Boosted Dark Matter Directionality in Large Liquid Scintillator Detector

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DM Direct Detection

1. Detector mass ~ Tons
2. Minimum DM mass ~ GeV

(PDG,2026)

Assume that DM interacts with nucleons.

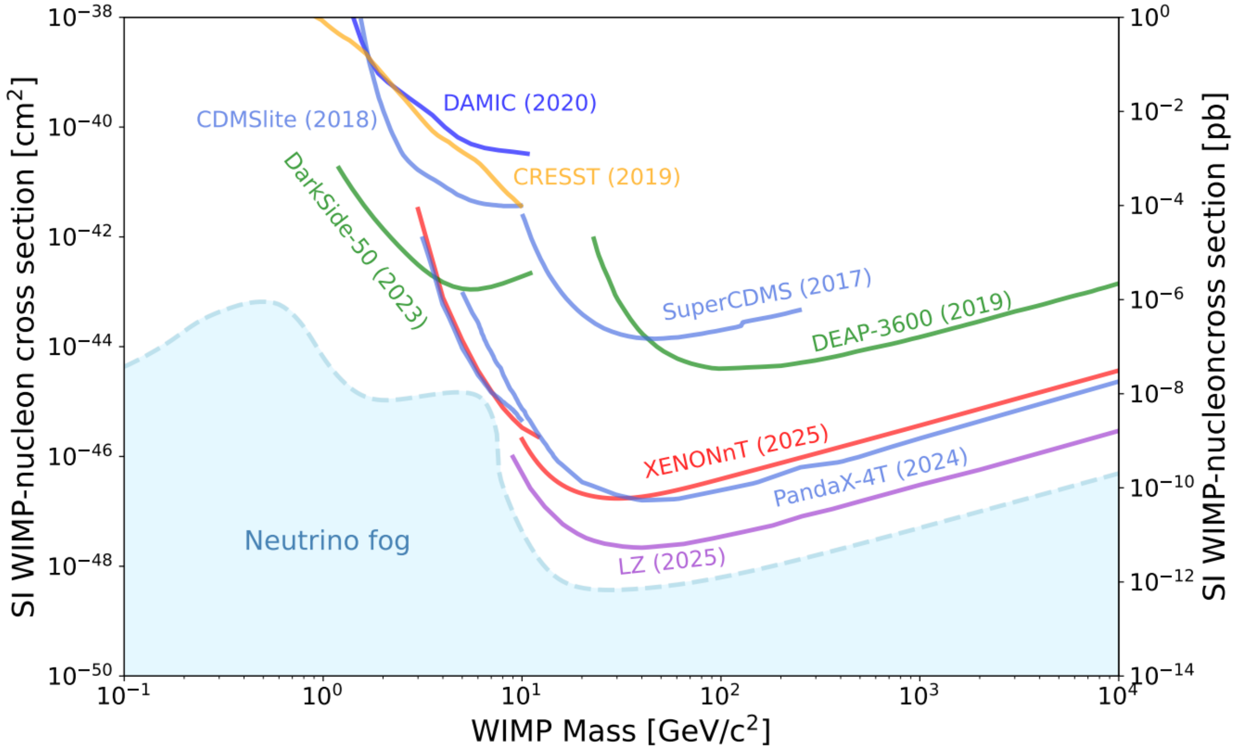


Figure 27.1: Upper limits on the SI DM-nucleon cross section as a function of DM mass.

(PDG,2026)

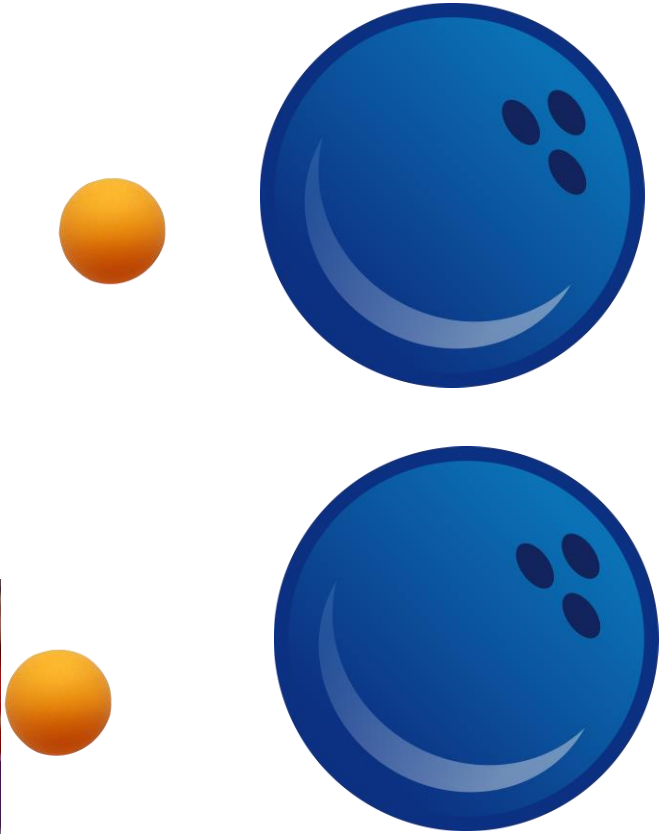
Table 27.1: Best constraints from direct detection experiments on the SI (at high >5 GeV and low < 5 GeV masses) and SD DM-nucleon couplings.

Experiment	Target	Fiducial mass [kg]	Cross section [cm^2]	DM mass [GeV]	Ref.
		Spin independent high mass (>5 GeV)			
LUX-ZEPLIN	Xe	5500	2.2×10^{-48}	40	[117]
PandaX-4T	Xe	2480	1.6×10^{-47}	40	[118]
XENONnT	Xe	4000	1.7×10^{-47}	30	[119]
SuperCDMS	Ge	12	1.0×10^{-44}	46	[120]
DarkSide-50	Ar	20	1.9×10^{-43}	10	[121]
DEAP-3600	Ar	2000	3.9×10^{-45}	100	[122]
		Spin independent low mass (<5 GeV)			
DarkSide-50 (ionisation only)	Ar	20	1.4×10^{-42}	2	[121]
PandaX-4T (ionisation only)	Xe	3100	1.3×10^{-43}	3.5	[123]
PandaX-4T	Xe	3100	1.6×10^{-42}	3	[124]
XENONnT	Xe	4000	3.2×10^{-42}	3	[125]
SuperCDMS (CDMSlite)	Ge	0.6	2×10^{-40}	2	[126]
CRESST	$CaWO_4$ - O	0.024	1×10^{-39}	2	[127]
CRESST	Si	0.0035	4.5×10^{-32}	0.15	[128]
CRESST	Al_2O_3	0.0006	1.0×10^{-32}	0.1	[129]
DAMIC	Si	0.3	1×10^{-40}	4	[130]
NEWS-G	Ne	0.3	1×10^{-38}	2	[131]
		Spin dependent proton			
NEWS-G	CH_4	0.114	3.1×10^{-35}	0.76	[132]
PICO60	C_3F_8 - F	49	3.2×10^{-41}	25	[133]
PandaX-4T	Xe	2480	7.7×10^{-41}	40	[118]
LUX-ZEPLIN	Xe	5500	9.8×10^{-42}	40	[117]
XENONnT	Xe	4000	8.5×10^{-41}	25	[119]
		Spin dependent neutron			
PandaX-4T	Xe	2480	2.7×10^{-42}	40	[118]
LUX-ZEPLIN	Xe	5500	3.7×10^{-43}	46	[117]
XENONnT	Xe	4000	2.8×10^{-42}	25	[119]

Boosted Dark Matter (BDM)

- Hypothesis: The mass of DM particles in our galaxy halo are too light and too cold to trigger observable signals in current detectors.

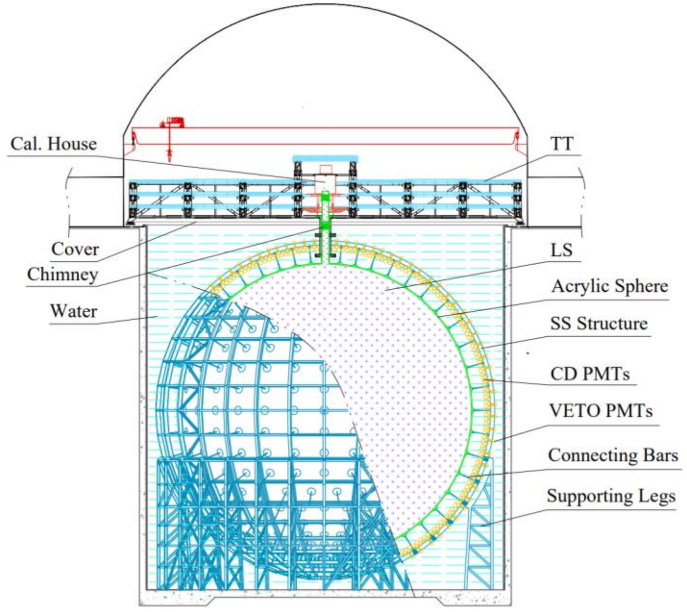
- DM particles that been boosted to relativistic speed by certain mechanism, could trigger our detectors, and possibly leave a directional signature.



Large Liquid Scintillator Detectors (LLSD)

Purpose: **Neutrino Physics**

The Jiangmen Underground Neutrino Observatory (JUNO)



(Abusleme et al., 2021)

Relativistic BDM ≈ Neutrino

Benefits:

1. Compare to traditional DM detectors:

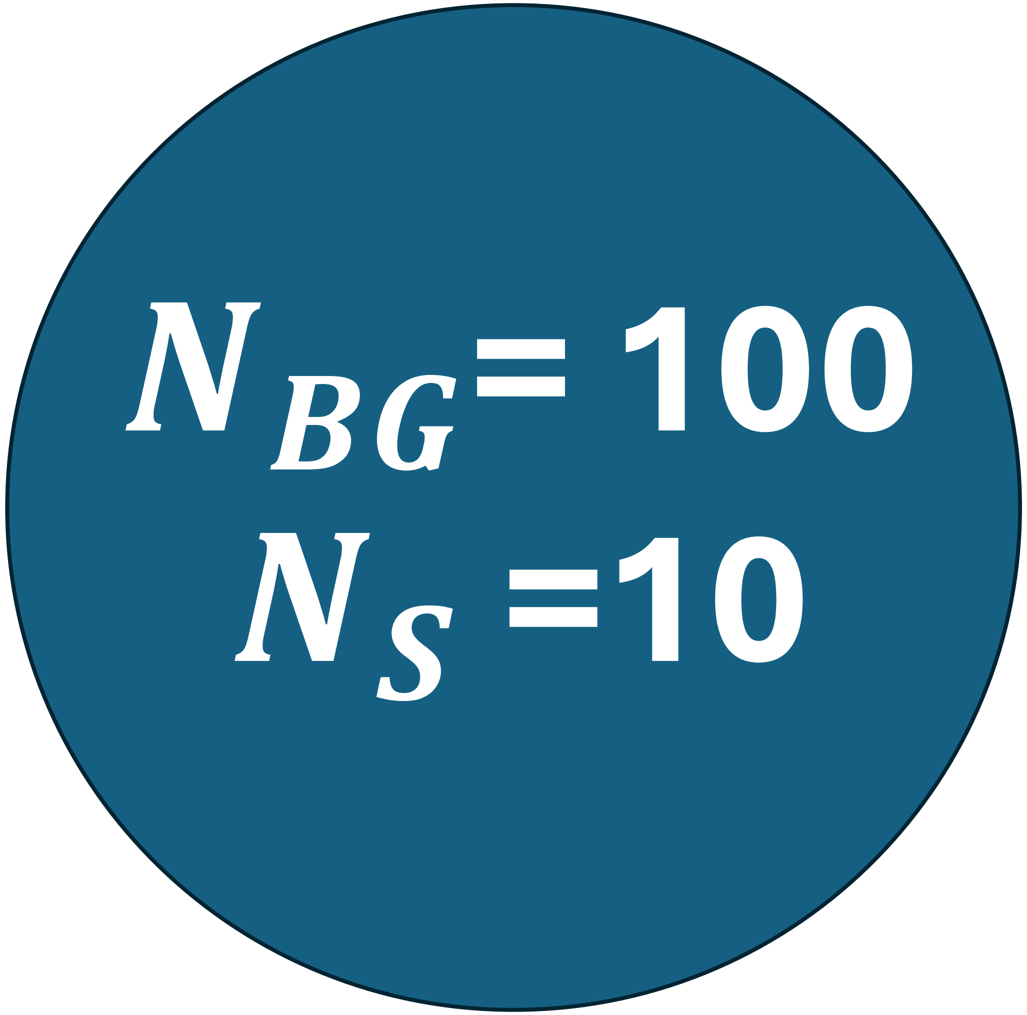
tons → kilotons (Scale × 10000 !)

2. Compare to Water Cherenkov detectors:

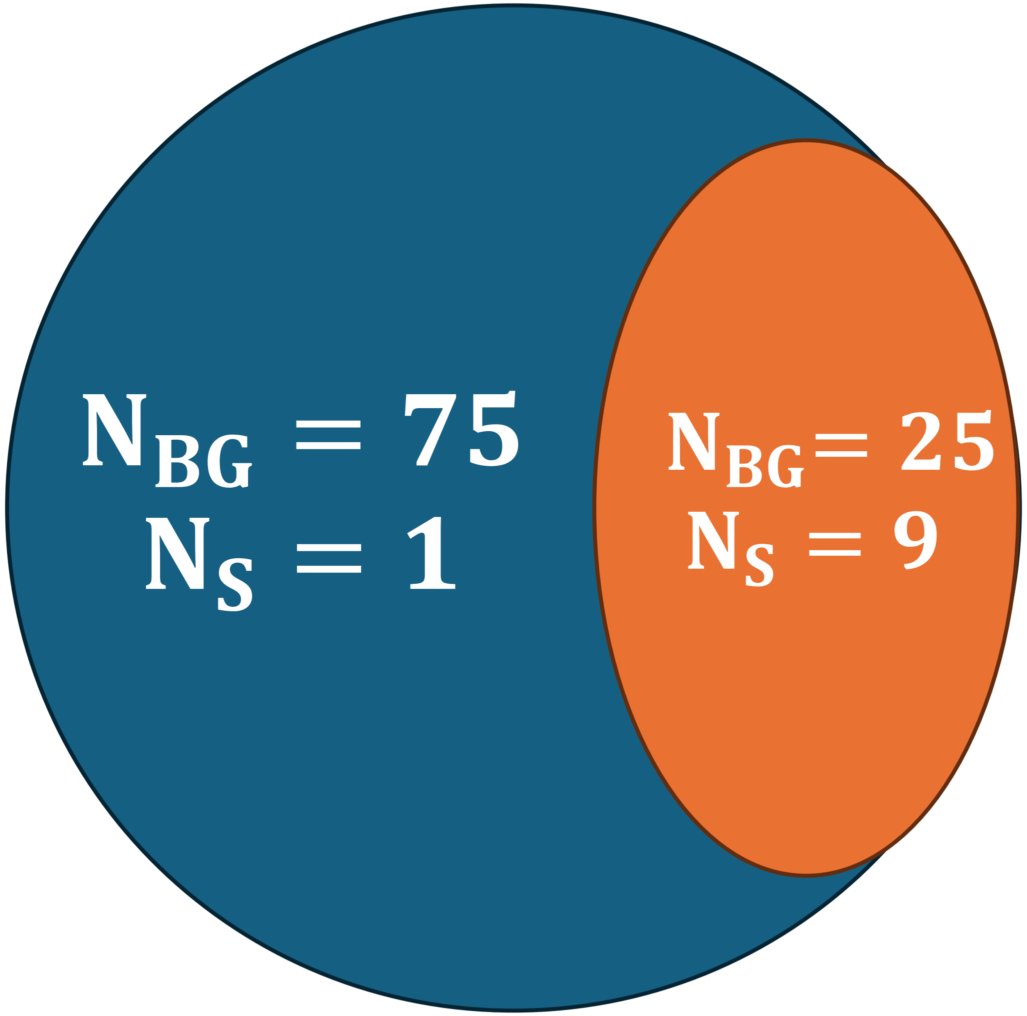
- Lower energy threshold. (Doesn't require Cherenkov light)
- Excellent energy resolution. (3% at 1 MeV for JUNO)

In this work, we will estimate the sensitivity limit for an LLSD with an exposure of 100 kt·yr.

Why Directionality?



$$\frac{N_S}{N_{BG}} = \frac{1}{10}$$



$$\frac{N_S}{N_{BG}} = \frac{9}{25}$$

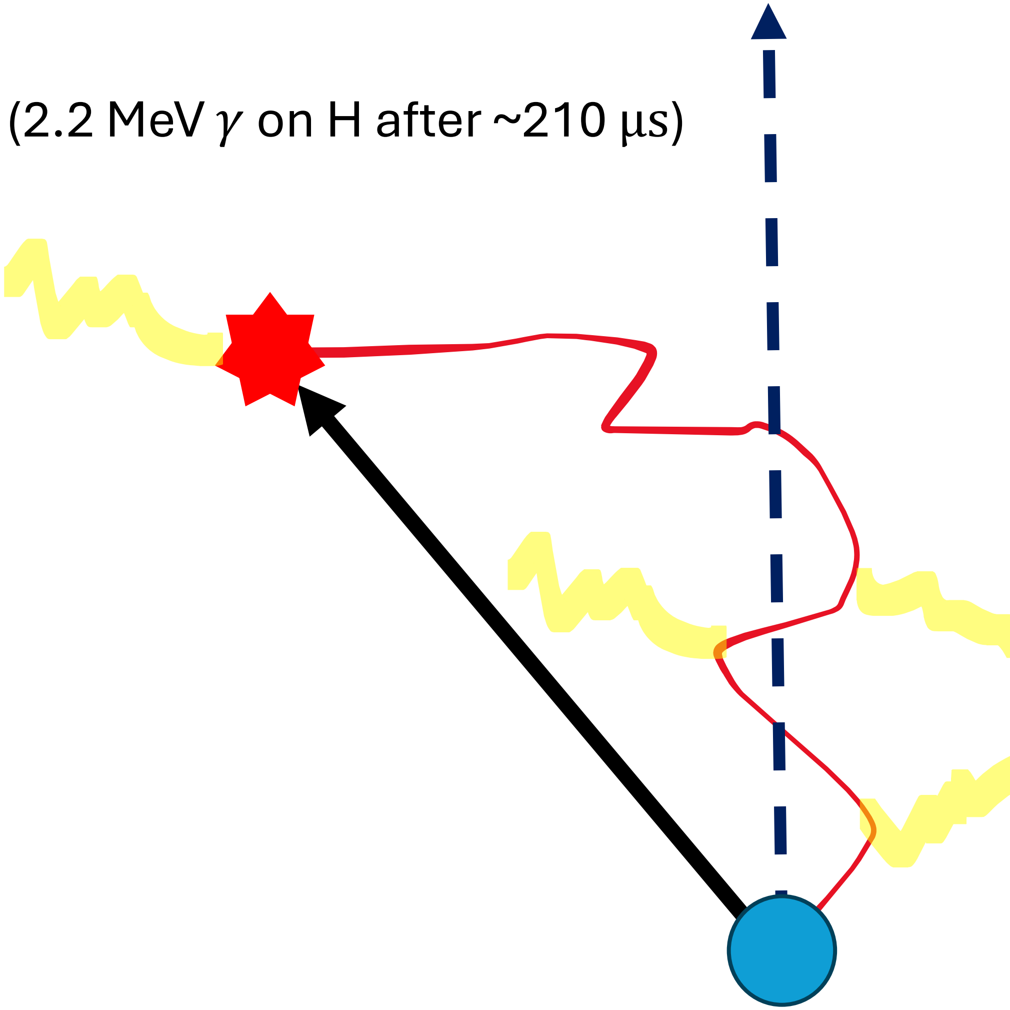
Neutron Directionality Reconstruction (Fischer et al.,2015) (Liu & Ng, 2026)

- Traditionally, charged particle **directionality** will be lost due to scintillation light.

- We will use **neutron interaction points** to reconstruct directionality. (neutron tagging efficiency ~ 1)

- A displacement vector between the neutron emission point and capture point.

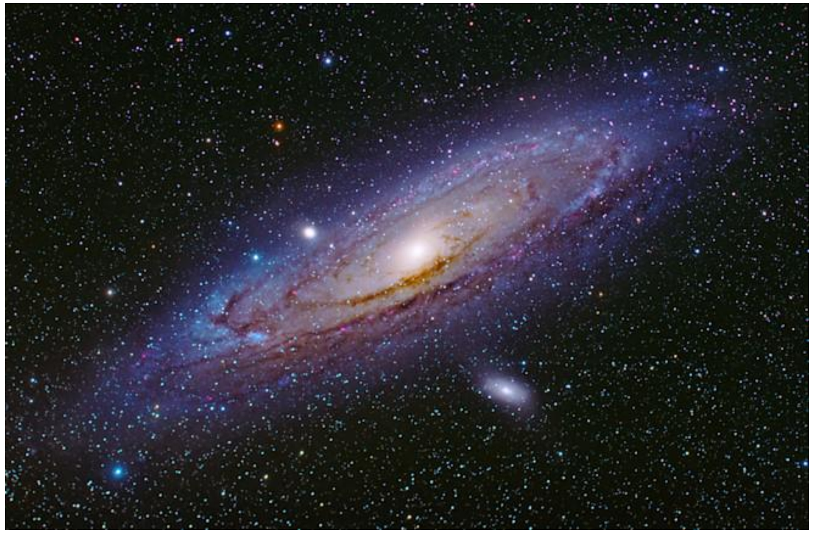
- See if directionality preserves **after diffusion**.



Can directional information can improve sensitivity?

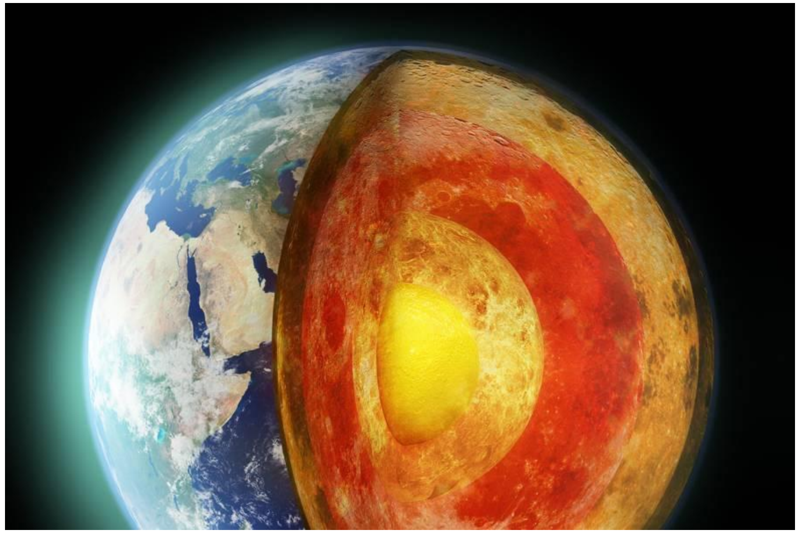
Outline:

1.



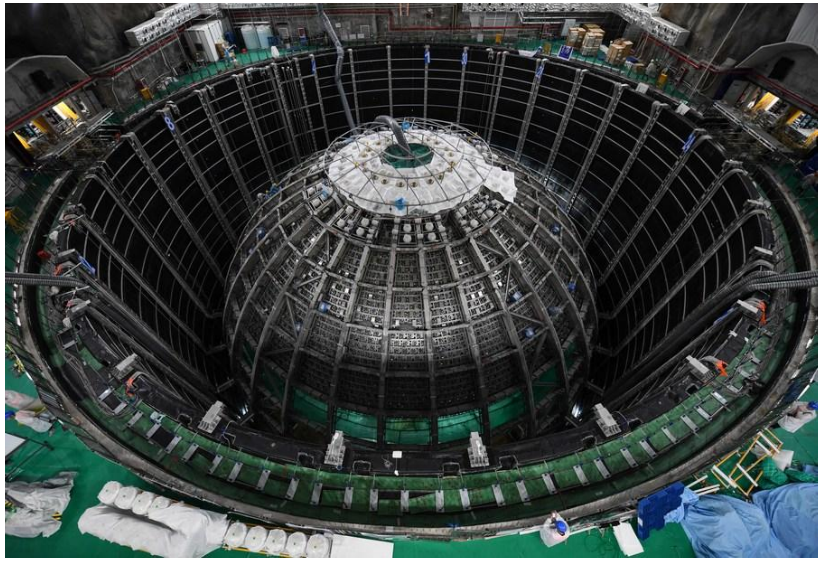
BDM Flux From Milky Way

2.



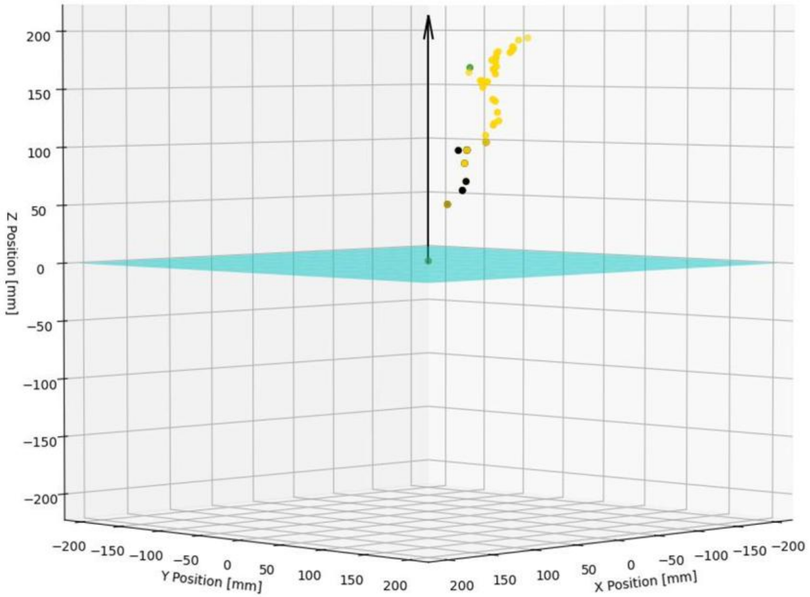
Earth Crust Stopping BDM

3.



BDM Knocking Neutrons

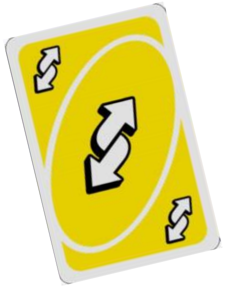
4.

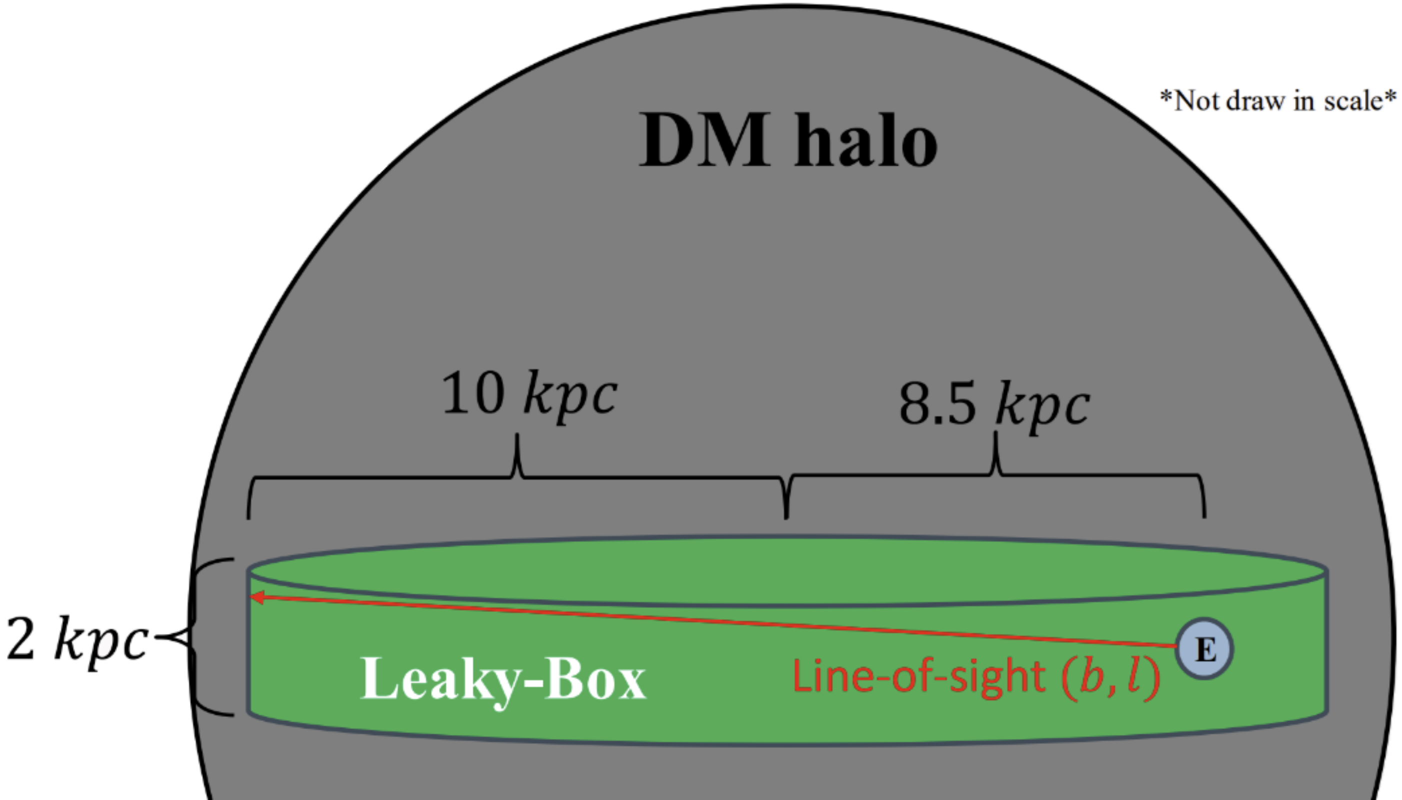


Neutrons Diffuse and Capture

Boosted Dark Matter by Cosmic Rays (Bringmann & Pospelov., 2019) (Ema et al., 2021)

Detector's nucleon ↔ DM ↔ Cosmic ray





- DM density profile follows NFW profile.
- Cylindrical Leaky-Box Model
- Cosmic rays(p and He only) are assumed to be isotropic and homogeneous.

Boosted Dark Matter Flux

DM model: Dirac fermion χ with a scalar mediator ϕ to interact with Standard Model particle .

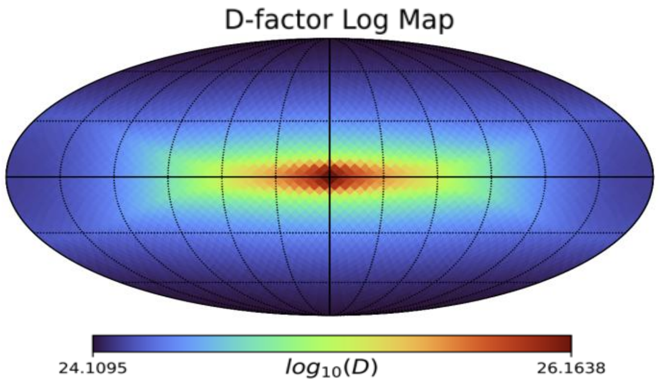
DM-Nucleus Coherent Scattering

$$\frac{\mathrm{d}\Phi_\chi}{\mathrm{d}K_\chi \mathrm{d}\Omega} = \frac{\mathrm{D(b,l)}}{\mathrm{m}_\chi} \sum_A \int_{K_{A_{min}}}^{\infty} dK_A \underbrace{\frac{d\Phi_A}{\mathrm{d}K_\mathrm{A}\mathrm{d}\Omega}}_{\text{LIS cosmic ray Flux}} \cdot \overbrace{\frac{d\sigma_{A\chi}}{dK_\chi}}^{\text{DM-Nucleus Coherent Scattering}}$$

LIS cosmic ray Flux

$$D(b,l) = \int_{l.o.s} \rho_\chi \cdot dl$$

Found by NFW profile with Cylindrical Leaky Box (Galactic Disk Size)



Earth Attenuation Effect

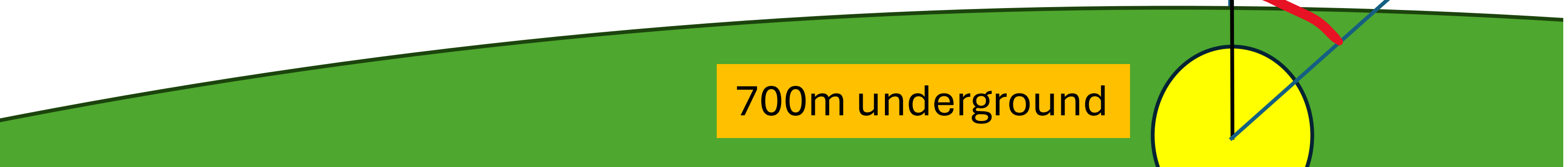
Assumptions:

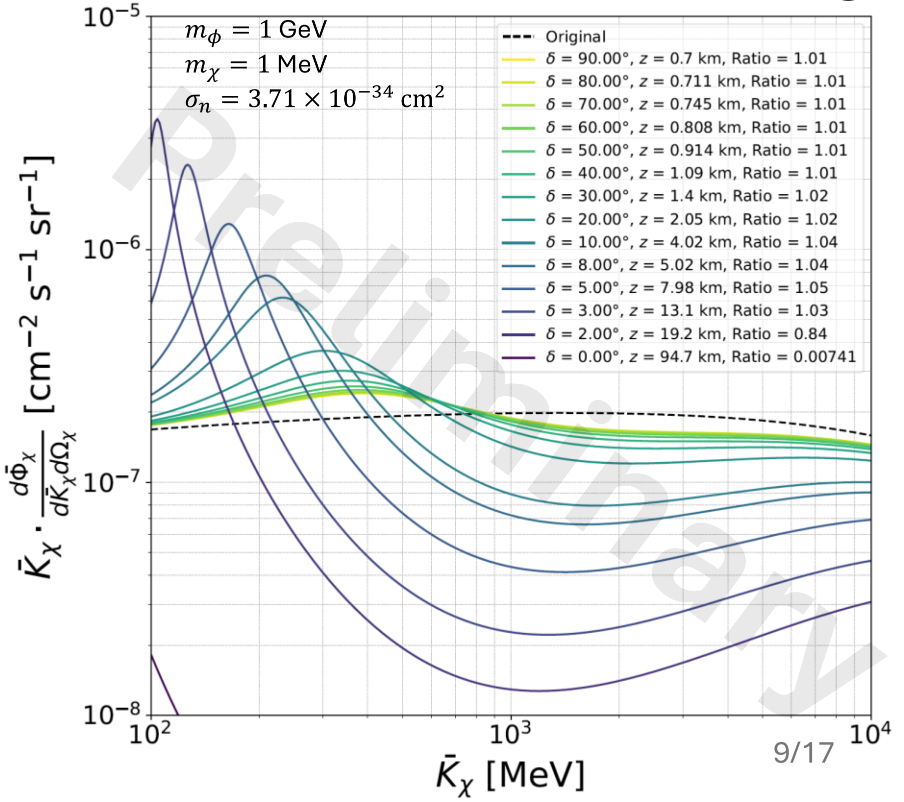
1. The energy loss at each scattering as its averaged value:

$$\frac{d\overline{K_\chi}(z)}{dz} = -n_T \int_0^{K_T-max} dK_T\, K_T \frac{d\sigma_{\chi T}}{dK_T}(\overline{K_\chi}, K_T)$$

2. The particles are protons and neutrons (1:1).

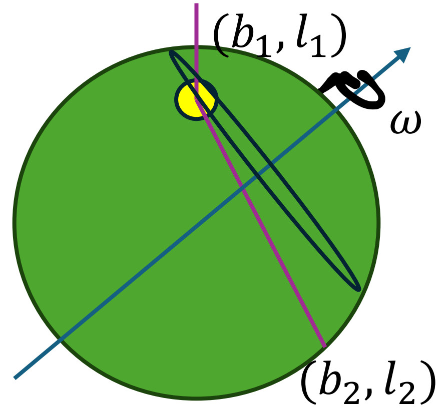
3. No change in direction for BDM after each scattering.

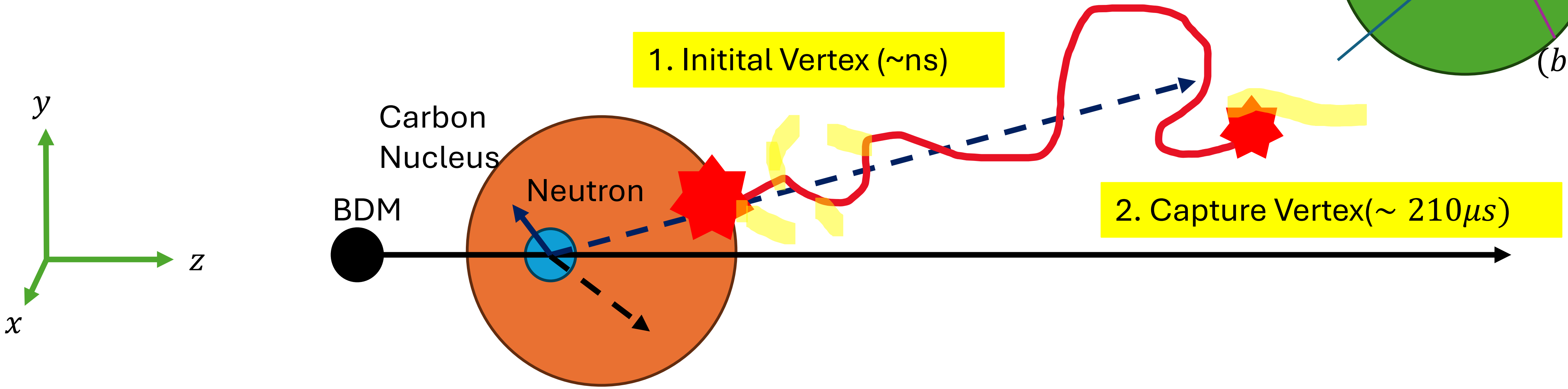




Neutron Triggered Rate: (Bodek & Cai, 2019)(Gong et al., 2026)

$$\frac{dN}{dK_n{}'d\Omega_n'} = N_C \cdot \int d\Omega_\chi \int dt \int d\bar{K}_\chi \frac{d\bar{\Phi}_\chi}{d\bar{K}_\chi d\Omega_\chi} \cdot \frac{d\sigma_{QES}}{dK_n{}'d\Omega_n{}'}$$





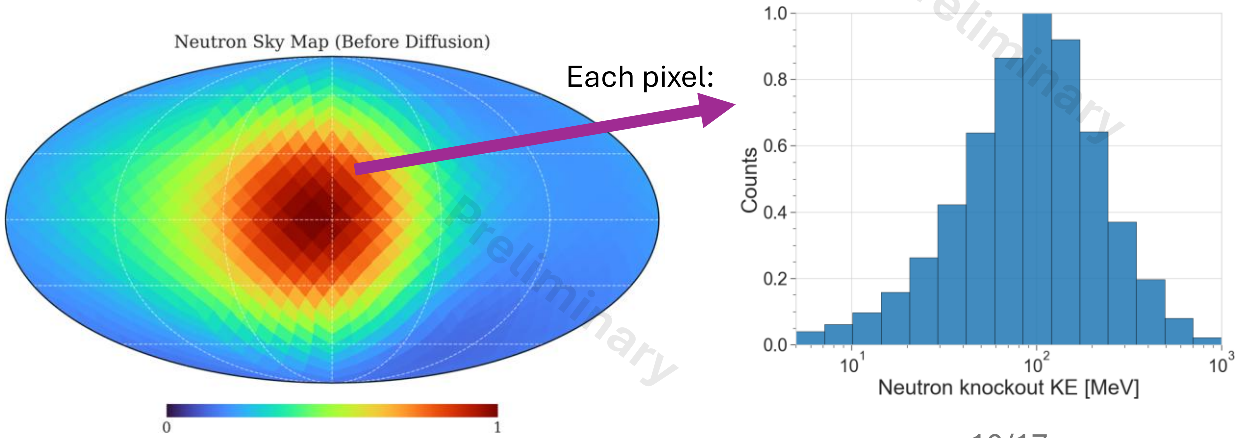
Kinematics:

- Quasi-Elastic Scattering (QES), $|q_3| > 350$ MeV
- Relativistic Fermi Gas model, $p_F = 221$ MeV.
- $\langle E_R \rangle = 27.1$ MeV.

Nuclear Effect: **(Assumed no change in direction)**

- Pauli Blocking
- Final State Interaction – Nuclear optical potential

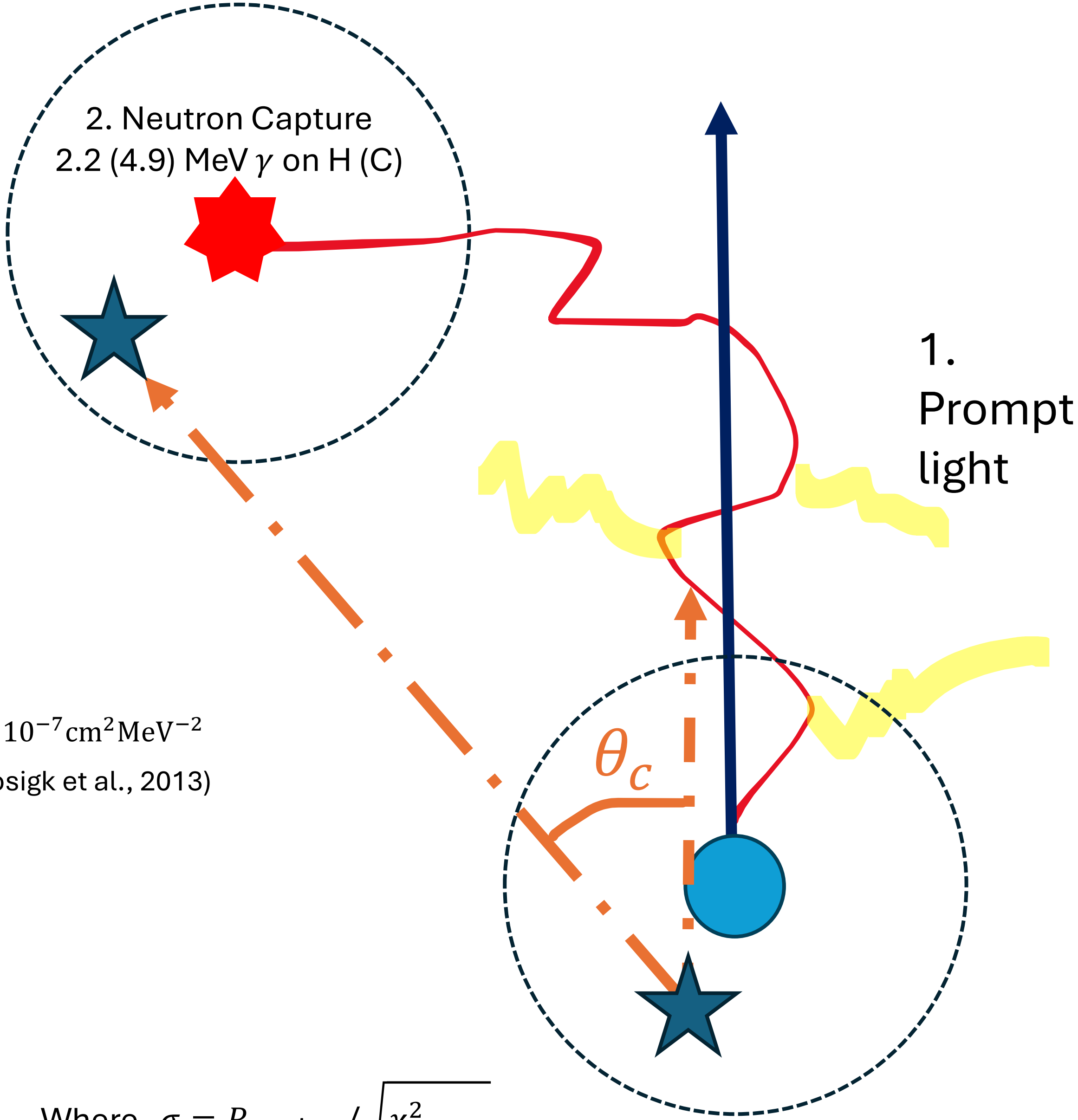
For a fixed $(m_\chi, m_\phi, \bar{\sigma}_n)$:



Neutron Diffusion: Geant4

For each KE, we shoot 10^5 neutrons and record:

Reconstructed Position:
(x', y', z')



1. Prompt Light Deposited Energy (quenching effect):

Sum
$$p^+/A: \quad \Delta E_{prompt} = \left[1 + k_B\left(\frac{\Delta E}{\Delta d}\right) + C\left(\frac{\Delta E}{\Delta d}\right)^2\right]^{-1} \Delta E$$

$$e^+/e^-: \quad \Delta E_{prompt} = \Delta E$$

$k_B = 0.0098$ cm MeV^{-1} and $C = 1.0 \times 10^{-7}$ cm^{2}MeV^{-2}
(Krosigk et al., 2013)

2. Neutron Capture Angle:

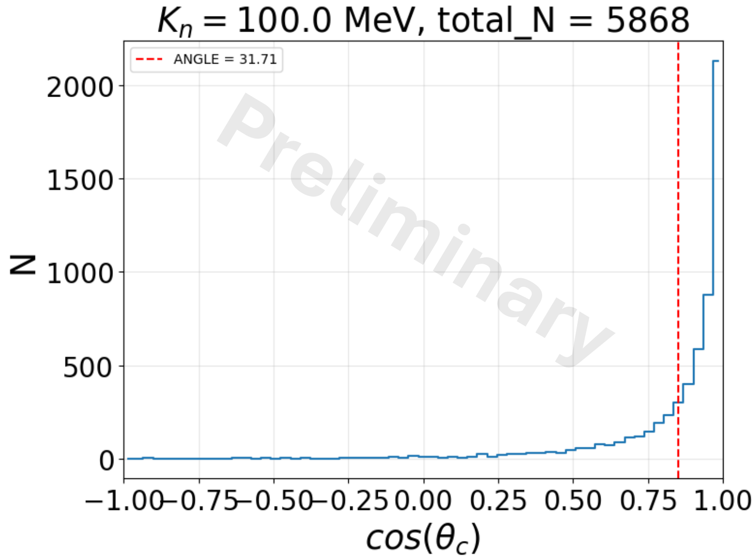
$\boldsymbol{\theta_c}$

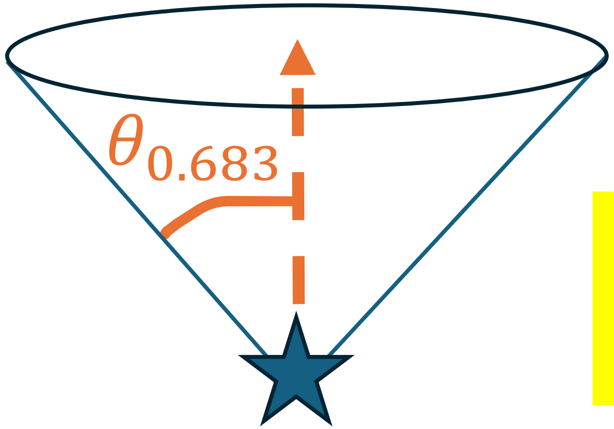
1D Gaussian Probability for new position:

$$f(x_i') = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x_i' - x_i)^2}{2\sigma^2}\right)$$ Where $\sigma = R_{\text{vertex}}/\sqrt{\chi^2_{0.683,3}}$

Remarks: Record for events with **only one** neutron being captured

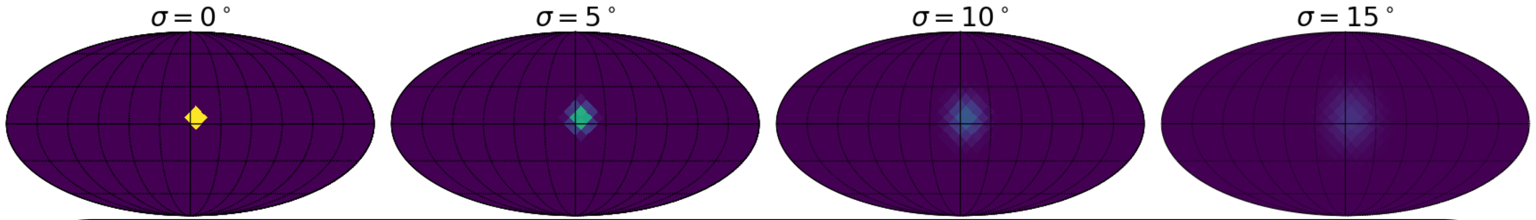
Simulation Results:

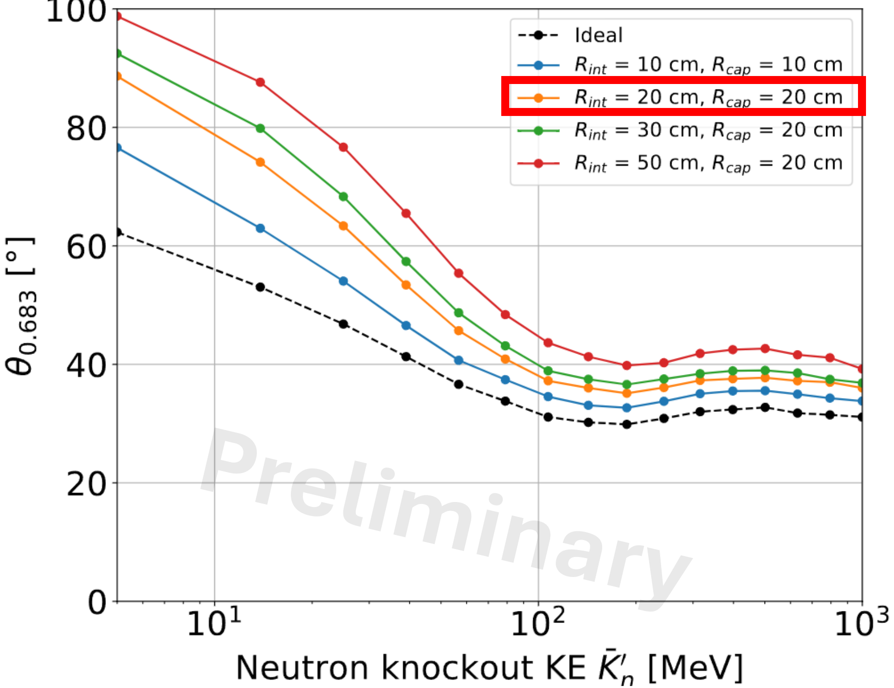




68.3% of the events fall into this cone

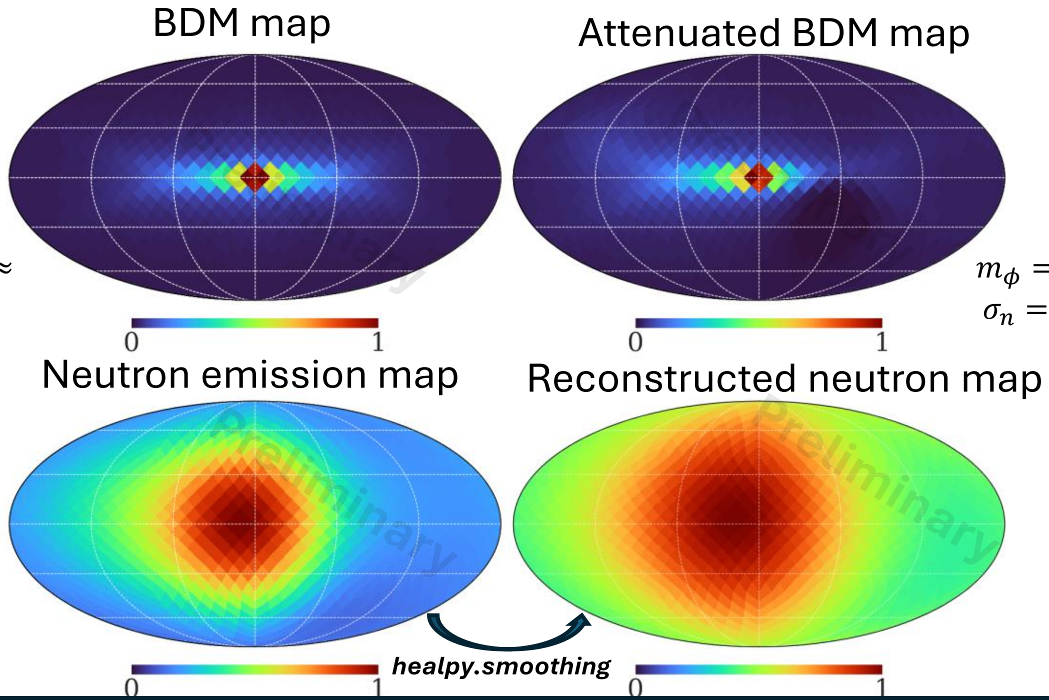
To model the diffusion effect:
We used $\theta_{0.638}$ as the sigma input to *healpy.smoothing* to smear the skymap.





Deposit Energy ≈ [5 MeV ~ 1 GeV]

Sky bin size ≈ 7.3° × 7.3°

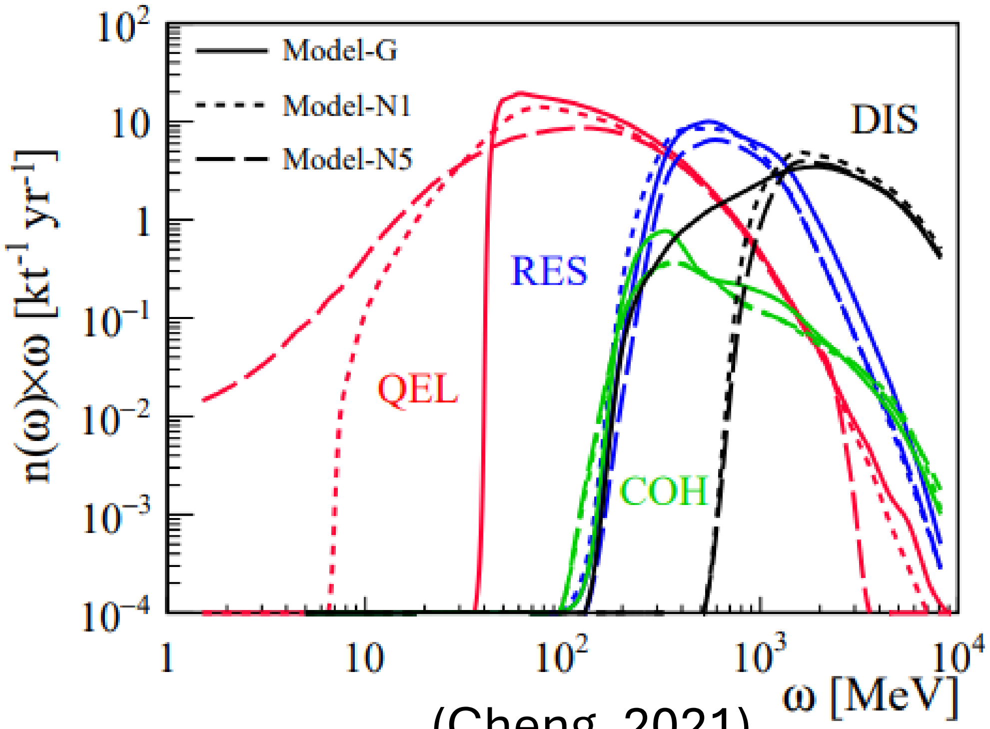


m_ϕ = 1 GeV , m_χ = 1 MeV ,
$\sigma_n = 3.71 \times 10^{-34}\ \mathrm{cm}^2$

Background:

We only considered the Indistinguishable BG:

Atmospheric Neutrino Neutral-Current QES



(Cheng, 2021)

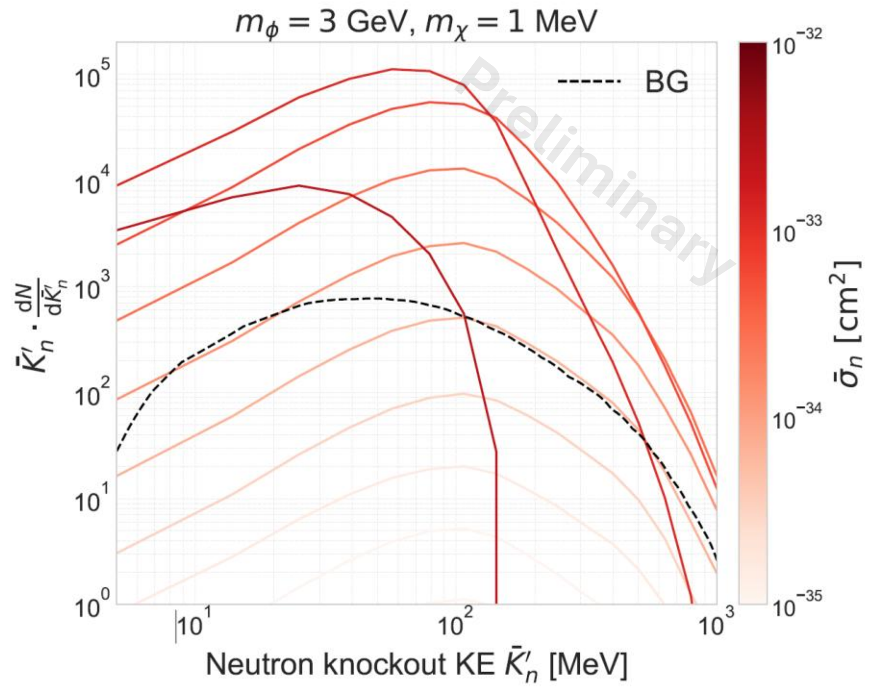
$\nu - C^{12}$ NCQES neutron spectrum

We choose Model-G, which is GENIE with RFGs

(Cheng et al., 2021)

Assumed to be Isotropic in galactic coordinates due to Earth rotation and mostly isotropic production

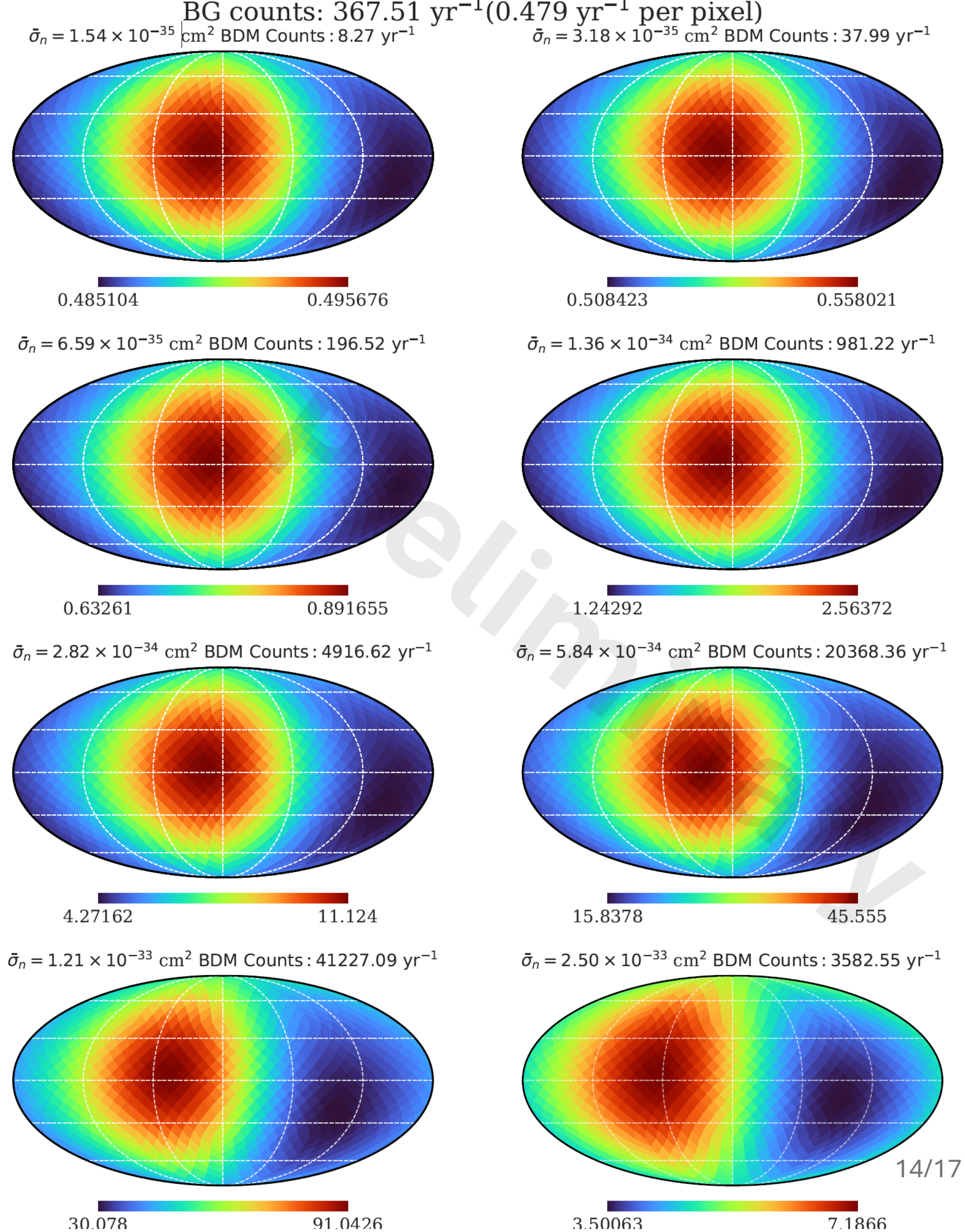
Signal and Background

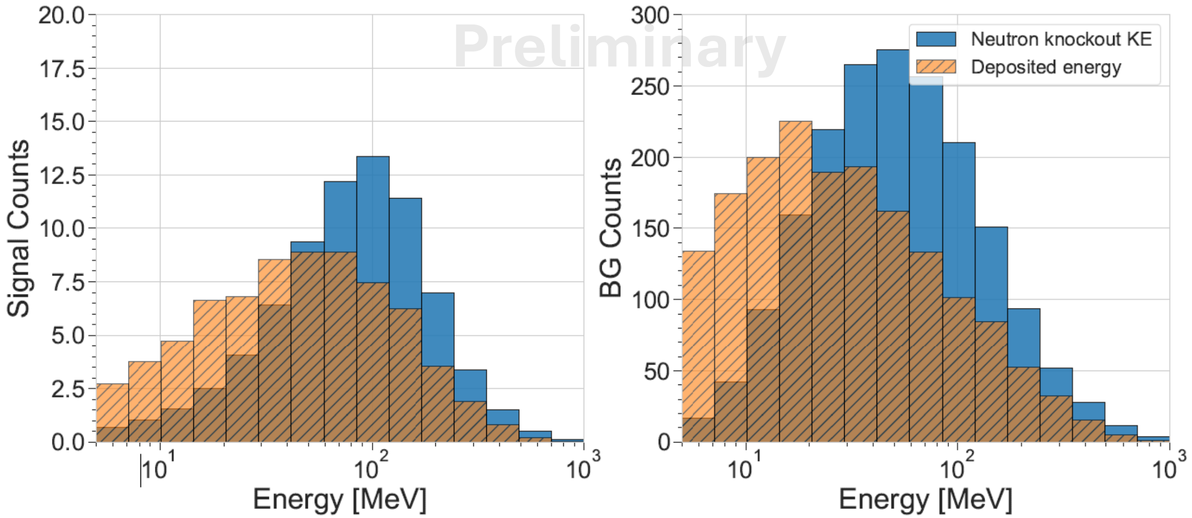


91.5 kton yr

Prompt Energy ≈ [5 MeV ~ 1 GeV]

Sky bin size ≈ 7.3° × 7.3°





$m_\phi = 1$ GeV , $m_\chi = 1$ MeV , $\sigma_n = 2.56 \times 10^{-35}$ cm^2

95% CL Sensitivity Limit for LLSD (100 kt·yr)

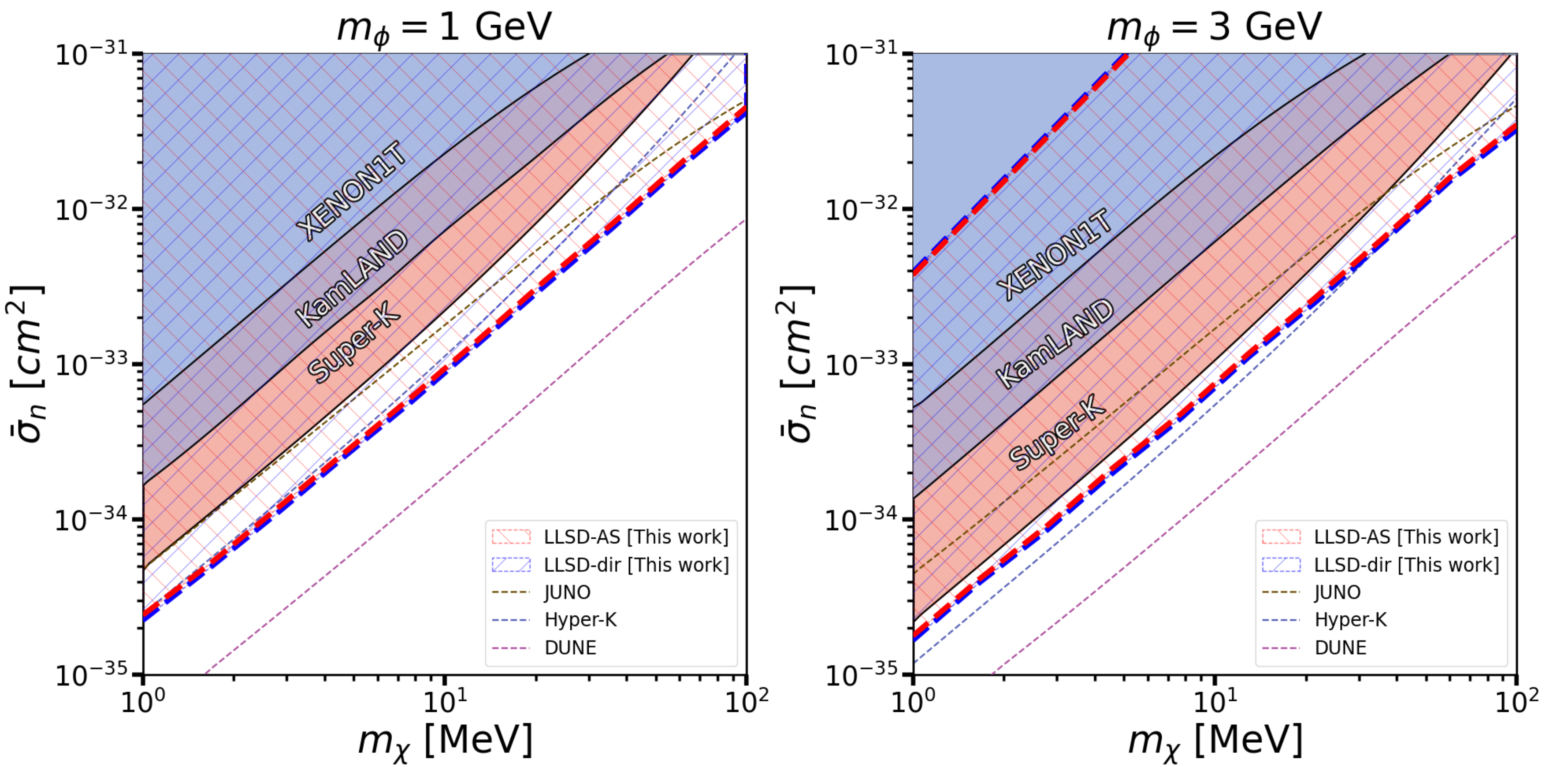
(Cowan et al., 2011)

Test Statistics: $TS = -2\ln\frac{L(N_{\mathrm{BDM}})}{L(N_{\mathrm{BDM}}=0)}$

Likelihood: $L = \prod_{i=1}^{N} P_i(k_i \mid \lambda_i)$

Poisson distribution $P_i(k_i \mid \lambda_i) = \frac{\lambda_i^{k_i} e^{-\lambda_i}}{k_i!}$

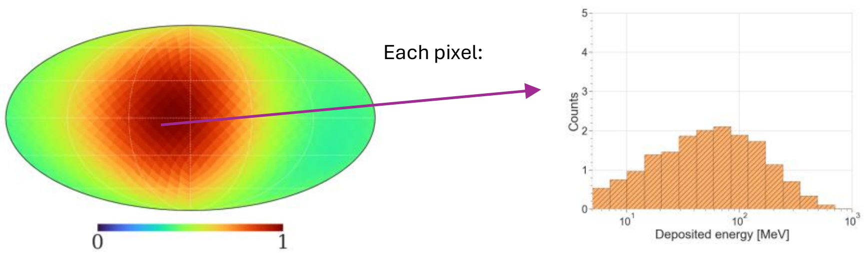
Set $TS = 2.71$



Compared to protons results from (Ema et al.,2021)

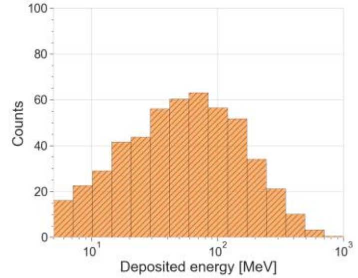
1. **With** directionality information:

$\mathrm{N} = 768$ sky bins $\times$ 15 energy bins $= 11520$ bins



2. **Without** directionality information:

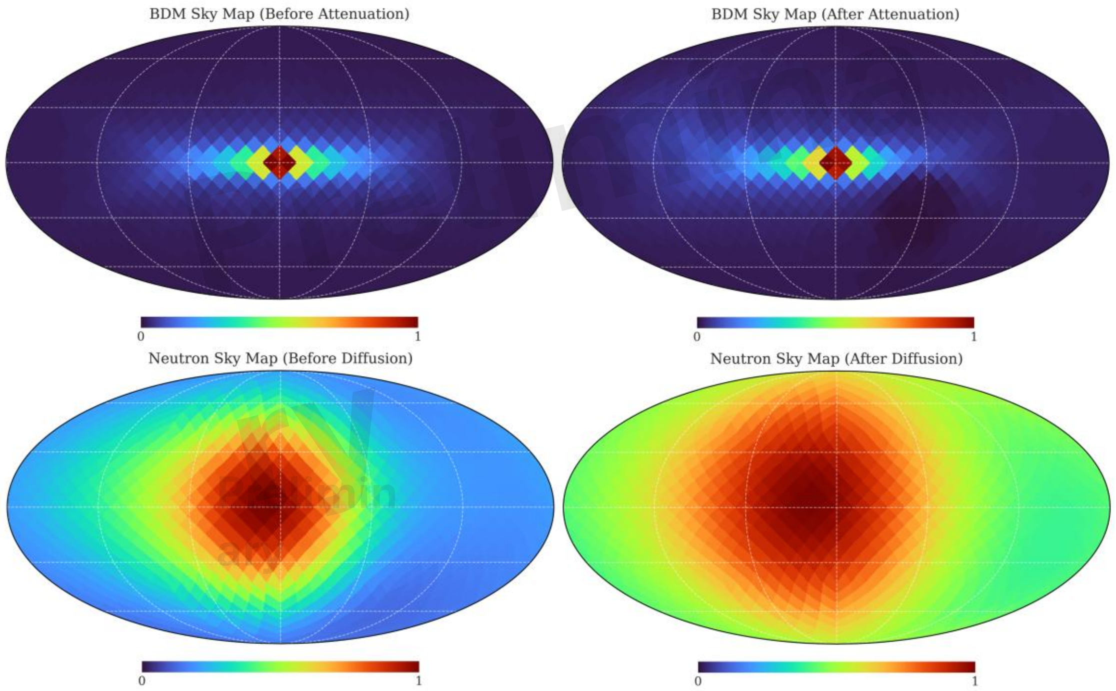
$\mathrm{N} = 1$ all sky bin $\times$ 15 energy bins $= 15$ bins



1. Directionality improvement is mild.
2. Ceiling appears due to Earth Attenuation.
3. Neutron channel can be better than proton channel. (Same exposure)

Discussion:

- In this work, we make two optimistic assumptions:
  - Earth attenuation does not affect the incoming BDM direction.
  - Nuclear effects do not affect the outgoing neutron direction.



- The initial neutron knockout angle is still not enough.

- **Using solely neutron directional information cannot improve much.**

- Other than CRBDM,
  Maybe DM annihilation + IBD events could yield better results.

$$\int_{l.o.s} \rho_\chi^2 \ dL$$

Event by event
neutrino direction

Conclusion:

- Knockout neutrons interaction positions **retain partial directionality** of the incoming particle.

- The contrast in the neutron sky maps is **insufficient** to produce a visible improvement in sensitivity limit.

Thanks For Listening

Reference:

- [1] Particle Data Group, F. Takahashi *et al.*, "Review of Particle Physics," *Int. J. Mod. Phys. A* 41, 2630011 (2026). [Online: https://pdg.lbl.gov/]
- [2] A. Abusleme et al. (JUNO Collaboration), "Design, Status and Physics Potential of JUNO," Chin. Phys. C 46, 123001 (2022), arXiv:2203.14087 [physics.ins-det].
- [3] V. Fischer et al., JCAP 08, 032 (2015), arXiv:1504.05466[astro-ph.IM].
- [4] Q. Liu and K. C. Y. Ng, (2026), arXiv:2606.12155 [hep-ph].
- [5] T. Bringmann and M. Pospelov, "Novel Direct Detection Constraints on Light Dark Matter," Phys. Rev. Lett. 122, 181802 (2019), arXiv:1810.10543 [hep-ph].
- [6] Y. Ema, F. Sala, and R. Sato, "Light Dark Matter at Neutrino Experiments," SciPost Phys. 10, 072 (2021), arXiv:2011.01939 [hep-ph].
- [7] G. Gong, F. Lin, N. Liu, L. Su, and L. Wu, "Detecting Light Dark Matter with Prompt-Delayed Events in Neutrino Experiments," arXiv:2504.13007 [hep-ph] (2026).
- [8] A. Bodek and T. Cai, "Removal Energies and Final State Interaction in Lepton Nucleus Scattering," Eur. Phys. J. C 79, 293 (2019), arXiv:1801.07975 [hep-ex].
- [9] B. von Krosigk, L. Neumann, R. Nolte, S. Röttger, and K. Zuber, "Measurement of the proton light yield of different scintillators with a broad-spectrum neutron beam," Eur. Phys. J. C 73, 2390 (2013), arXiv:1301.6403 [physics.ins-det].
- [10] J. Cheng, Y.-F. Li, L.-J. Wen, and S. Zhou, "Neutral-current background induced by atmospheric neutrinos at large liquid-scintillator detectors. II. Methodology for in situ measurements" Phys. Rev. D 103, 0530012(2021), arXiv:2009.04085 [hep-ex].
- [11] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, "Asymptotic formulae for likelihood-based tests of new physics," Eur. Phys. J. C 71, 1554 (2011) [erratum: Eur. Phys. J. C 73, 2501 (2013)], arXiv:1007.1727 [physics.data-an].

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