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A novel window into Dirac vs. Majorana neutrinos using CEνNS

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Based on
2110.02233

in collaboration with

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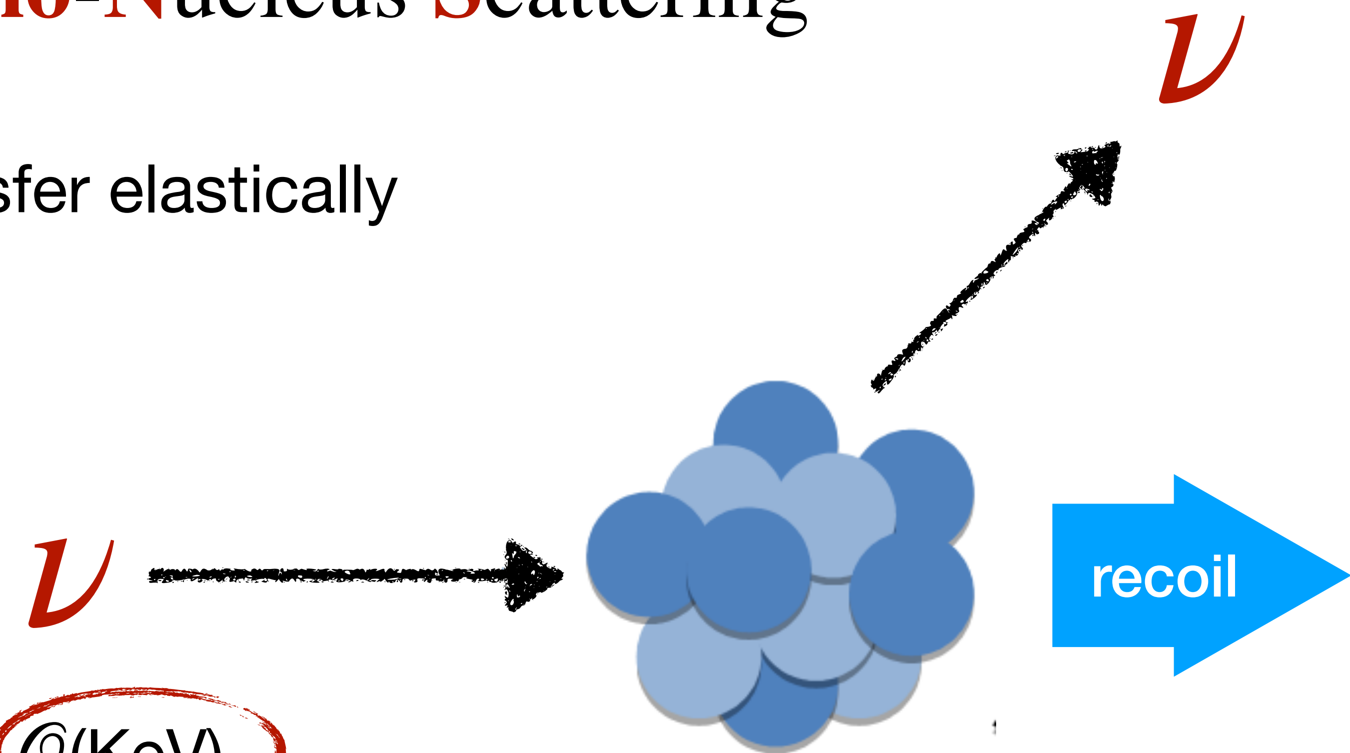
CEνNS

Coherent Elastic Neutrino-Nucleus Scattering



Neutrino scatters with low momentum transfer elastically from entire nucleus

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

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

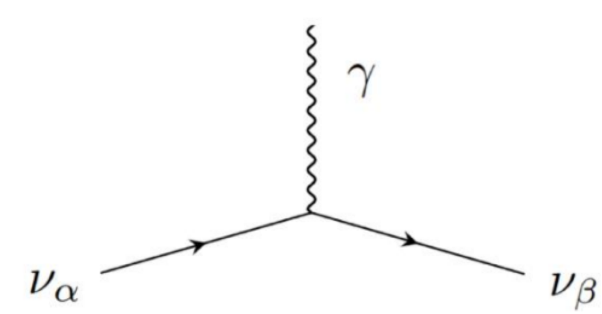
SM allowed process but hard to observe due to small nuclear recoil energy!

Akimov et al. Science 2017

First observation: Aug 2017 by COHERENT Experiment | Threshold: A few keV

NUCLEUS Experiment @ CHOOZ | Threshold: 10's of eV !

Sensitive to exotic ν interactions e.g. neutrino magnetic moment

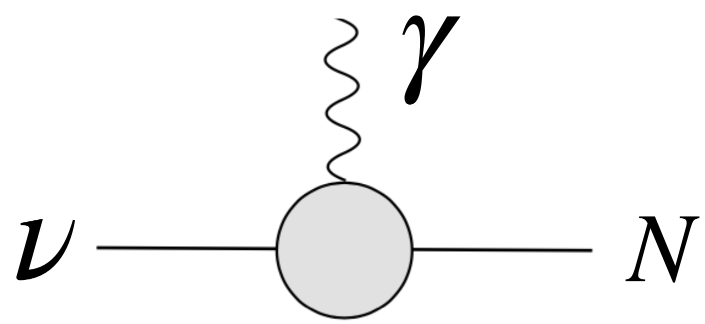


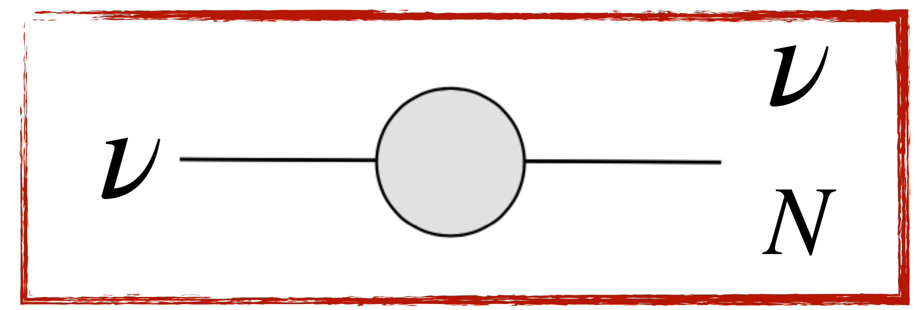
Other physics potentials by Danny and Valentina on Friday

Key ingredients

sterile neutrino + active-sterile transition magnetic moment

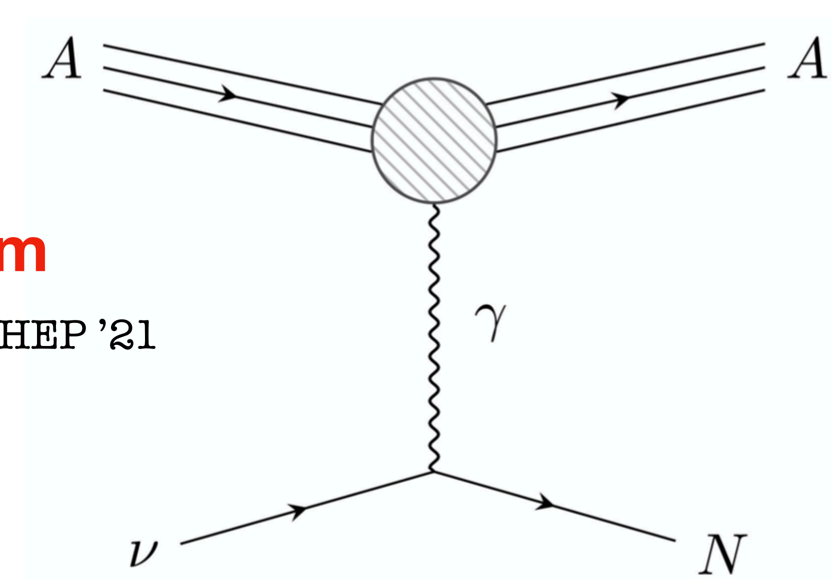
$$\mathcal{L} \supset \mu^{\alpha}_{\nu N} \bar{\nu}_{\alpha L} \sigma_{\mu\nu} P_R N F^{\mu\nu} + \mu_{N'N} \bar{N}' \sigma_{\mu\nu} P_R N F^{\mu\nu} + \text{h.c.}$$





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

Primakoff upscattering process $\nu A \to NA$



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

limit on the transition mag. mom

Miranda, Papoulias, Sanders, Tortola, Valle JHEP '21

cannot give information about the nature of N

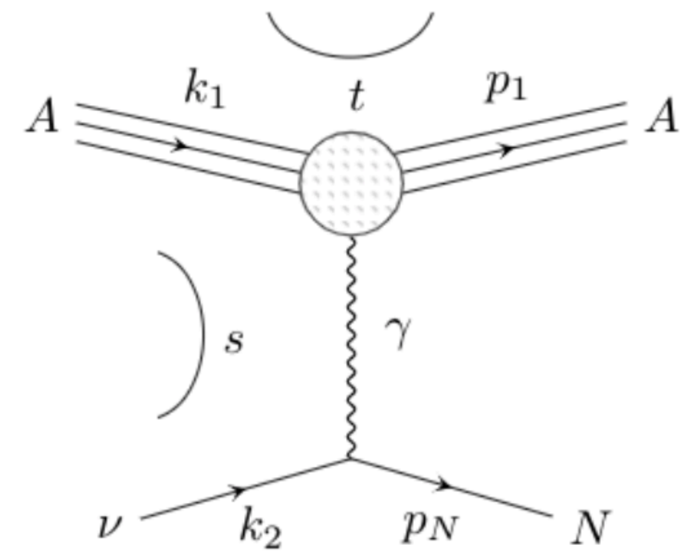
But what if the N decays to $N \to \nu\gamma$?

Kinematics

The kinematics and differential distribution is more involved than simple upscattering

phase space

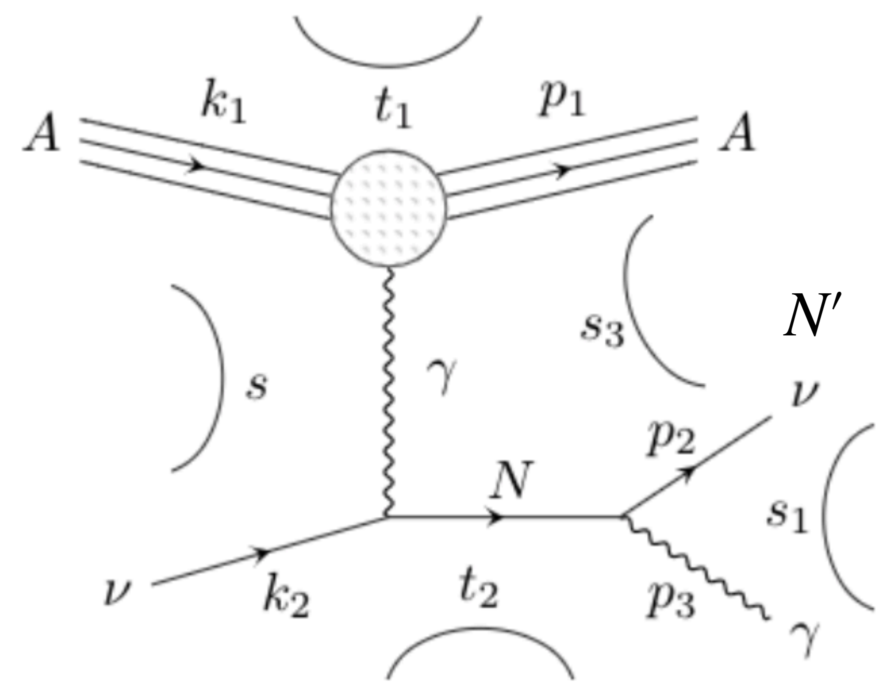
$$d^5\sigma_{\nu_\alpha A\to\nu_\beta A\gamma} = \frac{1}{2(s-m_A^2)}\frac{1}{2}\sum_{\text{spins}}|\mathcal{M}^{\text{D(M)}}_{\nu_\alpha A\to\nu_\beta A\gamma}|^2 d\Phi_3$$



Amplitude depends on: Dirac vs. Majorana mediator

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

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



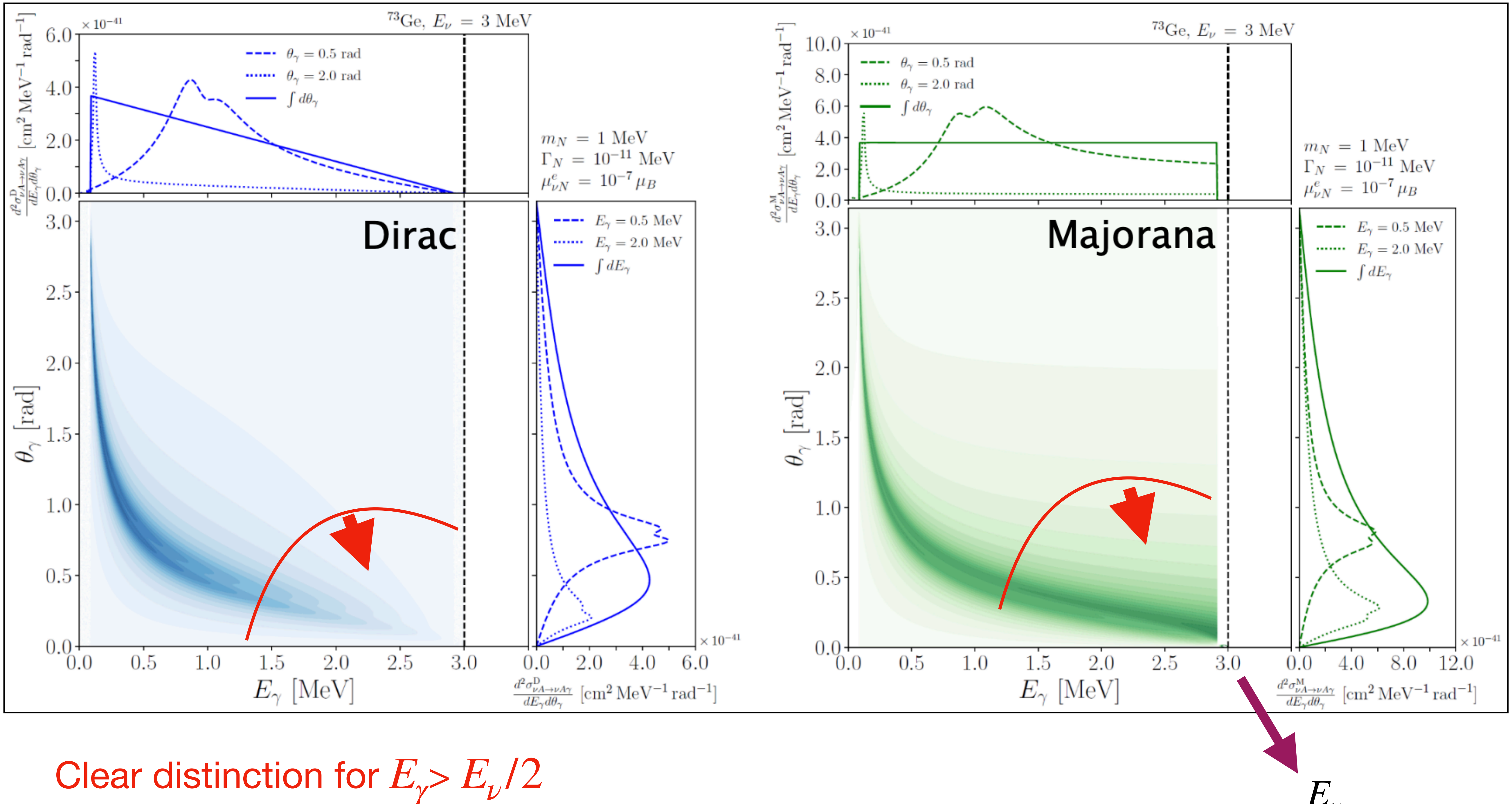
Integrate over the free phase space parameters
=> differential distributions in desired lab frame variables

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

$$\mathcal{B}_{N\to X_\gamma}P_{\text{decay}} = \frac{\Gamma_{N\to X_\gamma}}{\Gamma_N^{\text{inv}}+\Gamma_{N\to X_\gamma}}\left[1-\exp\left(-\frac{L_{\text{det}}(\Gamma_N^{\text{inv}}+\Gamma_{N\to X_\gamma})}{\beta\gamma}\right)\right]$$

Details in the "shine": Dirac vs Majorana sterile

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



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

Coincidence for BG rejection: realistic @ experiments like NUCLEUS

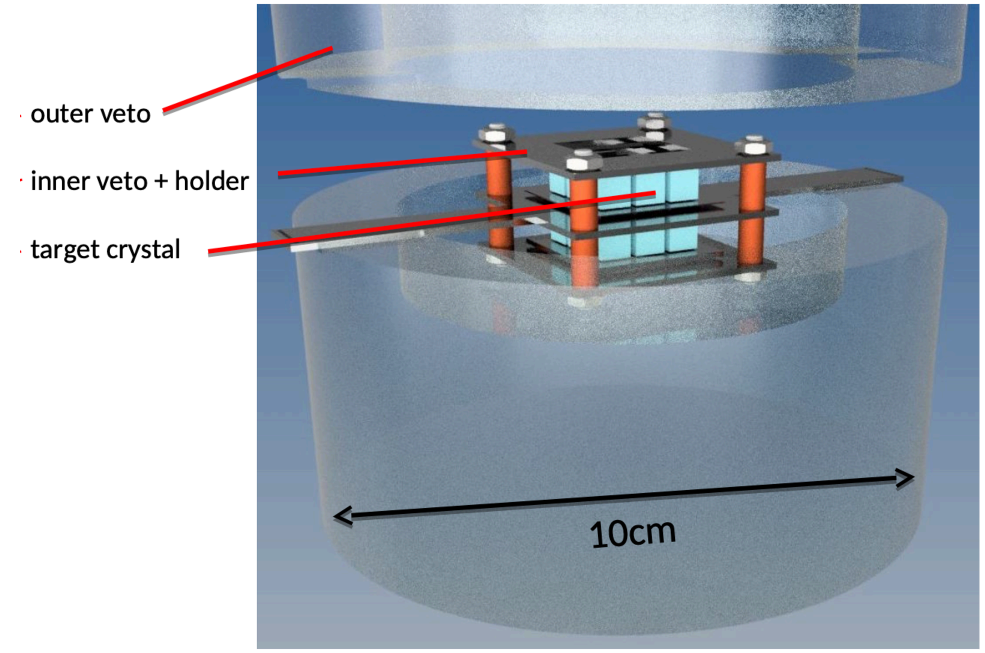
For a realistic experiment: integrated over the flux + sterile decay width from detector dimensions

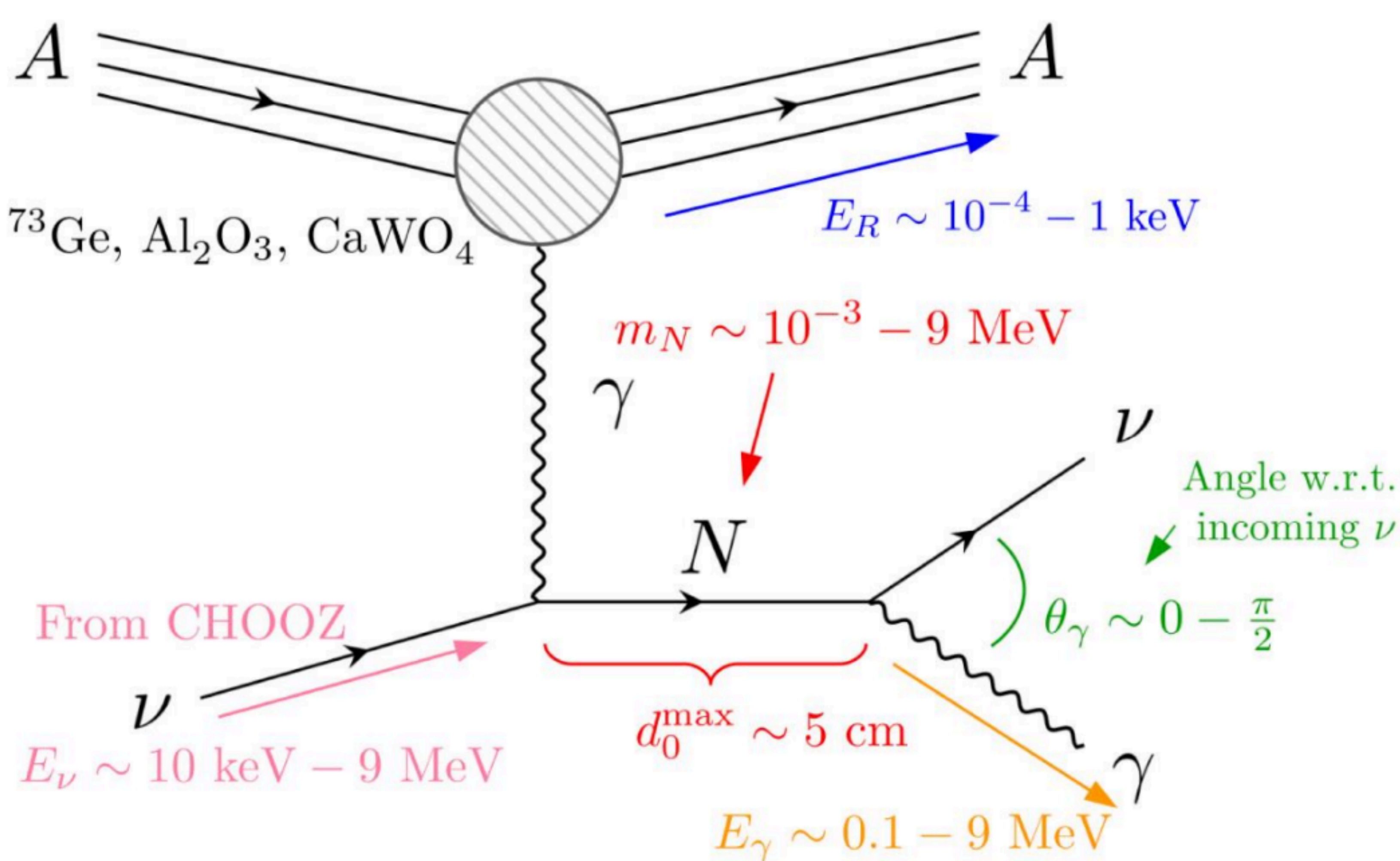
Taking NUCLEUS @ CHOOZ as a case study

- 10g $Al_2O_3/CaWO_4$ for NUCLEUS-Phase 1: L~5 cm
- Future 1kg Ge upgrade possibility: L~ 25 cm
- Sensitivity to photon energy: 1 keV to 10 MeV

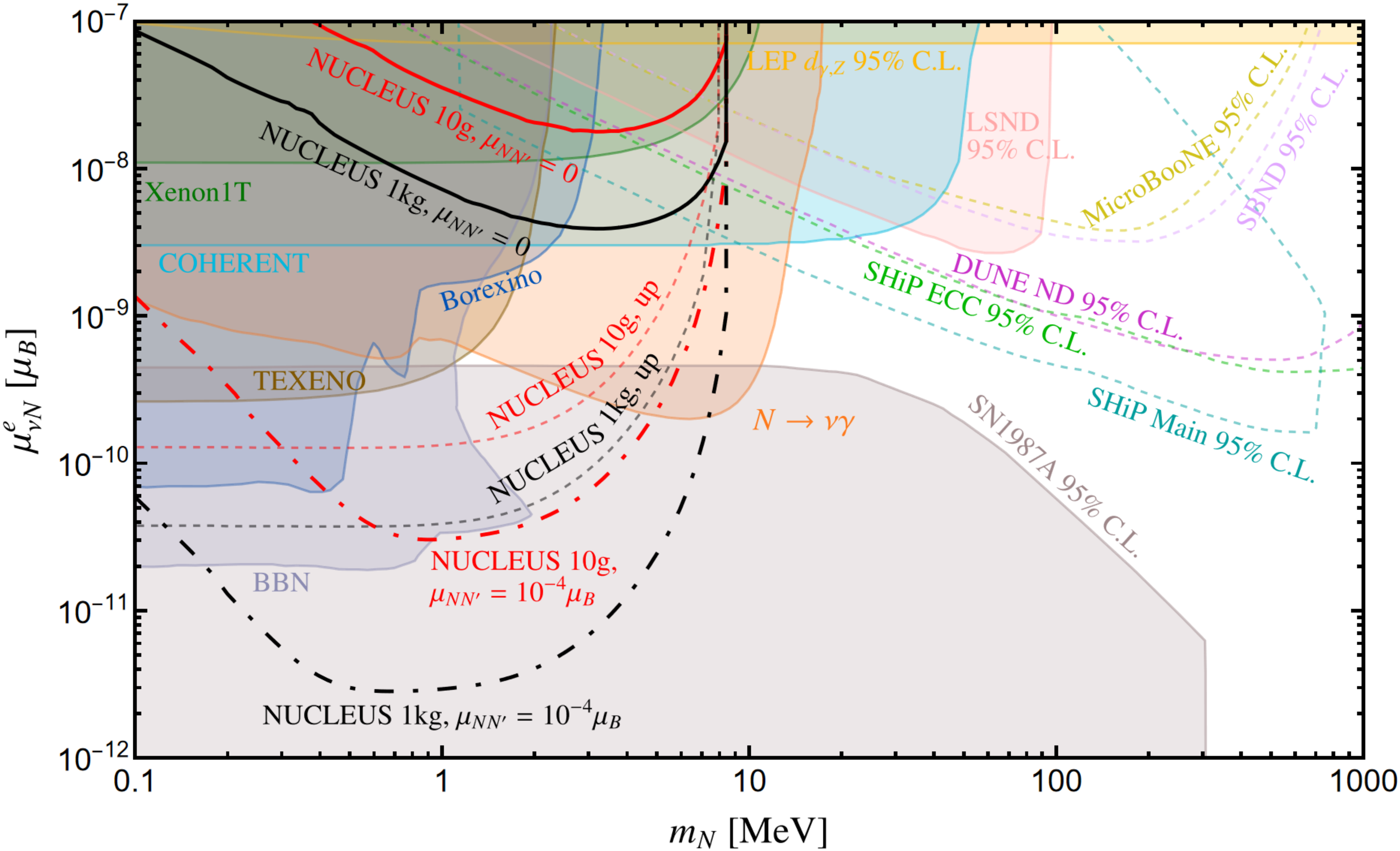
  @ Cryogenic outer veto

energy resolution: 50-100 keV @MeV energies





Sensitivity @ NUCLEUS



$\nu A \to \nu A \gamma$ distribution consistent with Dirac/Majorana mediator => ?

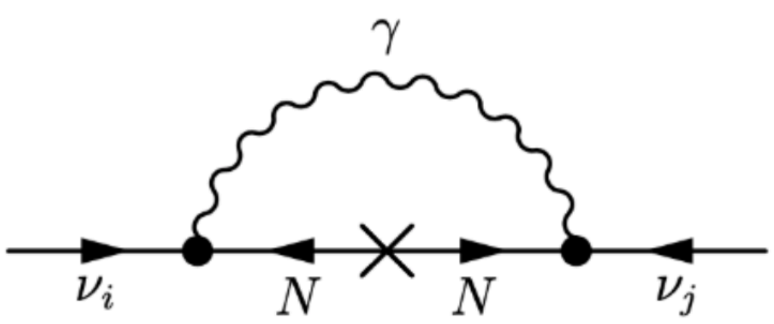
Insights into the

(i) Dirac vs. Majorana nature

(ii) mass mechanism

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

For a distribution consistent with Dirac N

no conclusive statement can be made about the nature of ν!

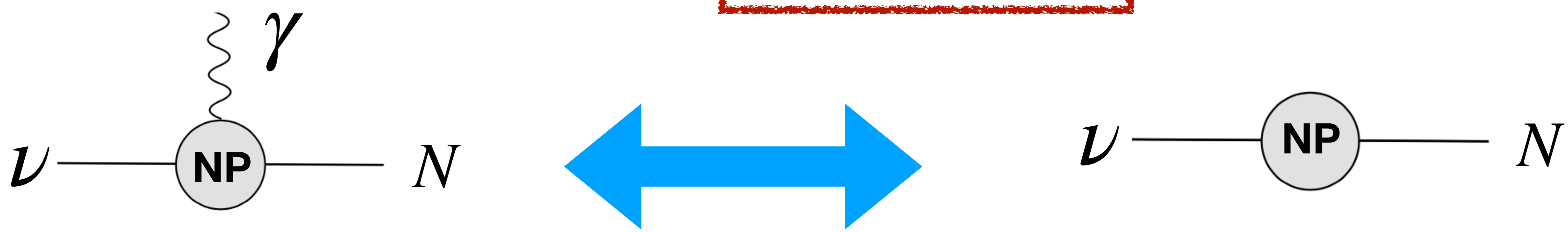
$\nu A \to \nu A\gamma$ distribution consistent with Majorana sterile

Transition magnetic moment via loop diagram with heavy NP (Λ)=>

Dirac mass term $m_{\nu N}\,\bar{\nu}_L N_R$

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

Magill, Plestid, Pospelov, Tsai '18



SM+sterile states => transition magnetic moment via loop diagrams with 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 '81, Shrock '82

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

preferred scenarios: **Symmetry driven models** **("unnatural" cancellation with tree level mass term)**

$\nu A \to \nu A\gamma$ 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=>

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

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

Concluding remarks

- Experiments e.g. NUCLEUS (and COHERENT) will be able to detect high energy γ

  ⇒ Search for $\nu A \to \nu A \gamma$

  ⇒ Coincidence signal with low background

  ⇒ Constrains on active-sterile/sterile-sterile transition magnetic moment

- If there exists N with large active-sterile magnetic moment : ⇒

  Try to measure outgoing $E\gamma$ and $\theta\gamma$
  distributions can distinguish Dirac vs. Majorana nature of N
  Insights into active neutrino mass mechanisms

Thank you for your attention!

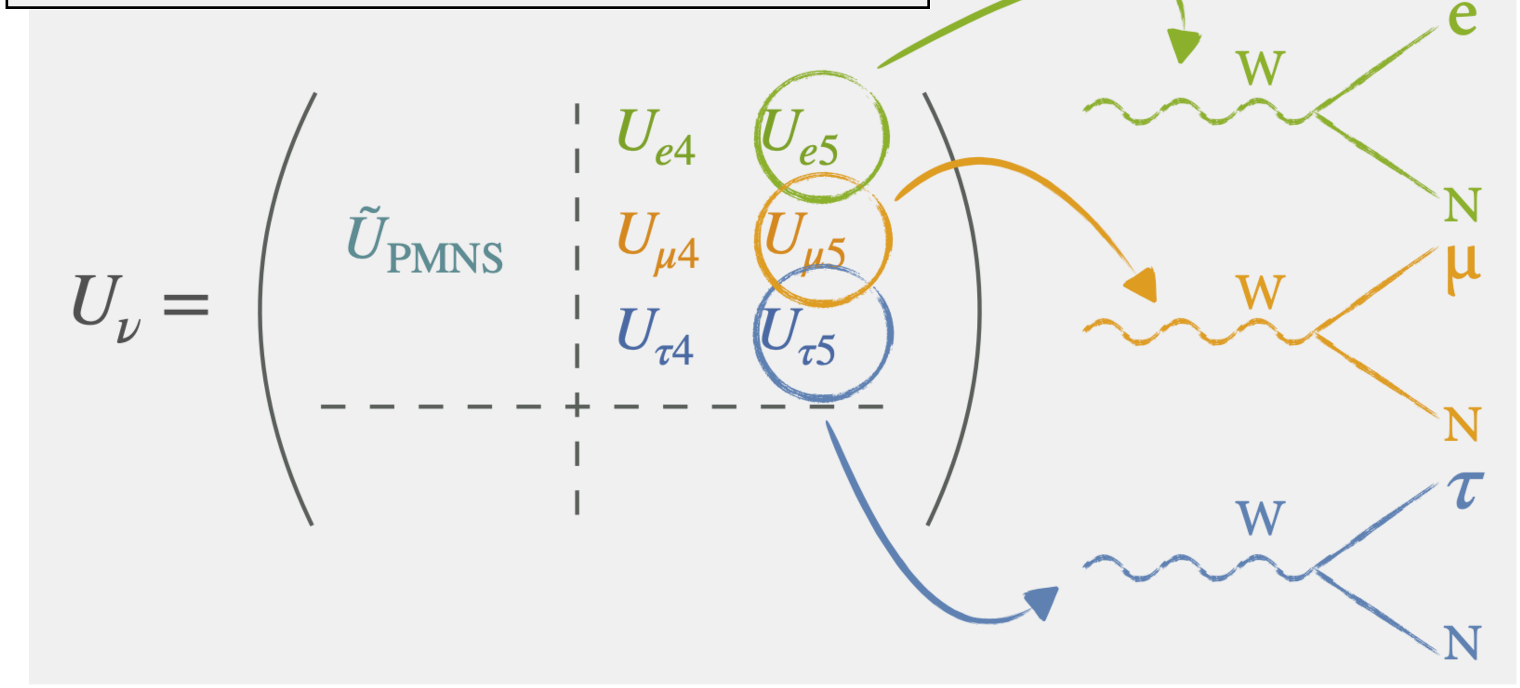
LNV: Sterile neutrinos

"Sterile": uncharged under SM gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$

Mostly interacts through active-sterile mixing (we will discuss an exception in detail)

3+n steriles masses: $m_\nu = (m_{\nu_1}, m_{\nu_2}, m_{\nu_3}, m_4, m_5, \dots)$

3+n unitary mixing matrix:



Sterile masses and mixings as free parameters: give different seesaw limits

$$\mathcal{L}_\nu = \mathcal{L}_{\rm old} - \lambda_{\alpha i} L^\alpha H N^i - \sum_{i=1}^{3} \frac{M_i}{2} N^i N^i + H.c. \qquad \mu = \lambda \langle H^0 \rangle$$

$M = 0$ **: 3 Dirac pairs**

$M \sim \mu$ **: 6 similar masses + very large mixing**

$M \gg \mu$ **: type I seesaw**

$M \ll \mu$ **: quasi-Dirac + maximal mixing**

NUCLEUS @ CHOOZ as a case study

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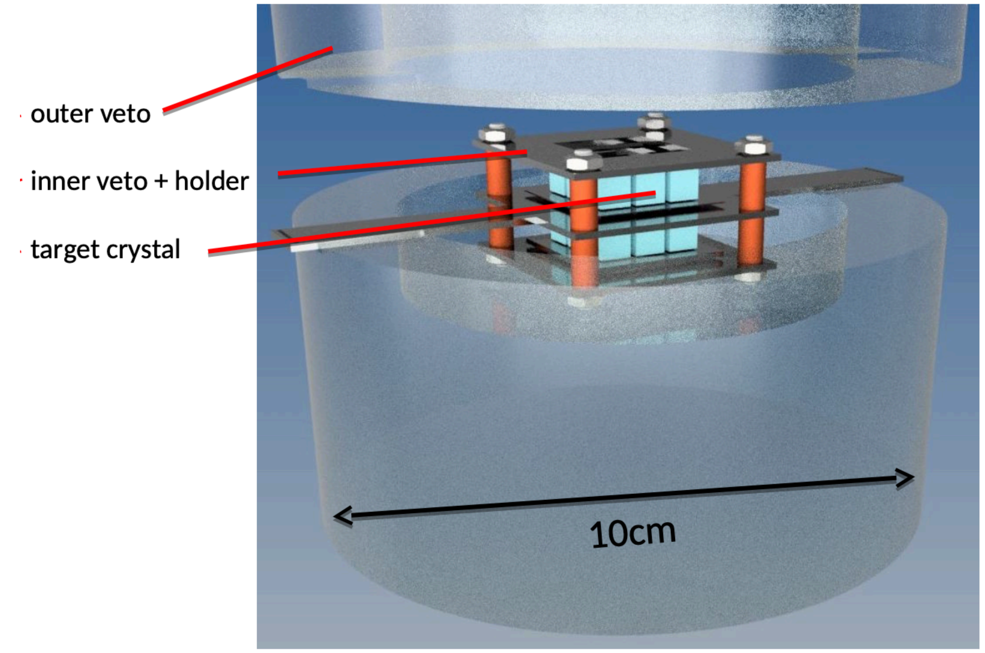

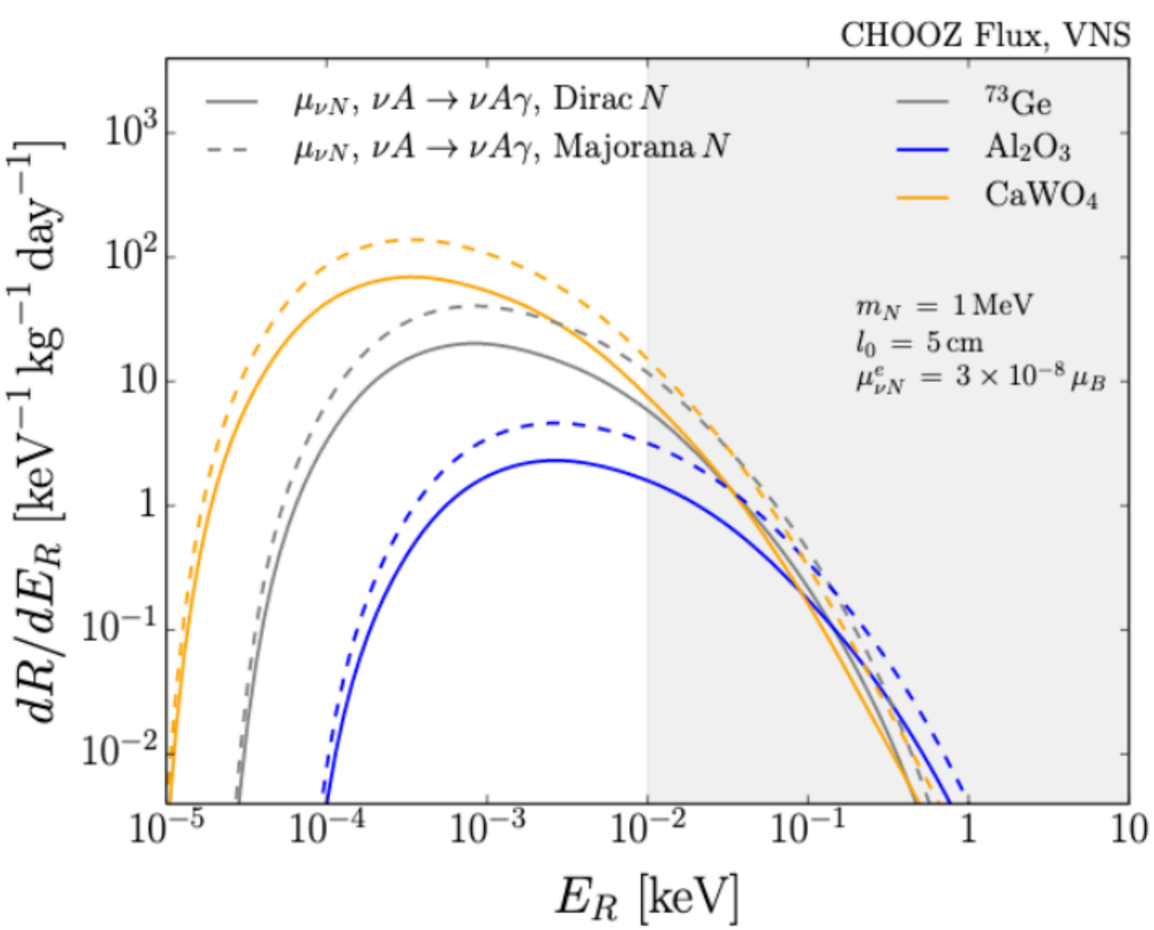

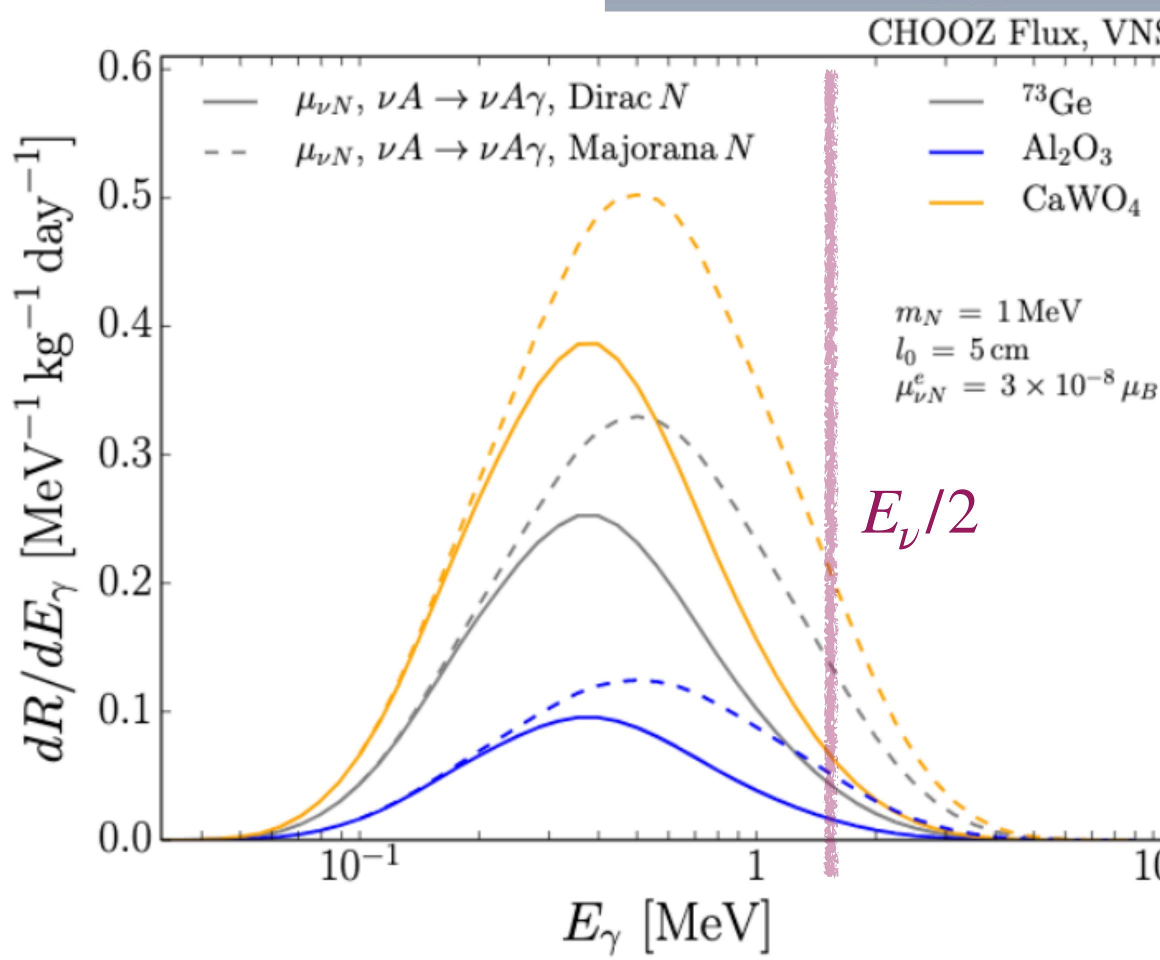

Dirac case photon energy distribution falls off very quickly after $E_\gamma > E_\nu/2$

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