Luminous Solar Neutrinos

Dipole portals arXiv:2010.04193

Mass-mixing portals arXiv:2010.09523

Ryan Plestid | May 2021 | PHENO 2021

Motivation: Lifetime Frontier

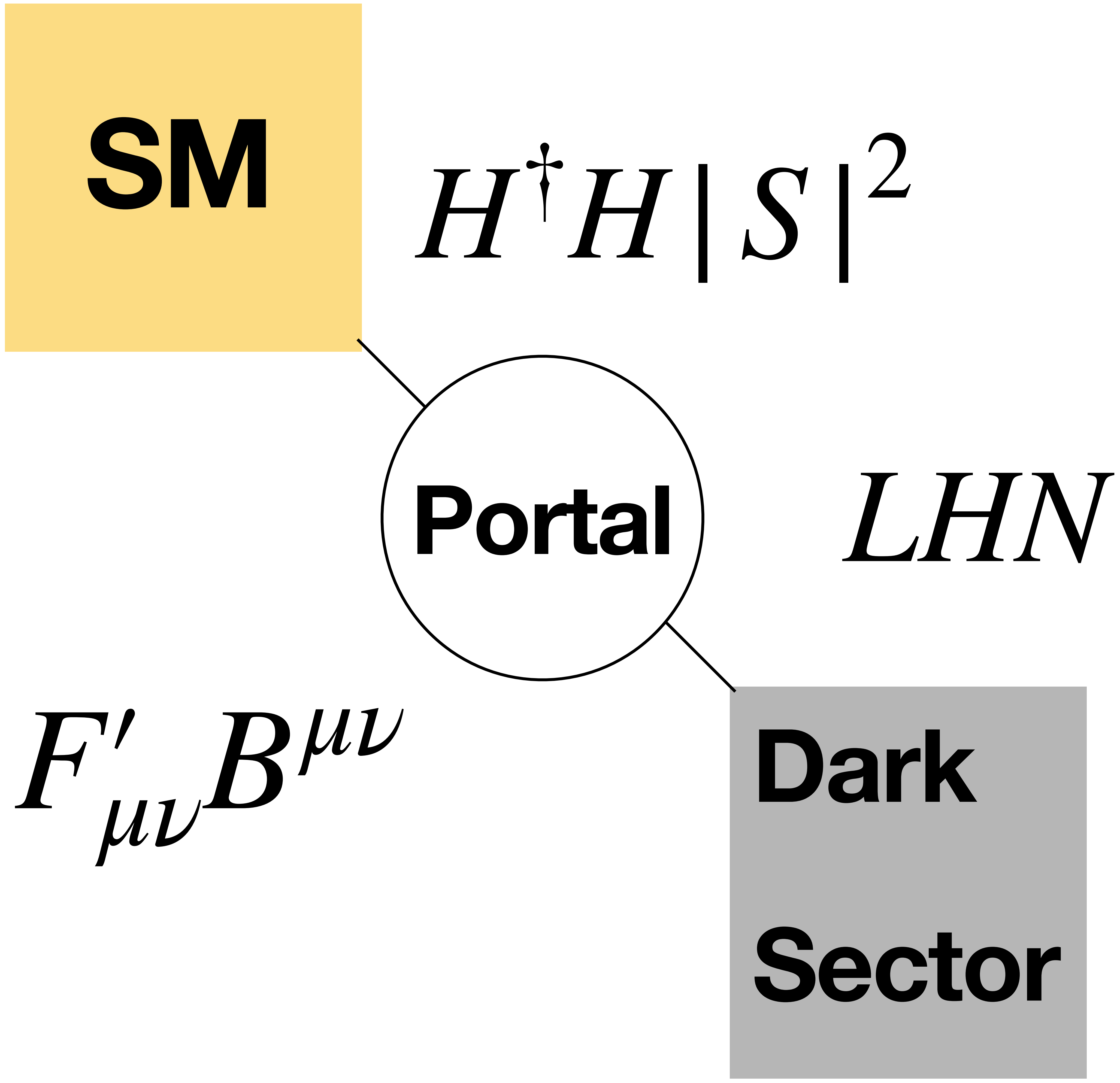
Dark Sector 101

- 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



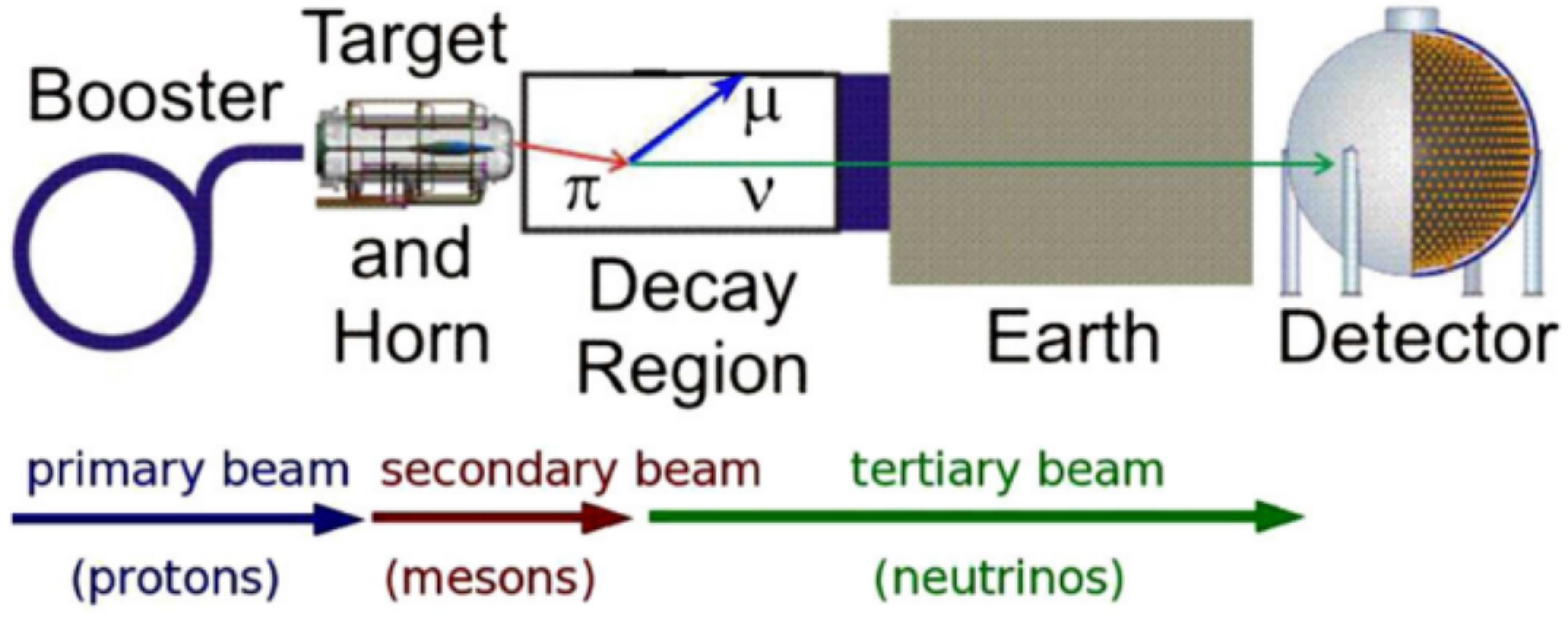
Long-lived particles

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

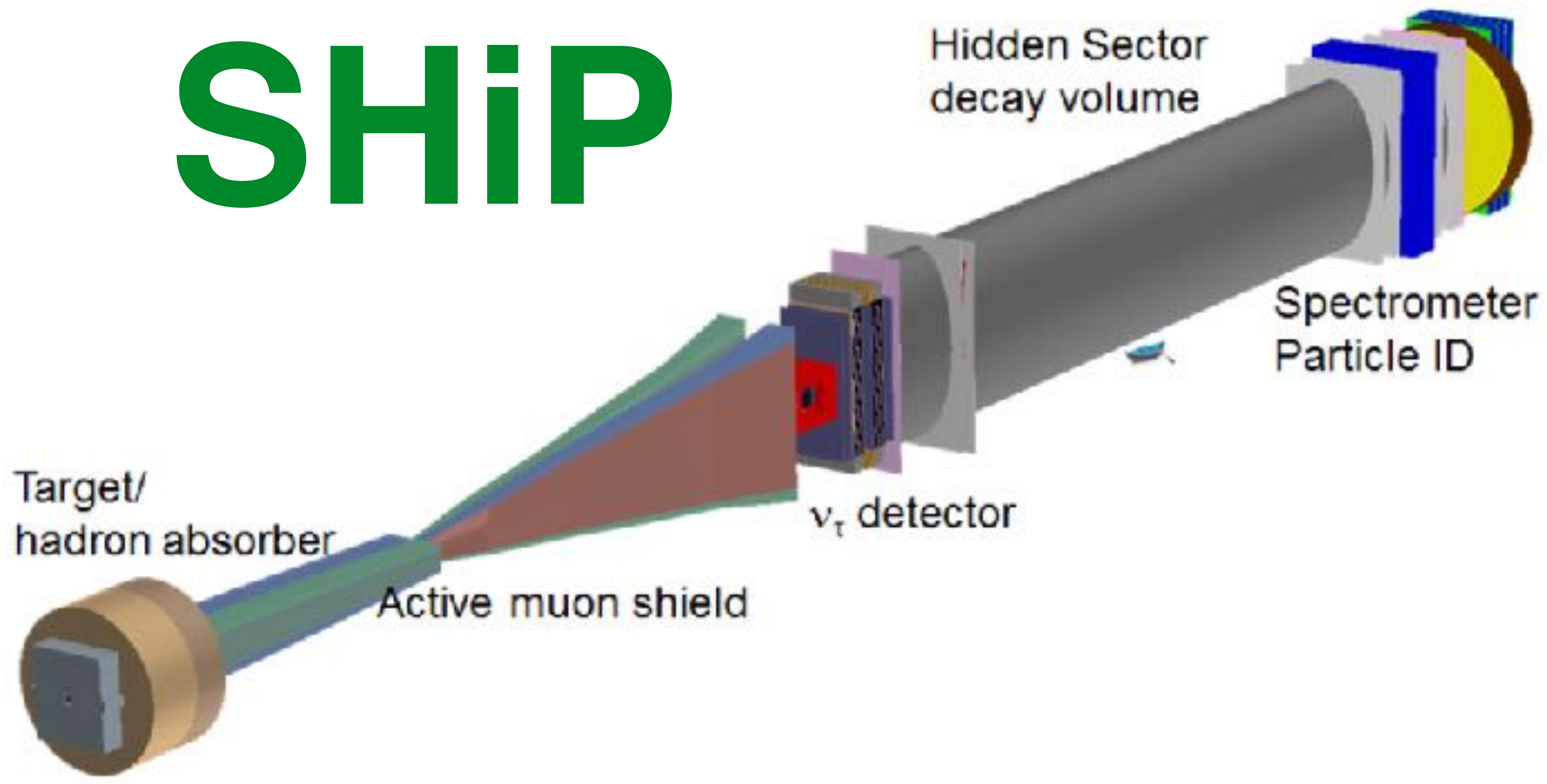
- Dark sector particles can decay within the dark sector.
- But… lightest dark sector particles should be “dark stable”.
- If dominant decay modes are to SM particles then the generic consequence is that the particle will be long-lived.

Active program searching for long live particles

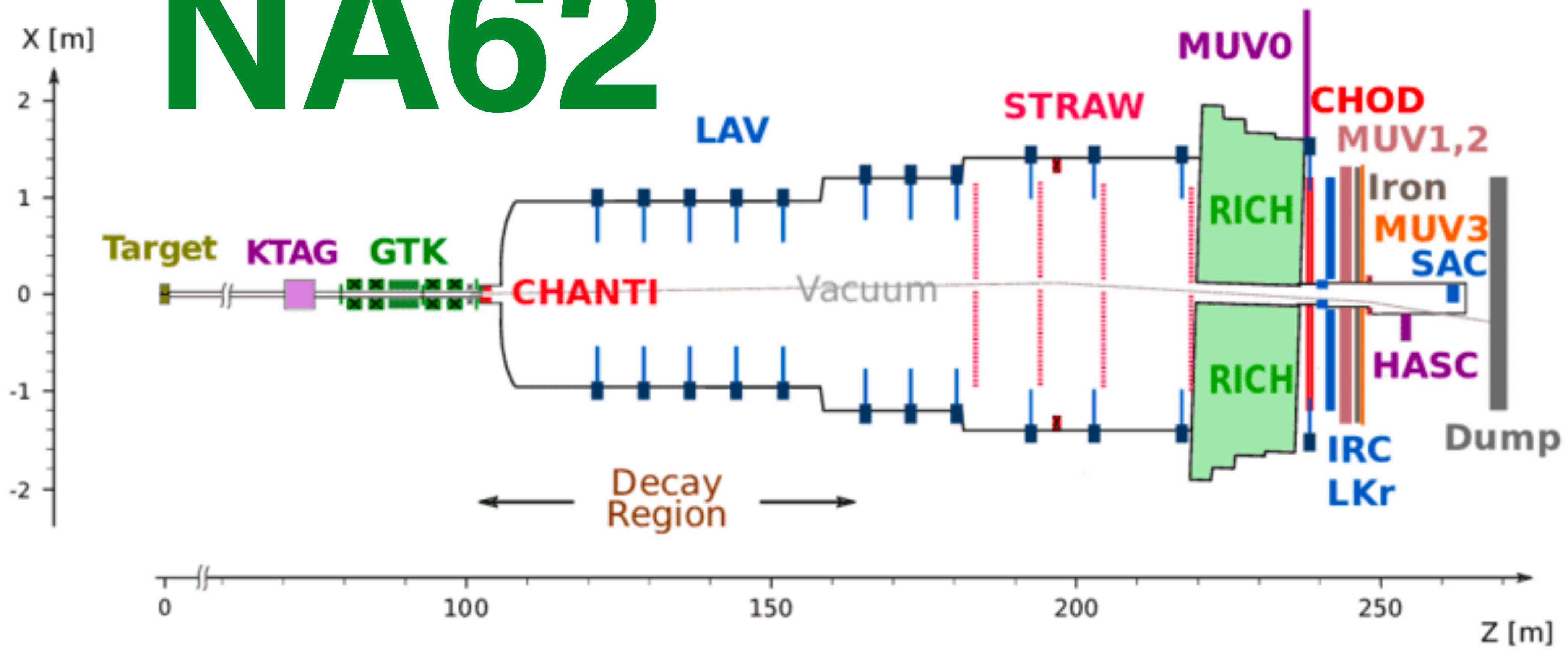
MiniBooNE



SHiP



NA62



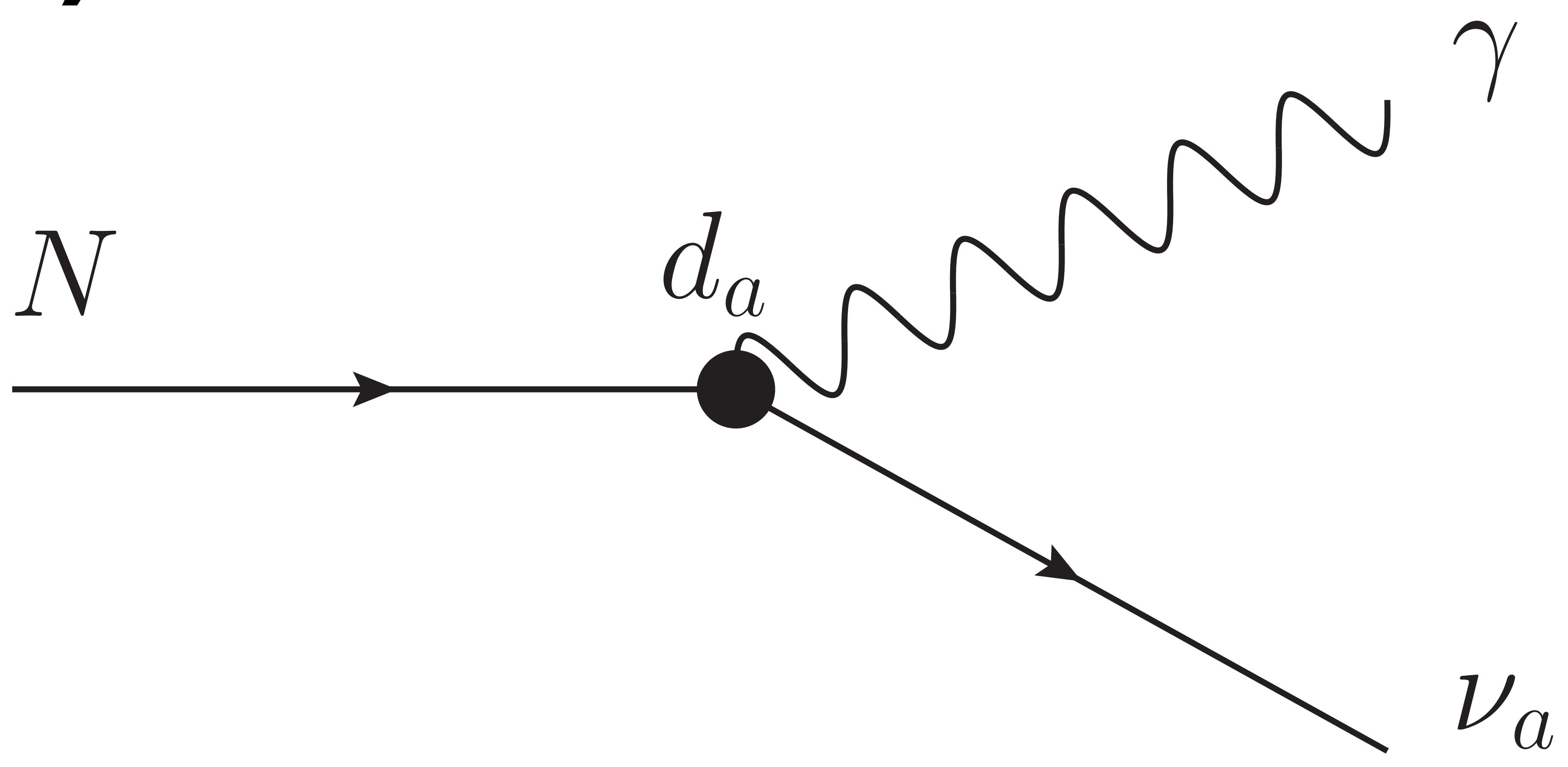
MATHUSLA

DUNE

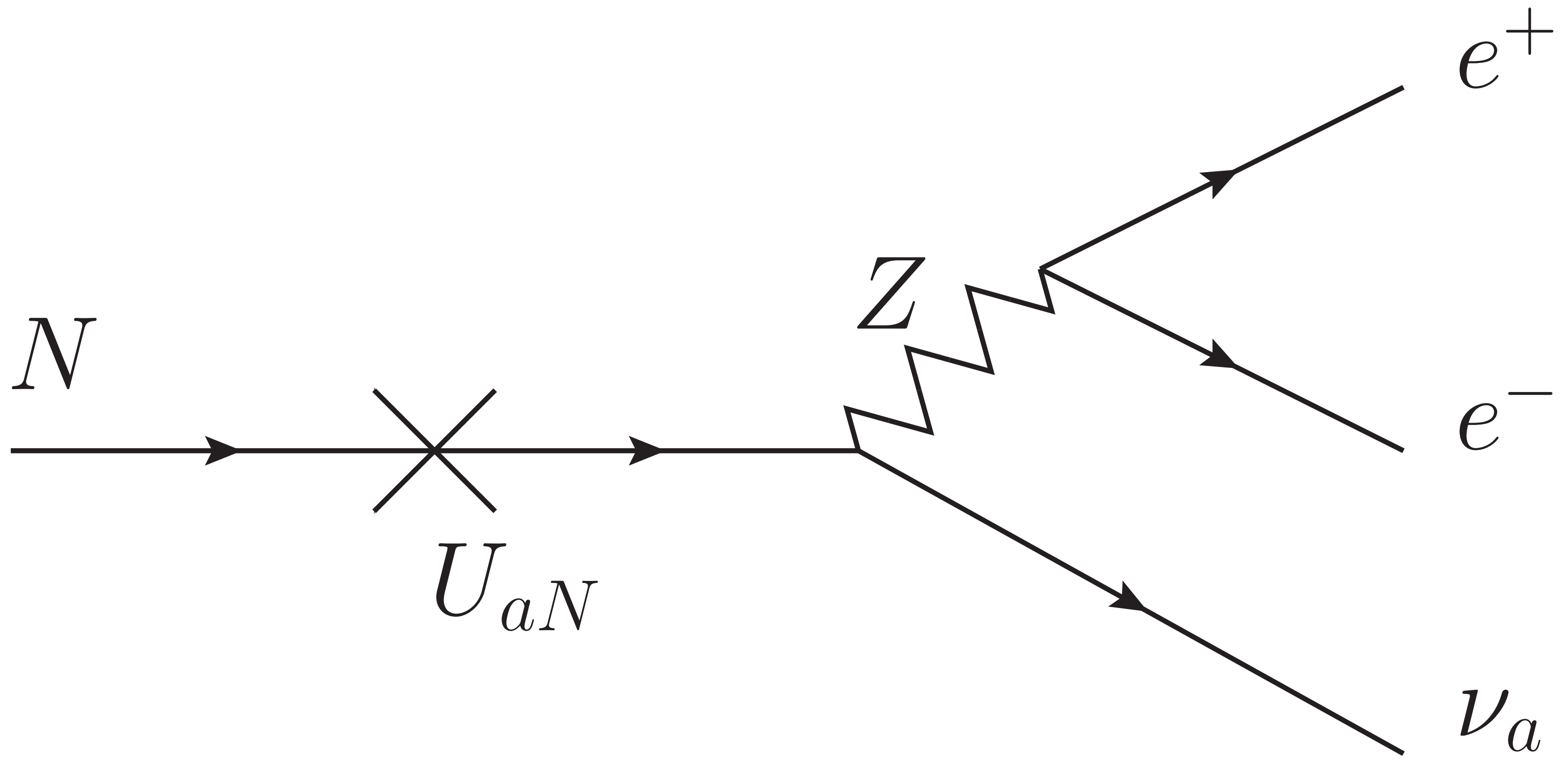
Neutrino Portals

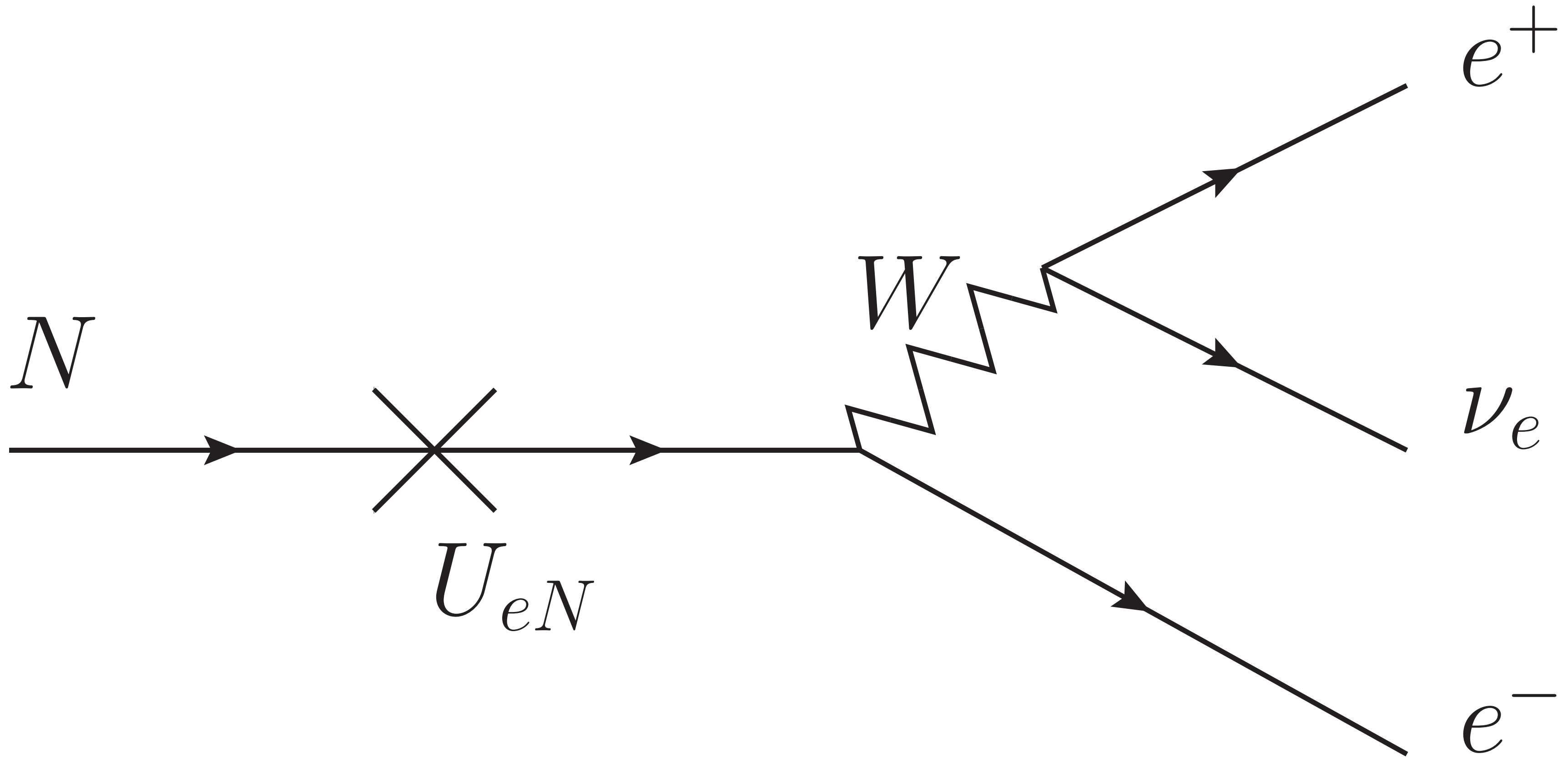
Two neutrino portals

Dipole portal (Dim-5)



Mass-mixing portal (Dim-4)





Decays are the most robust signature of HNLs for ***both*** portals

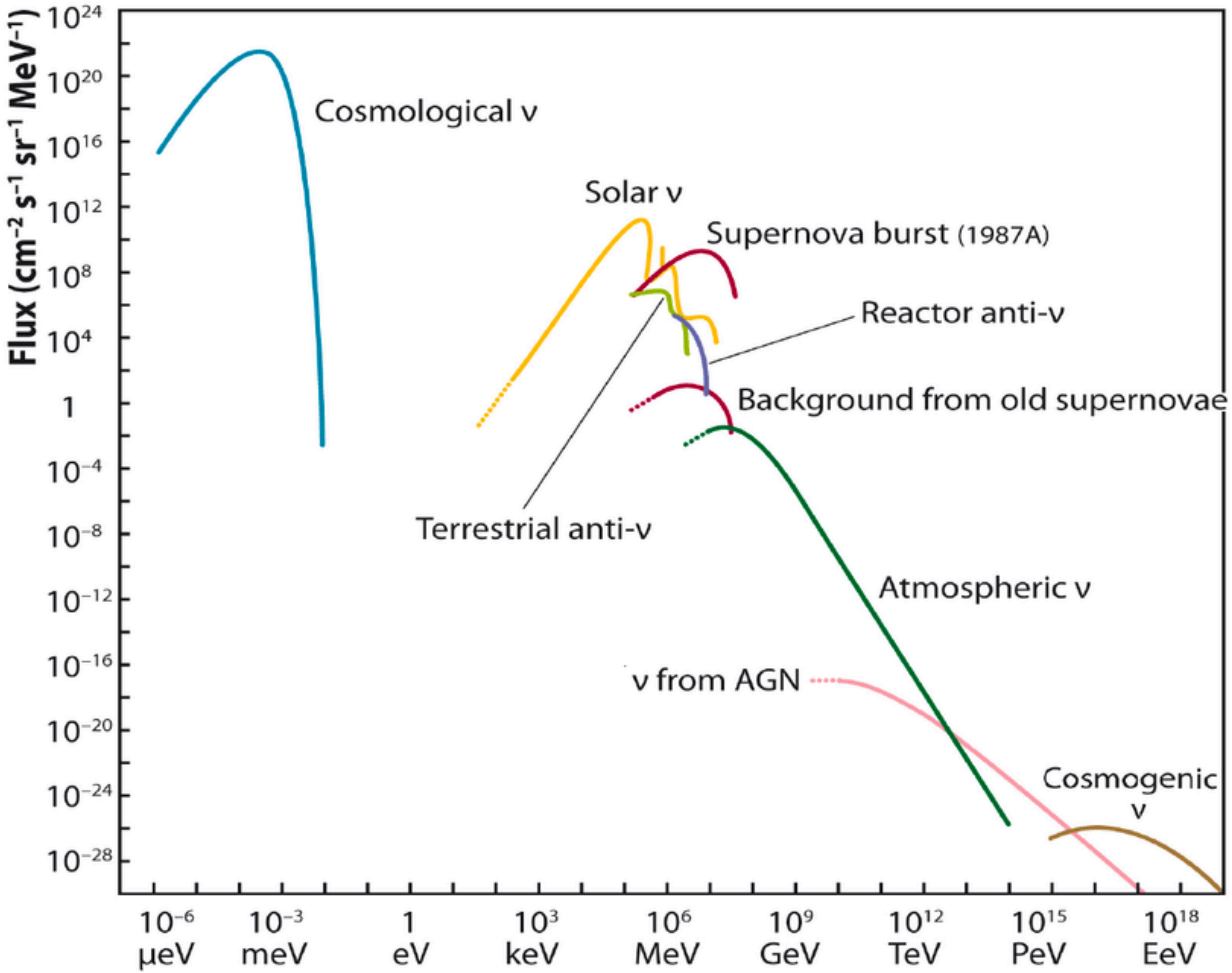
But…

Decay lengths can be very long

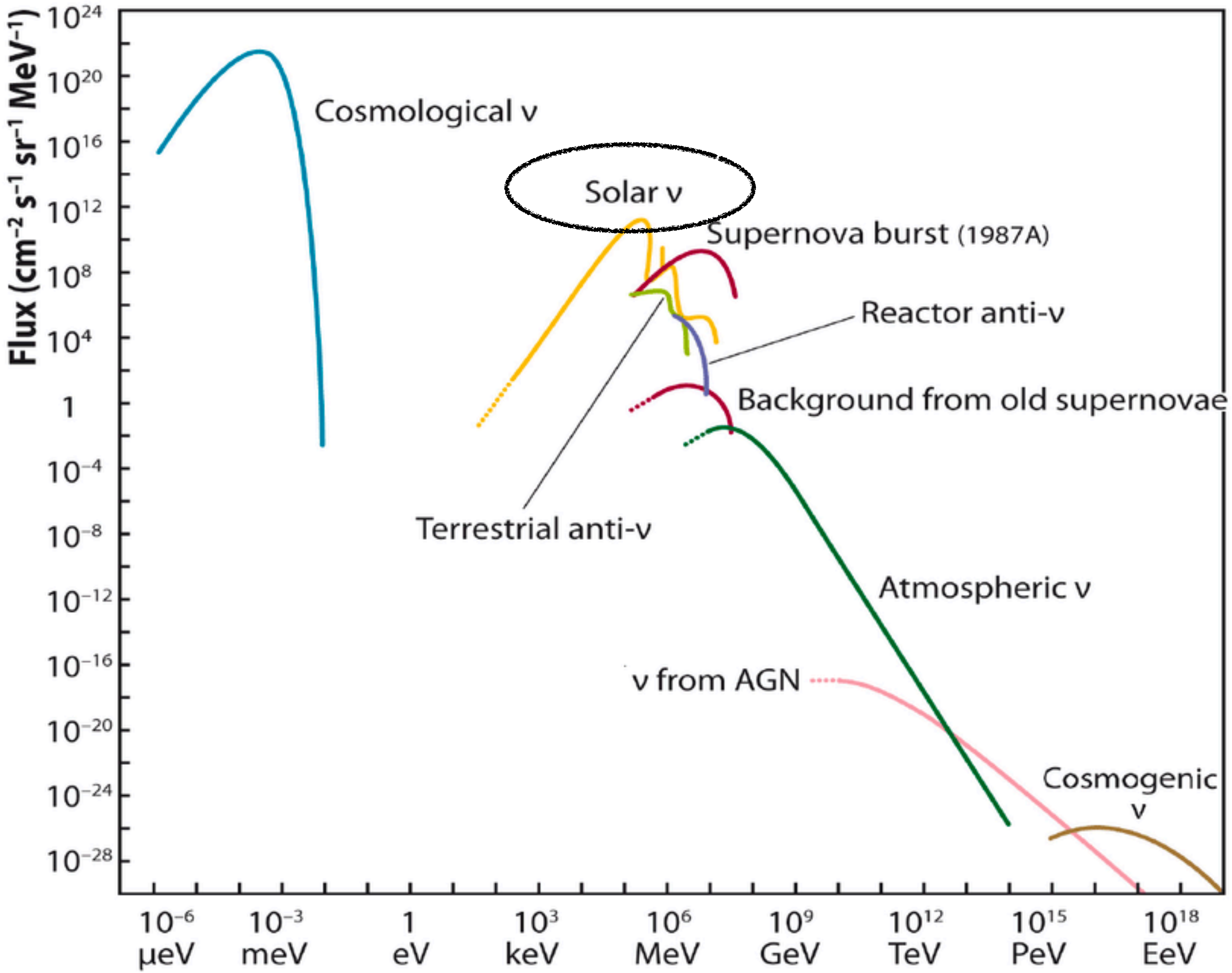
$$L_{\rm dec} \sim \frac{1}{d^2 m_N^4}$$

$$L_{\rm dec} \sim \frac{1}{m_N^6 U_{aN}^4}$$

Solar Neutrinos

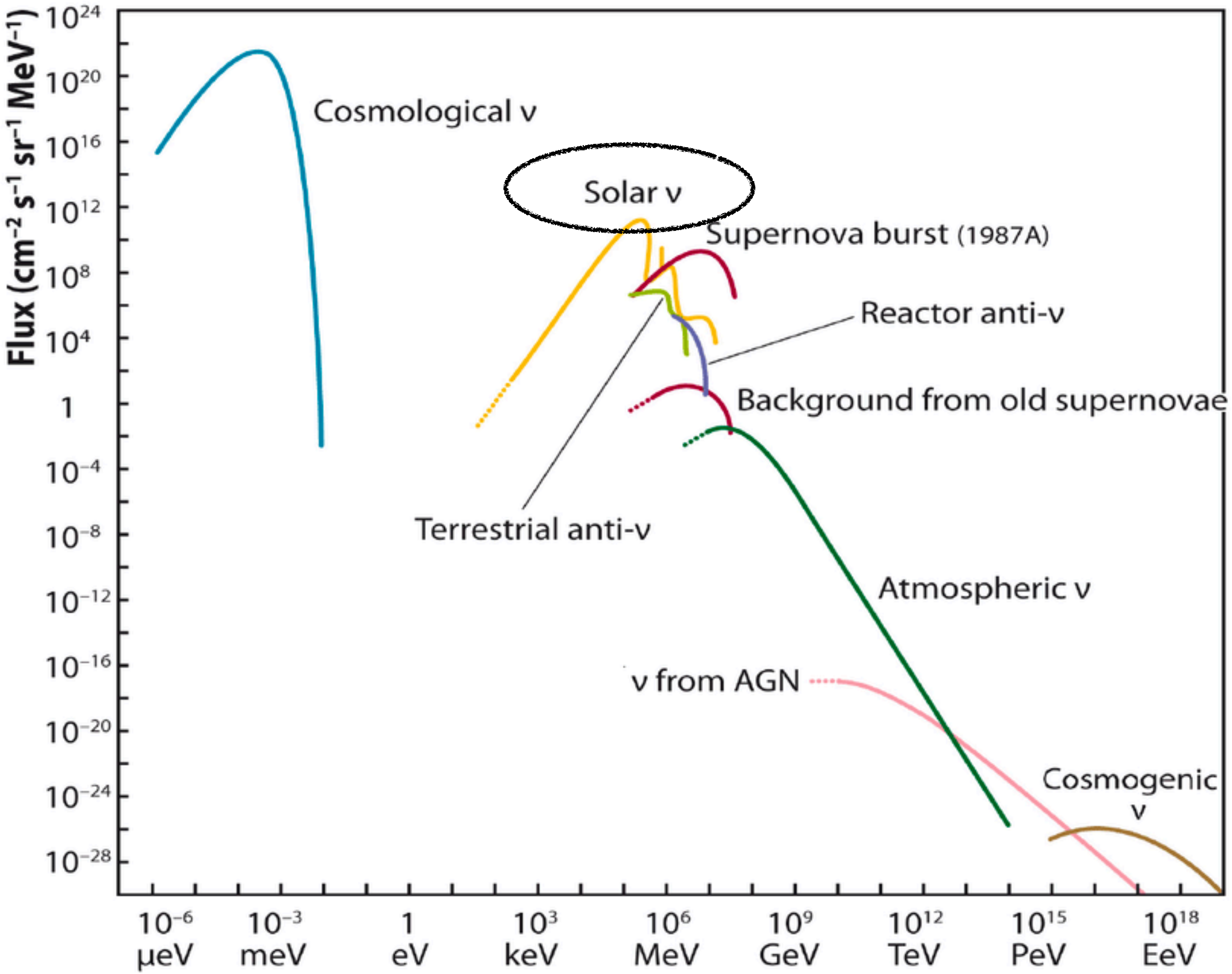


Solar Neutrinos



Solar Neutrinos

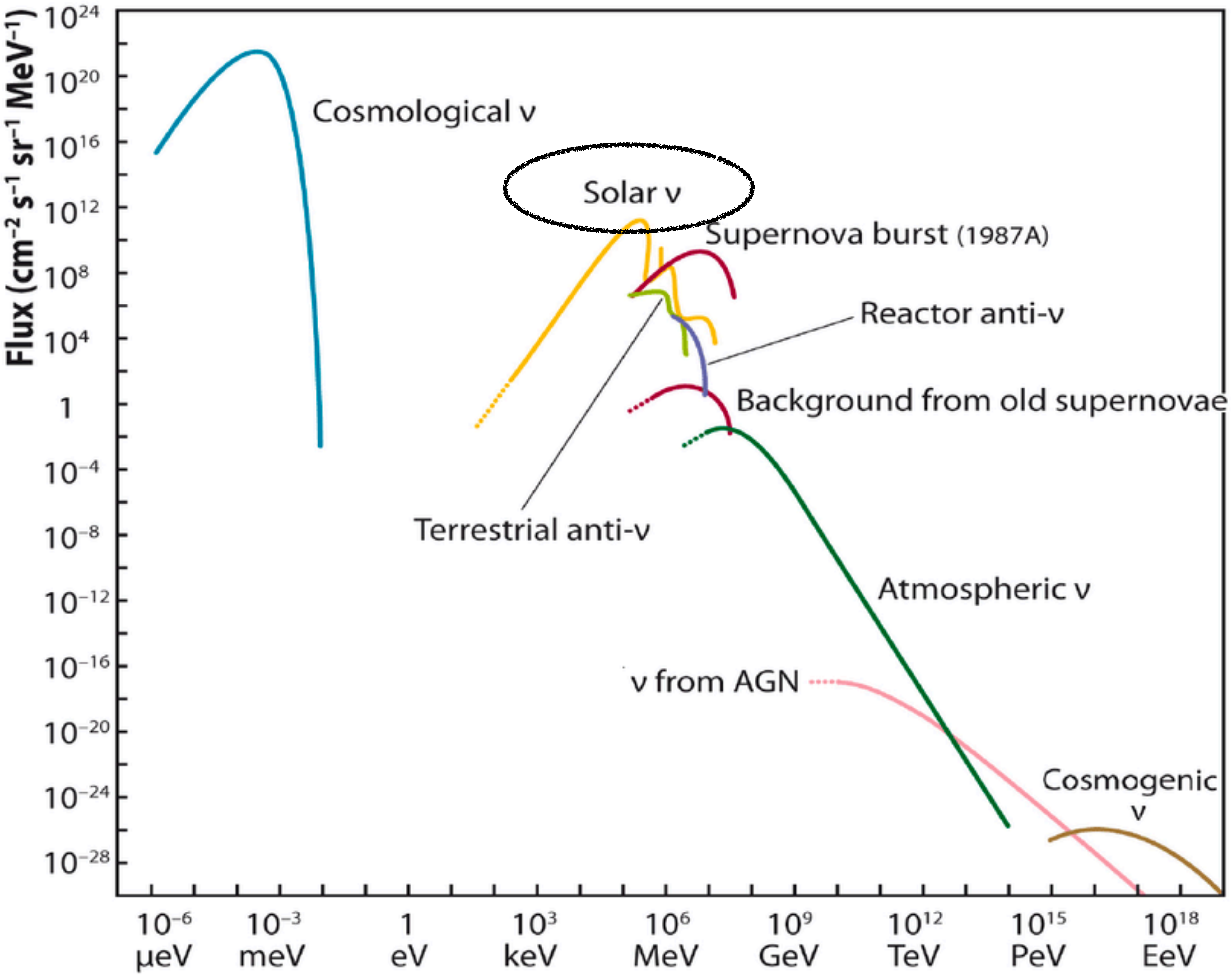
Clearly a resource



Solar Neutrinos

Clearly a resource

What can we do with them?

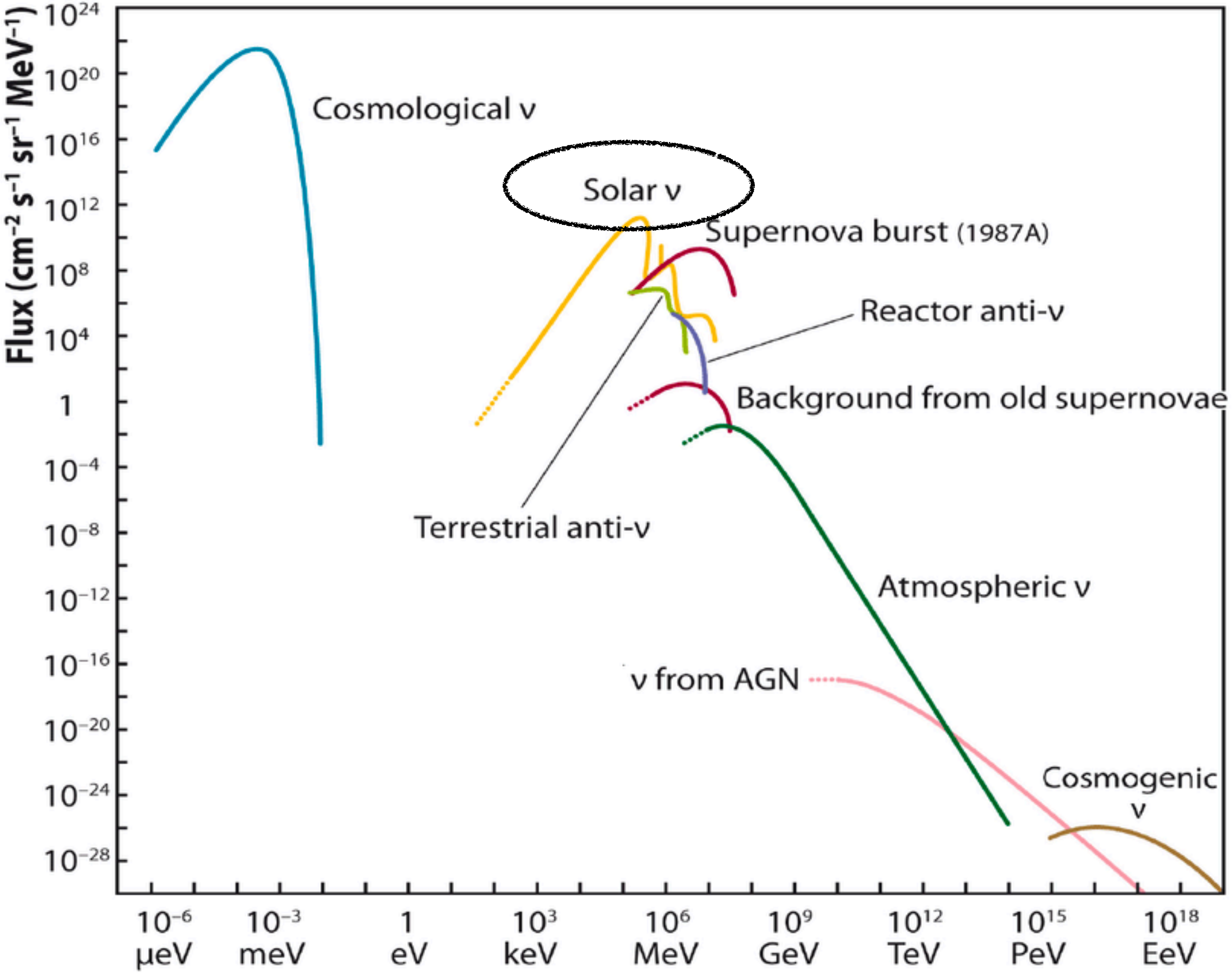


Solar Neutrinos

Clearly a resource

What can we do with them?

$$E_\nu \lesssim 20\ \mathrm{MeV}$$



Solar Neutrinos

Clearly a resource

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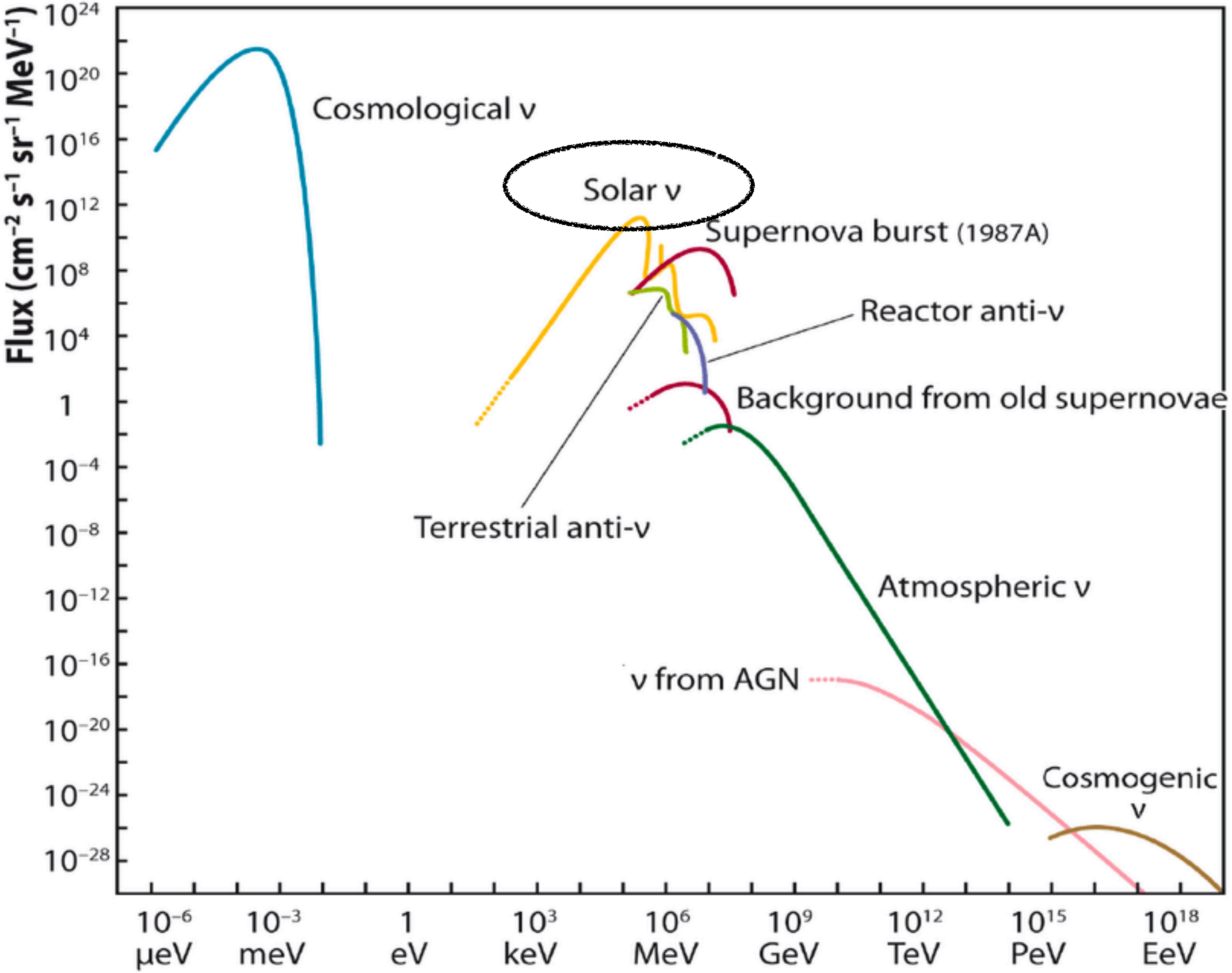
Sufficient for low-mass HNL searches



Solar Neutrinos

Clearly a resource

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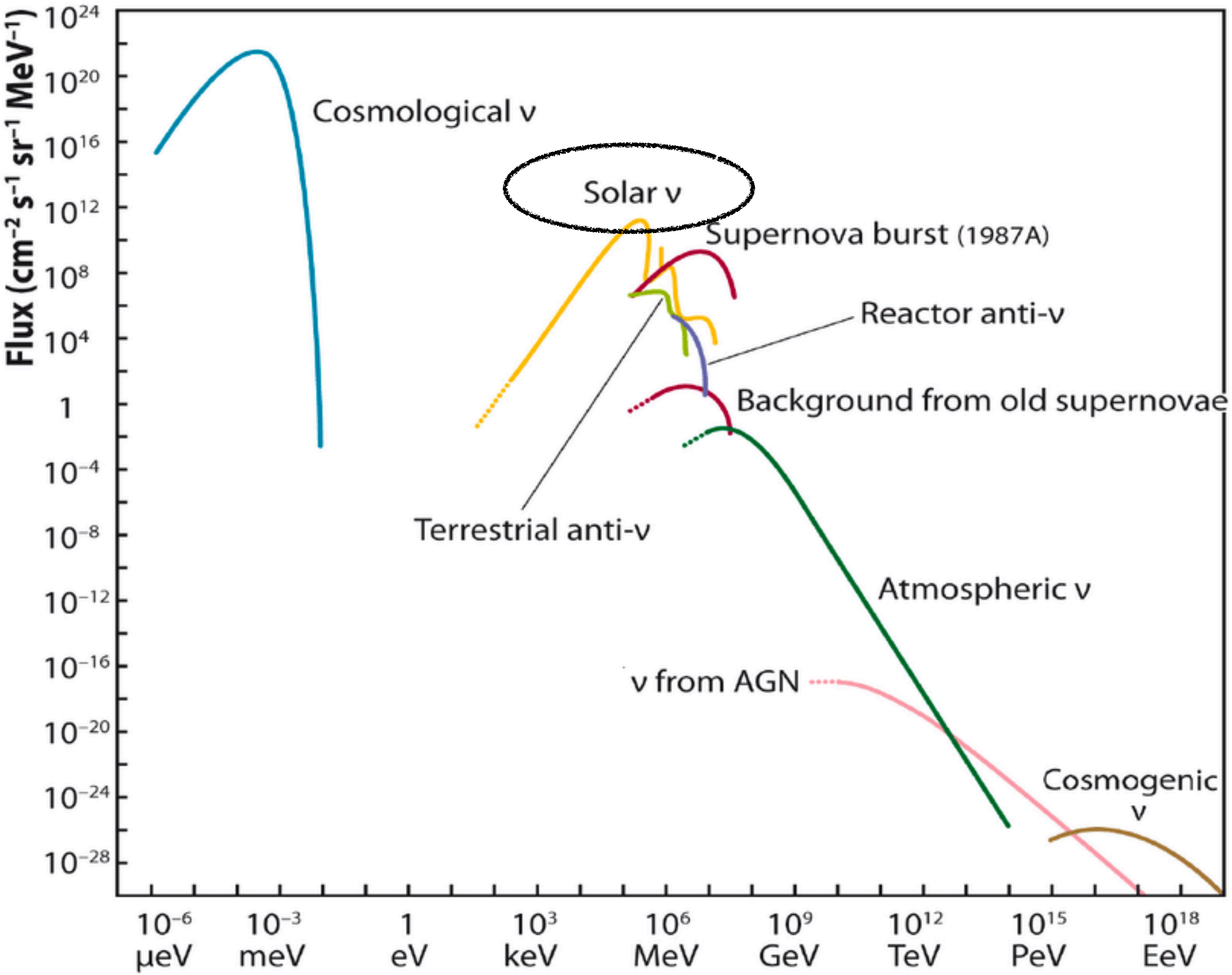
Sufficient for low-mass HNL searches

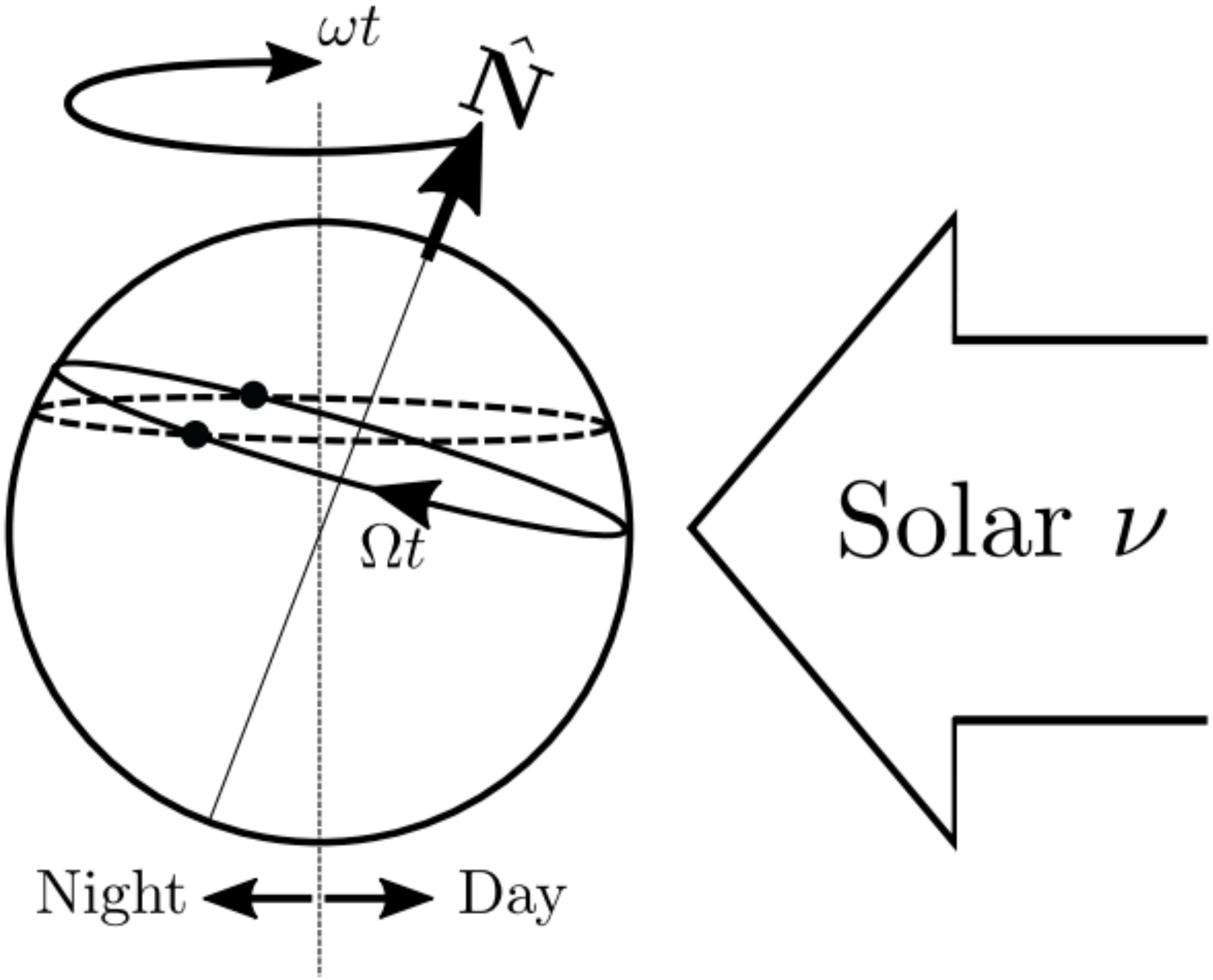
$$m_N \lesssim 20 \text{ MeV}$$



Solar neutrinos and upscattering inside the Earth

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.



Upscatter + Decay of Solar Neutrinos

Step by step

1. Neutrino upscatters inside the Earth's mantle. Neutrino upscattering cross section on nuclei.

2. HNL travels toward detector. Probability of arrival depends on decay length & decay length depends on energy.

3. HNL decays (or doesn't) inside detector. Also depends on decay length.

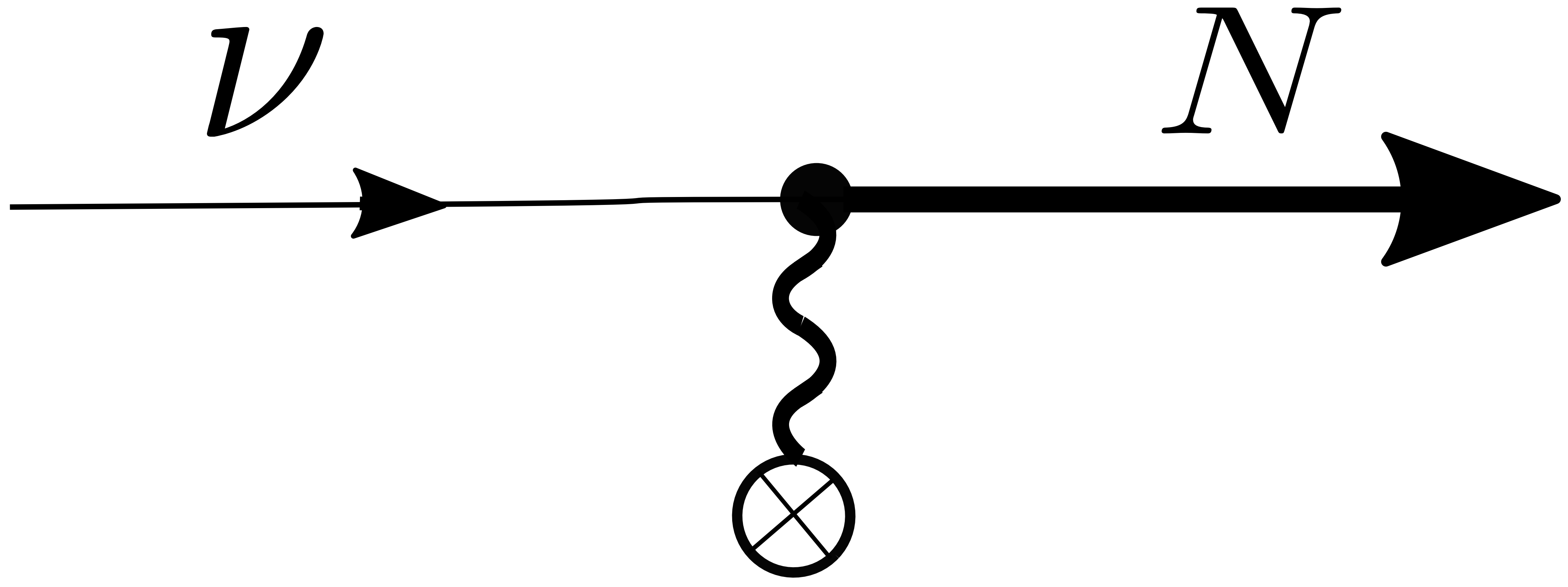
Upscattering on nuclei

- In both models scattering is coherent. Nuclei dominate.

- 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.



$$E_N = E_\nu$$

Arrival probability I: The basics

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- Start with up-scattered flux from tiny volume element.

$$\mathrm{d}\Phi_N = \mathrm{d}z\ \Phi_\nu(E)\sigma n_A$$

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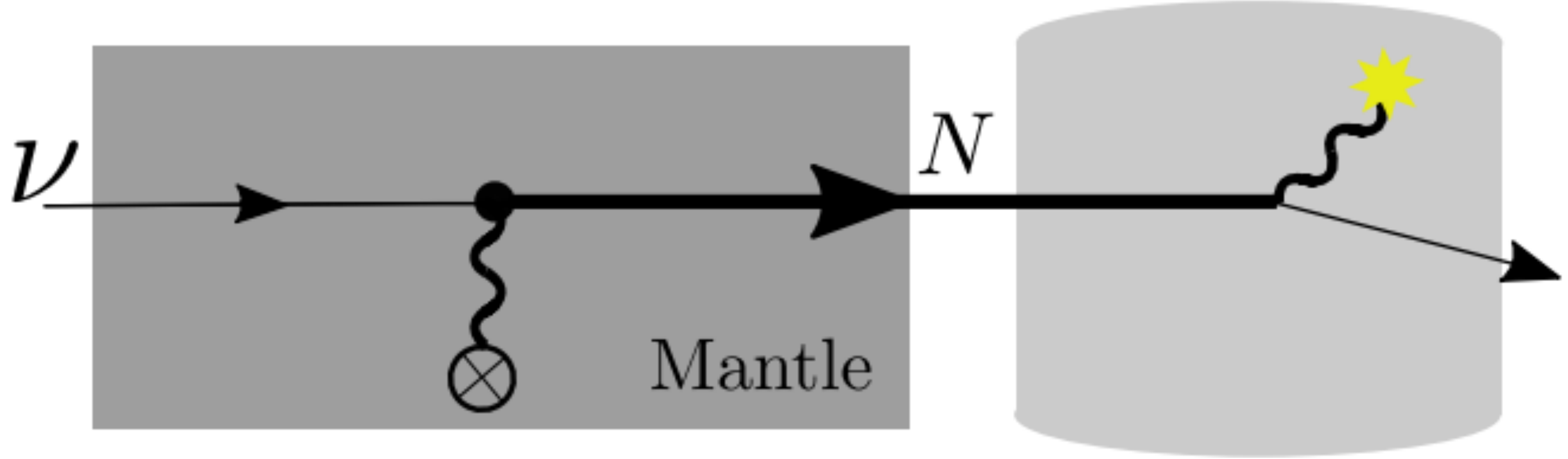
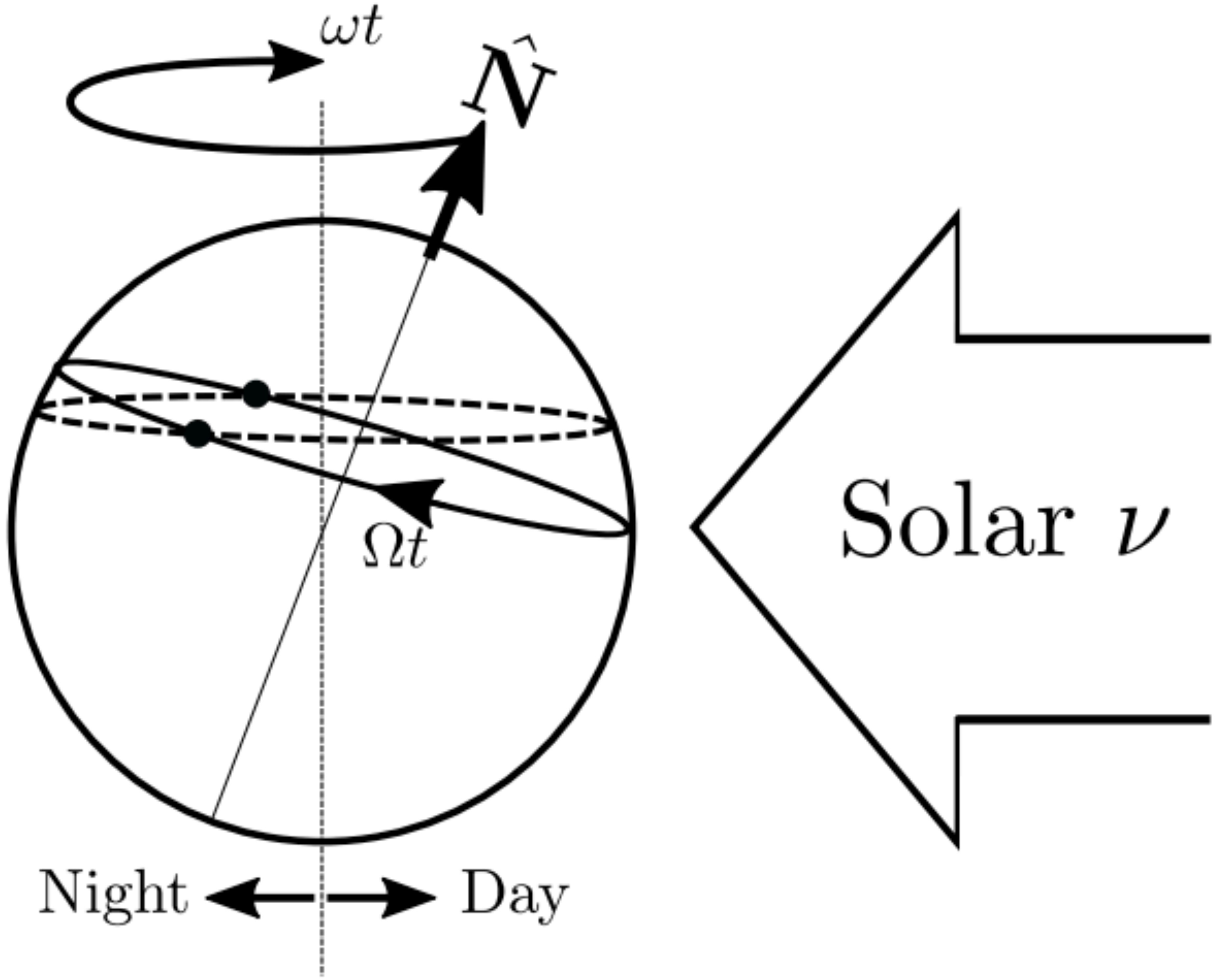
- Integrate over path through Earth.

$$\int_{\mathrm{LOS}} \mathrm{d}z\ \ \mathrm{e}^{-z/\lambda(E)} \frac{\mathrm{d}\Phi_N}{\mathrm{d}z}$$

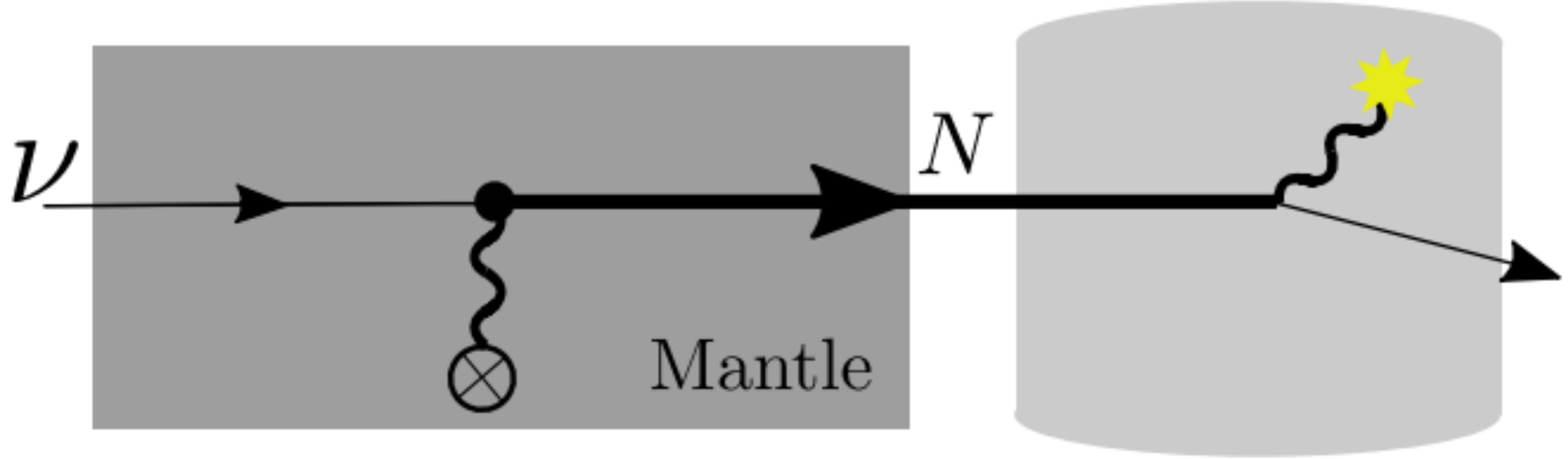
Dipole Portal





Dipole Portal

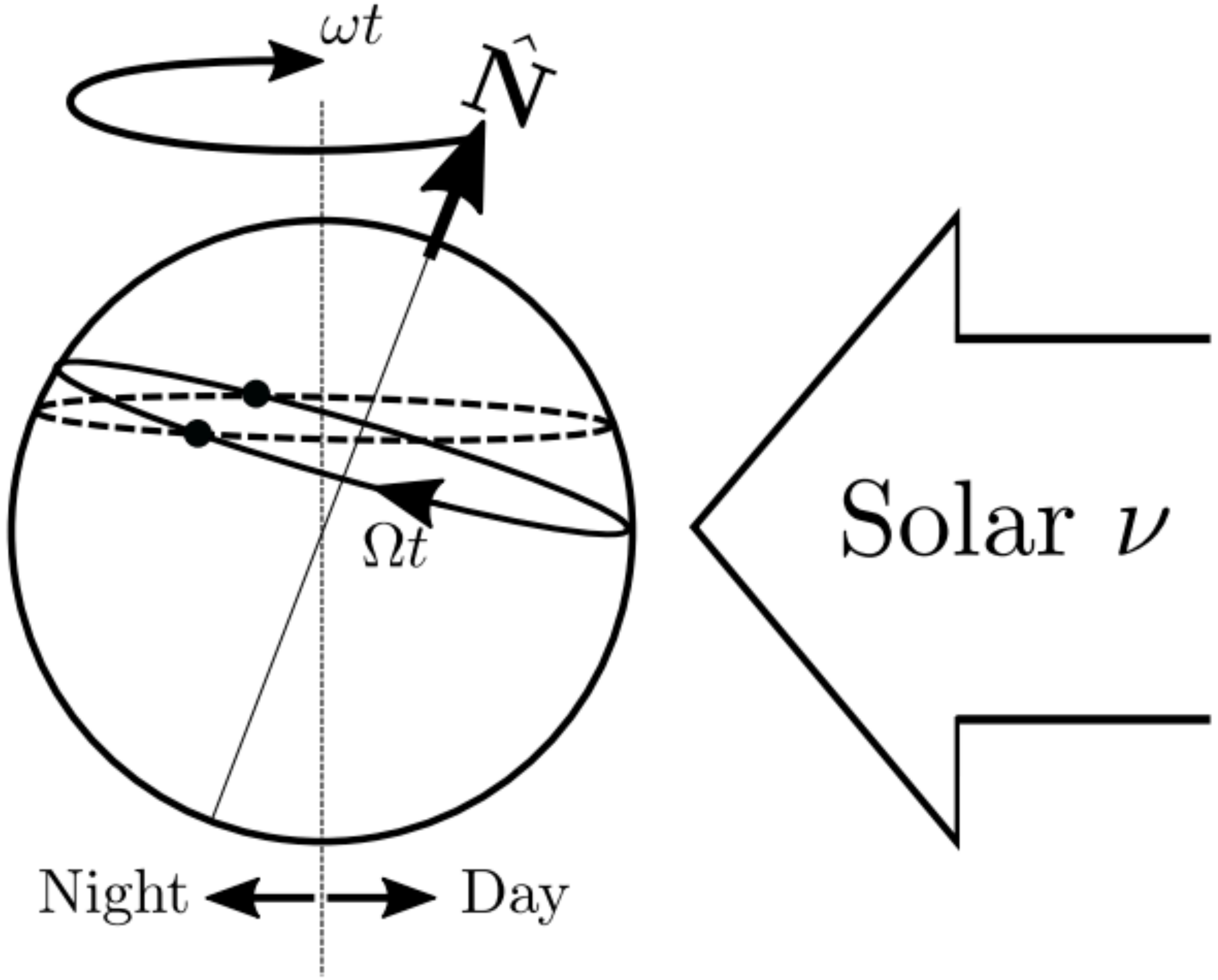
Production in high-Z, high density mantle



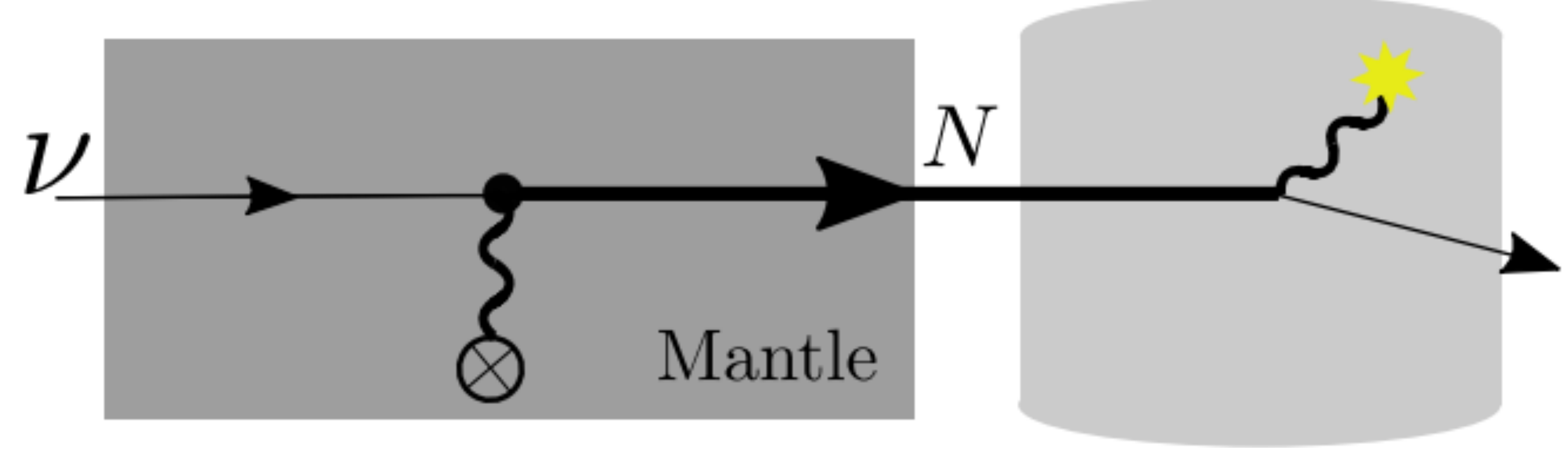
$$\Phi_N \sim \Phi_{\nu_\oplus} n_A^\perp \times \sigma_{\nu\to N}$$

$$\sigma_{\nu\to N} \approx 16\alpha Z^2 d^2 \log(2E_\nu/m_N)$$

Mostly forward!



Dipole Portal



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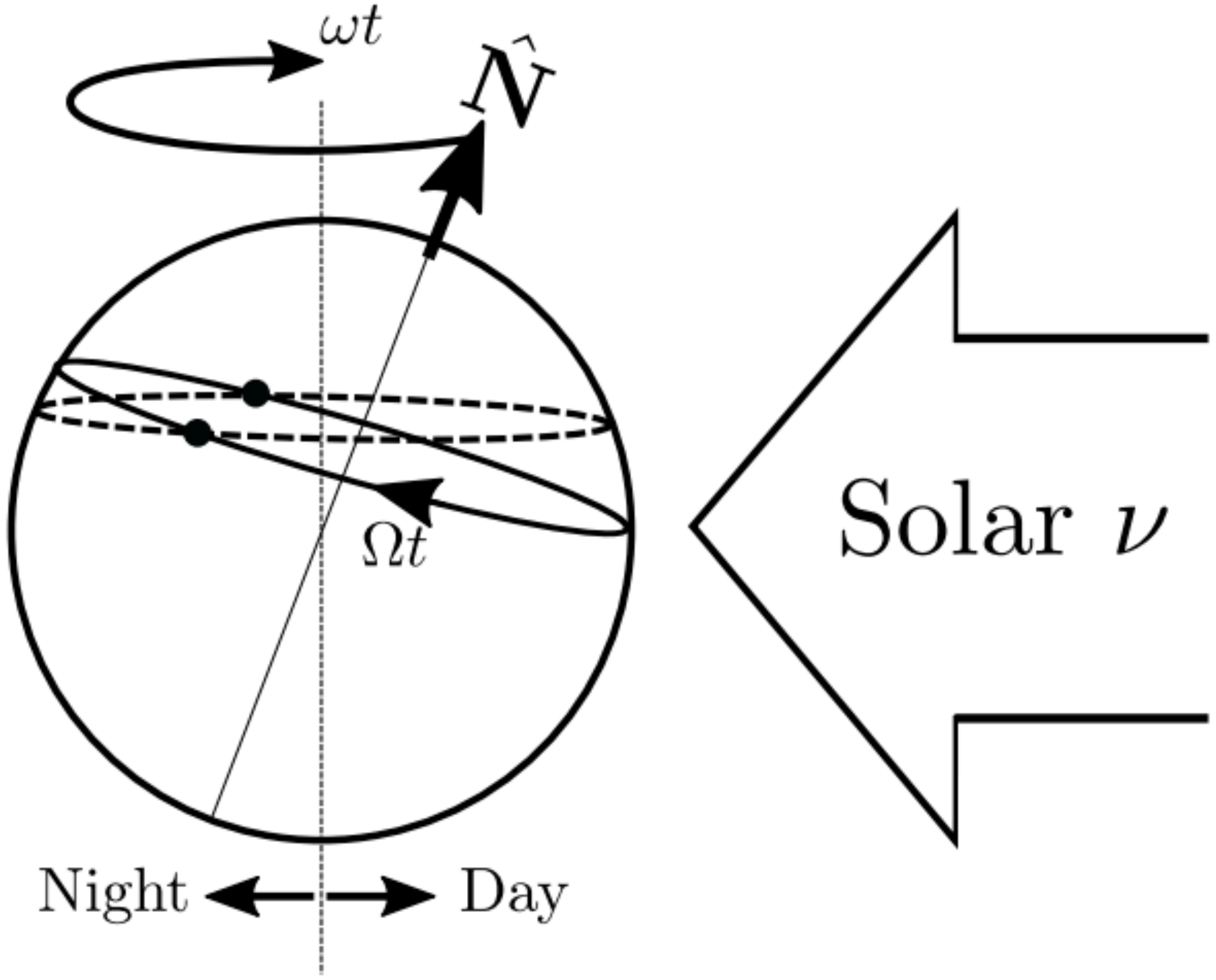
<u>**Mostly forward!**</u>

Column density scales with decay length

$$\text{Rate} \sim A_{\text{det}}(1 - e^{-L_{\text{det}}/L_{\text{dec}}}) \times \int_0^{L_{\text{slab}}} \mathrm{d}z \;\; \mathrm{e}^{-z/L_{\text{dec}}}$$

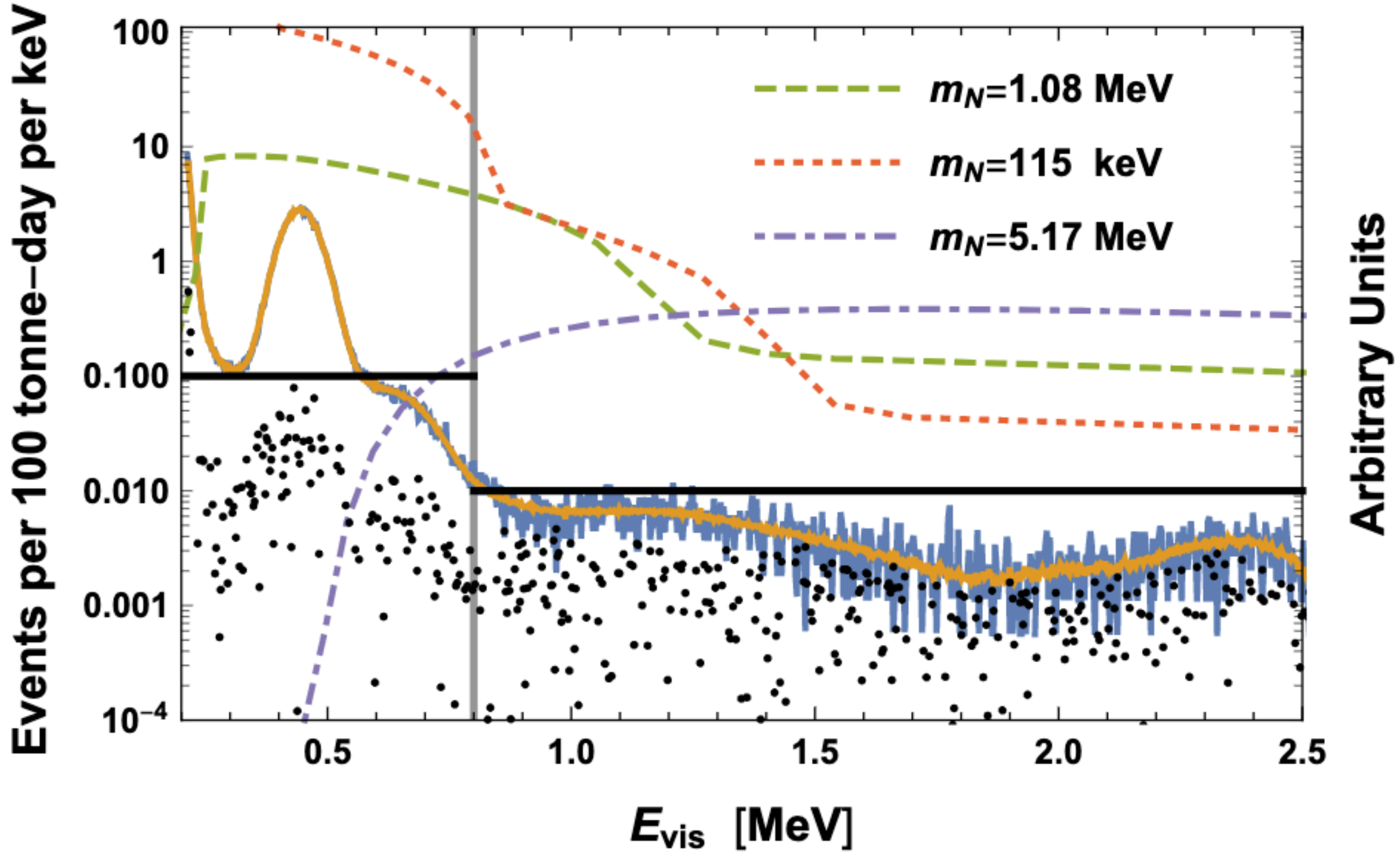
$$\sim \frac{V_{\text{det}}}{L_{\text{dec}}} \times L_{\text{dec}}(1 - \mathrm{e}^{-L_{\text{slab}}/L_{\text{dec}}})$$

$$\sim V_{\text{det}} \times (1 - \mathrm{e}^{-L_{\text{slab}}/L_{\text{dec}}})$$



Dipole Portal

$$\langle \text{Rate} \rangle_{1\text{y}} \sim V_{\text{det}} \overline{n}_A \sigma_{\nu \to N} \Phi_{\nu_\odot} \times I(\zeta)$$



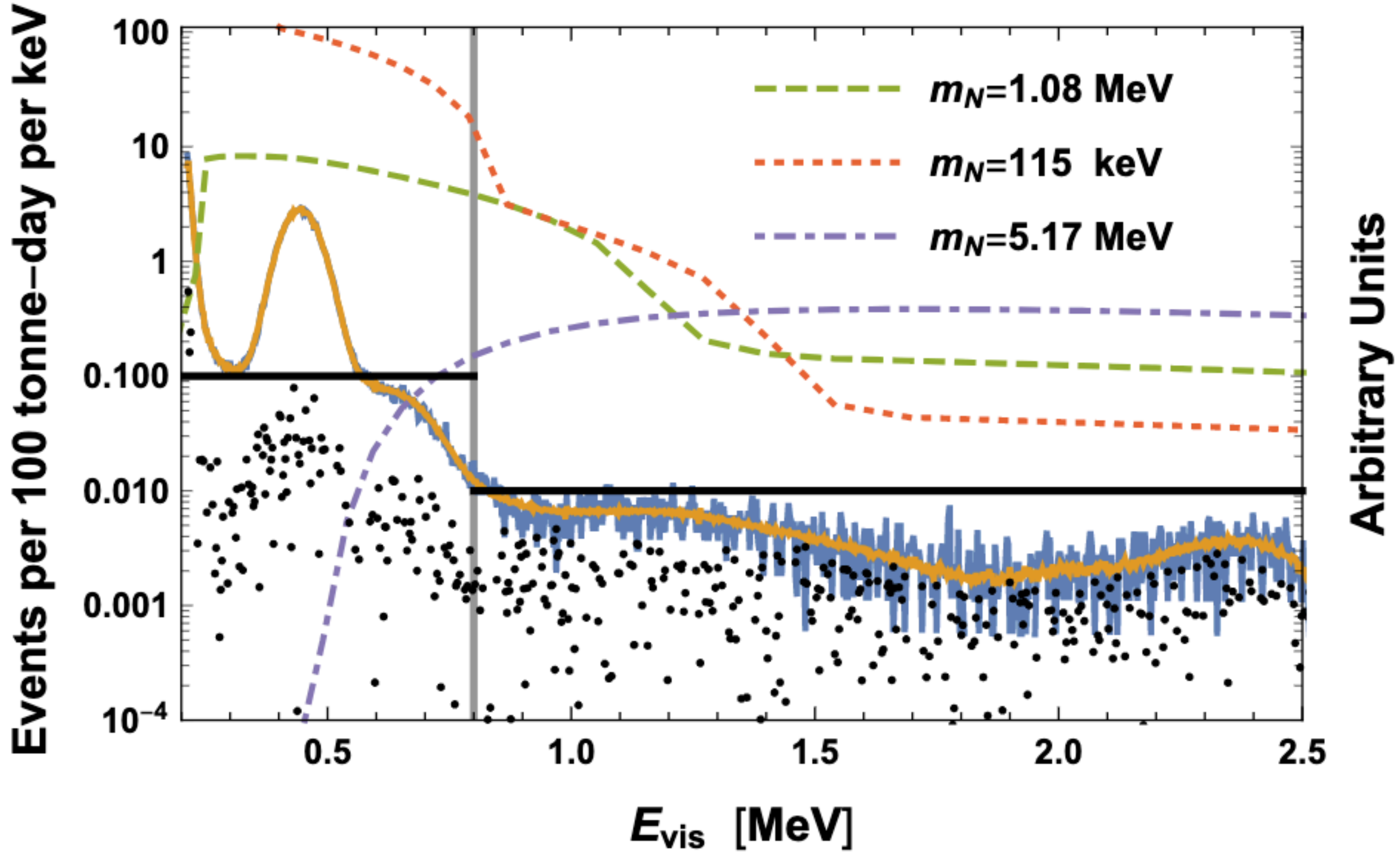
Dipole Portal

$$\langle \text{Rate} \rangle_{1y} \sim V_{\text{det}} \bar{n}_A \sigma_{\nu \to N} \Phi_{\nu_\odot} \times I(\zeta)$$

- 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

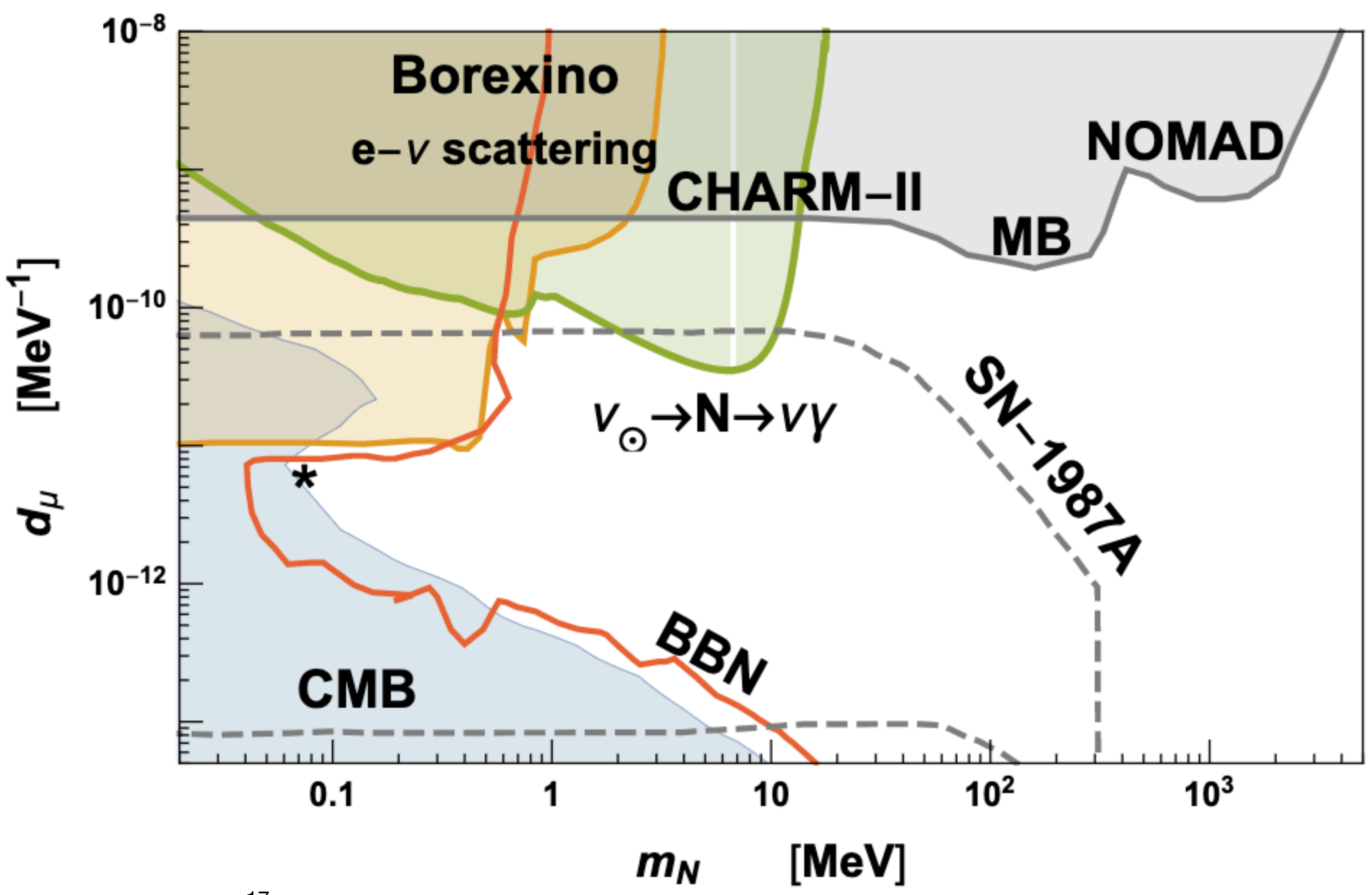
$$I(\zeta) = \begin{cases} \frac{1}{2} & L_{\rm dec} \ll R_\oplus \\ \frac{\langle L_{\rm slab} \rangle_{\rm 1y}}{L_{\rm dec}} & L_{\rm dec} \gg R_\oplus \end{cases}$$

Exclusions obtained with year-averaged rate only.

Could use spectral shape.

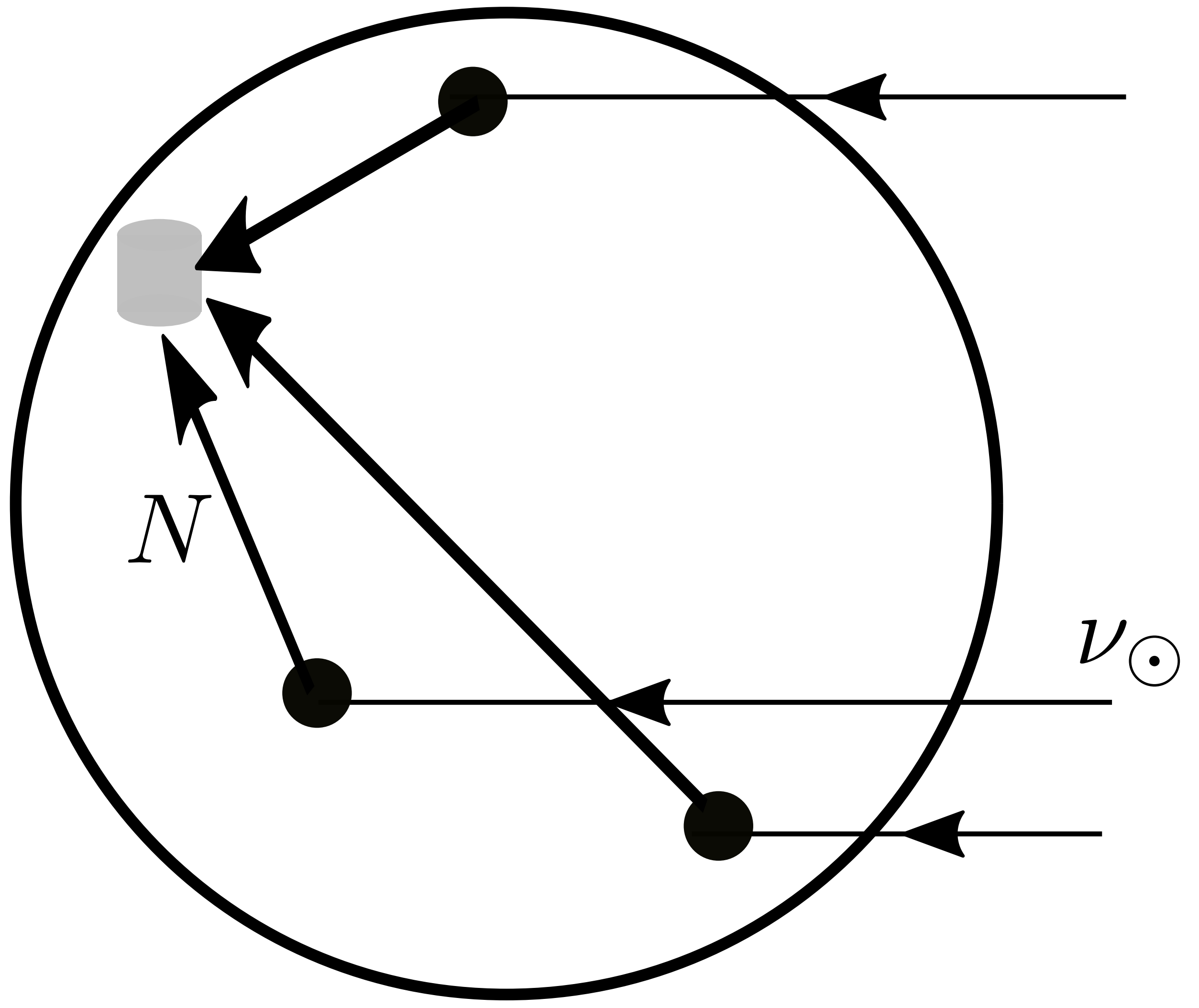
Day-night asymmetry.

Muon-flavour only

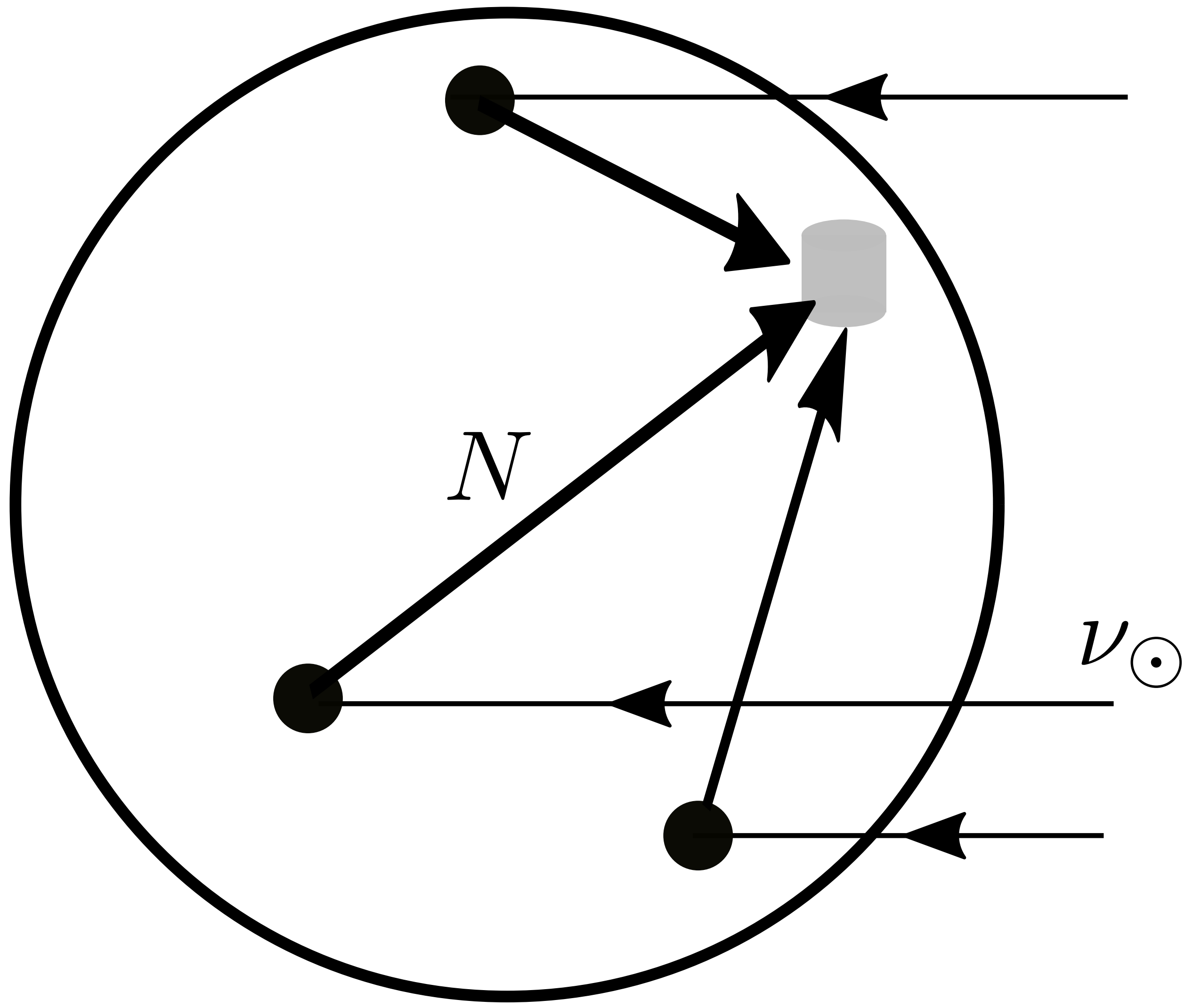


Mass-Mixing Portal

Night

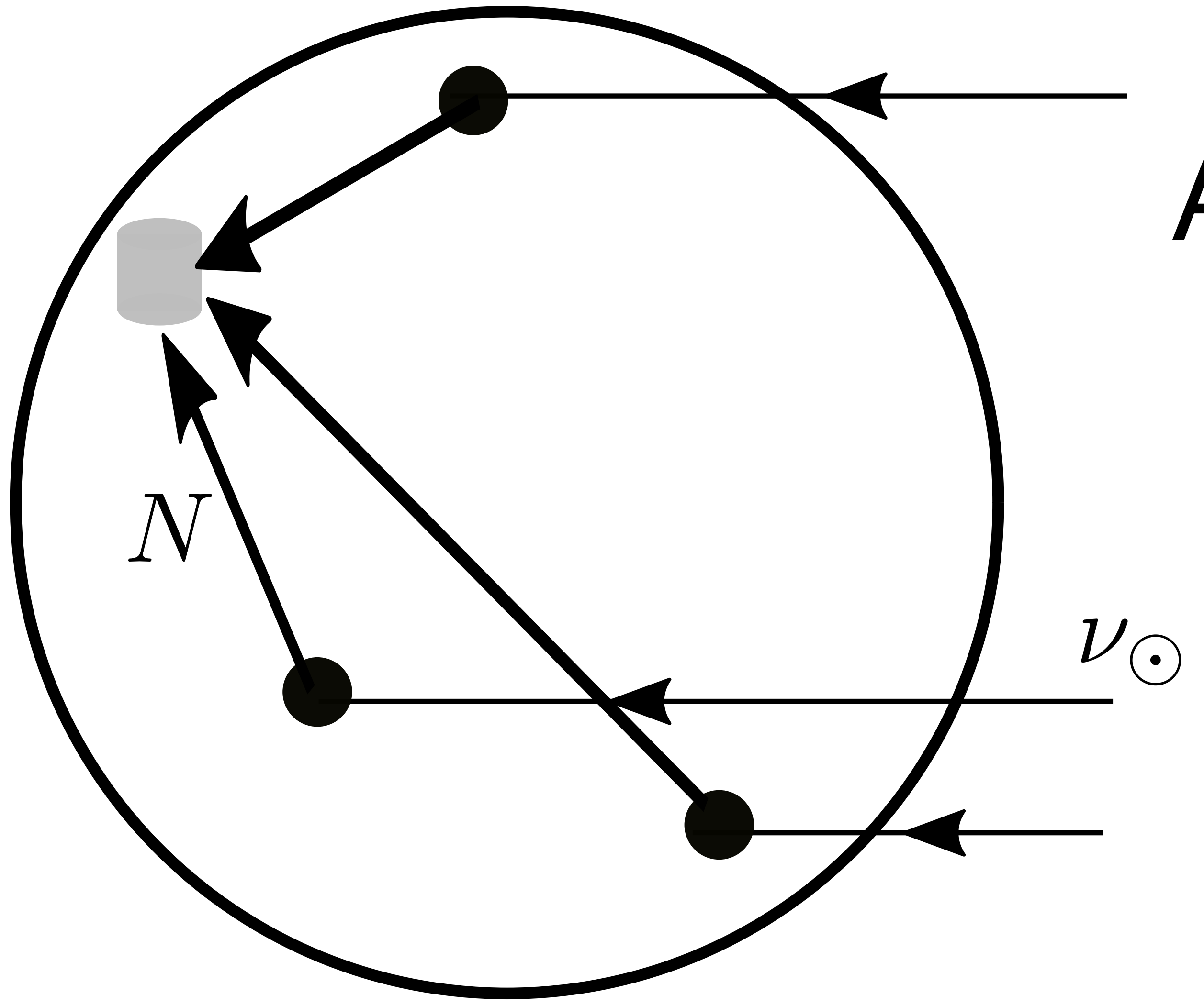


Day



Mass-Mixing Portal

Night

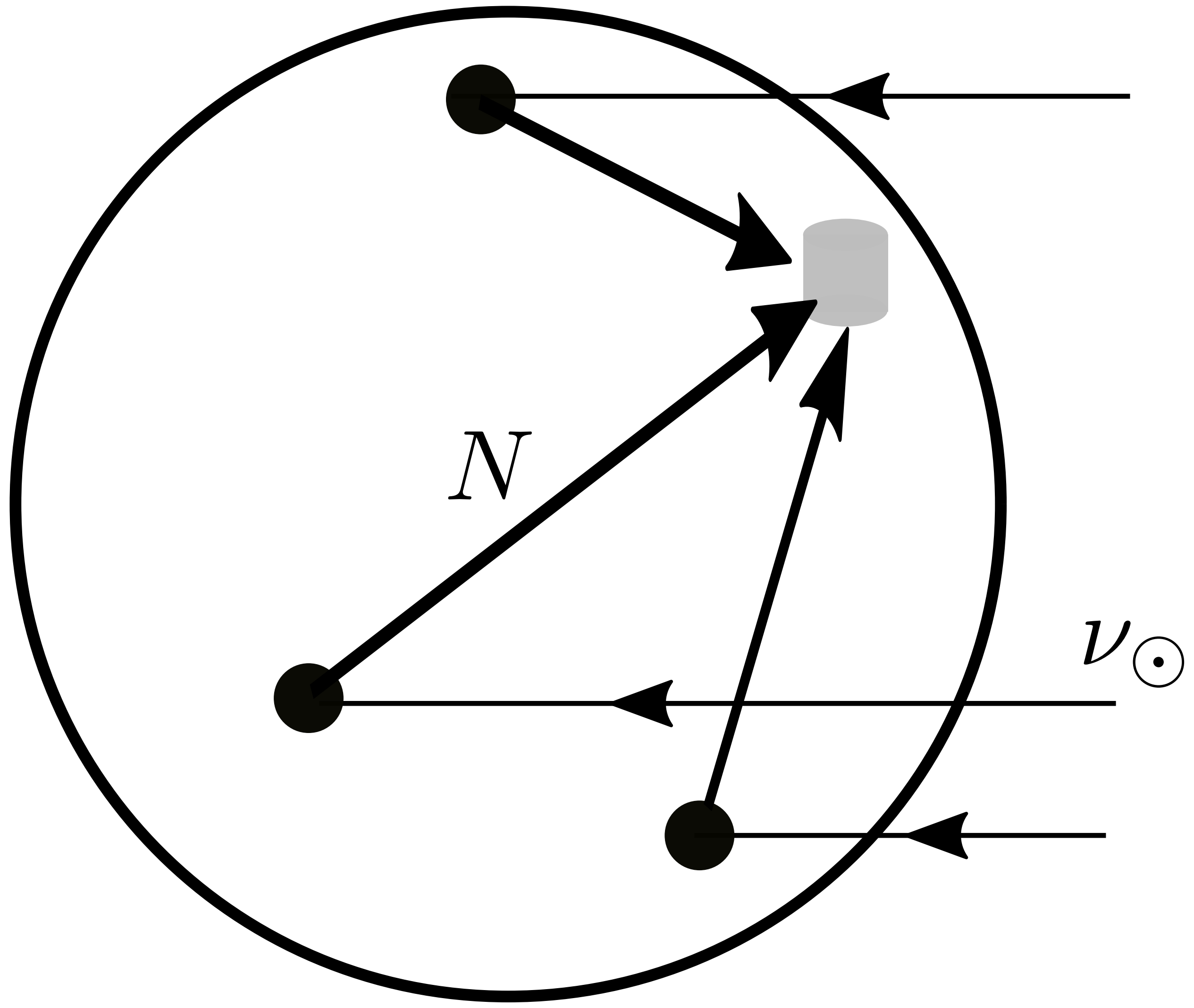


Approximate upscattering cross section as isotropic

$$\text{Rate} \sim A_{\text{det}}(1 - e^{-\ell/\lambda}) \times \int_{\oplus} \mathrm{d}^3x \quad \frac{\mathrm{e}^{-|x-x_0|/\lambda}}{4\pi|x-x_0|^2}$$

$$\sim \frac{V_{\text{det}}}{L_{\text{dec}}} \times \frac{1}{2} R_{\oplus} \quad \text{for} \quad L_{\text{dec}} \gg R_{\oplus}$$

Day



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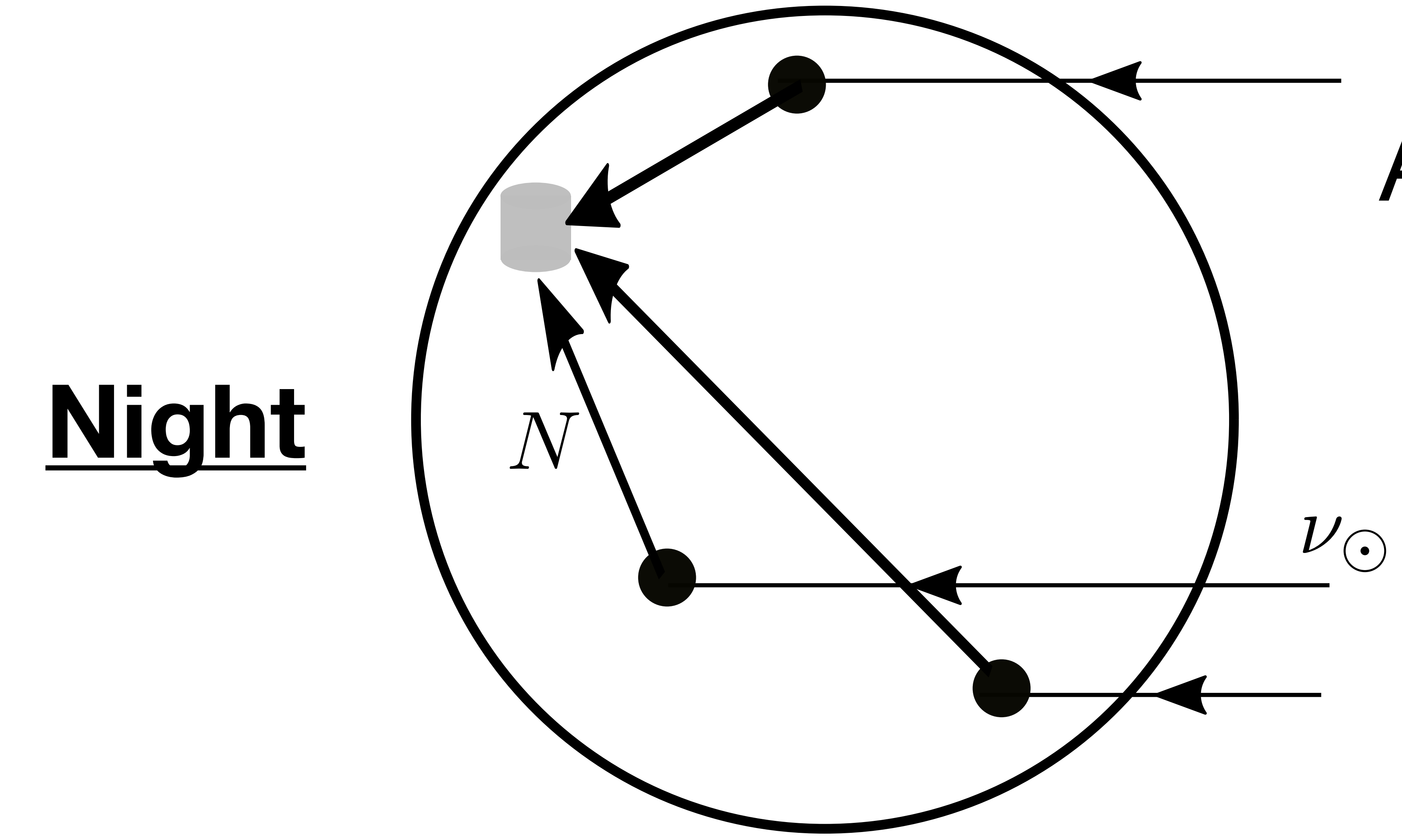

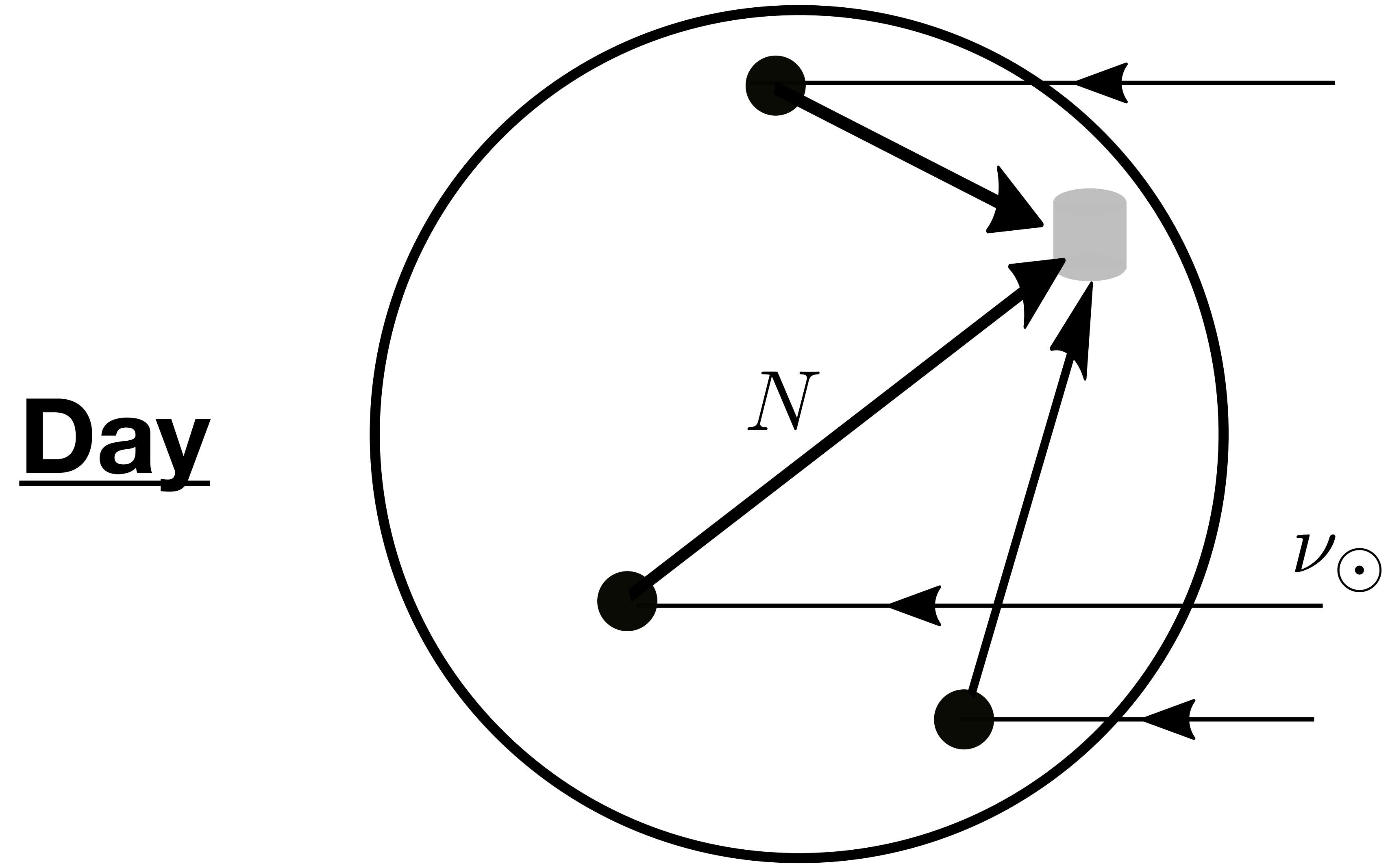

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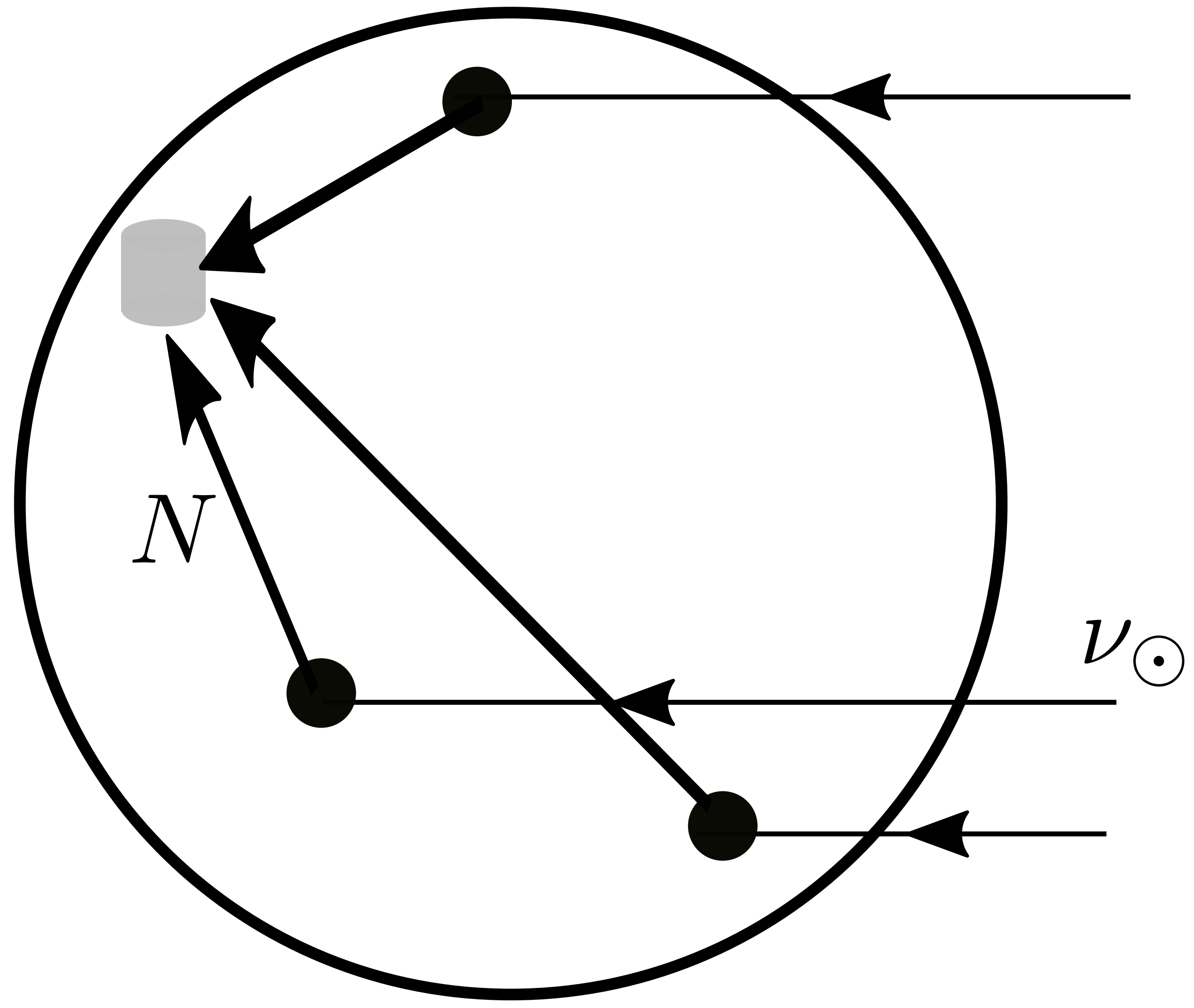
$$\sim \frac{V_{\text{det}}}{L_{\text{dec}}} \times \frac{1}{2} R_\oplus \quad \text{for} \quad L_{\text{dec}} \gg R_\oplus$$

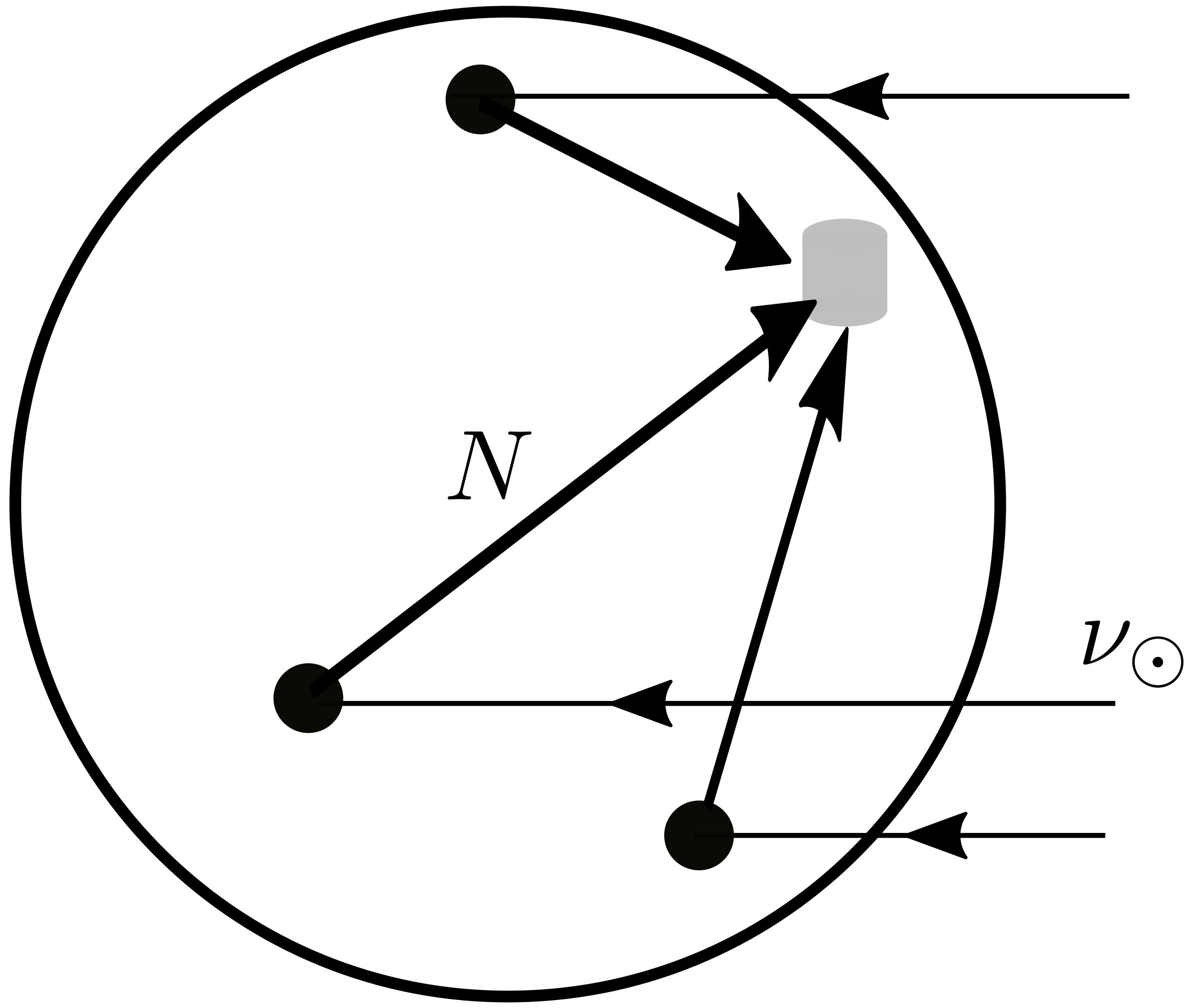
Quasi-isotropic (especially after 1y avg)

Mass-Mixing Portal

Night



Day



$$\sigma_{\nu\to N} \approx \frac{3}{\pi} |U_{aN}|^2 G_F^2 E_\nu^2$$

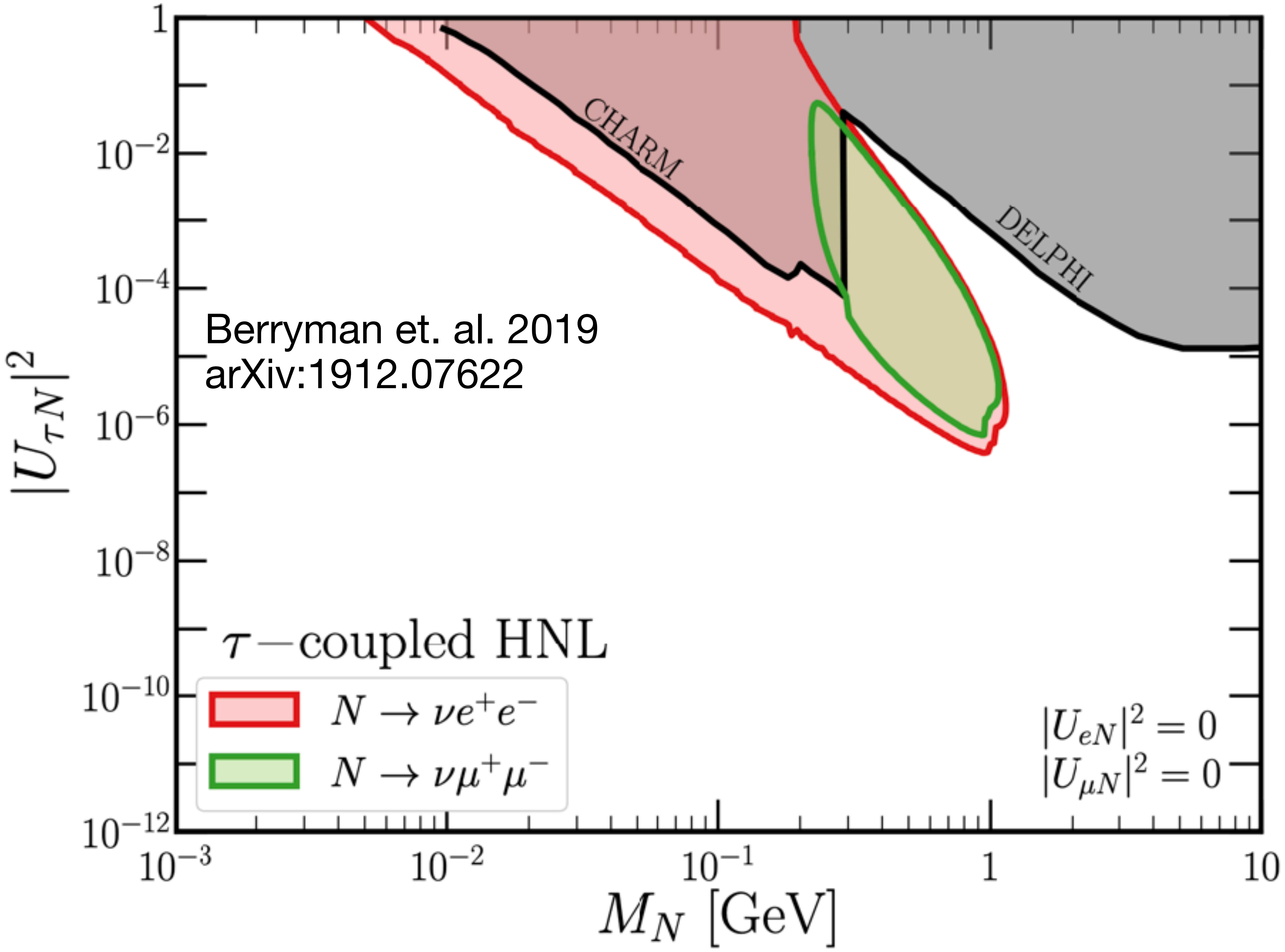
$$\Gamma \sim \frac{1}{192\pi^3} m_N^5 G_F^2$$

$$\lambda \sim 10^6 R_\oplus$$

Event rates are much smaller than dipole

Electron and muon hopeless, but tau….

Mass-Mixing Portal



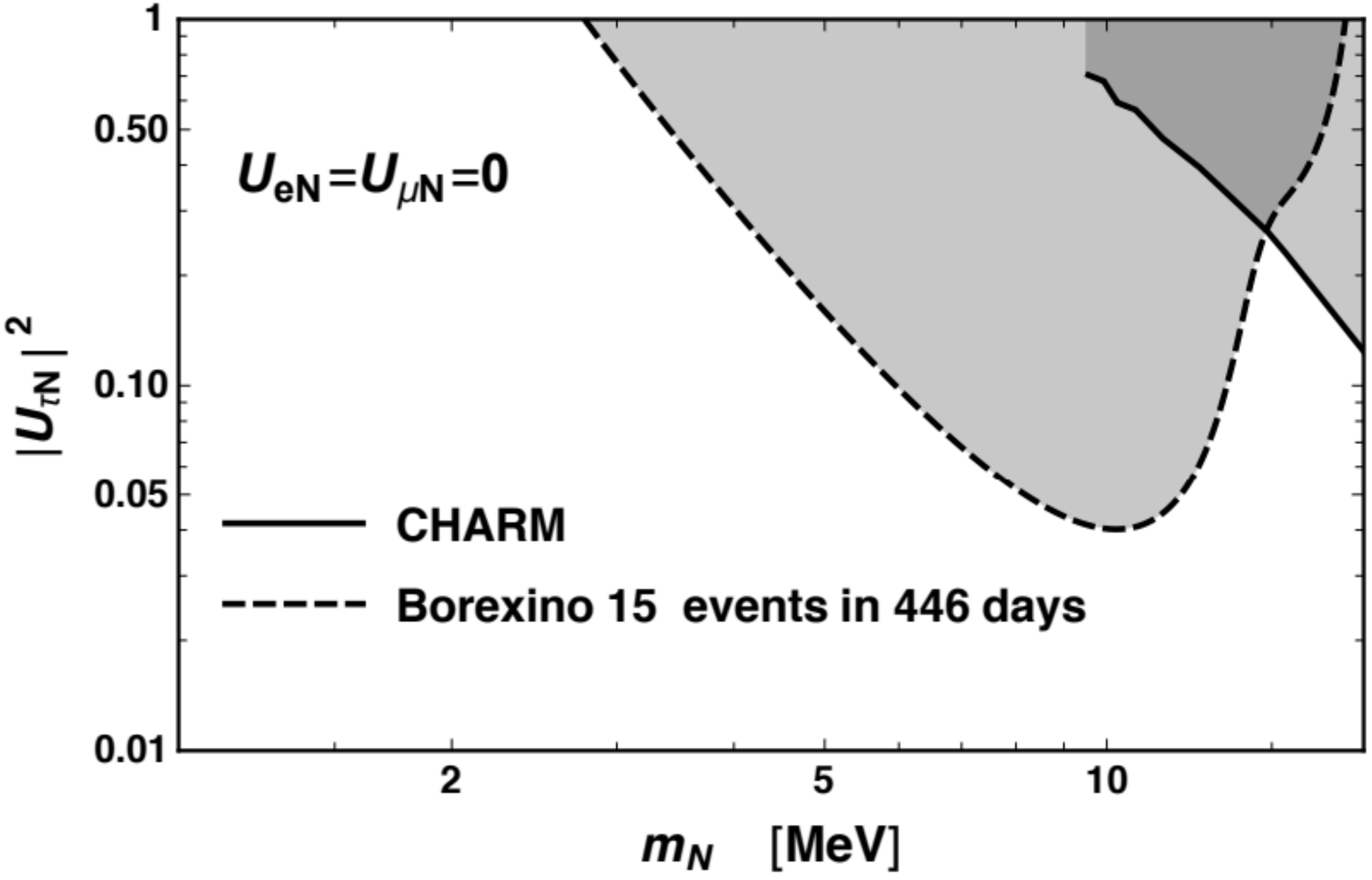
$$\lambda \sim \frac{1}{m_N^6 U_{aN}^4}$$

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!

Take home messages

- Searchinig for decaying particles eminating from the Earth is **well motiviated.**

- Existing large volume detector datasets can be used to set **previously overlooked** constraints on very minimal and generic models of light new physics.

- A program to search for decays inside large volume detectors is well motivated. SK, JUNO, DUNE etc. should include in core BSM seach strategy.