Boosted Dark Matter Directionality in Large Liquid Scintillators

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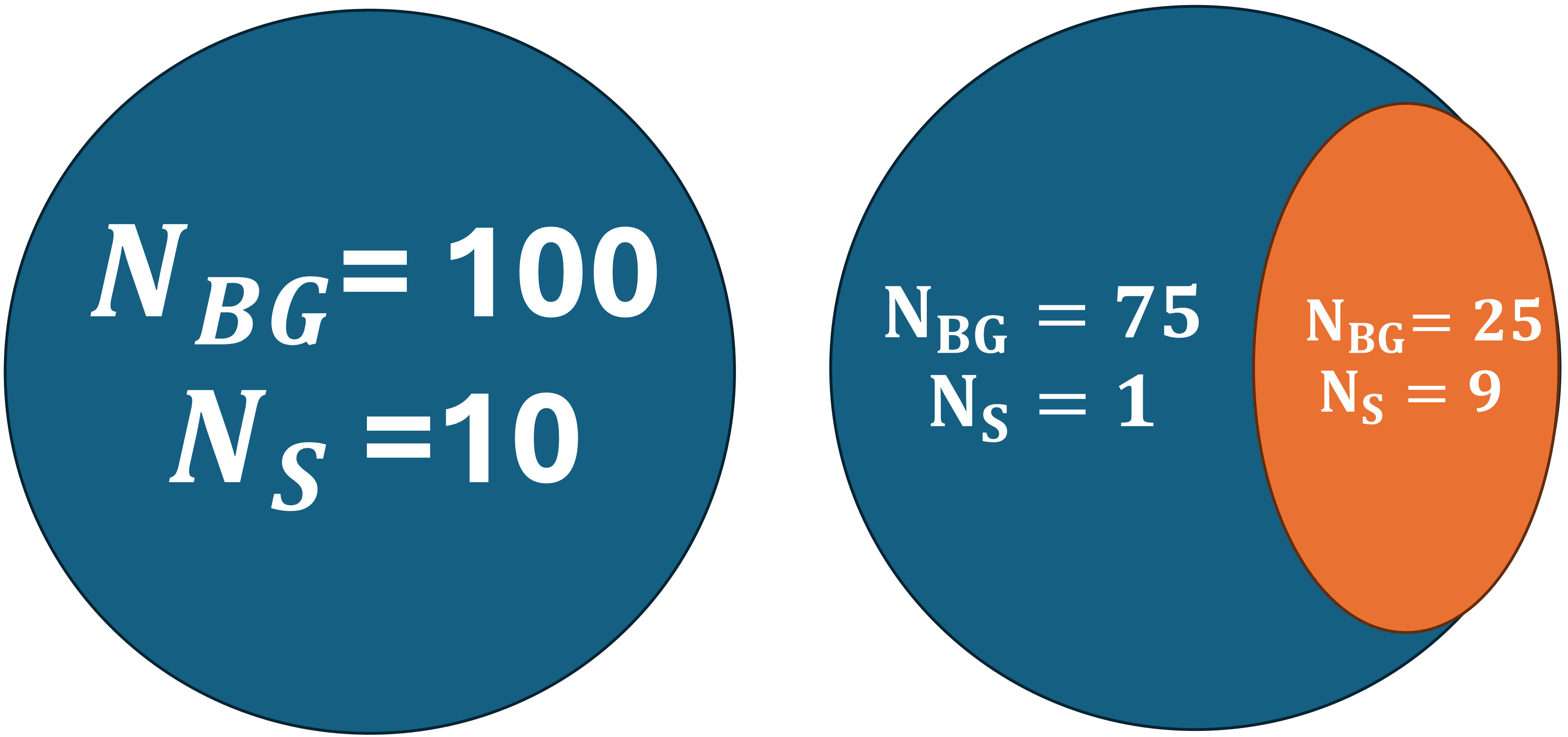
Boosted Dark Matter Directionality in Large Liquid Scintillators

- **No Successful DM detection has announced yet.**
- 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.

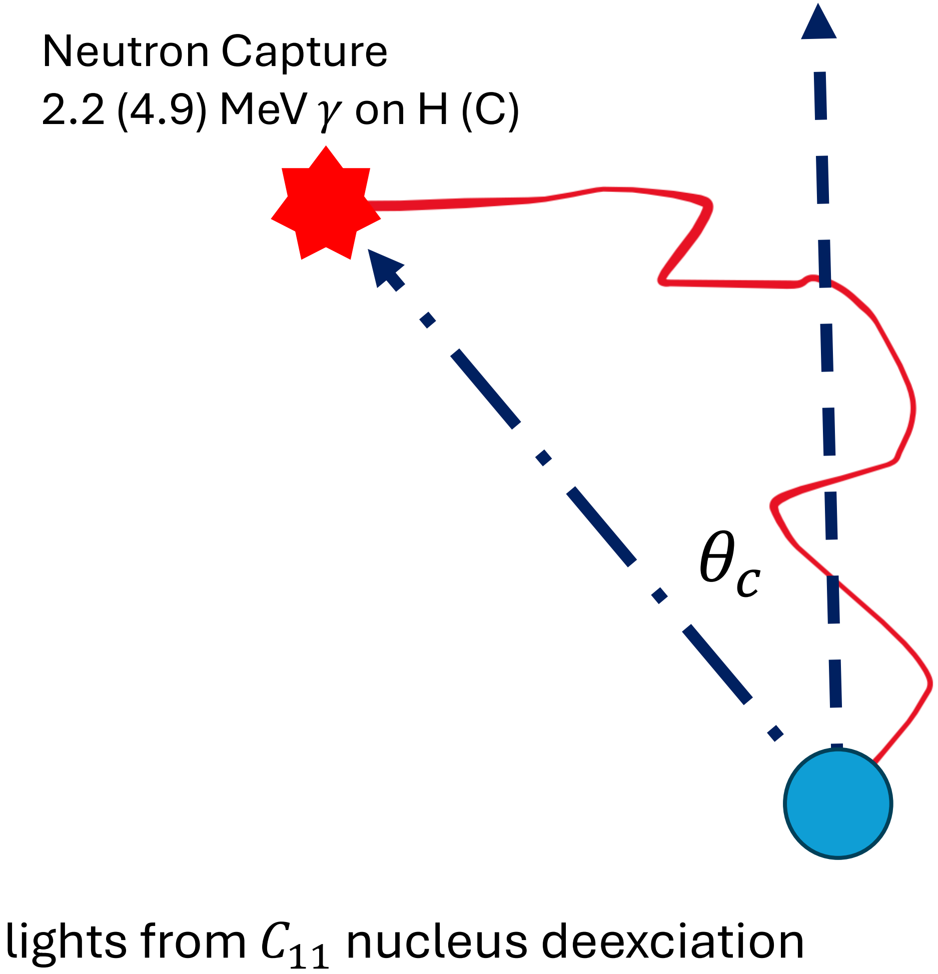
Boosted Dark Matter **Directionality** in Large Liquid Scintillators



$$\frac{N_S}{N_{BG}} = \frac{1}{10} \qquad \frac{N_S}{N_{BG}} = \frac{9}{25}$$

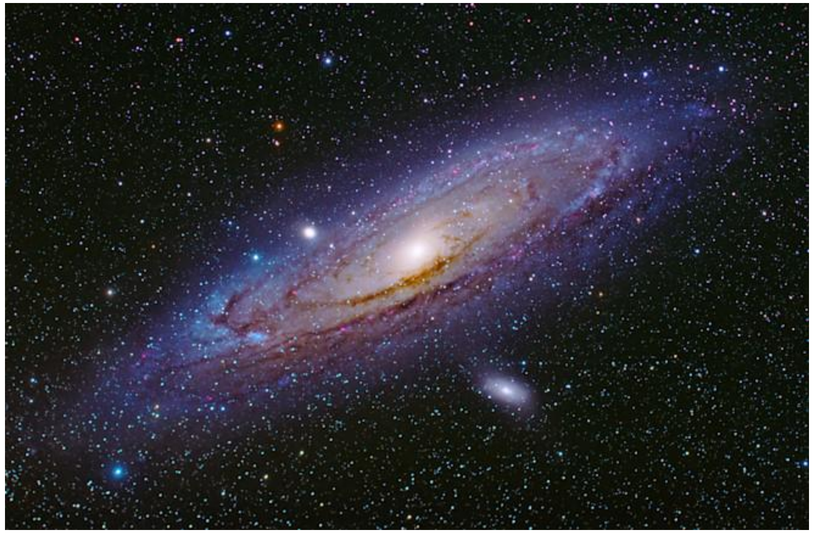
Boosted Dark Matter Directionality in Large Liquid Scintillators

- Traditionally, charged particle **directionality** will be lost due to scintillation light.
- We will use **neutron interaction points** to reconstruct directionality.
- Lower energy threshold than Water Cherenkov detector.



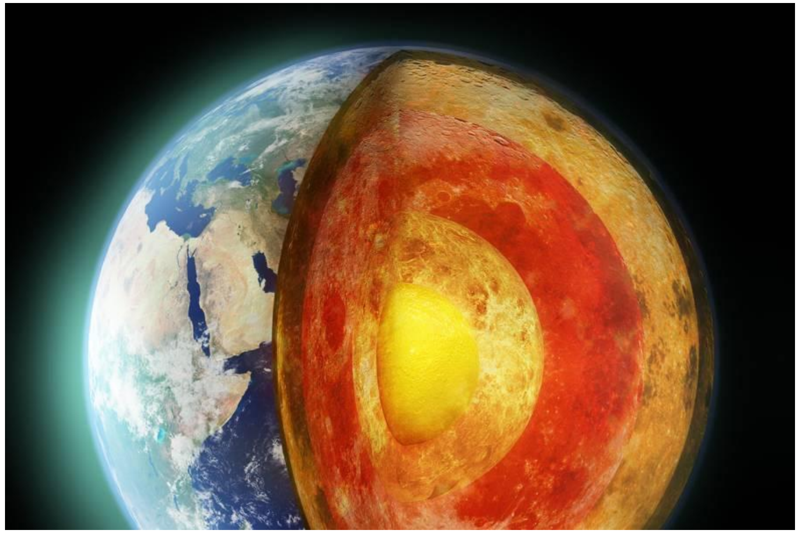
Outline:

1.



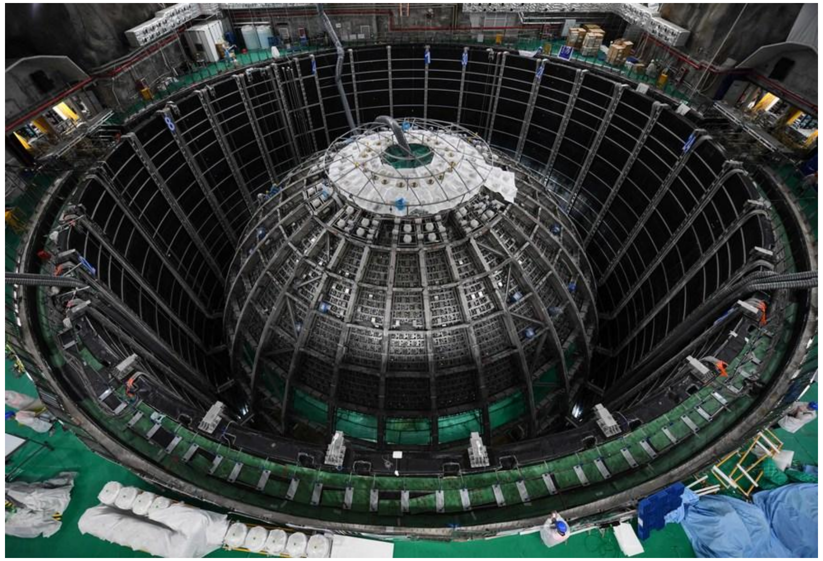
BDM Flux From Milky Way

2.



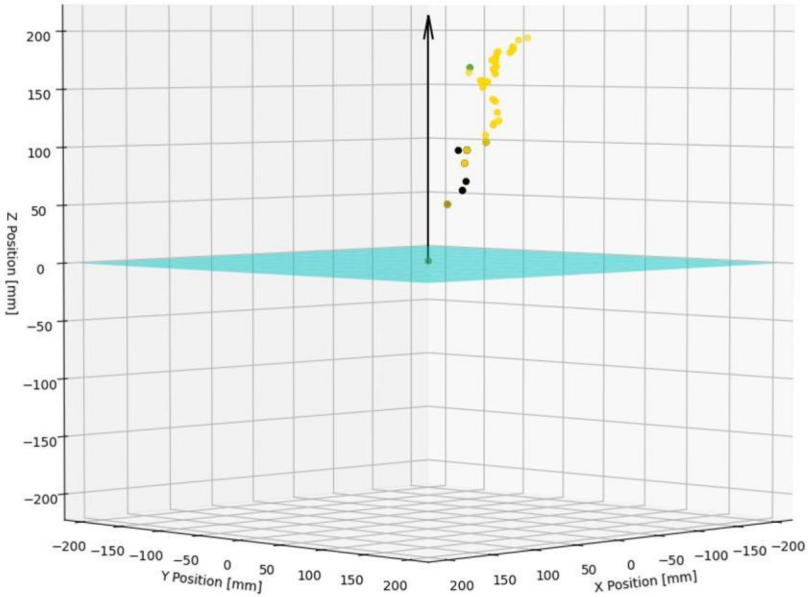
Earth Crust Stopping DM

3.



DM Knocking Neutrons

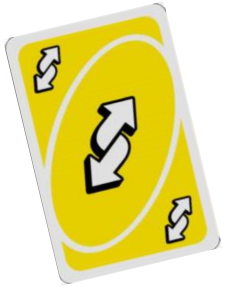
4.



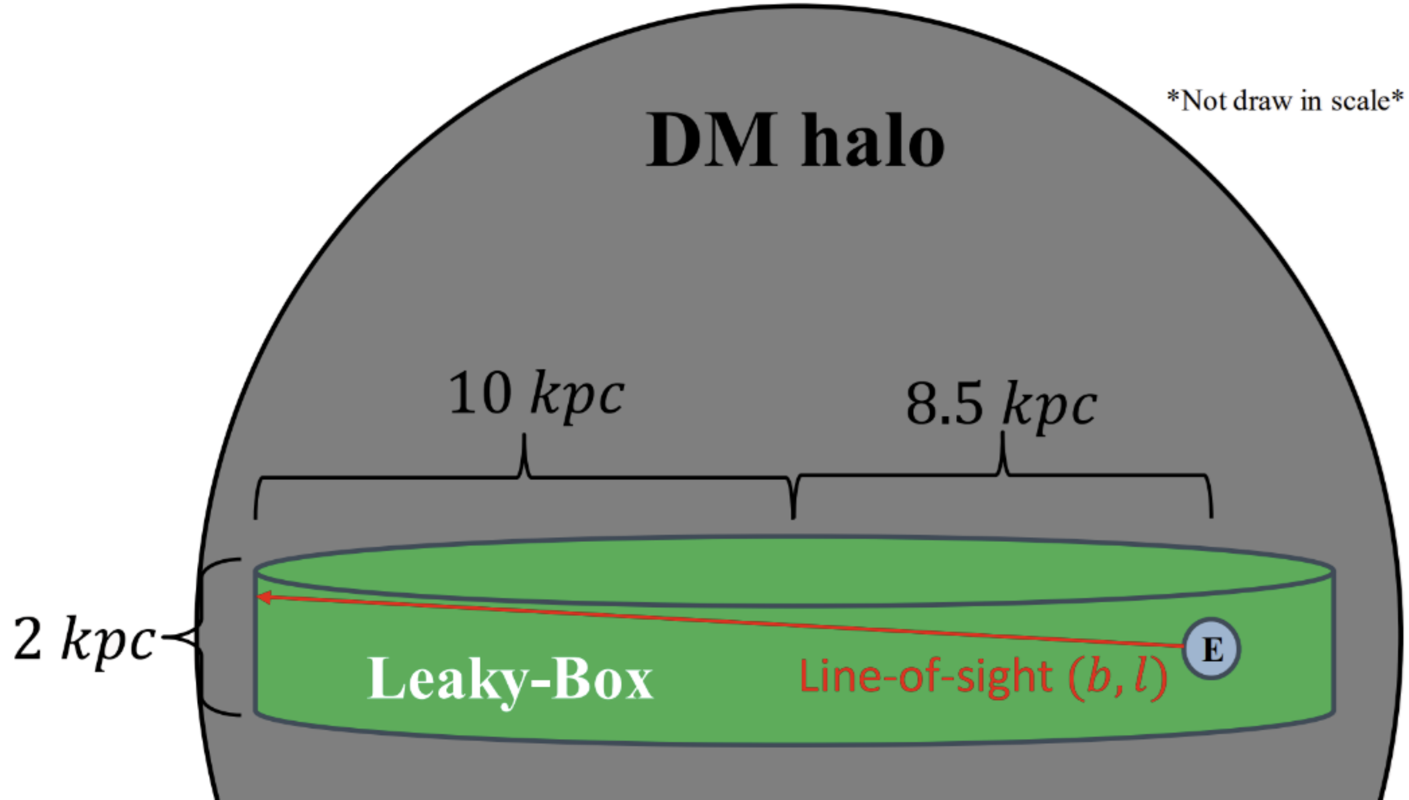
Neutrons Diffuse and Capture

Boosted Dark Matter by Cosmic Rays

Detector's nucleon ↔ DM ↔ Cosmic ray



We Follow [Ema,2021] scheme to obtain BDM Flux.



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

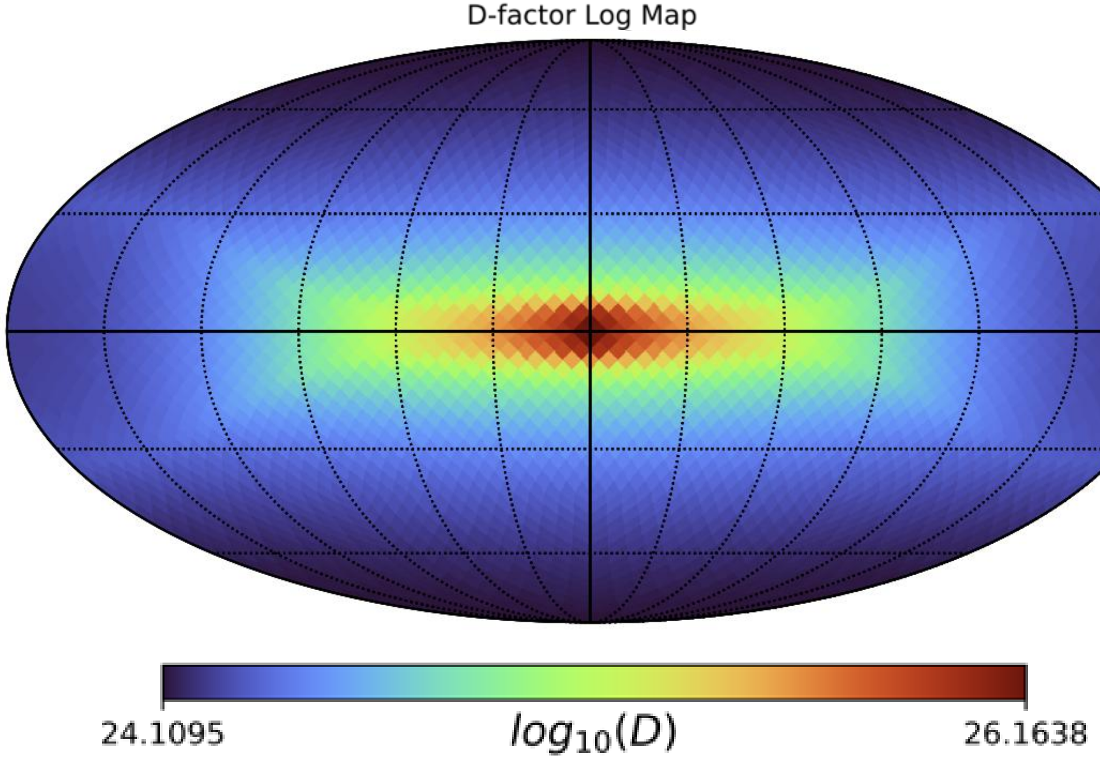
Boosted Dark Matter Flux

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

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

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

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



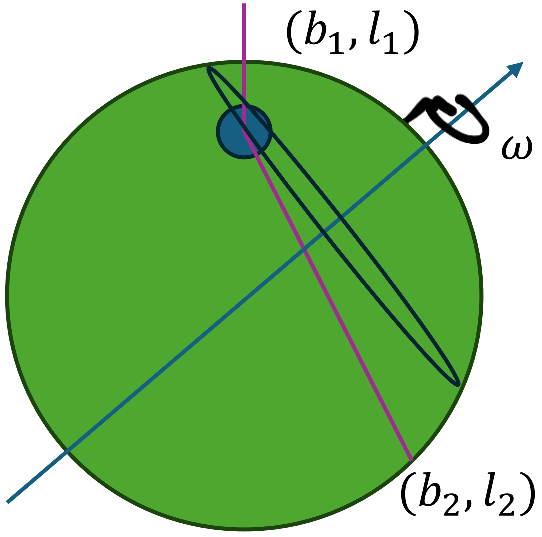
DM Flux Peaked at Galactic Center

Earth Attenuation Effect (Ema,2021) & (Bringmann,2019)

Assumptions:

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

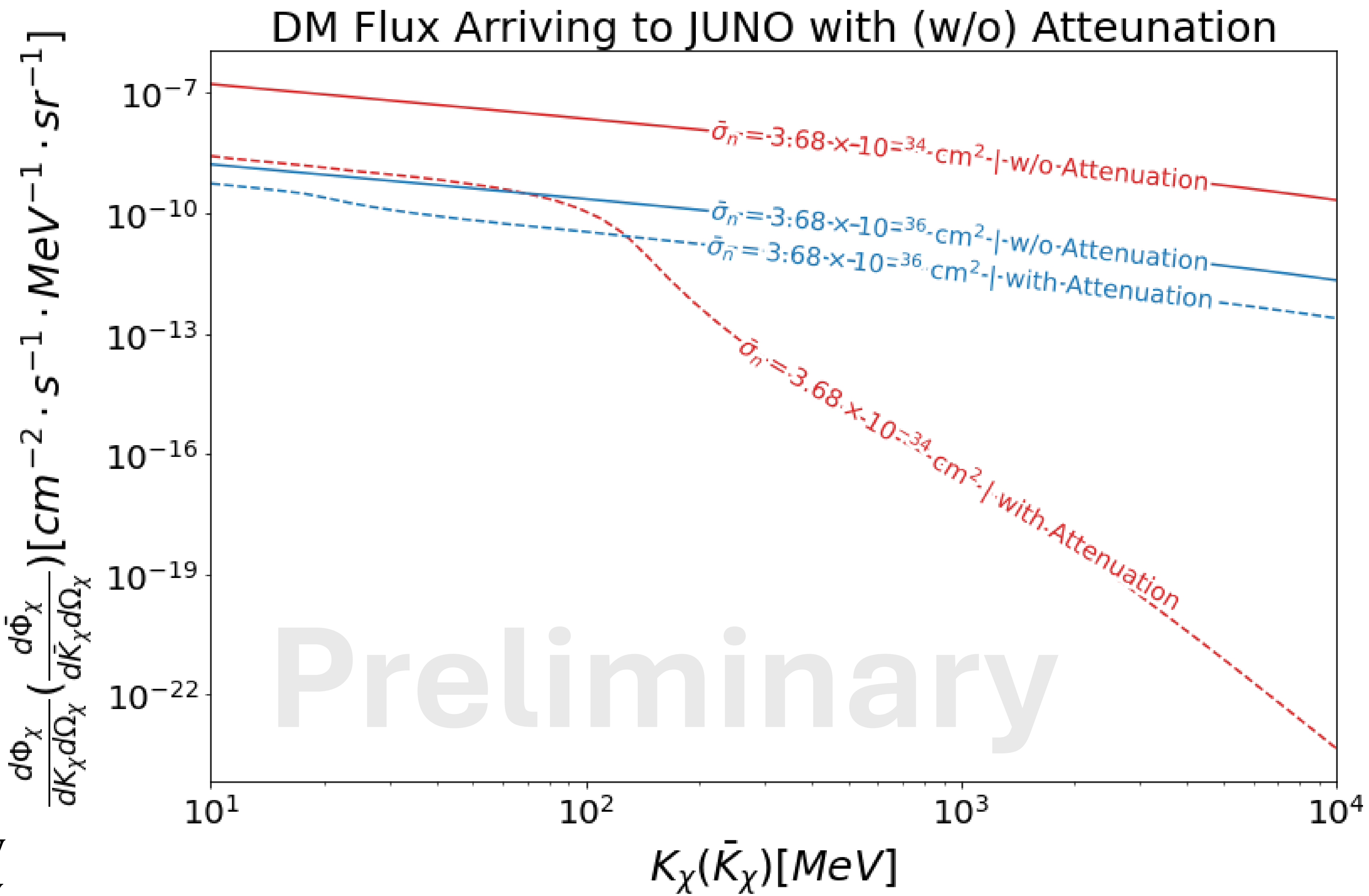
$$\frac{d\overline{K_\chi}(z)}{dz} = -n_T \int_0^{K_T - max} dK_T \, K_T \frac{d\sigma_{\chi T}}{dK_T}\left(\overline{K_\chi}, K_T\right)$$



2. The target particles are protons and neutrons (1:1) and we assume form factor $F_A(q^2) \approx 1$.

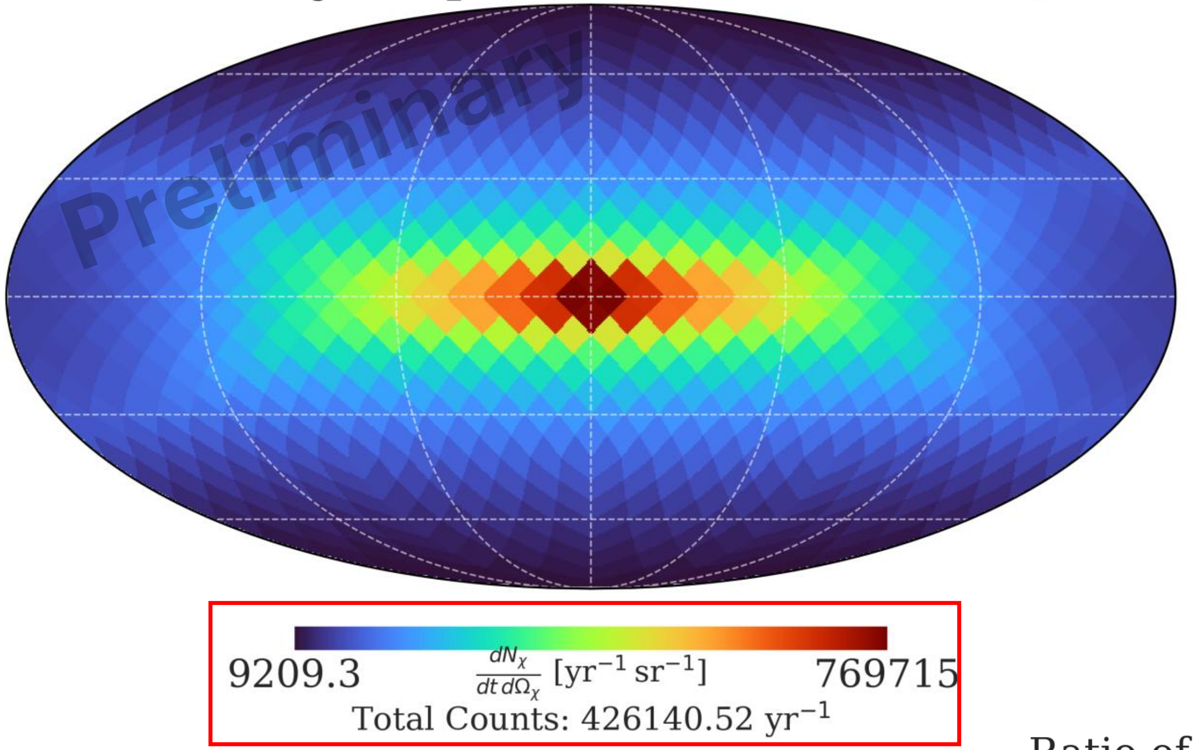
3. No change in direction for DM at each scattering.

This approximation serves as a **conservative limit**.
It **overestimates the stopping power of Earth Crust** than simulation.
(Emken, 2018)

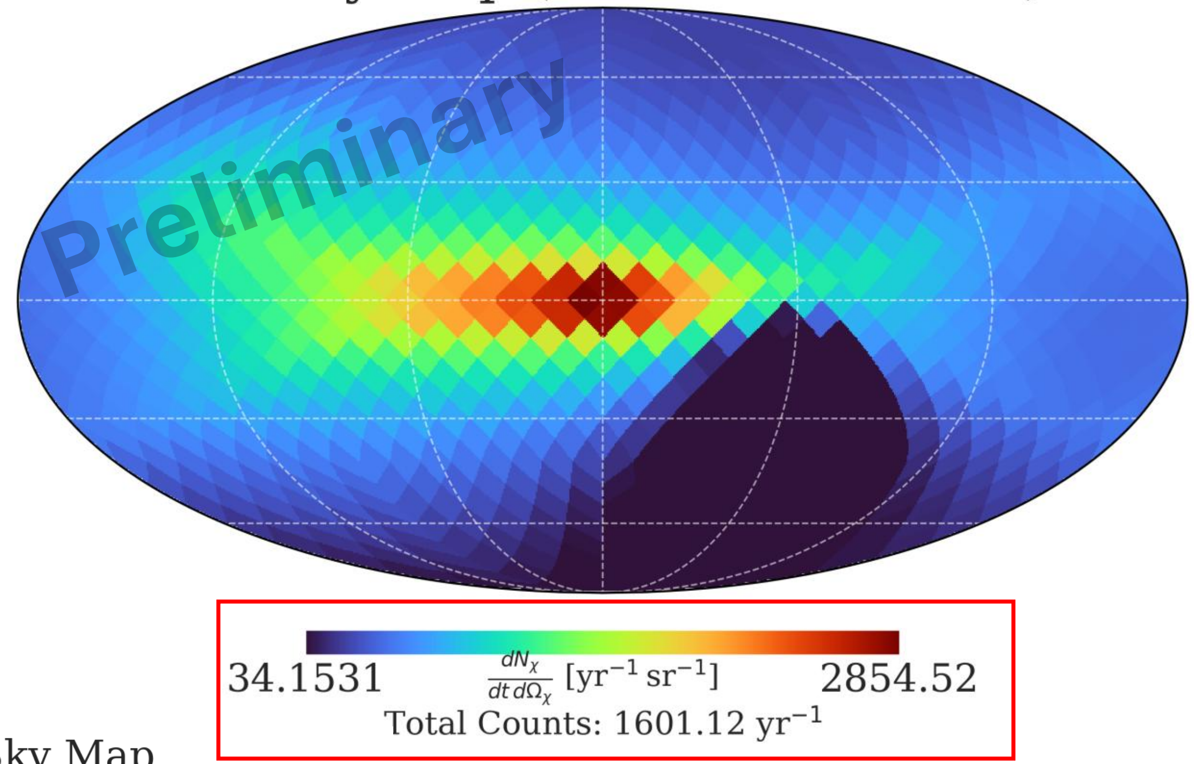


$m_\chi = 1$ MeV
$m_\phi = 1\ GeV$

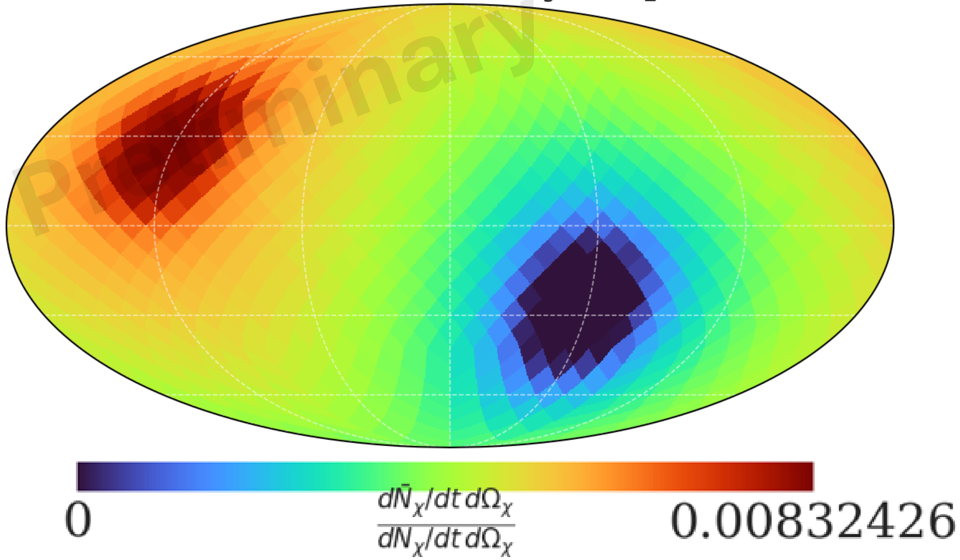
DM Sky Map (Before Attenuation)



DM Sky Map (After Attenuation)



Ratio of DM Sky Map

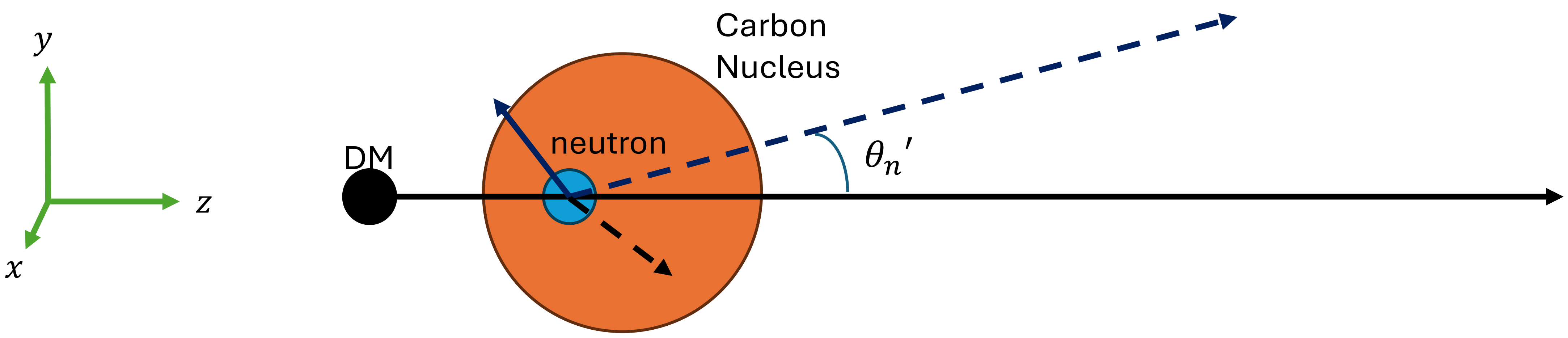


$$K_\chi(\bar{K}_\chi) = [10\ MeV \sim 10\ GeV]$$

$$m_\chi = 1\ \mathrm{MeV}$$
$$m_\phi = 1\ GeV$$
$$\bar{\sigma}_n = 3.68 \times 10^{-34}\ cm^2$$

Neutron Triggered Rate: (Lin,2025) (Bodek, 2019)

$$\frac{dN}{dK_n' d\Omega_n'} = N_{JUNO} \cdot \int d\Omega_\chi \int dt \int d\bar{K}_\chi \frac{d\bar{\Phi}_\chi}{d\bar{K}_\chi d\Omega_\chi} \cdot \frac{d\sigma_{QEL}}{dK_n' d\Omega_n'}(\bar{K}_\chi, K_n', \theta_n')$$



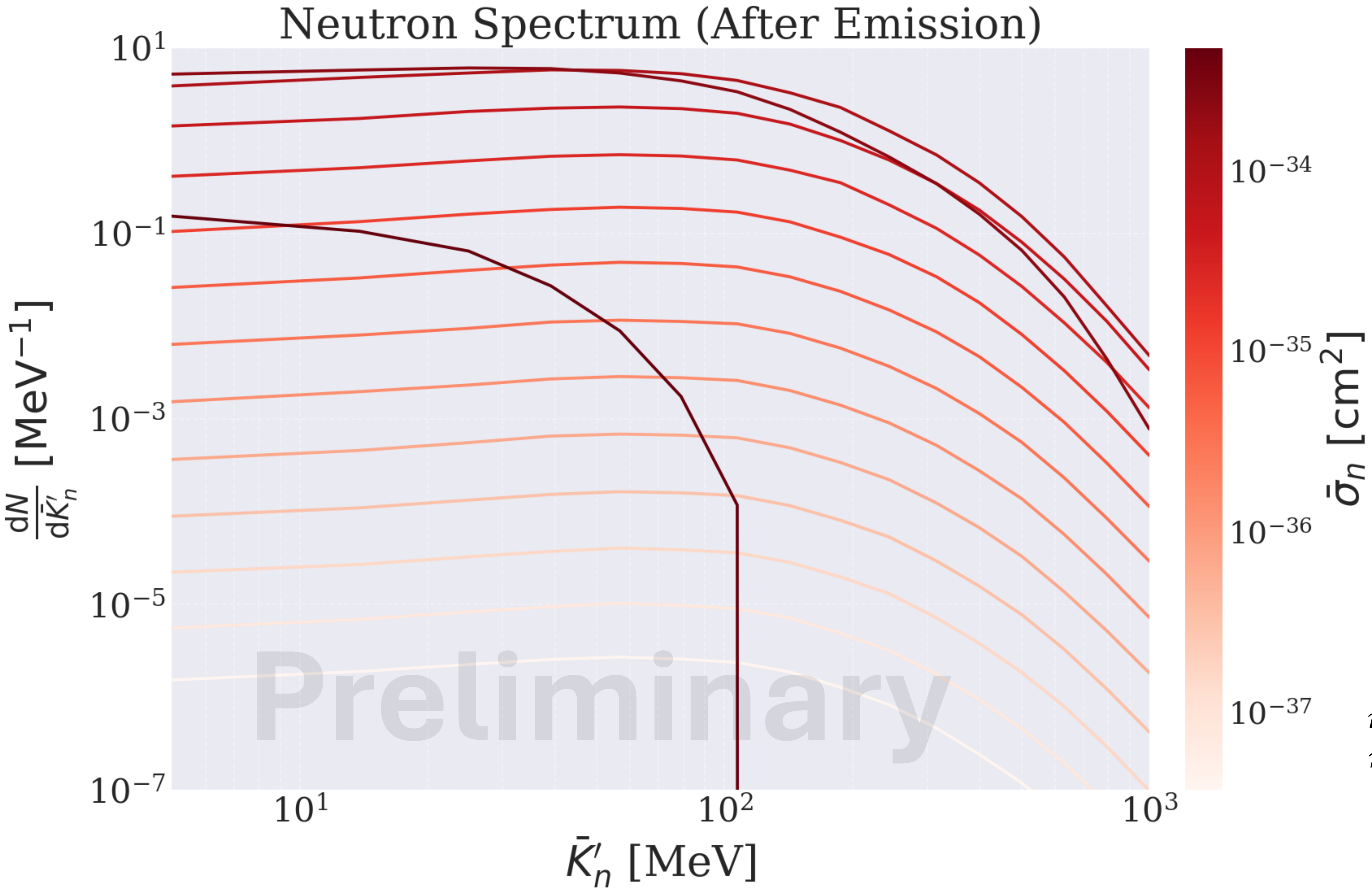
Kinematics:

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

Nuclear Effect:

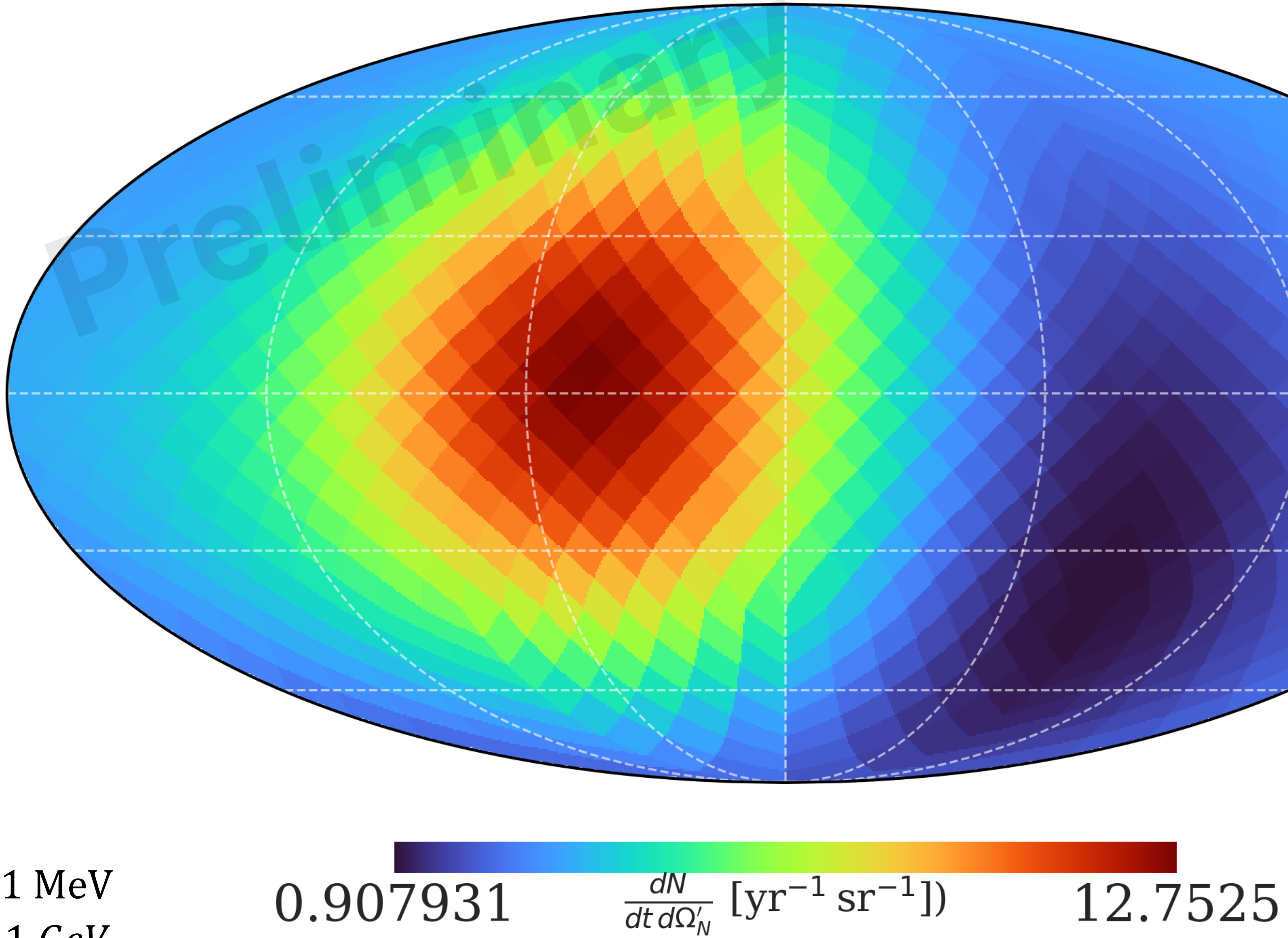
- Pauli Blocking
- Final State Interaction

$$\begin{bmatrix} \bar{E}_\chi \\ 0 \\ 0 \\ \bar{k} \end{bmatrix} + \begin{bmatrix} E_N \\ p_x \\ py \\ pz \end{bmatrix} = \begin{bmatrix} {E_\chi}' \\ k_x \\ k_y \\ k_z \end{bmatrix} + \begin{bmatrix} E_N' \\ 0 \\ p' sin\theta_n' \\ p' cos\theta_n' \end{bmatrix} + \begin{bmatrix} E_R \\ 0 \\ 0 \\ 0 \end{bmatrix}$$



$m_\chi = 1$ MeV
$m_\phi = 1\ GeV$

Neutron Emission Sky Map



$\bar{K}'_N = [5\ MeV, 1\ GeV]$

$m_\chi = 1$ MeV

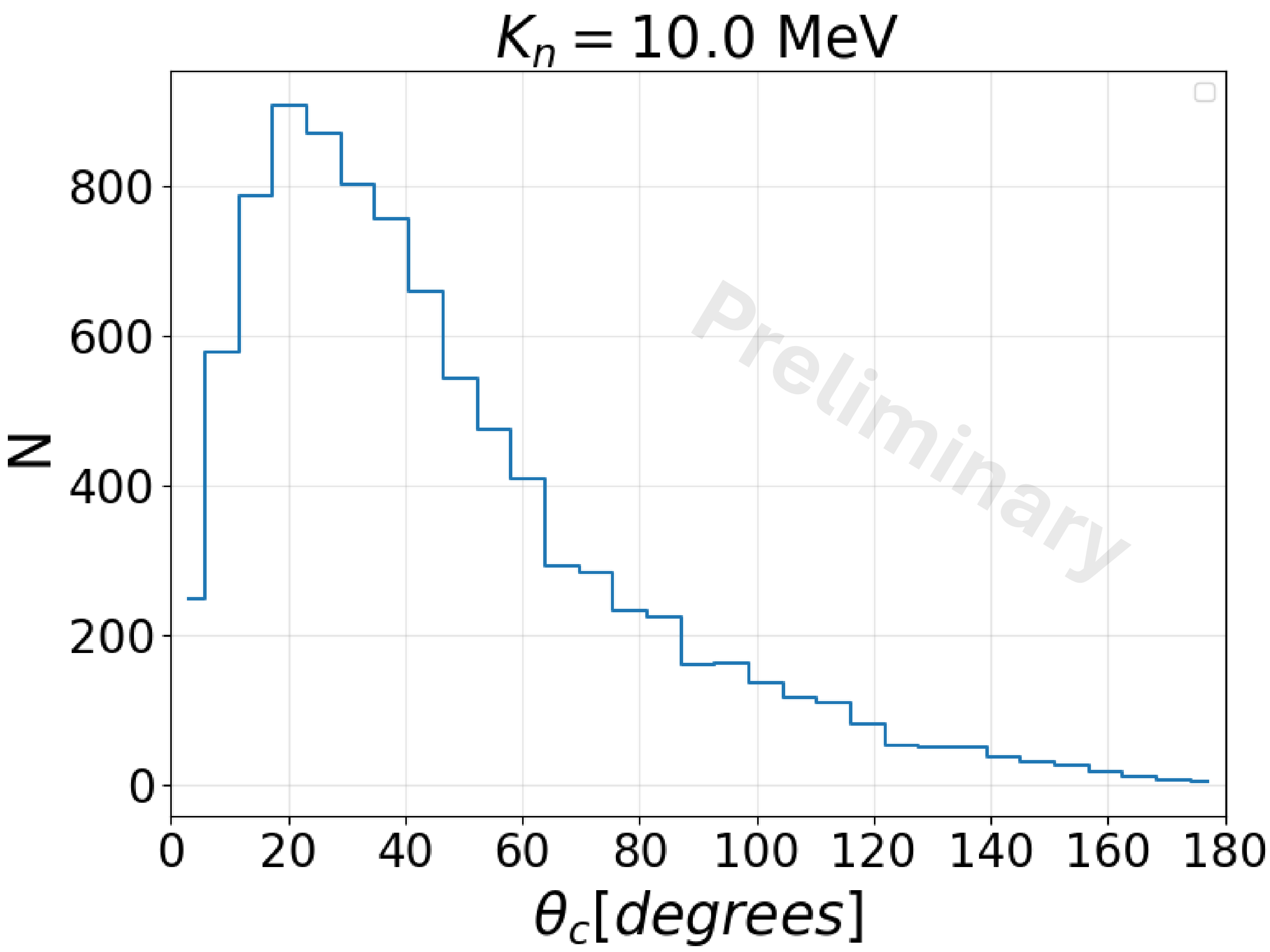
$m_\phi = 1\ GeV$

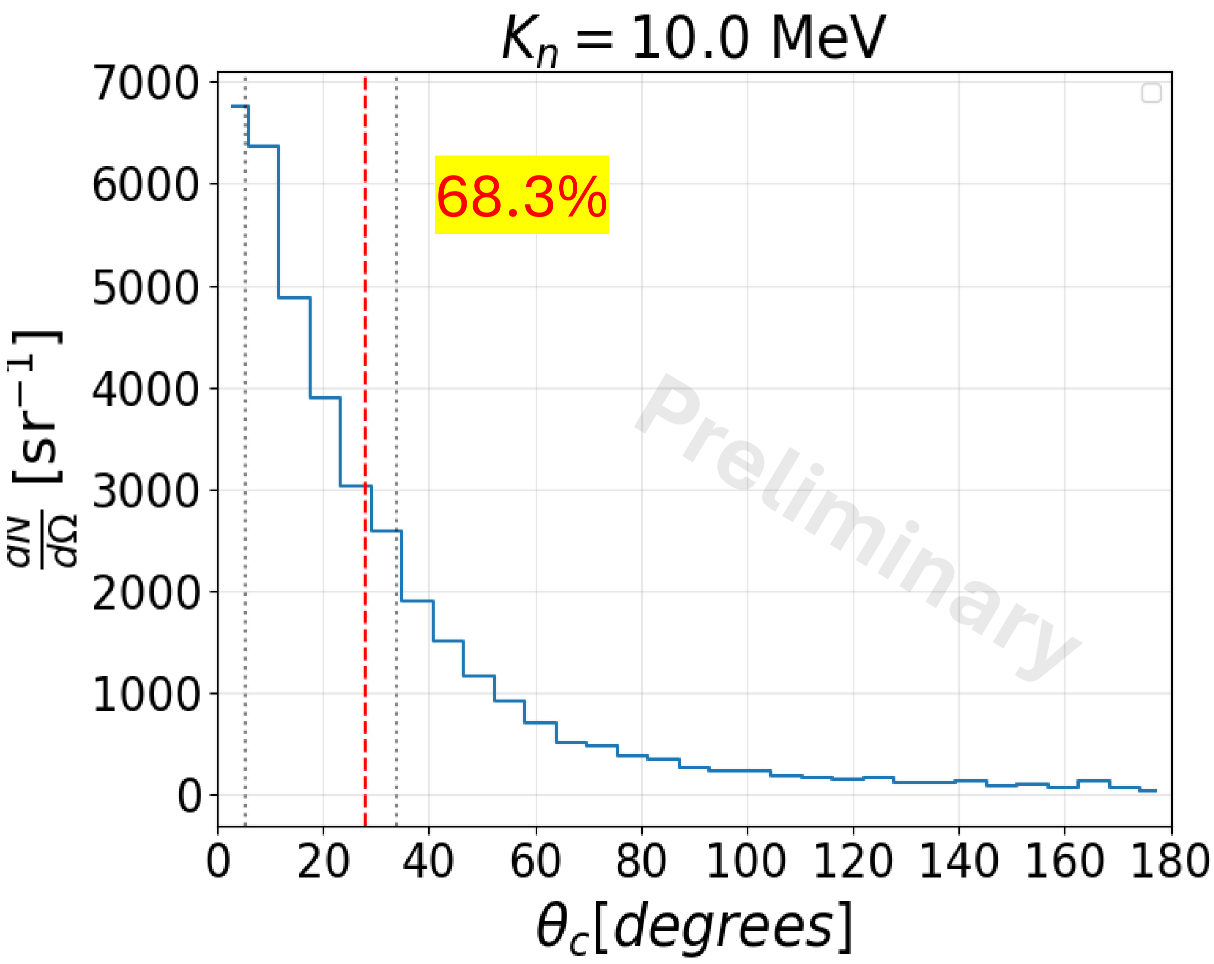
$\bar{\sigma}_n = 3.68 \times 10^{-34}\ cm^2$

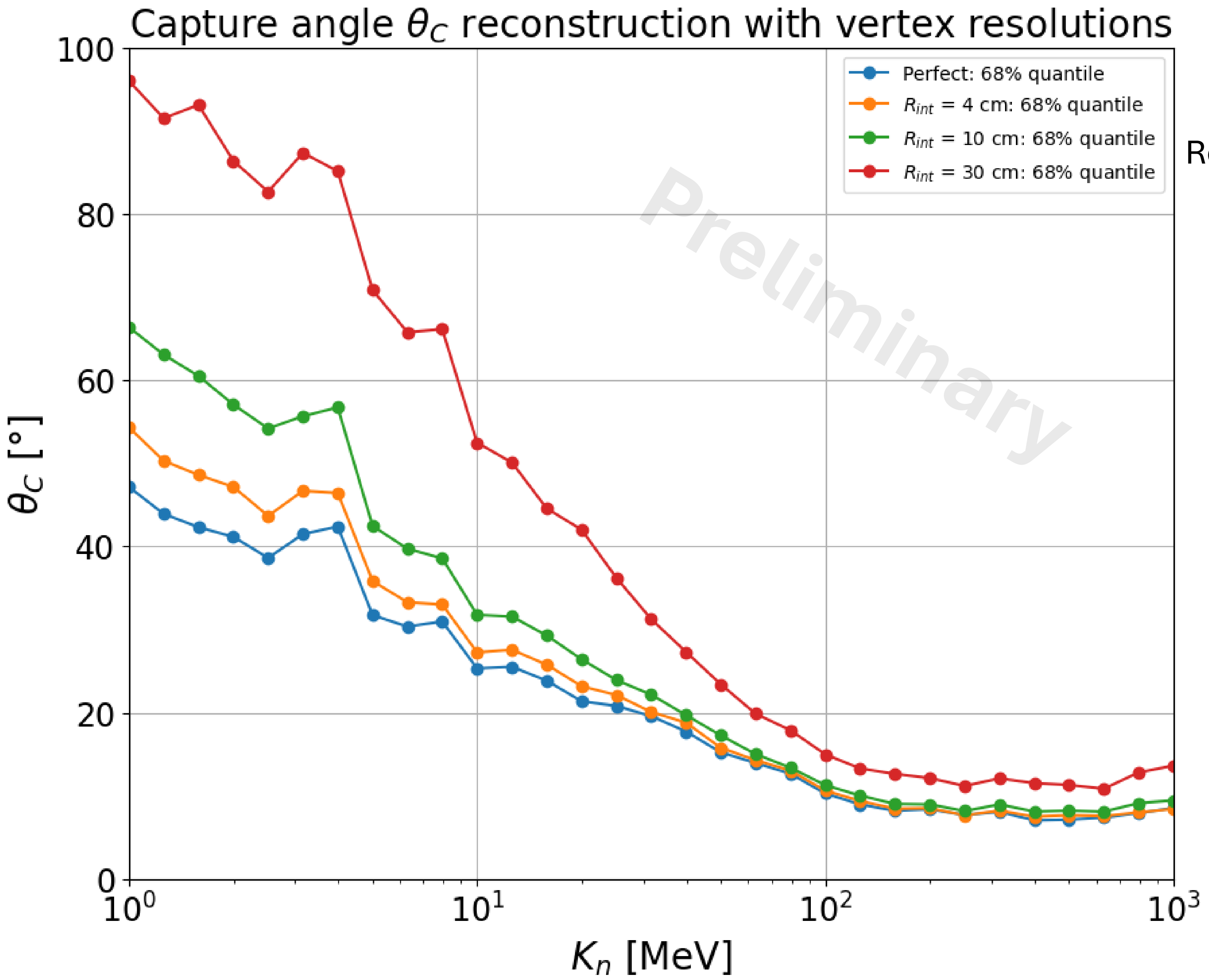
Total Counts: 58.53 yr^{-1}

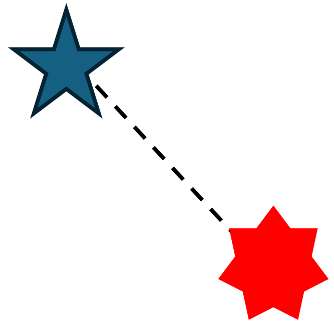
Simulated Capture Angle in Geant4 + Vertex Resolution

For each K_n bin, $N = 10000$



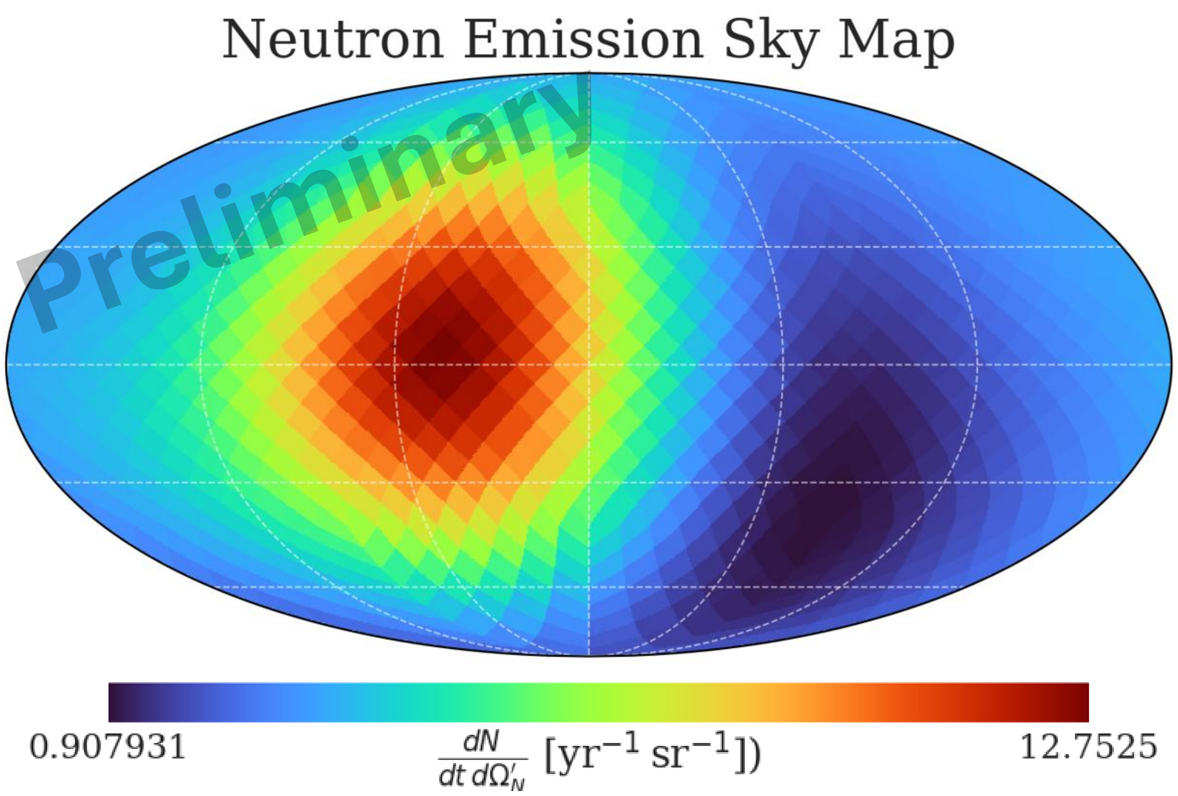






‘The vertex reconstruction bias is kept within 4 cm level throughout the detector (JUNO) and resolution for events with around 1 MeV energy deposition is estimated to be approximately 9 cm.’ (Takenaka, 2025)

Before Diffusion



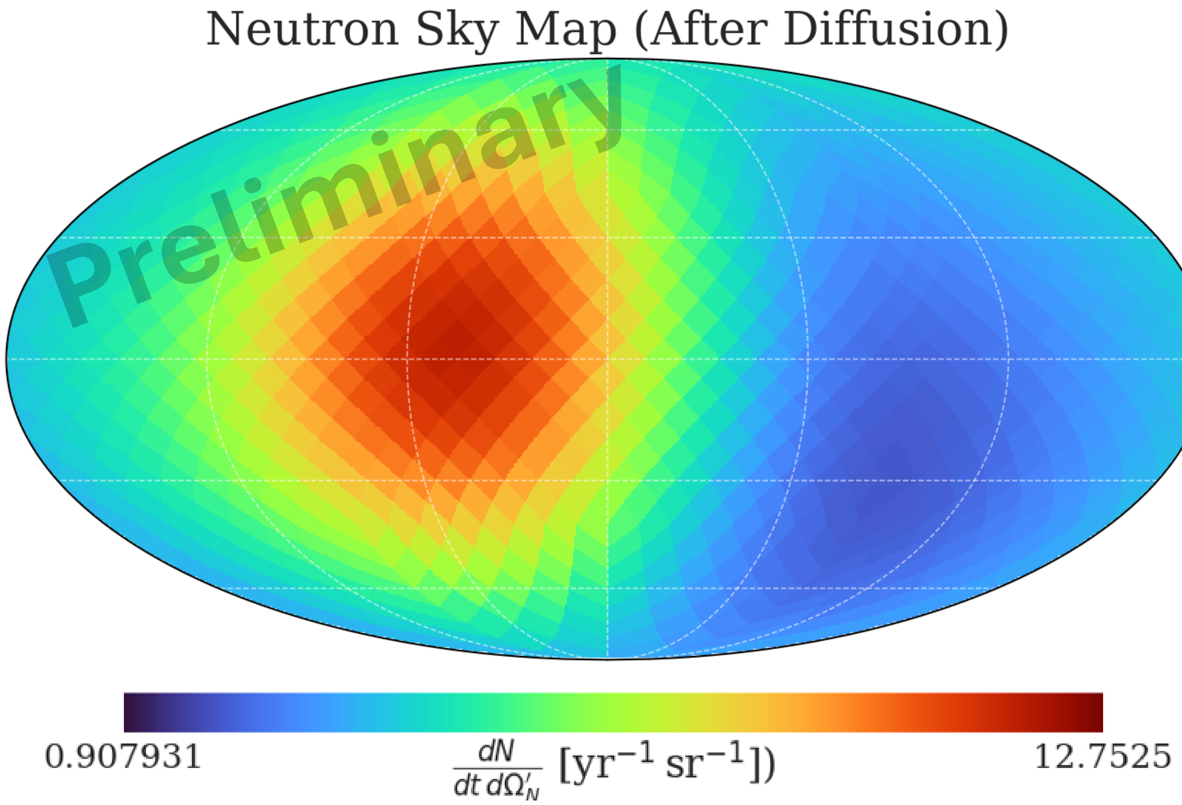
$\frac{\Delta N_{max}}{\Delta N_{min}} = 14.01$

$m_\chi = 1$ MeV

$m_\phi = 1\ GeV$

$\bar{\sigma}_n = 3.68 \times 10^{-34}\ cm^2$

After Diffusion



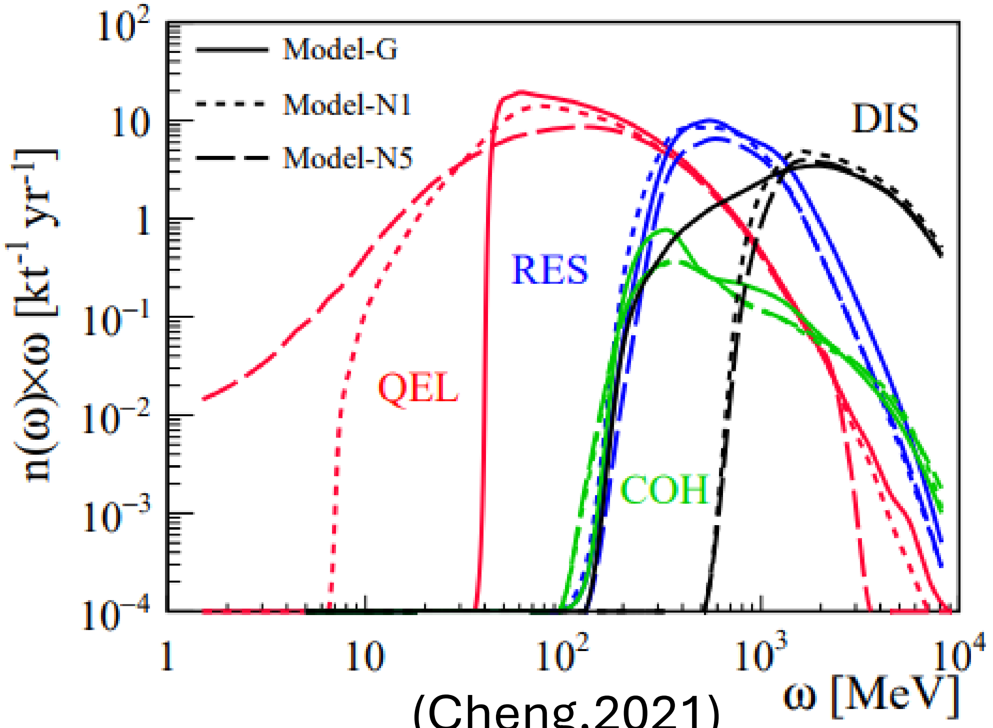
$\frac{\Delta N_{max}}{\Delta N_{min}} = 5.61$

$\bar{K}'_n = [5\ MeV, 1\ GeV]$

Background Estimation:

We only considered the Indistinguishable BG:

Atmospheric Neutrino-Neutron Neutral-Current QEL interaction.



(Cheng,2021)

Energy transfer for $\nu - C^{12}$ NC interacion in LS
We choose Model-G, which is GENIE with RFGs
(Cheng,2021)

For 5 yrs with 18.3 ktons in JUNO for $\overline{K}_n' = [5\ MeV, 1\ GeV]$

$$N_{BG} \approx 1131.05$$

We also assume they will be isotropic

Likelihood and Constraint:

To obtain a 95% CL line, we used joint likelihood function for the 768 pixels:

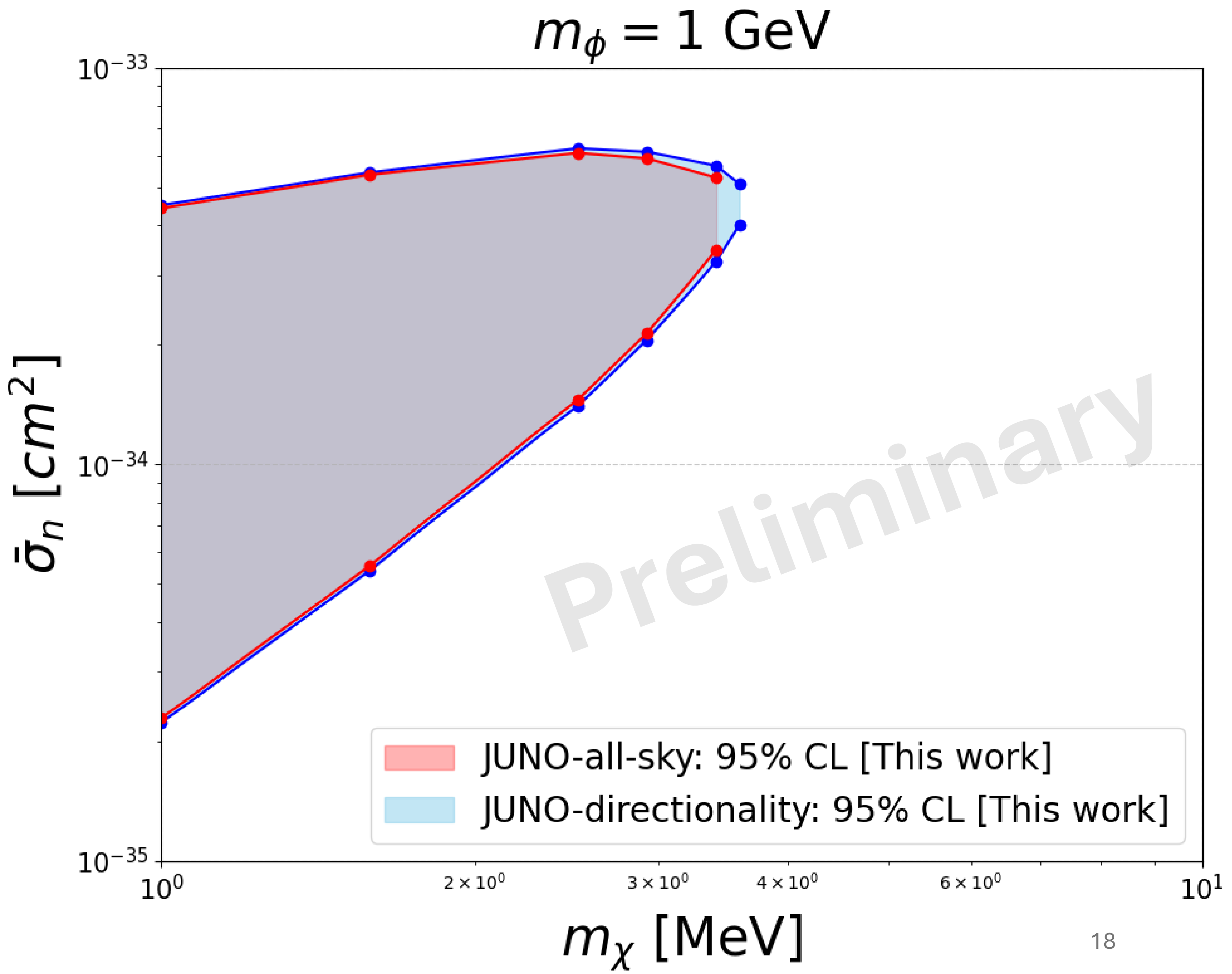
$$L = \prod_{i}^{N=768} \frac{\lambda_i^{k_i} e^{-\lambda_i}}{k_i!}$$

Where $\lambda_i = n_S + n_{BG}, k_i = n_{BG}$.

Then we use the log likelihood ratio: (Cowan, 2013)

$$TS = -2ln\frac{L(N_S)}{L(N_S = 0)} = 2.71$$

We also plot the all-sky curve, with one single “All-sky” bin is used .



Conclusion:

- **Neutrons retain the directional signature of the BDM.**
- Leveraging this directionality provides a sightly better constraint than a single 'All-Sky' bin, with the enhancement becoming more significant at higher DM masses.
- A further refinement of the energy bin range is expected to increase the signal-to-background ratio, thereby strengthening our constraints.

Thank you!

Backup Slides

Neutron Diffusion: Geant4

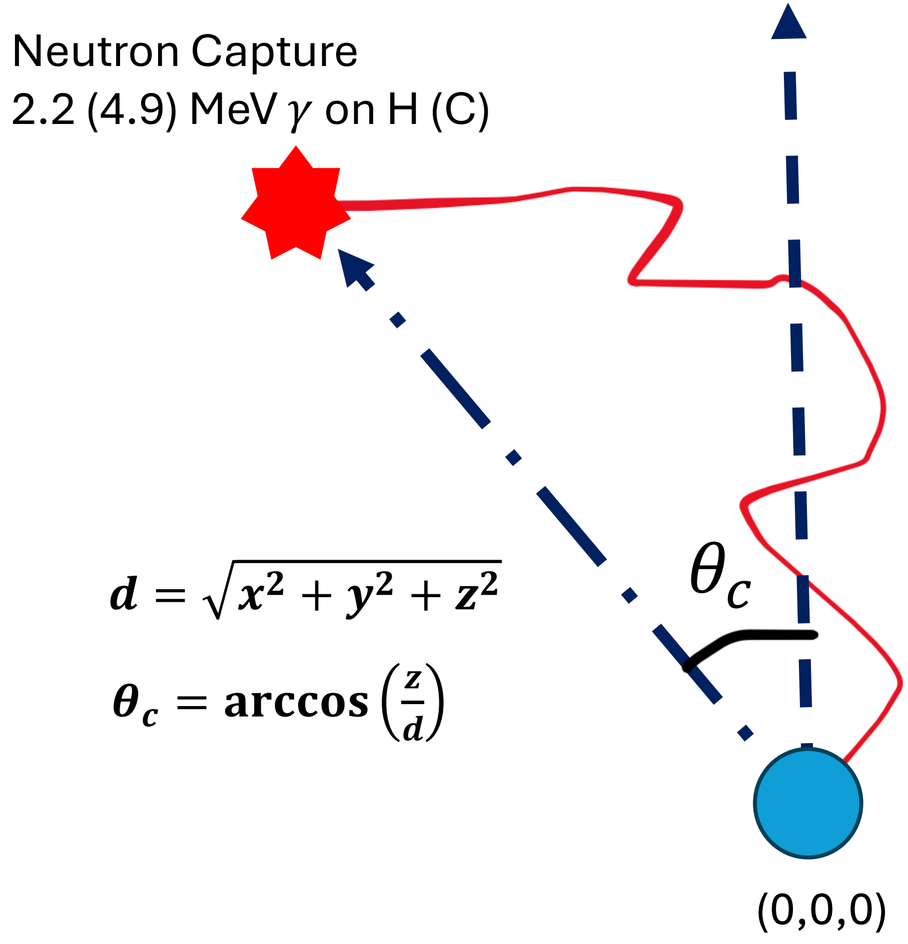
Physics list:

1. G4HadronPhysicsFTFP_BERT_HP()
2. G4HadronElasticPhysics()
3. G4EmStandardPhysics()

Configuration:

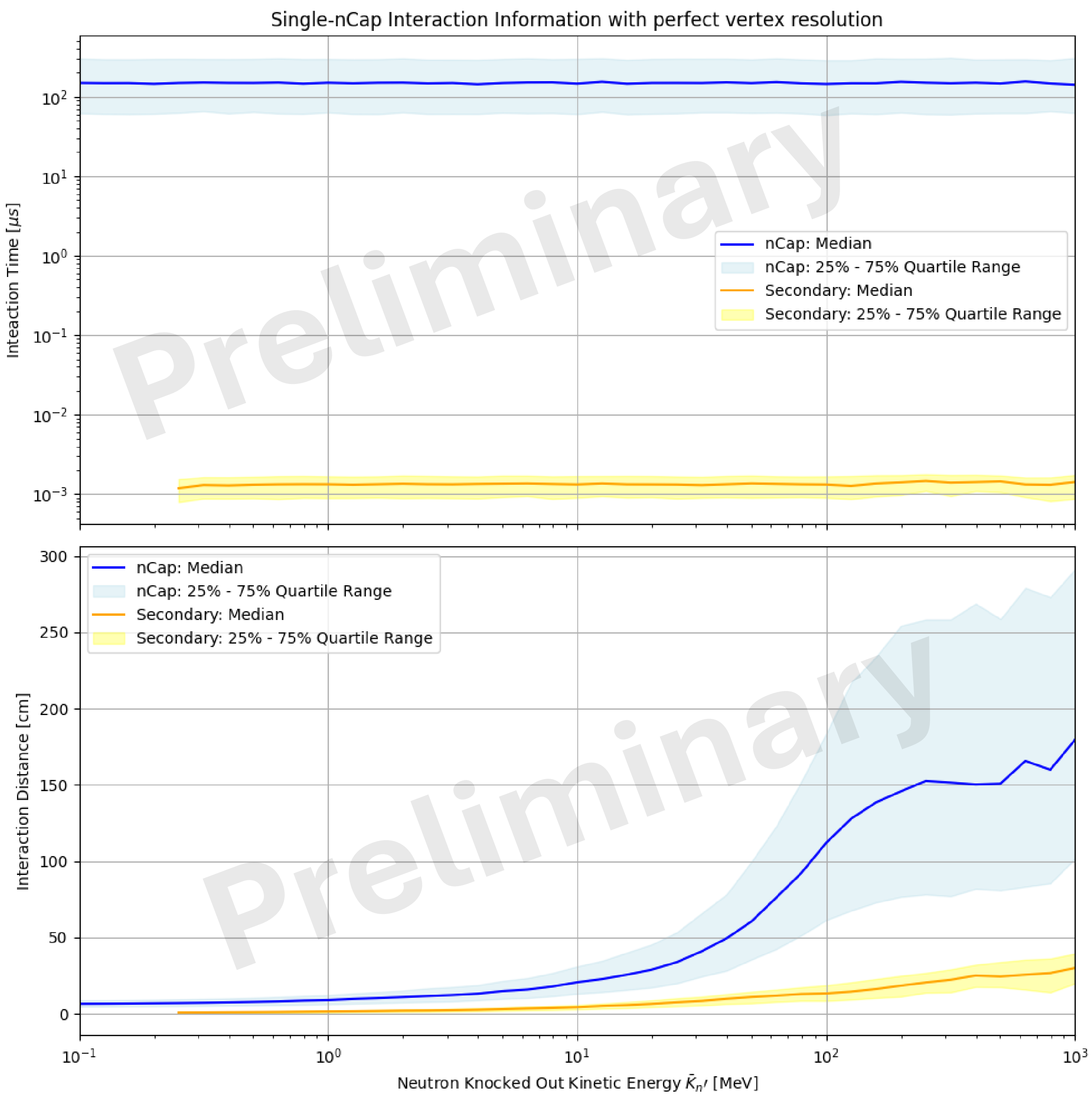
1. Linear alkylbenzene(LAB)
2. 2,5-diphenyloxazole (PPO)
3. p-bis-(o-methylstyryl)-benzene (bis-MSB)

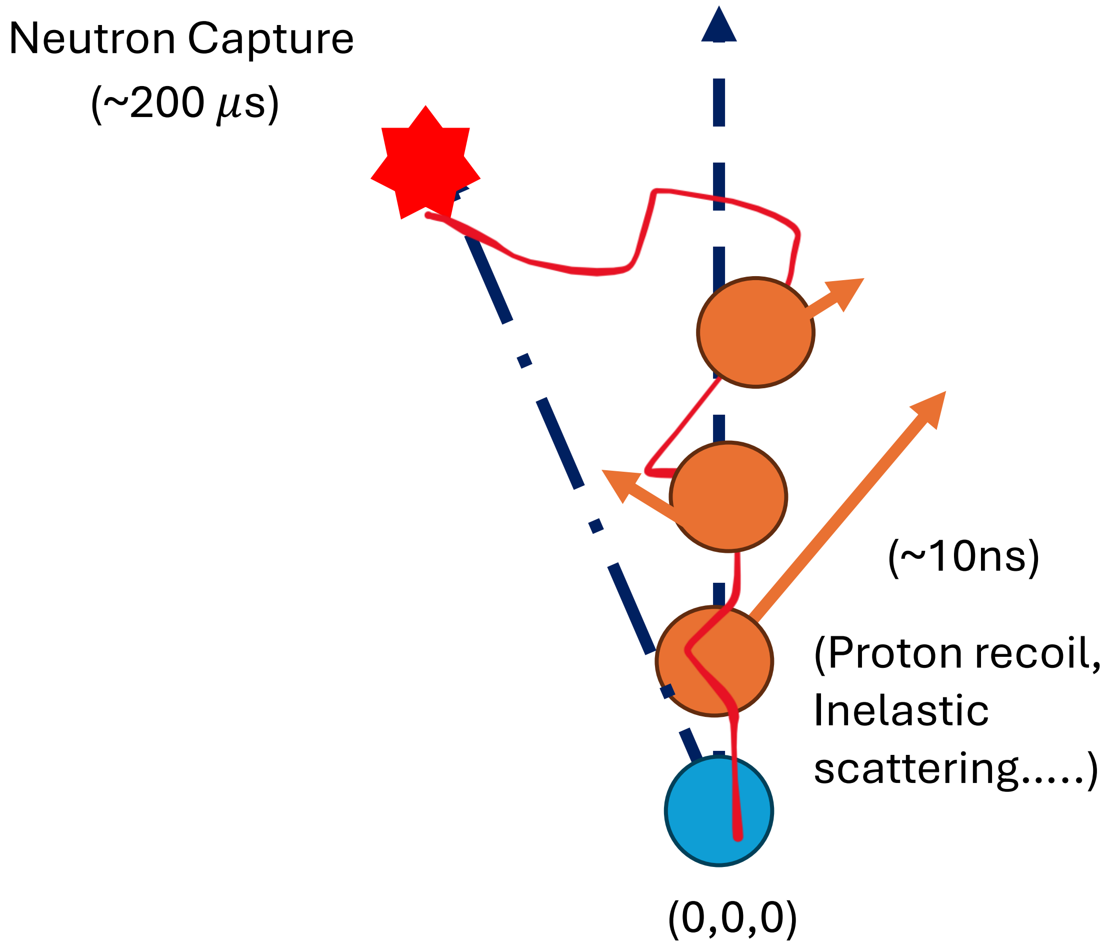
Chemicals	Chemicals Composition	Density (g/cm^3)
LAB	C=18, H=30	0.855985 (99.6%)
PPO	C=15, H=11, N=1, O=1	0.003 (0.3%)
Bis-MSB	C=24, H=22	0.000015



$$d = \sqrt{x^2 + y^2 + z^2}$$

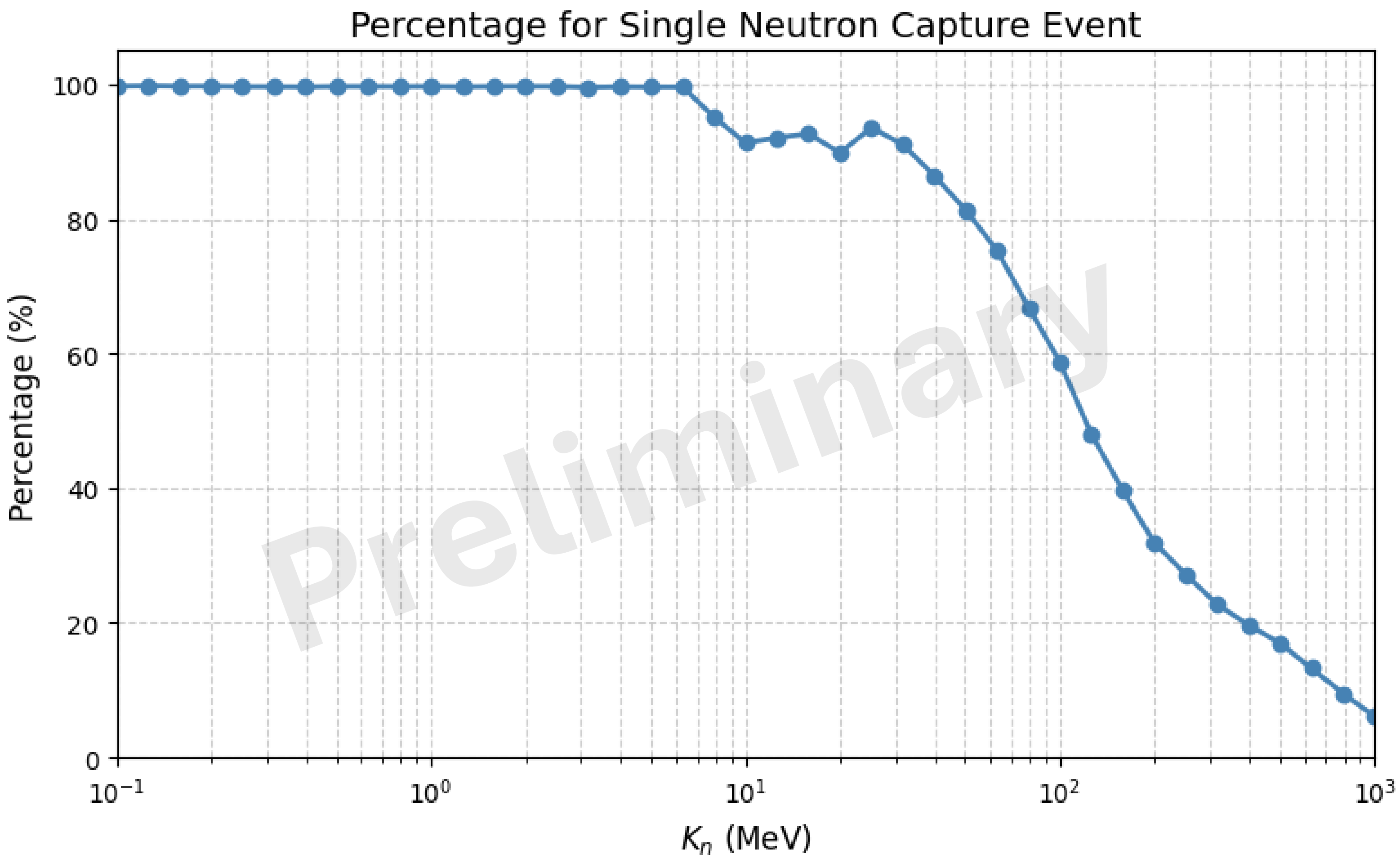
$$\theta_c = \arccos\left(\frac{z}{d}\right)$$

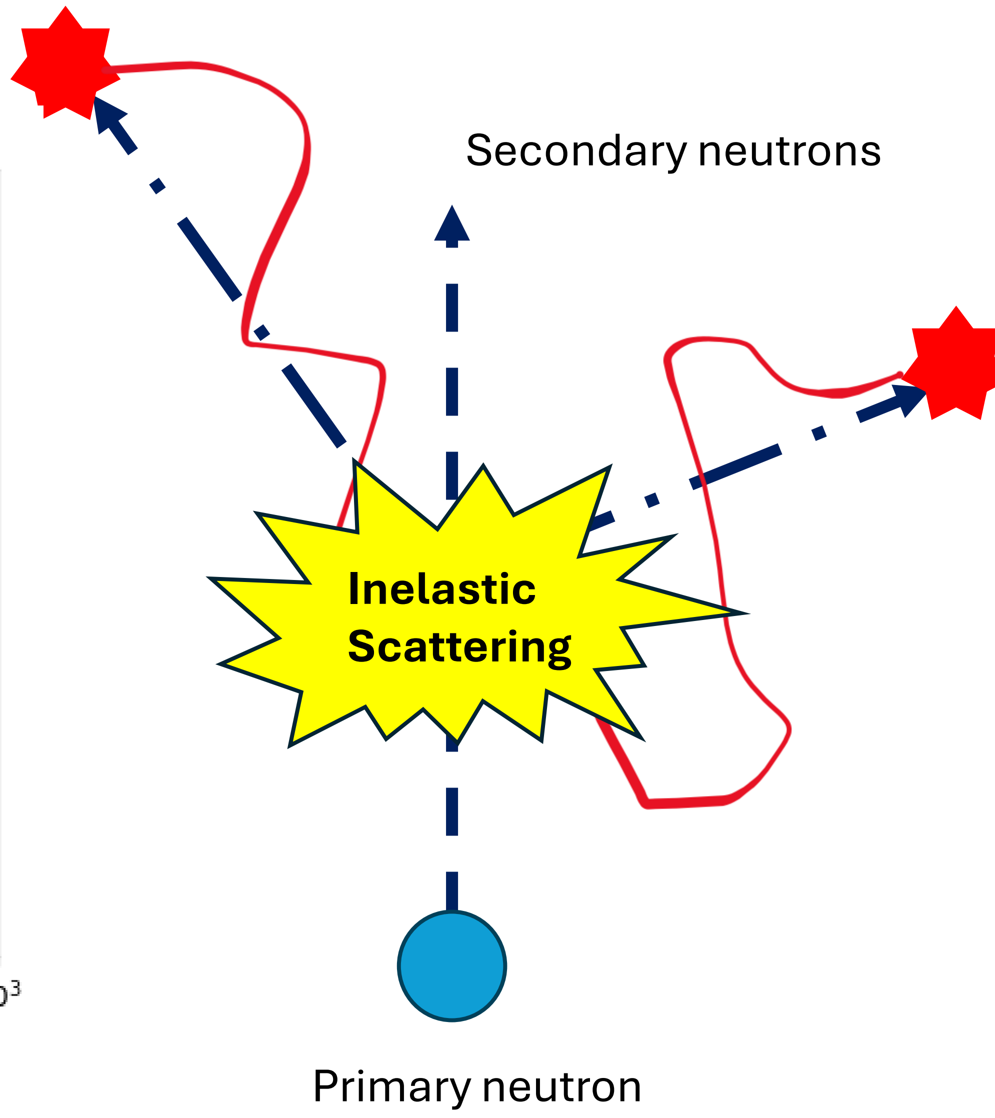




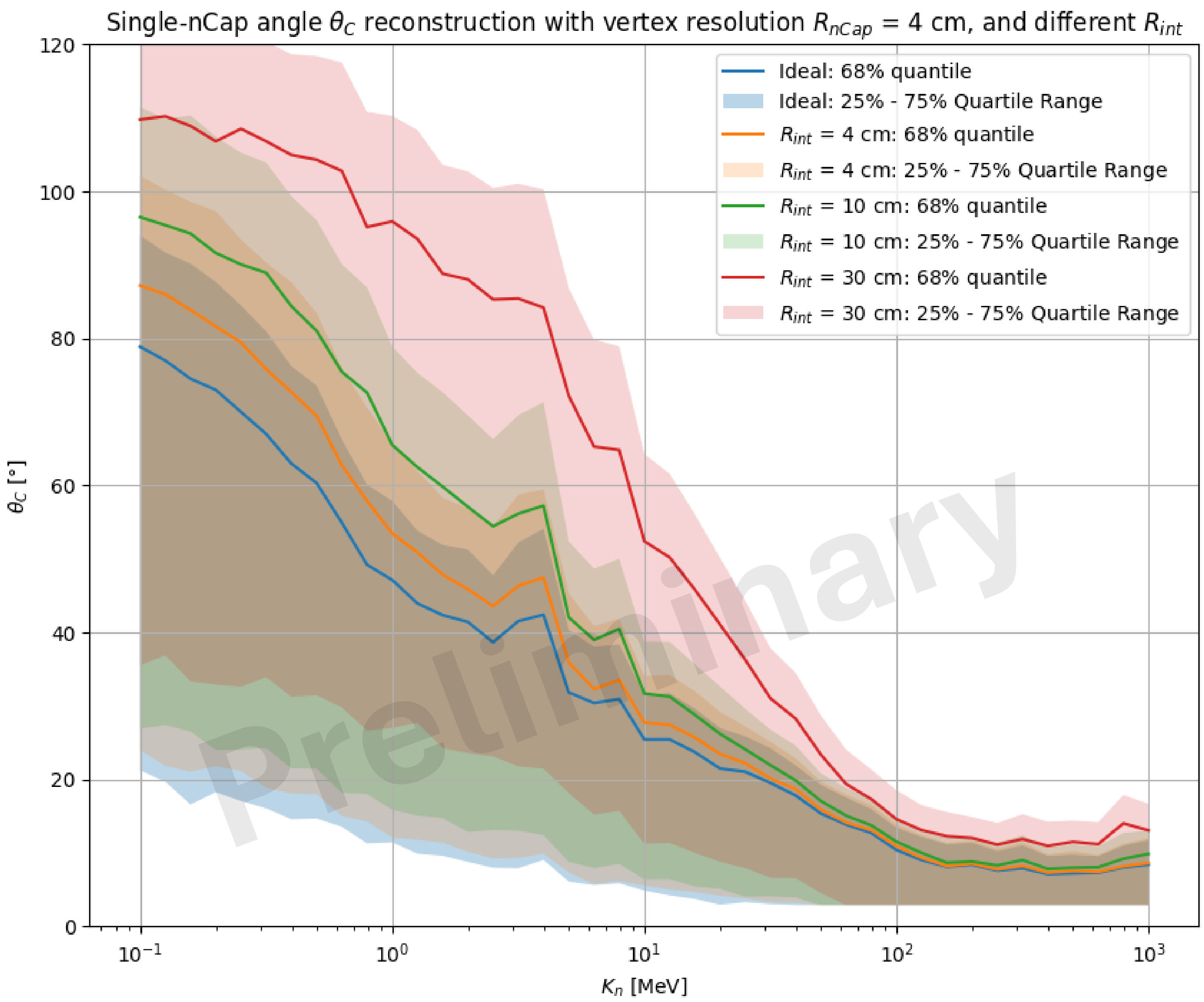
Set at time cut when doing analysis!
(2ns)

Filtering of Single Neutron Capture Event





Simulated Capture Angle in Geant4 + Vertex Resolution



Suppose the actual neutron capture position to be:

$$(x_0', y_0', z_0')$$

We randomly generates a new position to model the position where the detector's reconstructs it. the distribution in each direction follows:

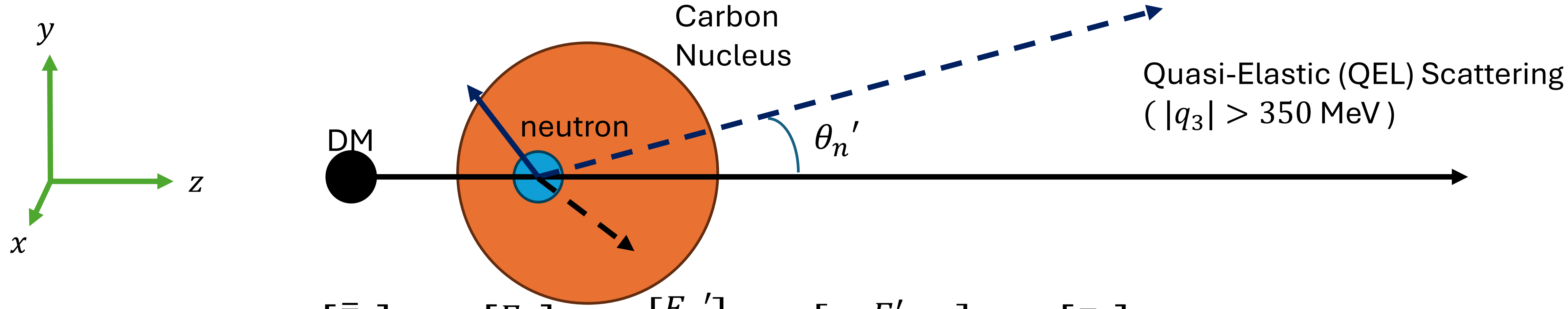
$$f(x_i) = \frac{1}{\sigma_r \sqrt{2\pi}} e^{-\frac{(x_i - x_i')^2}{2\sigma_r^2}}$$

Where the standard deviation σ_r will be found by

$$\sigma_r = \frac{R_{vertex}}{1.878}$$

We look for the 68.3% quantile line for $\frac{dN}{d\Omega}$ and set it as a standard deviation σ_θ for using healpy.smoothing accounting for diffusion effect, which assumed to be gaussian.

$$\frac{dN}{dK_n{}'d\Omega_n'} = N_{JUNO} \cdot \int d\Omega_\chi \int dt \int dK_\chi \frac{d\Phi_\chi}{dK_\chi d\Omega_\chi} \cdot \frac{d\sigma_{QEL}}{dK_n{}'d\Omega_n{}'}(\overline{K_\chi}, K_n{}', \theta_n{}')$$



$$\begin{bmatrix} \bar{E}_\chi \\ 0 \\ 0 \\ \bar{k} \end{bmatrix} + \begin{bmatrix} E_N \\ p_x \\ py \\ pz \end{bmatrix} = \begin{bmatrix} E_\chi{}' \\ k_x \\ k_y \\ k_z \end{bmatrix} + \begin{bmatrix} E_N' \\ 0 \\ p'sin\theta_n{}' \\ p'cos\theta_n' \end{bmatrix} + \begin{bmatrix} E_R \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

(Relativistic Fermi Gas model, $\mathrm{p_n} \leq p_F = 221$ MeV.)

(The averaged removal energy are $E_R = 27.1$ MeV.)

Nuclear Effect:

1. **Pauli Blocking**: By adding a factor in $\frac{d\sigma_{QEL}}{dK_n{}'d\Omega_n{}'}$ for $q_3 < 2p_F$:

$$B(q^3) = \frac{3}{4}\frac{|\mathrm{q_3}|}{\mathrm{p_F}}\left(1 - \frac{1}{12}\left(\frac{|\mathrm{q_3}|}{\mathrm{p_F}}\right)^2\right)$$

2. **Final State Interaction**: By using nuclear optical Potential to modify the knocked out energy:

$$\overline{K}_n' = K_n{}' + \min[0, -29.1 + (\frac{40.9}{GeV^2})|p'|^2]$$

For CRBDM production and Earth attenuation:

$$\frac{d\,\sigma_\phi}{dK_f} = \frac{1}{K_{\max}} \frac{g_{\chi\phi}^2 g_{N\phi}^2}{16\pi s} \frac{\left(-t + 4m_\chi^2\right)\left(-t + 4m_A^2\right)}{\left(m_\phi^2 - t\right)^2} n_A^2\, F_A^2(-t)\,\Theta(K_{\max} - K_f)\,,$$

For Neutron Knocked out Stage:

$$\frac{d\sigma_{QES}}{dK_n{}'d\Omega_n{}'} = \frac{g_{\chi\phi}^2 g_{n\phi}^2}{16\pi} \int d\vec{p}^3\, P(\vec{p}) \frac{\left(4m_\chi^2 + Q^2\right)\left(1 + \frac{\tilde{Q}^2}{4m_n^2}\right)}{\left(m_\phi^2 + Q^2\right)^2} \mathrm{F_n}(\mathrm{Q}^2) B(q^3)(\delta(E_\chi + E_n - E_\chi' - E_n' - E_{removal})$$

Earth Attenuation Effect (Ema,2021) & (Bringmann,2019)

Assumptions:

1. The target particles are protons and neutrons (1:1) and we assume form factor $F_A(q^2) \approx 1$ for light dark matter.
2. **No change in direction for DM at each scattering.**
3. The energy loss at each scattering as its averaged value:

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

This method serves as a conservative limit. It overestimates the stopping power of Earth Crust than simulation. (Emken, 2018)

For now, I assumed Earth is constant density. $n_T \approx \frac{M_E}{m_p V_E}$

We took JUNO's geological location(East longitude 112 ° 31' 05'' and North latitude 22° 07' 05'') and use python library Astropy to look for the relative depth DM travelled at different sky location and time in 1 day. Hence, we found the Attenuated Kinetic Energy for BDM $\overline{\mathrm{K}_\chi}$.