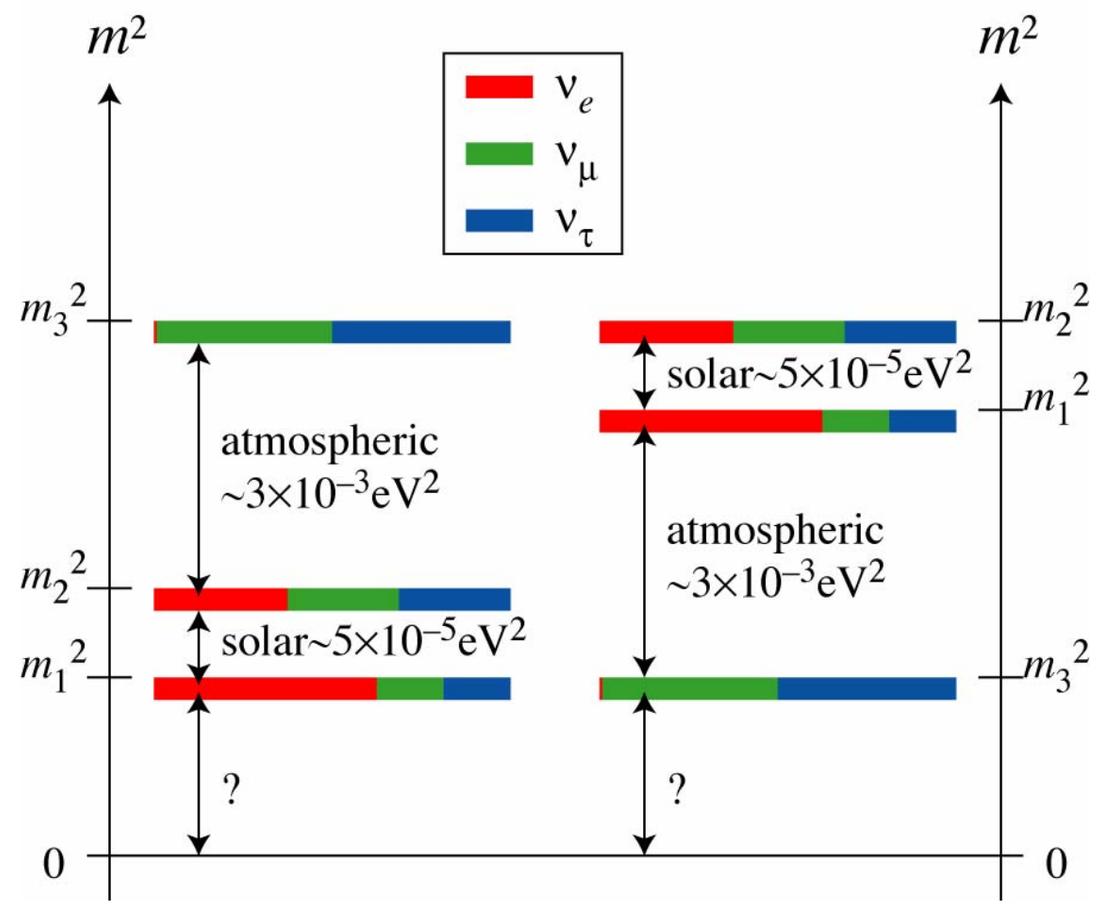
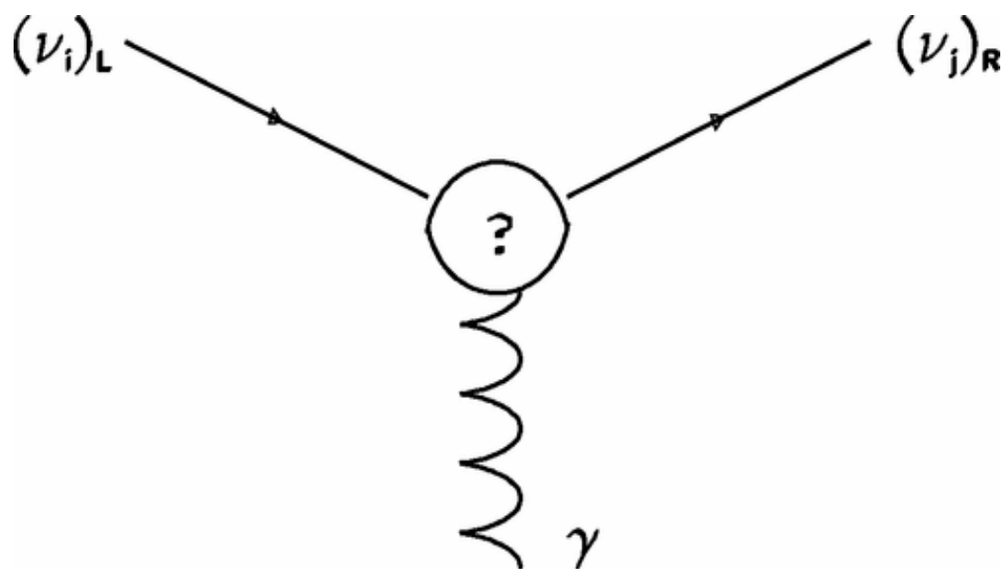
New Technologies for Neutrino Properties

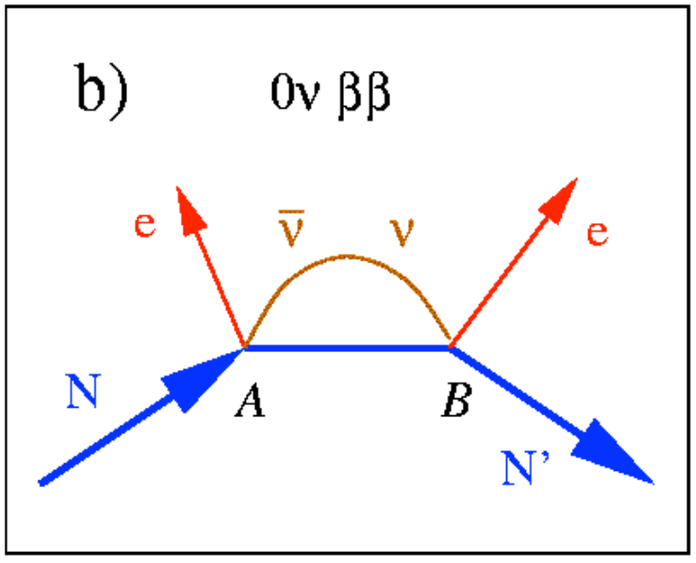
Phil Barbeau, Duke

What we don't know

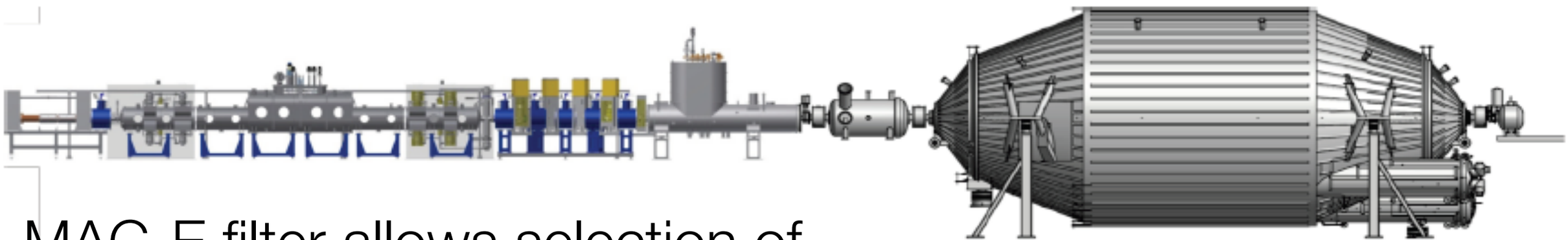
- Mass Hierarchy
- CP violating phases
- Sterile's
- **Absolute Mass Scale**
- **Majorana Nature**
- **Magnetic Moment**
- …



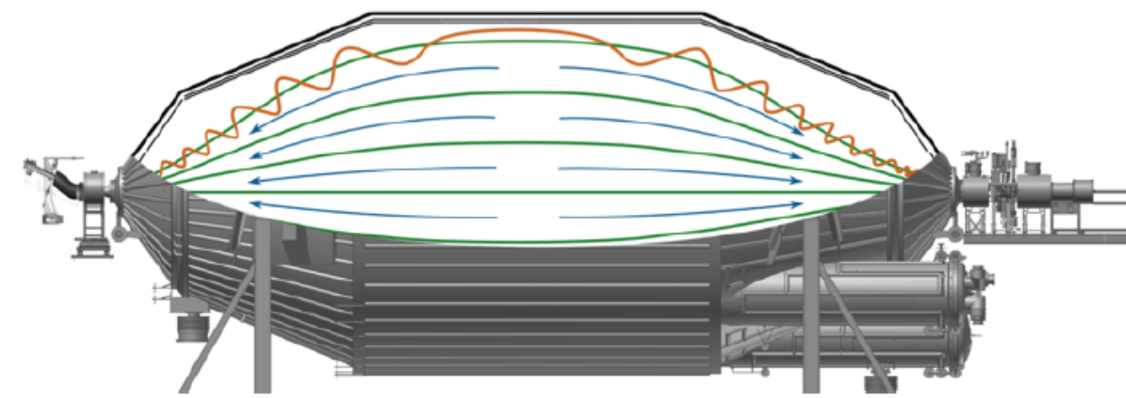


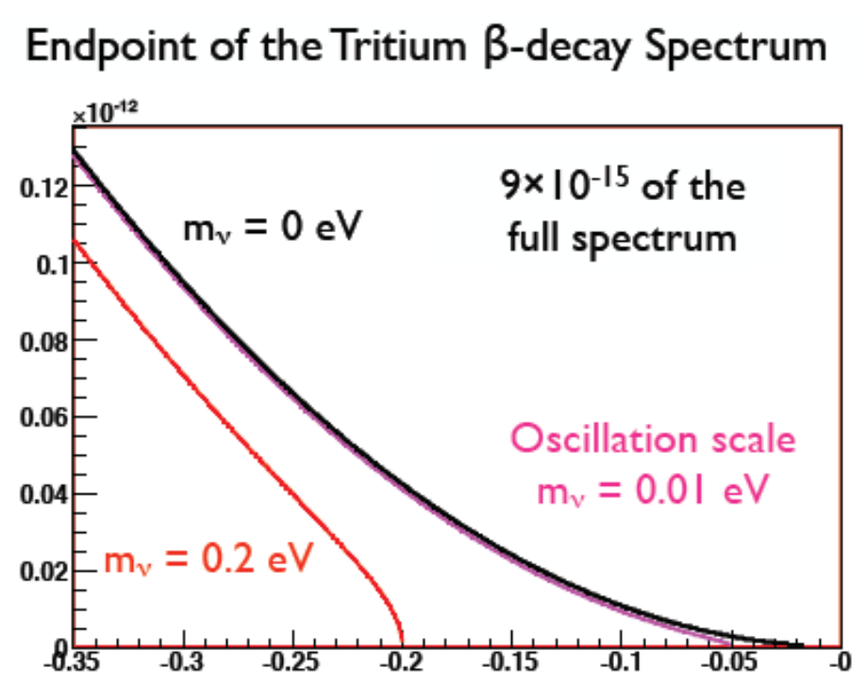


Endpoint Measurement Techniques: KATRIN



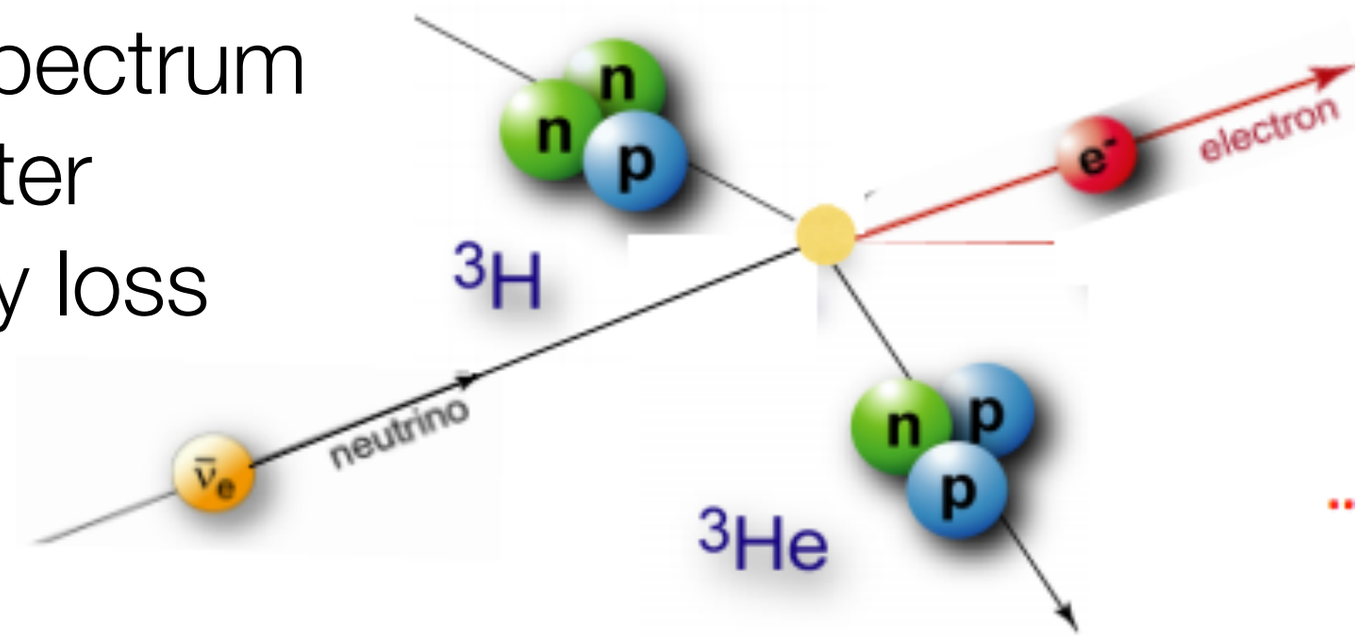
- MAC-E filter allows selection of electron energies
- Overall sensitivity: 200 meV
- Tritium source is the largest contributor of systematics





Endpoint Measurement Techniques: PTOLEMY

- MAC-E filter to truncate spectrum with TES-based Calorimeter
- Can be sensitive to energy loss mechanisms



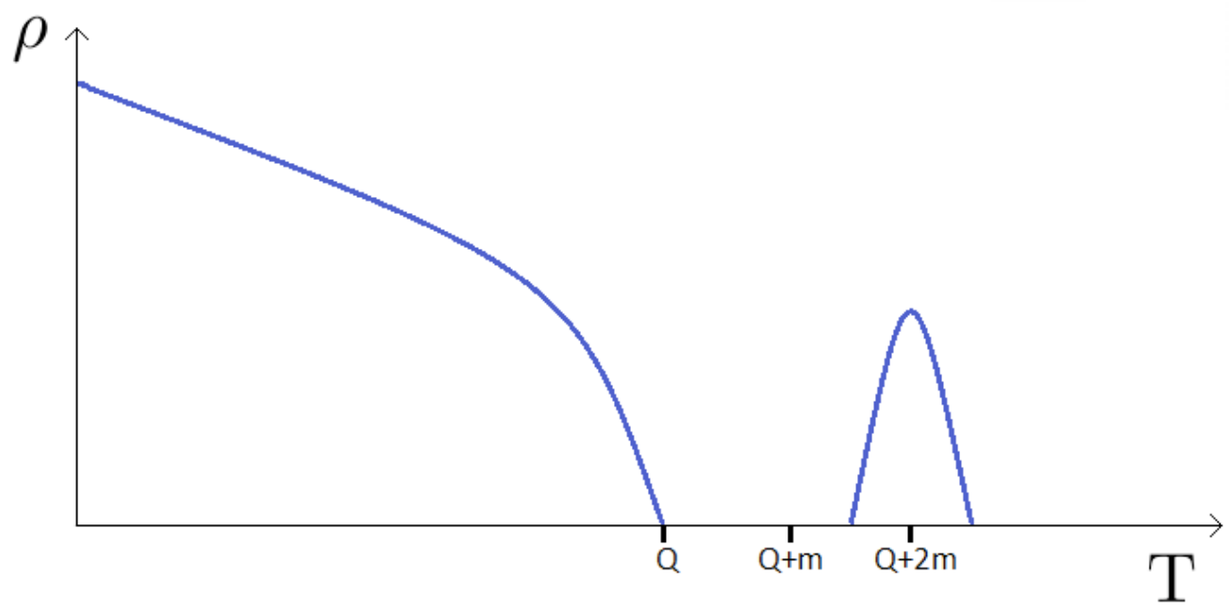
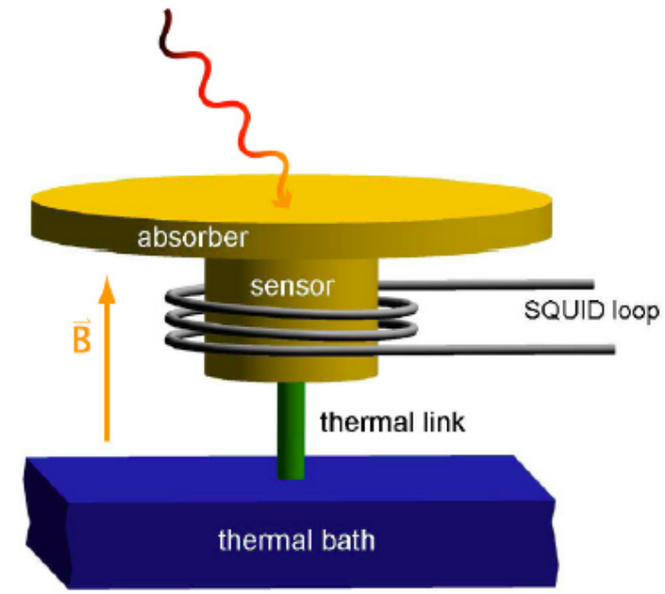


Figure 1: Emitted electron density of states vs kinetic energy for neutrino capture on beta decaying nuclei. The spike at $Q + 2m$ is the CNB signal

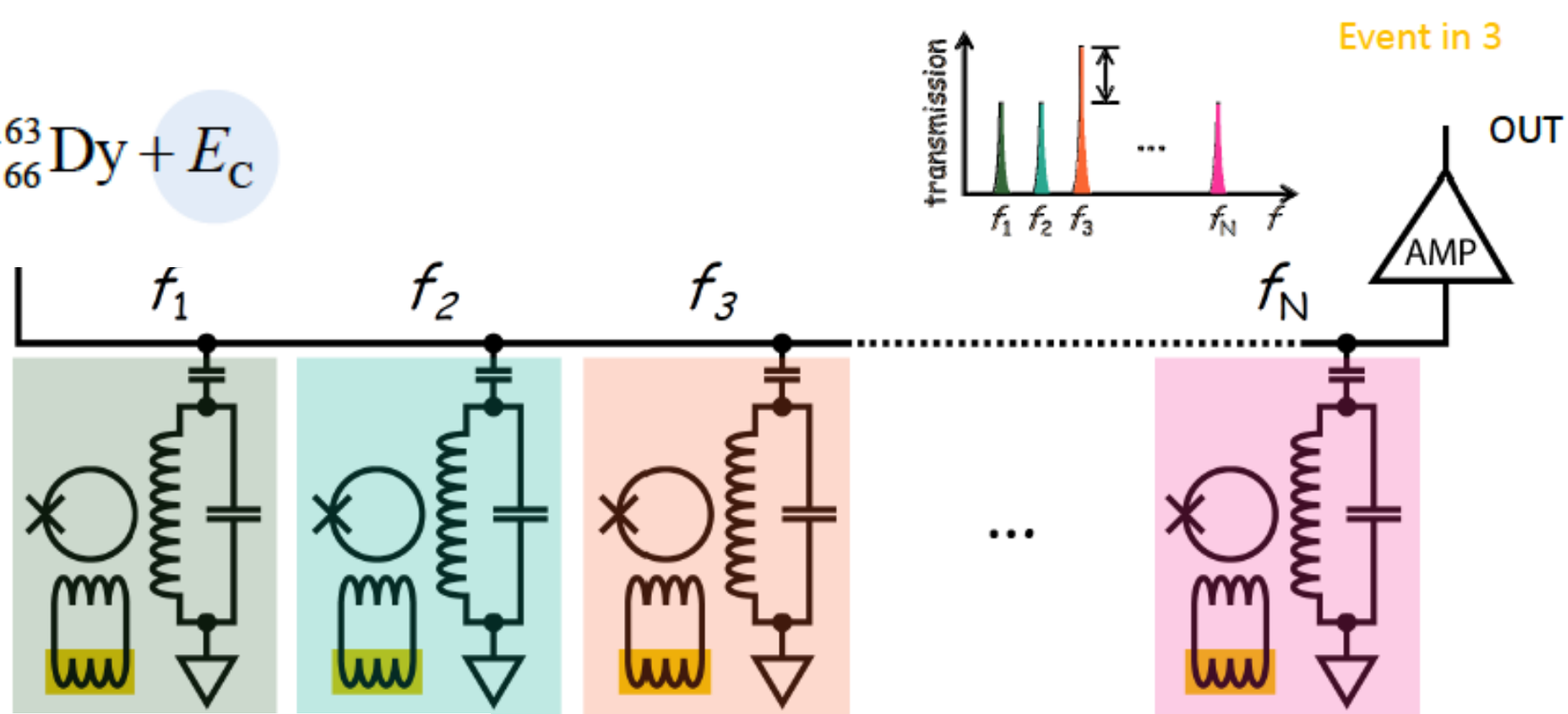
Endpoint Measurement Techniques: ECHO

- Embedding Ho-163 in low temperature Metallic Magnetic Calorimeter (MMC)
- Microwave Squid Multiplexing means a single amplifier can read out 100-1000 detectors.



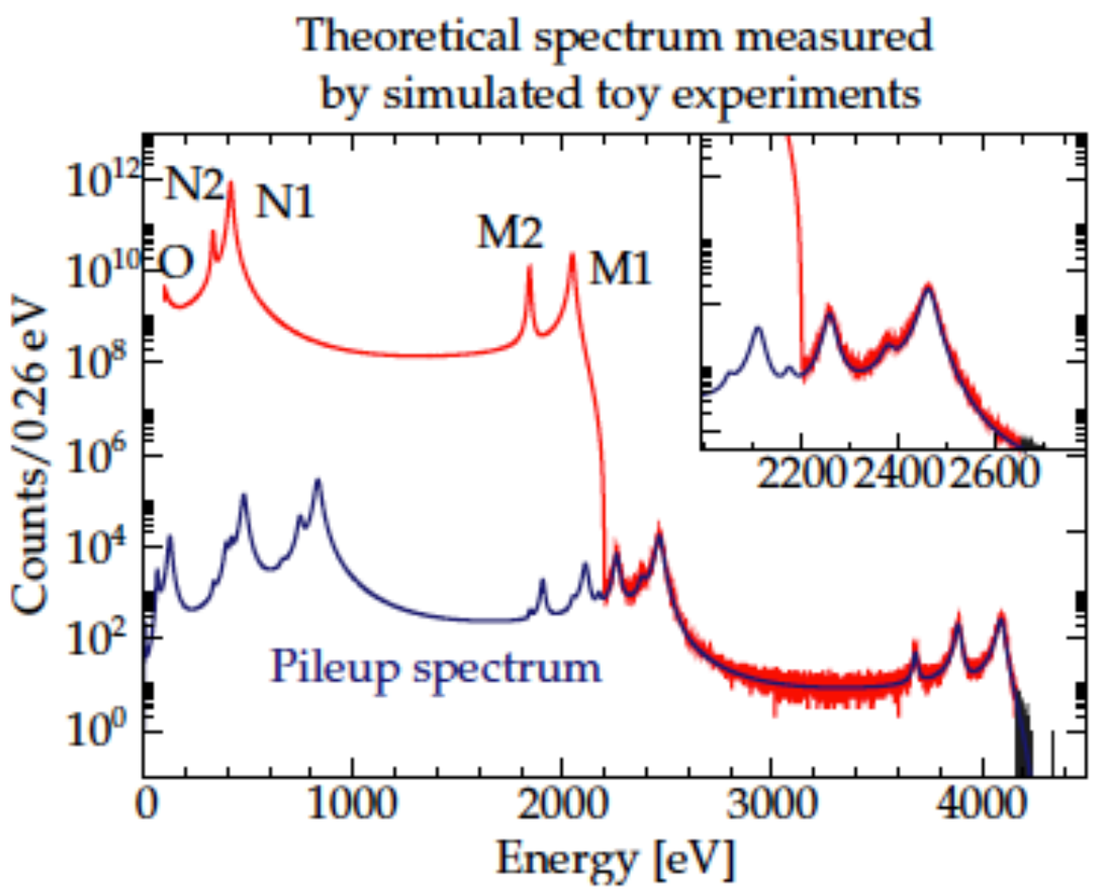
$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^{*} + \nu_e$$

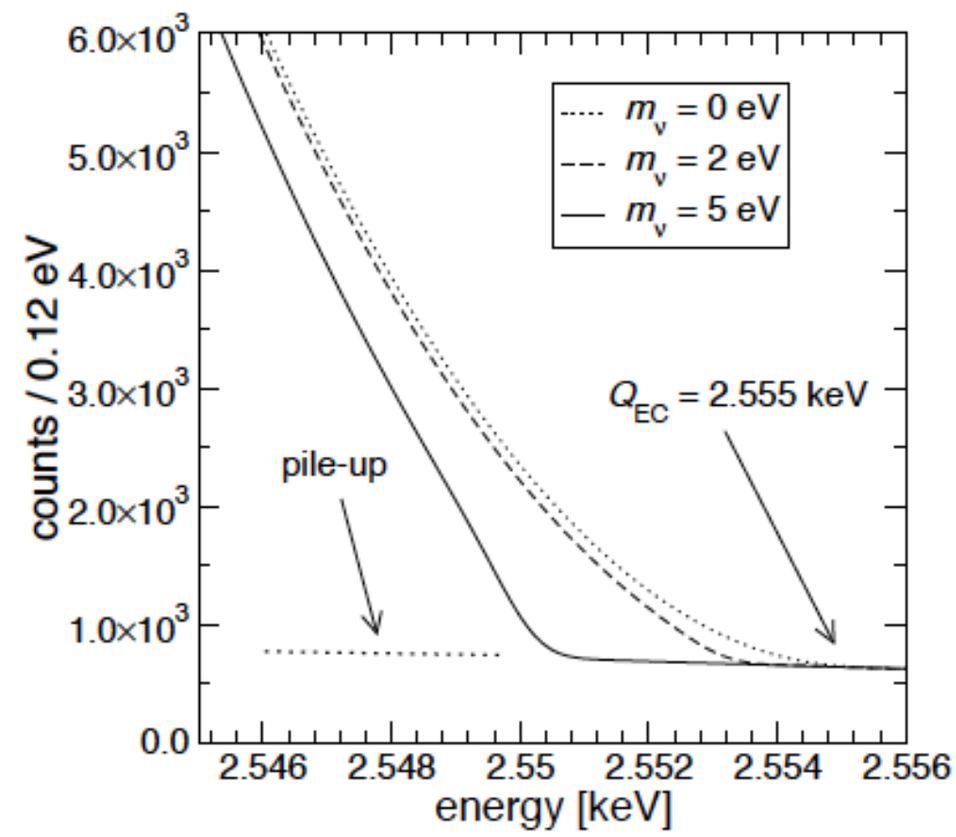
$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow ^{163}_{66}\mathrm{Dy} + E_C$$



Microwave SQUID Multiplexer for the Readout of Metallic Magnetic Calorimeters
S.Kempf et al., *J. Low. Temp. Phys.* **175** (2014) 850-860

Endpoint Measurement Techniques: HOLMES

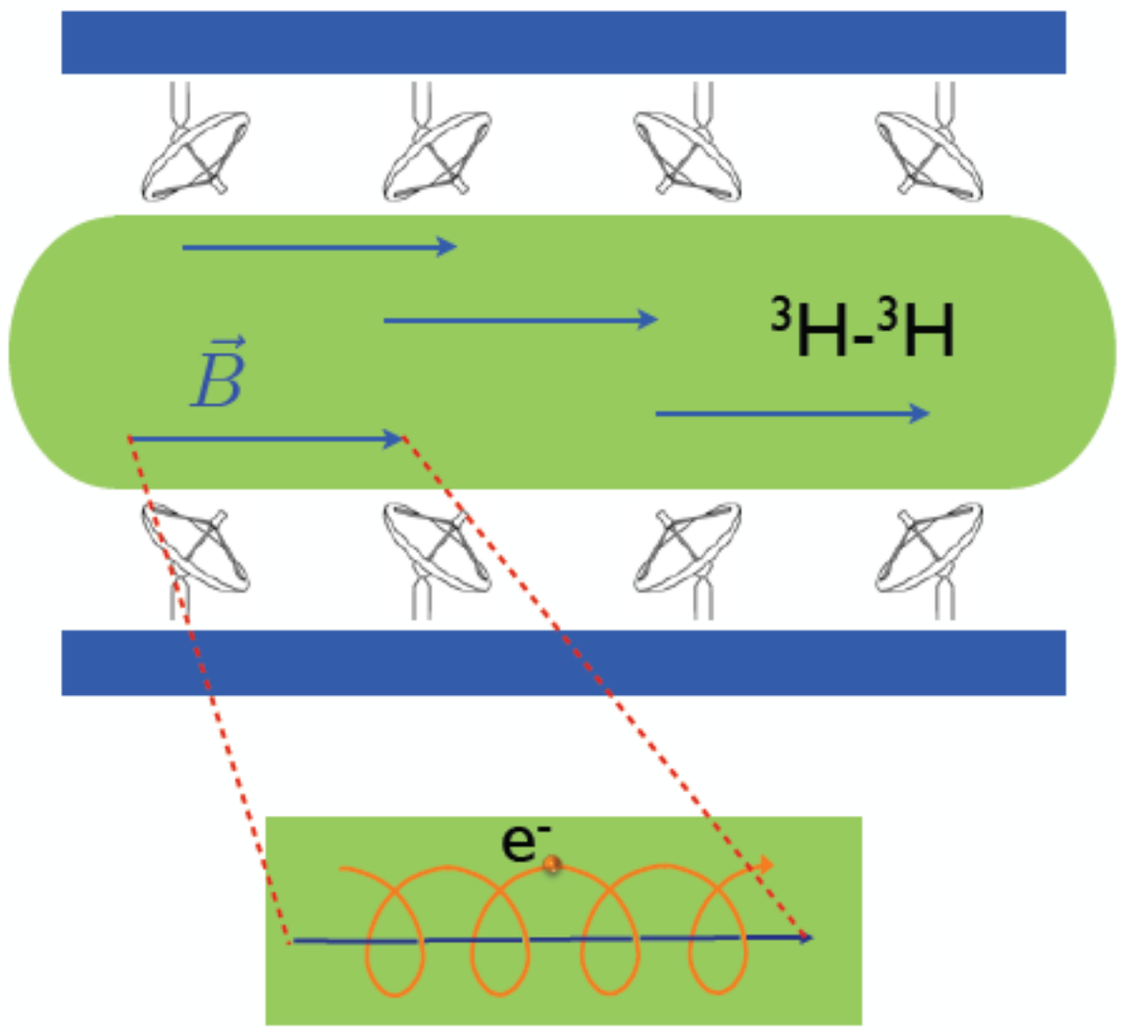


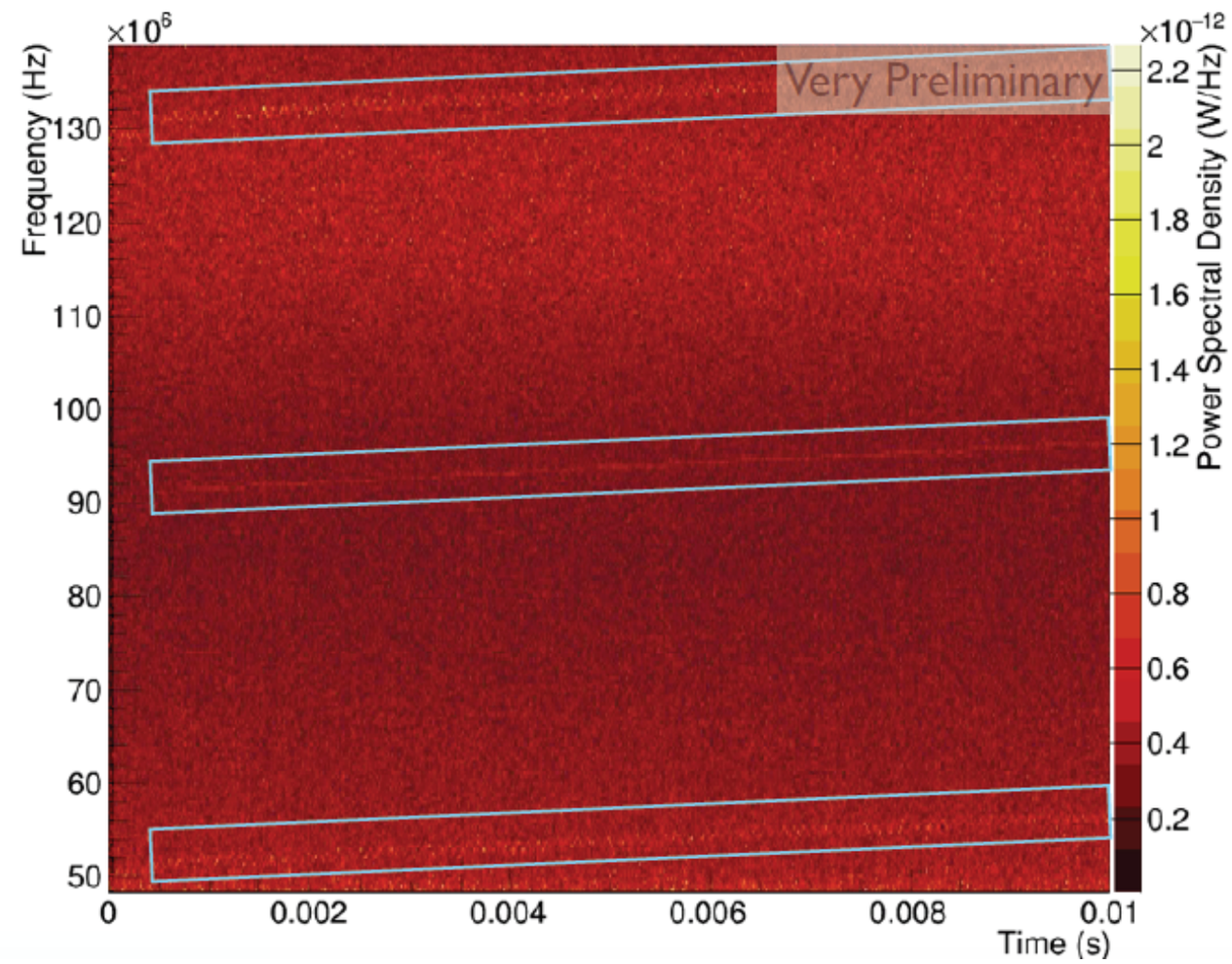


- ^{163}Ho Microcalorimeter experiment using TESs
- Background sensitive to pileup a function of the total embedded isotope

Endpoint Measurement Techniques: Project-8

Cyclotron Radiation Emission Spectroscopy





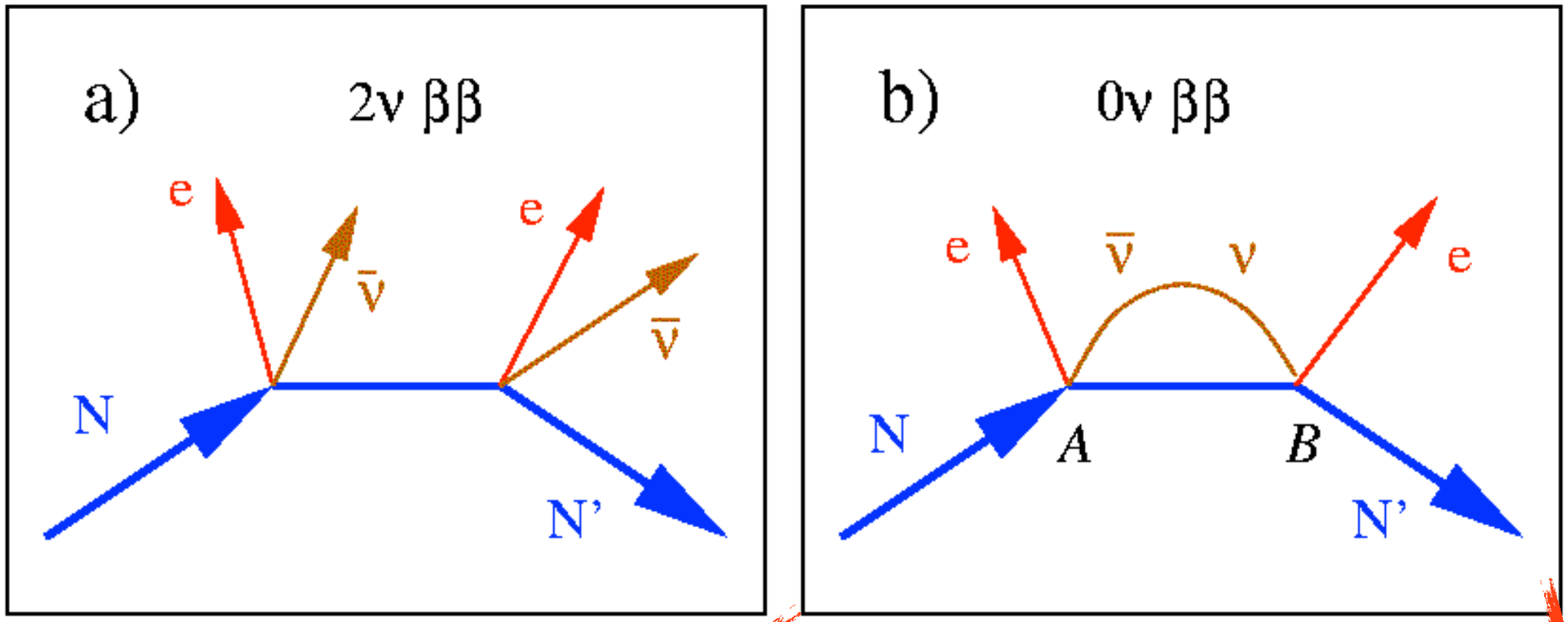
N. Oblath, TAUP 2015

- Attempt to solve source problem
- Ultimate resolution depends on detection time/field uniformity

Endpoint Measurement Technological Issues

- Endpoint measurements plagued by pileup
- Micro-calorimetric techniques are relatively insensitive to energy loss mechanisms, final state
- Microwave multiplexing is powerful at addressing large channel count
- ^{163}Ho is co-produced with ^{166m}Ho, which is a serious background
- Unknown structures in shape seen in ^{163}Ho spectra
- Project-8 eliminates separation of source and detector, but will be limited by systematic effects due to molecular ^{3}H, and density of source gas
    - Energy resolution improvements needed

Neutrinoless Double Beta Decay



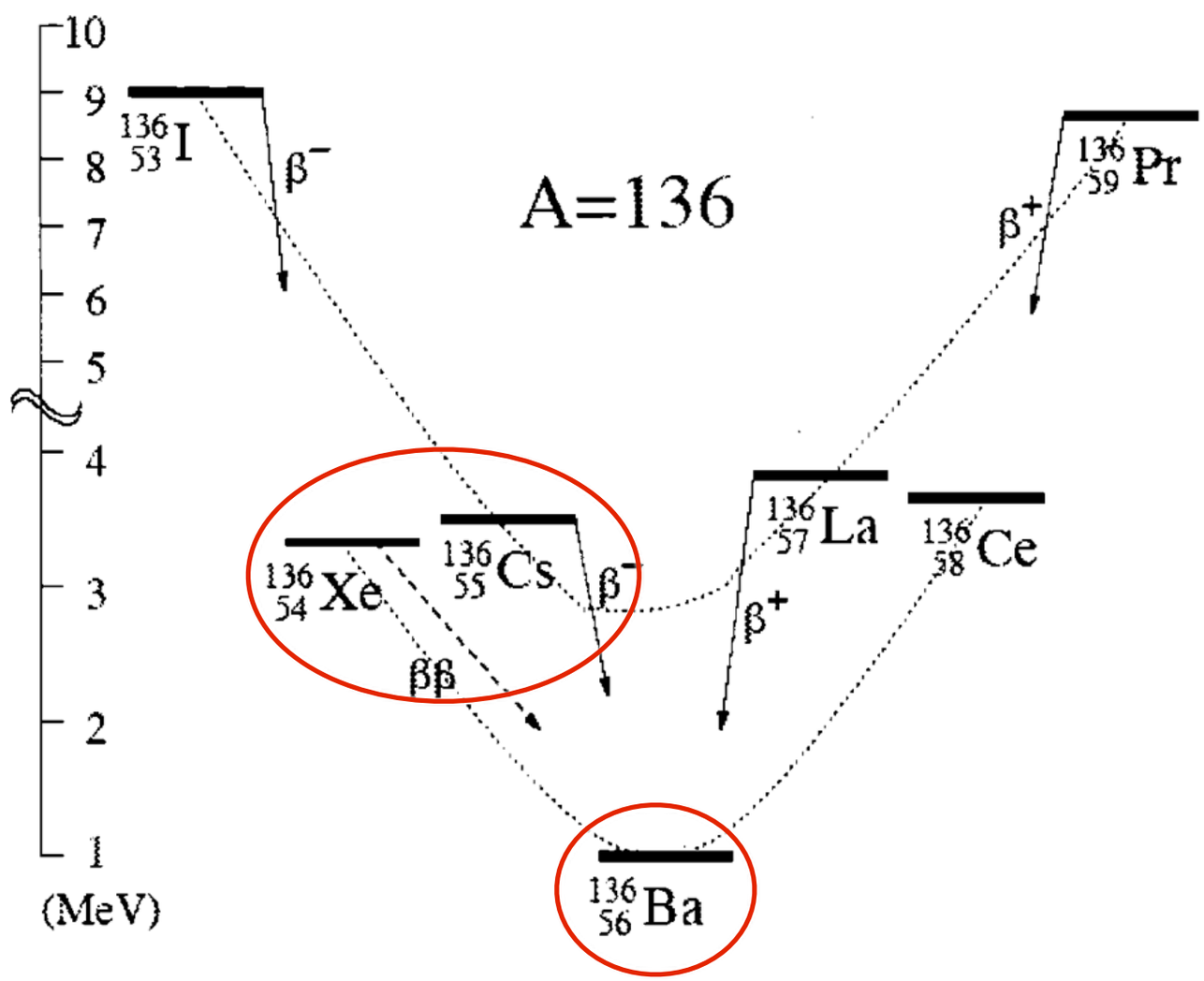
$$M_\nu \neq 0$$

$$|\Delta L| = 2$$

$$|\Delta(B-L)| = 2$$

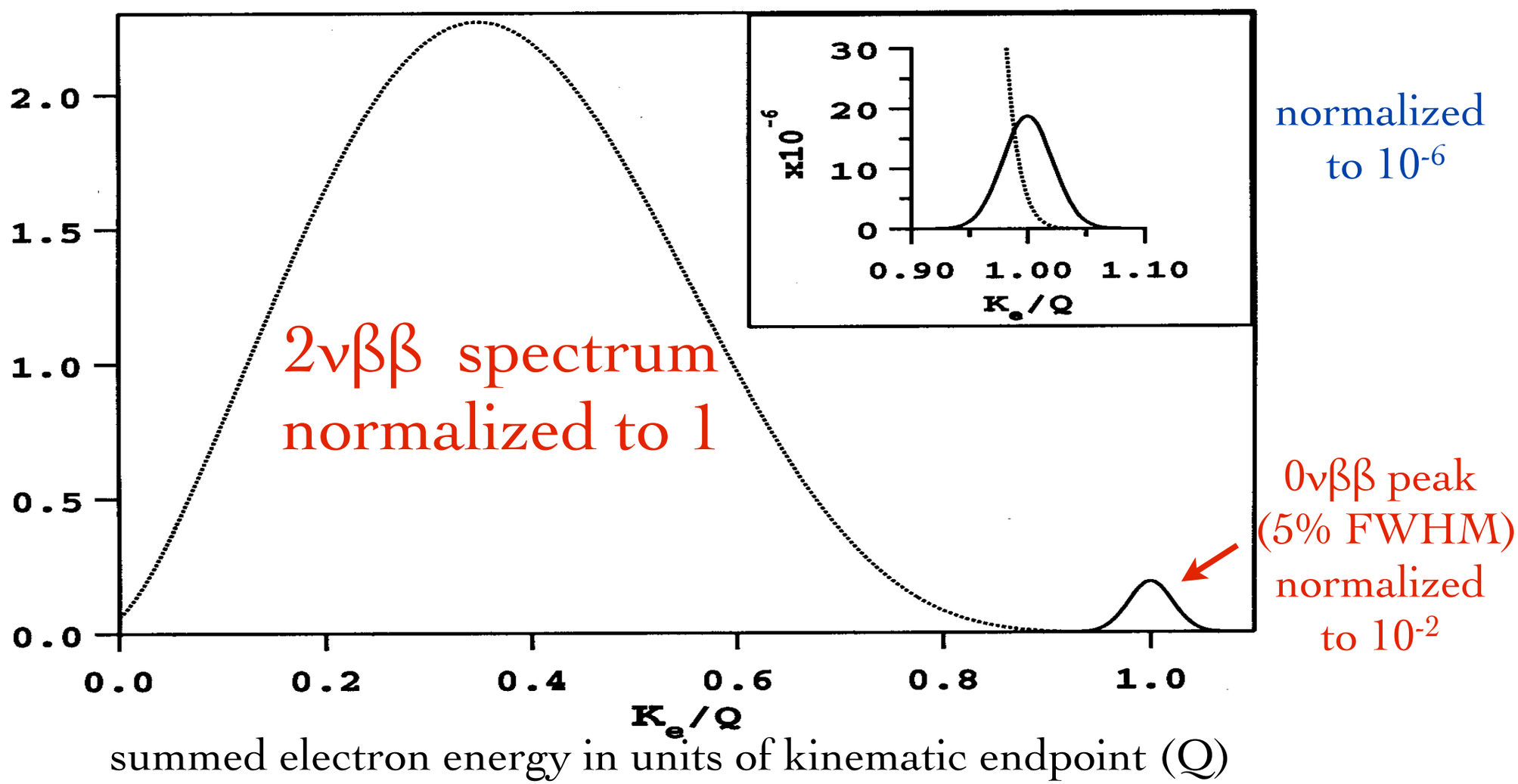
Majorana nature $\bar{\nu} = \nu$

Neutrinoless Double Beta Decay



- ββ decay: 2nd order process detectable if 1st order process is energetically forbidden

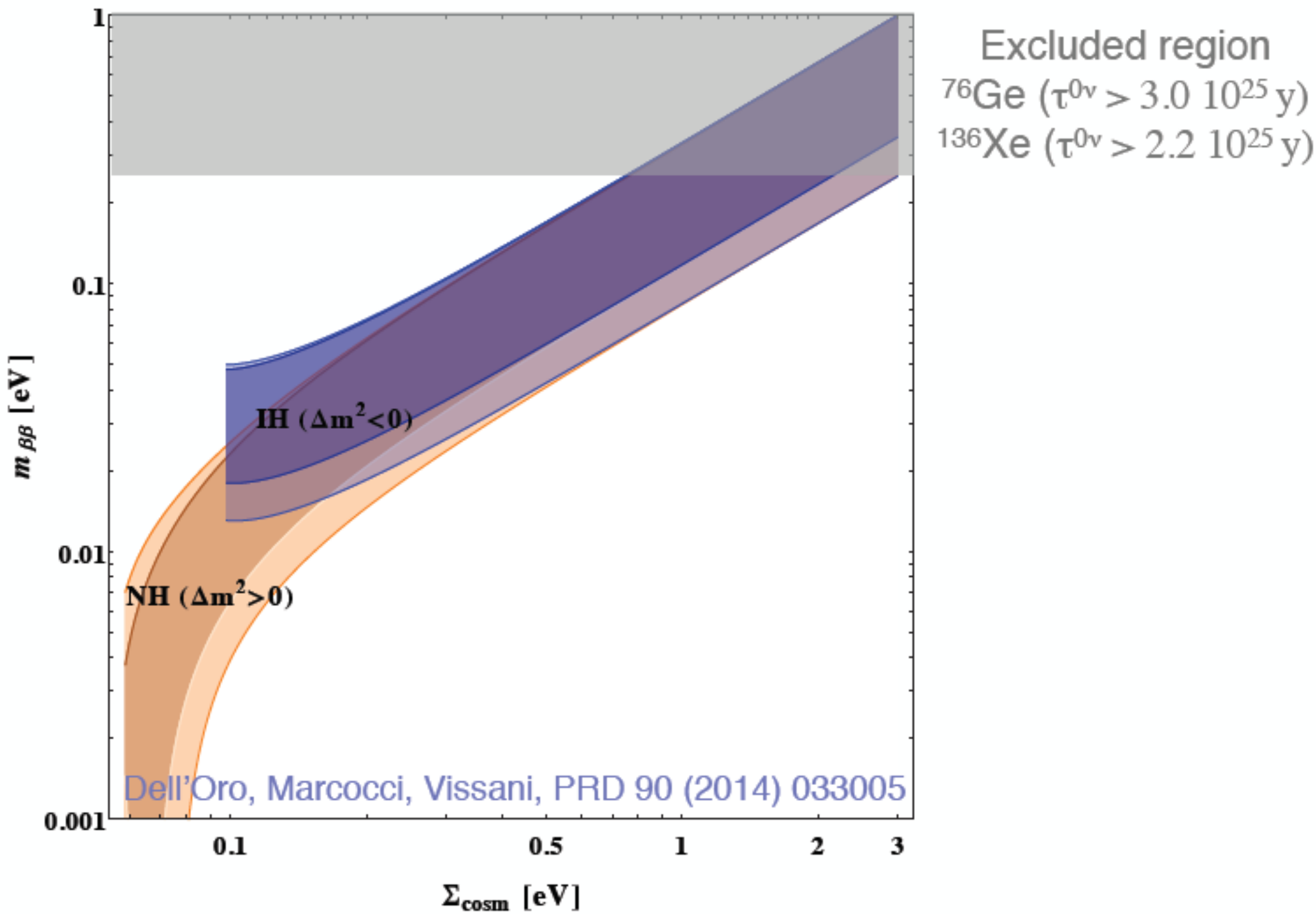
Neutrinoless Double Beta Decay



summed electron energy in units of kinematic endpoint (Q)

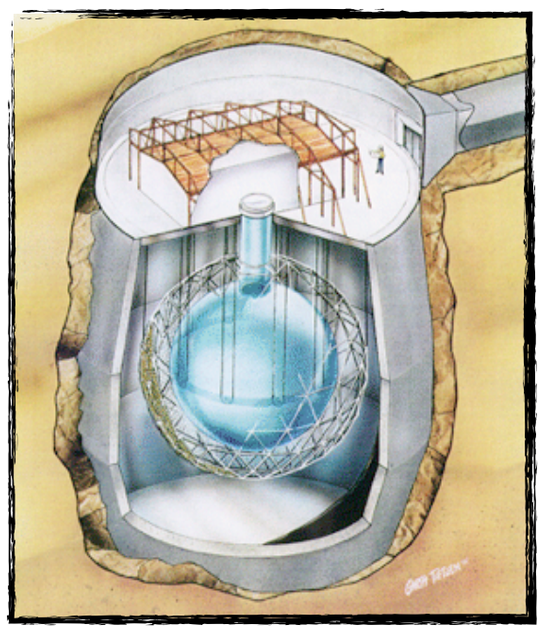
$$\langle m_\nu \rangle^2 = \left(T_{1/2}^{0\nu\beta\beta} \; G_{0\nu\beta\beta}(E_0, Z) \; |M_{0\nu\beta\beta}|^2 \right)^{-1}$$

Neutrinoless Double Beta Decay

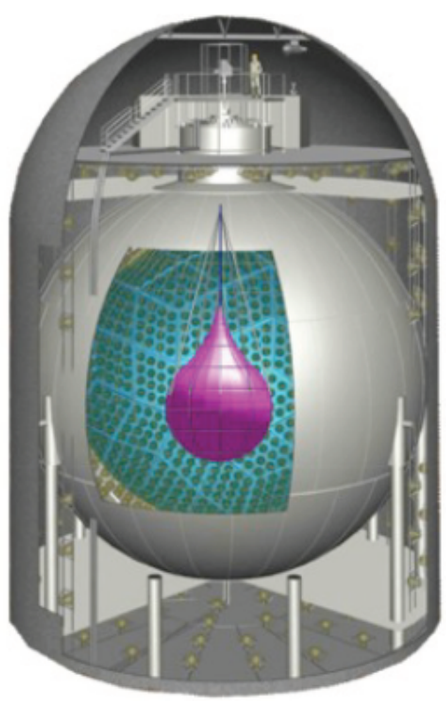


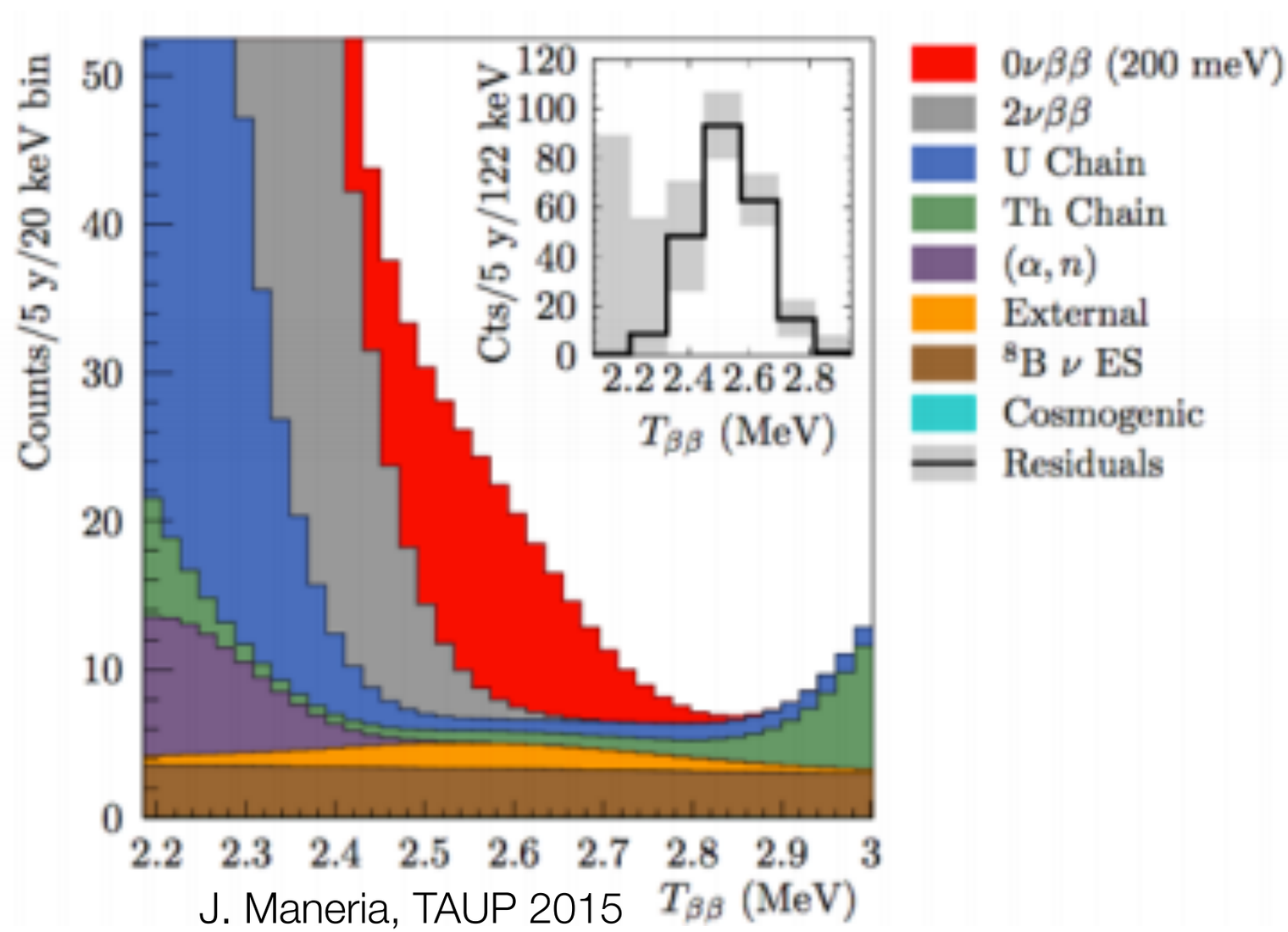
Neutrinoless Double Beta Decay: Dissolved Isotope

SNO+



KamLAND-Zen





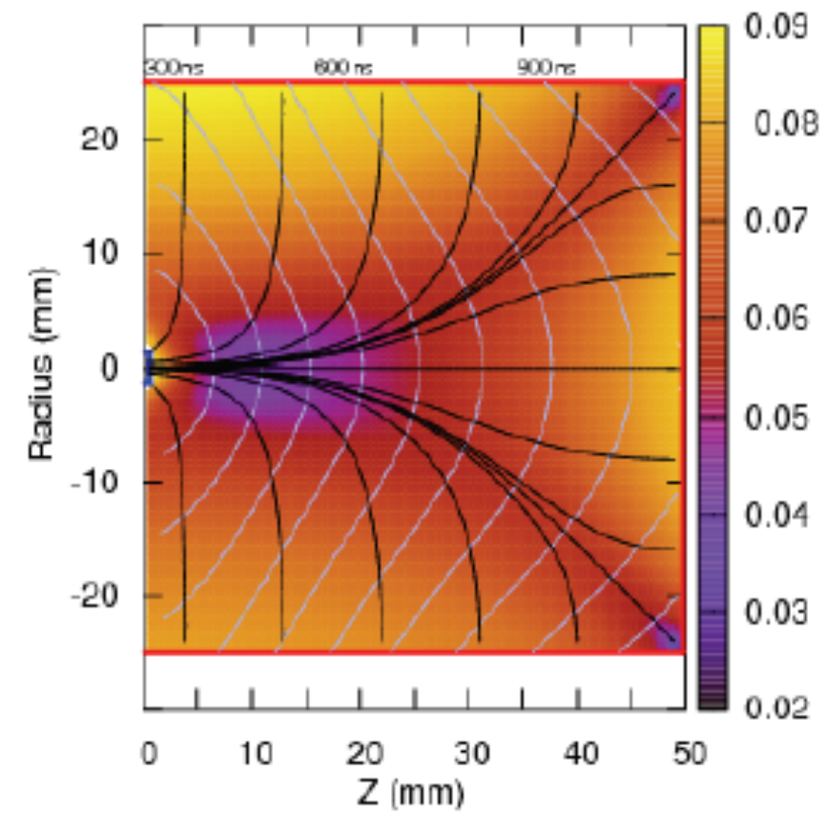
J. Maneria, TAUP 2015

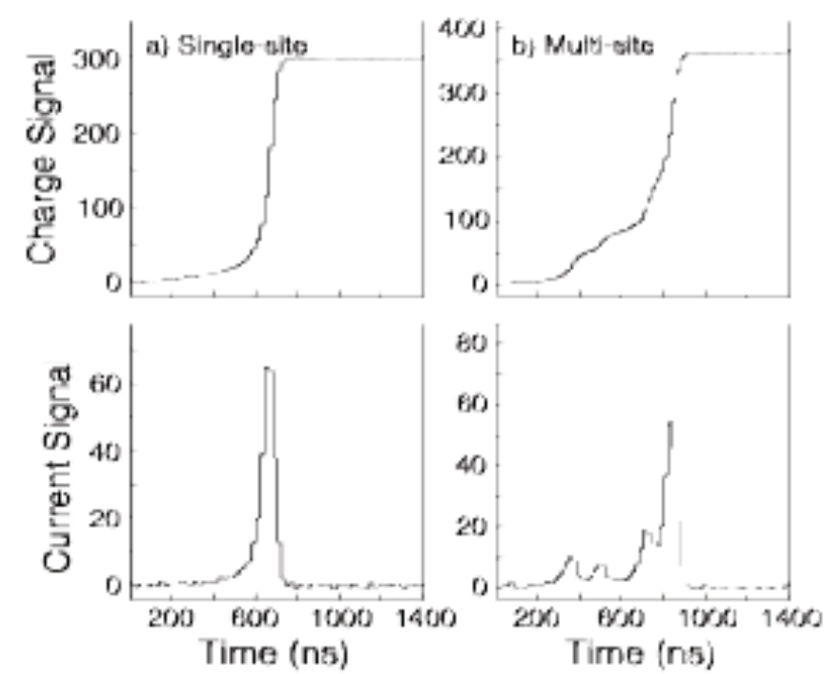
Neutrinoless Double Beta Decay: Source = Detector

- Germanium-Based experiments focus on energy resolution as a background rejector

- Use of P-type Point Contact (PPC) detectors reduces background from Compton scattered gammas

- Majorana: low-background passive components (Pb, Cu)



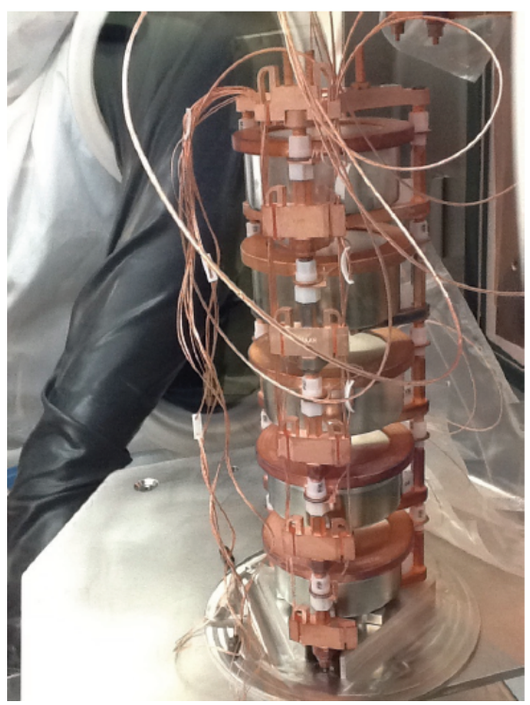


Neutrinoless Double Beta Decay: Source = Detector

- GERDA: Active LAr shielding
- Exploring hybrid approach for 1 T

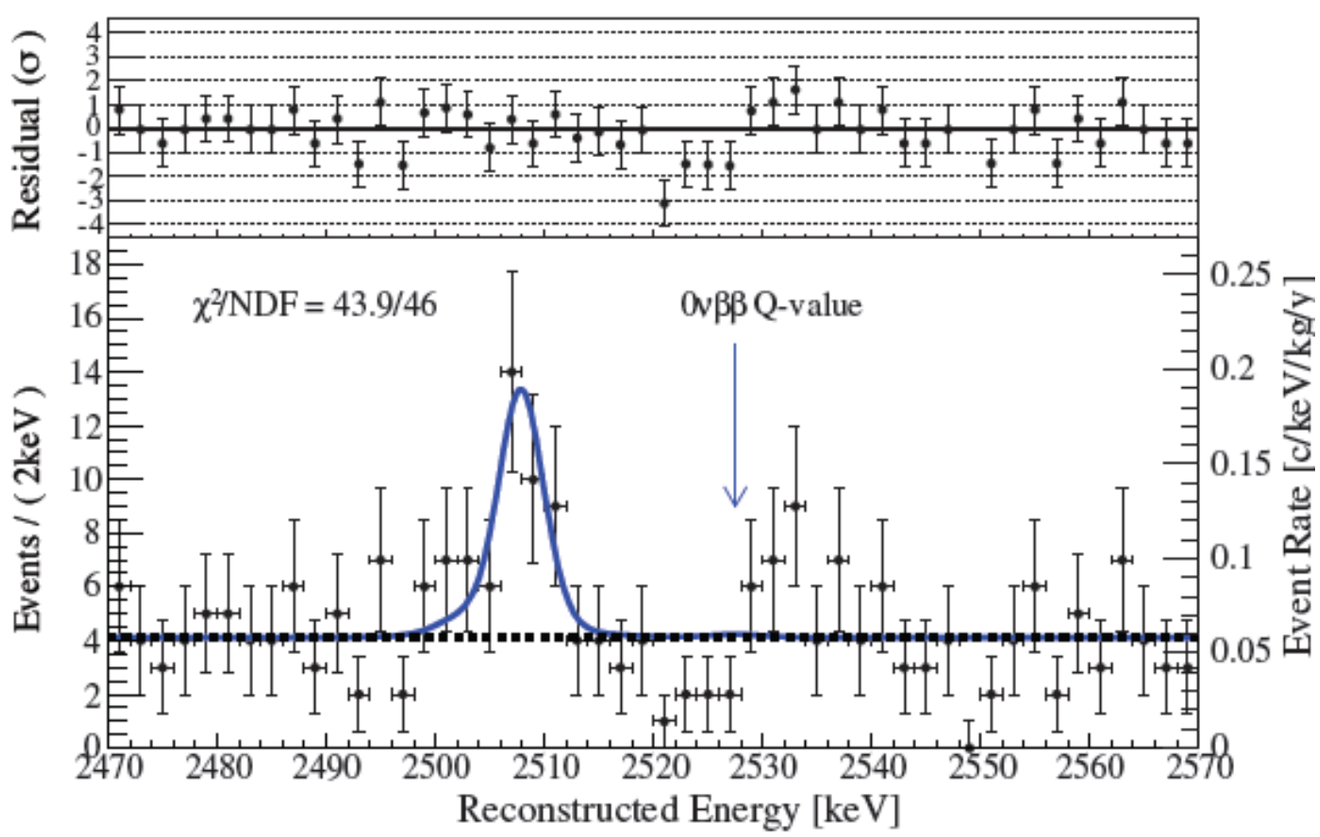
Neutrinoless Double Beta Decay: Source = Detector

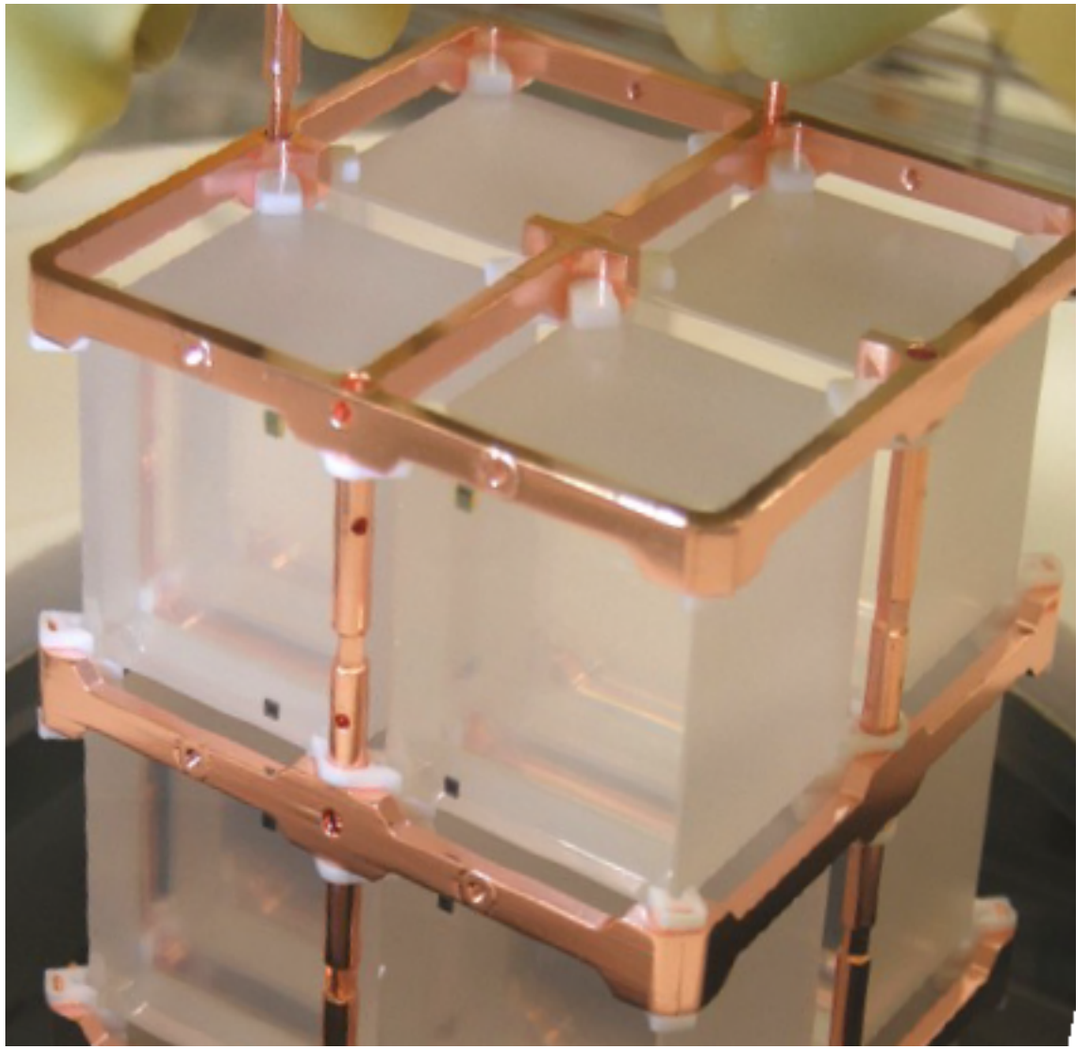
- GERDA: Active LAr shielding
- Exploring hybrid approach for 1 T
- Cable backgrounds are a big problem: Los Alamos exploring multiplexing in both time and frequency domain



Neutrinoless Double Beta Decay: Source = Detector

- Bolometric detectors: COURE (thermistors)
- good energy resolution ~ 1% FWHM
- Radioclean materials



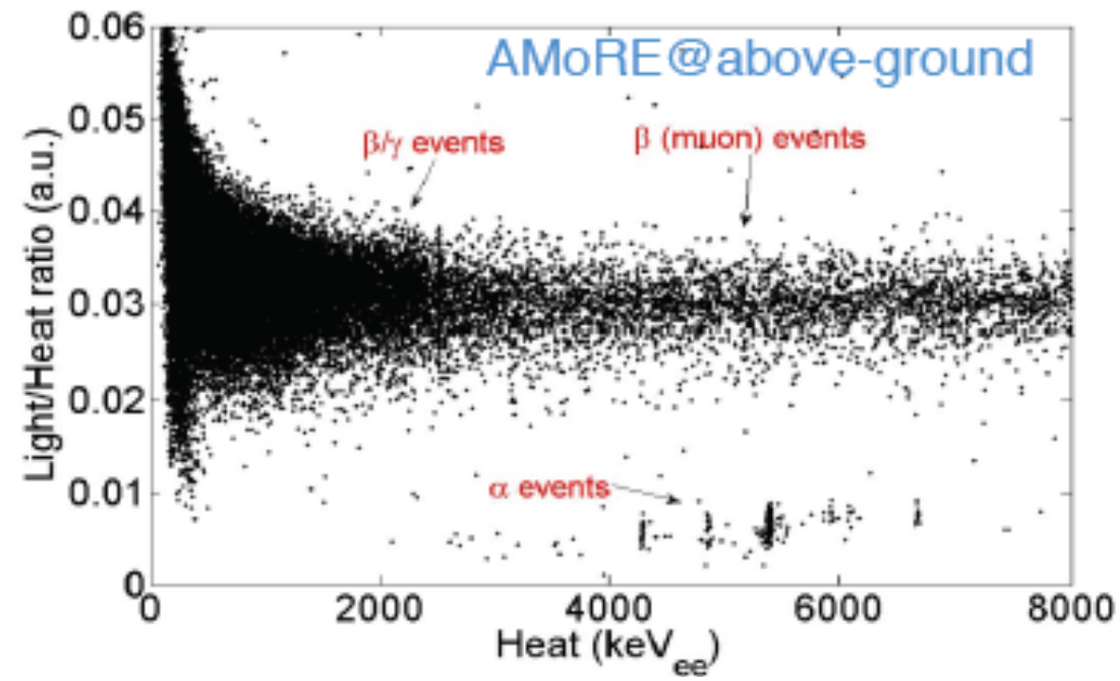


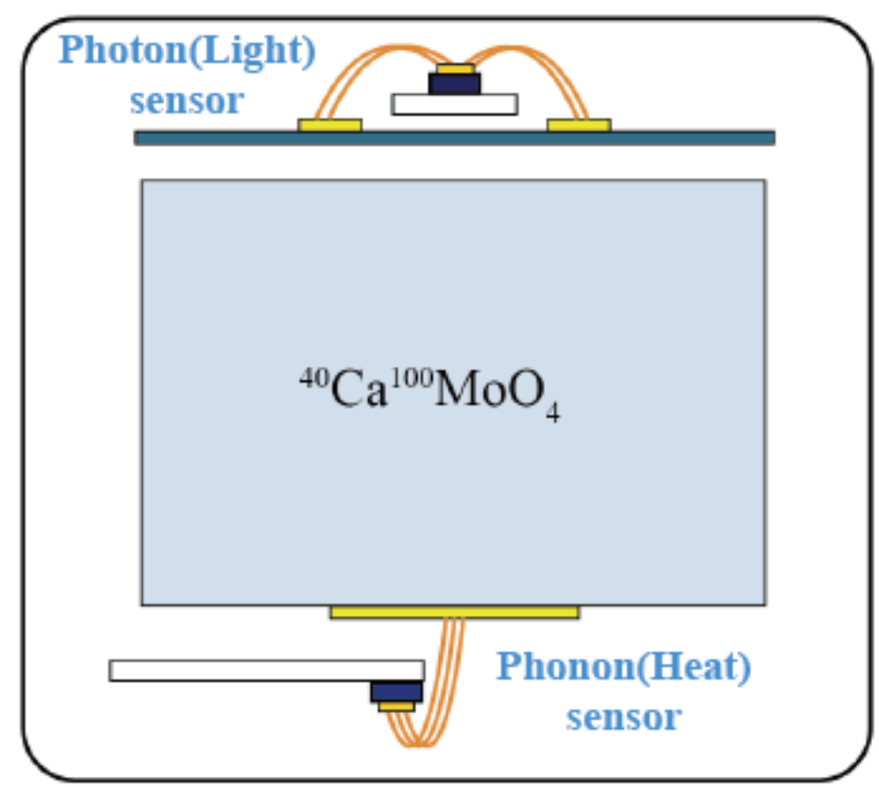
C. Bucci, TAUP 2015

Neutrinoless Double Beta Decay: Source = Detector

- A number of technologies include another detector channels for background rejection

- AMoRE (MMCs): Scintillation & Phonon PSD

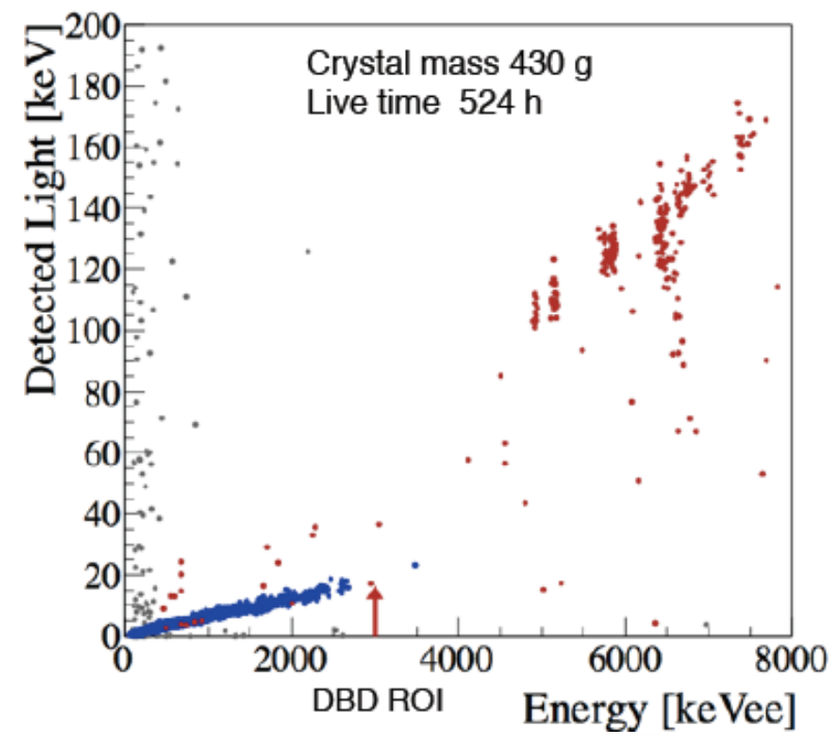


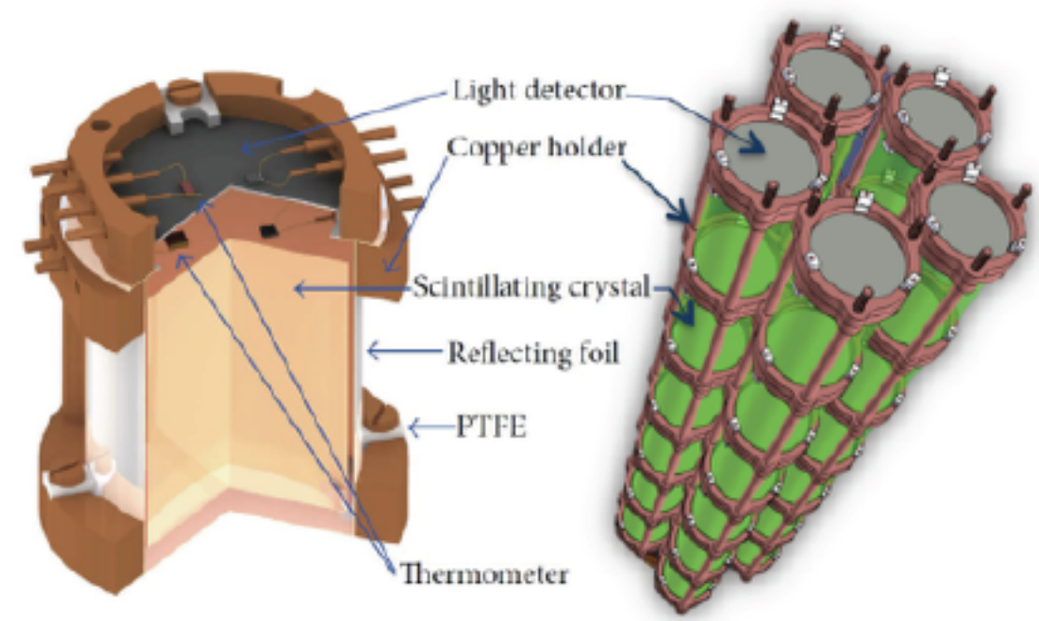


Neutrinoless Double Beta Decay: Source = Detector

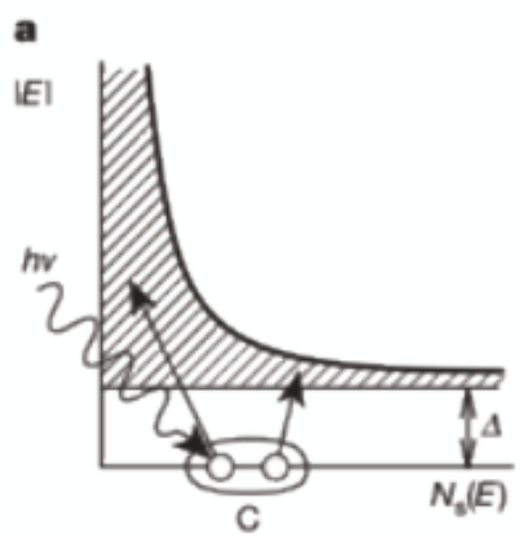
- LUCIFER (bolometers): Scintillation & Phonon PSD
- CALDER (bolometers): Cherenkov photons using kinetic inductance detectors

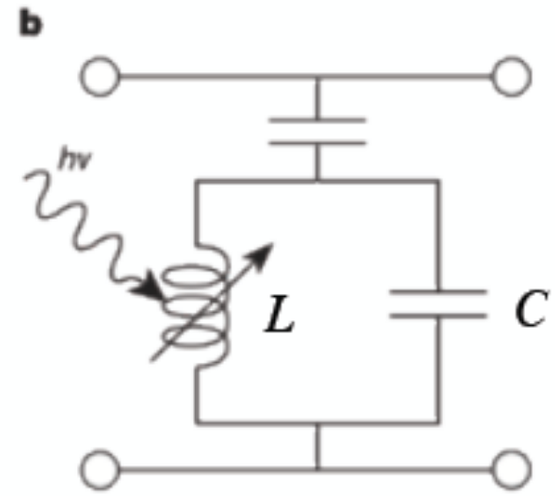
L. Pattavina, LUCIFER (TAUP 2015)



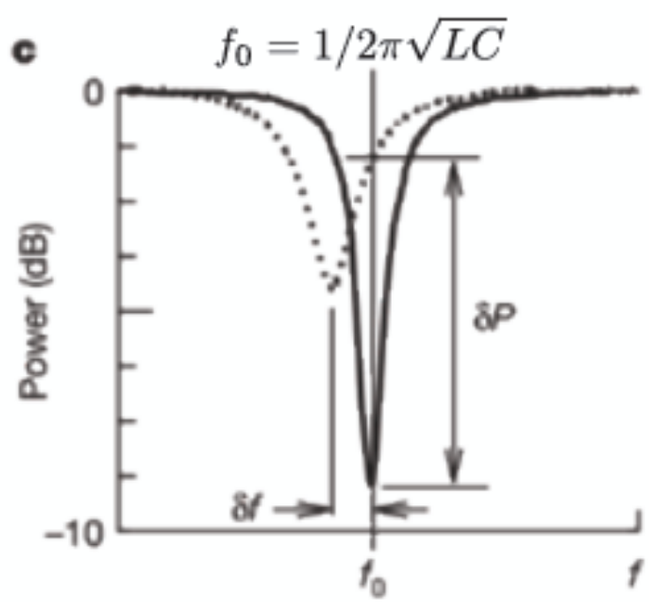


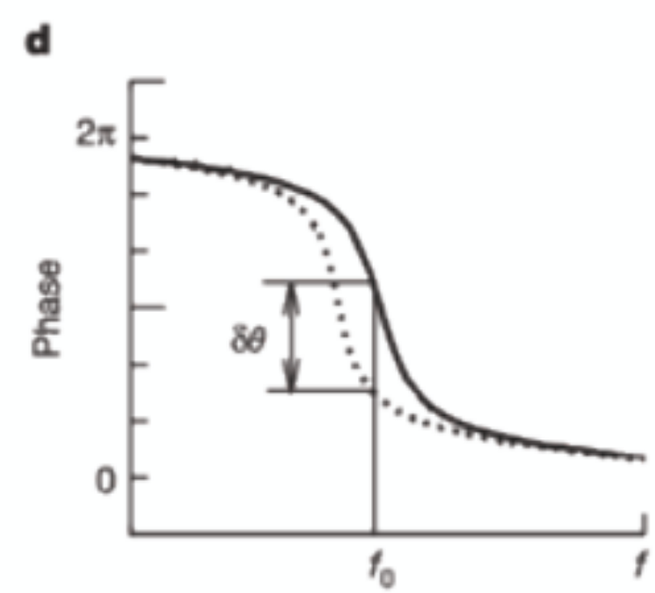
Neutrinoless Double Beta Decay: Source = Detector





Cooper pairs (cp) in a superconductor act as an inductance (*L*).
Absorbed photons change cp density and *L*.





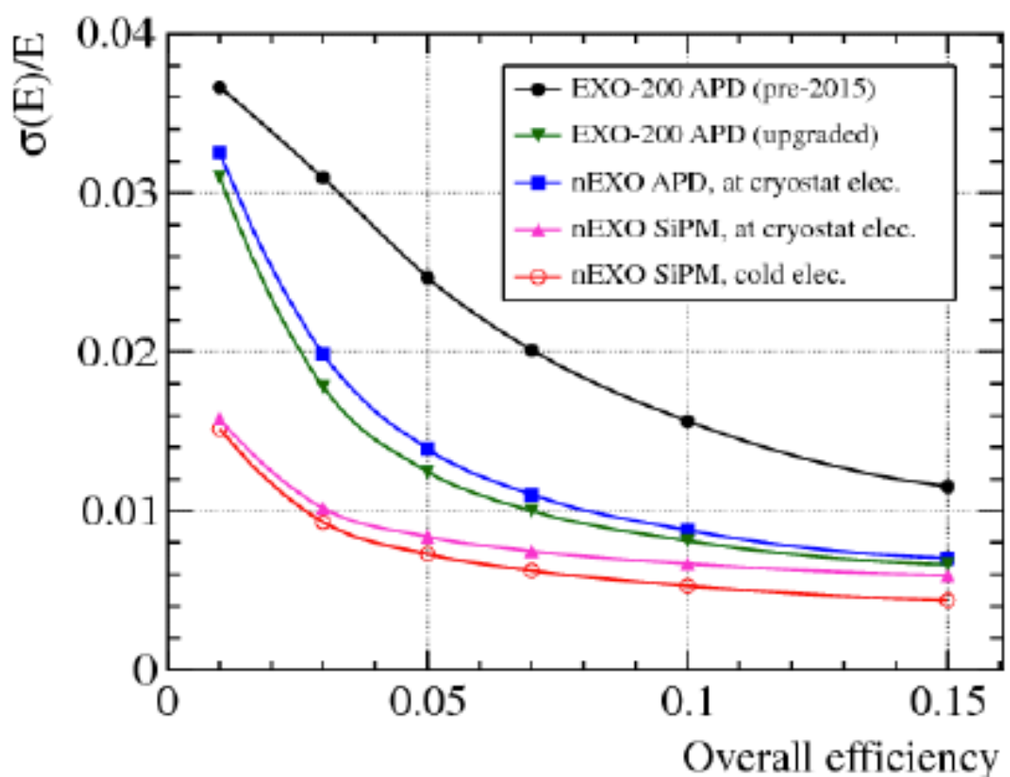
High quality factor (*Q*) resonating circuit biased with a microwave (GHz):
signal from amplitude and phase shift.

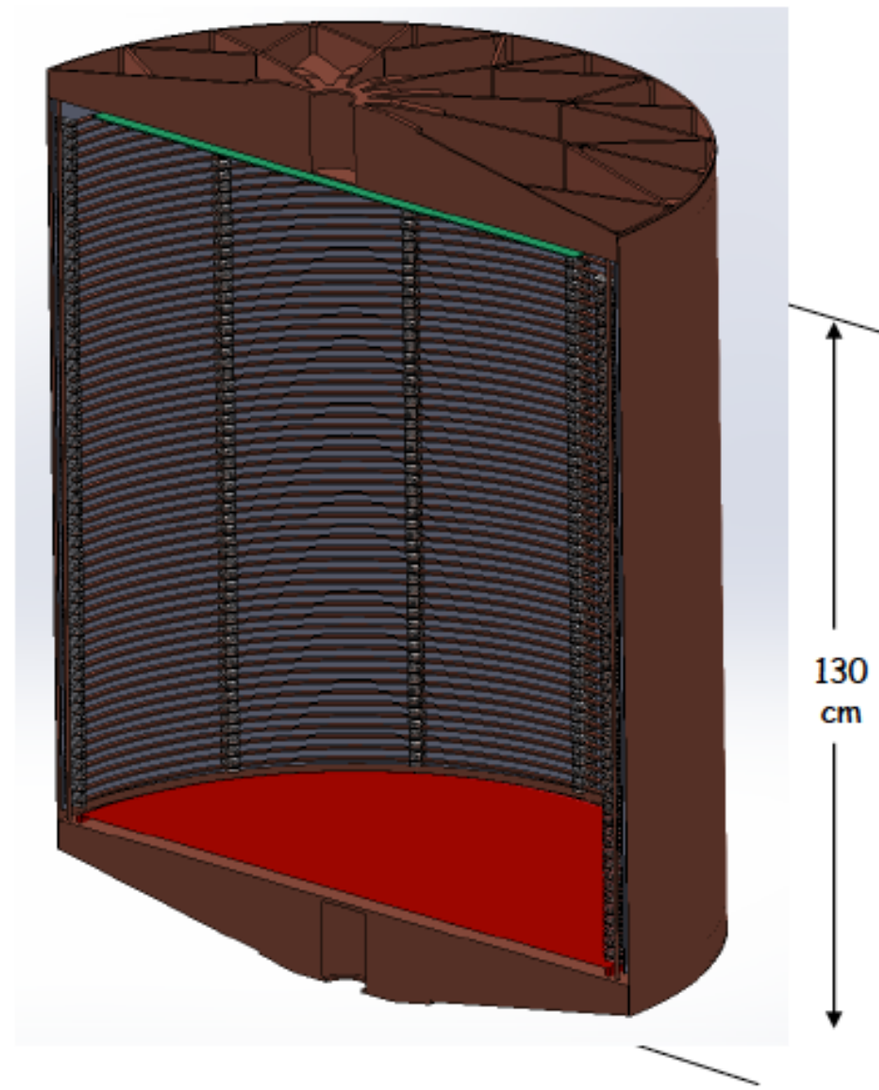
Day et al., Nature 425 (2003) 817

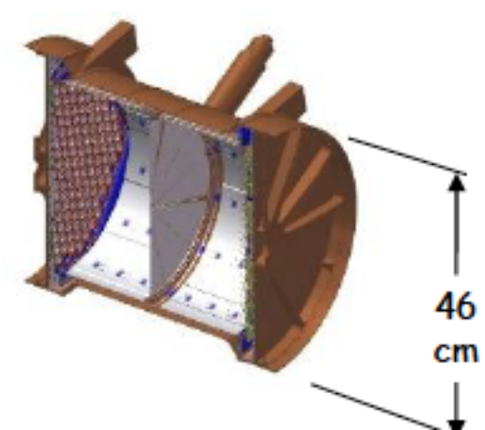
Neutrinoless Double Beta Decay: Source = Detector

nEXO:

- The combination of light and charge gives the best energy resolution in LXe
- Also alpha background discrimination
- Large standoff removes background contributors from sensitive volume
- Replace EXO-200 APDs with SiPMs
- Fully integrated cold electronics
- The possibility of tagging the daughter Ba is being investigated (~zero background experiment)



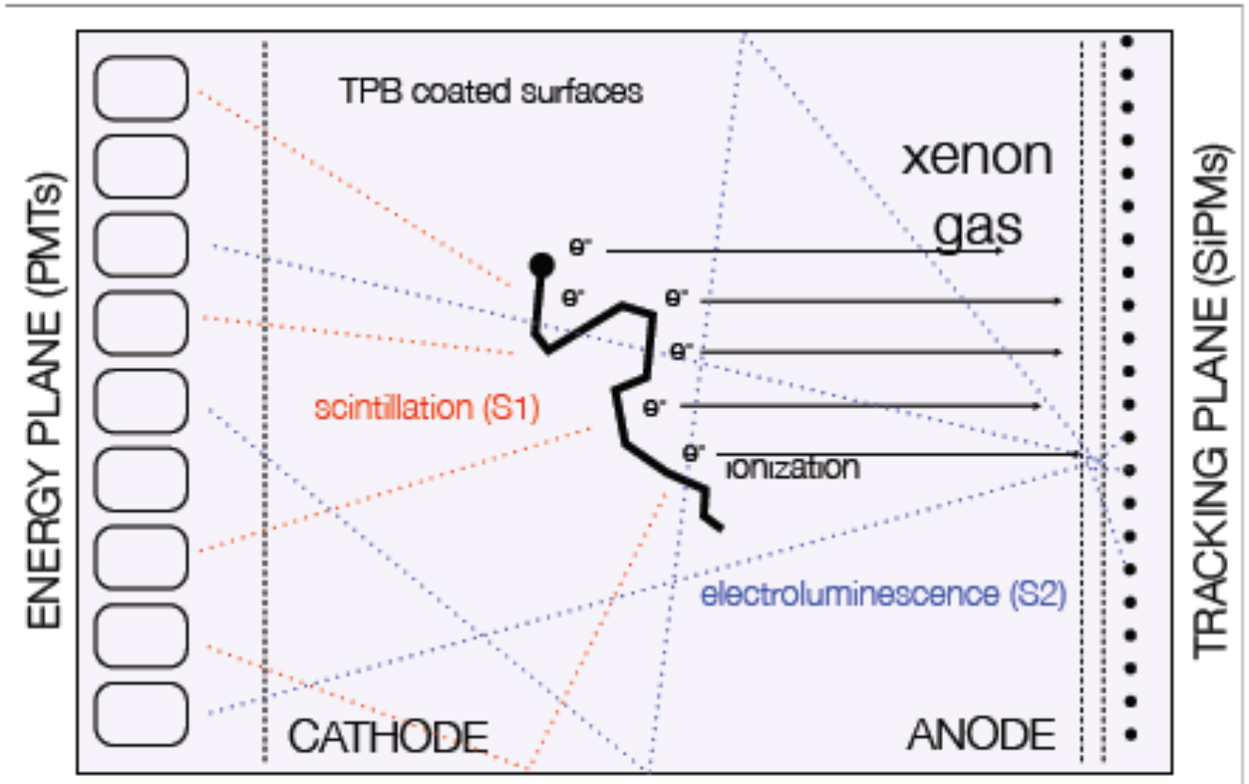


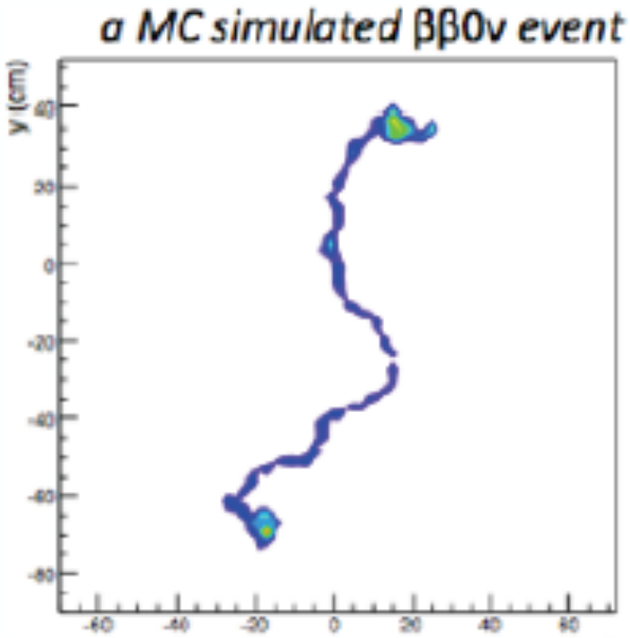


Neutrinoless Double Beta Decay: Source = Detector

NEXT:

- There is more topological information available in gas
- Energy resolution extrapolates to 0.5% FWHM at Q value (from calibrations)
- Ba tagging is also a possibility in





Double Beta Decay Technological Issues

- The most effective technological advances (so far) are in low-radioactivity techniques: It is always better to start with zero background
- Nearly every experiment requires high resolution, low-noise photon detection
  - SiPMs in nEXO and NEXT
  - Cryogenic photon detection technologies (phonon sensors coupled to light convertor)
    - Metallic Magnetic Calorimeter
    - NTD thermistors
    - TES sensors
    - Luke effect
- Frequency Domain Multiplexing plays a major role
- Event & particle discrimination can play an important role in reaching zero background (but there are only so many ways to slice a pizza and still have anything worthwhile to eat)
- @zeroBackgrounds, we are still fighting Avogadro's number: enriching~10^{28} moles

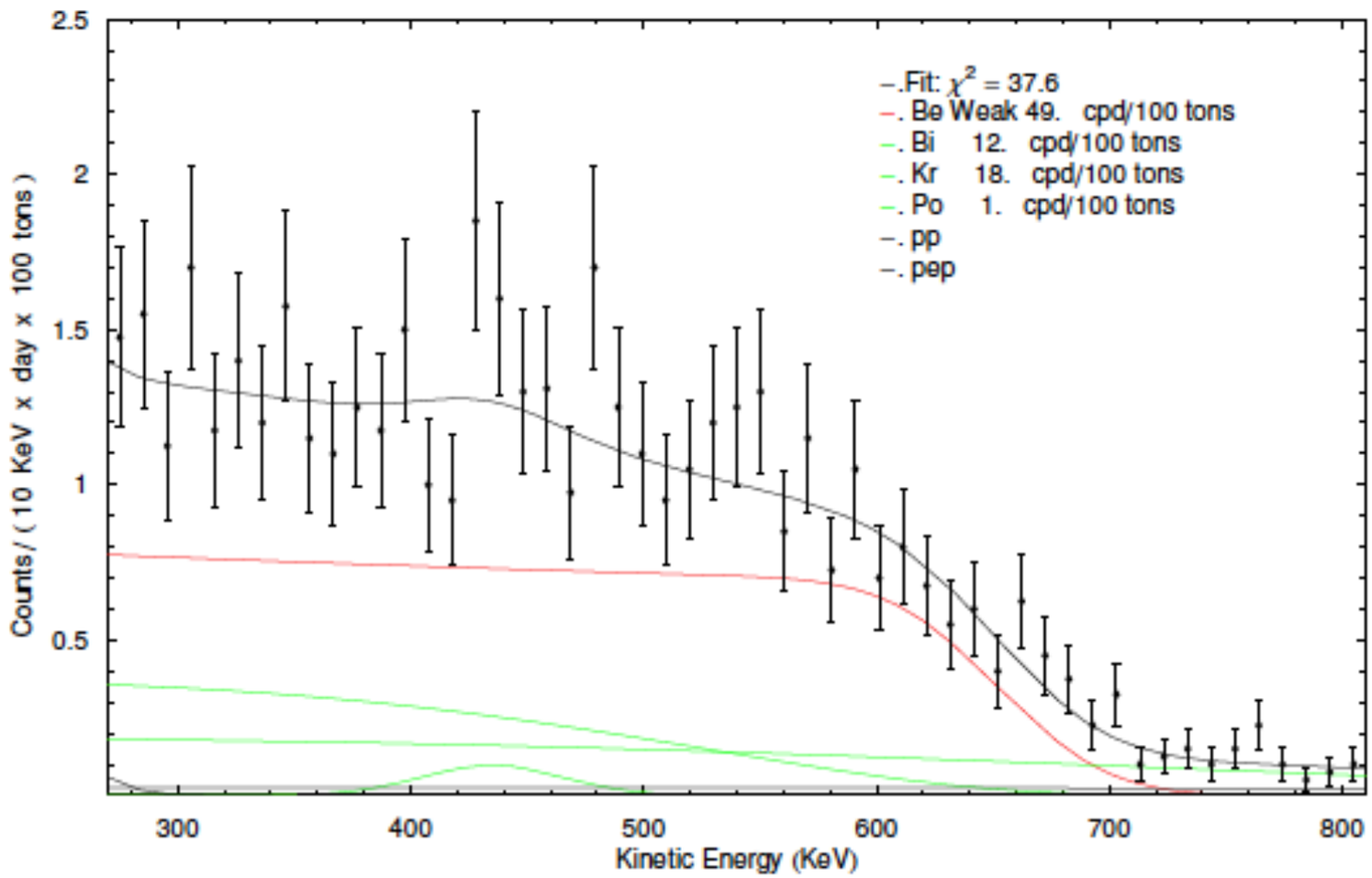
Neutrino Magnetic Moment

- The existence of a finite neutrino mass means that there must be electromagnetic properties
- For Dirac neutrinos $\mu_\nu = 2.3 \times 10^{-19} \mu_B \left(\frac{m_\nu}{1eV} \right)$
- Astrophysical arguments constrain this to be $\mu_\nu < 3 \times 10^{-12} \mu_B$
- There are many BSM physics reasons why this is interesting
  - For Majorana neutrinos, large values are possible

$$\mu_\nu \approx 10^{-14} \rightarrow 10^{-12} \mu_B$$

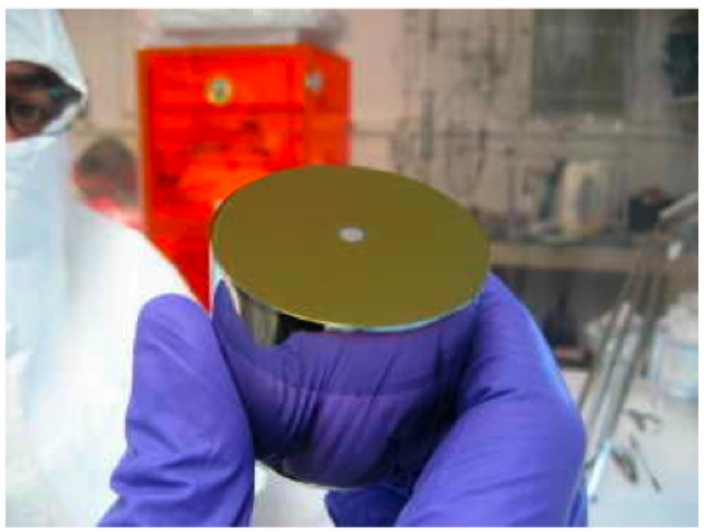
Neutrino Magnetic Moment: Experiments

- Borexino shape deformation limits $\mu_\nu < 5.4 \times 10^{-11} \mu_B$

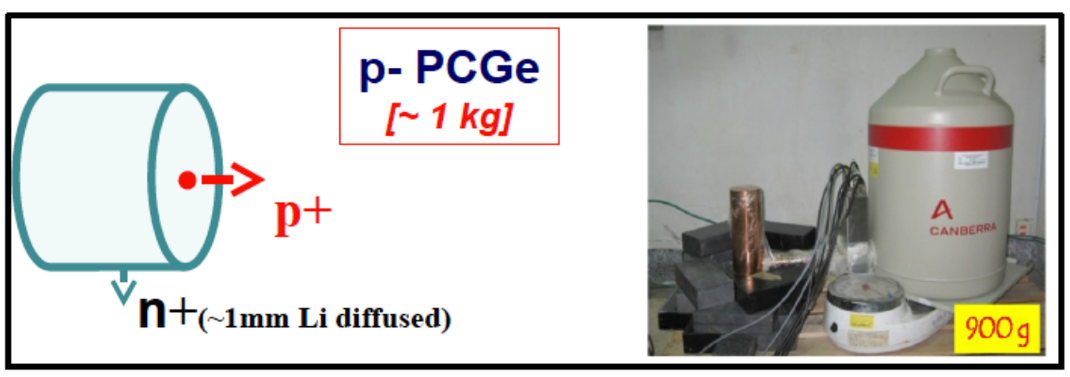


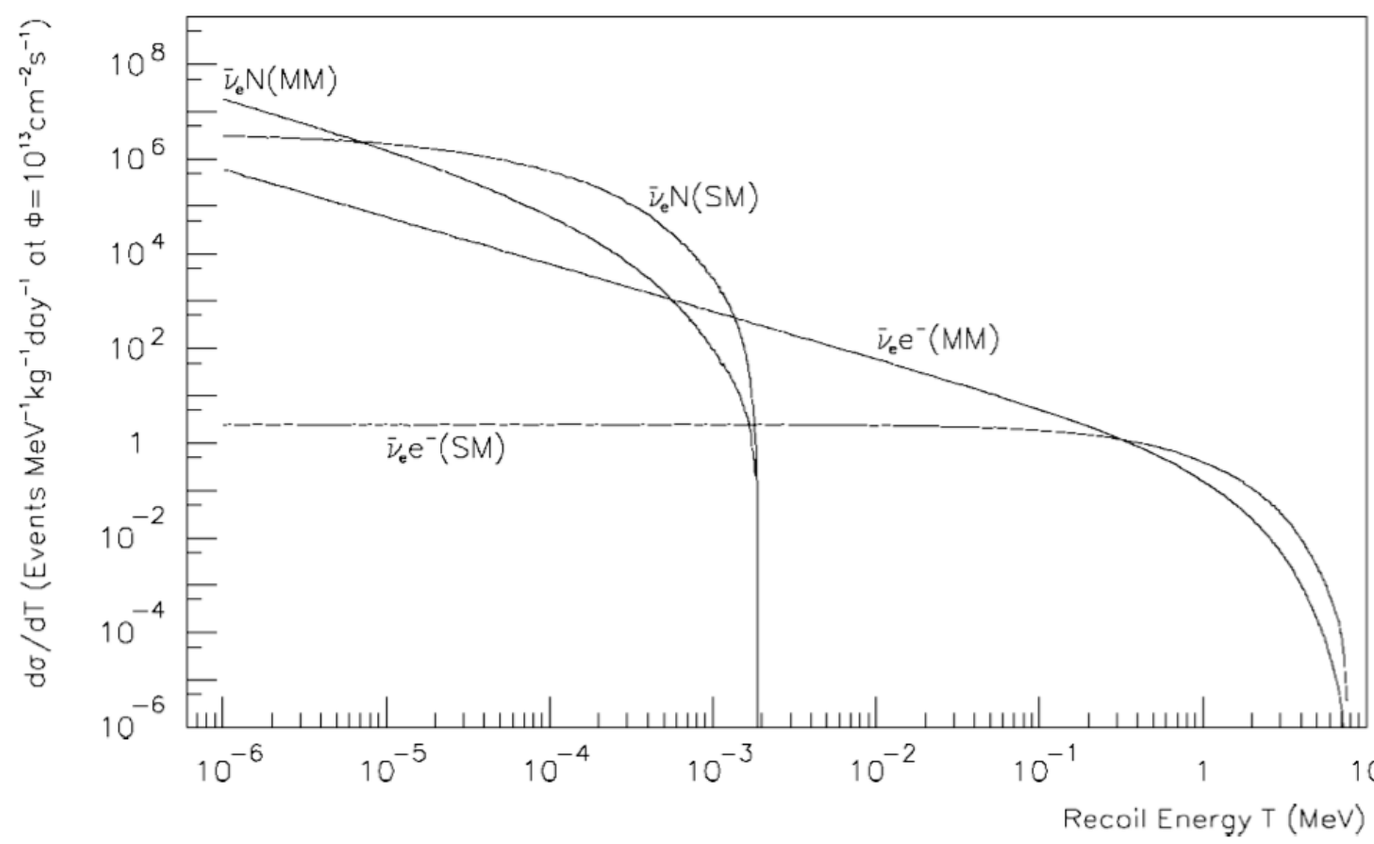
Neutrino Magnetic Moment: Experiments

- Best results (GEMMA) look at neutrino-electron scattering in low-threshold detectors from reactors $\mu_\nu < 2.9 \times 10^{-11} \mu_B$



$$\frac{d\sigma_{EM}}{dT} = \frac{\pi \alpha_{em}^2 \mu_\nu^2}{m_e^2} \left[\frac{1}{T} - \frac{1}{E_\nu} \right]$$





TEXONO

Neutrino Magnetic Moment: technical limitations

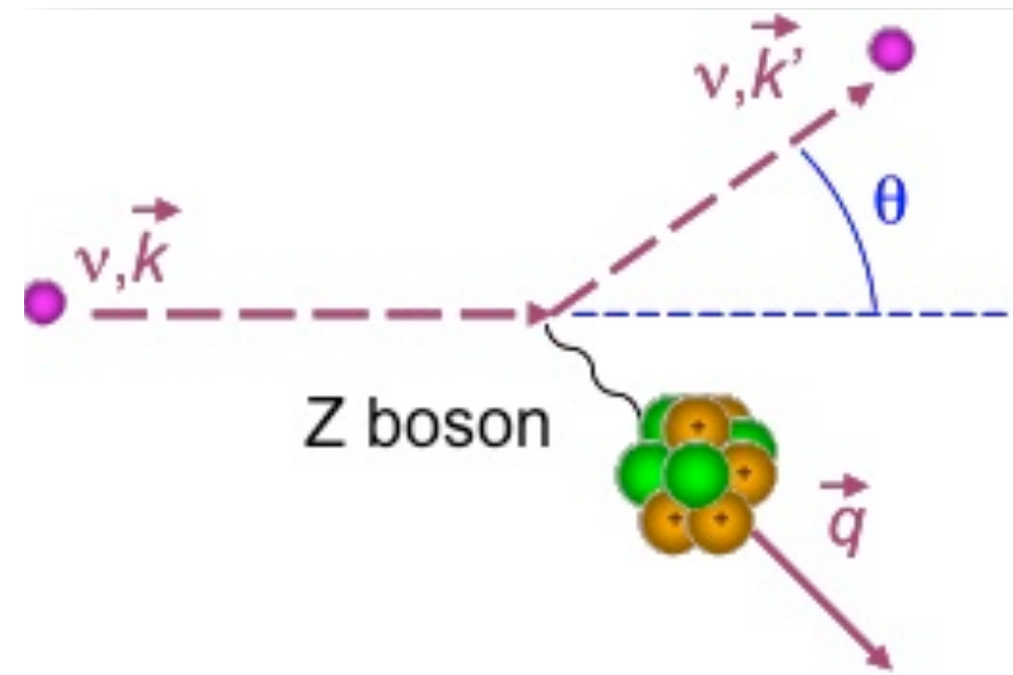
- In a background limited scenario, the sensitivity improves as

$$\mu_\nu \propto \frac{1}{\sqrt{N_\nu}} \left(\frac{B}{Mt}\right)^{1/4}$$

- Experiments limited by the amount of mass that can be deployed (factor of 10 improvement would need 10 tons of Ge)
- There are no 300 GW_{th} power reactors…
- The 1/T improvements limited by energy thresholds
- CEvNS becomes a background
- At some point, you run out of electrons (binding energy)

Coherent ν-Nucleus Scattering

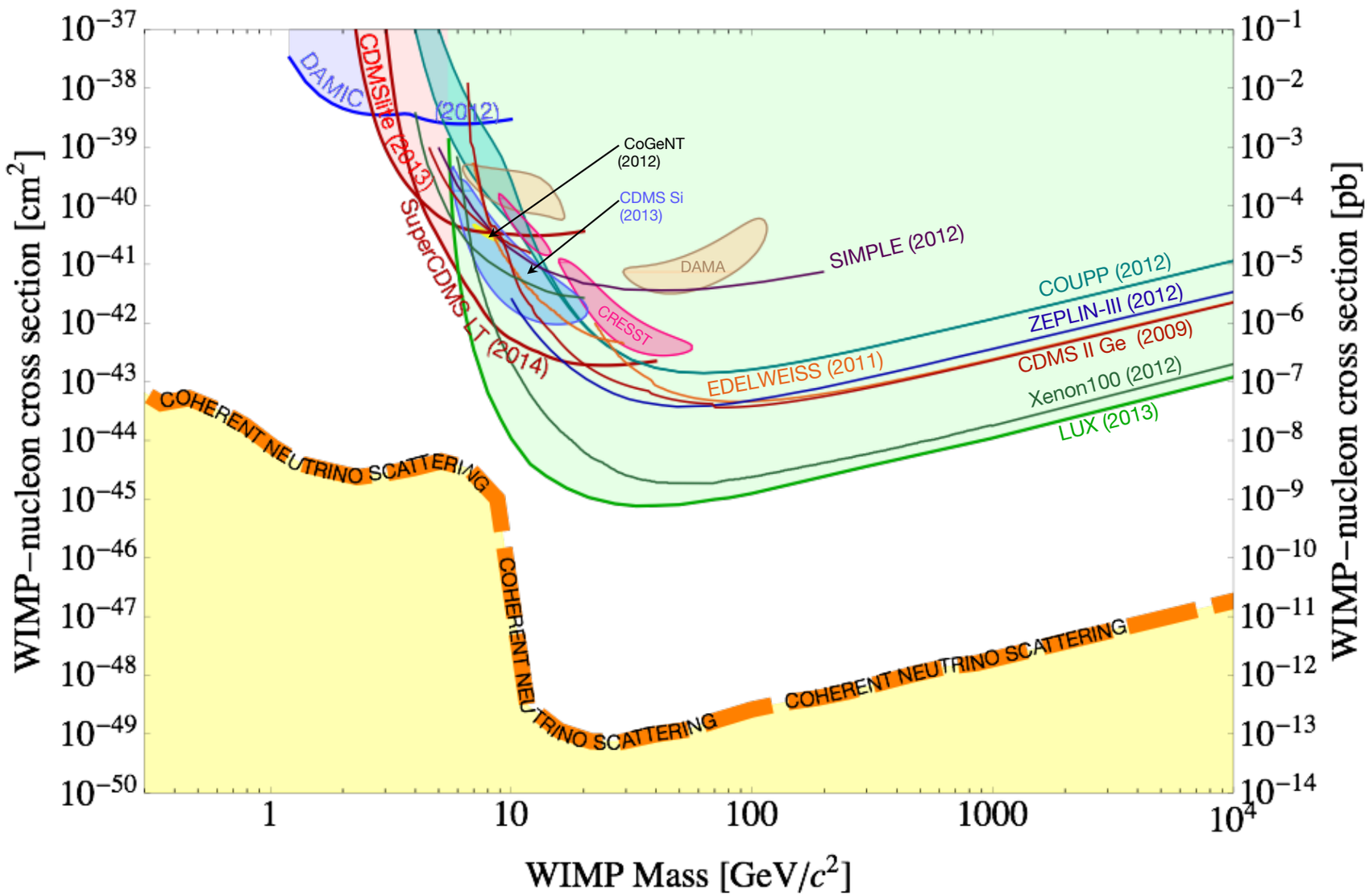
- Predicted in 1974 with the realization of the weak neutral current: as yet unobserved
- Neutrino scatters coherently off all Nucleons → cross section enhancement: $\sigma \propto \mathbf{N^2}$
- Initial and final states must be identical: Neutral Current elastic scattering
- Nucleons must recoil in phase →low momentum transfer qR <1 → *very* low energy nuclear recoil



D. Z. Freedman, PRD 9 (5) 1974

Coherent ν-Nucleus Scattering

- CEvNS is an irreducible background from WIMP searches, and should be measured in order to validate background models and detector responses.

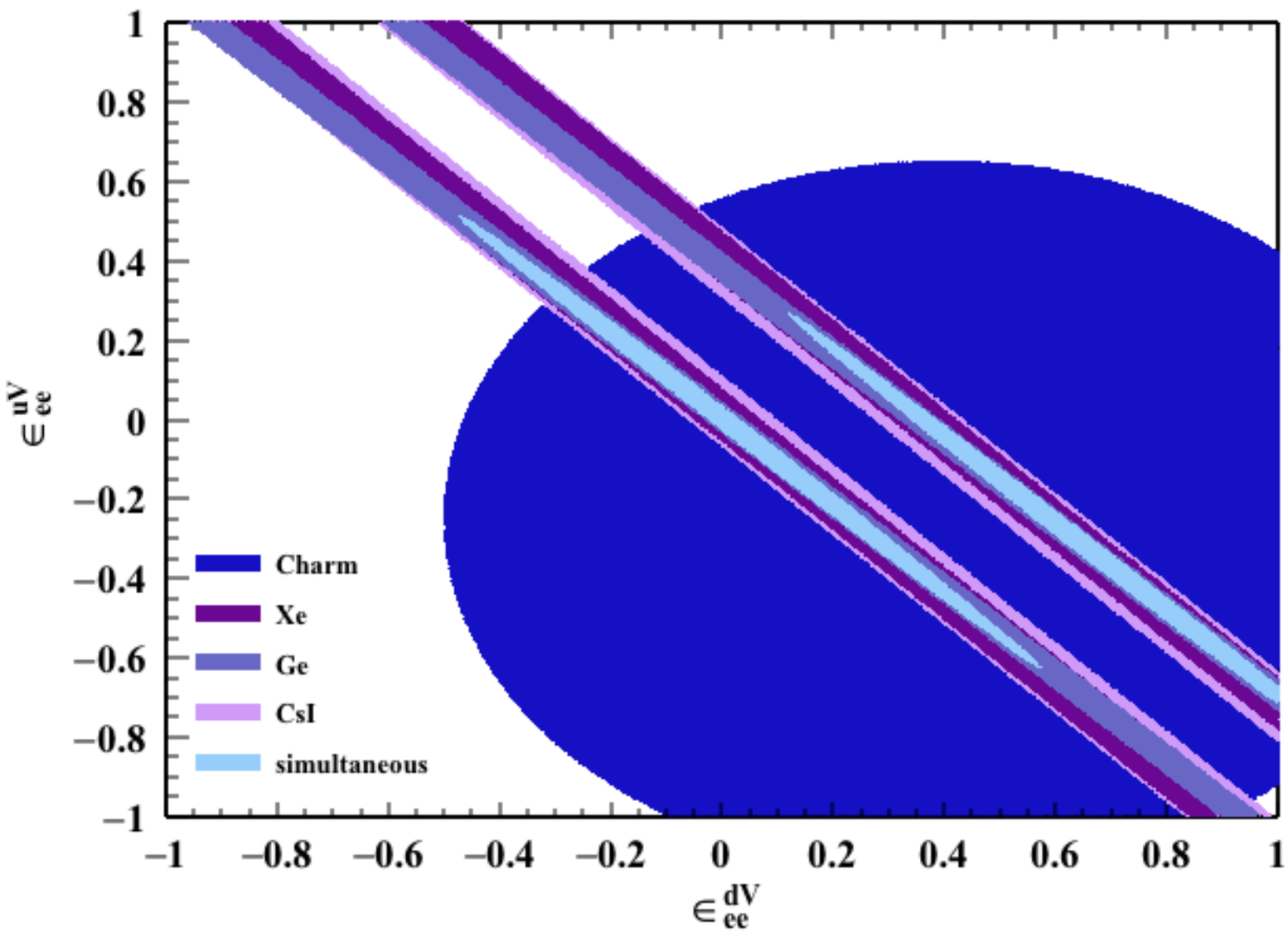


Coherent ν-Nucleus Scattering

- By measuring the relative rates on several nuclear targets we dramatically extend the sensitivity of searches for Non-Standard ν Interactions

K. Scholberg, Phys.Rev.D73:033005,2006

J. Barranco et al., JHEP0512:021,2005



Coherent ν-Nucleus Scattering

- A high-σ, neutral current detector would be a clean way to search for sterile ν's

  A. Drukier & L. Stodolsky, PRD 30 (84) 2295

- The development of a coherent neutrino scattering detection capability provides perhaps the best way to explore any sterile neutrino sector that could be uncovered with ongoing experiments.

  A. J. Anderson et al., PRD 86 013004 (2012)

- Coherent σ proportional to Q_w^2. A precision test of σ is a sensitive test of new physics above the weak scale. M_{top} and M_{higgs} are known → Remaining theoretical uncertainties ~0.2%

  L. M. Krauss, PLB 269, 407

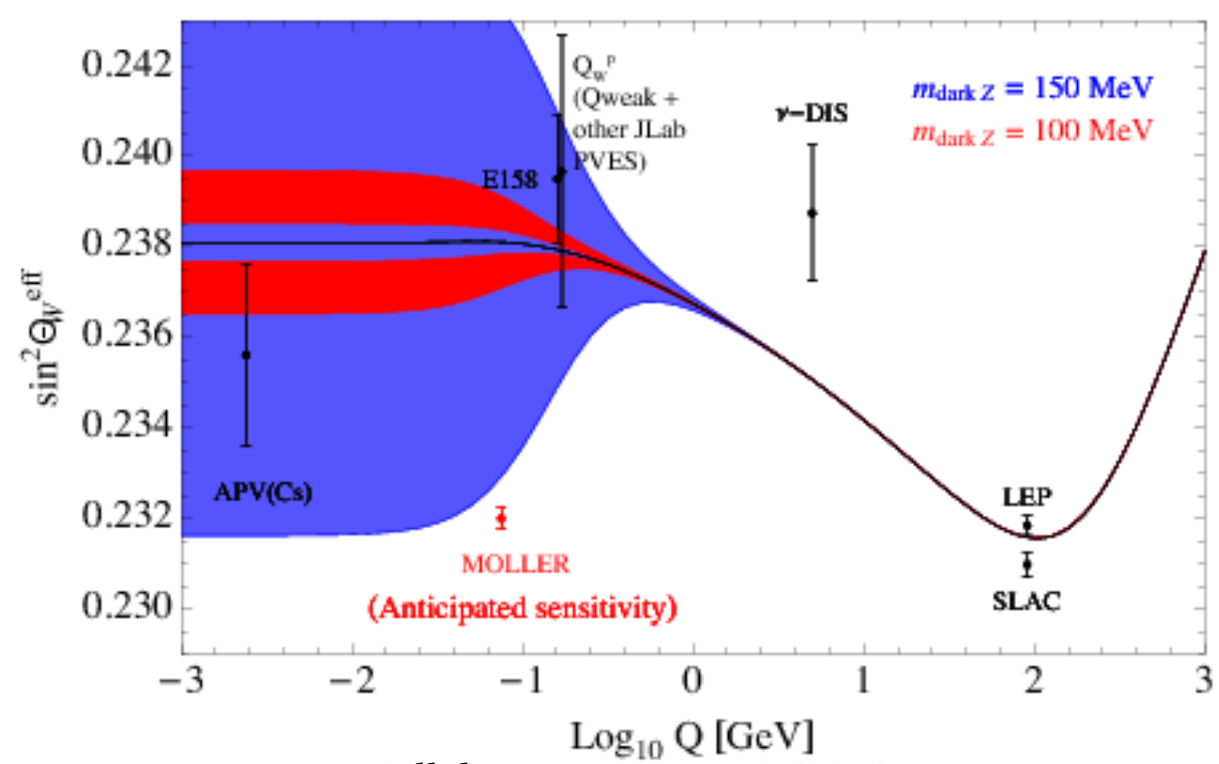
$$\sigma_{coh} \sim \frac{G_f^2 E^2}{4\pi}(Z(4\ sin^2\theta_w - 1) + N)^2$$

- **Neutrino Magnetic Moments**

  A. C. Dodd, et al., PLB 266 (91), 434

- Measuring the neutron distribution functions (Form Factors)

  K. Patton, et al., PRC 86, 024216

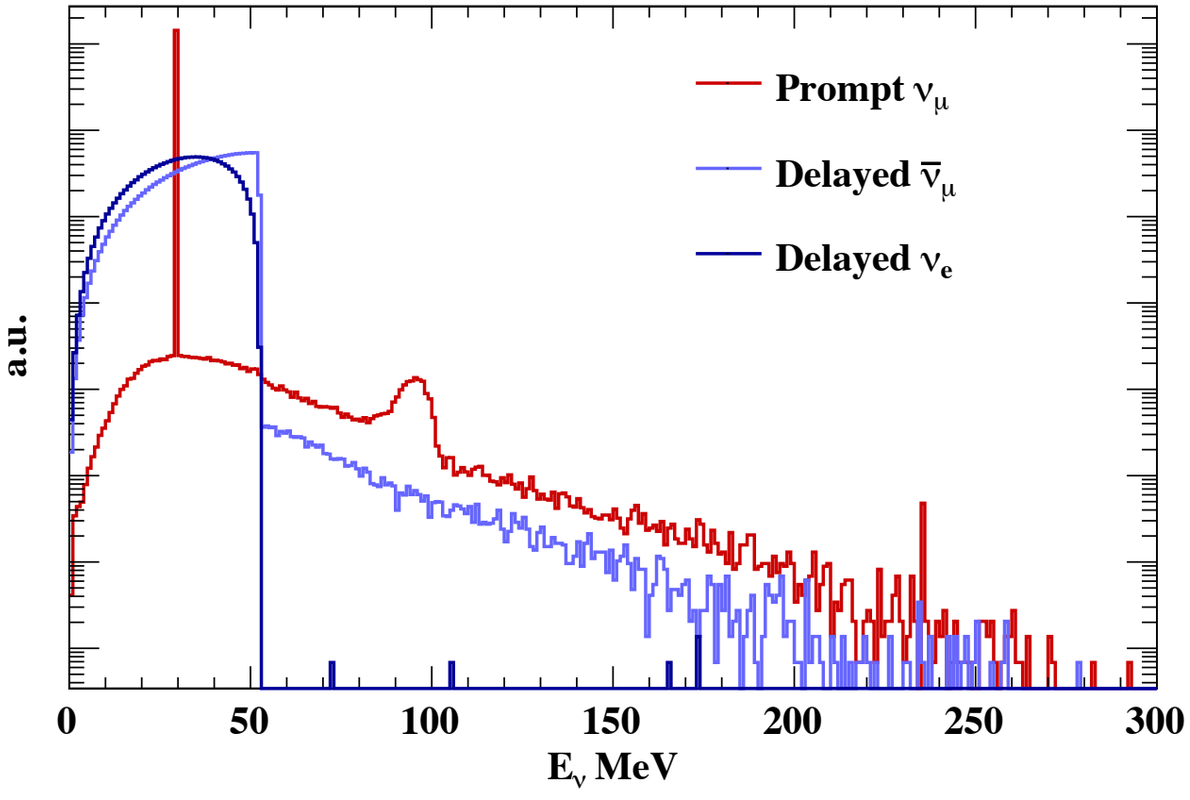


MOLLER Collaboration, arXiv:1411.4088

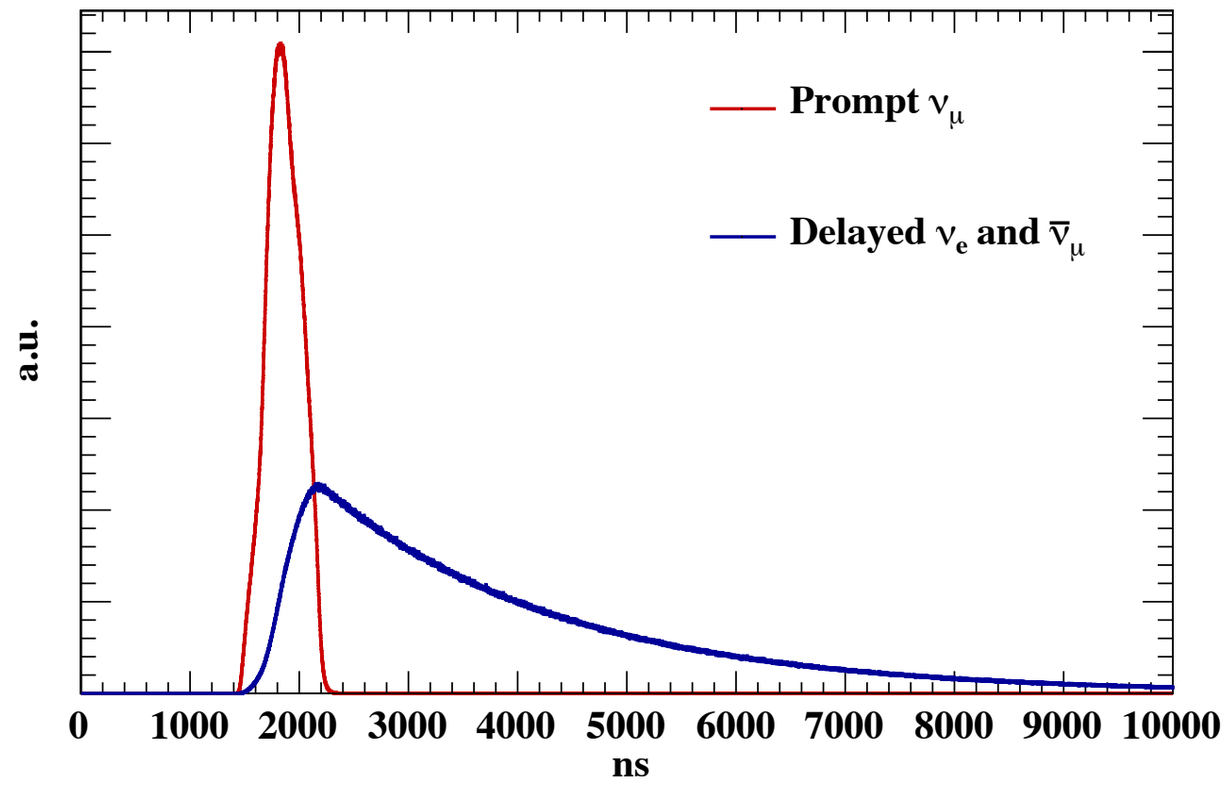
Stopped Pion Sources (SNS)

- Decay-at-Rest Neutrino Source
- ν flux 4.3×10^{7} ν cm^{-1} s^{-1} at 20 m
- Pulsed: 350 ns half-width at 60 Hz

<1% contamination from non-CEvNS scatters

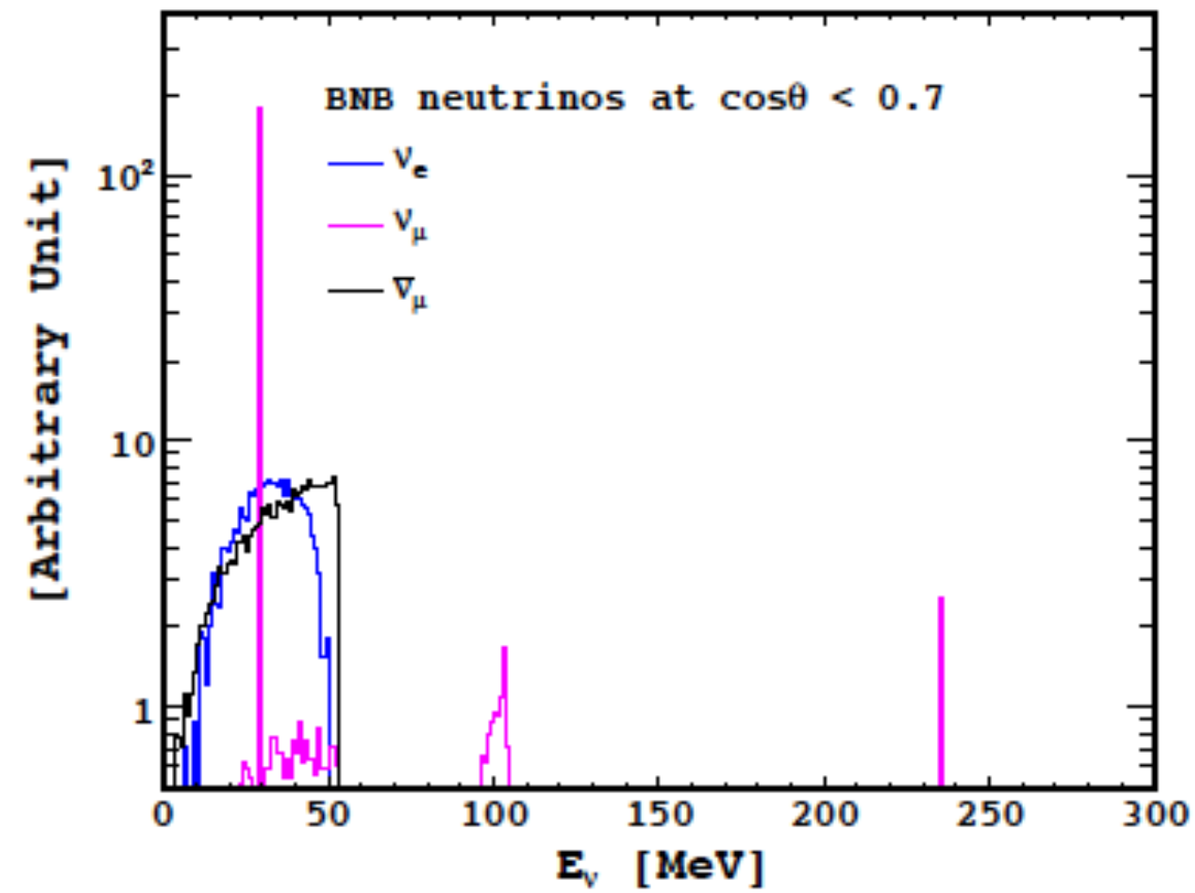


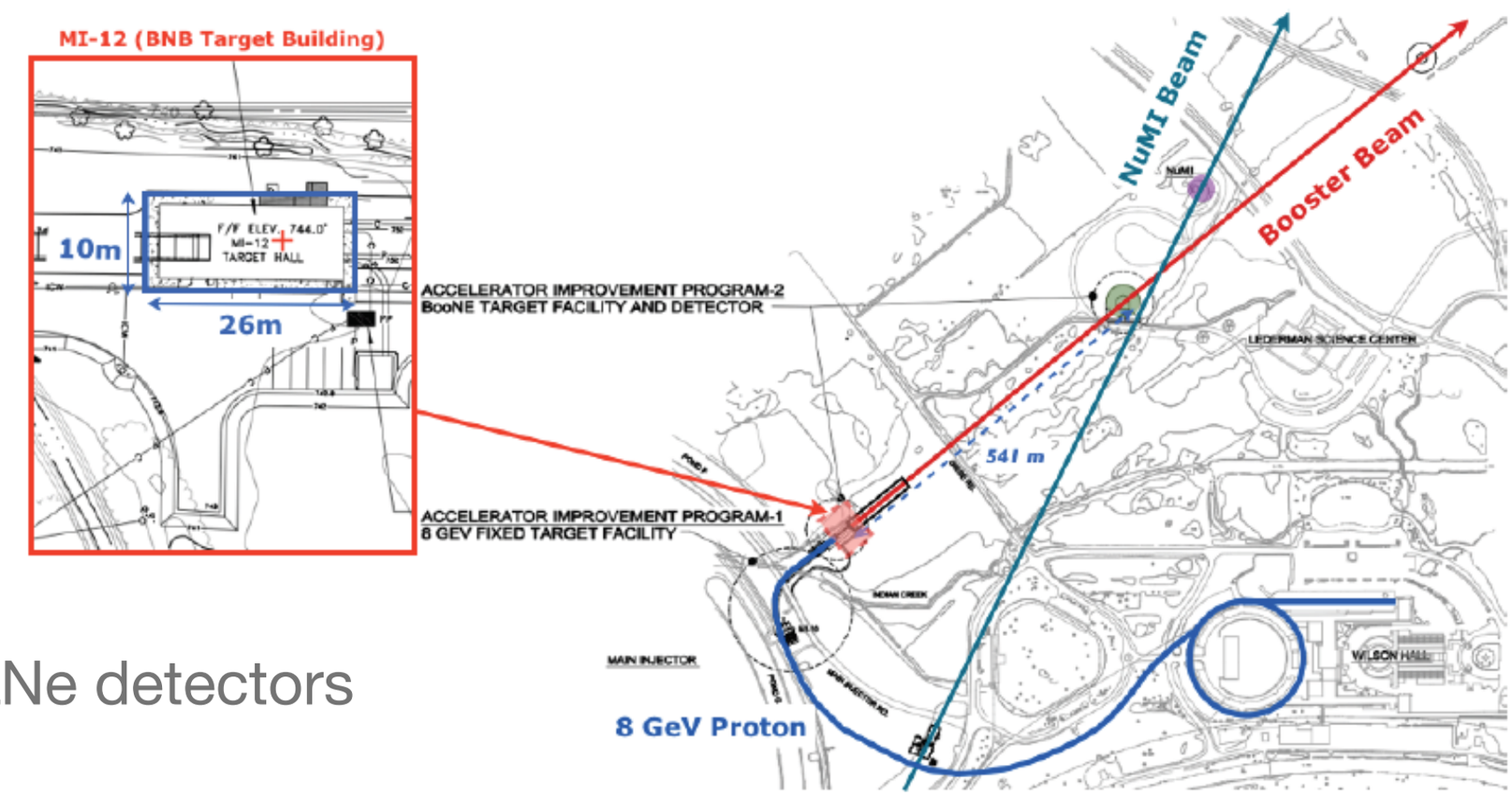
~4x10^-5 background reduction



Stopped Pion Sources (BNB)

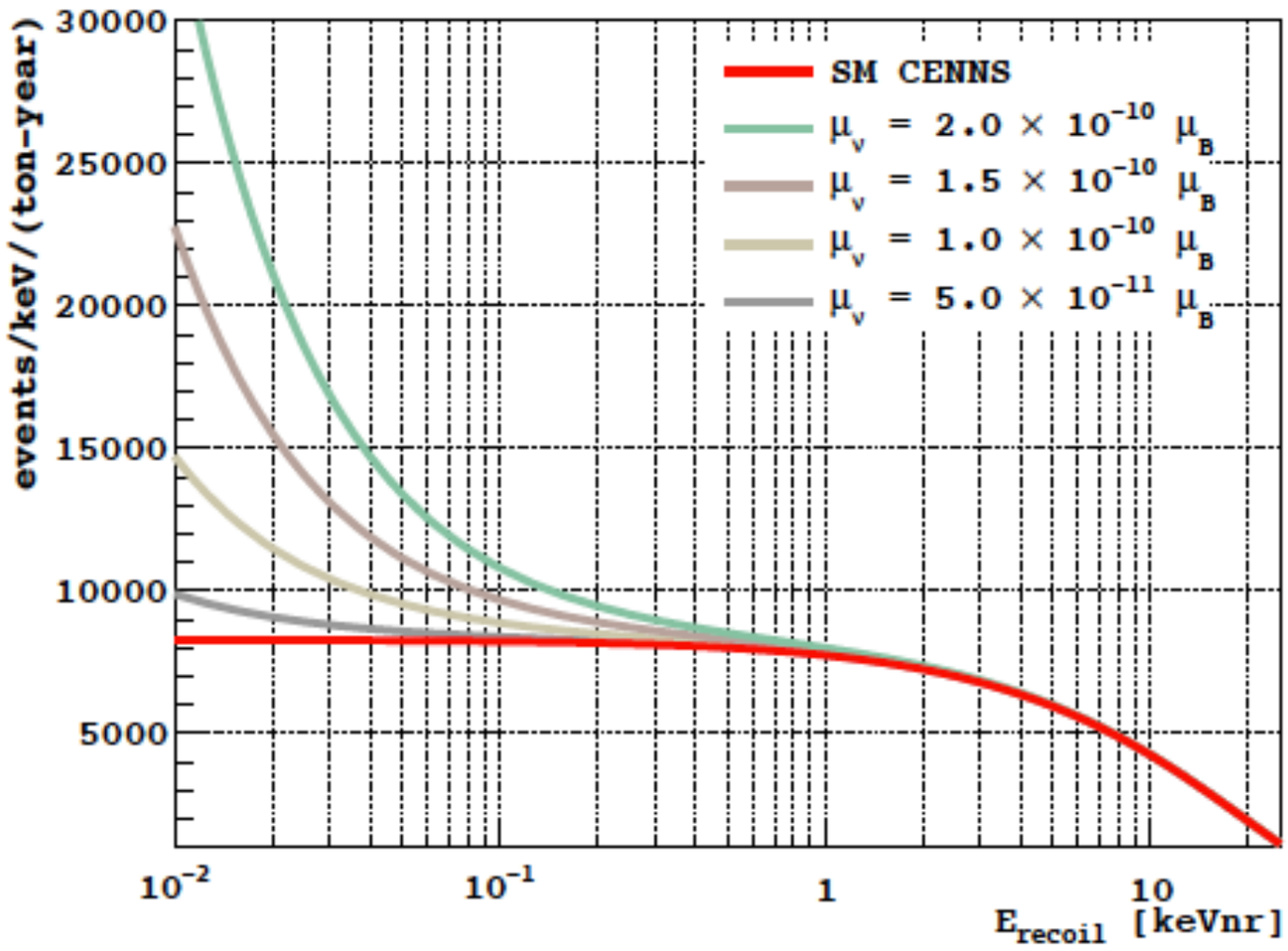
- Minimize Decay-in-Flight Neutrinos Source off-axis
- ν flux 5×10^5 ν cm^{-1} s^{-1} at 20 m
- Pulsed: 1.6 μs half-width at 5 Hz





- Plan to deploy LAr or LNe detectors

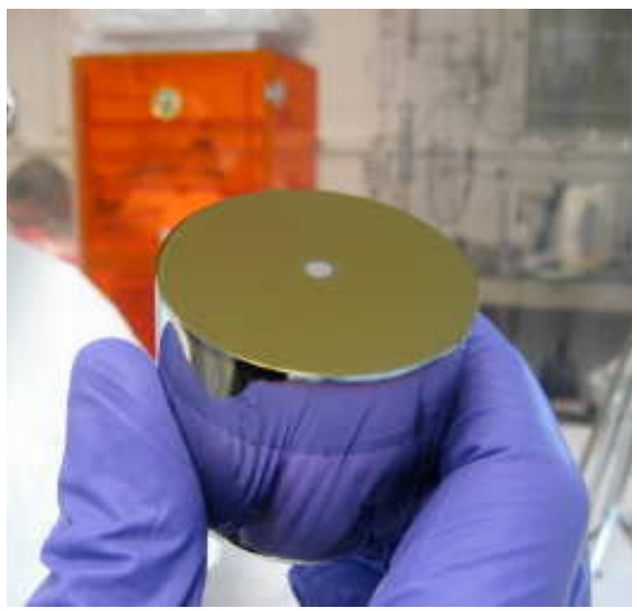
Stopped Pion Sources (BNB): Neutrino Magnetic Moment



- Limited by neutrino flux
- Ultimately limited by unknowns in shape of CEvNS recoil spectrum due to detector response uncertainties
- Have to be careful to use even-even nuclei (uncertainty in axial current cross-sections)

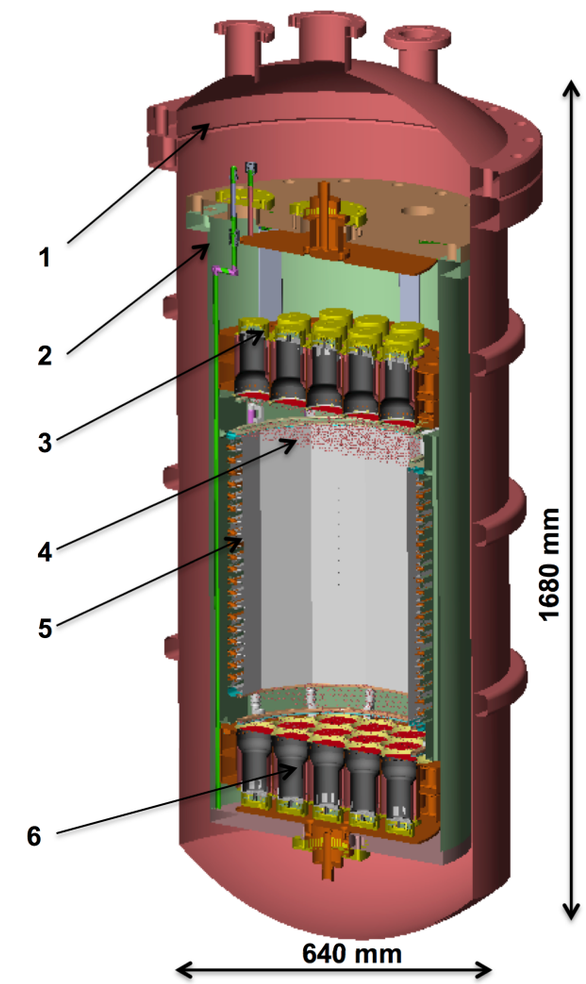
Coherent ν-Nucleus Scattering:
Large Mass, Low-Threshold, Low-Background Detectors

- The COHERENT Collaboration's goal is the unambiguous measurement of CEvNS at Spallation Neutron Source (SNS)



P-Type Point Contact HPGe

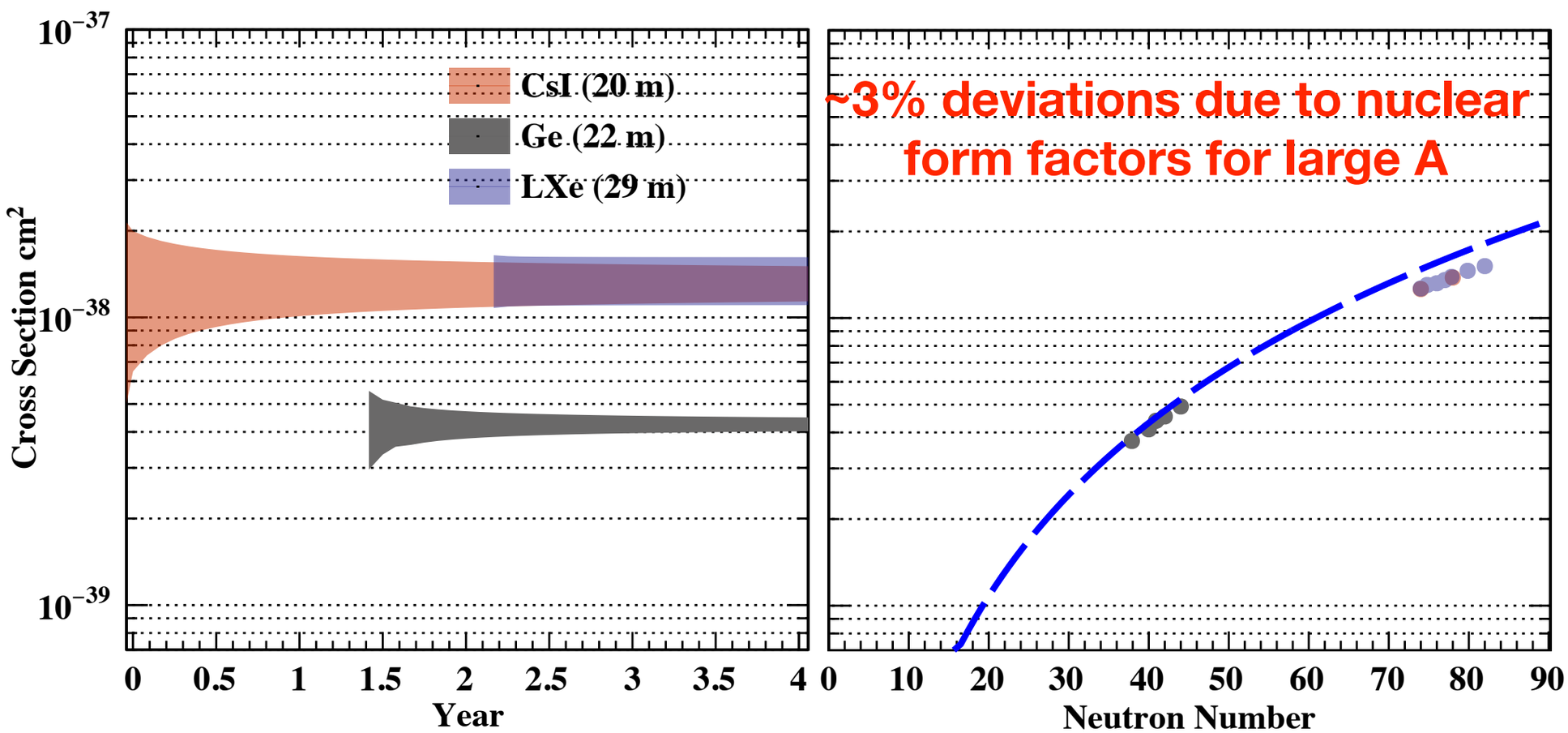
Low-Background CsI(Na)



2-Phase LXe

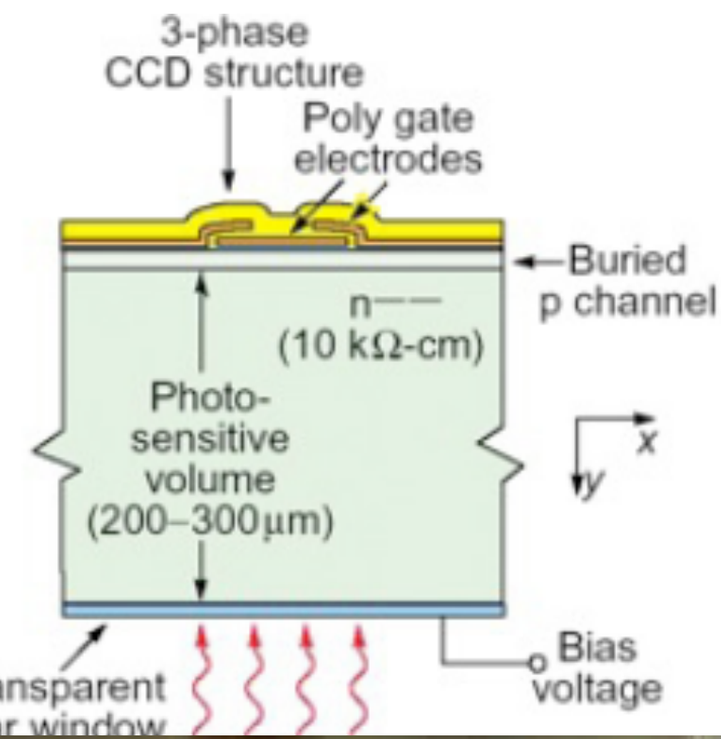
Coherent ν-Nucleus Scattering:
An unambiguous measurement

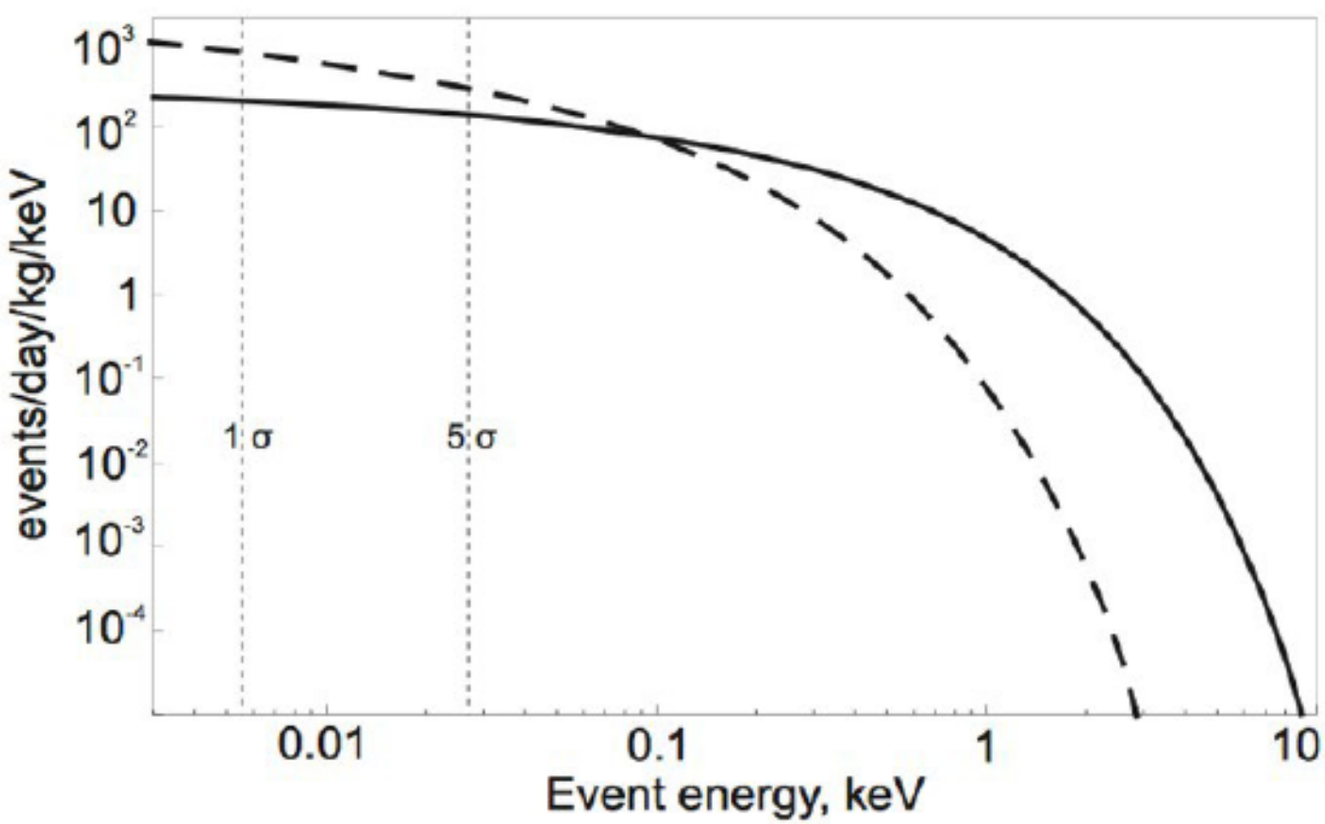
- Observe the pulsed ν time-structure
- Observe the 2.2 μs characteristic decay of delayed ν's
- Observe the N^2 cross-section behavior between targets

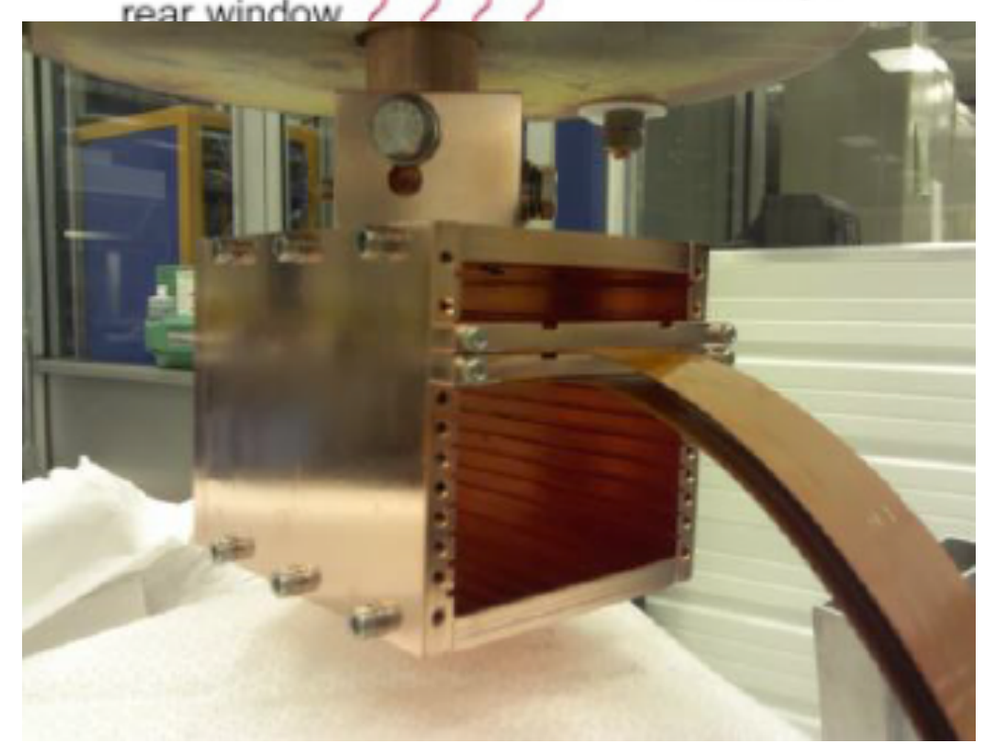


Coherent ν-Nucleus Scattering: Reactors

- The CONNIE experiment aims to lower detector thresholds, sc that they can observe higher flux Rx neutrinos
- Related technology to the DAMIC dark matter search
- 10 g's deployed 30 m from 4 GW_{th} Rx
- 7.2 eV noise in CCDs

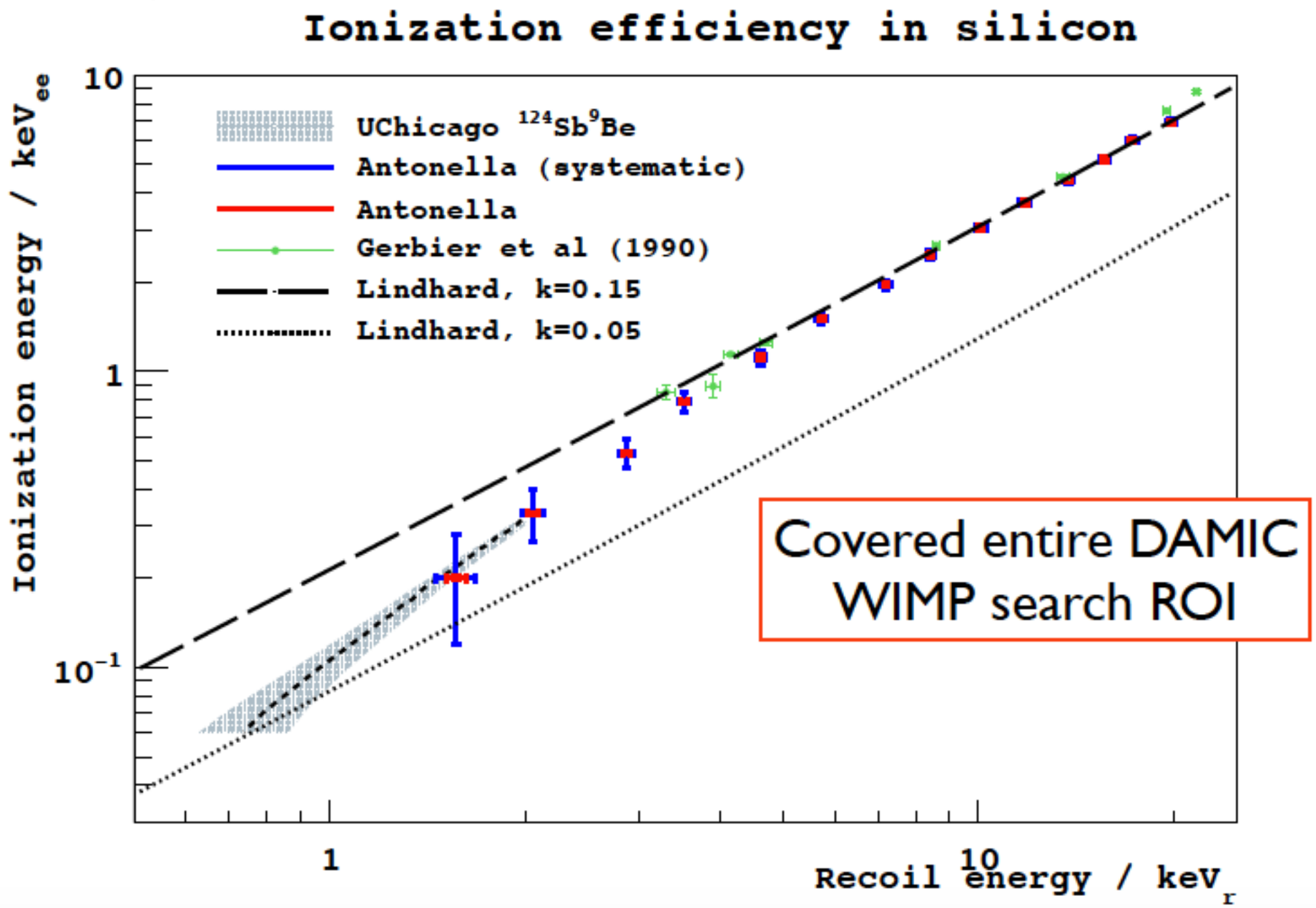






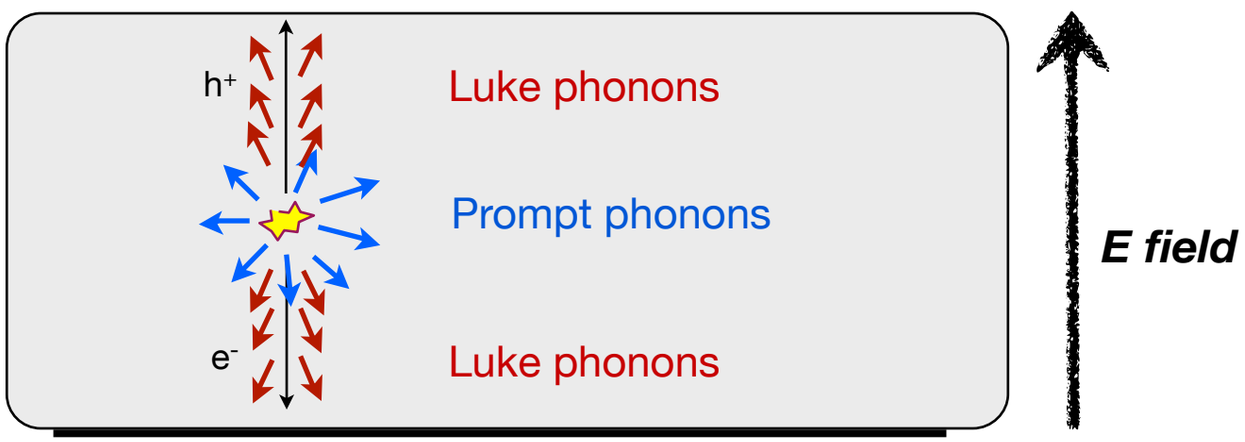
Coherent ν-Nucleus Scattering: Reactors

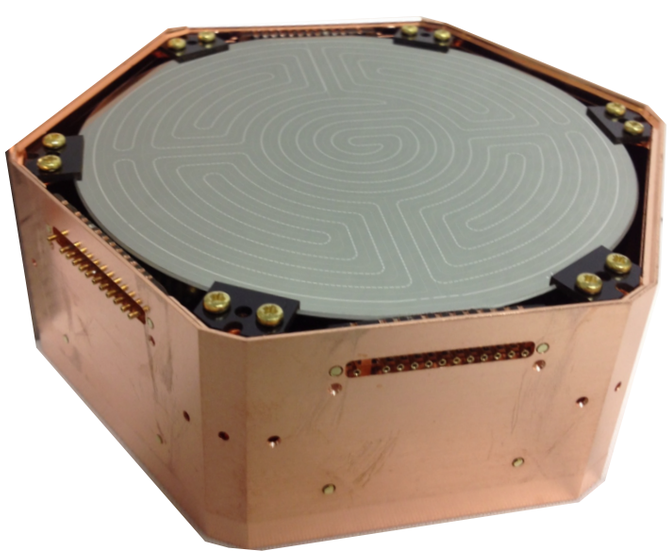
- Like all CEvNS experiments, CONNIE limited by systematic unknowns in detector response

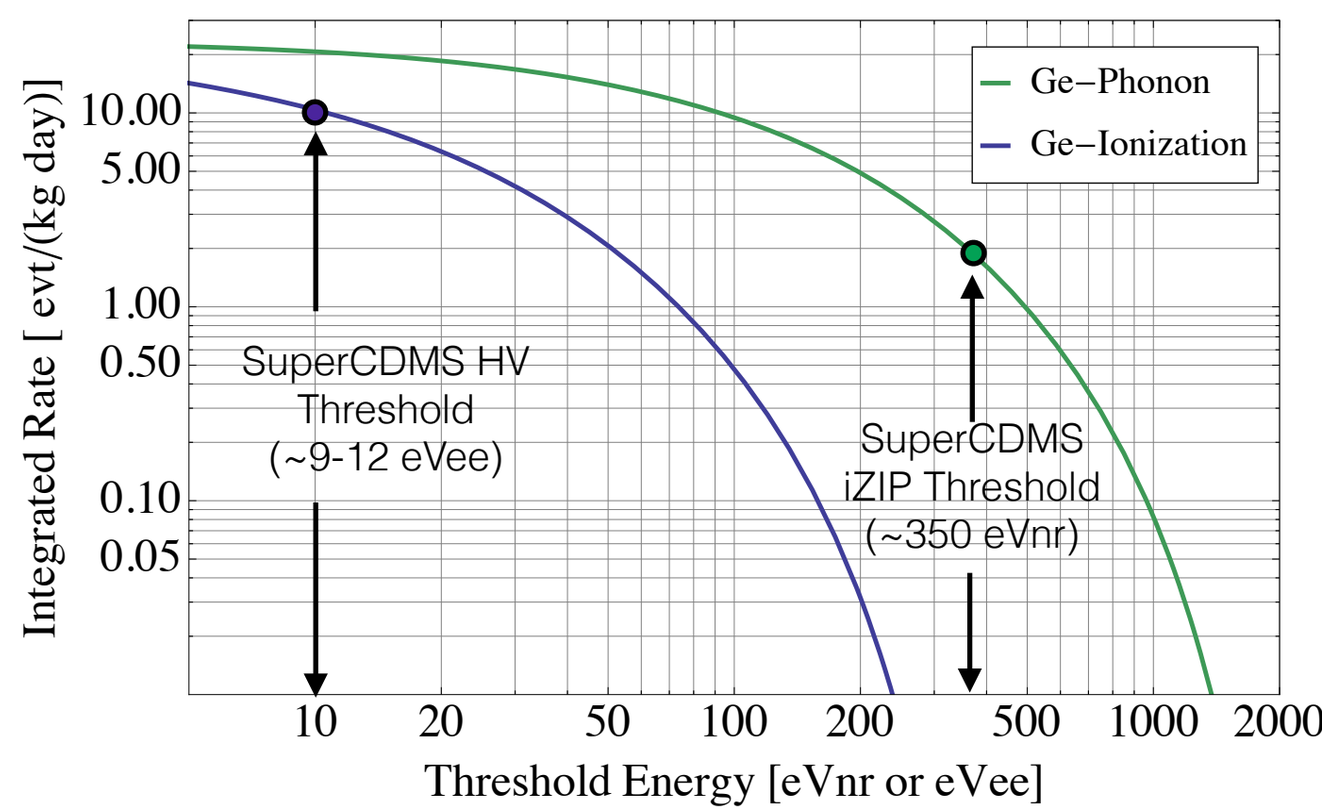


Coherent ν-Nucleus Scattering: Reactors

- Apply SuperCDMS technology to neutrino physics
- New SuperCDMS high-voltage design will enable ultra-low ionization thresholds down to ~9-12 eVee
- 1 SuperCDMS SNOLAB tower with 4 Si detectors (2.4 kg) and 2 Ge detectors (2.8 kg) can see more that 1000 CNS events a month at the Advanced Test Reactor

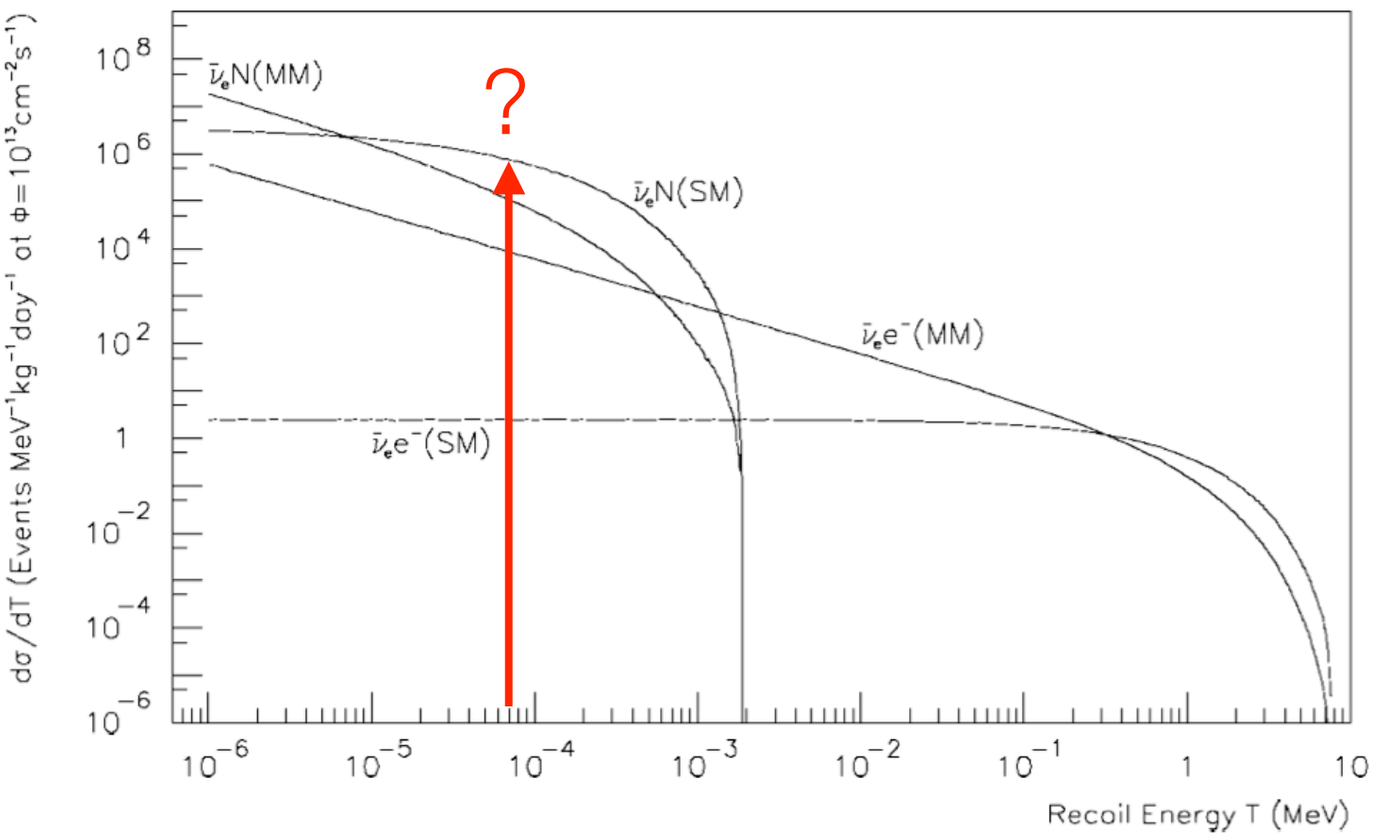


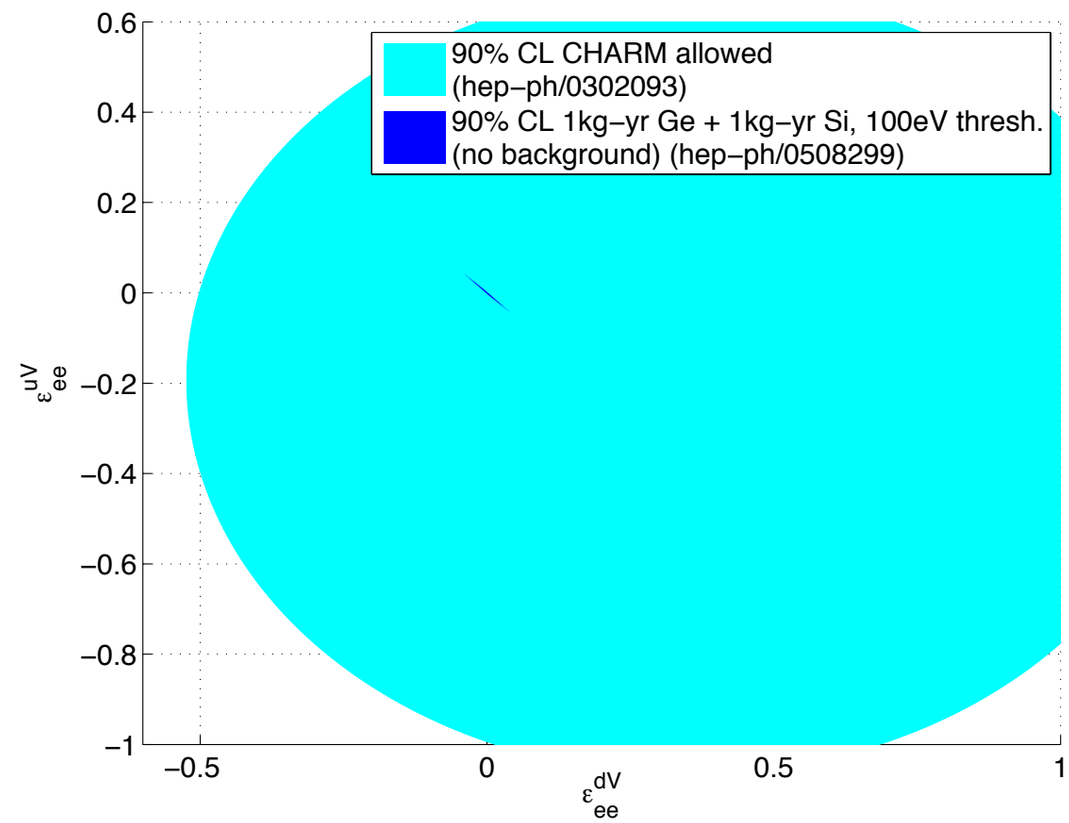




Coherent ν-Nucleus Scattering: Reactors

- Sensitivity to NSI
- and neutrino magnetic moments





Coherent $\boldsymbol{\nu}$-Nucleus Scattering: Technical Limitations

- First and foremost: Process needs to be observed before physics can be done
- Detector technology moving hand-in-hand with dark matter community
- Experiments generally limited in experiment reach by detector response uncertainties to nuclear recoils
- Also need to keep an eye out for theoretical uncertainties in the isotope of choice (axial currents).
  - Benefit from enrichment.
- Also by deployable exposure (either deployable mass or neutrino flux)
  - Is it fair to put neutrino facilities on here as a technical limitation?

New Technologies for Neutrino Properties: Broader View of Technical Limitations

- Most experimental techniques need lower noise and/or lower threshold electronics
- Intensity needs require large channel readouts and novel approaches to multiplexing (frequency vs time domain)
- Background rejection is nice, but zero-background is better
- Most of the physics goals could benefit from investment in an isotope enrichment program, given a specific technological approach