Light Dark Matter from Inelastic Cosmic Ray Collisions

Miguel D. Campos

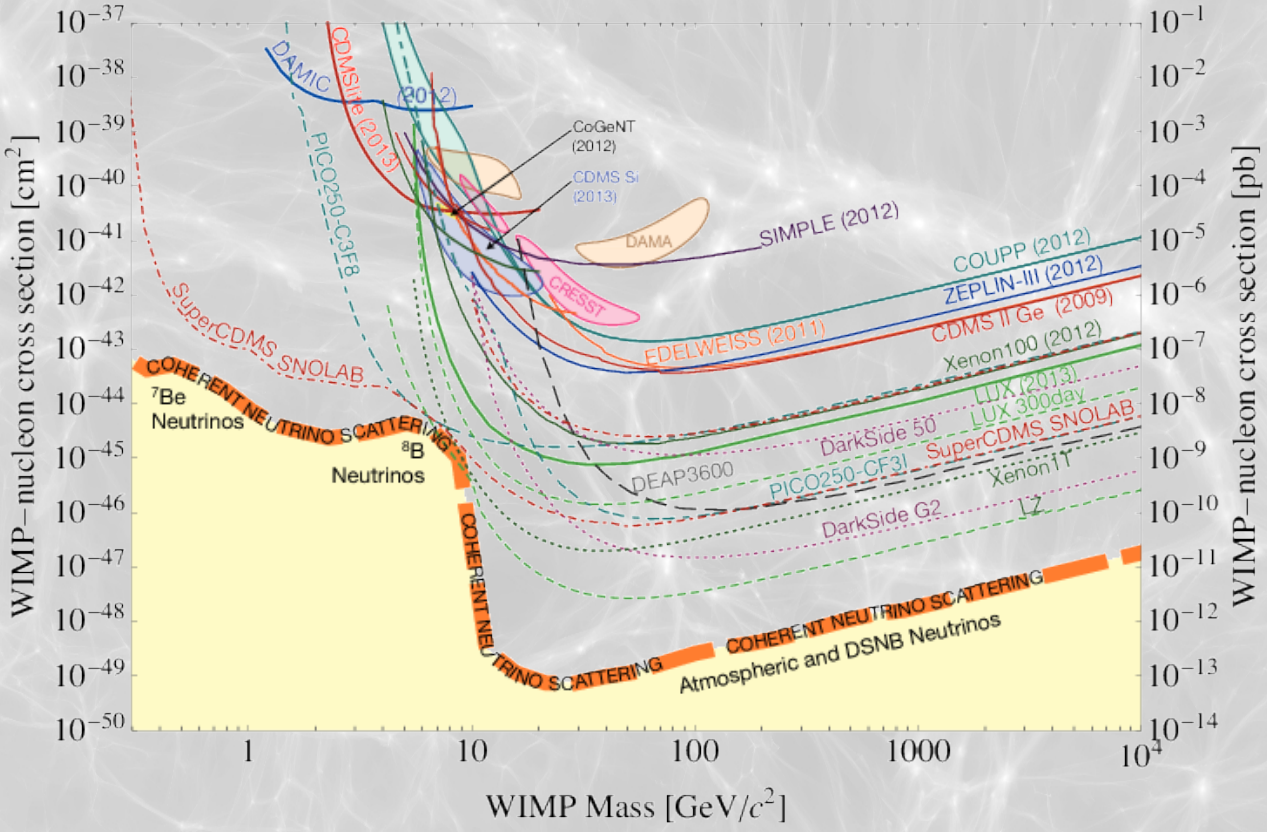
based on **arXiv:1905.05776**

in collaboration with Malcolm Fairbairn, Tevong You and James Alvey.

Warsaw, Poland

Beyond GR and the Cosmological SM,
July 2019.

The Unexplored Parameter Space.



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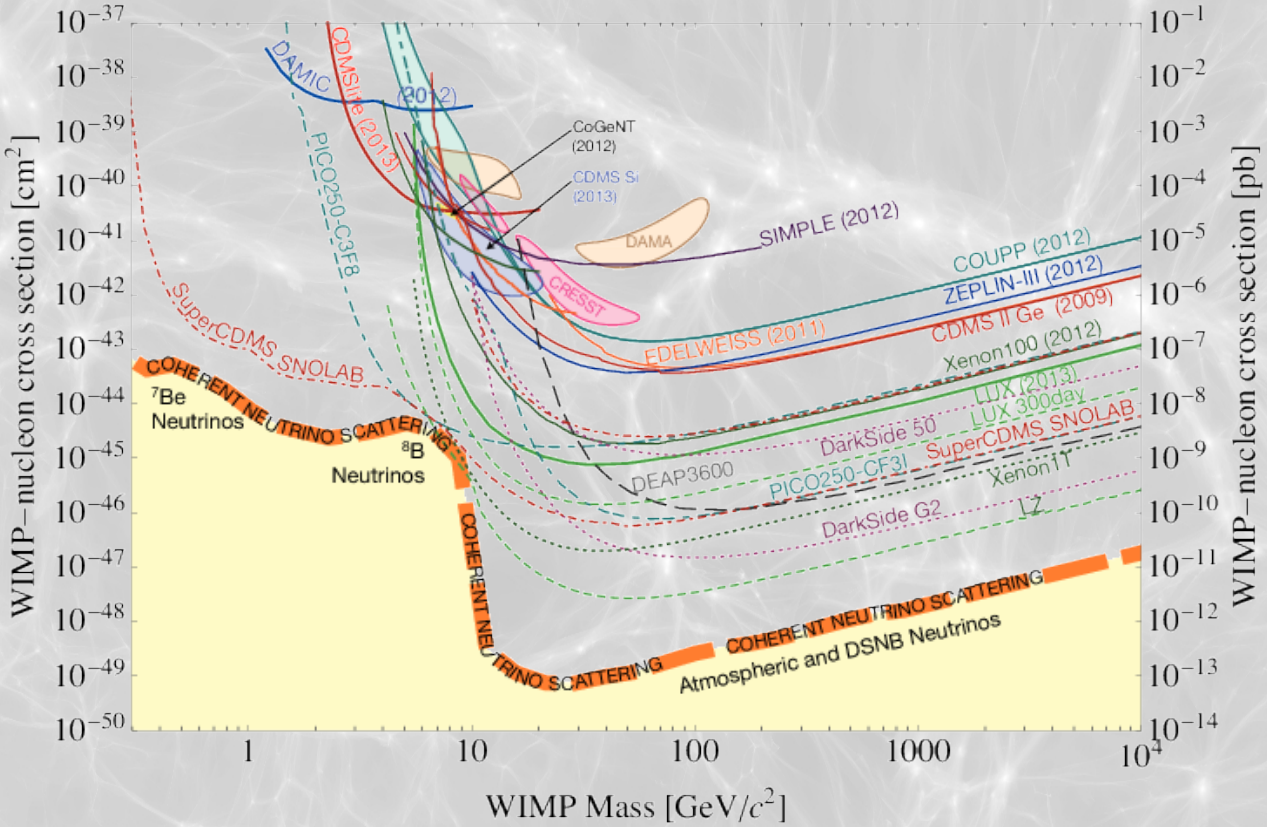

The problem with low mass DM
→ DD experiments are not sensitive to them.

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New Ideas using CRs

- If CRs interact with SIDM, elastic scattering can modify the spectrum of detected CRs on Earth:

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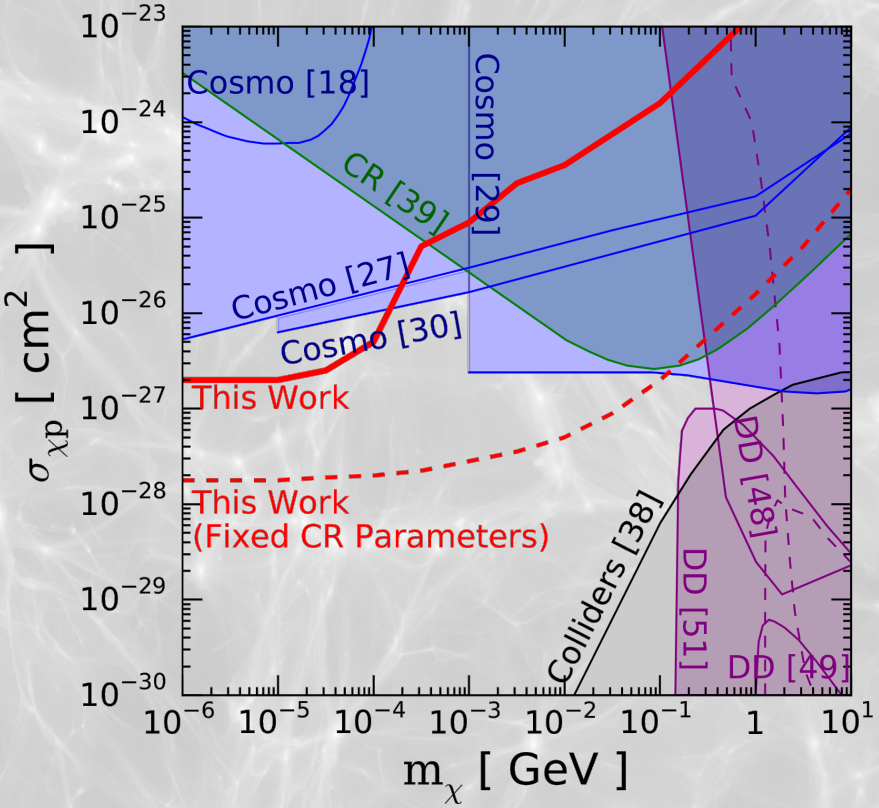

Extracted from [*Phys. Rev.* ***D 99***, *063004 (2019), J. Beacom et al*]

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- In the same interaction, momentum is transferred to the DM particles, that receive a boost, increasing the sensitivity of DD:

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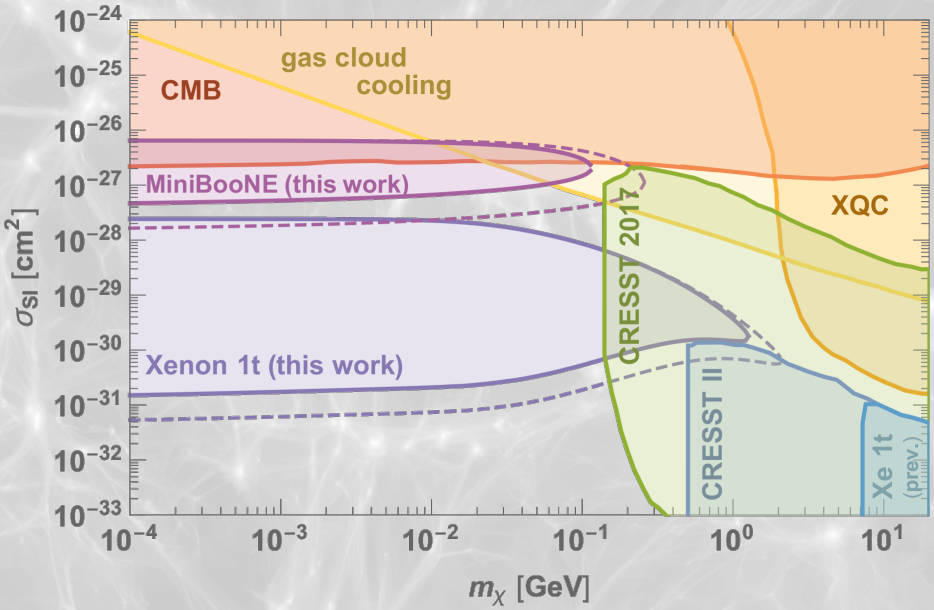

Extracted from [*Phys. Rev. Lett.* ***122***, *171801 (2019), M. Pospelov et al*]

The Process.

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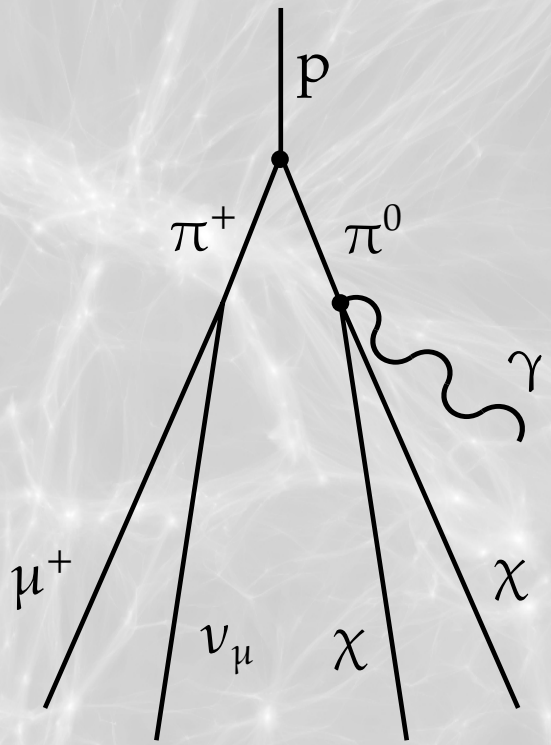

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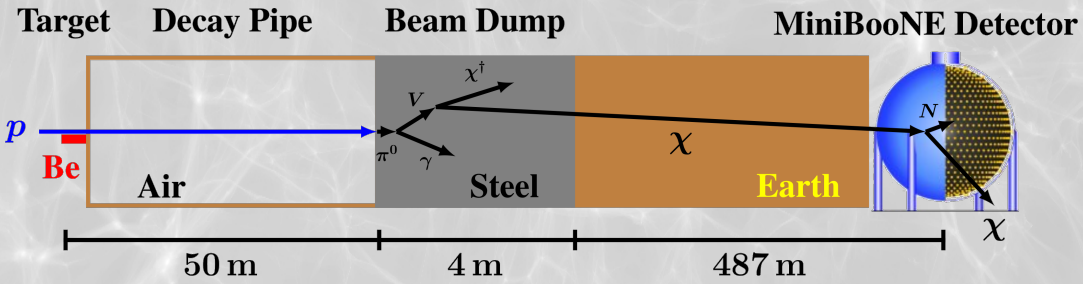
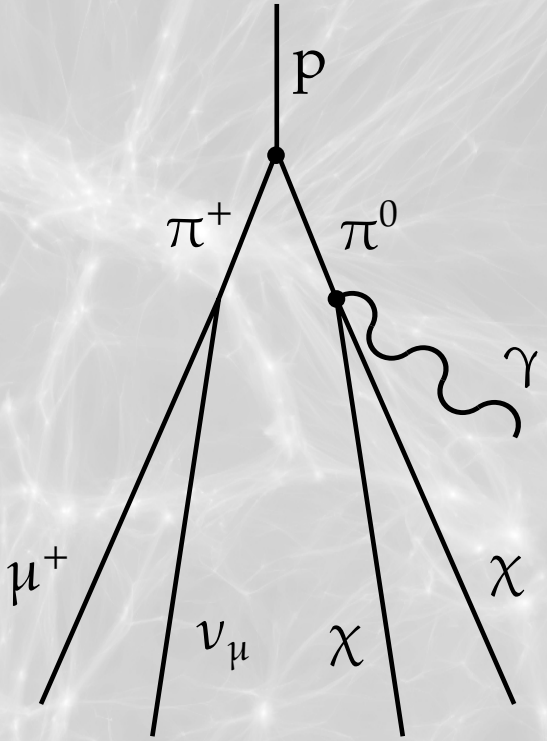


Extracted from [*Phys. Rev. Lett.* ***118***, *221803 (2017), MiniBooNE Collaboration.*]



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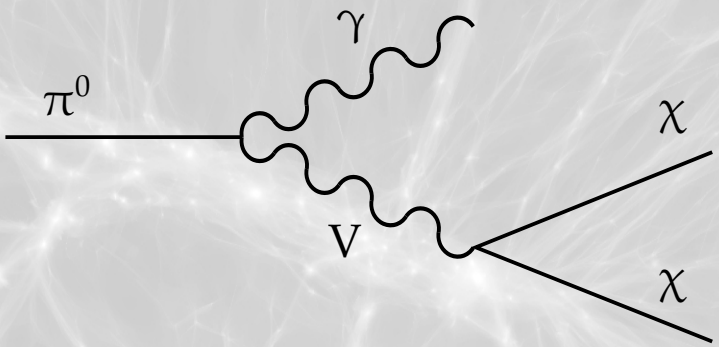

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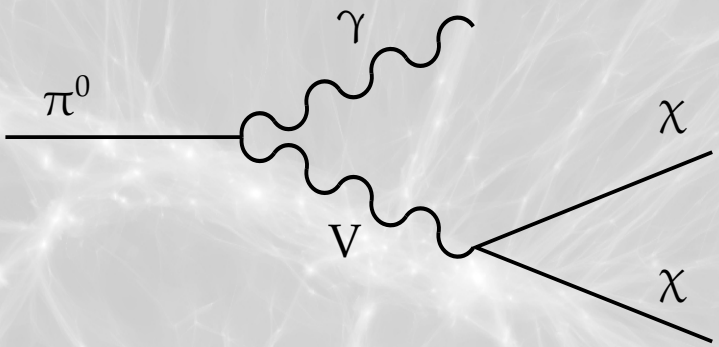

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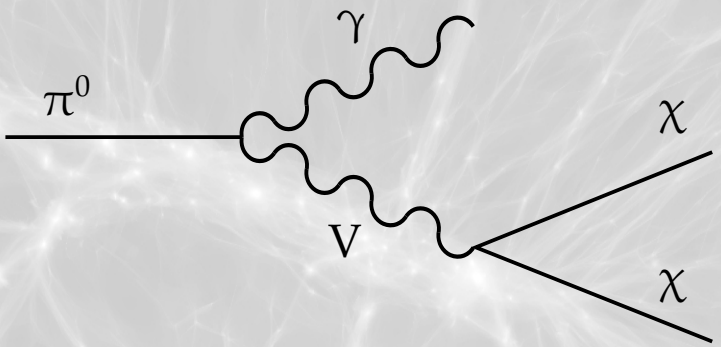

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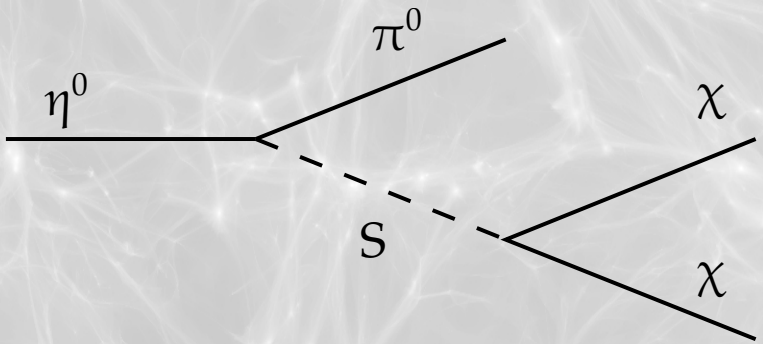

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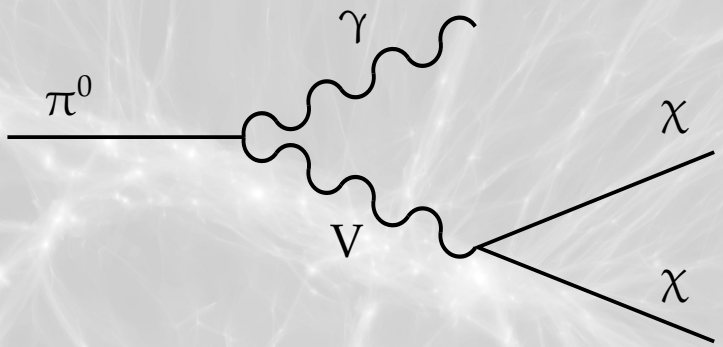

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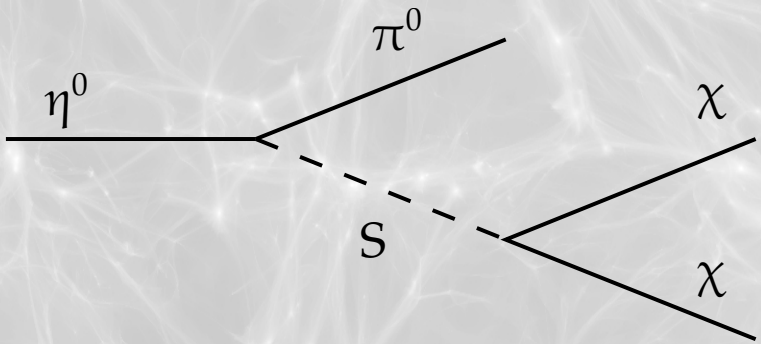

In CRs pions are produced 10 times more often than eta-mesons, but its branching ratio into *invisible* is 10 $\sim$ 100 times more constrained.

The Simulation.

We simulate the collisions with nitrogen in the atmosphere using the CRMC package[†] and describe the effect of the atmosphere as

$$\frac{d\Phi_p}{dT_p}(T_p, h) \equiv Y(h) \cdot \frac{d\Phi_p}{dT_p}(T_p).$$

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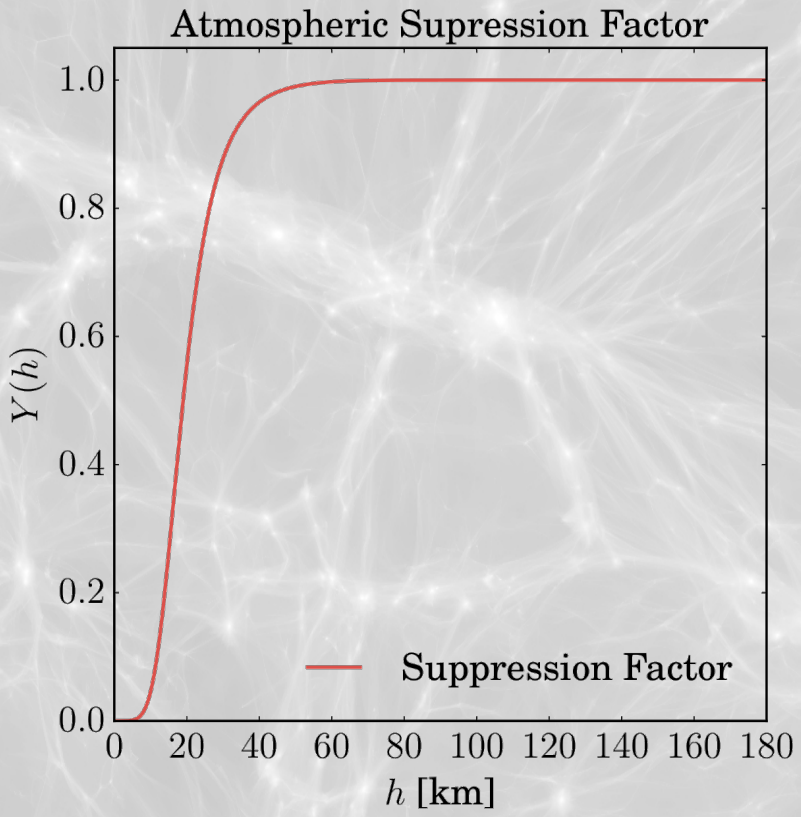

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The Flux.

We can obtain the dark matter flux as measured by a detector on Earth (at depth z_d) as

$$\frac{d\Phi_\chi}{dT_\chi} = \frac{d\Phi_p}{dT_p} n_N^0 H_{\text{eff}} \sigma_{pN\to M} BR_{M\to\chi\chi}$$

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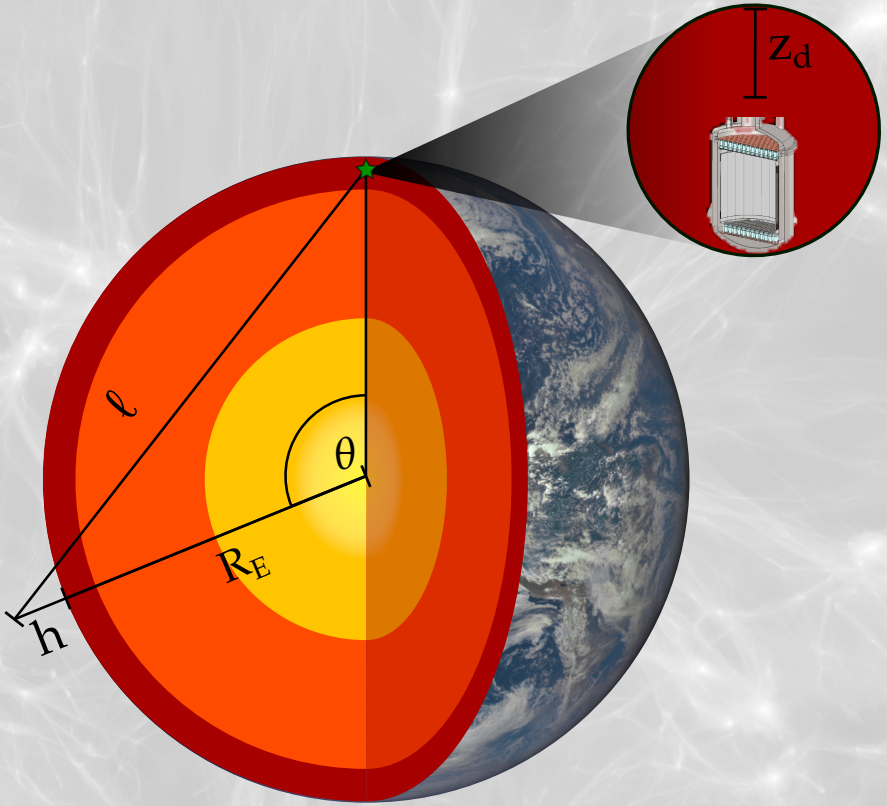

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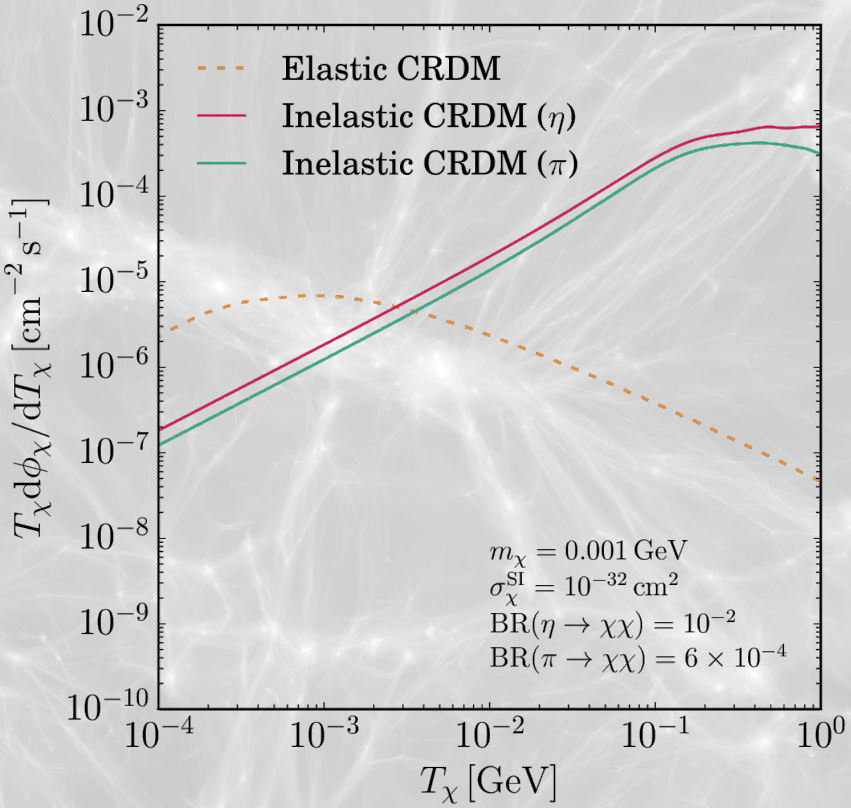

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When the cross section is higher than a certain value, Earth effects start to play an important role.

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$$T_\chi^0 = \frac{2m_\chi T_\chi^z e^{l_E/L}}{2m_\chi + T_\chi^z(1 - e^{l_E/L})}$$

with the mean free path length given by

$$L \equiv \left(\sum_N n_N \sigma_{\chi N} \frac{2m_N m_\chi}{(m_\chi + m_N)^2} \right)^{-1} .$$

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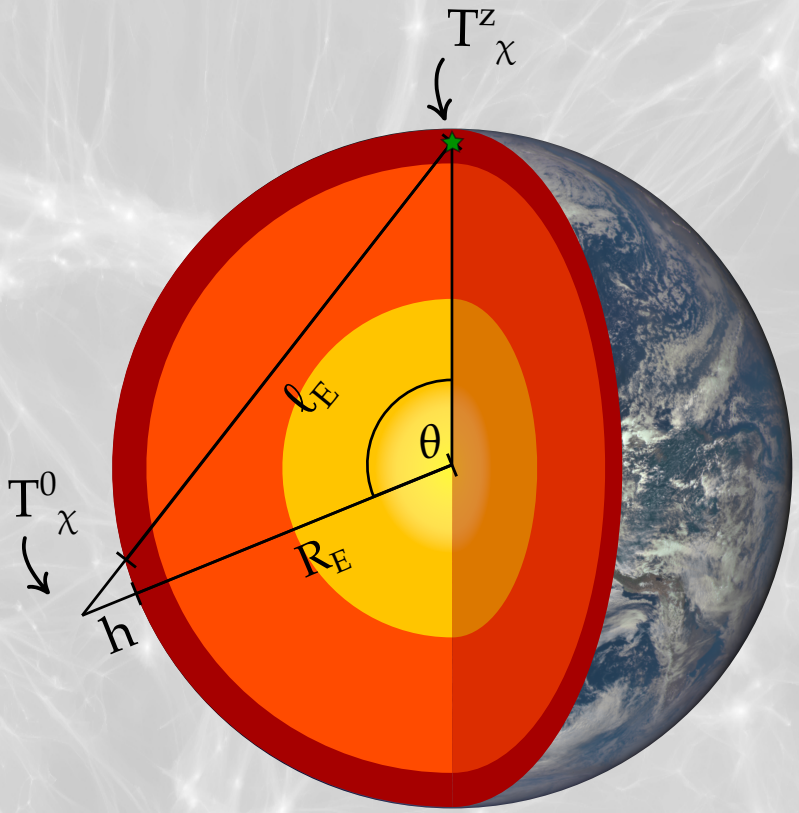

The Rate.

The expected rate coming from the ICRDM contribution at a detector is given by

$$\Gamma_N = N_T \int_{T_1}^{T_2} dT_N \int_{T_\chi^{\min}(T_N)}^{\infty} dT_\chi \epsilon(T_N) \frac{d\Phi_\chi}{dT_\chi} \frac{d\sigma_{\chi N}}{dT_N} ,$$

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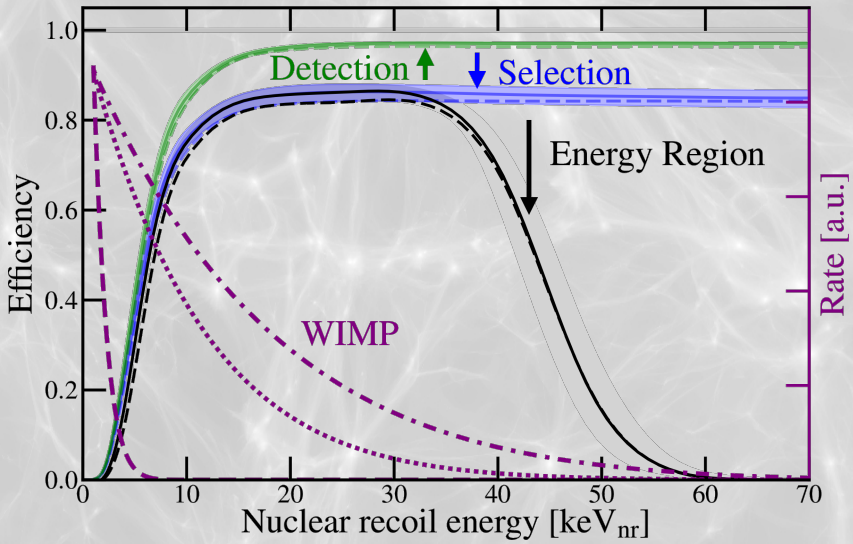
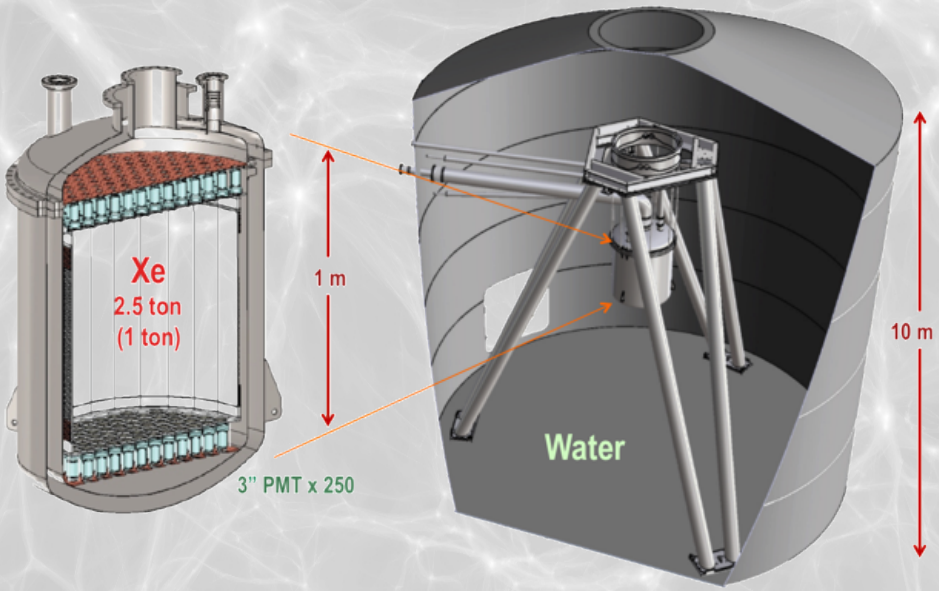
where N_T is the number of target atoms, ϵ is the detector nuclear recoil energy efficiency.



Taken from [*Phys. Rev. Lett.* ***121***, *111302 (2018)*]

(Current) Experiment: XENON1T



Characteristics

- $T = 278.8$ live days.
- $M = 1300 \pm 10$ kg fiducial mass.
- $E = [4.9, 40.9]$ keV$_{\rm nr}$.
- $N(90\%\,\text{C.L.}) = 3.56$

Data from [*Phys. Rev. Lett.* ***121***, *111302 (2018)*]

(Projected) Experiment: LUX-ZEPLIN

Characteristics

- $T = 1000$ live days.
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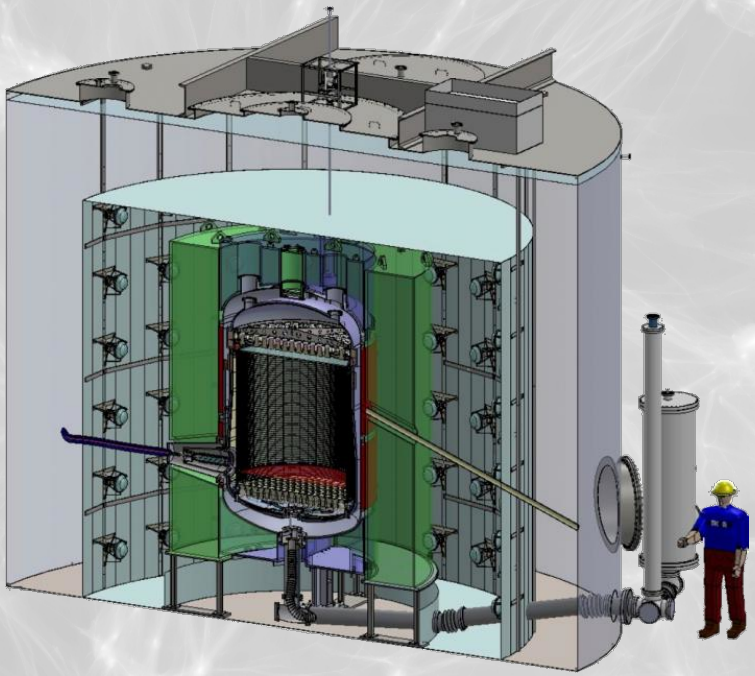
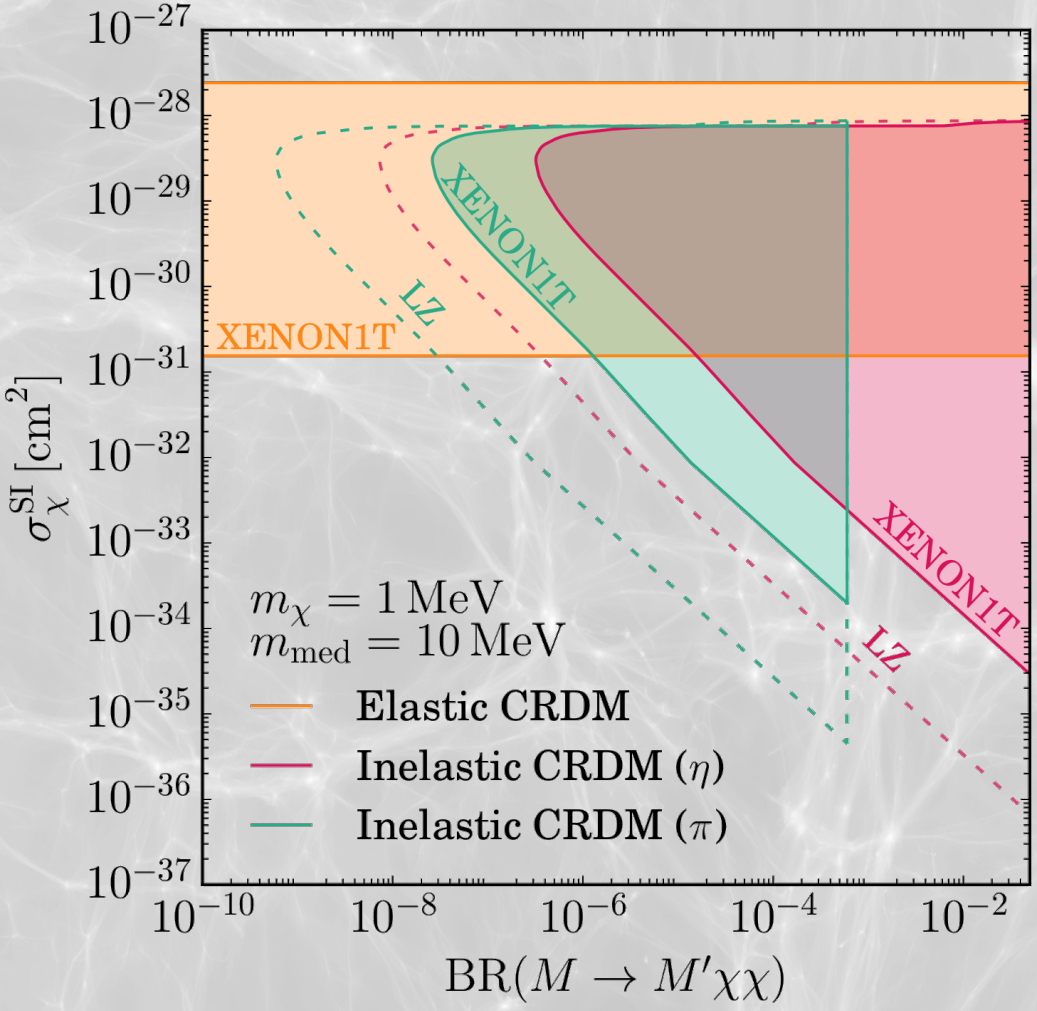


Data from [*arXiv:1802.06039 [astro-ph.IM]*]

The Limits.


10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
$\sigma_\chi^{\rm SI}\,[{\rm cm}^2]$
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
${\rm BR}(M \to M'\chi\chi)$
XENON1T
LZ
XENON1T
XENON1T
LZ
$m_\chi = 1\,{\rm MeV}$
$m_{\rm med} = 10\,{\rm MeV}$
Elastic CRDM
Inelastic CRDM (η)
Inelastic CRDM (π)

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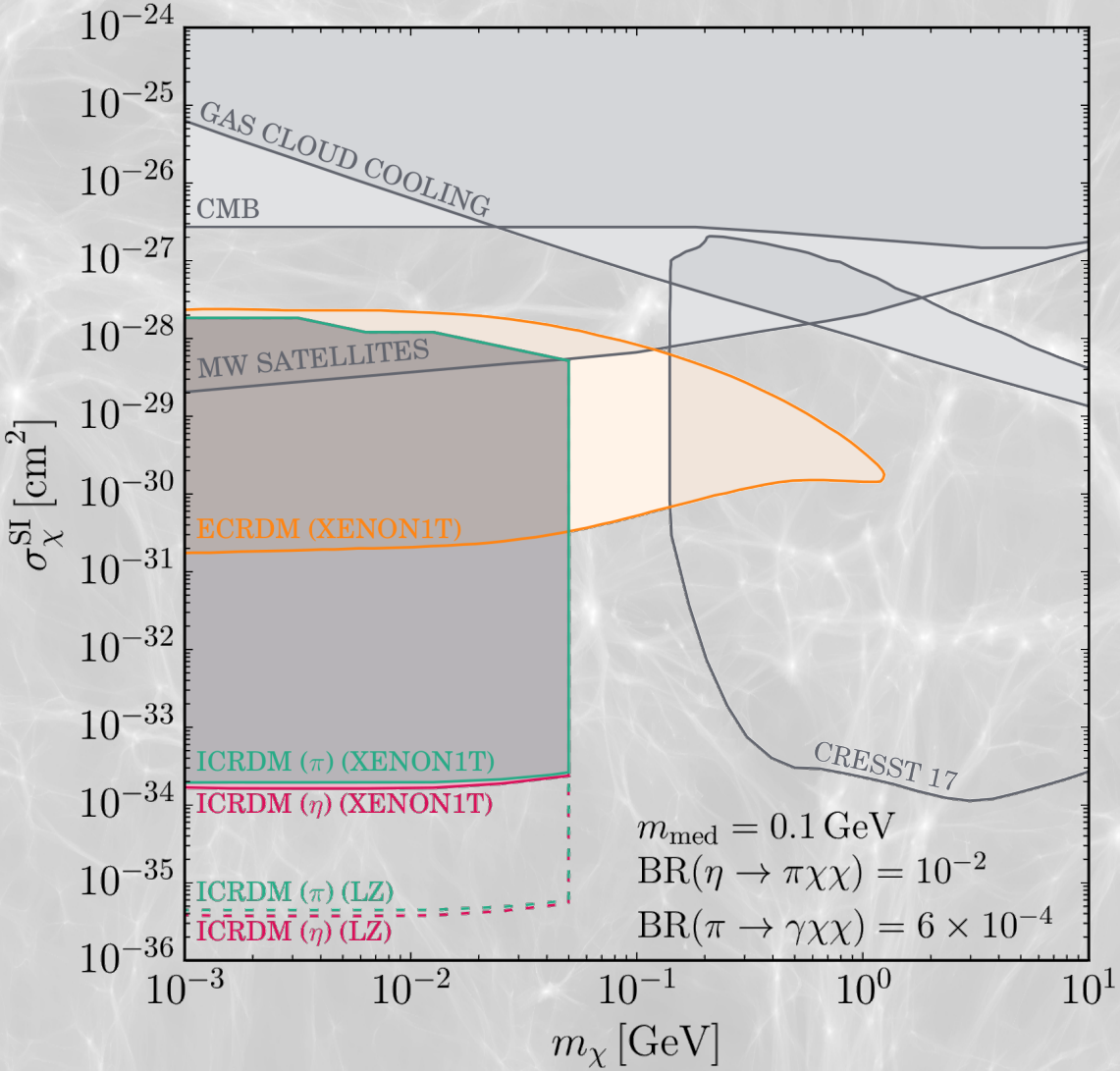
GAS CLOUD COOLING
CMB
MW SATELLITES
ECRDM (XENON1T)
ICRDM (π) (XENON1T)
ICRDM (η) (XENON1T)
ICRDM (π) (LZ)
ICRDM (η) (LZ)
CRESST 17
$m_{\rm med} = 0.1\,{\rm GeV}$
${\rm BR}(\eta \to \pi\chi\chi) = 10^{-2}$
${\rm BR}(\pi \to \gamma\chi\chi) = 6 \times 10^{-4}$
$\sigma_\chi^{\rm SI}\,[{\rm cm}^2]$
$m_\chi\,[{\rm GeV}]$
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}

A Particular Model.

If we consider a hadrophilic scalar mediator model[‡]

$$\mathcal{L} \supset -g_\chi S \bar{\chi}_L \chi_R - g_u S \bar{u}_L u_R + \text{h.c.},$$

we end up with four free parameters: m_χ, m_S, g_χ and g_u.

[‡] Batell *et al*, arXiv:1812.05103

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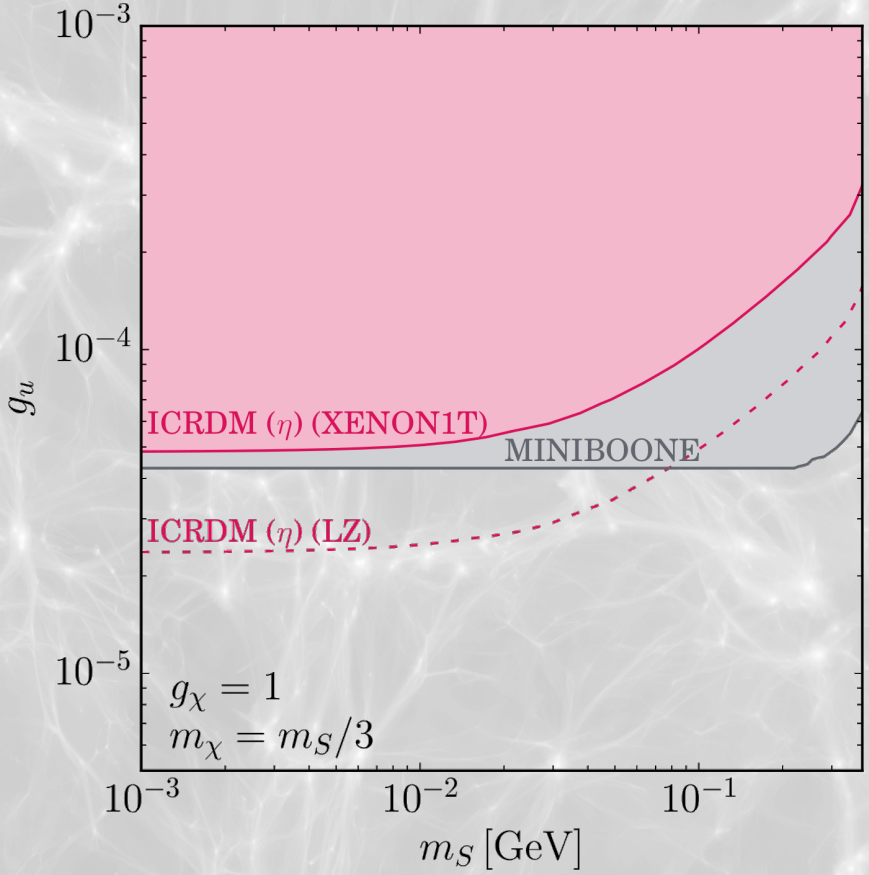

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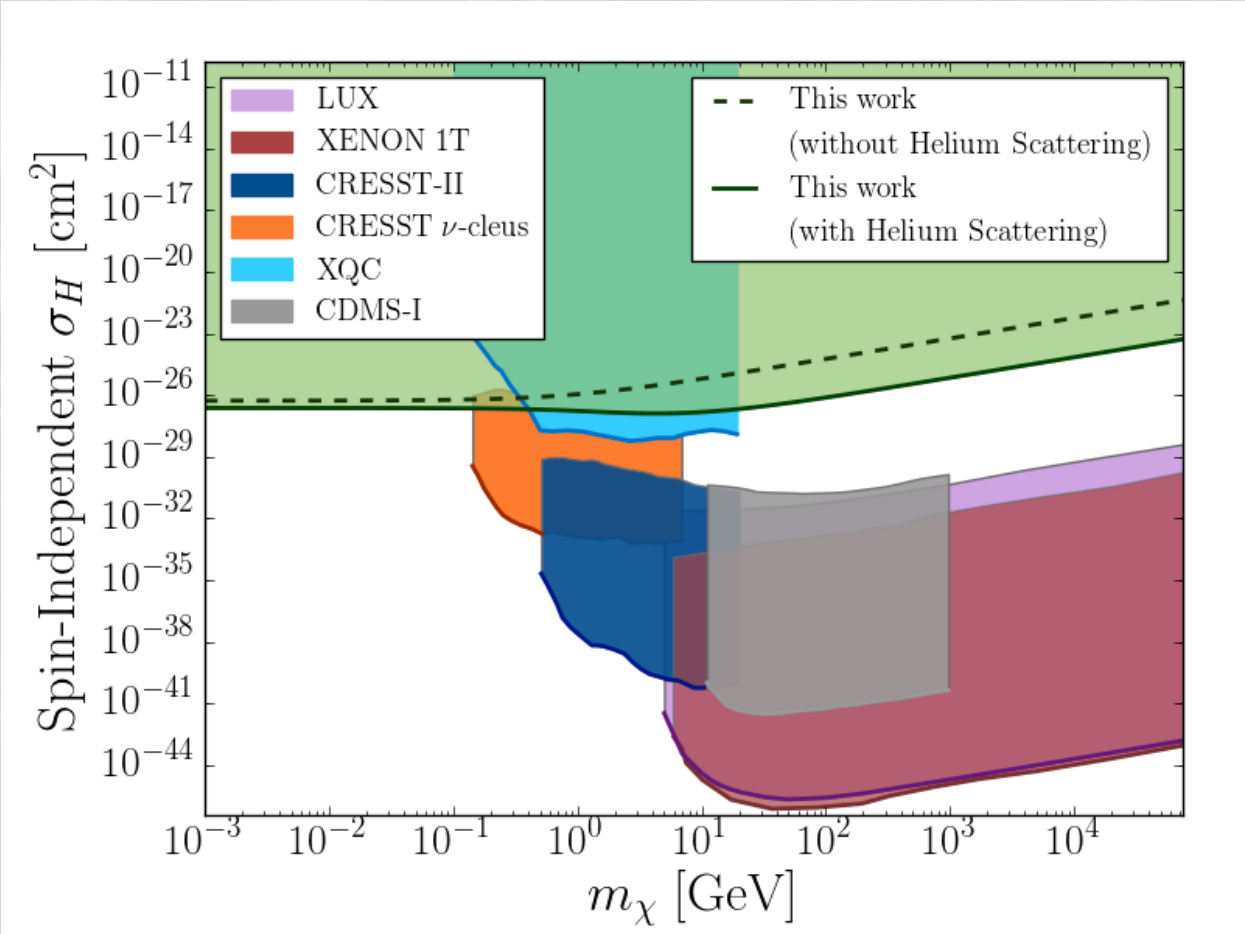
- A particular model has been presented, in which XENON1T presents competitive limits, comparable to those coming from dedicated experiments like MiniBooNE.
- In the future we intend to explore other hidden sectors, independently of dark matter, using similar methods.

Thank you!

Backup Slides: Other Limits



Extracted from [*Phys. Rev.* ***D97***, *103530 (2018)*]

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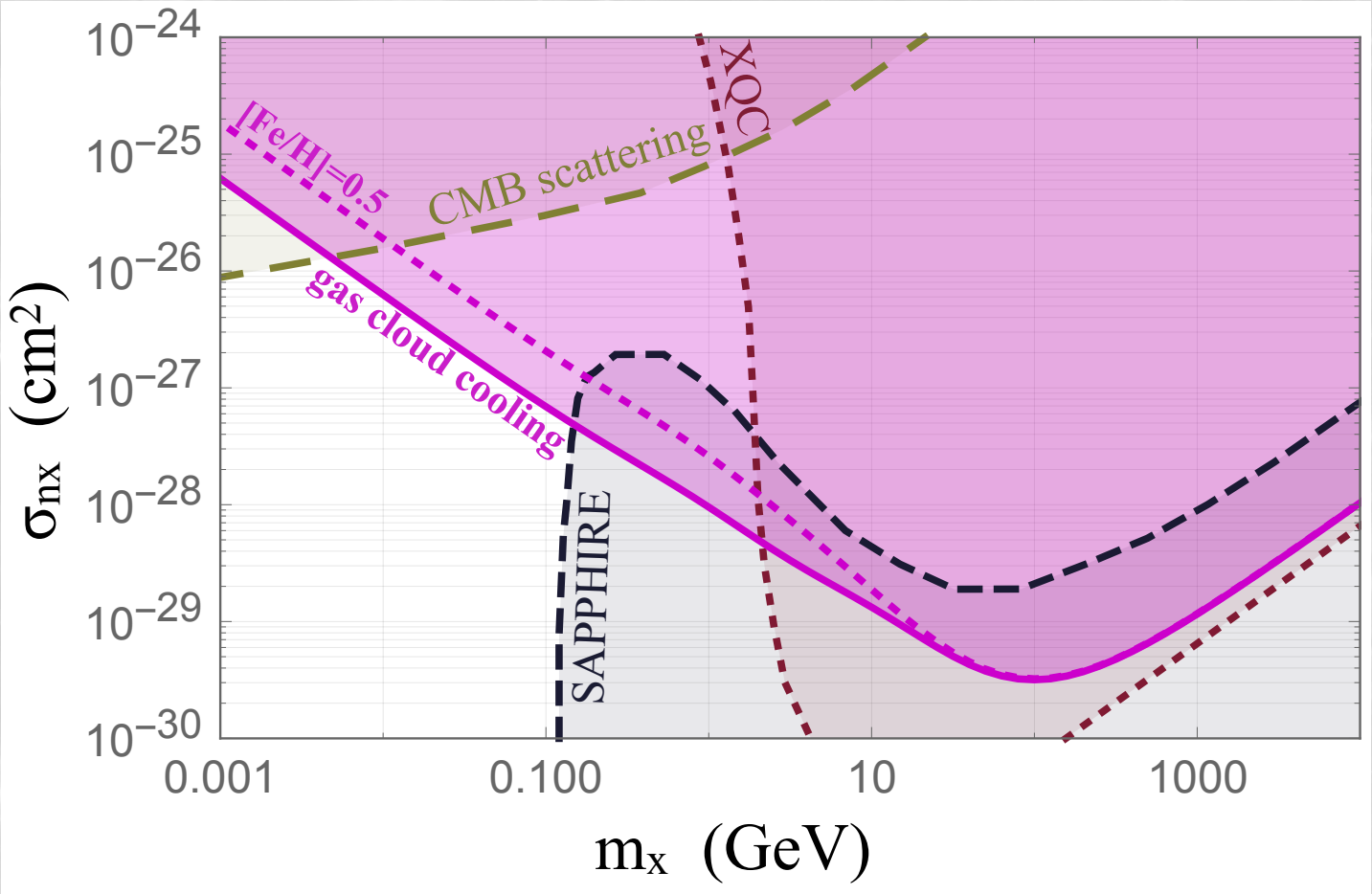

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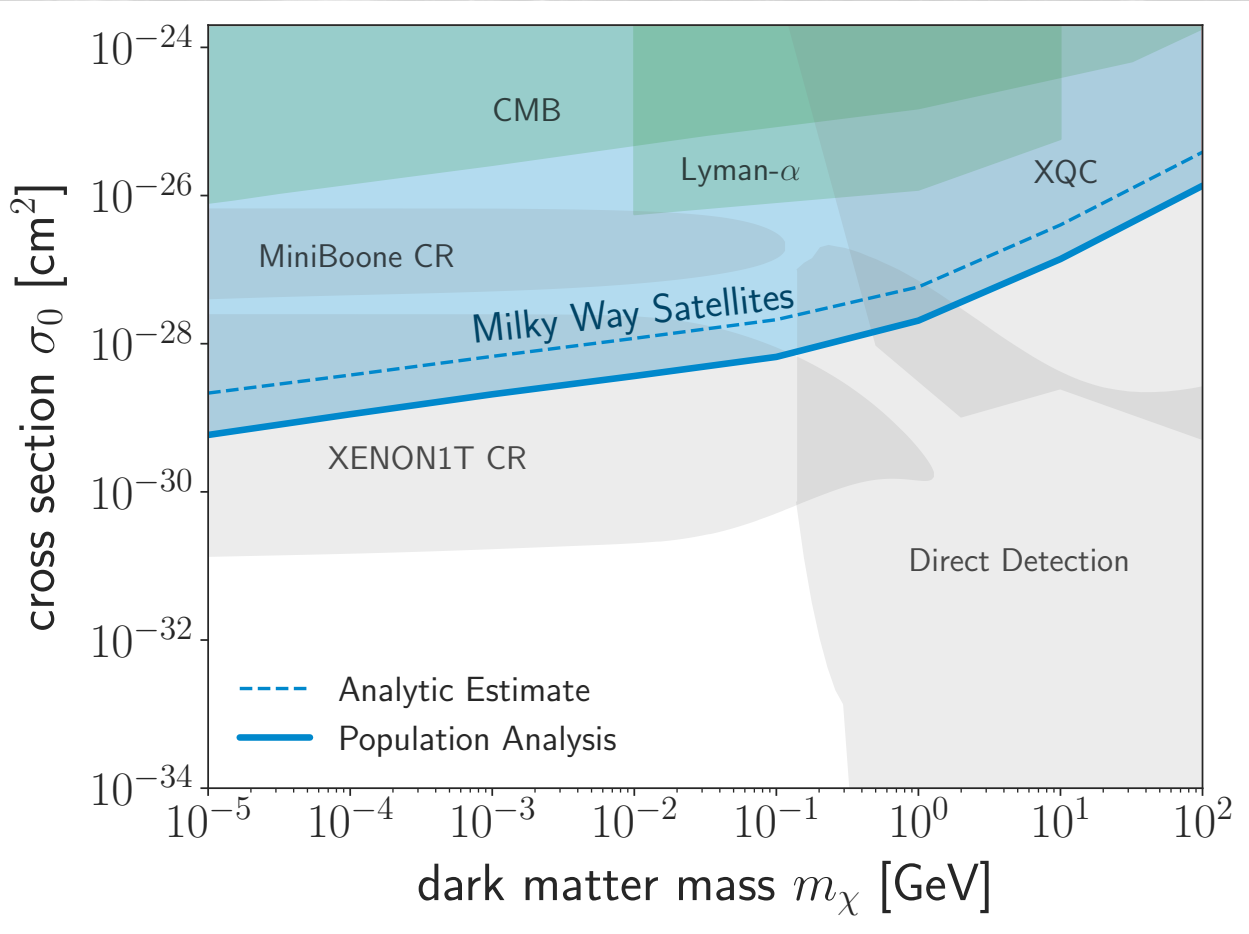

Extracted from [*arXiv:1904.10000 [astro-ph.CO]*]

The ISM vs The Atmosphere.

In this talk: cosmic rays colliding inelastically with a target, producing mesons that might decay into boosted dark matter particles.
The source for the target can be the Interstellar Medium or the Atmosphere

	Typical Density	Typical Length
ISM	10^0 cm^{-3}	$\mathcal{O}(10)$ kpc
Earth's Atm	10^{19} cm^{-3}	$\mathcal{O}(10)$ km