The neutrino portal to heavy neutral leptons in the current experiments

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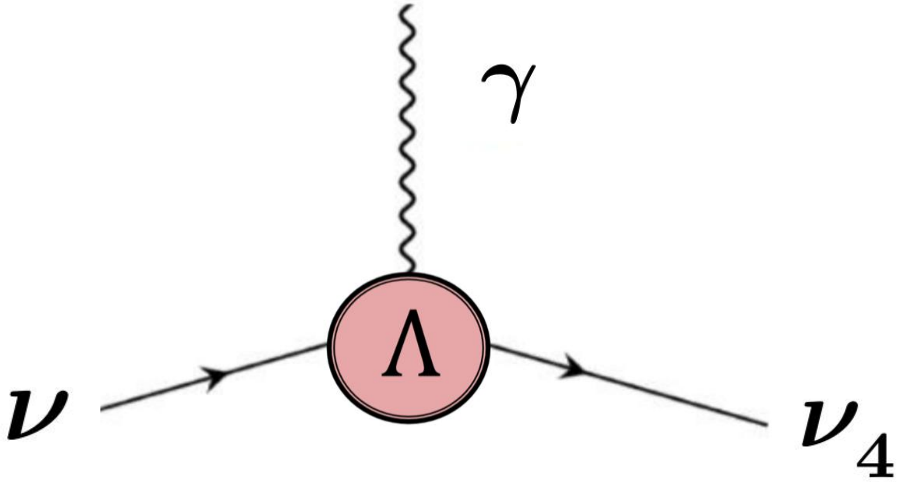
Motivations:

The neutrino portal to heavy neutrinos (active-sterile neutrino transition magnetic moments):

$$\mathcal{L} = d_\alpha \overline{\nu}_{\alpha L} \sigma^{\mu\nu} \nu_4 F_{\mu\nu} + \mathrm{h.c.}$$



- This Lagrangian is technically only valid at energies below the EW scale;
- Above the EW scale, we need construct UV-completion theory (Model dependent) ;
- Agnostic about the UV origin of this operator and study its phenomenological implications at energies below EW scale in most experiments.
- Other new physics (mediated by Z, Z' bosons or scalar field).

- A promising way to test the existence of sterile neutrinos
- Anomalies(XENON1T, ANITA, MiniBooNE, muon g-2 anomalies)
- A possible way to answer the questions: are neutrinos Dirac or Majorana particles?

C_x0008_urrent constraints or sensitivies:

The bounds on d_α (α=e, μ, τ) come from various laboratory, astrophysical and cosmological observations, for example the ones derived from

- neutrino oscillation experiments (solar, atmospheric, reactor),
- dark matter experiments,
- the observation of high-energy neutrinos

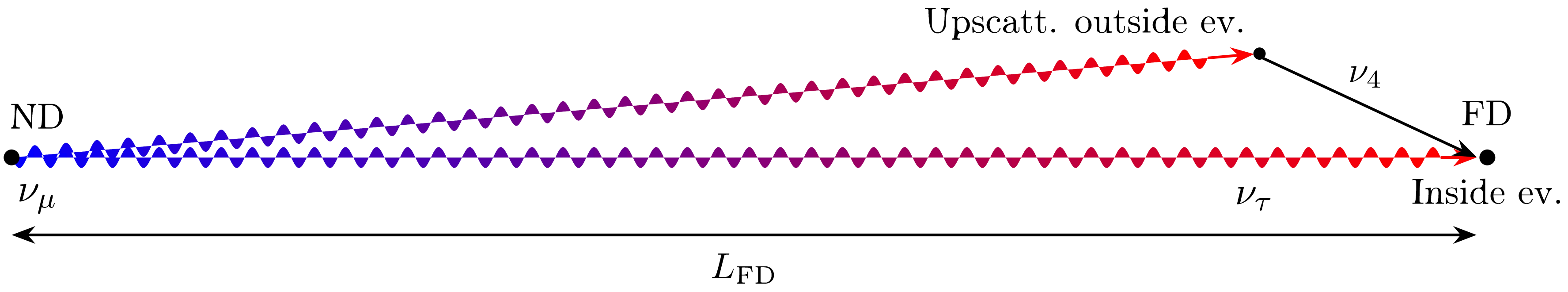
by studying

- coherent elastic neutrino-nucleus scattering (CEνNS),
- elastic neutrino-electron scattering,
- deep inelastic interactions

etc.

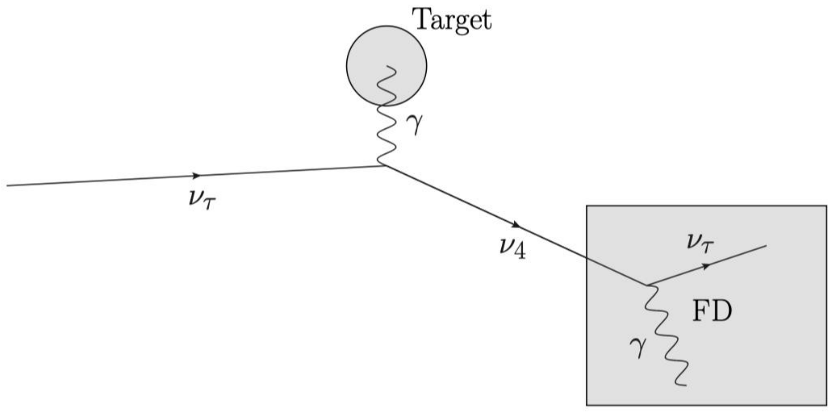
Methods at DUNE

We start with the tau neutrino flux generated by the neutrino oscillations and consider coherent scattering off nuclei and incoherent scattering off protons, neutrons and electrons.



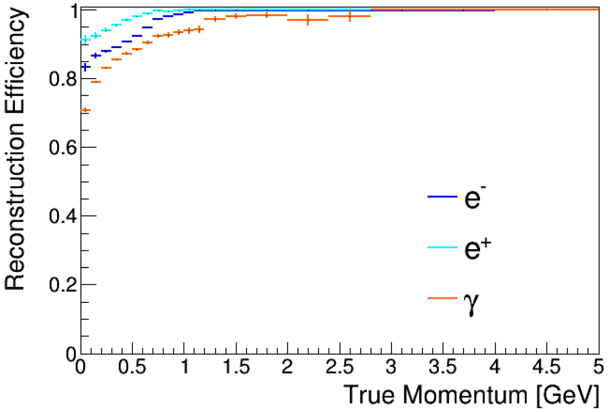
Assumptions:

- Dirac neutrinos
- The heavy neutrino flavor mixing with active neutrinos is negligible and the dipole interaction dominates



[Schwetz, Zhou, Zhu, 2105.09699]

Signal



Dune TDR, Vol. II

Outside events: The up-scattering happens outside detector, so the signature is a single-photon event.

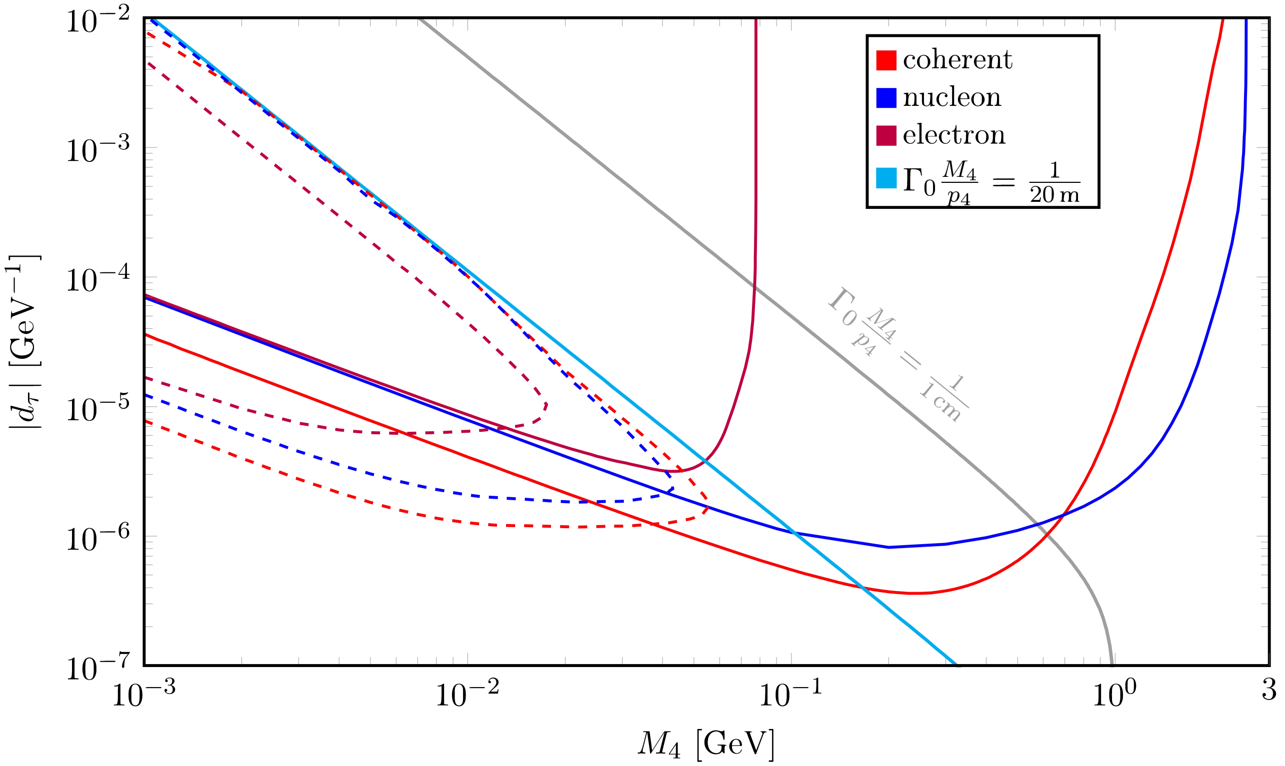
Inside events, coherent: The coherent up-scattering leaves a nuclear recoil of low energy, which is not easy to observe in the detector, so the signature is a single-photon event.

Inside events, incoherent: the signature will be either a NC-like (the up-scattering on nucleons) or single-electron type event (the up-scattering on electrons) together with the displaced single-photon event from the heavy-neutrino decay.

Background

The relevant backgrounds for the dipole signal are the single photon process NC1γ and highly asymmetric NCπ_0-decays, where the two photons from the pion decay cannot be distinguished.

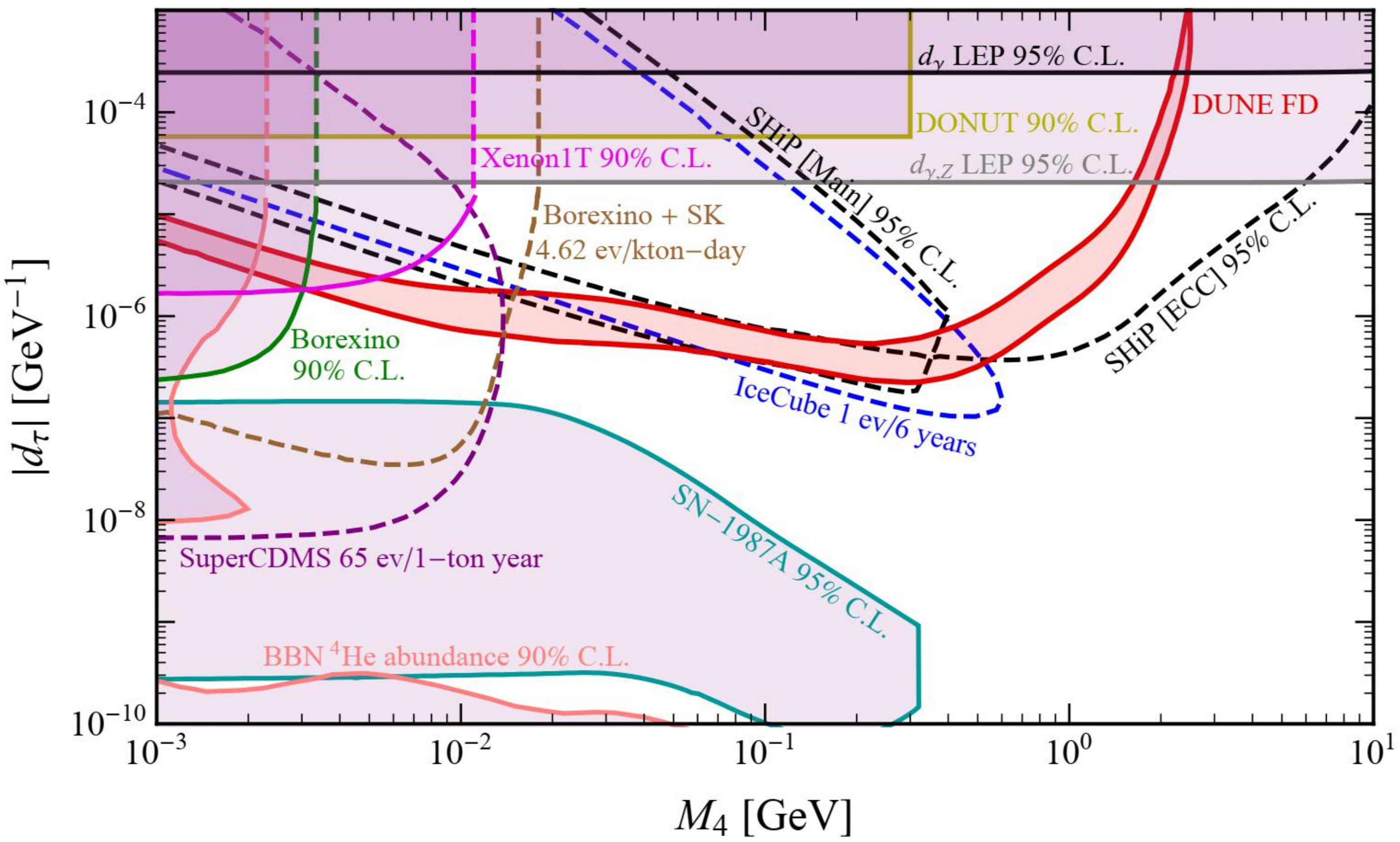
Results



The 6-events/year curve for inside (solid) and outside (dashed) events at the DUNE FD.

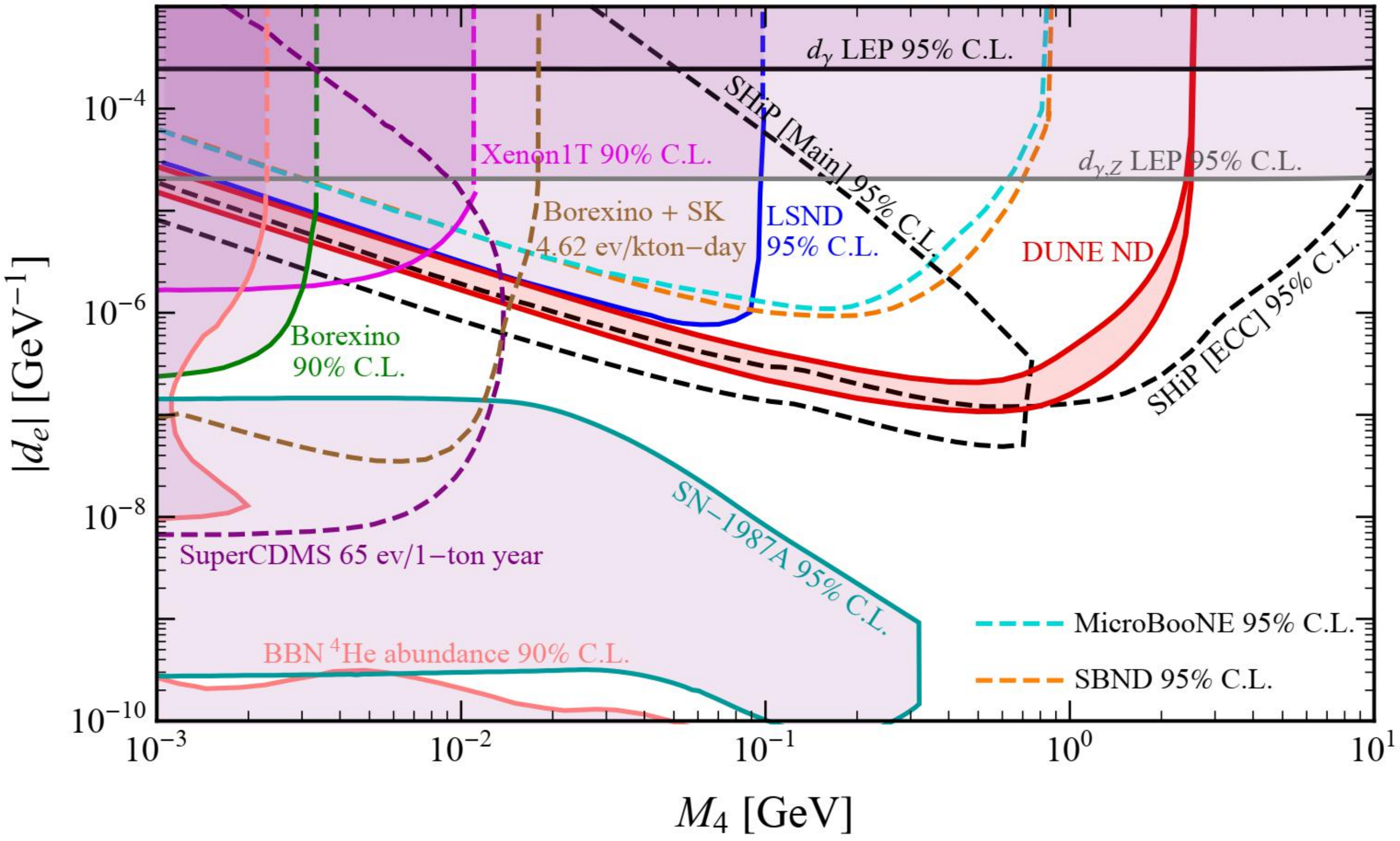
- Coherent scattering on nuclei (red),
- Incoherent scattering on nucleons (blue)
- Scatterings on electrons (purple)

Global picture of d_T



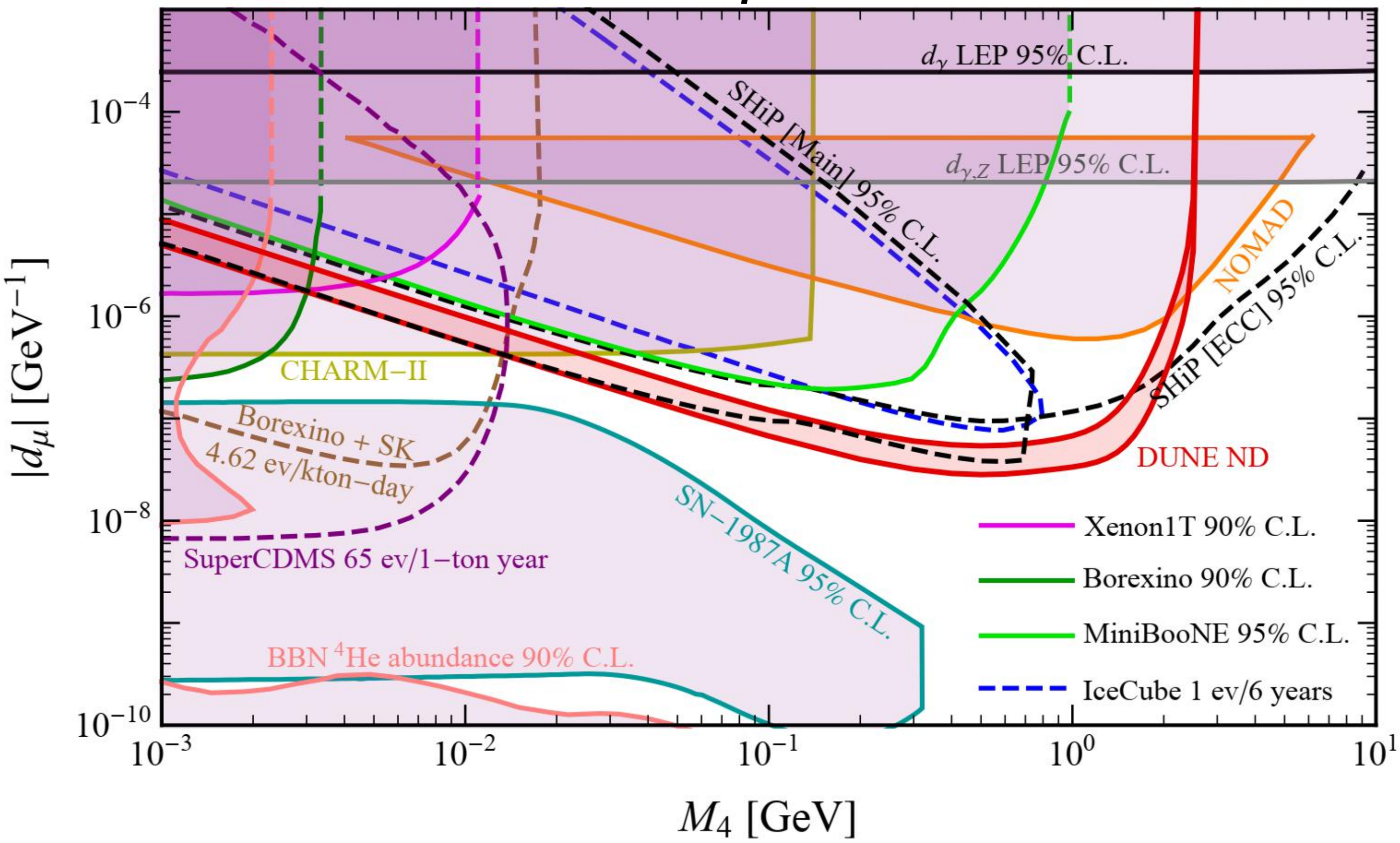
The band represents the region with 2 – 20 events/year, corresponding to 95% C.L. sensitivity over 5 years with 25 – 2500 background events

Global picture of d_e



Due to the sizeable primary υ_e and υ_μ fluxes, the HNL transition moments d_e and d_μ are more efficiently probed at the near detector in the same way.

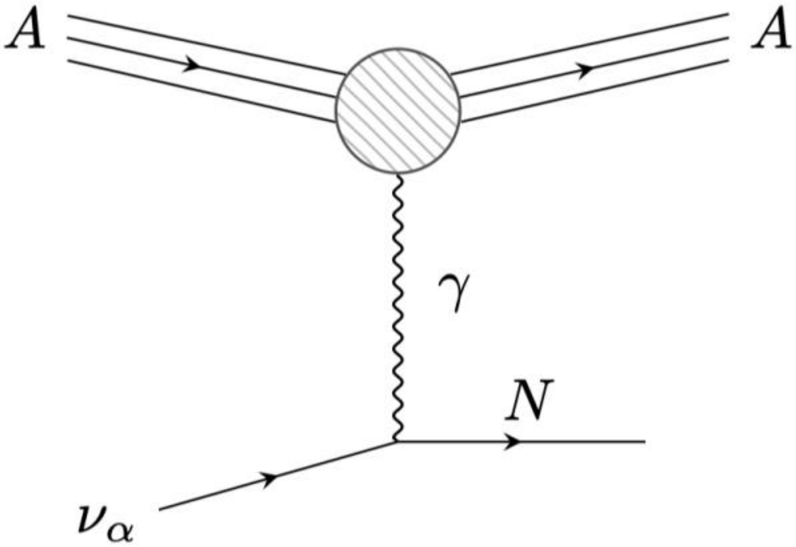
Global picture of d_μ



The primary flux of tau neutrinos in the beam has been estimated in the literature, from which we can estimate that the sensitivity of the d_τ-induced event rate in the ND is much smaller than the one in the FD.

Coherent neutrino-nucleus elastic scttering (CEvNS)

$$\frac{d\sigma_{\nu_\alpha A\to NA}}{dE_R} \approx (\mu^\alpha_{\nu N})^2 \alpha Z^2 \left[\frac{1}{E_R} - \frac{m_N^2}{4E_R E_\nu^2}\right]$$

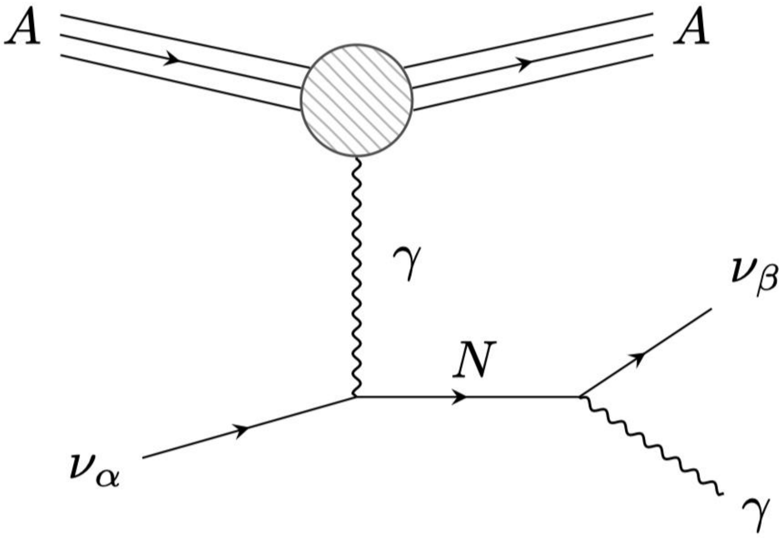


Primakoff Upscattering

Signal: recoil energy

Not sensitive to Dirac vs. Majorana nature of N

$$\left.\frac{d\sigma^{\mathrm{D(M)}}_{\nu_\alpha A\to\nu_\beta A\gamma}}{dE_R}\right|_{\mathrm{NWA}} = \frac{d\sigma^{\mathrm{D(M)}}_{\nu_\alpha A\to NA}}{dE_R}\frac{\Gamma^{\mathrm{D(M)}}_{N\to\nu_\beta\gamma}}{\Gamma_N}$$



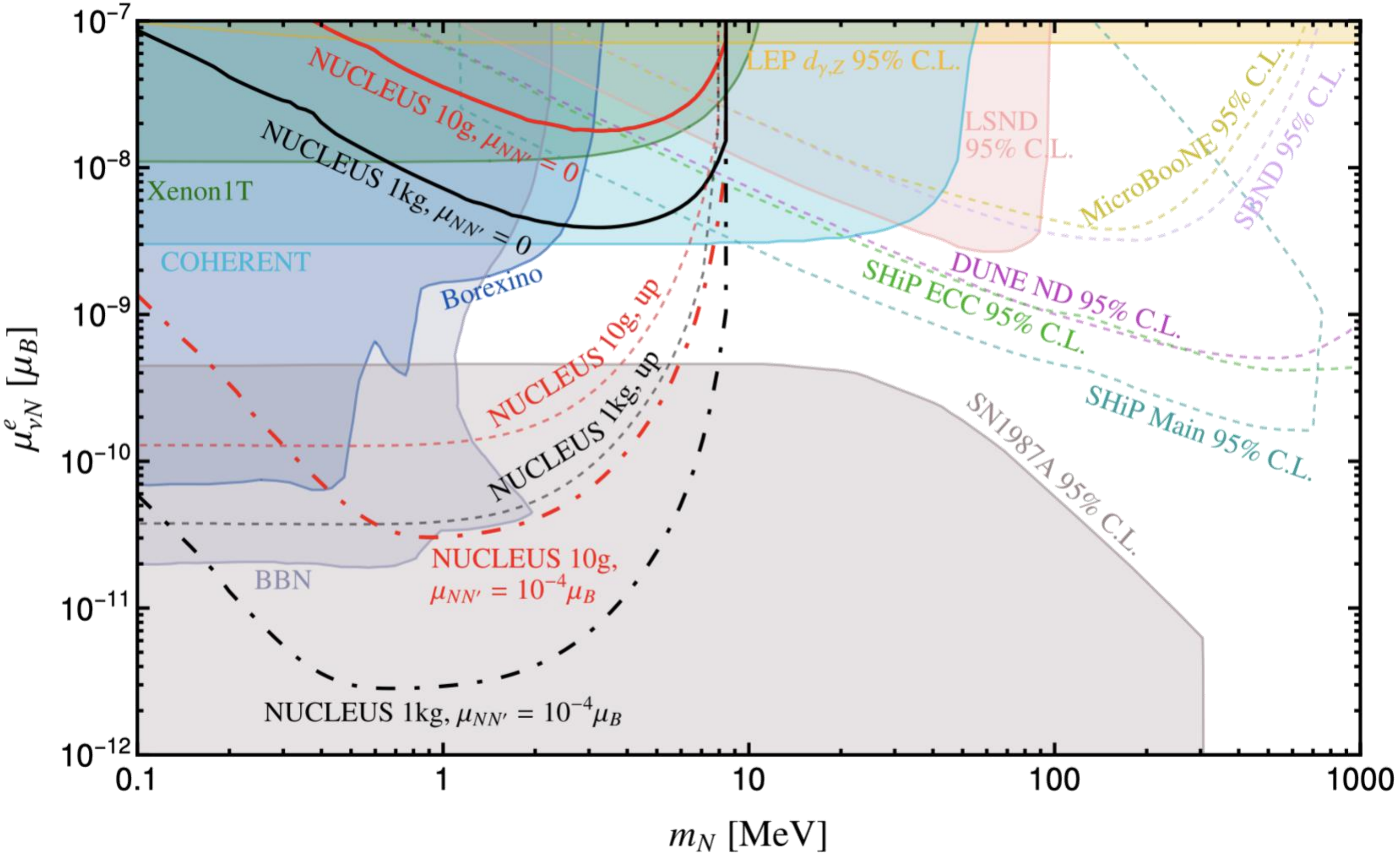
Radiative Upscattering

Signal: recoil energy plus photon

Sensitive to Dirac vs. Majorana nature of N

[Bolton, Deppisch, Fridell, Harz, Hati, Kulkarni, 2110.02233]

Constraints



[Bolton, Deppisch, Fridell, Harz, Hati, Kulkarni, 2110.02233]
[Bolton, Invisible22]

Dirac or Majorana?

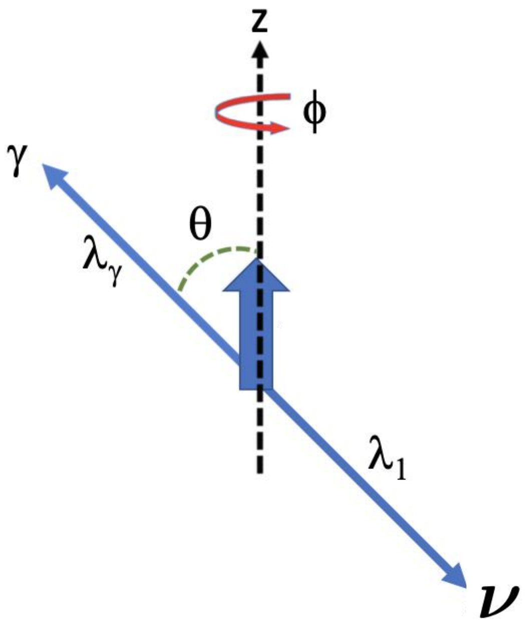
In the Dirac case, we have to introduce additional right handed Weyl field (sterile)

$$m_\nu \ll E_\nu$$

The rates for processes involving Dirac or Majorana active neutrinos are identical
[Kayser, Phys.Rev.D 26 (1982) 1662]

$$m_N \sim E_N$$

The difference between the rates for Dirac or Majorana sterile neutrinos will be relevant



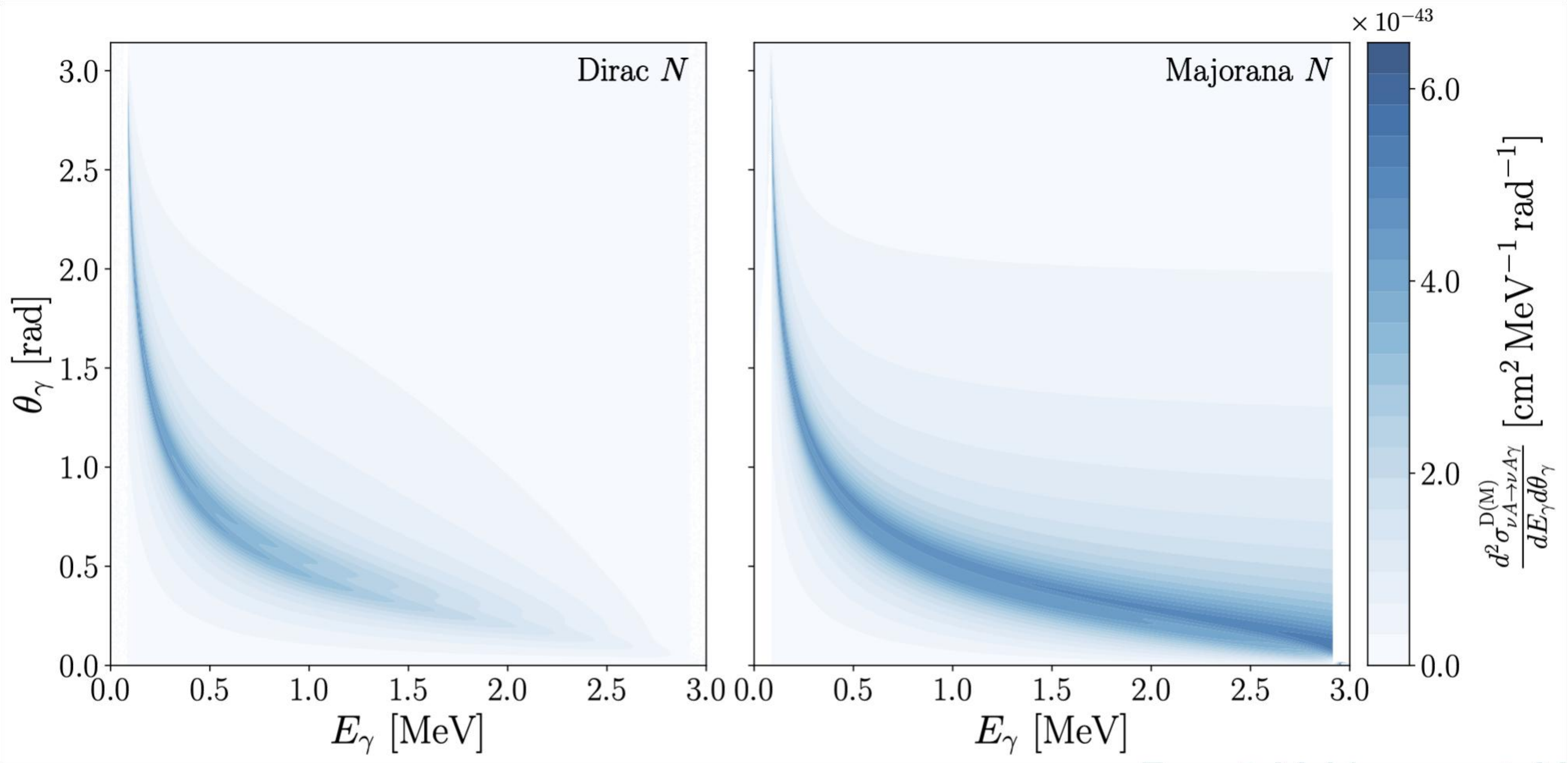
[Balantekin, Kayer, 1805.00922]

$$\Gamma^{\mathrm{M}}_{N\to\nu_\beta\gamma} = 2\Gamma^{\mathrm{D}}_{N\to\nu_\beta\gamma} = \frac{(\mu^{\beta}_{\nu N})^2 m_N^3}{4\pi}$$

[Bolton, Invisible22]

Twice more events in the Majorana case

Dirac or Majorana?



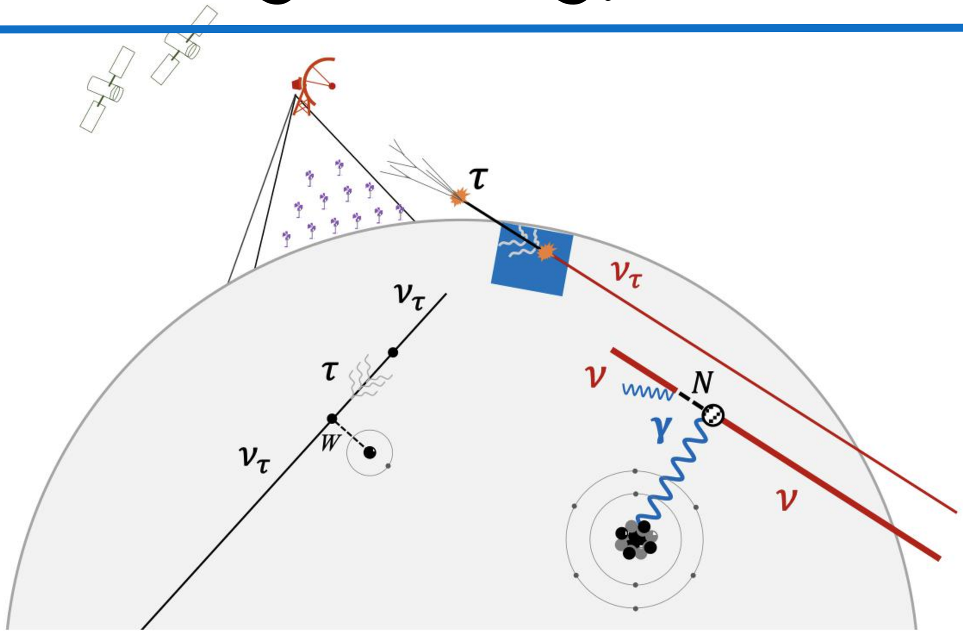
$E_\nu = 3$ MeV, $m_N = 1$ MeV

More forward emissions of high energy γ in Majorana vs. Dirac case

Clear distrinction for $E_\gamma > E_\nu/2$

[Bolton, Invisible22]

Ultrahigh energy neutrino telescopes



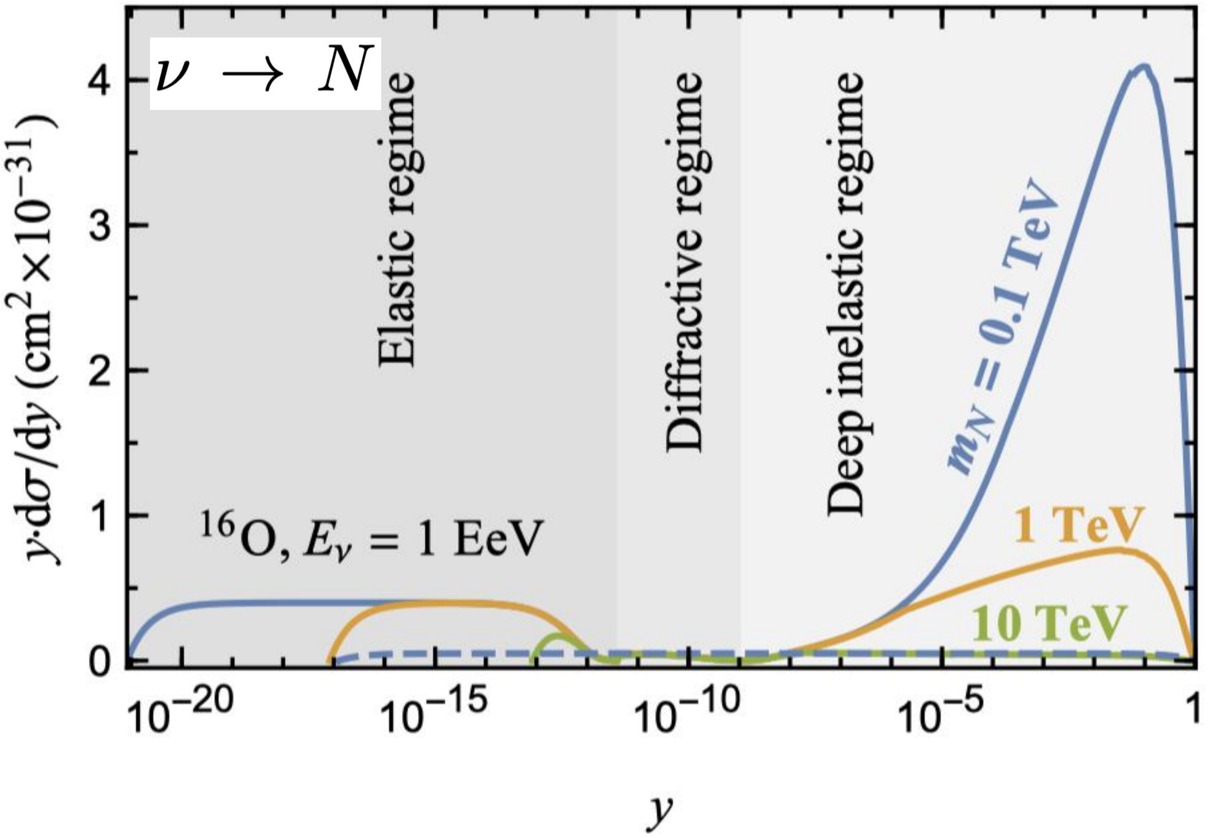
- The incoming neutrino flux can be severely affected by the conversion process before reaching the neutrino detector
- The UHE neutrinos are then detected by an in-ice volume (for all neutrino flavors), and an atmospheric radio or imaging telescope (for tau neutrinos)

Assumptions:

- The neutrino mass operator, being a Lorentz scalar, is symmetric and forbidden under a new exchange SU(2) symmetry
- The neutrino magnetic moment operator, being a Lorentz tensor, is anti-symmetric and allowed under the SU(2) symmetry and will remain agnostic about the possible connection between the magnetic moment and the neutrino masses
- Particles inside the loop should carry masses larger than the sterile neutrino mass and the scattering energy scale (EFT)

[Huang, Jana, Lindner, Rodejohann, 2204.10347]

Ultrahigh energy neutrino telescopes

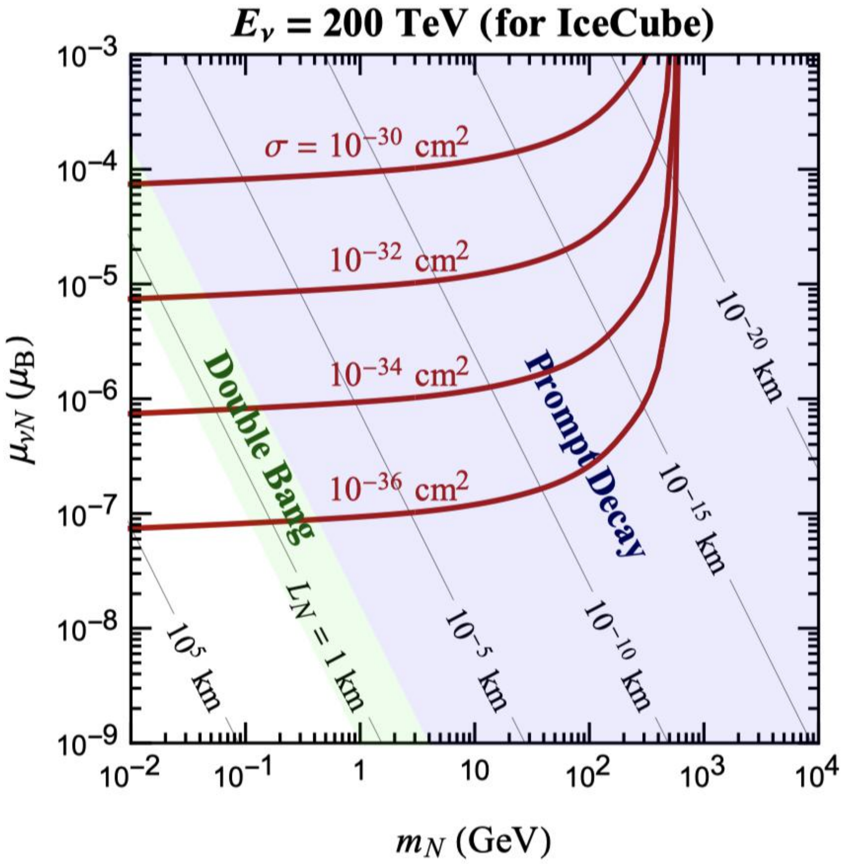


y: thehe energy loss parameter

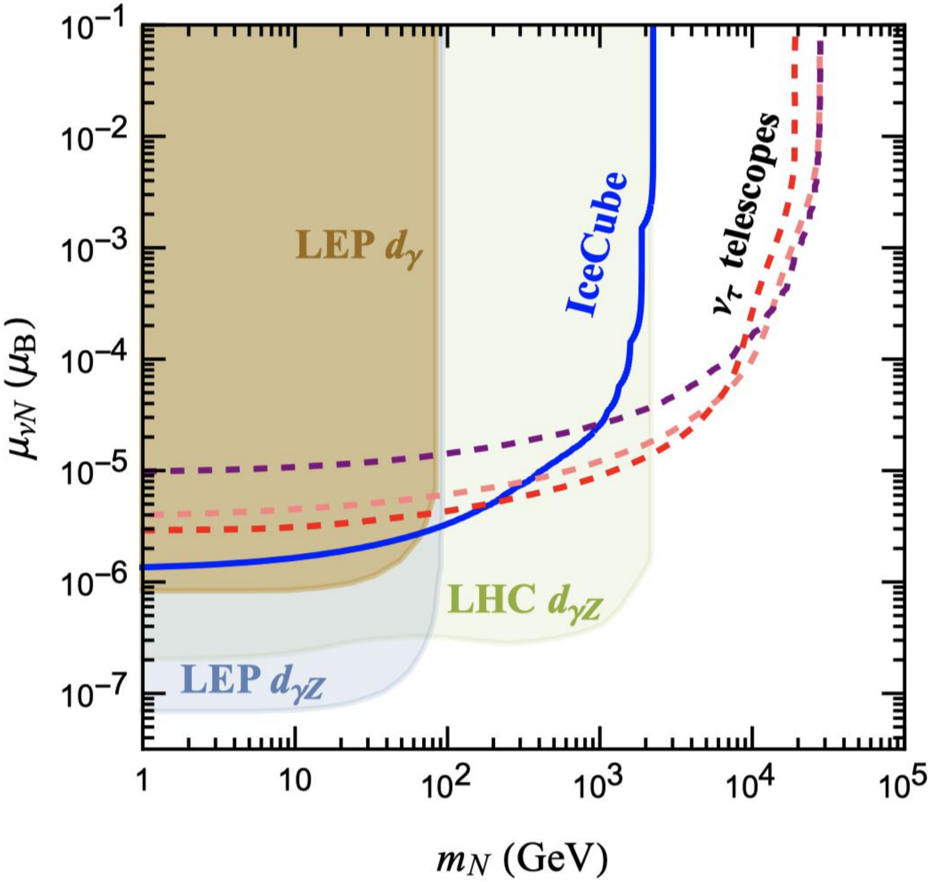
(i) the elastic coherent scattering off the whole nucleus
(ii) the diffractive (quasi-elastic) scattering off each individual nucleons
(iii) the deep inelastic scattering (DIS) with partons in the nucleon.

[Huang, Jana, Lindner, Rodejohann, 2204.10347]

Constraints

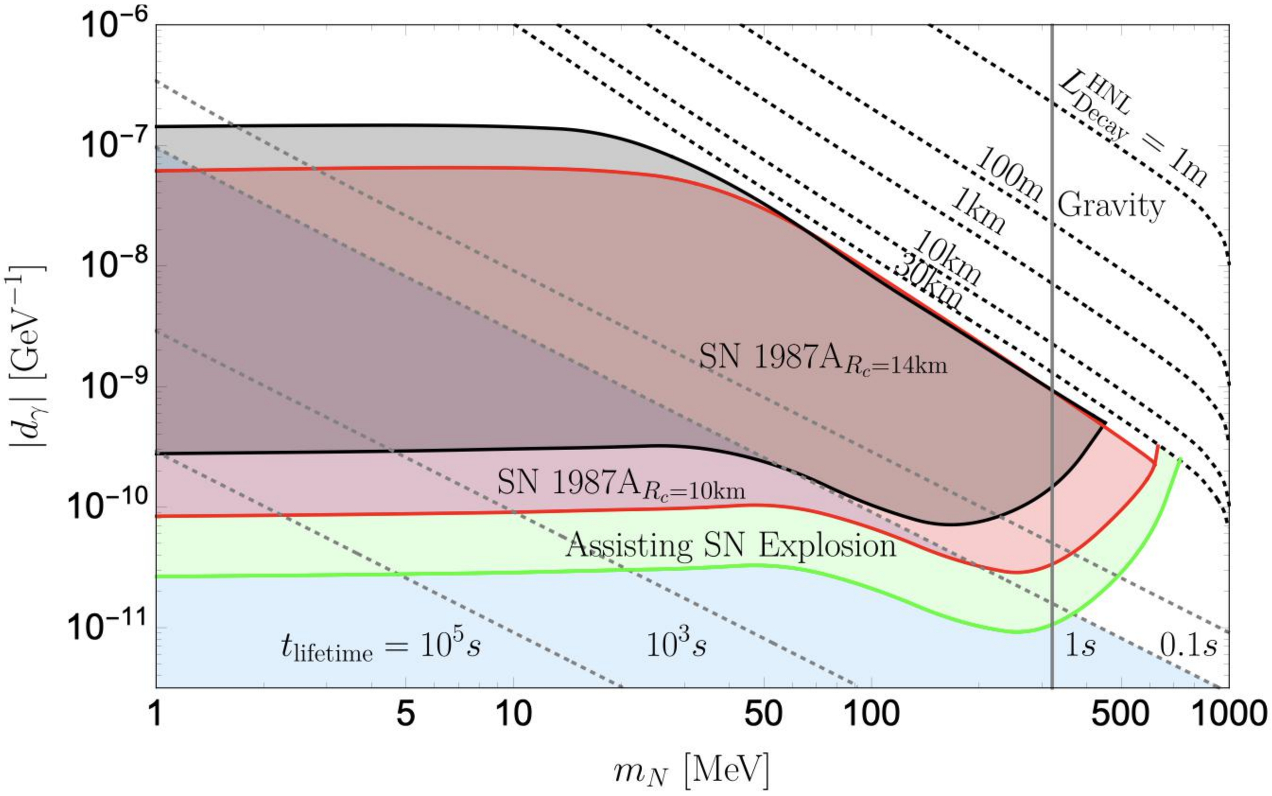


Contours of nucleon-averaged cross sections



GRAND
POEMMA
Trinity

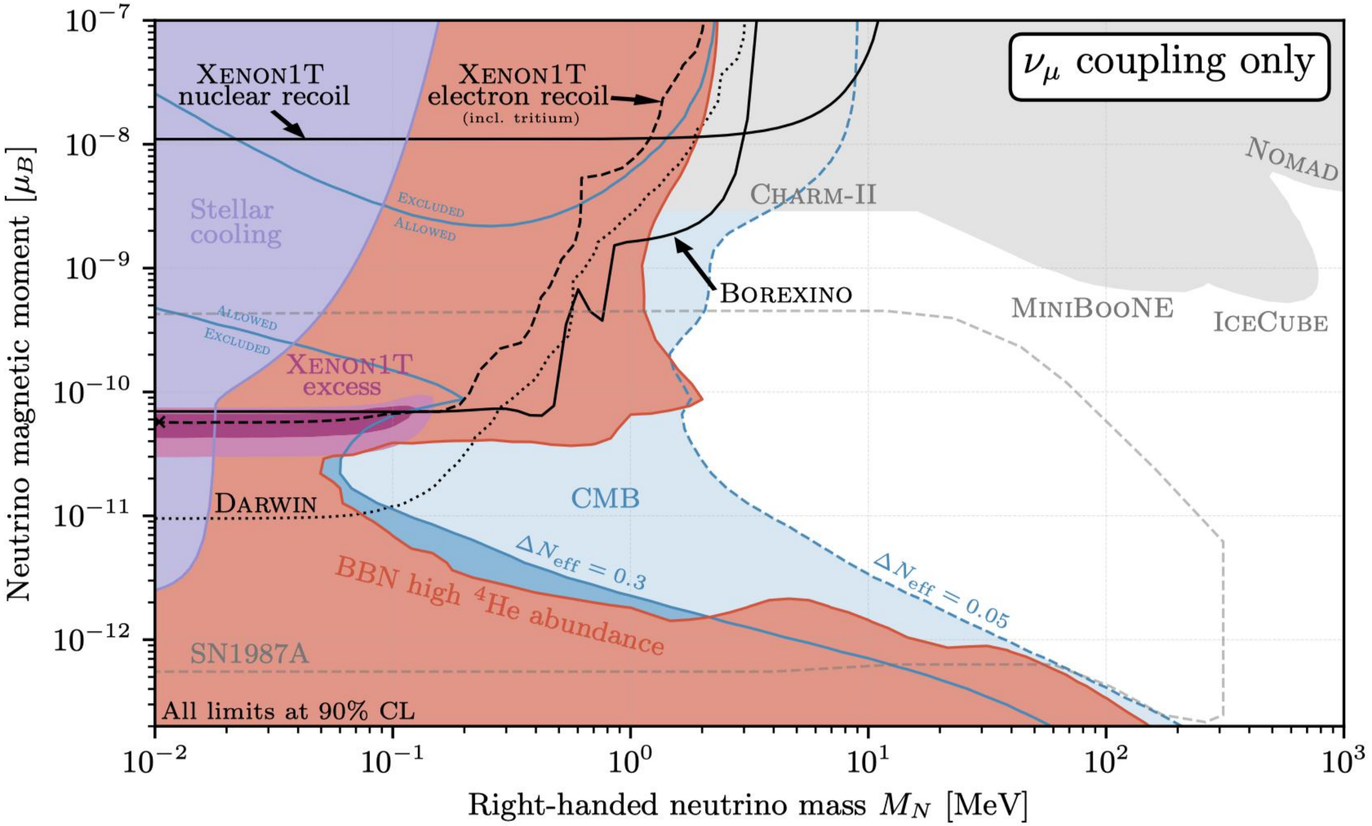
Supernova neutrinos



[Magill, Plestid, Pospelov, Tsai,1803.03262]

- Below the curve, the induced cooling effect is too weak
- Above the interaction becomes strong enough so that steriles cannot escape the collapsing core
- If the sterile is too heavy, the gravitational pull will also prevent it from leaving the supernova, leading to the vertical cut-off of the exclusion curve

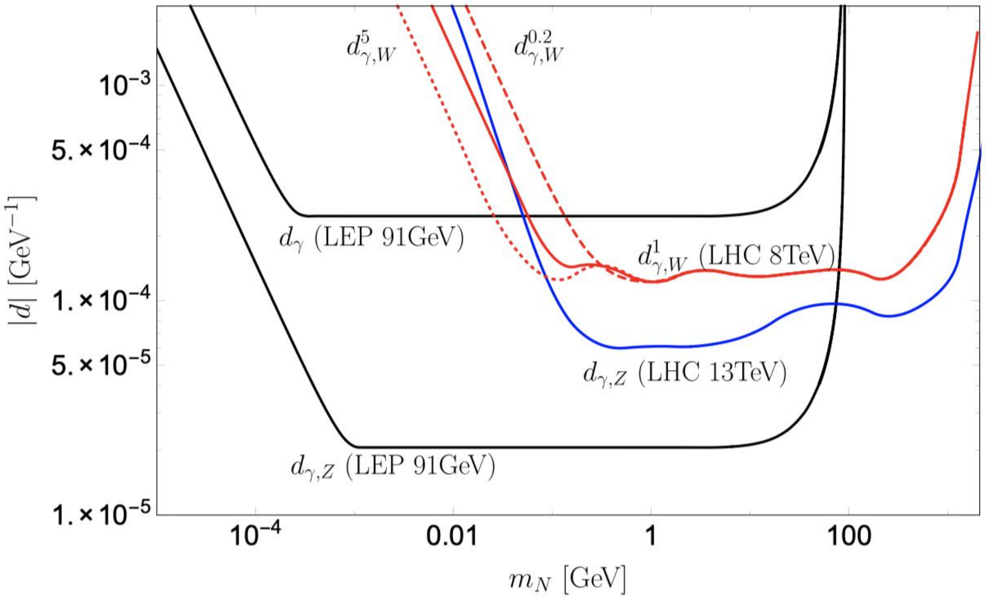
Cosmology



The dipole interaction alters the expansion and cooling rates of the universe, leading to a corrected neutron-to-proton ratio and baryon-to-photon ratio. The final ^{4}He abundance depends on M_N and neutrino magnetic moment.

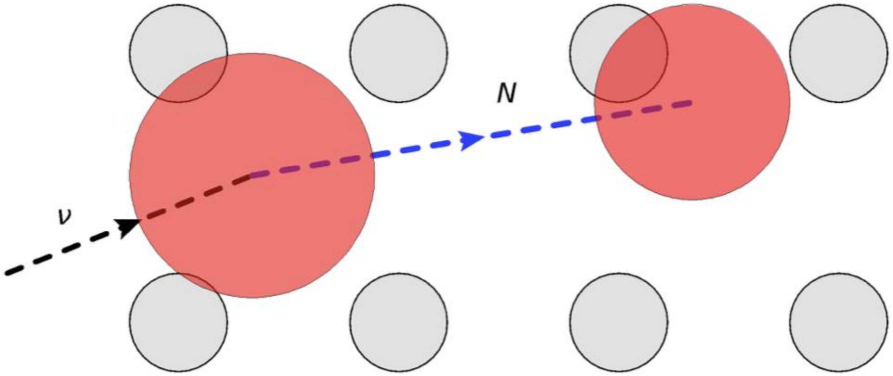
Badar, Greljo, Kopp, Opferkuch, 2007.15563

More...



Exp.	Plot Label	Assumptions	Probed d
LEP	d_γ	$\overline{d_\mathcal{W}} = 0,\ d_Z = 0$	$\overline{d_B}$
	$d_{\gamma,Z}$	$\overline{d_\mathcal{W}} = 0$	$\overline{d_B}$
LHC	$d_{\gamma,Z}$	$\overline{d_\mathcal{W}} = 0$	$\overline{d_B}$
	$d^a_{\gamma,W}$	$d_\gamma = a \times \overline{d_\mathcal{W}}$	$\overline{d_\mathcal{W}}$

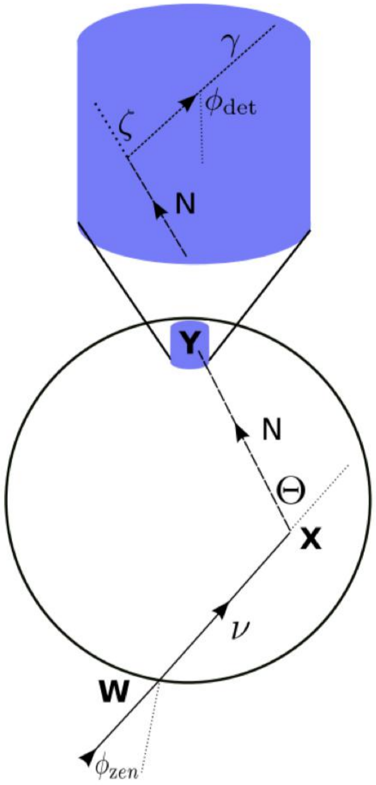
[Magill, Plestid, Pospelov, Tsai,1803.03262]



A double-bang event in IceCube

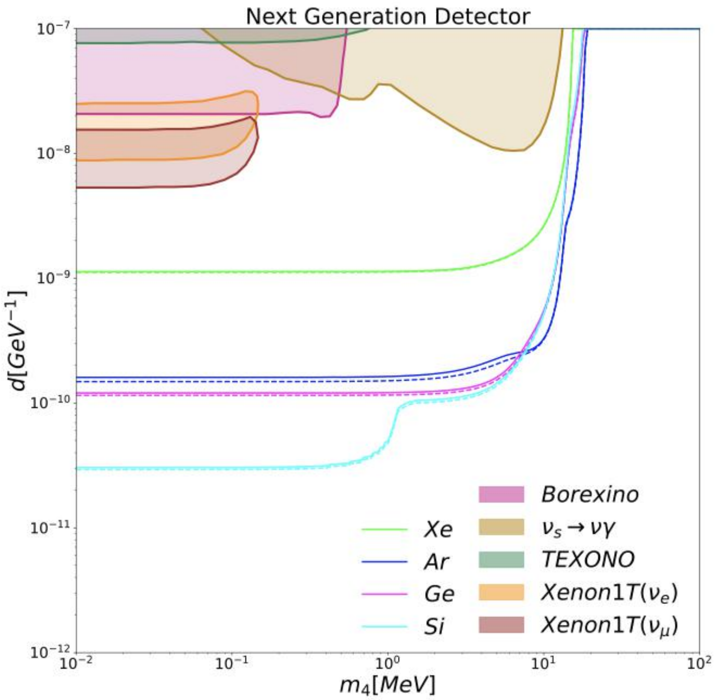
[Coloma, Machado,Martinez-Soler,Shoemaker, 1707.08573]

More...



Upscattering of atmospheric neutrinos in the interior of the Earth

[Gustafson,Plestid,Shoemaker,2205.02234]



Solar neutrinos

[Li, Xia, 2203.16525]

...
2007.05513
2010.04193
2105.09357
2108.12998
2109.05032
2109.09545
2110.02233
etc.

Summary

- We discussed the constraints of the dipole protal to heavy neutrinos (leptons) from neutrino experiments, dark matter experiments, and cosmological and astrophysical observations.

- Once we observed some Primakoff upscattering due to large active-sterile neutrino magnetic moment, it's possible to probe the followed single-photon event, which can be used to distinguish Dirac vs. Majorana nature of heavy neutrinos.

- If the new physics exists at very high energy scale, we can turn to UHE cosmic neutrinos from neutrino telescope.

Thank you for your attention!