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

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TUM, Munich

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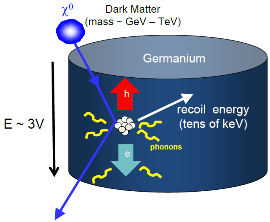
Based on [1506.03386] (JCAP '15)

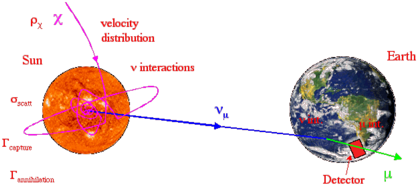
Francesc Ferrer, Alejandro Ibarra, SW

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:

- $\rho_{\mathrm{DM}} \simeq (0.3 \pm 0.1)\,\mathrm{GeV/cm^3} \;\rightarrow$ 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), ???

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$\Rightarrow$ What is the impact of choosing different $f(\vec{v})$ on the upper limit on σ?

Common approach:

$\boxed{\text{upper limit on } R \text{ or } C \text{ from experiment}}$

$\downarrow$

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

$\downarrow$

$\boxed{\text{upper limit on } \sigma_{\mathsf{DM\text{-}nucleon}}}$

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This talk:
halo-independent
upper limit

Our method for obtaining a halo-independent limit

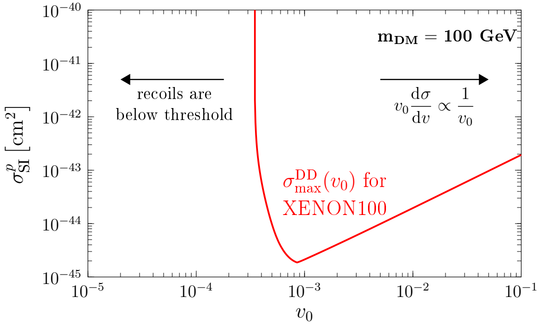
Outline for the rest of the talk

Step 1: Only consider **pure streams**, i.e. $f(\vec{v}) = \delta^{(3)}(\vec{v} - \vec{v}_0)$
$\hookrightarrow$ We construct an upper limit on σ, which is independent of $\vec{v}_0$

$$\downarrow$$

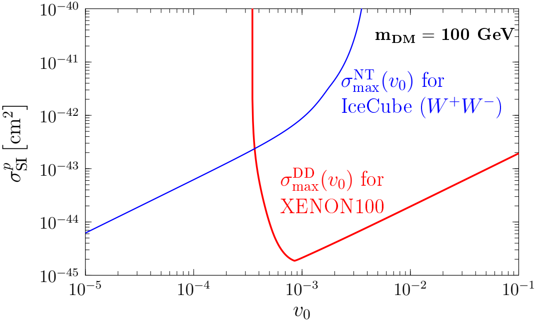
Step 2: We show **analytically** that this upper limit for stream distributions **automatically implies** an upper limit on σ which is valid for all possible $f(\vec{v})$

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



- The following discussion is for fixed $m_{\rm DM}$, and for SI scattering
- $\sigma^{\rm DD}_{\rm max}(v_0)$: upper limit from direct detection, for $f(\vec{v}) = \delta^{(3)}(\vec{v} - \vec{v}_0)$
- We calculate $\sigma^{\rm DD}_{\rm max}(v_0)$ for various experiments taking into account detector efficiencies, form factors, etc.

Step 1: adding the neutrino telescopes



- $\sigma^{\rm NT}_{\rm max}(v_0)$: upper limit from neutrino telescopes, for $f(\vec{v}) = \delta^{(3)}(\vec{v} - \vec{v}_0)$
  $\hookrightarrow$ 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)
- In contrast to direct detection, the capture process is kinematically favored for **small** dark matter velocities v_0

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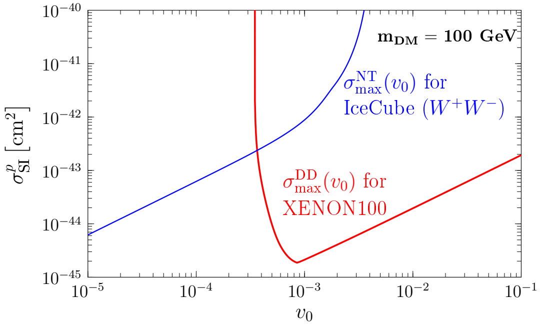

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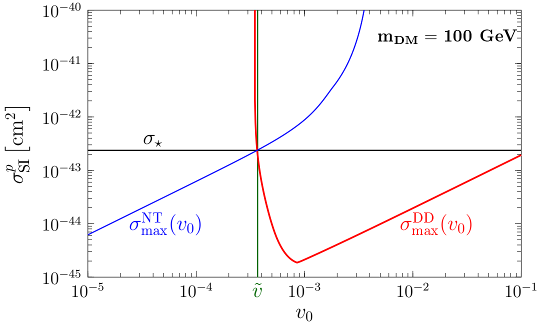
$\Rightarrow$ Direct detection and capture in the Sun are sensitive to **different, overlapping parts** of the velocity space

Upper limit on σ valid for all stream distributions



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

$$\sigma_{\max}^{\mathrm{NT}}(v_0) \le \sigma_\star \quad \text{for } 0 \le v_0 \le \tilde{v}$$
$$\sigma_{\max}^{\mathrm{DD}}(v_0) \le \sigma_\star \quad \text{for } \tilde{v} \le v_0 \le v_{\max}$$

$$\Downarrow$$

$\sigma_\star$ is an upper limit valid for **all stream distributions**

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

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

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

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

$\Rightarrow$

Main idea:

a) By construction, $\sigma^{\mathsf{DD}}_{\mathsf{max}}(v_0)$ and $\sigma^{\mathsf{NT}}_{\mathsf{max}}(v_0)$ are bounded by $\sigma_\star$

b) $1/\sigma^{\mathsf{DD/NT}}_{\text{upper limit for} f(\vec{v})}$ is a **normalized superposition** of $1/\sigma^{\mathsf{DD/NT}}_{\mathsf{max}}(v_0)$

$\Rightarrow$ There exists an upper bound on σ which is **independent** of $f(\vec{v})$!

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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Sketch of the proof: (all details in the paper)

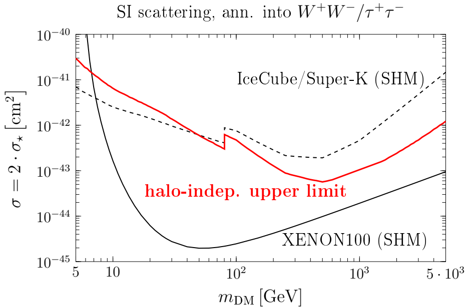
$$\sigma^{\mathsf{DD}}_{\text{upper limit for } f(\vec{v})} = \left[\int \mathrm{d}^3 v_0 \, \frac{f(\vec{v}_0)}{\sigma^{\mathrm{DD}}_{\mathrm{max}}(v_0)} \right]^{-1} , \quad \sigma^{\mathrm{DD}}_{\mathrm{max}}(v_0) \leq \sigma_\star \text{ for } \tilde{v} \leq v_0 \leq v_{\mathrm{max}}$$

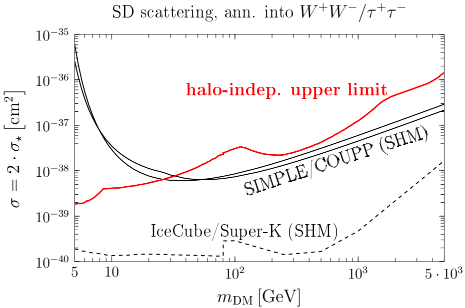
$$\sigma^{\mathsf{NT}}_{\text{upper limit for } f(\vec{v})} = \left[\int \mathrm{d}^3 v_0 \, \frac{f(\vec{v}_0)}{\sigma^{\mathrm{NT}}_{\mathrm{max}}(v_0)} \right]^{-1} , \quad \sigma^{\mathrm{NT}}_{\mathrm{max}}(v_0) \leq \sigma_\star \text{ for } 0 \leq v_0 \leq \tilde{v}$$

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

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

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:

- $v_{\max} = (533 + 244)$ 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 $\tau_{\text{equilibrium}}$)
- Numerical value of the limit depends on the annihilation channel

In particular, our limits do apply for...

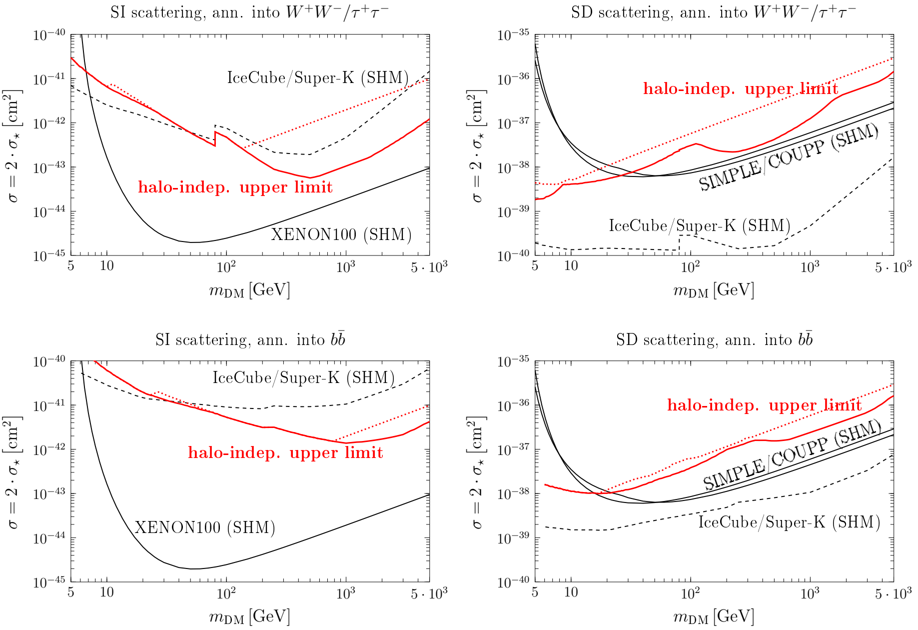
- non-maxwellian $f(\vec{v})$, arbitrary number of streams, dark disc(s), ...
- anisotropic velocity distributions

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

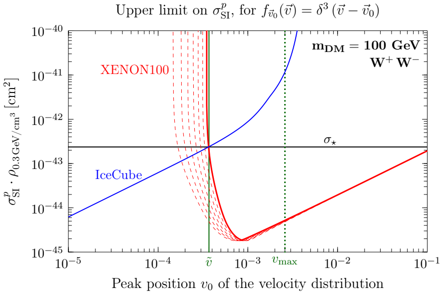
Relation to other works:

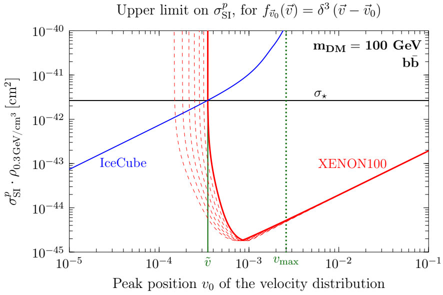
- All other halo-independent approaches (Fox et. al., Gondolo et. al., Kahlhoefer et. al.) directly compare DD experiments, without obtaining upper limits on σ_p

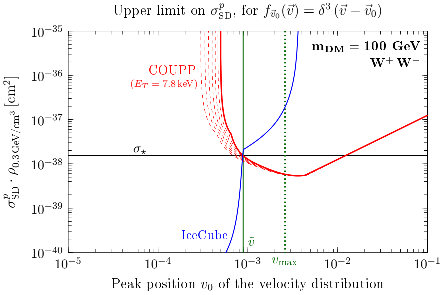
Halo-independent upper limits: all cases

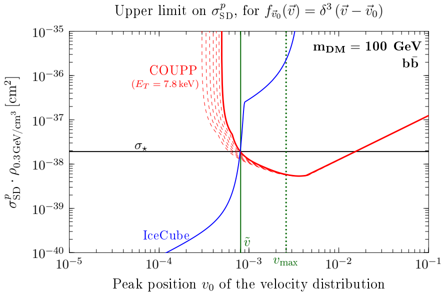


Construction of the halo-independent upper limits









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