Update on cosmic ray up-scattered dark matter

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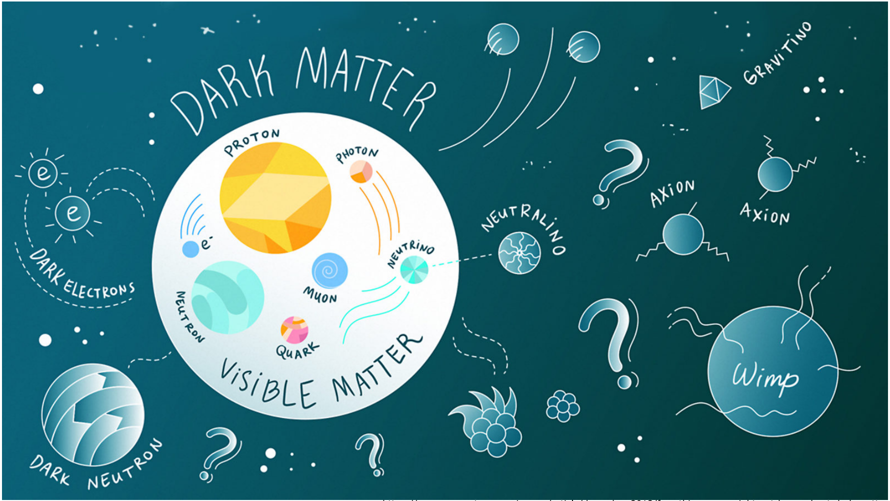
With T. Bringmann (University of Oslo) and J. Alvey (University of Amsterdam)

There is a strong evidence for something called "dark matter". But what is the nature of this matter?



https://www.symmetrymagazine.org/article/december-2013/four-things-you-might-not-know-about-dark-matter

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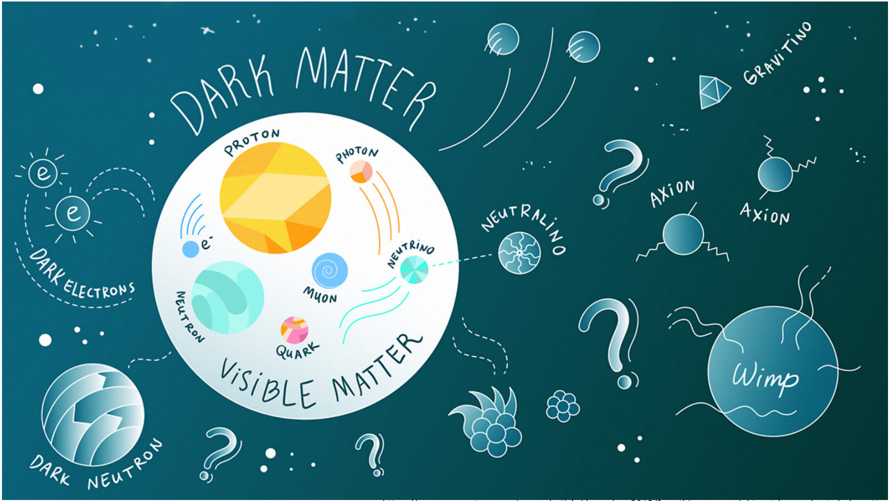


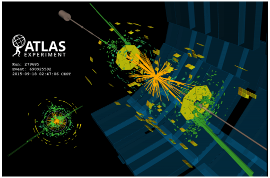
https://www.symmetrymagazine.org/article/december-2013/four-things-you-might-not-know-about-dark-matter

This talk: what it is NOT.

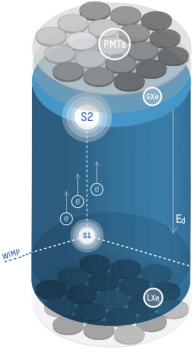
Outline

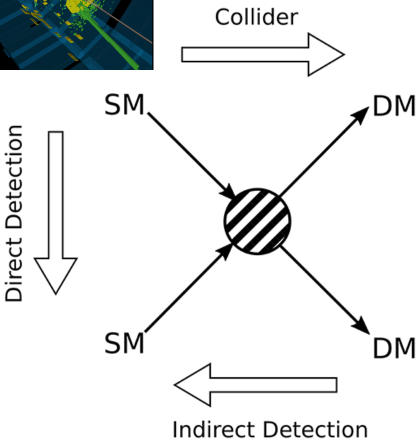
1. Standard dark matter detection techniques
2. Direct detection limits based on cosmic ray up-scattered dark matter
3. Improving ↑:
   - ✓ Improved treatment of attenuation in the Earth's crust
   - ✓ Taking into account specific DM models

Probing the nature of dark matter



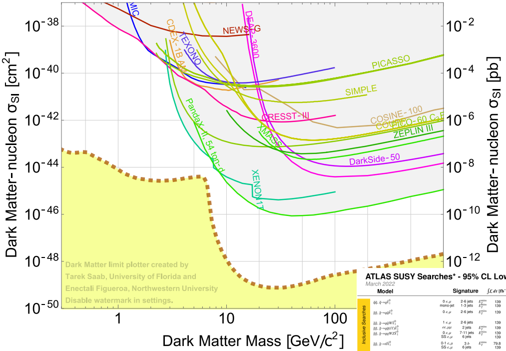
credit: wikipedia.org

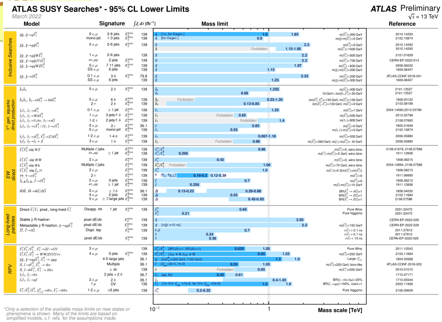




credit: fermi.gsfc.nasa.gov

Negative results up to now!





Direct detection experiments

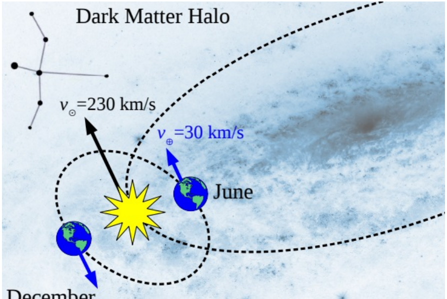
- Velocity distribution of DM particles in the halo:

$$f(v) \simeq N\, e^{v^2/v_0^2}\, \theta(v - v_{\rm esc})$$

with $v_0 \simeq 220\,\mathrm{km/s}$ and $v_{\rm esc} \simeq 544\,\mathrm{km/s}$

- Moreover, the Earth is moving with respect to the DM halo:

$$v_{\rm E} \simeq 230\,\mathrm{km/s} + (15\,\mathrm{km/s}) \cos[\omega(t - t_0)]$$



credit: Schumann (1903.03026)

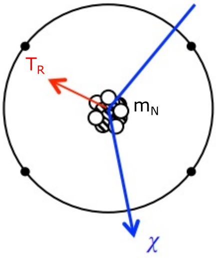
Direct detection experiments: kinematics

- Experiments search for nuclear recoils of halo dark matter
- Detectable signal for $T_R \sim \mathcal{O}(\text{keV})$

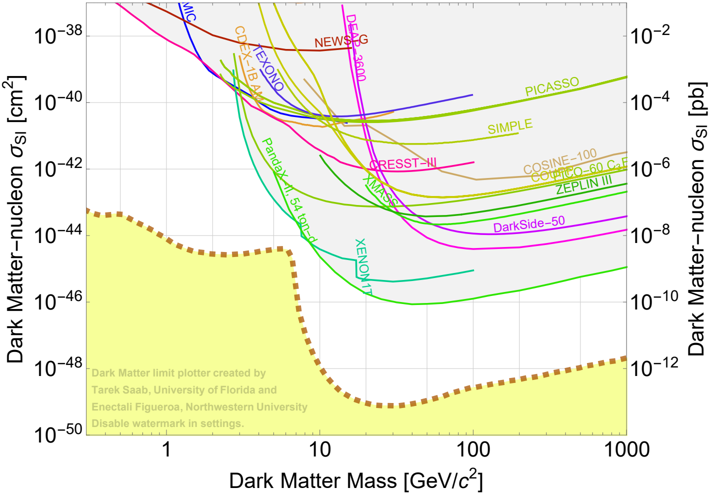
$\Rightarrow$ Minimal velocity for DM particle to be detectable:

$$v_{\min} = \sqrt{\frac{m_N T_R}{2\mu_{\chi N}^2}} \quad \left\langle \begin{array}{l} m_\chi \gg m_N : 21.2\,\text{km/s}\,\sqrt{\frac{T_R}{\text{keV}}}\sqrt{\frac{100\,\text{GeV}}{m_N}} \\ m_\chi \ll m_N : 2120\,\text{km/s}\,\frac{\text{GeV}}{m_\chi}\sqrt{\frac{T_R}{\text{keV}}}\sqrt{\frac{m_N}{100\,\text{GeV}}} \end{array} \right.$$

($\mu_{\chi N}$: reduced mass of the DM-nucleus system)



Standard Direct Detection limits



Direct detection experiments: DM-nucleus cross section

- Spin-independent cross section: scalar or vector effective Lagrangian

$$\mathcal{L}_S \sim \bar{\chi}\chi\bar{q}q \quad \text{or} \quad \mathcal{L}_V \sim \bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$$

↪ contributions of individual nucleons σ_n^{SI} sum coherently:

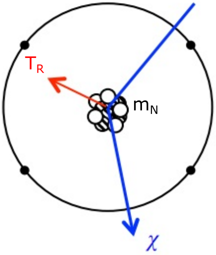
$$\sigma_N^{\mathrm{SI}} = \sigma_n^{\mathrm{SI}} \frac{\mu_{\chi N}^2}{\mu_{\chi n}^2} A^2$$

(assuming equal coupling of χ to proton and neutron, μ: reduced mass)

- Simplified differential cross section used for interpretation of the results:

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

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



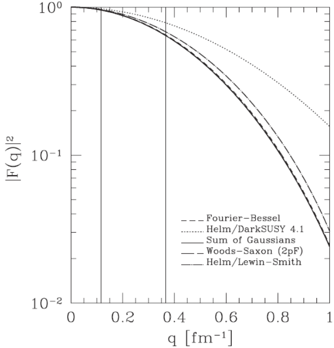
Nuclear form factors

- 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

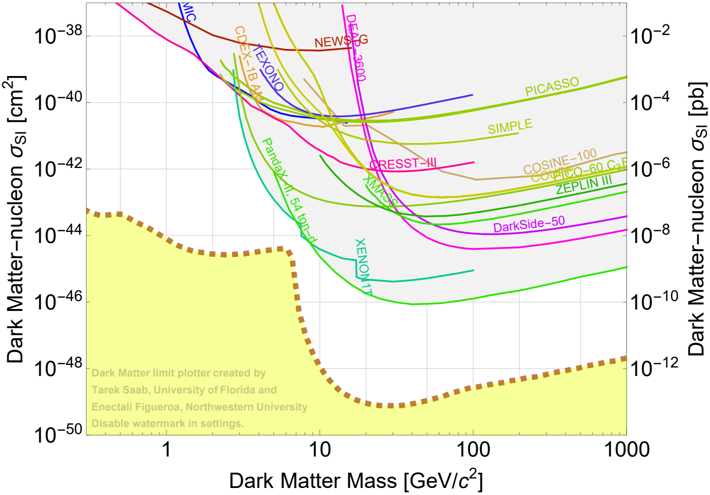
- Model independent form factors - more accurate than Helm form factors



[Duda et al.: JCAP04(2007)]

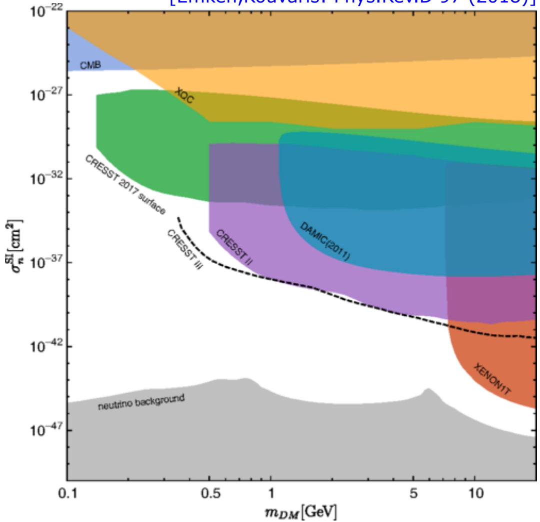
$d\sigma/dT_R \propto F^2(Q^2) \Rightarrow$ **suppression of the cross section for large** Q^2!

Standard Direct Detection limits



Standard Direct Detection limits

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



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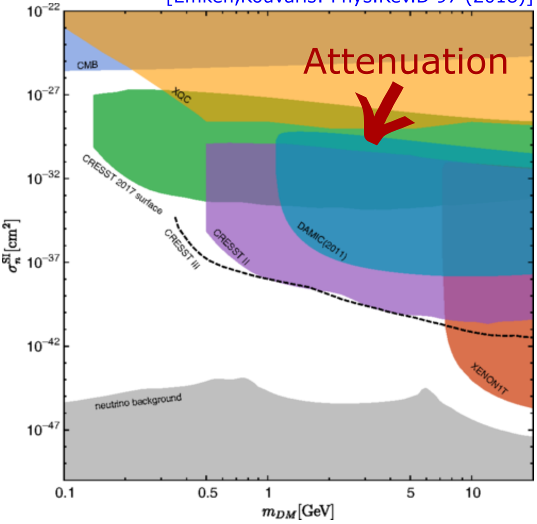

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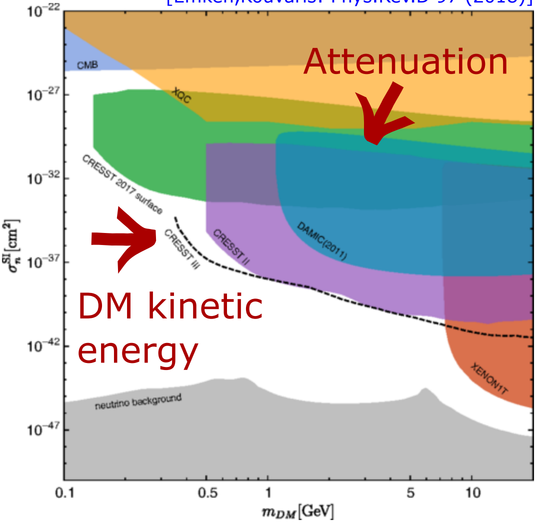

Window for strongly interacting dark matter?

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

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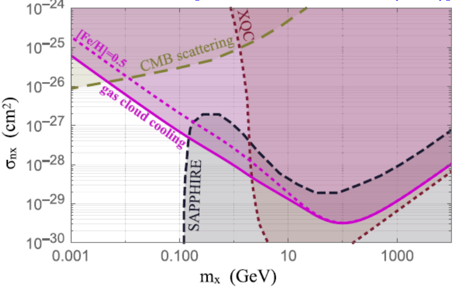

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- Gas cloud cooling [Bhoonah et al.: PRL 121 (2018) & PRD 100 (2019)]
- Updated constraints based on structure formation:
  - Milky Way satellite population [DES: PRL 126 (2021)]
  - Lyman alpha forest [Rogers et al.: PRL 128 (2022)]

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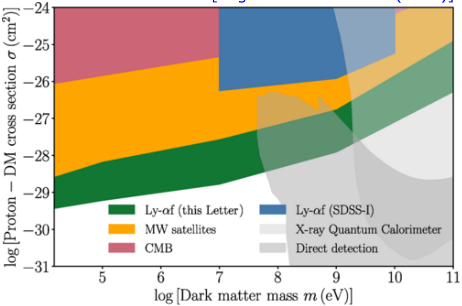

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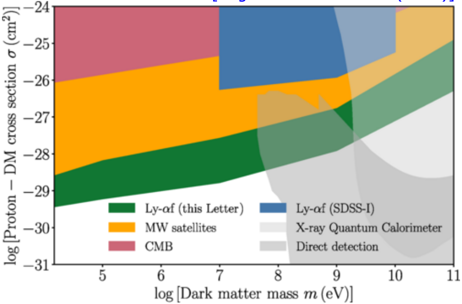
- Updated constraints based on structure formation:
  - Milky Way satellite population [DES: PRL 126 (2021)]
  - Lyman alpha forest [Rogers et al.: PRL 128 (2022)]
- Resonant scattering in case of strong attractive ineraction
  [Xu and Farrar: 2101.00142]
- Finite thermalization efficiency for experiments 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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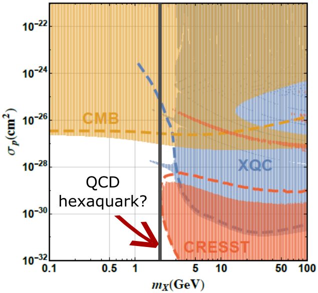
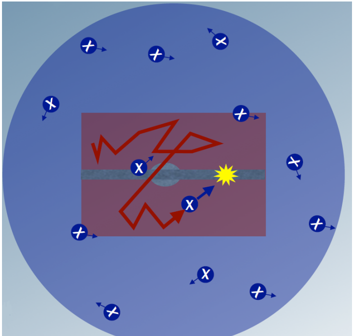


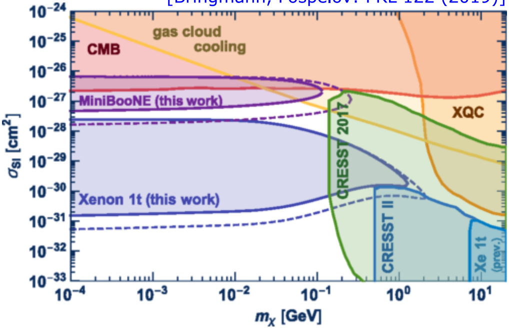
Cosmic ray up-scattered dark matter

- 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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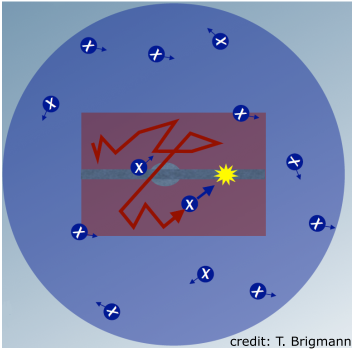

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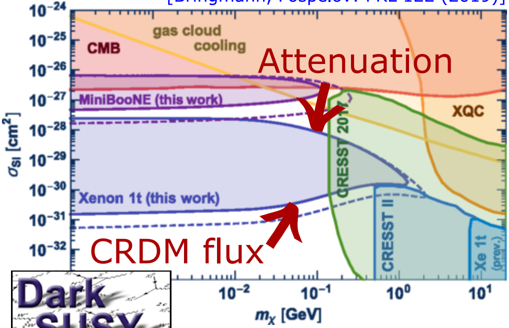
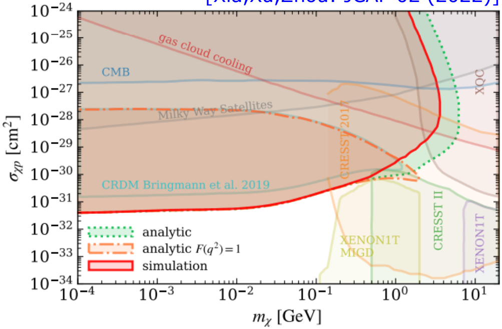


Cosmic ray up-scattered dark matter - updates

- 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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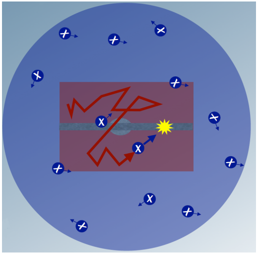
CRDM flux



Spacial integral — Sum over CR elements — CR kinetic energy

DM kinetic energy

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

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

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

CRDM flux

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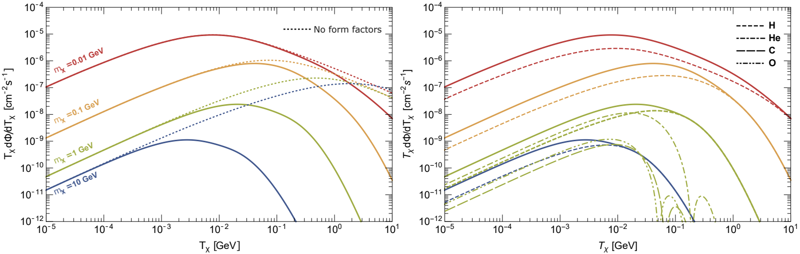


Attenuation in the Earth's crust

Energy loss equation:

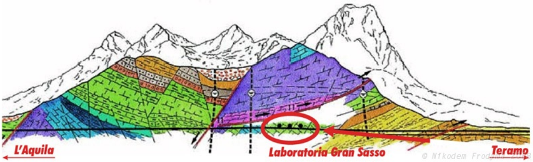
$$\frac{dT_\chi}{dz} = -\sum_N n_N \int_0^{\omega_\chi^{\max}} d\omega_\chi \, \frac{d\sigma_{\chi N}}{d\omega_\chi} \omega_\chi$$

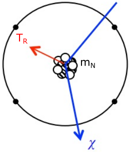
n_N - number density of nuclei N

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

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

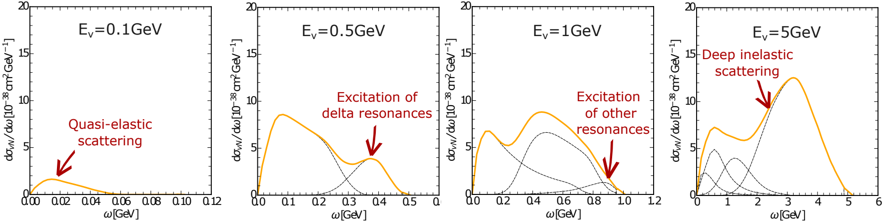
- Form factors ⇒ large suppression of stopping power for high-energy DM!
- Inclusion of inelastic scattering changes considerably the results!





Intermezzo: Inelastic scattering with nuclei

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



GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

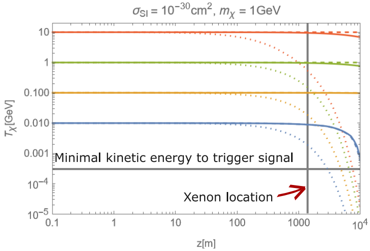
(dependence of neutrino-oxygen differential cross section per nucleon on energy transfer $\omega_\nu \equiv E_\nu - E'_\nu$ obtained by GiBUU code [gibuu.hepforge.org])

Effect of inelastic scattering on attenuation of DM flux

- 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!



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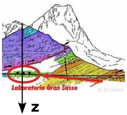
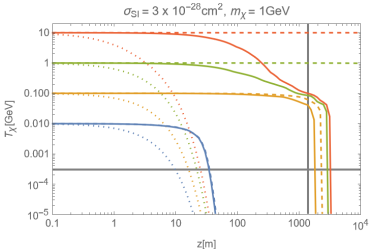
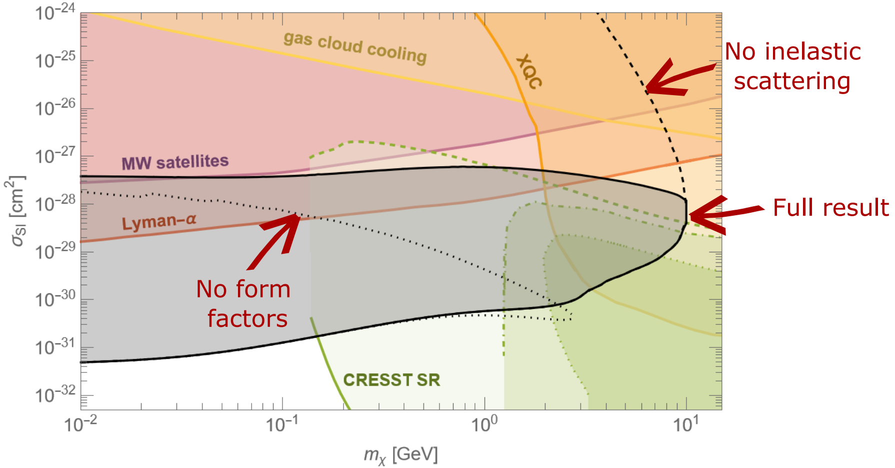




Xenon1T limits

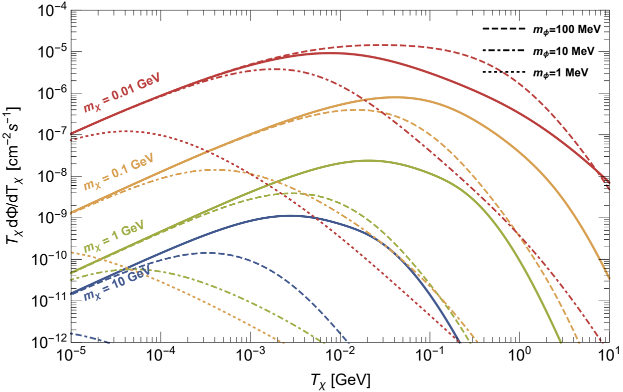


Q^2-dependent DM cross section

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

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

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



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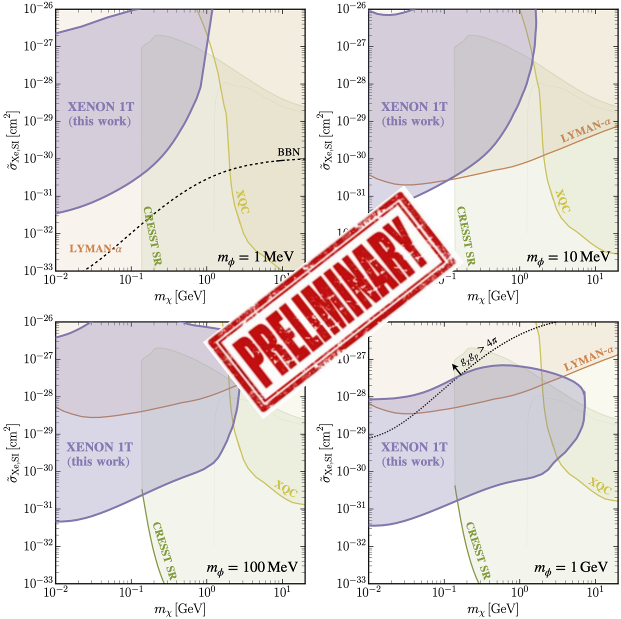
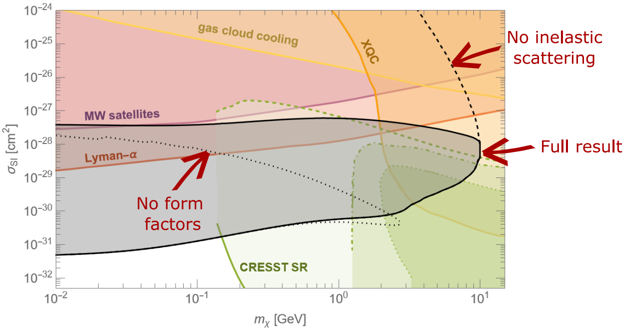


Conclusions

- 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



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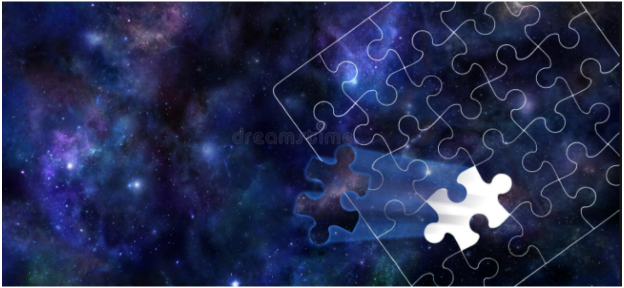
We know slightly better what dark matter is not like...



Thanks for attention!