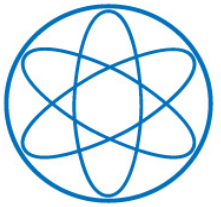
Addressing theory uncertainties in direct dark matter searches

Alejandro Ibarra

Technische Universität München

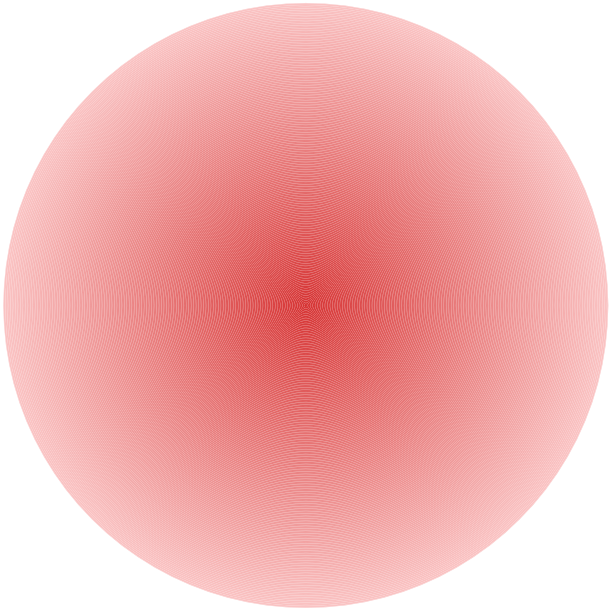


In collaboration with Anja Brenner, Gonzalo Herrera, Andreas Rappelt, Bradley Kavanagh, Shunghyun Kang, Stefano Scopel and Gaurav Tomar

Physics in LHC and Beyond
Matsue
May 2022

Direct dark matter searches

The Sun (and the Earth) might be moving through a “gas” of dark matter particles.



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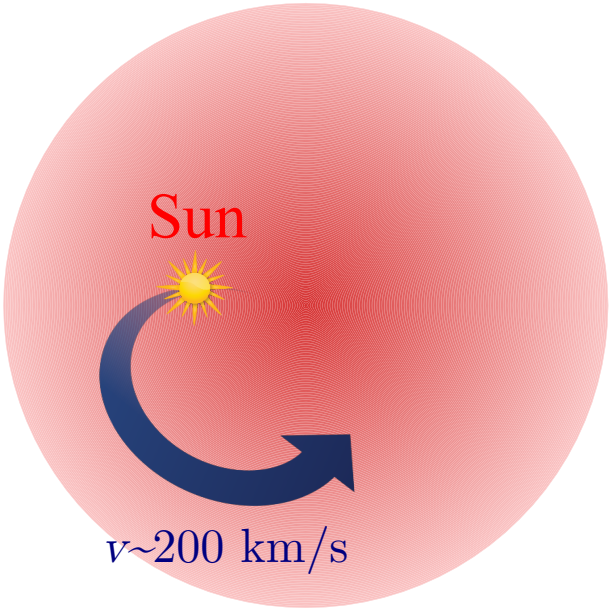

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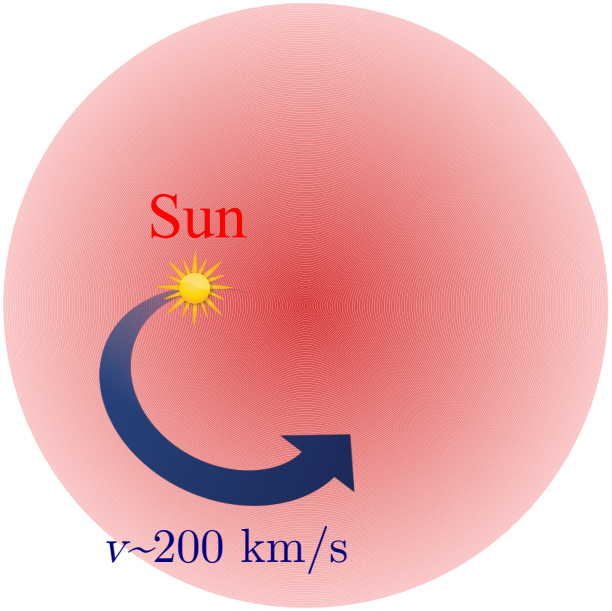

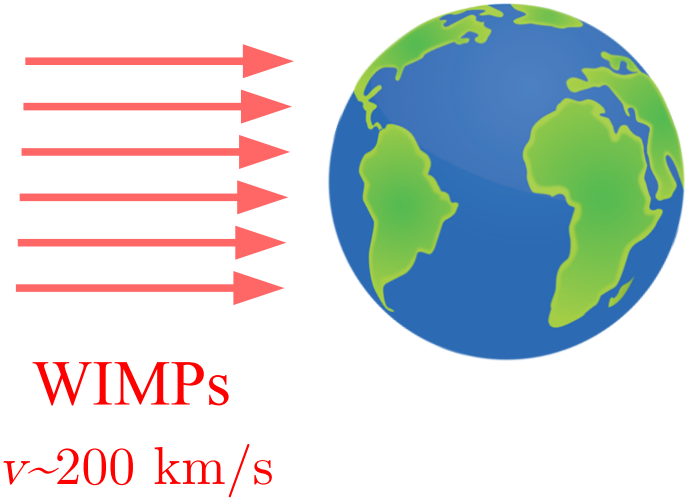

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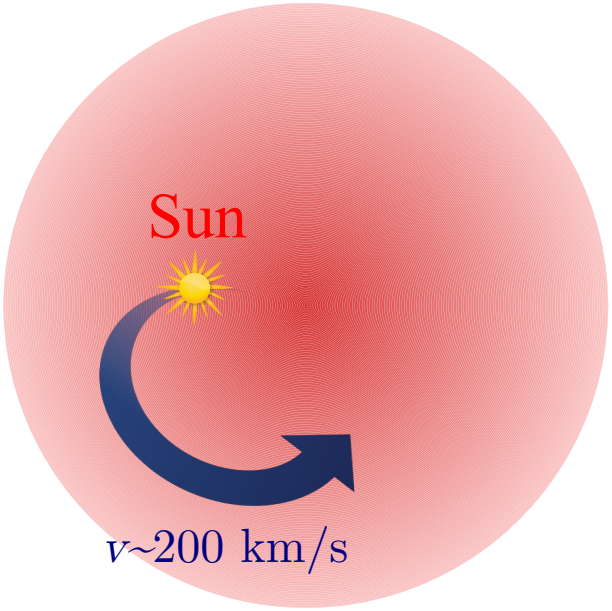
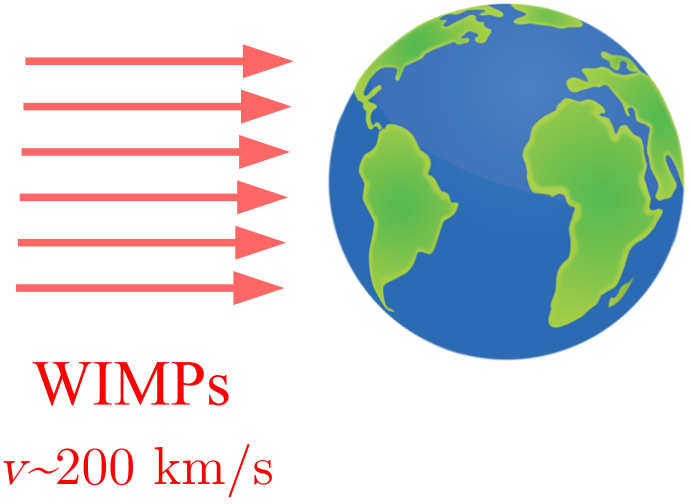
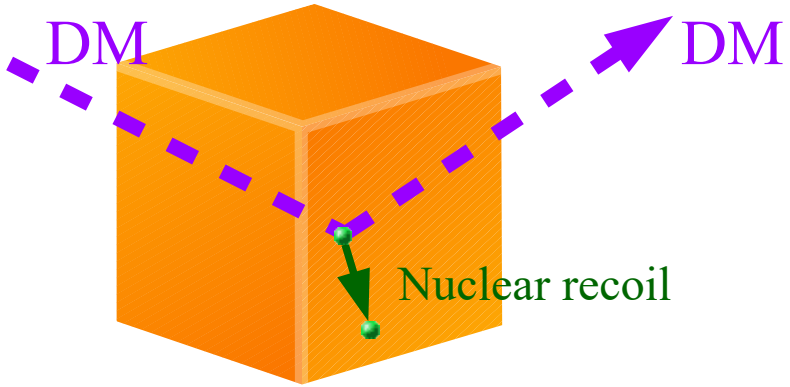




Once in a while a dark matter particle will interact with a nucleus. The nucleus then recoils, producing vibrations, ionizations or scintillation light in the detector.



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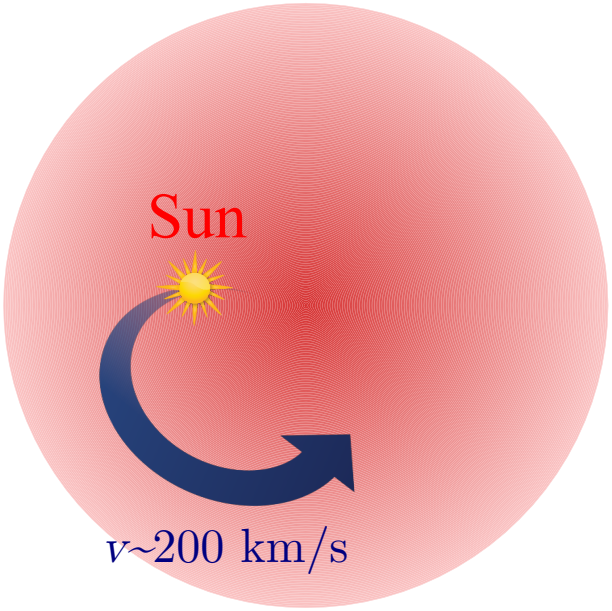

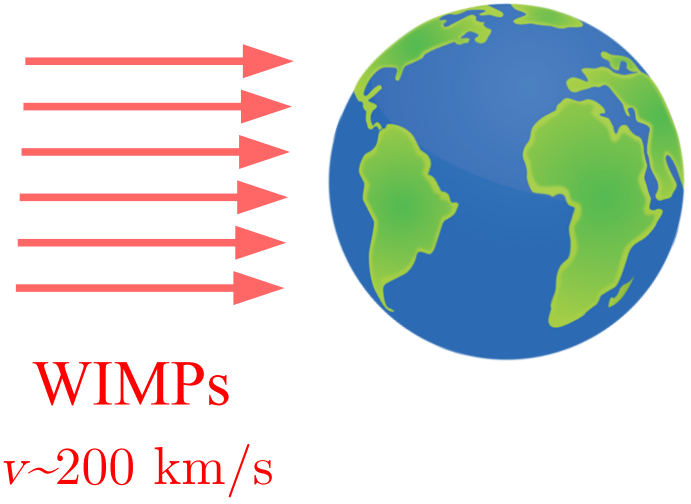

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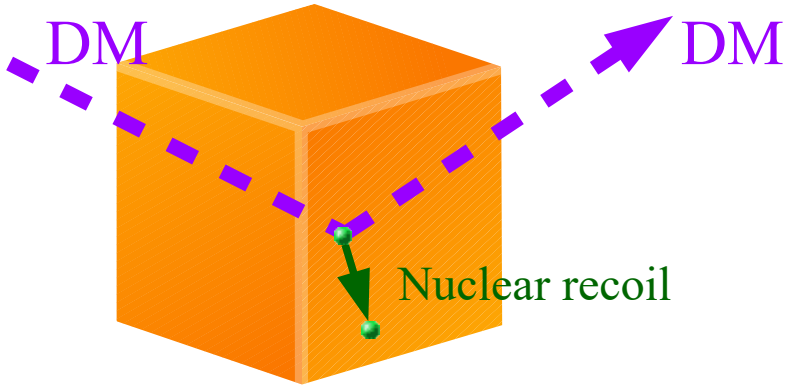
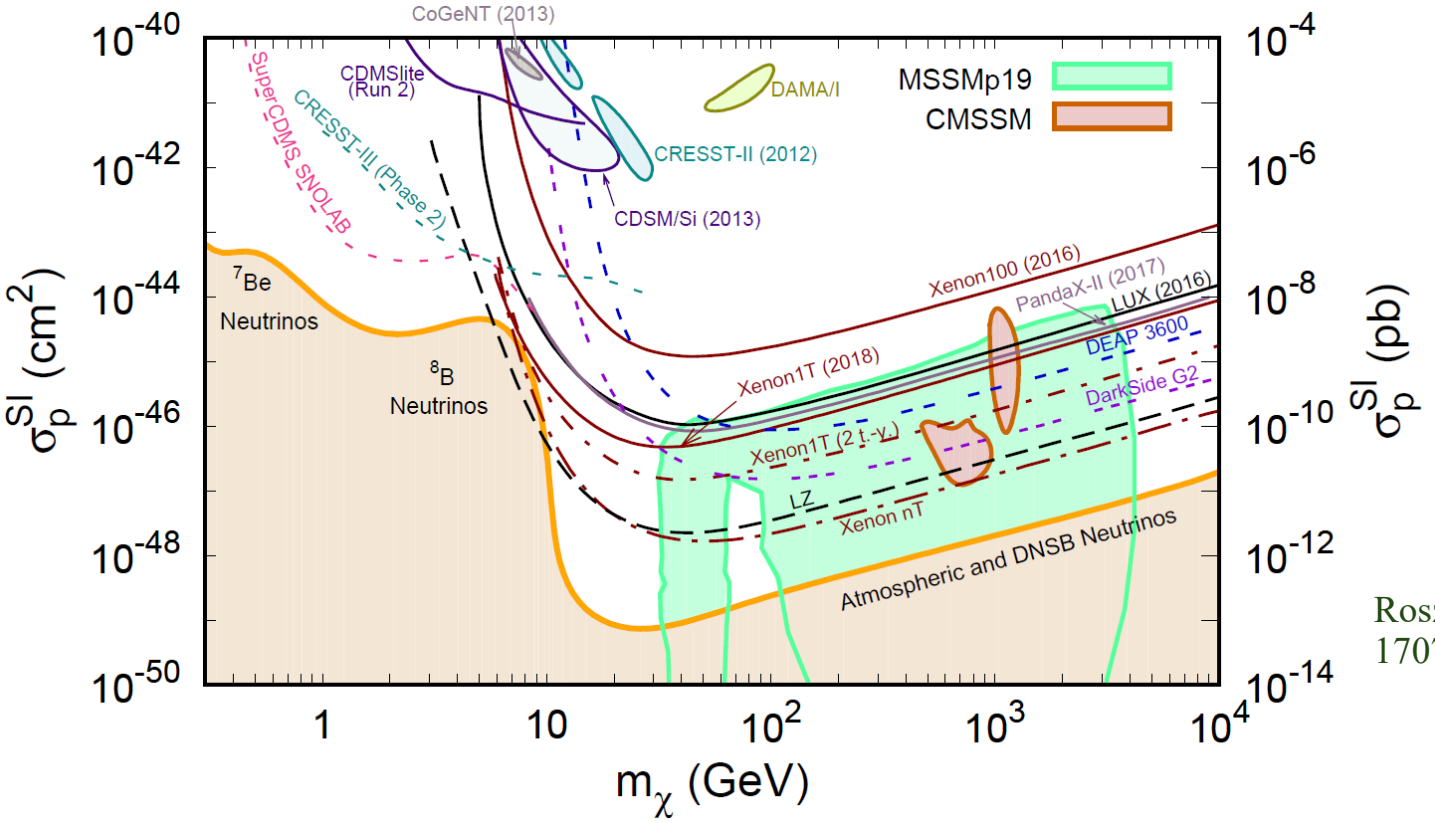


experiment	$N_{\mathcal{E}}^{\mathrm{obs}}$	$N_{\mathcal{E}}^{\mathrm{bck}}$
XENON1T	14	7.36
PICO-60 (1st bin)	3	1
PICO-60 (2nd bin)	0	0

No significant excess detected so far

Theoretical interpretation of experimental results



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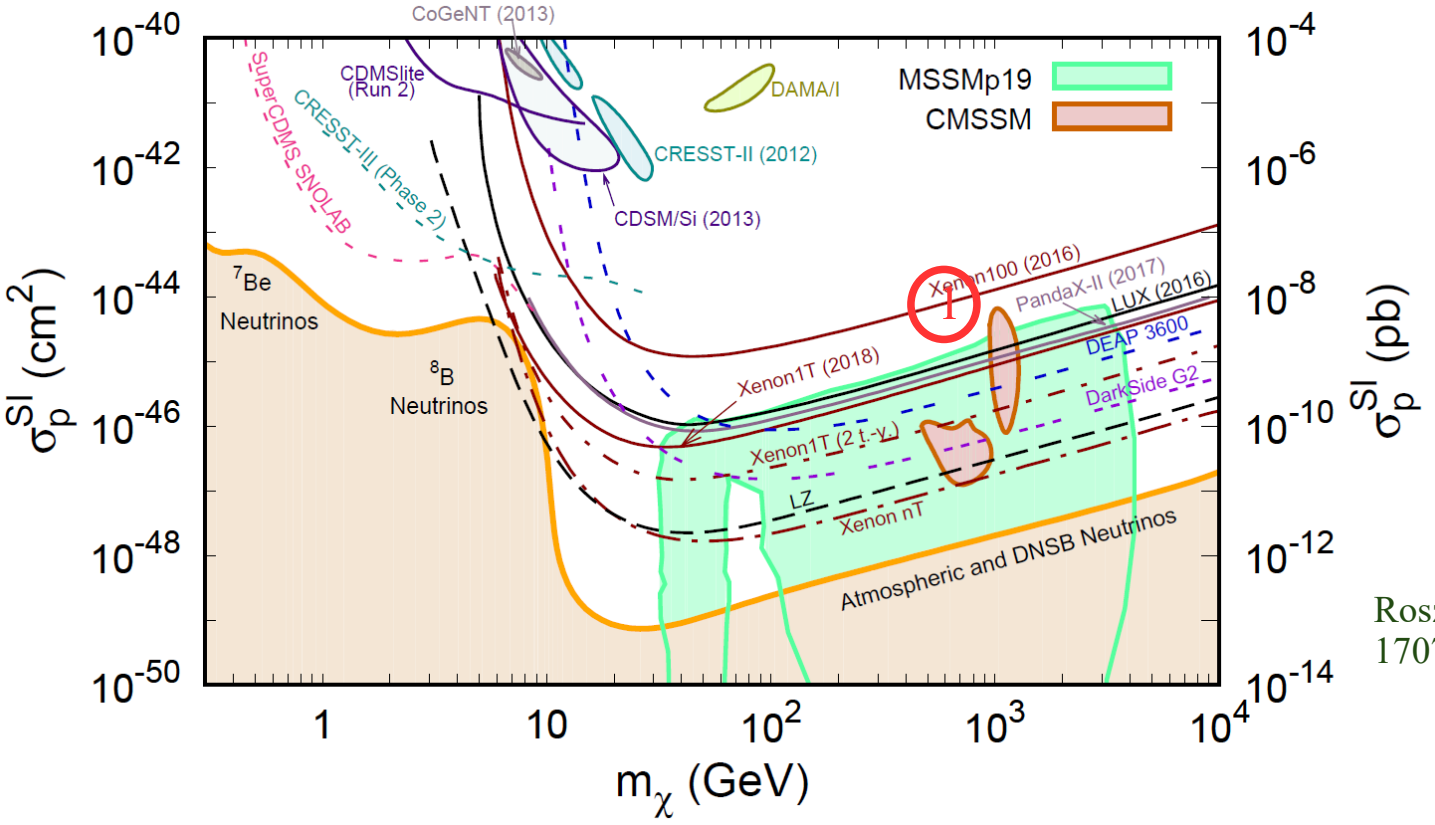

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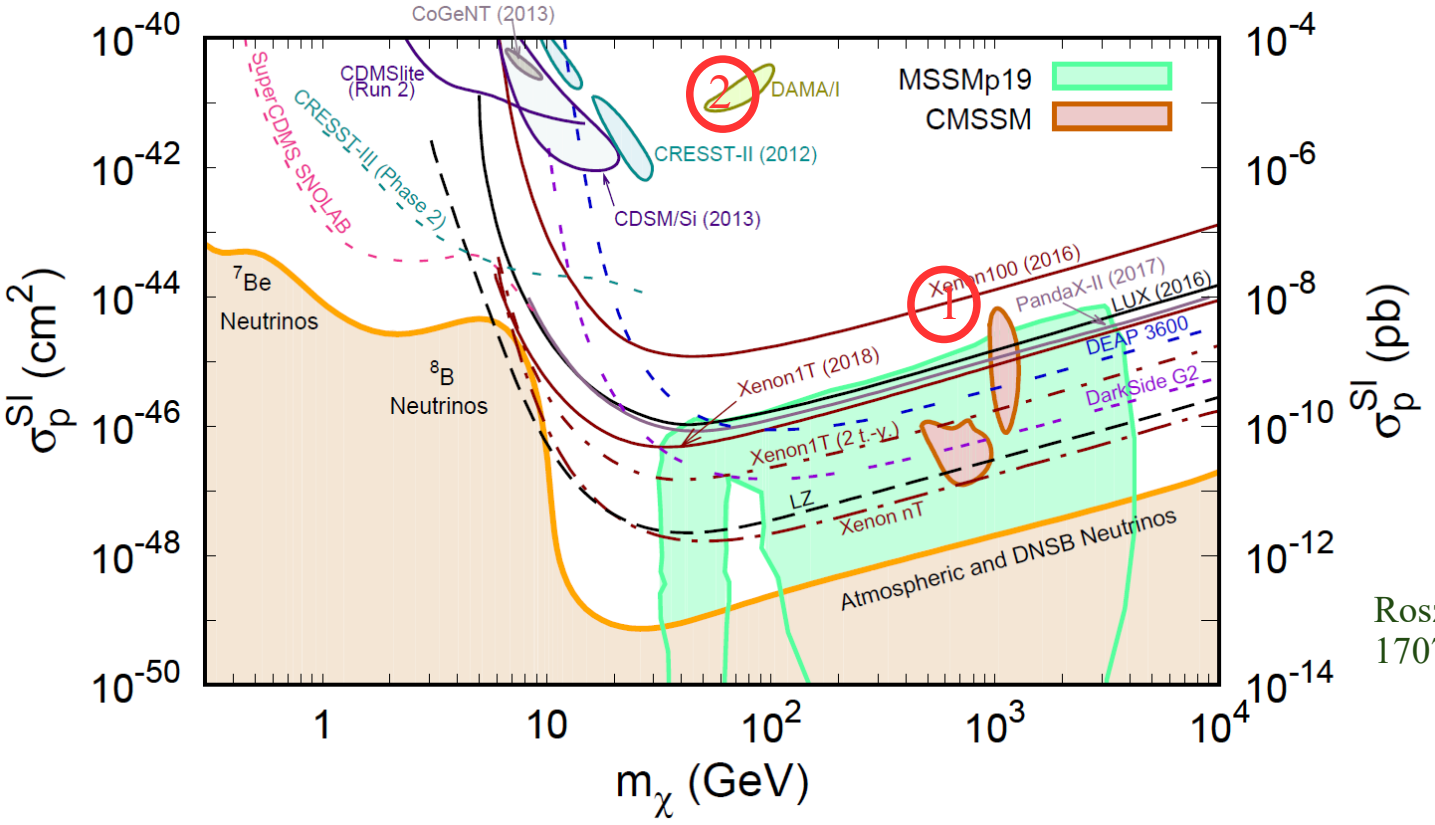

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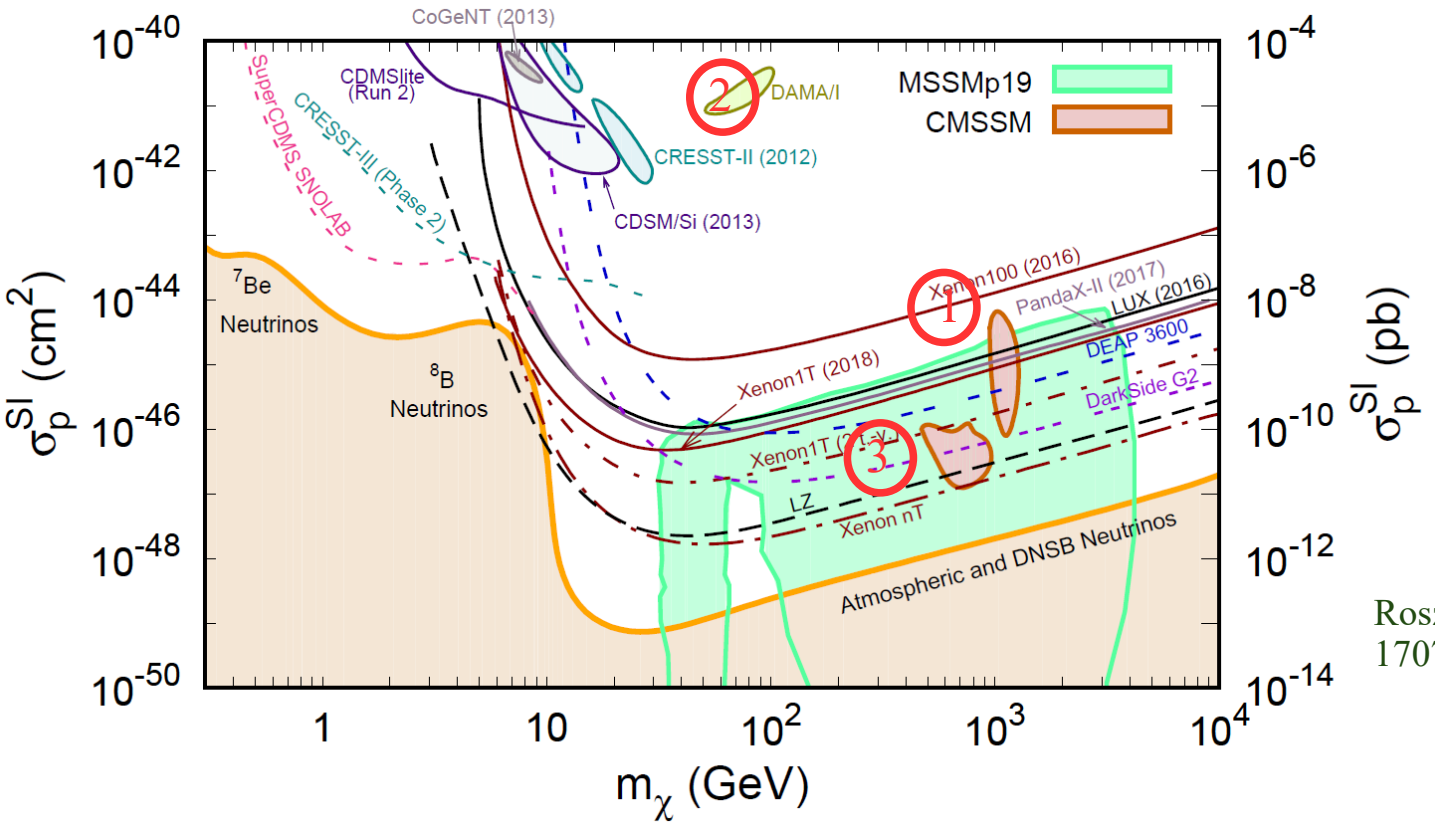

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1. is ruled out (by XENON1T, among others)
2. explains the DAMA results, but is ruled out by other direct detection experiments and by neutrino telescopes
3. is allowed by current experiments, and will be tested by LZ.

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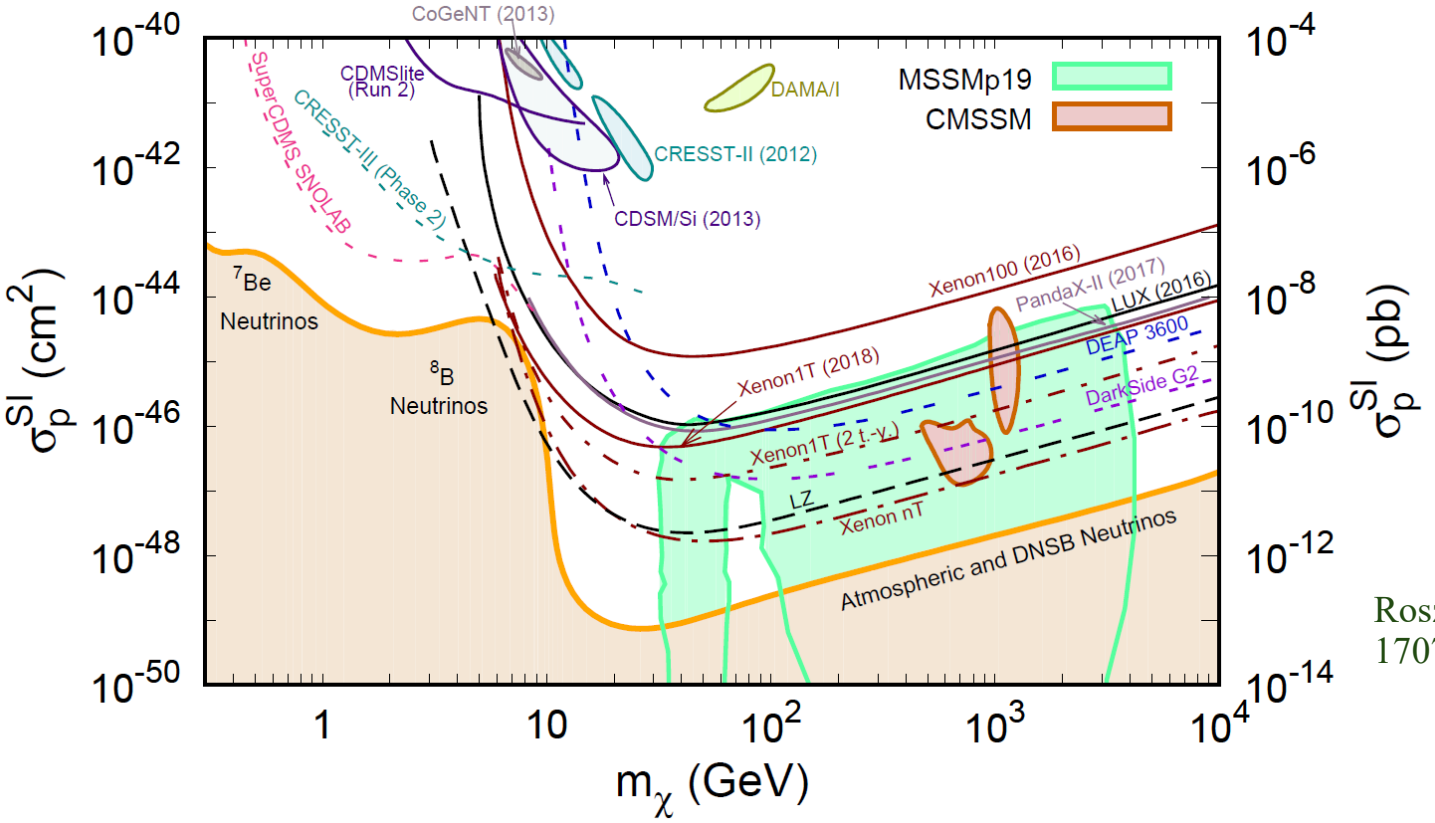

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Smallprint:

- DM interacts only through the spin-independent interaction
- DM couples with equal strength to protons and neutrons (isoscalar)
- Local DM density ρ=0.3 GeV/cm3.
- DM velocity distribution given by a Maxwell-Boltzmann, truncated at the escape velocity.

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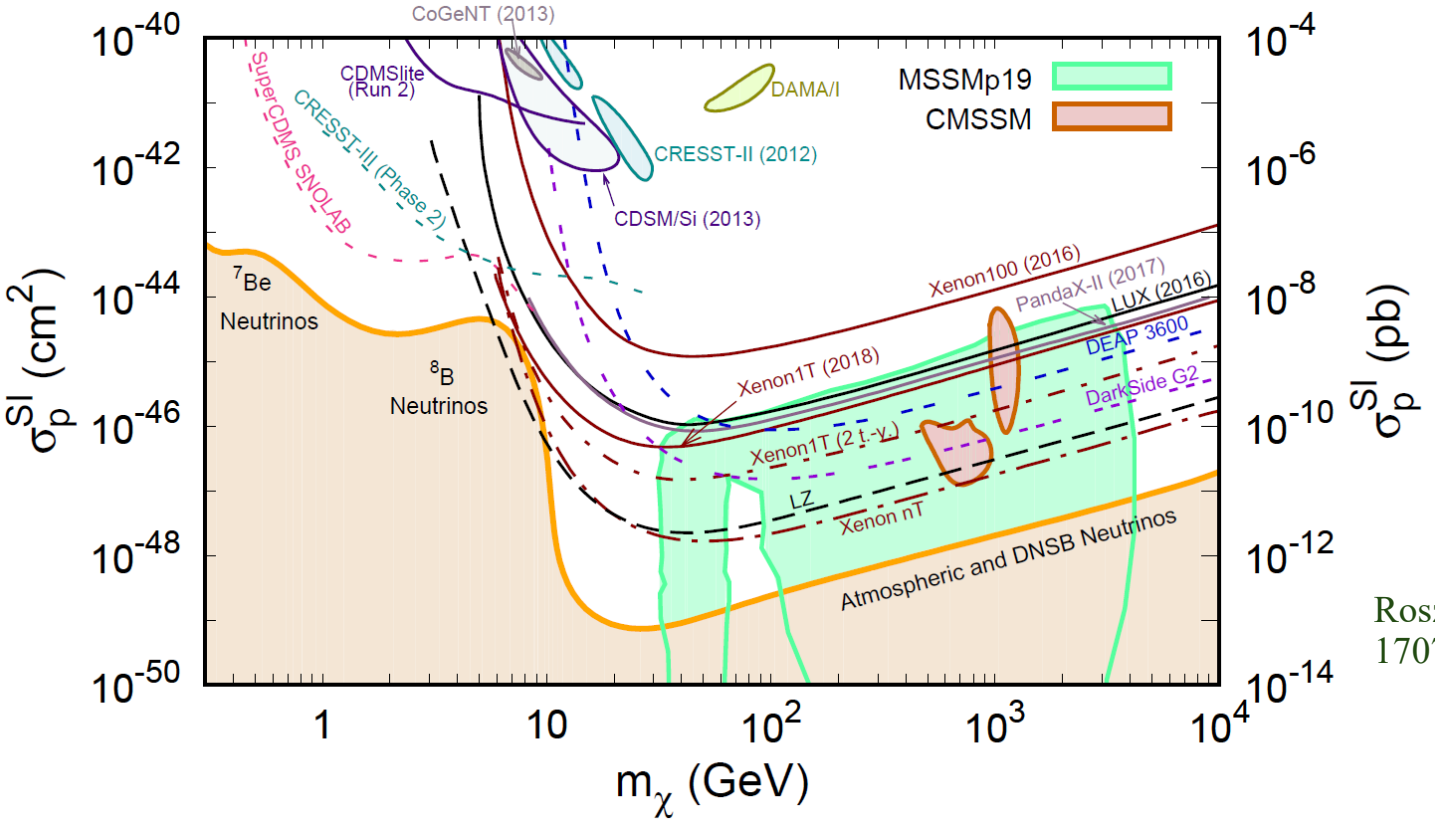

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Differential recoil rate

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

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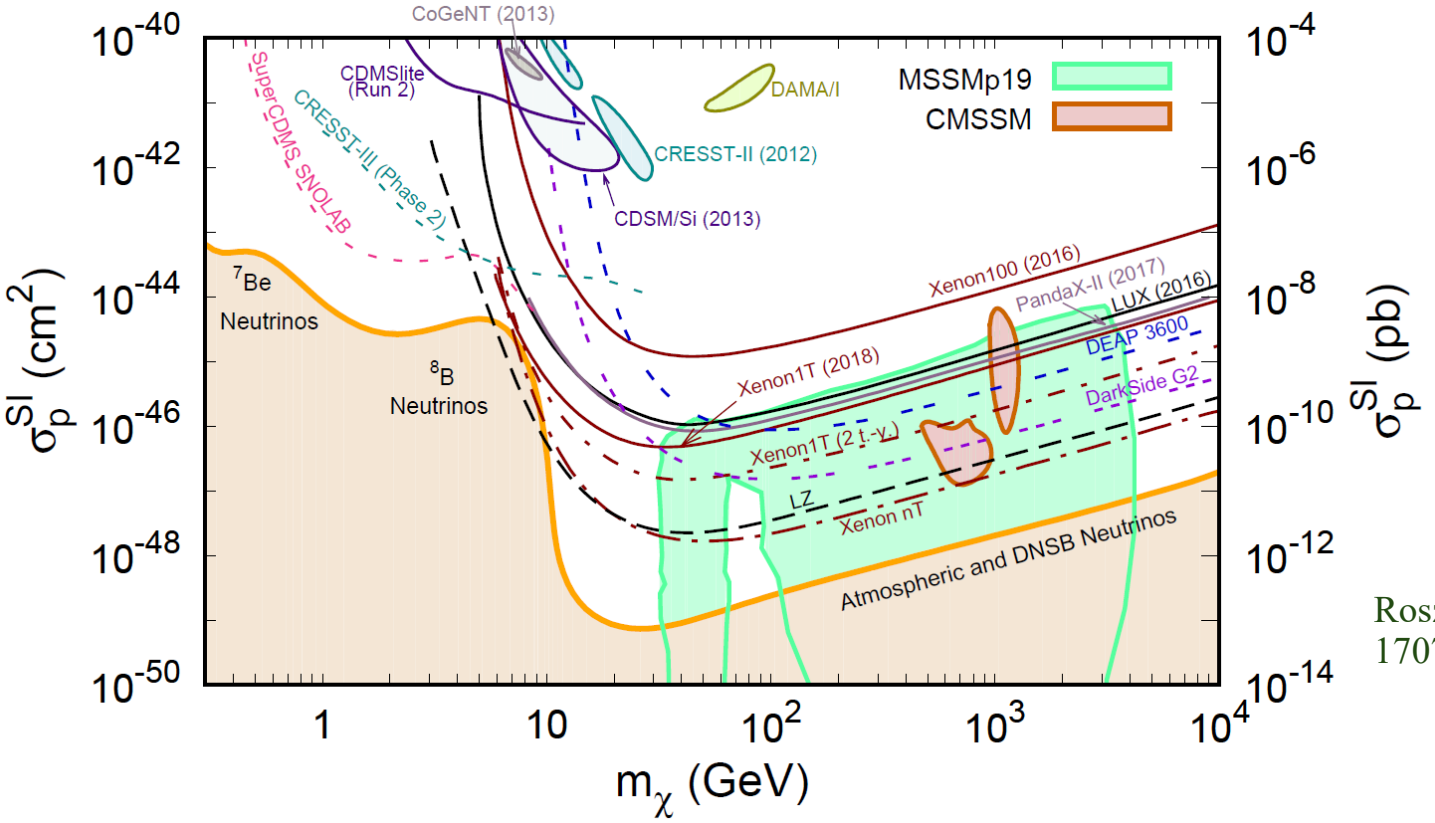

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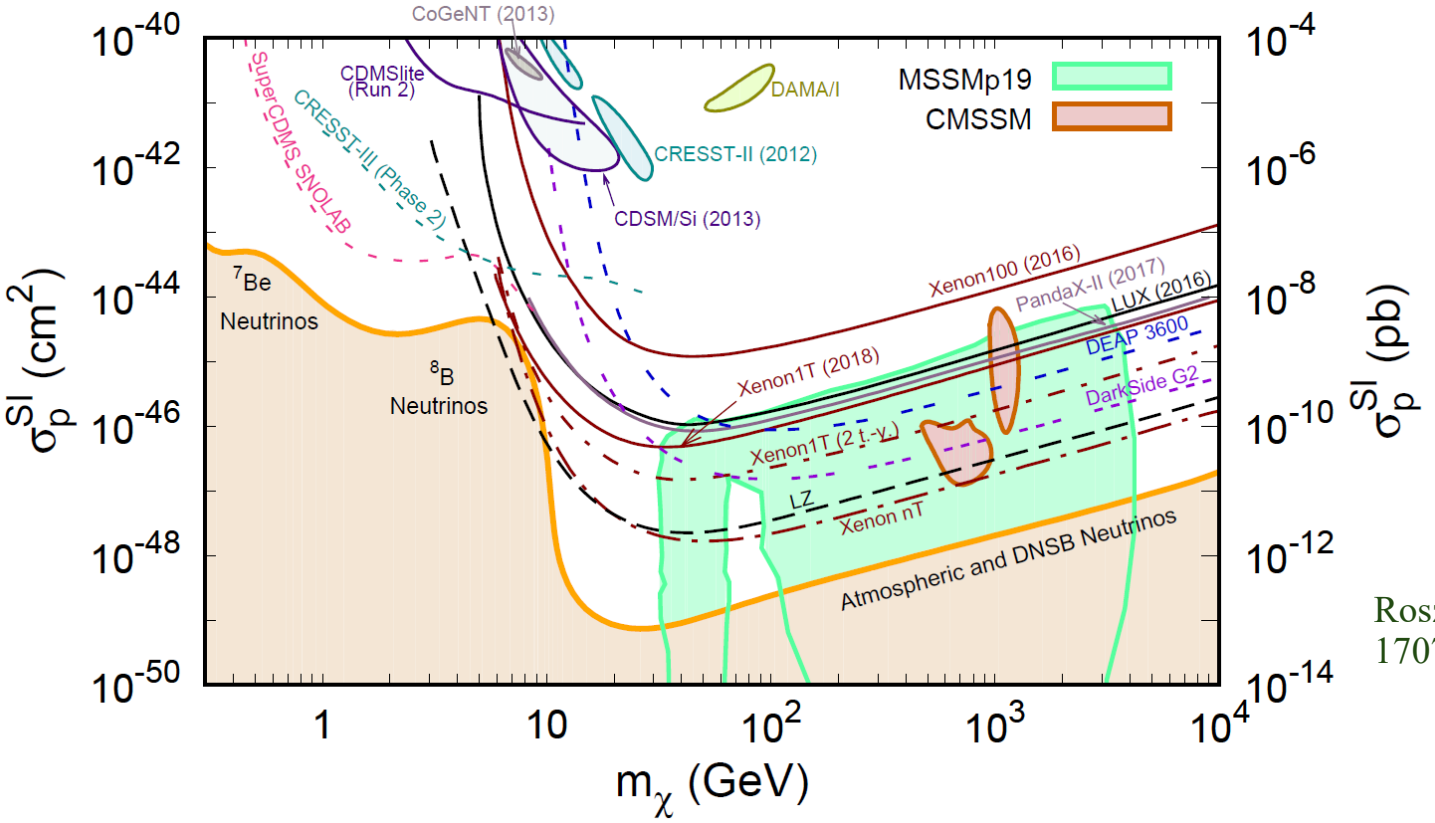

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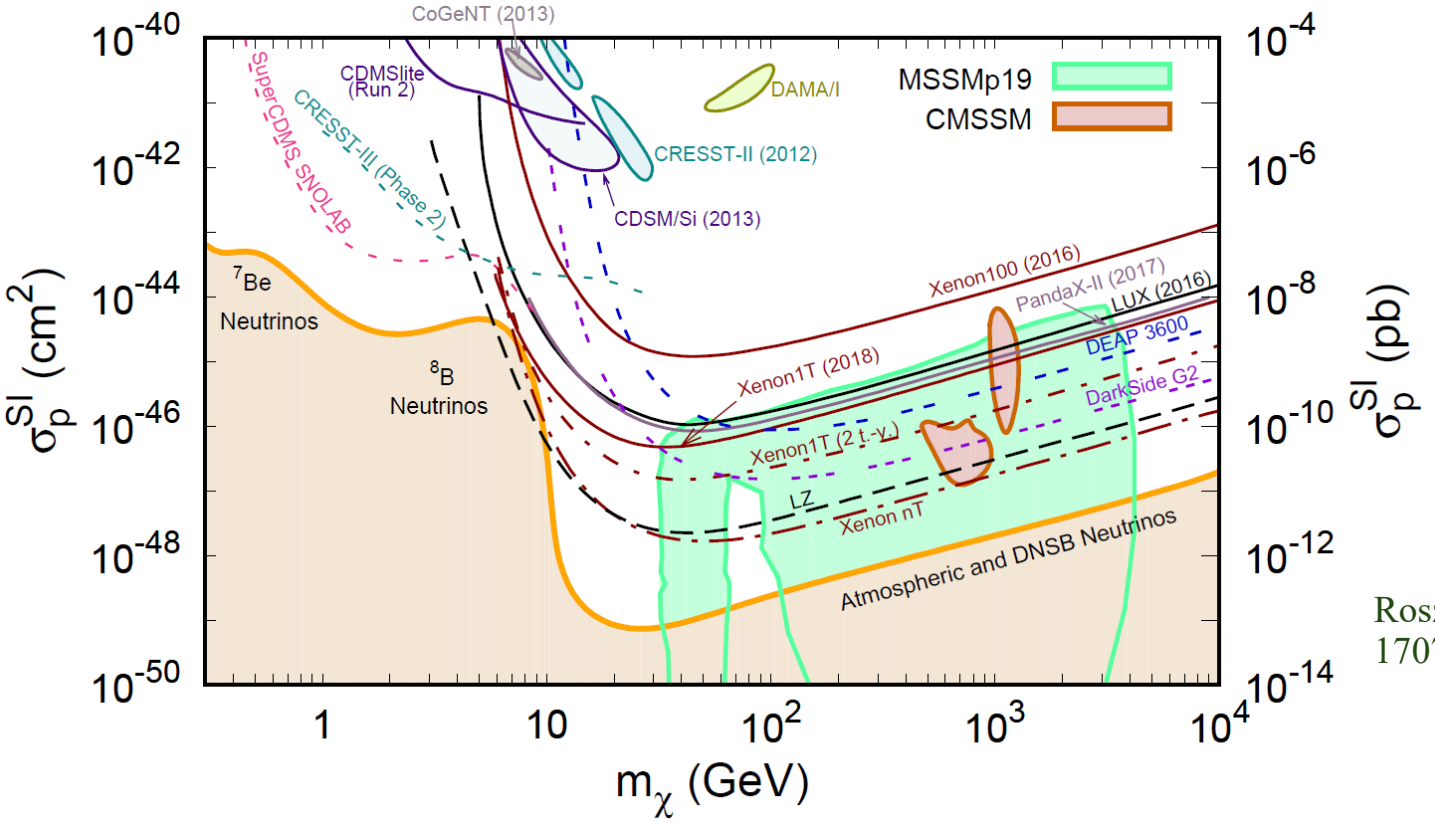

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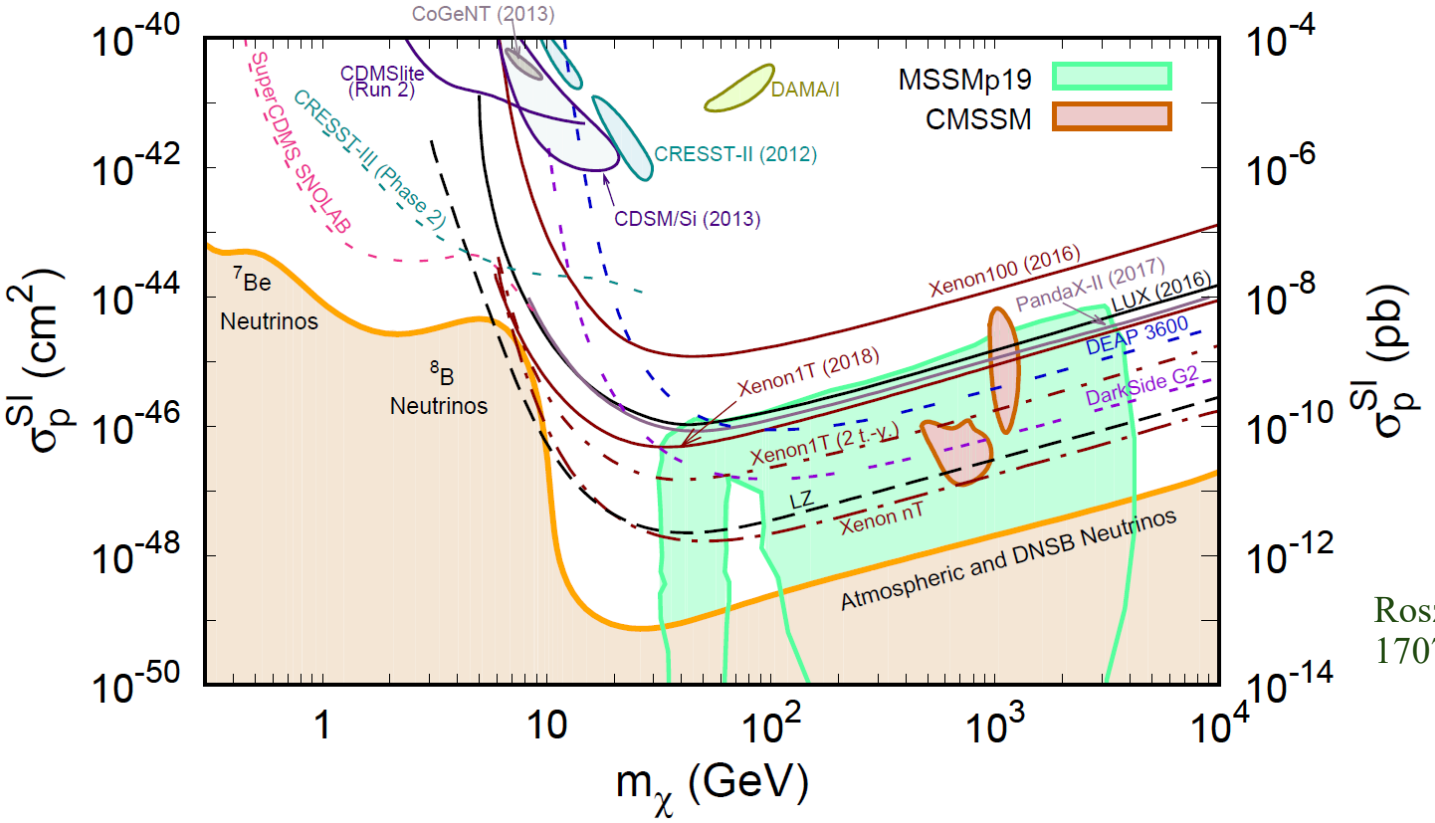

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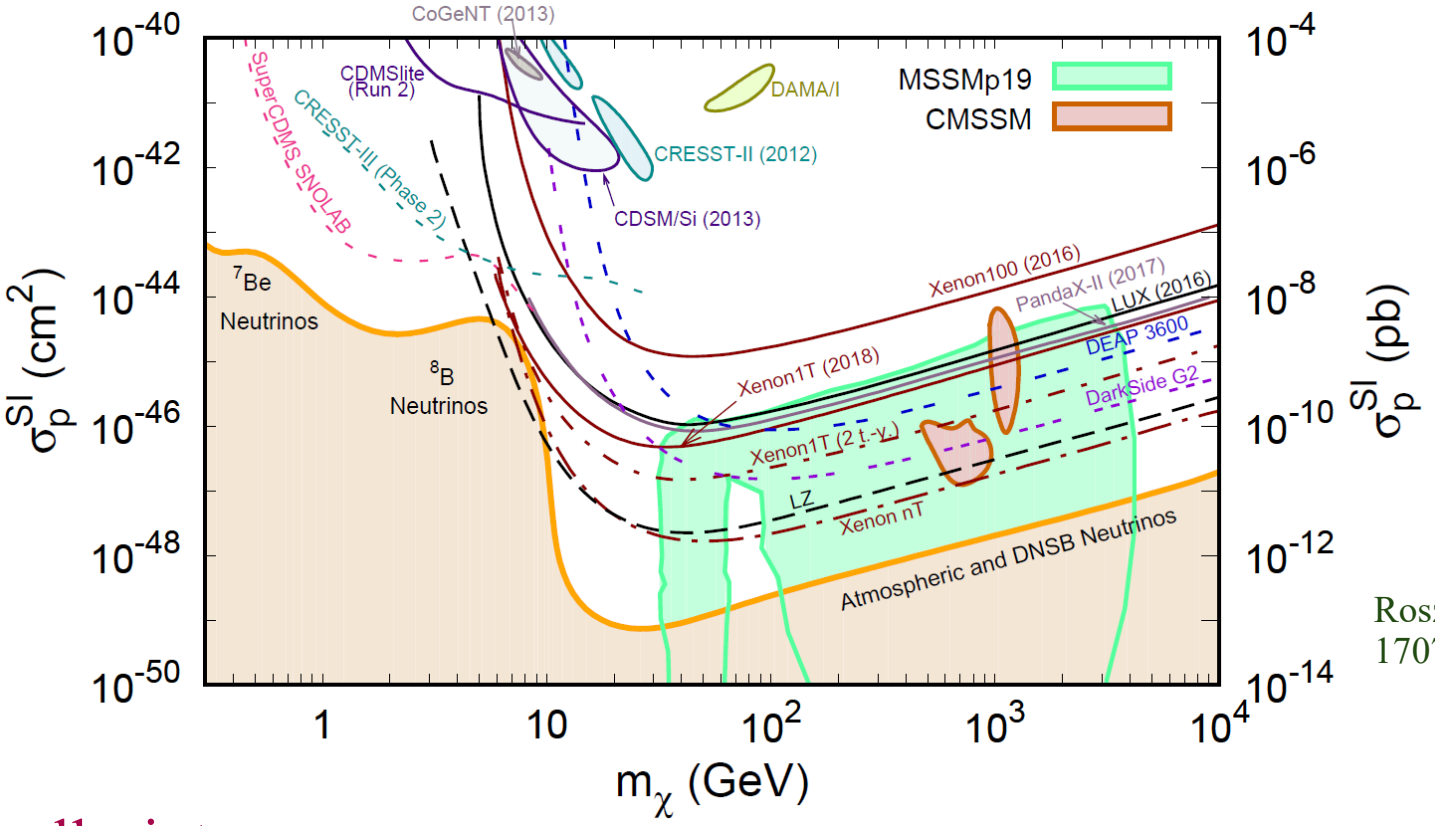

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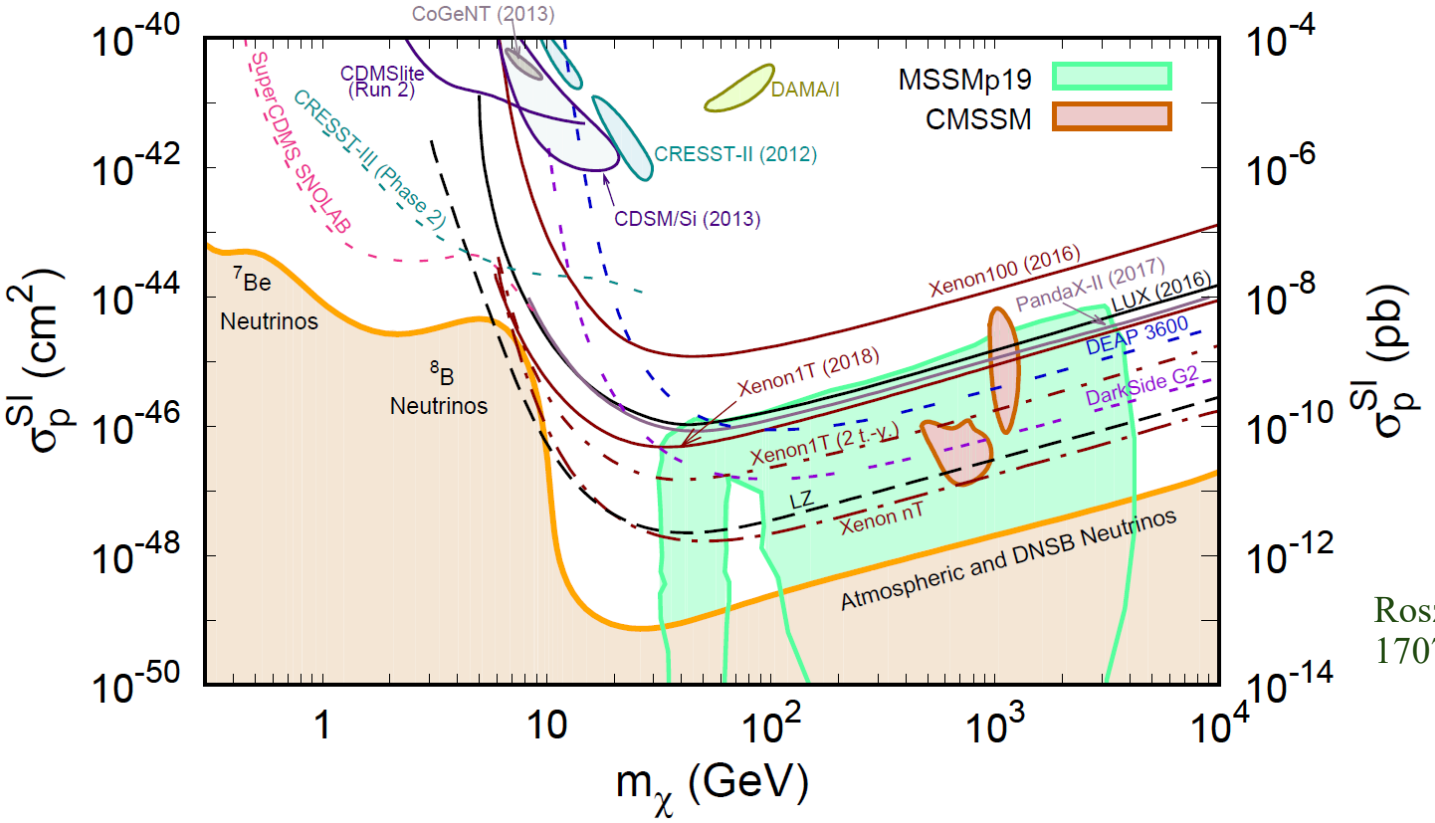

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DM does not necessary couple with equal strength to protons and neutrons.
Is there a limit applicable to all scenarios with SI interaction?

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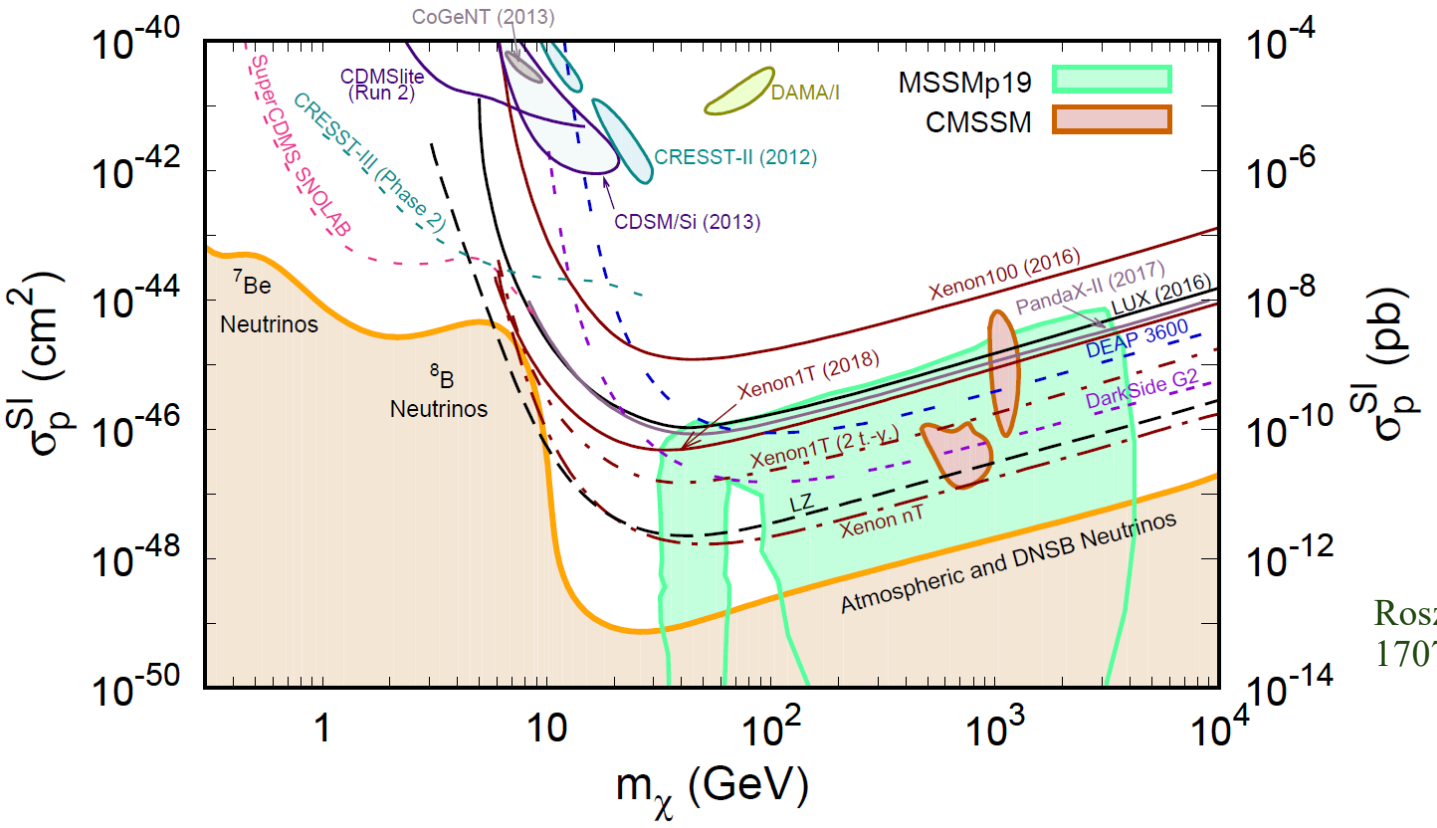

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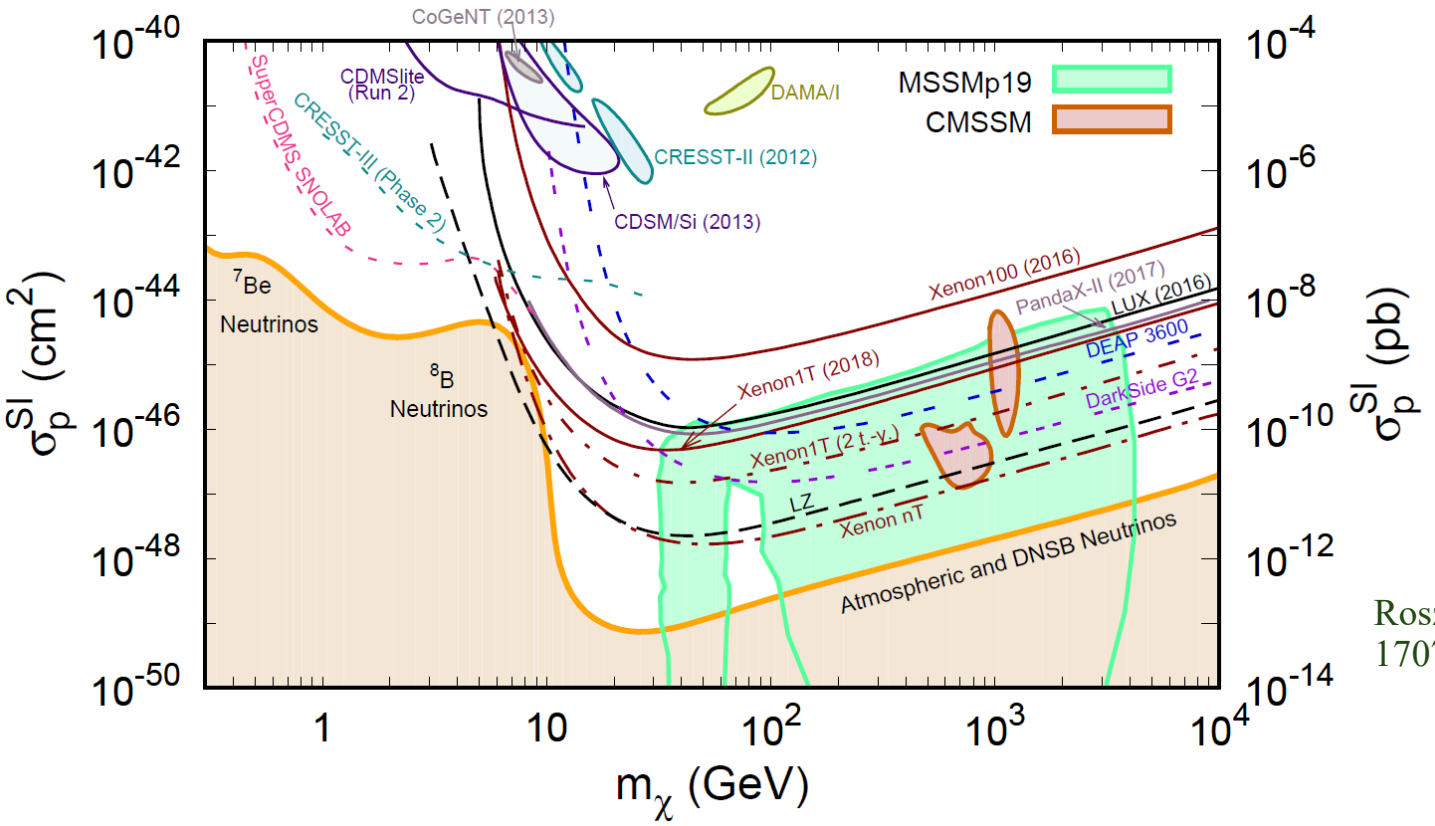

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What is the impact of the astrophysical uncertainties on these conclusions?

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

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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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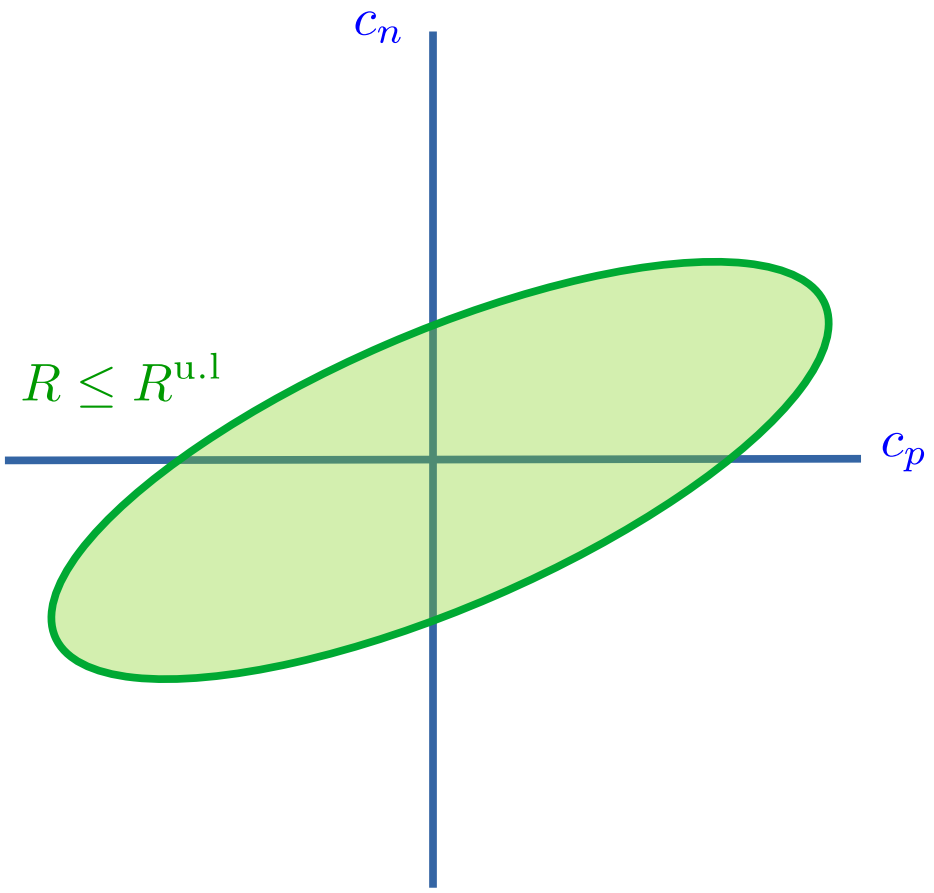

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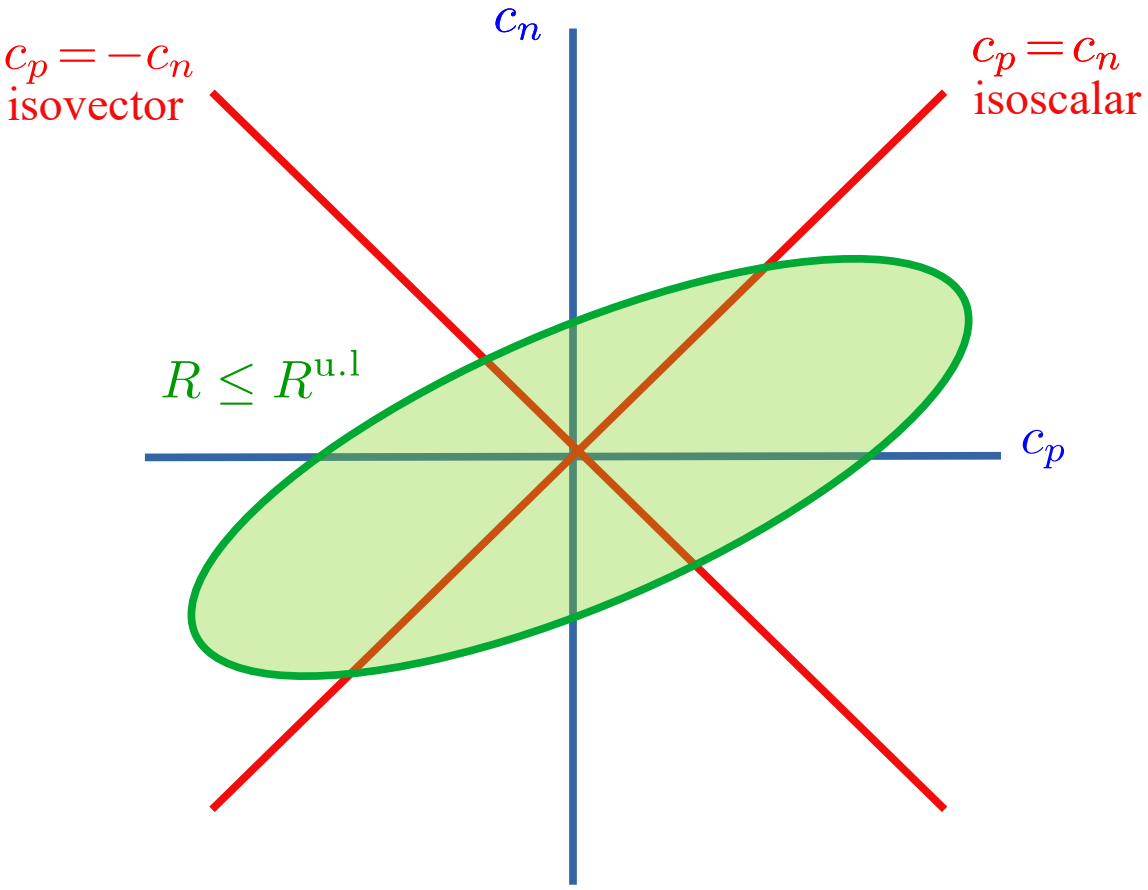

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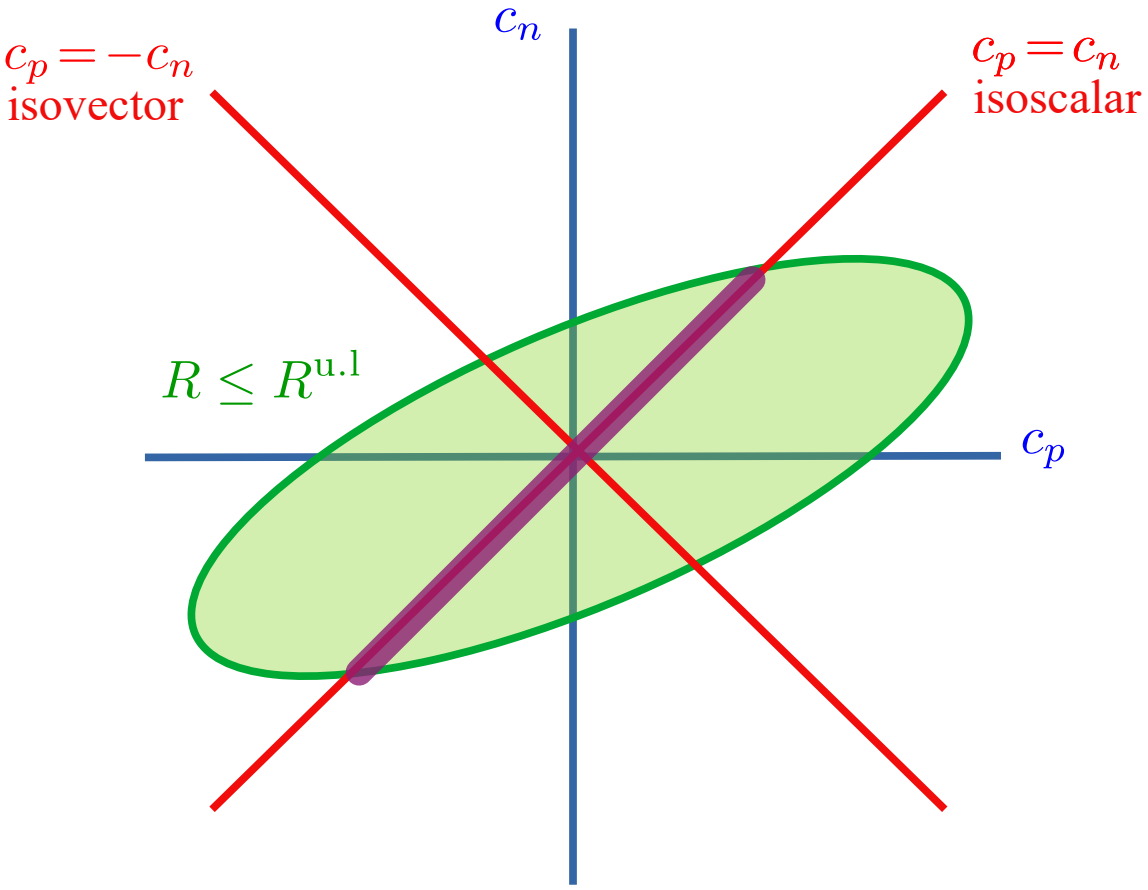

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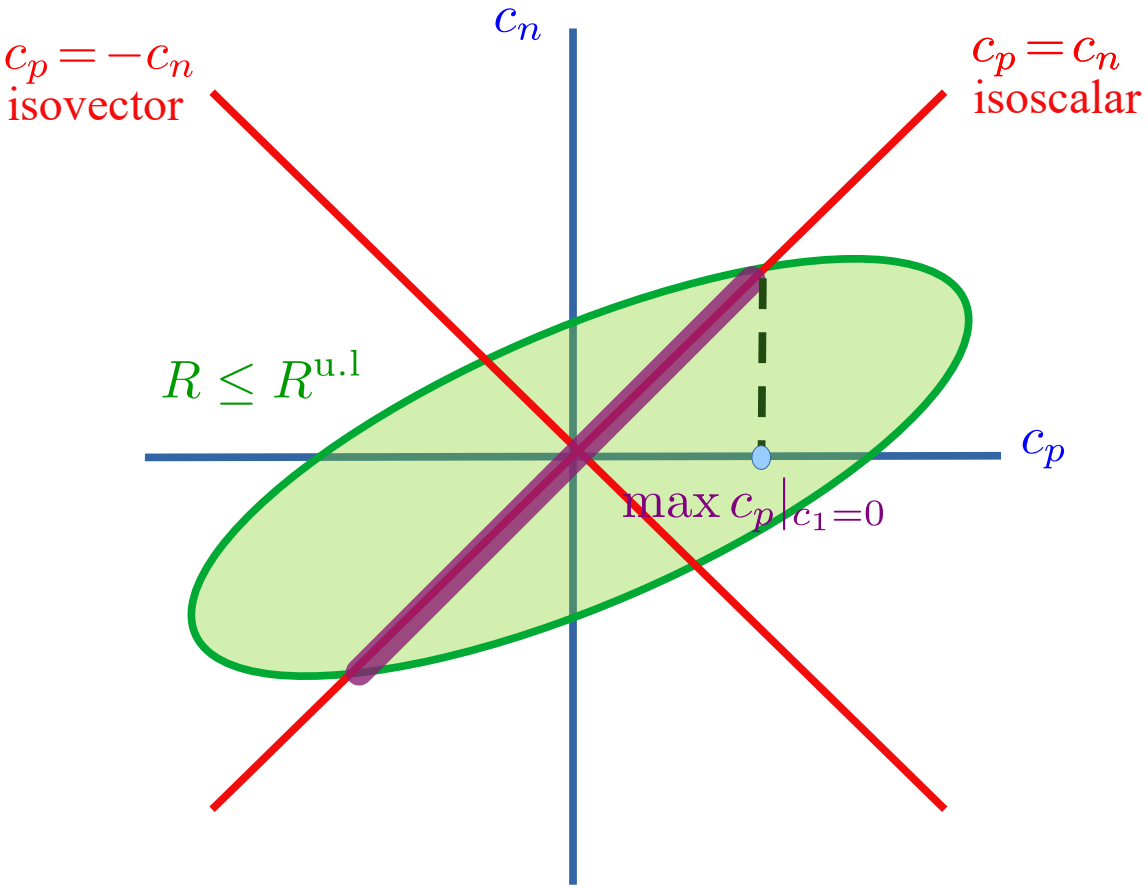

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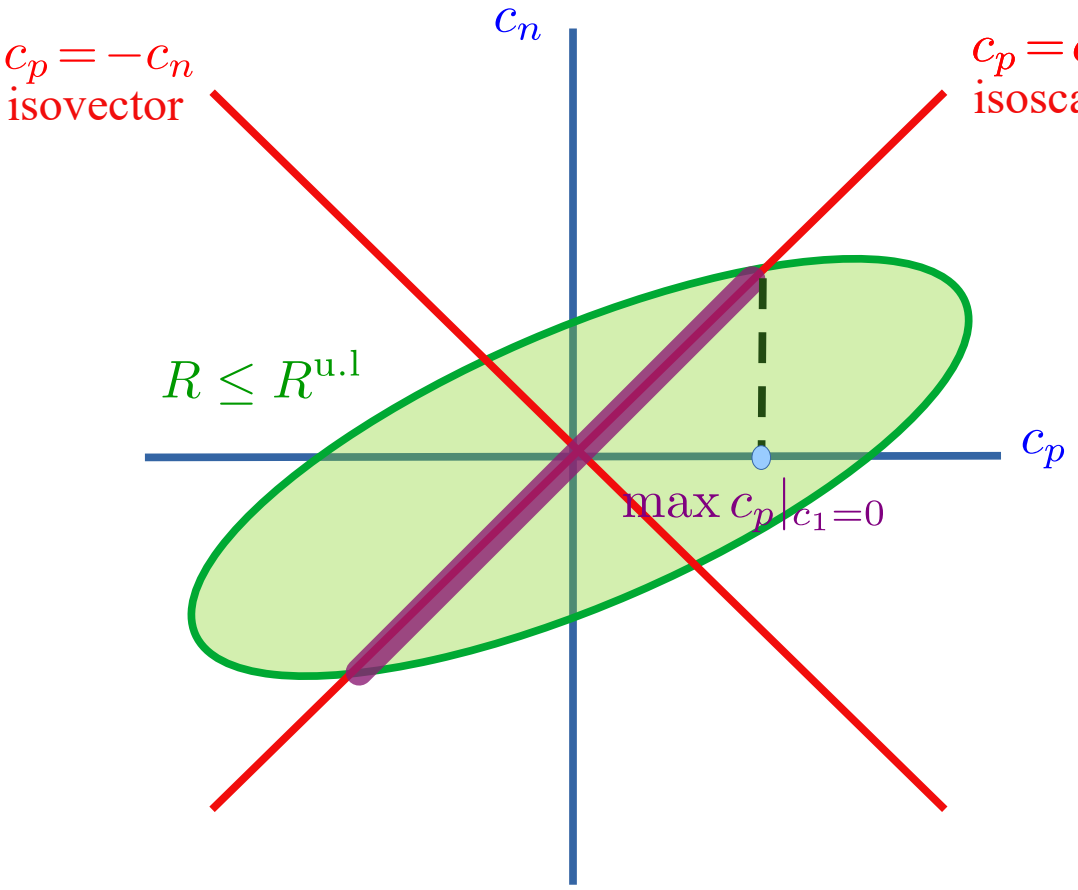

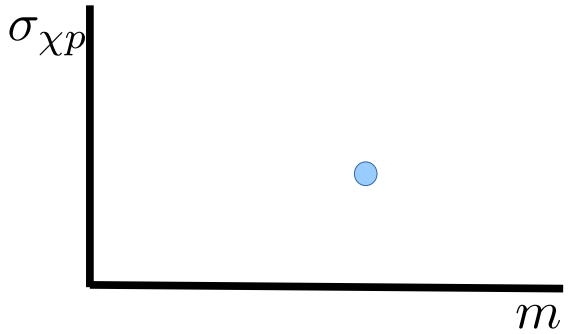

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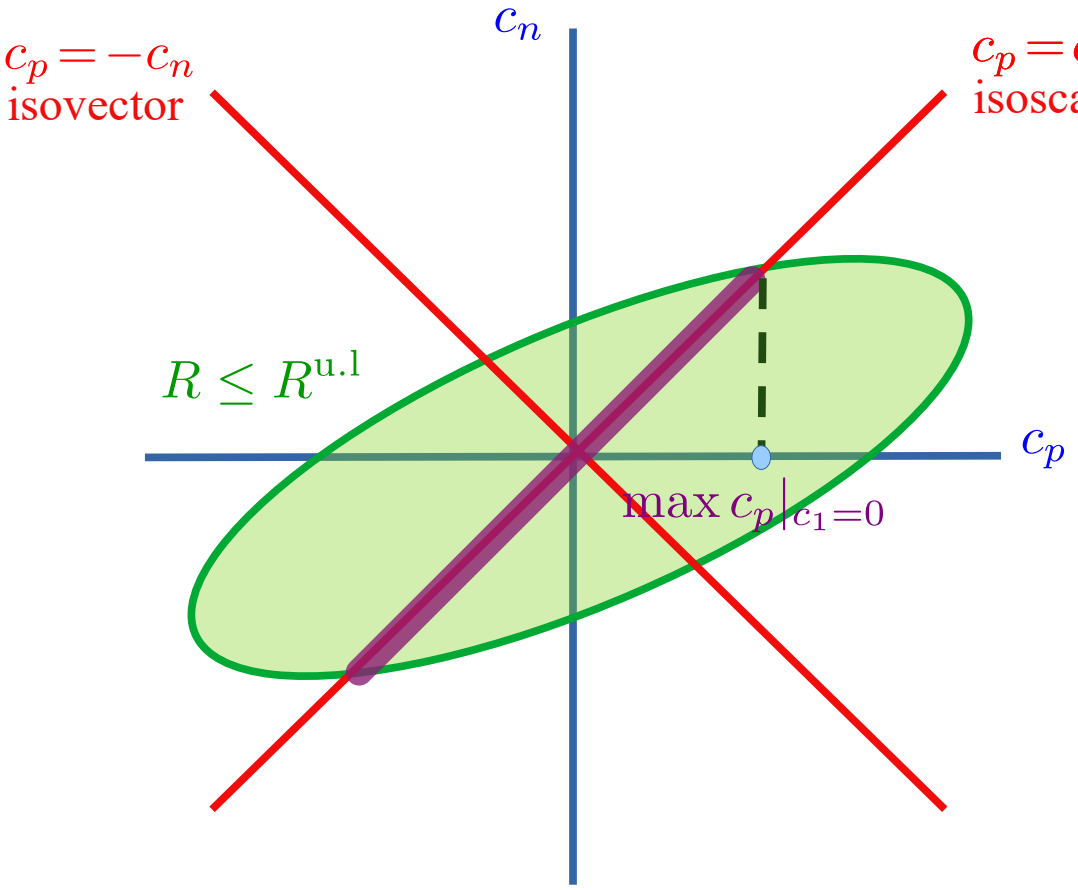

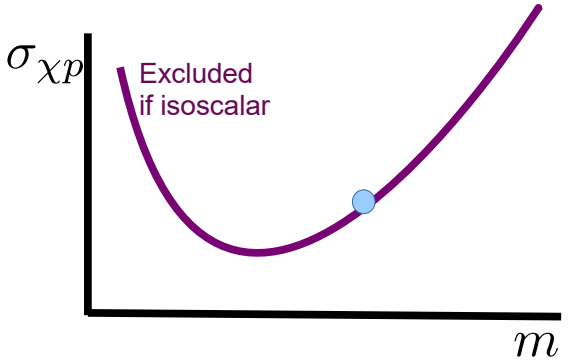

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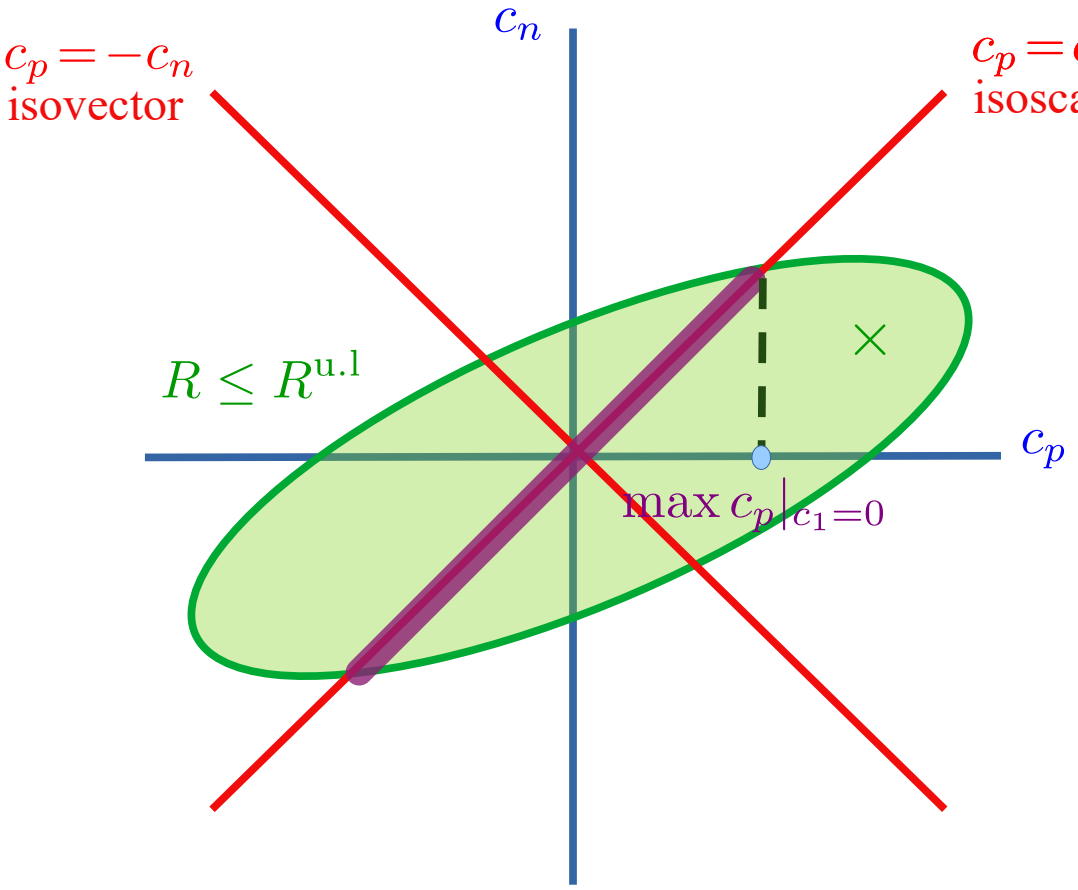

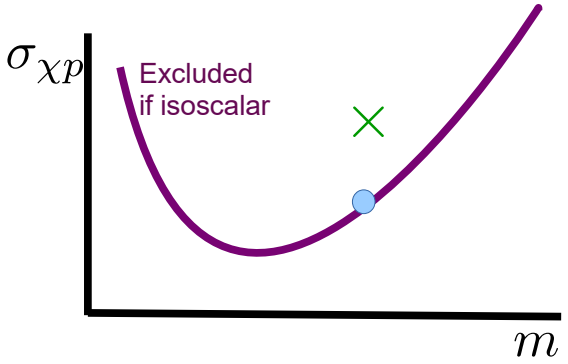

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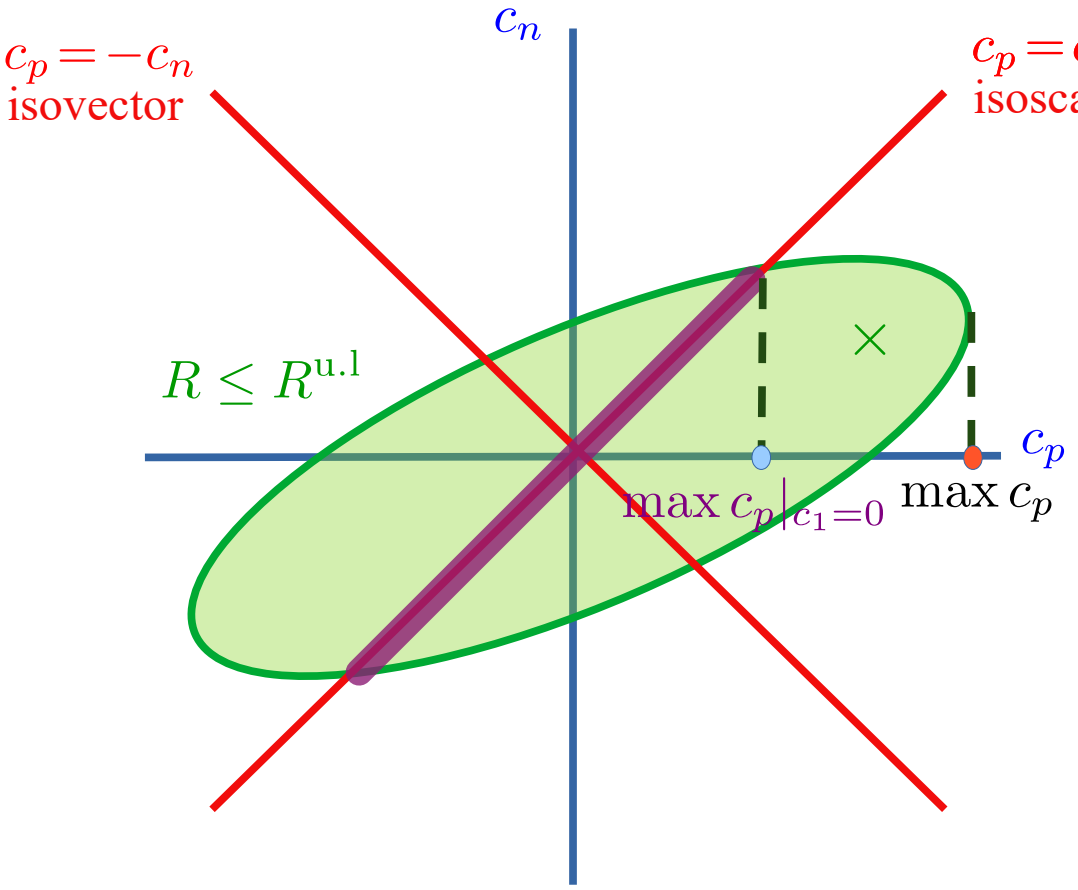

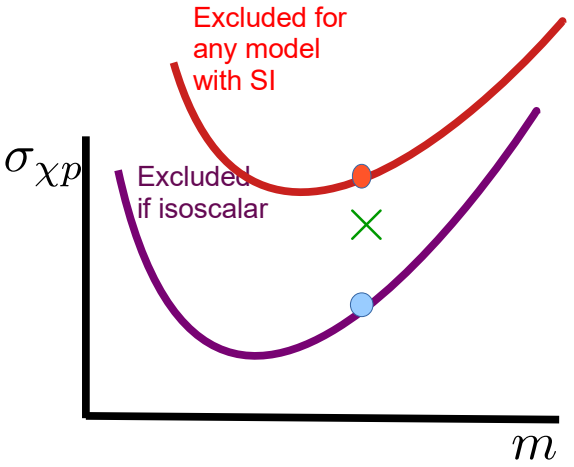

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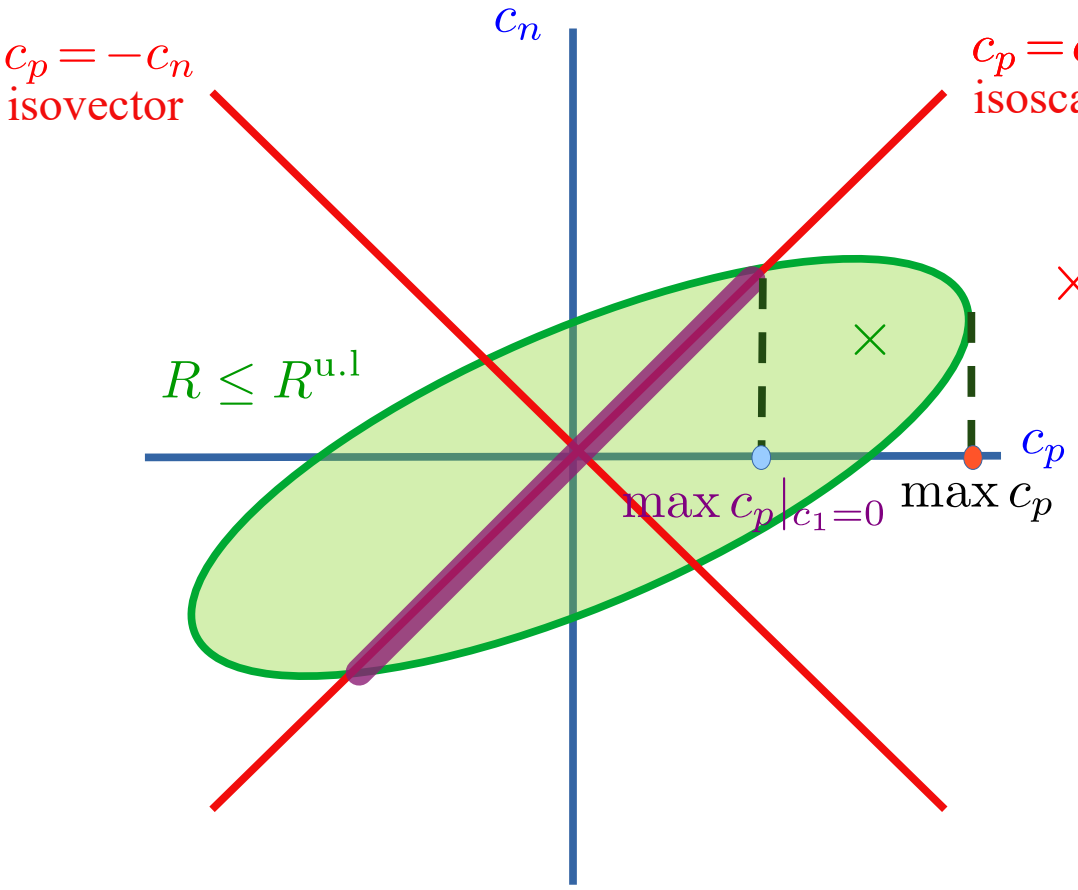

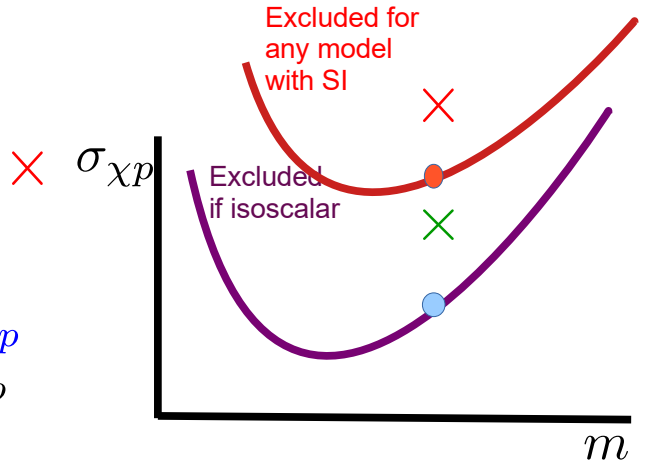

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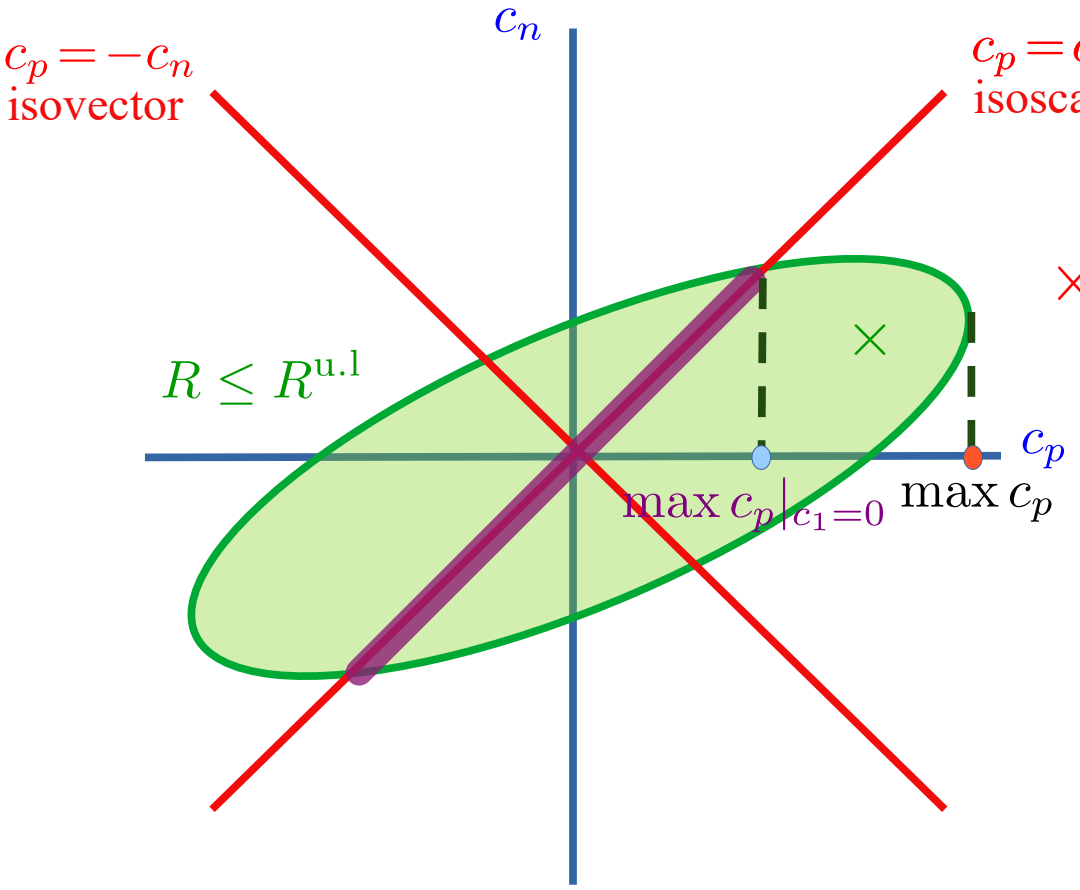
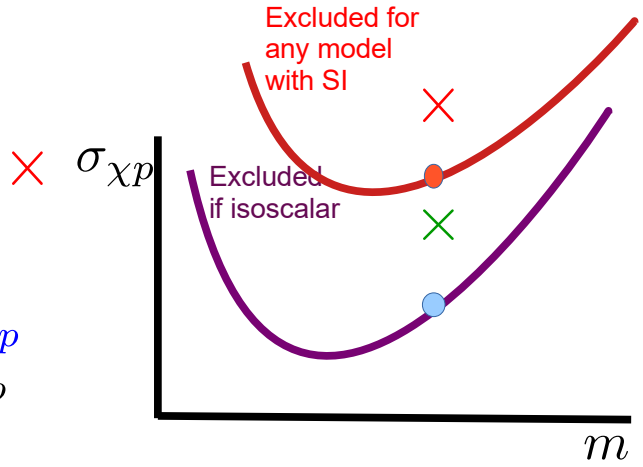
Scattering rate $\sim \left|\mathcal{H}\right|^2 \sim \begin{pmatrix} c_p & c_n \end{pmatrix} \begin{pmatrix} R_{pp} & R_{pn} \\ R_{np} & R_{nn} \end{pmatrix} \begin{pmatrix} c_p \\ c_n \end{pmatrix} = \mathbf{c}^T \mathbb{R} \mathbf{c}$



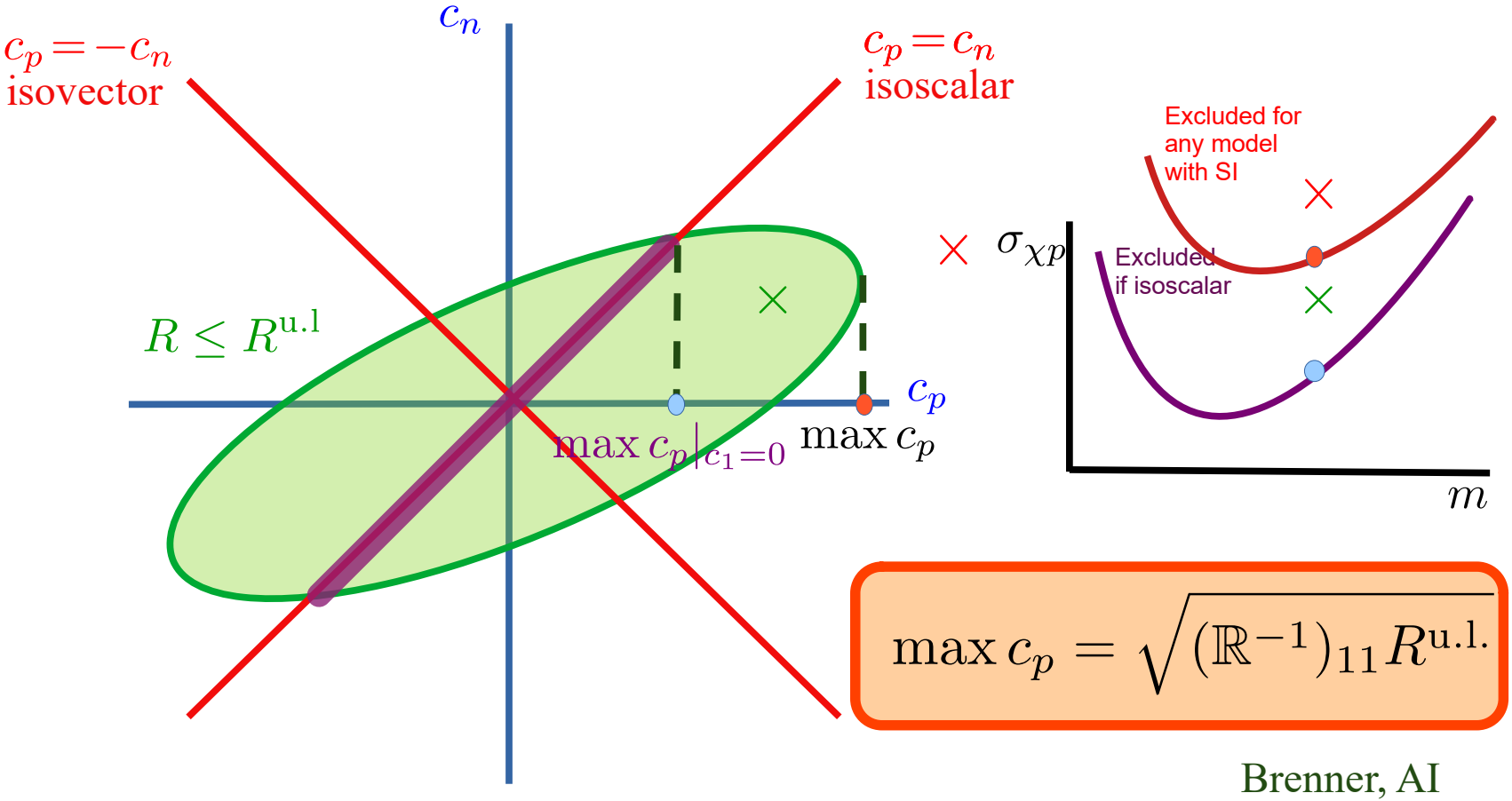


Impact of operator interference

Consider the Hamiltonian of the SI interaction:

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

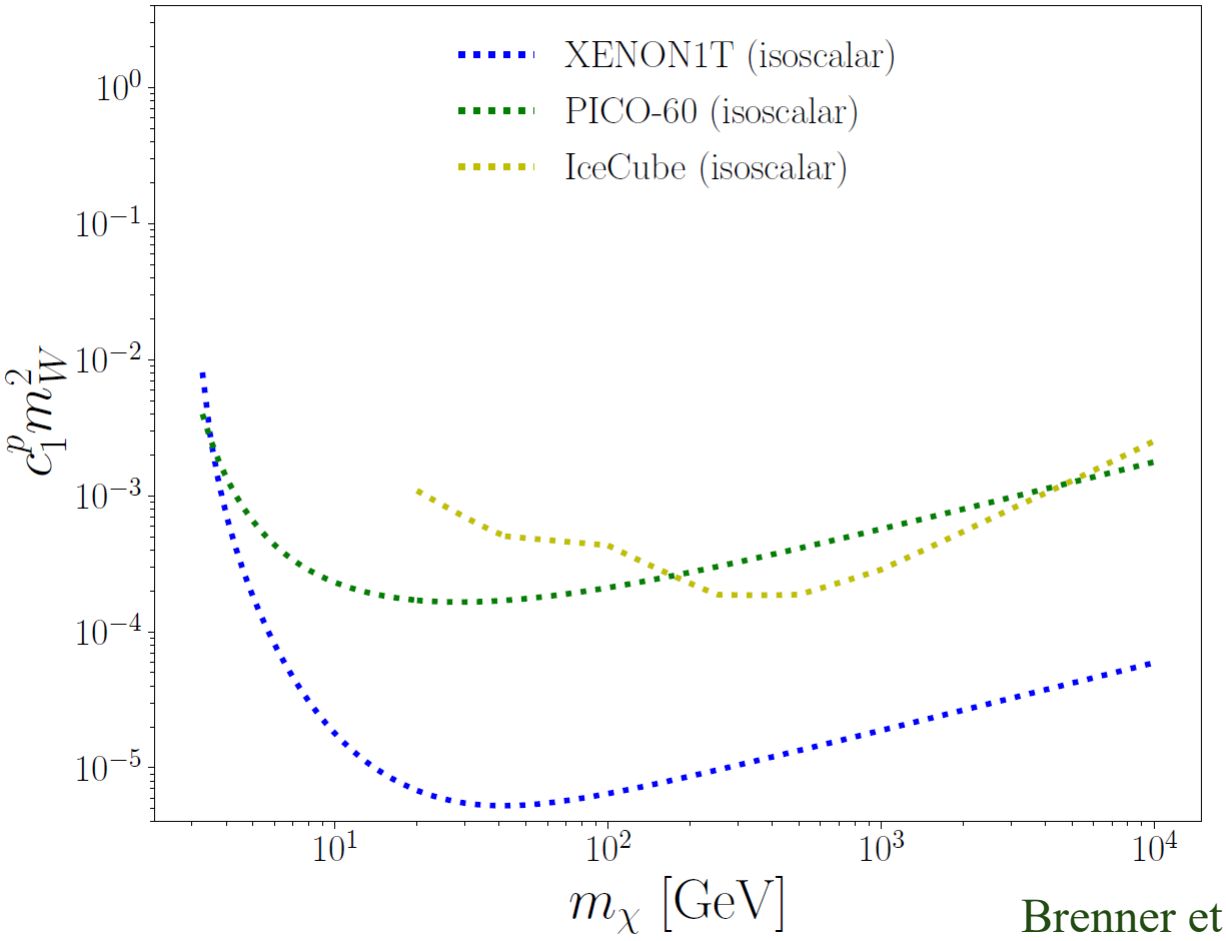
Scattering rate $\sim |\mathcal{H}|^2 \sim \begin{pmatrix} c_p & c_n \end{pmatrix} \begin{pmatrix} R_{pp} & R_{pn} \\ R_{np} & R_{nn} \end{pmatrix} \begin{pmatrix} c_p \\ c_n \end{pmatrix} = \mathbf{c}^T \mathbb{R} \mathbf{c}$



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

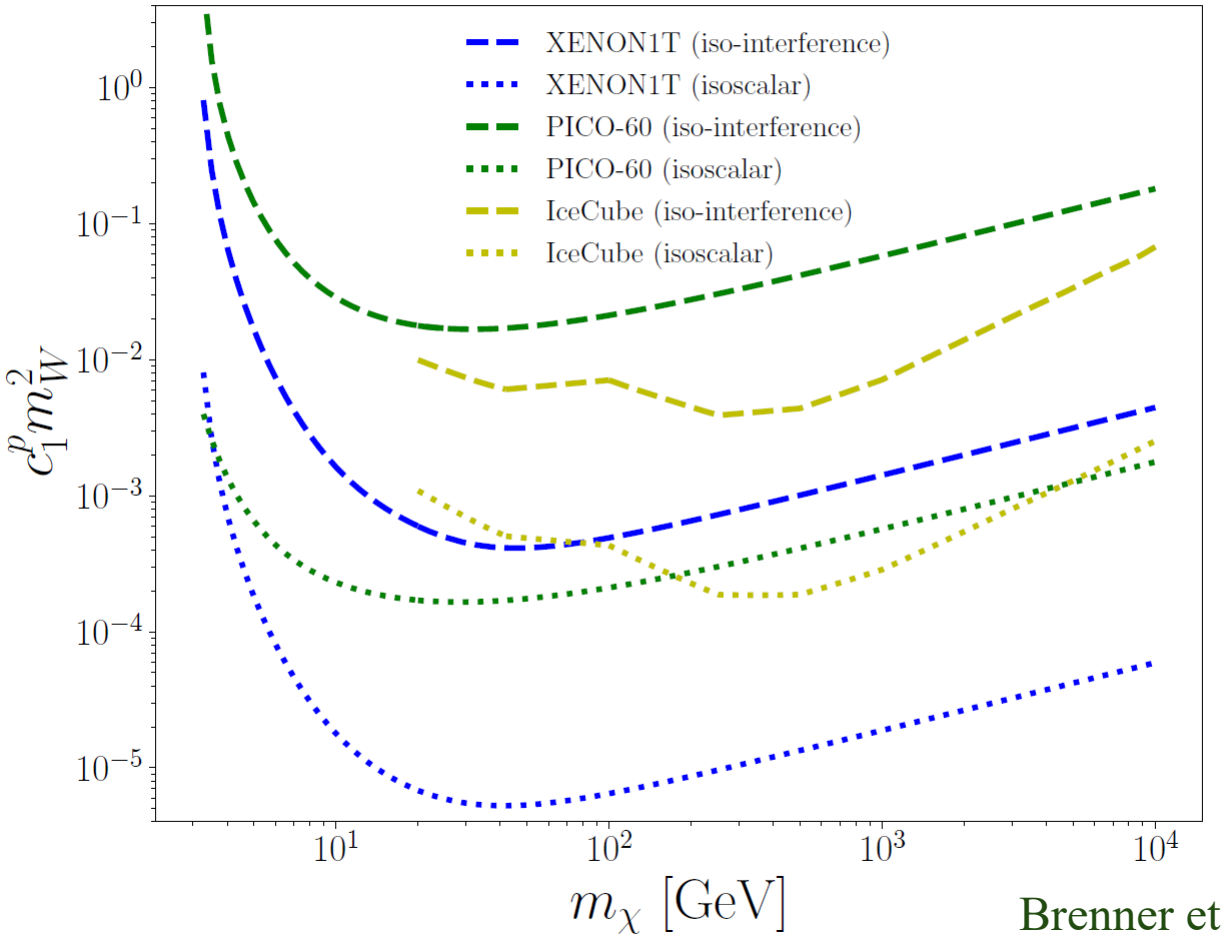
Brenner, AI
2011.02929

Impact of operator interference



Brenner et al. 2203.04210

Impact of operator interference



Brenner et al. 2203.04210

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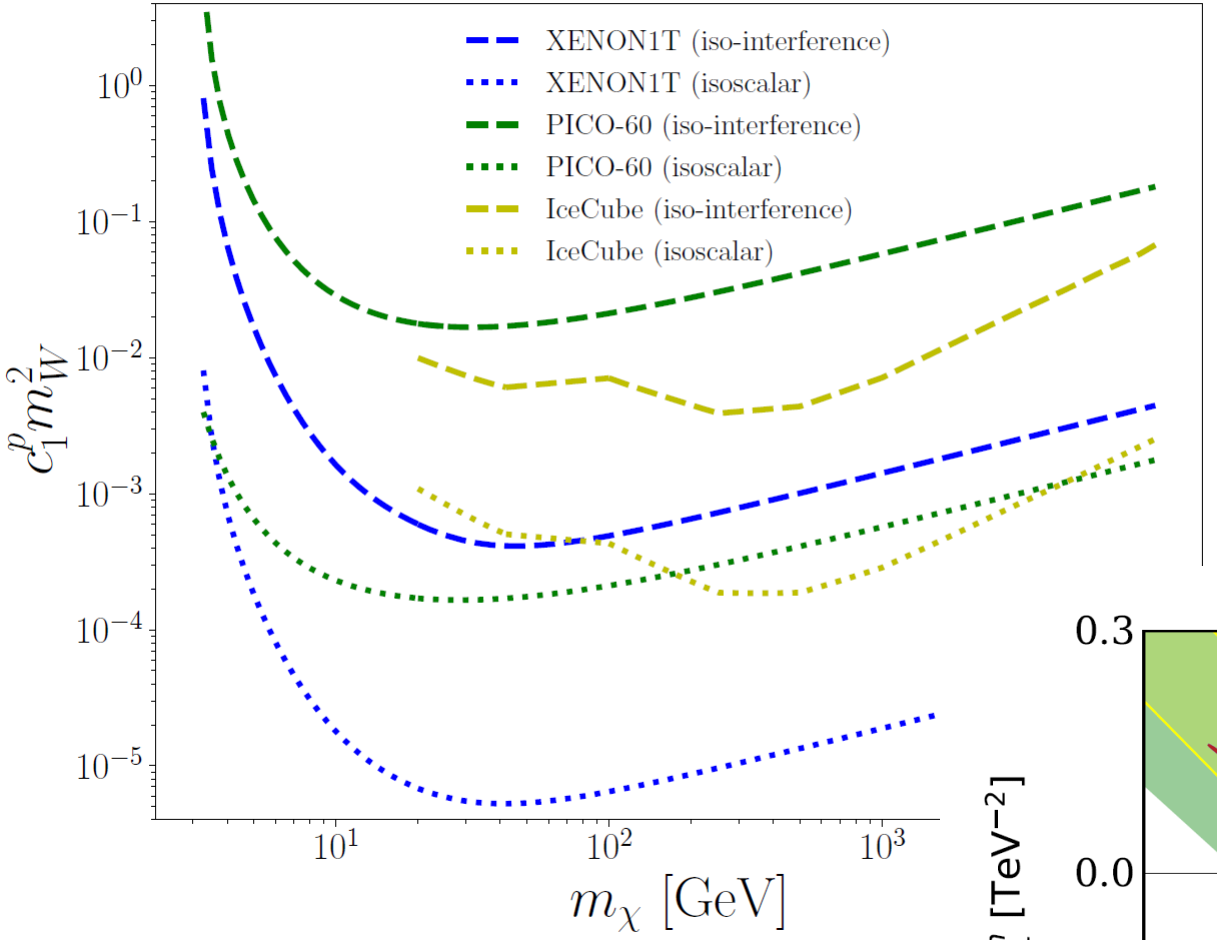
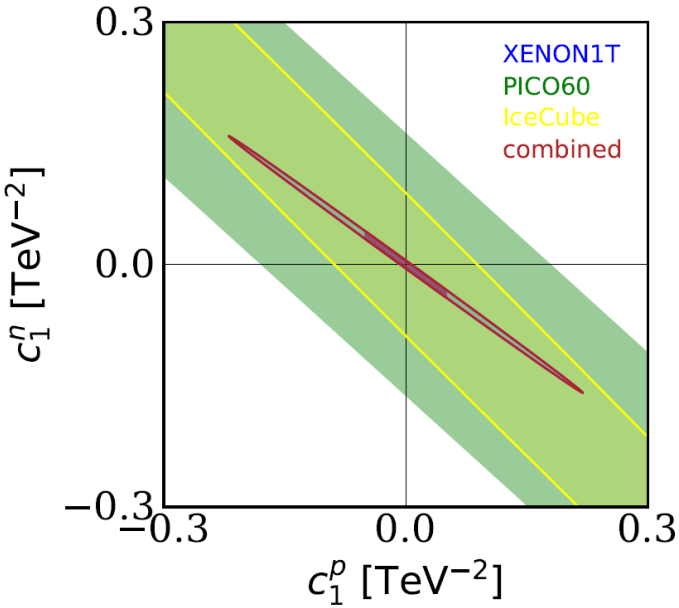
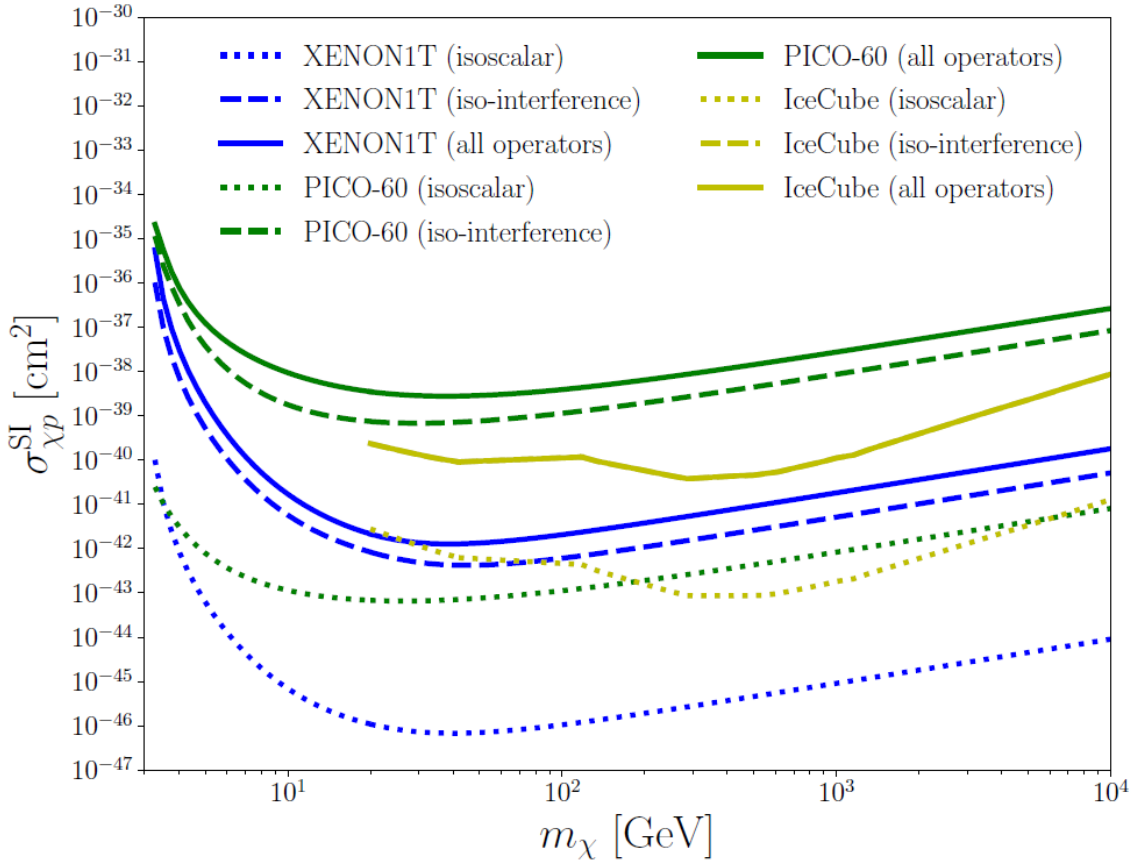




Impact of operator interference

DM-proton spin-independent cross-section



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

Brenner et al. 2203.04210

Impact of operator interference

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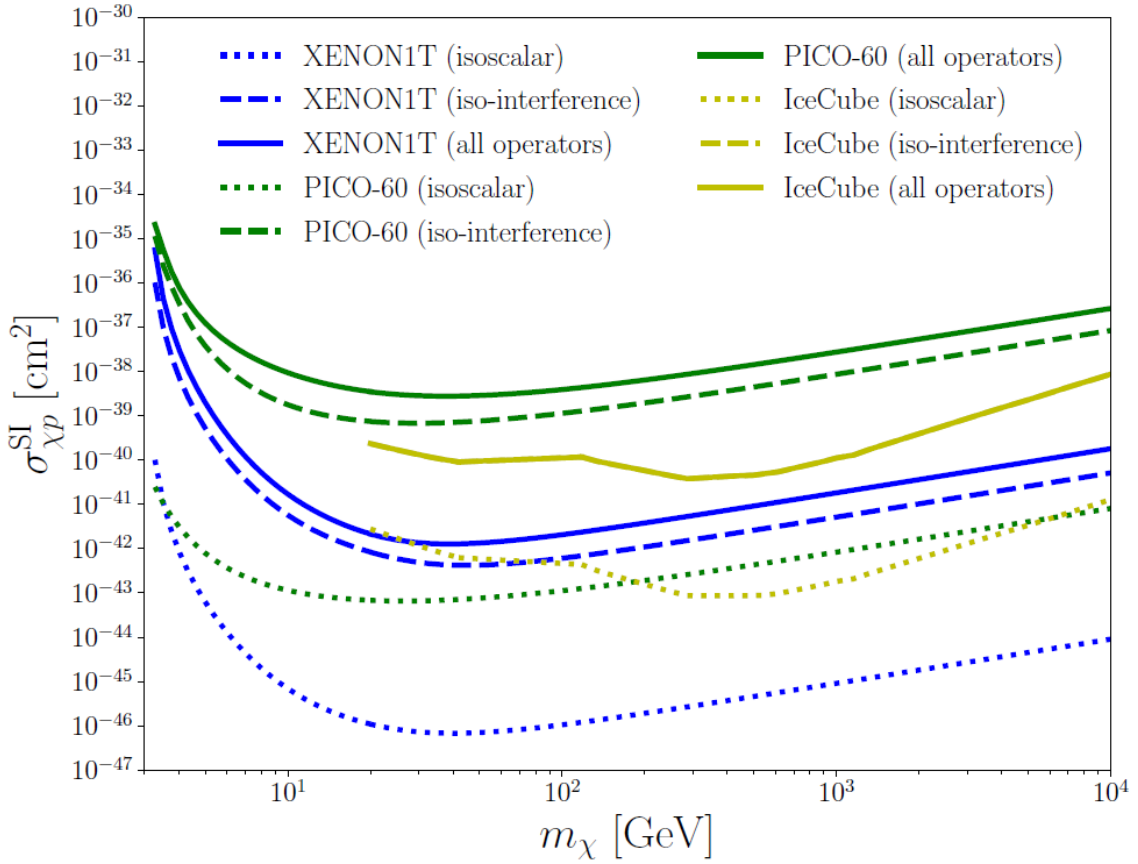

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Brenner et al. 2203.04210

$\mathcal{O}_1 = 1_\chi 1_N$	$\mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$
$\mathcal{O}_3 = i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$
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$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$	$\mathcal{O}_{14} = i(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \vec{v}^\perp)$
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Fitzpatrick et al. 1203.3542

Impact of operator interference

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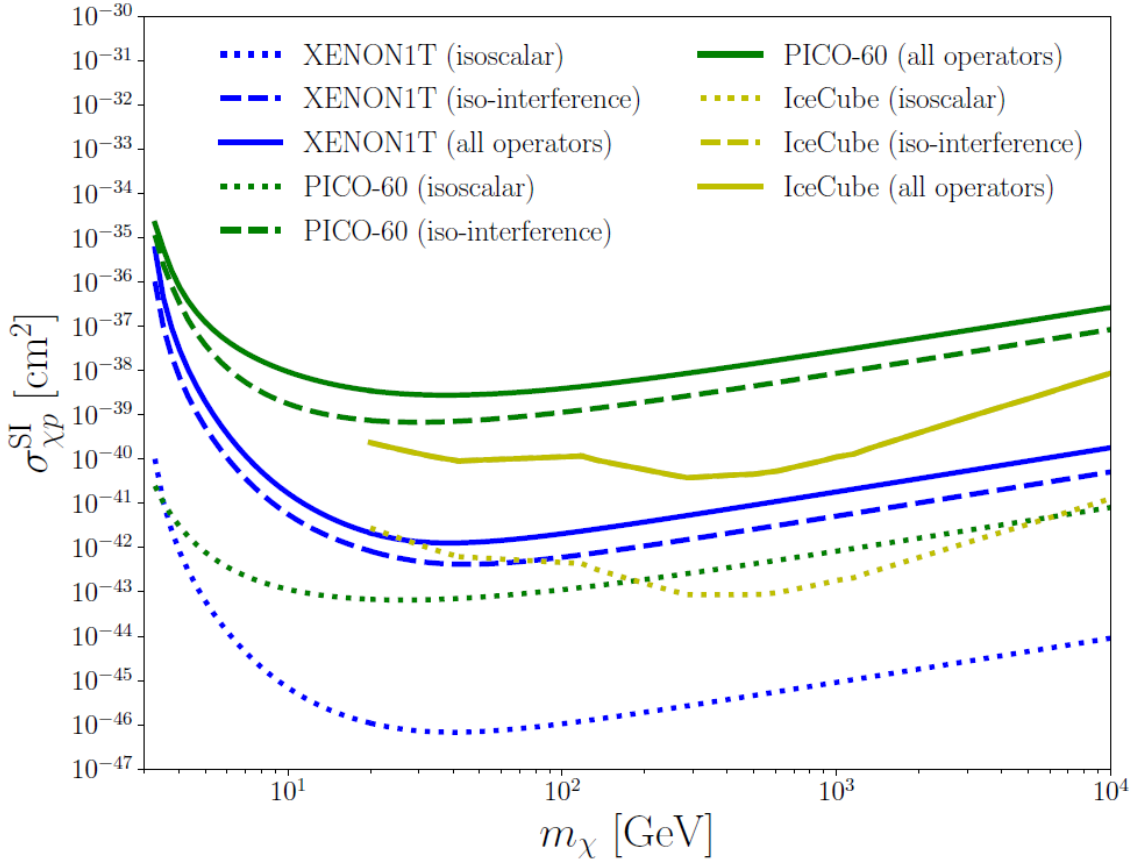

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Brenner et al. 2203.04210

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Fitzpatrick et al. 1203.3542

Impact of operator interference

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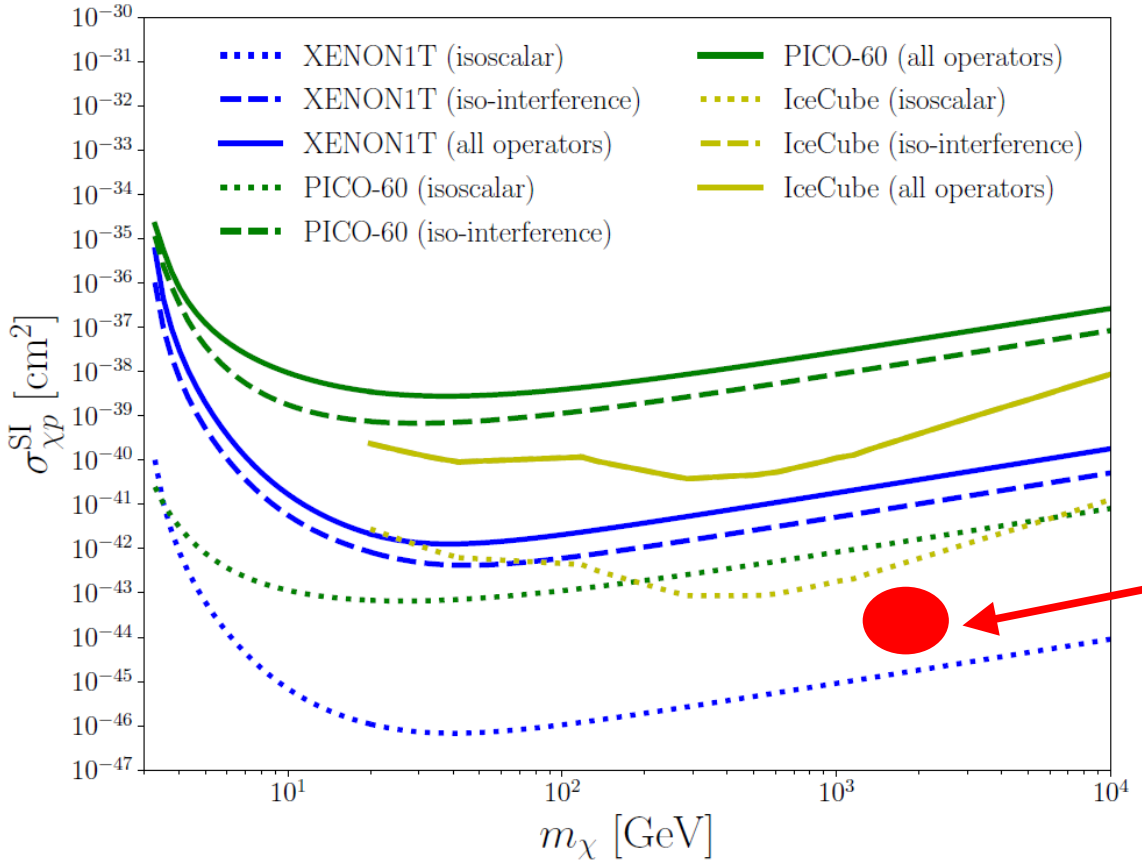

$$\sigma^{\rm SI}_{\chi p} = \frac{(c_p^1)^2 \mu^2_{\chi p}}{\pi}$$

Ruled out by XENON1T
if isoscalar O_1 interaction.

Brenner et al. 2203.04210

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Fitzpatrick et al. 1203.3542

Impact of operator interference

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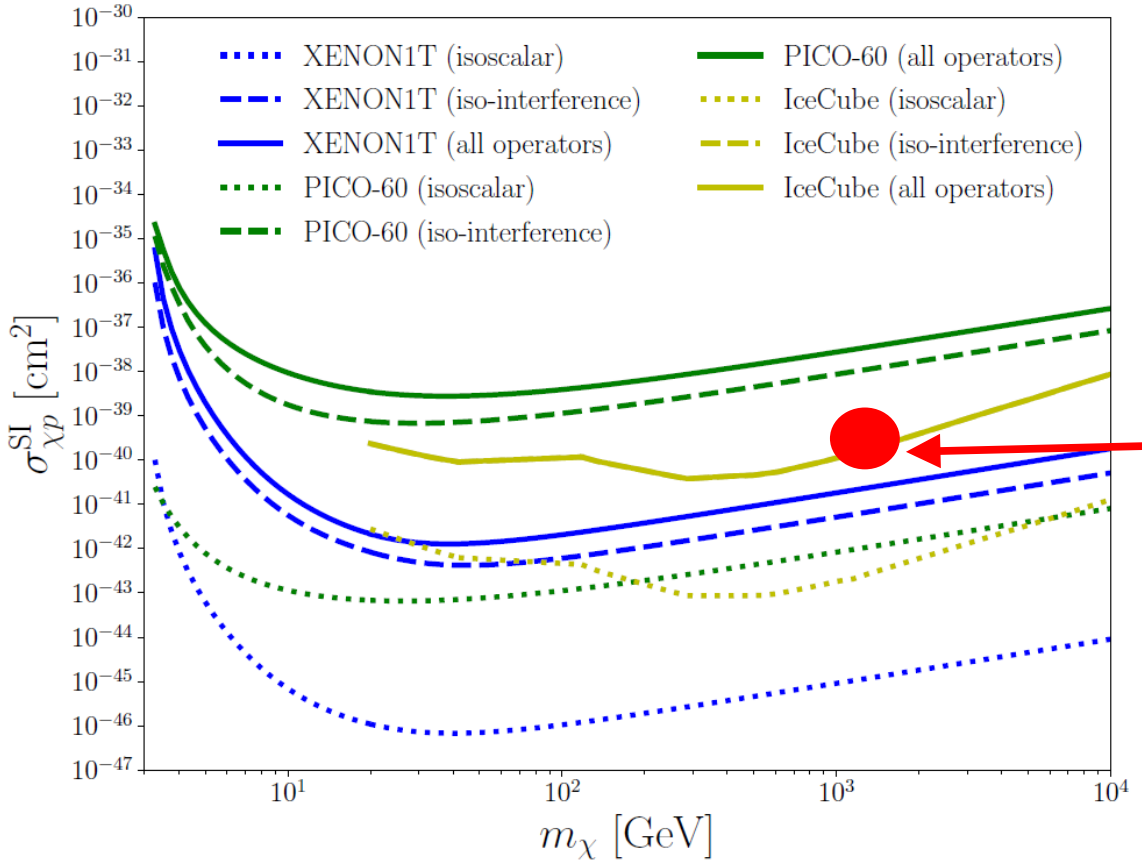

$$\sigma^{\rm SI}_{\chi p} = \frac{(c_p^1)^2 \mu^2_{\chi p}}{\pi}$$

Ruled out by XENON1T *in the full EFT*

Brenner et al. 2203.04210

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Fitzpatrick et al. 1203.3542

Addressing astrophysical uncertainties in dark matter detection

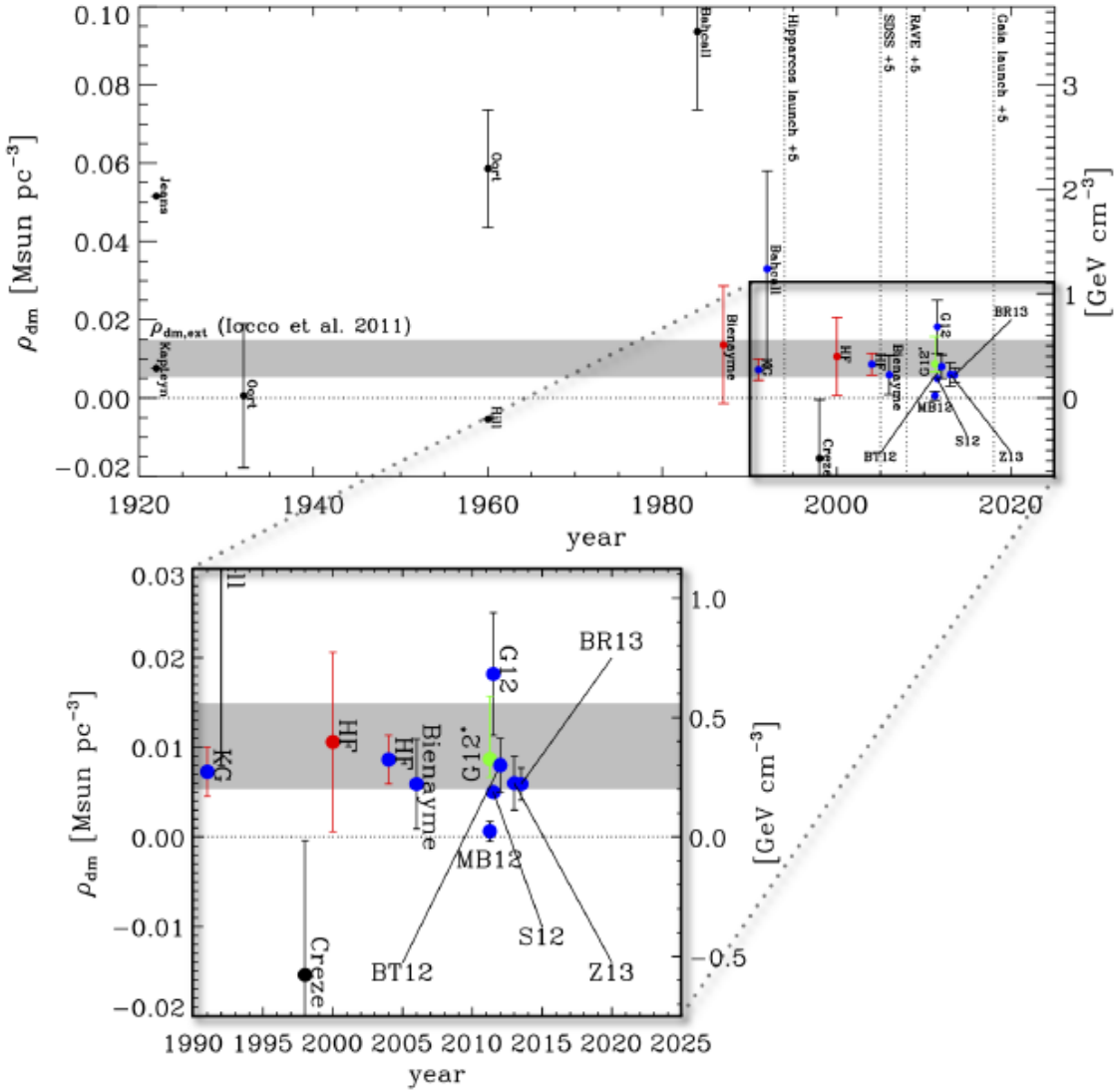
Local dark matter density

- "local measurements":

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

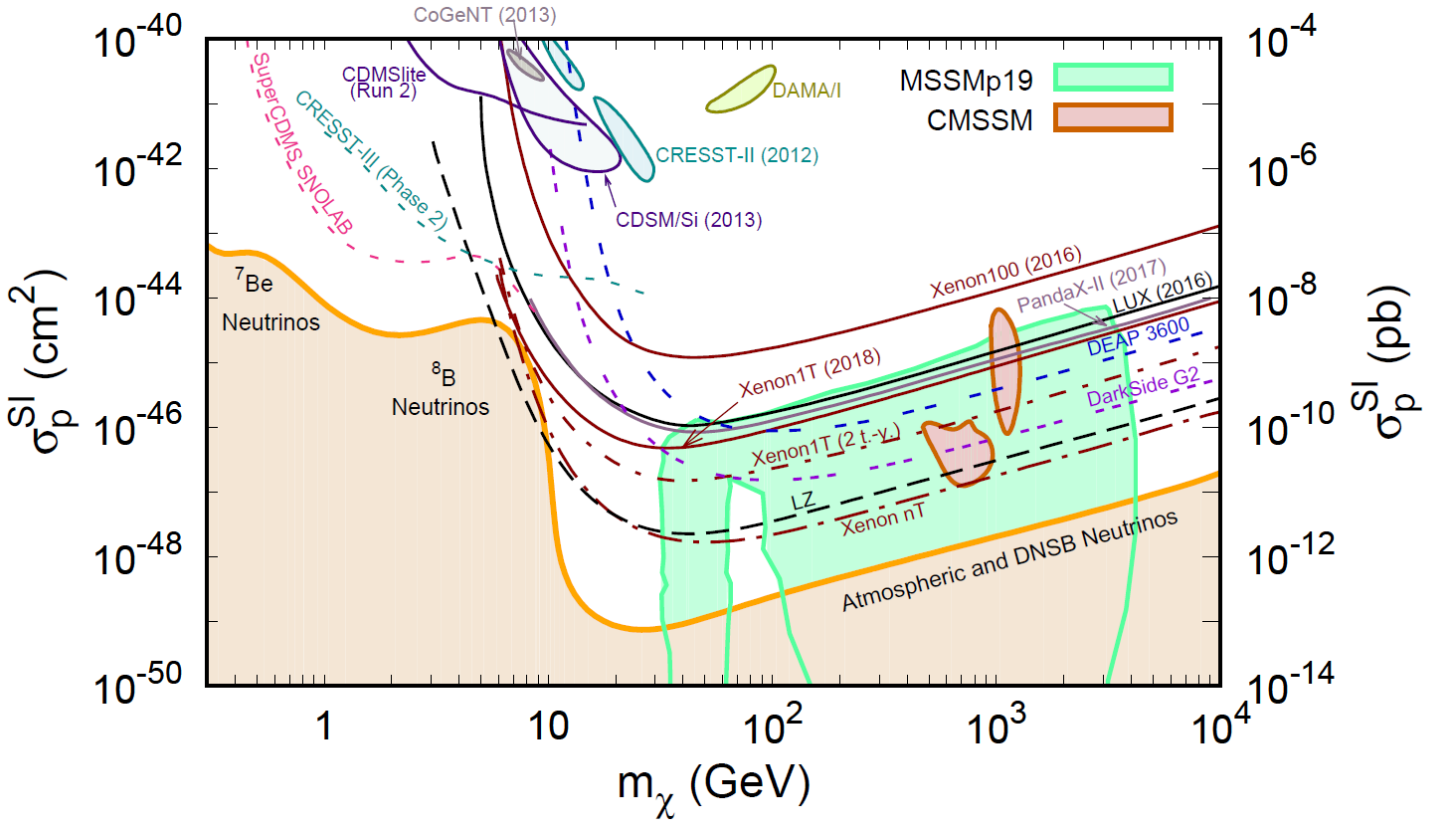
- "global measurements":

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

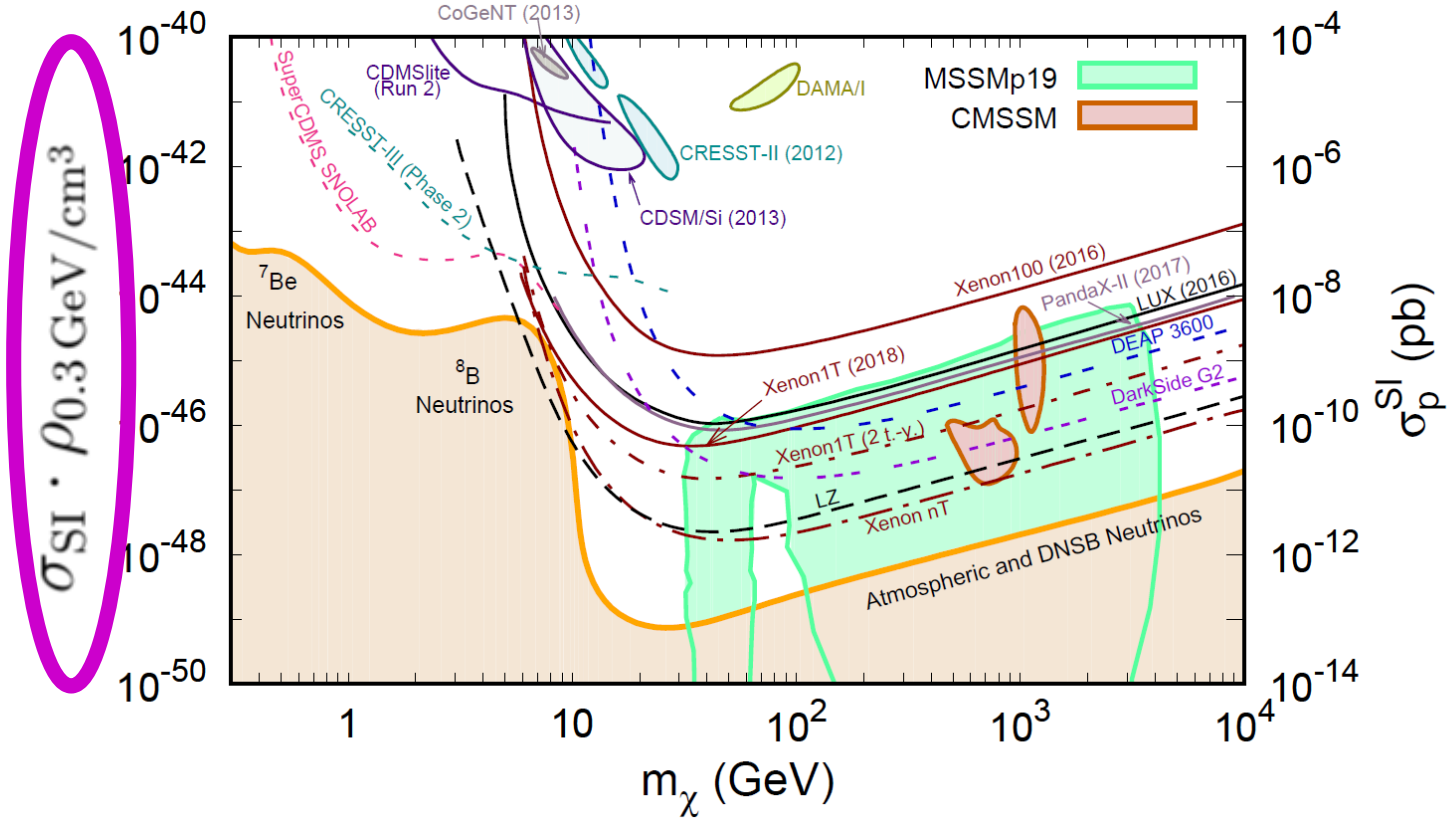


Read '14

Local dark matter density



Local dark matter density



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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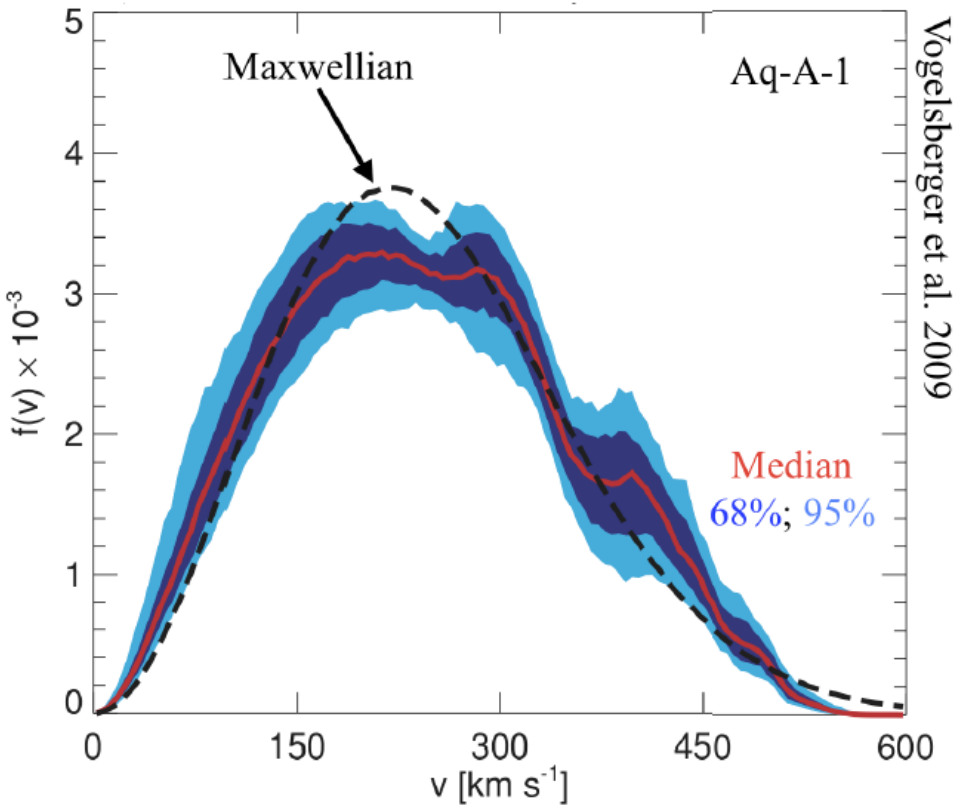
Completely unknown. Rely on theoretical considerations

- 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



Local dark matter velocity distribution

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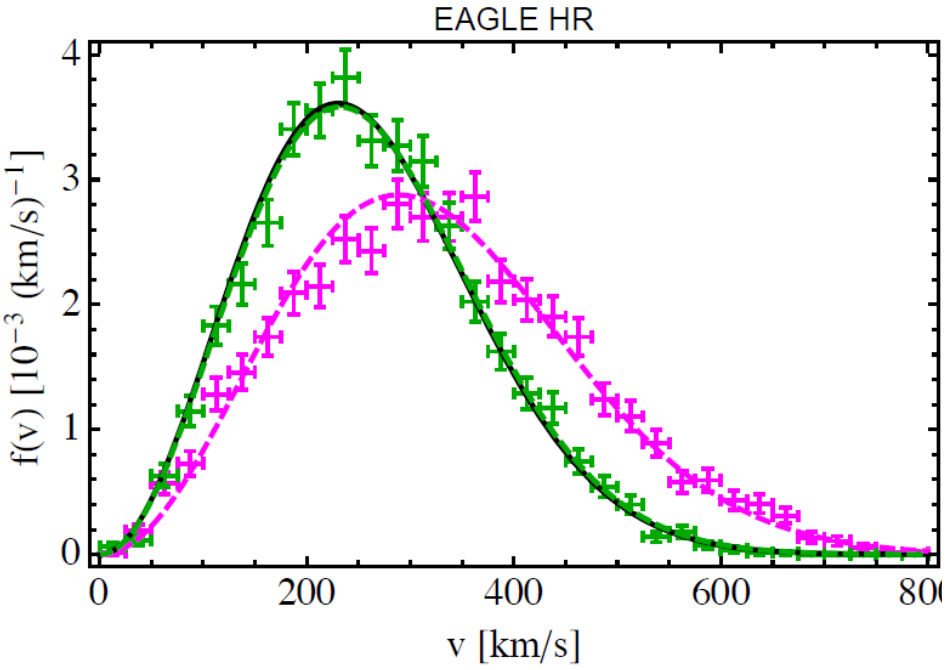
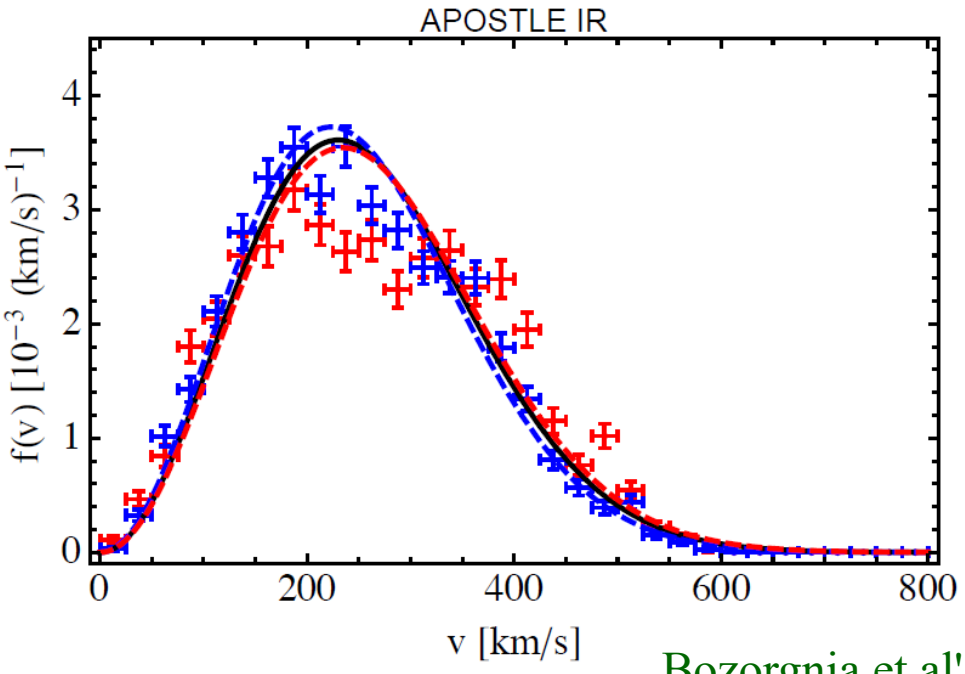
- Dark matter-only simulations. Show deviations from Maxwell-Boltzmann
- Hydrodynamical simulations (DM+baryons). Inconclusive at the moment.



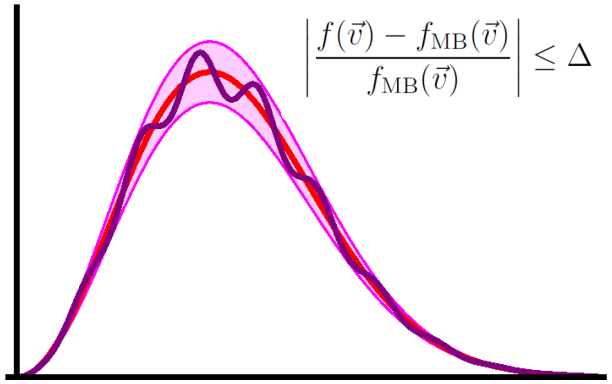


Bozorgnia et al'16

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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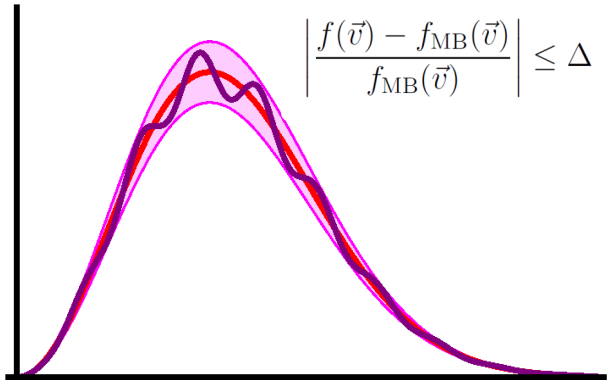

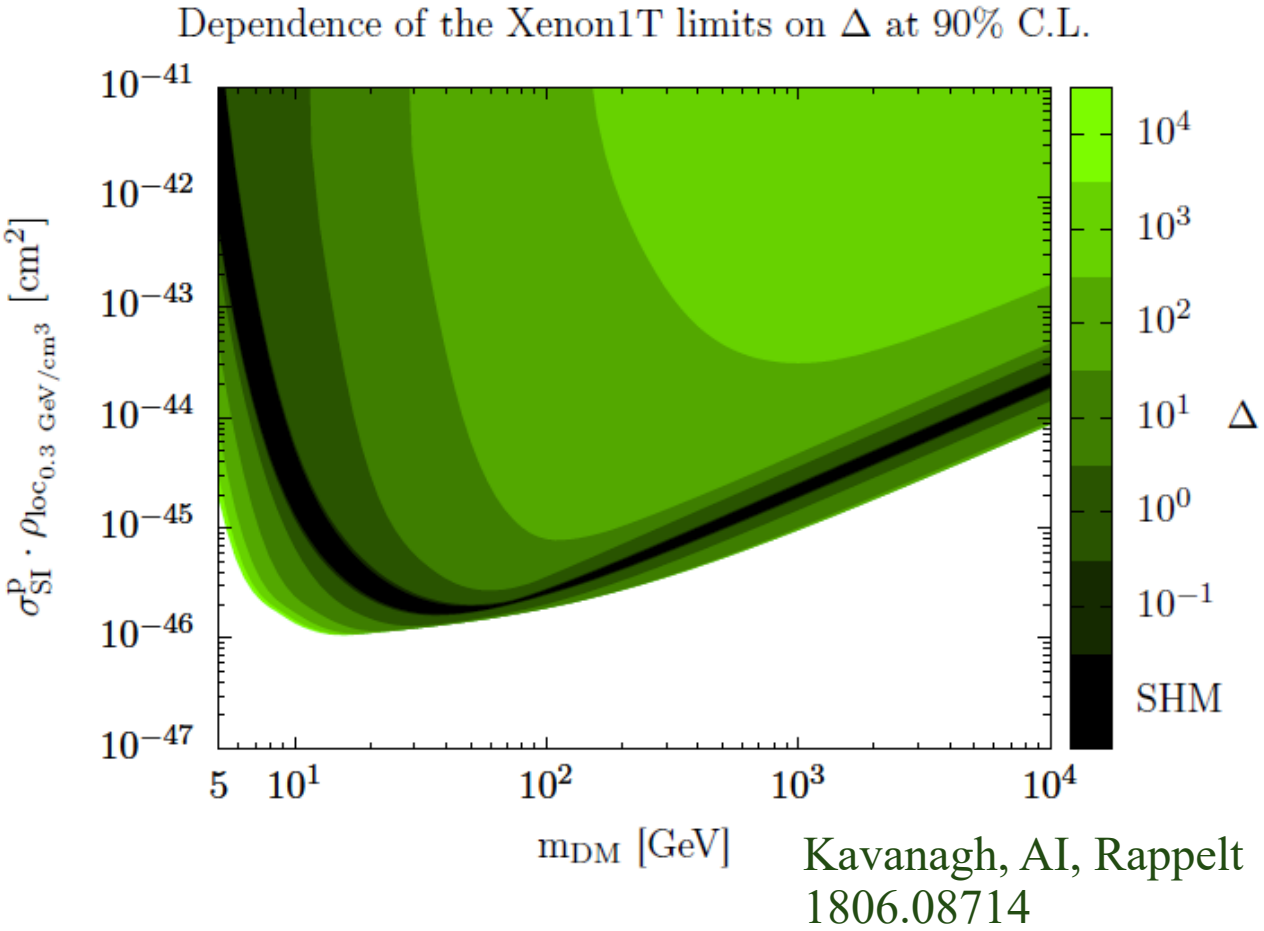

Kavanagh, AI, Rappelt
1806.08714

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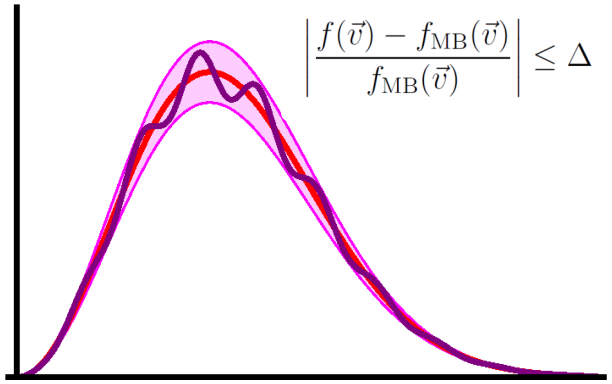

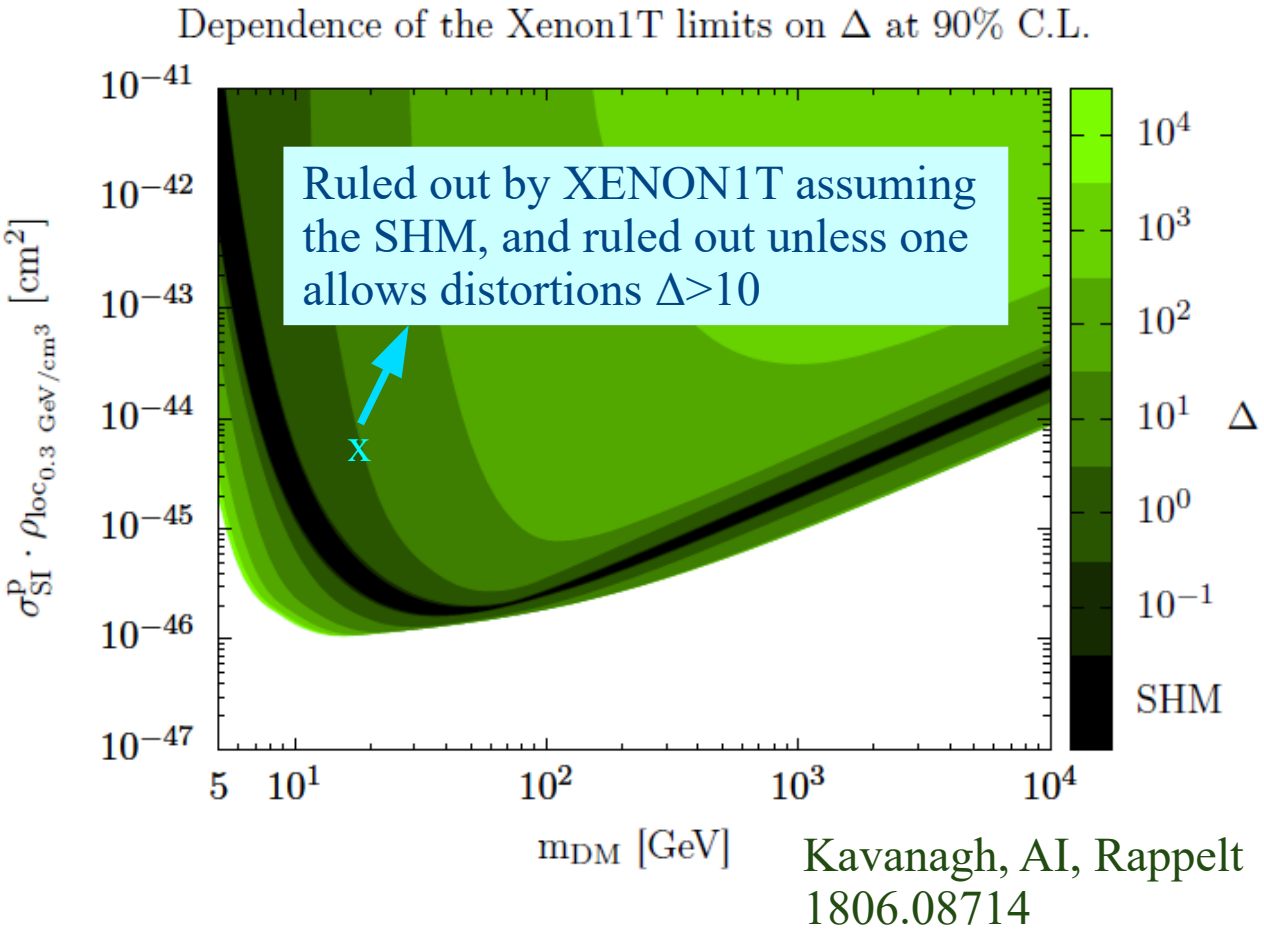

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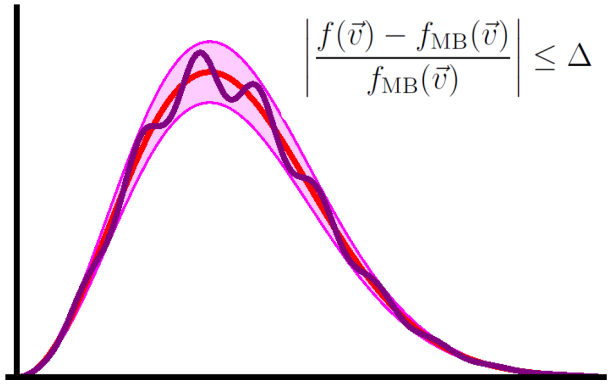

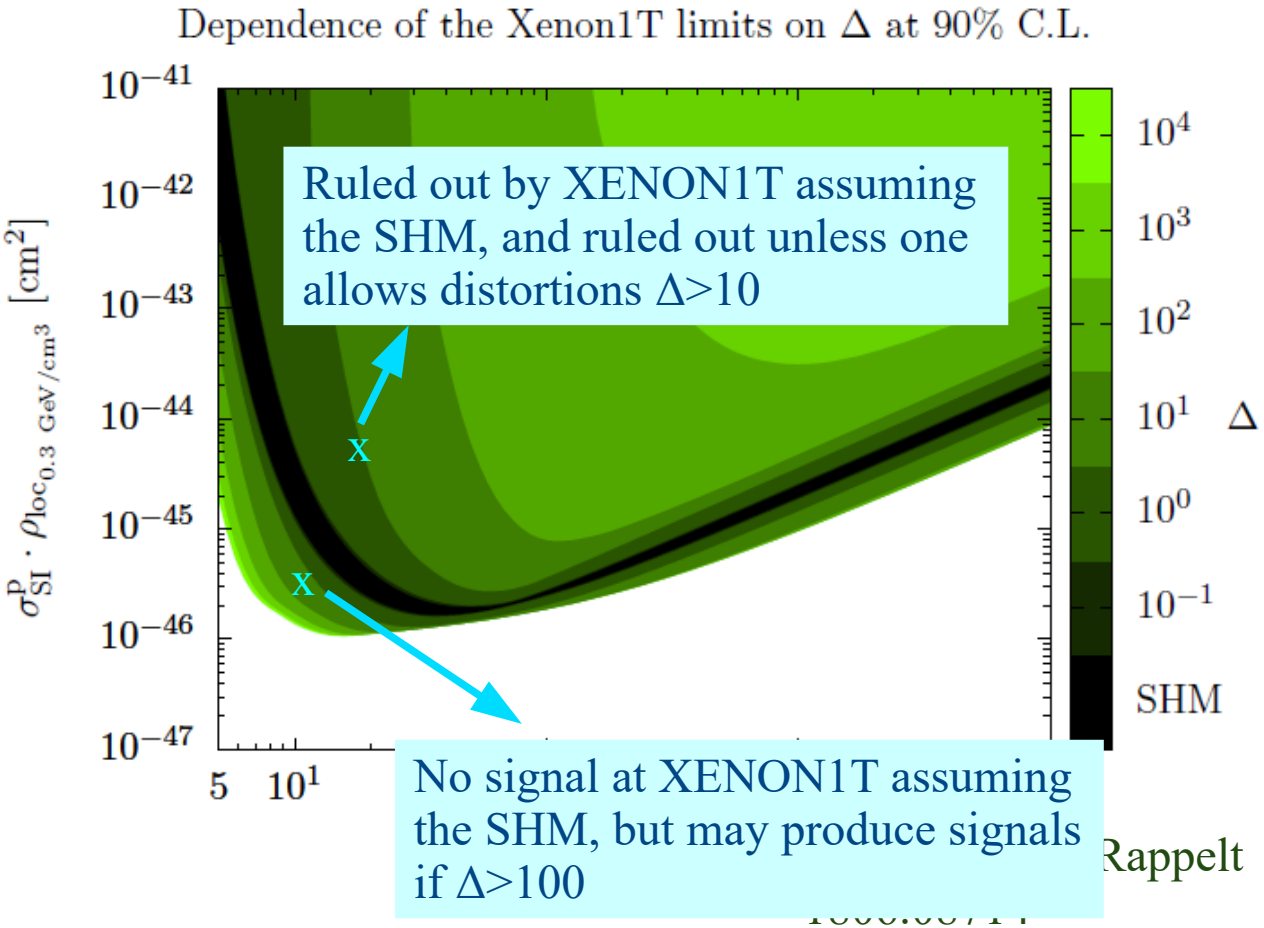

Rappelt

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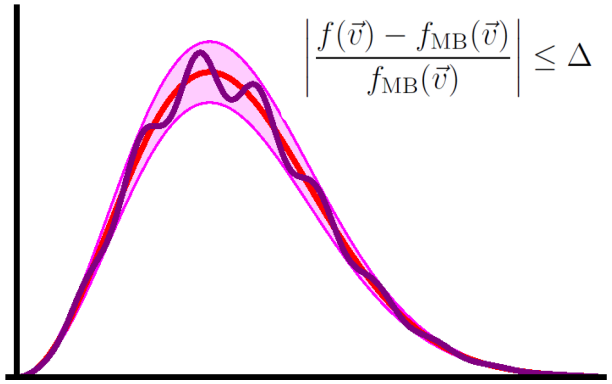

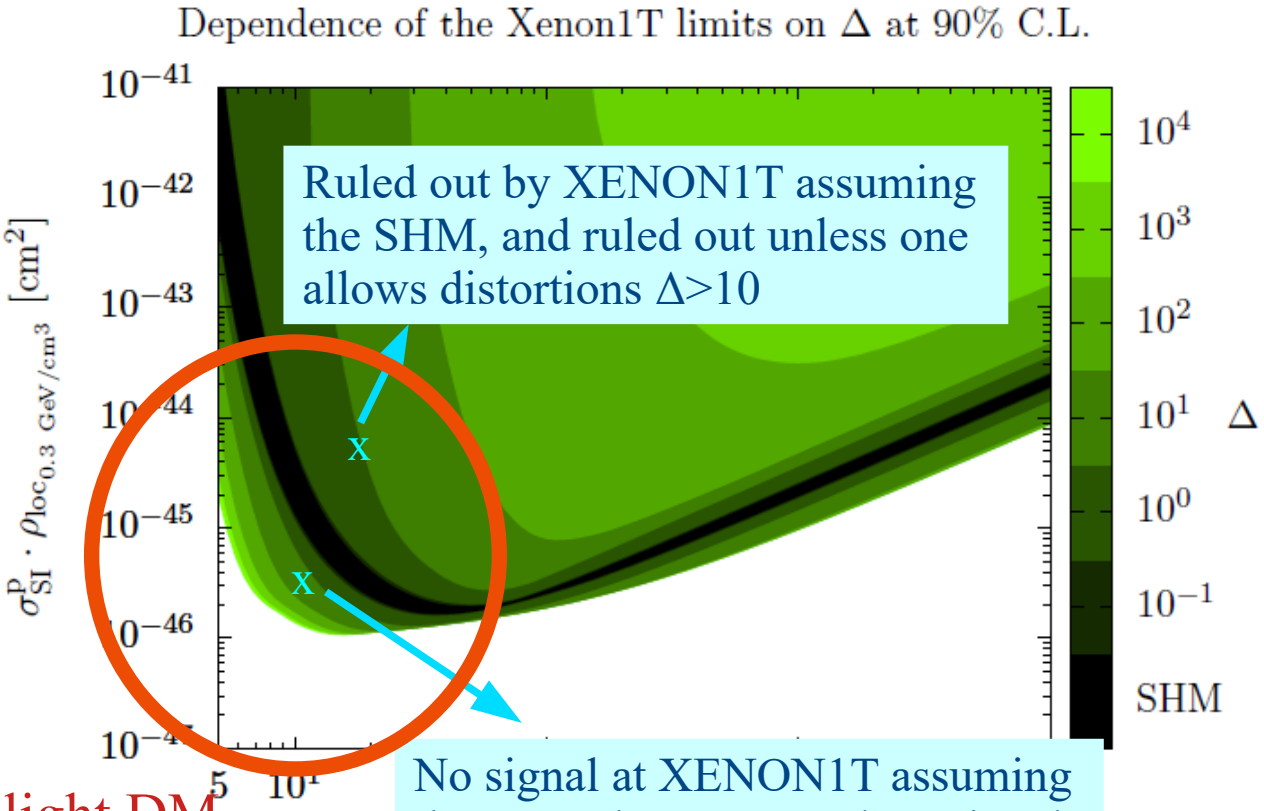

• Significant differences for light DM.

Rappelt

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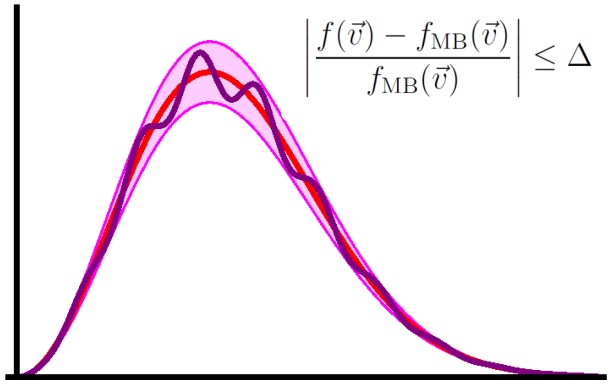

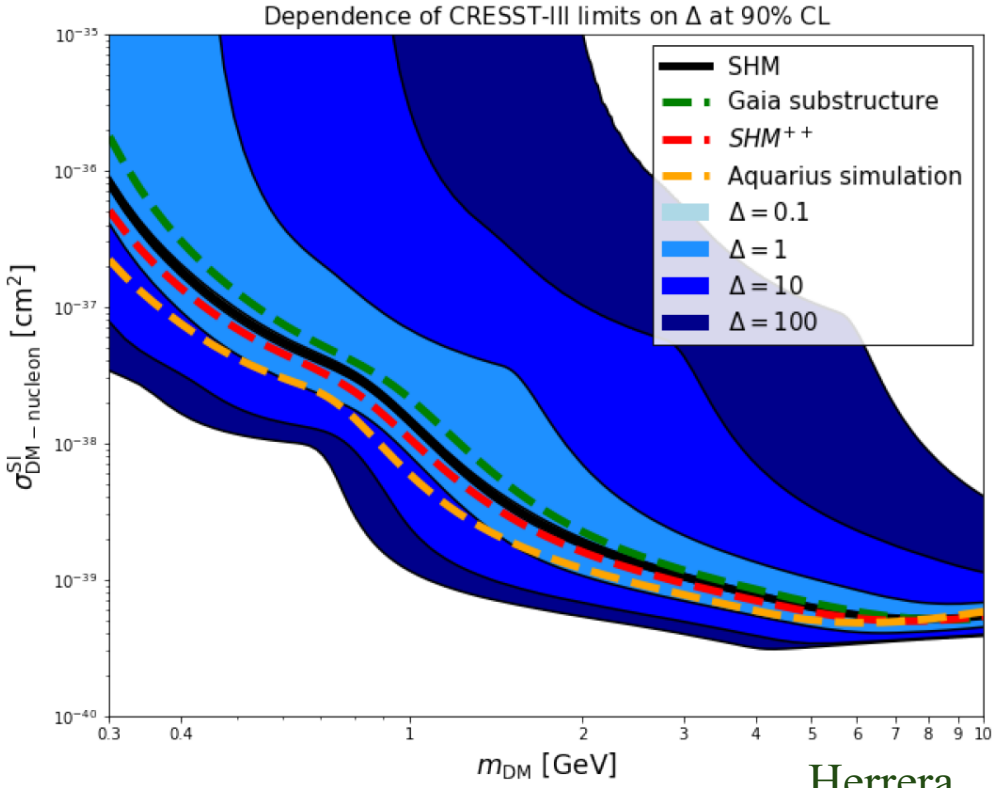

Herrera

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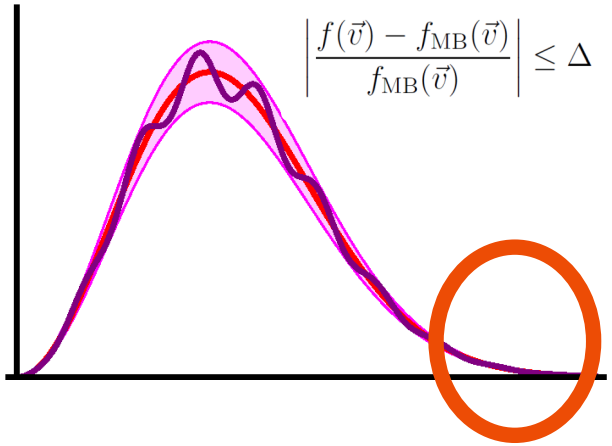

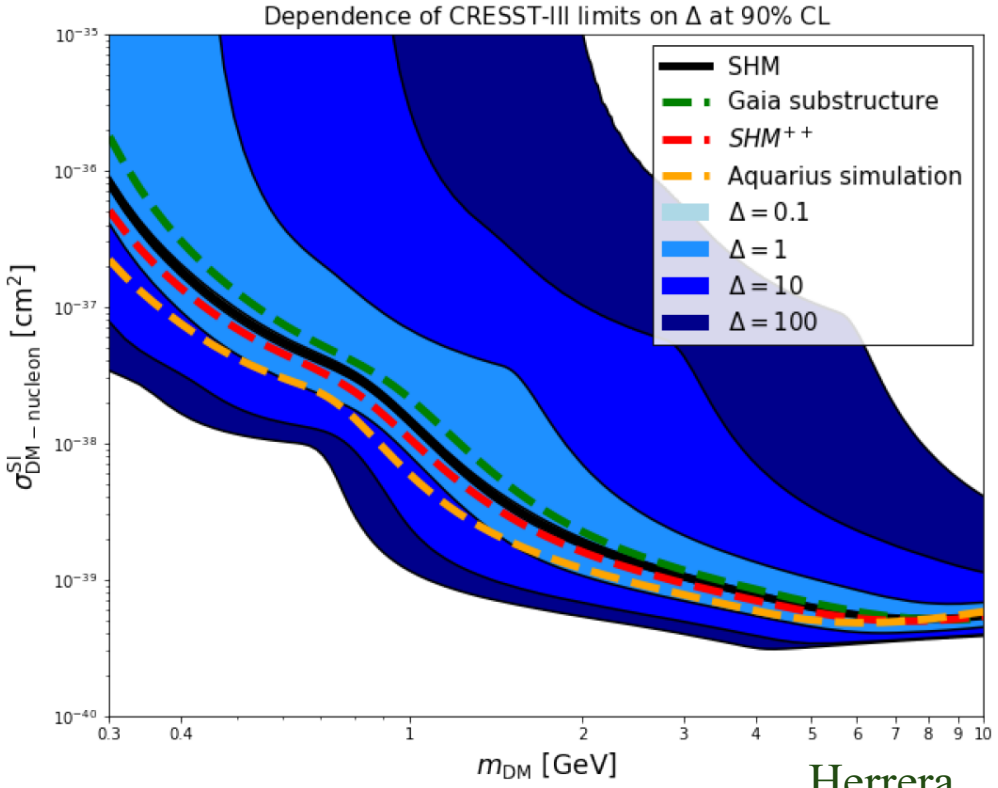

Herrera

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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.

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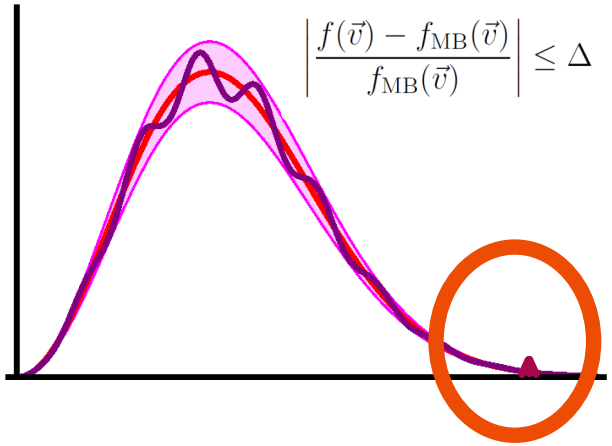

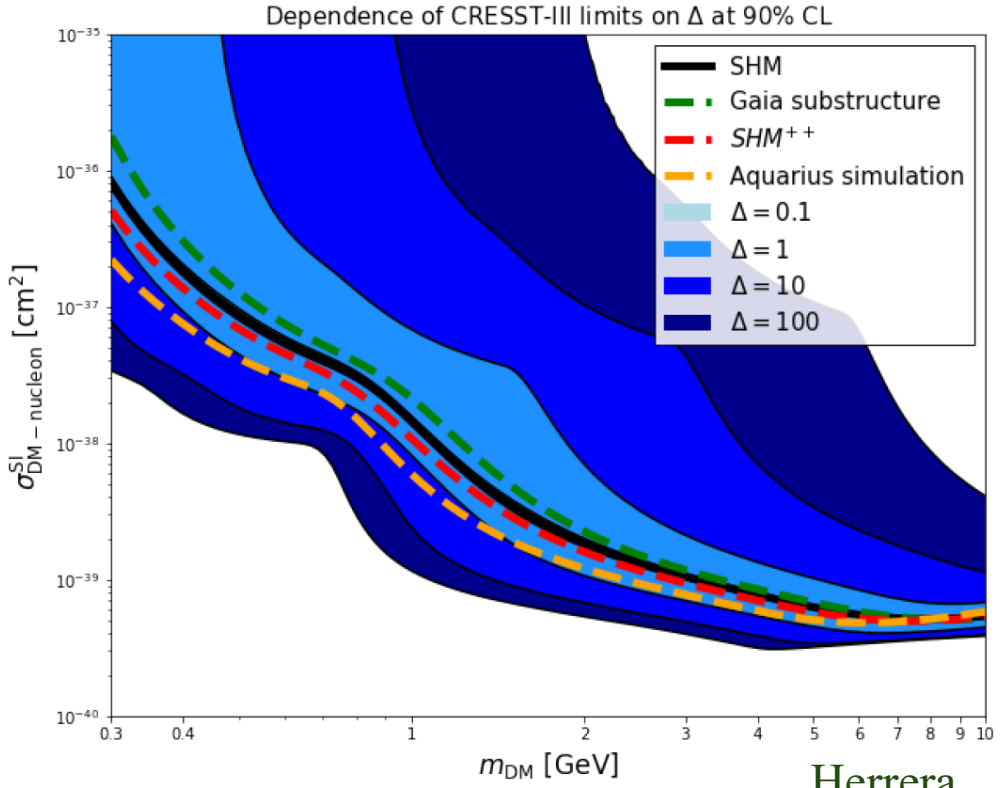

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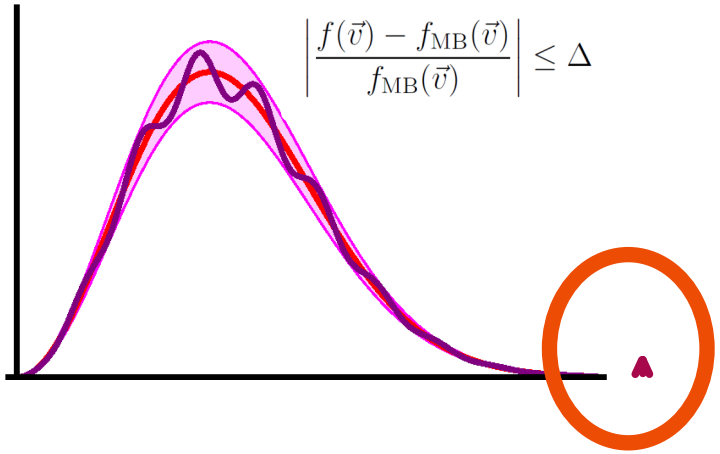
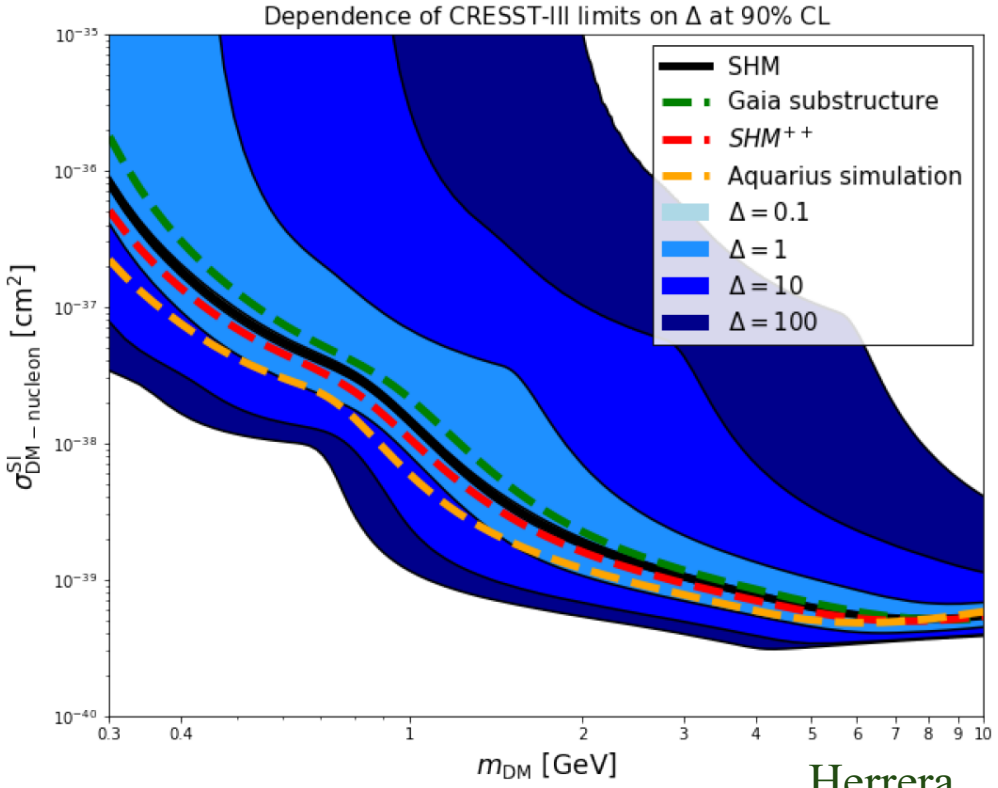
• Consider "distortions" of the MB distribution, at most at a distance Δ from the MB distribution.





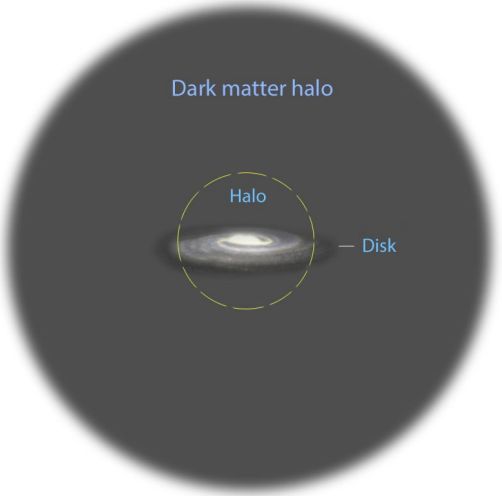
Herrera

• 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. **Likely for non-galactic dark matter (with $v > v_{esc}$).**

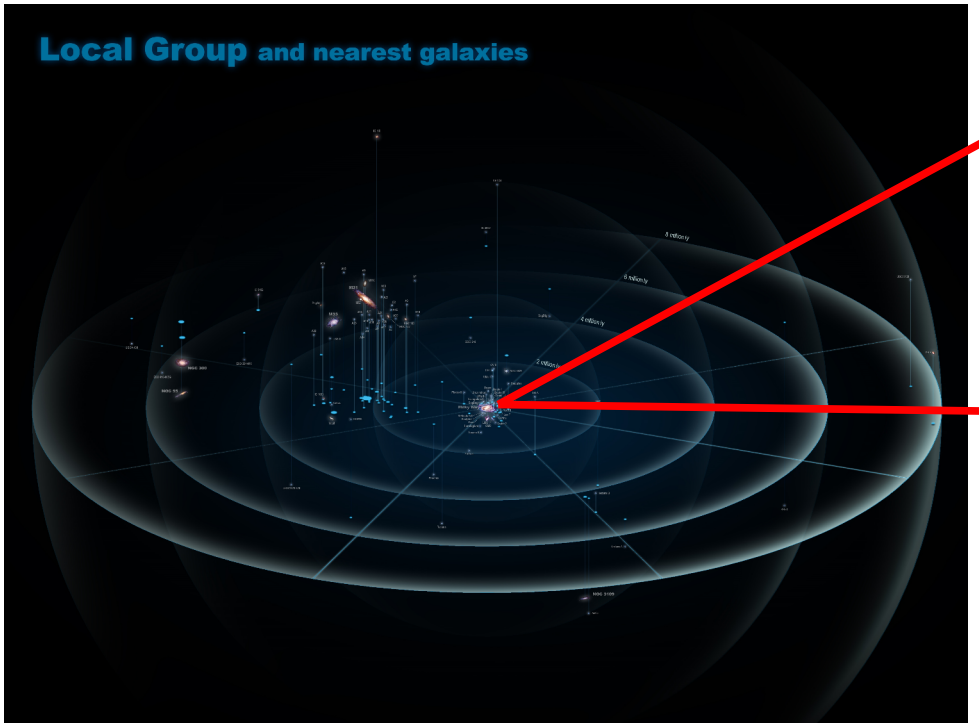
Non-galactic dark matter

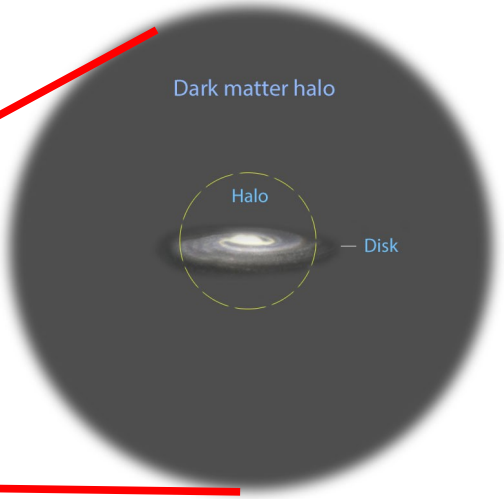
The Milky Way is not an isolated galaxy.



Non-galactic dark matter

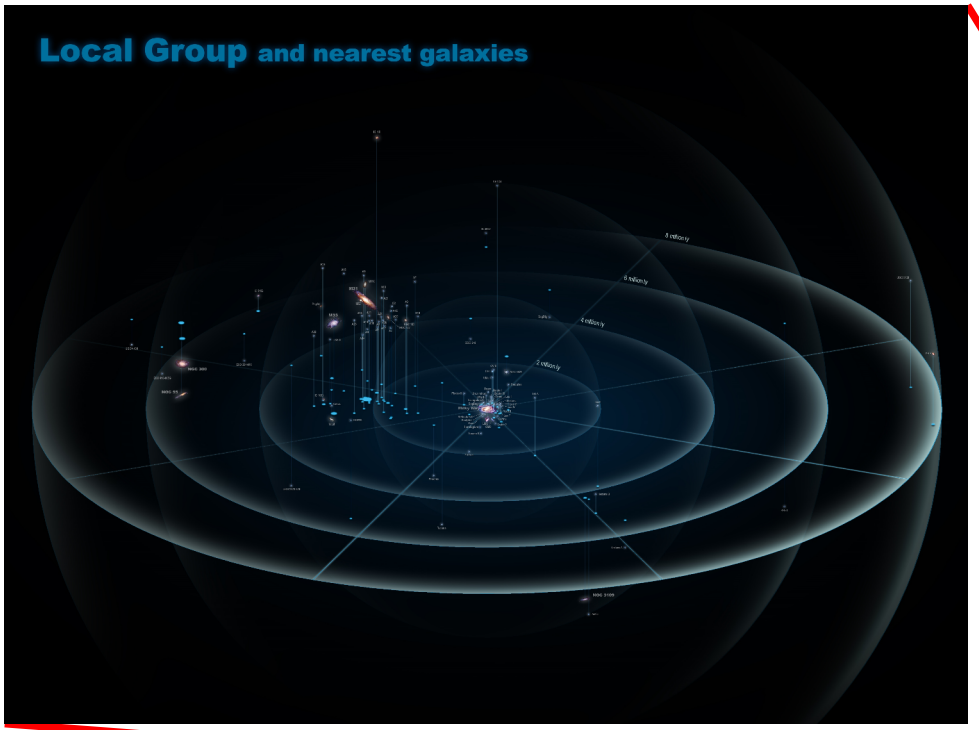
The Milky Way is not an isolated galaxy.

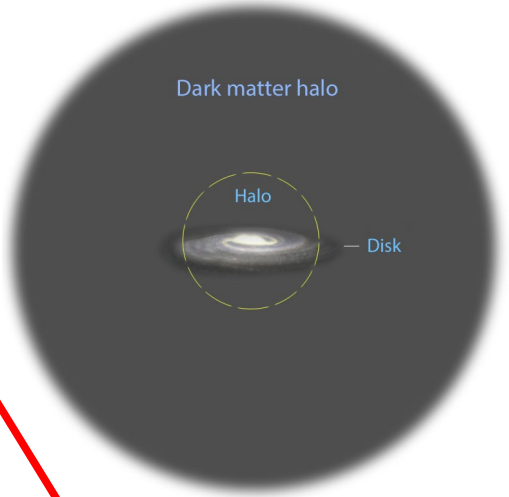


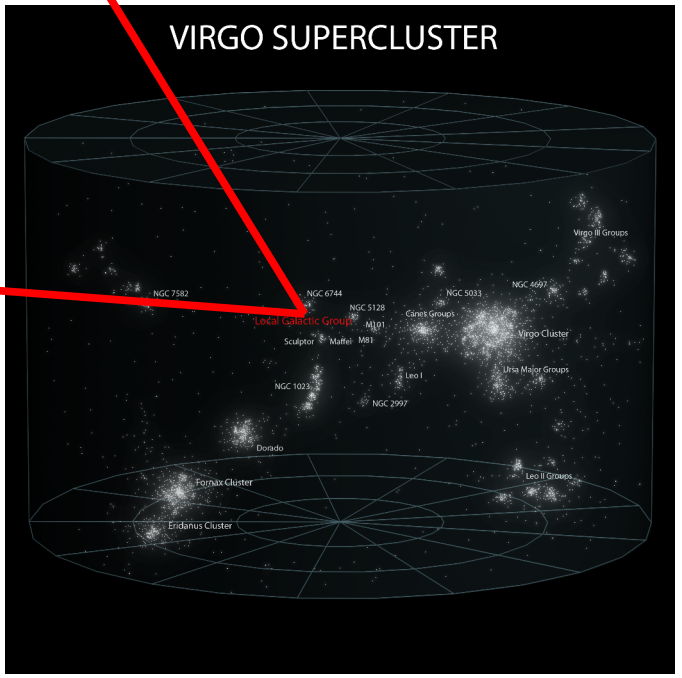


Non-galactic dark matter

The Milky Way is not an isolated galaxy.



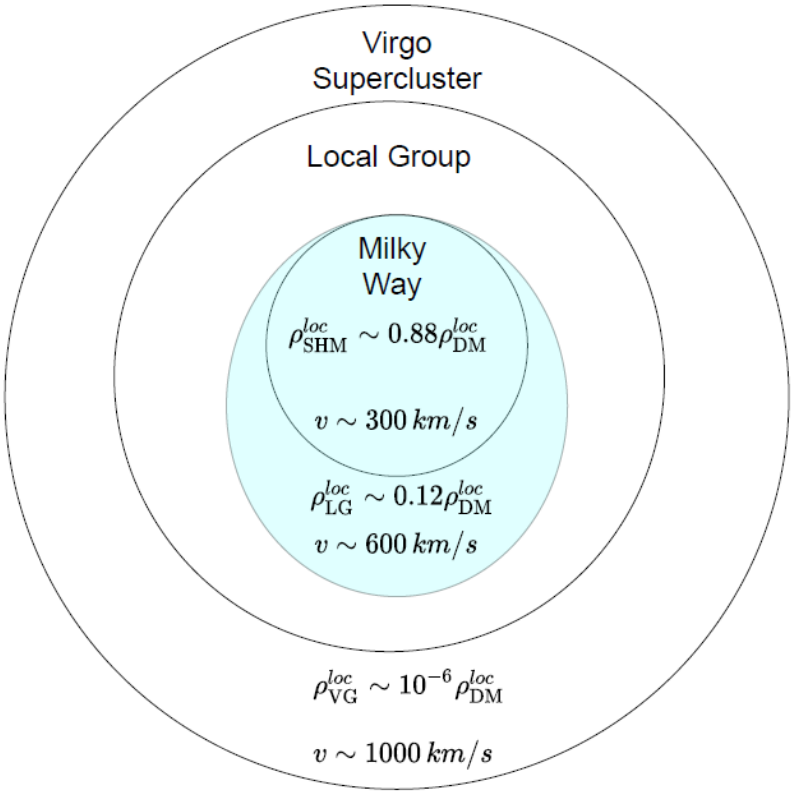


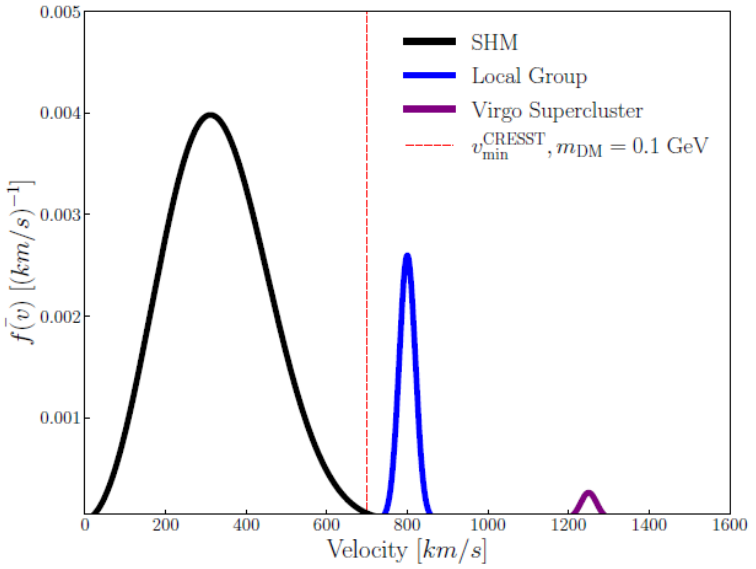


Non-galactic dark matter

- The diffuse DM component of the Local Group could penetrate in the Milky Way, contributing ~ 12% to the local DM density.
- The Virgo Supercluster DM particles are expected to contribute marginally ~ 0.00003%, but with large velocities.

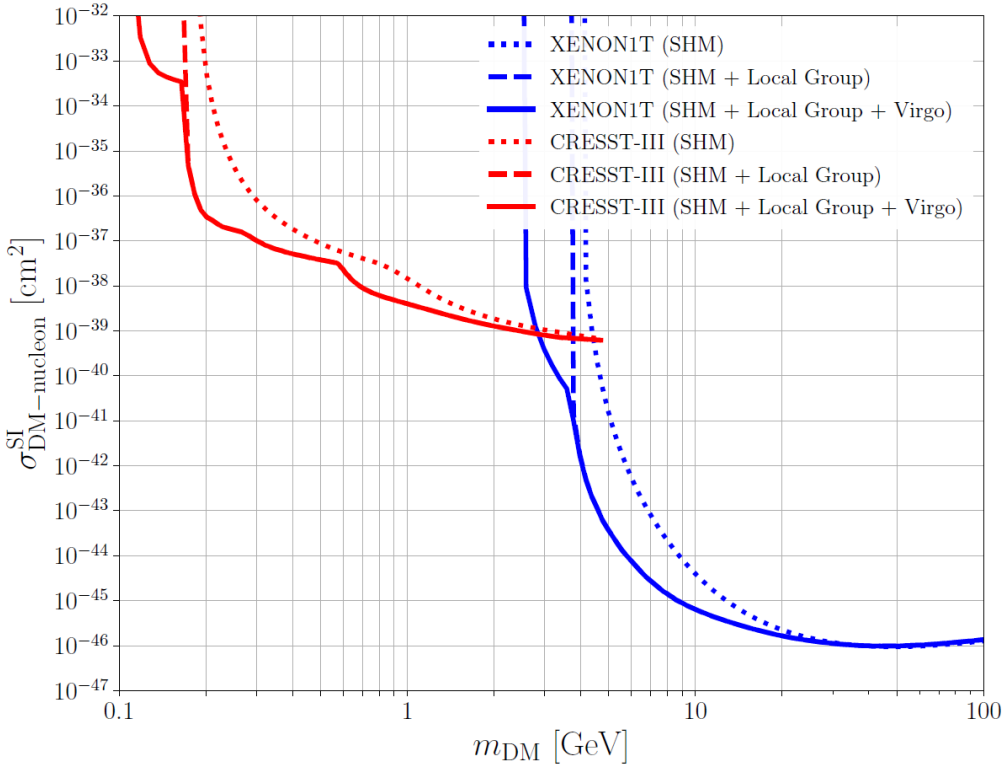
Kahn, Woltjer '59
Makarov, Karachentsev '11
Baushev, '13

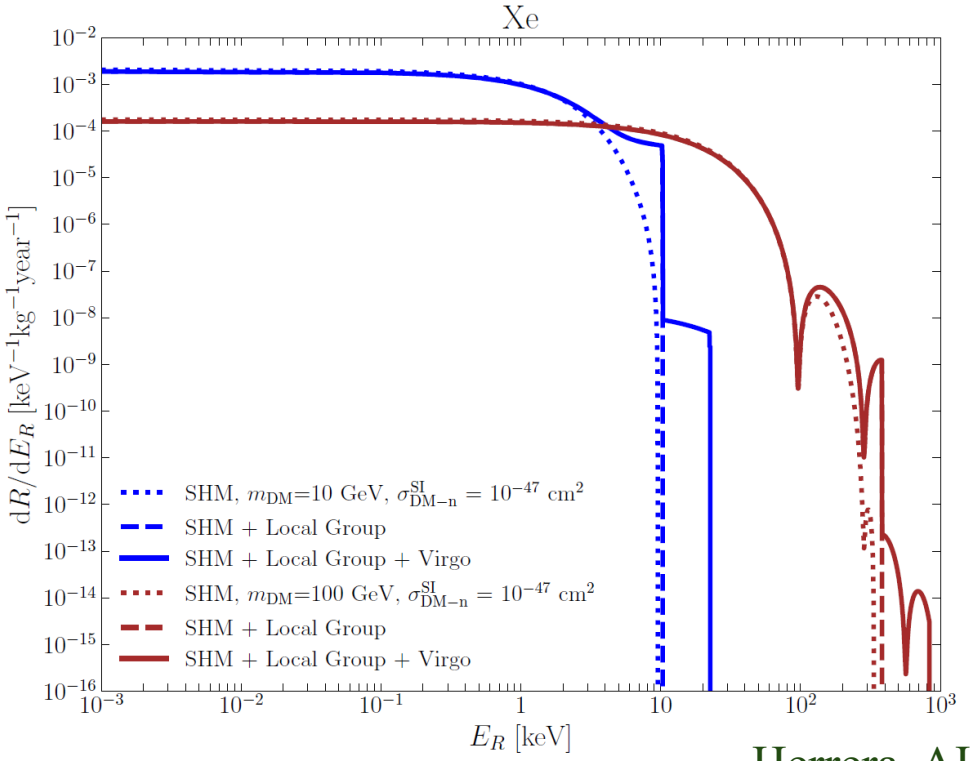




Very significant "distortion" of the MB distribution at high velocities

Non-galactic dark matter: impact on nuclear recoils

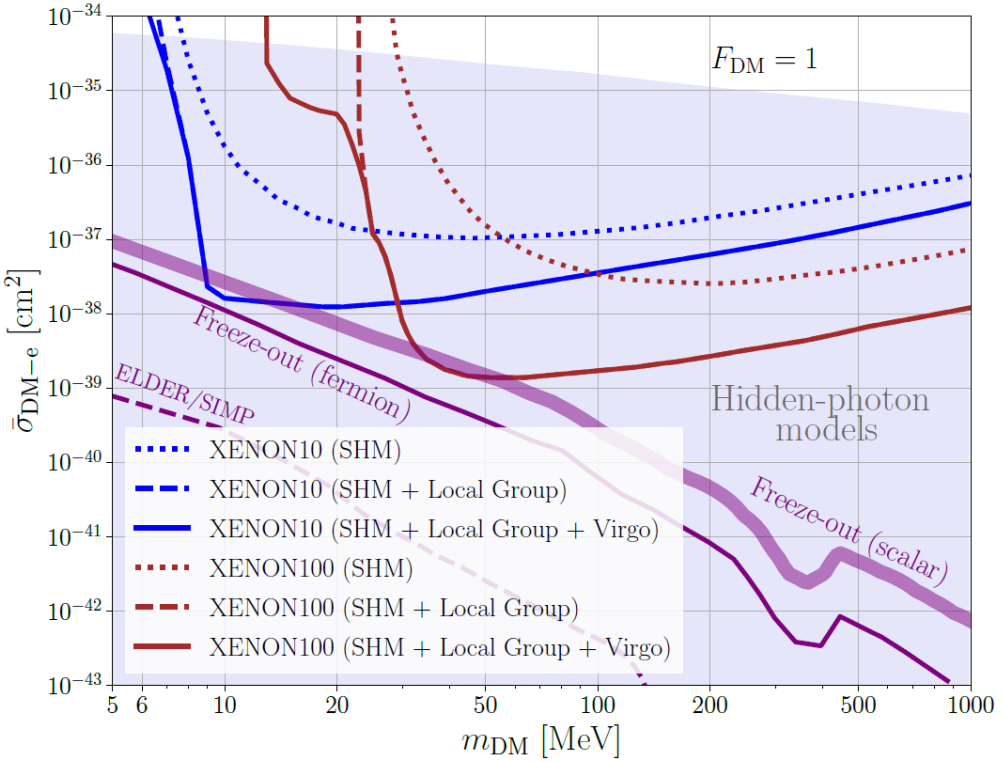


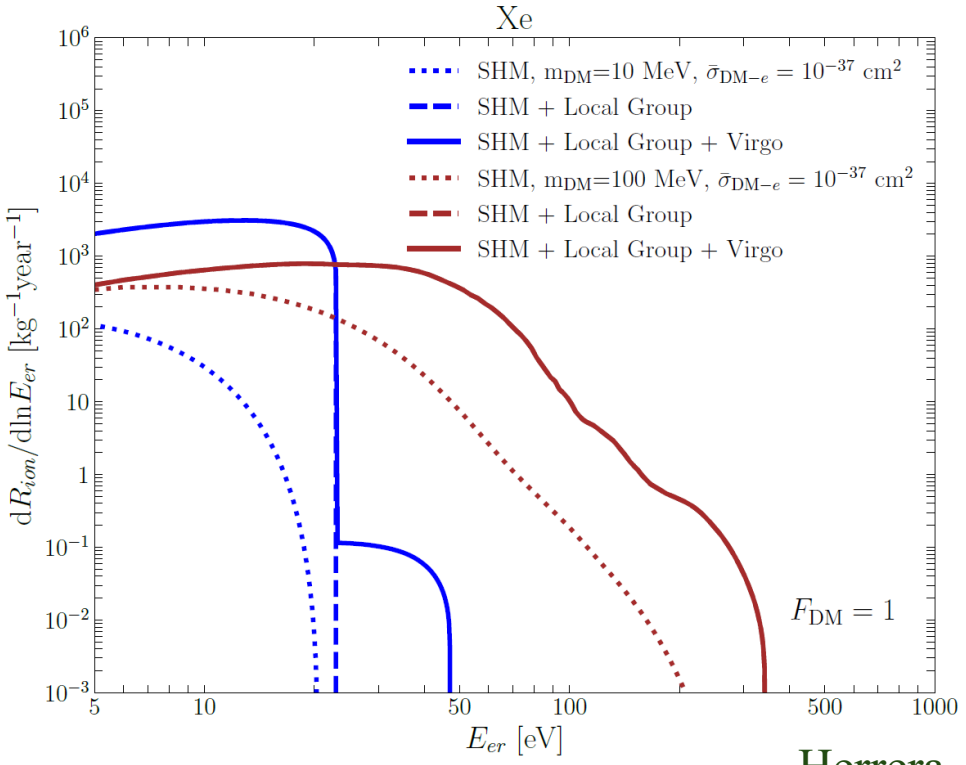


Herrera, AI
2104.04445

- 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
2104.04445

- 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 including operator interference (isoscalar, isovector, EFTs).
- 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.