UNIVERSITY OF MARYLAND 1856
DEPARTMENT OF PHYSICS

Probing Dark Matter-Neutrino Interactions via Supernova Neutrinos

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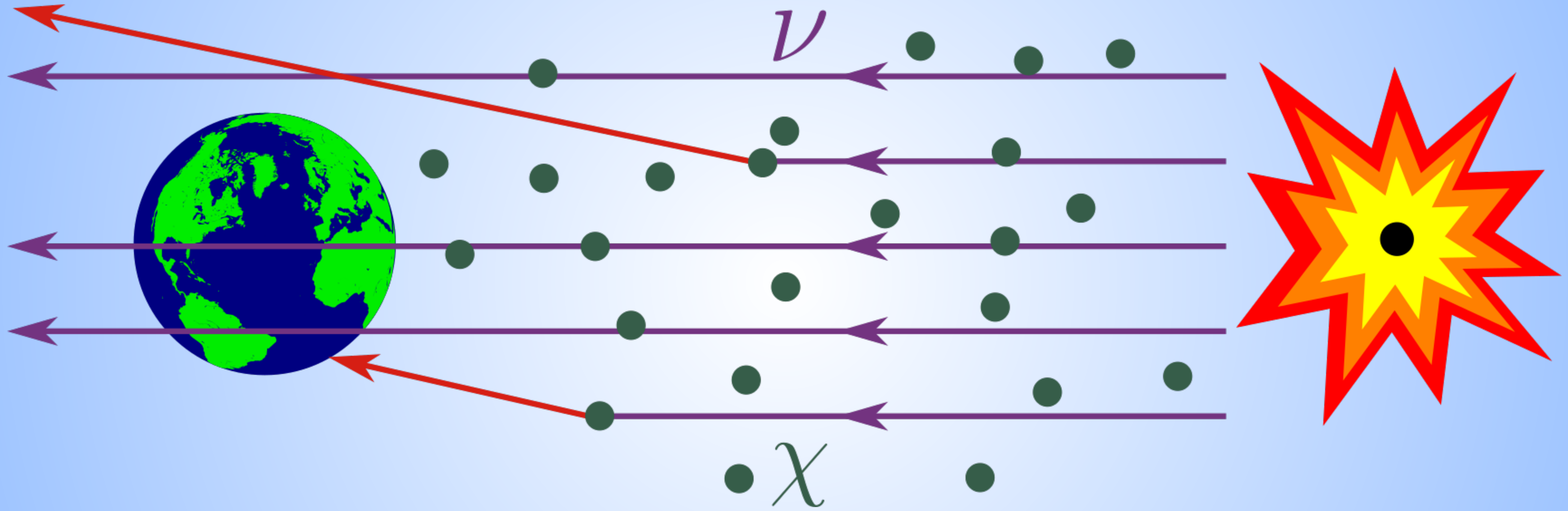
Motivating ν-DM interactions

- Neutrino physics and neutrino portal
  - Neutrinos observable, but weakly interacting with rest of SM
  - Various astrophysical neutrino sources that could interact with DM halo
- Upcoming experiments Hyper-K, DUNE, JUNO could be sensitive to neutrino non-standard interactions
- Nature of DM still unknown:
  - WIMPs, Axions/ALPs, or something else?

How can we see these interactions?

- Neutrinos move through DM medium, interactions cause change in flux



- Modeled by cascade equation:

$$\frac{\mathrm{d}\varphi(E,\eta)}{\mathrm{d}\eta} = -\,\sigma(E)\,\varphi(E,\eta) + \int_E^\infty \mathrm{d}\tilde{E}\,\frac{\mathrm{d}\sigma(\tilde{E},E)}{\mathrm{d}E}\,\varphi(\tilde{E},\eta)$$

A. McMullen, A. Vincent, and C. Argüelles, A. Schneider [2107.11491]

Describing the cascade equation

$$\frac{\mathrm{d}\varphi(E,\eta)}{\mathrm{d}\eta} = -\sigma(E)\,\varphi(E,\eta) + \int_E^\infty \mathrm{d}\tilde{E}\,\frac{\mathrm{d}\sigma(\tilde{E},E)}{\mathrm{d}E}\,\varphi(\tilde{E},\eta)$$

Given ν-DM interactions, how does flux change with amount of DM?

- $\varphi = \mathrm{d}\Phi/\mathrm{d}E$ is neutrino flux per unit energy $[\mathrm{MeV}^{-1}\,\mathrm{sec}^{-1}\,\mathrm{cm}^{-2}]$
  - E is outgoing neutrino energy
- η is dark matter column density

Describing the cascade equation

$$\frac{\mathrm{d}\varphi(E,\eta)}{\mathrm{d}\eta} = -\,\sigma(E)\,\varphi(E,\eta) + \int_E^\infty \mathrm{d}\tilde{E}\,\frac{\mathrm{d}\sigma(\tilde{E},E)}{\mathrm{d}E}\,\varphi(\tilde{E},\eta)$$

First term describes loss of neutrino flux due to interactions

- $\varphi = \mathrm{d}\Phi/\mathrm{d}E$ is neutrino flux per unit energy $[\mathrm{MeV}^{-1}\,\mathrm{sec}^{-1}\,\mathrm{cm}^{-2}]$
- σ is ν-DM scattering cross section

Describing the cascade equation

$$\frac{\mathrm{d}\varphi(E,\eta)}{\mathrm{d}\eta} = -\,\sigma(E)\,\varphi(E,\eta) + \int_E^\infty \mathrm{d}\tilde{E}\,\frac{\mathrm{d}\sigma(\tilde{E},E)}{\mathrm{d}E}\,\varphi(\tilde{E},\eta)$$

Second term describes neutrinos down-scattering from higher energies $\tilde{E}$ to E

- $\tilde{E}$ is incoming neutrino energy

- $\mathrm{d}\sigma/\mathrm{d}E$ is ν-DM differential cross section

Solving the cascade equation

- Vectorize the equation, and convert into a linear matrix equation

$$\frac{d\overrightarrow{\phi}}{d\eta} = (-\text{diag}(\vec{\sigma}) + C) = -M\overrightarrow{\phi}$$

- Elements of matrix C are off-diagonal down-scattering terms

$$C_{ij} = \frac{\mathrm{d}\vec{\sigma}(E_i, \tilde{E}_j)}{\mathrm{d}E_i}\mathrm{d}\tilde{E}_j$$

- Solution is given by exponential

$$\overrightarrow{\phi} = \sum_{i=1}^{N} c_i \hat{\phi}_i e^{-\lambda_i \eta}$$

- $\hat{\phi}_i, \lambda_i$ are the eigenvectors and eigenvalues of M
- Coefficients c_i determined by $\sum c_i \hat{\phi}_i = \overrightarrow{\phi}_0$ when $\eta = 0$

A. Vincent, C. Argüelles, A. Kheirandish [1706.09895]

Details of the solution

$$\frac{d\overrightarrow{\phi}}{d\eta} = (-\mathrm{diag}(\vec{\sigma}) + C) = -M\overrightarrow{\phi};\ C_{ij} = \frac{\mathrm{d}\vec{\sigma}(E_i, \tilde{E}_j)}{\mathrm{d}E_i}\mathrm{d}\tilde{E}_j;\ \overrightarrow{\phi} = \sum_{i=1}^{N} c_i \hat{\phi}_i e^{-\lambda_i \eta}$$

- Attenuation is expected for opacity $\tau = \lambda\eta \sim 1$
  - $\eta \propto 1/m_\chi$
  - More sensitive to light dark matter: $m_\chi \lesssim \mathcal{O}(\mathrm{MeV})$

Inputs needed to solve cascade equation

$$\frac{d\overrightarrow{\phi}}{d\eta} = (-\text{diag}(\vec{\sigma}) + C) = -M\overrightarrow{\phi};\ C_{ij} = \frac{\mathrm{d}\vec{\sigma}(E_i, \tilde{E}_j)}{\mathrm{d}E_i}\mathrm{d}\tilde{E}_j;\ \overrightarrow{\phi} = \sum_{i=1}^{N} c_i \hat{\phi}_i e^{-\lambda_i \eta}$$

- Source and model of neutrino flux $\varphi(E)$
- Dark matter column density η
- ν-DM interaction model to obtain σ and $\mathrm{d}\sigma/\mathrm{d}E$

Neutrino source: local supernova

- Hypothetical galactic supernova 10 kpc away
- Modeling the neutrino flux emitted by SN:
  - Obtained from numerical simulations
  - Begin with pinched Fermi-Dirac distribution

$$\phi^0_{\nu_\beta}(t, E_\nu) = \frac{L_{\nu_\beta}(t)}{\langle E_{\nu_\beta}\rangle(t)} \frac{(\alpha_{\nu_\beta}(t)+1)^{\alpha_{\nu_\beta}(t)+1}}{\langle E_{\nu_\beta}\rangle(t)\,\Gamma(\alpha_{\nu_\beta}(t)+1)} \left(\frac{E_\nu}{\langle E_{\nu_\beta}\rangle(t)}\right)^{\alpha_{\nu_\beta}(t)} \exp\left(-\frac{(\alpha_{\nu_\beta}(t)+1)\,E_\nu}{\langle E_{\nu_\beta}\rangle(t)}\right)$$

  - Integrate spectrum over time of neutrino burst

$$F^0_{\nu_\beta}(E_\nu) = \int_{t_{\rm ini}}^{t_{\rm end}} \phi^0_{\nu_\beta}(t, E_\nu)\,\mathrm{d}t$$

R. Hajjar, O. Mena, S. Palomares-Ruiz [2303.09369]

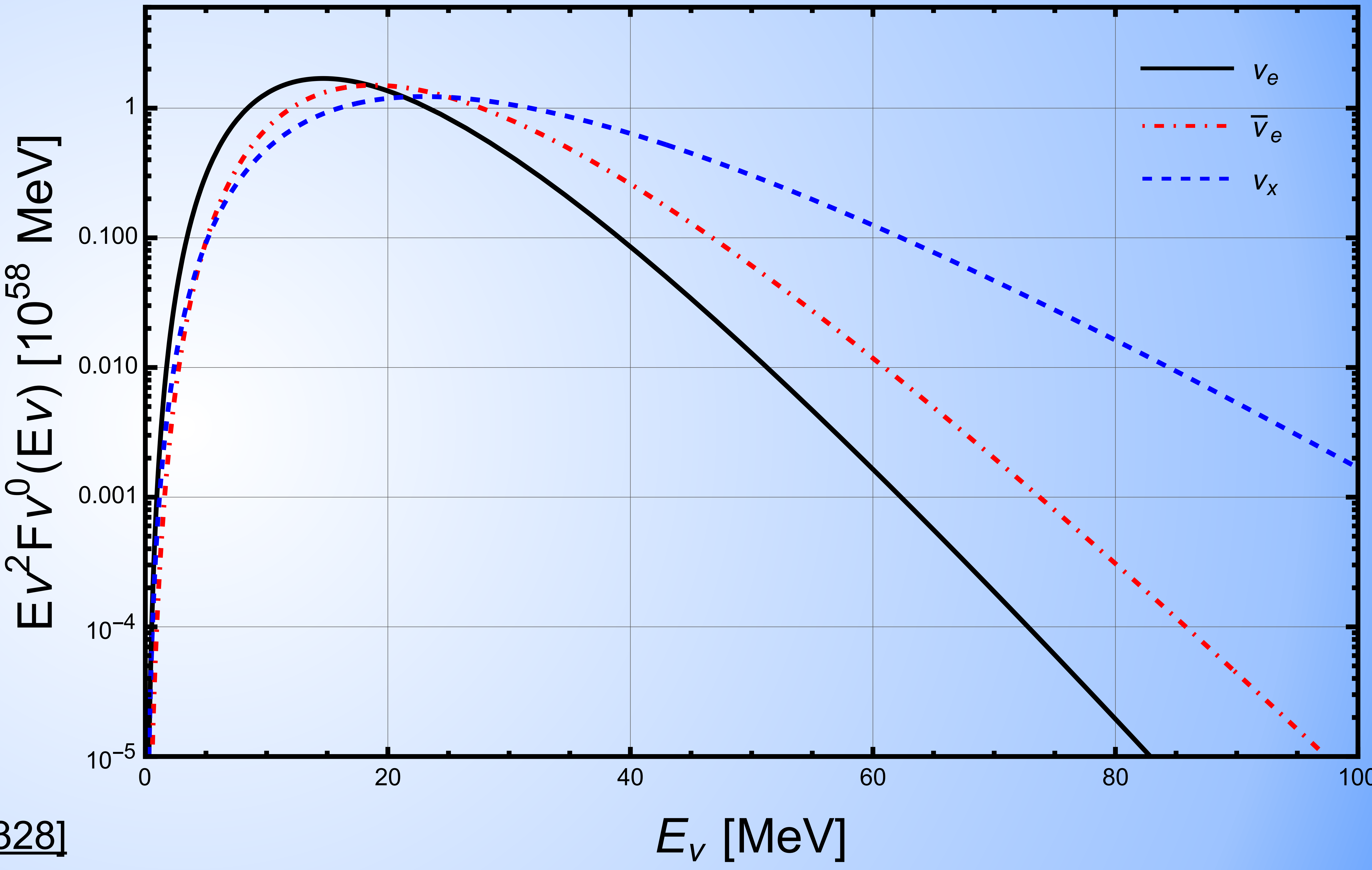
Neutrino source: local supernova

- Hypothetical galactic supernova 10 kpc away

- Use best-fit parameters for time-integrated $L_{\nu_\beta}, \langle E_{\nu_\beta} \rangle, \alpha_{\nu_\beta}$ with progenitor mass $20\ M_\odot$

M. Warren, S. Couch, E. O'Connor, V. Morozova [1912.03328]

Reproducing Fig 1 Warren $20 M_\odot$ of 2303.09369



R. Hajjar, O. Mena, S. Palomares-Ruiz [2303.09369]

Neutrino source: local supernova

- Modeling the neutrino flux observed on Earth:
  - Neutrino mass eigenstates travel incoherently
  - Detected as flavor eigenstates

$$F^D_{\nu_e} = p\, F^0_{\nu_e} + (1-p)\, F^0_{\nu_x}\ ;\ F^D_{\nu_x} = \frac{1-p}{2}\, F^0_{\nu_e} + \frac{1+p}{2}\, F^0_{\nu_x}$$

$$F^D_{\bar{\nu}_e} = \bar{p}\, F^0_{\bar{\nu}_e} + (1-\bar{p})\, F^0_{\nu_x}\ ;\ F^D_{\bar{\nu}_x} = \frac{1-\bar{p}}{2}\, F^0_{\bar{\nu}_e} + \frac{1+\bar{p}}{2}\, F^0_{\nu_x}$$

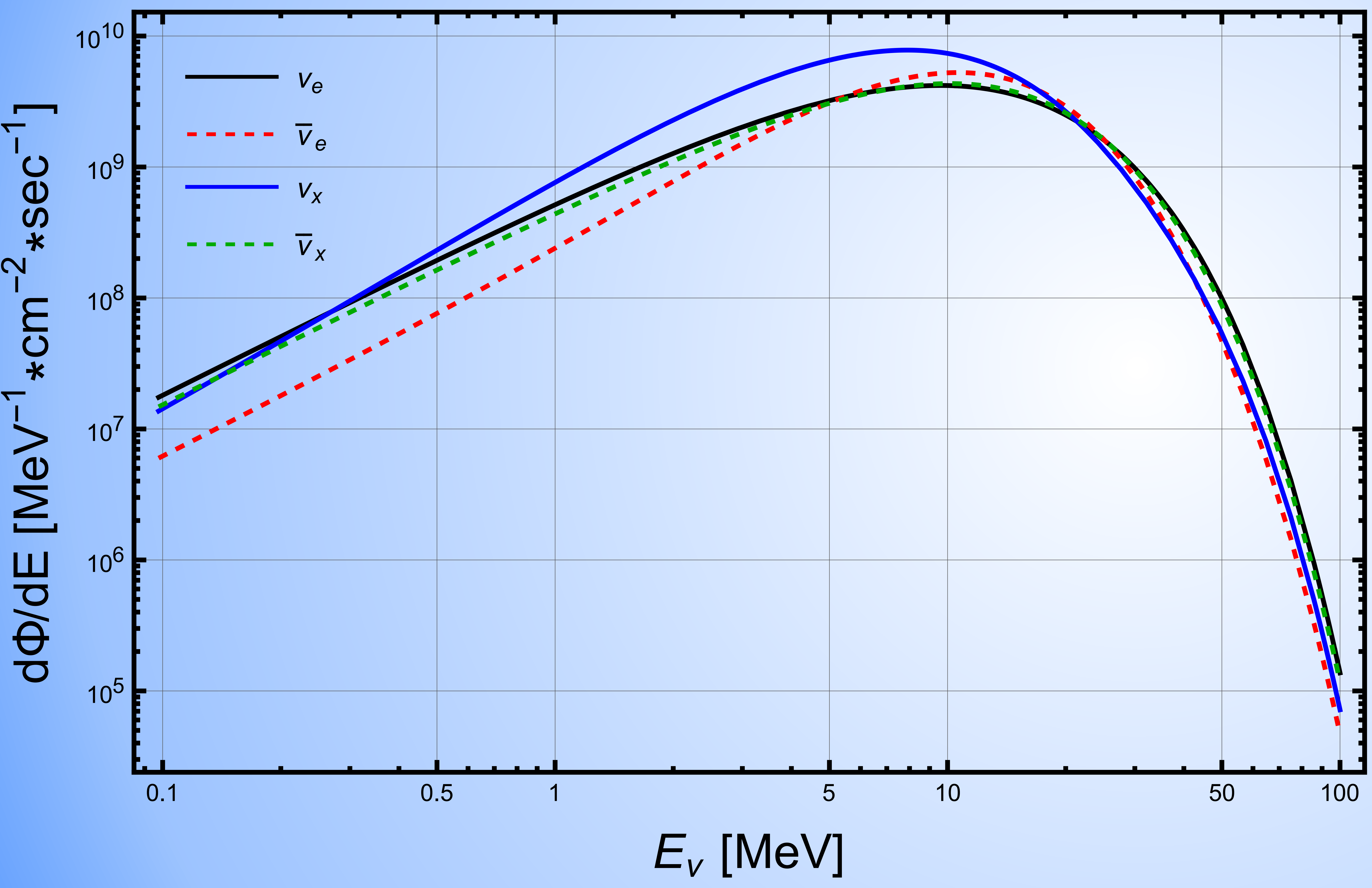
  - Apply inverse square law

R. Hajjar, O. Mena, S. Palomares-Ruiz [2303.09369]

$$\varphi_{\nu_\beta} = \frac{\mathrm{d}\Phi^D_{\nu_\beta}}{\mathrm{d}E_\nu} = \frac{F^D_{\nu_\beta}}{4\pi d^2_{\mathrm{SN}}}$$

Neutrino source: local supernova

Plot of dΦ/dE at Earth



- With $\mathrm{d}\Phi^D_{\nu_\beta}/\mathrm{d}E_\nu$, predict event rate distributions for DUNE, Hyper-K, JUNO
- Focus on inverse beta decay process:

$$\bar{\nu}_e + p \to e^+ + n$$

- Consider $\bar{\nu}_e$ flux interacting with DM

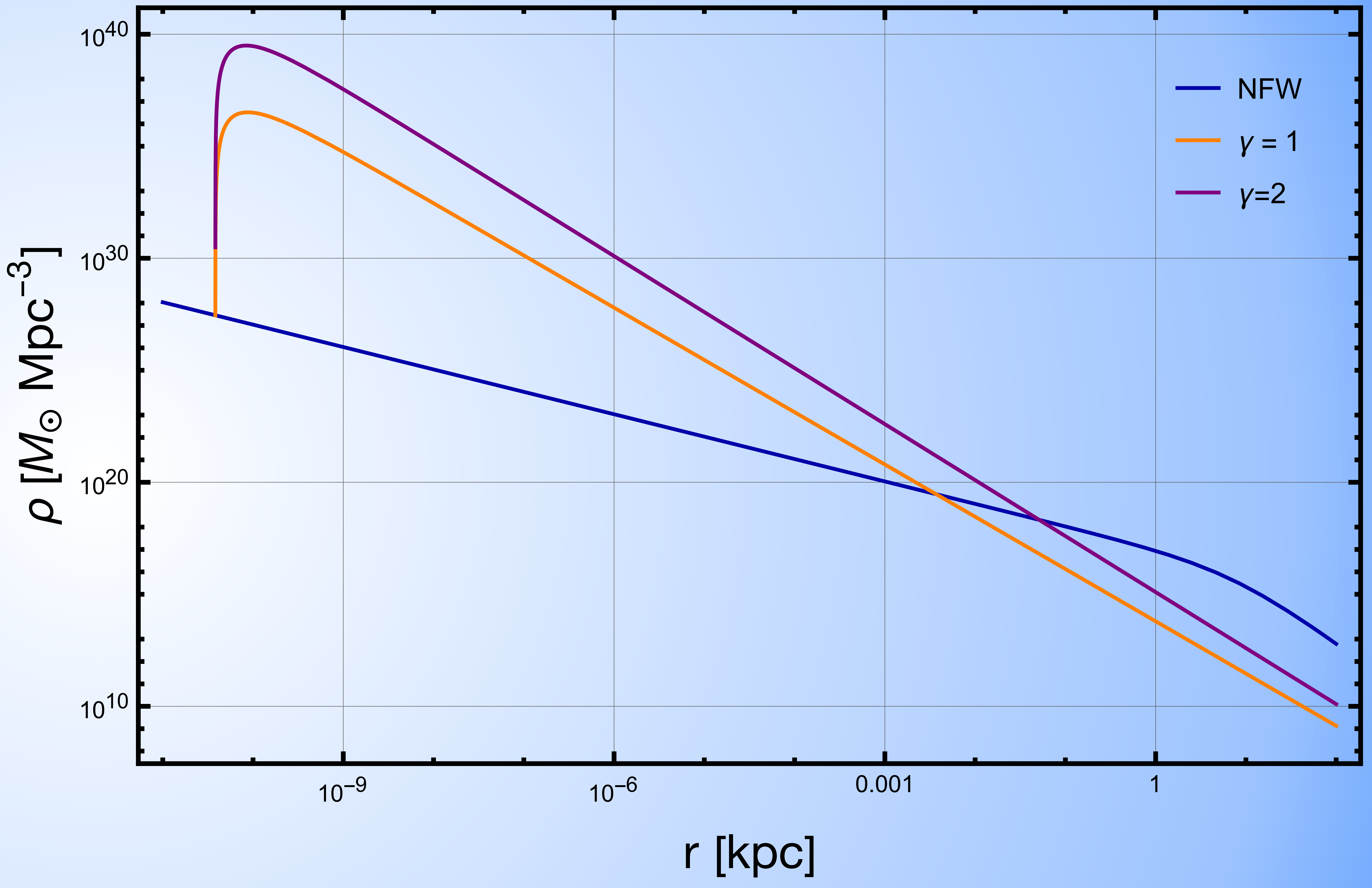
DM column density

- How much dark matter do neutrinos travel through?
- Model DM halo surrounding Milky Way:
  - NFW profile $\rho_\chi(r) = \dfrac{\rho_0}{\left(\frac{r}{r_s}\right)\left[1+\frac{r}{r_s}\right]^2}$
  - Could consider spike profile
- Obtain column density

$$\eta\left(d_{\mathrm{SN}}, l, b\right) = \frac{1}{m_\chi}\int_0^{d_{\mathrm{SN}}} \rho_\chi\left[r\left(s, l, b\right)\right] \mathrm{d}s$$

- Depends on galactic coordinates: more DM closer to galactic center

Comparing DM profiles



J.F. Navarro, C.S. Frenk, S. D. M. White [astro-ph/9508025]

H. Nishikawa, E. Kovetz, M. Kamionkowski, J. Silk [1708.08449]

H. Lin, X. Li [1906.08419]

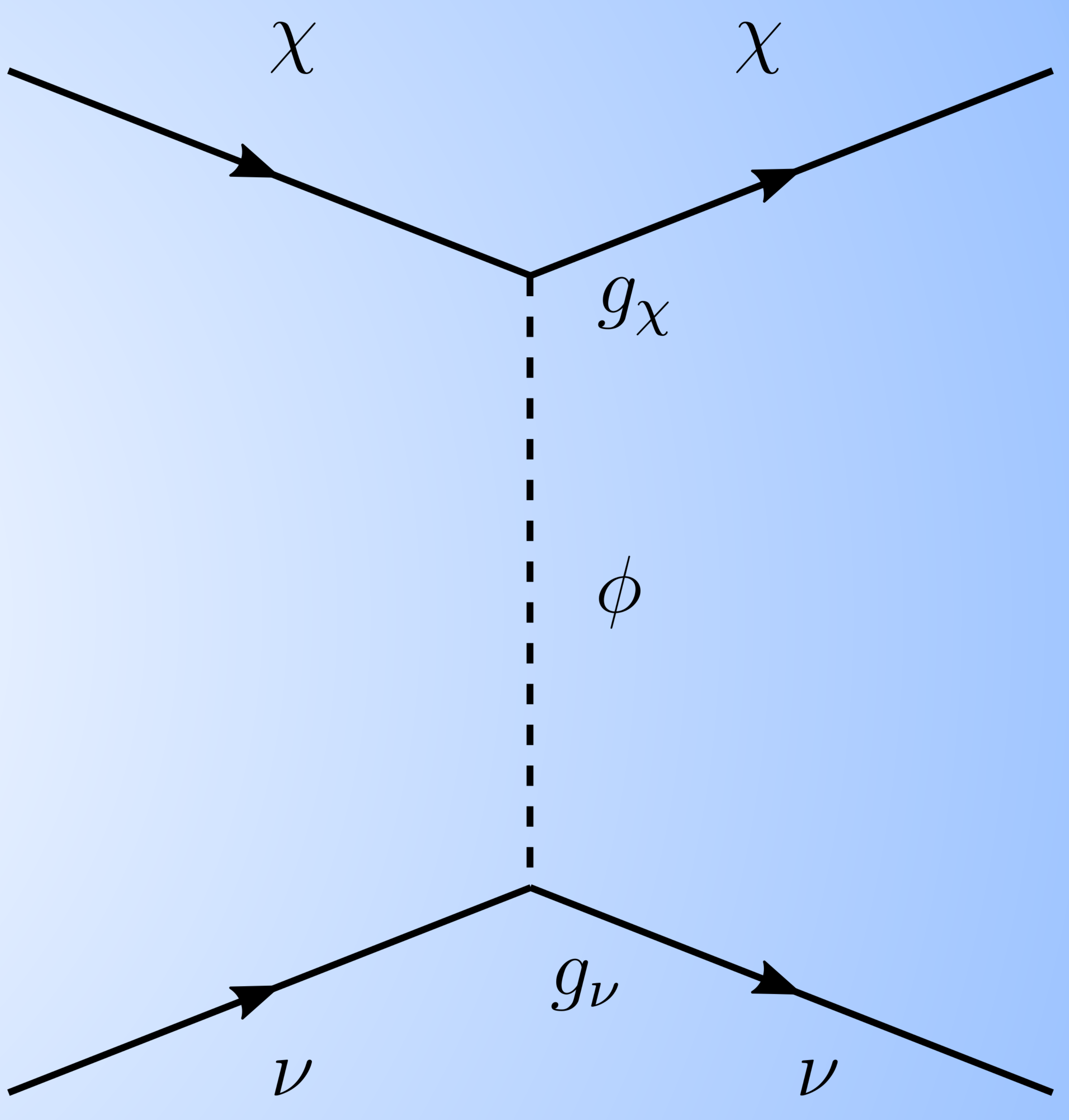
Modeling ν-DM interactions

- Consider fermion DM, scalar mediator

$$\mathscr{L} = -g_\nu \phi \bar{\nu} \nu - g_\chi \phi \bar{\chi} \chi$$

- Obtain total and differential cross sections

- Constraints on this model:
  - BBN N_{eff}, DM cluster constraint, collisional damping, Tremaine-Gunn bound
  - Can avoid some constraints: consider this dark sector to compose ~10% of total DM
  - Ongoing work: imposing all constraints



J. Carpio, A. Kheirandish, K. Murase [2204.09650]

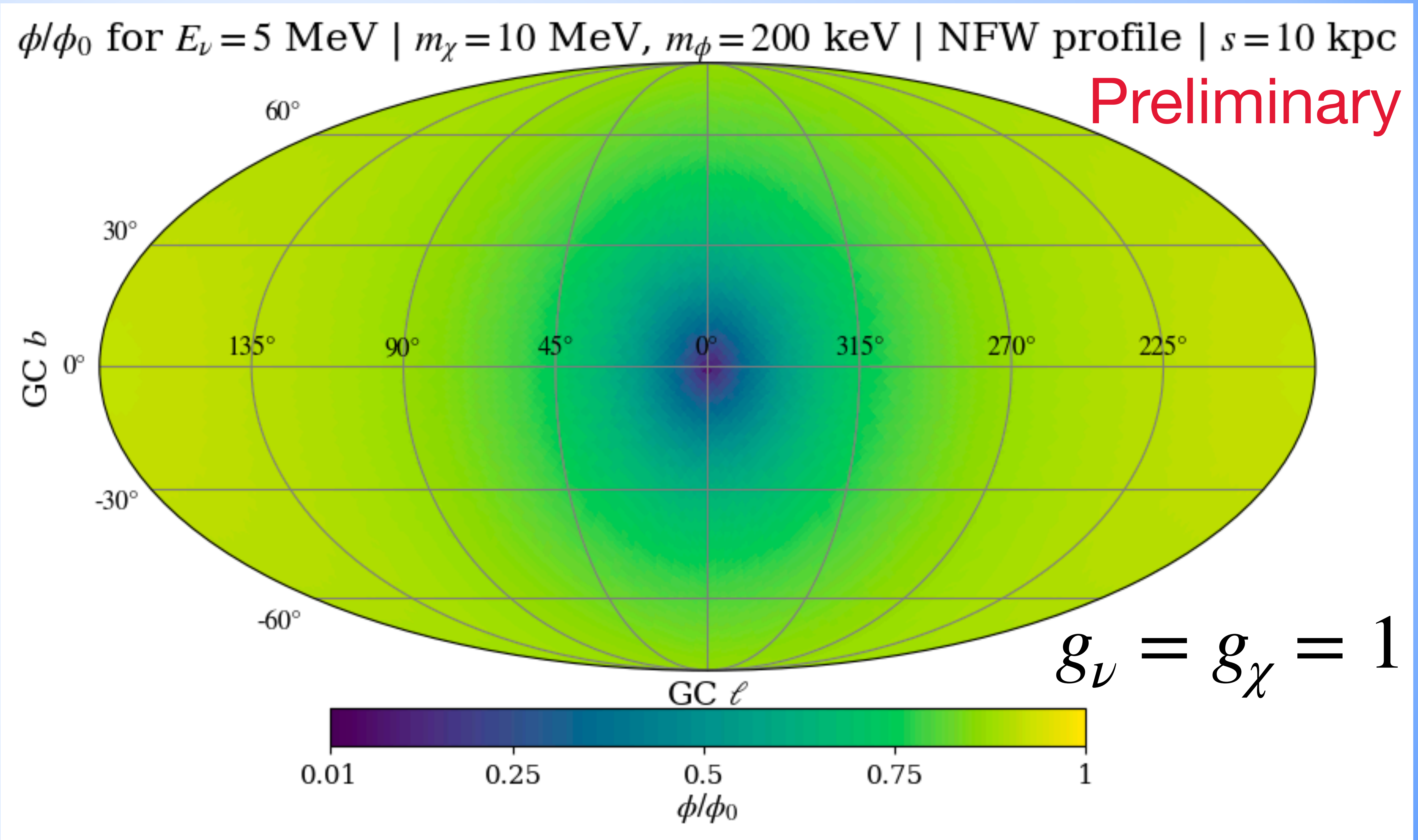
A. O. Campo, C. Bœhm, S. Palomares-Ruiz, S. Pascoli [1711.05283]

Visualizing survival rate of neutrino flux

- Cascade equation gives survival rate Φ/Φ_0 as a function of E and opacity

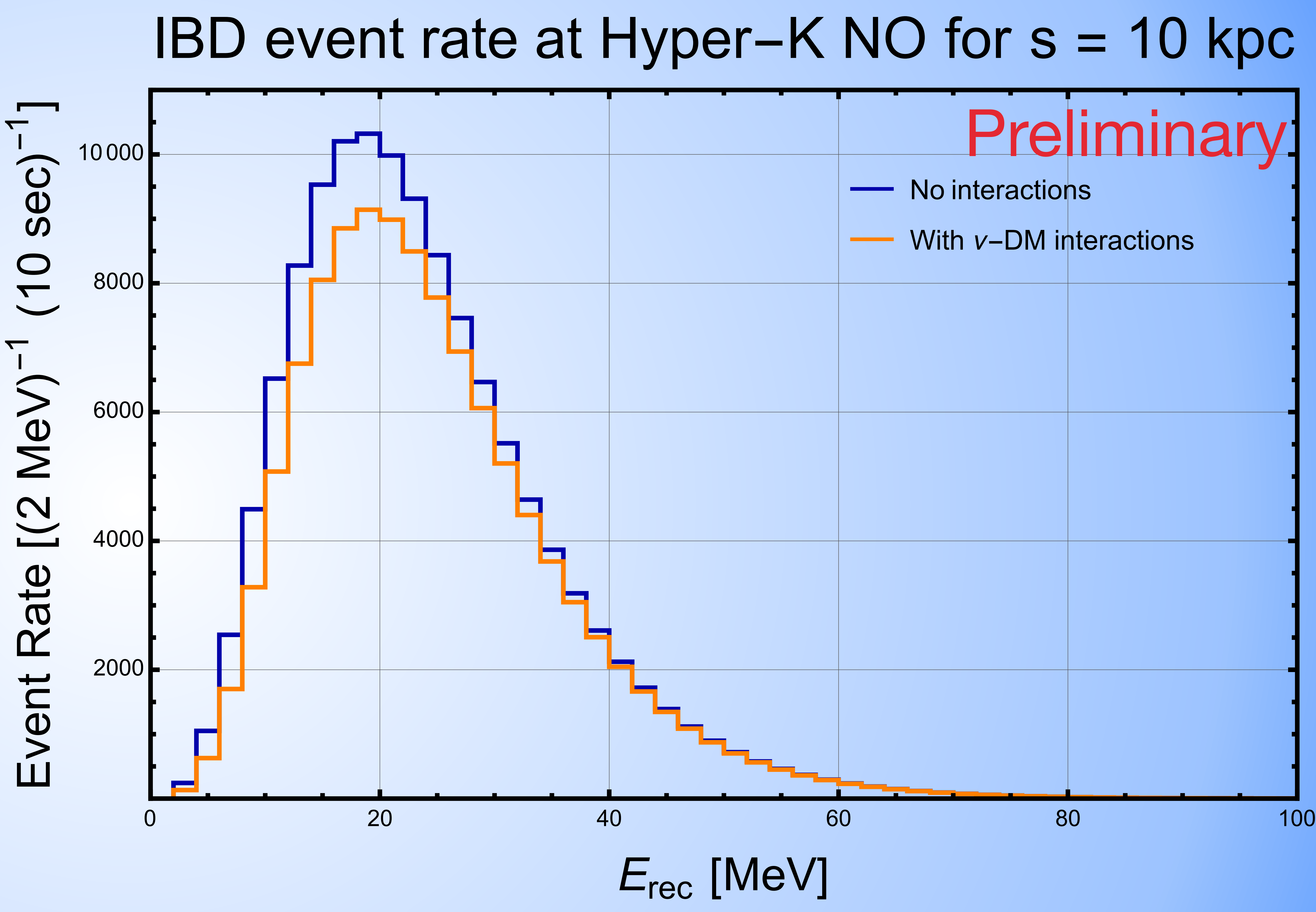
$$\frac{\Phi}{\Phi_0} \sim \exp(-\lambda\eta)$$

- Fix measured E_ν, vary η for all b, l, and plot Φ/Φ_0



How will the event rate plot change?

- For a supernova at a fixed point $s = 10\,\mathrm{kpc}, b = 0, l = \pi/8$
- Predict event rate at Hyper-K using modeled SN flux
- ν-DM interactions would change the event rate, especially at lower E_ν



R. Hajjar, O. Mena, S. Palomares-Ruiz [2303.09369]

Summary and future work

- Probe ν-DM interactions with observables from neutrino detection experiments
  - Source: galactic supernova
  - Medium: galactic DM halo
- Consider other neutrino sources
- Implement other DM models
  - Scalar DM, Vector DM
  - Fermion, Vector mediators
- Is this method sensitive to other neutrino NSI?

Backup Slides

Obtaining event rate from IBD

- Given a SN electron anti-neutrino flux at Earth $\mathrm{d}\Phi_\nu^D/\mathrm{d}E_\nu$, the event rate is

$$\frac{\mathrm{d}N_{\bar{\nu}_e}(\mathrm{rec})}{\mathrm{d}E(\mathrm{rec})} = N_t \int \mathrm{d}E_{\mathrm{true}}\,\mathrm{d}E_\nu\,\epsilon(E_{\mathrm{true}})\,\mathscr{R}(E_{\mathrm{true}}, E_{\mathrm{rec}})\,\frac{\mathrm{d}\Phi_\nu^D}{\mathrm{d}E_\nu}\,\frac{\mathrm{d}\sigma_{\mathrm{IBD}}(E_e, E_\nu)}{\mathrm{d}E_e}$$

- Where $\mathscr{R}$ is a Gaussian resolution function

R. Hajjar, O. Mena, S. Palomares-Ruiz [2303.09369]

$$\mathscr{R}(E_{\mathrm{true}}, E_{\mathrm{rec}}) = \frac{1}{\sqrt{2\pi}\sigma_{\mathrm{det}}}\exp\left(-\frac{(E_{\mathrm{true}} - E_{\mathrm{rec}})^2}{2\sigma_{\mathrm{det}}^2}\right)$$

- As an estimate, we take $E_{\mathrm{true}} = E_\nu$ and efficiency ϵ to be constant, simplifying the event rate:

$$\frac{\mathrm{d}N_{\bar{\nu}_e}(\mathrm{rec})}{\mathrm{d}E(\mathrm{rec})} = N_t\,\epsilon \int \mathrm{d}E_\nu\,\mathscr{R}(E_\nu, E_{\mathrm{rec}})\,\frac{\mathrm{d}\Phi_\nu^D}{\mathrm{d}E_\nu}\,\sigma_{\mathrm{IBD}}(E_e, E_\nu)$$

K. Møller, A. Suliga, I. Tamborra, P. Denton [1804.03157]