# Impact of astrophysical uncertainties in local DM searches

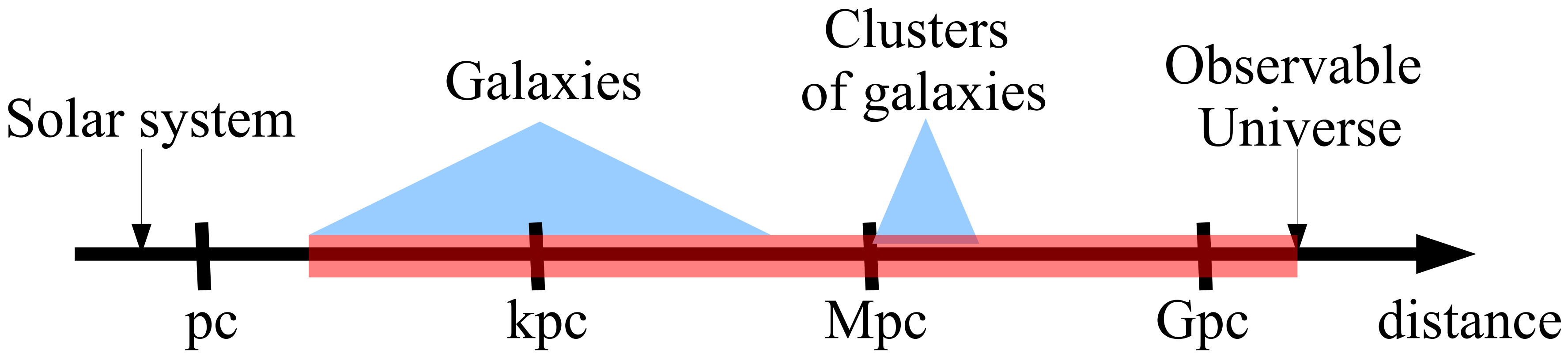
Alejandro Ibarra

Technische Universität München

Based on: AI, Rappelt, arXiv:1703.09168
AI, Kavanagh, Rappelt, arXiv:1806.08714
AI, Kavanagh, Rappelt, arXiv:1908.00747

PICTP
Beijing
October 2019

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



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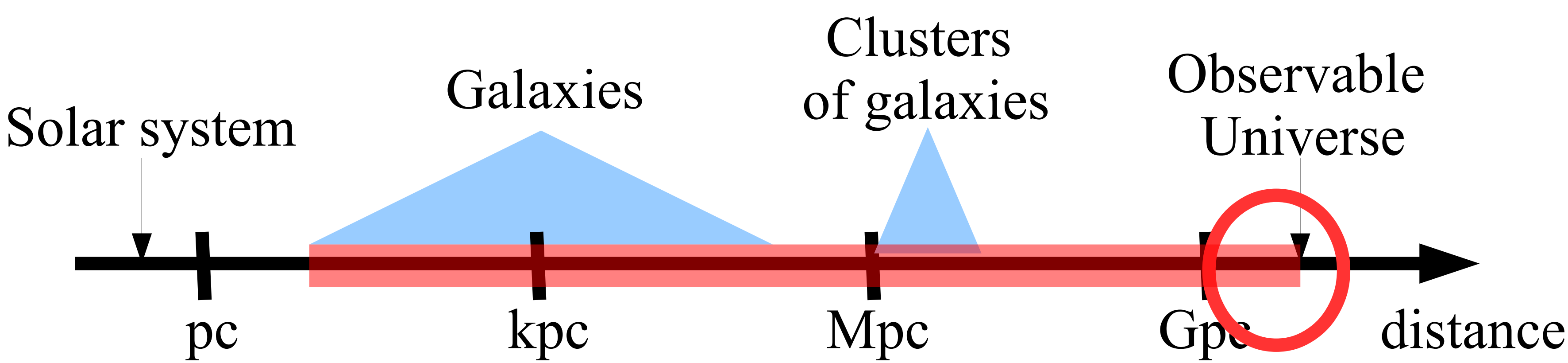


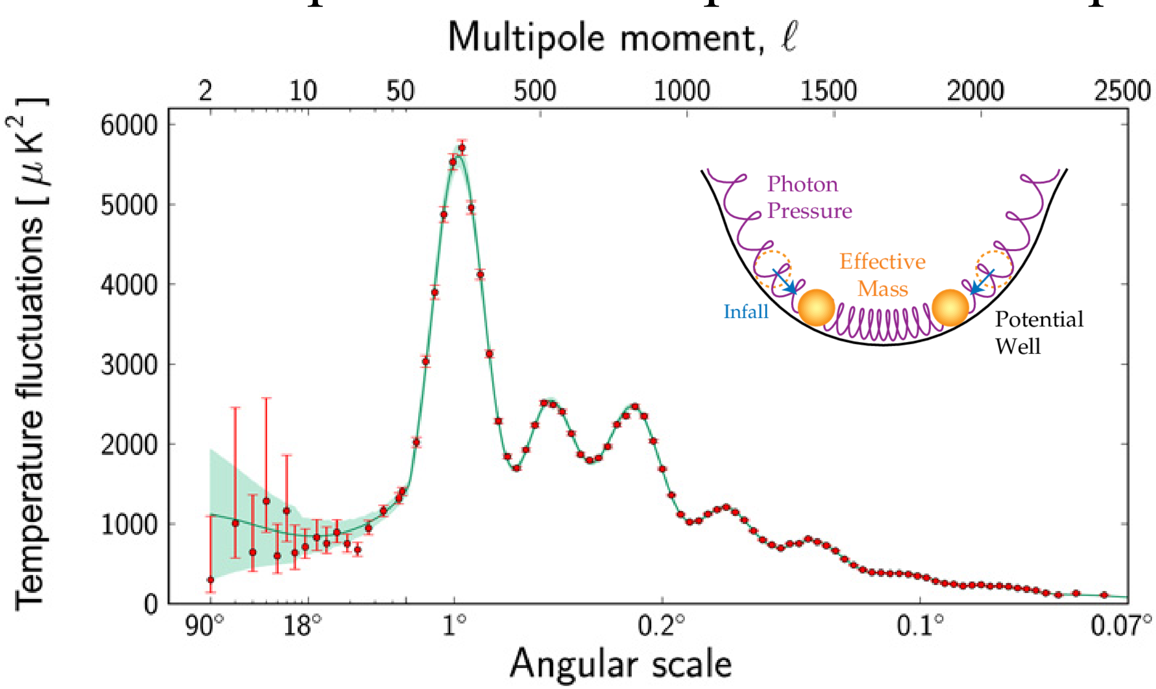


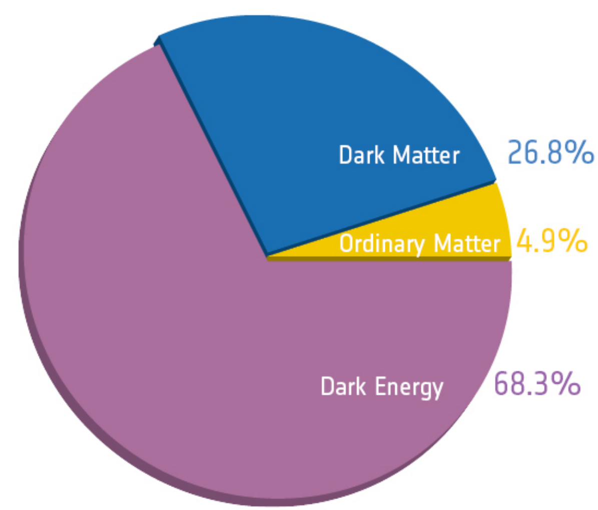

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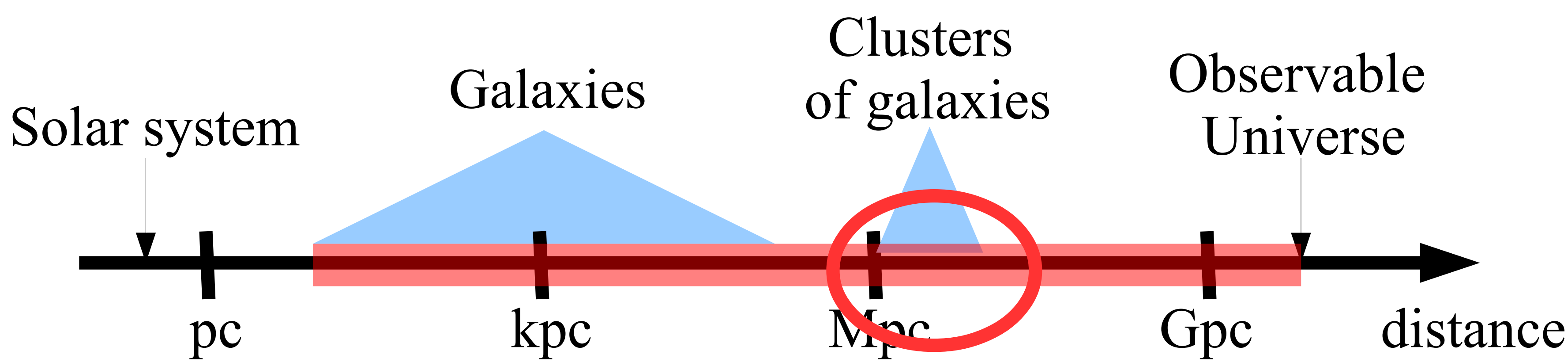


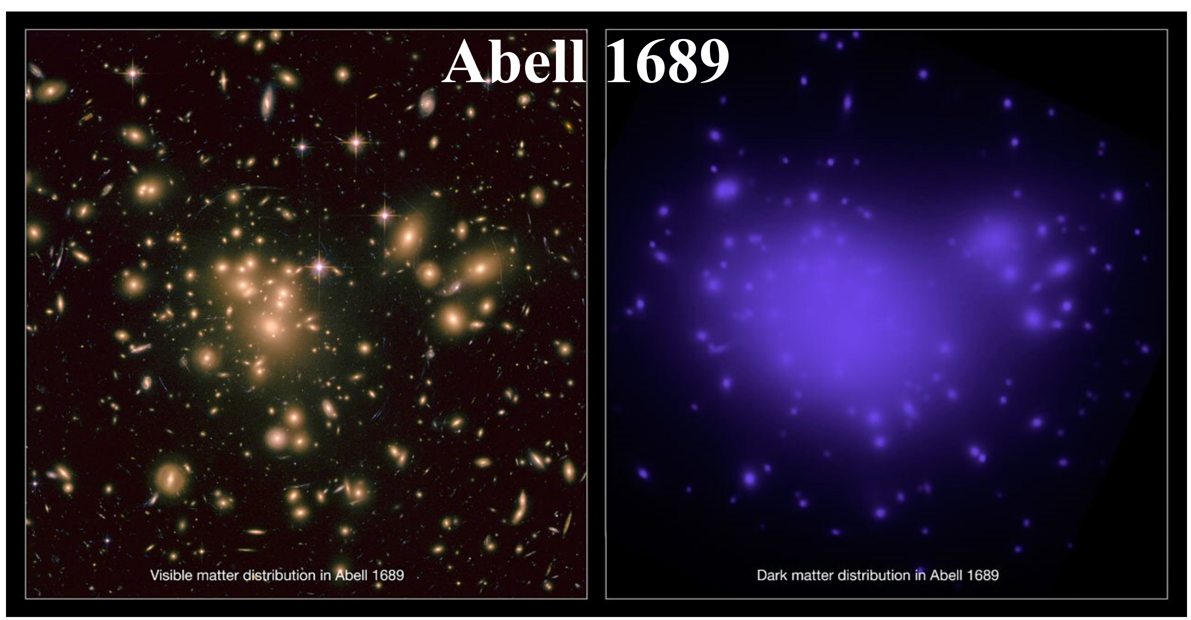

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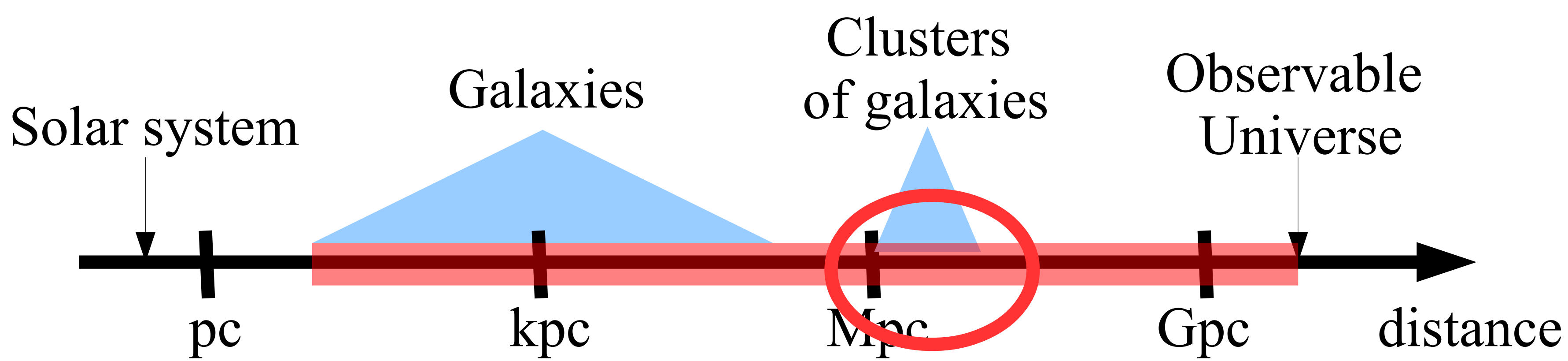


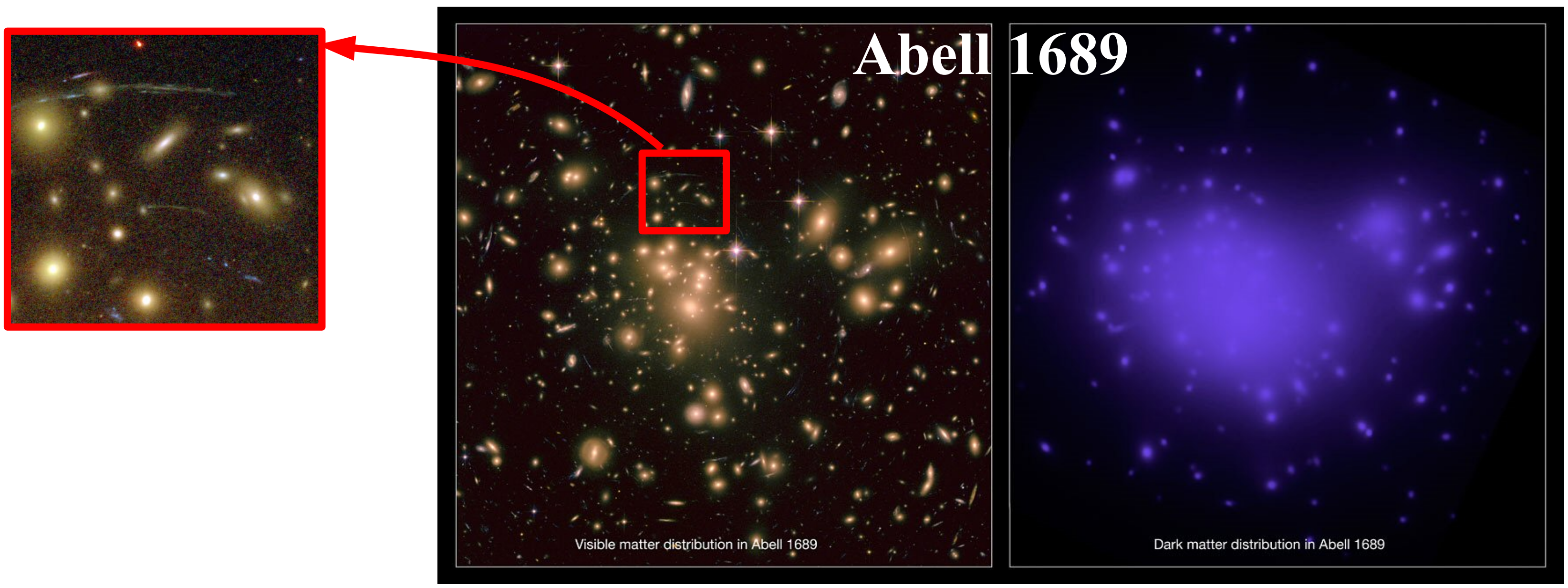

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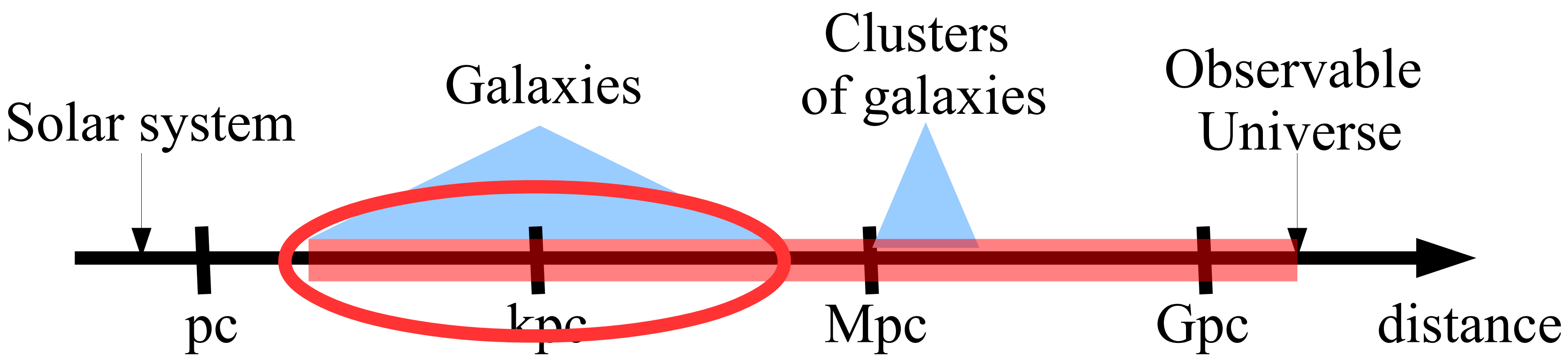


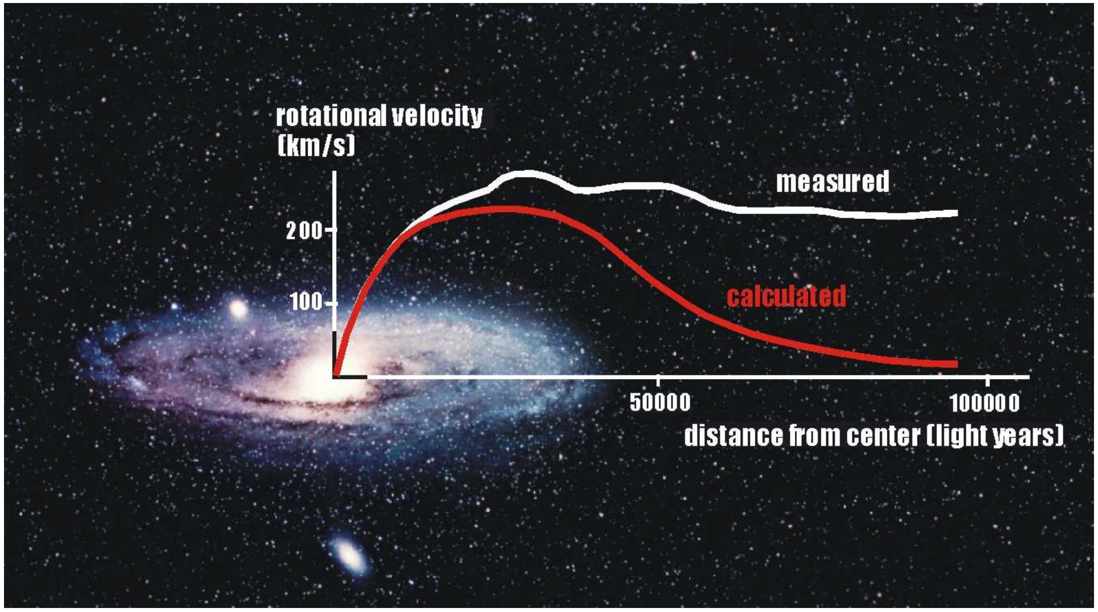

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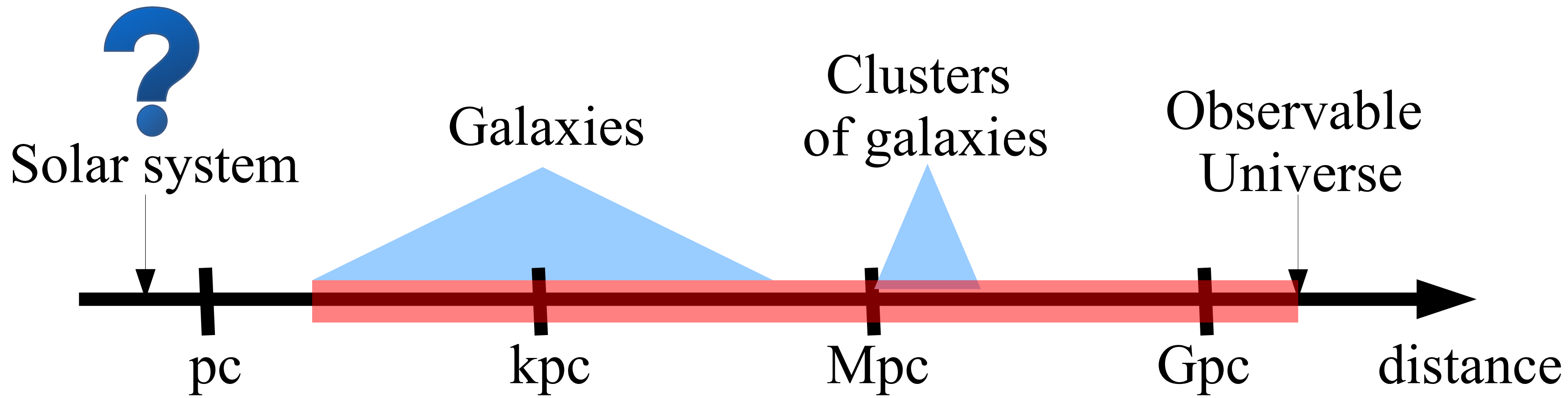


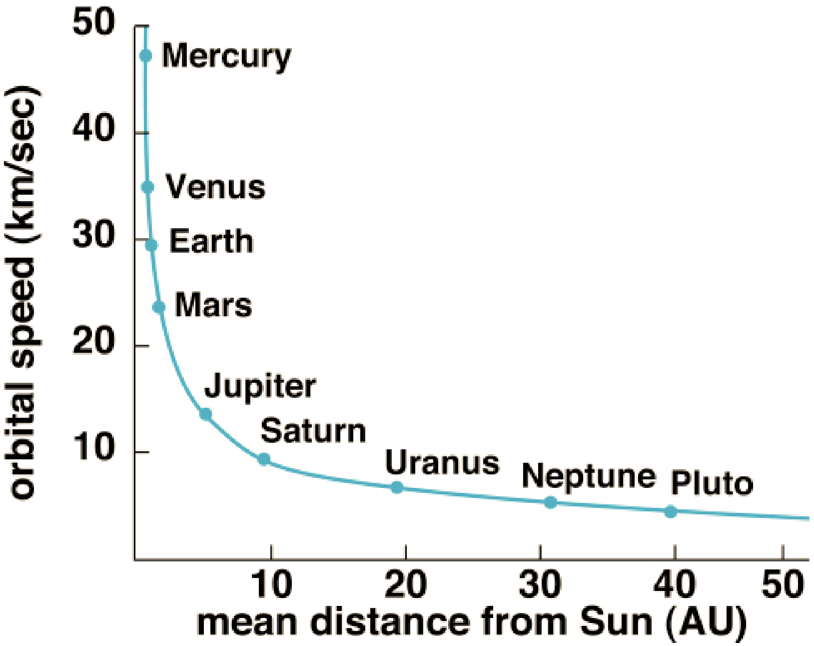

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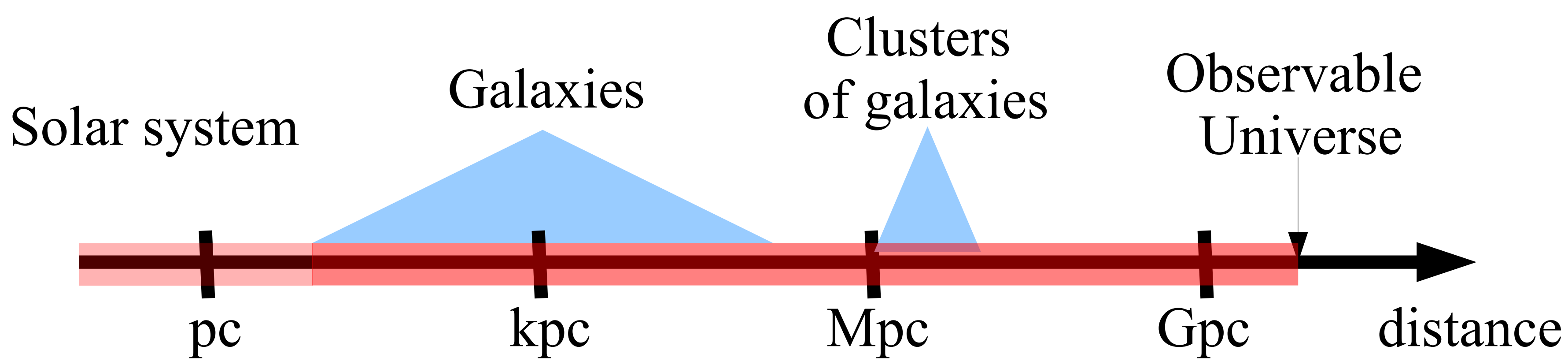
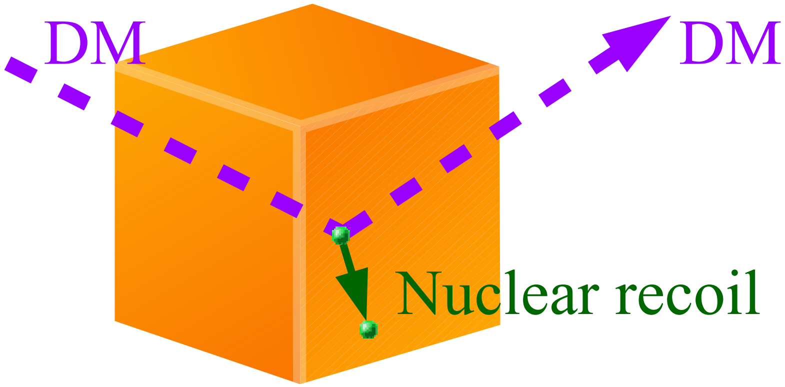



Assumption,
but well motivated

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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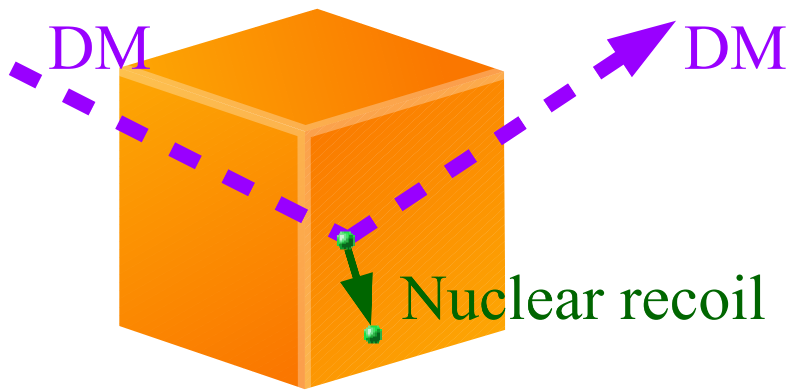


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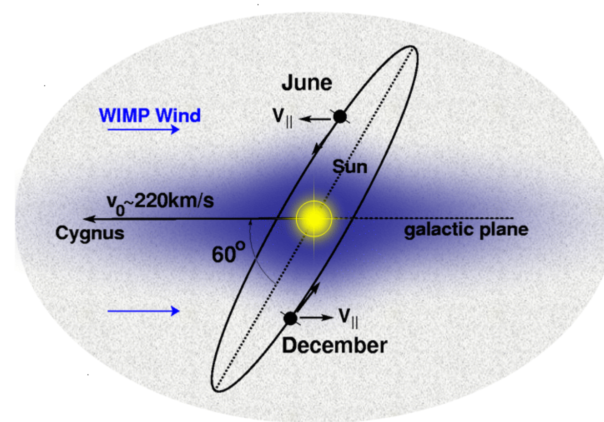


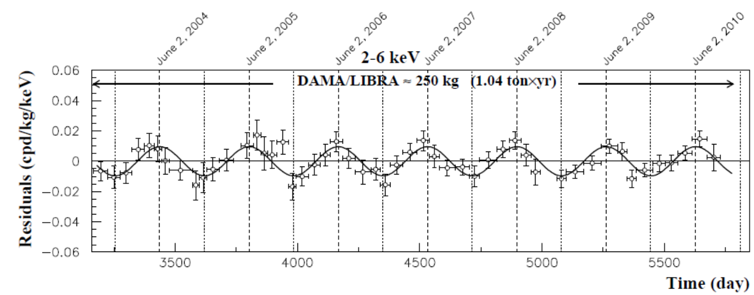

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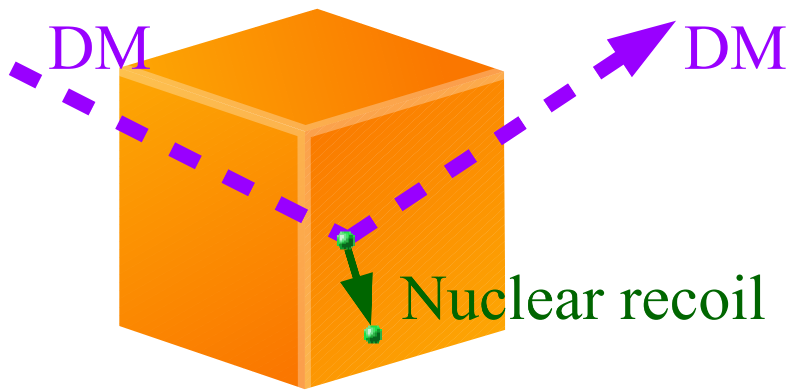


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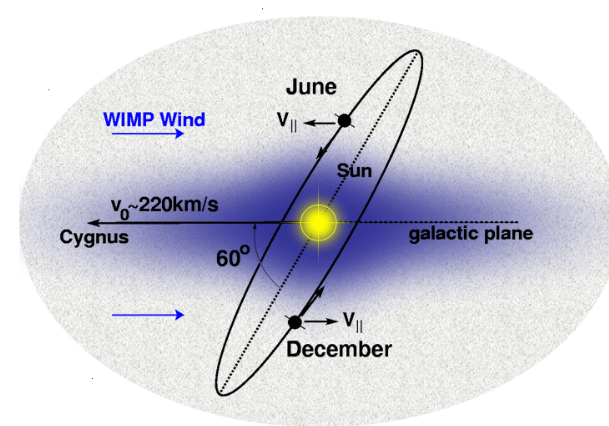


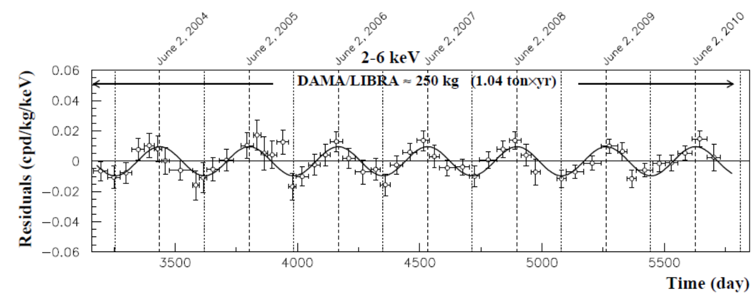


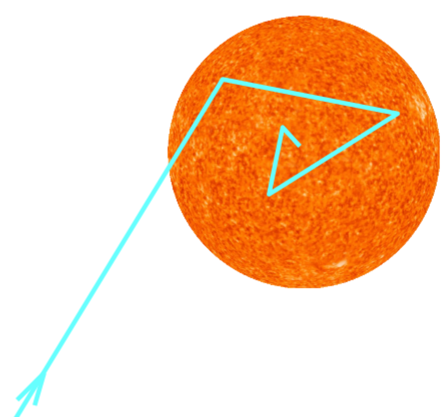

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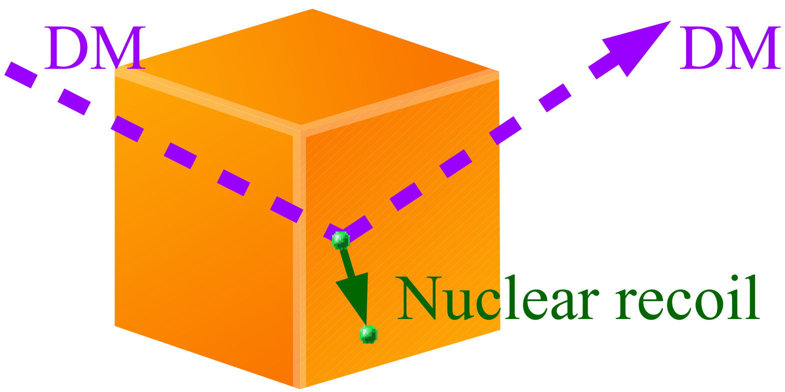


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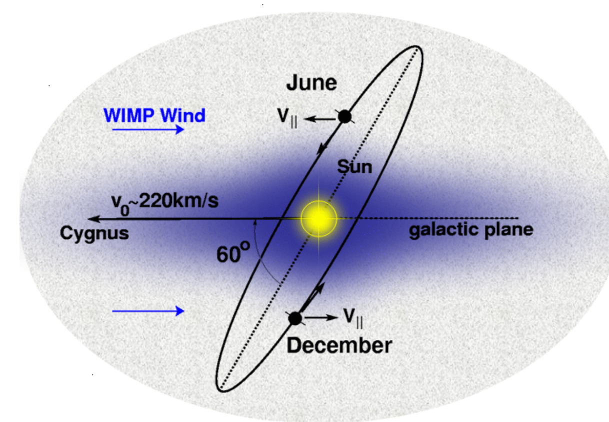


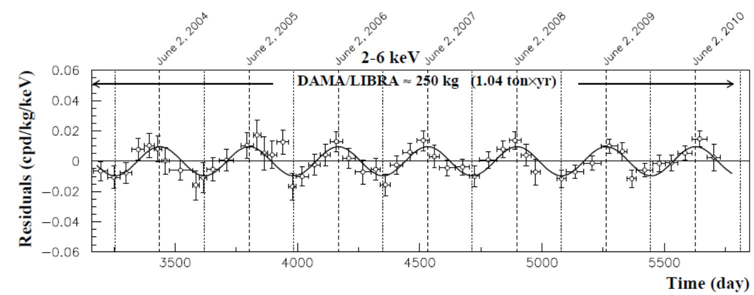


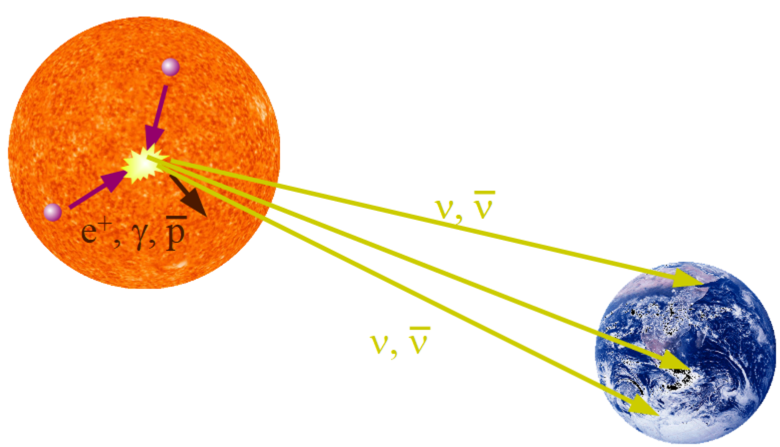


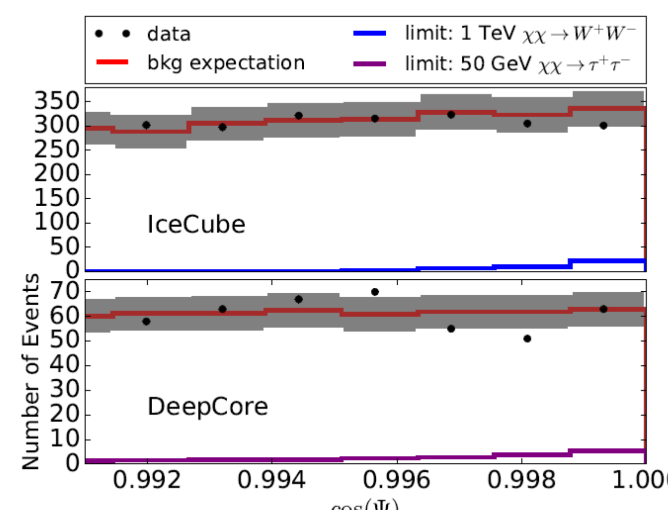


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# Theoretical interpretation of the experimental results

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- Differential rate of DM-induced scatterings

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

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

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

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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, $m_{\rm DM} = \text{few MeV} - 100 \text{ TeV}$

- Differential cross section?

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

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

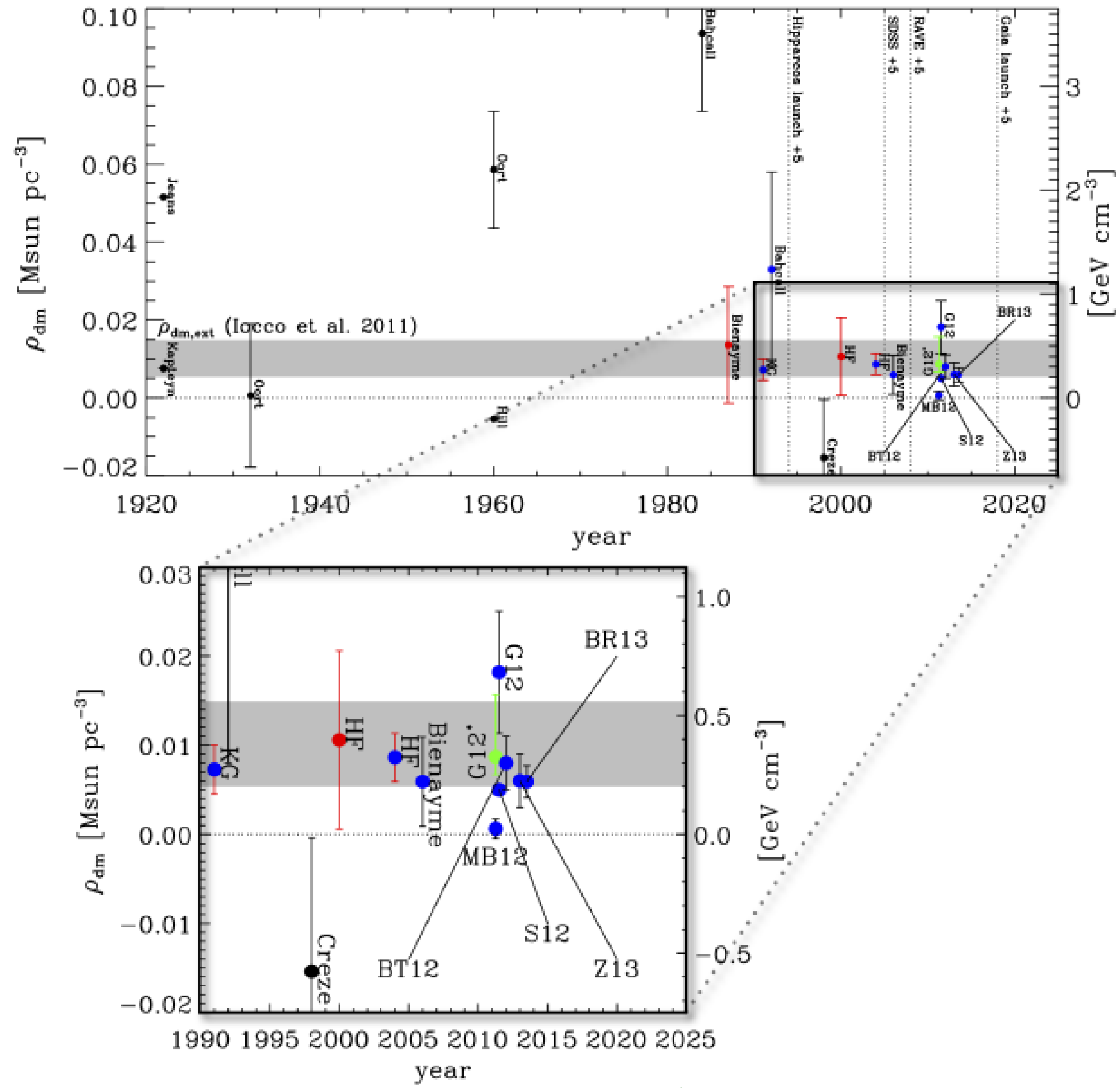
- Local dark matter density?

  - "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.

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

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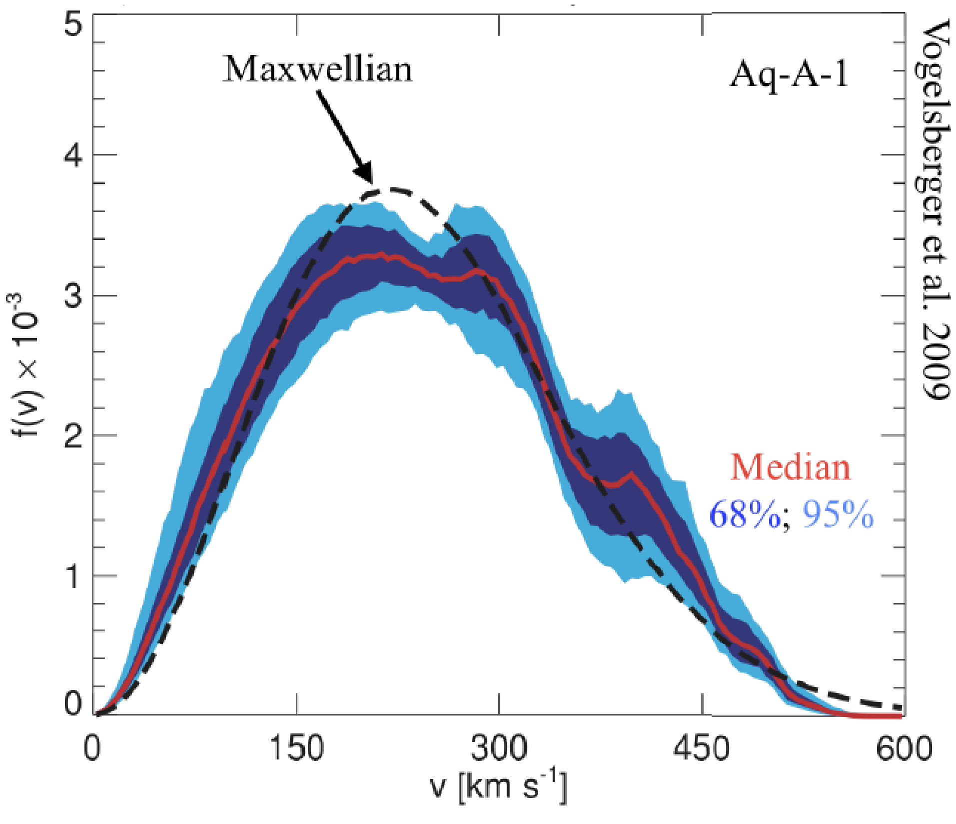

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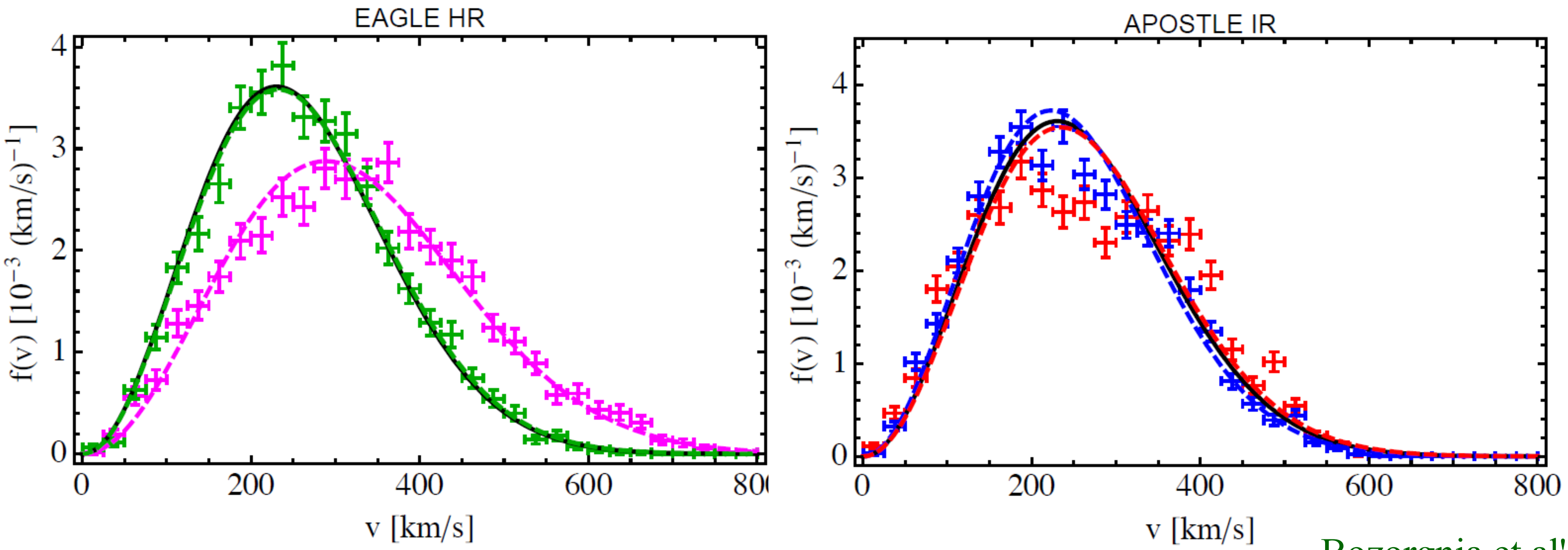
  - If the density distribution follows a singular isothermal sphere profile, the velocity distribution has a Maxwell-Boltzmann form.
  - Dark matter-only simulations. Show deviations from Maxwell-Boltzmann
  - Hydrodynamical simulations (DM+baryons). Inconclusive at the moment.

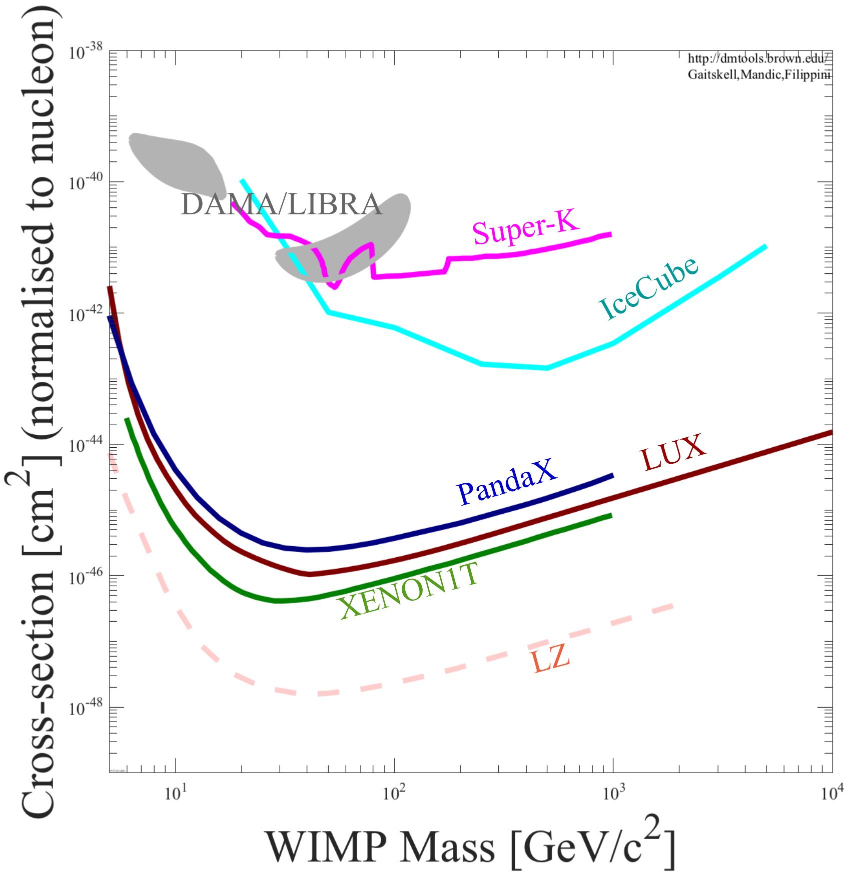



Bozorgnia et al'16

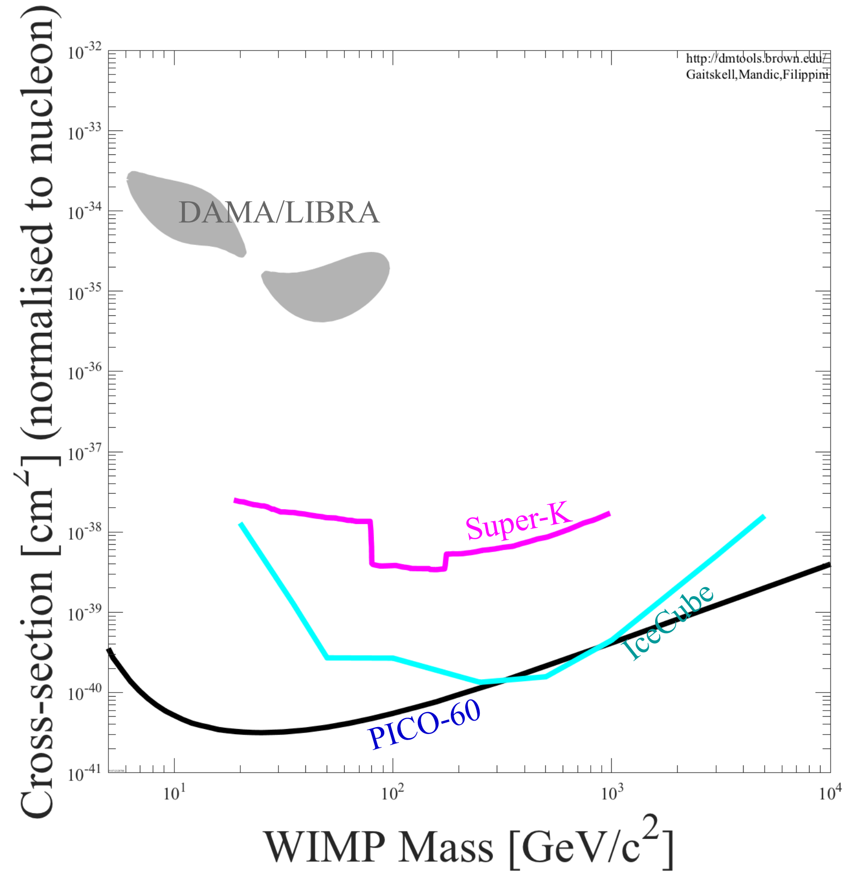
# Theoretical interpretation of the experimental results

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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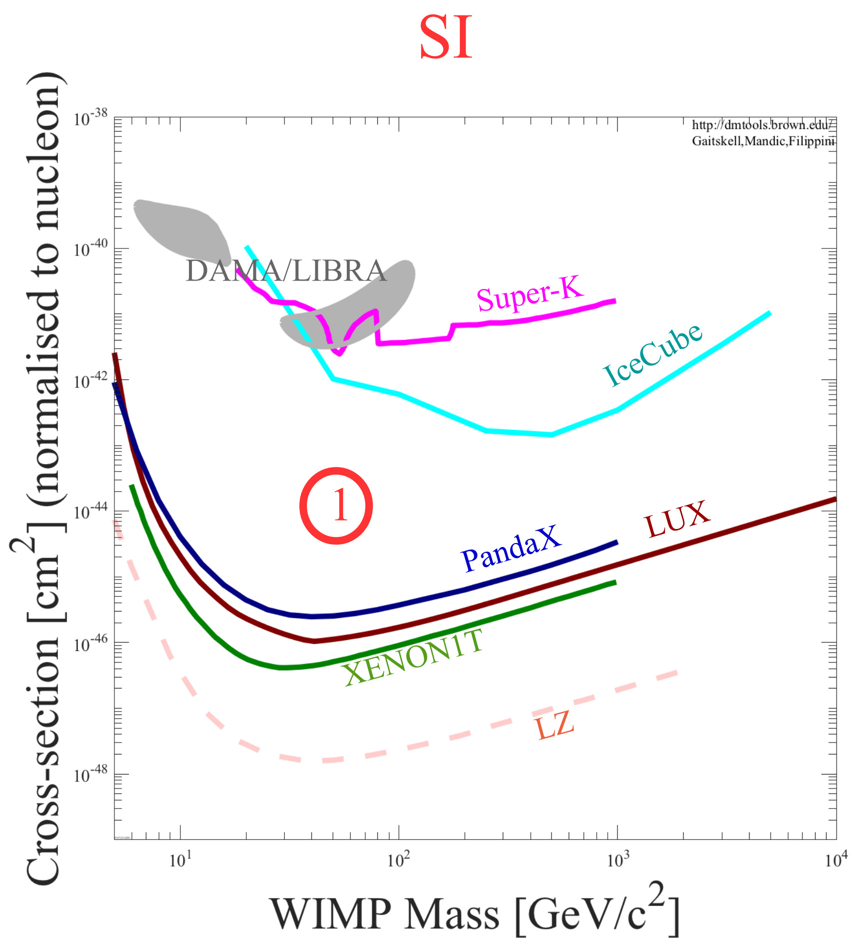


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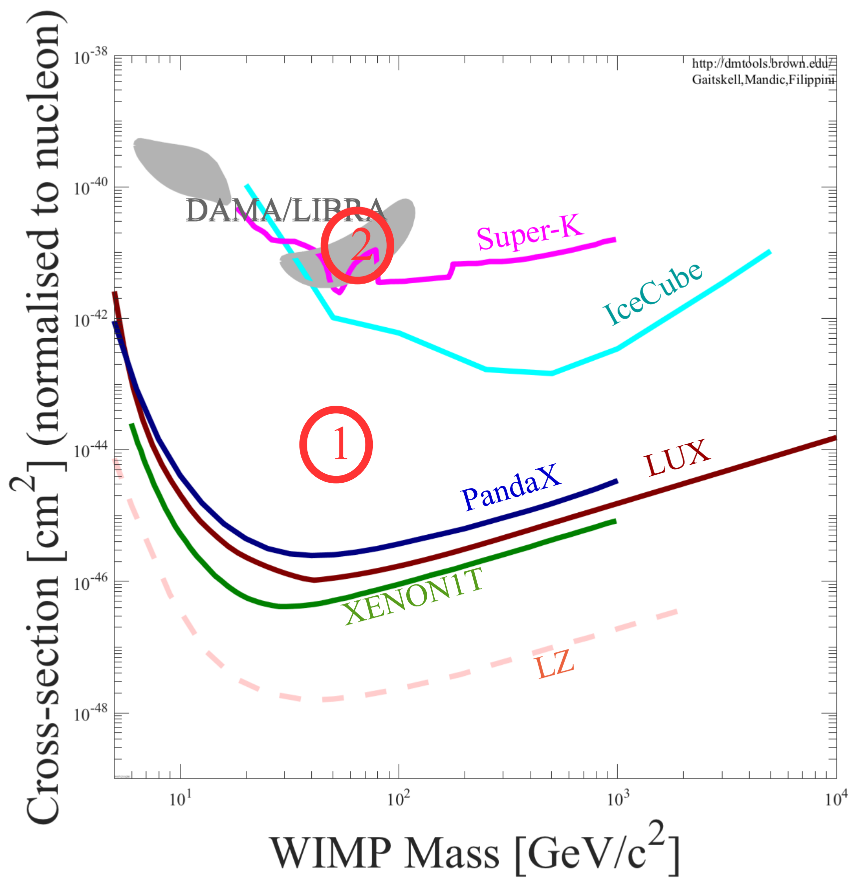


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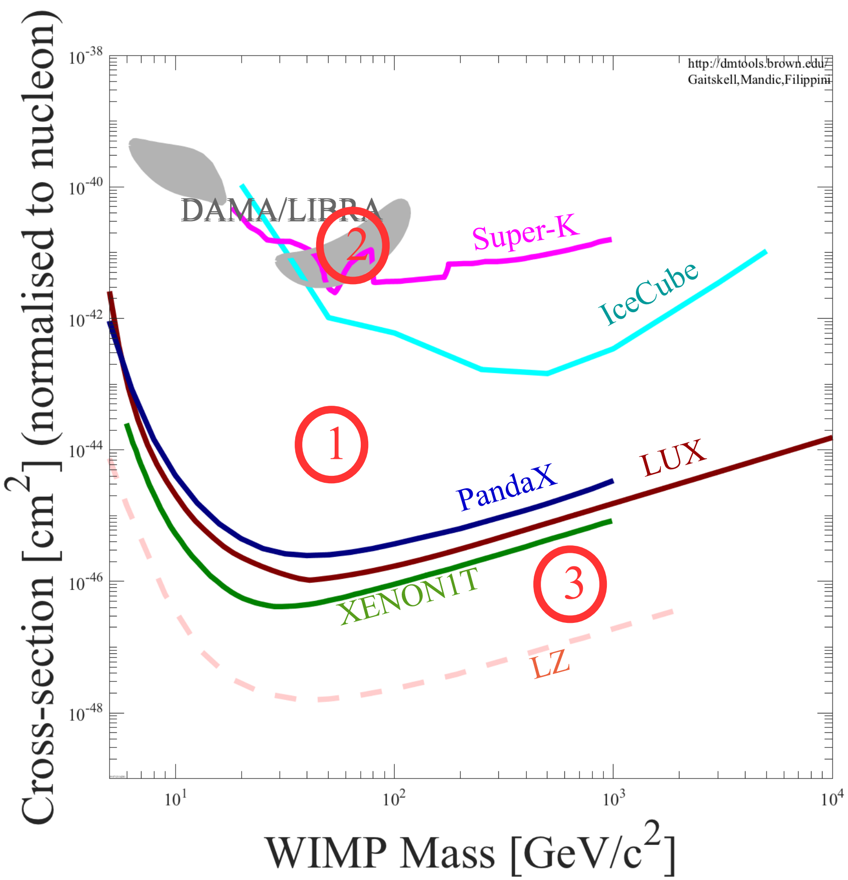


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(3) is allowed by current experiments, and will be tested by LZ.

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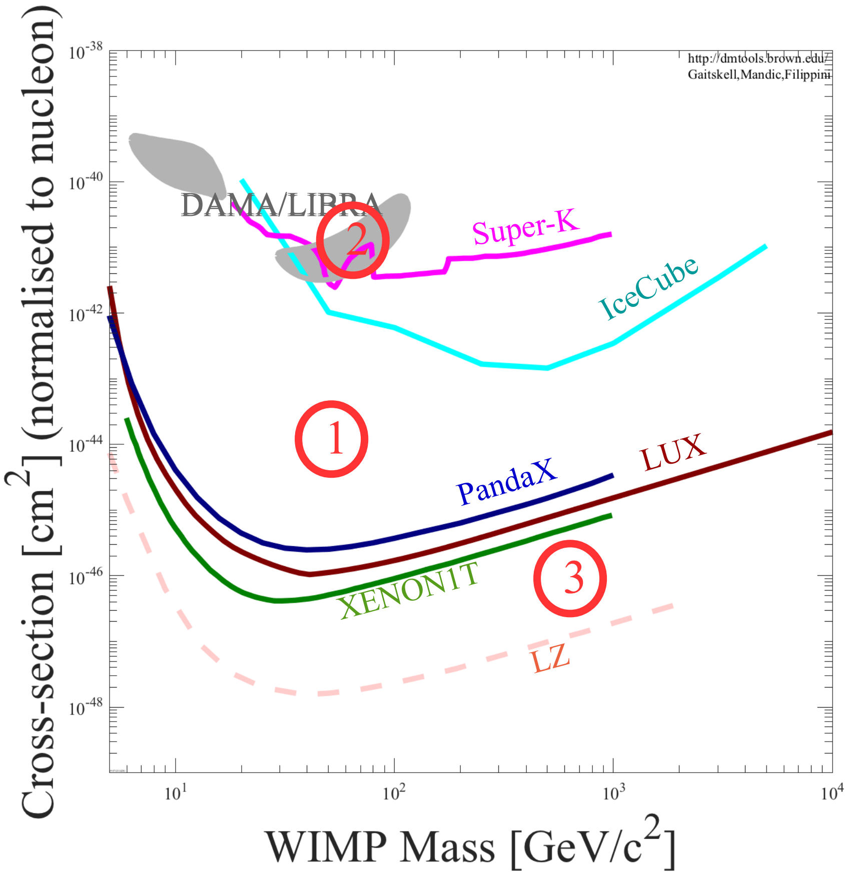


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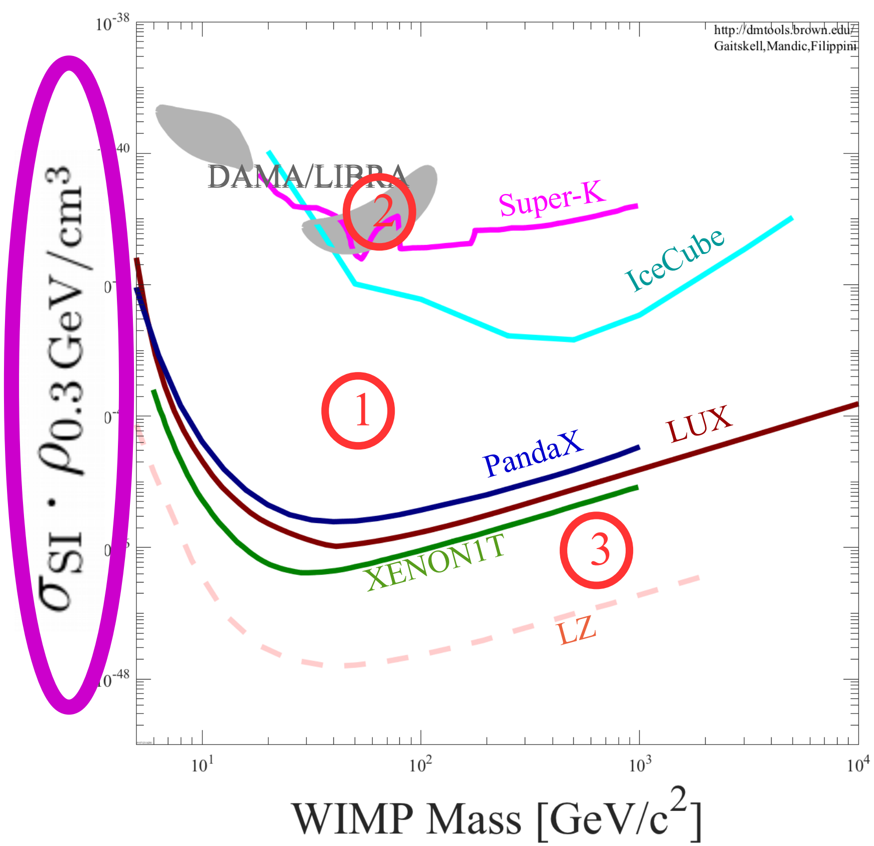


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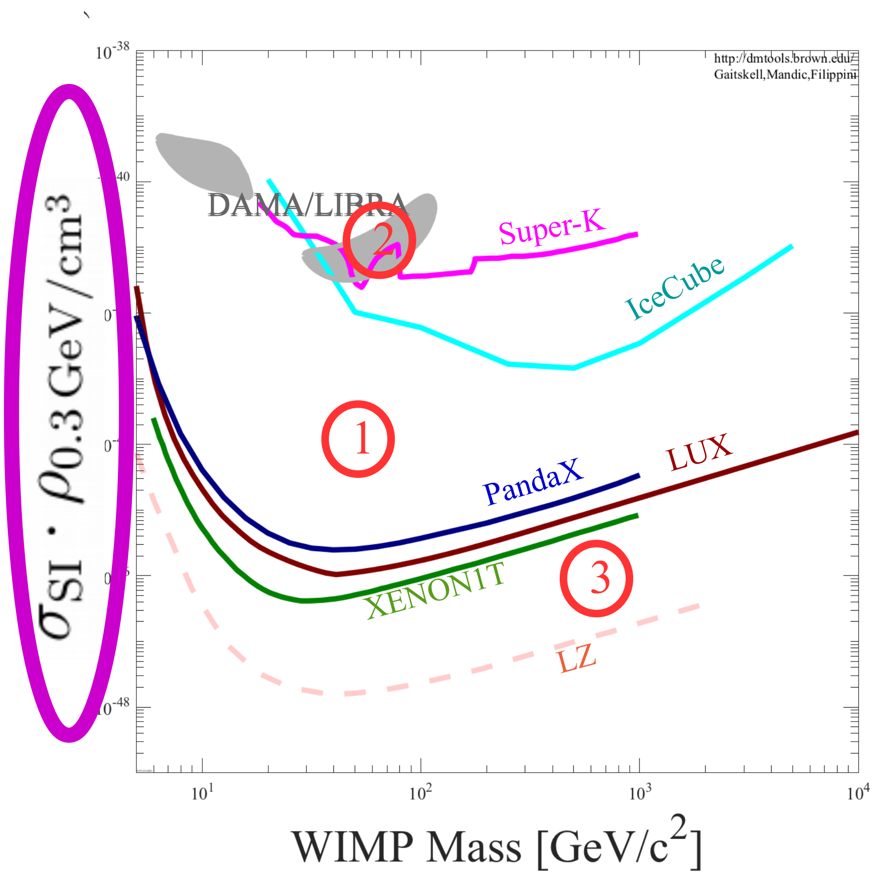


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What is the impact of the astrophysical uncertainties on these conclusions?

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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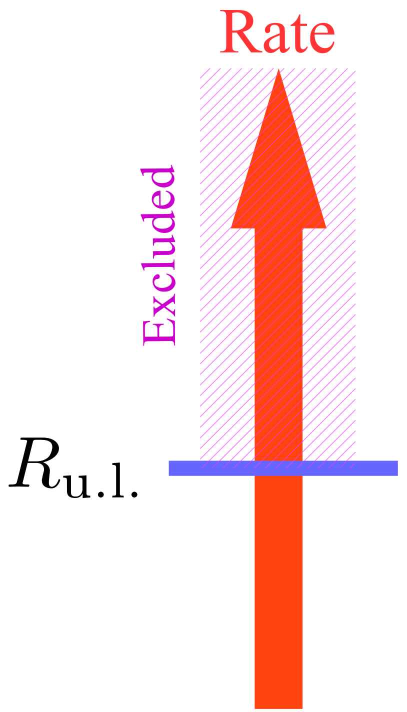

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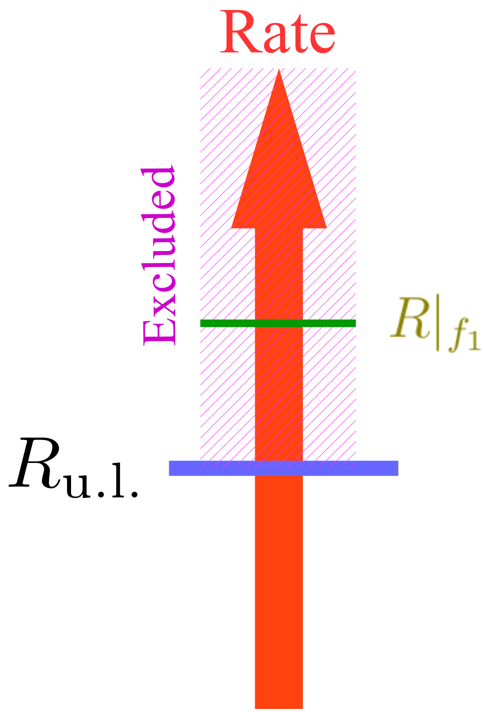

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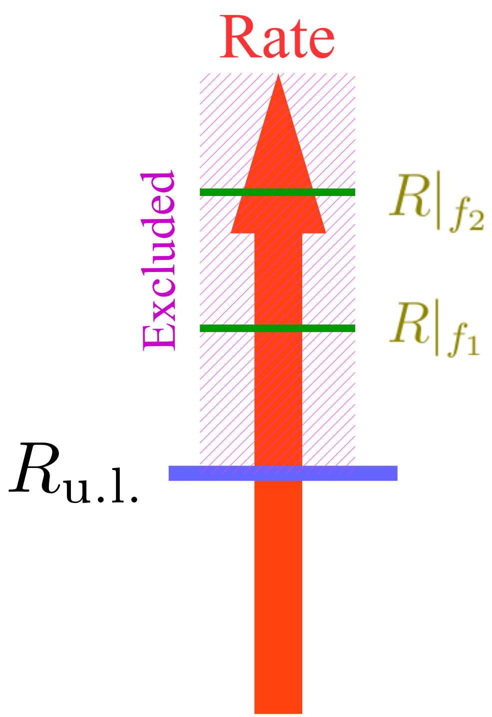

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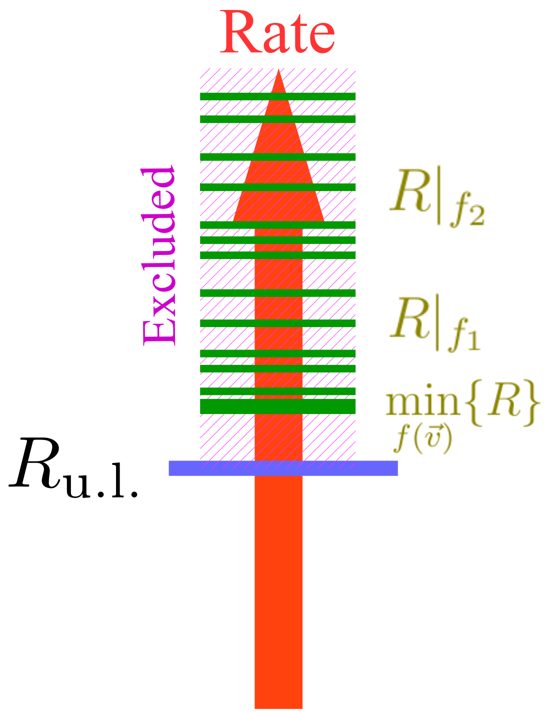

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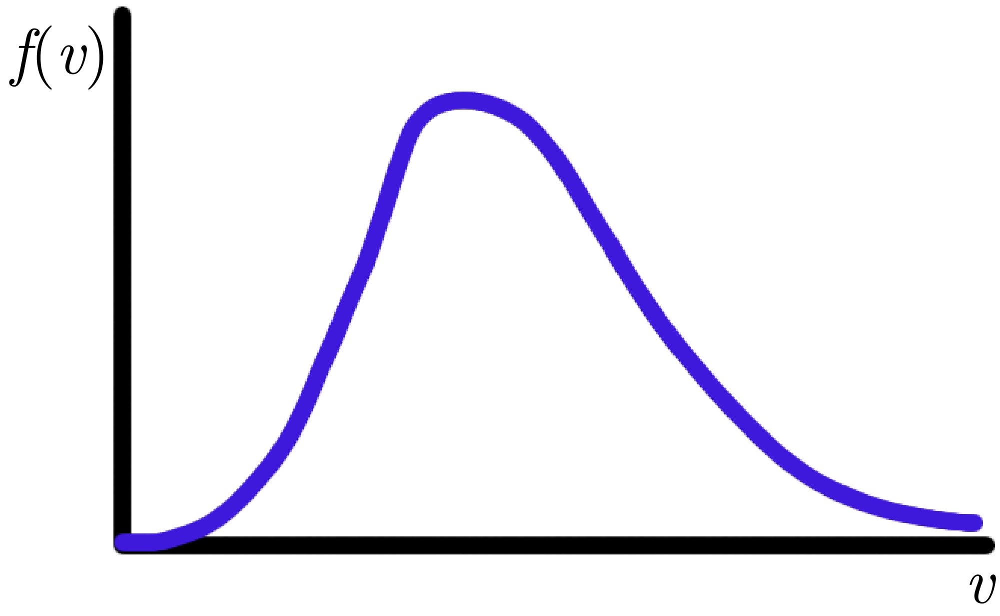

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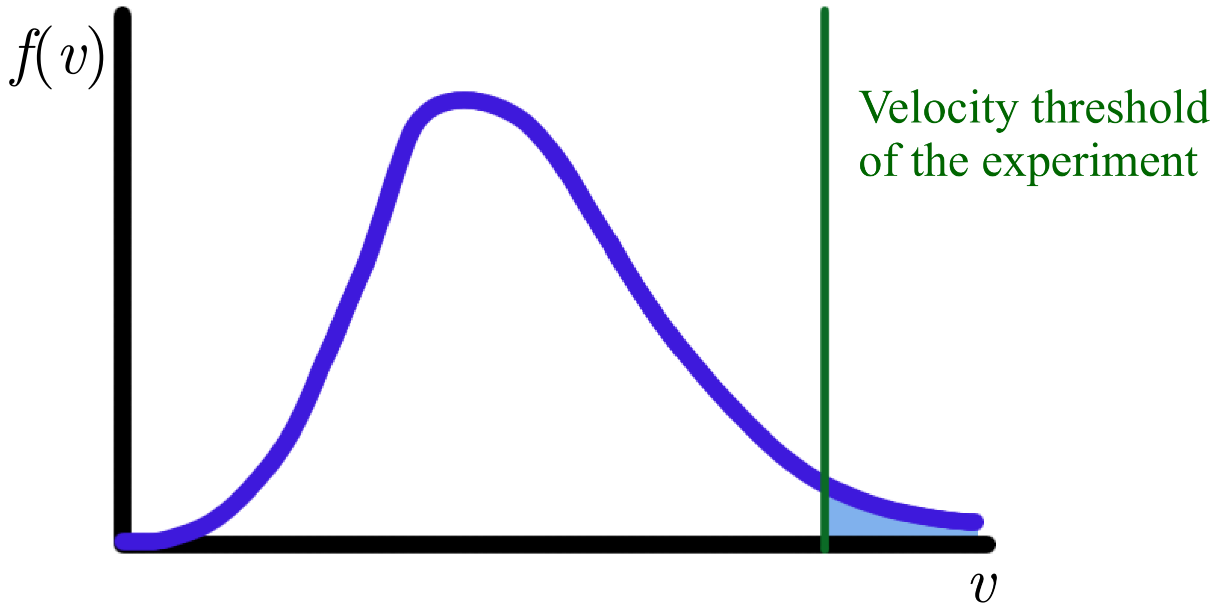

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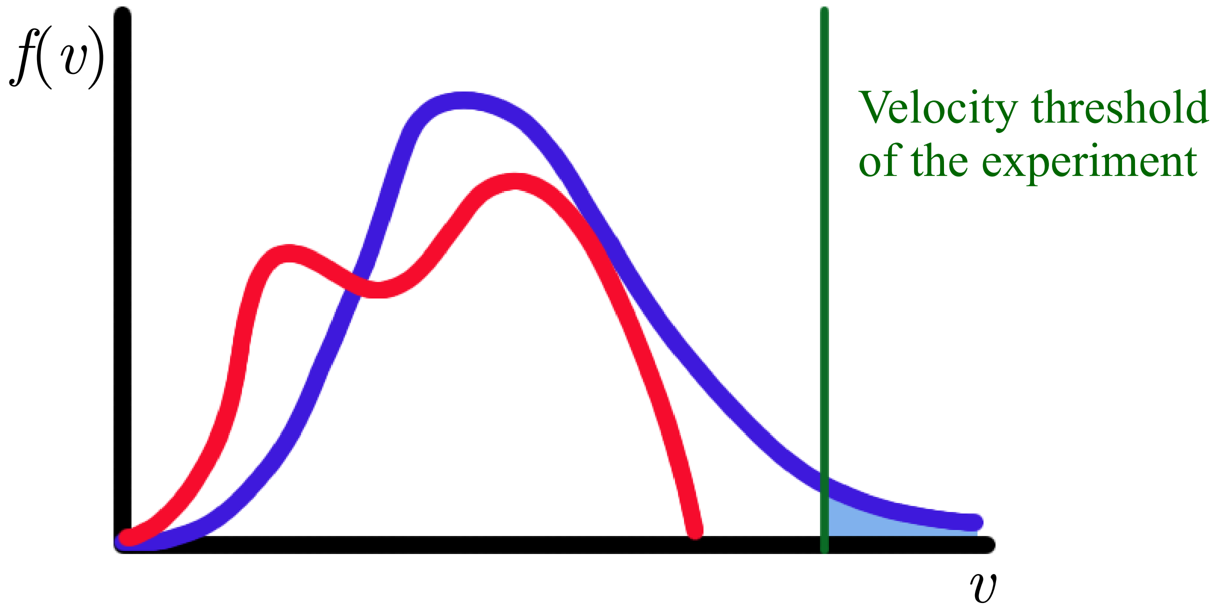


Some velocity distributions will
escape detection in the experiment

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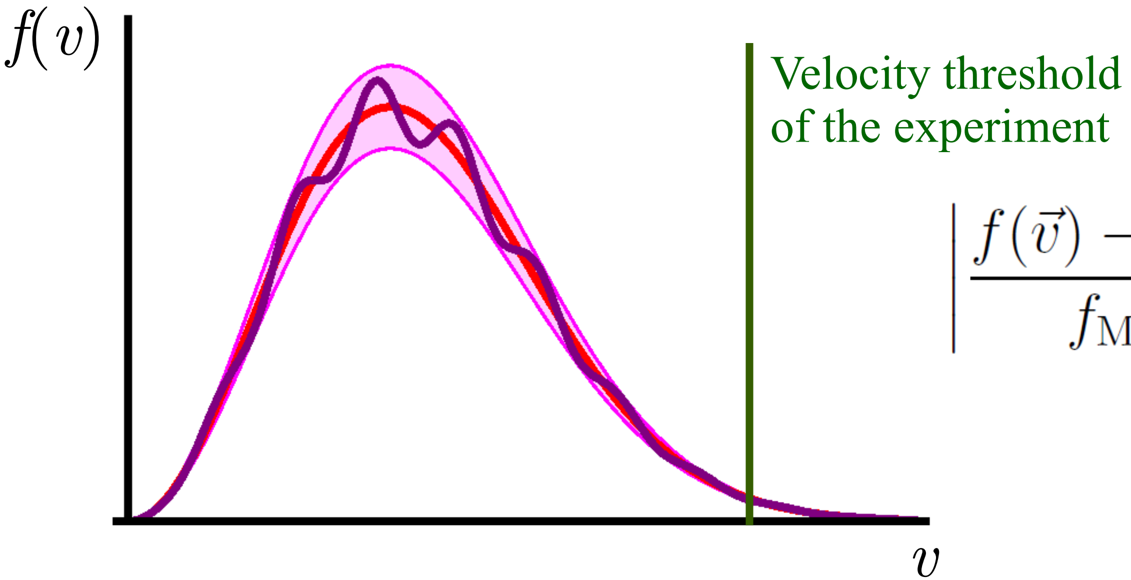


$$\left| \frac{f(\vec{v}) - f_{\rm MB}(\vec{v})}{f_{\rm MB}(\vec{v})} \right| \leq \Delta$$

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

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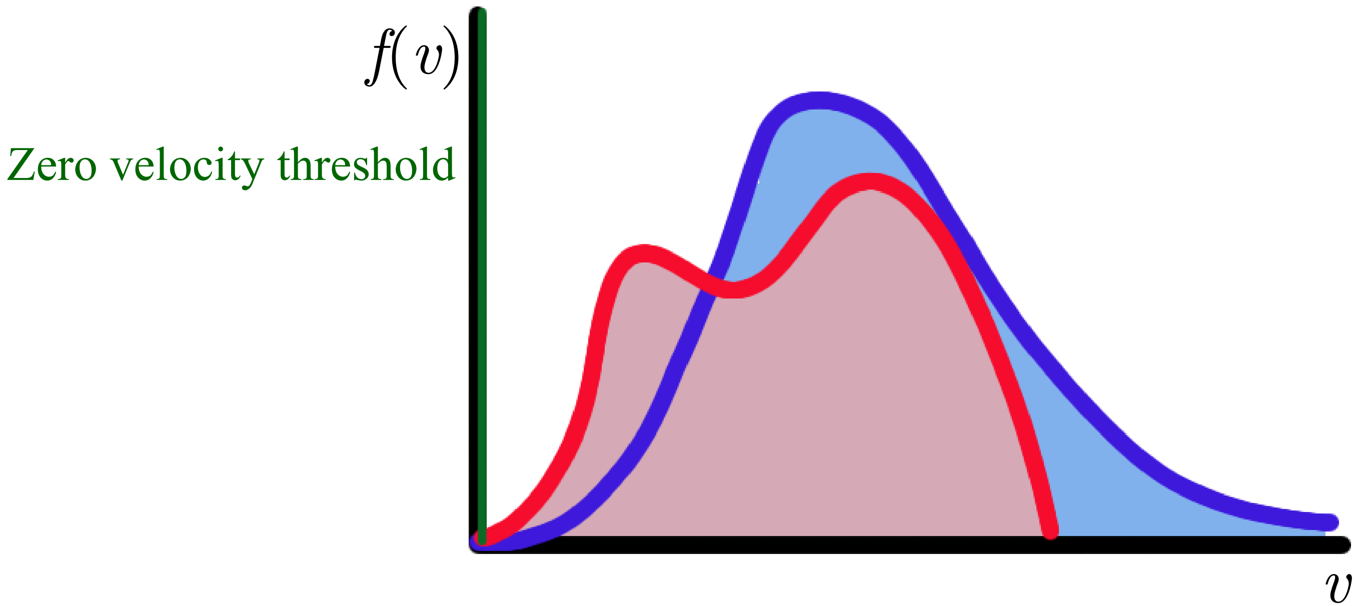


Possibility 2: Design an experiment with zero velocity threshold

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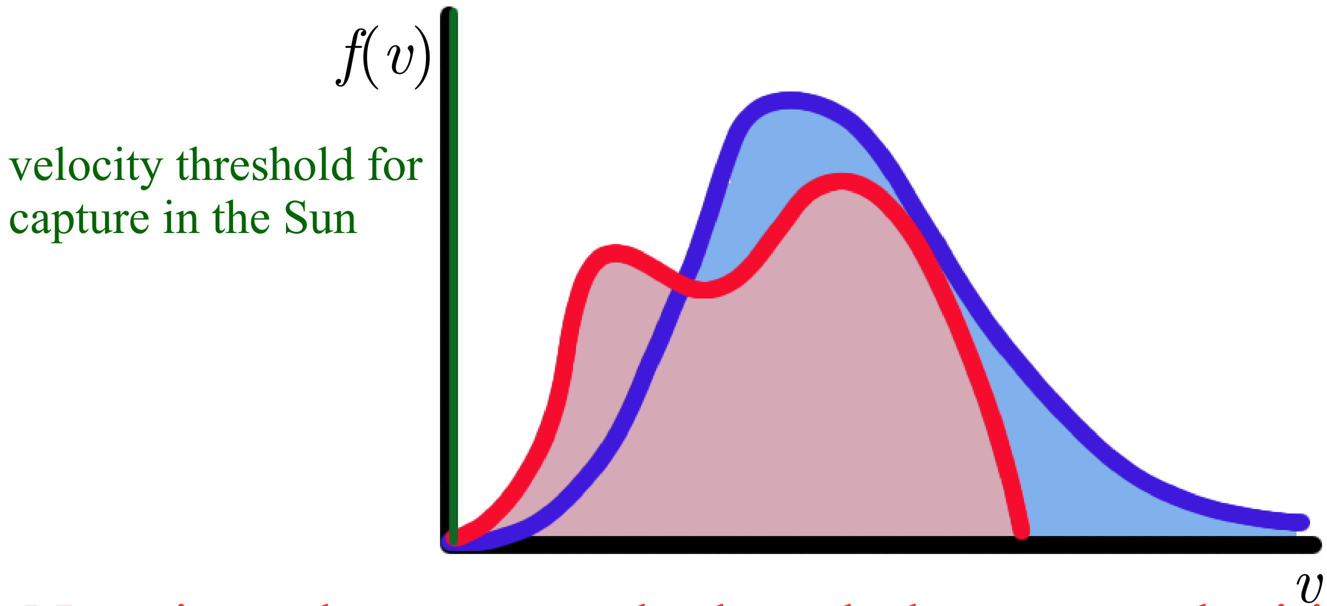
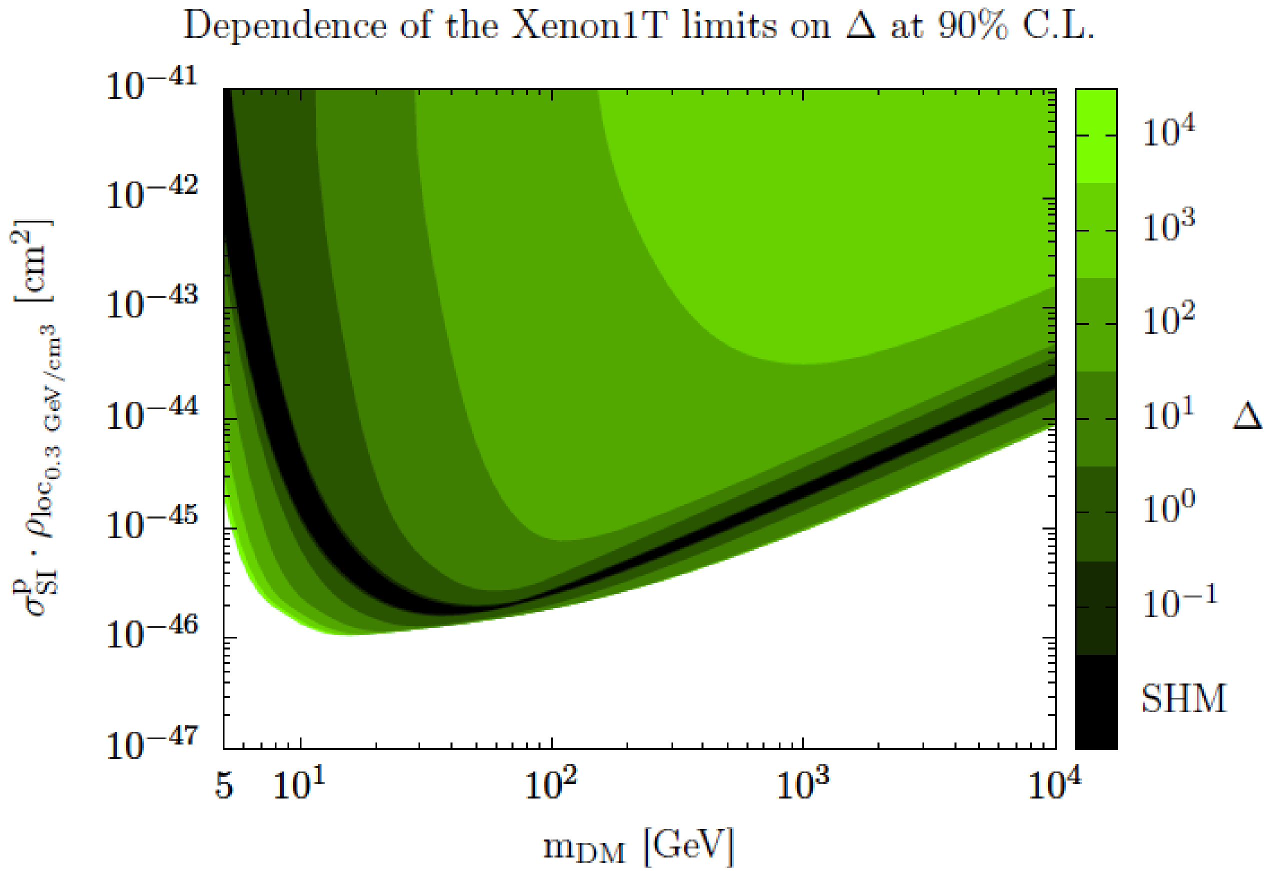


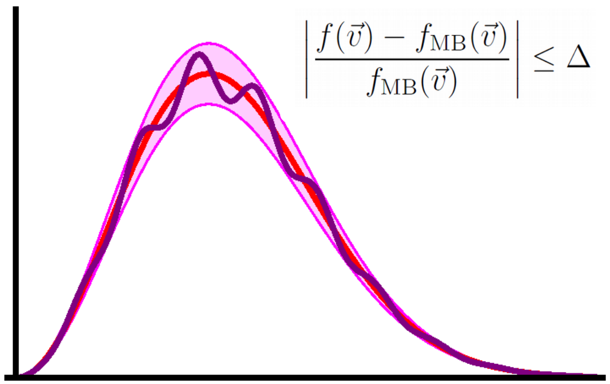

Neutrino telescopes probe low dark matter velocities. In combination with direct detection experiments, one can probe the whole velocity space

# 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:

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



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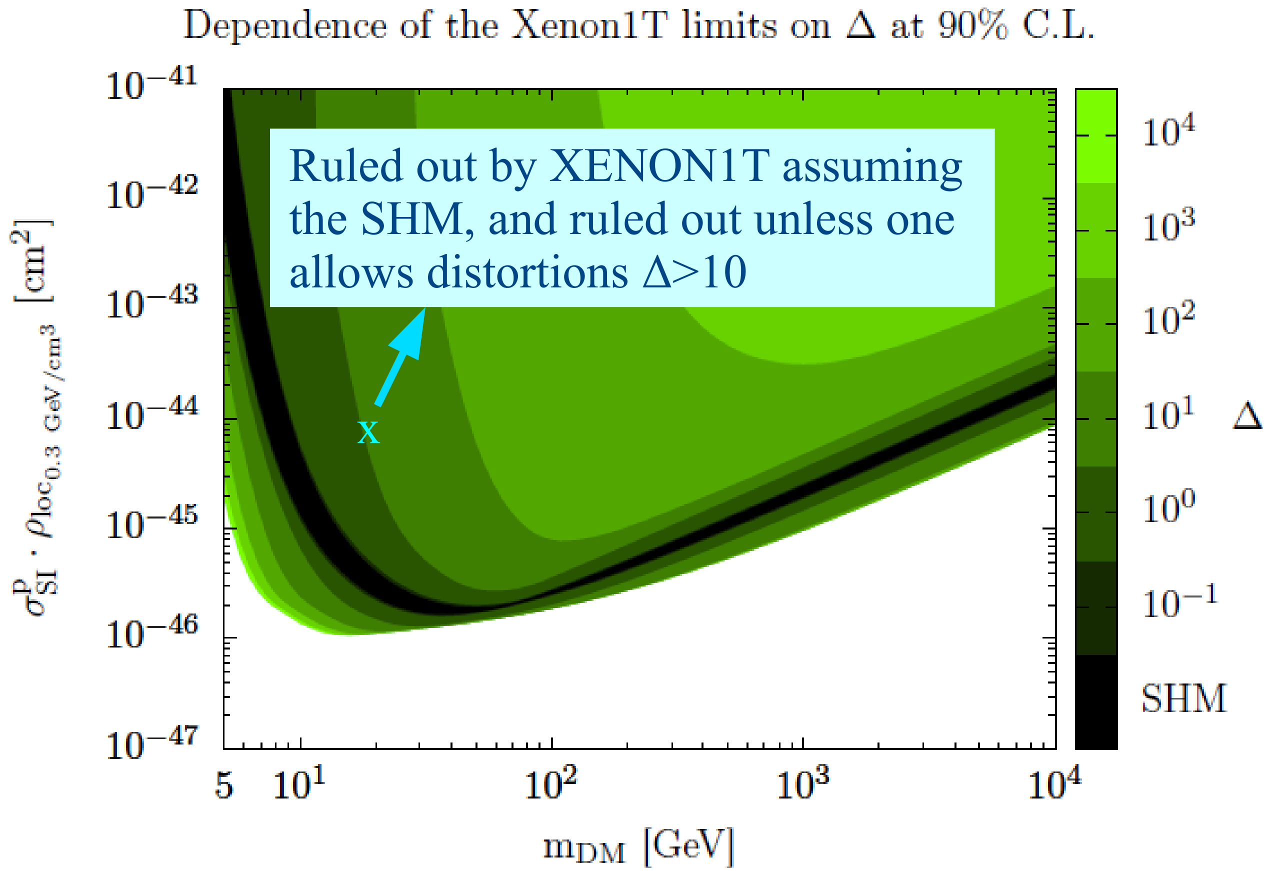


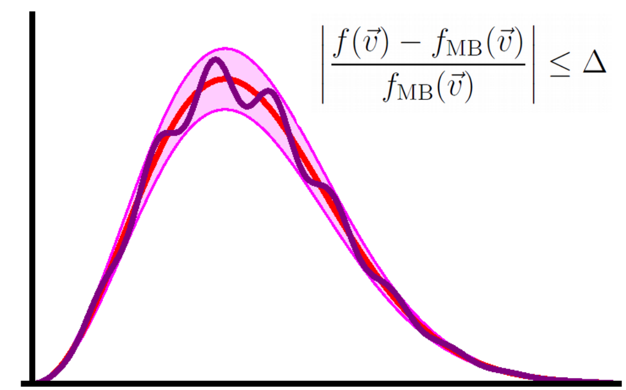

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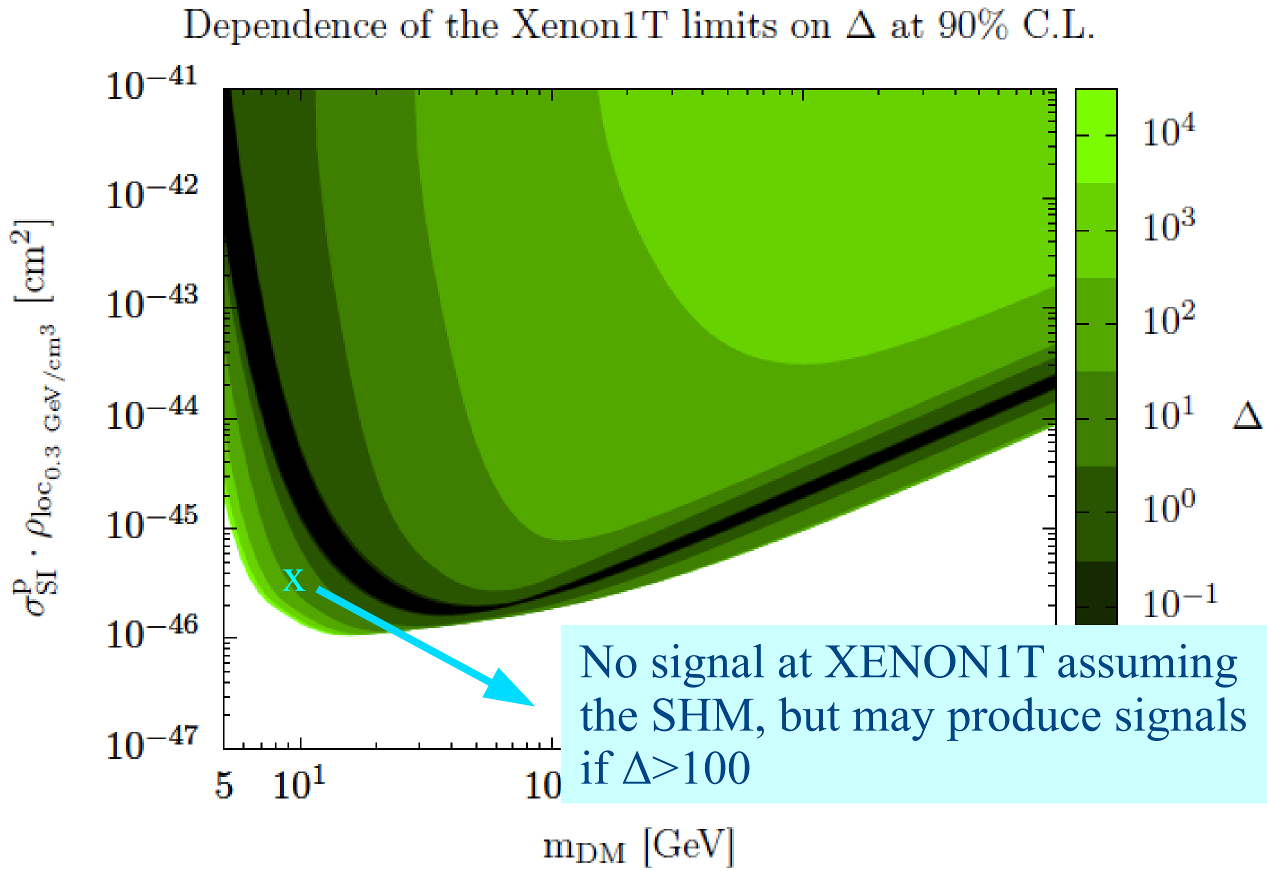


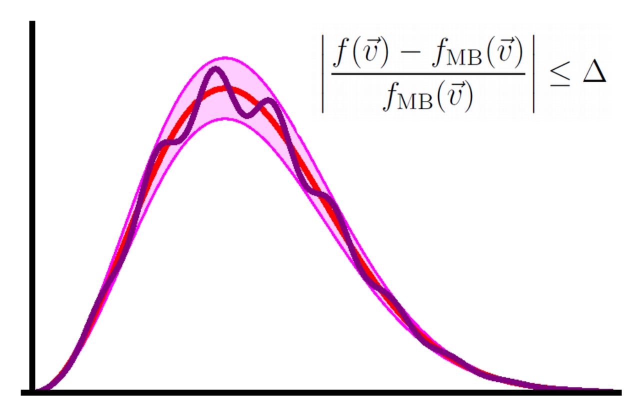

## Upper limit on the scattering cross section from combining PandaX and IceCube/SK.

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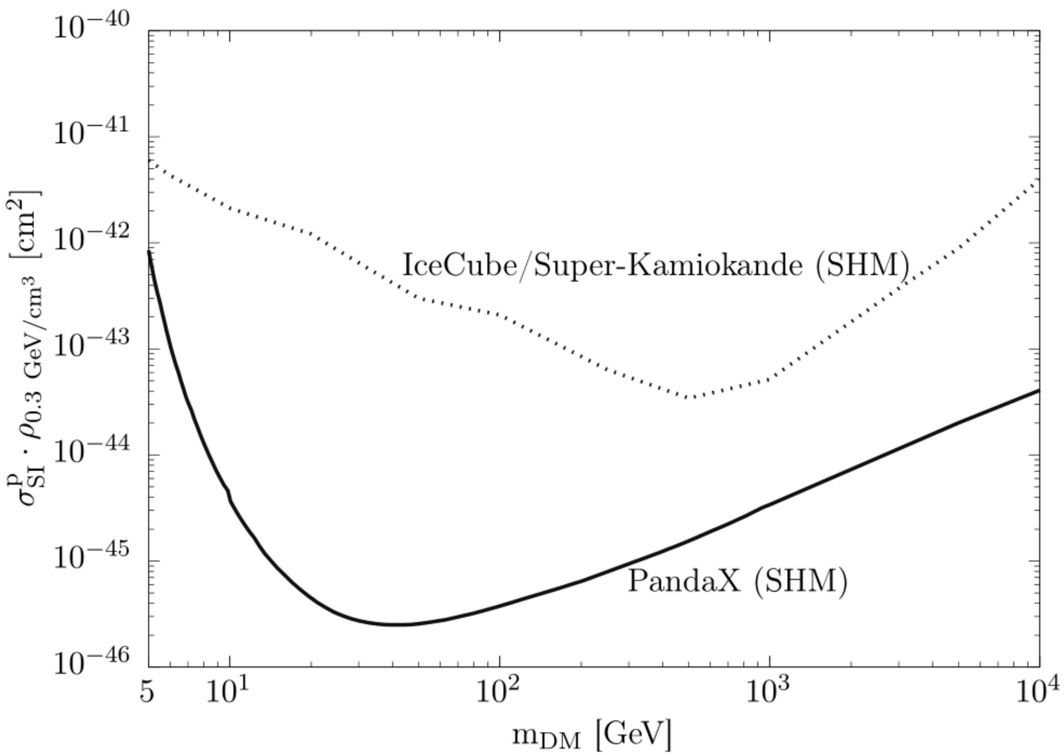


AI, Rappelt'17

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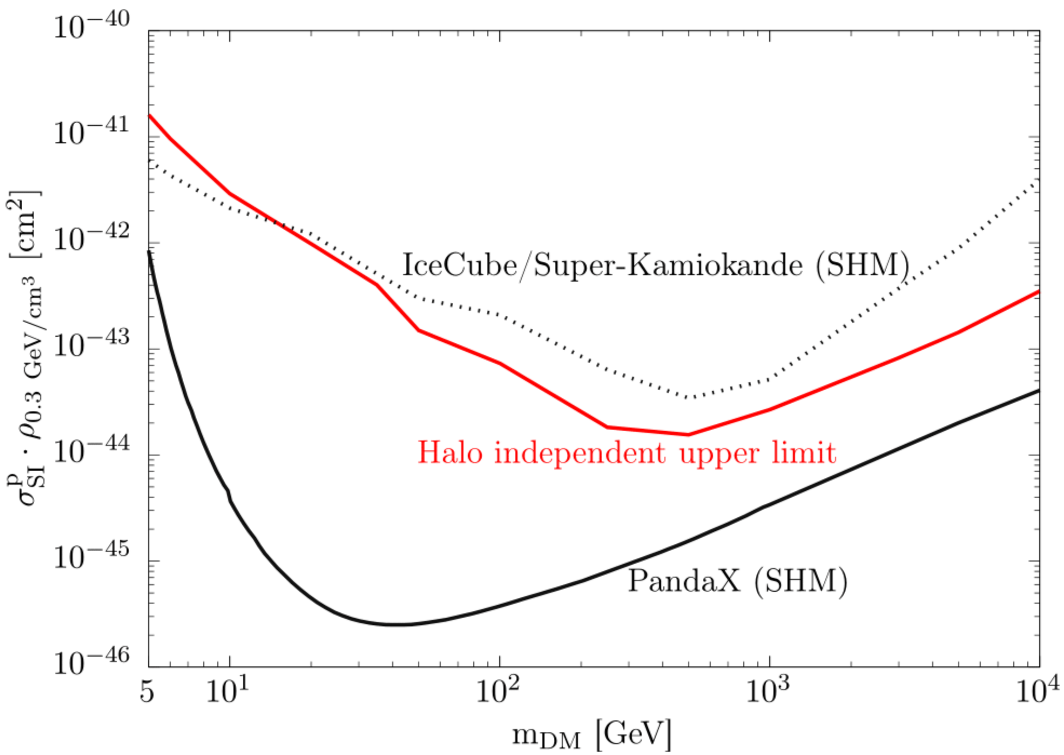


AI, Rappelt'17

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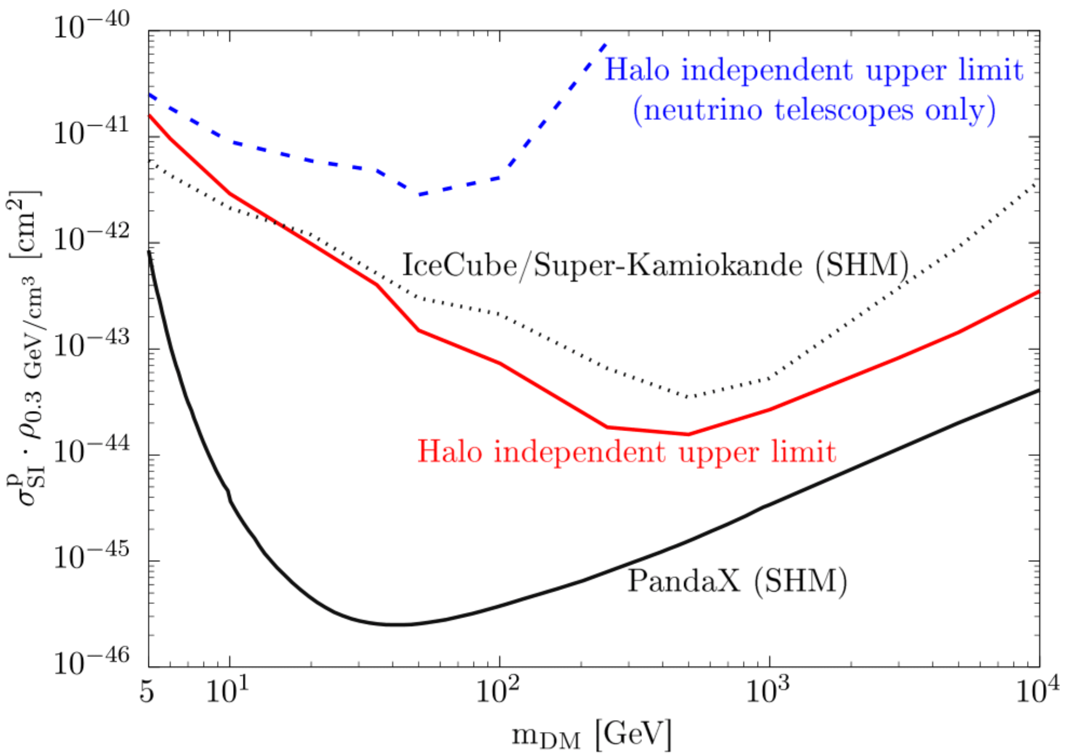


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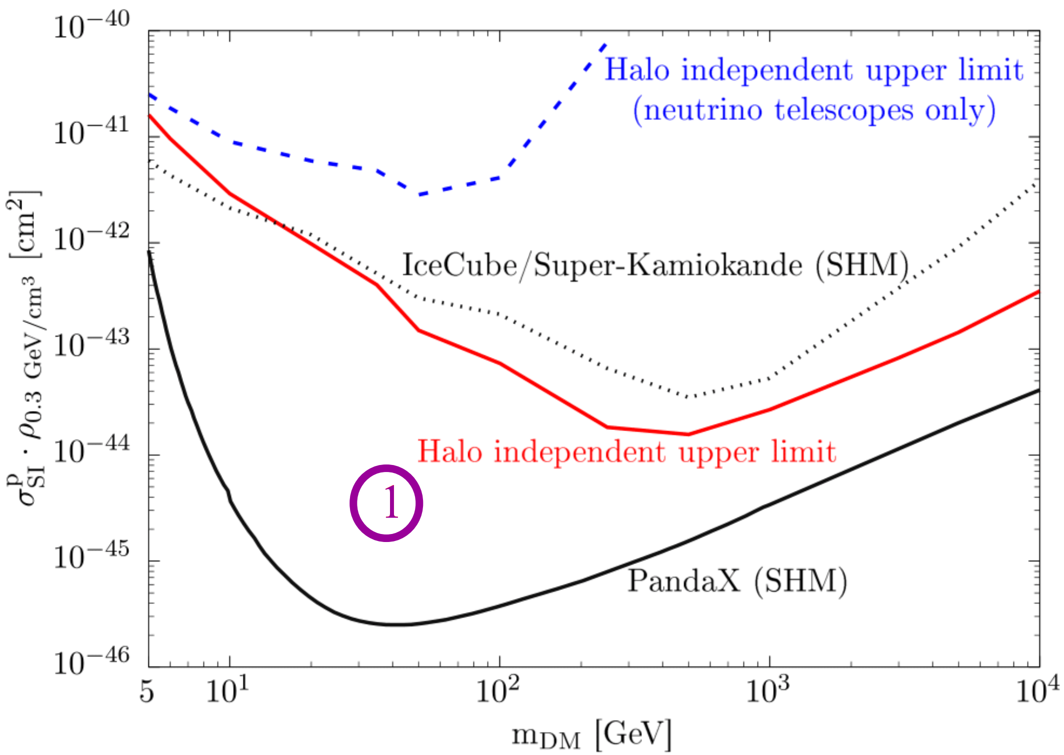


AI, Rappelt'17

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

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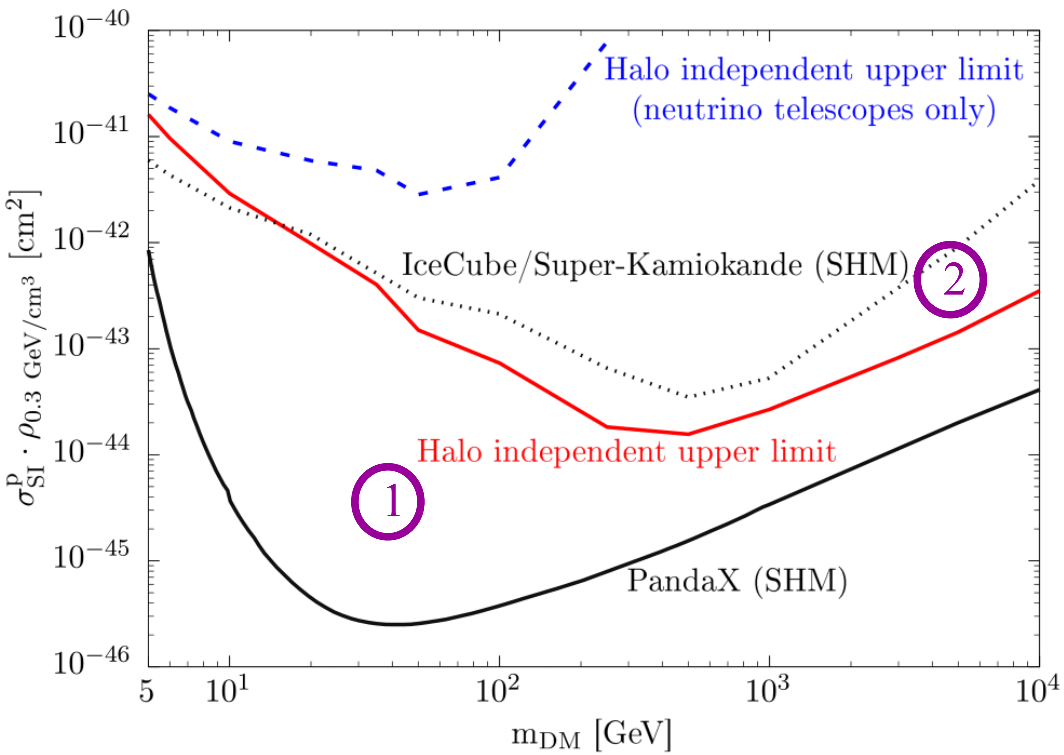


AI, Rappelt'17

(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.

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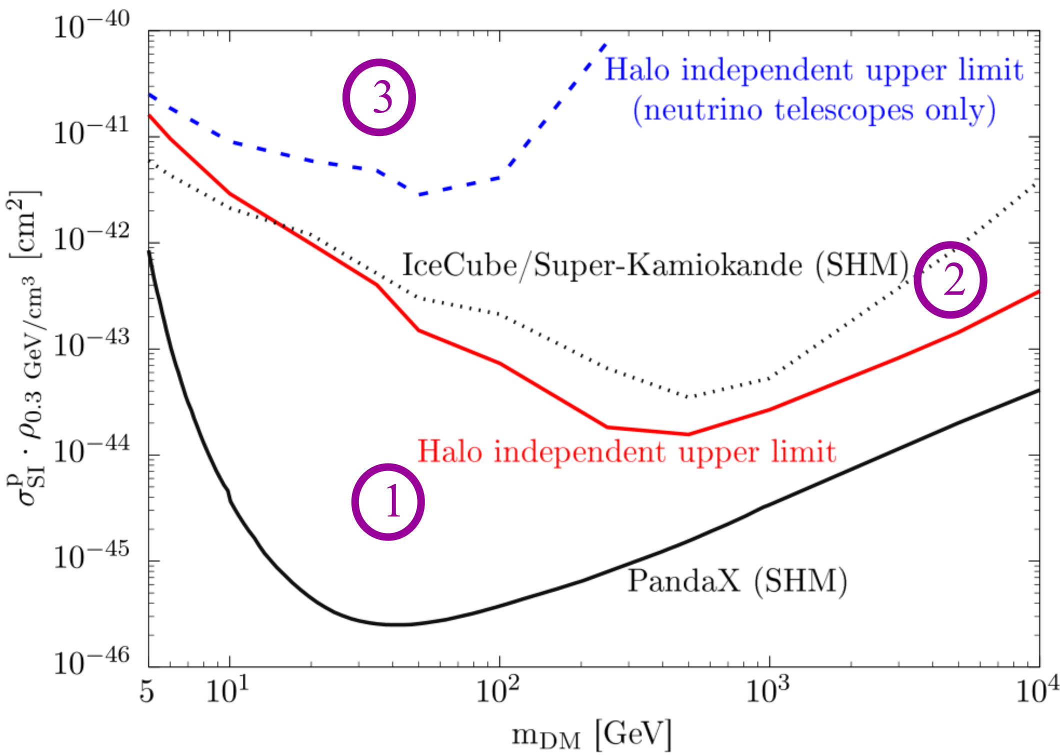



AI, Rappelt'17

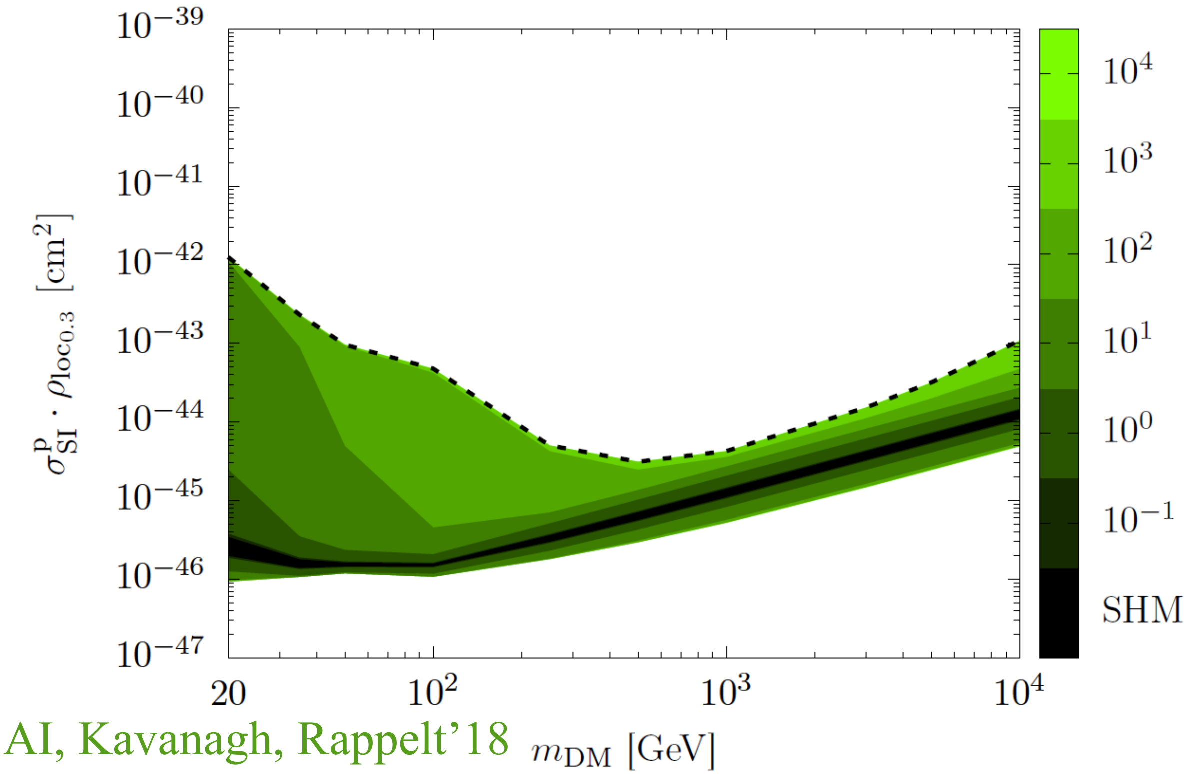
1. is ruled out by PandaX assuming the SHM, but allowed for some velocity distributions
2. is ruled out from combining PandaX and neutrino telescopes, for *any* velocity distribution.
3. is ruled out by neutrino telescopes only, for *any* velocity distribution.

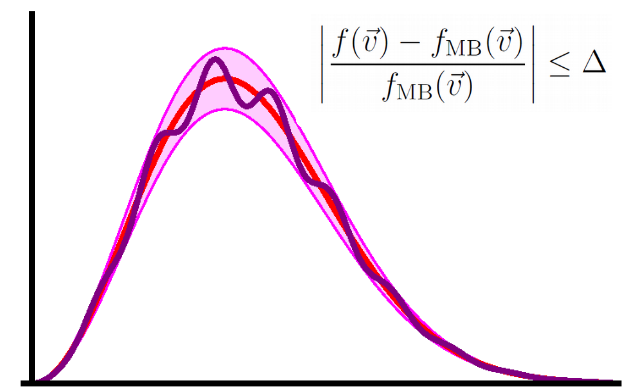
# Upper limit on the scattering cross section from combining PandaX and IceCube/SK: extension

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:

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

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




AI, Kavanagh, Rappelt'18

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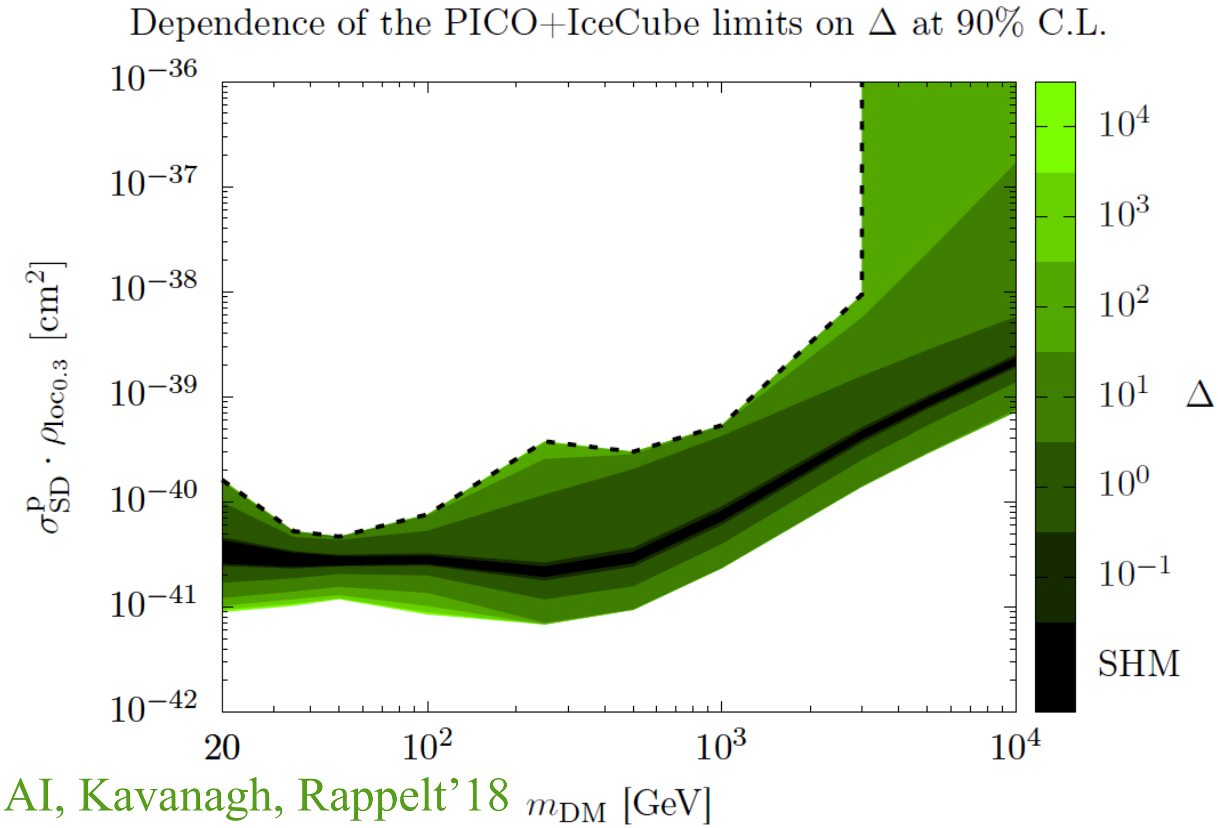
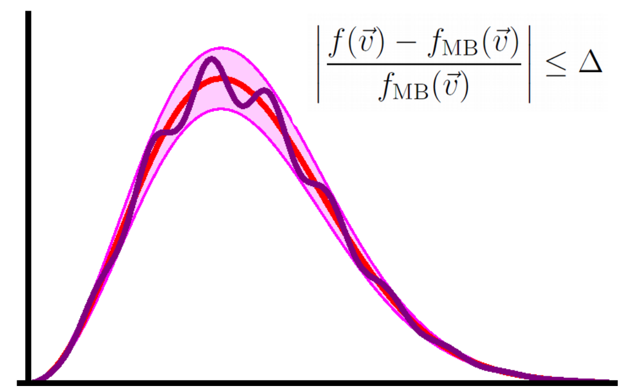



AI, Kavanagh, Rappelt'18



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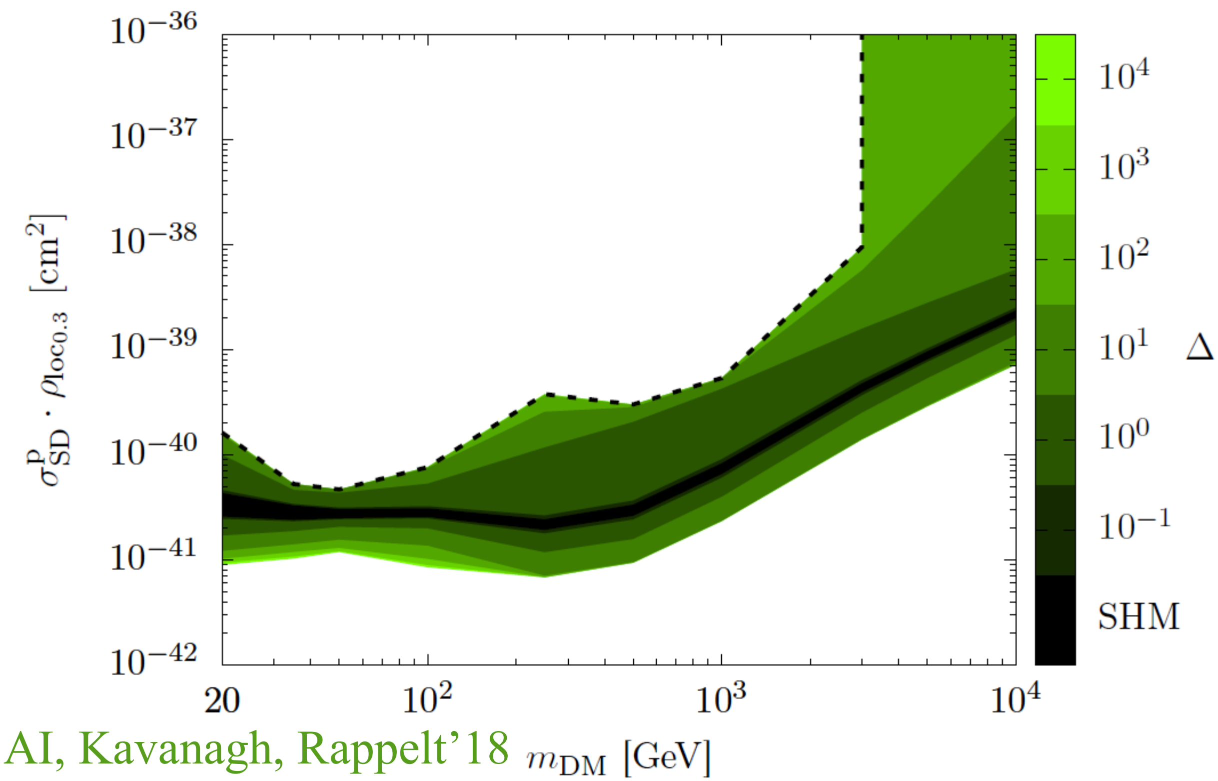
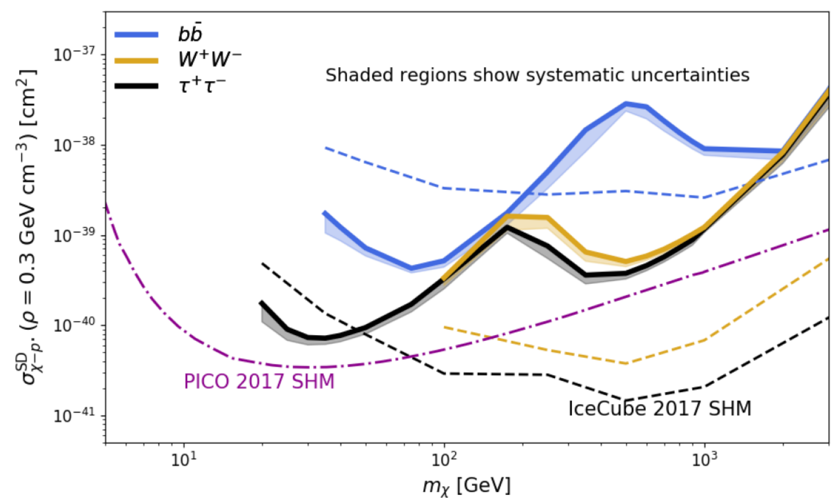
Dependence of the PICO+IceCube limits on Δ at 90% C.L.




AI, Kavanagh, Rappelt'18



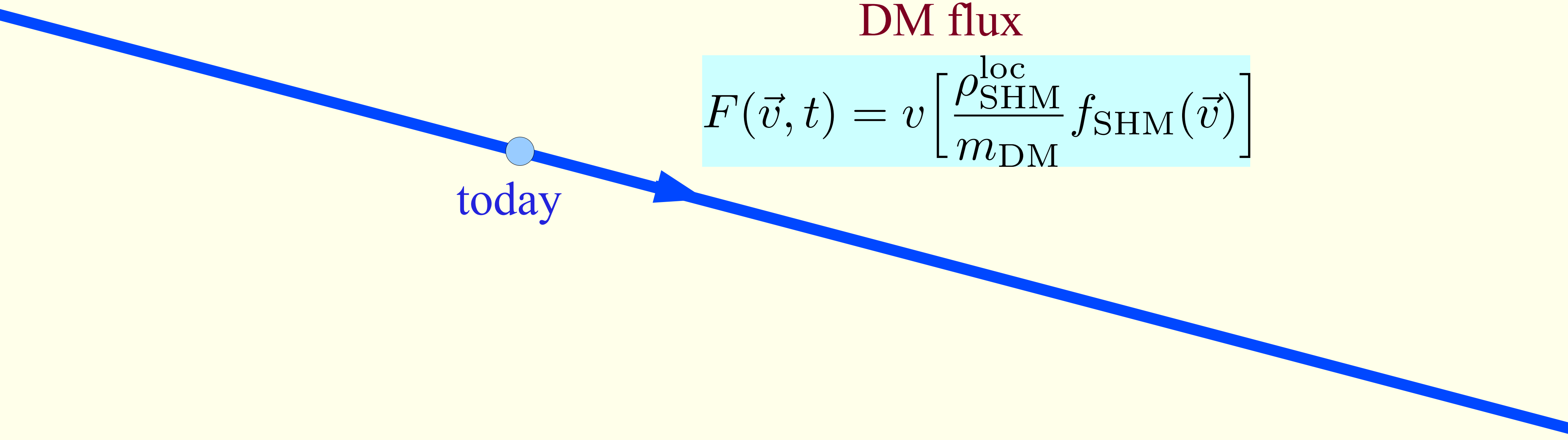

IceCube+PICO coll.'19

# A concrete case:

# Milky Way sub-halos

## DM flux

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



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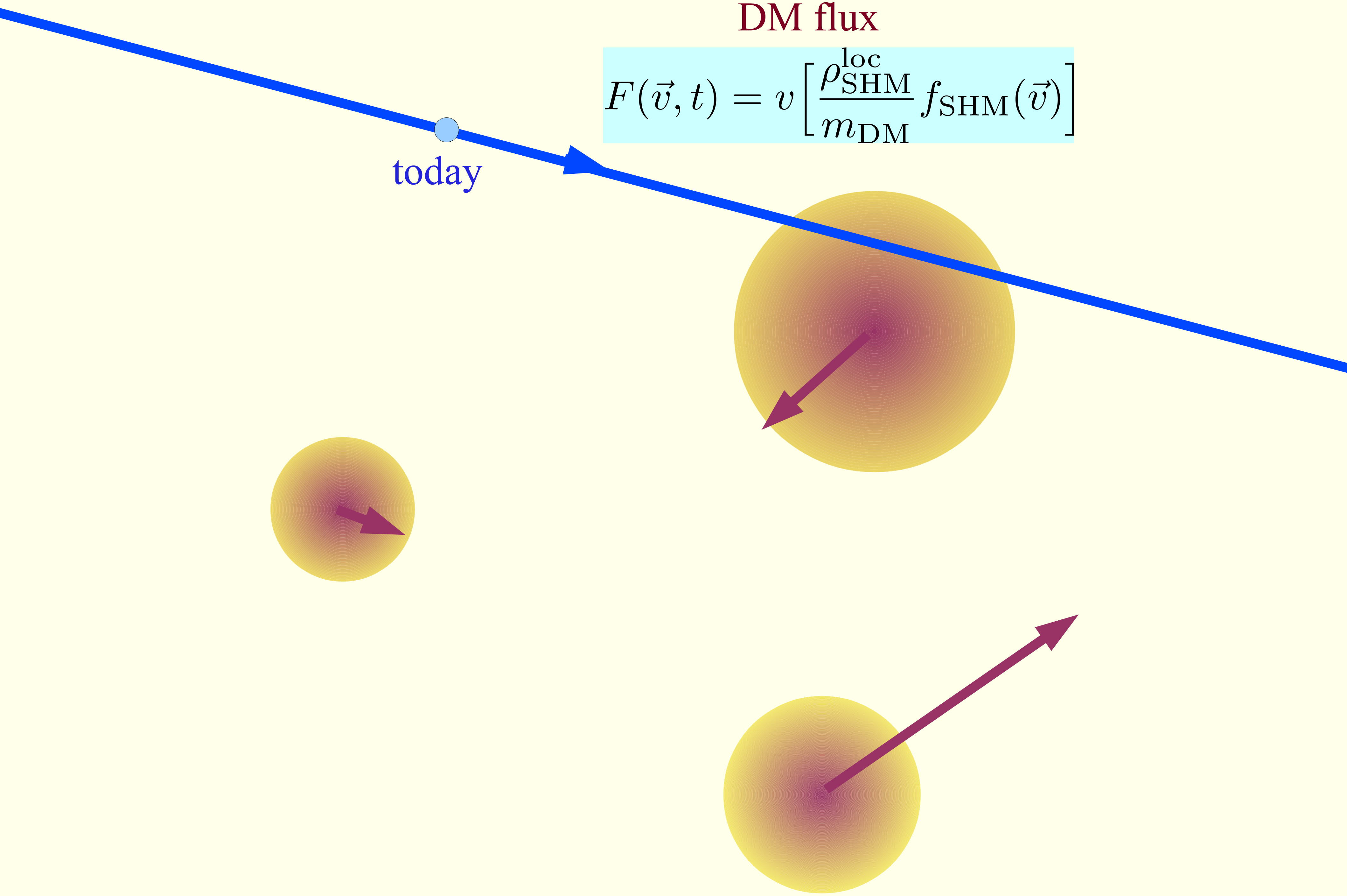
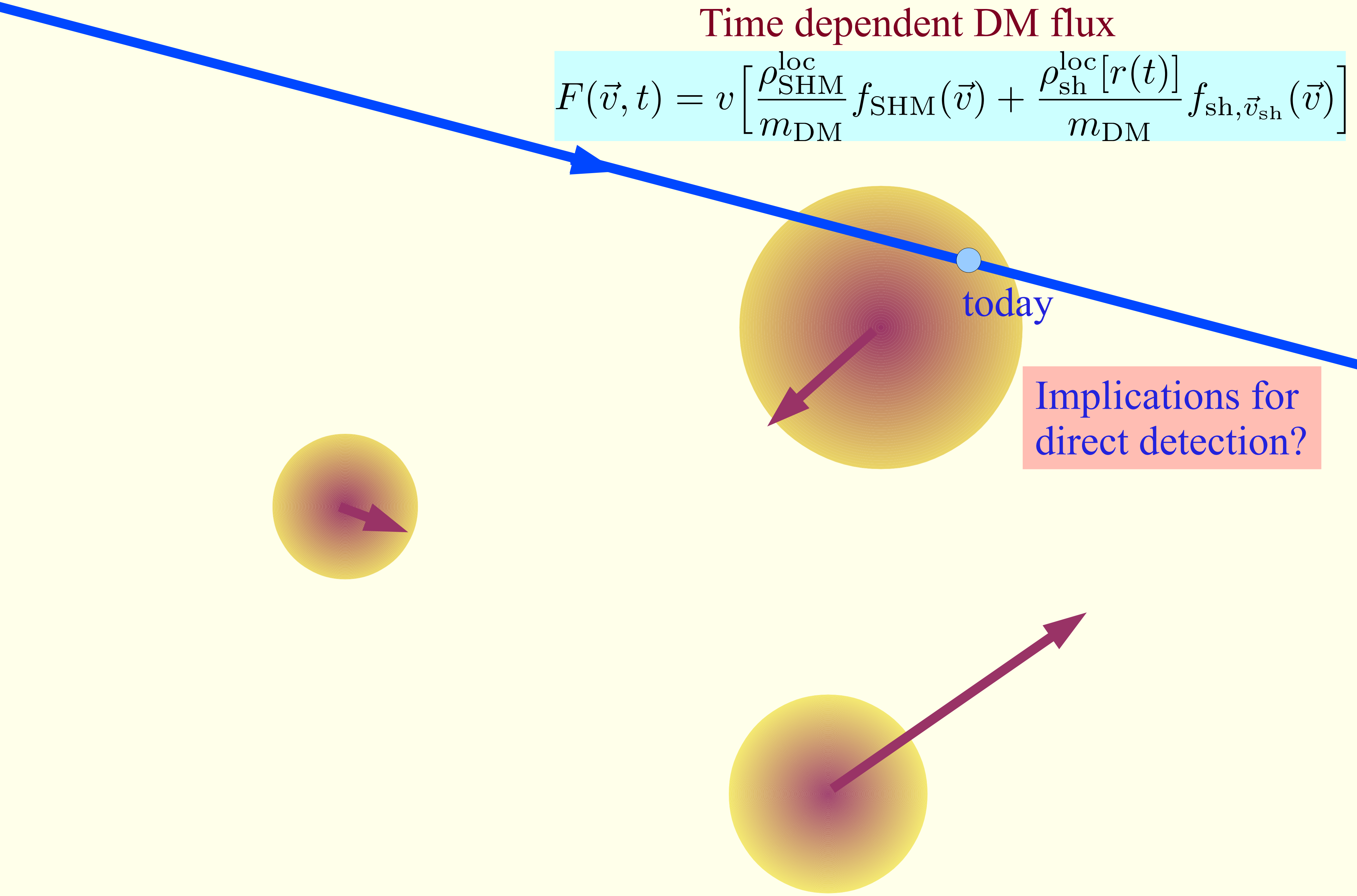


# Time dependent DM flux

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




Implications for direct detection?

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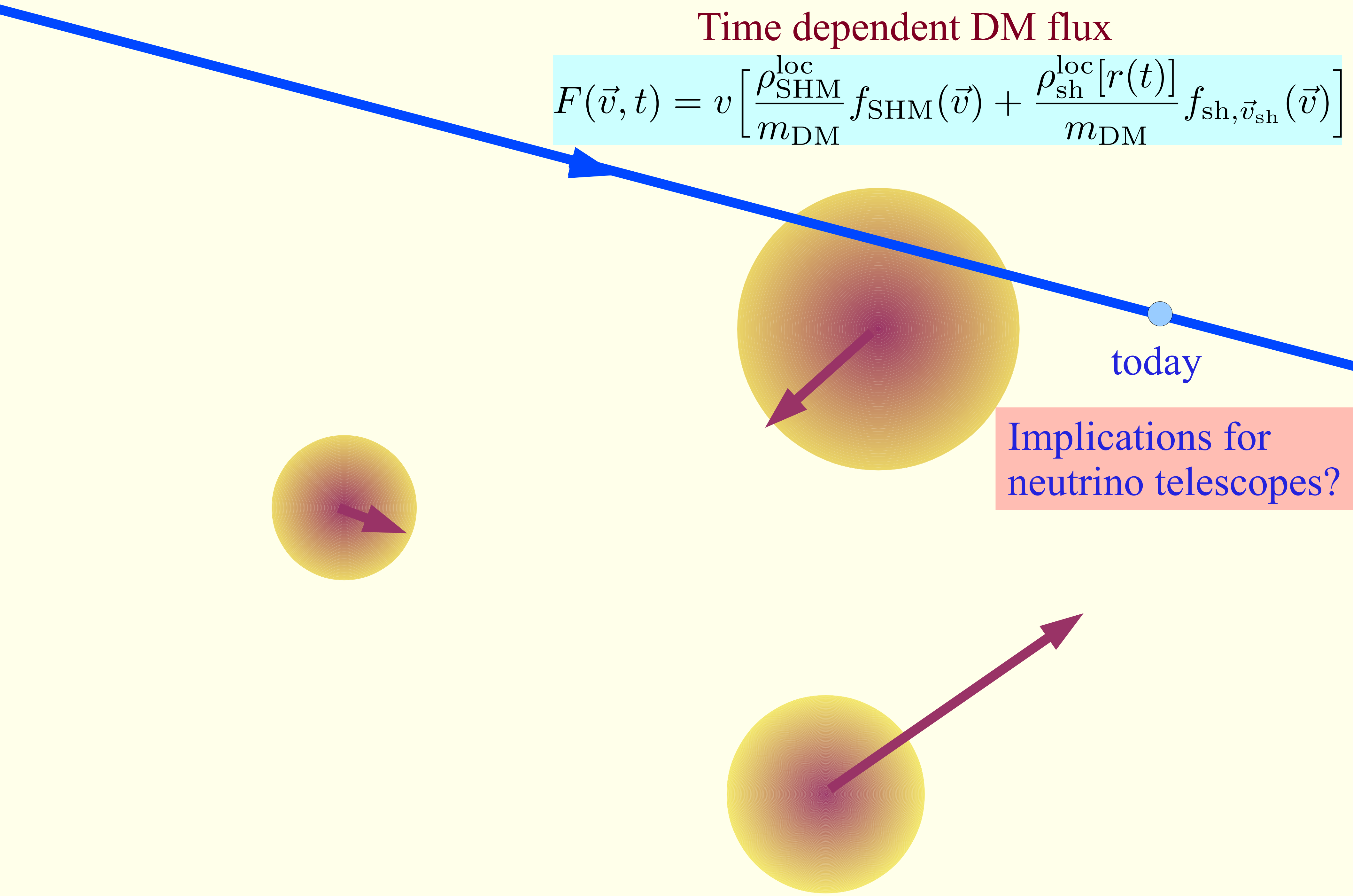


Implications for neutrino telescopes?

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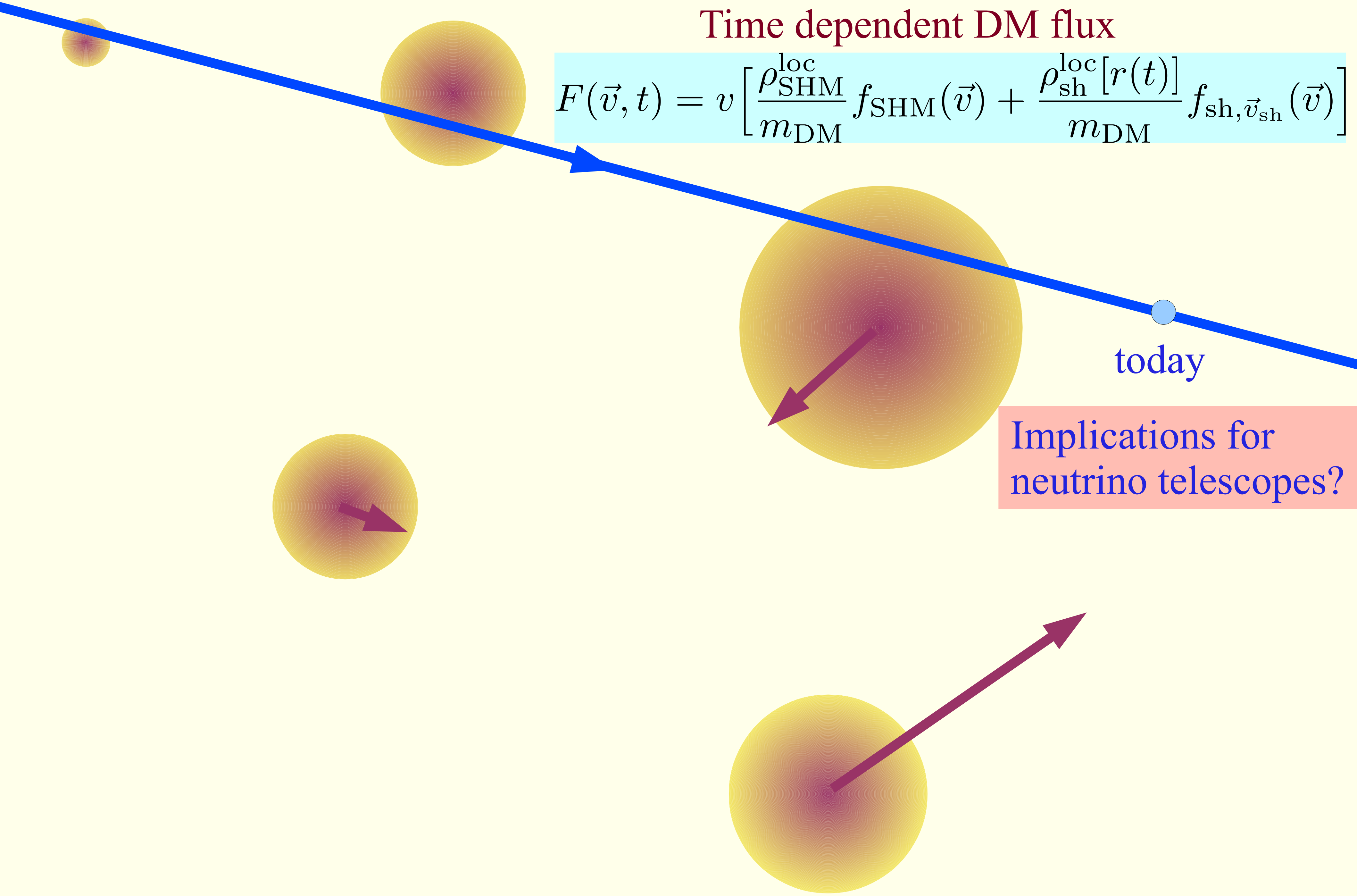
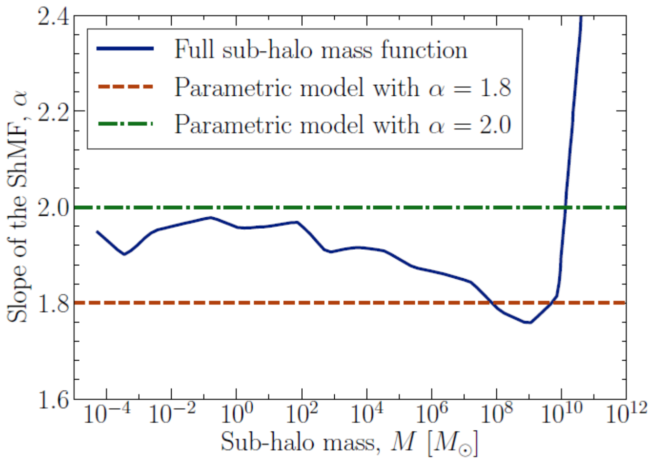



Implications for neutrino telescopes?

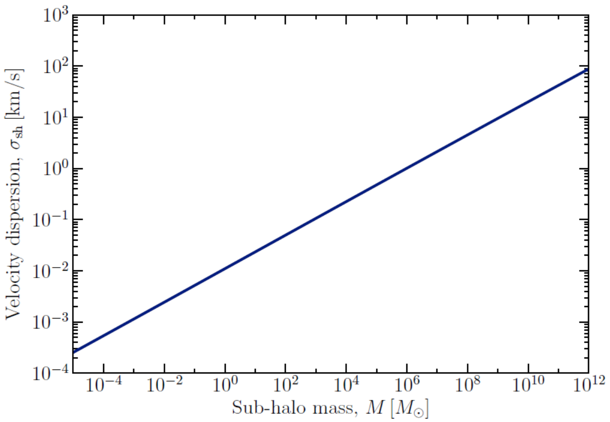
# Impact of sub-halos in local DM searches

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

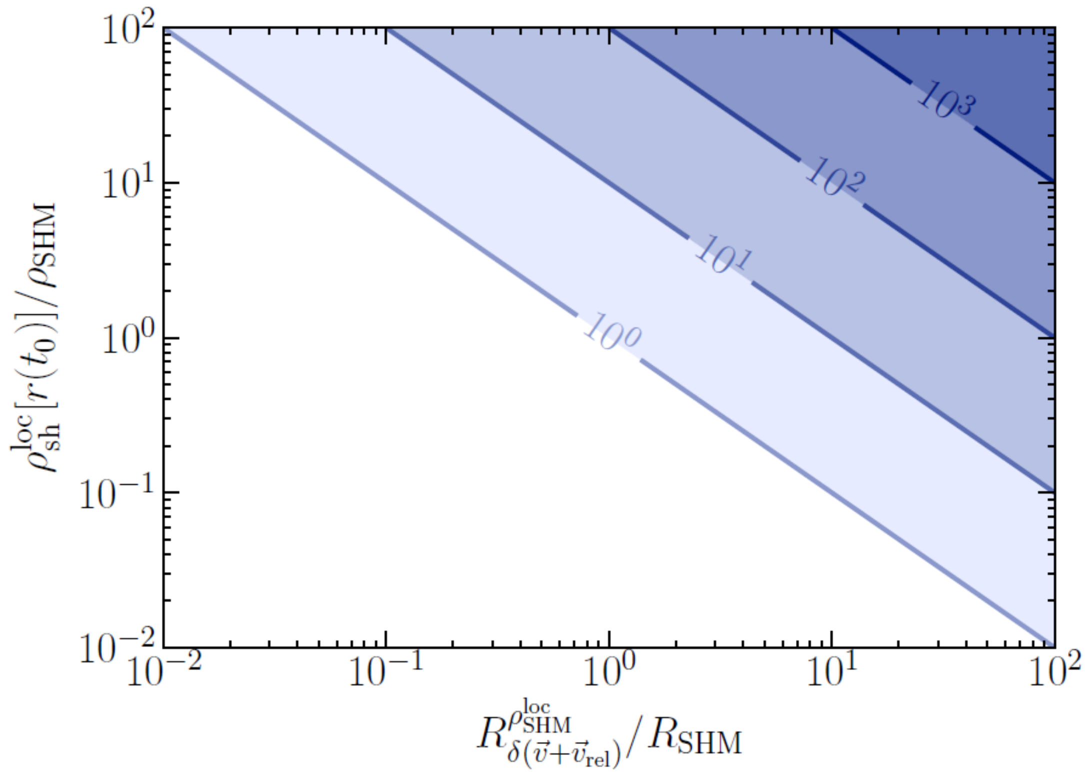


# Impact of sub-halos in direct detection experiments

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

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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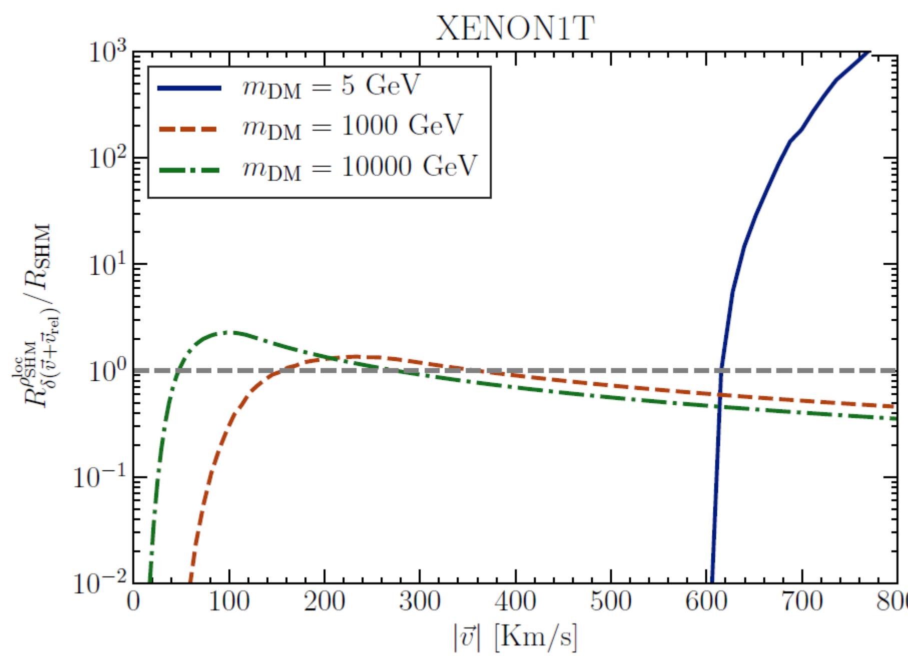

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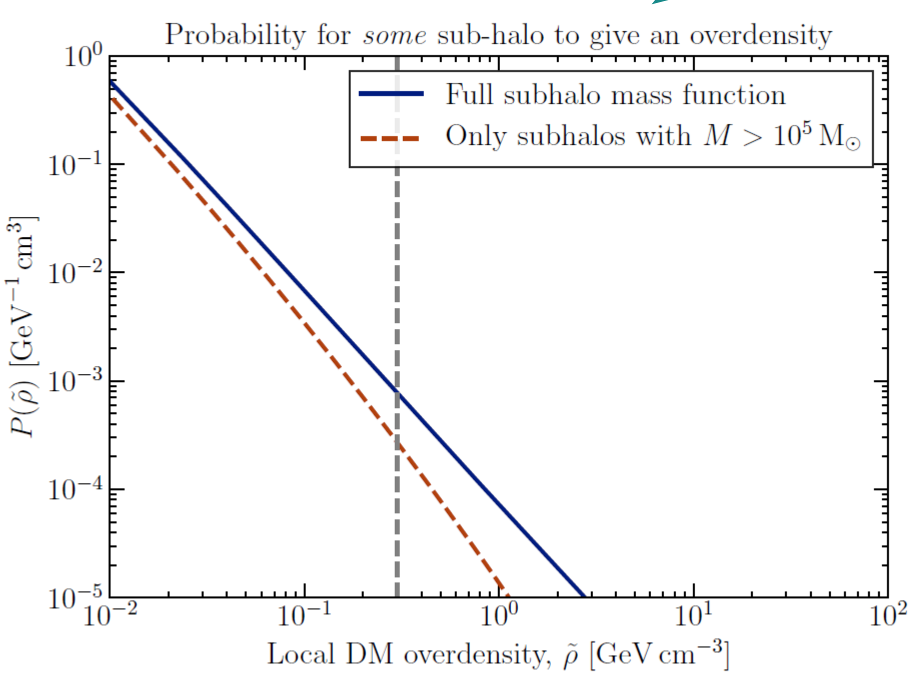


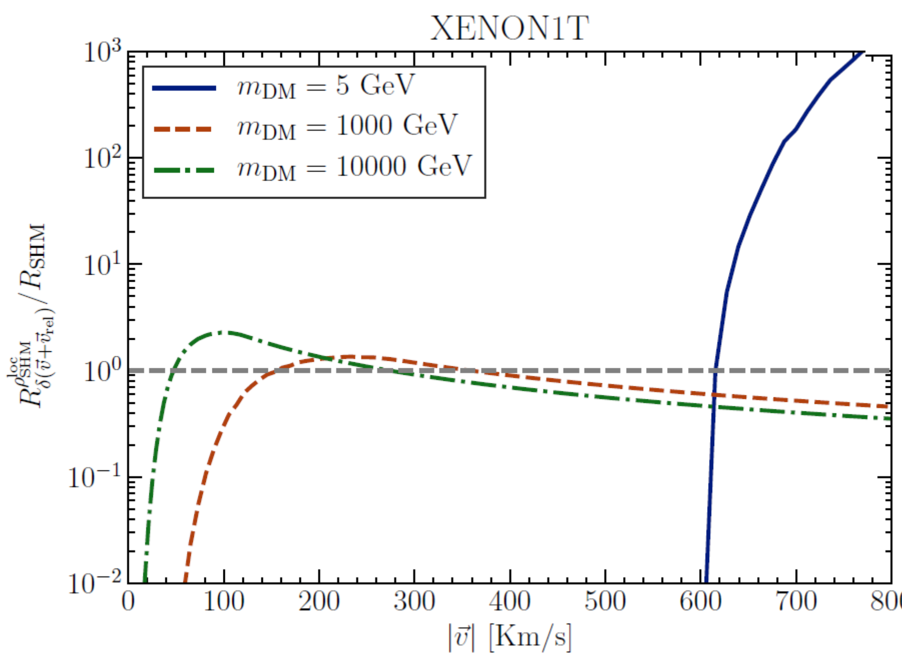

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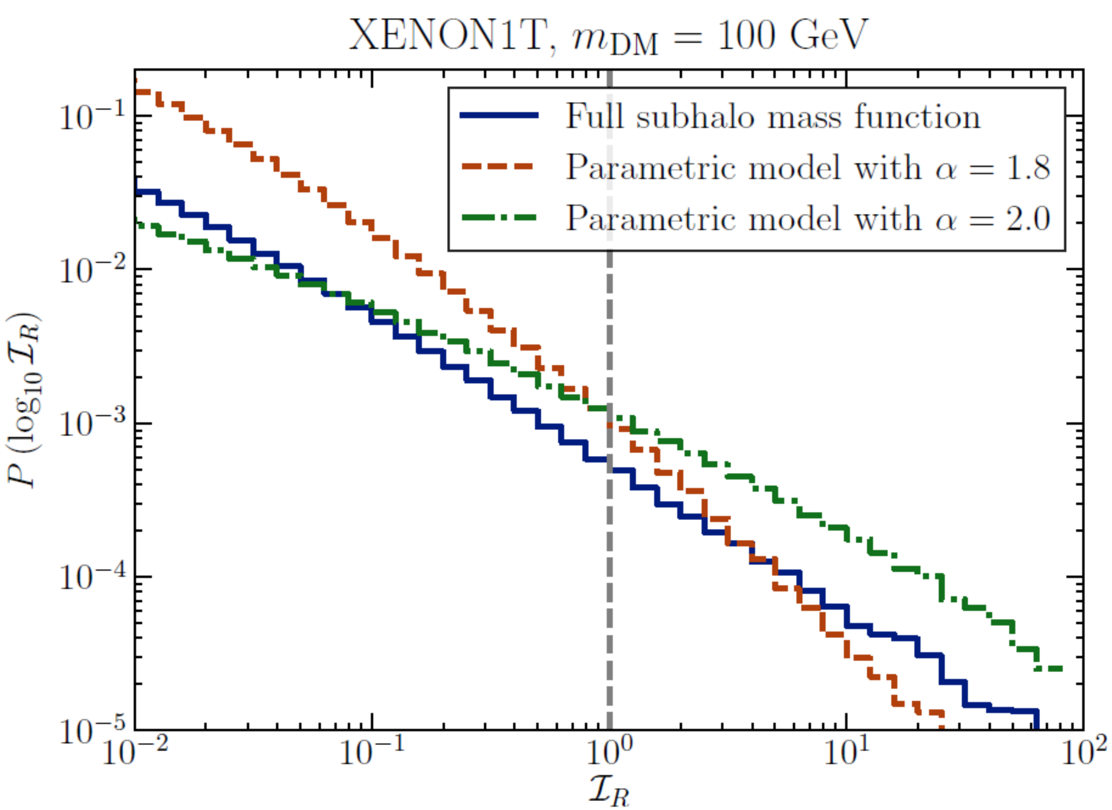
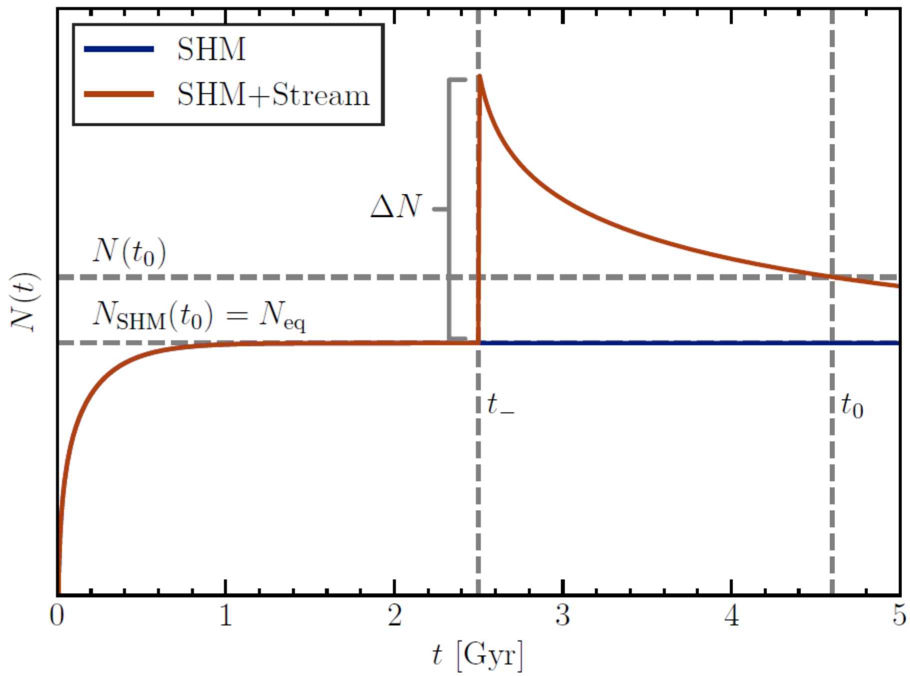


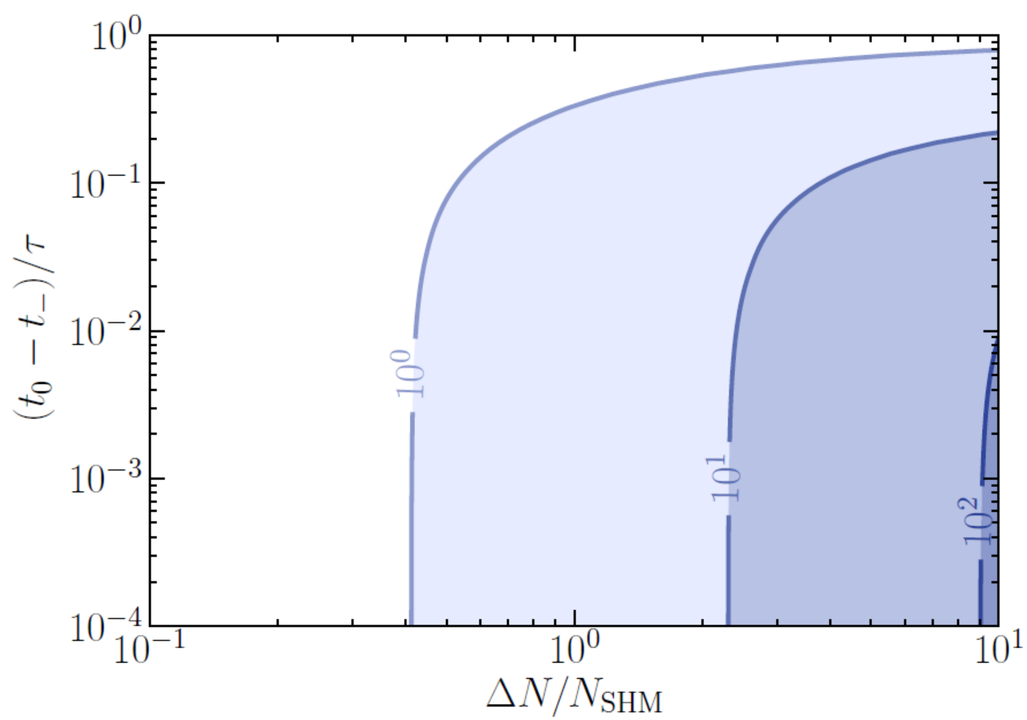
# Impact of sub-halos in the neutrino flux from the Sun




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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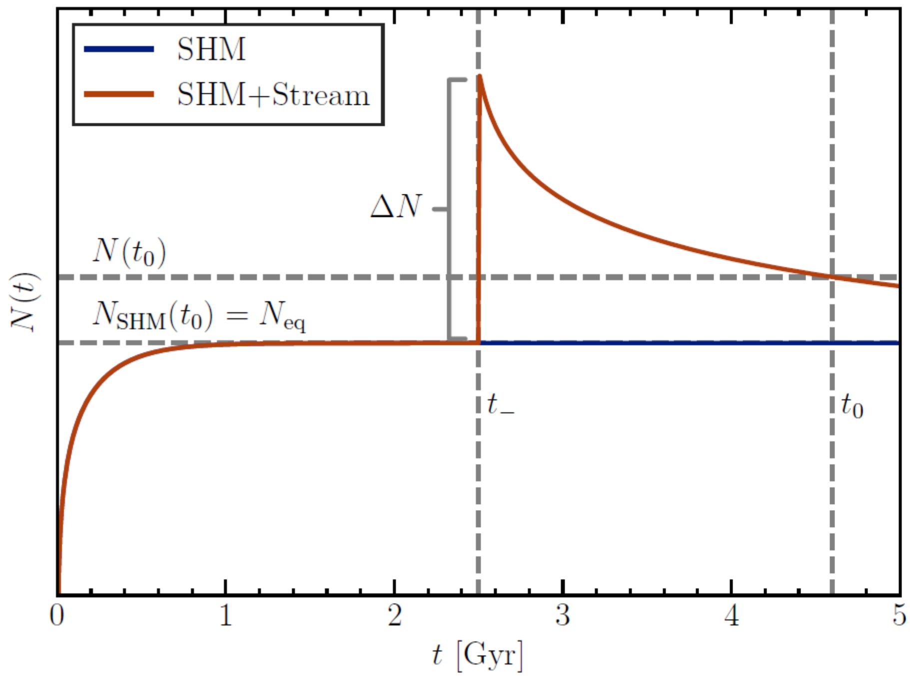


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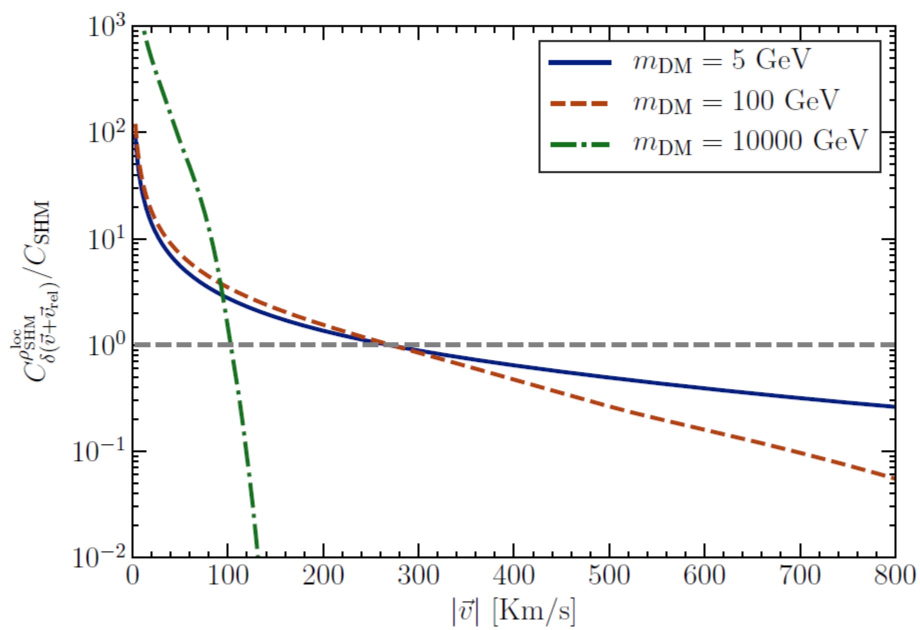

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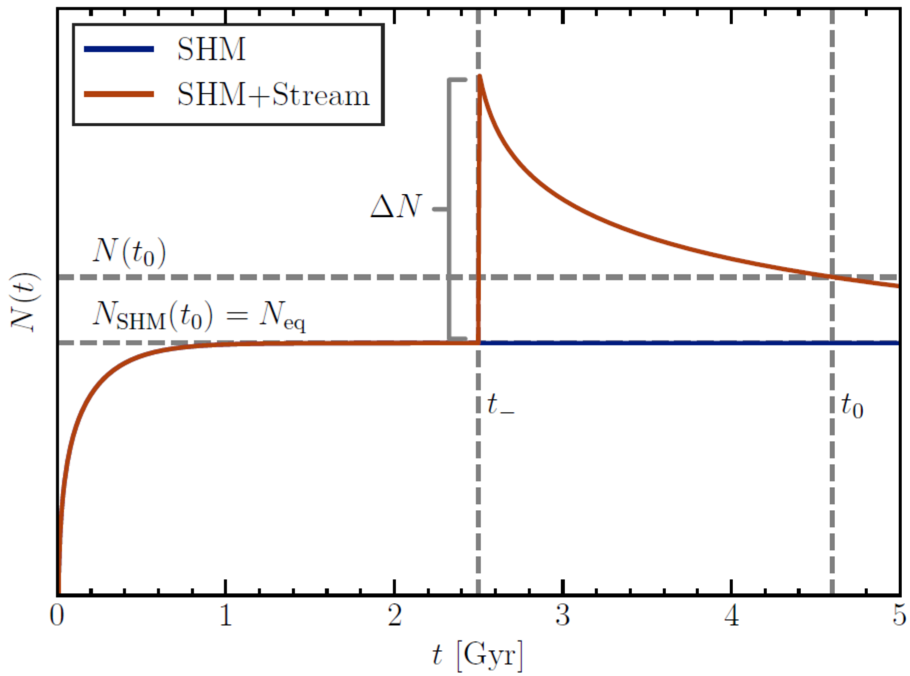


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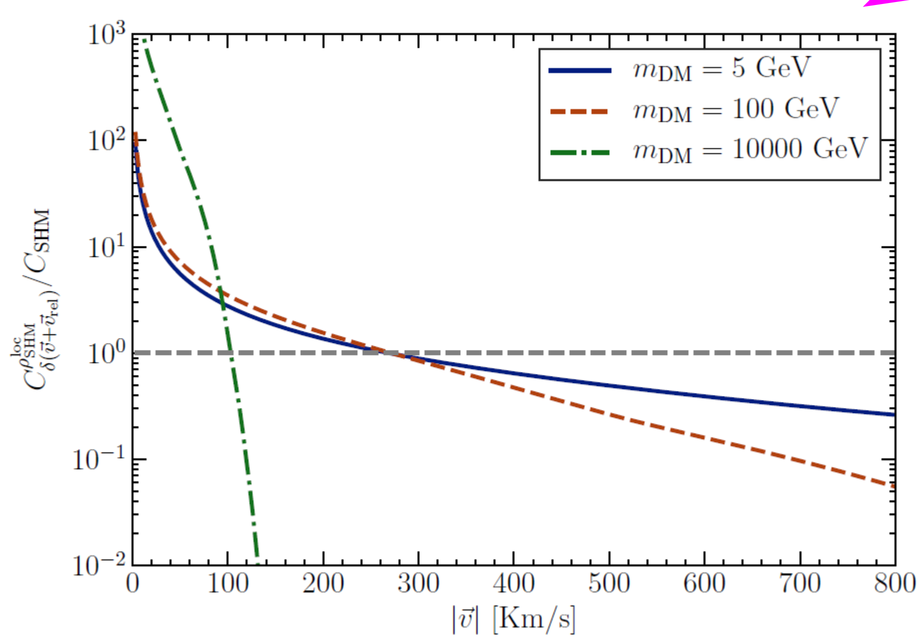
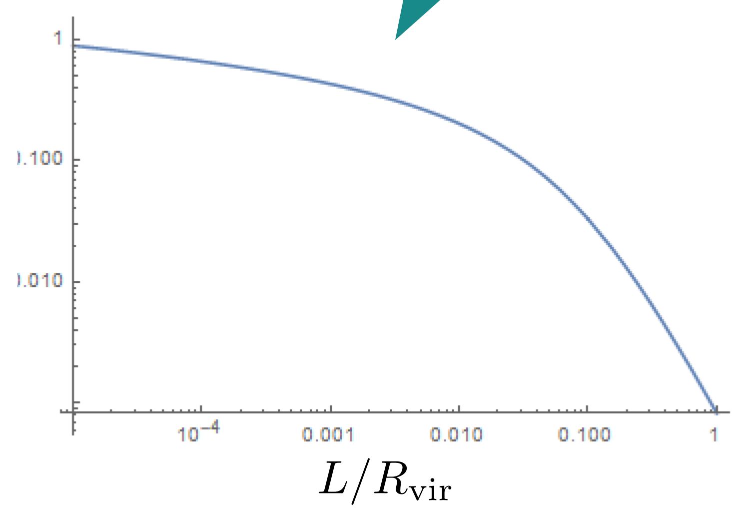
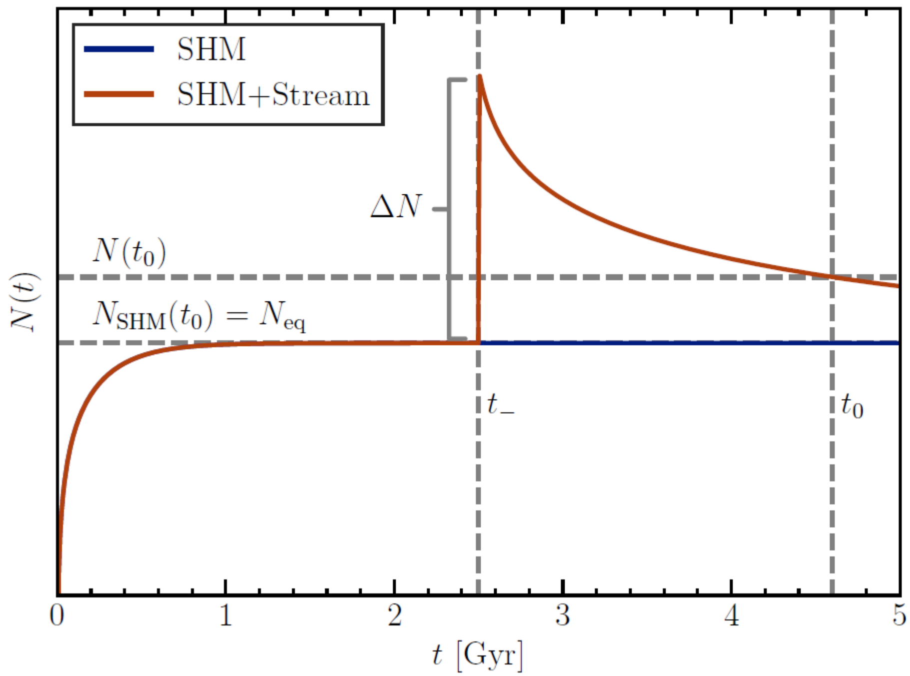


# Impact of sub-halos in the neutrino flux from the Sun

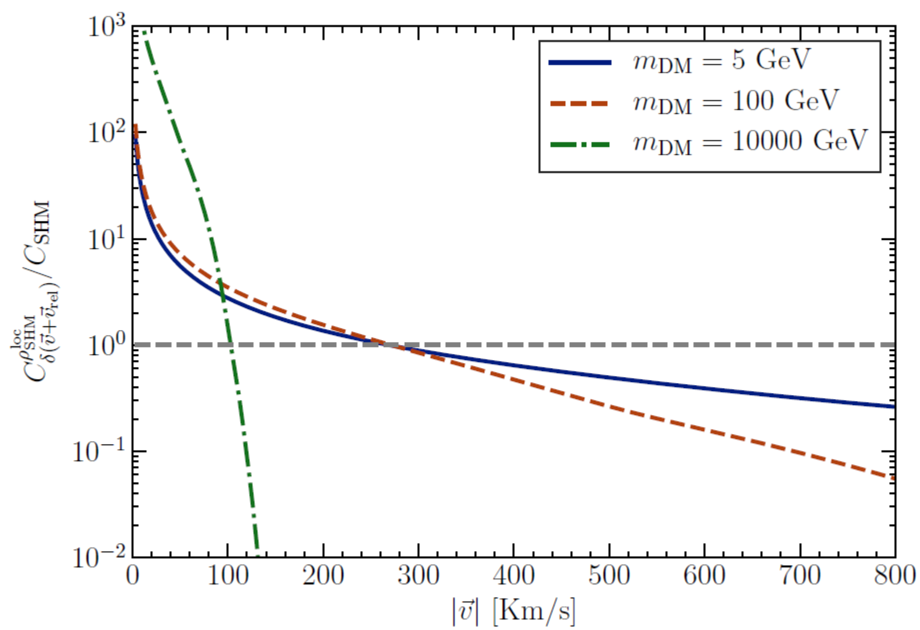


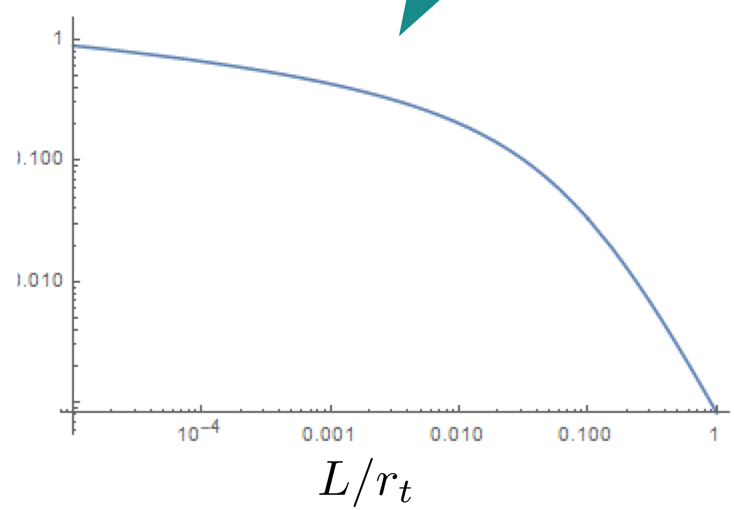

The increment in the number of DM particles captured depends on:

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

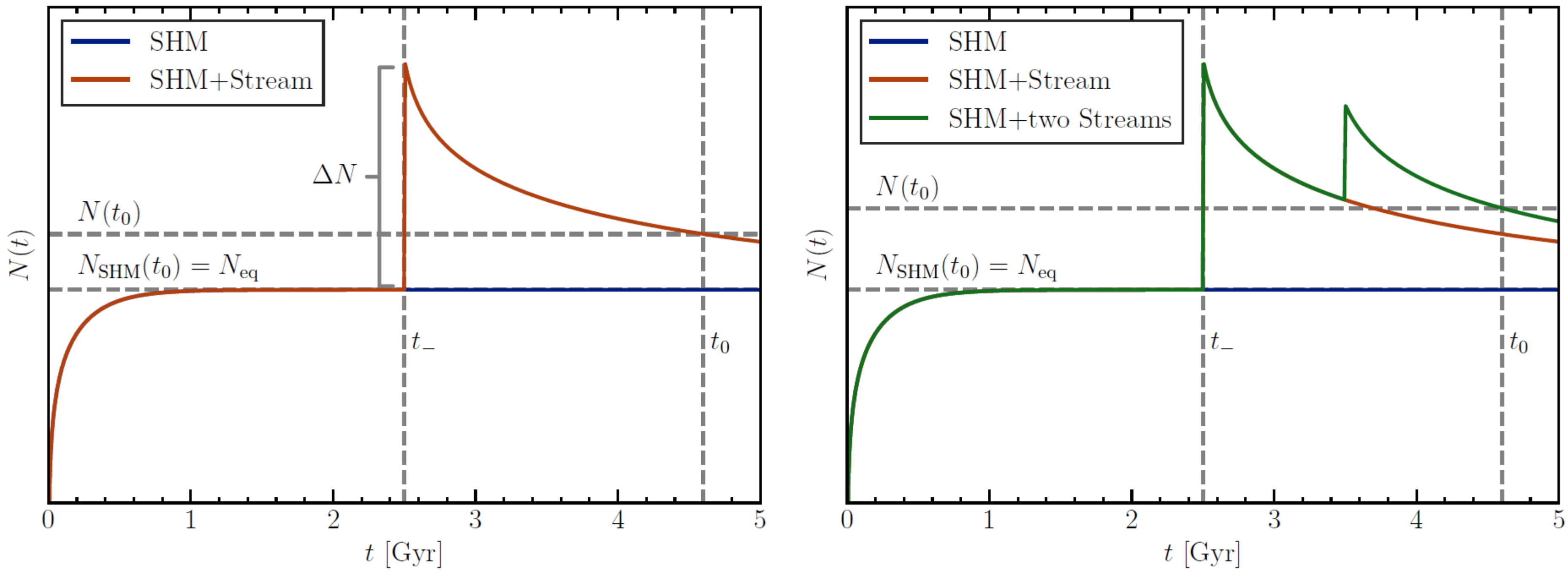
$$\Delta t = 2\sqrt{r_t^2 - L^2}/v_{\rm rel}$$

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

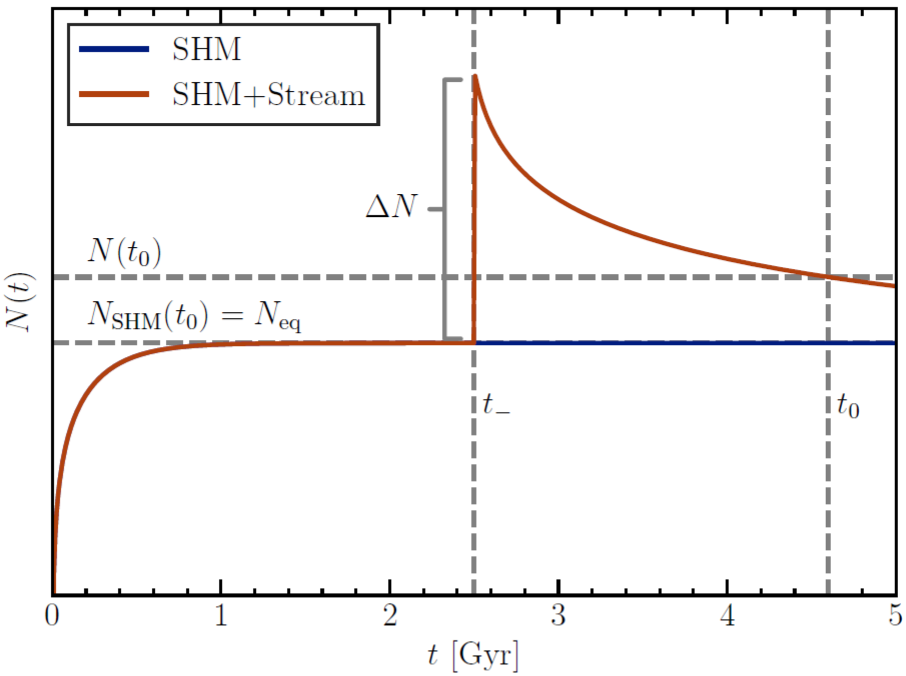


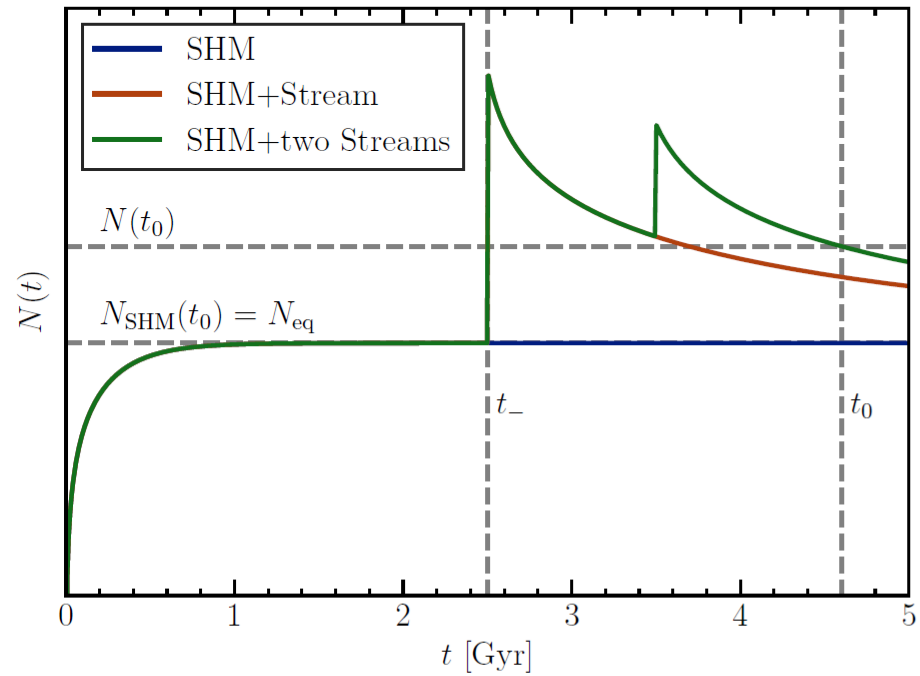



# Impact of sub-halos in the neutrino flux from the Sun

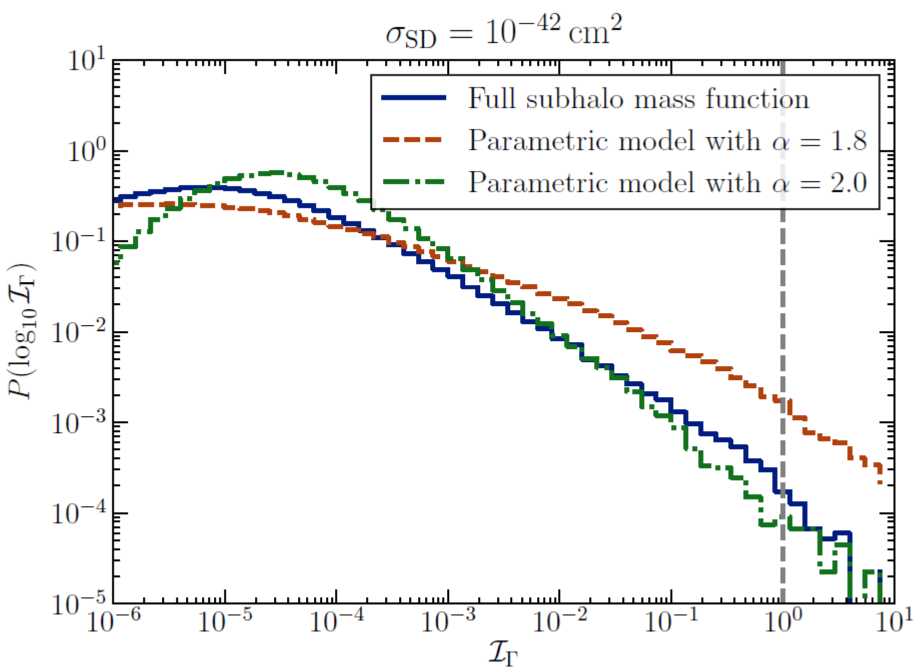


# Impact of sub-halos in the neutrino flux from the Sun




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



# 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.