Light Dark Matter from Inelastic Cosmic Ray Collisions

Miguel D. Campos

based on **arXiv:1905.05776**

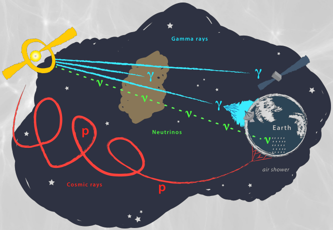
in collaboration with Malcolm Fairbairn, Tevong You and James Alvey.

King's College London

London DM Forum, May 2019.

Cosmic Rays.

- Highly energetic massive particles with mostly extrasolar origins, whose movement has been randomized due to the galactic magnetic field.



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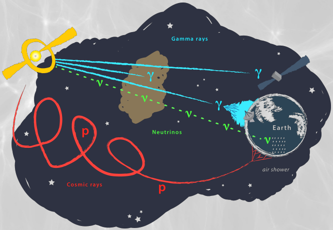
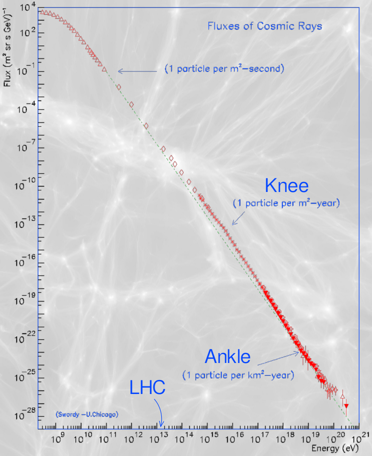
- Its flux peaks around 1 GeV and extends up to 10^{11} GeV.





The Situation in the 90's.

Nature

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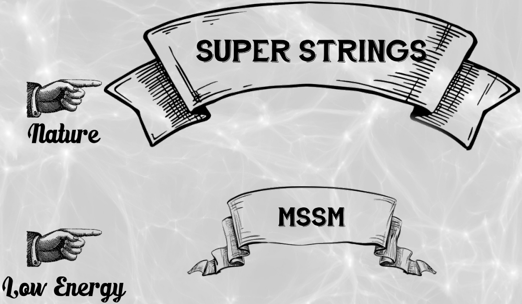

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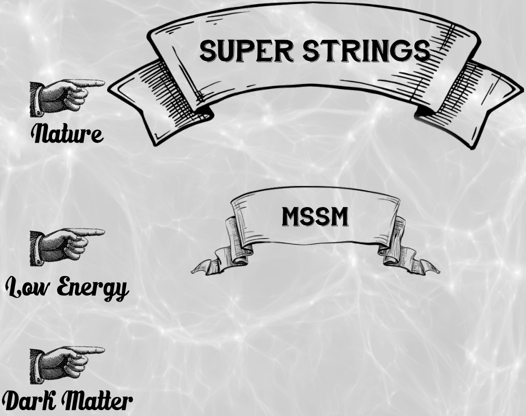

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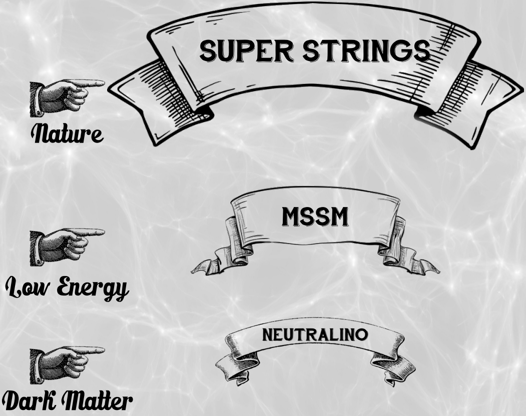

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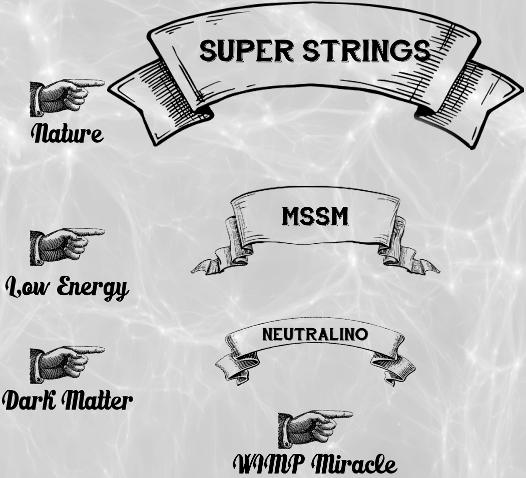


The Situation in the 90's.

SUPER STRINGS

Nature

MSSM

Low Energy

NEUTRALINO

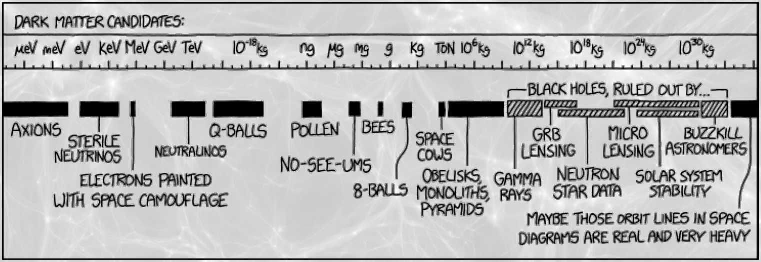
Dark Matter

WIMP Miracle

DM DD

The Situation in the 90's.

The Unexplored Parameter Space.



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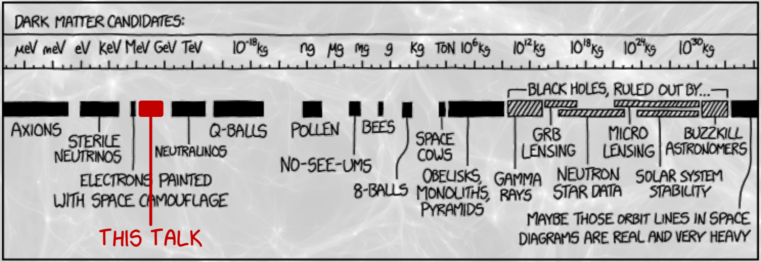

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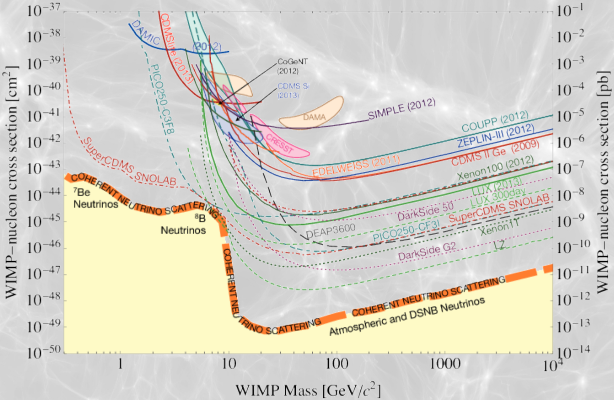

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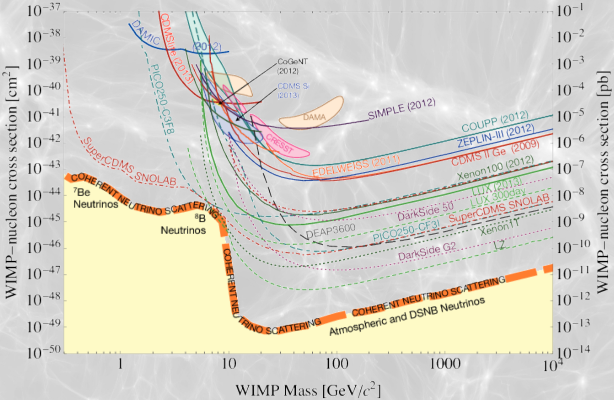

The problem with low mass DM
→ DD experiments are not sensitive to them.

The Unexplored Parameter Space.

New Ideas using CRs

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

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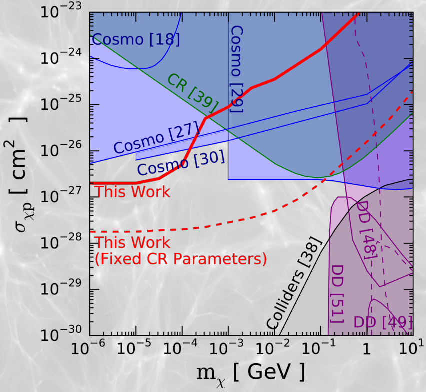

Extracted from [*Phys. Rev.* ***D 99***, *063004 (2019), J. Beacom et al*]

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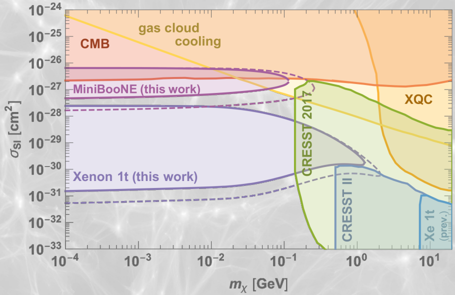

Extracted from [*Phys. Rev. Lett.* ***122***, *171801 (2019), M. Pospelov et al*]

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.
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Earth's Atm	10^{19} cm^{-3}	$\mathcal{O}(10)$ km

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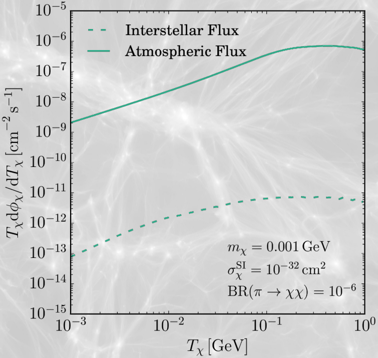

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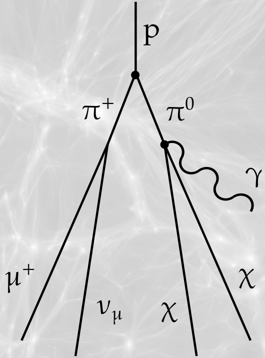

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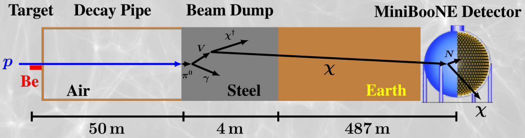

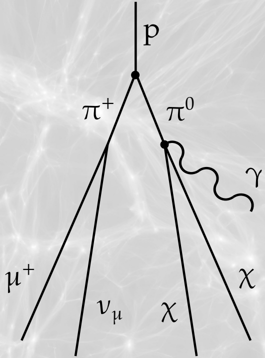

Extracted from [*Phys. Rev. Lett.* ***118****, 221803 (2017), MiniBooNE Collaboration.*]

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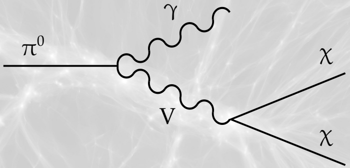

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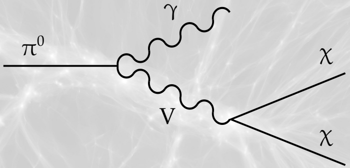

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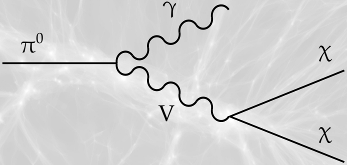

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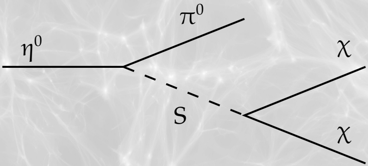

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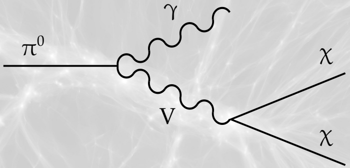

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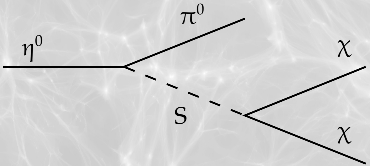

In CRs pions are produced 10 times more often than eta-mesons, but its branching ratio into *invisible* is $\sim 10^4$ times more constrained.

The Simulation.

Starting with the proton flux as measured by AMS-02, we simulate the collisions with nitrogen in the atmosphere using the CRMC package†.

We describe the cosmic rays interaction point as

$$\frac{d}{dh}\left(\frac{d\Phi_p}{dT_p}\right) = \sigma_{pN}(T_p)n_N(h)\frac{d\Phi_p}{dT_p}.$$

†by R. Ulrich *et al*, https://github.com/alisw/crmc

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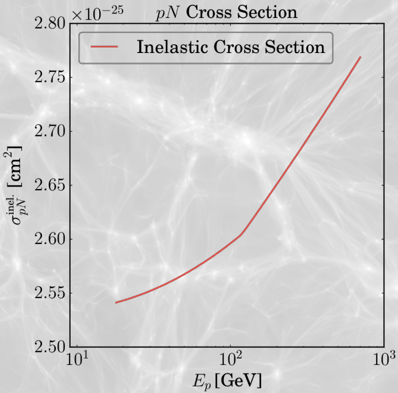

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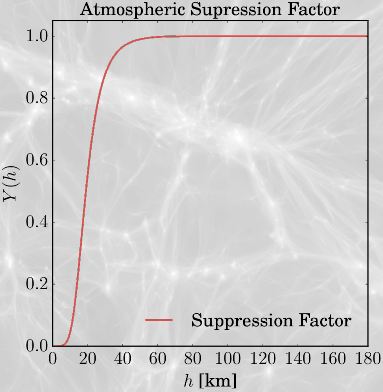

The Flux.

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

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

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$$n_N^0 \equiv 5\times 10^{19}\,\mathrm{cm}^{-3},$$

$$H_{\rm eff} \equiv \int_{R_E}^{R_E+h} R^2 dR \int_0^{2\pi} d\phi \int_{\cos\theta_{\rm max}}^{1} \frac{d(cos\theta)}{2\pi l(R,\theta,z_d)^2} \times y(R-R_E)$$

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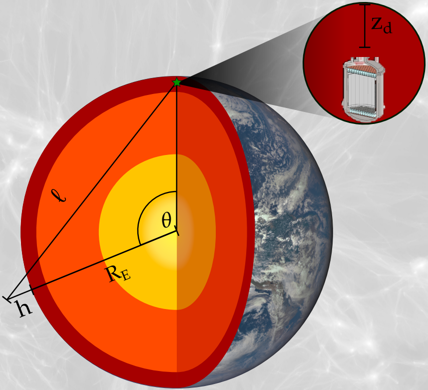

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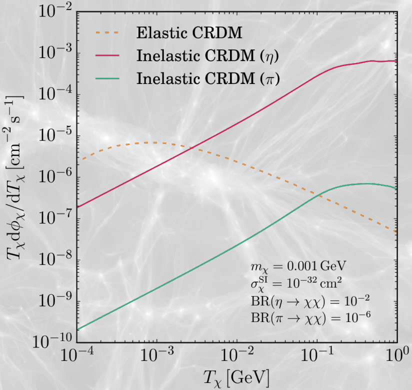

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$$T_\chi^0 = \frac{2m_\chi T_\chi^z e^{l_E/L}}{2m_\chi + T_\chi^z(1 - e^{l_E/L})}$$

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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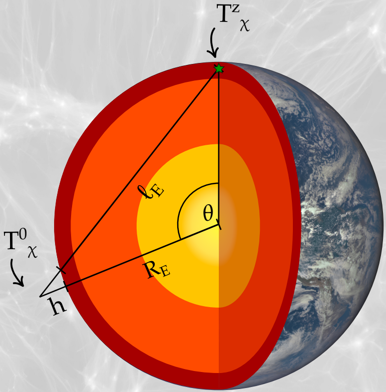

The Rate.

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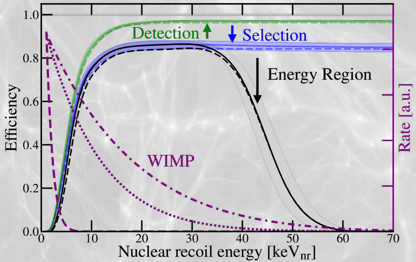
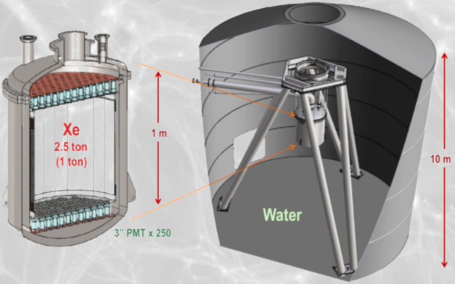
where N_T is the number of target atoms, ϵ is the detector nuclear recoil energy efficiency.



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

(Current) Experiment: XENON1T



Characteristics

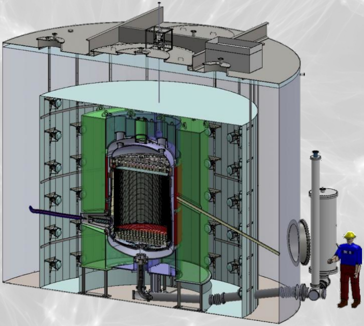
- $T = 278.8$ live days.
- $M = 1300 \pm 10$ kg fiducial mass.
- $E = [4.9, 40.9]$ keV$_{\rm nr}$.

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

(Projected) Experiment: LUX-ZEPLIN

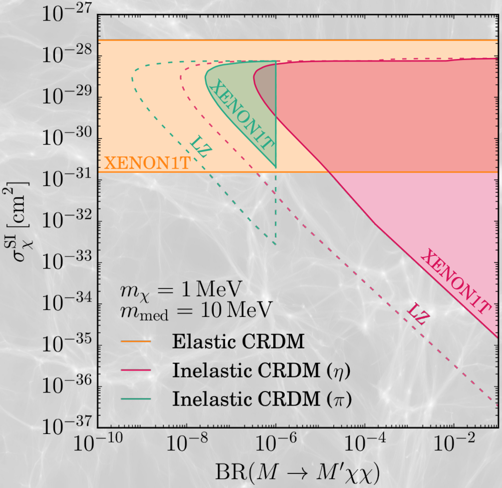
Characteristics

- $T = 1000$ live days.
- $M = 5600$ kg fiducial mass.
- $E = [4.9, 40.9]\ \mathrm{keV_{nr}}$.



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}
$\sigma_\chi^{\mathrm{SI}}\,[\mathrm{cm}^2]$
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
$\mathrm{BR}(M \to M'\chi\chi)$
XENON1T
LZ
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$m_\chi = 1\,\mathrm{MeV}$
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Elastic CRDM
Inelastic CRDM (η)
Inelastic CRDM (π)

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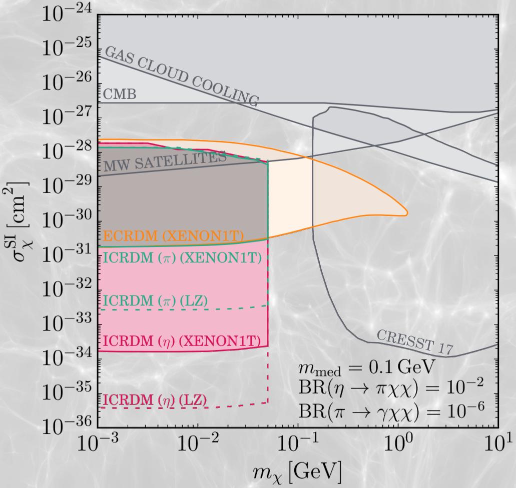

GAS CLOUD COOLING
CMB
MW SATELLITES
ECRDM (XENON1T)
ICRDM (π) (XENON1T)
ICRDM (π) (LZ)
ICRDM (η) (XENON1T)
ICRDM (η) (LZ)
CRESST 17
$m_{\rm med} = 0.1\,\mathrm{GeV}$
$\mathrm{BR}(\eta \to \pi\chi\chi) = 10^{-2}$
$\mathrm{BR}(\pi \to \gamma\chi\chi) = 10^{-6}$
$\sigma_\chi^{\rm SI}\,[\mathrm{cm}^2]$
$m_\chi\,[\mathrm{GeV}]$

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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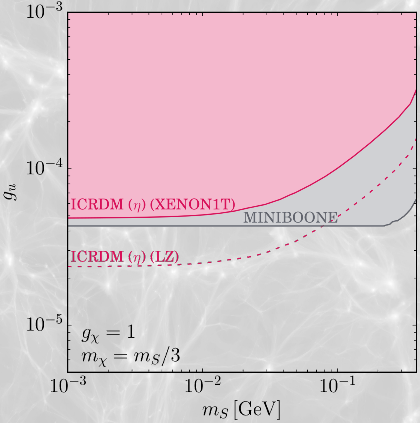

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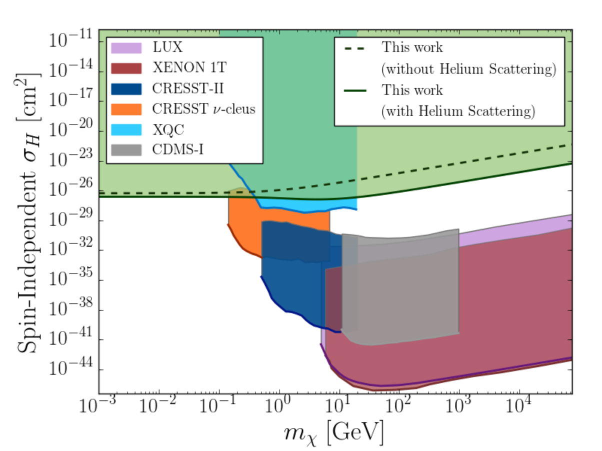
- The possibility of extending the sensitivity of direct detection experiments to low dark matter masses using a *cosmic beam dump*-like effect has been explored.
- A particular model has been presented, in which XENON1T presents competitive limits, comparable to those coming from dedicated experiments like MiniBooNE.

Thank you!

Backup Slides: Other Limits



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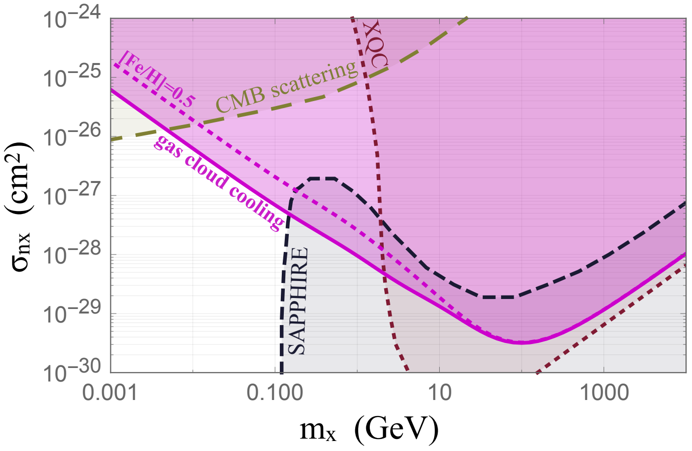

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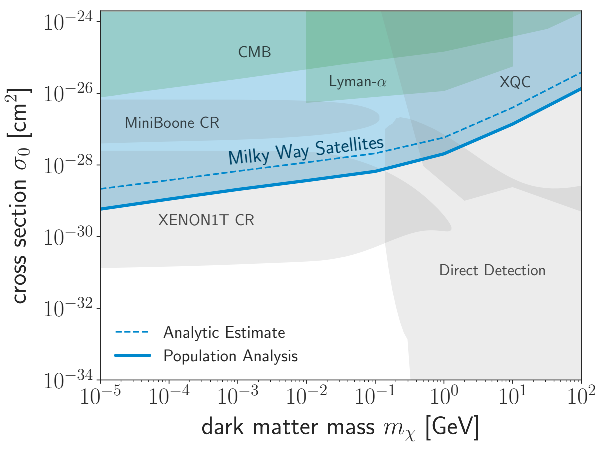

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