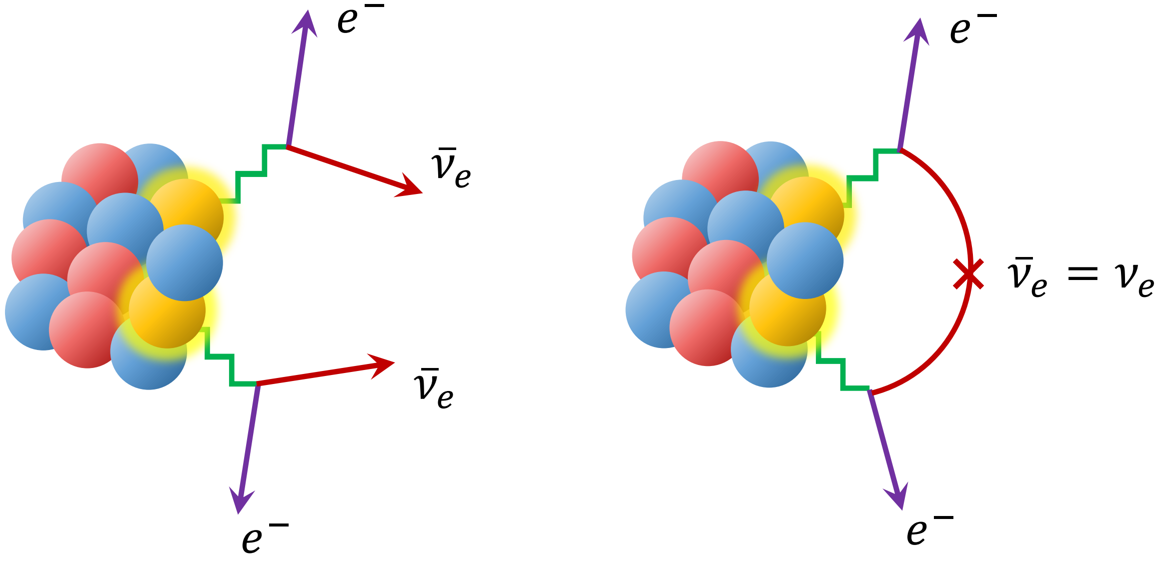
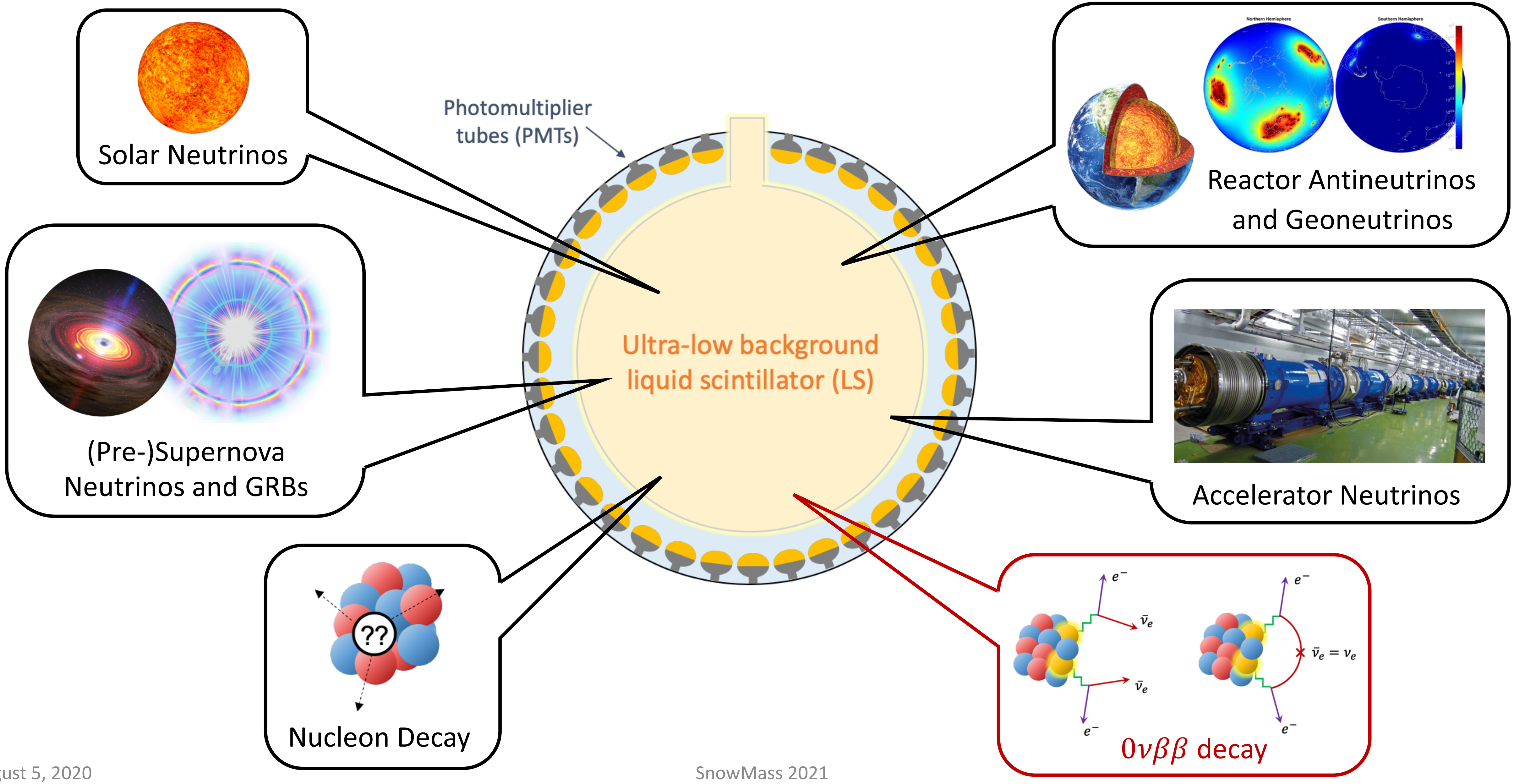


KamLAND-Zen and Future R&D

Christopher Grant

Boston University

Pursuing Crosscutting Science with Big Detectors



KamLAND-Zen

Located in Kamioka Mine at 2700 m.w.e.

Mini-balloon:

- 25-μm-thick nylon film (durable)
- Fabricated in class-1 clean room
- Highly transparent (~99% at 400 nm)

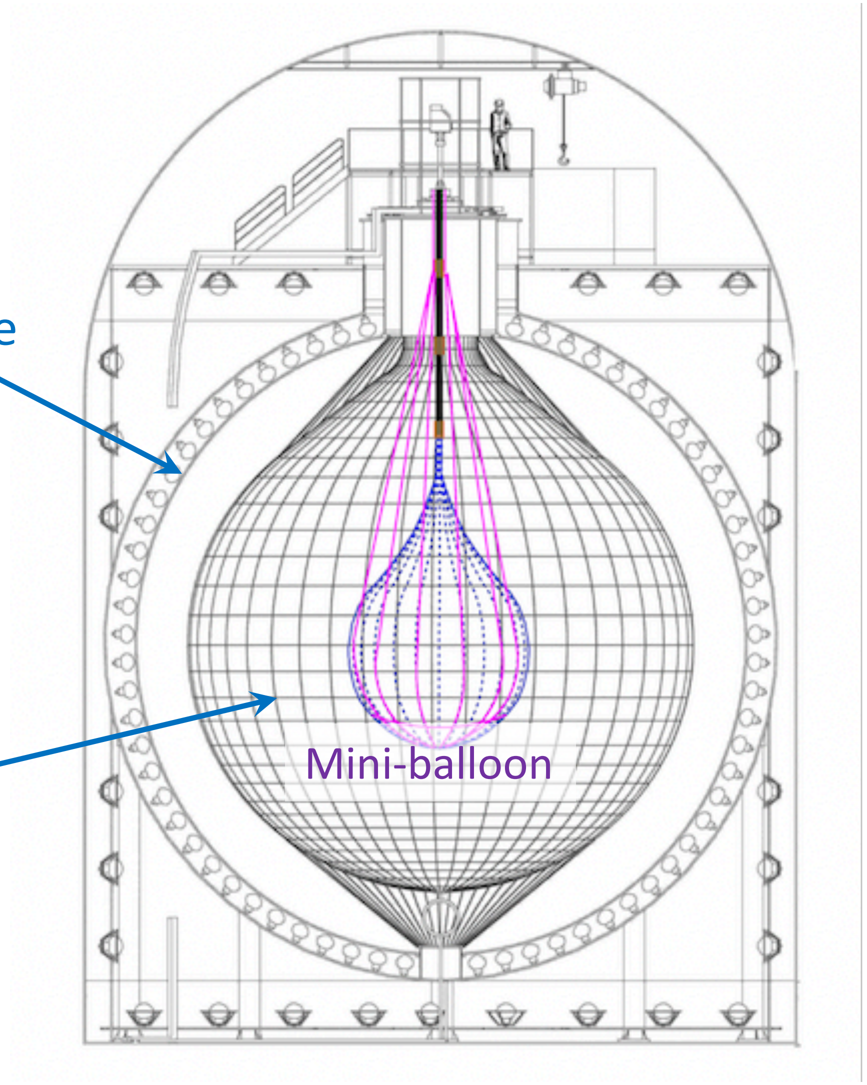
Xenon loading:

- Chemically stable (noble gas)
- Good solubility (3.2% wt in LS)
- Removable from LS
- Purification is well-established

~34% photocoverage

~1 kiloton LS

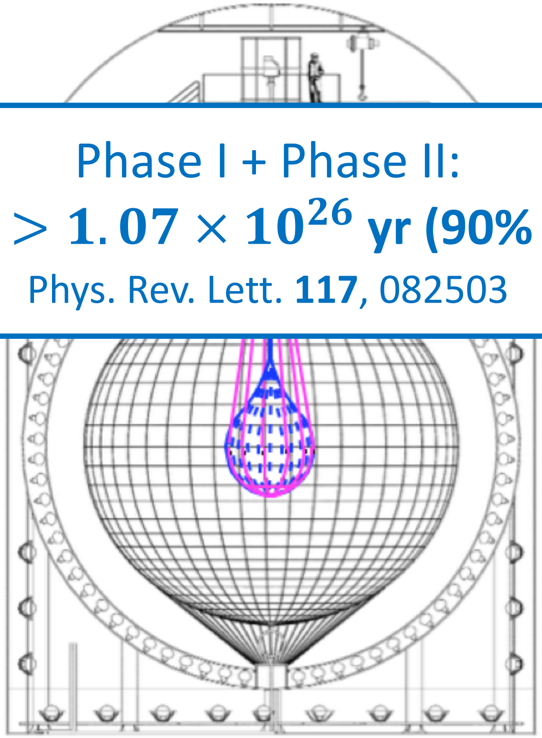
- 20% PC
- 80% n-dodecane
- 1.36 g/L PPO



91% enriched ^{136}Xe loaded in LS inside mini-balloon (Q value = 2.4578 MeV)

Evolution of KamLAND-Zen

Past



Phase I + Phase II:

$T_{1/2} > 1.07 \times 10^{26}$ **yr (90% C.L.)**

Phys. Rev. Lett. **117**, 082503

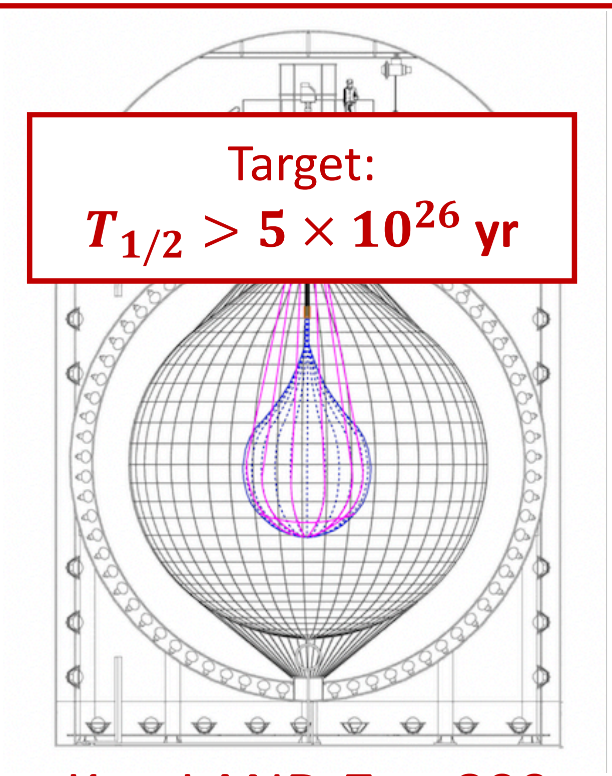
KamLAND-Zen 400

Mini-balloon Radius = 1.54 m

Xenon mass = 320 ~ 380 kg

2011 ~ 2015

Current



Target:

$T_{1/2} > 5 \times 10^{26}$ **yr**

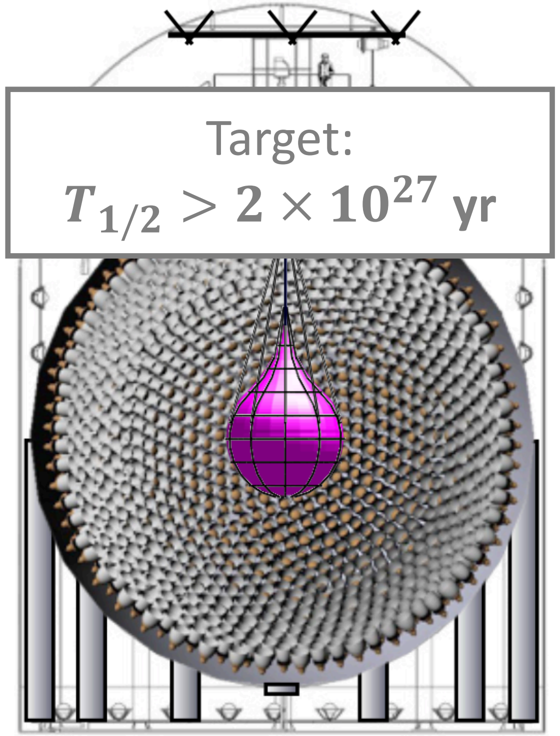
KamLAND-Zen 800

Mini-balloon Radius = 1.90 m

Xenon mass = 745 kg

Started January 2019

Future



Target:

$T_{1/2} > 2 \times 10^{27}$ **yr**

KamLAND2-Zen

Xenon mass ~ 1 ton

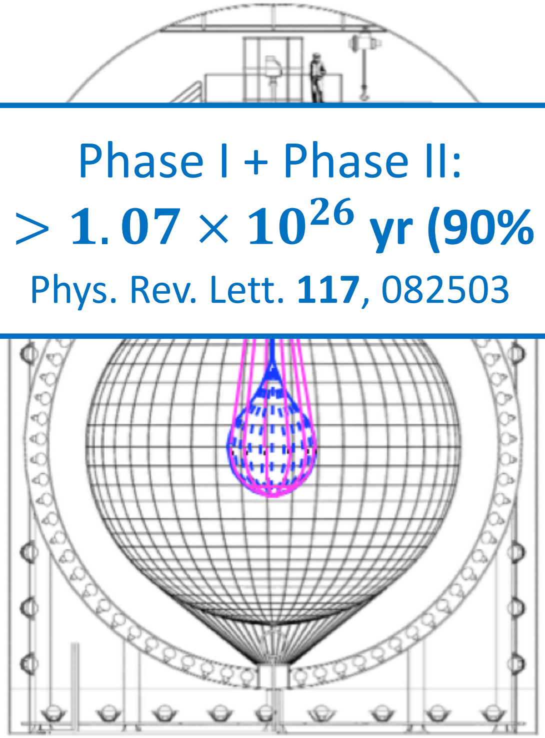
× 5 increase in light collection

Scintillation balloon film

KamLAND-Zen Experience

All of this has been successfully demonstrated!

<u>Past</u>



Phase I + Phase II:
$T_{1/2} > 1.07 \times 10^{26}$ yr (90% C.L.)
Phys. Rev. Lett. **117**, 082503

KamLAND-Zen 400

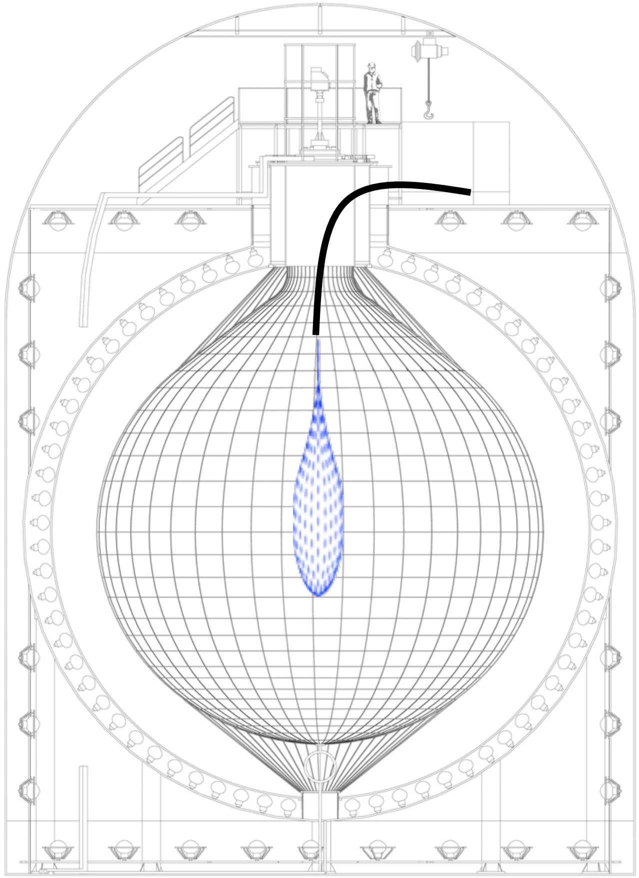
Mini-balloon Radius = 1.54 m

Xenon mass = 320 ~ 380 kg

2011 ~ 2015

- **Low cost and quick start** ✓
  Re-used existing detector and infrastructure
- **Backgrounds are manageable** ✓
  Fiducialization with large volume provides good sensitivity
- **In-situ purification** ✓
  Ability to operate the detector while removing LS backgrounds
- **Measurements with and without isotope** ✓
  Xenon can be removed from LS and put back in (as often as needed)
- **Detector is multi-purpose** ✓
  Continue to pursue a diverse physics program in parallel
- **Easily scalable** ✓
  Larger (and cleaner!) balloons can be made for increased isotope mass
- **LS technique has been shown to be formidable** ✓
  Achieved the world's best limit on $0\nu\beta\beta$ decay half-life

KamLAND-Zen 800 Mini-Balloon Installation



New mini-balloon was fabricated inside Class 1 cleanroom and installation was finished in May 2018

LS Purification and Xe Loading

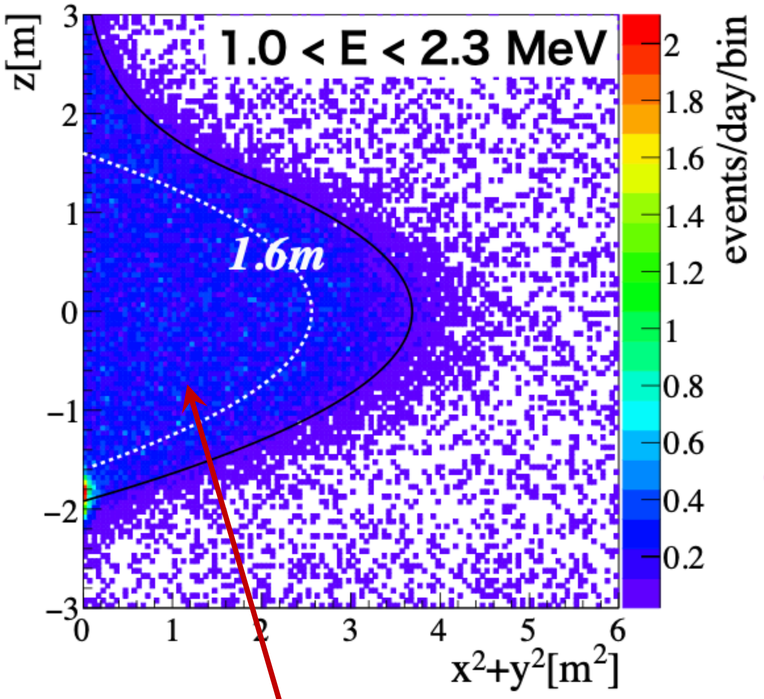
June 2018 – Oct 2018 | Nov 2018 – Jan 2019 | Jan 2019 – present

(Balloon installed)

LS purification
H_2O extraction, distillation, N_2 purging to reduce instrinsic backgrounds

Xe loading
Total of 745 kg (~3.0% wt)

Data taking
New results expected soon!

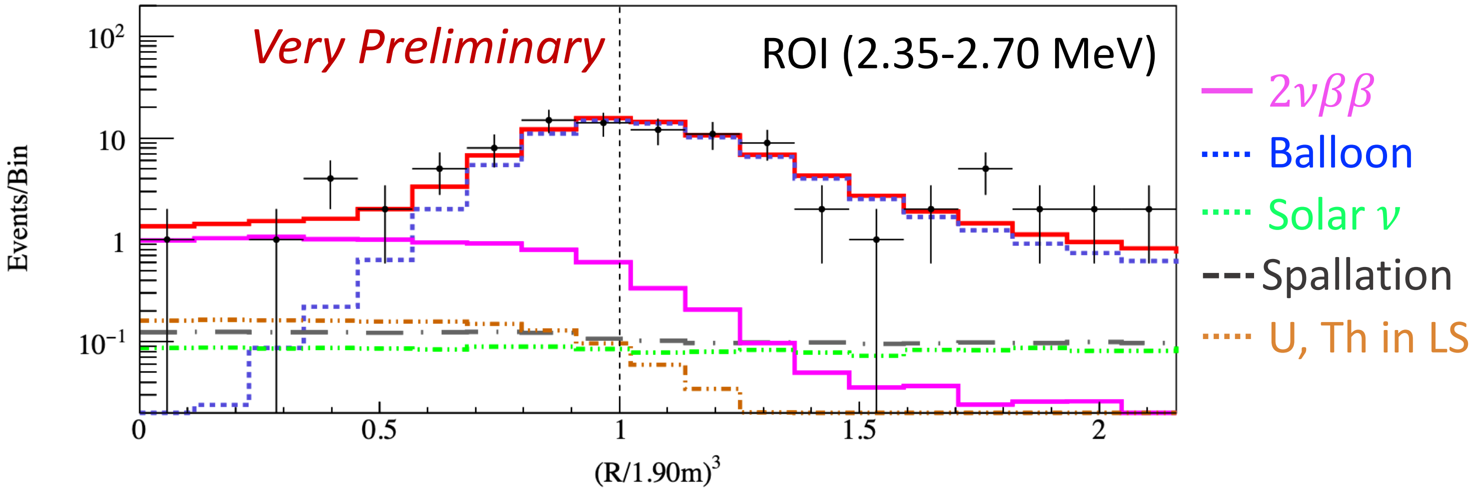


Rate dominated by $2\nu\beta\beta$ decays

Balloon film backgrounds:

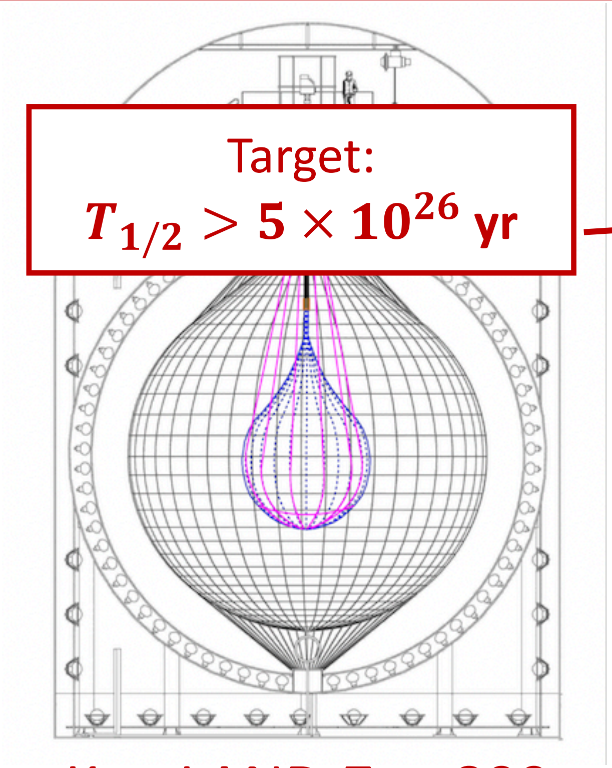
$^{238}U \sim 3 \times 10^{-12}$ g/g
$^{232}Th \sim 4 \times 10^{-11}$ g/g

×10 reduction compared to KLZ 400 mini-balloon



R&D has paved the way forward

Current



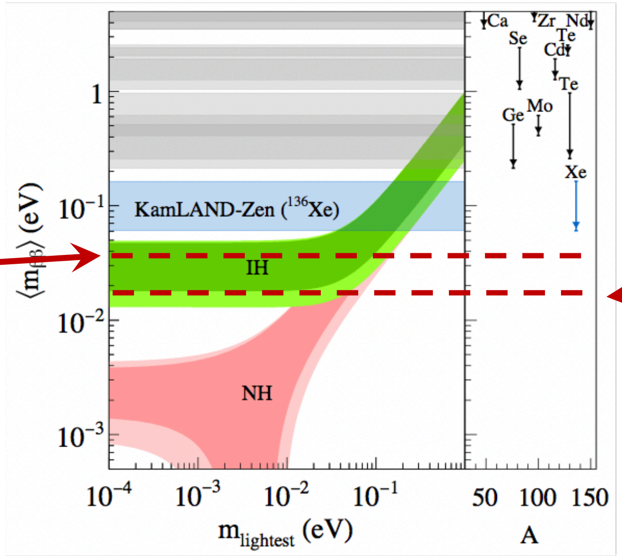
Target:
$T_{1/2} > 5 \times 10^{26}$ yr

KamLAND-Zen 800

Mini-balloon Radius = 1.90 m

Xenon mass = 745 kg

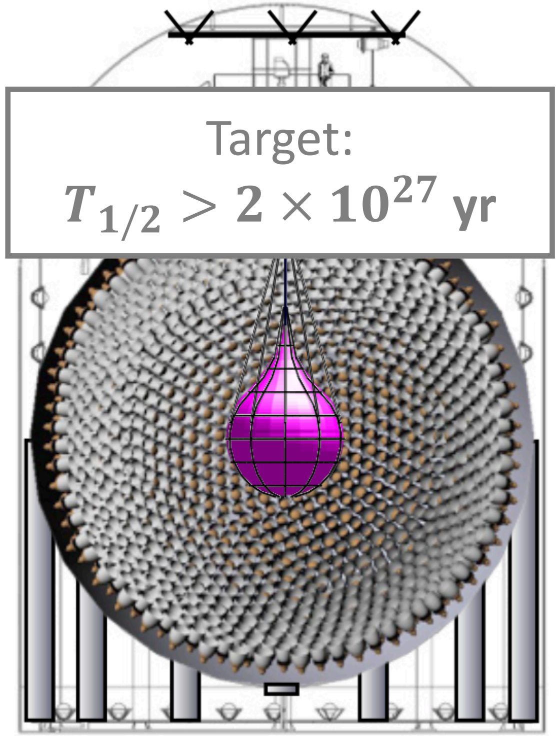
Started January 2019



The R&D required for the KamLAND2-Zen conceptual design is finished

Plan is to turn on in ~2027-2028

Future



Target:
$T_{1/2} > 2 \times 10^{27}$ yr

KamLAND2-Zen

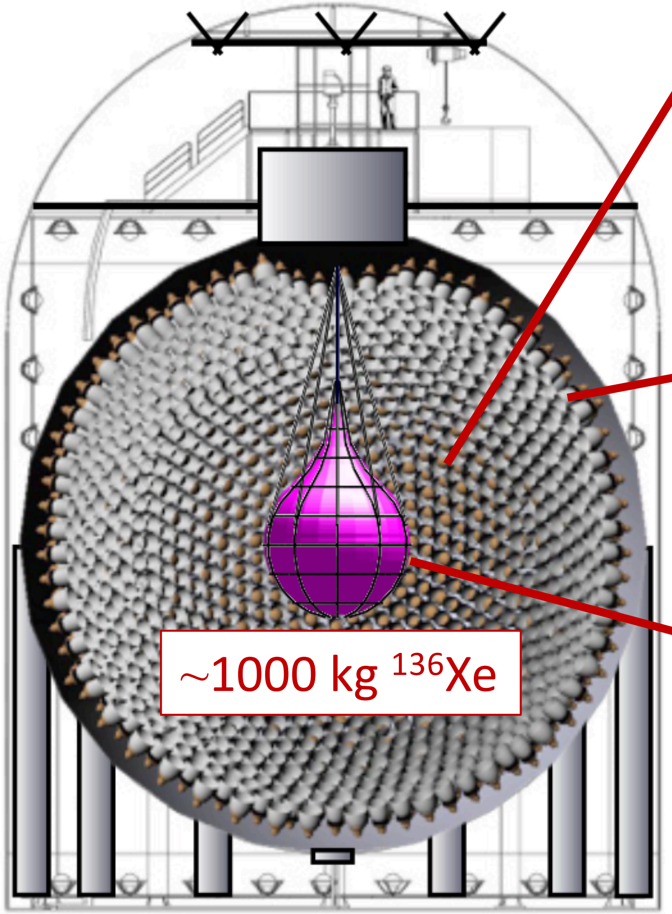
Xenon mass ~ 1 ton

× 5 increase in light collection

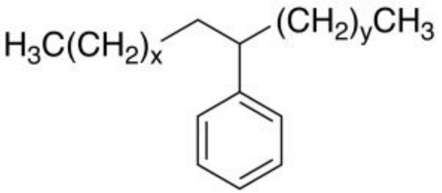
Scintillation balloon film

KamLAND2-Zen

Target:
$T_{1/2} > 2 \times 10^{27}$ yr



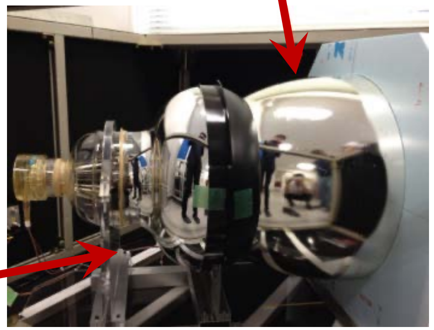
Linear Alkylbenzene (LAB)
Scintillator (high transparency)



Improve light collection → x1.4
Purification testing successful

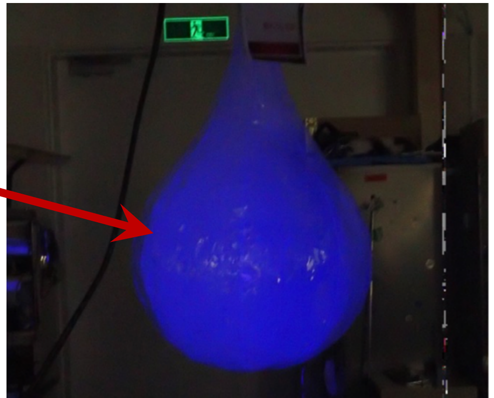
Energy Resolution @ 2.6 MeV
improves from ~4% to ~2%!

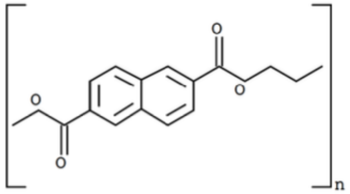
Winston cones on High Quantum Eff. PMTs



Improve light collection:
HQE PMTs → x1.9
Winston cones → x1.8
x3.4 increased light

Scintillating Balloon - PolyEthylene Naphthalate (PEN)
Identify and reject film backgrounds


UV Light Test of PEN Balloon



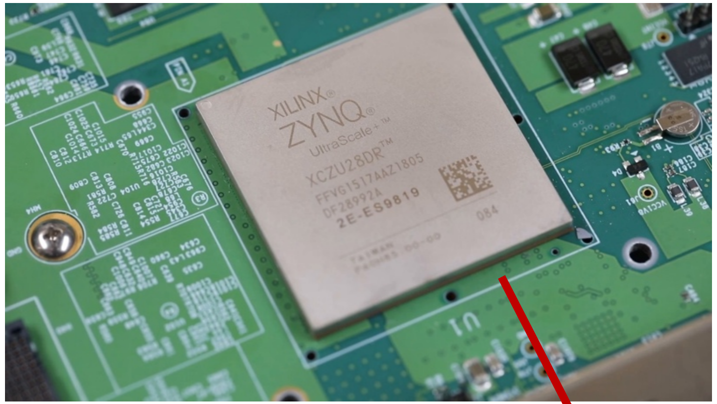
LY = 10,500 photons / MeV
Peak emission $\lambda = 425$ nm
U, Th < 3 ppt

Utilize the full
volume of ^{136}Xe
inside mini-balloon

New MoGURA2 Electronics Upgrade

RFSoC (RF System-on-a-chip) integrates the following in a single chip:

- 16 channel 2GSPS ADC
- 16 channel 4GSPS DAC
- Powerful Xilinx FPGA



BOSTON UNIVERSITY

TOHOKU UNIVERSITY

Deep Memory Buffers

Record the entire duration of a supernova

Digital Baseline Recovery

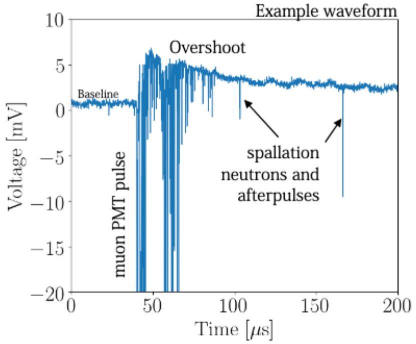
Reduce cosmogenic backgrounds

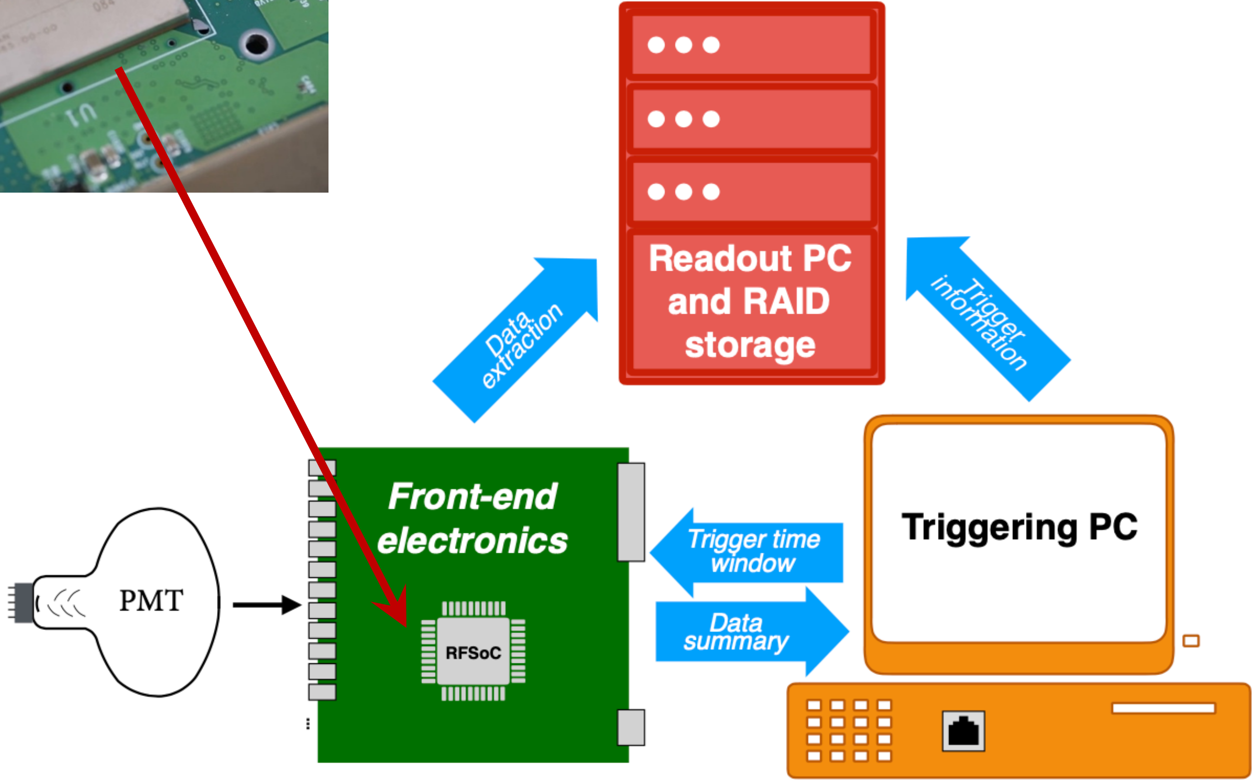
High-speed digitization

Signal processing in digital domain

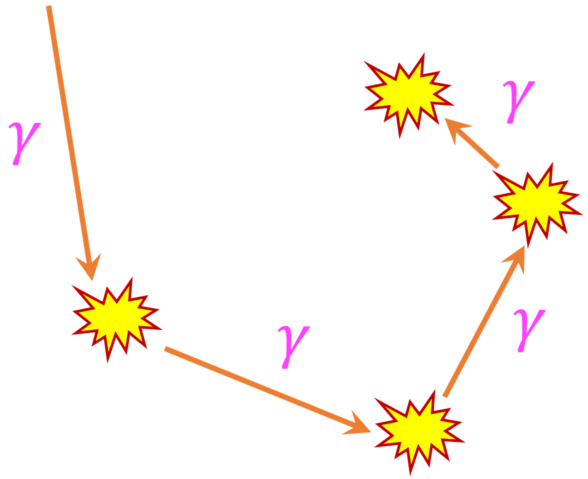
Flexible triggering system

Advanced dynamic triggering with Deep Learning



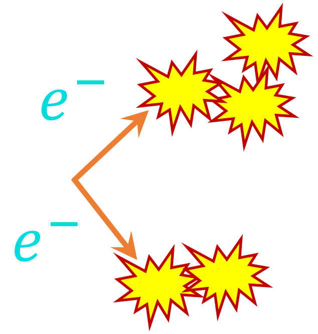


Background Rejection with Deep Learning

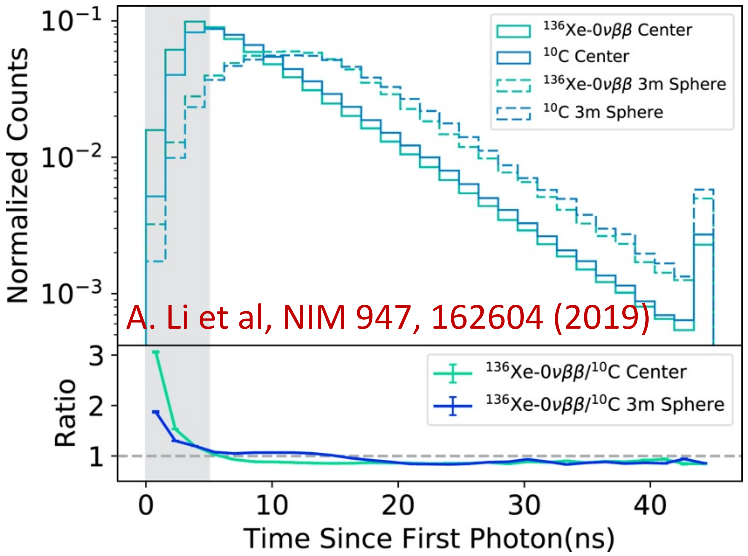


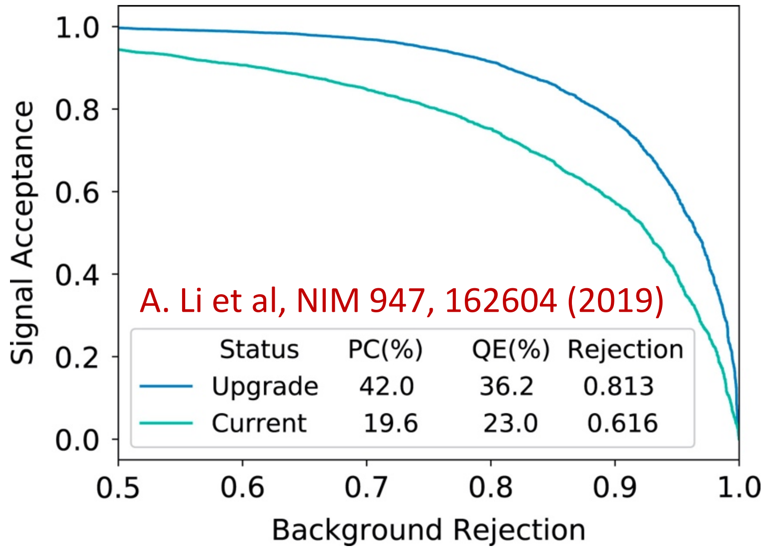
Background decays with ~MeV gamma-rays typically have energy deposits (Compton scatters) spread over distances of tens-of-centimeters.

Decays only containing ~MeV electrons are more localized.

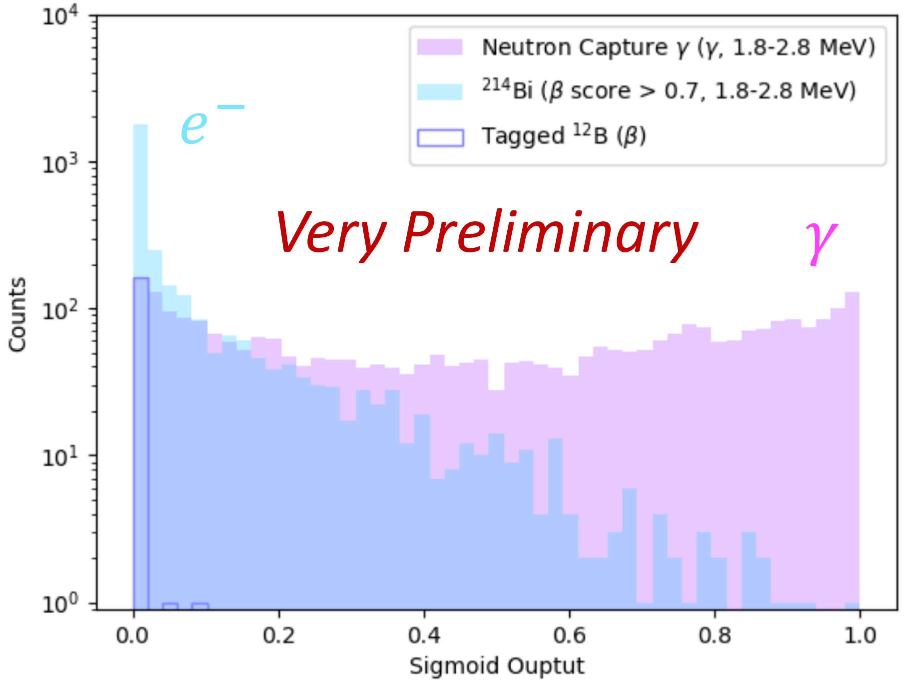


CNN applied to MC of ^{10}C and $0\nu\beta\beta$ events in a KLZ-like detector





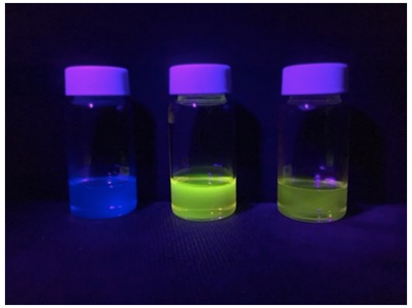
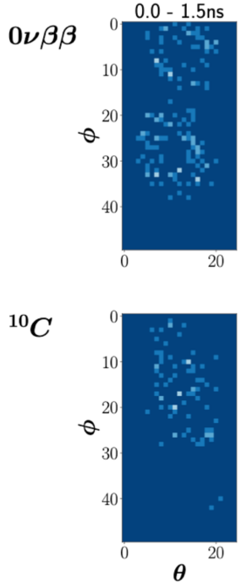
Spherical CNN applied to subset of KLZ-800 data

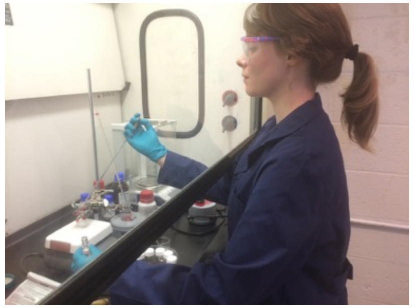
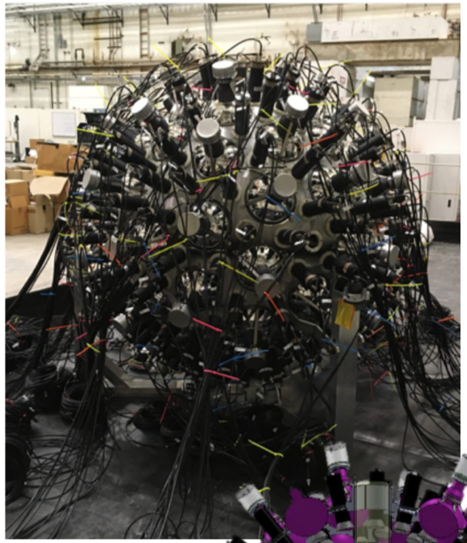
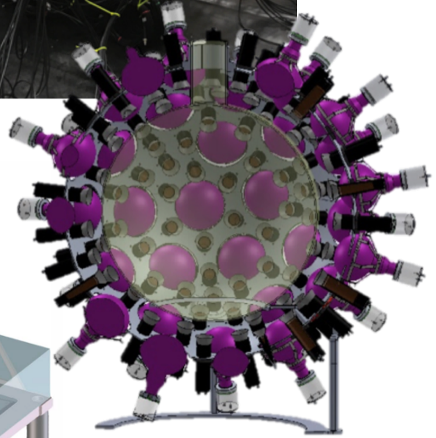
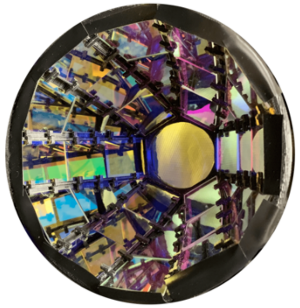
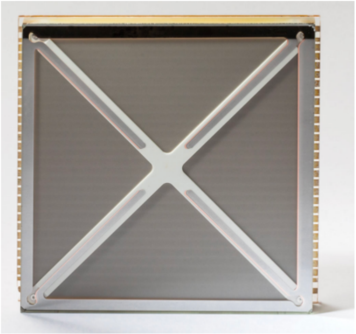
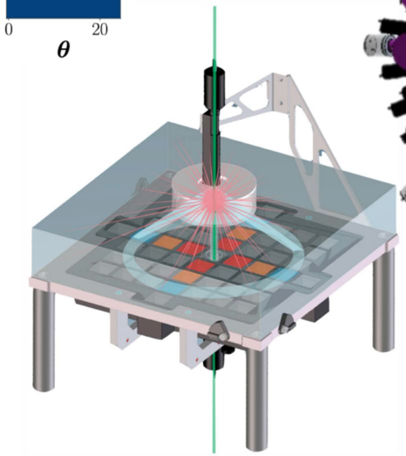


R&D towards $T_{1/2}^{0\nu\beta\beta} > 10^{28}$ years

There is a clear R&D plan for a next-generation experiment that incorporates many **crosscutting technologies** (see Bob Svoboda's talk on Theia):

- Machine Learning (CNNs, Spherical CNNs)
- State-of-the-art DAQ electronics (RFSoCs)
- Fast-timing photosensors (LAPPDs)
- Nanotechnology and Novel loading chemistry (Quantum dots, organometallic Tellurium à la SNO+, pressurized Xenon loading à la KLZ)
- Novel Enrichment Techniques (^{48}Ca)
- Cherenkov/Scintillation separation (CHESS, NuDot, Dichroicons)

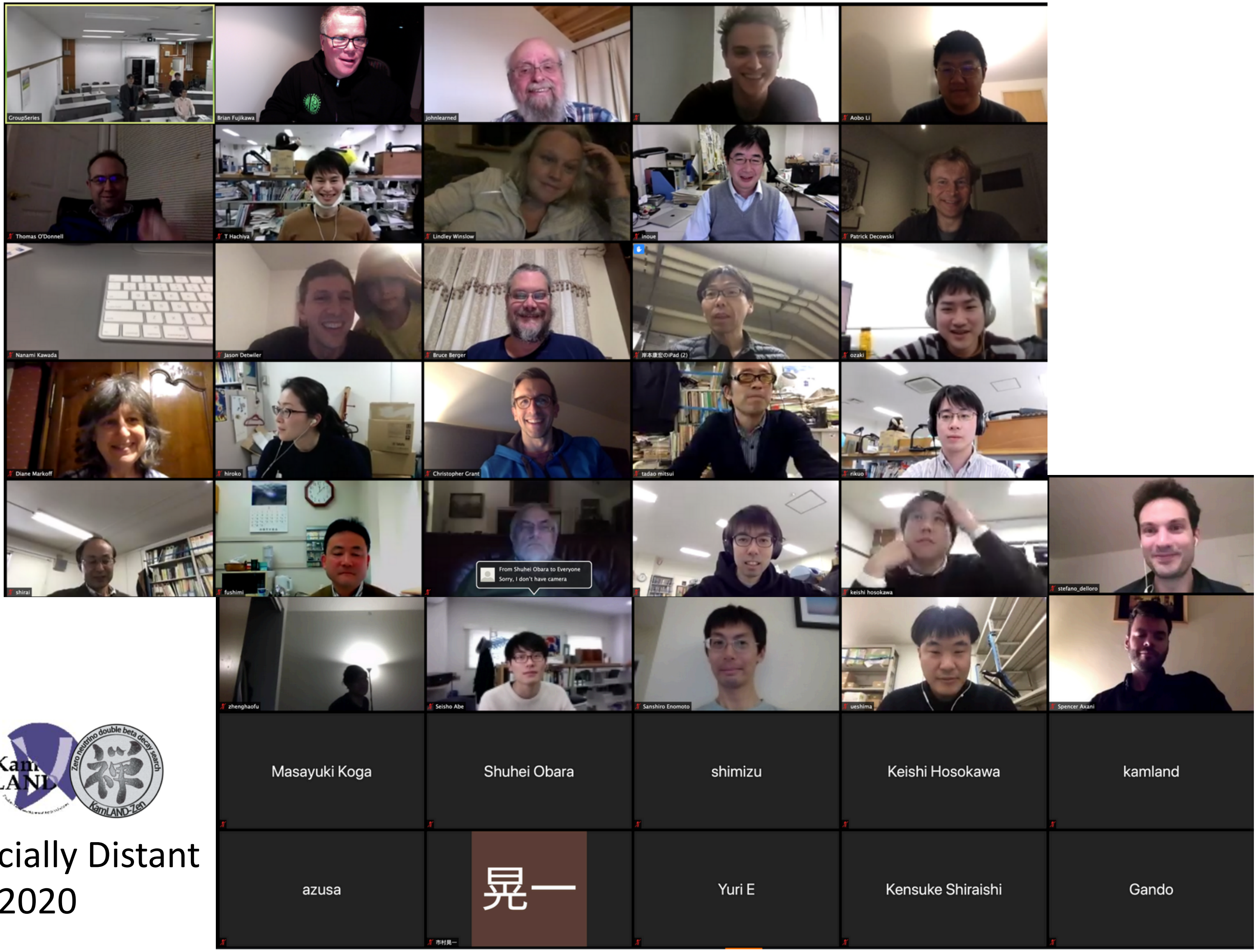







KamLAND-Zen Collaboration

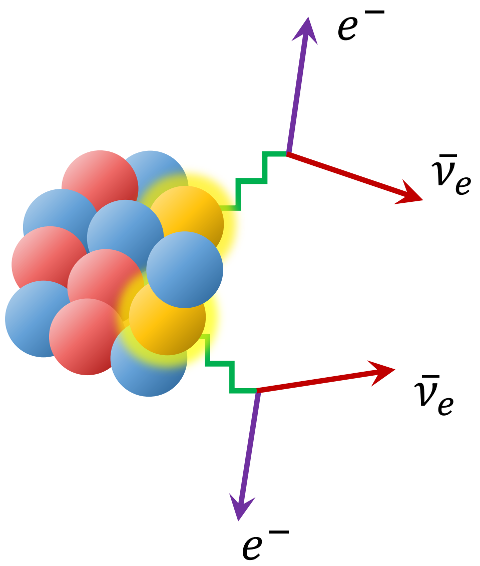
RCNS, Tohoku Univ.
Kavli-IPMU Univ. of Tokyo
Osaka Univ.
Tokushima Univ.
Kyoto Univ.

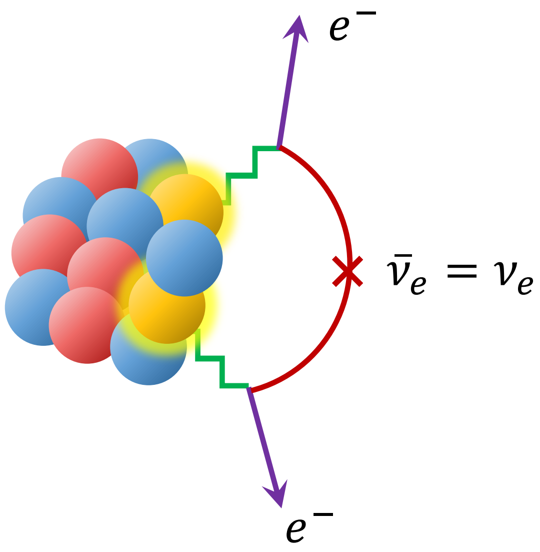
Lawrence Berkeley National Lab
Univ. of Tennessee
Triangle Univ. Nuclear Lab
Univ. of Washington
Massachusetts Institute of Technology
Virginia Polytechnic Institute and State Univ.
Univ. of Hawaii
Boston Univ.

Nikhef, Univ. of Amsterdam



Socially Distant in 2020





Thank you!