Emmy Noether-Programm
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Physik Department T70
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Distinguishing Dirac vs Majorana Neutrinos @ CEνNS experiments

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Based on arXiv:2108:XXXX (to appear soon!) in collaboration with

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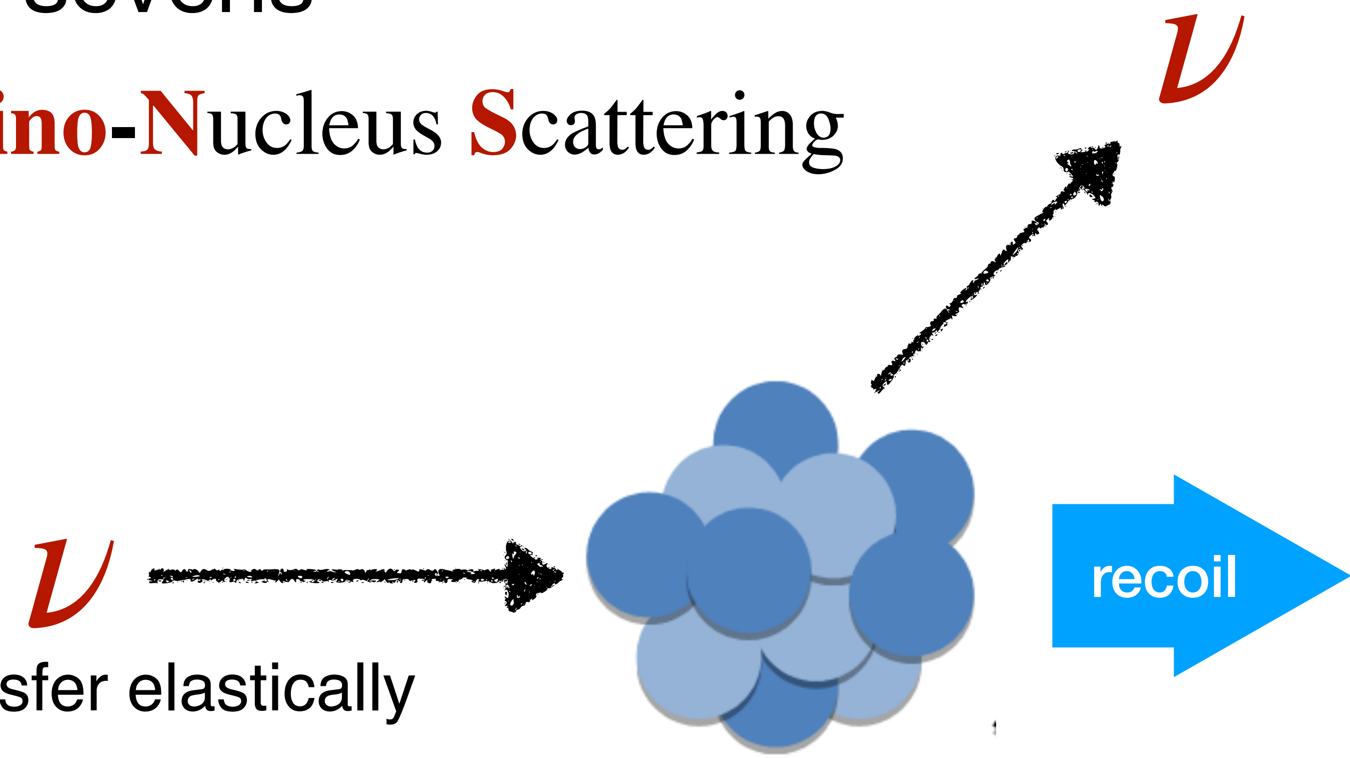
Introduction

CEνNS: pronounced “sevens"

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

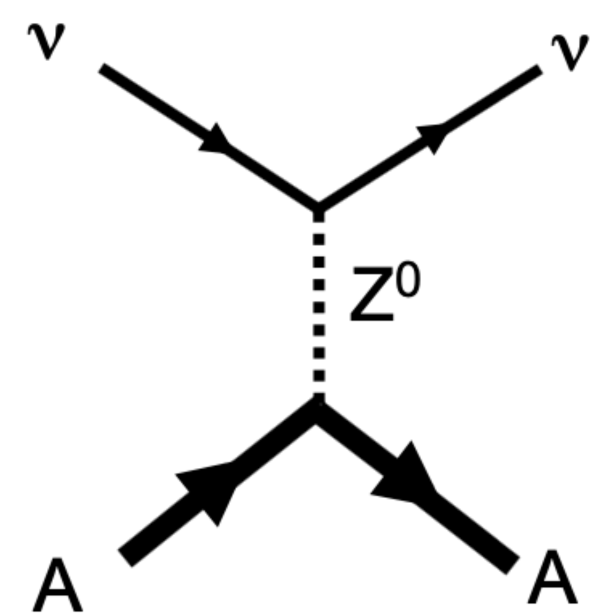
First proposed 47 years ago! **Freedman ’74**



Neutrino scatters with low momentum transfer elastically from entire nucleus

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

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



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) ++

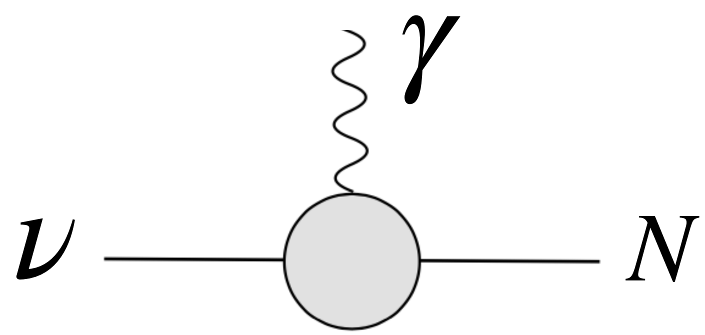
- non-standard interactions

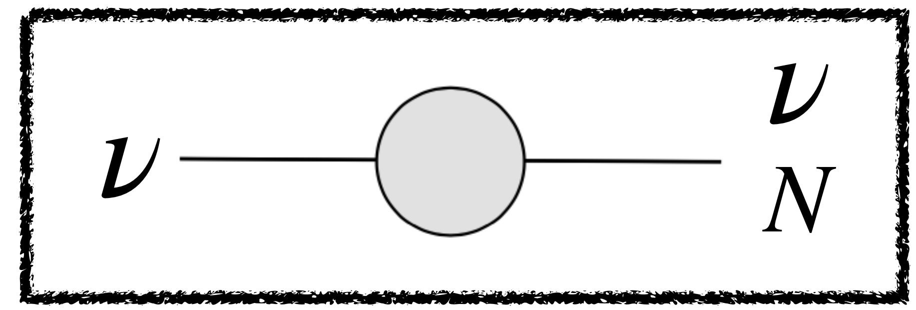
Bhupal Dev et al., 1907.00991
Coloma et al., JHEP 02 023 (2020)
Khan et al., PRD 104 015019 (2021) ++

Key BSM ingredients

sterile neutrino + active sterile transition magnetic moment

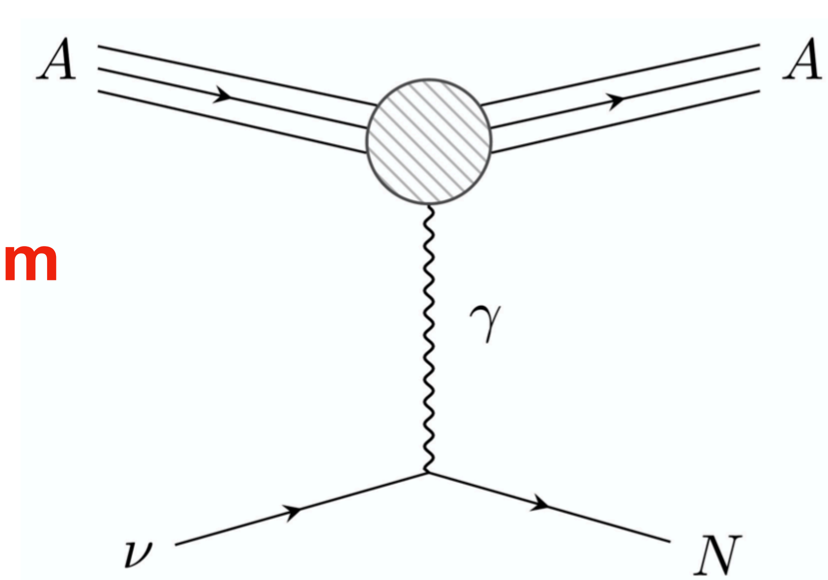
$$\mathcal{L} \supset \mu^{\alpha}_{\nu N} \bar{\nu}_{\alpha L} \sigma_{\mu\nu} N_R F^{\mu\nu} + \text{h.c.}$$





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

Primakoff up scattering process $\nu A \to NA$



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

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

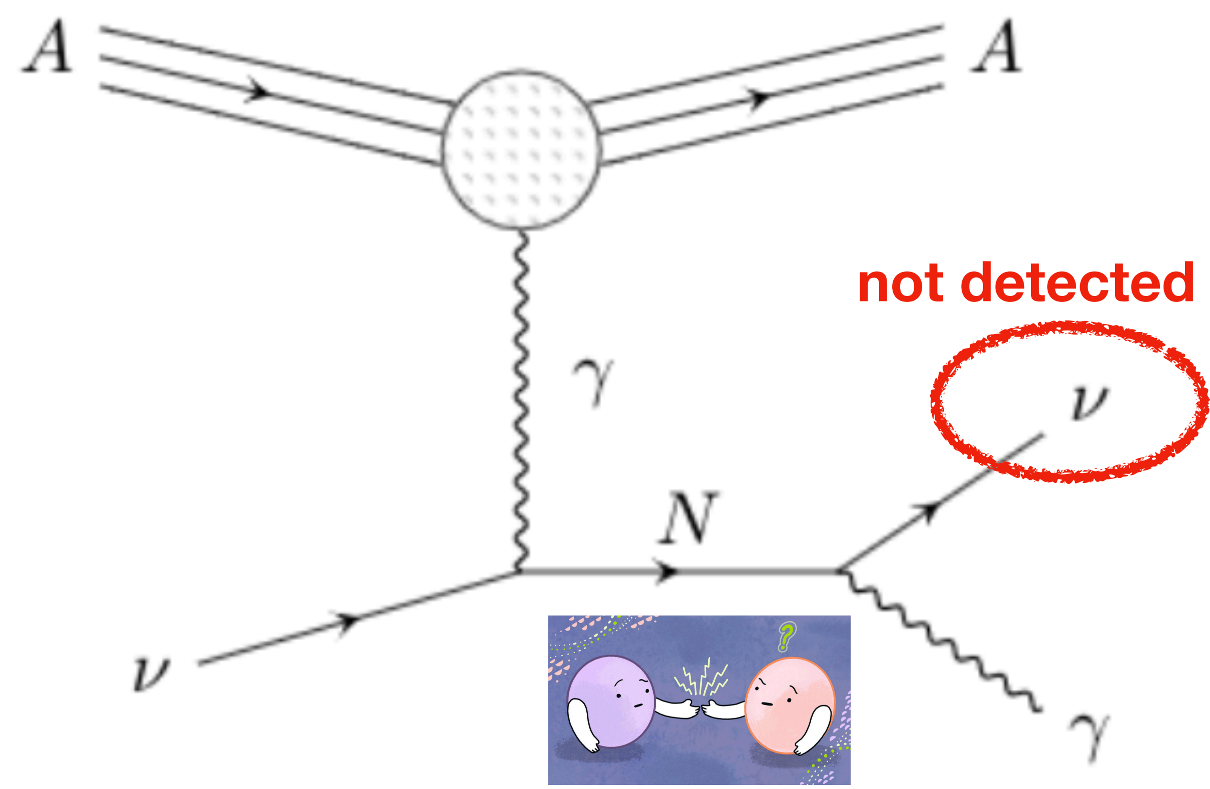
Three body final state

Differential distributions can give a lot of different information

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

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

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

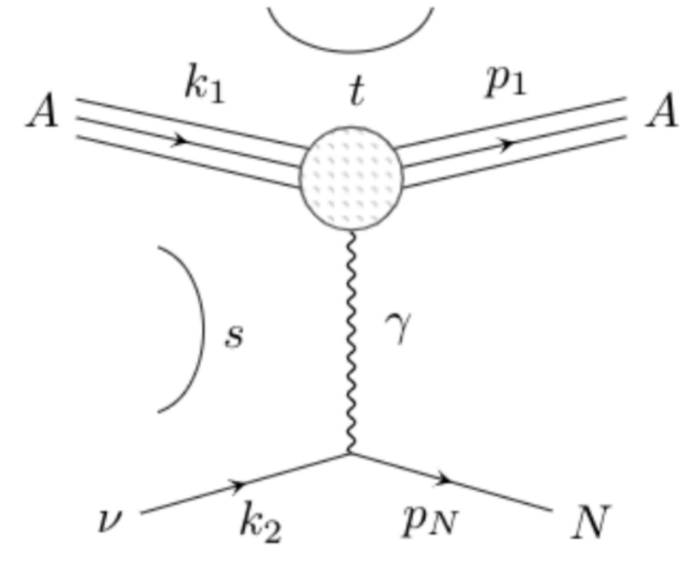
The kinematics

The kinematics and differential distribution is more involved than simple upscattering

Technical details in paper!

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

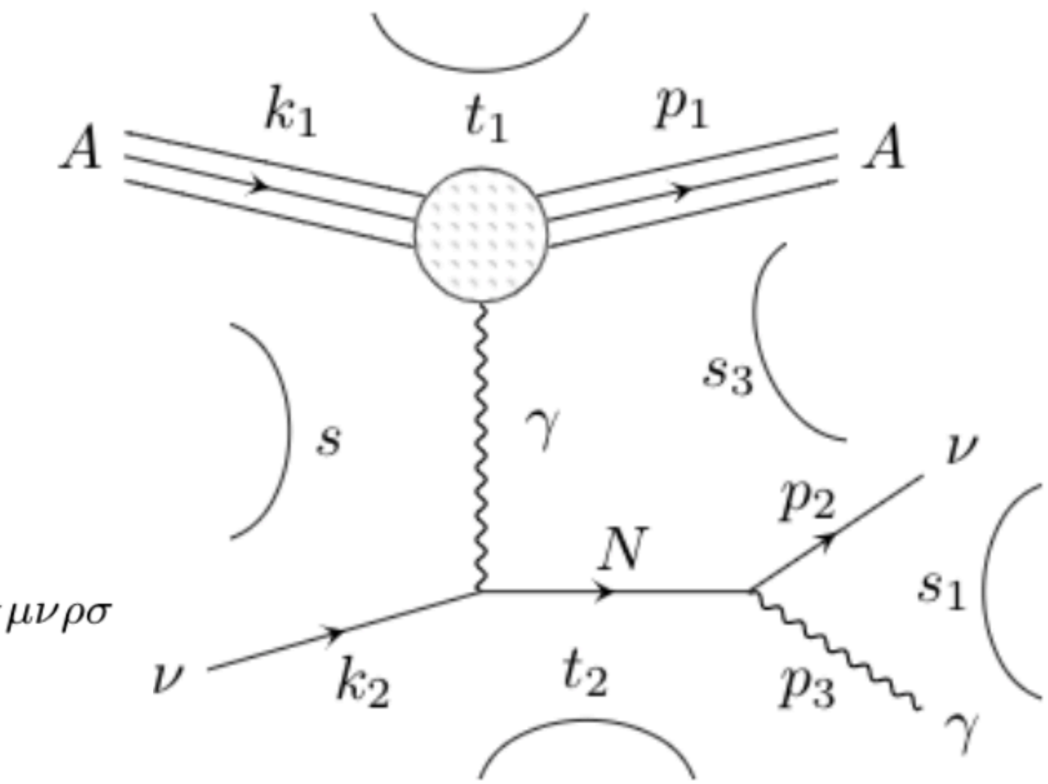
phase space



Dirac vs Majorana

$$i\mathcal{M}^{\text{D}}_{\nu_\alpha A\to\nu_\beta A\gamma} \propto \bar{u}_{\nu_\beta}\sigma_{\mu\nu}P_R(\not{p}_N + m_N)\sigma_{\rho\sigma}P_L u_{\nu_\alpha}X^{\mu\nu\rho\sigma}$$

$$i\mathcal{M}^{\text{M}}_{\nu_\alpha A\to\nu_\beta A\gamma} \propto \bar{u}_{\nu_\beta}\sigma_{\mu\nu}(P_L + P_R)(\not{p}_N + m_N)\sigma_{\rho\sigma}P_L u_{\nu_\alpha}X^{\mu\nu\rho\sigma}$$



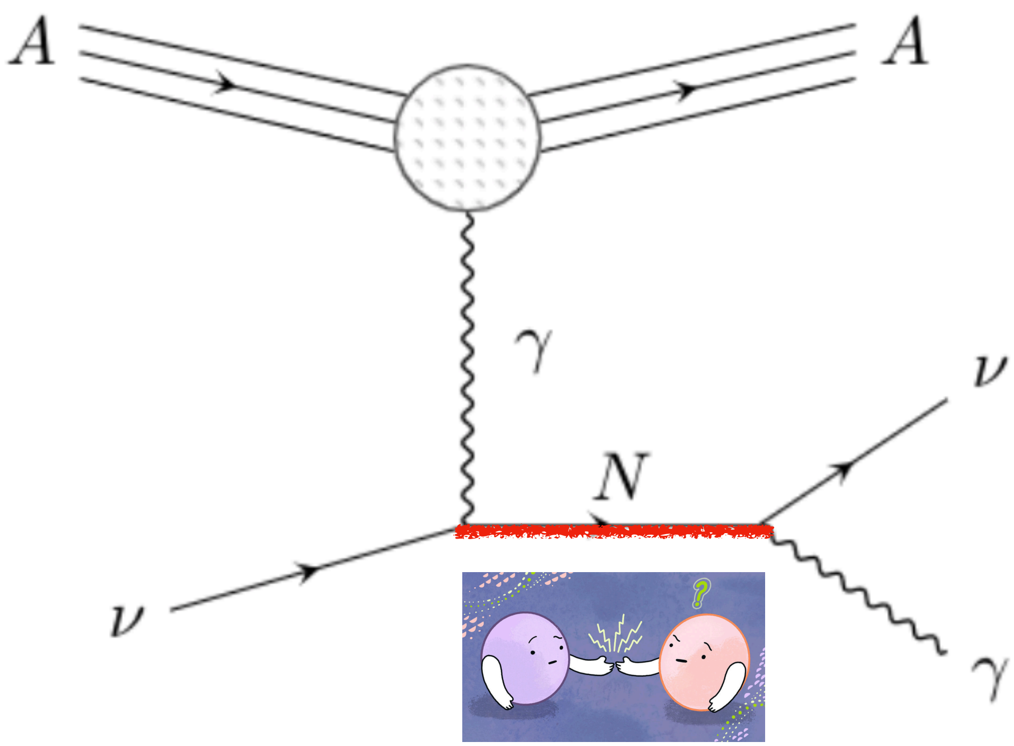
lab frame transformation +
integrating over the other free phase space parameters
=> differential distributions in desired lab frame variables

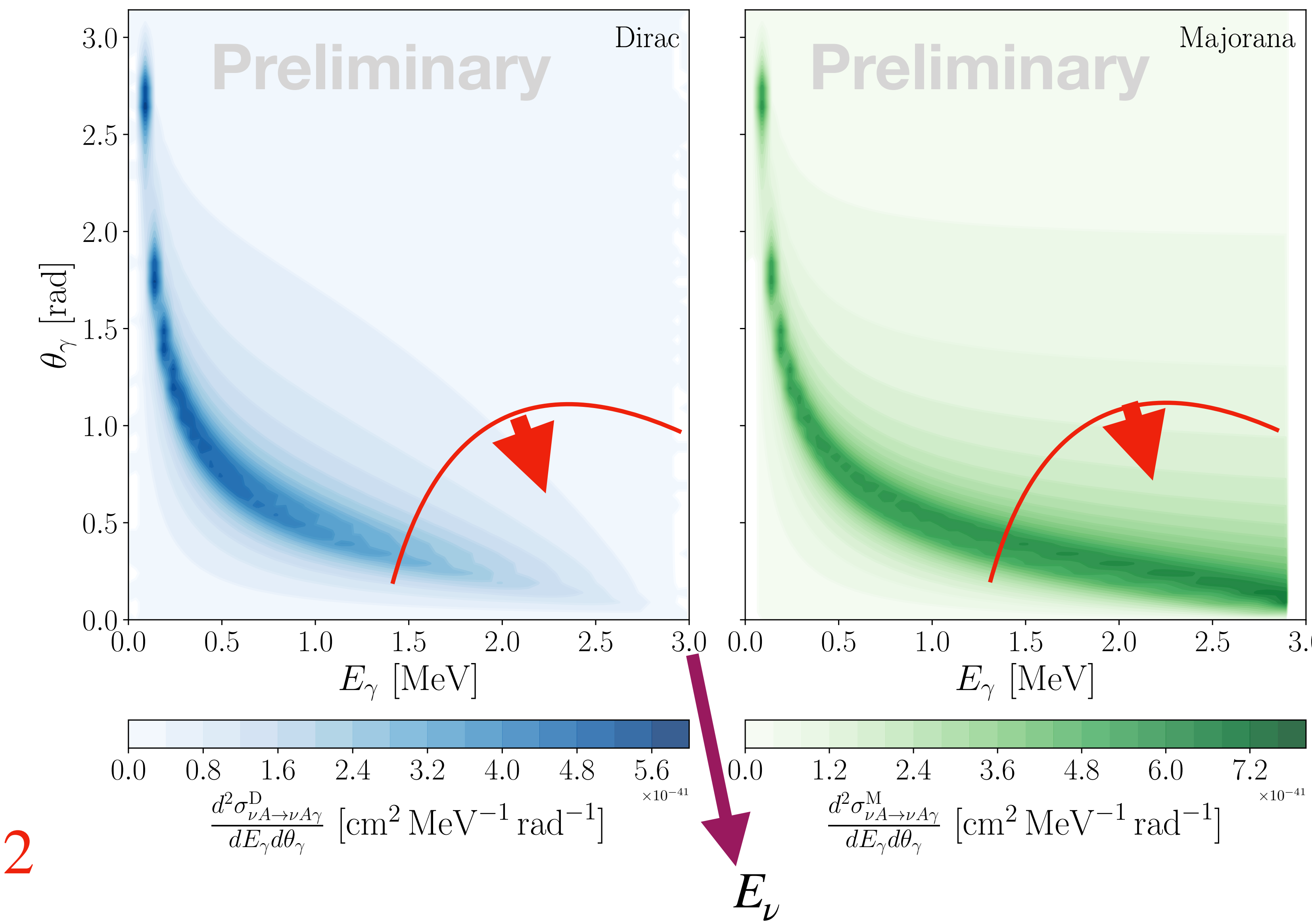
$$\frac{d^2\sigma^{\text{D(M)}}_{\nu_\alpha A\to\nu_\beta A\gamma}}{dE_\gamma d\theta_\gamma} \qquad \frac{d\sigma^{\text{D(M)}}_{\nu_\alpha A\to\nu_\beta A\gamma}}{dE_R}$$

Details are in the "shine": Dirac vs Majorana sterile state

Benchmark choices: $E_\nu = 3\ \mathrm{MeV}$ $m_N = 1\ \mathrm{MeV}$ $\mu^e_{\nu N} = 10^{-7}\ \mu_B$

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





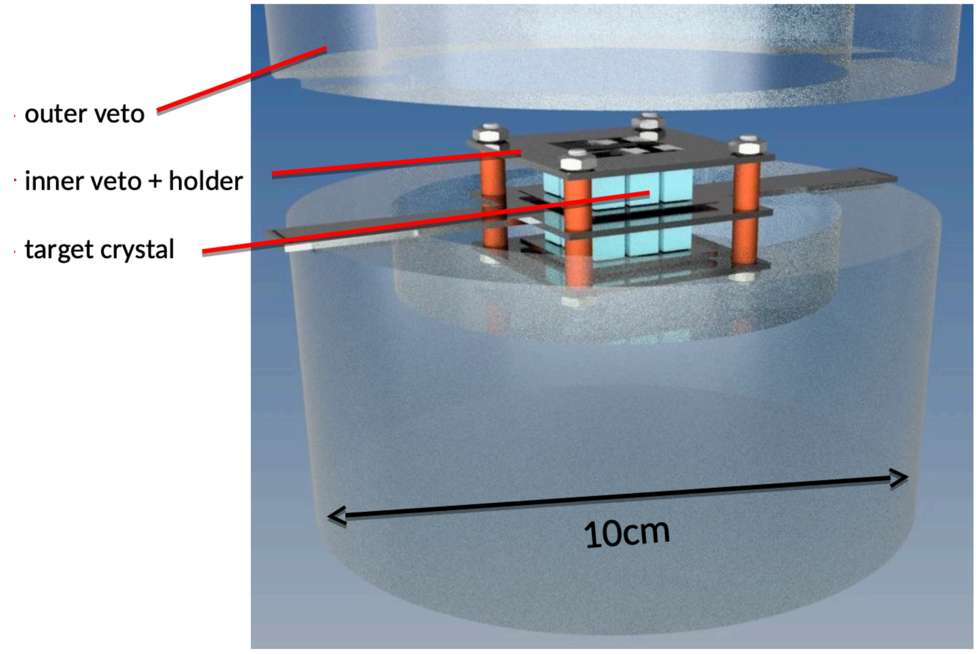
Clear distinction for $E_\gamma > E_\nu/2$

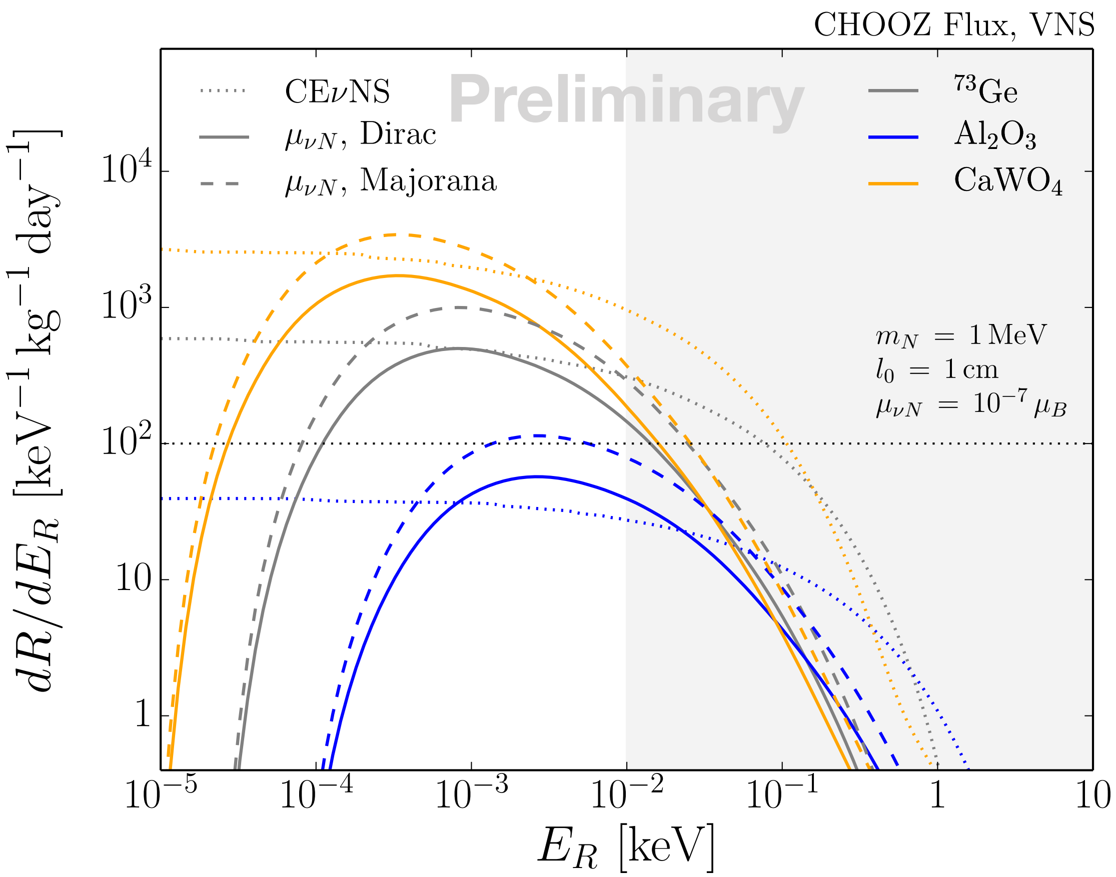
Different reactor neutrino energy -> access to wider sterile mass range

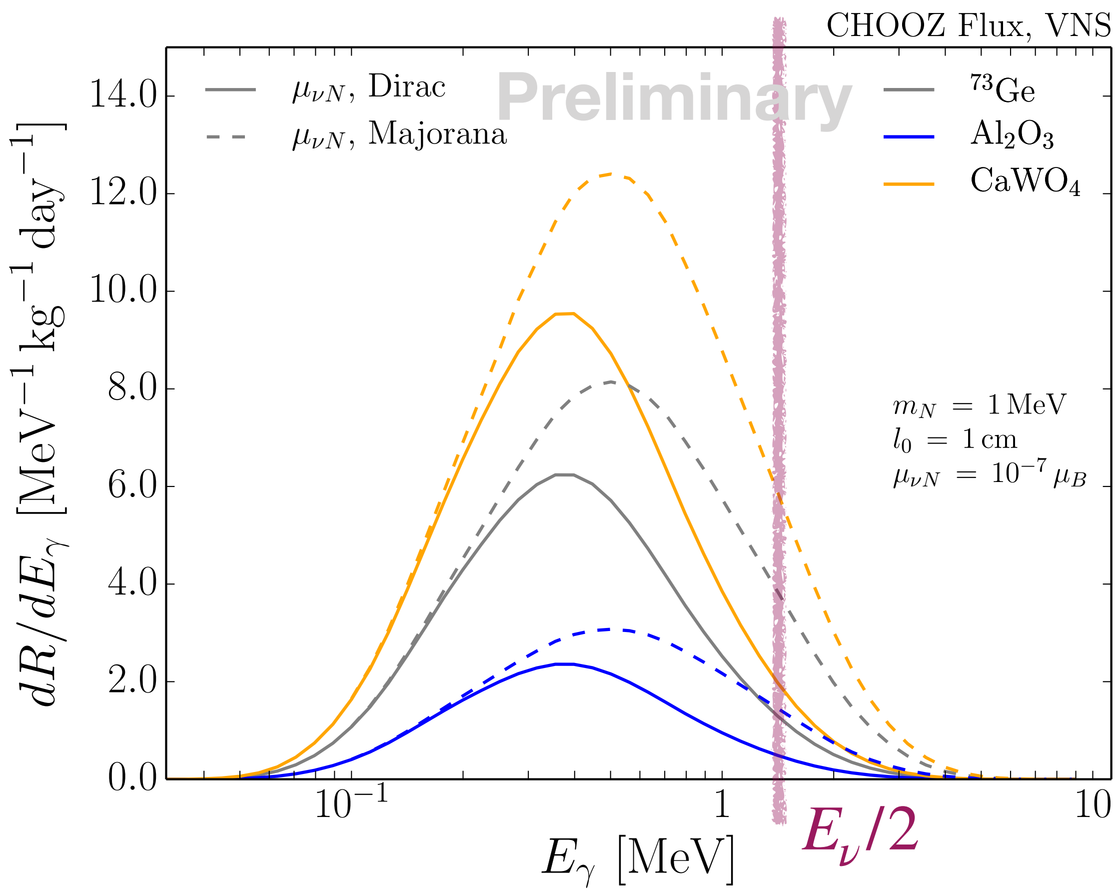
Coincidence for BG rejection: realistic @ experiments like NUCLEUS

Taking NUCLEUS @ CHOOZ as a case study

- 10g for NUCLEUS-Phase 1 (funded, work ongoing)
- Future 1kg upgrade possibility
- <5cm distance to cryogenic outer veto
- Sensitivity to photon energy: 1 keV to 10 MeV







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

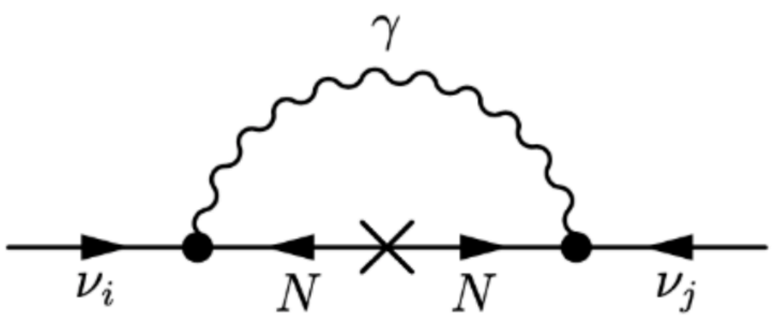
NUCLEUS can provide an energy resolution: 50-100 keV @MeV energies

What can we learn about 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

What can we learn about the neutrino mass mechanism?

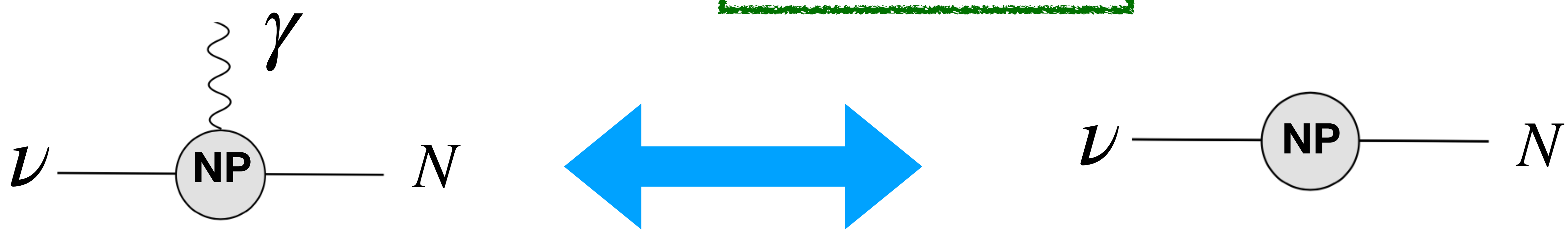
$\nu A \to \nu A\gamma$ **distribution consistent with Majorana sterile**

For the Type-I seesaw:

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

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

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)

Concluding remarks

Unprecedented sensitivity within reach in CEνNS experiments in near future.

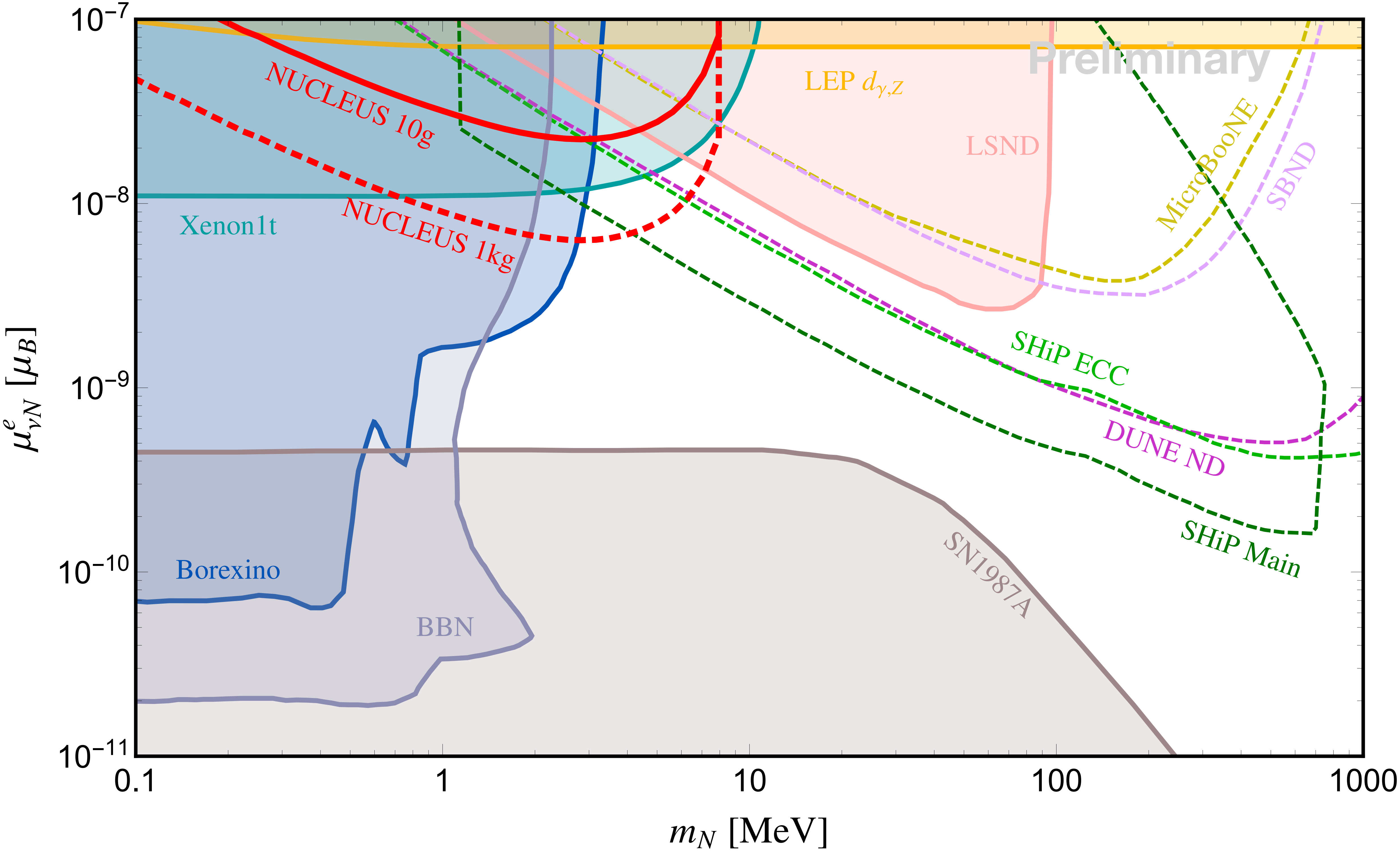
Radiative CEνNS ($\nu A \to \nu A\gamma$) distributions can give very exciting insights into neutrino mass in the presence of active-sterile transition magnetic moment.

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

Realistic possibility to probe such distributions @ CEνNS experiments like NUCLEUS

An observation of Radiative CEνNS can provide valuable hints on active neutrino mass mechanism

Backup-I



Preliminary
NUCLEUS 10g
NUCLEUS 1kg
Xenon1t
Borexino
BBN
LEP $d_{\gamma,Z}$
LSND
MicroBooNE
SBND
SHiP ECC
DUNE ND
SHiP Main
SN1987A
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0.1
1
10
100
1000
$\mu^{e}_{\nu N}$ [μ_B]
m_N [MeV]

Backup-II

Dirac steriles + tran mag mom:

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=>

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

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