Managing astrophysical uncertainties in direct dark matter detection

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Outline

Introduction

Astrophysical uncertainties in DM detection

- Indirect detection – The density distribution
- Direct detection – the velocity distribution

A halo-independent bound

FF, A. Ibarra & S. Wild, JCAP 09052 (2015); J. Phys. Conf. Ser. 718 (2016)

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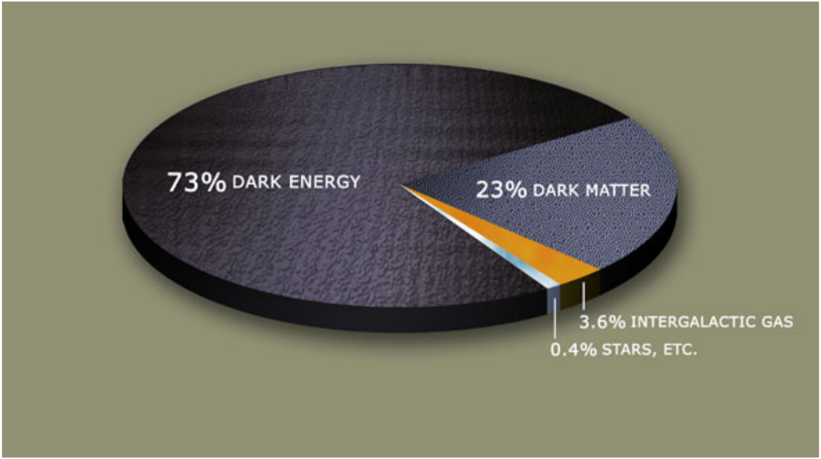

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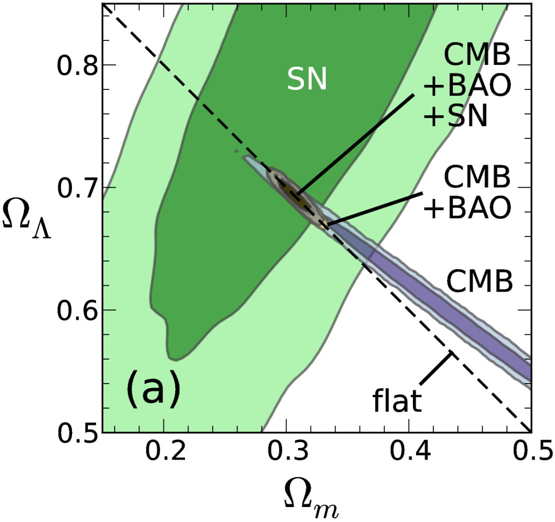
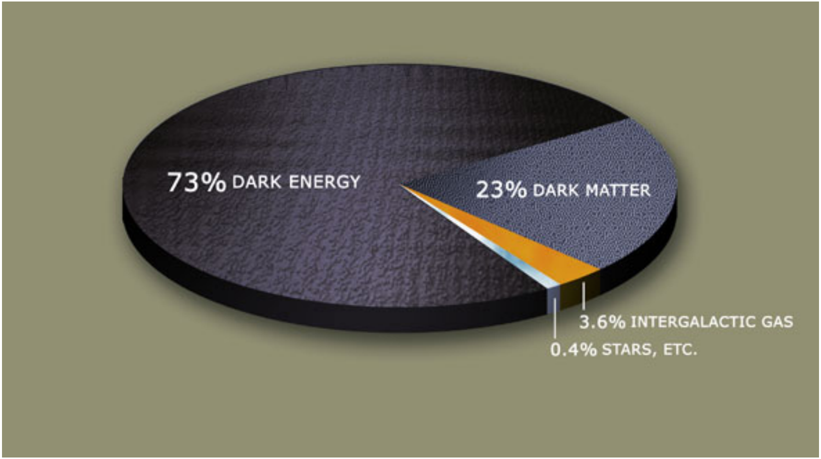
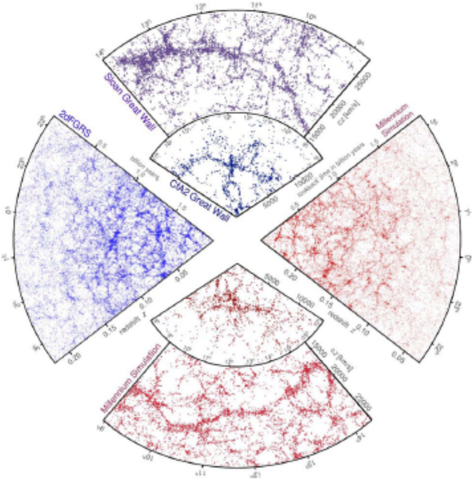
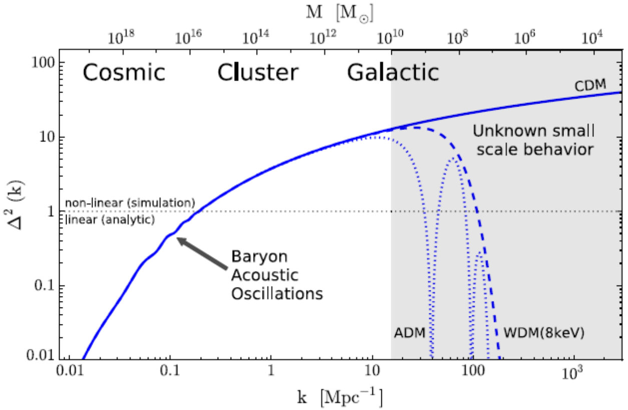


SN
CMB
+BAO
+SN
CMB
+BAO
CMB
(a)
flat
0.8
0.7
0.6
0.5
0.2
0.3
0.4
0.5
Ω_Λ
Ω_m


73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.



Frenk & White 12



Kuhlen, Vogelsberger & Angulo 12

Cold Dark Matter

- Exotic, i.e. non-baryonic
- Non-relativistic, i.e. cold
- Required to explain cosmological expansion; dynamics of galaxies, clusters, . . . ; the existence of structure itself.

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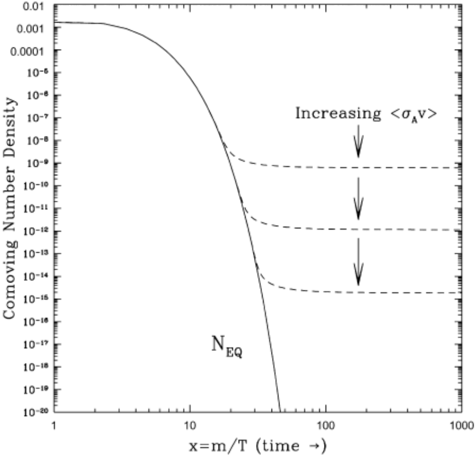
Thermal relics



The WIMP miracle

For $10\,\mathrm{GeV} \lesssim m_\chi \lesssim 10\,\mathrm{TeV}$ weak-scale interactions produce observed abundance from thermal decoupling:

$$\Omega_\chi h^2 = 0.1 \frac{3 \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{< \sigma v >}$$

The same interactions make it potentially detectable:

- $\chi\chi \to \gamma\gamma,\ \pi^0,\ e^\pm, \ldots$
- $\chi N \to \chi N$

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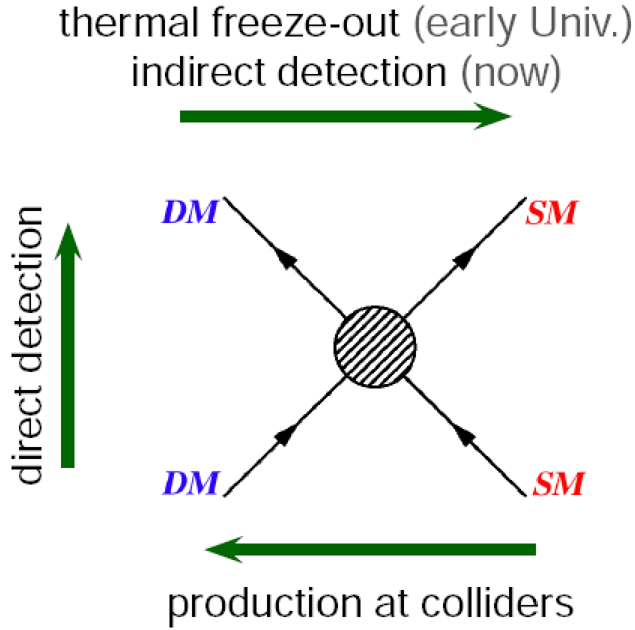
thermal freeze-out (early Univ.)
indirect detection (now)
direct detection
DM
SM
DM
SM
production at colliders

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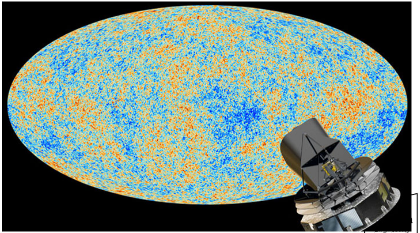
Indirect detection of DM



$$\Phi = \underbrace{\frac{N_i}{8\pi m_\chi^2}\langle\sigma v\rangle}_{\text{\# collisions/volume giving SM particles}} \times \underbrace{\int_{\text{line of sight}} \mathrm{d}s\,\rho^2}_{\text{Amount of DM}^2}$$

- Sensitive to the annihilation cross-section, which sets also the relic density.
- Requires knowledge of the dark matter density profile (and velocity distribution in some cases) at the local, galactic, . . . level.

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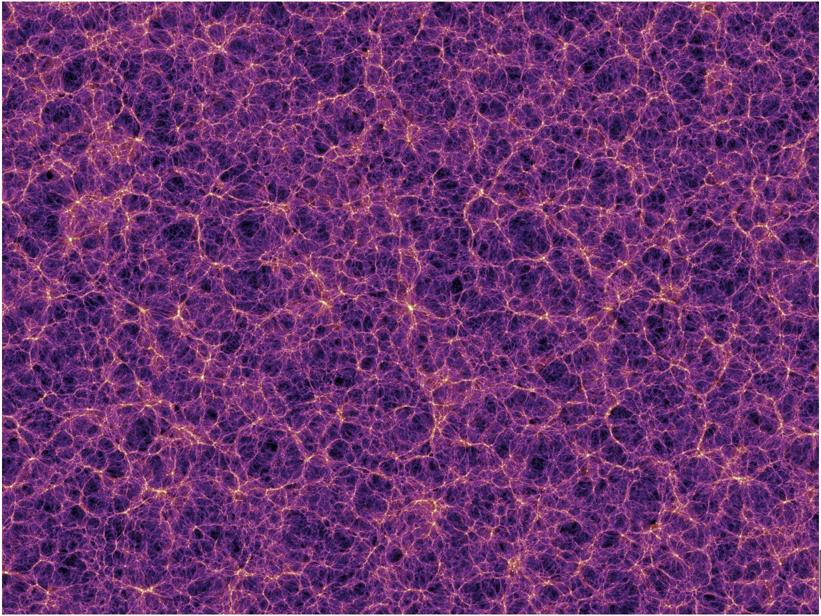
Simulations



N-body simulations (DM only)

- Follow about 10^{14} particles, each weighting $10^3 M_\odot / 10^9 M_\odot / 10^{12} M_\odot$, using $> 10^6$ CPU-hours.
- DM halos follow a *universal* profile:

$$\rho_{NFW} = \frac{\rho_0 a^3}{r(a+r)^2}$$

$$\rho_{Einasto} = \rho_0 \exp\left(-\frac{2}{\gamma}\left[\left(\frac{r}{a}\right)^\gamma - 1\right]\right)$$

- Substructure down to Earth mass clumps

$$\frac{\mathrm{d}N}{\mathrm{d}M} \propto M^{-2}$$

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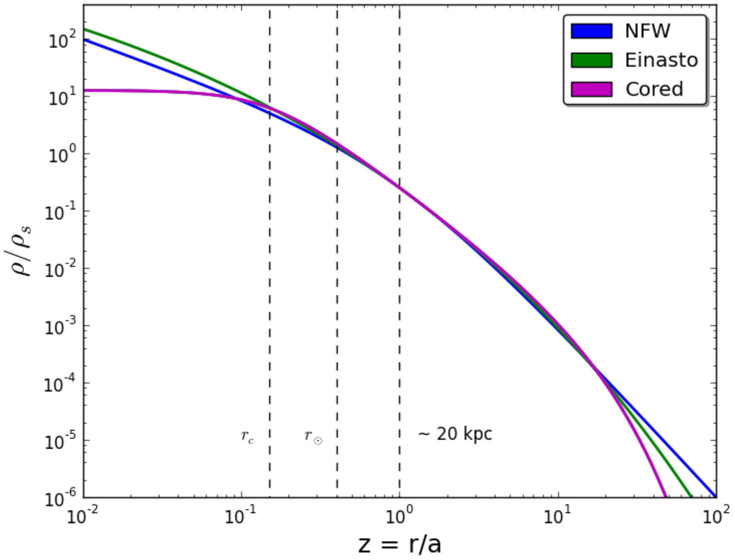

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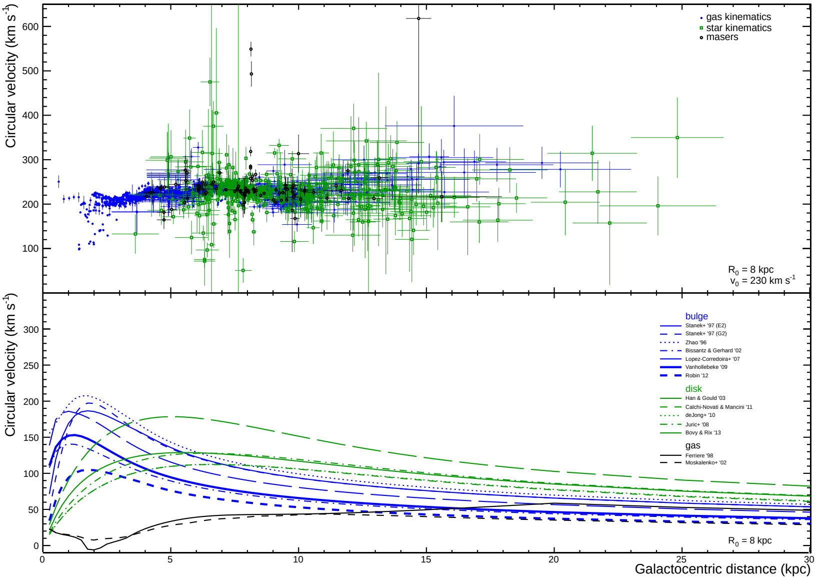
Stadel et al. 09

Einasto provides a slightly better fit to DM only simulations, $c \approx 6 - 18$, $\alpha \approx 0.08 - 0.32$, $\Delta M(r_{\odot}) \approx 4$.

Observations



Iocco, Pato & Bertone 2015

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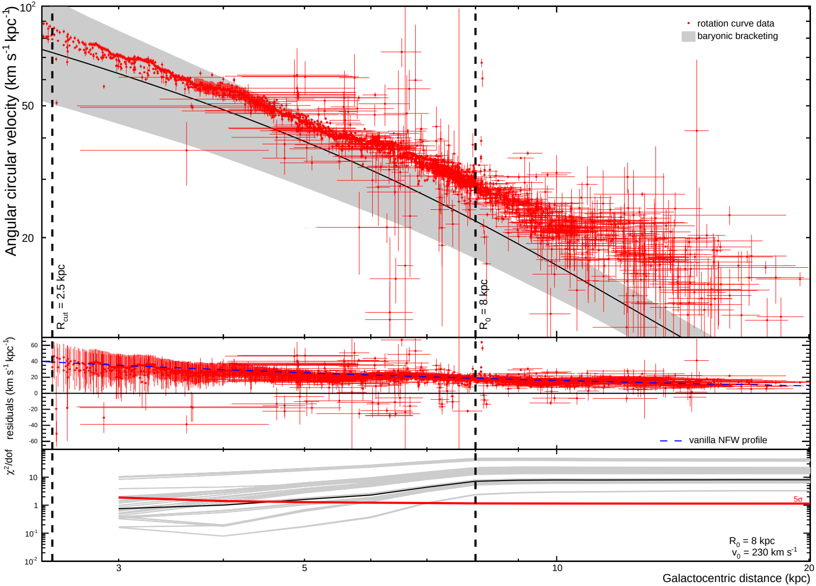

Iocco, Pato & Bertone 2015

Baryonic effects

Several physical processes can modify the structure of DM haloes:

- Smooth and slow accretion: *adiabatic contraction*, $rM(r) =$ const.
- Dinamical friction: *expansion*. Satellite/clumpy accretion, galactic bars, ...
- Gas outflows: *expansion*. Strong mass outflows cause rapid perturbations to potential, particles gain energy on average.

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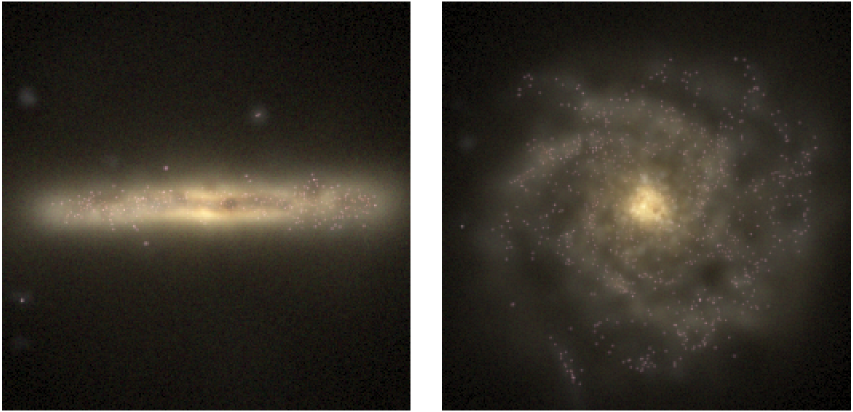
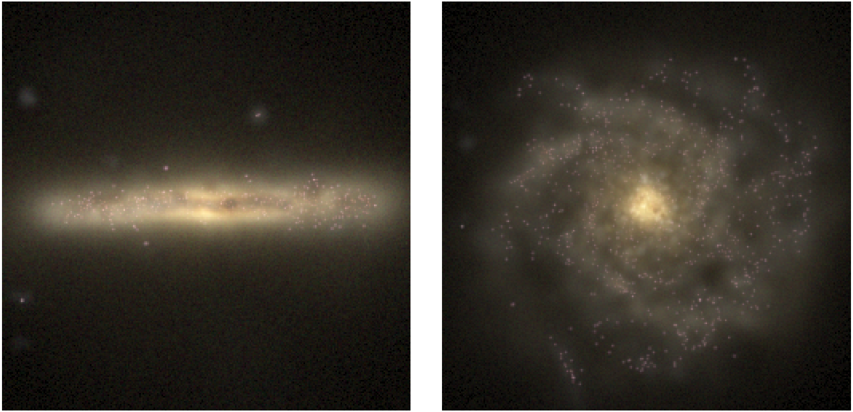


Calore et al. 16

Fit to MW stellar mass, rotation curve and galaxy shape instead of total virial mass.



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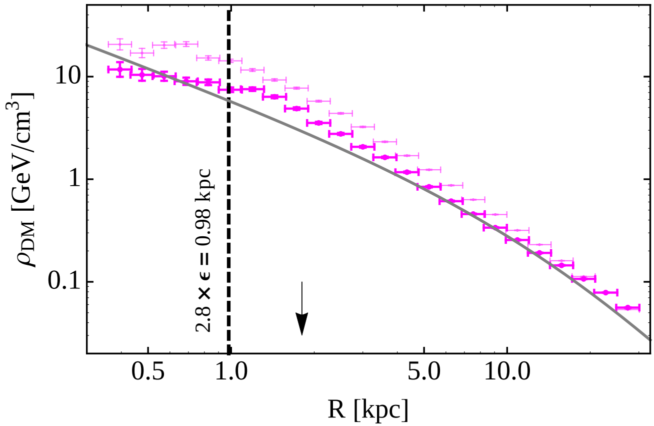
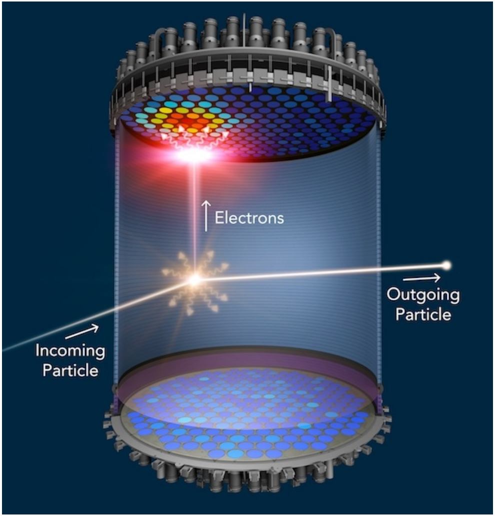


The ten selected galaxies exhibit consistent DM profiles inside the solar circle. Baryonic effects make the halo shallower than required to explain the Fermi GeV excess.

Direct detection



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Expected recoil events at a DD experiment:

$$R = \mathcal{E} \cdot \sum_i \int_0^\infty \mathrm{d}E_R \, \epsilon(E_R) \frac{\xi_i \rho_{\mathrm{loc}}}{m_{A_i} m_{\mathrm{DM}}} \times$$

$$\int_{v \geq v_{\mathrm{min},i}^{(\mathrm{DD})}(E_R)} \mathrm{d}^3 v \, v f(\vec{v} + \vec{v}_{\mathrm{obs}}(t)) \, \frac{\mathrm{d}\sigma_i}{\mathrm{d}E_R} \, .$$

Probes the DM scattering cross section with nuclei:

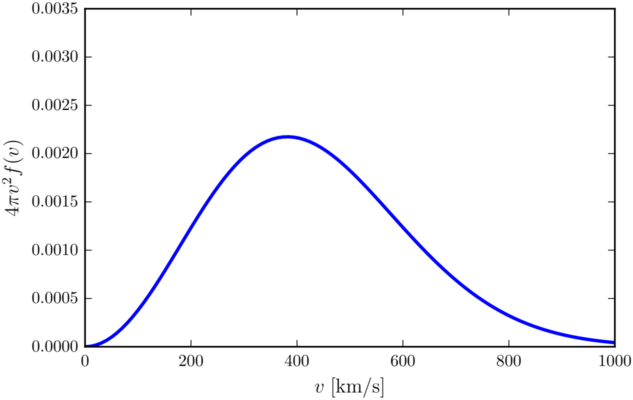
$$\frac{\mathrm{d}\sigma_i}{\mathrm{d}E_R} = \frac{m_{A_i}}{2\mu_{A_i}^2 v^2}\left(\sigma_{\mathrm{SI}} F_{i,\mathrm{SI}}^2(E_R) + \sigma_{\mathrm{SD}} F_{i,\mathrm{SD}}^2(E_R)\right),$$

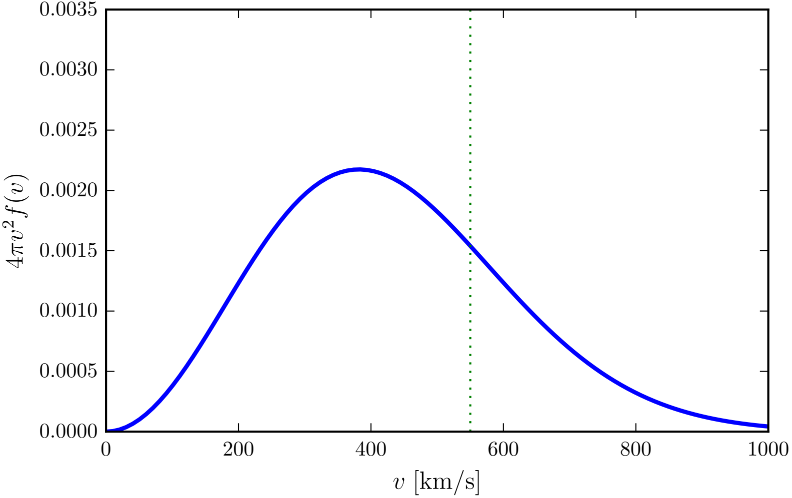
Astrophysical inputs required:

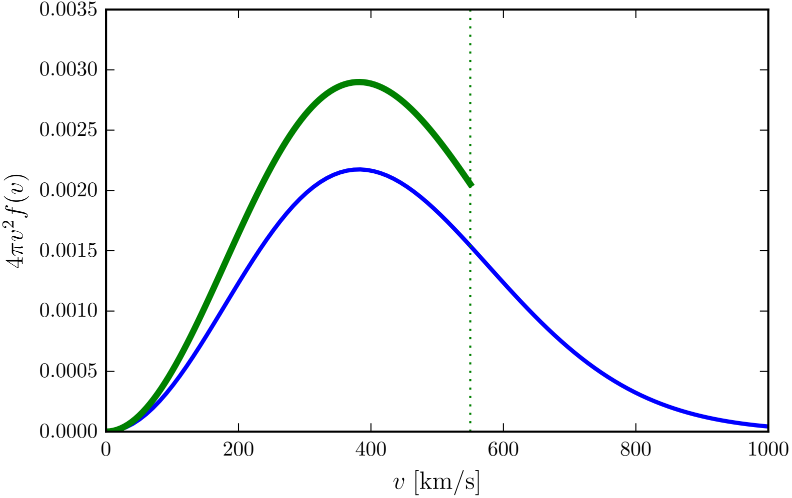
- Local DM density ρ_{loc}
- Local velocity distribution $f(\vec{v} + \vec{v}_{\text{obs}}(t))$.
- Minimum DM velocity to trigger a recoil event

$$v_{\text{min}} = \sqrt{\frac{m_T E_R}{2\mu_T^2}}$$

The Standard Halo Model




0.0035
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
$4\pi v^2 f(v)$
0
200
400
600
800
1000
v [km/s]



0.0035
0.0030
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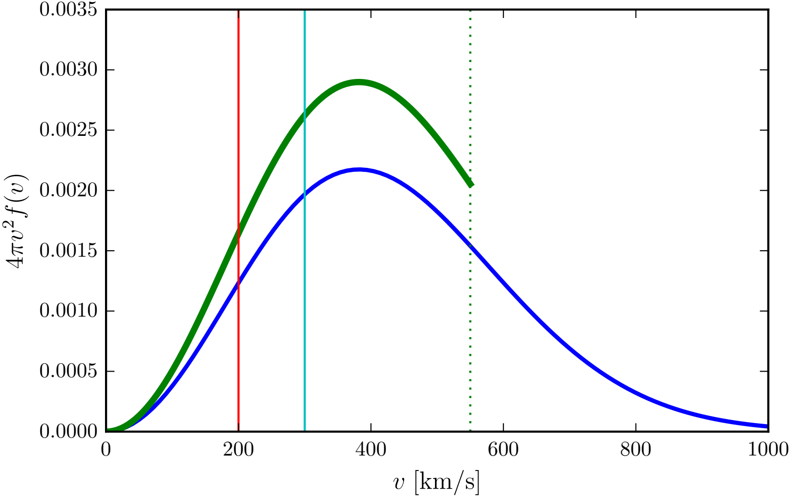

0.0035
0.0030
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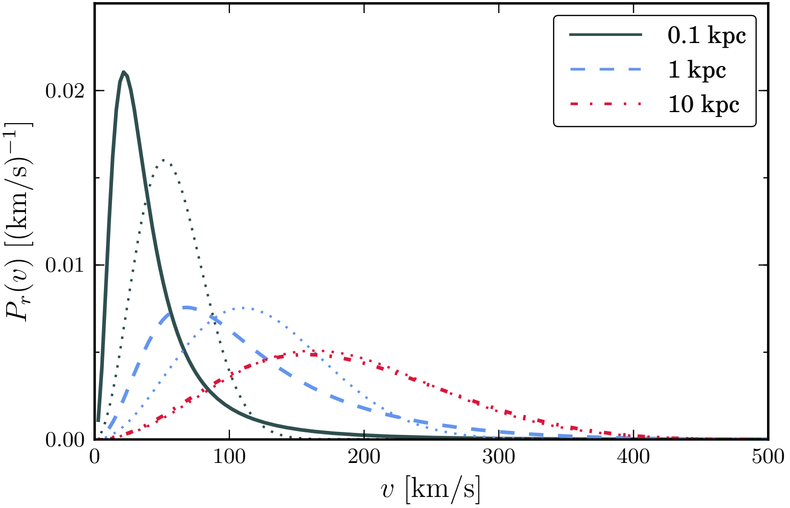
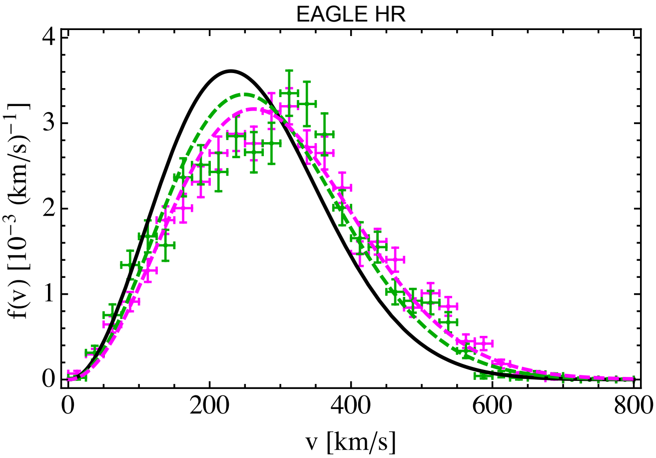
For an NFW profile

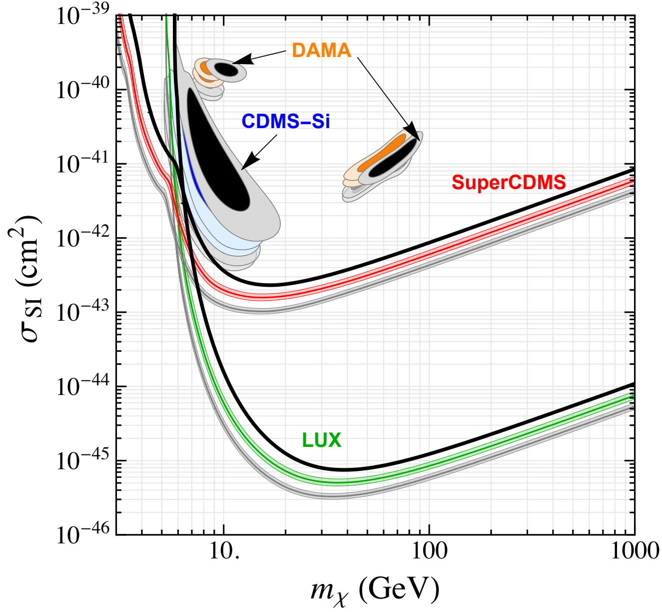


FF, D. Hunter 13

The velocity distribution from simulations



Bozorgnia *et al.* 1601.04707



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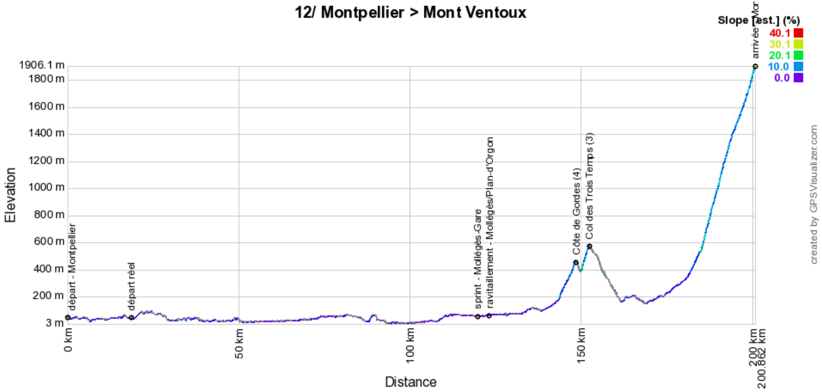

12/ Montpellier > Mont Ventoux
Slope [est.] (%)
40.1
30.1
20.1
10.0
0.0
Elevation
1906.1 m
1800 m
1600 m
1400 m
1200 m
1000 m
800 m
600 m
400 m
200 m
3 m
départ - Montpellier
départ réel
sprint - Mollégès-Gare
ravitaillement - Mollégès/Plan-d'Orgon
Côte de Gordes (4)
Col des Trois Temps (3)
0 km
50 km
100 km
150 km
200 km
200.862 km
Distance
created by GPSVisualizer.com

Halo independent methods

$$\eta\left(v_{\min}, t\right) \equiv \frac{\rho\sigma_{\text{ref}}}{m_\chi}\int_{v_{\min}}^{\infty} dv \frac{f(v,t)}{v}$$

$$\frac{dR}{dE_R} = \frac{N_T M_T}{2\mu^2}\eta\left(v_{\min}, t\right)$$

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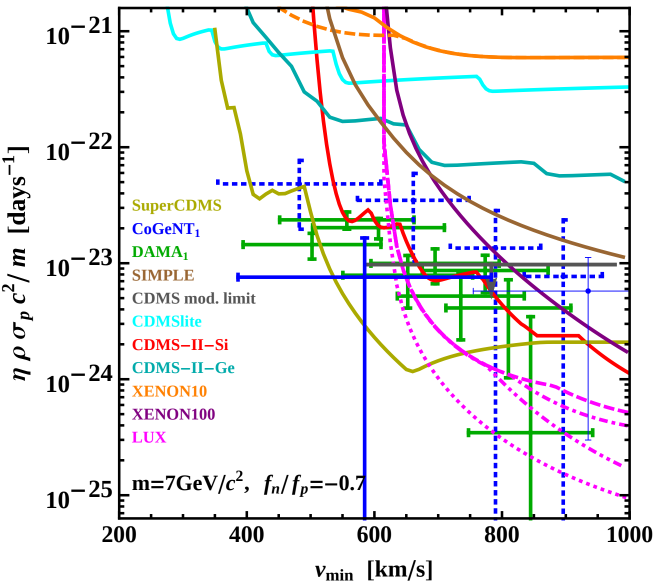

Del Nobile *et al.* 2014

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Inputs:

- Neither direct detection experiments nor neutrino telescopes have detected dark matter.

Assumptions:

- The dark matter density and velocity distribution at the position of the Sun and the Earth are identical and constant over 10 – 100 million years.

Output:

- An upper bound on the DM-nucleon scattering cross section that is independent of the velocity distribution.

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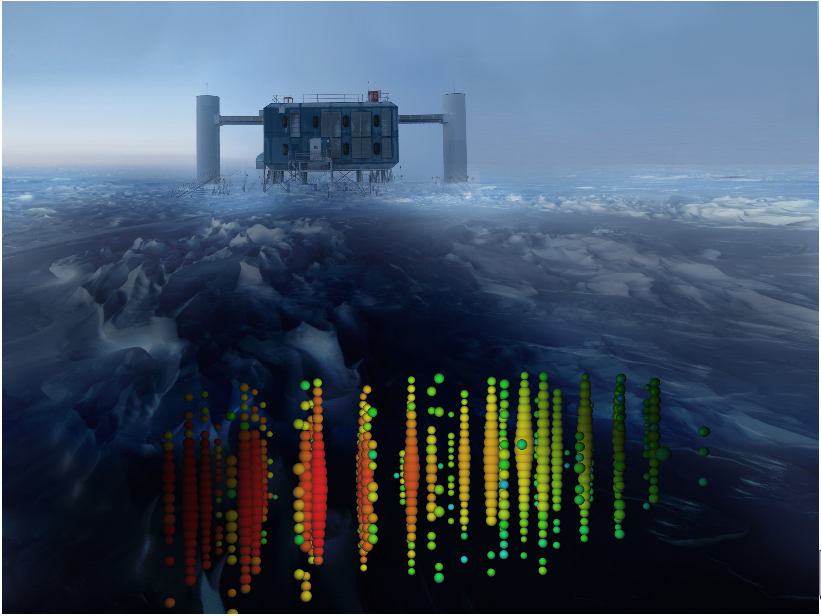
Neutrino telescopes



The neutrino flux is determined by the capture rate:

$$C = \sum_i \int_0^{R_\odot} 4\pi r^2 \mathrm{d}r \, \eta_i(r) \frac{\rho_{\mathrm{loc}}}{m_{\mathrm{DM}}} \times$$
$$\int_{v \le v_{\mathrm{max},i}^{(\mathrm{Sun})}(r)} \mathrm{d}^3 v \, \frac{f(\vec{v})}{v} \left(v^2 + [v_{\mathrm{esc}}(r)]^2 \right) \times$$
$$\int_{m_{\mathrm{DM}} v^2/2}^{2\mu_{A_i}^2 \left(v^2 + [v_{\mathrm{esc}}(r)]^2 \right)/m_{A_i}} \mathrm{d}E_R \, \frac{\mathrm{d}\sigma_i}{\mathrm{d}E_R} \,,$$

DM as a superposition of streams

We can view the DM velocity distribution in the solar system as a superposition of hypothetical streams with fixed velocity $\vec{v}_0$ with respect to the solar frame:

$$f(\vec{v}) = \int_{|\vec{v}_0| \leq v_{\max}} \mathrm{d}^3 v_0 \, \delta^{(3)}(\vec{v} - \vec{v}_0) f(\vec{v}_0) \, ,$$

We can express the expected scattering events R in a direct detection experiment and the capture rate in the Sun C as:

$$R = \int_{|\vec{v}_0| \leq v_{\max}} \mathrm{d}^3 v_0 \, f(\vec{v}_0) \, R_{\vec{v}_0} \, ,$$

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By construction,

$$R_{\vec{v}_0} \leq R_{\text{max}}$$

This gives a limit on $\sigma_{\widetilde{\chi}N}$.

For a given $v_0 \equiv |\vec{v}_0|$ find the weakest limit amongst all angles between $\vec{v}_0$ and the fixed Earth velocity $\vec{v}_E$. By construction,

$$R_{\vec{v}_0}(\sigma) \geq R_{\text{max}} \quad \text{for} \quad \sigma \geq \sigma^{\text{DD}}_{\text{max}}(v_0).$$

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Similarly, for every stream there is an upper limit on the scattering cross section which is allowed by a neutrino telescope:

$$C_{\vec{v}_0} \leq C_{\max}.$$

The most conservative upper limit, $\sigma_{\max}^{\mathrm{NT}}(v_0)$, for a given stream speed v_0 satisfies

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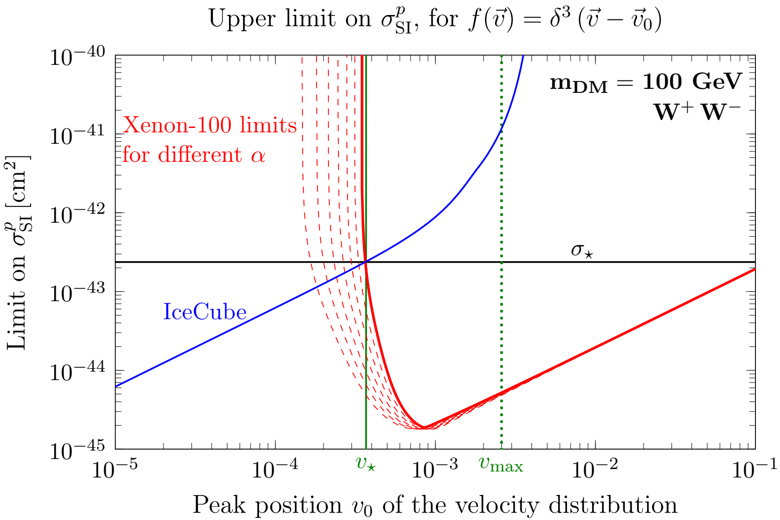
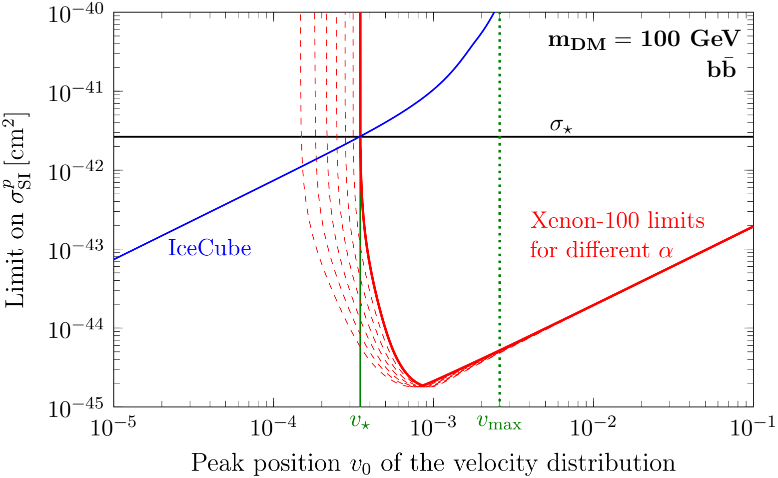
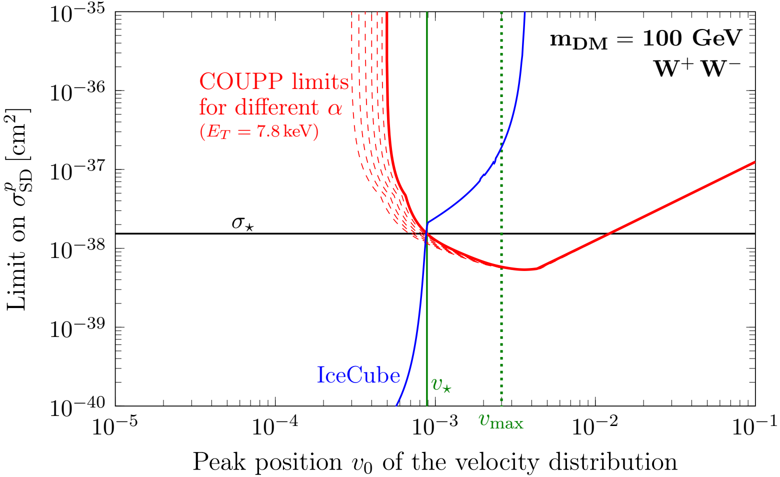


Upper limit on $\sigma^p_{\rm SI}$, for $f(\vec{v}) = \delta^3(\vec{v} - \vec{v}_0)$
$\mathbf{m_{DM} = 100\ GeV}$
$\mathbf{W^+ W^-}$
Xenon-100 limits
for different α
$\sigma_\star$
IceCube
Limit on $\sigma^p_{\rm SI}\,[\rm cm^2]$
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-5}
10^{-4}
$v_\star$
10^{-3}
$v_{\rm max}$
10^{-2}
10^{-1}
Peak position v_0 of the velocity distribution

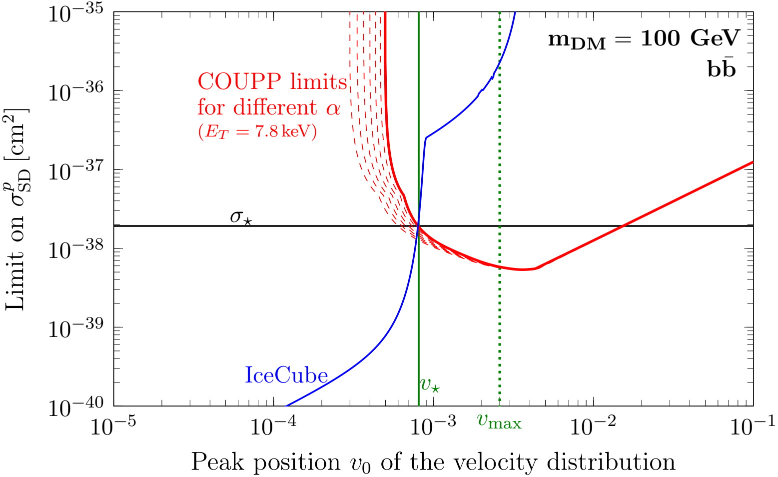
Upper limit on σ_{SI}^{p}, for $f(\vec{v}) = \delta^3(\vec{v} - \vec{v}_0)$



Upper limit on $\sigma^p_{\rm SD}$, for $f(\vec{v}) = \delta^3(\vec{v} - \vec{v}_0)$



Upper limit on $\sigma^p_{\rm SD}$, for $f(\vec{v}) = \delta^3(\vec{v} - \vec{v}_0)$



Knowing $\sigma_{\text{max}}^{\text{DD/NT}}(v_0)$ we can calculate limits for a general $f(\vec{v})$. Since

$$R_{\vec{v}_0}(\sigma) = \frac{\sigma}{\sigma_{\text{max}}^{\text{DD}}(v_0)} R_{\vec{v}_0}[\sigma_{\text{max}}^{\text{DD}}(v_0)] \geq \frac{\sigma}{\sigma_{\text{max}}^{\text{DD}}(v_0)} R_{\text{max}},$$

we have

$$R(\sigma) \geq \int_{|\vec{v}_0| \leq v_{\text{max}}} \mathrm{d}^3 v_0 f(\vec{v}_0) \frac{\sigma}{\sigma_{\text{max}}^{\text{DD}}(v_0)} R_{\text{max}}.$$

Requiring $R(\sigma) \leq R_{\text{max}}$, we deduce

$$\sigma \leq \left[\int_{|\vec{v}_0| \leq v_{\text{max}}} \mathrm{d}^3 v_0 \frac{f(\vec{v}_0)}{\sigma_{\text{max}}^{\text{DD/NT}}(v_0)} \right]^{-1}.$$

A halo-independent upper limit on $\sigma_{\tilde{\chi}N}$

DD experiments are insensitive to slowly moving WIMPs. But, these can be efficiently captured in the Sun.

They probe the WIMP population in a complementary way: for every stream speed v_0 there is a finite upper bound.

We can use this fact to our advantage. Consider the largest value allowed between 0 and $v_{\max}$:

$$\sigma_* \equiv \max\left\{\sigma^{\rm DD}_{\max}(\tilde{v}), \sigma^{\rm DD}_{\max}(v_{\max})\right\},$$

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By construction:

$$\sigma_{\max}^{\rm DD}(v_0) \le \sigma_* \quad \text{for } \tilde{v} \le v_0 \le v_{\max}$$
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Also

$$\begin{aligned} \sigma &\le \left[\int_{0 \le v_0 \le v_{\max}} d^3 v_0 \frac{f(\vec{v}_0)}{\sigma_{\max}^{\rm DD}(v_0)}\right]^{-1} \\ &\le \left[\int_{\tilde{v} \le v_0 \le v_{\max}} d^3 v_0 \frac{f(\vec{v}_0)}{\sigma_{\max}^{\rm DD}(v_0)}\right]^{-1} . \end{aligned}$$

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Defining

$$\delta_f \equiv \int_{\tilde{v} \le v_0 \le v_{\max}} \mathrm{d}^3 v_0 \, f(\vec{v}_0) \ ,$$

we obtain

$$\sigma \le \frac{\sigma_*}{\delta_f} \ . \qquad (1)$$

An analogous calculation for the neutrino telescope limit gives

$$\sigma \le \frac{\sigma_*}{1 - \delta_f} \ , \qquad (2)$$

Together, they imply:

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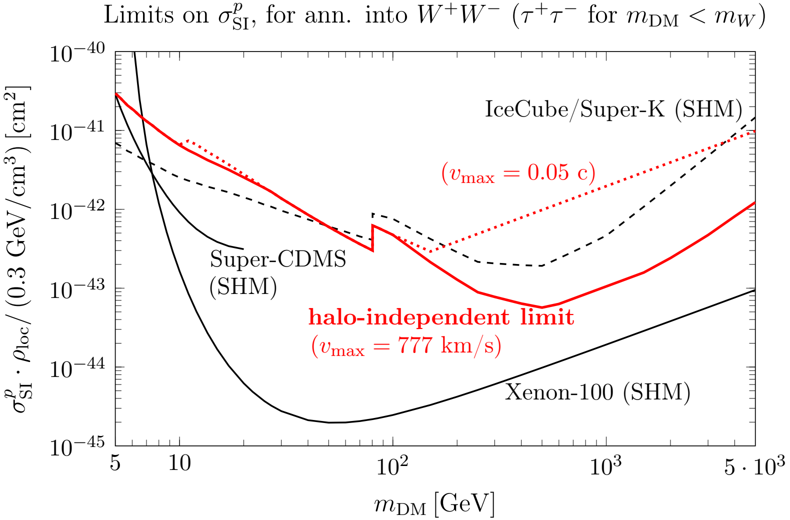
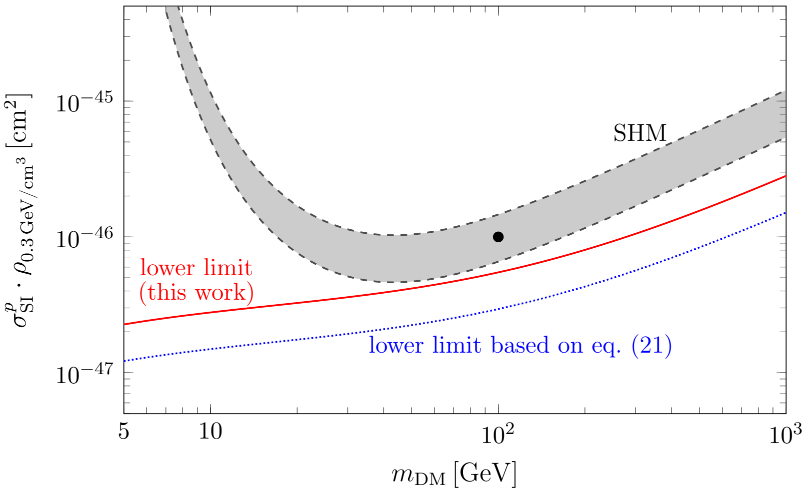
Comparison with model dependent limits



In case of a positive signal



Conclusions

- Knowledge of the density profile and velocity distribution is a crucial ingredient for dark matter searches.
- There is very little information about the inner region of the MW. Hydrodynamic simulations suggest a $\sim$ kpc core that seems at odds with a DM interpretation of the Fermi GeV excess.
- Null results from direct searches and neutrino telescopes imply a robust upper bound on the DM-nucleon cross section that is independent of the velocity distribution.

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$f(v)$ also matters

If there are new light particles mediating long-range forces between the dark matter,

$$\sigma \to \sigma \times \frac{\pi\alpha}{v}$$

the indirect detection fluxes will depend on $f(v)$. Instead of:

$$\Phi = \underbrace{\frac{N_i}{8\pi m_\chi^2}\boxed{\langle\sigma v\rangle}}_{\text{\# collisions giving SM particles}} \times \underbrace{\int_{\text{line of sight}} \mathrm{d}s\, \rho^2}_{\text{Amount of DM}^2}$$

We should be doing:

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Robertson, Zentner 12; FF, D. Hunter 13

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Obtaining the phase-space distribution

Assume that dark matter satisfies the colisionless Boltzmann equation,

$$\frac{\mathrm{d}f}{\mathrm{d}t} = 0$$

Very hard to solve! Only a few exact solutions known, found finding integrals of motion (*singular isothermal sphere*, Hernquist, Jaffe, ...).

Use Eddington's formula:

$$f(\mathcal{E}) = \frac{1}{\sqrt{8}\pi^2} \int_0^{\mathcal{E}} \frac{\mathrm{d}\Psi}{\sqrt{\mathcal{E} - \Psi}} \frac{\mathrm{d}^2\rho}{\mathrm{d}\Psi^2}. \tag{4}$$

Caveats: we are assuming $\beta = 0$.

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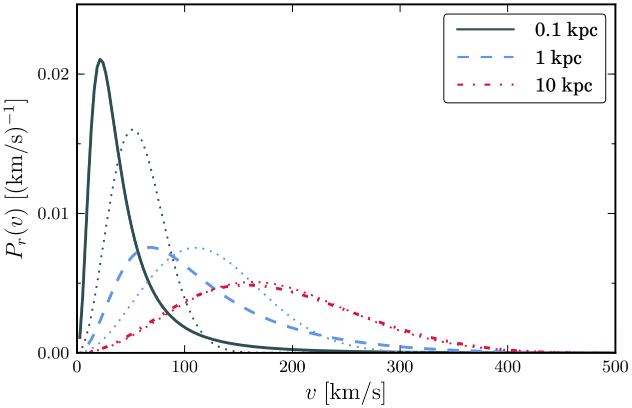
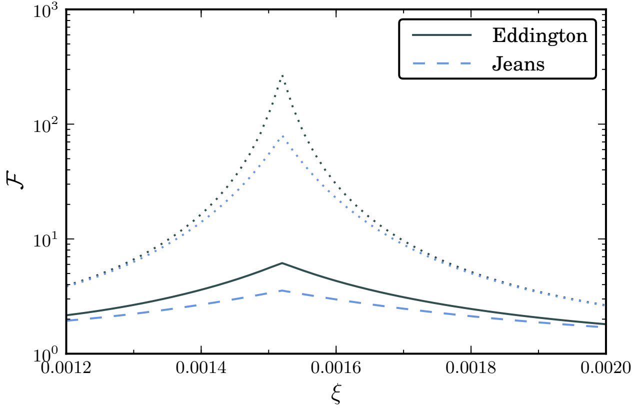

0.1 kpc
1 kpc
10 kpc
0.00
0.01
0.02
0
100
200
300
400
500
$P_r(v)$ [(km/s)$^{-1}$]
v [km/s]

Velocity distribution: Eddington



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Galactic center signals (IC, synchrotron) probably underestimated.

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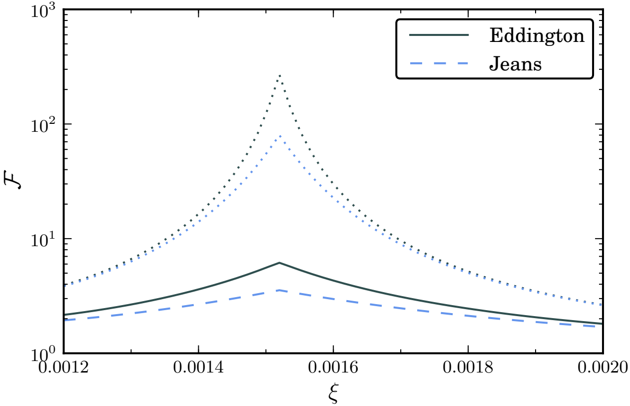

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