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Transition neutrino magnetic moments in CEνNS

Based on Patrick D. Bolton, Frank F. Deppisch, KF, Julia Harz, Chandan Hati, Suchita Kulkarni, arXiv:2109.XXXXX

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Introduction

- Coherent neutrino nucleus scattering (CEνNS) is a Standard model (SM) process that was first observed in 2017 at the COHERENT experiment [1].
- In CEνNS, an incoming neutrino scatters coherently with all nucleons inside a nuclei, producing a small nuclear recoil (keV range).
- The smallness of this recoil is part of what makes CEνNS difficult to observe experimentally.
- After its discovery, the novelty of CEνNS experiments is shifted from observing the scattering itself to using it as a tool, for example to constrain neutrino oscillation parameters [2], and to search for beyond-SM (BSM) physics such as non-standard interactions or neutrino magnetic moments [3].
- Several CEνNS experiments are planned or running currently. Out of these experiments, we focus our analysis especially on NUCLEUS [4], where the threshold in nuclear recoil energy will reach an unprecedented low of a few 10's of eV.
- NUCLEUS is designed to study reactor neutrinos, and is located next to the CHOOZ reactor in France.

Neutrino magnetic moment

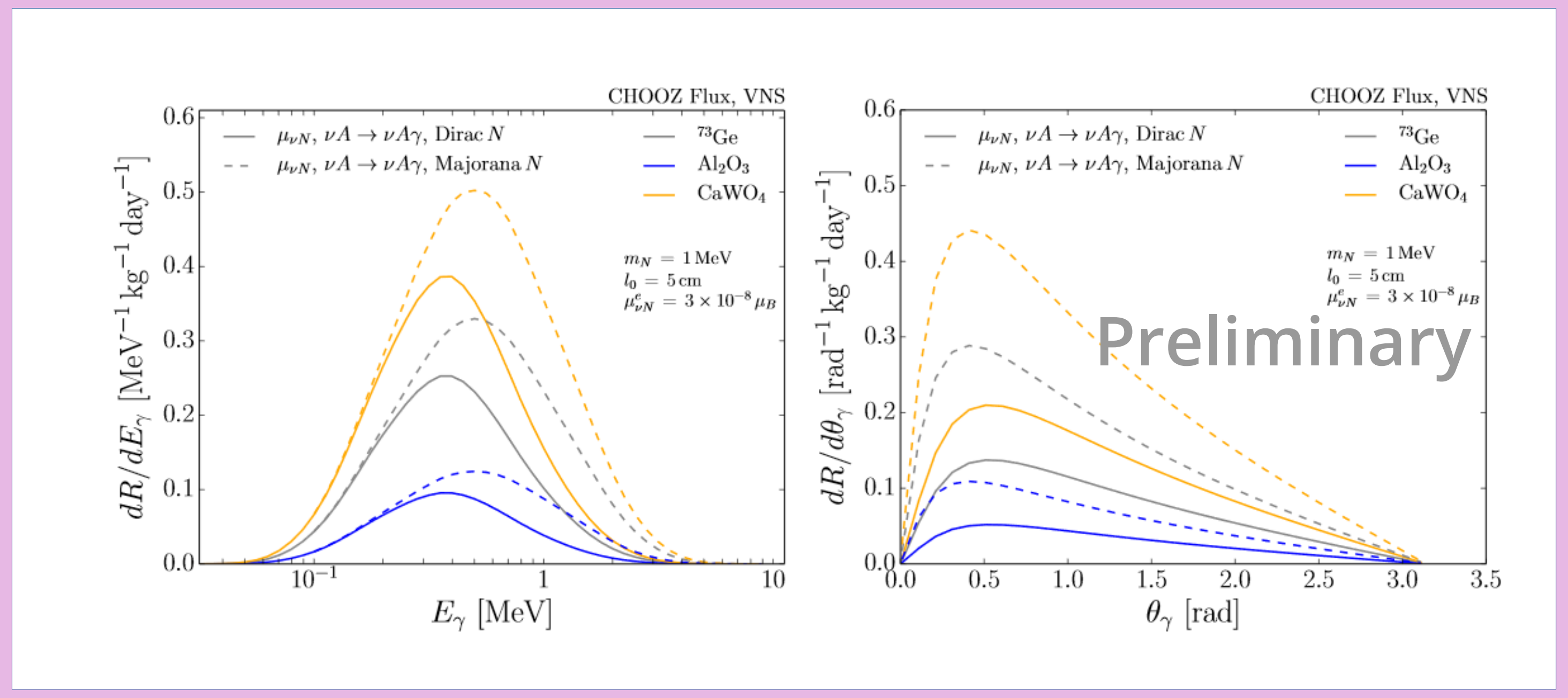
- Neutrino magnetic moments arise from vertices containing one incoming and one outgoing neutrino, as well as a photon.
- In this work we focus on transition magnetic moments, where one of the neutrinos is active and the other is sterile.
- Such a vertex can arise in for example renormalisable inverse see-saw models for both Dirac and Majorana active neutrinos [5].
- The magnetic moment vertex will itself contribute to a radiative active neutrino Majorana mass term.
- A transition magnetic moment further leads to the possibility of up-scattering in CEνNS processes, where an incoming neutrino transitions into a heavier sterile state when scattering with a nucleus.
- The nuclear recoil in up-scattering events is expected to be even lower than for regular CEνNS processes, therefore a very low threshold is needed.
- A subsequent decay of the heavy sterile state via the same magnetic moment vertex can provide a smoking-gun "shining CEνNS"-signal if observed.

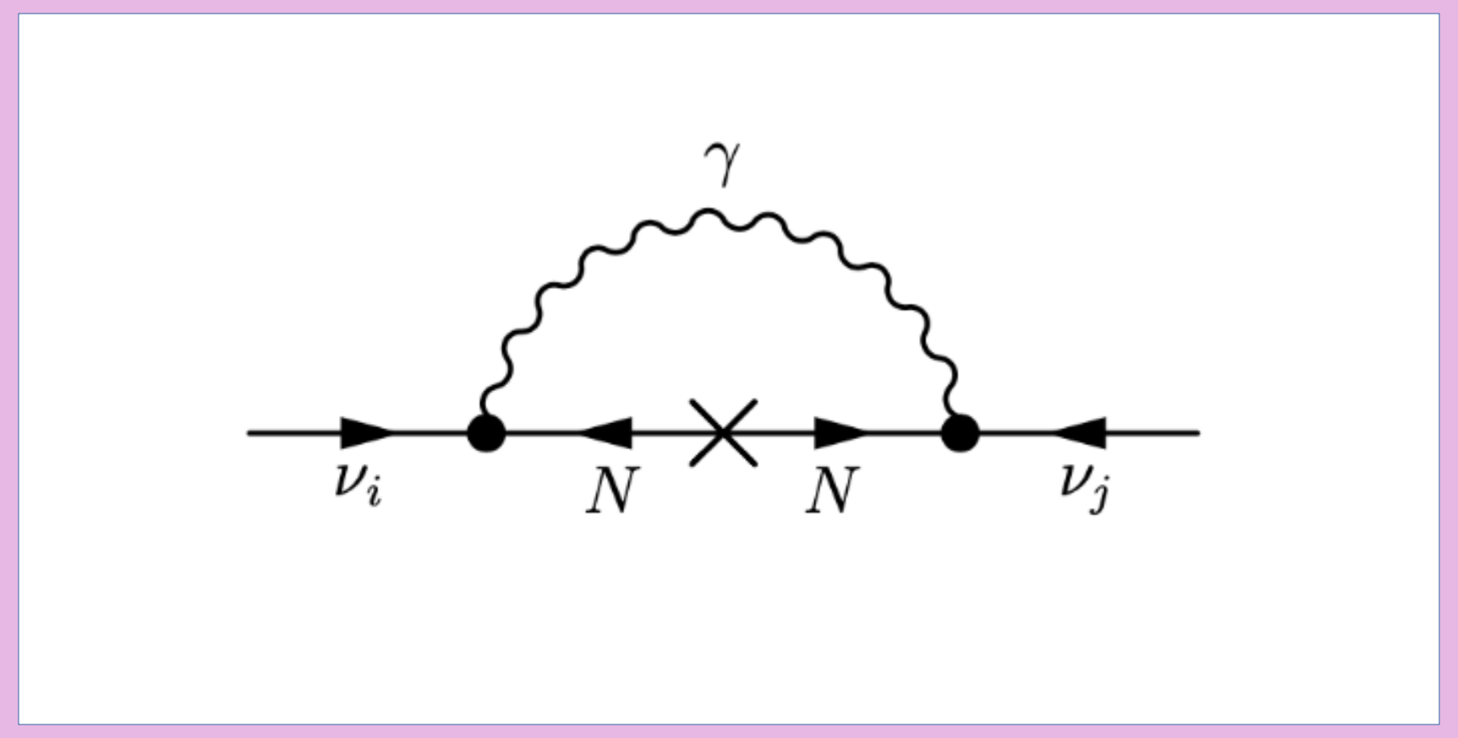
Constraints

- The neutrino magnetic moment coupling is constrained by many different experiments [6].
- Constraints on the μ-flavour are generally more stringent than those on the τ- and e-flavours, due to several experiments using neutrinos from pion decays as the source.
- Flavour-universal constraints coming from astrophysical observations mainly constrain the low sterile mass range of the parameter space.
- For the NUCLEUS experiment, the relevant constrains to consideer are those on the e-flavour, since the source of neutrinos at this experiment is a pair of nuclear reactors at CHOOZ, where electron flavoured neutrinos are produced in the rapid β-decays of fission by-products.
- Considering the full range of possible sterile neutrino decays, including decays into a photon + active neutrino as well as other exotic processes such as the decay into a photon + another generation of the sterile neutrino, the NUCLEUS experiment could probe well beyond current limits.

General scheme of the process that is considered. An incoming reactor neutrino ν with an energy of 10 keV – 9 MeV scatters with a nucleus A via a photon, and the nucleus recoils with an energy 10^{-4} – 1 keV. The neutrino has then transitioned into a sterile neutrino with a mass 10^{-3} – 9 MeV, which travels for a maximum distance of 5 cm before it subsequently decays into a photon and an active neutrino via the same transition magnetic moment coupling, where the final state photon has an energy 0.1 – 9 MeV and goes out with an angle between 0 and π/2 with respect to the incoming neutrino. In principle, the final state fermion could also be some other invisible fermion.

Distribution of photon energy (left) and photon angle with respect to the incoming neutrino (right) for the final state photon coming from the decay of a sterile neutrino that has been produced by scattering from a CEνNS target via a transition magnetic moment, for Dirac (solid) and Majorana (dashed) sterile neutrinos, and for different target materials ^{73}Ge (Grey), Al_2O_3 (Blue), and $CaWO_4$ (orange). Note that the energy is higher for Majorana sterile neutrinos, providing a possible distinction from Dirac sterile neutrinos.

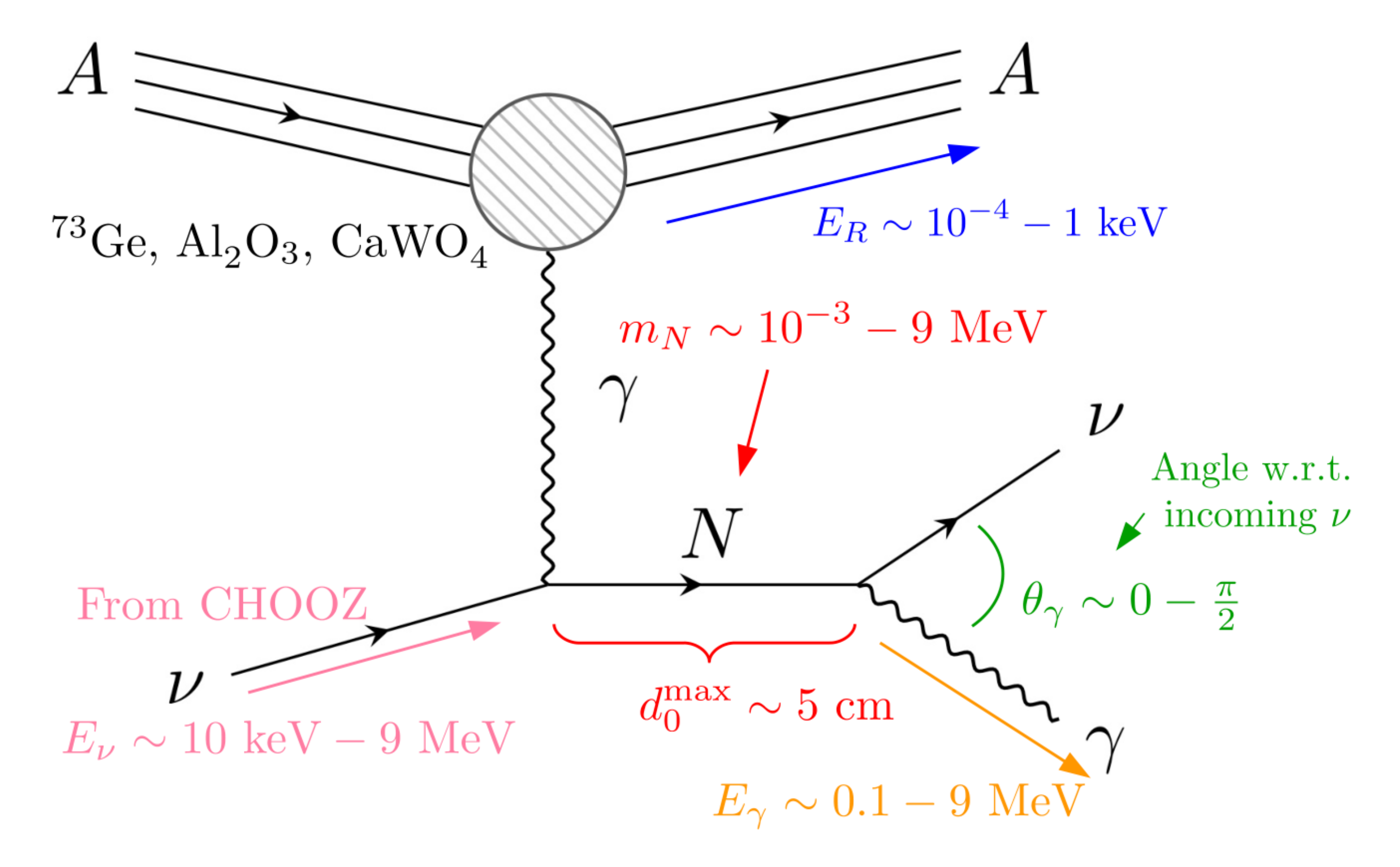




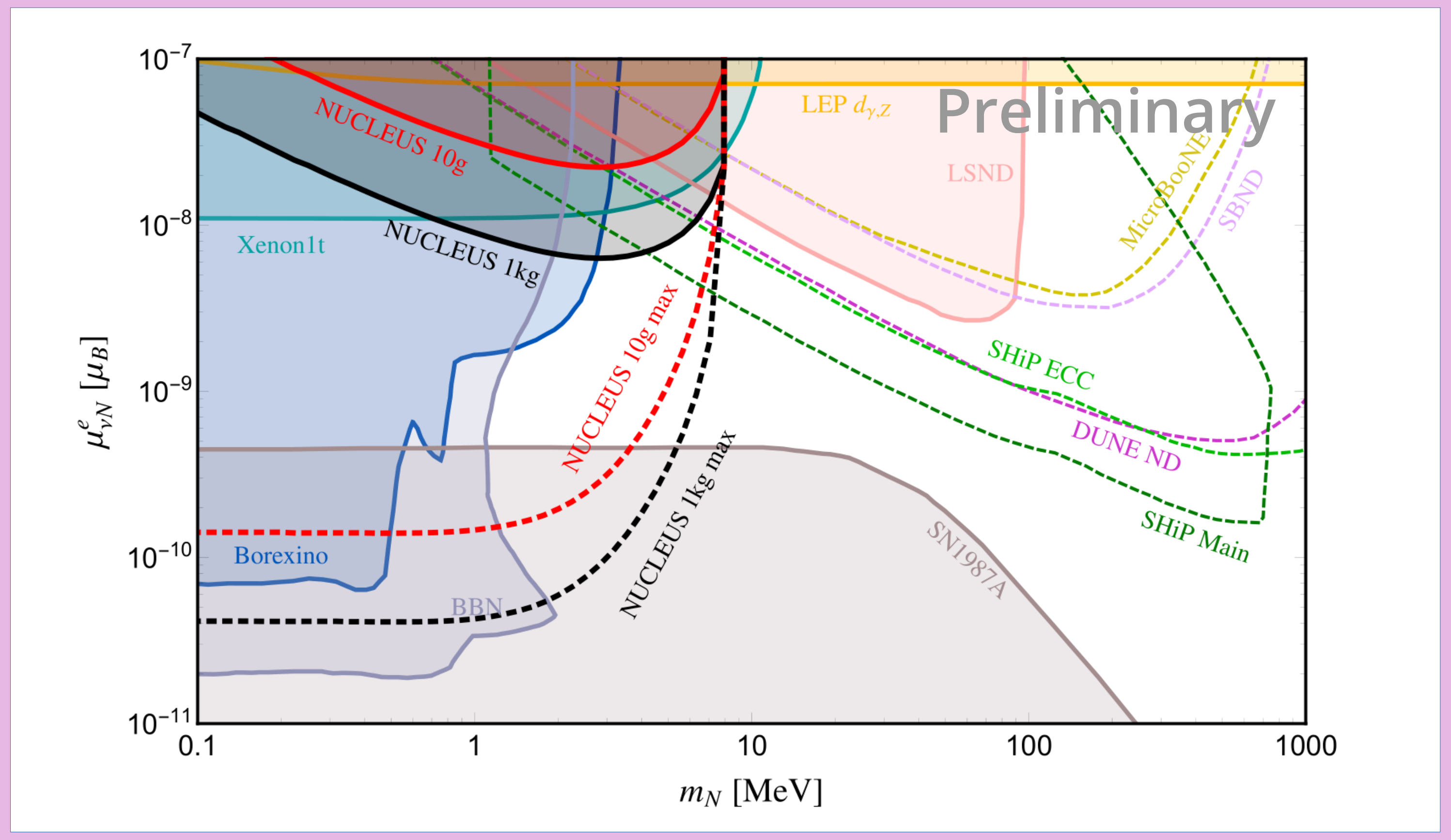
Two transition neutrino magnetic moment couplings along with a Majorana mass insertion contribute to a radiative active neutrino Majorana mass of the form

$$m_\nu \sim \left(\frac{\mu_{\nu N}}{\mu_B}\right)^2 \frac{\alpha}{16\pi}\frac{m_N\Lambda^2}{m_e^2}$$

Where Λ is the cut-off scale for the UV completion of the model that realises the magnetic moment coupling $\mu_{\nu N}$, m_N and m_e are the masses of the sterile neutrino and the electron, and μ_B is the Bohr magneton. For magnetic moment couplings close to current bounds, this mass contribution is small.



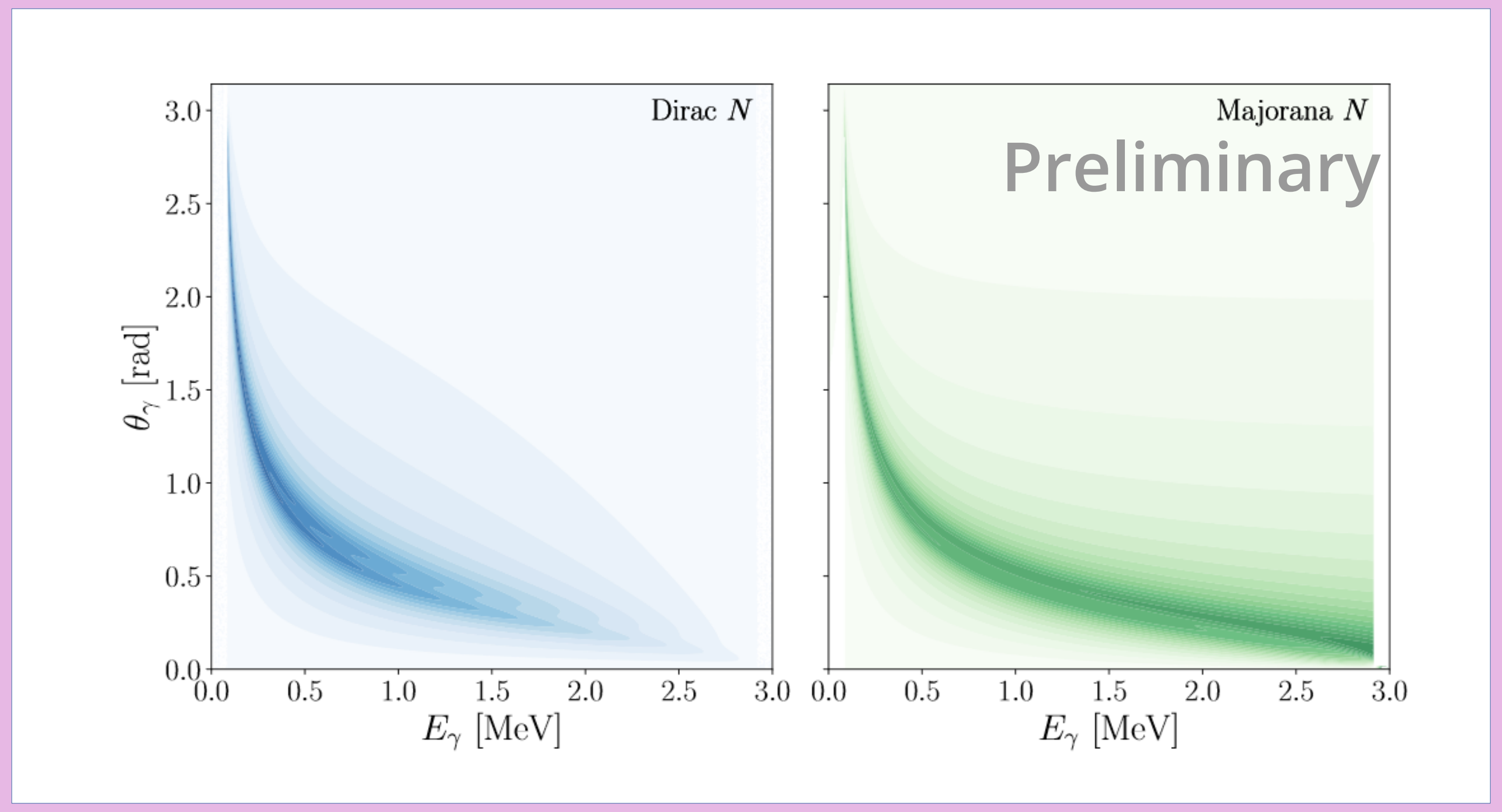
Constraints in the mass-coupling plane for the sterine neutrino N, where the coupling is only for the electron flavour. Note that the NUCLEUS 10g and 1kg lines correspond to up-scattering and decay via the same vertex with coupling $\mu_{\nu N}$, while the lines with "max" correspond to only upscattering. In the latter case, the sterile neutrino is assumed to decay into photon + invisible inside the detector.



Dirac vs Majorana

- In a "shining CEνNS" experiment, an incoming neutrino transitions into a heavy sterile neutrino when scattering with a nucleus, after which the sterile neutrino decays into a photon + fermion.
- The distribution in both angle and energy (~MeV) of the final state photon will depend on wether the sterile neutrino is Dirac or Majorana.
- The key mechanism behind this difference is the possibility of a Majorana mass insertion in the propagator for Majorana sterile neutrinos, flipping the helicity of the final state fermion. This mode is absent for Dirac sterile neutrinos.
- At the NUCELUS experiment, distinguishing Dirac from Majorana sterile neutrinos could be most effectively done in terms of the photon energy rather than the photon angle, since the angular difference is smaller than the energy difference.
- The NUCLEUS experiment does not yet have the capacity to detect the final state photons. We suggest a new type of experiment where these photons are captured.

Expected distribution of events in the mass-coupling plane for Dirac (left) and Majorana (right) sterile neutrinos, with arbitrary units (more intense color means more expected events). Note that the distribution for Majorana neutrinos extends all the way to the bottom right corner, while for Dirac neutrinos it fades off and is concentrated towards low masses. This is a possible signature that can be used experimentally to distinguish Dirac from Majorana sterile neutrinos



Results

- "Shining CEνNS" could be searched for with possible upgrades to existing and future experiments that include ways to detect the final state photon.
- We find that the difference in energy distribution of the final state photons for Dirac and Majorana sterile neutrinos could potentially be used to distinguish the two types.
- This holds true for a reactor-based CEνNS experiment such as NUCLEUS, where the incoming neutrinos have a wide energy spectrum. It could potentially also hold true for other sources of neutrinos, where a more narrow energy distribution could potentially help in the distinction.
- More than distinguishing between Dirac and Majorana, we find that CEνNS experiments with final state photon detection can be used to probe neutrino magnetic moment couplings beyond the current constraints.
- If more exotic decays of the sterile neutrino are considered, NUCLEUS will probe regions of parameter space well beyond current limits.

Conclusion

- We propose a new type of experiment where a photon detector is placed downstream of a CEνNS target, such that final state photons from two-body decays of sterile neutrinos can be detected.
- This new experiment can be realized as a plausible upgrade to current or future CEνNS experiments, with very exciting future prospects.
- We perform a case study for a potential upgrade to the NUCLEUS experiment, which uses reactor neutrinos as the source, but a similar upgrade could also be considered for experiments with other neutrino sources, such as solar or atmospheric neutrinos, or neutrinos from beam dumps.
- A positive signal in such an experiment would be a clear signal of New Physics beyond the SM, and could shed light on the mechanism that generates the mass of the active neutrinos.
- Based on the difference in the photon energy distribution coming from Dirac and Majorana sterile neutrinos, these two types could potentially be distinguished from each other.