Technische Universität München

Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

Probing Dirac vs Majorana nature of neutrinos @ CEνNS experiments

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Based on arXiv:2109:XXXX (to appear soon!) in collaboration with

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DESY THEORY WORKSHOP
21 - 24 September 2021

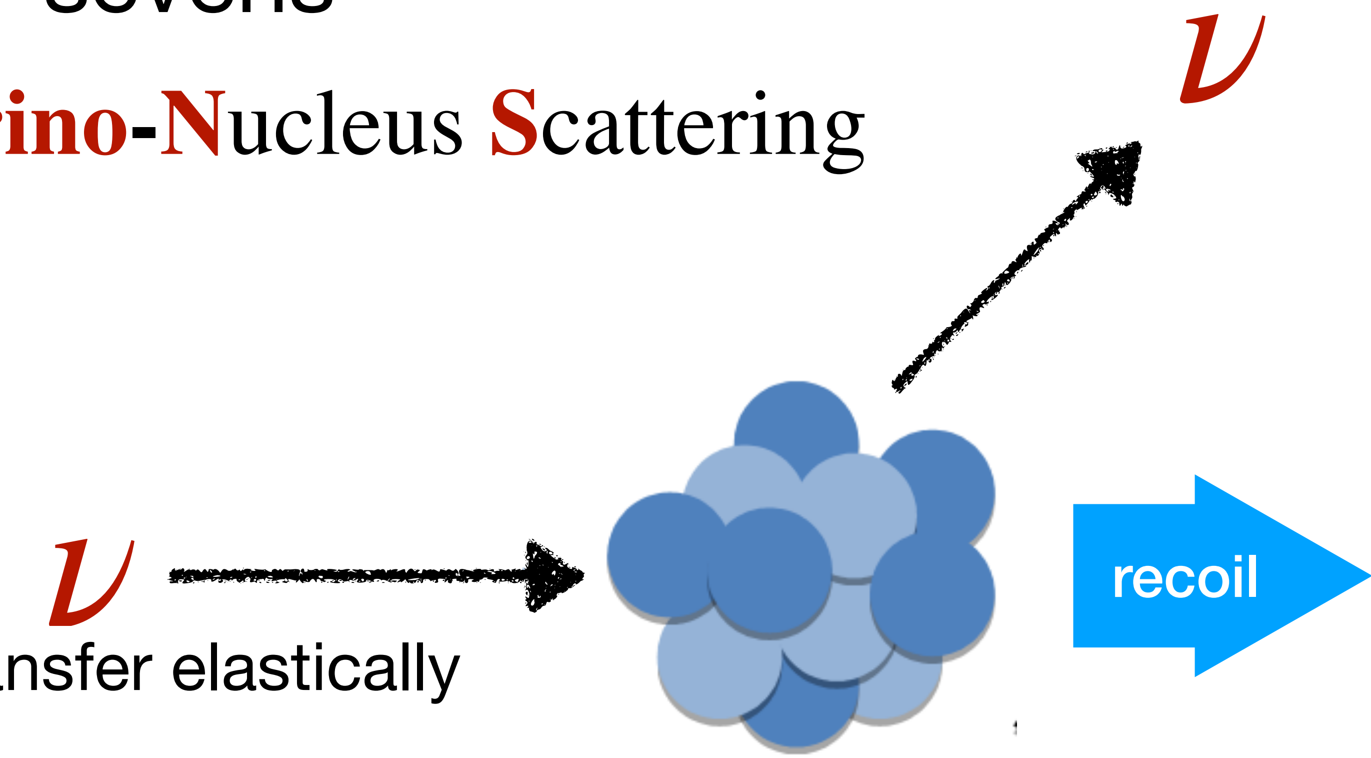
Bright ideas for a dark universe

21 September 2021

Introduction

CEνNS: pronounced "sevens"

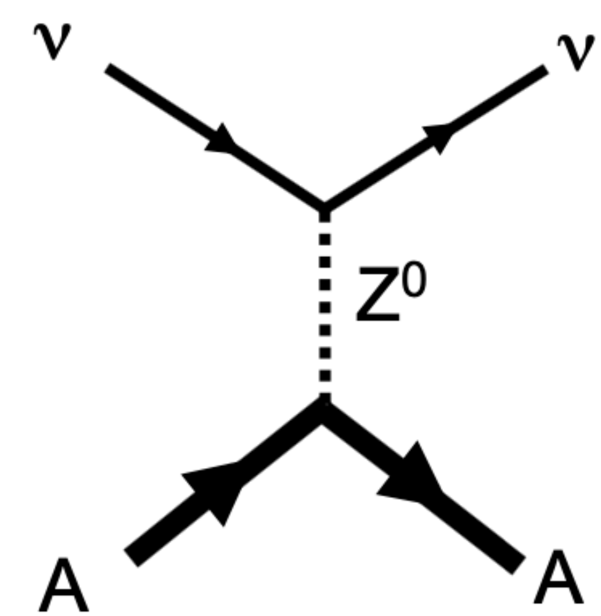
Coherent **E**lastic **Neutrino**-**N**ucleus **S**cattering



First proposed 47 years ago! **Freedman '74**

Neutrino scatters with low momentum transfer elastically from entire nucleus

$$E_\nu \lesssim \frac{hc}{R_N} \sim \mathcal{O}(10\ \text{MeV})$$ for coherence



The nuclear recoil energy: $E_r^{\text{max}} = \frac{2E_\nu^2}{M_A} \sim \mathcal{O}(\text{KeV})$

SM allowed process but hard to observe due to small nuclear recoil energy!

Experiments

First observation in Aug 2017 by

COHERENT Experiment

Akimov et al. Science 2017

Spallation Neutron Source @ Oak Ridge

Threshold:

A few keV

NUCLES Experiment @ CHOOZ

Threshold:

10's of eV !

- funded, work ongoing

Other experiments:

- CONUS (MPIK)
- MINER (US)
- RICOCHET (US+FR)
- CONNIE (int.)

Excellent current and future prospects in sensitivity

Beyond Standard Model: motivation

The only laboratory evidence of BSM physics so far:

neutrino oscillations => neutrino masses → **Dirac vs Majorana** / **generation mechanism**

Why CEνNS?

The physics potential of CEνNS is enormous!

Explore fundamental neutrino interactions and properties — **focus of this talk!**

Precision tests of electroweak theory

Nuclear form factors

Dark matter

Supernovae

Reactor physics

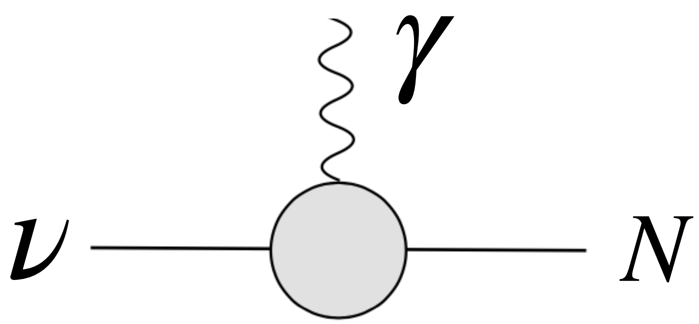
New detector technology ++

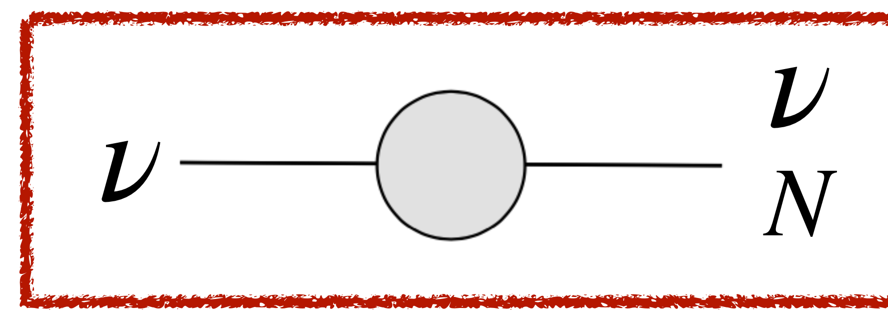
- ν magnetic moment
  Coloma et al., PRL 119 201804 (2017)
  Magill et al., PRD 98 115015 (2018)
  Miranda et al., JHEP 07 103 (2019)
  Schwetz et al., 2105.09699 ++
- ν oscillation parameters
  Coloma et al., PRD 94 055005 (2017)
  Coloma et al., PRD 96 115007 (2017)
  Denton et al., arXiv:2008.01110 (2020)
  Esteban et al. JHEP 06 055 (2019) ++
- non-standard interactions
  Bhupal Dev et al., 1907.00991
  Coloma et al., JHEP 02 023 (2020)
  Khan et al., PRD 104 015019 (2021) ++

Key BSM ingredients

sterile neutrino + active sterile transition magnetic moment

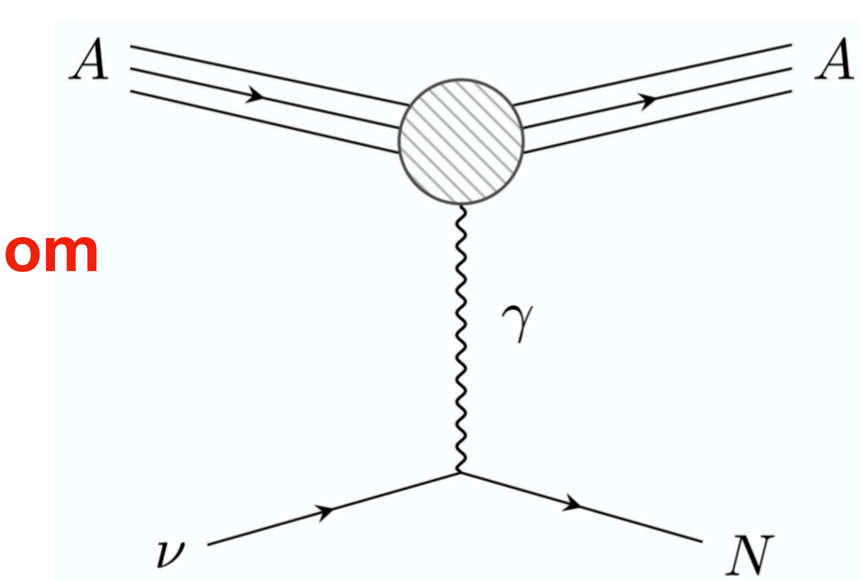
$$\mathcal{L} \supset \mu_{\nu N}^{\alpha} \bar{\nu}_{\alpha L} \sigma_{\mu\nu} N_R F^{\mu\nu} + \text{h.c.}$$





correlation with active neutrino mass (more on this later!)

Primakoff upscattering process $\nu A \to NA$



$$\frac{d\sigma}{dt} \propto \mu_{\nu N}^2$$

limit on the transition mag. mom

cannot give information about the nature of N

But what if the N decays to $N \to \nu\gamma$?

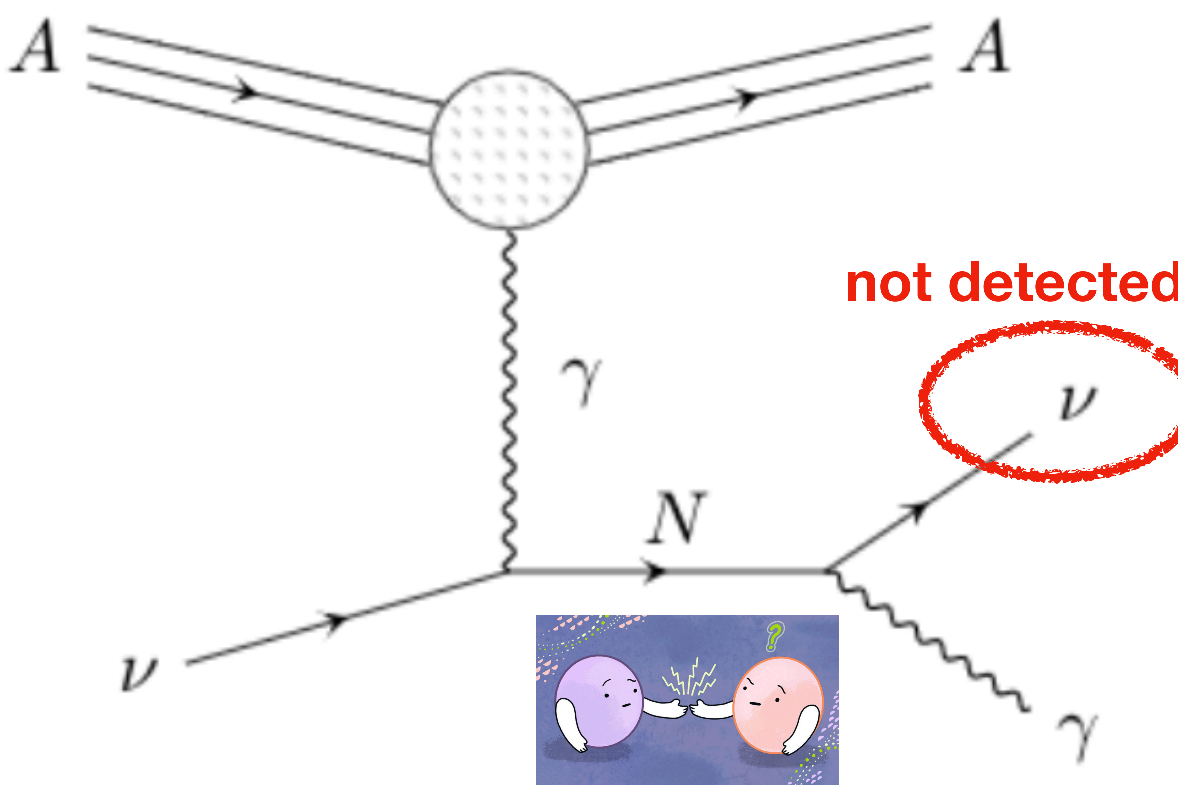
“Shining” CEνNS

Three body distributions can give a lot more information

For $M_N < E_\nu$, N can be produced on-shell: resonant enhancement

The outgoing ν can be a neutrino/anti-neutrino for Majorana N

The amplitude for the process looks different for Dirac vs Majorana N



Experimentally very exciting!

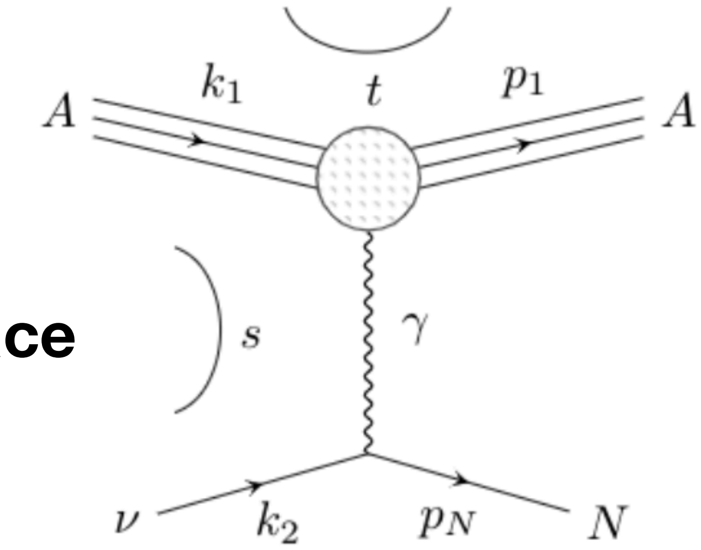
Realistic experimental possibility to detect the outgoing photon

Coincidence of nuclear recoil and outgoing photon can lead to excellent background rejection

The kinematics

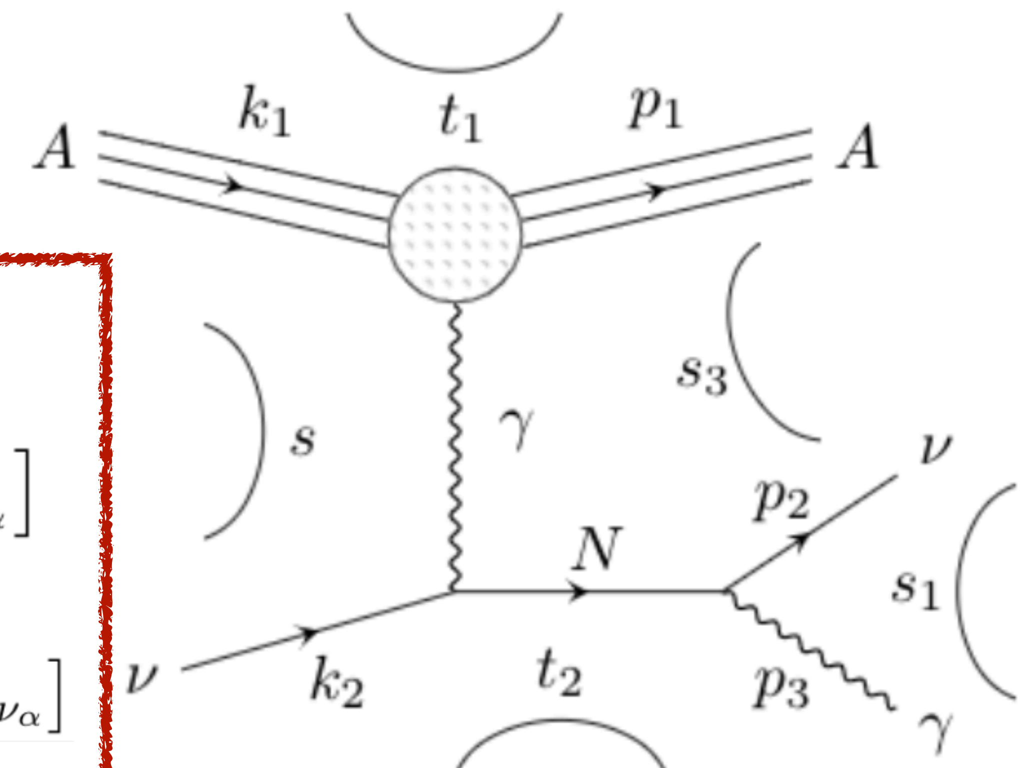
The kinematics and differential distribution is
more involved than simple upscattering

Technical details in paper!



phase space ↓

$$d^5\sigma_{\nu_\alpha A\to\nu_\beta A\gamma} = \frac{1}{2(s-m_A^2)}\frac{1}{2}\sum_{\text{spins}}|\mathcal{M}^{\text{D(M)}}_{\nu_\alpha A\to\nu_\beta A\gamma}|^2 d\Phi_3$$



Dirac vs Majorana

$$i\mathscr{M}_{\textbf{Dirac}} \propto \left[\bar{u}_{\nu_\beta}\sigma_{\lambda\xi}P_R\epsilon^{\lambda *}p_3^\xi i(\not{p}_N + m_N)\sigma_{\mu\rho}P_L q^\rho u_{\nu_\alpha}\right]$$

$$i\mathscr{M}_{\textbf{Maj}} \propto \left[\bar{u}_{\nu_\beta}\sigma_{\lambda\xi}(P_R - P_L)\epsilon^{\lambda *}p_3^\xi i(\not{p}_N + m_N)\sigma_{\mu\rho}P_L q^\rho u_{\nu_\alpha}\right]$$

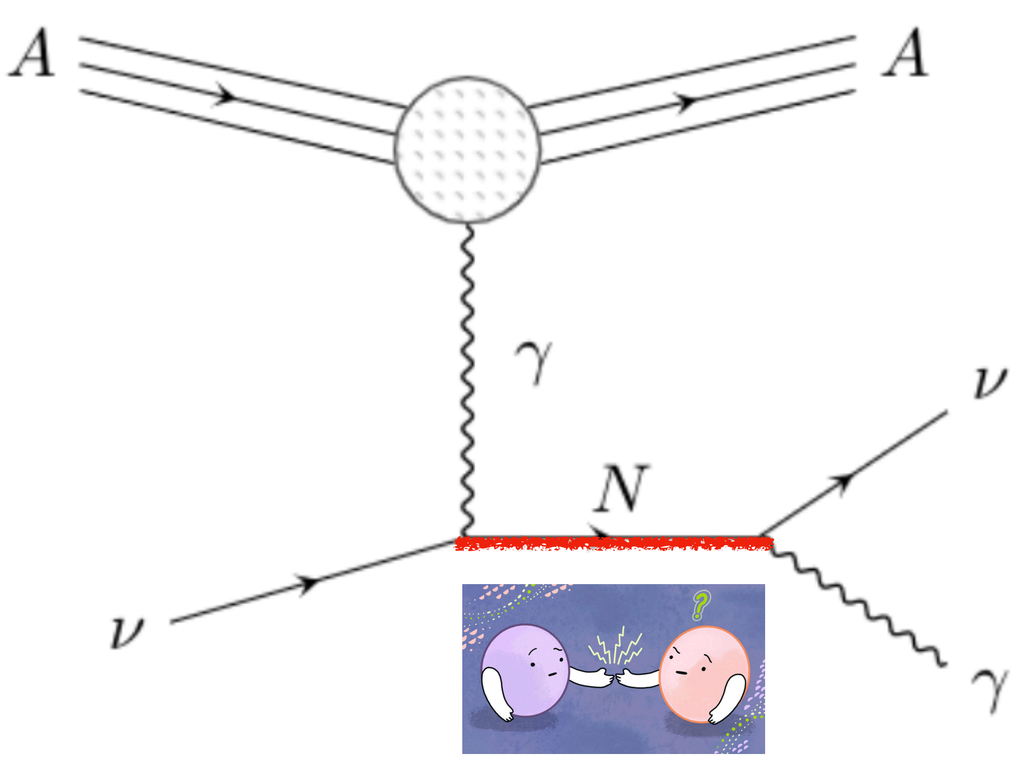
integrating over the other free phase space parameters
=> differential distributions in desired lab frame variables

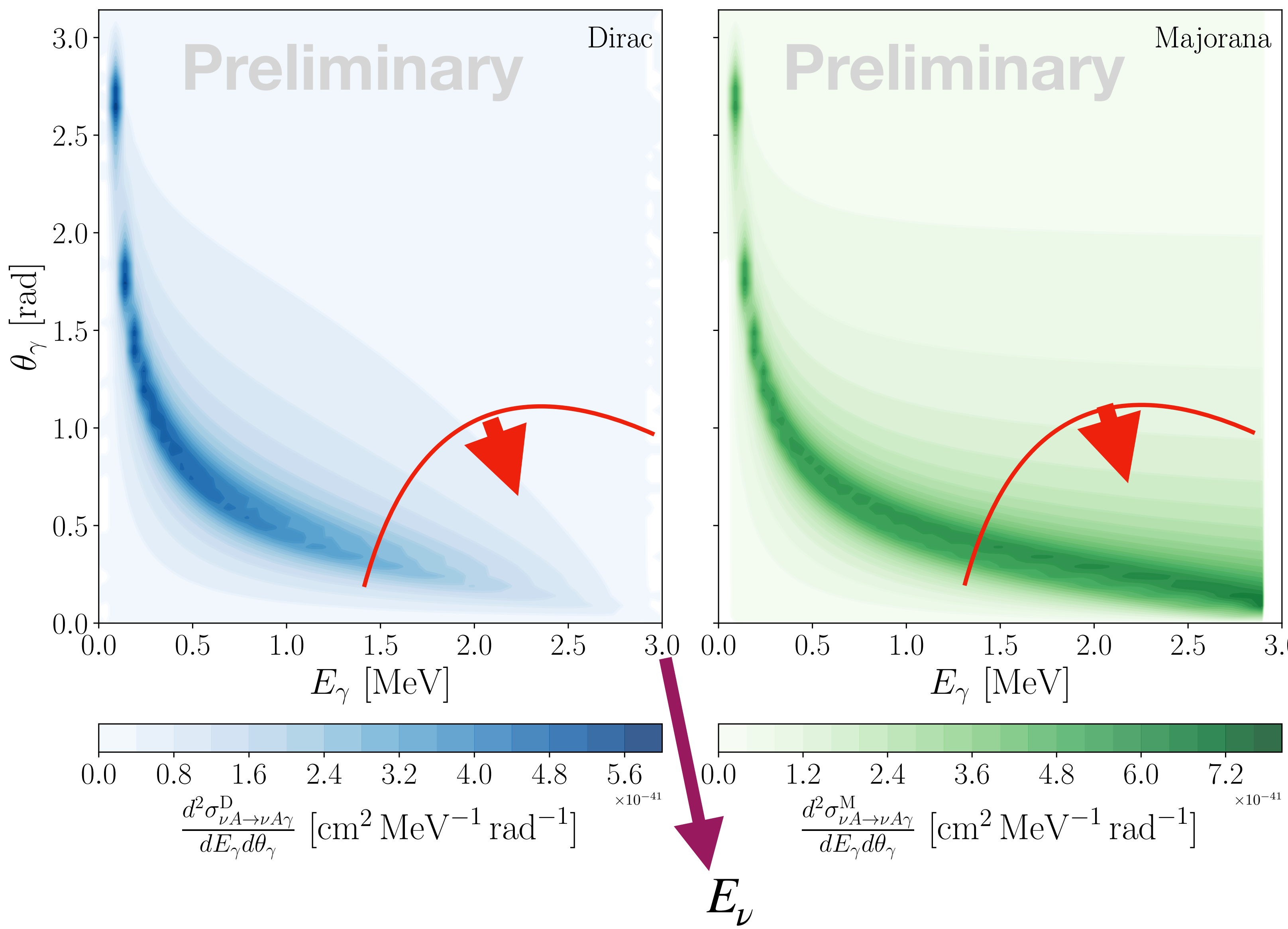
$$\frac{d^2\sigma^{\text{D(M)}}_{\nu_\alpha A\to\nu_\beta A\gamma}}{dE_\gamma d\theta_\gamma} \qquad \frac{d\sigma^{\text{D(M)}}_{\nu_\alpha A\to\nu_\beta A\gamma}}{dE_R}$$

Details in the "shine": Dirac vs Majorana sterile

Benchmark choices: $E_\nu = 3$ MeV $\quad m_N = 1$ MeV $\quad \mu^e_{\nu N} = 3\times 10^{-8}\mu_B$

For a realistic experiment: integrated over the flux + sterile decay width from detector dimensions





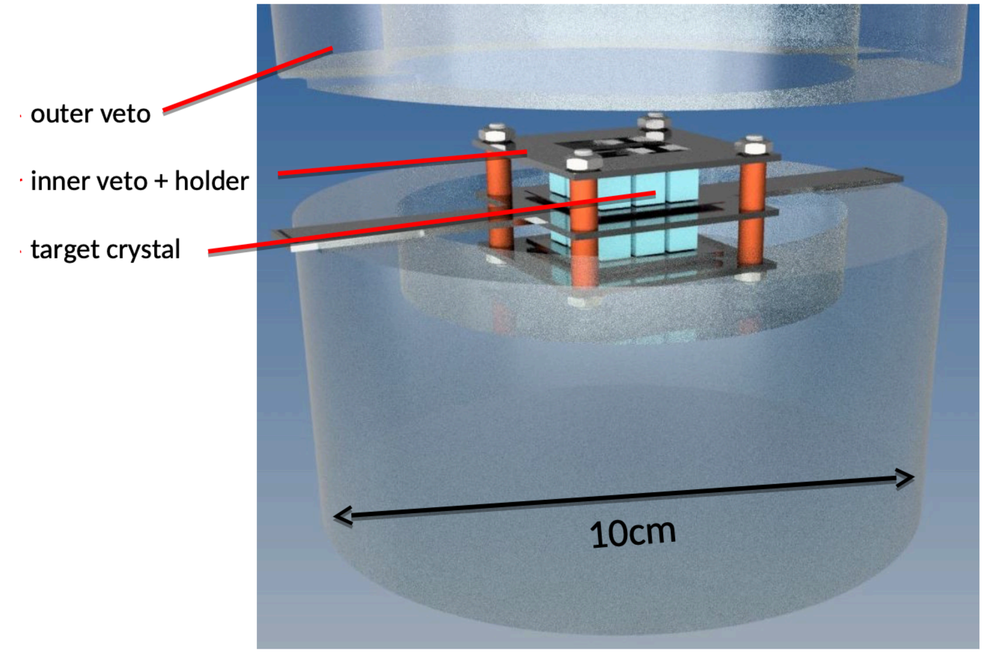
Clear distinction for $E_\gamma > E_\nu/2$

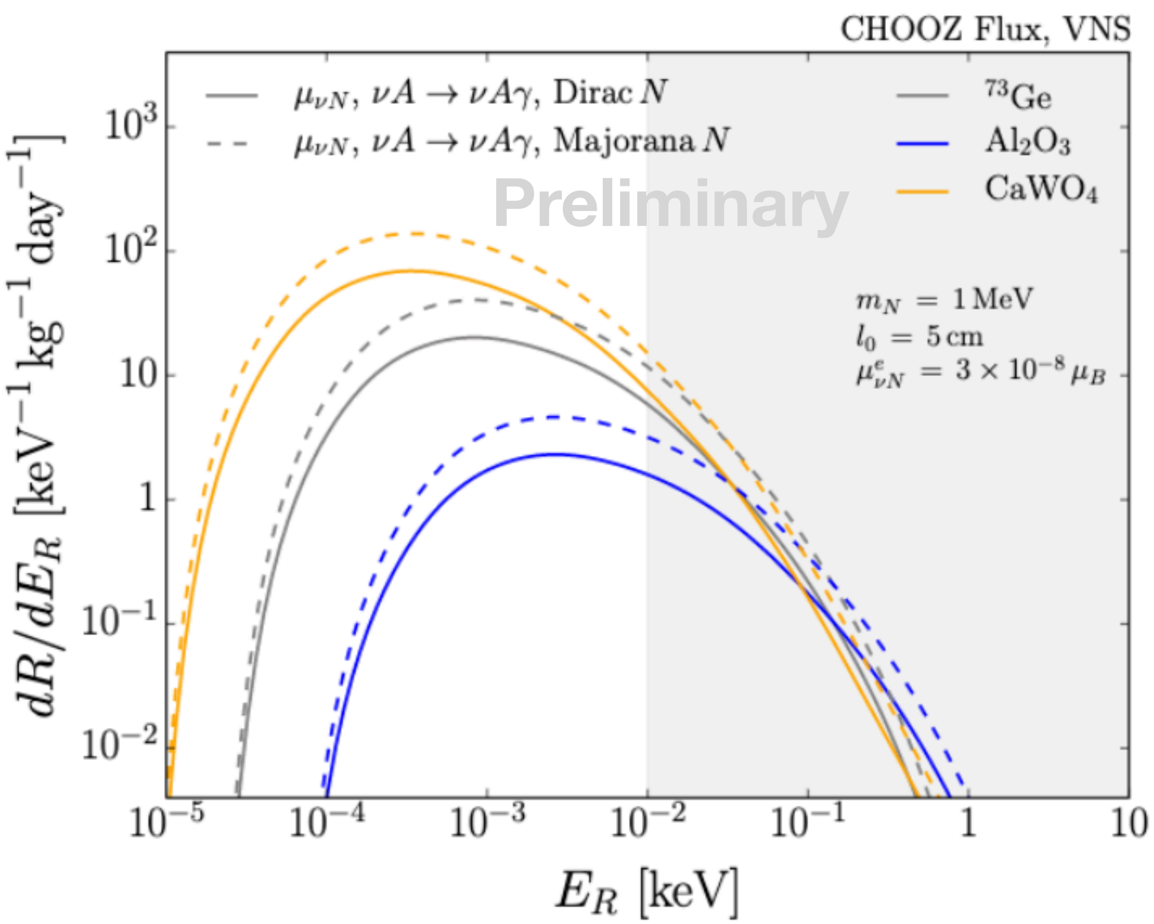
Different reactor neutrino energy -> access to wider sterile mass range

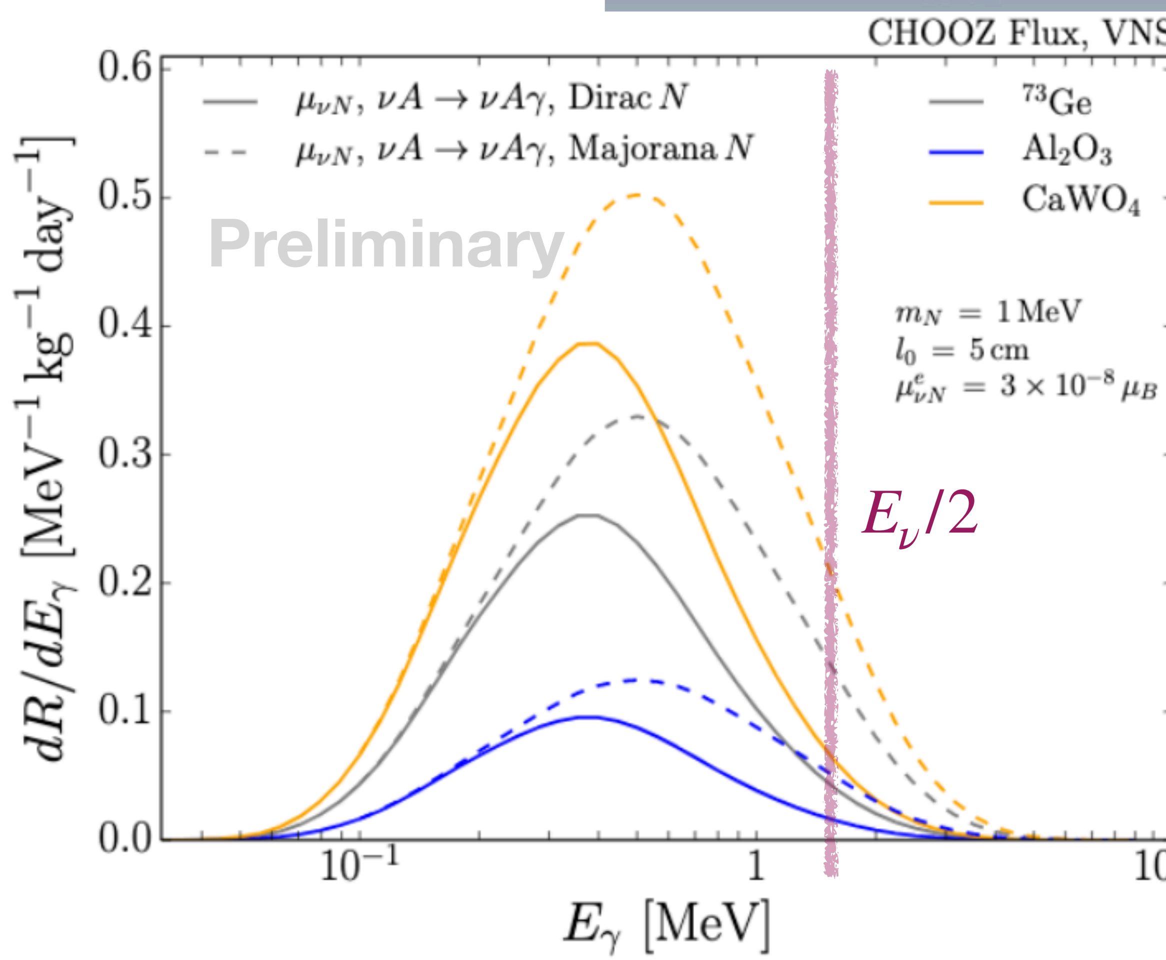
Coincidence for BG rejection: realistic @ experiments like NUCLEUS

Taking NUCLEUS @ CHOOZ as a case study

- 10g for NUCLEUS-Phase 1 (funded, work ongoing)
- Future 1kg upgrade possibility
- Sensitivity to photon energy: 1 keV to 10 MeV







Dirac case photon energy distribution falls off very quickly after $E_\gamma > E_\nu/2$

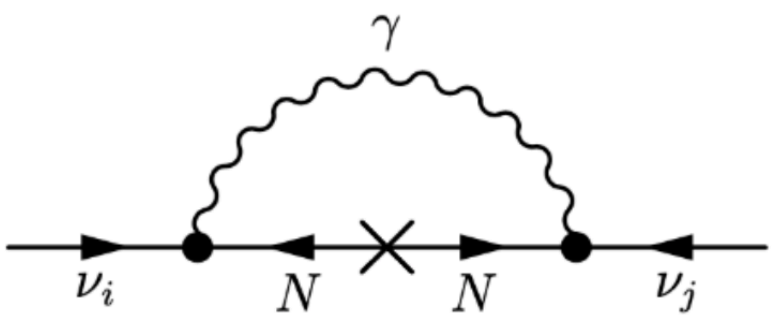
NUCLEUS can provide an energy resolution: 50-100 keV @MeV energies

Insight into the nature of active neutrinos?

For a distribution consistent with Majorana N

Majorana N + a transition dipole moment =>
majorana nature of active neutrino

$$m_\nu^{\textbf{Maj}} \sim \mu_{\nu N}^2 \frac{\Lambda^2 m_N^{\textbf{Maj}}}{16\pi^2}$$



Complimentary to $0\nu\beta\beta$ decay and LNV rare meson decays

Depending on the event rate distribution for $\nu A \to \nu A \gamma$,
limits can be drawn on the $\mu_{\nu N}$ vs m_N^{Maj} plane:
hints for active neutrino mass mechanisms

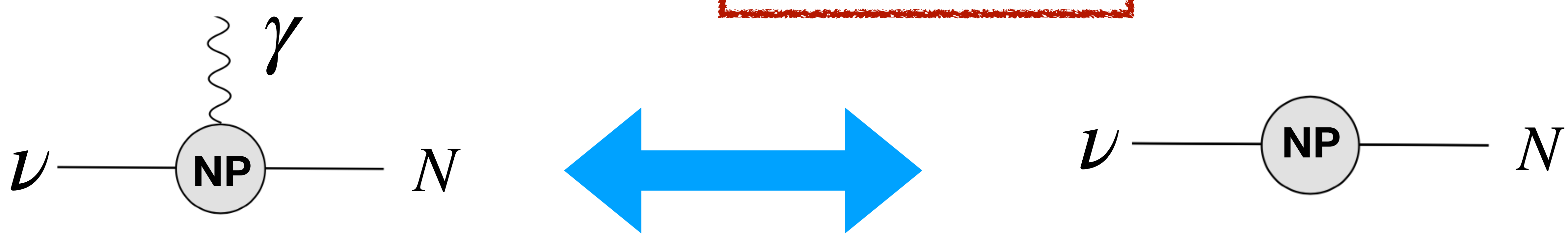
For a distribution consistent with Dirac N
no conclusive statement can be made about the nature of ν

Hints on the neutrino mass mechanism?

$\nu A \to \nu A \gamma$ **distribution consistent with Majorana sterile**

a transition magnetic moment via a loop diagram with heavy NP (Λ)=>
A Dirac mass term. $m_{\nu N}\,\bar{\nu}_L N_R$

$$\frac{\mu_{\nu N}}{\mu_B} \approx \frac{m_e\,\delta m_{\nu N}}{\Lambda^2}$$



sizeable mass mixing between active and sterile states =>
transition magnetic moment induced through loop diagrams involving charged leptons

$$\frac{|\mu_{\nu N}|}{\mu_B} = \frac{3 m_{\nu N} m_e}{16\pi^2}\frac{G_F}{\sqrt{2}} \sim 10^{-13}\left(\frac{m_{\nu N}}{1\ \mathrm{MeV}}\right)$$

Pal 1981, Shrock1982

too tight to explain a signal for radiative CEνNS for canonical type I seesaw !

preferred scenarios: **“Voloshin” mechanism**
Inverse seesaw etc.

(“unnatural” cancellation with tree level mass term)

Hints on the neutrino mass mechanism?

$\nu A \to \nu A \gamma$ **distribution consistent with Dirac sterile**

Basis of independent operators at d=6 Bell et al. PRL 2005

$$\mathcal{O}_1^{(6)} = g_1 \bar{L}\tilde{H}\sigma^{\mu\nu} N_R B_{\mu\nu}$$

$$\mathcal{O}_2^{(6)} = g_2 \bar{L}\tau^a \tilde{H}\sigma^{\mu\nu} N_R W^a_{\mu\nu}$$

$$\mathcal{O}_3^{(6)} = \bar{L}\tilde{H}N_R \left(H^\dagger H\right)$$

$$\frac{\mu_{\nu N}}{\mu_B} = -16\sqrt{2}\left(\frac{m_e v}{\Lambda^2}\right)\left[C_1^{(6)}(v) + C_2^{(6)}(v)\right]$$

$$\delta m_{\nu N} = -C_3^{(6)}(v)\frac{v^3}{2\sqrt{2}\Lambda^2}$$

operator mixing=>

$$\frac{|\mu_{\nu N}|}{\mu_B} \sim 10^{-15}\left(\frac{\delta m_{\nu N}}{1\ \text{eV}}\right) \textbf{ for } \quad \Lambda = 1\ \textbf{TeV}$$

Again: non-trivial mechanism/symmetry needed to get large mag. mom. without blowing up ν mass

Concluding remarks

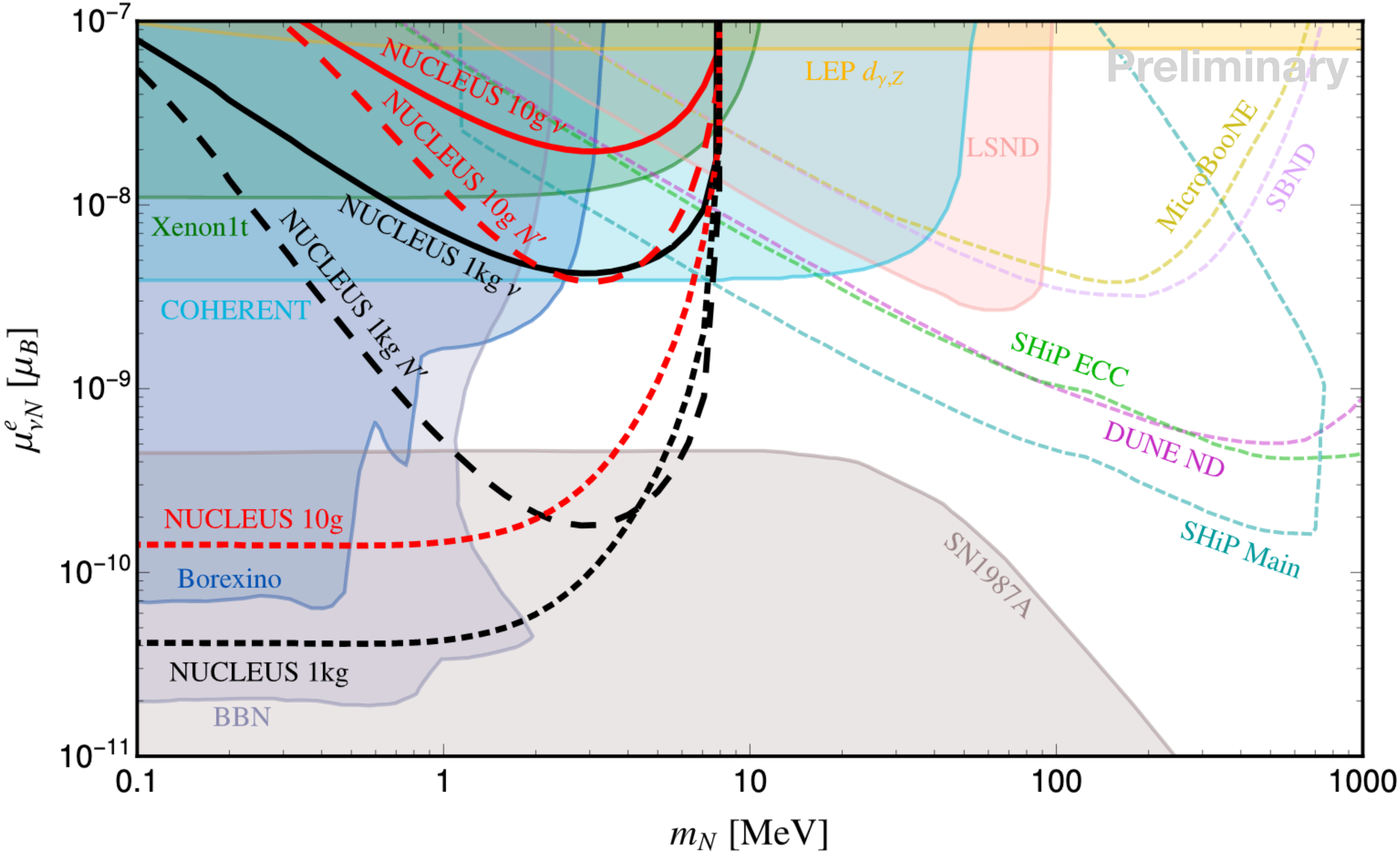
Radiative CEνNS ($\nu A \rightarrow \nu A\gamma$) distributions can give very exciting insights into neutrino mass in the presence of active-sterile transition magnetic moment.

Dirac vs Majorana sterile states lead to different and distinguishable distributions for outgoing photon

Unprecedented sensitivity within reach in CEνNS experiments in near future

Realistic possibility to probe such distributions @ CEνNS experiments like NUCLEUS

Backup-I



limits from different experiments or astrophysical processes (solid lines)

projected exclusion limits from future experiments (dashed lines)