Cosmic ray boosted dark matter

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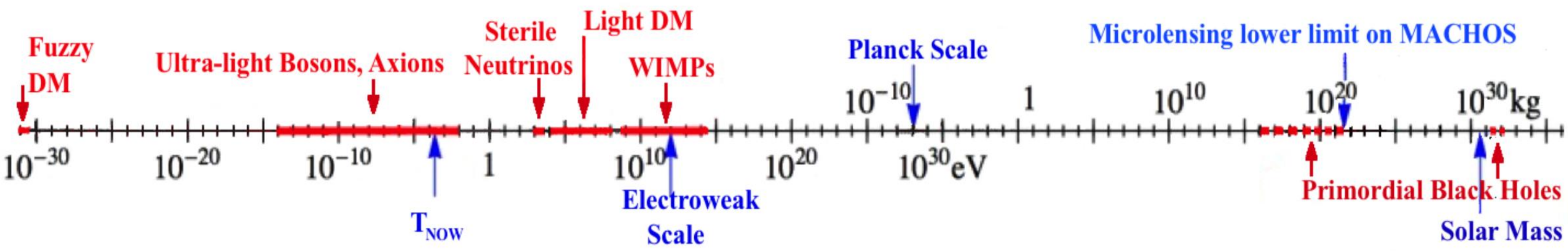
Yan-Hao Xu, Chen Xia, YFZ,
arXiv:2009.00353, arXiv:2111.05559, arXiv:2206.11454

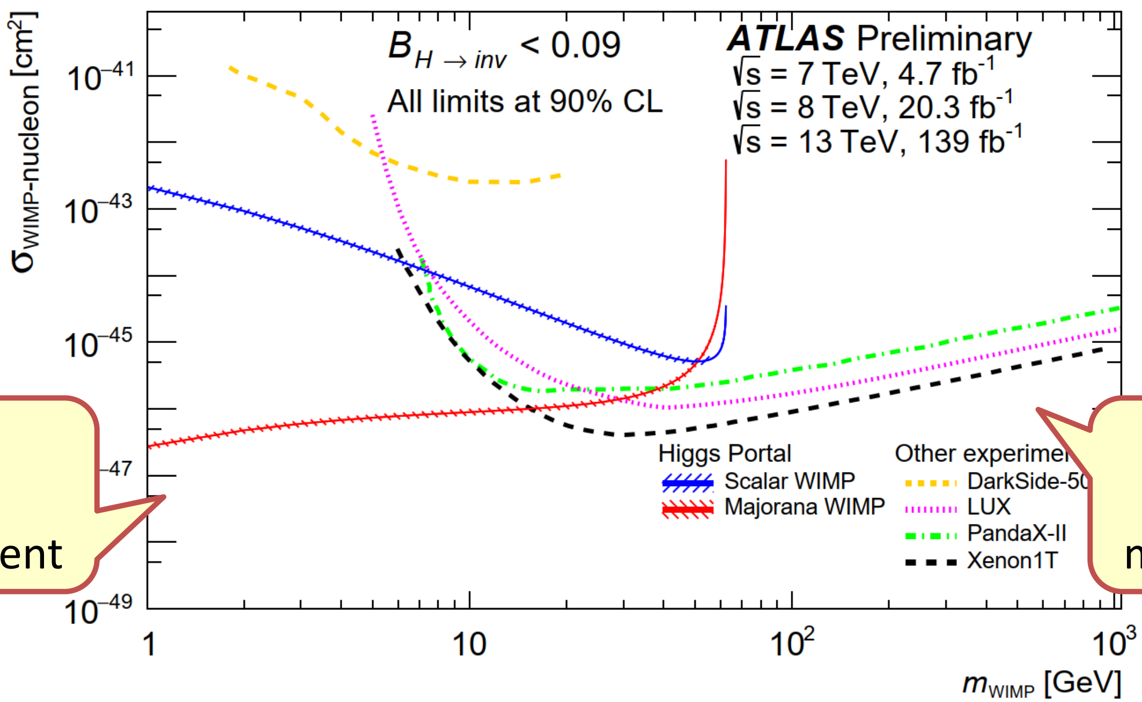
Outline

- Introduction: DM scattering in space
- CR boosted DM (CRDM) as a new probe for light DM
- Earth attenuation of CRDM
- Distinguishing CRDM from other boosted DM models
- Summary

Particle Dark Matter: mass, spin, interaction strength ?



Collider search vs Direct detection

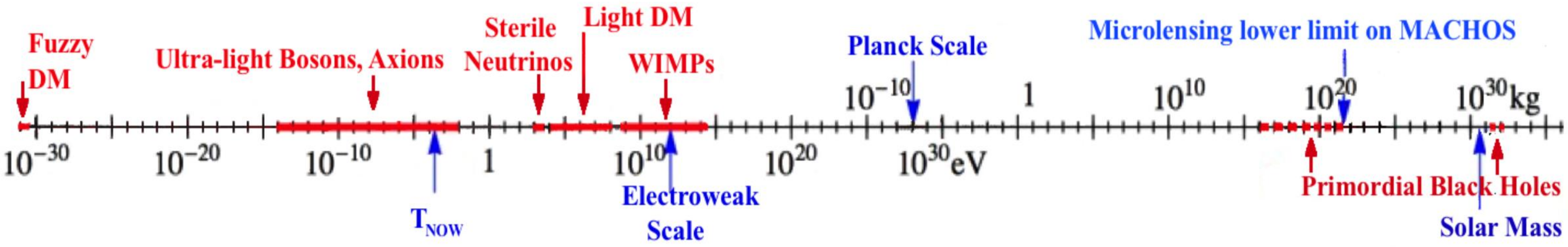


LHC:
top-down
model dependent

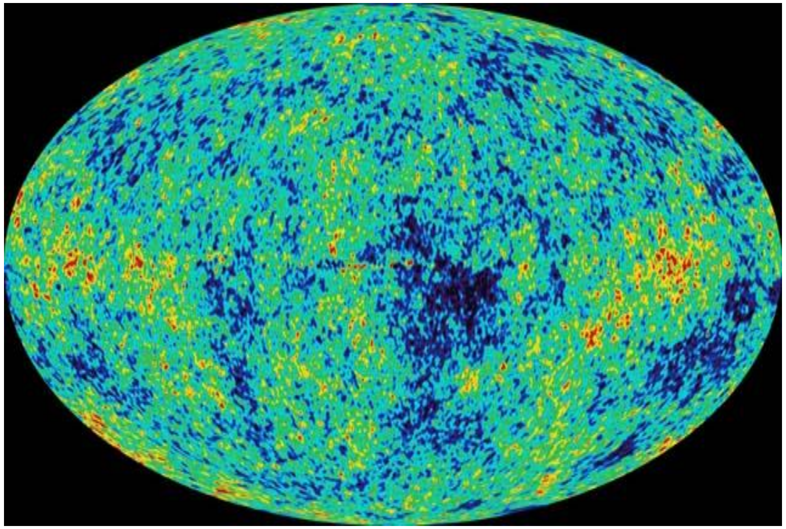
Direct Exps.
Bottom-up
model independent

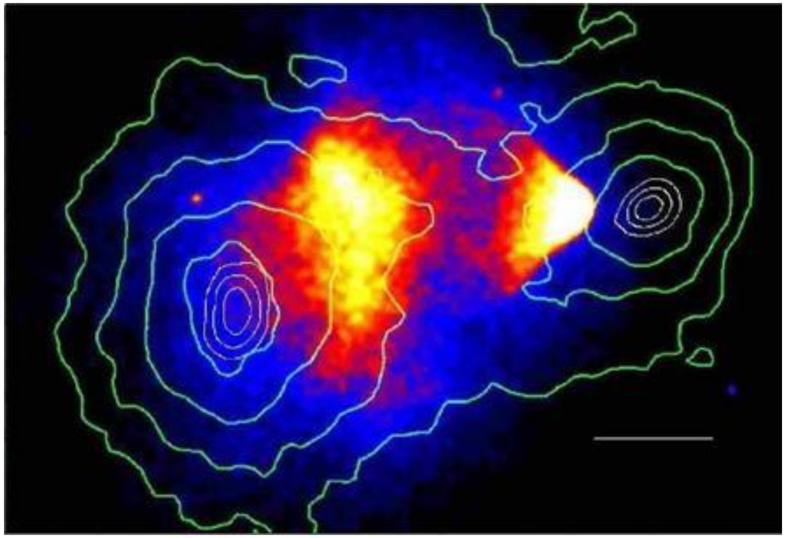
ATLAS-CONF-2020-052

Particle Dark Matter: mass, spin, interaction strength ?



DM can collide with matter everywhere in space !





CMB: $\sigma_{\chi N} < 10^{-27}\text{cm}^2 (m_\chi < \text{GeV})$

1E0657-56: $\sigma_{\chi N}/m_\chi < 1.7\text{cm}^2/\text{g}$

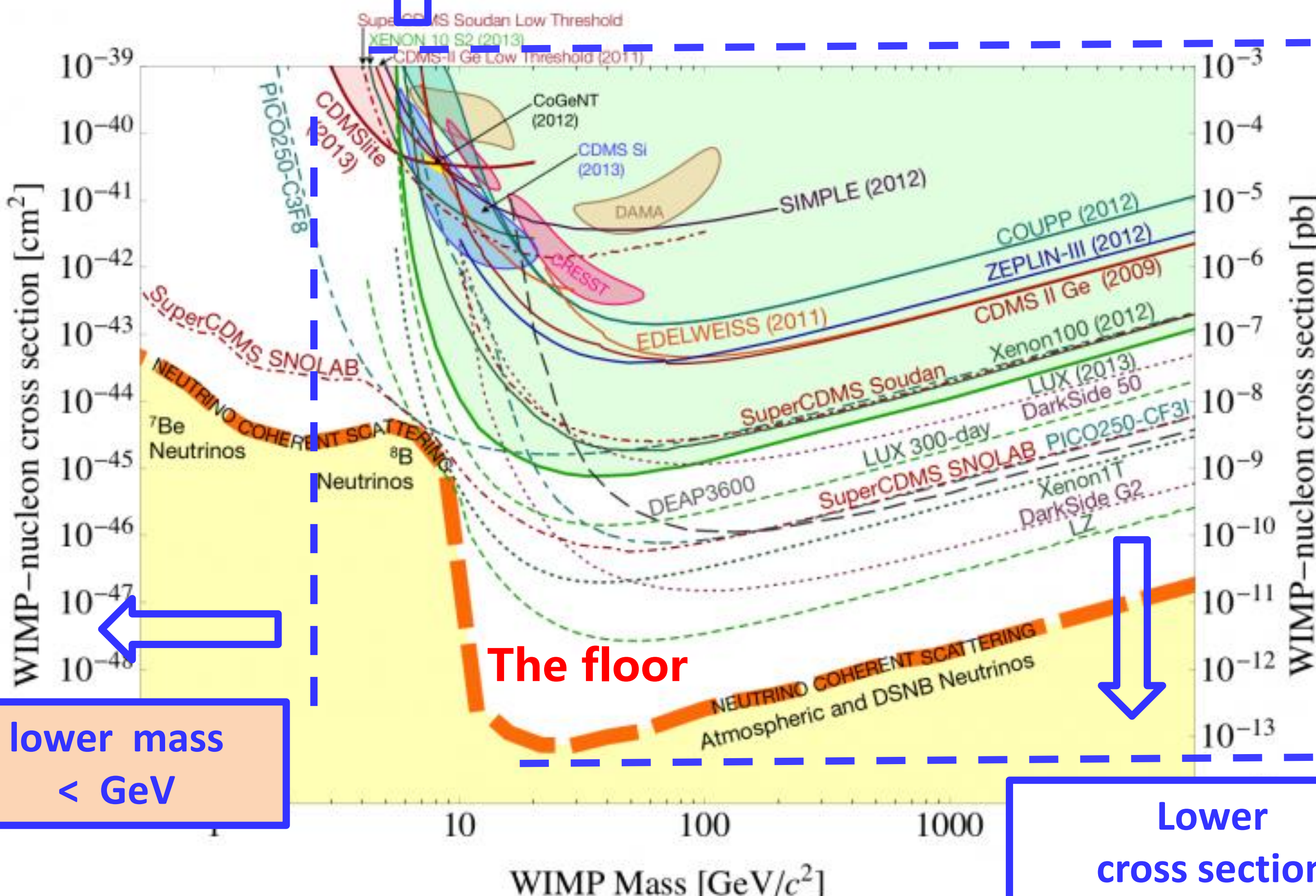
Gluscevic, Boddy, arXiv:1712.07133

Kahlhoefer, et al (2014)

Frontiers of DM direct searches

The ceiling

larger cross section
σ > 10^{-30} cm²



The floor

lower mass
< GeV

Lower
cross section

Frontier 1: Low DM particle mass (< GeV)

- Nuclear recoil energy depends on halo DM mass and velocity distribution

$$E_R = \frac{2m_N}{(1+m_\chi/m_N)^2}\left(\frac{m_\chi}{m_N}\right)^2 v_{\min}^2$$

Halo DM velocity is limited by the escape velocity $v_{esc} \sim 500\ km/s$

$$f_{\rm halo}(\boldsymbol{v}) = \frac{1}{N}\exp\left(-\frac{v^2}{v_0^2}\right)\Theta(v_{\rm esc}-v),$$

Difficulties in probing low mass DM

- low momentum of DM particles $\mathrm{p}_\chi \approx O(MeV)(m_\chi/GeV)$
- low energy transfer from elastic scattering process $\left(\frac{m_\chi}{m_N}\right)^2$

For 1 GeV DM and 100 GeV target, the maximal recoil energy is ~0.06 keV

But the typical direct detection thresholds is O(keV) !

Frontier 2: large scattering cross section (>10^{-30} cm^2)

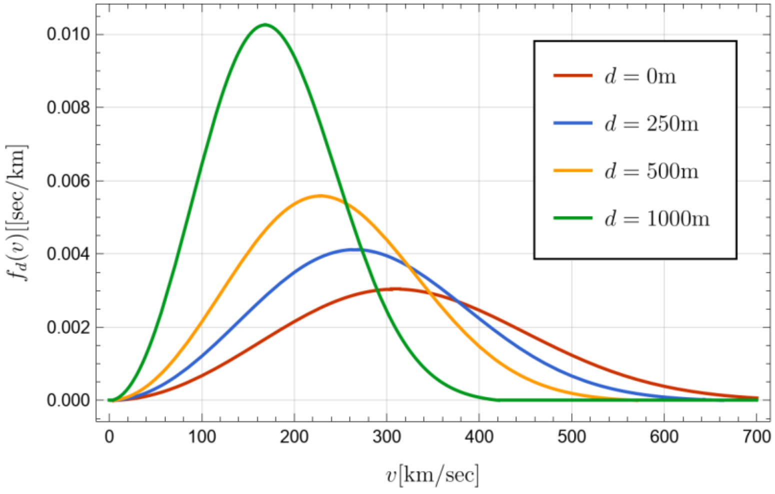
- DM lose energy after penetrating the Earth's crust (non-relativistic case: $dE/dz \approx E$)

$$\frac{\mathrm{d}E_\chi}{\mathrm{d}x} = -\sum_i n_i \frac{2\mu_{\chi i}^2 \sigma_{\chi i}^{tot}}{m_i m_\chi} E_\chi \,,$$

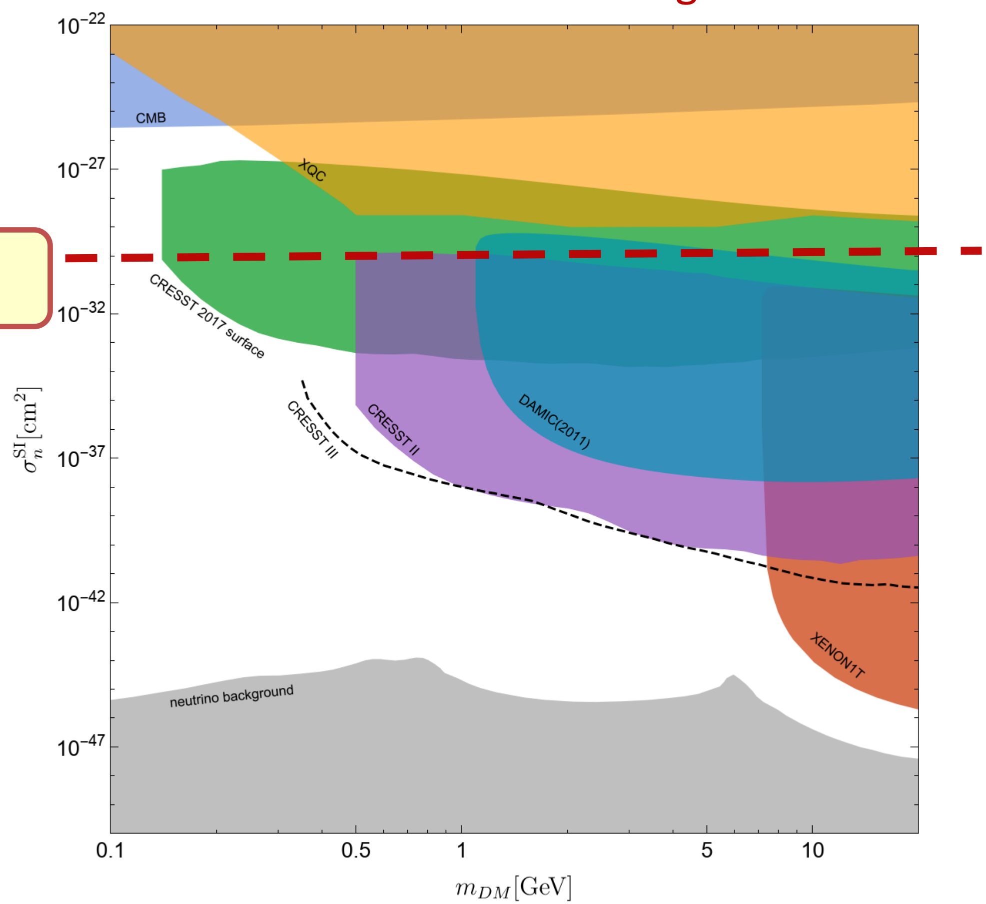
A critical cross section appears due to the energy cutoff

O(1) factor

$$\sigma_{\chi n} = \frac{m_\chi \mu_{\chi n}^2}{2\rho d \sum_i \frac{f_i \mu_{\chi i}^4 A_i^2}{m_i^2}} \log\left(\frac{E_\chi^{\rm ini}}{E_\chi^{\rm min}}\right) \,.$$



Detection ceilings



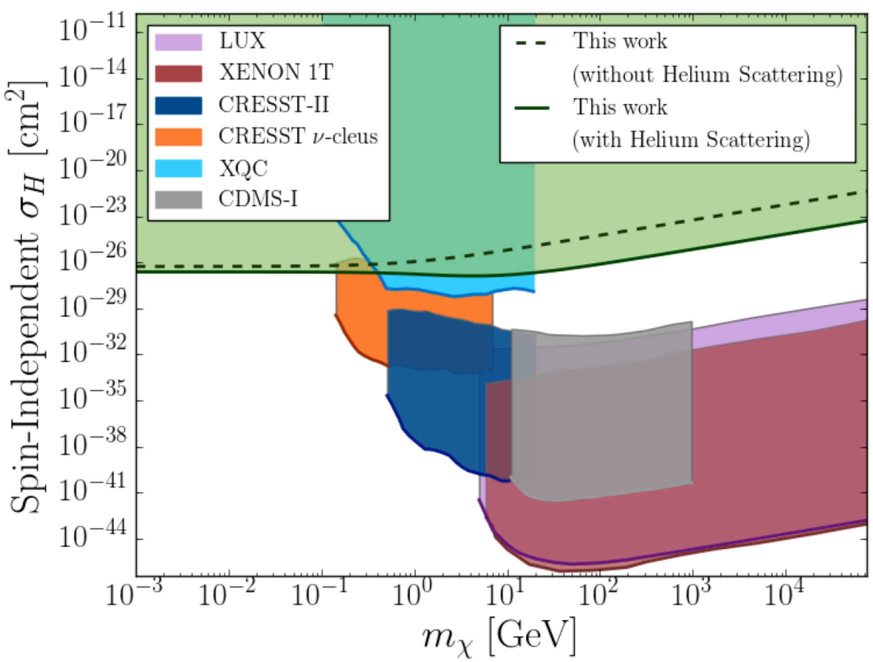
Emken & Kouvaris, arXiv:1802.04764

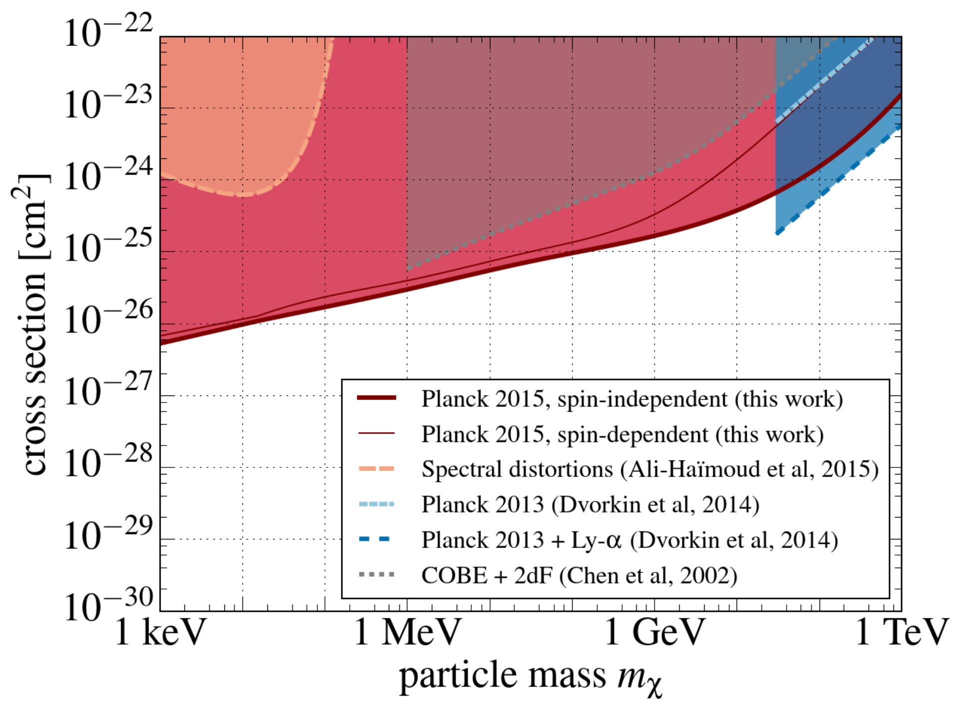
DM scattering in space: CMB

DM-proton scattering 380000 yrs after the Big Bang

- ❑ Distortion of CMB spectrum
- ❑ Suppression of small sale structure (drag force)

Constraints: $\sigma < 10^{-27}\,\mathrm{cm}^2$ for $m_\chi \ll$ GeV



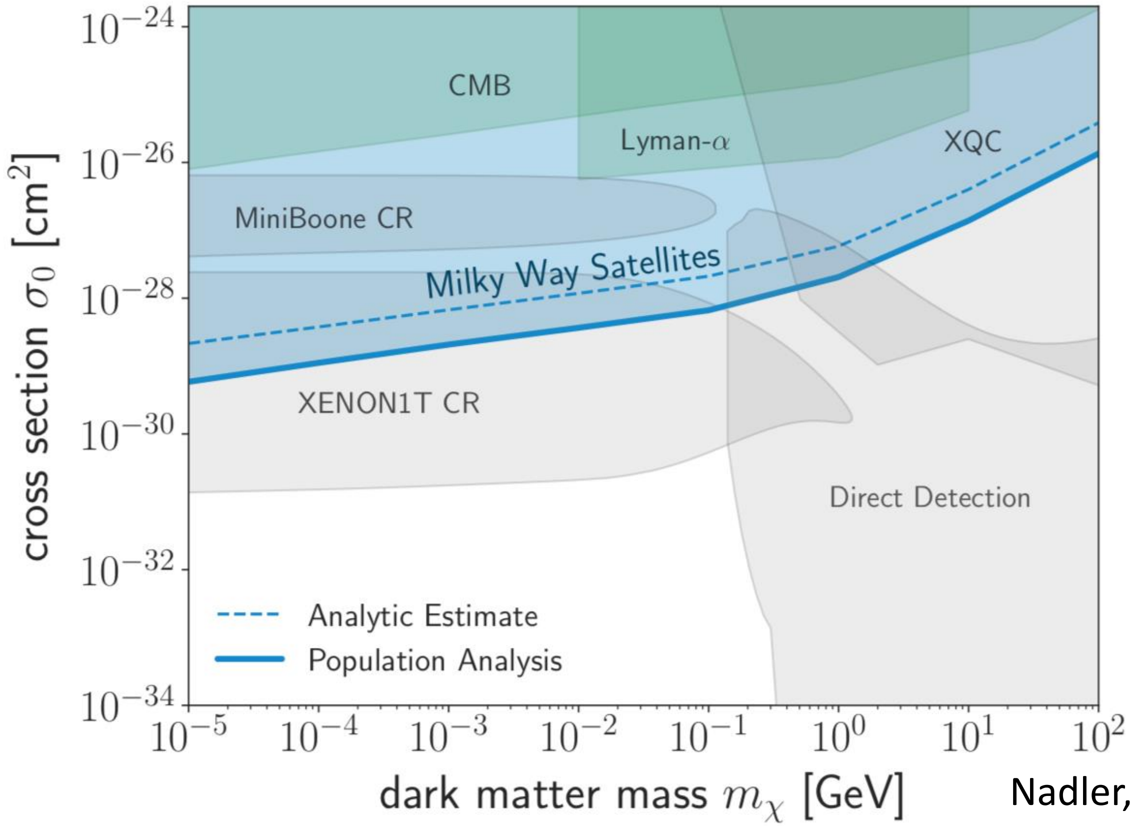


Constraints insensitive to DM particle mass

Gluscevic & Boddy, arXiv:1712.07133

DM scattering in space: structure formation

DM-proton scattering damp structure perturbation
Distribution of dwarf satellite galaxies is modified
$\sigma < 6\times10^{-30}$ cm^2 @ 10 keV, ($<10^{-27}$ cm^2 @ 10 GeV)
Upper limits scale with DM mass as $m^{1/4}$ for m <<1 GeV



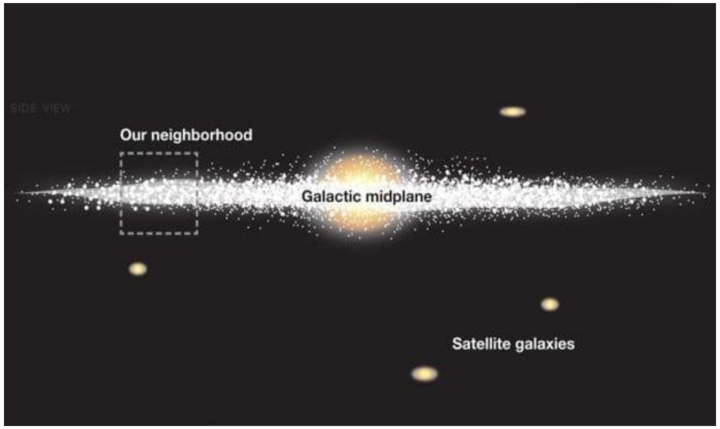
Nadler, et al., arXiv:1904.10000
DES, arXiv:2008.00022

Constraints insensitive to DM particle mass

DM scattering in space: gas cooling

DM above KeV has a temperature higher than the coldest atomic gas

$$T_x \sim m_x v_x^2 \simeq 10^4\ \mathrm{K} \left(\frac{m_x}{\mathrm{MeV}}\right)\left(\frac{v_x}{10^{-3}}\right)^2,$$

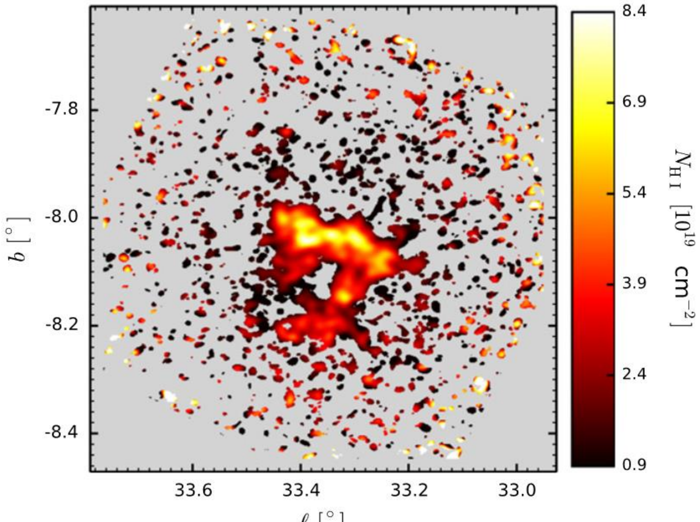


dwarf galaxies

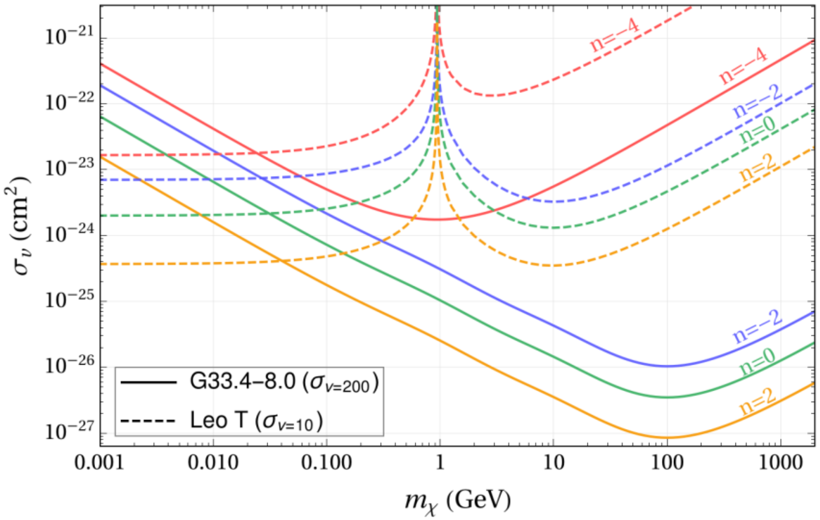
DM-proton scattering heat the gas and change its cooling rate

$\sigma < 10^{-(23\text{-}25)}\ \mathrm{cm}^2$ for a large mass range

10^{-23} eV -- 10^{-10} eV from dwarf galaxy Leo T



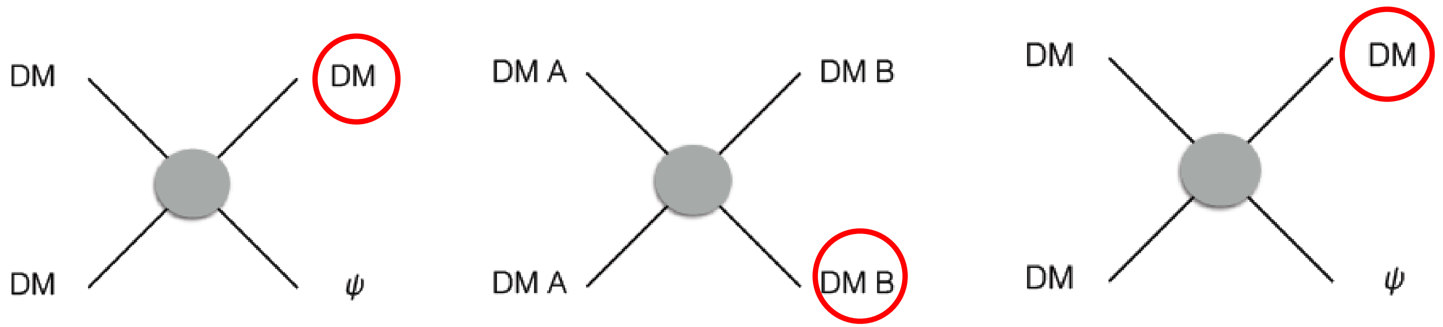
Gas cloud G33.4-8.0



Wadeker & Farrar, arXiv:1903.12190

Beyond halo DM: boosted DM sub-components ?

boosted DM subcomponents from dark sectors



- Decay $A \to \bar{B}B$

J. Berger, Y. Cui, Y.Zhao. JCAP, (2015)

$$\left(\frac{d\Phi_\chi}{dT_B d\Omega}\right)_{\rm dec} = \frac{1}{4\pi m_A \tau_A}\frac{dN}{dT_B}\int_{\rm l.o.s} d\ell \rho_\chi(\boldsymbol{r}),$$

- Energy spectra well-determined
- Known angular distributions

- Annihilation $\bar{A}A \to \bar{B}B$

$$\left(\frac{d\Phi_\chi}{dT_B d\Omega}\right)_{\rm ann} = \frac{\langle\sigma_{\rm ann} v\rangle}{8\pi m_A^2}\frac{dN}{dT_B}\int_{\rm l.o.s} d\ell \rho_\chi^2(\boldsymbol{r}),$$

- 3→2 Semi-annihilation

$$\left(\frac{d\Phi_\chi}{dT_B d\Omega}\right)_{3\to 2} = \frac{\langle\sigma_{3\to 2} v^2\rangle}{24\pi m_A^3}\frac{dN}{dT_B}\int_{\rm l.o.s} d\ell \rho_\chi^3(\boldsymbol{r}),$$

DM boosted by astrophysical sources

- Sun (evaporation, reflection)

Kouvaris, et.tal 1506.04316, An, et.al, 1708.03642

- Blazar/AGN (up-scattering)

Wang , et.al, arXiv:2202.07598,

- Supernova (up-scattering)

Lin, et.al, arXiv:2206.06864

- Supernova remnants (up-scattering)

Cappiello et.al, arXiv:2210.09448

- Blackholes (Hawking evaporation)

Calabrese, et.al, arXiv:2107.13001

Chao, et.al, arXiv:2108.05608

Kitabayashi, arXiv.2204.07898

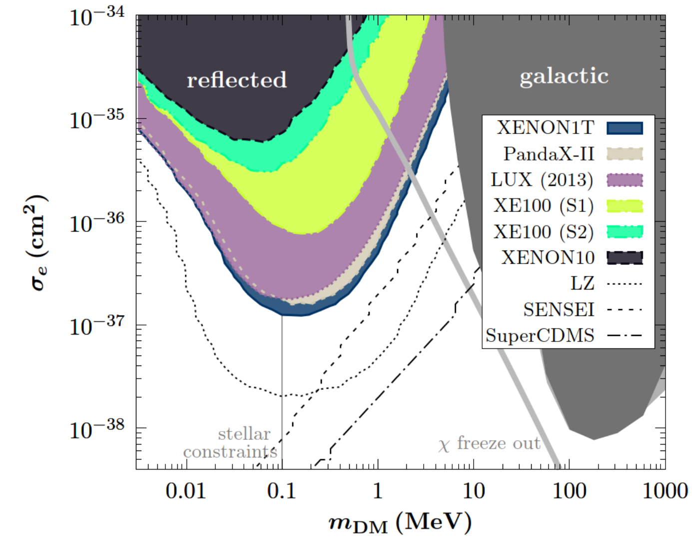
- Cosmic rays (up-scattering)

Bringmann, et.al, arXiv:1810.10543

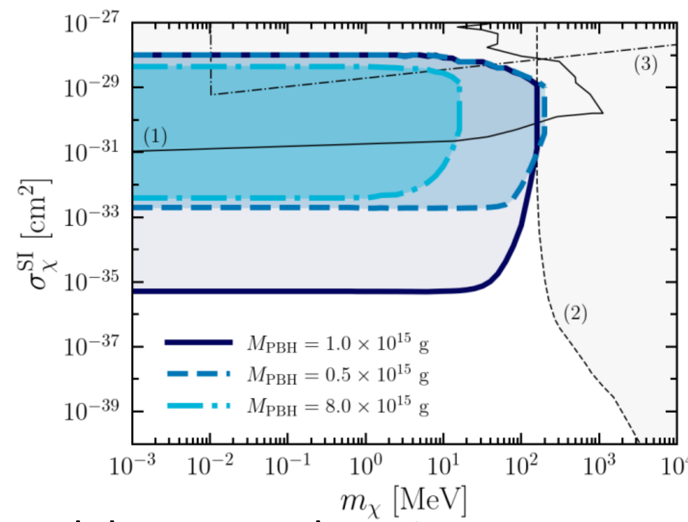
Ema, et.al, arXiv: 1811.00520

Cappiello, et.al, 1arXiv:906.11283

… …



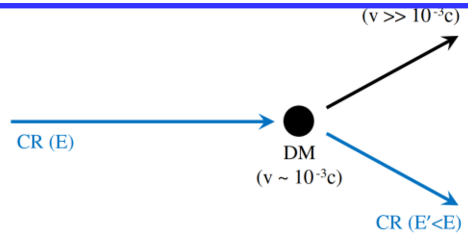
An, et.al, 1708.03642

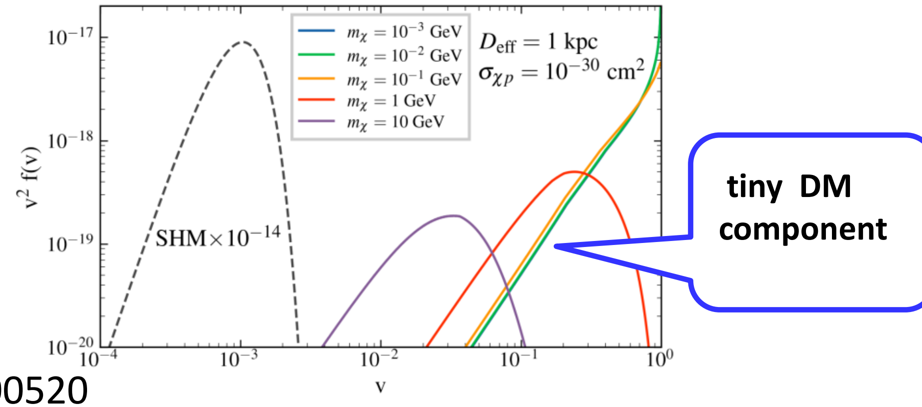


Calabrese, et.al, arXiv:2107.13001

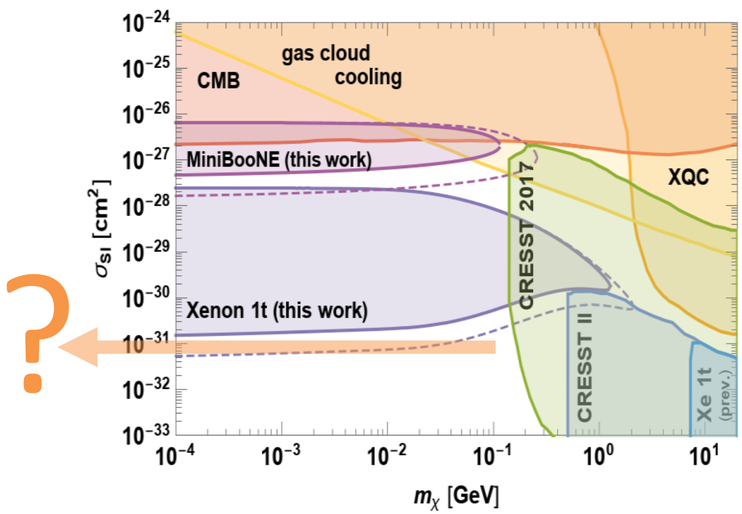
CR-DM scattering: CR boosted dark matter

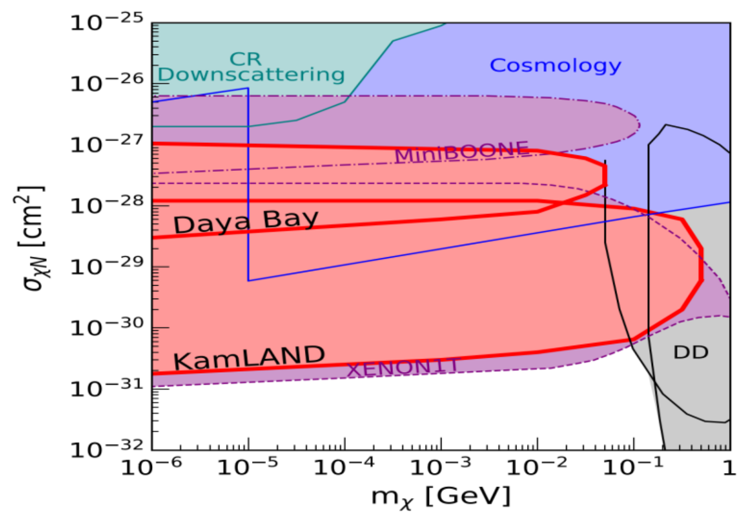
CR boosted DM: Inverse direct detection





Bringmann, et al 1810.10543, Y. Ema, et al, 1811.00520



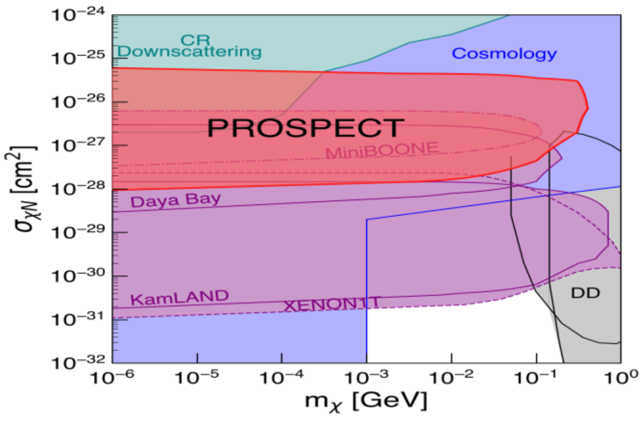


Cappiello, et al, (2019)

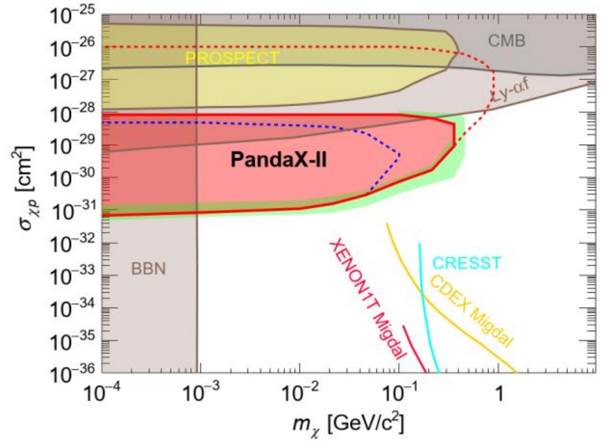
- ❑ Essentially no threshold problem
- ❑ Typical constraint $\sigma_{\chi p} < 10^{-(31-32)}\ cm^2$
- ❑ Constraints on $\sigma_{\chi N}$ highly insensitive to DM mass

Experimental searches for CRDM

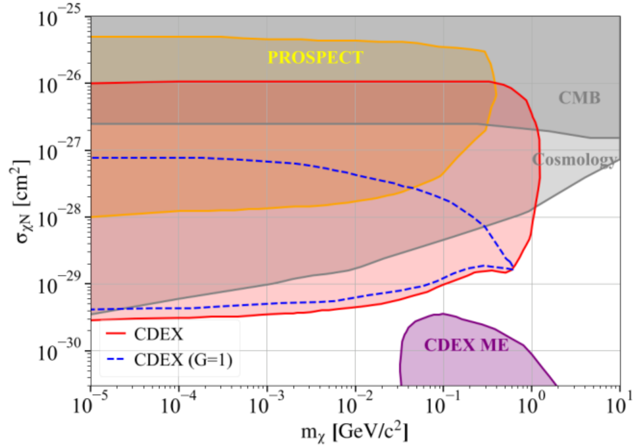
CR-boosted DM searched by virous experiments, e.g.



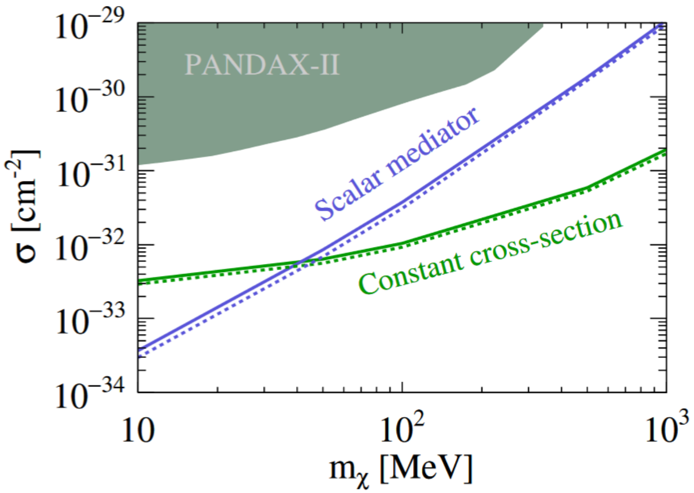
Prospect, arXiv:2104.11219



PandaX-II, arXiv:2112.08957



CDEX, arXiv:2201.01704



Super-K, arXiv:2209.14968

The spectrum of CRDM

- DM flux from CR species *i*=proton, He, …

$$\frac{d\Phi_\chi}{dT_\chi} = \int_{l.o.s} d\ell \int_{T_i^{\min}}^{\infty} dT_i \left(\frac{\rho_\chi}{m_\chi}\right)\left(\frac{d\sigma_{\chi i}}{dT_i}\right)\left(\frac{d\Phi_i}{dT_i}\right)$$

drop rapidly towards higher E

enhancement factor

- A simplification: CR flux is similar to the locally measured one $\frac{\mathrm{d}\Phi_i}{\mathrm{d}T_i} \approx \frac{\mathrm{d}\Phi_i^{LIS}}{\mathrm{d}T_i}$
- The DM distribution can be factorized out

(may not be accurate)

$$\frac{d\Phi_\chi}{dT_\chi} = \frac{\rho_\chi^{\rm loc} D_{\rm eff}}{m_\chi} \int_{T_i^{\min}}^{\infty} dT_i \left(\frac{d\sigma_{\chi i}}{dT_i}\right)\left(\frac{d\Phi_i^{\rm LIS}}{dT_i}\right)$$

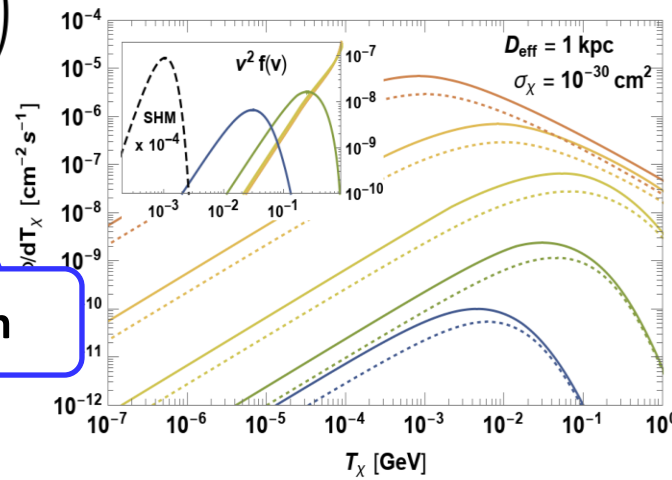
DM distribution

CR local distribution

with

$$D_{\rm eff} = \int_{l.o.s} d\ell \left(\frac{\rho_\chi}{\rho_\chi^{\rm loc}}\right)$$

- Typical value of $D_{\rm eff}$ ~ a few kpc。



Bringmann, et al 1810.10543

CRDM flux from a power-law CR source

a simple case: consider the CR flux (i=proton, He, etc.) as a power-law (index α) with a cutoff (typical for diffusive shock wave acceleration by SNRs)

$$\frac{d\Phi_i^{\rm LIS}}{d\gamma_i} = \Phi_i^0 \gamma_i^{-\alpha_i} \exp\left(-\frac{\gamma_i}{\gamma_{i,\rm cut}}\right)$$

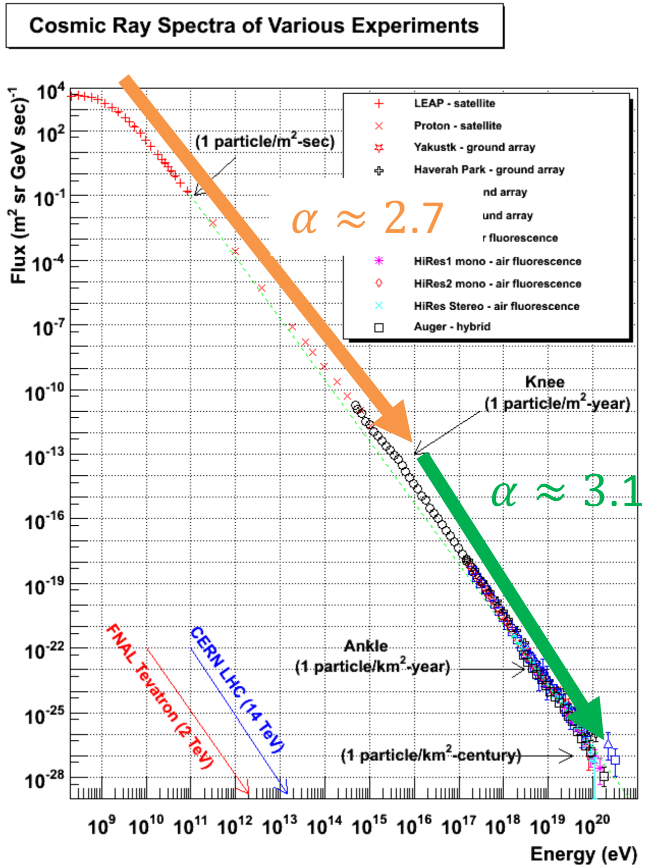
Analytical expression of the CRDM flux

$$\frac{d\Phi_\chi}{dT_\chi} = \frac{\sigma_{\chi i}\rho_\chi^{\rm loc} D_{\rm eff}\Phi_i^0 F^2}{2m_\chi^2 \gamma_{i,\rm cut}^{\alpha_i+1}} \Gamma(-(\alpha_i+1), t)$$

asymptotic behavior

$$\Gamma(a,t) = \begin{cases} -t^a/a & (\text{for } t \ll 1) \\ t^{a-1}\exp(-t) & (\text{for large } t) \end{cases}$$

$$t = T_\chi/(2m_\chi \gamma_{i,\rm cut}^2)$$



The observed CR all-particle spectrum

For CR with $\sim E^{-3}$, DM mass dependence disappears

1) before the cutoff, the CRDM is a power-law with a different power index

$$\frac{d\Phi_\chi}{dT_\chi} \approx \frac{2\sigma_{\chi i}\rho_\chi^{\rm loc} D_{\rm eff}\Phi_i^0 F^2}{\alpha_i + 1} T_\chi^{-2} \left(\frac{T_\chi}{2m_\chi}\right)^{(3-\alpha_i)/2}$$

- DM spectrum: a power-law with index $-(1+\alpha)/2$

  e.g. $\frac{d\Phi}{dT} \approx T^{-2}$ for $\alpha \approx 3$,

- mass dependence: $\sim m^{(\alpha-3)/2}$

DM flux becomes DM mass *independent* , provided $\alpha = 3$

2) A final cutoff appears at $T_{\chi,\rm cut}^{\rm max} = 2m_\chi \gamma_{i,\rm cut}^2$

$$\frac{d\Phi_\chi}{dT_\chi} \approx \frac{\sigma_{\chi i}\rho_\chi^{\rm loc} D_{\rm eff}\Phi_i^0 F^2}{2m_\chi^2 \gamma_{i,\rm cut}^{\alpha_i+1}} \left(\frac{T_\chi}{T_{\chi,\rm cut}^{\rm max}}\right)^{-\frac{\alpha_i+2}{2}} e^{-\left(\frac{T_\chi}{T_{\chi,\rm cut}^{\rm max}}\right)^{1/2}}$$

Y.H. Xu, C. Xia, YFZ, arXiv:2009.00353

Ultra-high energy CR: a power law $\sim E^{-3.1}$ up to 10^{20} eV

Indirect: ground based air-shower arrays

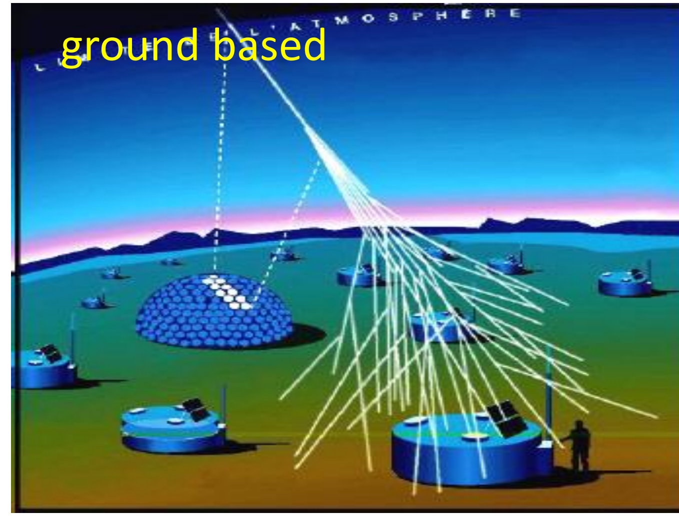
- ❑ Mass resolution limited to major groups
- ❑ Very large energy range: E~10^{20} eV,

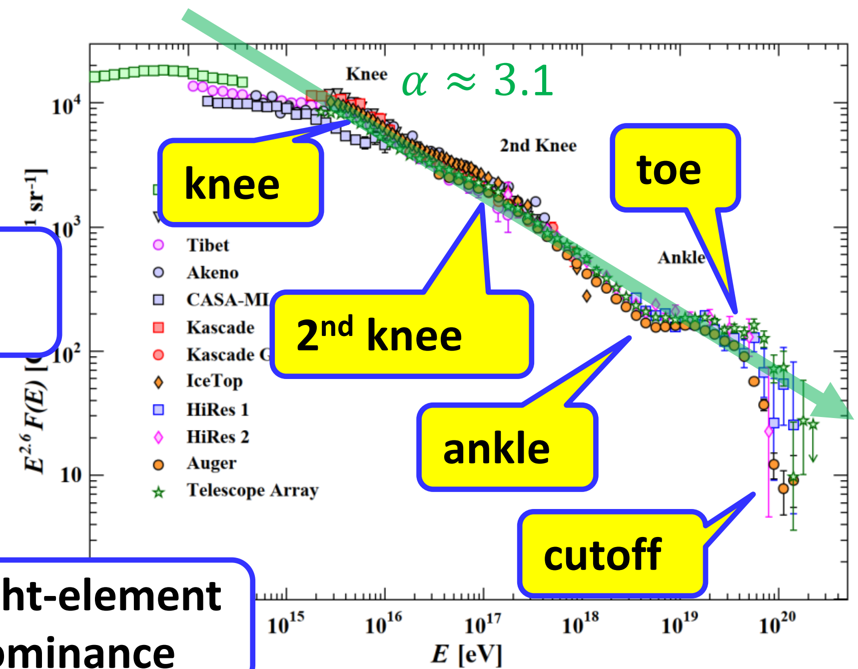
Spectral features in UHECR (E>PeV)

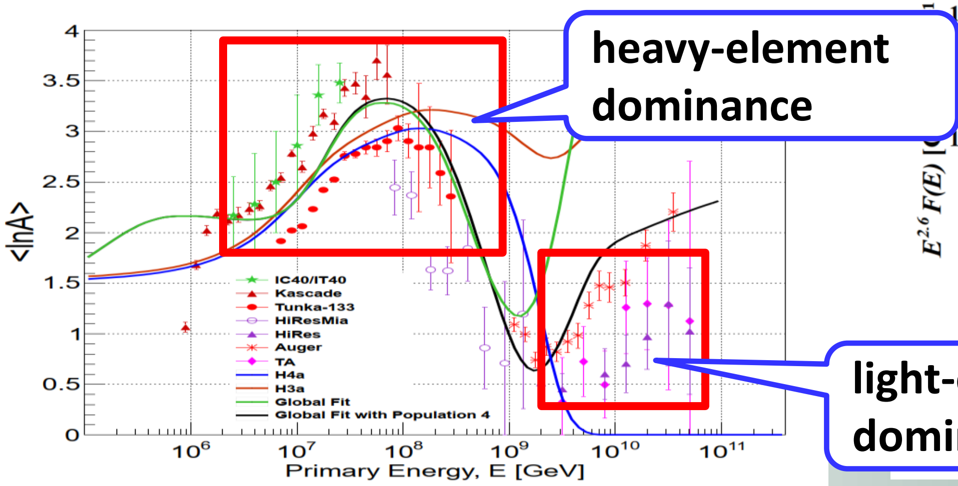
1) "knee" : $3 \times 10^{15}\, eV$
2) "second knee" : $10^{17}\, eV$
3) "ankle (dip)" : $8 \times 10^{18}\, eV$
4) "toe" : $3 \times 10^{19}\, eV$
5) "(GZK) cutoff" $10^{20}\, eV$

But, overall $\alpha \approx 3$ is a good approximation

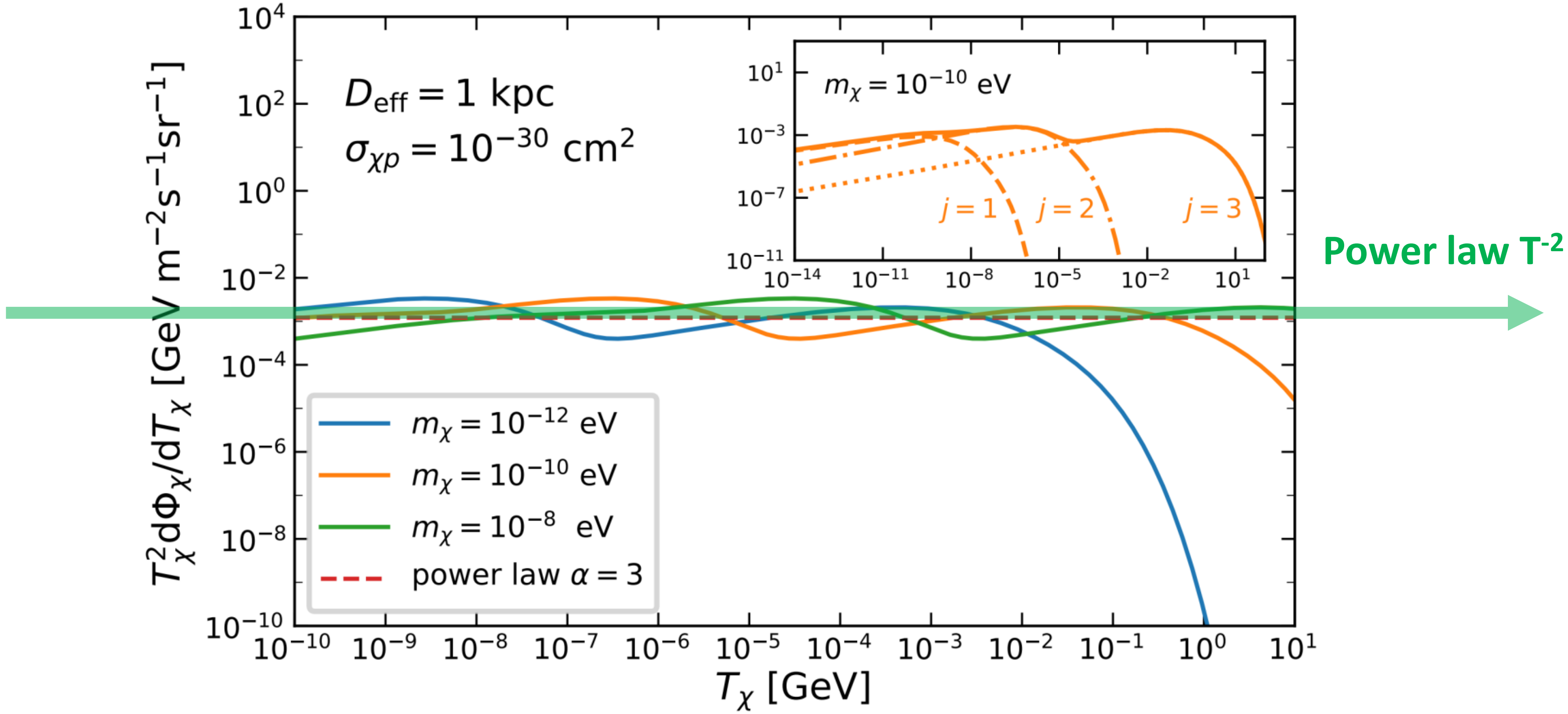
→ can speed up very low mass DM !







CRDM powered by UHECR



- ❑ below the cutoff, CRDM flux for light DM is almost universal (direct consequence of $\alpha \approx 3$)
- ❑ Lighter DM reaches cutoff earlier

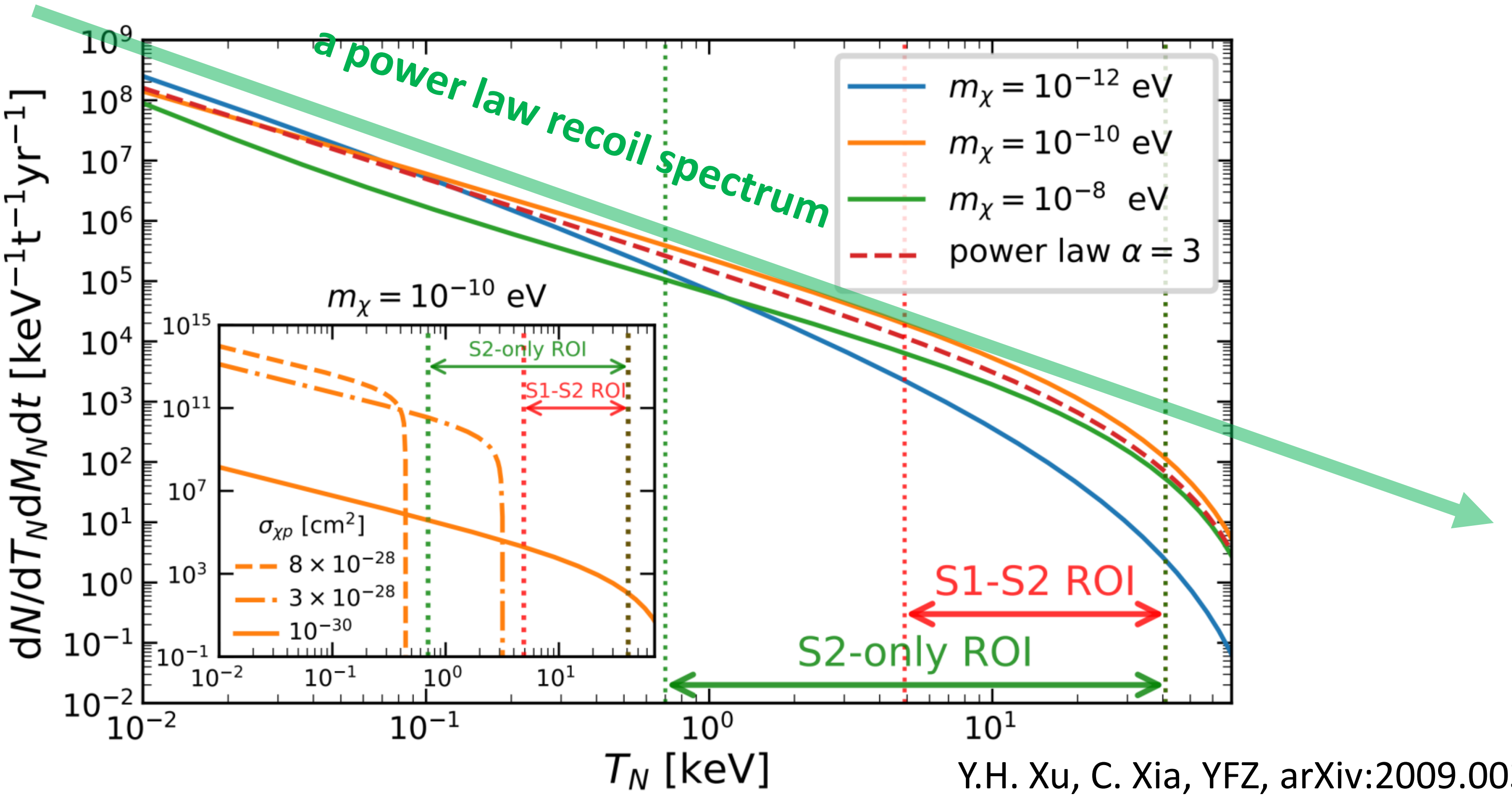
Y.H. Xu, C. Xia, YFZ, arXiv:2009.00353

Nuclear recoil spectrum is also a power-law

(Neglecting the form factor)

Recoil event spectrum: a power law (not an exponential spectrum)

$$\Gamma \approx \frac{\pi \sigma_{\chi N} \sigma_{\chi i} \rho_\chi D_{\rm eff} \Phi_i^0 F^2}{(1+\alpha_i)(3+\alpha_i) m_N^3} \left(\frac{m_N}{m_\chi}\right)^{\frac{3-\alpha_i}{2}} \left(\frac{T_N}{8 m_N}\right)^{-\frac{3+\alpha_i}{4}}$$



Y.H. Xu, C. Xia, YFZ, arXiv:2009.00353

Constraining CRDM in LXe detectors

natively rescaling the known WIMP search limits is NOT accurate

- Total number of quantum for given T_N

$$N_q = N_{ex} + N_i = \text{Bino}(T_N/W, L)$$

work function $W = 13.8$ eV.

- The Linderhard factor

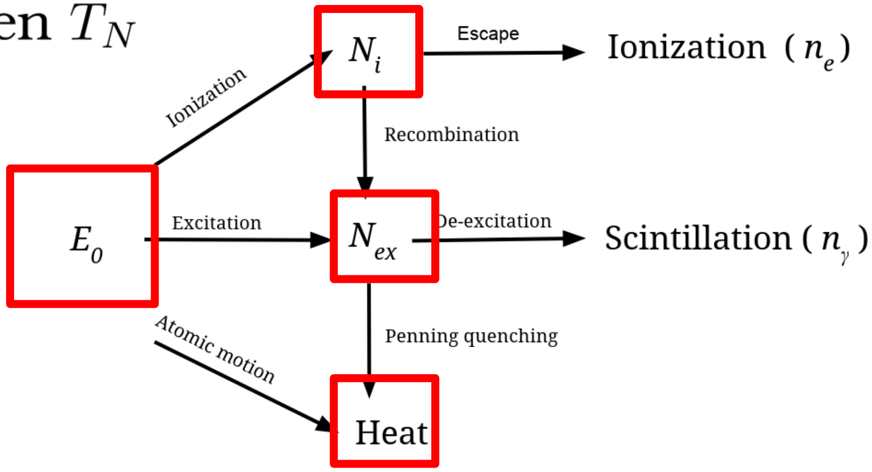
$$L = \frac{kg(\epsilon)}{1 + kg(\epsilon)}$$

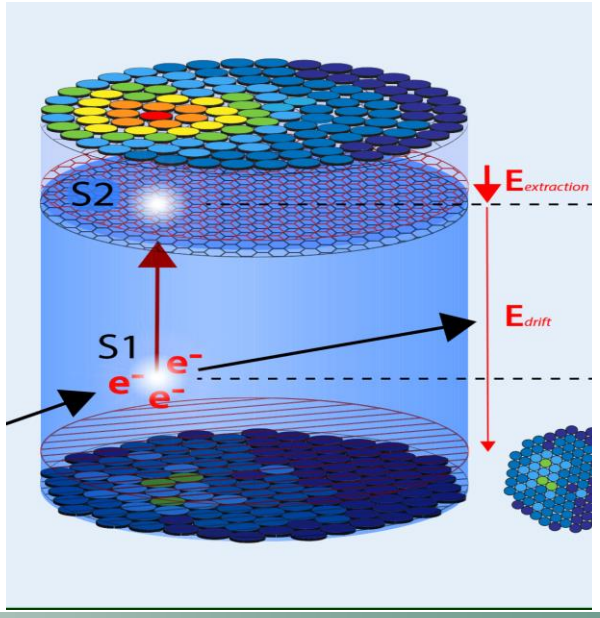
- Number of ions

$$N_i = \text{Bino}(N_q, 1/(1 + \langle N_{ex}/N_i \rangle))$$
$$N_{ex} = N_q - N_i$$

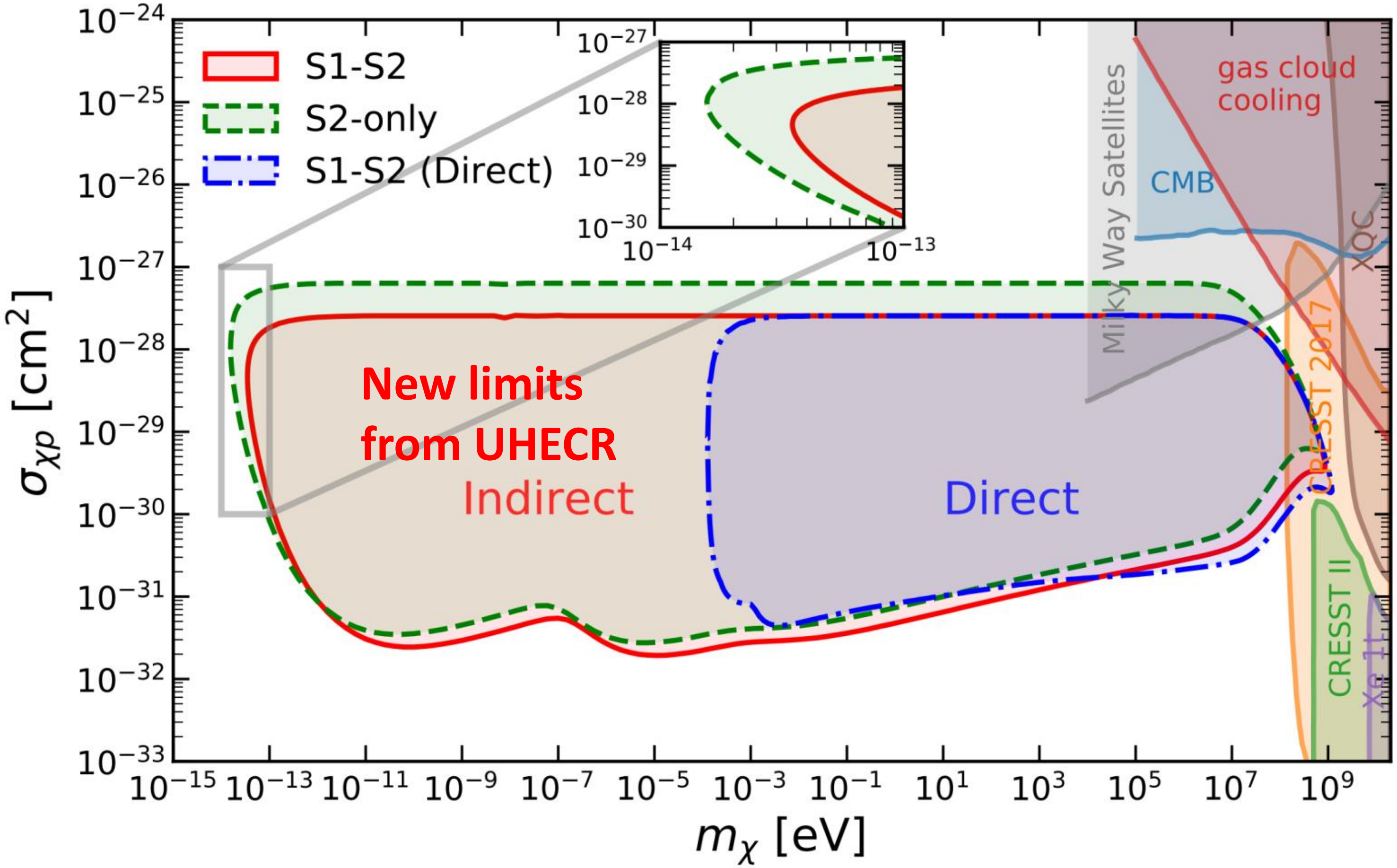
- Number of electrons and photons

$$N_e = \text{Bino}(N_i, 1 - r)$$
$$N_\gamma = N_{ex} + N_i - N_e$$





Constraints from Xenon-1T



Using UHECR, the limits can be extended down to ultra-low mass region

Y.H. Xu, C. Xia, YFZ, arXiv:2009.00353

BBN constraints (model dependent)

Any thermalized light species below MeV scale is constrained by BBN

Typical thermalization condition $\sigma_{\chi q} \leq 10^{-46} cm^2$. G.Krnjaic et.al, 1908.00007

Typical mass limits for benchmark models:

- Hardrophilic DM: 0.9 MeV (real scalar), 5.3 MeV (complex scalar), 5.0 MeV （Majorana fermion) 7.8 GeV(Dirac fermion), G.Krnjaic et.al, 1908.00007
- Electrophilic DM: 0.4 MeV (real scalar), 0.5 MeV (complex scalar), 0.5 MeV （Majorana fermion） 0.7GeV (Dirac fermion), Sabti, et. al ,1910.01649

Assumptions implied in BBN constraints

- DM mass is time-independent
- DM-nucleon coupling is time-independent
- Scattering/annihilation are of the same order of magnitude (typically 2-2)
- Standard cosmology (Hubble tension issue)

Exceptions:

- DM may become lighter today (change in VEV), e.g. the *morphon* models, Croon et.al, arXiv:2012.15284
- DM interactions depends on the local DM density , e.g. the *chameleon* models, K. Boddy et.al, arXiv:1208.4376
- DM interactions stronger today due to PhT (reduced mediator mass) e.g. *HYPER* DM, G. Elor et.al, arXiv:2112.03920

CRDM limits are based on the measurement of the **present-day, local Universe,** which is complementary to those from BBN and CMB

The ceiling: Earth attenuation (for constant $\sigma_{\chi N}$)

simple mean-free-path based estimation

relativistic

$$\frac{dT_\chi}{dz} = -\left(\frac{T_\chi}{\ell_E} + \frac{T_\chi^2}{2m_\chi \ell_E}\right)$$

non-relativistic

mean-free-path for E-loss

$$\ell_E \approx 3\ \mathrm{km}\left(\frac{10^{-27}\mathrm{cm}^2}{\sigma_{\chi p}}\right)\left(\frac{\mathrm{MeV}}{m_\chi}\right)$$

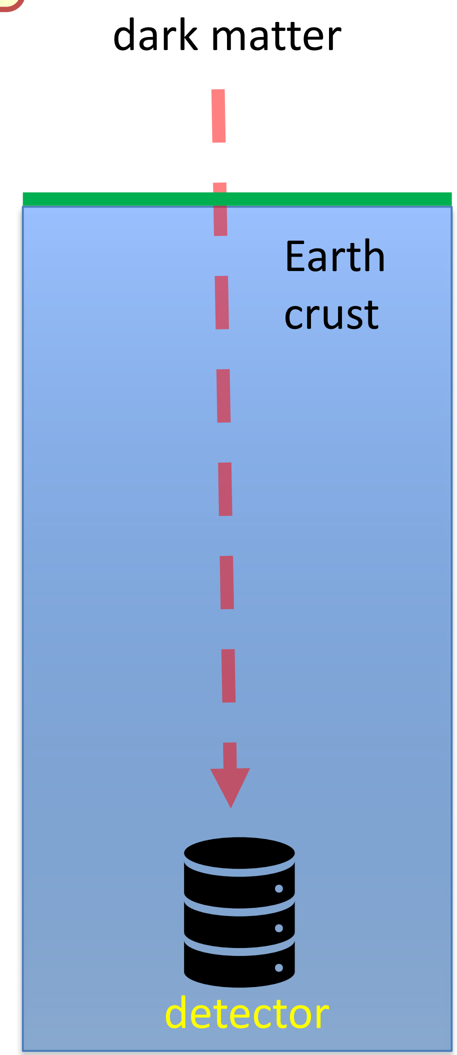
- relativistic limit

$$T_\chi(z) = \frac{T_\chi(0)}{1 + \frac{T_\chi(0)z}{2m_\chi \ell_E}}$$

Non-relativistic limit $T_\chi(z) = T_\chi(0)e^{-z/\ell_E}$
Energy-independent cutoff for $T_\chi(0) \to \infty$

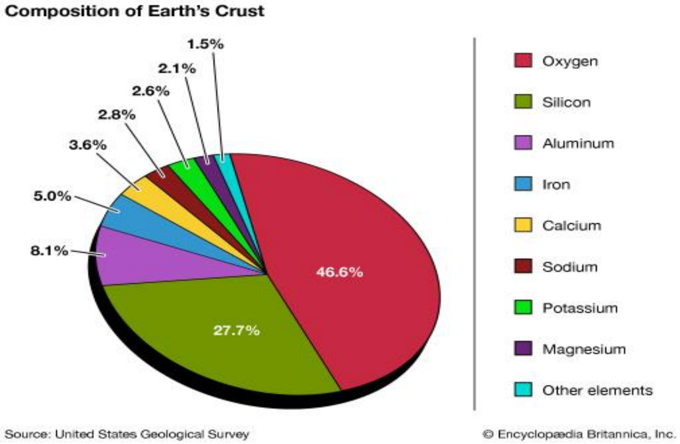
$$T_\chi^{\max}(z) \to \frac{2m_\chi \ell_E}{z}$$

If $T_\chi^{\max}(z)$ is too small, DM cannot be detected



Energy cutoff due to Earth attenuation

Consider spin-independent, isospin conserving case $\sigma_{\chi T} \approx A^2 \sigma_{\chi p}$
mass of the nucleus $m_T \approx A m_p$



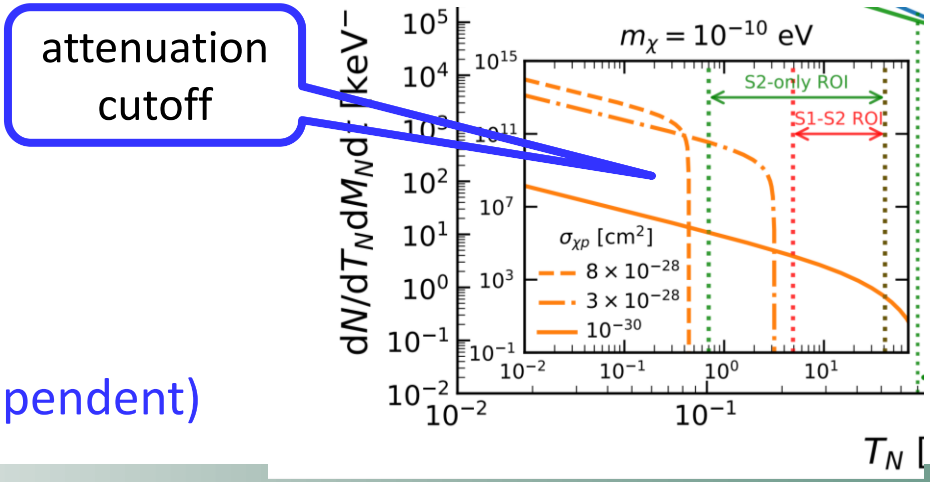
Consequence:
1) the mean-free-path

$$\ell_E^{-1} \approx \frac{2\rho_\oplus \sigma_{\chi p} m_\chi}{m_p^2}$$

independent of the chemical composition of the crust
2) the cutoff energy

$$T_\chi(z) \to \frac{m_p^2}{z \rho_\oplus \sigma_{\chi p}}$$

DM mass m_χ independent



Detection blind spot is DM mass independent)

nuclear form factor effect (energy-dependent cross section)

Even in the simplest case,
Form factor introduce addtional E-dependence to $\sigma_{\chi N}$

$$R(T_\chi) \equiv \frac{\sigma_{\chi N}}{\sigma^0_{\chi N}} = \int_0^{T_N^{\max}(T_\chi)} \frac{F^2(q^2)}{T_N^{\max}(T_\chi)} dT_N,$$

The Helm form factor

$$F(q^2) = \frac{3 j_1(qR_1)}{qR_1} e^{-\frac{1}{2}q^2 s^2}$$

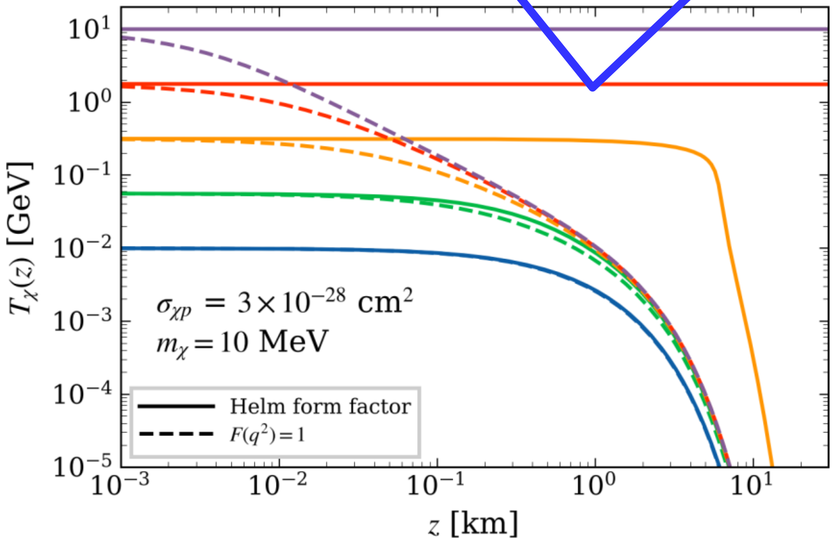
can be approximated as $F(q^2) \approx e_N^{-q^2/\Lambda^2}$

$$\frac{dT_\chi}{dz} \approx -\frac{1}{2} \sum_N n_N \sigma^0_{\chi N} T_N^{\max} f(4 m_N T_N^{\max}/\Lambda_N^2),$$

the energy suppression of $T_\chi(z)$ is reduced

$$T_\chi^3(z) \approx T_\chi^3(0) - \frac{3z}{32} \sum_N n_N \sigma^0_{\chi N} \frac{\Lambda_N^4}{m_N}.$$

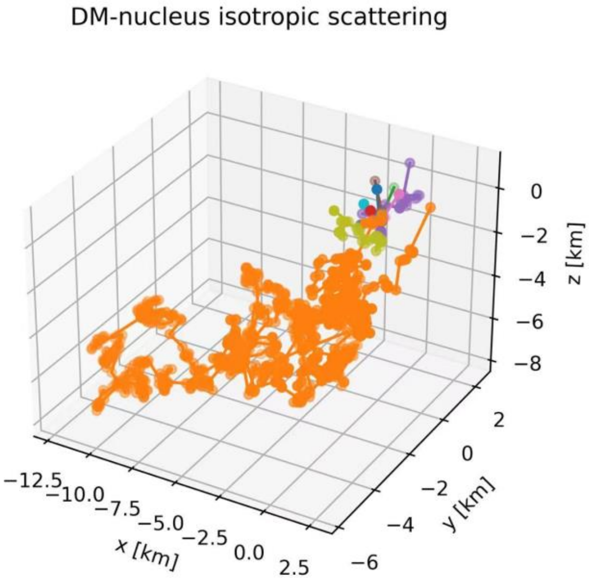
attenuation negligible for high-energy DM due to the form factor effect

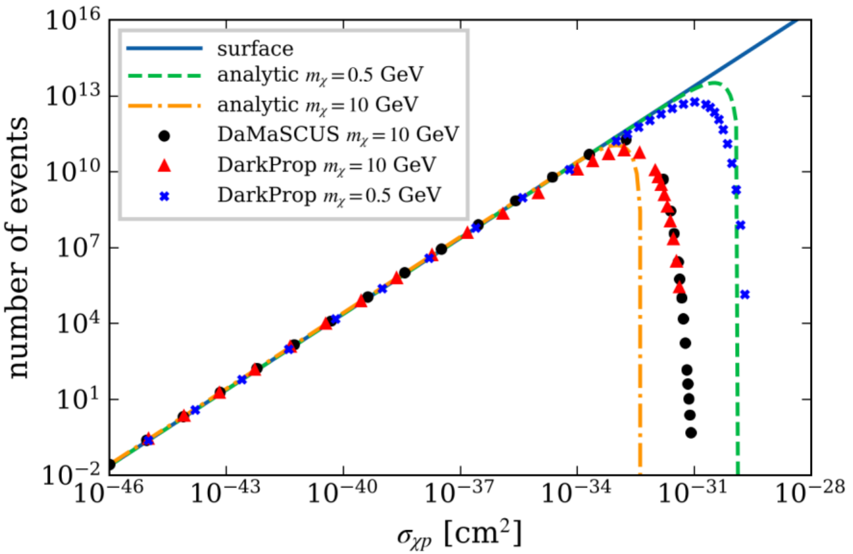


Y.H. Xu, C. Xia, YFZ, arXiv:2011.05559

DarkProp: a code for simulation DM propagation in the Earth

- Isotropic initial condition (to be updated to anisotropic case)
- A simple Earth model with chemical composition included
- For both relativistic and non-relativistic scattering
- Nuclear form factor implemented
- Cross-checked with `DaMasCUS`





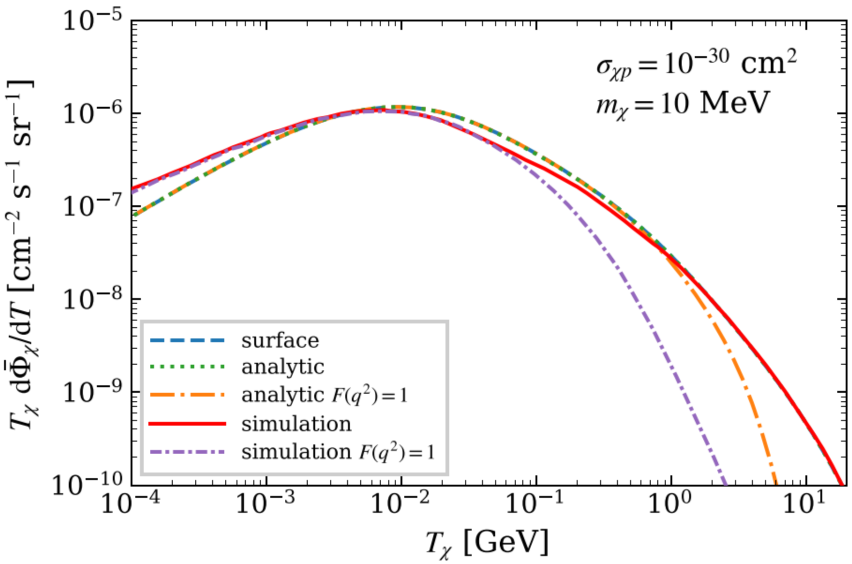
http://yfzhou.itp.ac.cn/darkprop

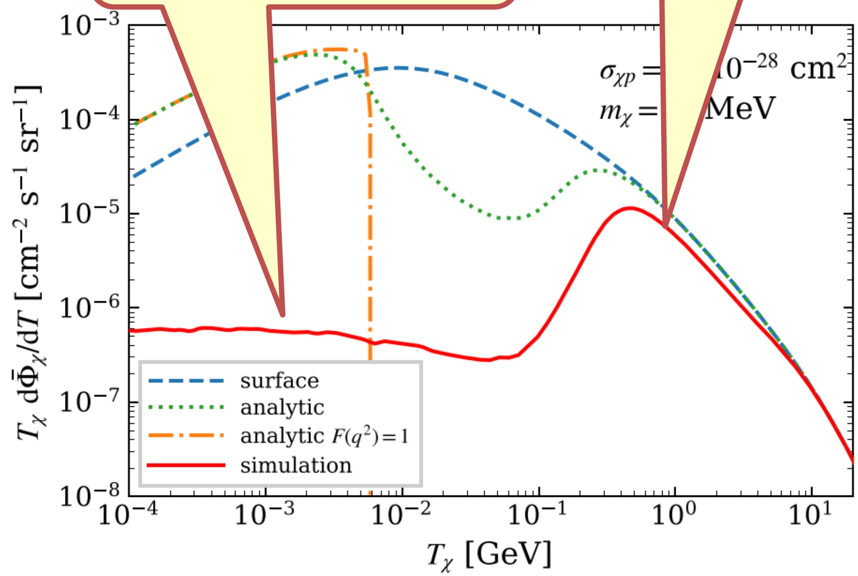
Underground DM flux from simulations

Underground DM spectrum is significantly distorted for large $\sigma_{\chi p}$

negligible attenuation at high T_χ

strong attenuation at low T_χ





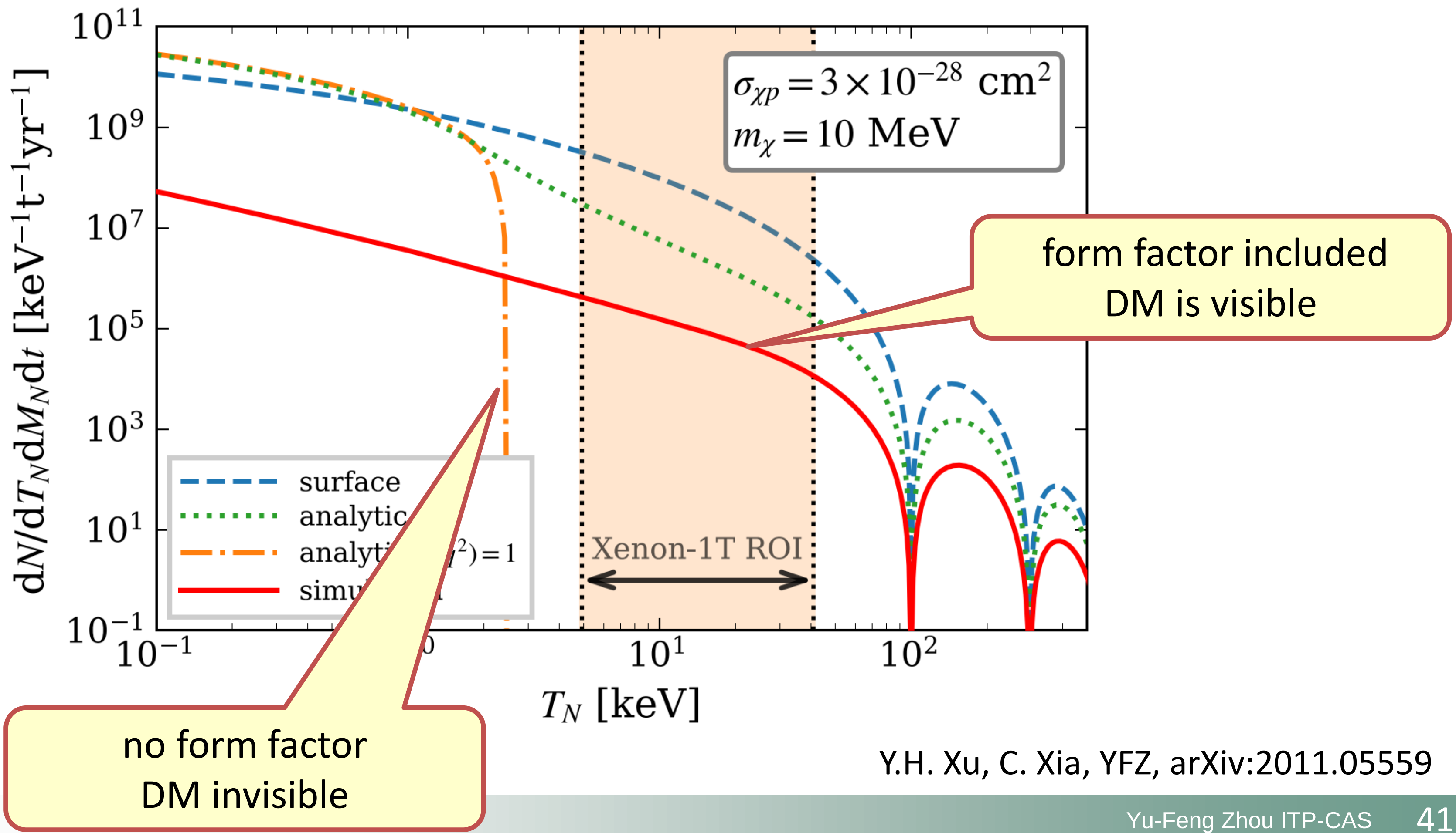
small cross section case
$\sigma_{\chi p} = 10^{-30}\ cm^2$

large cross section case
$\sigma_{\chi p} = 10^{-28}\ cm^2$

Y.H. Xu, C. Xia, YFZ, arXiv:2011.05559

Large cross section now can be probed

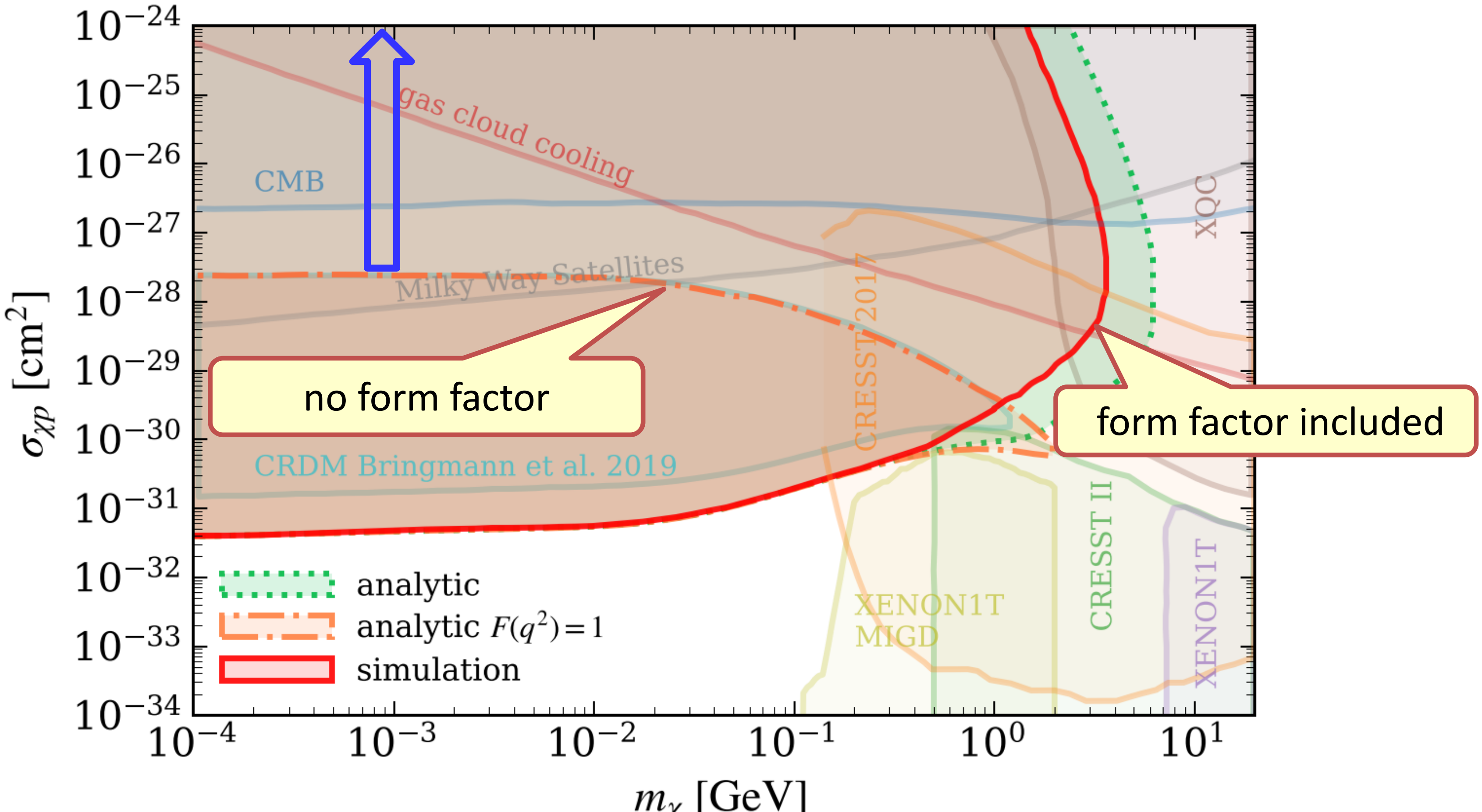
No spectrum cut off any more
DM particles can enter Xenon-1T ROI with large event rates



Y.H. Xu, C. Xia, YFZ, arXiv:2011.05559

(almost) no ceiling for CRDM

Y.H. Xu, C. Xia, YFZ, arXiv:2011.05559



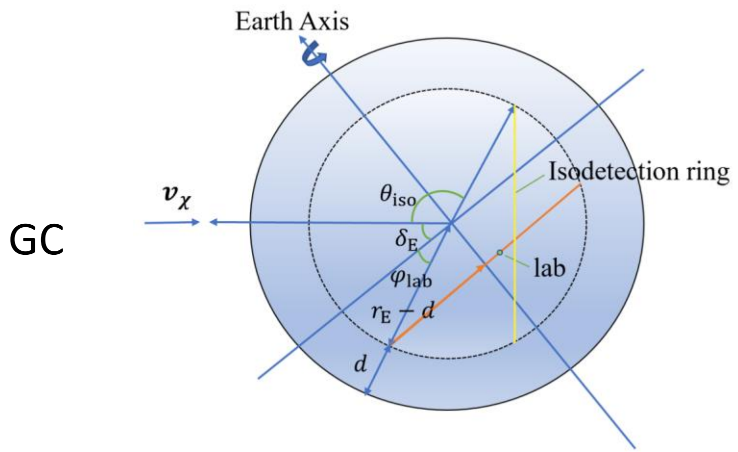
close the gap in the cross sections excluded by the XENON1T experiment and that by the astrophysical measurements such that for the cosmic microwave background (CMB), galactic gas cloud cooling, and structure formation, etc..

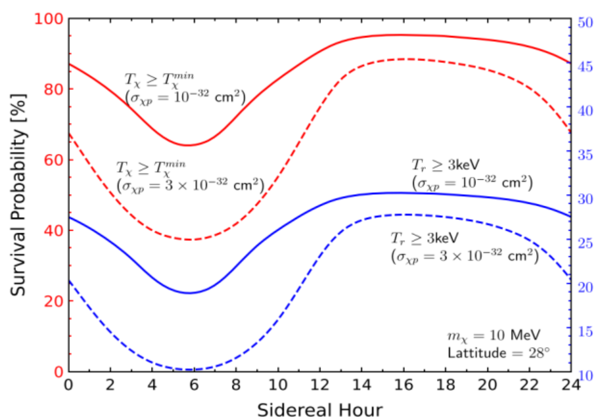
Angular distribution of CRDM

- CRDM has a preferred direction due to
  - inhomogeneous distribution of DM profile (centered towards GC)
  - inhomogeneous distribution of CRs (not centered towards GC)

- Most of the current DM detection exps. cannot distinguish direction
  - Observables: scintillation, ionization, heat

- For large enough $\sigma_{\chi p}$, if the earth attenuation is significant, diurnal modulation of the event rate may appear due to the anisotropic CRDM flux





Ge, et al, arXiv2005.09480

Probing the morphology of CRDM flux

Cherenkov detectors can tell the arrival direction of DM

Detectors for neutrino experiments

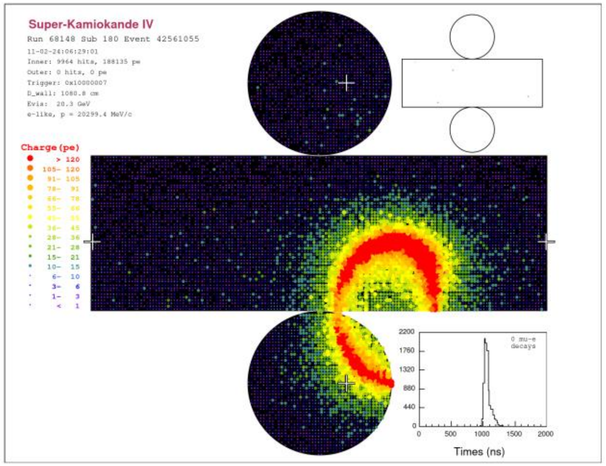
1) Liquid scintillator detectors: Borexino, *Dune*

Low threshold (keV), no direction identification

2) Water Cherenkov detectors: *Super-K, SNO*

High threshold (MeV), can measure direction

3) Hybrid detectors, 1)+2): SNO+



For boosted DM, the threshold is no longer a problem --> good news for neutrino experiments

- ❑ neutrino Exps. have huge exposures

e.g. SK: 50 kt

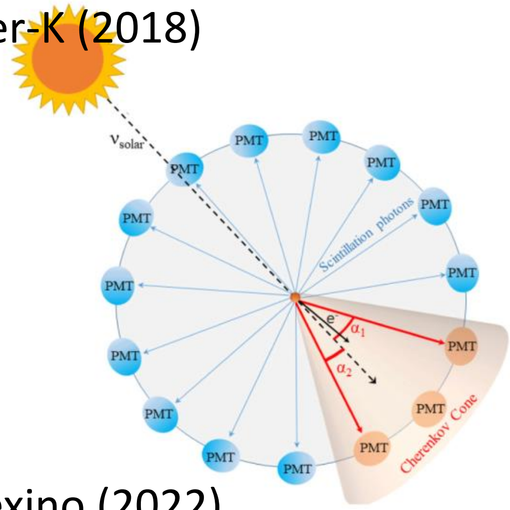
- ❑ Water Cherenkov detectors can measure direction

recoil electrons (and protons) following the direction of DM

SK has good angular resolution ~ 3°

elastic electron scattering

Super-K (2018)



Borexino (2022)

Unique morphological feature of the CRDM flux

Distribution of DM flux close follows the sources

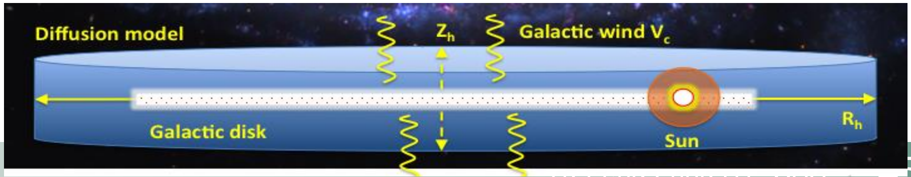
- DM boosted by the Sun, supervona, etc, point-like
- DM boosted by the dark sector diffuse, azimuthal symmetric
  - decay $$\left(\frac{d\Phi_\chi}{dT_B d\Omega}\right)_{\rm dec} = \frac{1}{4\pi m_A \tau_A}\frac{dN}{dT_B}\int_{\rm l.o.s} d\ell \rho_\chi(\boldsymbol{r}),$$
  - annihilation $$\left(\frac{d\Phi_\chi}{dT_B d\Omega}\right)_{\rm ann} = \frac{\langle\sigma_{\rm ann} v\rangle}{8\pi m_A^2}\frac{dN}{dT_B}\int_{\rm l.o.s} d\ell \rho_\chi^2(\boldsymbol{r}),$$
  - $3 \to 2$ process $$\left(\frac{d\Phi_\chi}{dT_B d\Omega}\right)_{3\to 2} = \frac{\langle\sigma_{3\to 2} v^2\rangle}{24\pi m_A^3}\frac{dN}{dT_B}\int_{\rm l.o.s} d\ell \rho_\chi^3(\boldsymbol{r}),$$
- DM boosted by CRs diffuse, azimuthal **asymmetric**

$$\frac{d\Phi_\chi}{dT_\chi d\Omega} = \int_{\rm l.o.s} d\ell \frac{\rho_\chi(\boldsymbol{r})}{m_\chi}\int_{T_e^{\rm min}} dT_e \frac{\sigma_{\chi e}}{T_\chi^{\rm max}}\frac{d\Phi_e(\boldsymbol{r})}{dT_e},$$

Distribution of CR source

$$q(R,z) = \left(\frac{R}{R_\odot}\right)^a \exp\left(-b\frac{R-R_\odot}{R_\odot}\right)\exp\left(-\frac{|z|}{z_s}\right),$$

Diffusion halo $z_h \ll R_h$



Azimuthal symmetry breaking in CRDM flux

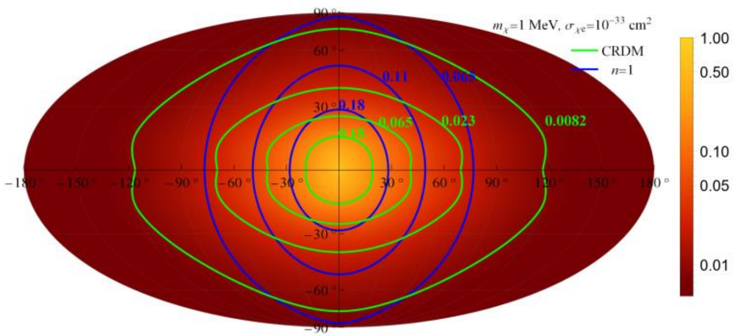
Harmonic expansion

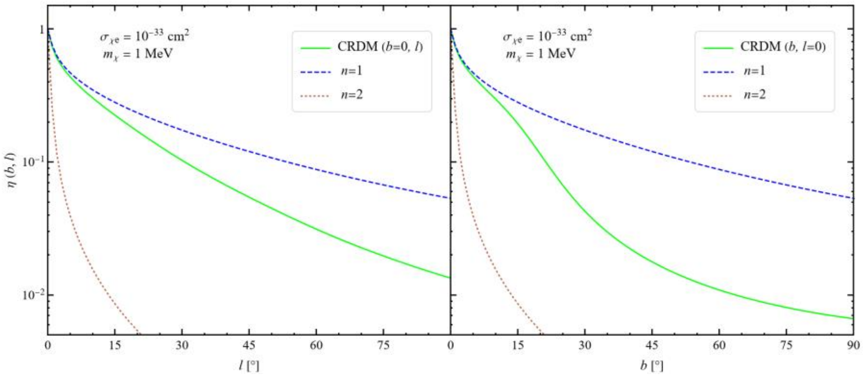
$$\frac{d\Phi_\chi}{d\Omega}(\theta,\varphi)=\sum_{l=0}^{\infty}\sum_{m=-l}^{l}a_{l,m}Y_{l,m}(\theta,\varphi),$$

Coefficients

$$a_{l,m}=\int d\Omega Y^*_{l,m}(\theta,\varphi)\frac{d\Phi_\chi}{d\Omega}(\theta,\varphi).$$

- $a_{l,m}$ independent of $\sigma_{\chi e}$
- nonvanishing $a_{l,m}$ with $m\neq 0$ $\rightarrow$ azimuthal symmetry breaking





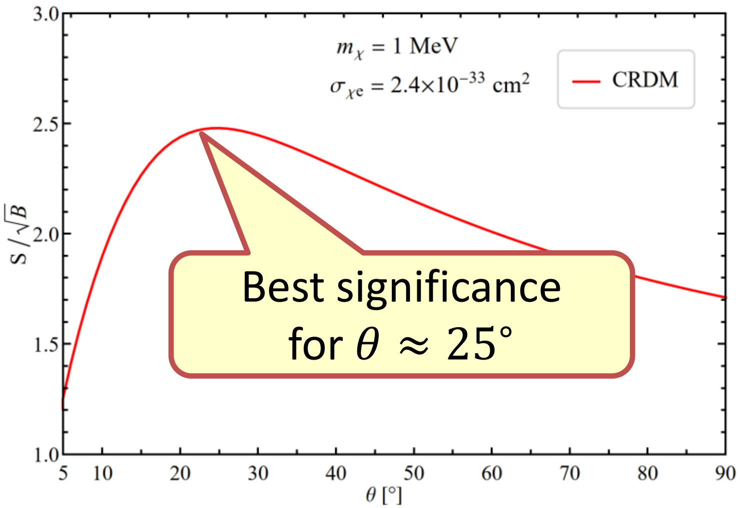
		$\tilde a_{1,0}$	$\tilde a_{2,0}$	$\tilde a_{3,0}$	$\tilde a_{4,0}$	$\tilde a_{5,0}$	$\tilde a_{2,2}$	$\tilde a_{3,2}$	$\tilde a_{4,2}$	$\tilde a_{4,4}$	$\tilde a_{5,2}$	$\tilde a_{5,4}$
NFW	CRDM	1.00	0.90	0.77	0.63	0.52	0.12	0.12	0.11	0.02	0.09	0.02
	BDM ($n=1$)	0.63	0.37	0.24	0.17	0.13	0	0	0	0	0	0
	BDM ($n=2$)	1.28	1.33	1.32	1.29	1.27	0	0	0	0	0	0
Einasto	CRDM	1.06	1.00	0.88	0.75	0.64	0.11	0.11	0.10	[illegible]	0.09	0.02
	BDM ($n=1$)	0.68	0.43	0.30	0.22	0.17	0	0	0	[illegible]	0	0
	BDM ($n=2$)	1.36	1.46	1.47	1.45	1.42	0	0	[illegible]	[illegible]	[illegible]	[illegible]

symmetry breaking term

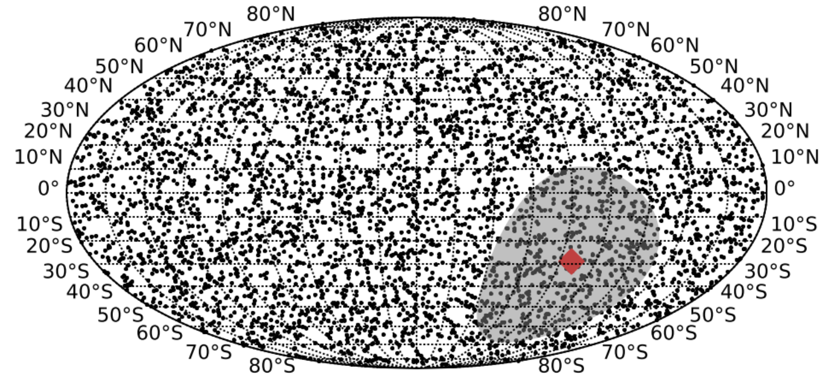
Yan-Hao Xu, Chen Xia, YFZ, 2206.11454

Constraints on DM-electron scattering from SK-IV data

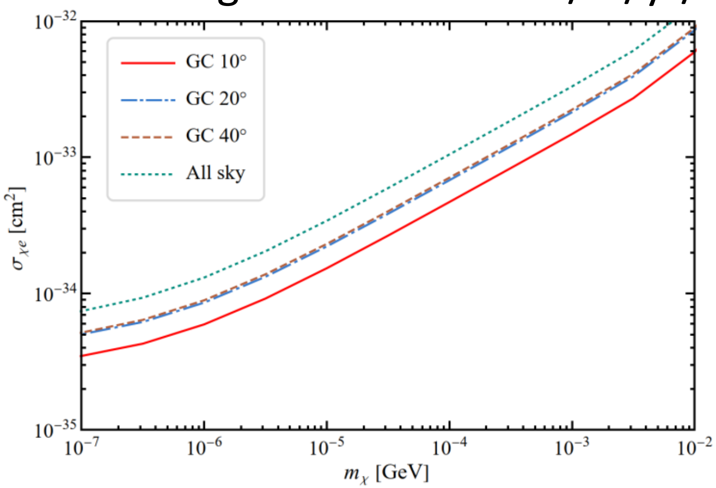
Optimize the search cone



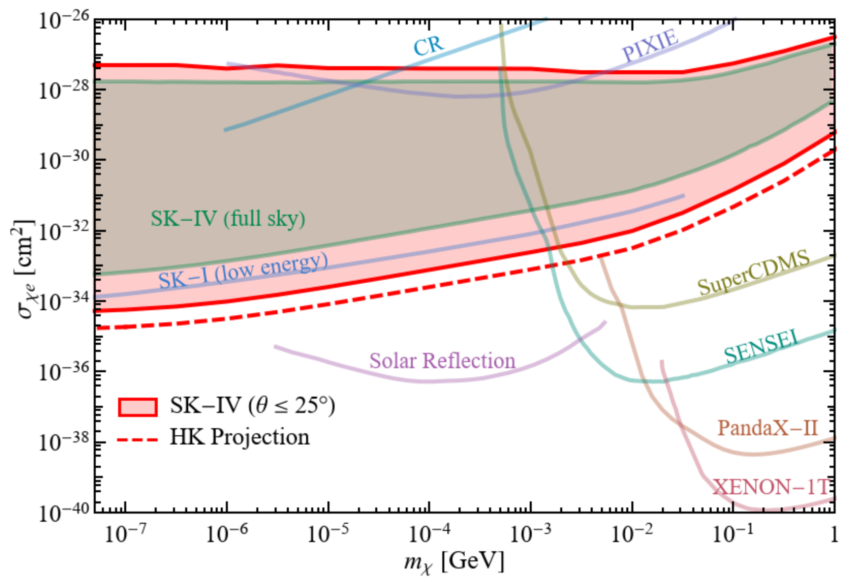
SK-IV all-sky data, 0.1–1.33 GeV



SK-IV background level: 1.96/kt/yr/sr



Limits at different cut-angles θ



So far the most stringent limit

$$\sigma_{\chi e} \leq 2.4 \times 10^{-33} cm^2 @1\ MeV$$

Yan-Hao Xu, Chen Xia, YFZ, 2206.11454

Distinguishing CRDM from other boosted DM models

Define an azimuthal asymmetric parameter

$$A_R = \frac{N(\Omega_1) - N(\Omega_2)}{N(\Omega_1) + N(\Omega_2)},$$

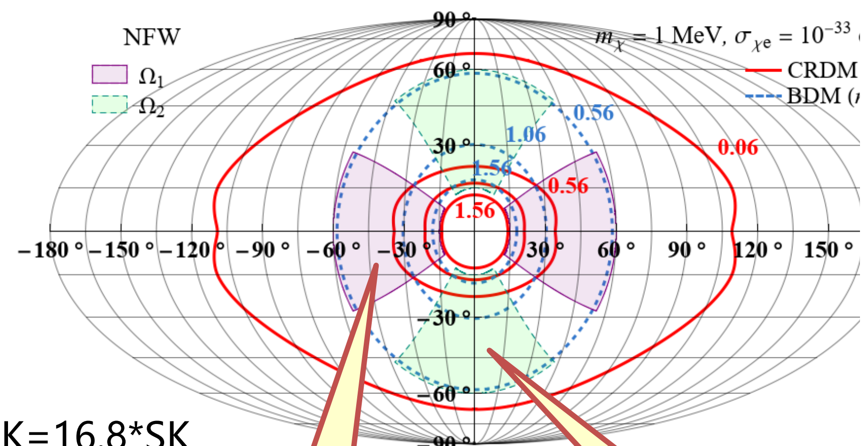
Regions Ω_1 and Ω_2 are related by a 90^0 rotation

Optimize Ω_1/Ω_2 to maximize A_{R}

According to the SK background rate

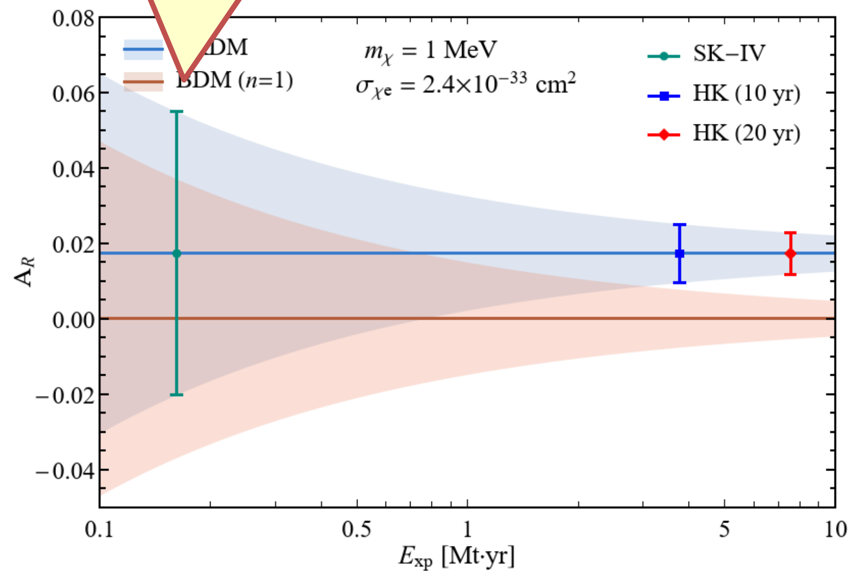
future $A_{\mathrm{R}}^{HK} = 0.017 \pm 0.0055$

now $A_{\mathrm{R}}^{SK} = 0.017 \pm 0.036$



HK=16.8*SK

Ω_1 Ω_2



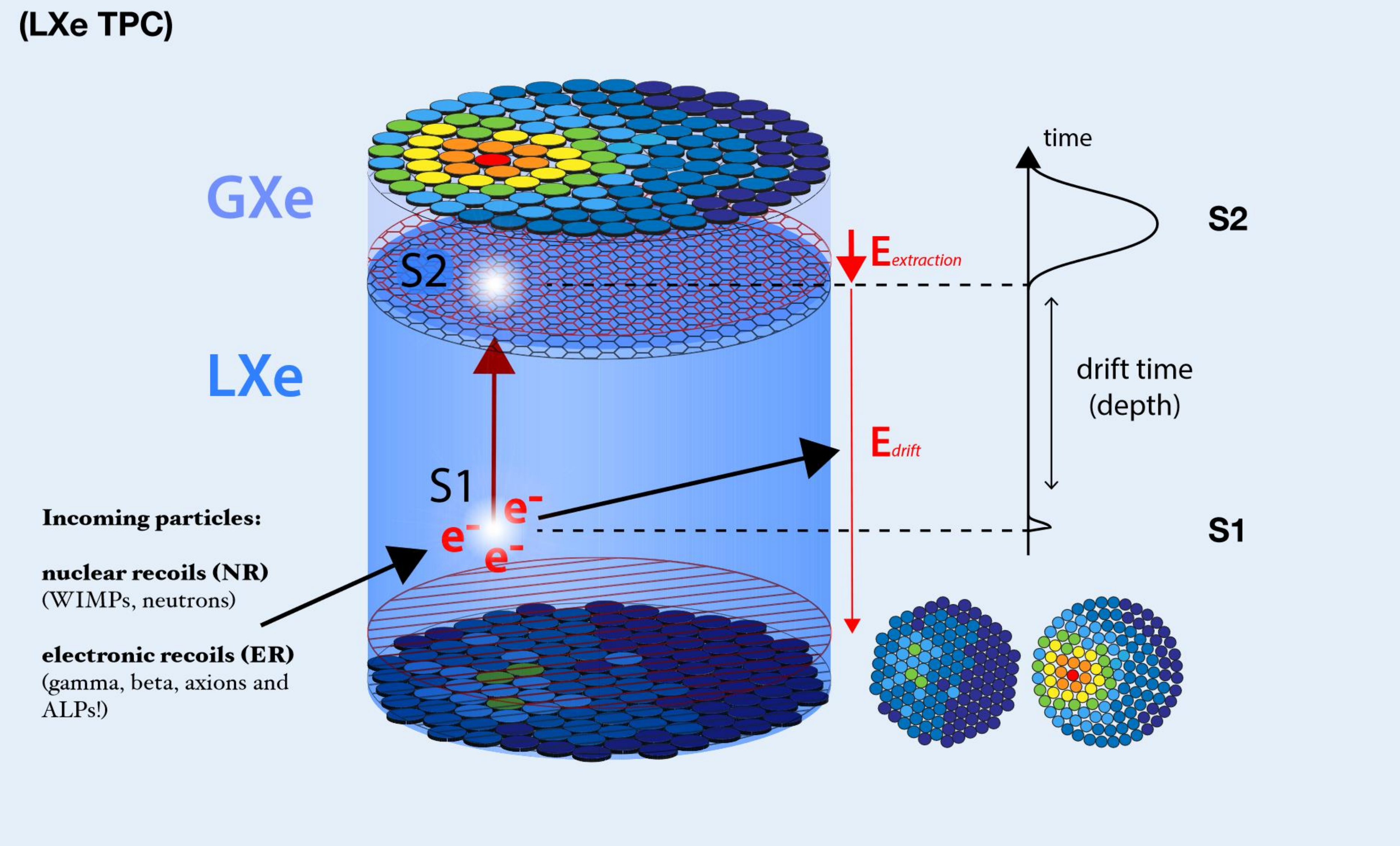
CRDM can be distinguished from other boosted DM models

Summary

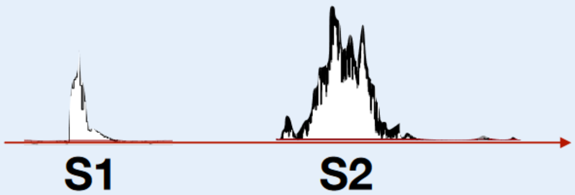
- For DM direct detection experiments, CRDM is an irreducible subcomponent of the Galactic DM
- CRDM do not suffer from the threshold problem, allowing for constraining ultra-light DM particles.
- For DM-nucleon scatterings, the nuclear formfactor suppresses the Earth attenuation of CRDM, making the Earth more transparent and enlarge the exclusion region of the cross section.
- The morphology of the CRDM is different from most of the other boost DM models, such a difference can be measured by future experiments such as hpyer-K

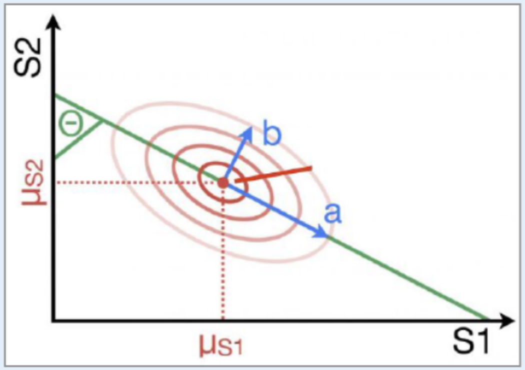
Thanks for your attention !

Backup slides


(LXe TPC)
GXe
LXe
S2
S1
e⁻
e⁻
e⁻
E extraction
E drift
time
S2
drift time
(depth)
S1
Incoming particles:
nuclear recoils (NR)
(WIMPs, neutrons)
electronic recoils (ER)
(gamma, beta, axions and
ALPs!)

Energy reconstruction



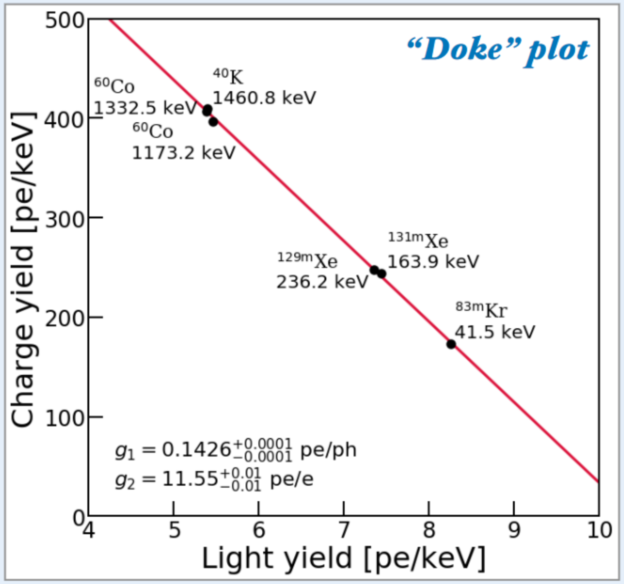


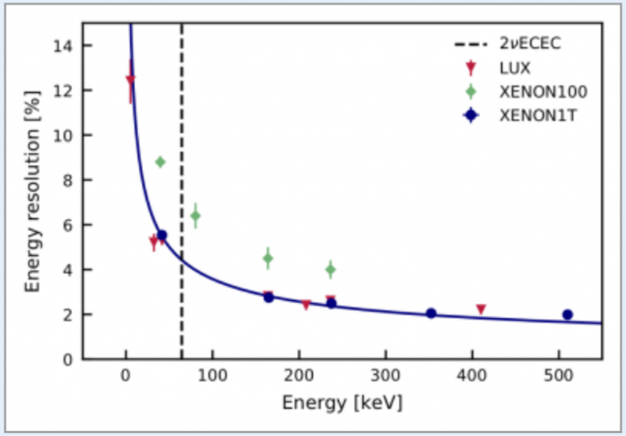
$$E = (N_{ph} + N_e) \cdot W = (\frac{S1}{g1} + \frac{S2}{g2}) \cdot W$$

where W = 13.7 eV/quanta

g1 and g2: detector-specific gain constants
extract g1/g2 from calibration data, use it to reconstruct energy of each event

Combined Energy Scale





Slide from Xenon-1T

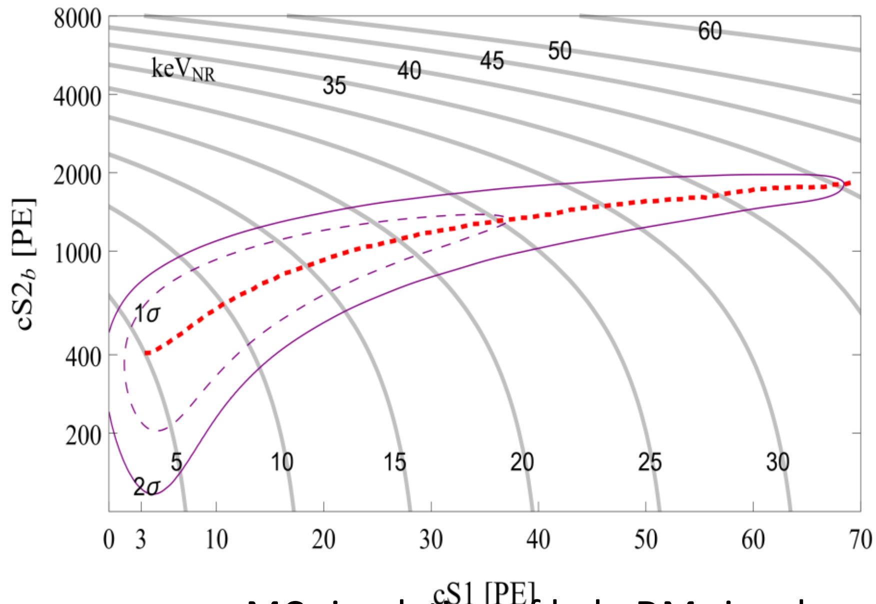
Statistic approaches

Statistic approaches

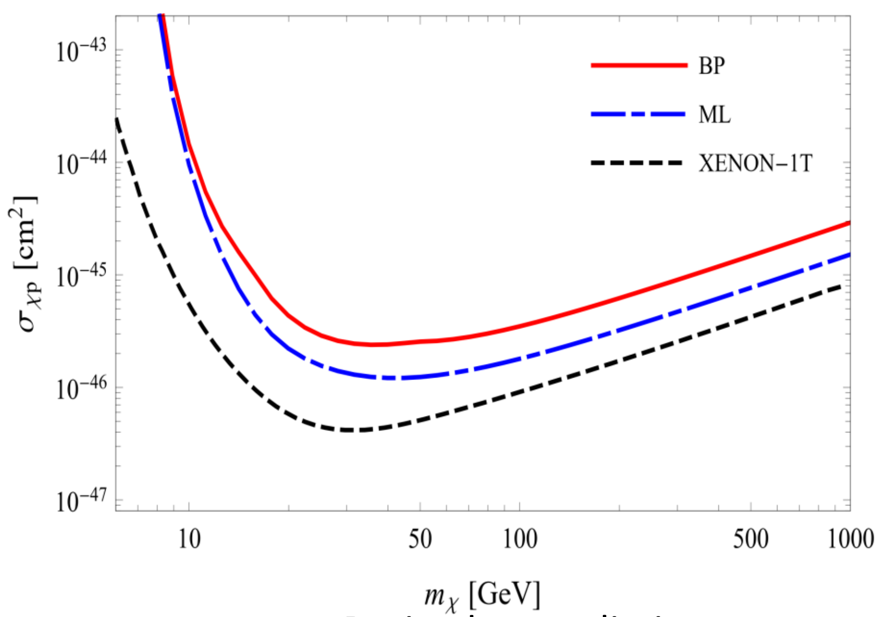
- Binned Poison
- Maximal likelihood

$$1 - \alpha = (1 - \alpha_{\rm bin})^{N_{\rm bin}}$$

$$\mathrm{TS} = -2\ln\frac{\mathcal{L}(m_\chi, \sigma_{\chi p})}{\mathcal{L}(\hat{m}_\chi, \hat{\sigma}_{\chi p})},$$



MC simulation of halo DM signal (m_chi=???)



Derived upper limits

Go to indirect measurements of CR flux

Methods for measuring cosmic rays particles

- ❑ direct: space based calorimeters
  - ➢ Excellent mass resolution
  - ➢ Limited energy range, typically E<200 Tev

  (so far adopted by all the current analyses)
- ❑ Indirect: ground based air-shower arrays
  - ➢ Mass resolution limited to major groups
  - ➢ Very large energy range: $E \sim 10^{20}$ eV,