Halo independent limits on dark matter properties

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Technische Universität München

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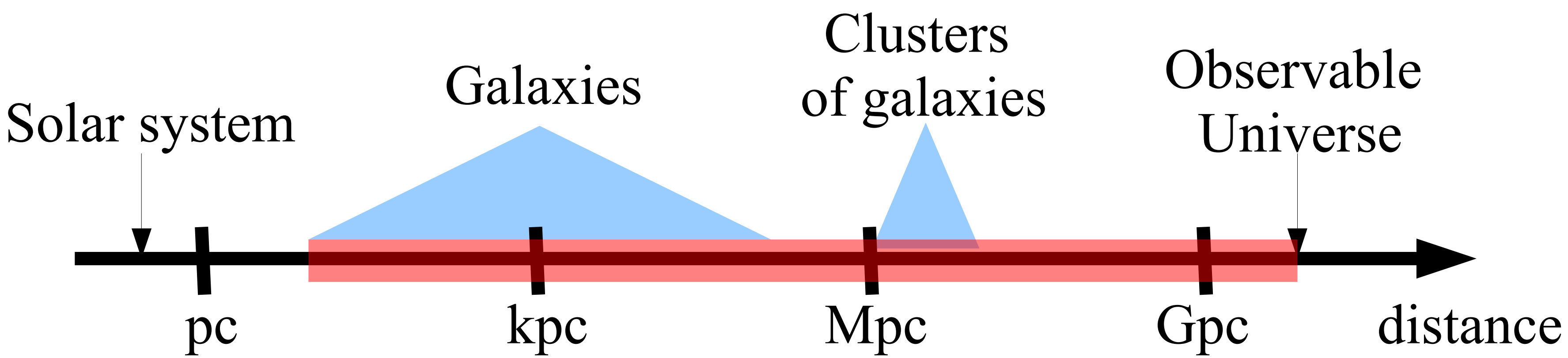
There is mounting evidence for the existence of dark matter in a wide range of distance scales



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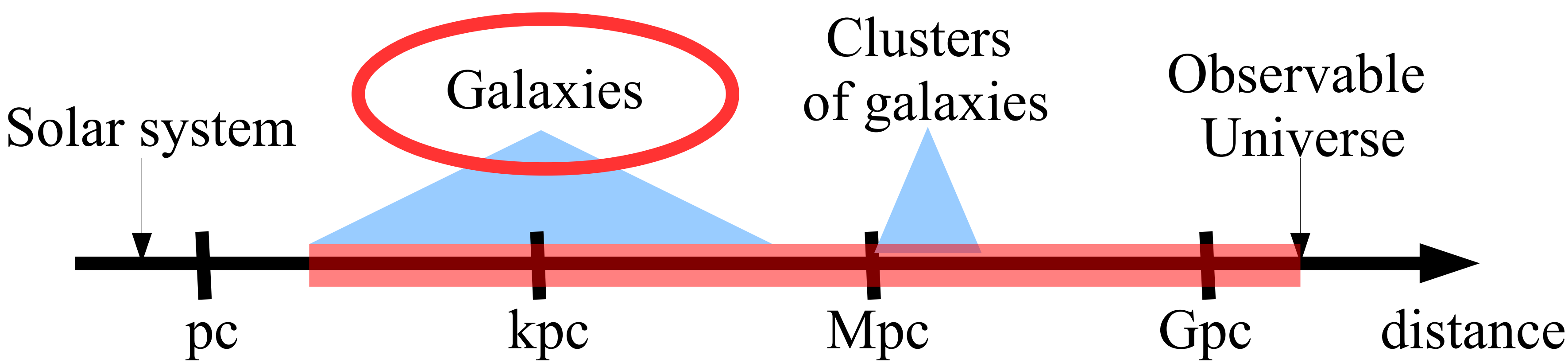

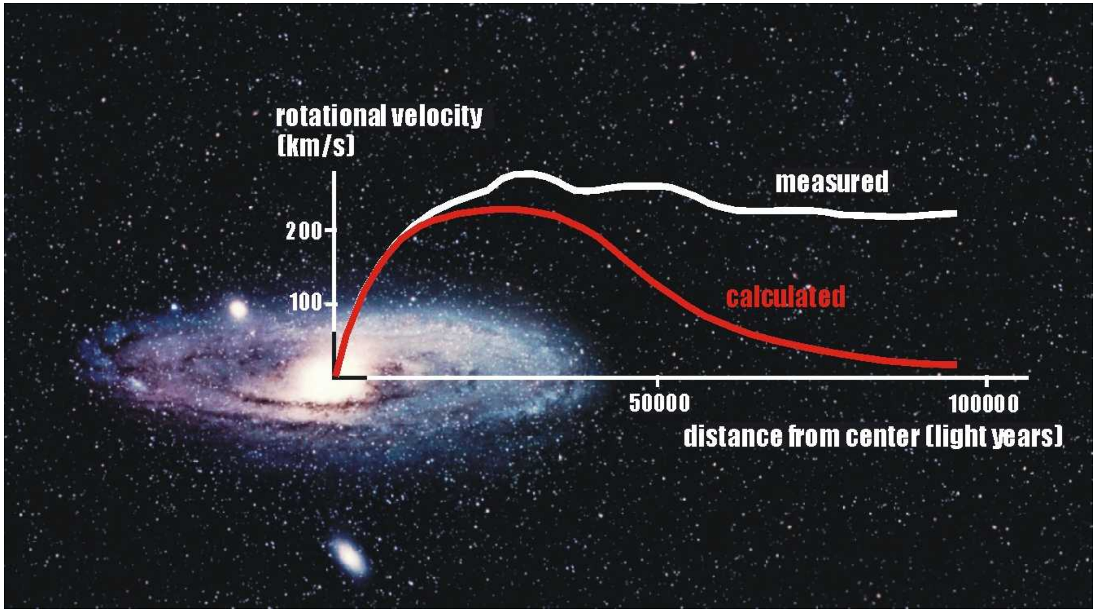

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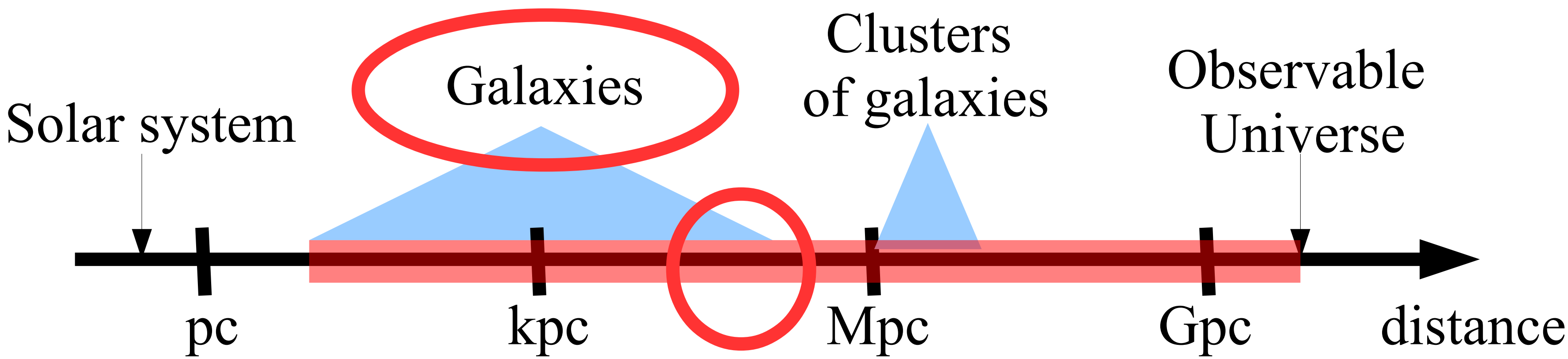

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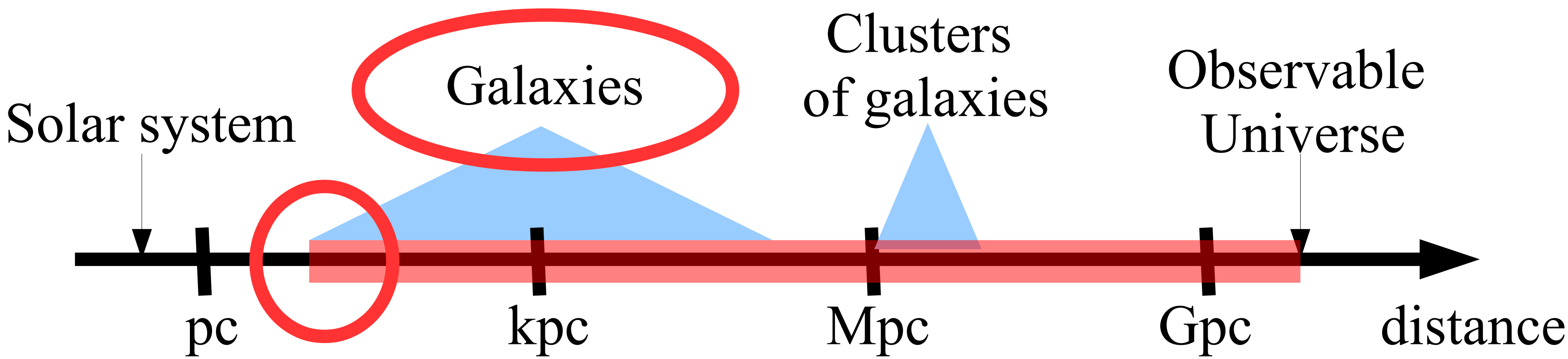

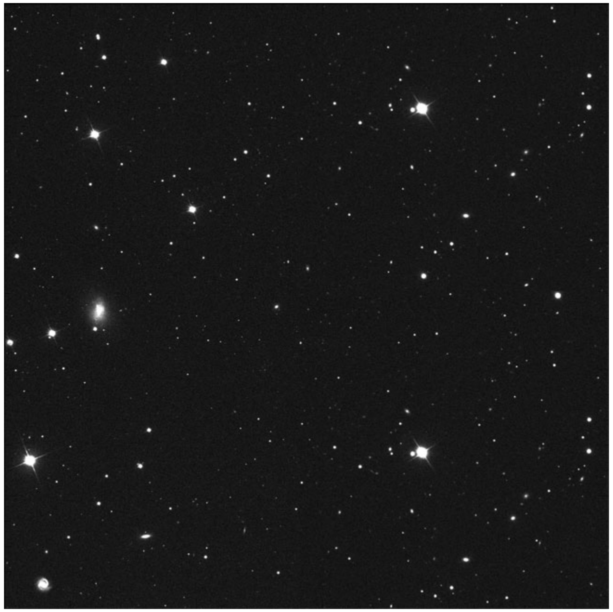

Segue 1

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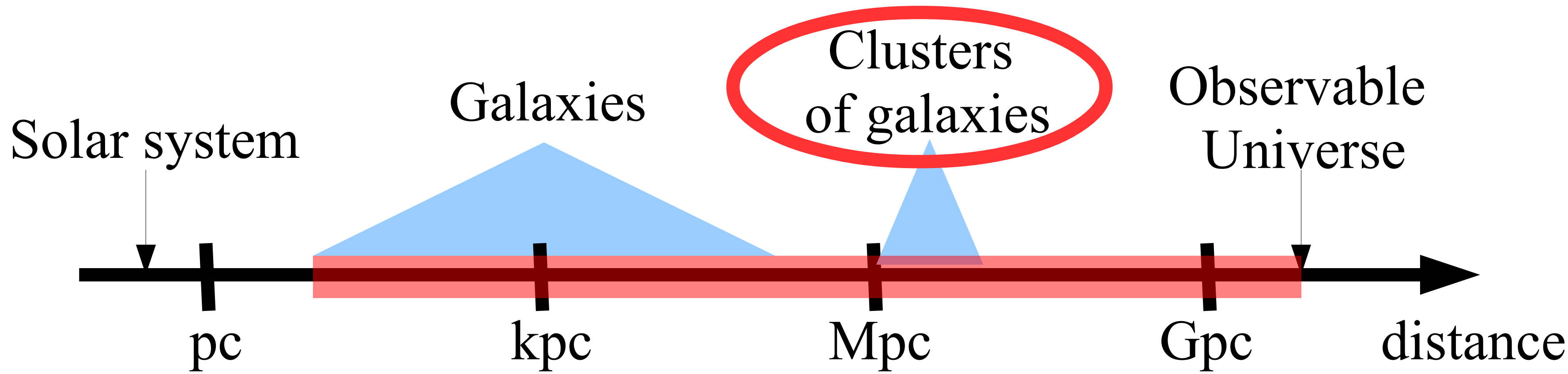

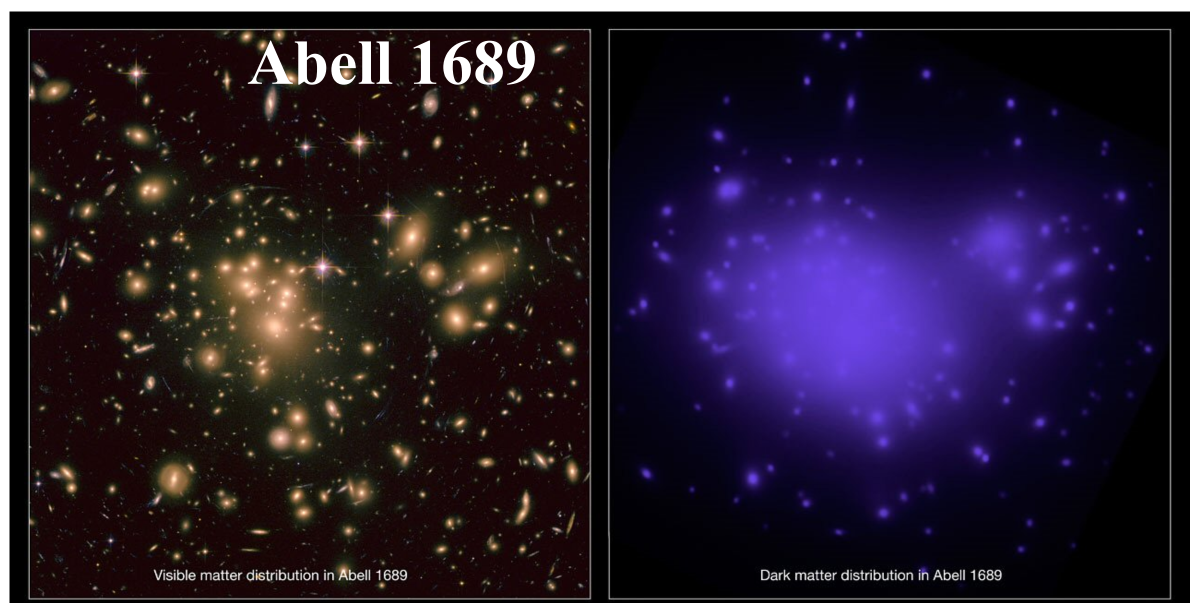

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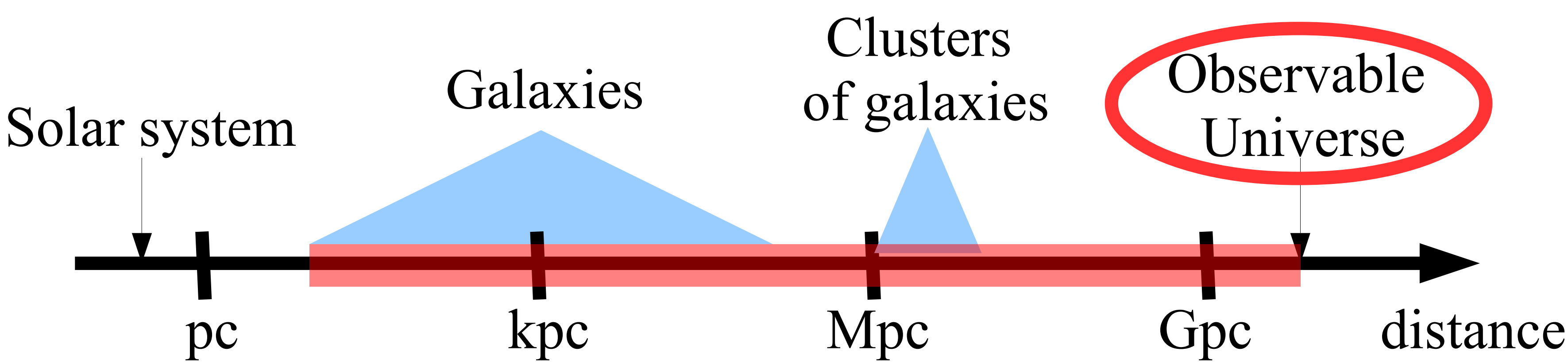

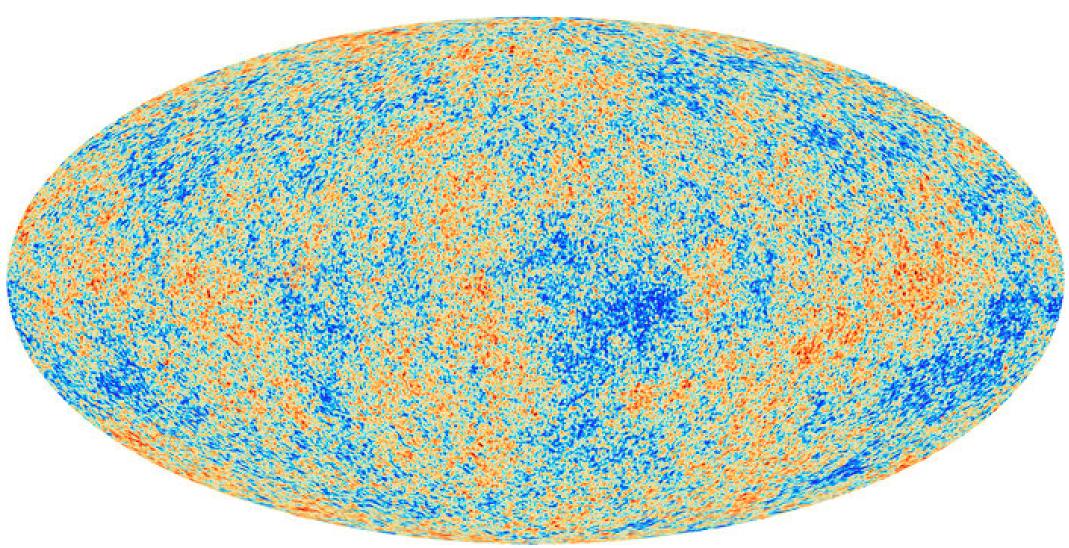

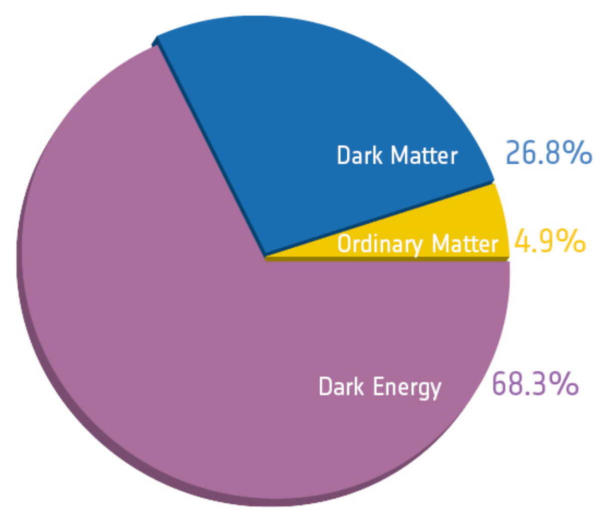

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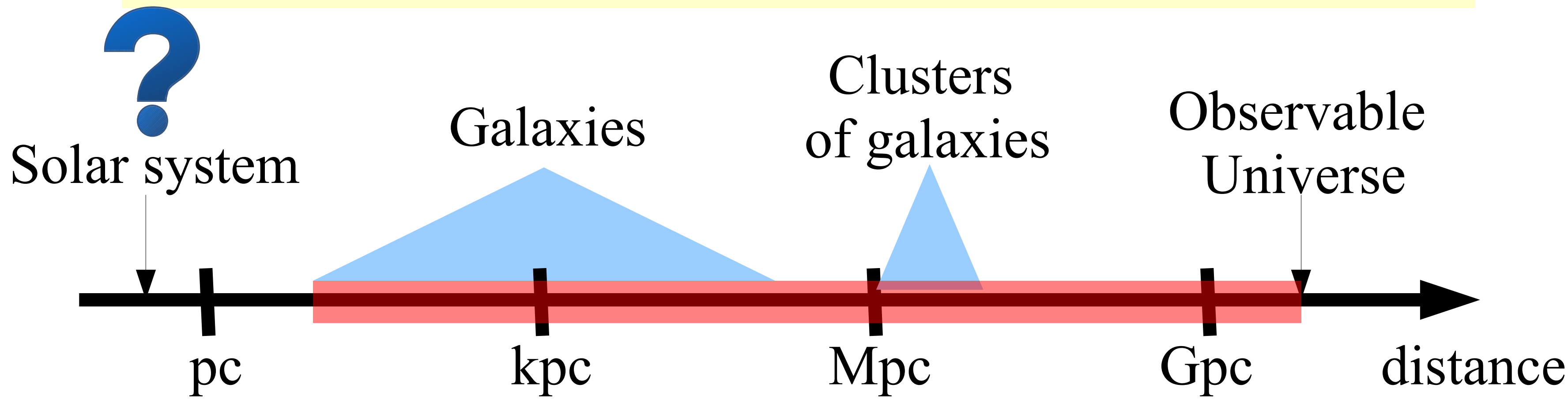
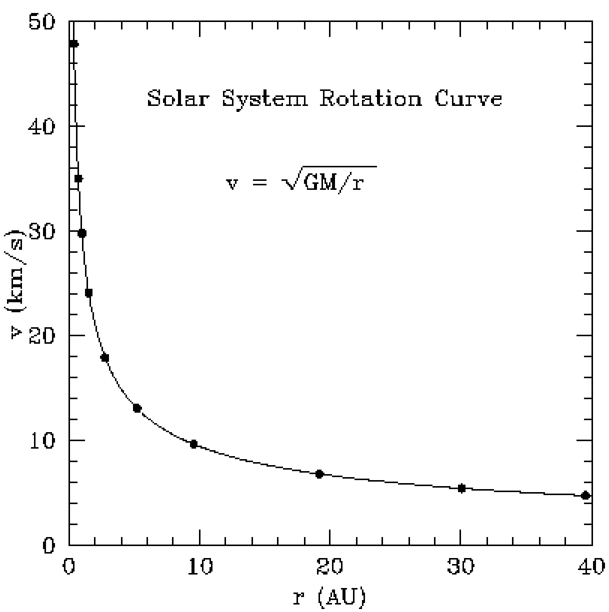




Three different methods

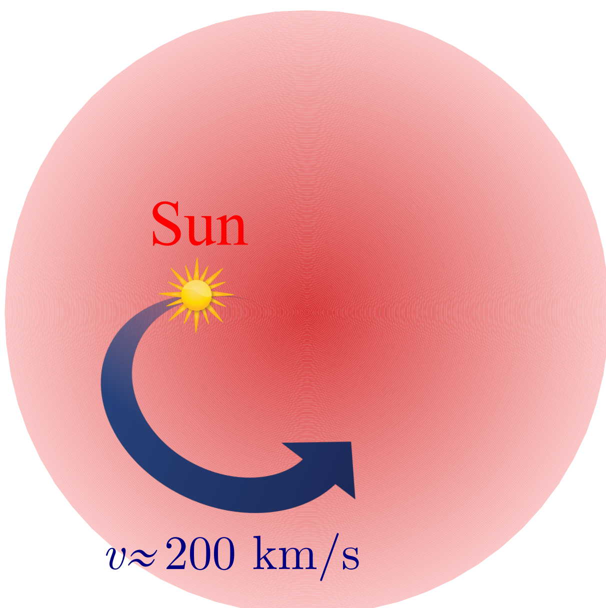
have been proposed

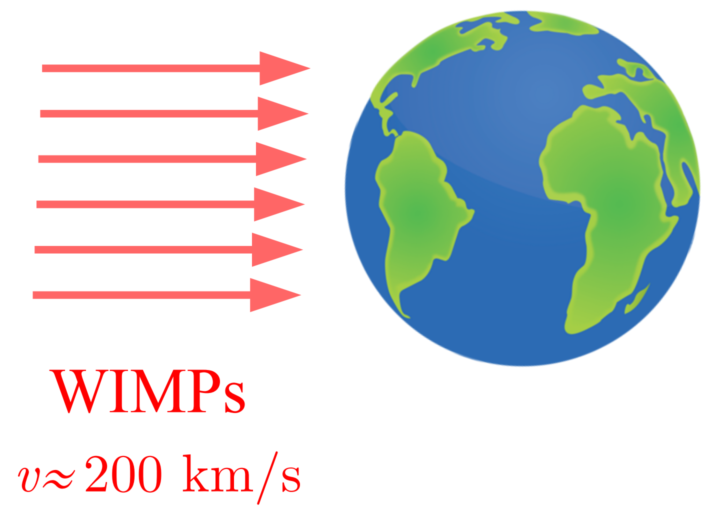
to probe WIMP dark matter

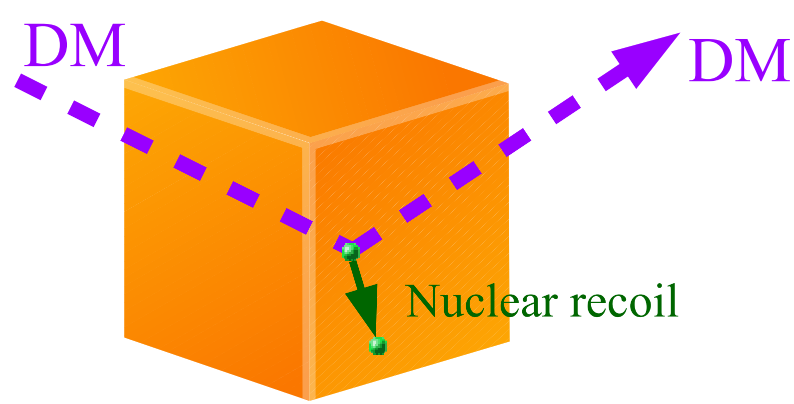
inside the Solar System

Direct detection

The Sun (and the Earth) is moving through a “gas” of dark matter particles, with density at the Solar System ρ_{loc} and velocity $f(\vec{v})$ with respect to the solar frame.







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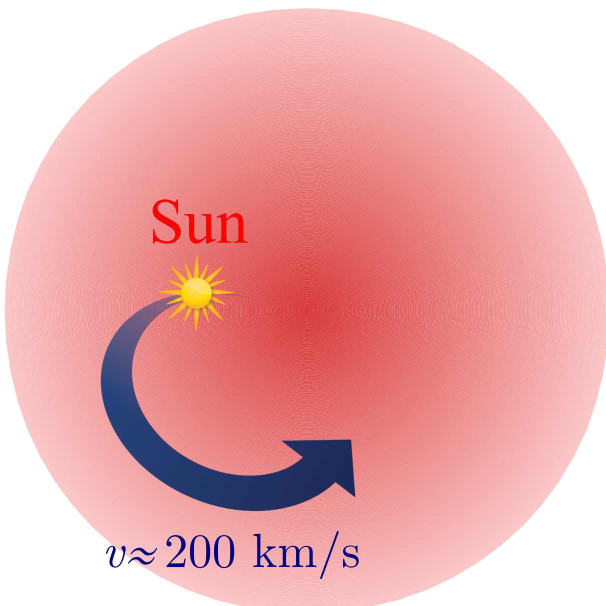
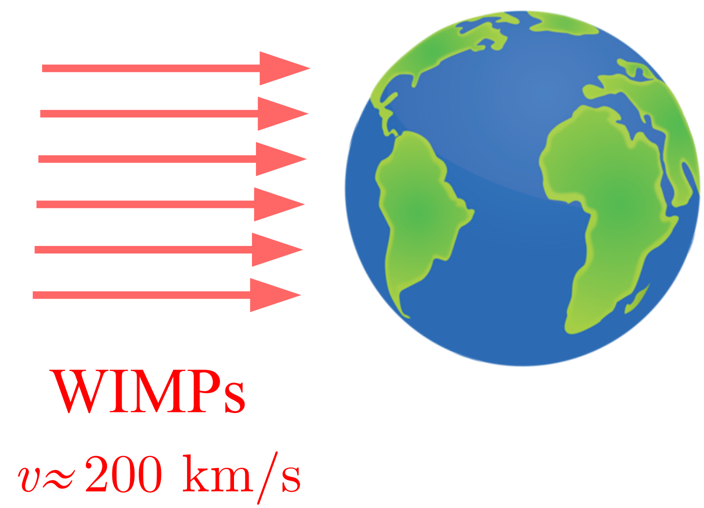
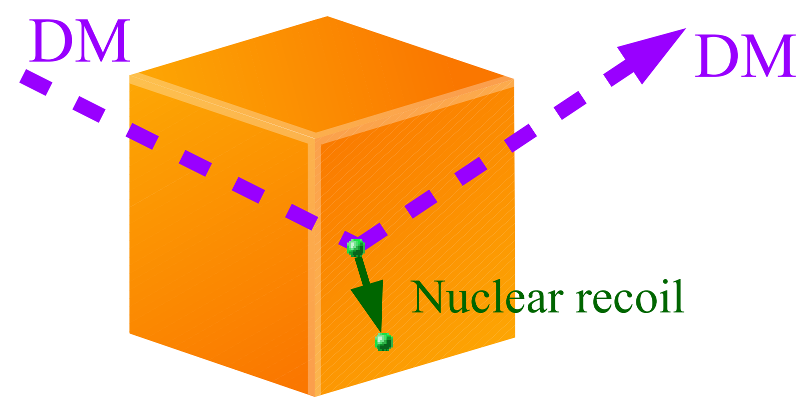


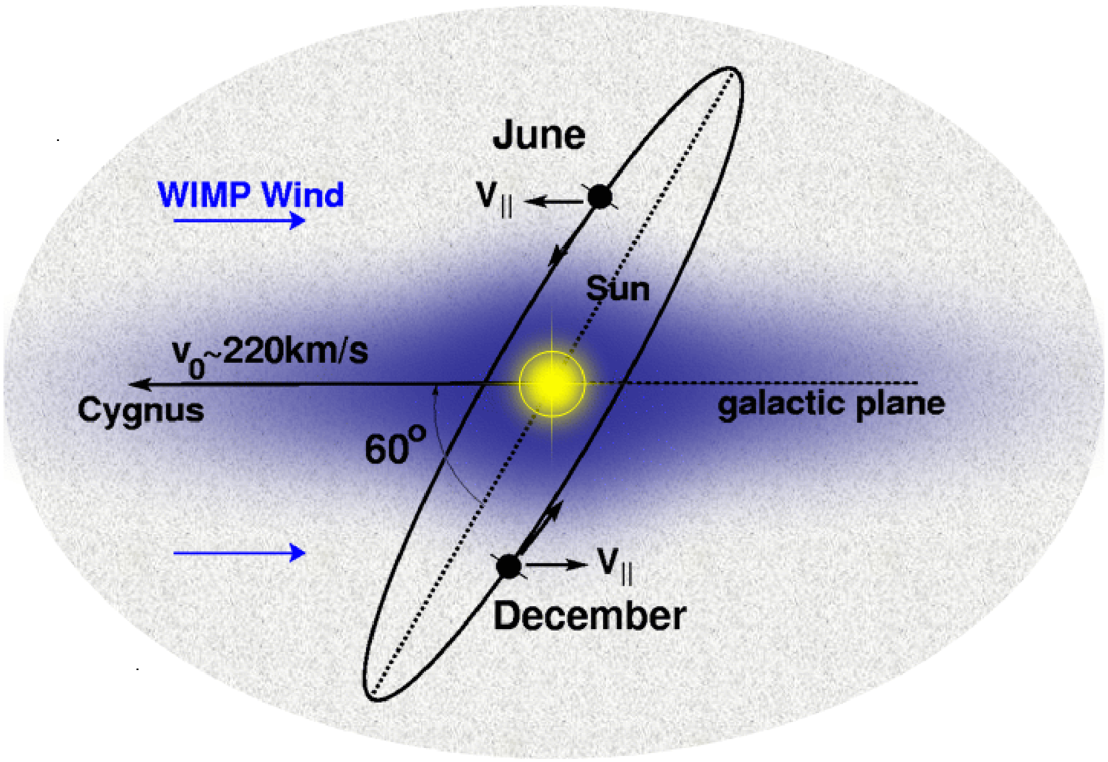


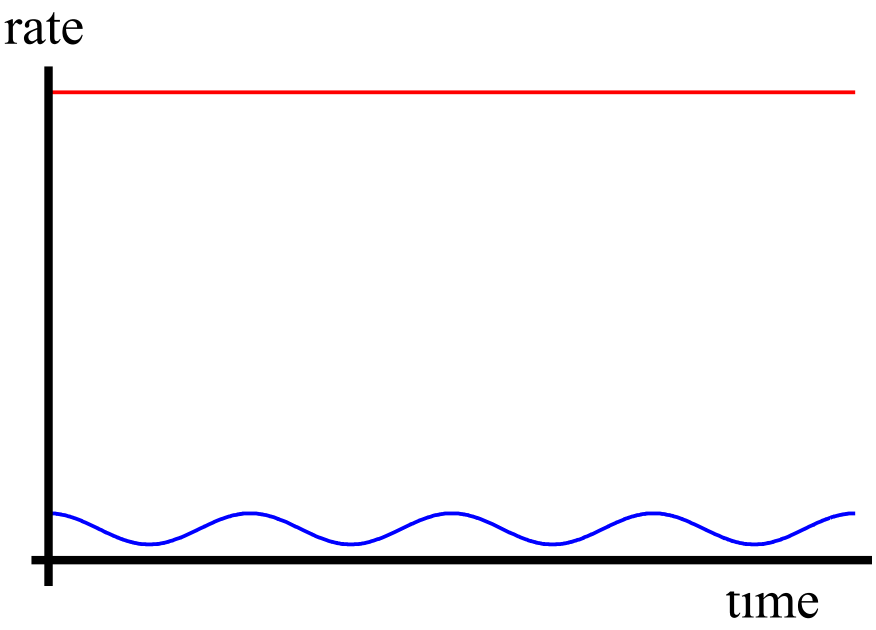


Upper limits on the number of events:

- PandaX, $\mathcal{N} < 6.7$
- PICO-60, $\mathcal{N} < 2.3$
- SuperCDMS, $\mathcal{N} < 16.6$

Annual modulation





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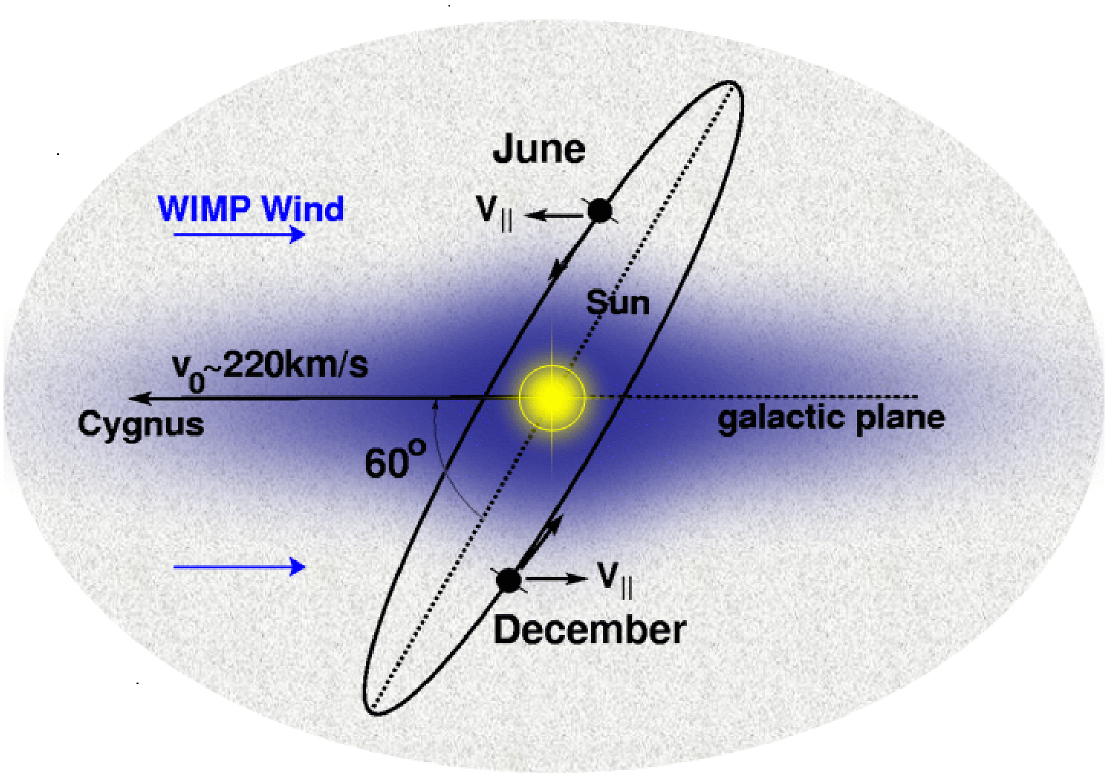

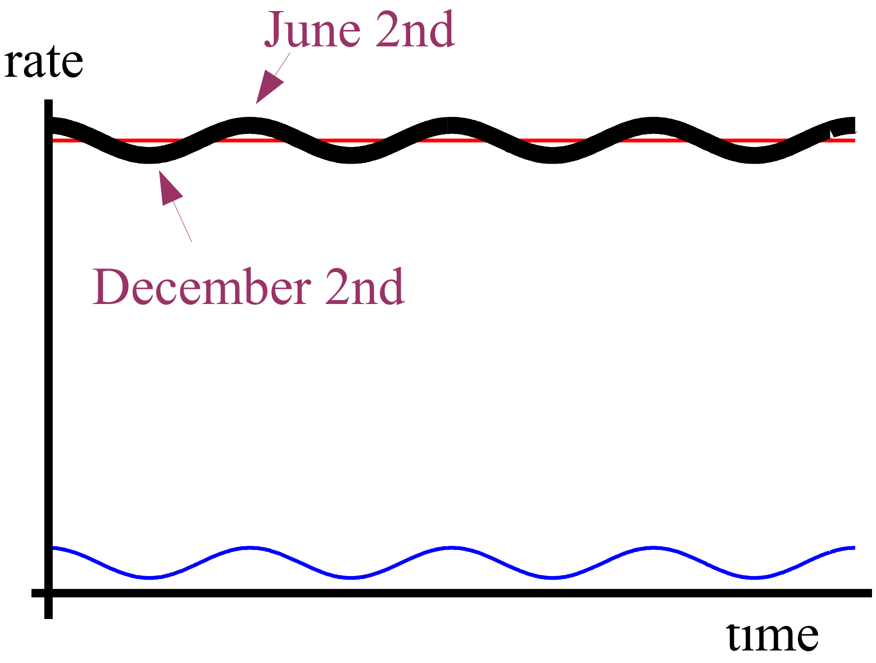

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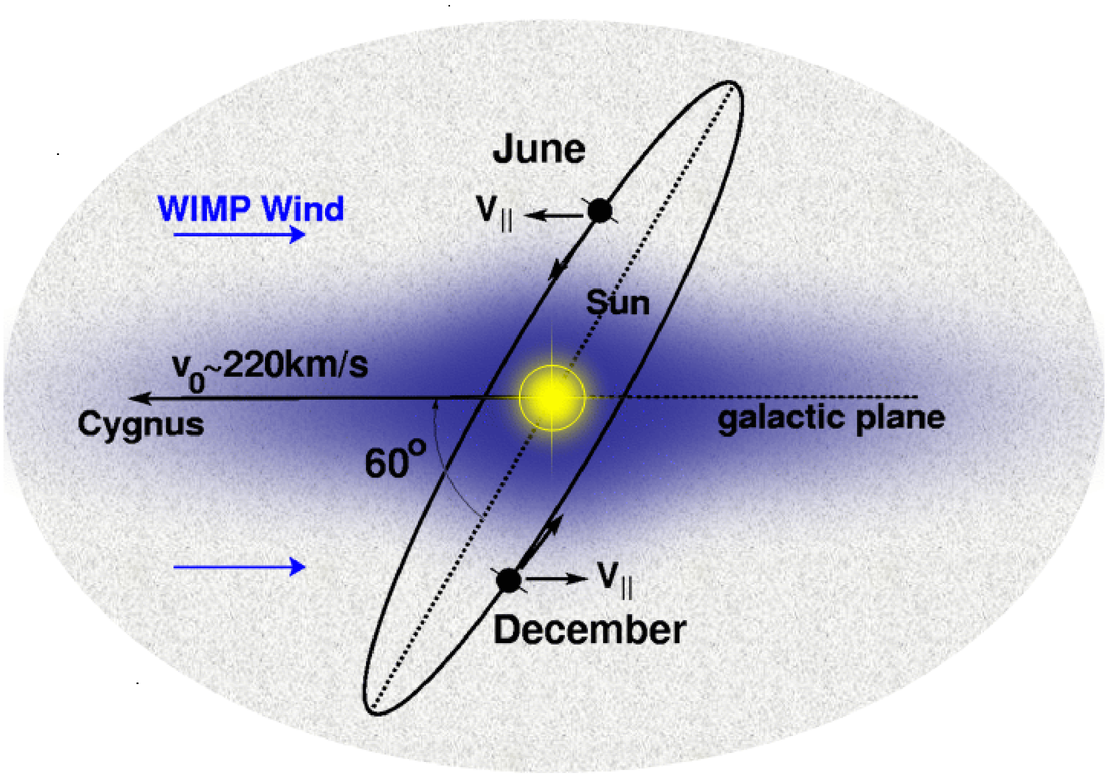
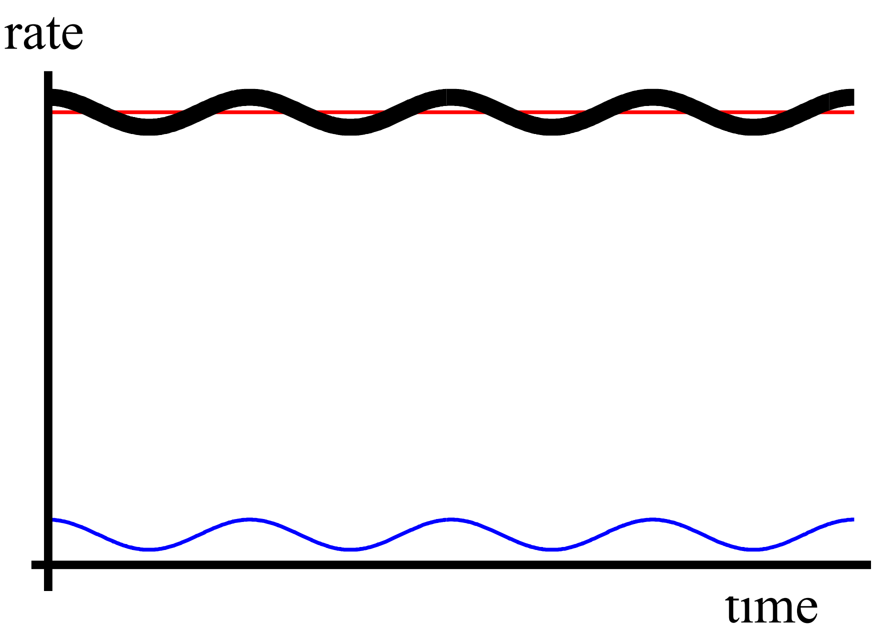
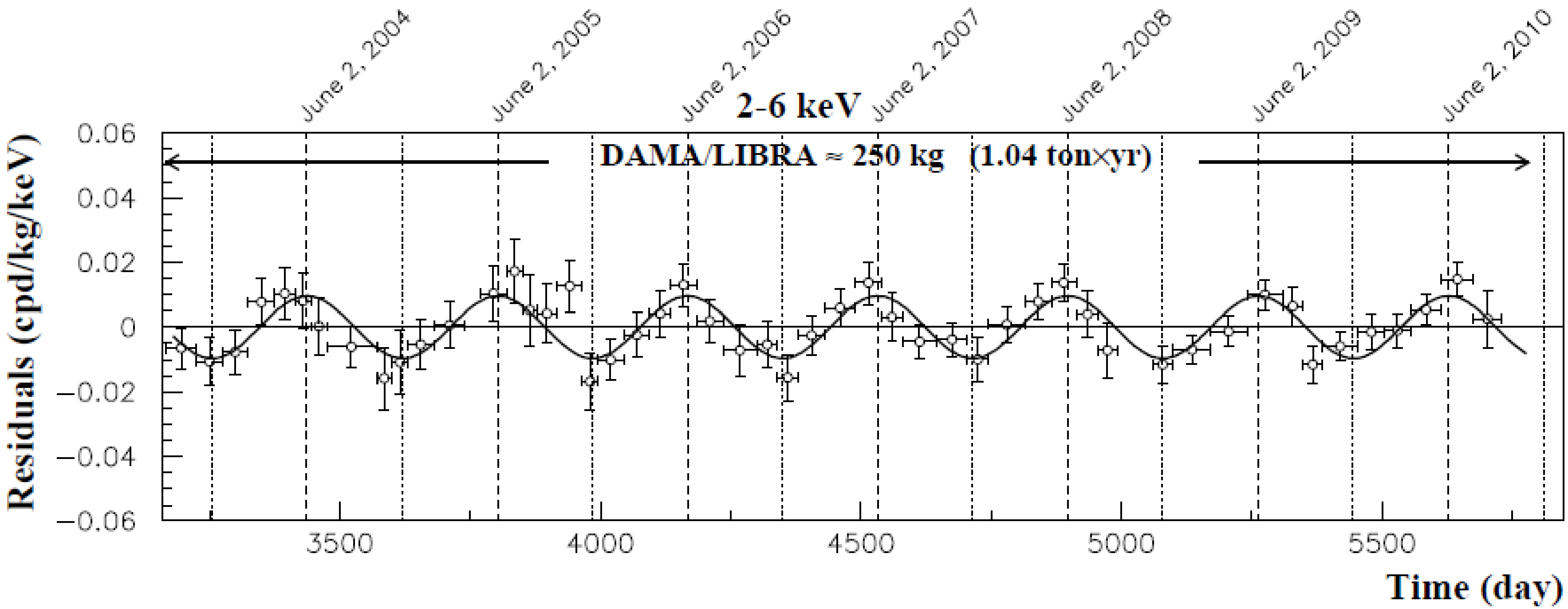




Modulation signal

$$S_{[E_-,E_+]} = \frac{1}{2}\frac{1}{E_+ - E_-}\left(R_{[E_-,E_+]}\Big|_{\text{June 1st}} - R_{[E_-,E_+]}\Big|_{\text{Dec 1st}}\right)$$

Annual modulation: the DAMA/LIBRA experiment



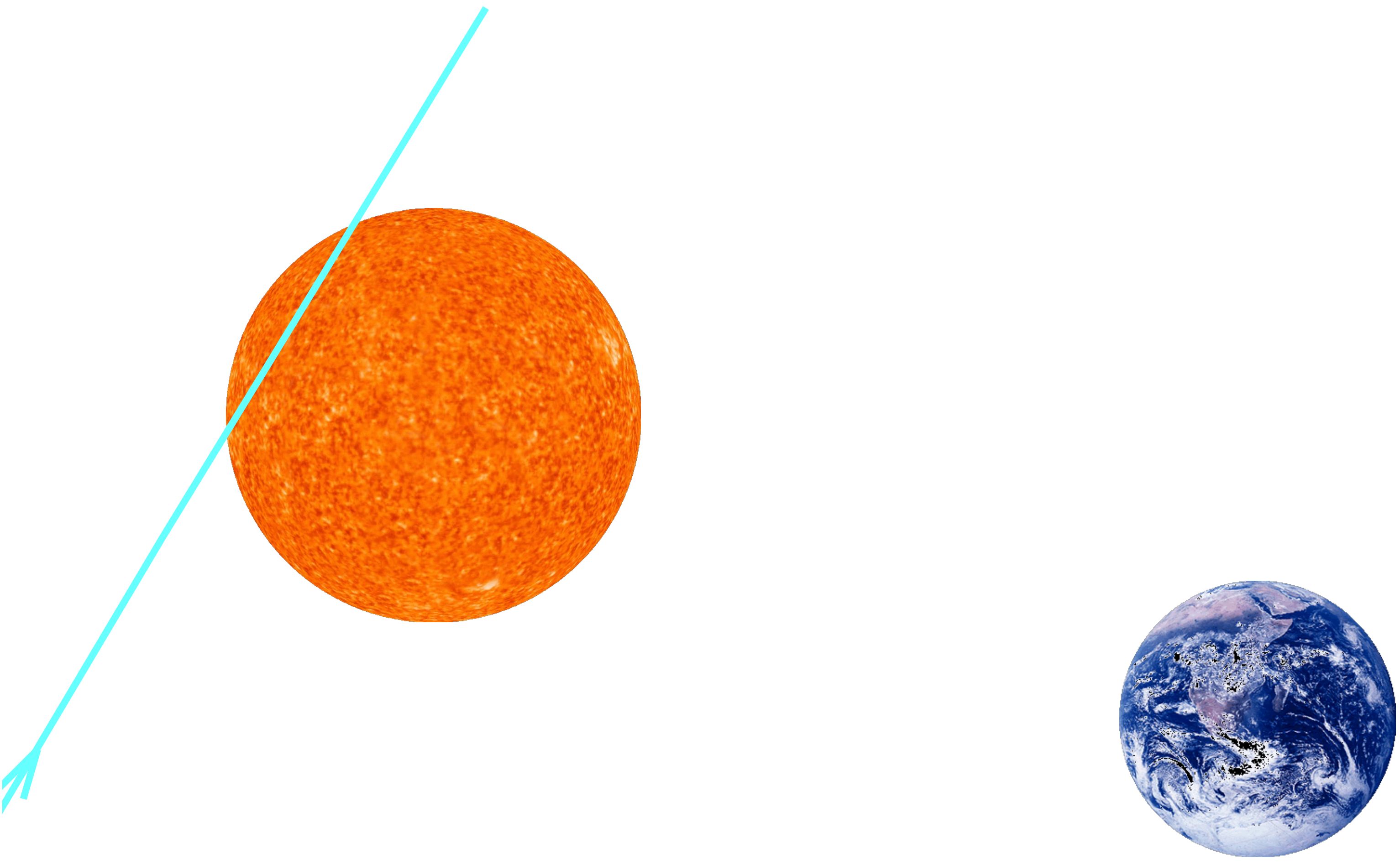
Modulation observed over 14 annual cycles, with a combined significance of 9.3σ.

$$S^{(\mathrm{DAMA})}_{[2.0,2.5]} = (1.75 \pm 0.37) \times 10^{-2}\ \mathrm{day}^{-1}\,\mathrm{kg}^{-1}\,\mathrm{keV}^{-1}$$

$$S^{(\mathrm{DAMA})}_{[2.5,3.0]} = (2.51 \pm 0.40) \times 10^{-2}\ \mathrm{day}^{-1}\,\mathrm{kg}^{-1}\,\mathrm{keV}^{-1}$$

$$S^{(\mathrm{DAMA})}_{[3.0,3.5]} = (2.16 \pm 0.40) \times 10^{-2}\ \mathrm{day}^{-1}\,\mathrm{kg}^{-1}\,\mathrm{keV}^{-1}$$

Neutrinos from annihilations in the Sun



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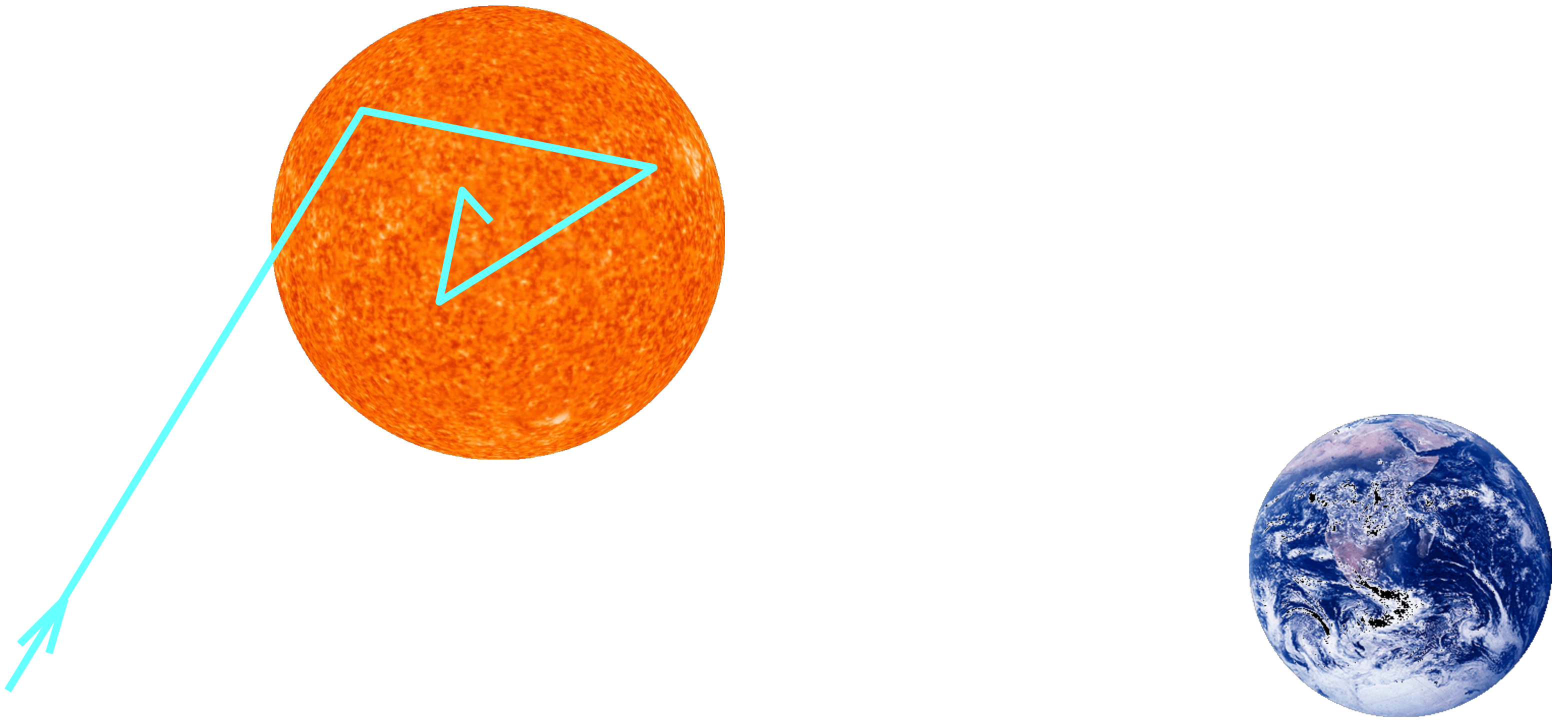

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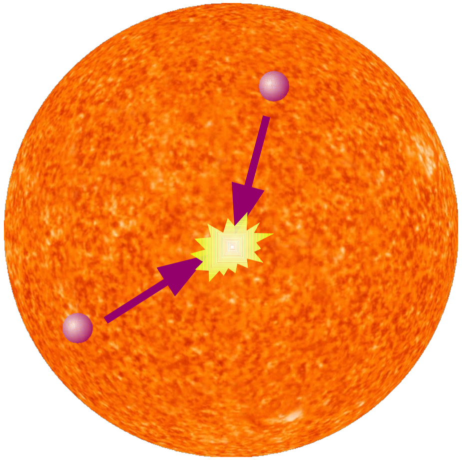

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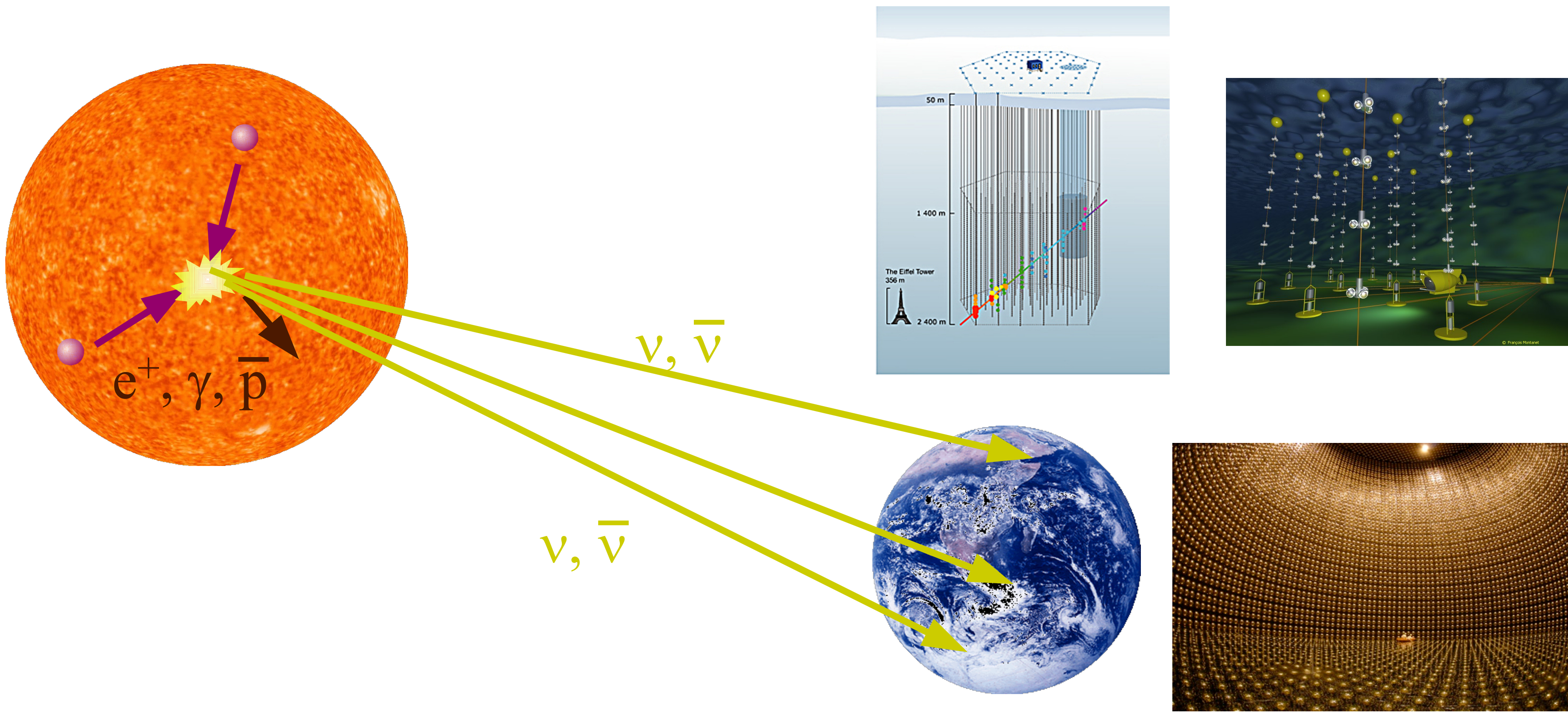
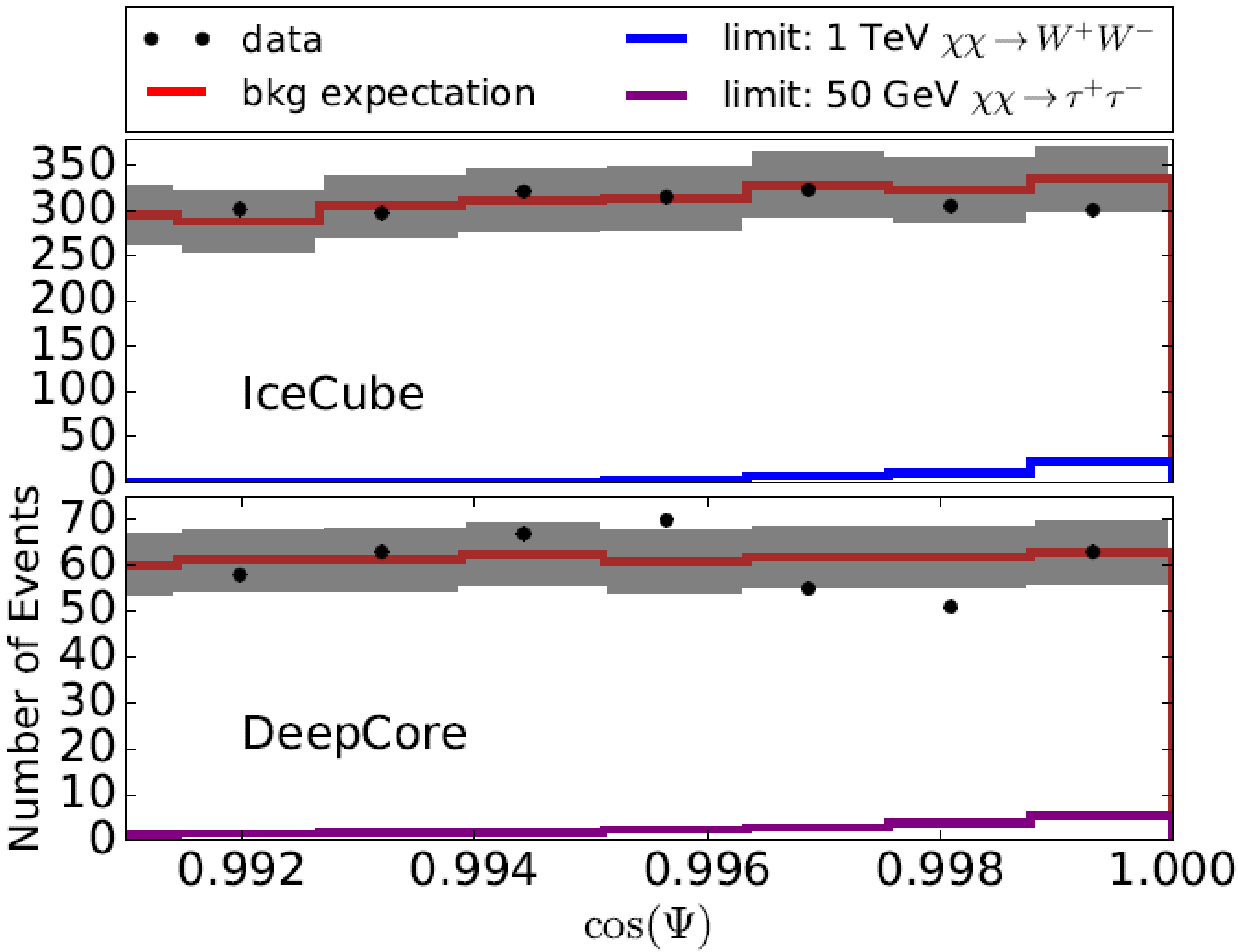


Neutrinos from annihilations in the Sun

Observations consistent with the background-only hypothesis



IceCube collaboration
ArXiv:1612.05949

Theoretical interpretation of the experimental results

- 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, $m_{\rm DM}$ = few MeV – 100 TeV

- Differential cross section?

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

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

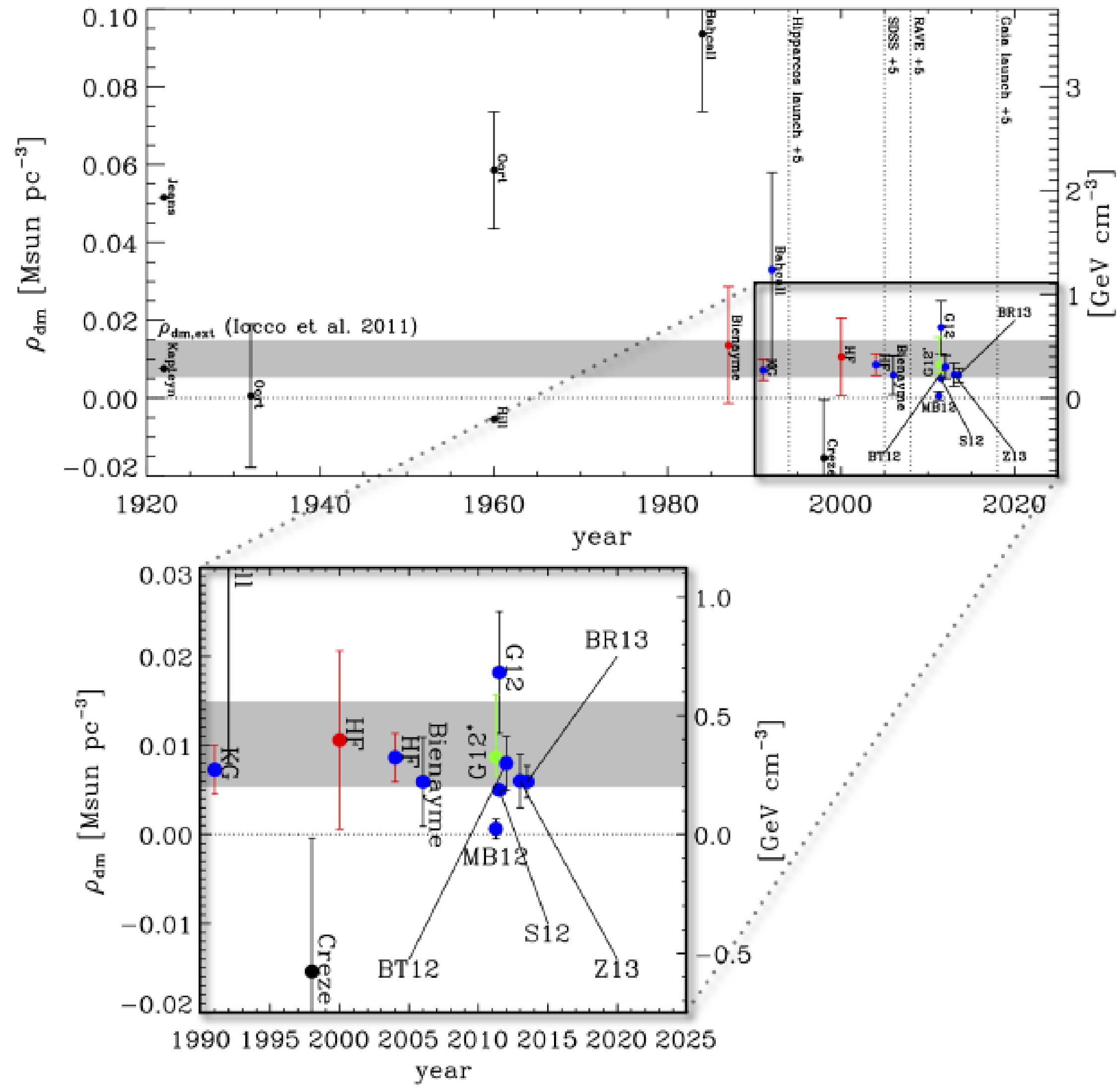
- Local dark matter density?

  - "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.

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

Theoretical interpretation of the experimental results

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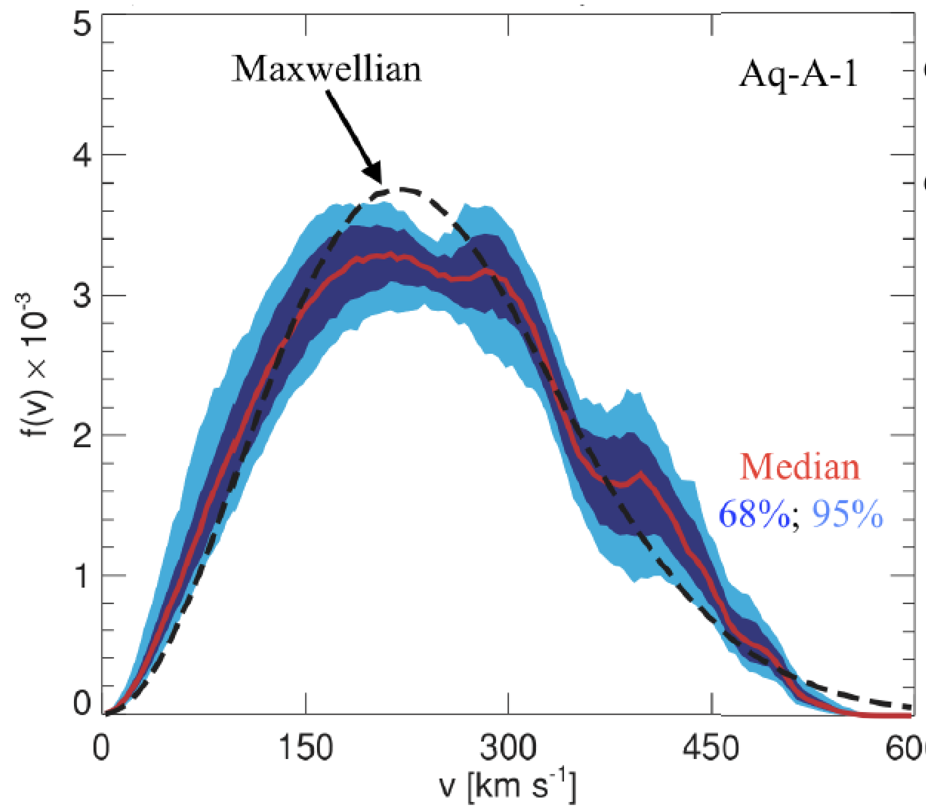
  - Dark matter-only simulations. Show deviations from Maxwell-Boltzmann



Vogelsberger et al. 2009

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.
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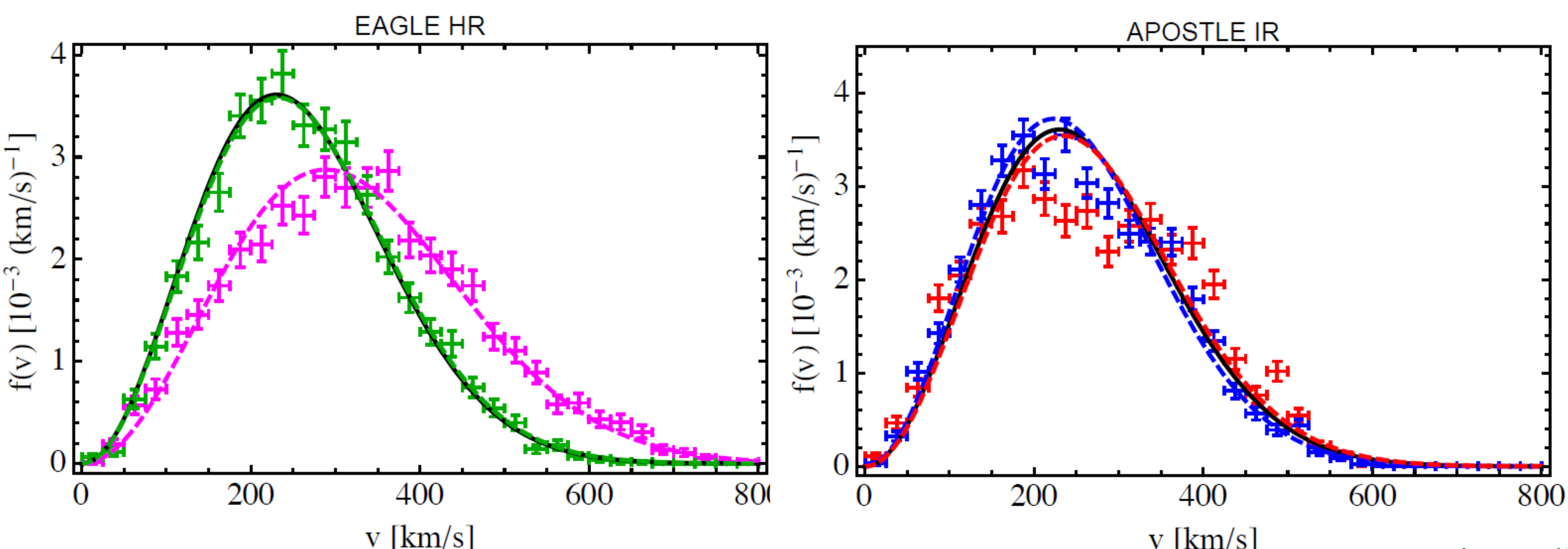
  - Hydrodynamical simulations (DM+baryons). Inconclusive at the moment.

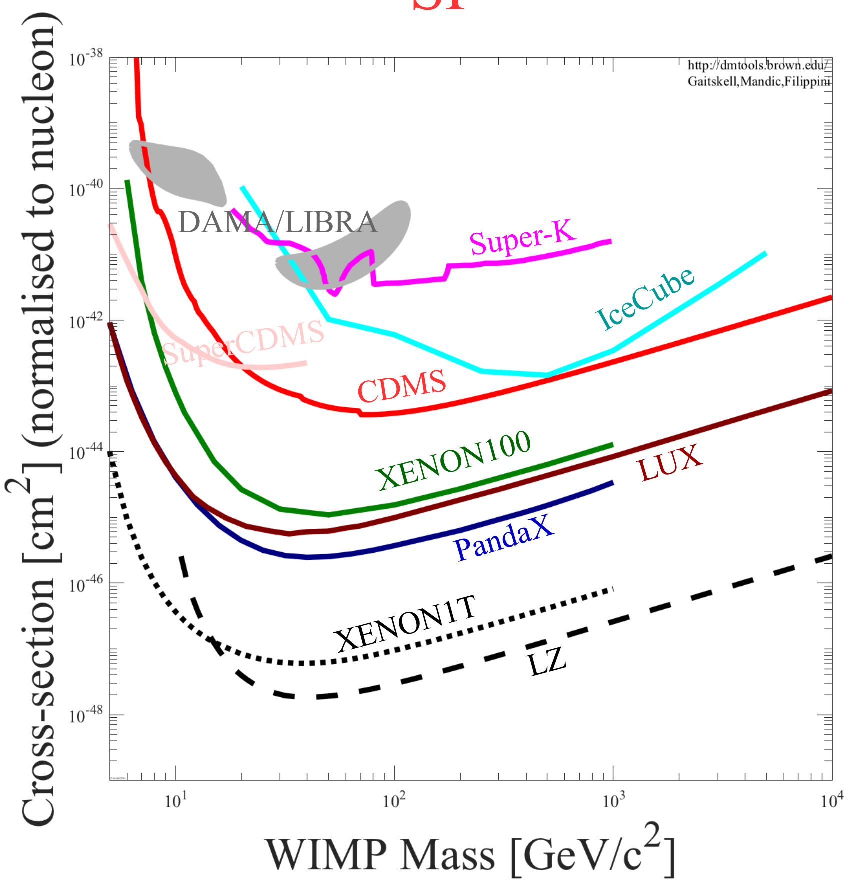


Bozorgnia et al'16

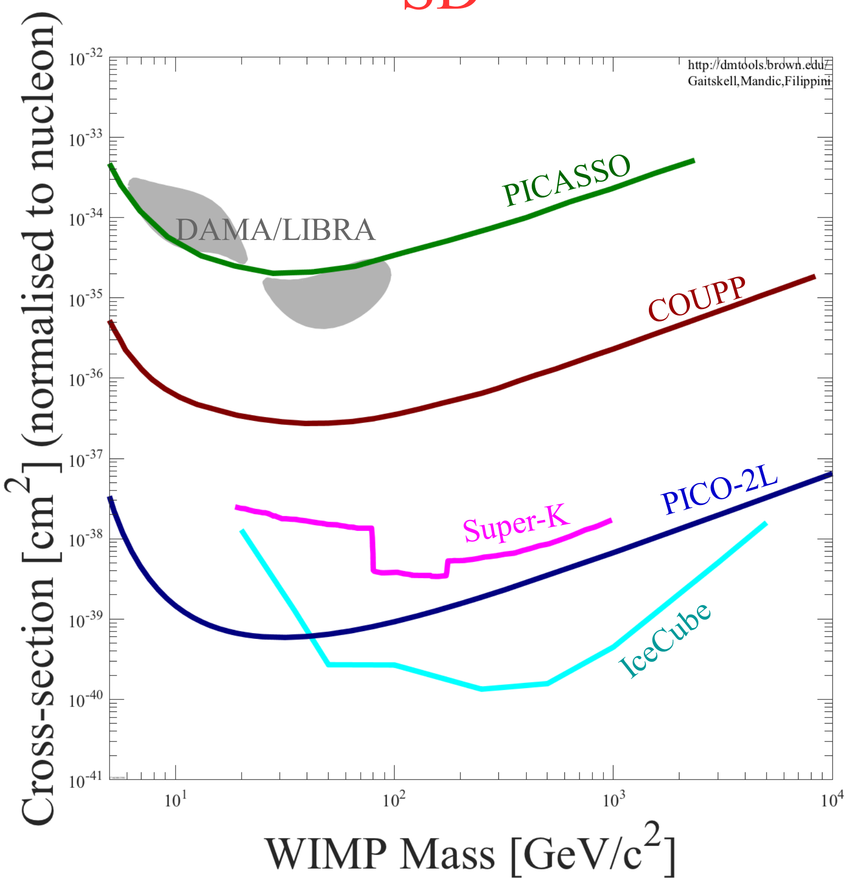
Theoretical interpretation of the experimental results

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

SI



SD



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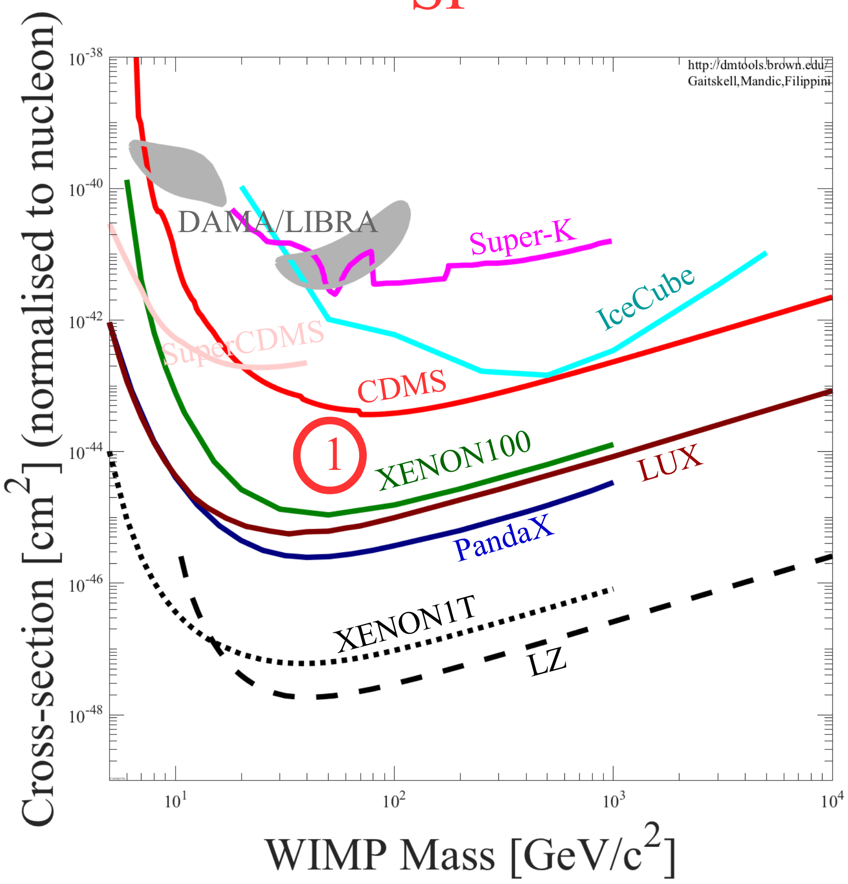

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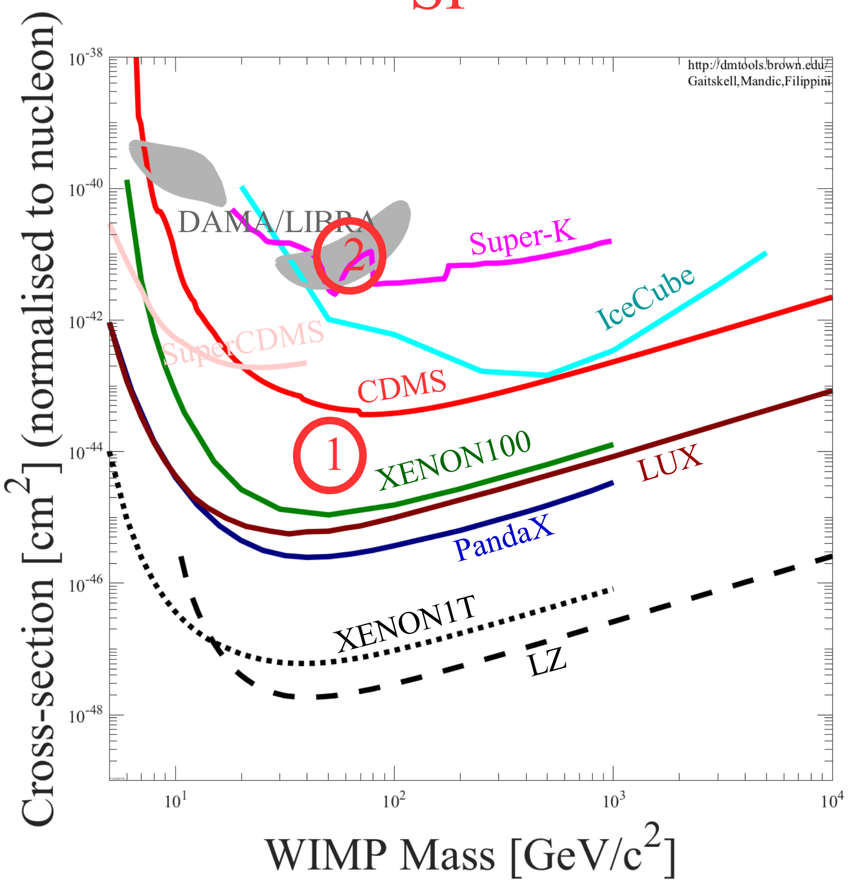

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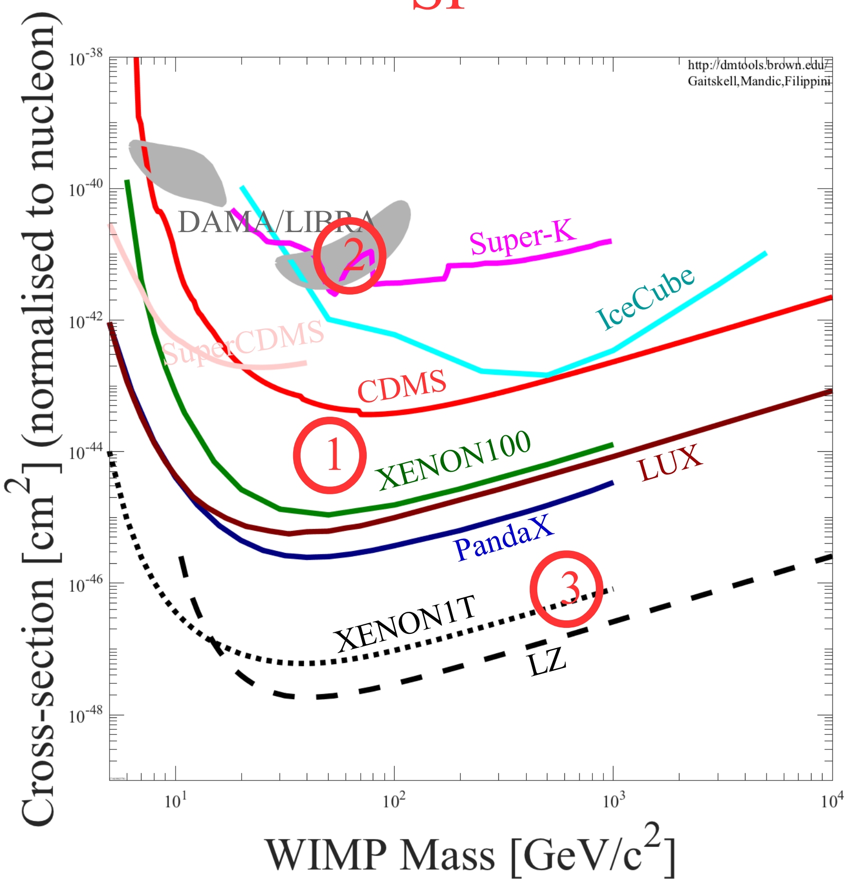

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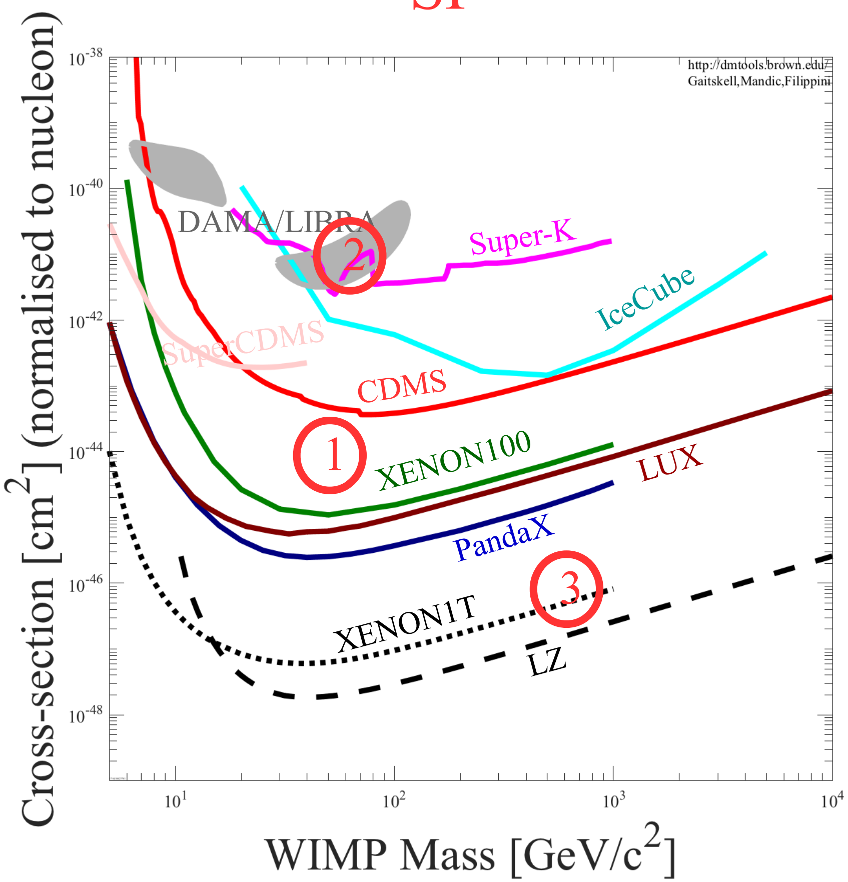

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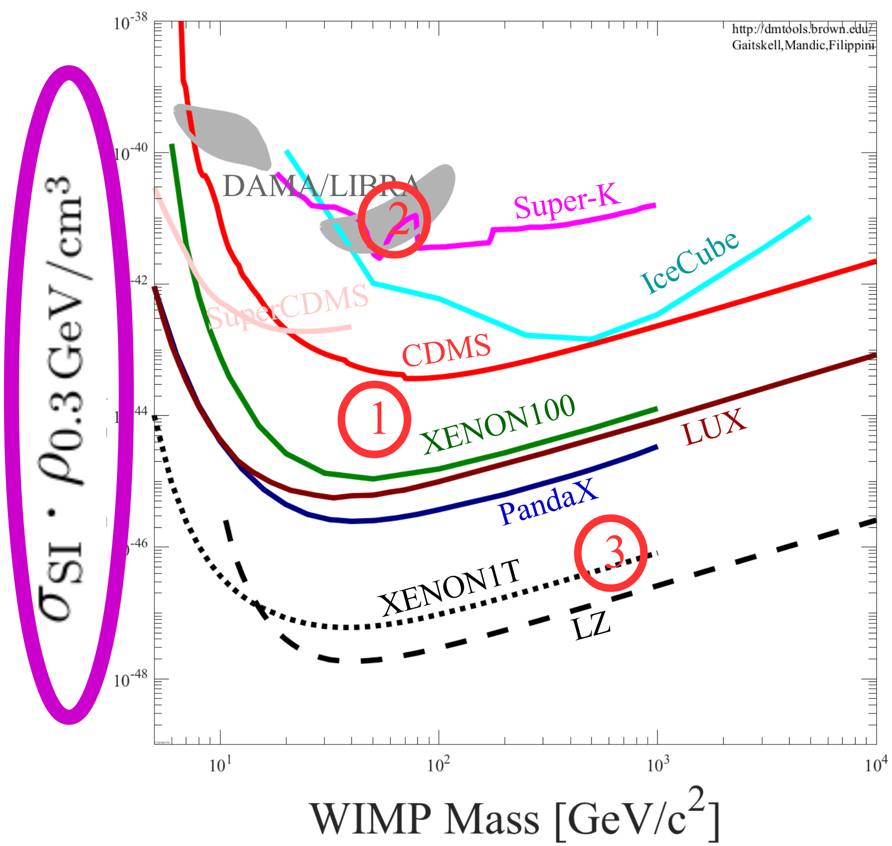

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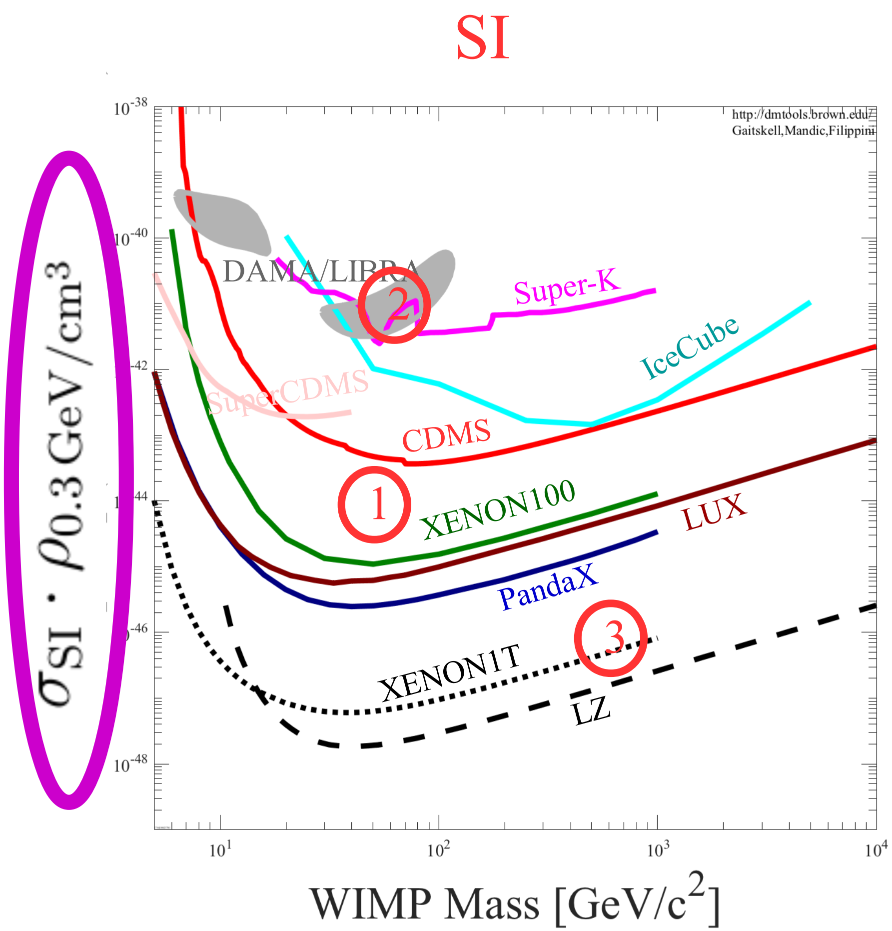

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What is the impact of the astrophysical uncertainties?

Do these conclusions hold for arbitrary velocity distributions?

Theoretical interpretation of the experimental results:

Halo independent approach:

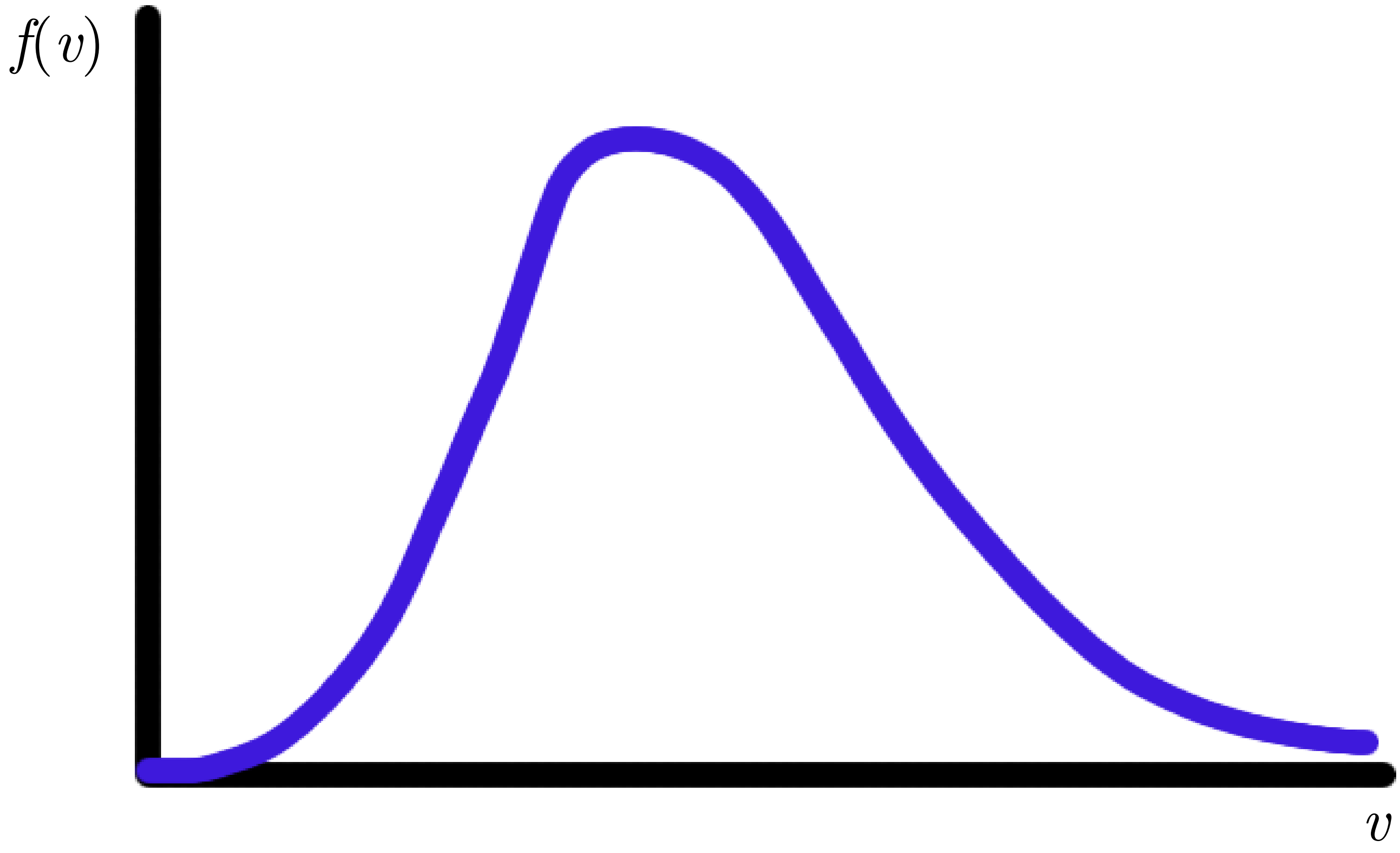
- $(\sigma, m_{\rm DM})$ is ruled out regardless of the velocity distribution if

$$\min_{f(\vec{v})} \Big\{ R(\sigma, m_{\rm DM}) \Big\} > R_{\rm max}$$

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

$$\max_{f(\vec{v})} \Big\{ R(\sigma, m_{\rm DM}) \Big\} < 1$$

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



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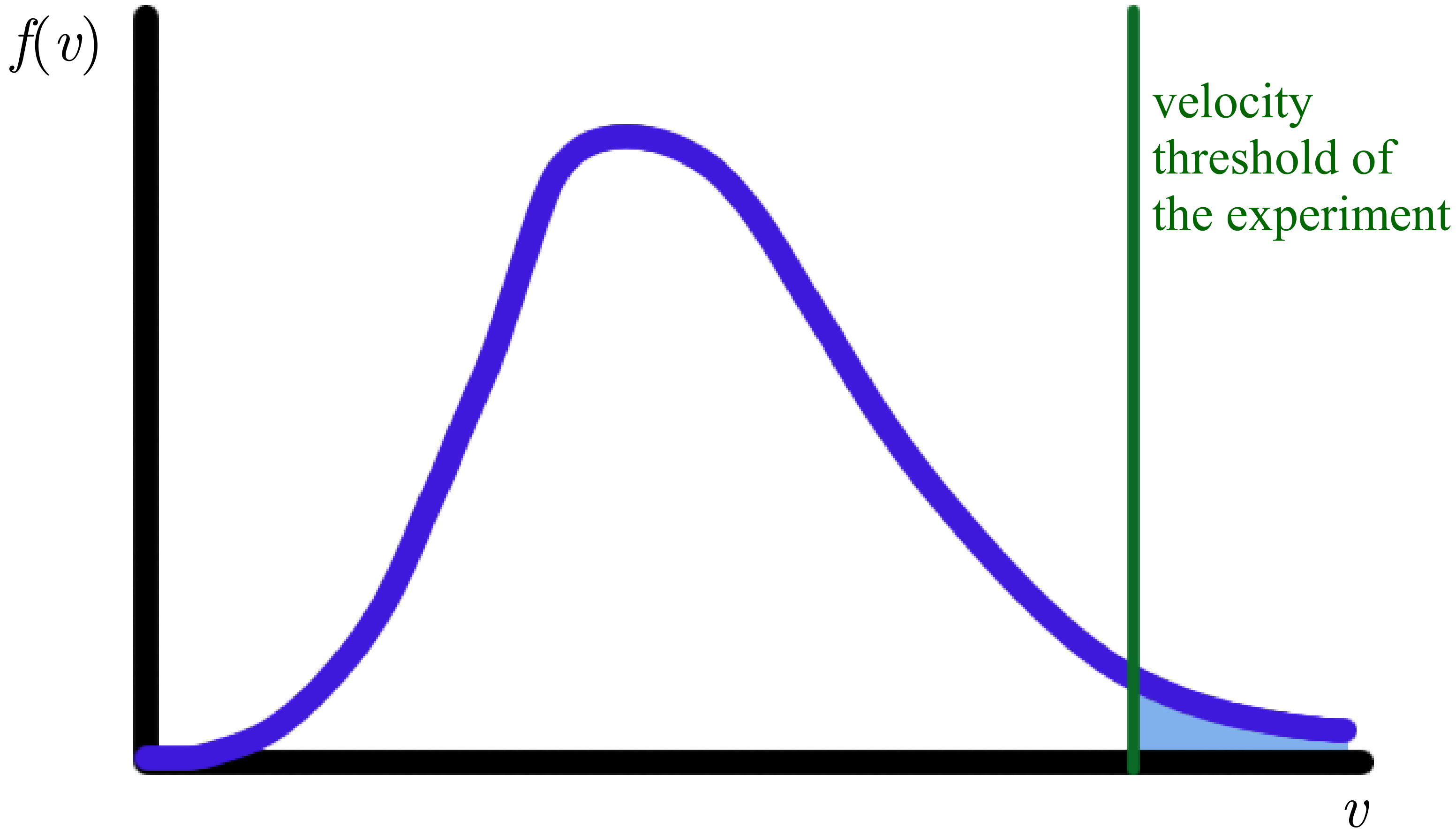

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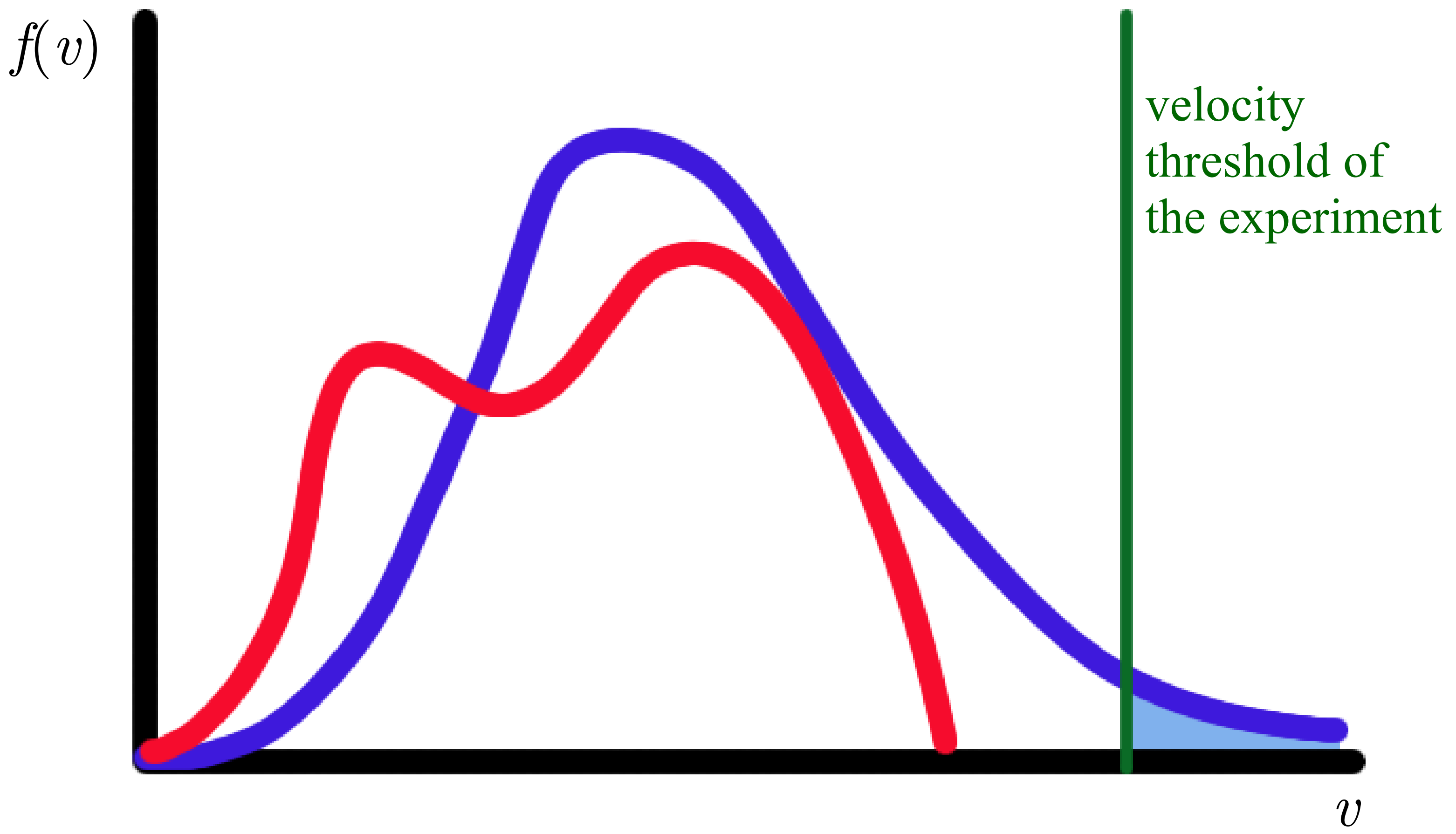
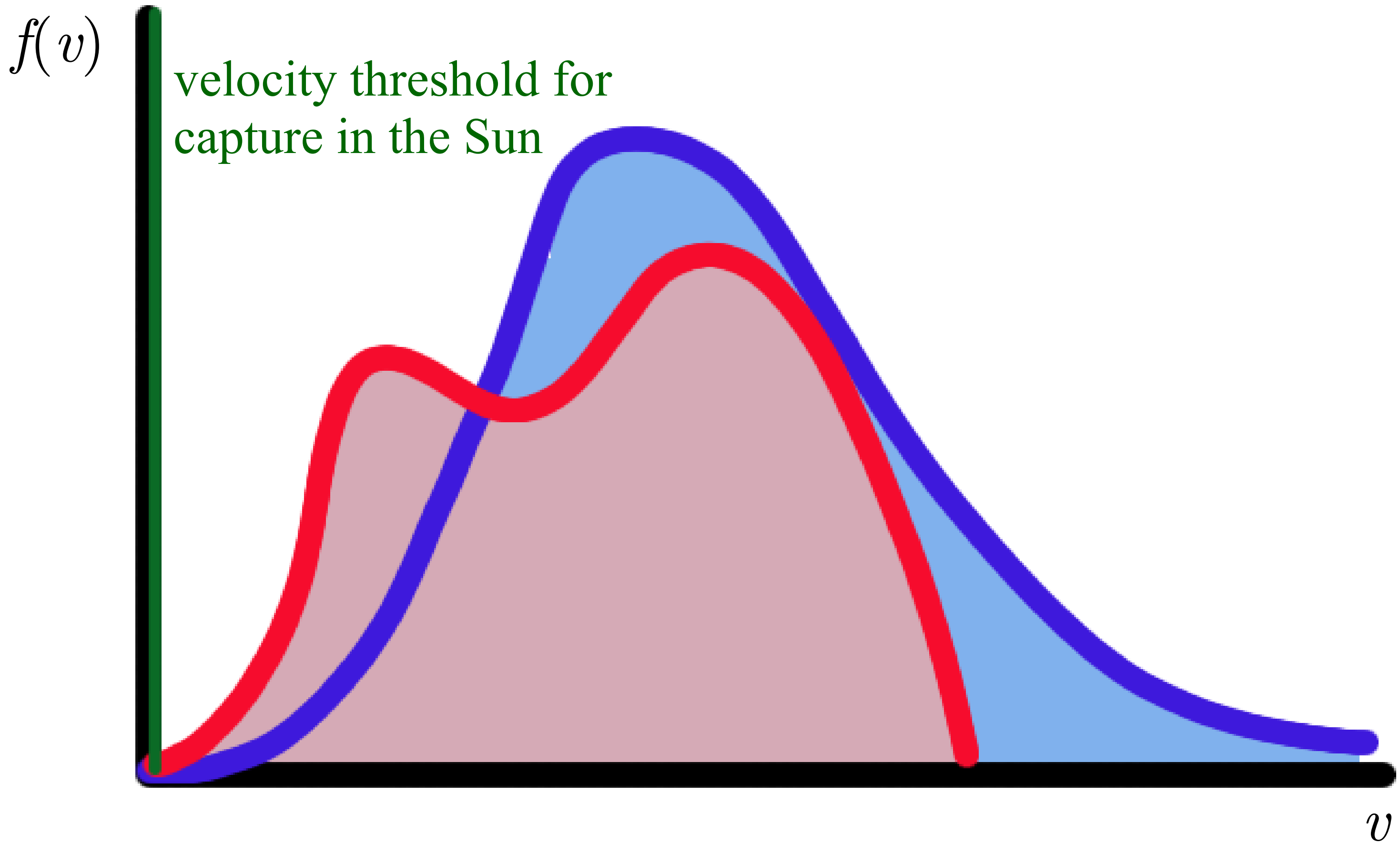


Some velocity distributions will escape detection in the experiment

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



Neutrino telescopes probe the whole velocity space and complement direct detection experiments.

Theoretical interpretation of the experimental results:

Halo independent approach:

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

$$\min_{f(\vec{v})} \left\{ R(\sigma, m_{\rm DM}) \right\} \Big|_{\substack{C(\sigma,m)\leq C_{\max} \\ \int f=1}} > R_{\max}$$

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

$$\max_{f(\vec{v})} \left\{ R(\sigma, m_{\rm DM}) \right\} \Big|_{\substack{C(\sigma,m)\leq C_{\max} \\ \int f=1}} < 1$$

Optimization problem over a continuous function with constraints

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

Express the velocity distribution as a superposition of many many streams:

$$f(\vec{v}) = \sum_{i=1}^{n} c_{\vec{v}_i}\ \delta(\vec{v} - \vec{v}_i)$$

Minimization problem. For given DM mass and cross-section:

$$\text{minimize} \quad R^{(\text{PandaX})}(c_{\vec{v}_1} \ldots, c_{\vec{v}_n}) = \sum_{i=1}^{n} c_{\vec{v}_i} R_{\vec{v}_i}^{(\text{PandaX})} \ ,$$

$$\text{subject to} \quad \sum_{i=1}^{n} c_{\vec{v}_i} C_{\vec{v}_i}^{(\text{NT})} \leq C_{\text{max}}^{(\text{NT})},$$

$$\text{and} \quad \sum_{i=1}^{n} c_{\vec{v}_i} = 1 \ ,$$

$$\text{and} \quad c_{\vec{v}_i} \geq 0, \quad i = 1 \ldots, n \ ,$$

The parameters σ and m_{DM} are excluded in a halo independent manner if :

$$\boxed{\min\left\{R^{(\text{PandaX})}(c_{\vec{v}_1} \ldots, c_{\vec{v}_n})\right\}\Big|_{\text{constraints}} > R_{\text{max}}^{(\text{PandaX})}}$$

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

Express the velocity distribution as a superposition of many many streams:

$$f(\vec{v}) = \sum_{i=1}^{n} c_{\vec{v}_i} \; \delta(\vec{v} - \vec{v}_i)$$

Minimization problem. For given DM mass and cross-section:

$$\text{minimize} \quad R^{(\text{PandaX})}(c_{\vec{v}_1} \ldots, c_{\vec{v}_n}) = \sum_{i=1}^{n} c_{\vec{v}_i} R_{\vec{v}_i}^{(\text{PandaX})}$$

$$\text{subject to} \quad \sum_{i=1}^{n} c_{\vec{v}_i} C_{\vec{v}_i}^{(\text{NT})} \leq C_{\max}^{(\text{NT})},$$

$$\text{and} \quad \sum_{i=1}^{n} c_{\vec{v}_i} = 1\,,$$

$$\text{and} \quad c_{\vec{v}_i} \geq 0, \quad i = 1 \ldots, n\,,$$

The objective function and the constraints are linear in the weights of the DM streams

$\hookrightarrow$ Optimize using linear programming techniques.

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

Express the velocity distribution as a superposition of many many streams:

$$f(\vec{v}) = \sum_{i=1}^{n} c_{\vec{v}_i}\ \delta(\vec{v} - \vec{v}_i)$$

Minimization problem. For given DM mass and cross-section:

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$$\text{subject to}\quad \sum_{i=1}^{n} c_{\vec{v}_i} C_{\vec{v}_i}^{(\text{NT})} \leq C_{\max}^{(\text{NT})},$$

$$\text{and}\quad \sum_{i=1}^{n} c_{\vec{v}_i} = 1\ ,$$

$$\text{and}\quad c_{\vec{v}_i} \geq 0,\quad i = 1\ldots, n\ ,$$

1) The solution lies at one of the vertices of the “feasible region”

2) The optimized velocity distribution contains either one or two streams (depending on the number of constraints that are not saturated).

Generalization

Calculate the maximum/minimum outcome in a direct detection experiment A, given the upper limits on the outcome of p experiments B_α, $\alpha = 1\ldots, p$, and the lower limits on the outcome of q experiments B_α, $\alpha = p+1\ldots, p+q$ (and the requirement that the velocity distribution is normalized to 1).

$$\text{optimize} \quad F(c_{\vec{v}_1}\ldots, c_{\vec{v}_n}) = \sum_{i=1}^{n} c_{\vec{v}_i} N_{\vec{v}_i}^{(A)} \ ,$$

$$\text{subject to} \quad \sum_{i=1}^{n} c_{\vec{v}_i} N_{\vec{v}_i}^{(B_\alpha)} \leq N_{\max}^{(B_\alpha)}, \quad \alpha = 1, \ldots, p \ ,$$

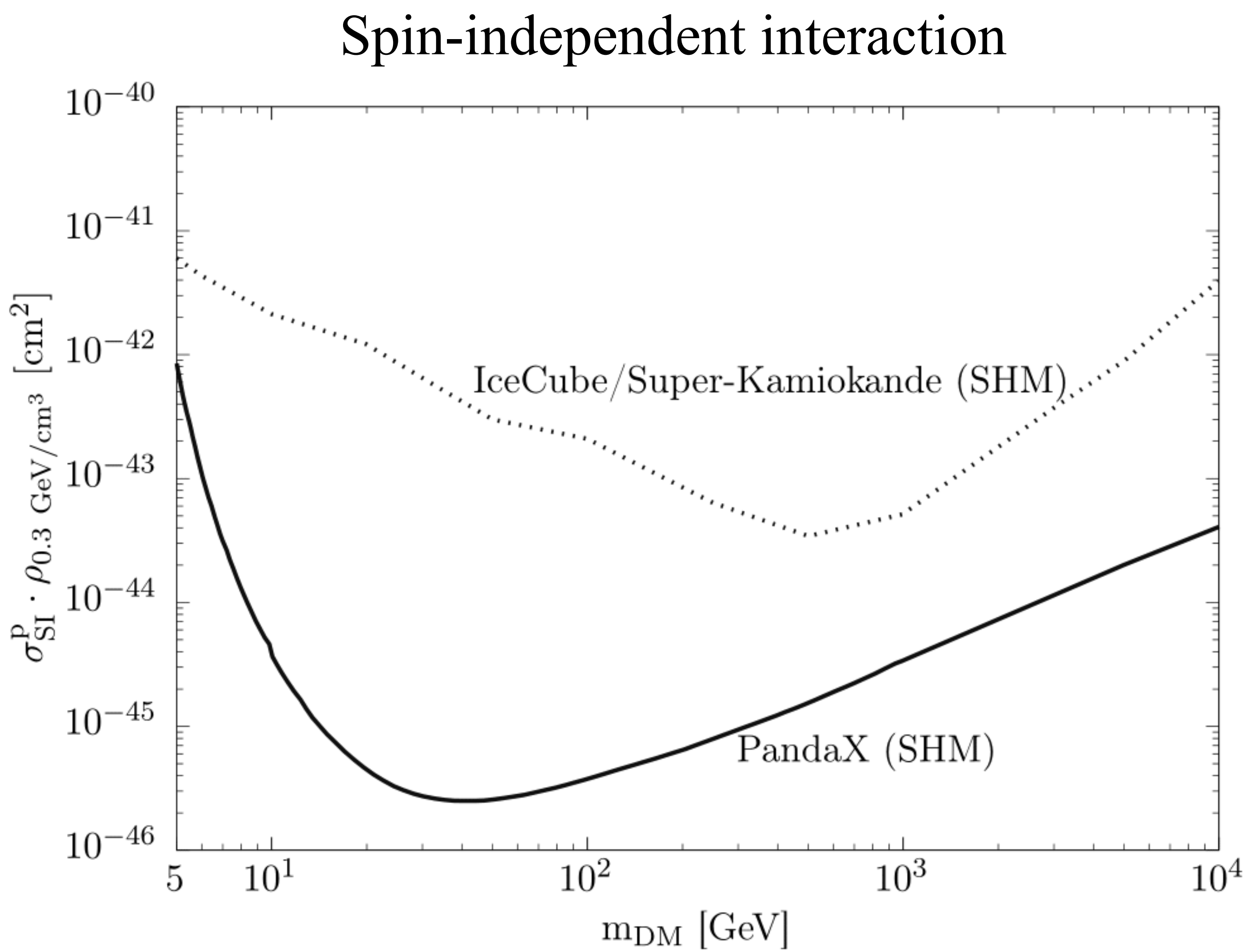
$$\text{and} \quad \sum_{i=1}^{n} c_{\vec{v}_i} N_{\vec{v}_i}^{(B_\alpha)} \geq N_{\min}^{(B_\alpha)}, \quad \alpha = p+1, \ldots, p+q \ ,$$

$$\text{and} \quad \sum_{i=1}^{n} c_{\vec{v}_i} = 1 \ ,$$

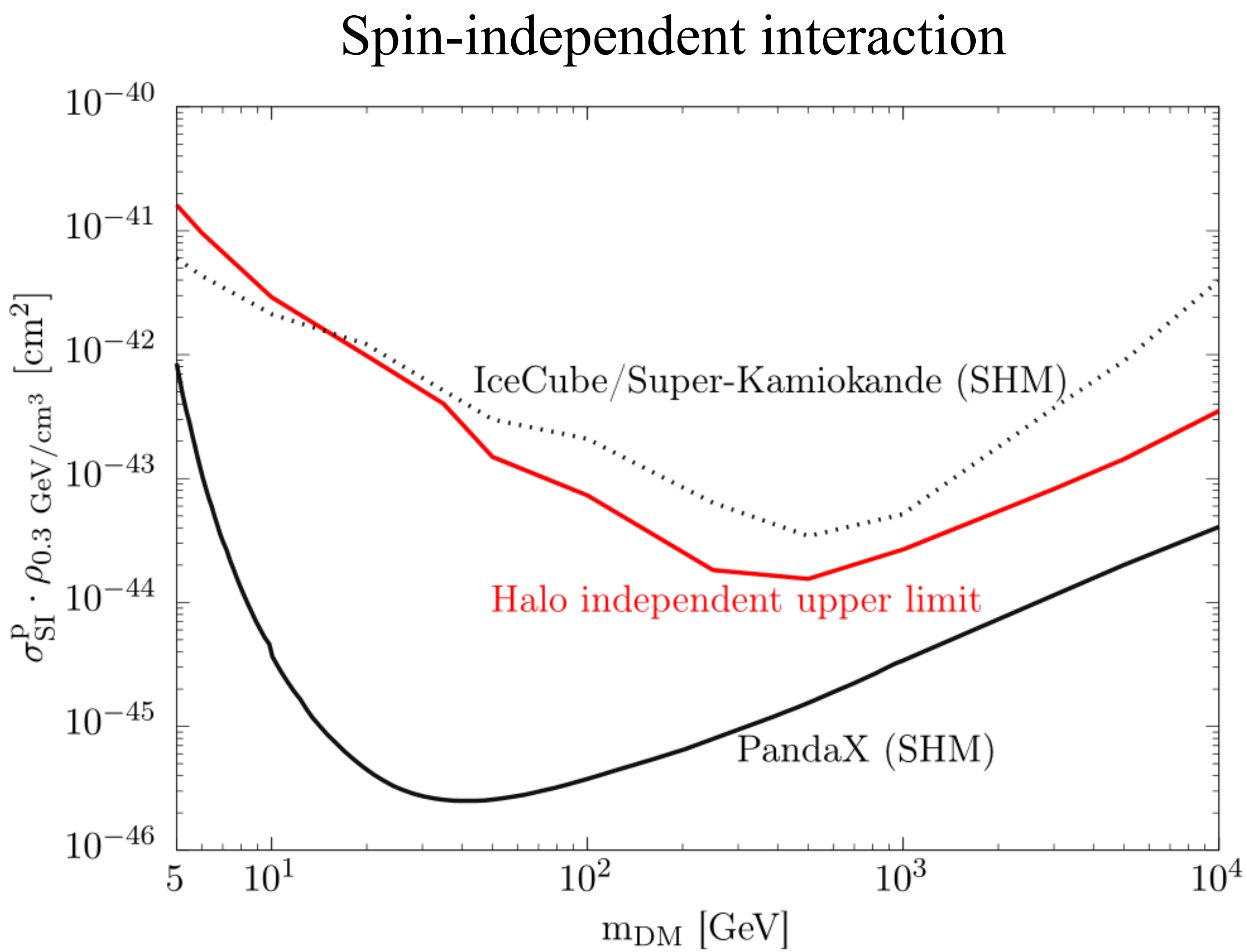
$$\text{and} \quad c_{\vec{v}_i} \geq 0, \quad i = 1\ldots, n \ ,$$

1) The solution lies at one of the vertices of the "feasible region".
2) The optimized velocity distribution contains between 1 and $p+q+1$ streams (depending on the number of constraints that are not saturated).

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



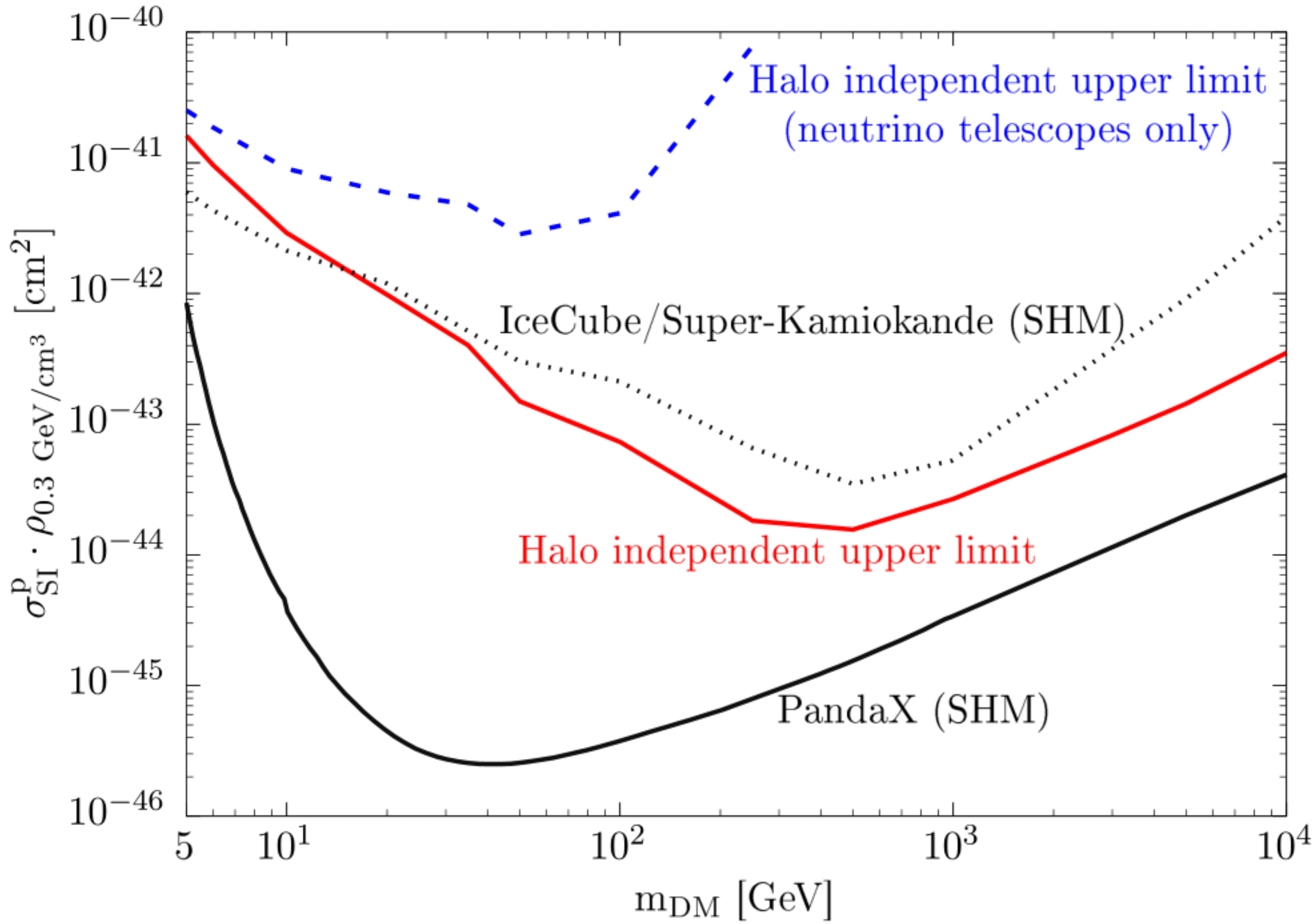
Upper limit on the scattering cross section from combining PandaX and IceCube/SK.



AI, Rappelt

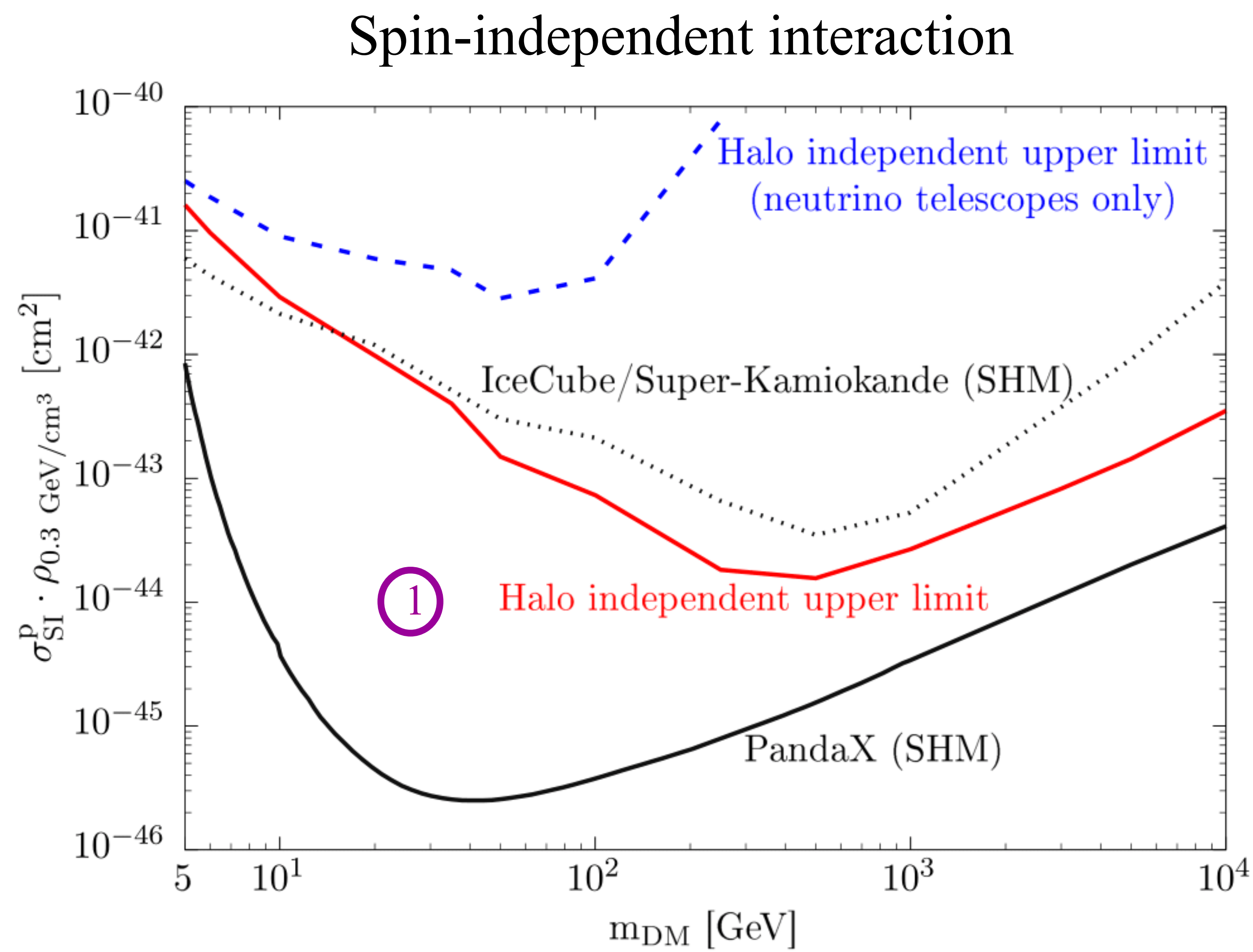
Upper limit on the scattering cross section from combining PandaX and IceCube/SK.

Spin-independent interaction



AI, Rappelt

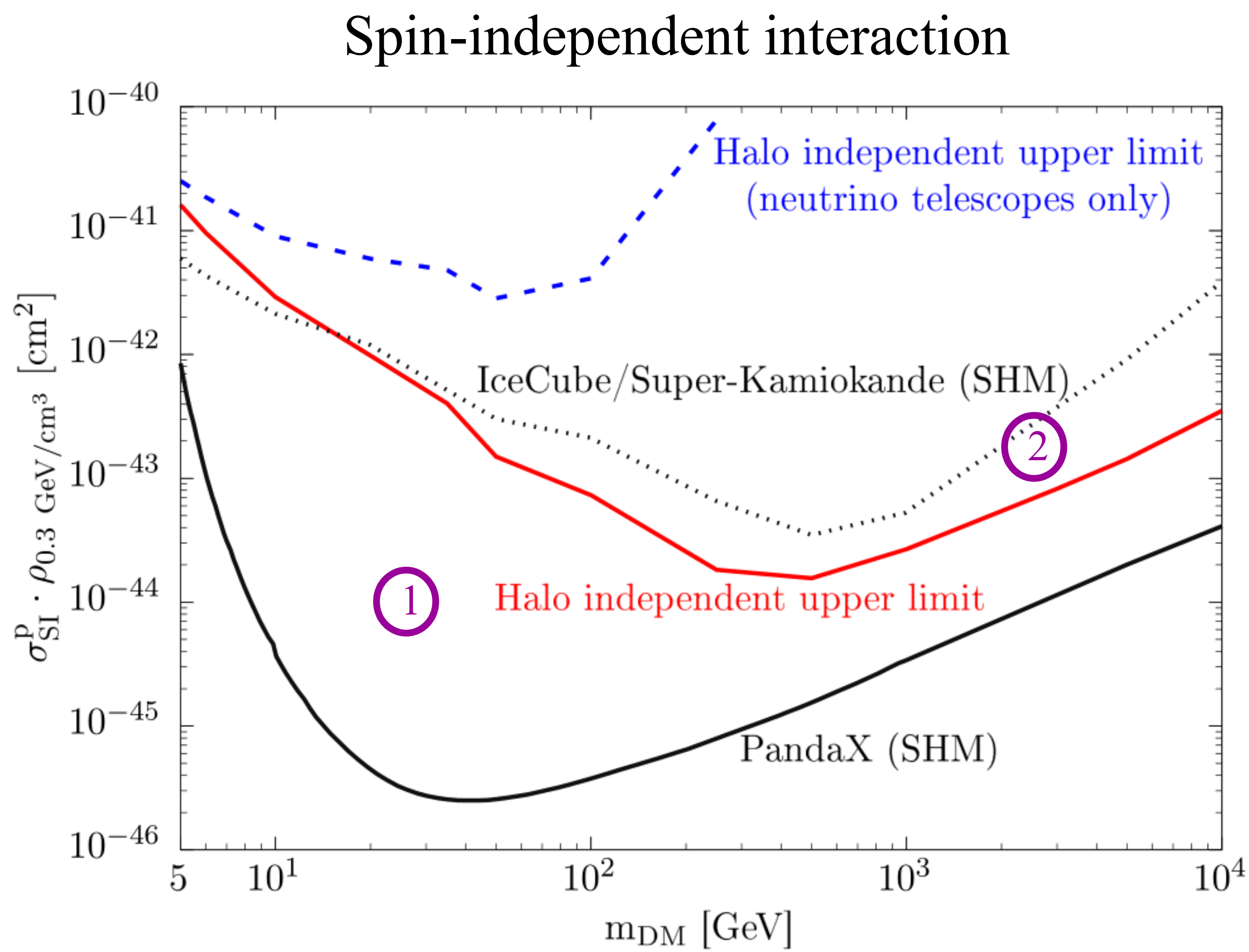
Upper limit on the scattering cross section from combining PandaX and IceCube/SK.



AI, Rappelt

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

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

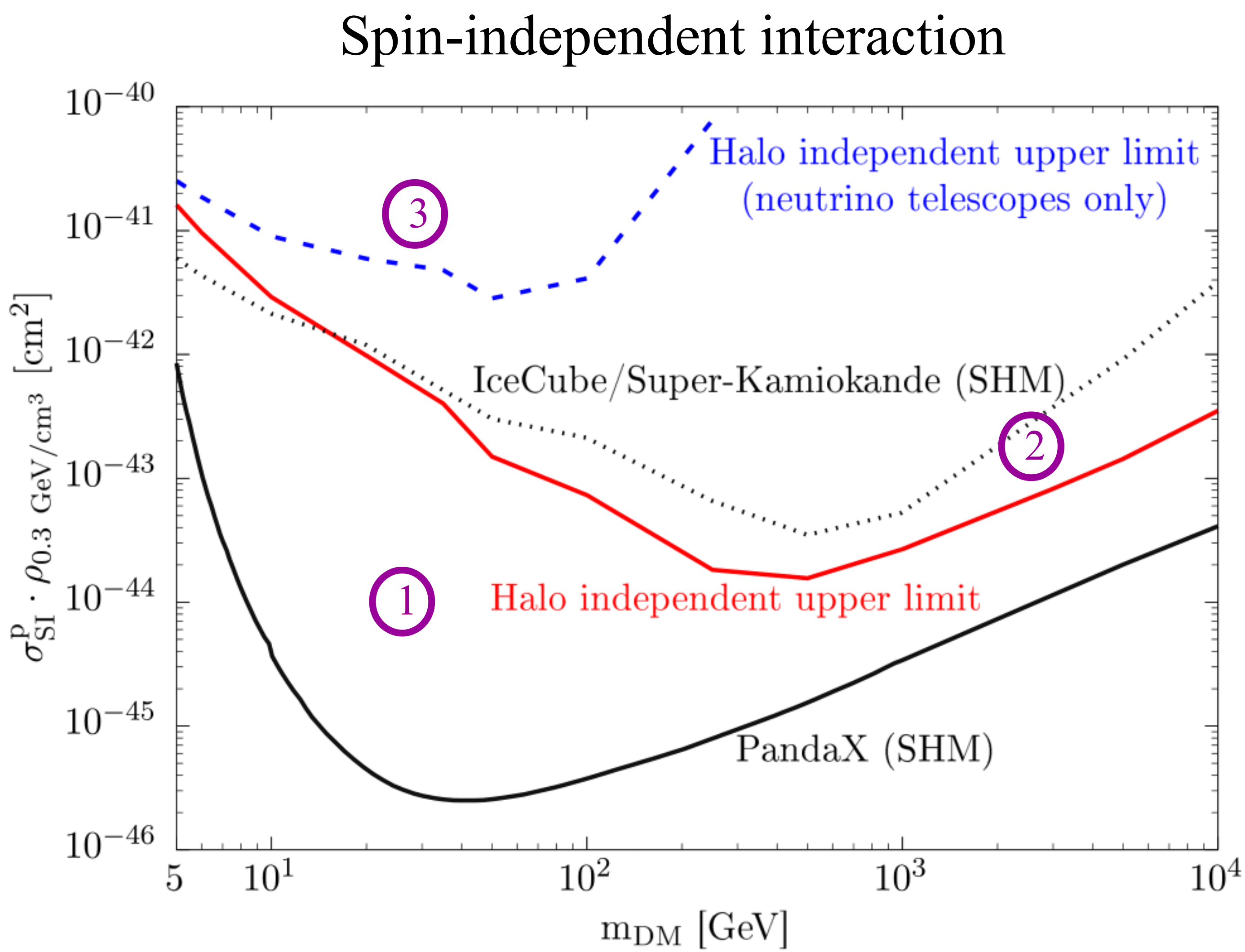


AI, Rappelt

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.



AI, Rappelt

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.

Prospects for LZ from current null results

LZ reach to the SI cross-section from null results at neutrino telescopes

$$\text{optimize} \quad R^{(\mathrm{LZ})}(c_{\vec{v}_1}\ldots, c_{\vec{v}_n}) = \sum_{i=1}^{n} c_{\vec{v}_i} R^{(\mathrm{LZ})}_{\vec{v}_i} \;,$$

$$\text{subject to} \quad \sum_{i=1}^{n} c_{\vec{v}_i} C^{(\mathrm{NT})}_{\vec{v}_i} \leq C^{(\mathrm{NT})}_{\max} ,$$

$$\text{and} \quad \sum_{i=1}^{n} c_{\vec{v}_i} = 1 \;,$$

$$\text{and} \quad c_{\vec{v}_i} \geq 0, \quad i = 1\ldots, n \;,$$

The parameters σ and m_{DM} are fully testable in a halo independent manner if :

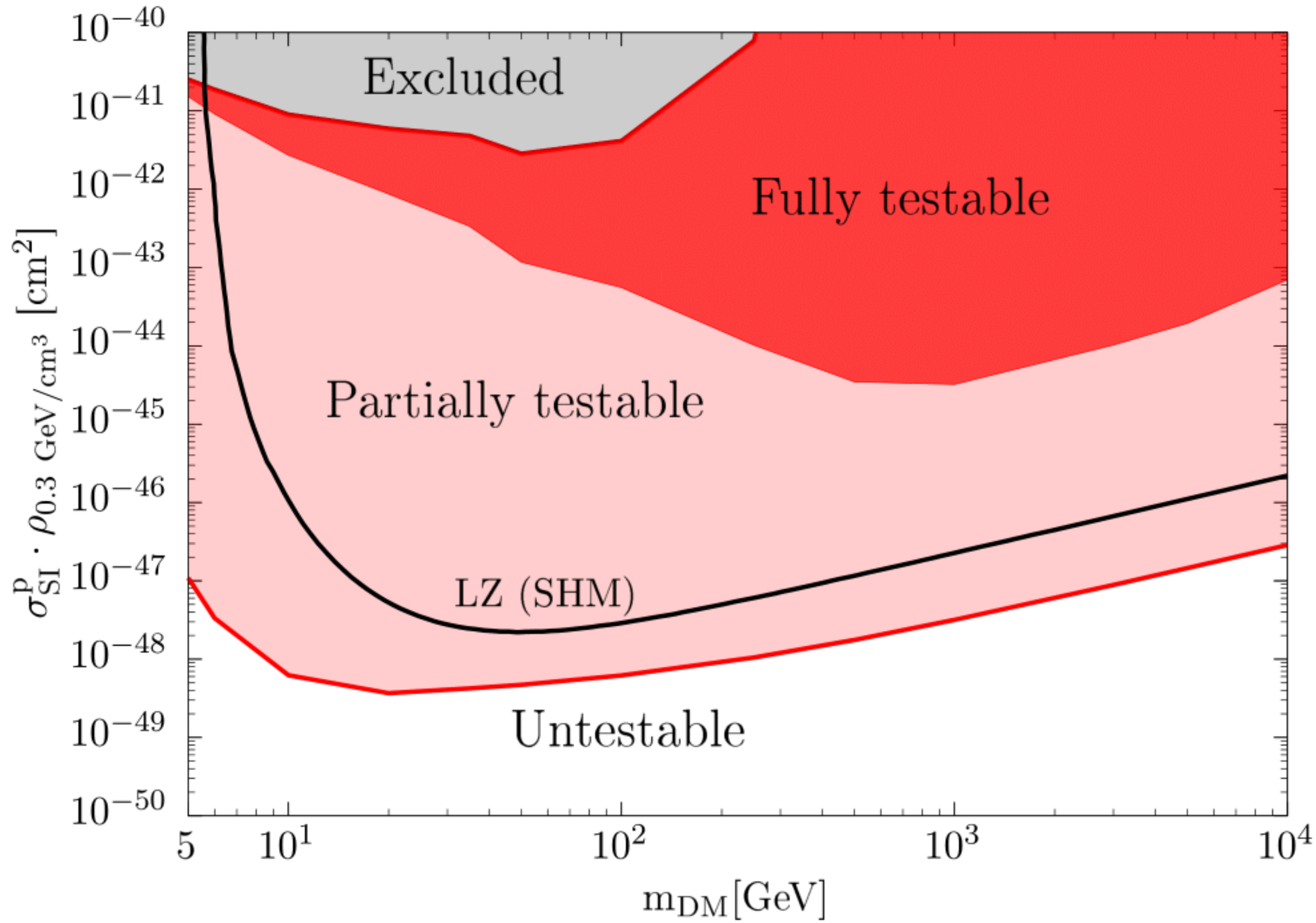
$$\boxed{\min_{f(\vec{v})} \left\{ R^{(\mathrm{LZ})}(\sigma, m_{\mathrm{DM}}) \right\} \Big|_{\text{constraints}} > 1}$$

The parameters σ and m_{DM} are untestable in a halo independent manner if :

$$\boxed{\max_{f(\vec{v})} \left\{ R^{(\mathrm{LZ})}(\sigma, m_{\mathrm{DM}}) \right\} \Big|_{\text{constraints}} < 1}$$

Prospects for LZ from current null results

LZ reach to the SI cross-section from null results at neutrino telescopes



AI, Rappelt

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 calculate the minimum/maximum number of signal events in an experiment probing the dark matter distribution inside the Solar System, in view of a number of constraints from direct detection experiments and/or neutrino telescopes.

- Some applications are:

  i) to derive a halo-independent upper limit on the cross section from a set of null results.

  ii) to assess, in a halo-independent manner, the prospects for detection in a future experiment given a set of current null results.

  iii) to confront in a halo-independent way a detection claim to a set of null results.

- The method could be extended to include other dark matter interactions, or to account for more realistic velocity configurations.

DAMA confronted to null results

1) DAMA confronted to PandaX (SI interaction only)

$$\text{minimize} \quad R^{(\mathrm{PandaX})}(c_{\vec{v}_1}\ldots, c_{\vec{v}_n}) = \sum_{i=1}^{n} c_{\vec{v}_i} R^{(\mathrm{PandaX})}_{\vec{v}_i} \ ,$$

$$\text{subject to} \quad \sum_{i=1}^{n} c_{\vec{v}_i} S^{(\mathrm{DAMA})}_{[E_-,E_+],\vec{v}_i} \leq S^{(\mathrm{DAMA})}_{[E_-,E_+],\max}, \quad \text{for } [2.0, 2.5],\ [2.5, 3.0] \text{ and } [3.0, 3.5] \text{ keV}$$

$$\text{and} \quad \sum_{i=1}^{n} c_{\vec{v}_i} S^{(\mathrm{DAMA})}_{[E_-,E_+],\vec{v}_i} \geq S^{(\mathrm{DAMA})}_{[E_-,E_+],\min}, \quad \text{for } [2.0, 2.5],\ [2.5, 3.0] \text{ and } [3.0, 3.5] \text{ keV}$$

$$\text{and} \quad \sum_{i=1}^{n} c_{\vec{v}_i} = 1 \ ,$$

$$\text{and} \quad c_{\vec{v}_i} \geq 0, \quad i = 1\ldots, n \ ,$$

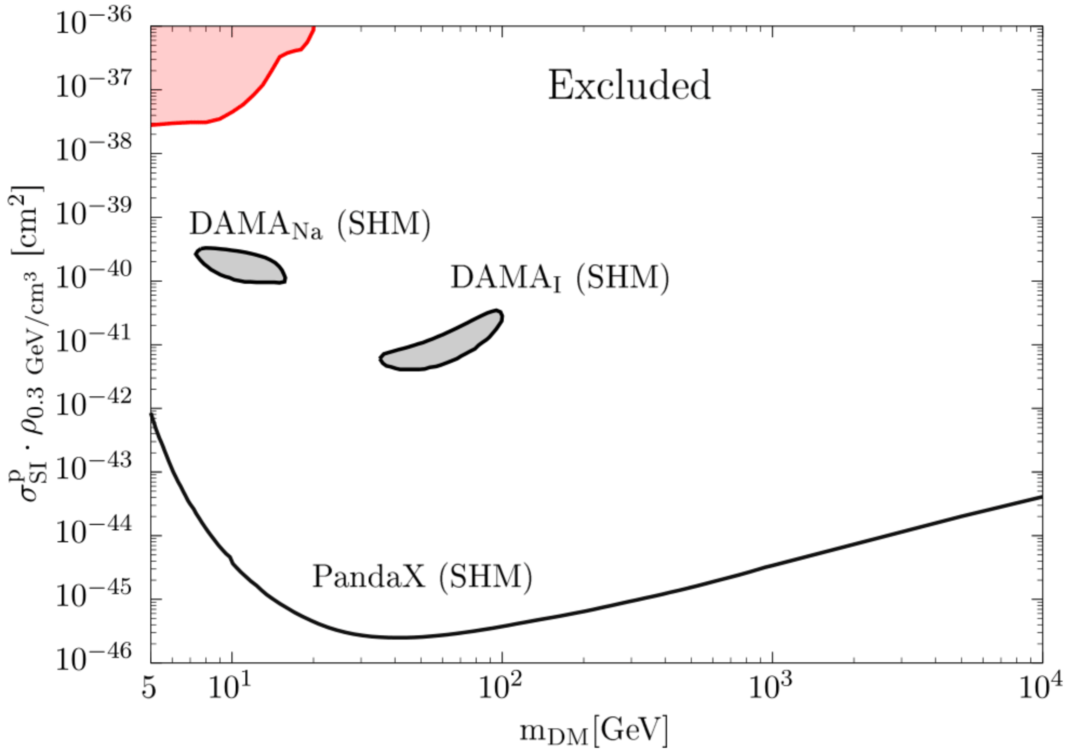
The parameters σ and m_{DM} are excluded in a halo independent manner if :

$$\boxed{\min_{f(\vec{v})} \left\{ R^{(\mathrm{PandaX})}(\sigma, m_{\mathrm{DM}}) \right\} \Big|_{\text{constraints}} \geq R^{(\mathrm{PandaX})}_{\max}}$$

(In total 7 constraints. However, 3 of these constraints are never saturated, therefore the optimized velocity distribution contains at most 4 streams.)

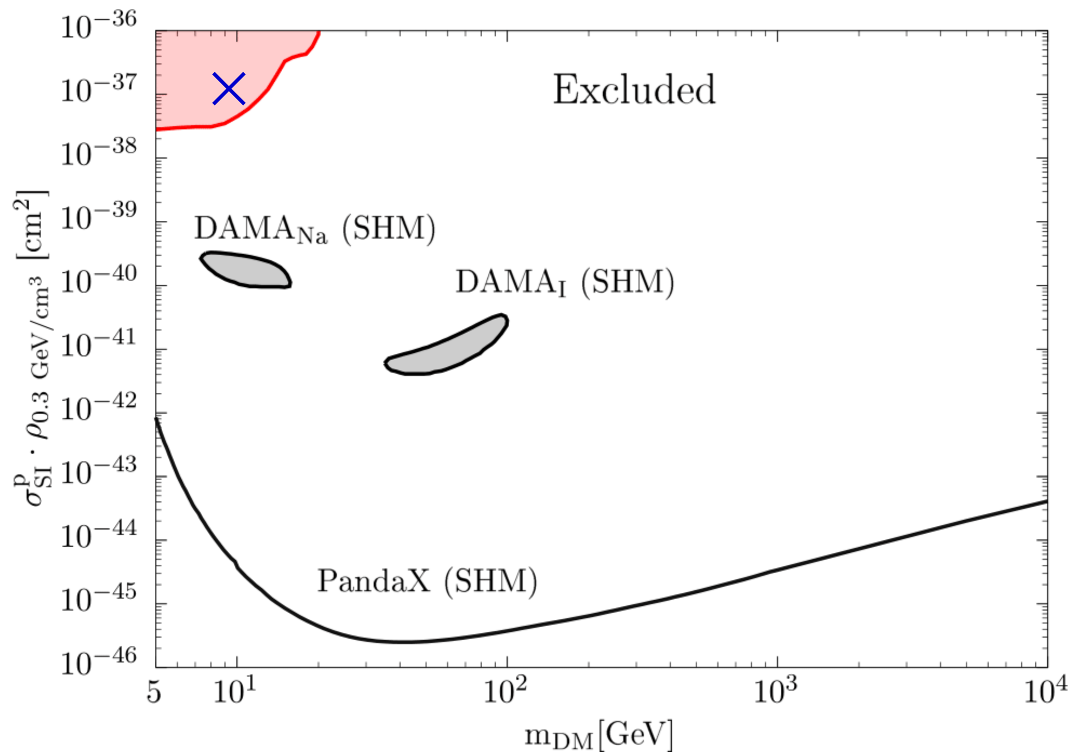
DAMA confronted to null results

1) DAMA confronted to PandaX (SI interaction only)



DAMA confronted to null results

1) DAMA confronted to PandaX (SI interaction only)

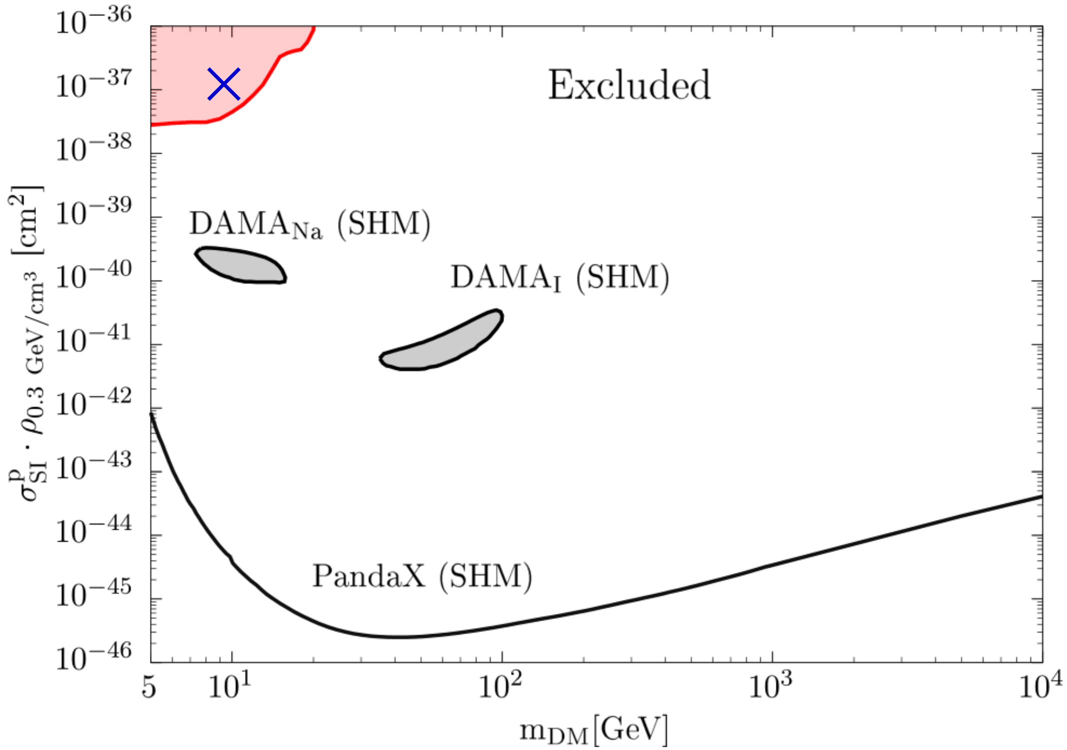


	stream #1	stream #2	stream #3	stream #4
$c_{\vec{v}_i}$	0.54	0.28	0.18	–
$\vec{v}_i$ [km/s]	$(-10, -123, 191)$	$(100, -167, -161)$	$(56, 119, -183)$	–
$\lvert\vec{v}^{\,(\mathrm{PandaX})}_{i,\max}\rvert$ [km/s]	257.1	264.3	255.1	–
$\lvert\vec{v}^{\,(\mathrm{DAMA})}_{i,\mathrm{June}}\rvert$ [km/s]	256.1	245.0	195.7	–
$\lvert\vec{v}^{\,(\mathrm{DAMA})}_{i,\mathrm{Dec}}\rvert$ [km/s]	198.8	263.2	255.1	–

For $m_{\mathrm{DM}} = 10$ GeV, $v^{(\mathrm{PandaX})}_{\min} = 259.6\,\mathrm{km/s}$ and $v^{(\mathrm{DAMA}[3.0,3.5])}_{\min} = 143.9\,\mathrm{km/s}$.

DAMA confronted to null results

1) DAMA confronted to PandaX (SI interaction only)



	stream #1	stream #2	stream #3	stream #4
$c_{\vec{v}_i}$	0.54	0.28	0.18	–
$\vec{v}_i$ [km/s]	$(-10, -123, 191)$	$(100, -167, -161)$	$(56, 119, -183)$	–
$\lvert\vec{v}_{i,\mathrm{max}}^{(\mathrm{PandaX})}\rvert$ [km/s]	257.1	264.3	255.1	–
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$\lvert\vec{v}_{i,\mathrm{Dec}}^{(\mathrm{DAMA})}\rvert$ [km/s]	198.8	263.2	255.1	–

For $m_{\mathrm{DM}} = 10$ GeV, $v_{\mathrm{min}}^{(\mathrm{PandaX})} = 259.6\,\mathrm{km/s}$ and $v_{\mathrm{min}}^{(\mathrm{DAMA[3.0,3.5]})} = 143.9\,\mathrm{km/s}$.

Possible, but very fine-tuned!

DAMA confronted to null results

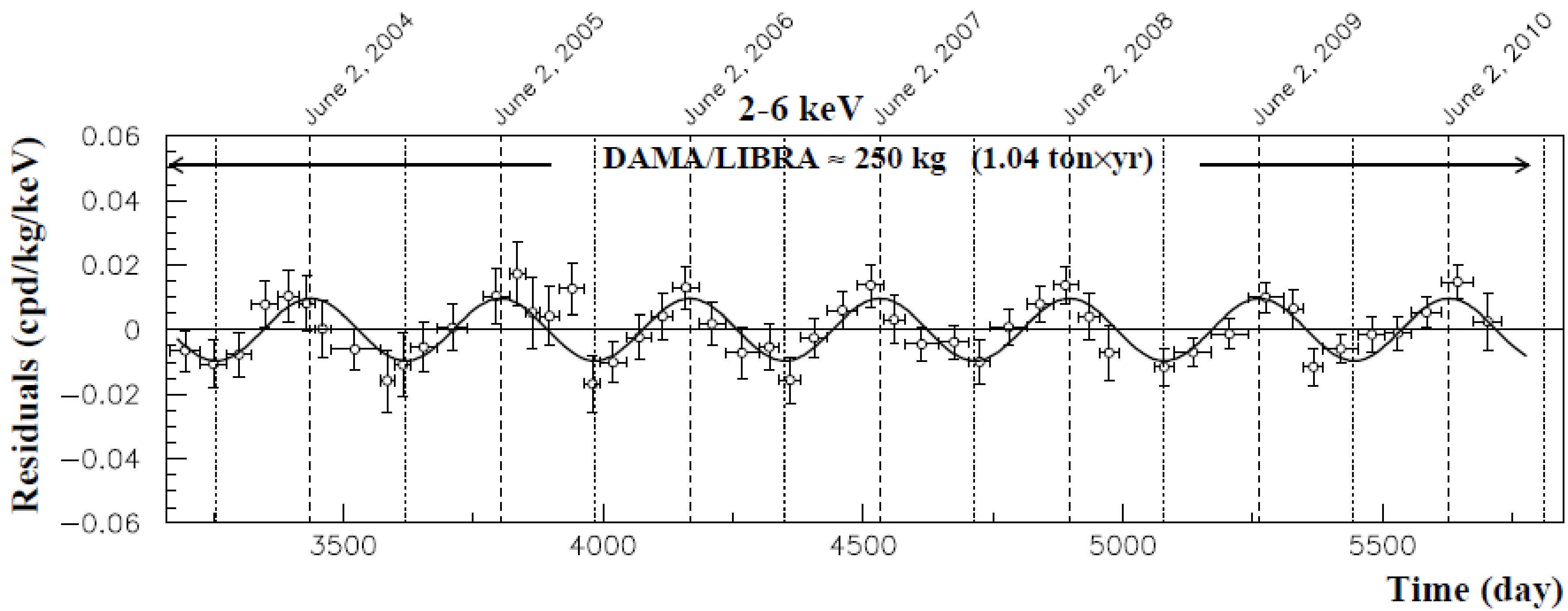
Only the modulation amplitudes were used...

$$S^{(\mathrm{DAMA})}_{[2.0,2.5]} = (1.75 \pm 0.37) \times 10^{-2}\ \mathrm{day}^{-1}\,\mathrm{kg}^{-1}\,\mathrm{keV}^{-1}$$

$$S^{(\mathrm{DAMA})}_{[2.5,3.0]} = (2.51 \pm 0.40) \times 10^{-2}\ \mathrm{day}^{-1}\,\mathrm{kg}^{-1}\,\mathrm{keV}^{-1}$$

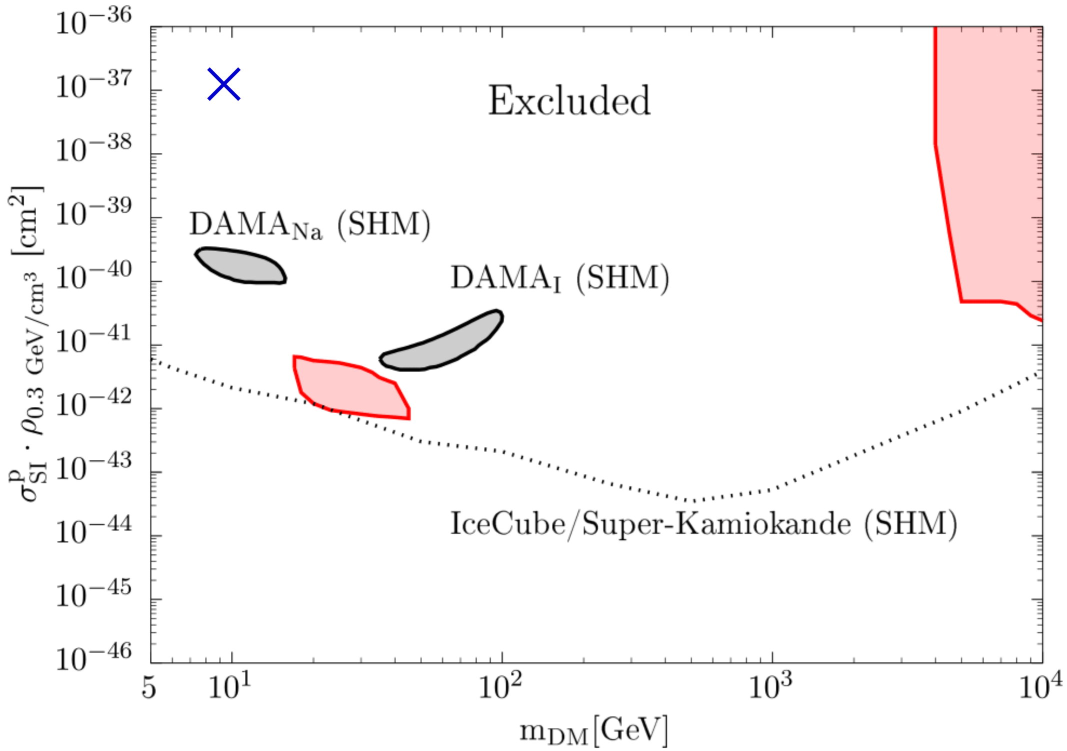
$$S^{(\mathrm{DAMA})}_{[3.0,3.5]} = (2.16 \pm 0.40) \times 10^{-2}\ \mathrm{day}^{-1}\,\mathrm{kg}^{-1}\,\mathrm{keV}^{-1}$$

… however, DAMA observes a modulation rate with a cosine dependence.



DAMA confronted to null results

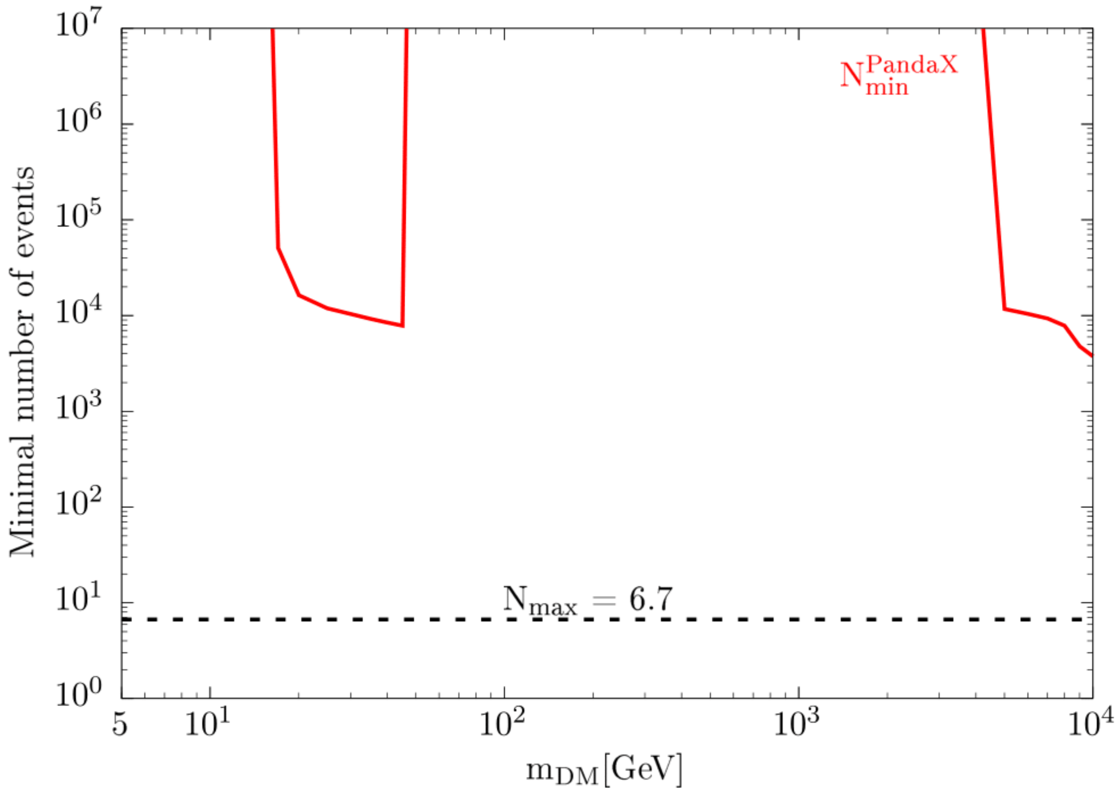
2) DAMA confronted to IceCube (SI interaction only)



	stream #1	stream #2	stream #3	stream #4
$c_{\vec{v}_i}$	0.56	0.44	6×10^{-5}	–
$\vec{v}_i$ [km/s]	$(120, -623, -357)$	$(110, -643, -337)$	$(110, 177, -297)$	–
$\lvert\vec{v}_i^{\,(\mathrm{Sun})}\rvert$ [km/s]	728.0	734.2	362.8	–
$\lvert\vec{v}_{i,\mathrm{June}}^{\,(\mathrm{DAMA})}\rvert$ [km/s]	728.0	735.4	333.0	–
$\lvert\vec{v}_{i,\mathrm{Dec}}^{\,(\mathrm{DAMA})}\rvert$ [km/s]	734.2	729.1	392.6	–

DAMA confronted to null results

3) DAMA confronted to PandaX and IceCube (SI interaction only)



If DAMA is explained by dark matter scattering via the SI interaction only, PandaX should have observed *at least* 3000 events.