New Signatures of Decaying HNLs in Large Scale Detectors

Dipole portals arXiv:[2010.04193]
Mass-mixing portals arXiv:[2010.09523]

Ongoing work with Ian Shoemaker & R. Andrew Gustafson (atmospheric neutrinos)
and Vedran Brdar (time modulation analysis)

Ryan Plestid | AstroDark 2021 IPMU | Dec 2021

Motivation:

Lifetime Frontier and neutrino portals

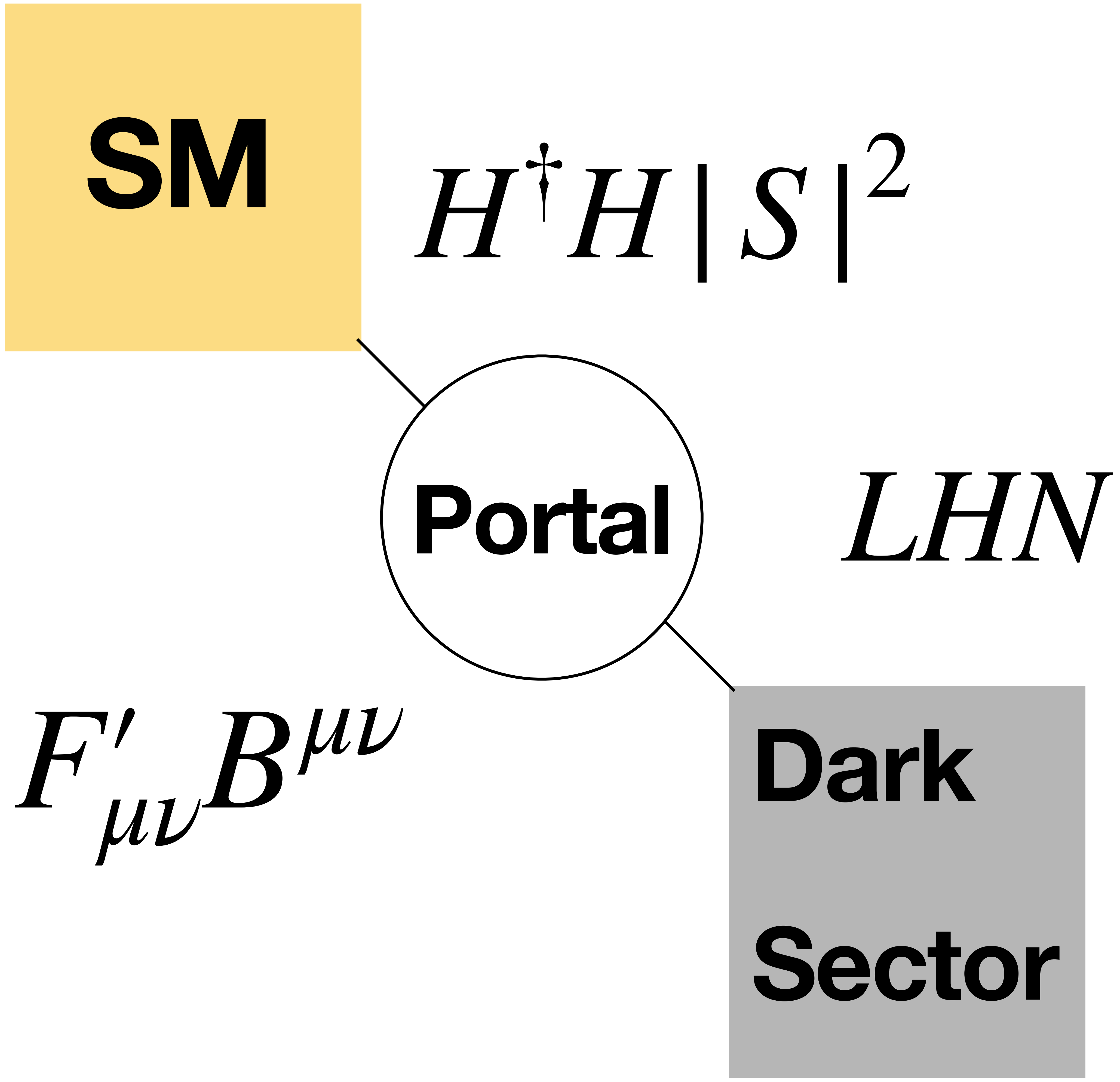
Dark Sector 101

- We have not found new physics … yet.
- This tells us that new physics is one of two things:

    1) Heavy.
    2) Weakly coupled to SM.

- Coupling is called a portal. Dark sector can be complex.

Portals



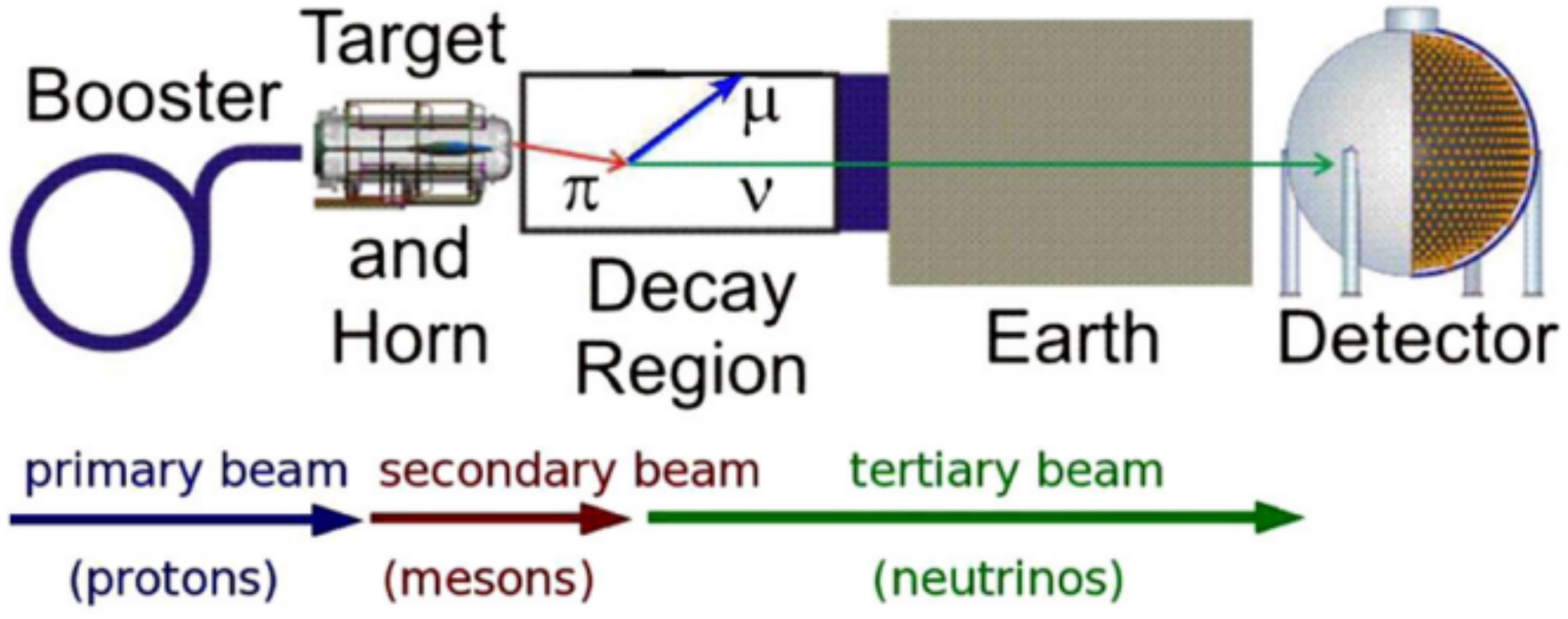
Long-lived particles

$$\Gamma \sim g^2 M \quad \text{or} \quad g^2 \frac{M^3}{\Lambda^2} \quad \text{or} \quad g^2 \frac{M^5}{\Lambda^4} := \text{Small}$$

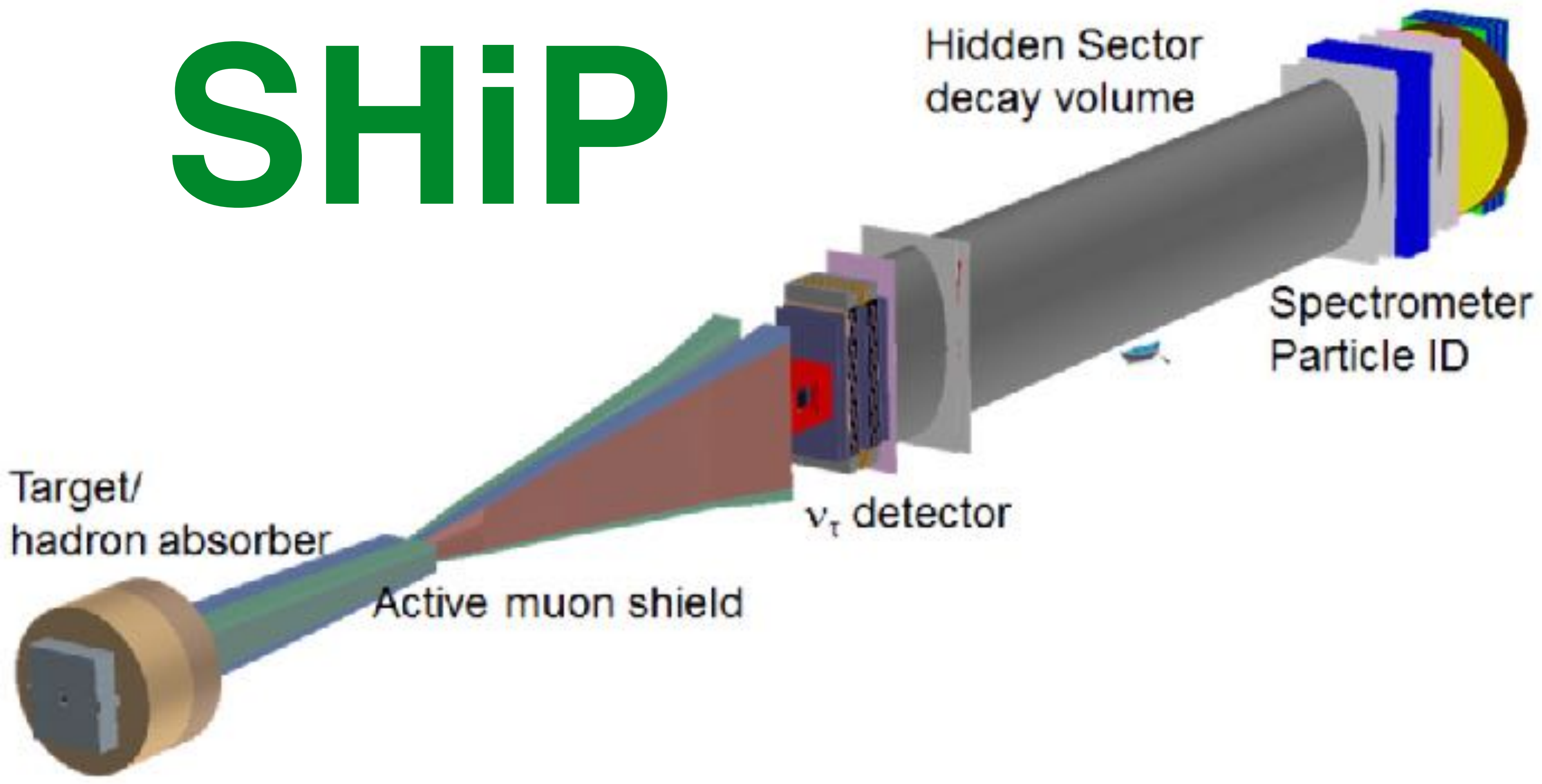
- Dark sector particles can decay within the dark sector.
- But… lightest dark sector particles should be “dark stable”.
- If dominant decay modes are to SM particles then the generic consequence is that the particle will be long-lived.

Active program searching for long live particles

MiniBooNE



SHiP



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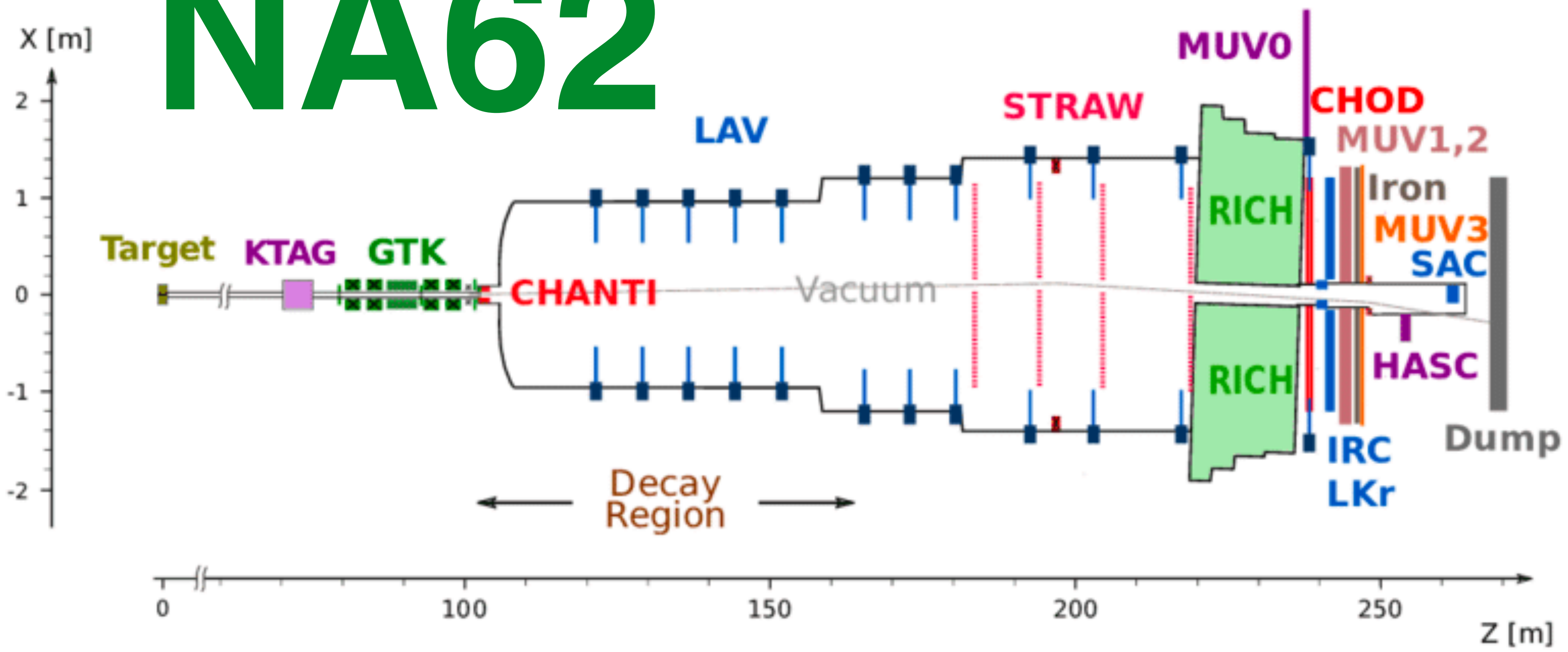


MATHUSLA

Two “relevant” neutrino portals

Dipole portal (Dim-5)

$$\mathscr{L} \supset d_a \left[\bar{N}\sigma_{\mu\nu}P_L\nu_a\right] F^{\mu\nu}$$

Mass-mixing portal (Dim-4)

Standard Weak 4-Fermi

$$\sigma \sim G_F^2 E_\nu^2 \text{ or } G_F^2 s$$

Dipole Coupling

$$\sigma \sim d^2 \log(Q_{\max}/Q_{\min})$$

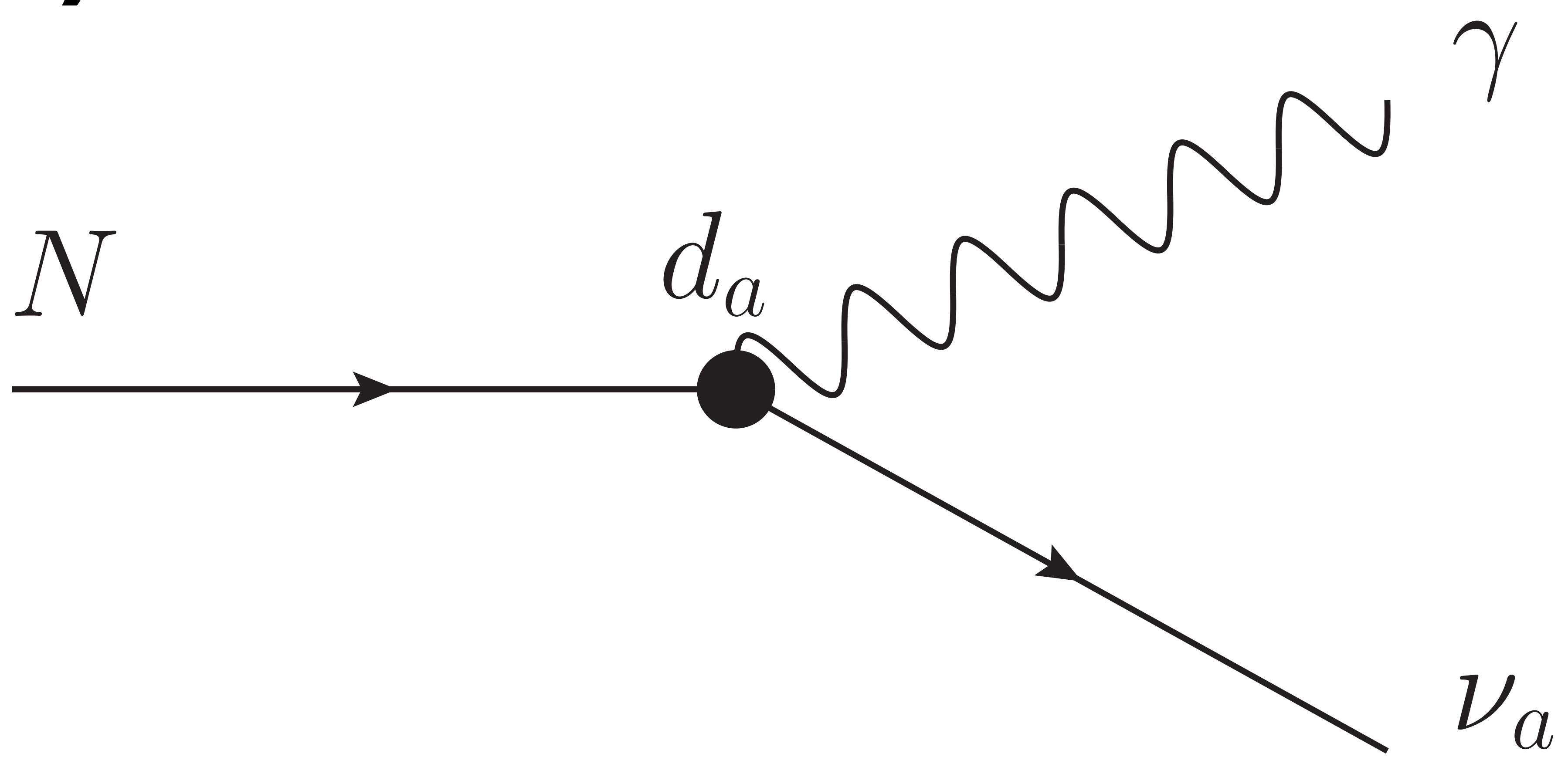
$$\frac{1}{G_F E_\nu} \sim \left[\frac{E_\nu}{1\text{ MeV}}\right] \times 10^8\text{ GeV} \qquad d \sim \frac{e v_{\text{EW}}}{\Lambda^2}$$

$$\Lambda \lesssim 10^6\text{ GeV} \times \left[\frac{1\text{ MeV}}{E_\nu}\right]$$

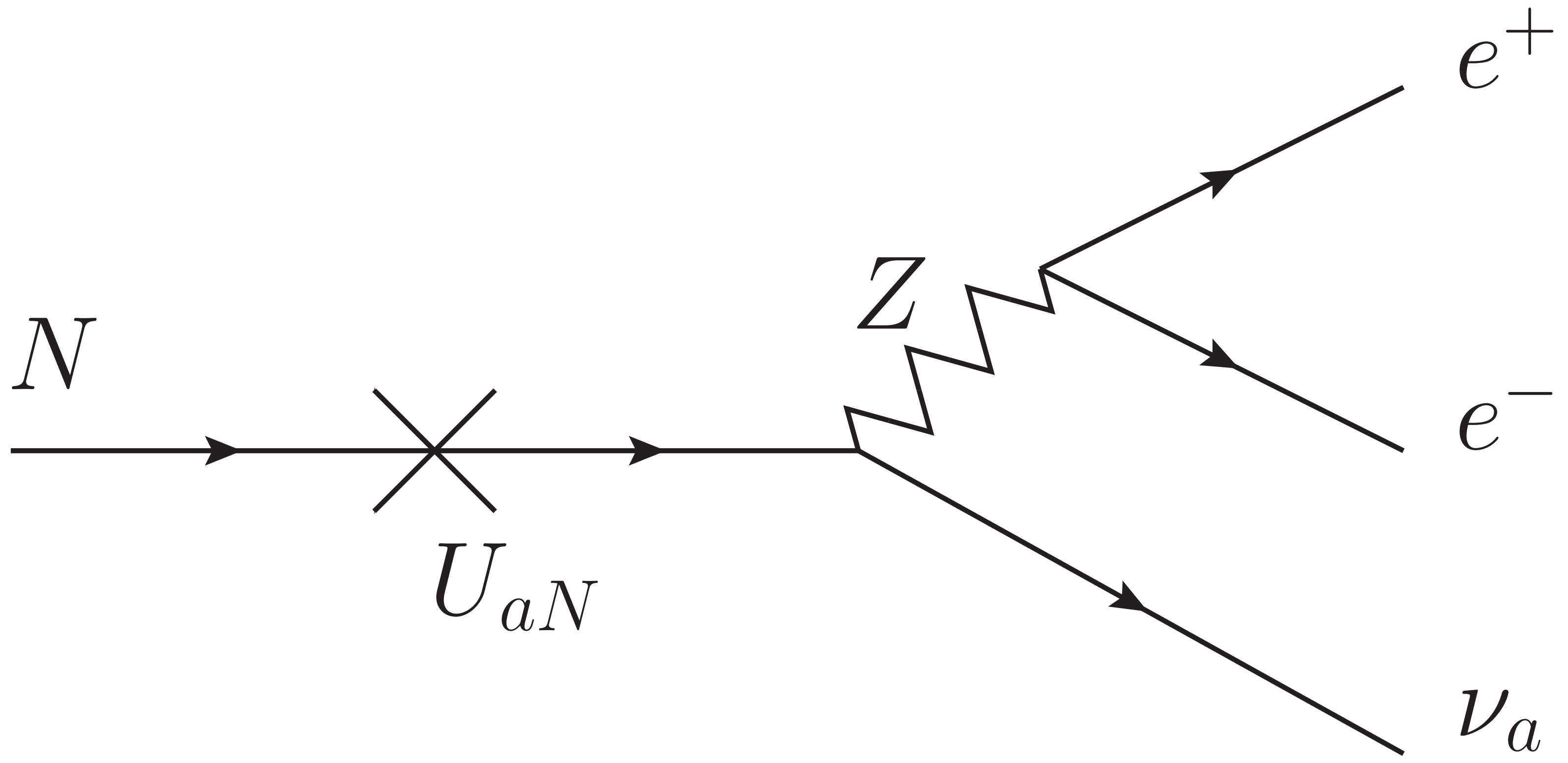
$$\mathscr{L} \supset U_{aN}\left\{\left[\bar{N}\gamma_\mu P_L \nu_a\right] J_Z^\mu + \left[\bar{N}\gamma_\mu P_L \ell_a\right] J_W^\mu\right\}$$

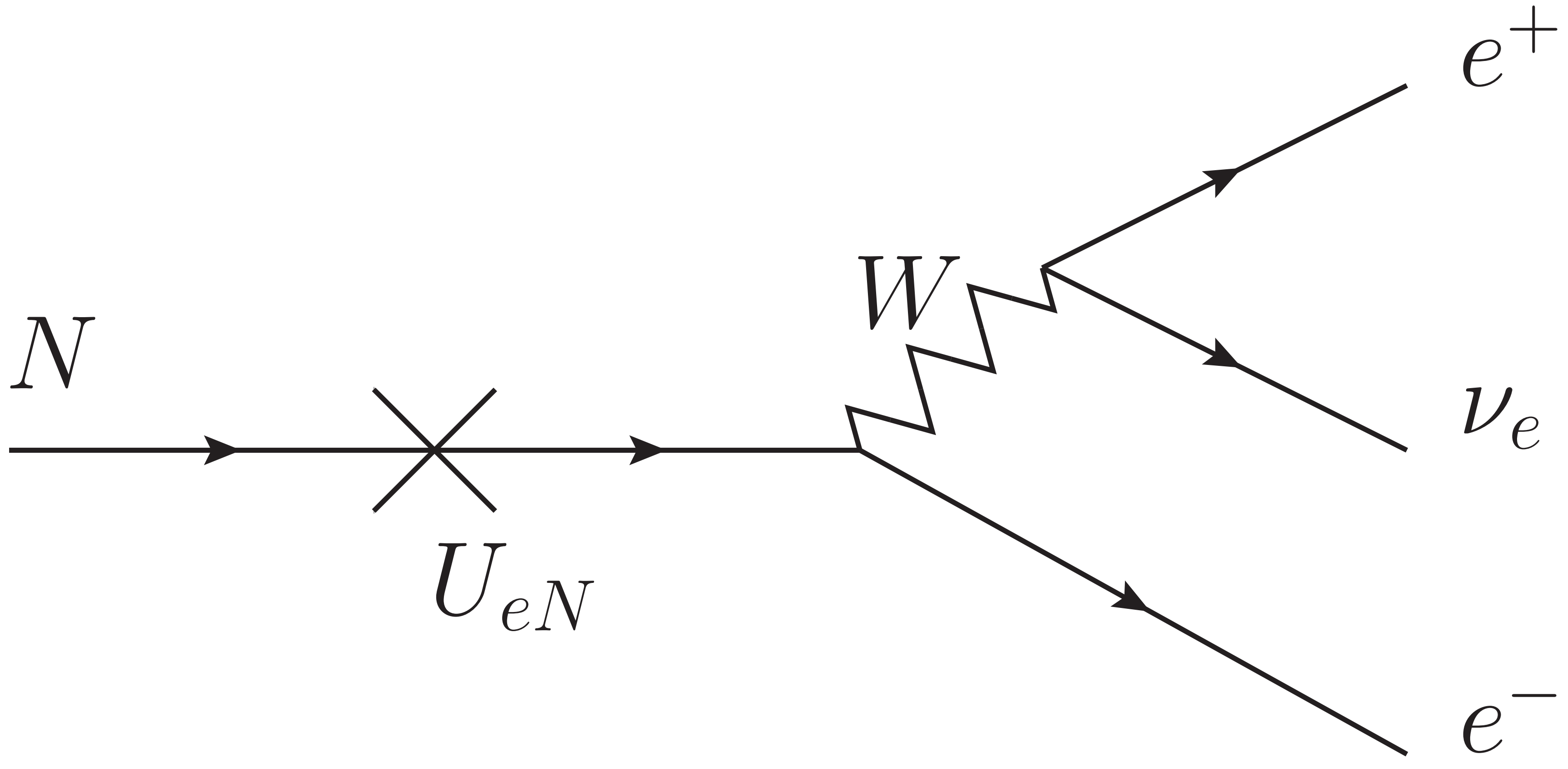
Two relevant neutrino portals

Dipole portal (Dim-5)



Mass-mixing portal (Dim-4)

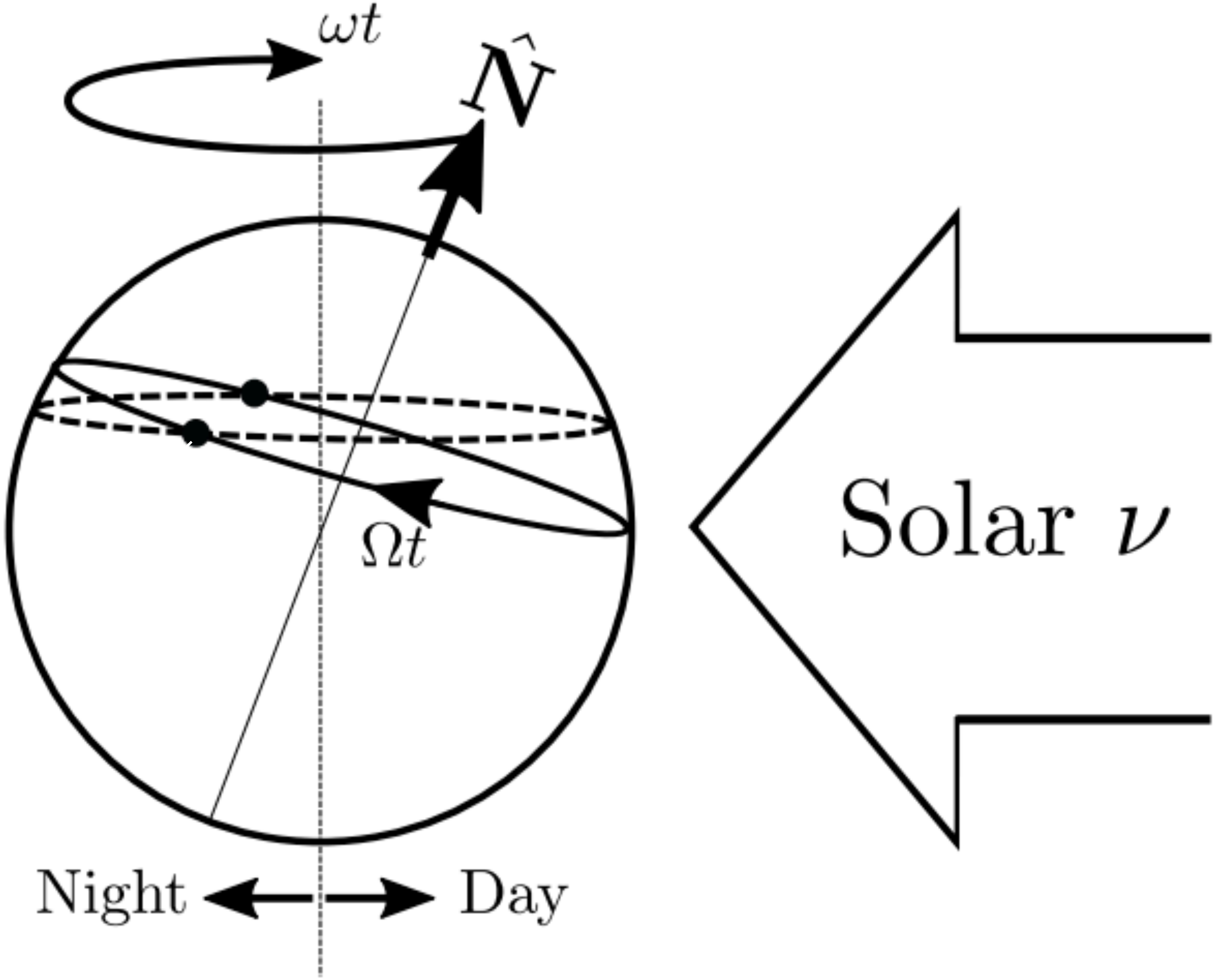




Terrestrial neutrino upscattering

Basic premise

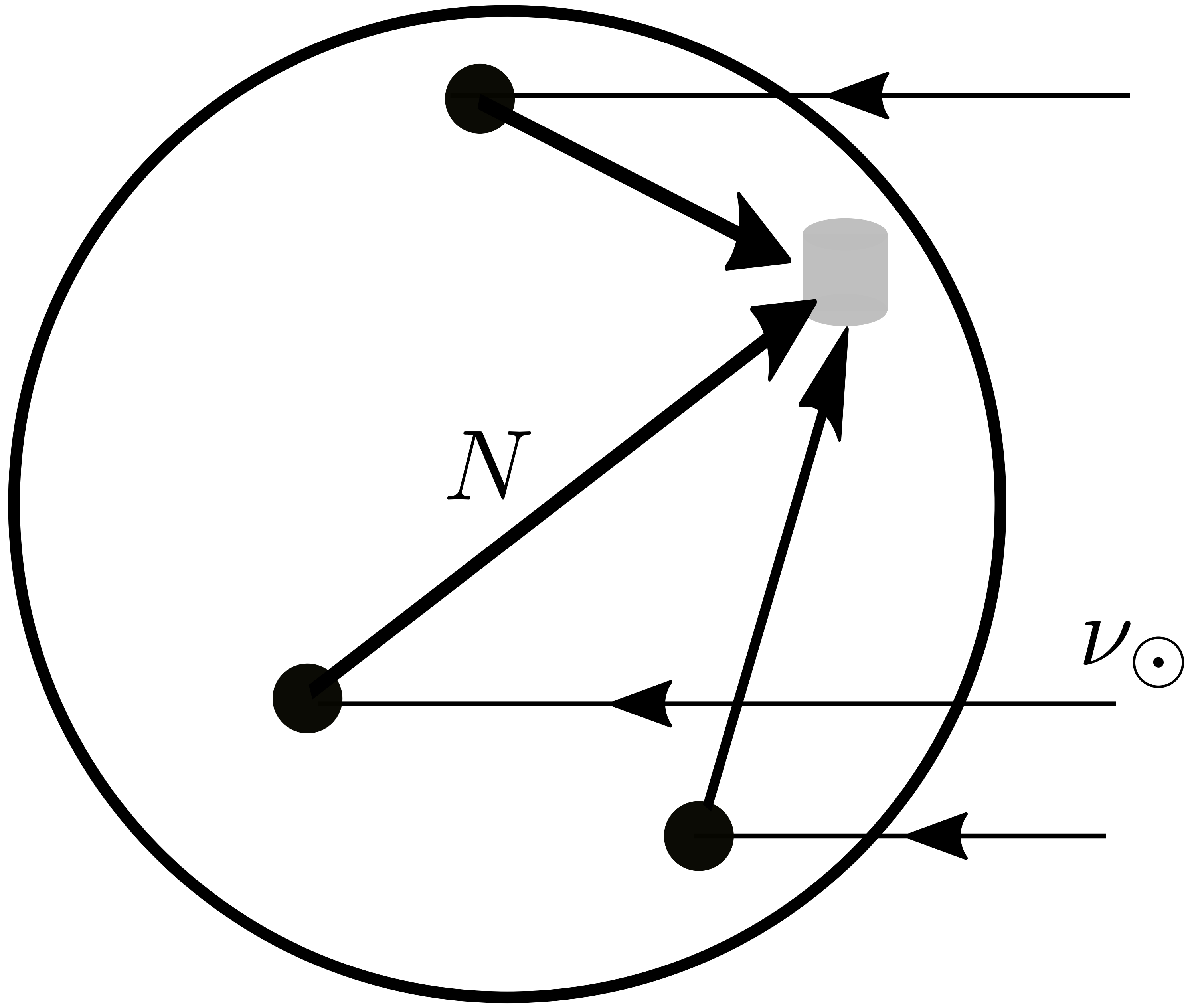
- Searching for long-lived particles is difficult if their decay lengths are long.
- Long dirt column is very helpful in compensating.
- Lets use the Earth as an upscattering source of new physics.

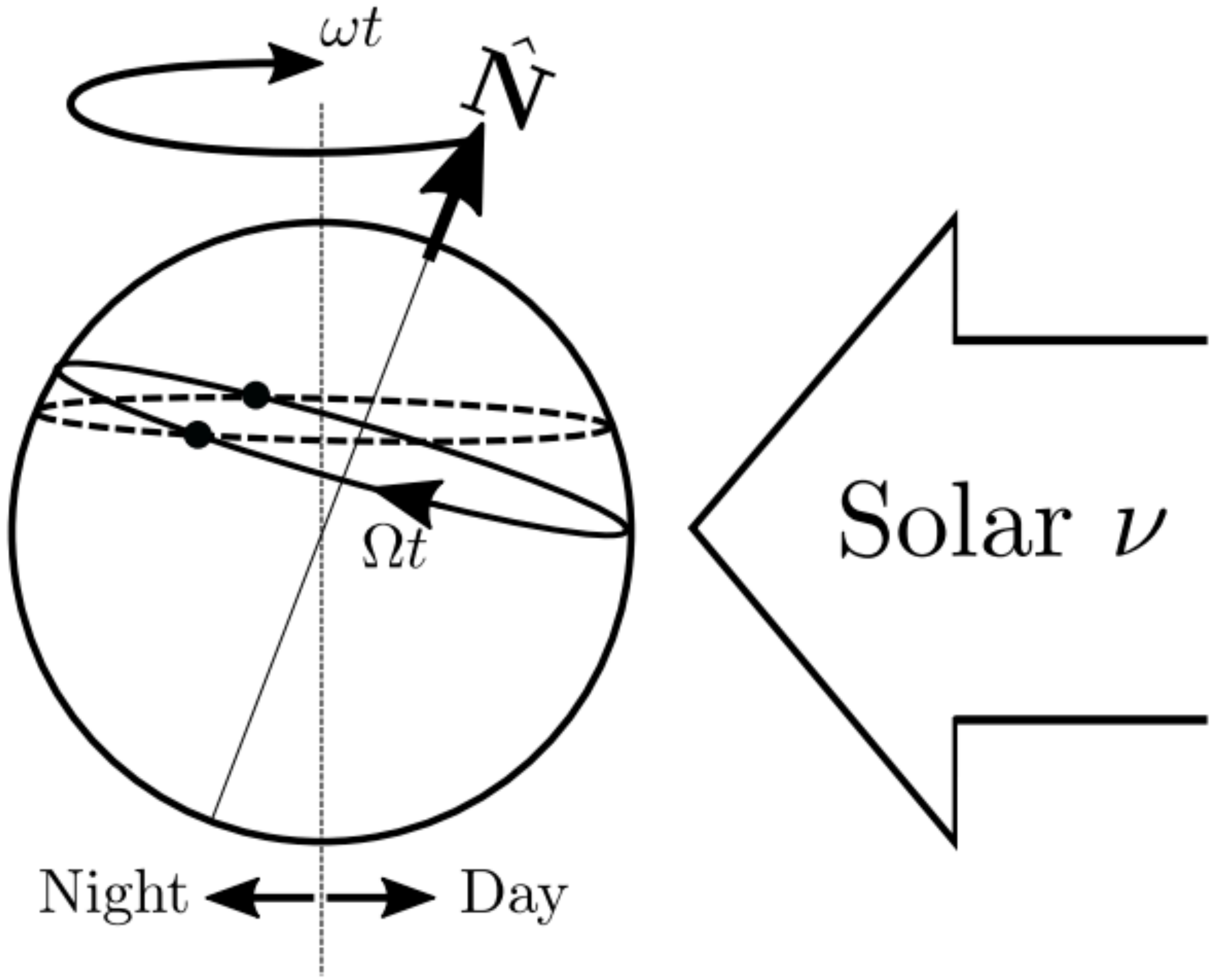


Upscattering rate

Assuming $\lambda^3 \gg V_{\rm det}$

$$\frac{\mathrm{d}^2\Phi_{N\to\nu\gamma}}{\mathrm{d}E_N\mathrm{d}t} = V_{\rm det} \times \int_\oplus \mathrm{d}^3x \quad \frac{\Phi_{\nu_\odot}}{\lambda} \frac{\mathrm{e}^{-|x-x_0|/\lambda}}{4\pi|x-x_0|^2} \sum_i n_i(x) \frac{\mathrm{d}\overline{\sigma}_i}{\mathrm{d}\cos\theta}$$





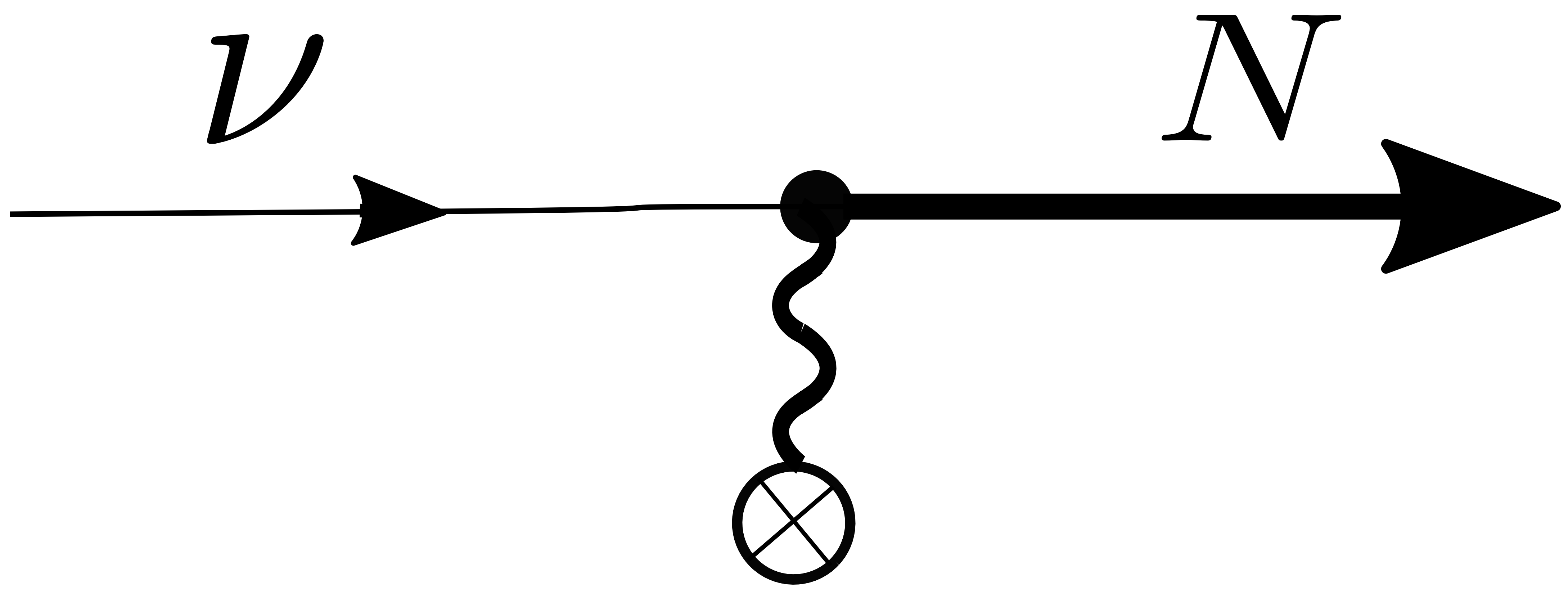
Solar neutrinos

- Coherent scattering on nuclei dominates.

- Neglect nuclear recoil. Good approximation at the level of ppm.

$$\frac{E_\nu^2}{M_A^2} \lesssim 10^{-6}$$

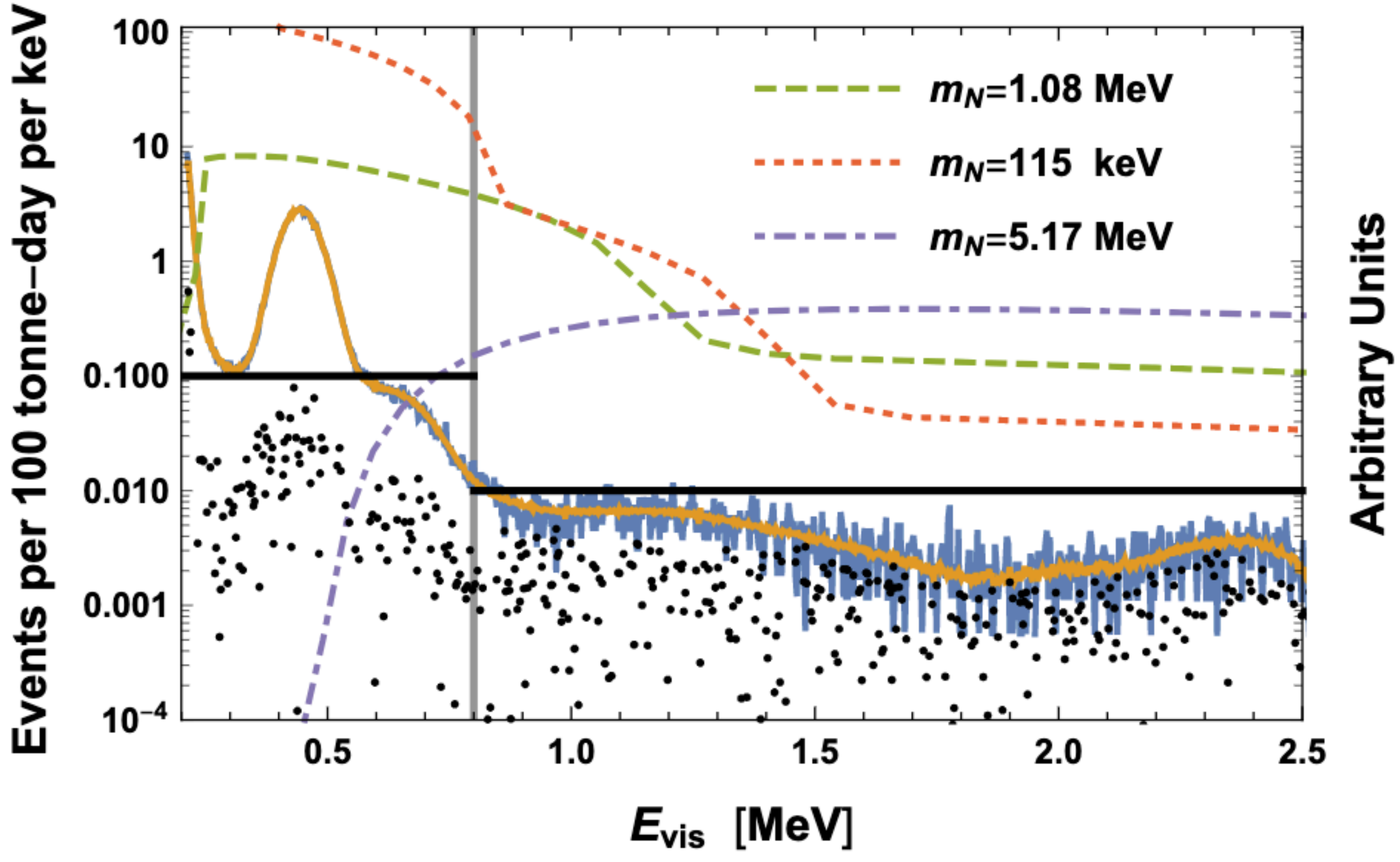
- Energy of HNL = Energy of neutrino.



$$E_N = E_\nu$$

Dipole Portal
Solar neutrinos

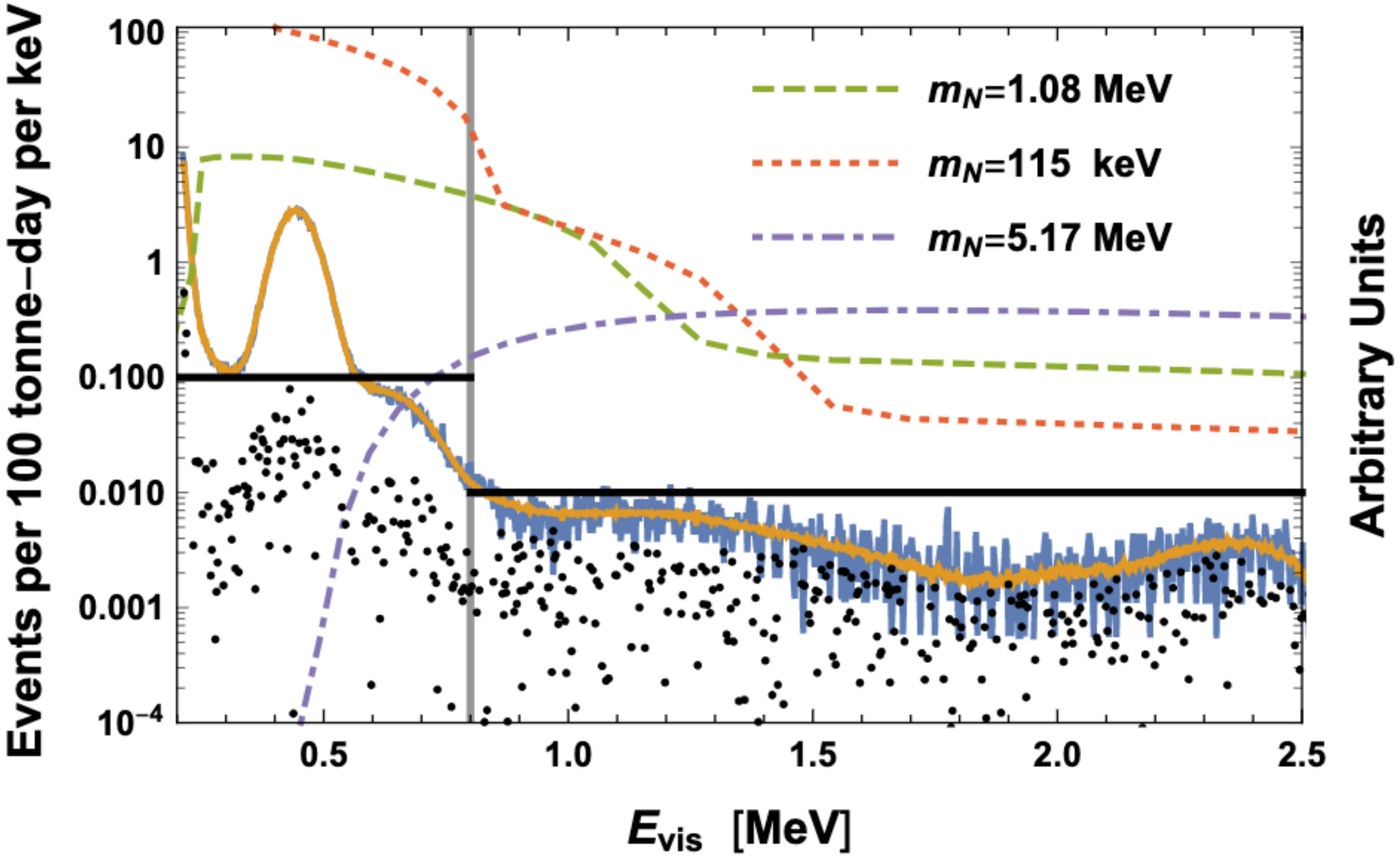
$$\langle \text{Rate} \rangle_{1\text{y}} \sim V_{\text{det}} \bar{n}_A \sigma_{\nu \to N} \Phi_{\nu_\odot} \times \frac{\min(R_\oplus, \lambda)}{\lambda}$$



Dipole Portal
Solar neutrinos

$$\langle \text{Rate} \rangle_{1\text{y}} \sim V_{\text{det}} \bar{n}_A \sigma_{\nu \to N} \Phi_{\nu_\odot} \times \frac{\min(R_\oplus, \lambda)}{\lambda}$$

- For simplicity focus on time-averaged rate.
- Treat Earth as sphere of uniform density
$$\bar{\rho} = 4 \text{ g/cm}^3$$
- Search for photons in Borexino's and Super-K's solar neutrino data.
- Conservative rate-only analysis.



Dipole Portal

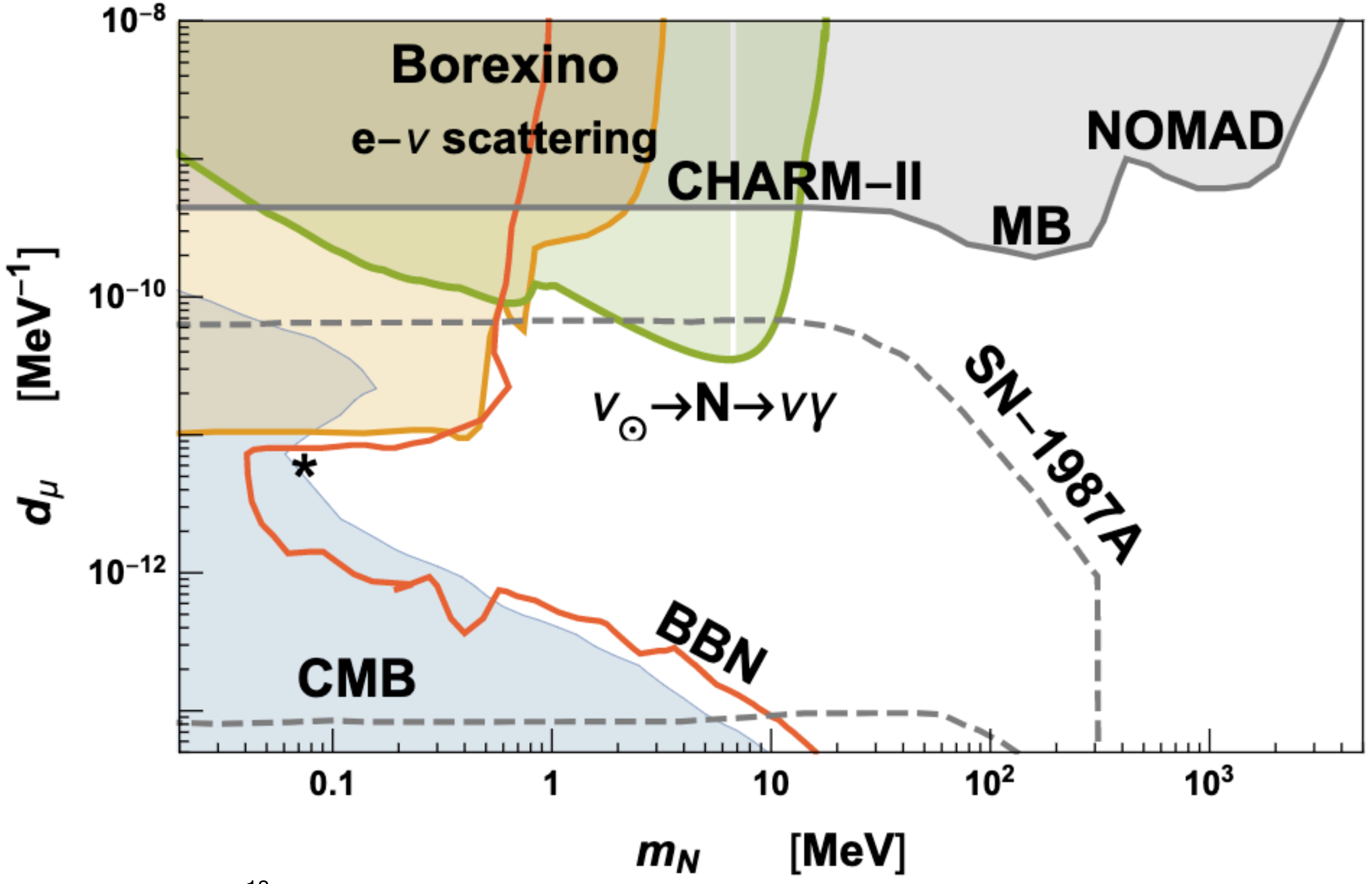
$$I(\zeta) = \begin{cases} \dfrac{1}{2} & L_{\rm dec} \ll R_\oplus \\ \dfrac{\langle L_{\rm slab}\rangle_{1\rm y}}{L_{\rm dec}} & L_{\rm dec} \gg R_\oplus \end{cases}$$

Exclusions obtained with year-averaged rate only.

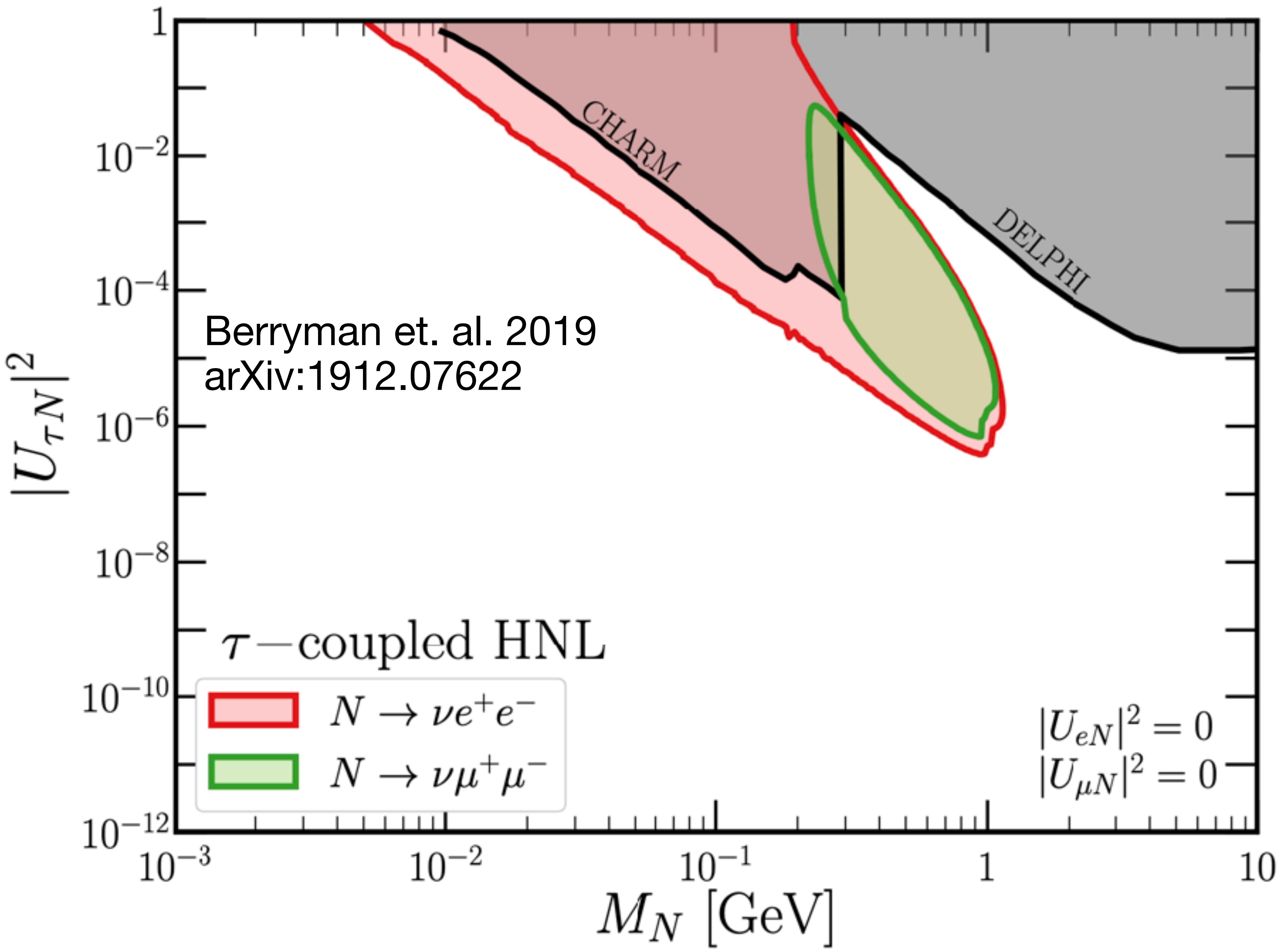
Could use spectral shape.

Day-night asymmetry.

Muon-flavour only



Mass-Mixing Portal



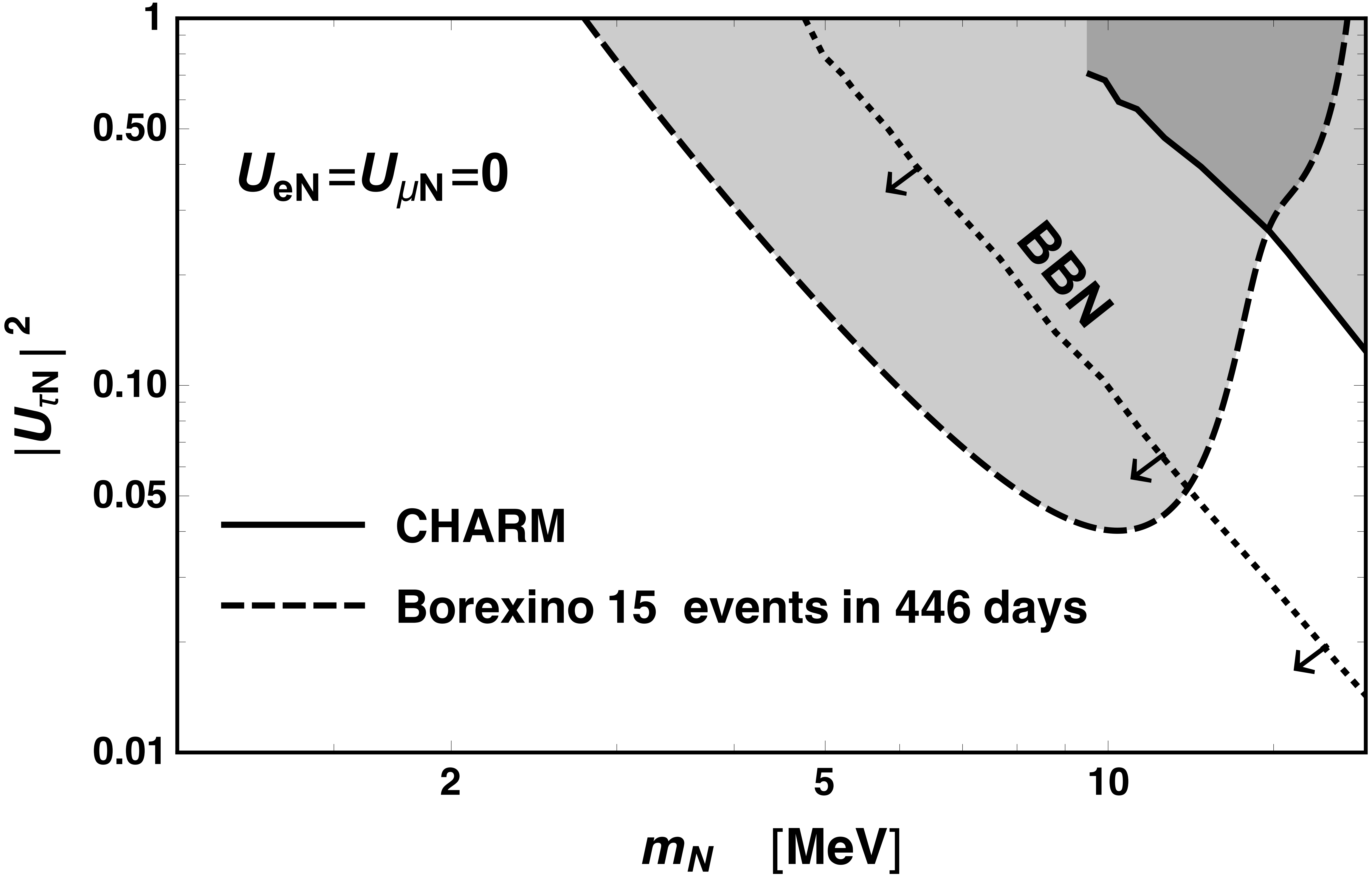
$$\lambda \sim \frac{1}{m_N^6 U_{aN}^4}$$

Constraints are non-existent at low mass for tau neutrinos.

The solar neutrino flux has a sizeable nu-tau component.

We can leverage this to get new constraints on HNLs at low mass.

Mass-Mixing Portal



Use Borexino search for decay-in-flight HNLs from the sun (arXiv:1311.5347).

Estimate 15 events as experimental sensitivity

New constraints from old data!

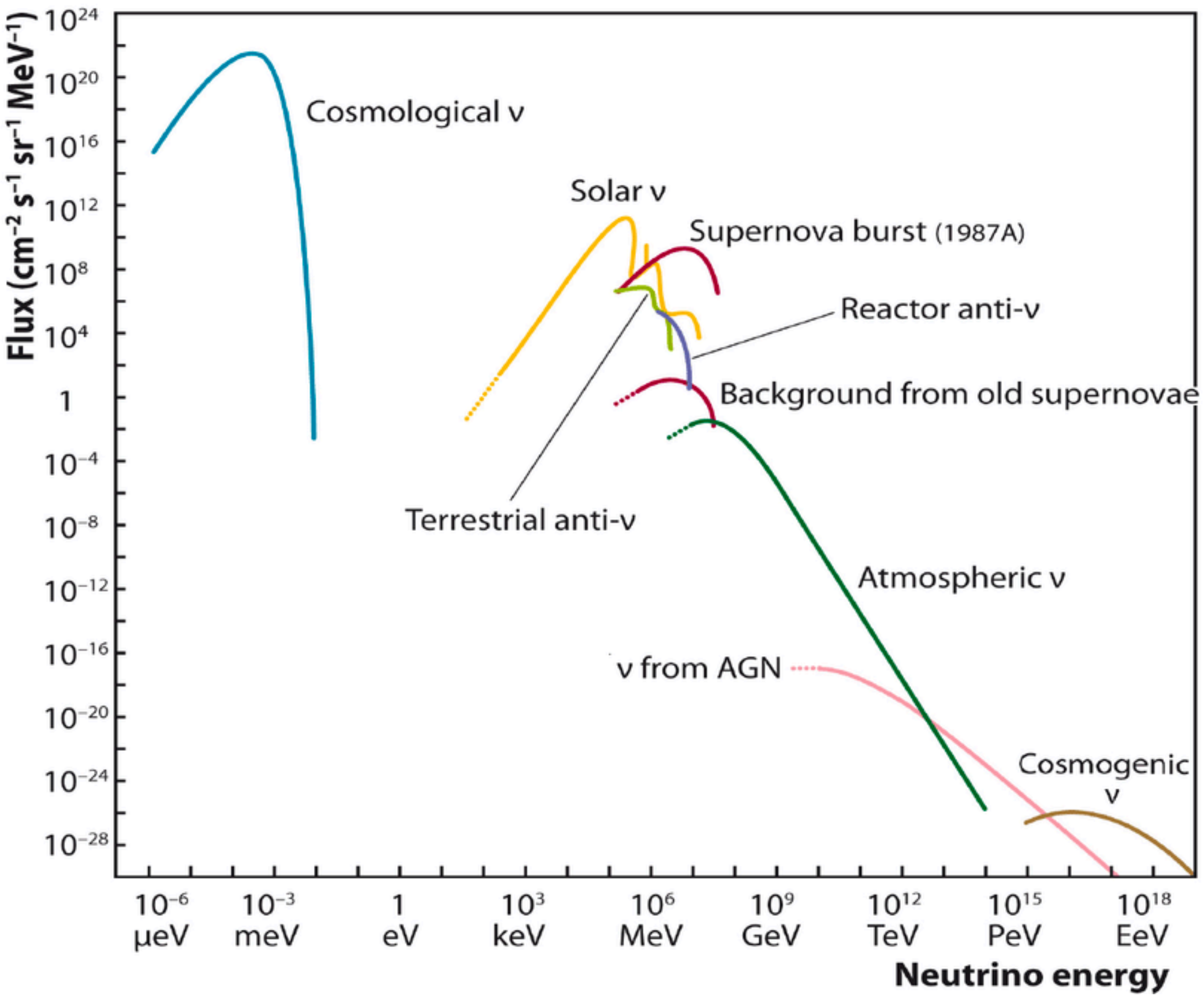
Ongoing work: Atmospheric Neutrinos

In collaboration with Ian Shoemaker & R. Andrew Gustafson (Virginia Tech)

Very talented Ph.D. student (first year)

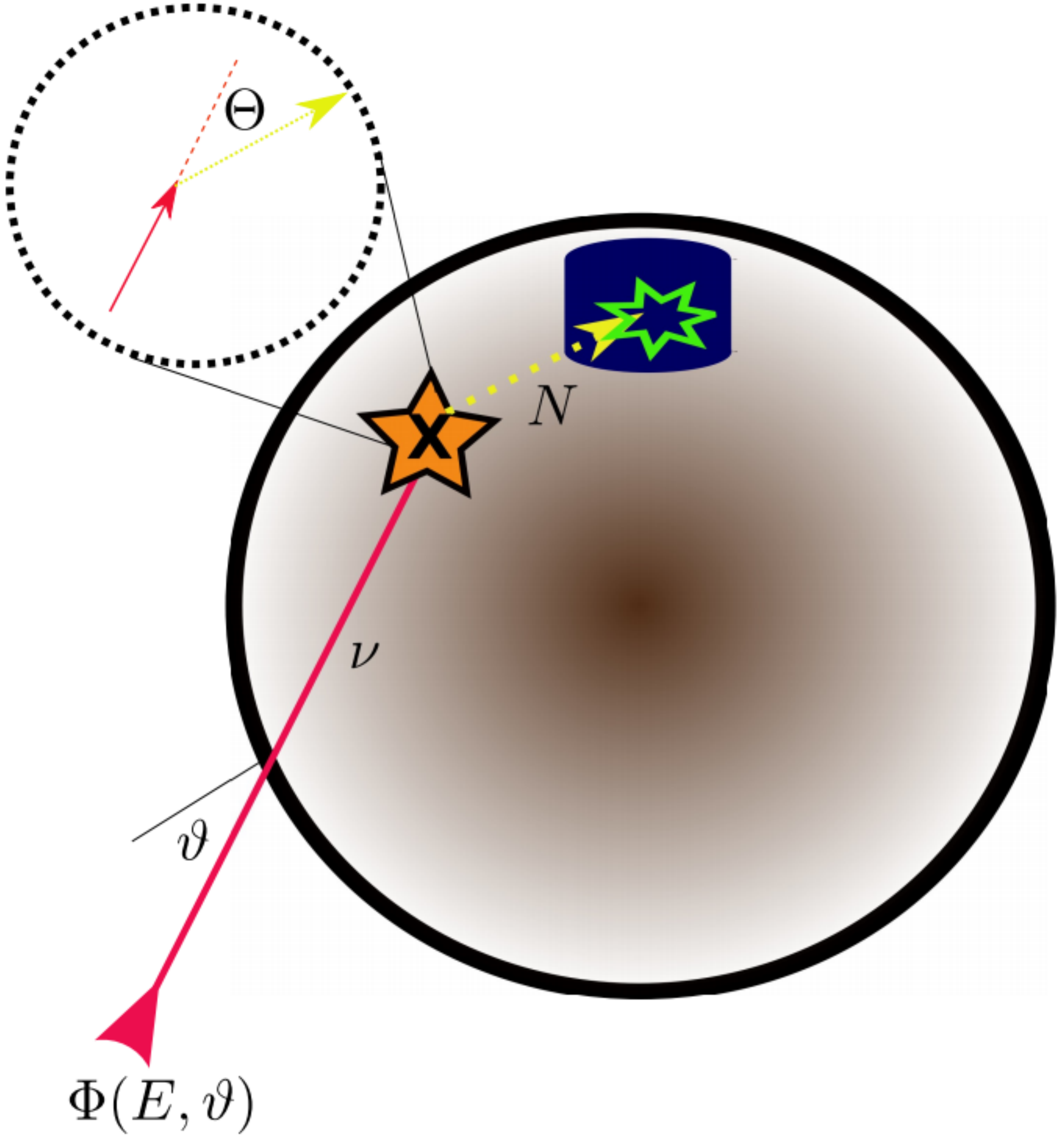
Solar vs Atmospherics

- Access to much higher energies.
- Much lower fluxes.
- Larger volume detectors with higher thresholds e.g. Super-Kamiokande.
- Can atmospherics set competitive limits?



Atmospheric upscattering: complications

- Neutrinos can oscillate from surface to interior.
- Flux depends on zenith angle at surface.
- Scattering is highly forward peaked for dipole portal.
- Short decay lengths mean only regions near detector contribute.



Atmospherics: Monte Carlo solution

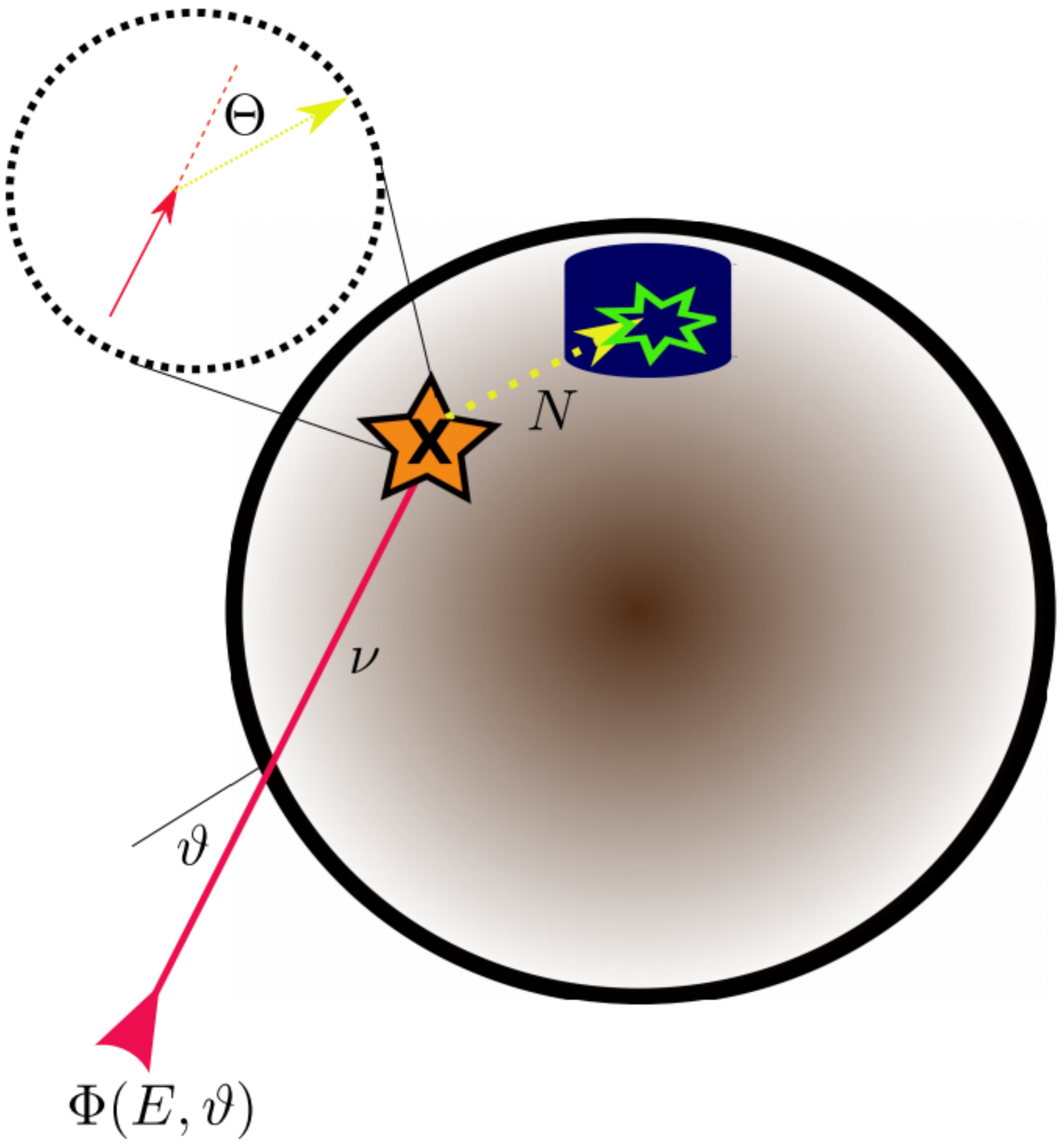
1. Sample neutrino energy first. Compute decay length.

2. Sample upscattering location using $\sim \mathrm{e}^{-r/\lambda}$.

3. Sample scattering angle using $\sim \mathrm{d}\sigma/\mathrm{d}\cos\Theta$.

4. Work backwards to find azimuthal angle at the Earth's surface.

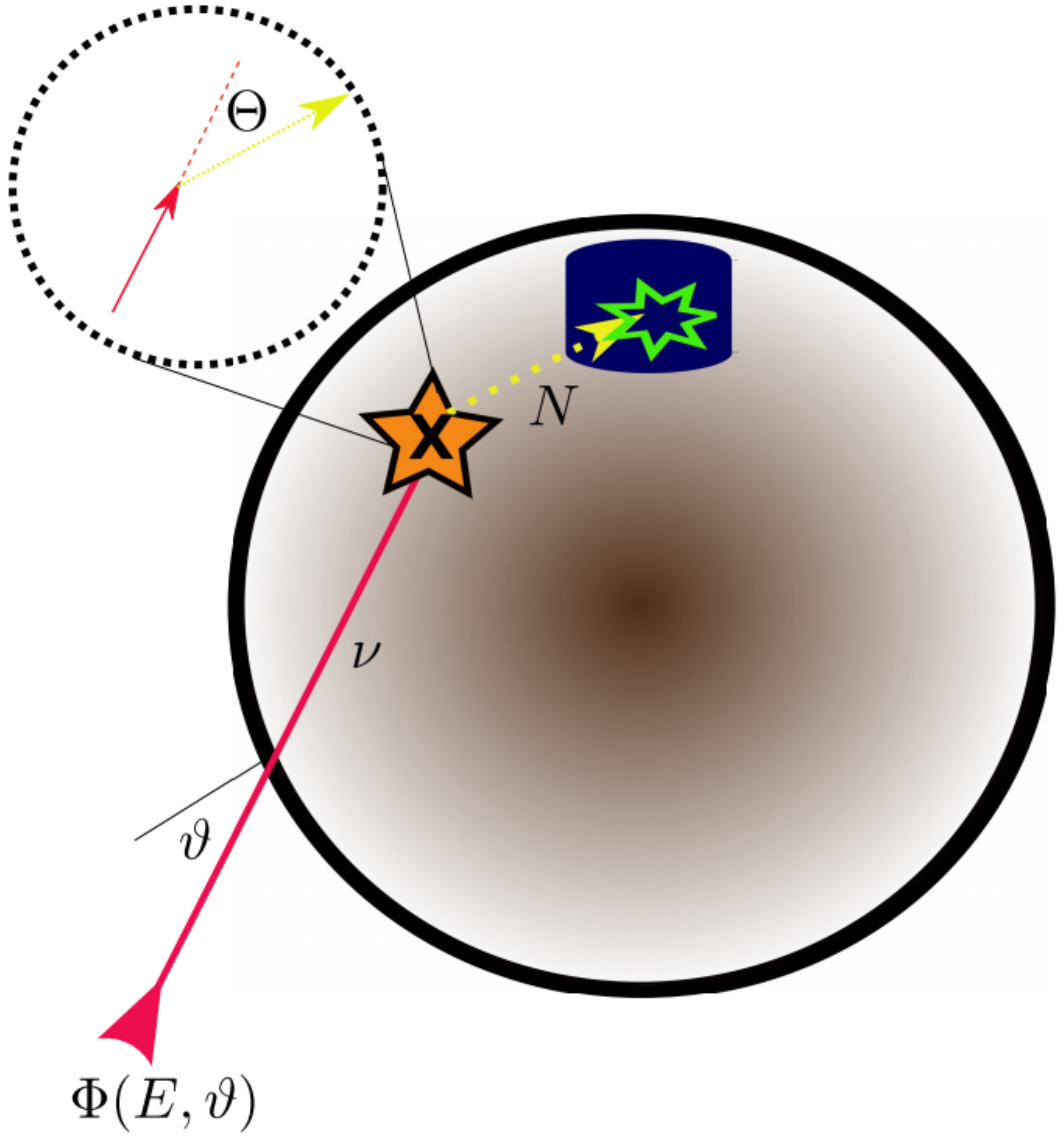
5. Solve Schrodinger equation for neutrino oscillations along path from surface to interior.



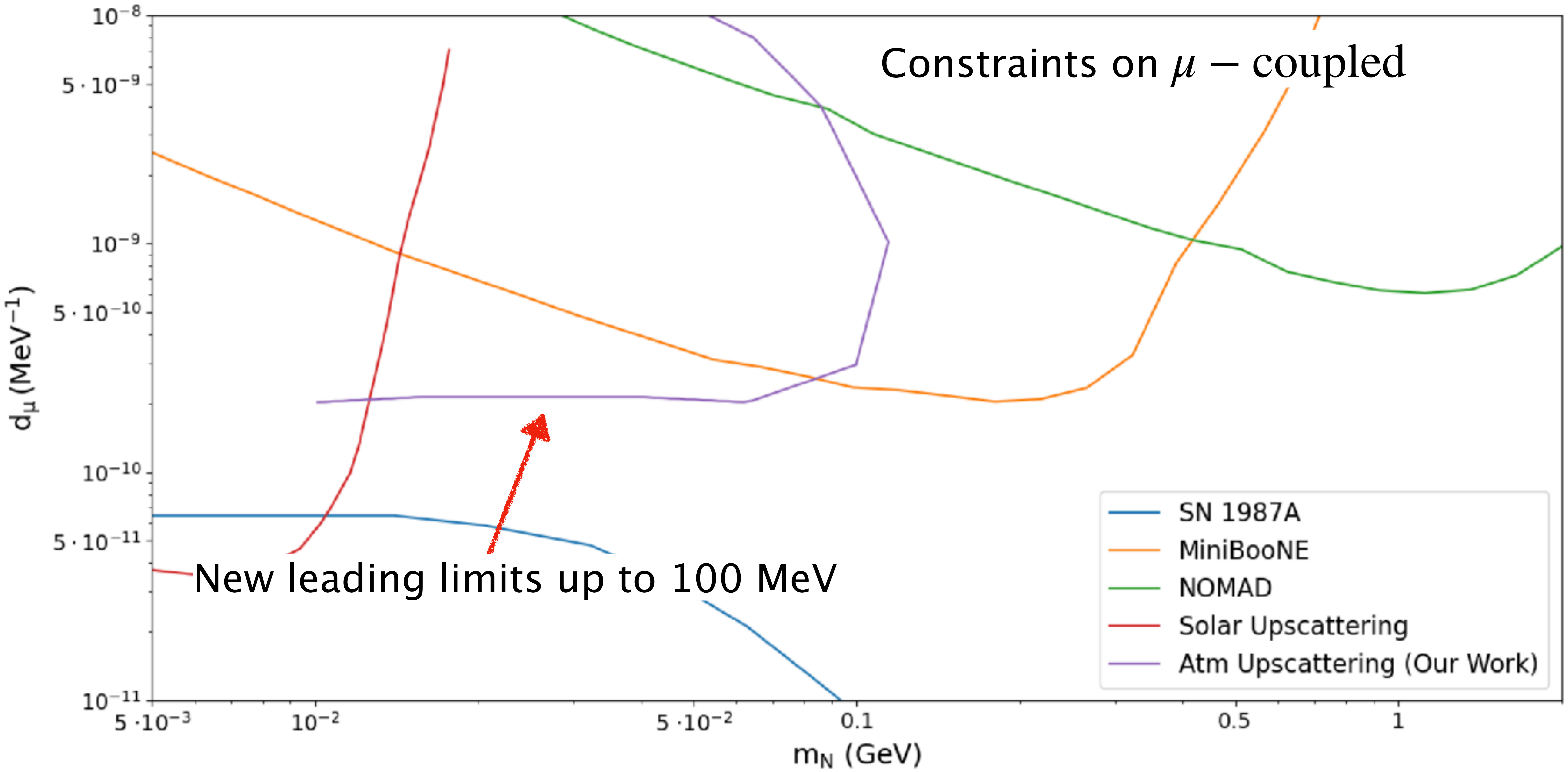
Atmospherics: Monte Carlo solution

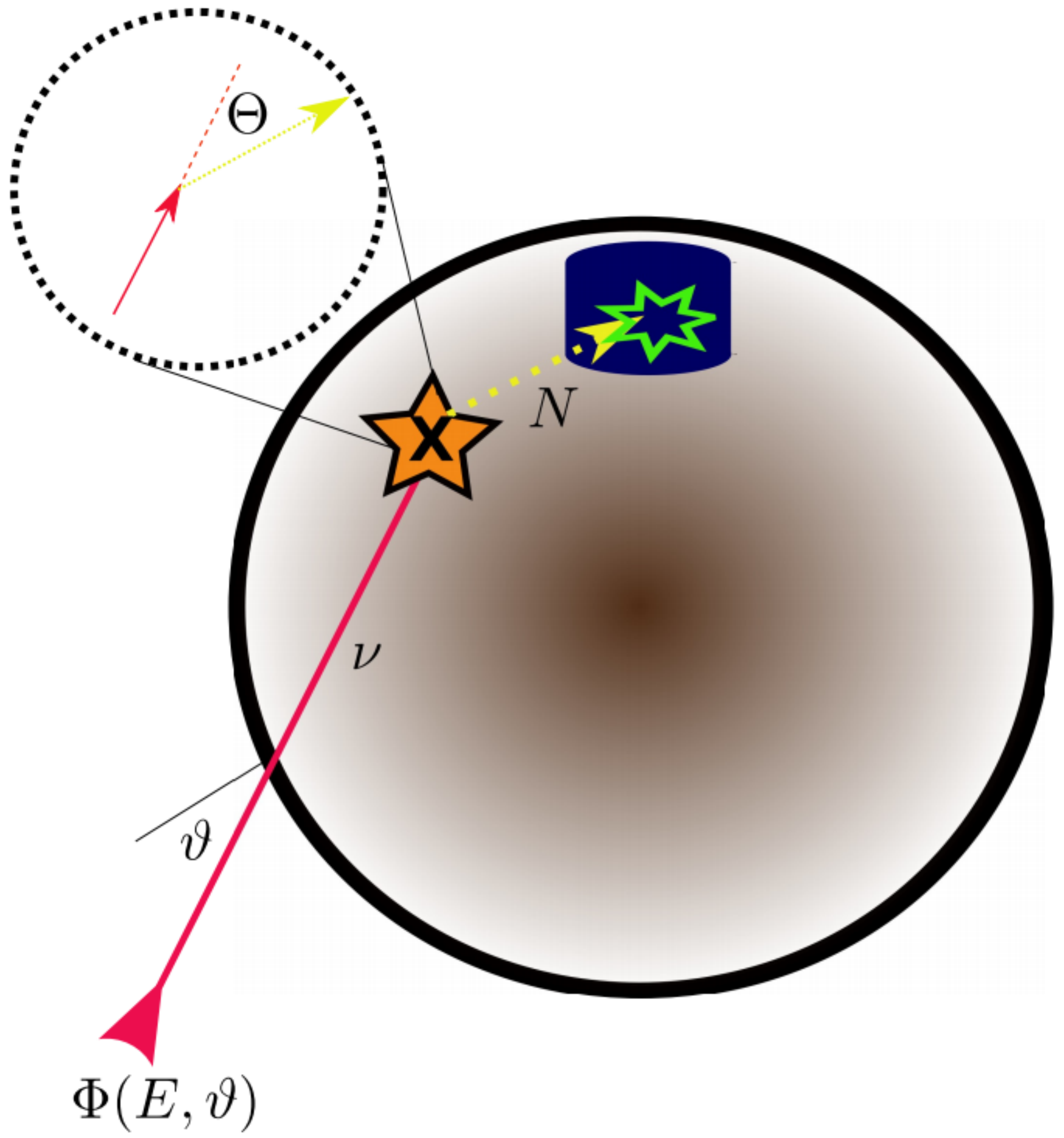
$$\frac{\mathrm{d}^2\Phi_{N\to\nu\gamma}}{\mathrm{d}E_N\mathrm{d}t} = V_{\mathrm{det}} \times \int_{\oplus} \mathrm{d}^3x \quad \frac{\Phi_{\nu_\odot}(x,\Omega)}{\lambda} \, \frac{\mathrm{e}^{-|x-x_0|/\lambda}}{4\pi|x-x_0|^2} \sum_i n_i(x) \frac{\mathrm{d}\overline{\sigma}_i}{\mathrm{d}\cos\theta}$$

- Neutrino flux/intensity now depends on position and angle.
- Broad range of energies, must include coherent and incoherent production.
- Oscillations are numerically intensive do reweighting.



Atmospherics: Dipole portal results





Using data from 10 year of Super Kamiokande.
Require > 155 events
Phys. Rev. D 91, 052019 (2015)

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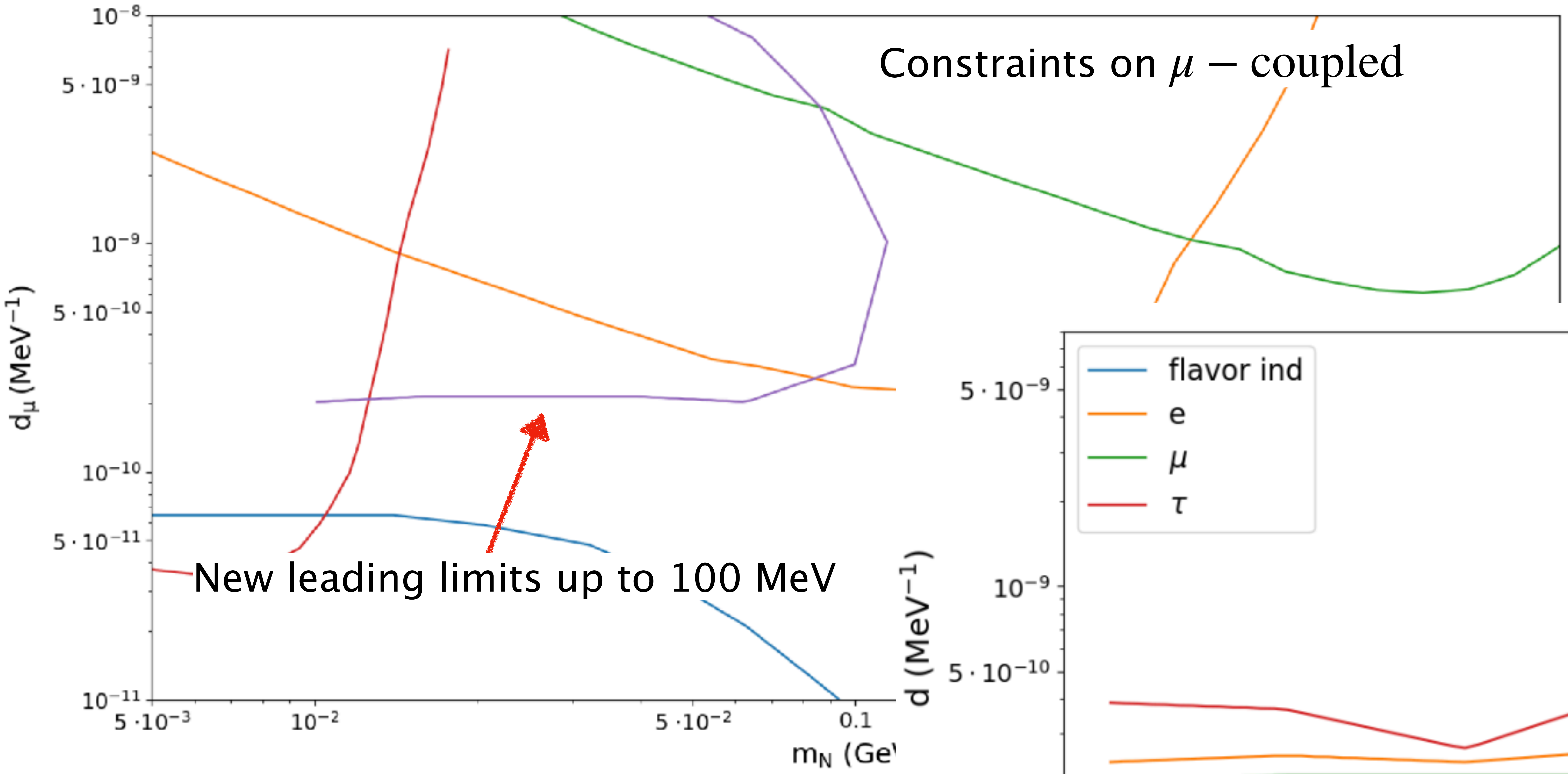
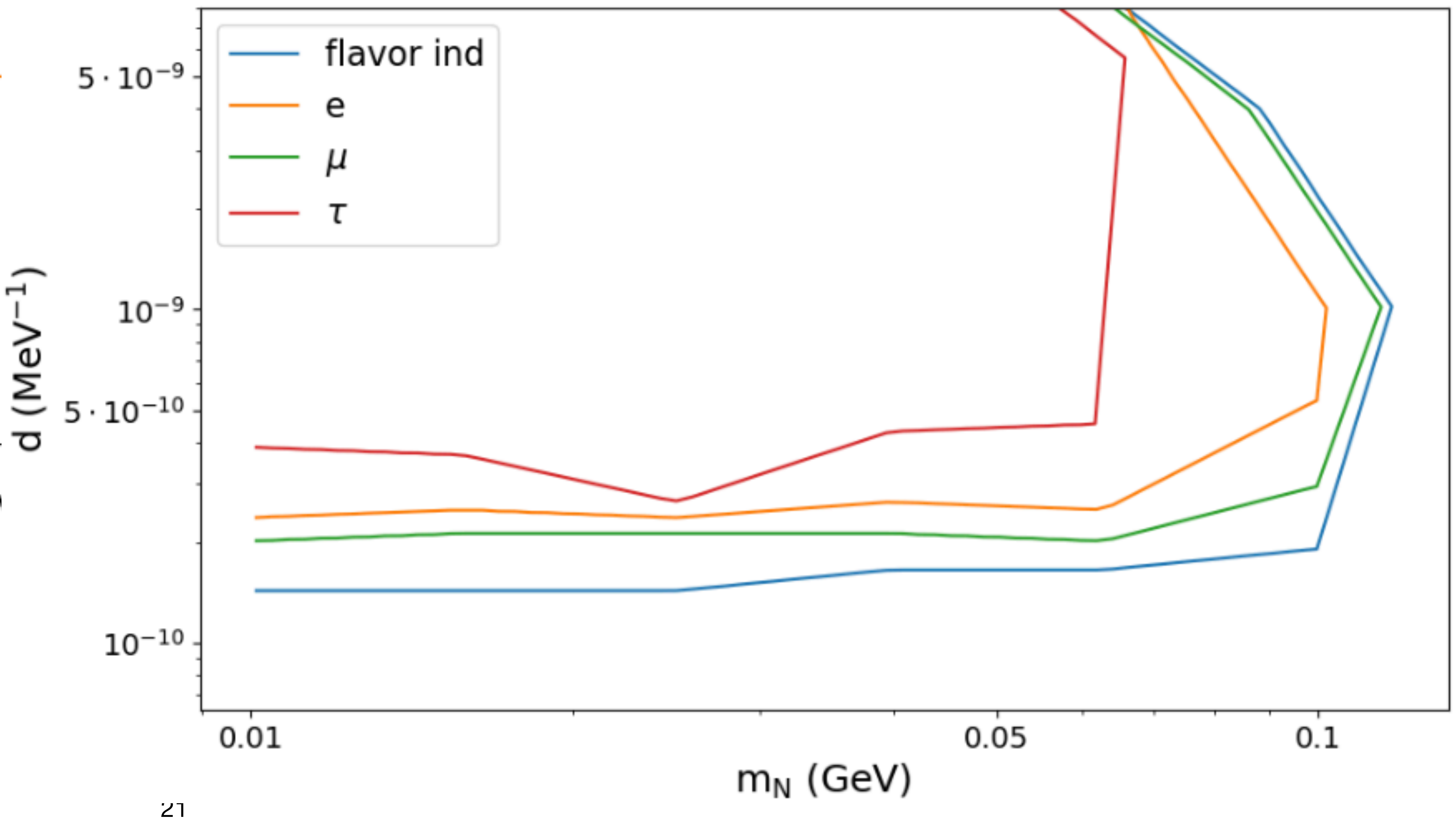
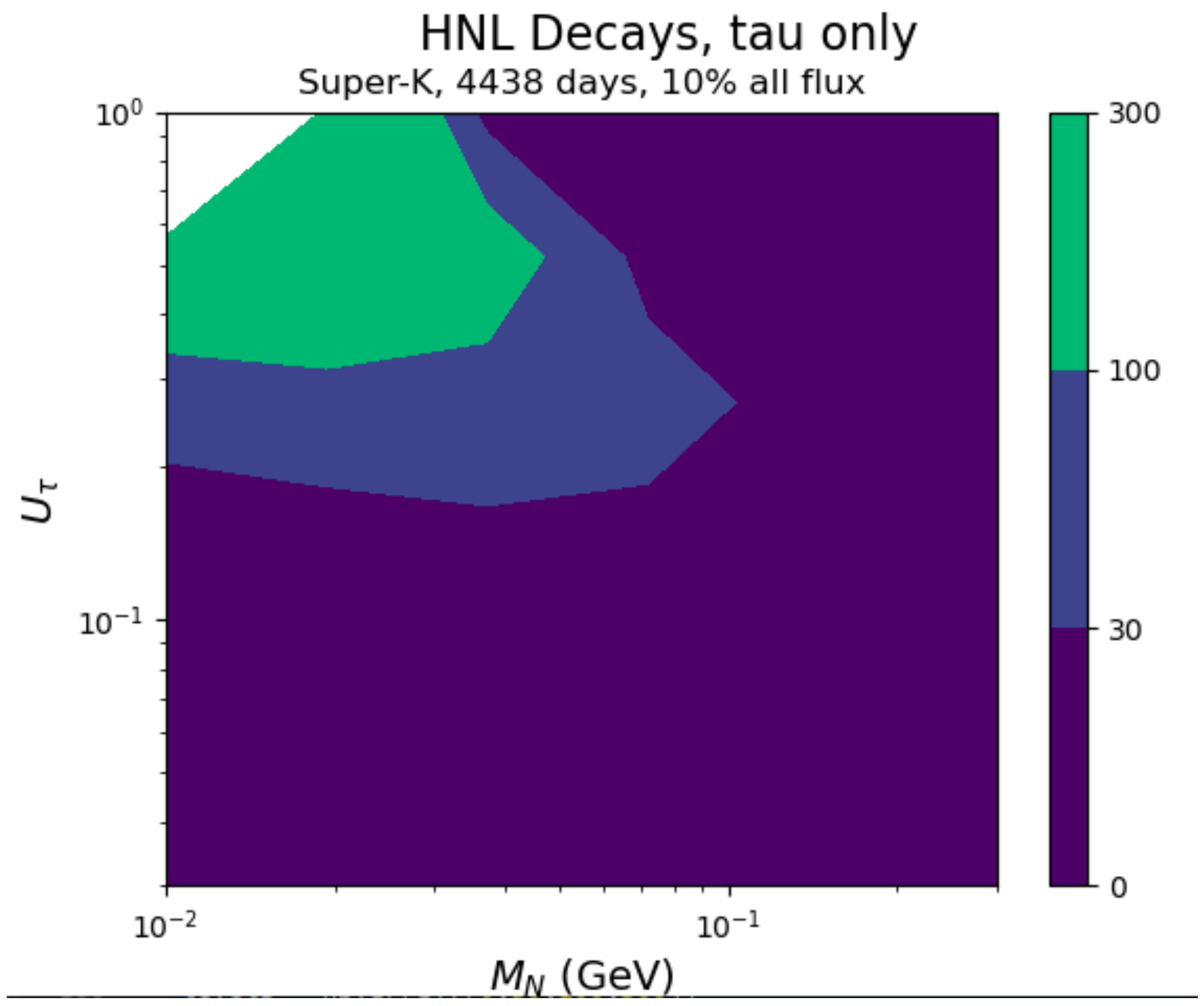




Using data from 10 year of Super Kamiokande.
Require > 155 events
Phys. Rev. D 91, 052019 (2015)

Atmospherics: Mass mixing portal results



Using data from 10 year of Super Kamiokande.
Require > 155 events
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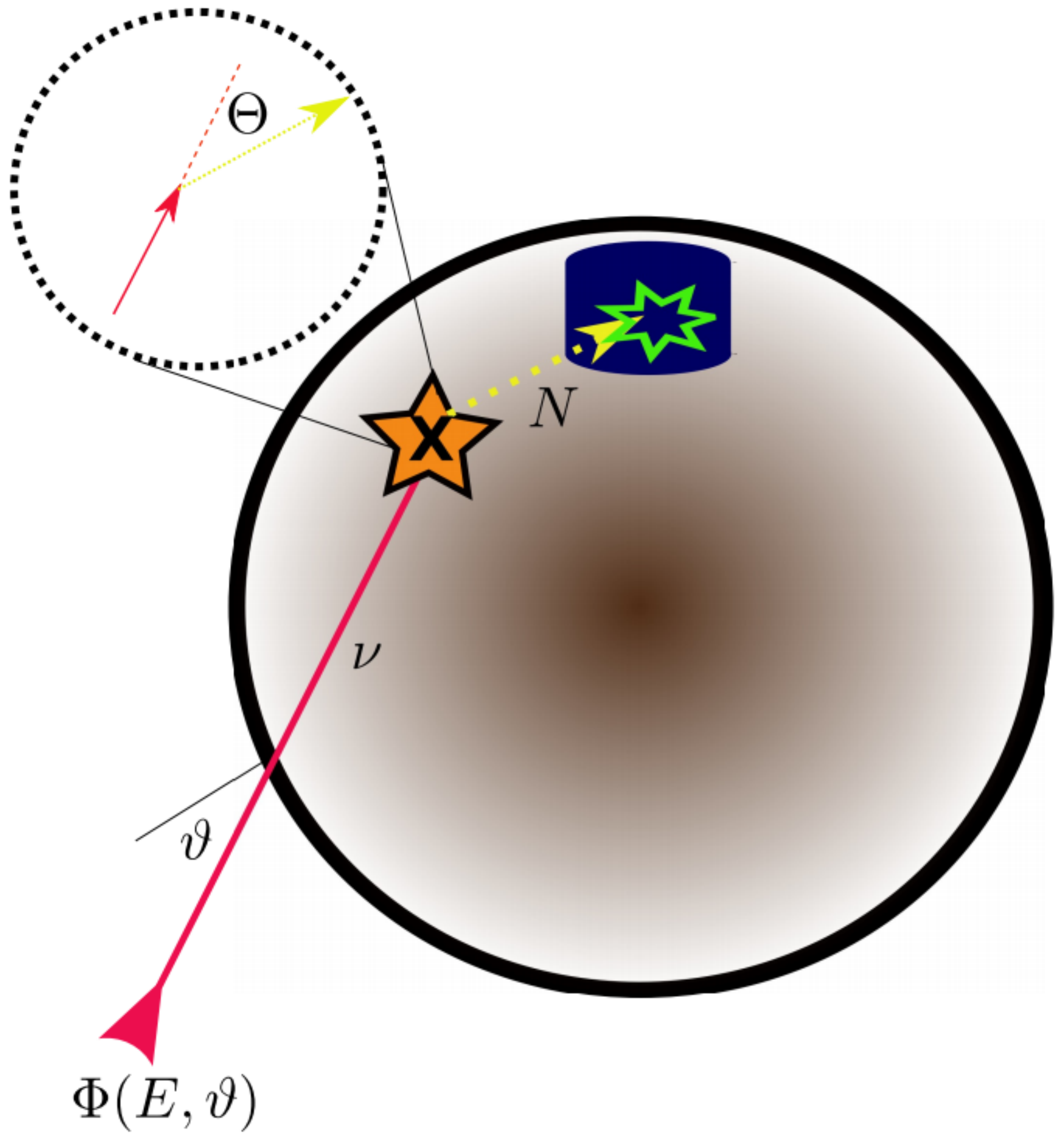
Mass mixing case is much more pessimistic.

Can get hundreds/thousands of events with large mixing angles, but have to fight with large atmospheric neutrino backgrounds.

Better search strategy uses double bangs to suppress backgrounds. See e.g. 2105.09357.



Ongoing work: Daily Modulation

In collaboration with Vedran Brdar (FNAL and NWU)

Time modulation

$$\frac{\mathrm{d}^2\Phi_{N\to\nu\gamma}}{\mathrm{d}E_N\mathrm{d}t} = V_{\mathrm{det}} \times \frac{\Phi_{\nu_\odot}}{\lambda}\int_{\oplus} \mathrm{d}^3x \quad \frac{\mathrm{e}^{-|x-x_0|/\lambda}}{4\pi|x-x_0|^2} n_A(x) Z_{\mathrm{eff}}^2(x) \frac{\mathrm{d}\overline{\sigma}}{\mathrm{d}\cos\theta}$$

This integral gives the flux of HNLs that decay in Borexino as a function of time.

We can use this to compute the rate of photon deposition in an energy window:

$$\frac{\mathrm{d}R}{\mathrm{d}t} = \int \mathrm{d}E_N \ \mathscr{F}(E_N) \frac{\mathrm{d}^2\Phi_{N\to\nu\gamma}}{\mathrm{d}E_N\mathrm{d}t}$$

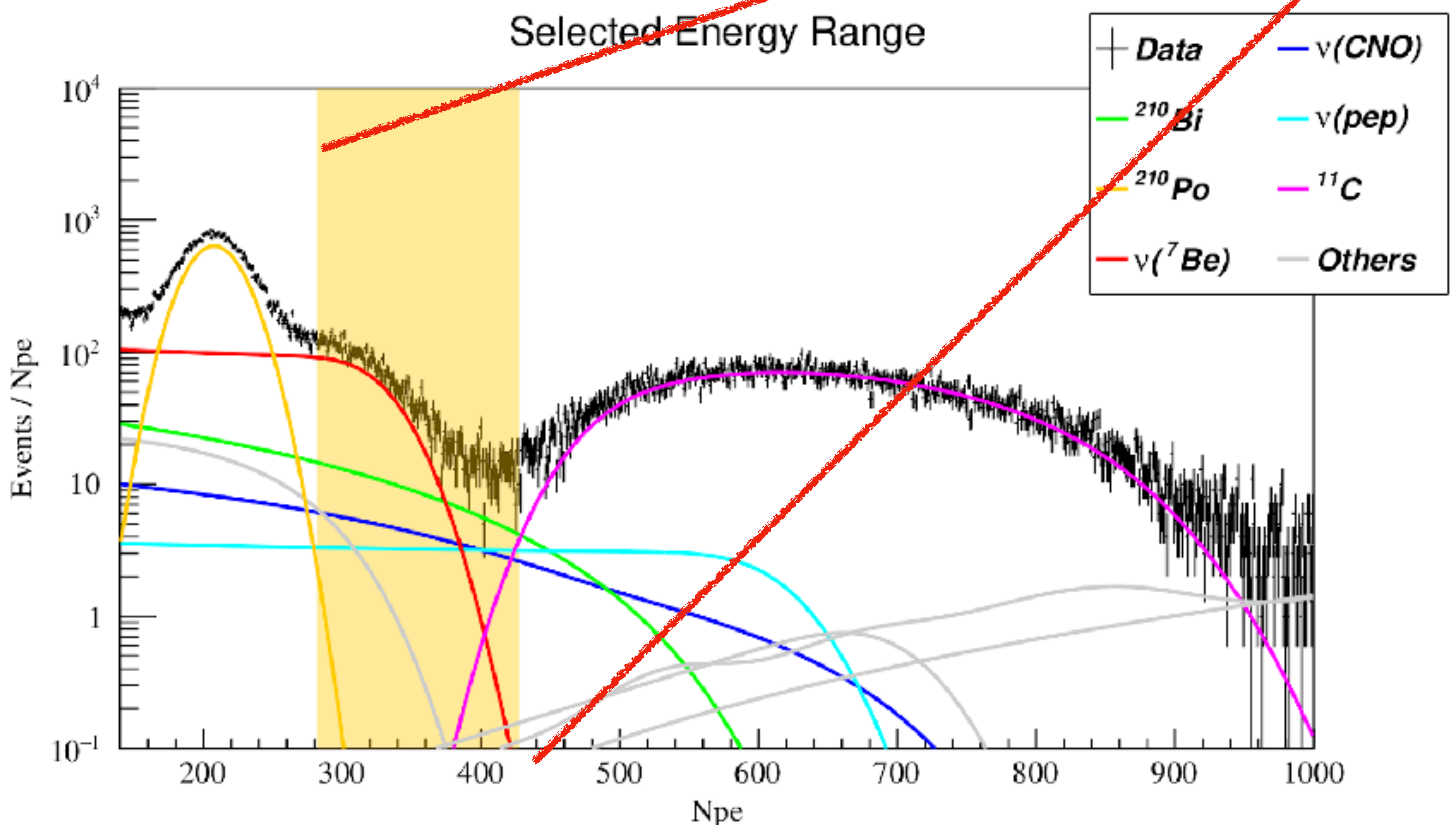
Fraction of photons in energy window

Energy quenching

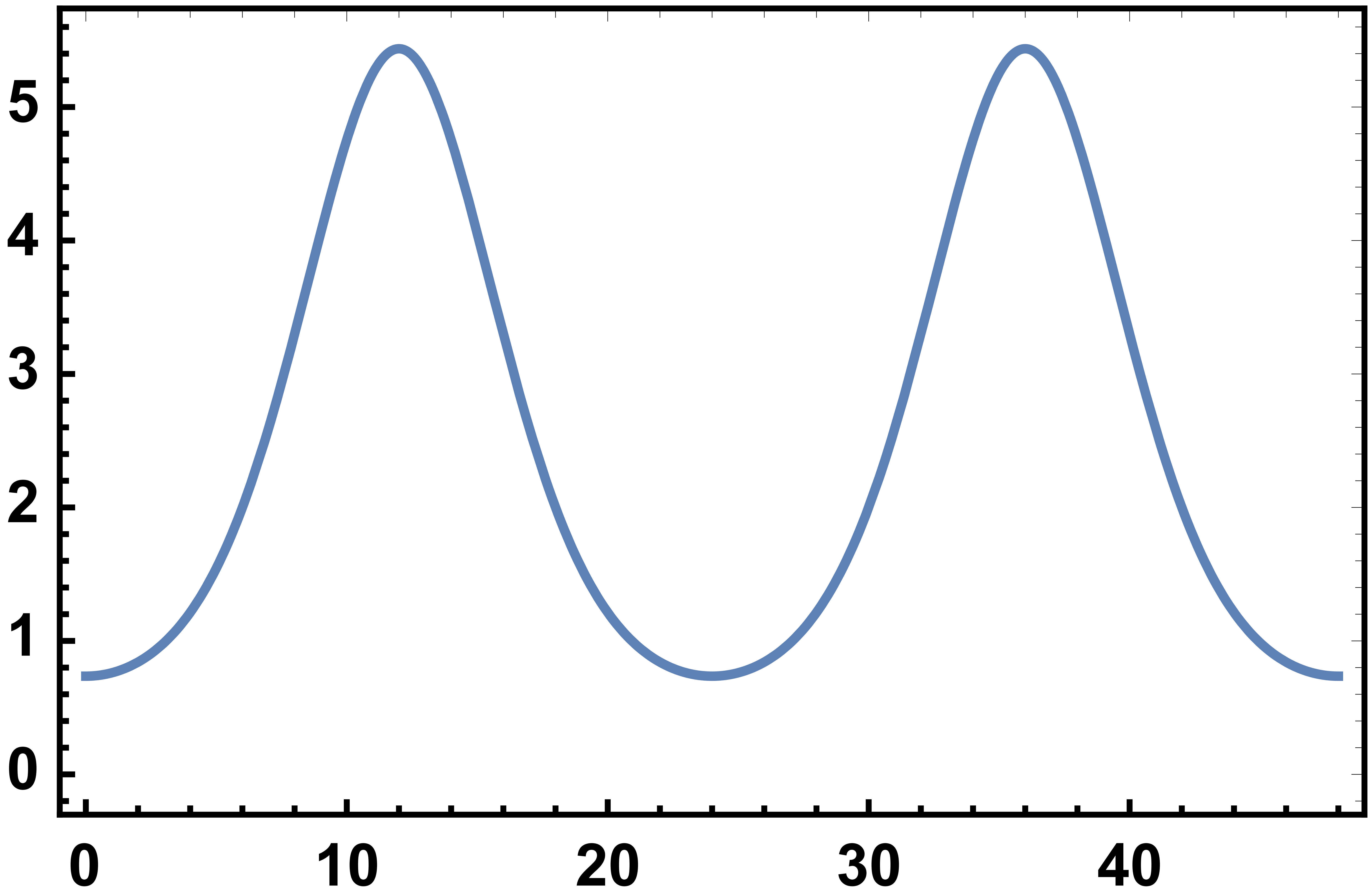
Invert quenching

$$\mathscr{F}(E_N) = \int_{E_\gamma^-}^{E_\gamma^+} \mathrm{d}E_\gamma \; P(E_\gamma \,|\, E_N) \qquad E_\gamma^\pm = Q^{-1}(\mathscr{E}^\pm)$$

Lab-frame spectrum of photons from HNL decay



All-together this gives us a time series



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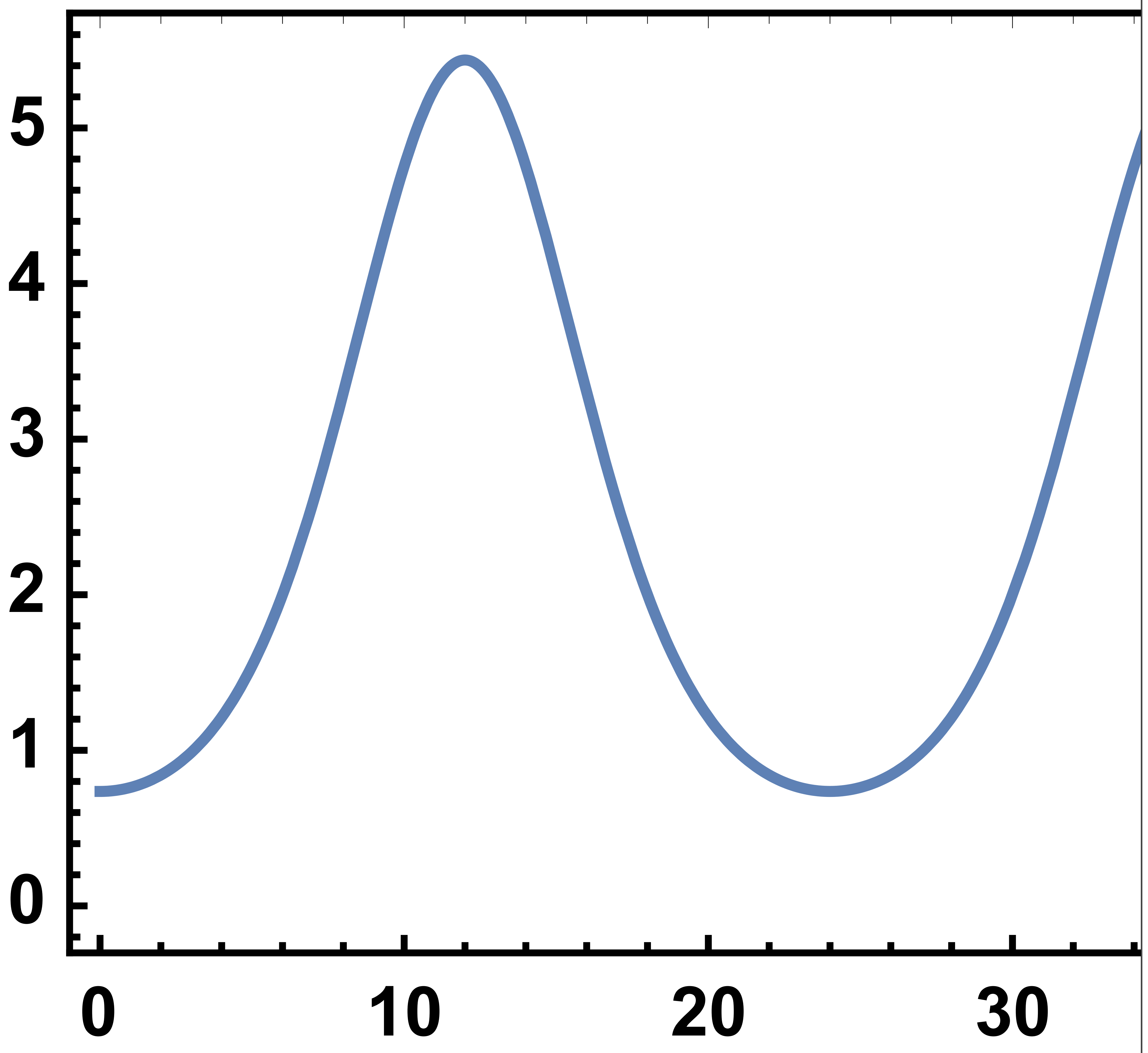
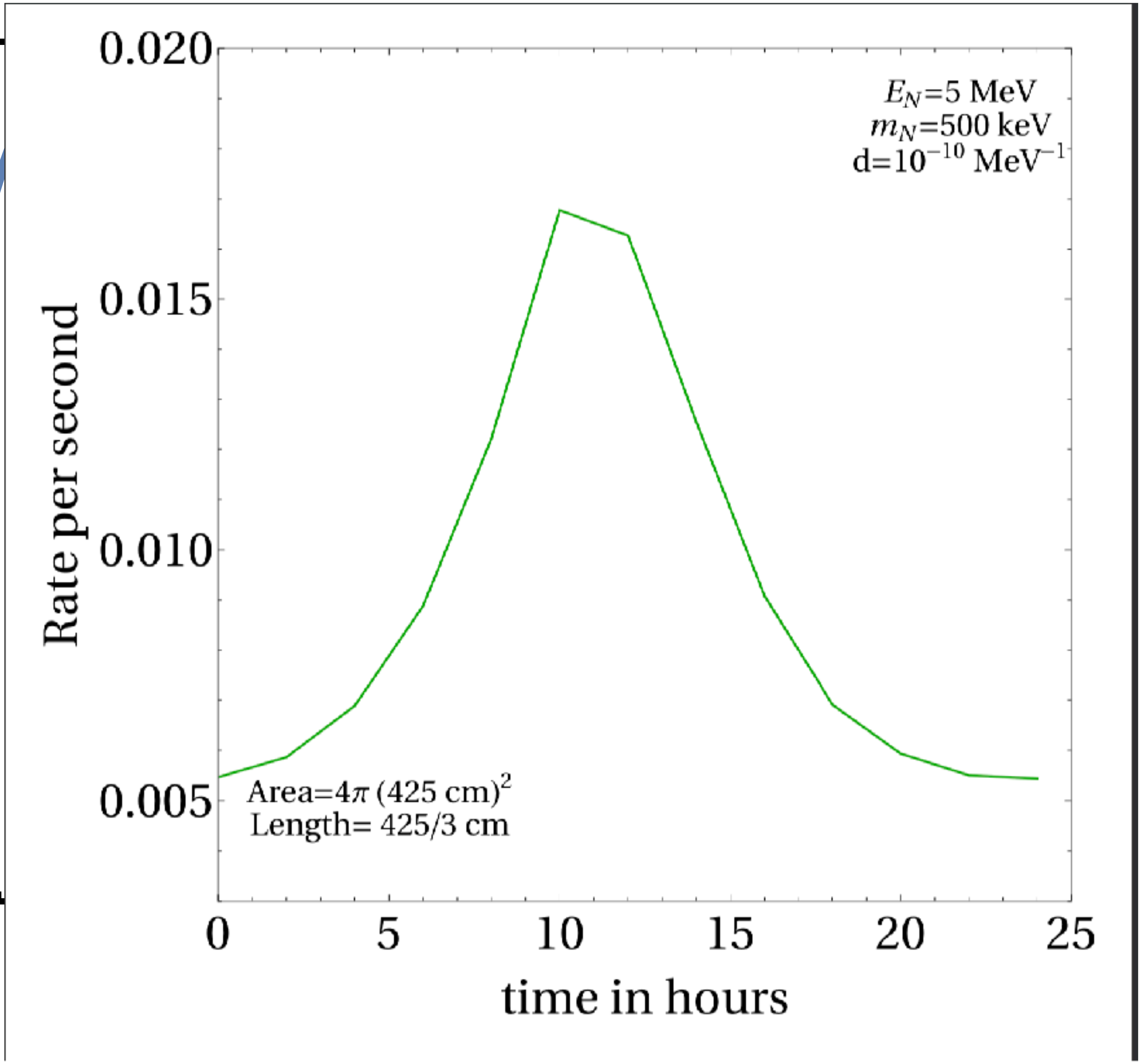
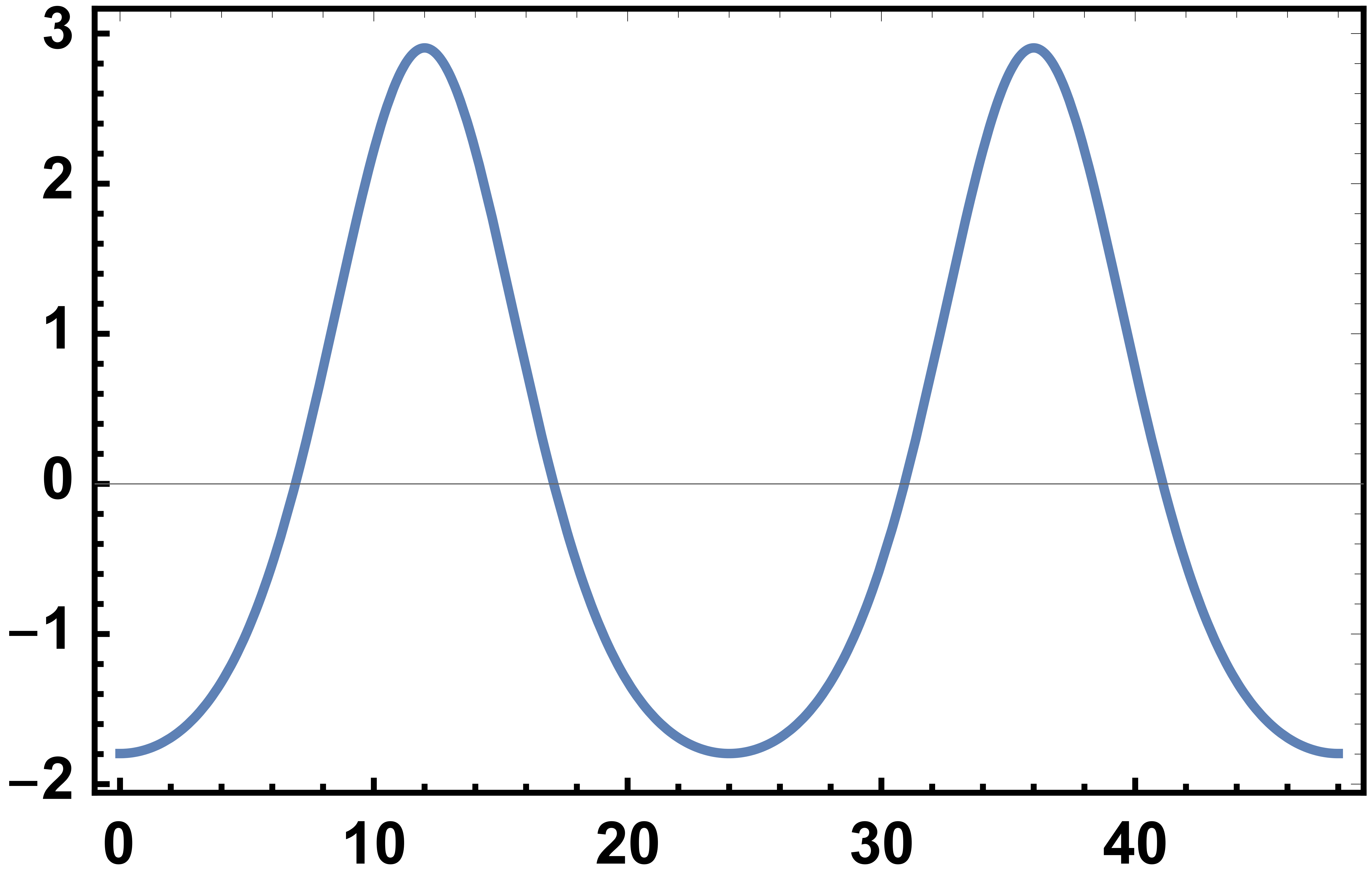
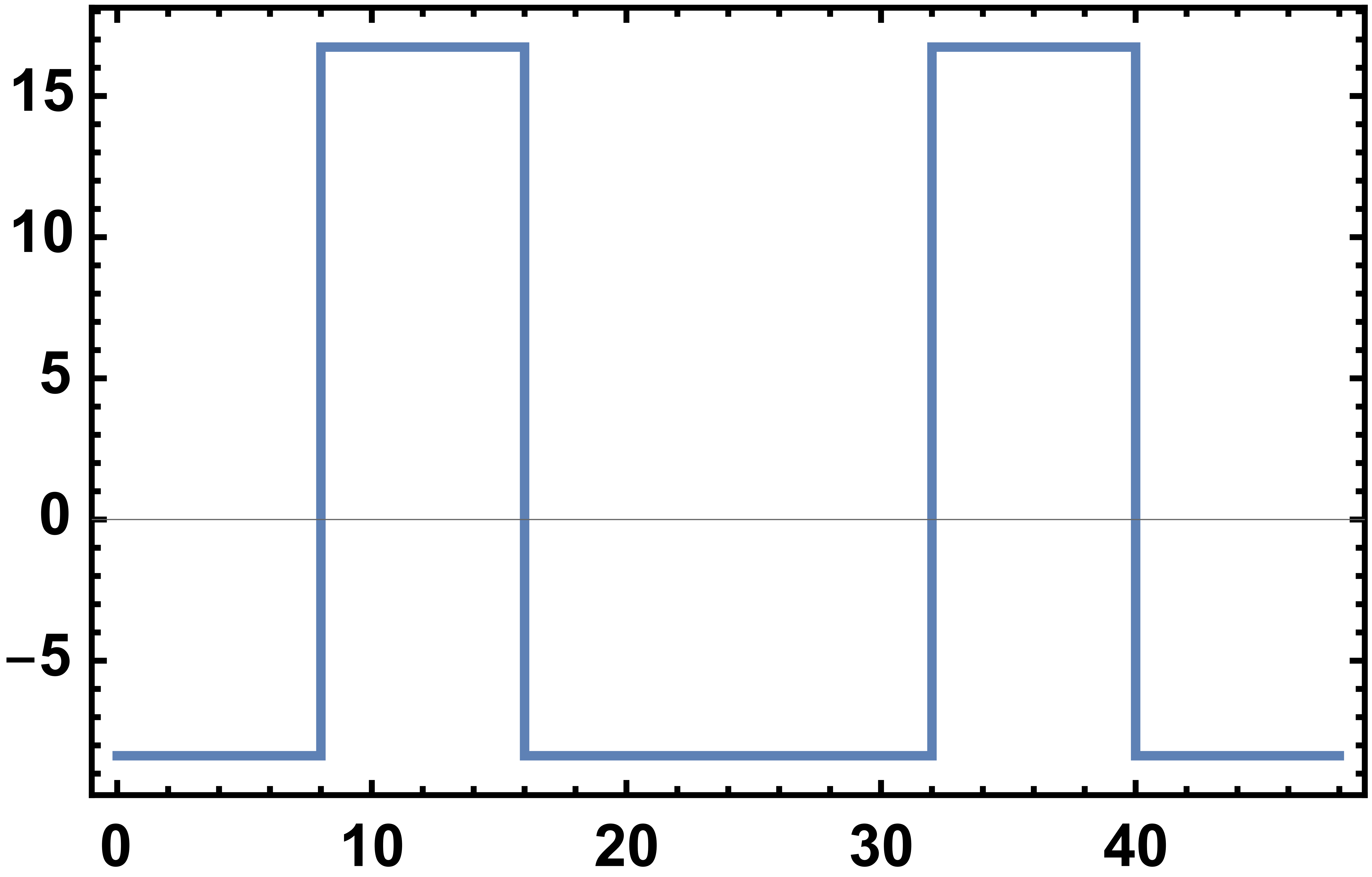




Subtract the mean —> Residual



Bin in 8 hour bins



Theory

$$[\{t_0, \lambda(t_0)\},\ \{t_1, \lambda(t_1)\},\ \{t_2, \lambda(t_2)\},\ \{t_3, \lambda(t_3)\},\ \ \ldots\ \ ]$$

Data

$$[\{t_0, R_0, \sigma_0)\},\ \{t_1, R_1, \sigma_1\},\ \{t_2, R_2, \sigma_2\},\ \{t_3, R_3, \sigma_3\},\ \ \ldots\ \ ]$$

$$\chi^2 = \sum_i \frac{(R_i - \lambda_i)^2}{\sigma_i^2}$$

Benchmark points with toy data

```
 --------
d = 0.63 x 1E-10 MeV^-1
mass = 0.2  MeV
rate multiplied by:  1
Events per day : 2.0635460835468287
RMS residual per day: 0.565995156750061
chi^2 :  1143.1085662633388
$\Delta \chi^2$ = 11.672216591402048
Critical \Delta chi Sq 3.841458820694124
Is excluded:  True
 --------
```

```
 --------
d = 1.0 x 1E-10 MeV^-1
mass = 2.1  MeV
rate multiplied by:  1
Events per day : 2.62257144498112
RMS residual per day: 0.6748186101028492
chi^2 :  1147.3963216086247
$\Delta \chi^2$ = 15.959971936687907
Critical \Delta chi Sq 3.841458820694124
Is excluded:  True
 --------
```

RMS residuals of ~0.1-0.2 events/day can be excluded.

Corresponds to 0.5-5 events per day in total rate.

10-100x better sensitivity than with rate-only analysis.

Conclusions

Take home messages

- Searchinig for decaying particles emanating from the Earth is **well motivated** and is a promising strategy for long-lived particles.
- Existing large volume detector datasets can be used to set new constraints on very minimal and generic models of light new physics.
- Large naturally occurring fluxes of neutrinos can serve as a resource for discovering new physics.
- Improved data analysis and extensions to atmospheric neutrinos can supply leading constraints on dipole portal over 2 decades of parameter space.