

Direct detection of dark matter: halo-independent methods

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DESY, Hamburg

mostly based on

1506.03386 (Ferrer, Ibarra, SW)

1607.04418 (Kahlhoefer, SW)



Theory Seminar
University of Oslo
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Outline

Evidence for dark matter & the idea of WIMPs

Direct detection of dark matter

Halo-independent determination of DM properties

- a) Interpreting (future) positive detections
- b) Upper limits from existing data

Conclusions

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Evidence for dark matter & the idea of WIMPs

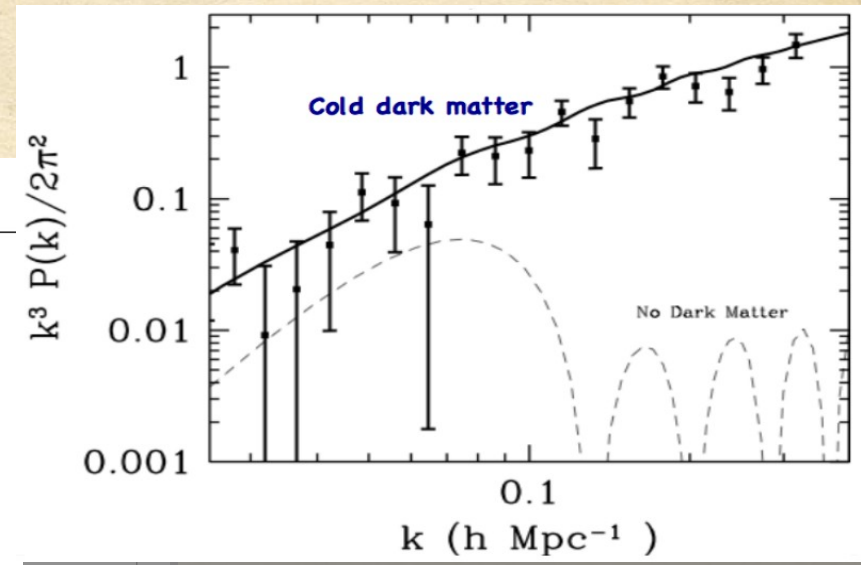
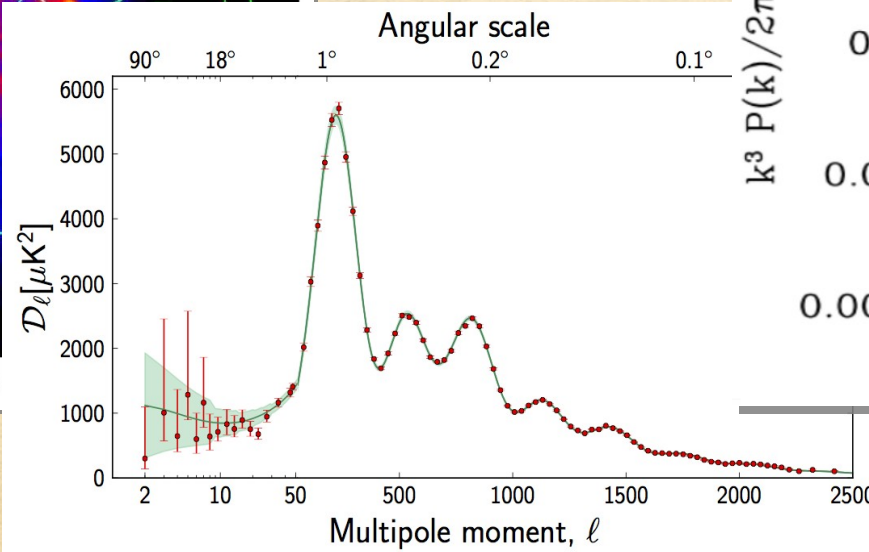
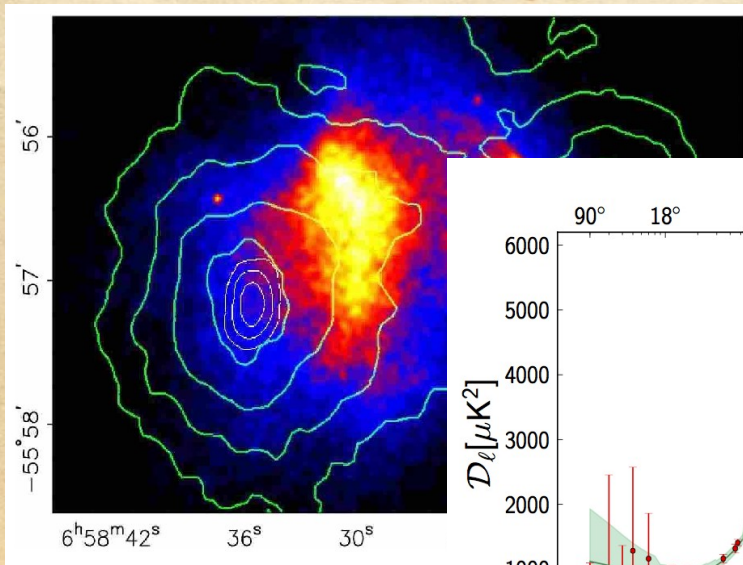
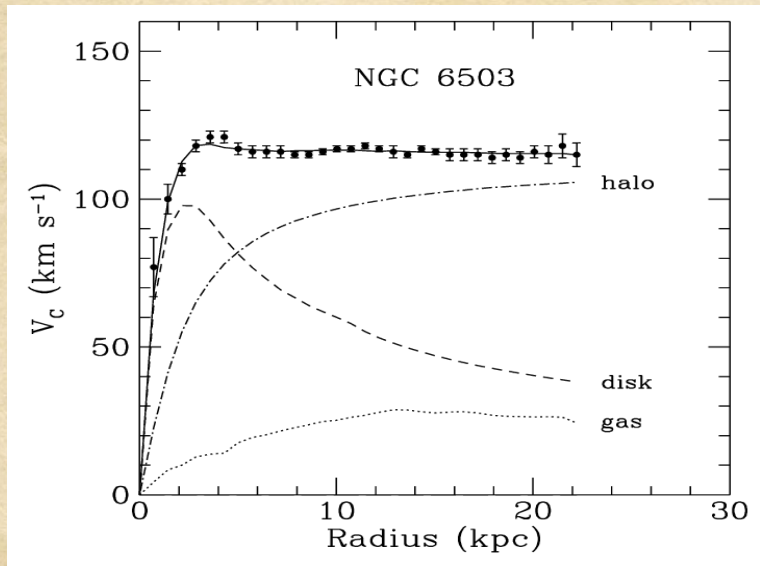
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Evidence for dark matter



The dark matter particle

What are the particle physics properties of dark matter?
→ mass, spin, quantum numbers, interactions ?

Dark matter has to be...

- **stable** on cosmological timescales
- (almost) electromagnetically **neutral**
- dominantly **non-baryonic**
- **cold**, i.e. non-relativistic during structure formation

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No viable candidate in the Standard Model of particle physics!

In the last decades, several classes of candidates have been proposed:

- Axions ($m \simeq \mu\text{eV}$)
- Sterile neutrinos ($m \simeq \text{keV}$)
- Primordial black holes ($m \simeq 10^{16}\text{g} - 10^{36}\text{g}$)
- **Weakly Interacting Massive Particles (WIMPs)** ($m \simeq \text{GeV} - \text{TeV}$)

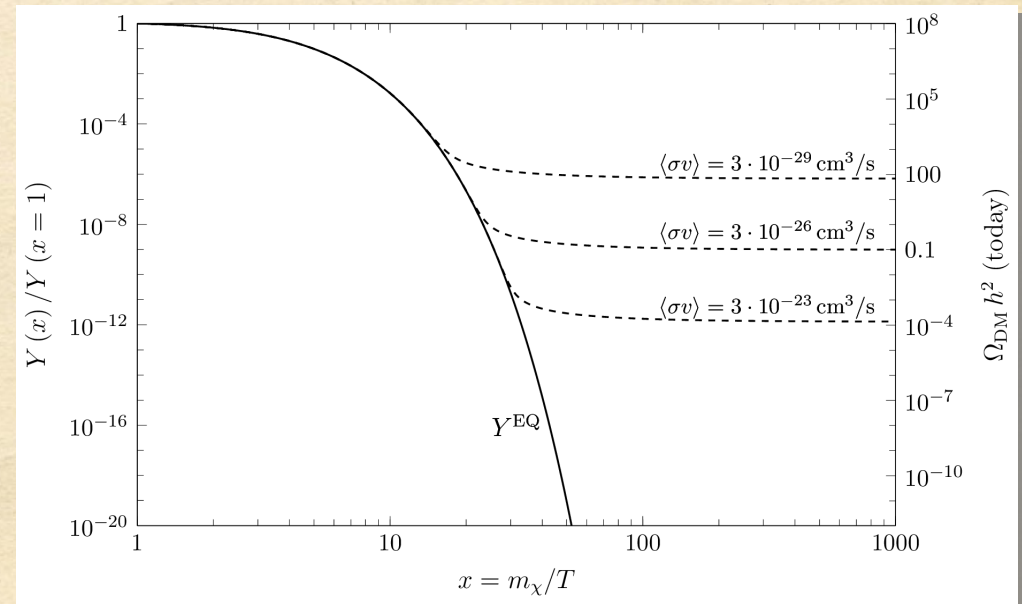
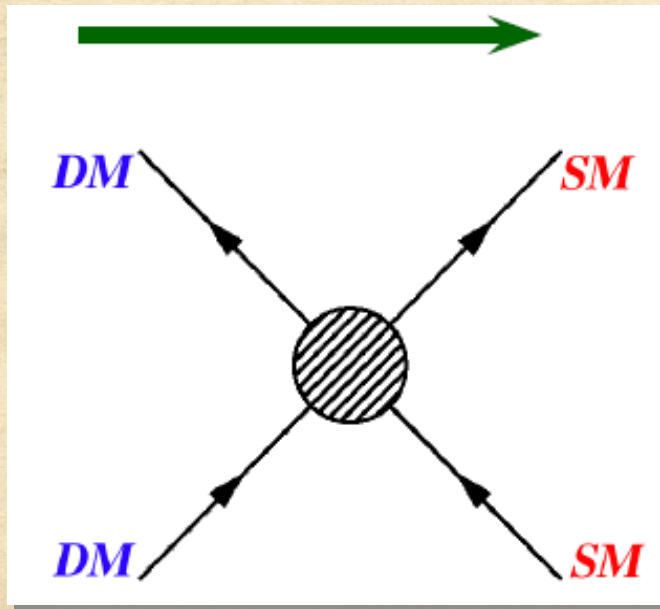
Rest of this talk



Motivation of WIMPs

Hypothesis: 1) $m_{\text{DM}} \simeq 1 \text{ GeV} \dots 100 \text{ TeV}$

2) DM has weak-scale interactions with SM particles



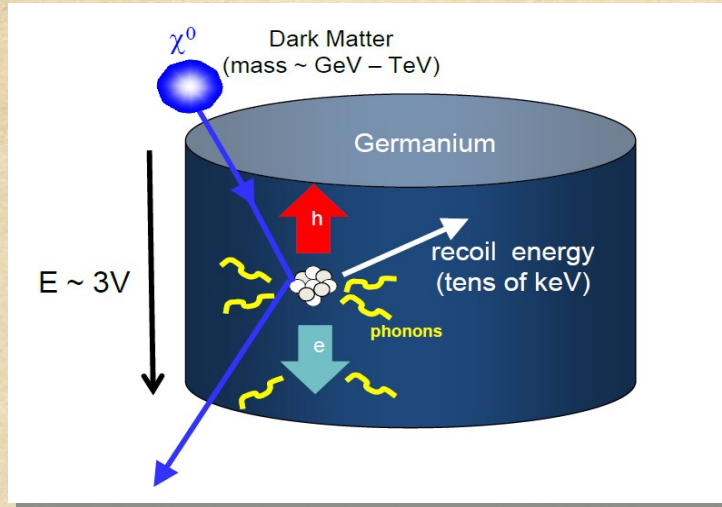
$$\Omega_{\text{DM}} h^2 \simeq 0.12 \cdot \frac{2.2 \cdot 10^{-26} \text{ cm}^3/\text{s}}{\langle \sigma v \rangle}$$

observed amount
of dark matter

arises naturally e.g. in SUSY or in other
extensions of the Standard Model!

→ “WIMP miracle”

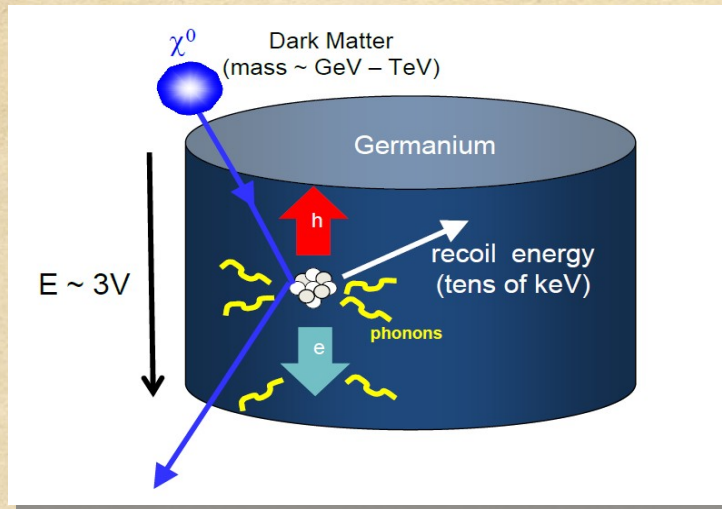
Detection of WIMPs



Direct detection:

$DM + \text{nucl.} \rightarrow DM + \text{nucl.}$

Detection of WIMPs



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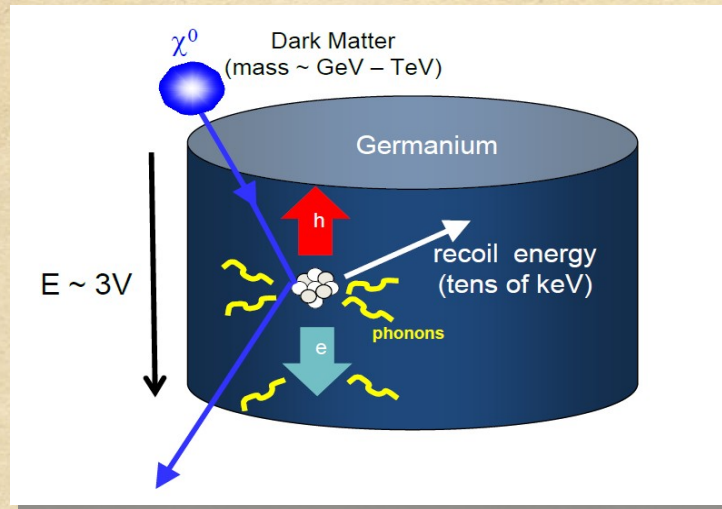
$\text{DM} + \text{nucl.} \rightarrow \text{DM} + \text{nucl.}$



Indirect detection:

$\text{DM} + \text{DM} \rightarrow \text{SM} + \text{SM}$

Detection of WIMPs



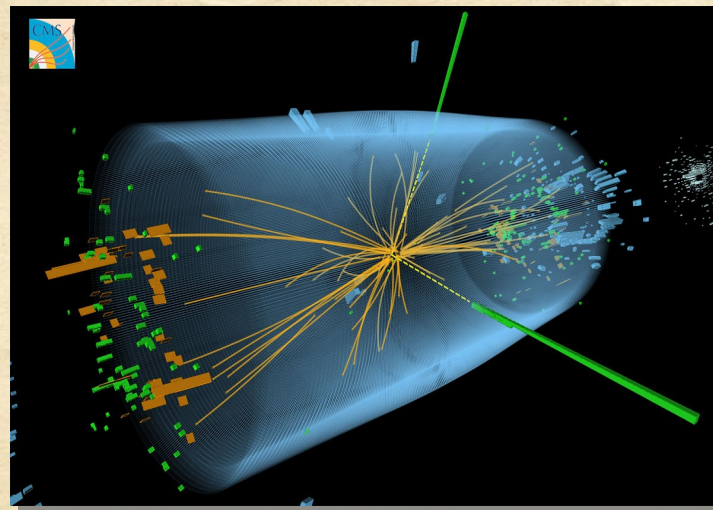
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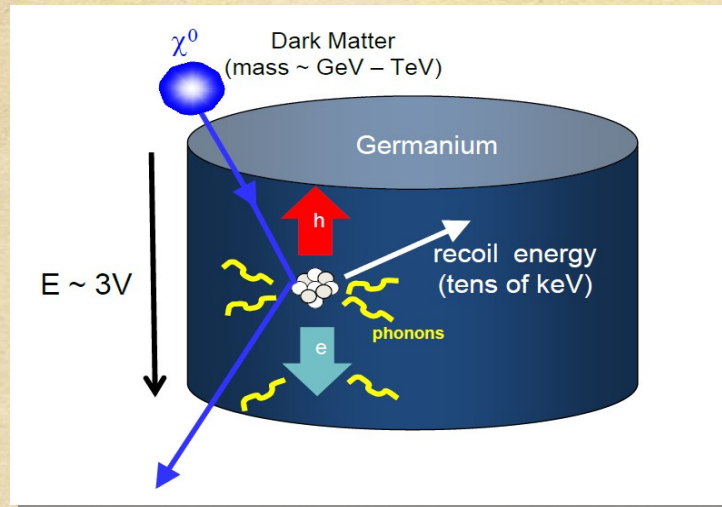
$\text{DM} + \text{DM} \rightarrow \text{SM} + \text{SM}$



Production at colliders:

$\text{SM} + \text{SM} \rightarrow \text{DM} + \text{DM}$

Detection of WIMPs



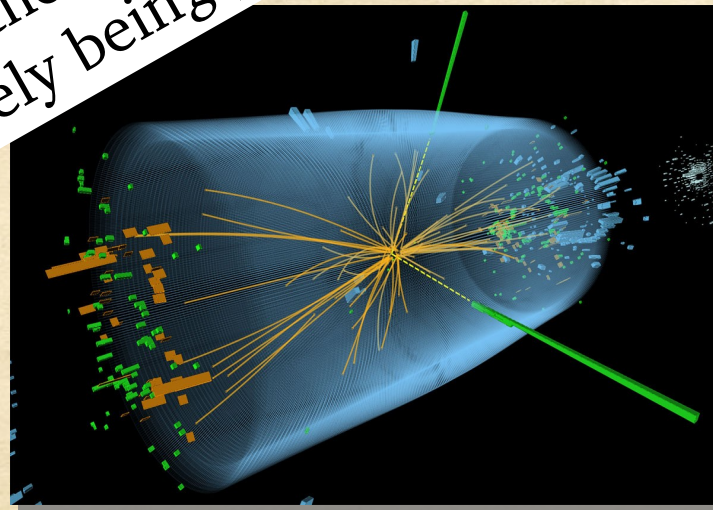
All of these techniques are nowadays actively being pursued by experiments!

Direct detection:

$\text{DM} + \text{nucl.} \rightarrow \text{DM} + \text{recoil}$

Indirect detection:

$\text{DM} + \text{DM} \rightarrow \text{SM} + \text{SM}$



Production at colliders:

$\text{SM} + \text{SM} \rightarrow \text{DM} + \text{DM}$

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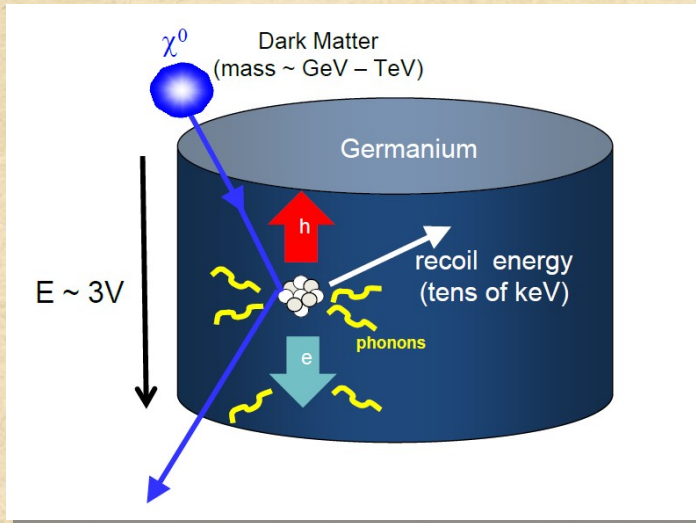
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Direct detection: the idea



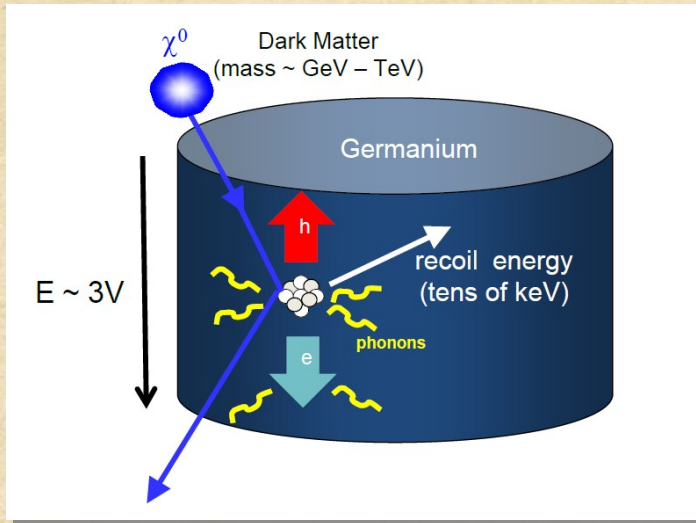
$$E_R < \frac{2\mu_T^2 v_{\text{DM}}^2}{m_T} \lesssim (10 - 100) \text{ keV}$$

$v_{\text{DM}} \simeq 10^{-3} c$

Expected recoil rate:

$$\frac{dR}{dE_R} = \frac{\rho_{\text{loc}}}{m_T m_{\text{DM}}} \int_{v_{\text{min}}(E_R)}^{\infty} dv v f(v) \frac{d\sigma}{dE_R}$$

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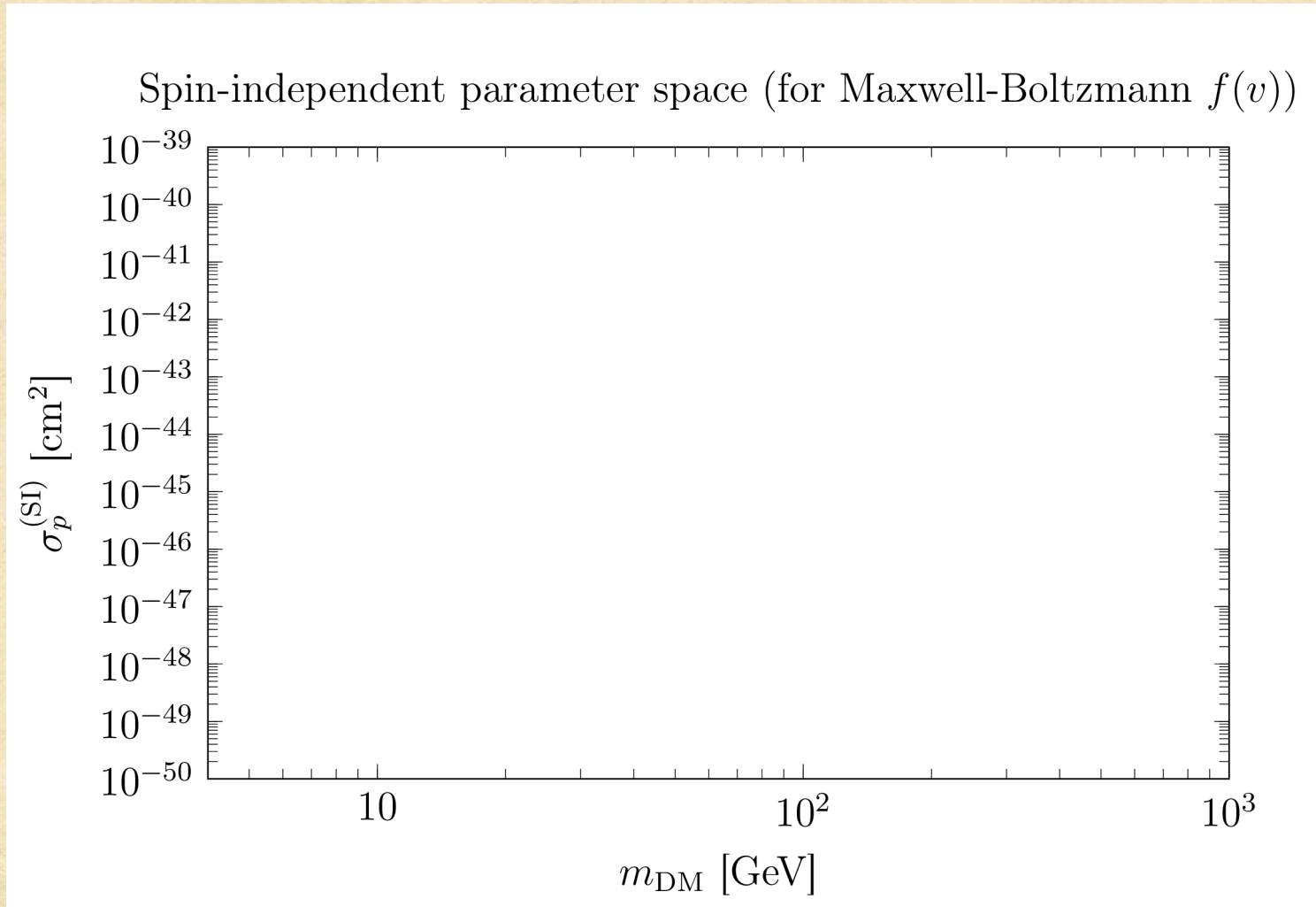
Astrophysical input:

- local dark matter density $\rho_{\text{loc}} \simeq (0.3 - 0.4) \text{ GeV}/\text{cm}^3$
- local velocity distribution $f(v)$
 - standard assumption: Maxwell-Boltzmann distribution

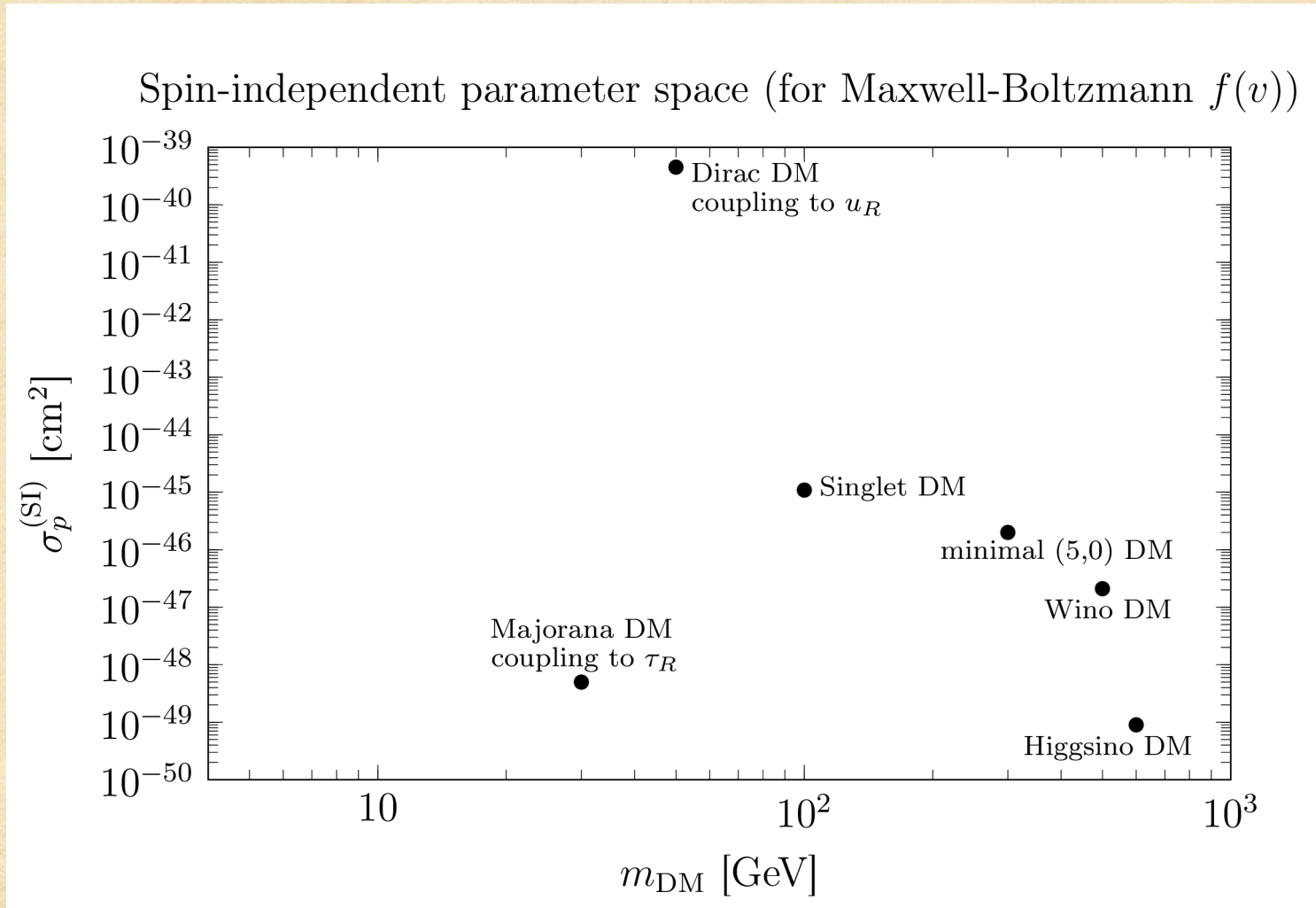
Particle physics input:

- dark matter mass m_{DM}
- scattering cross section $d\sigma/dE_R$
 - standard assumption: spin-independent (SI) or spin-dependent (SD)

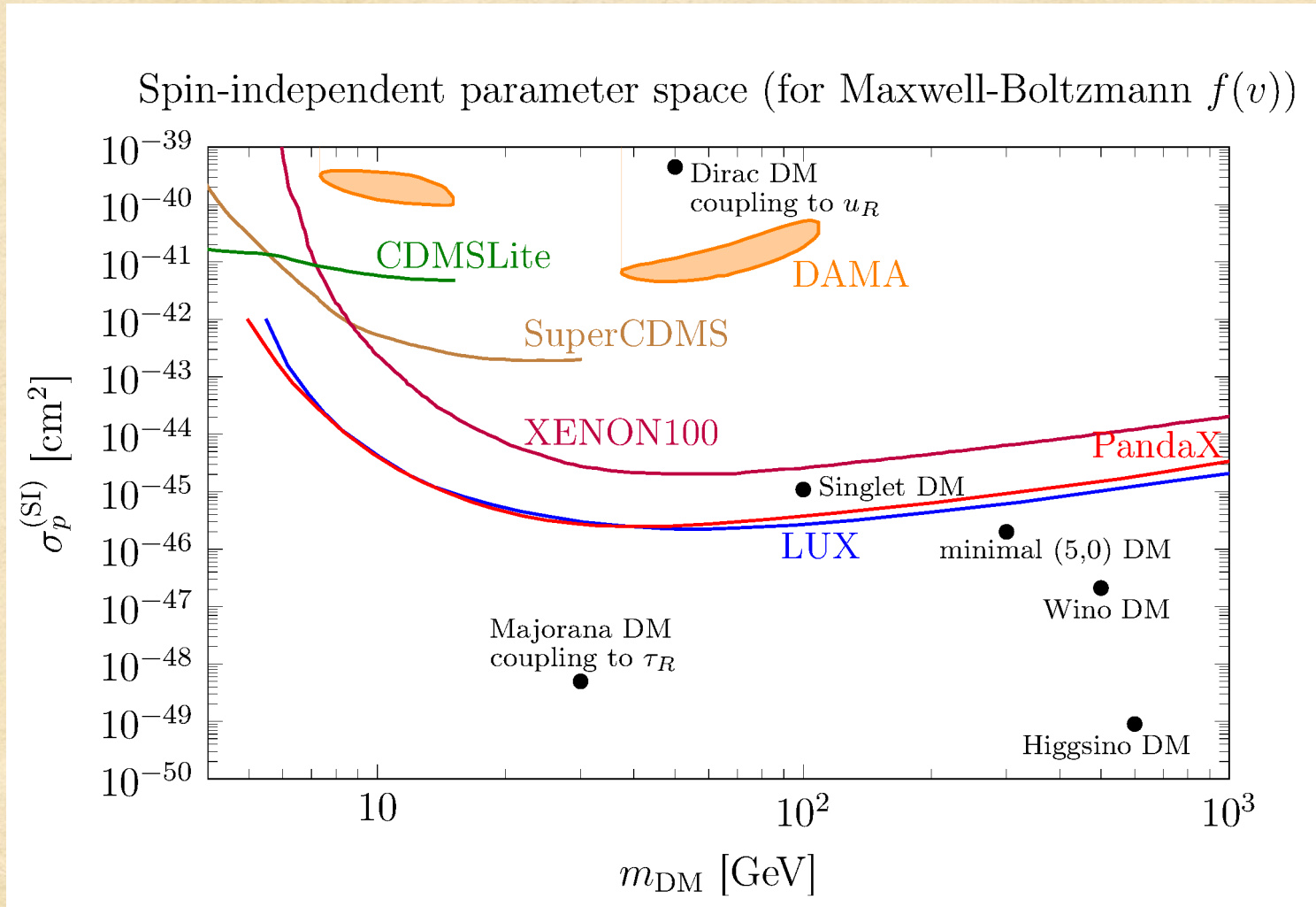
Experimental landscape



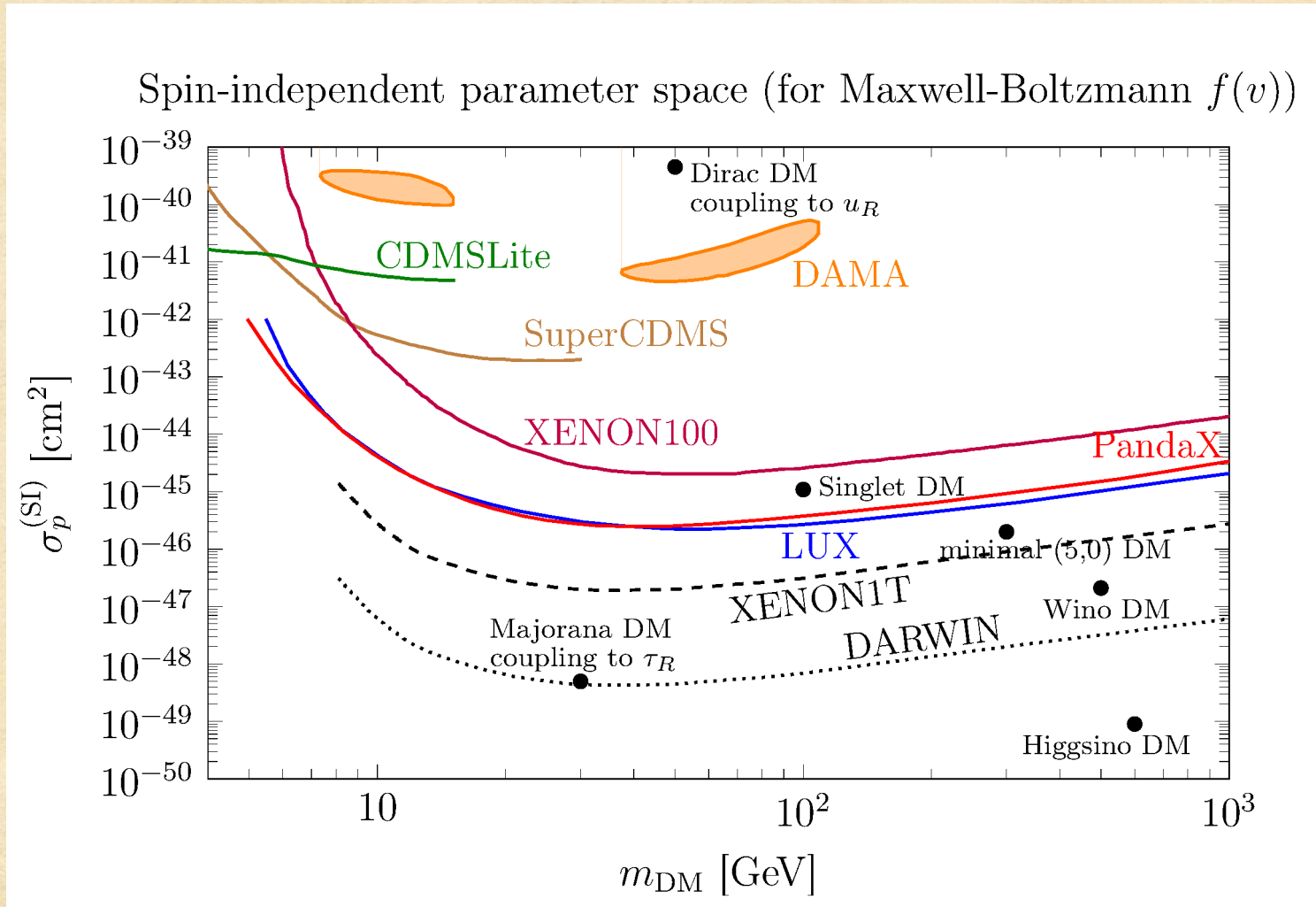
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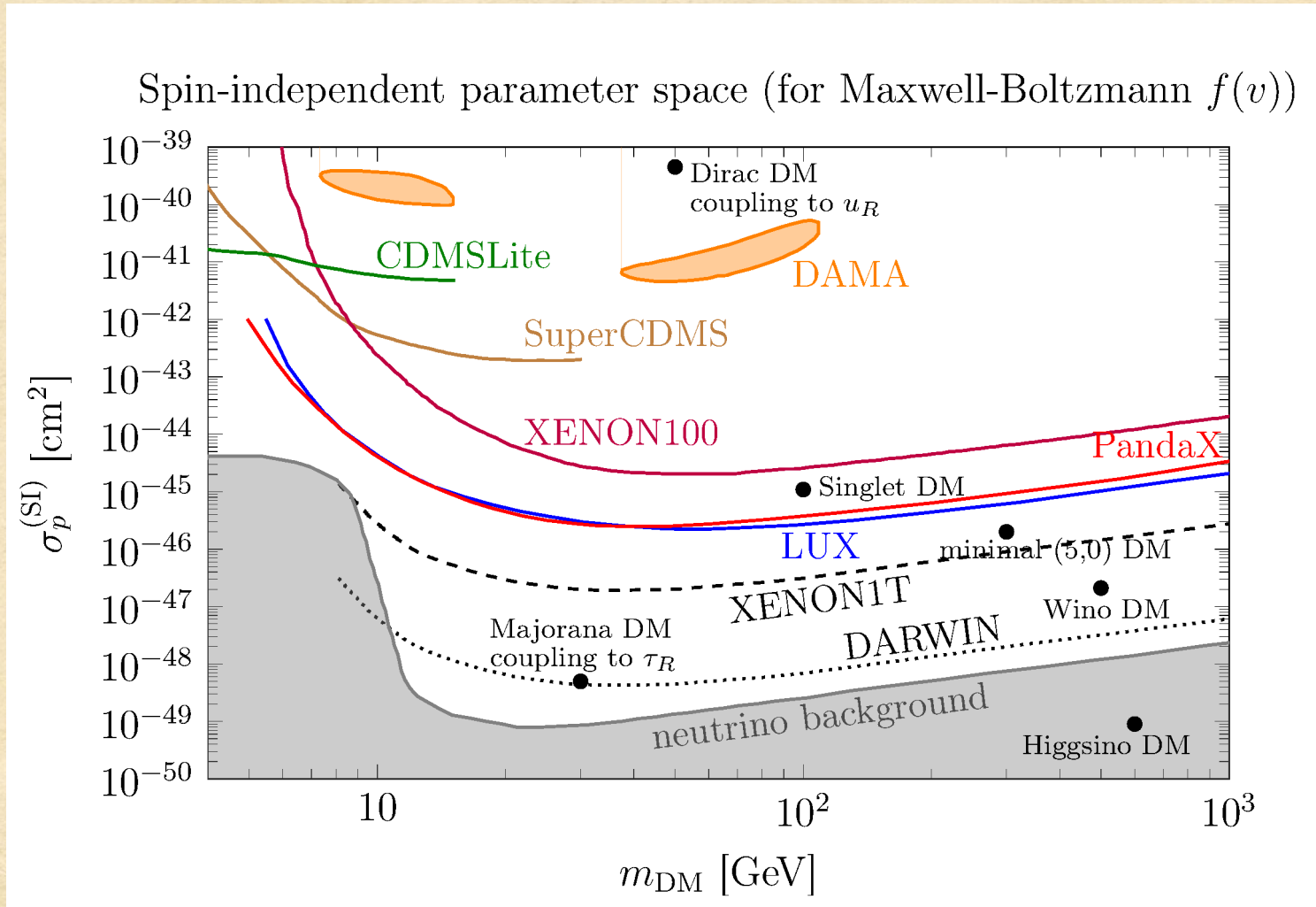
Experimental landscape



Experimental landscape



Experimental landscape



- We are getting close to the neutrino background!
- But there remain several well-motivated scenarios within the reach of the next-generation experiments

Direct detection: extended particle physics

$$\frac{dR}{dE_R} = \frac{\rho_{\text{loc}}}{m_T m_{\text{DM}}} \int_{v_{\text{min}}(E_R)}^{\infty} dv v f(v) \frac{d\sigma}{dE_R}$$

There is much more than standard SI and SD scattering!

- | | | |
|--|---|--|
| (a) spin-independent | $\mathcal{L} = f_N^{(\text{SI})} \bar{\chi} \chi \bar{N} N$ | |
| (b) spin-dependent | $\mathcal{L} = f_N^{(\text{SD})} \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{N} \gamma_\mu \gamma^5 N$ | |
| (c) anapole moment | $\mathcal{L} = \mathcal{A} \bar{\chi} \gamma^\mu \gamma^5 \chi \partial^\nu F_{\mu\nu}$ | $\left. \begin{array}{l} \\ \\ \end{array} \right\} \begin{array}{l} d\sigma/dE_R \text{ has} \\ \text{non-trivial depen-} \\ \text{dence on } E_R \text{ and } v \end{array}$ |
| (d) magn. dipole mom. | $\mathcal{L} = \mathcal{D}_{\text{magn}} \bar{\chi} \sigma^{\mu\nu} \chi F_{\mu\nu}$ | |
| (e) “dark” magnetic dipole moment | $\mathcal{L} = \mathcal{D}_{\text{magn}} \bar{\chi} \sigma^{\mu\nu} \chi F'_{\mu\nu}$ | |

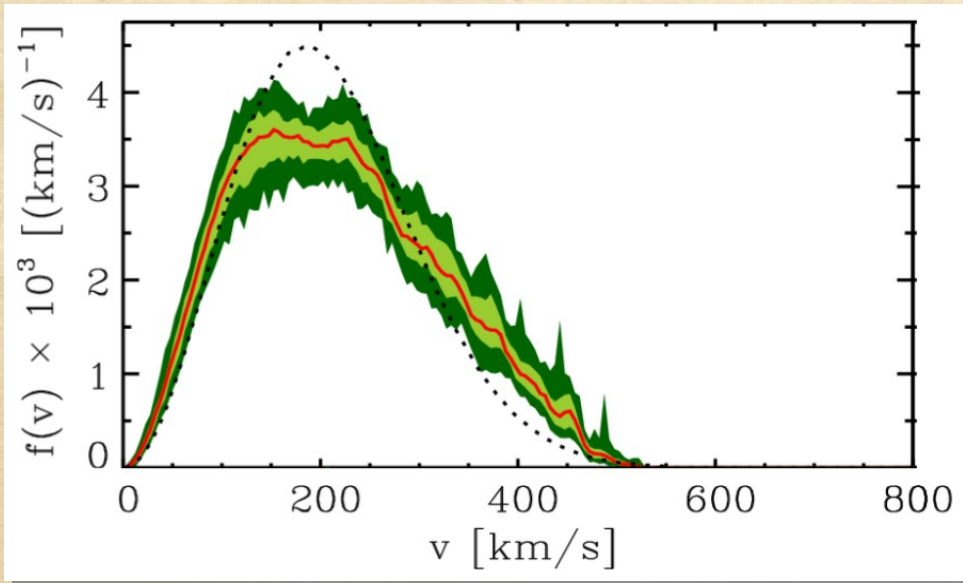
→ can these interaction scenarios be distinguished by future direct detection experiments?

Direct detection: extended astrophysics

$$\frac{dR}{dE_R} = \frac{\rho_{\text{loc}}}{m_T m_{\text{DM}}} \int_{v_{\text{min}}(E_R)}^{\infty} dv v f(v) \frac{d\sigma}{dE_R}$$

There is much more than the Maxwell-Boltzmann distribution!

[0912.2358]

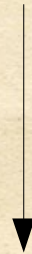


- non-equilibrated streams?
- dark disk?
- uncertainty in v_{esc}
- ...

→ how does this huge uncertainty impact our ability to infer particle physics properties from future experiments?

Outline of the next section

- 1) Assume that one or several future DD experiments **observe a signal** with $O(100)$ events.
- 2) Can we determine the interaction type of dark matter **from data alone, without relying** on a specific velocity distribution $f(v)$?



Halo-independent determination
of dark matter properties

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Rewriting the differential event rate

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

- For (almost) all interaction types of DM, we have $\Rightarrow \sqrt{m_T E_R / 2\mu_T^2}$

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

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- Let us further introduce the **velocity integrals**

$$g(v_{\min}) := \int_{v_{\min}}^{\infty} dv \, \frac{f(v)}{v}$$

$$h(v_{\min}) := \int_{v_{\min}}^{\infty} dv \, v f(v)$$

$$\rightarrow \boxed{\frac{dR}{dE_R} = \frac{\rho_{\text{loc}}}{m_T m_{\text{DM}}} \left(\frac{d\sigma_1}{dE_R} g(v_{\min}(E_R)) + \frac{d\sigma_2}{dE_R} h(v_{\min}(E_R)) \right)}$$

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

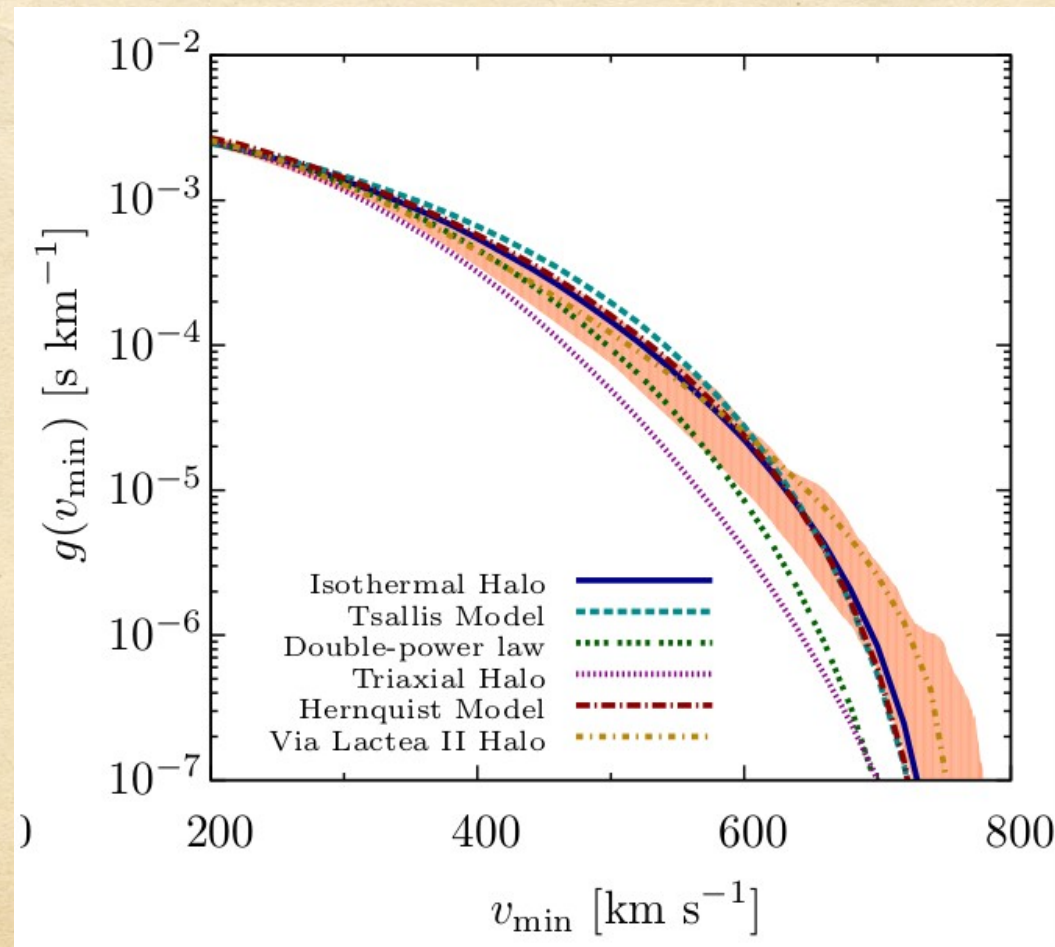
$$h(v_{\min}) = [-g(v)v^2]_{v_{\min}}^{\infty} + \int_{v_{\min}}^{\infty} dv 2v g(v)$$

Reinterpreting direct detection data

$$\frac{dR}{dE_R} = [\text{particle physics}] \times g(v_{\min})$$

observable quantity

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



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For a given observed recoil spectrum dR/dE_R , we can confirm/exclude a given particle physics model as follows:

- 1) Translate the measurement of dR/dE_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!**

Early related works: Fox& [1011.1915]

Frandsen& [1111.0292]

Gondolo& [1202.6359]

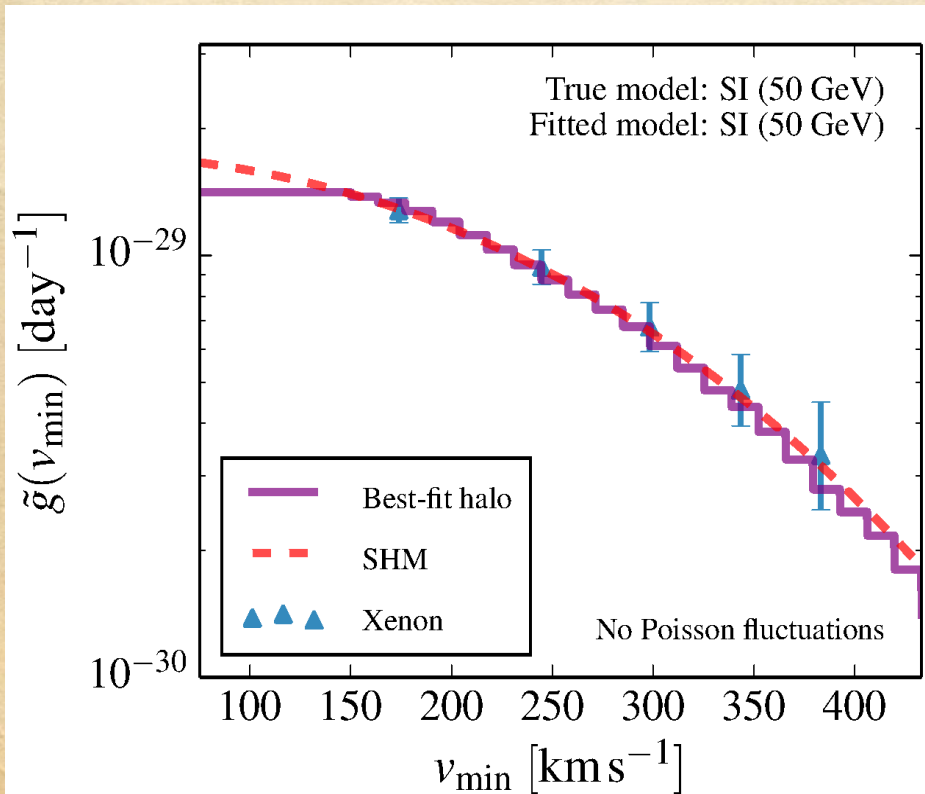
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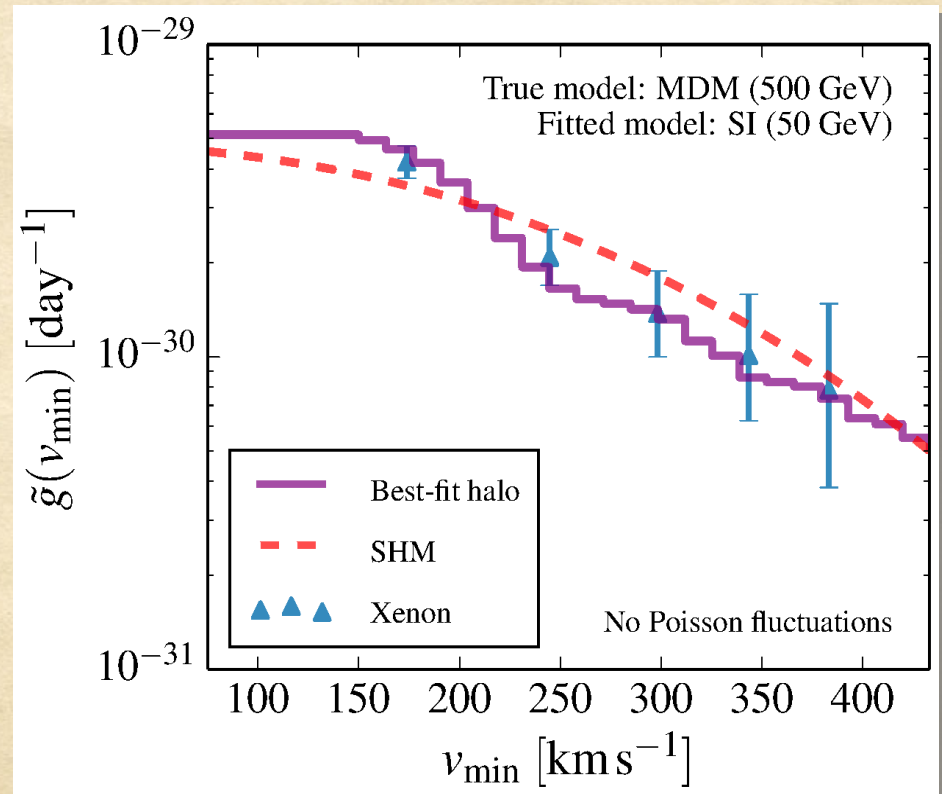
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true model: SI interaction
fitted model: SI interaction



true model: MDM interaction
fitted model: SI interactions



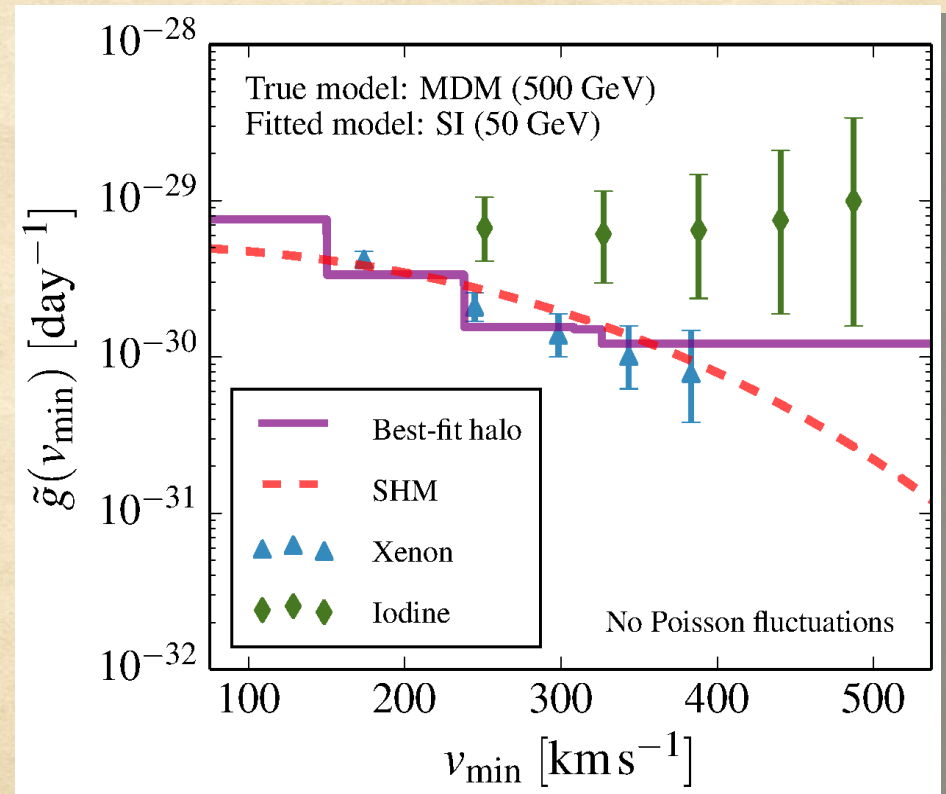
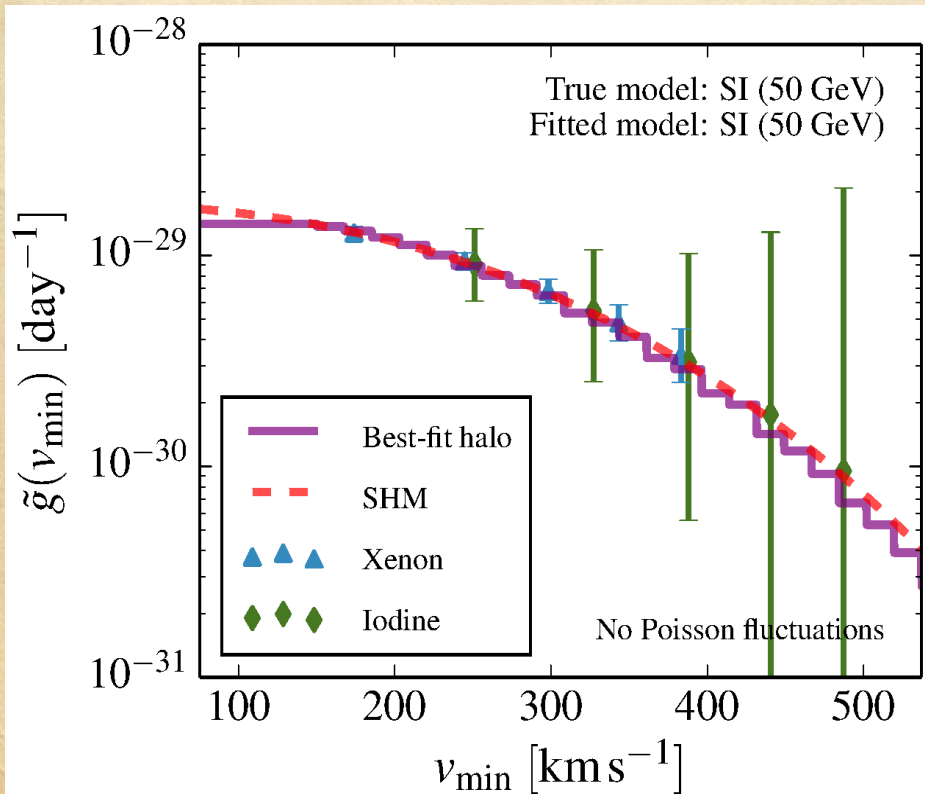
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... adding an iodine-based experiment to the xenon experiment ...



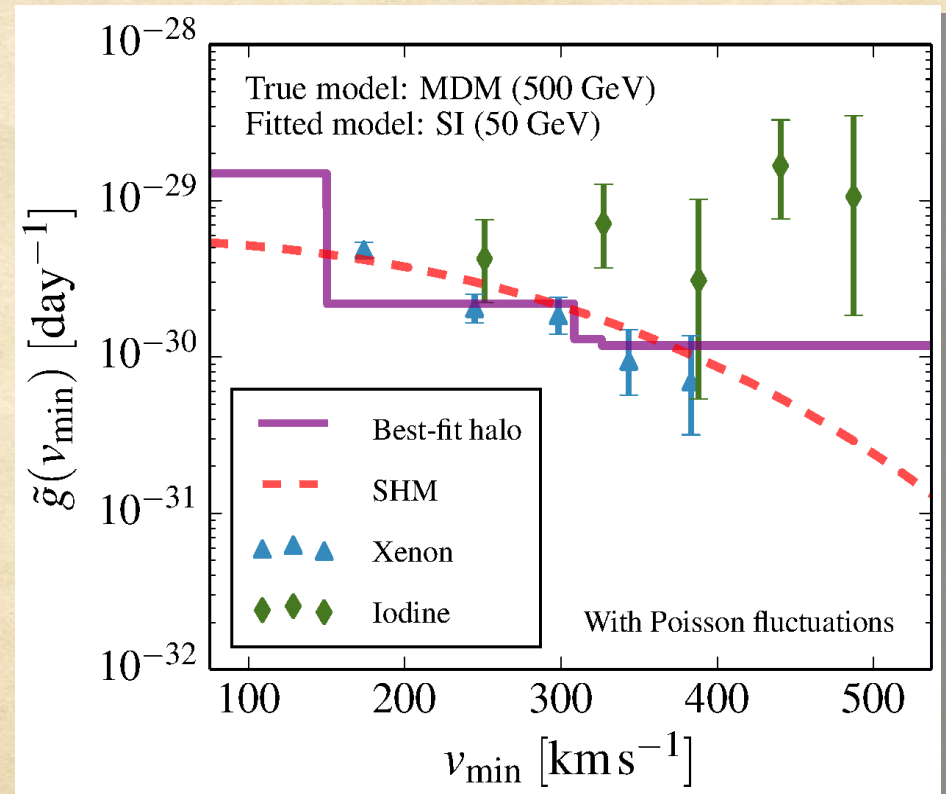
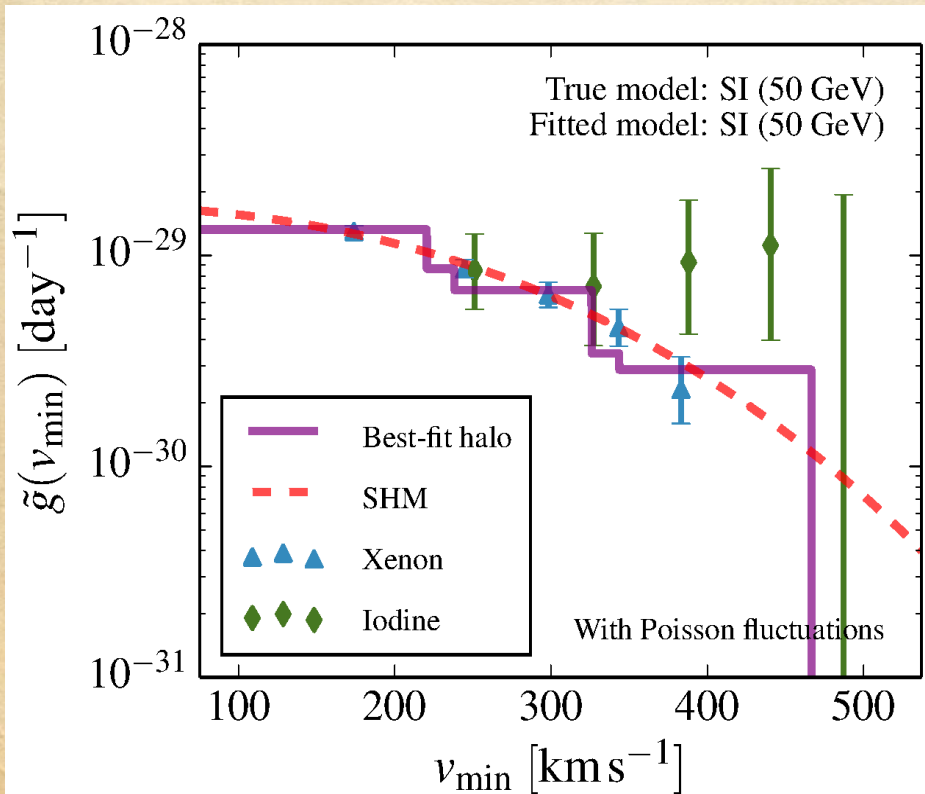
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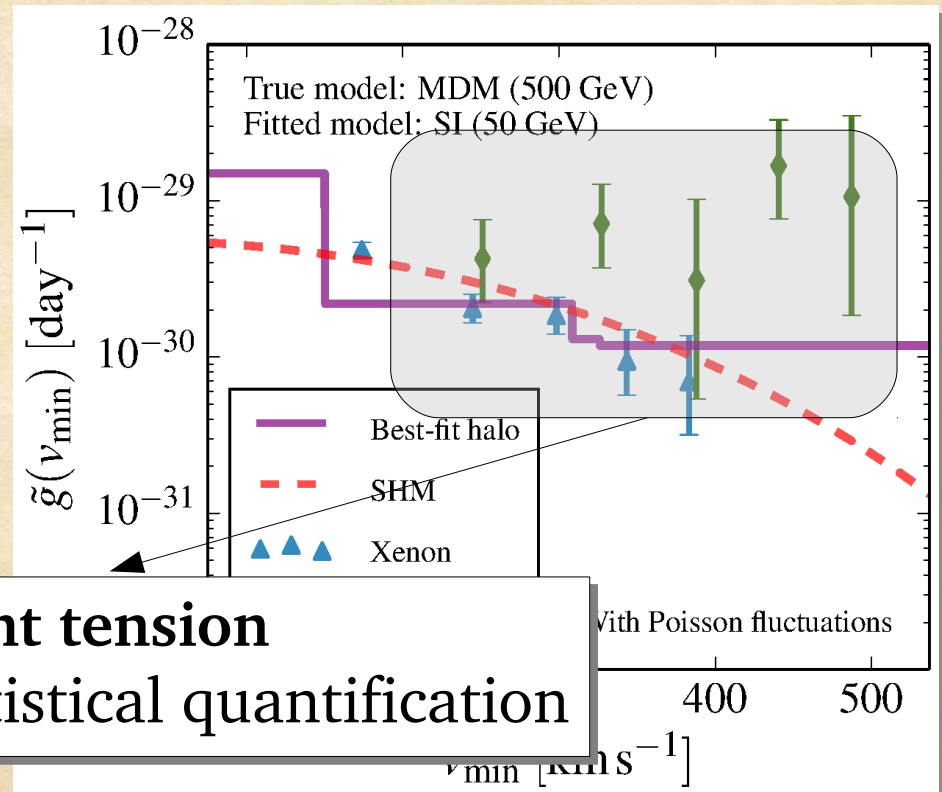
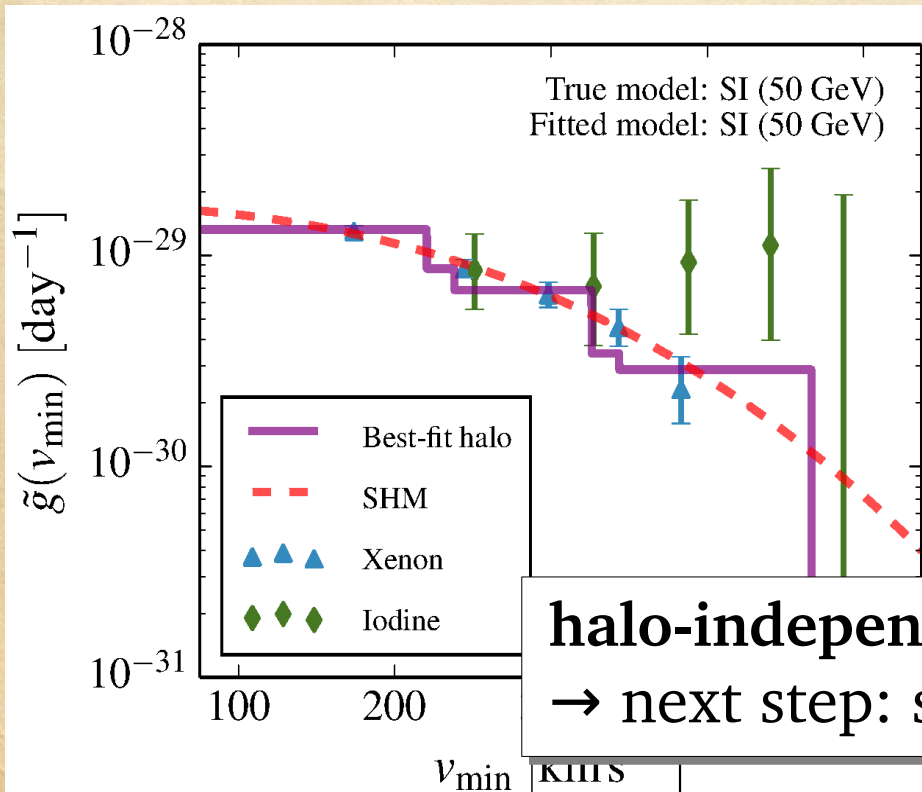
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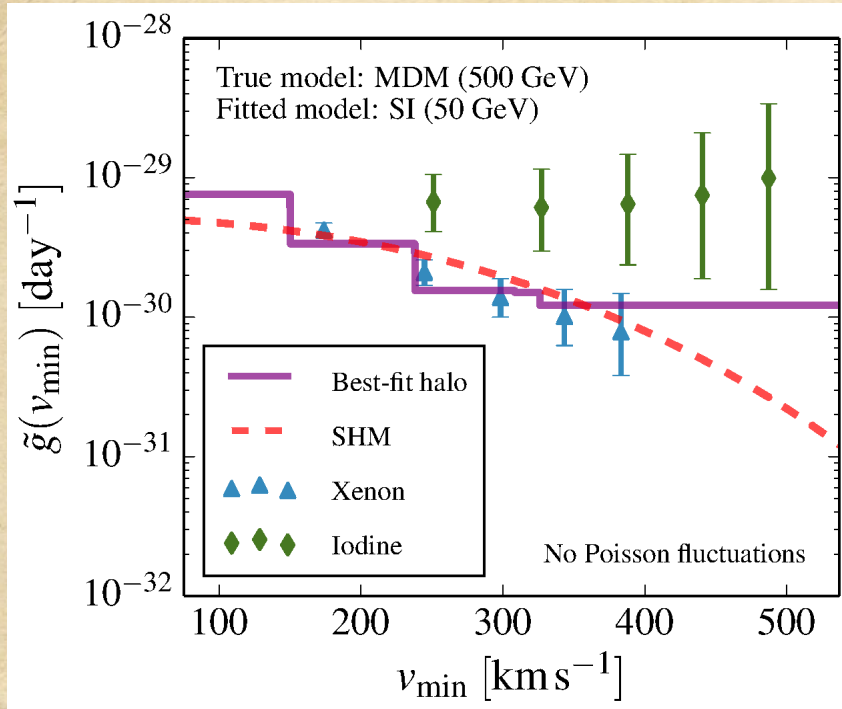
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halo-independent tension

→ next step: statistical quantification

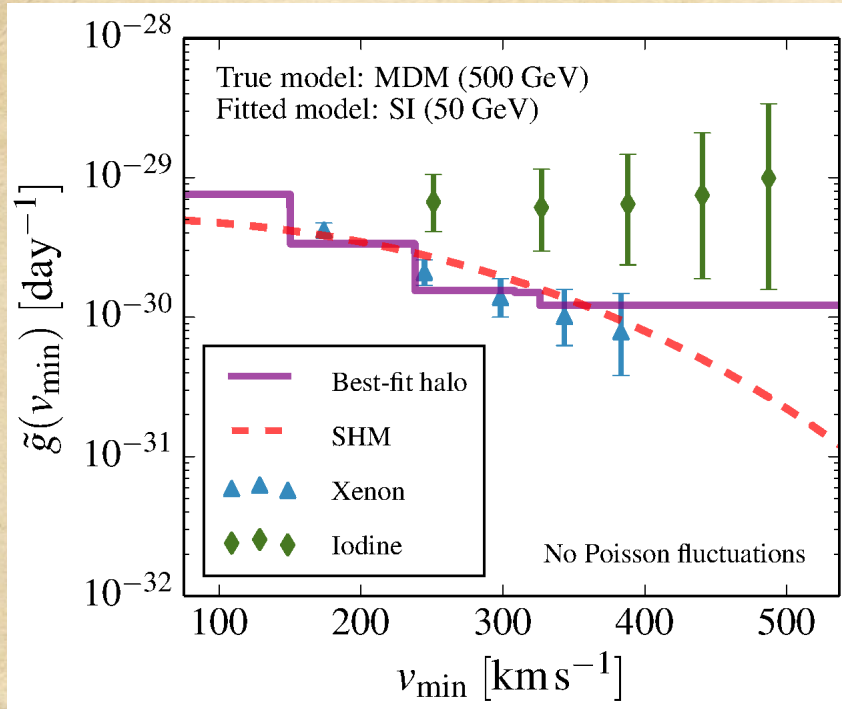
Fitting the velocity integral



- Question we want to answer:
is there **any** $g(v_{\min})$ providing a good fit?
- We parametrize $g(v_{\min})$ as a piecewise-constant function:
 $g(v_{\min}) = g_j$ for $v_{\min} \in [v_j, v_{j+1}]$
with $j = 1, \dots, N_s$

(Kahlhoefer et. al. [1403.4606])

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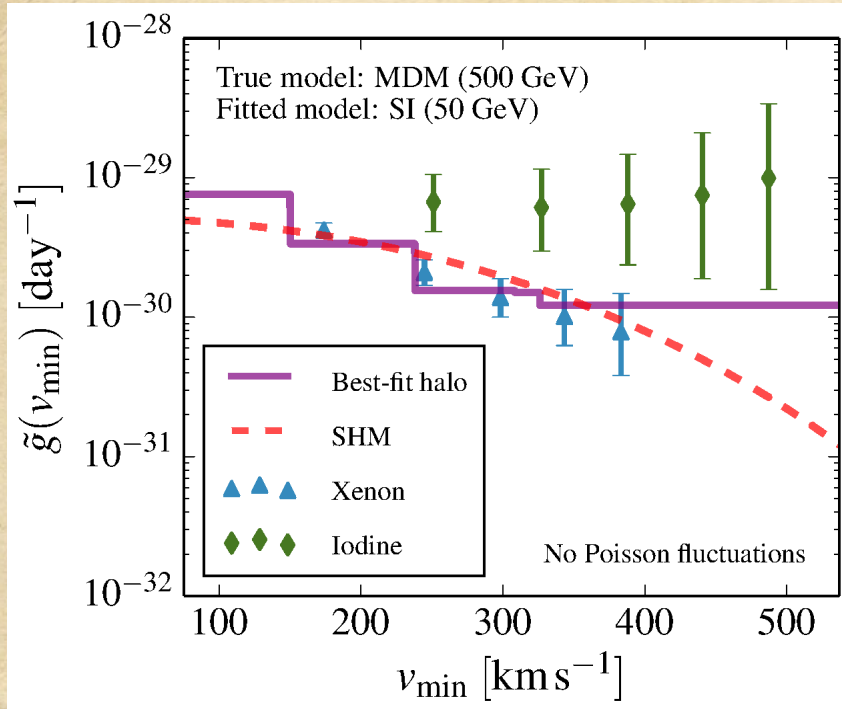
$$\Rightarrow R_i \equiv \int_{E_R^{(i)}}^{E_R^{(i+1)}} dE_R \frac{dR}{dE_R} = \sum_{j=1}^{N_s} D_{ij} g_j$$

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

matrix fully determined by the assumed
particle physics scenario

expected events
in bin i

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

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_{DM} and g_j),
assuming a given **fitted model**

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

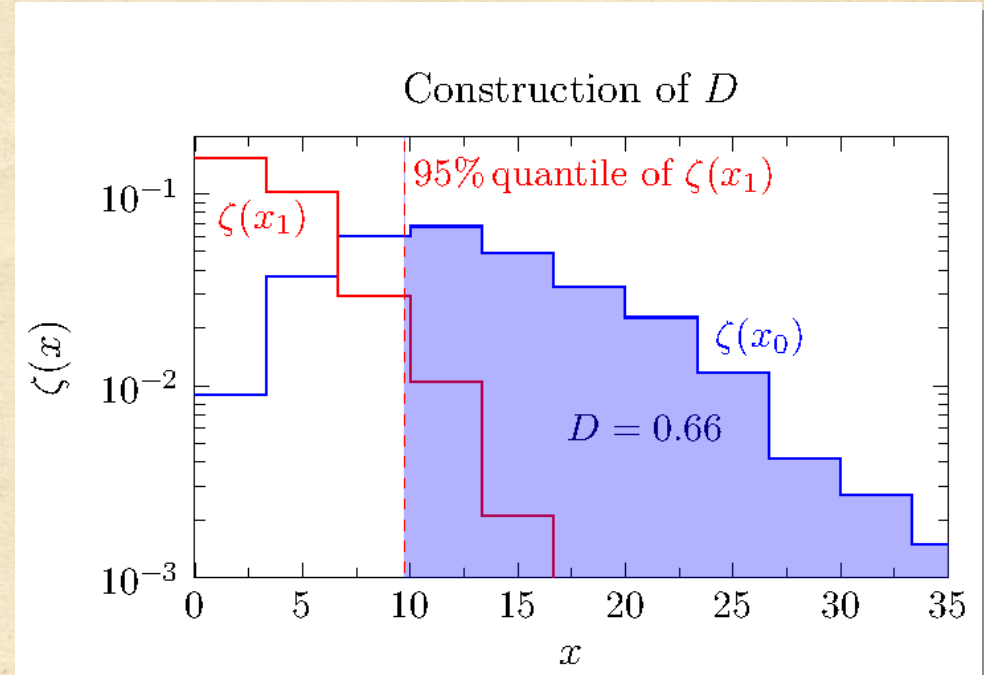
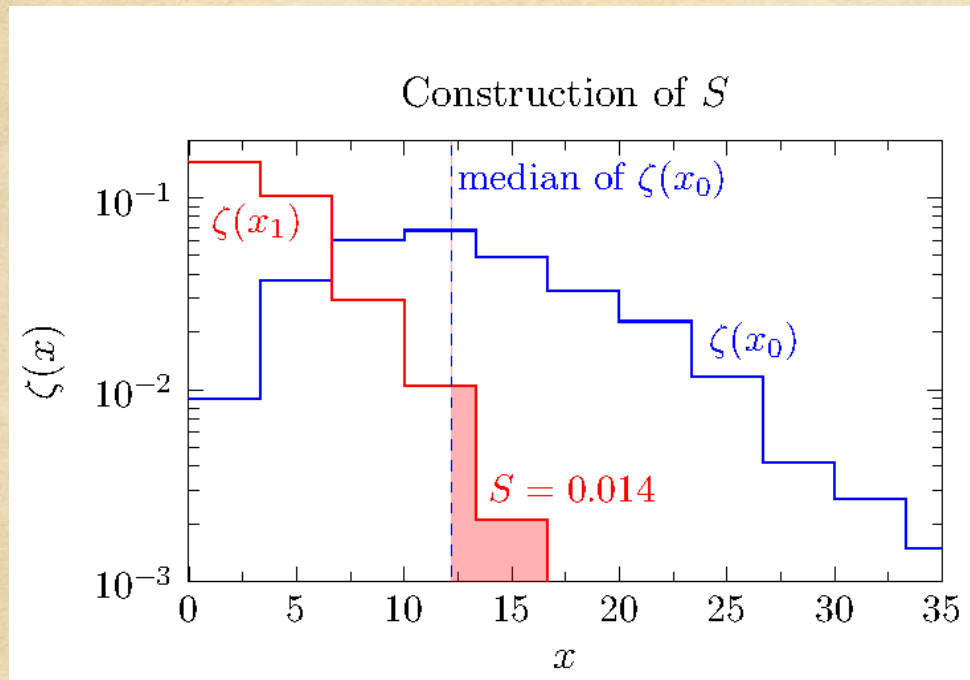
consider a typical prediction
of this **fitted model**

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
 $x_1 = -2 \log \mathcal{L}$

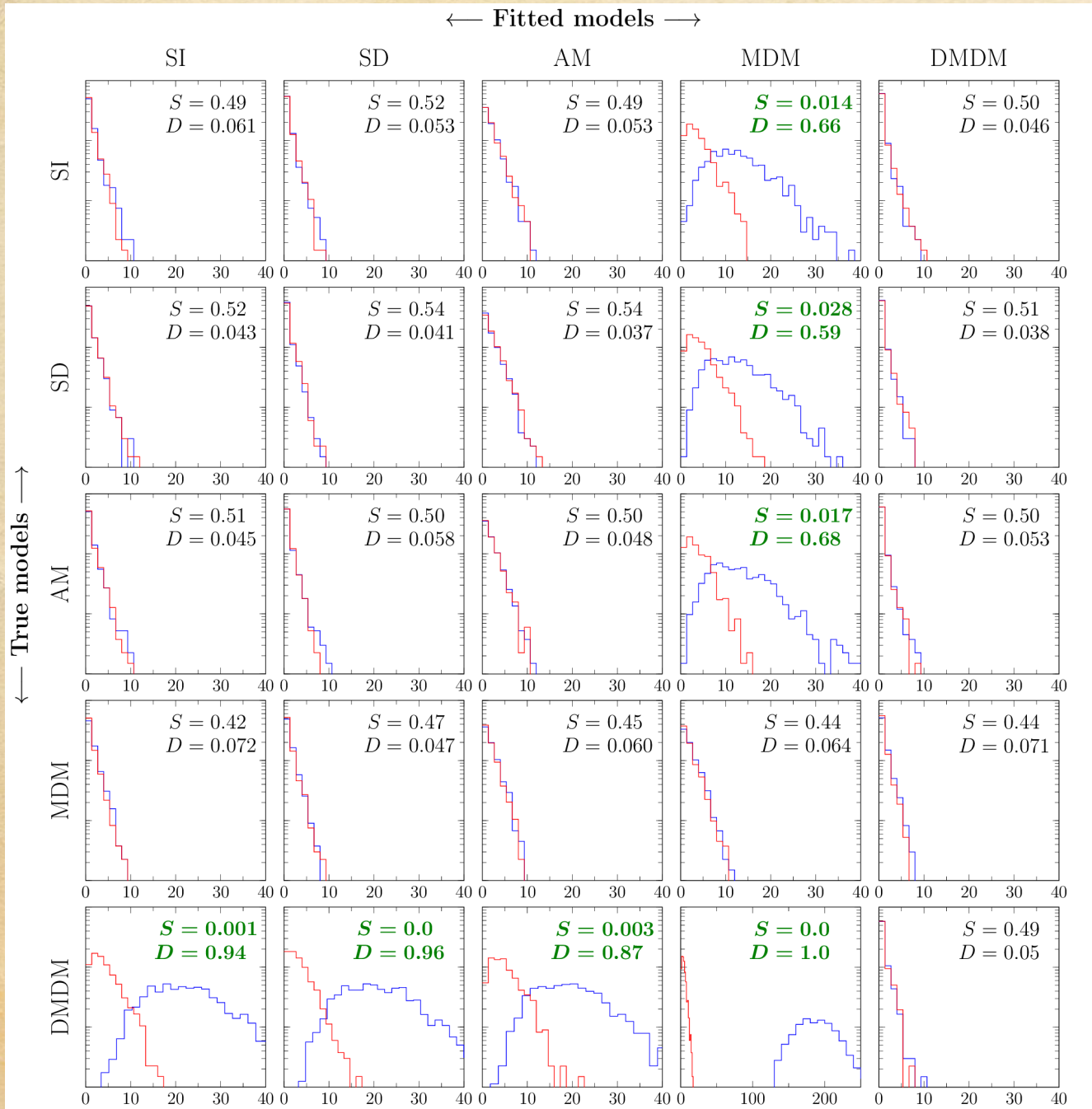
Similarity/Distinguishability of models



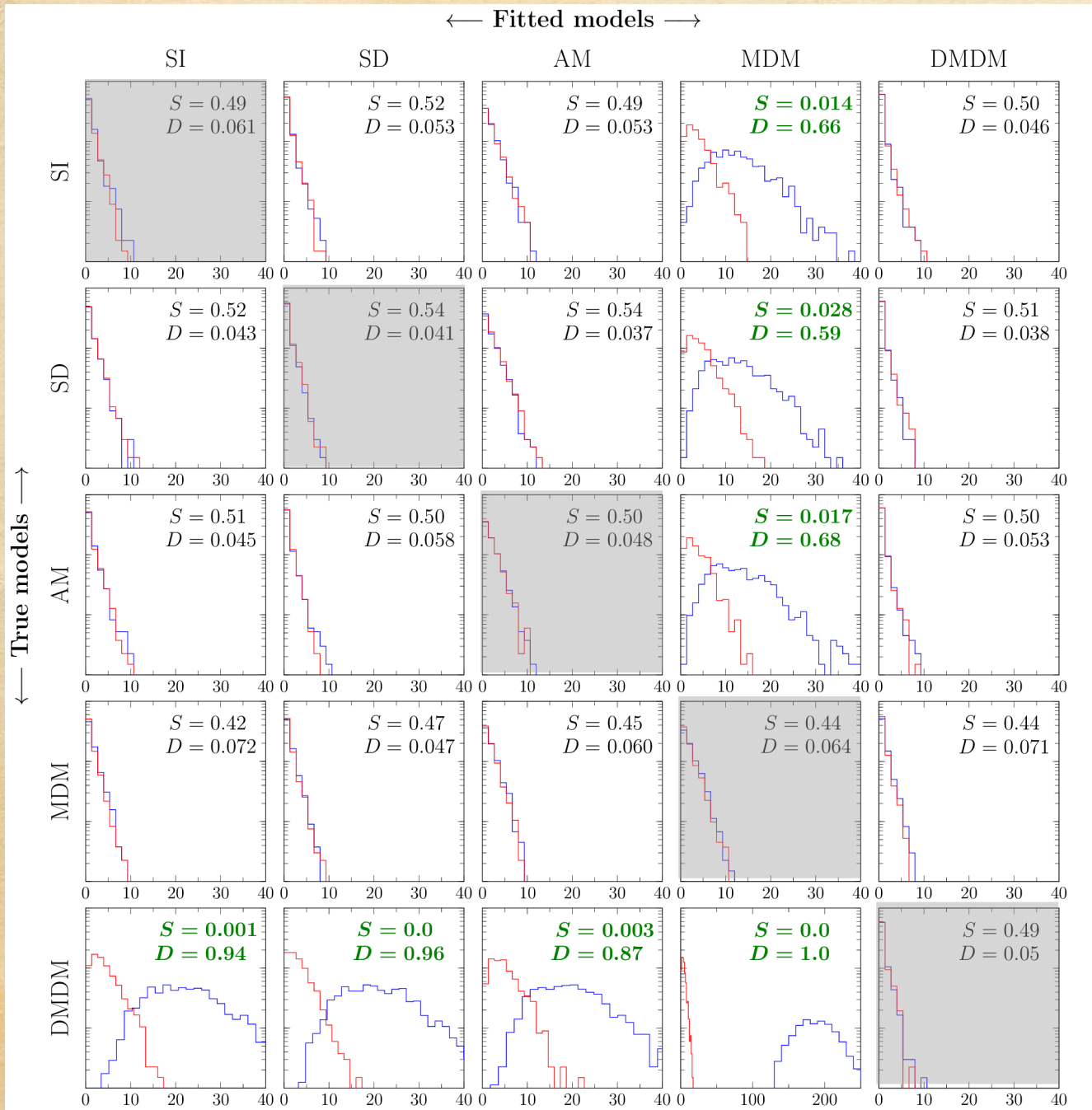
- Qualitative statement: if $\zeta(x_0)$ and $\zeta(x_1)$ look “sufficiently different”, the true model can be distinguished from the fitted model
 - Similarity S :** p-value of typical realization of the true model
 - Distinguishability D :** fraction of realizations with $p \leq 0.05$

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

Results (1): single xenon experiment



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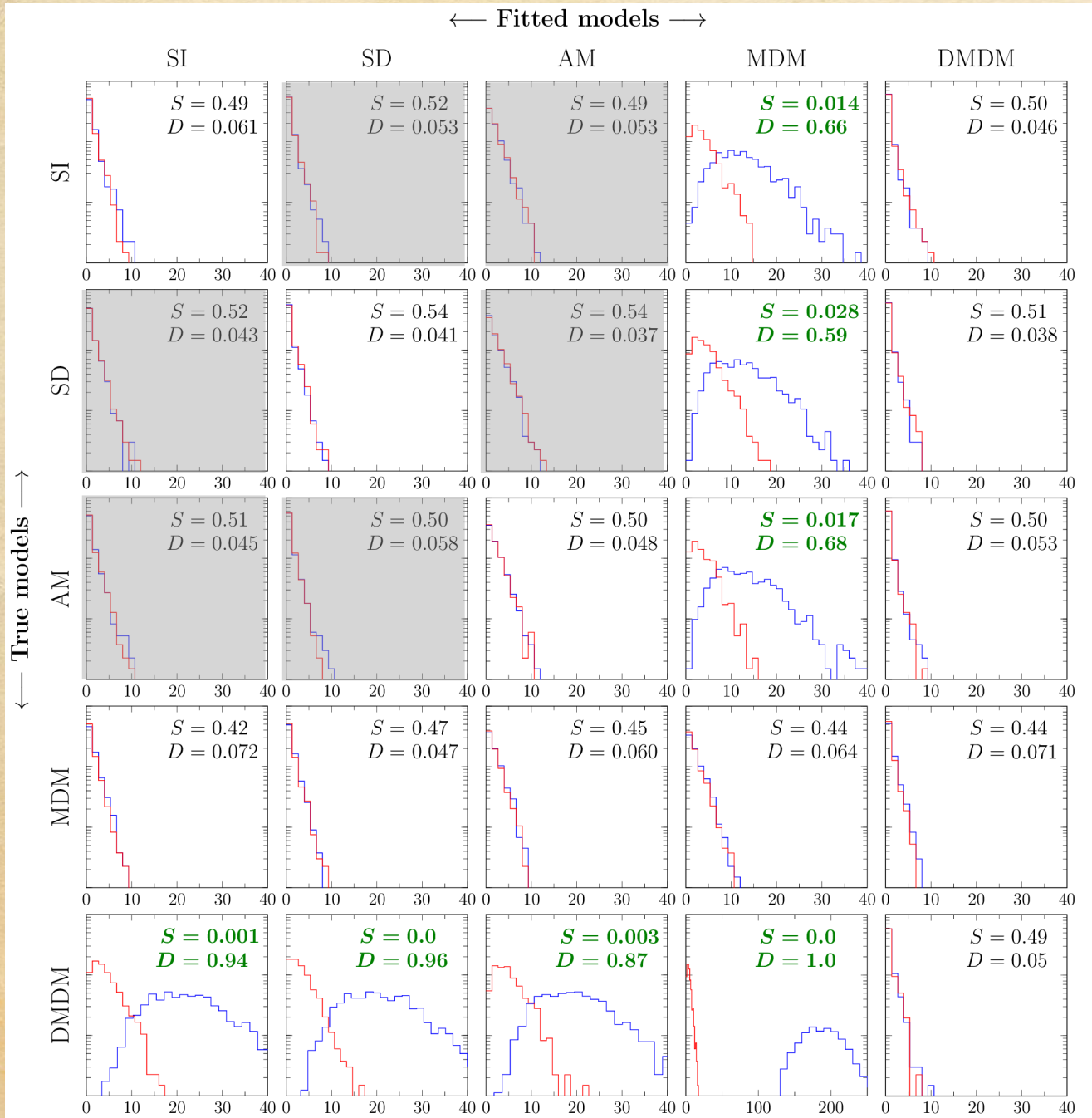


true model = fitted model

↓

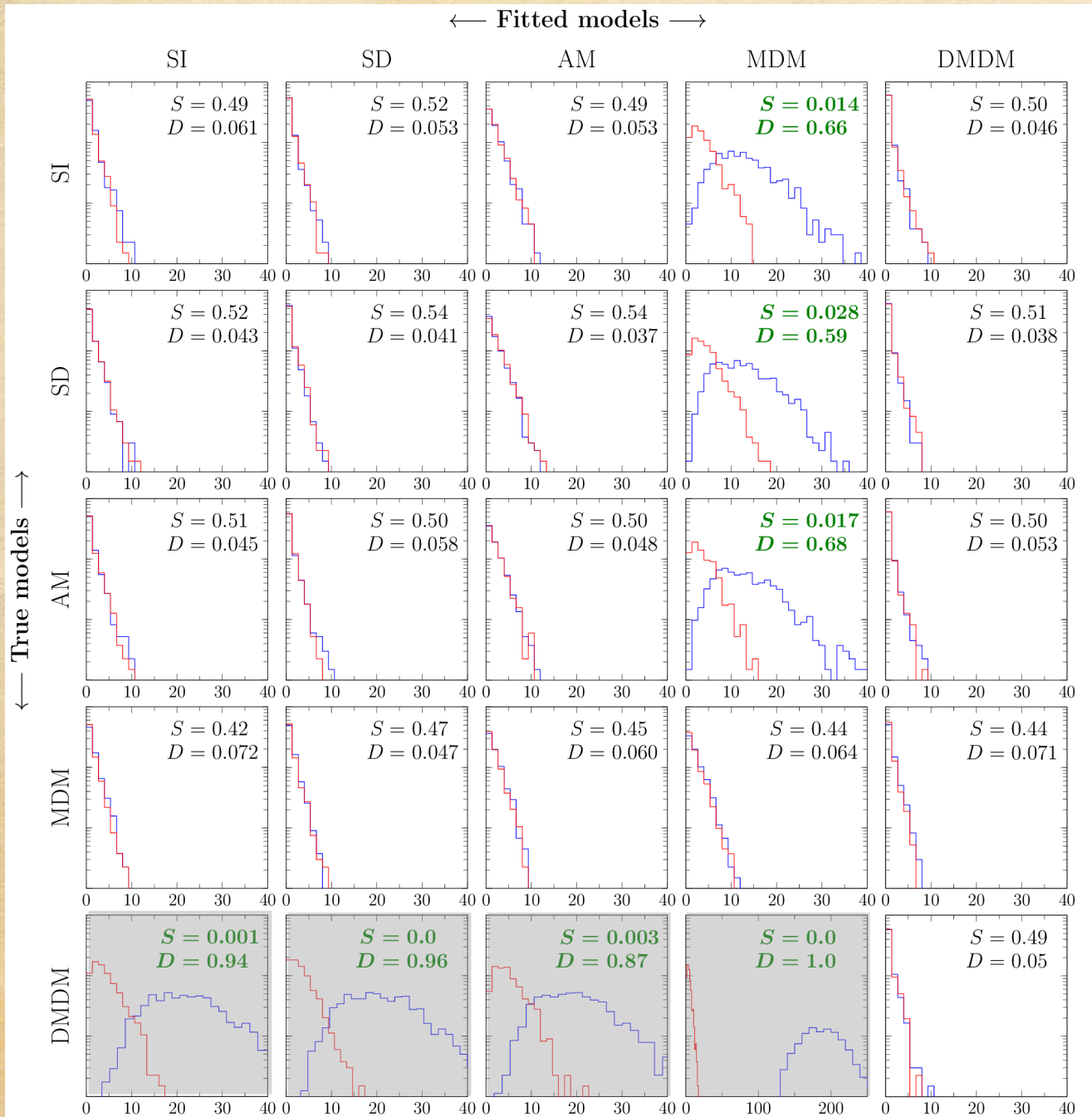
$$S \simeq 0.5, D \simeq 0.05$$

Results (1): single xenon experiment



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

Results (1): single xenon experiment

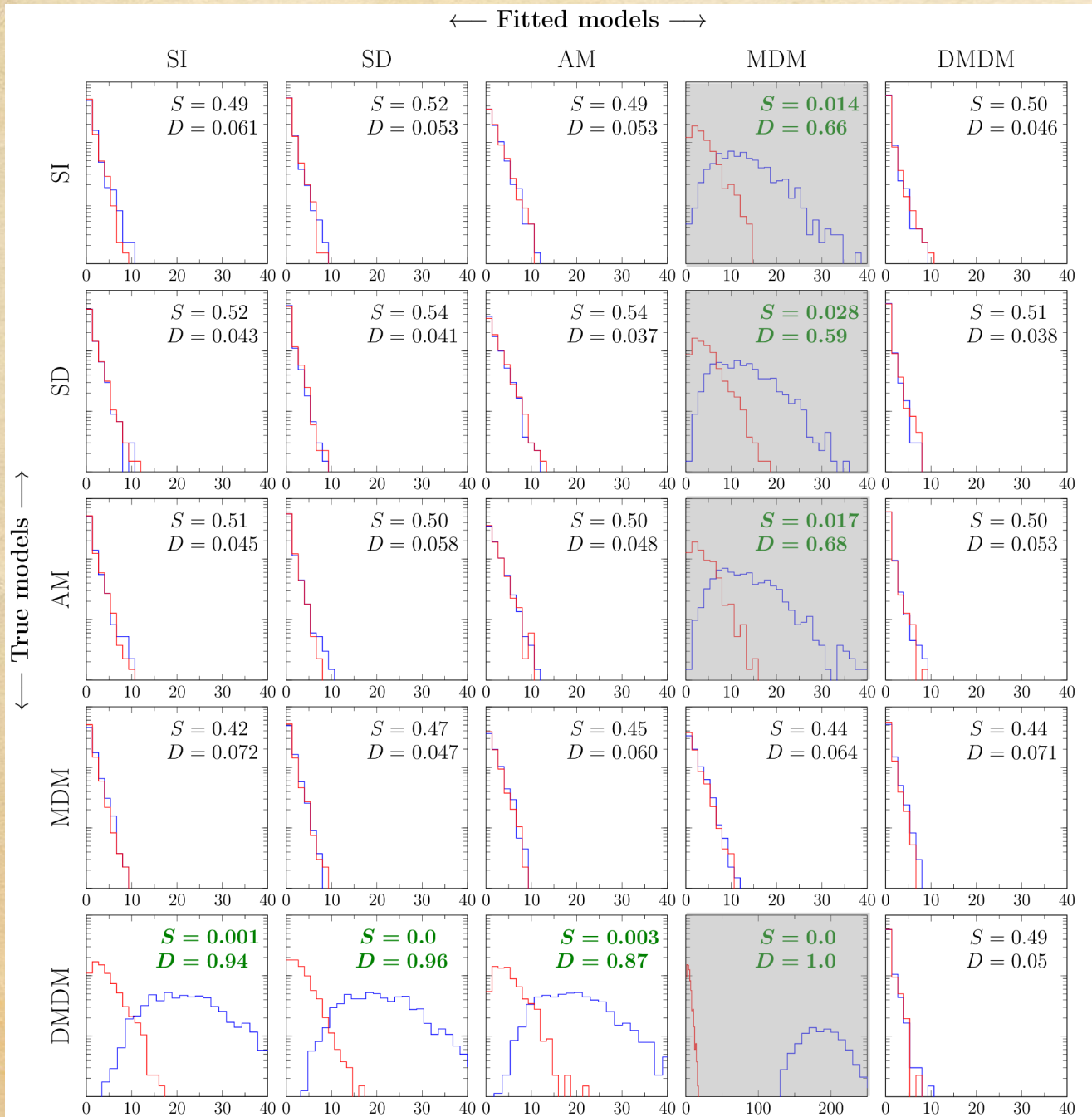


True model “dark magnetic magnetic dipole moment”
can be distinguished
from all other interactions!



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

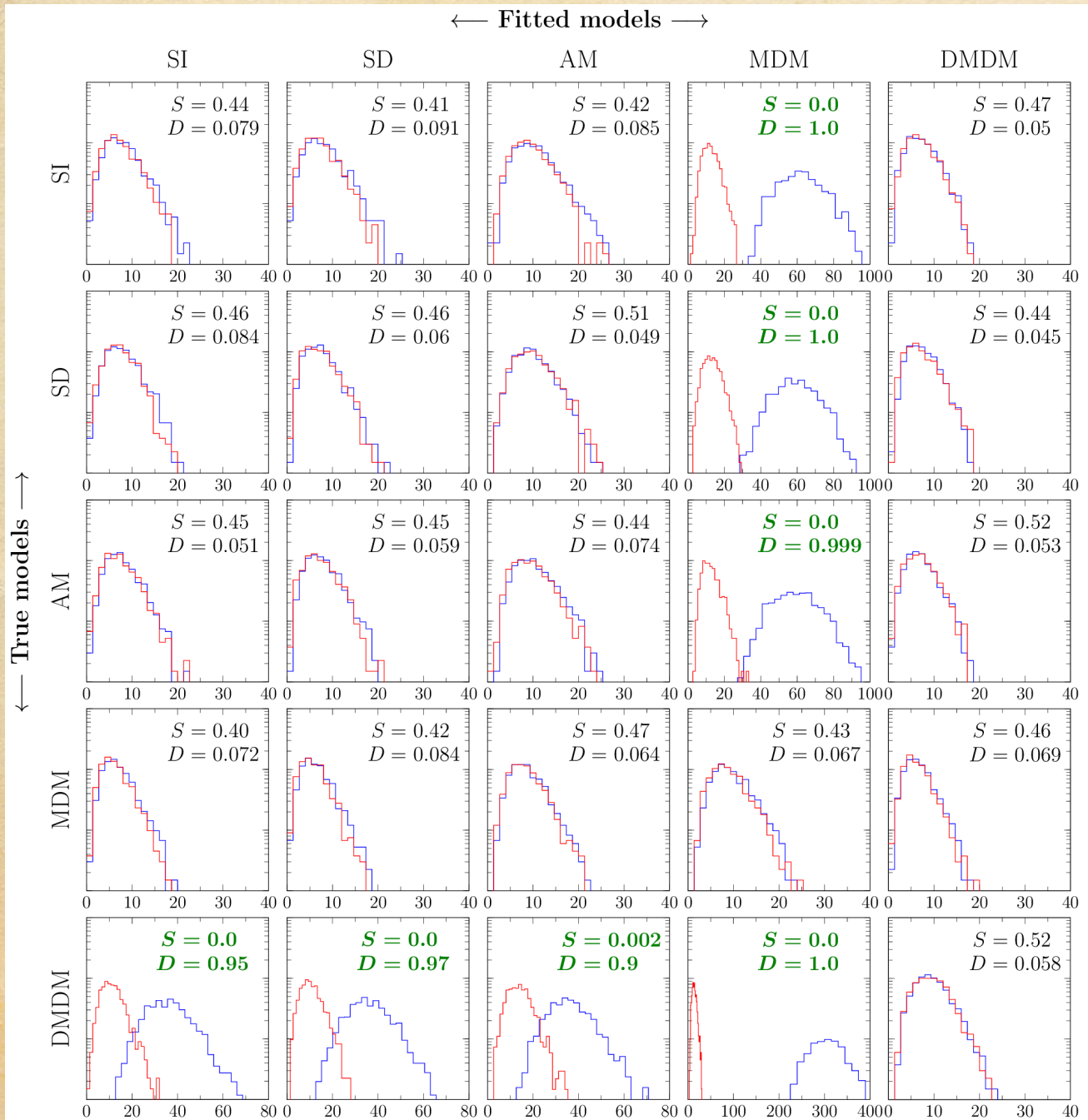
Results (1): single xenon experiment



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 $g(v_{\min})$

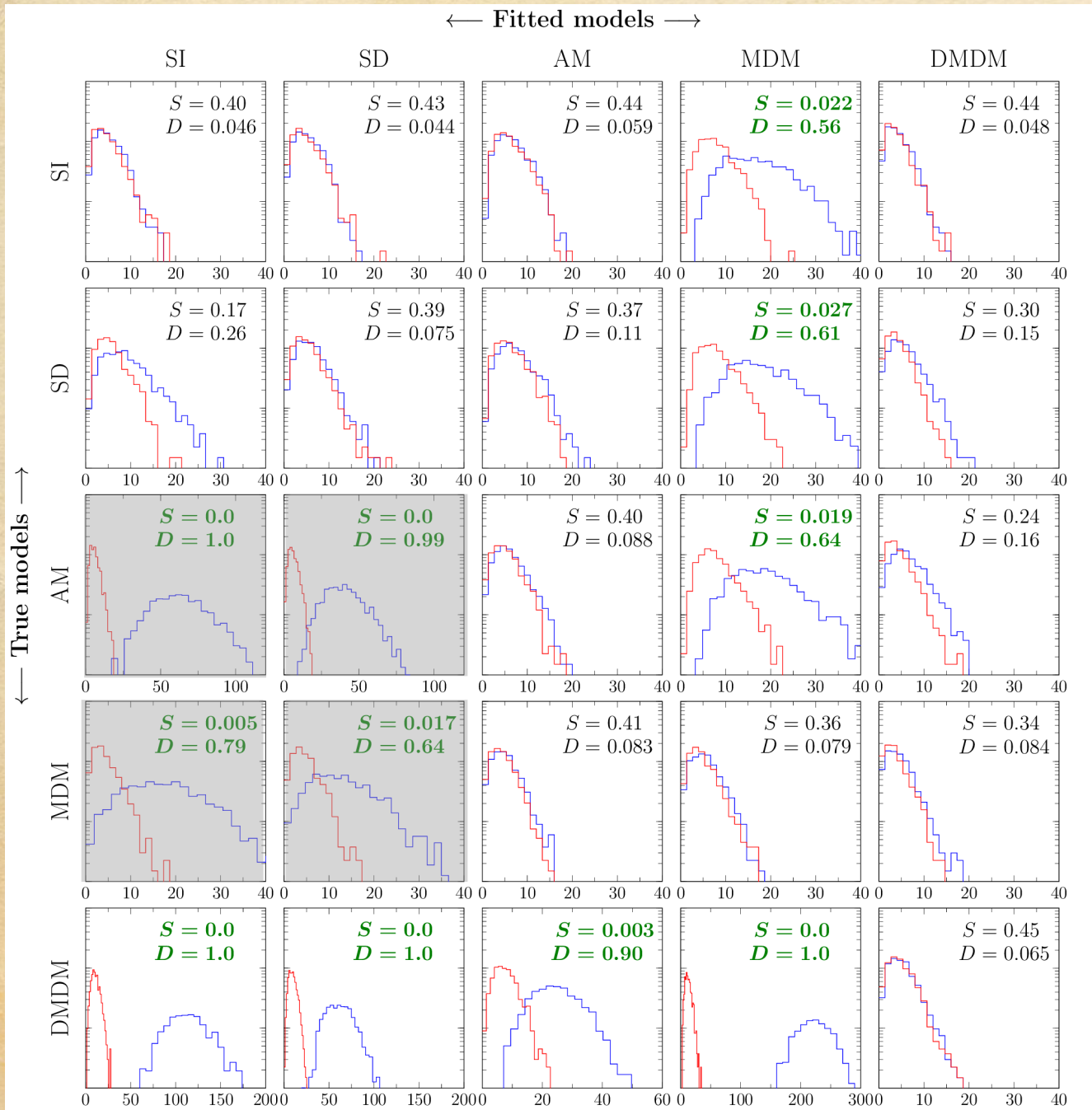
Results (2): xenon + germanium experiment



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: $\mu_{\text{magn}}^{(\text{I})} \gg \mu_{\text{magn}}^{(\text{Xe})}$

Outline

Evidence for dark matter & the idea of WIMPs

Direct detection of dark matter

Halo-independent determination of DM properties

- a) Interpreting (future) positive detections
- b) Upper limits from existing data

Conclusions

Halo-independent lessons from existing data?

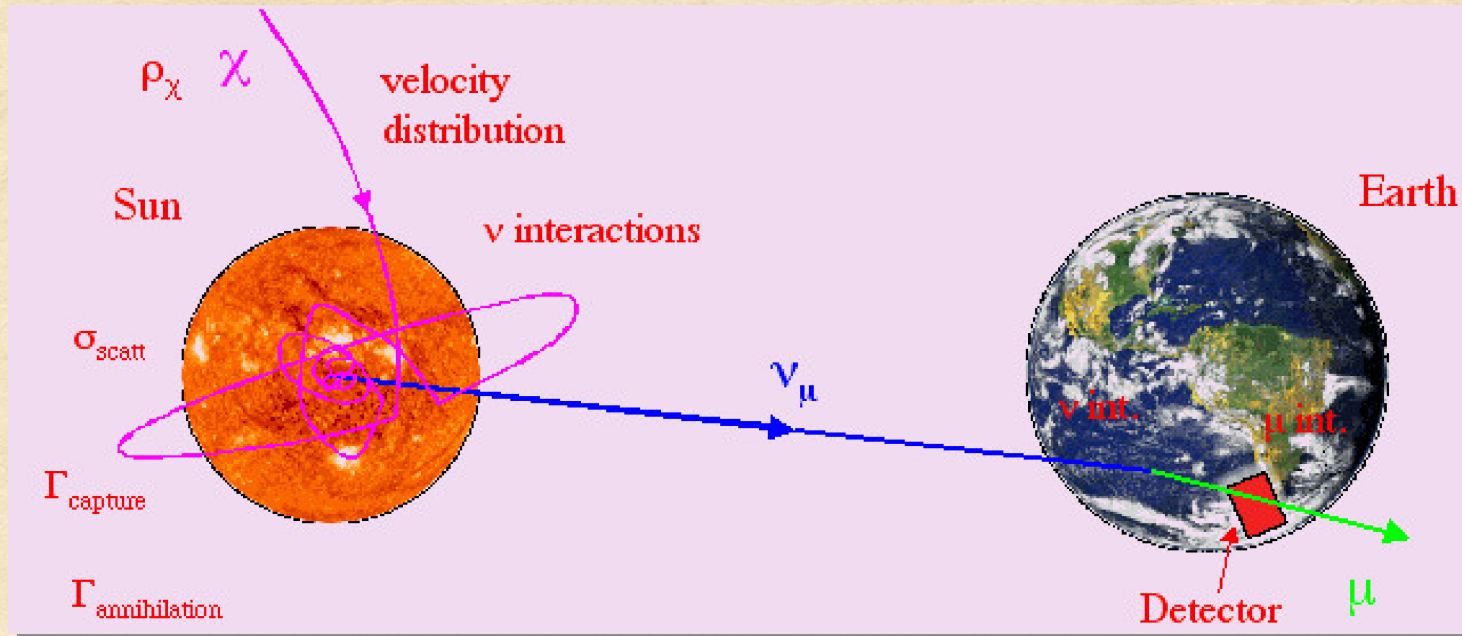
- So far, we are lacking a (conclusive) detection of DM in direct detection experiments
- Can we at least use the existing null search results for setting **upper limits** on $\sigma_{\text{DM}-p}$, independent of the choice of $f(v)$?
 - Problem: every direct detection experiment is insensitive in the limit $v \rightarrow 0$

Halo-independent lessons from existing data?

- So far, we are lacking a (conclusive) detection of DM in direct detection experiments
- Can we at least use the existing null search results for setting **upper limits** on $\sigma_{\text{DM}-p}$, independent of the choice of $f(v)$?
 - Problem: every direct detection experiment is insensitive in the limit $v \rightarrow 0$

→ There is no halo-independent upper limit on the DM scattering cross section from direct detection experiments alone!

Dark matter capture & annihilation in the Sun



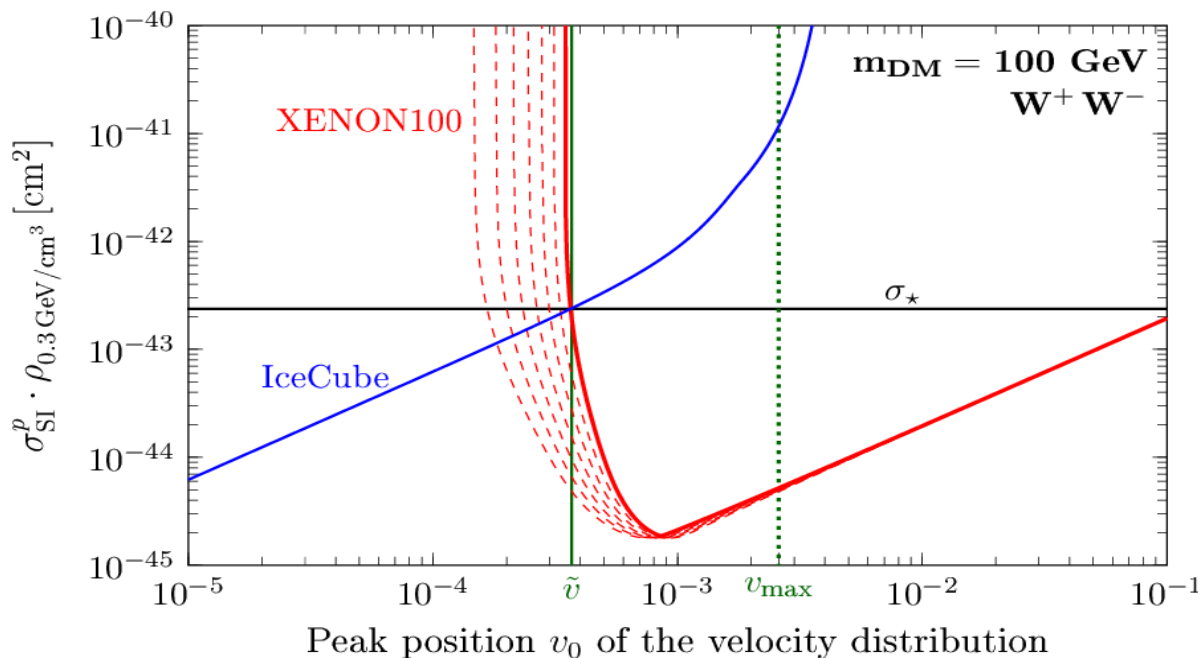
- DM scattering in the Sun: same process as direct detection!
- If energy loss is large enough $\rightarrow$ DM is **gravitationally bound**
- Trapped DM annihilates into SM particles
 - $\rightarrow$ high-energy neutrino flux correlated with the Sun's direction
 - $\rightarrow$ not observed so far by e.g. IceCube
- Crucial for our purposes:
capture rate is strongly enhanced in the limit $v \rightarrow 0$

Decomposing $f(v)$ into streams

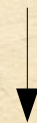
In order to quantify the complementarity of DD and capture in the Sun, we decompose the velocity distribution in (infinitely many) streams:

$$f(v) = \int_0^\infty dv_0 \delta(v - v_0) f(v_0)$$

Upper limit on σ_{SI}^p , for $f_{\vec{v}_0}(\vec{v}) = \delta^3(\vec{v} - \vec{v}_0)$

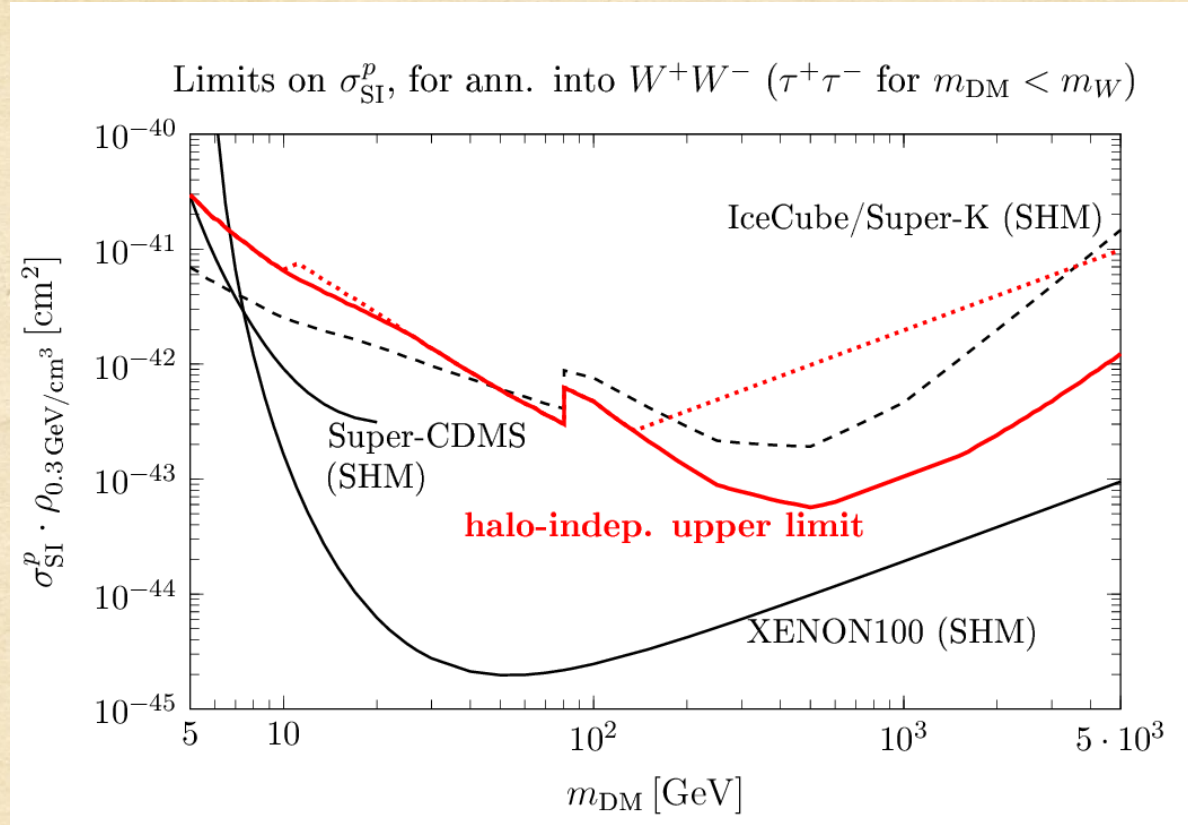


Either **direct detection** or **neutrino telescopes** lead to an upper limit on $\sigma_{\text{DM}-p}$, for *all* values of v_0



When combining DD and capture, one is sensitive to the **complete velocity space** of dark matter!

Halo-independent upper limits



Ferrer, Ibarra,
SW [1506.03386]

The complementarity of direct detection and neutrino telescopes leads to an **halo-independent upper limit** on $\sigma_{\text{DM}-p}$

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

Conclusions

- **WIMPs** are one of the most motivated (and most testable) particle candidates for dark matter
- **Direct detection** experiments look for the nuclear recoil produced by elastic scatterings of WIMPs
 - so far, no unambiguous signal has been detected
 - however, new experiments will probe significant new parts of the parameter space within the next decade!
- Can we determine particle physics properties from a future detection, even without making any assumption on the velocity distribution $f(v)$?
 - **yes**, depending on the experiment(s) and on the model
 - our method is based on finding the best-fit $f(v)$, and quantifying how good it can fit the experimental data
- We also derived a **halo-independent upper limit** on the DM-nucleon scattering cross section
 - for this, we combined DD with the information from capture and annihilation of DM in the Sun