A novel approach to derive halo-independent limits on dark matter properties

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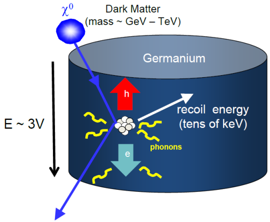
Based on arXiv:1506.03386 (to appear in JCAP)

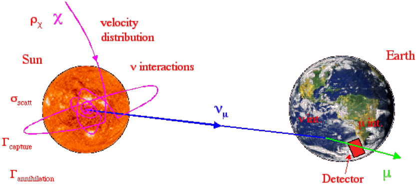
Francesc Ferrer, Alejandro Ibarra, SW

Direct detection vs. indirect detection with ν's from the Sun

Two methods of probing dark matter within in the Solar System:



Direct detection



Capture and annihilation of dark matter in the Sun

- Same particle physics:
  Both approaches probe the scattering cross section $\sigma_{\text{DM-nucleon}}$
- Different astrophysics:
  Complementary dependence on the **velocity distribution** of dark matter

Astrophysical input for DD and capture in the Sun

Astrophysics of dark matter entering the recoil and capture rate:

- $\rho_{\mathrm{DM}} \simeq (0.4 \pm 0.1)\,\mathrm{GeV/cm^3}$ $\rightarrow$ fixed in this talk
- $f(\vec{v})$: **not known!** $\rightarrow$ usual assumption: Maxwell-Boltzmann distribution
  $\hookrightarrow$ however, deviations are possible and actually expected!
  $\hookrightarrow$ stream(s), dark disc(s), ???

$\Rightarrow$ What is the impact of choosing a non-standard $f(\vec{v})$ on the upper limits on σ?

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Common approach: [see also the talk by Nassim Bozorgnia yesterday]

upper limit on R or C from experiment

$\downarrow$

assume a particular $f(\vec{v})$

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This talk:
halo-independent
upper limit

Our method for obtaining a halo-independent limit

Outline for the rest of the talk

Step 1: Only consider **pure streams**, i.e. $f(\vec{v}) = \delta^{(3)}(\vec{v} - \vec{v}_0)$

$\hookrightarrow$ we derive an upper limit on σ which is valid for all possible stream distributions

$\hookrightarrow$ "halo-independent" limit, but only valid for pure stream distributions

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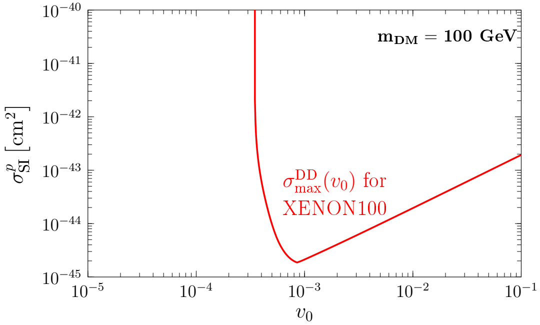
Step 2: We show **analytically** that this upper limit for stream distributions **automatically implies** an upper limit on σ which is valid for all possible $f(\vec{v})$

Step 1: upper limit for $f(\vec{v}) = \delta^{(3)}(\vec{v} - \vec{v}_0)$



- The following discussion is for fixed m_{DM}, and for SI scattering
- $\sigma_{\max}^{\mathrm{DD}}(v_0)$: upper limit from direct detection, for $f(\vec{v}) = \delta^{(3)}(\vec{v} - \vec{v}_0)$
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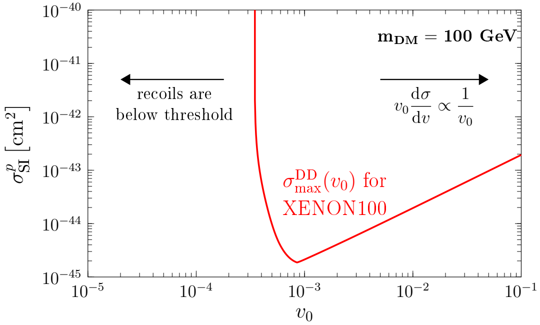

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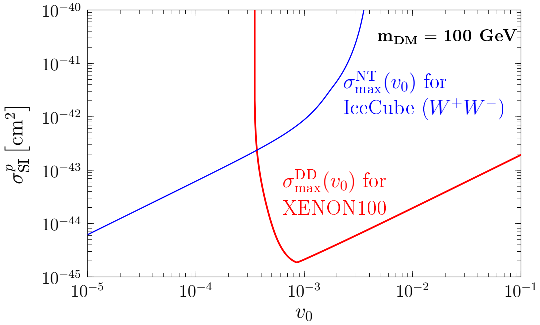

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  $\hookrightarrow$ for illustration, we fix the ann. channel to W^+W^-
- We calculate $\sigma^{\rm NT}_{\rm max}(v_0)$ with the usual techniques following Gould et. al. (Standard Solar Model, 29 elements, Gaussian form factor)
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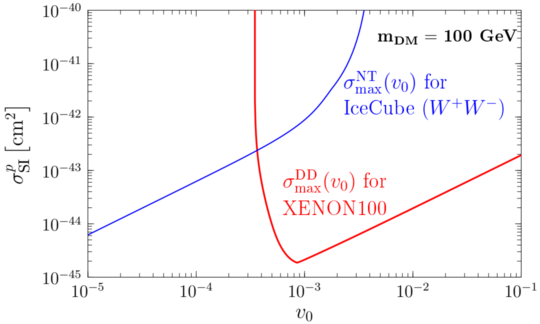

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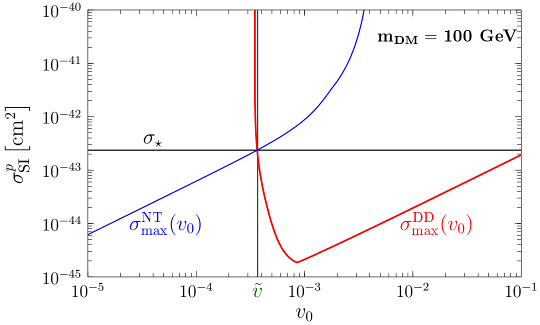
$\Rightarrow$ Direct detection and capture in the Sun are sensitive to **different, overlapping parts** of the velocity space

Upper limit on σ valid for all stream distributions



- We define $\sigma_\star$ by the requirements

$$\sigma^{NT}_{max}(v_0) \le \sigma_\star \quad \text{for } 0 \le v_0 \le \tilde{v}$$

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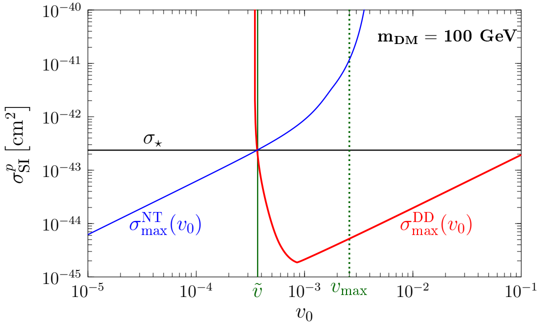

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- This requires one (small) restriction on the velocity distribution: $f(\vec{v}) \equiv 0$ for $v > v_{max}$ ($\triangleq$ galactic escape velocity, not crucial!)

Step 2: halo-independent upper limit on σ

Step 1 is done: $\sigma_\star$ is an upper limit on σ, valid for all possible stream distributions

Step 2: Upper limit on σ valid for all possible $f(\vec{v})$

- Any $f(\vec{v})$ can be **decomposed** into (infinitely many) streams:

$$f(\vec{v}) = \int \mathrm{d}^3 v_0 \, \delta^{(3)}(\vec{v} - \vec{v}_0) f(\vec{v}_0)$$

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- All rates are linear in $f(\vec{v})$ $\Rightarrow$ $1/\sigma_{\text{upper limit}}$ is linear in $f(\vec{v})$

$$\Rightarrow \quad \frac{1}{\sigma^{\text{DD}}_{\text{upper limit for } f(\vec{v})}} \equiv \int \mathrm{d}^3 v_0 \frac{f(\vec{v_0})}{\sigma^{\text{DD}}_{\text{max}}(v_0)}$$

$$\frac{1}{\sigma^{\text{NT}}_{\text{upper limit for } f(\vec{v})}} \equiv \int \mathrm{d}^3 v_0 \frac{f(\vec{v_0})}{\sigma^{\text{NT}}_{\text{max}}(v_0)}$$

$\Rightarrow$ The upper limit on σ corresponding to $f(\vec{v})$ can always be written as a **superposition** of limits $\sigma^{\text{DD/NT}}_{\text{max}}(v_0)$ corresponding to DM streams

Constructing a halo-independent upper limit on σ_p

Claim: $2 \cdot \sigma_\star$ is an upper limit valid for **all possible distributions** $f(\vec{v})$

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$$\Rightarrow \quad \sigma \leq \frac{\sigma_\star}{\delta_f} \quad \text{and} \quad \sigma \leq \frac{\sigma_\star}{1-\delta_f} \quad \text{with } \delta_f \equiv \int_{\tilde{v} \leq |\vec{v}_0| \leq v_{\rm max}} \mathrm{d}^3 v_0 \, f(\vec{v}_0)$$

$$\Rightarrow \quad \sigma = \delta_f \cdot \sigma + (1-\delta_f) \cdot \sigma \leq \sigma_\star + \sigma_\star = 2\sigma_\star \qquad \textit{q.e.d.}$$

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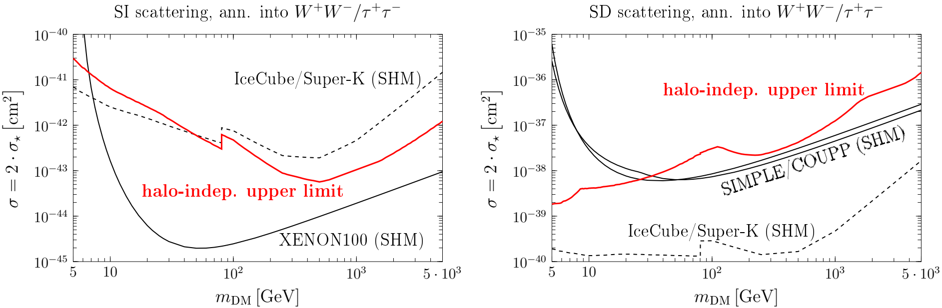
→ We then construct $\sigma_\star$ for every m_{DM}, for SI and SD scattering, and for annihilation into W^+W^- and $b\bar{b}$

Halo-independent upper limits: results



- The red curves show the **halo-independent upper limit**, valid in particular for non-maxwellian $f(\vec{v})$, streams, dark disc(s), anisotropic distributions, ...
- The limit is still degenerate with $\rho_{\rm local}$, which we fix to 0.3 GeV/cm^3
  $\hookrightarrow$ effectively, we constraint $\sigma \cdot \rho_{\rm local}$
- Black: upper limits assuming standard Maxwell-Boltzmann distribution

For some scenarios, the halo-independent upper limits are remarkably strong

Side remark: our method can also be used for setting a halo-independent *lower limit* on σ, arising from a positive signal in DD (see paper)

Conclusions

- Direct detection and capture in the Sun are sensitive to different, overlapping parts of the velocity space of dark matter
  $\hookrightarrow$ Taken together, they probe the **complete range** of relevant velocities
- First, we explicitly construct an upper limit on σ valid for all possible **stream distributions**
- We then show analytically that this upper limit leads to a **halo-independent upper limit** on σ
  $\hookrightarrow$ this limit applies in particular for anisotropic distributions, stream(s), dark disc(s), …
- For some cases, the halo-independent upper limits on σ can be remarkably strong

Backup slides

Halo-independent upper limits: comments

Only assumptions behind our halo-independent upper limits on σ_p:

- $v_{\rm max} = (533 + 244)$ km/s (not crucial)
- Equilibrium between capture and annhilation
  $\hookrightarrow$ ensured for $\langle \sigma v \rangle \gtrsim 10^{-28}$cm^3/s
- $f(\vec{v})$ is homogeneous on the scale of the Solar system
- $f(\vec{v})$ has been constant in time (on scales of $\tau_{\rm equilibrium}$)
- Numerical value of the limit depends on the annihilation channel

In particular, our limits do apply for...

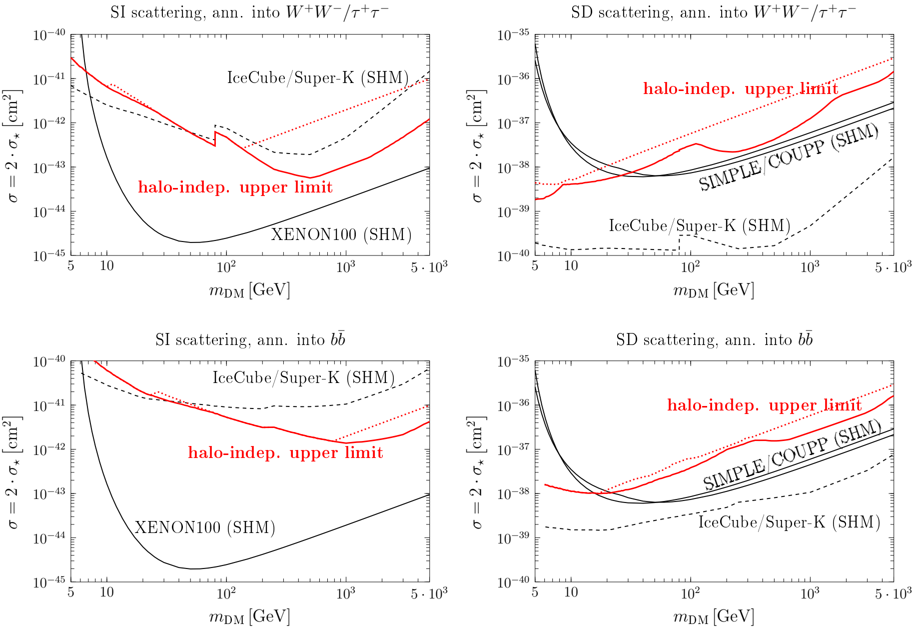
- non-maxwellian $f(\vec{v})$, arbitrary number of streams, dark disc(s), ...
- anisotropic velocity distributions

$\hookrightarrow$ Be aware: limit on σ_p is still degenerate with the local density $\rho_{\rm loc}$, of course.

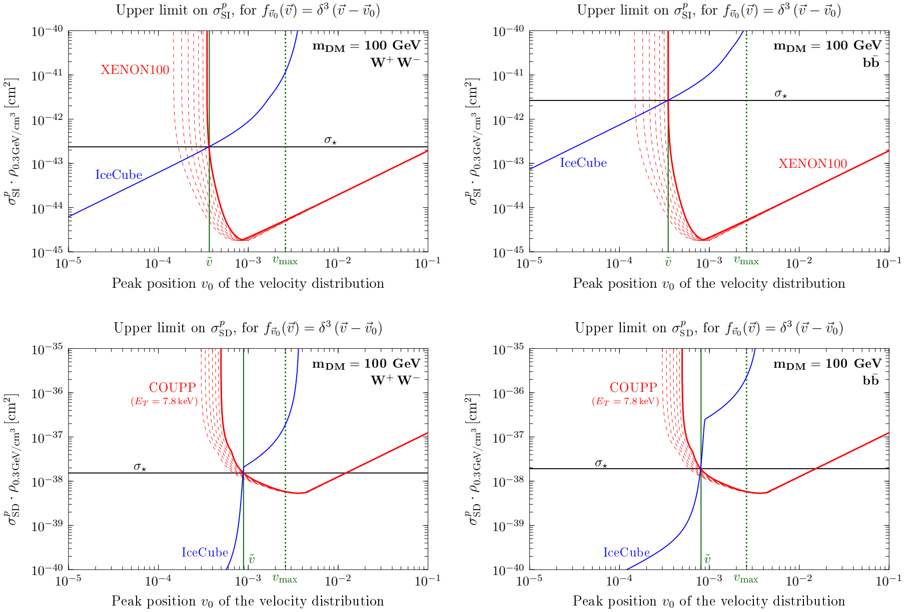
Relation to other works:

- All other halo-independent approaches (Fox et. al., Gondolo et. al., Kahlhoefer et. al.) directly compare DD experiments, without obtaining upper limits on σ_p

Halo-independent upper limits: all cases



Construction of the halo-independent upper limits



Halo-independent *lower* limit on the scattering cross section