# Attenuation of Cosmic-Ray Up-Scattered Dark Matter

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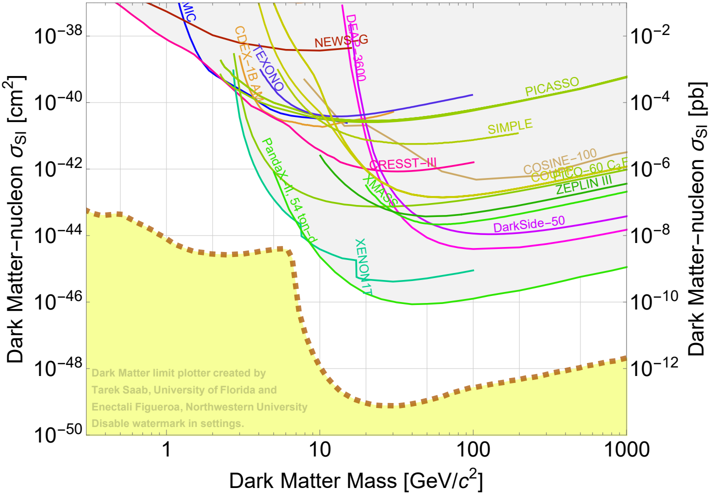
# Outline

1. Standard direct detection limits
2. Direct detection limits based on cosmic ray up-scattered dark matter
3. Improving ↑:
   - ✓ Further cosmic ray elements
   - ✓ Effect of nuclear form factors on attenuation
   - ✓ Effect of inelastic scattering on attenuation
   - ✗ Taking into account specific DM models

# Standard Direct Detection limits



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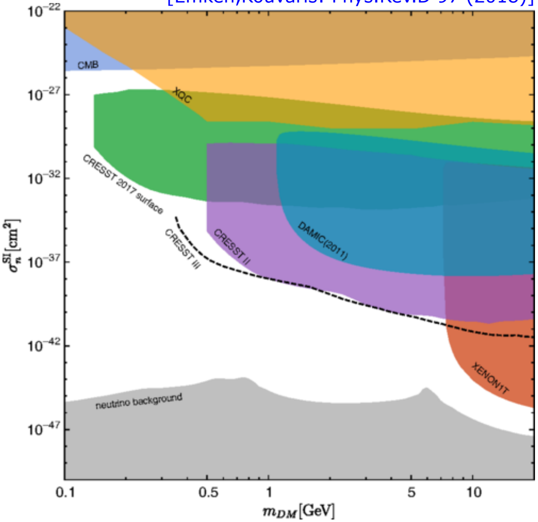
[Emken,Kouvaris: Phys.Rev.D 97 (2018)]



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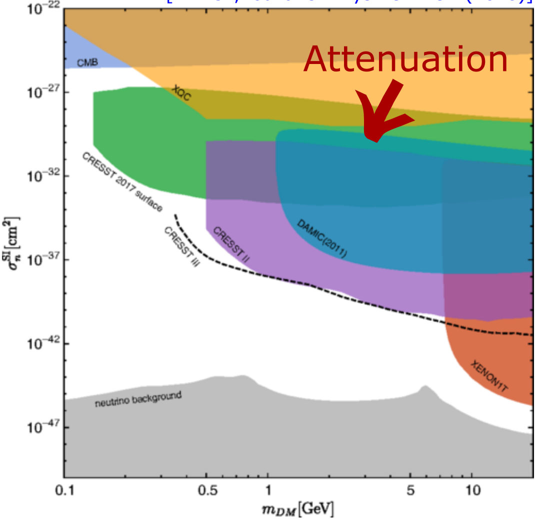

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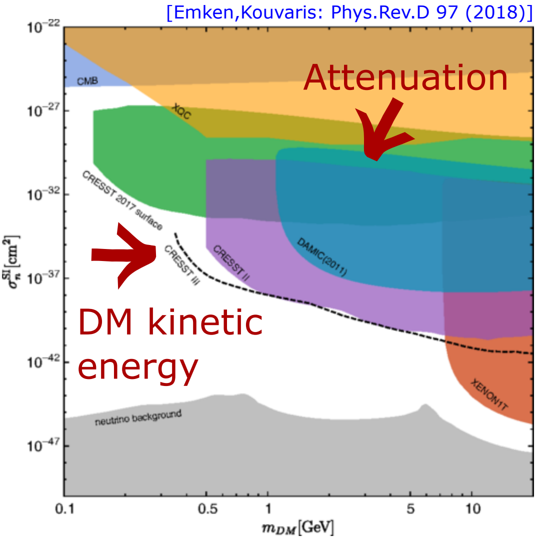

# Window for strongly interacting dark matter?

- Gas cloud cooling [Bhoonah et al.: Phys.Rev.D 100 (2019)]

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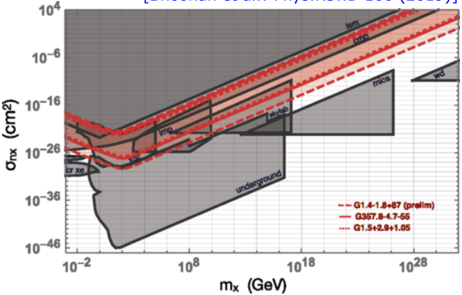

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- Gas cloud cooling [Bhoonah et al.: Phys.Rev.D 100 (2019)]
- Updated constraints based on structure formation:
  - Milky Way satellite population [DES: PRL 126 (2021)]
  - Lyman alpha forest [Rogers et al.: PRL 128 (2022)]

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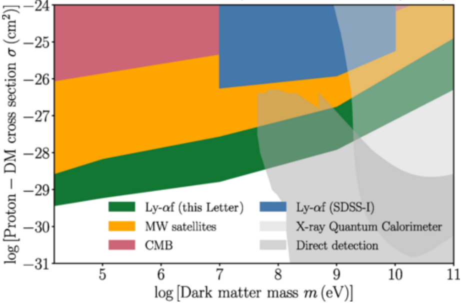

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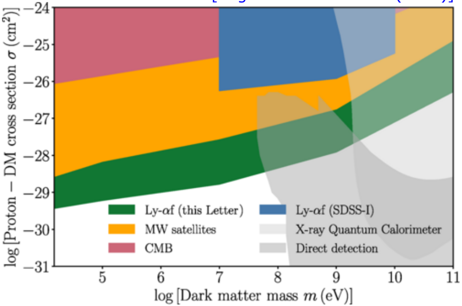
    - Milky Way satellite population [DES: PRL 126 (2021)]
    - Lyman alpha forest [Rogers et al.: PRL 128 (2022)]
- Resonant scattering in case of strong attractive ineraction [Xu and Farrar: 2101.00142]
- Finite thermalization efficiency for experiments like CRESST? [Mahdawi, Farrar: JCAP 10 (2018)]
-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

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

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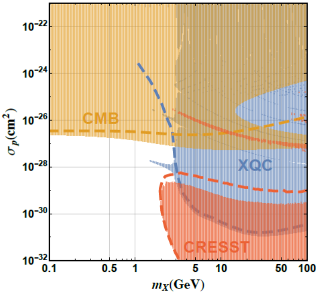
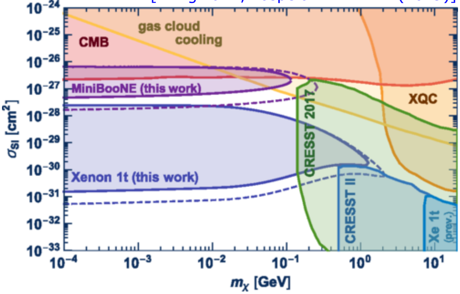


# Cosmic ray up-scattered dark matter

- 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!

[Bringmann, Pospelov: PRL 122 (2019)]




DarkSUSY

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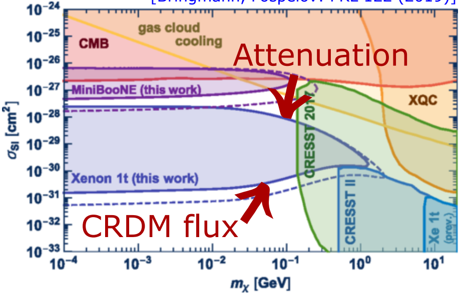
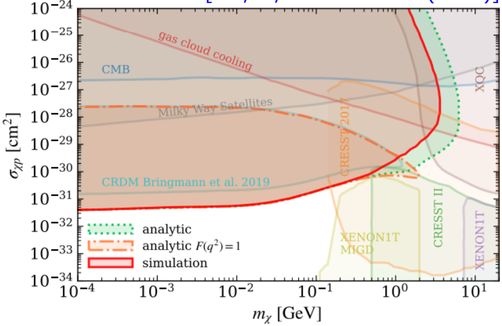


# Cosmic ray up-scattered dark matter - updates

- 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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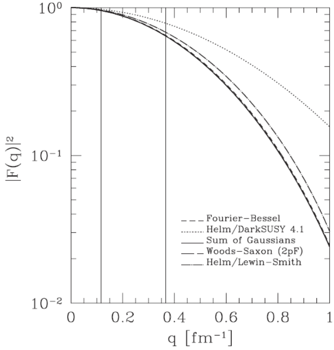
# Intermezzo: Nuclear form factors

- 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)]

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

# CRDM flux

Spacial integral — Sum over CR elements — CR kinetic energy — DM kinetic energy

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

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

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: $d\sigma_{\chi p}/dT_\chi = \sigma_{SI}/T_\chi^{max} \times F^2(Q^2)$ (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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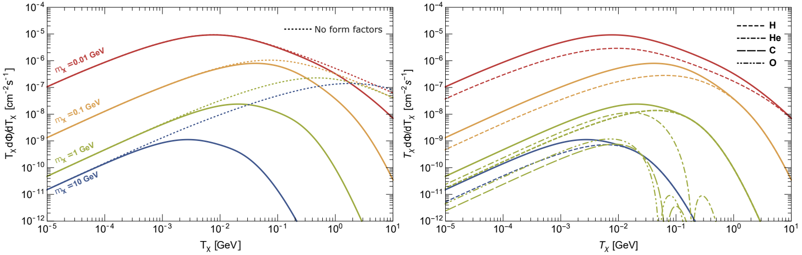


# Attenuation in the Earth's crust

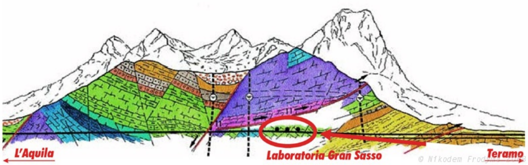
Energy loss equation:

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

$n_N$ - number density of nuclei $N$

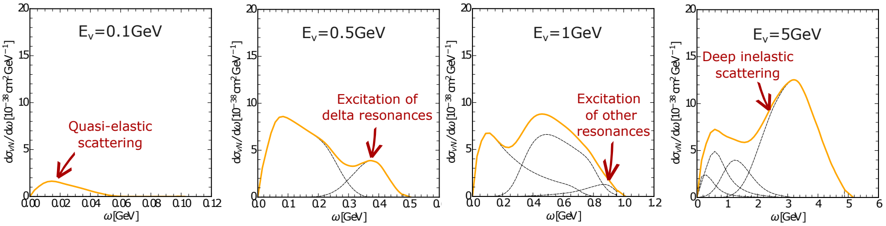
$\omega_\chi$ - DM energy loss $T_\chi - T'_\chi$

- "Constant" DM-nucleus scattering cross section assumed
- Form factors $\Rightarrow$ large suppression of stopping power for high-energy DM!
- Inclusion of inelastic scattering changes the results dramatically!



# Intermezzo: Inelastic scattering with nuclei

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

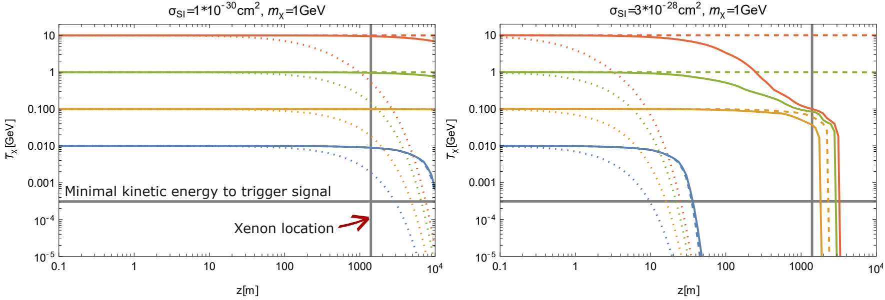



GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

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

# Effect of inelastic scattering on CRDM attenuation

- Estimate of DM-nucleus inelastic cross section based on rescaled GiBUU results on neutrino-nucleus cross sections
- Preliminary results:
  - Solid lines: form factors + inelastic scattering taken into account
  - Dashed lines: only form factors
  - Dotted lines: no form factors



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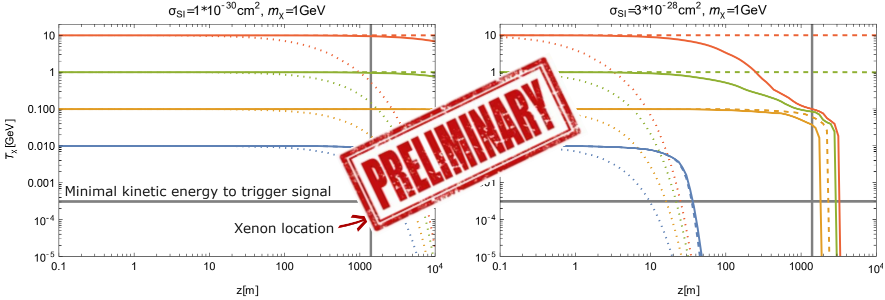
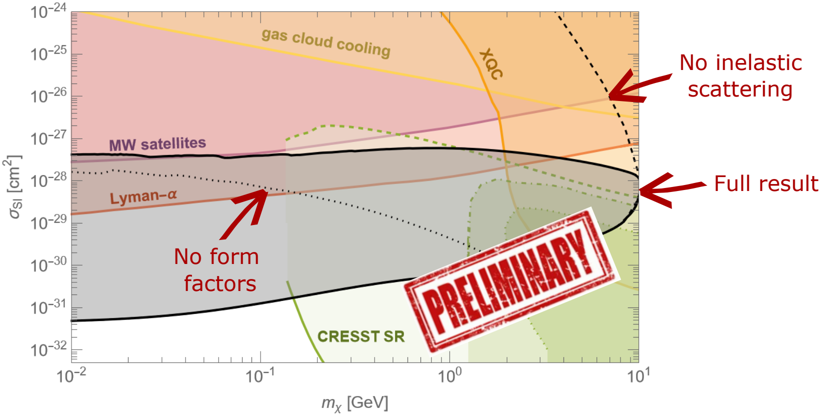


# Xenon1T limits

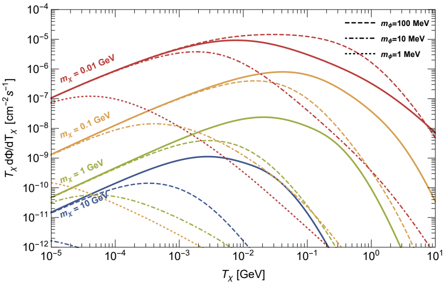


# $Q^2$ dependent DM cross section?

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

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

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



# 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 program!