The NuDot Detector at UD:
An R&D testbed for liquid scintillator technologies

Workshop on Cherenkov/Scintillator technologies
David Rittenhouse Laboratories, Room A4
University of Pennsylvania, Philadelphia
June 5th, 9:30am, 2025

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Big thanks to:
Prof. Lindley Winslow, Prof. J. Gruszko,
Masooma Sarfraz, Pierre-Simon Mangeard, Miles Garcia

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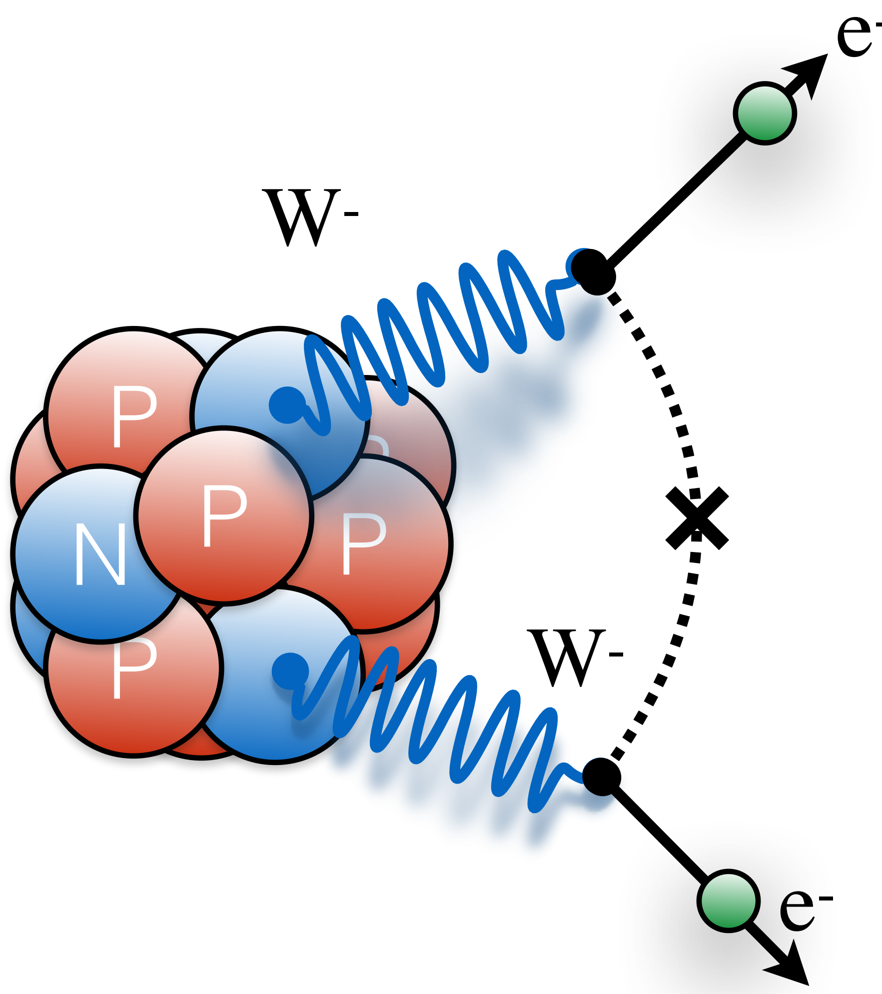
What is neutrinoless double beta decay (0vββ)?

Beta Decay
(Discovered 1899)

Double Beta Decay (2vββ)
(Discovered 1987)

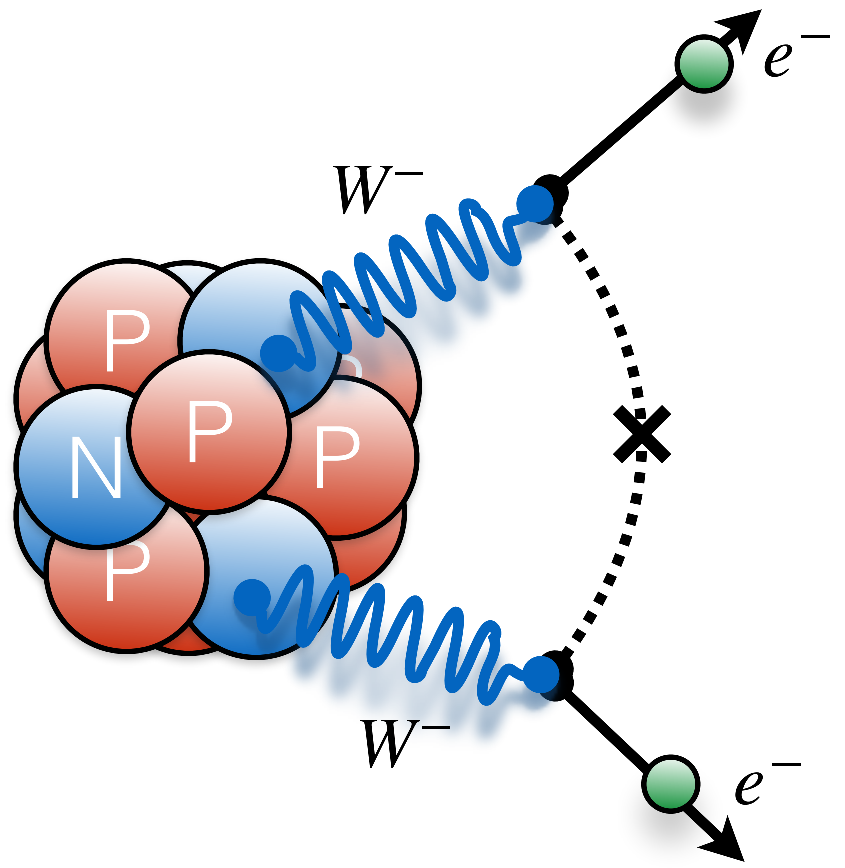
Half life ~ 10^{14-24} years



Neutrinoless Double Beta Decay (0vββ)
(Hypothetical)

Half life > 10^{26} years

$(Z, A) \rightarrow (Z+2, A) + 2e^-$



The search for **0νββ** is a well-motivated search for physics beyond the Standard Model.

If observed:

The neutrino is a Majorana particle. $\nu = \bar{\nu}$

Lepton number is violated. $\Delta L \neq 0$

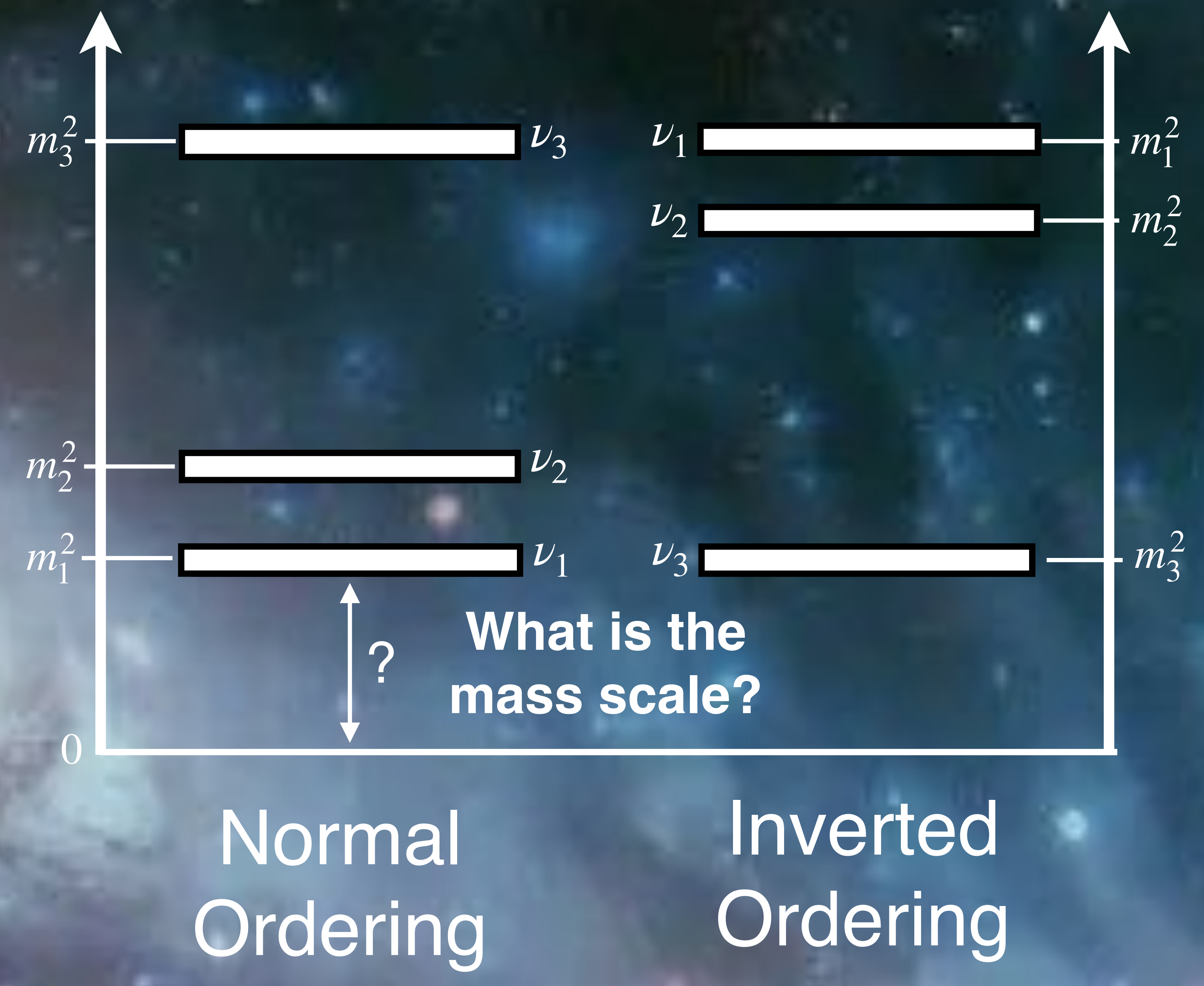
Neutrinos acquire mass through a new mechanism.

Other possible implications of 0νββ

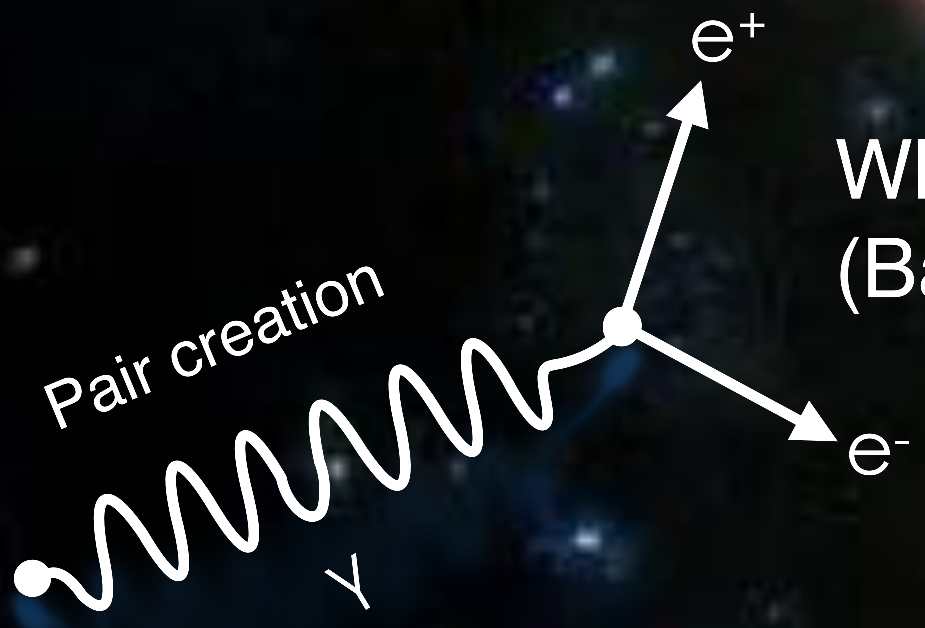
$$\nu = \bar{\nu}$$

Are there other processes that drive 0νββ? More Beyond the Standard Model physics?

What is the neutrino mass ordering?



May provide an explanation for why the neutrino mass is so small. (The Seesaw Mechanism)

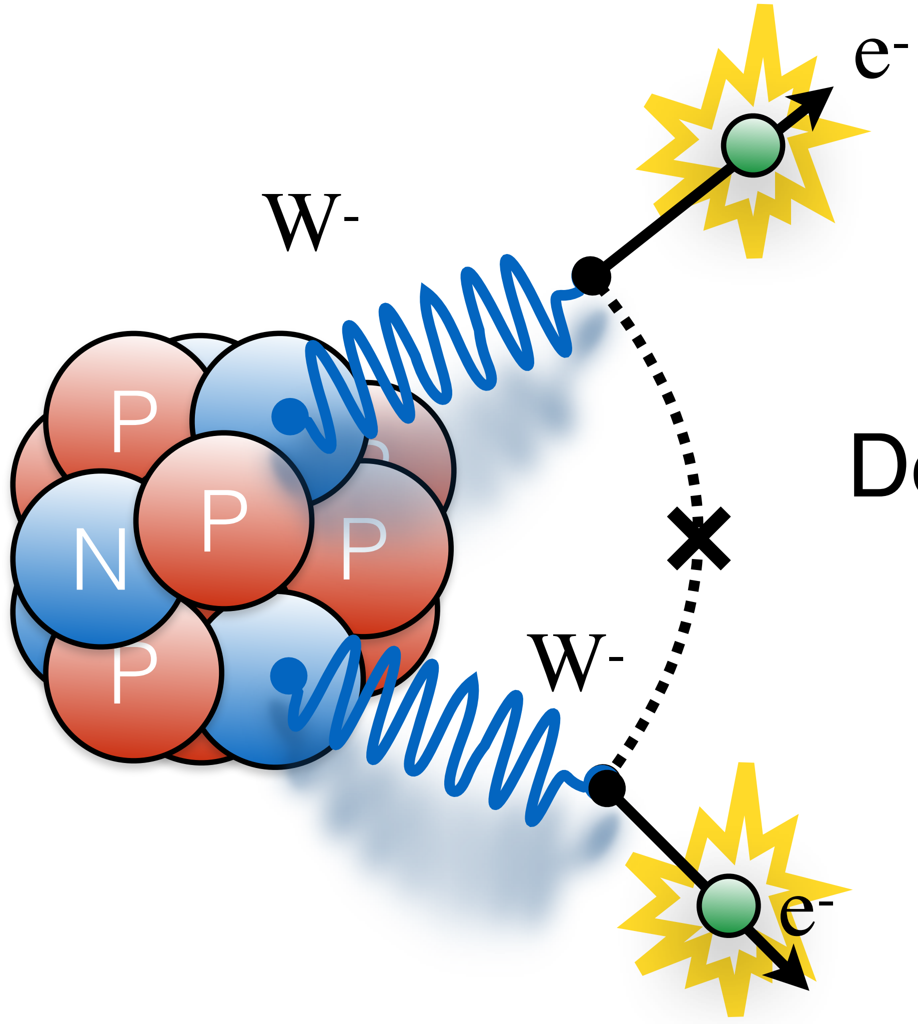


Why is the Universe dominated by matter? (Baryogenesis through Leptogenesis)

Significant implications in grand unified theories (GUTs), left-right symmetric models, and supersymmetry.

Observable signature of $0\nu\beta\beta$

Signal exception: mono-energetic energy deposition at the $Q_{\beta\beta}$ from back-to-back electrons.

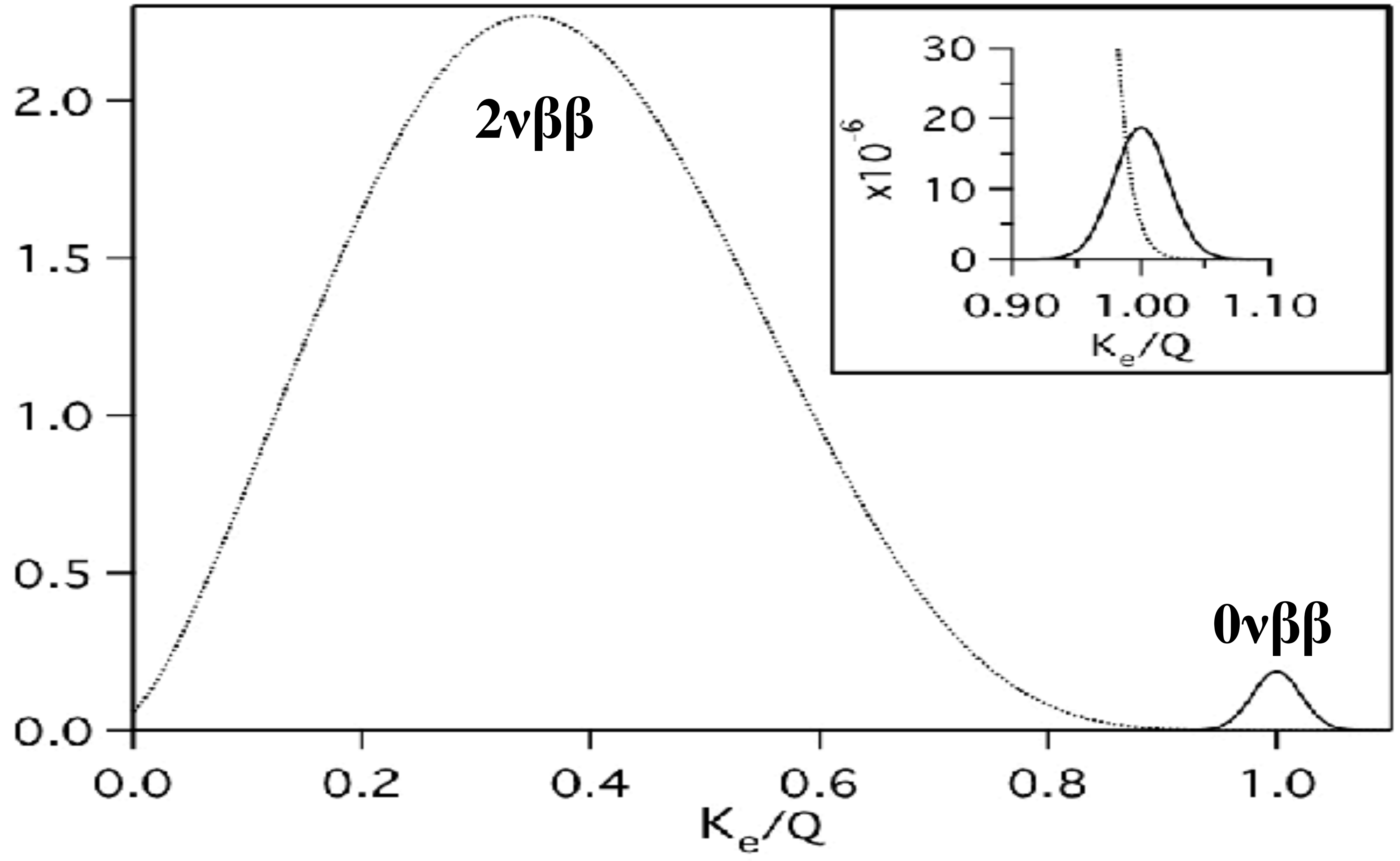


Decay energy ($Q_{\beta\beta}$) is shared by electrons.

Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$

Energy distribution of outgoing electrons



Isotope	Abundance [%]	Q-Value
^{136}Xe	8.86%	2.458MeV

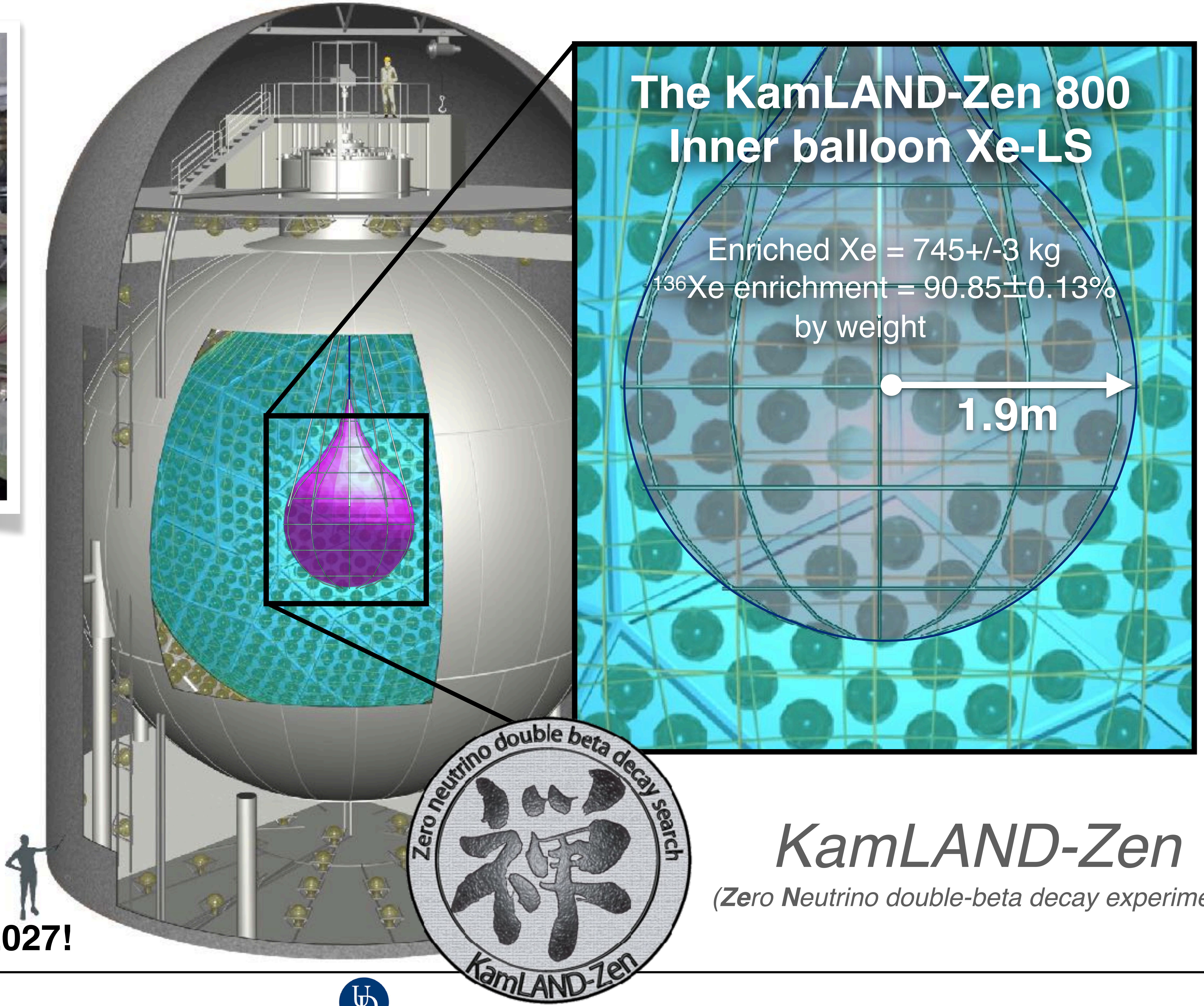
The observable is the **$0\nu\beta\beta$ event rate** (equivalently, a half-life $T_{1/2}$).

The KamLAND-Zen Detector

<u>KamLAND-Zen 400:</u>
Oct. 12 2011 - Oct.27 2015
Phase I: PRL 110,(2013) 062502
Phase II: PRL 117.8 (2016): 082503
Excited states: Nuc. Phys. A 946 (2016): 171-181

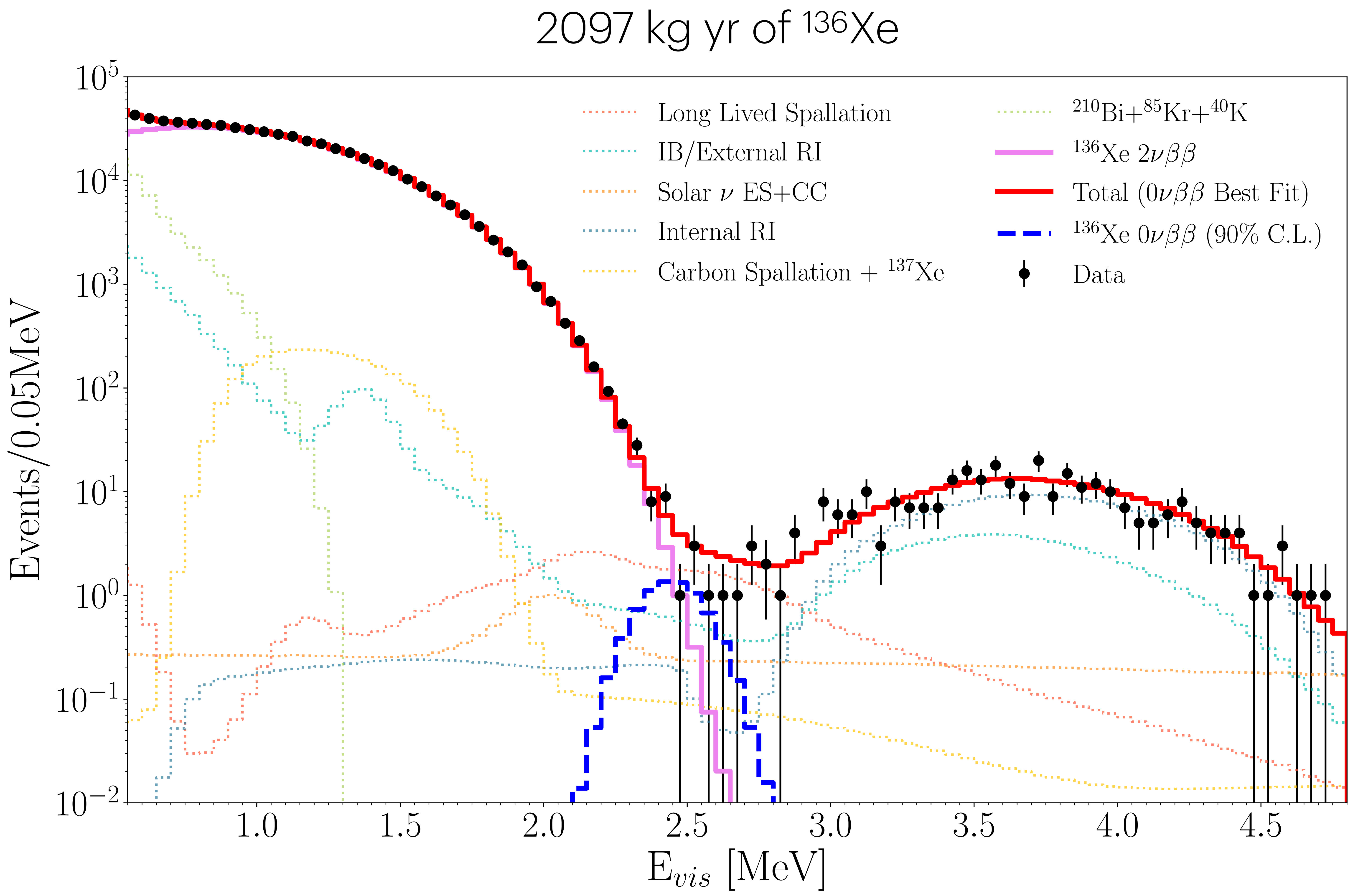
<u>KamLAND-Zen 800</u>
February 5, 2019 to August 27, 2024
Physical Review Letters 130.5 (2023): 051801
arXiv:2406.11438 (2025)

KamLAND2-Zen commissioning in 2027!

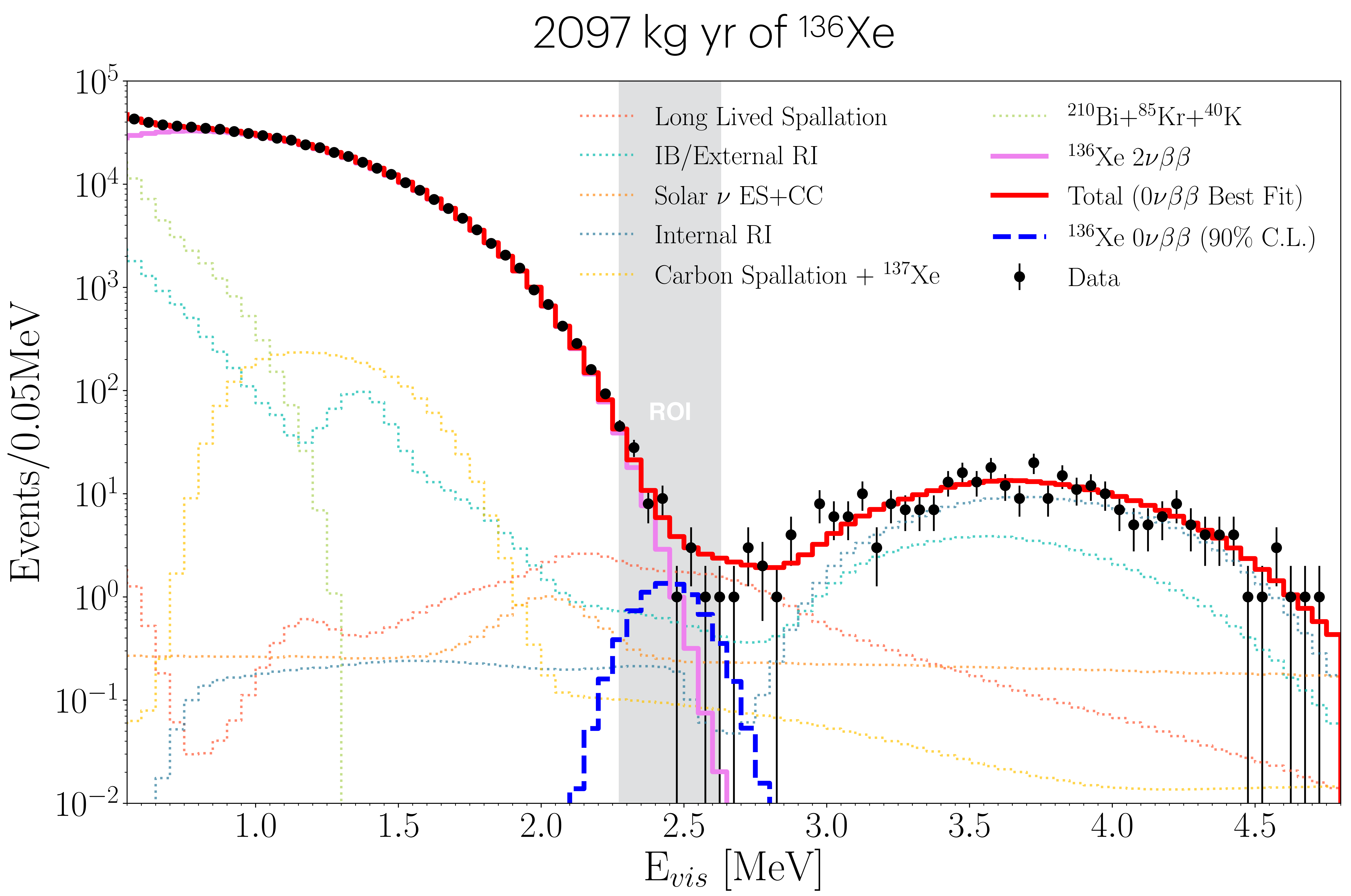


KamLAND-Zen
*(**Zero** **Neutrino** double-beta decay experiment)*

KamLAND-Zen 800 Complete Dataset

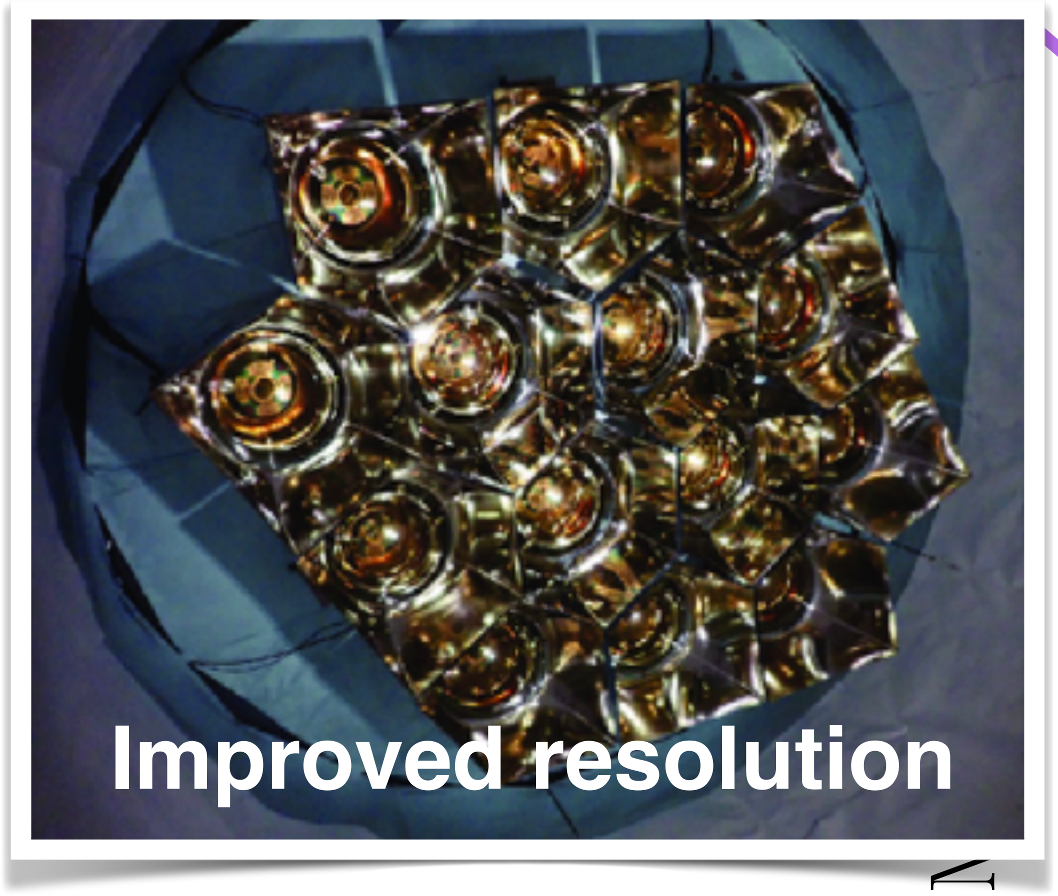


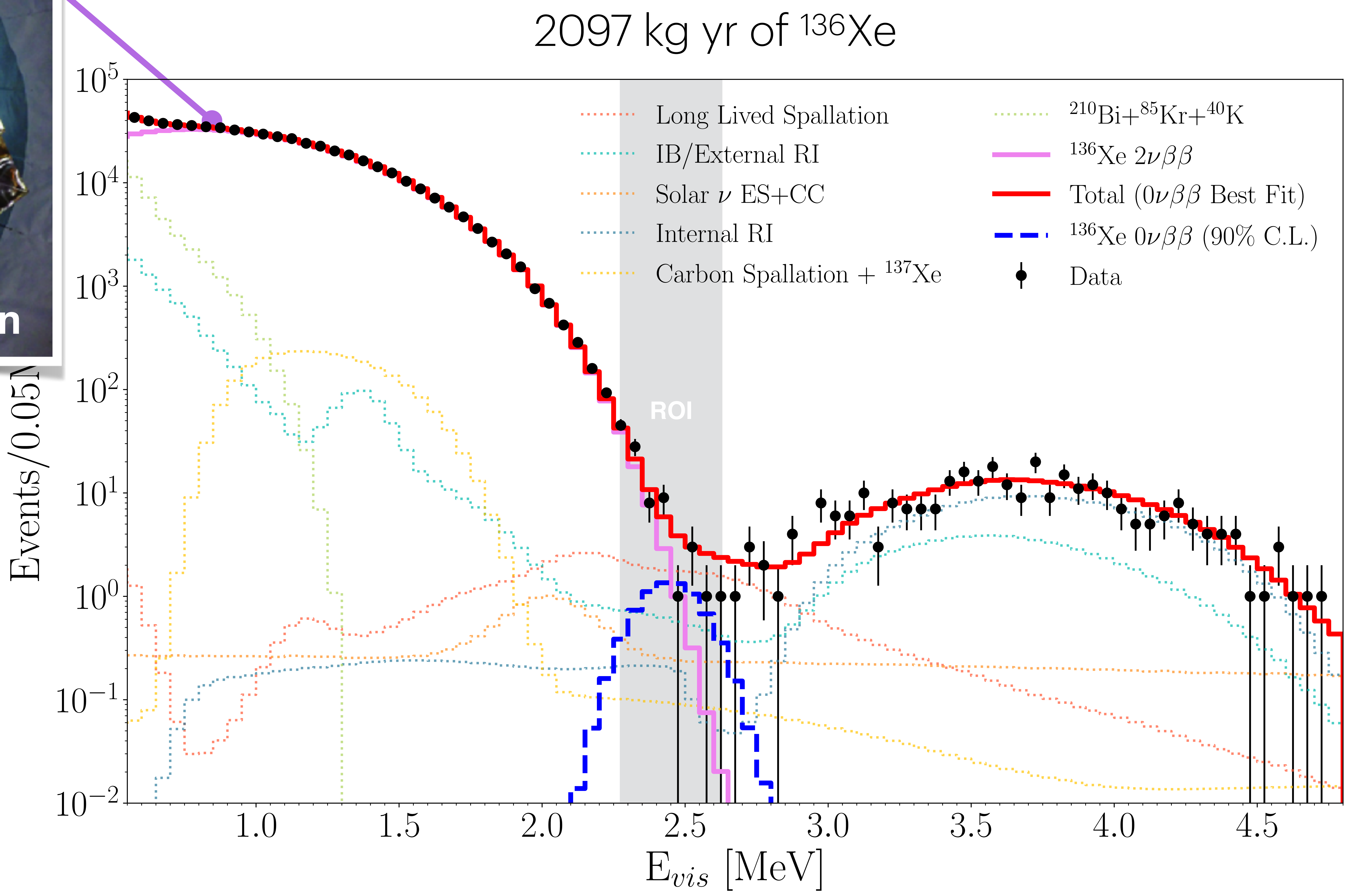
KamLAND-Zen 800 Complete Dataset



$$T_{1/2}^{0\nu\beta\beta} > 4.3 \times 10^{26} \text{yr } (90\,\%\,\text{CL})$$

Where do we go from here?





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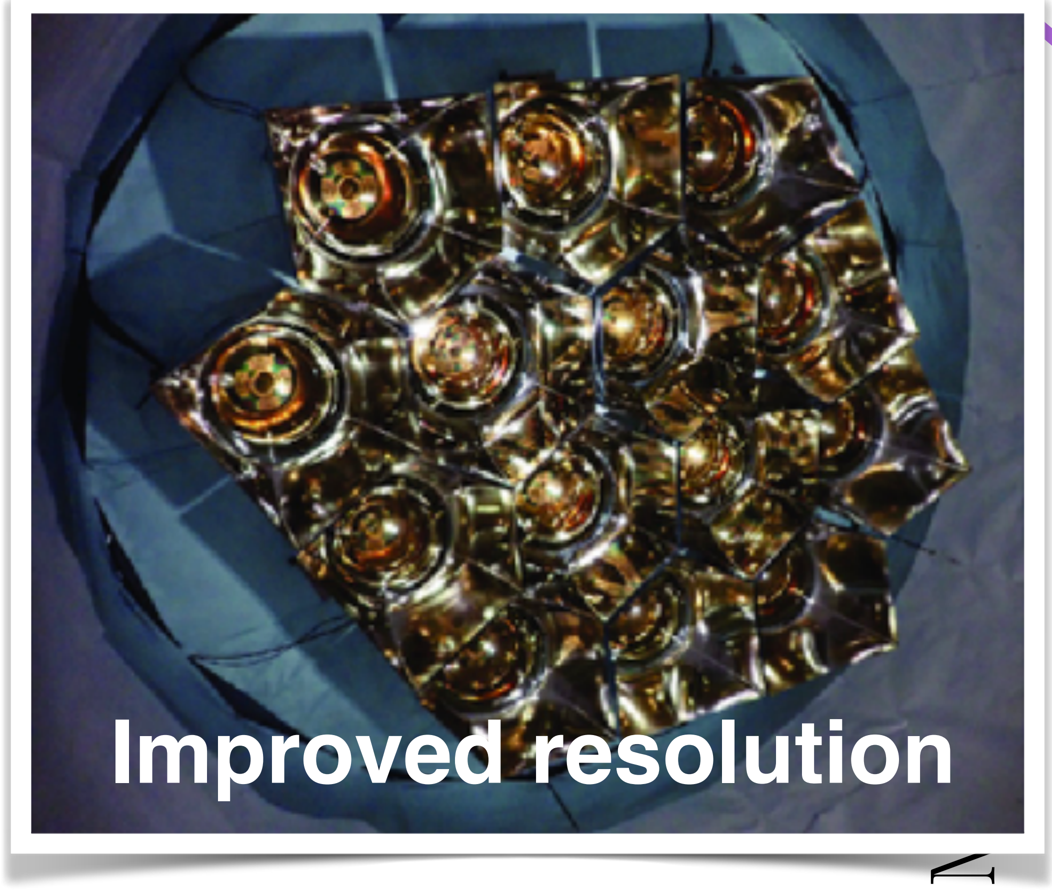

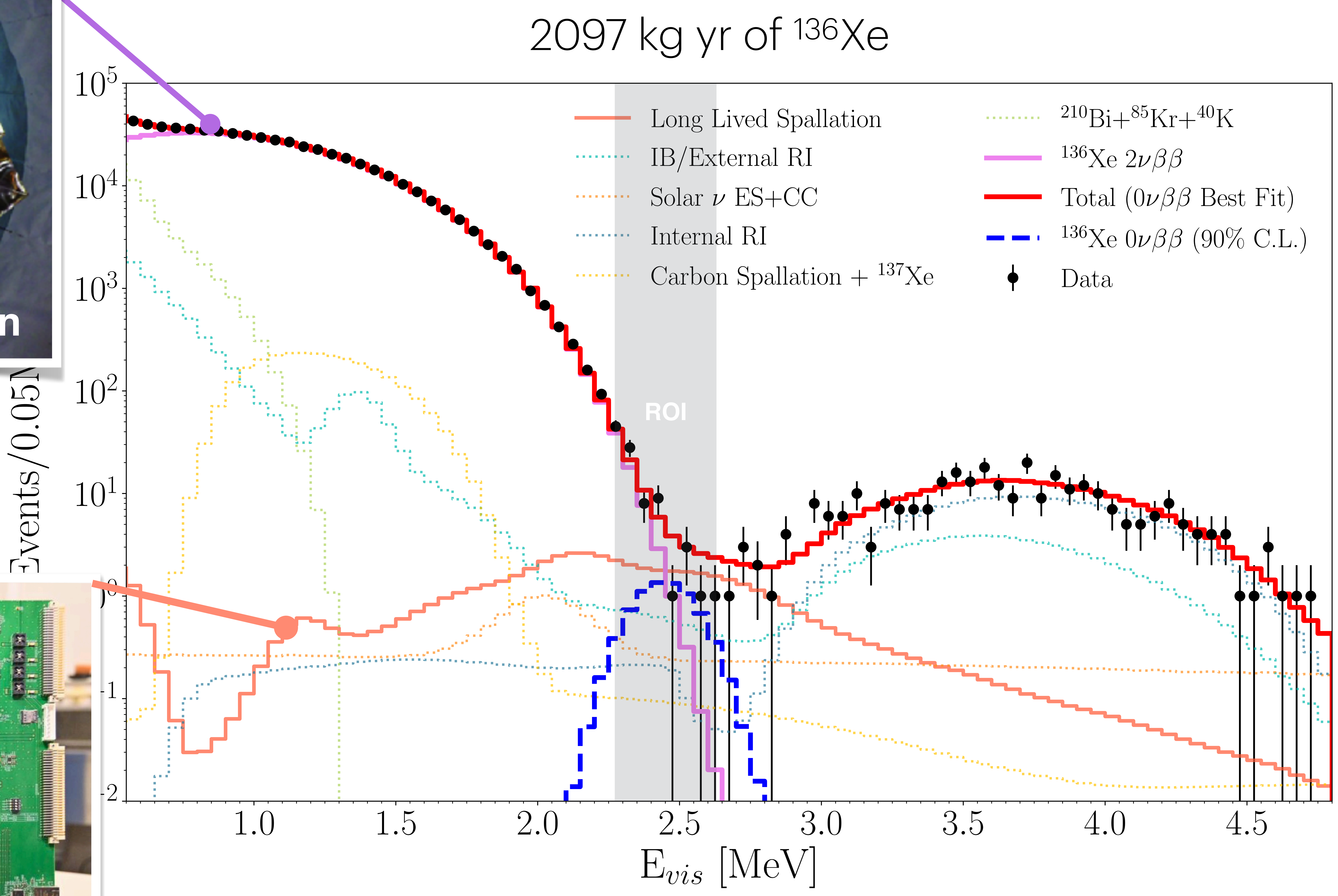

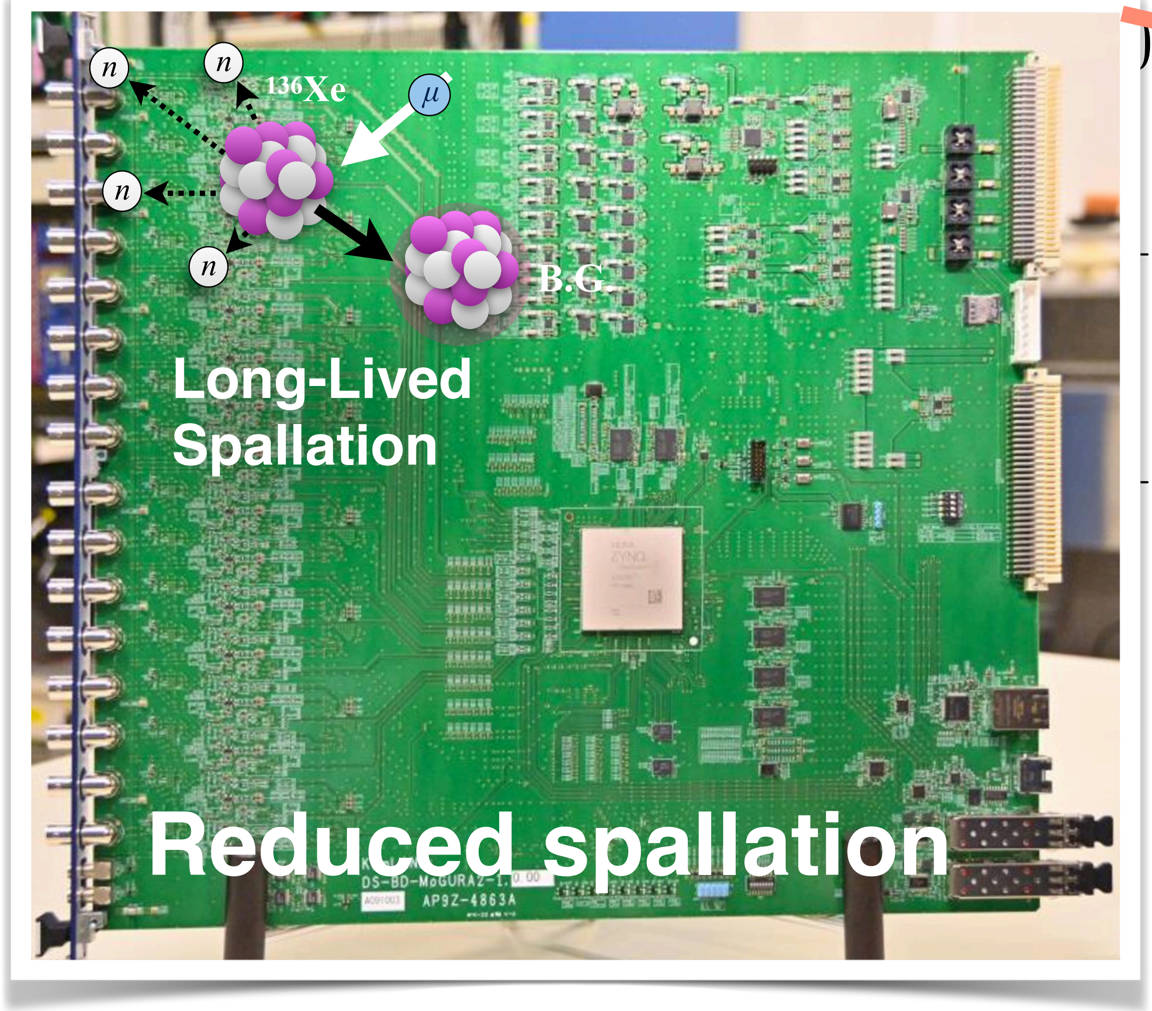

$$T^{0\nu\beta\beta}_{1/2} > 4.3 \times 10^{26}\text{yr (90 \% CL)}$$

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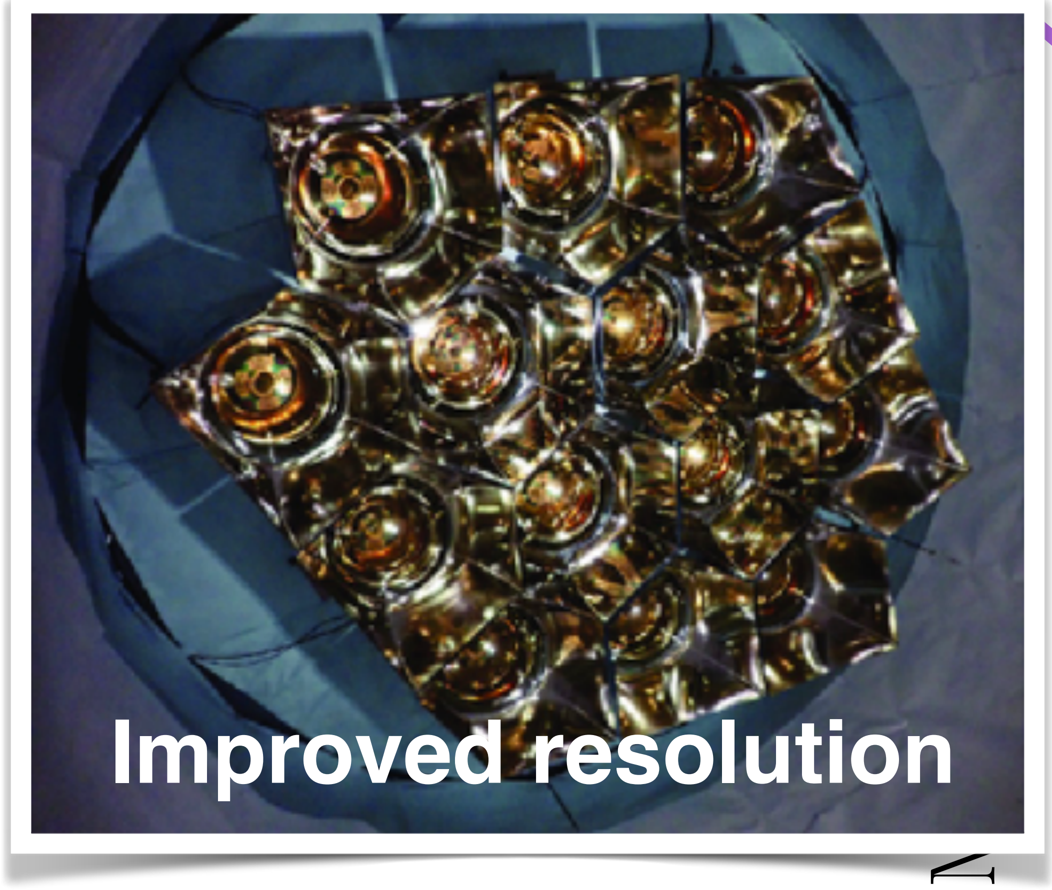

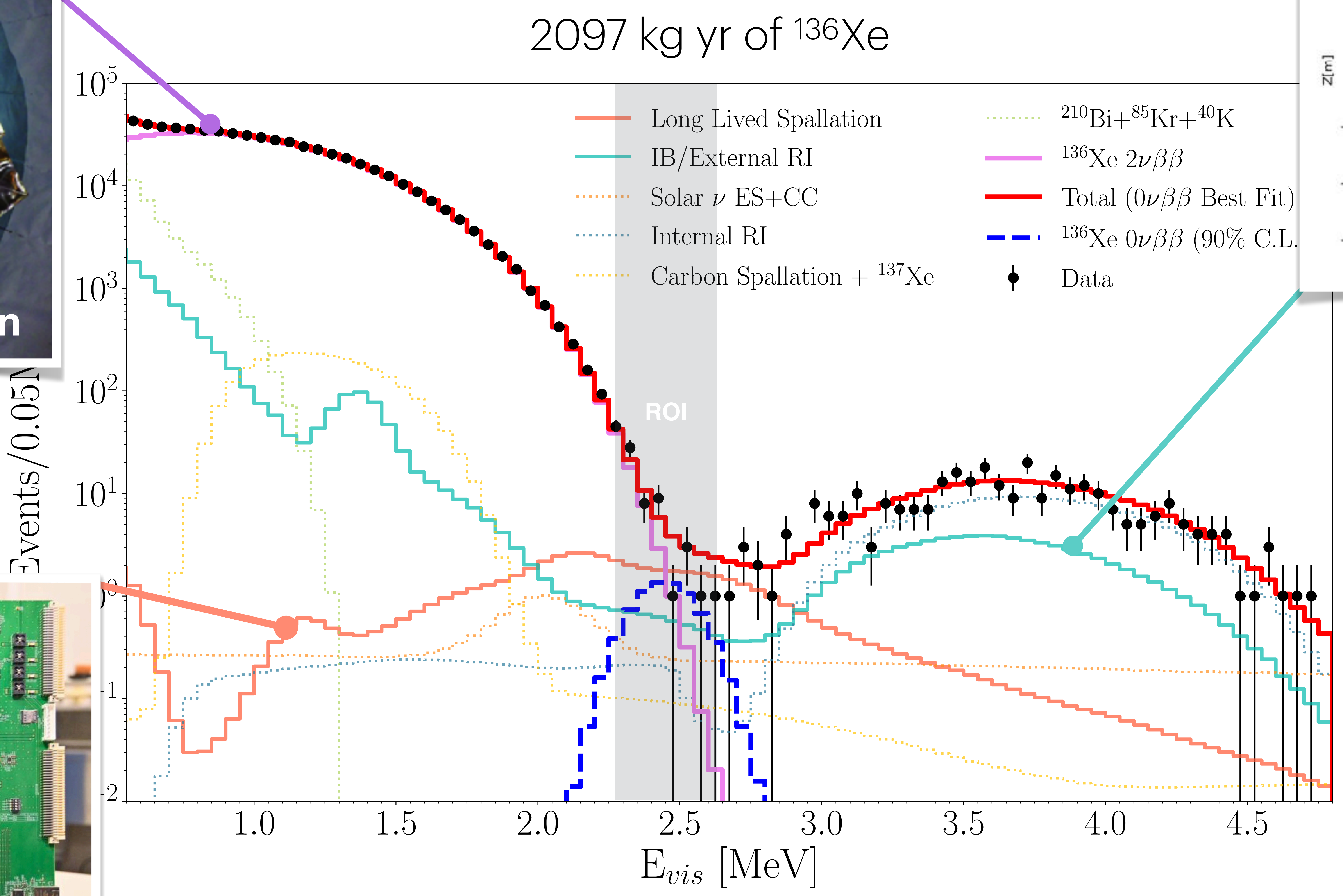

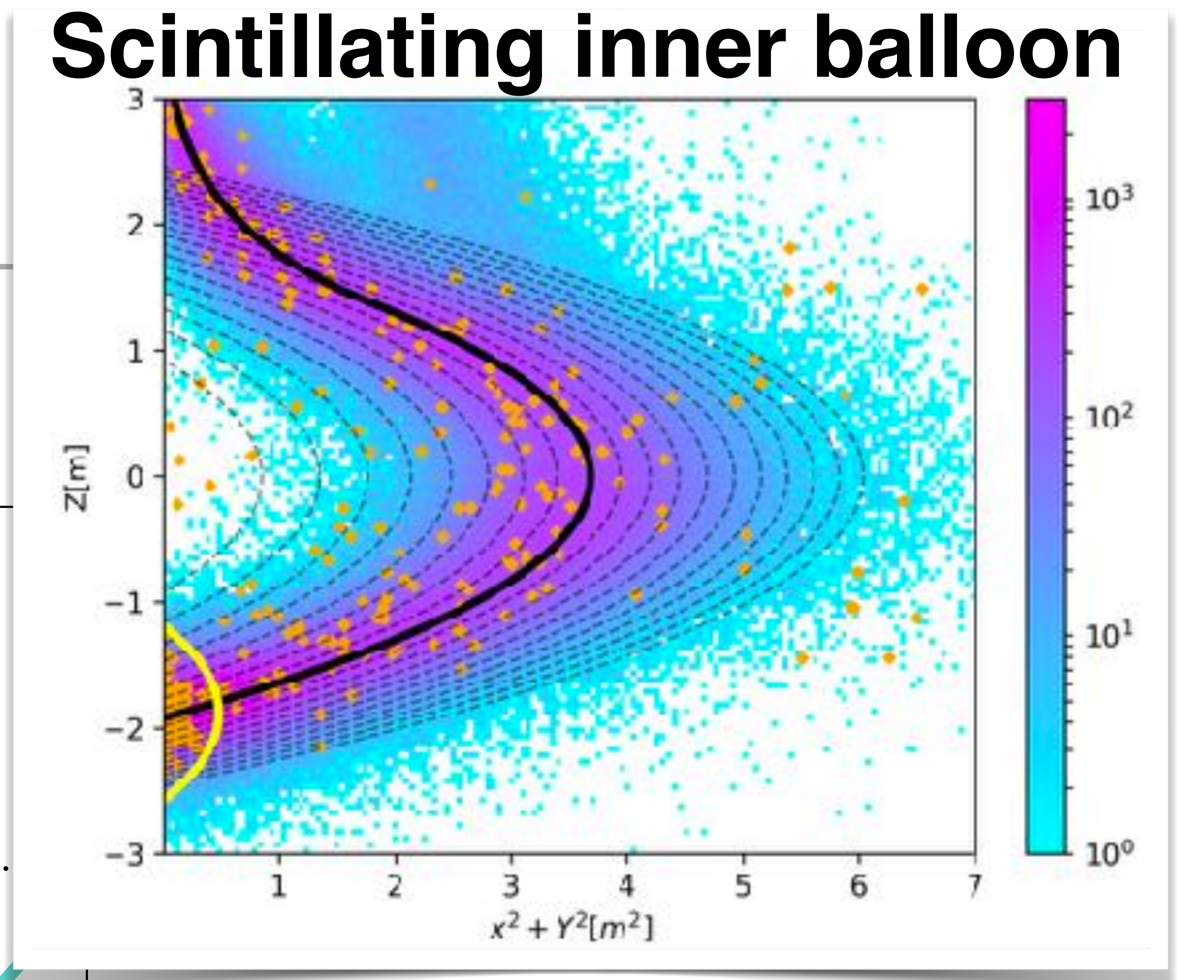

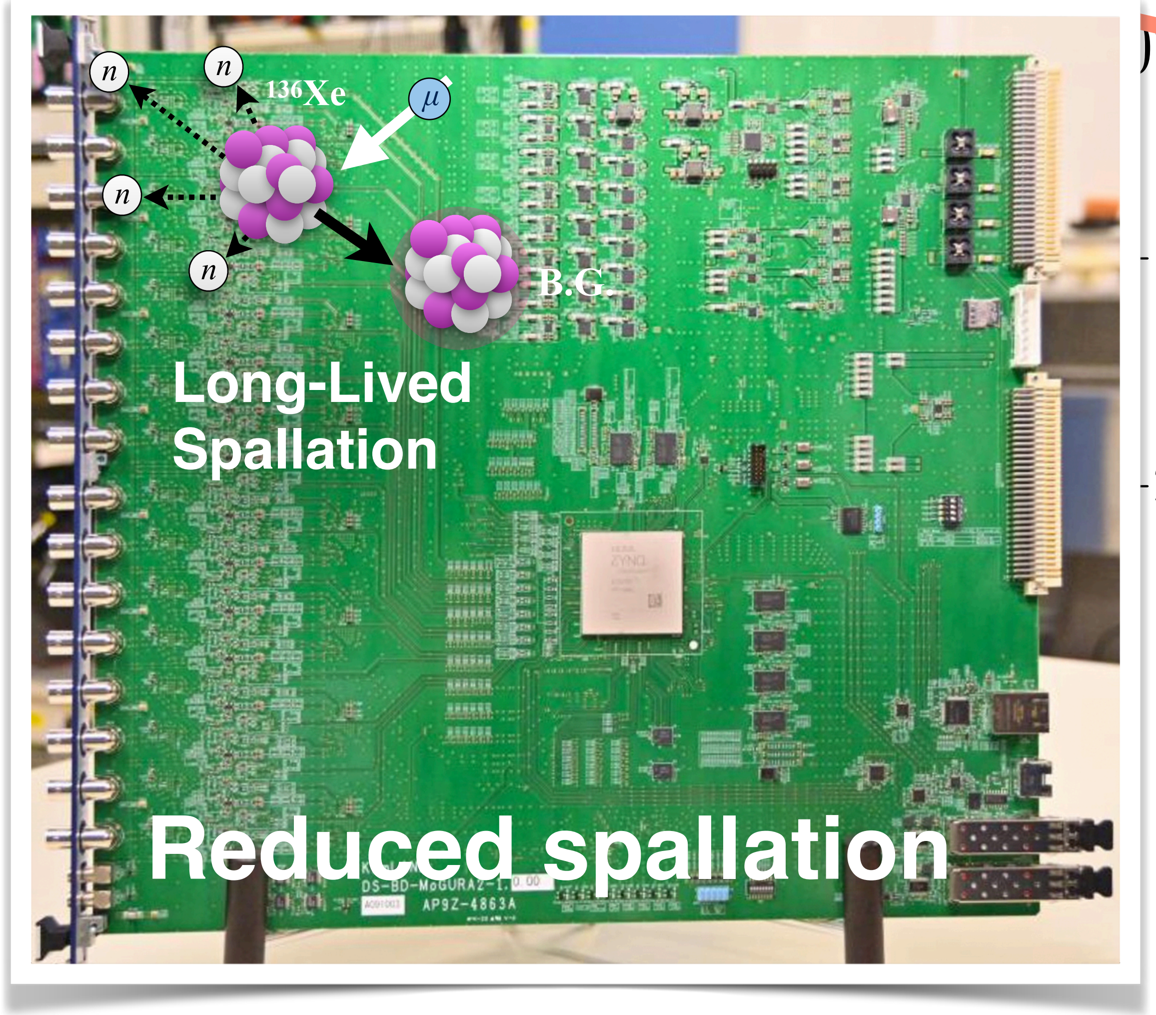

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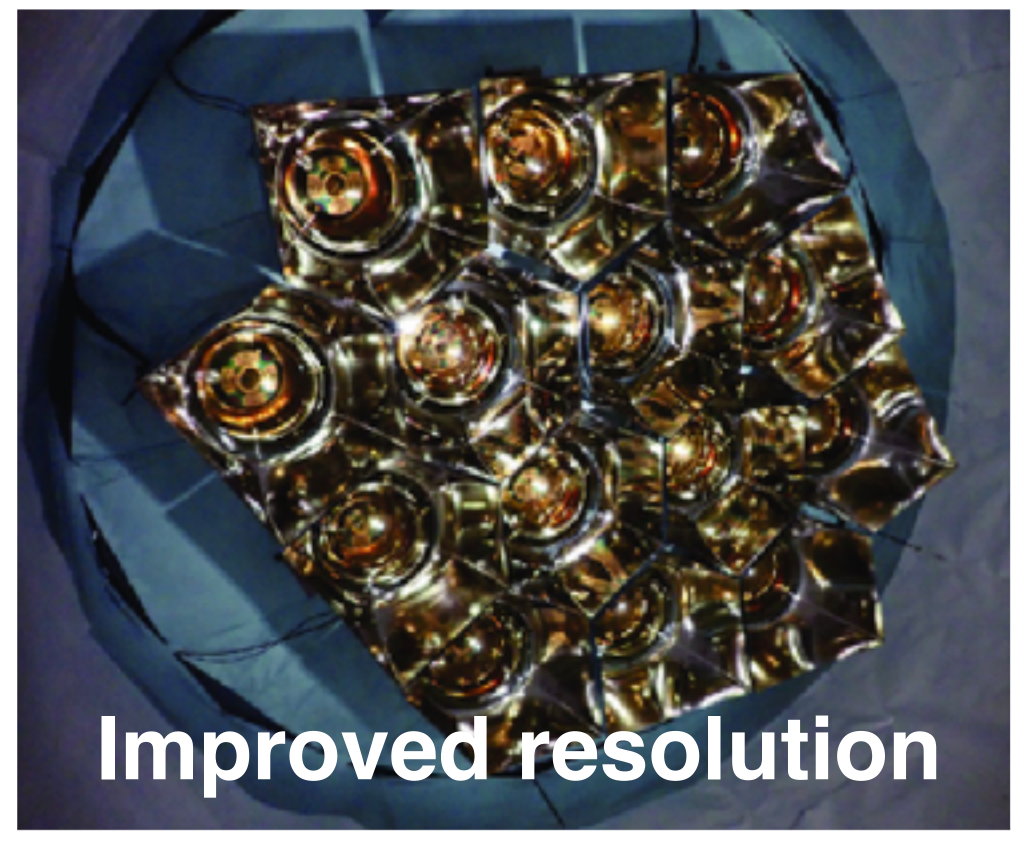
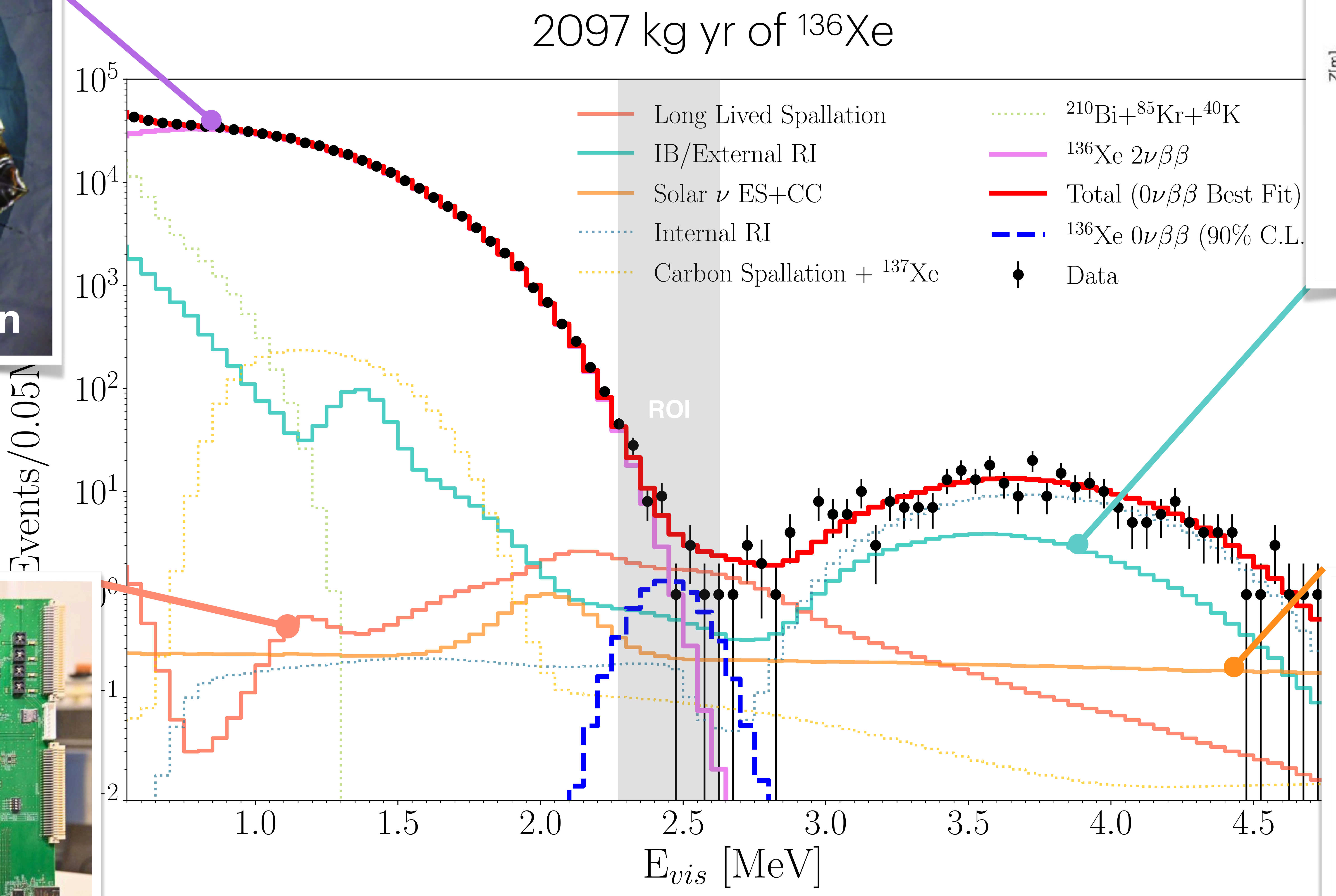
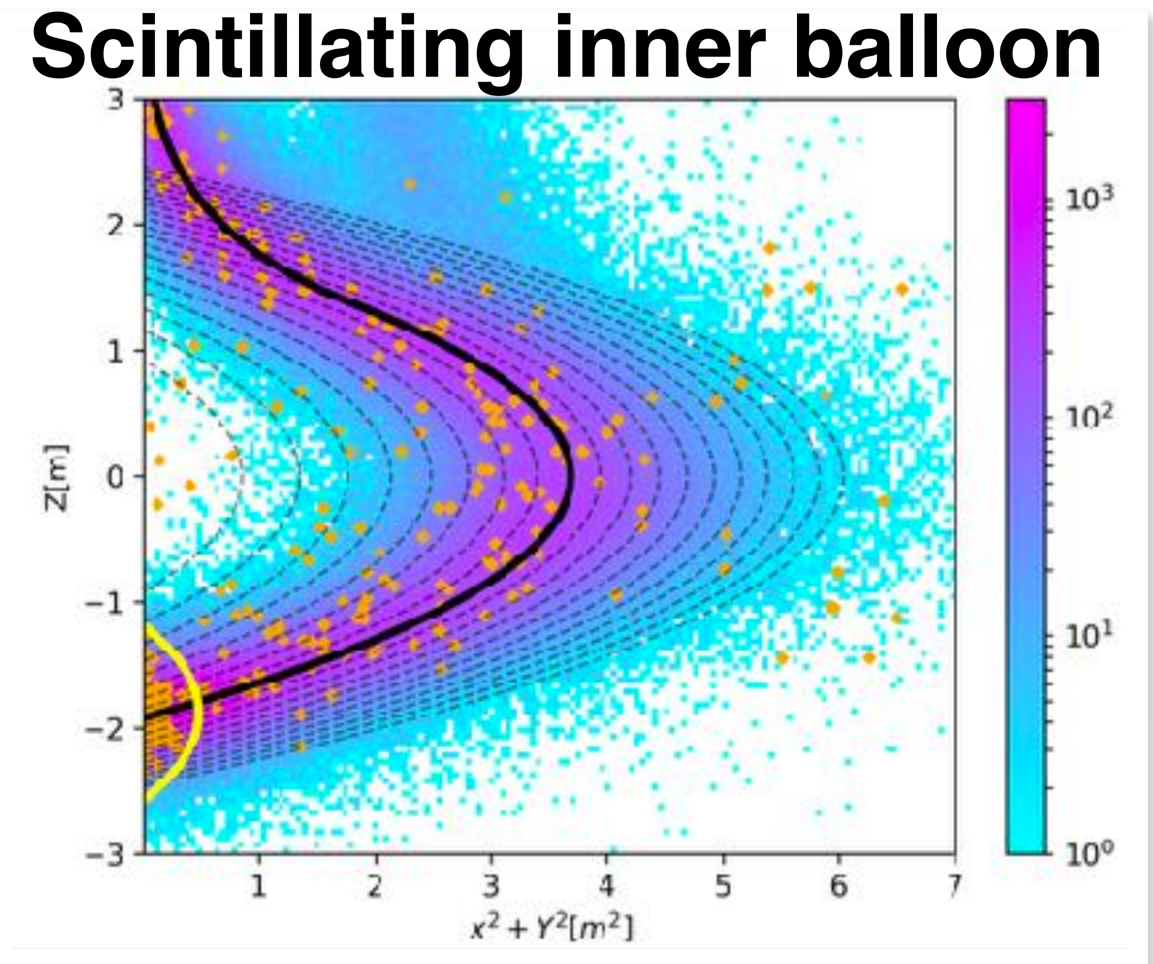
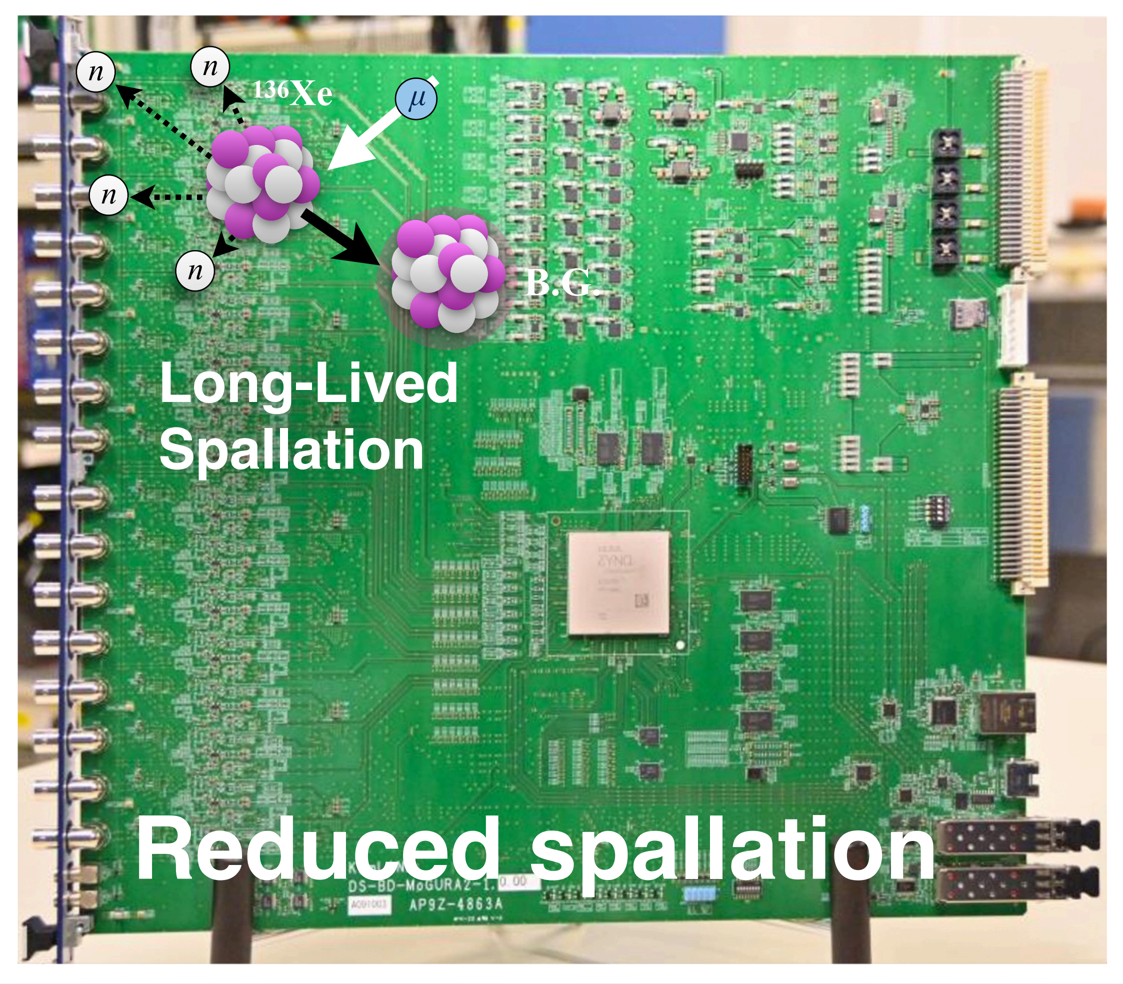
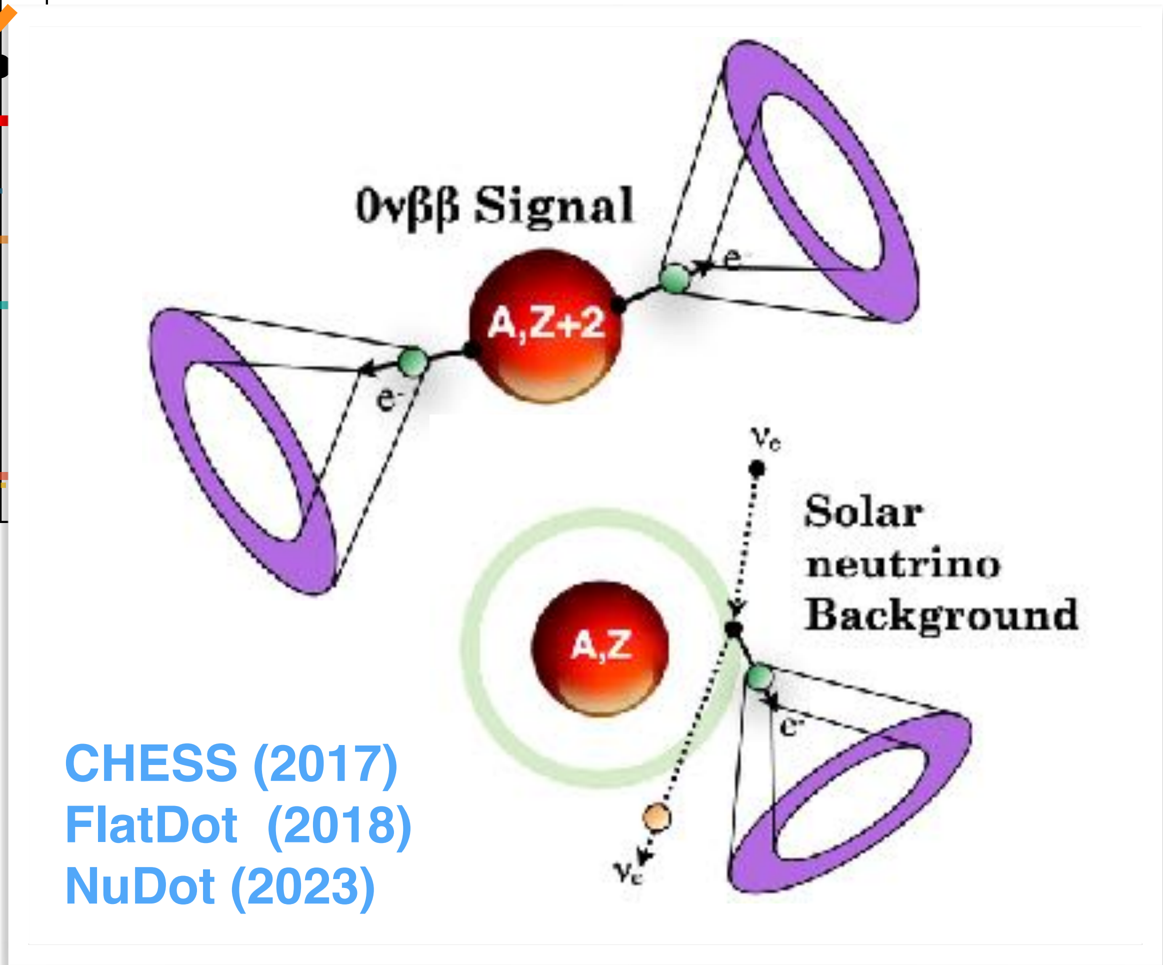






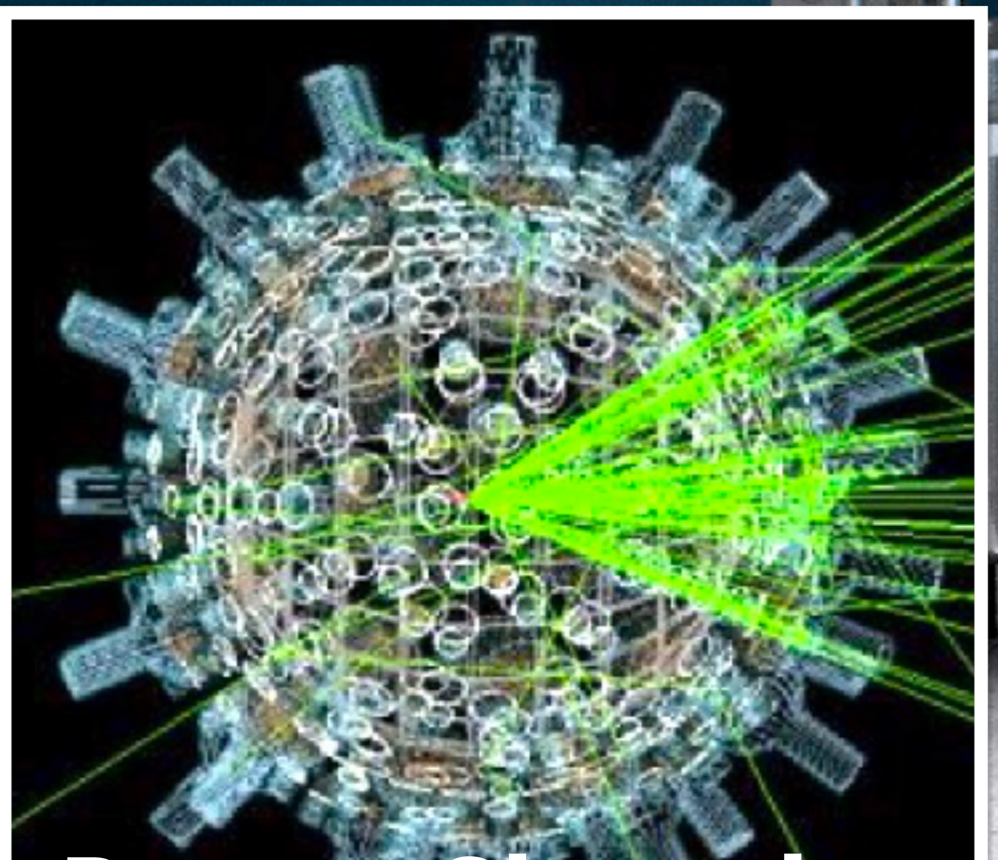




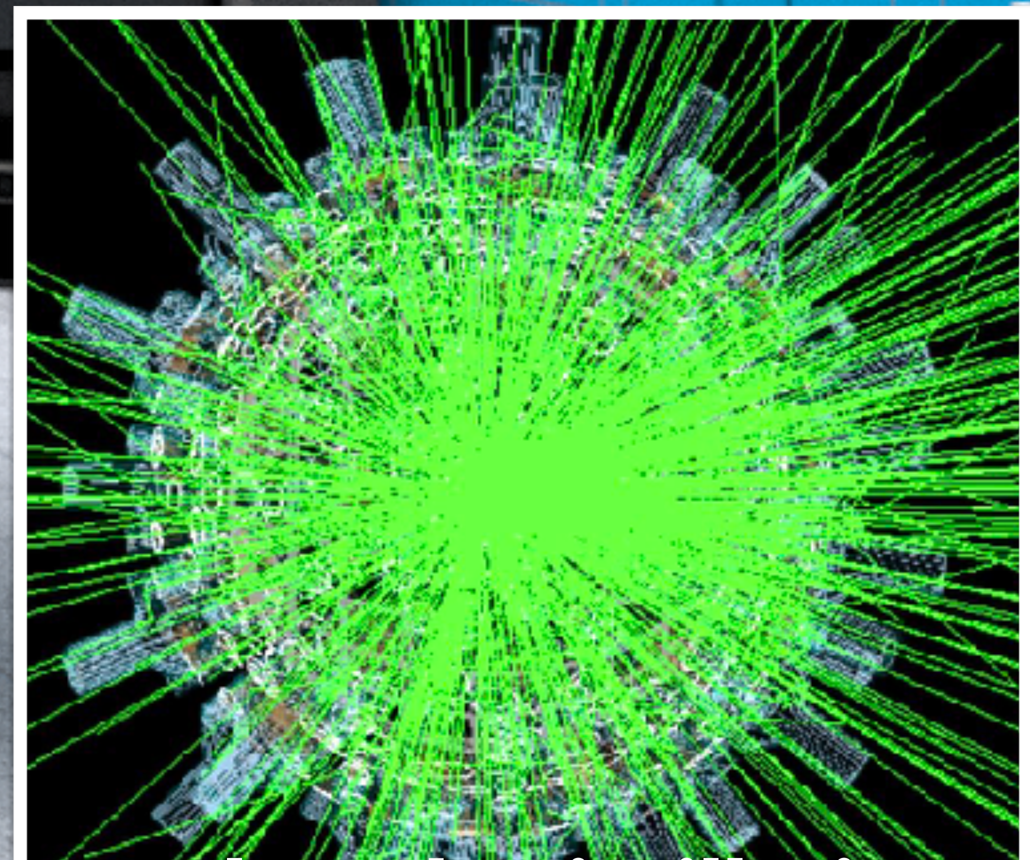
$$T_{1/2}^{0\nu\beta\beta} > 4.3 \times 10^{26}\text{yr } (90\,\%\text{ CL})$$

NuDot

First goal: demonstrate Cherenkov/scintillation separation at the ton-scale, through **directionality** and precision **timing**.



Prompt Cherenkov

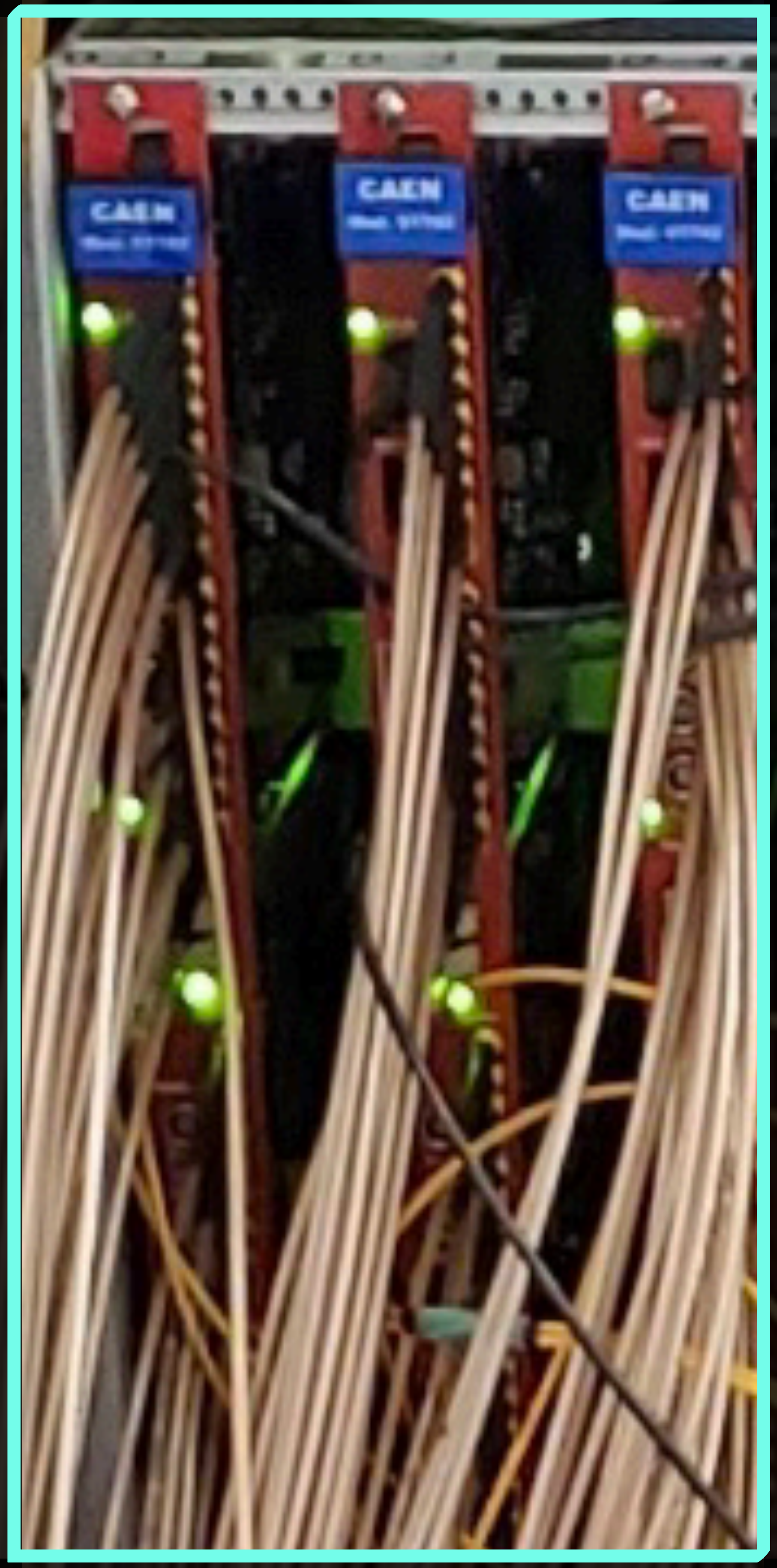


Delayed Scintillation


0.9m diameter Acrylic Sphere
800L of Linear Alkyl Benzene (LAB) + PPO
6-inch diameter neck for calibration to insert calibration devices
Suspended in 7500L of mineral oil
8” PMTs
x59 PMTs, assorted
34% photocathode coverage
Large light collect area
2” Hamamatsu R13089
x151 of them
6% photocathode coverage
TTS = 200ps (precision timing)
Winston cones
Mu-metal sheilding

PyNuDAQ: Python-based custom DAQ using CAEN C++ API

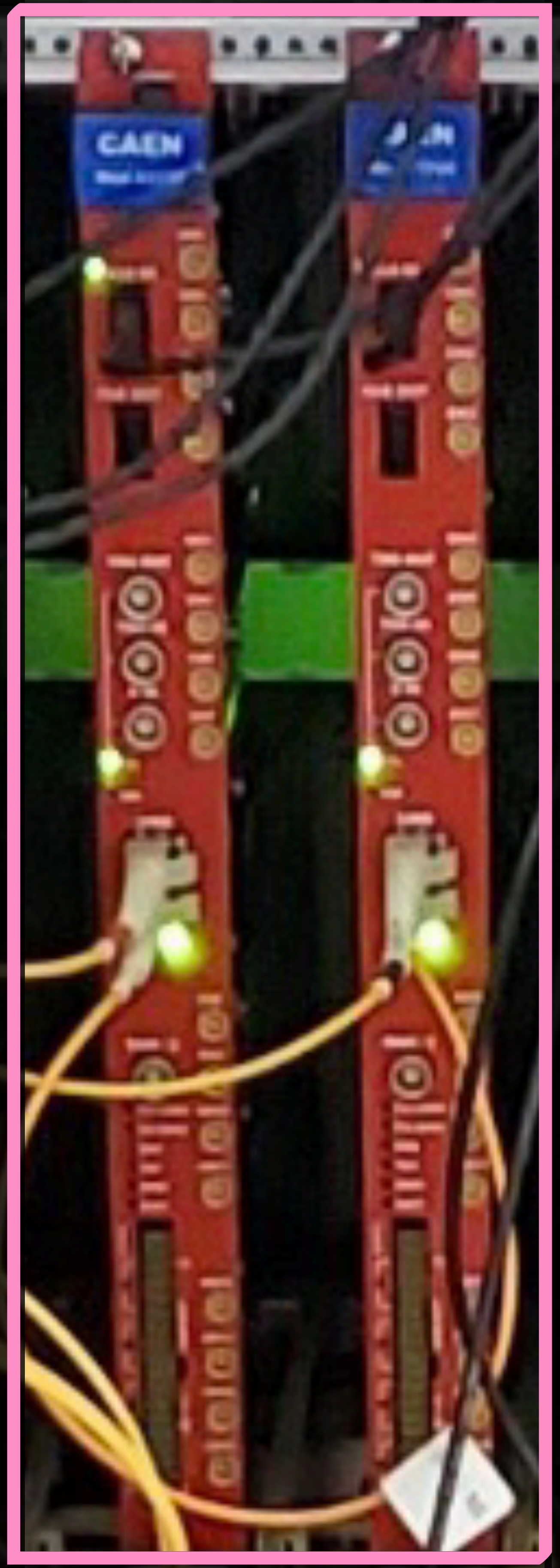
Pierre-Simon Mangeard



The 2” PMTs are readout on five v1742 CAEN digitizers.

v1742 Digitizer

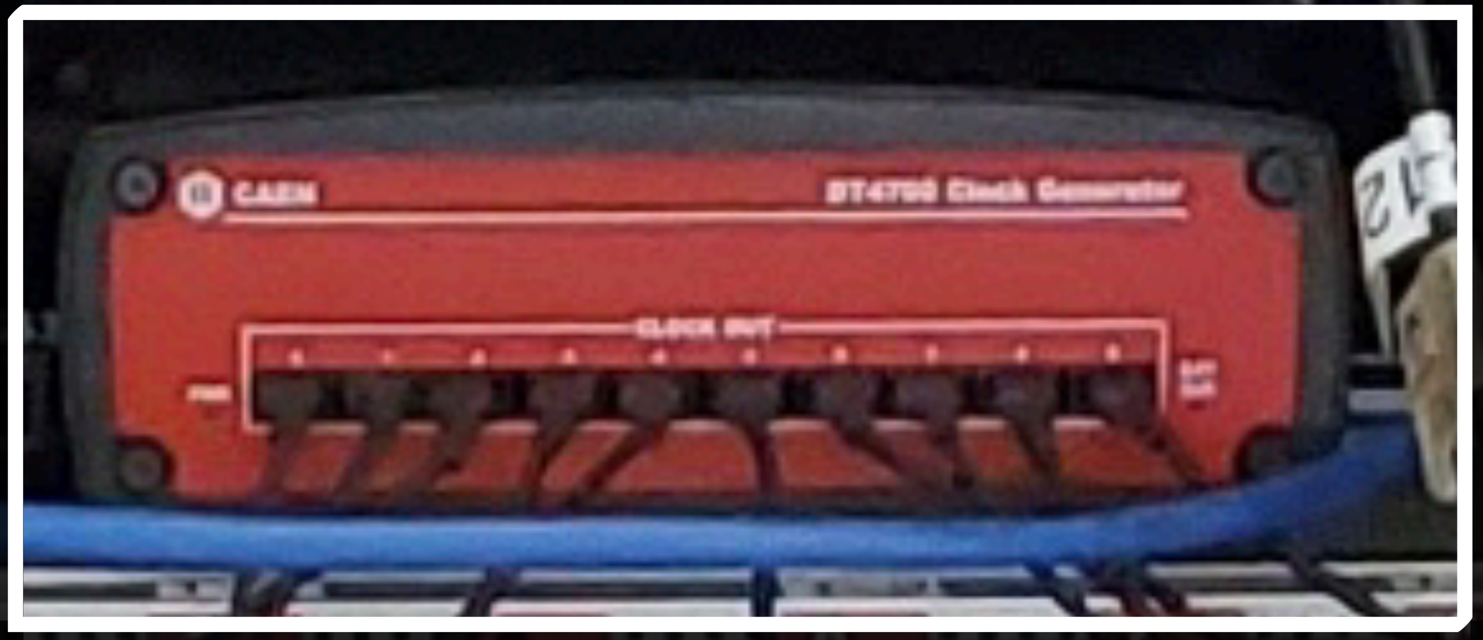
- 5 GSPS DRS4
- 32 channel MCX coaxial inputs
- 1Vpp dynamic range
- 12-bit, LSB = 0.24mV
- 181μs deadtime per trigger with trigger pulse digitization



The 8” PMTs are readout on five v1725 CAEN digitizers.

V1725 Digitizer

- 250 MSPS
- 16 channel MCX coaxial input
- 0.5Vpp or 2Vpp dynamic range
- 14-bit, LSB = 0.12mV @ 2Vpp
- Self-trigger AND decision



Digitizers are synced via an external clock.

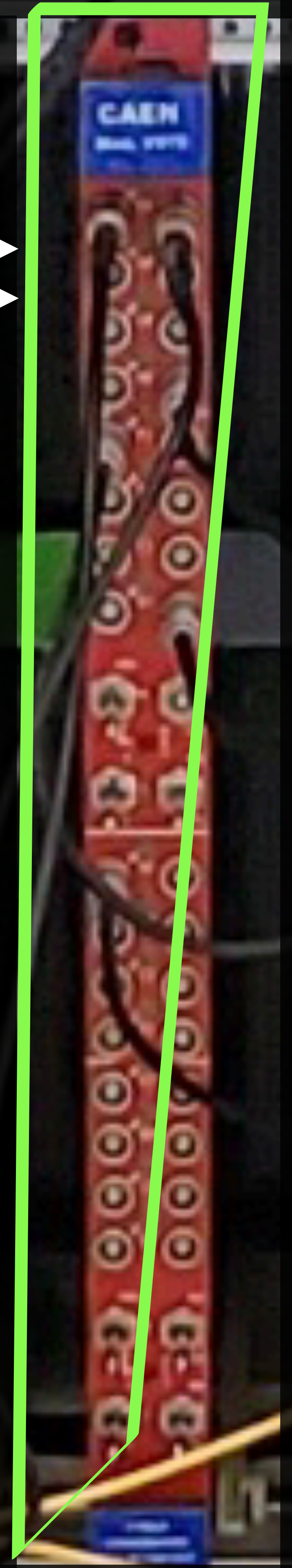
DT4700 clock Generator

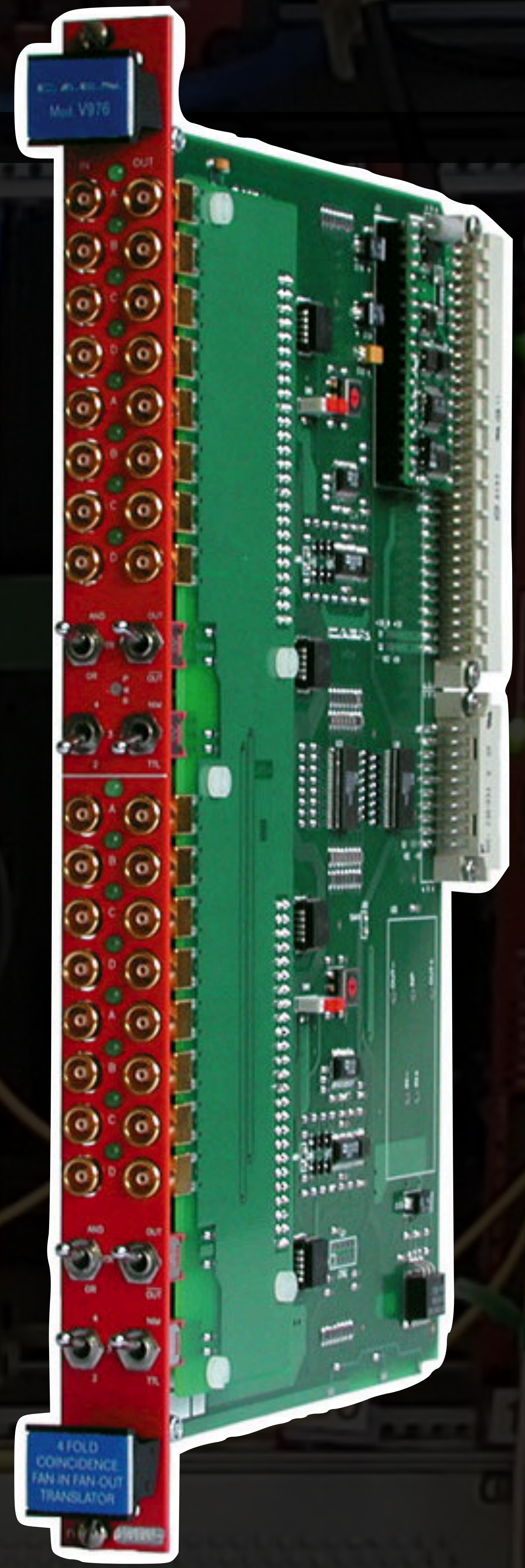
- 50 MHz, 62.5 MHz clock frequencies
- 10 differential LVDS outputs

Trigger signal initiated via the v1725 or externally, fanout to each digitizer.

External Trigger

Software Trigger from v1725





V976 Trigger Fanout

- Four independent sections, Four channels
- LEMO
- 4-Fold AND/OR/MAJ
- TTL and NIM outputs
- Fan In / Fan Out

HV supply for the 2” & 8“ PMTs is generated by a MPOD Wiener Crate.

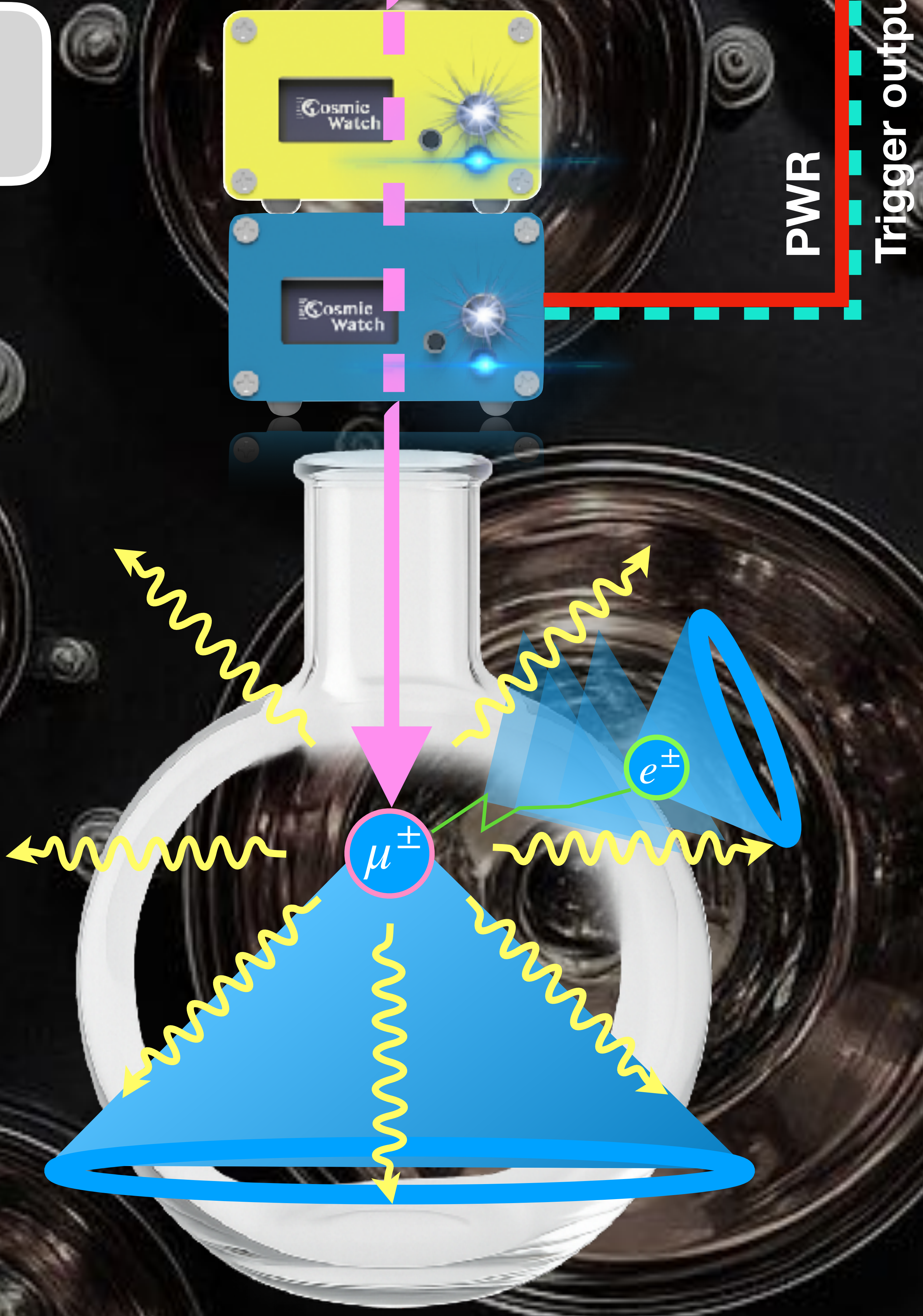
MPOD Full Size Crate.

- 10 slots
- Module size 6U x 8PU, 220mm deep
- 500 individually controlled channels
- Interfaces with 10/100 Ethernet, controlled via python GUI

Separate Cherenkov/Scintillation

Trigger sent to v976 fanout

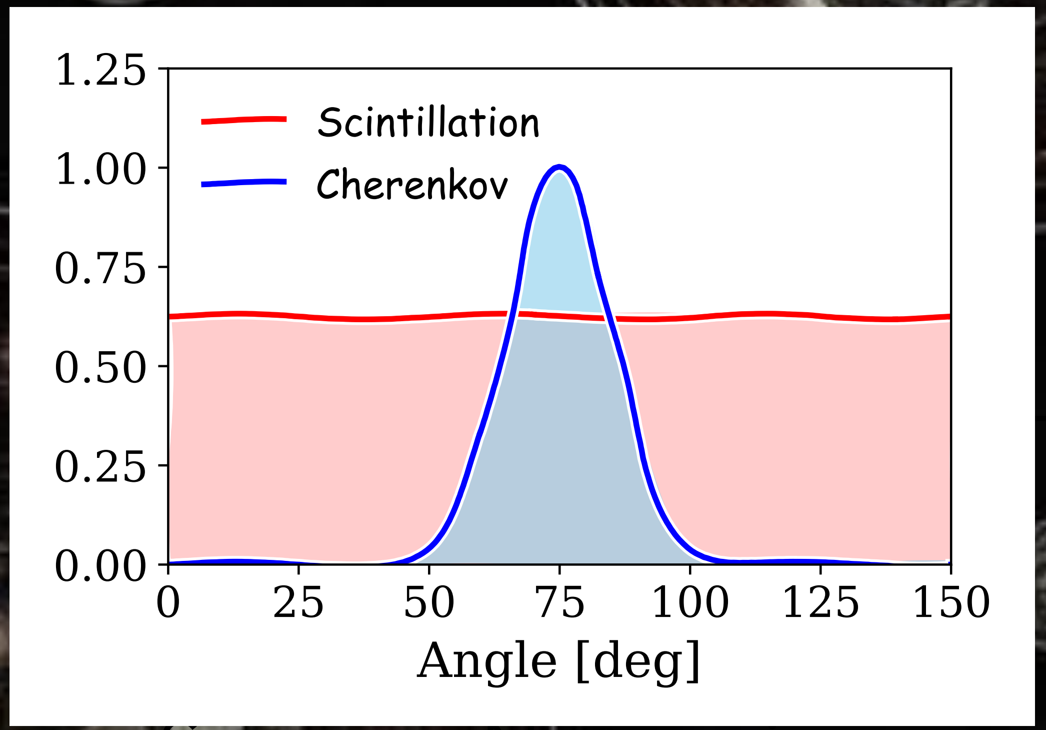
Downing muon tagged by CosmicWatch detectors



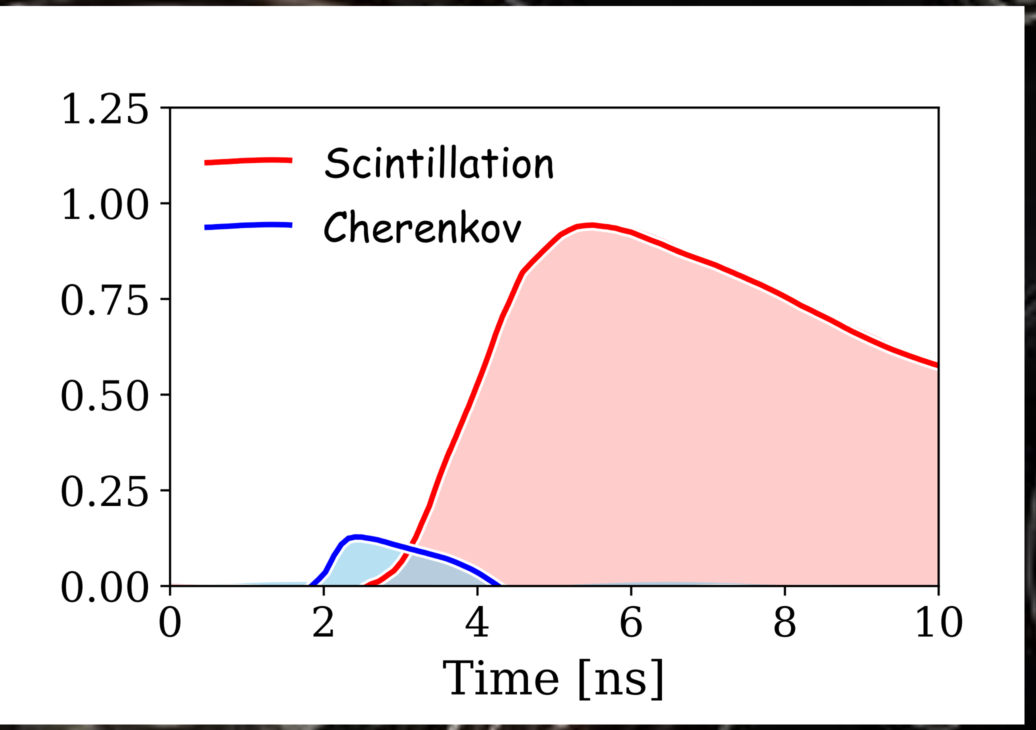
Tag delayed Michel to select stopping muons, using 8” PMTs (v1725)

Use 8” PMTs to measure energy spectrum of Michel electron

Delay v1742 trigger to search for Cherenkov from 10-50MeV Michel electron



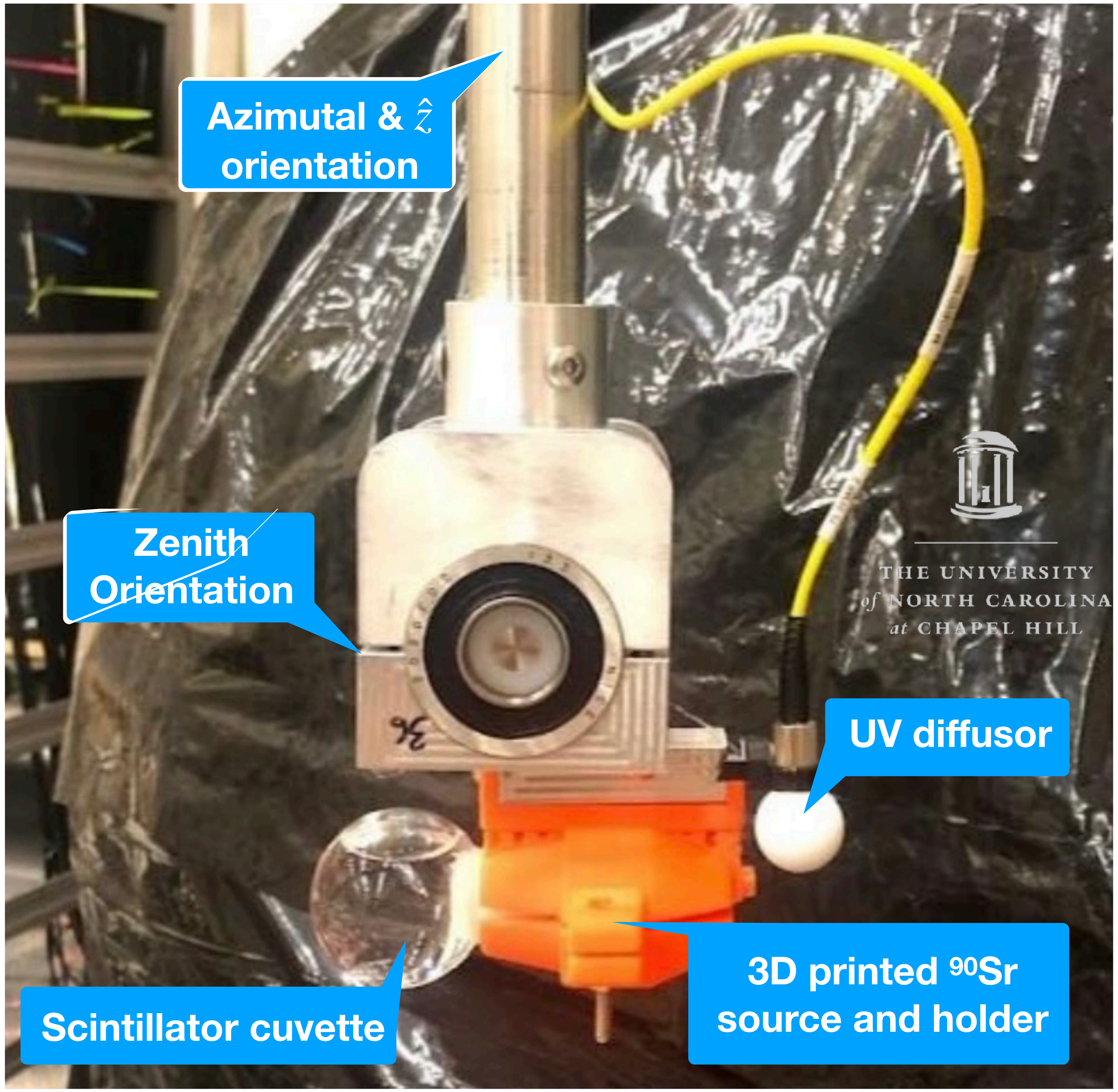
Offline waveform analysis to search for prompt down-going Cherenkov on 2” PMTs (v1742)



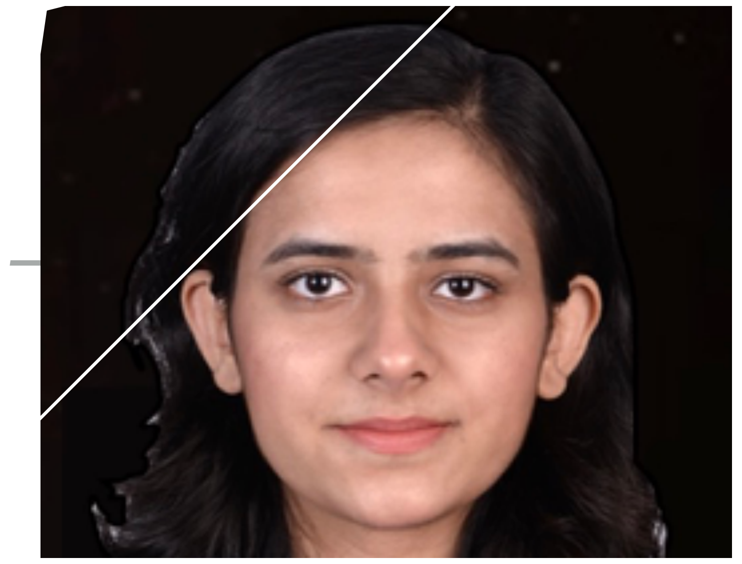
Demonstrate C/S separation with 1-2MeV betas

Automated calibration setup for directional beta studies

- Collimated ^{90}Sr beta source mounted in custom 3D-printed holder
- Source aligned with quartz cuvette filled with LS cocktail
- 3-axis motorized positioning system (azimuth, zenith, and z)
- Approximately 5° angular precision for directional control
- Remote-controlled via Raspberry Pi (RP) system
- Integrated UV diffuser for uniform optical calibration



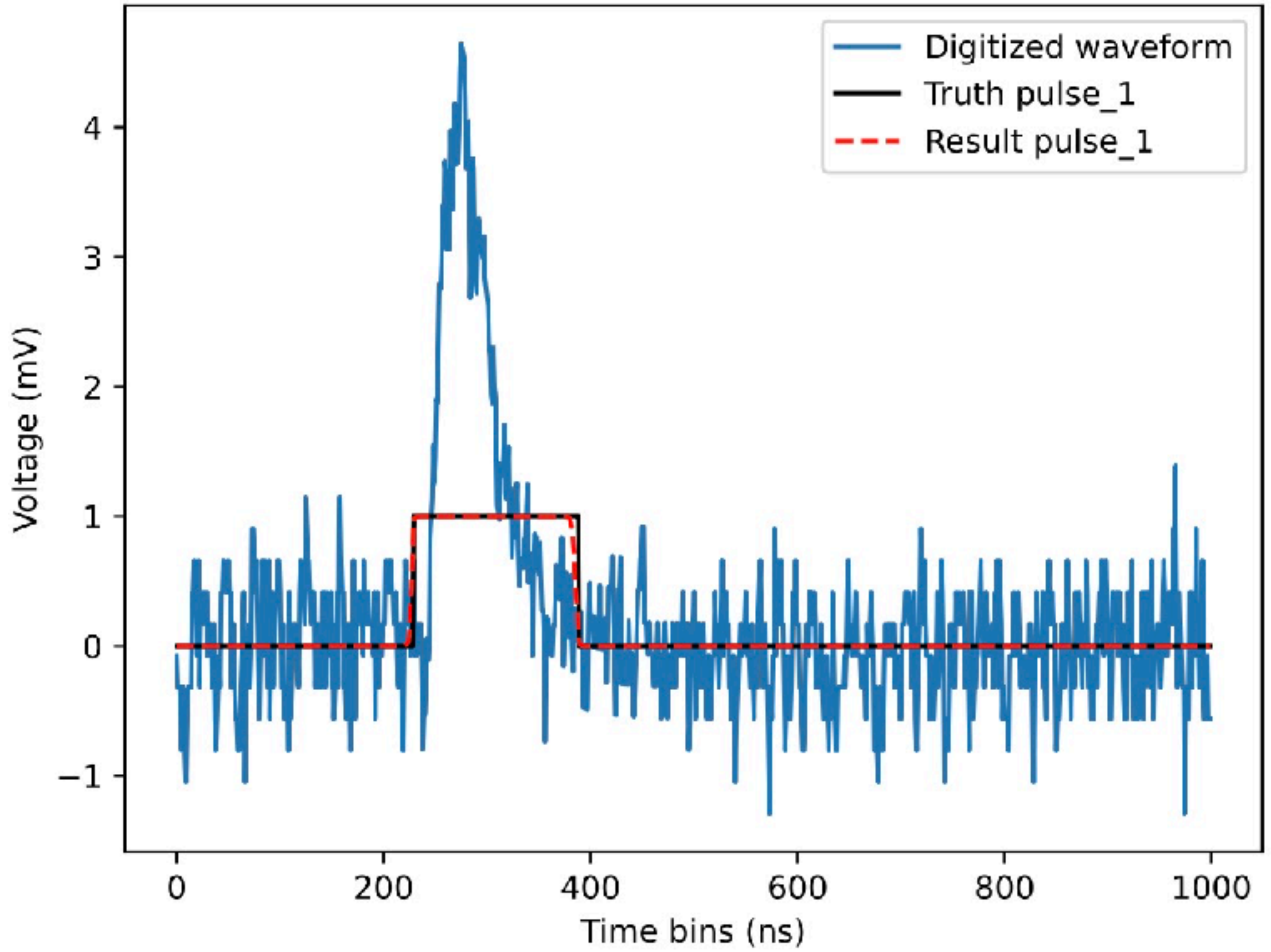
Pulse extraction using machine learning



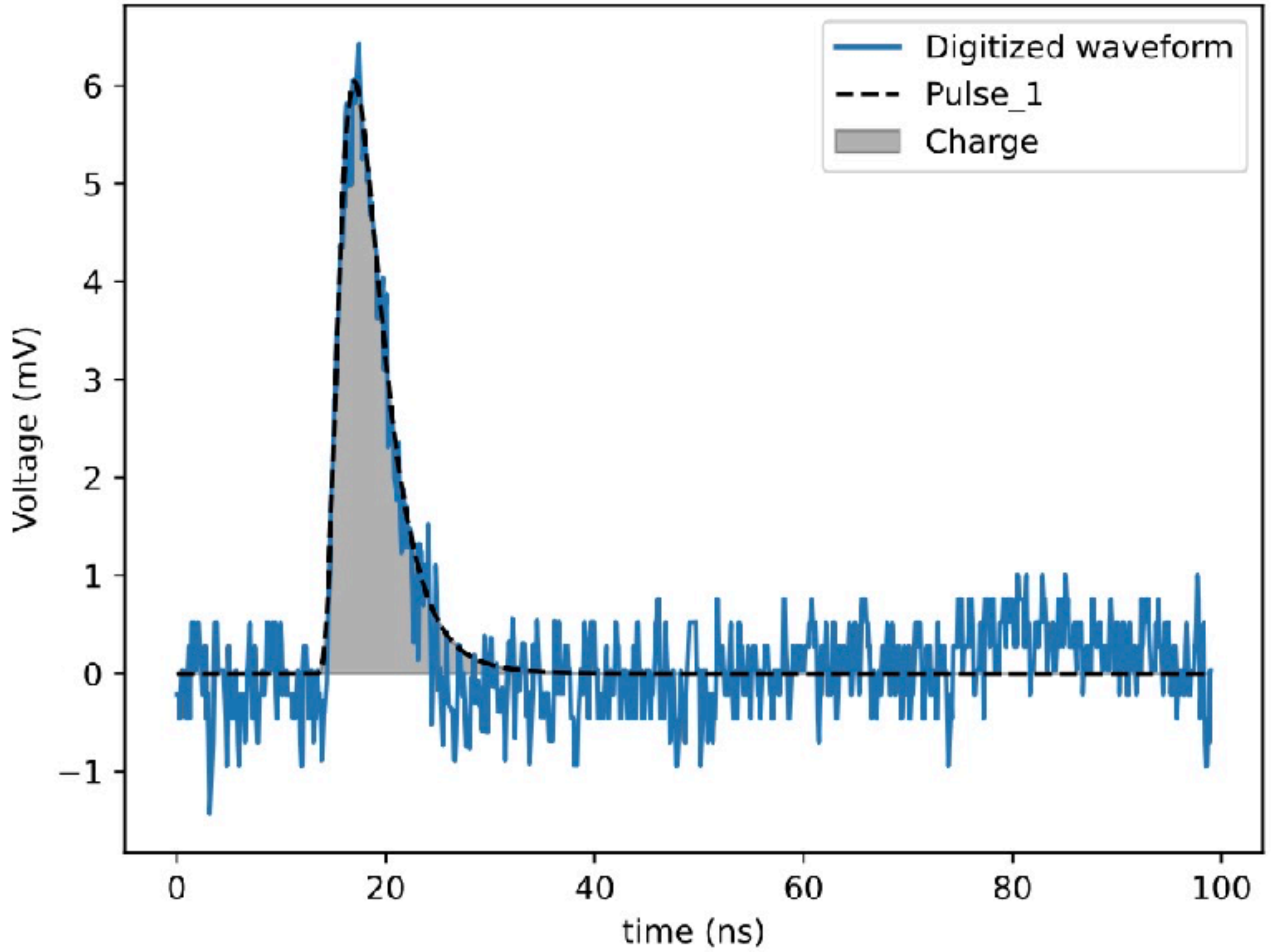
Masooma Sarfraz

Raw waveforms from triggered events are saved as HDF5 files. Single photoelectron hit times and charges are extracted using two UNET CNN-based ML algorithms.

Hit Timing
(Classification)

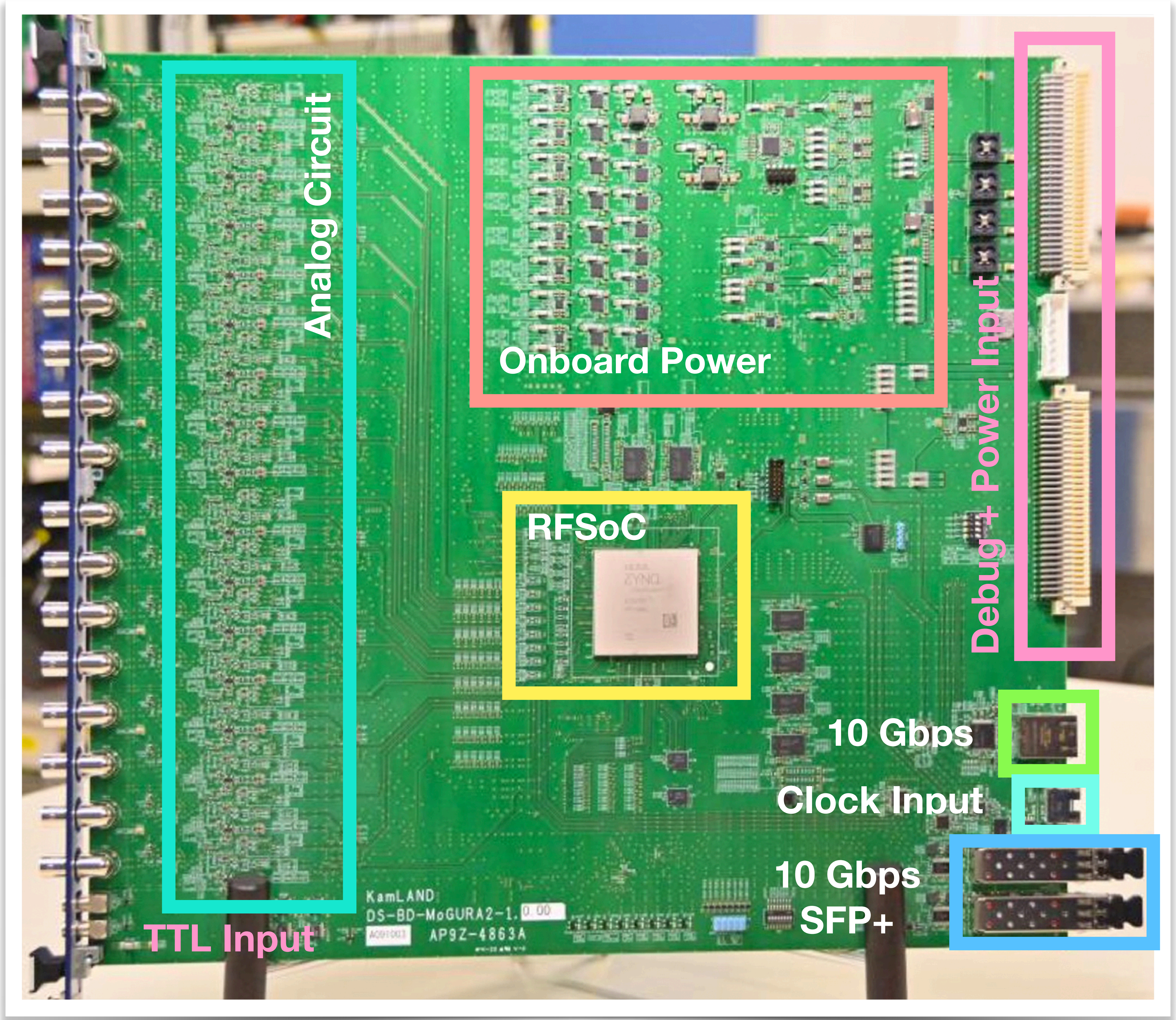


Hit Charge
(Regression)



Radio-Frequency System-on-a-Chip (RFSoC)

Deploy online pulse extraction on RFSoC system designed for KamLAND2-Zen.



16-channel prototype for KamLAND2-Zen

RFSoC: A monolithic chip with:

16x ADC: 5GSPS 14-bit

16x DAC: 10GSPS, 14-bit

Multi-core ARM processing

UltraScale+ FPGA processing

Reduction in PCB footprint	Machine learning on FPGA	*50% cost savings	*30-40% power consumption savings

Embedded AI:

- *Pulse extraction on-chip*
- *Streaming DAQ (zero deadtime)*
- *Advanced reconstruction*
- *Smart triggering*

Improved electronics:

- *Neutron extraction through*
- *Enhanced energy resolution*
  - *Extract fainter pulses (alphas near balloon)*

Summary

NuDot is a R&D testbed for future large-scale liquid scintillator detectors.

Current goal:

- Finish commissioning detector in Sharp Lab at UD this summer.
- Demonstrate the separation of prompt Cherenkov light from scintillation emission.
- Demonstrate AI pulse extraction

Future projects:

- Developing new RFSoC DAQ technologies, online pulse extraction, ML MPE pulse extraction
- Prototyping new scintillators → Quantum dots wavelength shifters, slow scintillators
- New fast timing photo-sensors → SiPM wallpapers, Digital SiPMs, LAPPDs
- ML PID development

Educational goals:

- Workforce development
- Graduate studies experimental apparatus for graduate PHYS646 Advanced Lab @ UD

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Acknowledgments

Current members

- Lindley Winslow, Julieta Gruzsko, Spencer Axani, Pierre-Simon Mangeard, Masooma Sarfraz, Miles Garcia, Maeve Owens, Collin Owens, Amanda Meng, Liam Roth

Past contributors:

- Chris Grant, Taritree Wongjirad, Ravi Patella, Sarah Vickers, Brian Naranjo, Caroline Laber-Smith, Diana Gooding, Eleanor Graham, Guadalupe Duran, Aobo Li, Hasung Song, Janet Lowden, Jesus Herrera, Johnathan Ouellet

Thanks!

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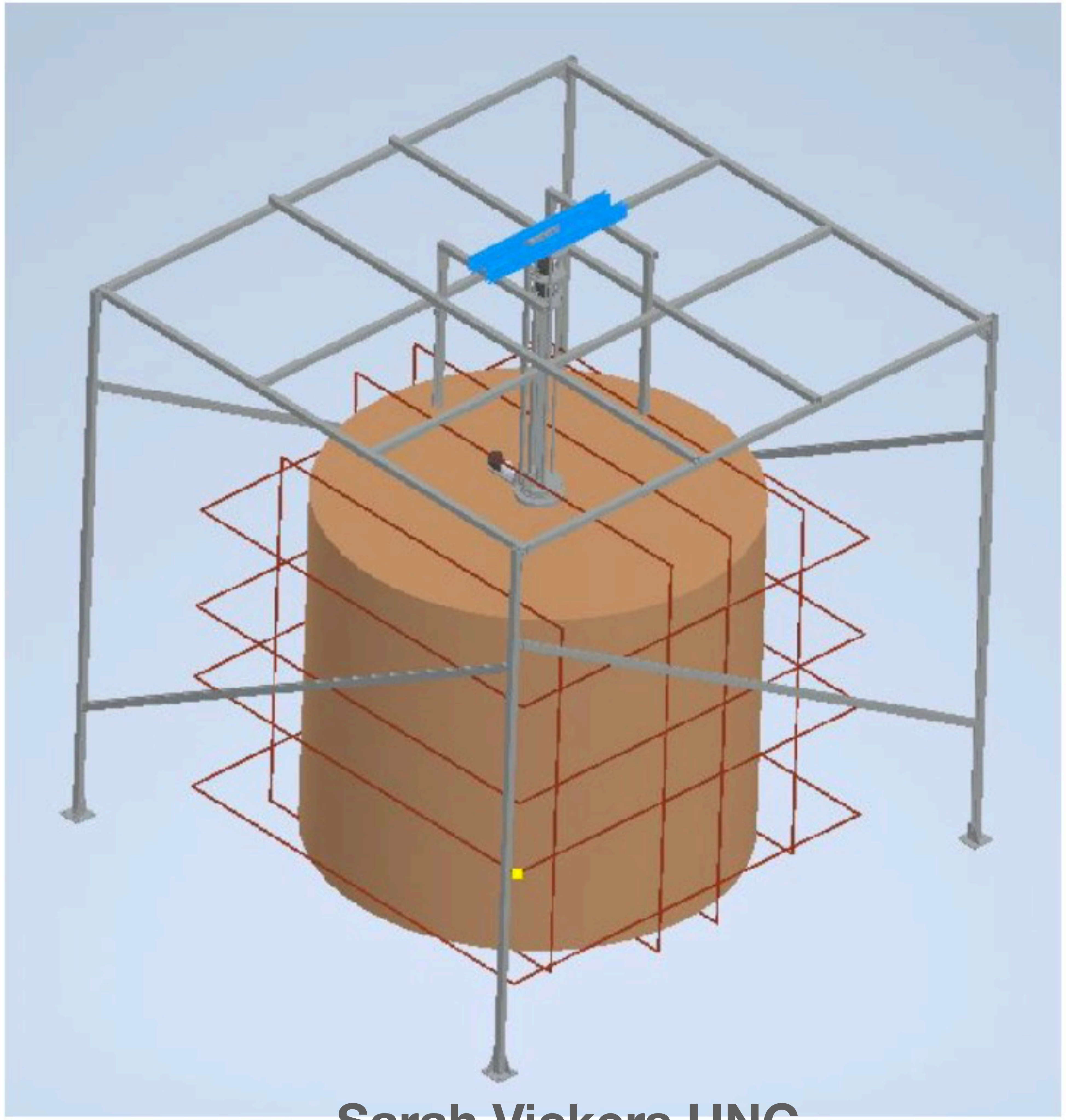
Compensation coils

- 20 awg copper motor wire
- Keithley power source
- Simple circuit to connect the four wires, taking into account resistance of the wire
- PVC pipe infrastructure, easy winding
- Tank will be resting on shipping pallets, allows the vertical coils to be fed underneath



Sarah Vickers UNC