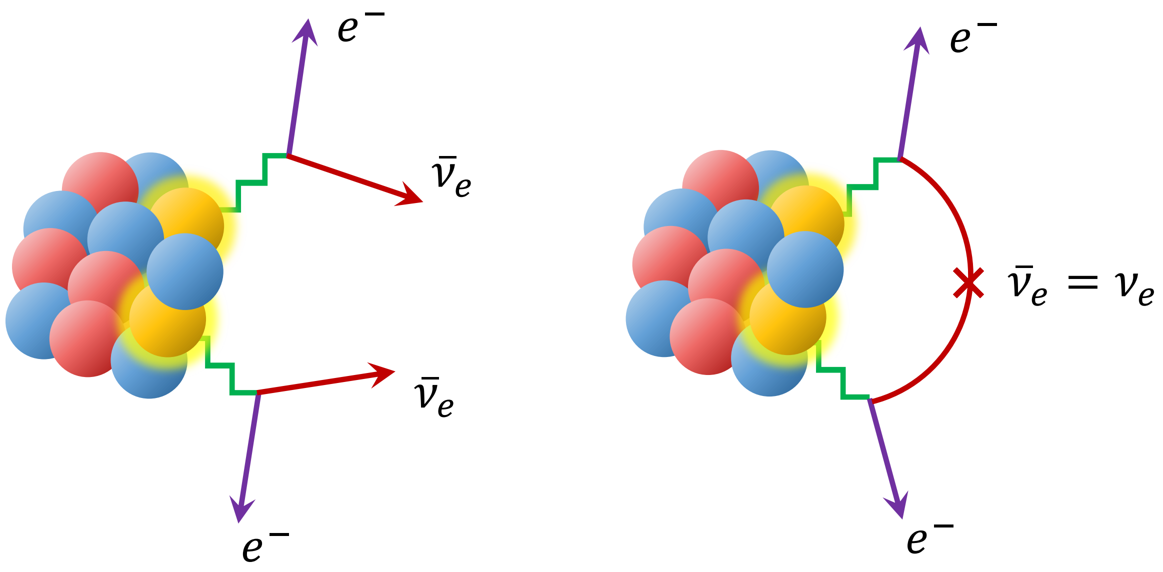


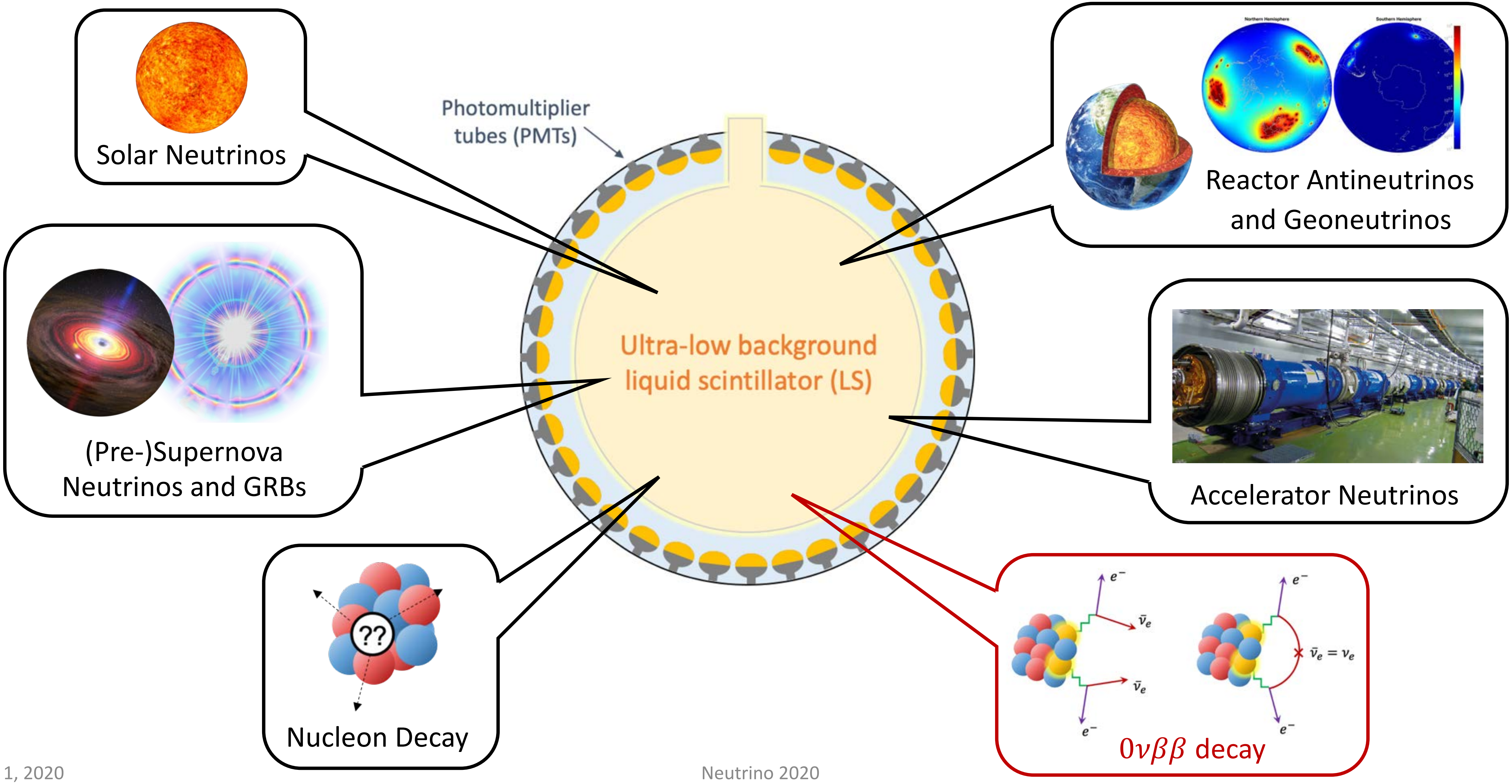
KamLAND-Zen and SNO+

Christopher Grant

Boston University

On behalf of the SNO+ and KamLAND-Zen Collaborations

Pursuing Crosscutting Science with Big Detectors



KamLAND-Zen

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

Mini-balloon:

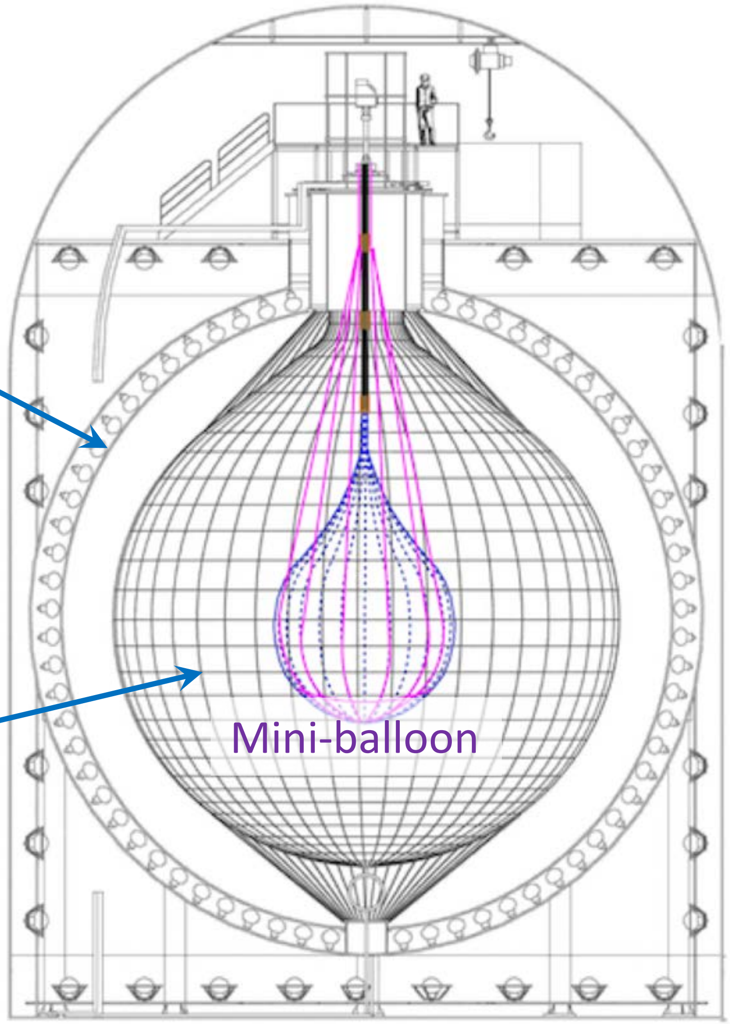
- 25-μm-thick nylon film (durable)
- Fabricated in class-1 clean room
- Highly transparent (~99% at 400 nm)

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

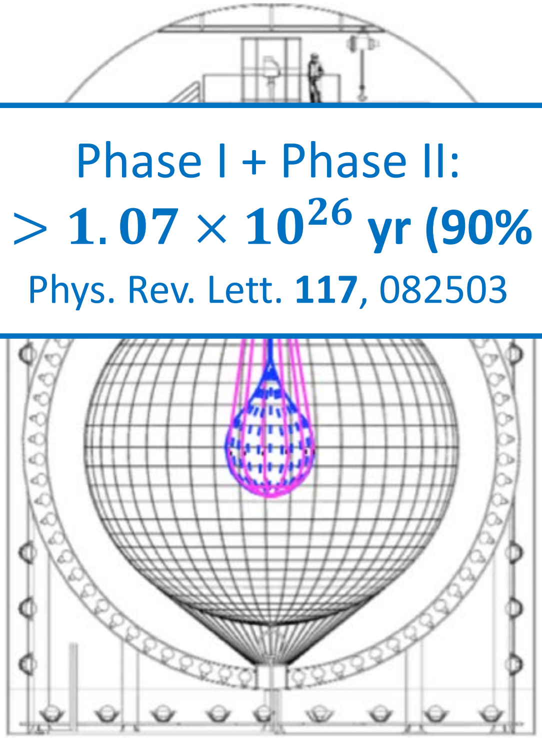


91% enriched ^{136}Xe loaded in LS inside mini-balloon (Q value = 2.4578 MeV)

Evolution of KamLAND-Zen

"Future Neutrinoless Double Beta Decay Experiments"
Jason Detwiler (next Session)

Past



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

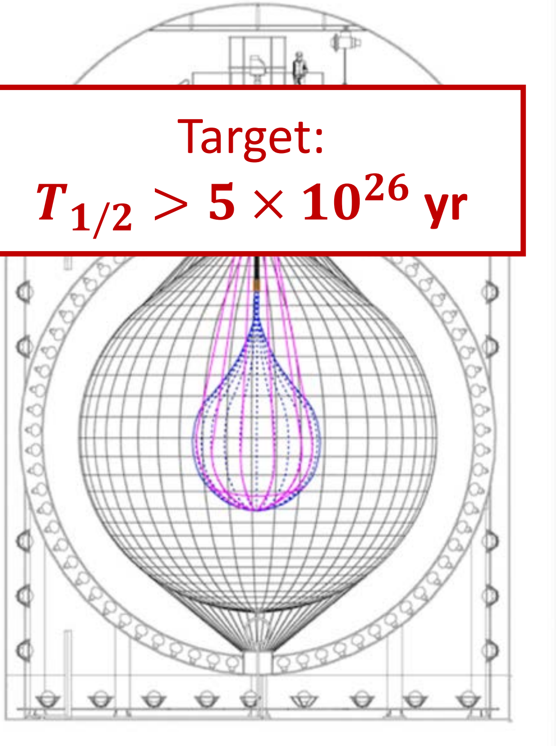
KamLAND-Zen 400

Mini-balloon Radius = 1.54 m

Xenon mass = 320 ~ 380 kg

2011 ~ 2015

Current



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

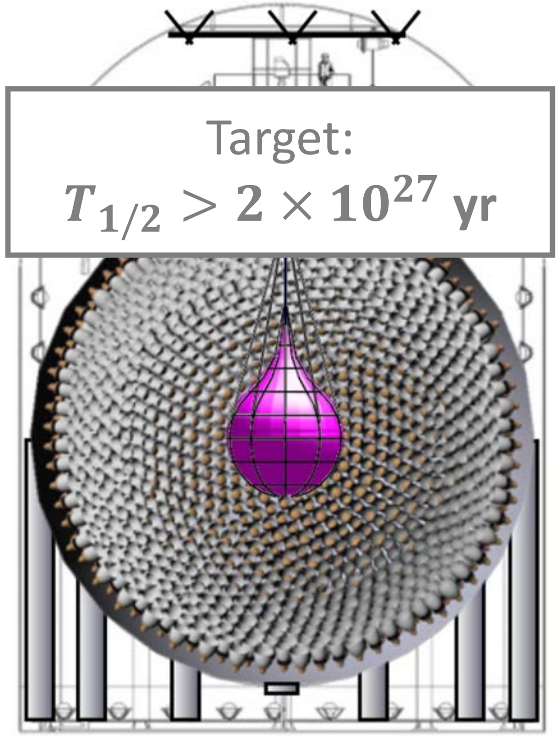
KamLAND-Zen 800

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

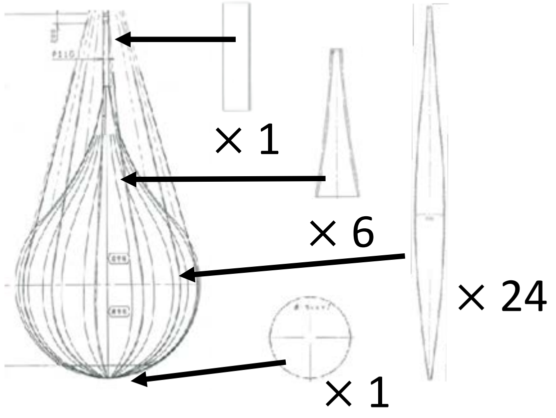
Xenon mass ~ 1 ton

× 5 increase in light collection

Scintillation balloon film

Mini-Balloon Fabrication in Sendai (2017 - 2018)

All work performed inside a Class 1 clean room in Sendai



① Film Washing

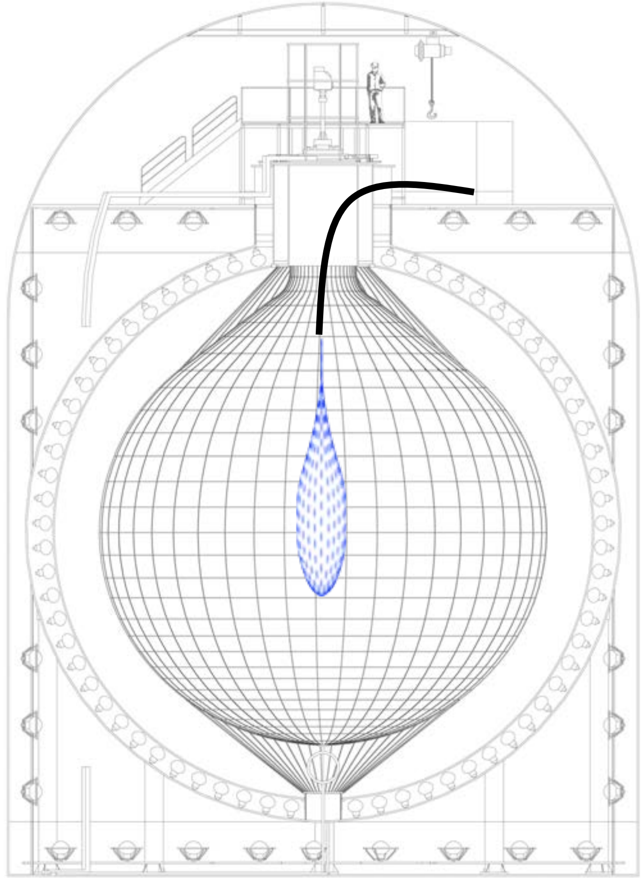
② Seam Welding

③ He leak test + repairs

④ Folding

⑤ Packaging

Mini-Balloon Installation (May 2018)



…after nearly 1.5 years, new mini-balloon fabrication and installation was finished

LS Purification and Xe Loading

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

(Balloon installed)

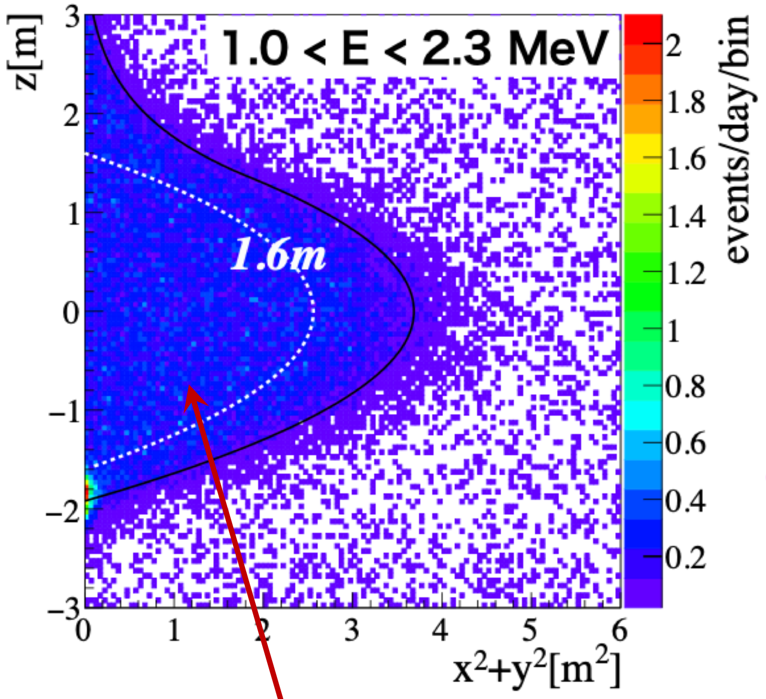
<u>LS purification</u>

H_2O extraction, distillation, N_2 purging to reduce instrinsic backgrounds

<u>Xe loading</u>

Total of 745 kg (~3.0% wt)

<u>Data taking</u>



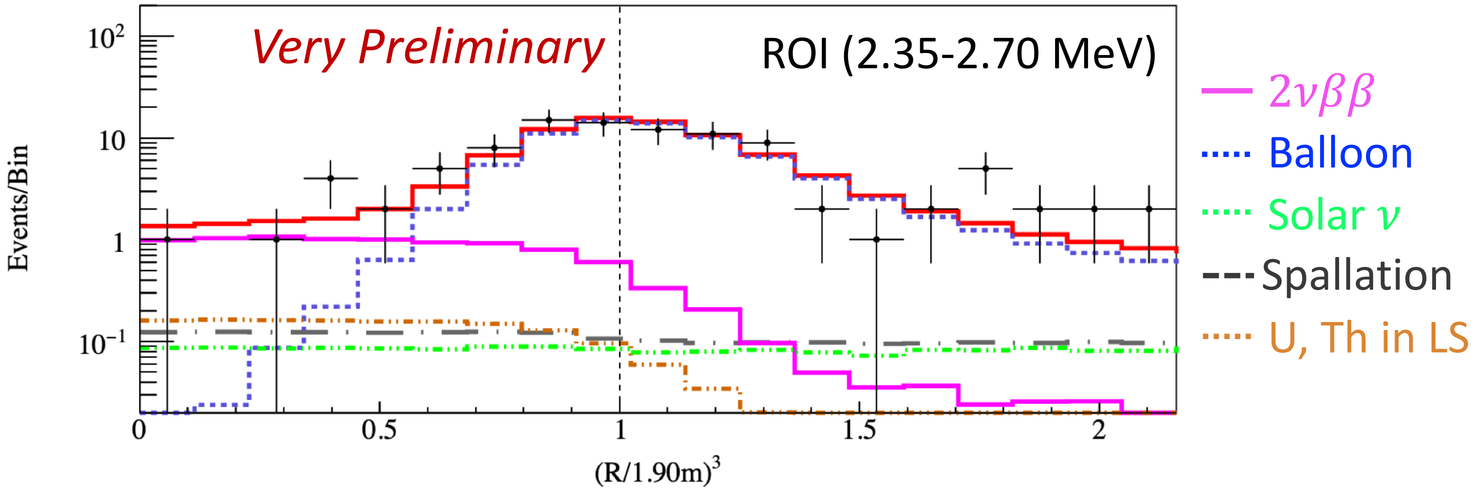
Rate dominated by $2\nu\beta\beta$ decays

Balloon film backgrounds:

^{238}U $\sim 3 \times 10^{-12}$ g/g

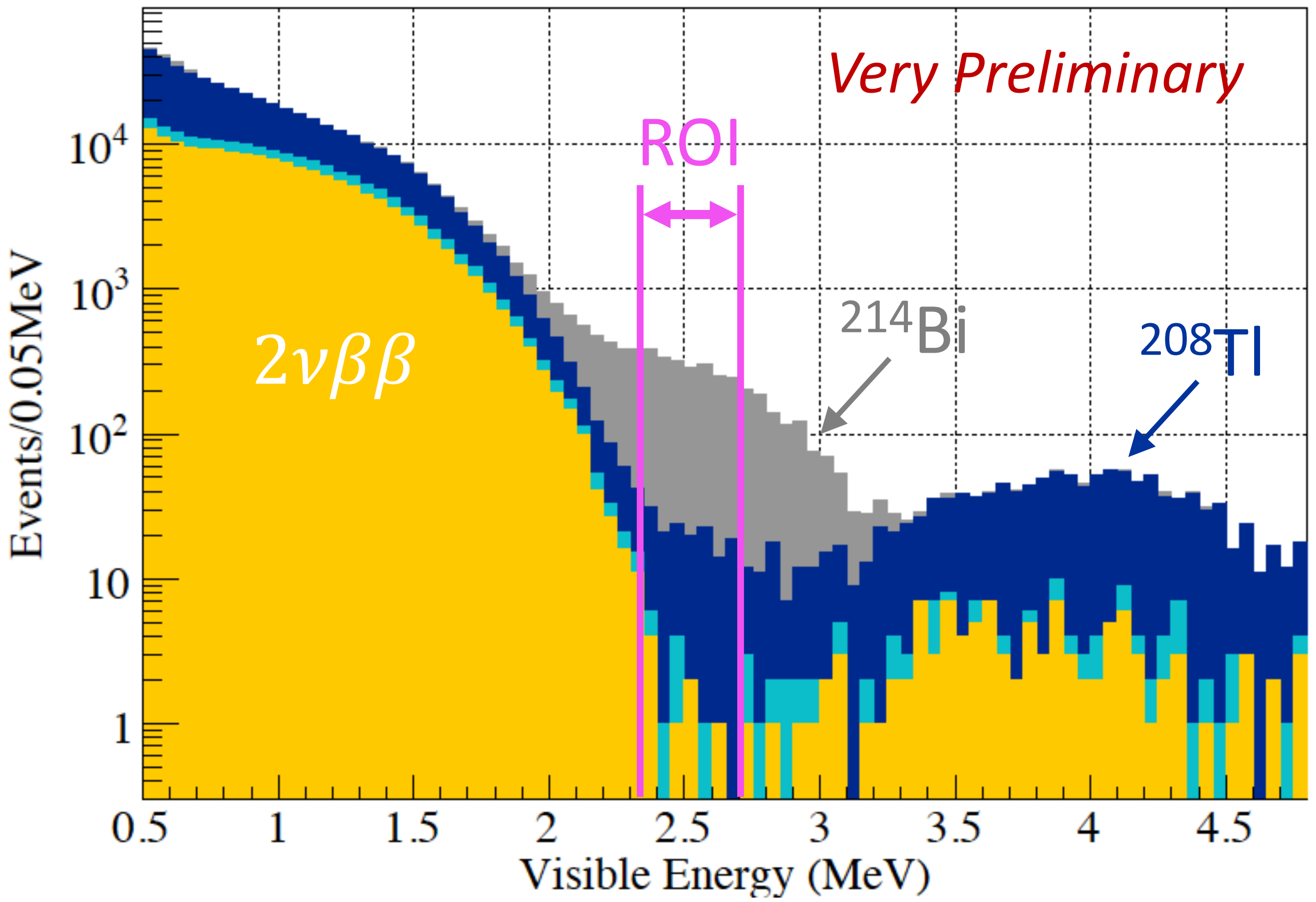
^{232}Th $\sim 4 \times 10^{-11}$ g/g

×10 reduction compared to KLZ 400 mini-balloon



Event Selection (the following was presented at TAUP 2019)

Total livetime of 132.7 days



Cuts used to reduce backgrounds:

r < 240 cm

Select events inside and just outside of the mini-balloon

Rn cut

Delayed coincidence cut for ^{214}Bi – ^{214}Po and ^{212}Bi – ^{212}Po

Fiducial volume cut

Further reduce backgrounds going from r < 240 cm to r < 157 cm

Spallation Cut

Remove events correlated with muons

Fitting the Data

- Simultaneously fit 40 equal volume bins inside of r < 2.5 m

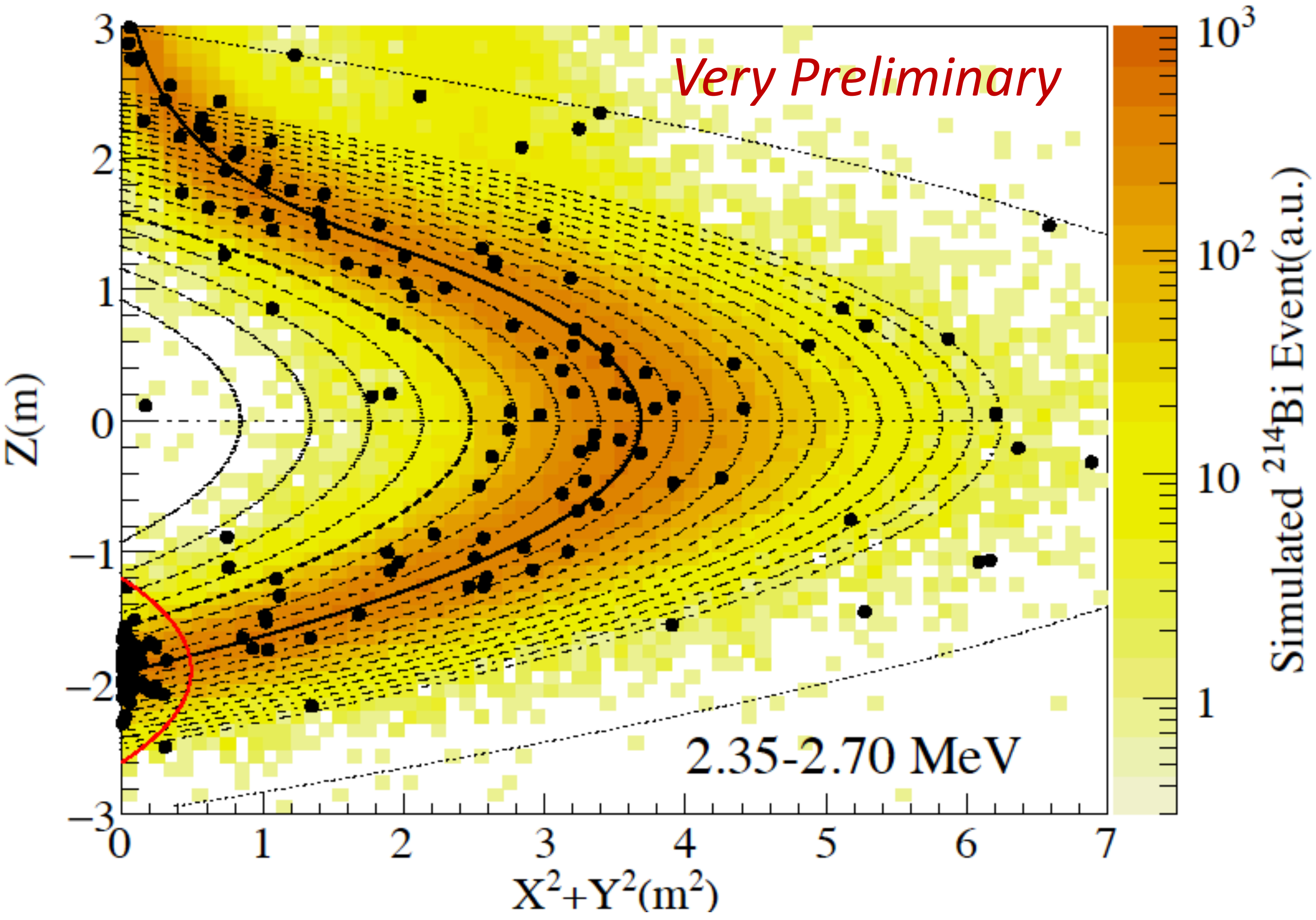
  Outer region → more sensitive to backgrounds on mini-balloon film (^{214}Bi, etc.)

  Inner region → more sensitive to $0\nu\beta\beta$ decay

- Excess events at bottom of the mini-balloon removed using spatial cut

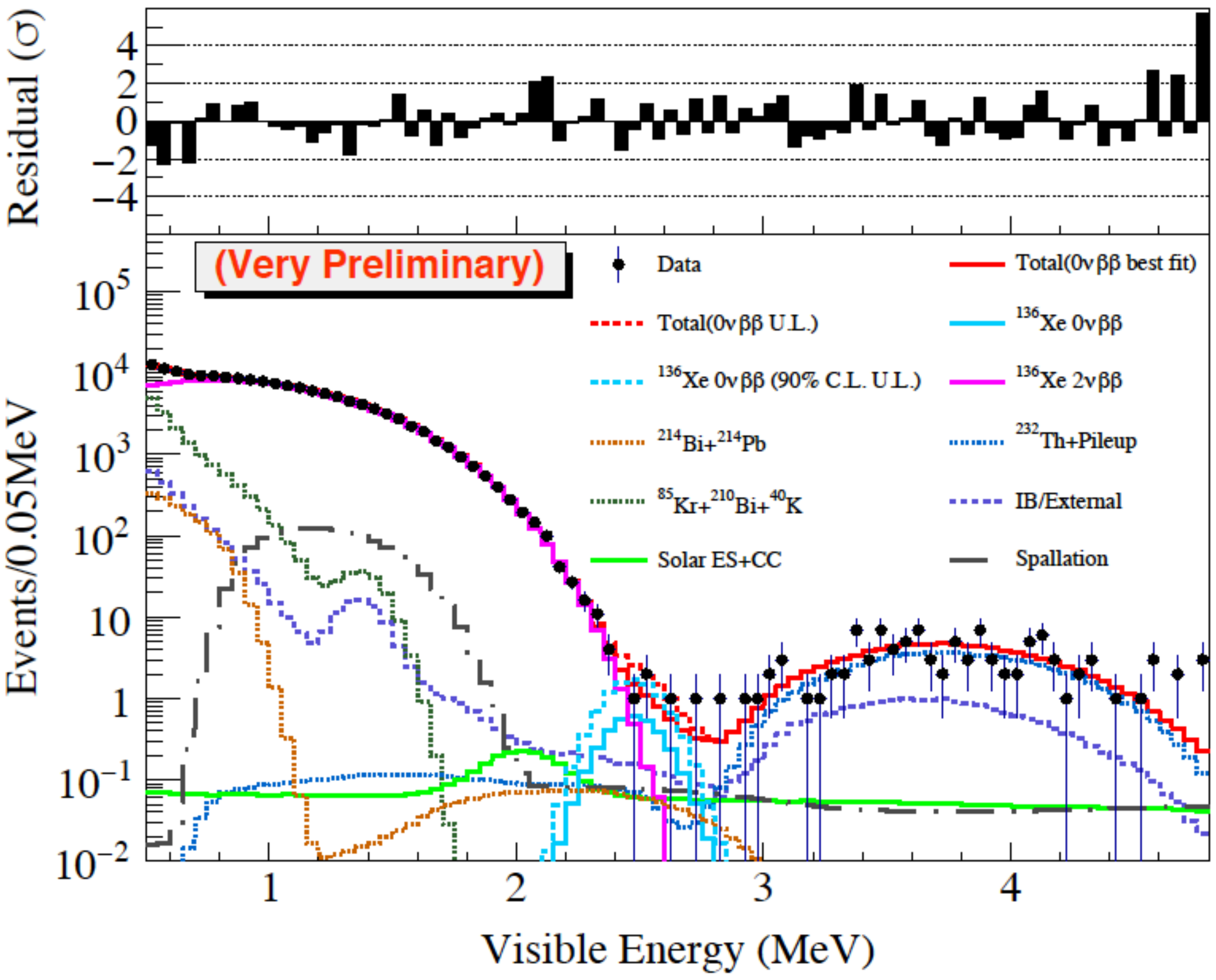
- Separate frequentist and Bayesian fitting analyses performed with 31 free parameters and 40 volume bins

Vertex distribution of events in the ROI overlayed on ^{214}Bi MC



Frequentist Fitting Results

*Data shown for r < 1.57 m



Summary for 246.1 kg-year of ^{136}Xe exposure

8 events observed in the ROI

$0\nu\beta\beta$ decay best-fit value:

2.8 events

Total ROI background best-fit value:

7.9 events

90% C.L. upper limit:

$T_{1/2}^{0\nu} > 4 \times 10^{25}$ years

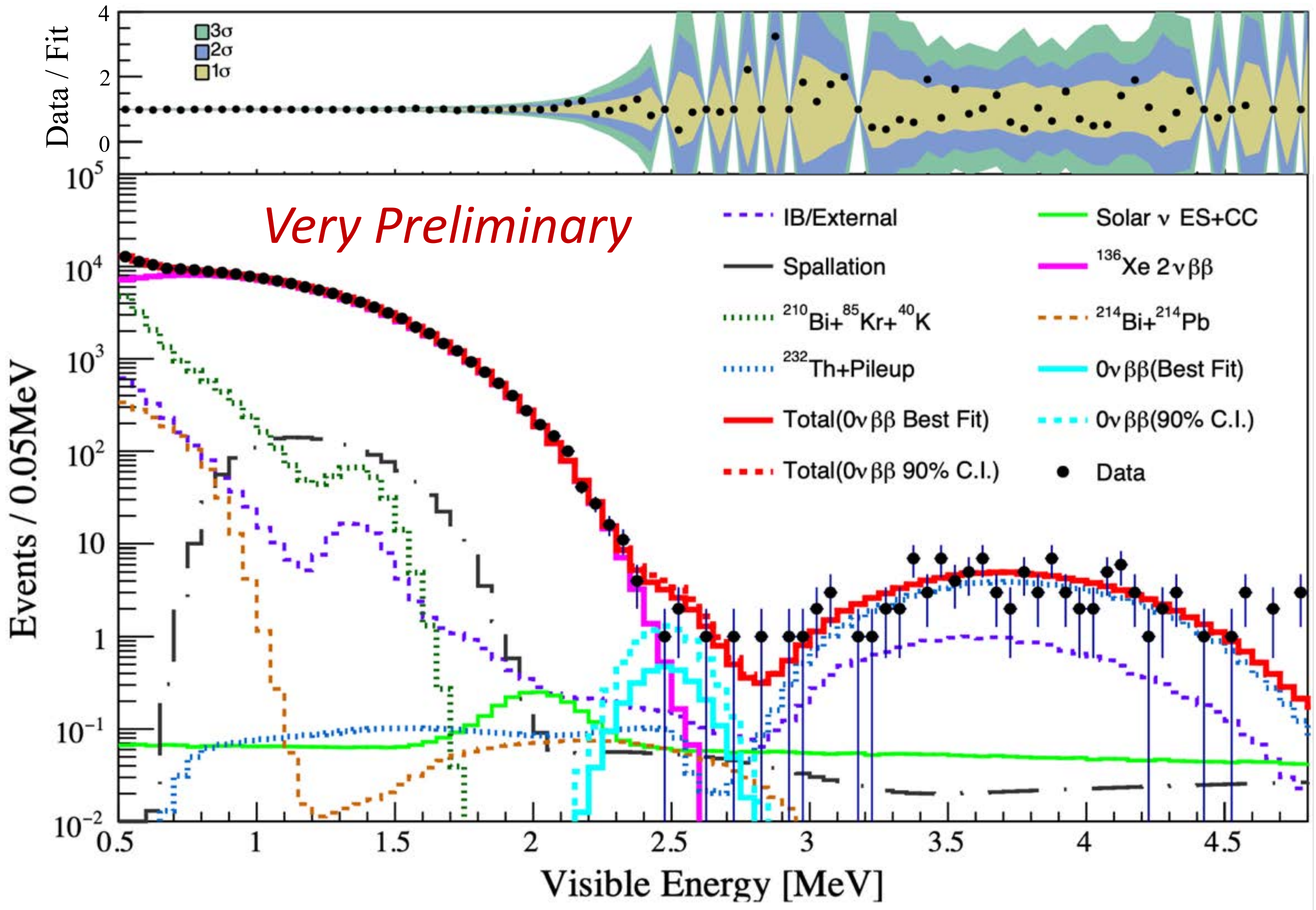
Median Sensitivity

$T_{1/2}^{0\nu} > 8 \times 10^{25}$ years

Bayesian Fitting Results

Poster #411 in Session 3
Aobo Li

*Data shown for r < 1.57 m



$0\nu\beta\beta$ decay best-fit value:

2.6 events

Total ROI background best-fit value:

8.1 events

90% C.L. upper limit:

$T_{1/2}^{0\nu} > 4.3 \times 10^{25}$ years

Frequentist and Bayesian analyses are in reasonable agreement.

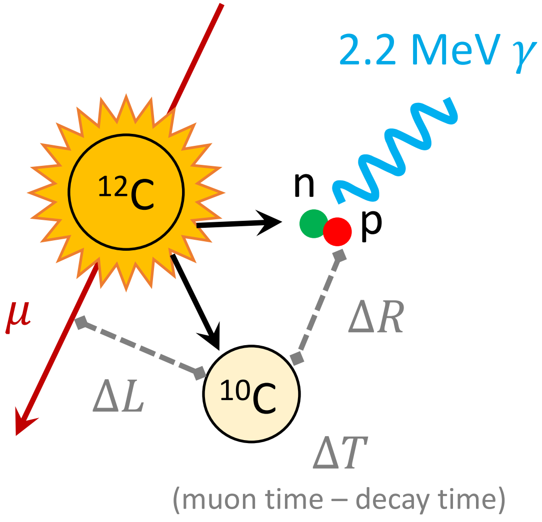
We now have nearly twice the additional exposure for a total of 482 kg-year which is currently being analyzed.

Very Preliminary

Analysis Improvements Since TAUP 2019

Muon spallation on ^{136}Xe is being studied extensively

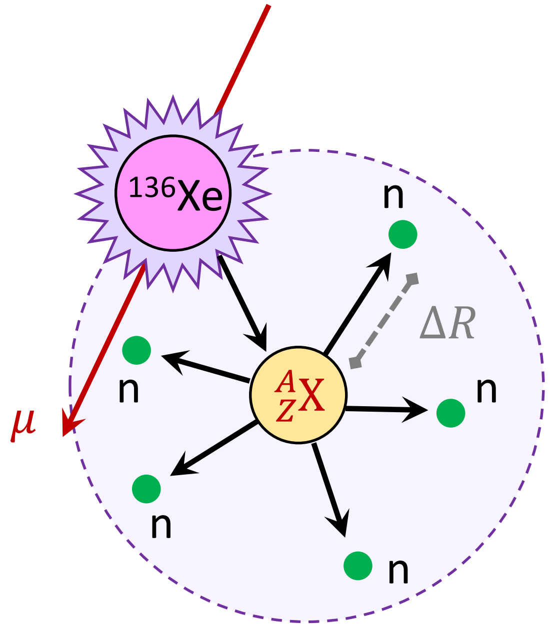
Spallation on ^{12}C



Isotopes with small A are rejected based on timing and spacial distance information (triple coincidence)

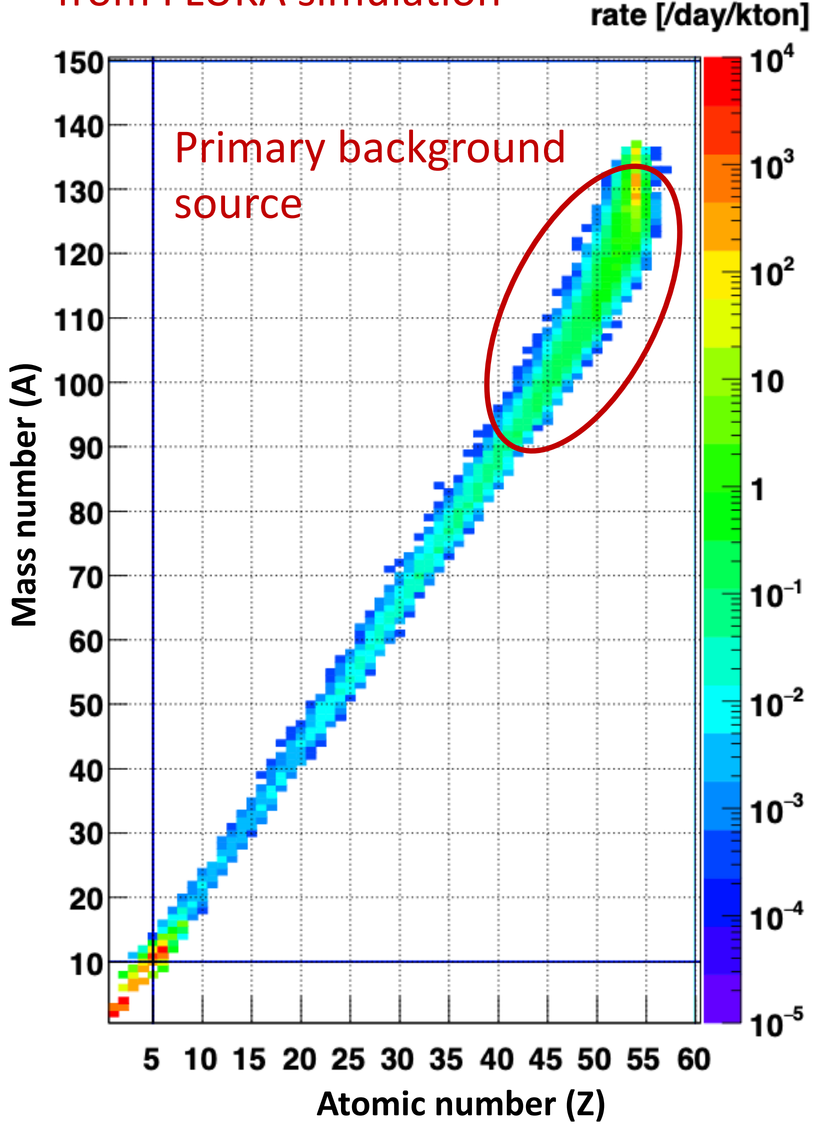
Poster #106 in Session 3
Yuto Kamei

(NEW) Spallation on ^{136}Xe



Can a similar technique be applied to high A isotopes with high neutron multiplicity?

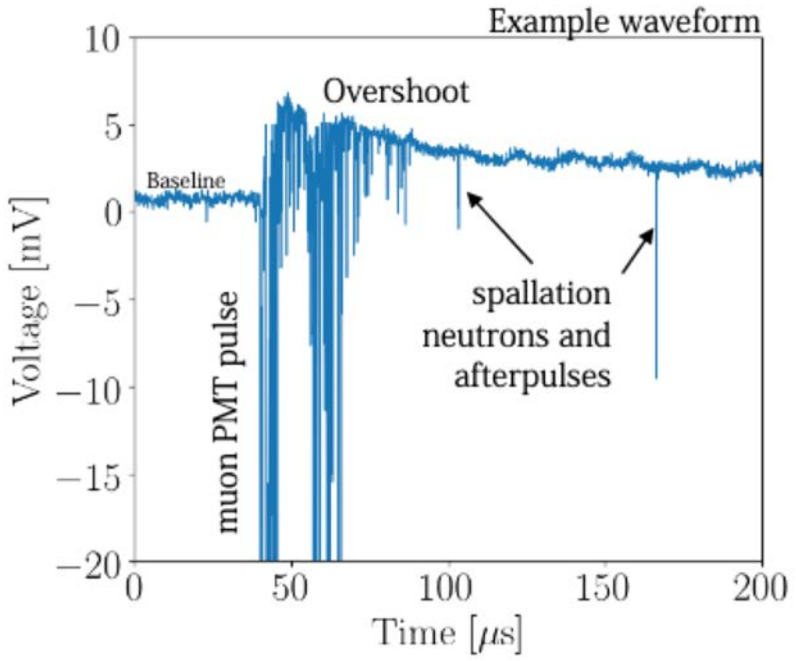
$\mu +$ ^{136}Xe spallation byproducts from FLUKA simulation

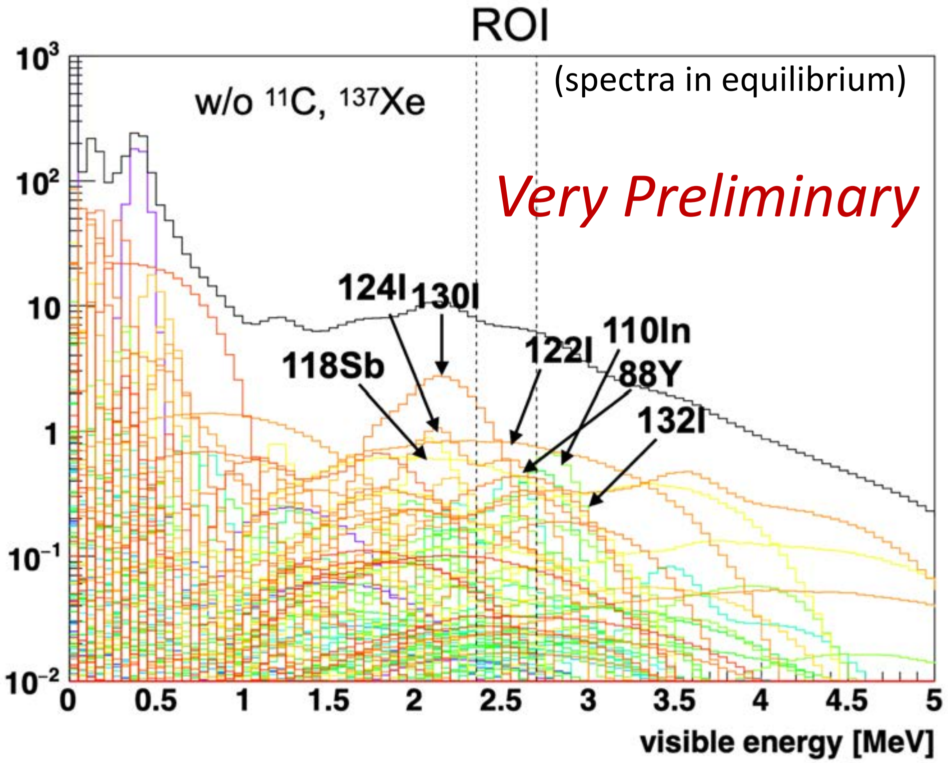


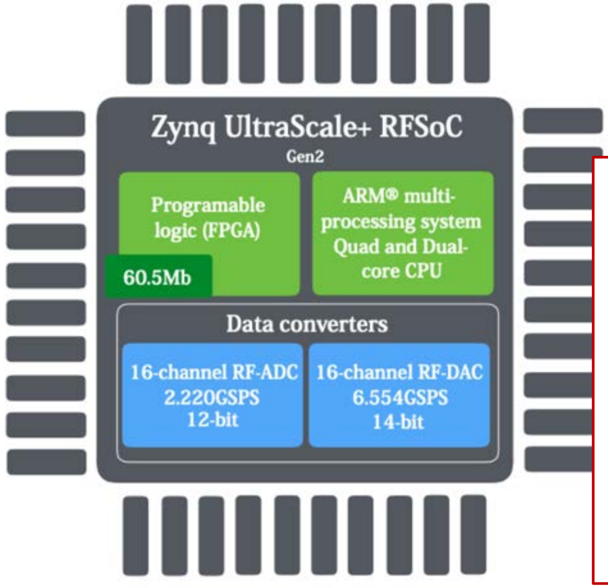
Long-Lived Spallation Rejection

High A spallation isotopes in the ROI have half-lives ranging from **several hours to several days – they also occur at a very low rate**

We've developed a special day-long spallation veto to efficiently remove at least 50% of these events from the analysis





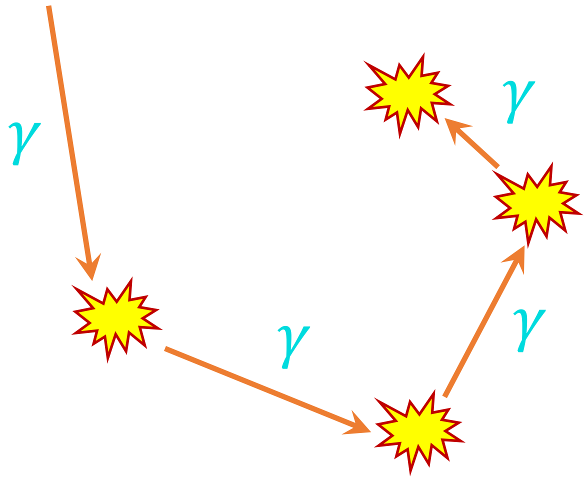


Poster #499 in Session 3
Spencer Axani

New MoGURA2 zero-deadtime electronics with active baseline restoration will improve spallation neutron tagging thereby improving long- and short-lived spallation rejection

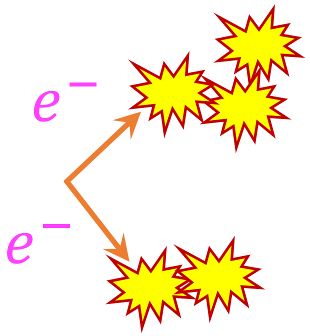
Background Rejection with Deep Learning

Poster #414 in Session 2
Zhenghao Fu

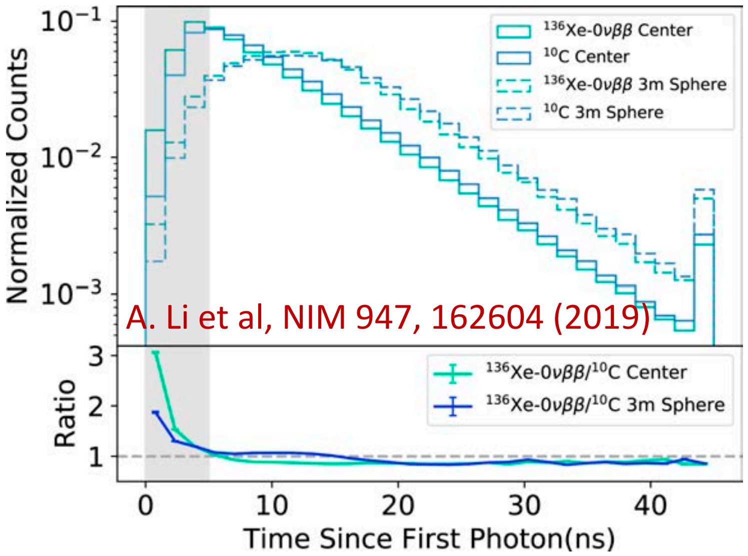


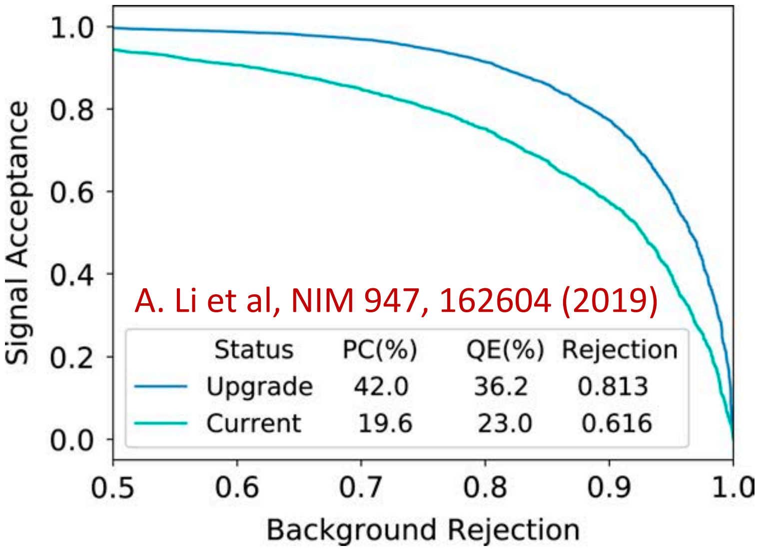
Background decays with ~MeV gamma-rays typically have energy deposits (Compton scatters) spread over distances of tens of centimeters.

Decays only containing ~MeV electrons are more localized.

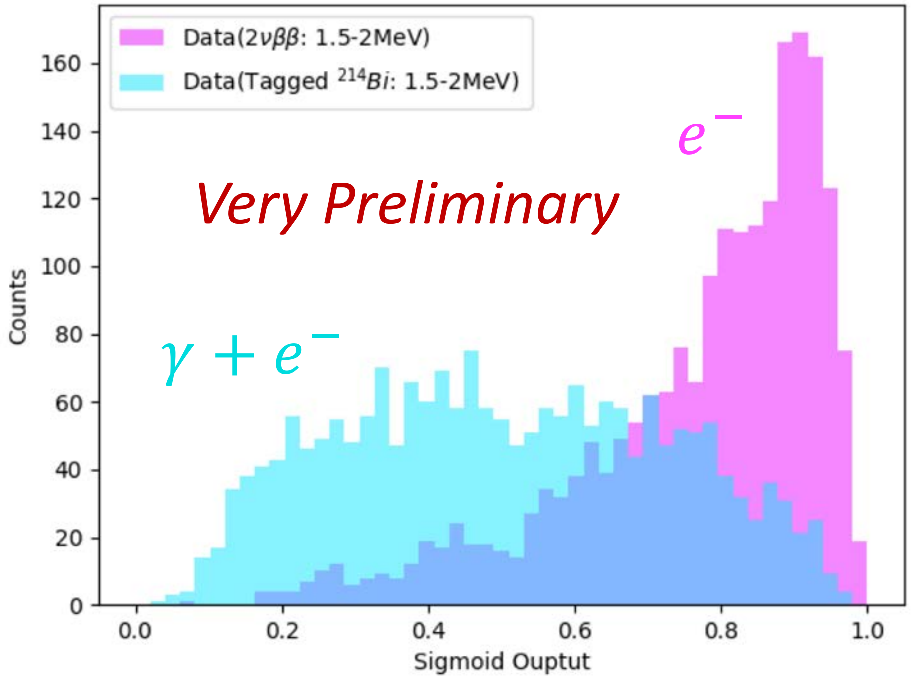


CNN applied to MC of ^{10}C and $0\nu\beta\beta$ events in a KLZ-like detector





Spherical CNN applied to subset of KLZ data



Now moving from KamLAND KamLAND-Zen to SNO+

SNO+

Located at 6800 ft depth in SNOLAB (6000 m.w.e.)

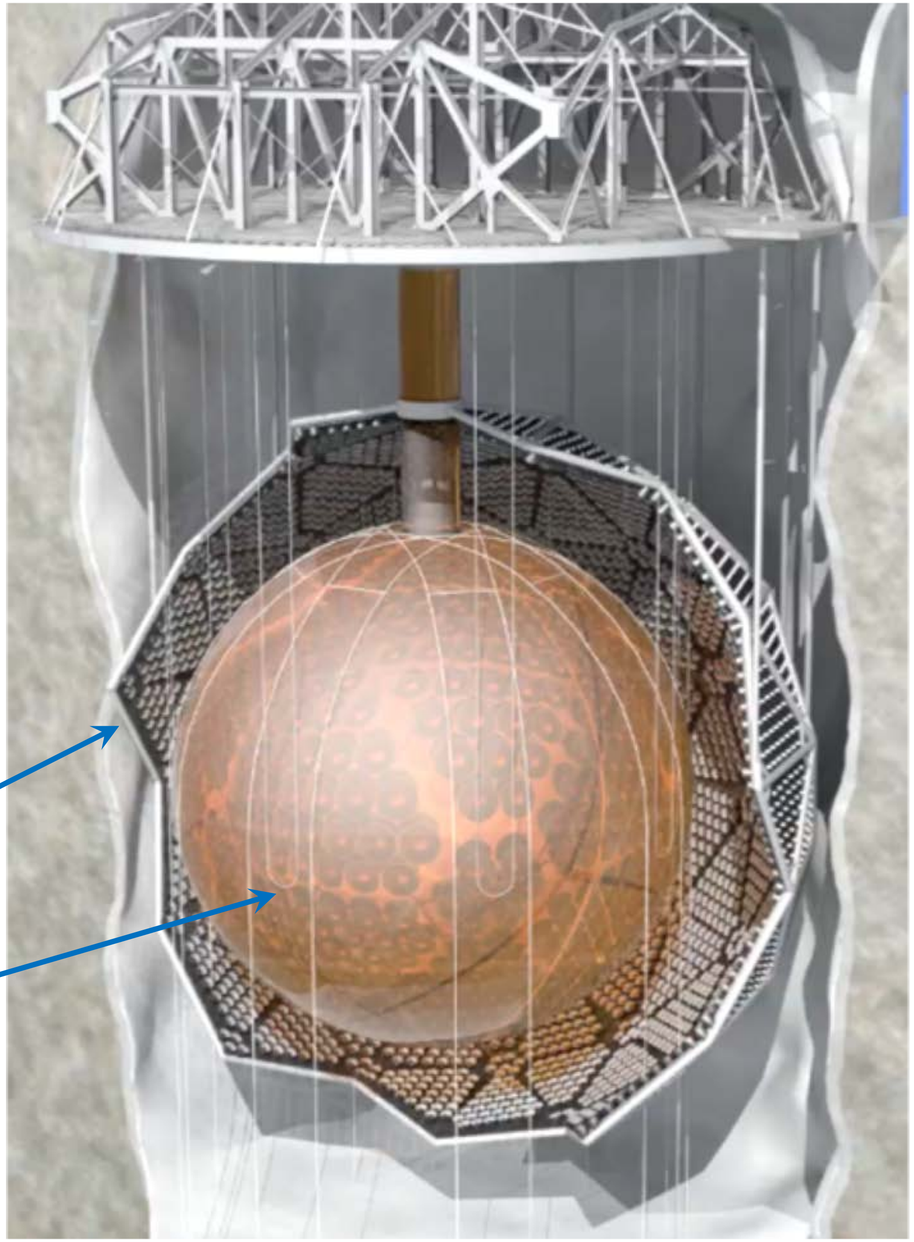
- 12m diameter acrylic vessel with 780 tons of LS
- ~9300 inward facing PMTs with light concentrators and ~90 outward facing PMTs for tagging cosmic rays

New:

- Addition of hold-down ropes to counter buoyancy of LS
- Upgraded electronics for higher data-taking rates
- New calibration systems for LS

~50% photocoverage

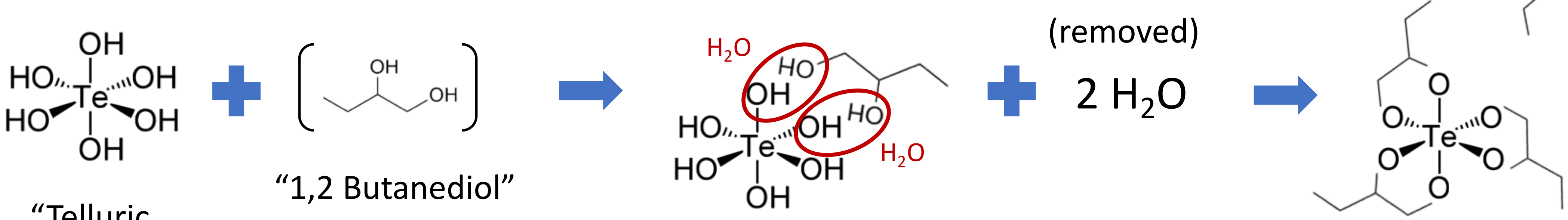
780 tons of LS
- LAB
- 2 g/L PPO



^{130}Te Loading in Liquid Scintillator

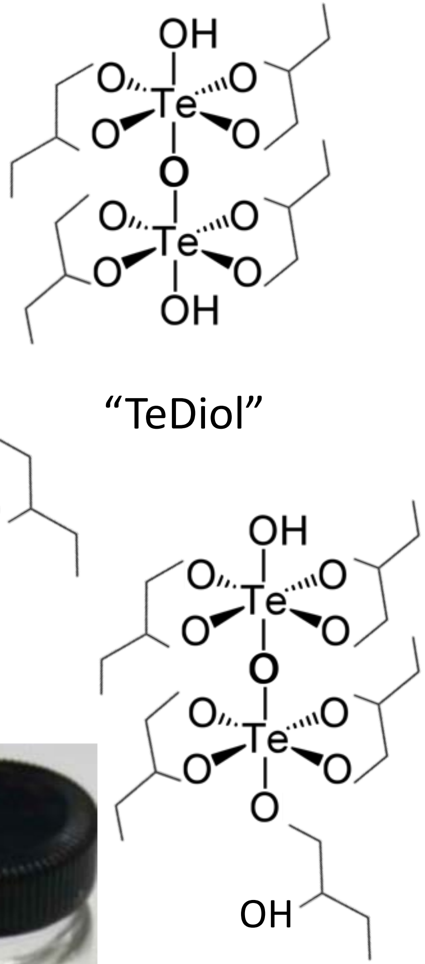
^{130}Te makes up 34% of the natural Te abundance (Q value = 2.5275 MeV)

Forming an organometallic compound from telluric acid and butanediol:



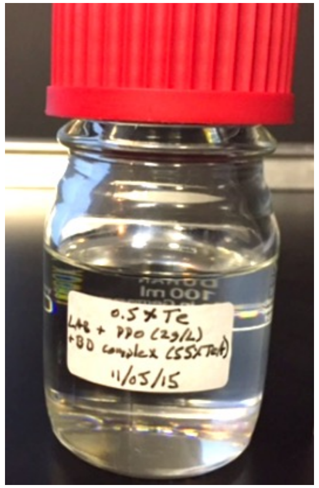
"Telluric Acid (TeA)"

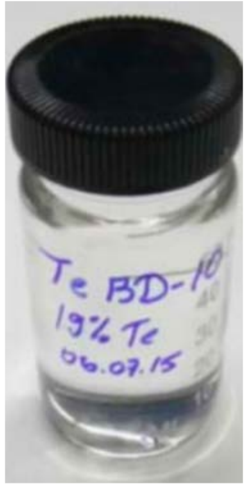
"1,2 Butanediol"



"TeDiol"

- TeDiol (TeBD) is mixed directly into SNO+ LS with 15 mg/L bis-MSB and a stabilizer called Dimethyldodecylamine (DDA)
- Optical transparency and light yield of the final Te-loaded LS cocktail are expected to produce ~ 460 p.e. / MeV in SNO+ for 0.5% ^{nat}Te loading by weight

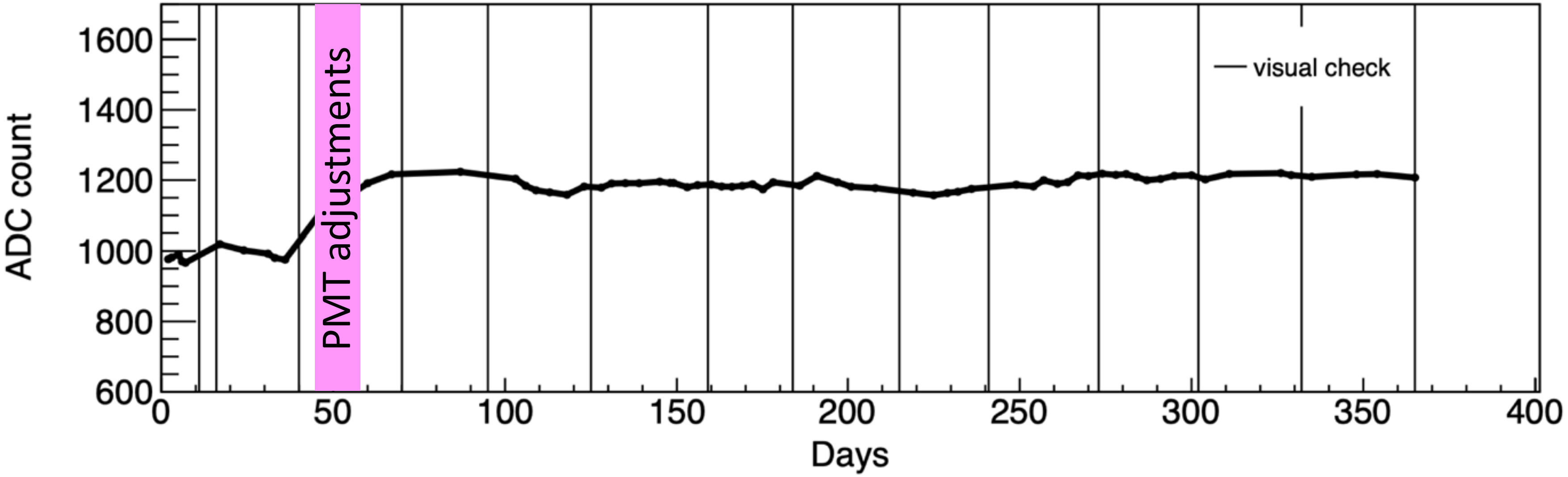


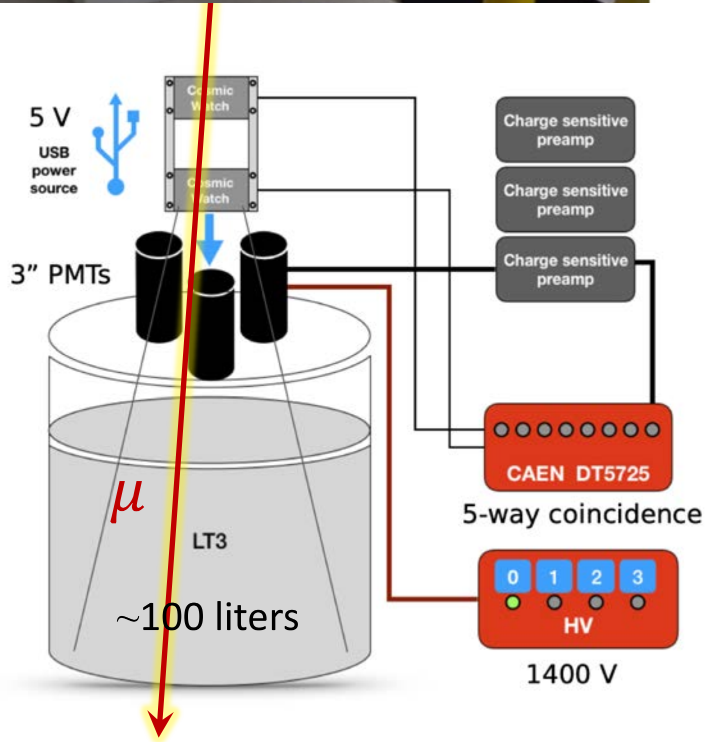


^{130}Te Loading in Liquid Scintillator

- Chemistry and long-term stability of Te-loaded LS has been studied extensively by SNO+
- One example: Light yield of ~**100 liters** 0.5% ^{nat}Te-loaded LS was measured by Long-Term Test Tank (LT^3) at BU. Light yield been stable for more than a year and counting.

*Courtesy of Kat Frankiewicz (BU postdoc)

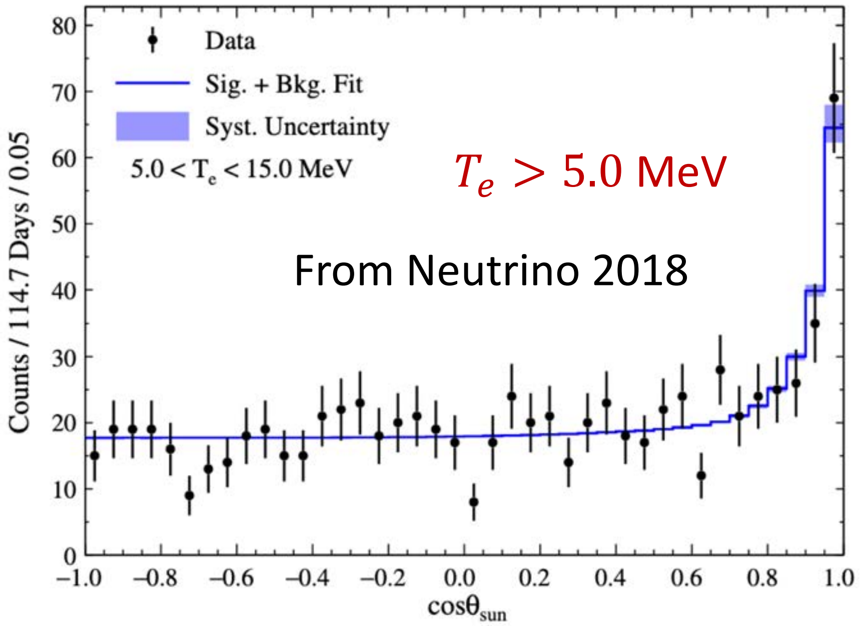




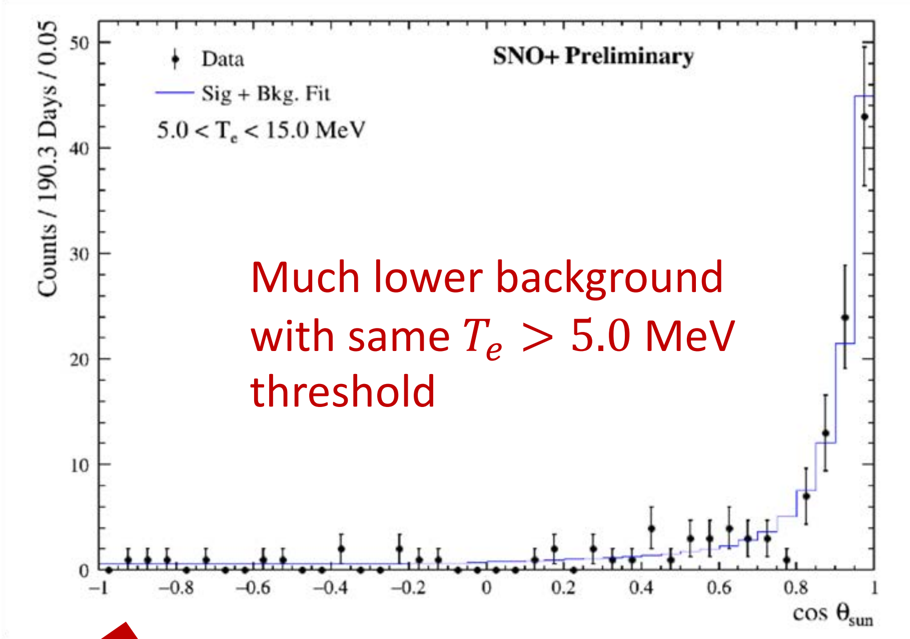
Improved Background Suppression in Water

Poster #424 in Session 4
Brian Krar

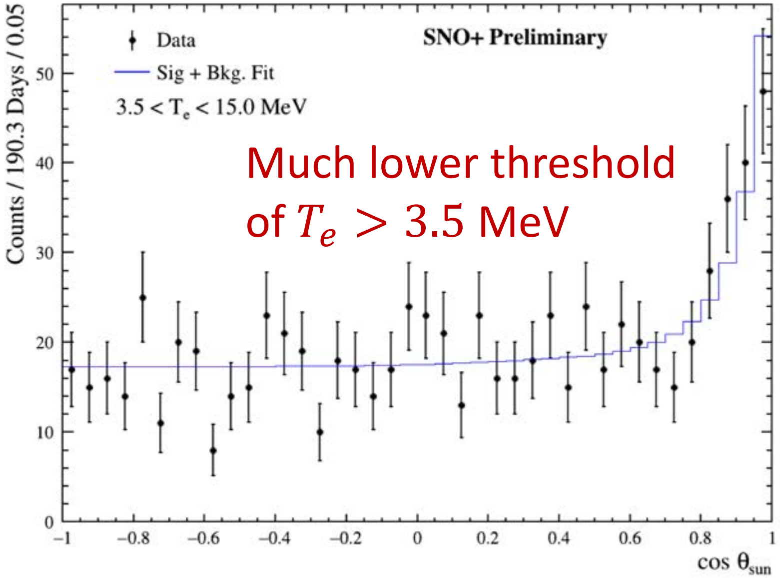
Phys. Rev. D **99**, 012012



NEW



NEW



Radon ingress down the neck of the detector was mitigated with a N_2 cover gas, further suppressing the already low backgrounds and enabling a much lower threshold on the solar neutrino analysis

Same strategy is being used during scintillator filling

LS Purification and Filling

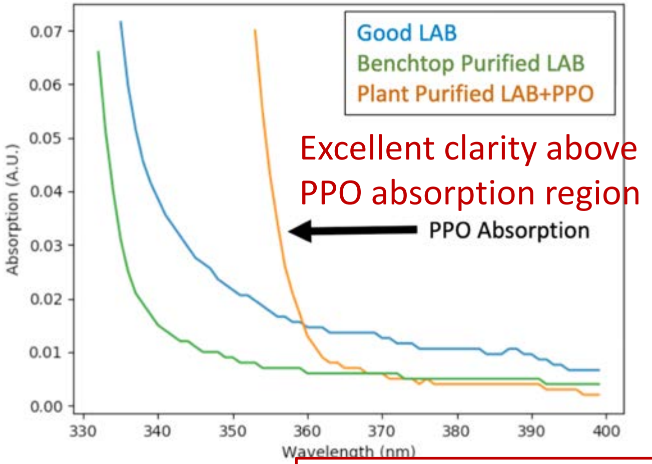
Purification and Filling Systems

Transfer of LAB from surface to underground in tank railcars at SNOLAB

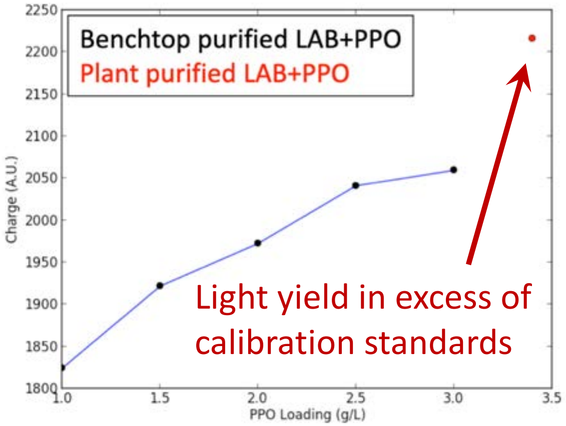
SNOLAB is leading the scintillator filling campaign

- Commissioned underground systems and began filling SNO+ in 2019.
- Filling was temporarily halted in April 2020 due to the pandemic, but as operations begin to fully resume, the scintillator fill will soon be completed.
- Right before pandemic we filled 75 tons in one week.

UV-Vis Absorption Spectrum

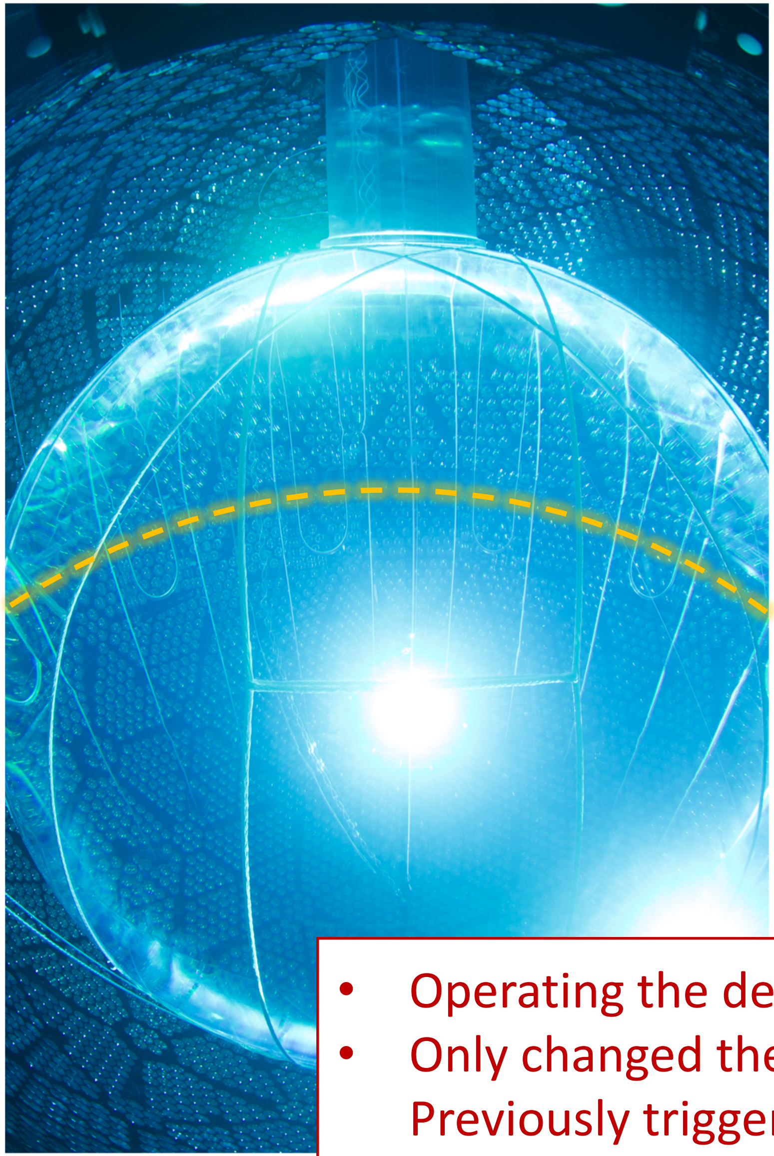


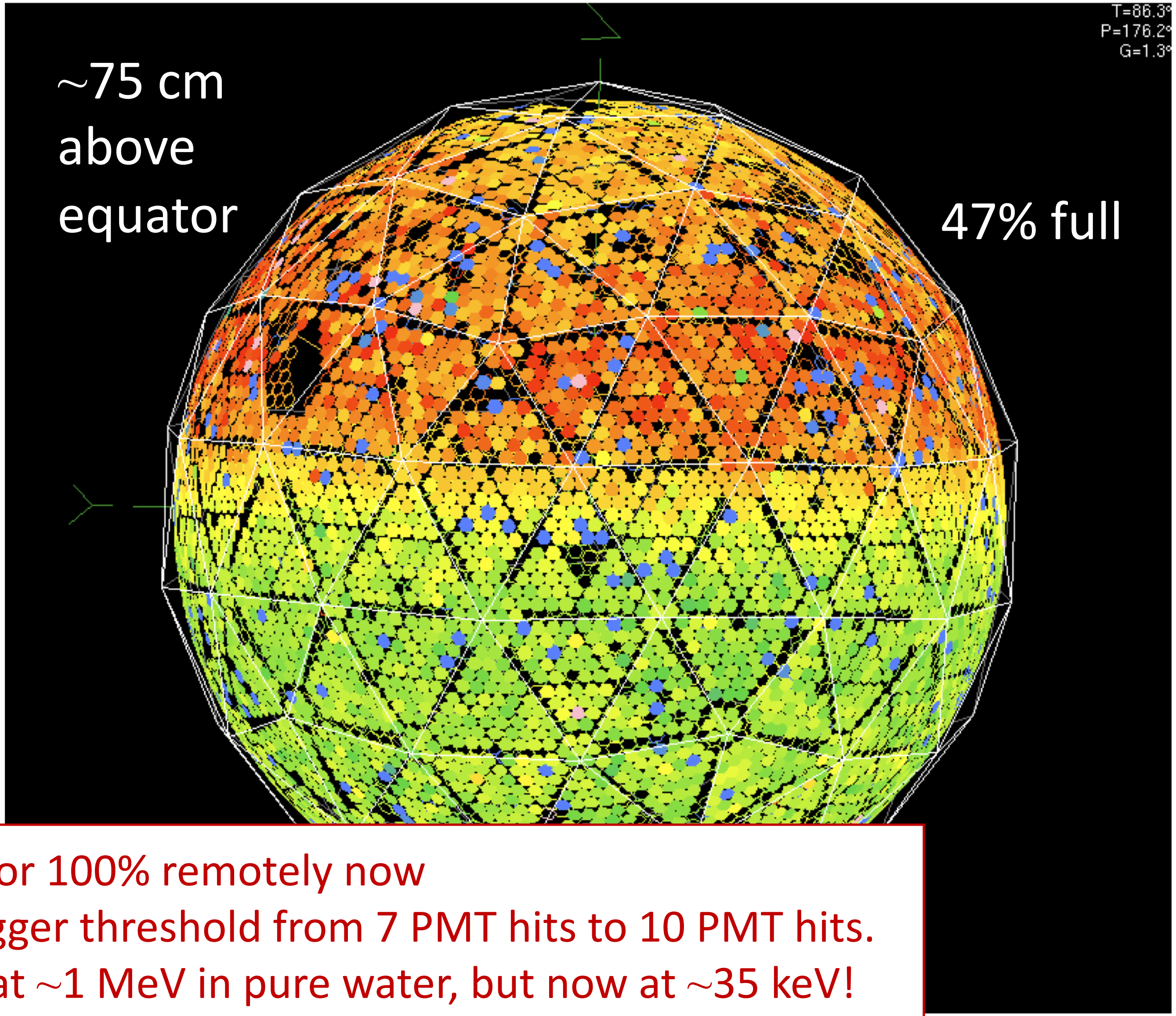
Relative Light Yield



LS quality is better than expected

Nearly half-filled with LS since April 2020



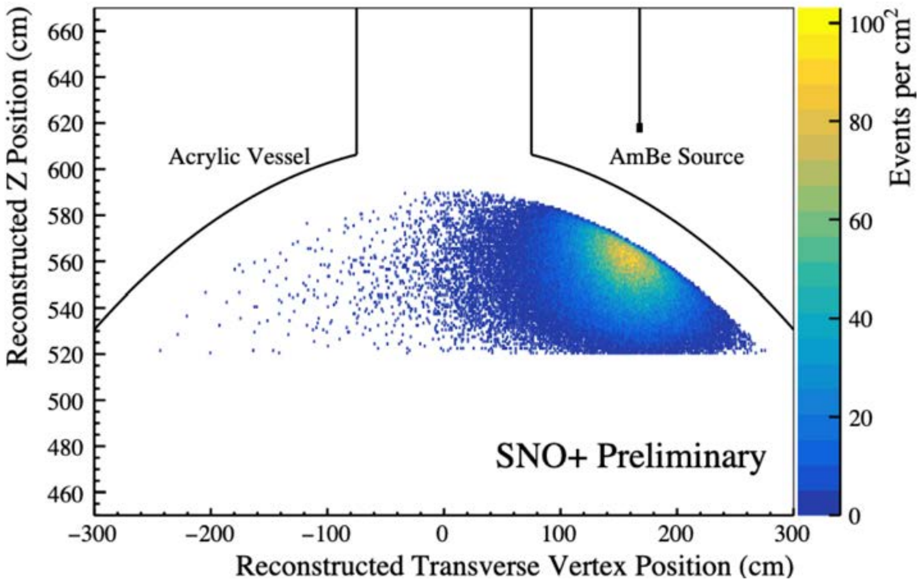


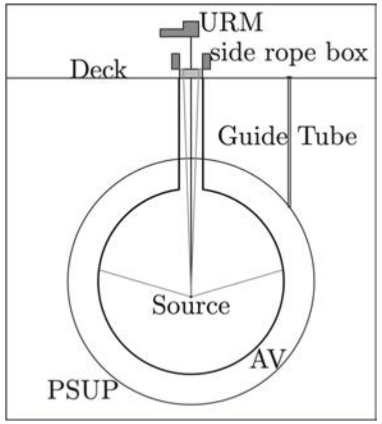
- Operating the detector 100% remotely now
- Only changed the trigger threshold from 7 PMT hits to 10 PMT hits. Previously triggered at ~1 MeV in pure water, but now at ~35 keV!

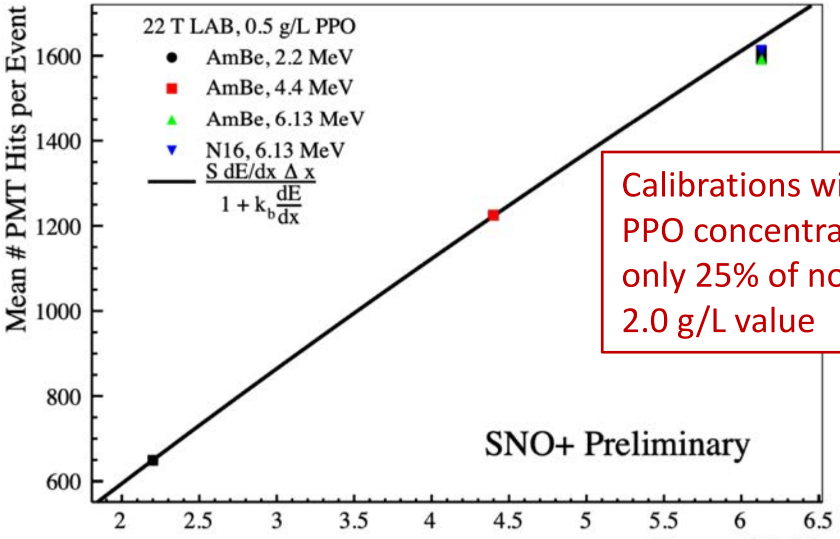
Partial LS Fill Detector Calibration

Poster #432 in Session 4
Ryan Bayes

- Detector response during LS fill was measured with optical and radioactive source calibrations
- Source deployments through guide tubes in regions outside the acrylic vessel leave the new LS undisturbed and avoid contamination
- Demonstrated the capability to reconstruct events in a hybrid LS/water detector







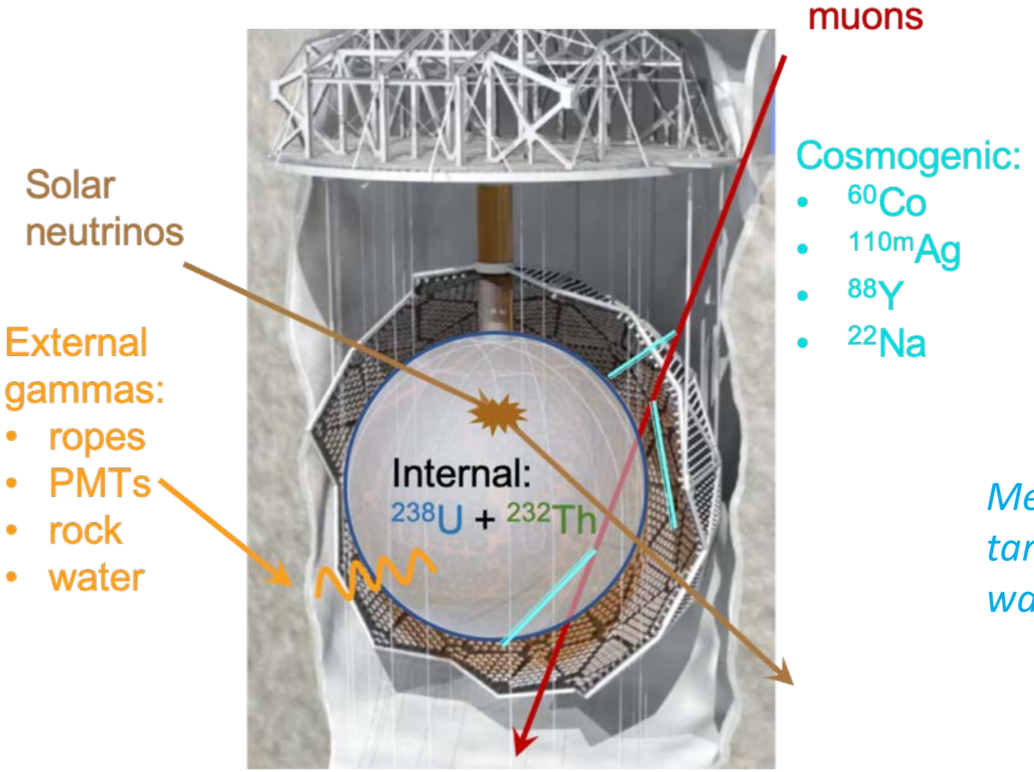
Calibrations with PPO concentration at only 25% of nominal 2.0 g/L value

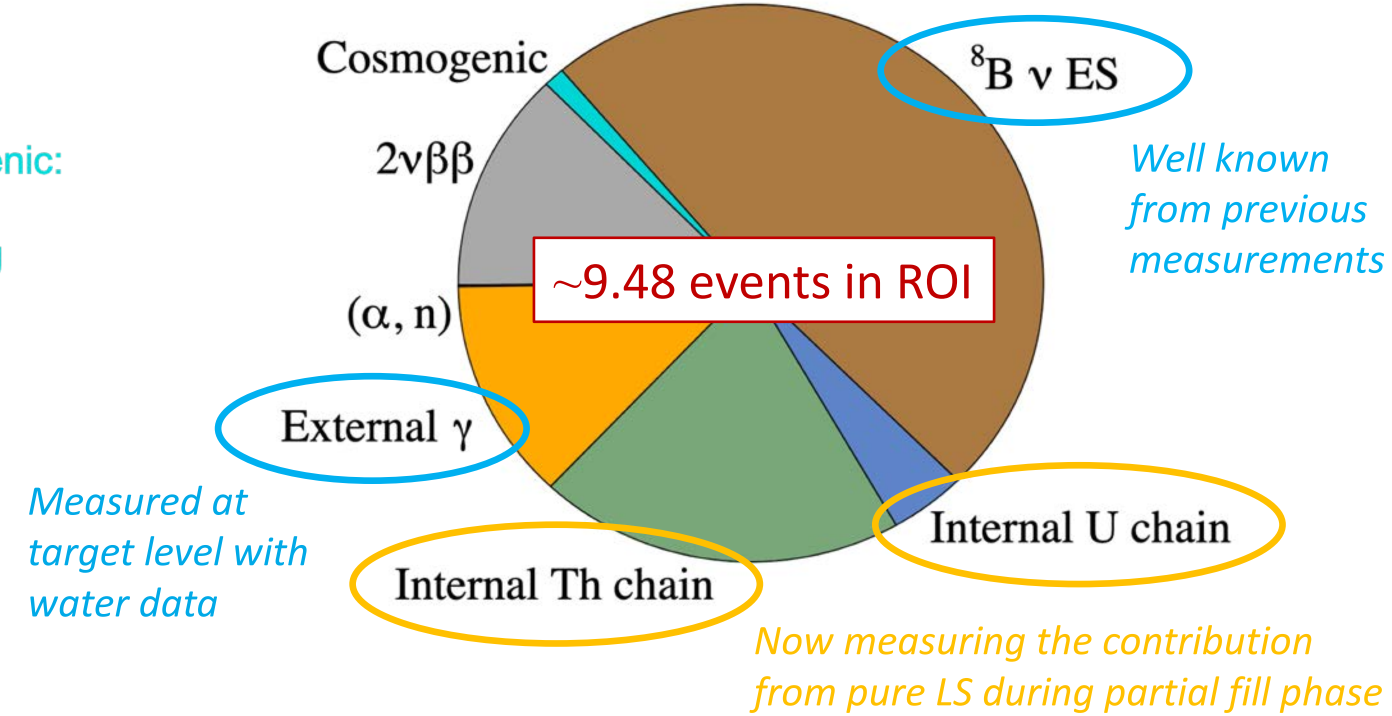
With a PPO concentration of only 0.5 g/L (25% of the nominal value) we see a light yield equivalent to ~300 p.e. / MeV

Extrapolates to ~650 p.e. / MeV at 2.0 g/L PPO

$0\nu\beta\beta$ Background Predictions

ROI: 2.42 – 2.56 MeV [-0.5σ - 1.5σ]





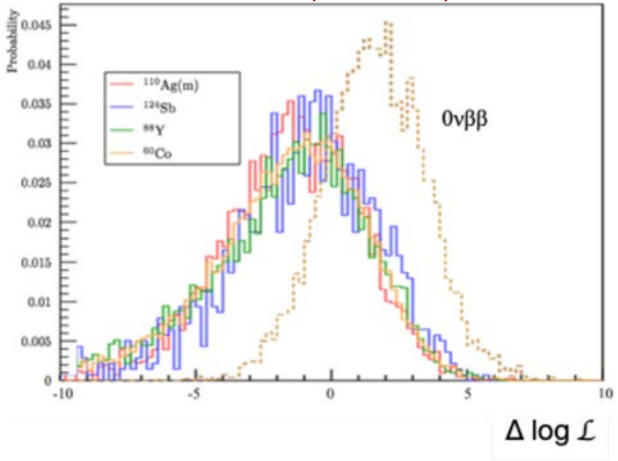
Target concentrations of less than 10^{-15} g/g U and 10^{-16} g/g Th in pure LS are required for $0\nu\beta\beta$ decay.

We're currently below our targets for U and Th in the partial LS phase.

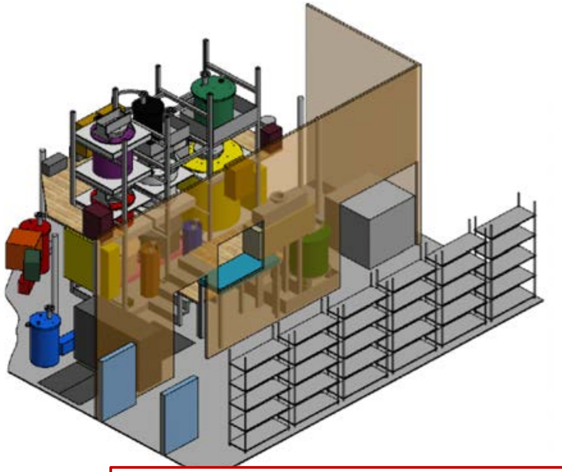
Remaining backgrounds will be measured during Te-loading!

Cosmogenic backgrounds will be verified by multi-site analysis

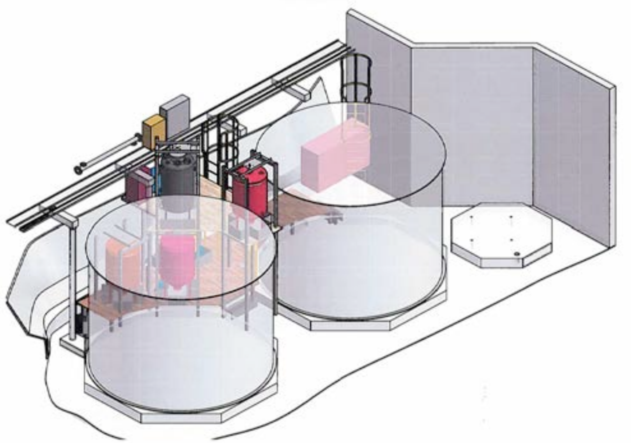
NIM 943, 162420, 2019



Commissioning Tellurium Plants



- Construction and installation of the purification and loading plants is finished
- Preparing for the first test batch of Te purification and synthesis when activities resume in the lab



Tellurium Purification Plant

~8 tons of telluric acid has been "cooling" underground for several years.

Ton-scale underground purification of telluric acid for further background reduction.

Tellurium Loading Plant

SNO+ Projected Sensitivity

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}|M|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

Likelihood analysis after 3 years at 0.5% Te loading:

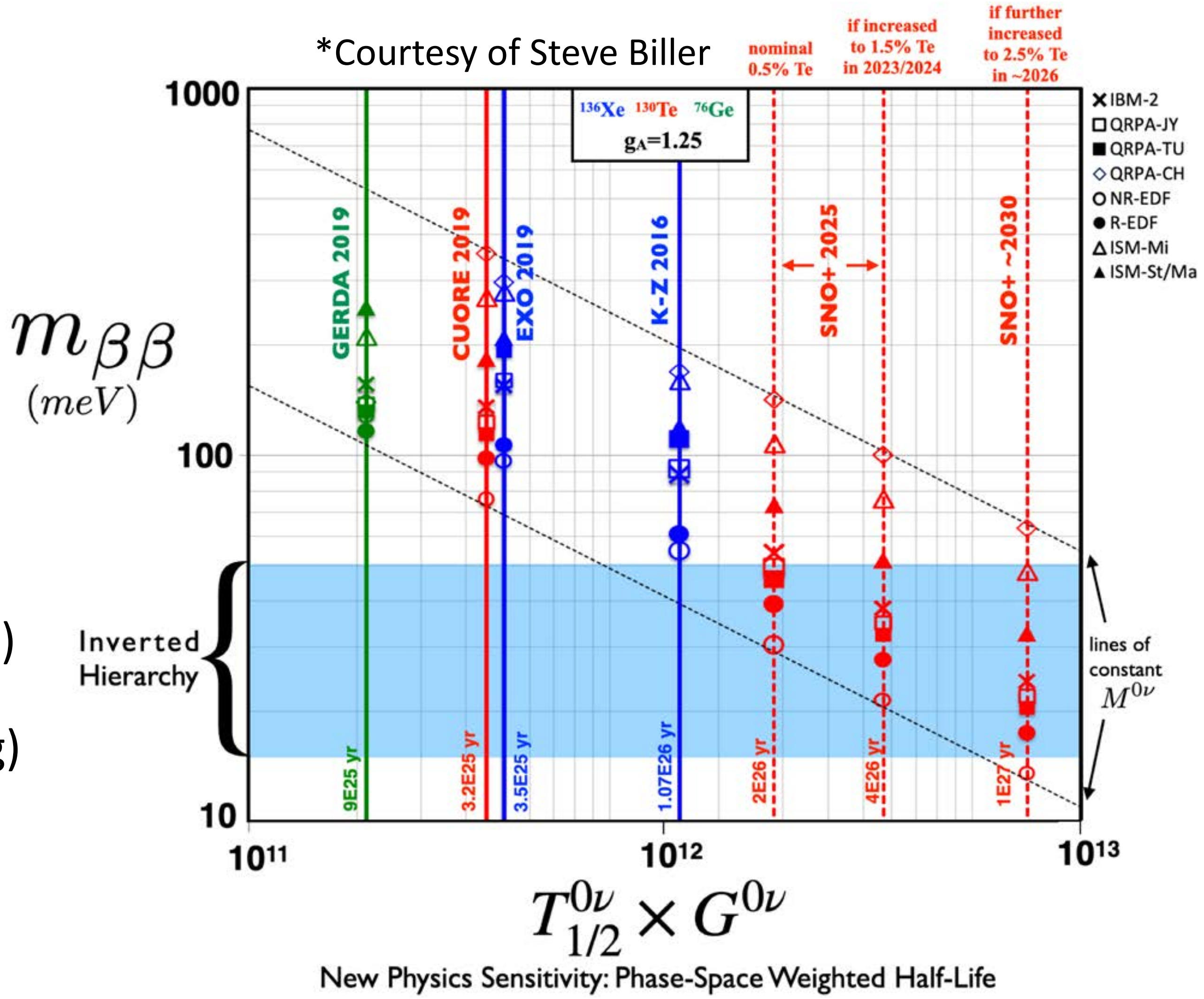
$T_{1/2}^{0\nu} > 2 \times 10^{26}$ years (90% C.L.)

Same analysis and same SNO+ detector for increased Te loading scenarios:

$T_{1/2}^{0\nu} > 4 \times 10^{26}$ years (90% C.L.) (1.5% loading)

$T_{1/2}^{0\nu} > 1 \times 10^{27}$ years (90% C.L.) (2.5% loading)

*Courtesy of Steve Biller



Future Outlook

- KLZ-800 is aiming for $T_{1/2}^{0\nu} > 5 \times 10^{26}$ years after 5 years of data taking.

- New analysis tools, including deep learning, and new MoGURA2 electronics upgrade will further improve background rejection.

- A future detector upgrade to KamLAND2-Zen is aiming for $T_{1/2}^{0\nu} > 2 \times 10^{27}$ years.

- Stay tuned for new exciting results from KLZ-800 to be released soon!

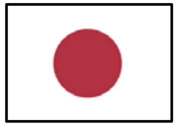
- LS filling will finish soon!

- We're preparing for tellurium loading (initially 0.5% ^{nat}Te by weight)

- Tellurium loading technique is highly scalable in LS and cost is relatively very low (< $2M per ton of $0\nu\beta\beta$ decay isotope)

- Increased loading to 2.5% could allow SNO+ to reach a half-life of $T_{1/2}^{0\nu} > 1 \times 10^{27}$ years after 4 years of data taking

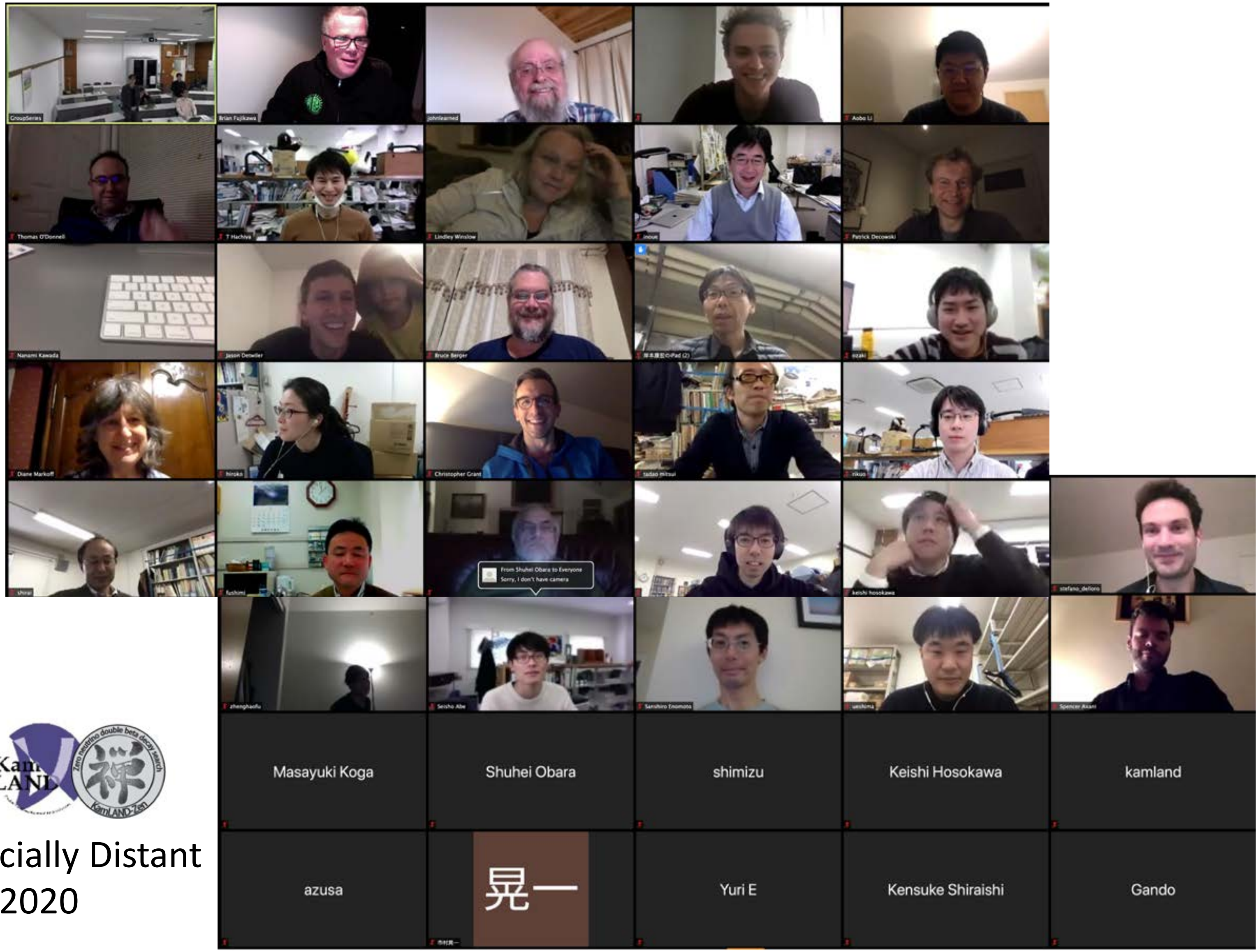
KamLAND-Zen Collaboration



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

SNO+ Collaboration

Univ. of Alberta
UC Berkeley / Lawrence Berkeley National Lab
Boston Univ.
Brookhaven National Lab
Univ. of Chicago
UC Davis
Technical Univ. of Dresden

Lancaster Univ.
Laurentian Univ.
LIP Lisbon and Coimbra
Univ. of Liverpool
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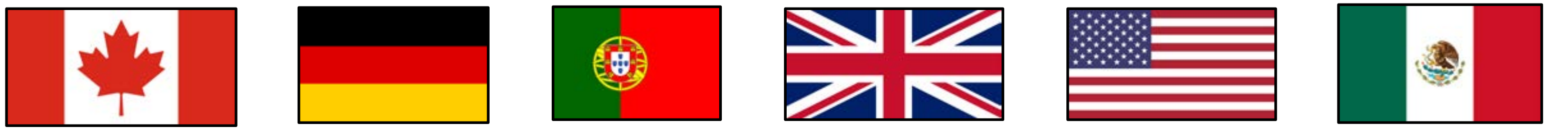
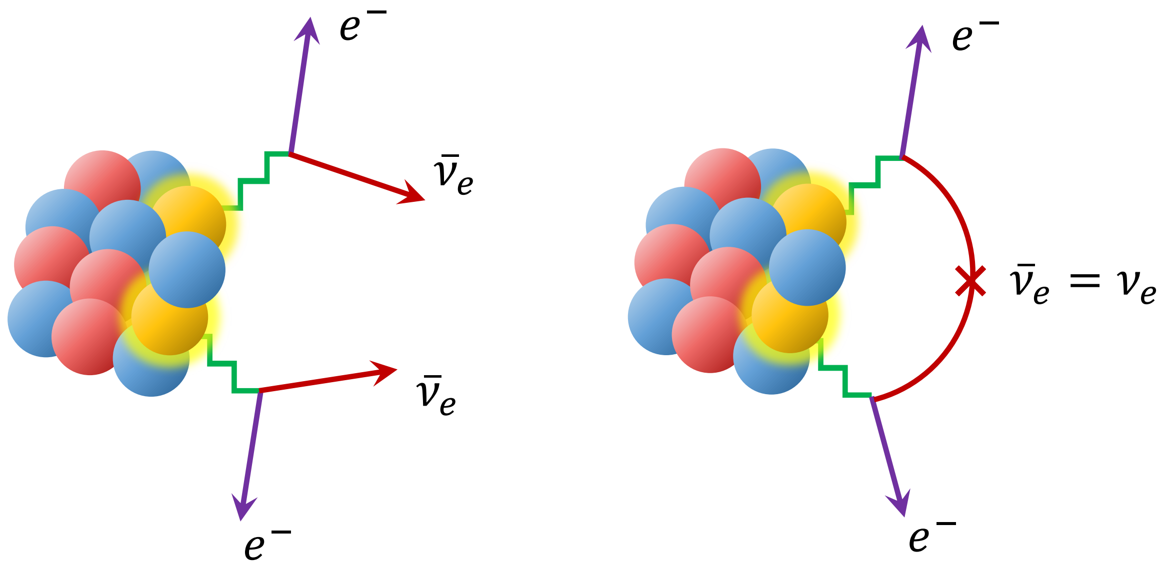
King's College London
Norwich Univ.

Univ. of Oxford
Univ. of Pennsylvania
Queen's Univ.
Queen Mary Univ. of London
SNOLAB
Univ. of Sussex
TRIUMF





Thank you!