Impact of astrophysical uncertainties in local DM searches

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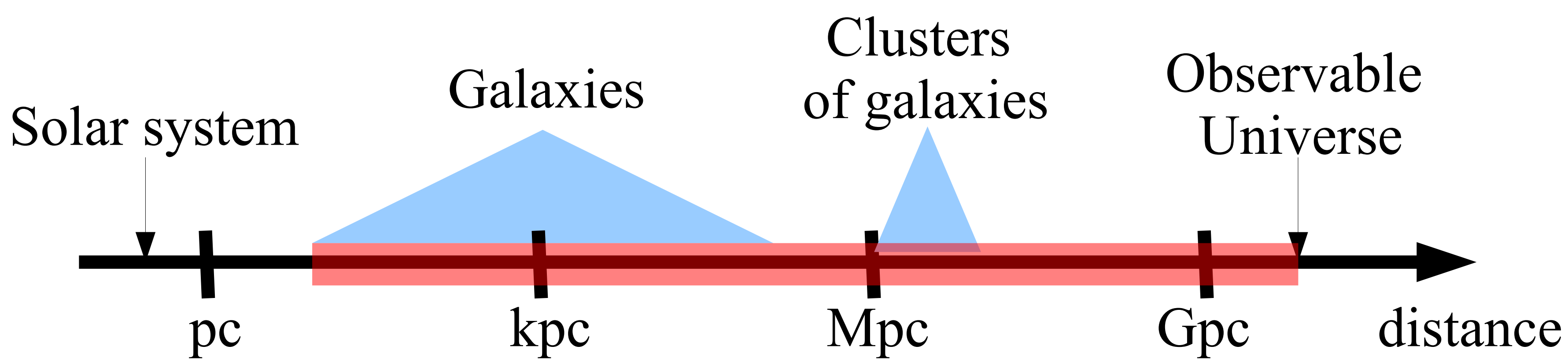
There is evidence for dark matter in a wide range of distance scales



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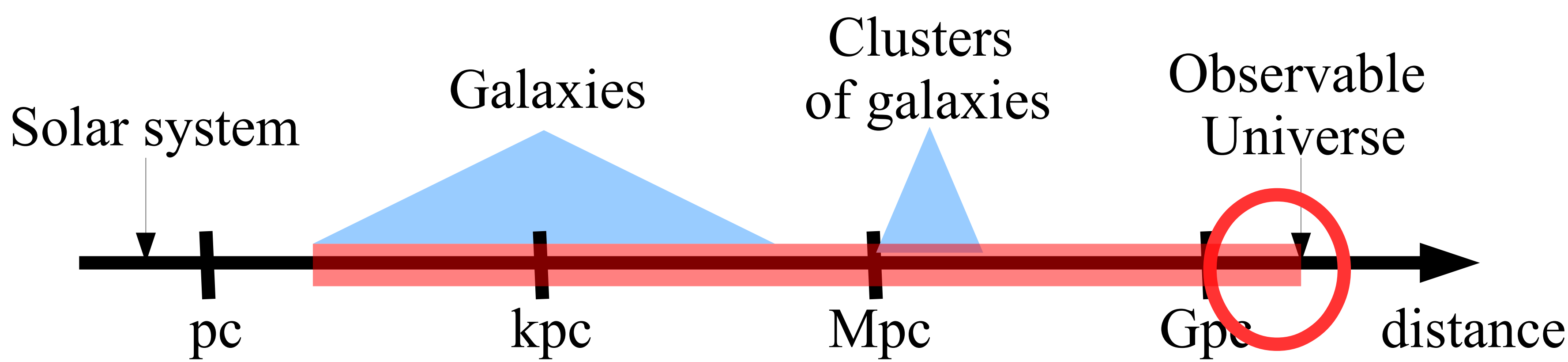

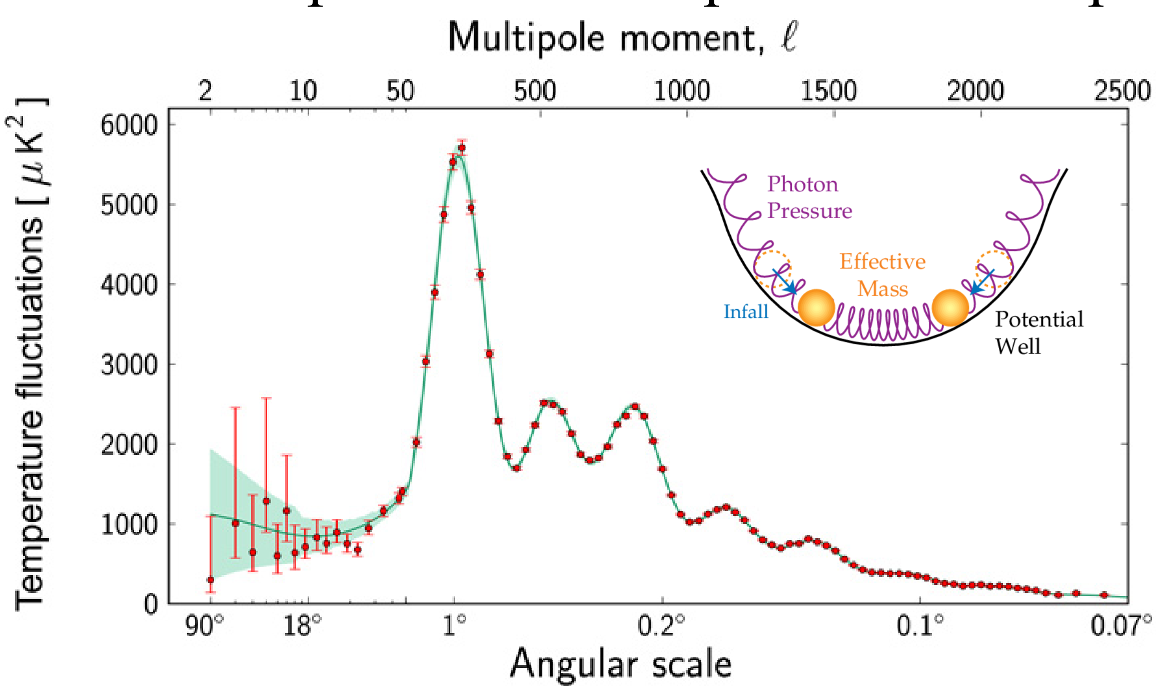

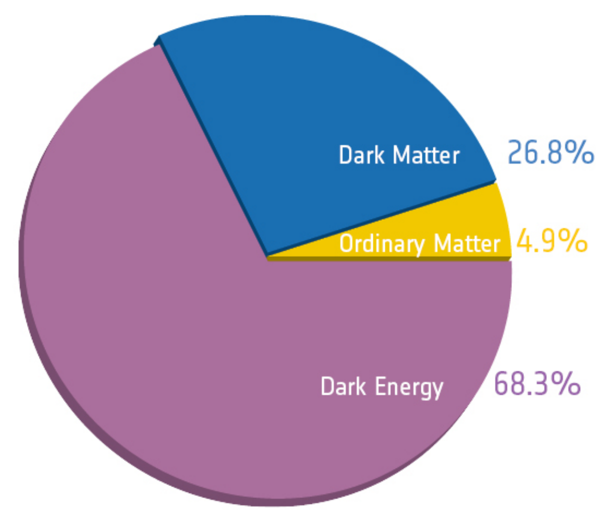

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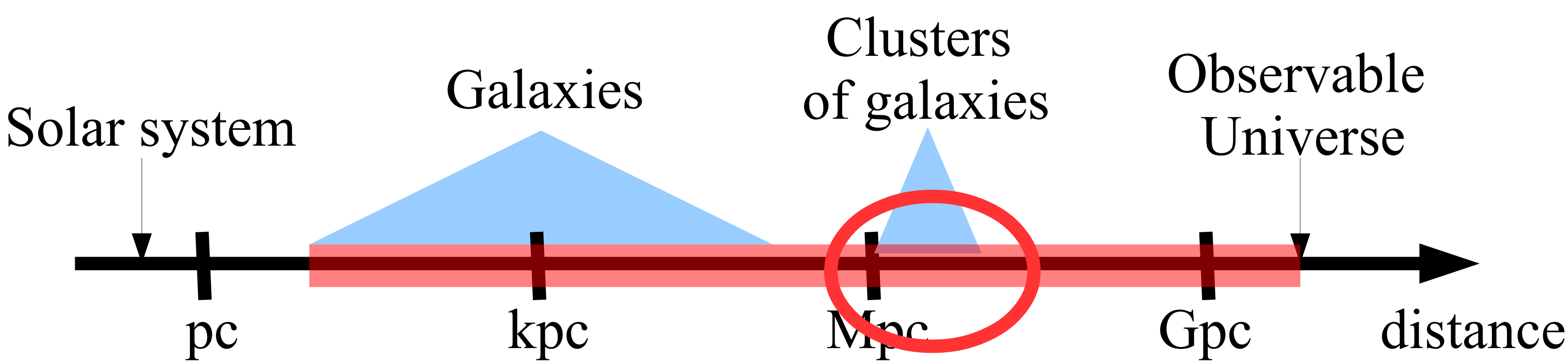

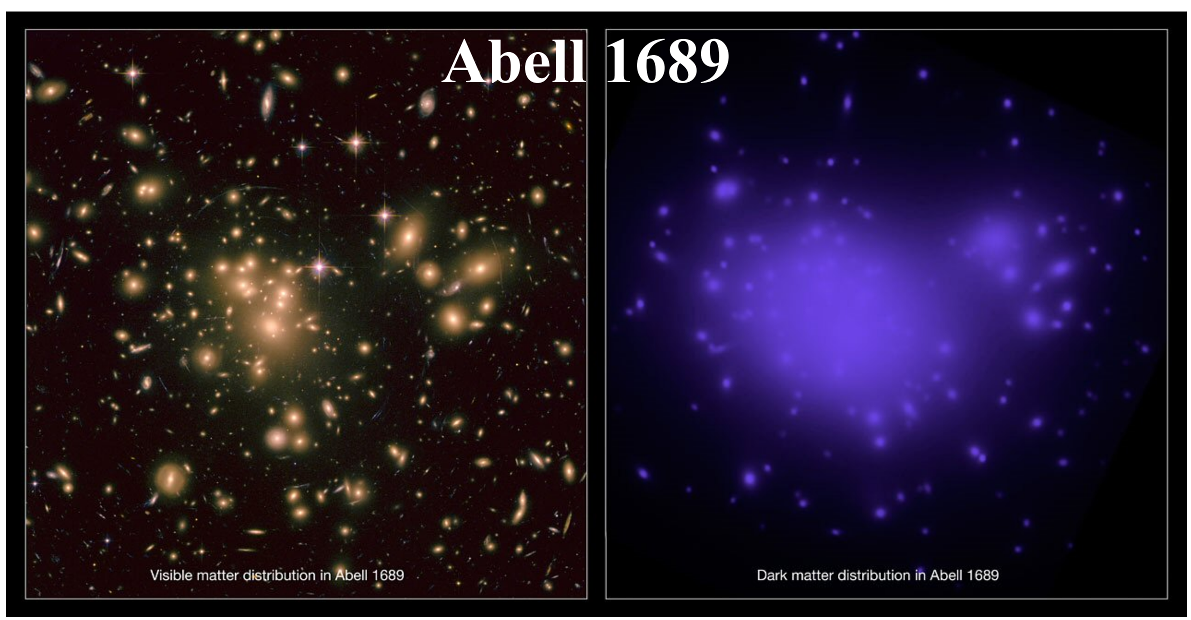

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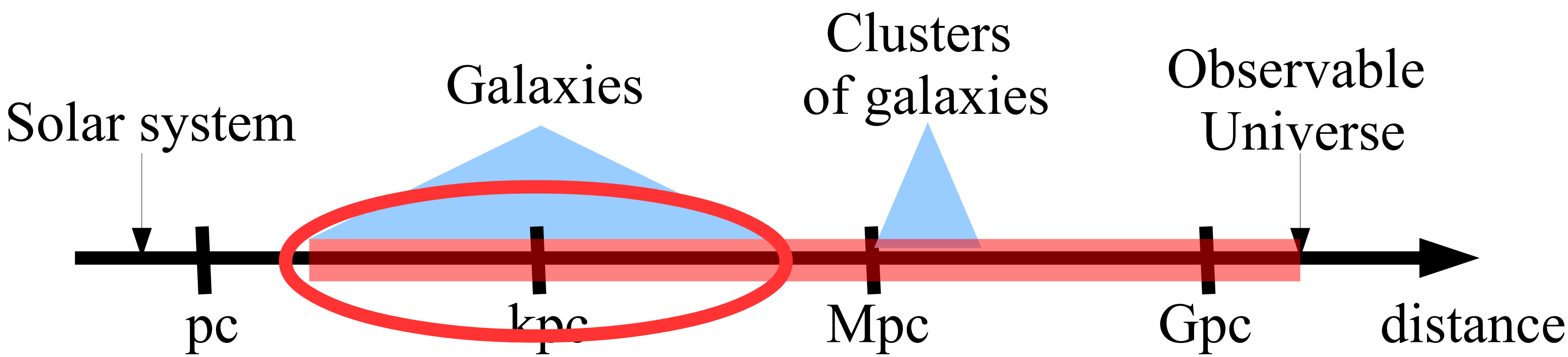

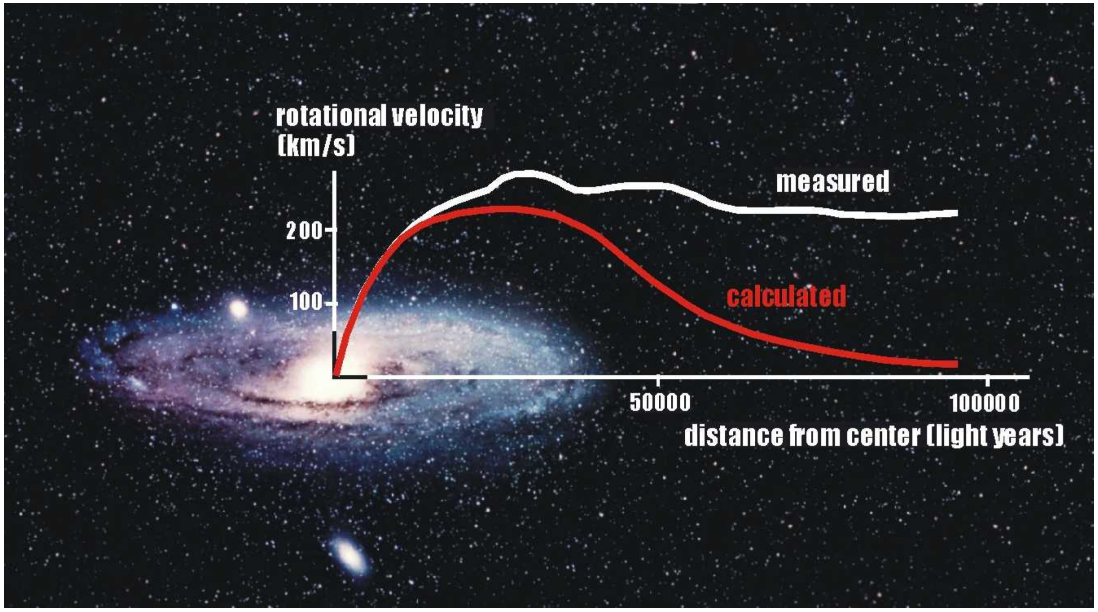

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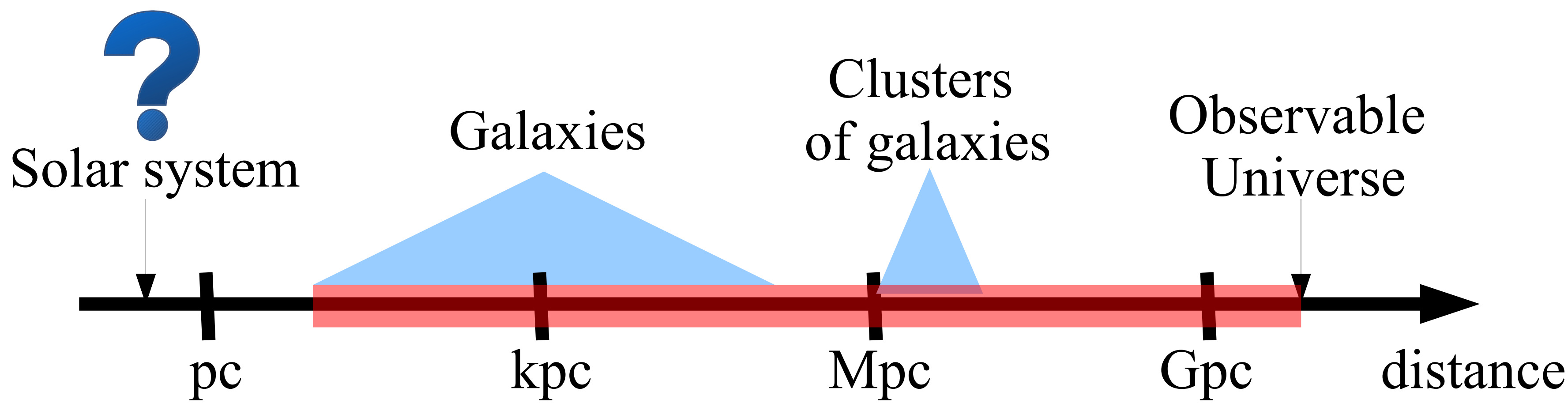

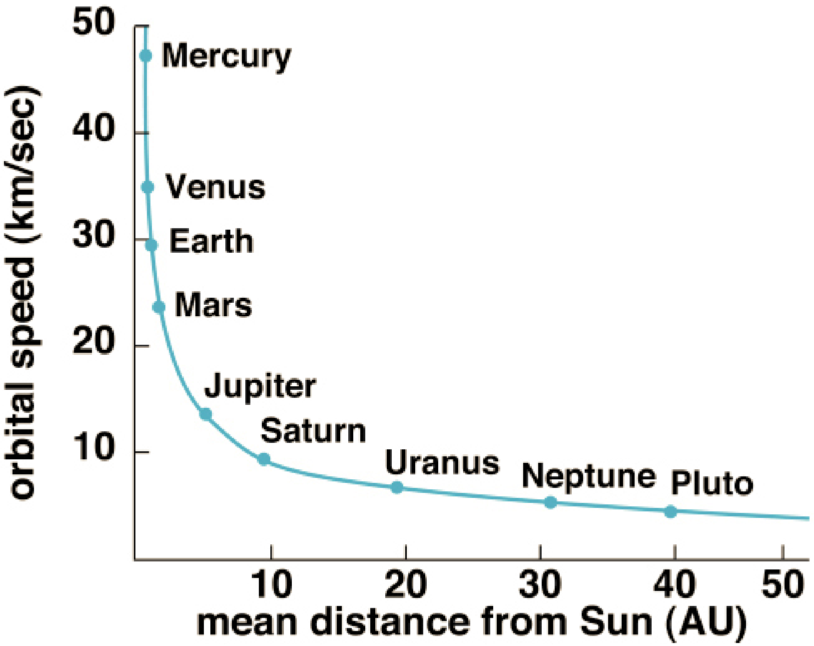

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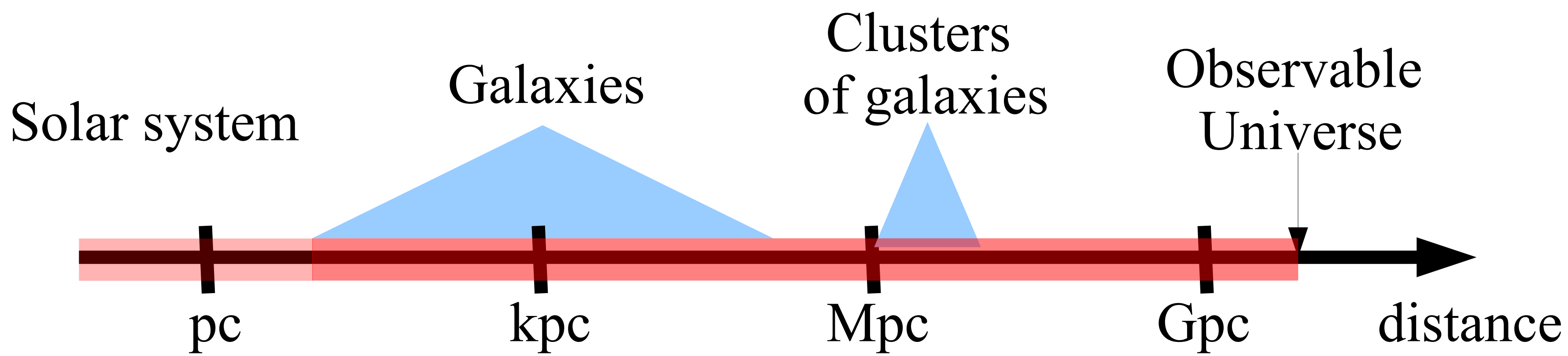
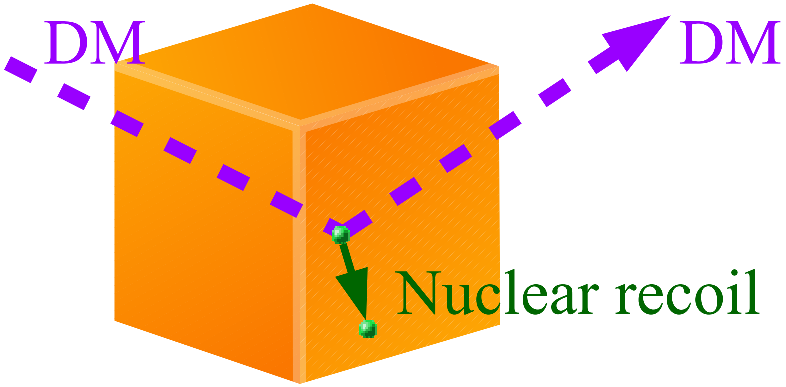


Assumption,
but well motivated

If the DM is made up of WIMPs, the DM population inside the Solar System could be detected

Searching for WIMP DM inside the Solar System



No significant excess detected so far

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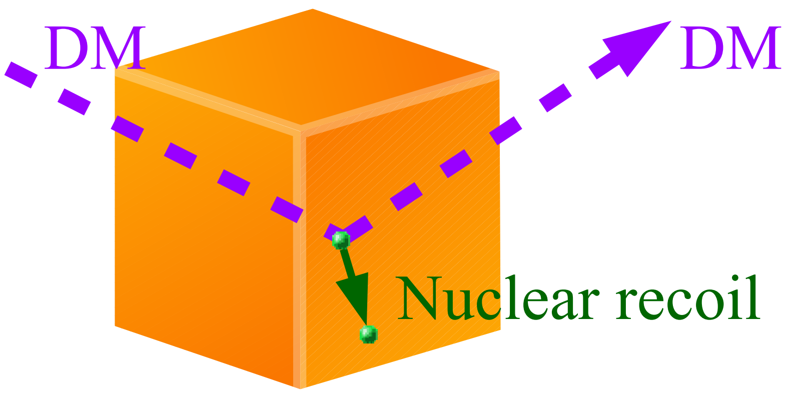

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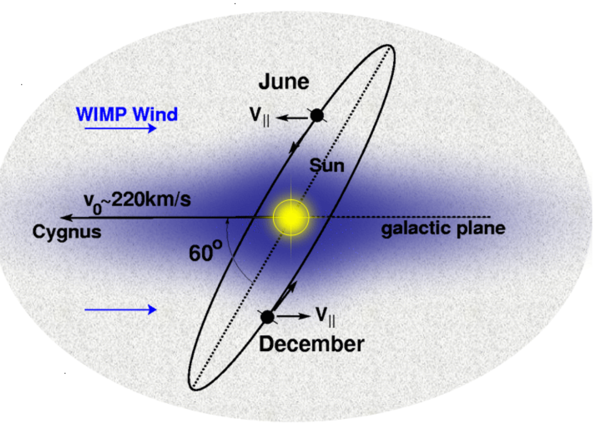

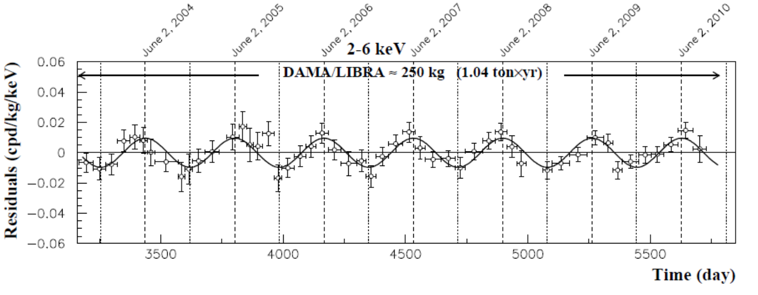

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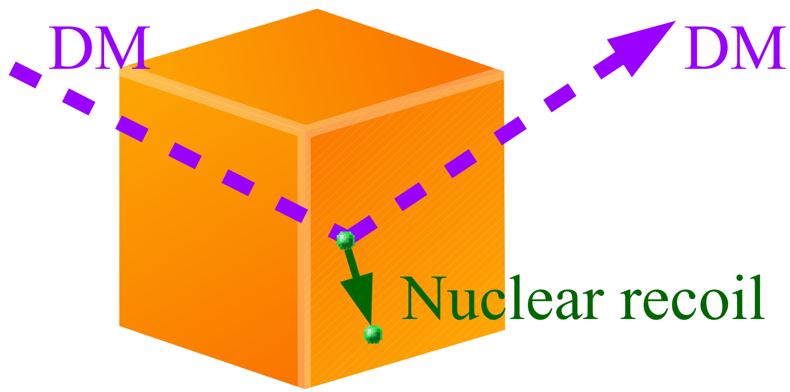

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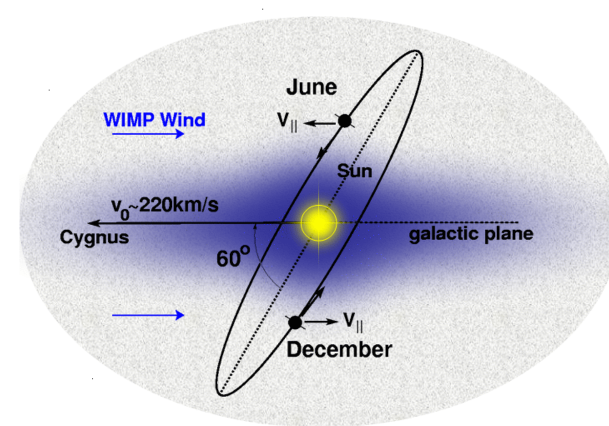

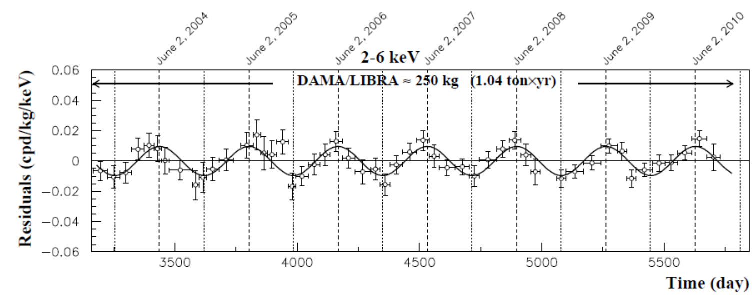

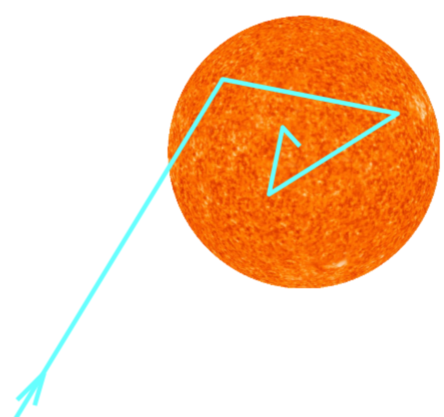

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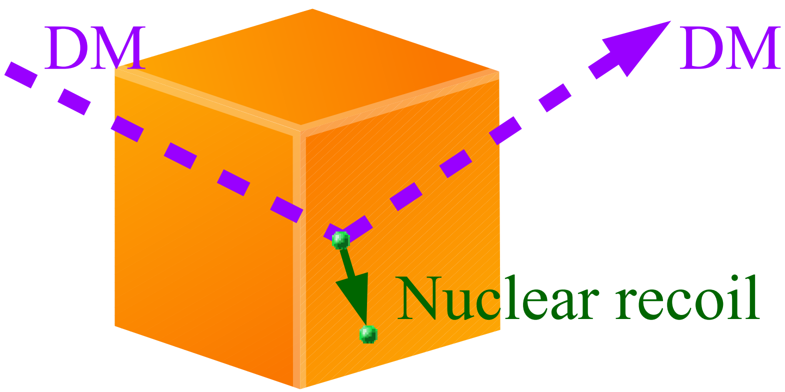

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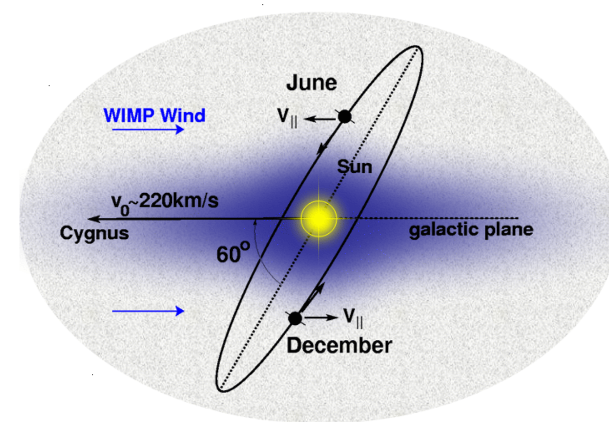

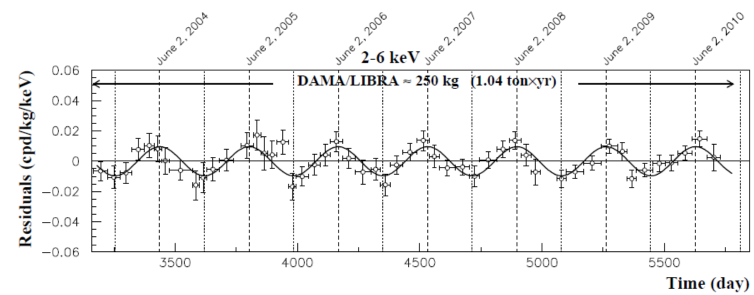

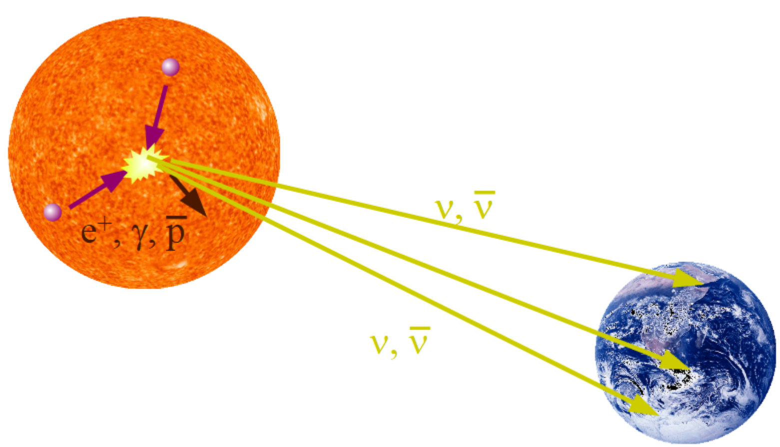

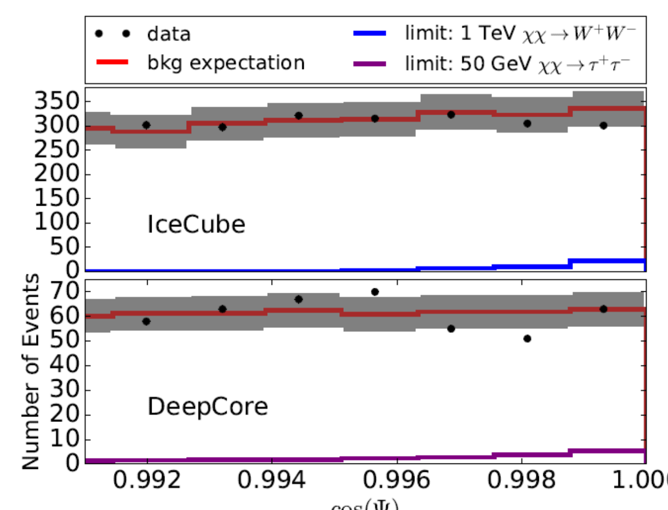

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Theoretical interpretation of the experimental results

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- Differential rate of DM-induced scatterings

$$\frac{dR}{dE_R} = \frac{\rho_{\rm loc}}{m_A m_{\rm DM}} \int_{v \geq v_{\rm min}(E_R)} \mathrm{d}^3 v \, v f(\vec{v} + \vec{v}_{\rm obs}(t)) \, \frac{\mathrm{d}\sigma}{\mathrm{d}E_R}$$

- The neutrino flux from annihilations inside the Sun is, under plausible assumptions, determined by the capture rate inside the Sun:

$$C = \int_0^{R_\odot} 4\pi r^2 \mathrm{d}r \, \frac{\rho_{\rm loc}}{m_{\rm DM}} \int_{v \leq v_{\rm max}^{\rm (Sun)}(r)} \mathrm{d}^3 v \, \frac{f(\vec{v})}{v} \left(v^2 + [v_{\rm esc}(r)]^2\right) \times \int_{m_{\rm DM} v^2/2}^{2\mu_A^2 \left(v^2 + [v_{\rm esc}(r)]^2\right)/m_A} \mathrm{d}E_R \, \frac{\mathrm{d}\sigma}{\mathrm{d}E_R}$$

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Uncertainties from particle/nuclear physics and from astrophysics

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Theoretical interpretation of the experimental results

Uncertainties from particle/nuclear physics.

- Dark matter mass?

For thermally produced dark matter, $m_{\mathrm{DM}} = \text{few MeV} - 100 \text{ TeV}$

- Differential cross section?

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_R} = \frac{m_A}{2\mu_A^2 v^2}\left(\sigma_{\mathrm{SI}} F_{\mathrm{SI}}^2(E_R) + \sigma_{\mathrm{SD}} F_{\mathrm{SD}}^2(E_R)\right)$$

Spin-independent and
spin-dependent cross sections
at zero momentum transfer

Nuclear form factors

(In some DM frameworks, other operators may also arise)

Theoretical interpretation of the experimental results

Uncertainties from astrophysics

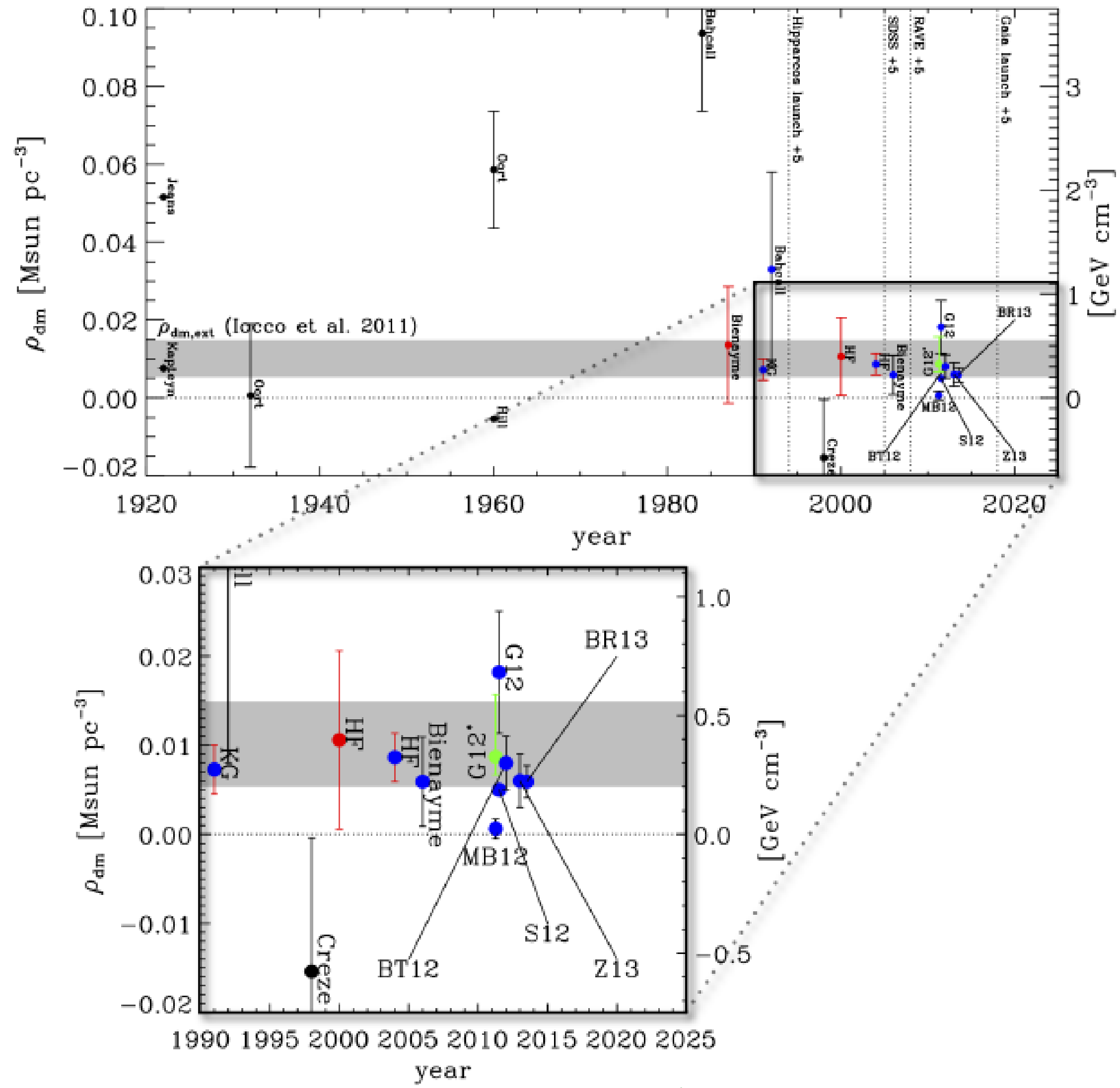
- Local dark matter density?

  - "local measurements":

    From vertical kinematics
    of stars near (~1 kpc) the Sun

  - "global measurements":

    From extrapolations of $\rho(r)$ determined from rotation curves at large r, to the position of the Solar System.



Read '14

Theoretical interpretation of the experimental results

Uncertainties from astrophysics

- Local dark matter velocity distribution?

  Completely unknown. Rely on theoretical considerations

  - If the density distribution follows a singular isothermal sphere profile, the velocity distribution has a Maxwell-Boltzmann form.

$$\rho(r) \sim \frac{1}{r^2} \longrightarrow f(v) \sim \exp(-v^2/v_0^2)$$

Theoretical interpretation of the experimental results

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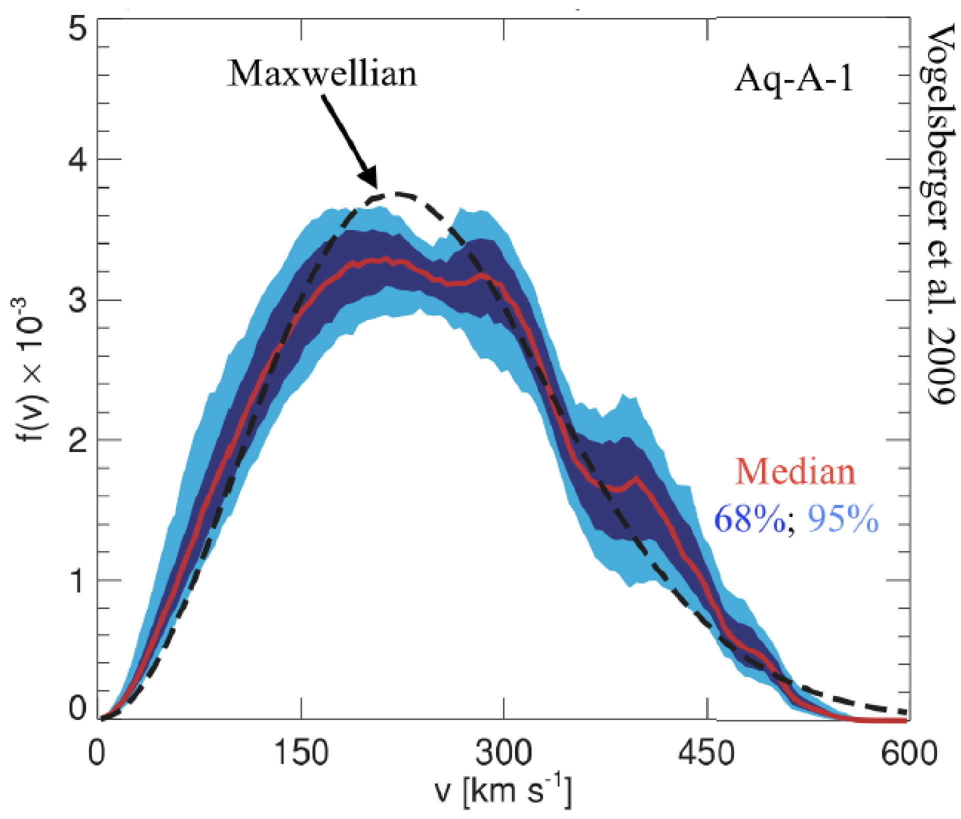
  - If the density distribution follows a singular isothermal sphere profile, the velocity distribution has a Maxwell-Boltzmann form.
  - Dark matter-only simulations. Show deviations from Maxwell-Boltzmann



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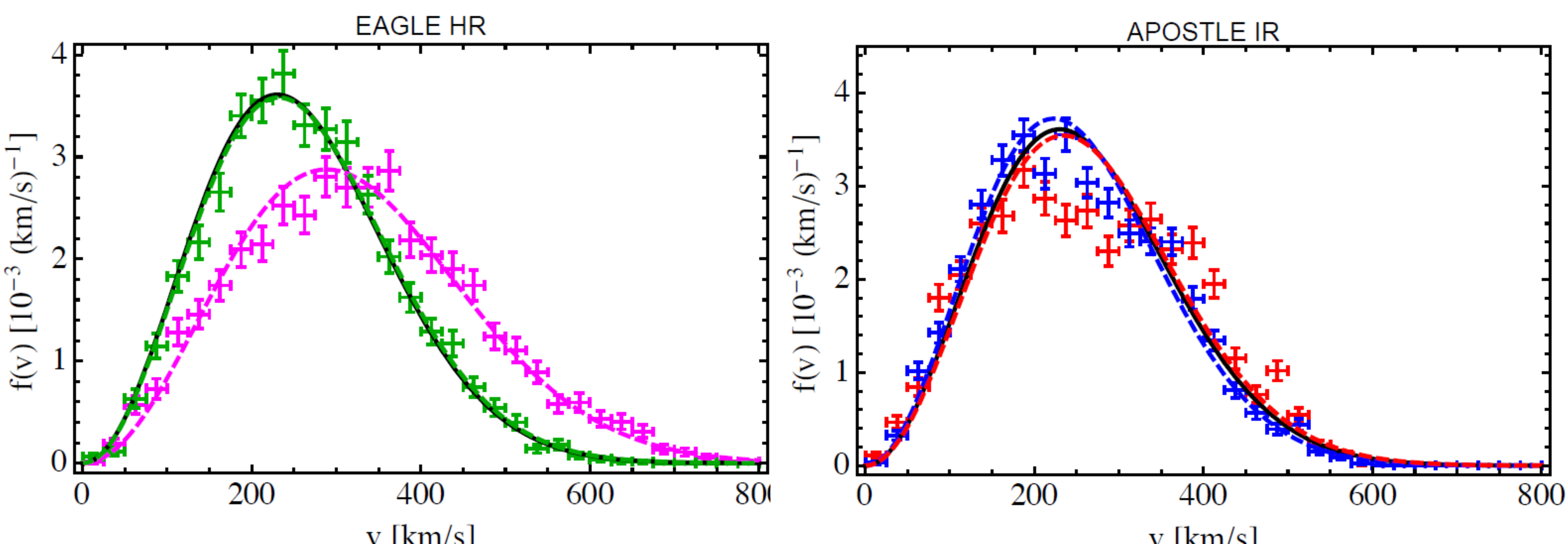
  - If the density distribution follows a singular isothermal sphere profile, the velocity distribution has a Maxwell-Boltzmann form.
  - Dark matter-only simulations. Show deviations from Maxwell-Boltzmann
  - Hydrodynamical simulations (DM+baryons). Inconclusive at the moment.

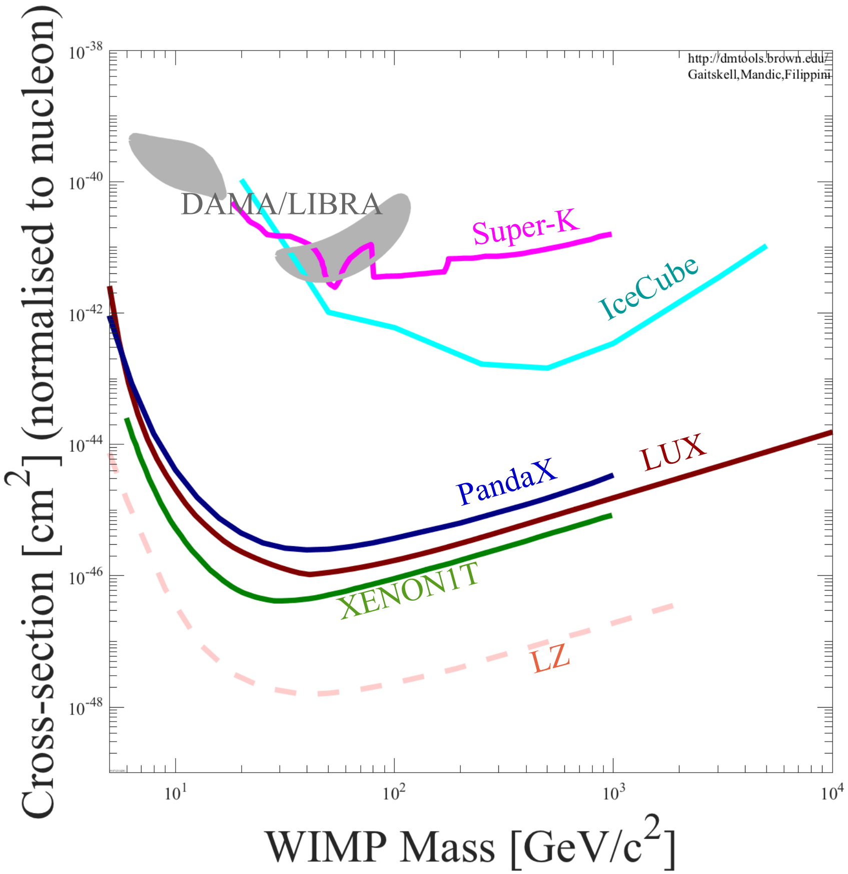


Bozorgnia et al'16

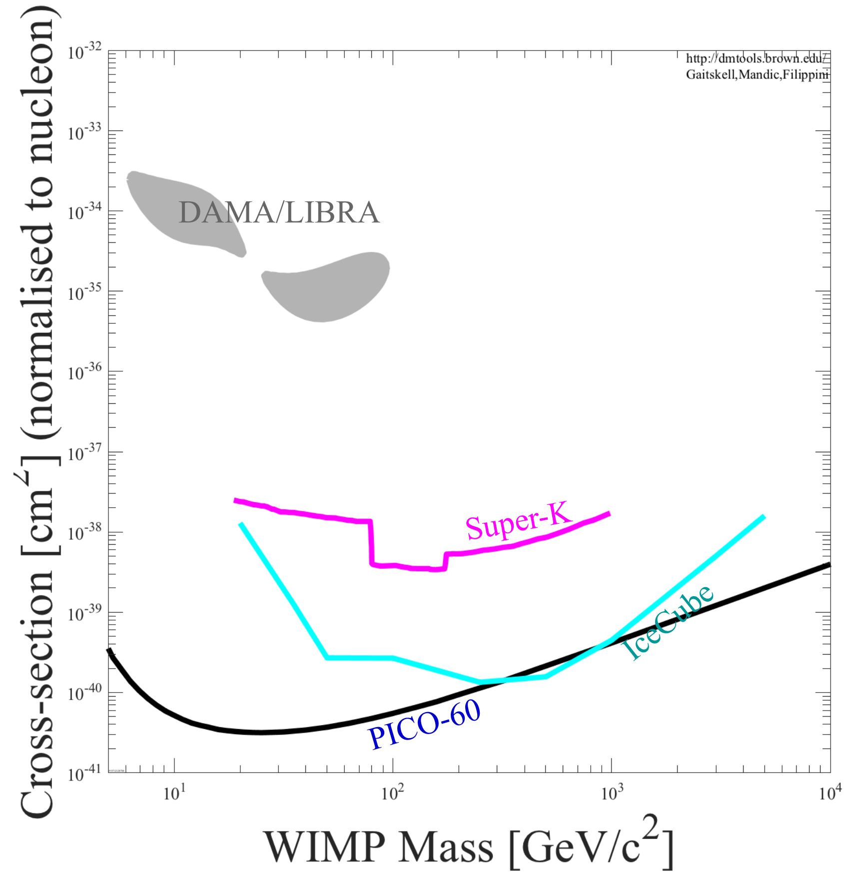
Theoretical interpretation of the experimental results

Common approach: assume SI or SD interaction only, assume $\rho_{loc} = 0.3\ GeV/cm^3$ and assume a Maxwell-Boltzmann velocity distribution

SI



SD



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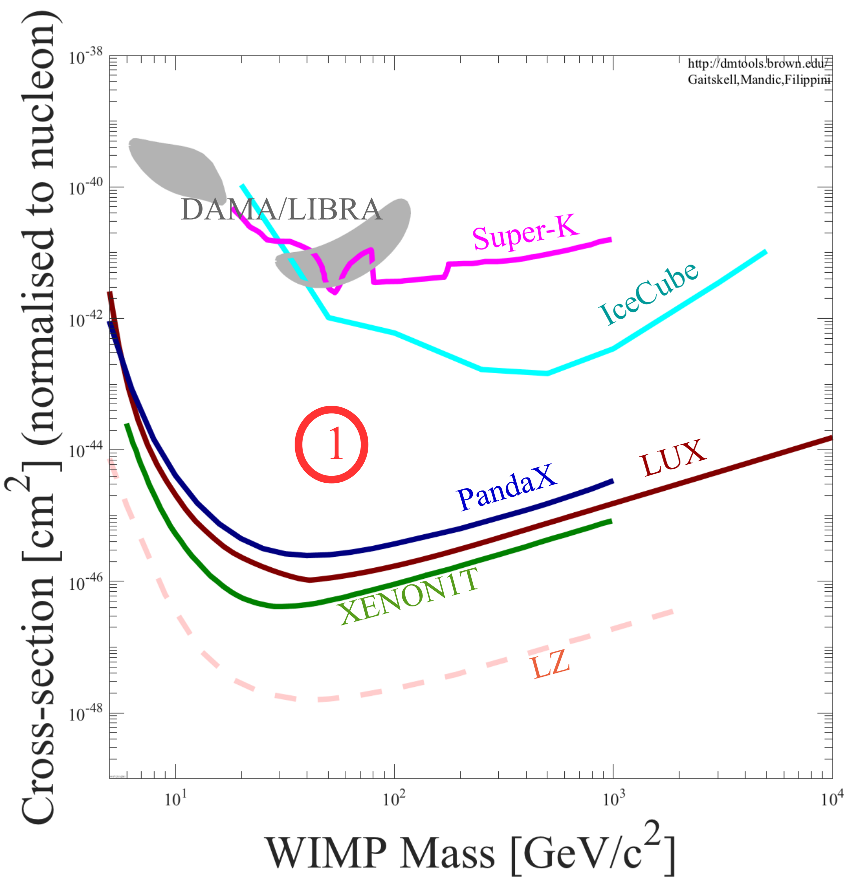

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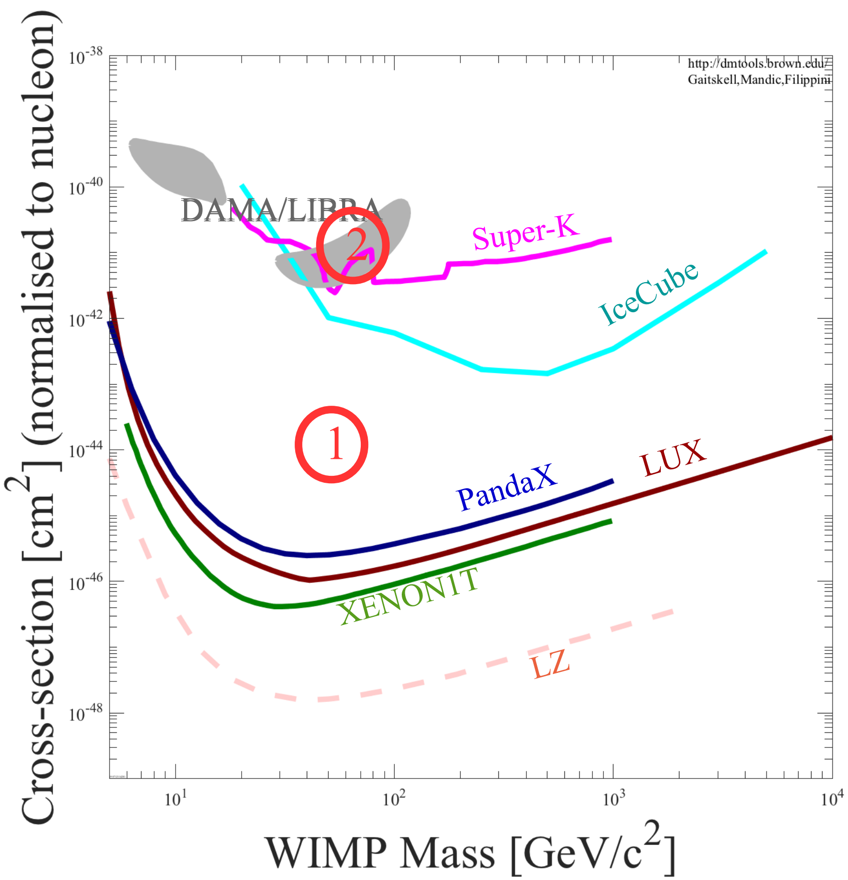

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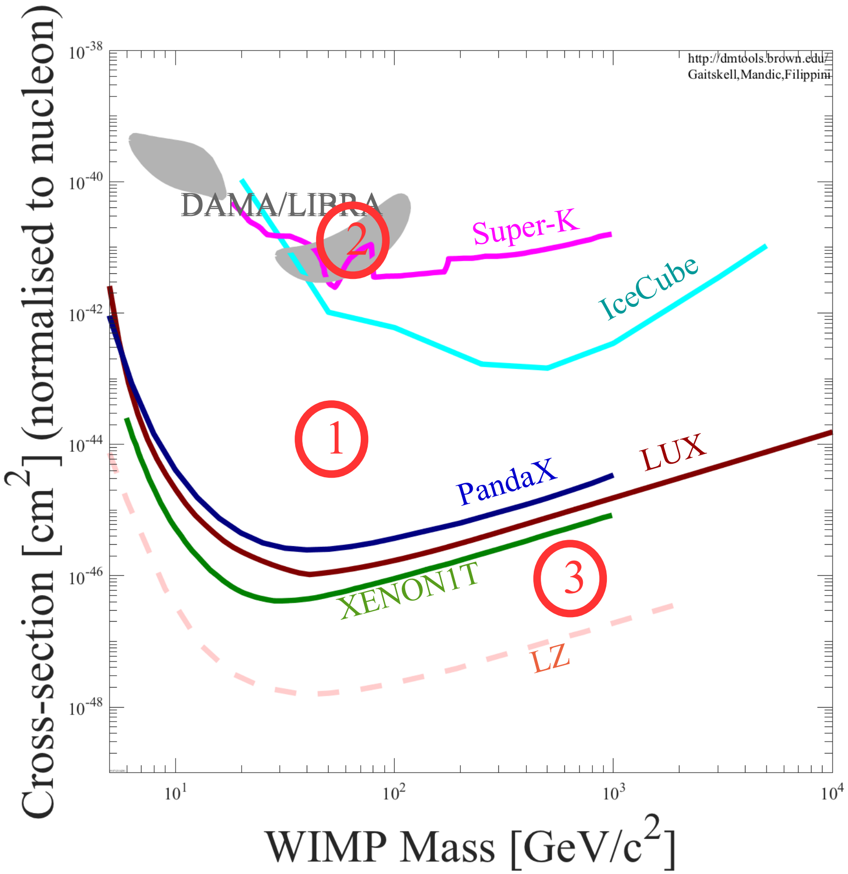

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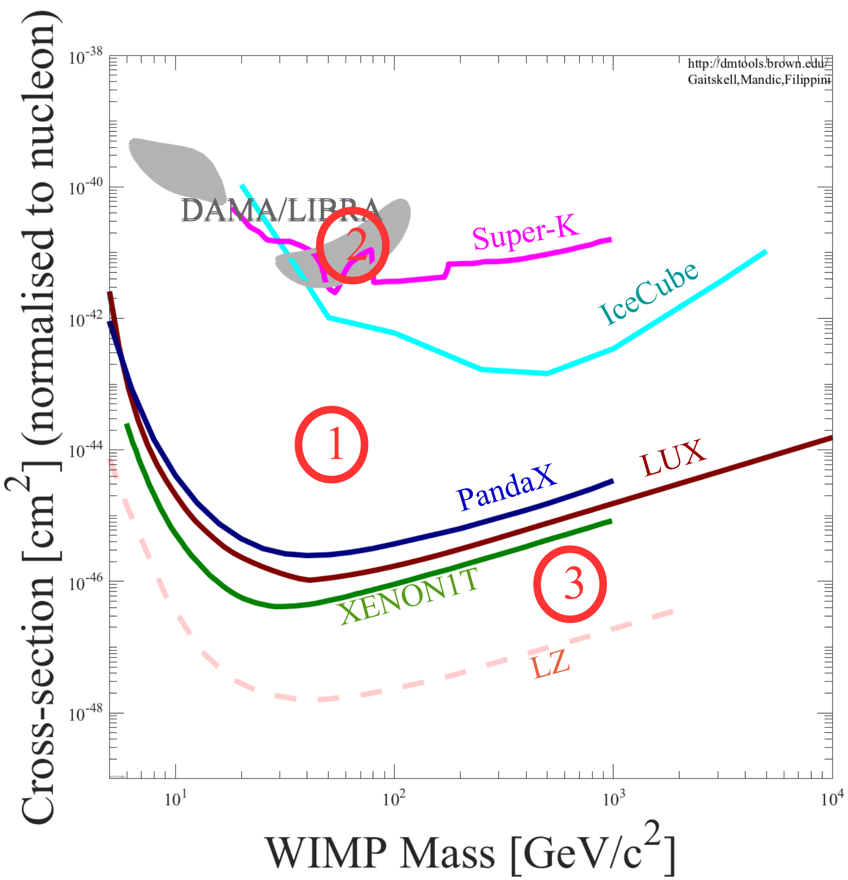

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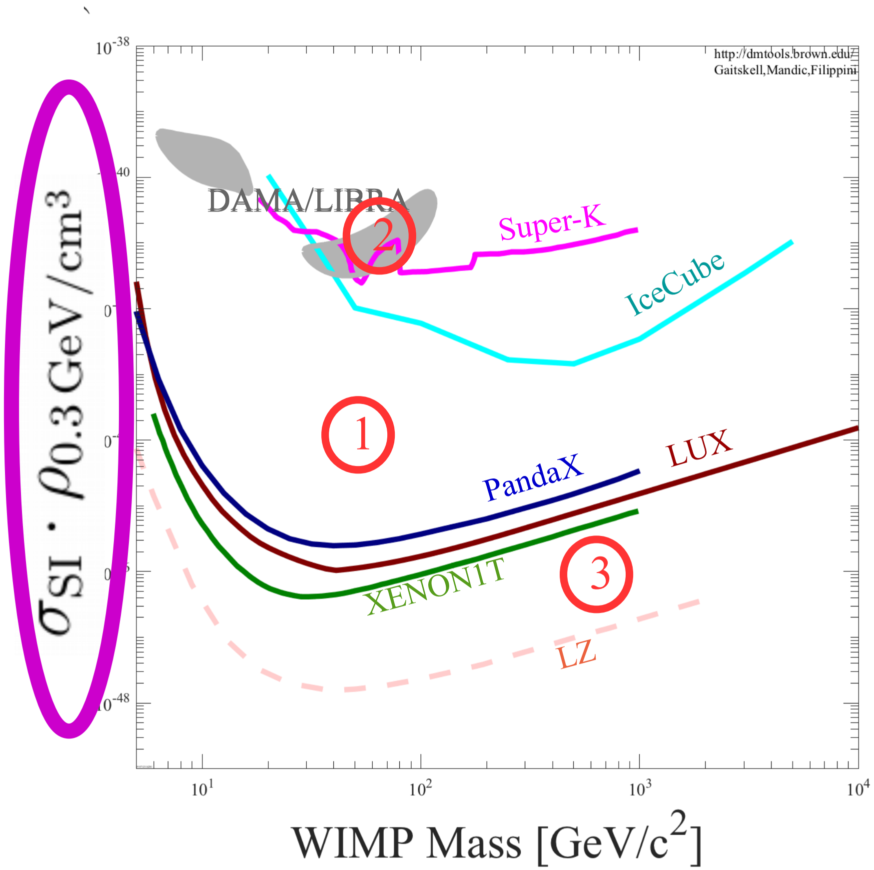

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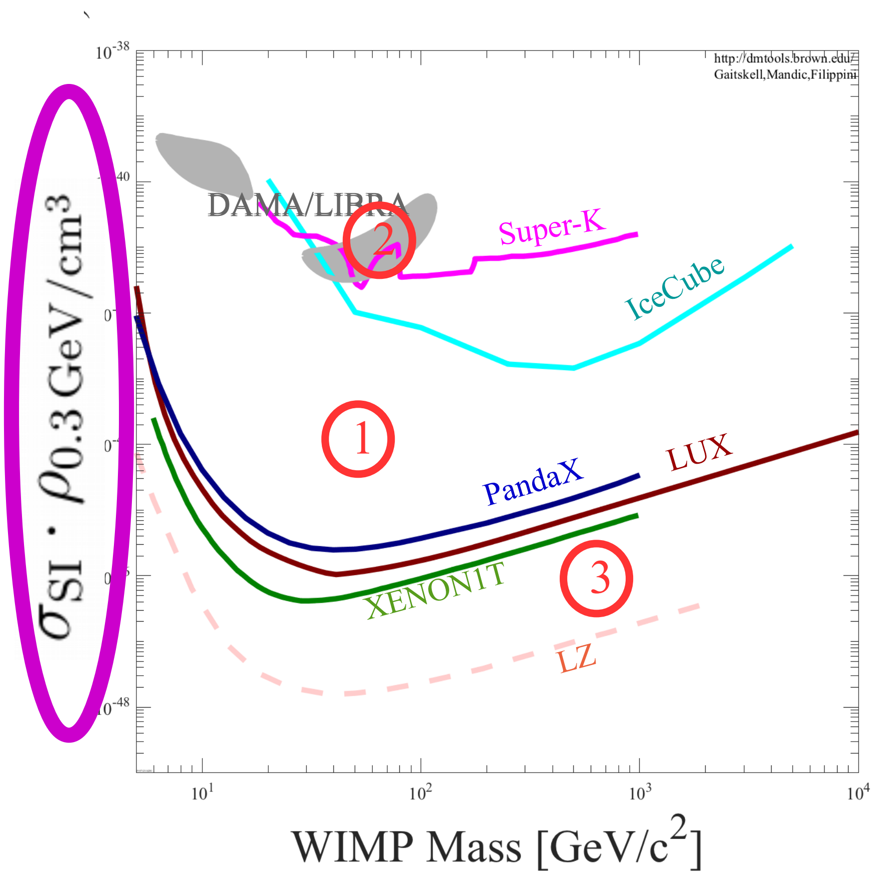

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Do these conclusions hold for arbitrary velocity distributions?

Addressing astrophysical uncertainties in dark matter detection

Halo-independent approach for DM frameworks

- $(\sigma, m_{\rm DM})$ is ruled out regardless of the velocity distribution if

$$\min_{f(\vec{v})} \left\{ R(\sigma, m_{\rm DM}) \right\} \Big|_{\int f=1} > R_{\rm u.l.}$$

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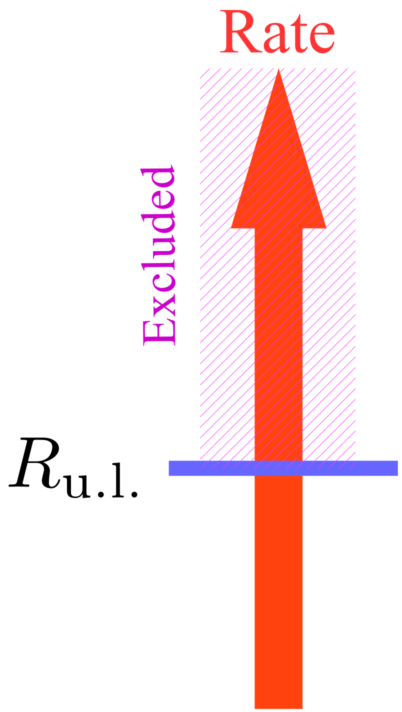

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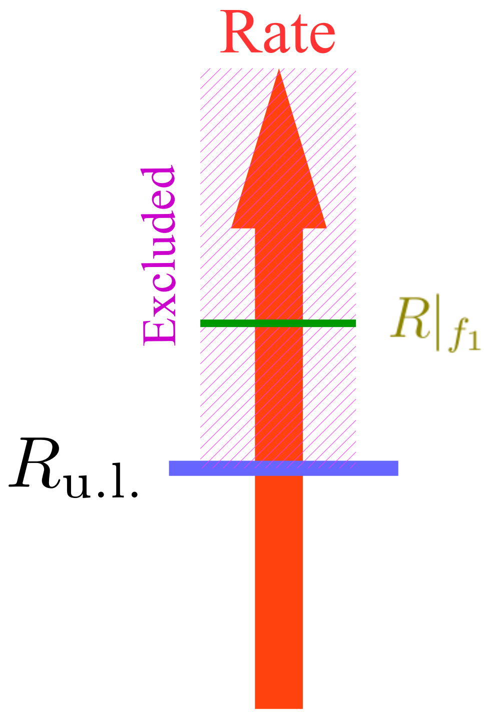

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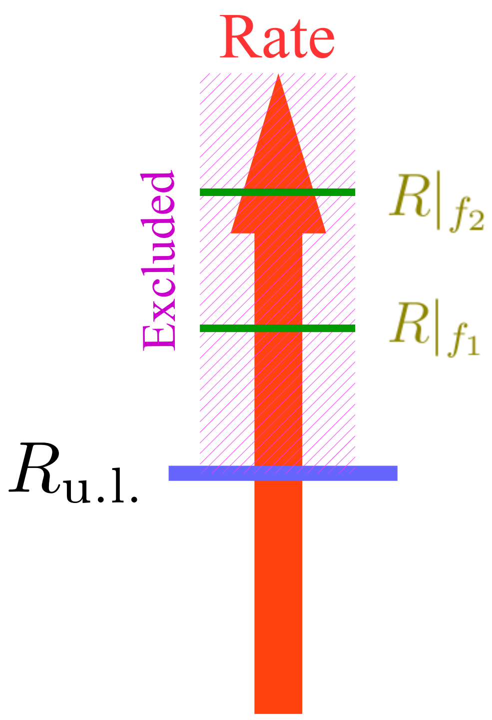

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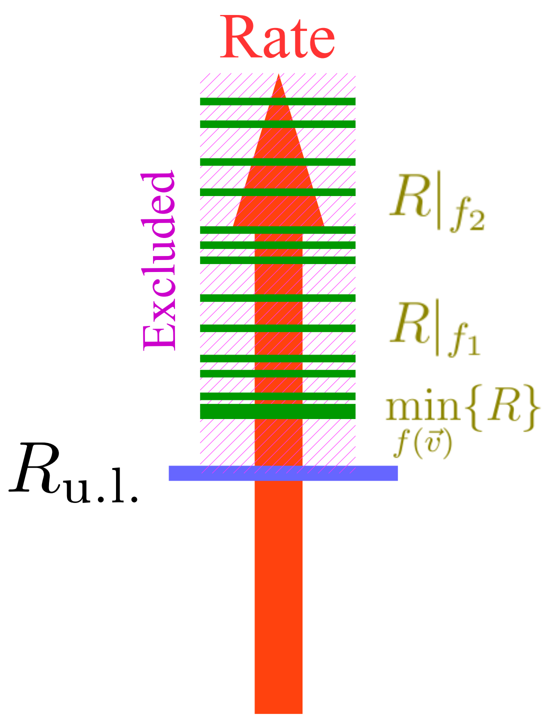

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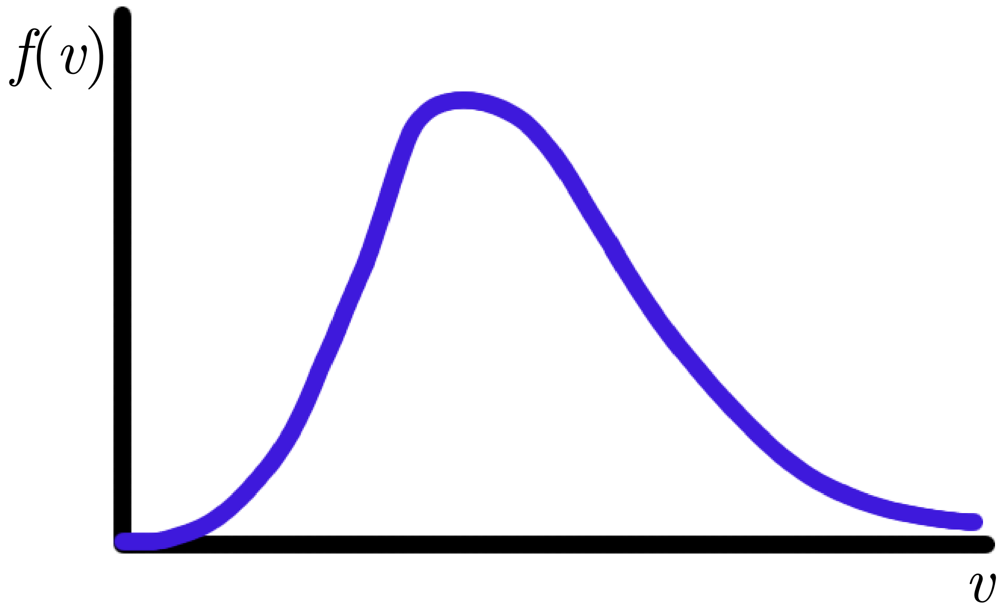
Note: one single direct detection experiment is not sufficient to probe a dark matter model in a totally halo-independent manner



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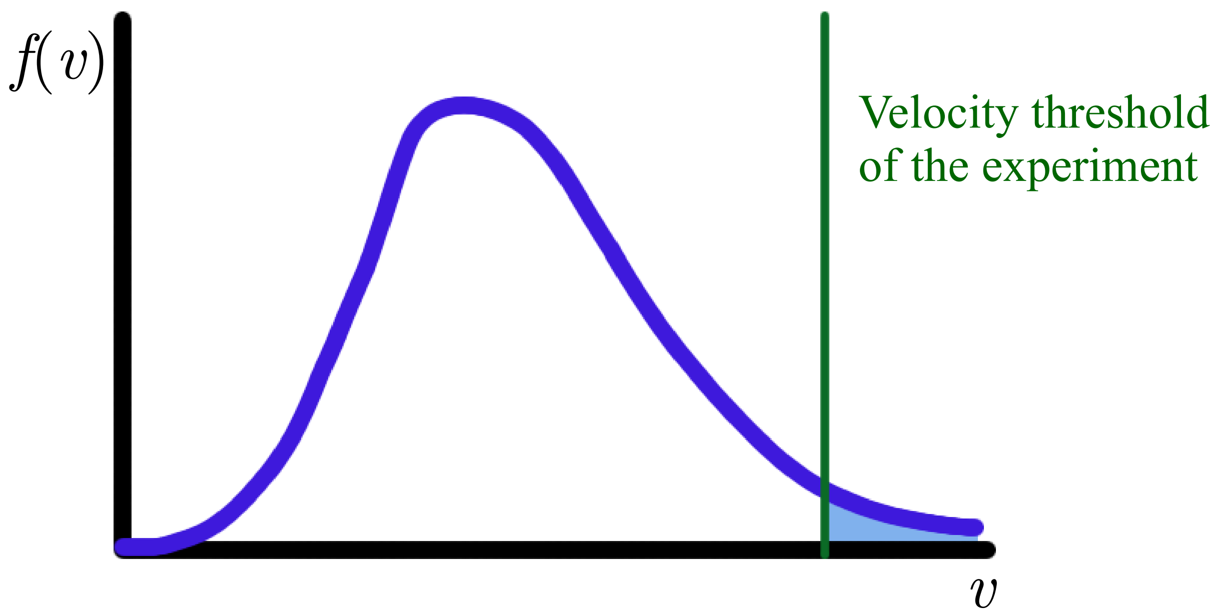

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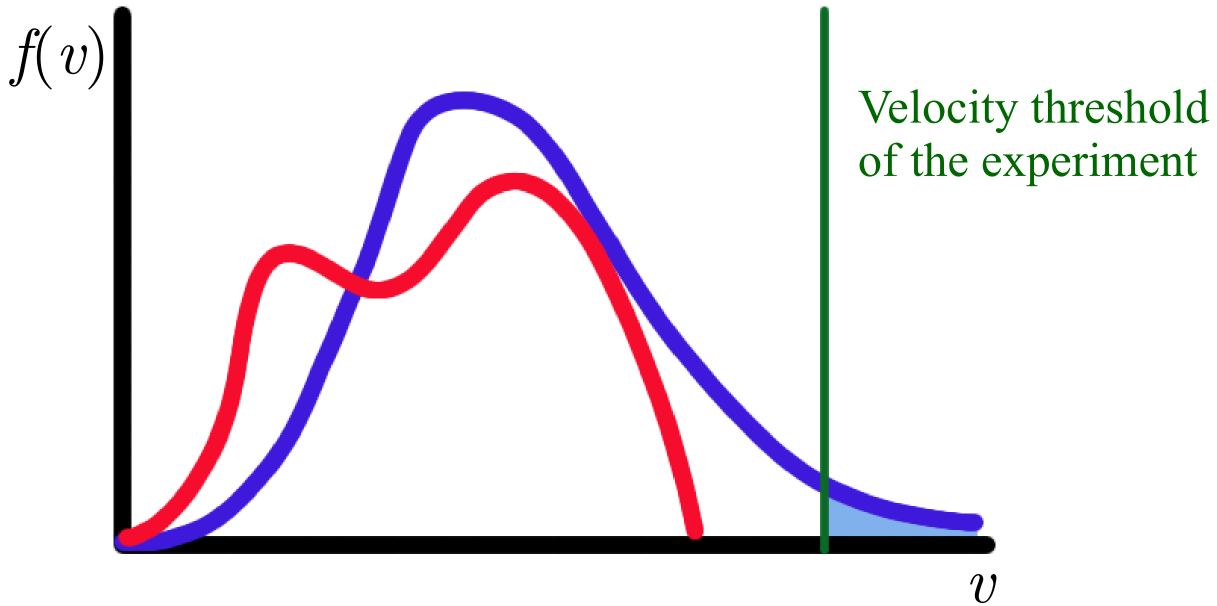

Some velocity distributions will escape detection in the experiment

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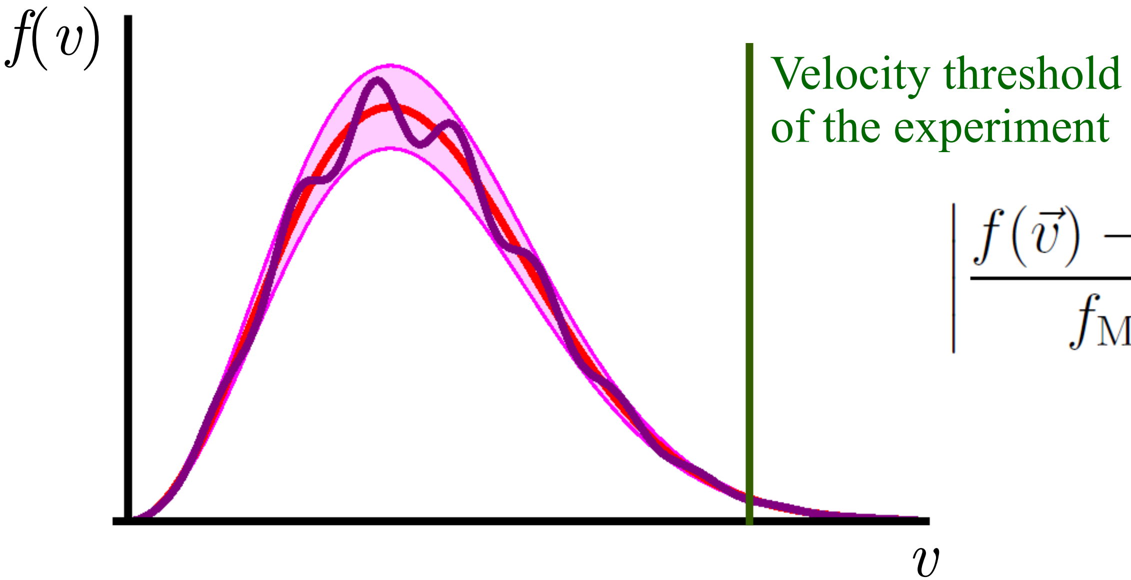

$$\left| \frac{f(\vec{v}) - f_{\rm MB}(\vec{v})}{f_{\rm MB}(\vec{v})} \right| \leq \Delta$$

Possibility 1: consider "distortions" of the Maxwell-Boltzmann distribution

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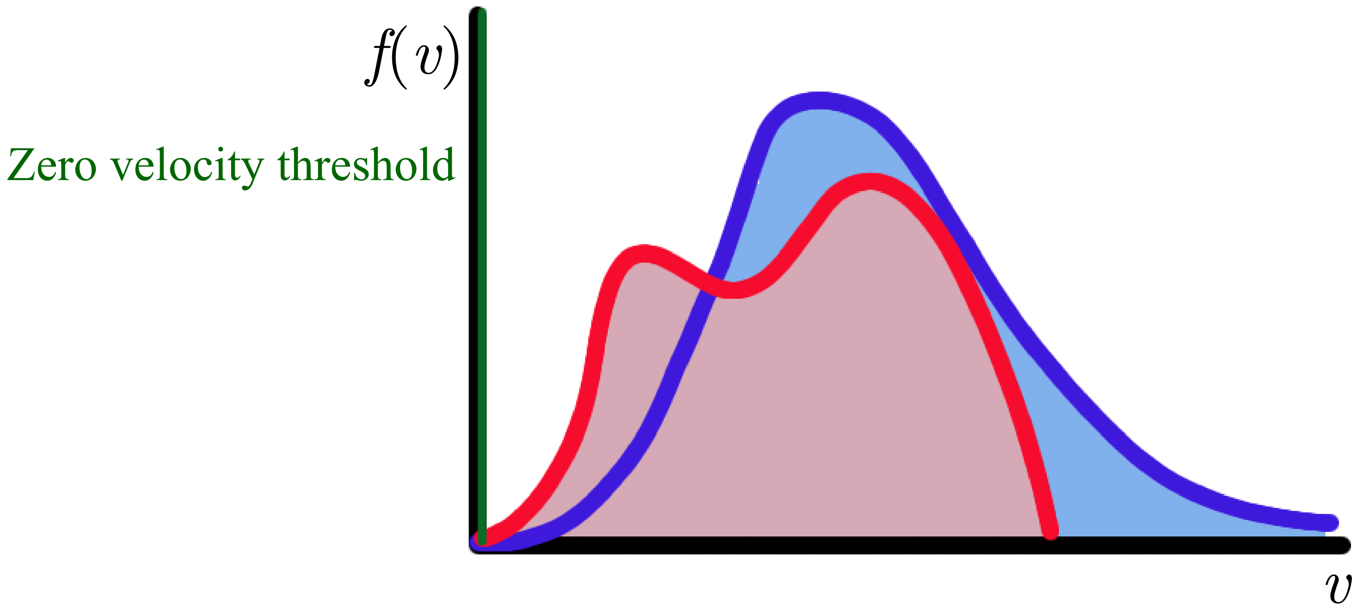

Possibility 2: Design an experiment with zero velocity threshold

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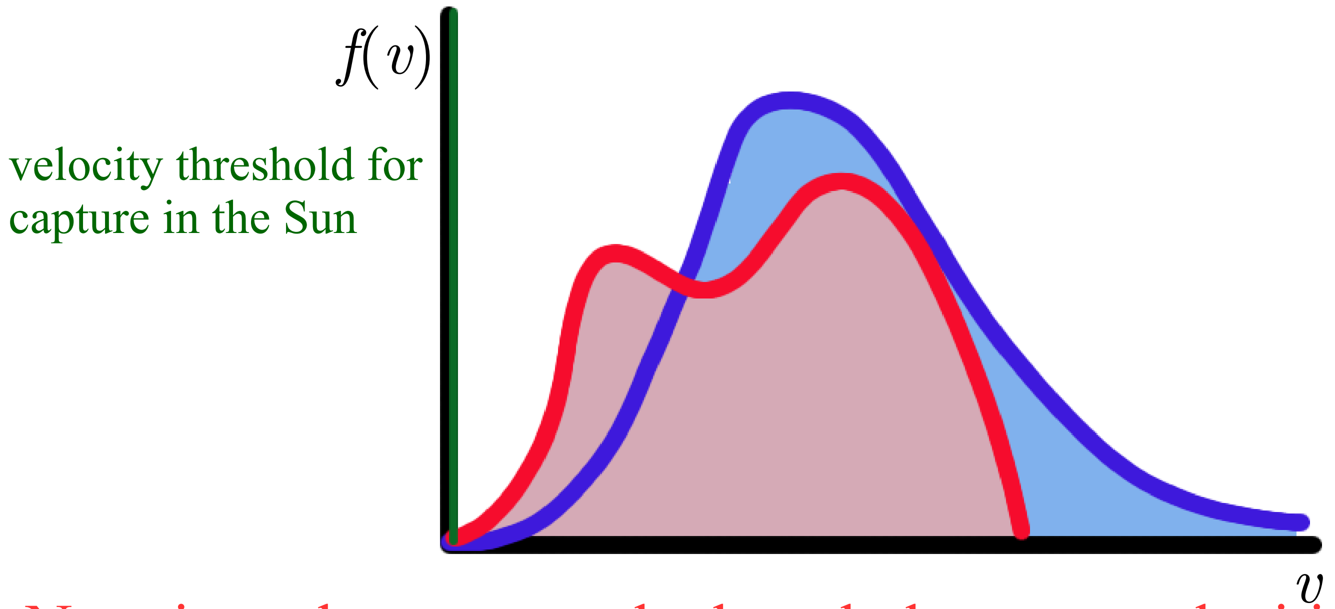
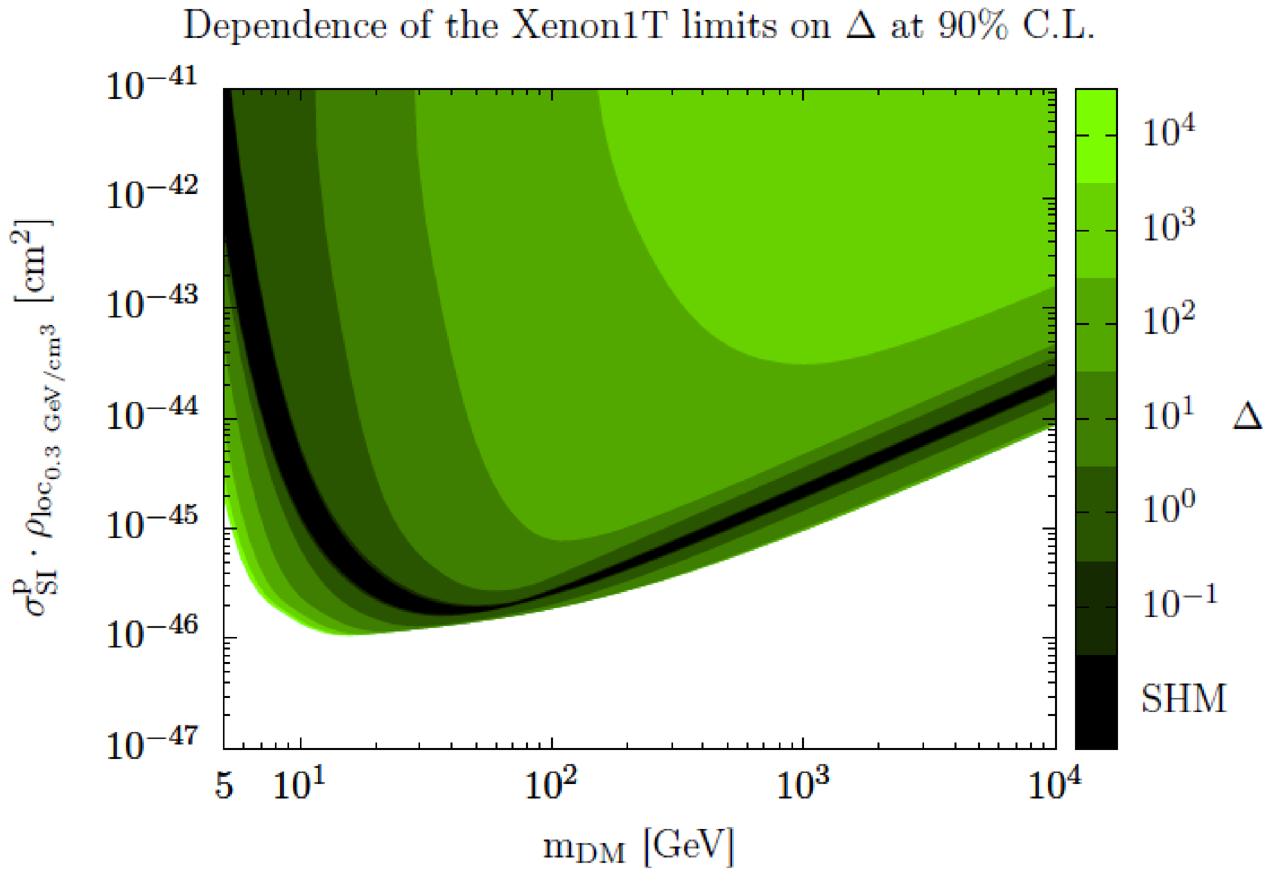


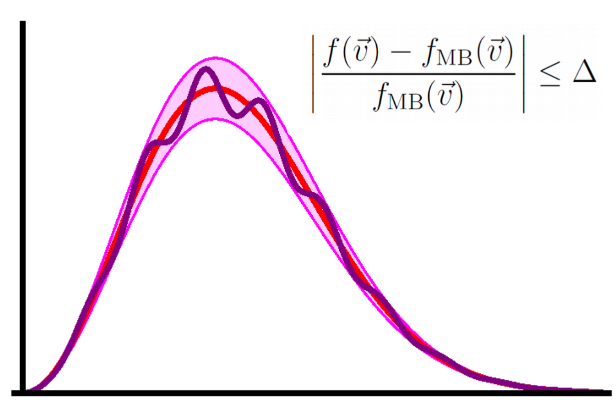
Neutrino telescopes probe low dark matter velocities. In combination with direct detection experiments, one can probe the whole velocity space

Distorting the Maxwell-Boltzmann distribution

Calculate for a given Δ the minimum of the scattering rate among all the velocity distributions within the band. A point in parameter space is excluded if:

$$\min_{f(\vec{v})} R(m_{\mathrm{DM}},\sigma)\Big|_{\substack{\int f=1 \\ f\ \text{within band}}} > R_{\mathrm{u.l.}}$$

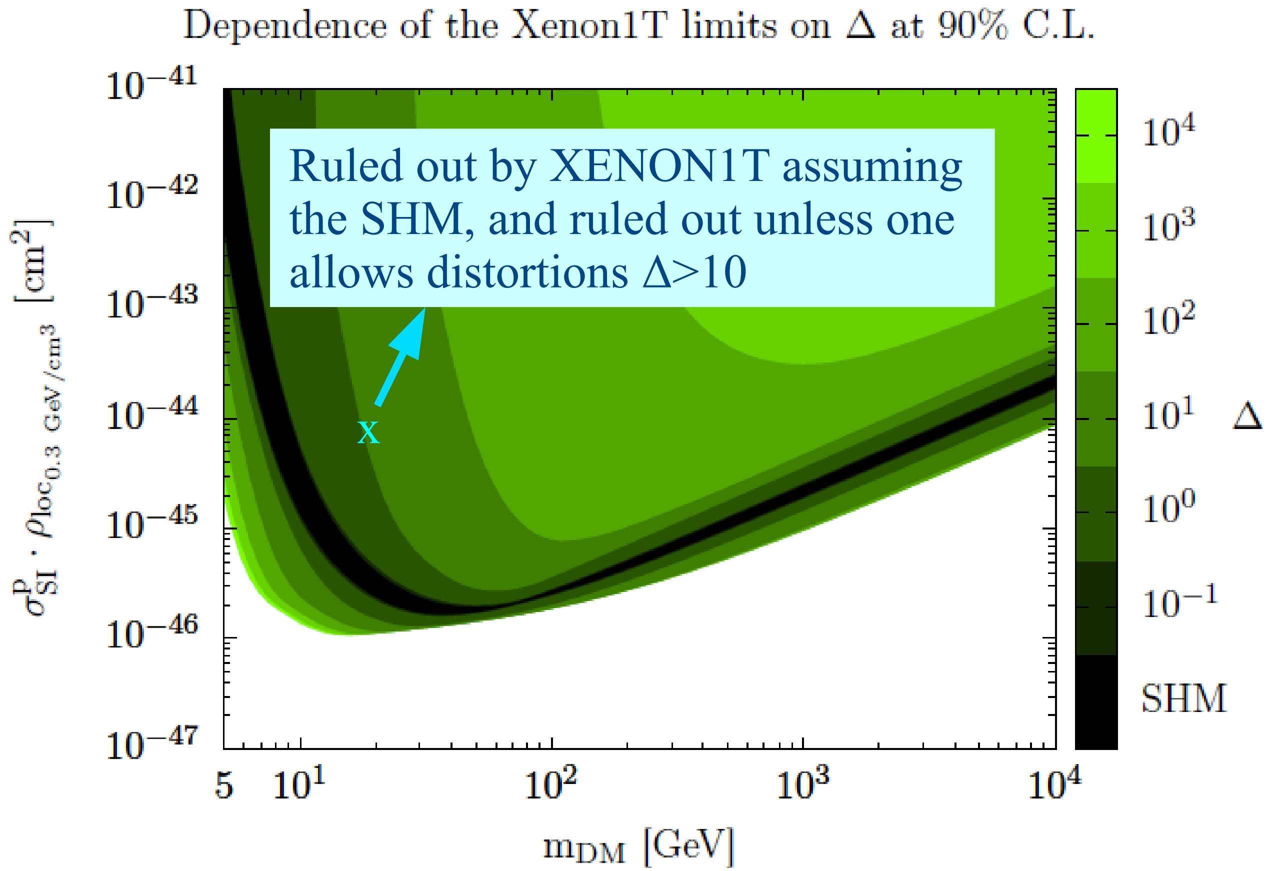


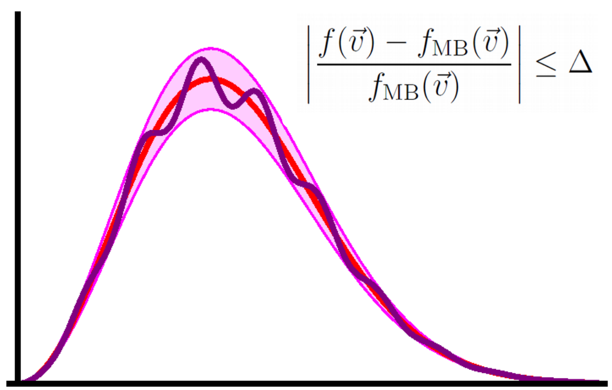


Distorting the Maxwell-Boltzmann distribution

Calculate for a given Δ the minimum of the scattering rate among all the velocity distributions within the band. A point in parameter space is excluded if:

$$\min_{f(\vec{v})} R(m_{\rm DM}, \sigma)\Big|_{\substack{\int f=1 \\ f \text{ within band}}} > R_{\rm u.l.}$$





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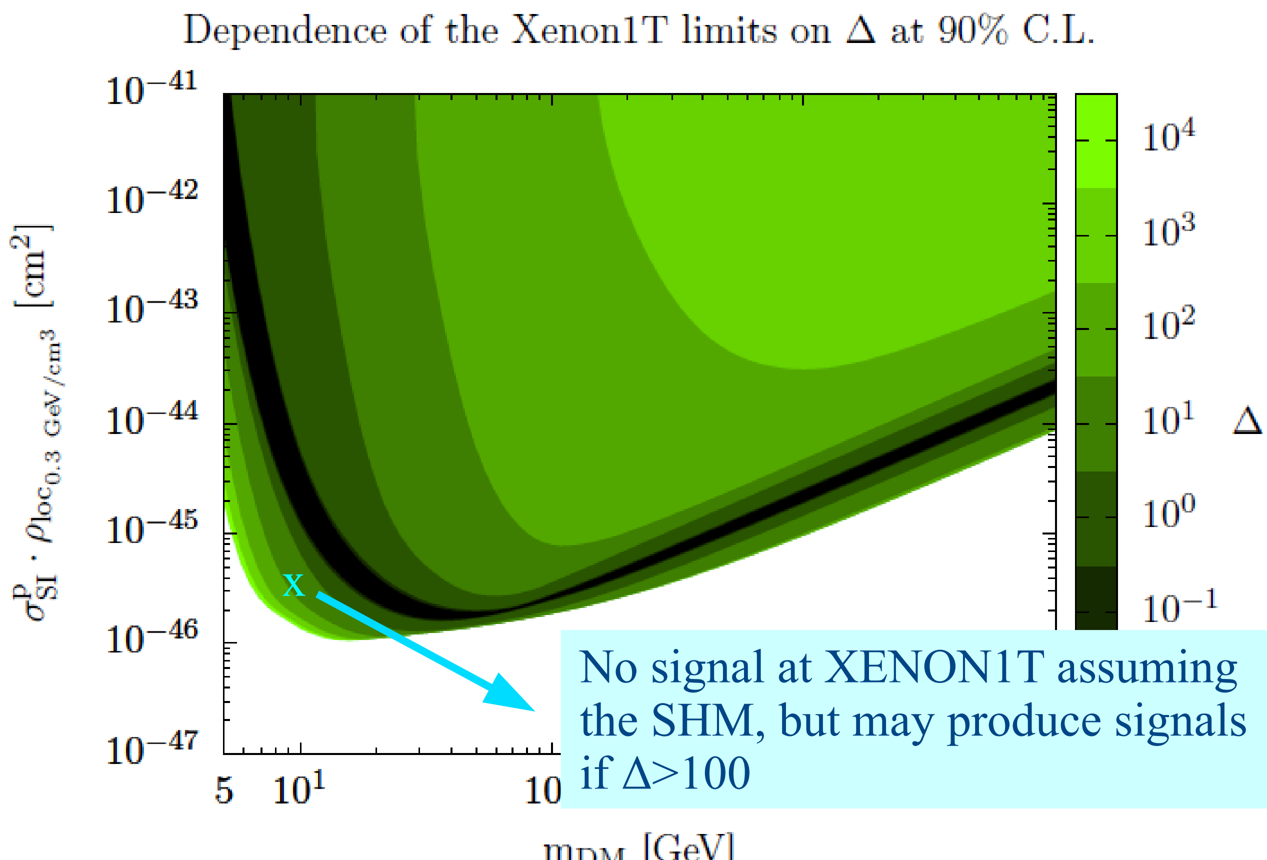
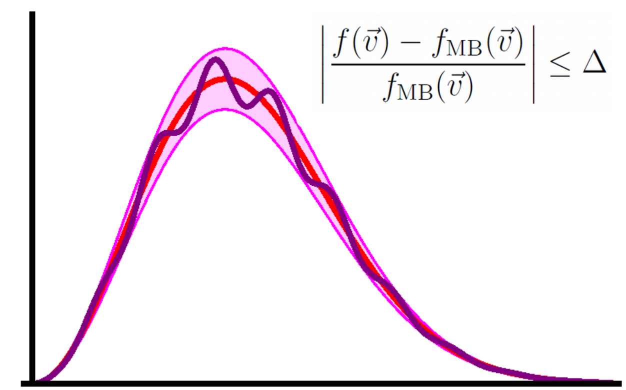


No signal at XENON1T assuming the SHM, but may produce signals if Δ>100



Upper limit on the scattering cross section from combining PandaX and IceCube/SK.

Calculate the minimum of the scattering rate among all the velocity distributions giving a capture rate in agreement with the constraints from neutrino telescopes. A point in parameter space is excluded if:

$$\boxed{\min_{f(\vec{v})} R(m_{\rm DM},\sigma)\Big|_{\substack{\int f=1 \\ C<C_{\rm u.l.}}} > R_{\rm u.l.}}$$

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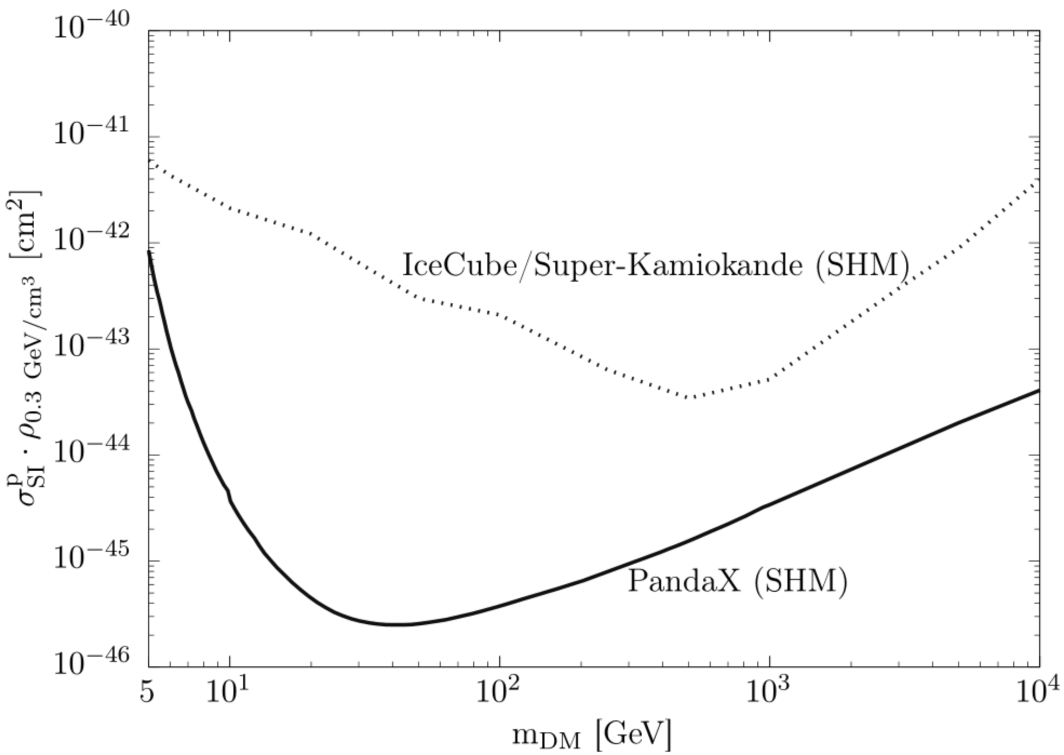

AI, Rappelt'17

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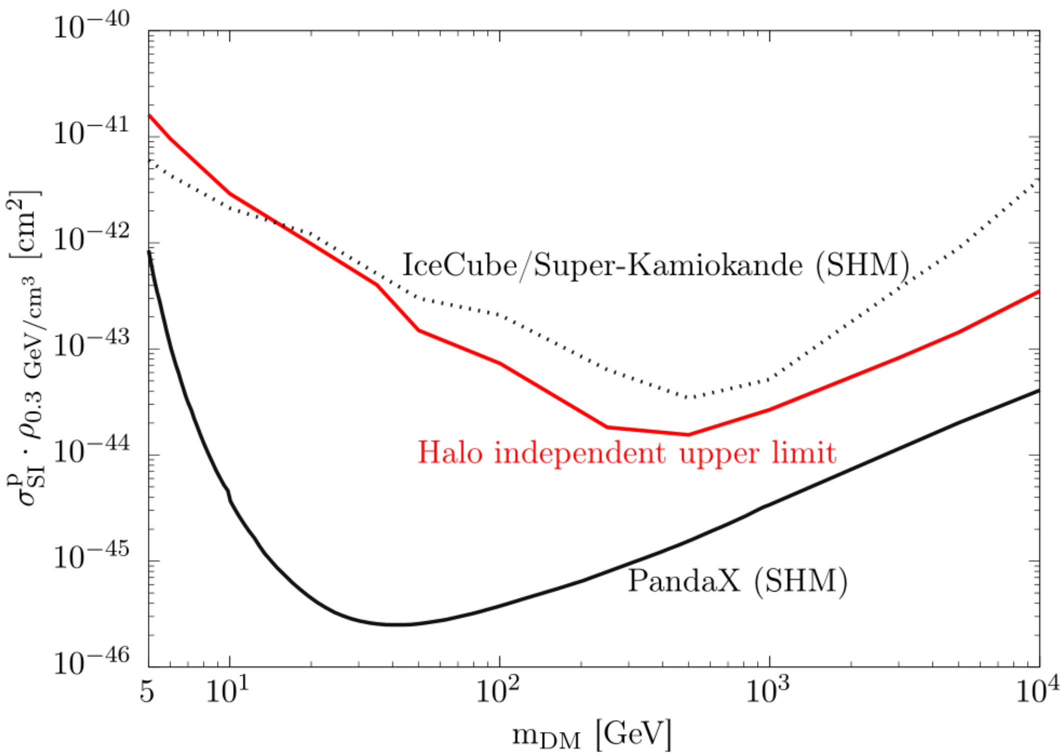

AI, Rappelt'17

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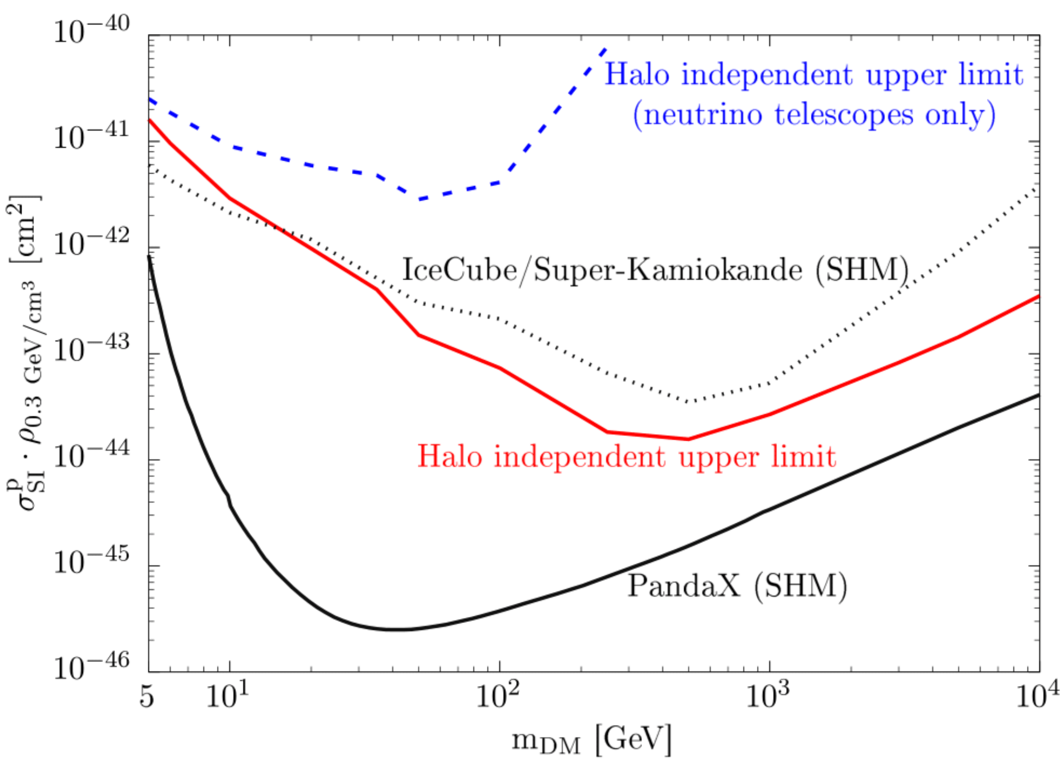

AI, Rappelt'17

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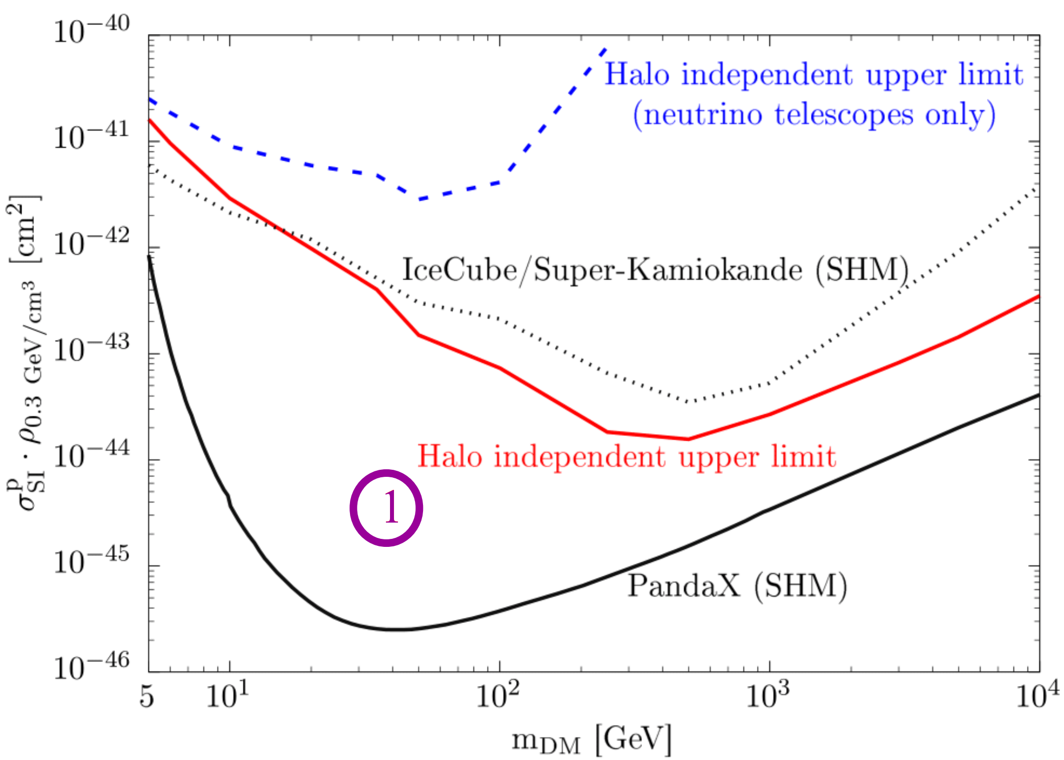

1 is ruled out by PandaX assuming the SHM, but allowed for some velocity distributions

AI, Rappelt'17

Upper limit on the scattering cross section from combining PandaX and IceCube/SK.

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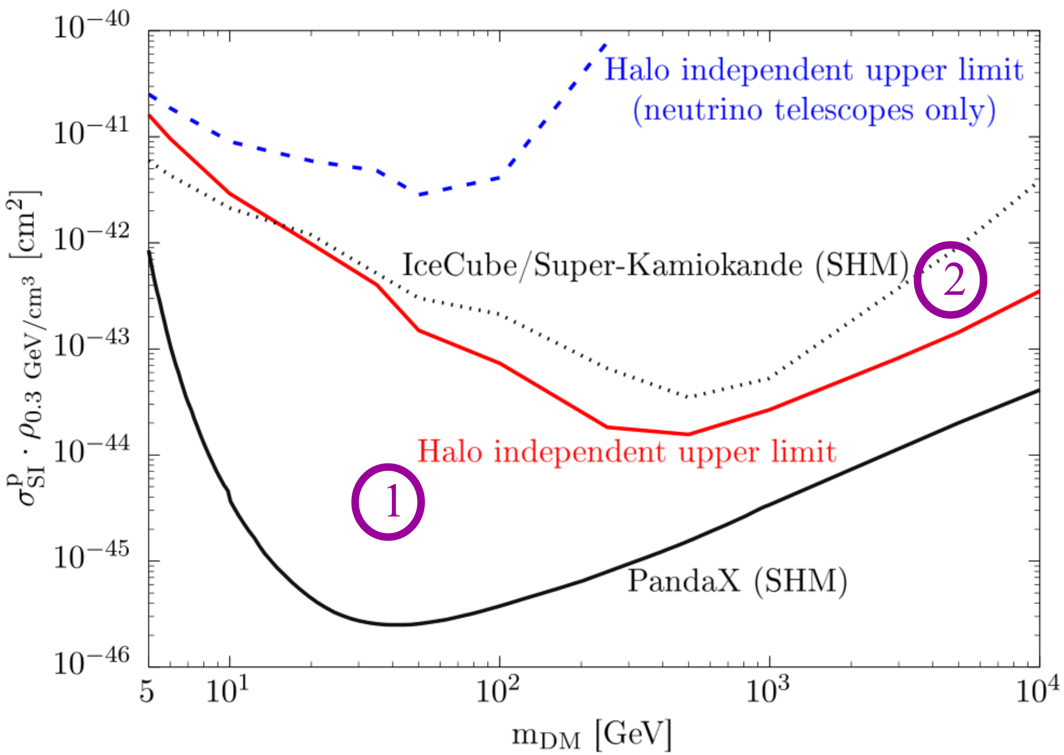


AI, Rappelt'17

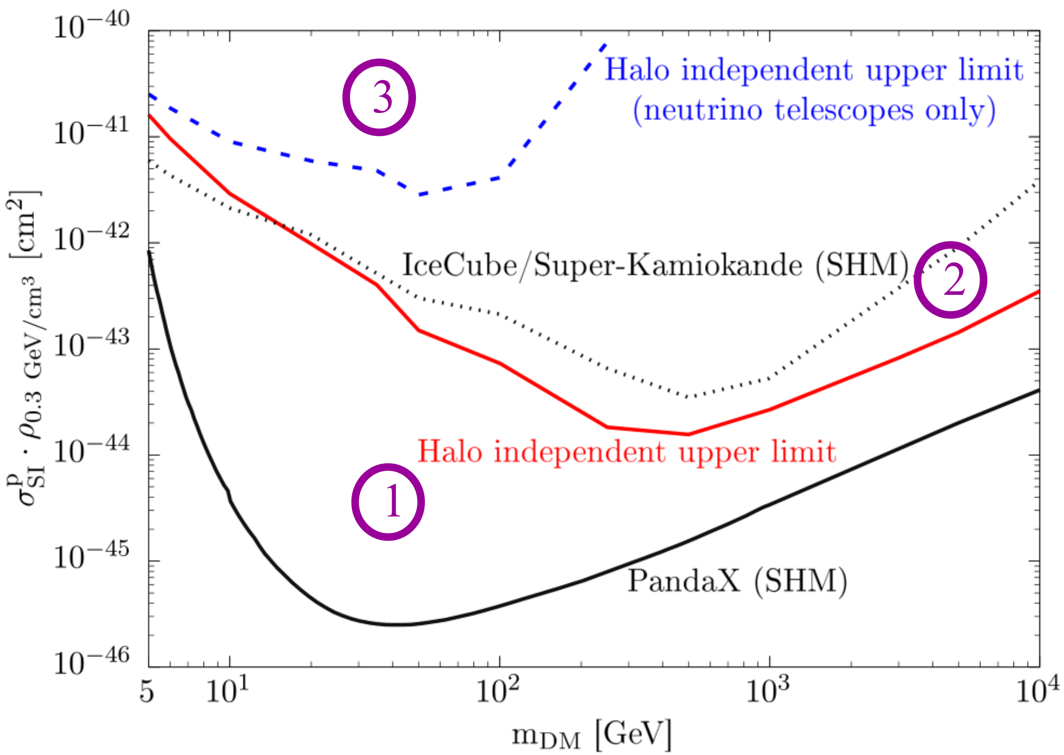
1 is ruled out by PandaX assuming the SHM, but allowed for some velocity distributions

2 is ruled out from combining PandaX and neutrino telescopes, for *any* velocity distribution.

Upper limit on the scattering cross section from combining PandaX and IceCube/SK.

Calculate the minimum of the scattering rate among all the velocity distributions giving a capture rate in agreement with the constraints from neutrino telescopes. A point in parameter space is excluded if:

$$\boxed{\min_{f(\vec{v})} R(m_{\mathrm{DM}}, \sigma)\Big|_{\substack{\int f=1 \\ C<C_{\mathrm{u.l.}}}} > R_{\mathrm{u.l.}}}$$



AI, Rappelt'17

1 is ruled out by PandaX assuming the SHM, but allowed for some velocity distributions

2 is ruled out from combining PandaX and neutrino telescopes, for *any* velocity distribution.

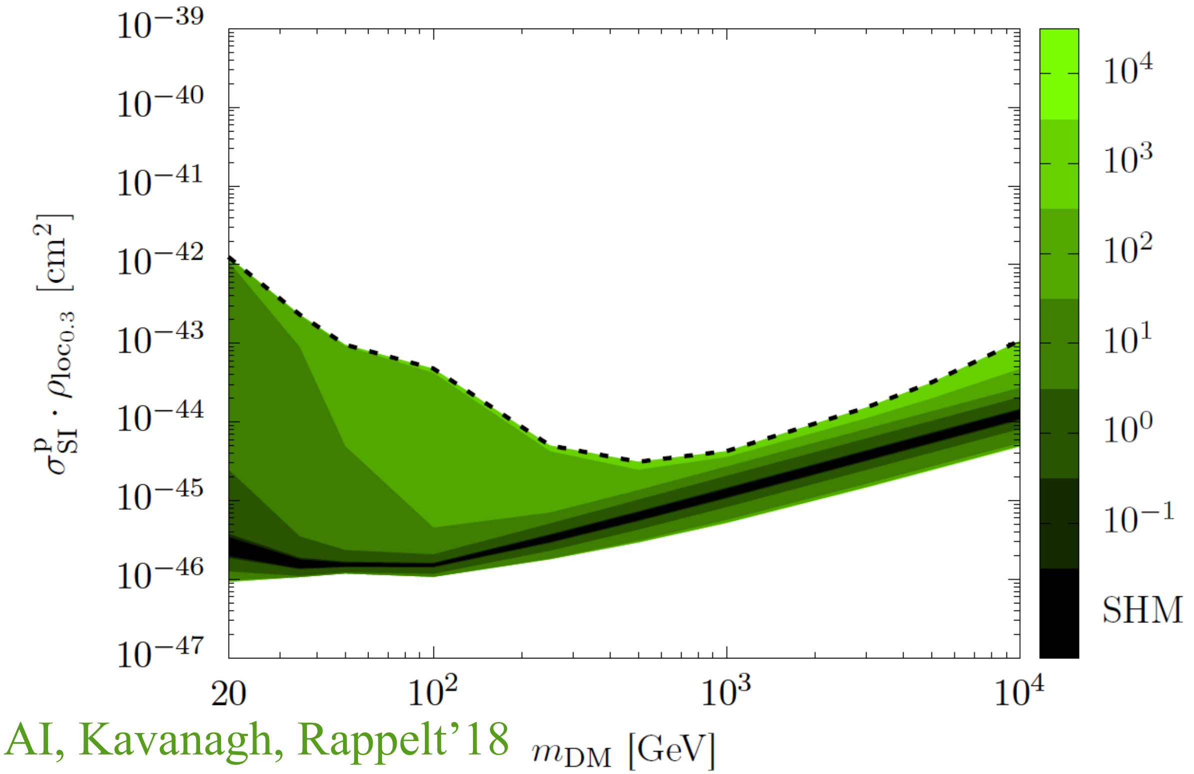
3 is ruled out by neutrino telescopes only, for *any* velocity distribution.

Upper limit on the scattering cross section from combining PandaX and IceCube/SK: extension

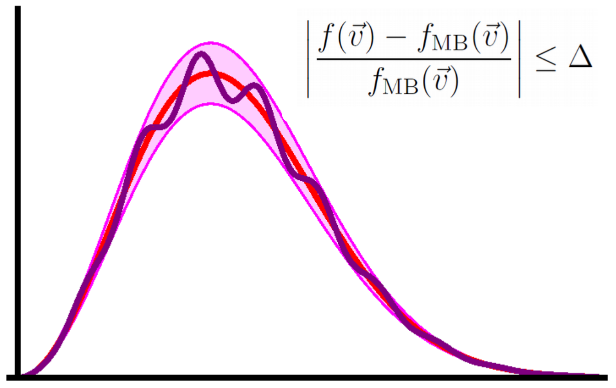
Calculate the minimum of the scattering rate among all the velocity distributions within the band of width Δ giving a capture rate in agreement with the constraints from neutrino telescopes. A point in parameter space is excluded if:

$$\boxed{\min_{f(\vec{v})} R(m_{\rm DM},\sigma)\Big|_{\substack{\int f=1\\ f\ \text{within band}\\ C<C_{\rm u.l.}}} > R_{\rm u.l.}}$$

Dependence of the XENON1T+IceCube limits on Δ at 90% C.L.



AI, Kavanagh, Rappelt'18



Upper limit on the scattering cross section from combining PandaX and IceCube/SK: extension

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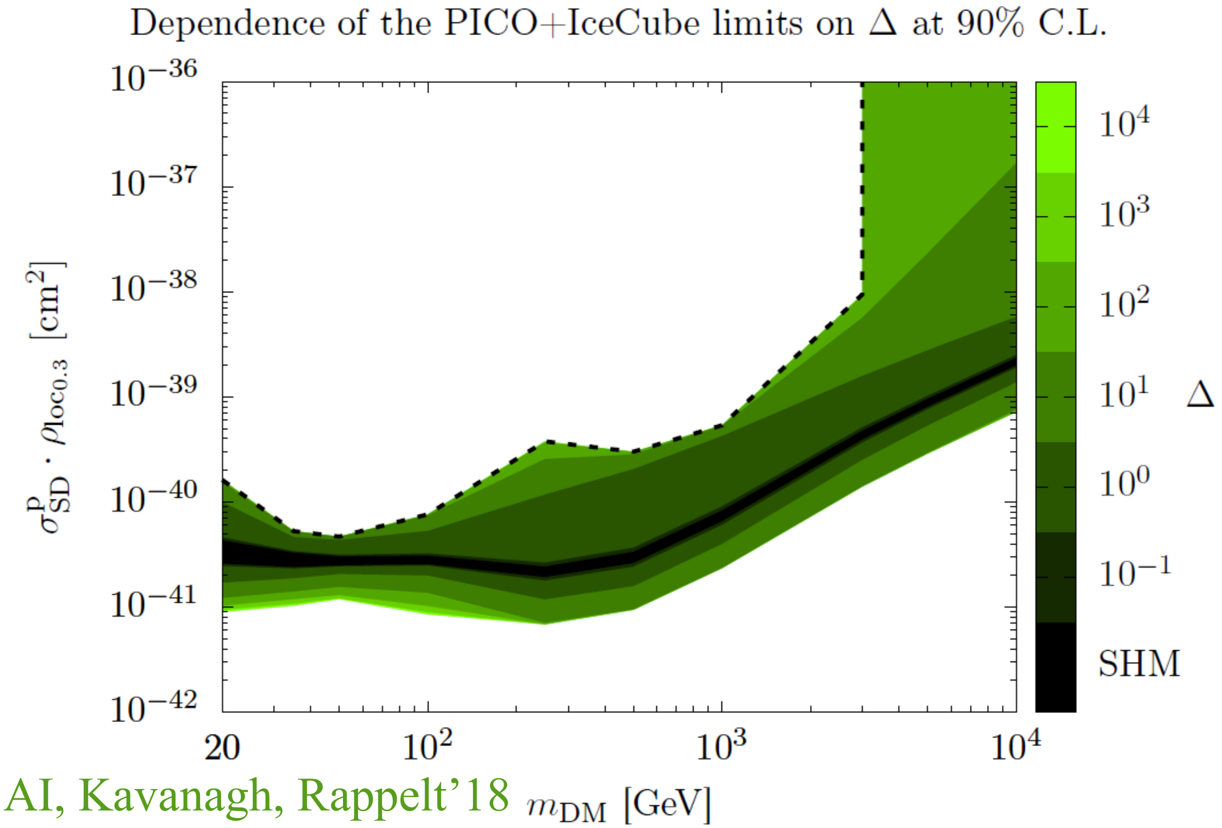
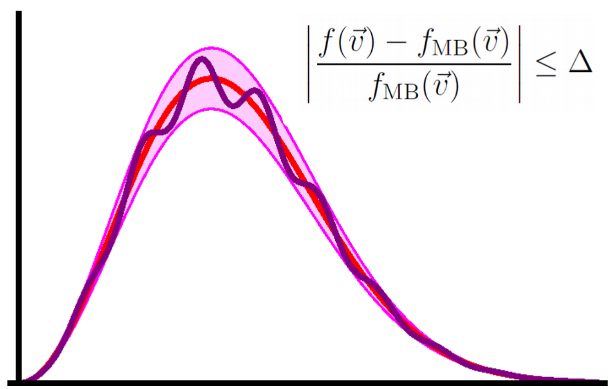


AI, Kavanagh, Rappelt'18



Upper limit on the scattering cross section from combining PandaX and IceCube/SK: extension

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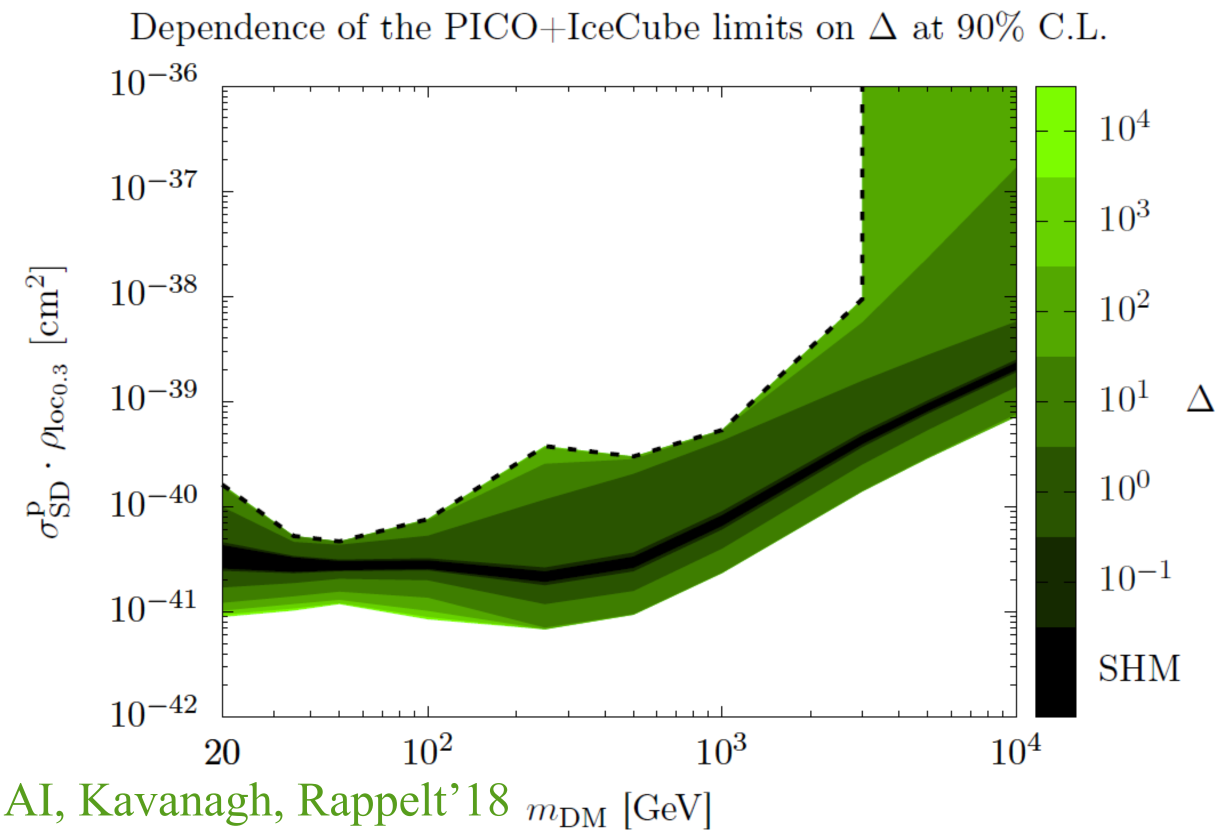
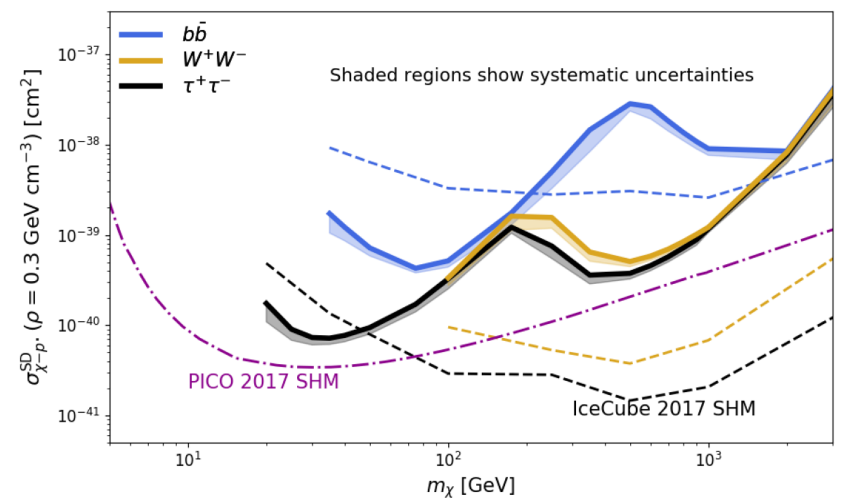


AI, Kavanagh, Rappelt'18



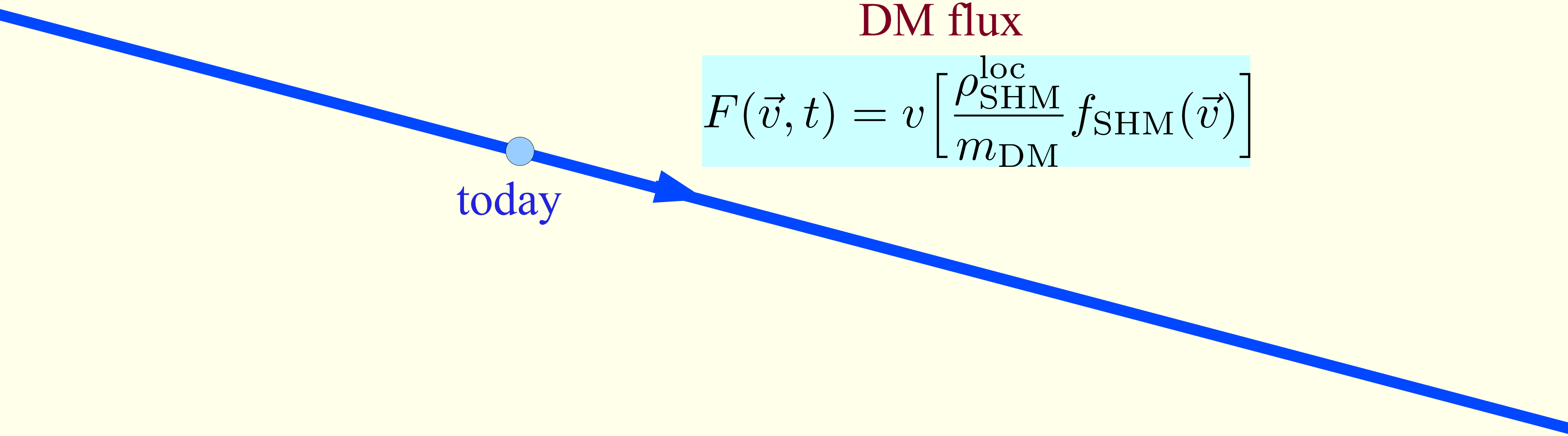
IceCube+PICO coll.'19

A concrete case:

Milky Way sub-halos

DM flux

$$F(\vec{v},t) = v\left[\frac{\rho^{\mathrm{loc}}_{\mathrm{SHM}}}{m_{\mathrm{DM}}} f_{\mathrm{SHM}}(\vec{v})\right]$$



DM flux

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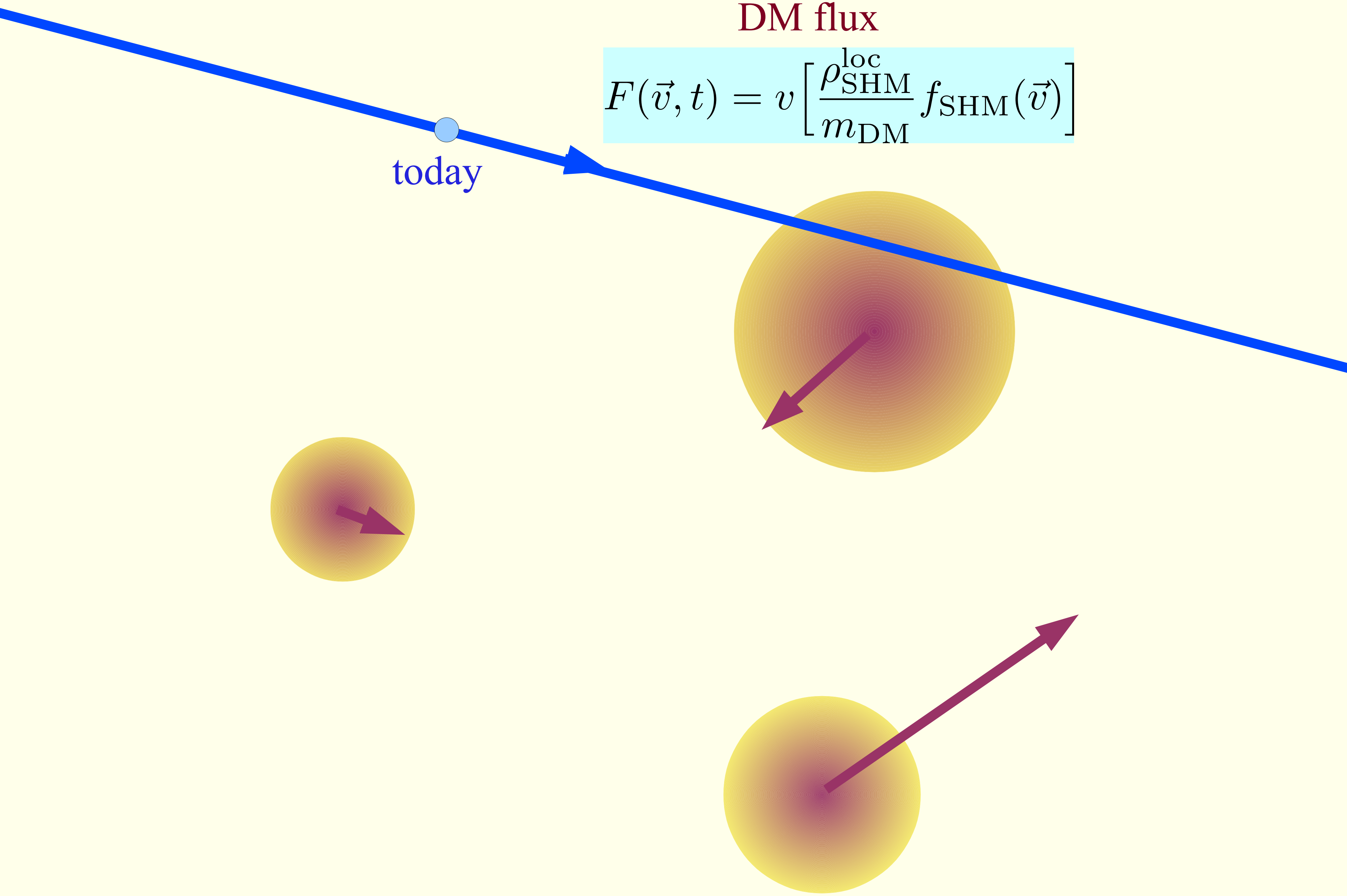
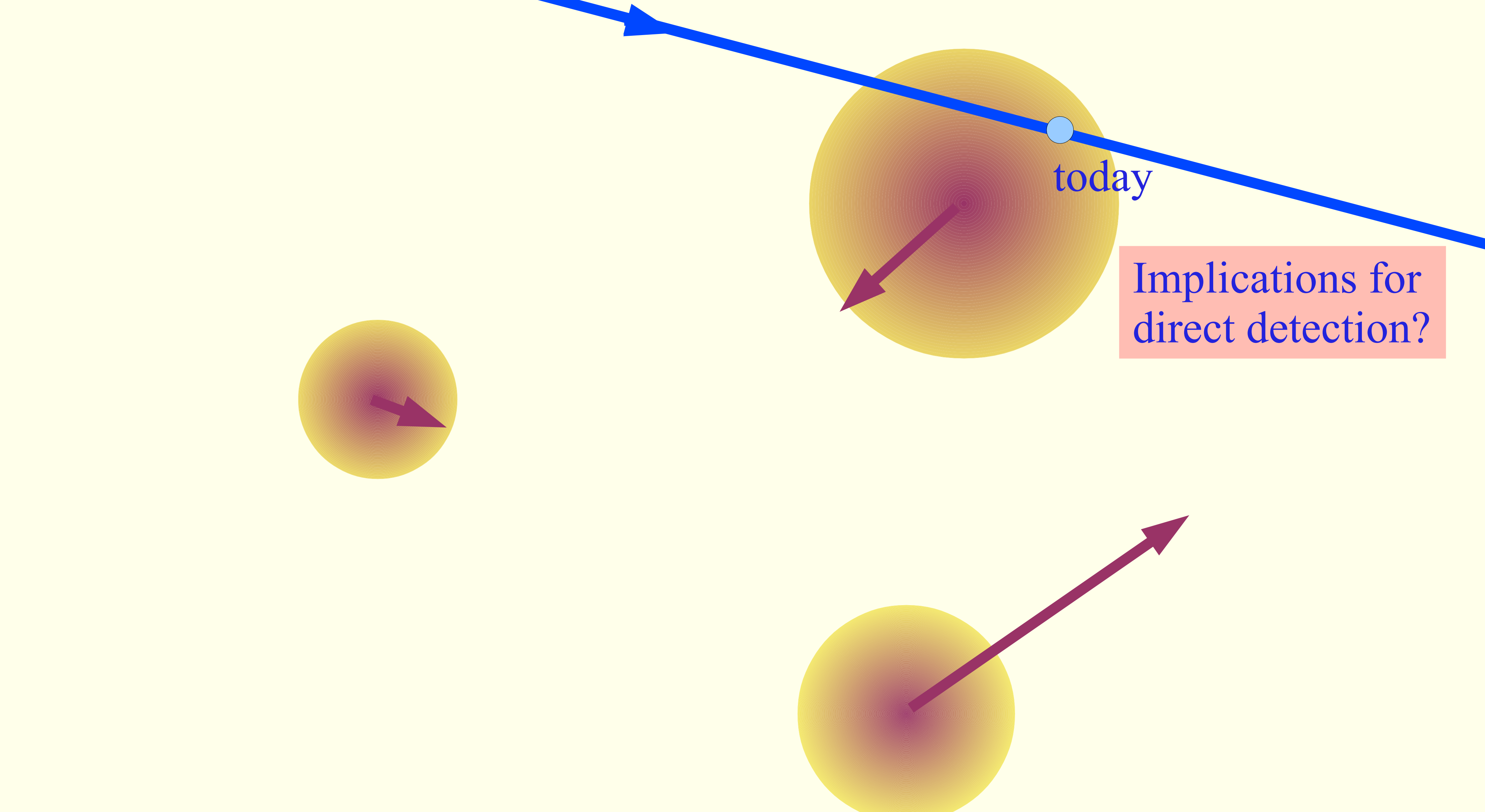


Time dependent DM flux

$$F(\vec{v},t) = v\left[\frac{\rho^{\rm loc}_{\rm SHM}}{m_{\rm DM}} f_{\rm SHM}(\vec{v}) + \frac{\rho^{\rm loc}_{\rm sh}[r(t)]}{m_{\rm DM}} f_{{\rm sh},\vec{v}_{\rm sh}}(\vec{v})\right]$$



Implications for direct detection?

Time dependent DM flux

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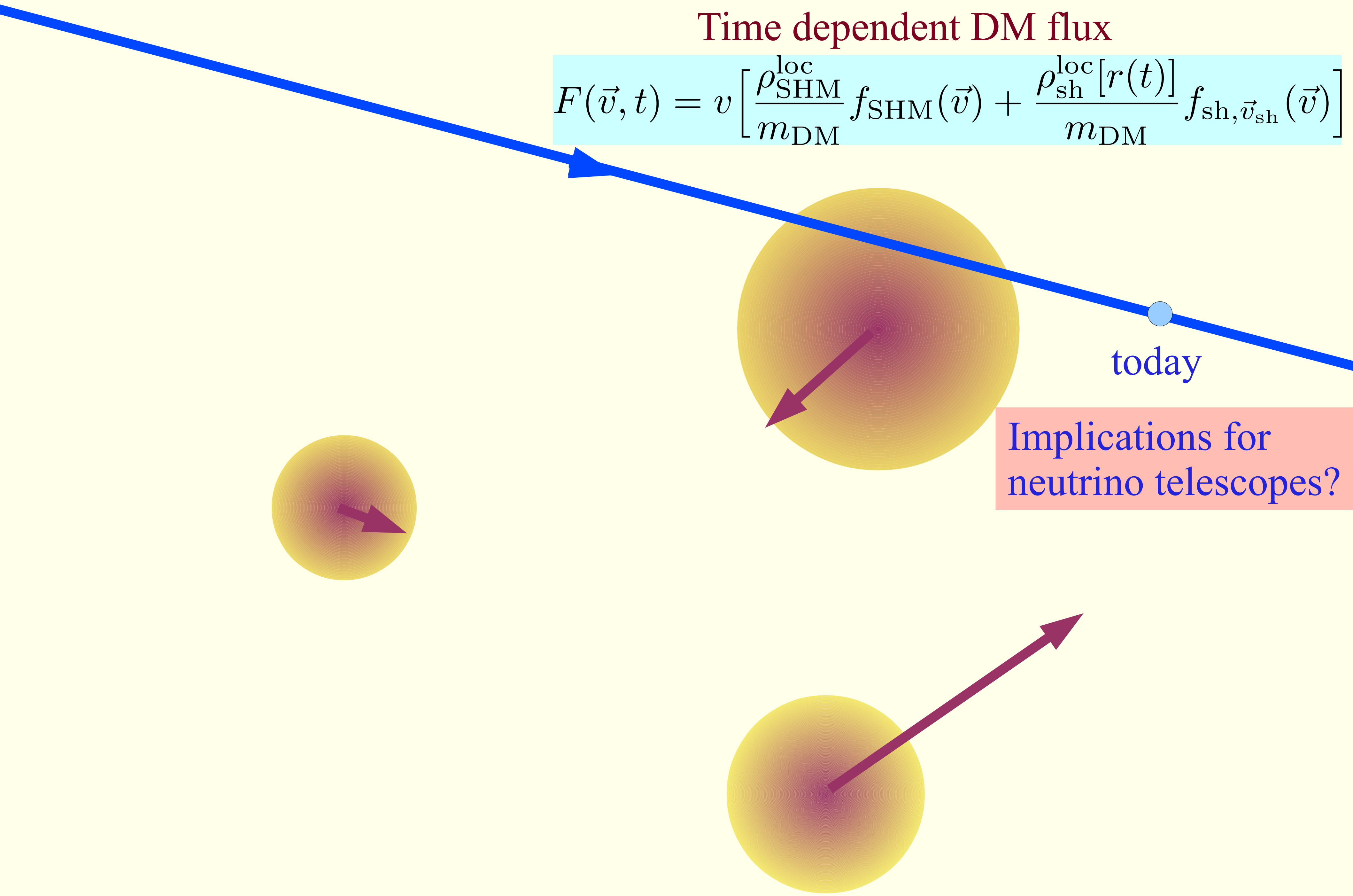

Implications for neutrino telescopes?

Time dependent DM flux

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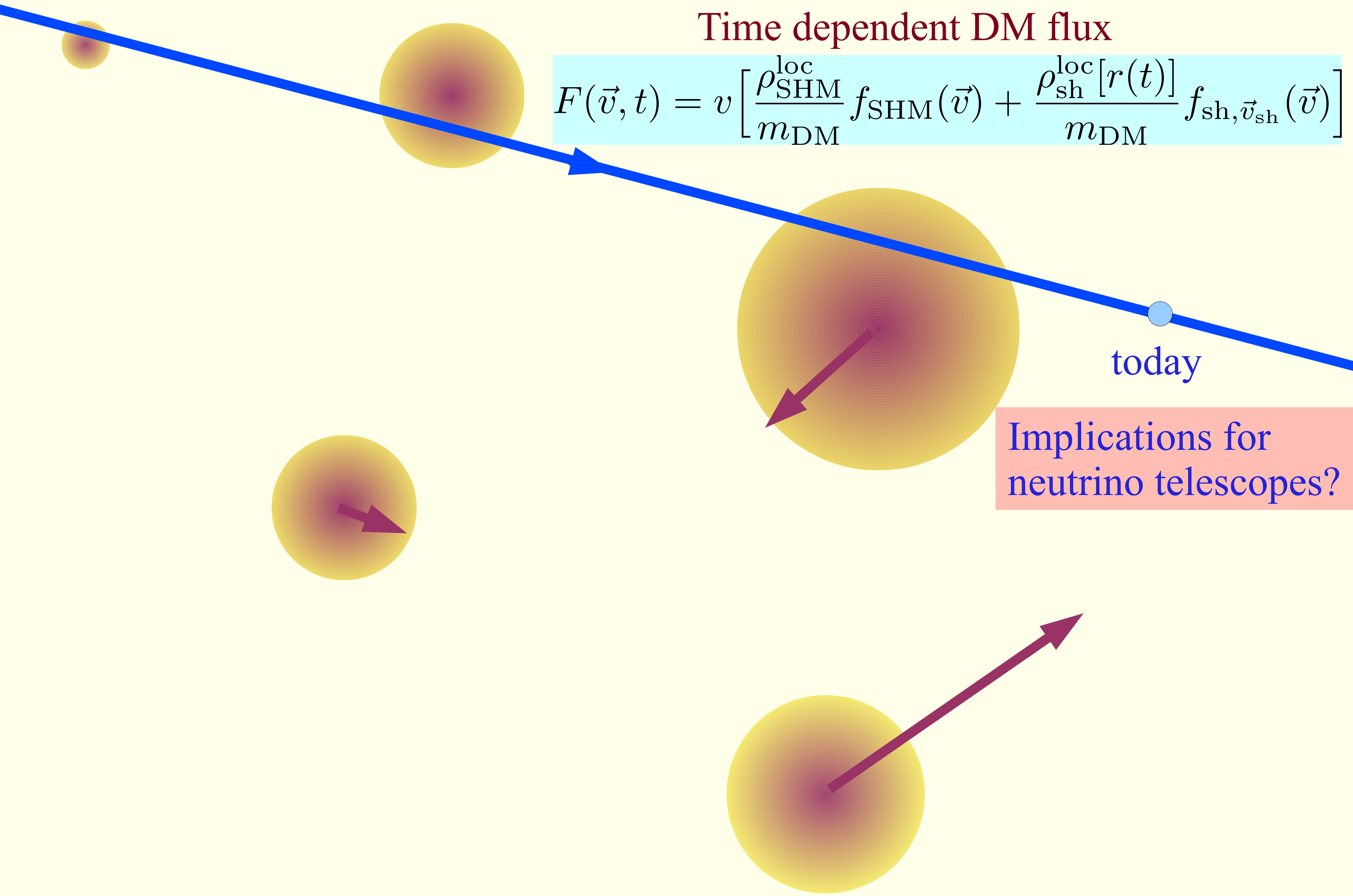
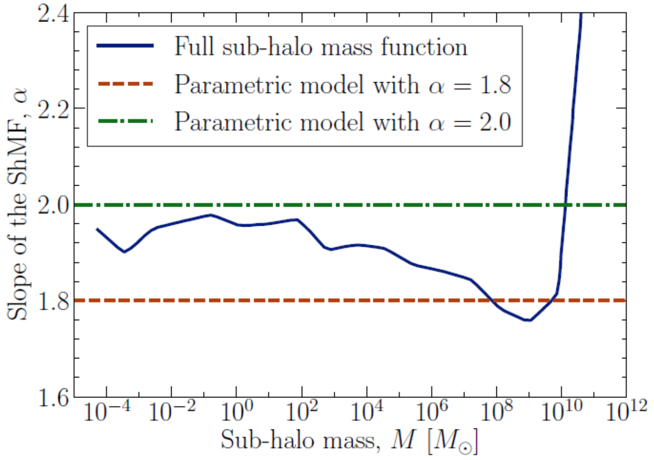


Implications for neutrino telescopes?

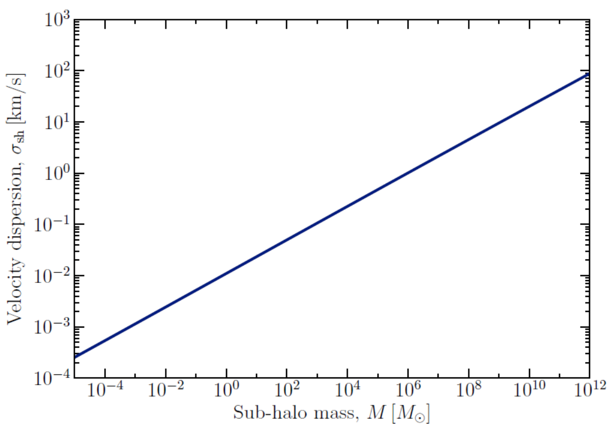
Impact of sub-halos in local DM searches

Assume:

- Sub-halos spatially distributed following an Einasto profile.
- Velocity distribution of sub-halos following Maxwell-Boltzmann.
- Sub-halo mass function from Hiroshima, Ando, and Ishiyama'18



- Internal density profile described by a truncated NFW profile.
- Concentration parameter following a log-normal distribution
- Internal velocity distribution described by a MB distribution

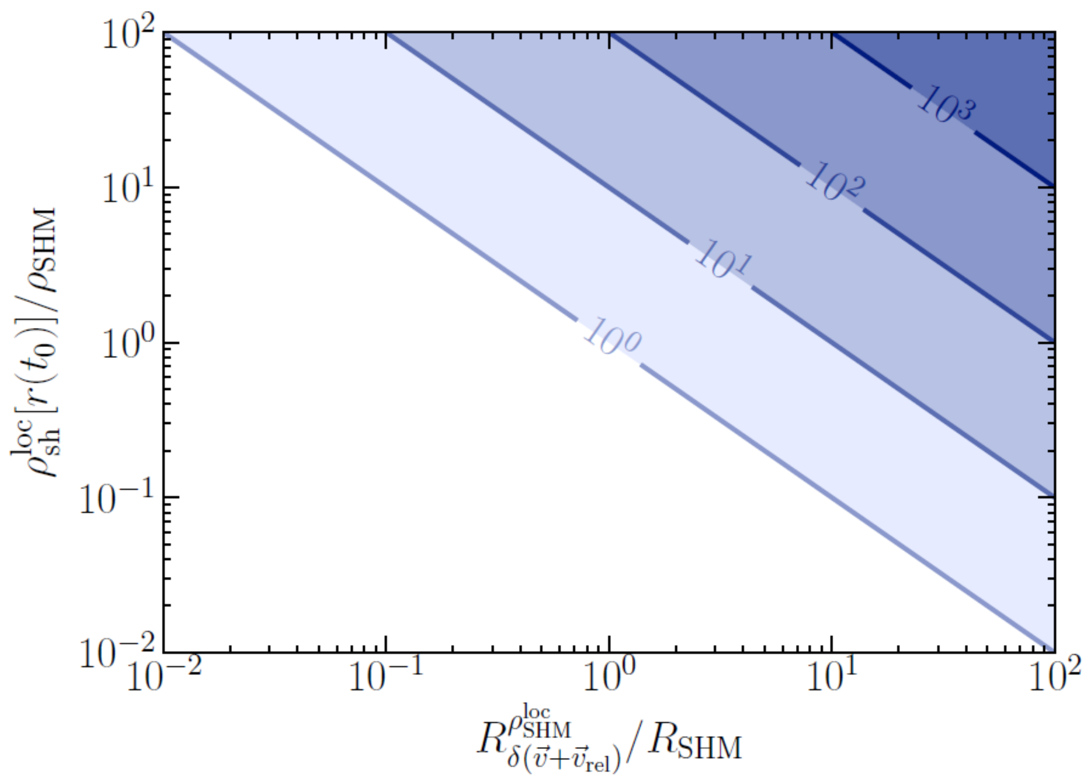


Impact of sub-halos in direct detection experiments

$$R = \sum_i \int_0^\infty \mathrm{d}E_R\, \epsilon_i(E_R) \frac{\xi_i}{m_{A_i}} \int_{v \geq v_{\mathrm{min},i}^{(E_R)}} \mathrm{d}^3 v F(\vec{v} + \vec{v}_{\mathrm{Earth}}, t_0) \frac{\mathrm{d}\sigma_i}{\mathrm{d}E_R}(v, E_R)\,.$$

Increment in the rate with respect to the SHM:

$$\mathcal{I}_R \equiv \frac{R}{R_{\mathrm{SHM}}} - 1 \simeq \frac{\rho_{\mathrm{sh}}^{\mathrm{loc}}[r(t_0)]}{\rho_{\mathrm{SHM}}} \frac{R^{\rho_{\mathrm{SHM}}^{\mathrm{loc}}}_{\delta(\vec{v}+\vec{v}_{\mathrm{sh}}+\vec{v}_\odot+\vec{v}_{\mathrm{Earth}})}}{R_{\mathrm{SHM}}}$$



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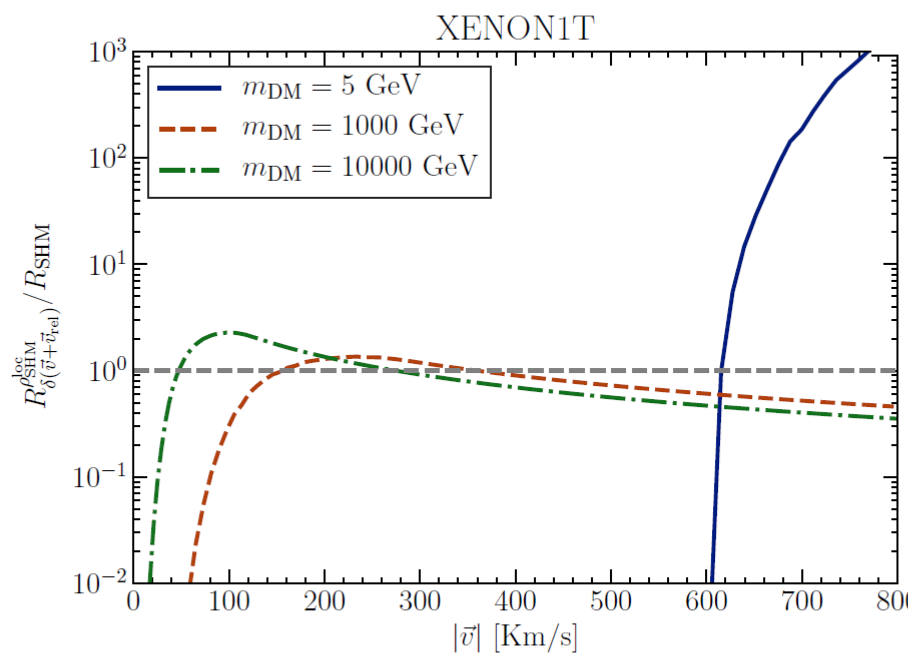

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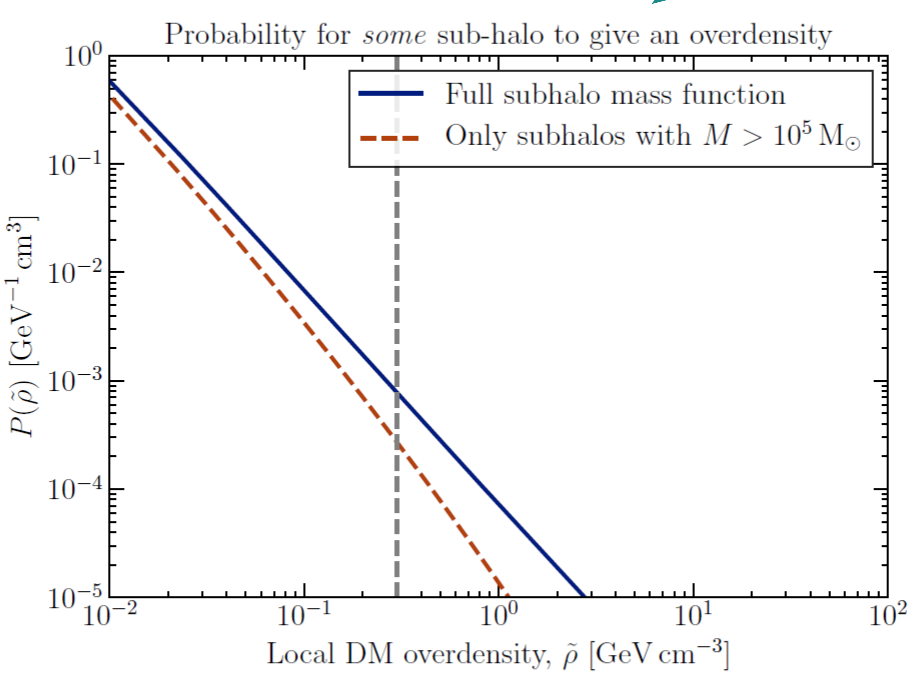

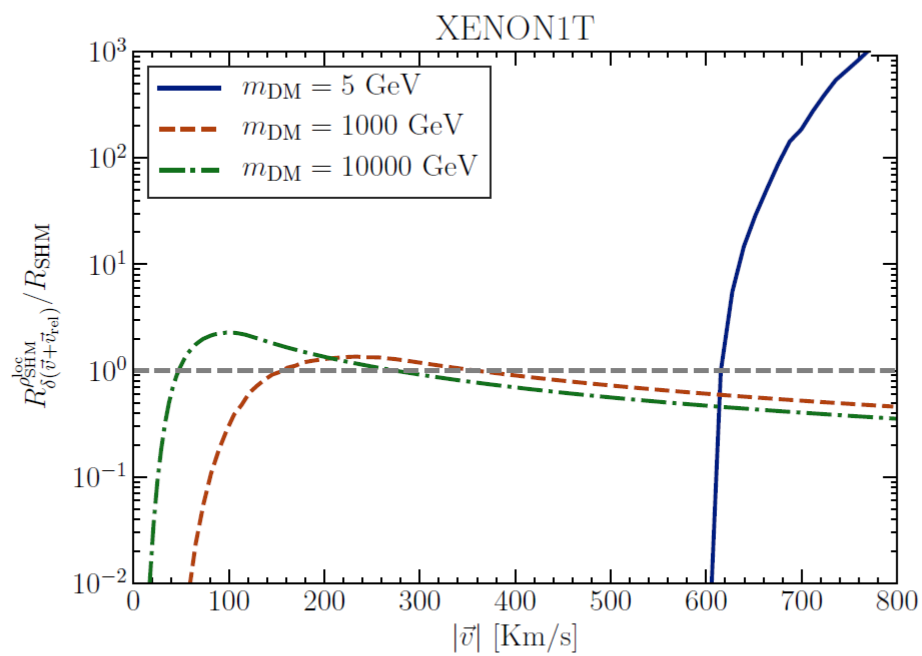

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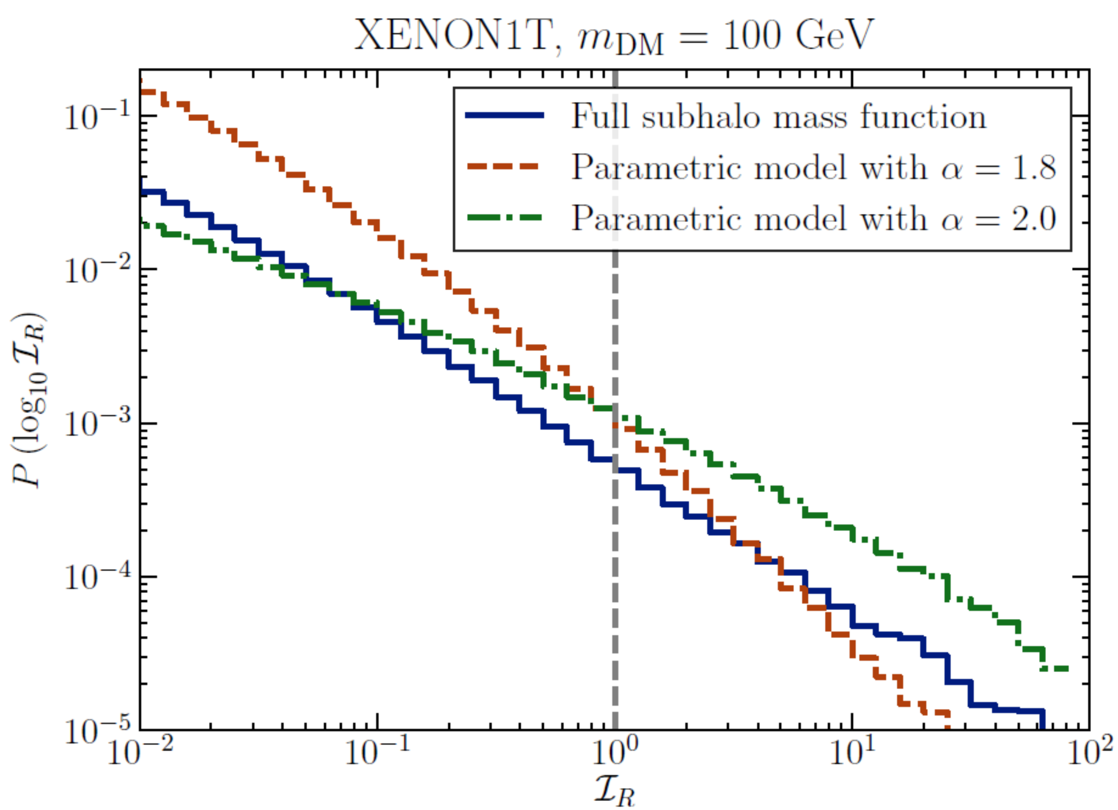
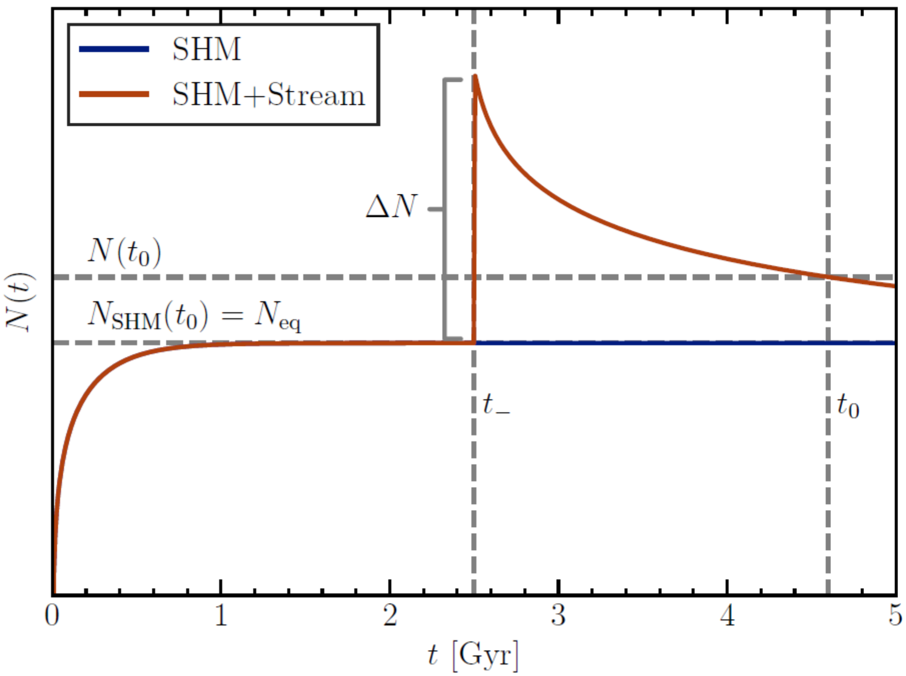


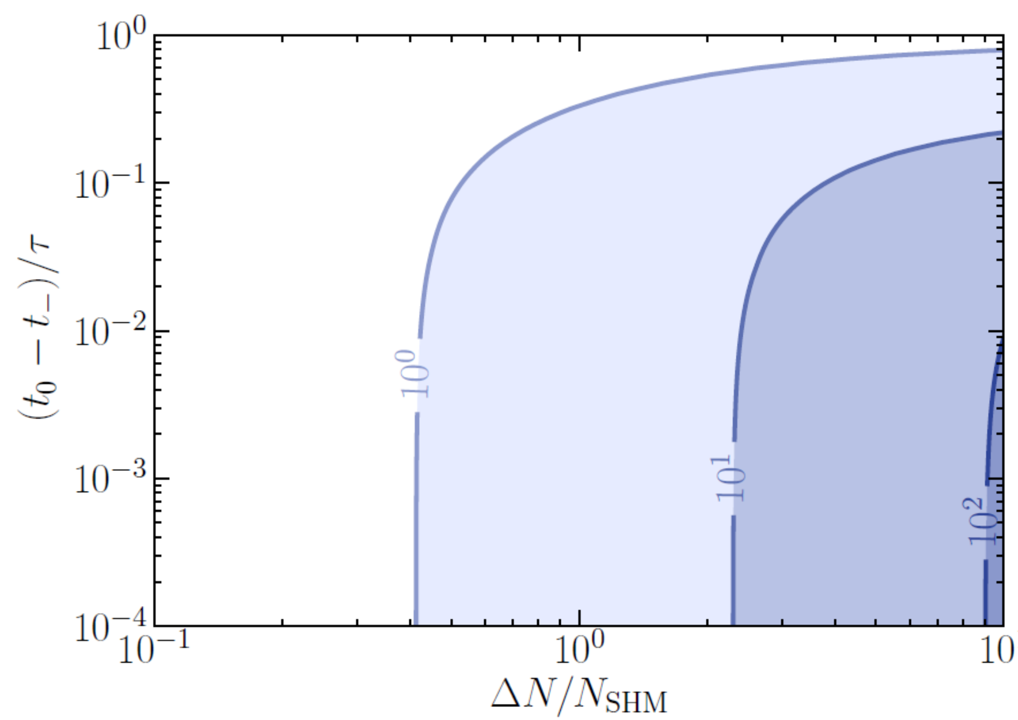
Impact of sub-halos in the neutrino flux from the Sun



The increment in the number of DM particles captured depends on:

$$\frac{t_0 - t}{\tau}$$

$$\Delta N \simeq N_{\rm eq} \frac{C^{\rho_{\rm SHM}}_{\delta(\vec{v}+\vec{v}_{\rm sh}+\vec{v}_{\odot})}}{C_{\rm SHM}} \frac{\langle \rho^{\rm loc}_{\rm sh}[r(t)] \rangle}{\rho_{\rm SHM}} \frac{\Delta t}{\tau}$$



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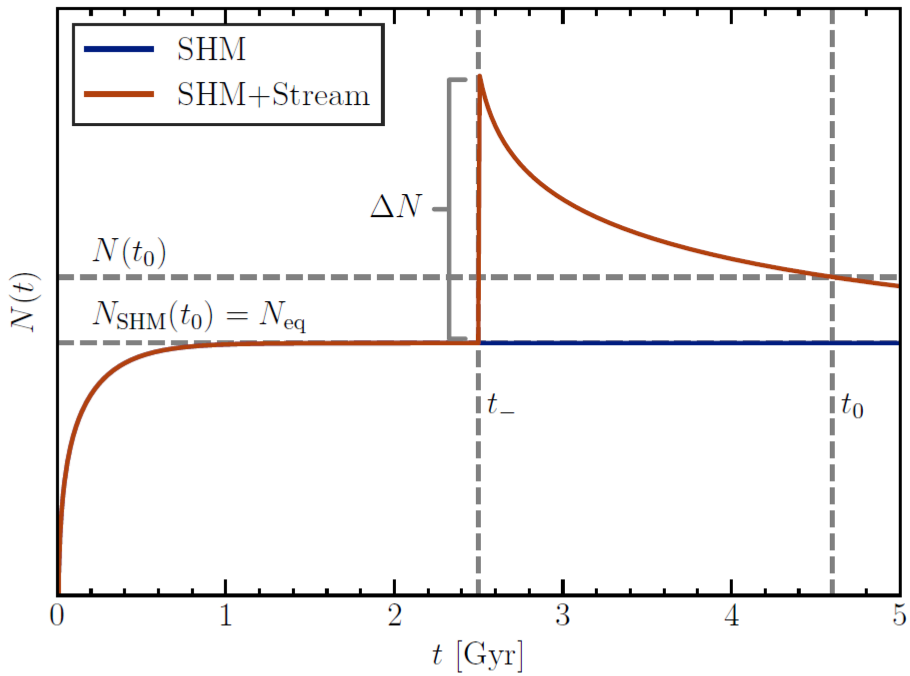

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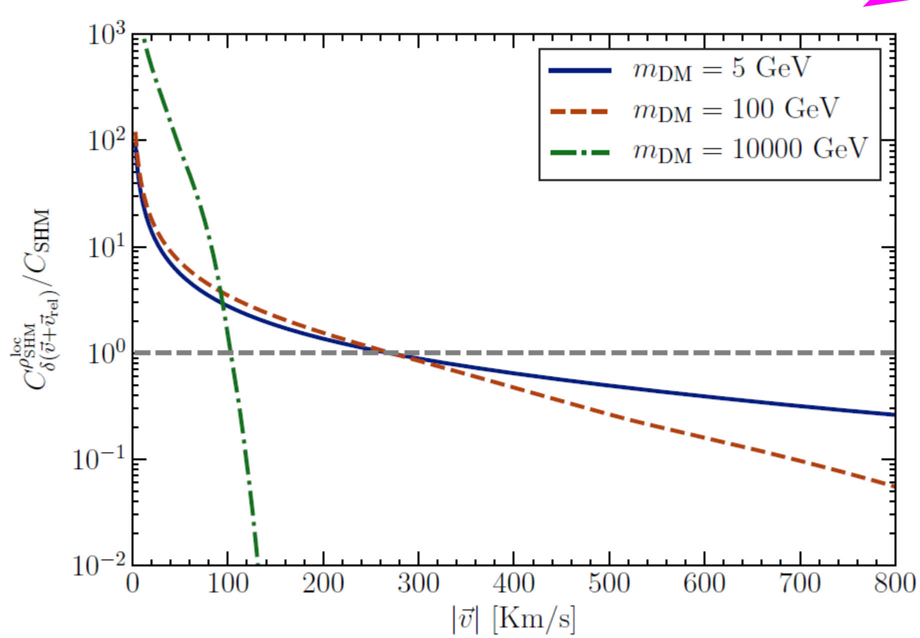

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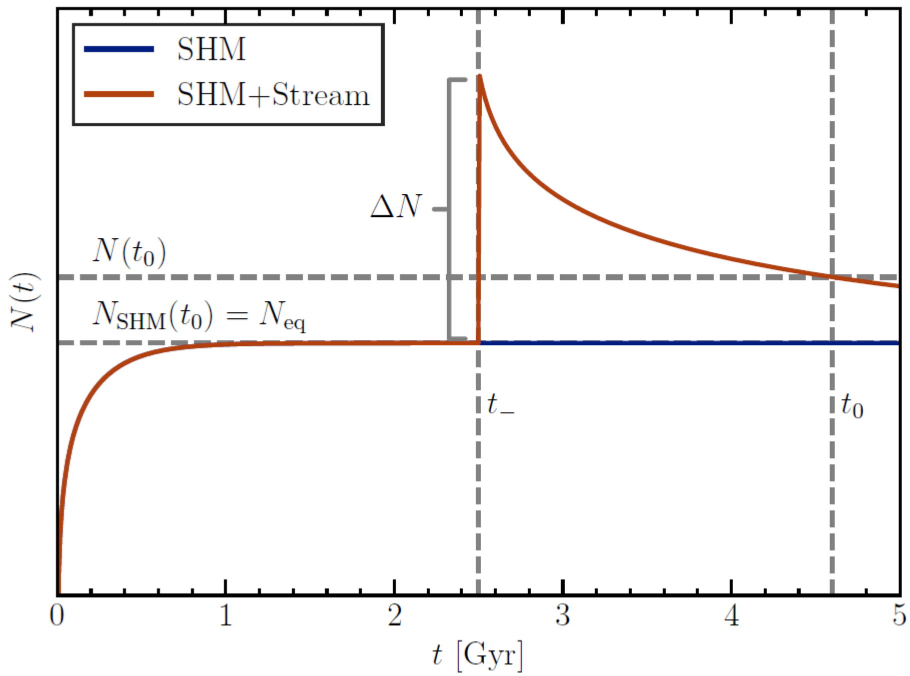

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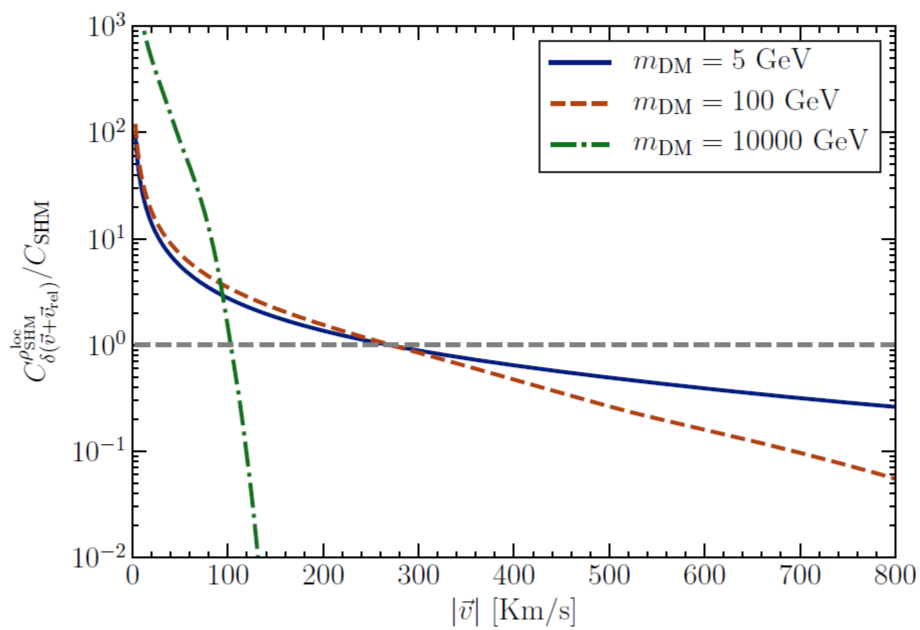
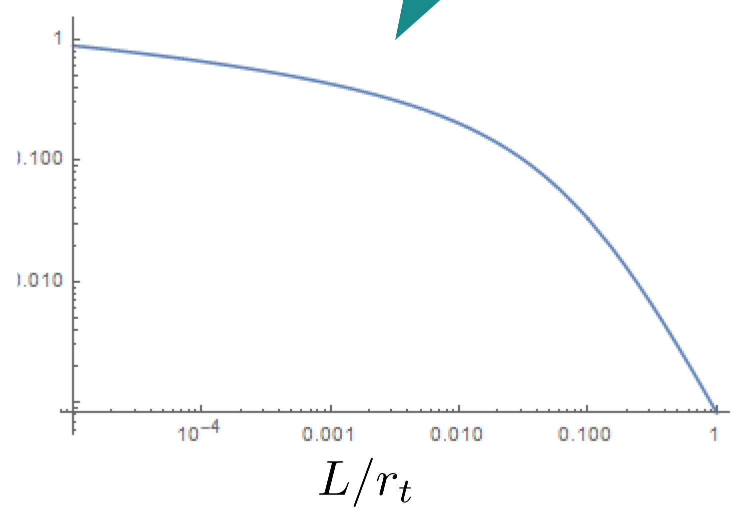
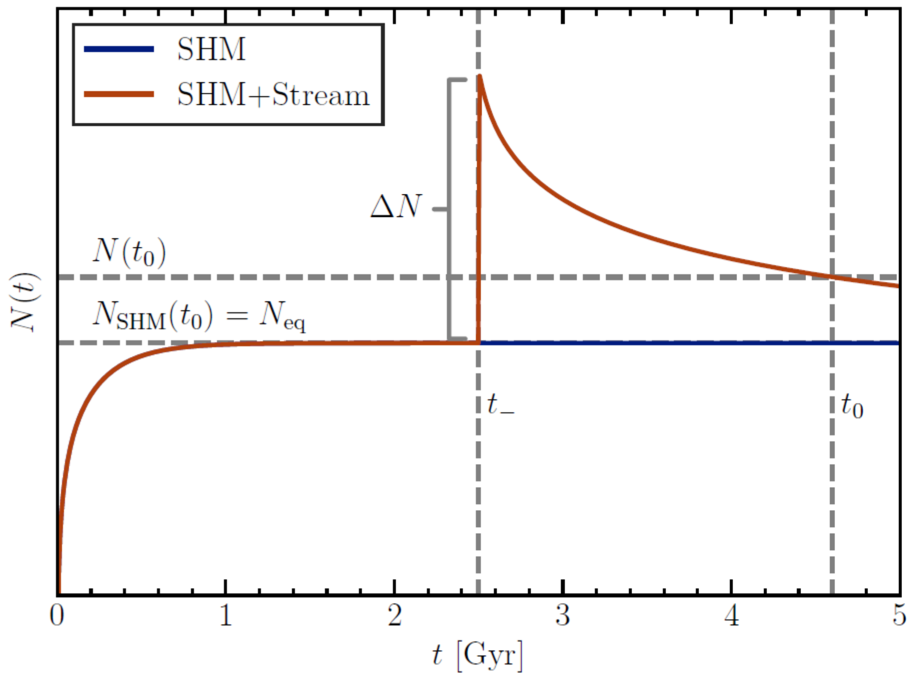




Impact of sub-halos in the neutrino flux from the Sun

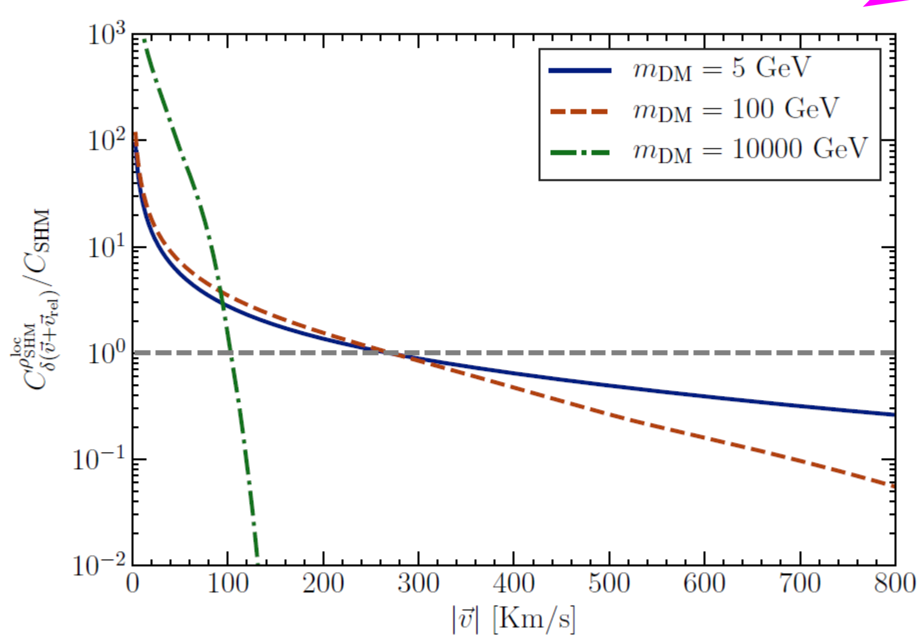


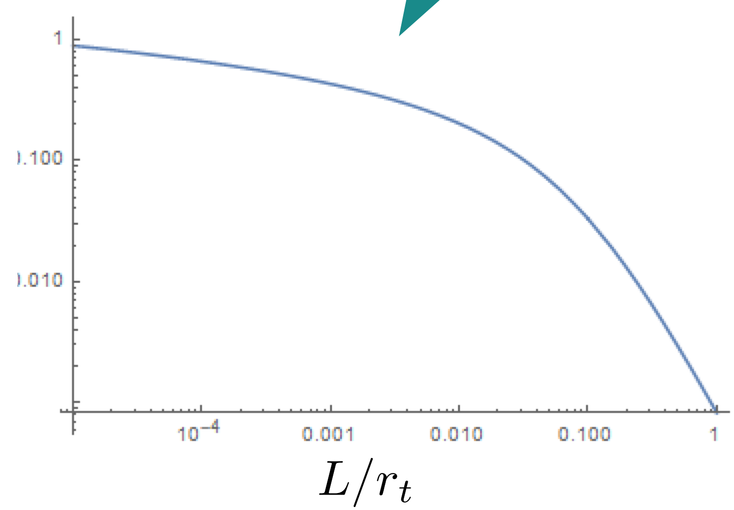
The increment in the number of DM particles captured depends on:

$$\frac{t_0 - t}{\tau}$$

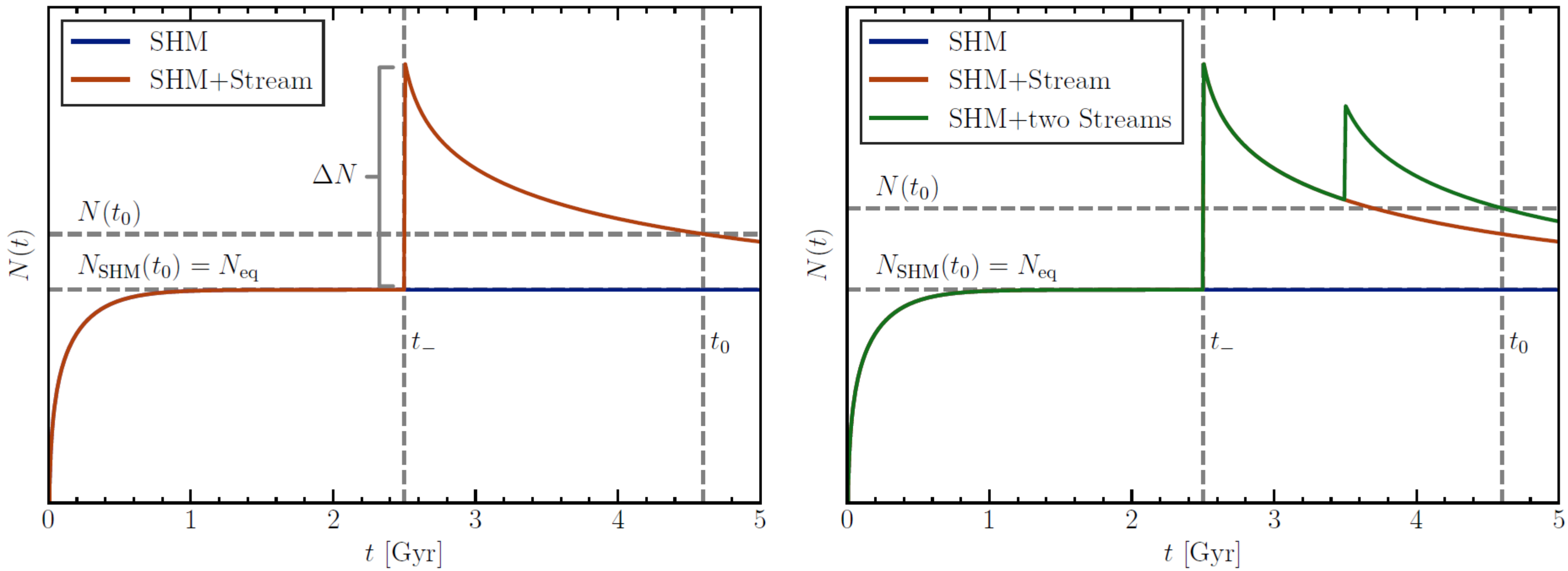
$$\Delta t = 2\sqrt{r_t^2 - L^2}/v_{\rm rel}$$

$$\Delta N \simeq N_{\rm eq} \frac{C^{\rho_{\rm SHM}}_{\delta(\vec{v}+\vec{v}_{\rm sh}+\vec{v}_{\odot})}}{C_{\rm SHM}} \frac{\rho_{\rm sh}^{\rm loc}[r(t)]}{\rho_{\rm SHM}} \frac{\Delta t}{\tau}$$

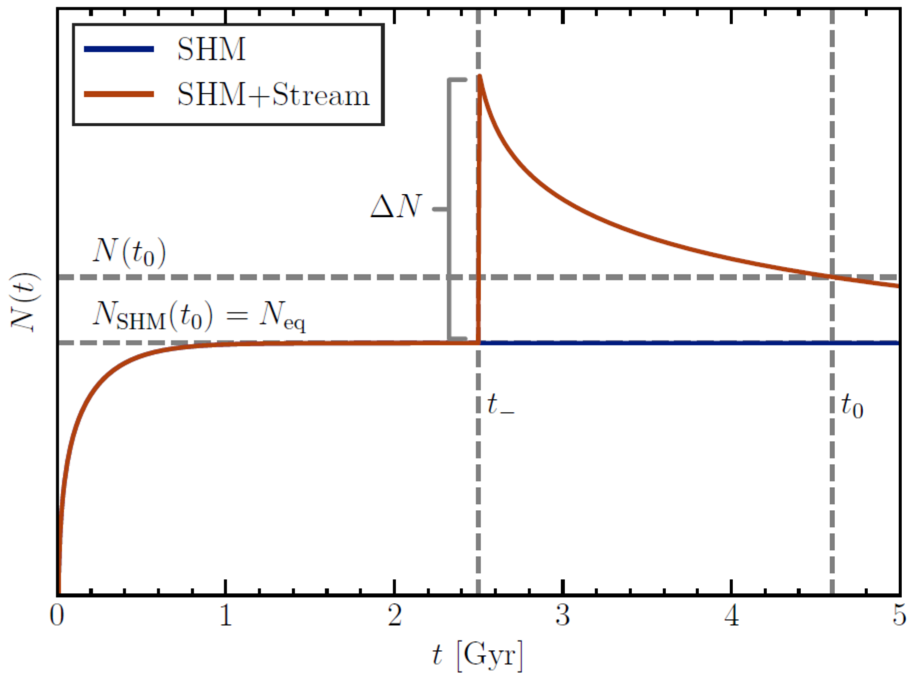


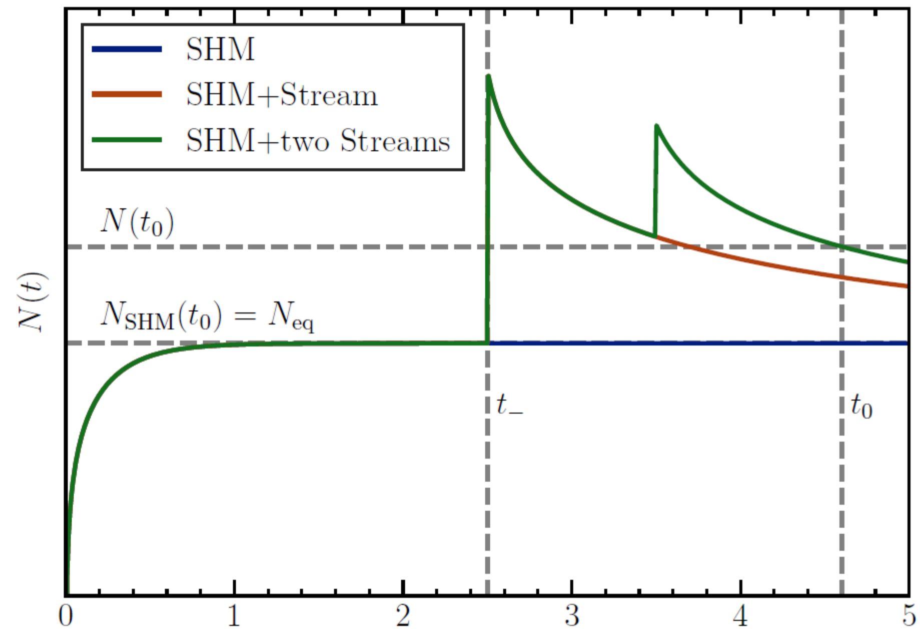


Impact of sub-halos in the neutrino flux from the Sun

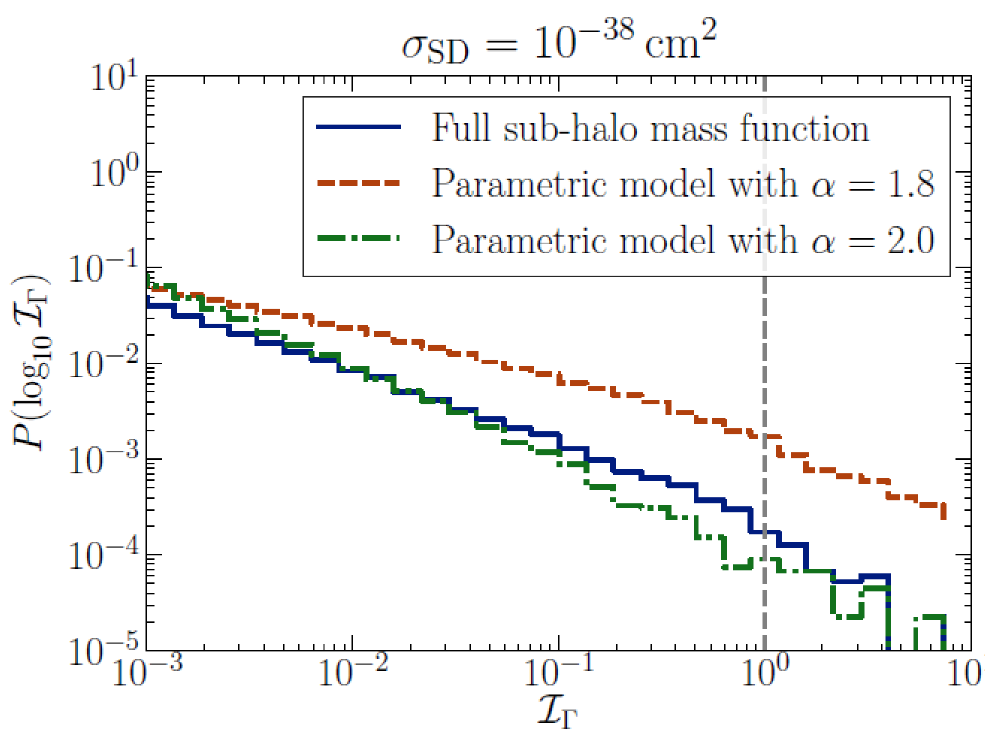


Impact of sub-halos in the neutrino flux from the Sun





$$\mathcal{I}_\Gamma = \frac{\Gamma(t_0)}{\Gamma_{\rm SHM}(t_0)} - 1$$



Conclusions

- The interpretation of any experiment probing the dark matter distribution inside the Solar System is subject to our ignorance of the local dark matter density and velocity distribution.

- We have developed a method to bracket the uncertainties in the velocity distribution when interpreting the results from direct searches, due to distortions in the Maxwell-Boltzmann distribution and/or by exploiting the synergy with dark matter searches in the Sun.

- Sub-halos in our Galaxy may induce a time-dependent DM flux at the Solar System. There is a probability of ~1 per mil of changing by an O(1) factor the signal rate at a direct detection experiment or at a neutrino telescope.