Research Overview: Prof. Michael Gold☆

Experimental Particle Physics

What is a neutrino anyway?

Why is neutrino-less double beta decay ($\beta\beta0\nu$) so important?

☆ With: Prof. Fields

undergrads Wes McClenaghan, Dylan Hall

Interact with W in flavor eigenstates:

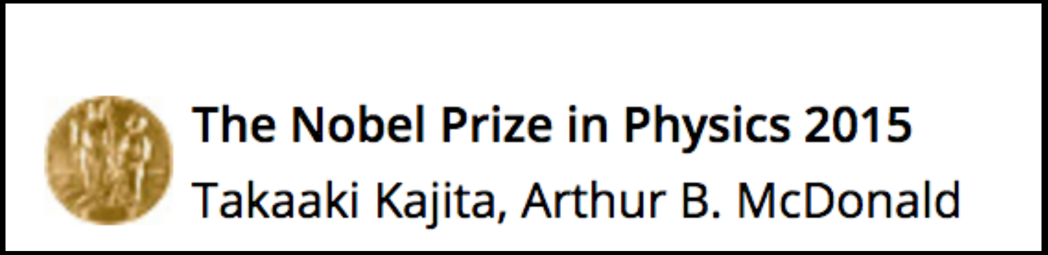
$W \to \nu_e e, W \to \nu_\mu \mu, W \to \nu_\tau \tau$

3 flavors

data: ν mix!

Solar $\nu_e \to \nu_x$

Atmospheric $\nu_\mu \to \nu_\tau$



The Nobel Prize in Physics 2015

Takaaki Kajita, Arthur B. McDonald

ν have mass!!

Propagate as mass eigenstates m_1, m_2, m_3

simplified 2 neutrino mixing

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{E}\frac{[\mathrm{eV}^2]\,[\mathrm{km}]}{[\mathrm{GeV}]}\right).$$

General ν mixing:

PNS has 3 angles, one CP violating phase

Majorana mass adds 2 CP violating phases

$$U = \overset{\text{Atmospheric}}{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}} \times \overset{\text{Cross-Mixing}}{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}} \times \overset{\text{Solar}}{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}} \times \overset{\text{Majorana CP-violating phases}}{\begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}}.$$

therefore, ν have mass < 1/4 eV (Planck data)

⇨ beyond Standard Model

phases violate CP: δ oscillation exp. DUNE , but not α's

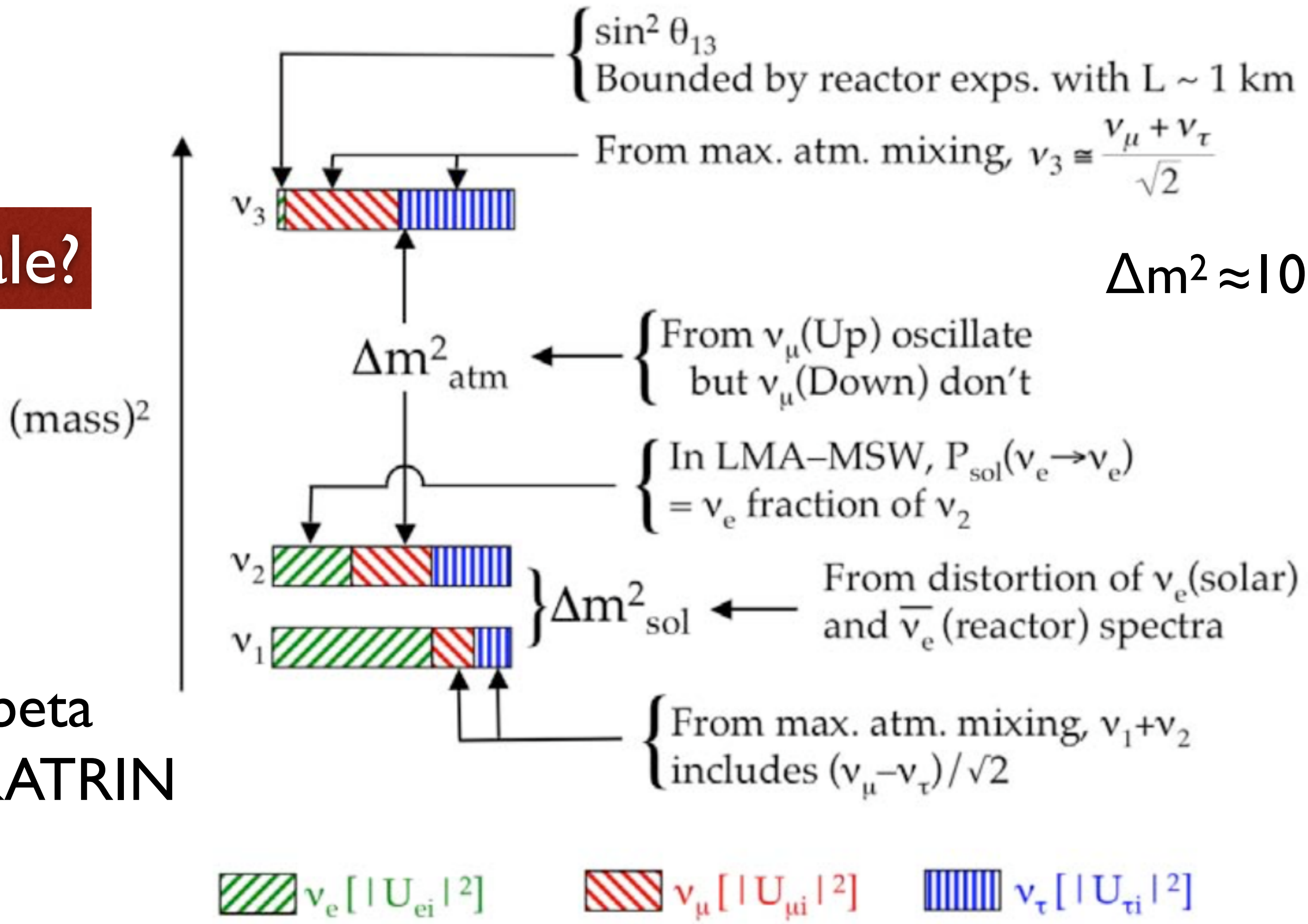
α's origin of matter/antimatter asym.?

B. Kaiser, 2014, summary of mixing

SLAC Summer Institute on Particle Physics (SSI04), Aug. 2-13, 2004

normal hierarchy

mass scale?



$\Delta m^2 \approx 10^{-4}, 10^{-3}$ ev^2

tritium beta
$\nu_e < 1$ ev, KATRIN

Figure 3: A three-neutrino (mass)^2 spectrum that accounts for all the neutrino oscillation data except those from LSND. The ν_e fraction of each mass eigenstate is shown by green right-leaning hatching, the ν_μ fraction is shown by red left-leaning hatching, and the ν_τ fraction by blue vertical hatching.

open questions (B. Kaiser)

1) How many neutrinos are there (>3)? sterile ? **CCM**

2) What are the masses? **KATRIN**

2b) Hierarchy **DUNE**

3) How large is θ_{13}? **DUNE**

4) Are neutrinos their own antiparticles? **$\beta\beta0\nu$**

5) Do neutrino interactions violate CP? **DUNE**

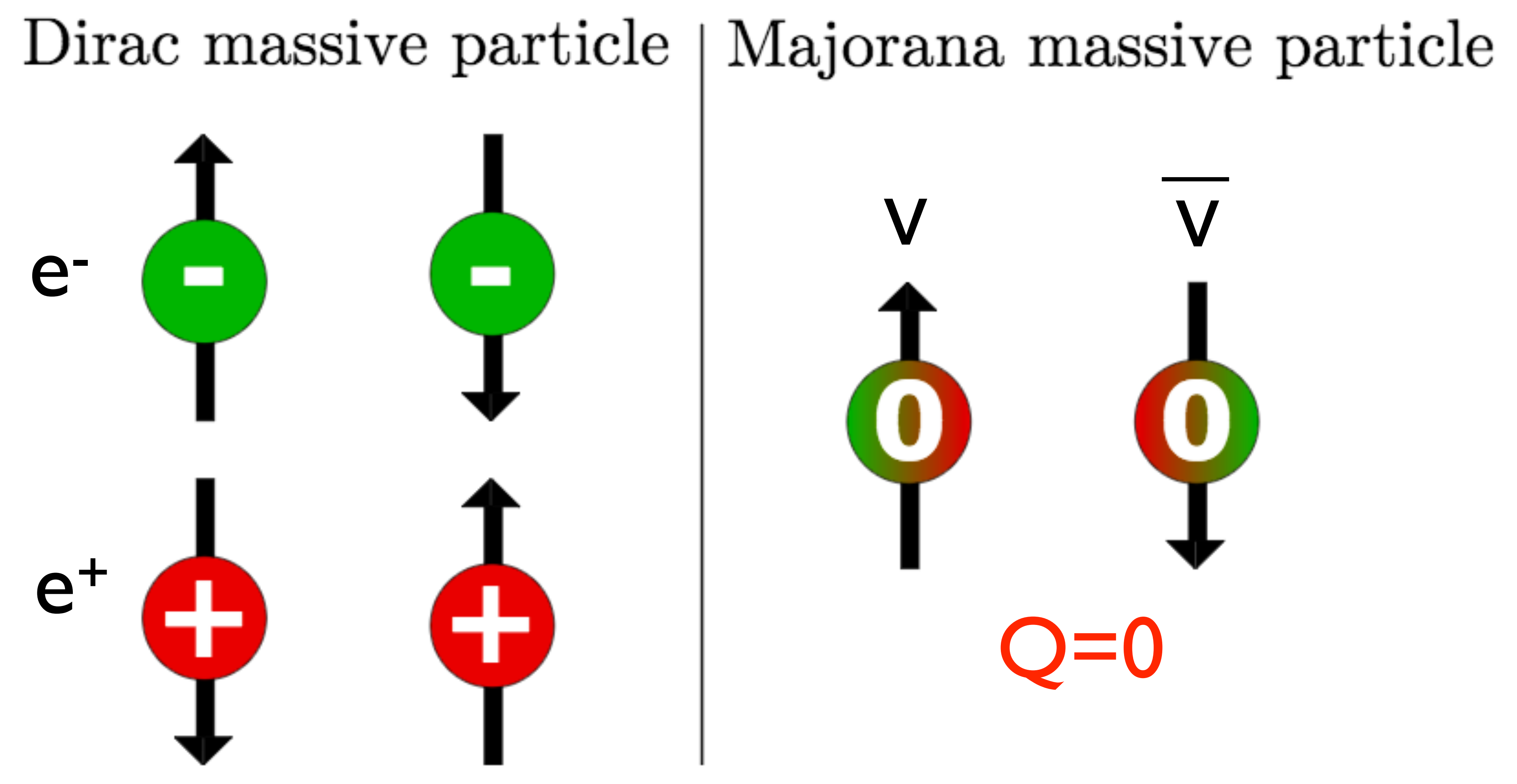
5b) Is neutrino CP violation the reason we exist (matter/antimatter asymmetry)? **$\beta\beta0\nu$**

DUNE = long baseline osc.

CCM = Coherent Captain-Mills

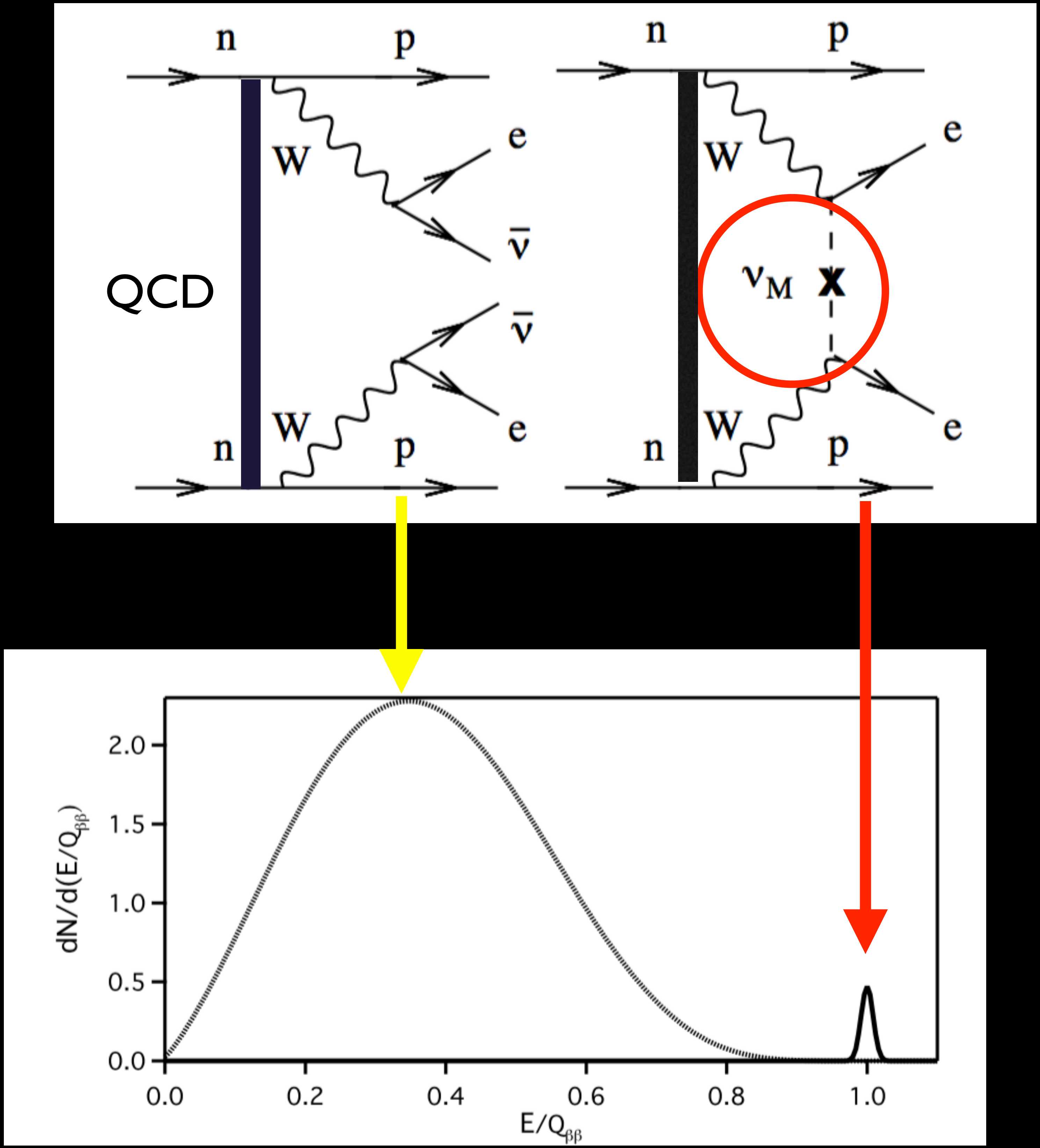
ββ0ν

This decay mode only if neutrino is own antiparticle



4 states ? 2 states

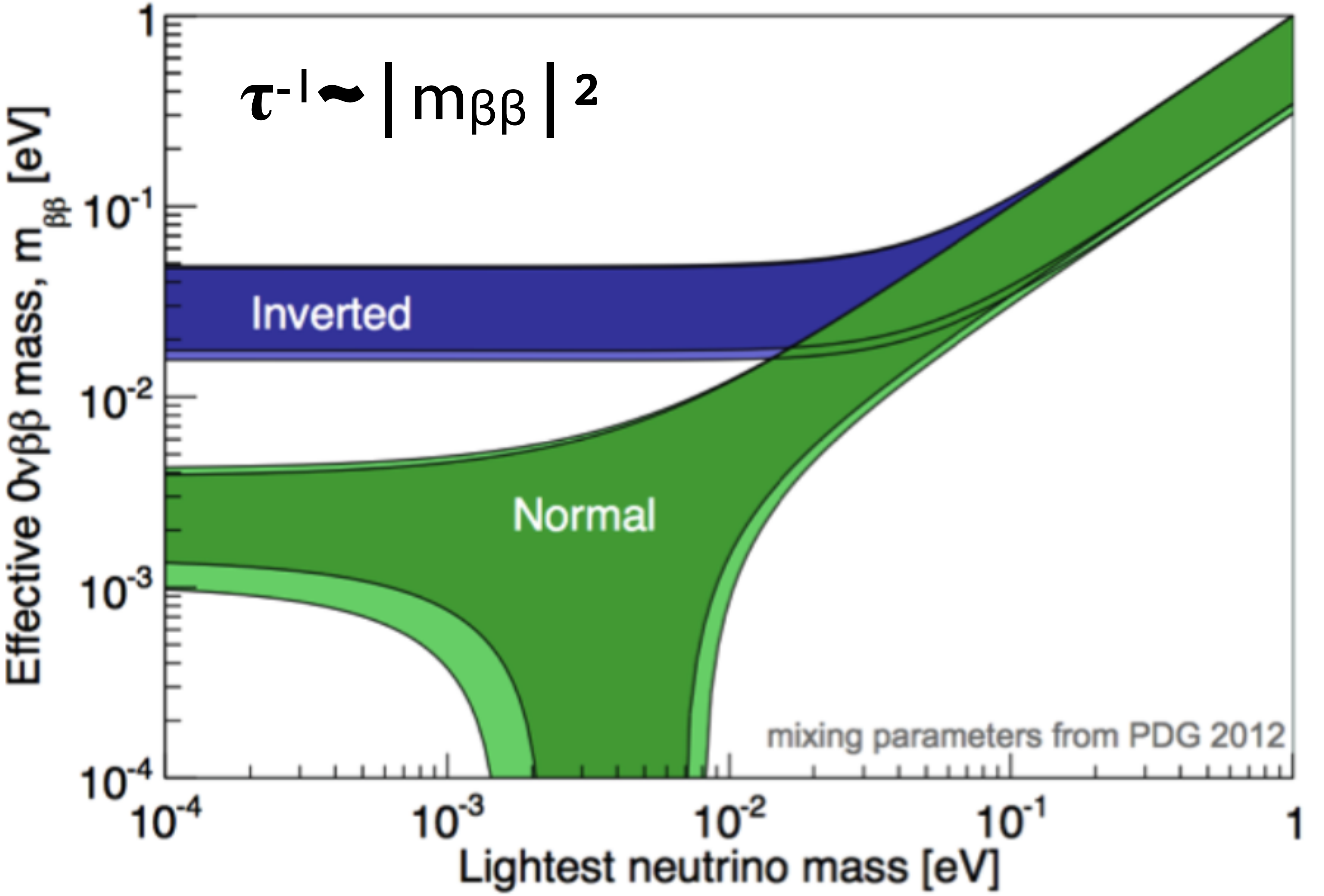
ββ decay



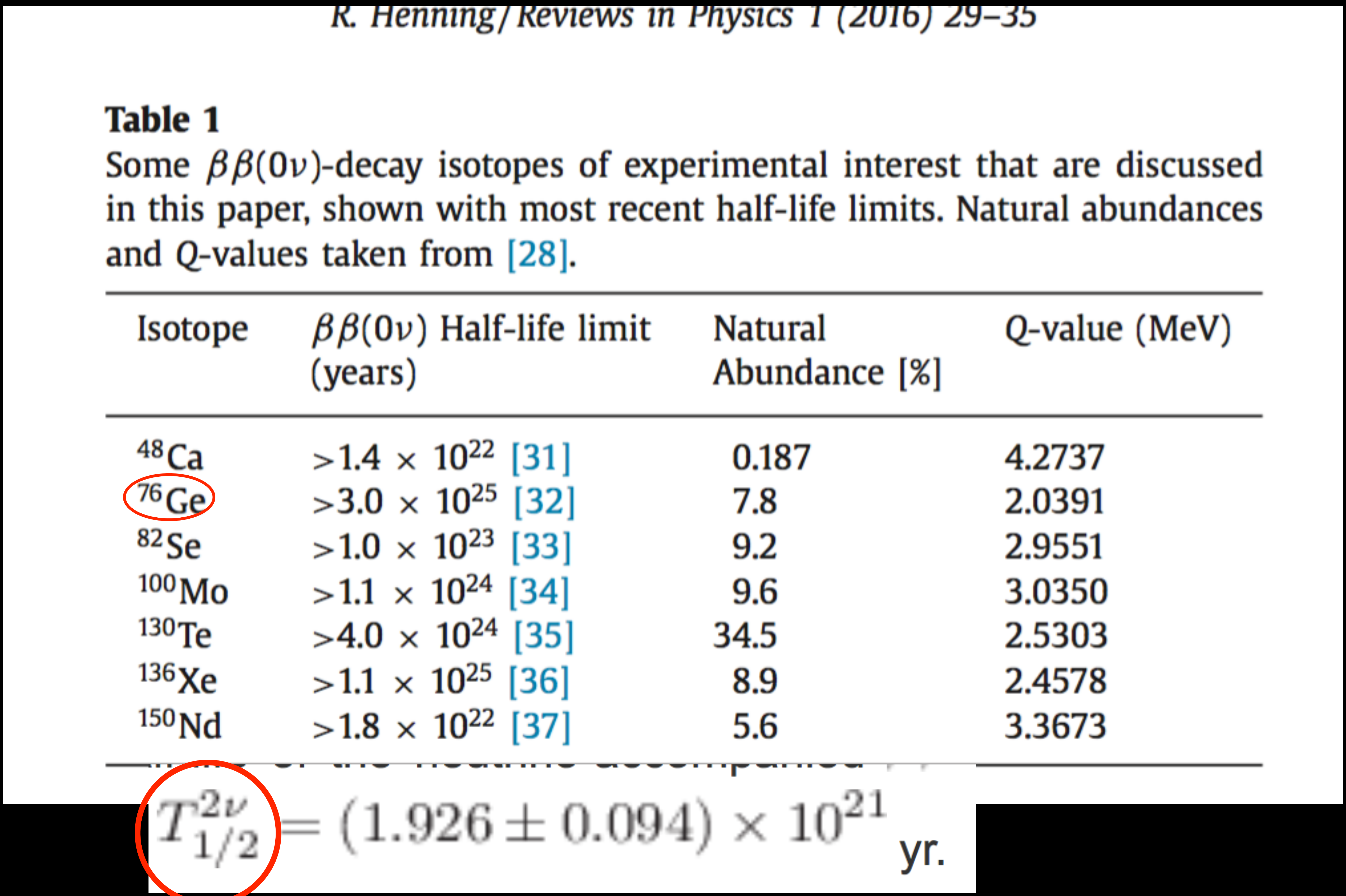
measure
ee energy

bump greatly
exaggerated

Katrin 2019 limit $m(\nu_e) < 1.1\,\mathrm{eV}$



$\tau^{-1} \sim |m_{\beta\beta}|^2$



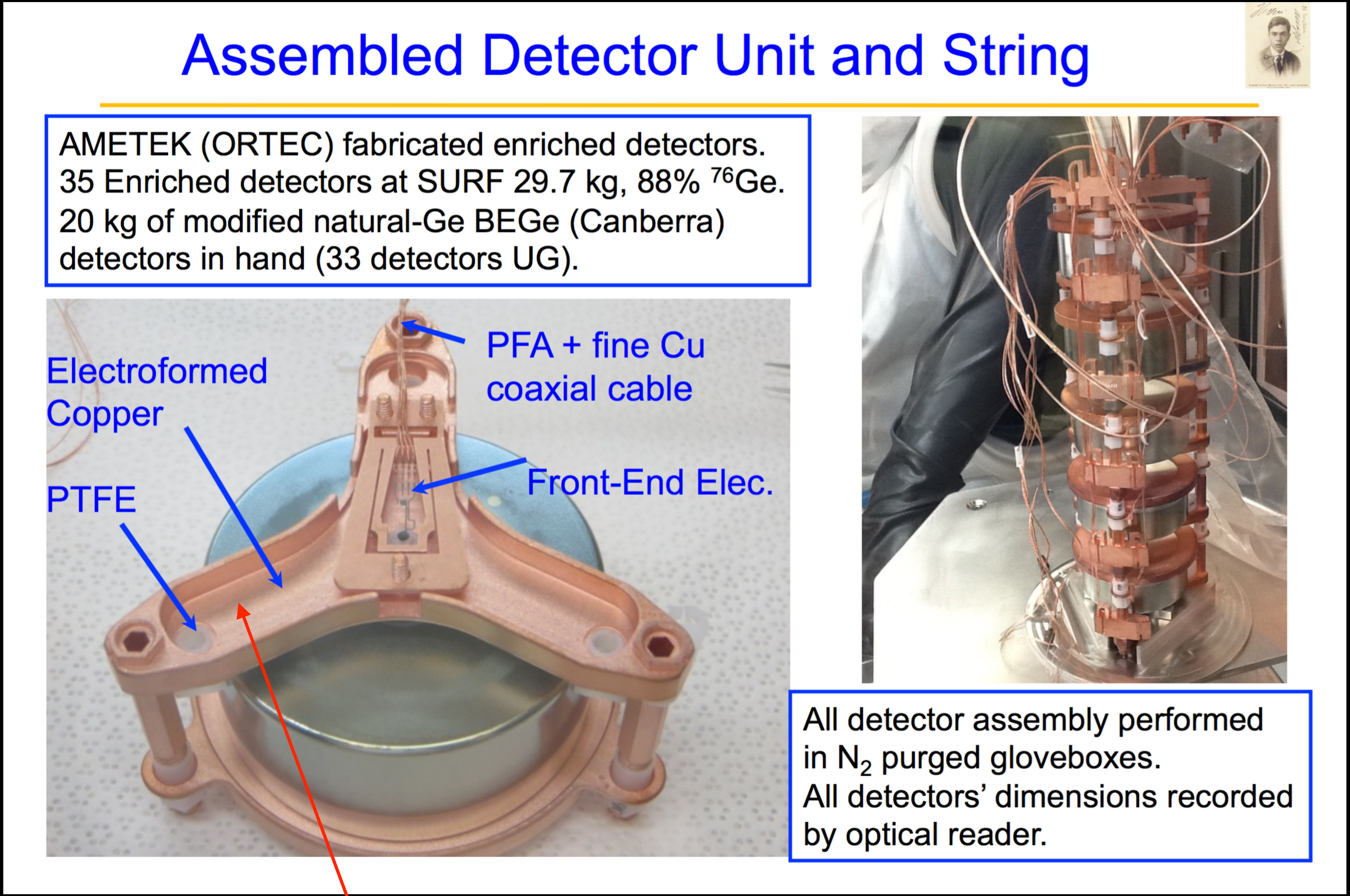
R. Henning/Reviews in Physics 1 (2016) 29–35

Table 1
Some $\beta\beta(0\nu)$-decay isotopes of experimental interest that are discussed in this paper, shown with most recent half-life limits. Natural abundances and Q-values taken from [28].

Isotope	$\beta\beta(0\nu)$ Half-life limit (years)	Natural Abundance [%]	Q-value (MeV)
^{48}Ca	$>1.4 \times 10^{22}$ [31]	0.187	4.2737
^{76}Ge	$>3.0 \times 10^{25}$ [32]	7.8	2.0391
^{82}Se	$>1.0 \times 10^{23}$ [33]	9.2	2.9551
^{100}Mo	$>1.1 \times 10^{24}$ [34]	9.6	3.0350
^{130}Te	$>4.0 \times 10^{24}$ [35]	34.5	2.5303
^{136}Xe	$>1.1 \times 10^{25}$ [36]	8.9	2.4578
^{150}Nd	$>1.8 \times 10^{22}$ [37]	5.6	3.3673

$$T^{2\nu}_{1/2} = (1.926 \pm 0.094) \times 10^{21}$$ yr.

Majorana demonstrator 20 kg



Assembled Detector Unit and String

AMETEK (ORTEC) fabricated enriched detectors.
35 Enriched detectors at SURF 29.7 kg, 88% ^{76}Ge.
20 kg of modified natural-Ge BEGe (Canberra) detectors in hand (33 detectors UG).

All detector assembly performed in N_2 purged gloveboxes.
All detectors' dimensions recorded by optical reader.

electro-formed underground

$^{63}Cu(n, \alpha)^{60}Co$

GERDA employed active LAr veto

“ROI”

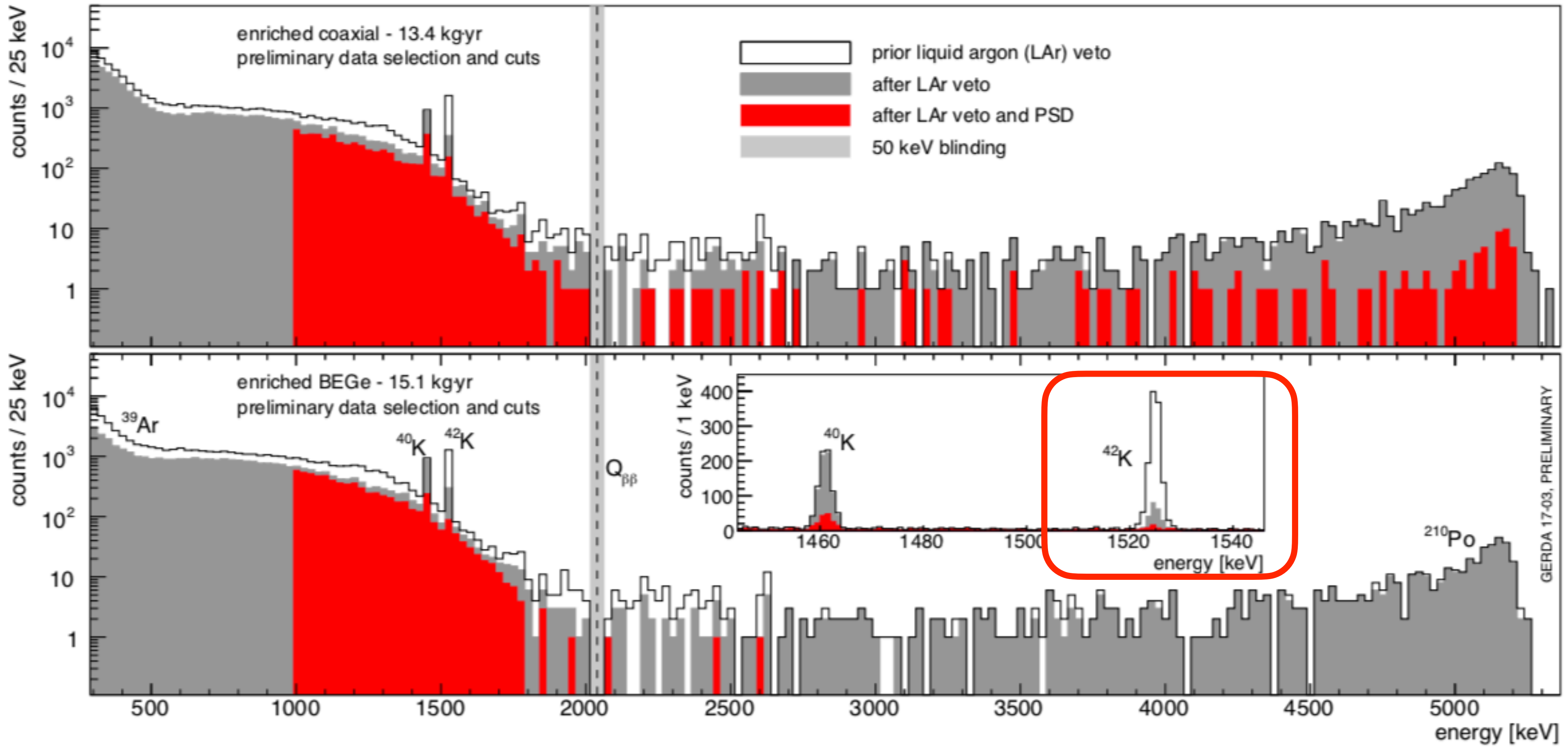
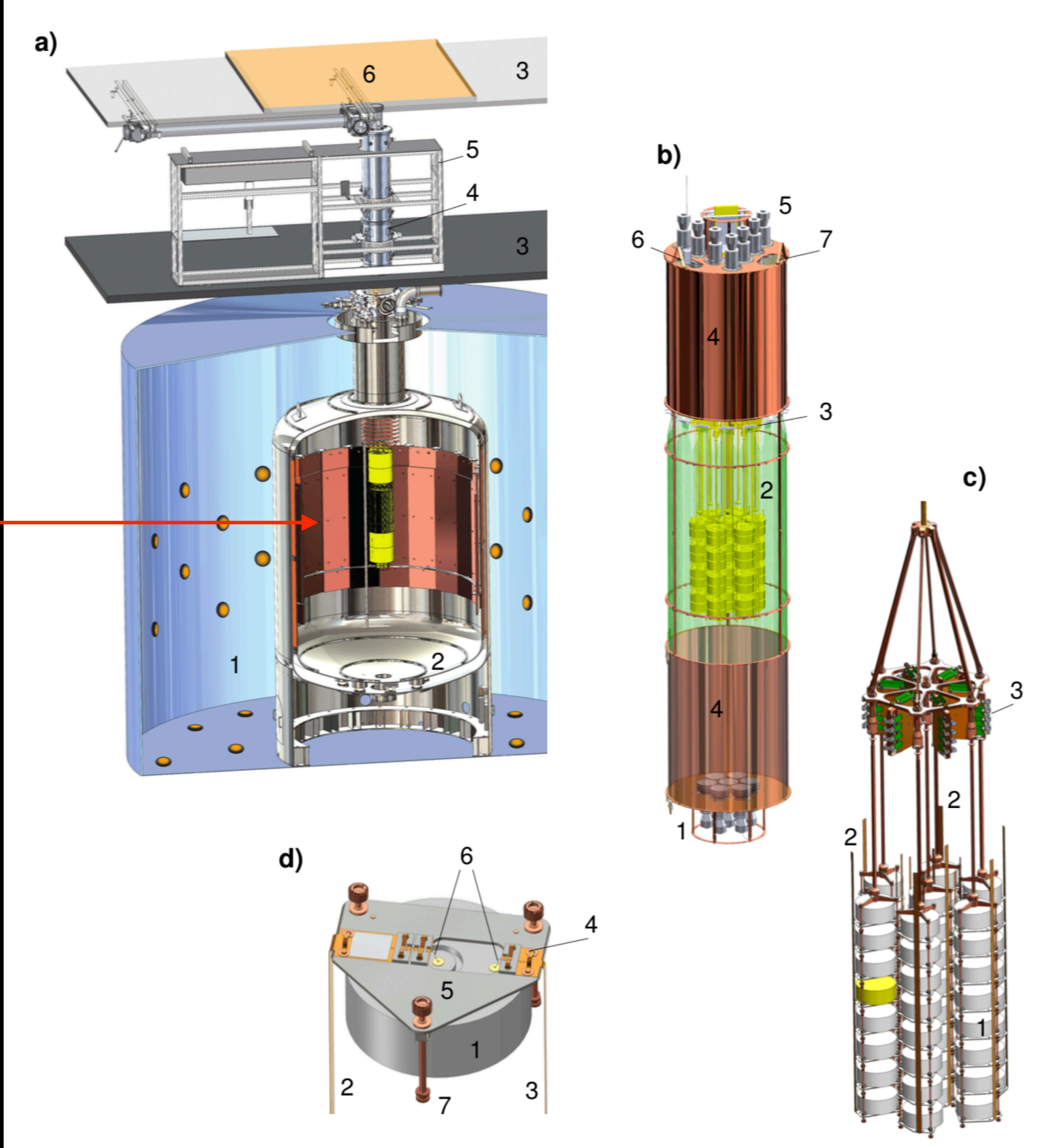


FIG. 5. For GERDA, the effect of the liquid argon veto and pulse shape discrimination on the physics spectrum for coaxial (top) and BEGe (bottom) detectors. The open histogram is before the cuts, in grey after the argon veto, in red after argon veto and PSD cuts. Events around $Q_{\beta\beta}$ are removed from the data set (blinded). The inset shows the spectrum around two potassium lines. The ^{40}K line is from electron capture decay, i.e. no energy is deposited in the argon and only random coincidences reject events. The ^{42}K line is from a β decay where up to 2 MeV is deposited in the argon.

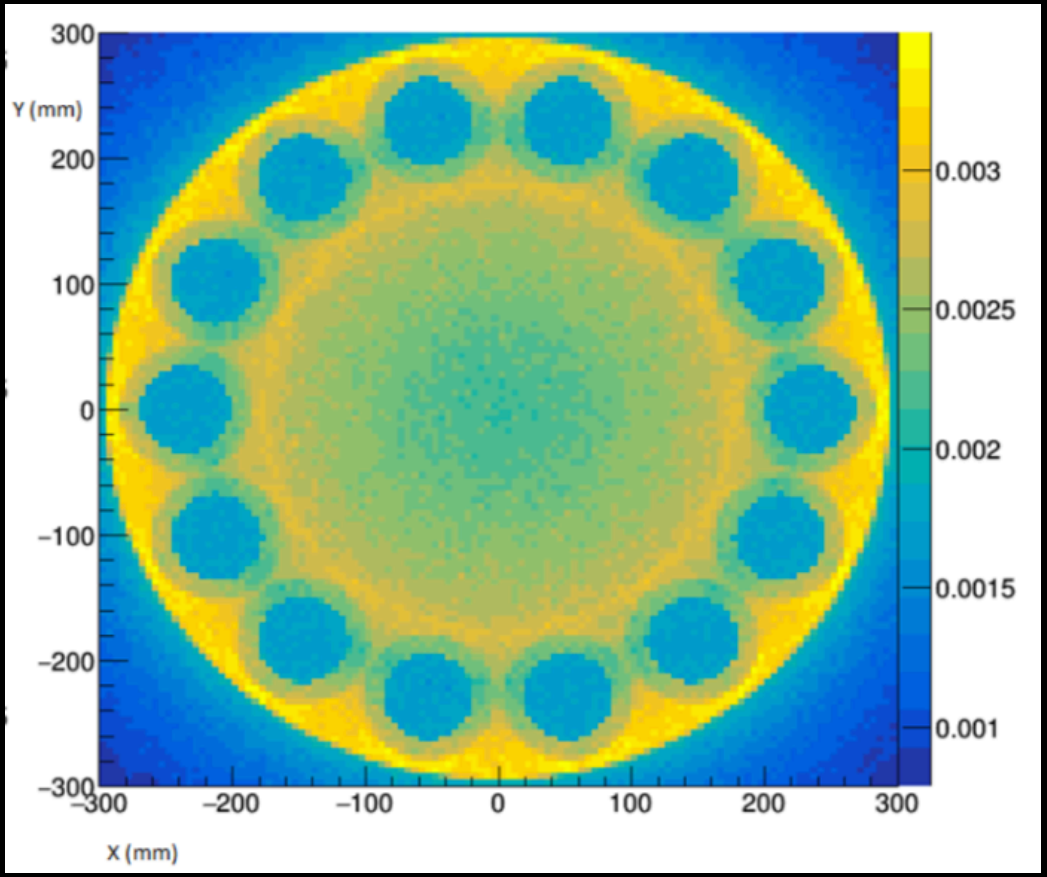
Ionization in LAr ➜ 128 nm scint.

LEGEND 200 kg ongoing @ LNGS



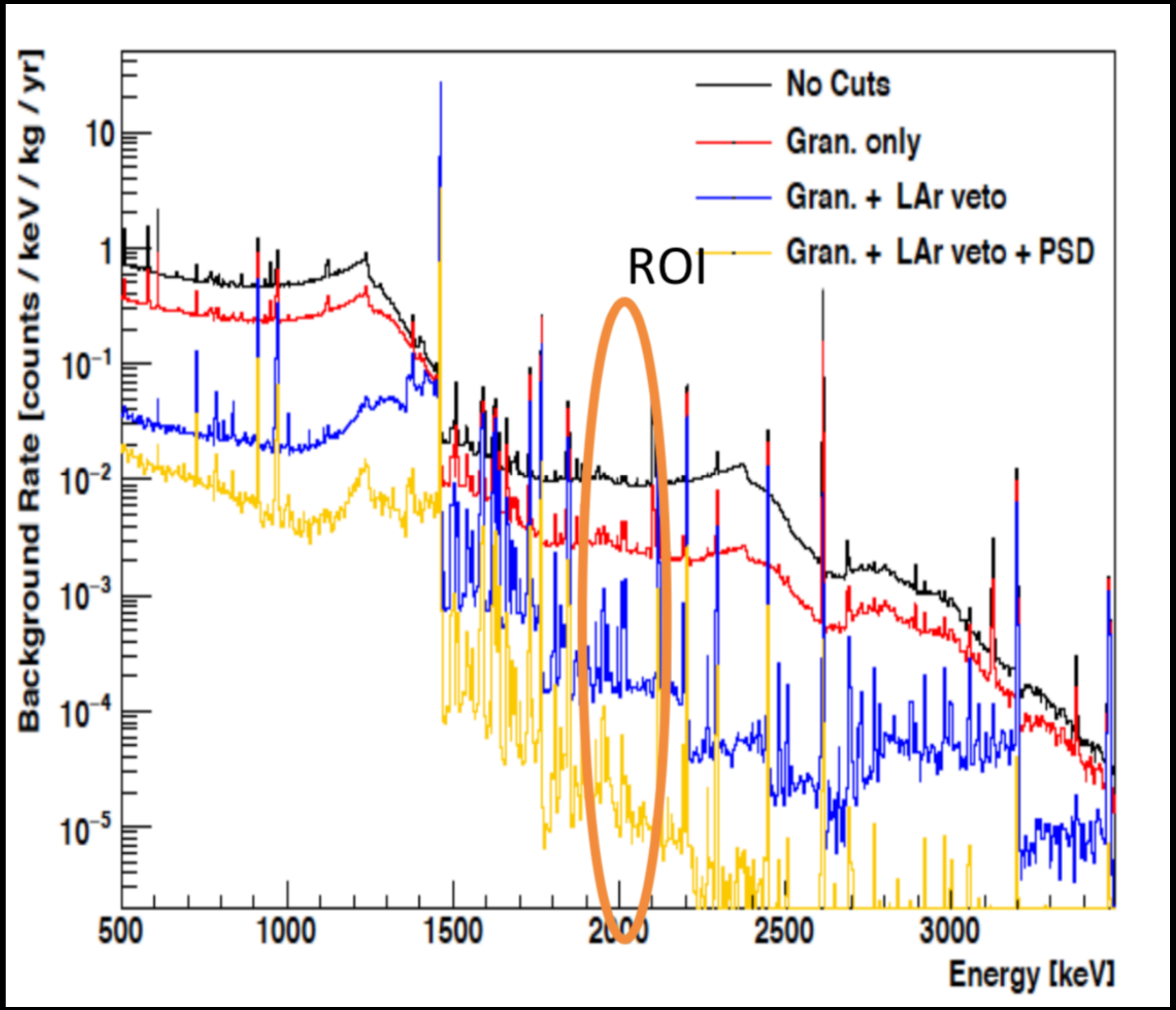
Active
LAr
veto

simulated light yield map



Legend-200 simulated Th background

from Cu holder

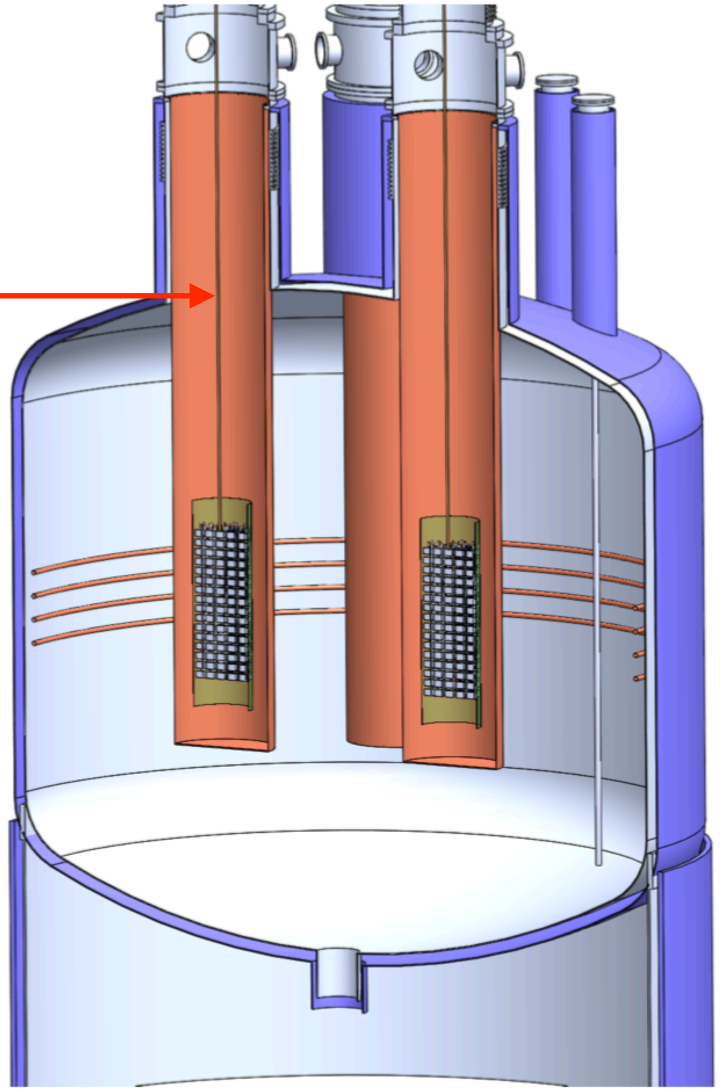


Neil McFadden, PhD 2020

https://digitalrepository.unm.edu/phyc_etds/230/

LEGEND 1000 kg enriched Ge

Wait 10 years collecting data



active LAr veto

FIG. 9. Sketch of baseline cryostat design for LEGEND-1000. The cryostat diameter is 6 m.

LEGEND-1000 expected sensitivity

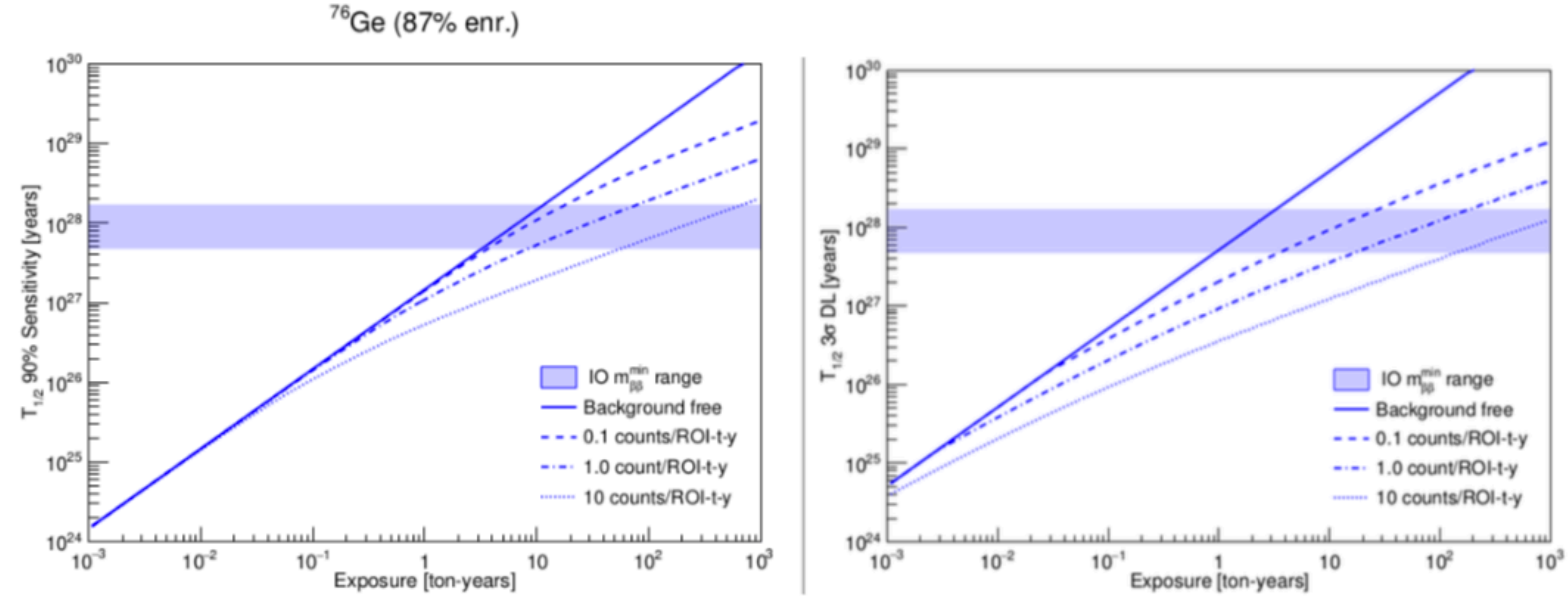
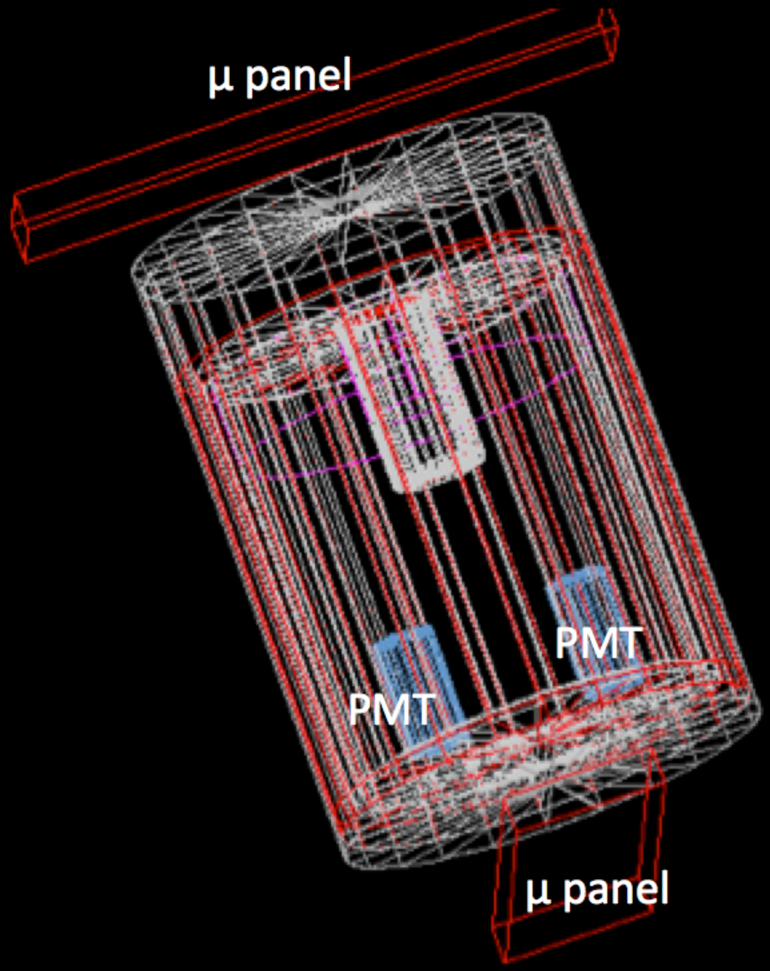


FIG. 7. Sensitivity for setting a limit (left) or a signal discovery (right) as a function of the exposure for different background levels. The colored band shows the expected half-life range for light Majorana neutrino exchange with $m_{\beta\beta} = 17$ meV using the range of matrix elements 3.5-5.5.

10^{28} y

1.7×10^{-2} eV

with LANL collaborators



Experiments and simulation of active LAr veto for LEGEND

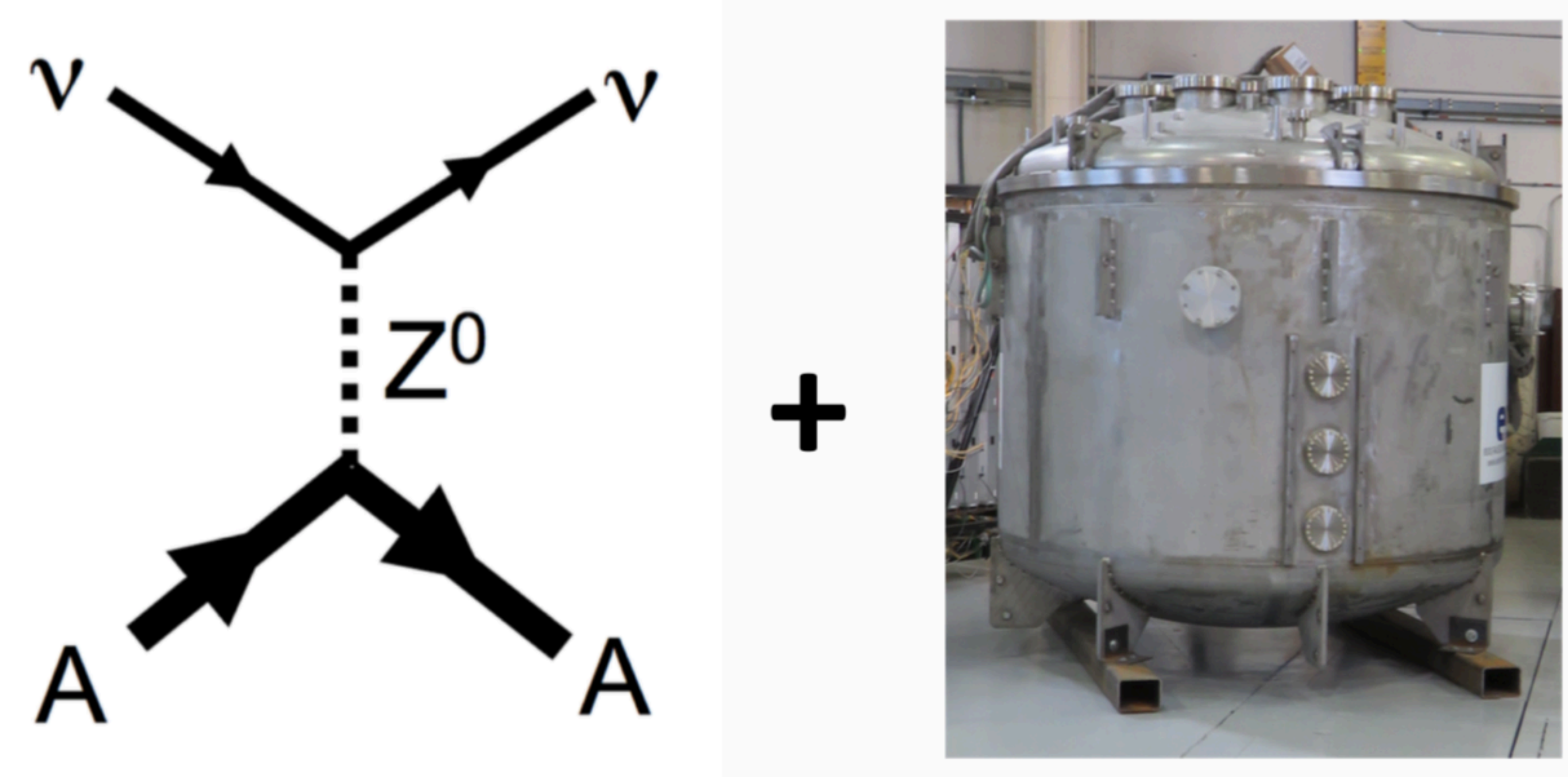
Full GEANT4 sim

Xe doping for improved veto?

Coherent CAPTAIN Mills "CCM"

$\pi \rightarrow \mu \nu_\mu$

LANL stopped pions



$\sigma \sim (\text{neutron } \#)^2$

CAPTAIN = "Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos"

LSND EXCESS: Sterile Neutrino?

circa 1997 with UNM B. Dieterle, R. Reeder

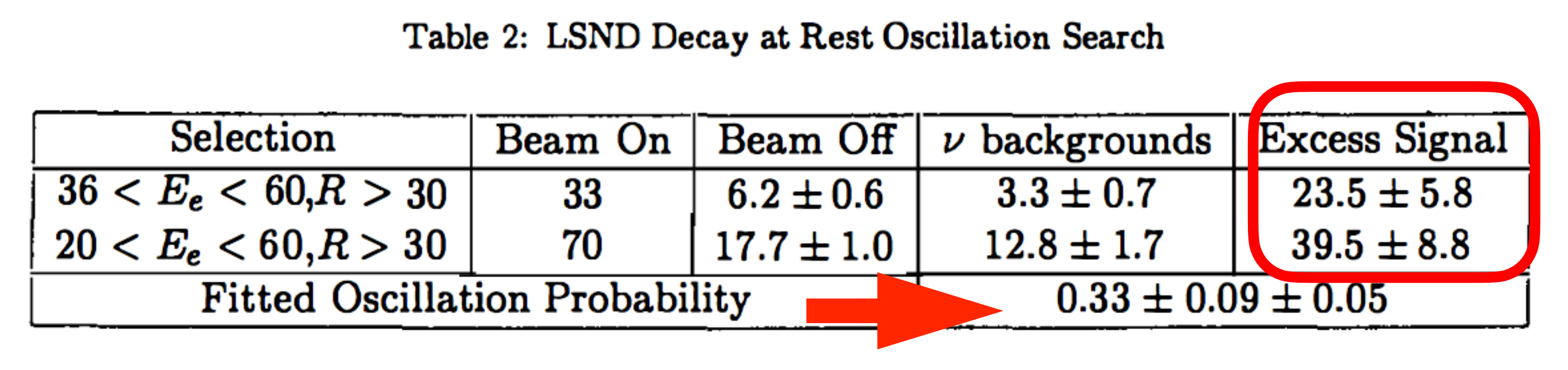
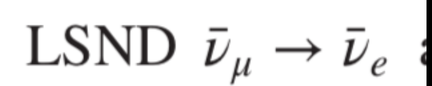


Table 2: LSND Decay at Rest Oscillation Search

Selection	Beam On	Beam Off	ν backgrounds	Excess Signal
$36 < E_e < 60, R > 30$	33	6.2 ± 0.6	3.3 ± 0.7	23.5 ± 5.8
$20 < E_e < 60, R > 30$	70	17.7 ± 1.0	12.8 ± 1.7	39.5 ± 8.8
Fitted Oscillation Probability			$0.33 \pm 0.09 \pm 0.05$	



LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance

oscillations inconsistent with 3 neutrino model

ν_{sterile} ~1 ev ??

MiniBooNE 2020

https://arxiv.org/abs/2006.16883

LSND $\bar{\nu}_\mu \to \bar{\nu}_e$

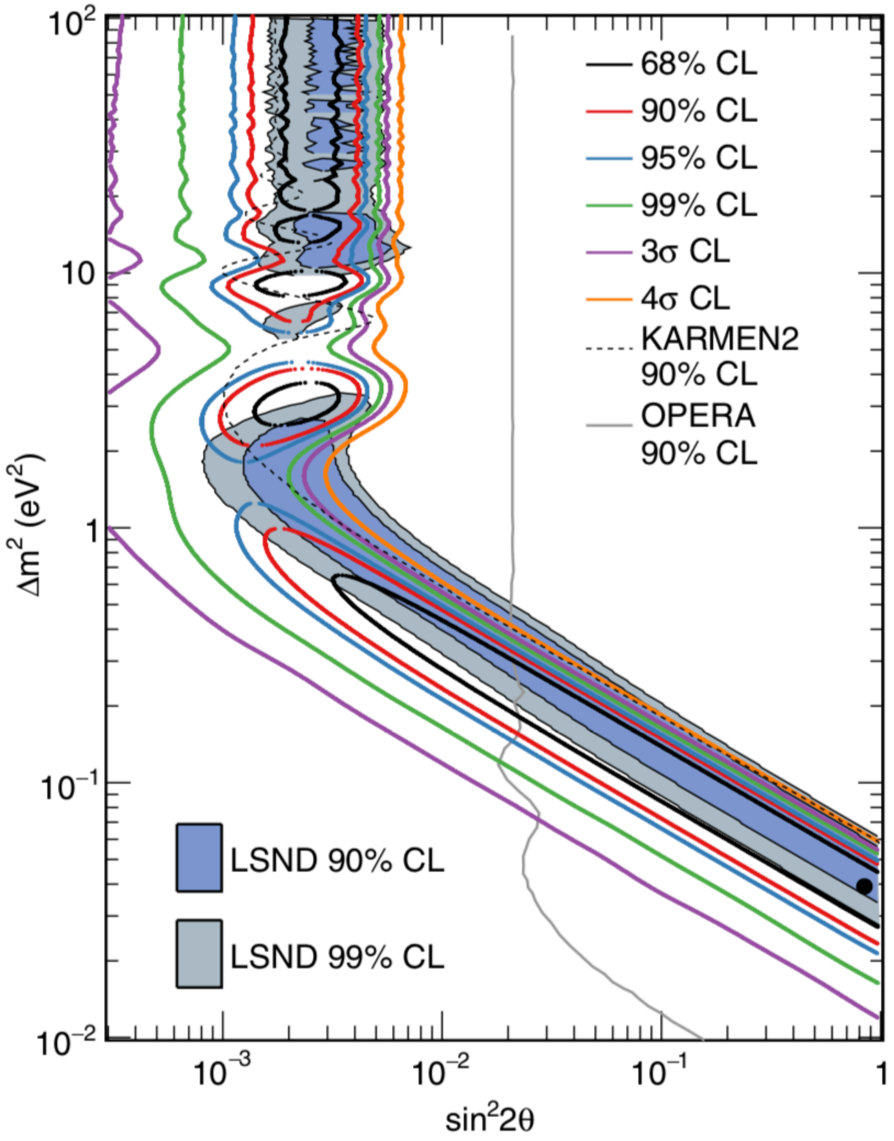


FIG. 3. MiniBooNE allowed regions in neutrino mode (12.84×10^{20} POT) for events with $200 < E_\nu^{\rm QE} < 3000$ MeV within a two-neutrino oscillation model. The shaded areas show the 90% and 99% C.L. LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ allowed regions. The black point shows the MiniBooNE best fit point. Also shown are 90% C.L. limits from the KARMEN [36] and OPERA [37] experiments.

excess

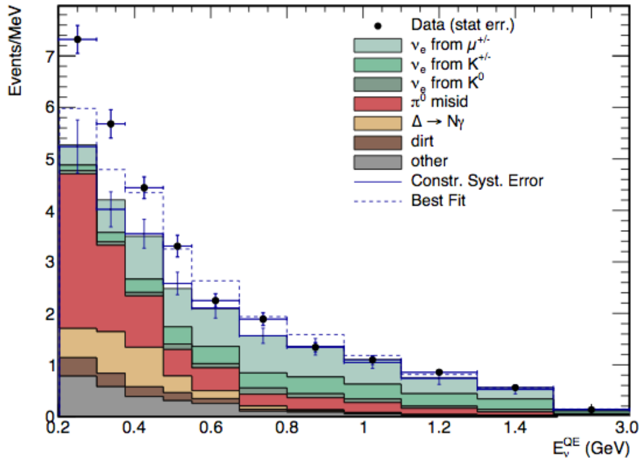


FIG. 6: The MiniBooNE neutrino mode E_ν^{QE} distributions, corresponding to the total 18.75×10^{20} POT data, for ν_e CCQE data (points with statistical errors) and predicted backgrounds (colored histograms). The constrained background is shown as additional points with systematic error bars. The dashed histogram shows the best fit to the neutrino-mode data assuming two-neutrino oscillations. The last bin is for the energy interval from 1500-3000 MeV.

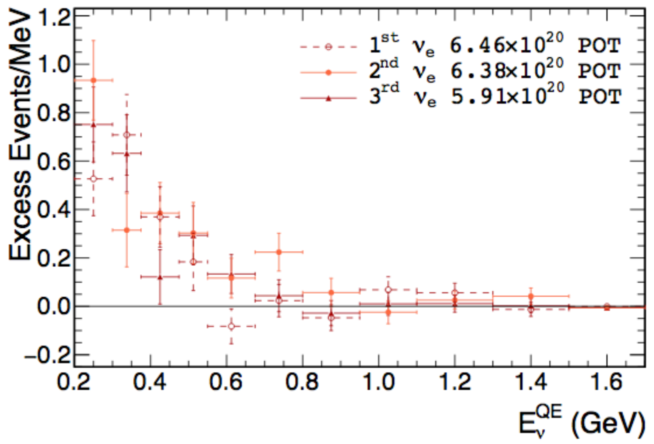
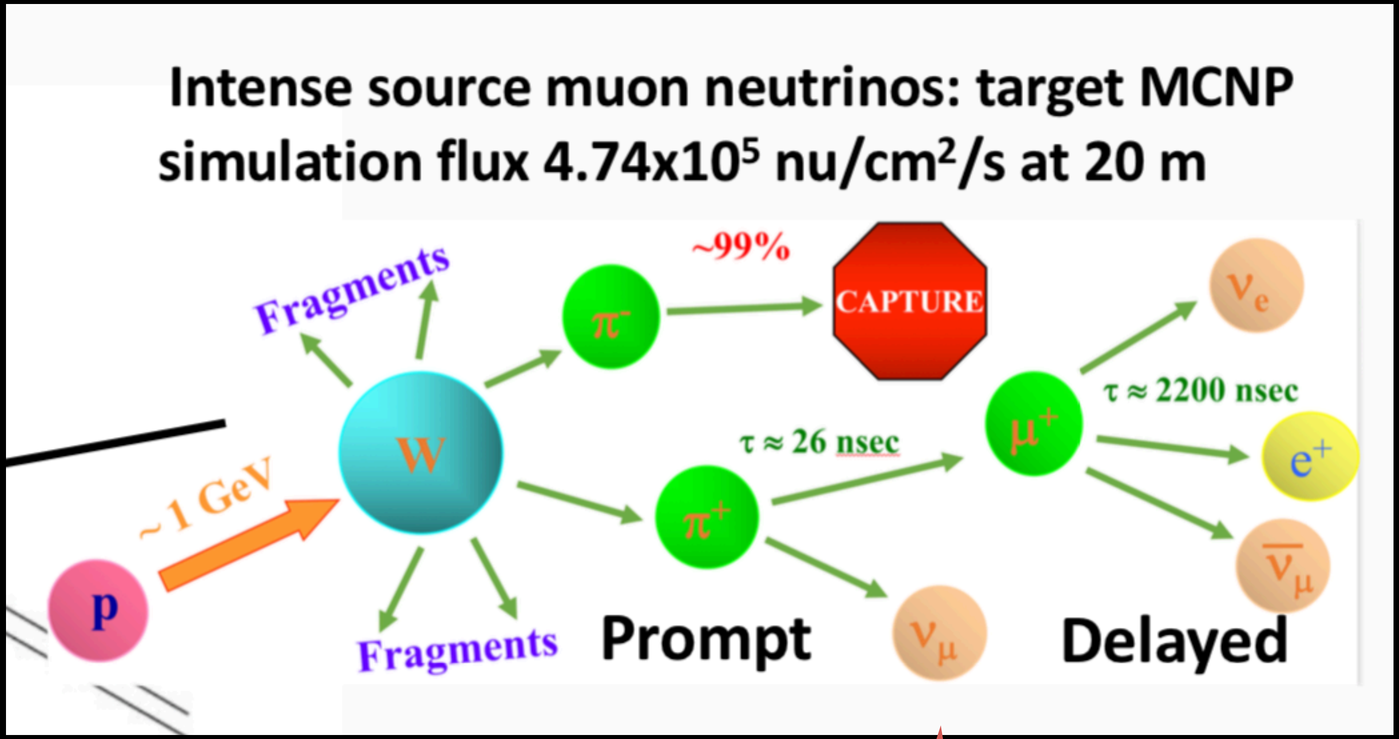


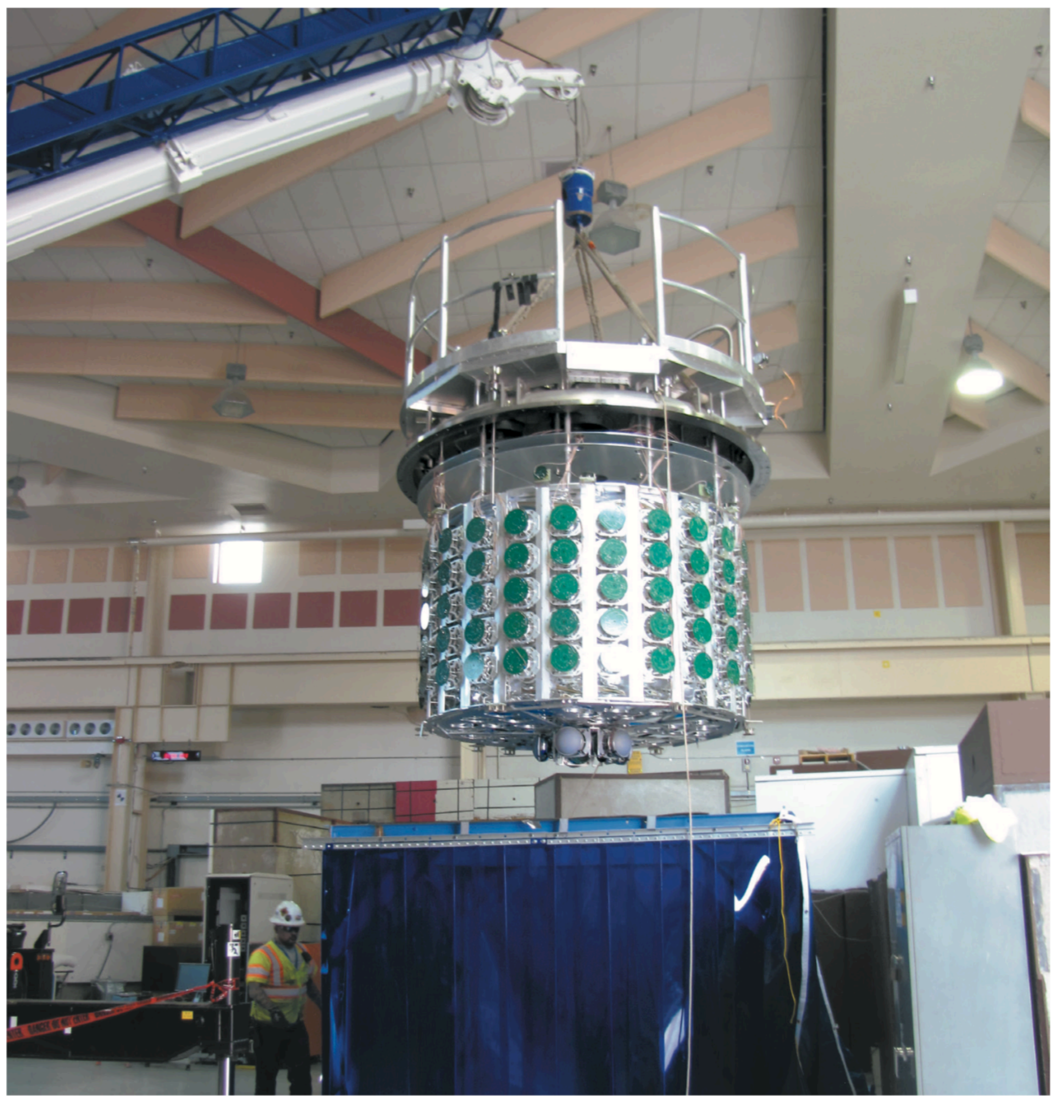
FIG. 7: The total event excesses in neutrino mode for the first, second, and third running periods. Error bars include only statistical uncertainties.

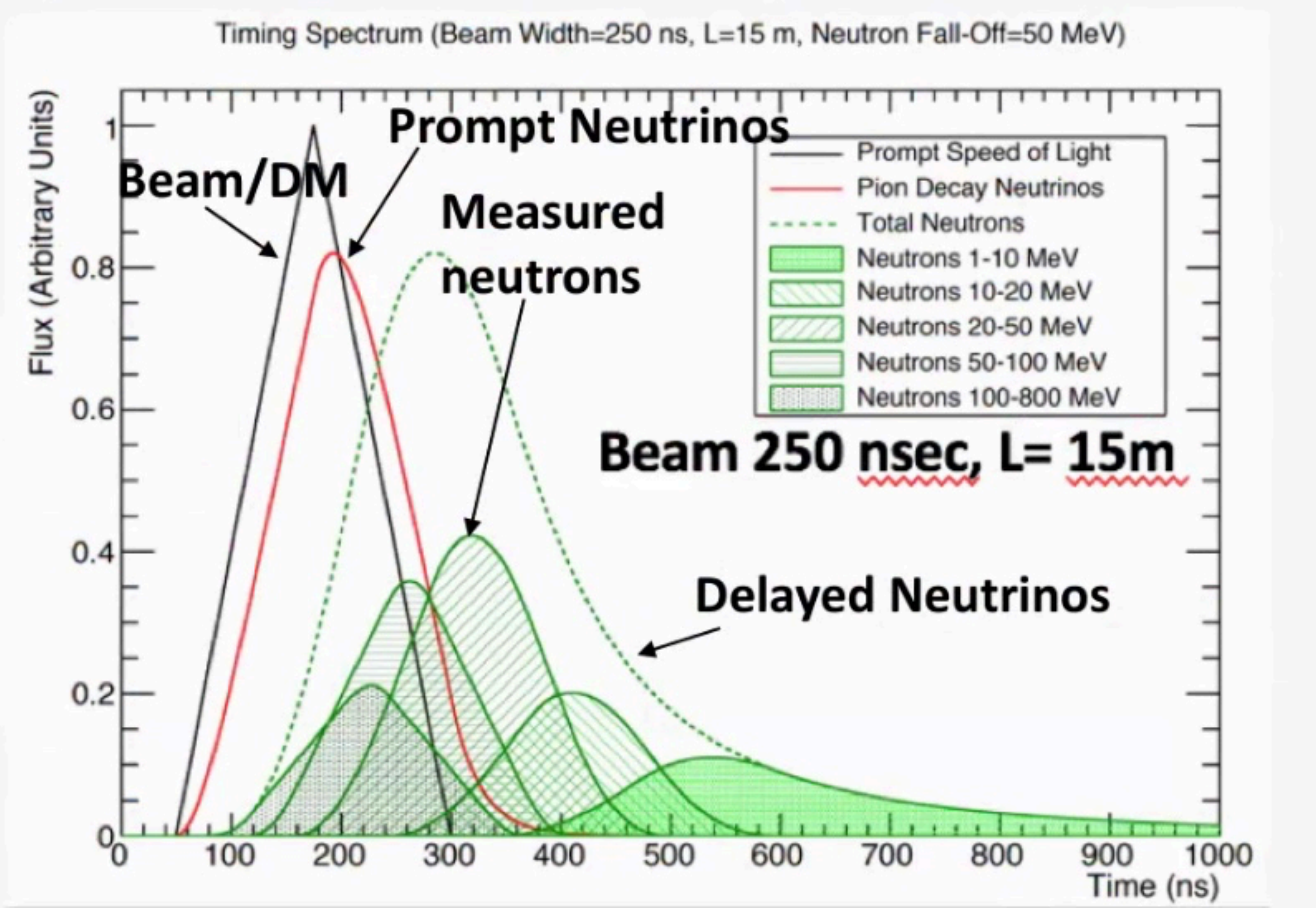
LANSCE-Lujan Facility
stopped pion source

CCM 10 m away



Intense source muon neutrinos: target MCNP simulation flux 4.74×10^5 nu/cm^2/s at 20 m





Xe doping?

Neutron background -pulse shape discrimination ?

“If it were easy,
it would have been done.”
- G. Goldhaber

so, enjoy what you do.