Data-driven Constraints on NME Calculations for Mo-100 0νββ with CUORE and CUPID

and other topics of potential interest

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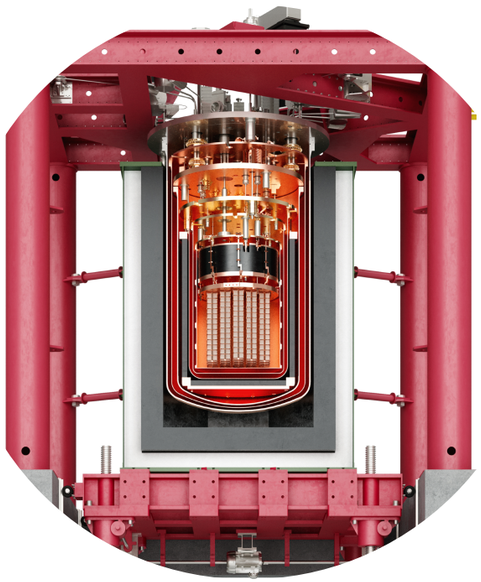
July 21, 2026



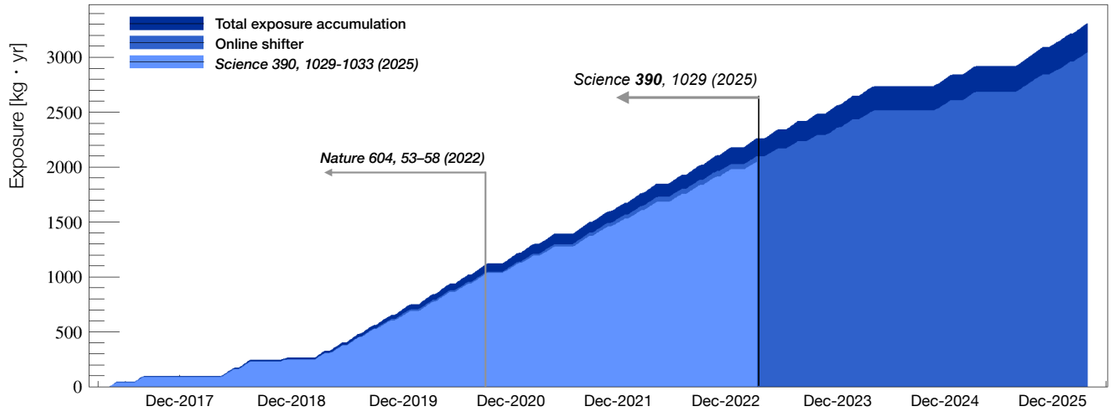
CUORE

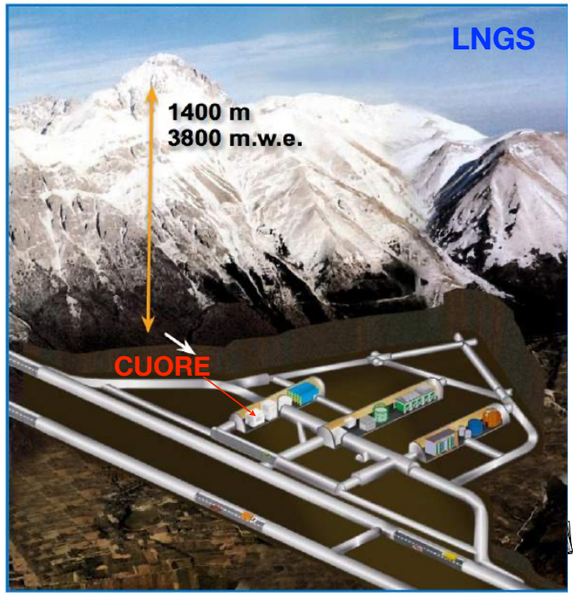
Array of 988 TeO_2 crystals

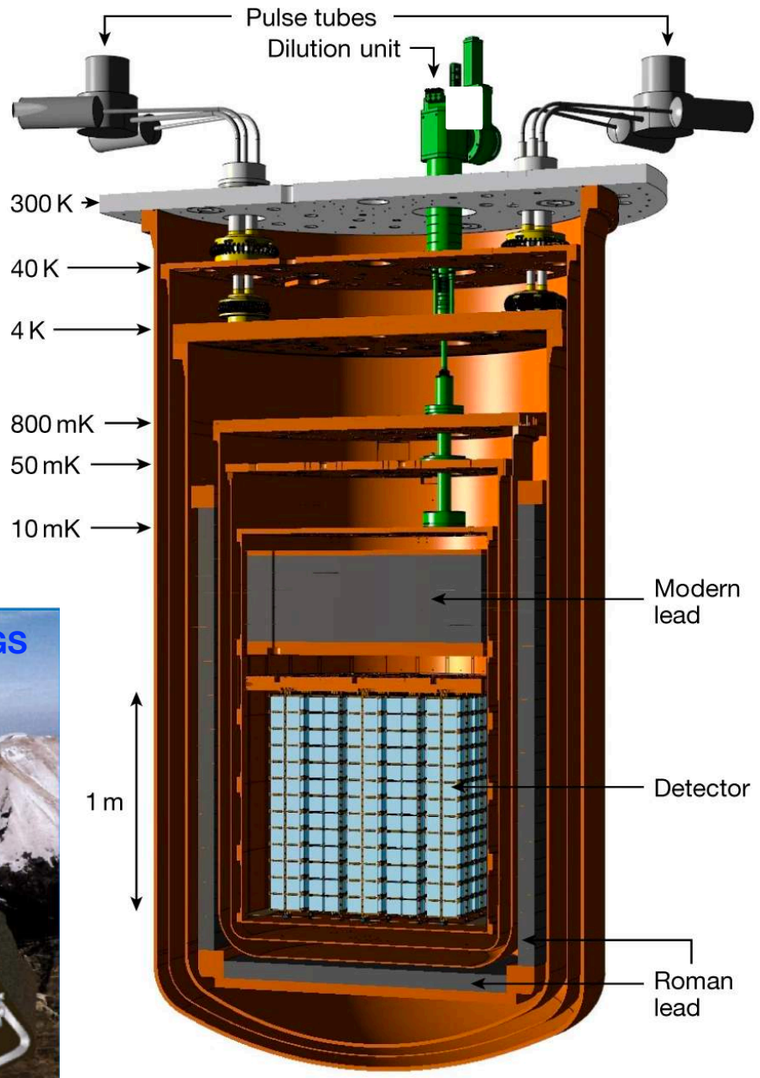
- **19** towers suspended in a cylindrical structure (988 crystals)
- 5x5x5 cm^3 (750g each); ^{130}Te: 34.1% natural isotope abundance

750 kg TeO_2 => 206 kg ^{130}Te

- Pulse tube refrigerator and cryostat: coldest m^3 in the Universe ! [arXiv:1410.1560]
- Radio-purity techniques and high resolution: low backgrounds
- Joint venture between Italy (INFN) and US (DOE, NSF) at LNGS in Italy
- Data taking since 2017, now >3 ton-years of TeO_2 exposure collected







Dell'Oro S. et al., Cryogenics 102, 9, (2019) https://doi.org/10.1016/j.cryogenics.2019.06.011

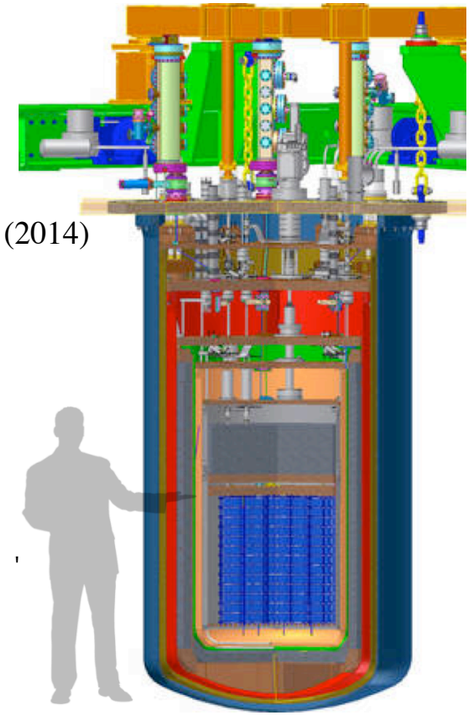
Adams D. et al. (CUORE collaboration), Prog.Part.Nucl.Phys. 122 (2022) 103902, https://doi.org/10.1016/j.ppnp.2021.103902

CUPID

Next-generation bolometric ton-scale experiment at LNGS

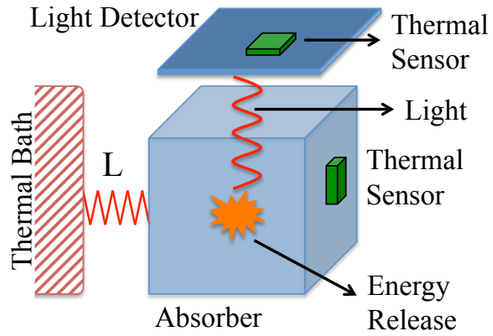
Mission: Discover $0\nu\beta\beta$ if $m_{\beta\beta} > 10$ meV (half-life in ^{100}Mo > 10^{27} years)

R. Artusa et al., Eur.Phys.J. **C74**, 3096 (2014)
pre-CDR: arXiv:1907.09376

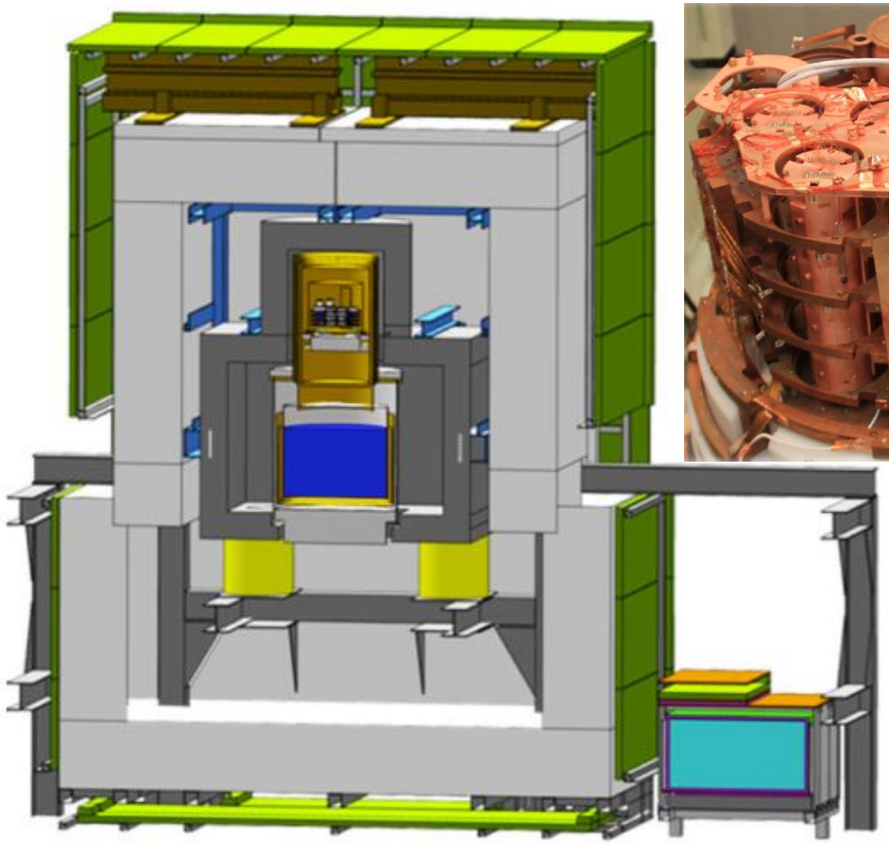


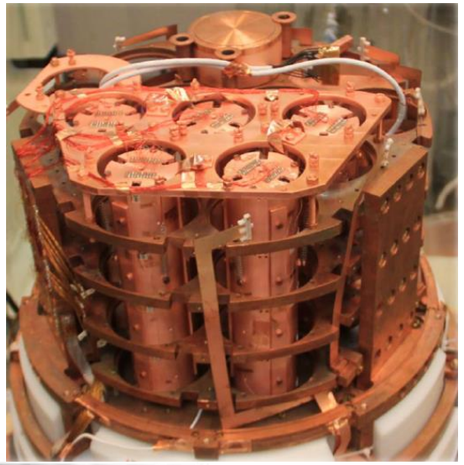
- Baseline: 1500 enriched Li_2MoO_4 crystals (~240 kg of ^{100}Mo)
- Demonstrated radio-purity, active background rejection
- Energy resolution ~5 keV
- Total background of <0.1 counts/(ton*kev*year)
- Phased deployment options up to 1 ton of ^{100}Mo (CUPID-1T)

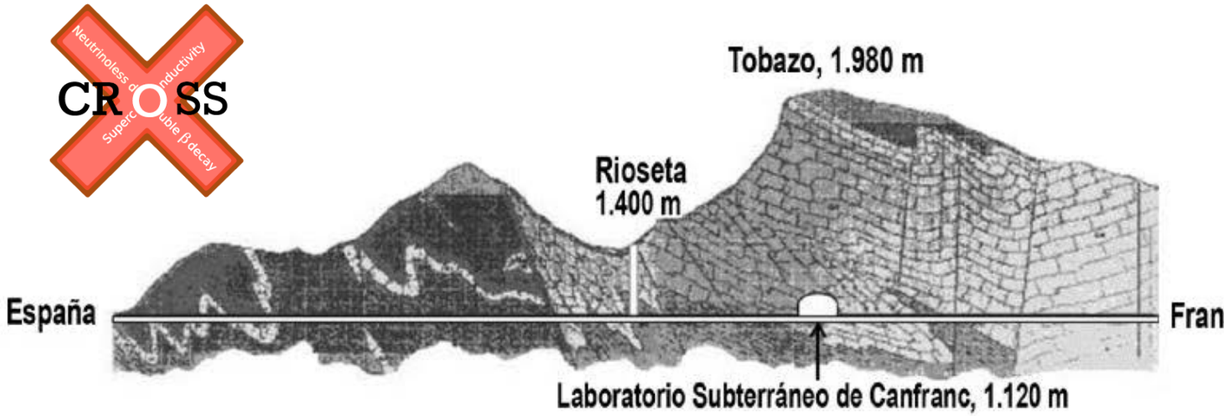
Based on CUORE cryogenic technologies and Scintillating Bolometer R&D by Lucifer/CUPID-0, LUMINEU, CUPID-Mo



CUPID Demonstrators and Prototypes

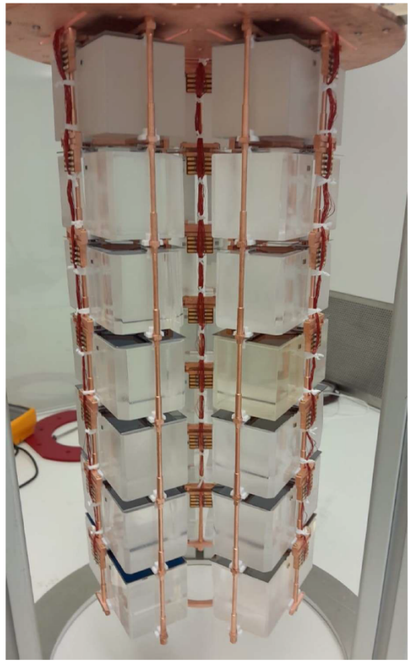






CUPID-Mo: 4 kg of enriched Li_2MoO_4 crystals
Operated 2019-2020 at LSM
1.48 kg×yr of ^{100}Mo exposure

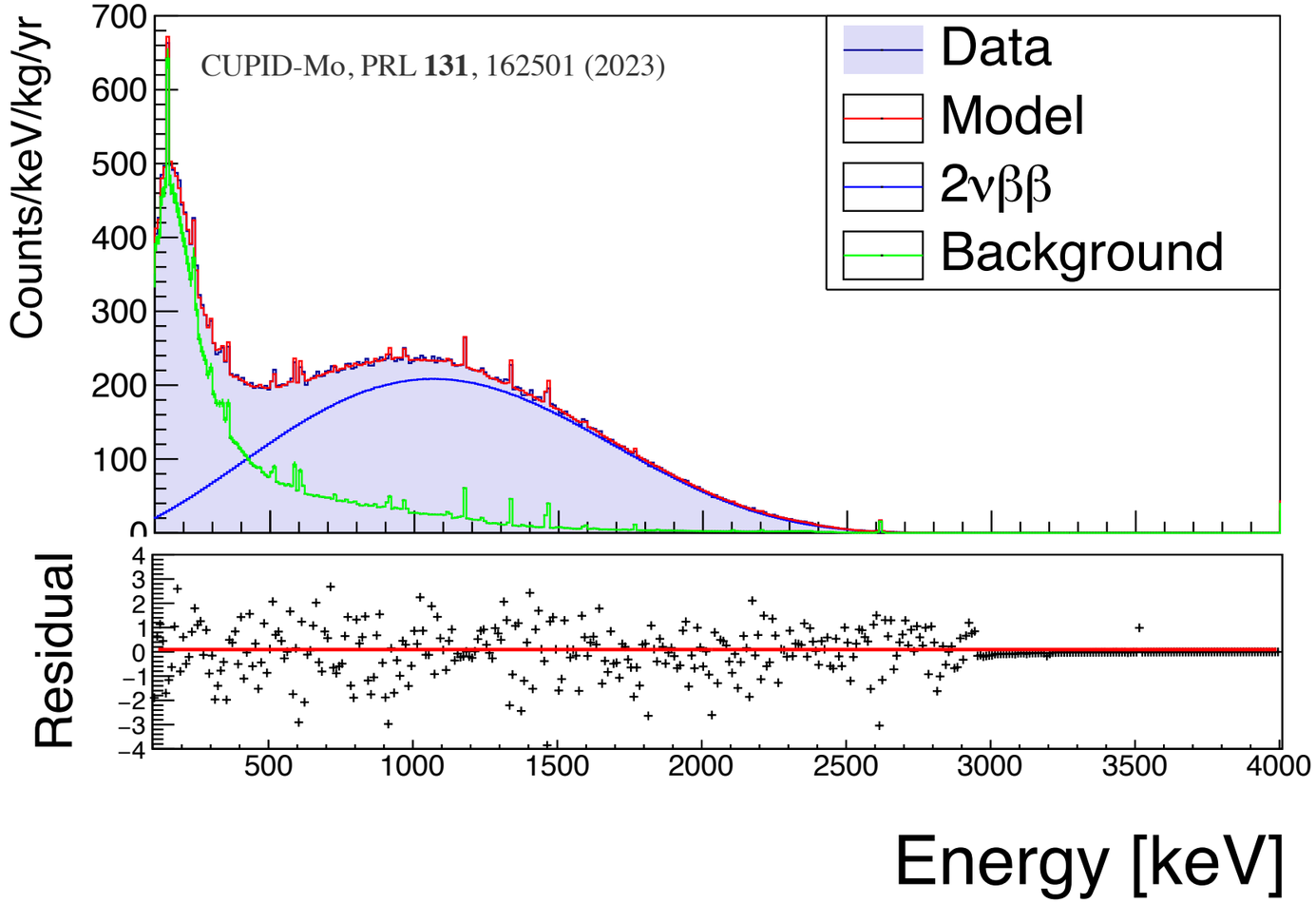
CROSS: 9 kg of enriched Li_2MoO_4 crystals (5 kg of ^{100}Mo) + 3.3 kg of enriched TeO_2 (2.4 kg of ^{100}Te). Open structure. Currently operating at LSC



Measurements Relevant to $0\nu\beta\beta$ NMEs

- Closed-packed bolometric detectors: high statistics, low energy thresholds, high efficiency, some spatial segmentation
- Measurements (possibly) relevant for NME calculations:
  - Precision measurements of $2\nu\beta\beta$ half-life **and** spectral shape
  - $2\nu\beta\beta$ decays to excited states of the daughter nuclei
  - Possibly $2\nu\beta\beta$ in multi-site events, sensitive to the energy distribution of individual electrons

Measurement of $2\nu\beta\beta$ half-life in ^{100}Mo in CUPID-Mo

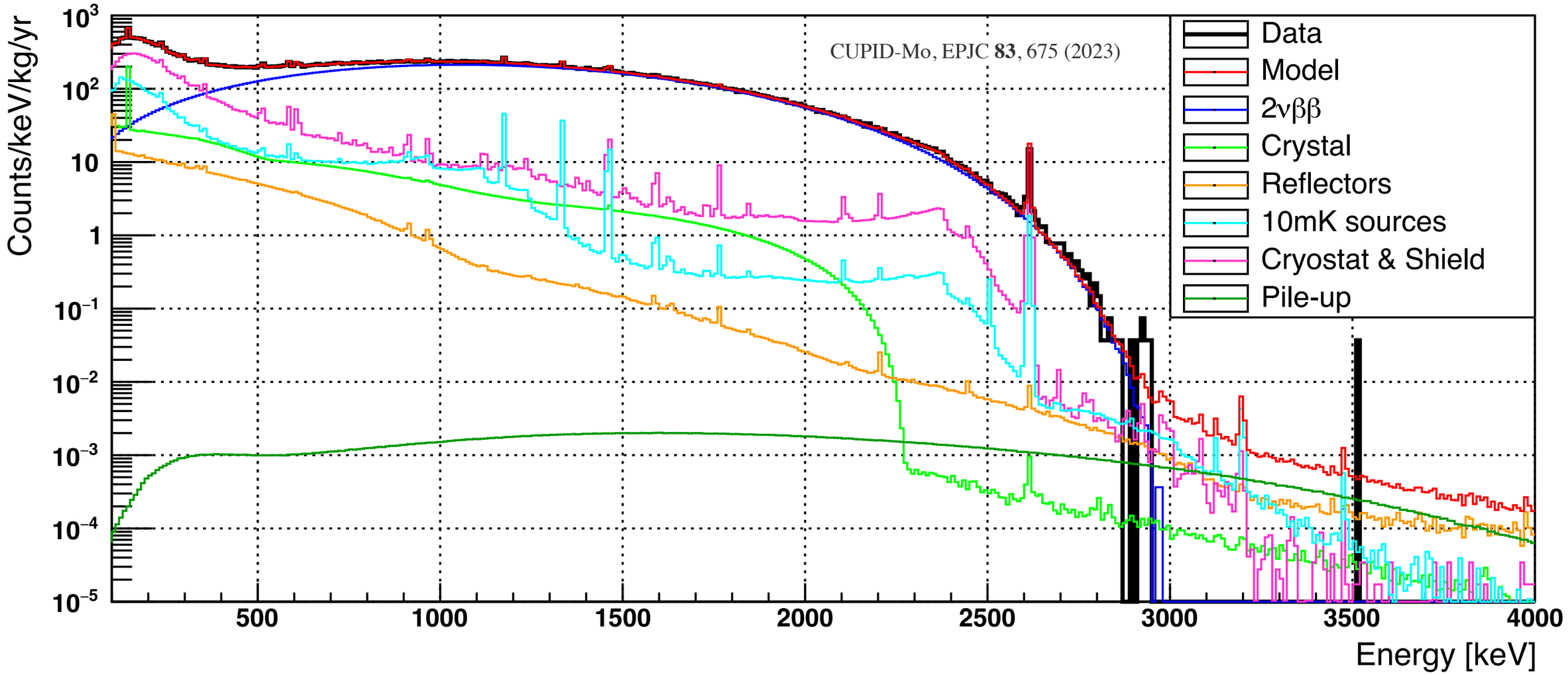


$$T^{2\nu}_{1/2} = (7.07 \pm 0.02\ (\text{stat.}) \pm 0.11\ (\text{syst.})) \times 10^{18}\ \text{yr}$$

One of the most precise measurements of $T_{1/2}$ in any isotope

- Precision measurement of half-life and spectral shape
- High statistics, low background
- Detailed background model fit with 41 sources at various locations in the detector
  - ☞ ^{238}U, ^{232}Th chains, ^{40}K, ^{90}Sr, cosmogenic and neutron-induced backgrounds
  - ☞ Constrain backgrounds by simultaneous fit to single- and multi-site, β/γ and α spectra
  - ☞ Signal efficiency constrained by the measured activity of a ^{56}Co calibration source

CUPID-Mo Background Model



Measurement of the $2\nu\beta\beta$ Spectrum in ^{100}Mo

- High statistics and low backgrounds allow constraints on the spectral shape of the $2\nu\beta\beta$ spectrum

☞ Sensitivity to the interplay between low- and high-energy excitations in the $2\nu\beta\beta$ transitions

☞ Taylor expansion of the energy spectrum in terms of spectral functions G(E) and "shape parameters" ξ sensitive to NME ratios

$$\frac{d\Gamma}{dE} = g_{A,\mathrm{eff}}^4 |M_{GT-1}|^2 \Big(\frac{dG_0}{dE} + \xi_{3,1} \frac{dG_2}{dE} + \frac{1}{3}\xi_{3,1}^2 \frac{dG_{22}}{dE} + \big(\frac{1}{3}\xi_{3,1}^2 + \xi_{5,1}\big) \frac{dG_4}{dE} \Big)$$

$$M_{GT-1}^{2\nu} \equiv M_{GT}^{2\nu}$$

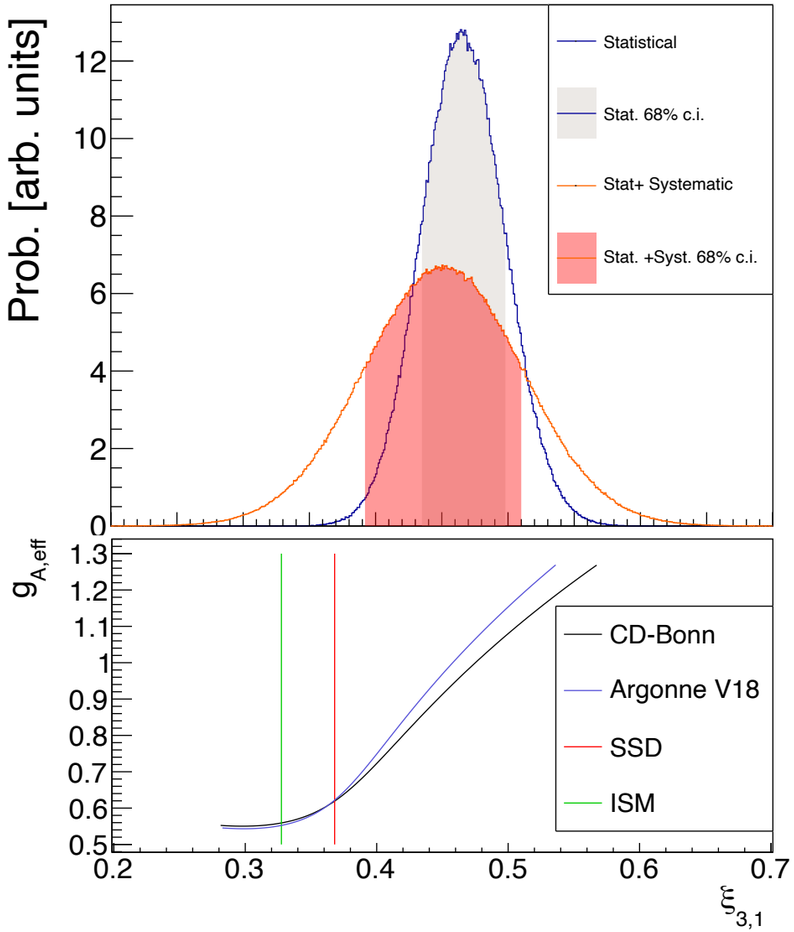
$$\xi_{31}^{2\nu} = \frac{M_{GT-3}^{2\nu}}{M_{GT-1}^{2\nu}}, \quad \xi_{51}^{2\nu} = \frac{M_{GT-5}^{2\nu}}{M_{GT-1}^{2\nu}}$$

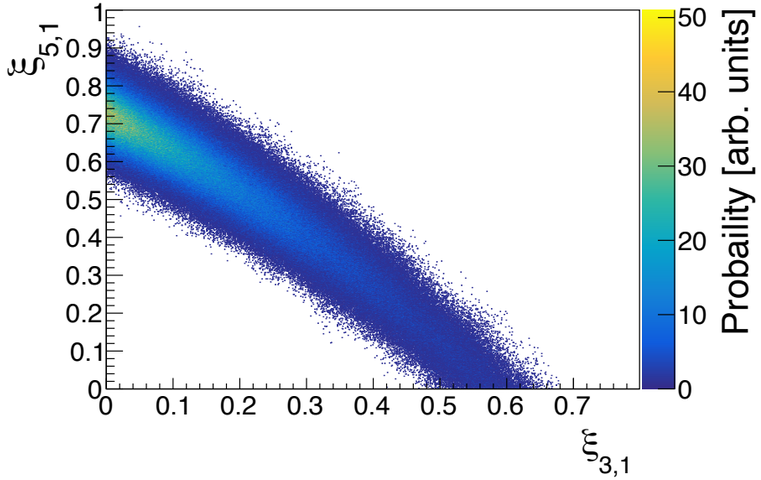
$$M_{GT-3}^{2\nu} = \sum_n M_n \frac{4\, m_e^3}{(E_n - (E_i + E_f)/2)^3},$$

$$M_{GT-5}^{2\nu} = \sum_n M_n \frac{16\, m_e^5}{(E_n - (E_i + E_f)/2)^5}.$$

F. Šimkovic, R. Dvornický, D. Stefánik, A. Faessler, Phys.Rev.C **97**, 034315 (2018)

Measurement of the $2\nu\beta\beta$ Spectrum

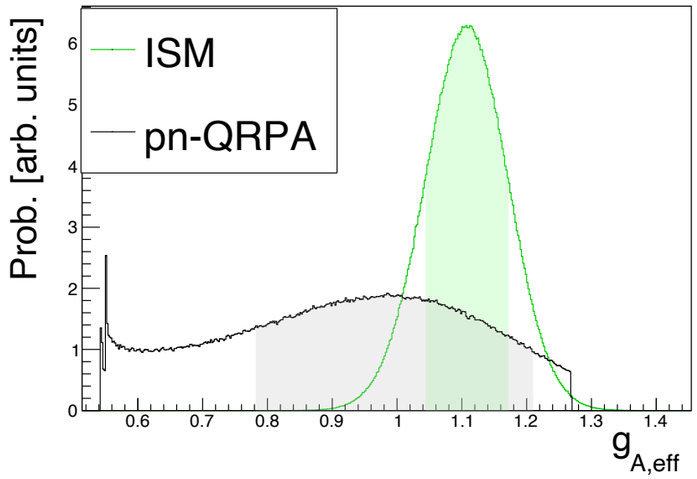




$\xi_{3,1}$ and $\xi_{5,1}$ highly correlated: fix the ratio to the prediction of each model

$g_{A,eff}$ constraint from the combination of half-life and $\xi_{3,1}$

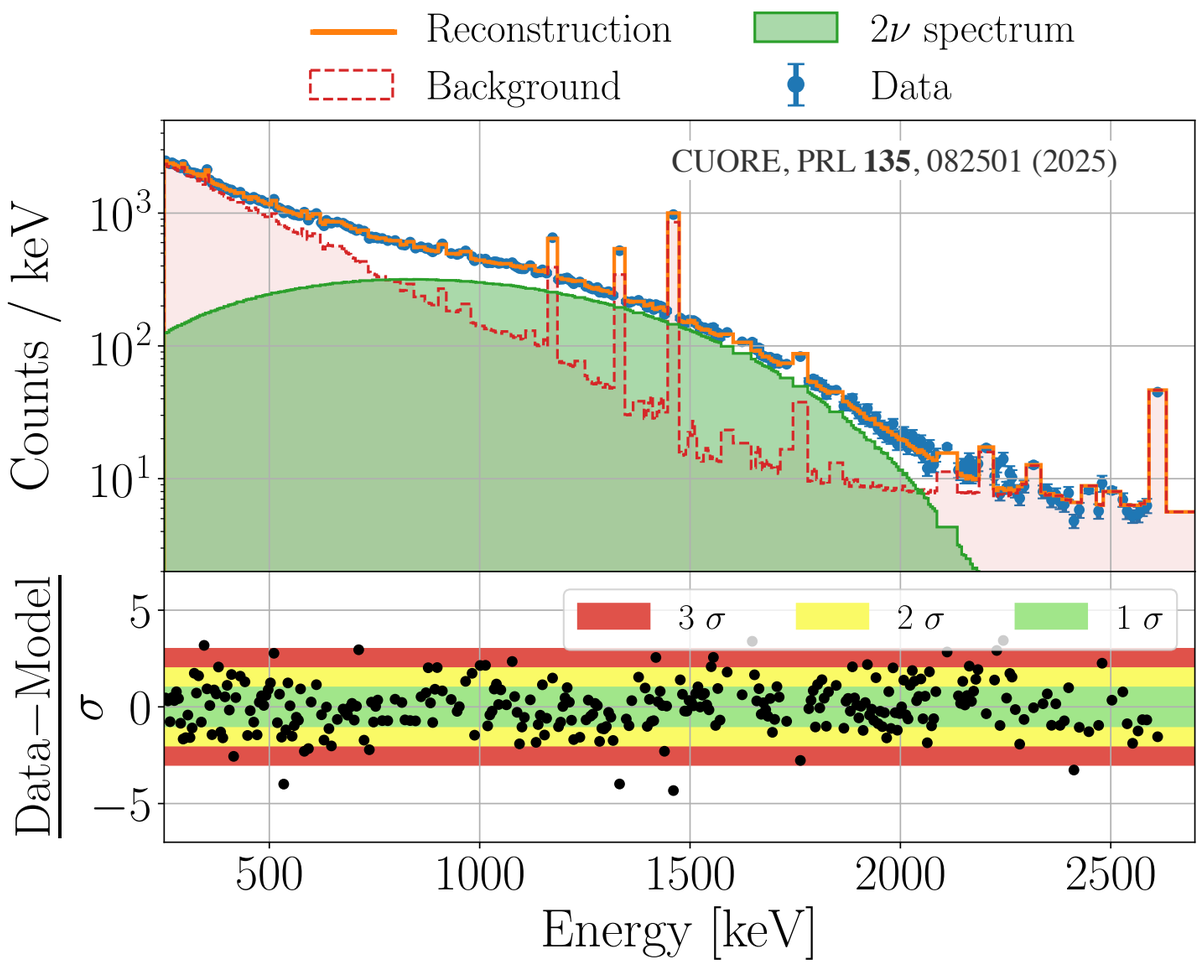
$$g^4_{A,\mathrm{eff}} = \frac{T^{-1}_{1/2} \times \xi^2_{3,1}}{M^2_{GT-3} G}$$



$\xi_{3,1} = 0.45 \pm 0.03\ (\mathrm{stat.}) \pm 0.05\ (\mathrm{syst.})$ CUPID-Mo, PRL **131**, 162501 (2023)

Inconsistent with HSD model, consistent with SSD (1.4σ), ISM [L. Coraggio et al., Phys. Rev. C **105**, 034312 (2022)] prediction disfavored at 2.1σ

Measurement of $2\nu\beta\beta$ half-life in ^{130}Te in CUORE

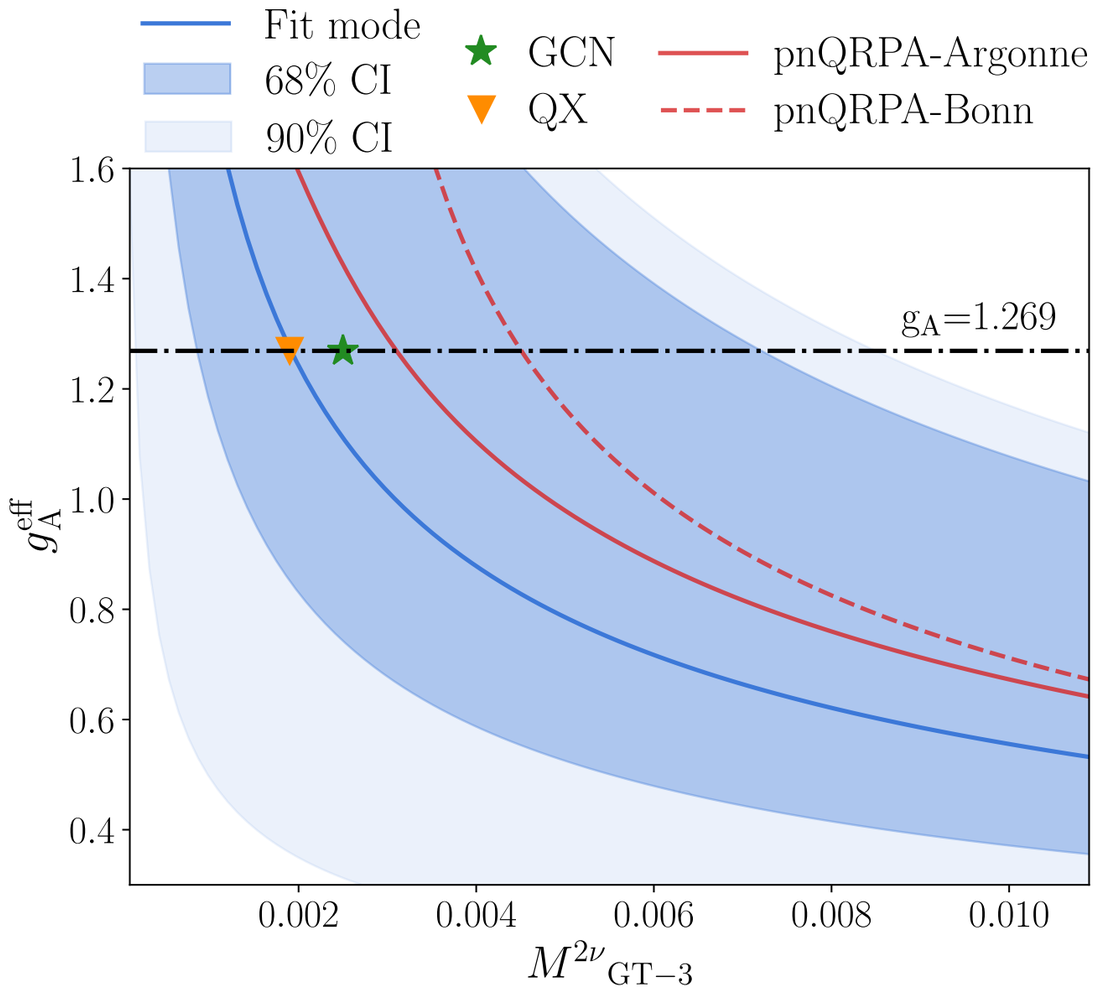


$$T^{2\nu}_{1/2} = \left(9.32\,^{+0.05}_{-0.04}\,\text{stat.}\,^{+0.07}_{-0.07}\,\text{syst.}\right) \times 10^{20}\ \text{yr.}$$

The most precise measurements of $T_{1/2}$ in any isotope

- Precision measurement of half-life and spectral shape
- High statistics, low-ish background
- Detailed background model fit
  - ☞ ^{238}U, ^{232}Th chains, ^{40}K, cosmogenic backgrounds
  - ☞ Constrain backgrounds by simultaneous fit to single- and multi-site spectra

Measurement of the $2\nu\beta\beta$ Spectrum in ^{130}Te

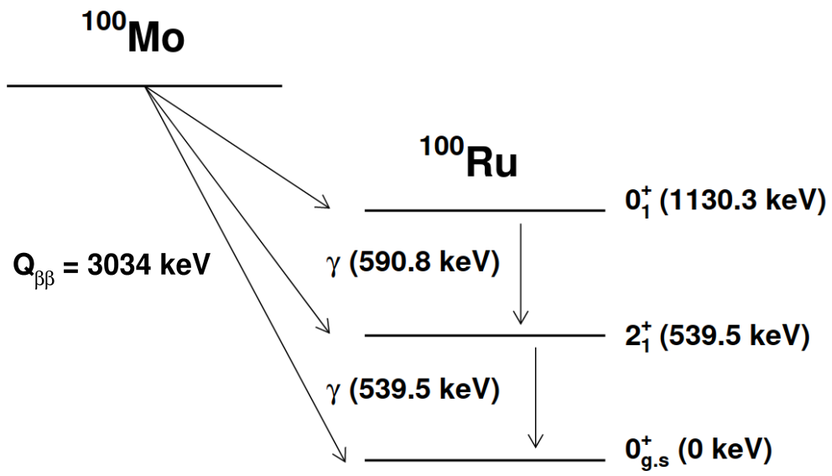


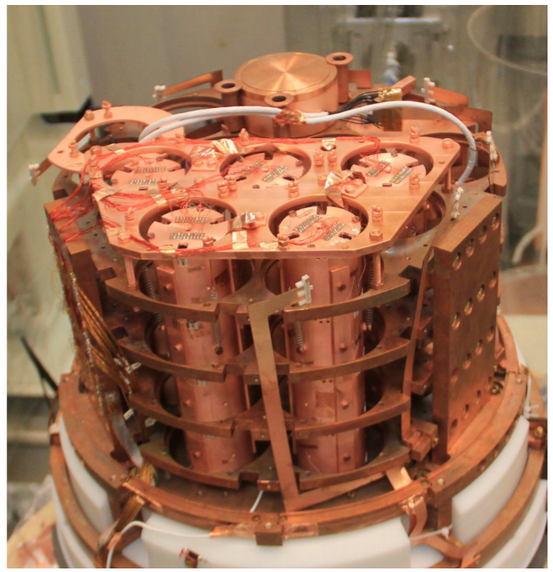
CUORE, PRL **135**, 082501 (2025)

Results consistent with nuclear models

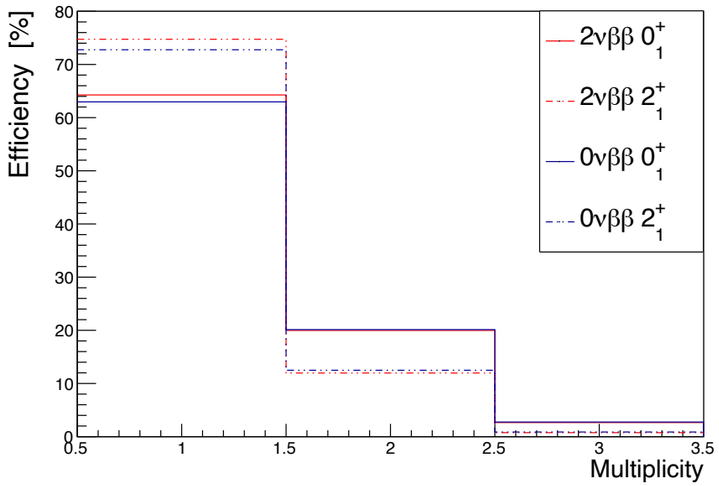
^{100}Mo $2\nu\beta\beta$ Decay to Excited States of ^{100}Ru

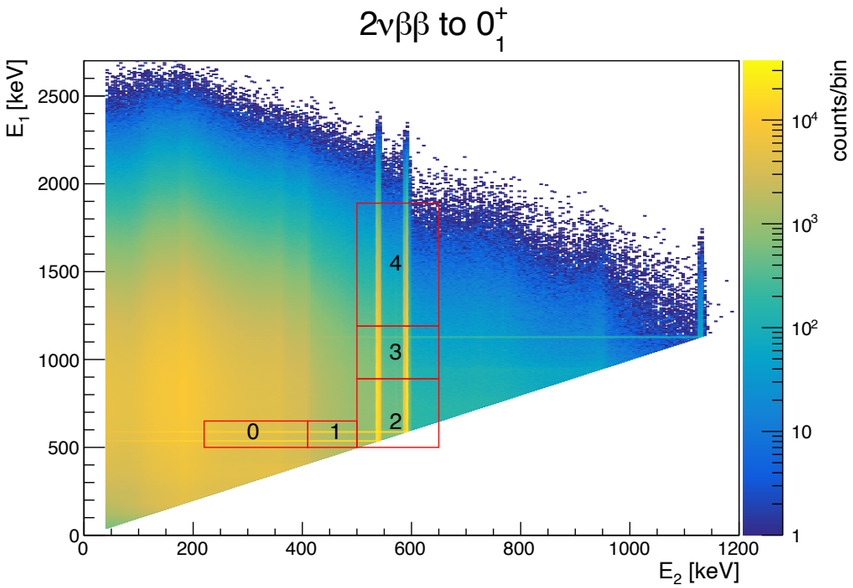
- The only $2\nu\beta\beta$ transition to 0^+ and 2^+ excited state measured so far
- Precision measurement of half-life provides sensitivity to nuclear structure and quantitative cross-check of NME models
- Segmented bolometers allow detection of high-multiplicity events with high efficiency and purity

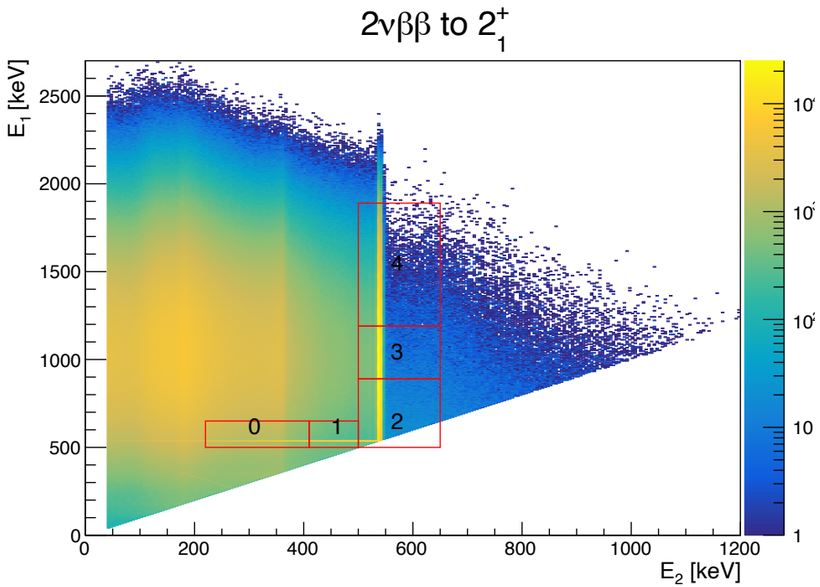


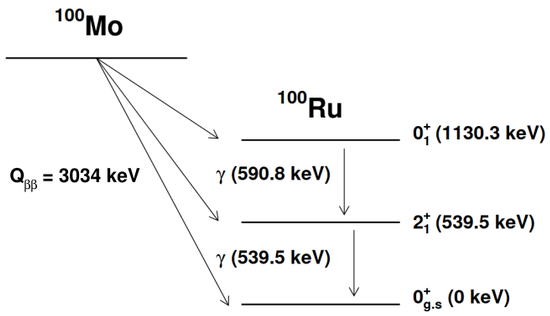


^{100}Mo $2\nu\beta\beta$ Decay to Excited States of ^{100}Ru





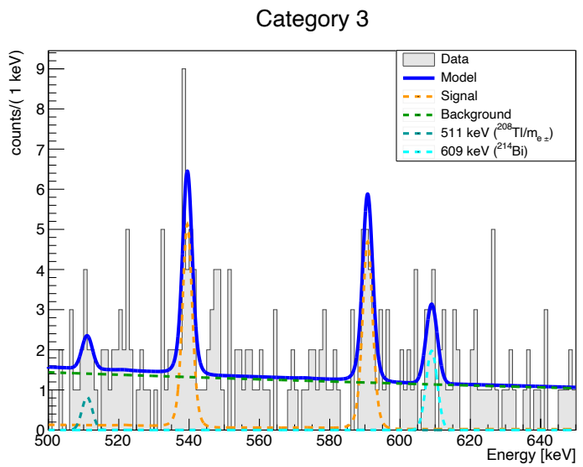


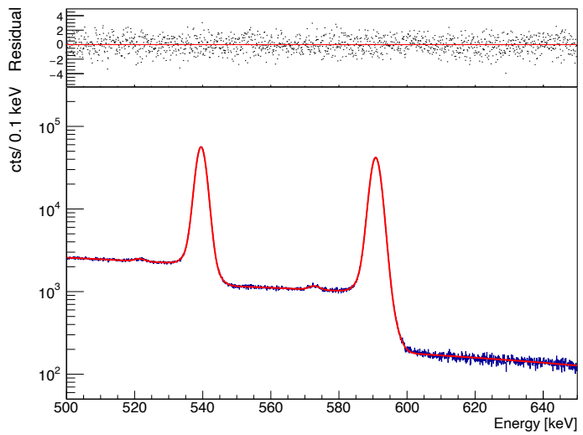


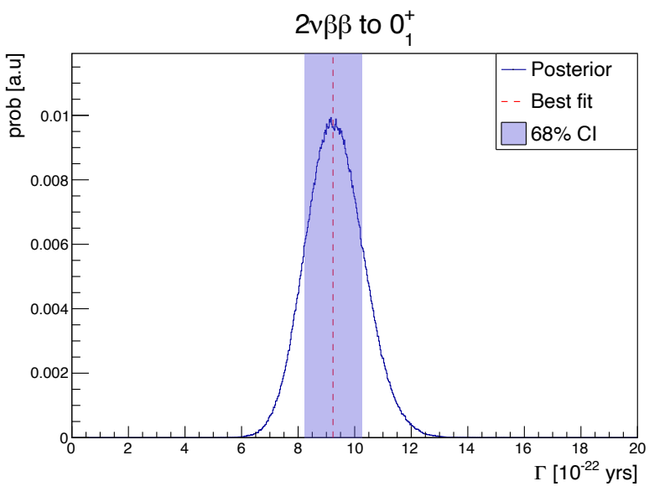
Cat.	Multiplicity	Peak Variable	Energy cuts	Interpretation
0	2	E_1	$E_2 \in [220, 410]$	γ in E_1, $\beta\beta$ in E_2
1	2	E_1	$E_2 \in [410, 500]$	γ in E_1, $\beta\beta$ in E_2
2	2	E_2	$E_1 \in [500, 890]$	γ in E_2, $\beta\beta$ in E_1
3	2	E_2	$E_1 \in [890, 1190]$	γ in E_2, $\beta\beta$ in E_1
4	2	E_2	$E_1 \in [1190, 1880]$	γ in E_2, $\beta\beta$ in E_1
5	3	E_2	-	γ in E_2, $\beta\beta$ in E_1, Compt. in E_3
6	3	$E_2 + E_3$	$E_2 < 500$	γ in $E_2 + E_3$ (shared Compt.), $\beta\beta$ in E_1

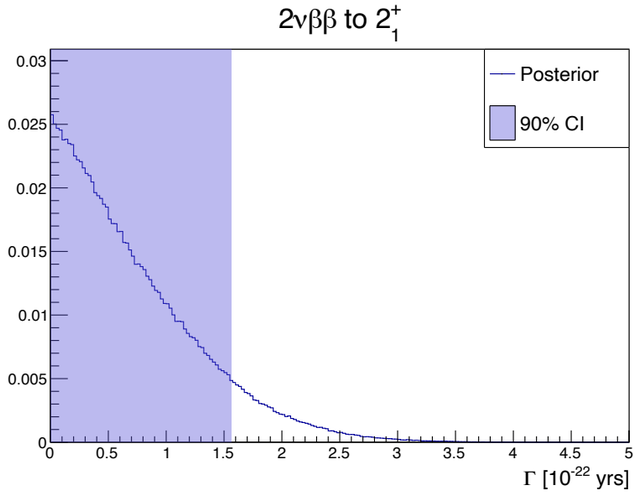
CUPID-Mo, Phys.Rev.C **107**, 025503 (2023)

^{100}Mo $2\nu\beta\beta$ Decay to Excited States of ^{100}Ru





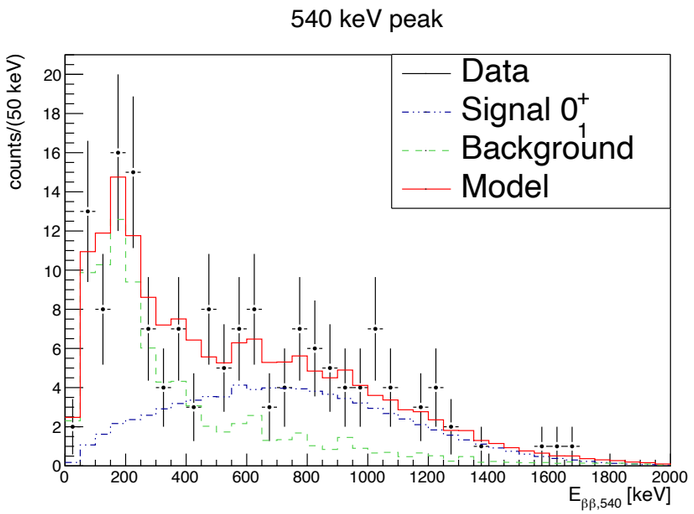


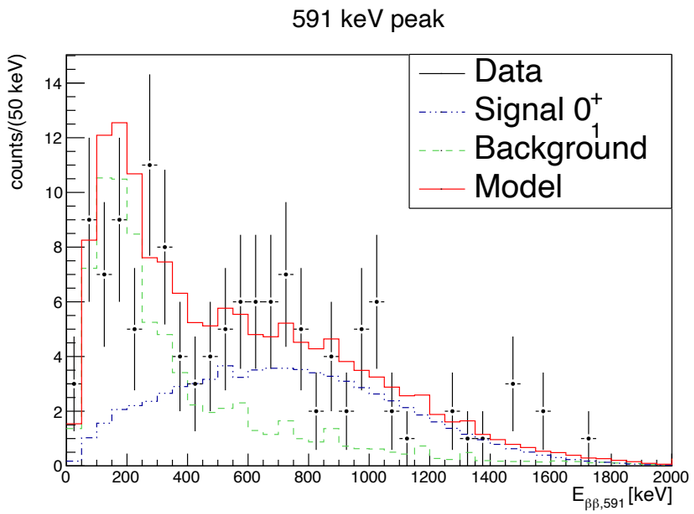


$$T_{1/2}^{2\nu\to 0_1^+} = (7.5 \pm 0.8\ (\text{stat.})\ ^{+0.4}_{-0.3}\ (\text{syst.})) \times 10^{20}\ \text{yr}$$

$$T_{1/2}^{2\nu\to 2_1^+} > 4.4 \times 10^{21}\ \text{yr}\ (90\%\ \text{c.i.})$$

$$M^{\text{eff}}_{2\nu\to 0_1^+} = 0.143 \pm 0.008\ (\text{stat.+syst.})$$



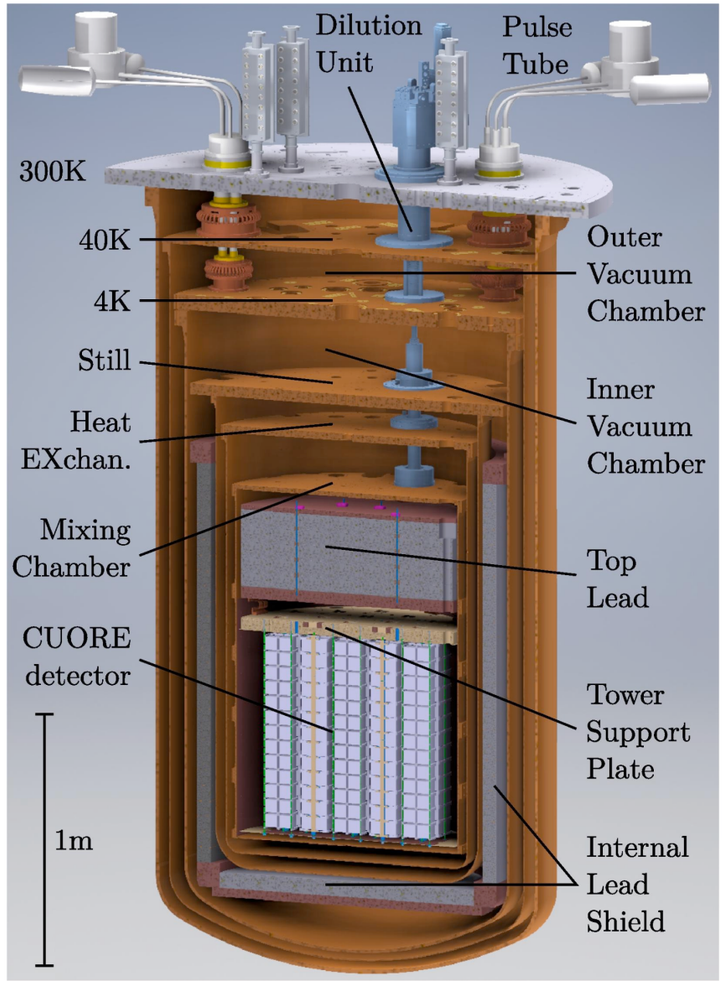


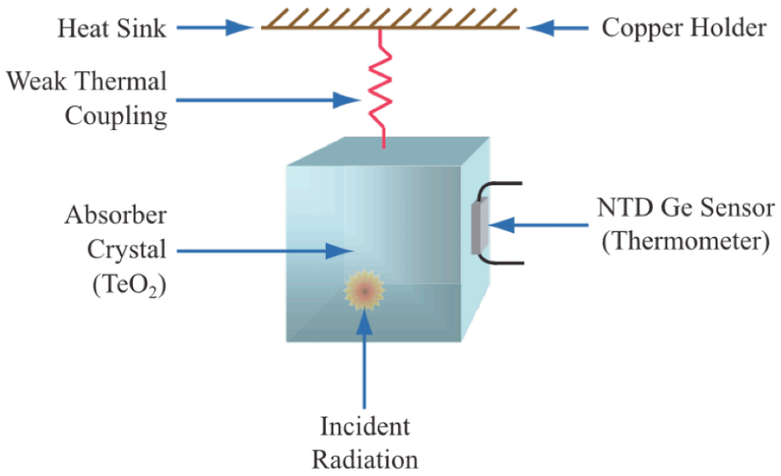
No shape sensitivity (yet) to distinguish NME models
But the models should be able to predict the matrix element / half-life

CUPID-Mo, Phys.Rev.C **107**, 025503 (2023)

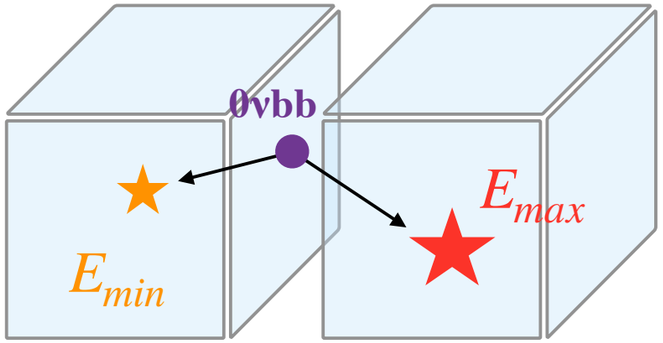
$0\nu\beta\beta$ in High-Multiplicity Events

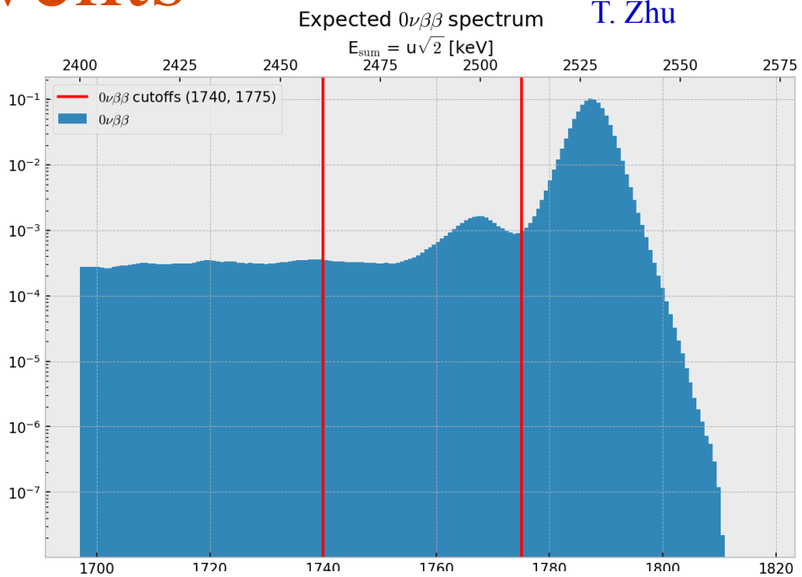
S. Wagaarachchi
T. Zhu



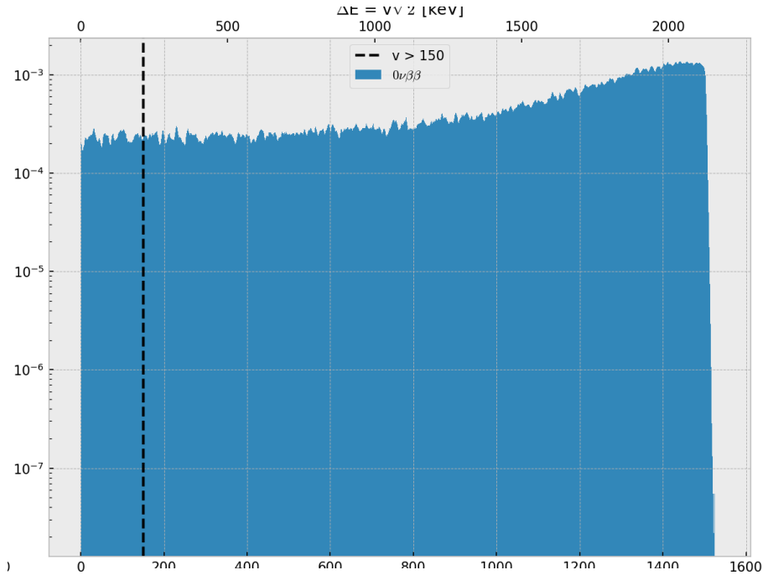


Schematic of a CUORE calorimeter





Energy sum [keV/sqrt(2)]



Energy difference [keV/sqrt(2)]

10-30% of events contained in multiple crystals
Opportunity for coincidence analysis to reduce backgrounds
Sensitivity to event topology in case of discovery

$0\nu\beta\beta$ in High-Multiplicity Events

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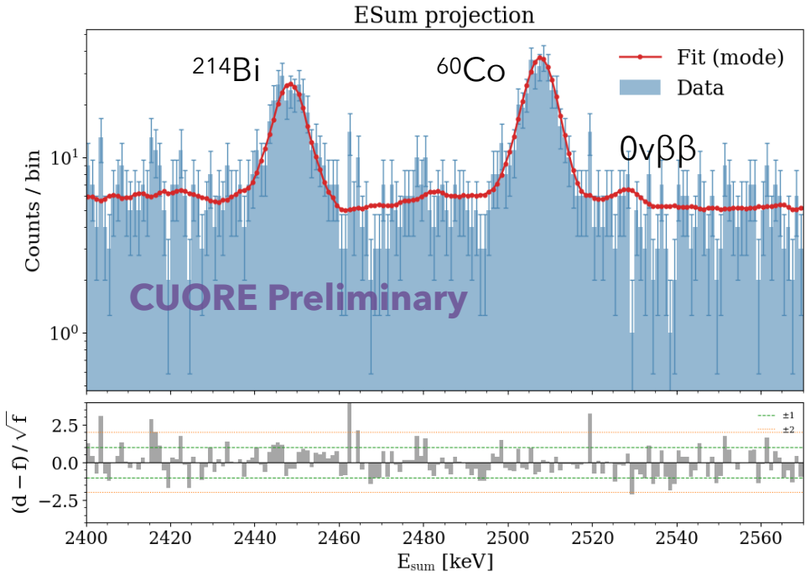
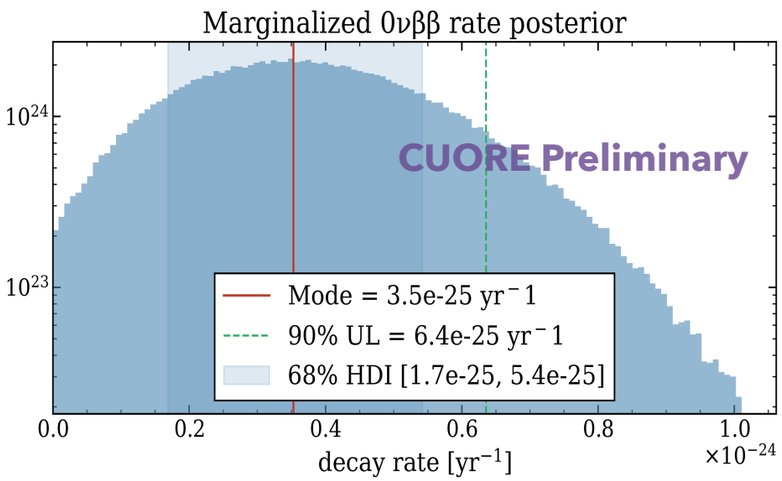
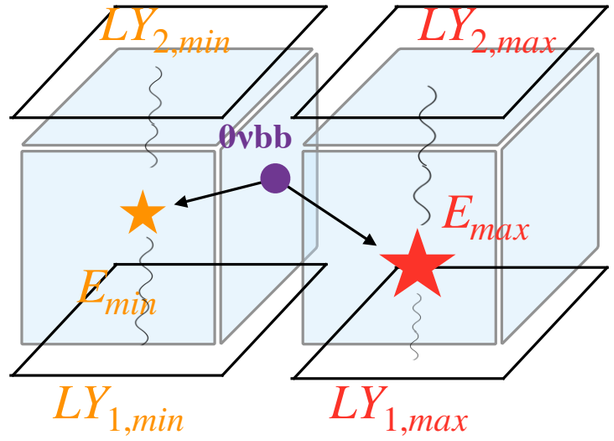
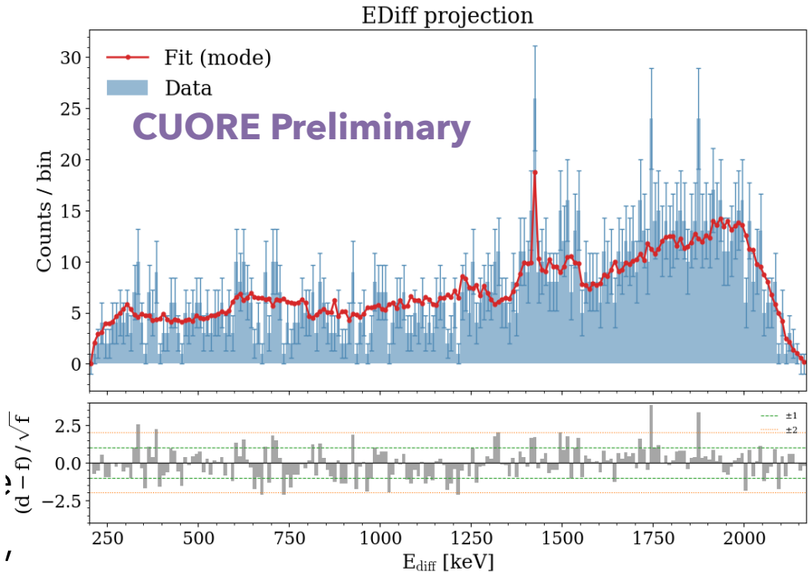
T. Zhu









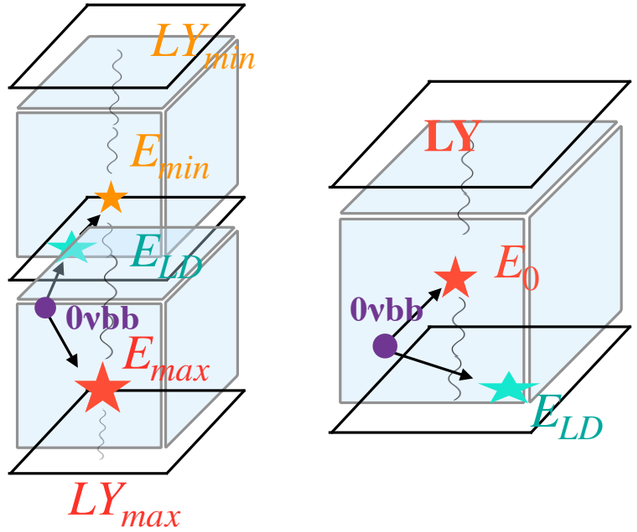
Fitted 0νββ rate:

$$\Gamma^{0\nu} = 3.5^{+1.9}_{-1.8} \times 10^{-25}\ \text{yr}^{-1}$$

90% C.I. on ^{130}Te 0νββ half-life:

$$\mathbf{T^{0\nu}_{1/2} > 1.1 \times 10^{24}\ yr.}$$

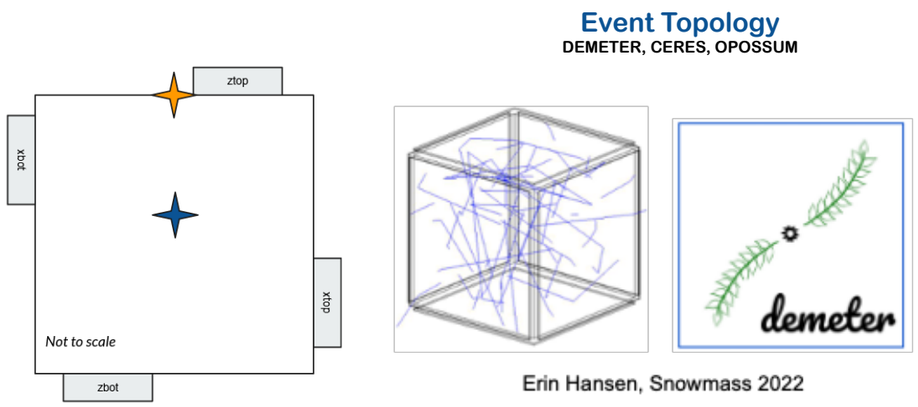
CUORE Preliminary



CUPID event topologies

Holy Grail: Quantum (Phonon) TPC

- Normal ordering scale experiment will require zero background at ton scale
  - Not possible with passive techniques
  - Requires topological reconstruction (single-site vs multi-site events), position fiducialization, active veto for external γs
  - While keeping excellent energy resolution
    - ☞ Phonon TPC: position-sensitive bolometers
    - ☞ Prototypes: DEMETER, CERES (Berkeley), OPOSSUM (LNGS)
    - ☞ External γ veto: BINGO
- Topological information may provide sensitivity to models ($0\nu\beta\beta$ and $2\nu\beta\beta$)



Erin Hansen, Snowmass 2022

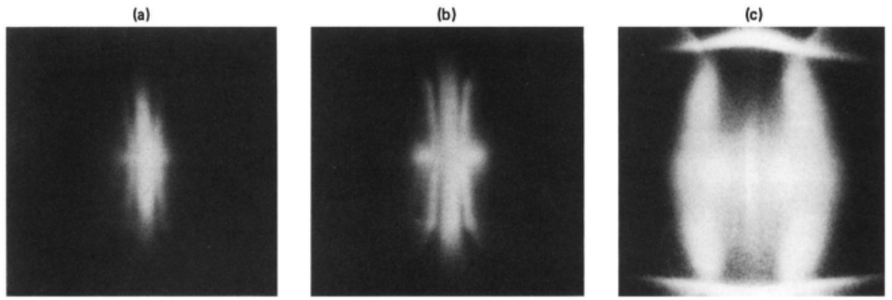
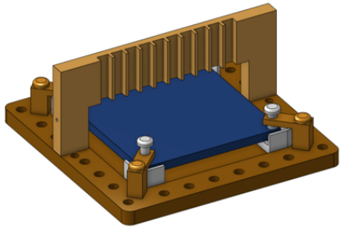
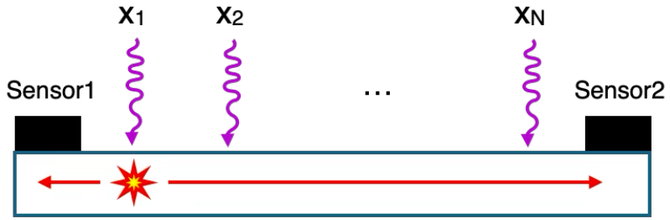


Image from D. C. Hurley, J. P. Wolfe, and K. A. McCarthy. Phys. Rev. B 33, 4189 (1986)





CERES: E. Brandani et al., in preparation

Detour: $\mu^- \to e^+$ Conversion in Nucleus

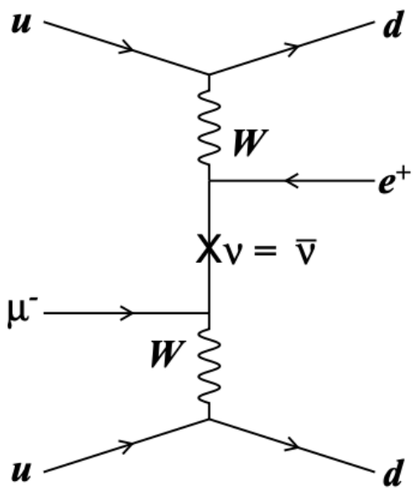
- Transition

$$\mu^- + A(Z,N) \;\to\; e^+ + A(Z-2, N+2)$$

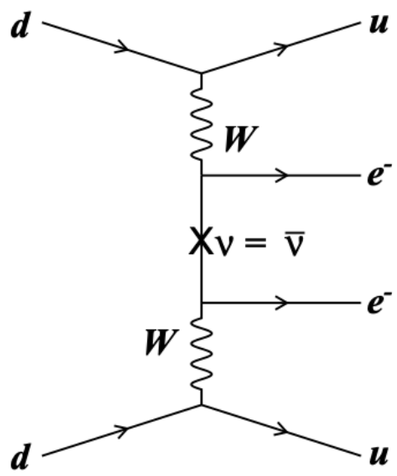
  - Incoherent conversion (2p→2n): no coherent enhancement
  - Large momentum transfer: transition to ground or excited state of the nucleus
    - ☞ Ground state branching fraction estimated to be ~41%
    - ☞ Most dominant excited state is a broad Giant Dipole Resonance

- Previous best measurement: SINDRUM-II

$$R_{\mu e+} \equiv \frac{\Gamma(\mu^- + {}^{48}\mathrm{Ti} \to e^+ + {}^{48}\mathrm{Ca}^{\mathrm{GS}})}{\Gamma(\mu^- + {}^{48}\mathrm{Ti} \to \nu_\mu + {}^{48}\mathrm{Sc}^*)} < 1.7 \times 10^{-12} \text{ (@90\% C.L.)}$$



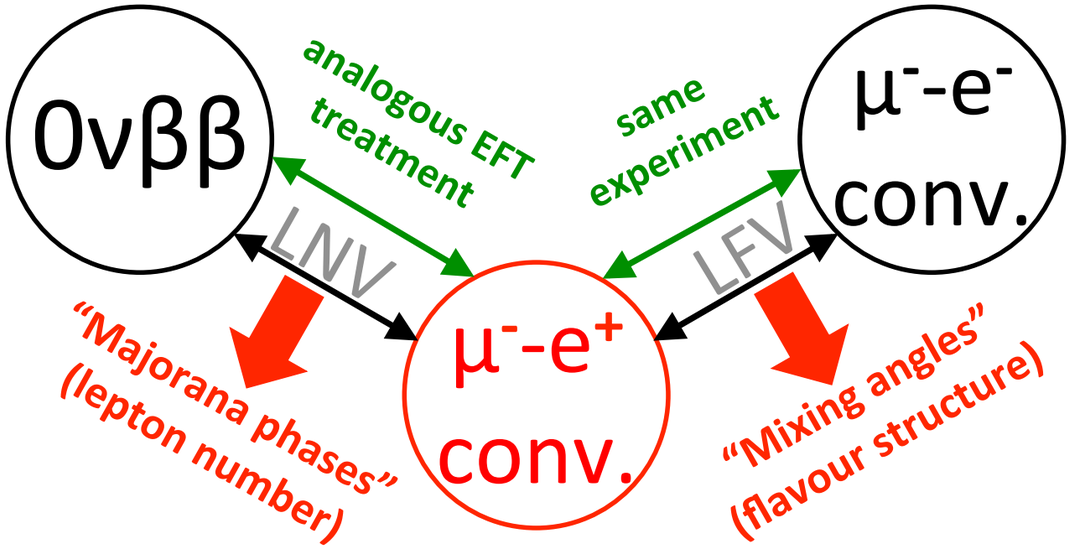
$\mu^- \to e^+$



$0\nu\beta\beta$

Diagram: M. Stortini

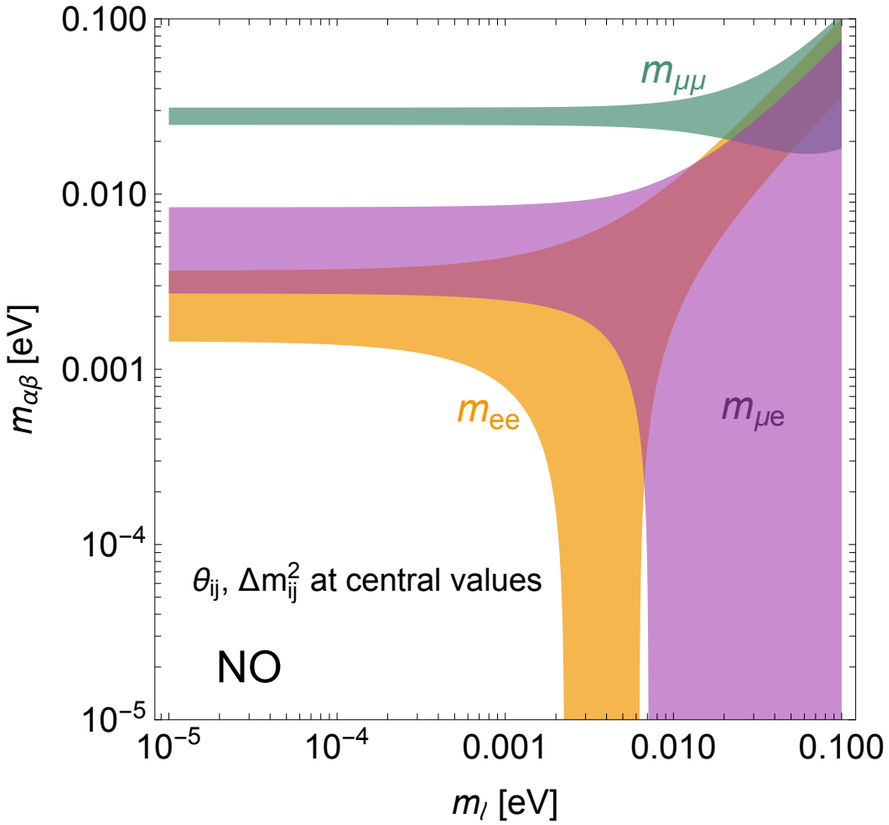
$\mu^- \to e^+$ Conversion: Complementarity



LNV-Alternatives:
μ^--μ^+ conversion
$K^+ \to \pi^+\mu^-\mu^-$

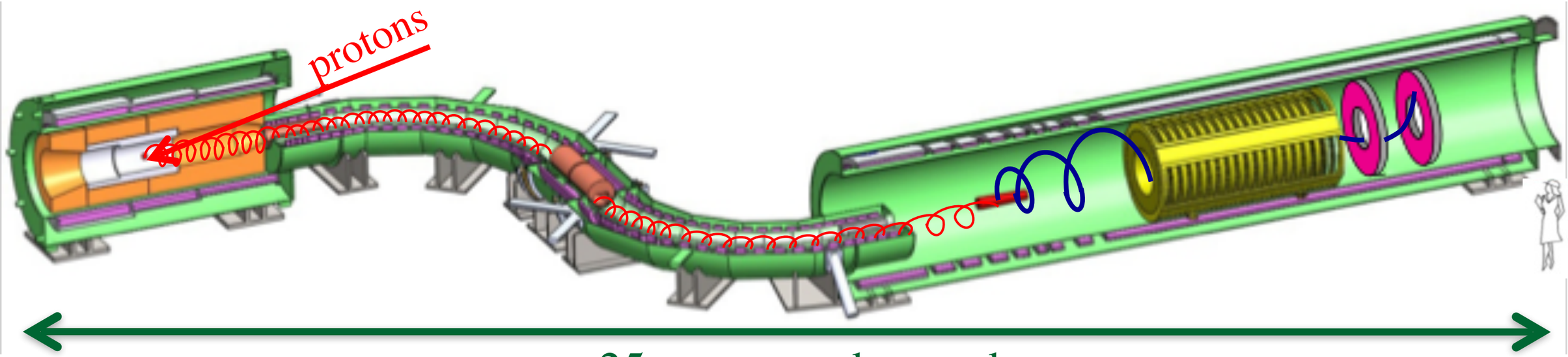
LFV-Alternatives:
$\mu \to e+\gamma$
$\mu \to 3e$

K. Zuber et al.



Complementarity between LFV and LNV measurements
Complementarity between nuclear (DBD) and particle physics (Mu2e) measurements
Complementarity between nuclear calculations (nuclear matrix elements)
"No-lose theorem" [Dery, Gori, Grossman, Ligeti, JHEP **10**, 100 (2024)]

Mu2e @ FNAL



~25 meters end-to-end

Mu2e @ Fermilab

Charge-symmetric spectrometer: will be able to search for both $\mu^- \to e^-$ and $\mu^- \to e^+$!

Also sensitivity to radiative muon capture (RMC) process, through both e^+ and γ detection

Detector ready to go, expect first beam in 2027 !

Radiative Muon Capture

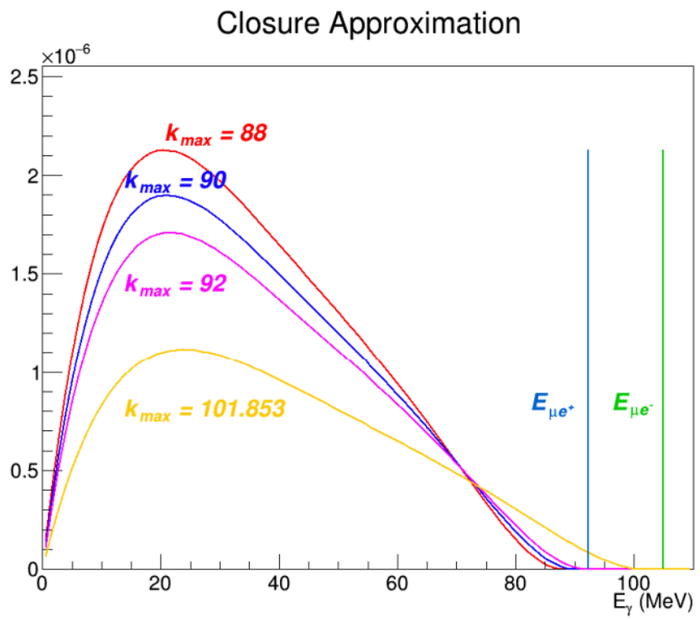
Radiative muon capture
$\mu^- + (Z, N) \rightarrow \nu_\mu + \gamma + (Z\text{-}1,N\text{+}1) \rightarrow \nu_\mu + e^+e^- + (Z\text{-}1,N\text{+}1)$ is the dominant background in $\mu^- \rightarrow e^+$ searches

Strongly depends on nuclear structure: RMC transitions to the ground state, excited states, or with neutron or proton emission

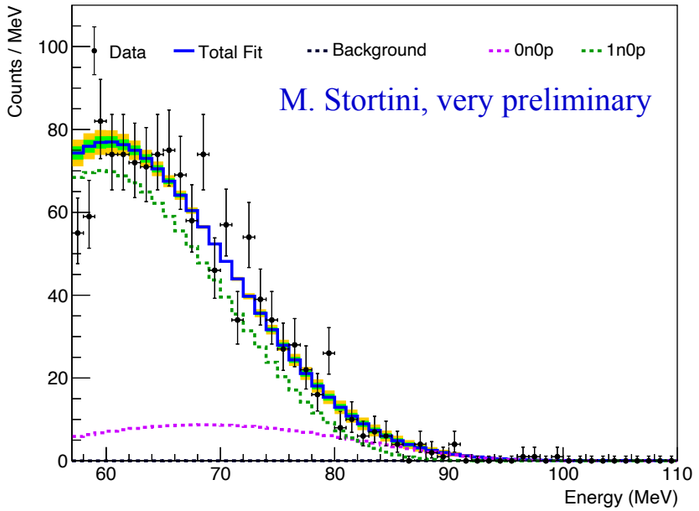
No predictions so far and scarcely any data ! — could use theory help

RMC endpoint spectrum on ^{27}Al will be measured by Mu2e within a week of data taking: opportunity to test nuclear models in a light nucleus

Also data (PSI) exists for Al, Si, Ca, Mo, Sn, Pb [M. Stortini, Ph.D. thesis, Yale, 2026; A. Trumic, UC Berkeley]



https://arxiv.org/pdf/2110.07093

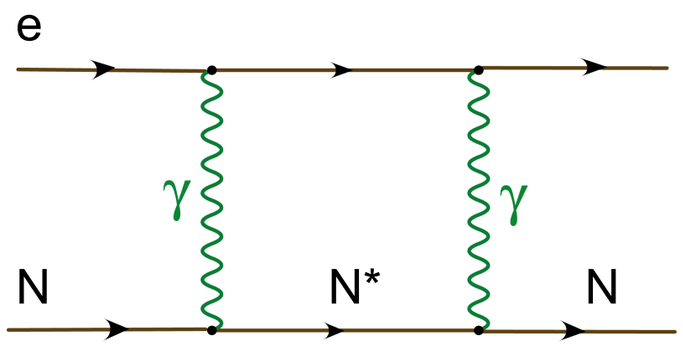


Transverse Asymmetries in Parity Violation Experiments

Beam-Normal Asymmetry in elastic electron-nucleus scattering

☞ **Electron beam polarized transverse to beam direction**

$$A_T \equiv \frac{2\pi}{\sigma^{\uparrow}+\sigma^{\downarrow}} \frac{d(\sigma^{\uparrow}-\sigma^{\downarrow})}{d\phi} \propto \vec{S}_e \bullet (\vec{k}_e \times \vec{k}'_e)$$

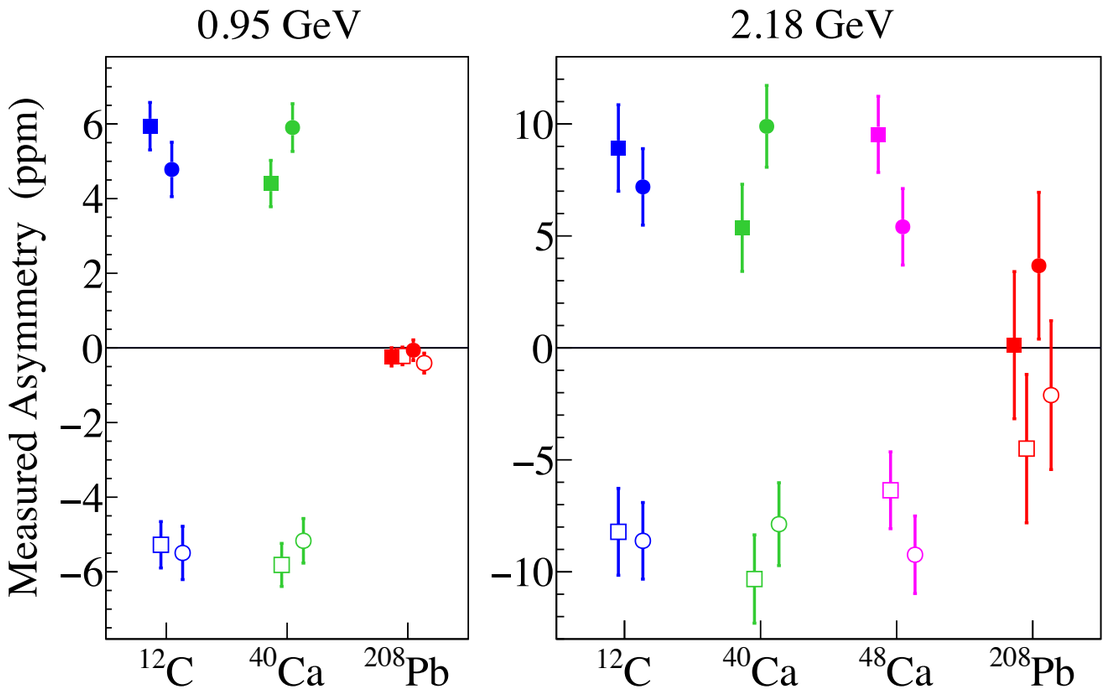


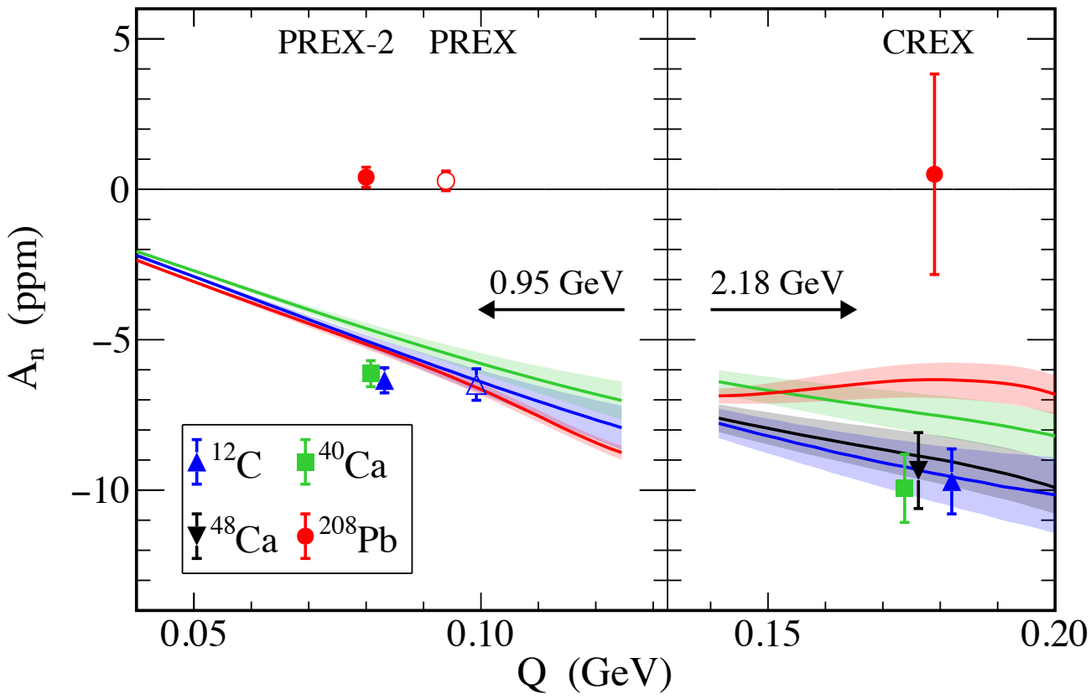
Interference between one- and two-photon exchange

$$A_T \propto \frac{\alpha m_e}{\sqrt{s}} \approx O(ppm)$$

Potentially sensitive to nuclear structure
Purely EM process, vector couplings, no g_A quenching
Momentum transfer of O(100 MeV): relevant for NLDBD ?

PREX/CREX Puzzle





Pb-208 result not currently understood

Potential interference between couplings to different excited states ?

Opportunity to bench-mark NME models ?

Additional measurements foreseen @ MAMI, MESA

Conclusions

- Spectroscopic measurements of $2\nu\beta\beta$ and other processes can be sensitive to nuclear models
- Opportunities to benchmark, tune, and possibly qualify models for the purposes of selecting $0\nu\beta\beta$ NMEs

→ Looking forward to discussing developments here !

Thanks to CUORE, CUPID, CUPID-Mo, Mu2e, E158, MOLLER collaborators