Addressing theoretical uncertainties in dark matter direct detection experiments

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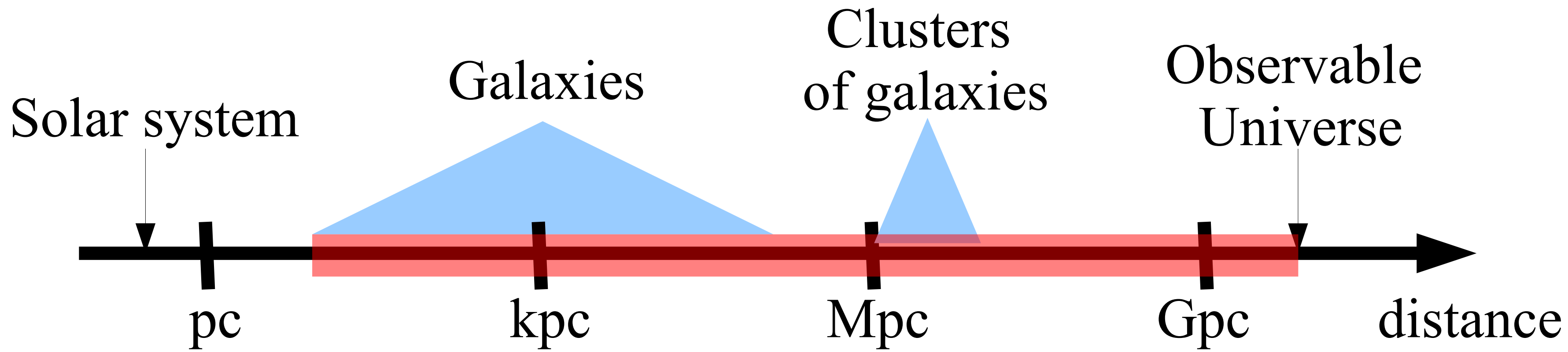
In collaboration with Anja Brenner, Gonzalo Herrera, Andreas Rappelt, Bradley Kavanagh, Shunghyun Kang, Stefano Scopel and Gaurav Tomar

DM+nu Forum
Virtual seminar
December 2021

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



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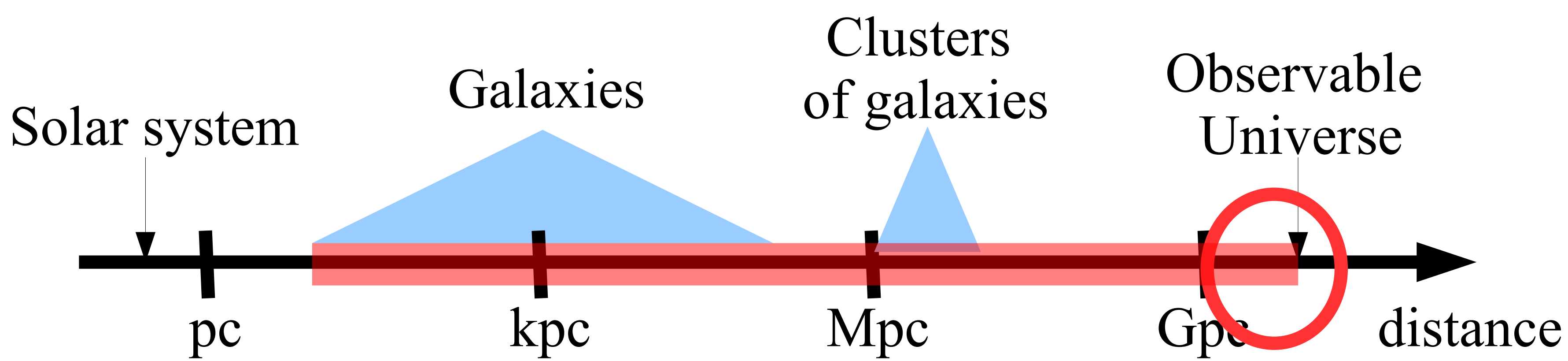

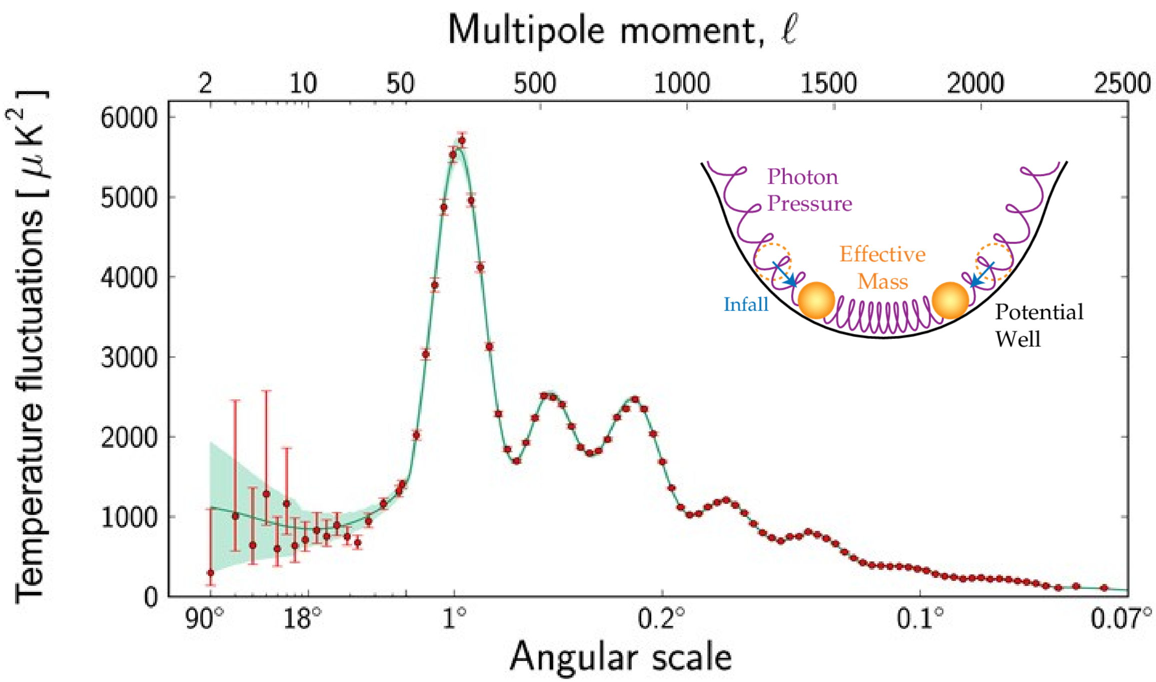

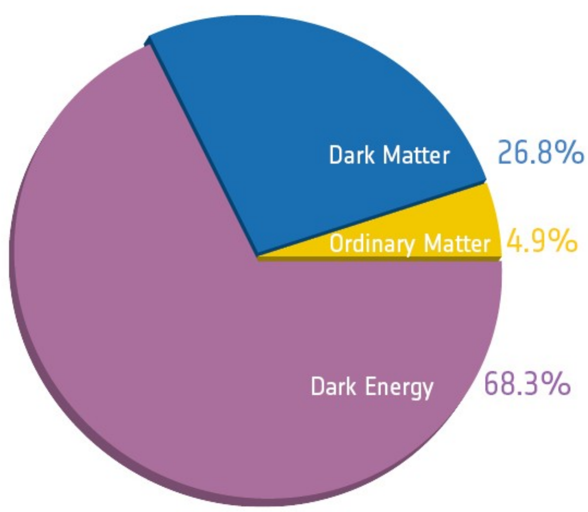

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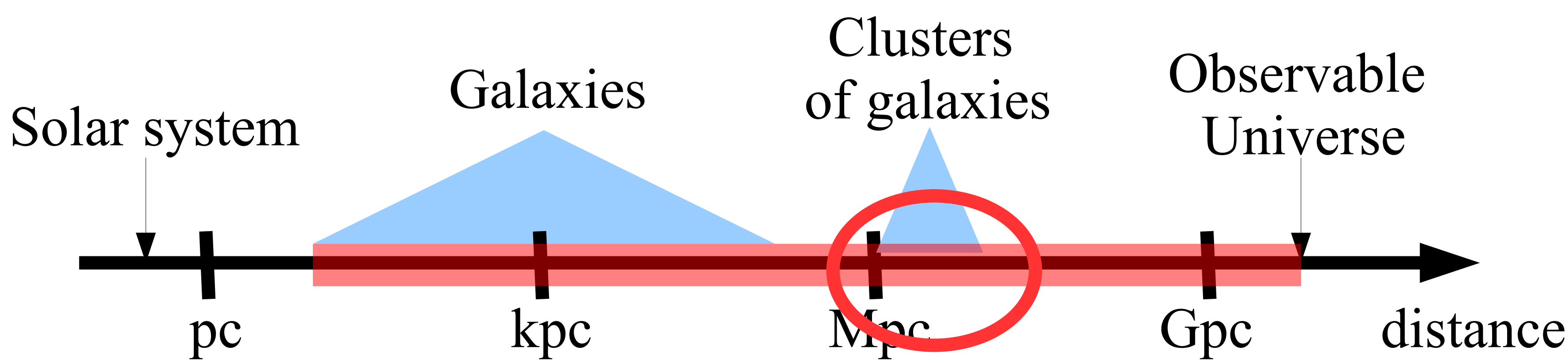

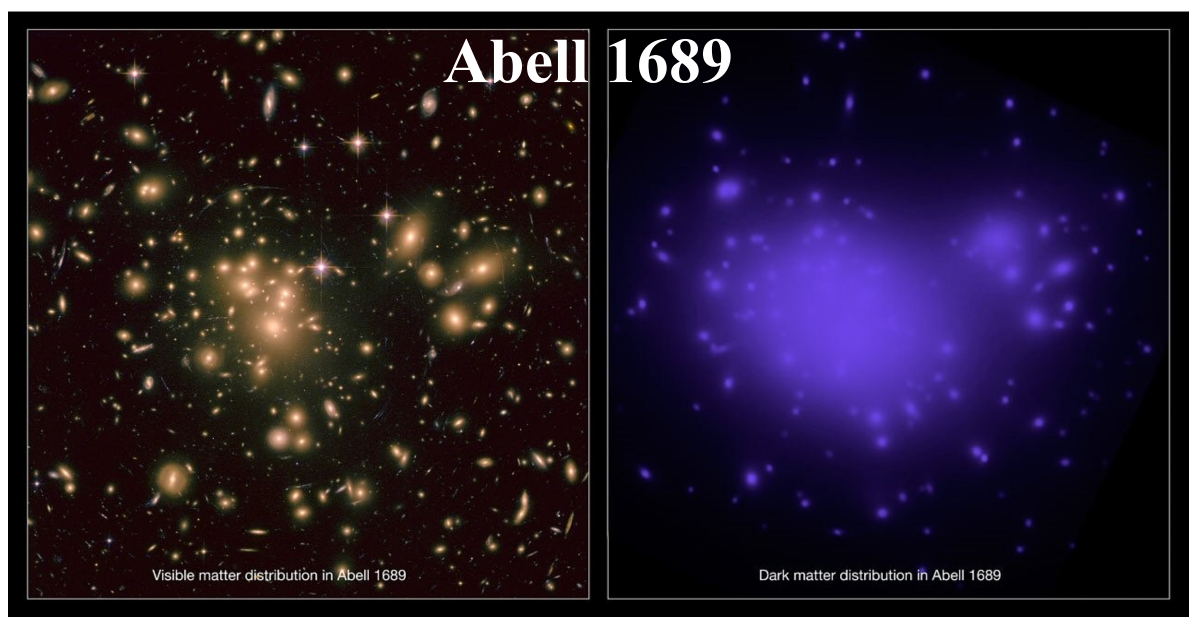

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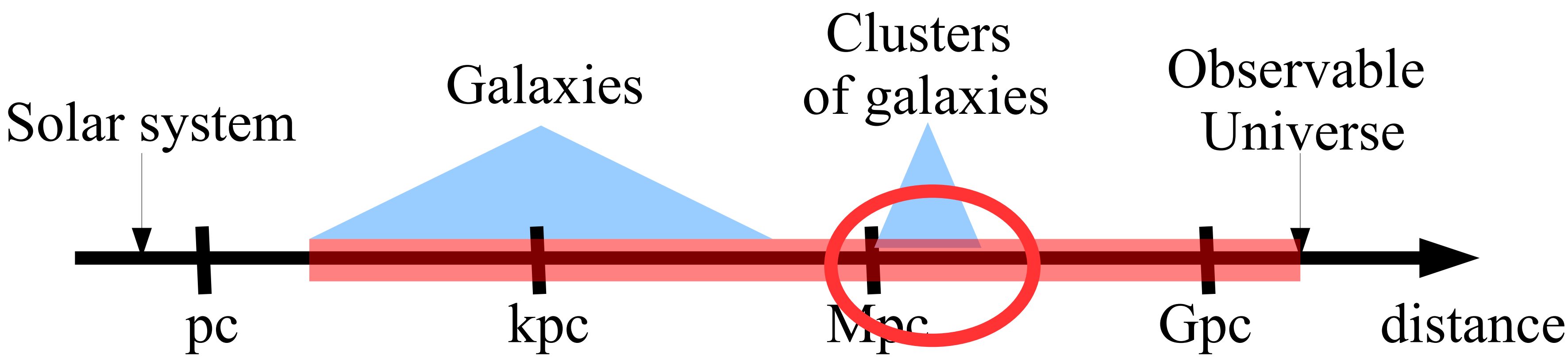

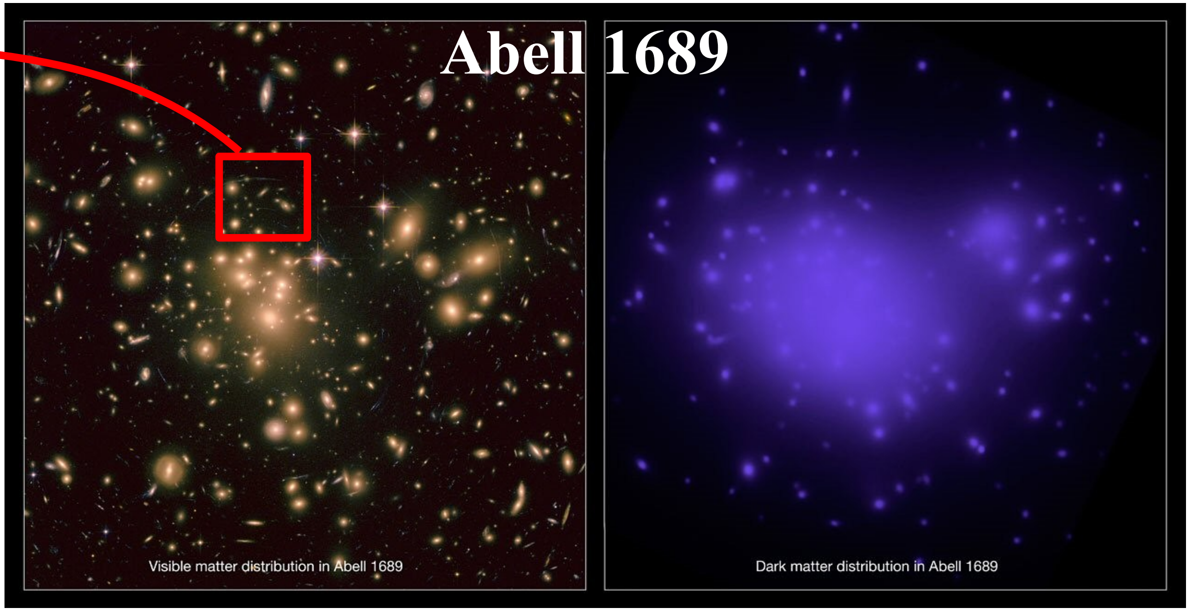

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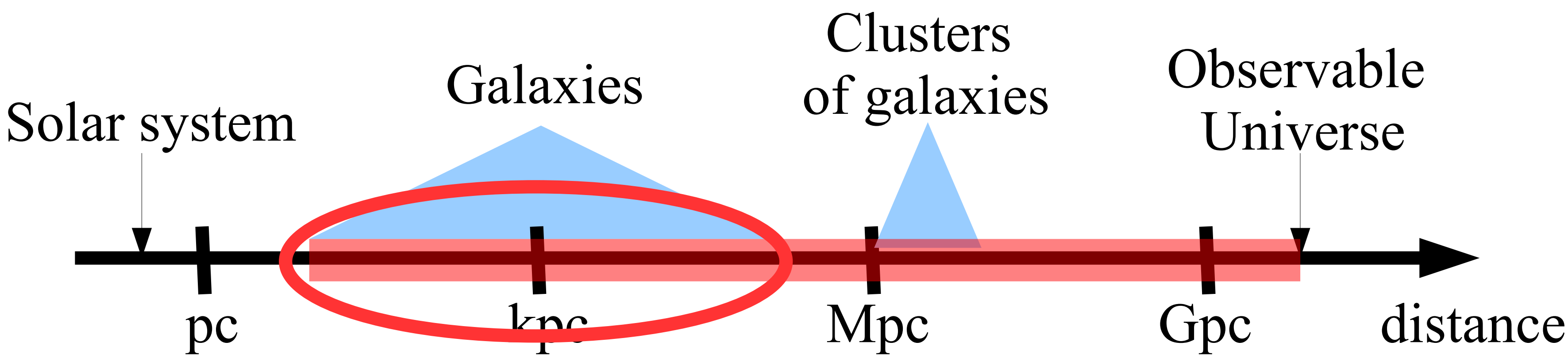

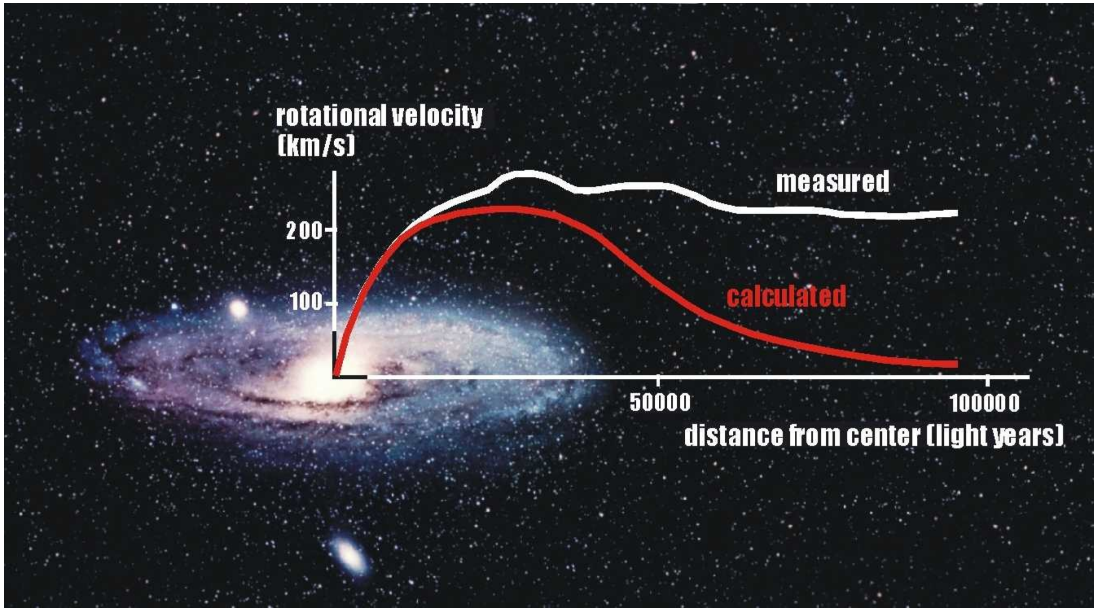

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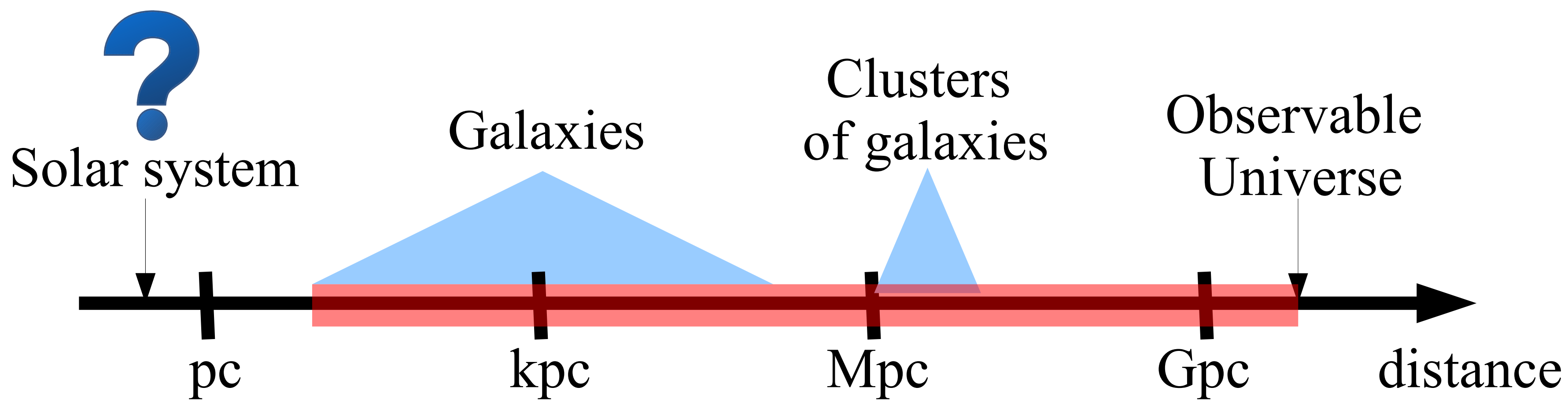

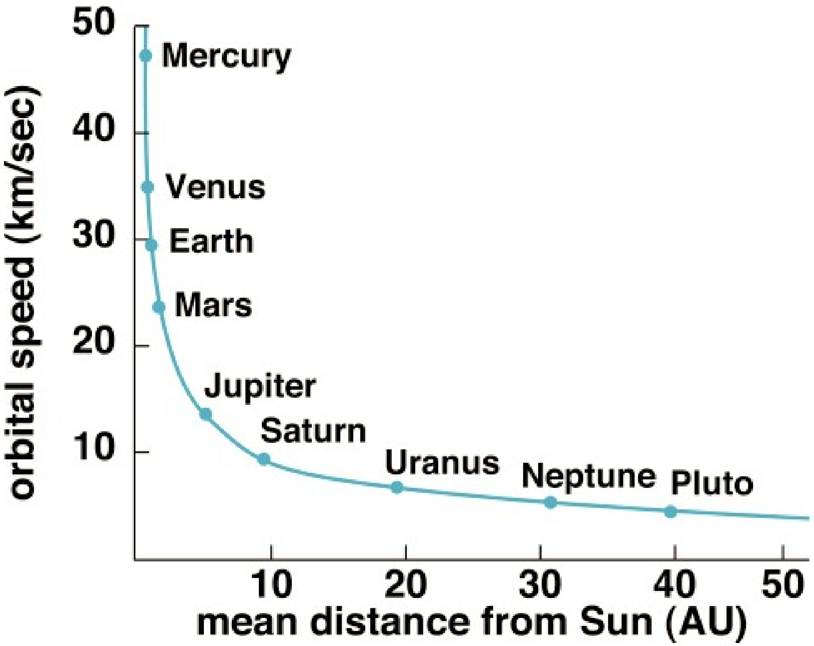

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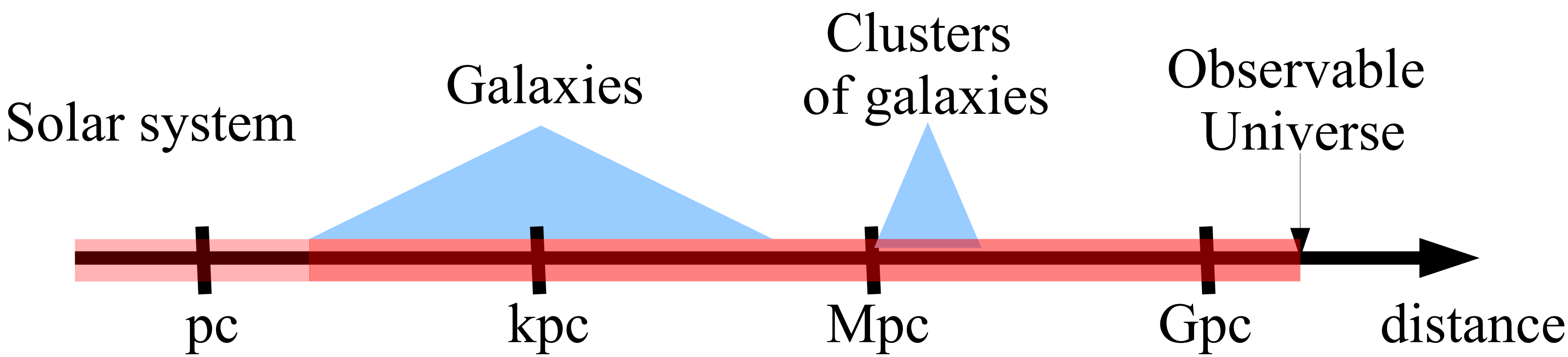
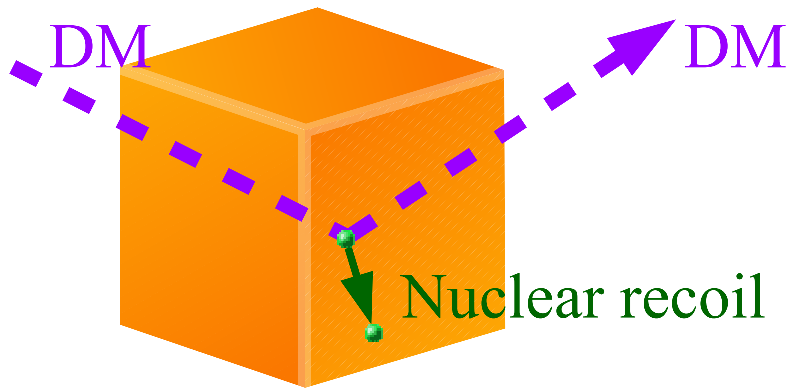


Assumption,
but well motivated

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

- Differential rate of DM-induced scatterings

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

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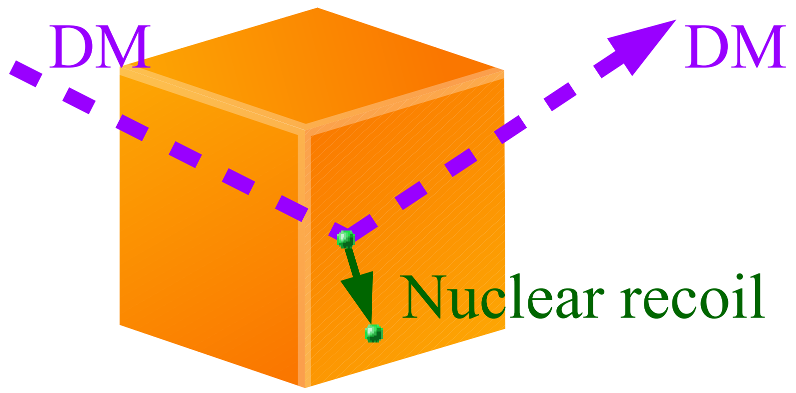

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Uncertainties from particle/nuclear physics and from astrophysics

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. Model dependent.

Nuclear form factors

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

Theoretical interpretation of the experimental results

Uncertainties from astrophysics

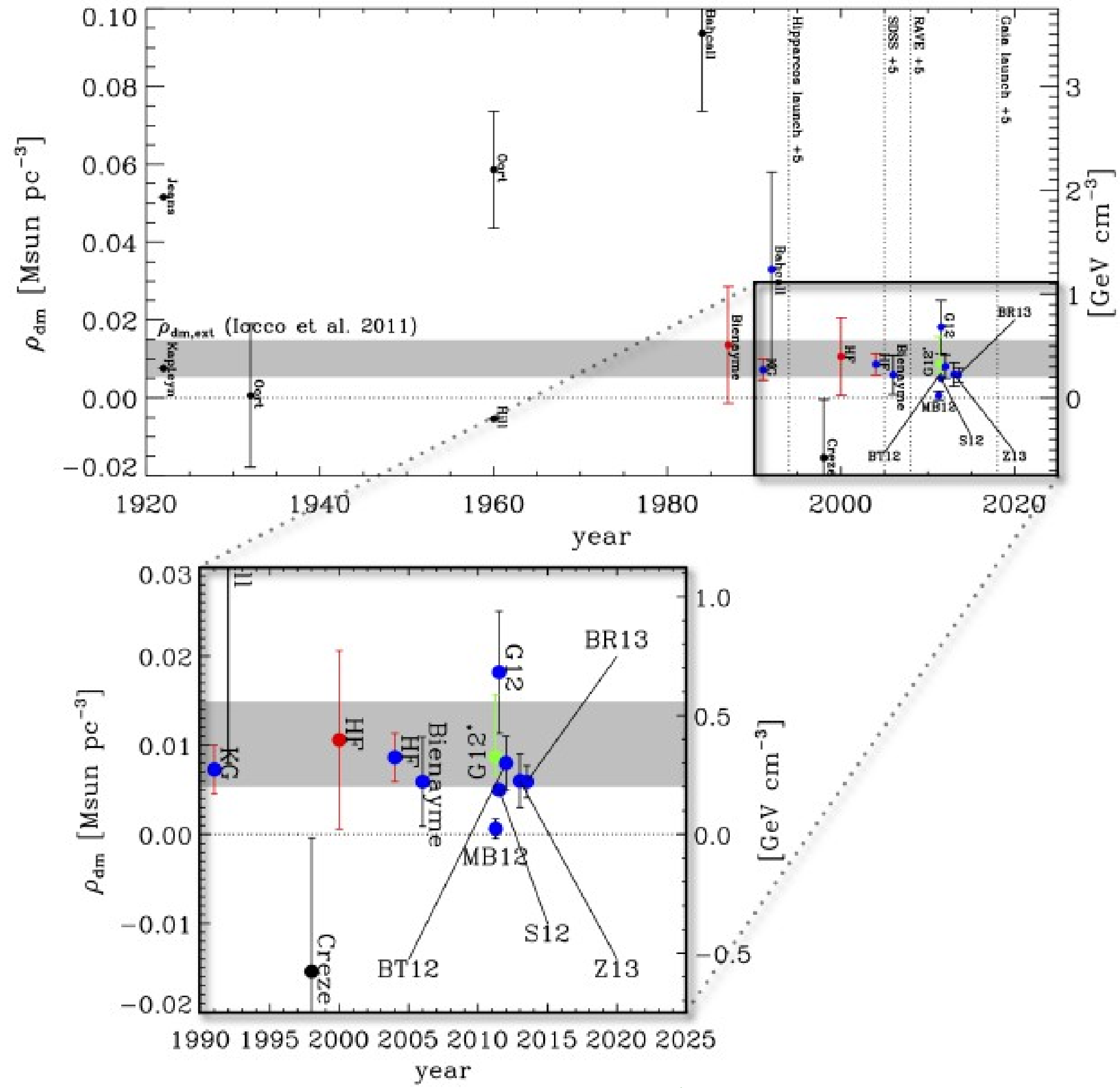
- Local dark matter density?

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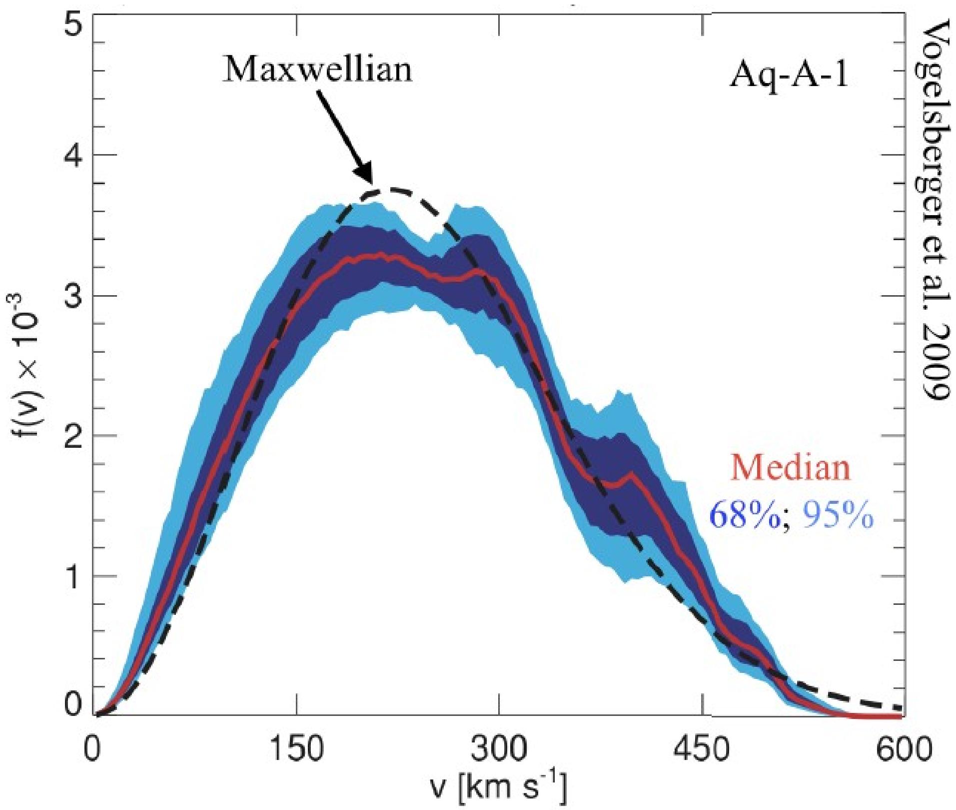
    - Dark matter-only simulations. Show deviations from Maxwell-Boltzmann



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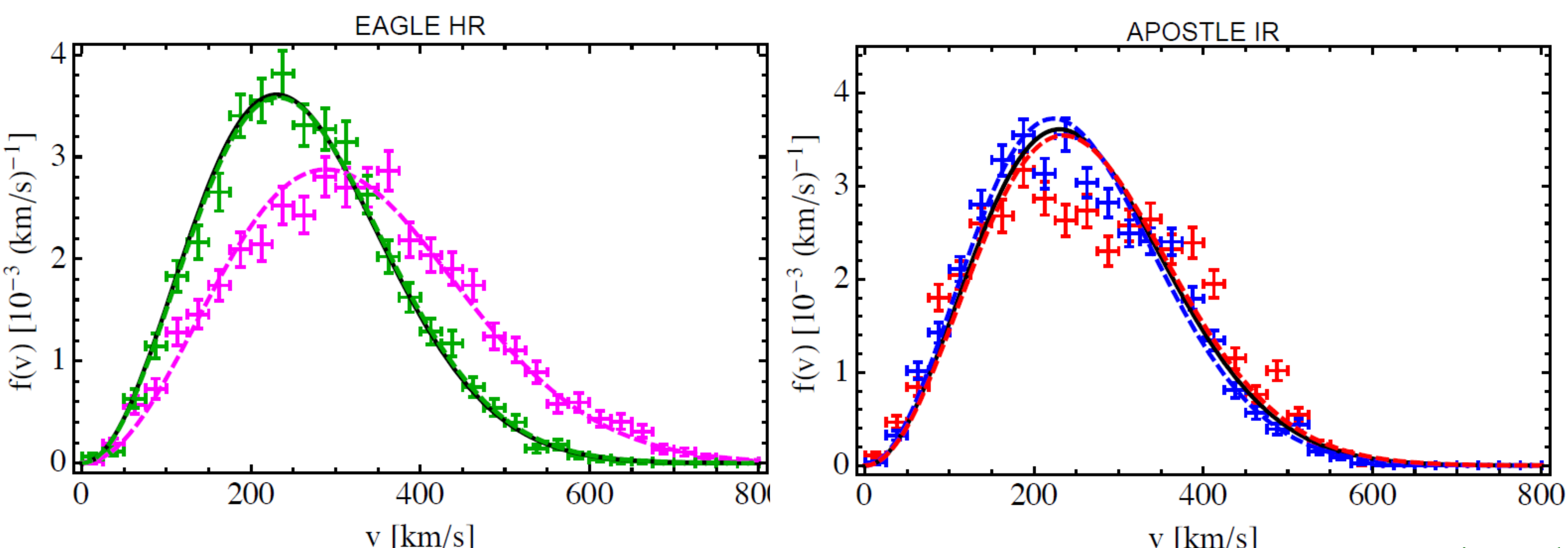
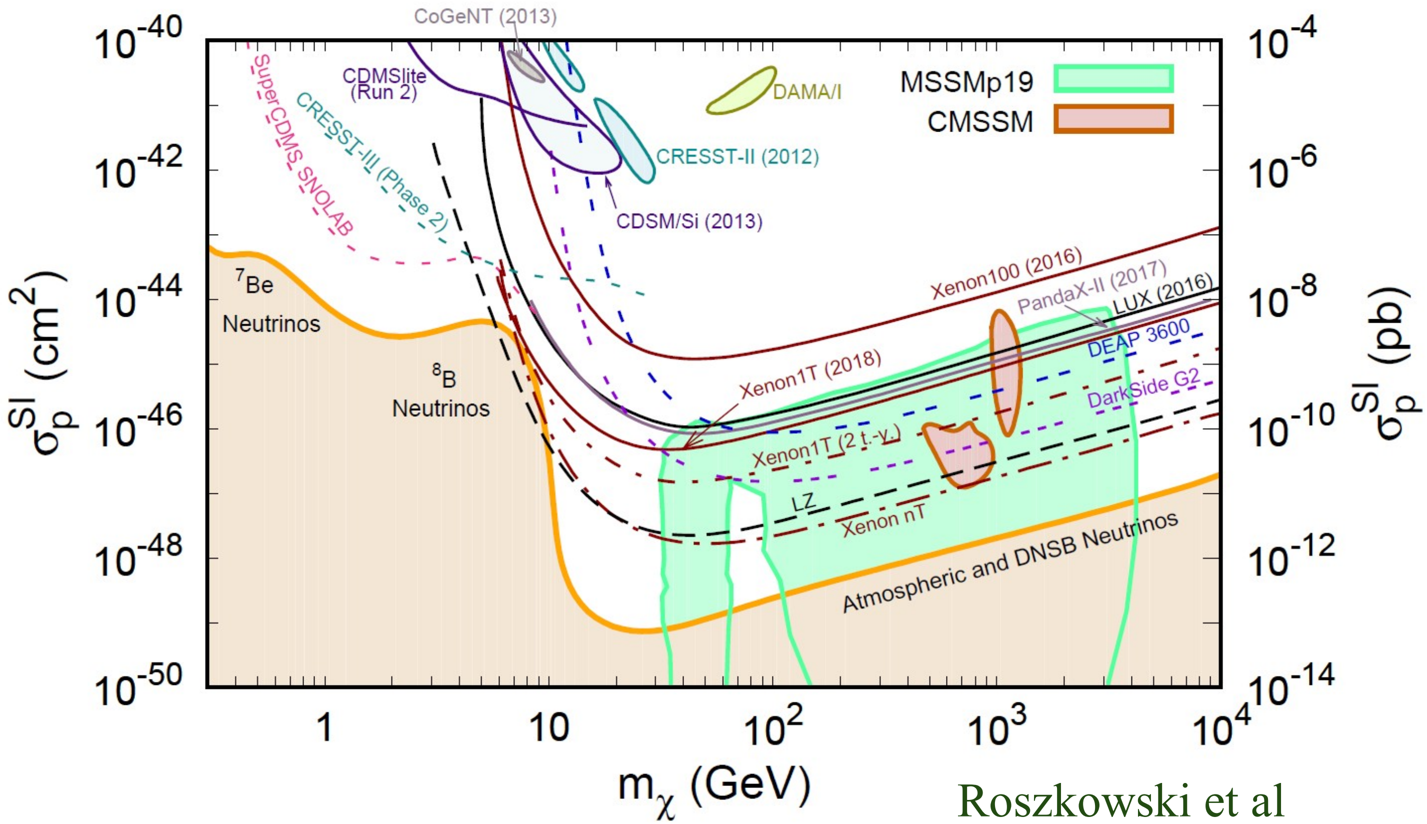
  - If the density distribution follows a singular isothermal sphere profile, the velocity distribution has a Maxwell-Boltzmann form.
  - Dark matter-only simulations. Show deviations from Maxwell-Boltzmann
  - Hydrodynamical simulations (DM+baryons). Inconclusive at the moment.



Bozorgnia et al'16

Theoretical interpretation of the experimental results

Common approach: assume SI or SD interaction only, assume that DM couples with equal strength to protons and to neutrons, assume ρ_{loc}= 0.3 GeV/cm^3 and assume a Maxwell-Boltzmann velocity distribution



Roszkowski et al
1707.06277

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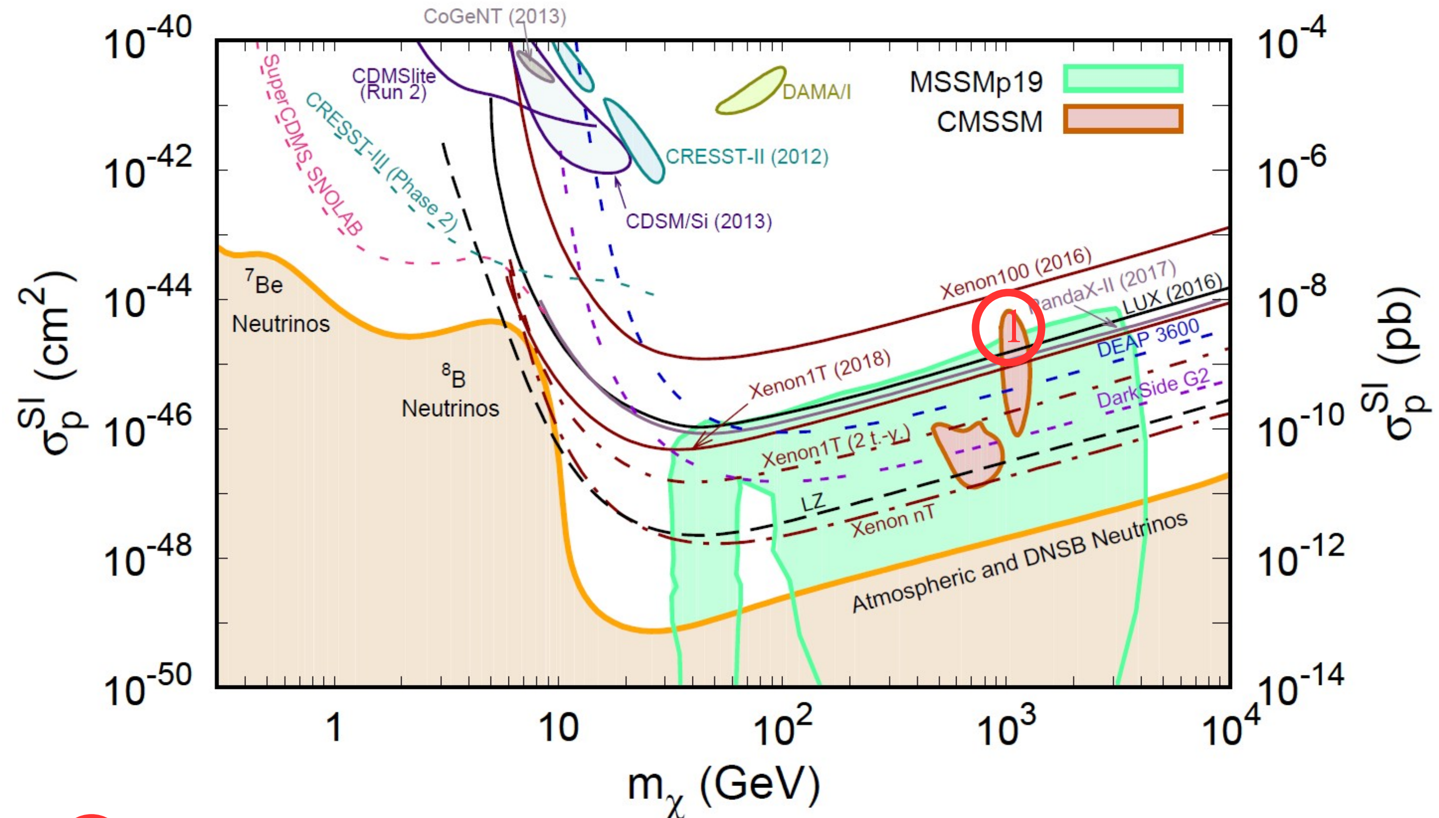

① is ruled out (by XENON1T, among others)

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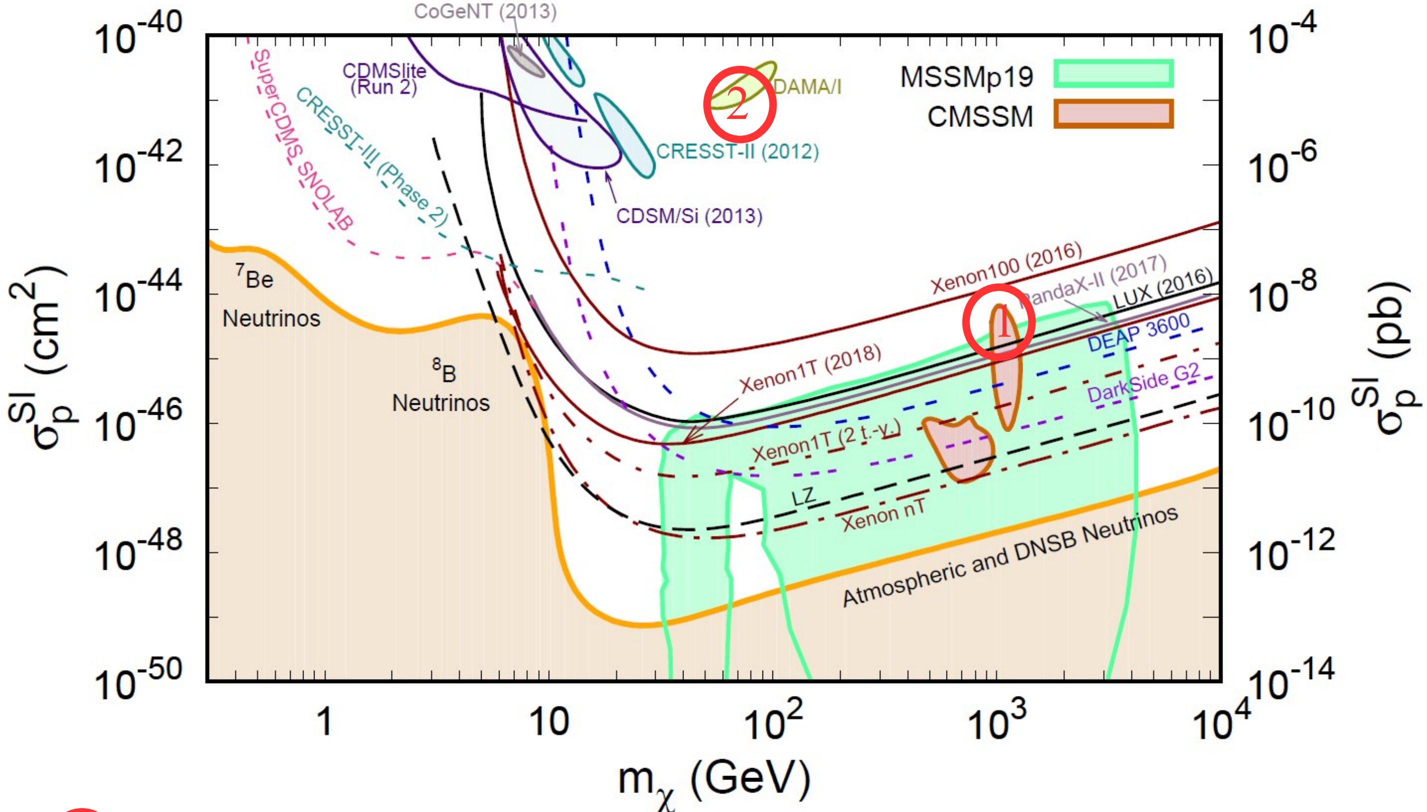

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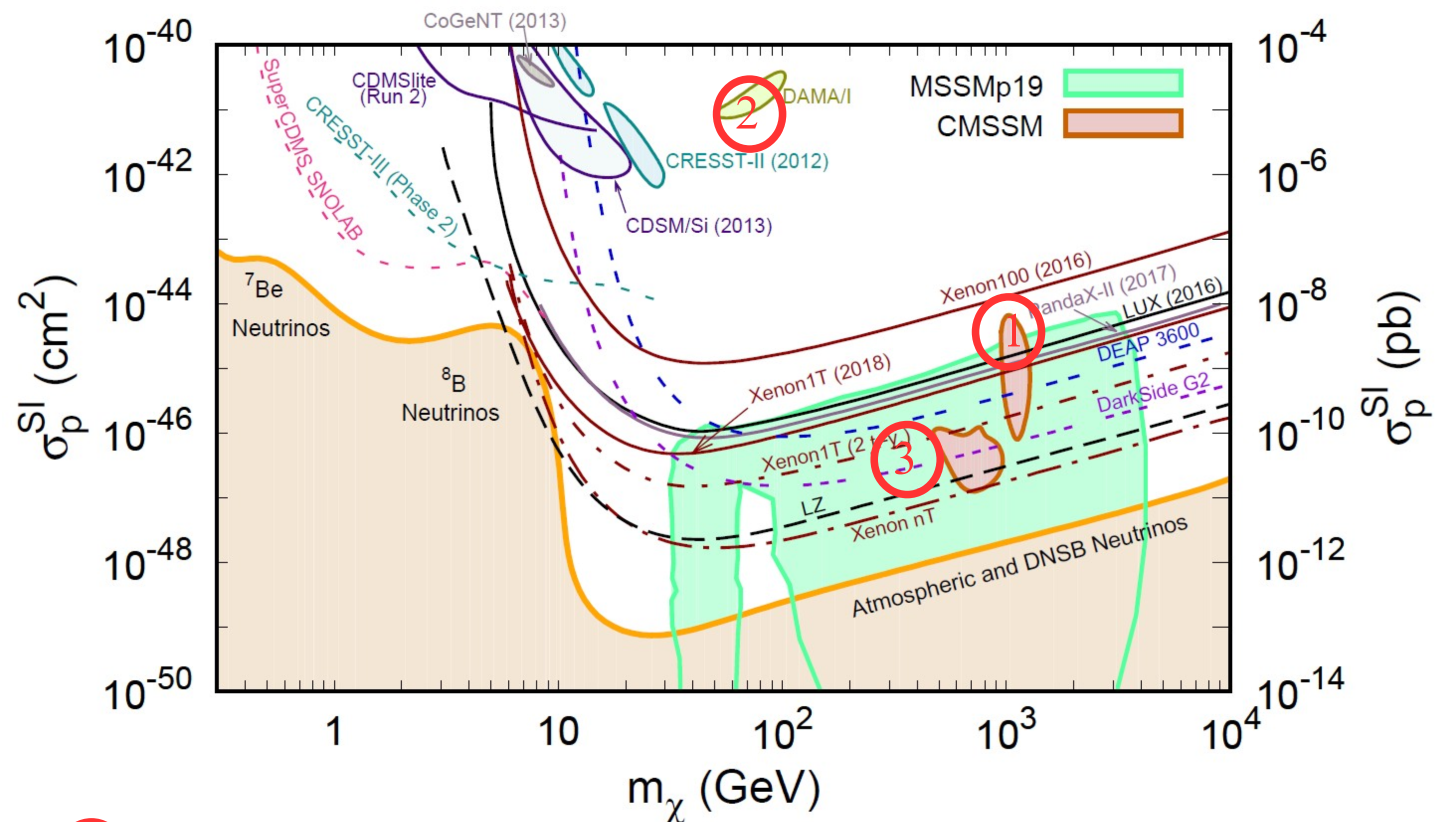

(1) is ruled out (by XENON1T, among others)

(2) explains the DAMA results, but is ruled out by other direct detection experiments and by neutrino telescopes

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

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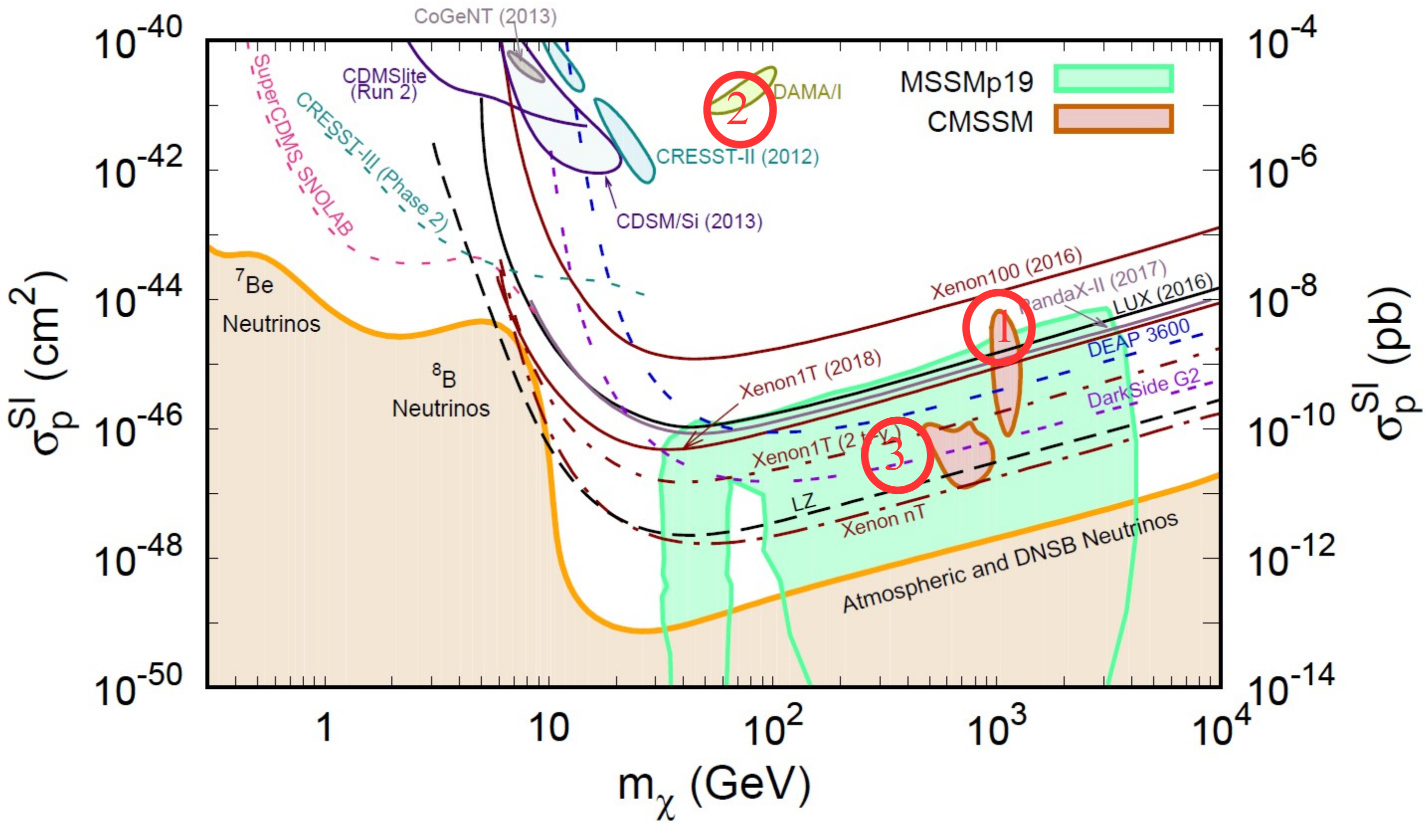

Note: not all points in the MSSM predict equal coupling to protons and neutrons.
Is there a limit applicable to all MSSM points?

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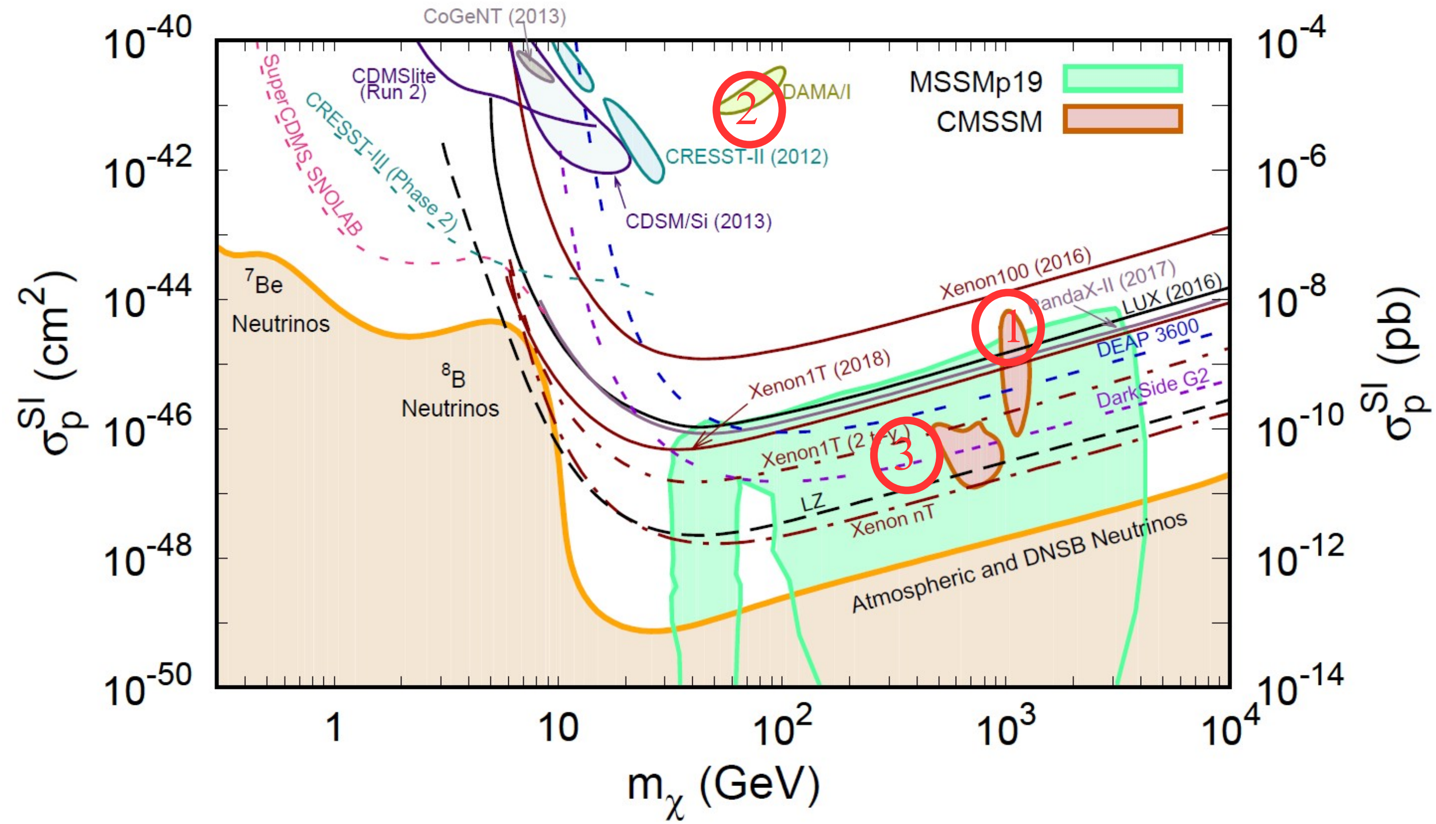

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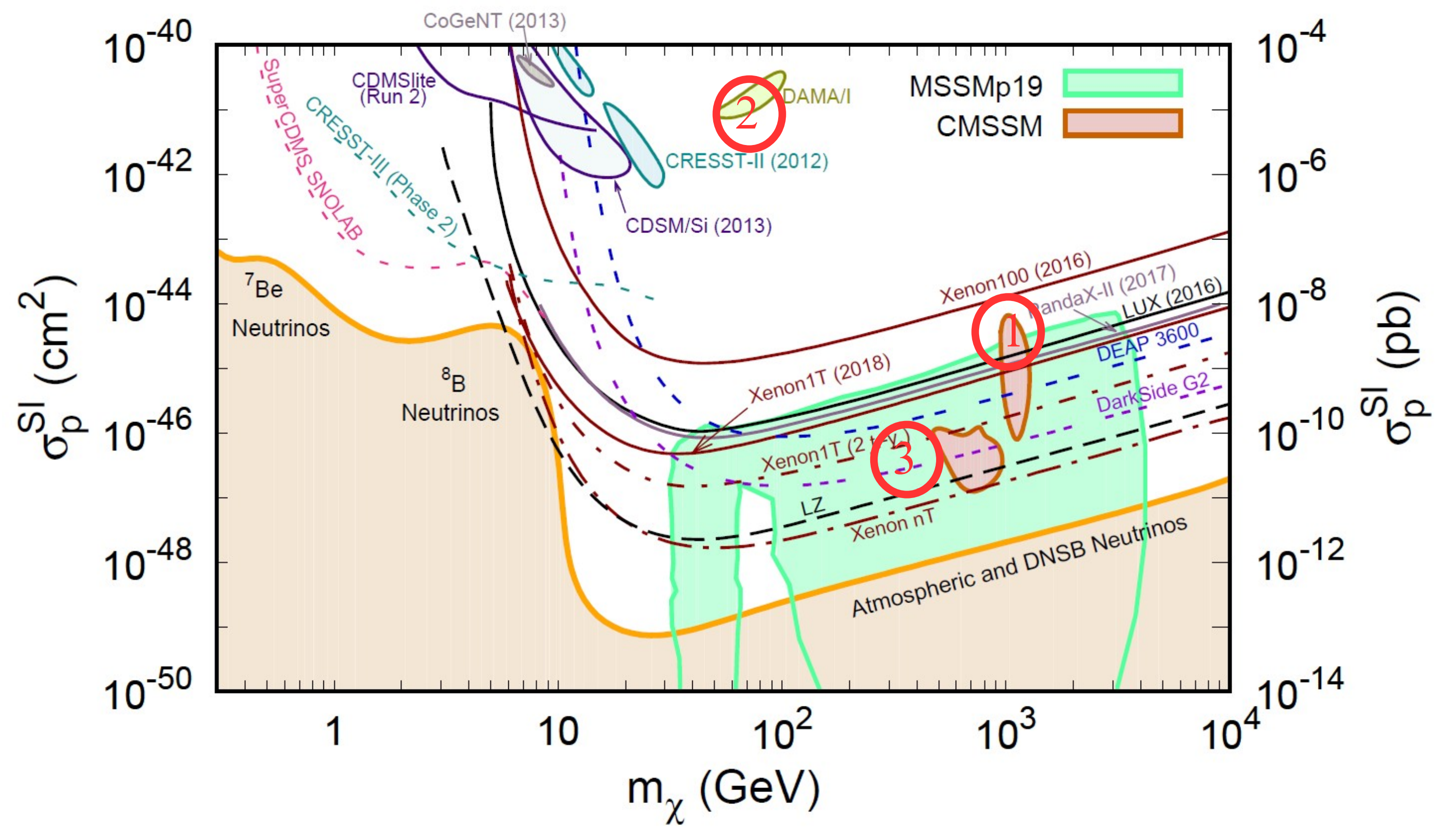

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Is there a limit applicable to all DM models?

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

Addressing particle physics uncertainties in dark matter detection

Impact of operator interference

Consider the Hamiltonian of the SI interaction:

$$\mathcal{H} = c_p(\overline{\chi}p)(\overline{p}\chi) + c_n(\overline{\chi}n)(\overline{n}\chi)$$

Scattering rate ~ $\left|\mathcal{H}\right|^2 \sim c_p^2 R_{pp} + 2c_p c_n R_{pn} + c_n^2 R_{nn}$

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Depend on the underlying particle physics model (couplings, mediator masses)

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Include response functions, detector efficiency, etc.
Depend on the DM mass (and astrophysics)

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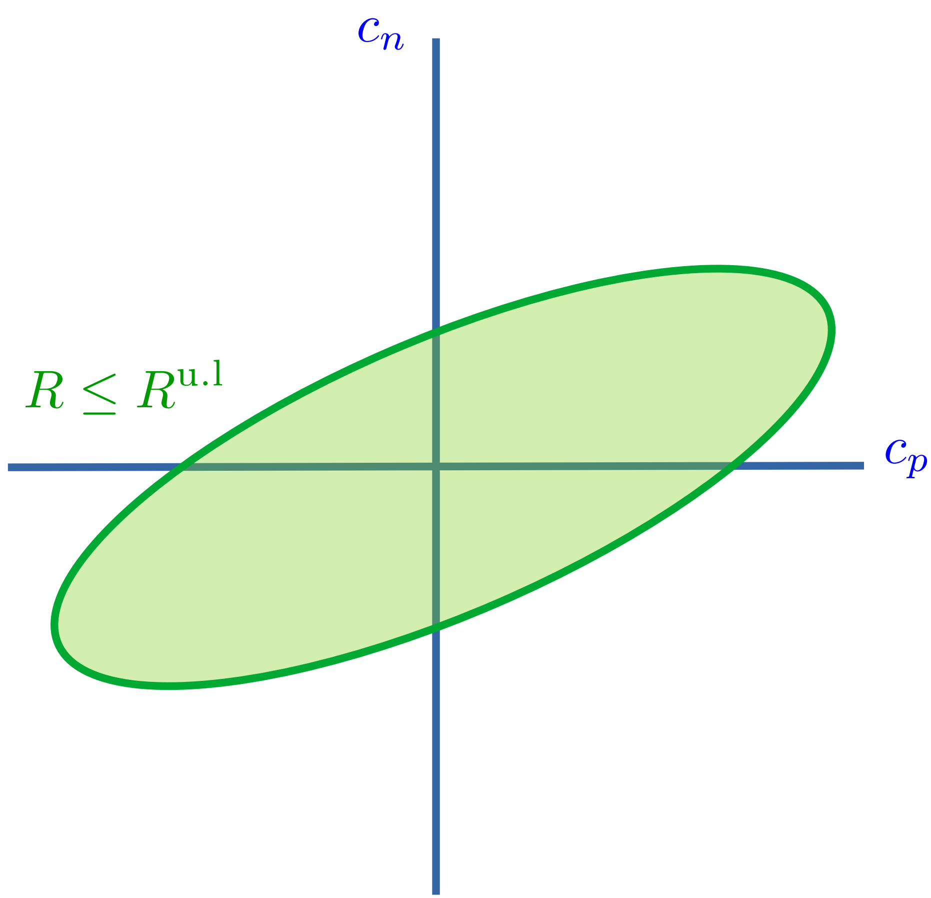

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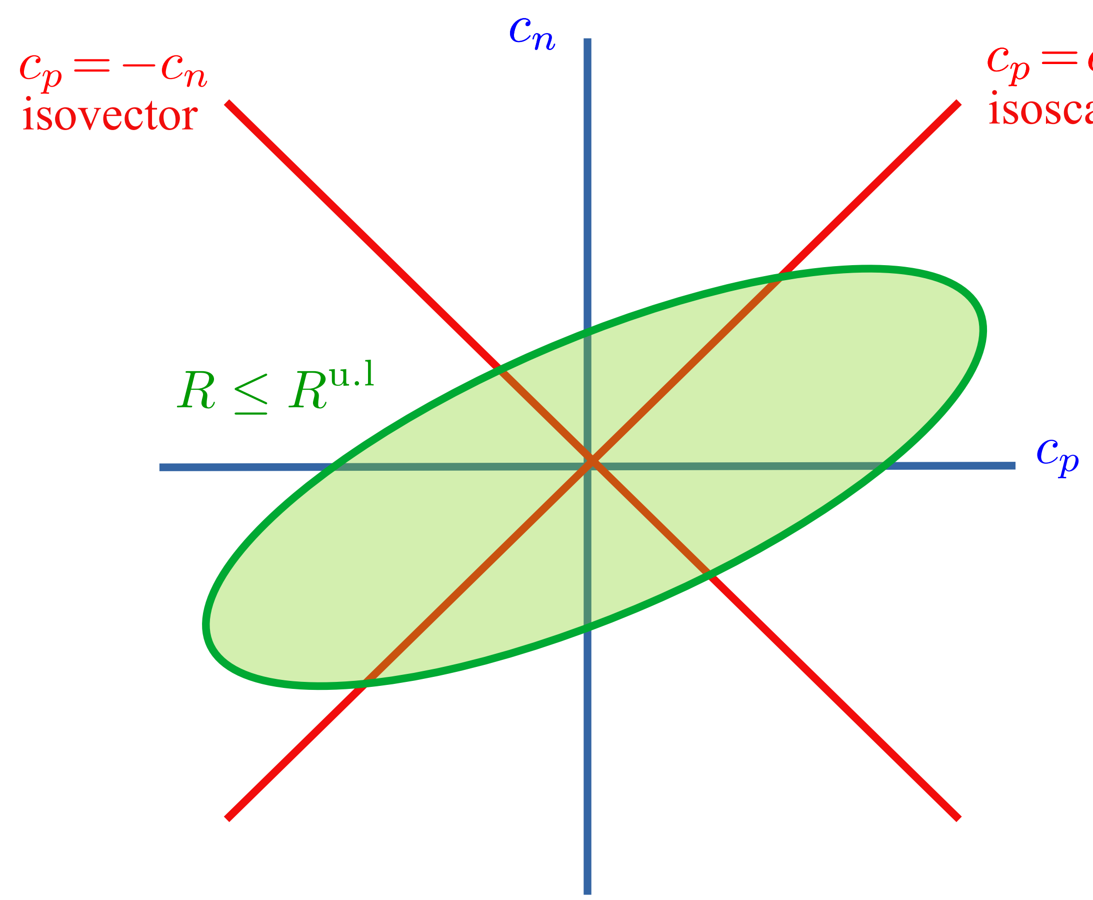

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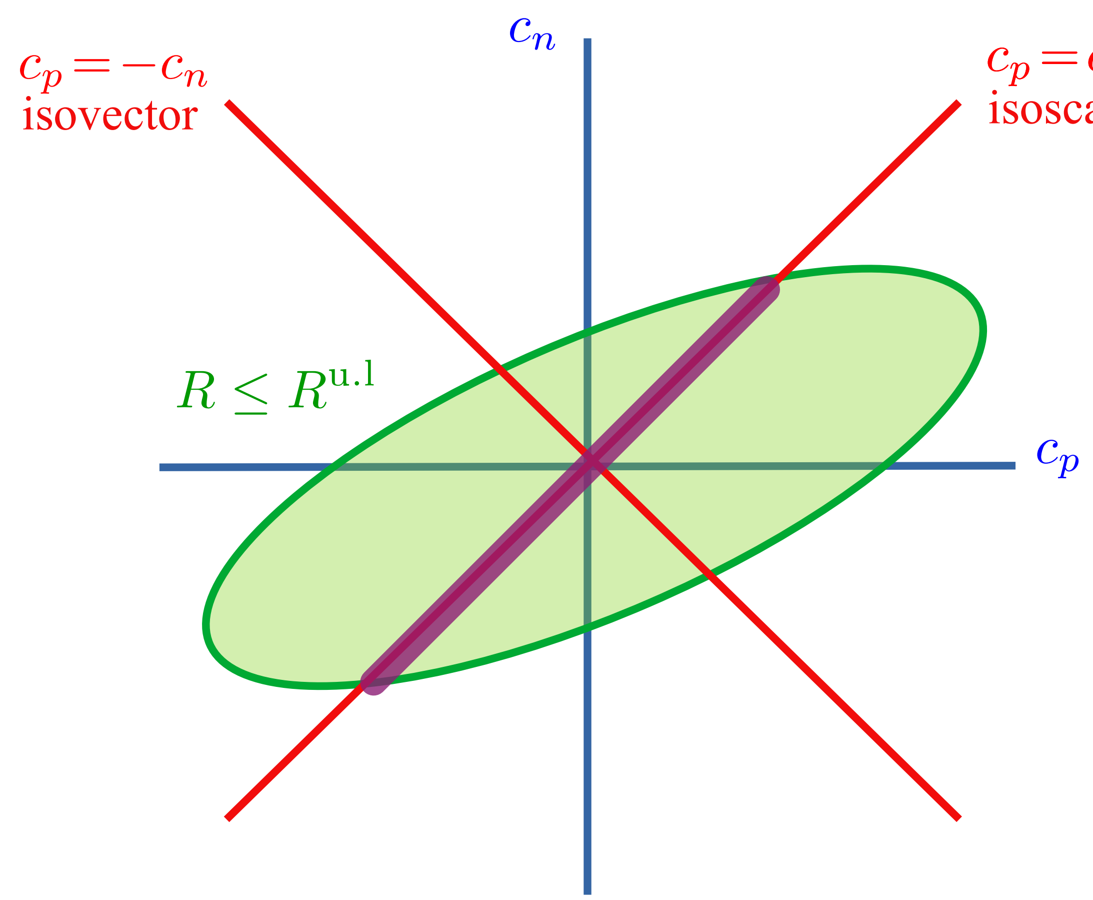

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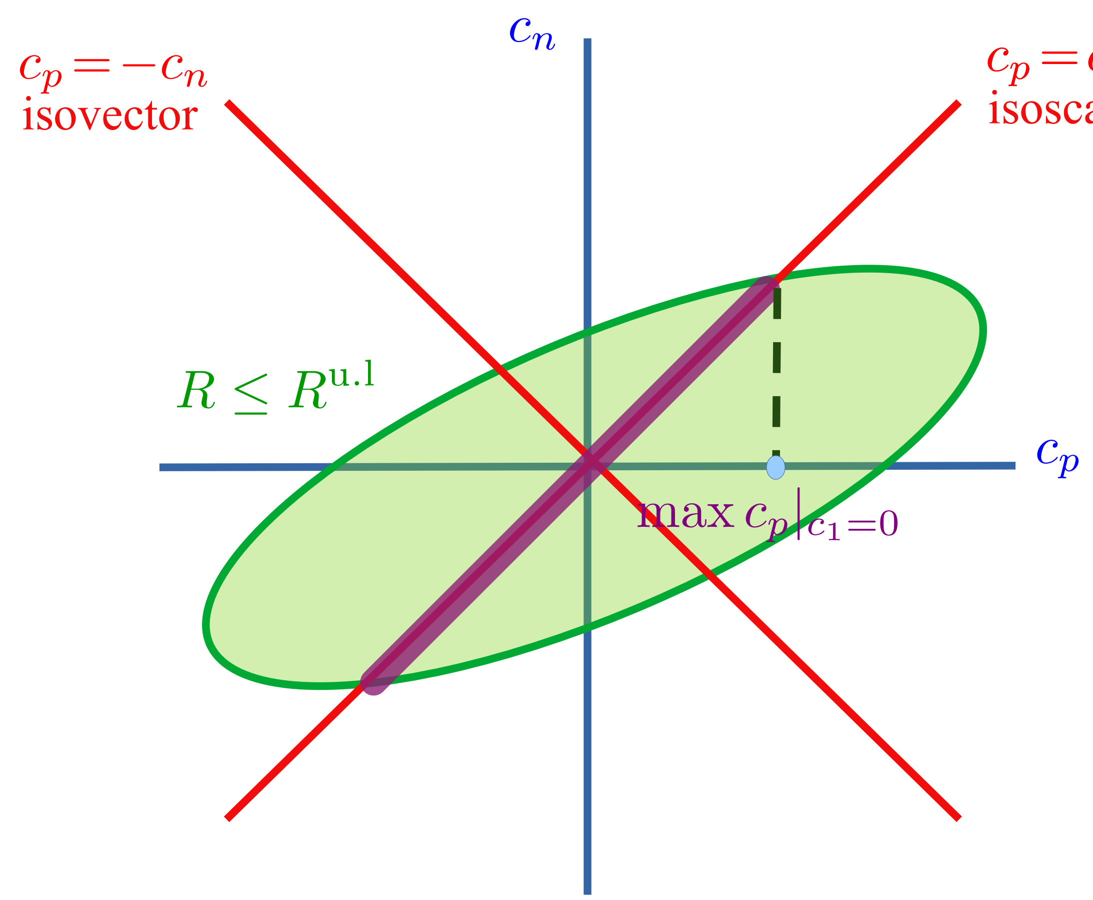

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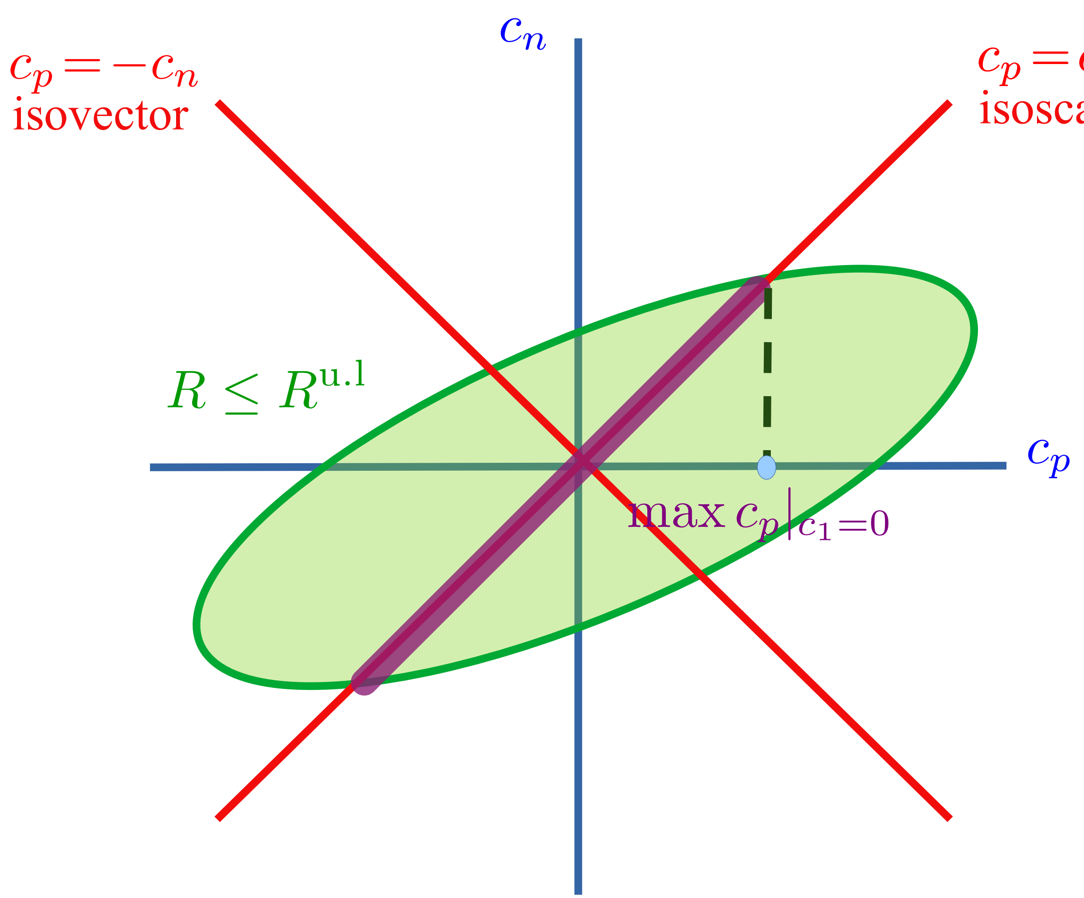

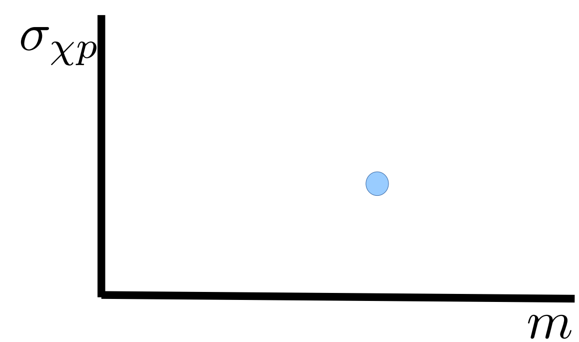

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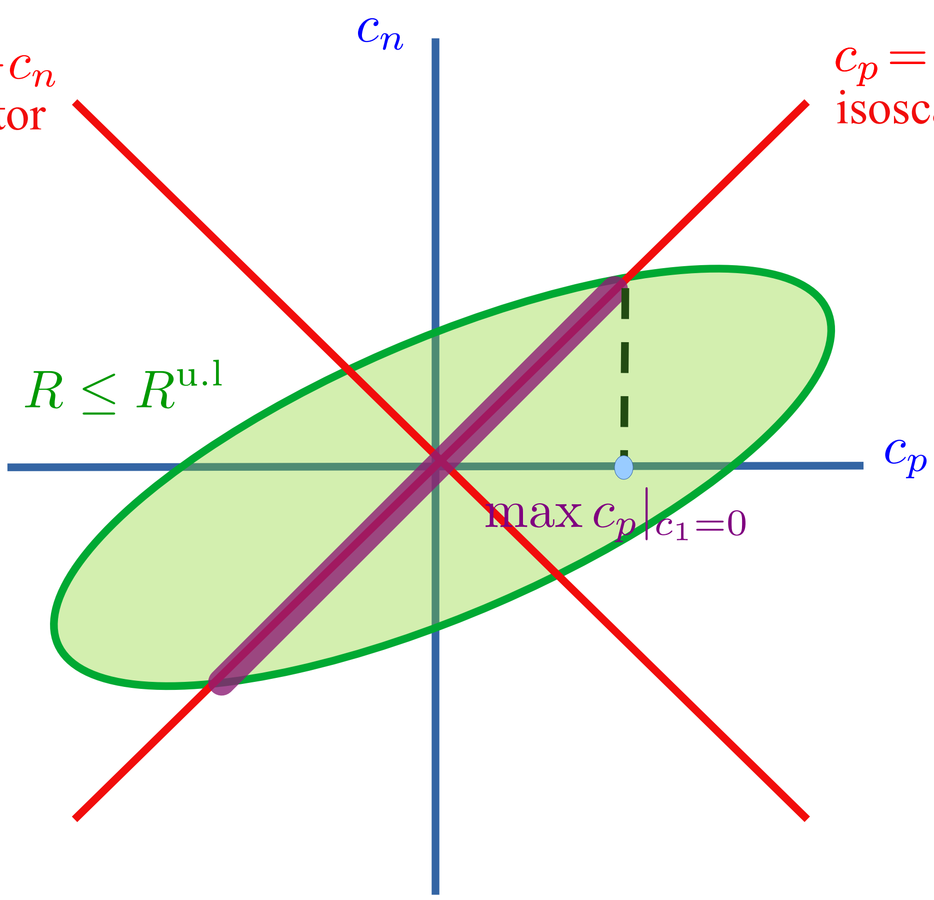

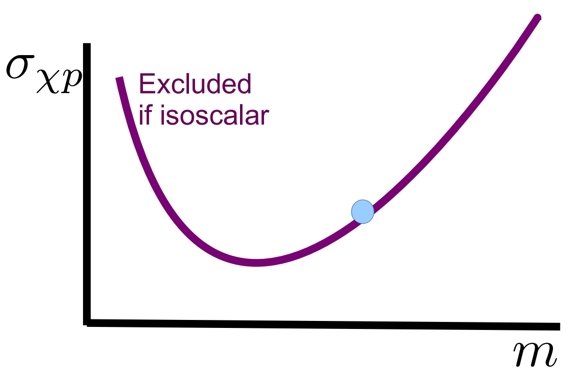

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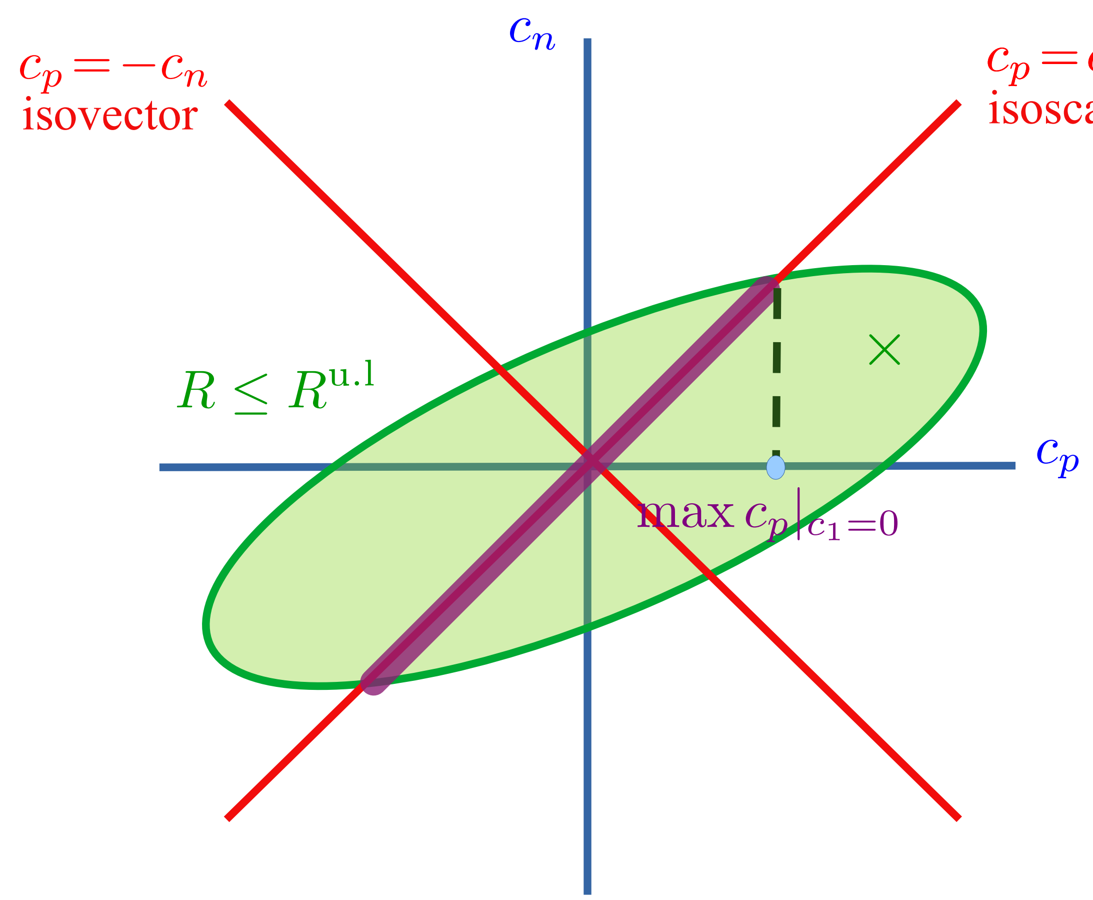

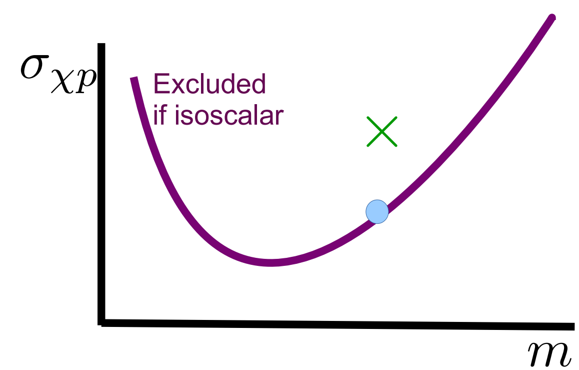

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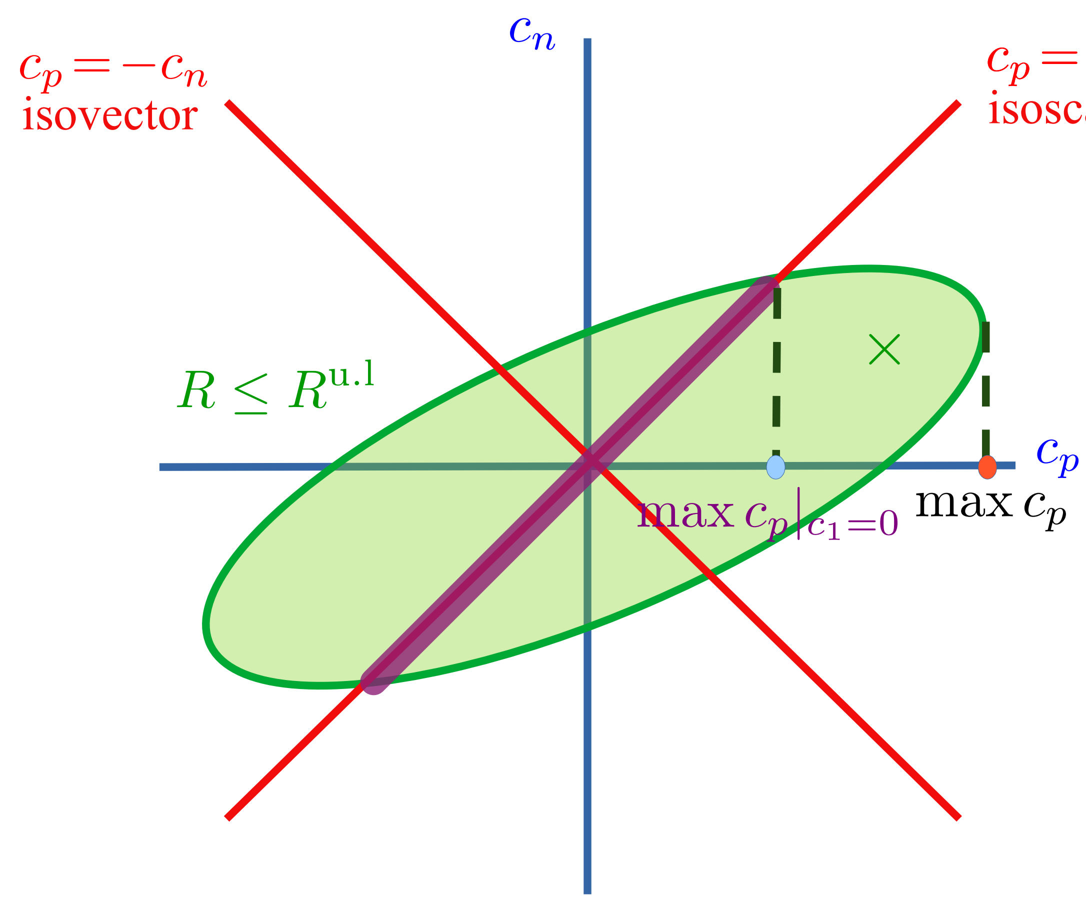

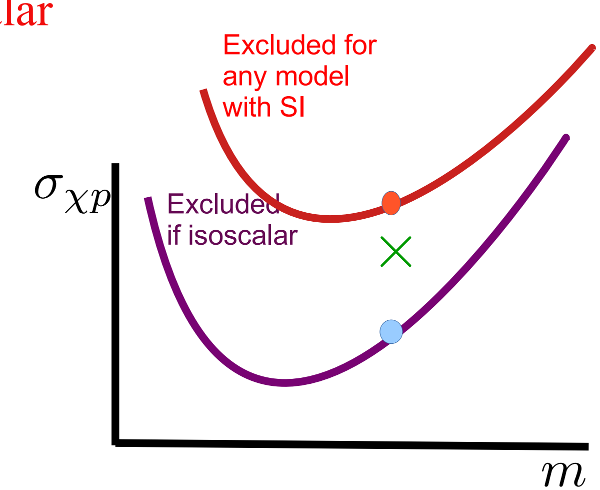

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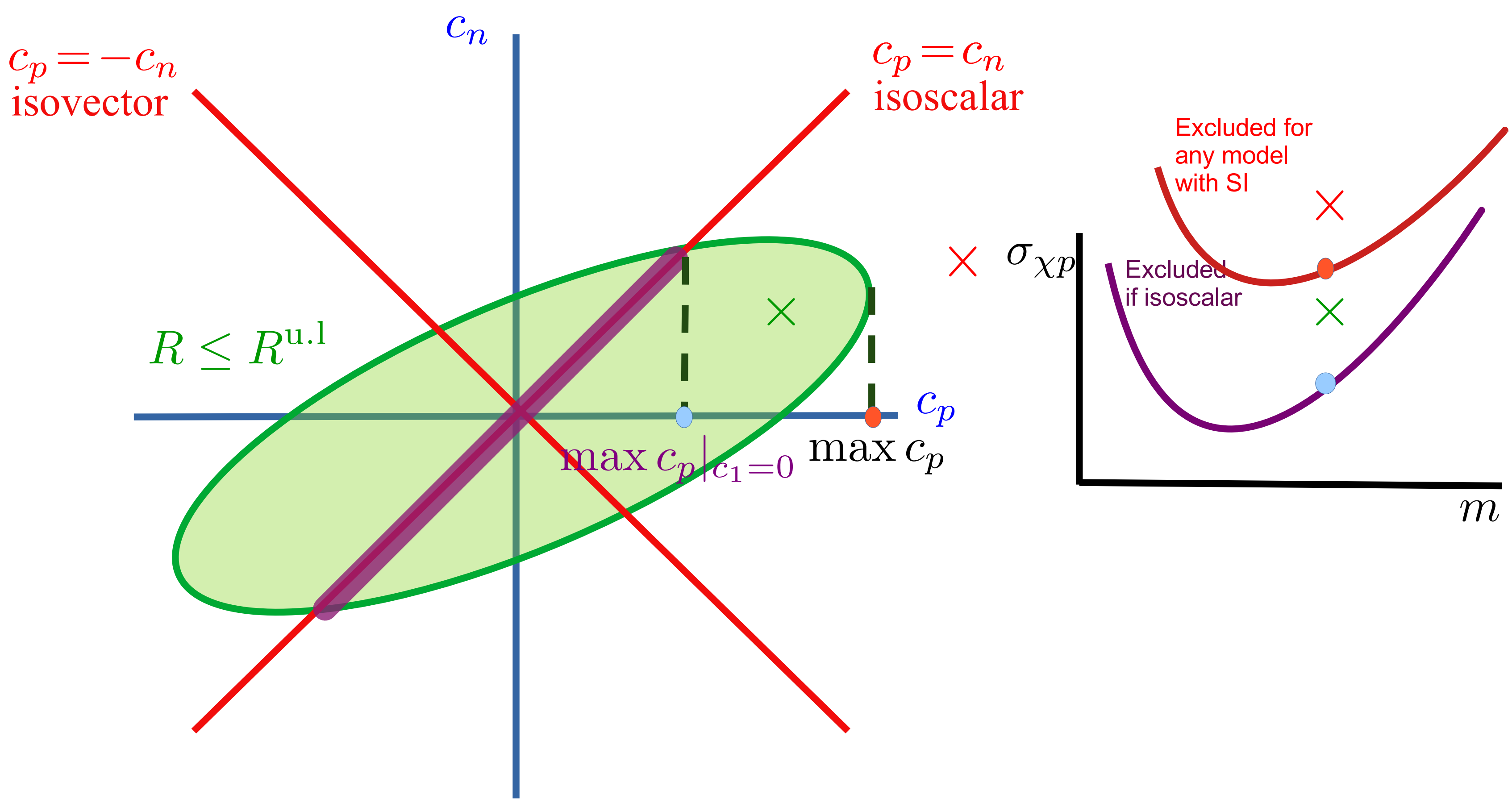

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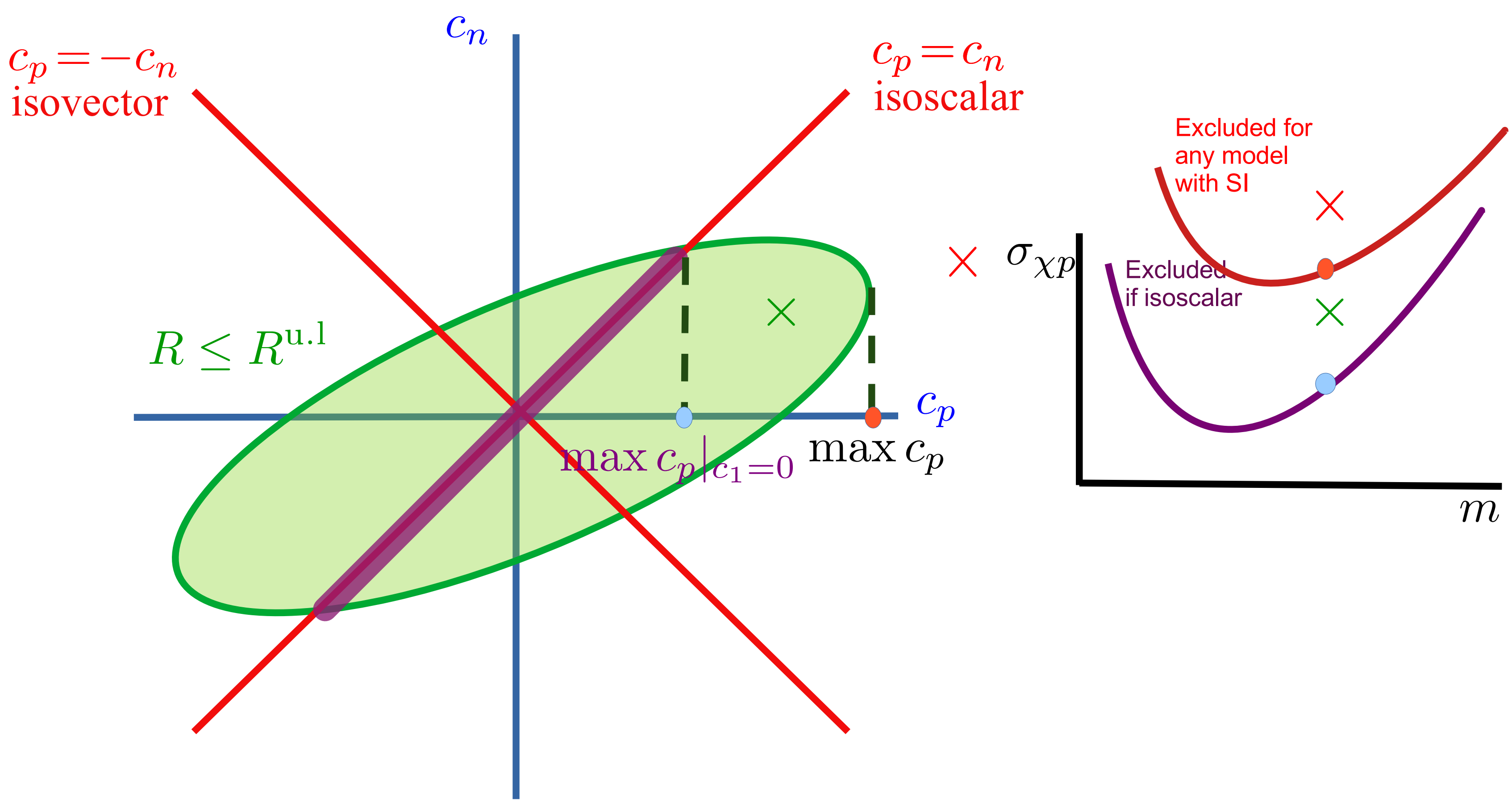

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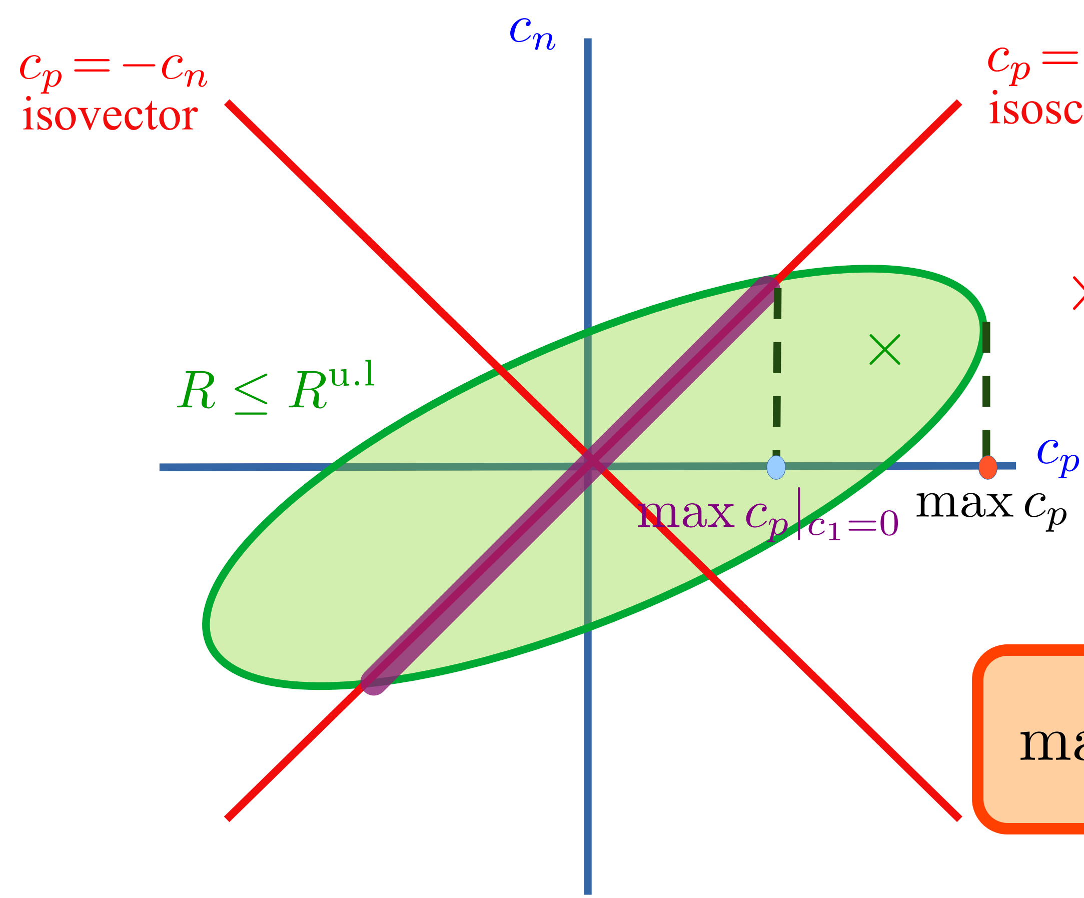

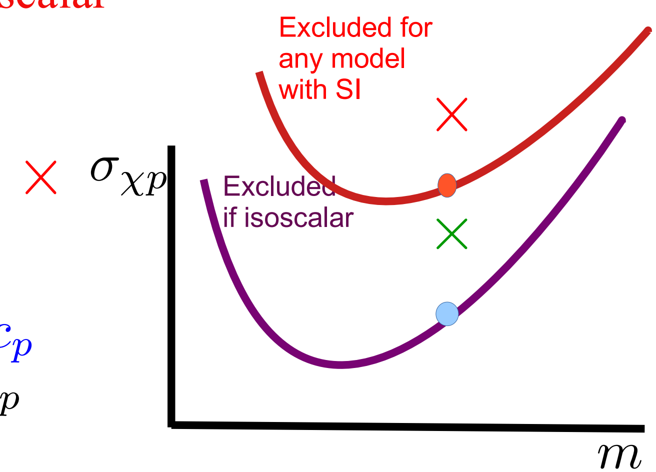

$$\max c_p = \sqrt{(\mathbb{R}^{-1})_{11} R^{\rm u.l.}}$$

Brenner, AI
2011.02929

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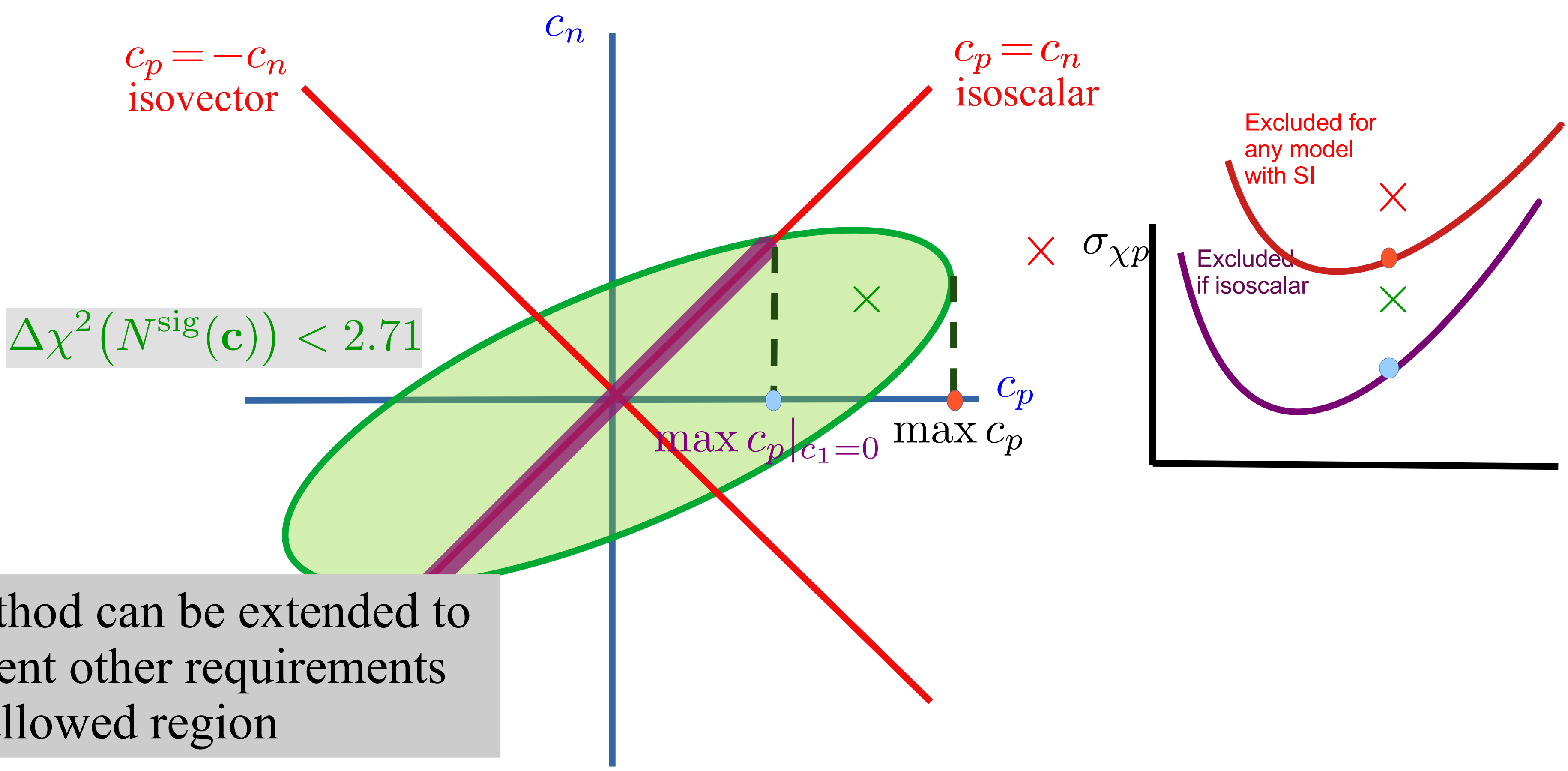
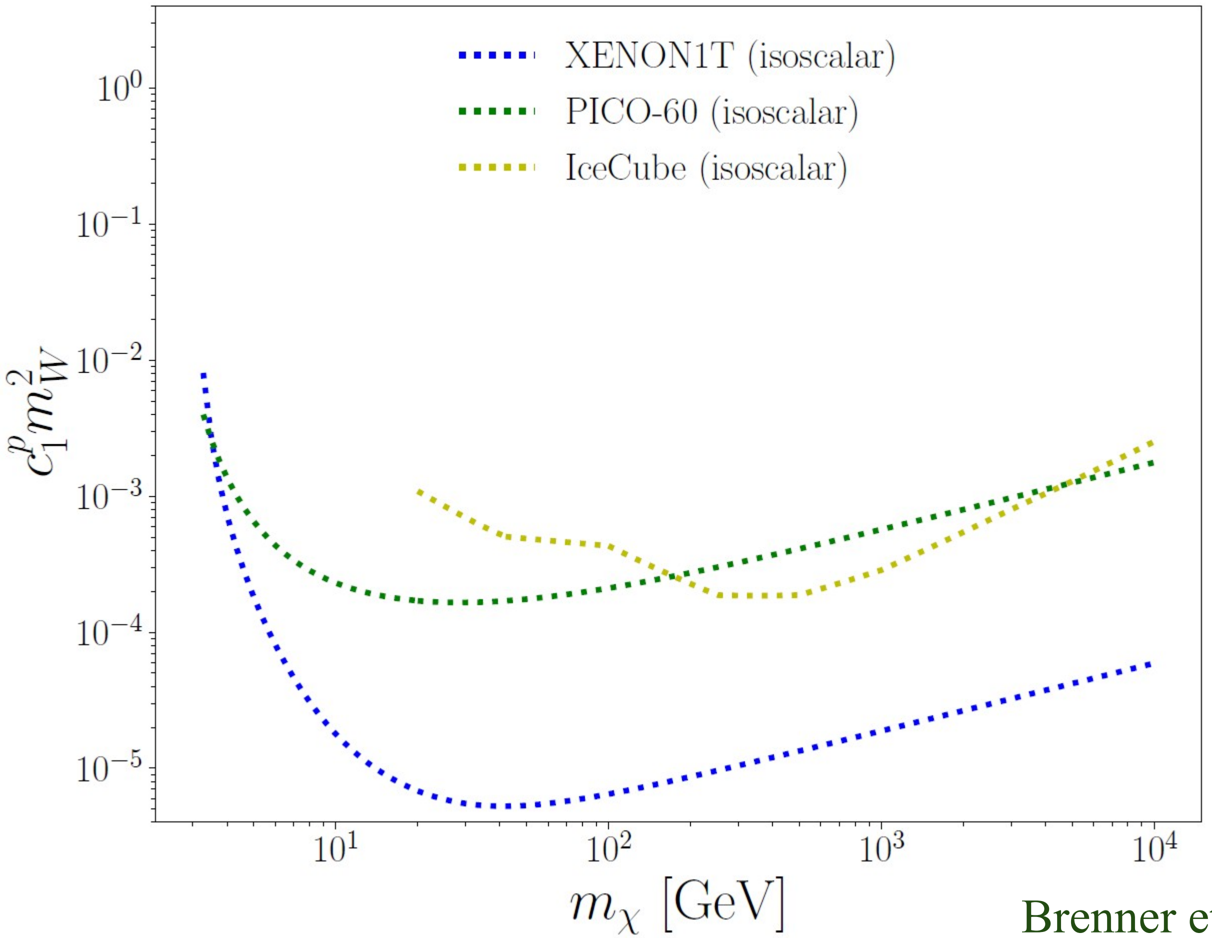


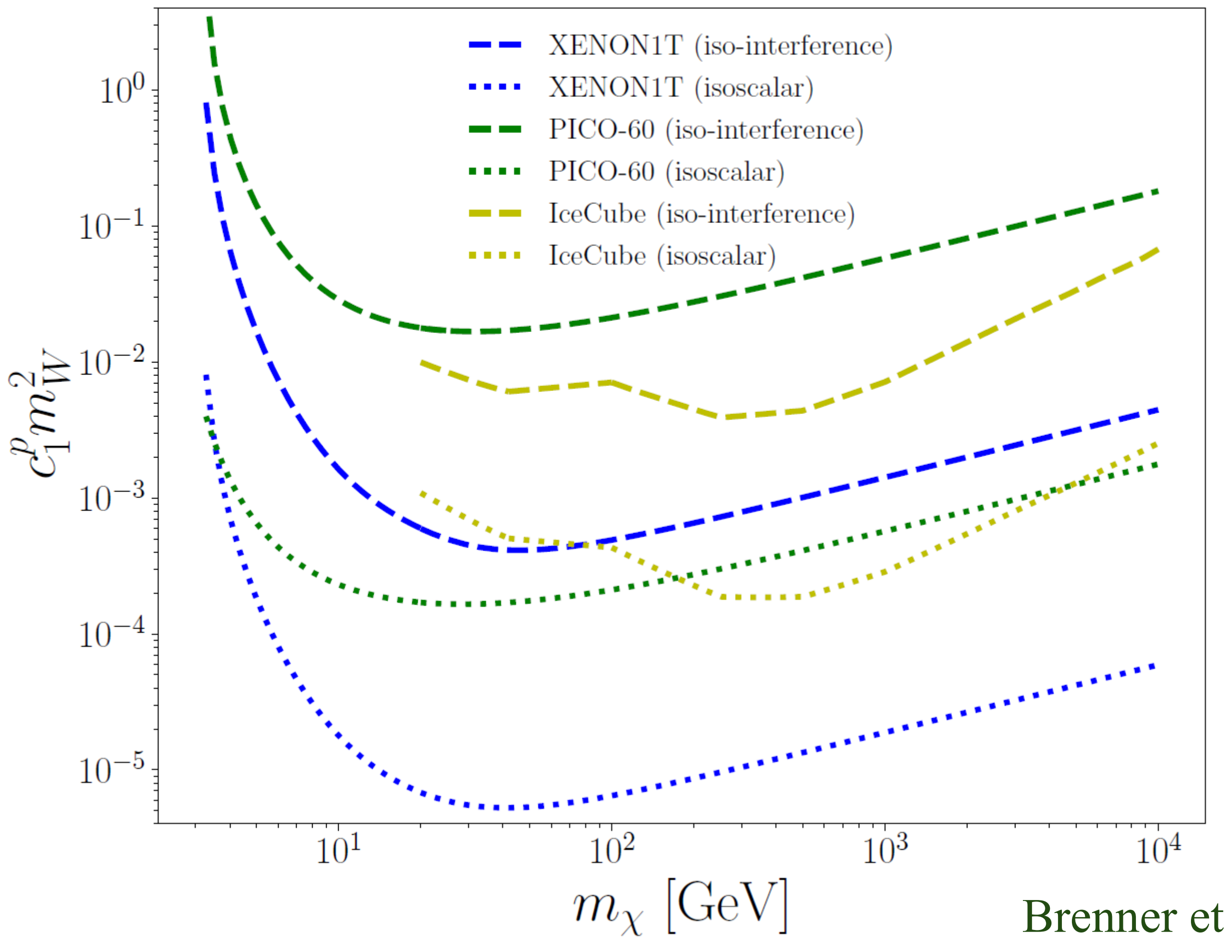
The method can be extended to implement other requirements on the allowed region

Impact of operator interference



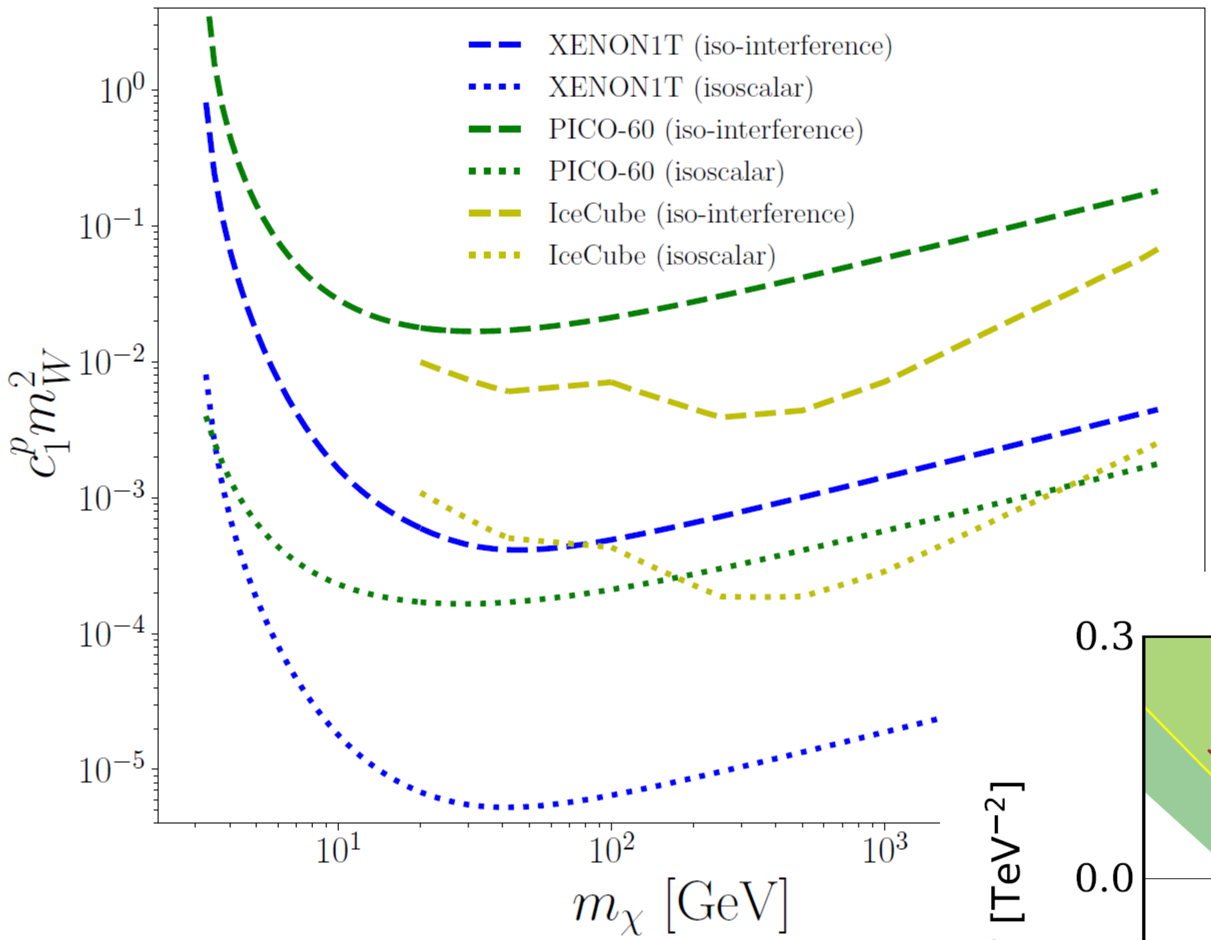
Brenner et al. To appear

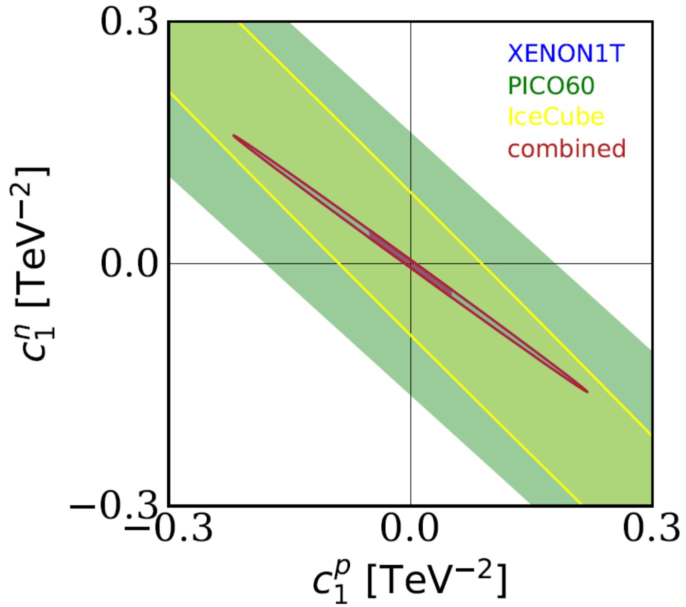
Impact of operator interference



Brenner et al. To appear

Impact of operator interference





Impact of operator interference: NREFT

In the non-relativistic theory of dark matter-nucleon interactions, there are 28 possible interactions for spin ½ DM (8 for spin 0):

$\mathcal{O}_1 = 1_\chi 1_N$	$\mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$
$\mathcal{O}_3 = i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$
$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$	$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$
$\mathcal{O}_5 = i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	$\mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$
$\mathcal{O}_6 = (\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$	$\mathcal{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^\perp)(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$
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Fitzpatrick et al. 1203.3542

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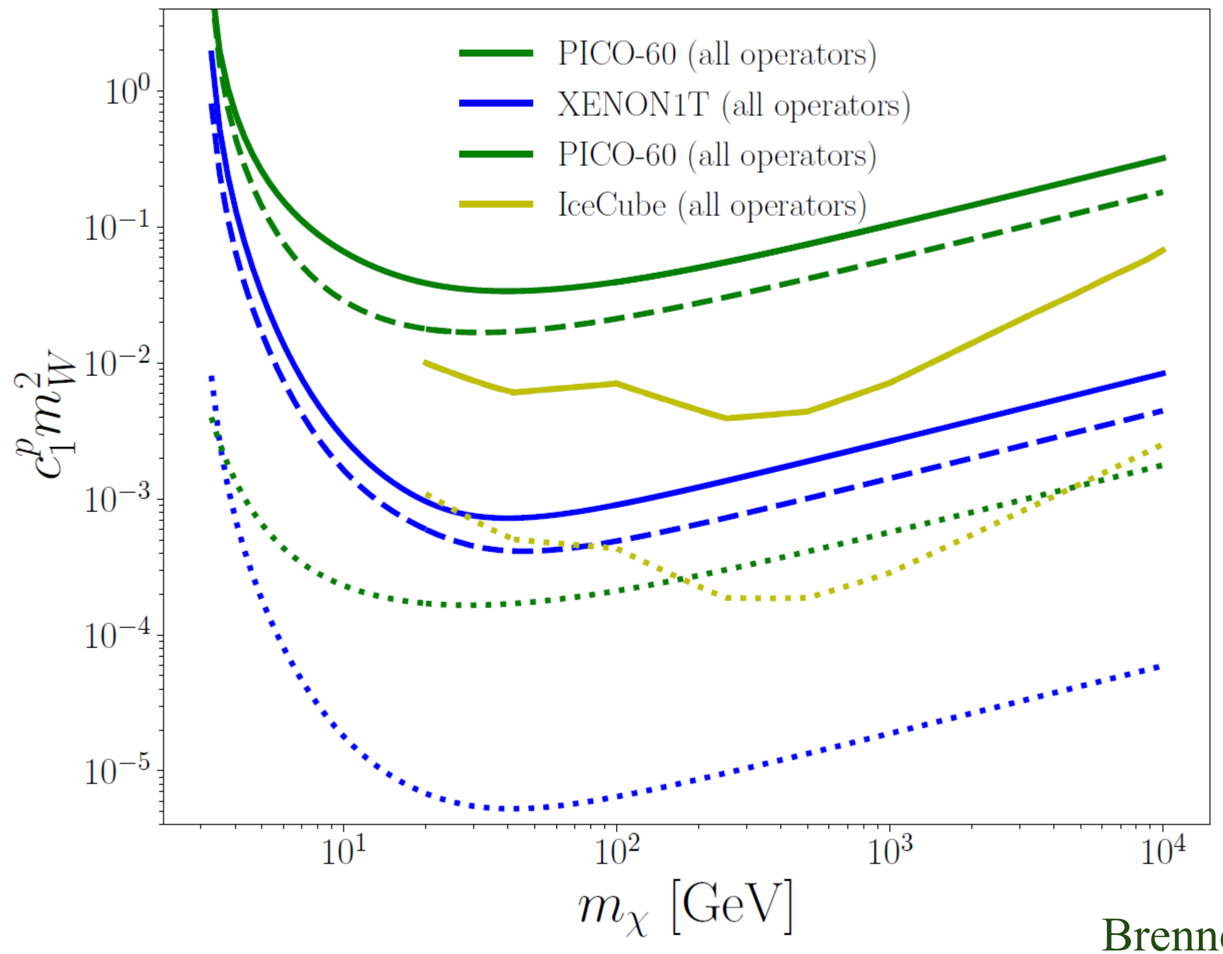
Fitzpatrick et al. 1203.3542

$$\mathcal{H} = \sum_{i=1}^{14} (c_p^i \mathcal{O}_i + c_n^i \mathcal{O}_i)$$

$$\text{Rate} = \mathbf{c}^T \mathbb{R}\, \mathbf{c}$$

$$\max c_\alpha = \sqrt{(\mathbb{R}^{-1})_{\alpha\alpha} R^{\text{u.l.}}}$$

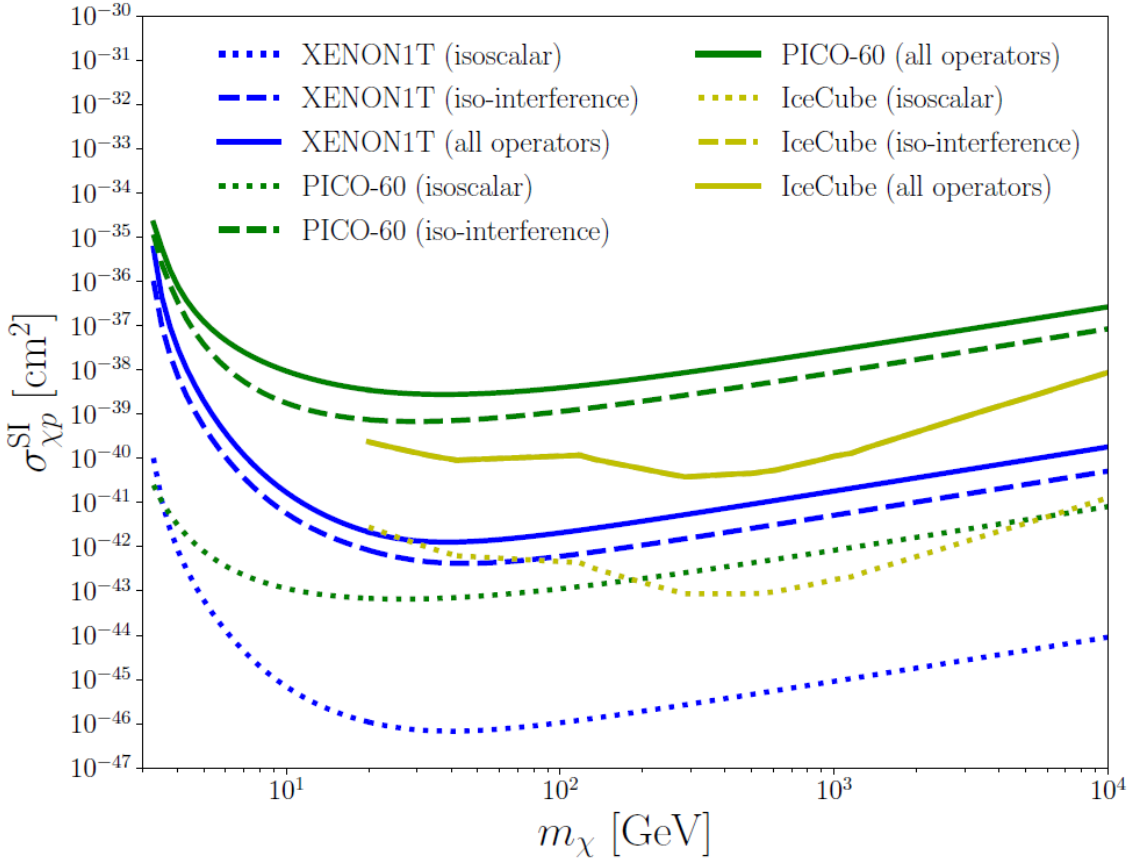
Impact of operator interference: NREFT



Brenner et al. To appear

Impact of operator interference: NREFT

DM-proton spin-independent cross-section



$$\sigma^{\rm SI}_{\chi p} = \frac{(c_p^1)^2 \mu_{\chi p}^2}{\pi}$$

Brenner et al. To appear

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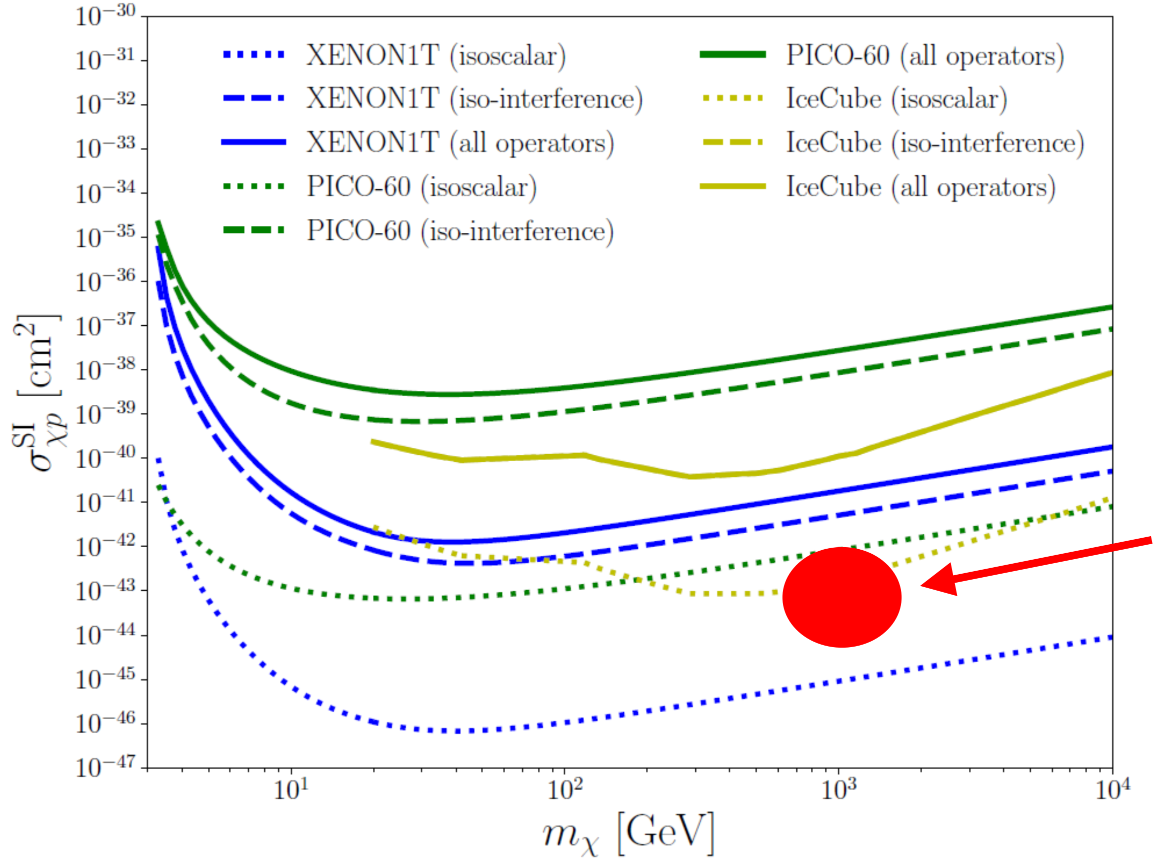

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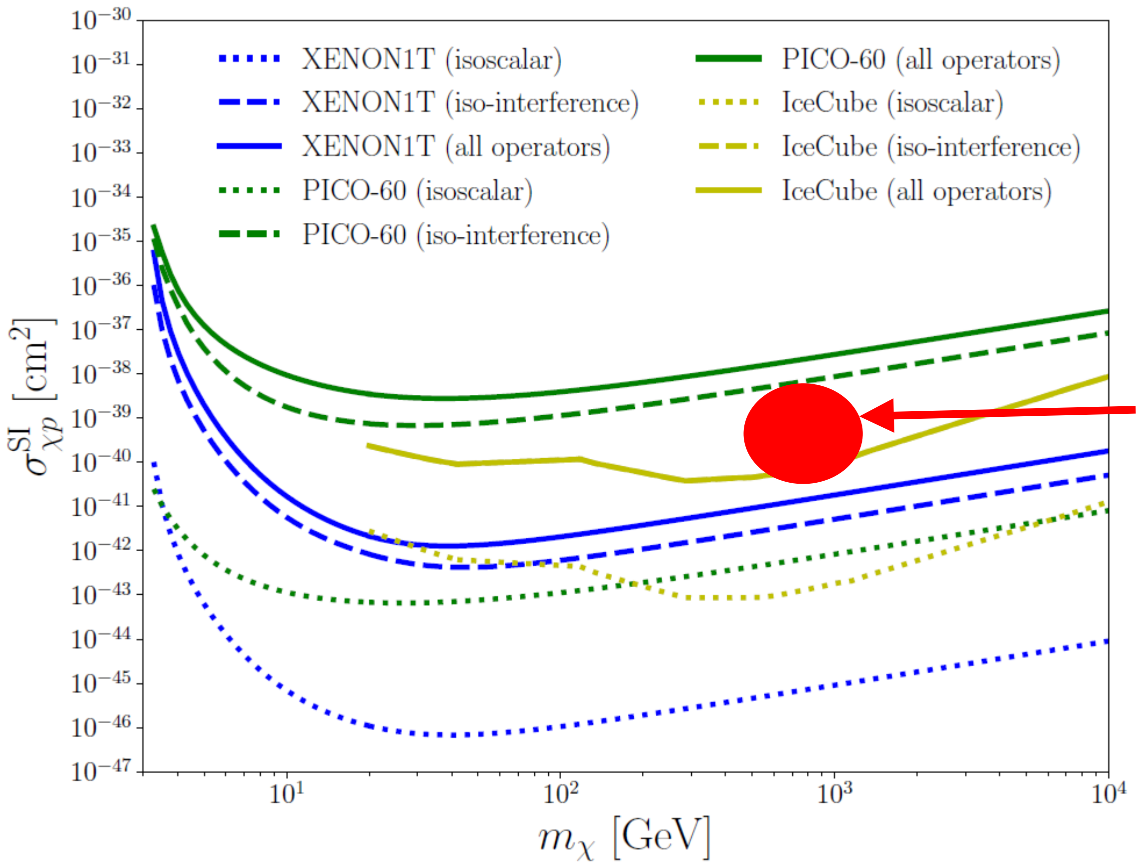

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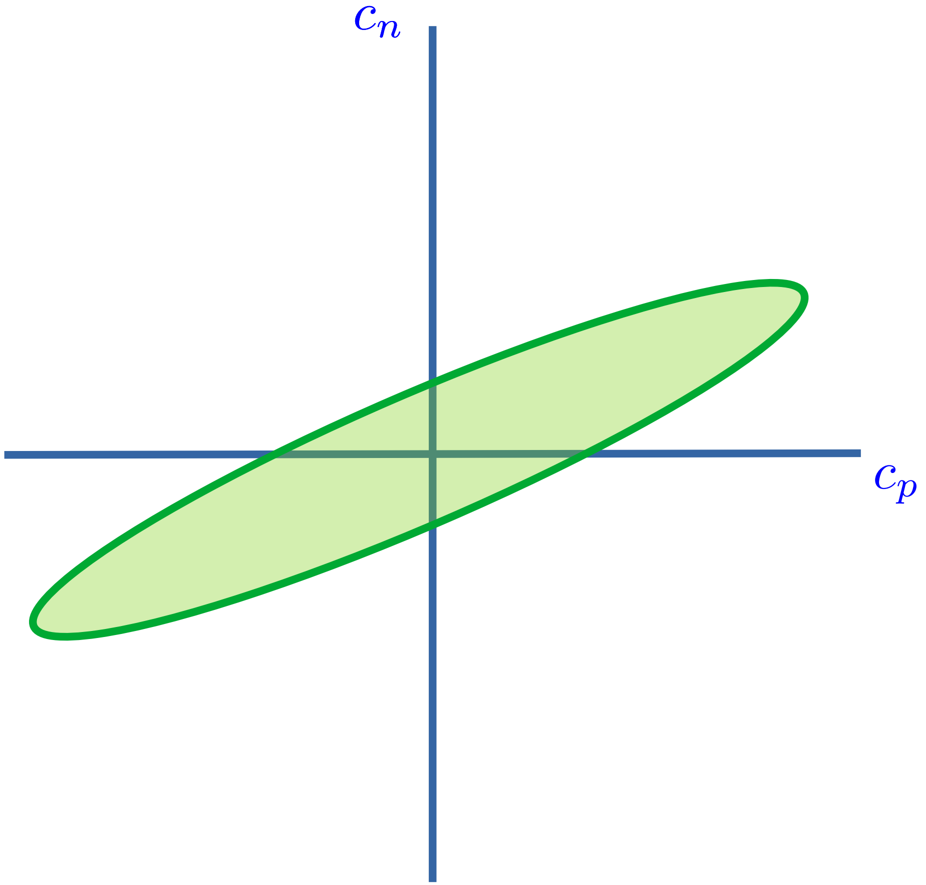
Ruled out by XENON1T *for all EFTs* (assuming SHM)

Brenner et al. To appear

Impact of operator interference: complementarity of experiments



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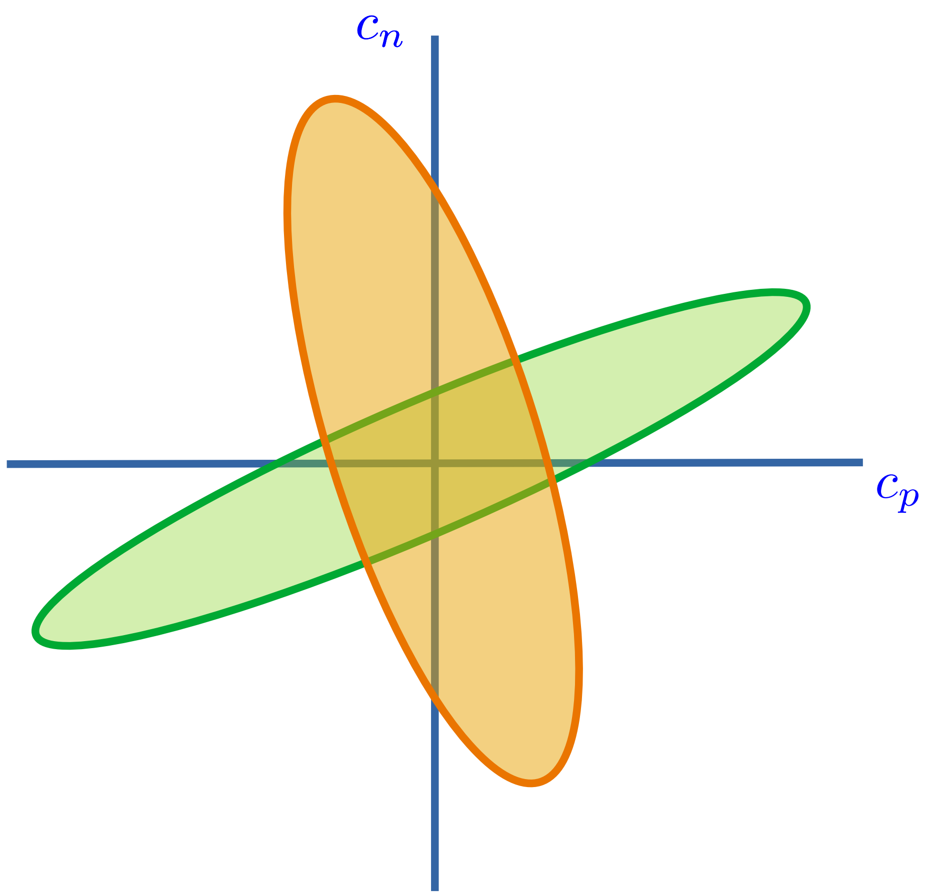

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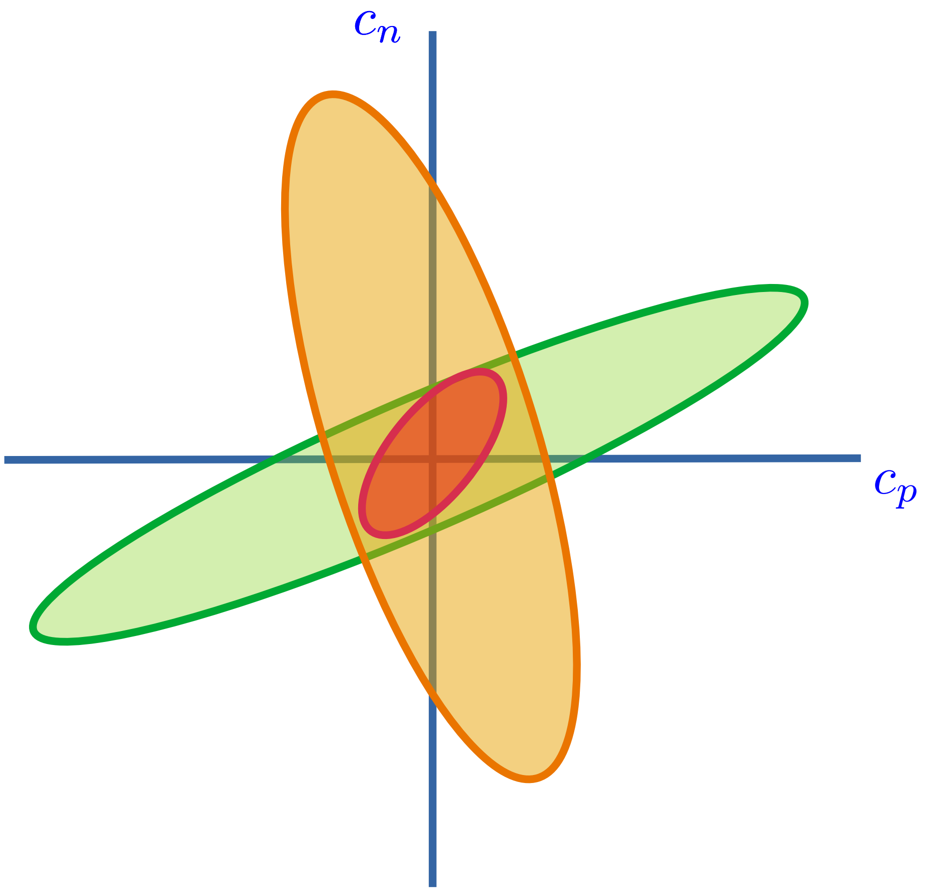

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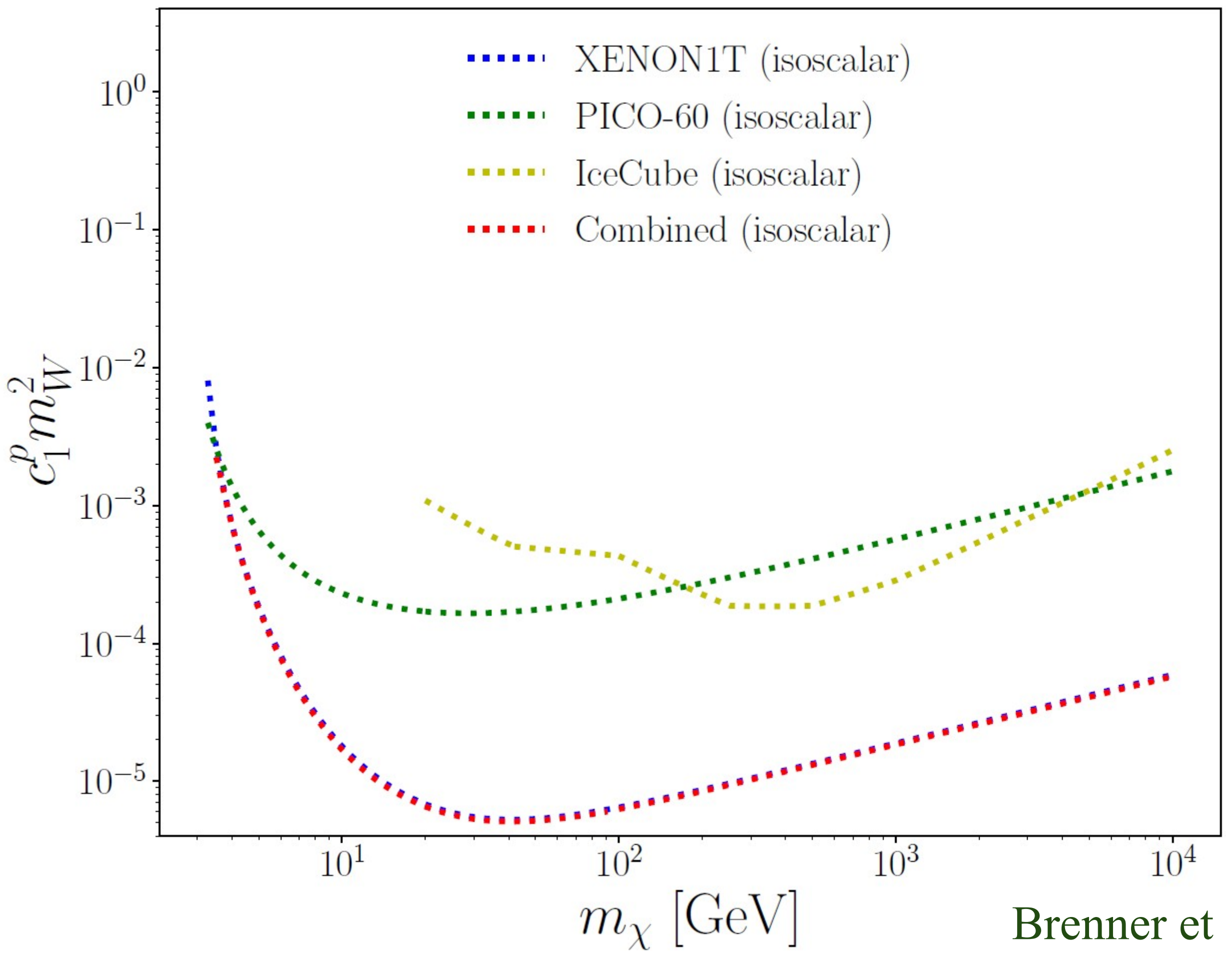

Brenner et al. To appear

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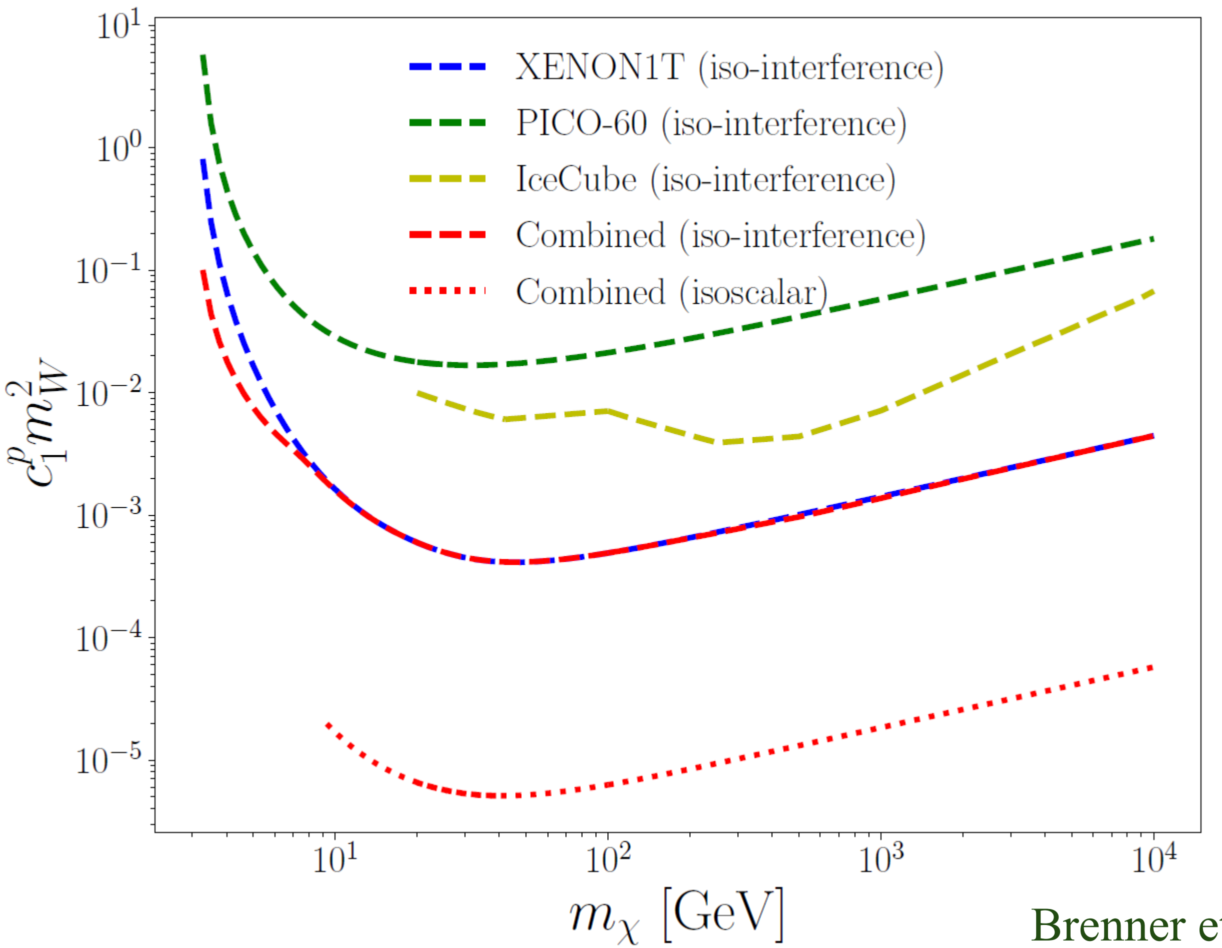

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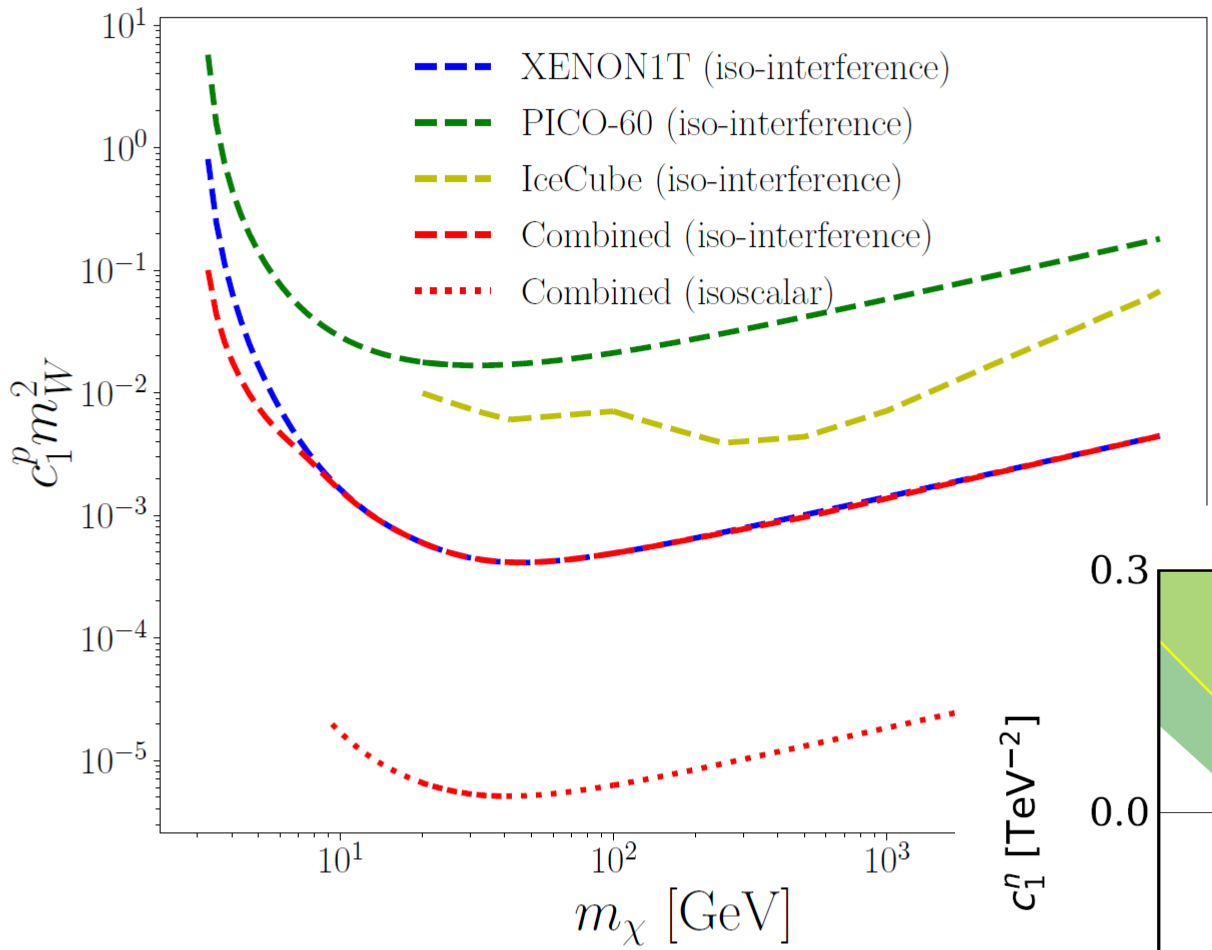

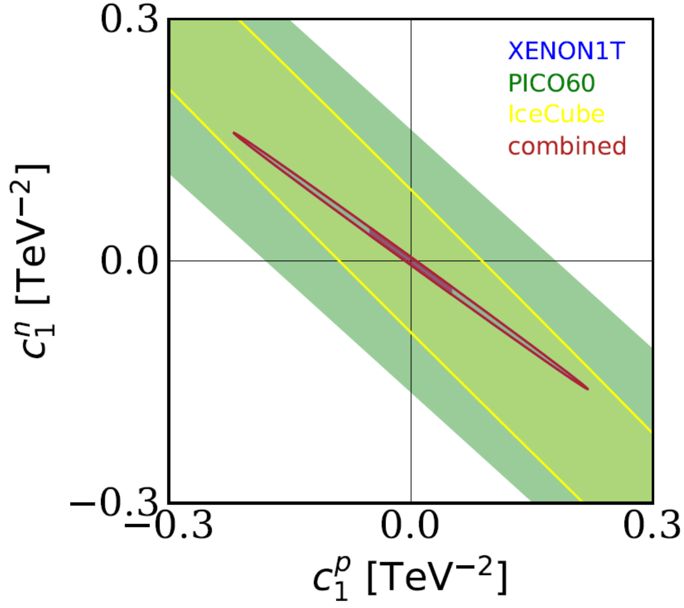

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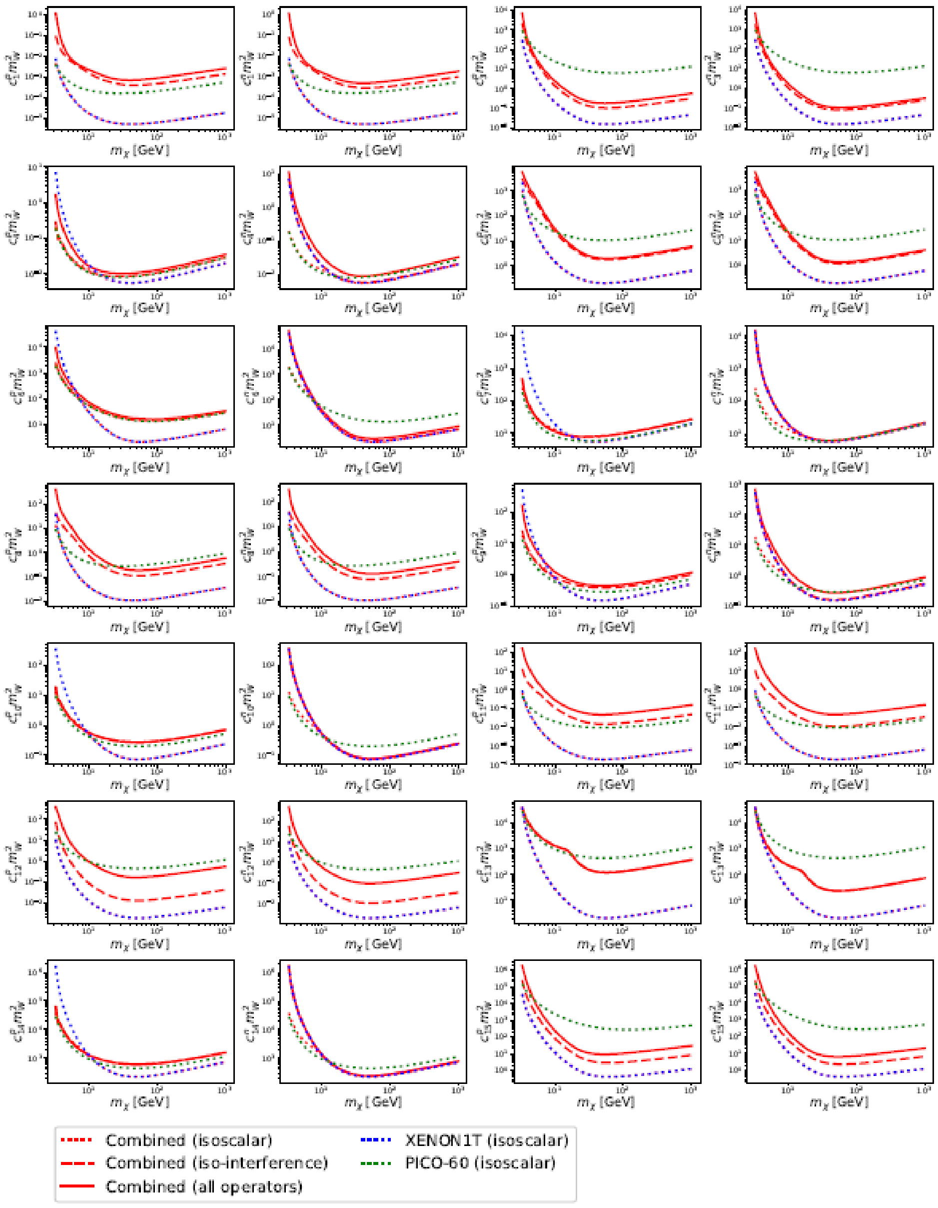

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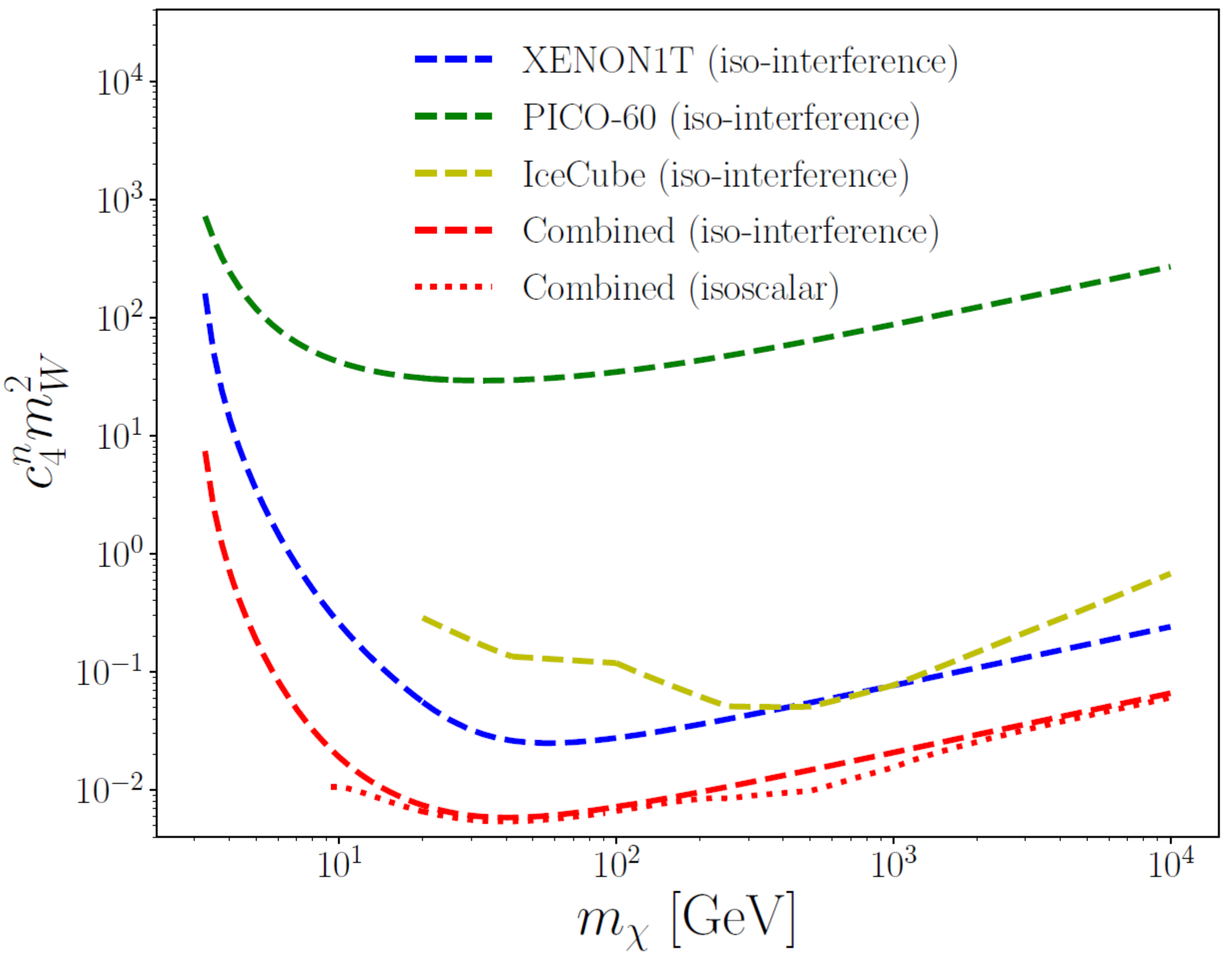
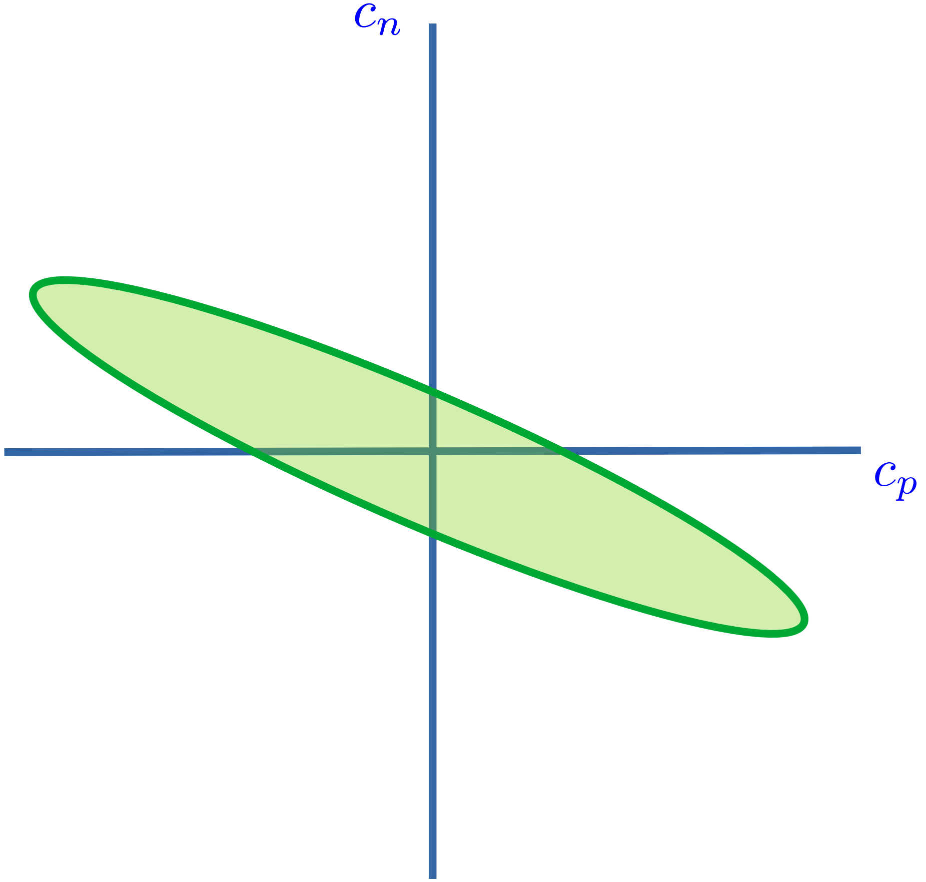


Impact of operator interference: complementarity of experiments

Note: the discovery potential increases if one uses targets probing different directions in parameter space



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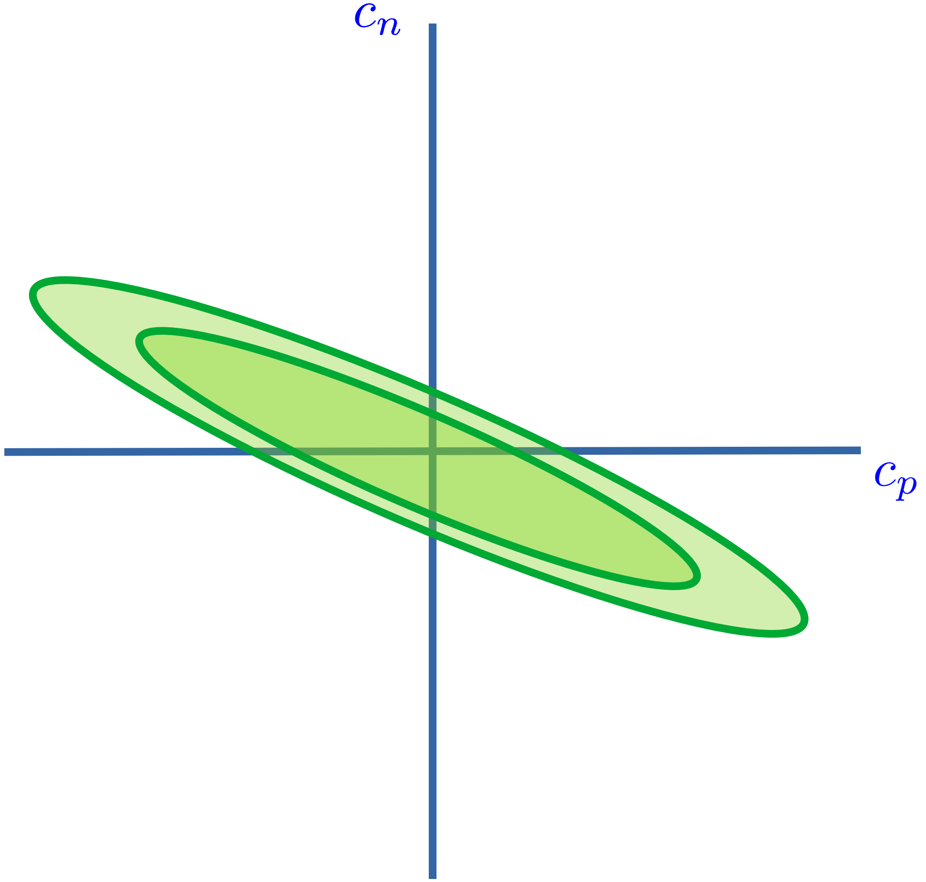

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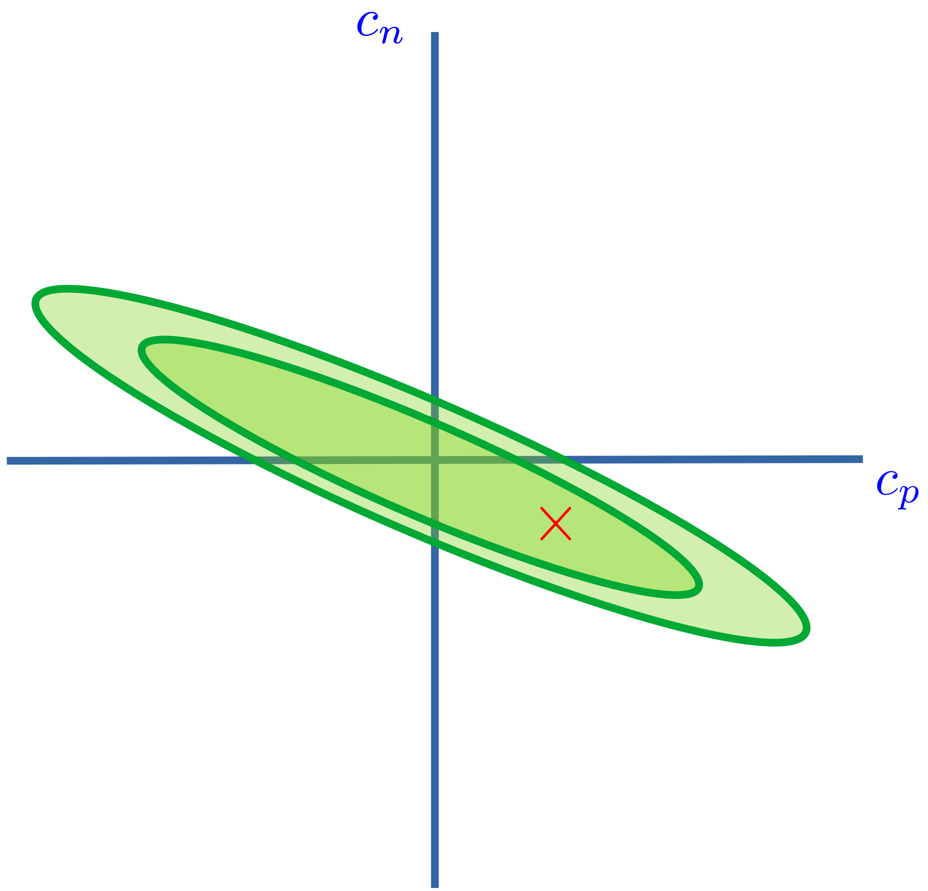

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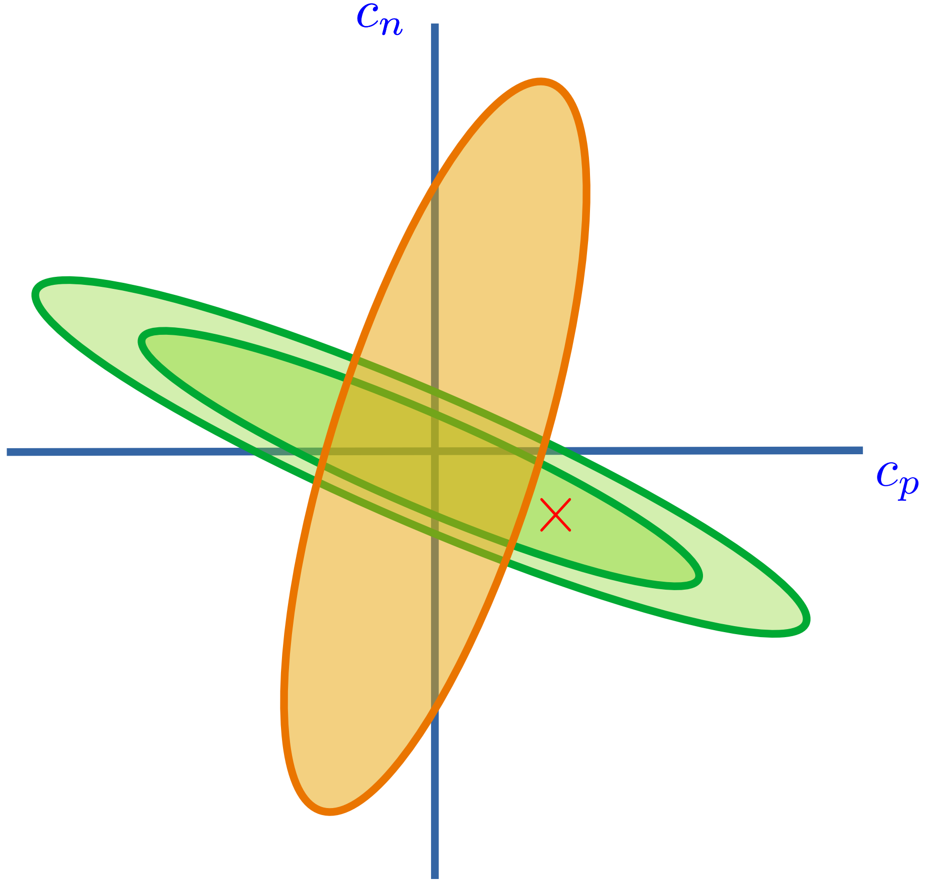
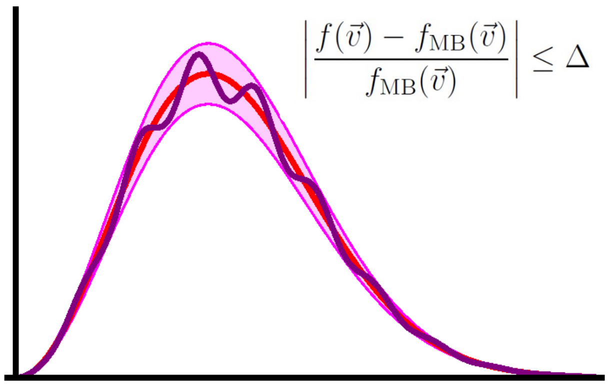


Addressing astrophysical uncertainties in dark matter detection

Distorting the Maxwell-Boltzmann distribution

• The DM velocity distribution in the Solar System is unknown. Most likely it deviates from the MB distribution, perhaps sizably.

• Consider "distortions" of the MB distribution, at most at a distance Δ from the MB distribution.



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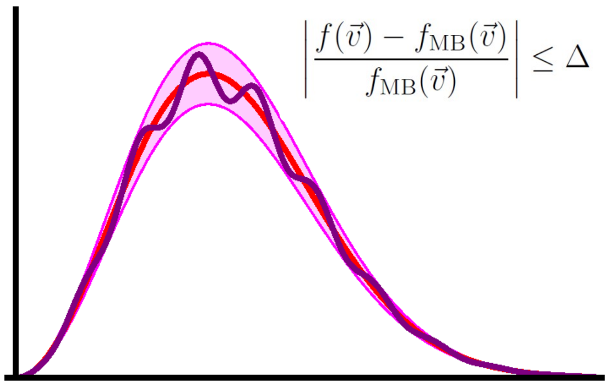

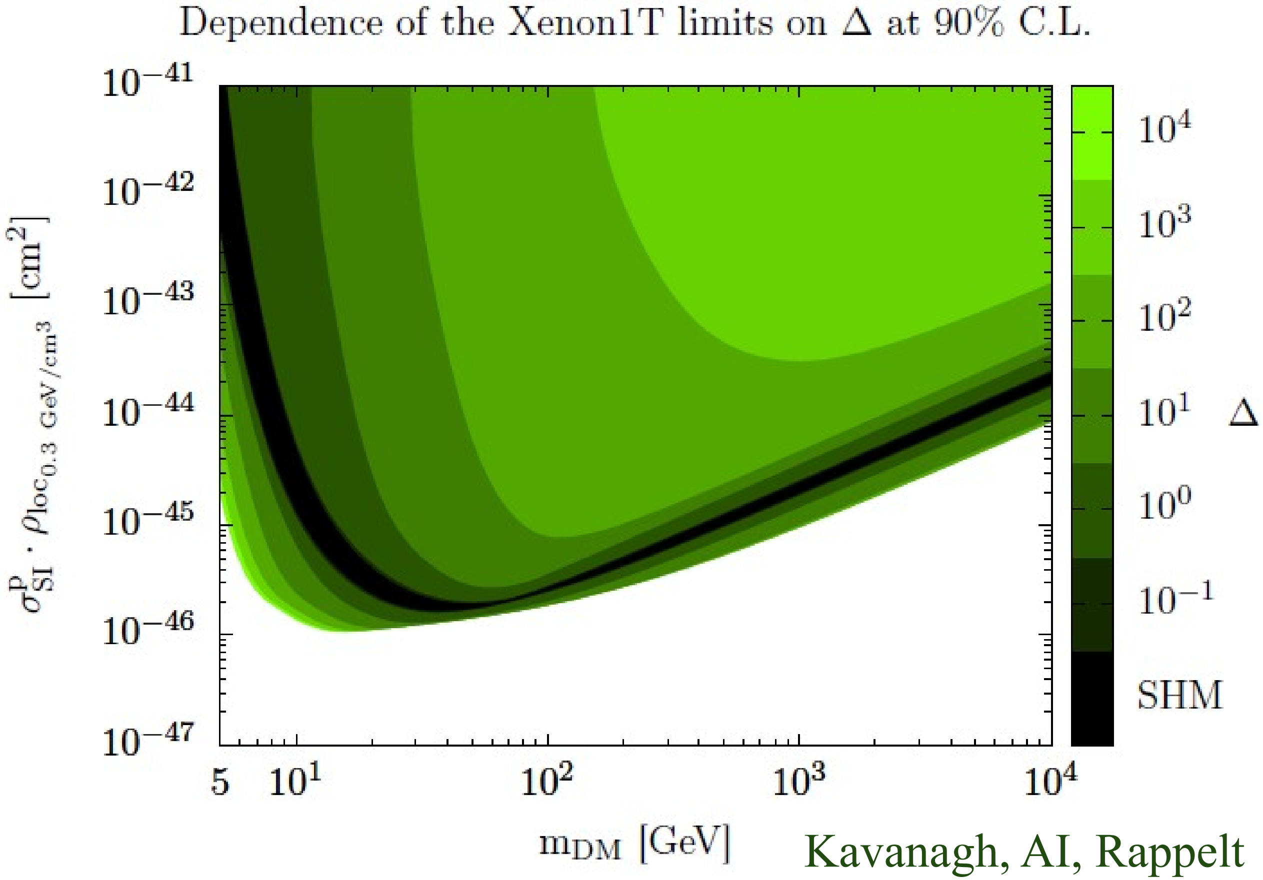

Kavanagh, AI, Rappelt

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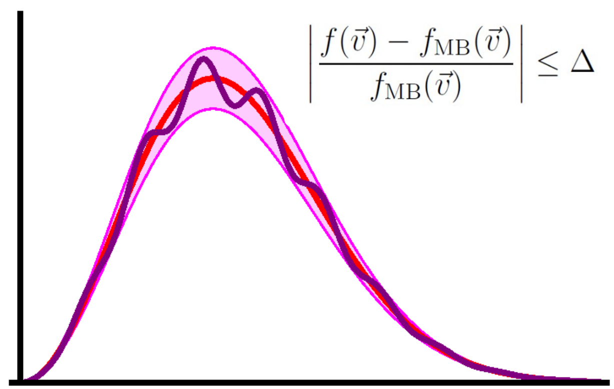

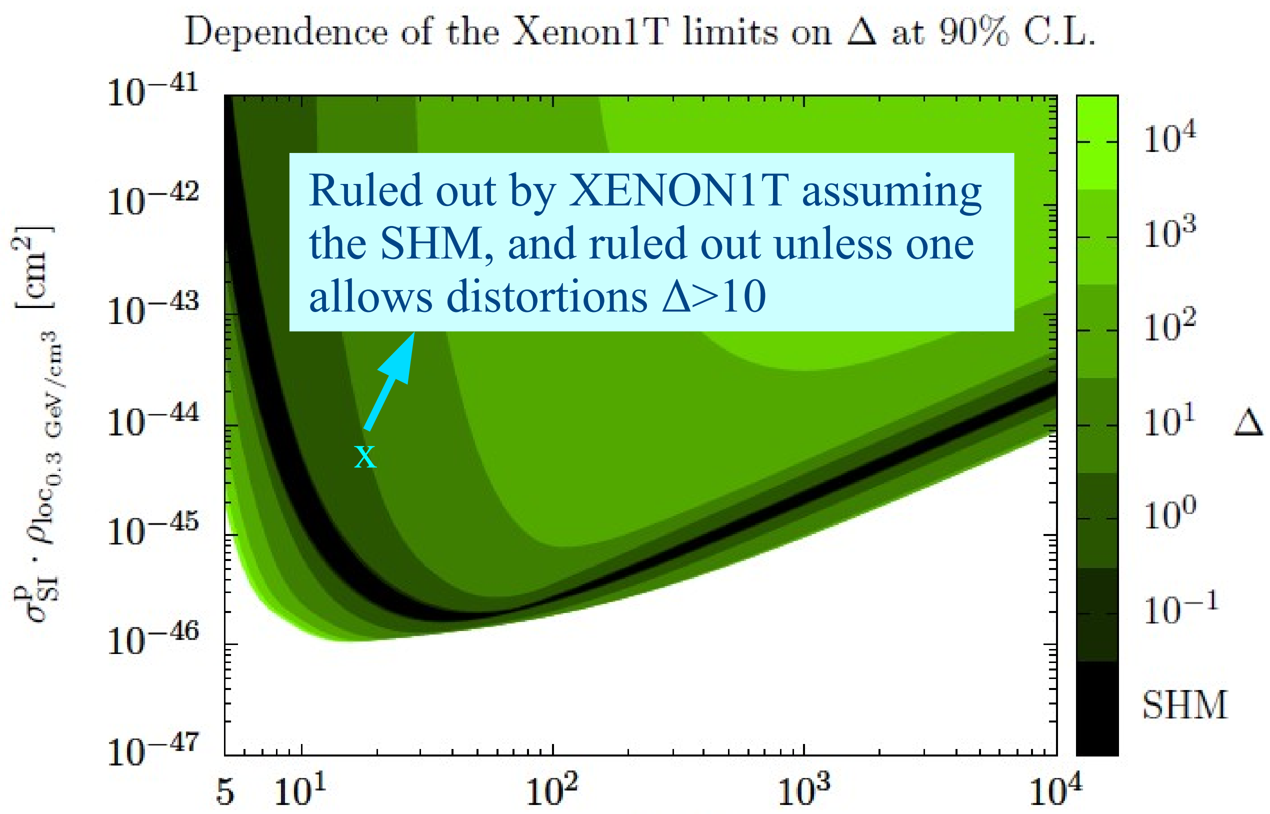

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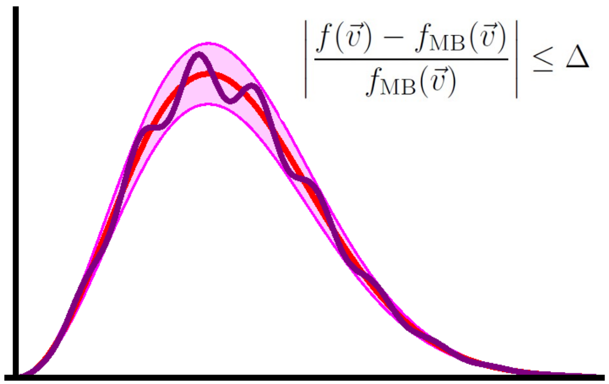

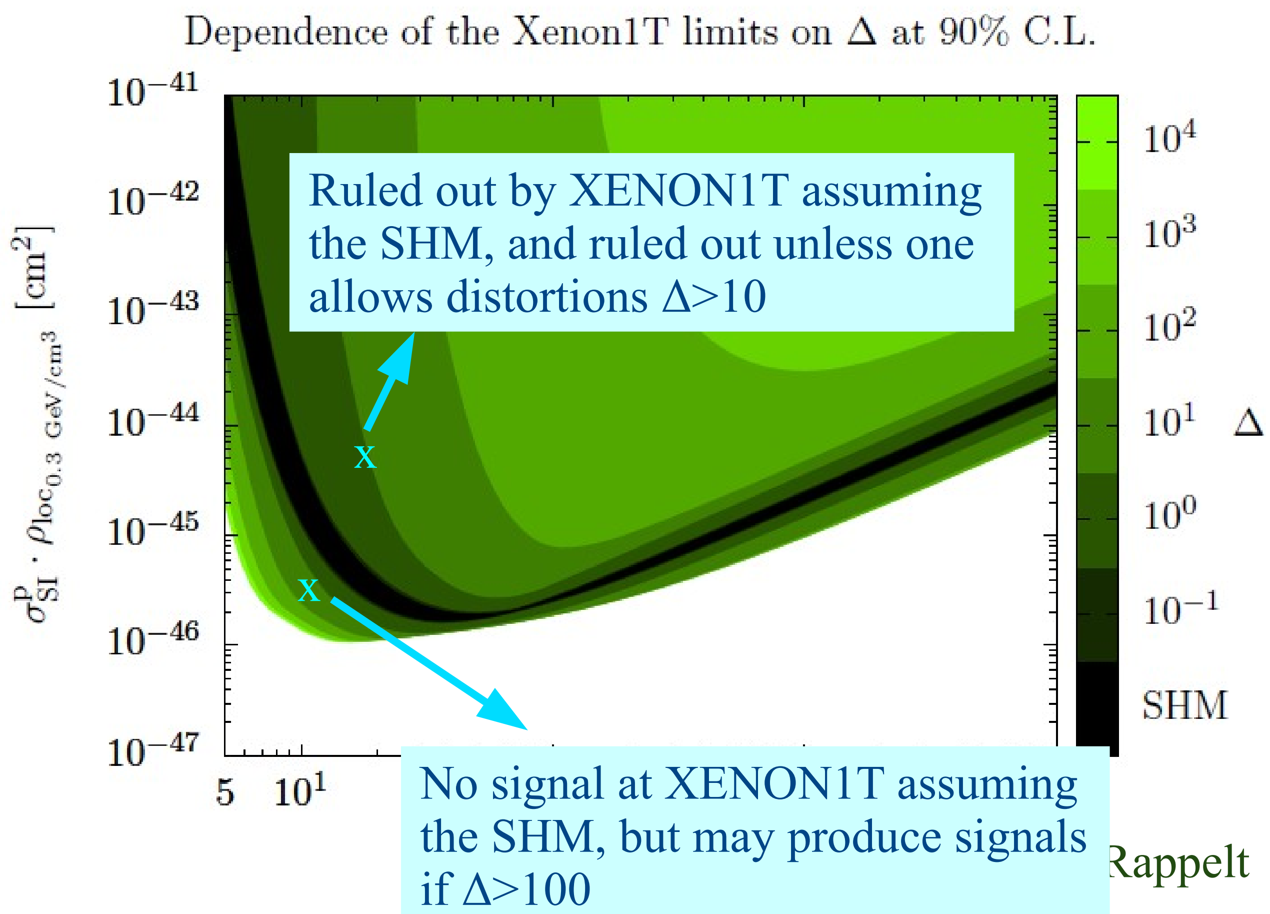

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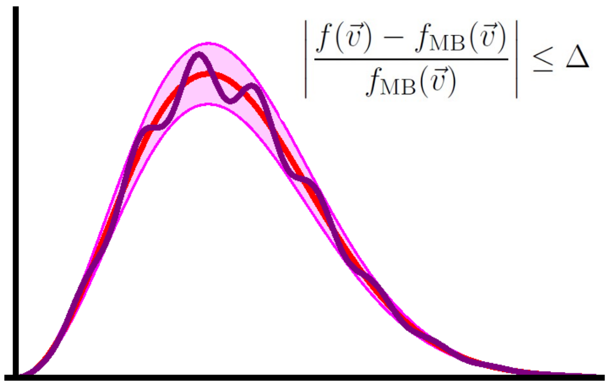

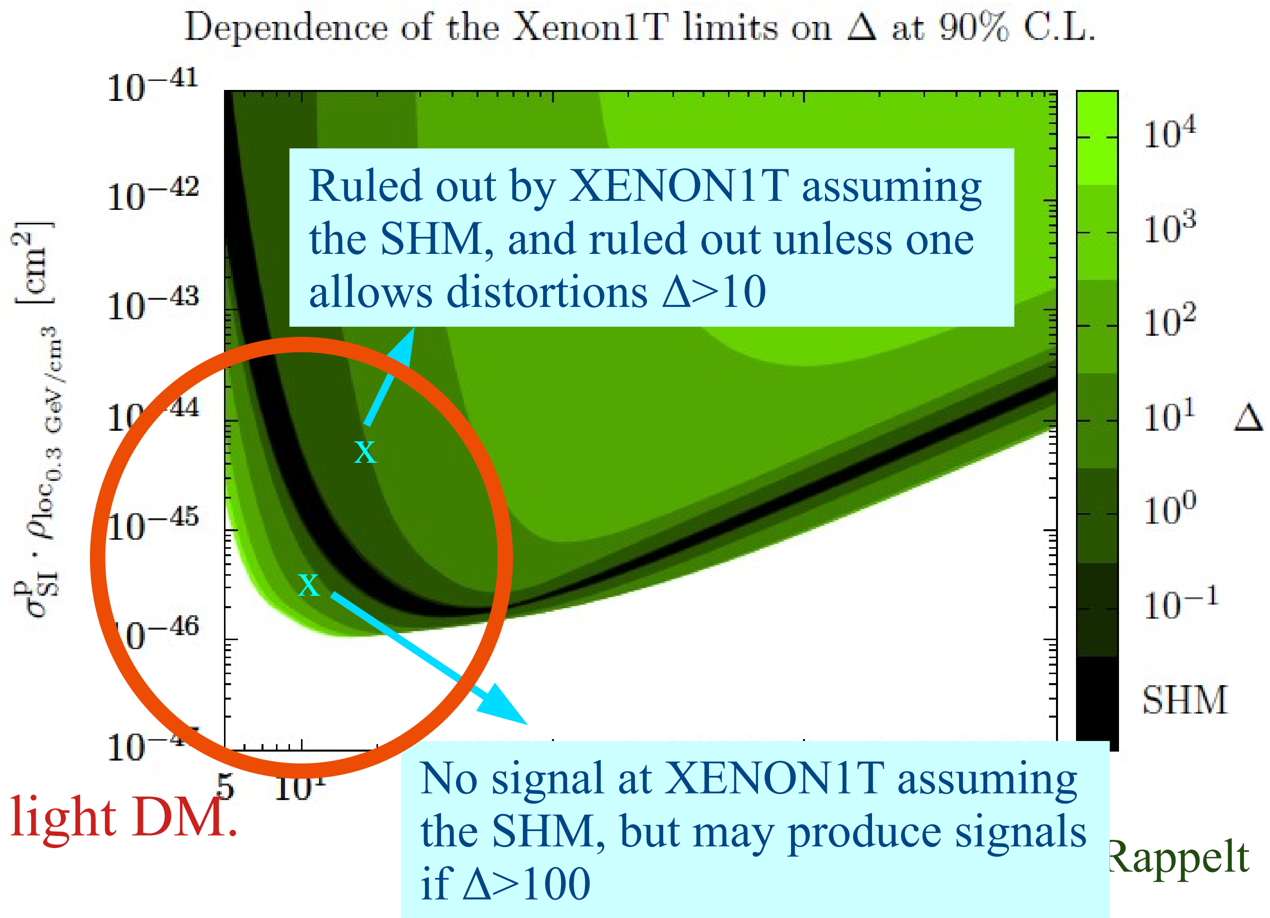

- Significant differences for light DM.

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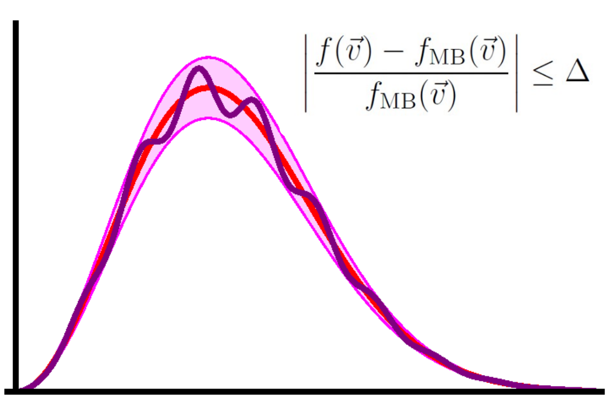

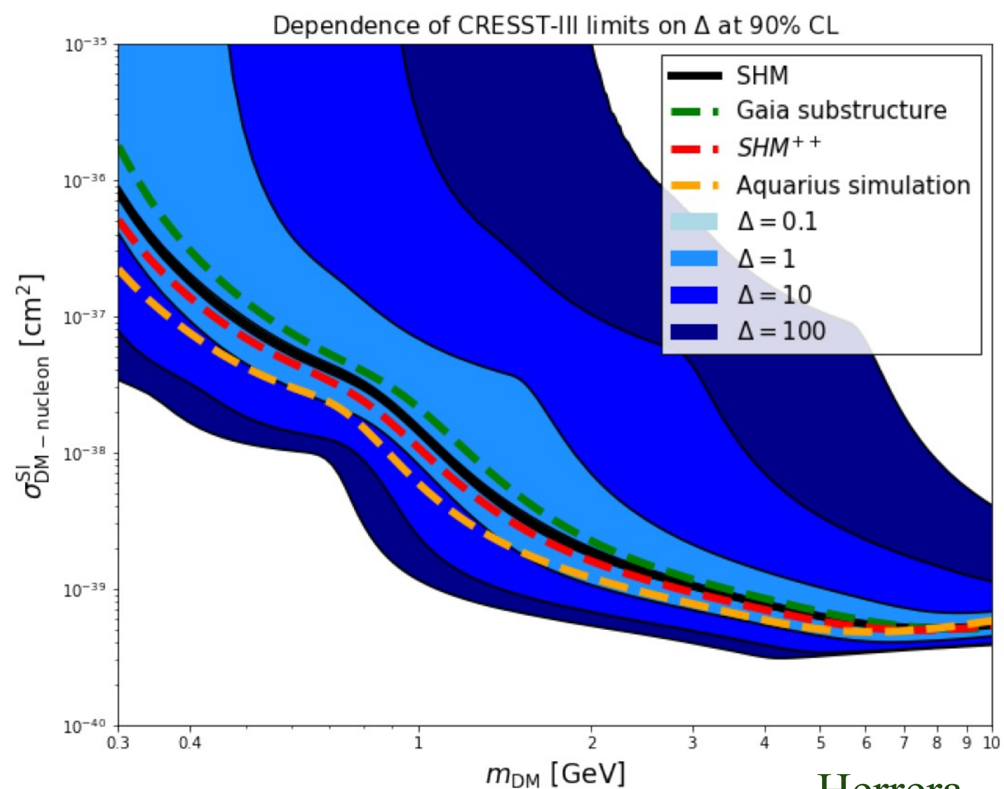

Herrera

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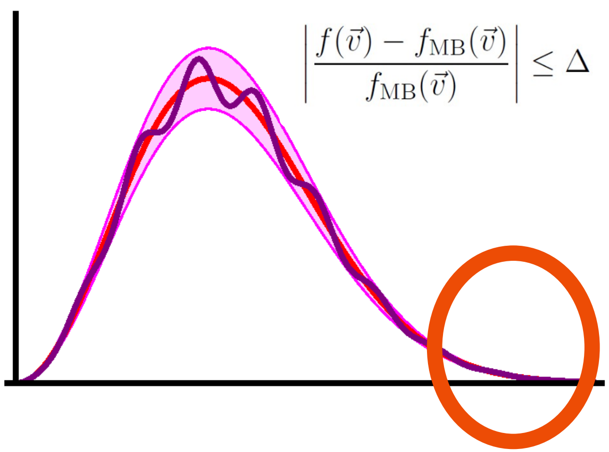

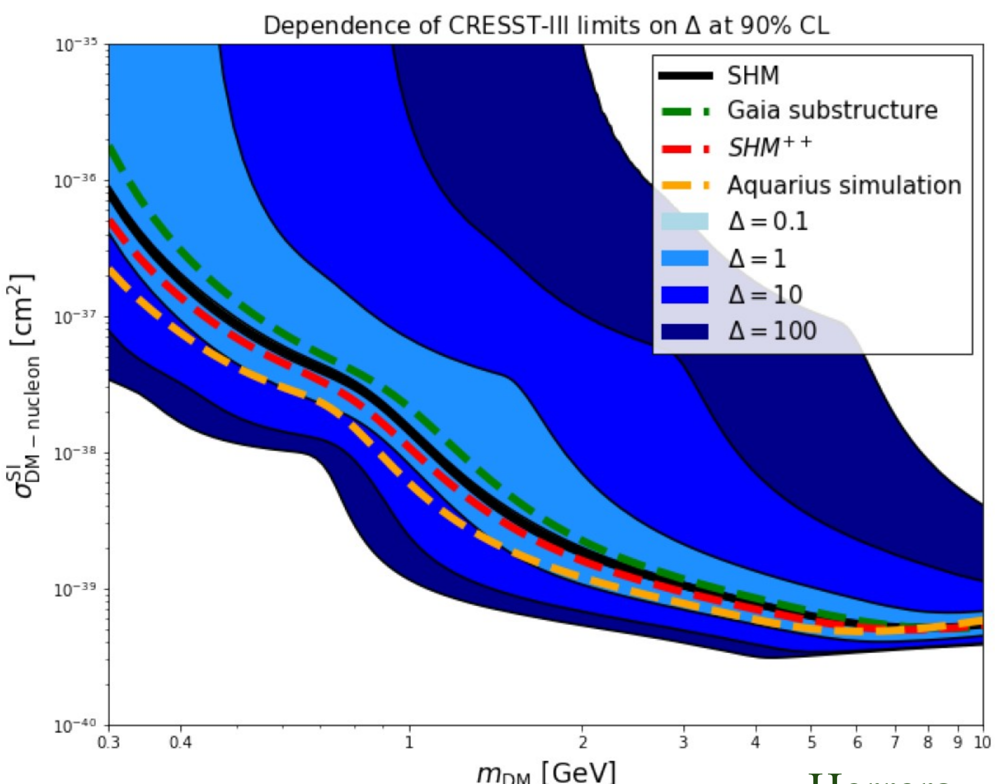

Herrera

• Significant differences for light DM.
• High sensitivity to the high velocity tail of the distribution at the location of the Solar System. Not unlikely for Galactic dark matter.

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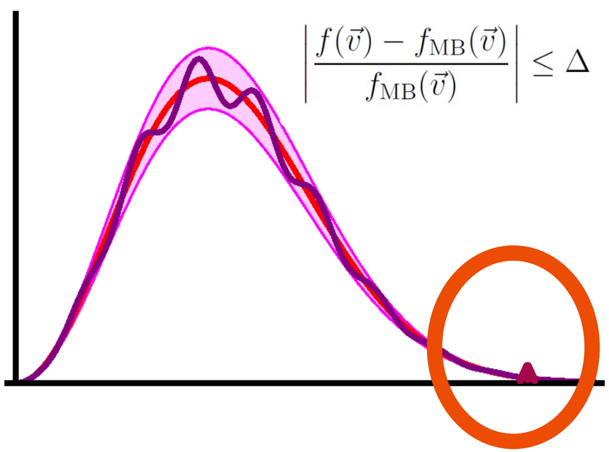

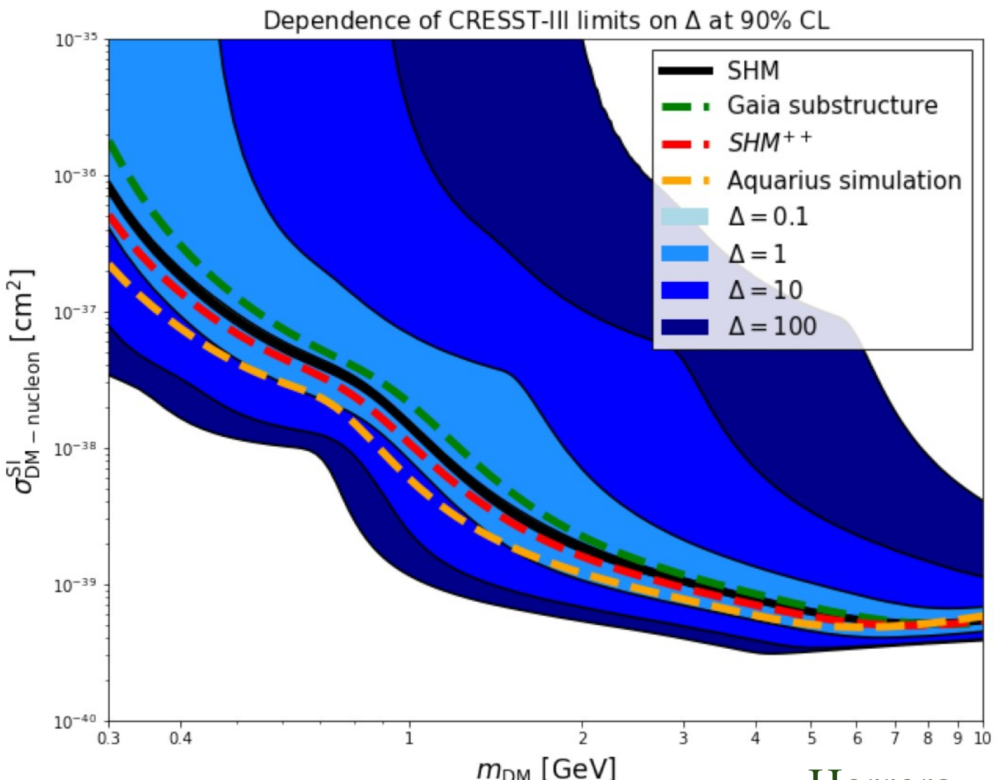

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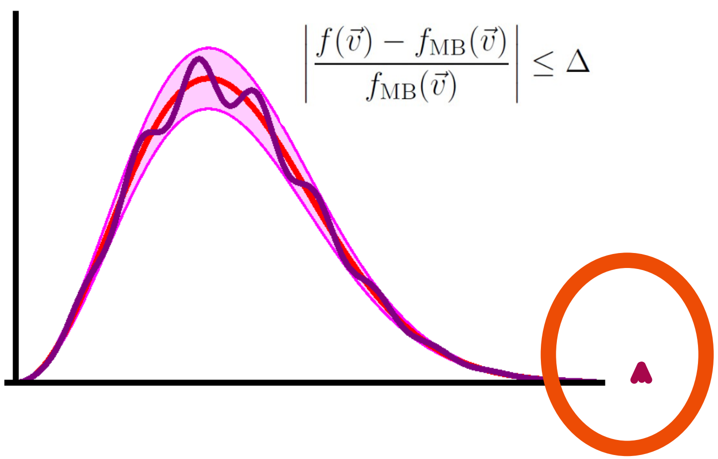

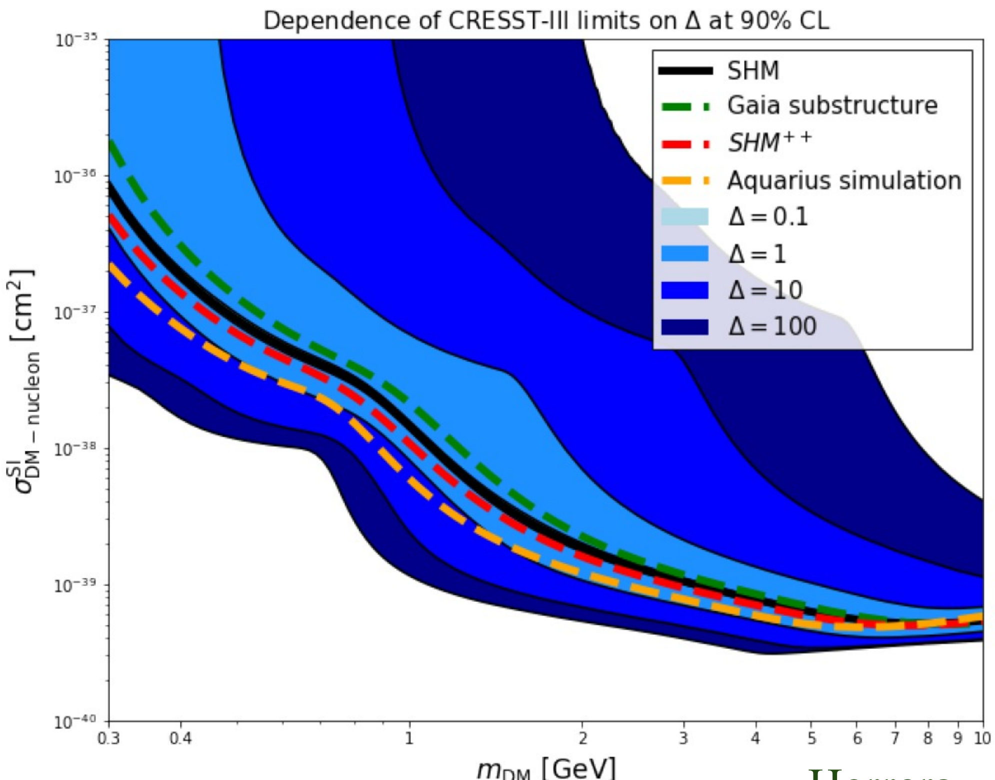

Herrera

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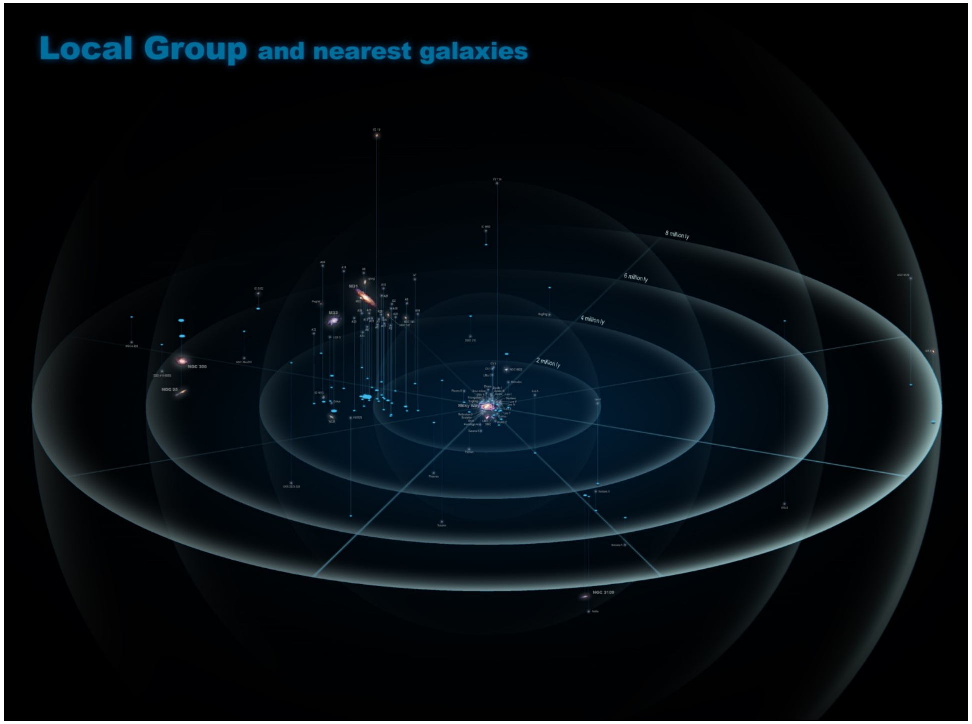
- High sensitivity to the high velocity tail of the distribution at the location of the Solar System. Not unlikely for Galactic dark matter. **Likely for non-galactic dark matter (with $v>v_{esc}$).**

Non-galactic dark matter

The Milky Way is not an isolated galaxy.



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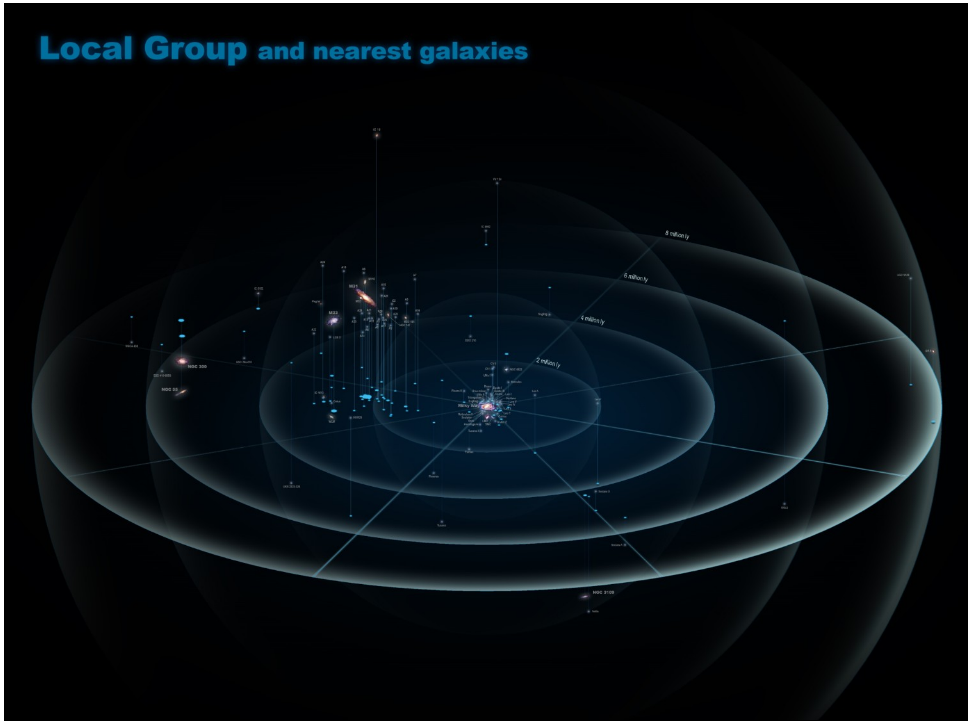
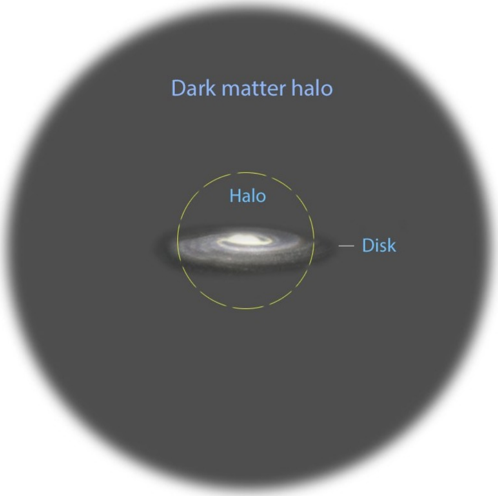
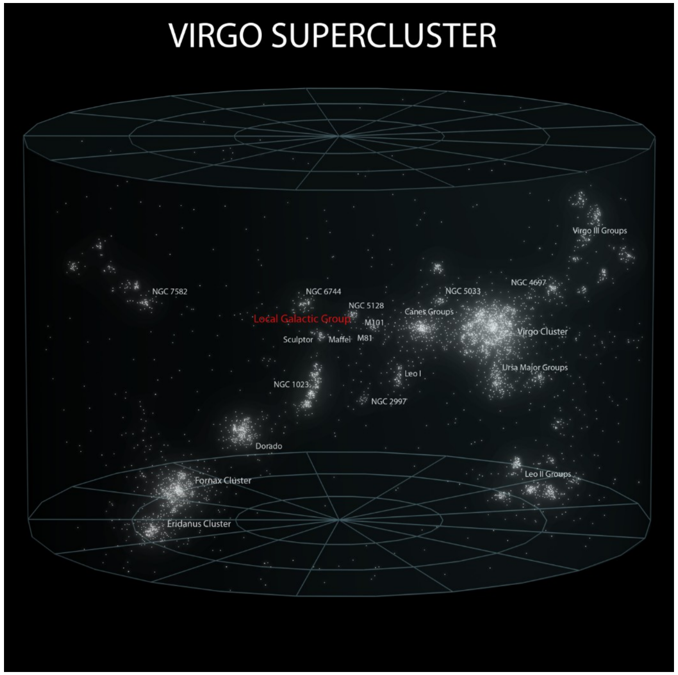




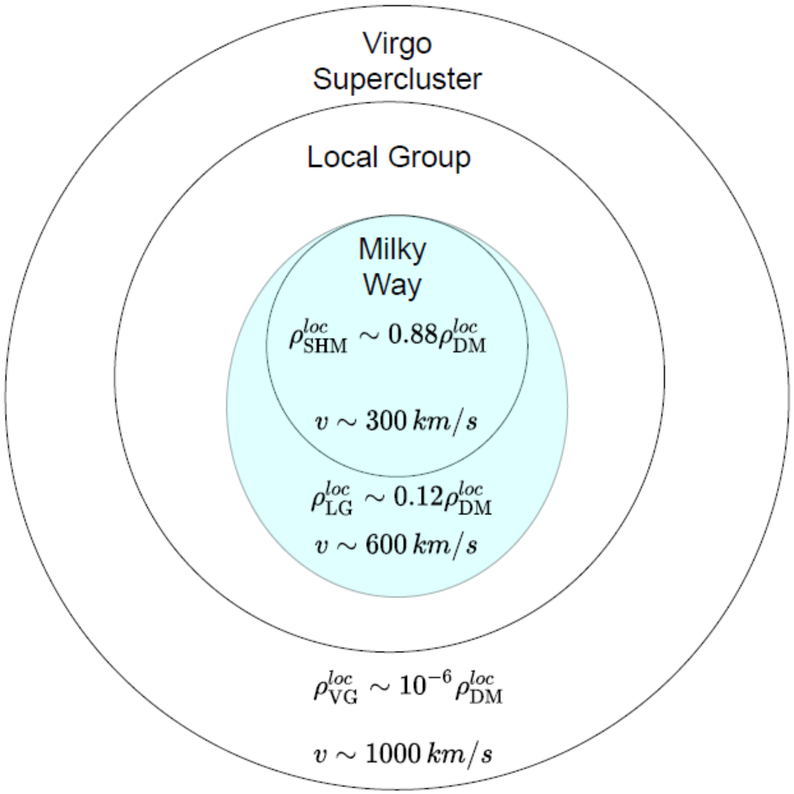


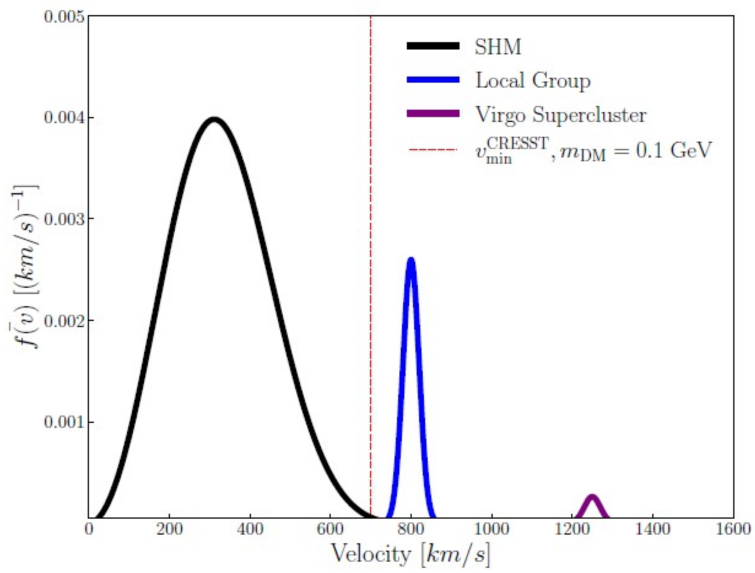
Non-galactic dark matter

- The diffuse DM component of the Local Group could penetrate in the Milky Way, contributing $\sim 12\%$ to the local DM density.

- The Virgo Supercluster DM particles are expected to contribute marginally $\sim 0.00003\%$, but with large velocities.

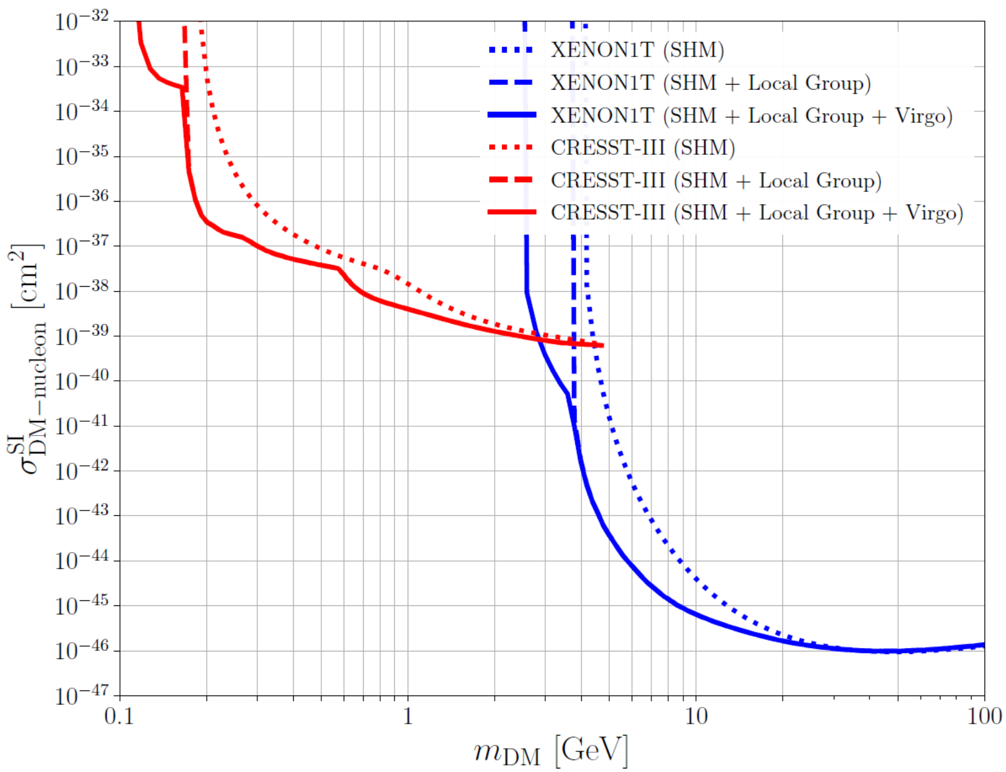
Kahn, Woltjer '59
Makarov, Karachentsev '11
Baushev, '13

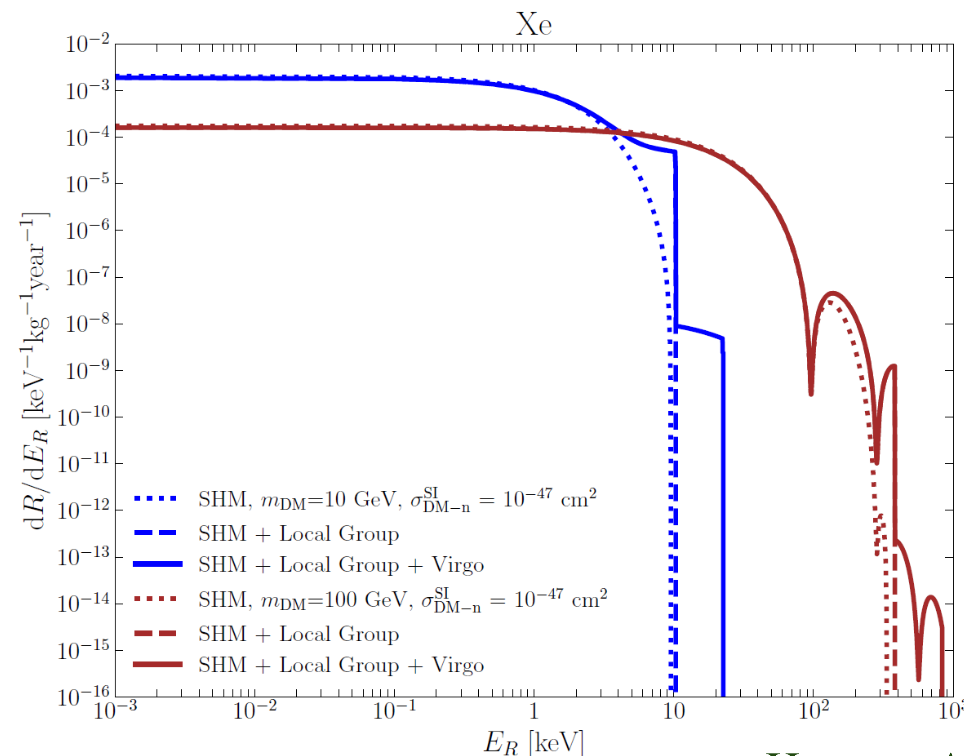




Very significant "distortion" of the MB distribution at high velocities

Non-galactic dark matter: impact on nuclear recoils

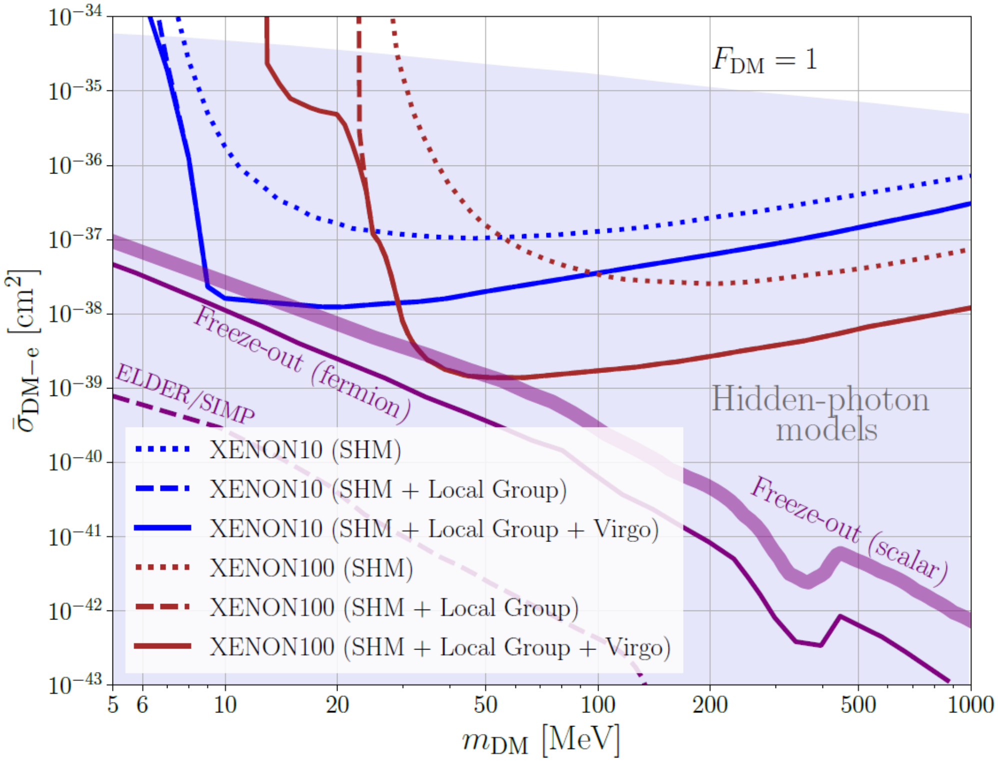


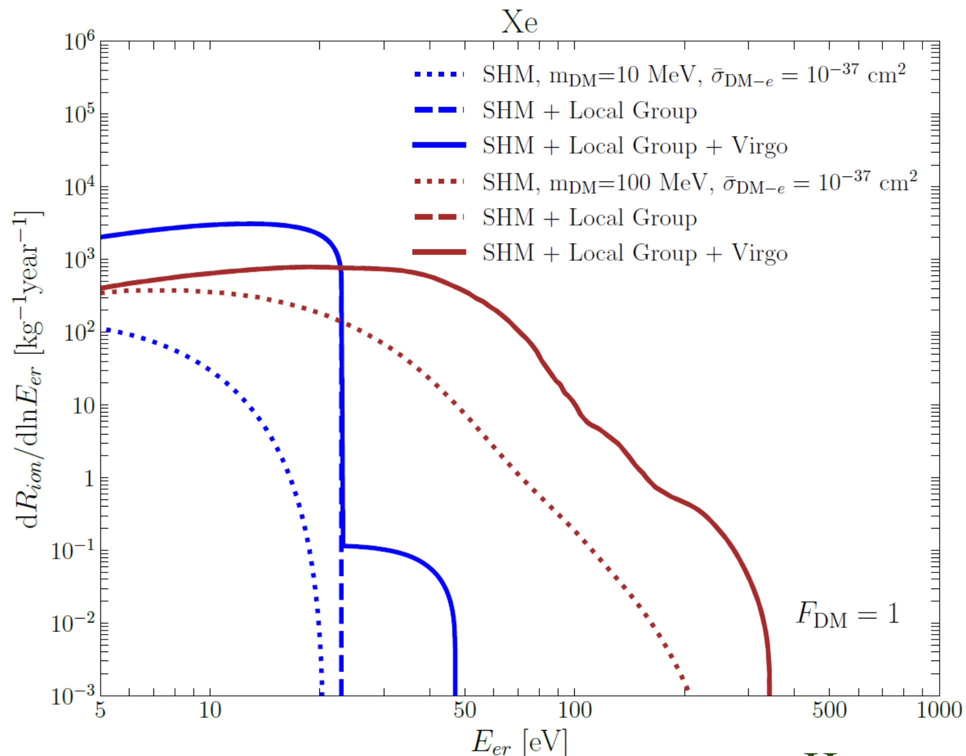


Herrera, AI

- Enhanced sensitivity for light DM. Up to one order of magnitude for m=10 GeV, and four orders of magnitude for m=4 GeV.
- Discovery potential for even lighter DM.
- Characteristic recoil spectrum.

Non-galactic dark matter: impact on electron recoils





Herrera, AI

- Enhanced sensitivity for *all* DM masses.
- Non-galactic DM might be pivotal for detection.

… but highly uncertain at the moment. More work needed!

Conclusions

- The interpretation of any experiment probing the dark matter distribution inside the Solar System is subject to our ignorance of the underlying dark sector microphysics, as well as of the local dark matter density and velocity distribution.
- We have developed a simple method to determine a lower limit on the coupling strengths of the effective field theory of dark matter-nucleon interactions including operator interference. The limits are applicable to all models.
- We have developed a method to bracket the uncertainties in the velocity distribution when interpreting the results from direct searches. Distortions in the local velocity distribution w.r.t. Maxwell-Boltzmann are likely, and may enhance the discovery potential of experiments.
- We have emphasized the important role of non-galactic dark matter in direct searches. The diffuse DM component of the local group contributes to the dark matter flux at Earth, and can increase the signal rate by orders of magnitude.