Neutrino Upscattering and Decays in Large Volume Detectors

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Abstract

In models of an extended dark sector, neutrinos may scatter off nuclei to produce a heavy neutral lepton (HNL). These HNLs are unstable, and eventually decay (e.g. into a neutrino and a photon). We consider the HNLs produced by solar and atmospheric neutrinos and their signatures in large volume detectors such as Super-Kamiokande. We find novel limits on HNL masses below a few hundred MeV that supercede constraints from fixed target experiments.

Introduction

Astrophysical neutrinos can scatter inside the Earth producing new dark particles through a "neutrino portal". In this poster we consider a simple Lagrangian called the *neutrino dipole portal*

$$\mathcal{L}_{\rm BSM} = \bar{N}(i\not{\partial} - m)N + dF_{\mu\nu}\bar{N}\sigma^{\mu\nu}P_L\nu \ + \ \text{c.c.} \qquad (1)$$

Neutrinos couple to new heavy neutral leptons (HNLs) and photons. Upscattering occurs via photon exchange with nuclei. HNLs are unstable, and after being created inside the Earth they can decay inside large-volume detectors.

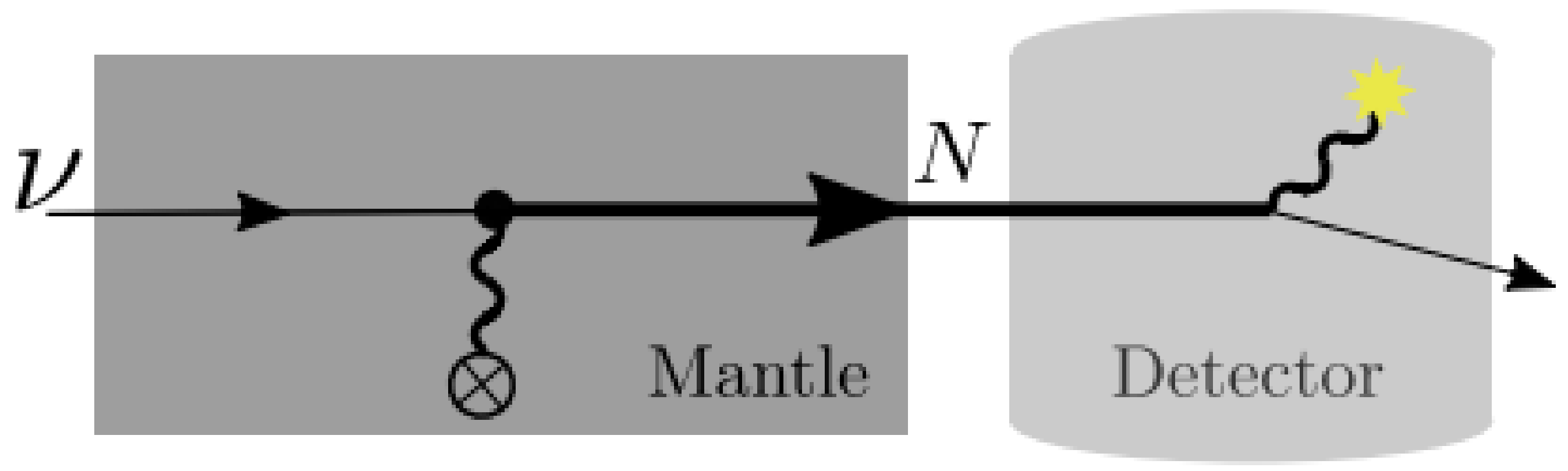

Figure 1: Schematic of upscattering and decay [1]. Neutrinos upscatter via a transition magnetic dipole operator by exchanging a virtual photon with the nucleus. The same operator controls the rate of decay inside the detector.

For small transferred momenta, the neutrino coherently scatters off the nucleus, giving a factor of Z^2 in the cross section [1].

$$\frac{d\sigma}{dt} = \frac{d^2Z^2\alpha}{t}|F(-t)|^2\big[4E_\nu^2 - m_N^2 + m_N^4/t\big] \qquad (2)$$

The characteristic decay length λ of the HNL goes as

$$\lambda = \frac{4\pi}{d^2 m_N^3} \times \gamma\beta \sim 10\ \text{m} - 10,000\ \text{km} \qquad (3)$$

Lower mass HNLs ($m_N \lesssim 10$ MeV) decay over much longer length scales (comparable to the size of the Earth). Higher mass HNLs ($m_N \gtrsim 10$ MeV) decay over much shorter distances.

Solar Neutrinos

Solar neutrinos have a high flux at energies extending to $E_\nu(\odot) \lesssim 18$ MeV. They can therefore be used to probe $m_N \lesssim 18$ MeV. The rate of photon deposition inside the detector scales as

$$R \propto P_{\text{up}-\text{scatt}} \times P_{\text{decay}} \sim A_{\text{det}} n_\perp^{\text{eff}} \sigma_{\text{up}} \Phi_{\nu_\odot} \times \frac{\ell_{\text{det}}}{\lambda} \qquad (4)$$

For $\lambda \ll R_\oplus$ and $\lambda \gg \ell_{\text{det}}$ the effective column density scales as $n_\perp^{\text{eff}} \sim \lambda$ such that the rate is insensitive to λ [1].

Atmospheric Neutrinos

For higher mass HNLs we can make use of atmospheric neutrinos. To compute the rate R of HNL decays in the detector, we must integrate over the volume of the Earth.

$$R = A_\perp \int \sum_Z \Big(\frac{d\sigma_Z}{d\cos\Theta} n_Z\Big)\Phi_\nu \frac{P_{\text{decay}}}{|\mathbf{Y} - \mathbf{X}|^2} d\mathbf{X}\, dE_\nu\, d\cos\Theta \qquad (5)$$

To account for nuances of a non-uniform Earth and angle dependent flux, we have developed a Monte Carlo routine that performs sophisticated importance sampling.

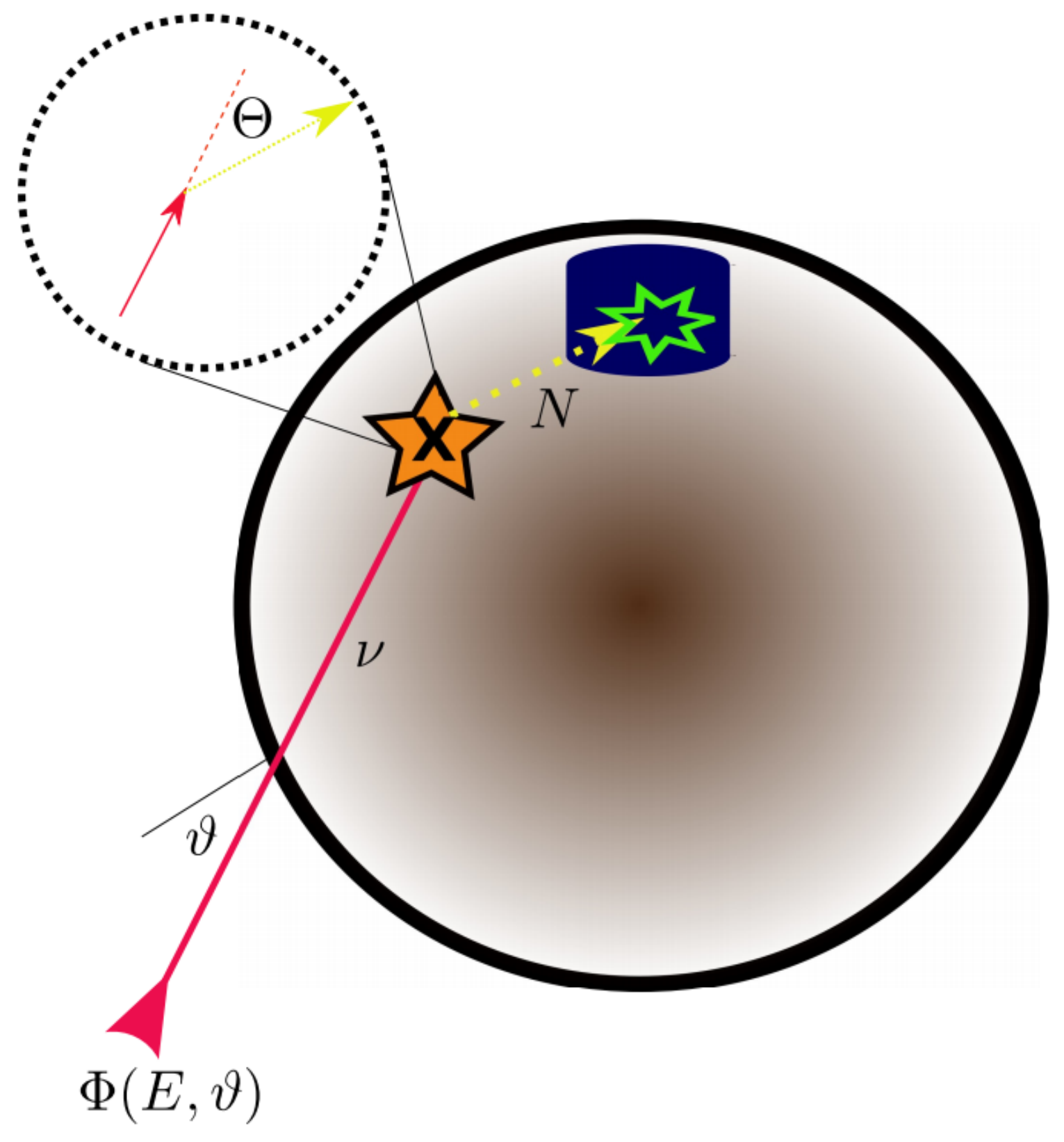

Figure 2: Schematic used for computing Monte Carlo integration for atmospheric neutrinos. 1) An atmospheric neutrino is produced at the Earth's surface with a flux calculated by NuFlux [2]. 2) The neutrino uspcatters somewhere inside the Earth producing an HNL. 3) The HNL travels towards the detector and decays within its volume.

Results

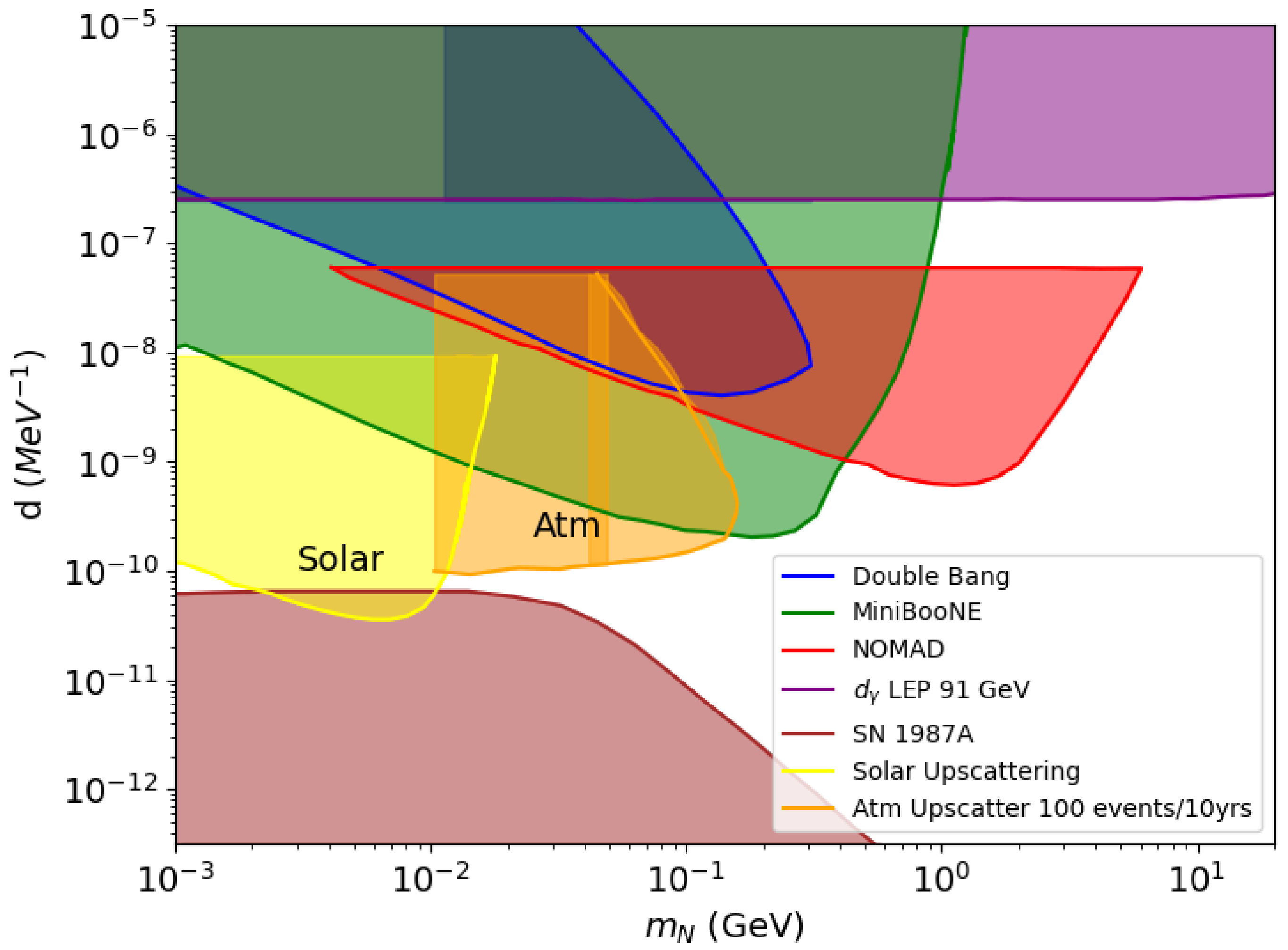

Figure 3: Parameter space ruled out by related works [3] [4] and contour for 100 events in 10 years of Super-Kamiokande. Many accelerator-based constraints apply only to muon neutrino dipole portals. Atmospheric and solar neutrino constraints are "flavour democratic". For the atmospheric upscattering, our lower bound is set by the rarity of upscattering (i.e. $\sigma \propto d^2$ and eventually "turns off". The diagonal contour that bounds the curve from above and from the right is set by the decay length becoming "short", $\lambda \lesssim 50$ m, at which point the finite volume and geometry of the detector becomes important. In this regime the event topology transitions into a "double bang" with upscattering inside the detector volume [4].

Ongoing Work

- Consider the contribution from incoherent scattering off of nucleons. (This is expected to be a minor effect, since coherent scattering is enhanced by Z^2).
- Consider flavor-dependent couplings to the dipole portal.
- Include effects of neutrino oscillations when considering flavor-dependent dipole couplings.

References

1. Plestid, R. (2020). Luminous solar neutrinos I: Dipole portals. arXiv preprint arXiv:2010.04193.
2. https://github.com/icecube/nuflux
3. Magill, G., Plestid, R., Pospelov, M., & Tsai, Y. D. (2018). Dipole portal to heavy neutral leptons. Physical Review D, 98(11), 115015.
4. Atkinson, M., Coloma, P., Martinez-Soler, I., Rocco, N., & Shoemaker, I. M. (2021). Heavy Neutrino searches through Double-Bang Events at Super-Kamiokande, DUNE, and Hyper-Kamiokande. arXiv preprint arXiv:2105.09357.