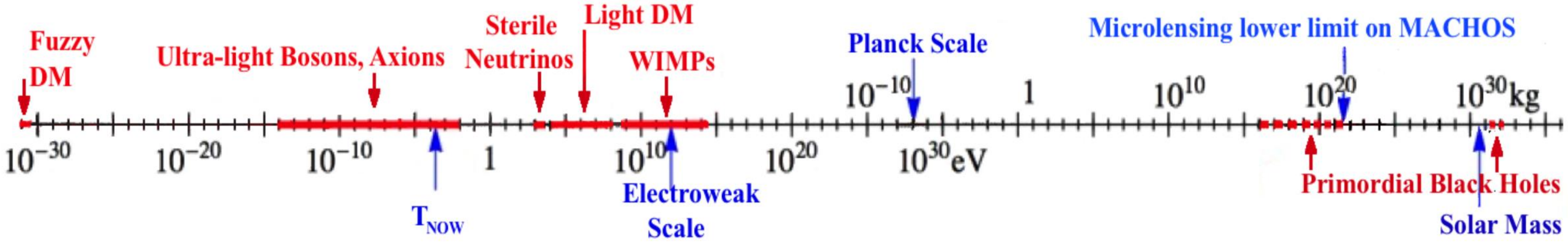
Connecting dark matter direct and indirect searches

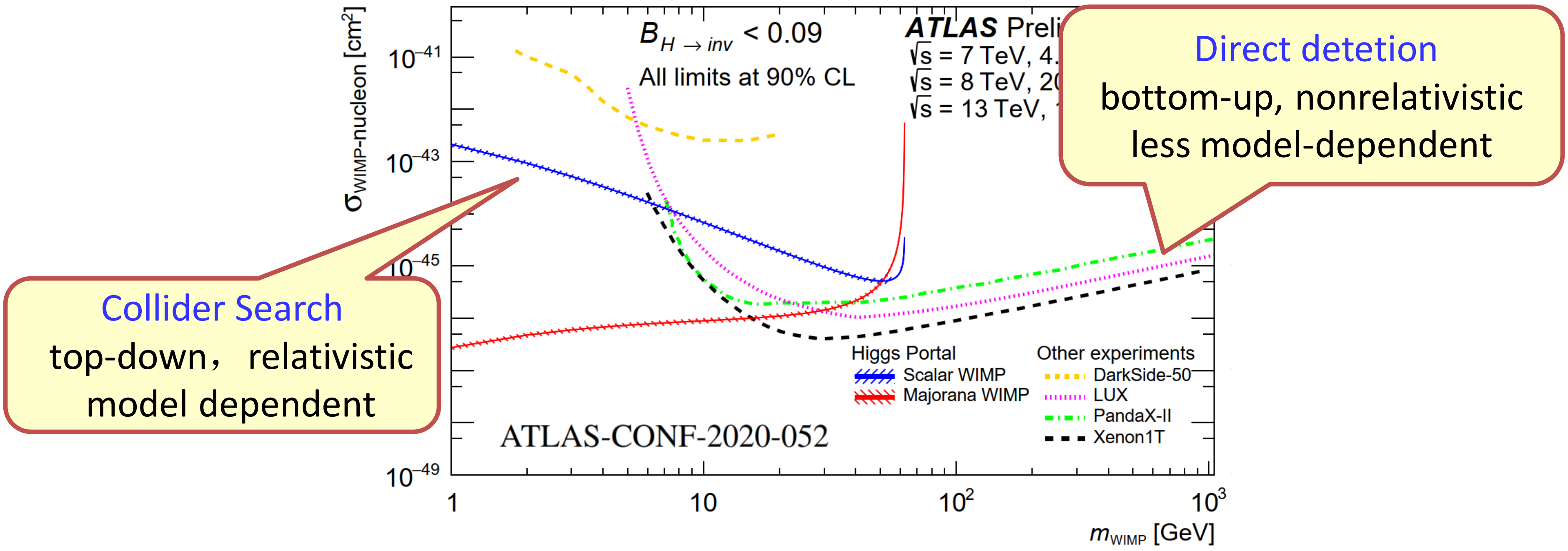
Yu-Feng Zhou

Institute of Theoretical Physics,
Chinese Academy of Sciences

Dark matter candidates and searches

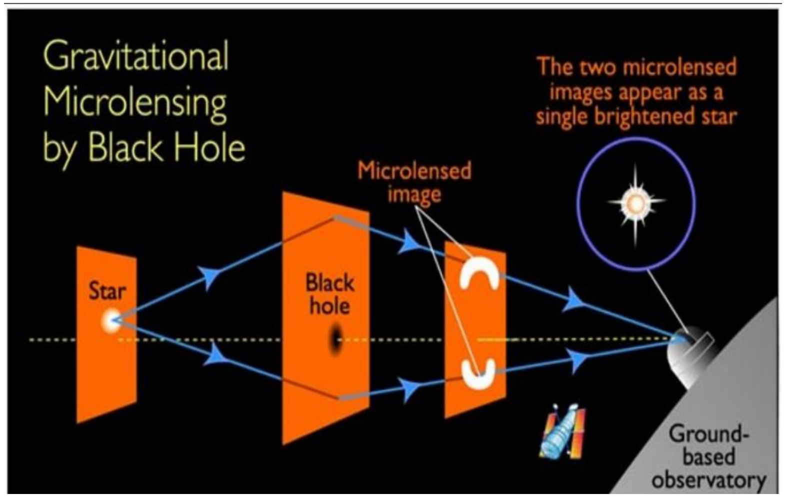


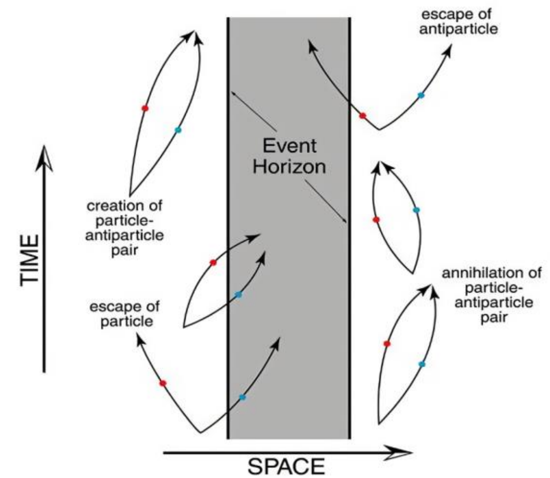
Collider search vs. Direct detection

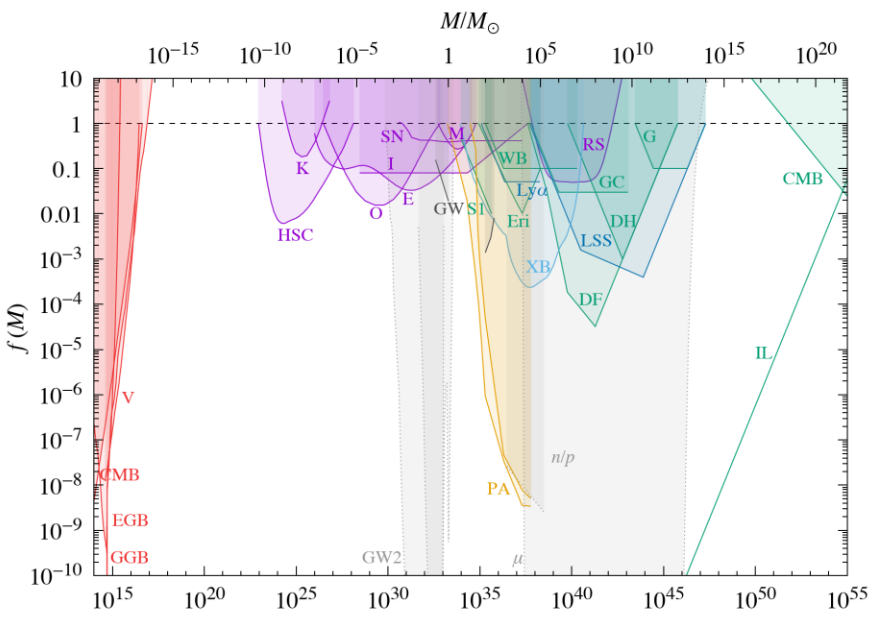


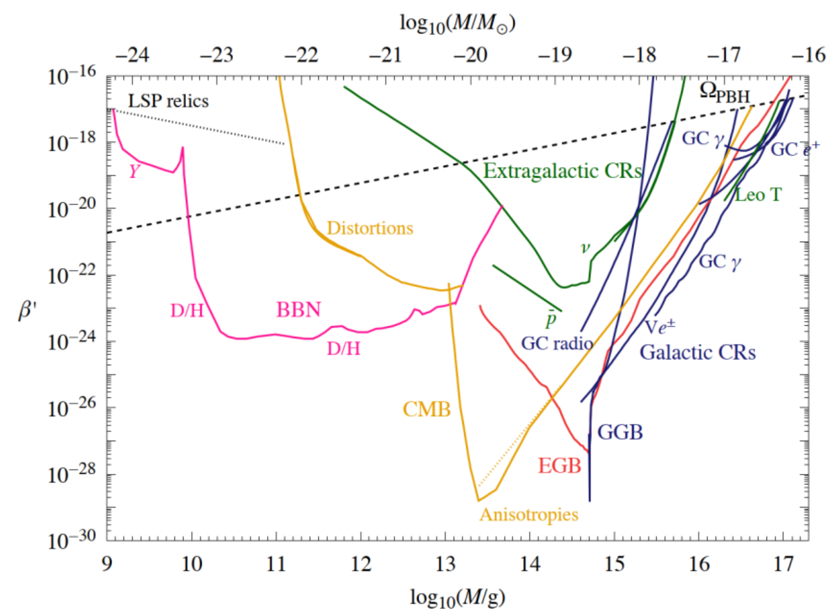
Searches for DM in a vast parameter space requires complementary approaches

Primordial black holes (PBHs): astrophysical candidates



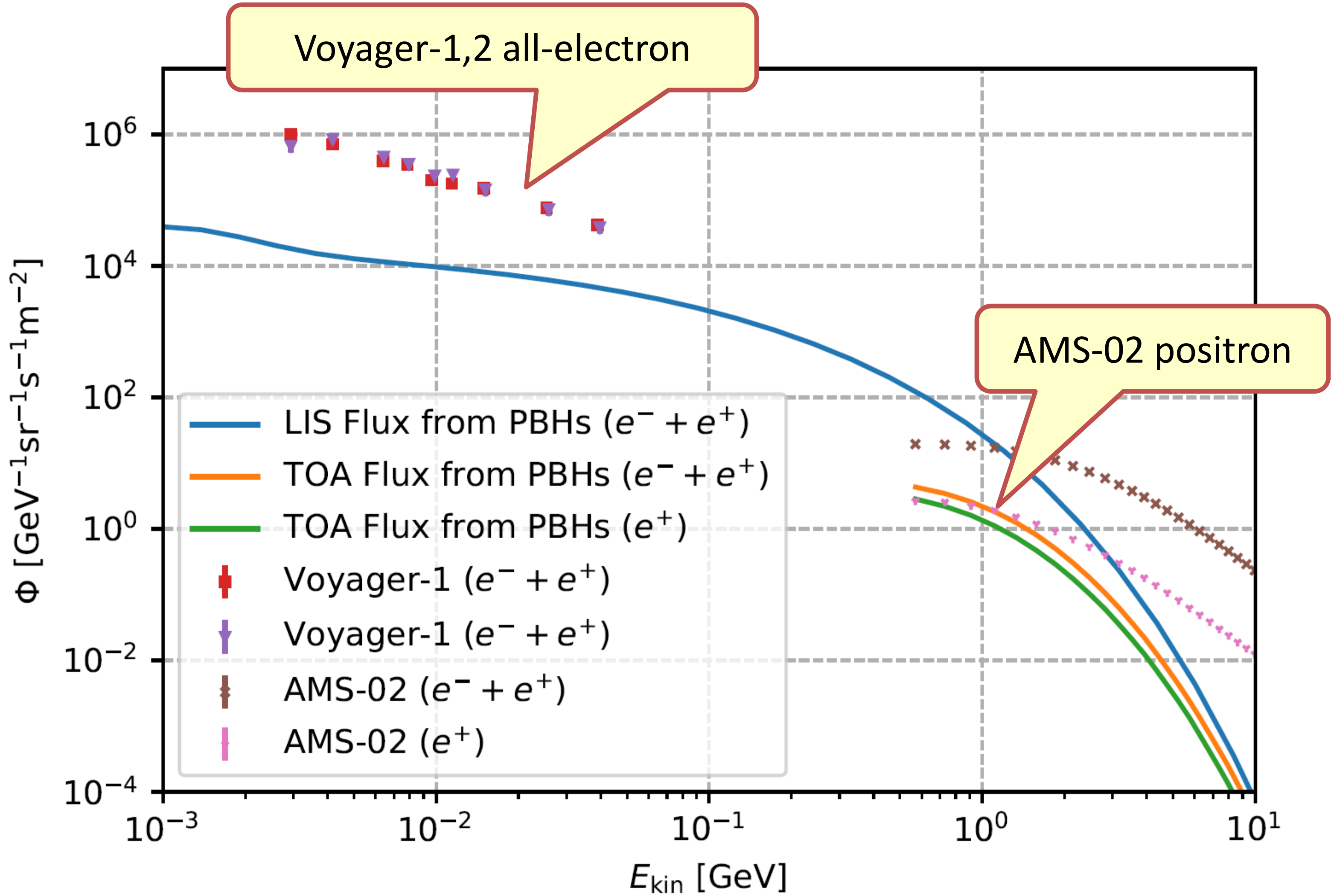






PBH as whole DM strongly constrained by gravitational lensing and evaporation effects

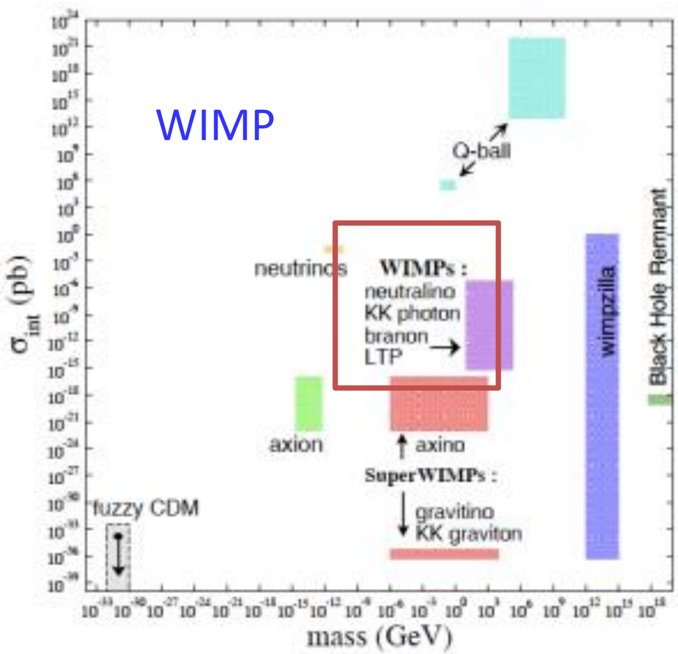
Stringent constraints on PBH from AMS-02 e^+ flux

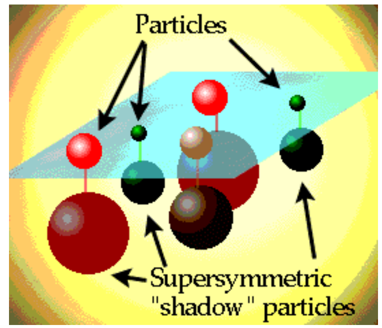


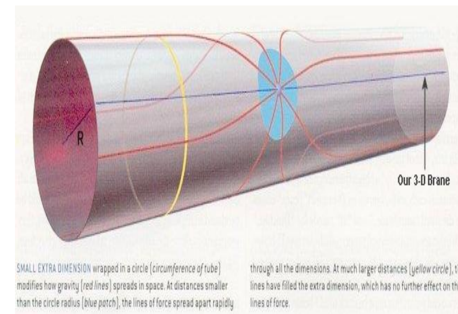
An analysis based on **Galprop+Helmod** framework

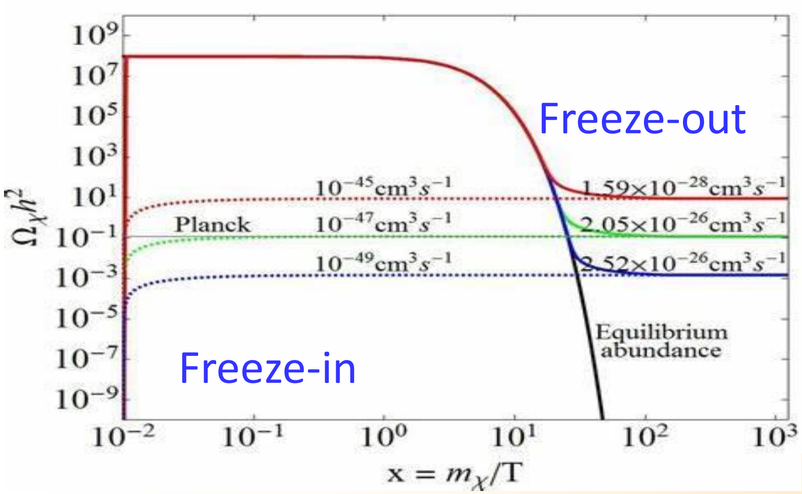
J. Z. Huang and YFZ, 2401.xxxx

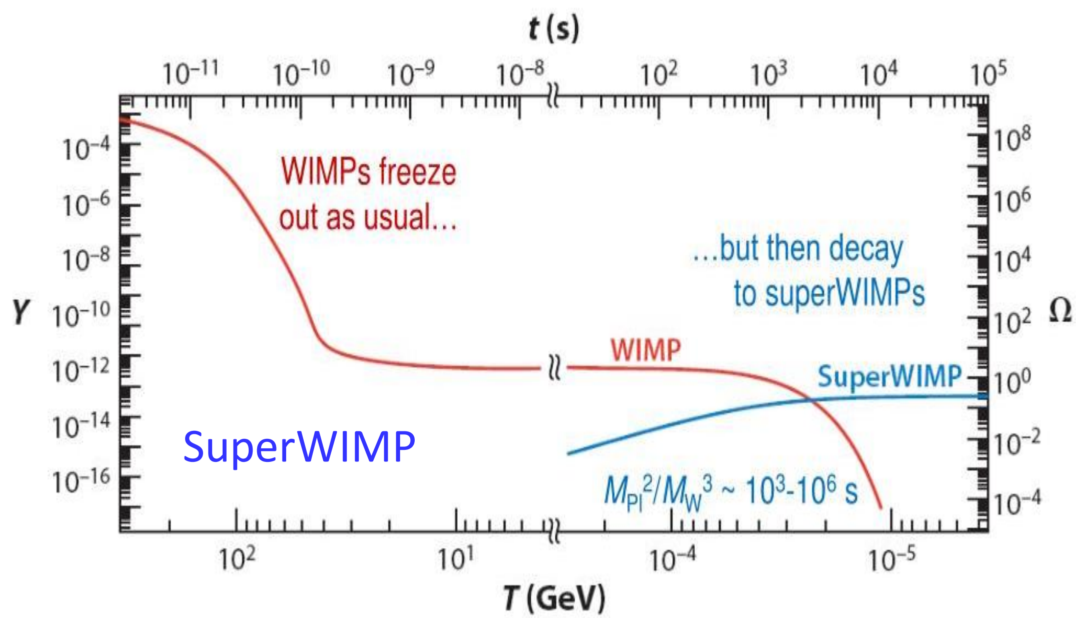
WIMPs, SuperWIMPs, Freeze-in









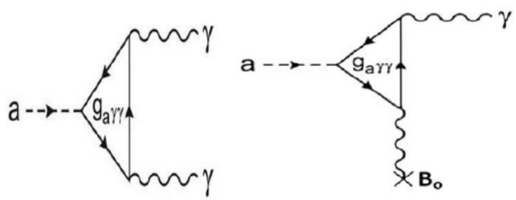


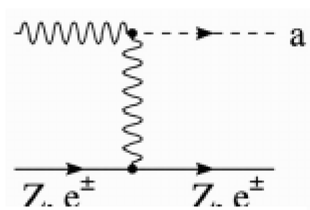
WIMPs: relic density ←→ interaction strength

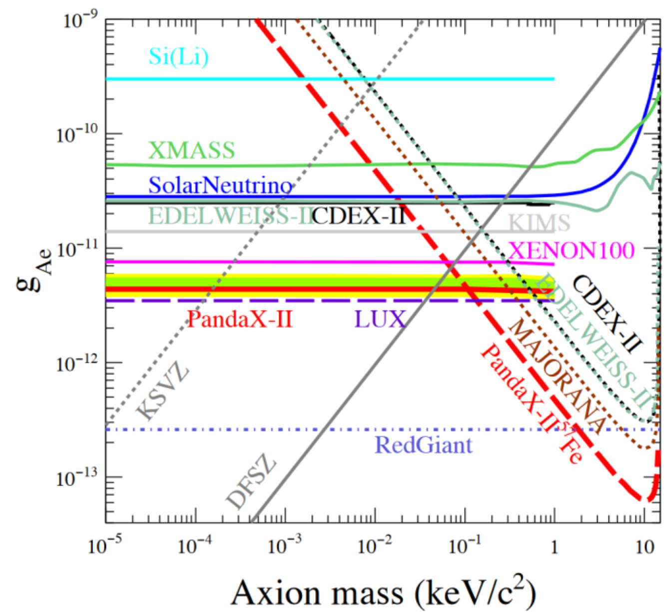
QCD axion and ALPs

Axions are well-motivated by the strong CP problem

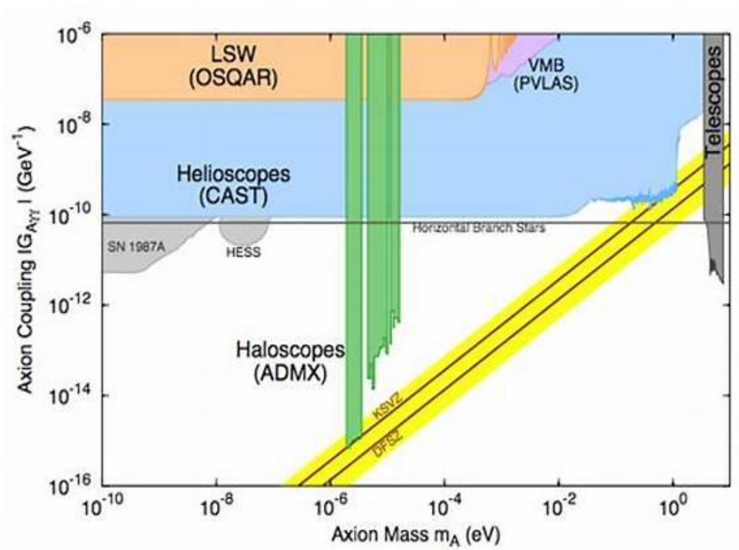
- Typically couple to photons
- Some axions couple to electrons and quarks （DSFZ)
- Can be cold DM, originated from misalighment

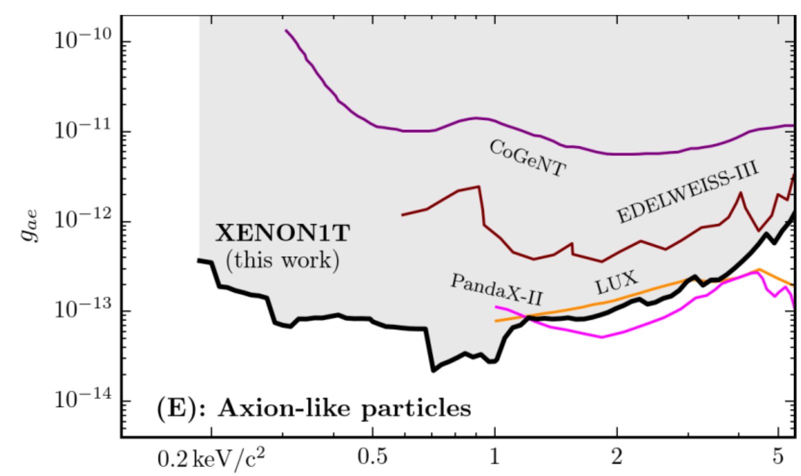






$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 + \frac{1}{2}(\partial_\mu a \partial^\mu a - m^2 a^2) + \frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} \,,$$

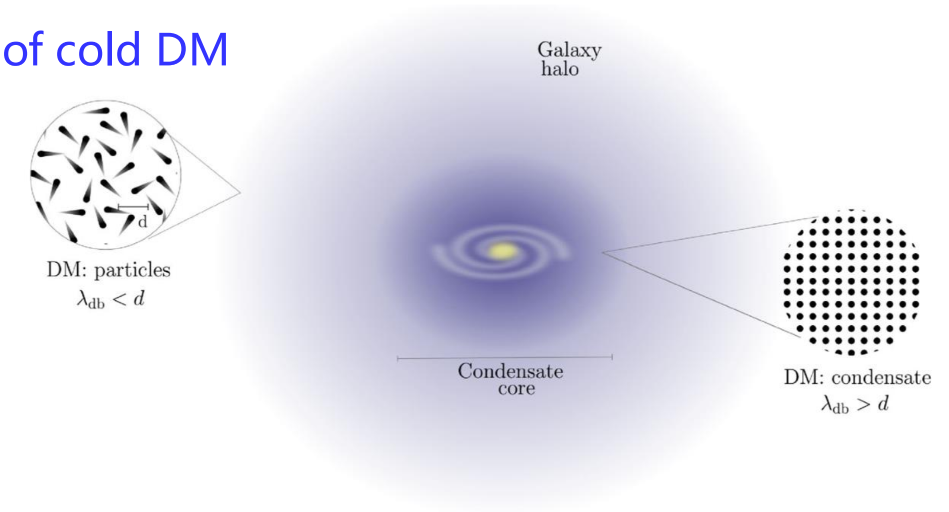




Ultra-light dark matter

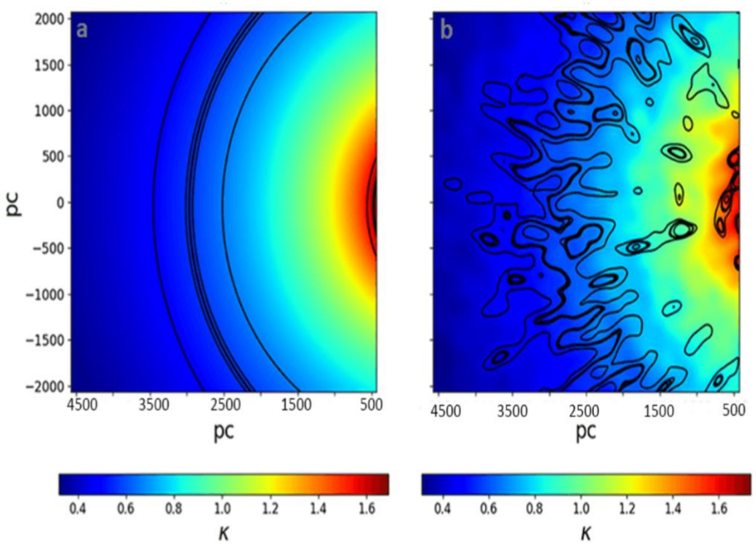
Motivated by small-scale problem of cold DM

I. Cusp-Core
II. Missing satellites
III. Too-big-to-fail

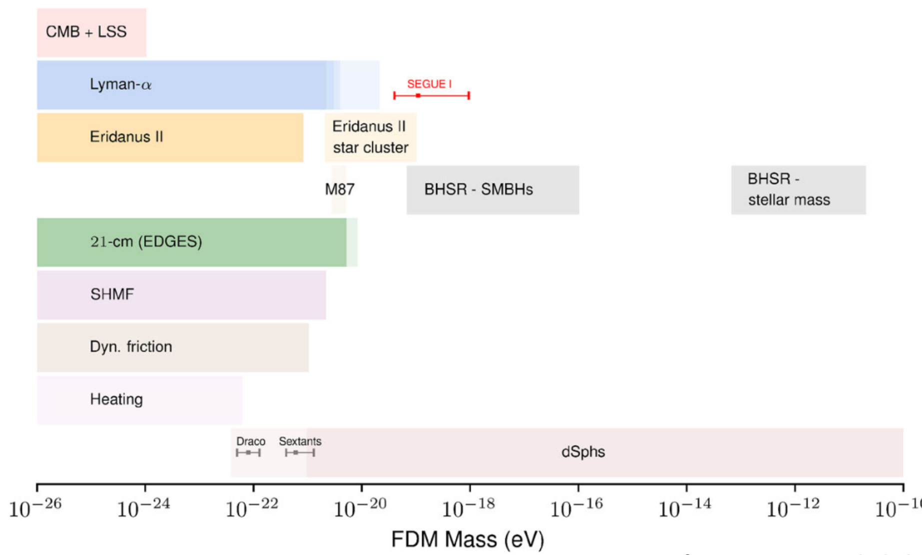


Ultra-light dark matter

- ❑ Formation of BEC, superfluid
- ❑ Change structure formation
- ❑ Change the propagation of light and GW wave

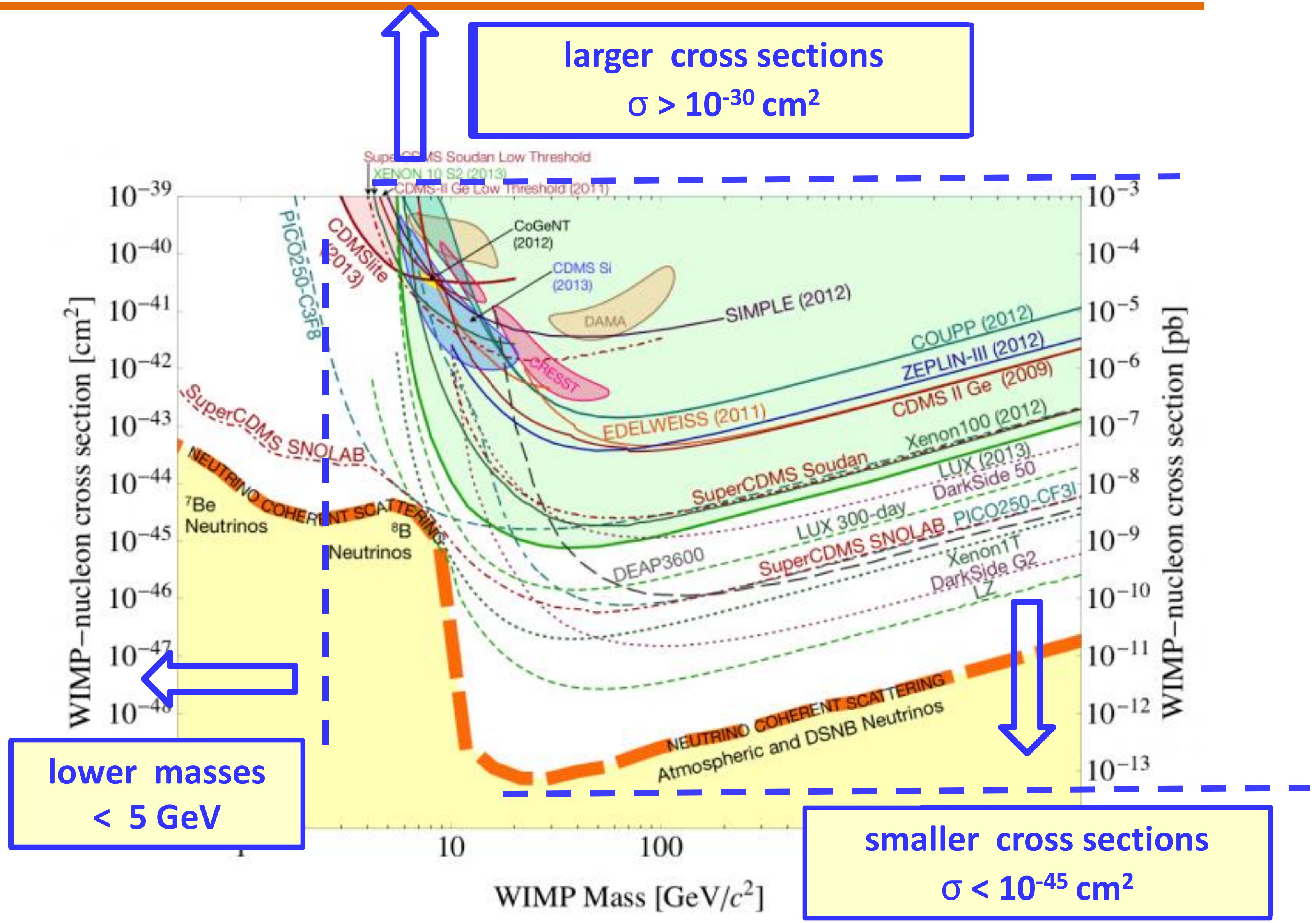


Amruth, et al, arXiv:2304.09895



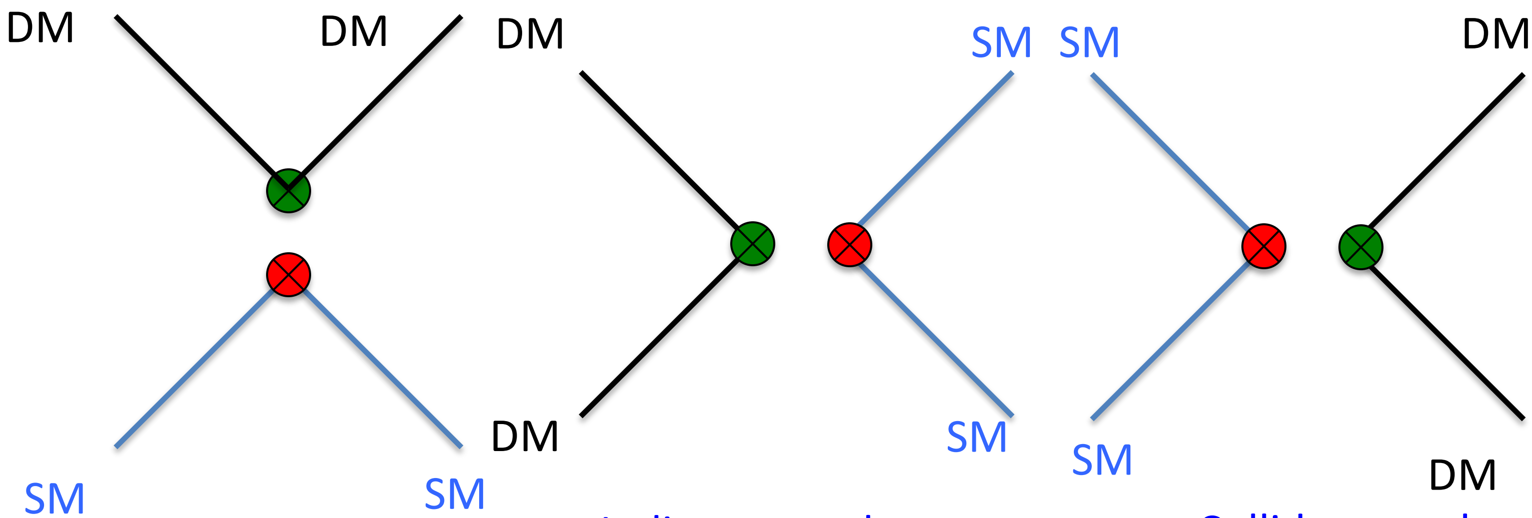
Ferreira, AAR,2021

Direct detection: DM scatterings underground



DM scatterings may occur everywhere

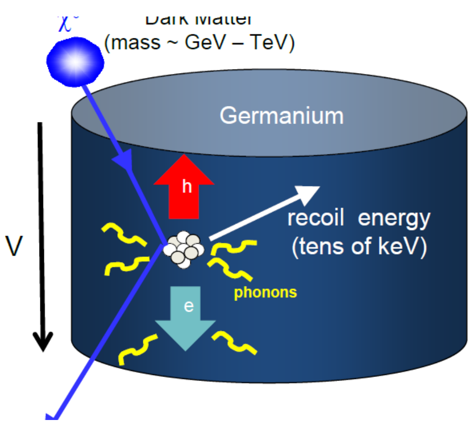
DM may interact with SM particles (weakly)

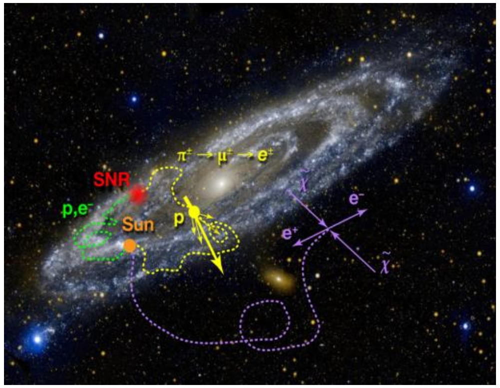


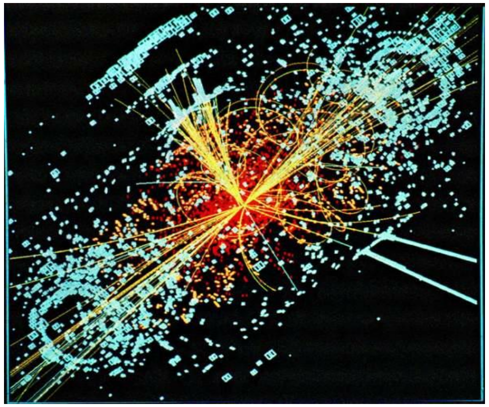
Direct searches

Indirect searches

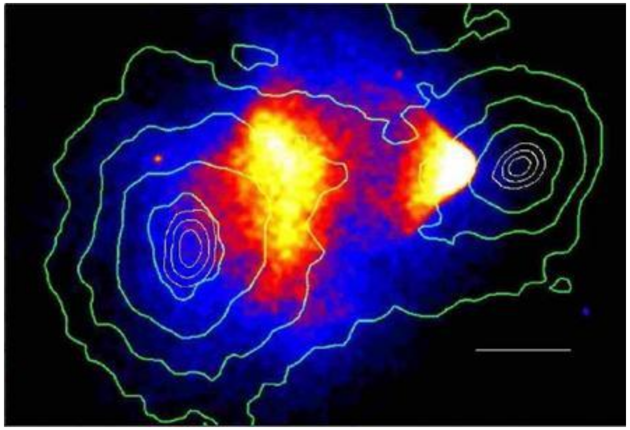
Collider searches



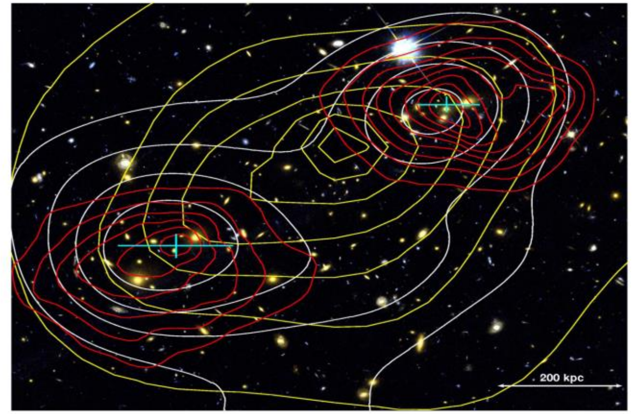




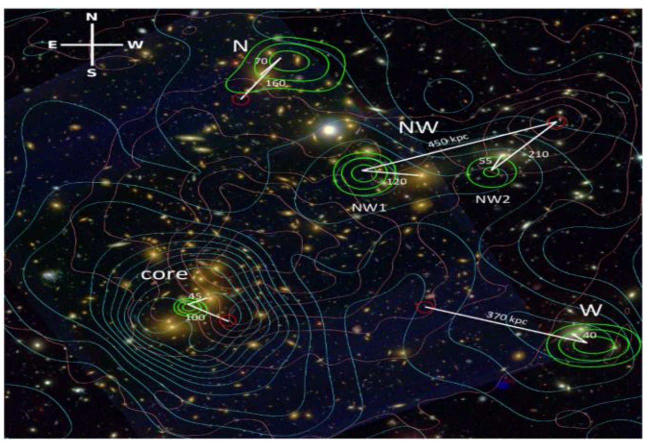
DM scattering in space: merging clusters



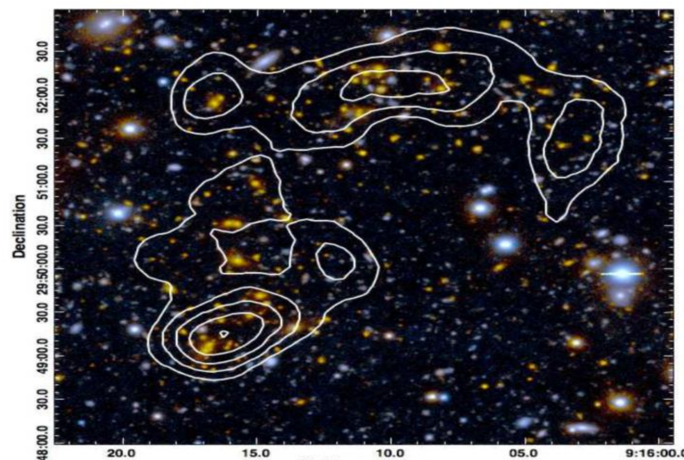
1E0657-56



MACS J0025.4−1222



Abel 2744



DLSCL J0916.2+2951

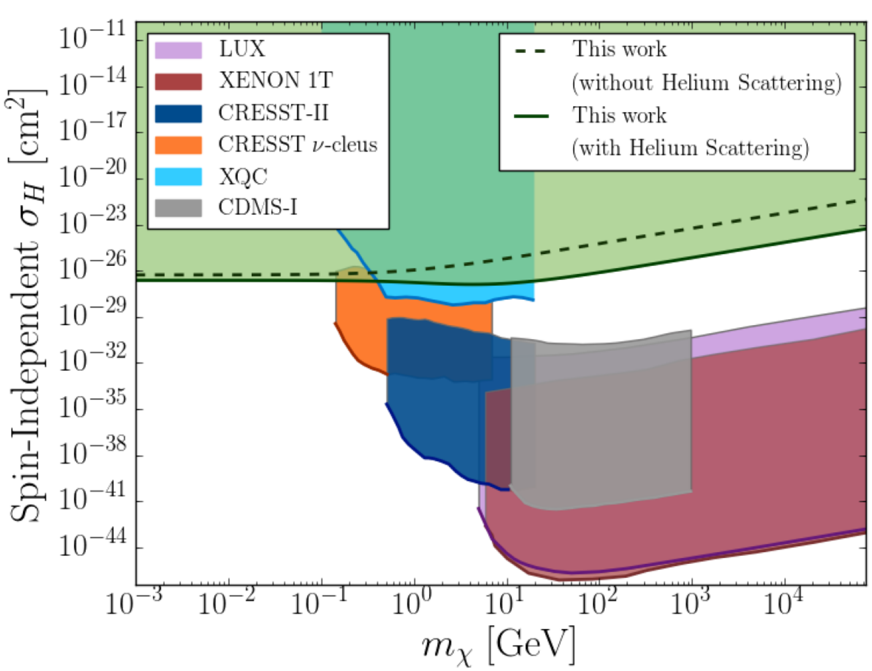
Typical constraints on self-scattering: $\frac{\sigma}{m_\chi} \leq O(10^{-24})\ cm^2/GeV$

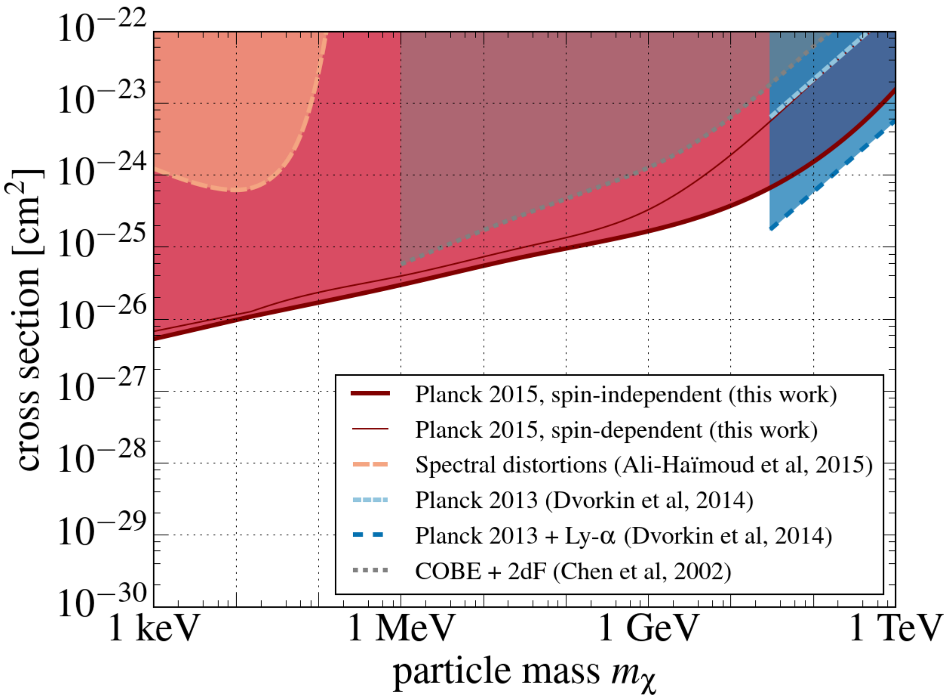
DM scatterings in space: CMB

DM-proton scattering in early universe

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

Constraints: $\sigma < 10^{-27}$ cm^2 @ 1 keV



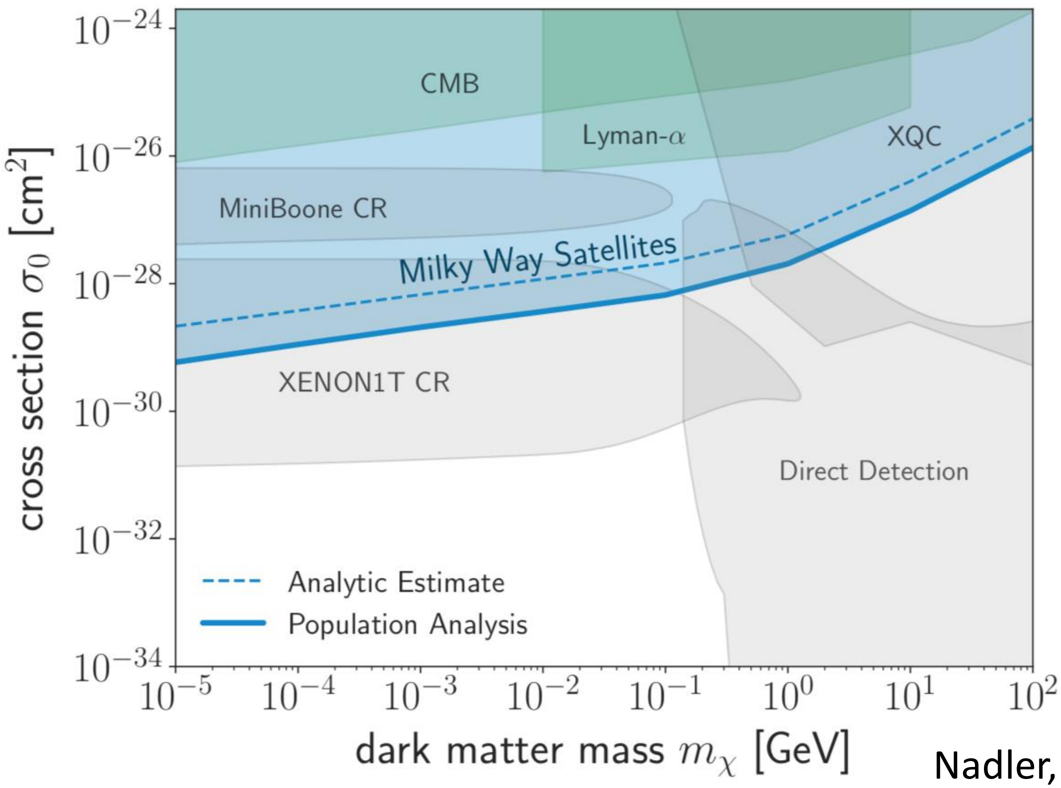


Constraints from CMB insensitive to DM particle mass

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 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, arXiv:2202.07598

- **Supernova** (up-scattering)

Lin, et.al, arXiv:2206.06864

- **Supernova remnants** (up-scattering)

Cappiello et.al, arXiv:2210.09448

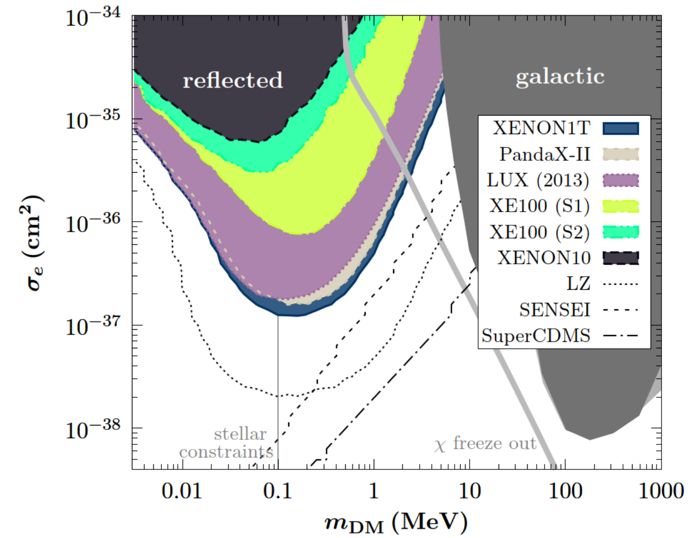
- **Blackholes** (Hawking evaporation)

Calabrese, et.al, arXiv:2107.13001
Chao, et.al, arXiv:2108.05608
Kitabayashi, arXiv.2204.07898

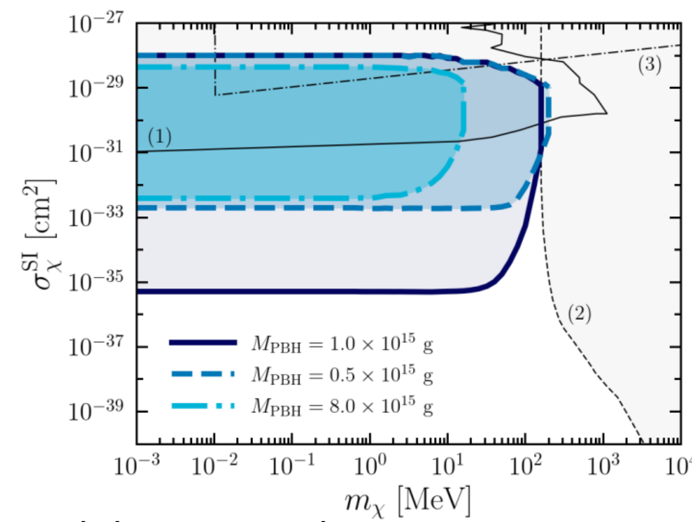
- **Cosmic rays** (up-scattering)

Bringmann, et.al, arXiv:1810.10543
Ema, et.al, arXiv: 1811.00520
Cappiello, et.al, 1arXiv:906.11283

> CR-DM scattering:
> an irreducible process for DM direct search

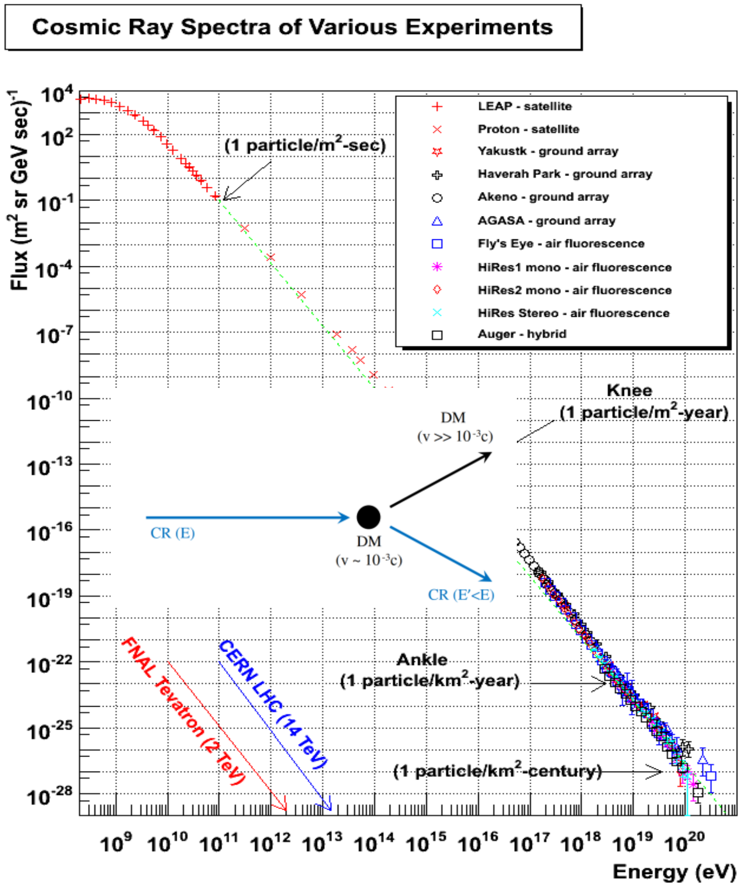


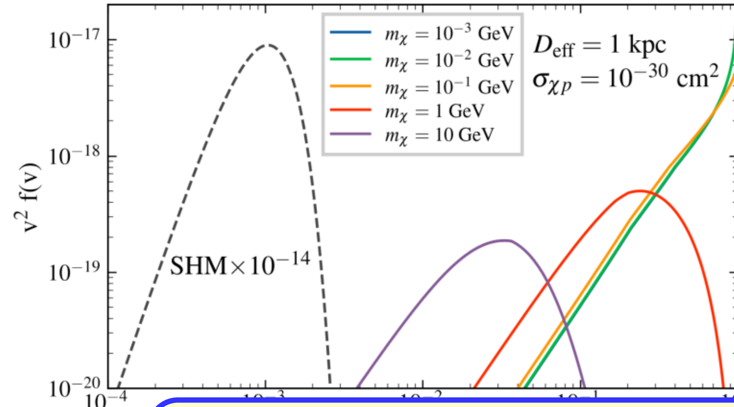
An, et.al, 1708.03642



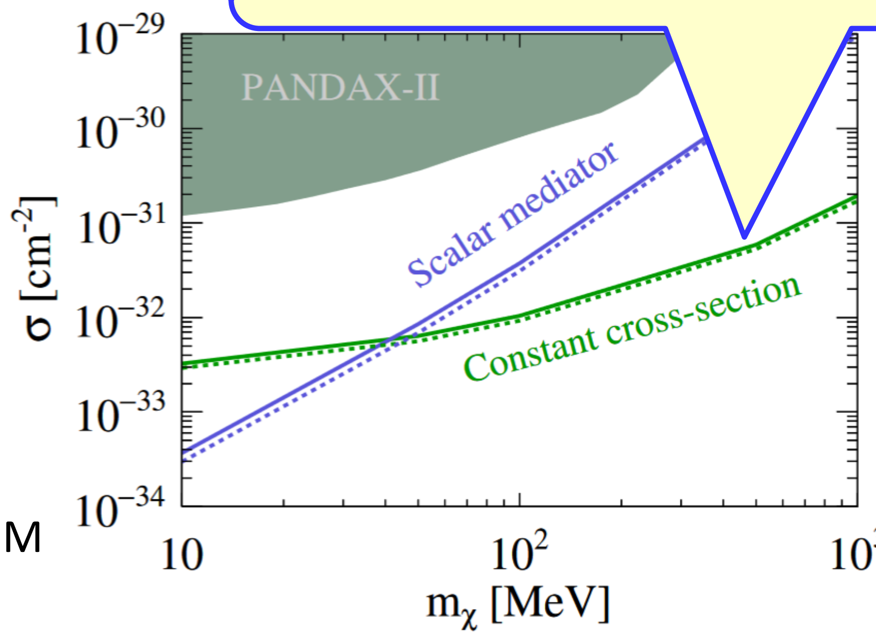
Calabrese, et.al, arXiv:2107.13001

CR-DM scattering: CR boosted dark matter





the most stringent limits on CRDM set by neutrino exps. now



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

Anisotropy in the boosted DM flux

Distribution of DM flux close follows the sources

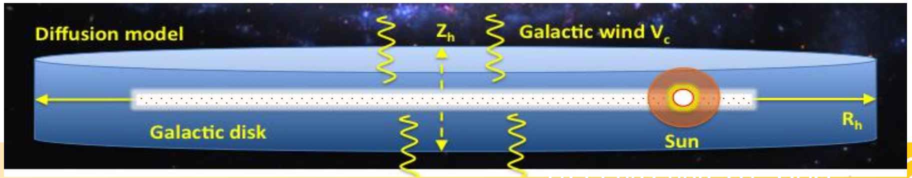
- DM boosted by the Sun, supervona, etc, point-like
- DM boosted by the dark sector diffuse, azimuthal symmetric
  - decay $$\left(\frac{d\Phi_\chi}{dT_B d\Omega}\right)_{\rm dec} = \frac{1}{4\pi m_A \tau_A}\frac{dN}{dT_B}\int_{\rm l.o.s} d\ell \rho_\chi(\boldsymbol{r}),$$
  - annihilation $$\left(\frac{d\Phi_\chi}{dT_B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

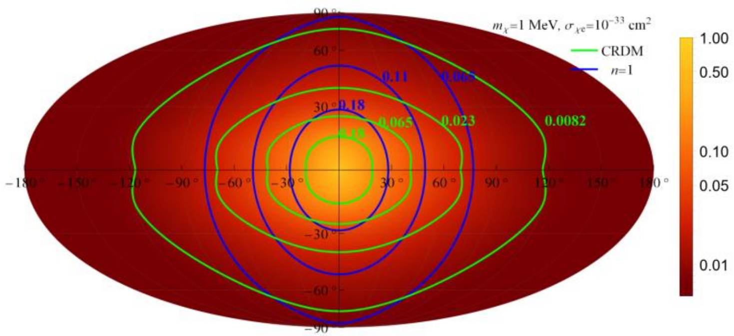
Harmonic expansion

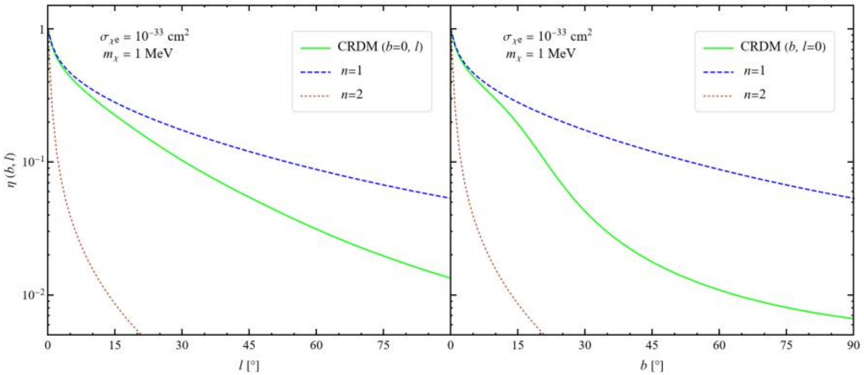
$$\frac{d\Phi_\chi}{d\Omega}(\theta,\varphi)=\sum_{l=0}^{\infty}\sum_{m=-l}^{l}a_{l,m}Y_{l,m}(\theta,\varphi),$$

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	[illegible]	0	0	0
	BDM ($n=2$)	1.28	1.33	1.32	1.29	1.27	0	0	[illegible]	0	0	0
Einasto	CRDM	1.06	1.00	0.88	0.75	0.64	0.11	0.11	[illegible]	[illegible]	[illegible]	[illegible]
	BDM ($n=1$)	0.68	0.43	0.30	0.22	0.17	0	0	[illegible]	[illegible]	[illegible]	[illegible]
	BDM ($n=2$)	1.36	1.46	1.47	1.45	1.42	0	0	[illegible]	[illegible]	[illegible]	[illegible]

symmetry breaking term only appears in CRDM

Yan-Hao Xu, Chen Xia, YFZ, 2206.11454

Probing the morphology of CREDM flux

Cherenkov detectors can tell the arrival direction of DM

Detectors for neutrino experiments

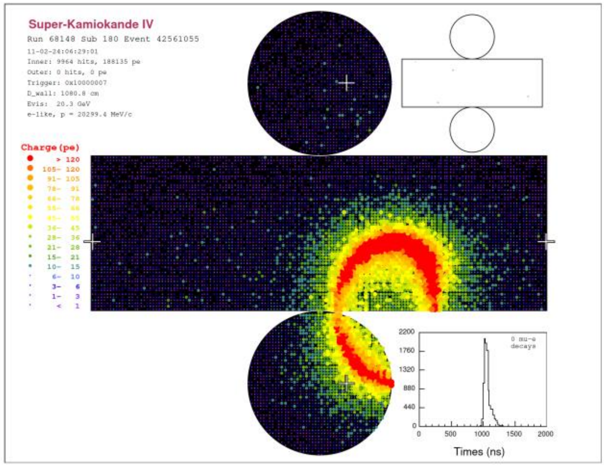
1) Liquid scintillator detectors: Borexino, *Dune*

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+



elastic electron scattering
Super-K (2018)

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

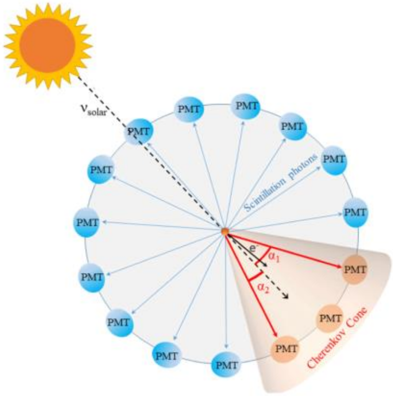
- ❑ neutrino Exps. have huge exposures

e.g. SK: 50 kt

- ❑ Water Cherenkov detectors can measure direction

recoil electrons (and protons) following the direction of DM

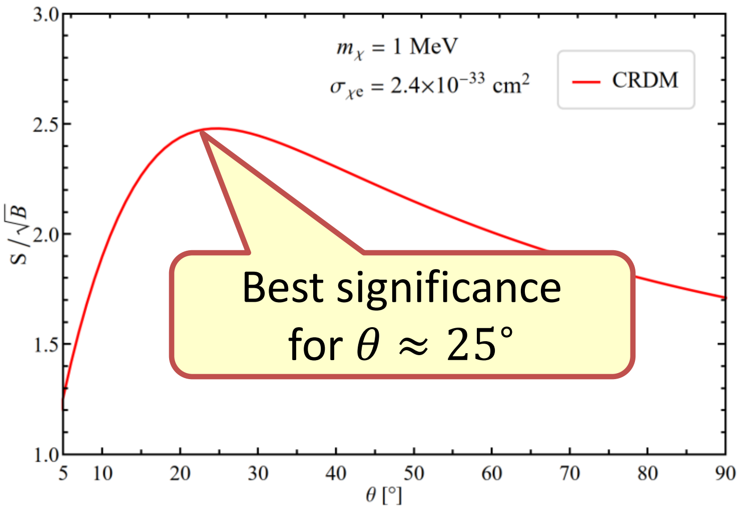
SK has good angular resolution ~ 3°



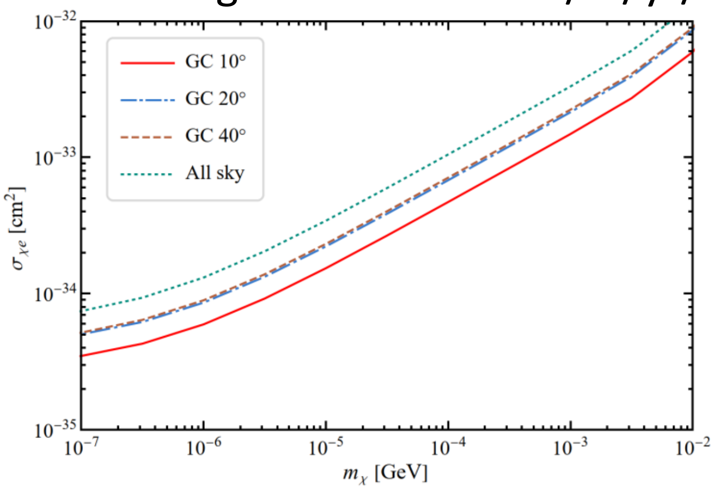
Borexino (2022)

Constraints on DM-electron scattering from SK-IV data

Optimize the search cone

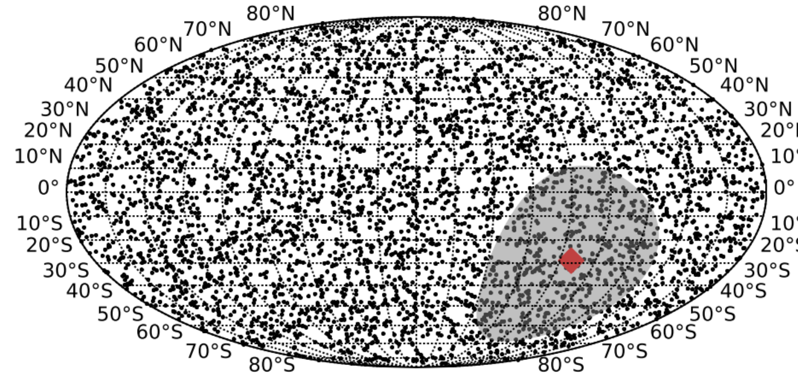


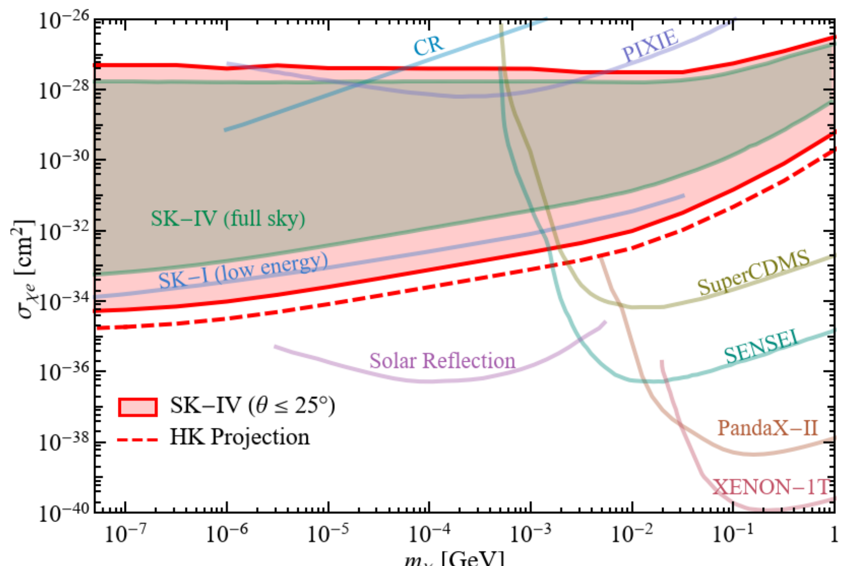
SK-IV background level: 1.96/kt/yr/sr



Limits at different cut-angles θ

SK-IV all-sky data, 0.1–1.33 GeV





We obtain 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 (PRD)

Distinguishing CRDM from other boosted DM models

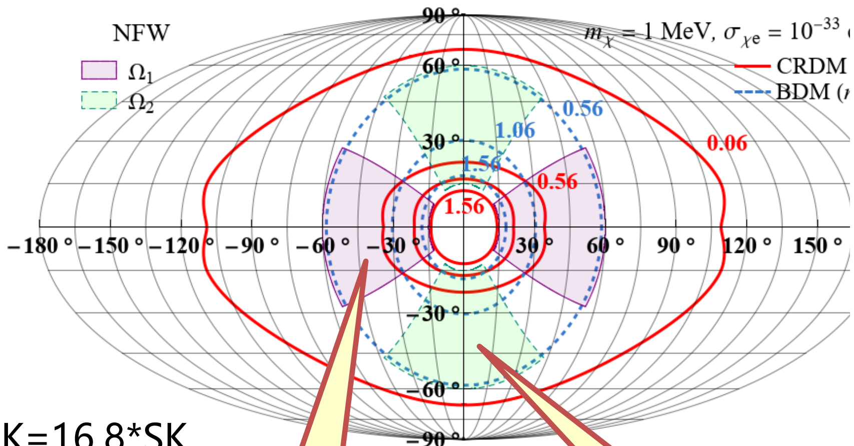
Define an azimuthal asymmetric parameter

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

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



HK=16.8*SK

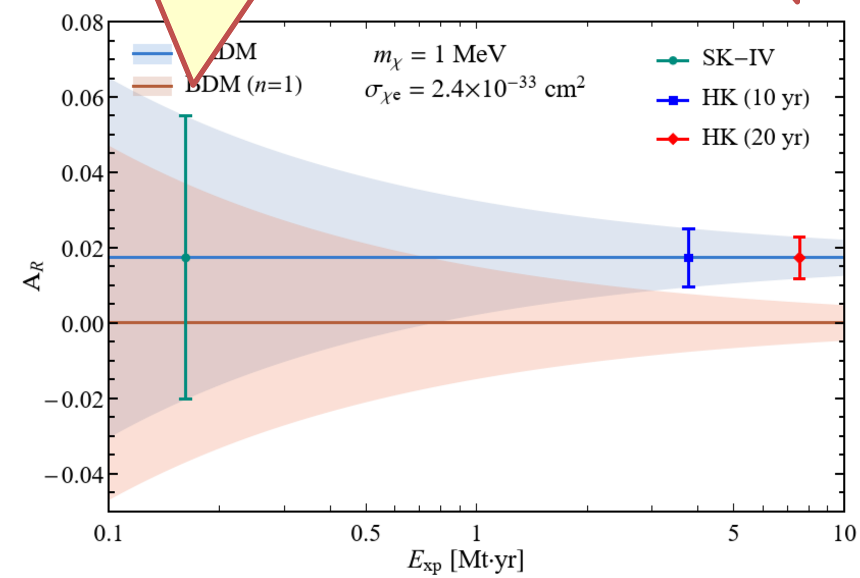
Ω_1

Ω_2

Yan-Hao Xu, Chen Xia, YFZ, 2206.11454 (PRD)

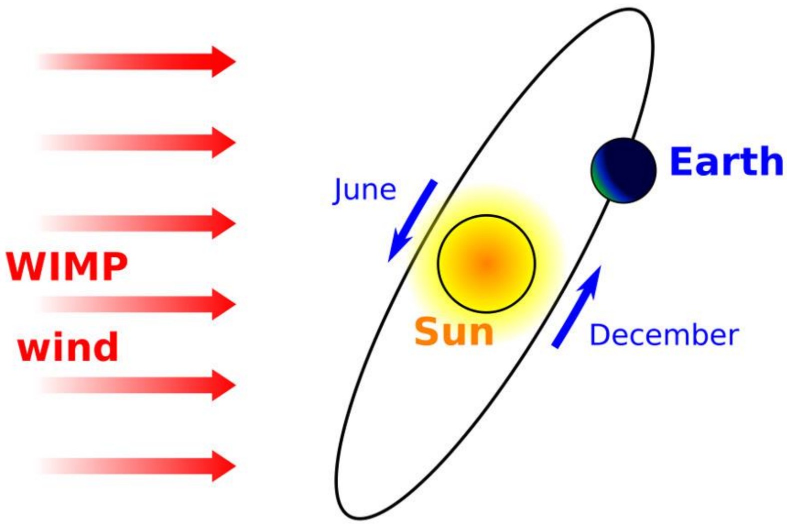
future $A_\mathrm{R}^{HK} = 0.017 \pm 0.0055$

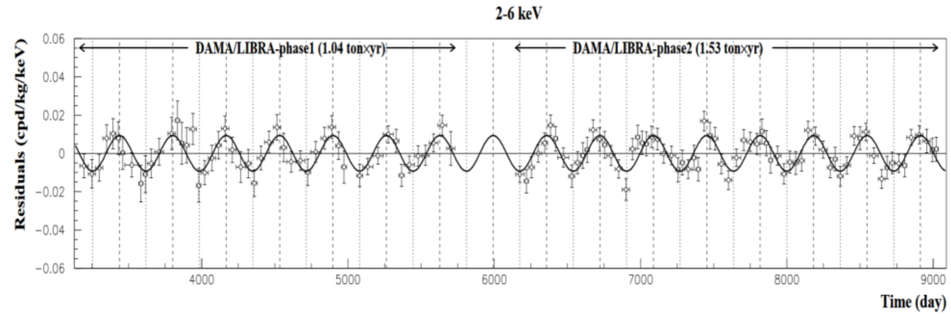
now $A_\mathrm{R}^{SK} = 0.017 \pm 0.036$



CRDM can be singled out from many boosted DM models

Anisotropic DM flux : annual modulaton

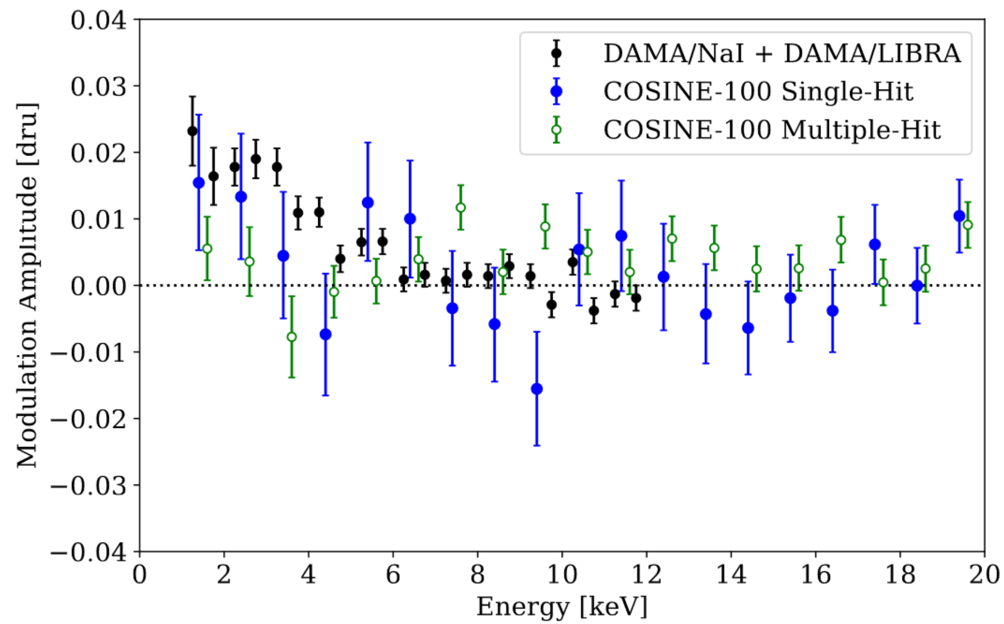




DAMA: arXiv:2209.00882

Standard halo model

$$f_{\rm halo}(\boldsymbol{v}) = \frac{n_0}{N}\exp\left(-\frac{\boldsymbol{v}^2}{v_0^2}\right)\Theta(v_{\rm esc}-|\boldsymbol{v}|),$$

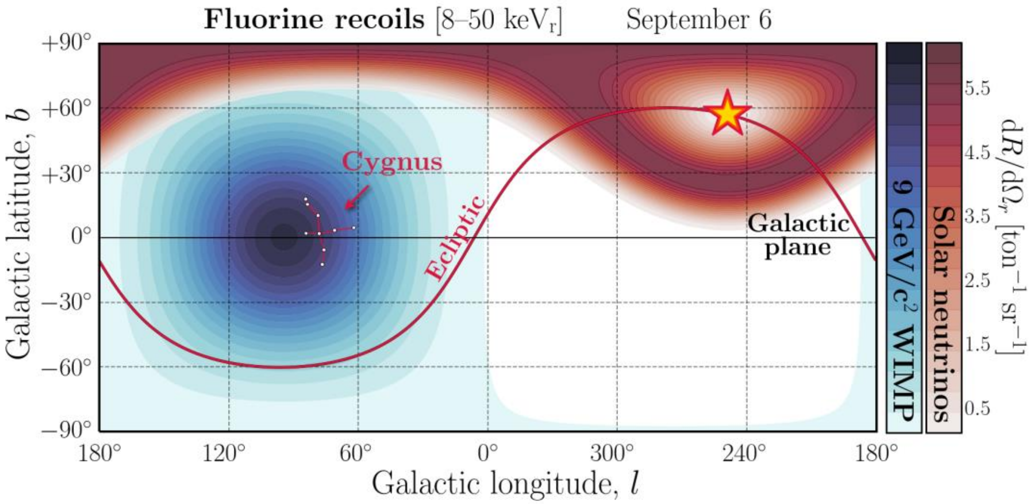


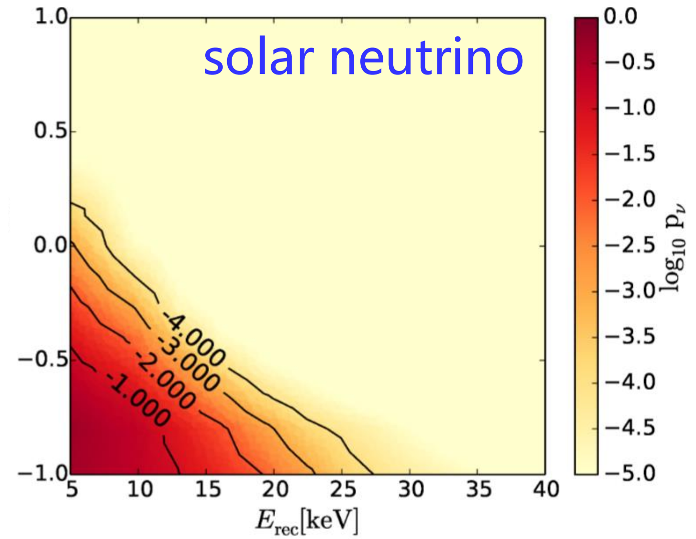
COSINE: arXiv:2111.08863

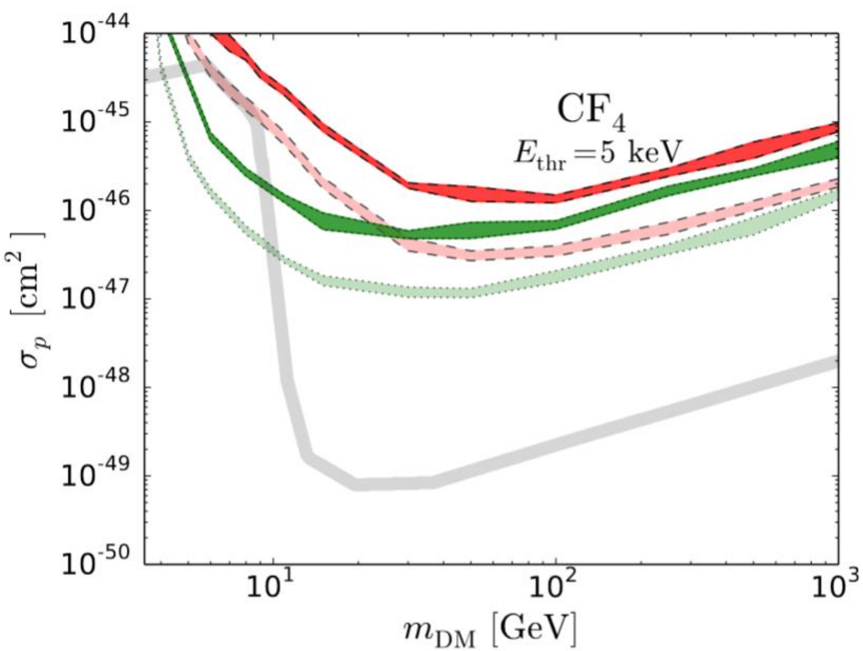
Advantages for DM search

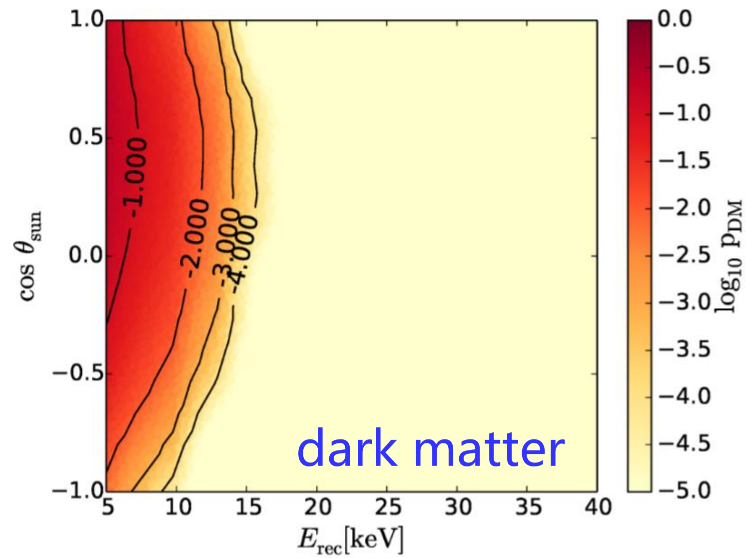
- ❑ reject all isotropic backgrounds
- ❑ go beyond the neutrino floor
- ❑ uniquely identify DM

Beyond the solar neutrino floor





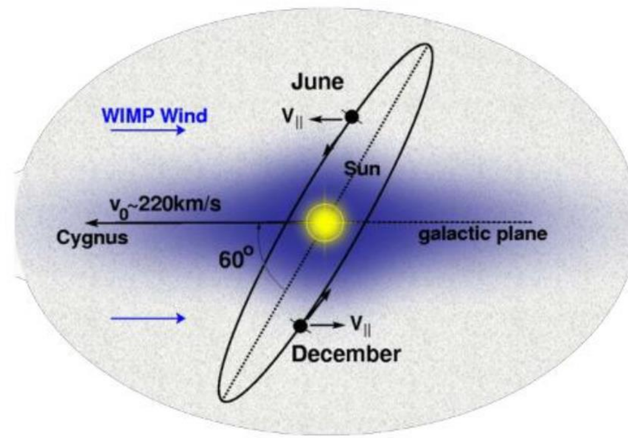




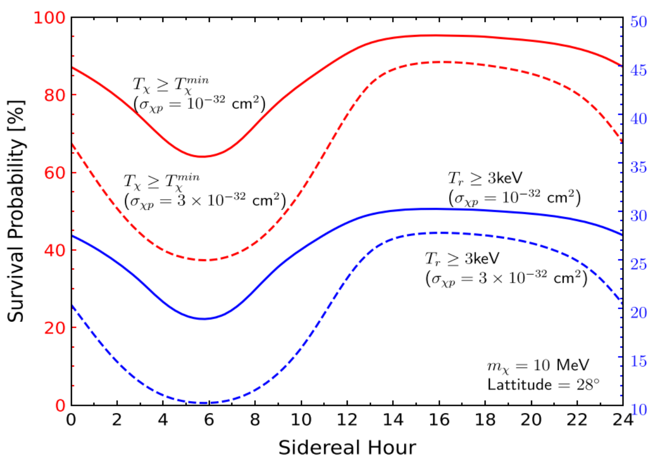
P. Grothaus, et al, arXiv:1406.5047

Anisotropic DM flux: diurnal modulation

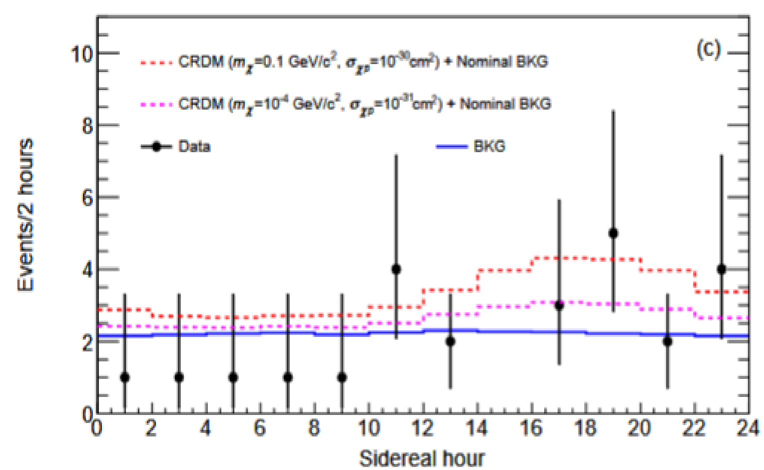
- **Annual modulation:** time-variation of DM flux
  - sensitive to halo DM (nonrelativistic)
  - apply to small cross section $\sigma_{\chi p} \sim O(10^{-40})$
  - modulation amplitudes typically small ($\leq 10\%$)



- **Diurnal modulation:** time-variation of underground DM flux
  - sensitive to both halo DM and boosted DM
  - require large cross section $\sigma_{\chi p} \sim O(10^{-30})$
  - modulation amplitudes can be much larger



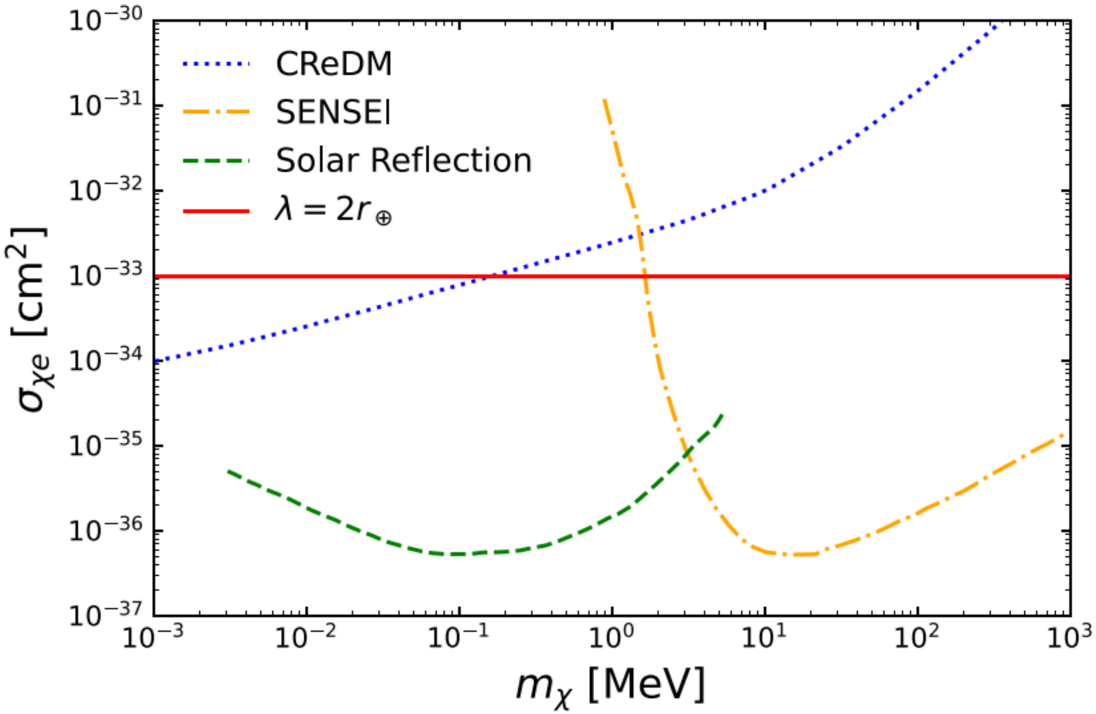
Ge, et al, arXiv:2005.09480 (PRL)



pandaX-II, arXiv:2112.08957 (PRL)

Diurnal modulation in electron events

Current constraints on DM-electron scattering cross section are strong enough



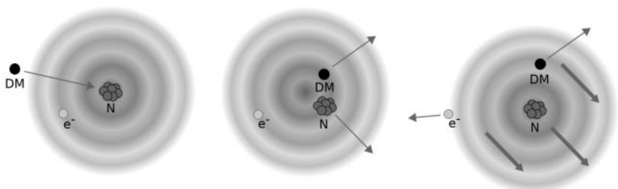
The DM mean-free-path is longer than the diameter of the Earth

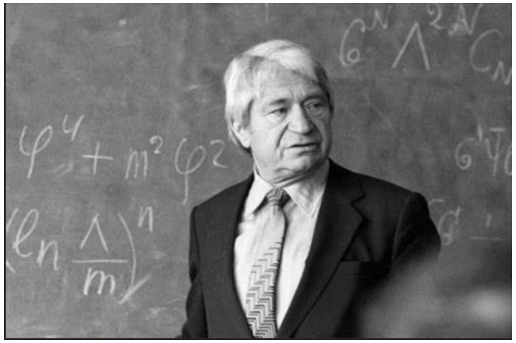
Impossible to see diurnal modulation in electron events ? No !

Electron signals from DM-nucleon scattering

❑ The Migdal effect:

Ionization electrons from nuclear scattering





cross section

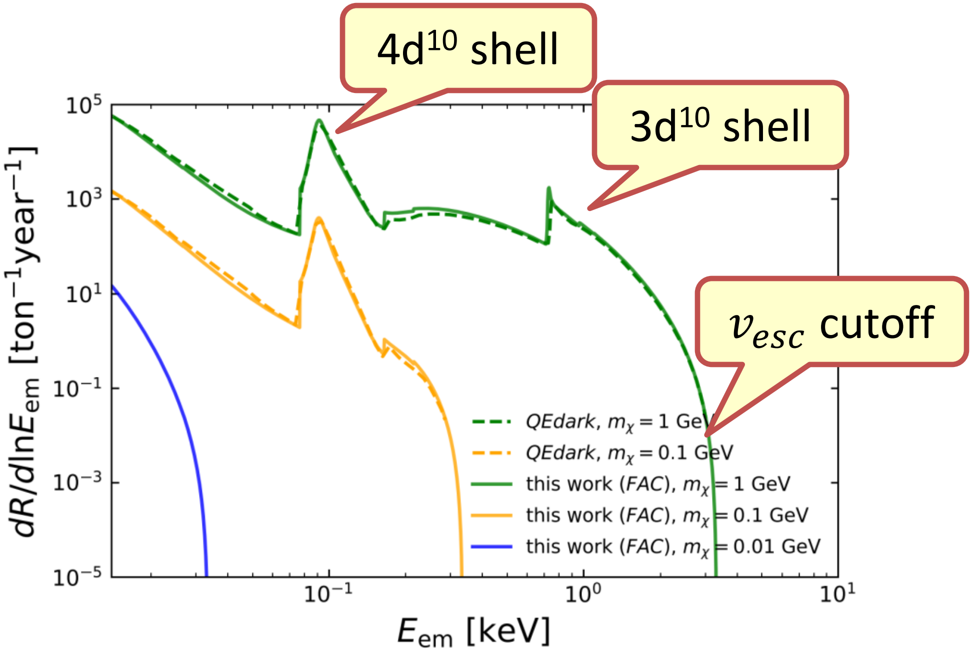
$$\frac{d\sigma_{\mathrm{Mig},nl}}{dT_N d\ln T_e} \approx \frac{1}{2\pi}\frac{d\sigma_{\chi N}}{dT_N}\frac{dP_{nl}}{d\ln T_e}(T_e,\, q_e)$$

Ionization probability

$$\frac{dP_{nl}}{d\ln T_e} \approx \frac{\pi}{2}\left|f_{nl}^{\mathrm{ion}}(k_e,\, q_e)\right|^2,$$

simple QM calculation

$$\left|f_{nl}^{\mathrm{ion}}(k_e,\, q_e)\right|^2 = \frac{2k_e}{\pi}\sum_{l'=0}^{\infty}\sum_{L=|l-l'|}^{l+l'}(2l'+1)(2l+1)(2L+1)\begin{pmatrix} l & l' & L \\ 0 & 0 & 0\end{pmatrix}^2\left|\int dr r^2 \widetilde{R}^*_{k_e l'} j_L(q_e r) R_{nl}\right|^2,$$



Underground DM flux

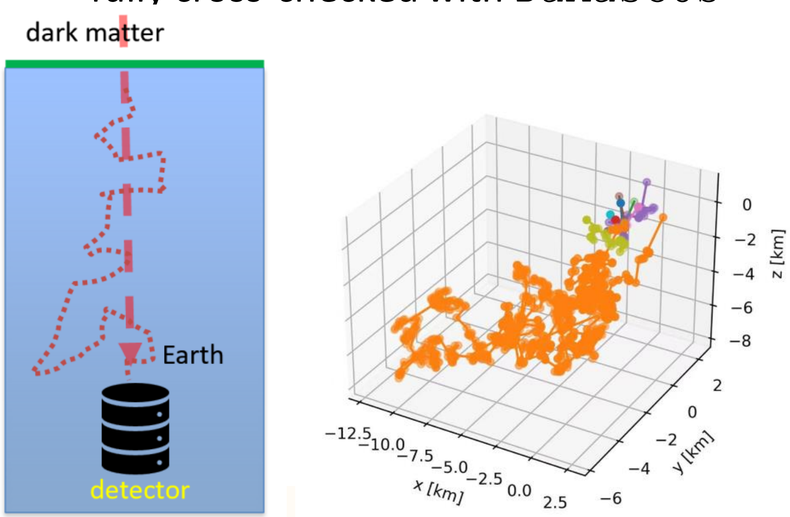
Mean energy-loss rate

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

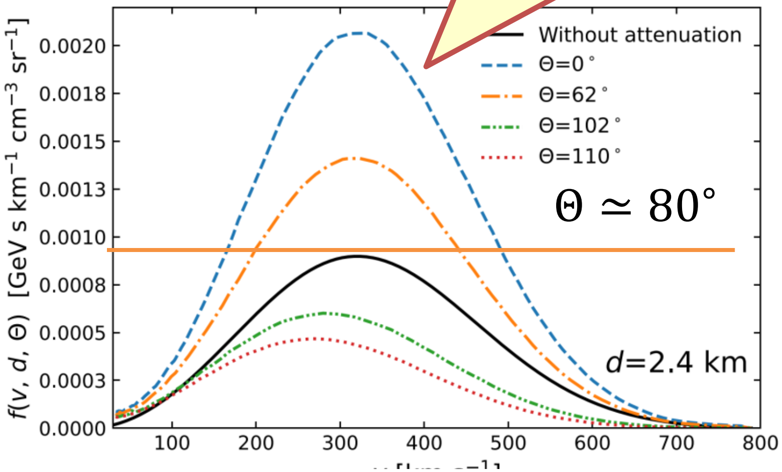
But, assuming simple ballistic trajectories can be misleading

The numerical code (`darkprop`)

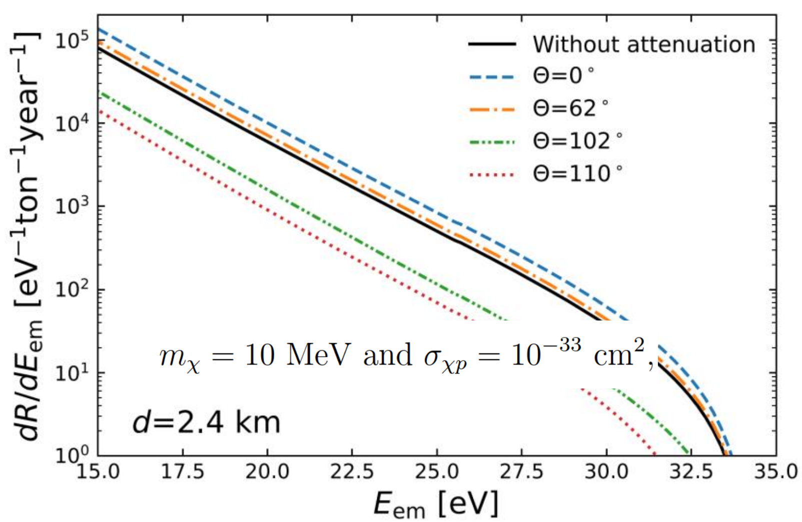
- ✓ anisotropic initial condition
- ✓ spherical Earth model with layers
- ✓ both relativistic and non-relativistic scatterings
- ✓ nuclear form factor
- ✓ fully cross-checked with `DaMasCUS`



Underground DM flux can be higher



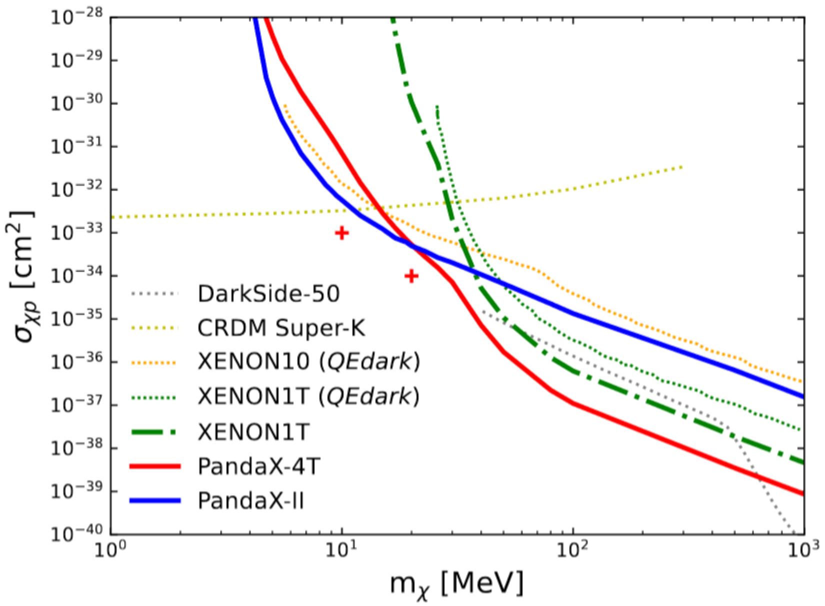
$$\frac{dR}{dE_{\rm em}} = \sum_{nl} \frac{1}{m_N} \int_0^\infty dT_N \int_{v_{\min}}^\infty dv \frac{d\sigma_{{\rm Mig},nl}}{dT_N dT_e} v f(v,\, d,\, \Theta)\,.$$



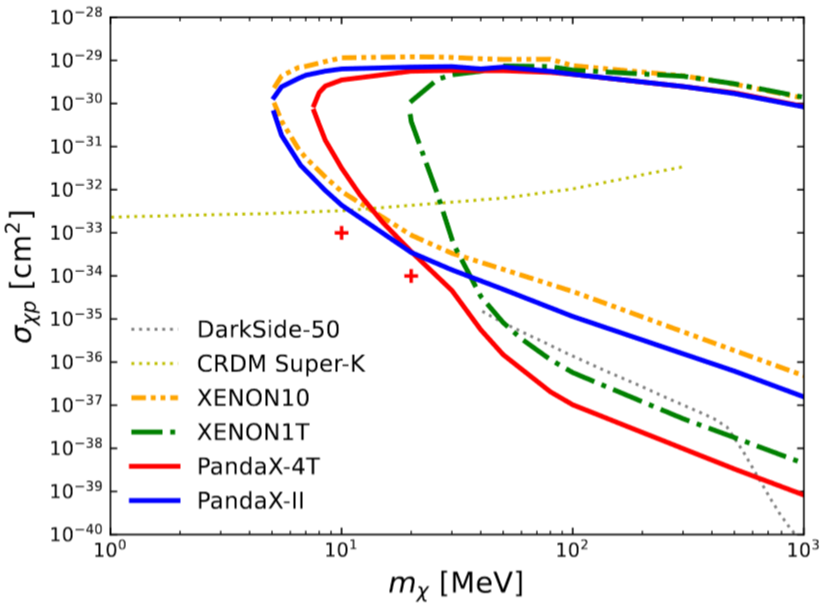
Constraints from PandaX-II/4T on the Migdal effect

binned Poisson method used to set limits at 90% C.L. from
PandaX-II (50-55 PE), Xenon-10 (41-68 PE) and Xenon-1T (42-70 PE)

w/o Earth shielding



w/ Earth shielding

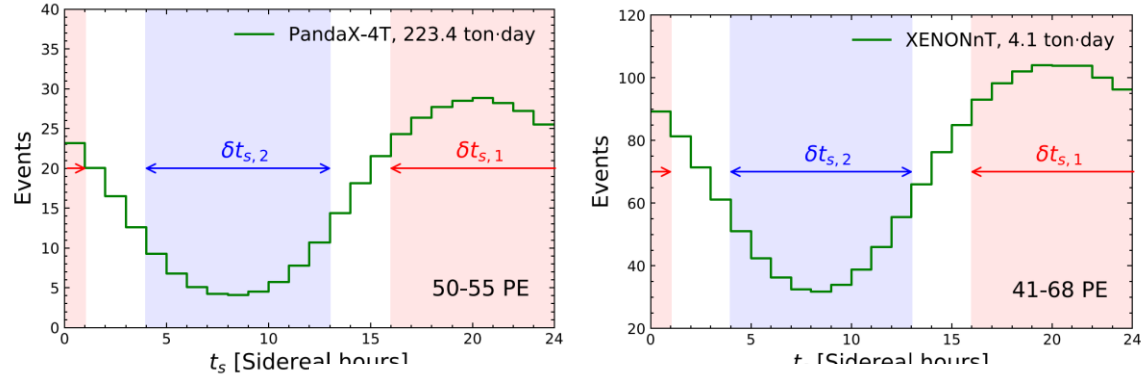


Mai Qiao, Chen Xia, YFZ, 2307.12820(JCAP)

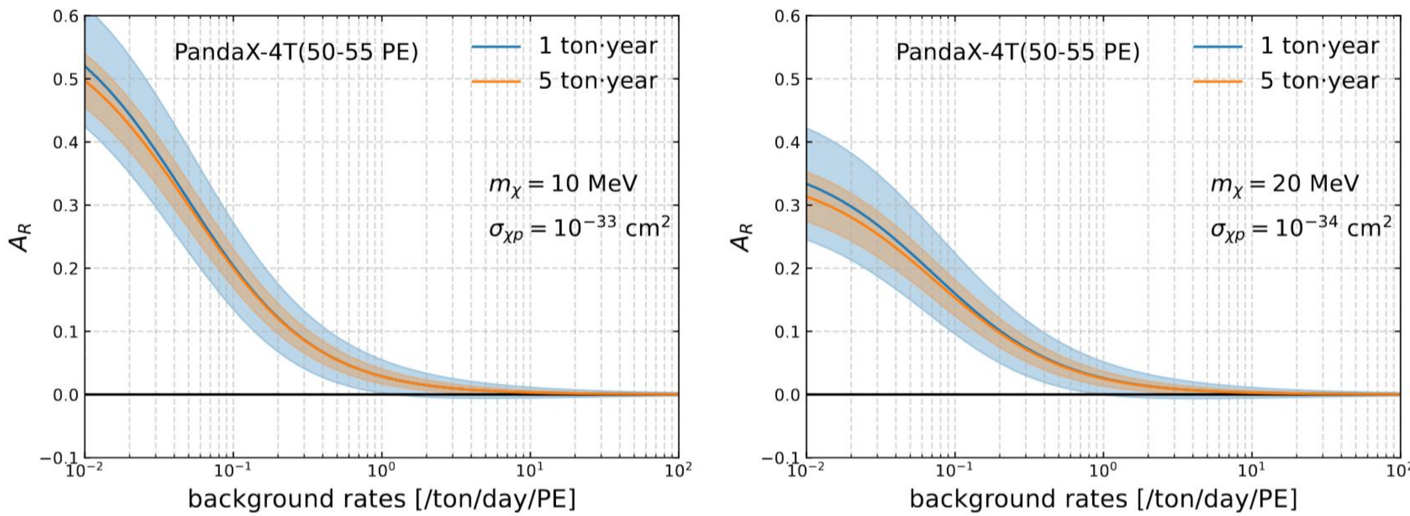
Predictions for diurnal asymmetry in electron event

- Diurnal asymmetry for optimized two time bins

$$A_R = \frac{N(\delta t_{s,1}) - N(\delta t_{s,2})}{N(\delta t_{s,1}) + N(\delta t_{s,2})},$$



- Predictions for pandaX-4T and Xenon-nT $m_\chi = 10$ MeV and $\sigma_{\chi p} = 10^{-33}$ cm^2,



Required background at 50-55 PE for 3σ significance

$$A_R = (2.11 \pm 0.70) \times 10^{-1} \quad \text{for} \quad b_{50} = 9.5 \times 10^{-2} \ /\text{ton/day/PE},$$

Mai Qiao, Chen Xia, YFZ, 2307.12820 (JCAP)

Summary

- Astrophysical observables can provide alternative constraints on DM-nucleon/electron scattering cross sections.
- The constraints are weaker but can be applied to broader range of DM particle masses.
- Many astrophysical boosting mechanism exist, which help the current underground DM experiments to explore light (sub-GeV) DM particles
- The morphology of the boosted DM flux can be useful to improve the constraints and distinguish different DM models. CRDM provides a good example for it.
- DM directional search are important to uniquely identify DM and distinguish different DM models. observing the diurnal modulation of electron events from DM-nucleus scattering (through Migdal effect) is possible, after considering all the current constraints

Thank you for your attention!