52nd Rencontres de Moriond, March 19-25, 2017

KamLAND-Zen $0\nu 2\beta$ Results and Status

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GRAPPA
GRavitation AstroParticle Physics Amsterdam

UNIVERSITEIT VAN AMSTERDAM

KamLAND-Zen Collaboration

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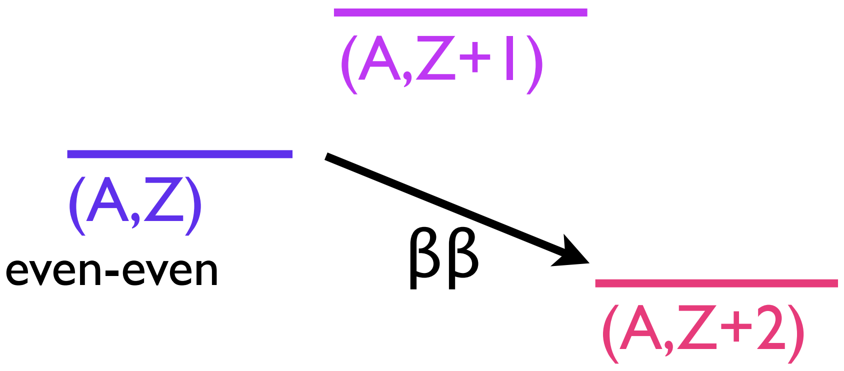
Double Beta Decay



^{136}Xe

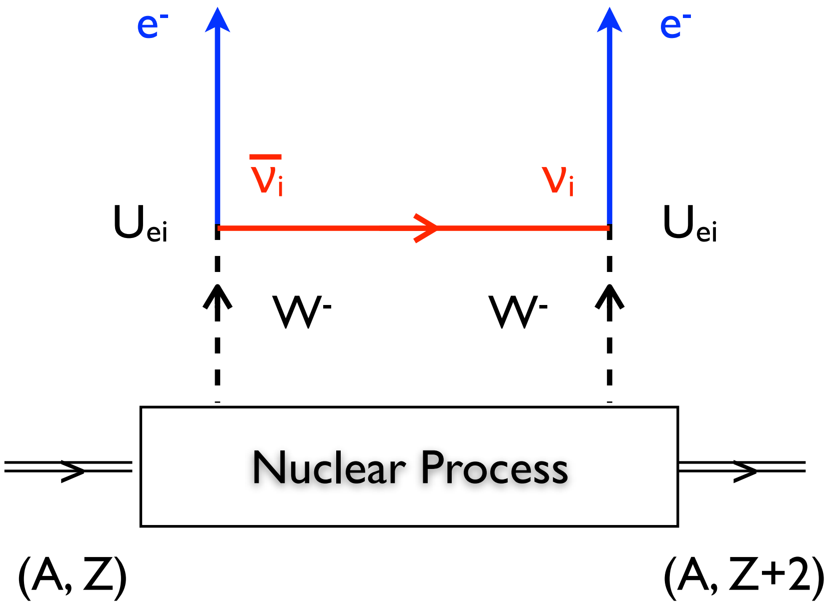
^{76}Ge

A second-order process only detectable if first-order beta decay is energetically forbidden

Rare, but Standard Model Process:

$$2\nu 2\beta : (A,Z) \rightarrow (A,Z+2) + e^- + e^- + \overline{\nu}_e + \overline{\nu}_e$$

Neutrinoless Double Beta Decay



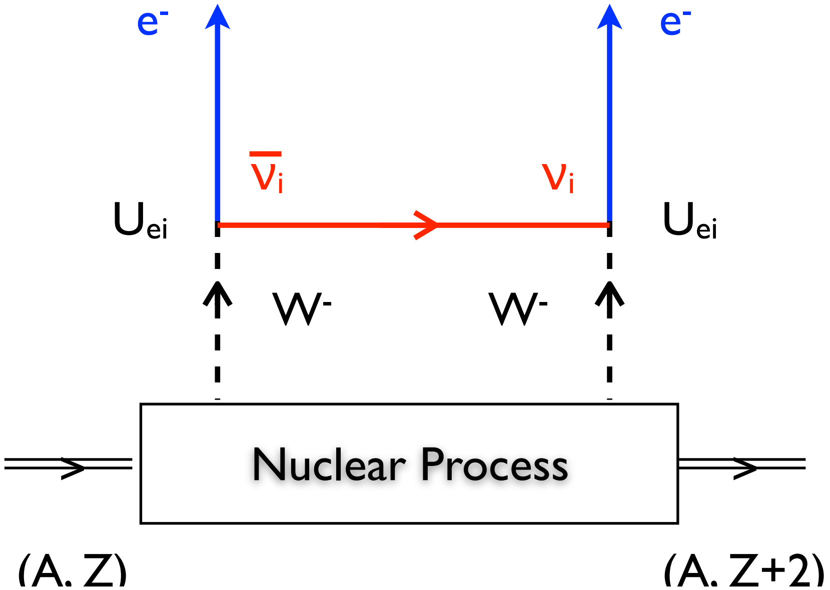
But what if ν is Majorana?

$$\begin{aligned} M_\nu &\neq 0 \\ |\Delta L| &= 2 \end{aligned}$$

$$0\nu 2\beta : (A,Z) \to (A,Z+2) + e^- + e^-$$

- Extremely rare process [W.H. Furry (1939): $T_{1/2} > 10^{16}$ yr]
- Requires massive Majorana neutrino
- Lepton Number Violation
  - Model dependent - Standard interpretation: light Majorana ν + SM interactions

Neutrinoless Double Beta Decay



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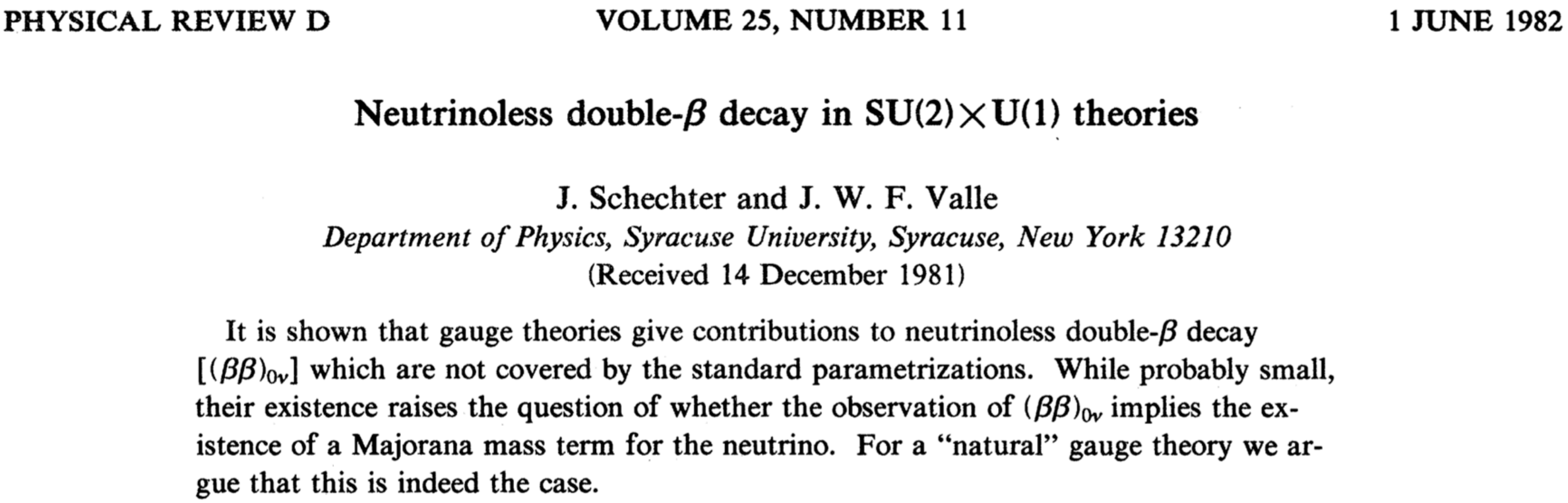

PHYSICAL REVIEW D VOLUME 25, NUMBER 11 1 JUNE 1982

Neutrinoless double-β decay in SU(2)×U(1) theories

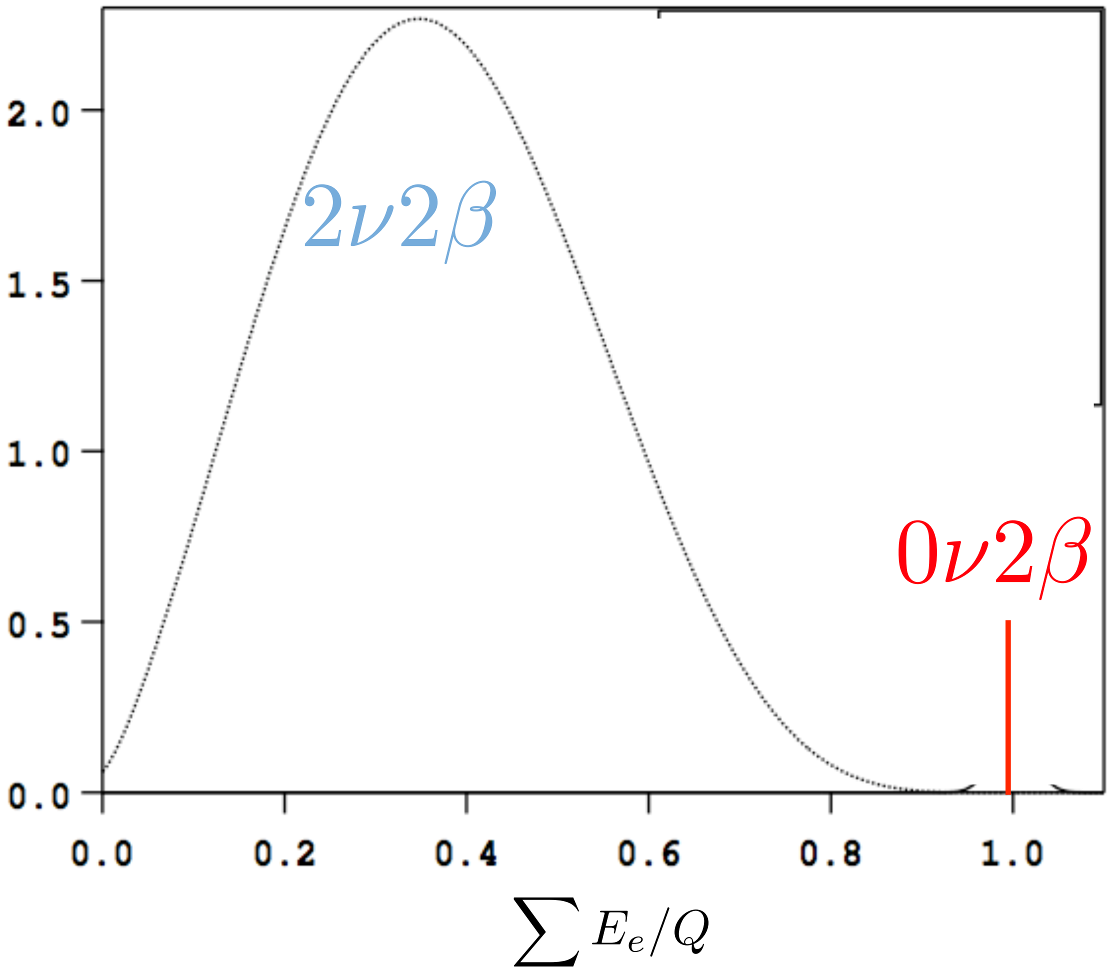
J. Schechter and J. W. F. Valle
Department of Physics, Syracuse University, Syracuse, New York 13210

(Received 14 December 1981)

It is shown that gauge theories give contributions to neutrinoless double-β decay [$(\beta\beta)_{0\nu}$] which are not covered by the standard parametrizations. While probably small, their existence raises the question of whether the observation of $(\beta\beta)_{0\nu}$ implies the existence of a Majorana mass term for the neutrino. For a "natural" gauge theory we argue that this is indeed the case.

Detecting 0ν2β Decay

Without energy resolution

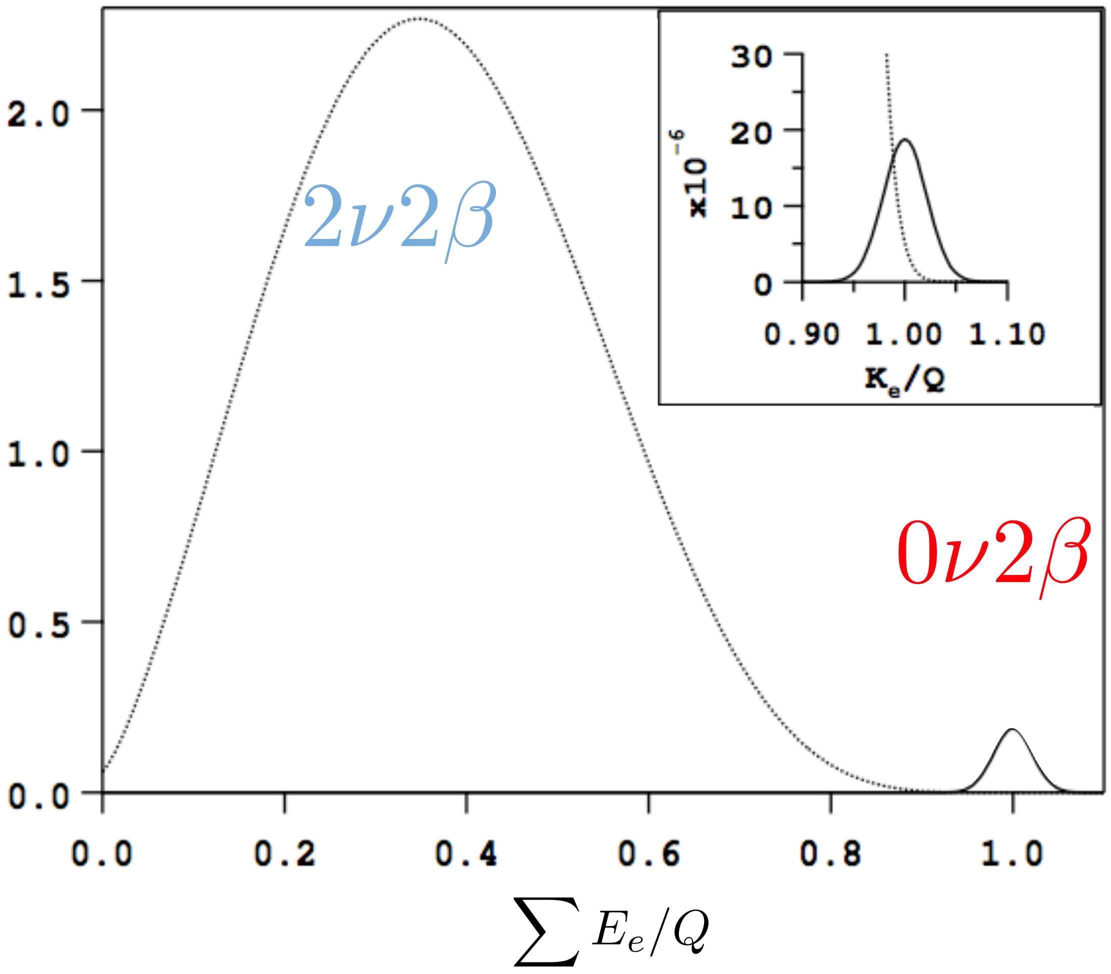


In ^{136}Xe:
$Q_{\beta\beta}$=2.458 MeV

- <u>General approach</u>: detect the two final-state electrons
- <u>Signature</u>: Two simultaneous electrons with summed energy $Q_{\beta\beta}$, the Q-value for the ββ decay in the isotope of study

Detecting 0ν2β Decay

With energy resolution



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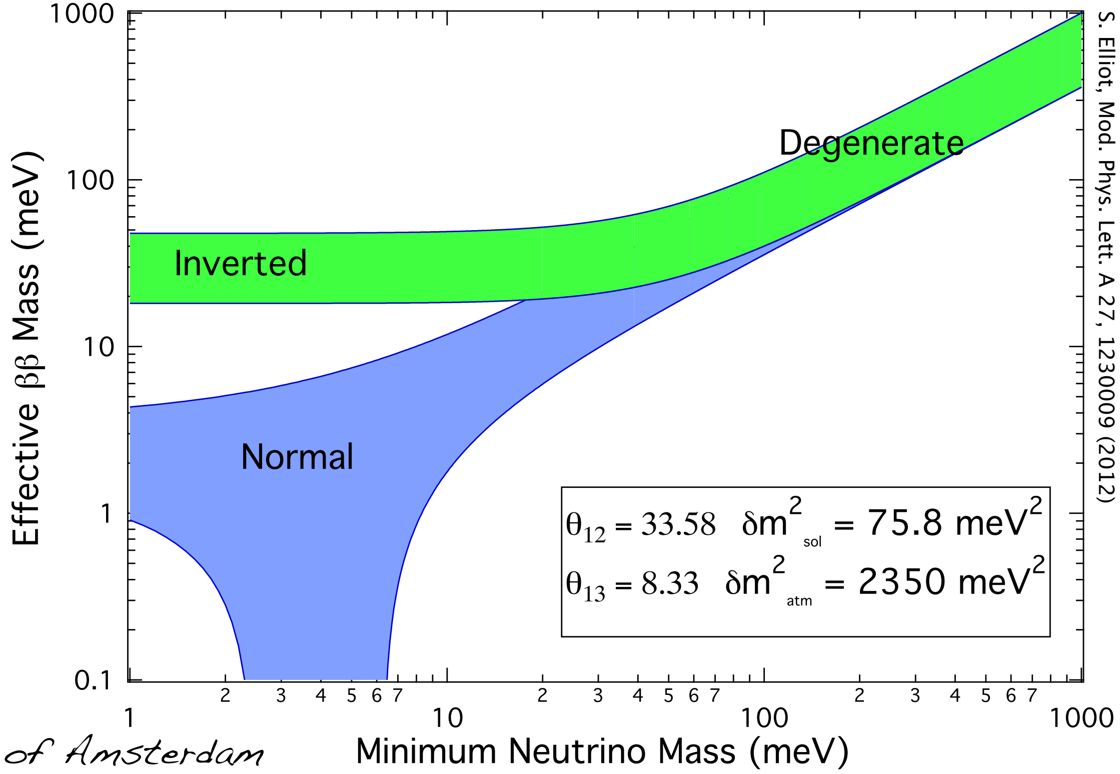
What mass does 0ν2β measure?

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q,Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

Phase Space factor:
Calculable

Nuclear Matrix Element:
Hard to calculate

Effective Majorana mass: $\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$ [coherent sum]



S. Elliot, Mod. Phys. Lett. A 27, 1230009 (2012)

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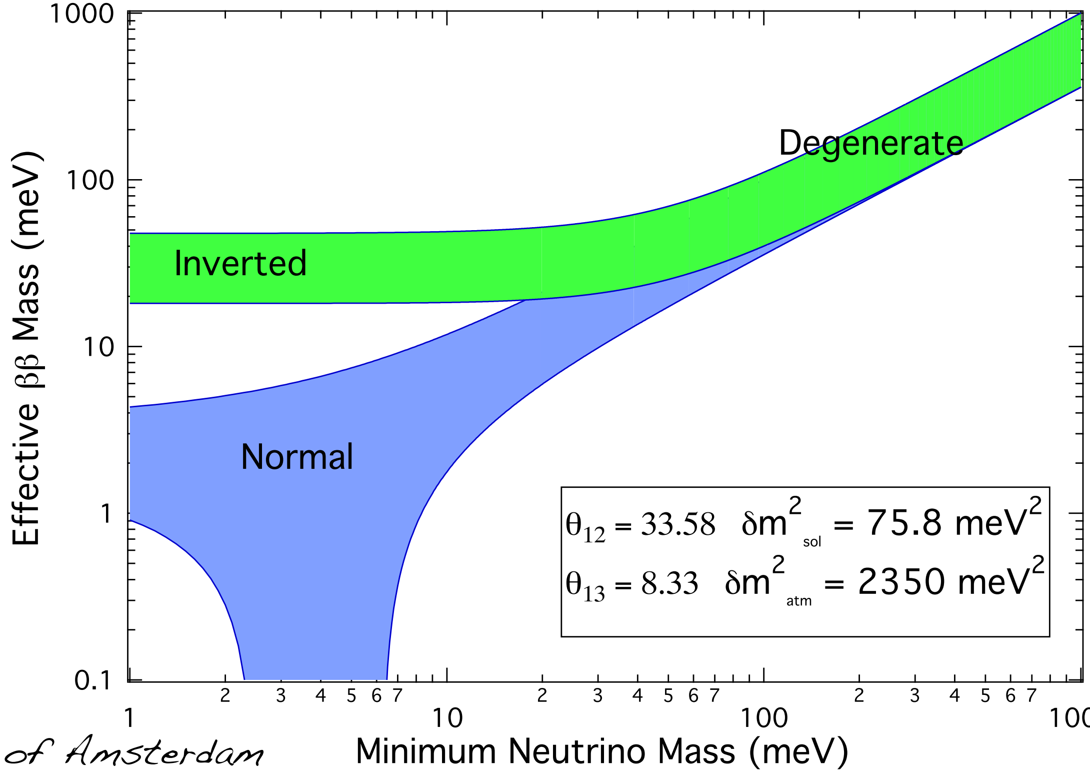
$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q,Z)|M_{0\nu}|^2 \boxed{\langle m_{\beta\beta}\rangle^2}$$

Phase Space factor:
Calculable

Nuclear Matrix Element:
Hard to calculate

Interesting physics

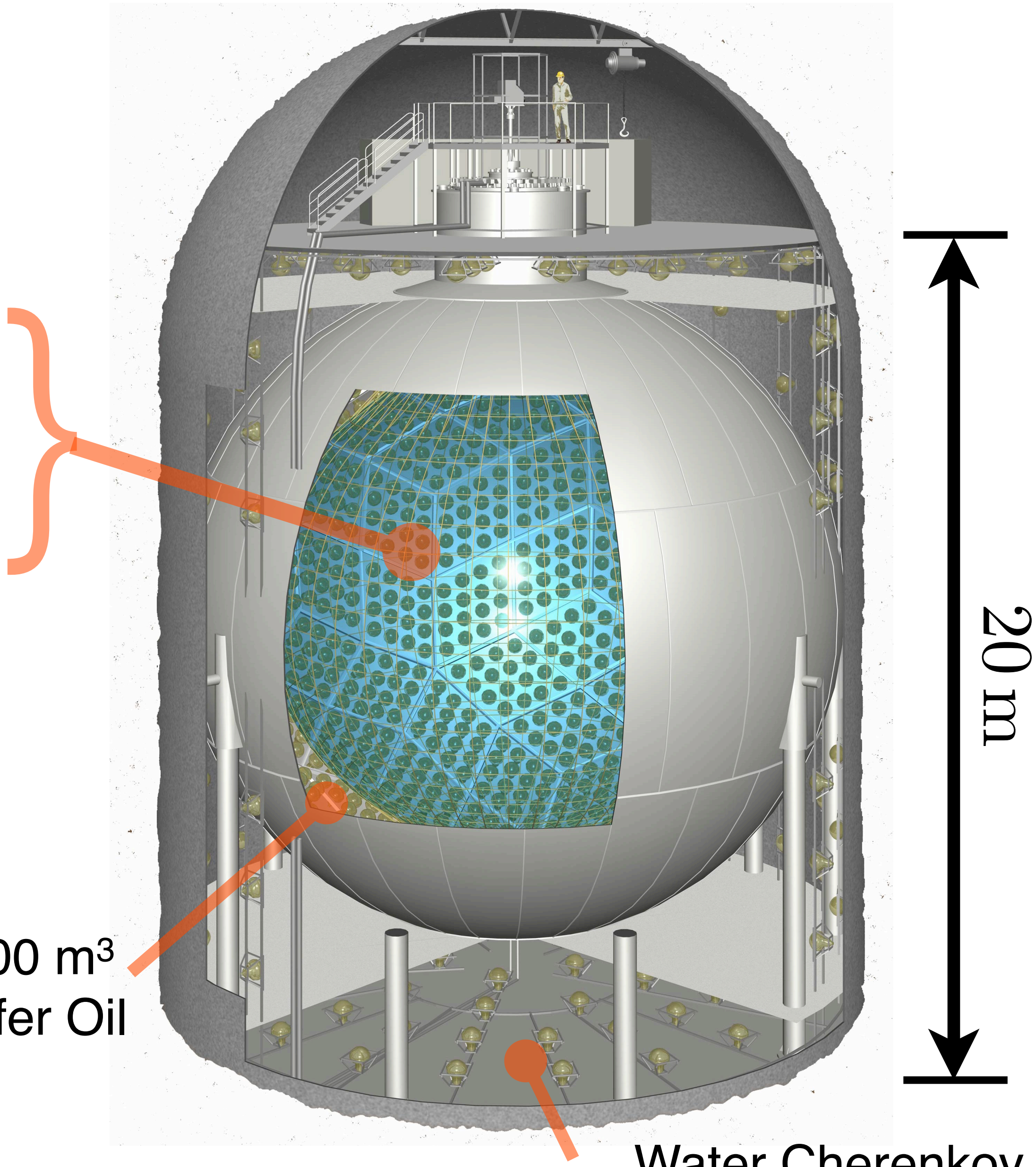
Effective Majorana mass: $\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$ [coherent sum]



S. Elliot, Mod. Phys. Lett. A 27, 1230009 (2012)

KamLAND(-Zen) detector

- 1 kton Scintillation Detector
  - 6.5m radius balloon filled with:
    - 20% Pseudocumene (scintillator)
    - 80% Dodecane (oil)
    - PPO
- 34% PMT coverage
  - ~1300 17” fast PMTs
  - ~550 20” large PMTs
- Water Cherenkov veto
- Operational since 2002



1800 m^3
Buffer Oil

3200 m^3

Water Cherenkov
Outer Detector

KamLAND(-Zen) detector

- 1 kton Scintillation Detector
  - 6.5m radius balloon filled with:
    - 20% Pseudocumene (scintillator)
    - 80% Dodecane (oil)
    - PPO
- 34% PMT coverage
  - ~1300 17” fast PMTs
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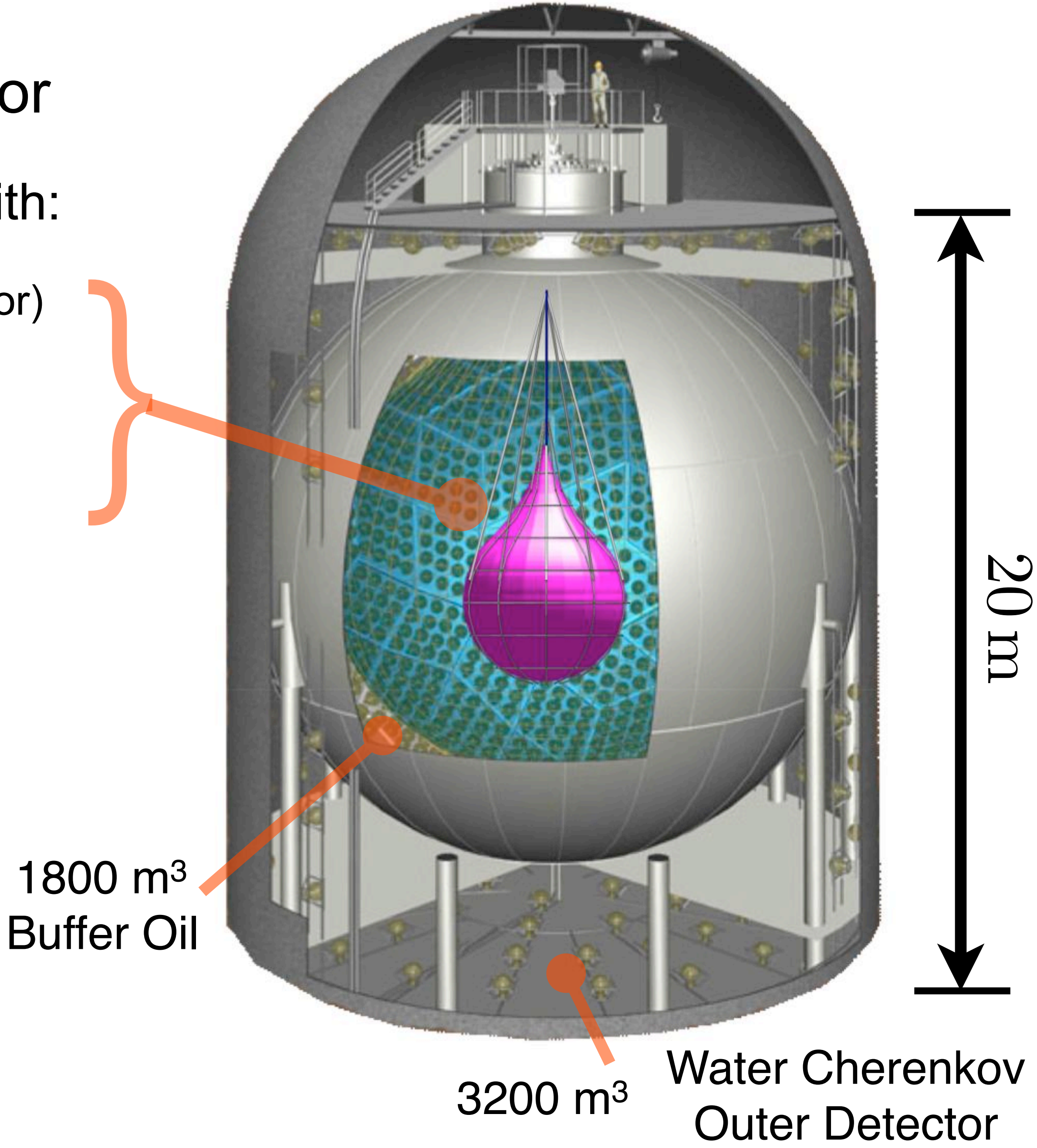
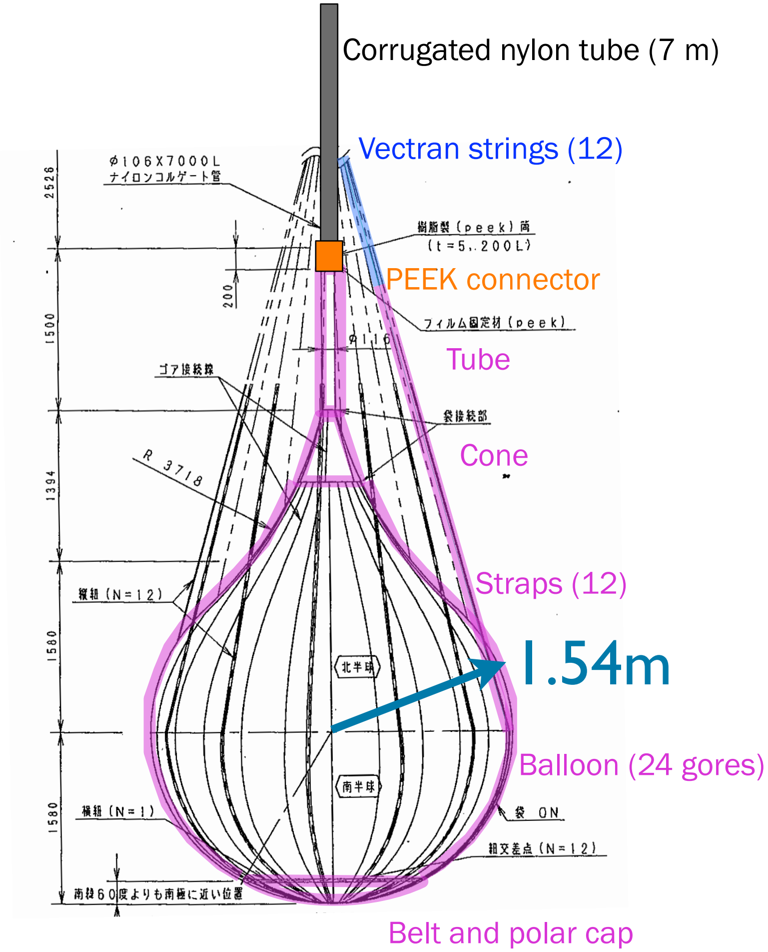
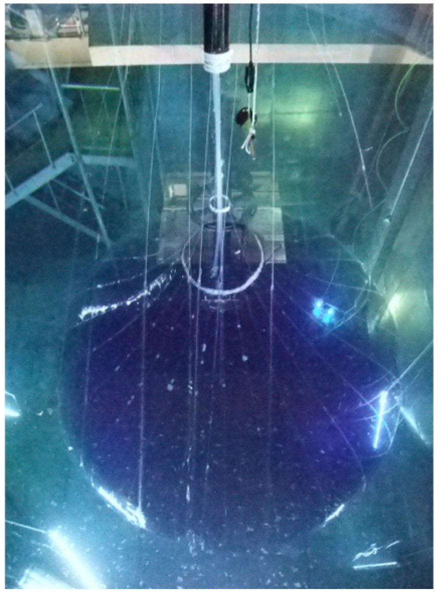
- Water Cherenkov veto
- Operational since 2002



Mini-Balloon

- Requirements
  - Chemical compatibility with LS
  - Mechanically strong, low radioactivity
  - Barrier against Xe:
    - loss < 220g/yr
  - Transmission of scintillation light
    - 99.4% at 400nm

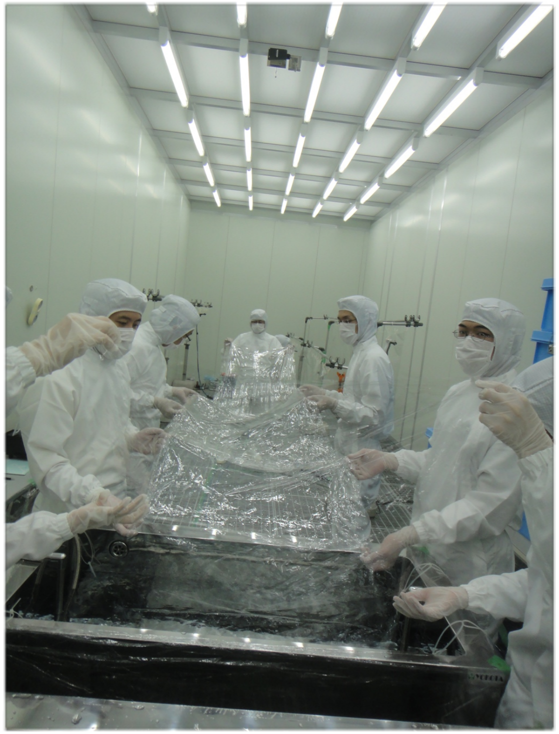


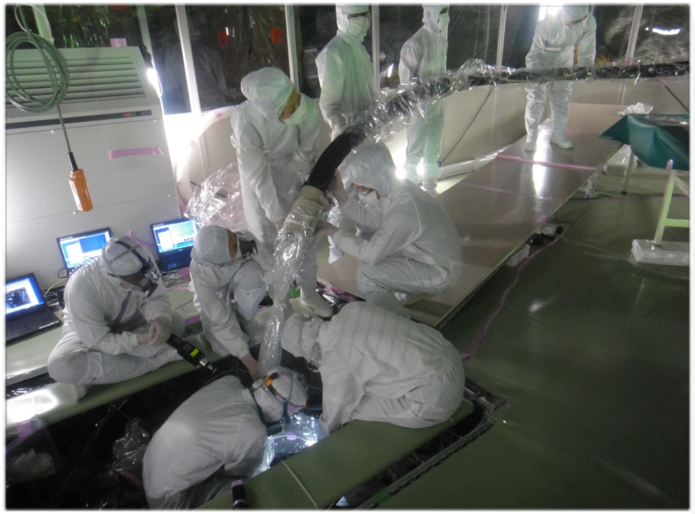


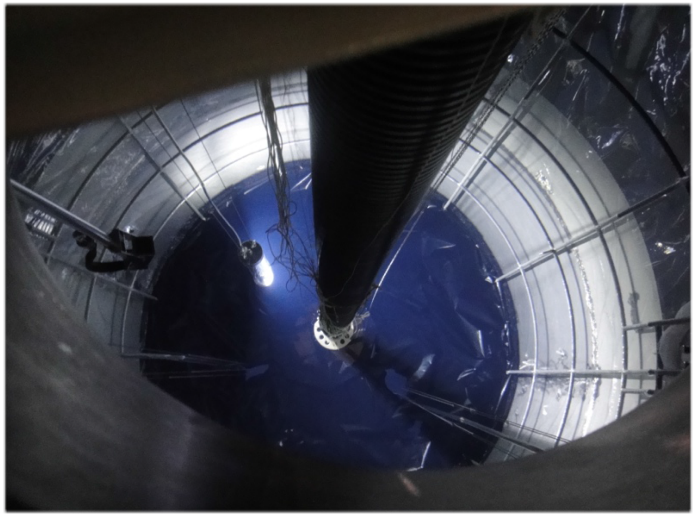
- Material: 25 μm thick ultra-pure nylon
  - U/Th/K ≲ 10^{-12} g/g
- 1/4 & full scale tests in air and water

Mini-Balloon Construction: May-Aug 2011

Near Sendai



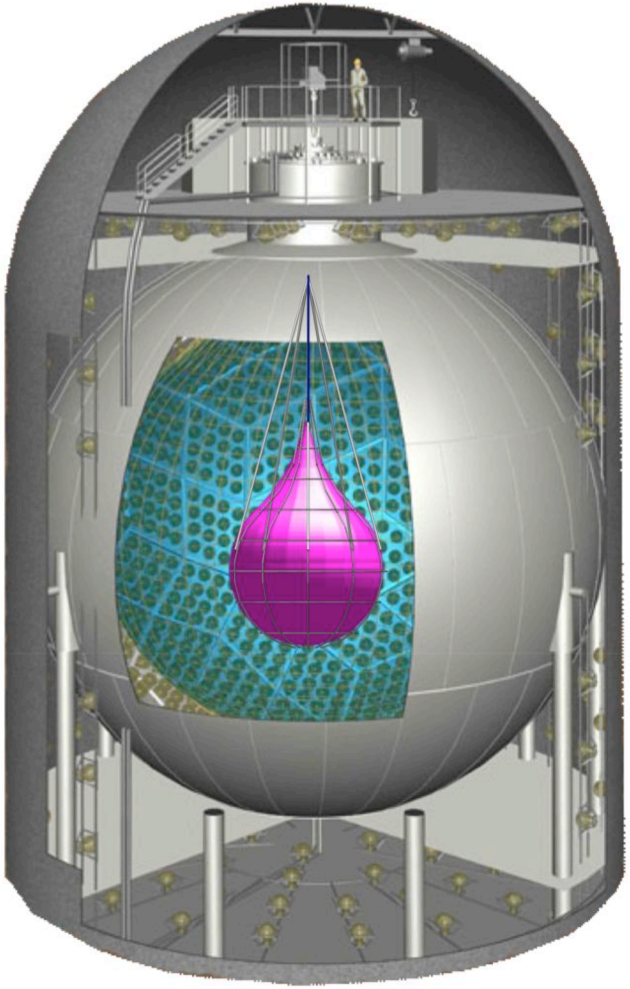




KamLAND-Zen advantages & disadvantages

- +Well-understood detector
- +Highly pure, self-shielding environment
- +Large ββ source mass, scalable
- -Relatively poor energy resolution
- -No particle identification

$$T^{0\nu}_{1/2} \propto \epsilon \frac{a}{A}\sqrt{\frac{Mt}{b\Delta E}}$$



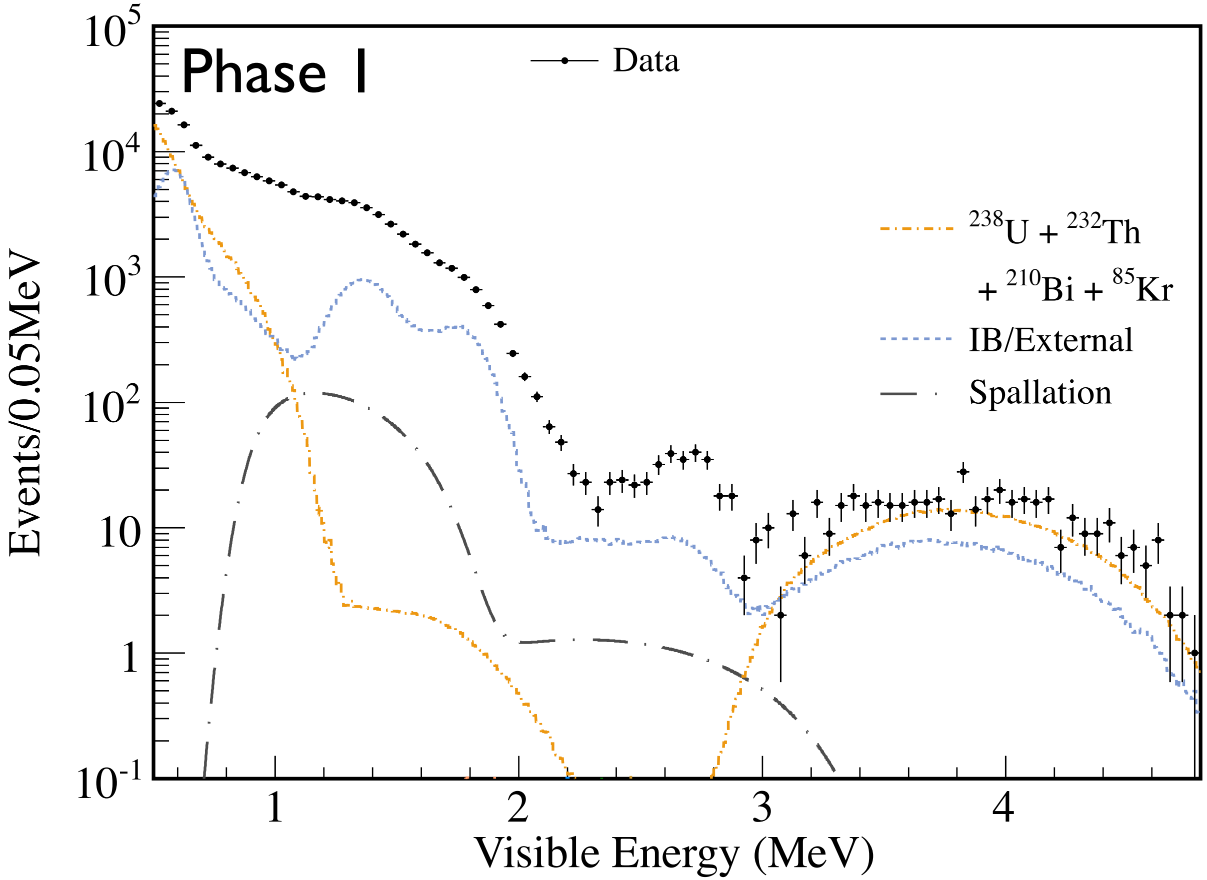
KamLAND-Zen Timeline

2011 | 2012 | 2013 | 2014 | 2015

Phase I

Sept '11:Start

90 kg-yr



KamLAND-Zen Collaboration, Phys.Rev.Lett. 110 (2013) 062502

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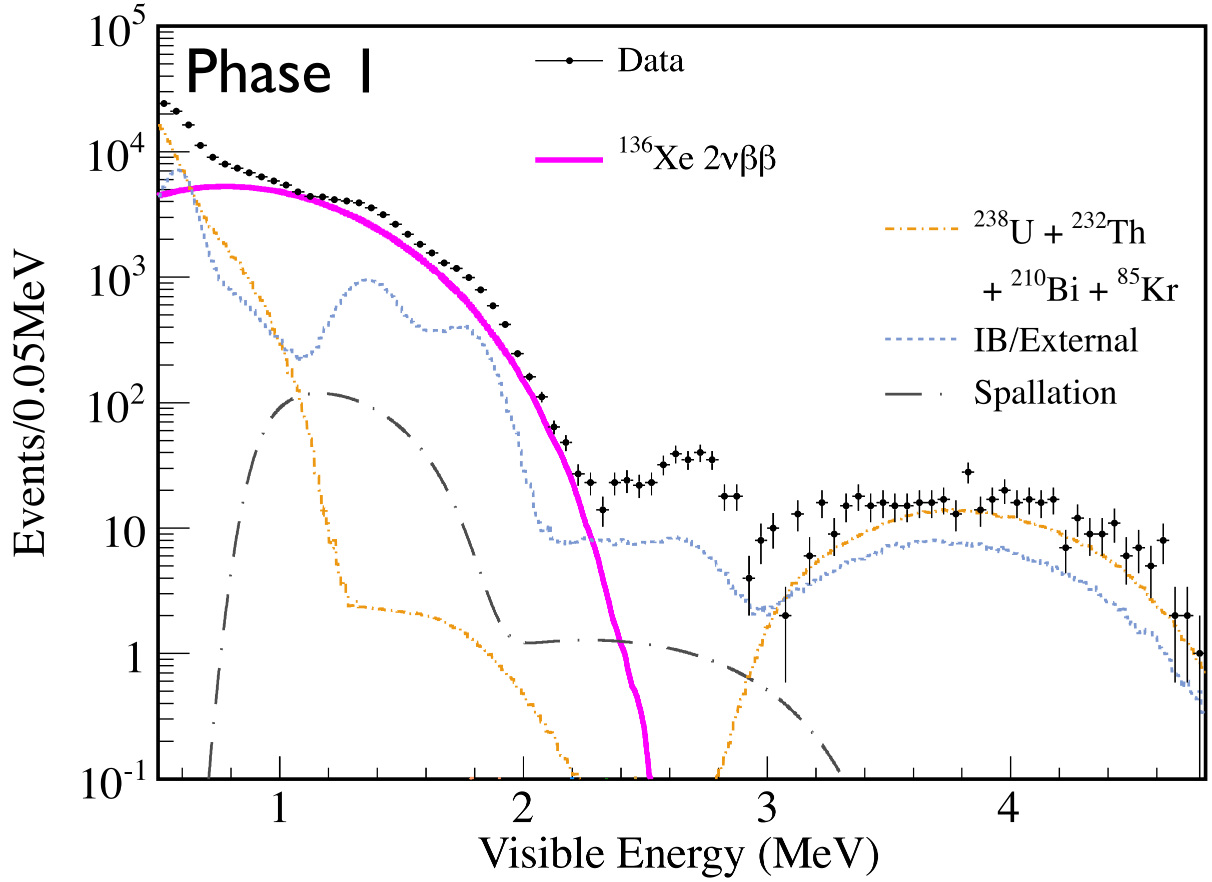
$$T^{2\nu}_{1/2} = 2.30 \pm 0.02\,(\mathrm{stat}) \pm 0.12\,(\mathrm{sys}) \times 10^{21}\,\mathrm{yr}$$



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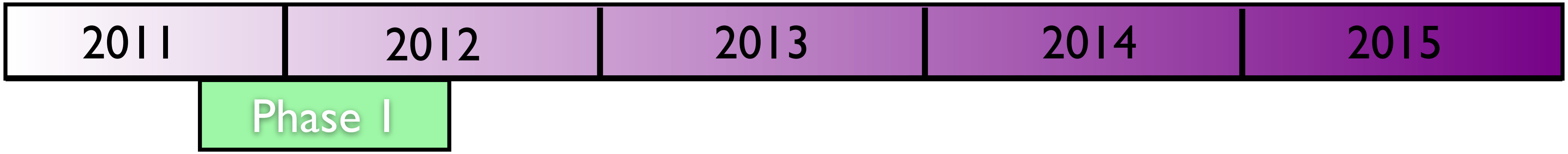

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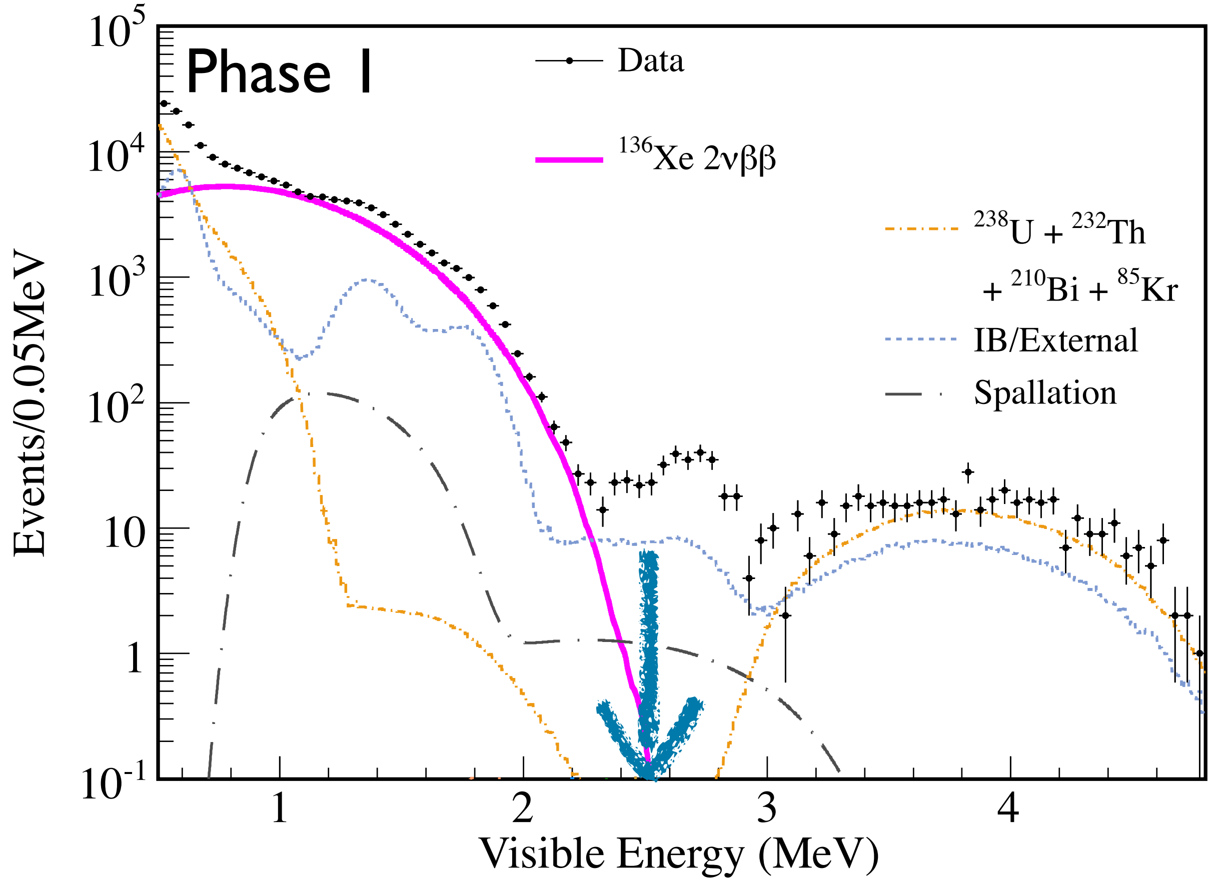

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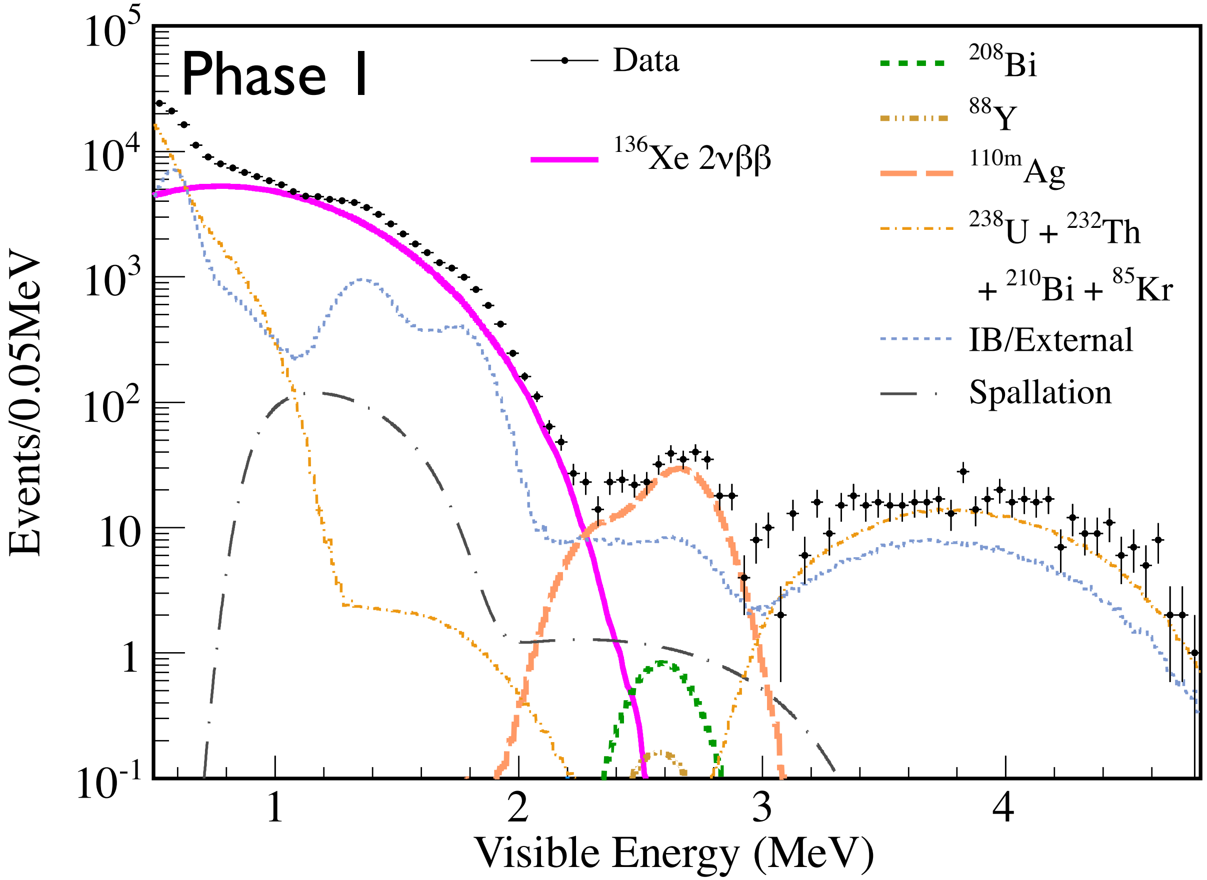
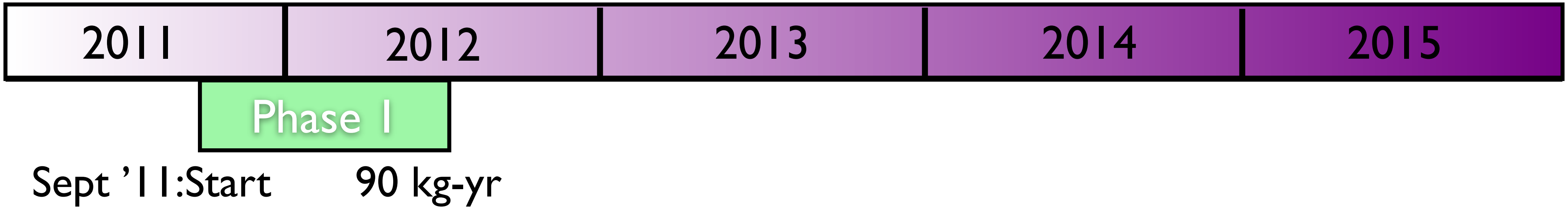


^{110m}Ag due to Fukushima-I nuclear fallout

KamLAND-Zen Collaboration, Phys.Rev.Lett. 110 (2013) 062502

KamLAND-Zen Timeline



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90 kg-yr

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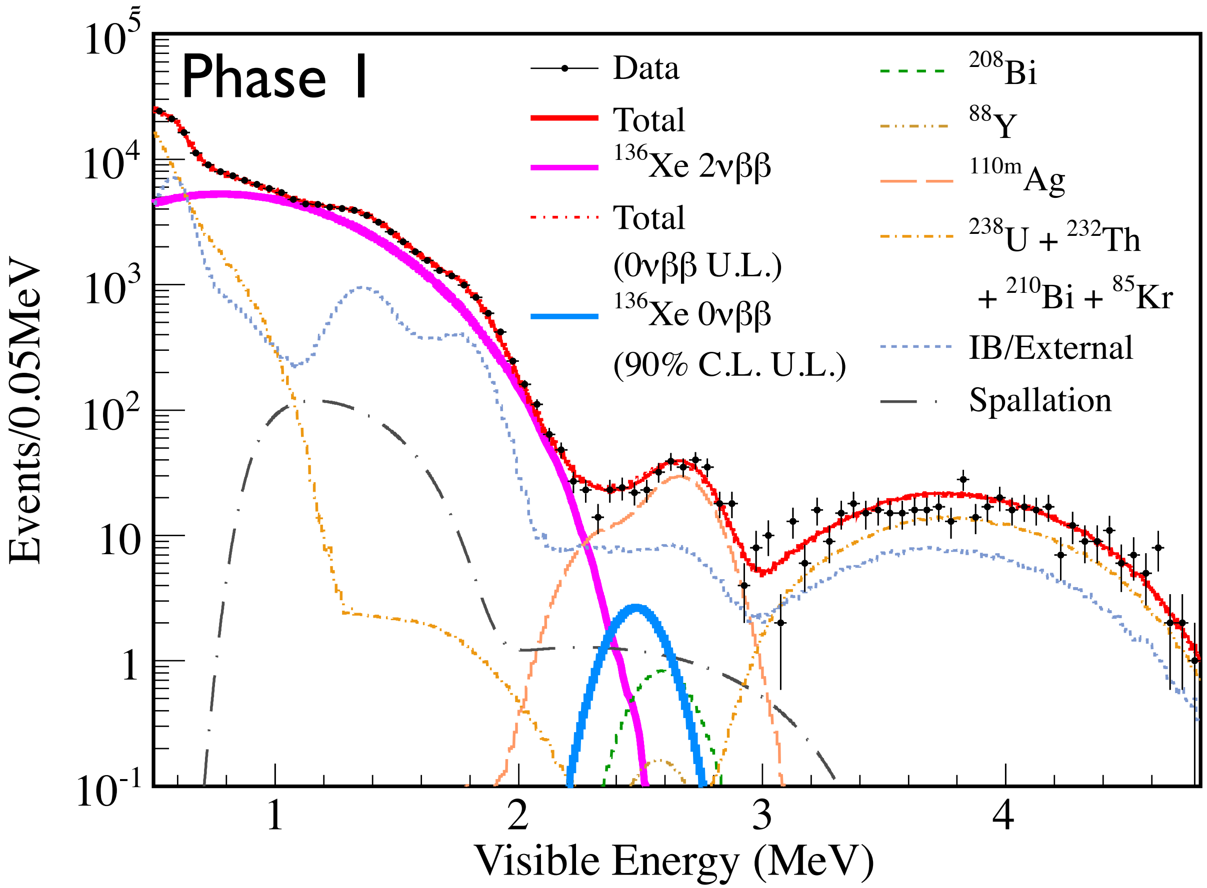
$T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr (90% CL)



^{110m}Ag due to Fukushima-I nuclear fallout

KamLAND-Zen Collaboration, Phys.Rev.Lett. 110 (2013) 062502

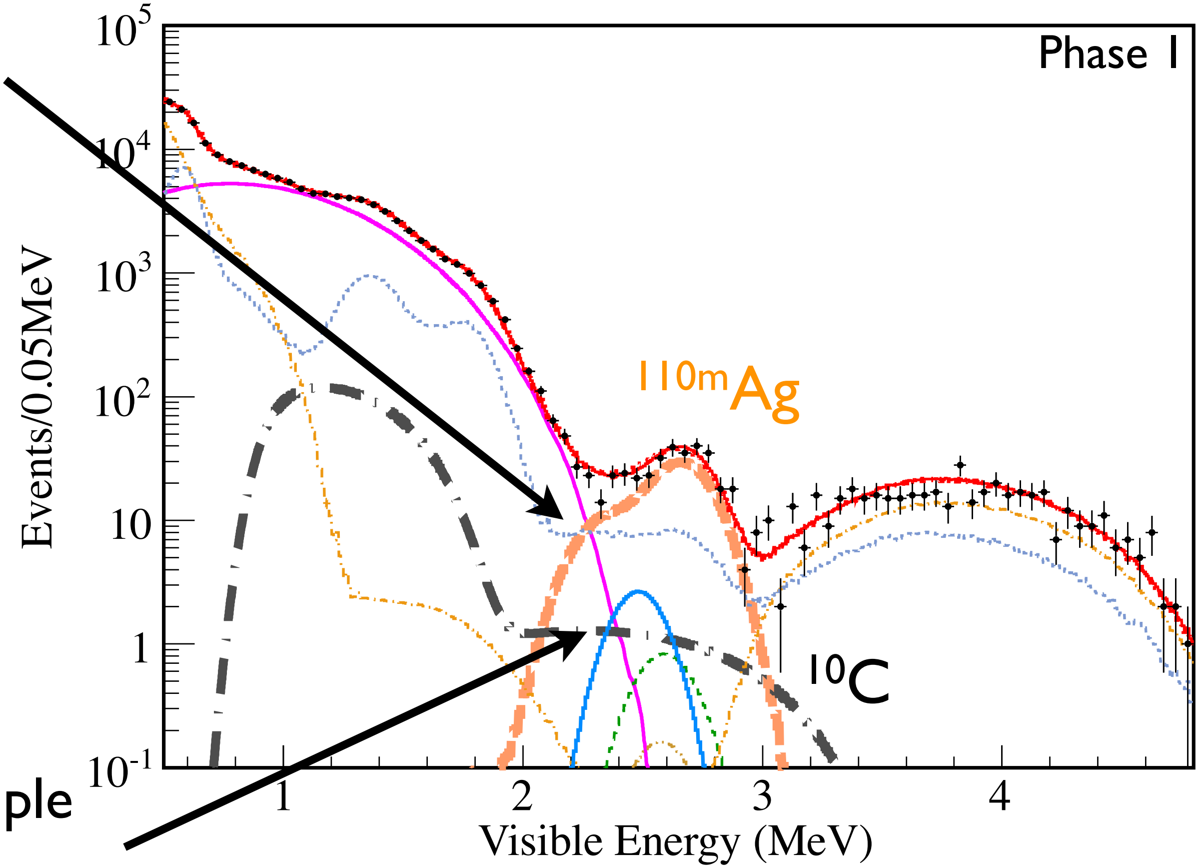
Phase I to Phase II Improvements

2011 | 2012 | 2013 | 2014 | 2015

Phase I | No Xe in MiniBalloon

Sept '11:Start | 90 kg-yr | **purification**

- Remove radioactive impurities with Xe-LS purification
  - long distillation campaign + new LS
- Increase the amount of Xe
  - 320kg → 383kg (+20%)
- Spallation cut after muon → ^{10}C rejection
  - muon-neutron-^{10}C (τ=27.8s) triple coincidence



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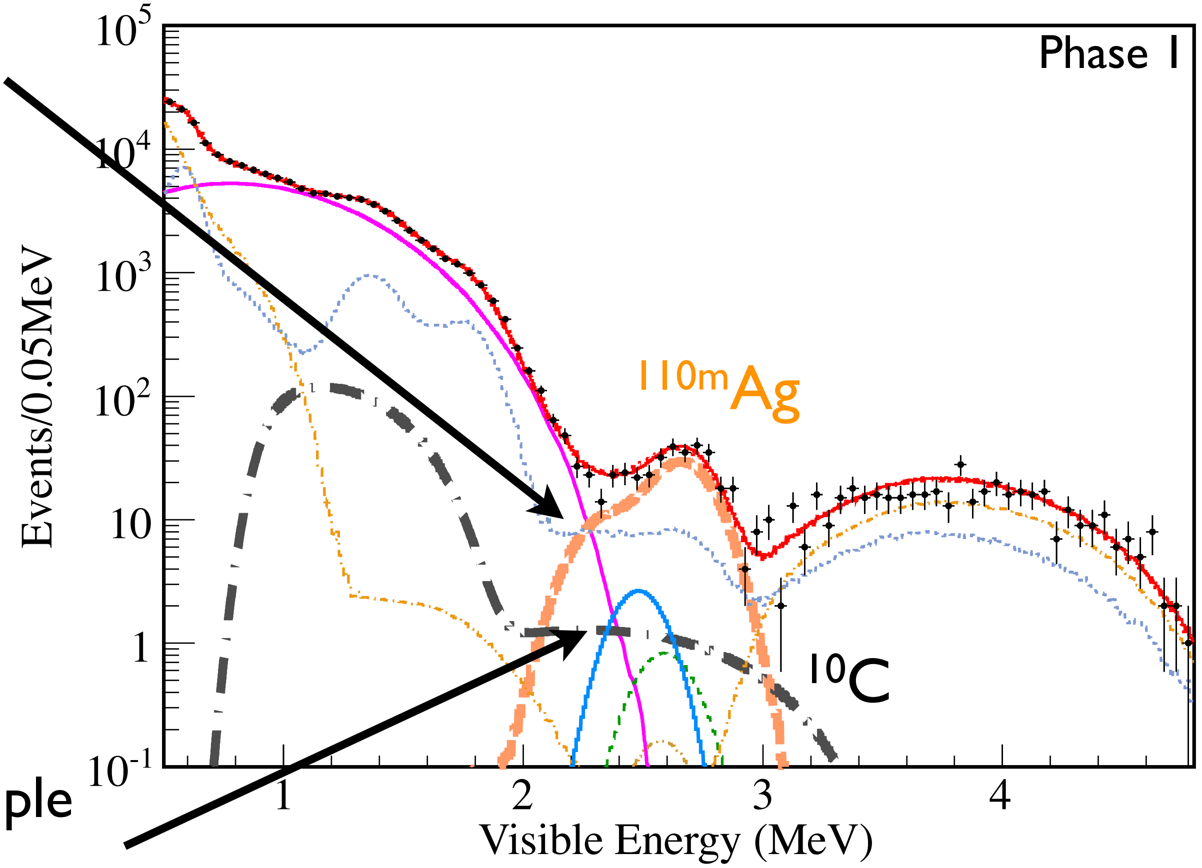
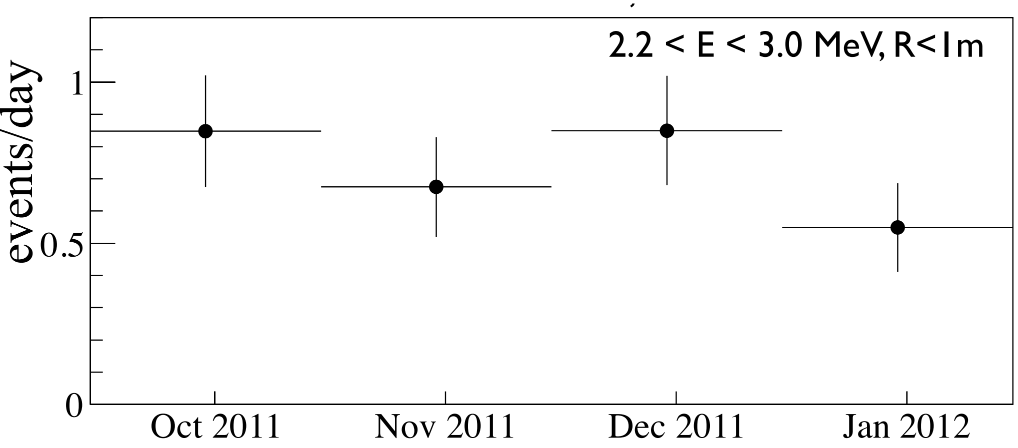


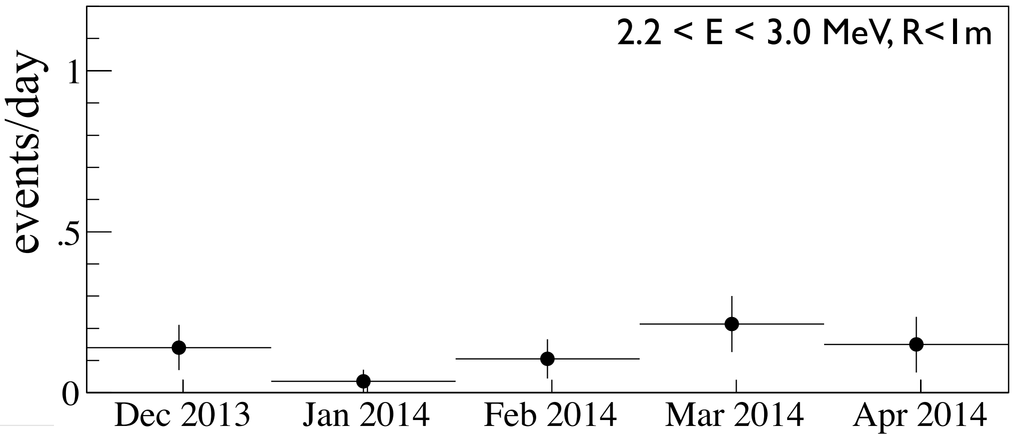
^{110m}Ag Background Reduction

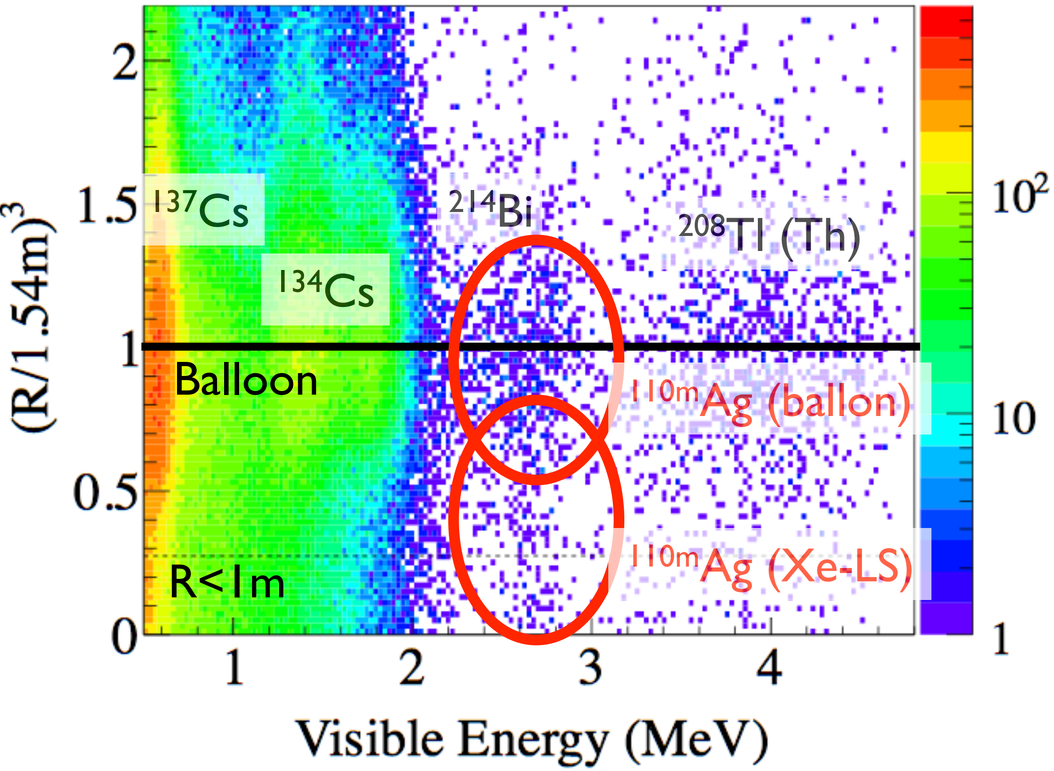
^{110m}Ag BG reduced < 1/10

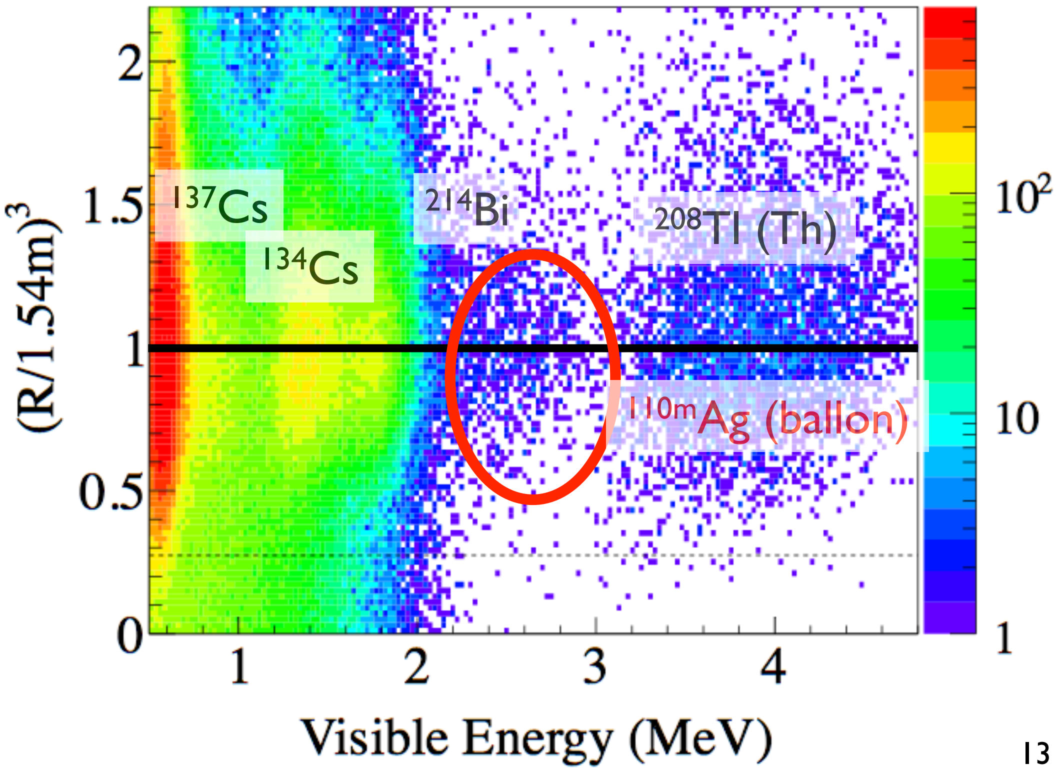
Phase I

First 115d of Phase II

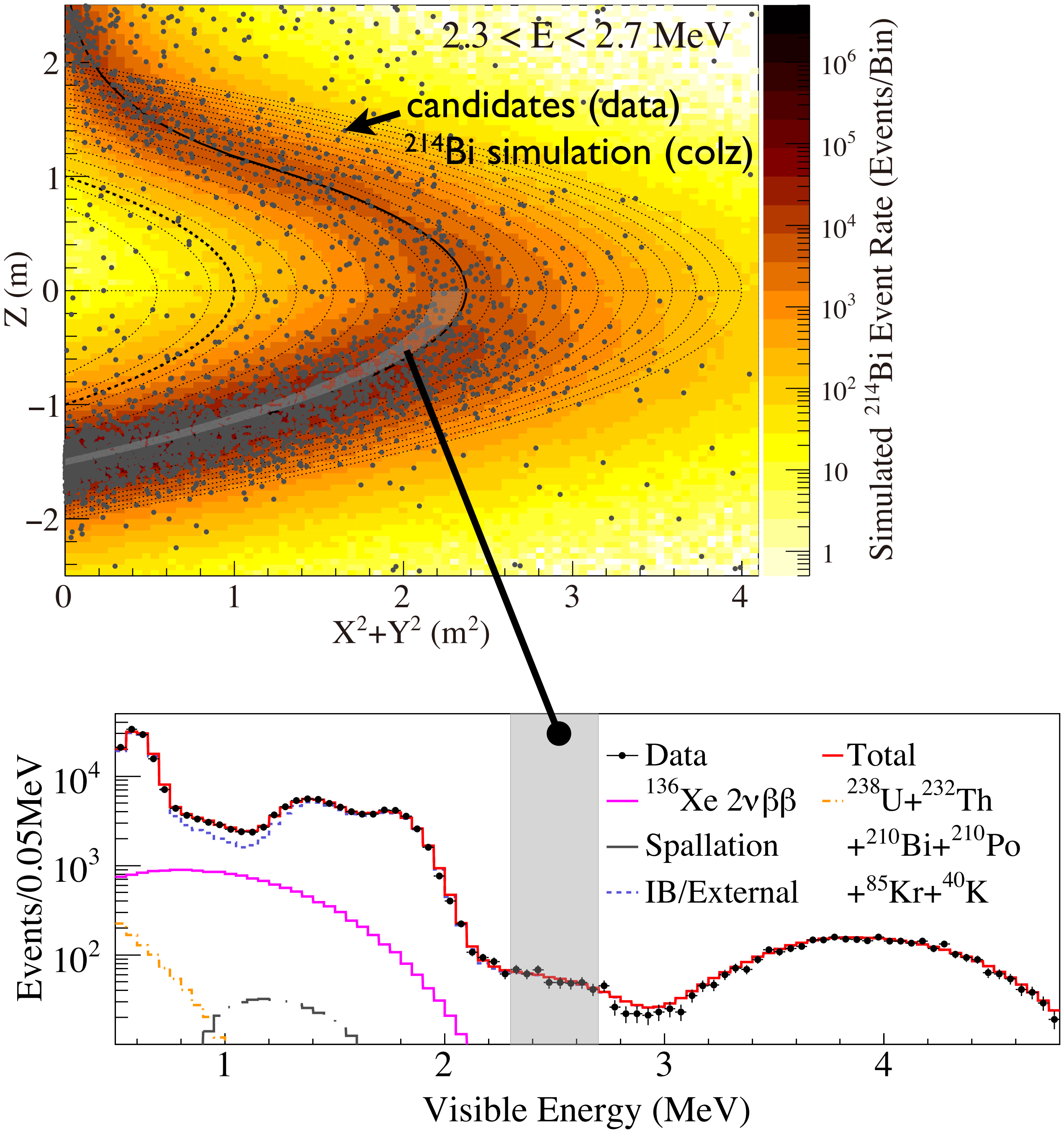








KLZ-400 Phase 2 Data



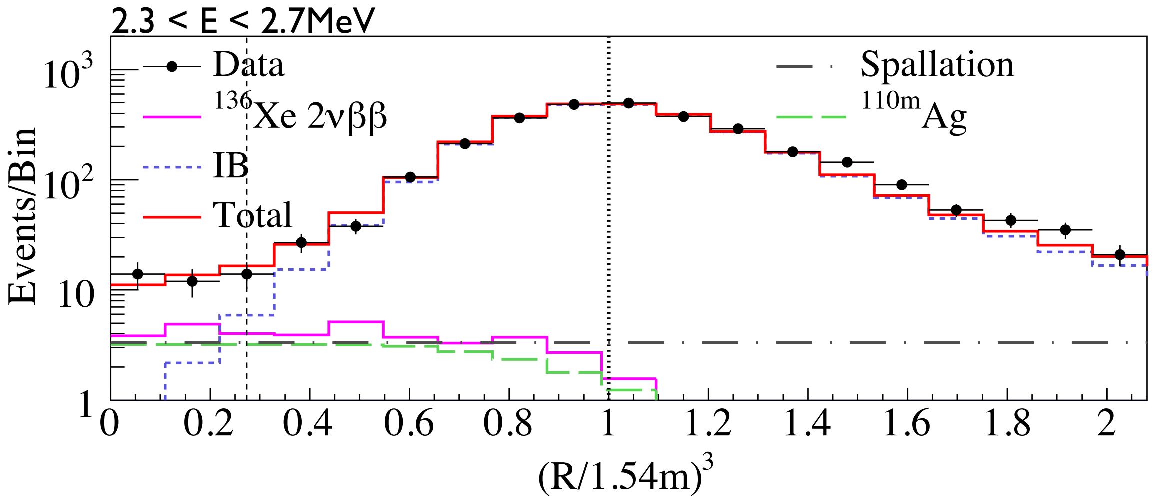
Event Selection:

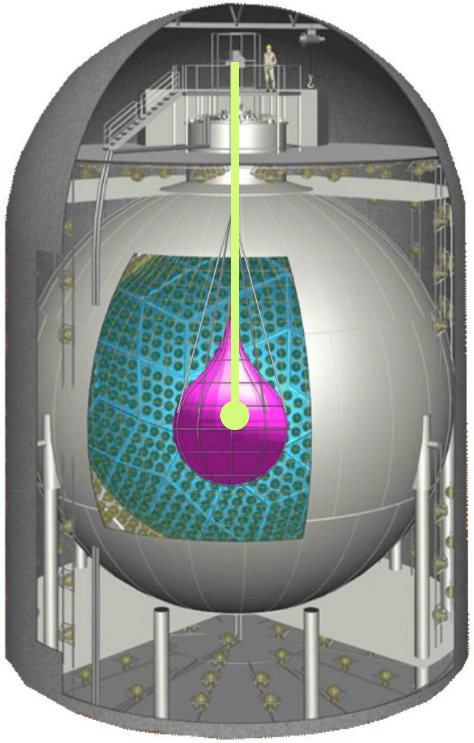
- i) R < 2m
- ii) ΔT > 2ms after muons
- iii) no ^{214}Bi-^{214}Po (τ=237μs)
- iv) no ^{212}Bi-^{212}Po (τ=0.4μs)
- v) no reactor neutrinos

We use 40 equal-volume bins to account for varying BG: Simultaneous spectral fit in all volume bins

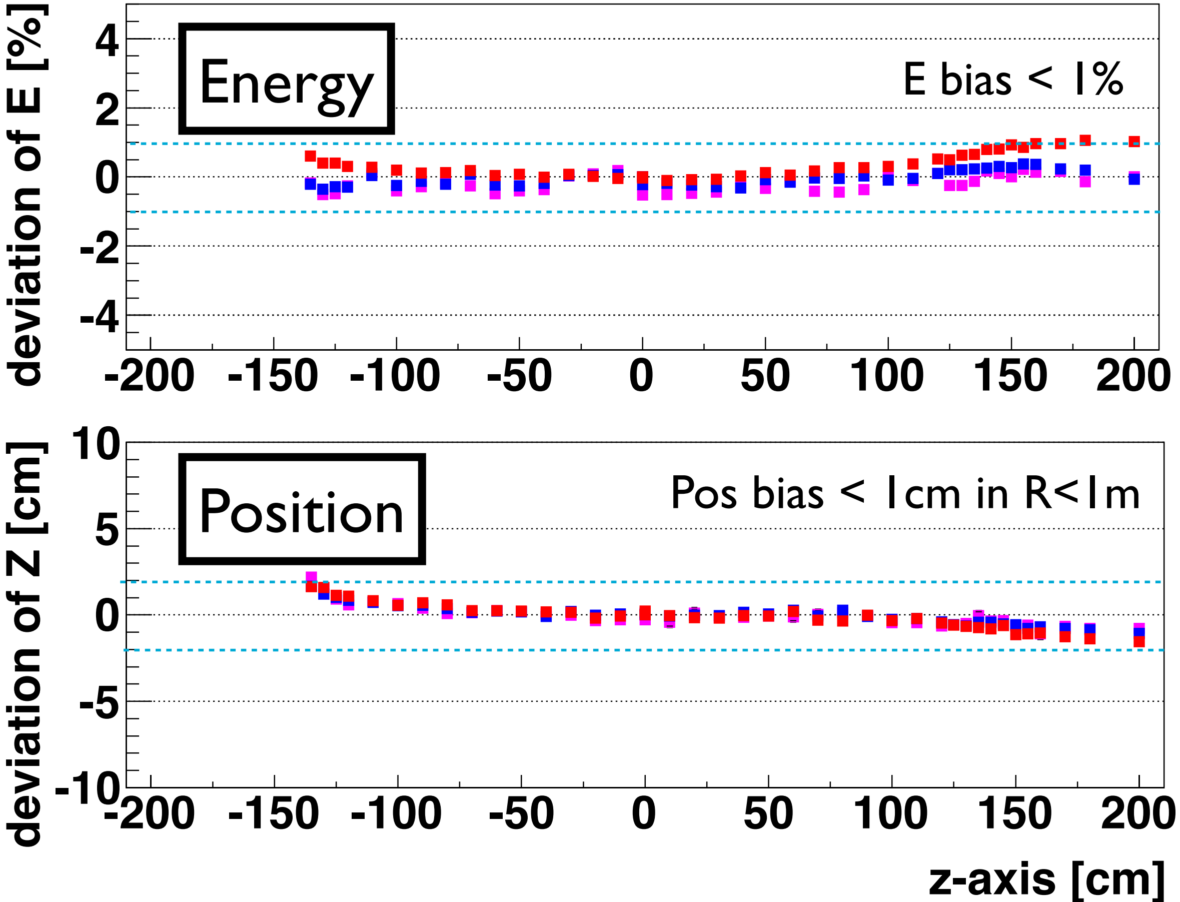
KamLAND-Zen Coll, Phys. Rev. Lett. 117, 082503 (2016); arXiv:1605.02889

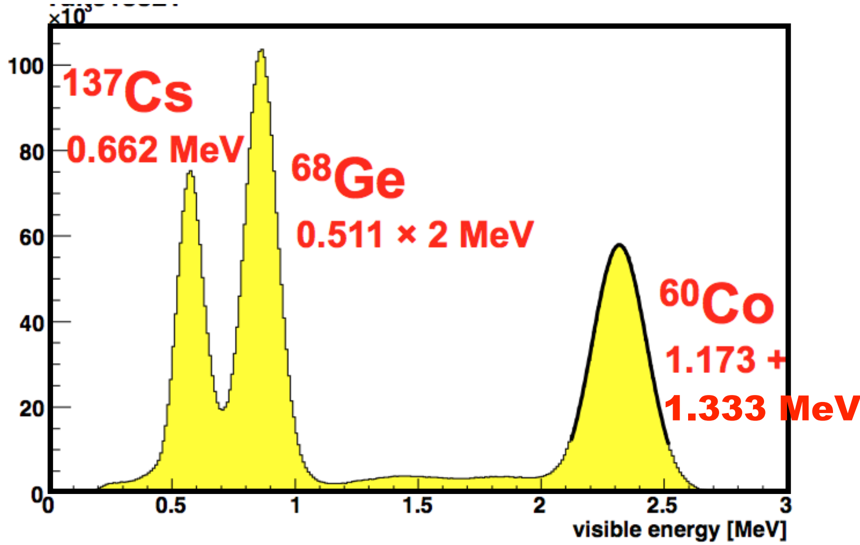
Position & Energy Calibration



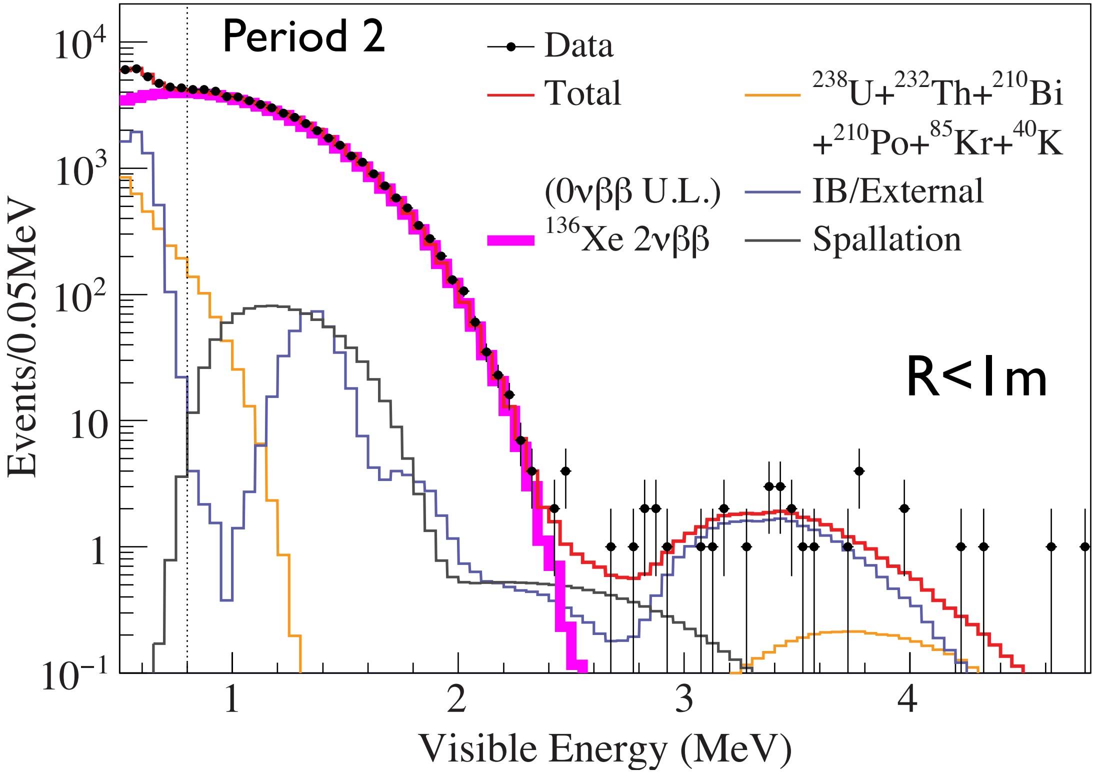


Dedicated calibration at end of Phase-2





Results for Phase-2

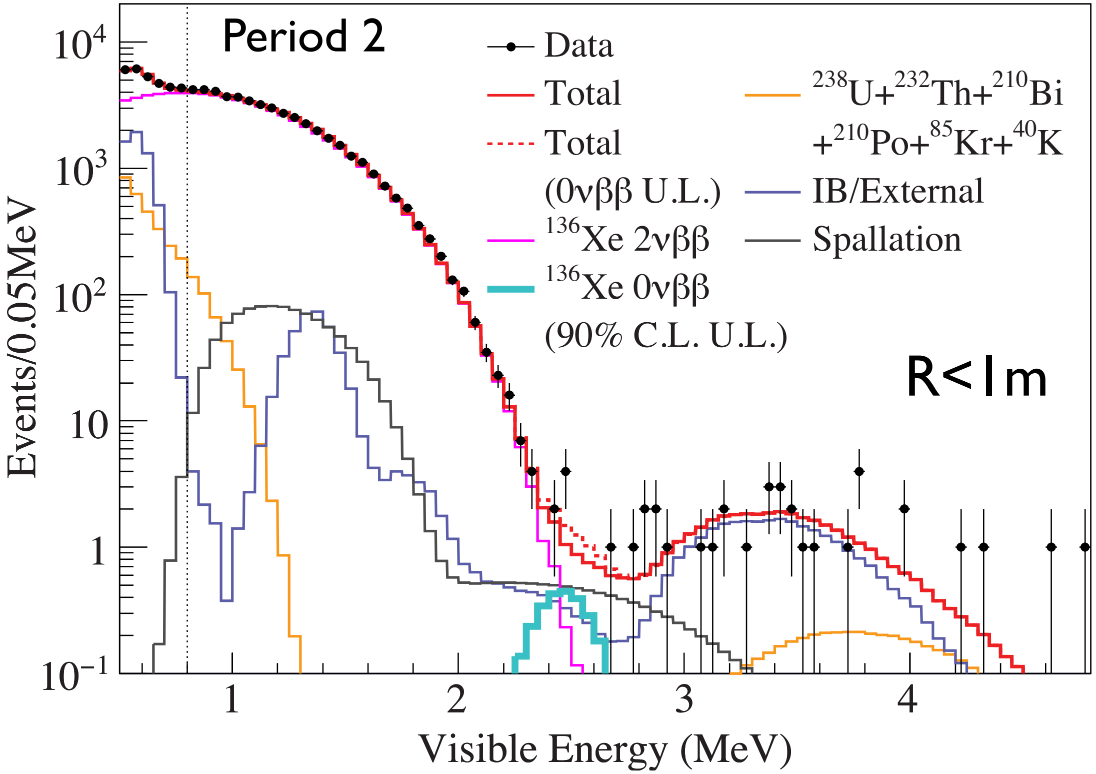


504 kg-yr exposure of ^{136}Xe

New 2ν2β value:

$T_{1/2}^{2\nu}$ = 2.21 ± 0.02 (stat) ± 0.07 (syst) x 10^{21} yr

Results for Phase-2



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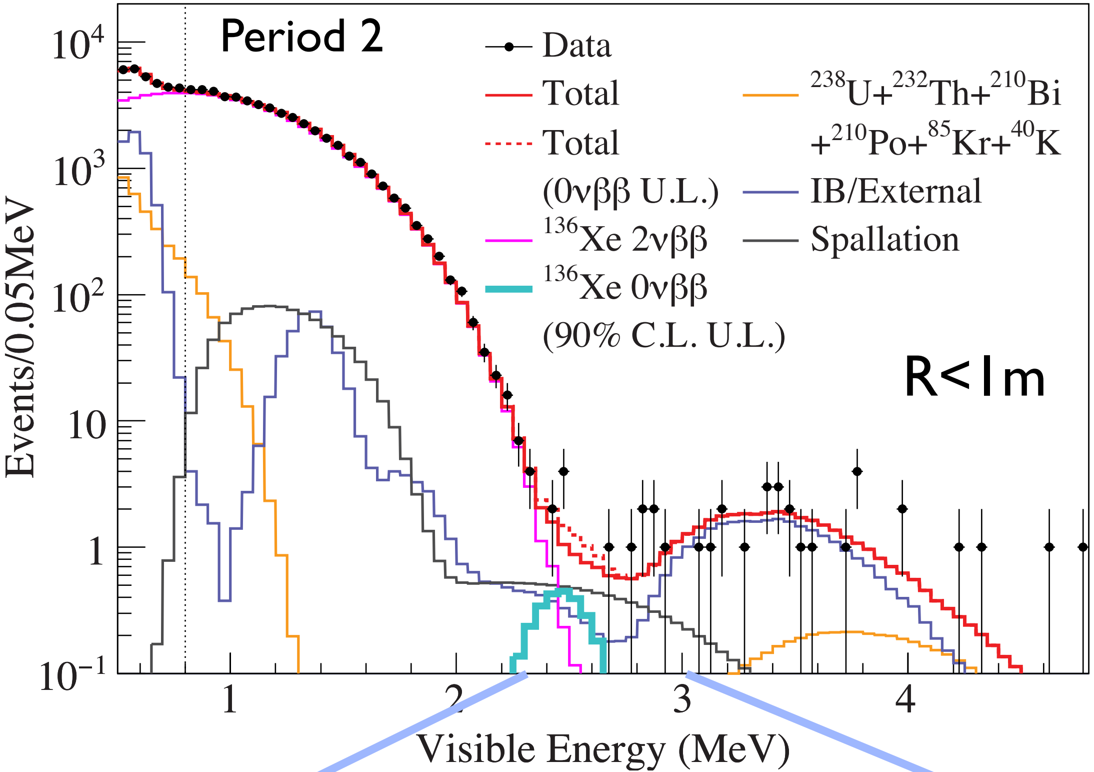

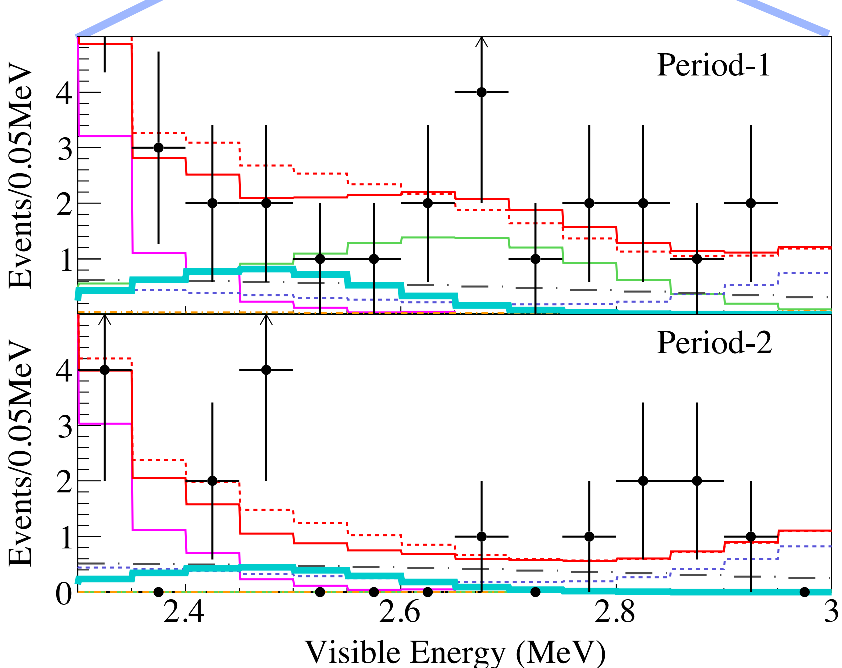

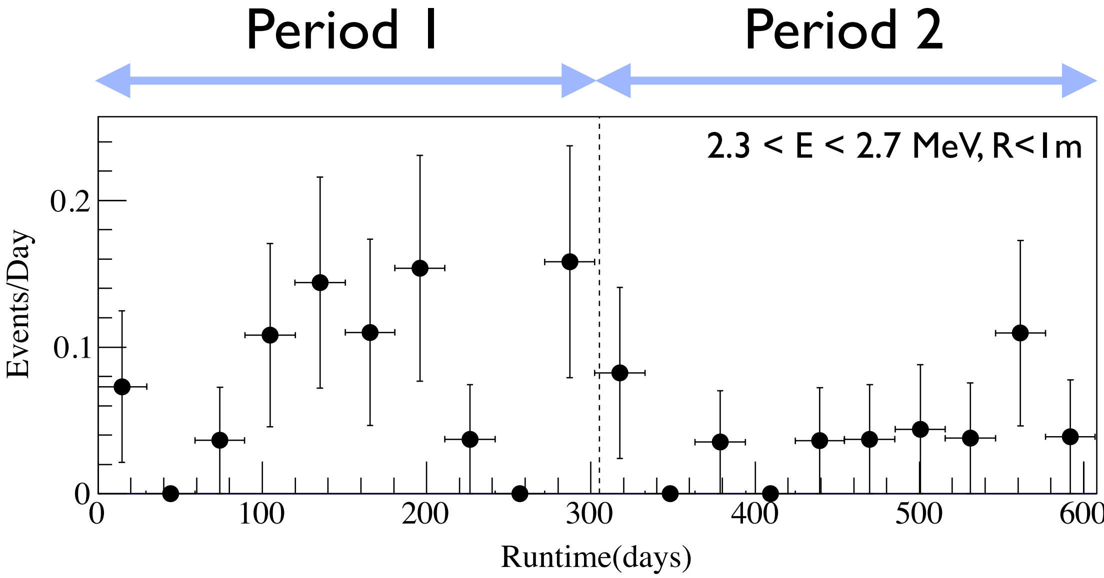

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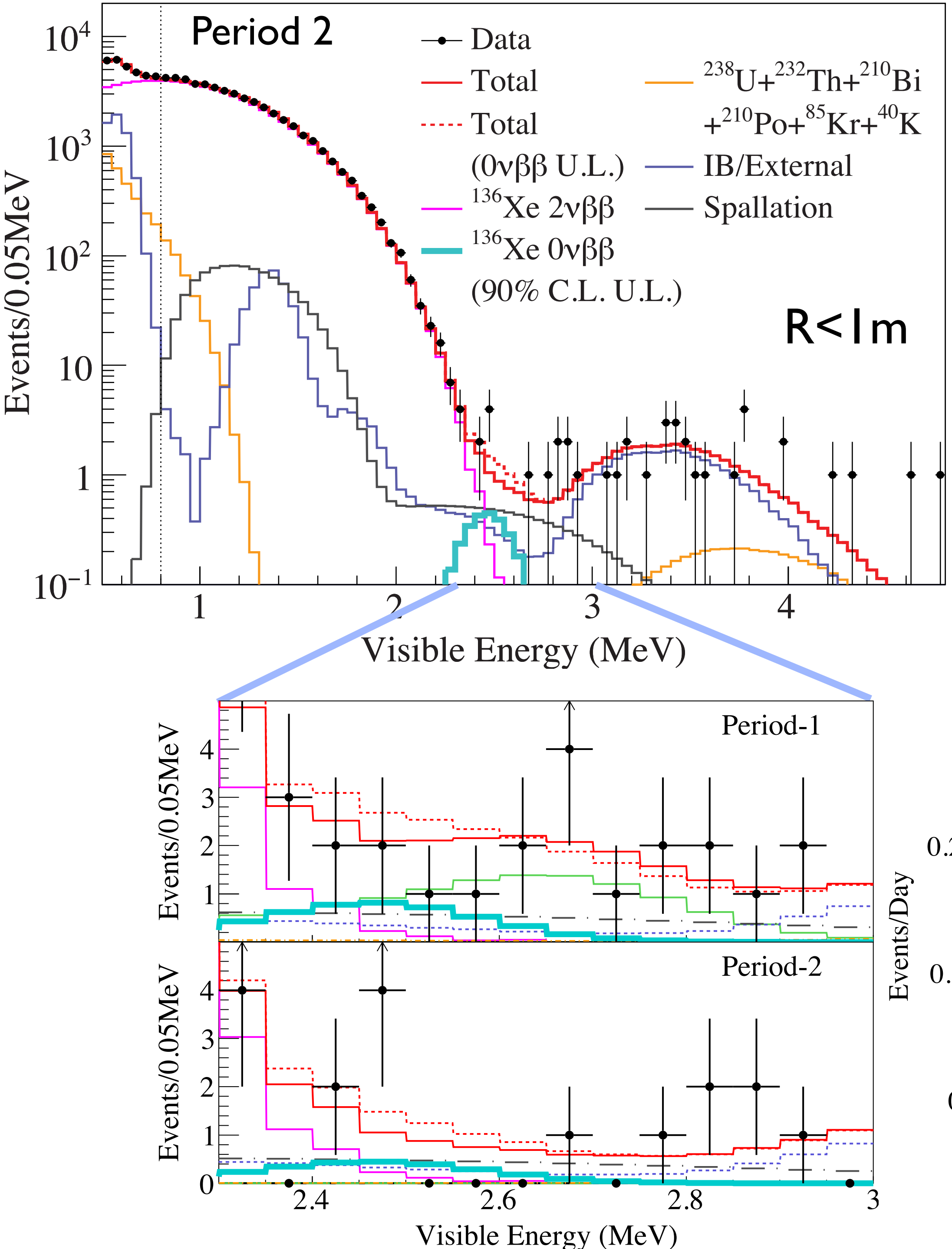
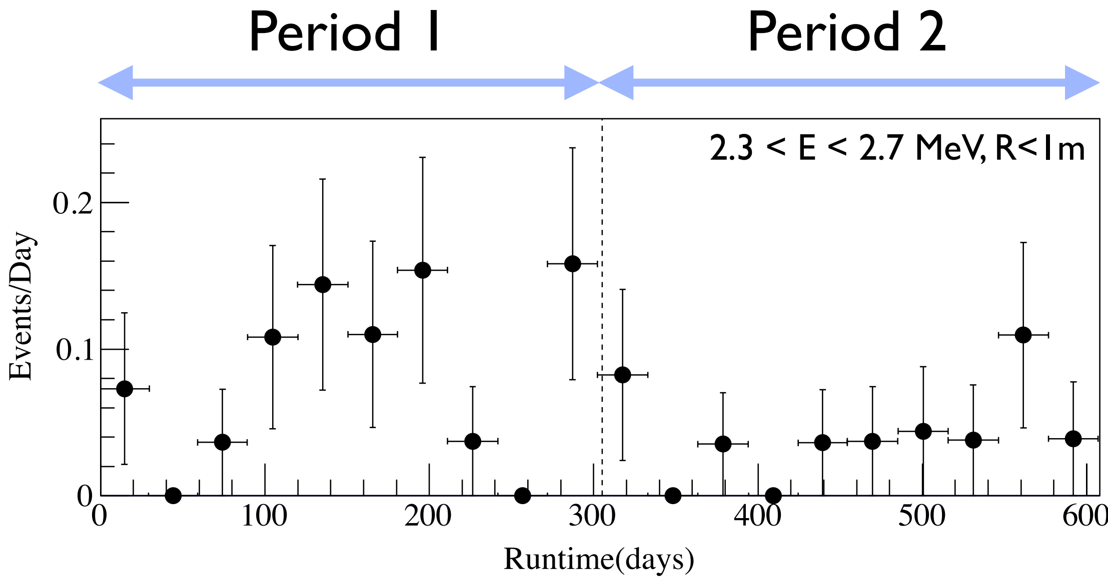


New 0ν2β limit:

$T^{0\nu}_{1/2} > 9.2 \times 10^{25}$ yr

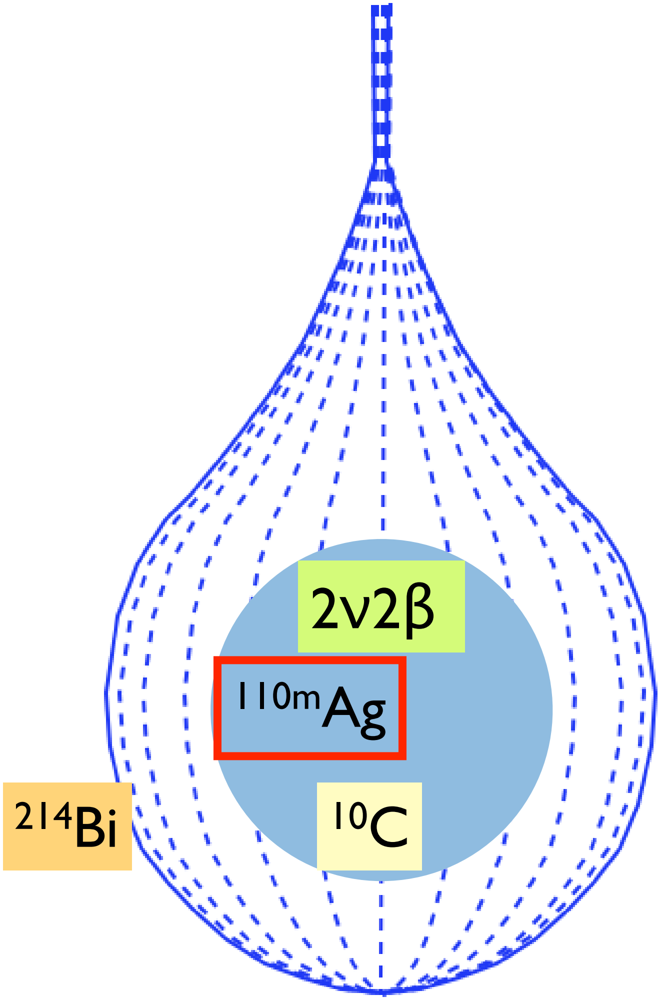
[sens: > 5.6 x 10^{25} yr]



Background Estimates

2.3 < E < 2.7 MeV, R < 1m

	Period-1		Period-2	
	(270.7 days)		(263.8 days)	
Observed events	22		11	
Background	Estimated	Best-fit	Estimated	Best-fit
^{136}Xe $2\nu\beta\beta$	-	5.48	-	5.29
Residual radioactivity in Xe-LS				
^{214}Bi (^{238}U series)	0.23 ± 0.04	0.25	0.028 ± 0.005	0.03
^{208}Tl (^{232}Th series)	-	0.001	-	0.001
^{110m}Ag	-	8.5	-	0.0
External (Radioactivity in IB)				
^{214}Bi (^{238}U series)	-	2.56	-	2.45
^{208}Tl (^{232}Th series)	-	0.02	-	0.03
^{110m}Ag	-	0.003	-	0.002
Spallation products				
^{10}C	2.7 ± 0.7	3.3	2.6 ± 0.7	2.8
^{6}He	0.07 ± 0.18	0.08	0.07 ± 0.18	0.08
^{12}B	0.15 ± 0.04	0.16	0.14 ± 0.04	0.15
^{137}Xe	0.5 ± 0.2	0.5	0.5 ± 0.2	0.4



Background Estimates

2.3 < E < 2.7 MeV, R < 1m

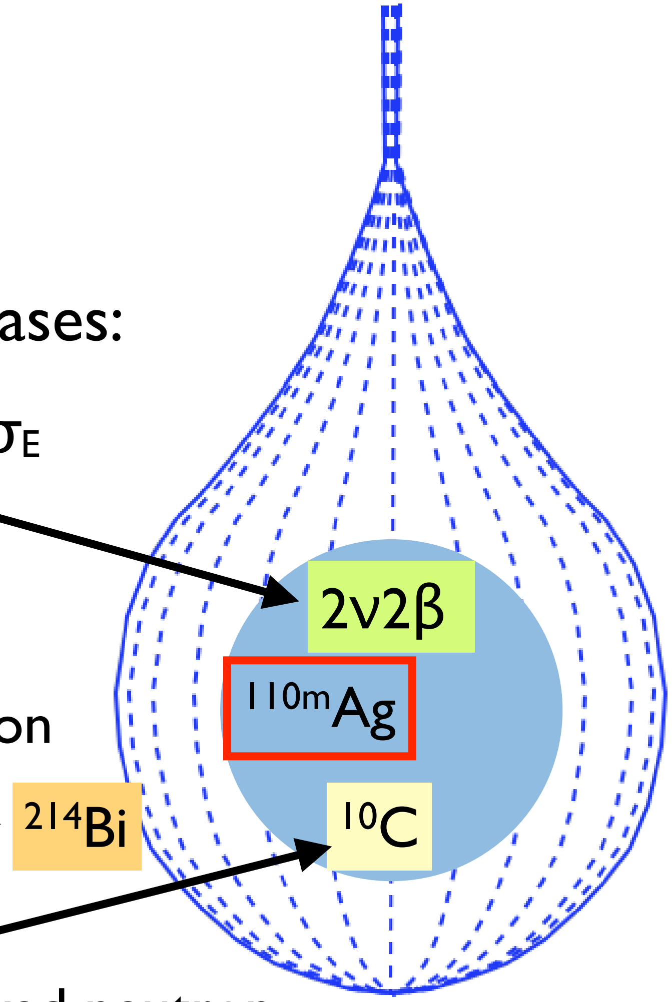
	Period-1 (270.7 days)		Period-2 (263.8 days)	
Observed events	22		11	
Background	Estimated	Best-fit	Estimated	Best-fit
^{136}Xe $2\nu\beta\beta$	-	5.48	-	5.29
Residual radioactivity in Xe-LS				
^{214}Bi (^{238}U series)	0.23 ± 0.04	0.25	0.028 ± 0.005	0.03
^{208}Tl (^{232}Th series)	-	0.001	-	0.001
^{110m}Ag	-	8.5	-	0.0
External (Radioactivity in IB)				
^{214}Bi (^{238}U series)	-	2.56	-	2.45
^{208}Tl (^{232}Th series)	-	0.02	-	0.03
^{110m}Ag	-	0.003	-	0.002
Spallation products				
^{10}C	2.7 ± 0.7	3.3	2.6 ± 0.7	2.8
^{6}He	0.07 ± 0.18	0.08	0.07 ± 0.18	0.08
^{12}B	0.15 ± 0.04	0.16	0.14 ± 0.04	0.15
^{137}Xe	0.5 ± 0.2	0.5	0.5 ± 0.2	0.4

Next phases:

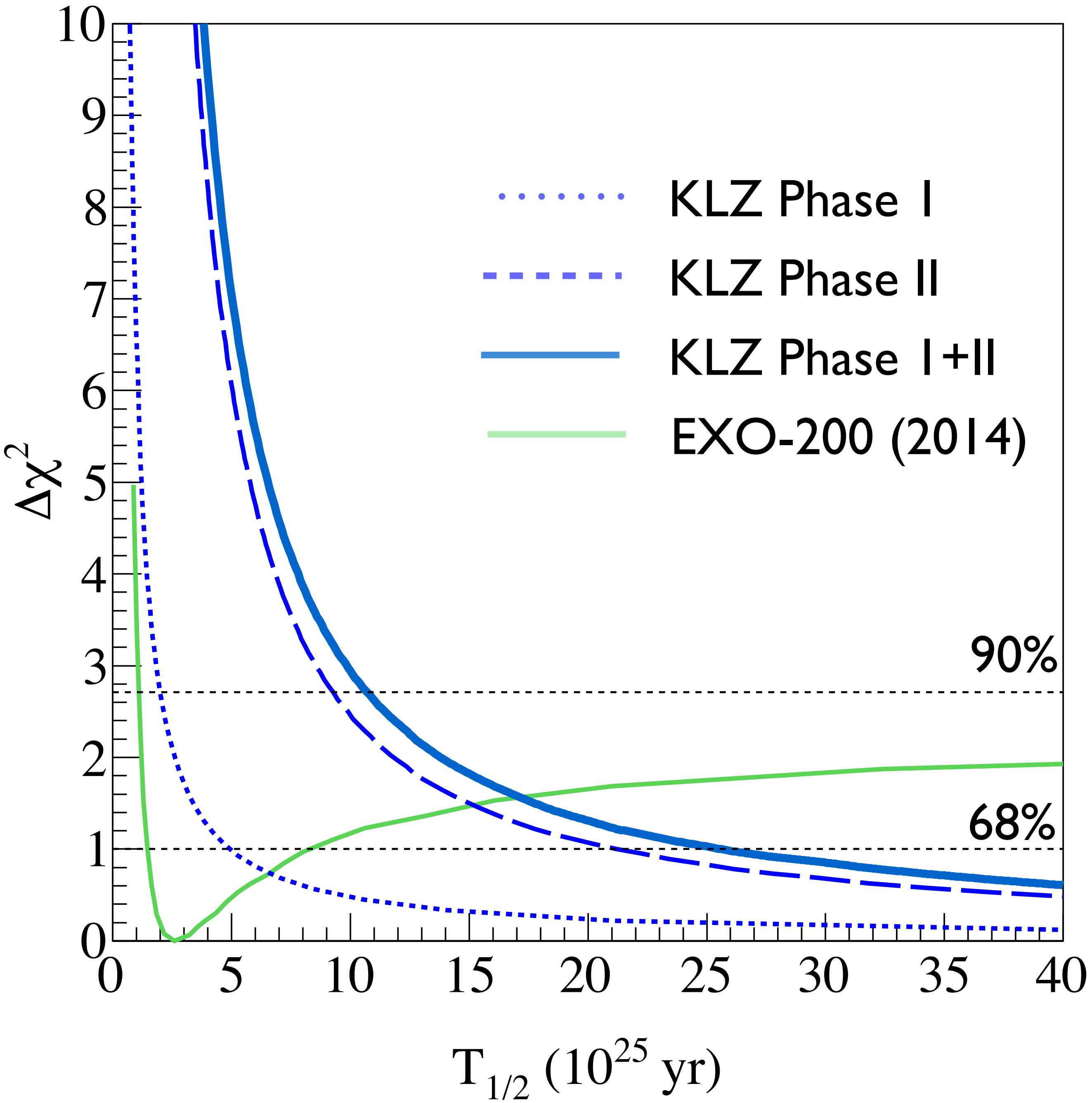
Better σ_E

New Balloon

Improved neutron detection



^{136}Xe 0ν2β Decay Half-life



KLZ Phase I:

$T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr

KLZ Phase II:

$T^{0\nu}_{1/2} > 9.2 \times 10^{25}$ yr

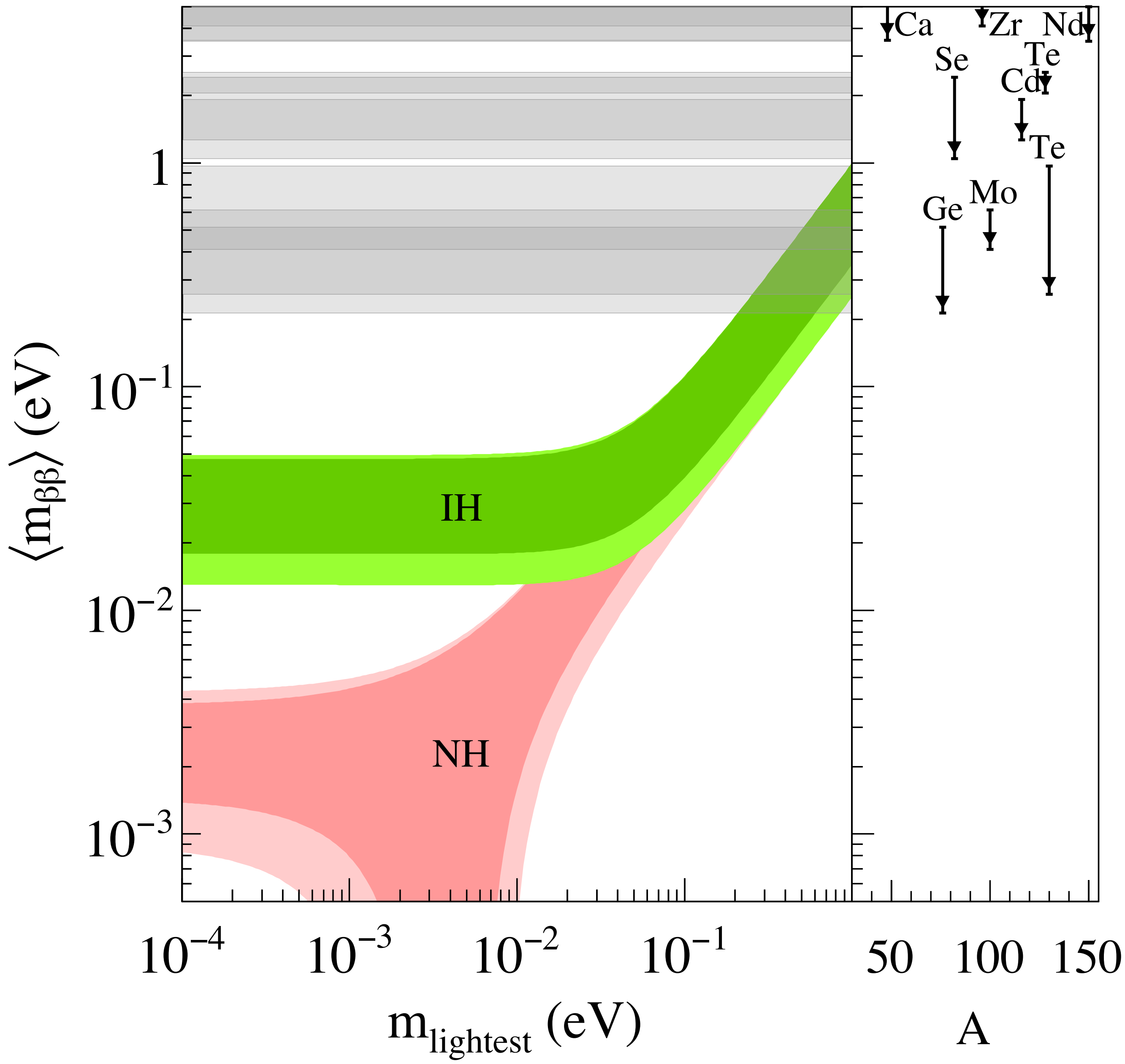
sens: $> 5.6 \times 10^{25}$ yr

KLZ Phase I+II:

$\boxed{T^{0\nu}_{1/2} > 1.07 \times 10^{26} \text{ yr}}$

(all @ 90% C.L.)

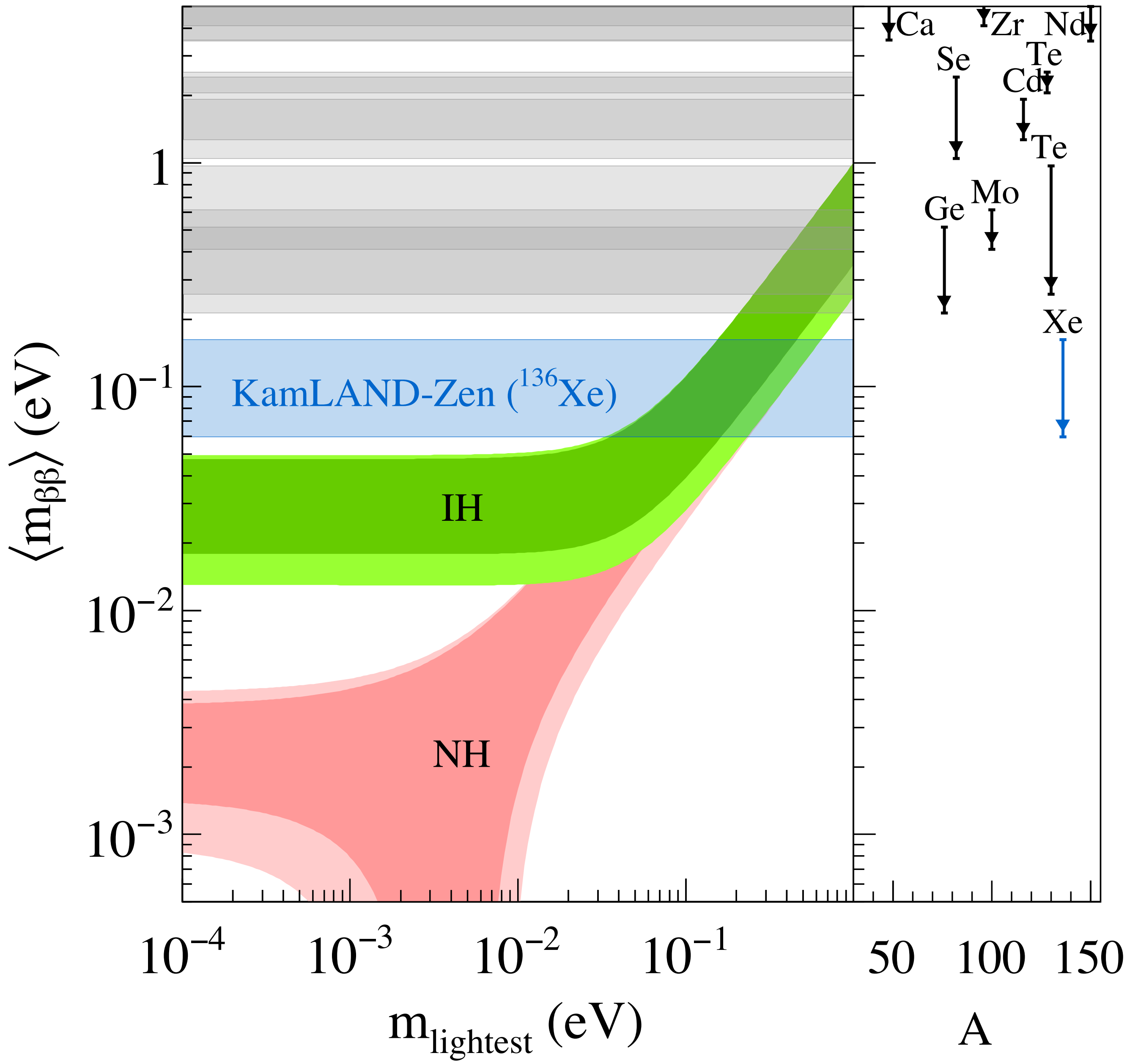
Effective Neutrino Mass



$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q,Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

KamLAND-Zen Coll, Phys. Rev. Lett. 117, 082503 (2016); arXiv:1605.02889

Effective Neutrino Mass

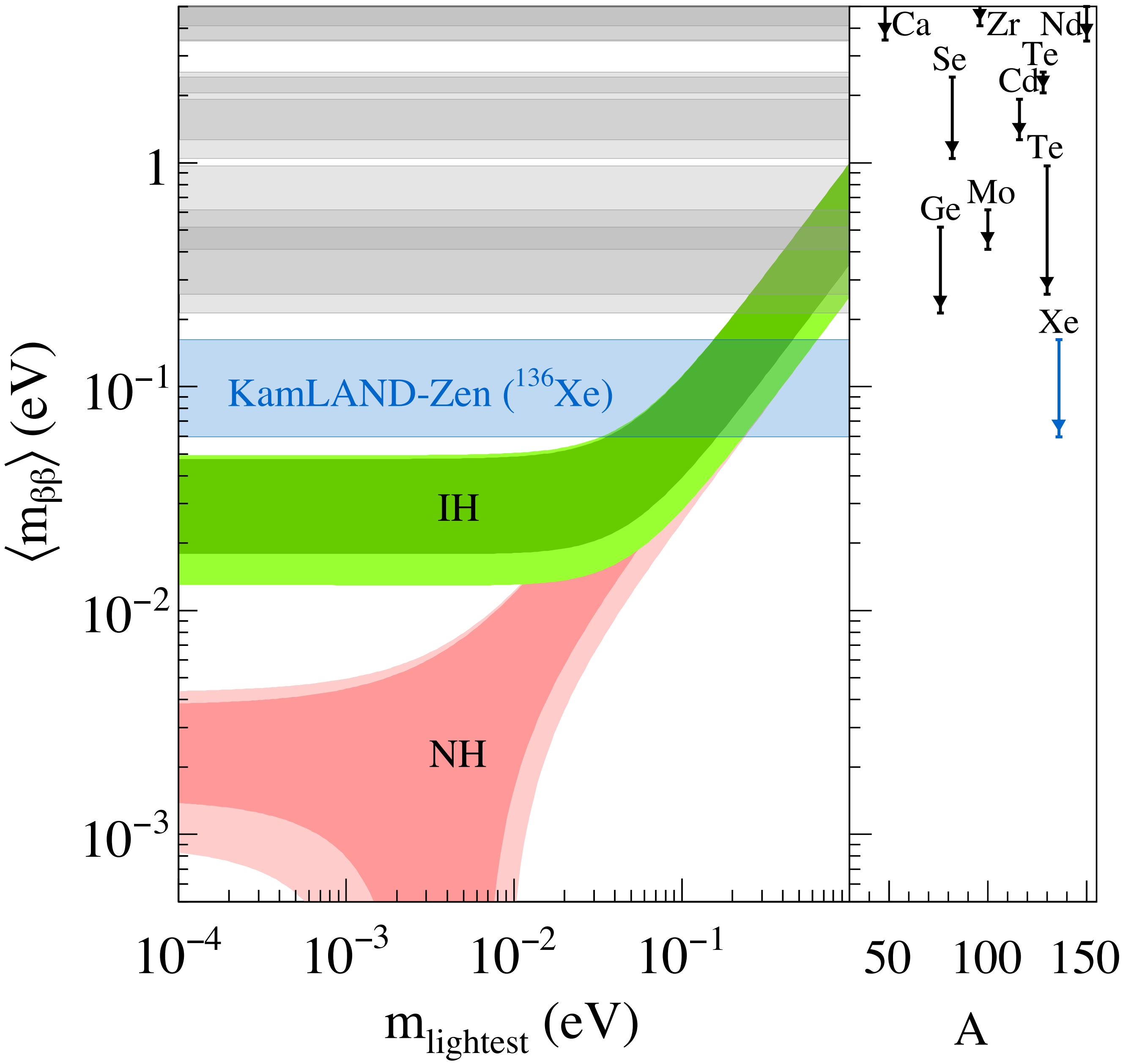


$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q,Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

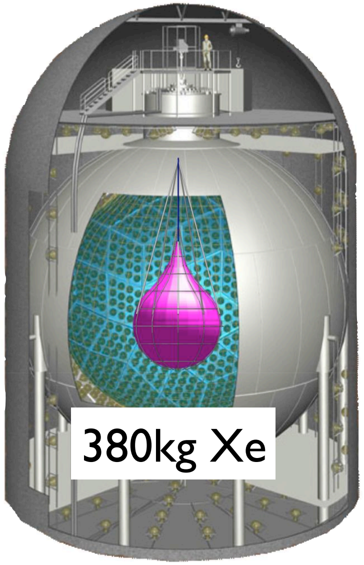
$\langle m_{\beta\beta} \rangle < 61 - 165$ meV

KamLAND-Zen Coll, Phys. Rev. Lett. 117, 082503 (2016); arXiv:1605.02889

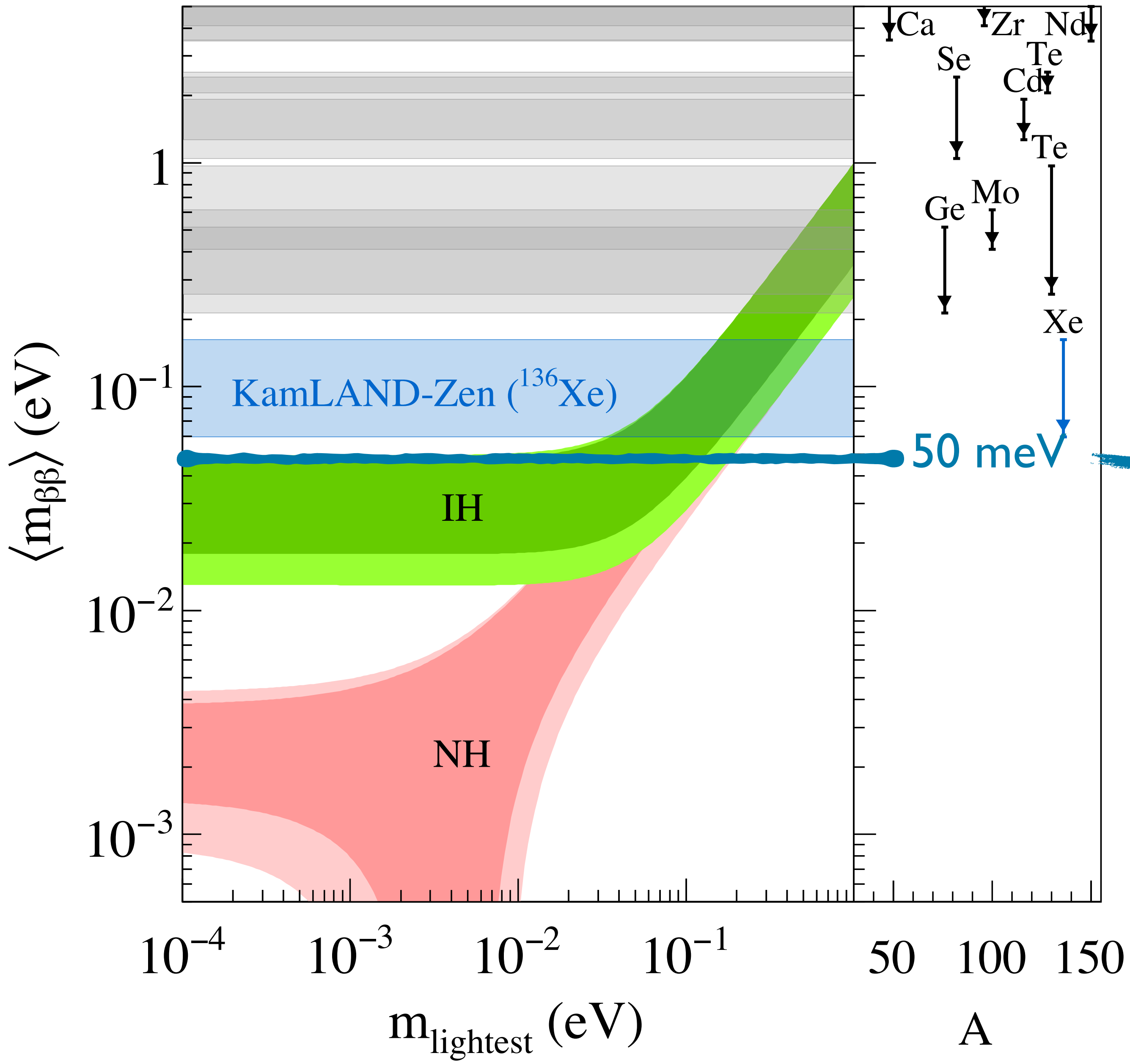
Future Goals



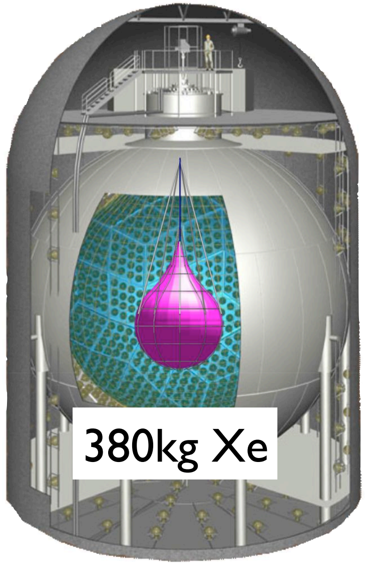
KamLAND-Zen 400



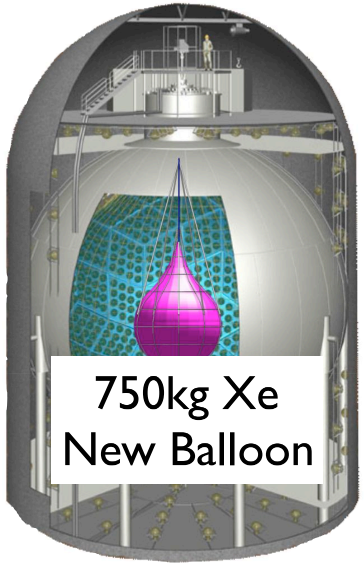
Future Goals



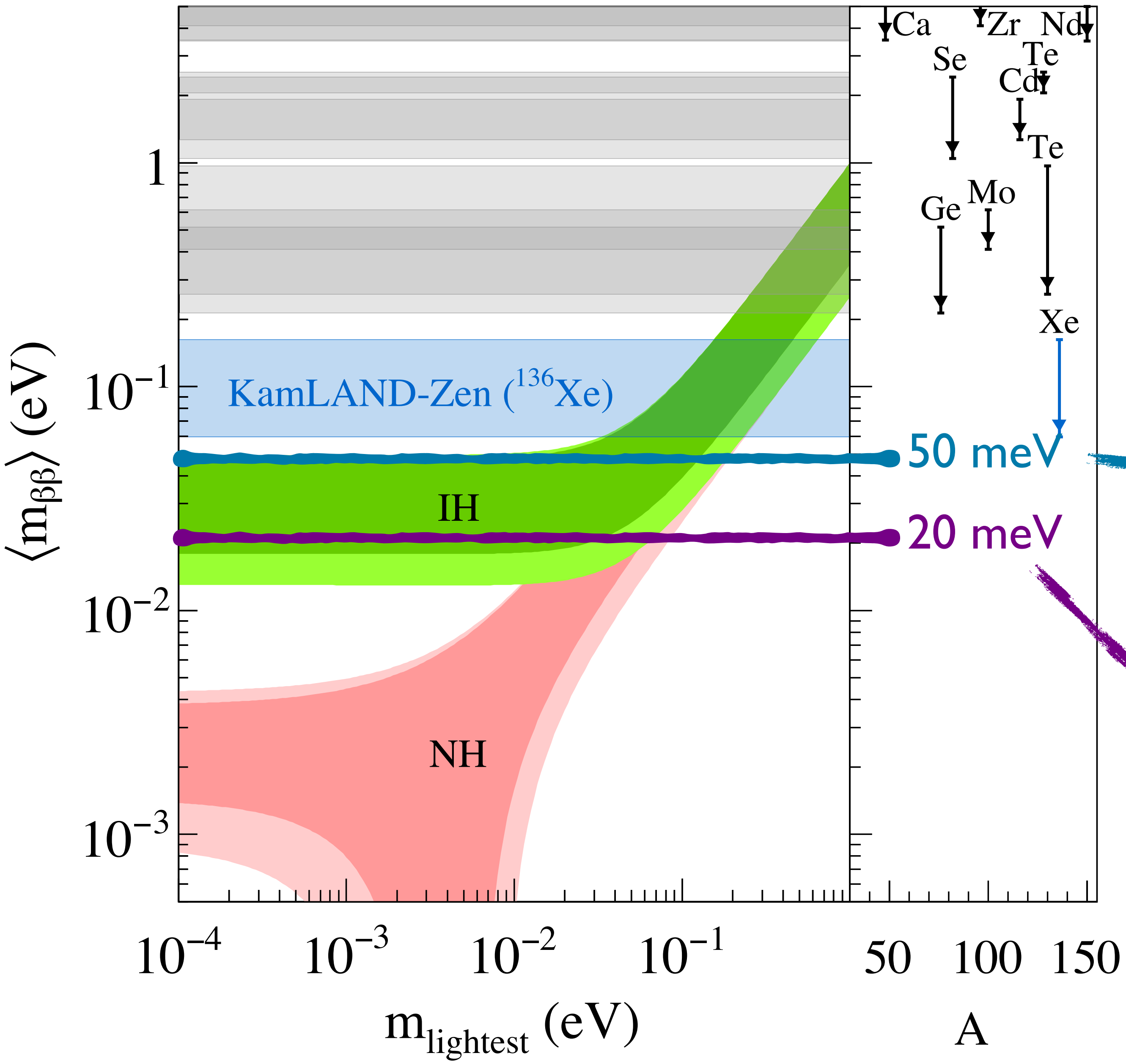
KamLAND-Zen 400



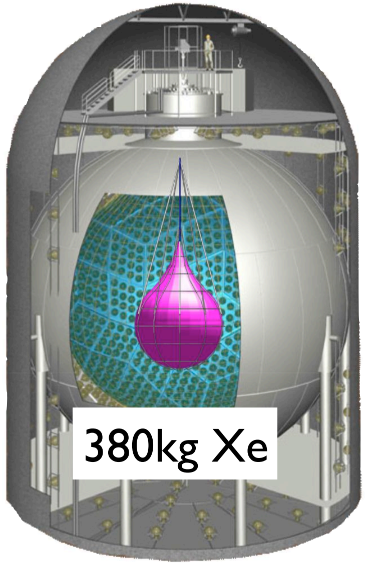
KamLAND-Zen 800



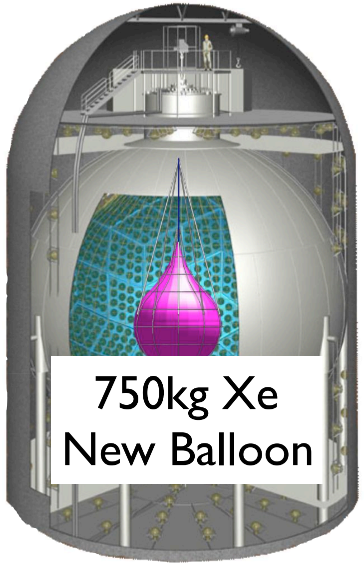
Future Goals



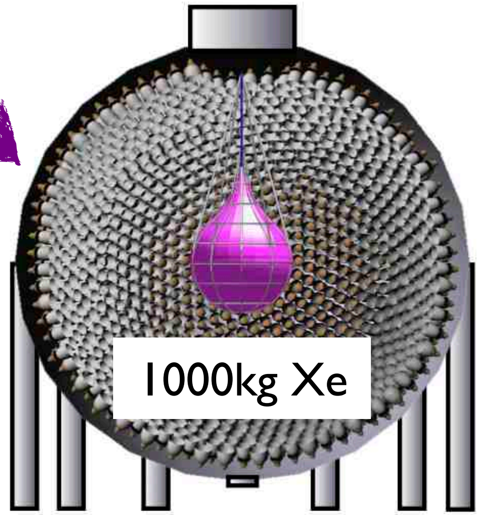
KamLAND-Zen 400



KamLAND-Zen 800

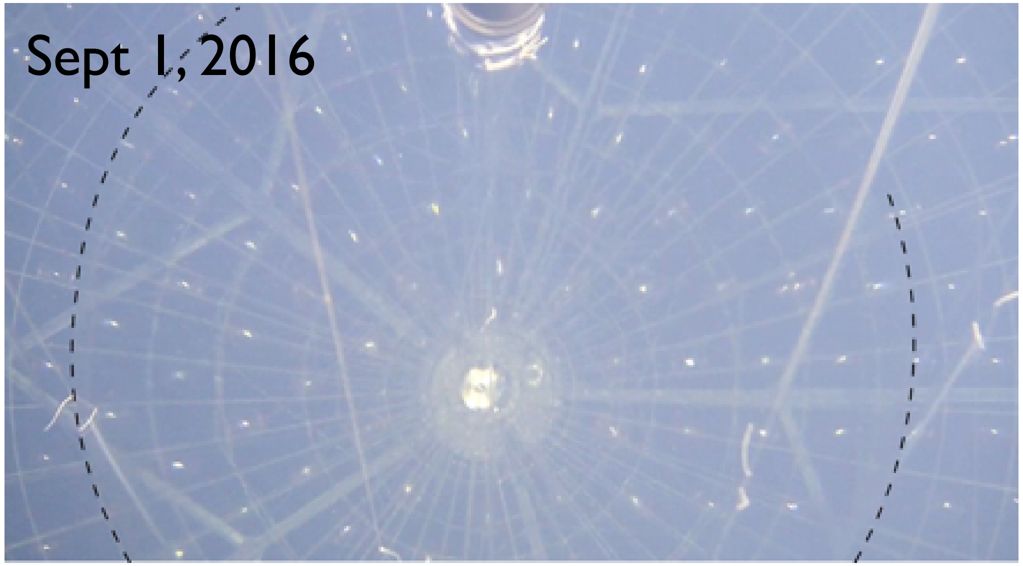


KamLAND2-Zen



New Balloon Installation

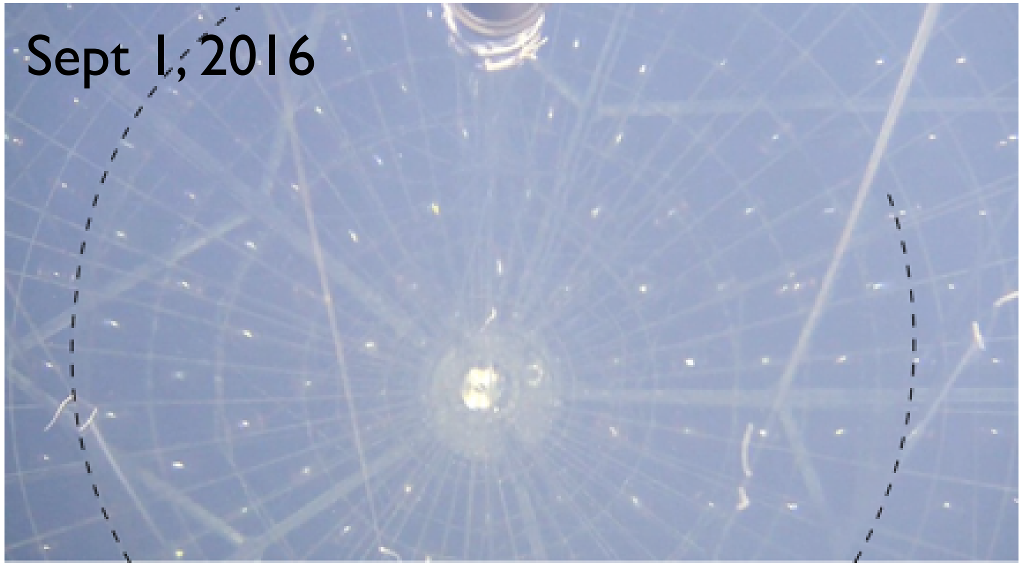
New Balloon installed in Aug, filled with UNLOADED liquid scintillator (no Xe)



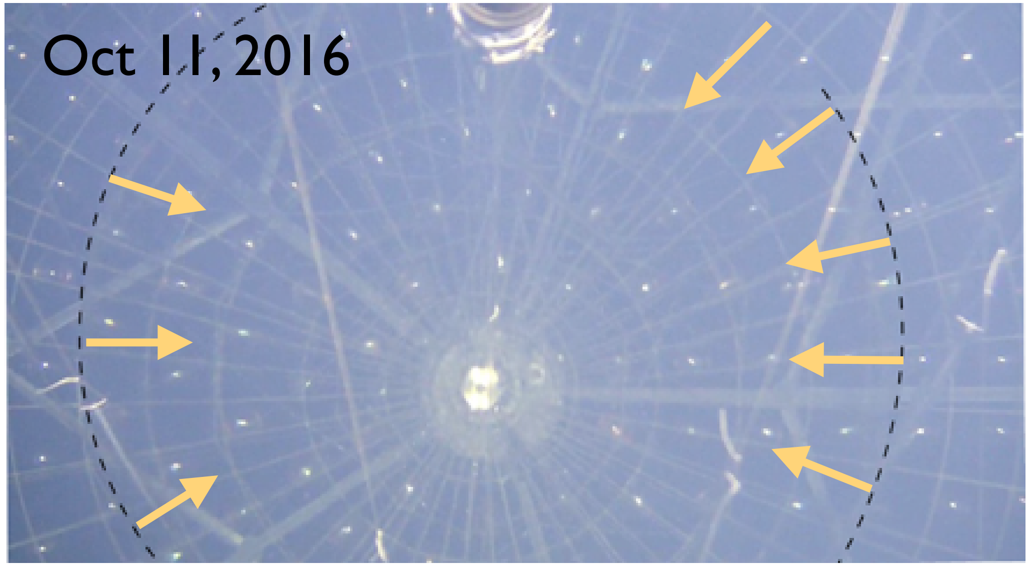
Sept 1, 2016

New Balloon Installation

New Balloon installed in Aug, filled with UNLOADED liquid scintillator (no Xe)



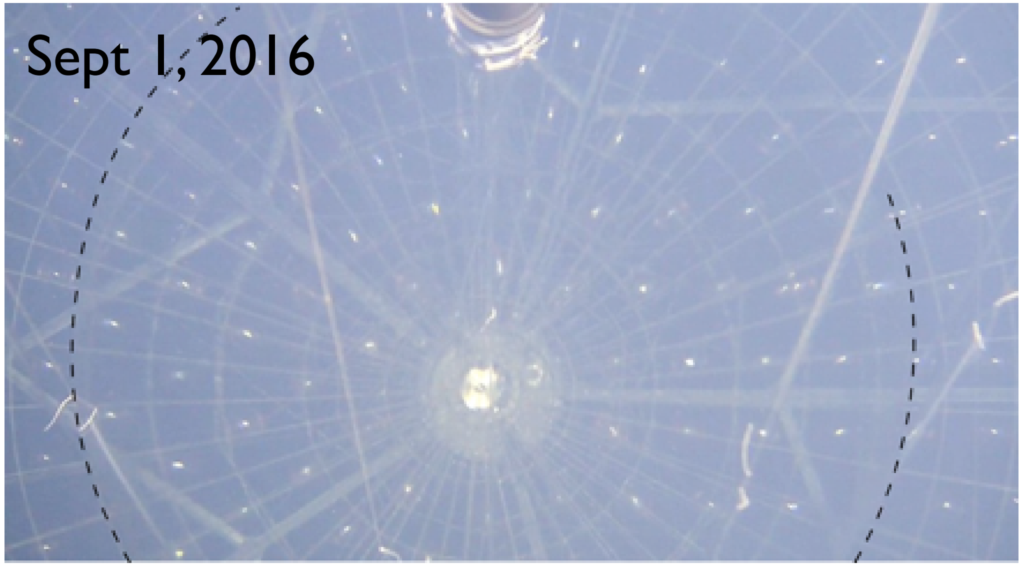
Sept 1, 2016



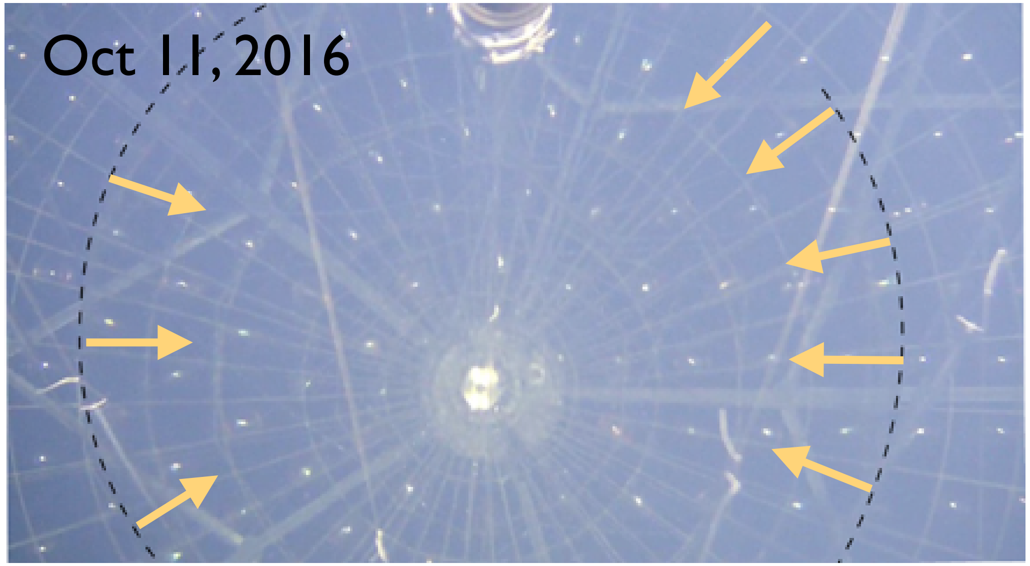
Oct 11, 2016

New Balloon Installation

New Balloon installed in Aug, filled with UNLOADED liquid scintillator (no Xe)



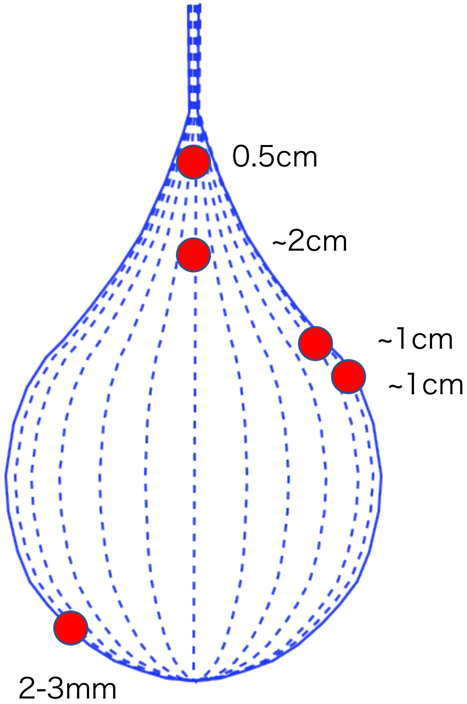
Sept 1, 2016



Oct 11, 2016

Leak detected:

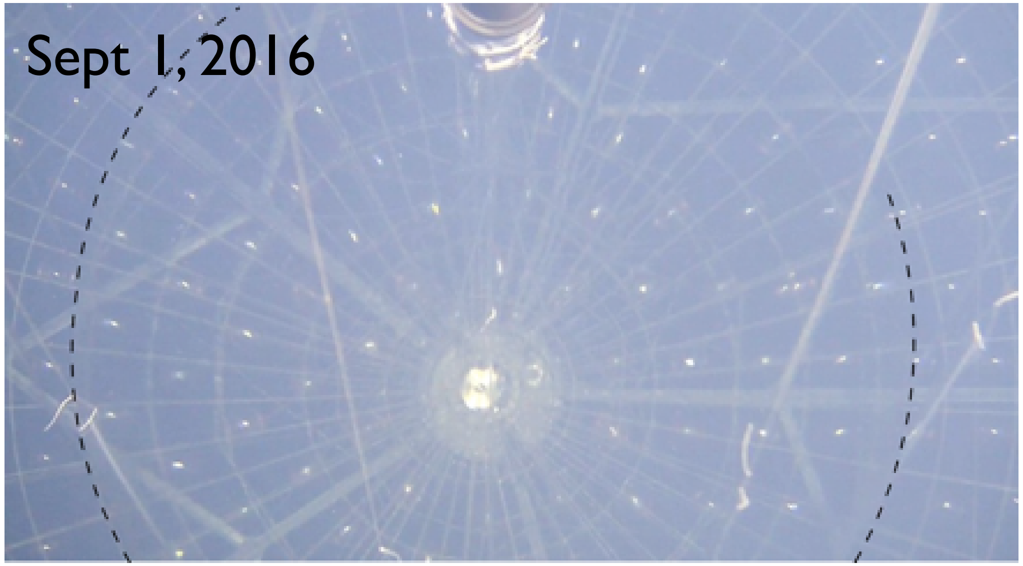
- Camera image
- Load cell
- Balloon shape reconstruction with ^{210}Po events
- Samples: Traces of outside LS inside balloon LS

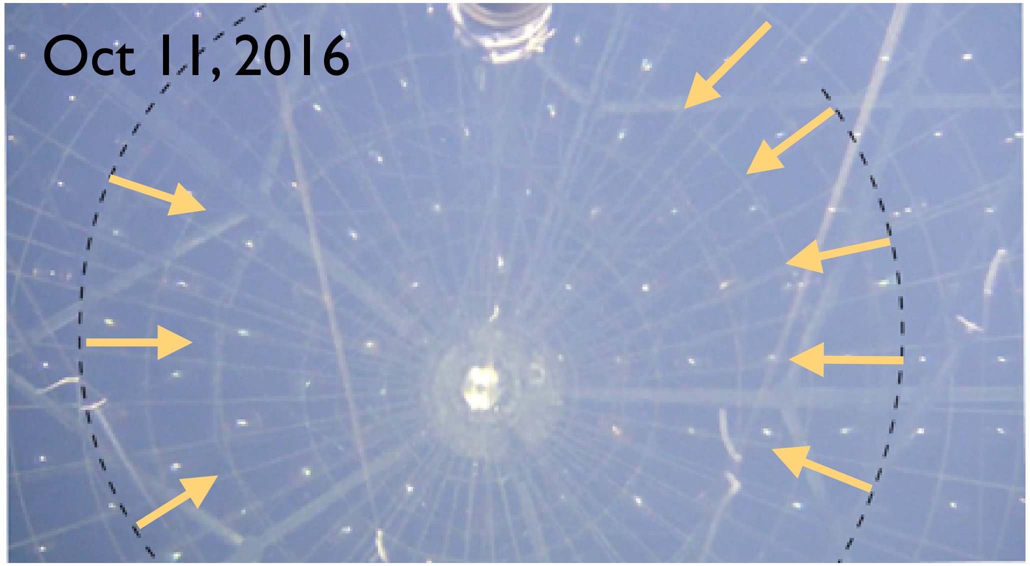


Balloon removed in Nov 2016

New Balloon Installation

New Balloon installed in Aug, filled with UNLOADED liquid scintillator (no Xe)



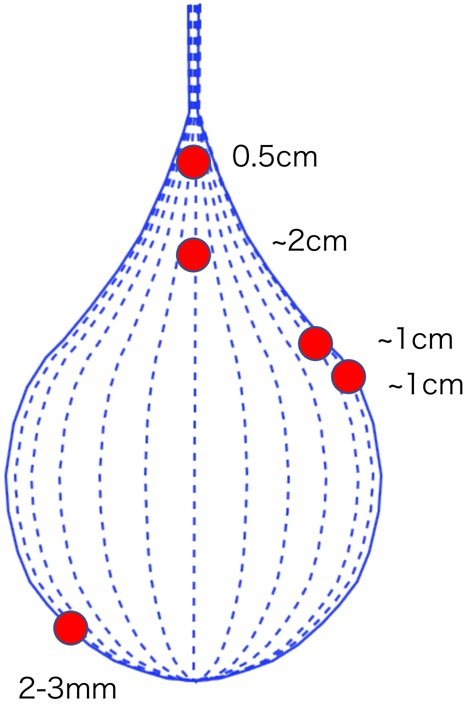


Leak detected:

- Camera image
- Load cell
- Balloon shape reconstruction with ^{210}Po events
- Samples: Traces of outside LS inside balloon LS

Balloon removed in Nov 2016

New balloon is being prepared, installation Fall 2017

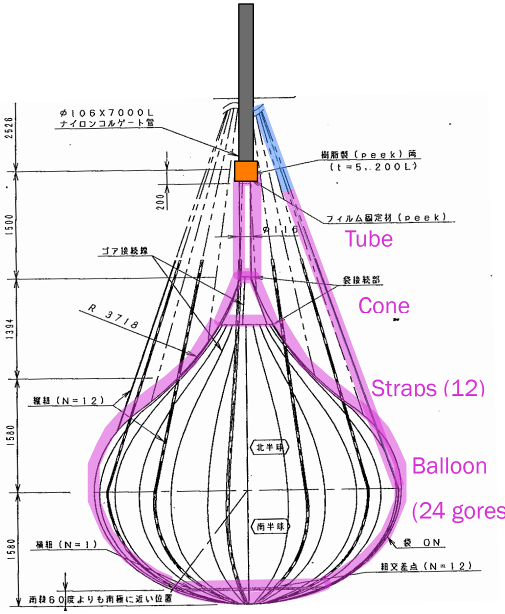


Summary

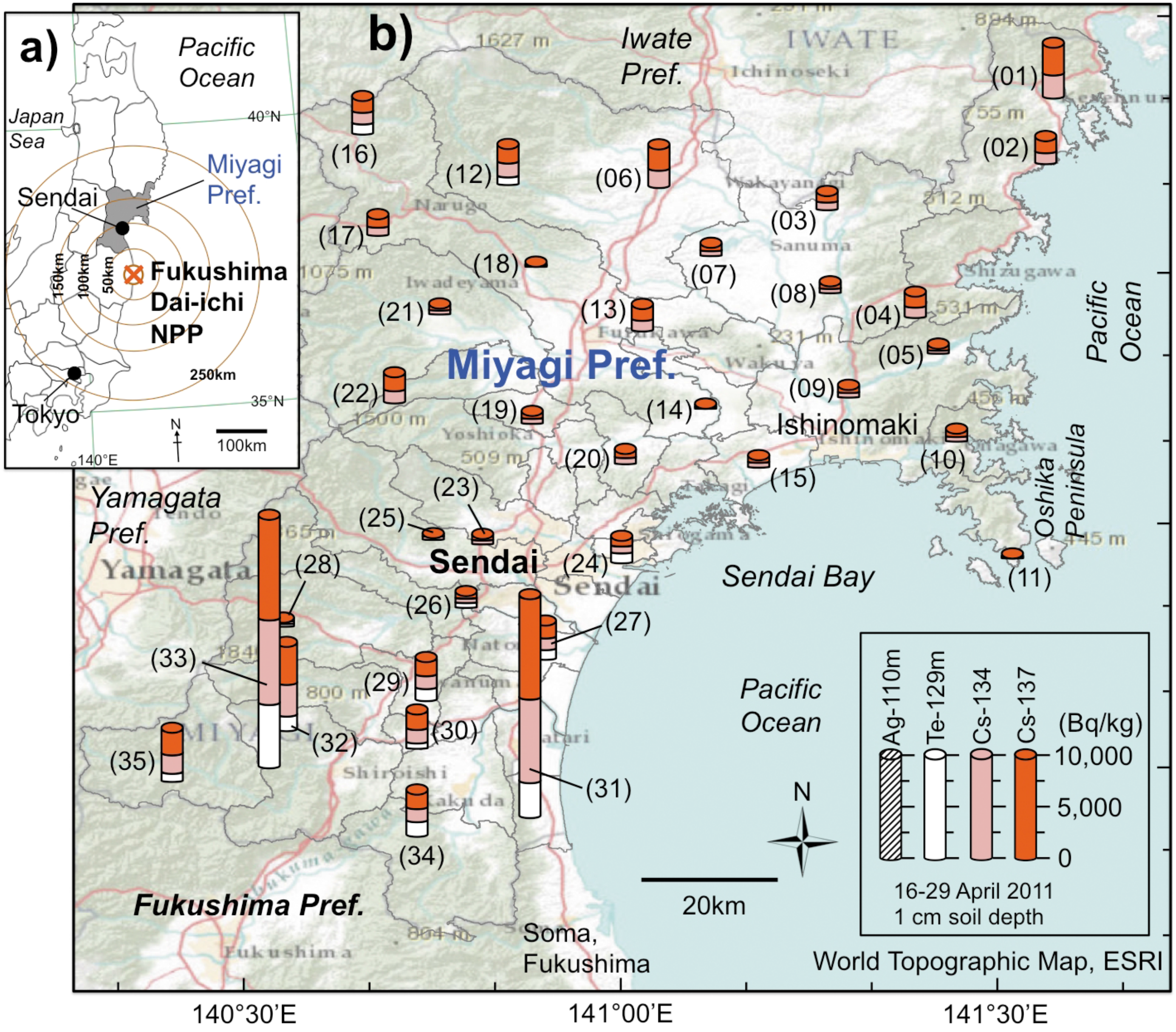
- KamLAND-Zen Phase-II data based on 504 kg-yr exposure:
  - $T_{1/2}^{0\nu} > 9.2 \times 10^{25}$ yr (90% C.L.)
  - Combined with Phase-1: $T_{1/2}^{0\nu} > 1.07 \times 10^{26}$ yr (90% C.L.)
    - $\langle m_{\beta\beta} \rangle < 61 - 165$ meV
- Best limit in the world - getting close to Inverted Hierarchy
- Move to KamLAND-Zen 800
  - ~750 kg ^{136}Xe and new mini-balloon in Fall 2017
  - Start to probe inside IH, goal is $\langle m_{\beta\beta} \rangle < 50$ meV [median NME]
- Meanwhile geo-neutrino (and reactor) measurements ongoing…

Is the background from Fukushima?

- Great Tohoku Earthquake & Fukushima in March'11
- Both ^{134}Cs and ^{137}Cs reconstructed on mini-balloon
  - Ratio ^{134}Cs / ^{137}Cs ~ 0.8, consistent with Fukushima fallout
  - Activity of Cs proportional to area of mini-balloon welds
  - → Introduced during manufacture in June 2011
- ^{110m}Ag was found in soil samples around Sendai
  - Plausible that ^{110m}Ag was also introduced during manufacture
  - Rates low. For DS-1/DS-2 (3.3 ± 0.4) day^{-1}/ (2.2 ± 0.4) day^{-1}
- However, we cannot exclude cosmic activation of Xe during air transport from Russia→ Japan
  - MC indicates that ^{110m}Ag and ^{88}Y can be made



Independent Fallout Measurement

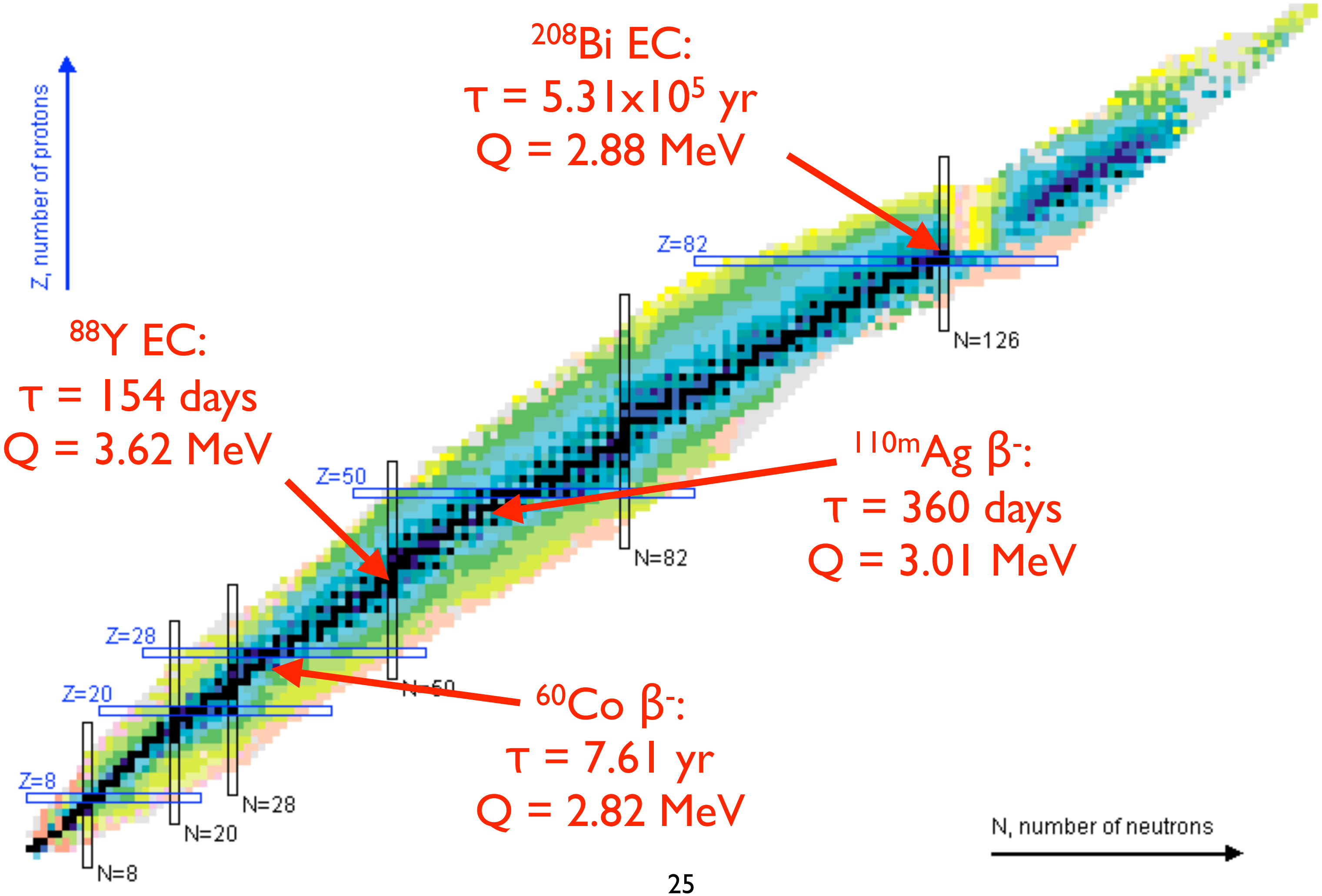


Geochemical Journal, Vol. 46, pp. 279 to 285, 2012

^{134}Cs / ^{137}Cs ~1

Results from the ENSDF search

- Search through *thousands* of isotopes in ENSDF and *millions* of decay paths that can give a peak between 2.4 MeV and 2.8 MeV
  - Account for all particle-dependent energy non-linearities
  - Require $\tau > 30$ days, or $100\text{s} < \tau < 30$ days if production cross section is fairly large



^{208}Bi EC:
$\tau = 5.31\times10^{5}$ yr
Q = 2.88 MeV

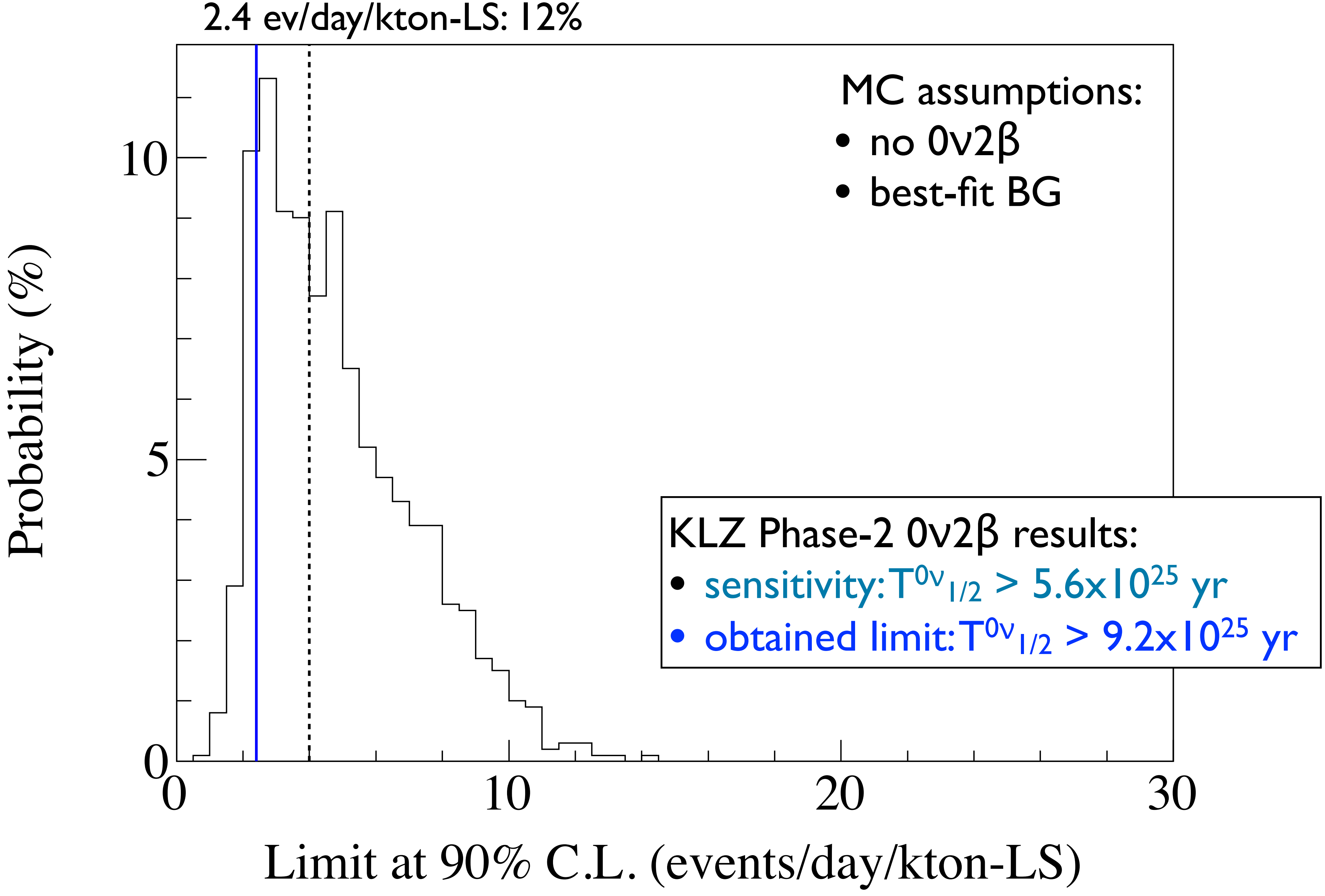
^{88}Y EC:
$\tau = 154$ days
Q = 3.62 MeV

^{110m}Ag β^-:
$\tau = 360$ days
Q = 3.01 MeV

^{60}Co β^-:
$\tau = 7.61$ yr
Q = 2.82 MeV

NuDat 2.6

Sensitivity Study



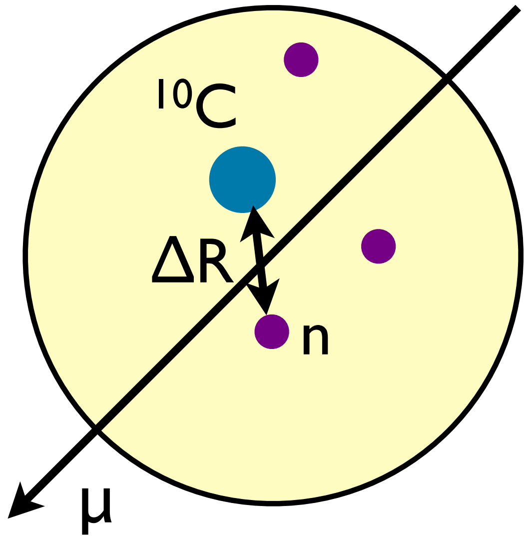
2.4 ev/day/kton-LS: 12%

MC assumptions:
- no $0\nu2\beta$
- best-fit BG

KLZ Phase-2 $0\nu2\beta$ results:
- sensitivity: $T^{0\nu}_{1/2} > 5.6\times10^{25}$ yr
- obtained limit: $T^{0\nu}_{1/2} > 9.2\times10^{25}$ yr

Rejecting ^{10}C with neutron tagging

muon-neutron-^{10}C tripple tag



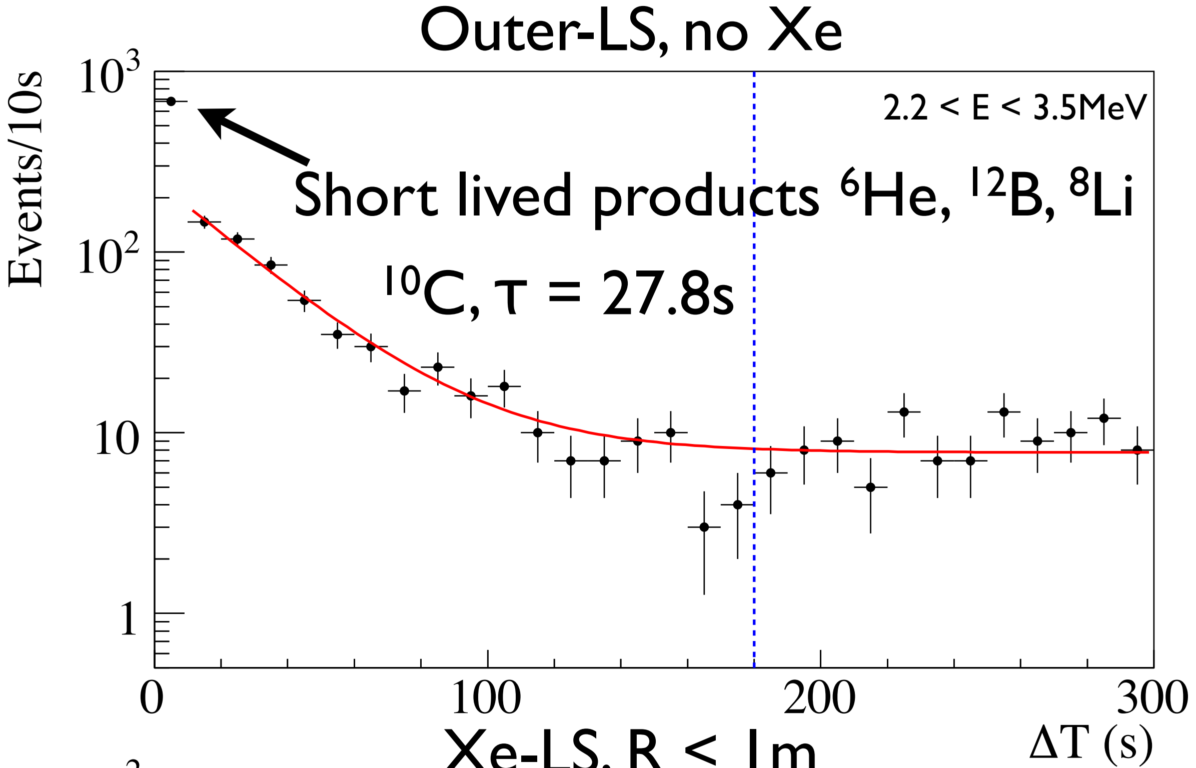
Space and time correlation cuts

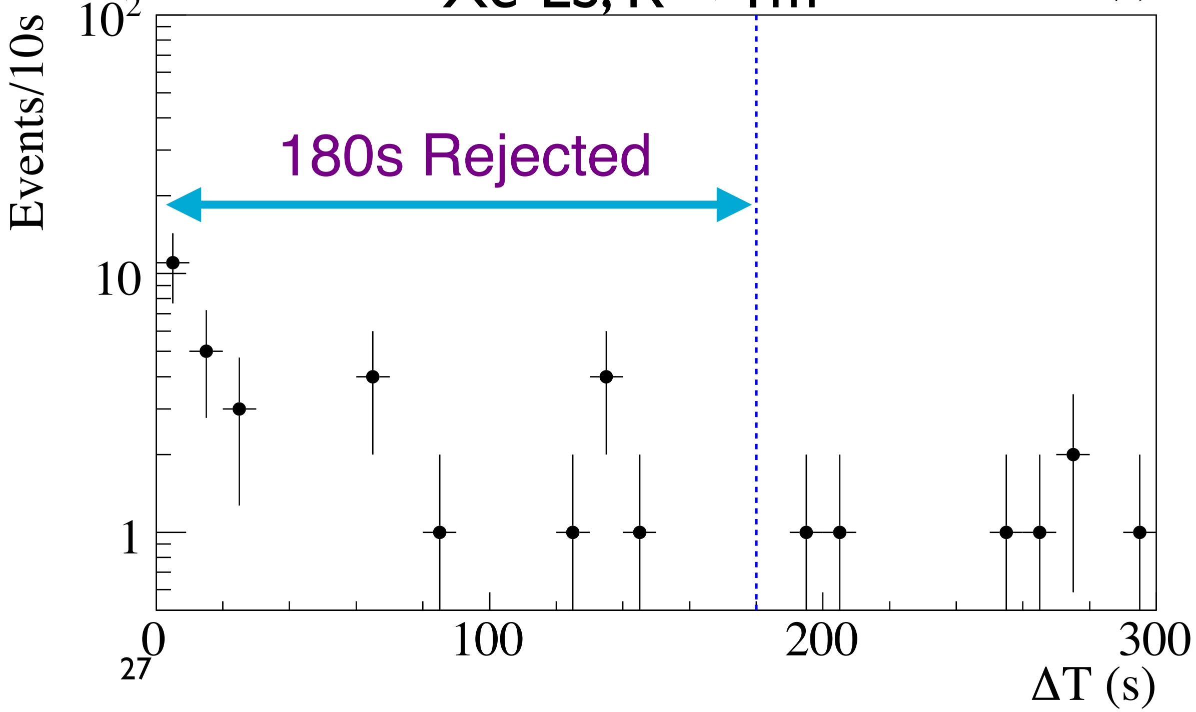
- ΔT < 180s
- ΔR < 1.6m

$\tau(^{10}C)$ =27.8s, τ(n capture) = 207.5 μs

Efficient BG rejection:

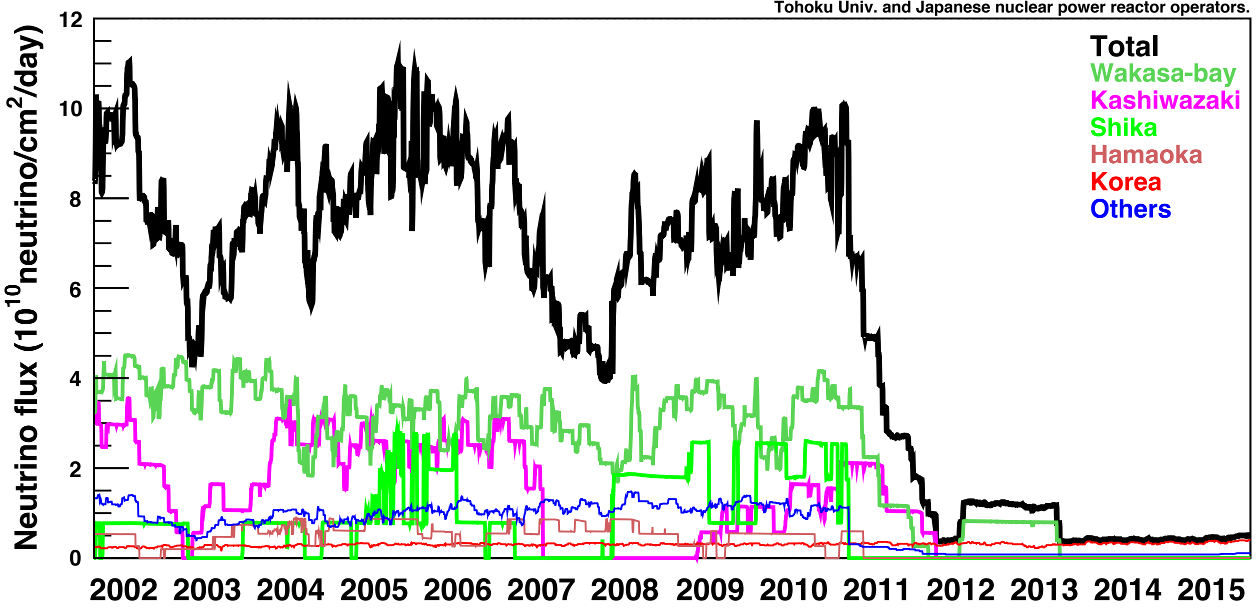
- ^{10}C rejection efficiency: 64 ± 4%
- Deadtime: 7%


Outer-LS, no Xe

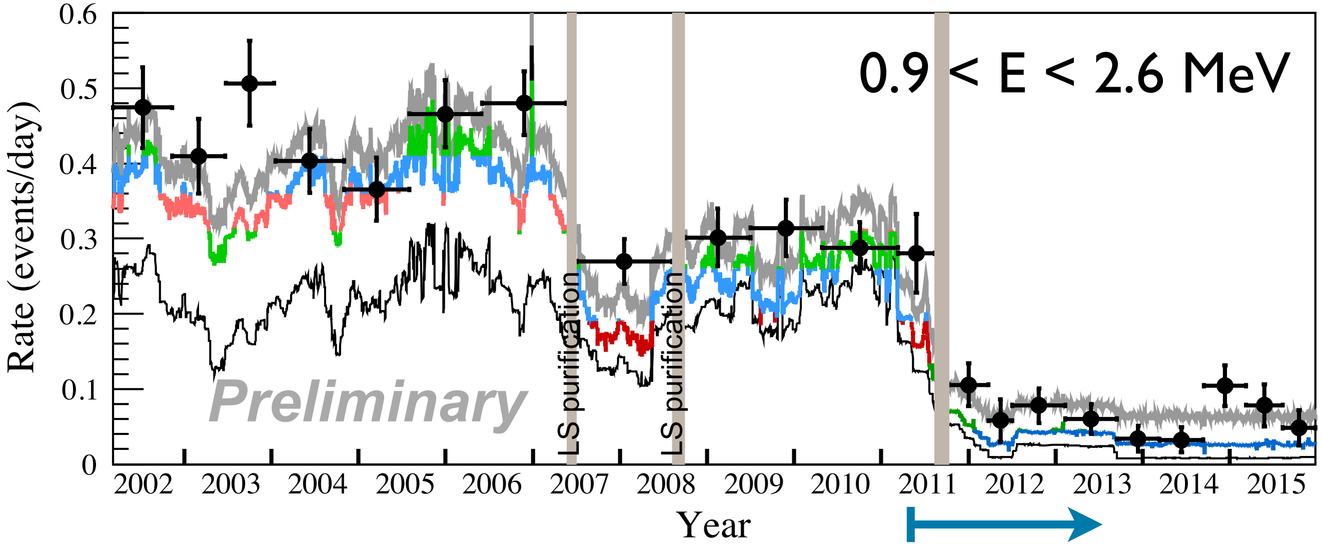

Xe-LS, R < 1m

Post Fukushima

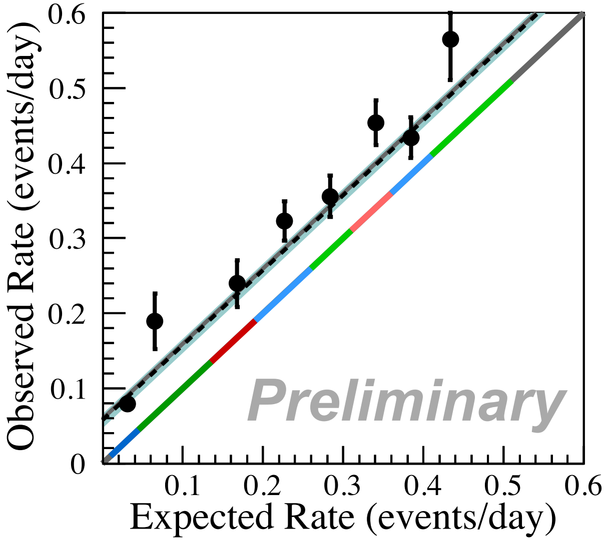
Data provided according to the special agreements between Tohoku Univ. and Japanese nuclear power reactor operators.



All Japanse reactors were OFF: excellent opportunity for geo-neutrino measurement



Post Fukushima



KamLAND data

Expected reactor $\bar{\nu}_e$ + backgrounds + geo $\bar{\nu}_e$

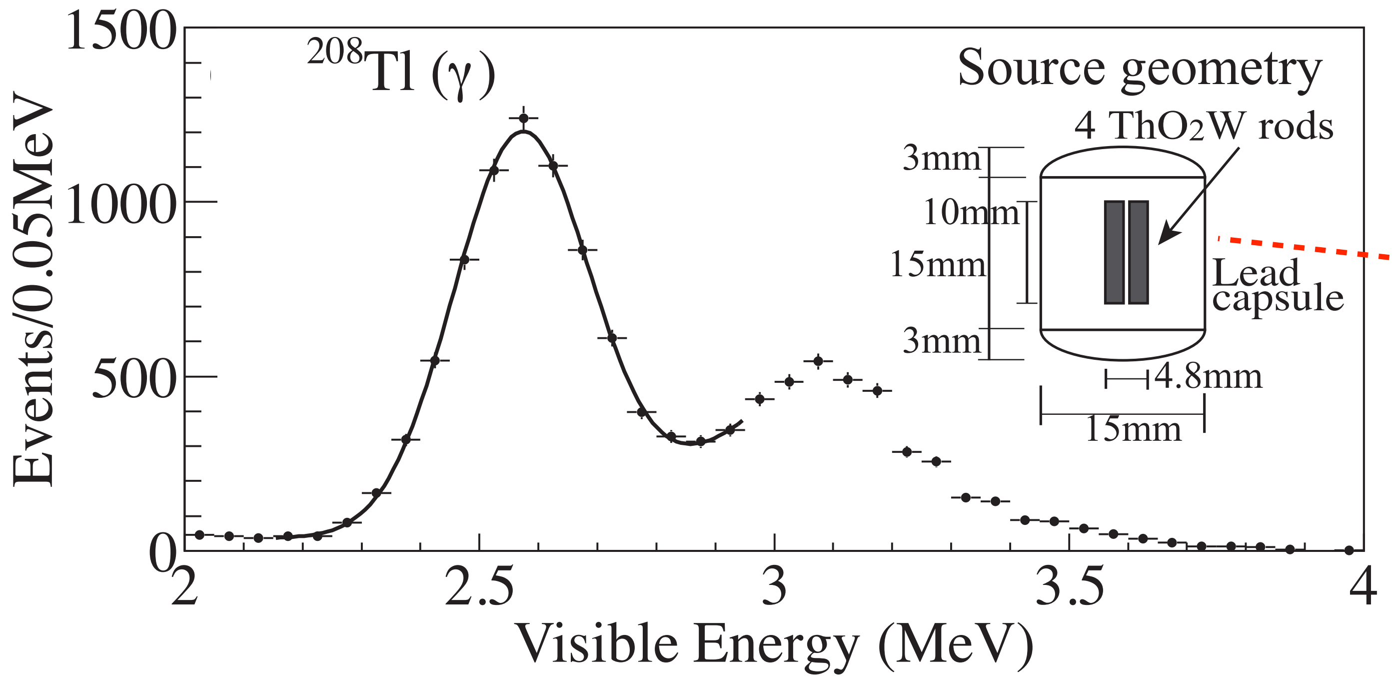
Expected reactor $\bar{\nu}_e$ + backgrounds

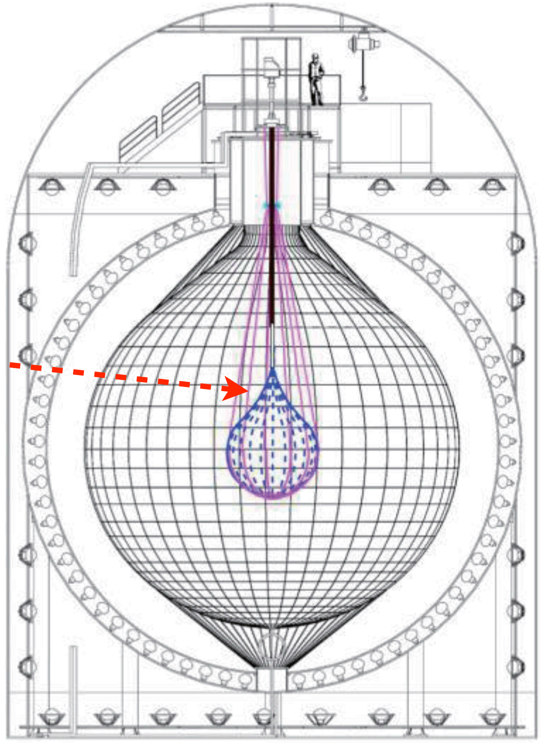
Expected reactor $\bar{\nu}_e$

Calibration

KamLAND is well-understood. Previous reconstruction algorithms can be easily adapted

External energy calibration





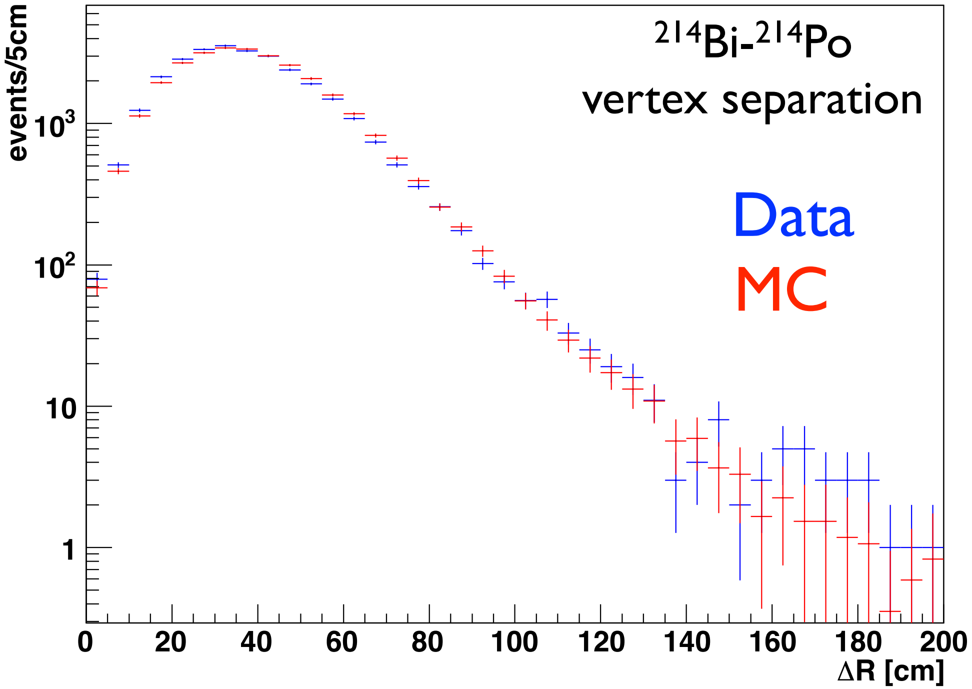
Internal calibration sources: tagged ^{214}BiPo, ^{222}Rn during filling, 2.225 MeV neutron capture γ

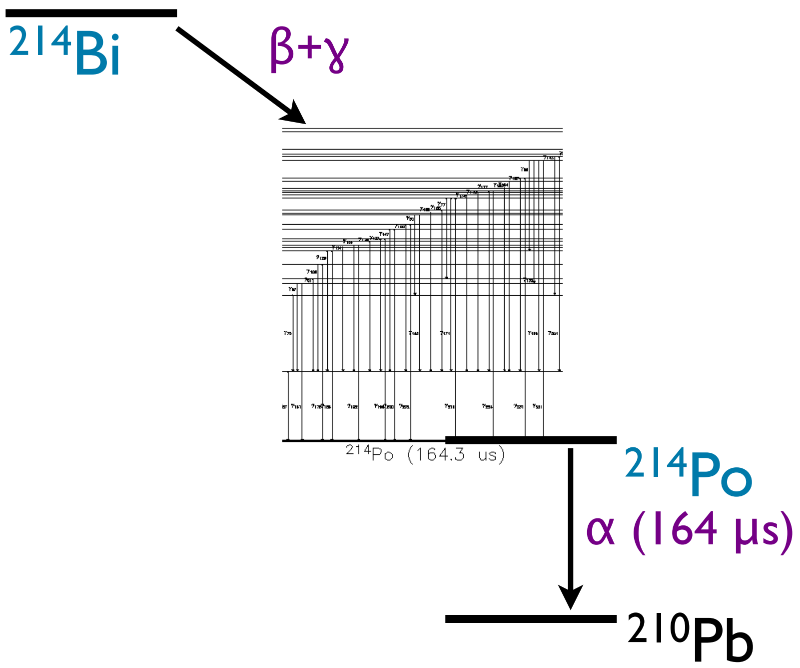
σ_P = 15cm / $\sqrt{E(\text{MeV})}$

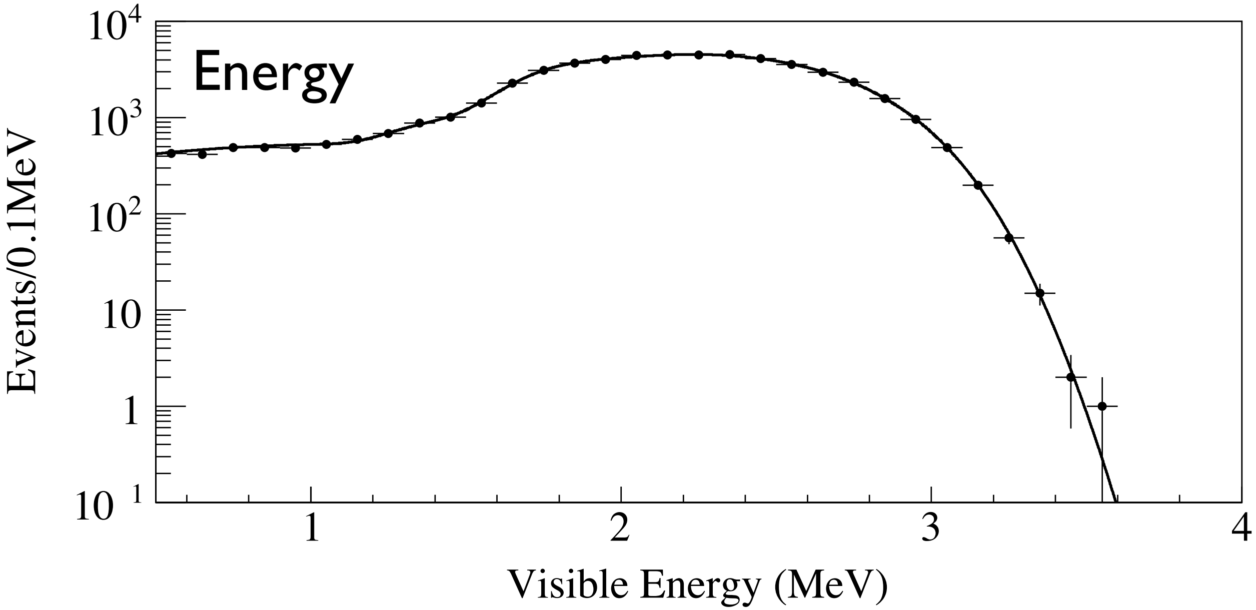
σ_E = (7.3 ± 0.3)% / $\sqrt{E(\text{MeV})}$

Detailed MC Model

MC tuned with ^{214}BiPo data







GEANT4 based MC with ^{214}Bi β+γ cascade, particle tracking, energy deposit, scintillation photon emission / propagation

R<1m comparison Period-1 & Period-2