Liquid Scintillator Based Double Beta Decay Experiments

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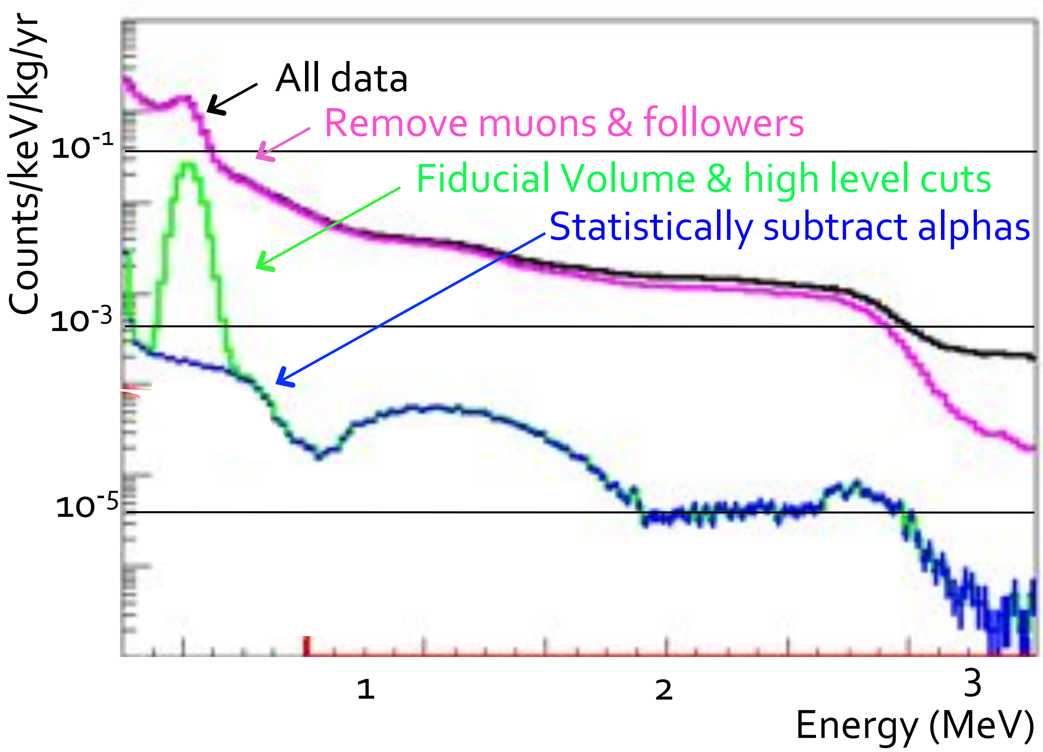
BLV 2015
April 29 2015

Why use Liquid Scintillator?

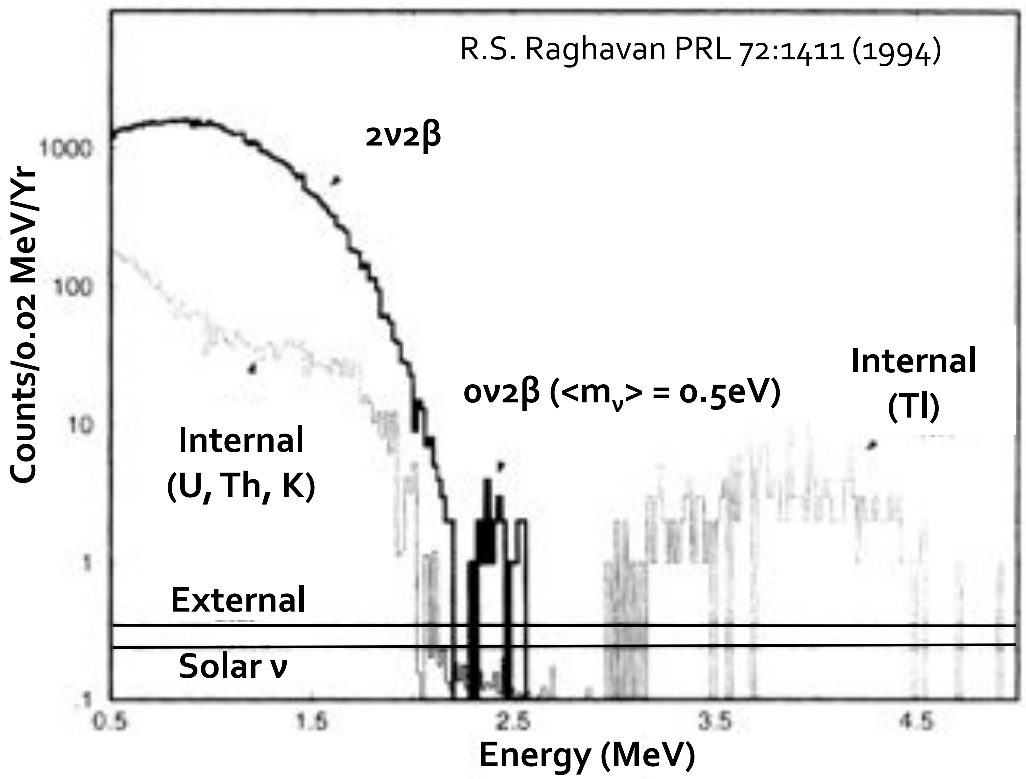
- Double beta decay experiments require high mass, good energy resolution, and low backgrounds
- Liquid scintillator based solar and reactor neutrino experiments have
  - Kilotonne-scale masses
  - Good energy resolution (few %)
  - Very low backgrounds (<10^{-5}/ keV/kg/yr)

Borexino Data: 150 tonne-years



Double Beta Decay in a Large Scintillator

- Raghavan, 1994: If double beta decay isotope can be added to one of these liquid scintillator experiments without degrading light yield or purity, a sensitive double beta decay search could be carried out

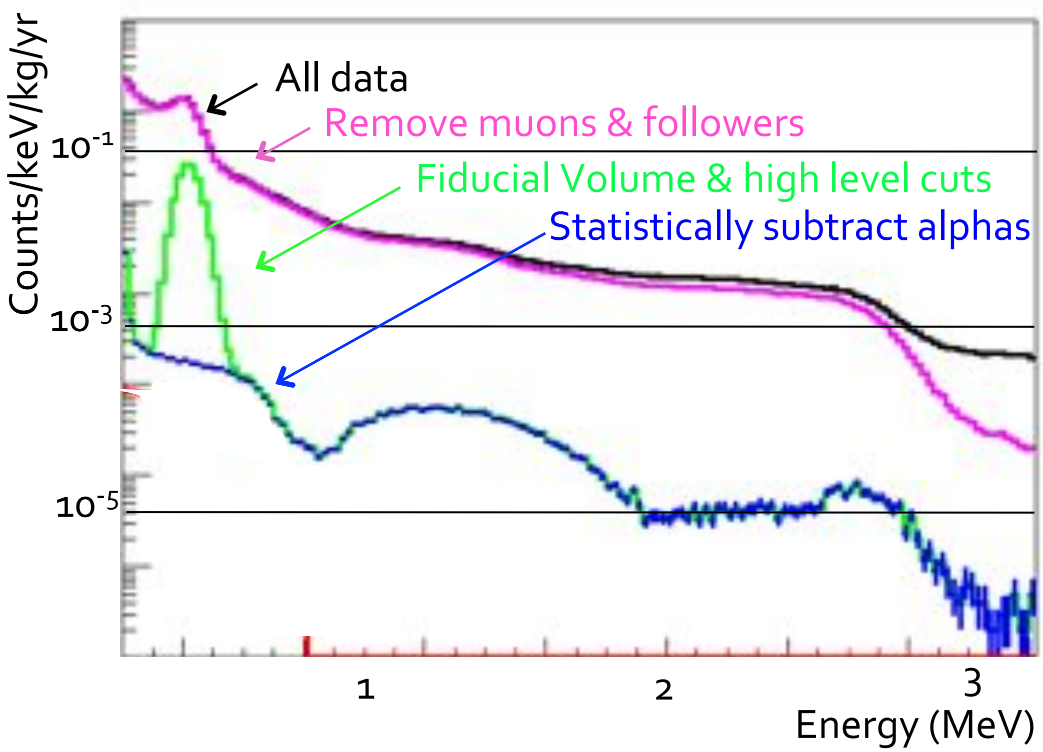


Large mass and extremely low background compensates for relatively modest energy resolution

Double Beta Decay in a Large Scintillator

- In addition:
  - Fiducialization to suppress external and “surface” backgrounds
  - High efficiency for rejecting muon follower and delayed-coincidence backgrounds
  - Pulse shape discrimination (both alphas and positrons)
  - Source in/source out capability
  - Possibility of re-purifying *in situ*
  - Possibility of deploying multiple sources

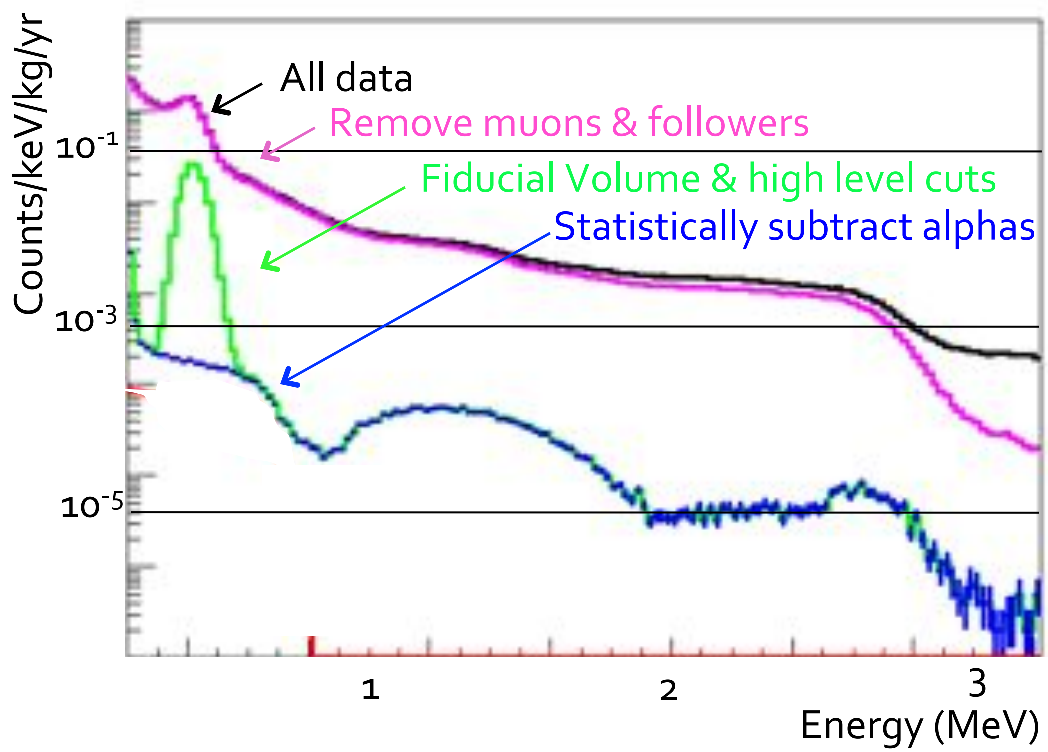
Borexino Data: 150 tonne-years



Double Beta Decay in a Large Scintillator

- Currently two liquid scintillator based DBD experiments:
  - KamLAND-Zen
  - SNO+
- Plus future prospects

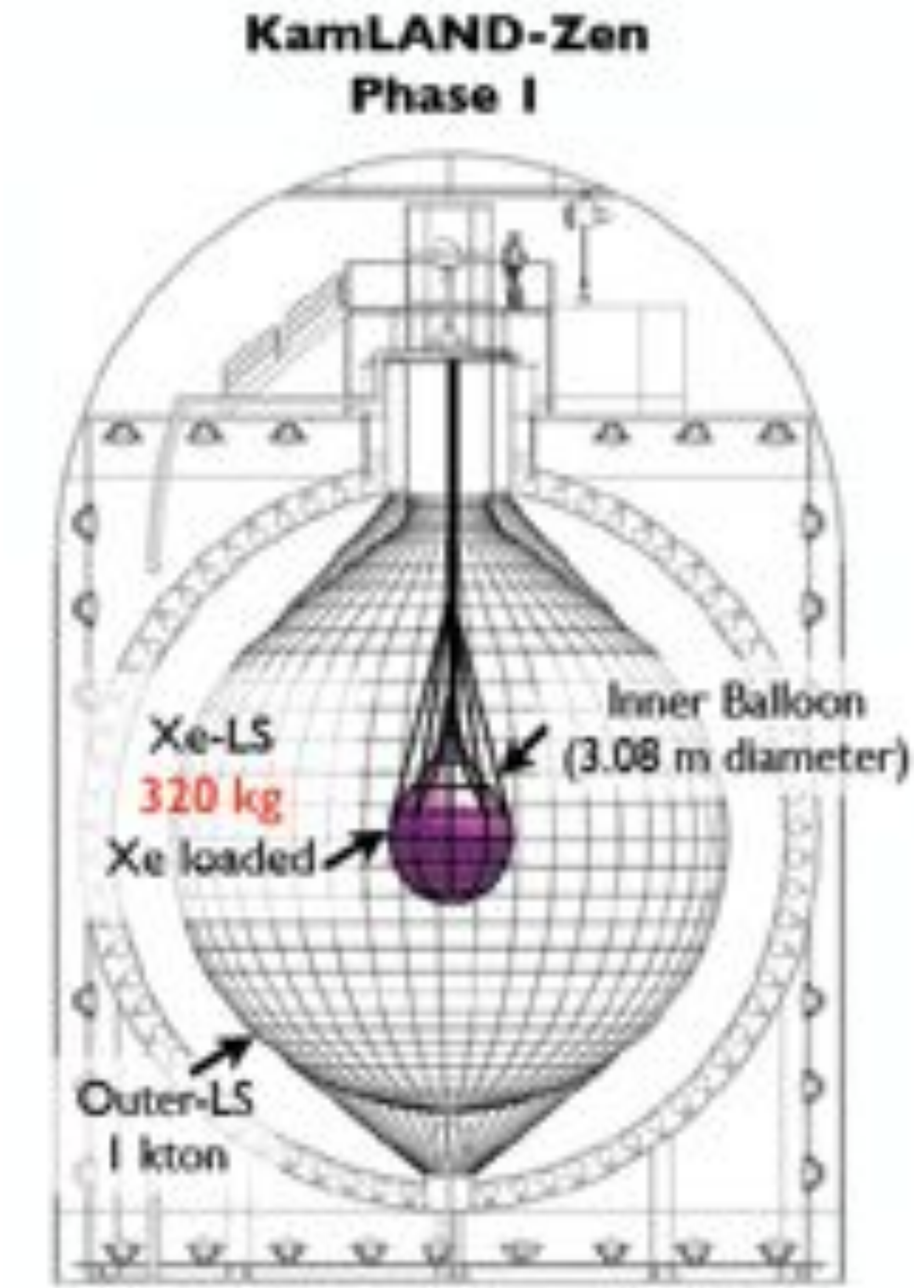
Borexino Data: 150 tonne-years



KamLAND-Zen

Kamioka Liquid Scintillator Anti-Neutrino Detector
Zero Neutrino Double Beta

Slides (modified) from Kunio Inoue and Itaru Shimizu (Neutrino2014)



- Double beta decay search using the KamLAND detector (designed for reactor anti-neutrino studies)
- "Inner balloon" deployed inside the detector and filled with LS loaded with ^{136}Xe

Xenon loaded LS (Xe-LS)	
decane	82%
pseudo-cumene	18%
PPO	2.7 g/liter
xenon	2.44 wt%

$\sigma_E(2.5\text{MeV}) = 4\%$

KamLAND-Zen status   89.5kg-yr   Phys.Rev.Lett, 110, 062502 (2013)

1. the **world best** limit

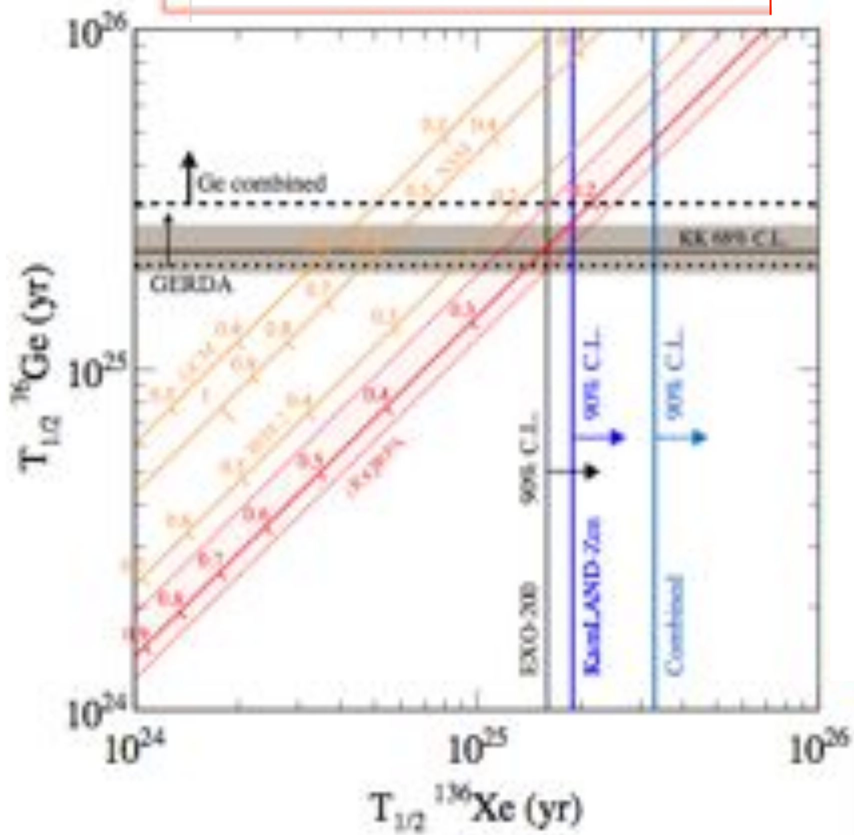
$T_{1/2} > 1.9\times10^{25}$ yrs (KL-Zen)

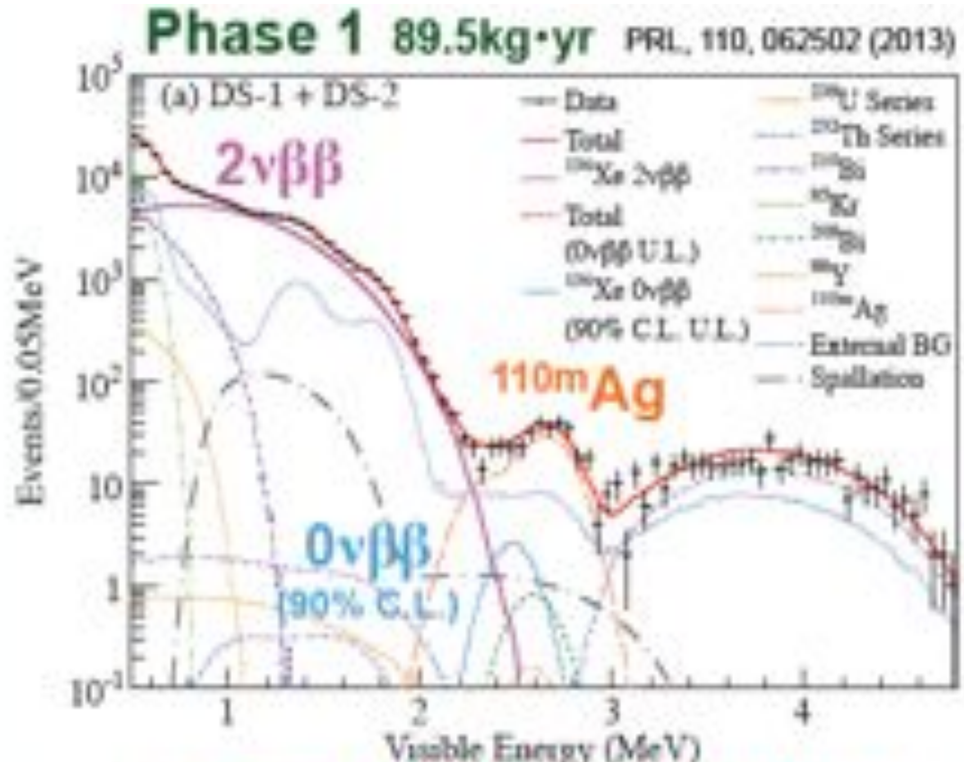
$> 3.4\times10^{25}$ yrs

(combined with EXO-200)

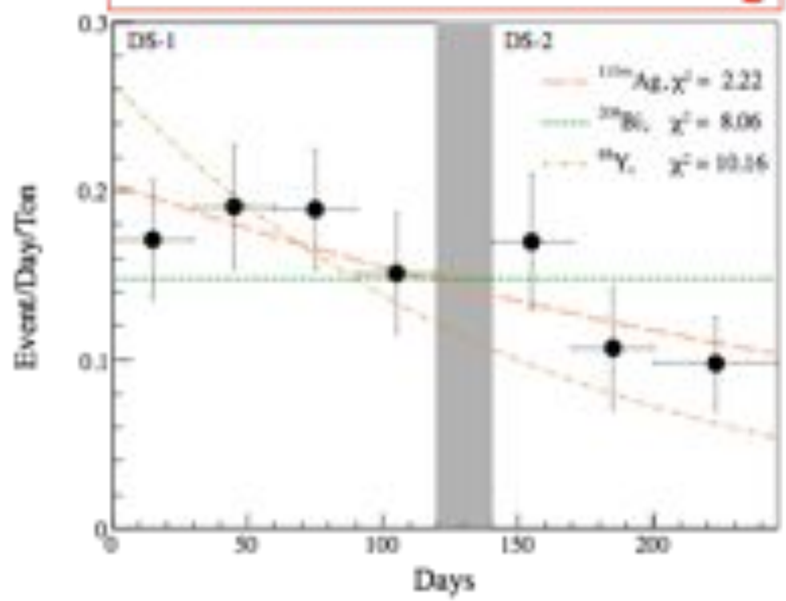
$\langle m_{\beta\beta}\rangle < 120 \sim 250\,\mathrm{meV}$

KK-claim refuted at 97.5% CL

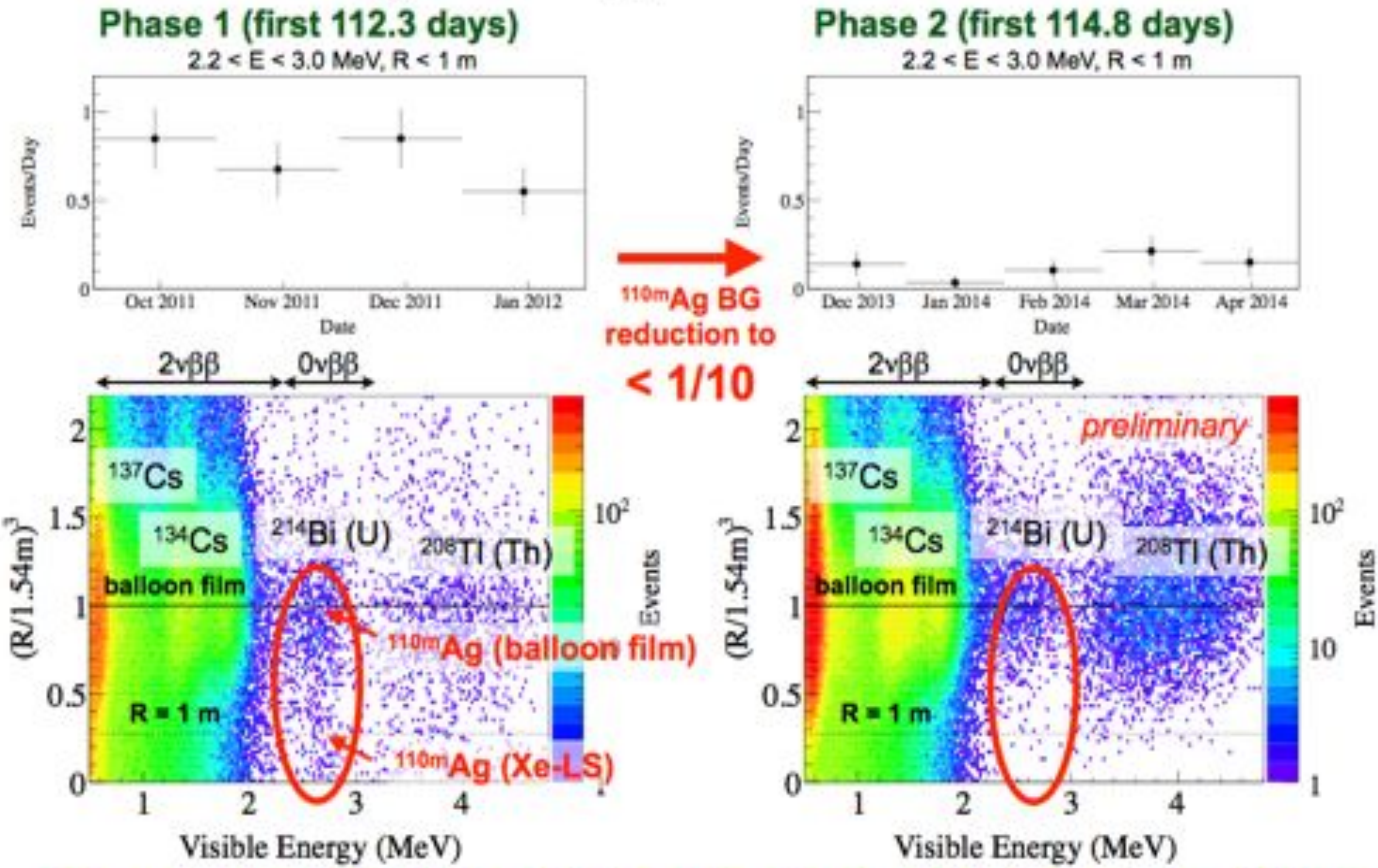




2. BG identified as ^{110m}Ag



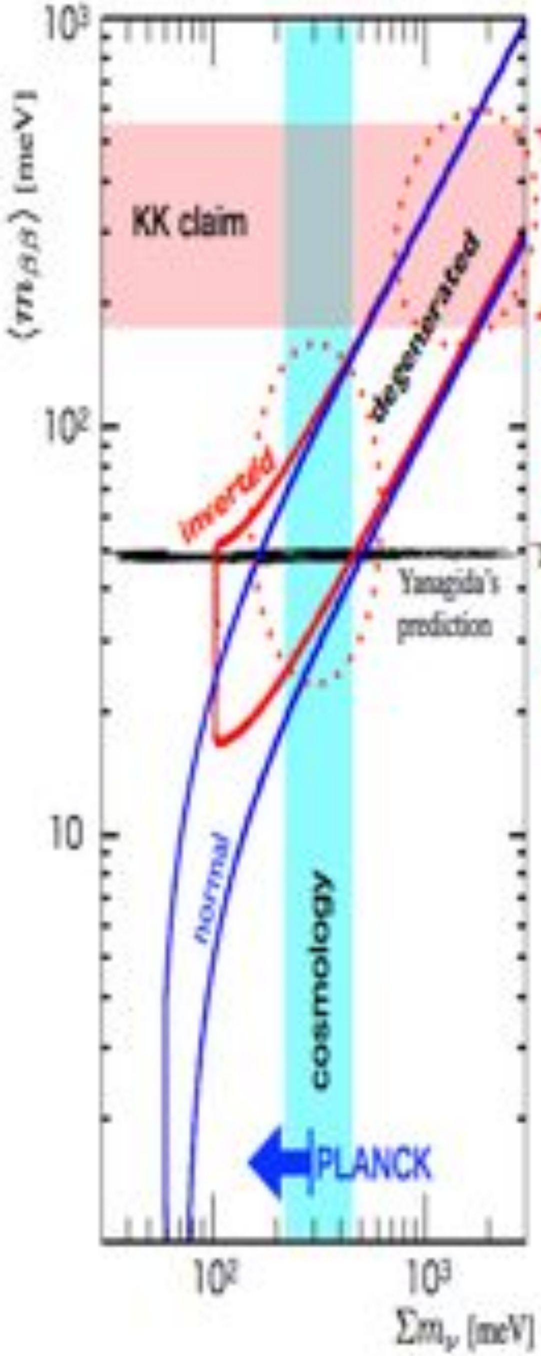
^{110m}Ag Background Reduction



Primary BG : ^{214}Bi (U) at balloon / spallation ^{10}C / remaining ^{110m}Ag?

Prospects

KamLAND-Zen is a top runner and being improved.



NME uncertainty

KamLAND-Zen 89.5 kg-yr
$\langle m_{\beta\beta}\rangle$ <160~330 meV @90% C.L.
the world best

after purification

Next target
KamLAND-Zen (w/ lower ^{110m}Ag)
just resumed with 380kg

2016~
KamLAND-Zen 700kg
with clean mini-balloon

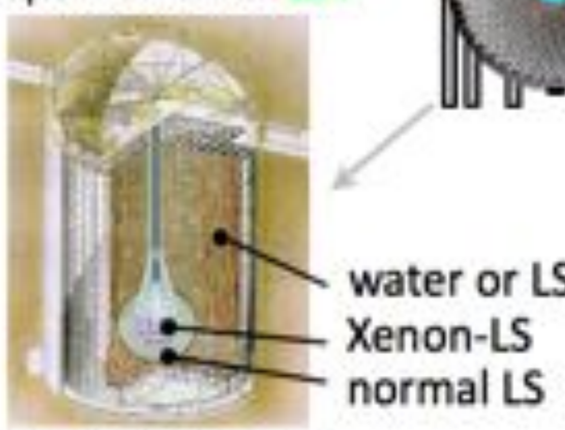
Future plan
KamLAND2-Zen : high QE PMT, high yield LS, light concentrator
σ_E(2.6MeV)=4%→ <2.5%

dream?
Super-KamLAND-Zen

R&D for pressurized Xe

R&D for scintillation film

R&D for β / γ discrimination
(high sensitivity imaging)



precision anti-neutrino physics is also possible.

- SNO heavy water replaced by 780 tonnes of liquid scintillator
- ~9500 PMTs
- 1700 + 5700 tonnes ultra-pure water shielding
- New rope net to hold down the 6m radius acrylic vessel
- 6800’ underground in SNOLAB

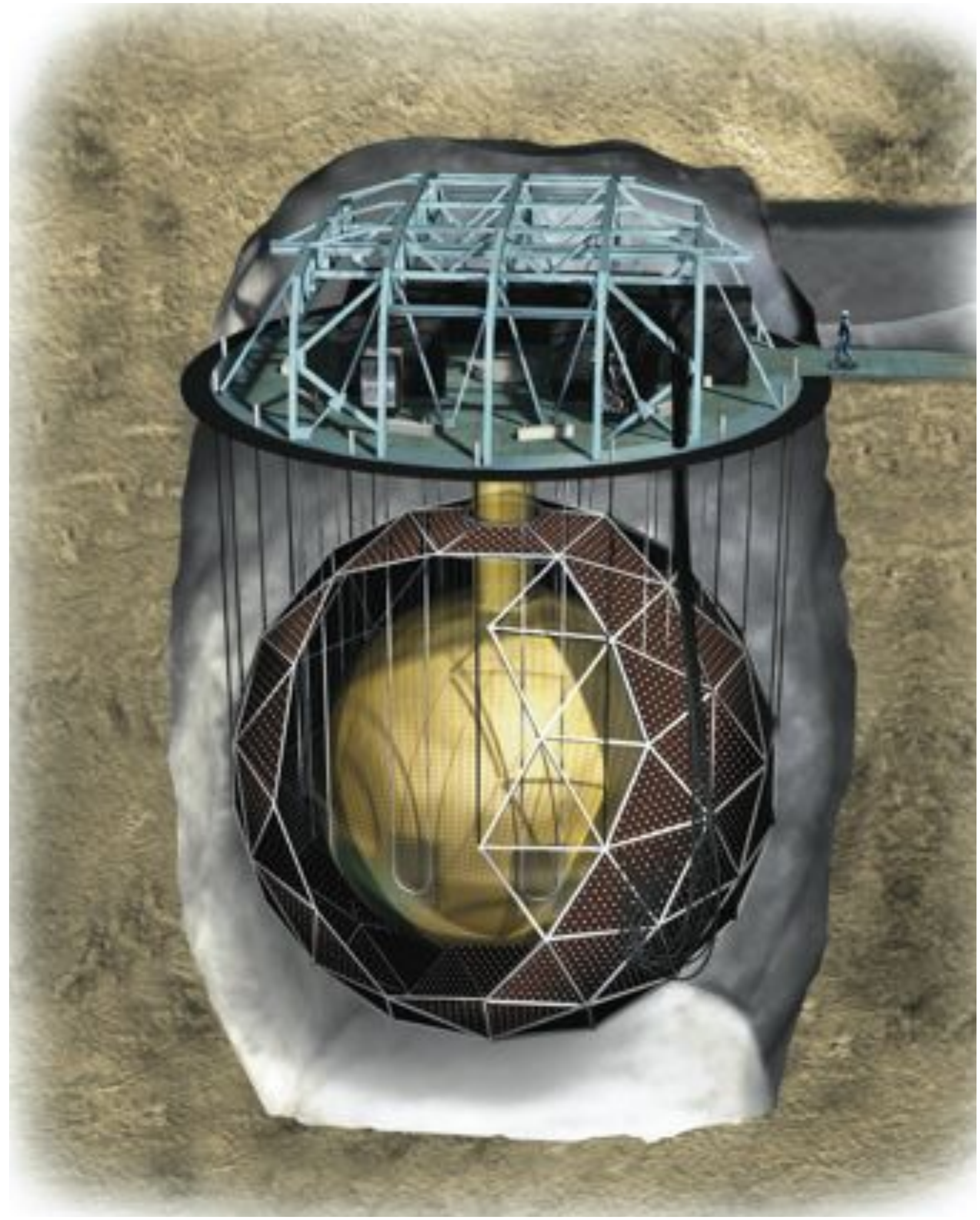
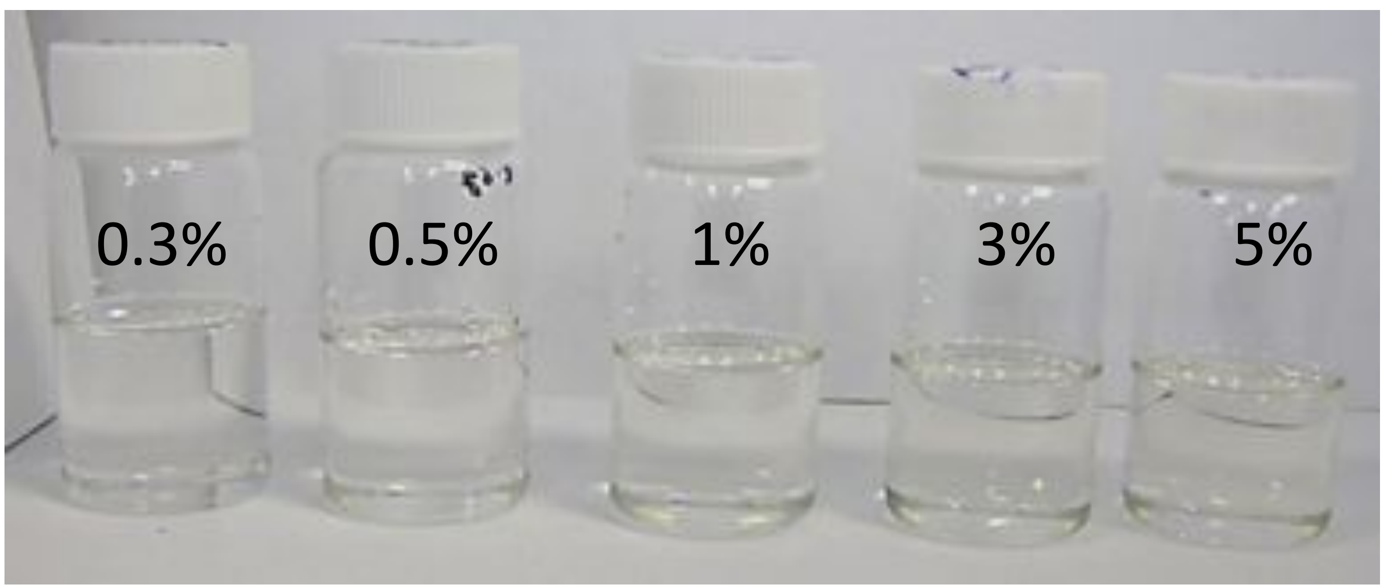


Image courtesy National Geographic

Load Tellurium into the SNO+ Scintillator

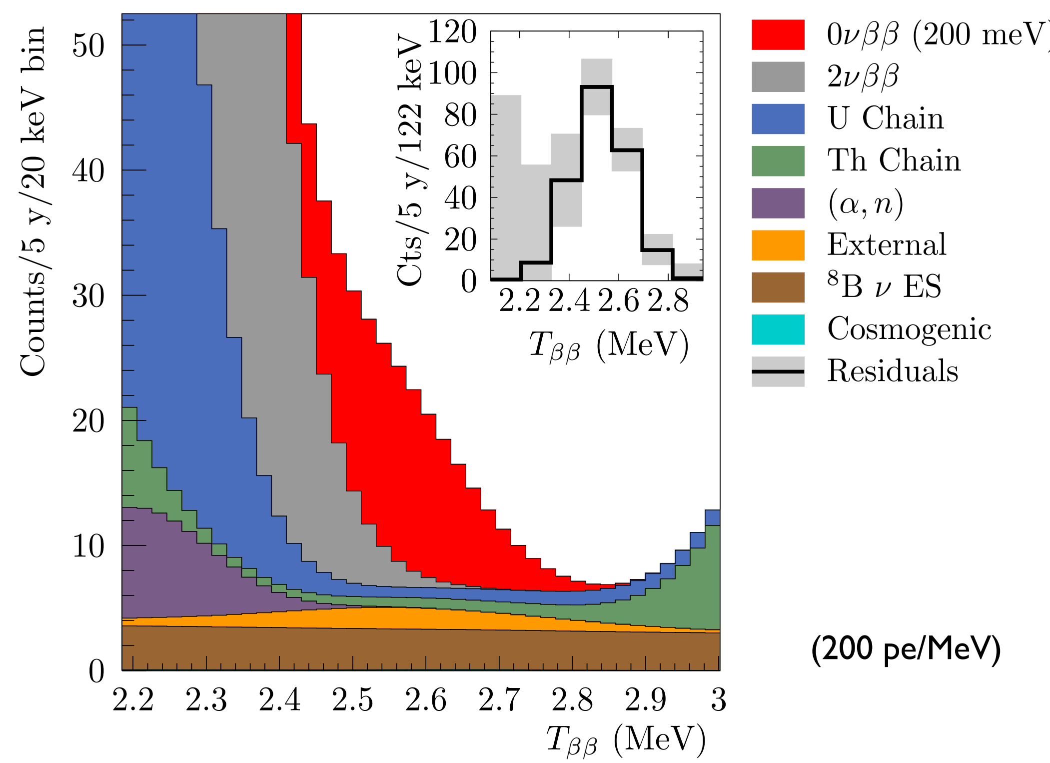
- Stable loading of aqueous $Te(OH)_6$ in SNO+ scintillator with good optical properties achieved by BNL
- 780 tonne detector and high ^{130}Te isotopic abundance gives large isotope mass
  - 0.3 – 0.5% Te (by weight) in SNO+ Phase I is 2.34 – 3.9 tonnes of Te or **800 – 1333 kg** of ^{130}Te
  - Percent-level loading is feasible
    - 3% Te in SNO+ Phase II would give **8 tonnes** of ^{130}Te

LAB scintillator with different Te loading



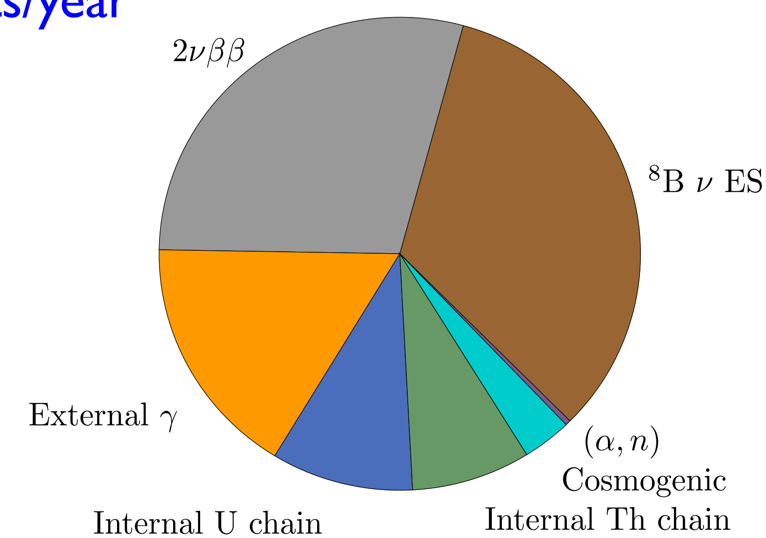
SNO+ Phase I

- Scintillator running begins mid-2016
  - Measure most background
  - Verify detector response models
- 0.3% Te loading begins early 2017
  - Stringent $0\nu\beta\beta$ limits for ^{130}Te
    - $T_{1/2}$>9.4×10^{25} y (90% CL)
    - 3σ detection at $T_{1/2}$= 6.9×10^{25} y
  - Verify purification techniques



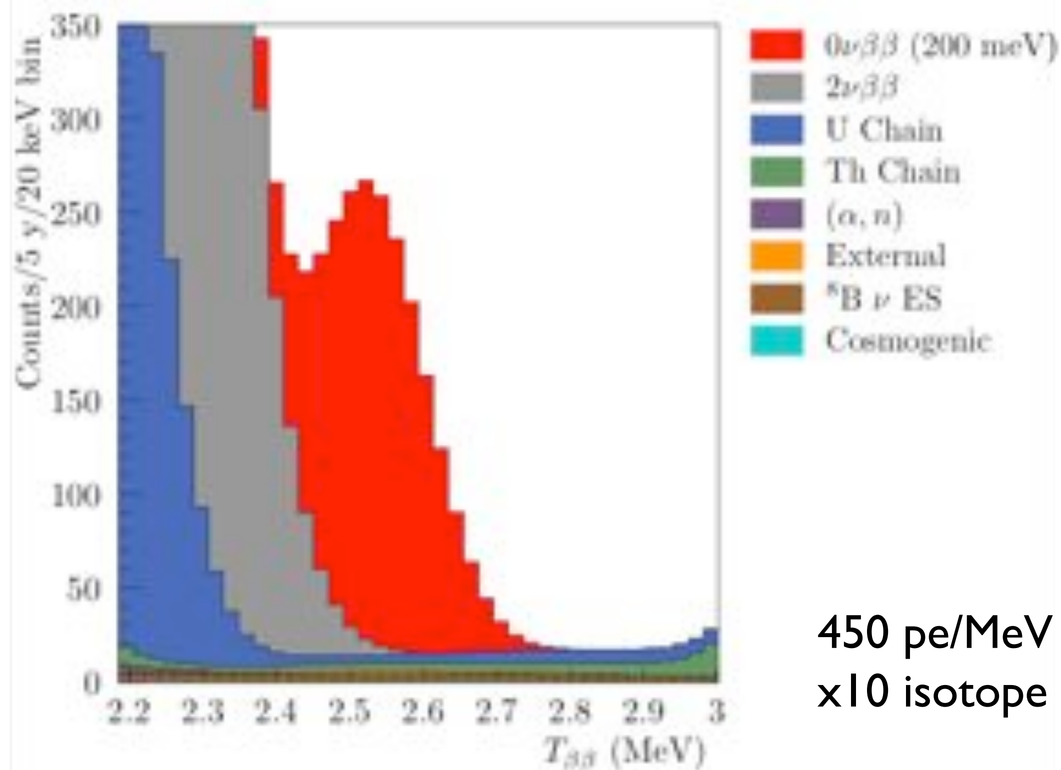
(200 pe/MeV)

Total background target = 21.3 events/year



SNO+ Phase II

$T_{1/2} > 7\times10^{26}$ y (90% CL)
3σ detection for
$T_{1/2} > 4\times10^{26}$ y



450 pe/MeV
x10 isotope

- 3% loading of Te (already demonstrated)
- Plug-in replacement of SNO+ PMTs with R5912-HQEs more than doubles light yield for phase II

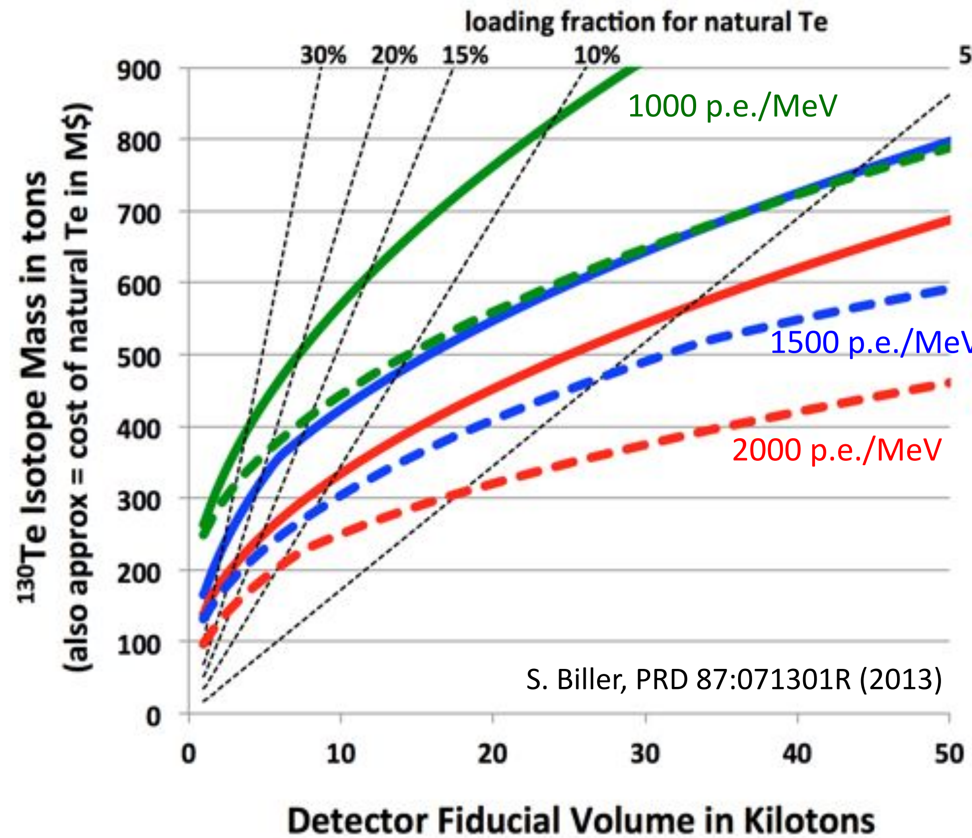
  Additional wavelength-shifter/loading R&D could further improve this
- Containment bag could reduce amount of isotope, improve cleanliness

  Can leverage KamLAND-Zen and BOREXINO knowledge

Probing the Normal Hierarchy

- "First order extrapolation" suggests that Te-LS based experiments might allow the normal hierarchy to be studied
  - Develop >10% isotope loading techniques with good light yield and transparency
    - ~10x loading increase from current technology
    - Current HQE PMTs could give sufficient light yield with high coverage
  - Internal backgrounds assumed to be less than the ^{8}B neutrino rate
    - <10x cleaner than SNO+ phase-I targets
  - Systematic uncertainties on the backgrounds in the ROI will be critical!

How much ^{130}Te is needed to Reach $m_{\beta\beta}$<2.5meV?

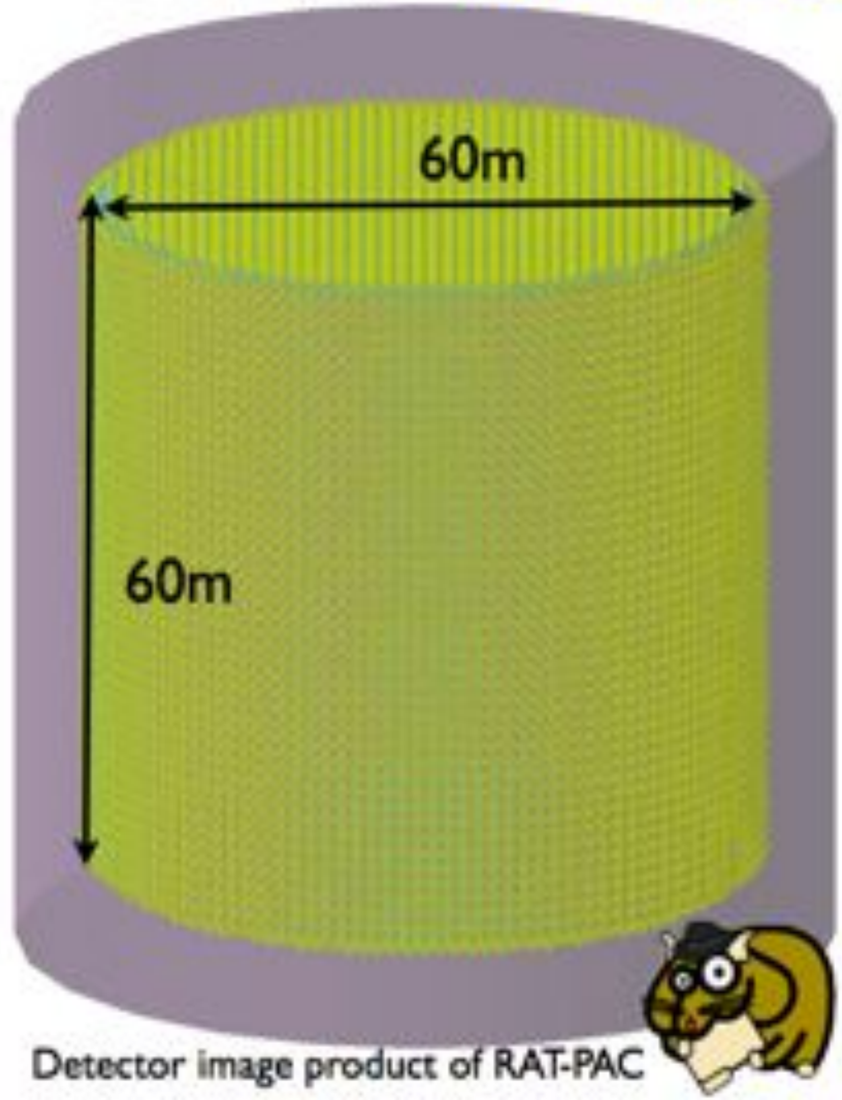


THEIA:
A realisation of the Advanced Scintillation Detector Concept (ASDC)

Slides from G.D. Orebi Gann
Concept paper - arXiv:1409.5864

- 50-100 kton Water Based Liquid Scintillator target
- High coverage with ultra-fast, high efficiency photon sensors
- 4800 m.w.e. underground (Homestake)
- Comprehensive low-energy program: solar neutrinos, supernova, DSNB, proton decay, geo-neutrinos, DBD
- In the LBNF beam: long-baseline program complementary to proposed LAr detector

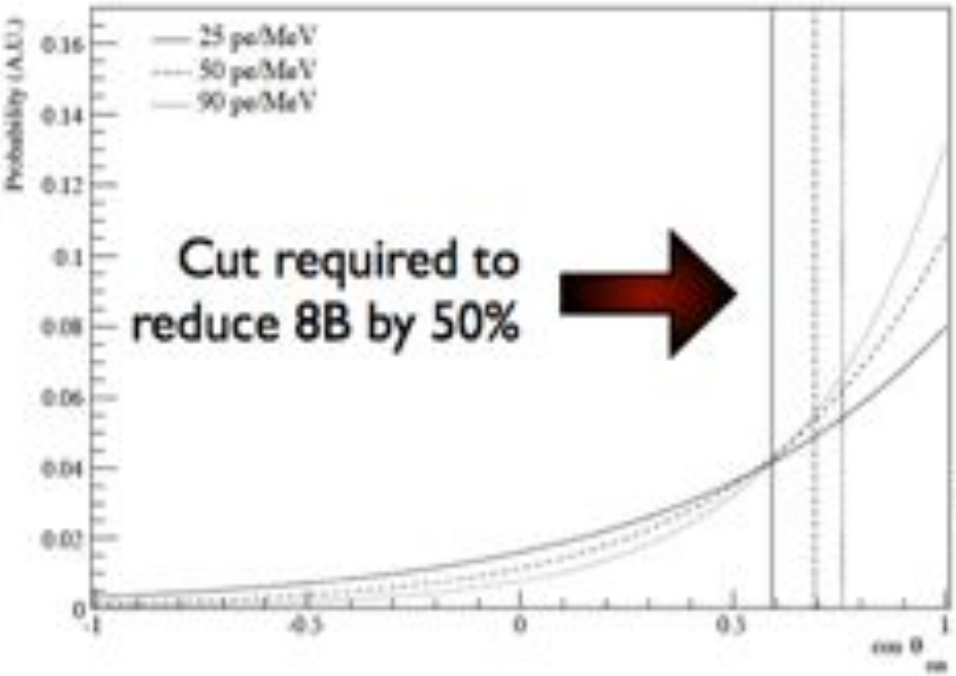
➡ **Broad physics program!**



Detector image product of RAT-PAC

THEIA Sensitivity

Directional resolution for different Cherenkov light yields



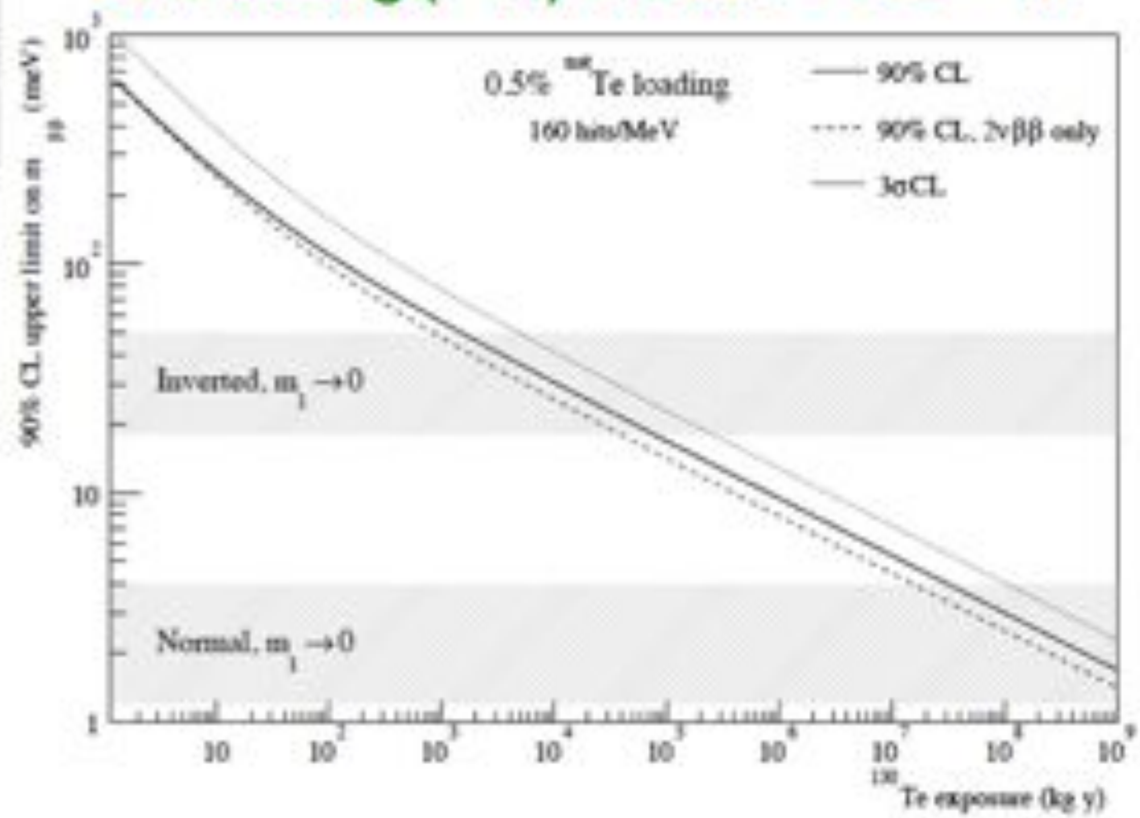
50kt detector

50% reduction of ^{8}B

Particle ID / coincidence tags for int r/a

R_{fit} > 5.5m from PMTs (30kt fid)

0.5% loading (^{nat}Te) in 50kt ⇒ 50t ^{130}Te



⇒ 3σ discovery for $m_{\beta\beta}$=15meV in 10 yrs

Future sensitivity into NH region...

All figs from arXiv:1409.5864

Conclusion

- The large mass and low background achievable in liquid scintillator detectors make them useful for staging searches for neutrinoless double beta decay
- KamLAND-Zen already has leading sensitivity, SNO+ to come online soon
  - Both experiments have proposed paths that cover the inverted hierarchy region
- Future projects may be able probe the normal hierarchy.