experiment …





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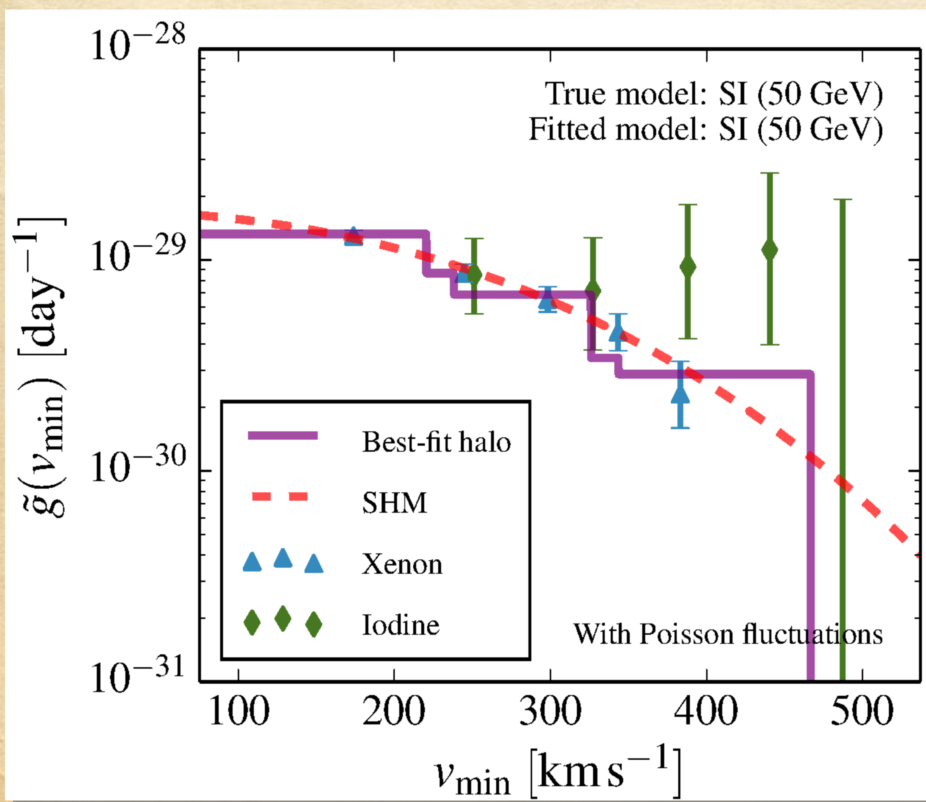

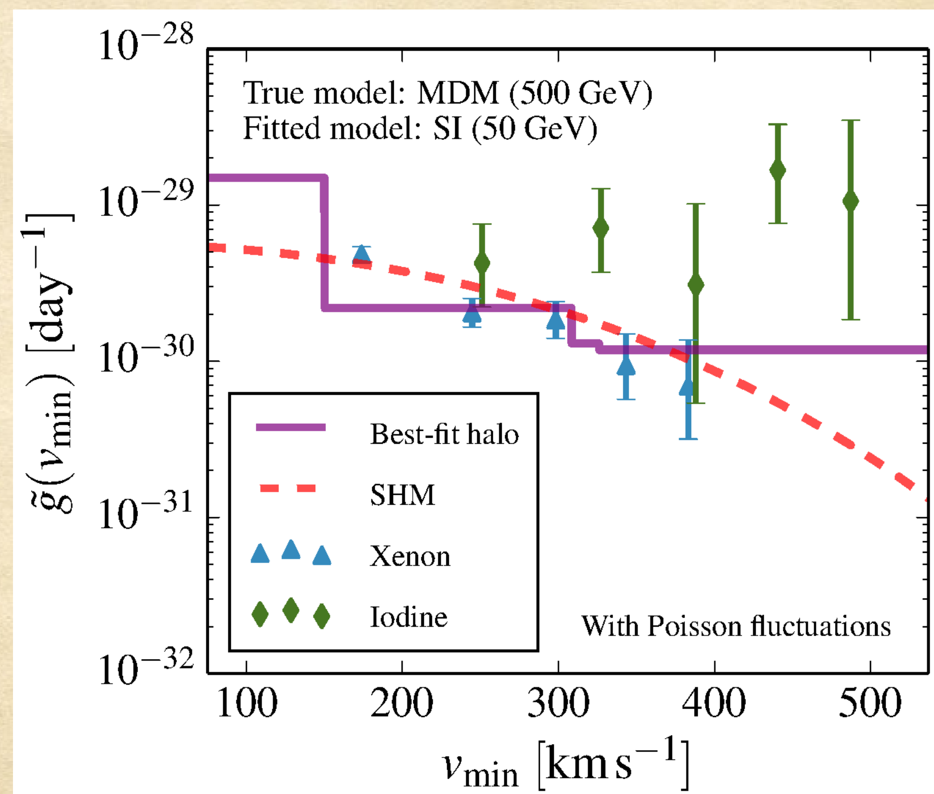

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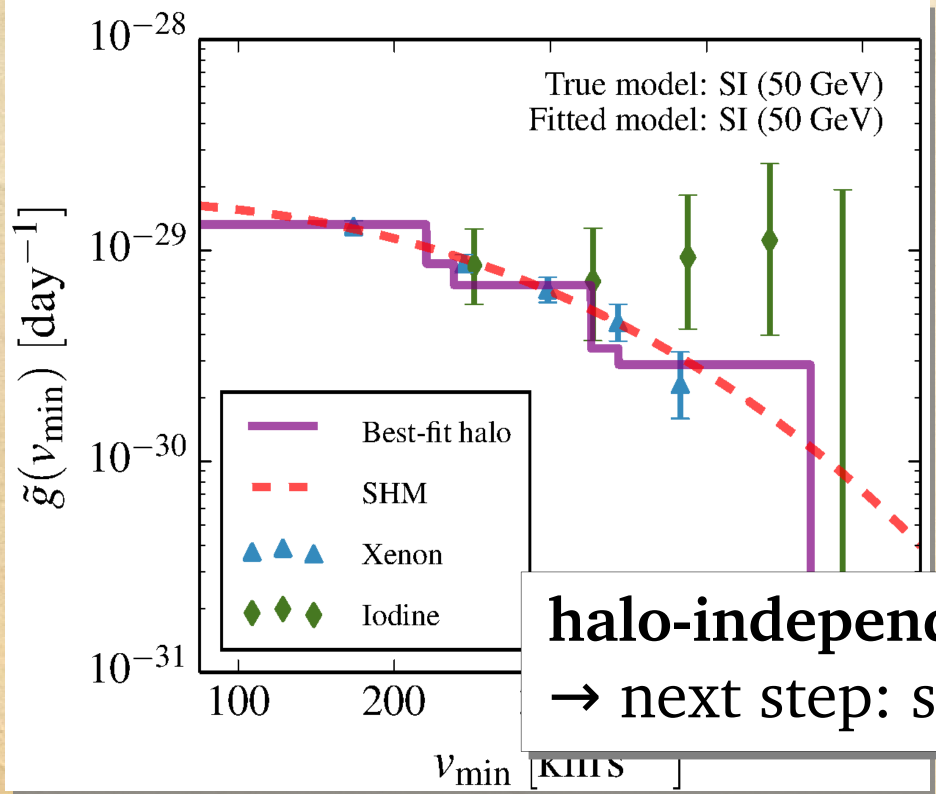

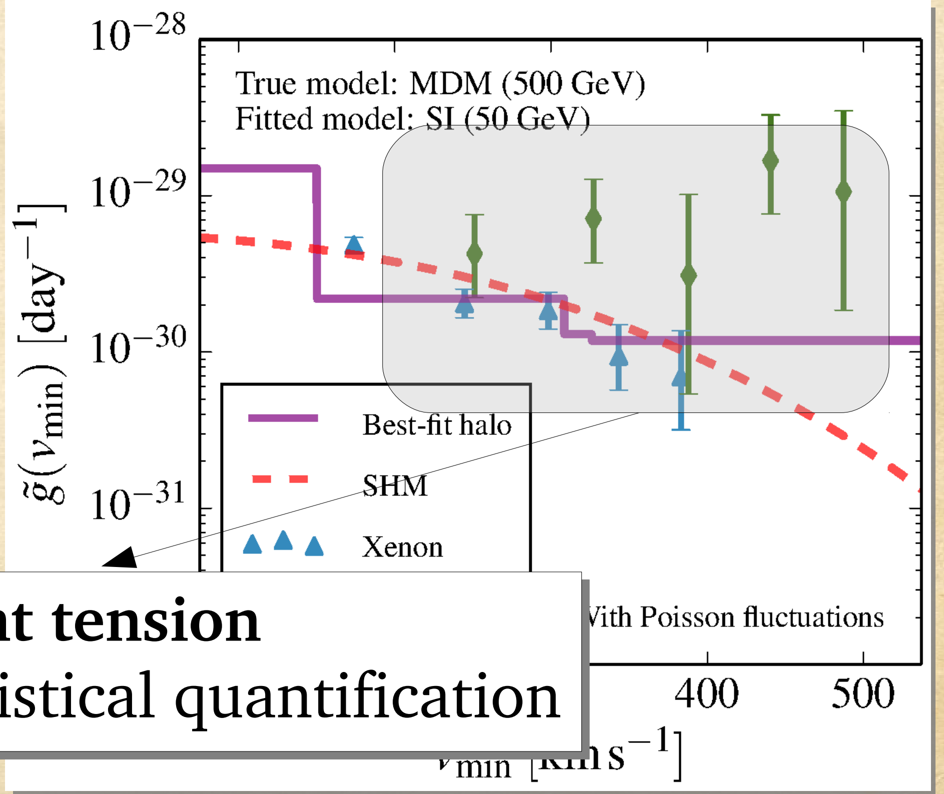

halo-independent tension

→ next step: statistical quantification

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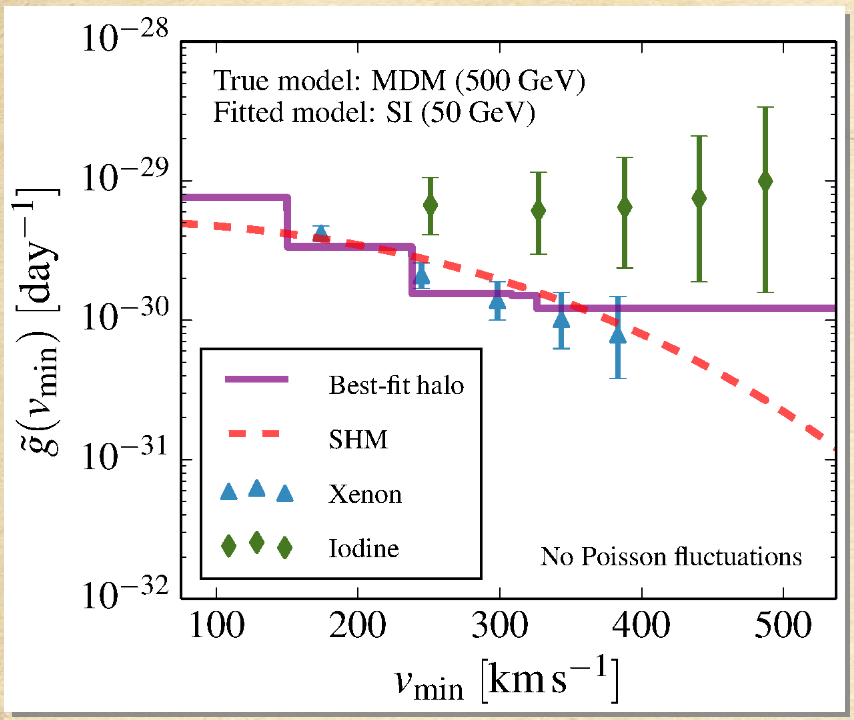
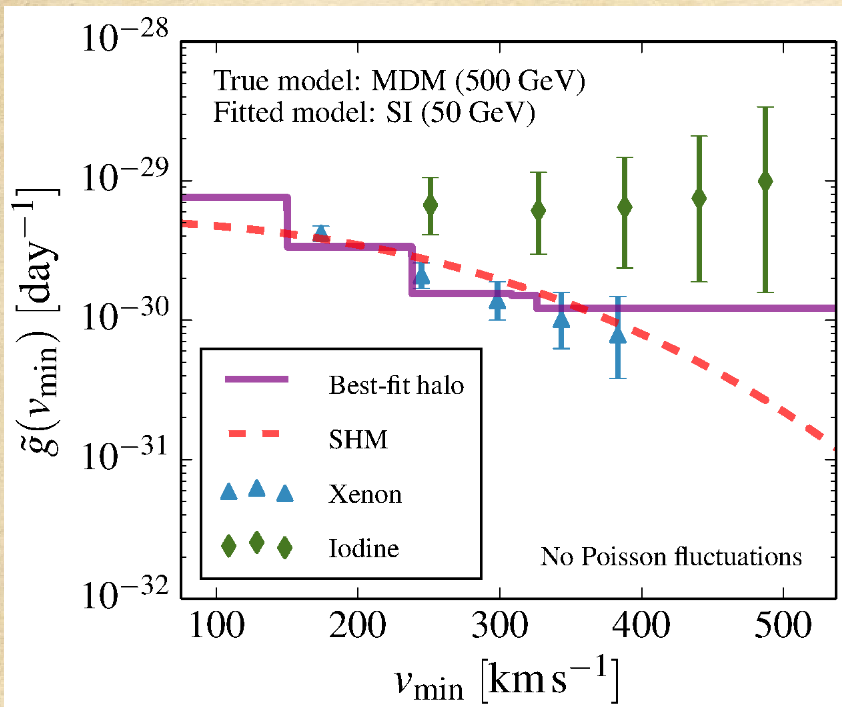
Fitting the velocity integral



- Question we want to answer:
  is there **any** $g(v_{\rm min})$ providing a good fit?

- We parametrize $g(v_{\rm min})$ as a piecewise-constant function:
  $g(v_{\rm min}) = g_j$ for $v_{\rm min} \in [v_j, v_{j+1}]$
  with $j = 1, \ldots, N_s$
  (Kahlhoefer et. al. [1403.4606])

Fitting the velocity integral



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$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = [\text{particle physics}] \times g(v_{\min}(E_R))$$

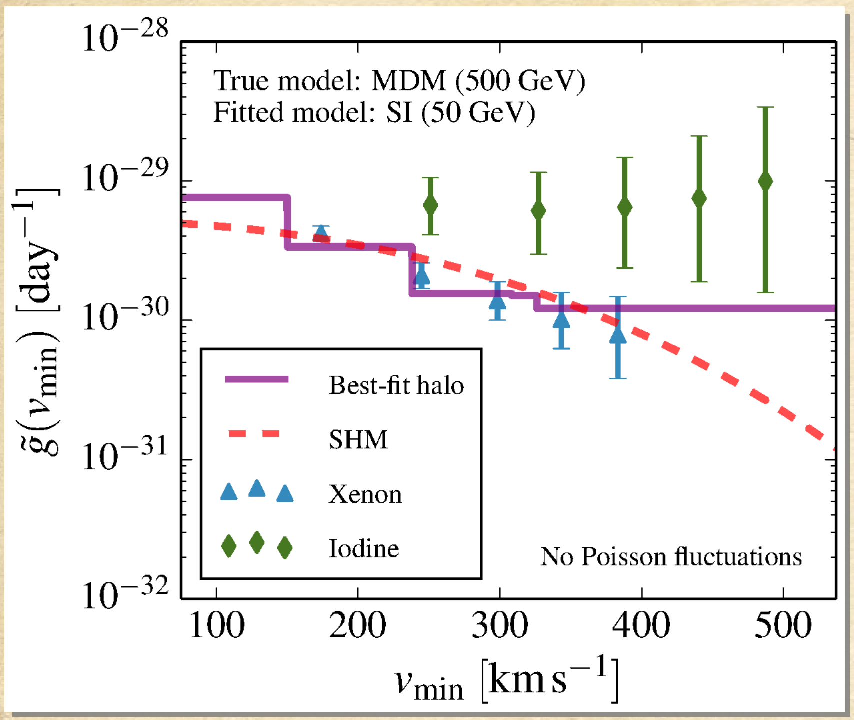
$$\Rightarrow \boxed{R_i \equiv \int_{E_R^{(i)}}^{E_R^{(i+1)}} \mathrm{d}E_R \frac{\mathrm{d}R}{\mathrm{d}E_R} = \sum_{j=1}^{N_s} D_{ij} g_j}$$

step heights, free to float in the fit to the data, only **monoticity constraint**!

matrix fully determined by the assumed particle physics scenario

expected events in bin *i*

Fitting the velocity integral



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Goodness-of-fit: $-2\log\mathcal{L} \equiv 2\sum_i R_i - N_i + N_i \log(N_i/R_i)$

Quantifying p-values

Assume a **true model** (SI, SD, Anapole, magn. dipole, or dark magn. dipole)

Generate mock data (many realizations)

For each realization of the mock data, perform the fit (i.e. vary $m_{\rm DM}$ and g_j), assuming a given **fitted model**

Distribution function $\xi(x_0)$ for $x_0 = -2\log\mathcal{L}$

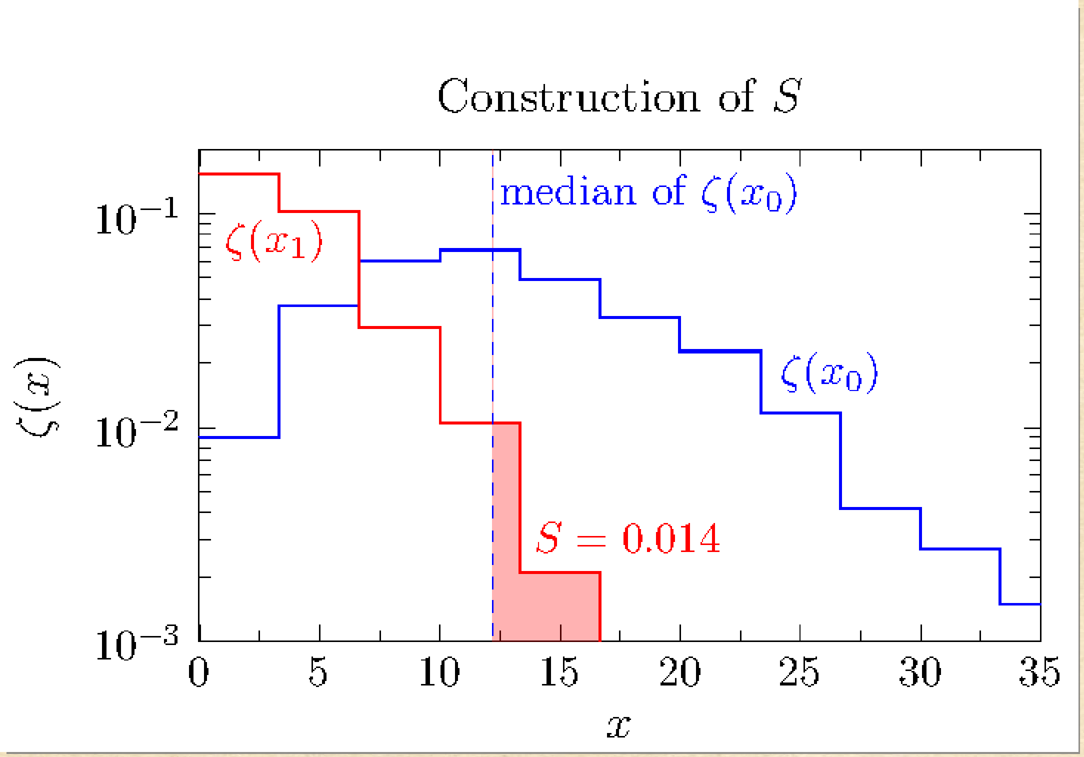
consider a typical prediction of this **fitted model**

Generate mock data (many realizations)

For each realization of the mock data, perform the fit, assuming the same **fitted model**

Distribution function $\xi(x_1)$ for $x_1 = -2\log\mathcal{L}$

Similarity of models



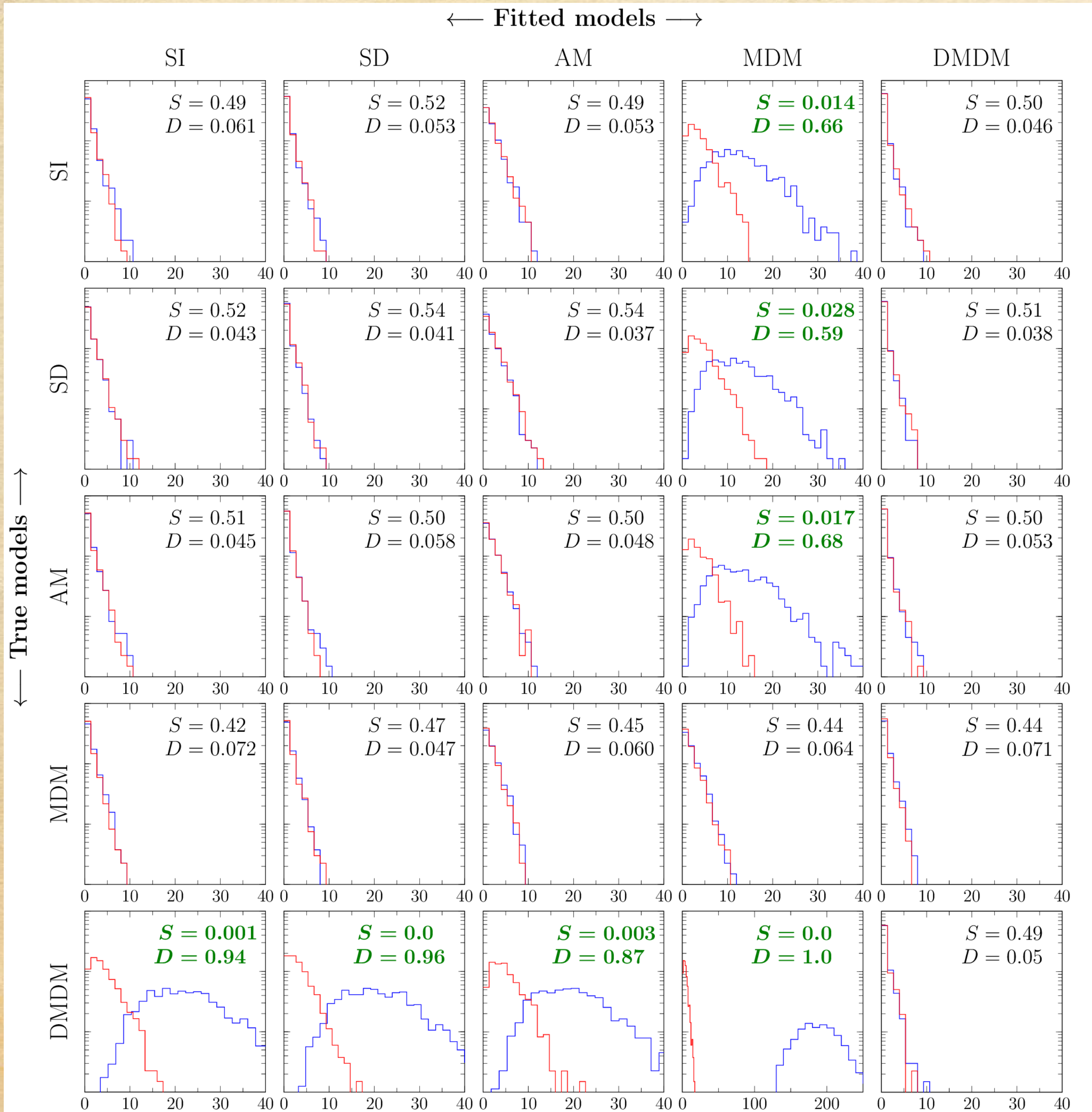
- If $\xi(x_0)$ and $\xi(x_1)$ look "sufficiently different", the true model can be distinguished from the fitted model

  → **Similarity S:** p-value of typical realization of the true model

> For small S, the fitted model can be ruled out as an explanation for the data generated by the true model

NB: distributions do *not* simply follow a χ^2, as there is no well-defined number of d.o.f. → Monte-Carlo approach necessary

Results (1): single xenon experiment



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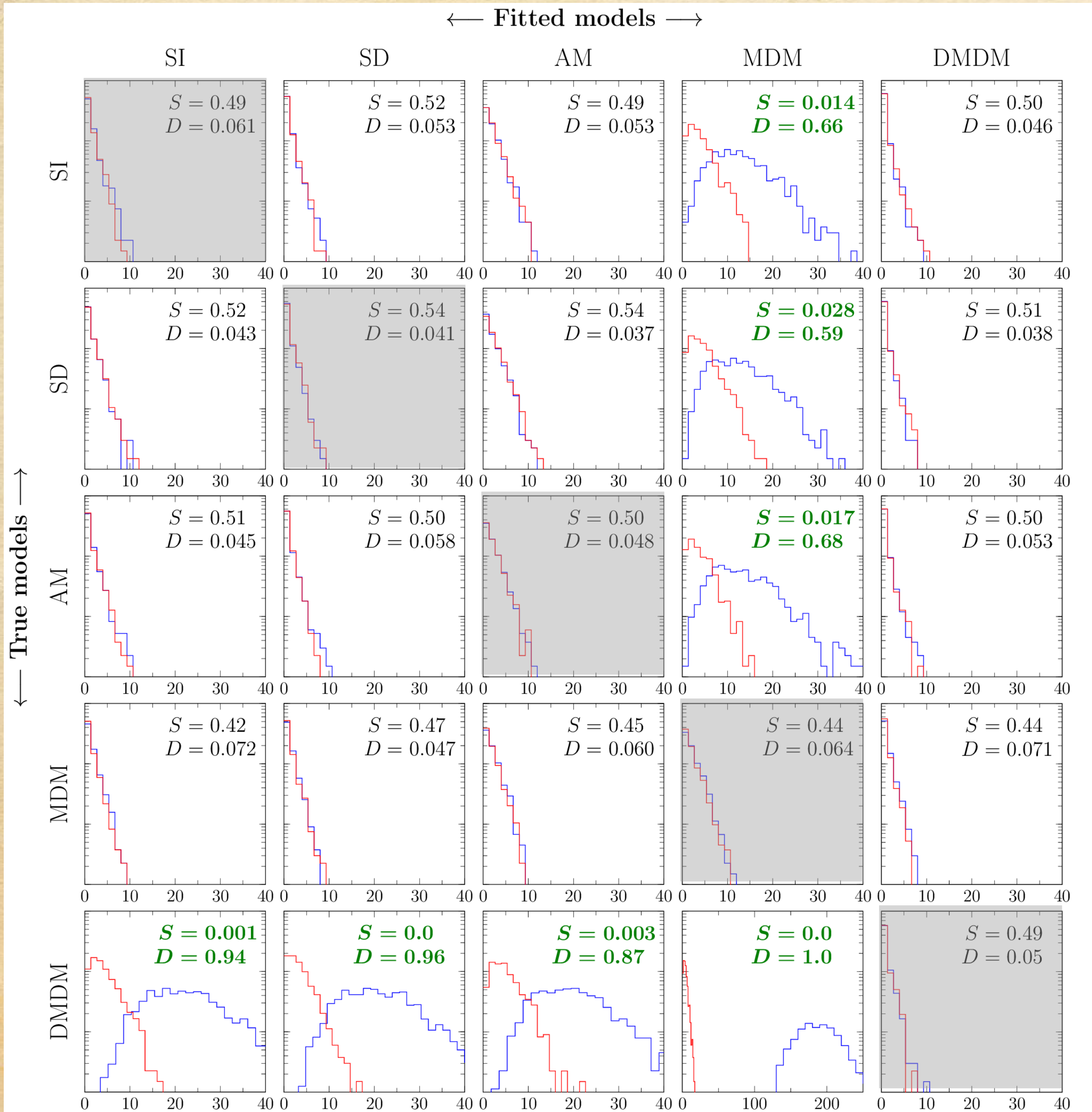
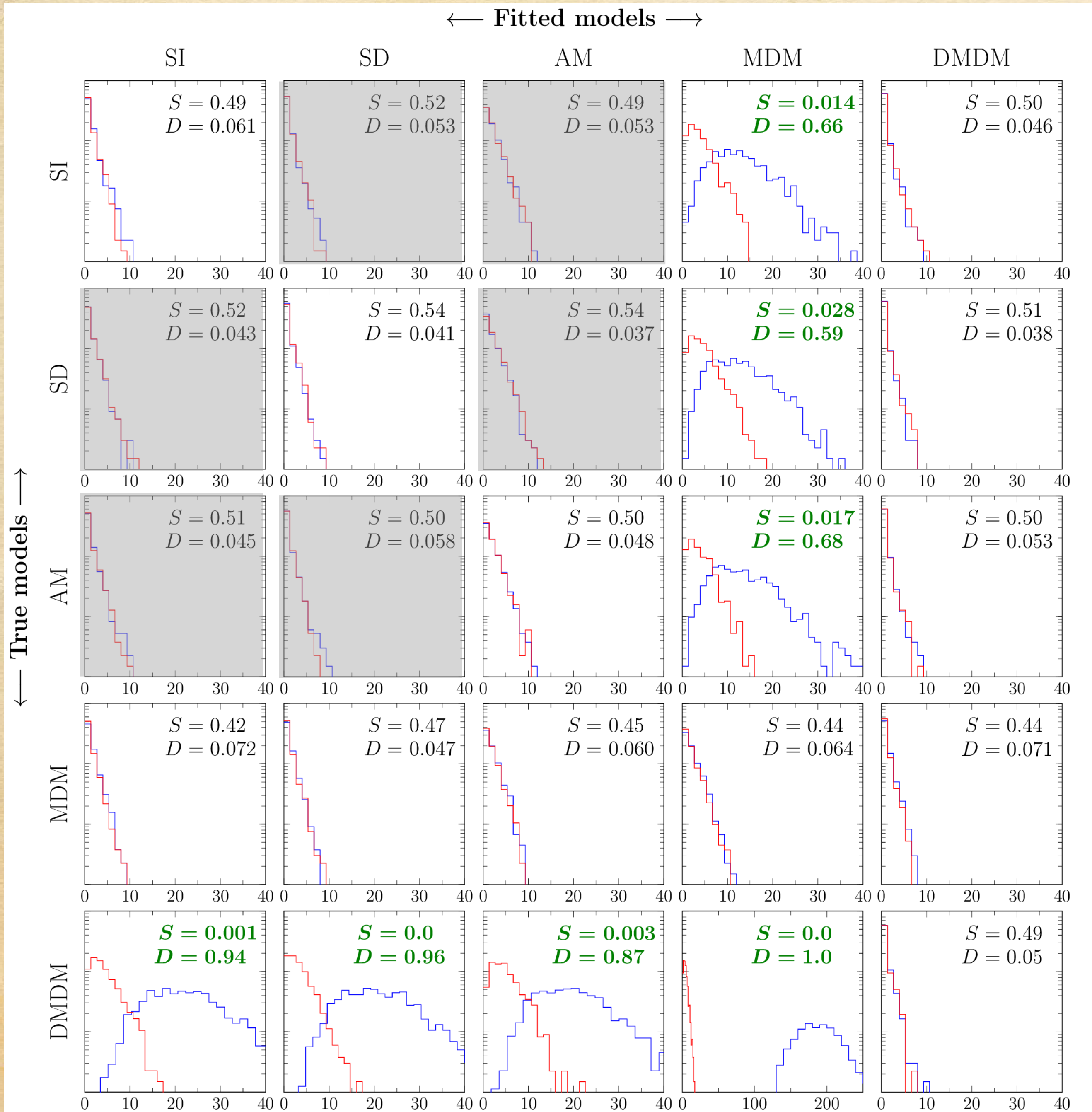


true model = fitted model

$\downarrow$

$S \simeq 0.5$

Results (1): single xenon experiment



SI, SD, anapole interactions are **indistinguishable** for a xenon-experiment! (once all possible velocity distributions are allowed)

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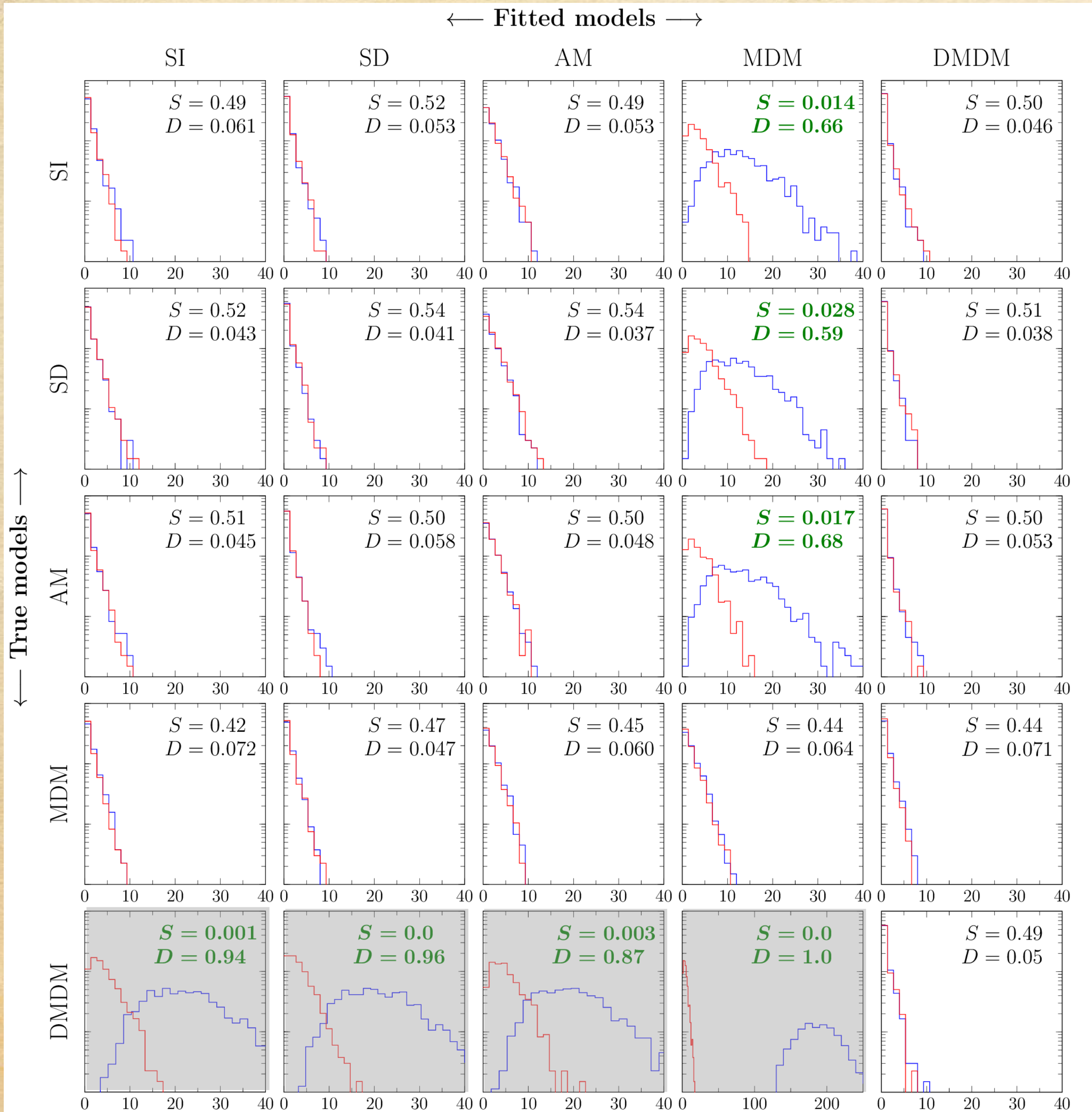
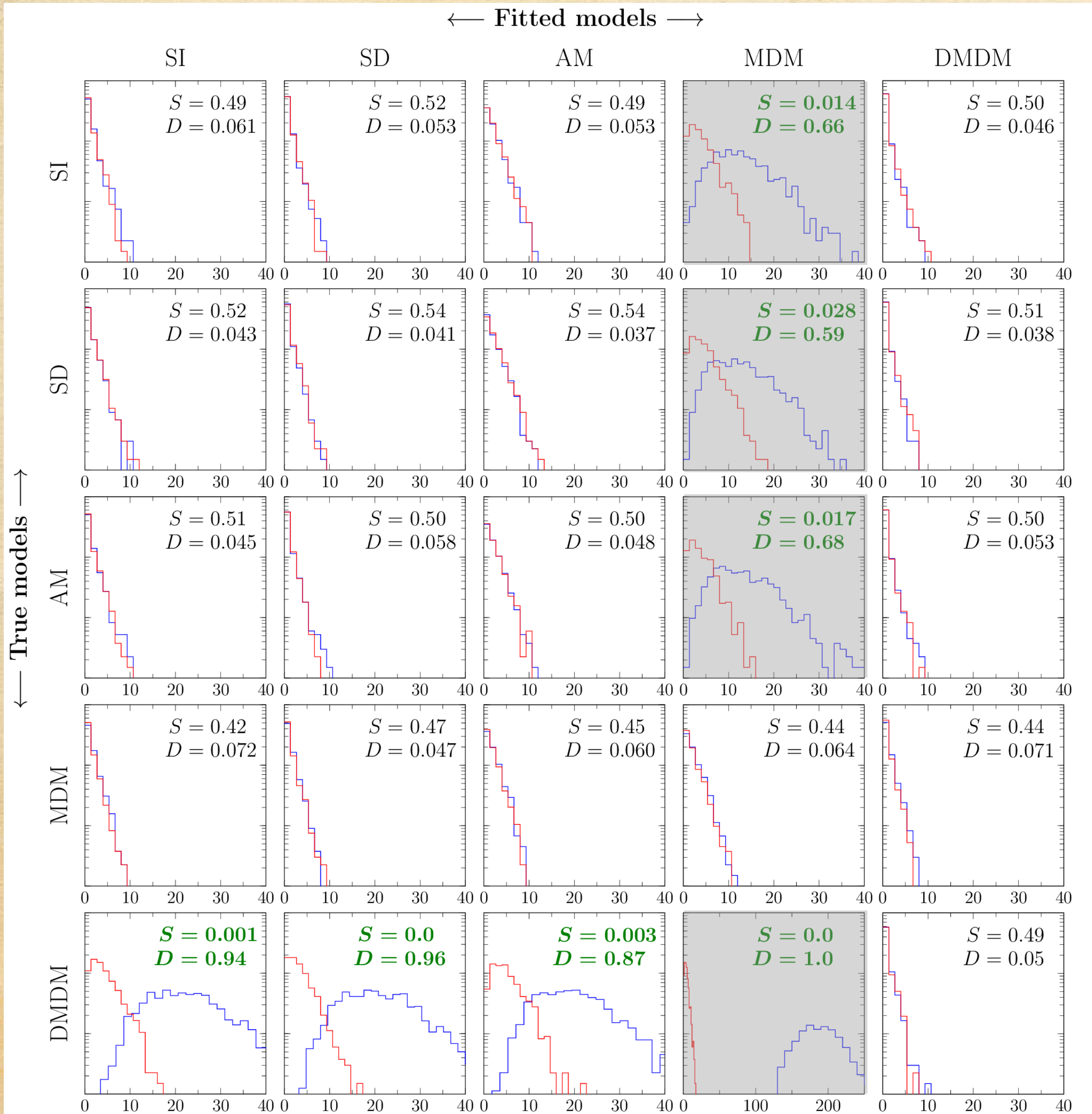


True model "dark magnetic magnetic dipole moment" **can be distinguished** from all other interactions!

Reason: this model predicts a non-monotonic recoil spectrum, which can not be mimicked by *any* decreasing function $g(v_{\min})$

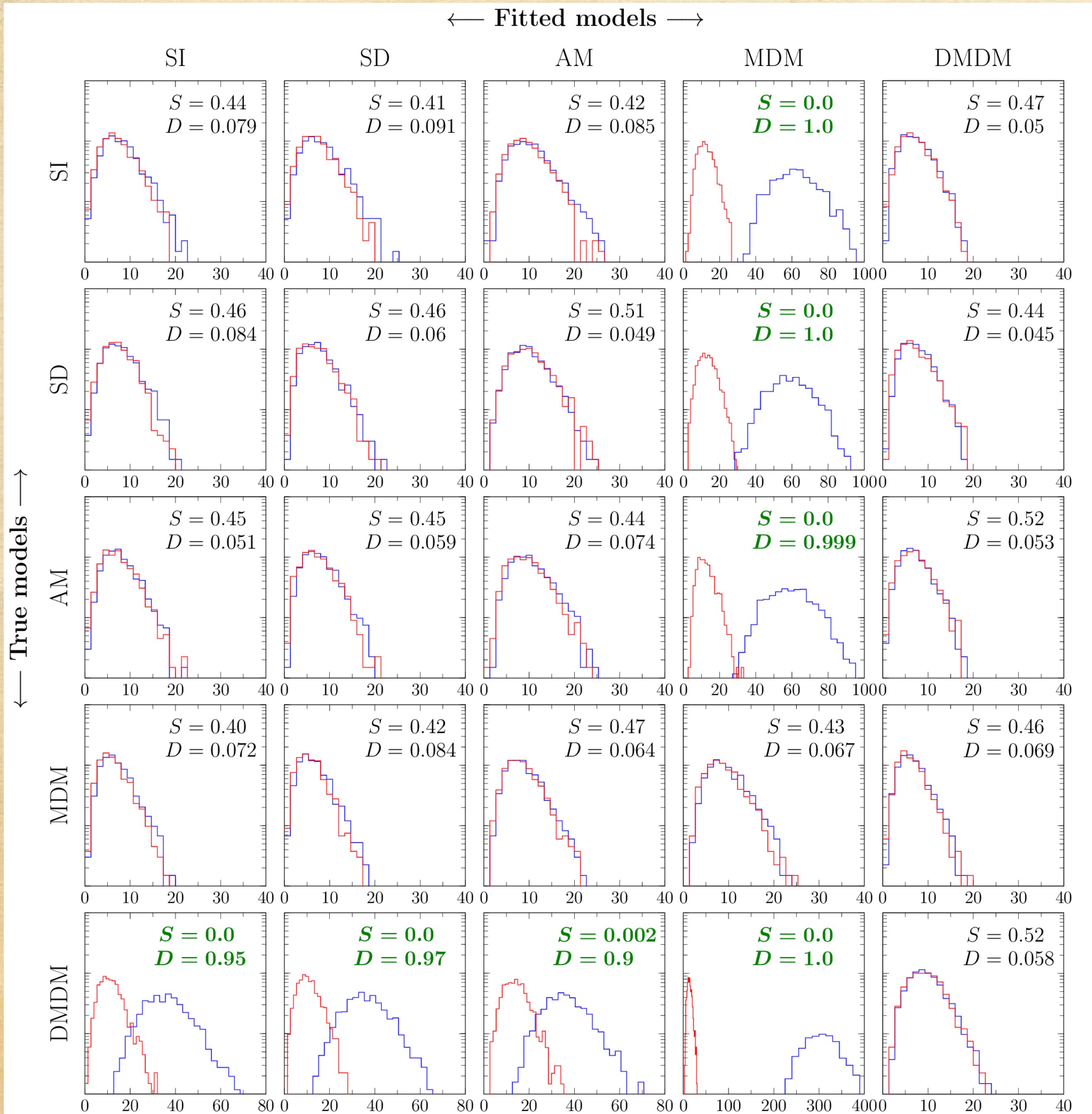
Results (1): single xenon experiment



The magnetic dip. moment model provides a **bad fit** to the data generated for all other true models!

Reason: for magn.dip.mom. dark matter the spectrum falls very steeply, which can not be compensated by any decreasing function $g(v_{\min})$

Results (2): xenon + germanium experiment



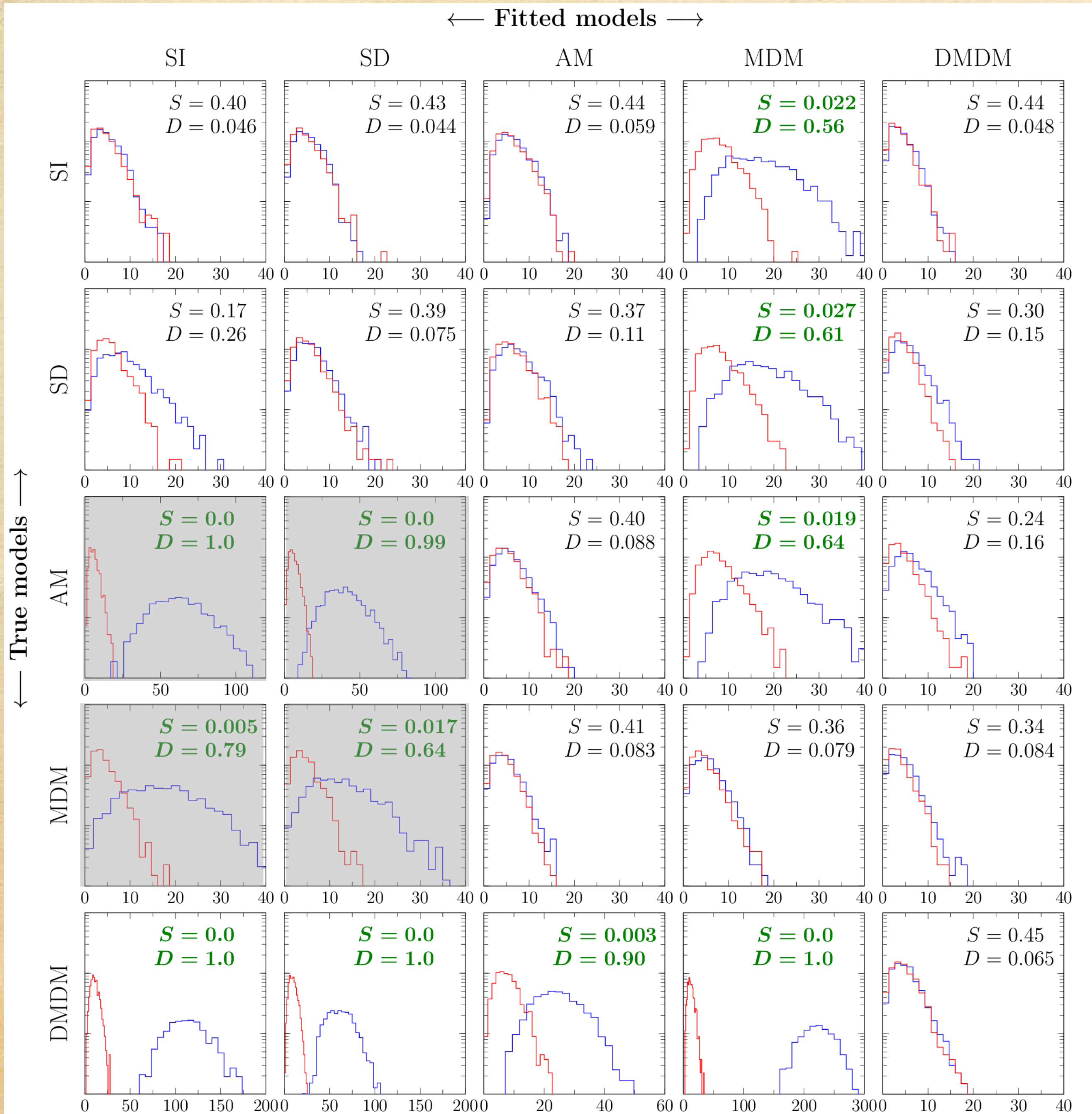
Would the detection of an additional signal in a **germanium** experiment help?

→ unfortunately, **no**!

Reason: xenon and germanium have similar nuclear properties

→ limited complementarity

Results (3): xenon + iodine experiment



Would the detection of an additional signal in a **iodine** experiment help?

→ **yes!**

Now, SI and SD scattering can be ruled out if the true model is anapole or magn. dip. moment scattering

→ Reason: $\mu^{(\mathrm{I})}_{\mathrm{magn}} \gg \mu^{(\mathrm{Xe})}_{\mathrm{magn}}$

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- Halo-independent methods are a useful bottom-up approach to the problem of astrophysical uncertainties in direct detection

- Focus of this talk: **halo-independent reconstruction** of the particle physics scenario governing the DM-nucleon interaction
  → we have in mind potential future discoveries at XENON1T, LZ, ...
  → our method is based on finding the best-fit velocity integral, and quantifying how good it can fit the data

- Main results:
  → some pairs of interactions **can be robustly discriminated** without making any assumptions about f(v)
  → in some cases, this is already possible with a discovery in a single experiment
  → Xe+Ge have very limited complementarity, while the combination Xe+I could be very powerful