Attenuation of cosmic-ray up-scattered dark matter

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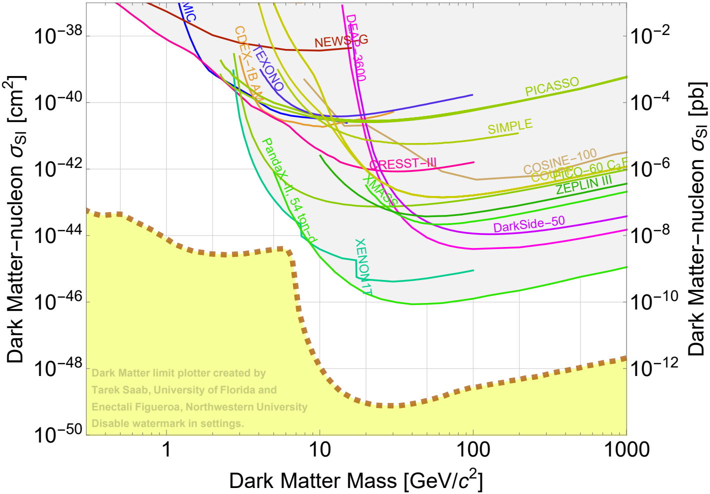
With T. Bringmann (University of Oslo) and J. Alvey (University of Amsterdam)

Outline

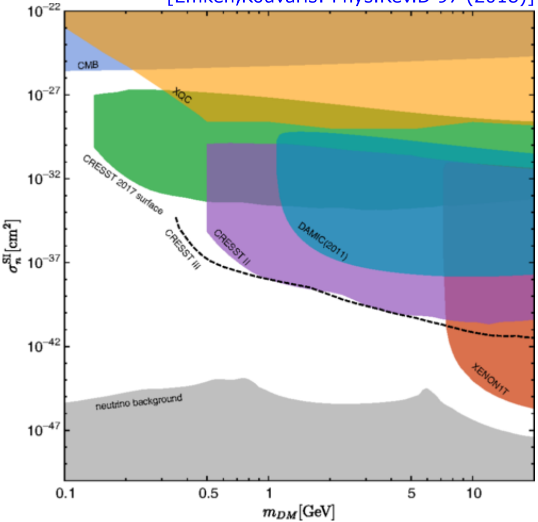
1. Standard direct detection limits
2. Direct detection limits based on cosmic ray up-scattered dark matter
3. Improving ↑:
   - ✓ Heavier cosmic ray elements
   - ✓ Effect of nuclear form factors on attenuation
   - ✓ Effect of inelastic scattering on attenuation
   - ✓ Taking into account specific DM models (specific Q^2-dependence of the DM-nucleon cross section)

Standard Direct Detection limits



Standard Direct Detection limits

[Emken,Kouvaris: Phys.Rev.D 97 (2018)]



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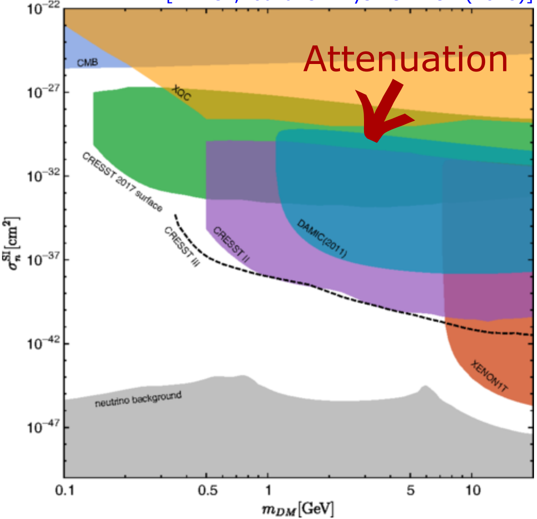

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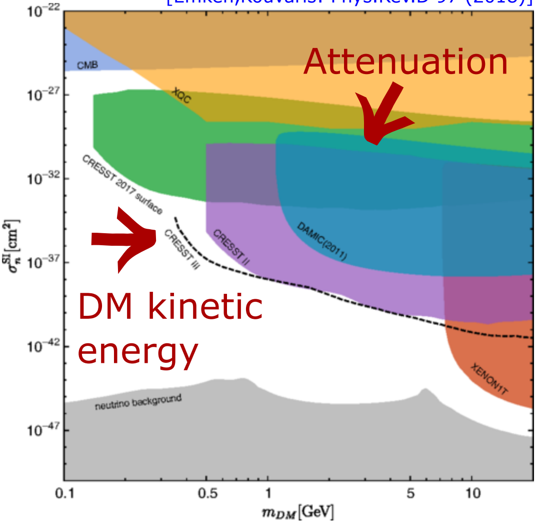


Direct detection experiments: DM-nucleus cross section

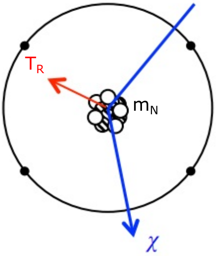
- Spin-independent cross section: scalar or vector effective Lagrangian
  ↪ contributions of individual nucleons $\sigma_n^{\rm SI}$ sum coherently:

$$\sigma_N^{\rm SI} = \sigma_n^{\rm SI} \frac{\mu_{\chi N}^2}{\mu_{\chi n}^2} A^2$$

  (assuming equal coupling of χ to proton and neutron, μ: reduced mass)
- Simplified differential cross section used for interpretation of the results:

$$\frac{d\sigma}{dT_R} = \frac{\sigma_{\rm tot}}{T_R^{\rm max}} F^2(Q^2)$$

- $F(Q^2)$: nuclear form factor ($Q^2 = 2m_N T_R$)

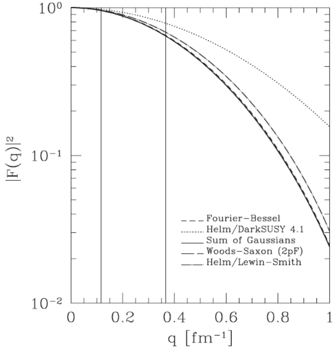


Nuclear form factors

- Capture finite size of the nucleus: Fourrier transform of the charge density distribution
- E.g., charge density $\propto e^{-r/r_0} \Leftrightarrow$ dipole form factor:

$$F(Q^2) = \frac{1}{(1 + Q^2/\Lambda^2)^2}$$

  - applicable for protons, more complicated shape for heavier nuclei
- Model independent form factors - more accurate than Helm form factors



[Duda et al.: JCAP04(2007)]

$d\sigma/dT_R \propto F^2(Q^2) \Rightarrow$ **suppression of the cross section for large** Q^2!

Window for strongly interacting dark matter?

- Gas cloud cooling [Bhoonah et al.: PRL 121 (2018) & PRD 100 (2019)]

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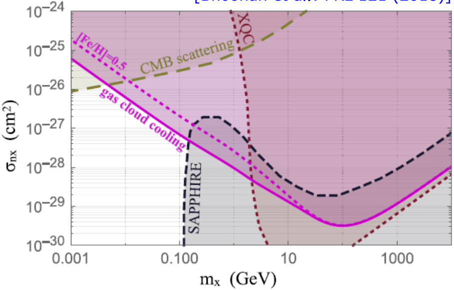

Window for strongly interacting dark matter?

- Gas cloud cooling [Bhoonah et al.: PRL 121 (2018) & PRD 100 (2019)]
- Updated constraints based on structure formation:
  - Milky Way satellite population [DES: PRL 126 (2021)]
  - Lyman alpha forest [Rogers et al.: PRL 128 (2022)]

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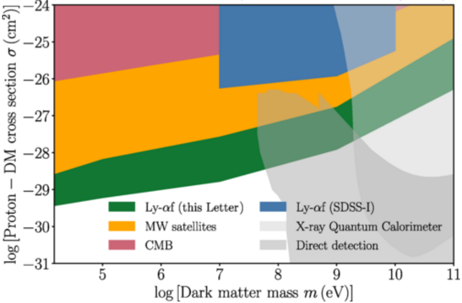

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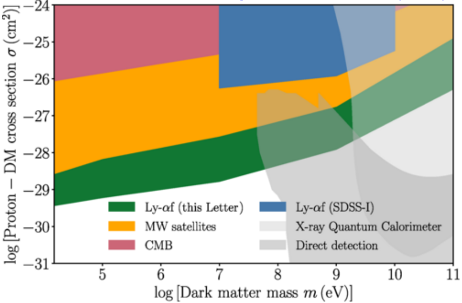
- Updated constraints based on structure formation:
  - Milky Way satellite population [DES: PRL 126 (2021)]
  - Lyman alpha forest [Rogers et al.: PRL 128 (2022)]
- Resonant scattering in case of strong attractive ineraction [Xu and Farrar: 2101.00142]
- Finite thermalization efficiency for experiments like CRESST? [Mahdawi, Farrar: JCAP 10 (2018)]
- Room for strongly interacting DM candidates like QCD hexaquark? [Farrar, Wang, Xu: 2007.10378]

[Rogers et al.: PRL 128 (2022)]



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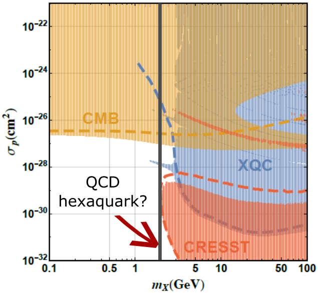
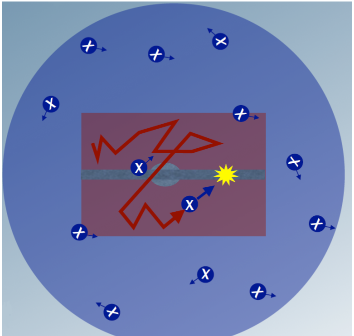


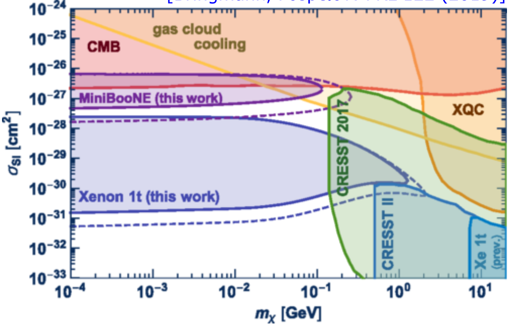
Cosmic ray up-scattered dark matter

- DM interacting strongly with baryons ⇒ DM accelerated by interactions with cosmic rays (≡**CRDM**)
- Flux of relativistic DM particles arriving to Earth ⇒ sub-GeV DM detectable by direct detection experiments like Xenon or neutrino experiments like MiniBooNE!



credit: T. Brigmann

[Bringmann, Pospelov: PRL 122 (2019)]



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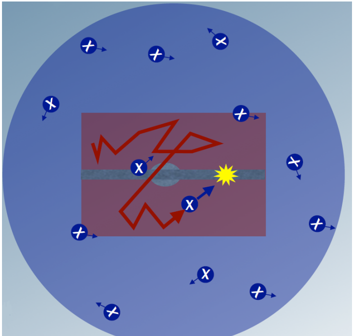
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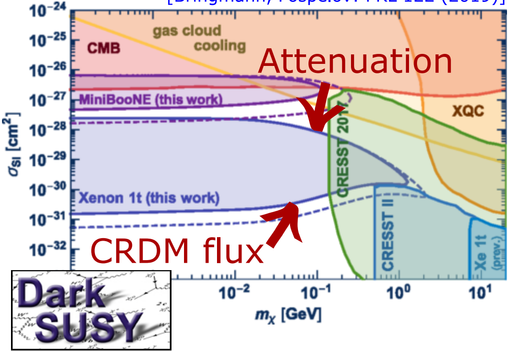
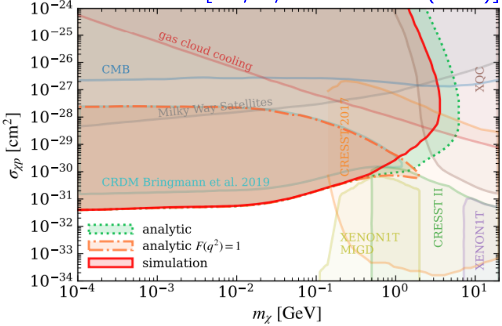


Cosmic ray up-scattered dark matter - updates

- CRDM limits are being widely updated/applied
- Example: [Xia, Xu and Zhou: JCAP 02 (2022)]
  - CRDM limits based on Xenon1T
  - Acceleration of DM also by heavier cosmic ray elements
  - Nuclear form factors, Monte Carlo simulations taken into account for attenuation of the CRDM flux in the Earth's crust
  - CRDM limits reaching to extremely large cross sections?

[Xia,Xu,Zhou: JCAP 02 (2022)]



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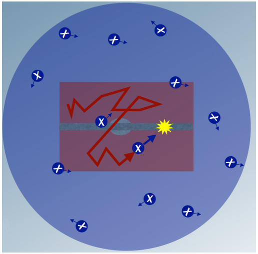
CRDM flux



Spacial integral — Sum over CR elements — CR kinetic energy

DM kinetic energy

$$\frac{d\Phi_\chi}{dT_\chi} = \int \frac{d\Omega}{4\pi} \int_{\mathrm{l.o.s.}} d\ell \, \frac{\rho_\chi}{m_\chi} \sum_N \int_{T_N^{\mathrm{min}}}^{\infty} dT_N \, \frac{d\sigma_{\chi N}}{dT_\chi} \frac{d\Phi_N}{dT_N}$$

$$\equiv D_{\mathrm{eff}} \frac{\rho_\chi^{\mathrm{local}}}{m_\chi} \sum_N \int_{T_N^{\mathrm{min}}}^{\infty} dT_N \, \frac{d\sigma_{\chi N}}{dT_\chi} \frac{d\Phi_N^{\mathrm{LIS}}}{dT_N}$$

DM density — CR-DM cross section — CR flux

- CR elements H, He, C, O included
- CR local interstellar spectra (LIS) based on [Boschini et al.: APJ 250:27 (2020)]
- Effective distance $D_{\mathrm{eff}} = 10\,\mathrm{kpc}$ considered
- "Constant" cross section with protons assumed: $d\sigma_{\chi p}/dT_\chi = \sigma_{SI}/T_\chi^{\mathrm{max}} \times F^2(Q^2)$ (NB: $Q^2 = 2m_\chi T_\chi$)
- Coherent enhancement factor $A^2\mu_{\chi N}^2/\mu_{\chi p}^2$ included for heavier nuclei
- Model independent nuclear form-factors included in DM-CR cross sections

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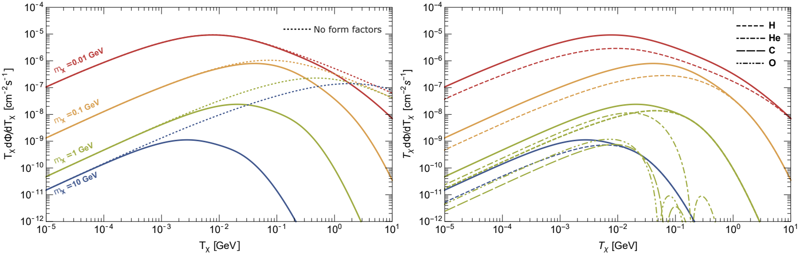


Attenuation in the Earth's crust

Energy loss equation:

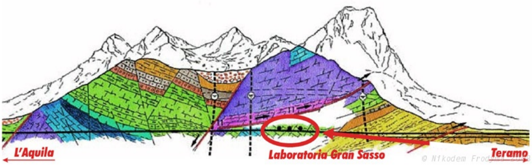
$$\frac{dT_\chi}{dz} = -\sum_N n_N \int_0^{\omega_\chi^{\max}} d\omega_\chi \frac{d\sigma_{\chi N}}{d\omega_\chi}\omega_\chi$$

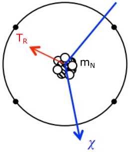
n_N - number density of nuclei N

ω_χ - DM energy loss ($\omega_\chi = T_R$ for elastic scattering with nuclei at rest)

$$\frac{d\sigma_{\chi N}}{d\omega_\chi} = \frac{\sigma_{\chi N}}{T_R^{\max}} F^2(Q^2) + \frac{d\sigma_{\chi N}^{\text{inel}}}{d\omega_\chi}$$

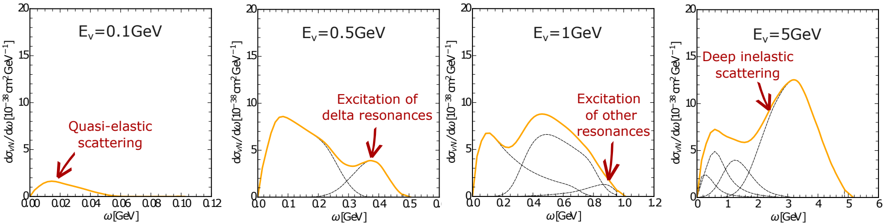
- Form factors $\Rightarrow$ large suppression of stopping power for high-energy DM!
- Inclusion of inelastic scattering changes considerably the results!

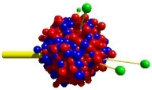




Intermezzo: Inelastic scattering with nuclei

- Inspiration: neutral current neutrino-nucleus scattering
- For $E_\nu \gtrsim 0.1\,\mathrm{GeV}$ different inelastic processes appear:





GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

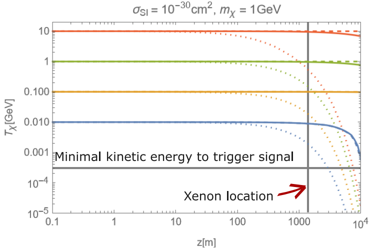
(dependence of neutrino-oxygen differential cross section per nucleon on energy transfer $\omega_\nu \equiv E_\nu - E'_\nu$ obtained by GiBUU code [gibuu.hepforge.org])

Effect of inelastic scattering on CRDM attenuation

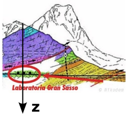
- Estimate of DM-nucleus inelastic cross section:
  GiBUU results on neutrino-nucleus cross sections rescaled by the ratio of the DM-nucleon and neutrino-nucleon cross sections

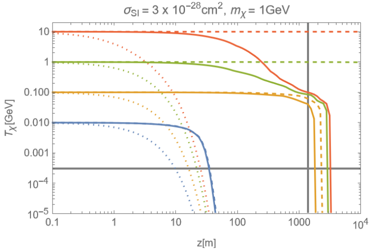
$$\frac{d\sigma_{\chi N}^{\text{inel}}}{d\omega_\chi} \approx \frac{d\sigma_{\nu N}^{\text{GiBUU}}}{d\omega_\nu} \times \frac{\frac{d\sigma_{\chi n}}{d\omega_\chi}}{\frac{d\sigma_{\nu n}}{d\omega_\nu}}$$

- Large σ_{SI}: energetic DM particles slowed down in the Earth's crust due to inelastic scattering with nuclei!

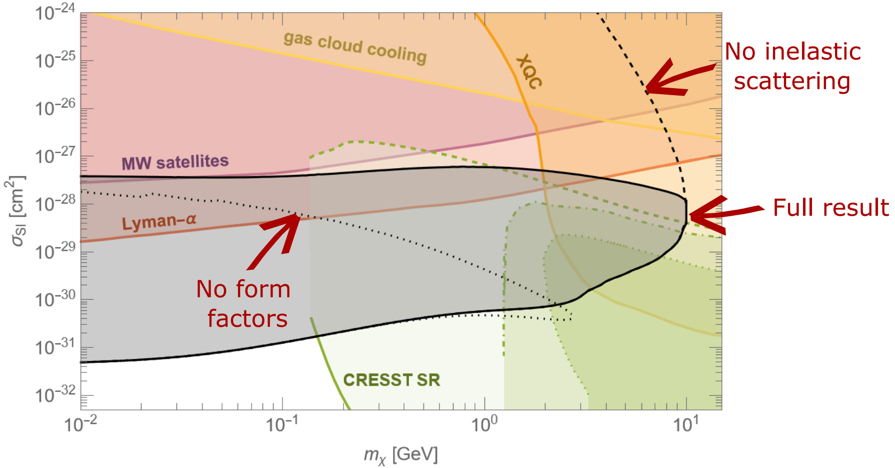


	FF	inel.
——— (solid)	✓	✓
- - - - (dashed)	✓	x
.... (dotted)	x	x





Xenon1T limits

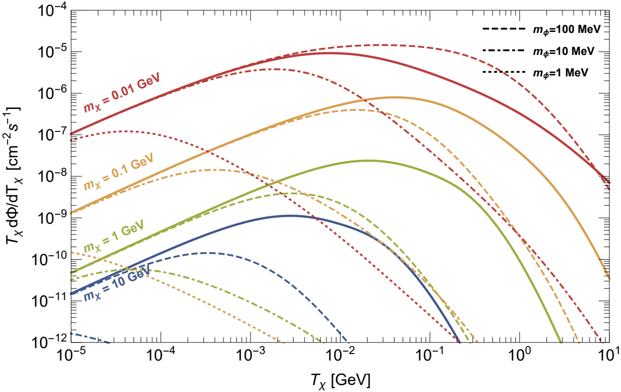


Q^2-dependent DM cross section

- Different motivated Q^2 dependent cross sections studied
- Example: DM-nucleon scattering via scalar mediator ϕ

$$\frac{d\sigma_{\chi N}}{dT_\chi} \propto \frac{Q^2 + 4m_\chi^2}{Q^2 + m_\phi^2}$$

$\Rightarrow$ CRDM flux enhanced for light DM, suppressed for light mediator



Conclusions

- Direct detection limits based on cosmic ray up-scattered dark matter complementary to standard direct detection and cosmological limits
- Inclusion of inelastic scattering crucial for obtaining realistic results for attenuation in Earth's crust
- Limits extended to larger DM masses compared to no-form-factor case
- Coming soon: limits in case of Q^2-dependent cross sections
- To be implemented as a part of DarkSUSY