Light Dark World, Karlsruhe, 20 September 2023

Dark matter up-scattered by cosmic rays

Closing the window of strongly interacting DM ?

Torsten Bringmann

Based on

TB & Pospelov, PRL '18

Bondarenko, Boyarsky, TB,
Hufnagel, Schmidt-Hoberg &
Sokolenko, JHEP '20

Alvey, TB & Kolešová, JHEP '23

UiO : University of Oslo

Direct detection in a nutshell

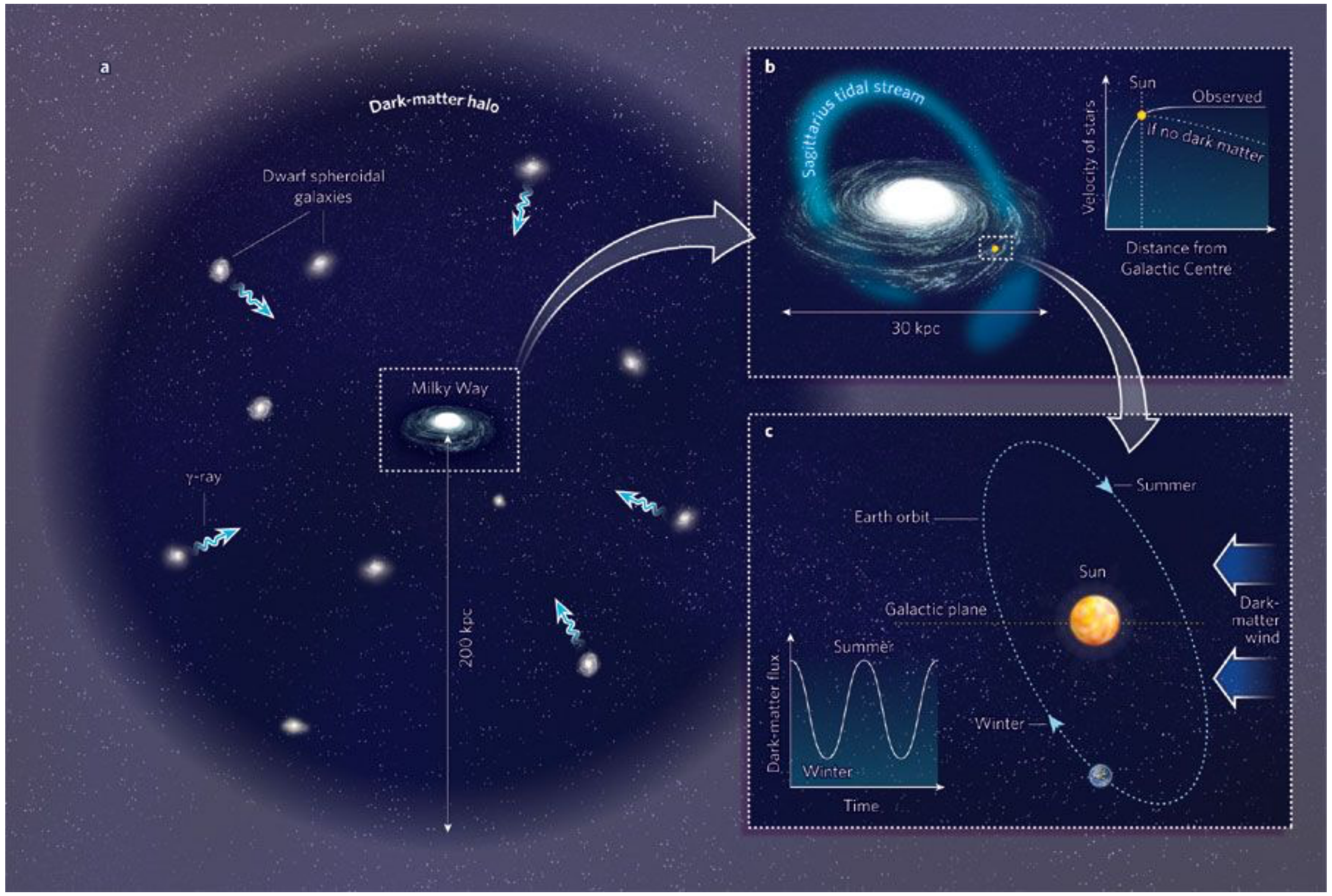
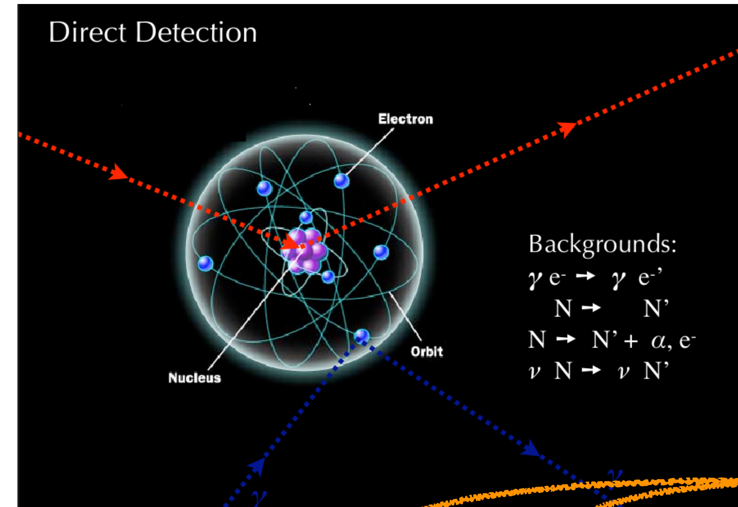


Fig.: Caldwell & Kamionkowski, Nature '09



astro input

$$\frac{dR}{dE_R} = \frac{\rho_\odot^\chi}{m_\chi m_N} \int_{v_{\min}}^{v_{\max}} \frac{d\sigma_{\chi N}}{dE_R} v f(v) dv$$

standard halo model:

$$f(v) \sim (\pi v_0^2)^{-\frac{3}{2}} e^{-\frac{\mathbf{v}^2}{v_0^2}} \qquad v_0 \sim 220\,\mathrm{km/s}$$

Recoil energy:

$$E_R = \frac{Q^2}{2m_N} = \frac{4 m_\chi m_N T_\chi}{(m_\chi + m_N)^2} \frac{1 - \cos\theta_{\mathrm{cm}}}{2} \Rightarrow \boxed{v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}}}$$

$m_\chi \gg m_N$:

$$21.2\,\frac{\mathrm{km}}{\mathrm{s}} \times \left(\frac{E_R}{\mathrm{keV}}\right)^{\frac{1}{2}} \left(\frac{m_N}{100\,\mathrm{GeV}}\right)^{-\frac{1}{2}}$$

$\ll v_0 \rightsquigarrow$ *sample full* $f(v)$

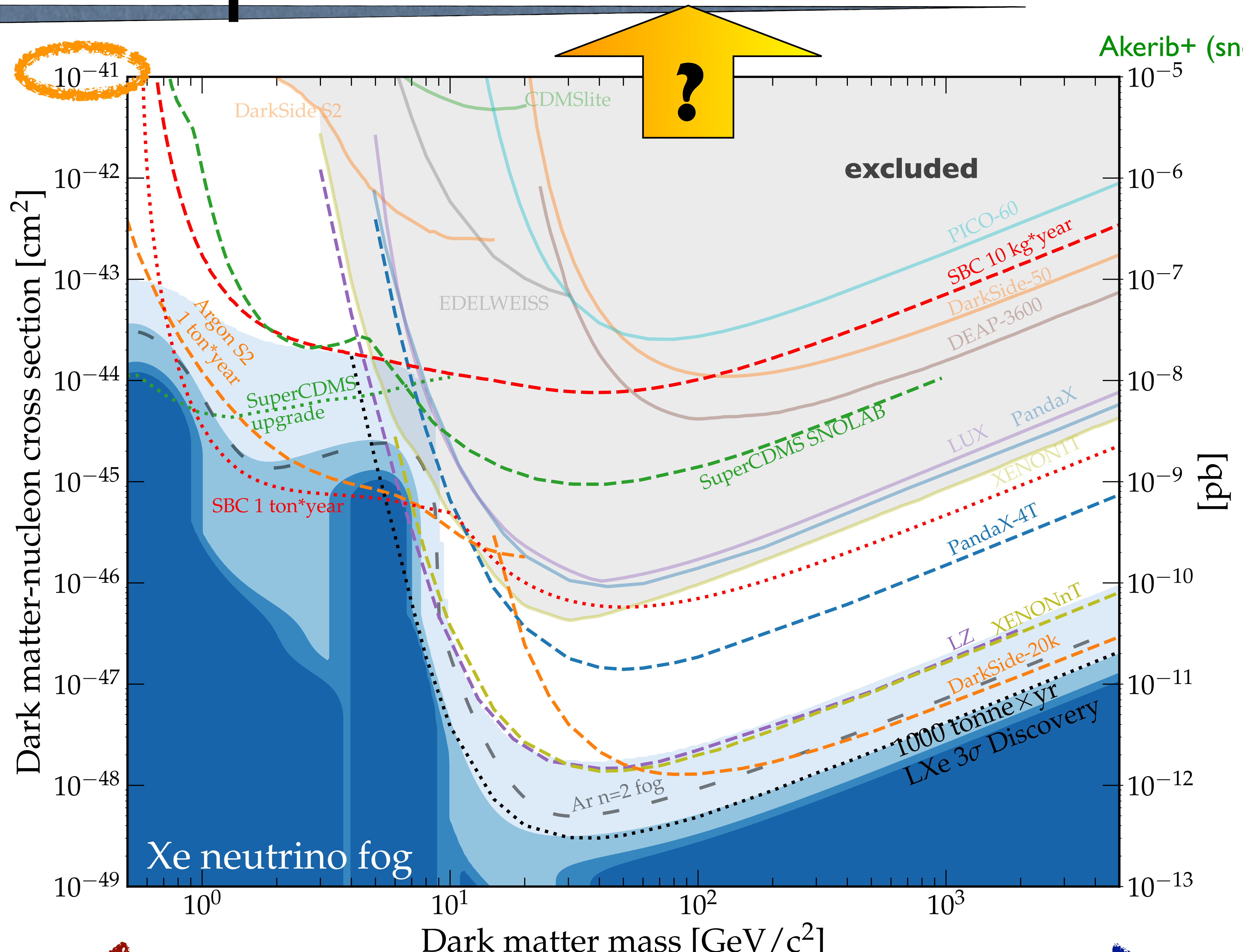
$m_\chi \ll m_N$:

$$2120\,\frac{\mathrm{km}}{\mathrm{s}} \times \left(\frac{m_\chi}{\mathrm{GeV}}\right)^{-1} \left(\frac{E_R}{\mathrm{keV}}\right)^{\frac{1}{2}} \left(\frac{m_N}{100\,\mathrm{GeV}}\right)^{\frac{1}{2}}$$

$\gg v_0 \rightsquigarrow f(v)$ *exp. suppressed*

A vast experimental effort

Akerib+ (snowmass2021), 2203.08084



Need lower threshold

$v_{\min} \gg v_0$

(rate exponentially suppressed)

$v_{\min} \ll v_0$

(rate $\propto n_\chi \propto m_\chi^{-1}$)

Need higher exposure (mass)

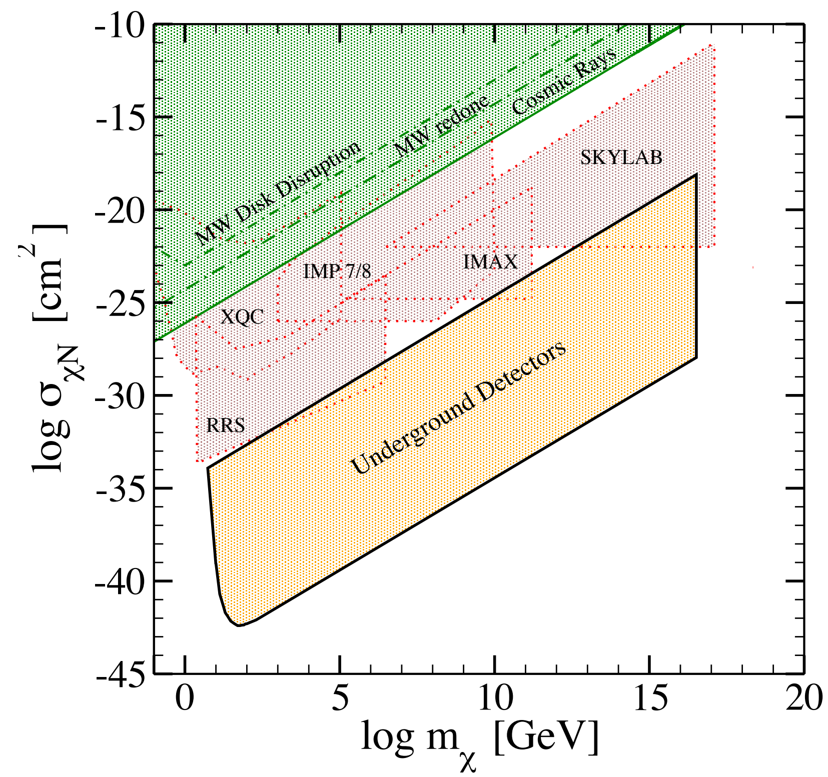
Strongly interacting dark matter ?

- Dark matter scattering too efficiently with nucleons would not reach the detector!

  Starkman, Gould, Esmailzadeh & Dimopoulos, PRD '90

  - Possibility of unconstrained window of strongly interacting dark matter ?

    Zaharijas & Farrar, PRD '05
    Mack, Beacom & Bertone, PRD '07
    ...



- Simplest approach: model continuous loss of *average* energy down to detector location

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

ω_χ : DM energy loss per collision
= nuclear recoil energy

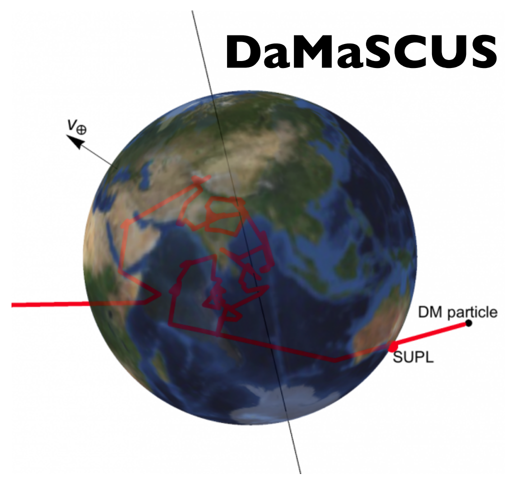
⇨ exponential suppression, with mean free path $\ell \sim \left(\sum_N n_N \sigma_{\chi N} \right)^{-1}$

Simulations

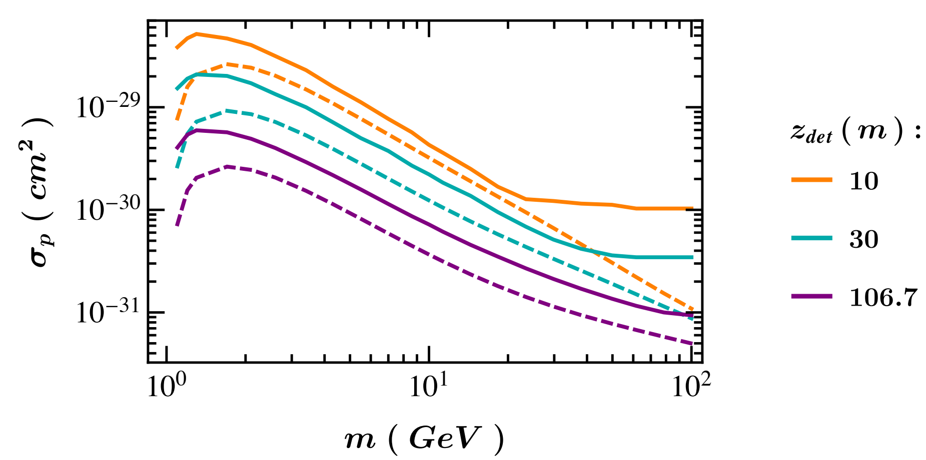
- Analytic approach rather simplistic:
  - particles do not only arrive from azimuthal direction
  - multiple scatterings in overburden
  - (high-energy tail has higher penetration power)
  - …

E.g. Emken & Kouvaris, PRD ‘18

- In principle, full simulations needed:



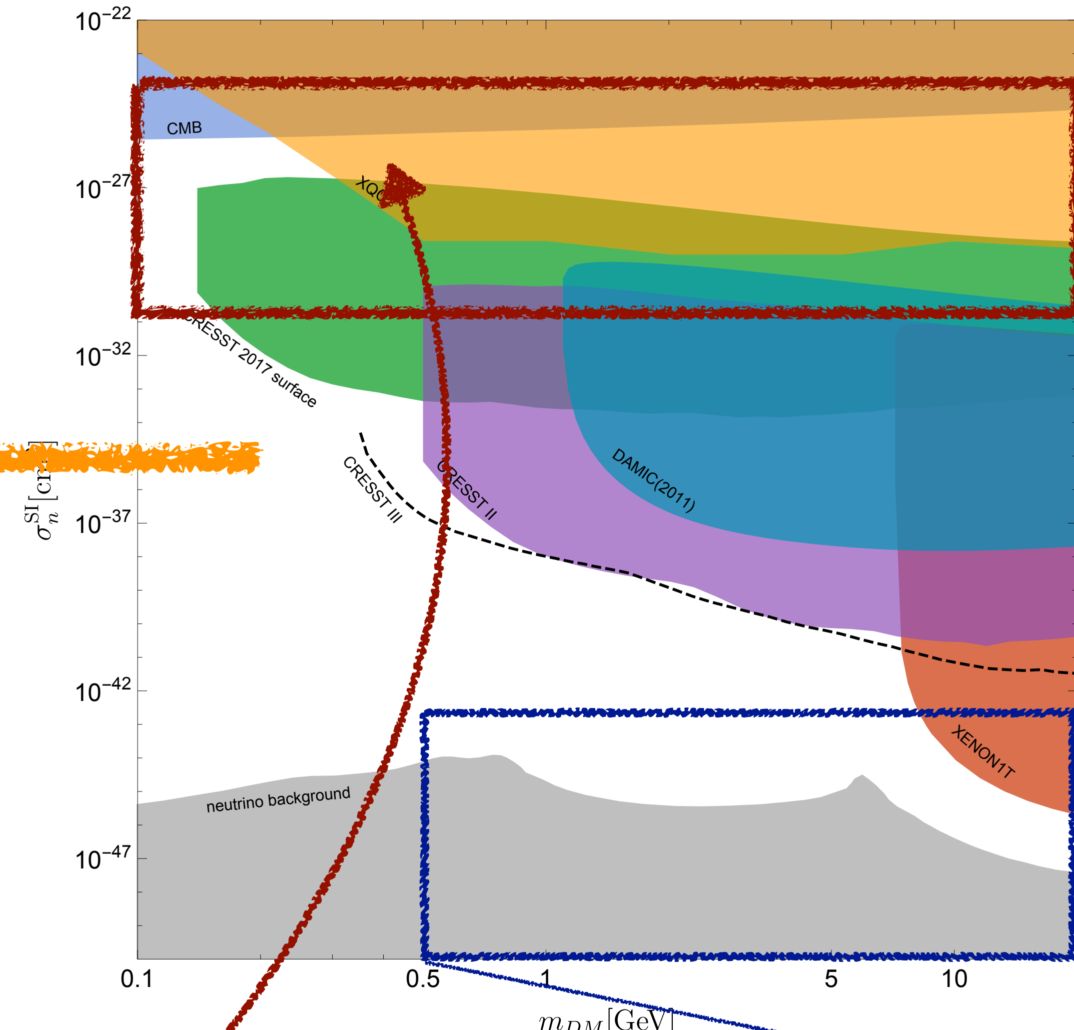
Emken & Kouvaris, JCAP ‘17



Mahdawi & Farrar, 1712.01170

- Stopping power in overburden typically *less* efficient
  - actual (upper) exclusion region increases by a factor of ~few
  - disclaimer: this relies on *constant* scattering cross sections, less clear otherwise…

Status at low masses / large interactions

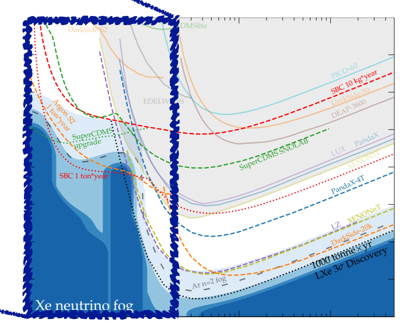


DaMaSCUS

+ CRESST / Xenon

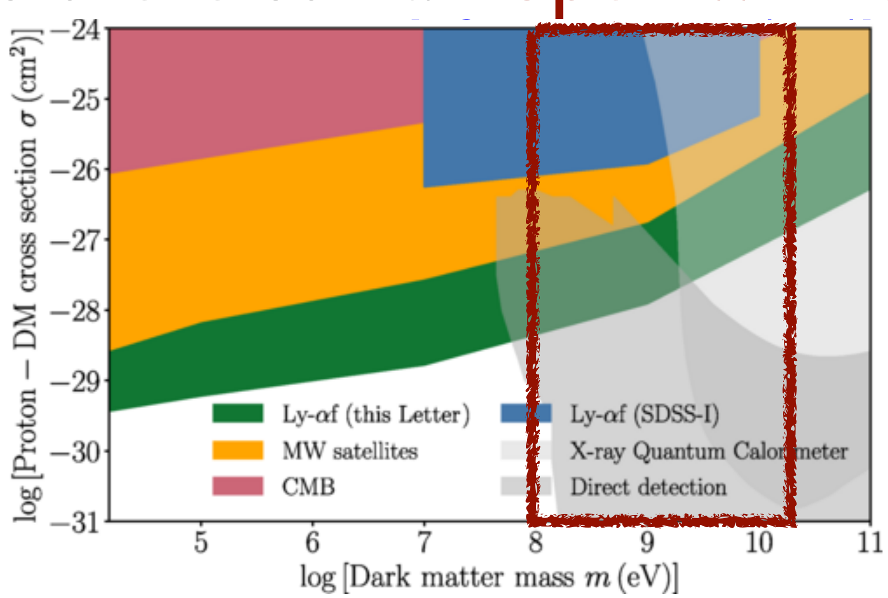
Emken & Kouvaris, PRD '18

would need larger DM momenta to probe this region!

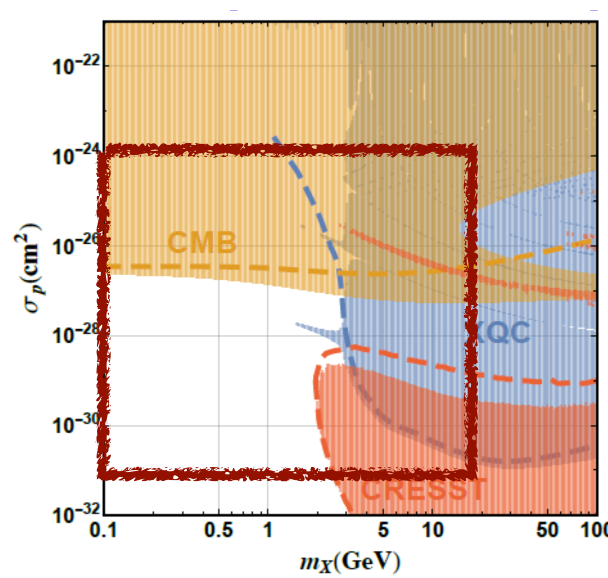


(snowmass overview)

- Is there still an open window ?



Rogers+, PRL '22



Xu & Farrar, 2101.00142

The dark matter + diffusive halo

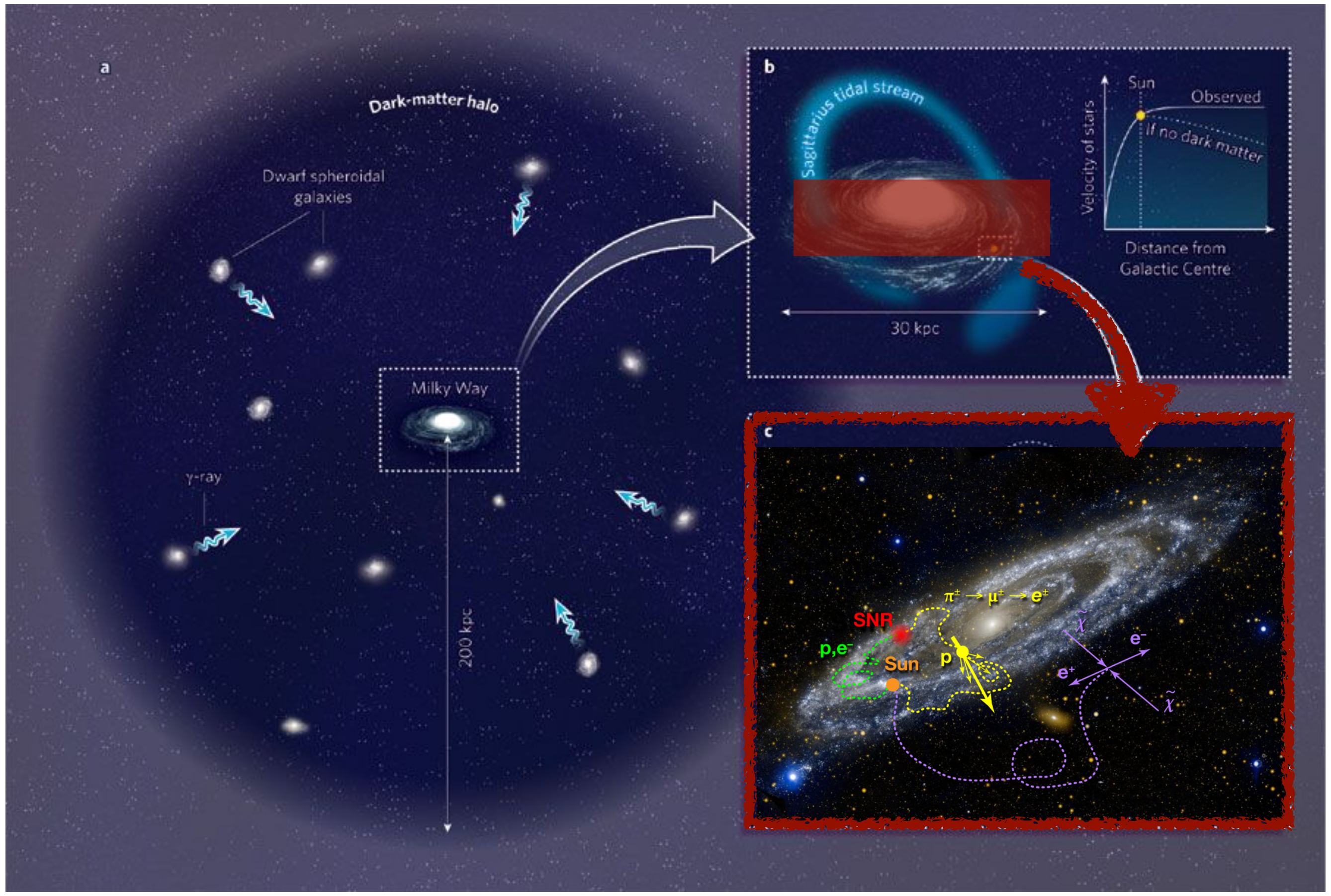
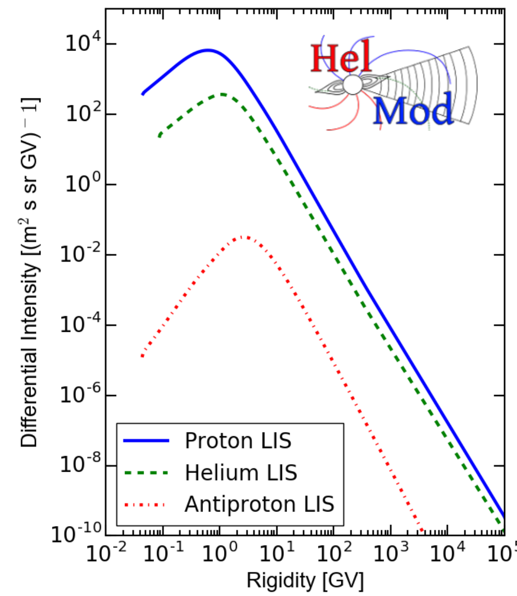
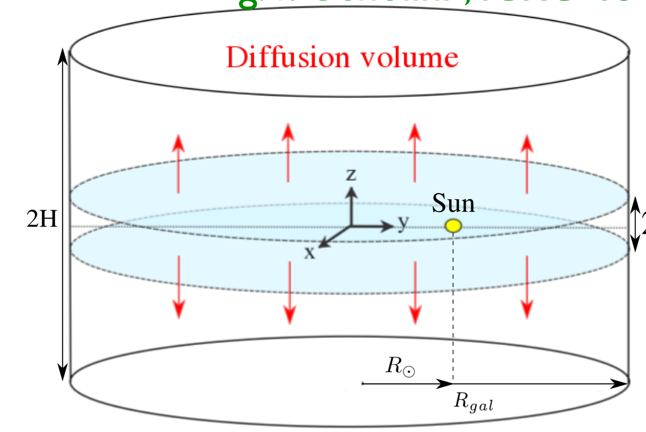


Fig.: Caldwell & Kamionkowski, Nature '09



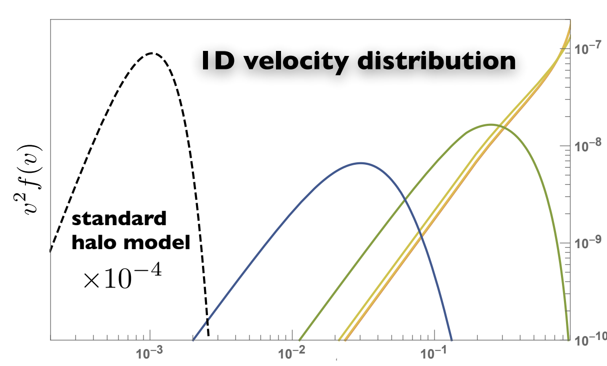
- Local interstellar flux well constrained by Voyager, AMS, …

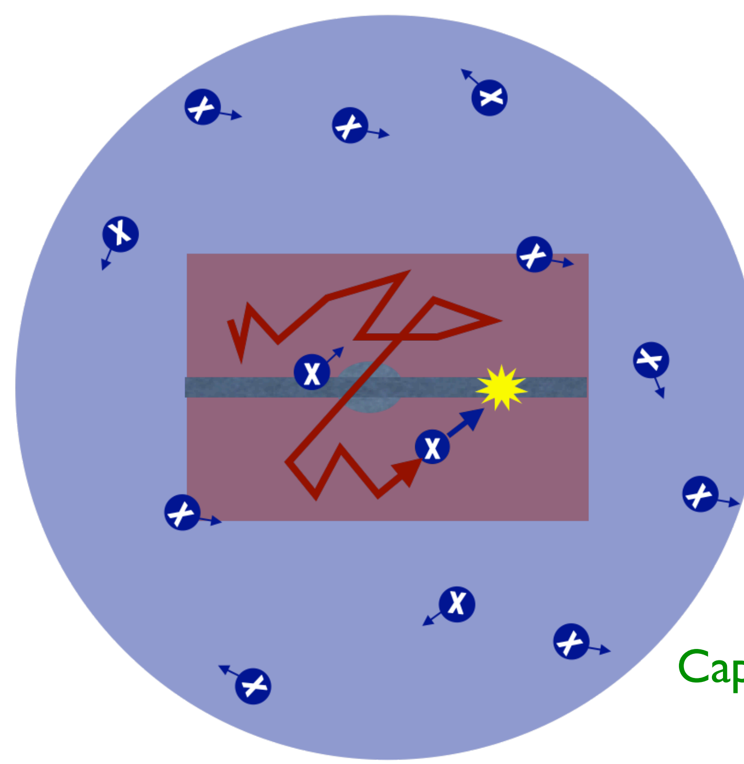
Fig: Y. Genolini , ICRC '15



- Below ~1 PeV, cosmic rays confined by magnetic fields

- This leads to an inevitable **CRDM** component
  - very high velocities
  - ~isotropic





'reverse direct detection'

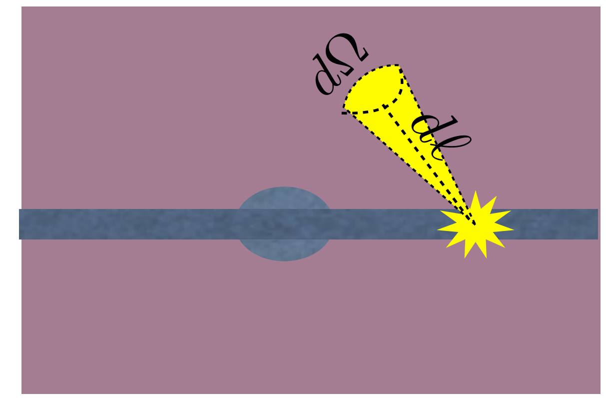
TB & Pospelov, PRL '18
Cappiello, Ng & Beacom, PRD '19

CRDM flux

- Differential flux at top of the atmosphere (TOA)

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

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



~10 kpc — single parameter captures well astrophysical uncertainties TB & Pospelov, PRL '18
Xia, Xu & Zhou, JCAP '22

Recoil energy of DM particle initially at 'rest':

$$T_\chi = T_\chi^{\max}\frac{1-\cos\theta_{\mathrm{cm}}}{2},\quad T_\chi^{\max} = \frac{T_i^2 + 2m_iT_i}{T_i + (m_i+m_\chi)^2/(2m_\chi)} \quad \rightsquigarrow T_i^{\min}(T_\chi) \;\widehat{=}\; v_{\min}(E_R) \text{ in standard DD}$$

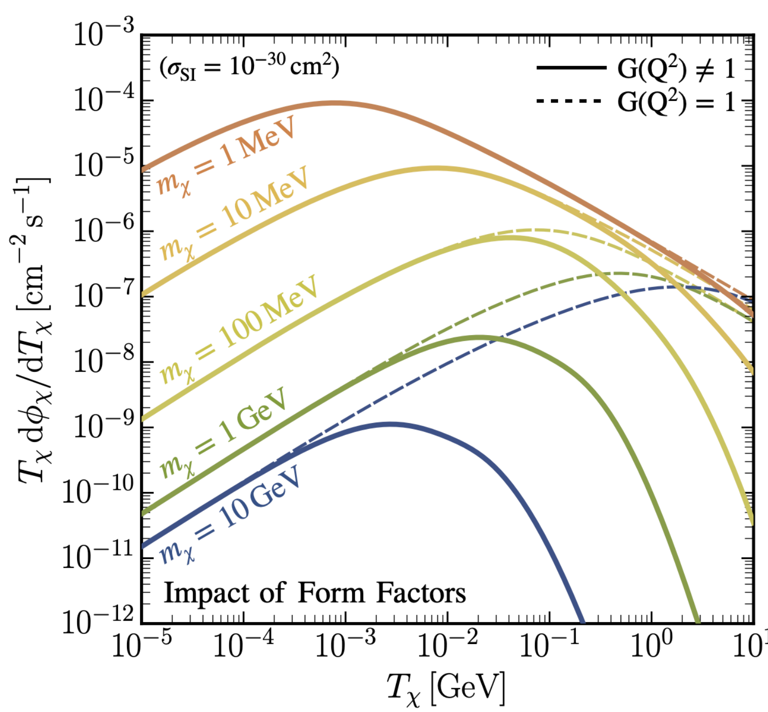
additional terms compared to corresponding (non-rel.) DD expression

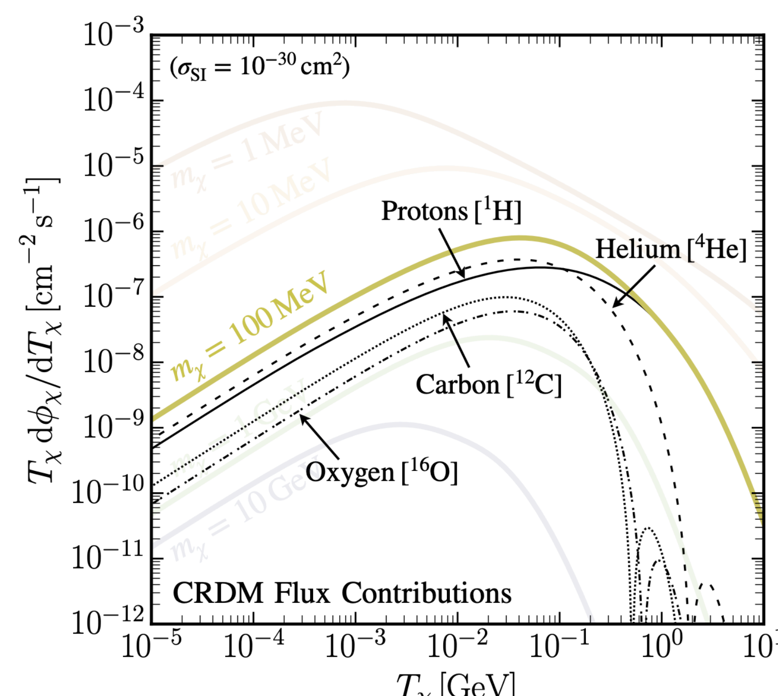
- Recent updates

Alvey, TB & Kolesova, JHEP '23

  - More CR elements
  - Updated CR spectra
  - Improved treatment of form factors

DarkSUSY





… commercial break …

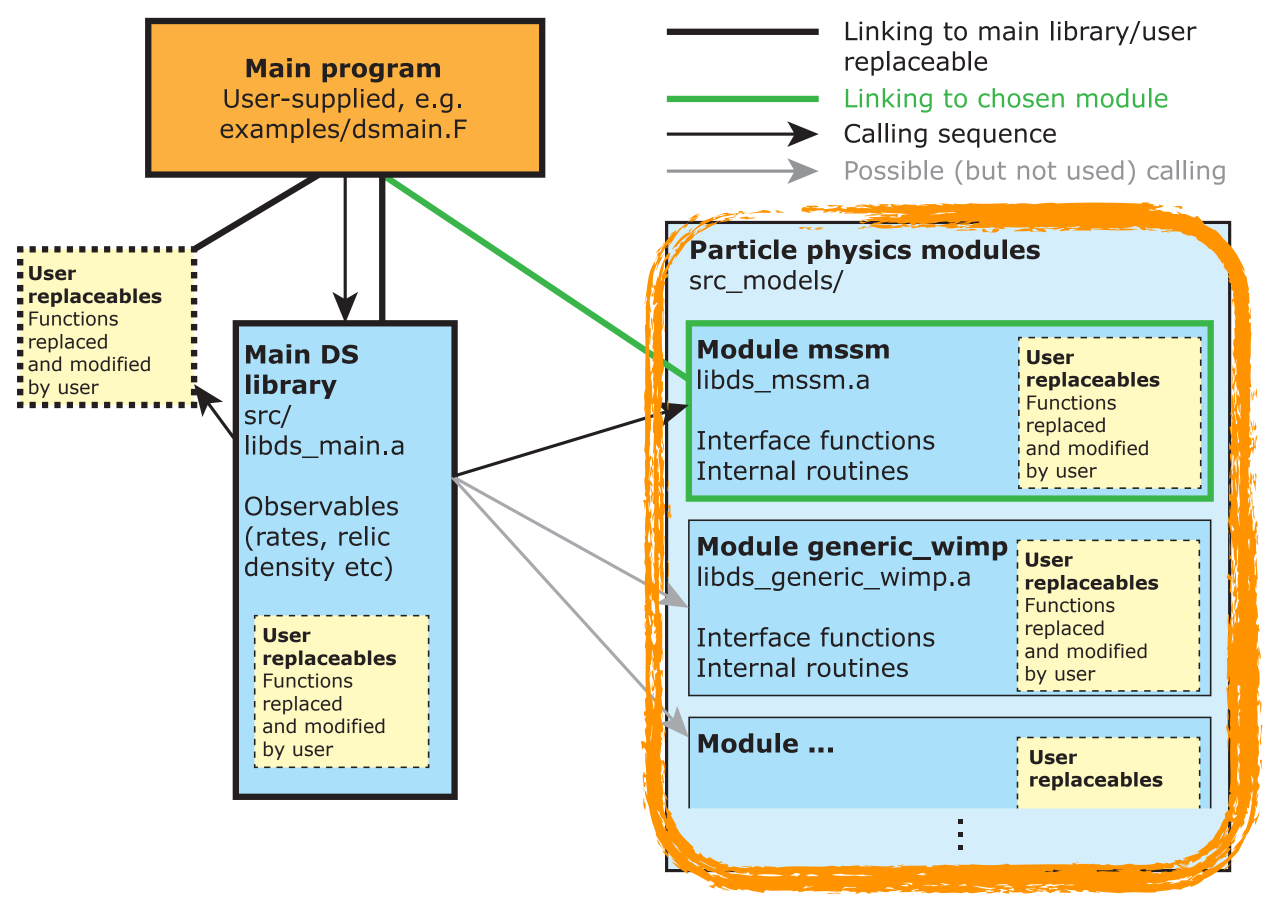
DarkSUSY

TB, Edsjö, Gondolo, Ullio & Bergström, JCAP '18

http://www.darksusy.org

Since 2018 (v6): no longer restricted to supersymmetric DM !

- Numerical package to calculate 'all' DM-related observables:
  - *precision relic density & kinetic decoupling*
  - *cosmic ray propagation*
  - *large database of particle yields for generic DM annihilation or decay*
  - *indirect detection rates: gammas, positrons, antiprotons, neutrinos*
  - *direct detection rates*
  - *DM self-interactions*
  - *general dark sector support:* $T_{\rm dark}(T_\gamma), \Delta N_{\rm eff}, \ldots$
  - …



most recent new features:
…
v6.2: cosmic-ray upscattered DM
v6.3: freeze-in
v6.4: asymmetric DM

From TOA flux to detector rates

- Follow standard approach for attenuation of TOA flux, but extend to fully relativistic kinematics

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

- Recoil rate in experiment:

$$\boxed{\frac{d\Gamma_N}{dT_N} = \int_{T_\chi(T_\chi^{z,\min})}^{\infty} dT_\chi \frac{d\sigma_{\chi N}}{dT_N}\frac{d\Phi_\chi}{dT_\chi}}$$

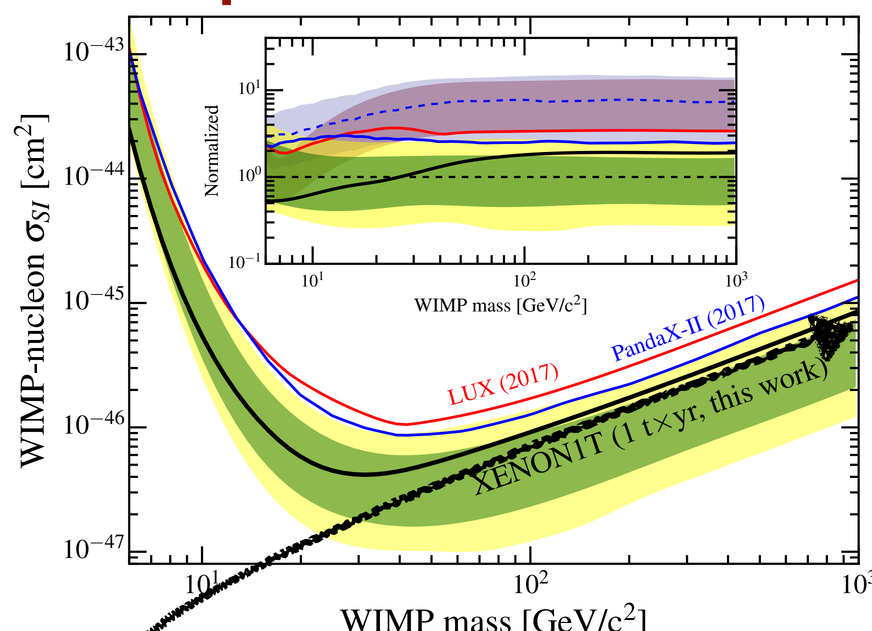
NB: For constant cross section

- no T_χ dependence
- dependence on $Q^2 = 2m_N T_N$ identical to NR case

➡ ***straight-forward to re-interpret published limits!***

TB & Pospelov, PRL '18

- Example: Xenon 1t



- expected rate for high masses:

$$\Gamma = \int dT_{\rm Xe}\left(\frac{d\Gamma}{dT_{\rm Xe}} = \frac{\rho_\odot^\chi}{m_\chi m_N}\int_{v_{\min}}^{v_{\max}} \frac{d\sigma_{\chi N}}{dT_{\rm Xe}} v f(v) dv\right)$$

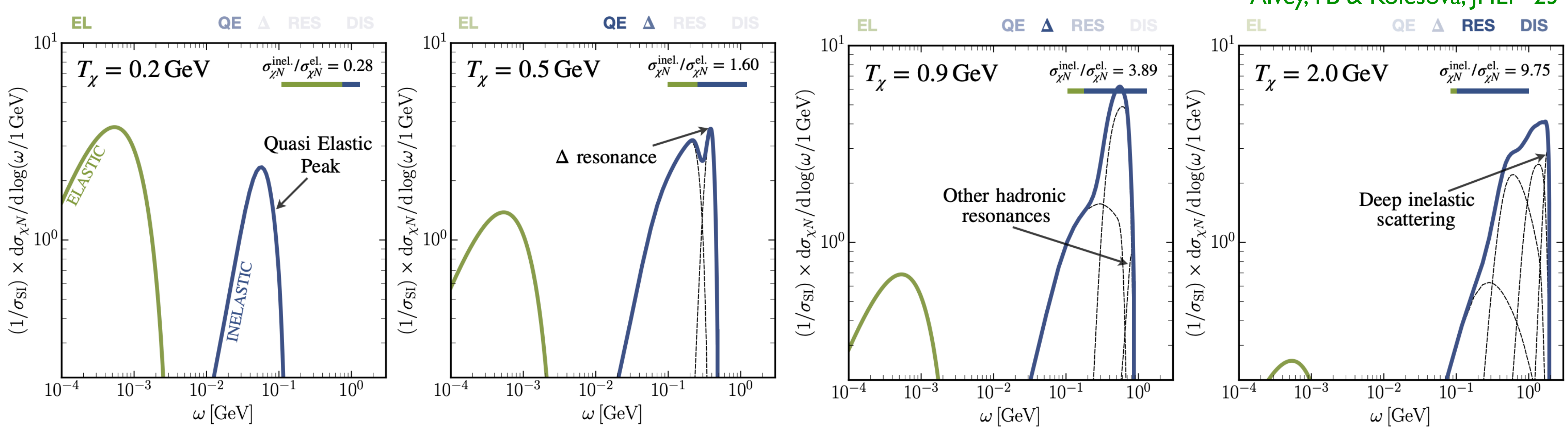
$$\xrightarrow[m_{\rm DM} \gg m_N]{} \boxed{\kappa \frac{\sigma_{\chi N}^{\rm DM}}{m_{\rm DM}} (\bar v\, \rho_{\rm DM})^{\rm local}}$$

Inelastic scattering

- Inelastic scattering increasingly important at higher energies
- In general complicated, model-dependent
- Gain inspiration from neutrino scattering on nuclei
  - Focus on neutral current interactions
  - public GiBBU code
  - Idea: keep ratio of inelastic to elastic contribution
  - identify characteristic momentum transfer Q^2 per sub-process

GiBUU gibuu.heforge.org
The Giessen Boltzmann-Uehling-Uhlenbeck Project

Alvey, TB & Kolesova, JHEP '23



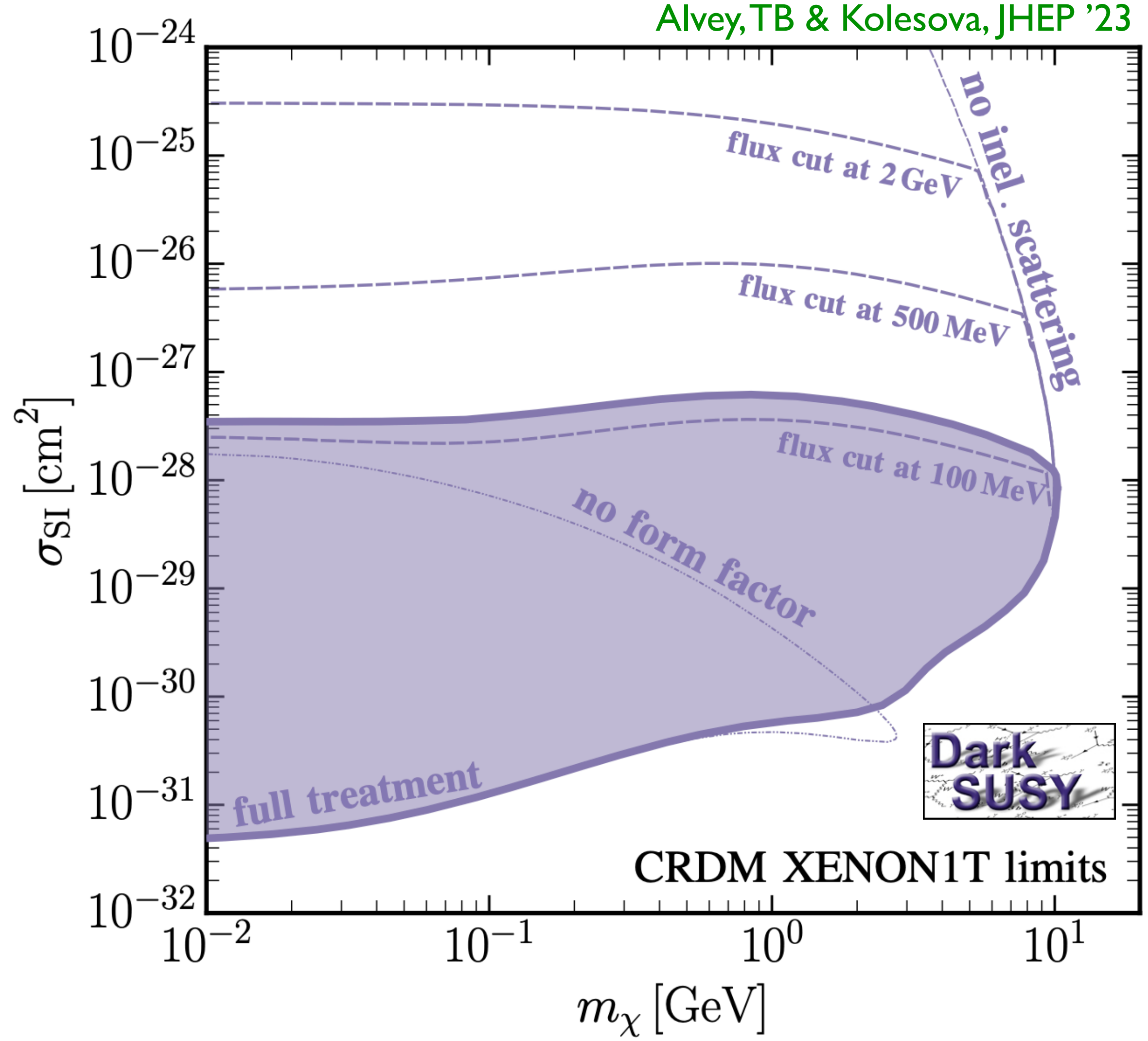
ω: energy loss

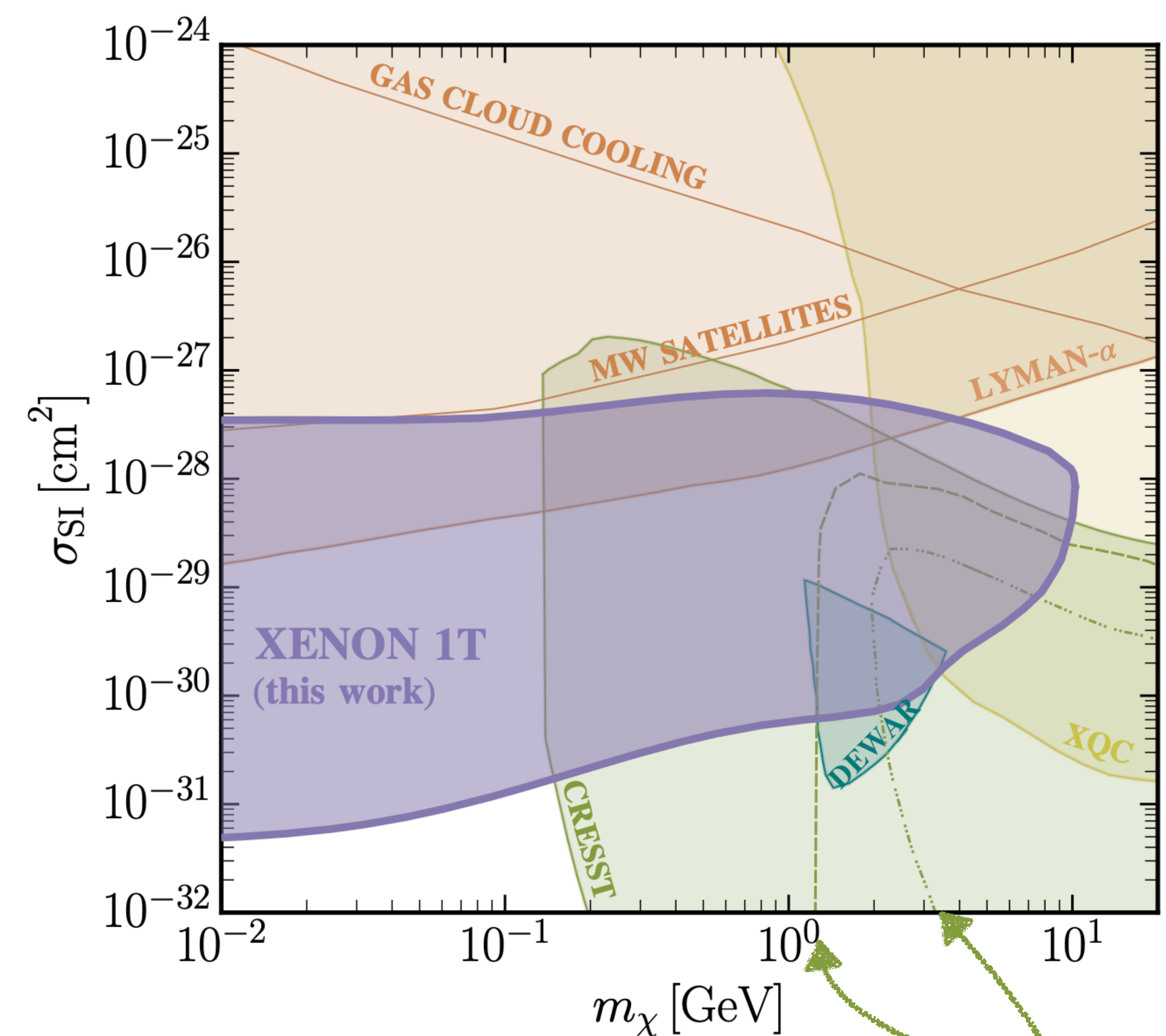
Resulting limits

- As expected, DM mass no longer an issue for relativistic particles
  - even ~MeV recoils possible $\rightsquigarrow$ can use neutrino detectors for direct DM detection!

TB & Pospelov, PRL '18

Alvey, TB & Kolesova, JHEP '23





CRESST limits re-interpreted by Farrar+

- Neglecting form factor suppression too conservative…
- …but inelastic scattering (at high Q^2) is very efficient

Concrete models

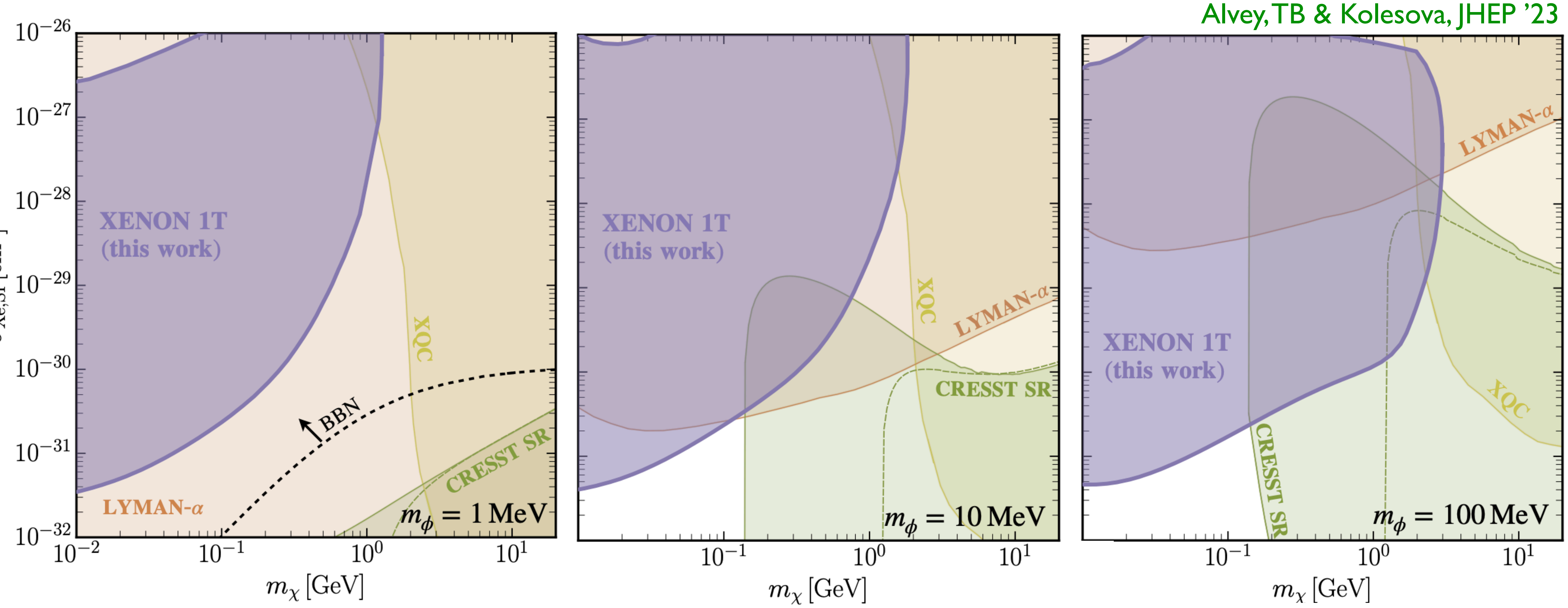
- 'constant' cross section unrealistic
  - Standard benchmark for *non-relativistic* scattering…
  - …but low mass DM & effective operators are ruled out by LHC

E.g. Athron+, EPJC '21

- E.g. light mediators
  - Suppression of high-E attenuation — but also of CRDM production
  - Important to use full relativistic expression for cross section (e.g. scalar vs. vector mediator)

$$\sigma \propto \frac{m_\phi^4}{(Q^2 + m_\phi^2)^2}$$

Alvey, TB & Kolesova, JHEP '23



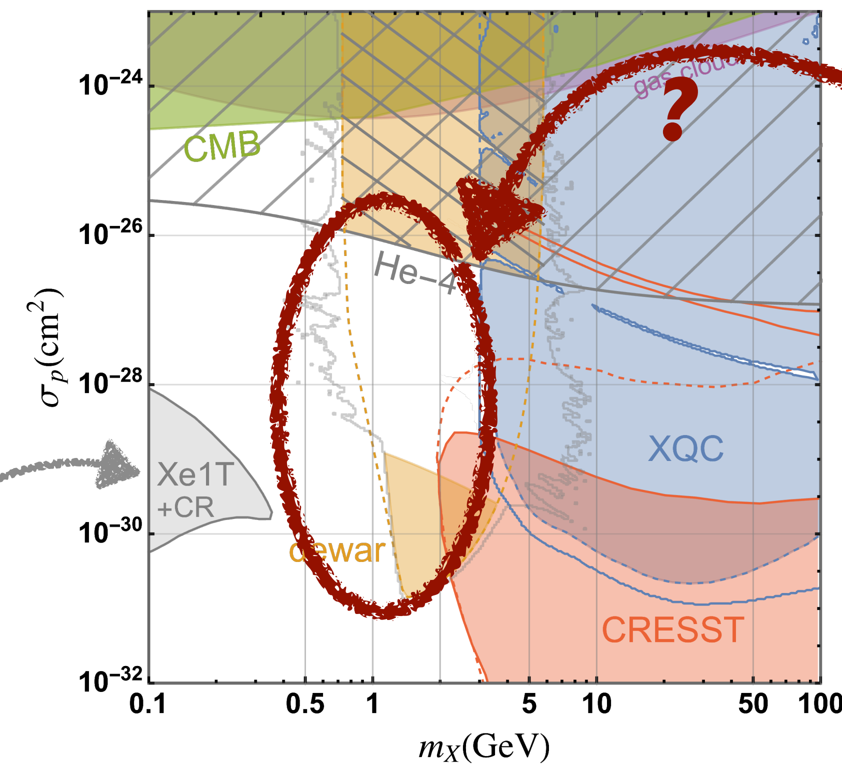
cross section at reference momentum

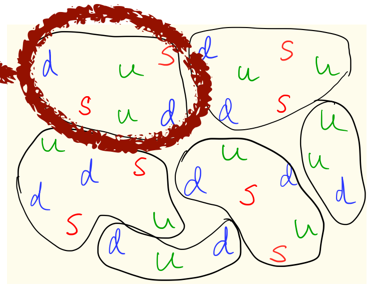
$Q_{\mathrm{Xe,ref}} = 35\,\mathrm{MeV}$

scalar mediator

Hexaquark dark matter

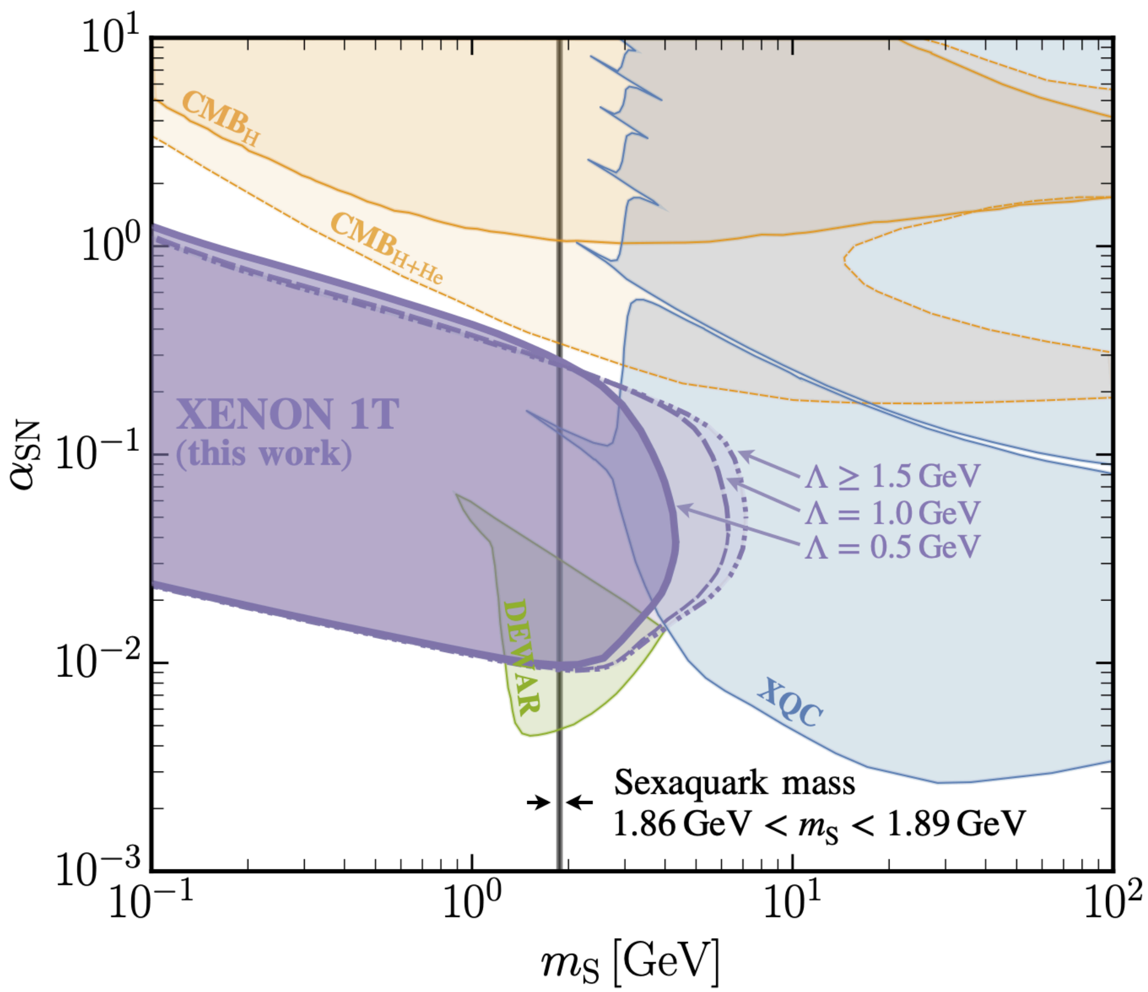
- A loophole to realize baryonic DM ? Farrar+, 03-22





Xu & Farrar, 2112.00707

NB: CRDM limits assuming no form factor suppression!

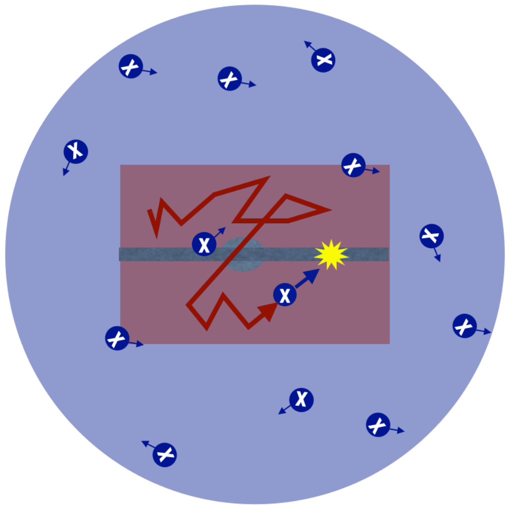


Alvey, TB & Kolesova, JHEP '23

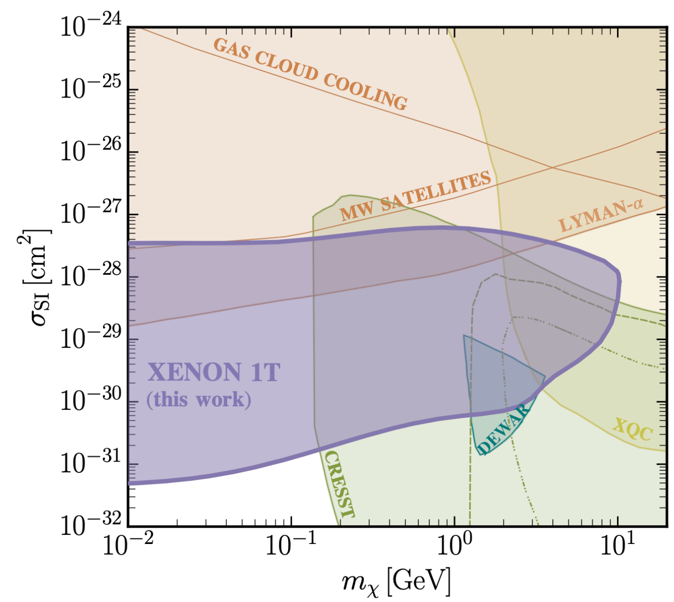
➡ Increasingly difficult for *any* such DM candidate to 'hide' in this region…!

Conclusions

- Cosmic rays inevitably produce a subdominant, relativistic component of Galactic DM



- This places highly complementary limits for light as well as strongly interacting DM



- Want to explore these effects yourself (and much more)? Download DarkSUSY! 😉

Thanks for your attention!

Elastic scattering cross section

- Spin-independent interactions couple to nuclear ***mass***
  (from scalar, vector and tensor couplings)

$$\sigma_N^{\rm SI} \sim \sigma_p^{\rm SI} \left(\frac{\mu_{\chi N}}{\mu_{\chi p}}\right)^2 [Z f_p + (A-Z) f_n]^2 \xrightarrow{f_p = f_n} \boxed{\sigma_N^{\rm SI} = \sigma_\chi^{\rm SI} A^2 \left(\frac{m_N (m_\chi + m_p)}{m_p (m_\chi + m_N)}\right)^2}$$

per **nucleus** (measured)

per **nucleon** (reported limit)

➡ coherent enhancement of A^2 to A^4 !

- Spin-dependent interactions couple to nuclear ***spin***
  (from axial-vector couplings)

$$\boxed{\sigma_N^{\rm SD} \sim \mu_{\chi N}^2 G_F^2 \frac{S_N + 1}{S_N} \left[a_p \langle S_p \rangle + a_n \langle S_n \rangle\right]^2}$$

- Form-factor *(or spin-structure function)* suppression for large momentum transfer

$$\boxed{\sigma_N \to \sigma_N^{q=0} \times G_N(q^2)}$$