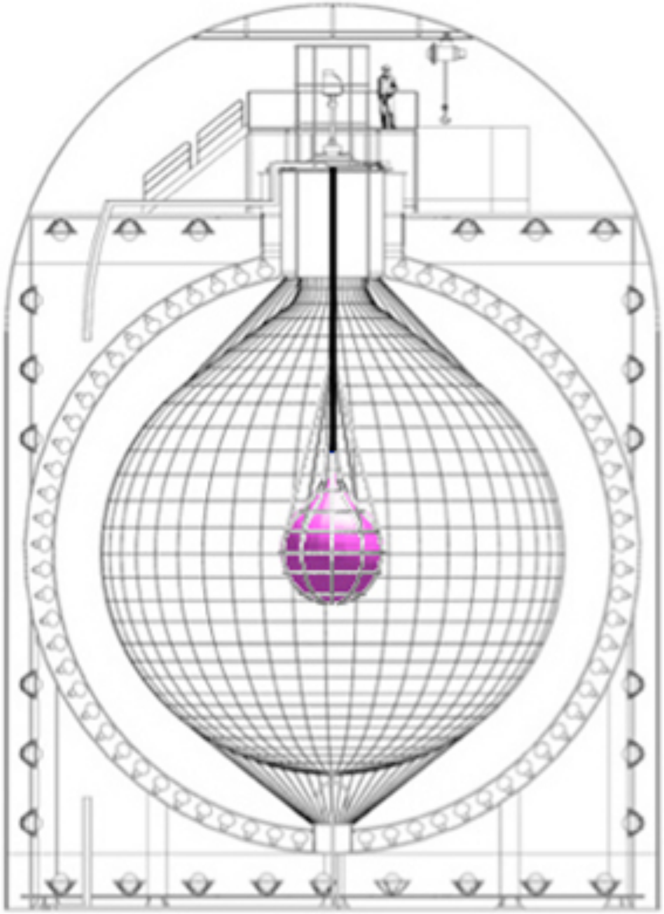
KamLAND-Zen:
Results, Status, and Prospects

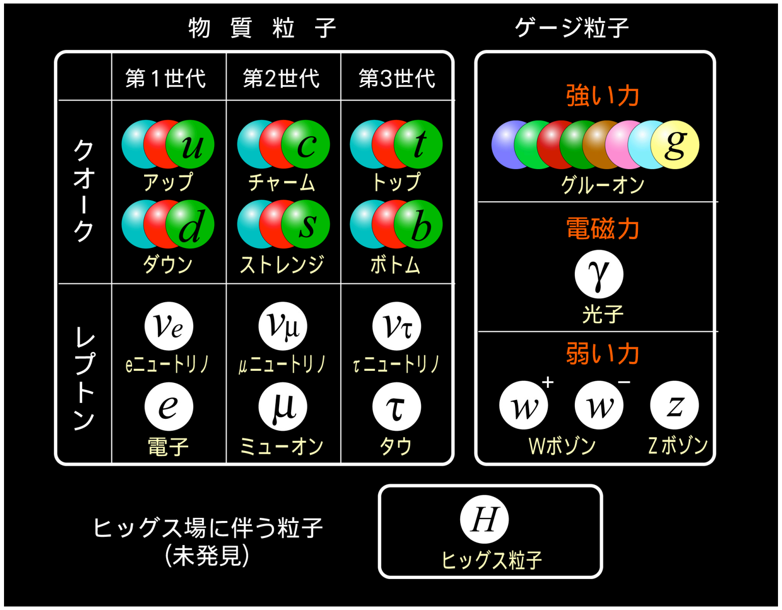
- Introduction
  - -> Why are Neutrinos Interesting?
  - -> Neutrinoless Double Beta Decay
- KamLAND
- KamLAND-Zen: Zero Neutrino
  - -> Detector
  - -> Backgrounds
  - -> Results: $2\nu\beta\beta$ and $0\nu\beta\beta$
  - -> Future



Neutrinos

Neutrinos in the Standard Model

- Spin-1/2 fermion
- No charge
  (electromagnetic or color)
- Only interact weakly
  Labeled by weak interaction mode
  (how they couple to the W)
- Zero mass



Neutrino mixing measurements

- Neutrinos have mass
- Neutrino mass eigenstates are not the same as
  the weak interaction eigenstates

Neutrino Oscillation

Neutrino oscillation involves two basic ideas
from quantum mechanics:

1. Two sets of basis states:

-> The Standard Model includes three neutrino flavor states: ν_e, ν_μ, ν_τ, defined by how they interact

-> If neutrinos have mass, the neutrino mass states can be different: ν_1, ν_2, ν_3, with masses m_1, m_2, m_3

-> The two basis states are related by a unitary transformation called the "MNSP" (Maki-Nakagawa-Sakata-Pontecorvo) matrix (analogous to the CKM matrix for quarks)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

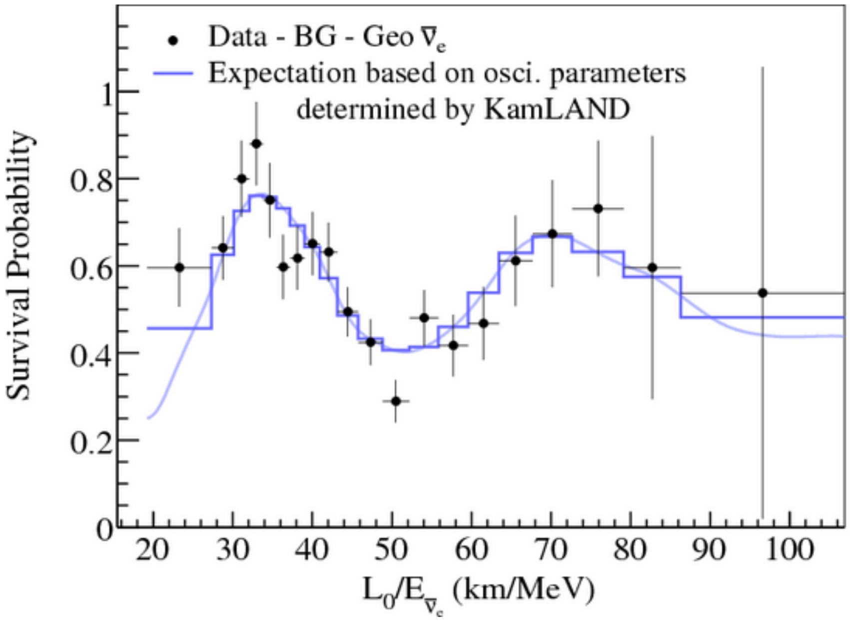
Neutrino Oscillation

2. Time evolution of energy eigenstates

$$|\nu_i(t)\rangle = e^{-i(E_i t - p_i L)}\,|\nu_i(0)\rangle = e^{-i m_i^2 \frac{L}{2E}}\,|\nu_i(0)\rangle$$

When the neutrino interacts, mass states are projected back into the interaction basis

-> phases interfere -> neutrino oscillation



Two-Flavor Oscillation

- Suppose we only have to consider two flavors:

$$\begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} \\ -\sin\theta_{12} & \cos\theta_{12} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

- If I start with a pure ν_e state, then after it travels a distance L it is:

$$\left|\nu(L)\right\rangle = e^{-im_1^2\frac{L}{2E}} \cos\theta_{12}\left|\nu_1\right\rangle + e^{-im_2^2\frac{L}{2E}} \sin\theta_{12}\left|\nu_2\right\rangle$$

- The probability to detect the state as a ν_e after distance L is:

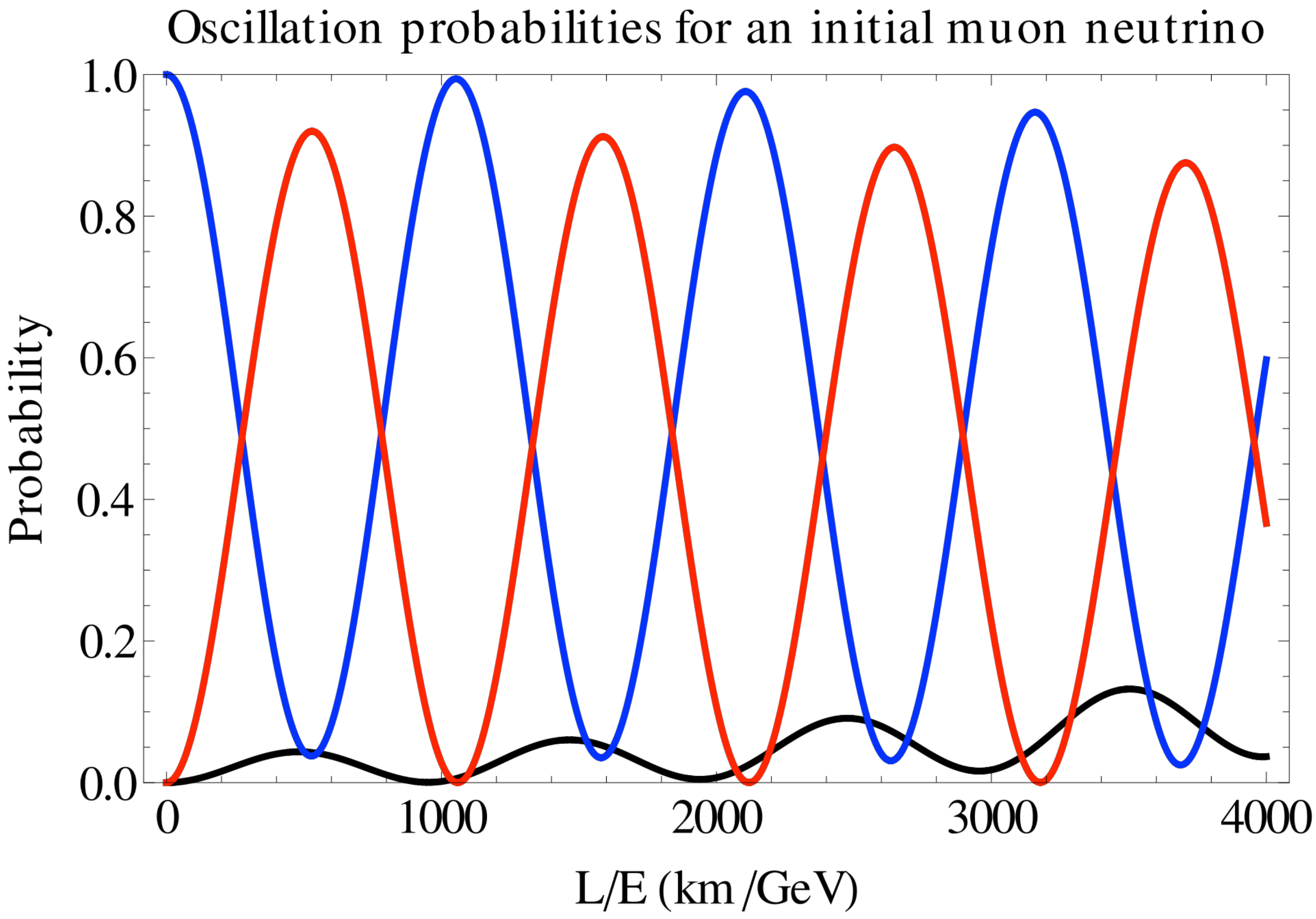
$$\begin{aligned} P(\nu_e \to \nu_e) &= |\langle \nu_e | \nu(L) \rangle|^2 \\ &= 1 - \sin^2\theta_{12} \sin^2\left(1.27\Delta m_{12}^2 \frac{L}{E}\right) \end{aligned}$$

- The phases interfere with each other to produce the oscillation

- Only get interference if the masses differ

Δm^2 in eV^2
L in km [or m]
E in GeV [or MeV]

Three-Flavor Oscillation



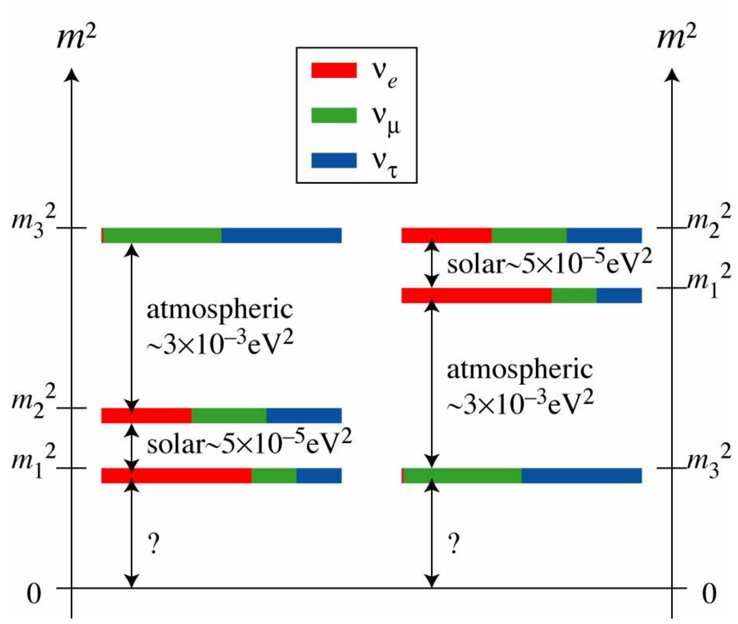
For δ_{CP}=0. From Wikipedia: “Neutrino Oscillation”

Three Flavor Picture

- The MNSP matrix:

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

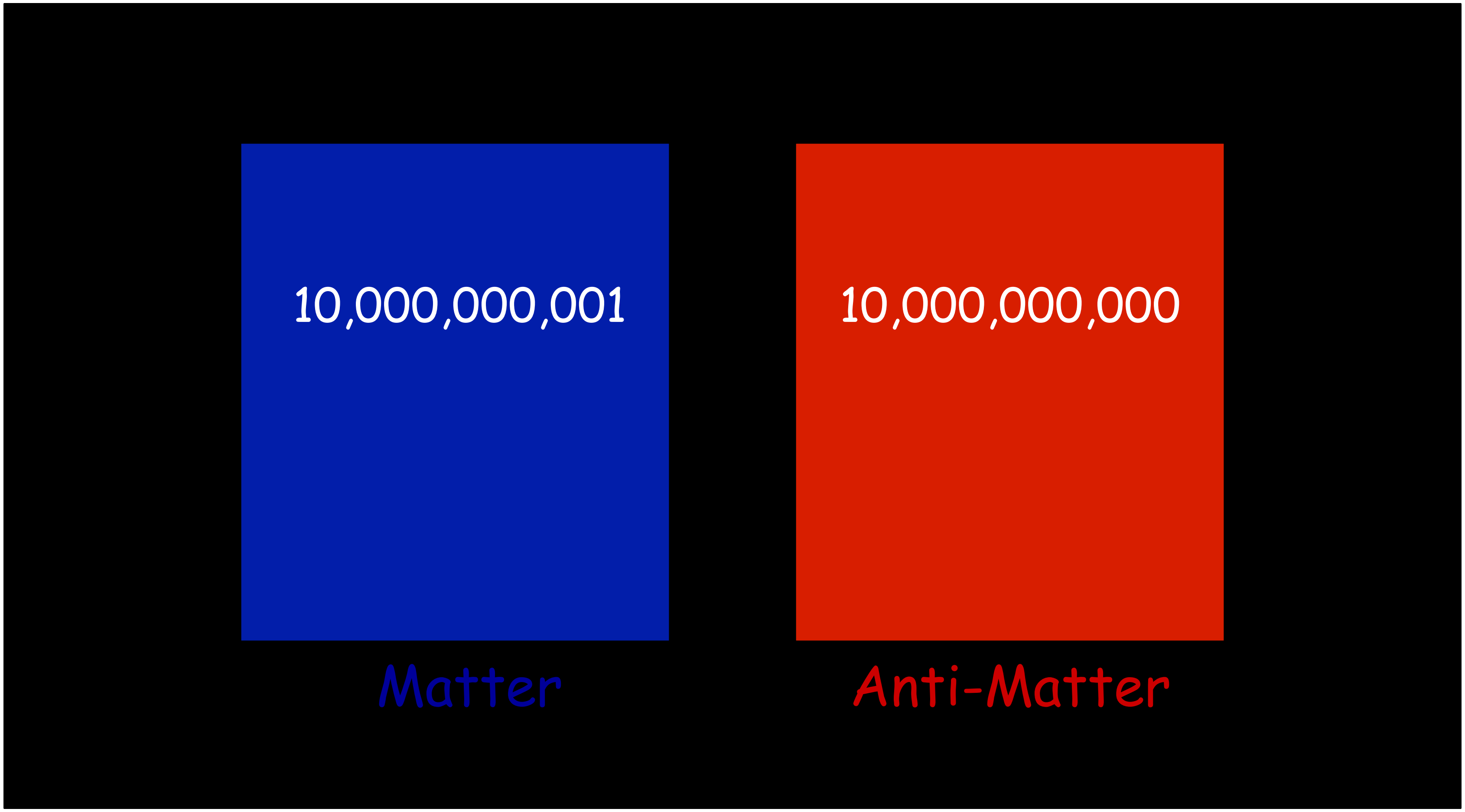
- Oscillation/mixing measurements have told us:
  - "Solar" θ_{12}, Δm^2_{21}
    - -> Includes sign of Δm^2_{21}
    - -> Solar experiments, KamLAND
  - "Atmospheric" θ_{23}, Δm_{23}
    - -> No sign information for Δm^2_{23}
    - -> Atmospheric, accelerator expts.
  - θ_{13} Measurements
    - -> Reactor, accelerator expts.
  - Initial constraints on δ_{CP}
    - -> Reactor, accelerator combined



- We don't know:
  - absolute mass scale or hierarchy
  - nature of neutrino

Why is the Universe dominated by matter?

Matter and Anti-Matter: Early Universe



10,000,000,001

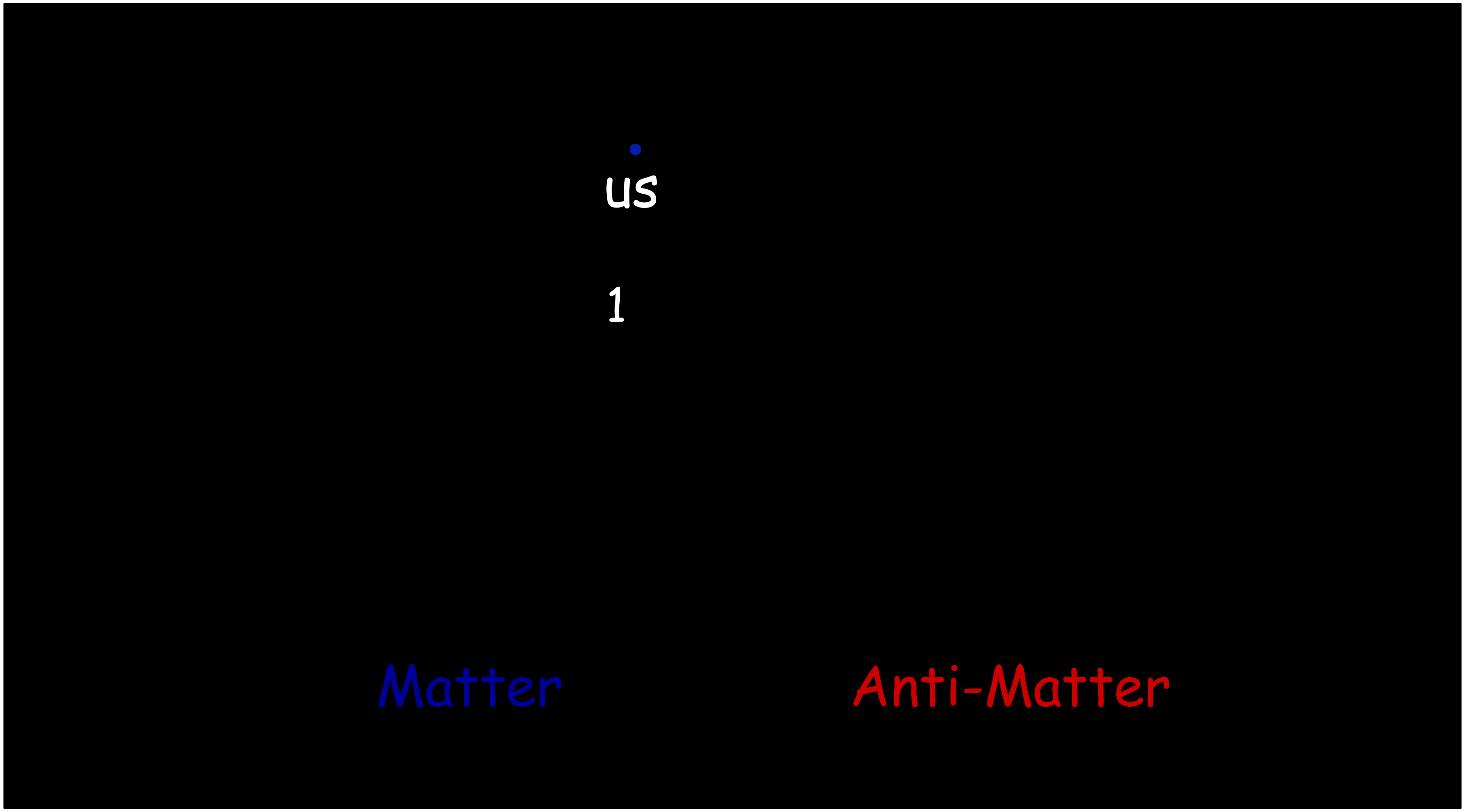
Matter

10,000,000,000

Anti-Matter

-> CP violation gives a very small matter/antimatter asymmetry

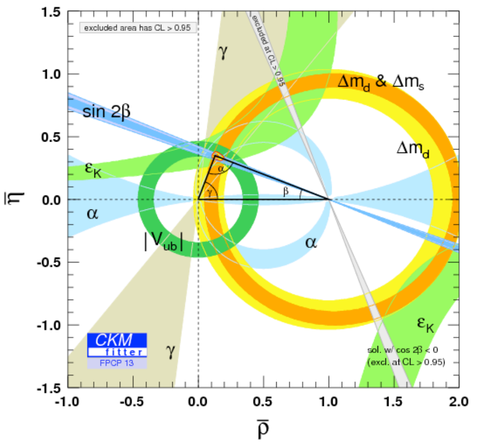
Matter and Anti-Matter: Current Universe



-> Everything has annihilated away except for the small difference

CP Violation

CP Violation in the Standard Model



Quarks:

- CP violation first observed in neutral kaon decays
- Measured extensively in B decays
- However: not large enough to explain baryon asymmetry

Strong CP violation?

- CP violation should be 'natural' in the QCD Lagrangian
- Experimentally, the strong interaction conserves CP
- Requires 'fine tuning' the QCD parameter θ to be zero (expt: $\theta < 10^{-9}$)
- Various ideas for solving the 'Strong CP Problem,' e.g. axions

With massive neutrinos, CP violation is also possible in neutrino mixing

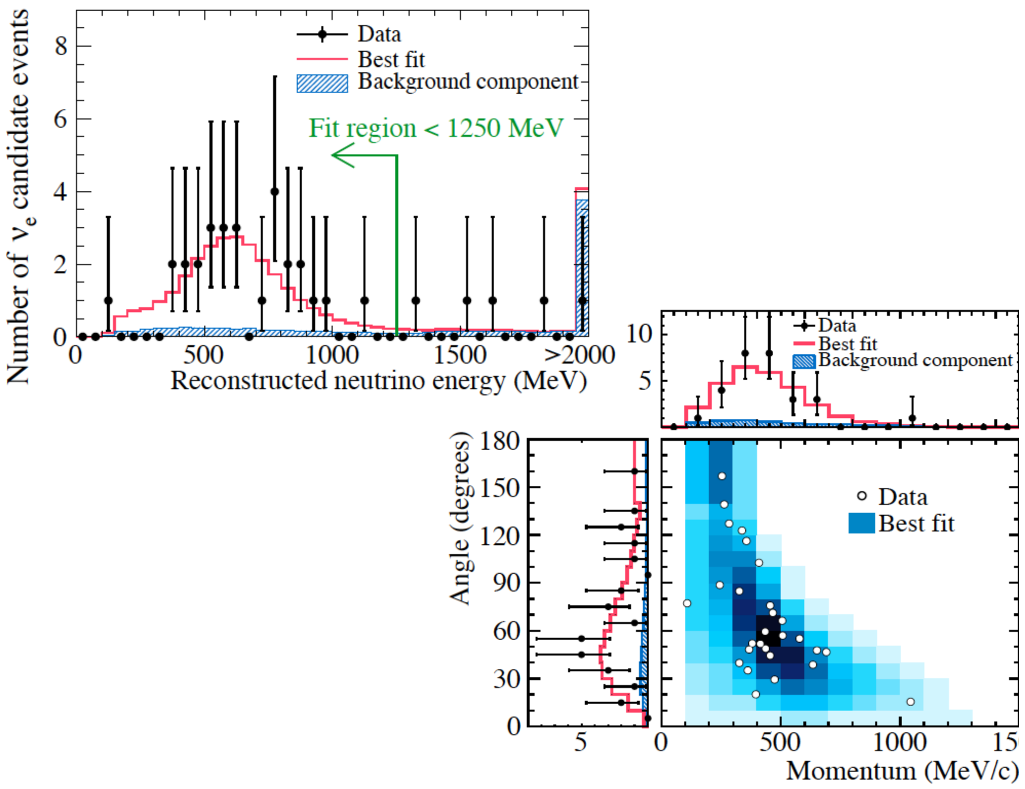
-> Experiments are now starting to constrain the phase δ_{CP}

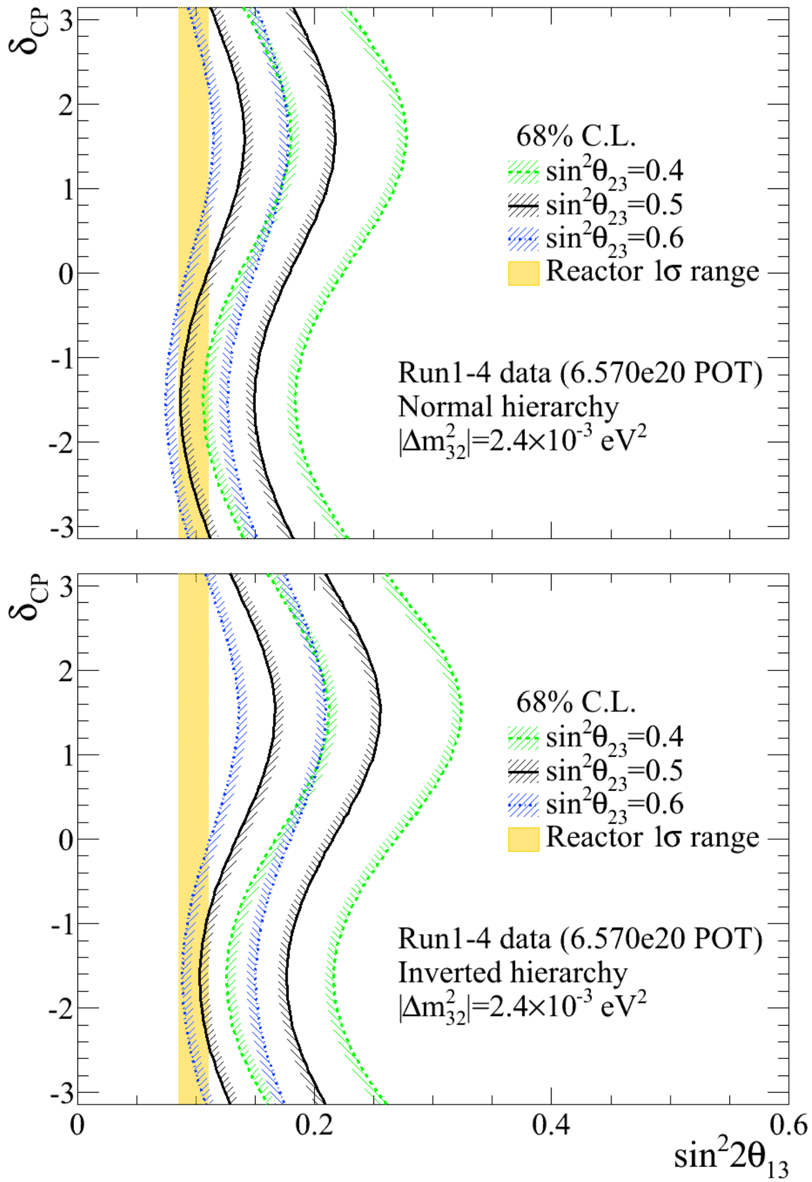
T2K ν_e Appearance Results

-> 7.3σ significance for non-zero θ_{13}

-> Result sensitive to θ_{23}

-> Some tension with reactor results



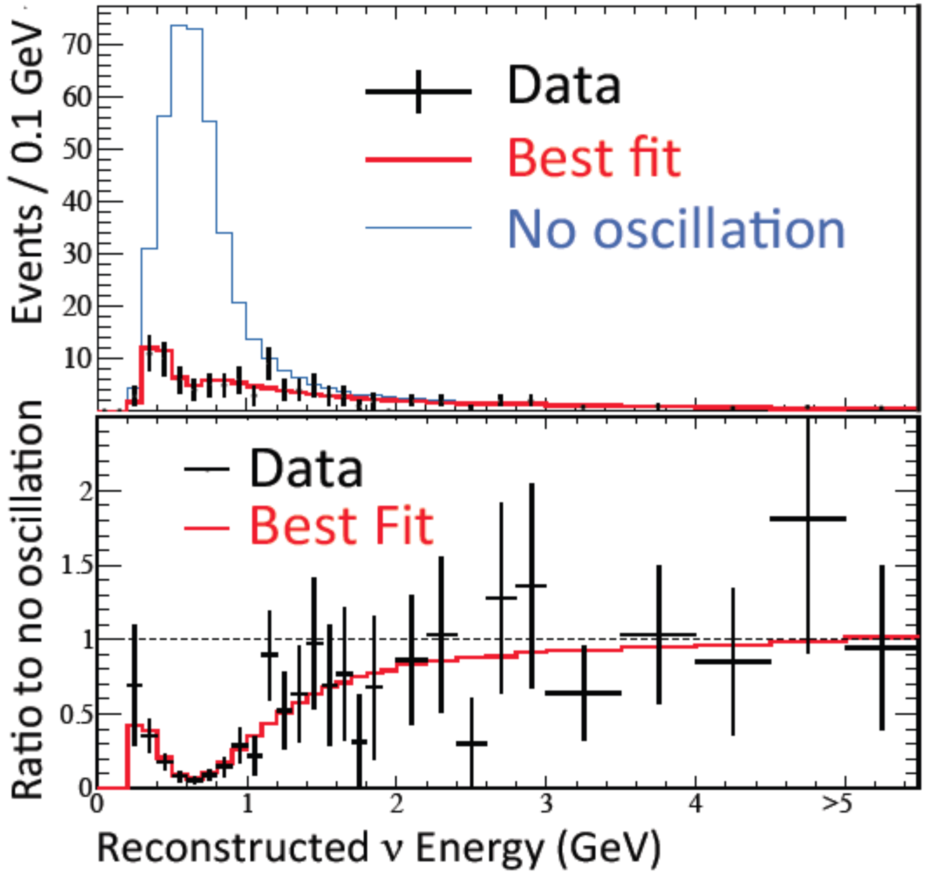


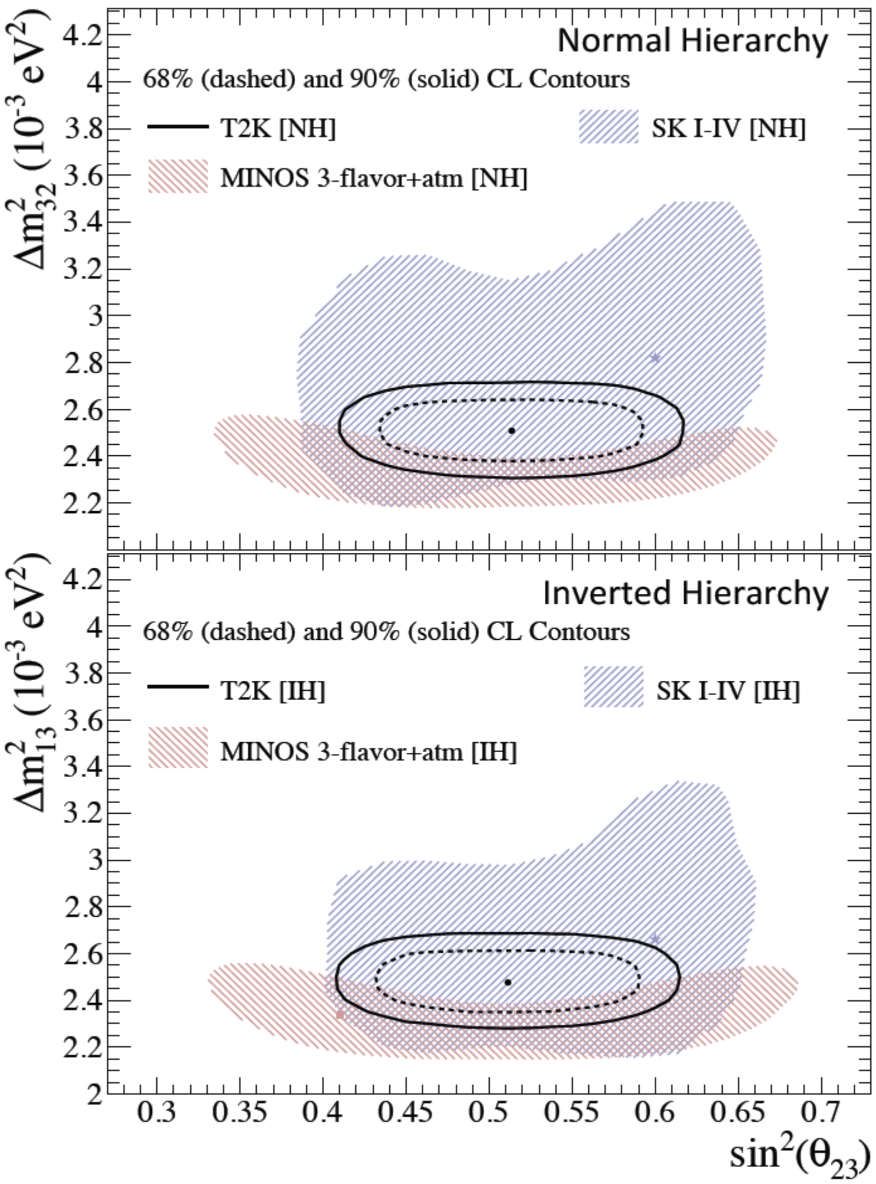
Note: contours are 1D contours at
fixed values of δ_{CP}, not 2D contours

PhysRevLett.112.061802/arXiv:1311.4750

T2K ν_μ Disappearance Results

-> Best constraints on θ_{23}





arXiv:1403.1532

Joint $\nu_e + \nu_\mu$ Analysis

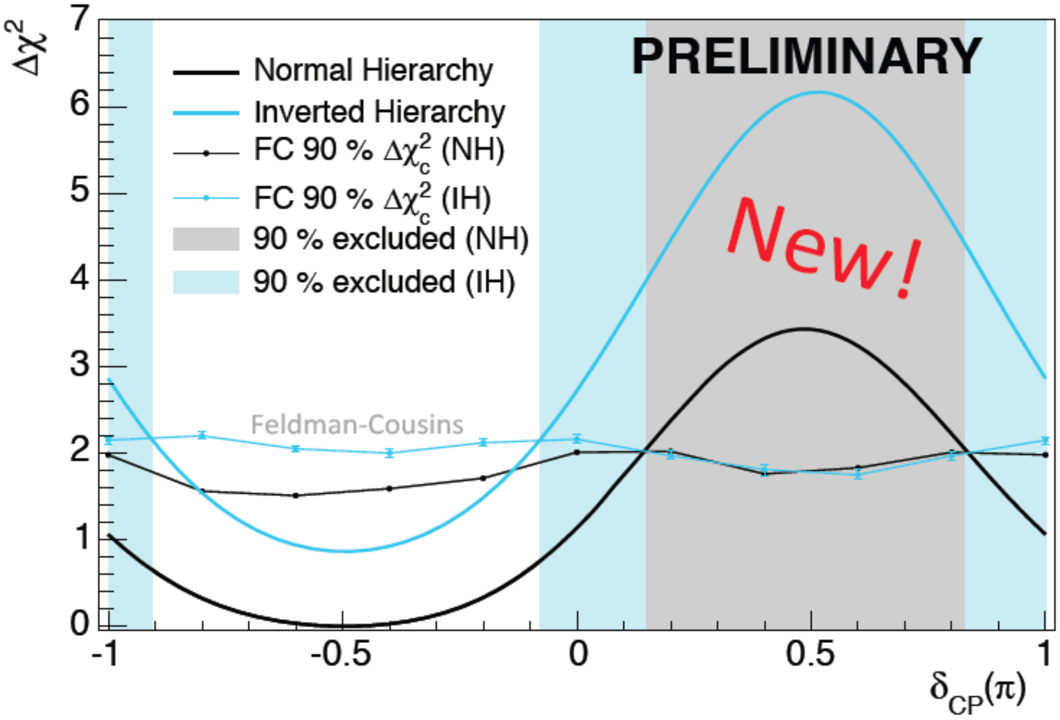
- New joint fit to appearance and disappearance data
- Fit accounts for correlations

  -> in parameter space (θ_{23}, θ_{13}, δ_{CP}, Δm^2_{32})

  -> in systematics
- Includes constraints from short-baseline reactor antineutrino disappearance

  $\sin^2\theta_{13} = 0.095 \pm 0.010$

  (PDG 2013)
- Joint fits are now starting to constrain δ_{CP}!



	90% CL Inclusion
NH	$\delta_{CP} \in [-1.17, 0.15]\pi$
IH	$\delta_{CP} \in [-0.91, -0.08]\pi$

PRELIMINARY

But…

- CP violation in neutrino mixing
  can give us a lepton number asymmetry

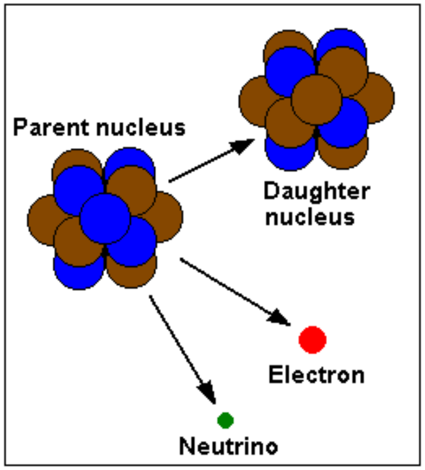
- How do we get a baryon number asymmetry?

- We need some more pieces
  -> This is where Majorana neutrinos
  and neutrinoless double beta decay come in.

Beta Decay

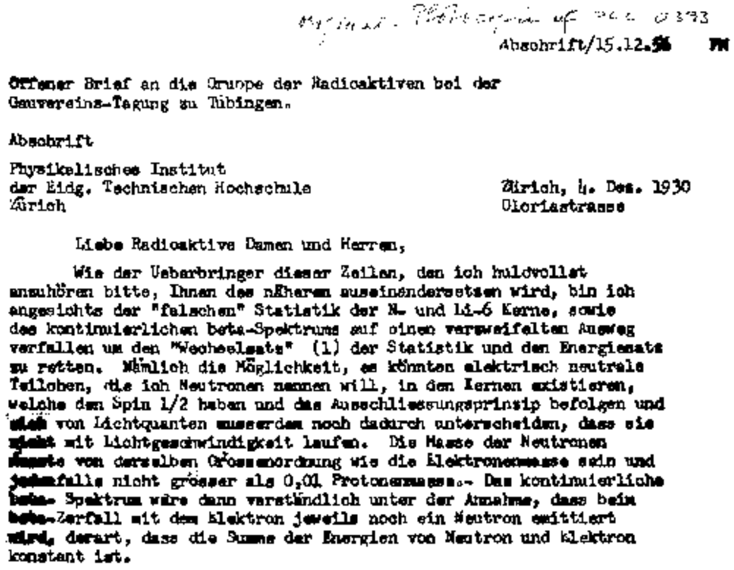
- The neutrino was first proposed by Wolfgang Pauli in 1930 to conserve energy and conserve angular momentum in nuclear beta decay
- A two-body decay should give a single electron energy, but the spectrum is continuous

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$



Beta decay

"Dear Radioactive Ladies and Gentlemen"



Original: Photocopy of PLC 0393

Abschrift/15.12.56 PW

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

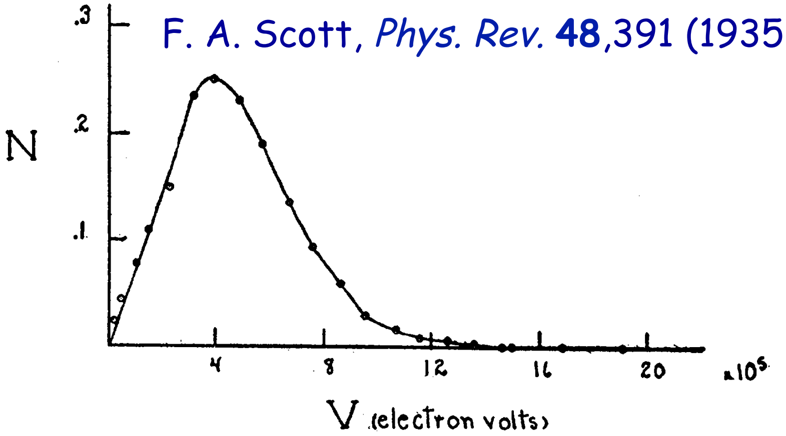
Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

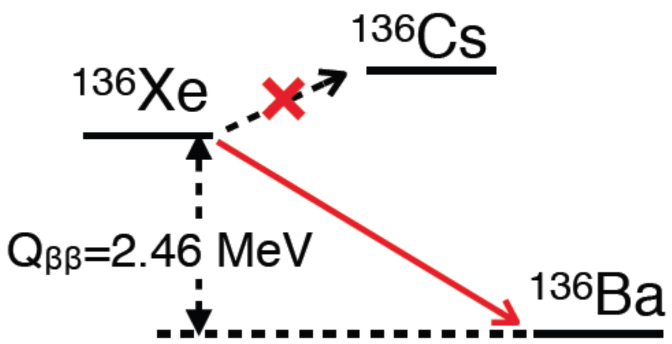


F. A. Scott, *Phys. Rev.* **48**,391 (1935)

FIG. 5. Energy distribution curve of the beta-rays.

Double Beta Decay

- Double beta decay is a rare process observable in some even-even nuclei



- In these nuclei ordinary β-decay is energetically forbidden

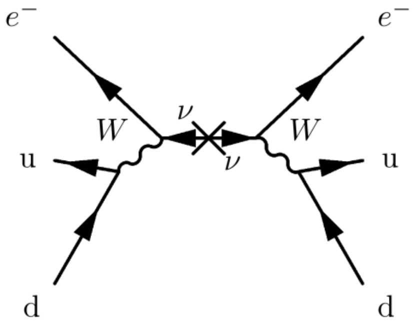
- Two simultaneous β-decays are allowed

- More than 60 double-beta decay nuclei are known, e.g. ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd, etc.

- These decays have extremely long half-lives: $T_{1/2} > 10^{19}$ yr

Neutrinoless Double-Beta Decay

- Majorana neutrinos are their own antiparticles
- If neutrinos are Majorana, double-beta decay can proceed by a loop diagram with no neutrinos in the final state
- This process is sensitive to a Majorana mass, a weighted sum over all three neutrino masses, all mixing angles, δ_{CP}, plus new phases (weighted by U_{e1}, U_{e2}, U_{e3}: m_1, m_2 dominate)



$$\left\langle m_{\beta\beta} \right\rangle = \sum_{i=1}^{3} \left| U_{ei} \right|^2 m_i \, \varepsilon_i$$

Leptogenesis

Leptogenesis is a mechanism for generating the matter/antimatter asymmetry starting from a lepton number asymmetry (c.f. baryogenesis)

Requirements (at least in one picture):

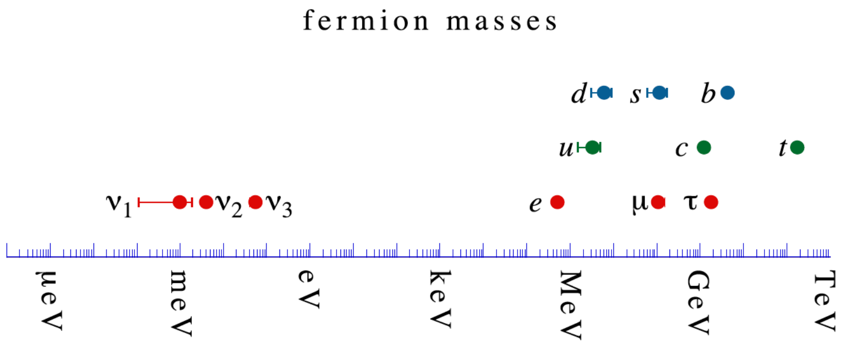
- CP violation in the neutrino sector:
  δ_{CP} is a major goal of the neutrino oscillation program
- Majorana neutrinos
- Seesaw mechanism

-> Decays of right-handed neutrinos produce L violation, which the B-L conserving sphaleron process in the SM converts to a baryon number asymmetry

Seesaw Mechanism

Why are neutrinos so much lighter than other fundamental fermions?

- In the Standard Model,
  particles acquire mass
  through the Higgs mechanism
- Much lower neutrino mass
  suggests additional effect



schematic view, normal hierarchy
(lowest neutrino mass not known)

- Simple (Type I) Seeaw:
  - Majorana neutrinos naturally allow
    adding additional elements to the model:
    -> right-handed neutrinos
    -> off-diagonal elements *M* to the mass matrix
  - Diagonalizing the matrix to find the physical states can give:
    -> light left-handed neutrinos
    -> heavy right-handed neutrinos
- Heavy right-handed neutrinos would decay in the early universe
  via $\Delta L = 2$ processes, giving rise to a lepton number asymmetry.

What is the Sphaleron Process?

Psychotic Quartet
"Sphaleron"

Survey:

"It's the part of the Standard Model they don't teach experimentalists in graduate school."
- an experimental colleague

"The Sphaleron process is something to ask theorists about at dinner to make them uncomfortable."
- my wife

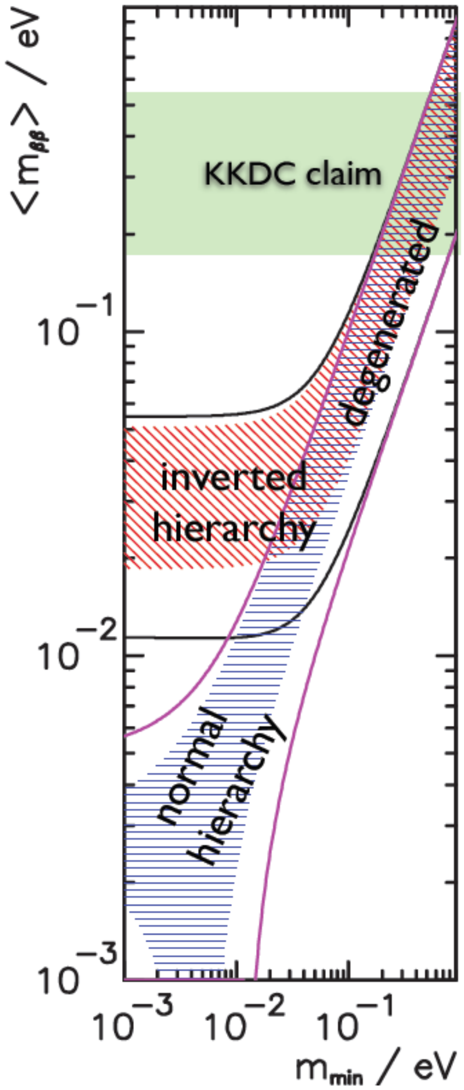
Sphaleron process in the Standard Model:

- The Standard Model always conserves B-L
- Sphaleron process is a nonperturbative process
  -> Can't be represented by Feynman diagrams
- Converts e.g. 3 baryons to 3 antileptons
  -> Can convert a lepton asymmetry to a baryon asymmetry

Neutrinoless Double-Beta Decay

Known mixing parameters allow two regions of
phase space, depending on the mass heirarchy
-> widths due to parameter uncertainties

- Regions overlap in degenerate region
- Inverted hierarchy has a minimum $<m_{\beta\beta}>$
  -> If we don't observe $0\nu\beta\beta$
  and we know that the heirarchy is inverted,
  then: neutrinos are Dirac
  or there is new physics
- Under normal hierarchy $<m_{\beta\beta}>$ can be unobservable even if neutrinos are Majorana
- Controversial positive claim in ^{76}Ge by Klapdor-Kleingrothaus et. al.
- Not shown: cosmological limits, direct mass limits



Neutrino Mass Limits

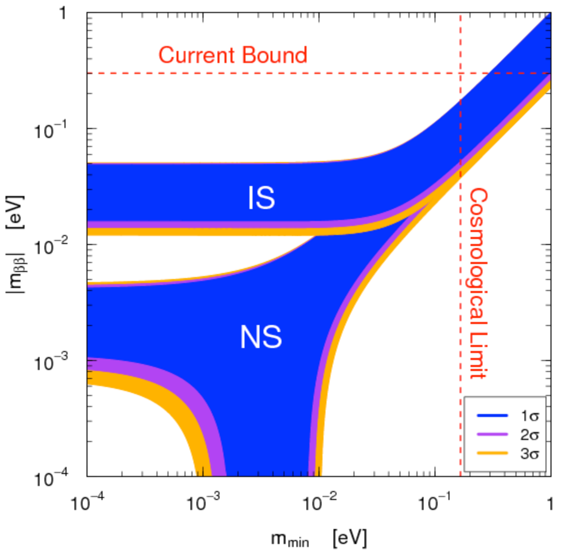
Other constraints on neutrino mass:

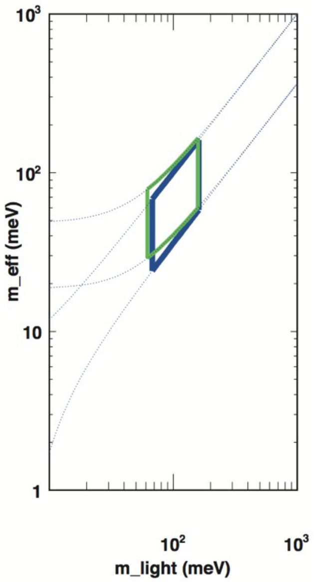
Tritium beta decay

- Massive neutrinos distort the endpoint of the beta decay spectrum
- Best limit is $m_\beta < 2.3$ eV
- KATRIN goal: 0.2 eV

Cosmology

- Global fits to cosmological data set limits on the total mass of all neutrino flavors
- Planck 2013: $\Sigma m_\nu < 0.23$ eV (arXiv:1303.5076)
- Limits depend on datasets used, cosmological model
- Some recent fits favor neutrino masses around the Planck limit PhysRevLett.112.051303; arXiv:1403.4599





Nuclear Matrix Elements

Phase space factor

Nuclear matrix element

$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}|M^{0\nu}|^2|\langle m_{\beta\beta}\rangle|^2$$

Decay half-life

Effective Majorana neutrino mass

$$m_{\beta\beta} \equiv \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$

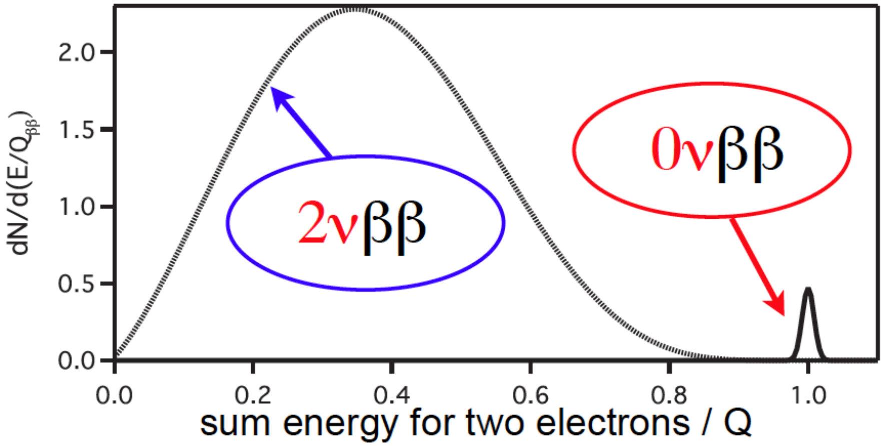
- $G^{0\nu}$ is straightforward to calculate
- $M^{0\nu}$ is not known, must be estimated theoretically
  -> estimates vary by factor os ~2, depending on method
- For $m_{\beta\beta}$ = 50 meV, estimated half lives are 10^{25} – 10^{27} years, depending on the nuclear system

Detecting 2νββ

- KamLAND-Zen is sensitive to the total energy of the two β's

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

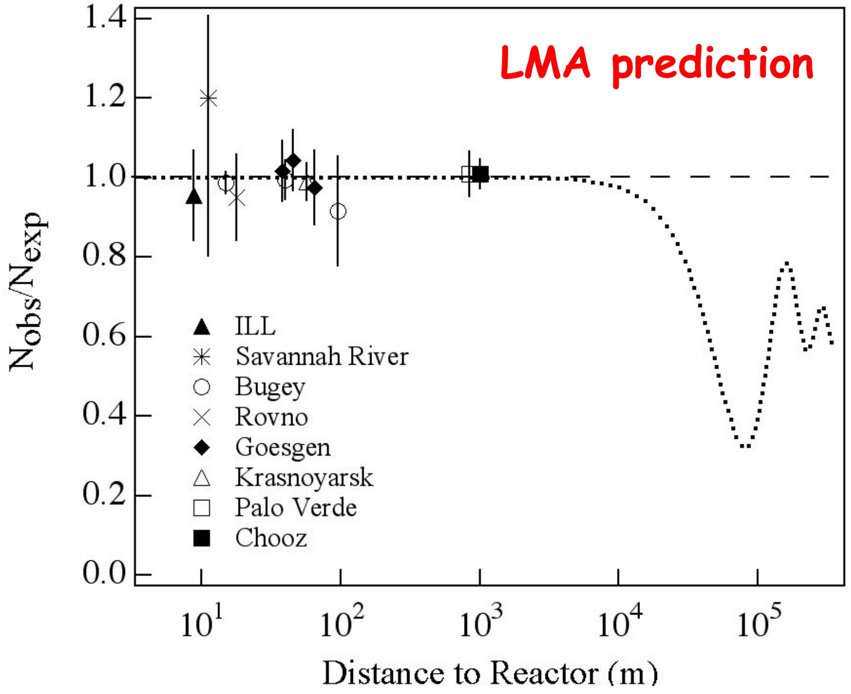
$$\boxed{0\nu\beta\beta}\ (Z,A) \rightarrow (Z+2,A) + 2e^-$$



- 0νββ experimental goals:
  -> Low background under 0νββ peak
  -> Good energy resolution
  -> 2νββ can be a background!

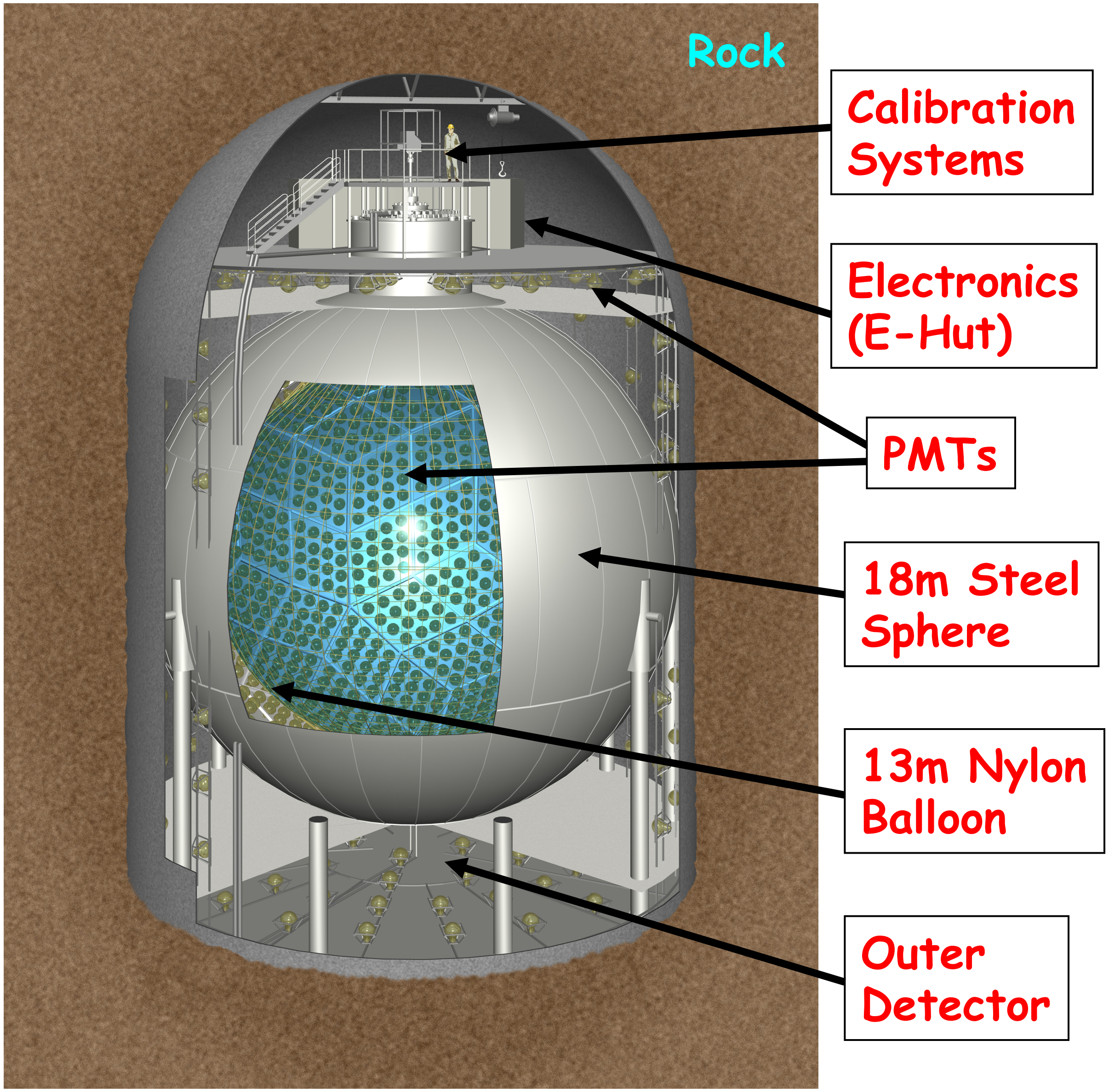
KamLAND

- KamLAND (Kamioka Liquid-scintillator AntiNeutrino Detector)
- Designed to measure or rule out neutrino oscillations at the solar LMA parameters with a terrestrial antineutrino source: nuclear reactors
- KamLAND is located in the same mine near Kamioka, Japan as Super-K, in the former site of Kamiokande
- Previous reactor neutrinos flux measurements shown with flux vs. distance prediction from LMA



KamLAND Detector

- 1 kton liquid scintillator
- Mineral oil buffer
  outside 120-μm
  nylon balloon
- 1879 PMTs
  1325 17" - fast
  554 20" - efficient
- Water Čerenkov
  Outer Detector
- Event position from
  light arrival times
  ~12 cm resolution
- Event energy from
  total light yield
  ~6.2%/$\sqrt{E}$(MeV)
  resolution



Calibration Systems

Electronics (E-Hut)

PMTs

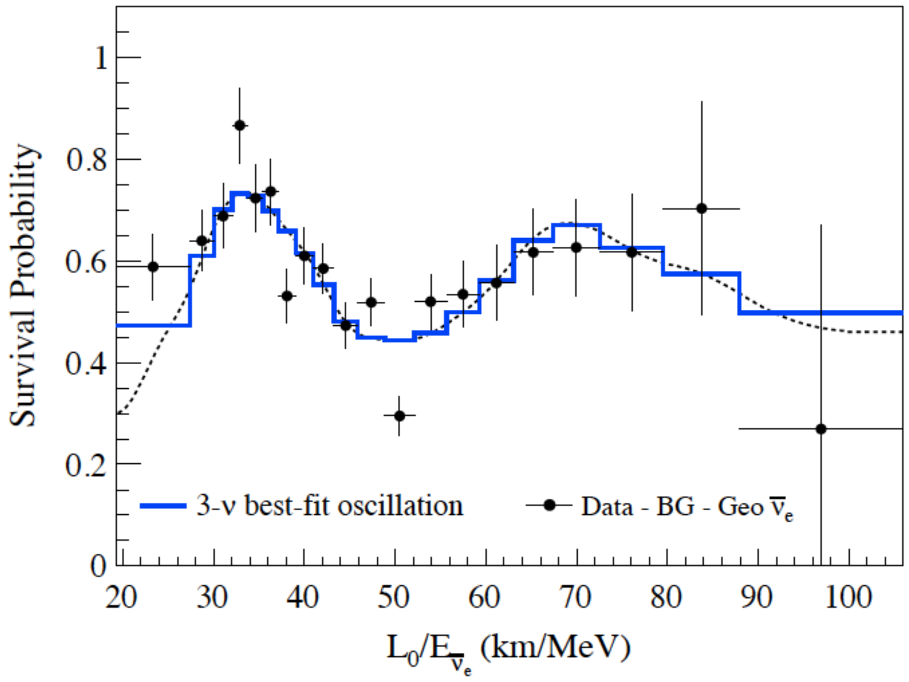
18m Steel Sphere

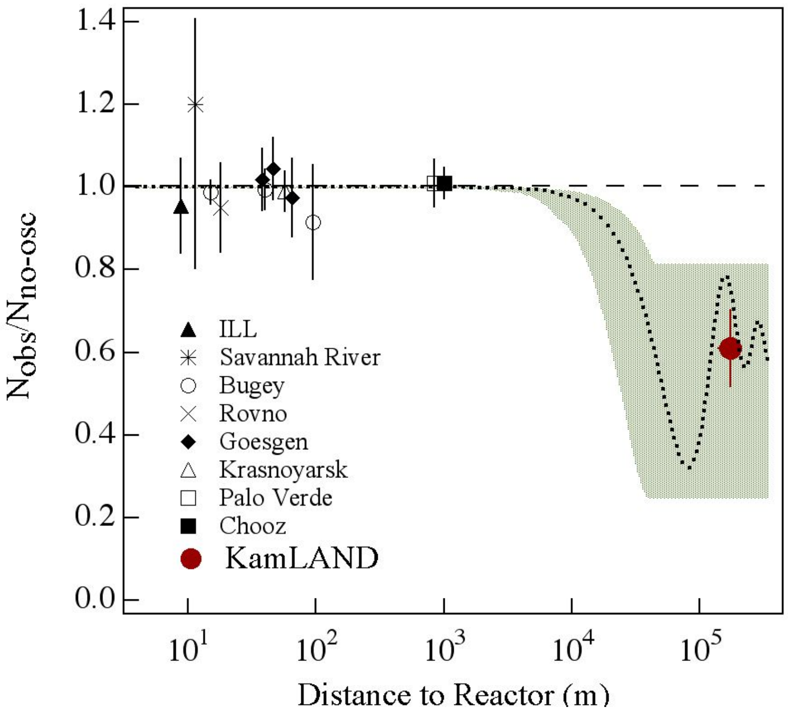
13m Nylon Balloon

Outer Detector

KamLAND Results

Primary results: reactor antineutrino oscillations

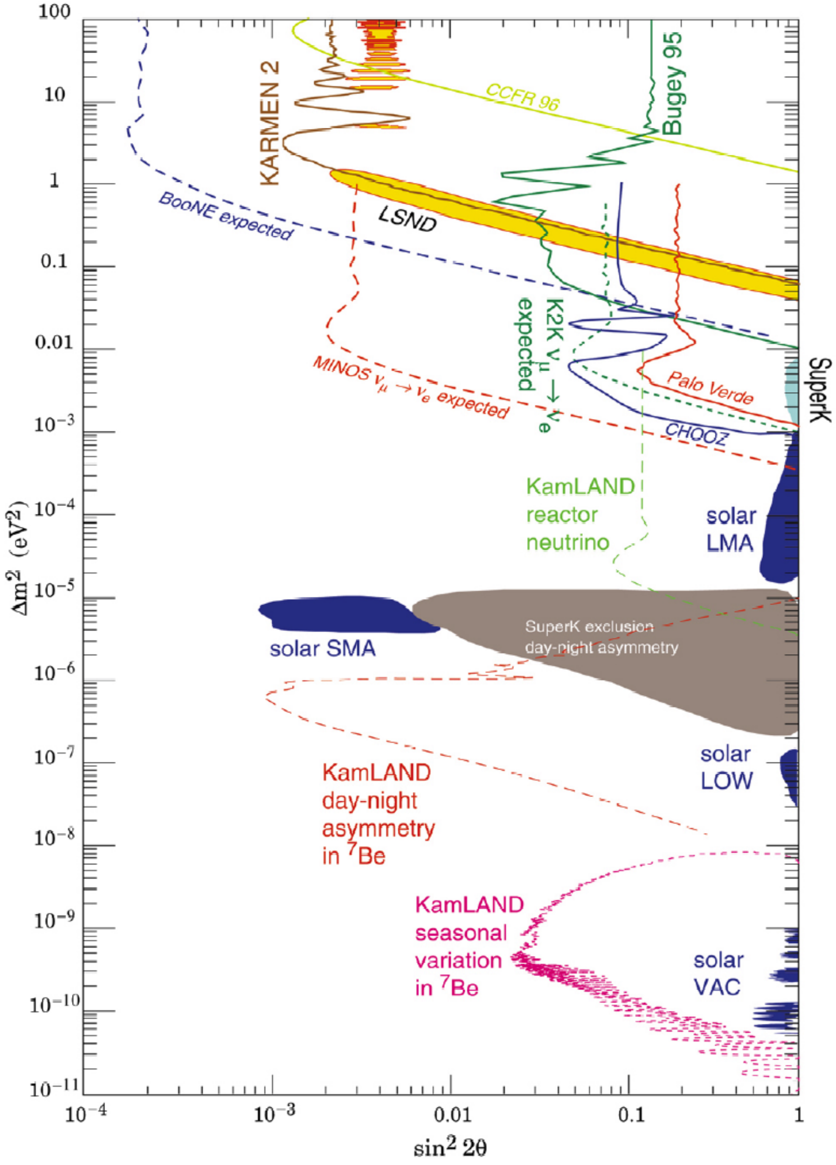




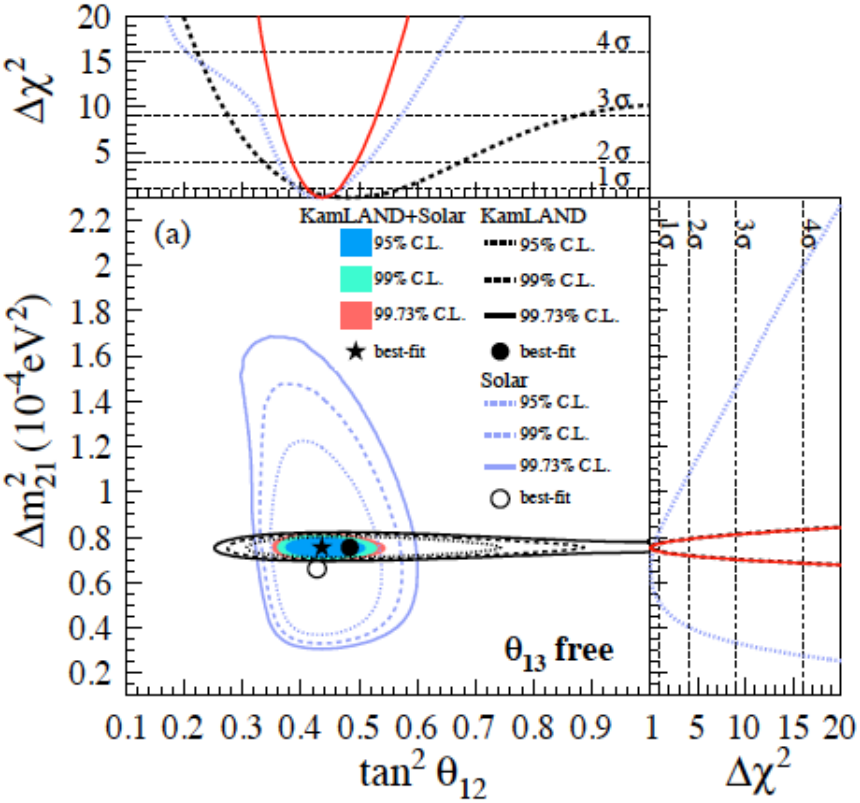
Other topics: geoneutrinos, solar neutrinos, spallation measurements, limits on astrophysical antineutrinos, nucleon decay

Now and Then

PDG 2000



Solar and KamLAND constraints



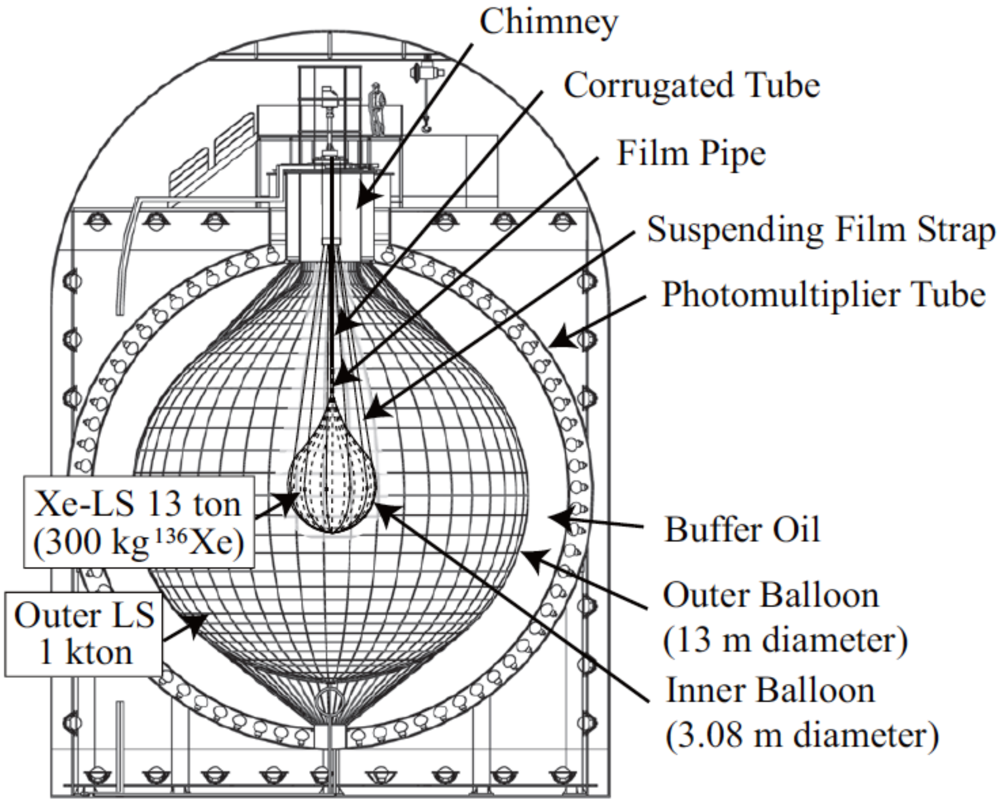
KamLAND-Zen

Basic idea: Deploy a mini-balloon full of Xe-loaded scintillator into the middle of KamLAND

Running detector
-> relatively low cost, quick start
-> detector well understood
-> experience with balloons,
LS purification
-> ongoing antineutrino program
outside Xe mini-balloon

Large and clean
-> negligible external backgrounds
-> no escaping/invisible β/γ energy

Highly scalable
-> 100s of kg of ^{136}Xe in first phase
-> up to several tons
with larger mini-balloon



Disadvantage: energy resolution (4.0% at 2.458 MeV)

Xe-Loaded LS

Technical challenges: Xe-loaded liquid scintillator (LS)

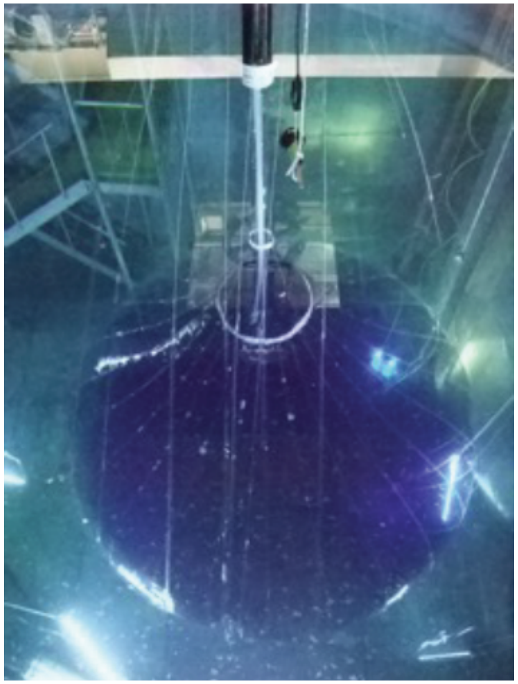
- Match light yield to existing KamLAND LS
  -> Achieved: matched to within 3%
- Similar overall density to existing KamLAND LS,
  for mini-balloon integrity
  -> Tuned to 0.10% higher density
- Xe loading: (2.52 ± 0.07) % by weight
- Composition:
  82% decane
  18% pseudocumene
  2.7 g/L PPO
  (2.52 ± 0.07) % Xe
- Xe is (90.93 ± 0.05)% ^{136}Xe, (8.89 ± 0.01)% ^{134}Xe
- 129 kg ^{136}Xe in the fiducial volume

Mini-Balloon

Technical challenges: Mini-Balloon

- Very thin: 25 μm nylon
- Welded seams (!)
- Must be Xe barrier
- High transparency
- Low contaminations of U, Th, K

Tests in water to establish procedures for deployment, inflation, LS replacement



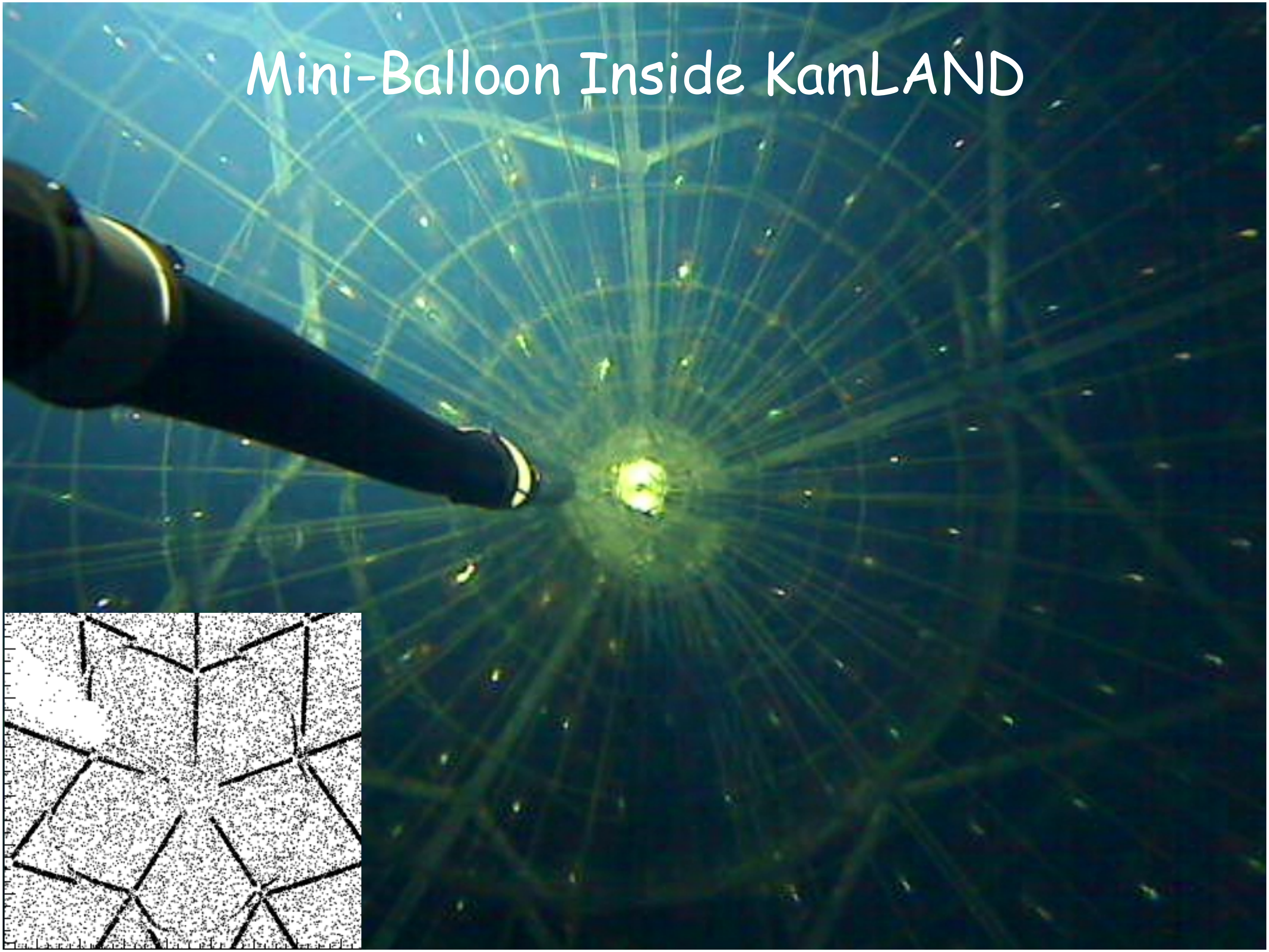
80 μm polyethylene test balloon

25 μm Nylon 6 balloon

Mini-Balloon Deployment

Mini-ballon rolled into 'snake' to fit through 50 cm opening
Class 100 clean room on top of the detector

Mini-Balloon Inside KamLAND

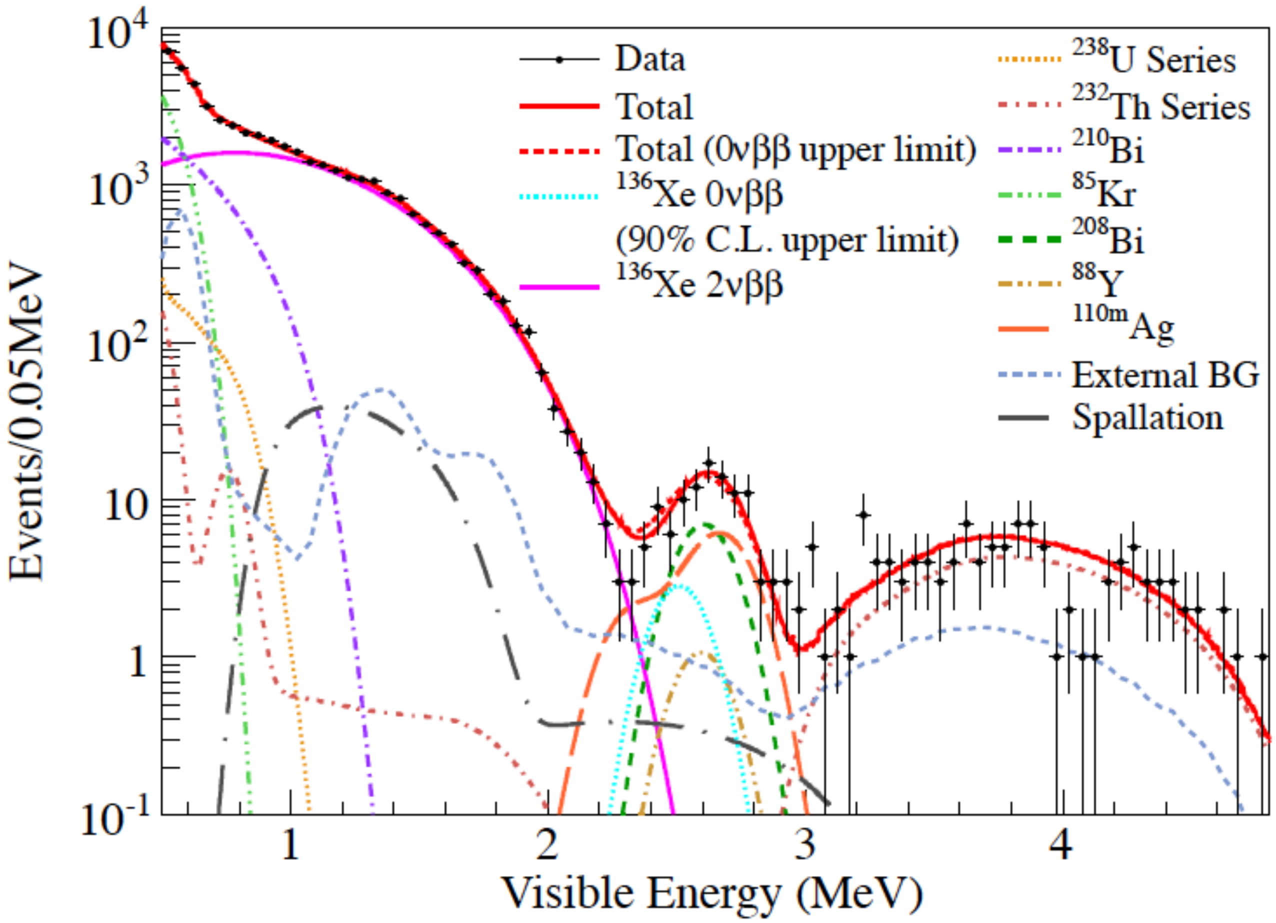


First Results

77.6 days of data, 129 kg ^{136}Xe in fiducial volume (1.2 m radius)

-> Clear 2$\nu\beta\beta$ signal

-> Very interesting peak just above 2.458 MeV…



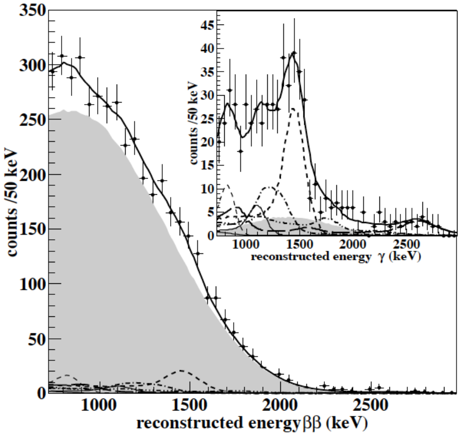
^{136}Xe 2νββ Half Life

First measured by EXO-200 (2011)

$T^{2\nu}_{1/2}$ = 2.11 ± 0.04 (stat) ± 0.21 (syst) x 20^{21} yr

PRL 107, 212501 (2011)

-> 5x larger than 2002 DAMA limit

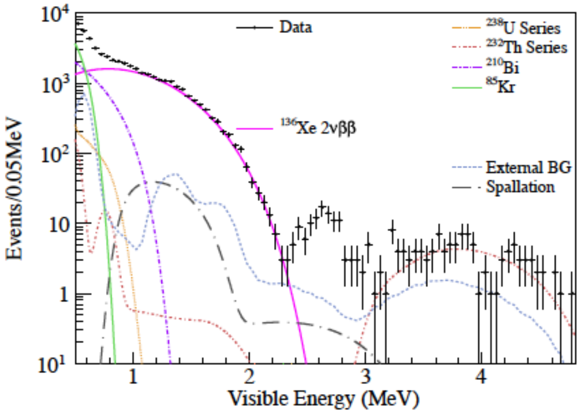


KamLAND-Zen (2012)

$T^{2\nu}_{1/2}$ = 2.38 ± 0.02 (stat) ± 0.14 (syst) x 20^{21} yr

Phys.Rev.C 85, 045504 (2012)

-> Consistent with EXO-200 result



Current results:

KamLAND: $T^{2\nu}_{1/2}$ = 2.30 ± 0.02 (stat) ± 0.12 (syst) x 20^{21} yr

Phys.Rev.C 86, 021601 (2012)

EXO-200: $T^{2\nu}_{1/2}$ = 2.172 ± 0.017 (stat) ± 0.060 (syst) x 20^{21} yr

Phys.Rev. C 89 015502 (2013)

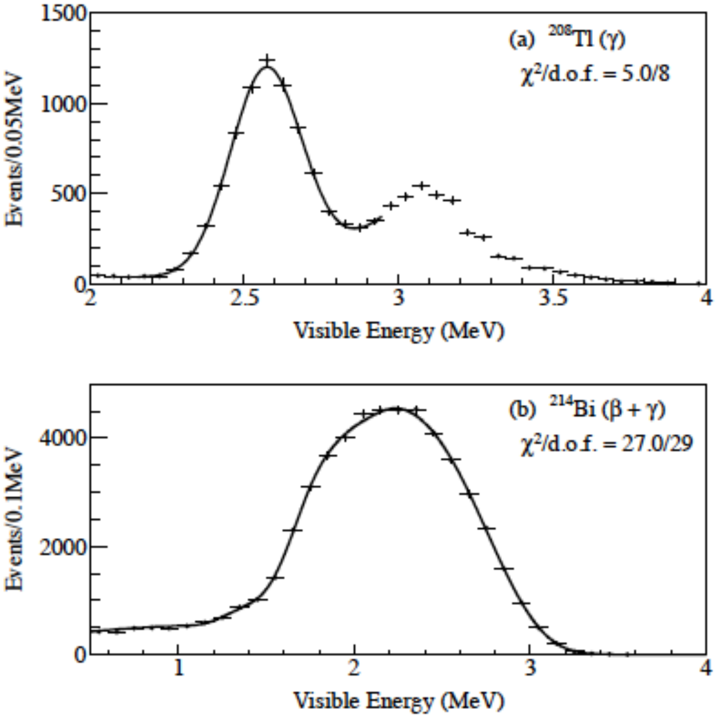
What's that peak?

Should we get excited?

-> If the peak is $0\nu\beta\beta$, it's at about the level of the KKDC claim…

-> Energy is a bit high (2.6 MeV, vs. 2.5 MeV),
but what if the energy calibration is off?

However:

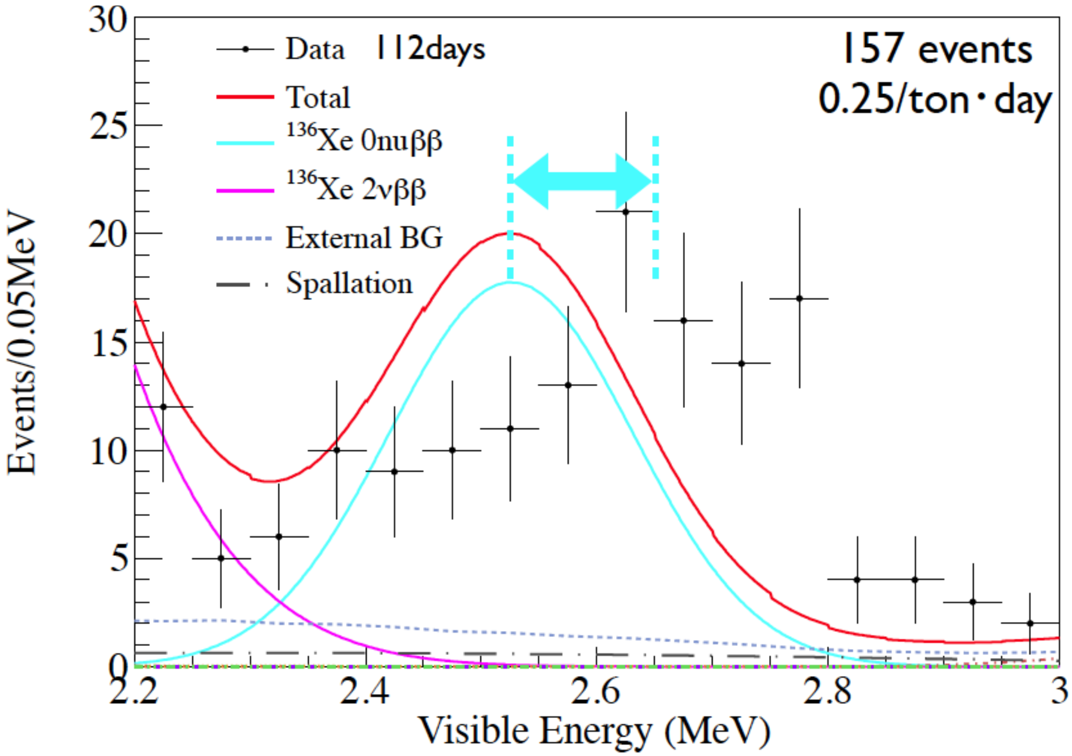


-> Calibration with ^{208}Tl (2.614 MeV γ)
does not show an energy shift
(ThO_2W source just outside
Mini Balloon)

-> ^{214}Bi spectrum in Xe-LS also correct
(from radon decays,
radon contamination/tracers
introduced during filling)

What's that peak?

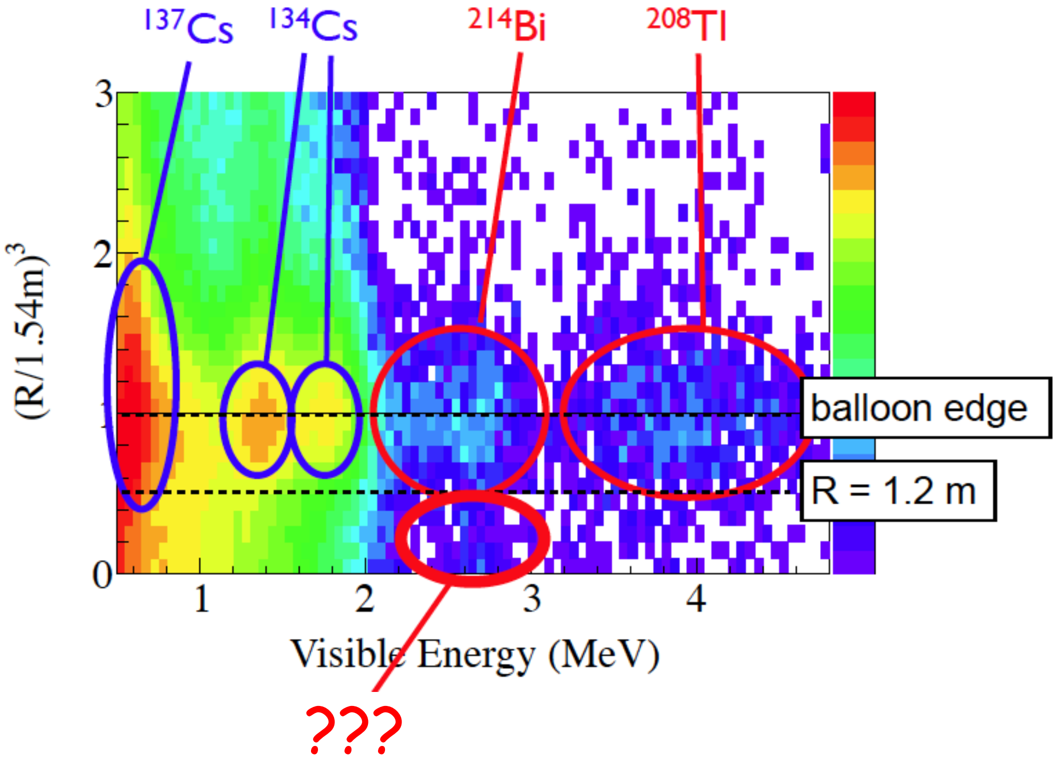
Peak fit with 0νββ signal:



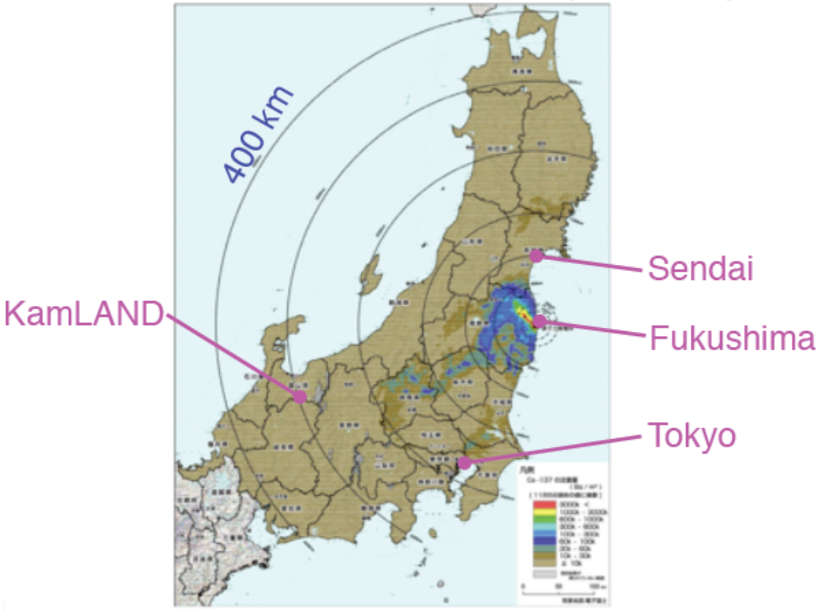
-> Peak position different from that expected from 0νββ

-> 0νββ only rejected at 8σ

Backgrounds



Fukushima-I reactor fallout (ex.^{137}Cs)



http://radioactivity.mext.go.jp/ja/contents/6000/5233/24/5600_201203131000_press.pdf

Observed backgrounds vs. position:

- ^{137}Cs, ^{134}Cs do not occur naturally
  - -> ratio consistent with Fukushima-I fallout
  - -> likely introduced during mini-balloon fabrication, don't leach into LS
- ^{214}Bi on the mini-balloon limits the fiducial volume for $0\nu\beta\beta$
- ^{208}Tl on the balloon is above the analysis region, doesn't affect analysis

ENSDF Search

2.6 MeV background properties

- uniformly distributed in the Xe-LS
  -> not seen in LS outside the mini-balloon
- no correlation with muon events
- long-lived background: stable on ~30 day timescale

-> Exhaustive search of all decays in the ENSDF database

LBNL Isotopes Project Evaluated Nuclear Structure Data File
http://ie.lbl.gov/databases/ensdfserve.html

-> Short list – peak in the $0\nu\beta\beta$ region, $T_{1/2} > 30$ days

- ^{110m}Ag $T_{1/2} = 250$ days
- ^{208}Bi $T_{1/2} = 3.68 \times 10^5$ years
- ^{88}Y $T_{1/2} = 107$ days
- ^{60}Co $T_{1/2} = 5.27$ years

(Side note: ^{110m}Ag is a component of reactor fallout
Assayed soil at Tohoku, where the mini-balloon was produced
Saw ^{110m}Ag! - though this does not rule out the others…)

Background source?

Fallout:

-> Already observed Cesium likely from Fukushima-I

-> ^{110m}Ag is a component of reactor fallout

-> ^{110m}Ag found in assayed of soil at Tohoku,
where the mini-balloon was produced

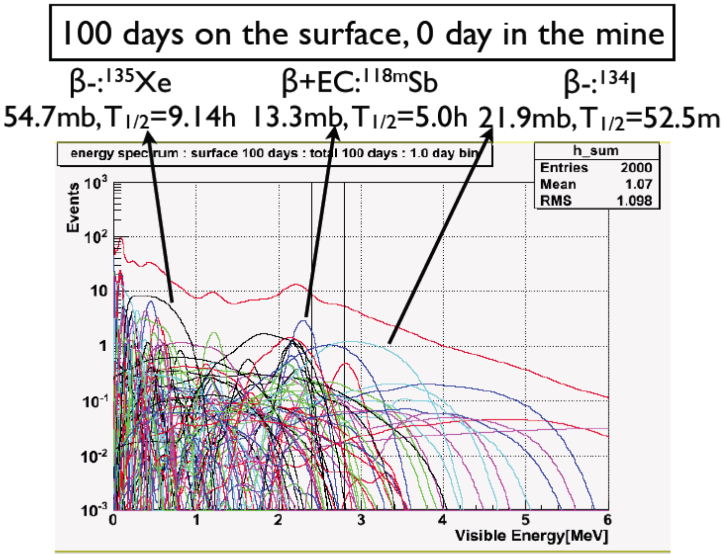
Spallation:

-> Estimated spallation production of
many isotopes on ^{136}Xe

-> Large uncertainties due to limited data

-> Spallation production underground should
be negligible based on GEANT4 simulation

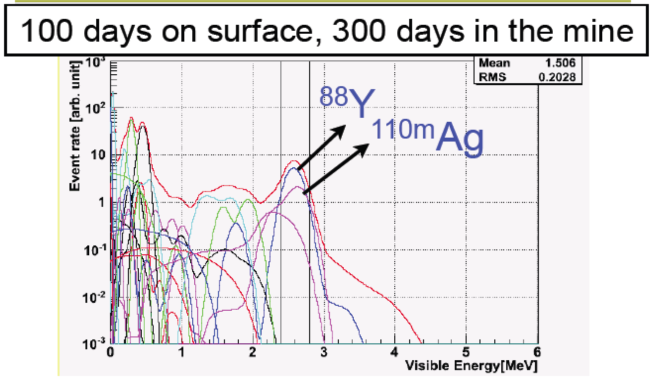
-> Spallation production above ground
before the ^{136}Xe was brought into the mine
is a possible source of ^{110m}Ag, ^{88}Y


100 days on the surface, 0 day in the mine

β-:^{135}Xe 54.7mb,$T_{1/2}$=9.14h

β+EC:^{118m}Sb 13.3mb,$T_{1/2}$=5.0h

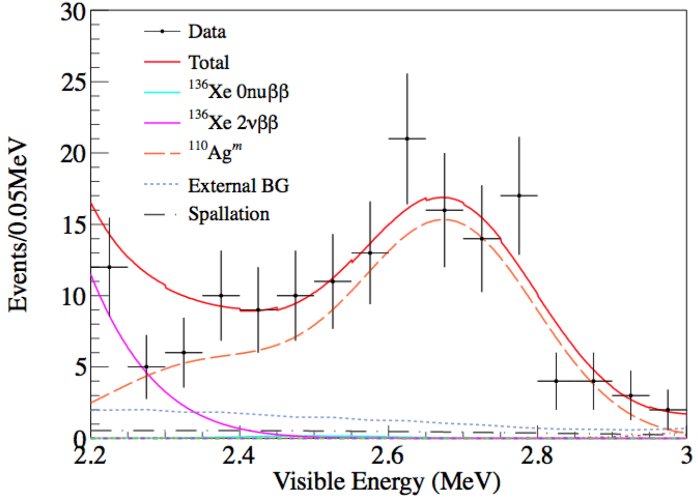
β-:^{134}I 21.9mb,$T_{1/2}$=52.5m

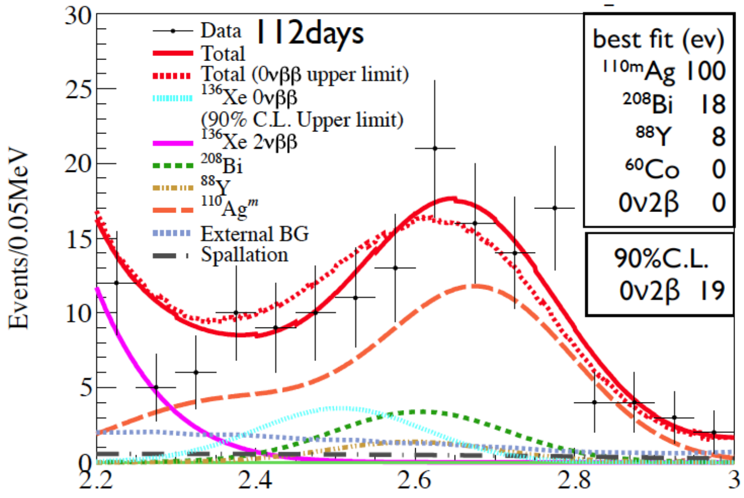

100 days on surface, 300 days in the mine

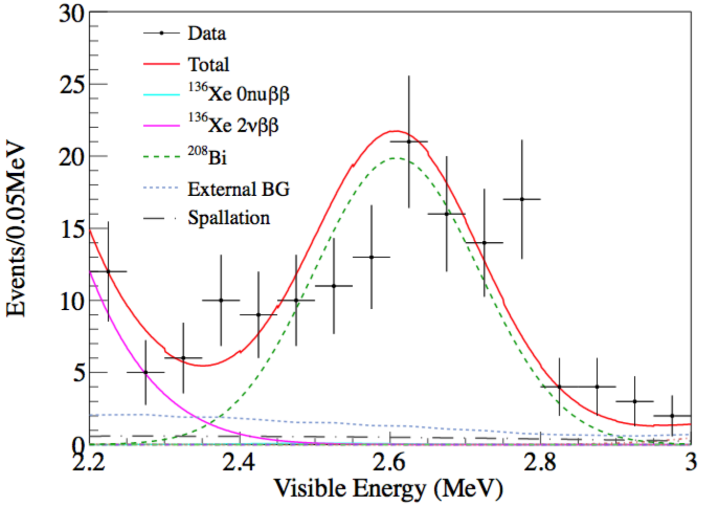
Background candidate fits

Background shape fits prefer ^{110m}Ag

Fit	χ^2
0ν + all candidates	11.6
0ν + ^{110m}Ag	13.1
0ν + ^{208}Bi	22.7
0ν + ^{88}Y	22.2
0ν + ^{60}Co	82.9
0ν only	85.0

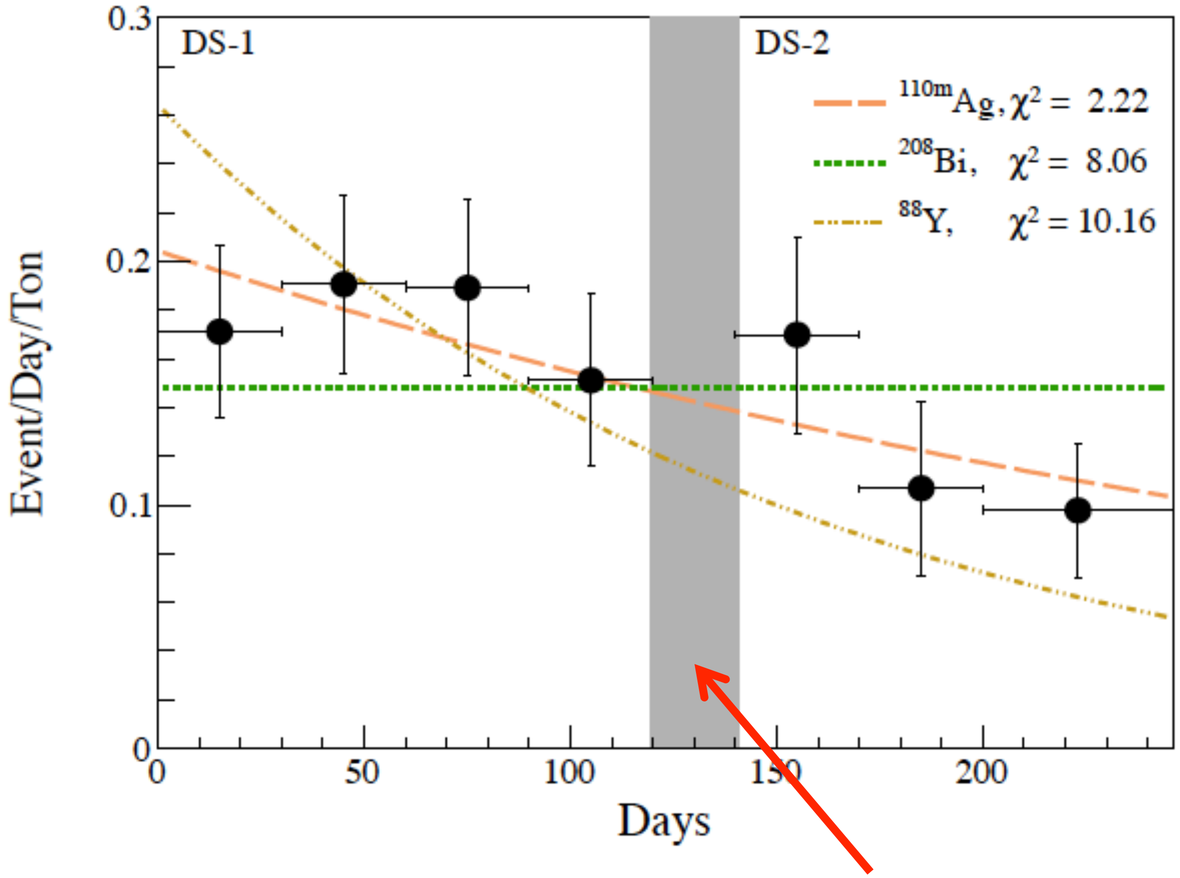

^{110m}Ag + 0νββ χ^2 = 13.1


Best fit with all candidates χ^2 = 11.6


^{208}Bi + 0νββ χ^2 = 13.1

Background Decay

With more data, background event rate vs. time also prefer ^{110m}Ag



Filtration campaign:
remove background if particulate

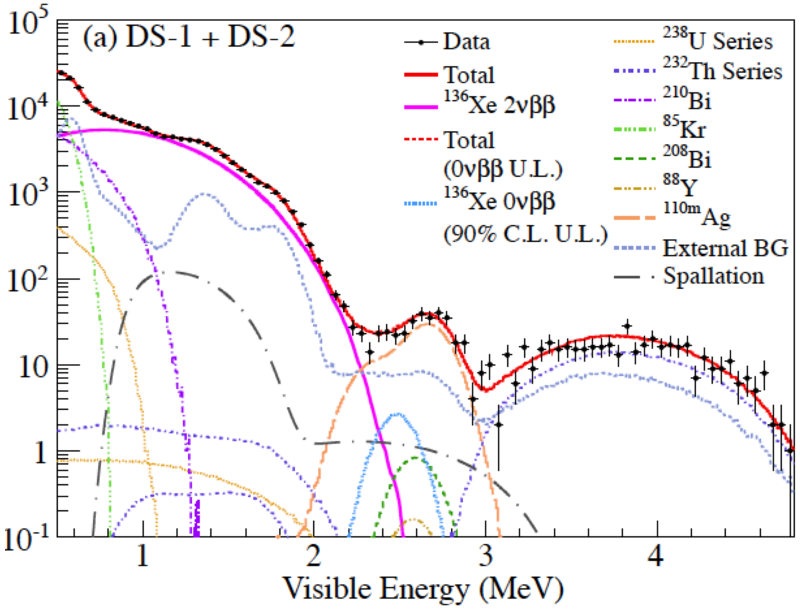
^{136}Xe 0νββ Results

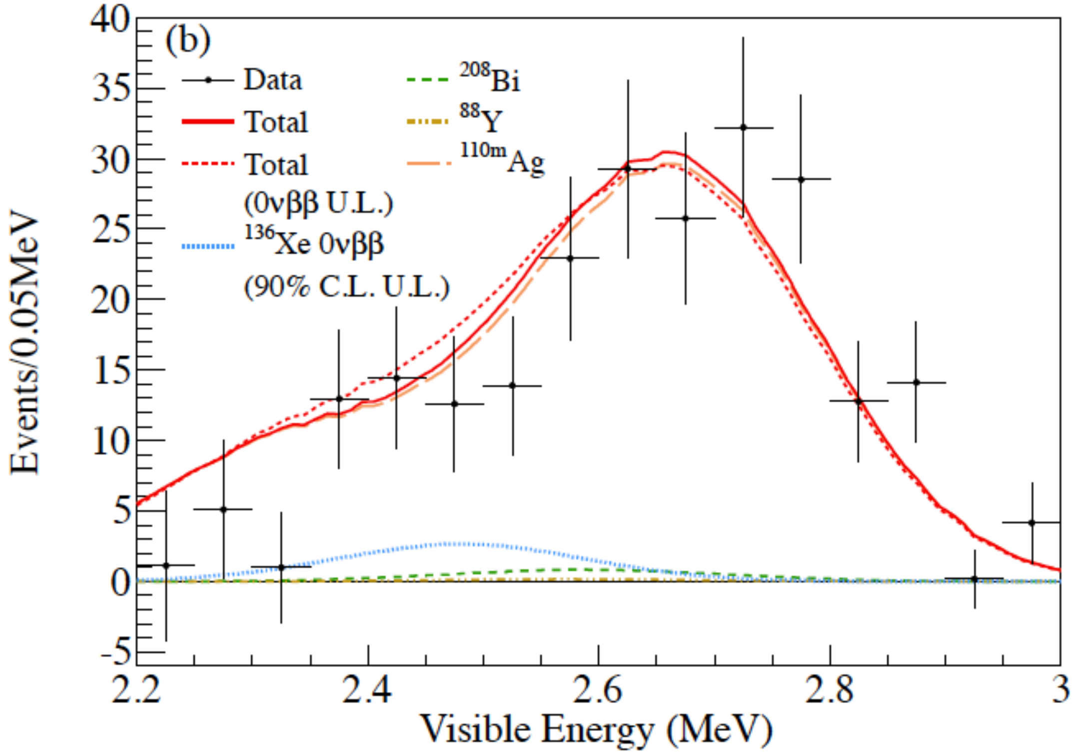
Full Phase I data: 213.4 days

90% CL: $T_{1/2}$ (^{136}Xe 0νββ) > 1.9 x 10^{25} yr

PRL 110, 062502 (2013)

Note: Sensitivity: 1.0 x 10^{25} yr





Comparison with KK

Comparisons between isotopes are complicated
by nuclear matrix element (NME) uncertainties

Plot $T_{1/2}$ (^{76}Ge) vs. $T_{1/2}$ (^{136}Xe):
NME models are diagonal lines, marked by $\langle m_{\beta\beta} \rangle$ in eV

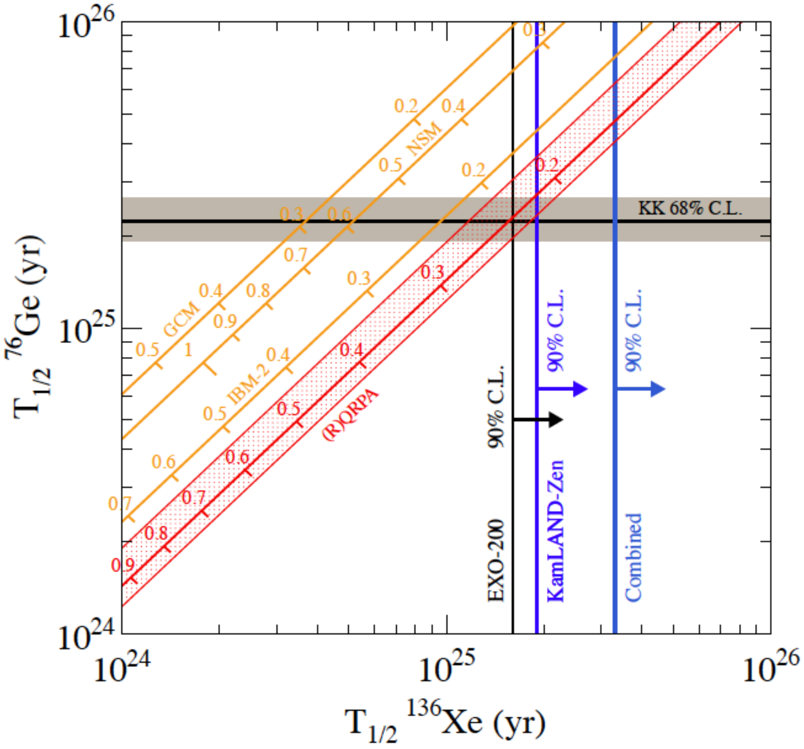
KamLAND-Zen: $T_{1/2}$ (^{136}Xe) > 1.9×10^{25} yr

EXO-200: $T_{1/2}$ (^{136}Xe) > 1.6×10^{25} yr
PRL 109, 032505 (2012)

Combined: $T_{1/2}$ (^{136}Xe) > 3.4×10^{25} yr

(Sensitivity: 1.6×10^{25} yr)

-> Incompatible with KK claim
at 97.5% CL



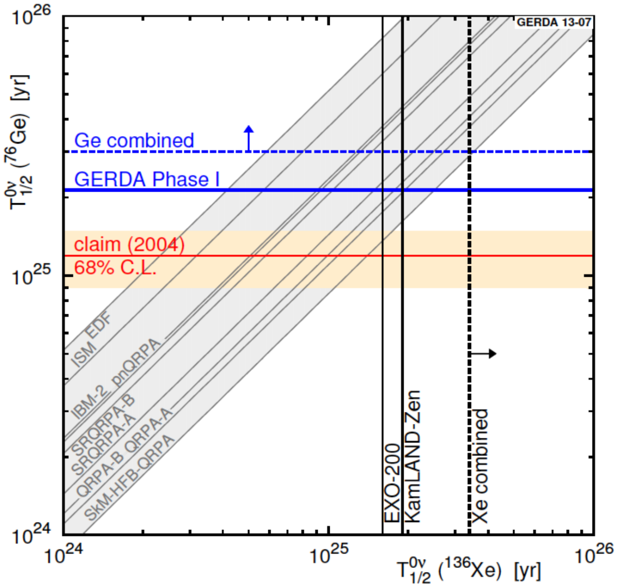
Further Results

GERDA: (PhysRevLett.111.122503)

- ^{76}Ge – same isotope as KK

GERDA: $T_{1/2}$ (^{76}Ge) > 2.1 x 10^{25} yr

Combined: $T_{1/2}$ (^{76}Ge) > 3.0 x 10^{25} yr

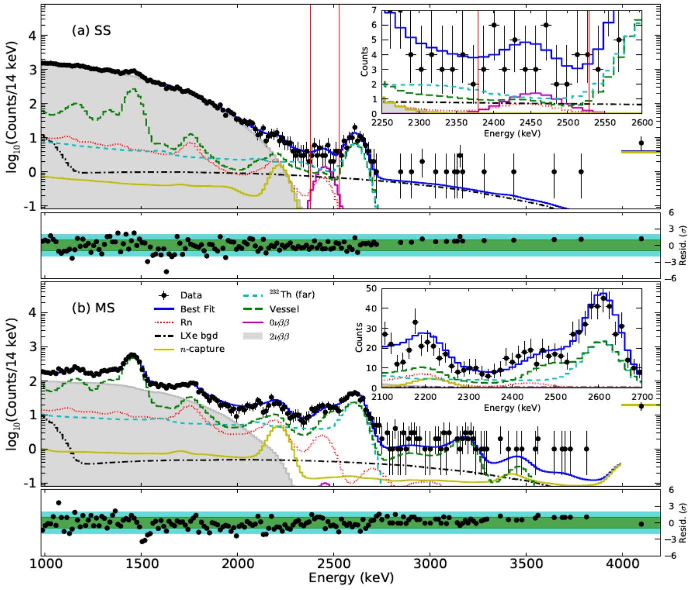


Updated EXO-200: (arXiv:1402.6956)

2012: $T_{1/2}$ (^{136}Xe) > 1.6 x 10^{25} yr

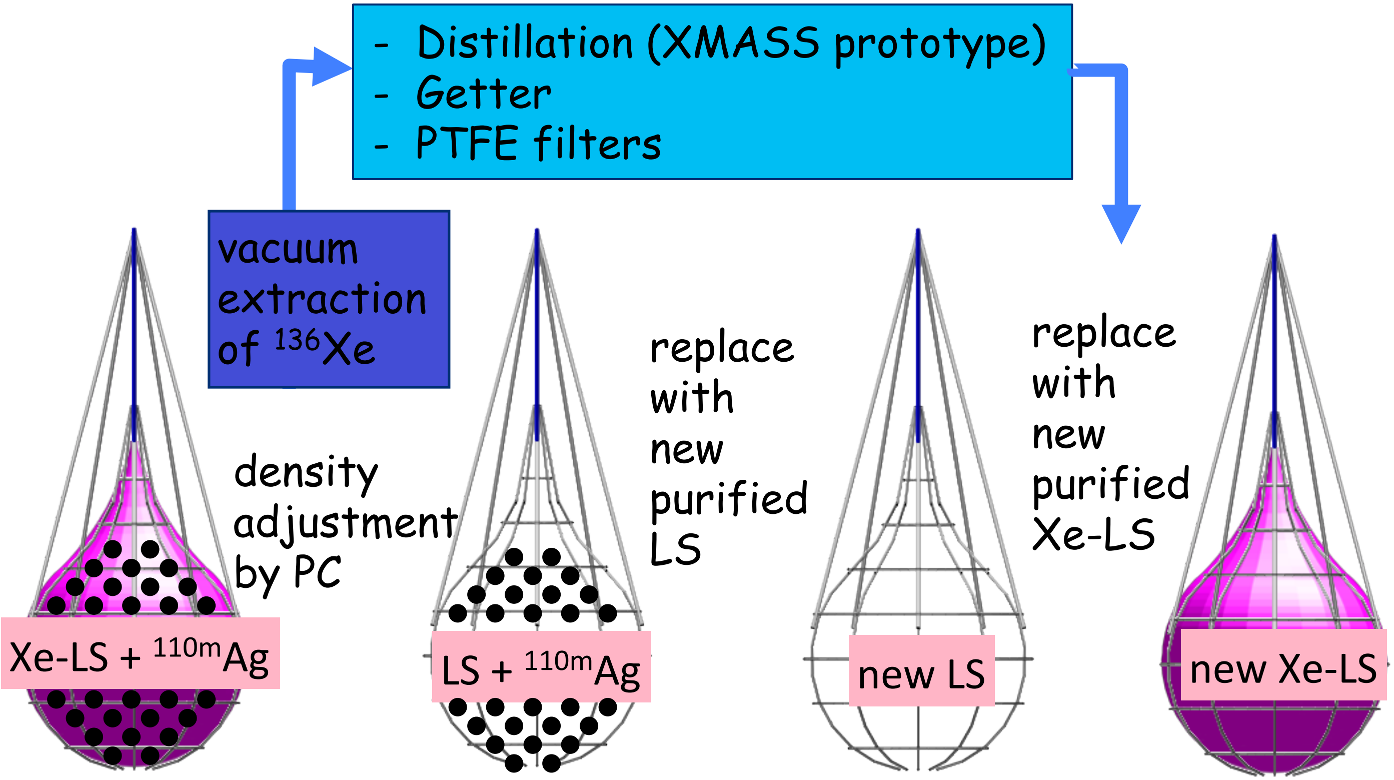
2014: $T_{1/2}$ (^{136}Xe) > 1.1 x 10^{25} yr

(Sensitivity: 1.9 x 10^{25} yr)



Current Run: Background Reduction

- Run began Nov. 2013
- ^{110m}Ag reduced by > 10x



^{136}Xe purification

- Distillation (XMASS prototype)
- Getter
- PTFE filters

vacuum extraction of ^{136}Xe

density adjustment by PC

replace with new purified LS

replace with new purified Xe-LS

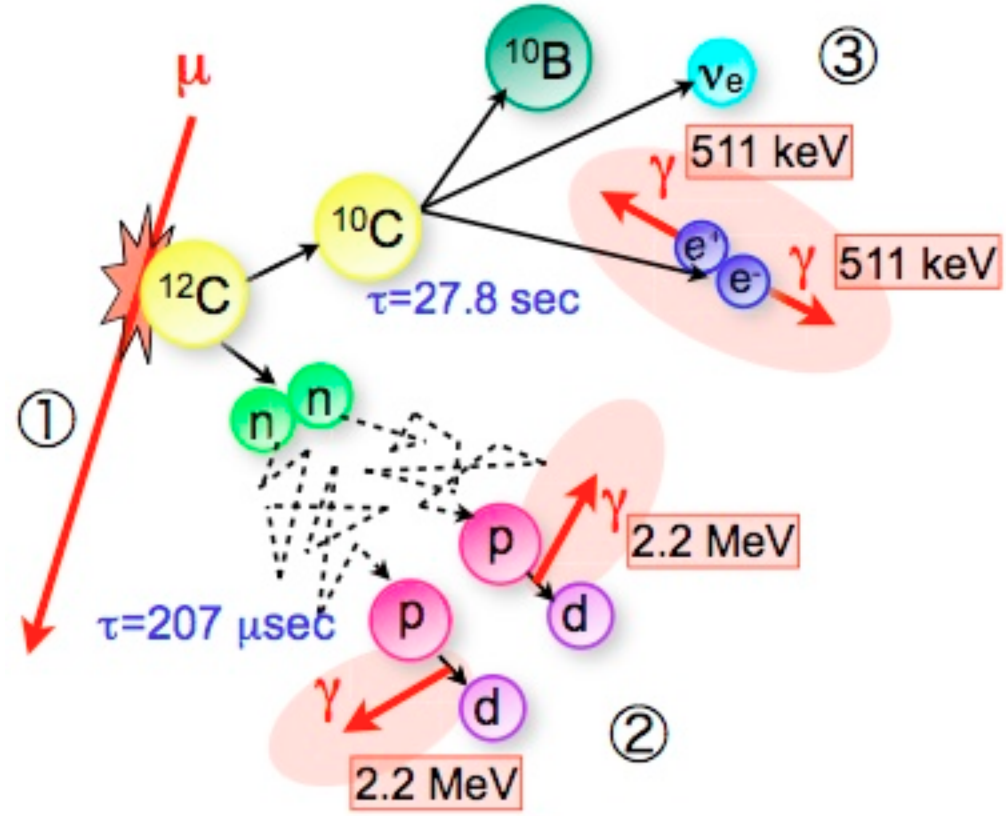
Confirm ^{110m}Ag remains in LS

Confirm ^{110m}Ag removal

BG reduction

^{10}C Background Reduction

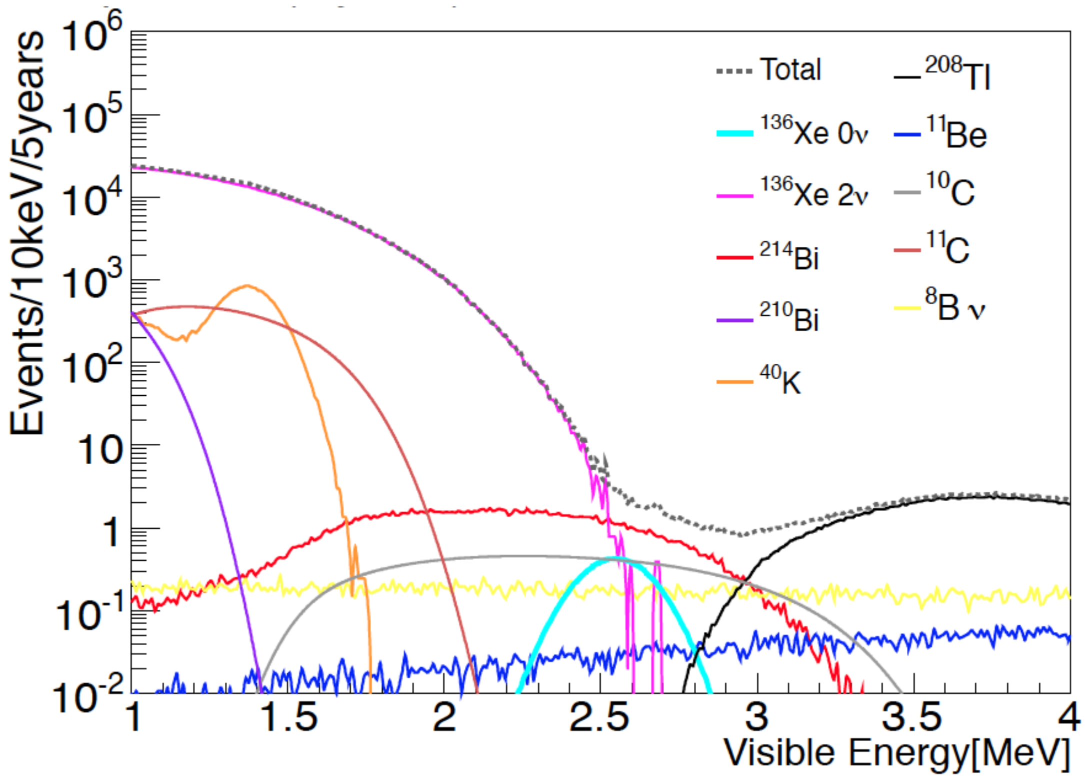
- Exploit triple coincidence to tag ^{10}C
- Made possible by electronics upgrades



600 kg Phase

- ^{136}Xe in hand
- Larger, clean balloon

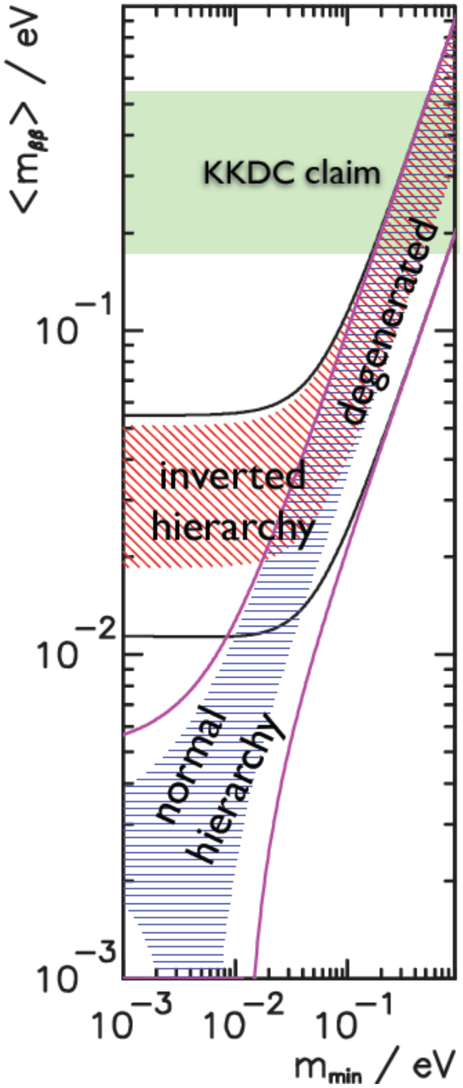
~5 × 10^{26} years ,$<m_\nu>$ = (32-65) meV for 5 years

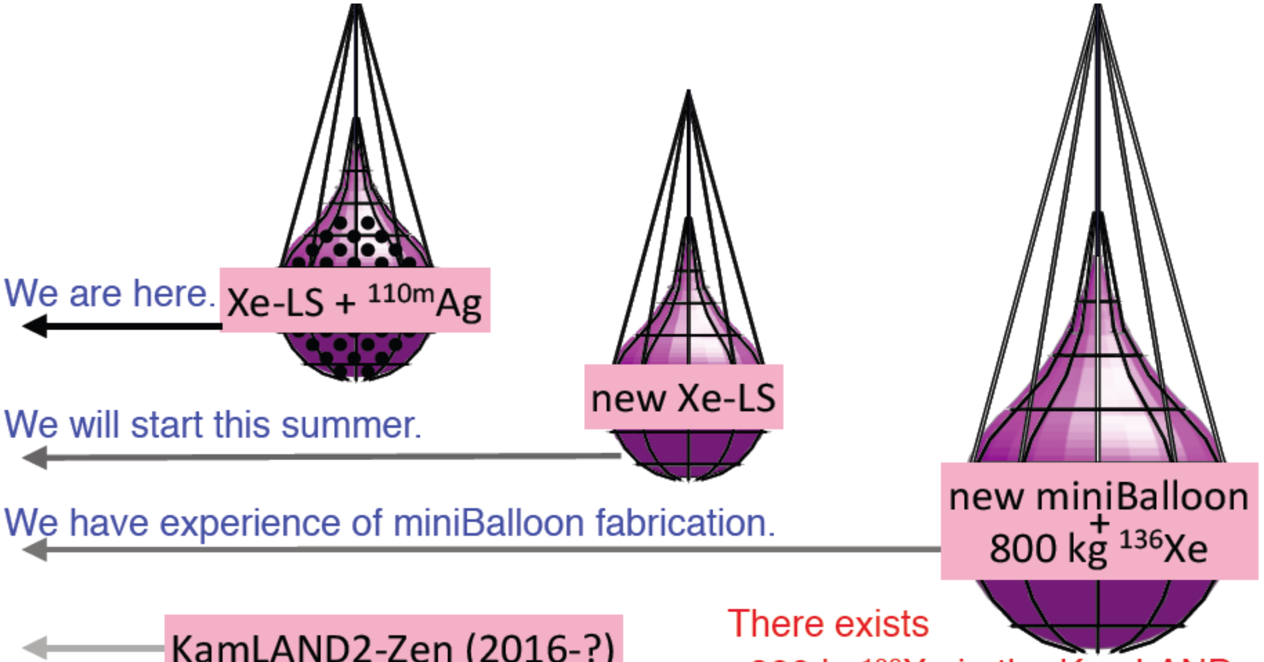


- R<1.62m, 439kg in fiducial volume
- mini-balloon (^{238}U, ^{232}Th, ^{40}K) = (3.0×10^{-12}, 3.0×10^{-12}, 2.4×10^{-11})[g/g]
- ^{10}C 90% tag
- $T_{1/2}(2\nu\beta\beta) = 2.30\times10^{21}$ yr (KamLAND-Zen)

$T_{1/2}(0\nu\beta\beta) = 5\times10^{26}$ yr

Future KamLAND-Zen Upgrades





We are here. Xe-LS + ^{110m}Ag

We will start this summer. new Xe-LS

We have experience of miniBalloon fabrication. new miniBalloon + 800 kg ^{136}Xe

KamLAND2-Zen (2016-?)

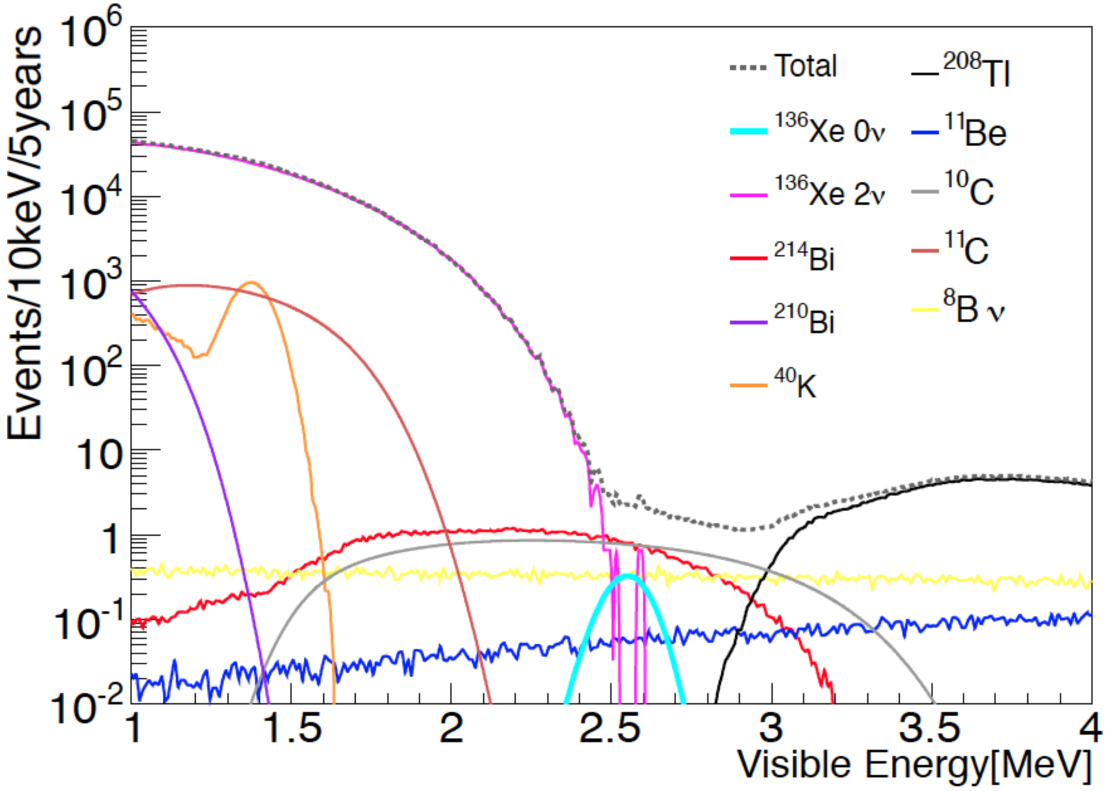
There exists ~800 kg^{136}Xe in the KamLAND site.

Ongoing R & D

- Light collector
- LS replacement
- γ/β discrimination
- **Open KamLAND**
- New photo senser
-
-

KamLAND2-Zen

~2 × 10^{27} years ,$<m_\nu>$ = (16-32) meV for 5 years



- R<1.62m, 439kg in fiducial volume
- mini-balloon (^{238}U, ^{232}Th, ^{40}K) = (3.0×10^{-12}, 3.0×10^{-12}, 1.0×10^{-11})[g/g]
- with tag2 (^{214}Pb/^{214}Bi event)
- ^{10}C 90% tag
- $T_{1/2}(2\nu\beta\beta) = 2.30\times10^{21}$ yr (KamLAND-Zen)

$T_{1/2}(0\nu\beta\beta) = 2\times10^{27}$ yr

- Covers most of inverted hierarchy region

Conclusions

- Discovery of the Majorana nature of the neutrino via neutrinoless double beta decay helps address several critical questions:
  - -> absolute neutrino mass
  - -> neutrino mass mechanism
  - -> matter dominance of the Universe
- KamLAND-Zen measurements to date
  - -> $T_{1/2}$ (^{136}Xe $0\nu2\beta$) > 1.9×10^{25} yr
  - -> $m_{\beta\beta} < (0.16\text{-}0.33)$ eV
- Combined analysis of KamLAND-Zen and EXO-200 excludes the Klapdor-Kleingrothaus claim at 97.5% CL
- Backgrounds have been reduced by > 10x in the current run
- Future phases of KamLAND-Zen and KamLAND2-Zen will allow us to push the limit to the inverted hierarchy region

KamLAND/KamLAND-Zen Collaboration