Broad Overview of Neutrino Physics

International Workshop：

Neutrino Research and Thermal Evolution of the Earth

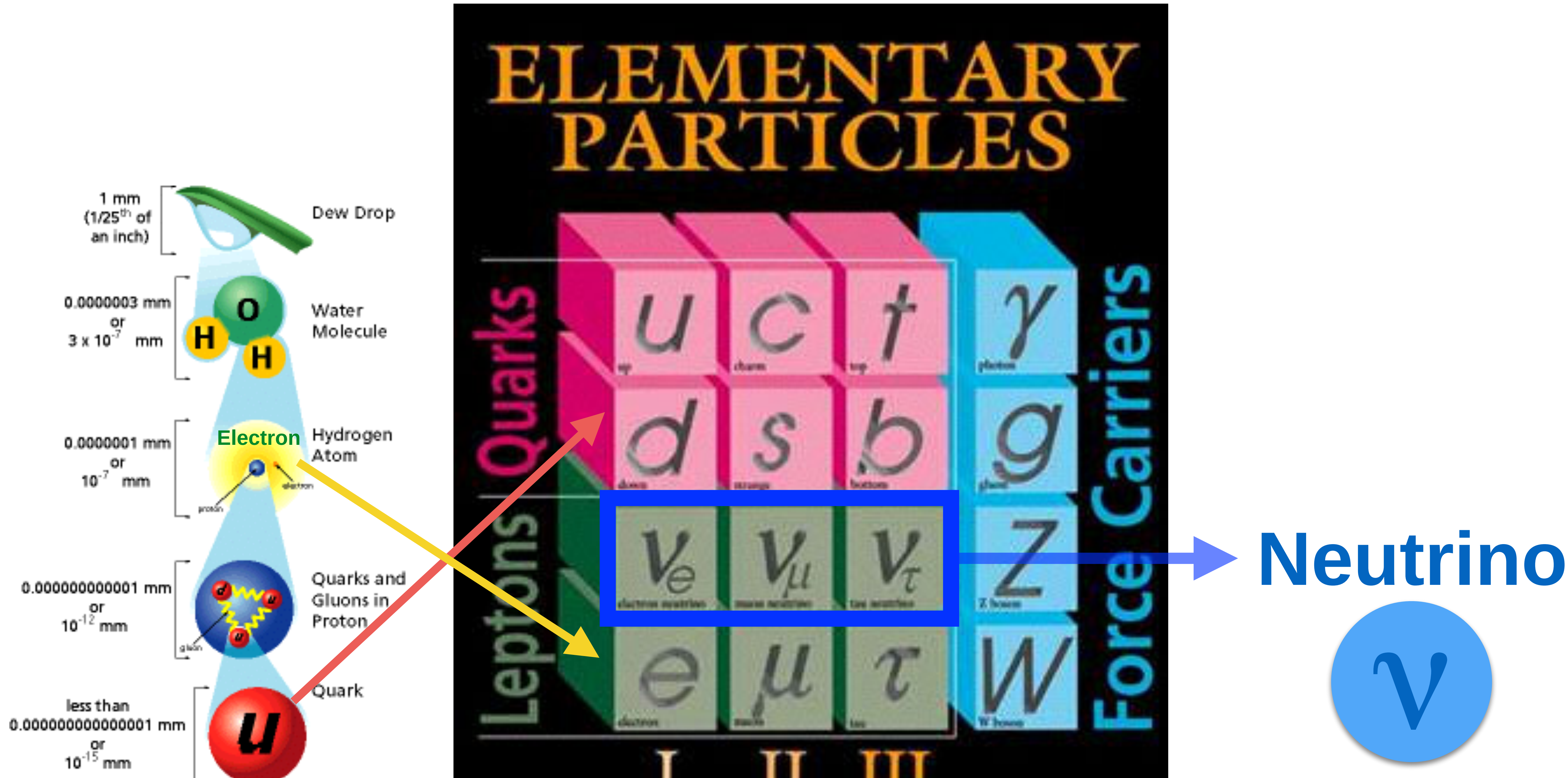
Oct. 20, 2016

Itaru Shimizu (Tohoku Univ.)

Contents

- Introduction to neutrino physics
- Neutrino oscillation
- Double beta decay
- Open questions about neutrino
- Neutrino astrophysics

What is Neutrino?



Fermilab

no electric charge

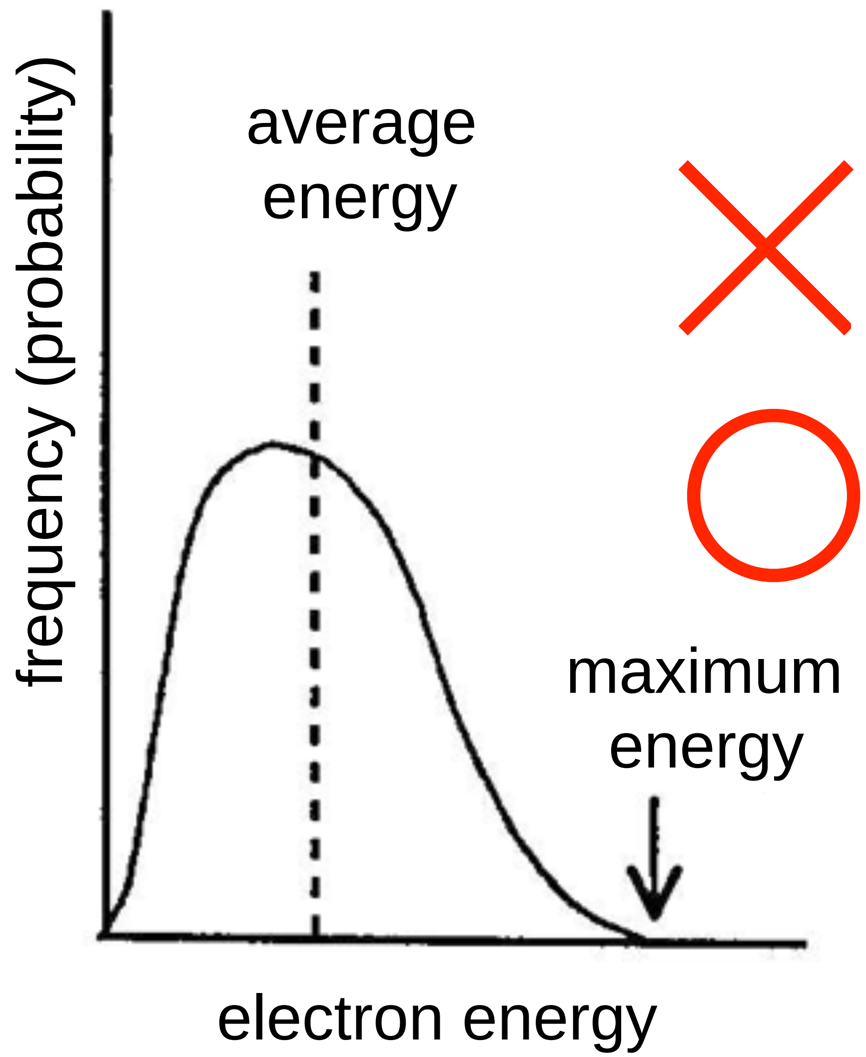
↓

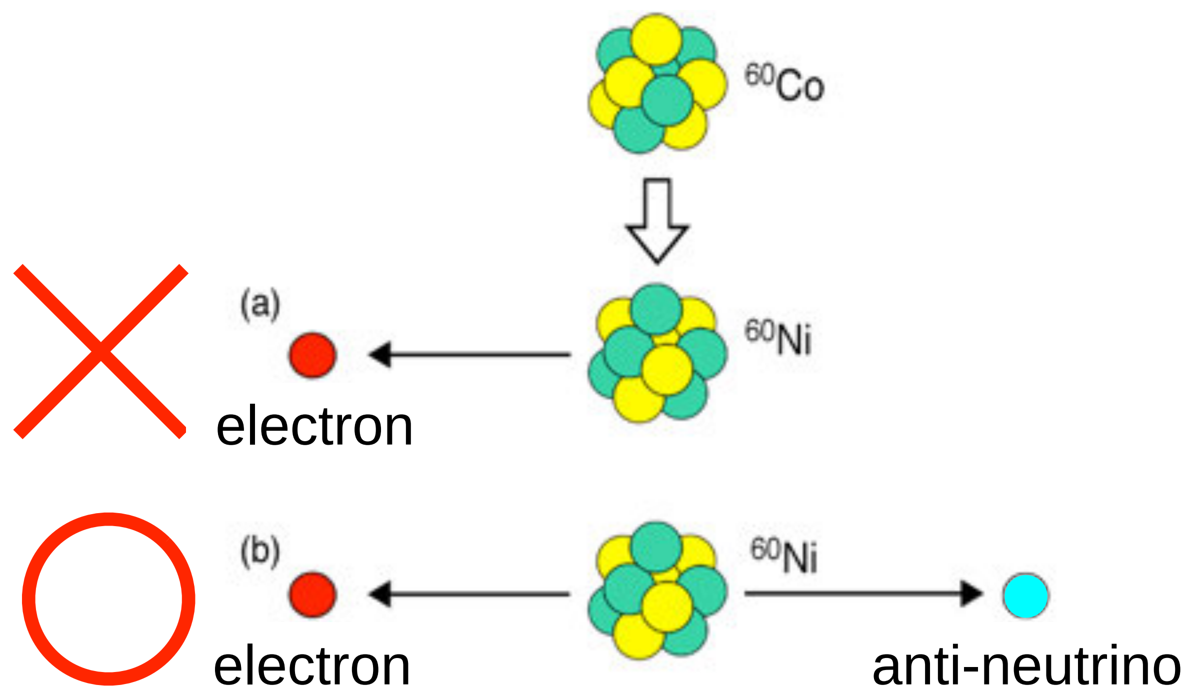
only "weak interaction"

elementary particles = fundamental constituent of matter

Neutrino Hypothesis

Neutrino is light neutral particle suggested by W. Pauli in 1930 to explain the continuous energy spectrum of emitted electron in β-decay





W. Pauli

energy is split between the neutrino and electron

For the case of no neutrino emission, the electron energy becomes constant (maximum)

Neutrinos slip out of the detector because of the weak interaction

Neutrino Detection

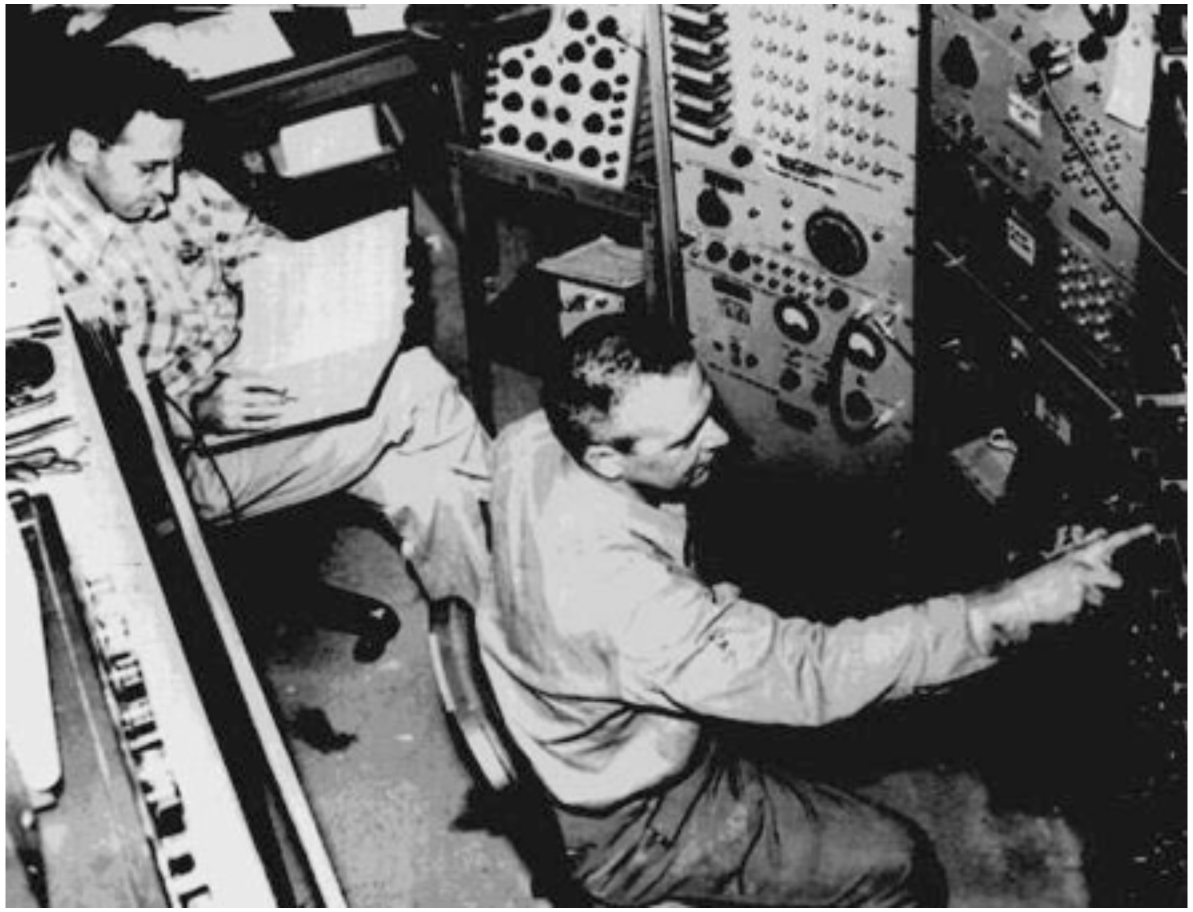
Neutrinos react so seldom with matter (high permeability)

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

need thickness of 20 light-year in water to react

× ~ 1000

In those days, people thought the neutrino detection is experimentally impossible …



Intense production of neutrinos by **nuclear reactor** and development of detection technique

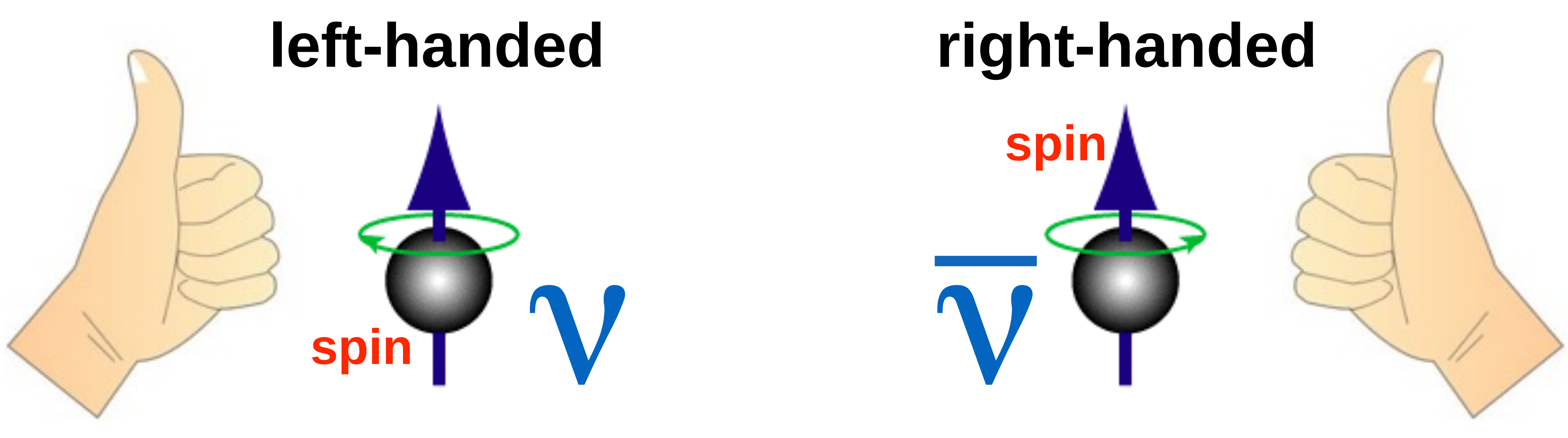
↓

In 1953, neutrinos are detected by Reines and Cowan finally!

Neutrino in Standard Model

- Mass of neutrino is zero
- 3 flavor lepton number (e, ν_e) (μ, ν_μ) (τ, ν_τ) is conserved
- All neutrinos are left-handed, and all anti-neutrinos are right-handed
- Neutrino and anti-neutrino can be distinguished

2 component neutrino model



Neutrino Oscillation

Assuming

1. **Neutrinos have tiny masses (beyond Standard Model)**
2. **Flavor (weak) states are superpositions of mass states**

$$|\nu_\alpha> = \sum_i U_{\alpha i} |\nu_i>$$

flavor — mass

↑ no diagonal unitary matrix

MNS (Maki-Nakagawa-Sakata) Matrix

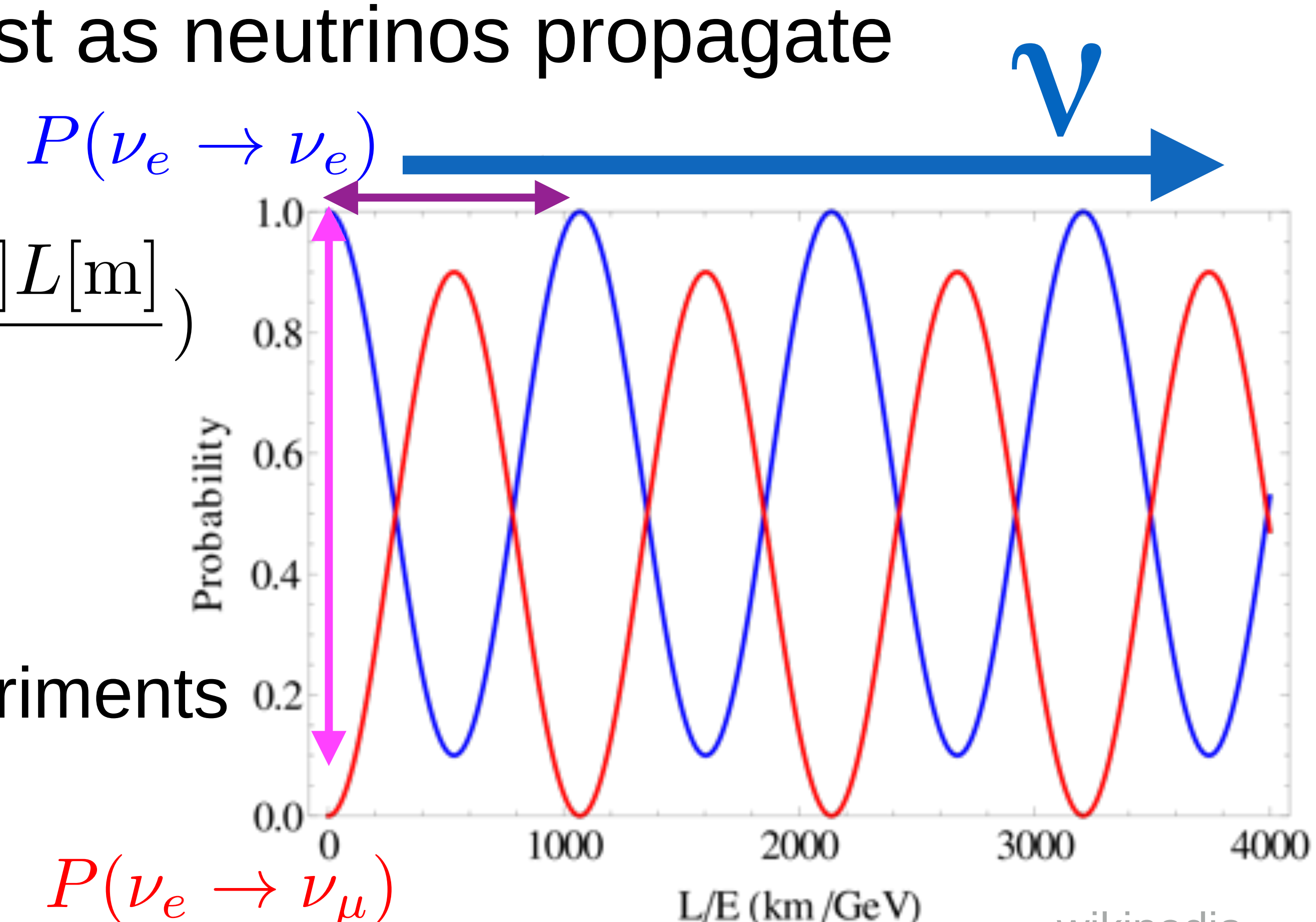
$$U_{MNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

flavor oscillations must exist as neutrinos propagate

2 flavor case

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2[\mathrm{eV}^2]L[\mathrm{m}]}{E[\mathrm{MeV}]}\right)$$

amplitude ($\sin^2 2\theta$) **frequency** (Δm^2)

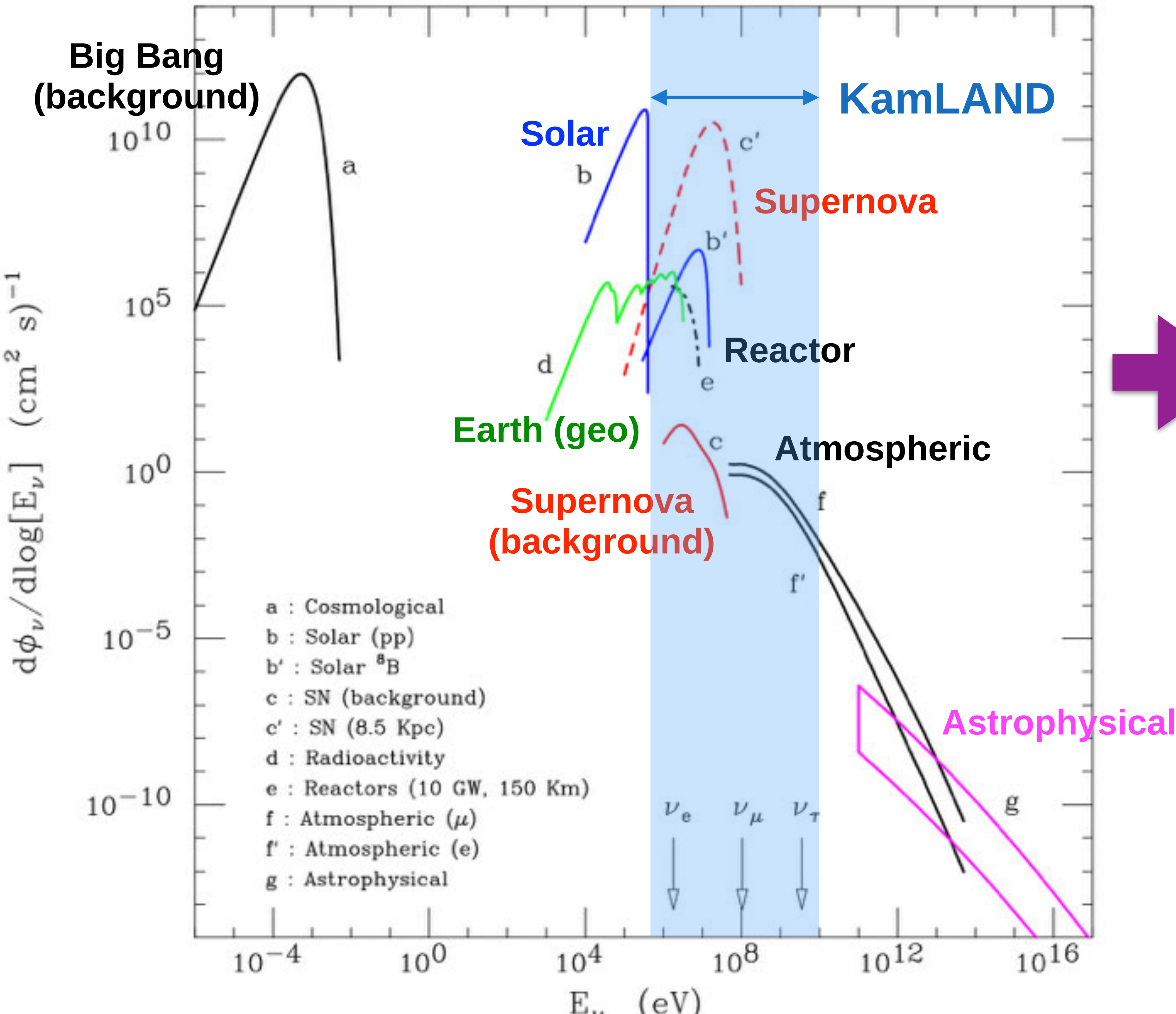


wikipedia

- L / E depends on the condition of experiments
- Disappearance or Appearance

Where are neutrinos coming from?

Neutrino Energy v.s. Flux



P. Lipari, Introduction to Neutrino Physics (2002)

neutrino flux & neutrino energy

↓

~20 orders of magnitude!

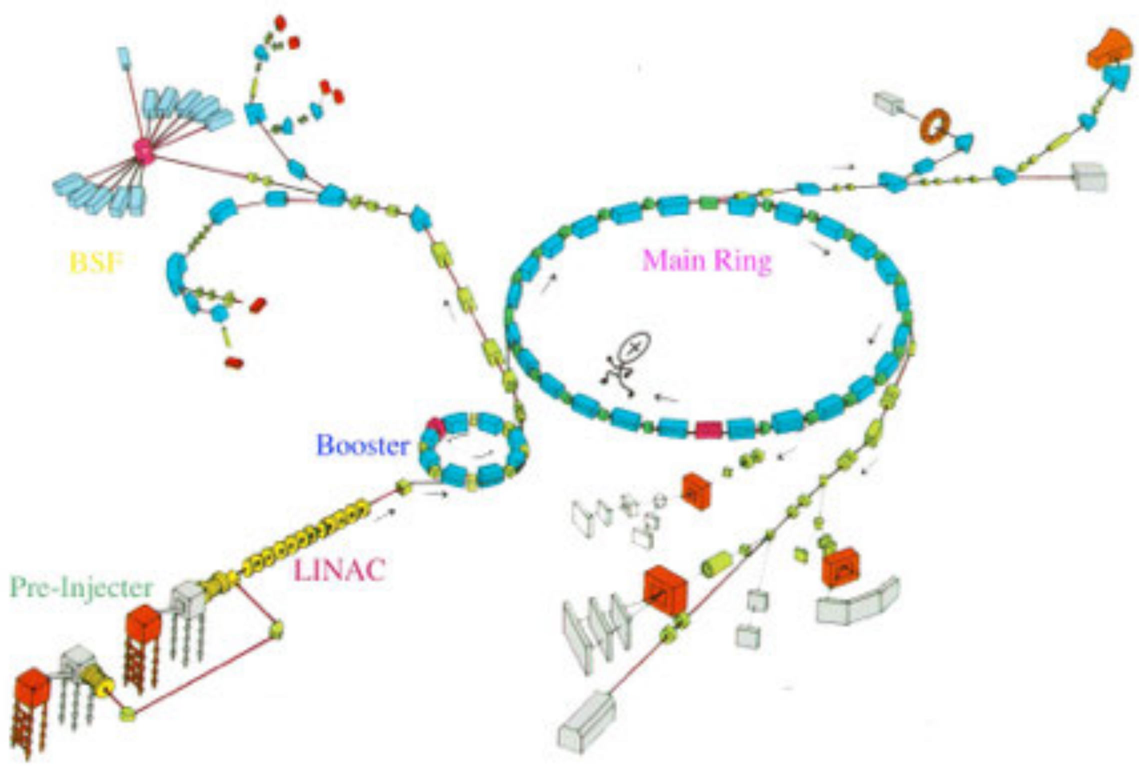
Natural neutrinos

+ **Man-made** Reactor neutrinos

+ **Man-made** Accelerator neutrinos

Man-made Neutrino

Accelerator



$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

etc.

expensive!

Reactor

$$^{235}\mathrm{U} + \mathrm{n} \rightarrow \mathrm{X} + \mathrm{Y} + 6.1\mathrm{e}^- + 6.1\bar{\nu}_\mathrm{e} + 2.5\mathrm{n} + 202\,\mathrm{MeV}$$

also $^{239}\mathrm{Pu},\ ^{238}\mathrm{U},\ ^{241}\mathrm{Pu}$

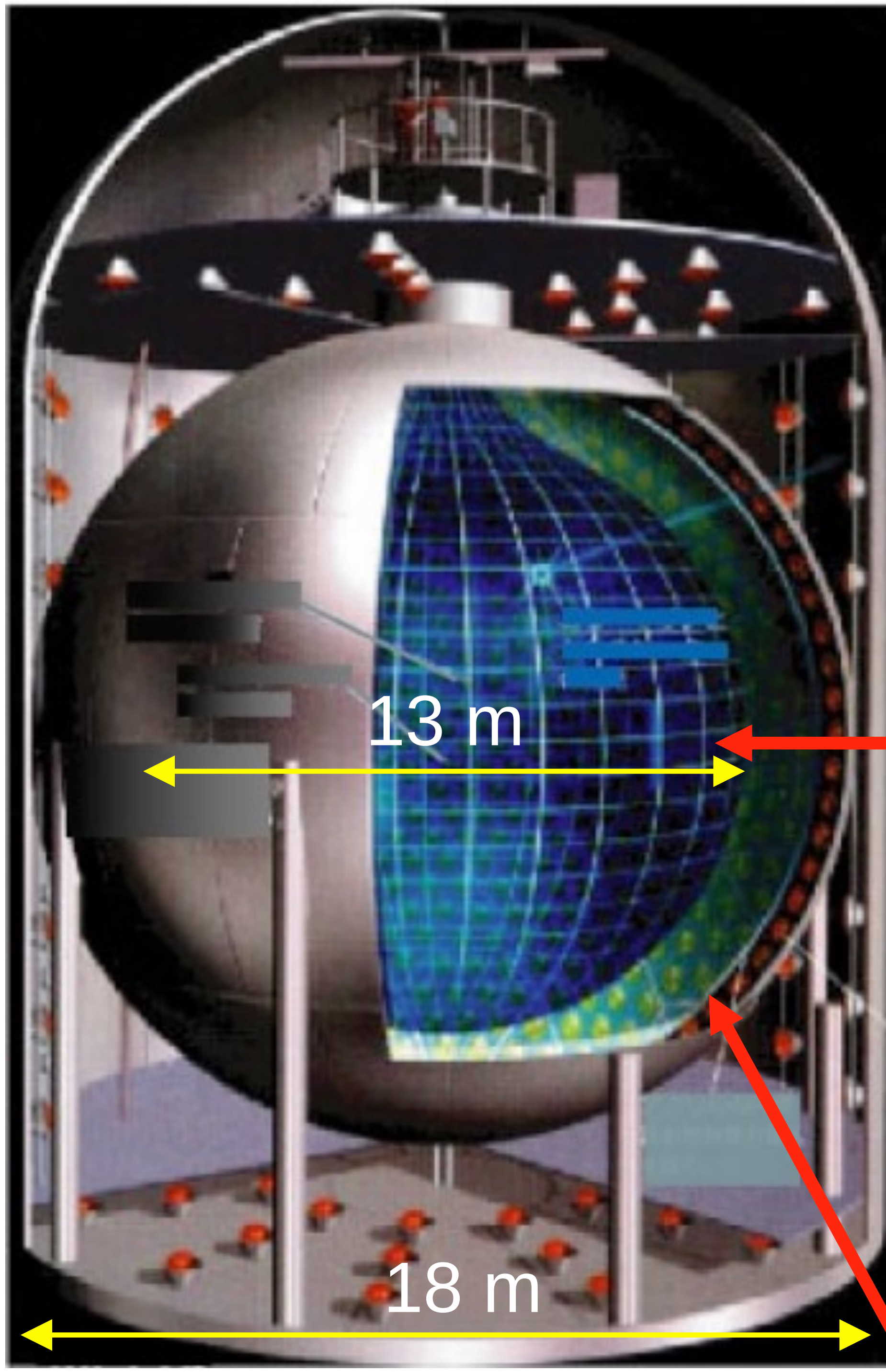
no charge

electron anti-neutrinos are emitted

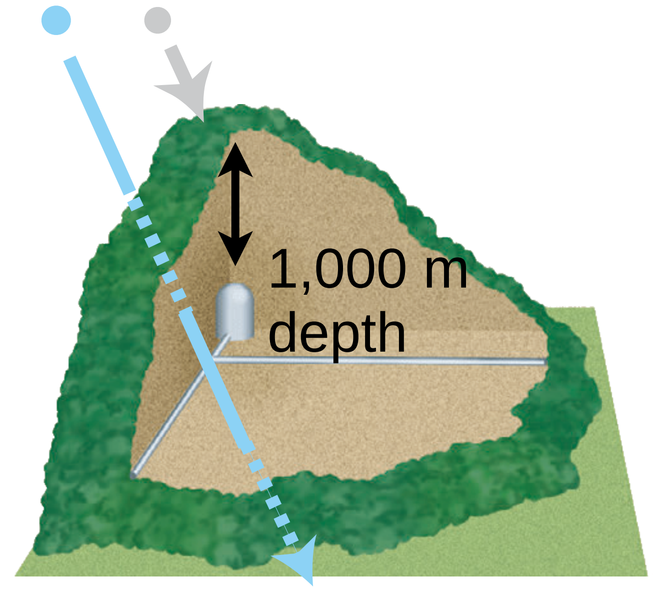
Well-controlled man-made sources are more appropriate for a precise investigation of the neutrino property

KamLAND

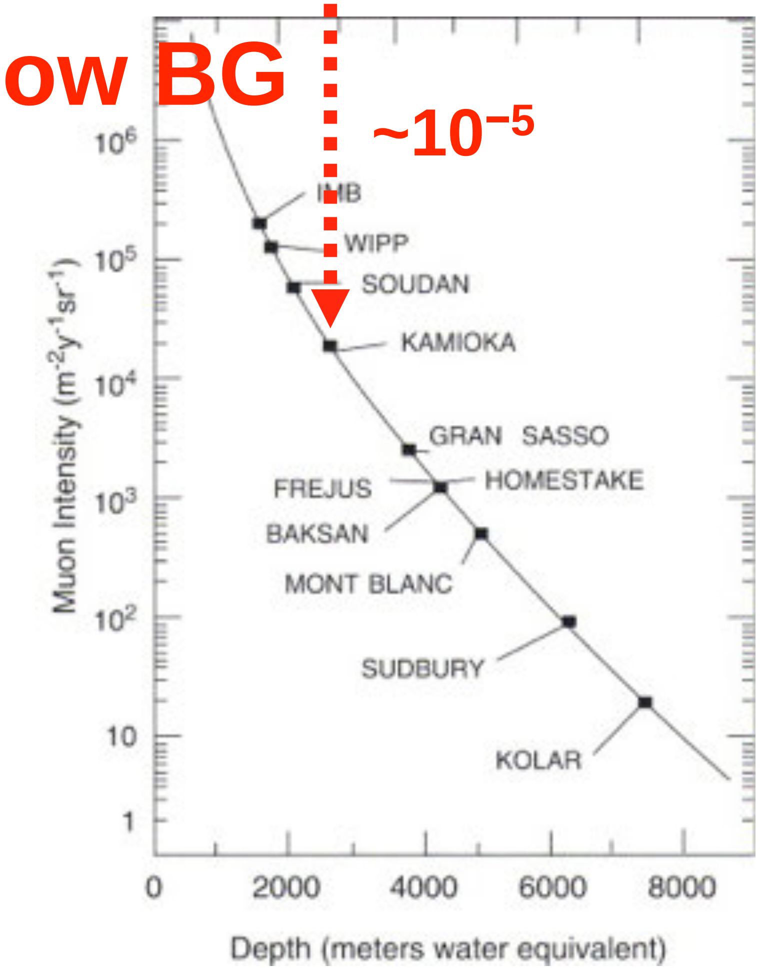
operated since 2002



neutrino , cosmic-ray



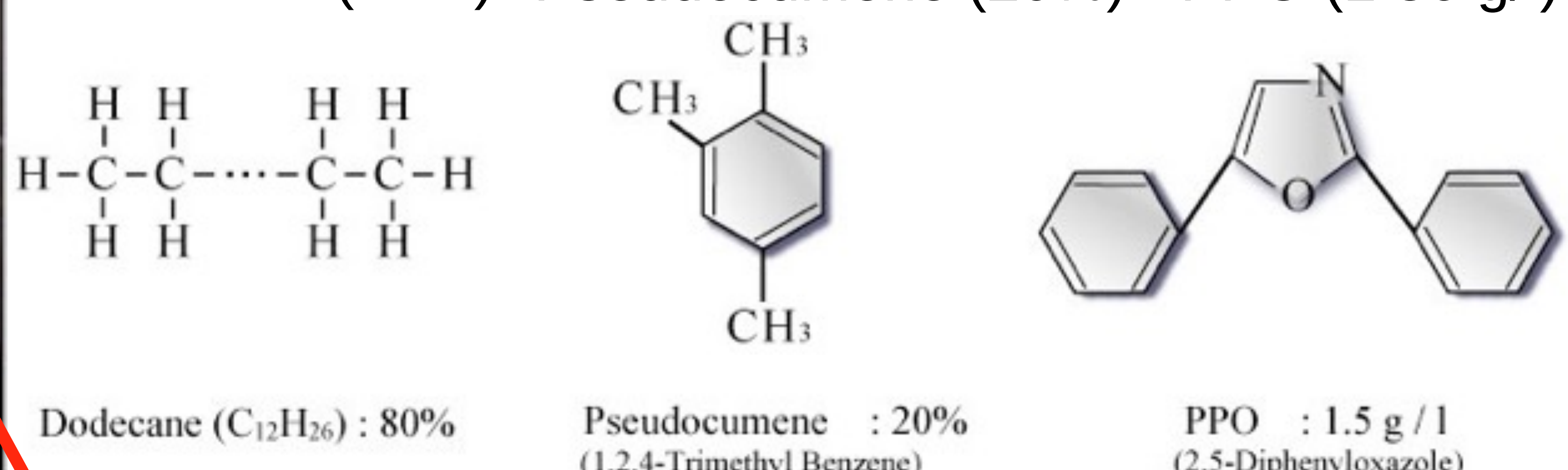
low BG



large volume

1,000 ton Liquid Scintillator

Dodecane (80%) Pseudocumene (20%) PPO (1.36 g/l)



~500 p.e./MeV

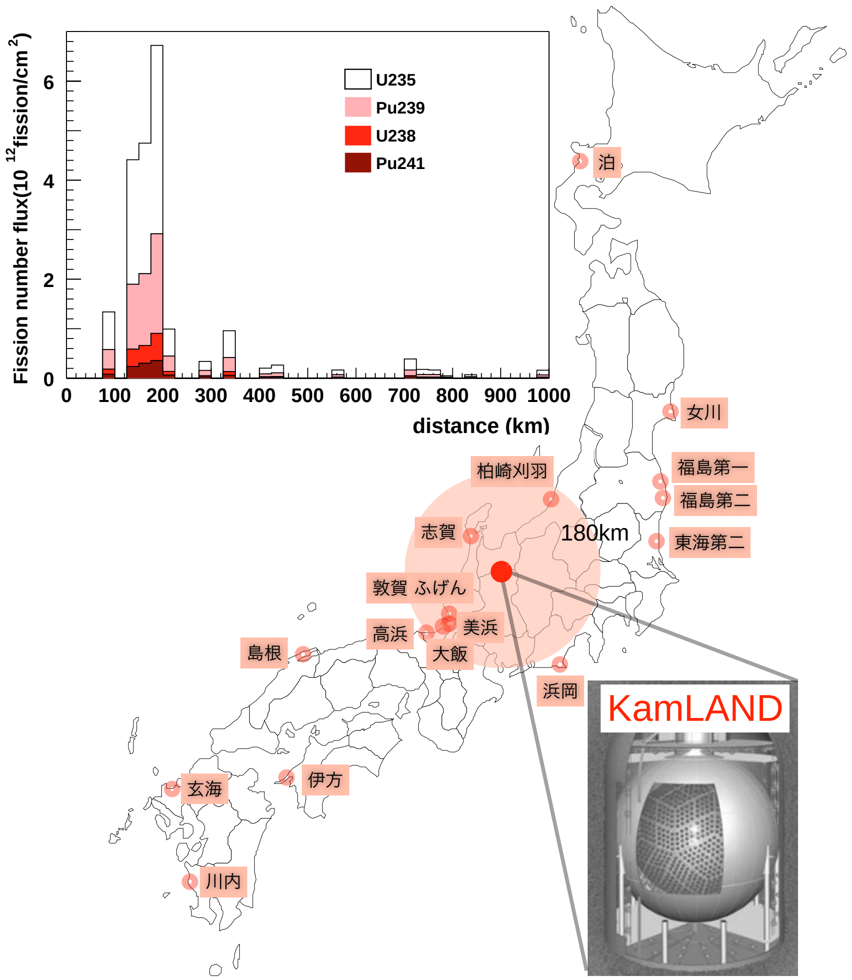
high light yield

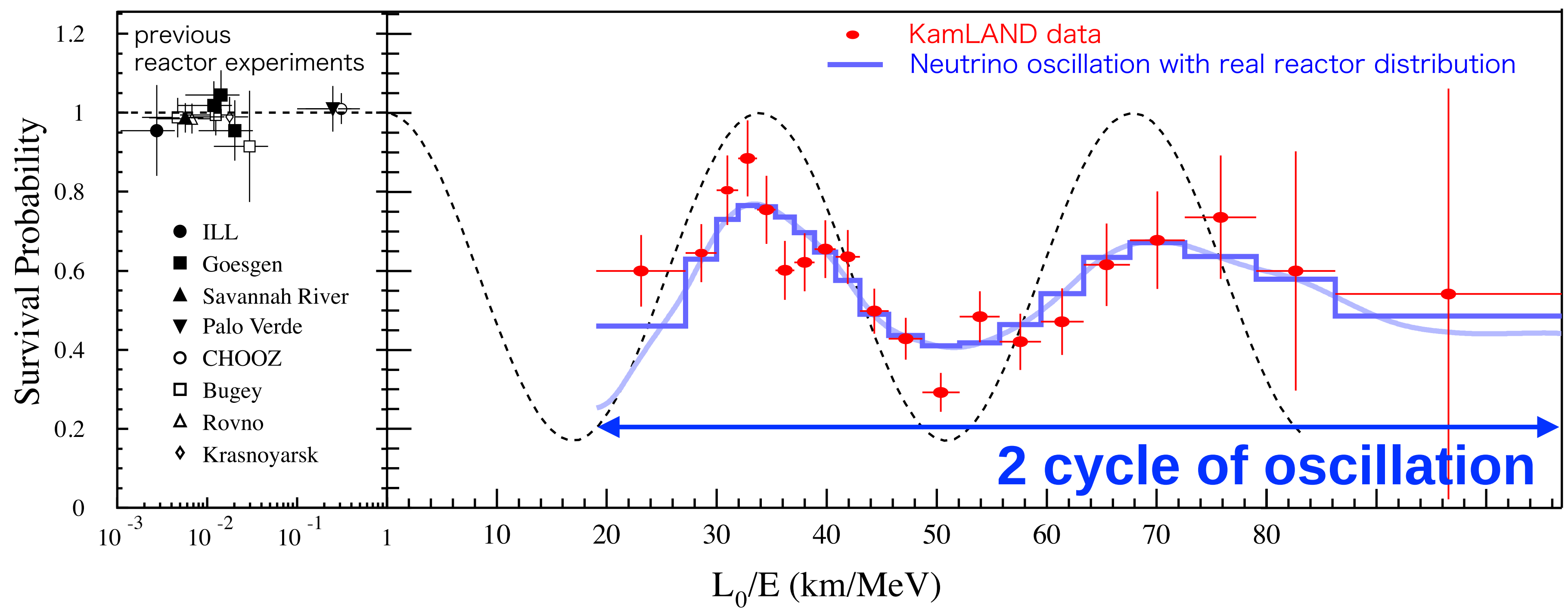
1,325 17 inch + 554 20 inch PMTs

Reactor Neutrino

2 flavor neutrino oscillation (disappearance)

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta \sin^2(\frac{1.27\Delta m^2[\mathrm{eV}^2] l[m]}{E[\mathrm{MeV}]})$$





strong evidence of neutrino oscillation

If mass of neutrino is zero, this quantum interference is not allowed

Neutrino oscillation experiments require 3 different mass states

Neutrino has nonzero mass

Neutrino Oscillation Experiments

MNS Matrix

$$U_{MNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

3 flavor oscillation

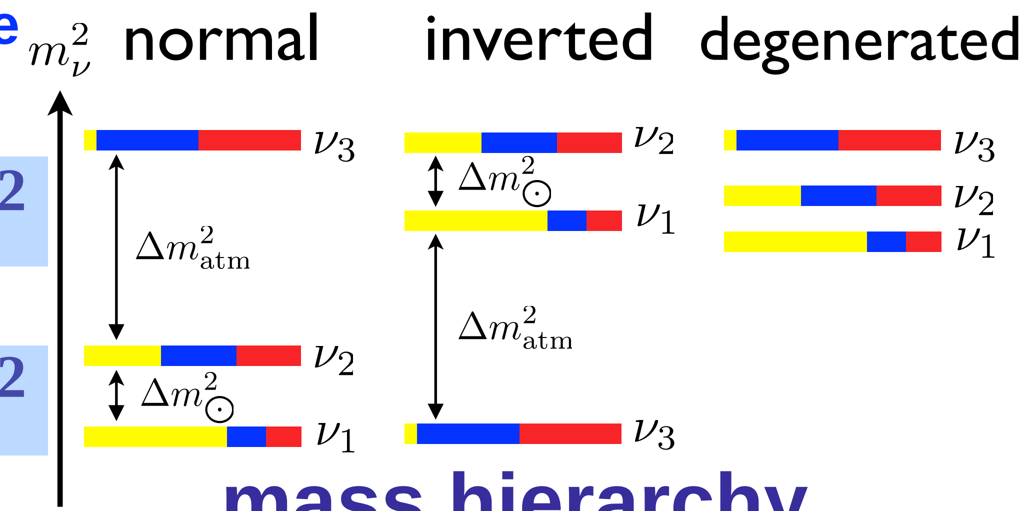
mixing θ_{23} θ_{13} **CP phase** θ_{12}

not determined

relative mass

Δm_{32}^2

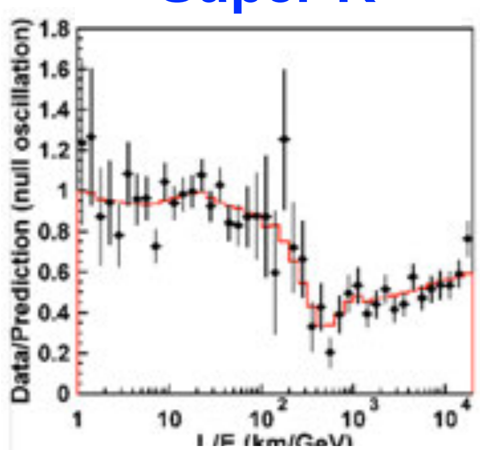
Δm_{21}^2



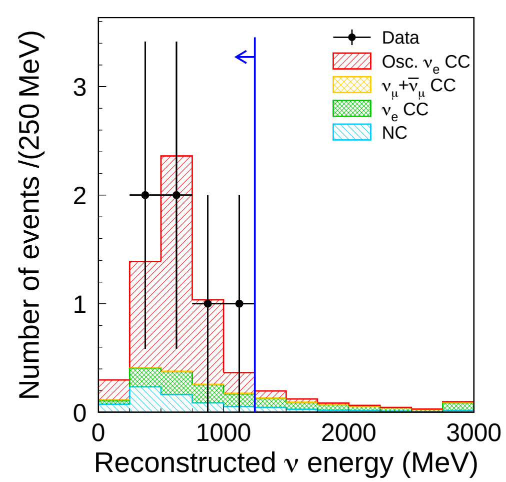
mass hierarchy

not determined

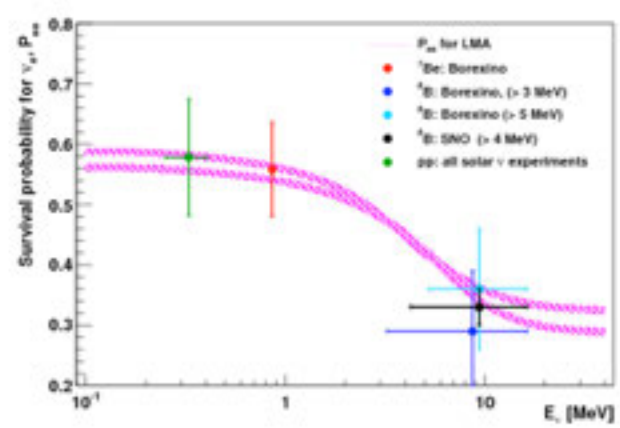
Super-K



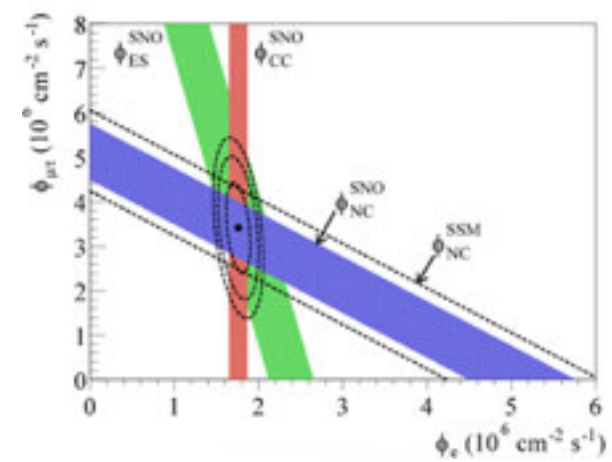
T2K



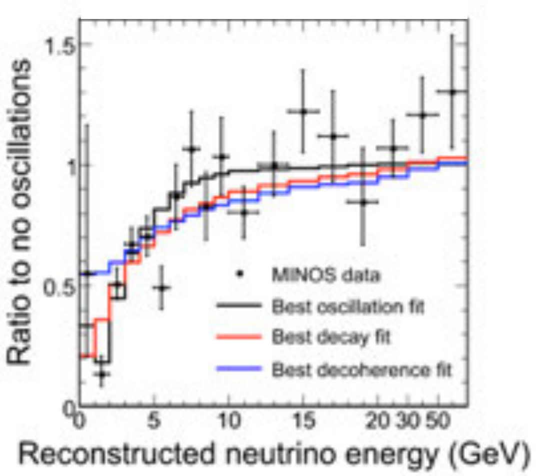
Borexino



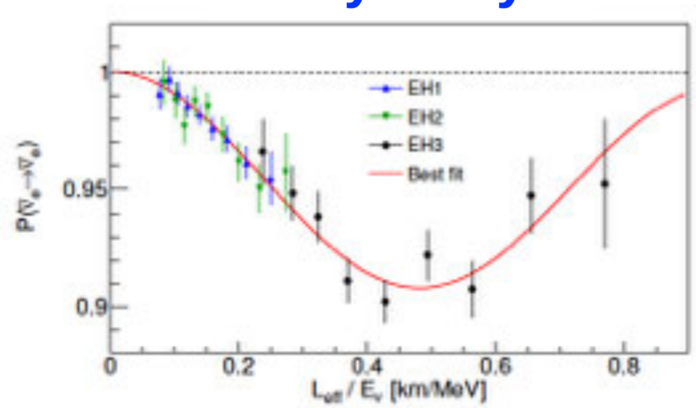
SNO



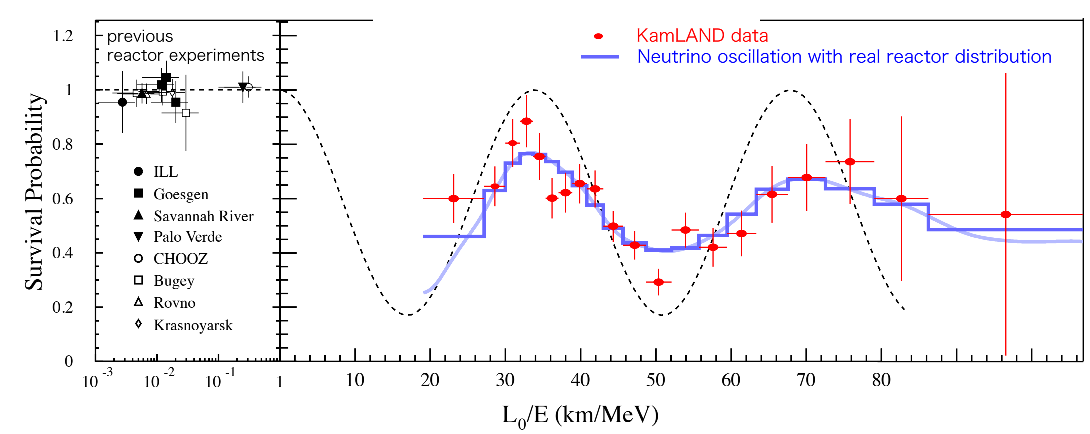
MINOS



Daya-Bey



KamLAND



Neutrino in Standard Model

- Mass of neutrino is zero ✕
- 3 flavor lepton number (e, ν_e) (μ, ν_μ) (τ, ν_τ) is conserved ✕
- All neutrinos are left-handed, and all anti-neutrinos are right-handed ✕
- Neutrino and anti-neutrino can be distinguished ?

chiral partner must exist for neutrino and anti-neutrino

Dirac neutrino — ~~2~~ 4 **component neutrino model**

weak interaction	weak interaction	no weak interaction	no weak interaction
left-handed	**right-handed**	**left-handed**	**right-handed**

Neutrino in Standard Model

- Mass of neutrino is zero ✗
- 3 flavor lepton number (e, ν_e) (μ, ν_μ) (τ, ν_τ) is conserved ✗
- All neutrinos are left-handed, and all anti-neutrinos are right-handed ✗
- Neutrino and anti-neutrino can be distinguished ?

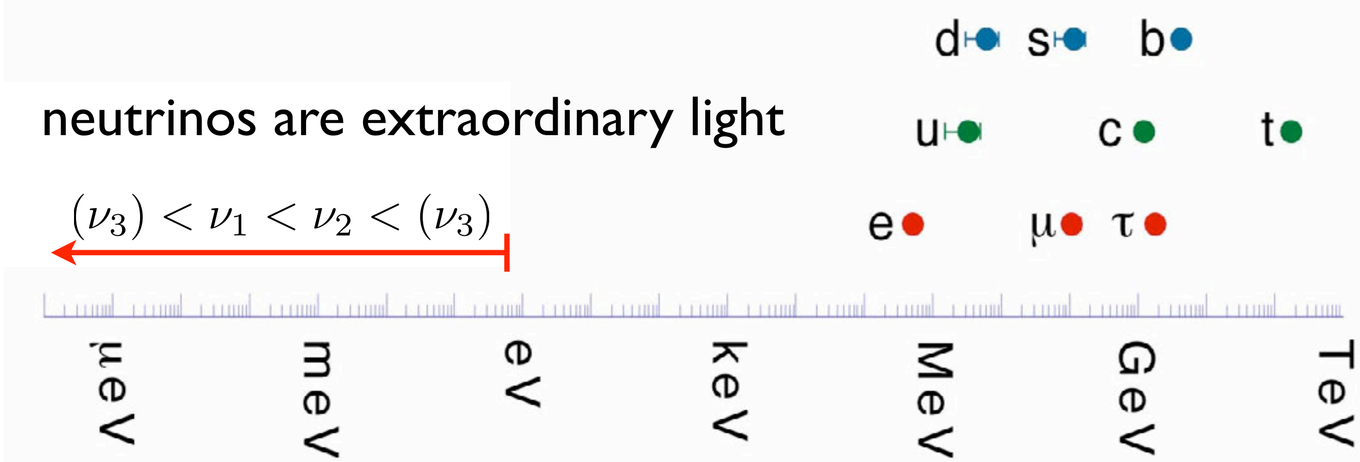
Majorana neutrino ~~2~~ 4 **component neutrino model**

chiral partner must exist for neutrino and anti-neutrino

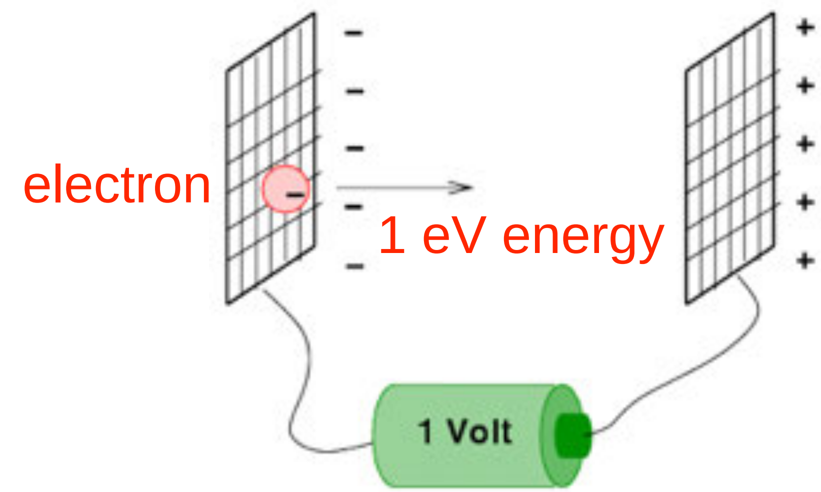
weak interaction	weak interaction	no weak interaction	no weak interaction
left-handed	**right-handed**	**left-handed**	**right-handed**

Light Neutrino Mass

Particle mass



mass = energy



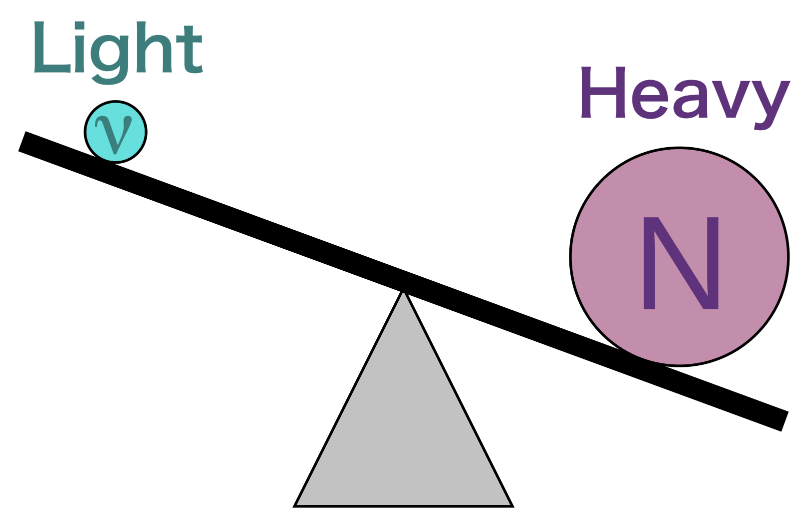
Seesaw mechanism

Mass of existing light neutrino

$$M_\nu = \frac{M_D^2}{M_N}$$

Masses of quarks and charged leptons

Mass of heavy neutrino



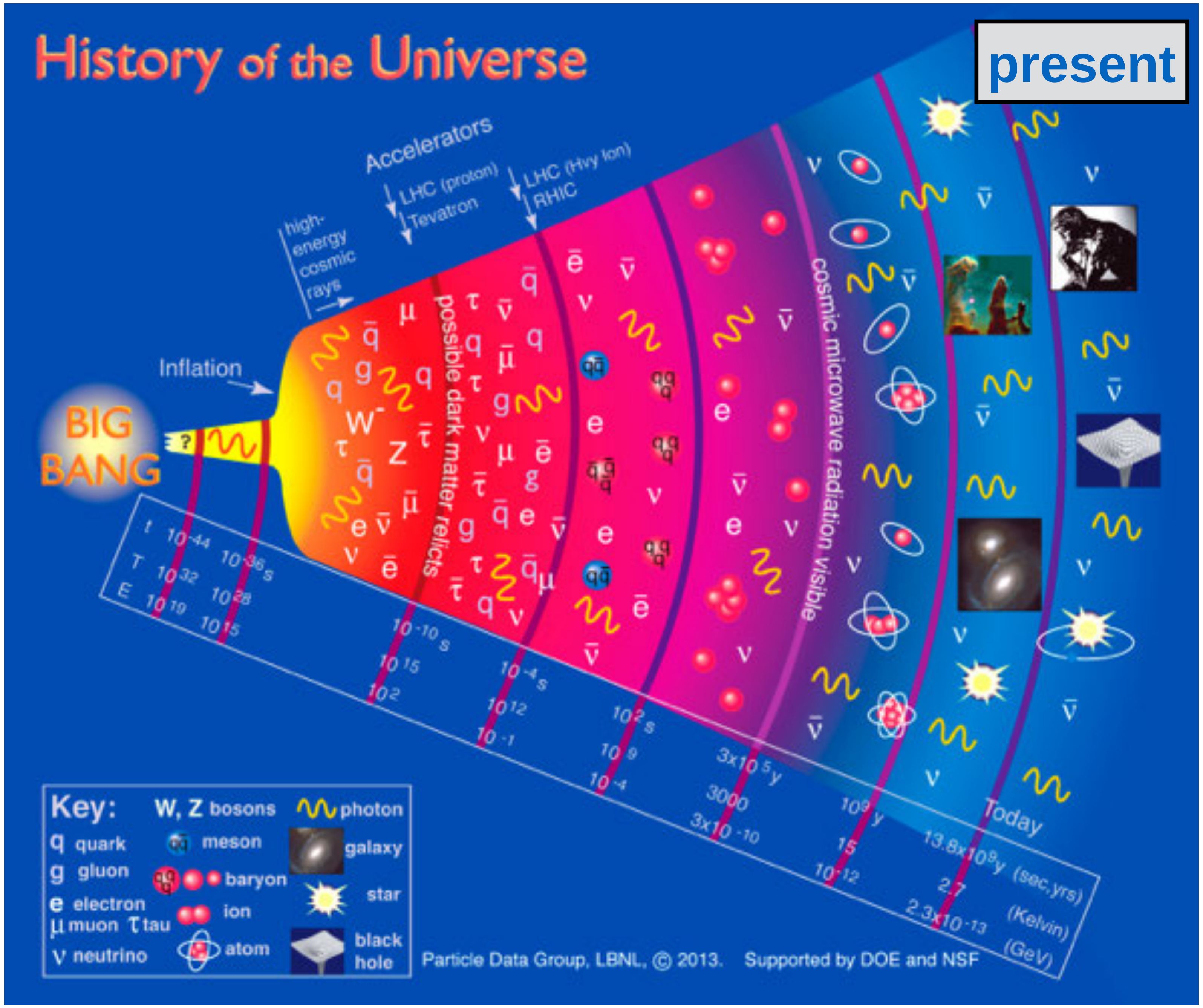
The mass of heavy neutrino can be as heavy as 10^{23} eV!

(10^{10} times of energy attained by world's largest accelerator)

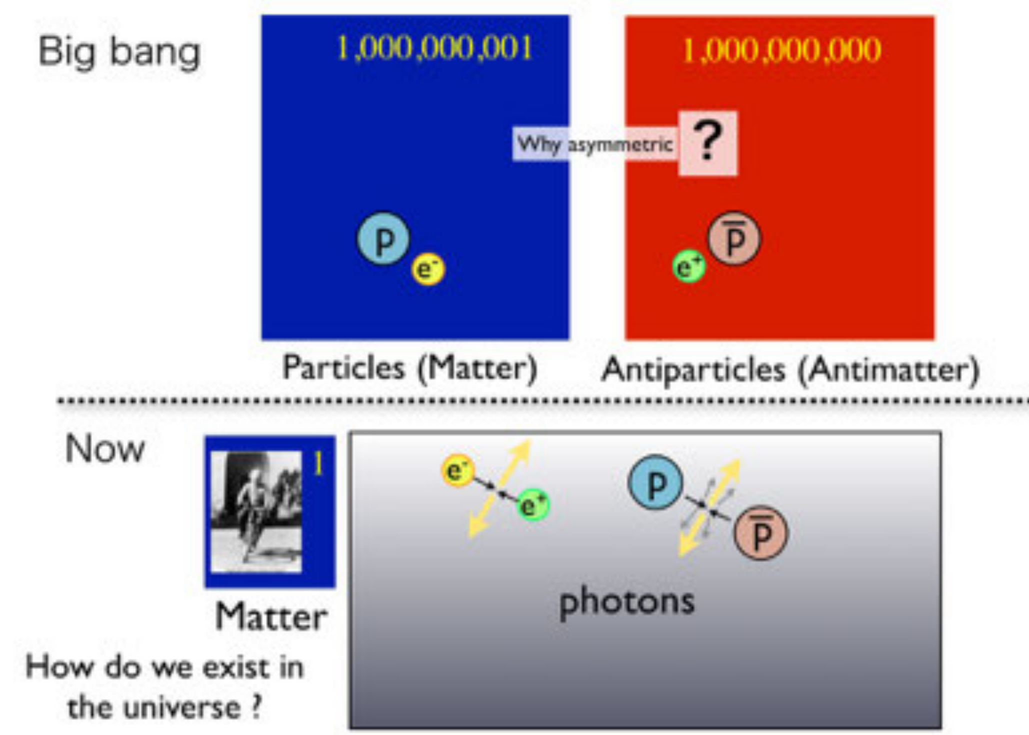
Heavy neutrino (just below GUT scale) naturally explains

"finite but light neutrino mass"

Matter Dominated Universe



- significant **asymmetry** between matter and anti-matter



- **neutrinos** and photons are the most abundant particle

neutrinos / nucleon ~ 10^9

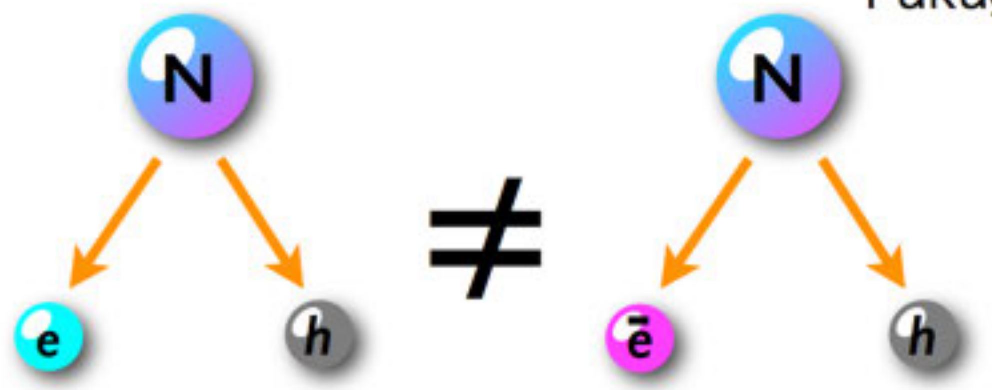
Neutrinos may play a key role to explain matter/anti-matter asymmetry

Matter Production

<u>Leptogenesis theory</u>

Fukugita, Yanagida,'86

violation of B−L



CP-violating decay

(sphaleron) ⋯⋯→ $\frac{n_B}{s}$(observed) = $(0.88 \pm 0.02) \times 10^{-10}$

Three Sakharov conditions

- Violation of B–L. Guaranteed if neutrinos are Majorana particles.
- C and CP violation. Guaranteed if the neutrino Yukawa couplings contain physical phases.
- Departure from thermal equilibrium. Guaranteed, due to the expansion of the Universe.

A. Ibarra, Leptogenesis, INSS 2012

CP violating decay of heavy neutrino explains

"matter dominance in the universe"

Neutrinoless Double-Beta Decay

Nucleus ββ-decay emitting two electrons

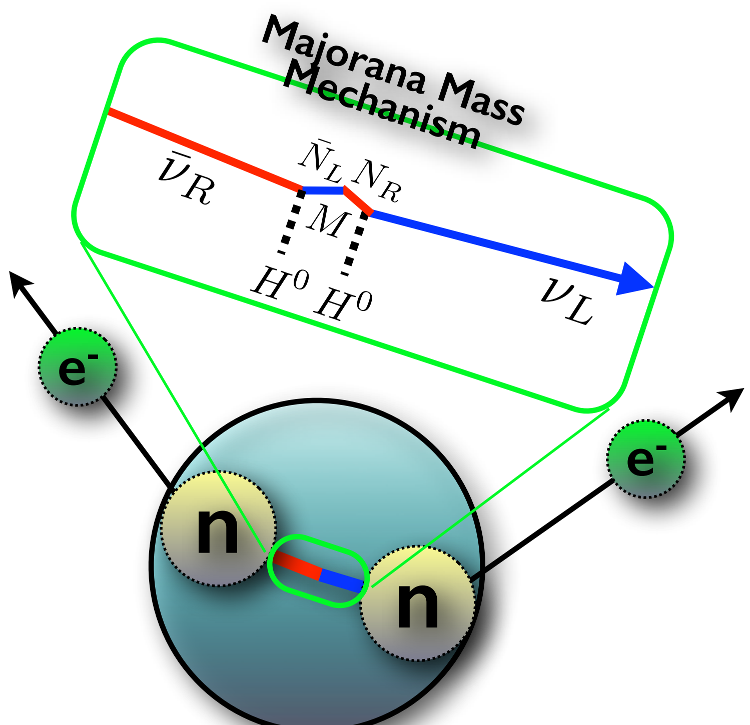
$$(Z, A) \rightarrow (Z+2, A) + 2e^-$$

$\Delta L = 2$

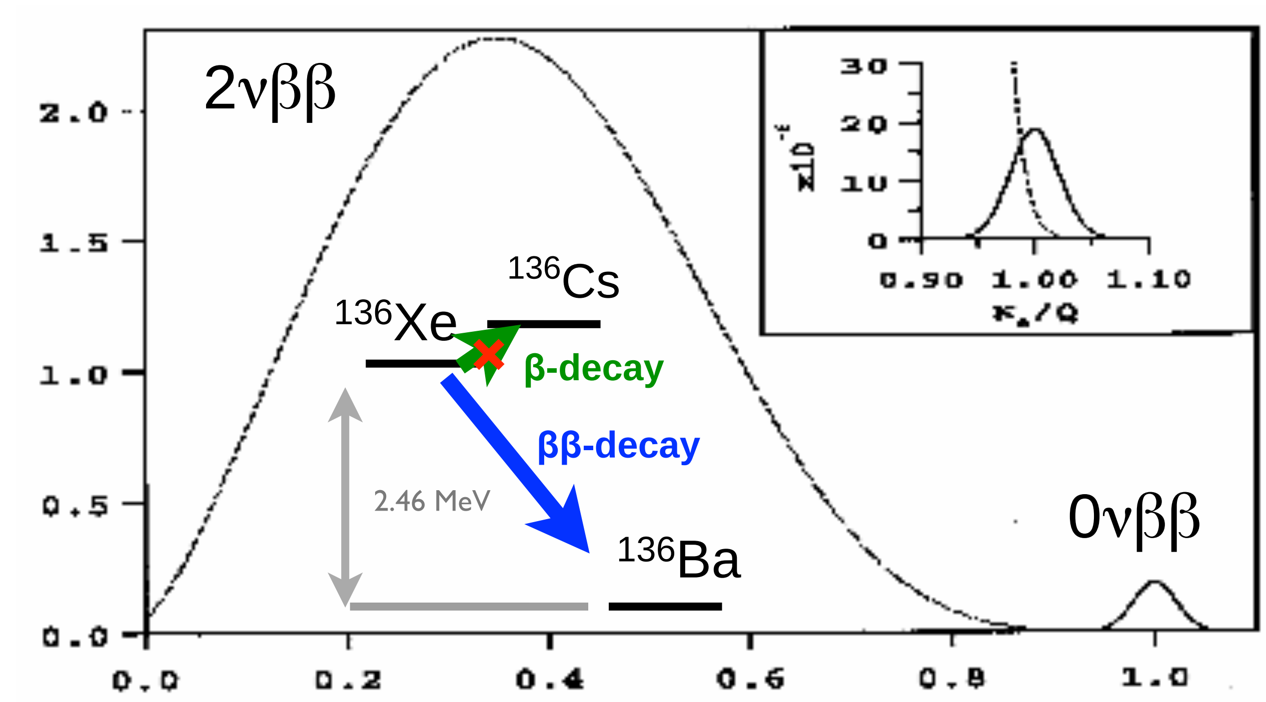
lepton number violation

0νββ

neutrinoless double beta-decay



$$\nu = \bar{\nu}$$



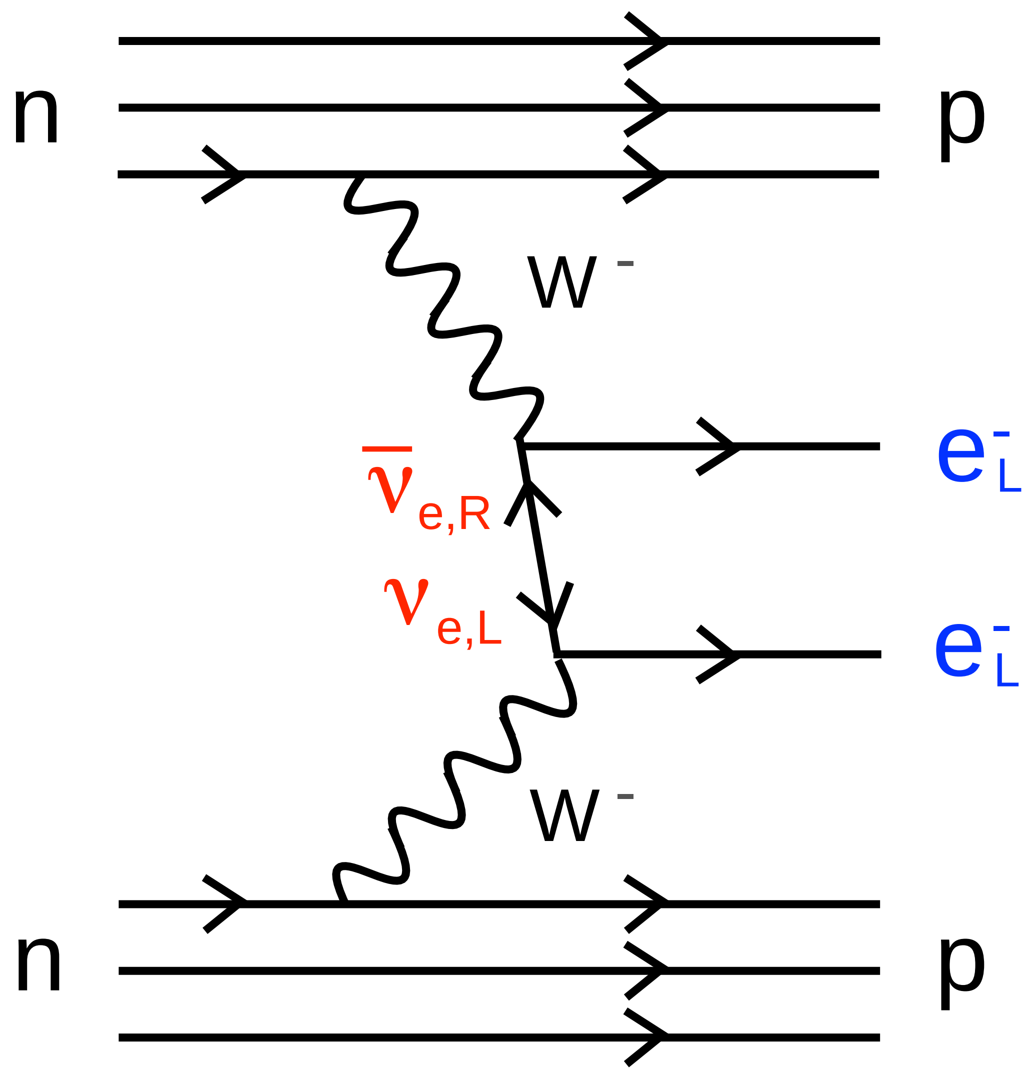
sum energy for two electrons / Q

Require the neutrino **Majorana nature**

- Heavy neutrino naturally explains **“finite but light neutrino mass”**
- CP violating decay of heavy neutrino explains **“matter dominance in the universe”** (Leptogenesis theory)

Light Majorana Neutrino Exchange

mass mechanism



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

effective neutrino mass

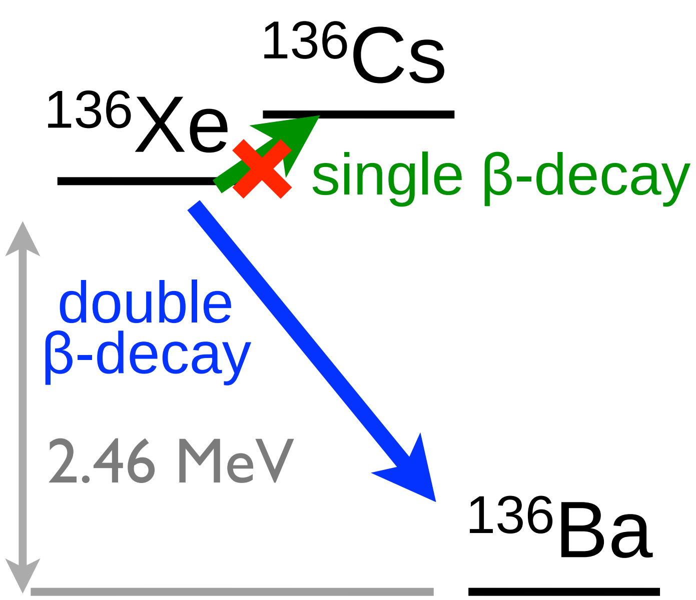
Possible contributions also from
Majoron, SUSY, right-handed current, ...

<u>Effective neutrino mass <$m_{\beta\beta}$></u>

$$\langle m_{\beta\beta} \rangle = \left| |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_1} m_2 + |U_{e3}|^2 e^{i\alpha_1} m_3 \right|$$

- Unknown parameters : α_1, α_2, m_{min}
- Mass hierarchy is not determined
- Cancellations due to CP phases (α_1, α_2)

How to measure <$m_{\beta\beta}$>?

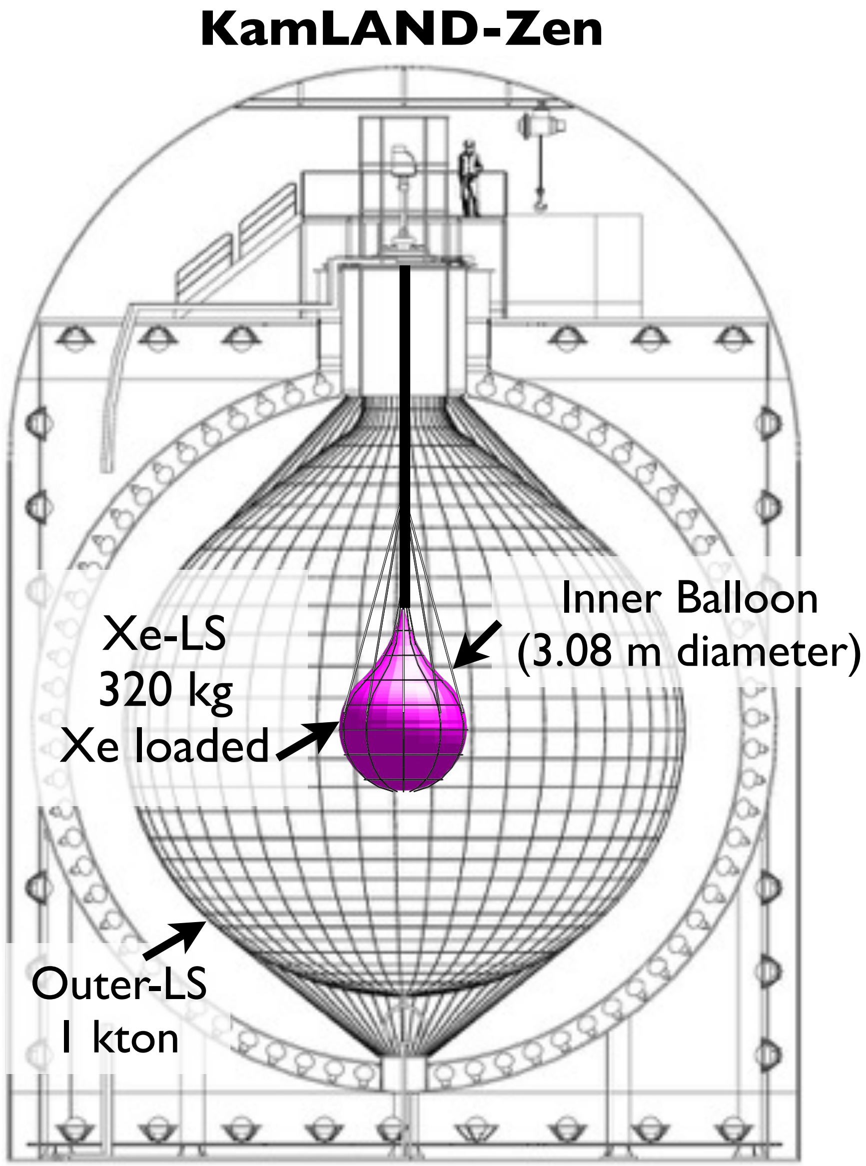


determine the decay rate using large number of ββ-decay nuclei

KamLAND-Zen

Kamioka Liquid Scintillator Anti-Neutrino Detector

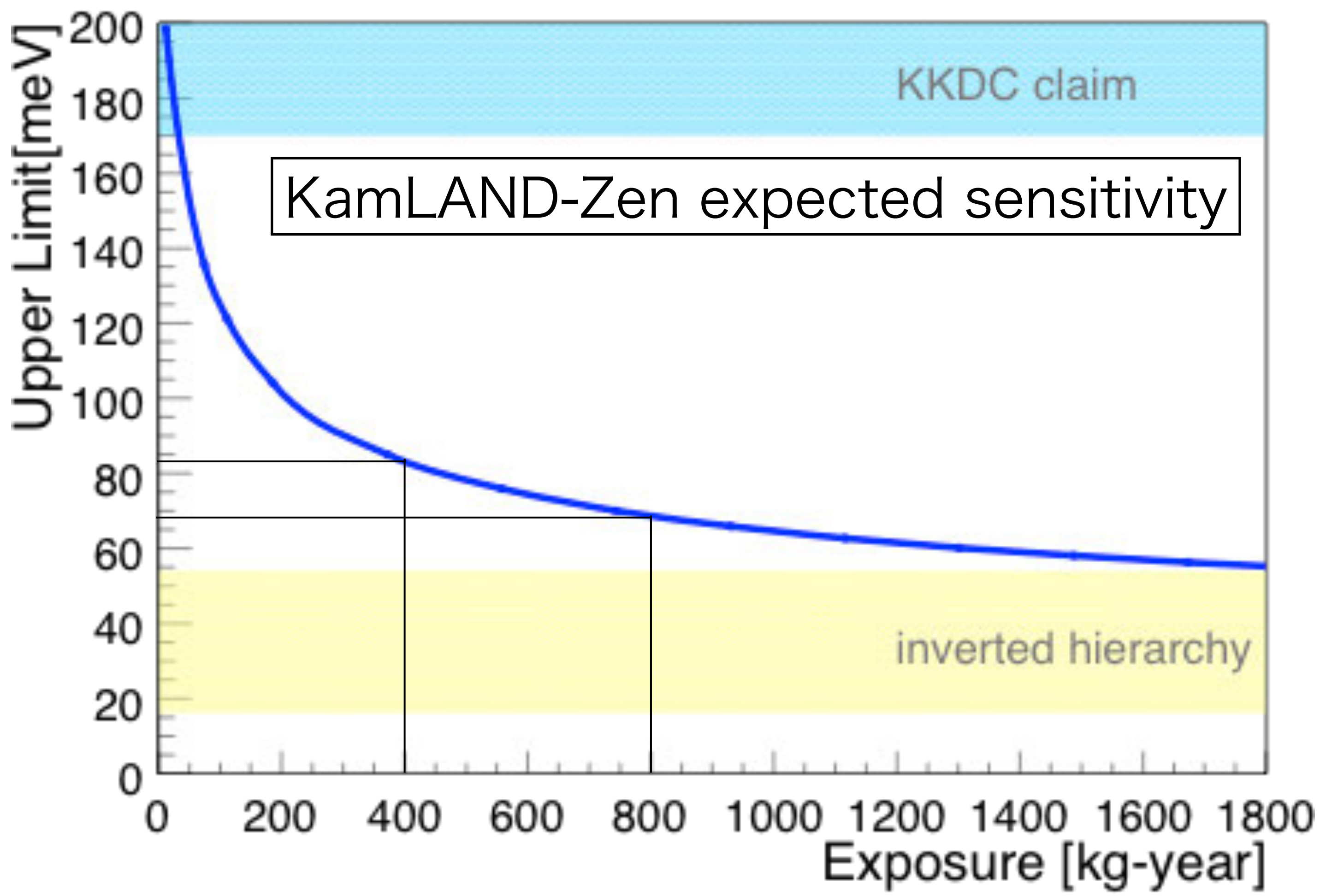
Zero Neutrino Double Beta



Advantage of KamLAND

- running detector : start quickly with relatively low cost
- big and pure : no BG from external gamma-rays
- purification of LS, replacement of mini-balloon are possible

⟶ **high scalability** (a few ton of Xe)



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

σ_E(2.5MeV) = 4%

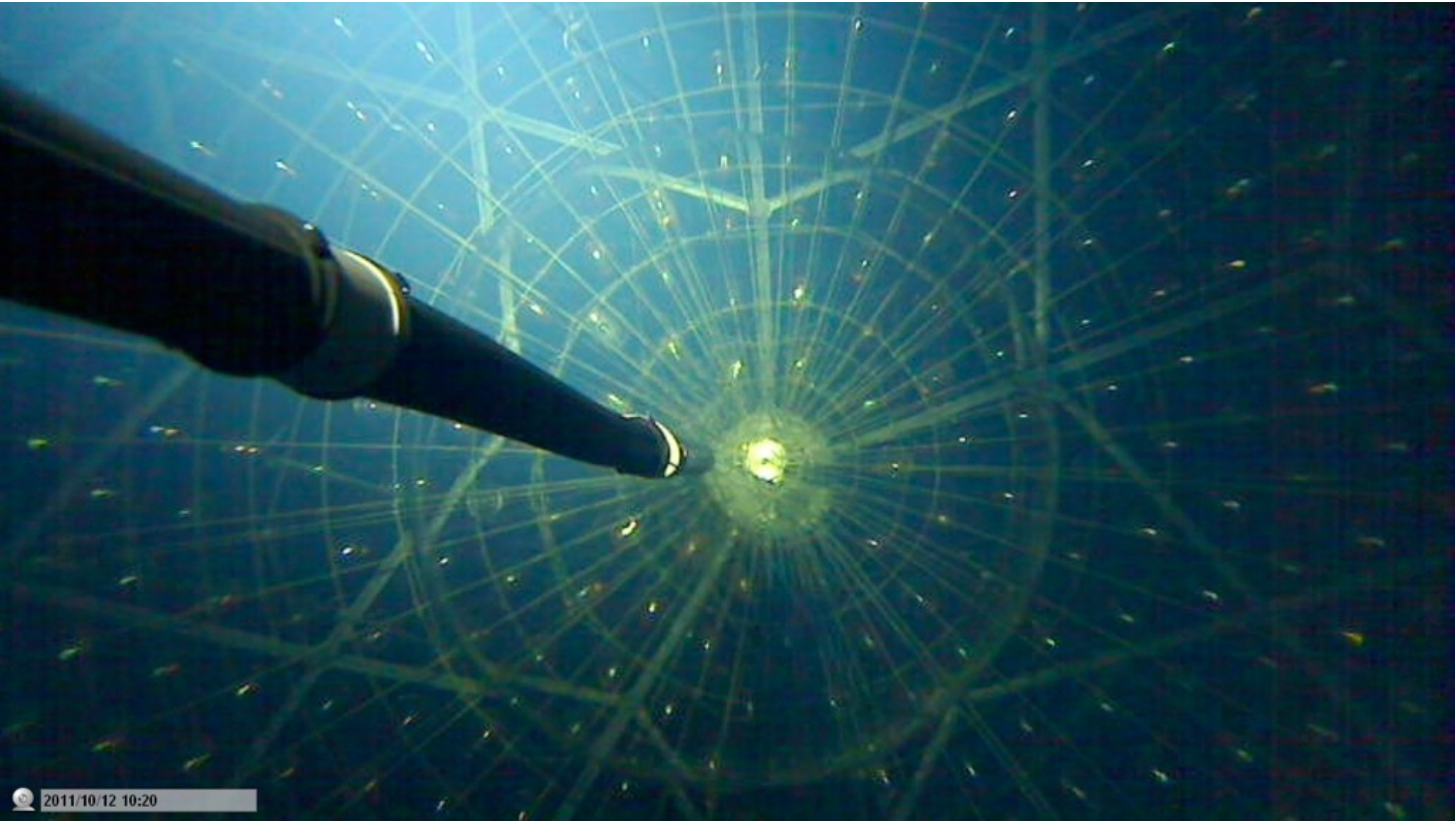
target $\langle m_{\beta\beta} \rangle$ ~ 60 meV / 5 year

Nylon Film with Low Radioactivities

Specially made 25 μm nylon film
for low radioactivities in U/Th/K

<u>effect of ultrasonic cleaning</u>

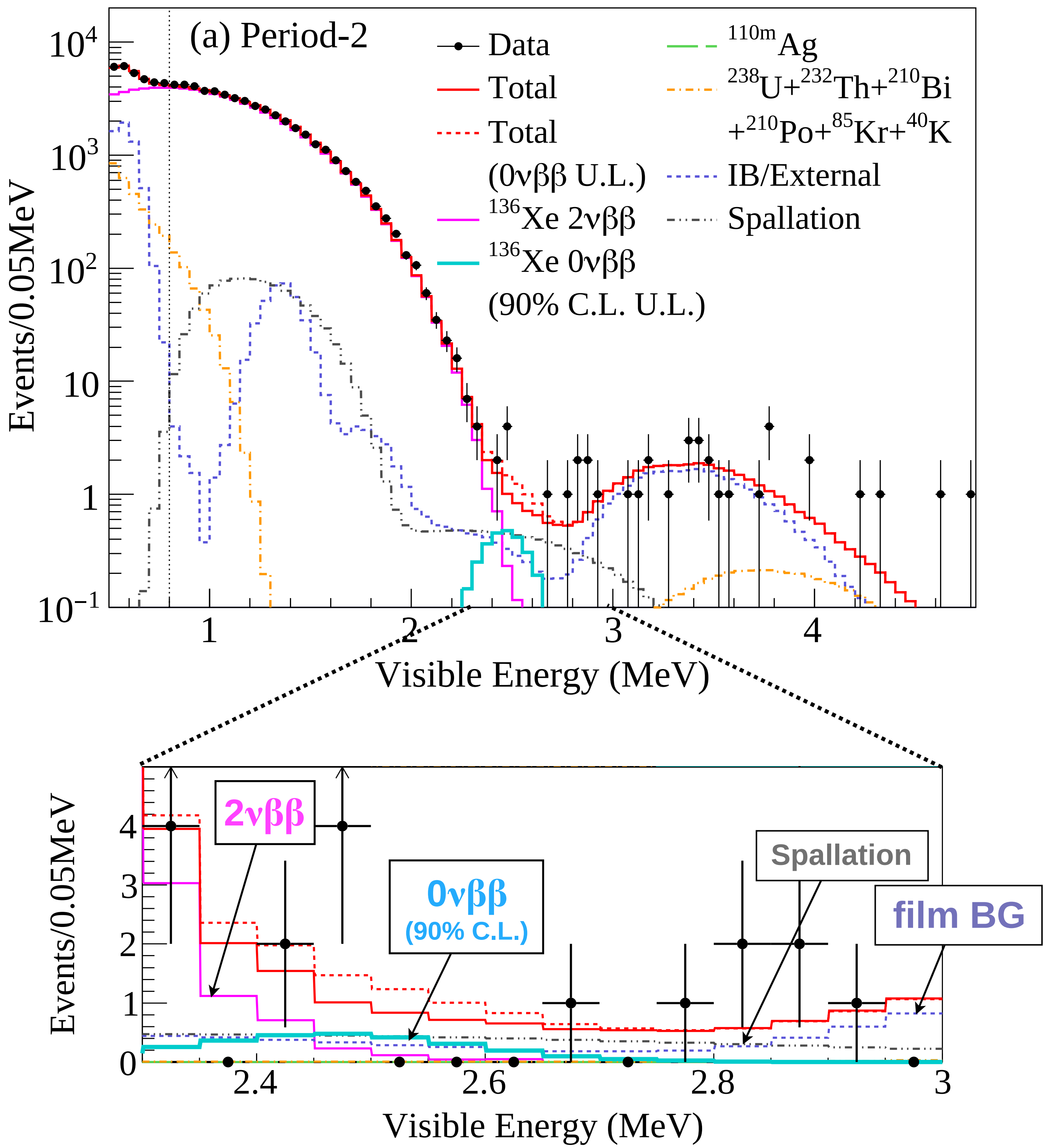
U	:	150 → 2×10^{-12}g/g
Th	:	59 → 3×10^{-12}g/g
^{40}K	:	140 → 2×10^{-12}g/g



Data-taking restarted in September 2011

KamLAND-Zen Phase-II (2016)

Phase-II **Period-2 (263.8 days)**



KamLAND-Zen Phase-II search after Xe-LS purification

found no significant 0νββ signal

↓

obtain lower limit on half-life

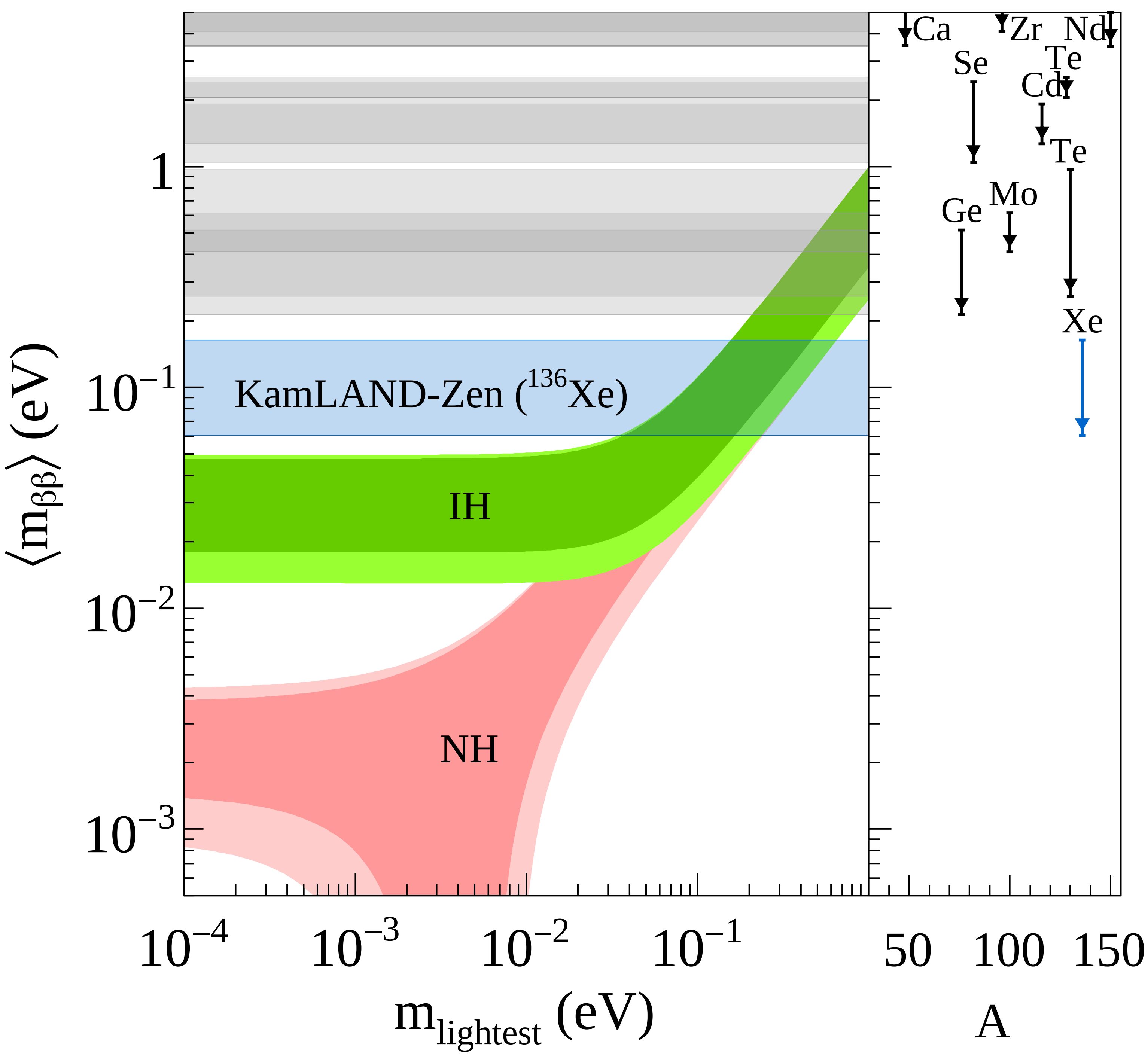
↓

Half-life limit at 90% C.L.

Phase-I	$T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr
Phase-II	$T^{0\nu}_{1/2} > 9.2 \times 10^{25}$ yr
Combined	$\mathbf{T^{0\nu}_{1/2} > 1.07 \times 10^{26}}$ **yr**

Limits on Neutrino Mass

90% C.L. upper limit



KamLAND-Zen (^{136}Xe)

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

$m_{lightest}$ < 180-480 meV

including uncertainties from CP phases and ν-osci. par.

NME calculations assuming $g_A \sim 1.27$

small ↑

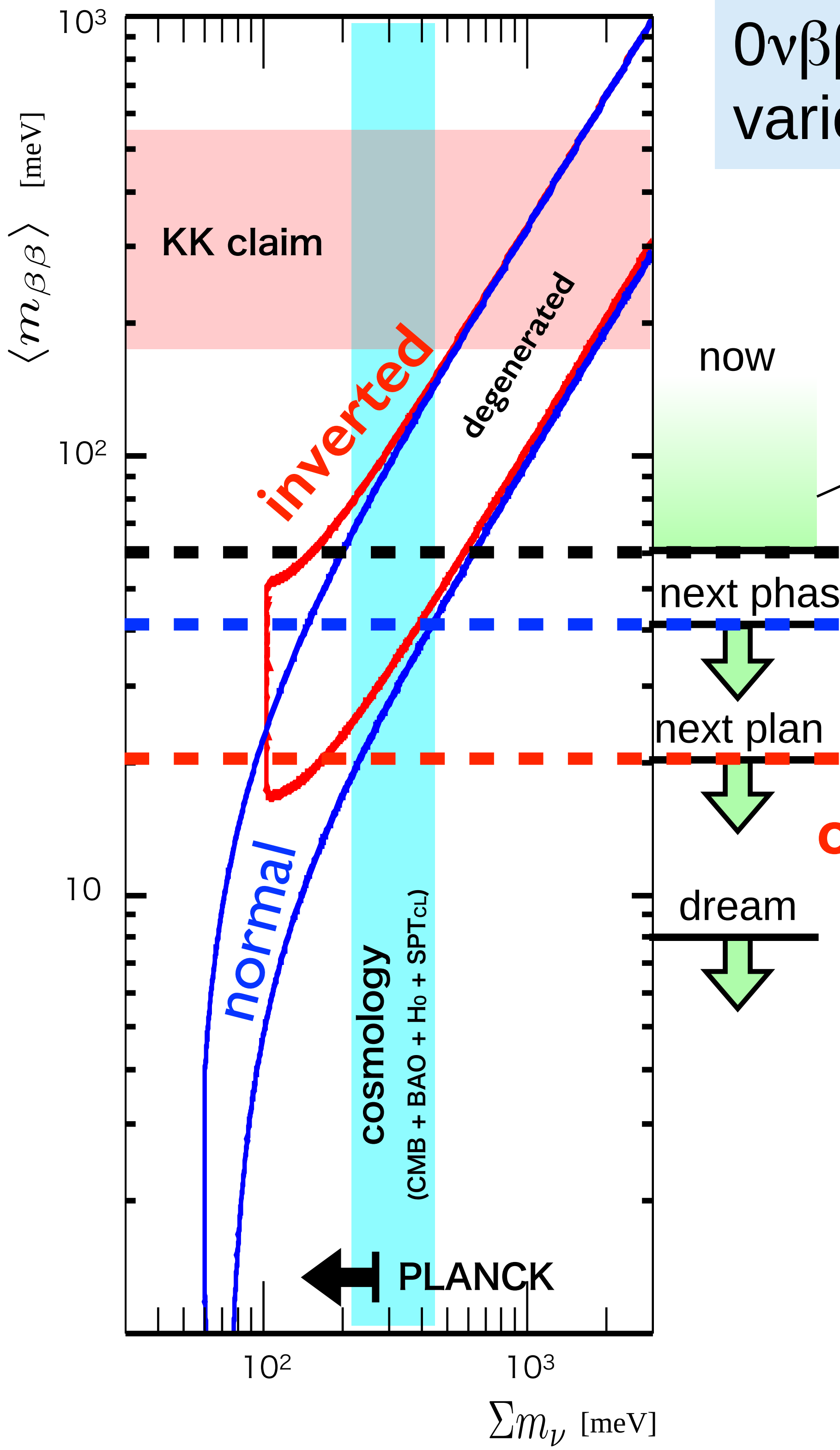
SkM-HFB-QRPA (PRC87, 064302 (2013))
ISM (Nucl. Phys. A 818, 139 (2009))
QRPA (PRC 87, 045501 (2013))
SRQRPA (J. High Energy Phys. 02, 025 (2013))
pnQRPA (PRC 91, 024613 (2015))
IBM-2 (PRC 91, 034304 (2015))
EDF (PRL 105, 252503 (2010))

large ↓

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

First search below 100 meV ~ near IH region

Prospects of KamLAND-Zen

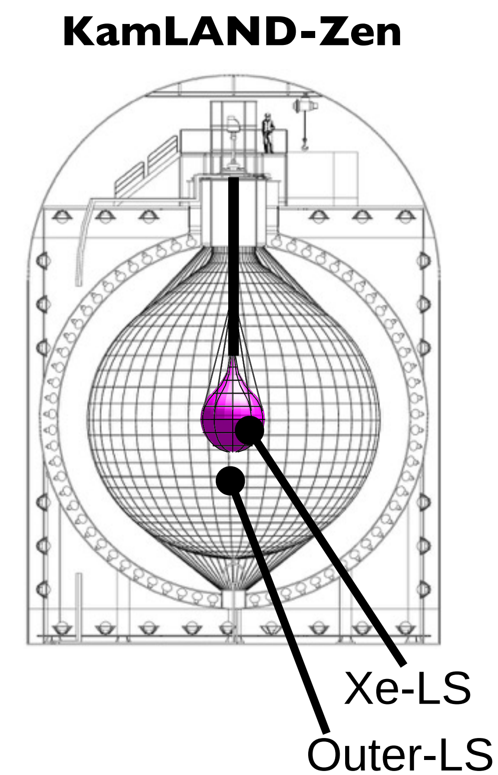


0νββ search sensitivity can be enhanced by various KamLAND-Zen upgrade plans

KamLAND-Zen 400 (Phase-I + Phase-II)

$\langle m_{\beta\beta} \rangle$ < 61-165 meV @ 90% C.L.

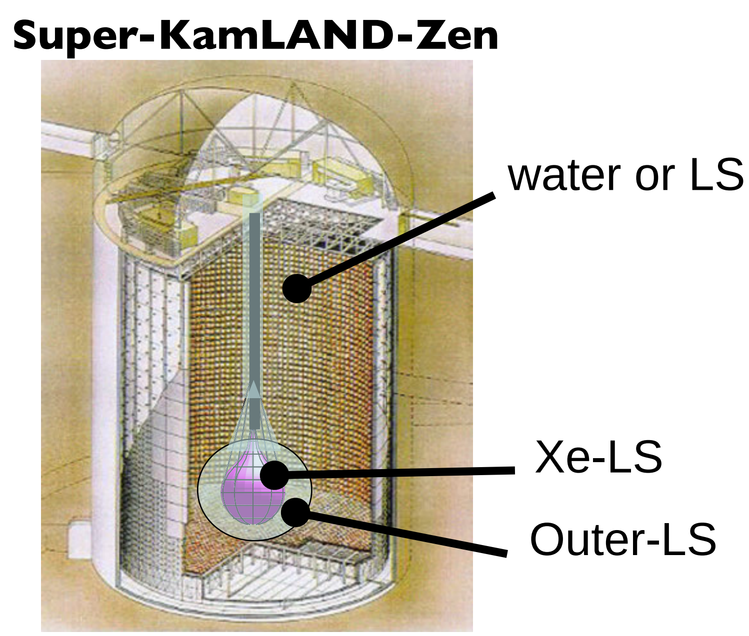
uncertainty of nuclear matrix element



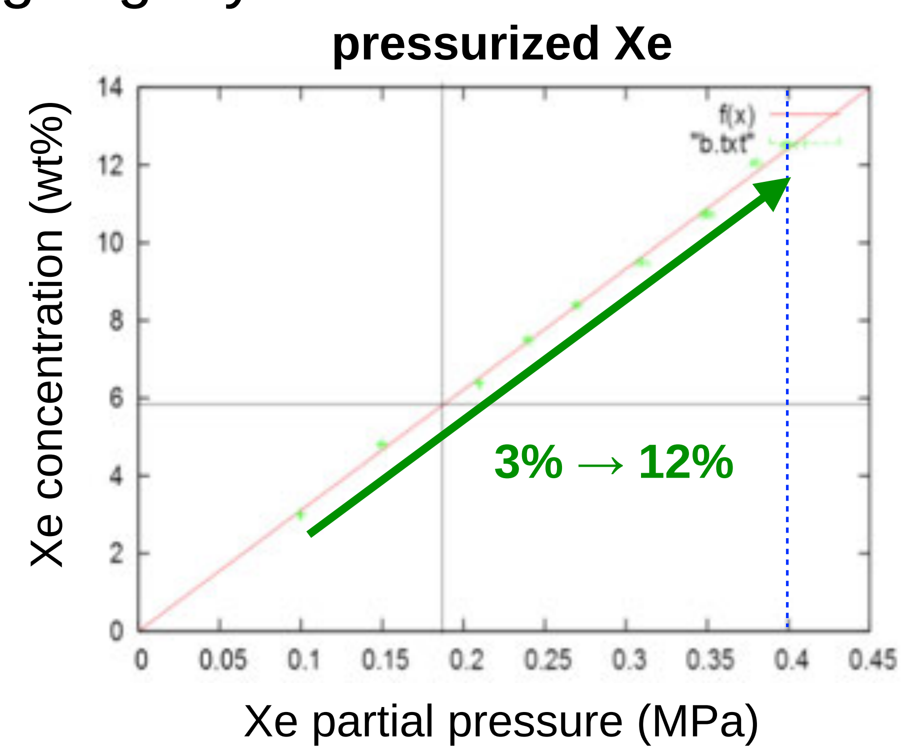
KamLAND-Zen 800 (750 kg Xe), high purity mini-balloon

KamLAND2-Zen 1000 kg, high light yield LS

σ_E(2.5MeV) = 4% → 1.8%



increase decay target nuclei by pressurized Xe



4 times at 30 m depth

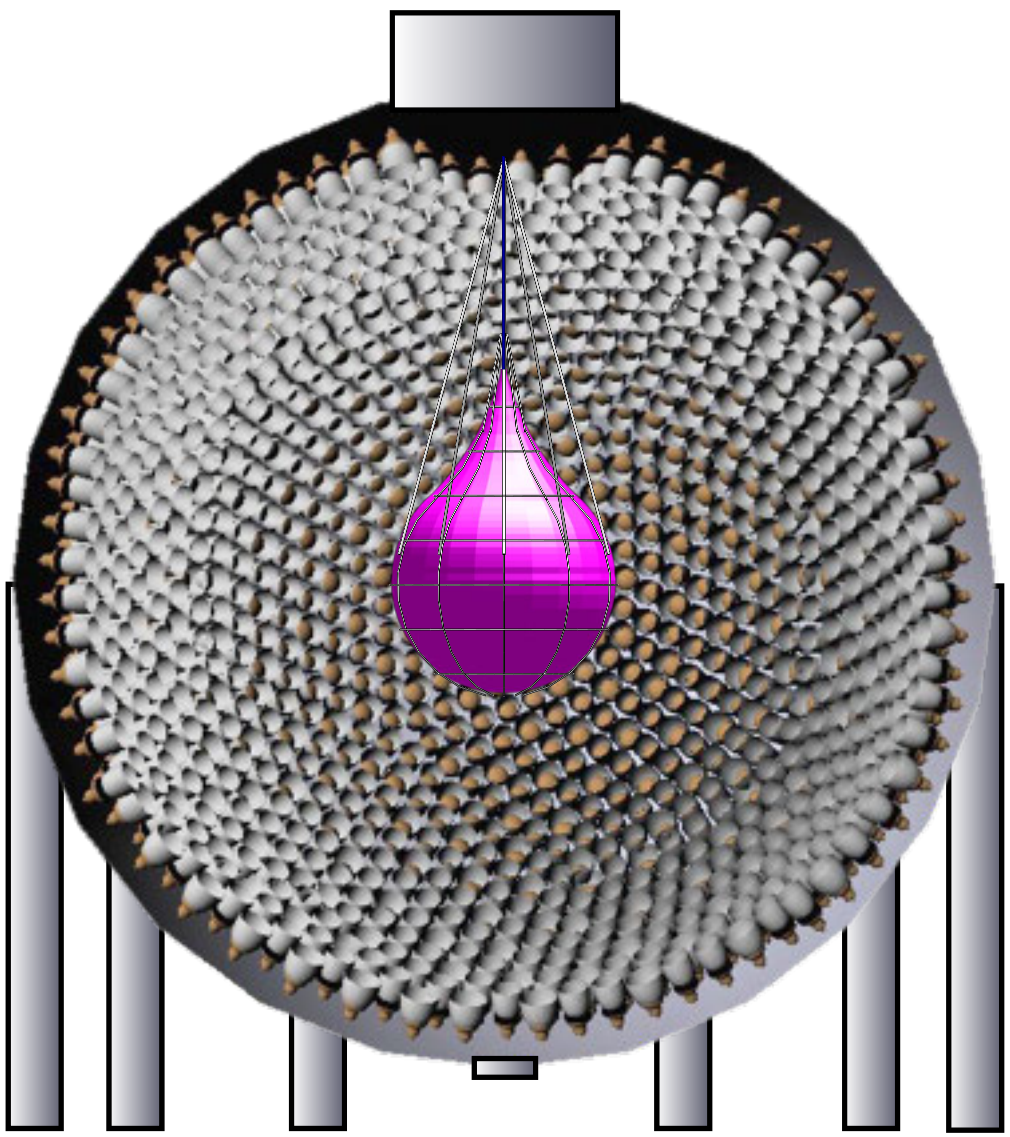
KamLAND2-Zen

General-purpose

larger crane
strengthen floor
enlarge opening

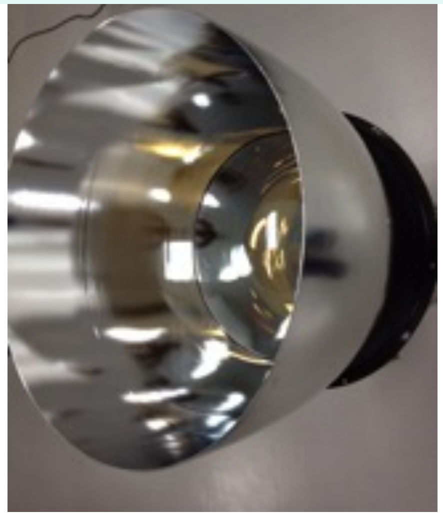
accommodate various devices
CaF_2, $CdWO_4$, NaI, …

1000 kg enriched Xe

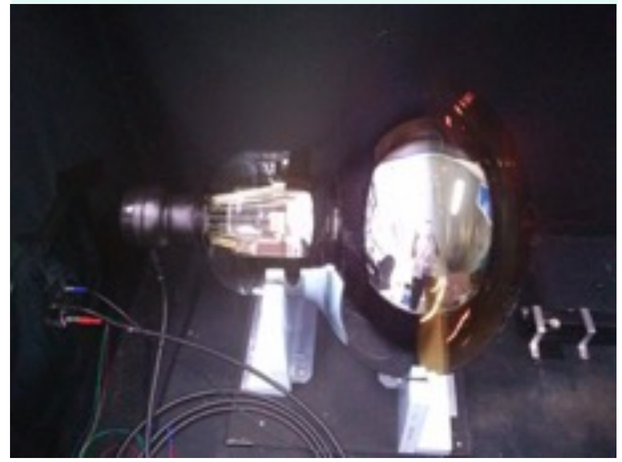


High performance

Winstone Cone



High Q.E. PMT



17”Φ→20”Φ, ε=22% → 30%

Photo-coverage > **x2**

Light Collection Eff. > **x1.8**

x1.9

New Liquid Scintillator

x1.4

KamLAND liquid scintillator	8,000 photon/MeV
typical liquid scintillator	12,000 photon/MeV

σ(2.6MeV)= 4% → < 2.5%

naive calc. < 2%

target $\langle m_{\beta\beta} \rangle$ ~ 20 meV / 5 year

Open Questions

- CP phase (δ) ν oscillation

  Is phase δ violating CP symmetry non-zero?

- Mass hierarchy ν oscillation, 0νββ decay

  $\nu_1 < \nu_2 << \nu_3$, $\nu_3 < \nu_1 << \nu_2$, $\nu_1 \sim \nu_2 \sim \nu_3$?

- Sterile neutrino ν oscillation, cosmology

  Is there 4th sterile neutrino?

- Absolute mass scale β-decay, 0νββ decay, cosmology

  What is the absolute neutrino mass scale?

- Dirac or Majorana 0νββ decay

  Is neutrino Dirac particle or Majorana particle?

Current & Future experiments

ν oscillation

KamLAND, Borexino, Super-K, SNO, T2K, MINOS, NOVA, LBNE, OPERA, Double-Chooz, Daya Bay, RENO, Nucifer, Stereo, CeLAND, SOX, Sage2, LENS, IsoDAR, MicroBooNE, ICARUS, …

0νββ decay

KamLAND-Zen, EXO, GERDA, CUORE, SuperNEMO, SNO+, CANDLES, MOON, DCBA, Majorana, Lucifer, AMORE, COBRA, NEXT, …

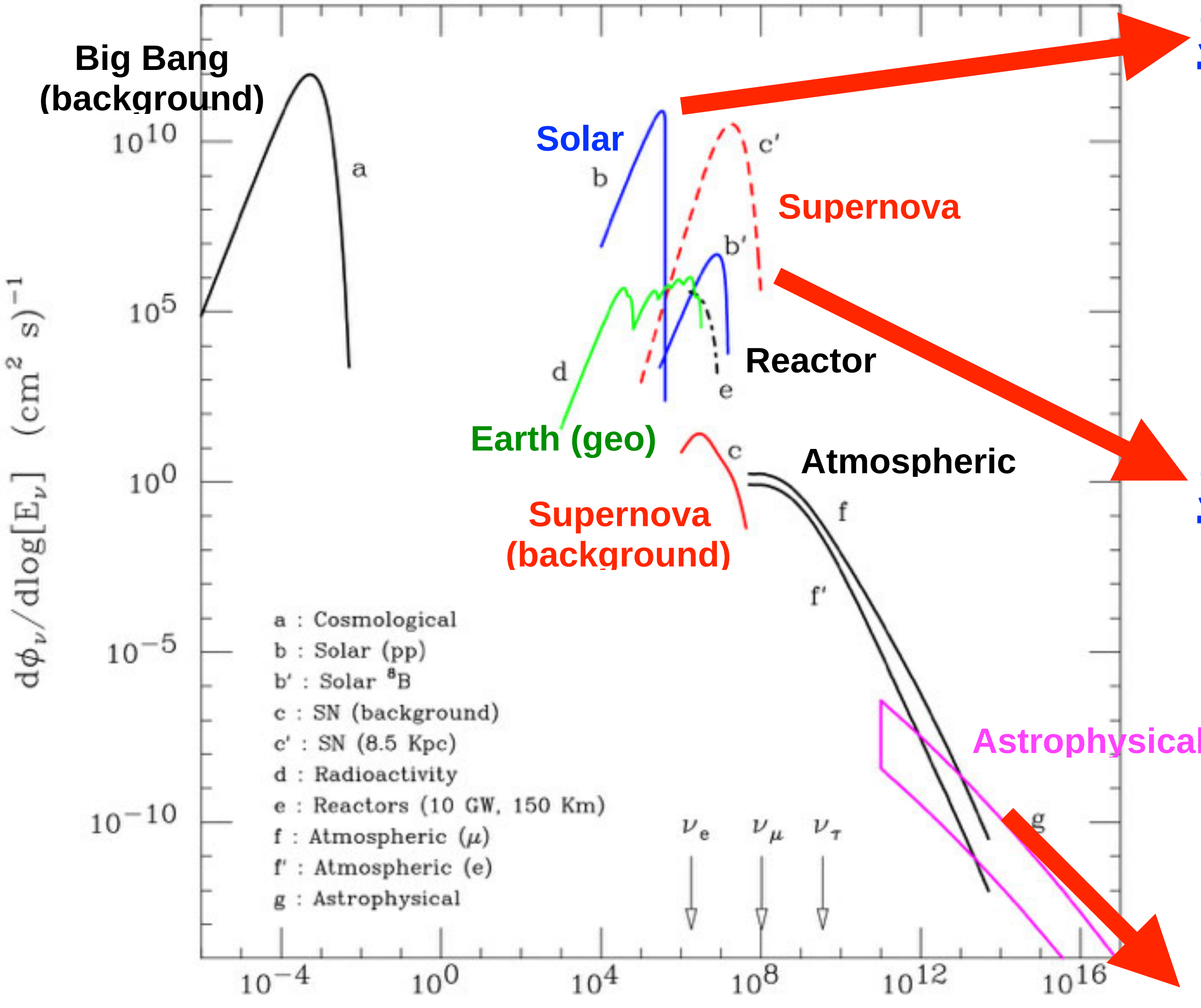
β decay

KATRIN, Project 8

Many experiments to answer the open questions!

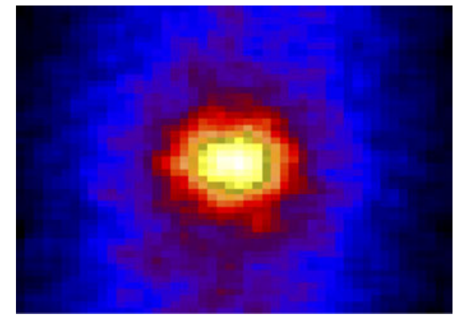
Neutrino Astrophysics

Neutrino Energy v.s. Flux

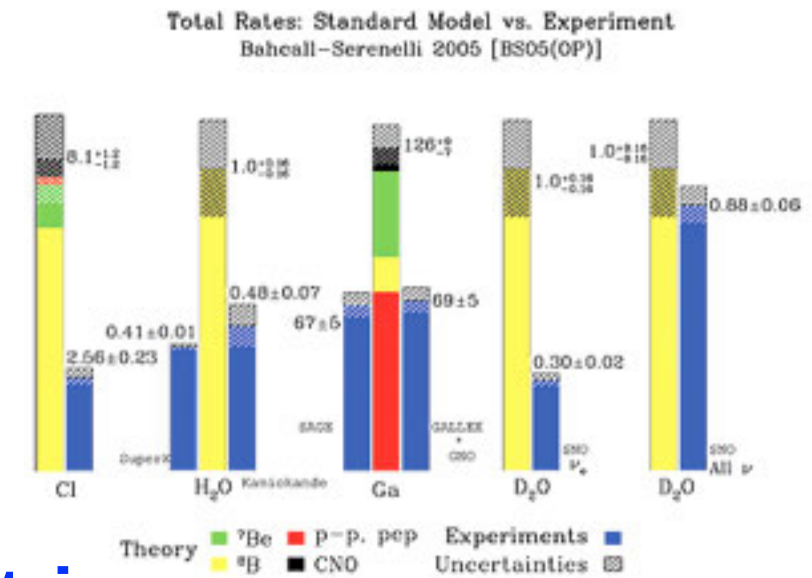


P. Lipari, Introduction to Neutrino Physics (2002)

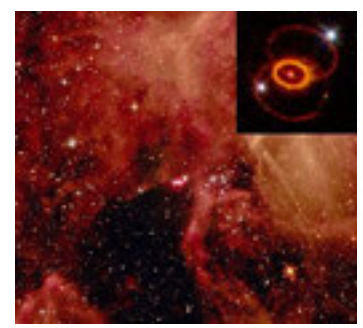
Solar neutrino

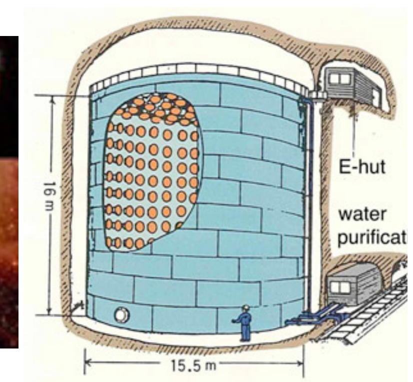


Super-K

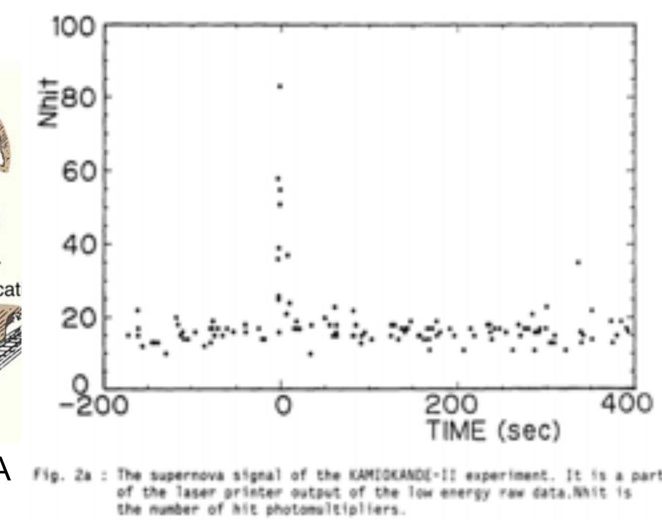


Supernova neutrino

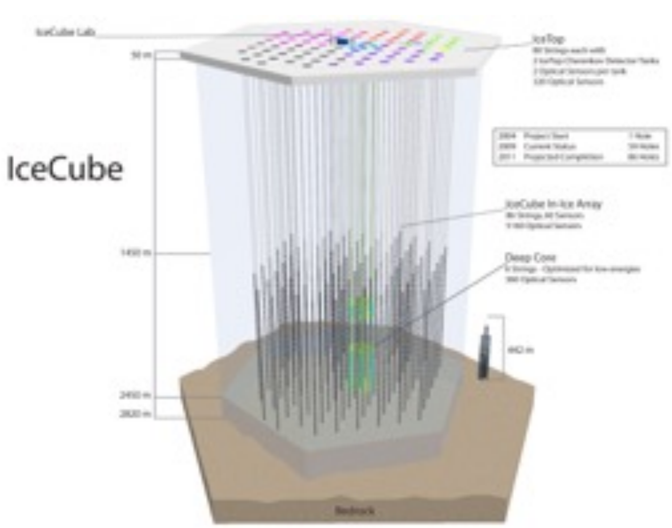


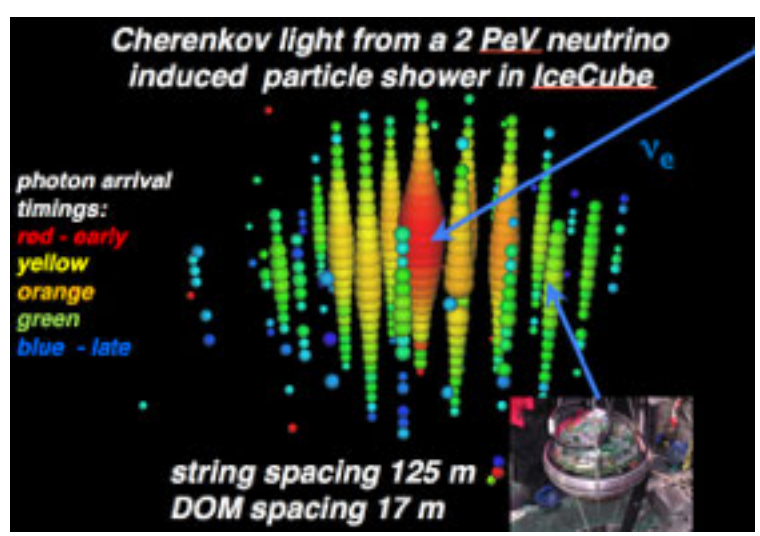


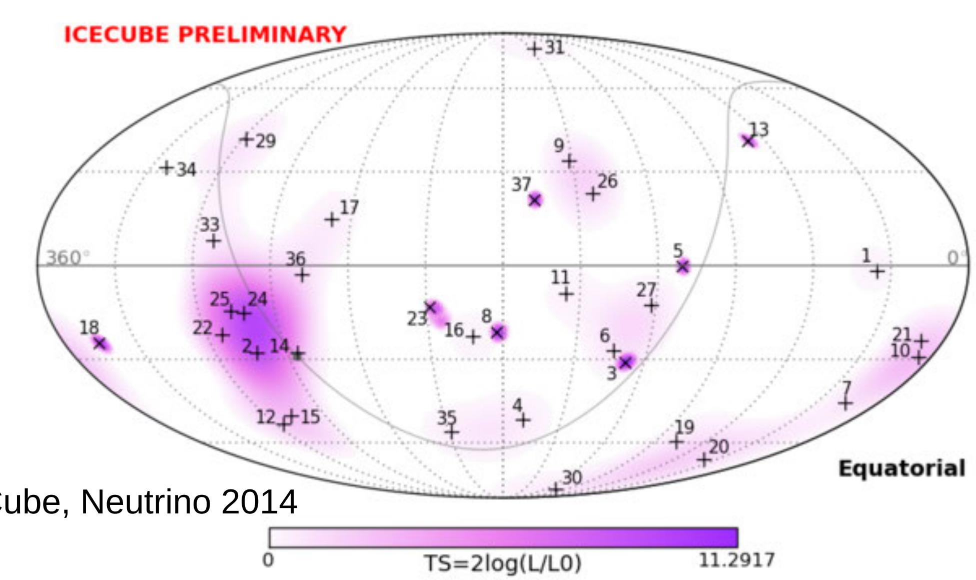
Kamiokande, 1987A



Astrophysical neutrino



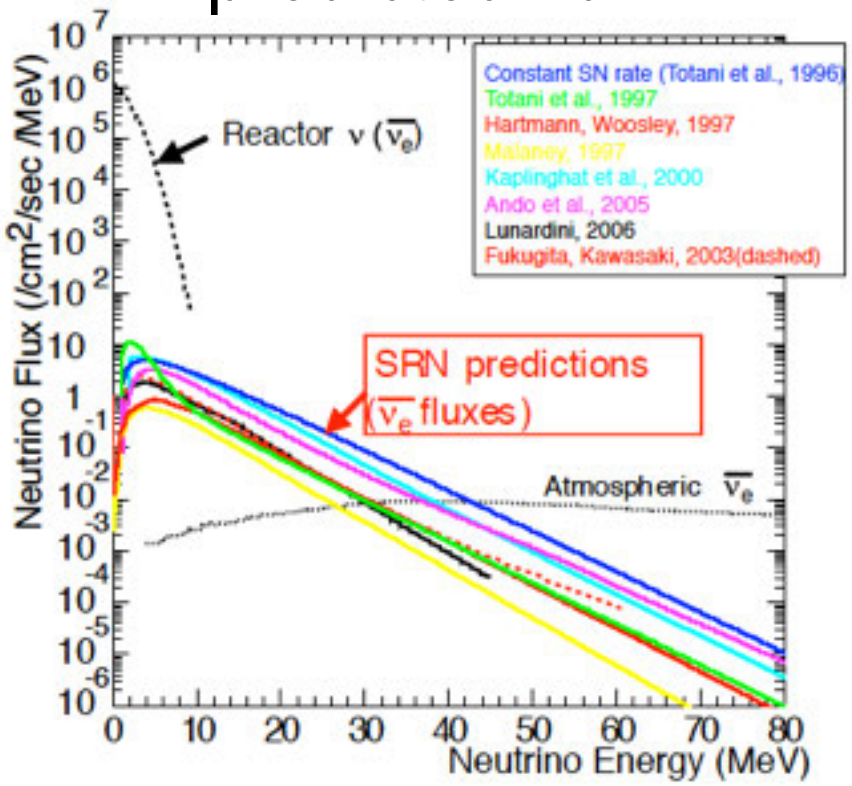




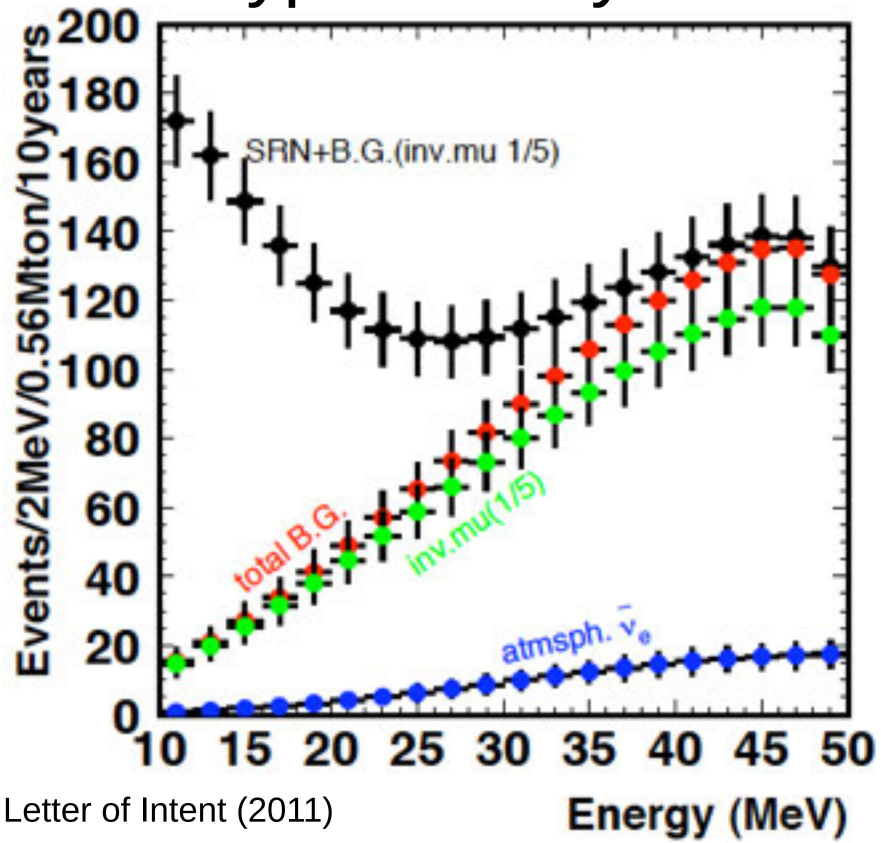
IceCube, Neutrino 2014

Relic Supernova Neutrino

predicted flux



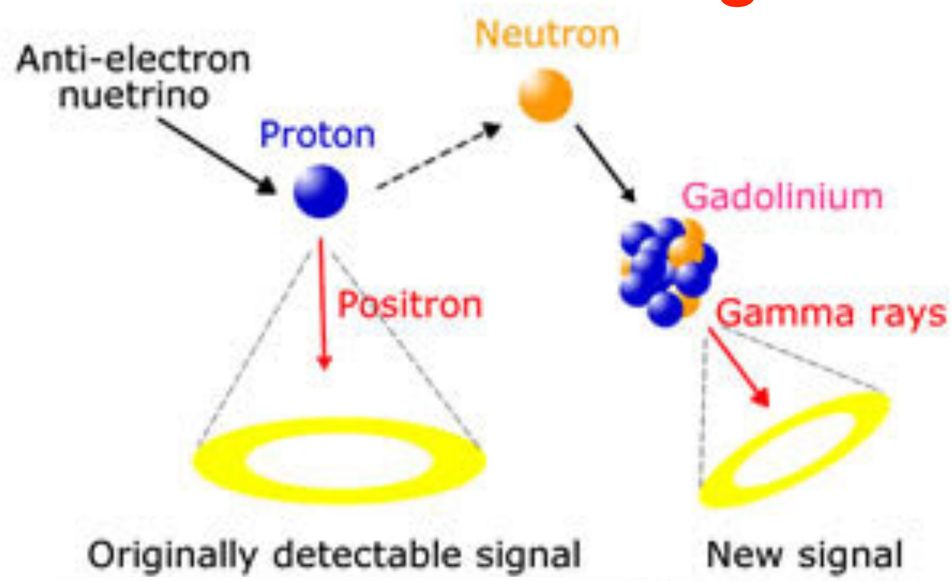
Hyper-K 10 years

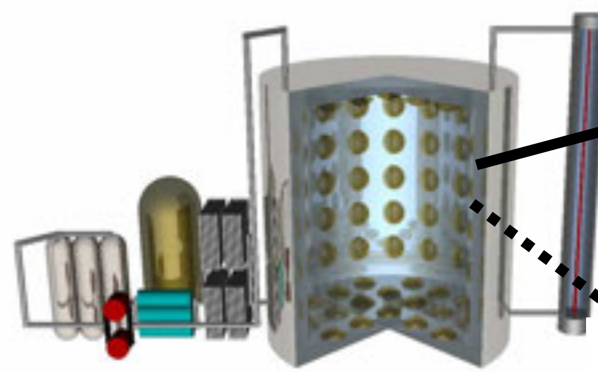


Letter of Intent (2011)

GADZOOKS!

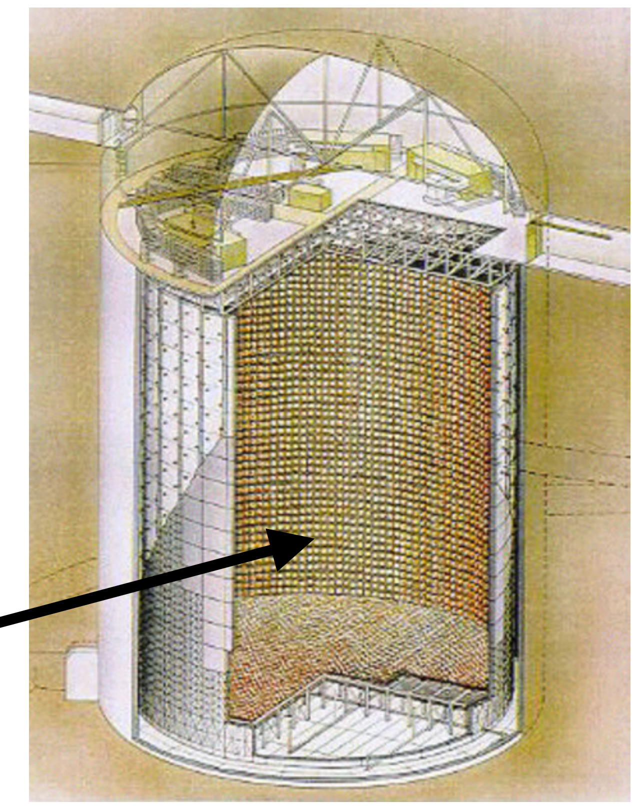
low background



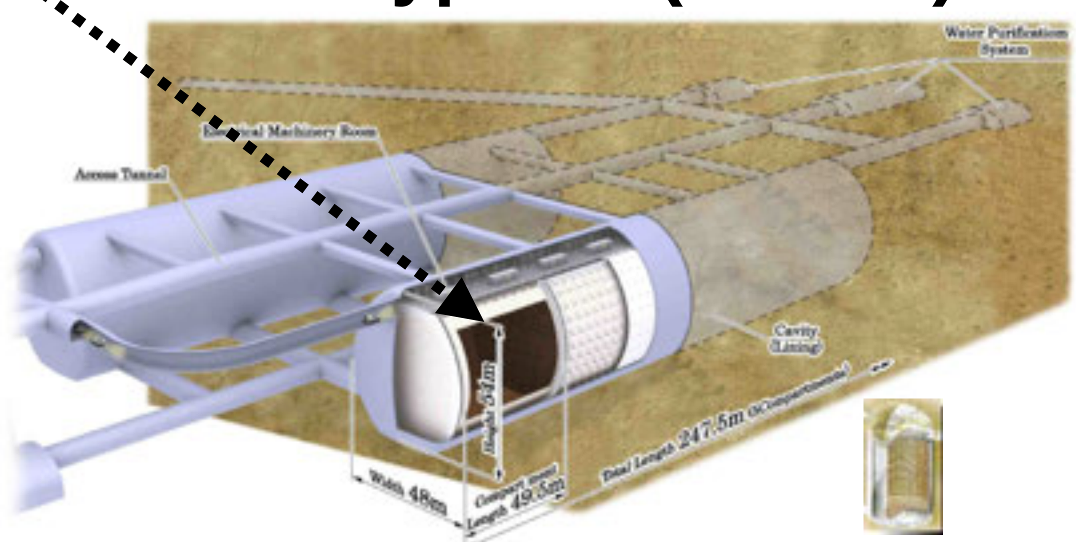


Gd loaded Water

Super-K (50 kton)



Hyper-K (1 Mton)



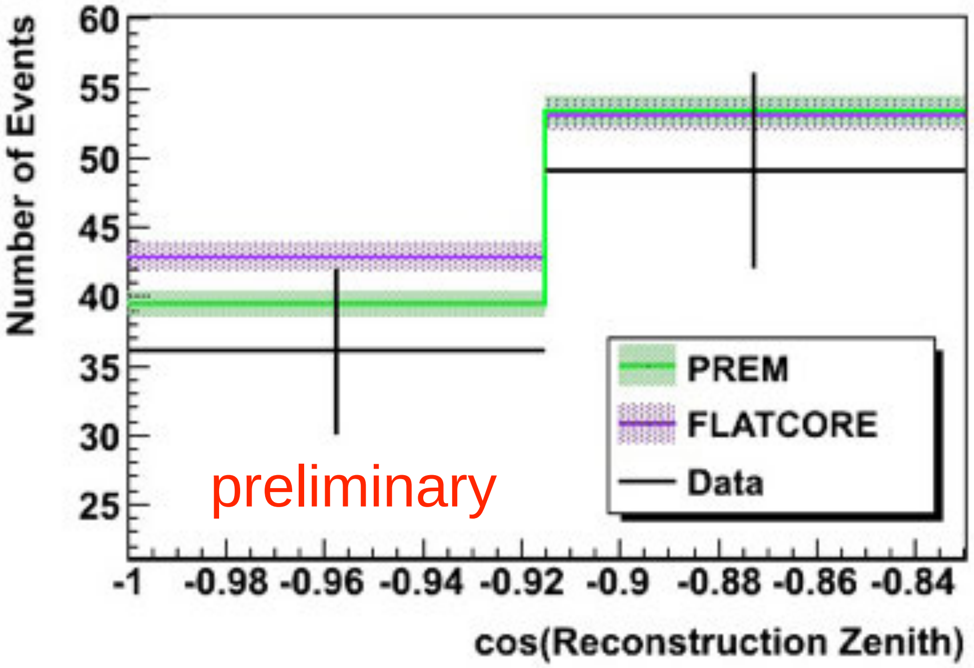
Size of Super-K

high statistics

Investigation of star formation history

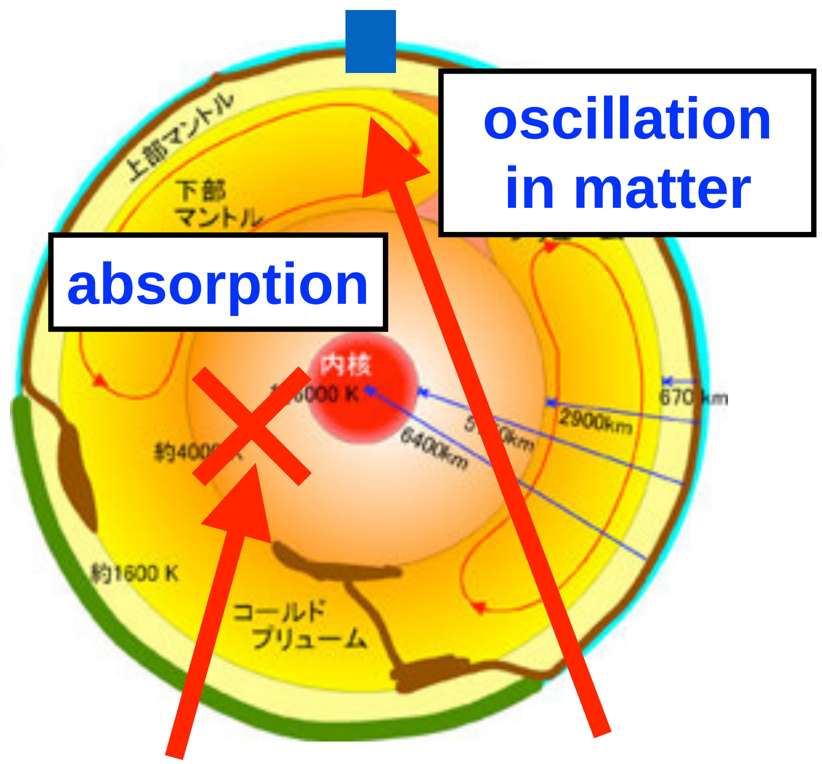
Neutrino Radiography

IceCube



Hoshina, Neutrino GeoScience (2013)

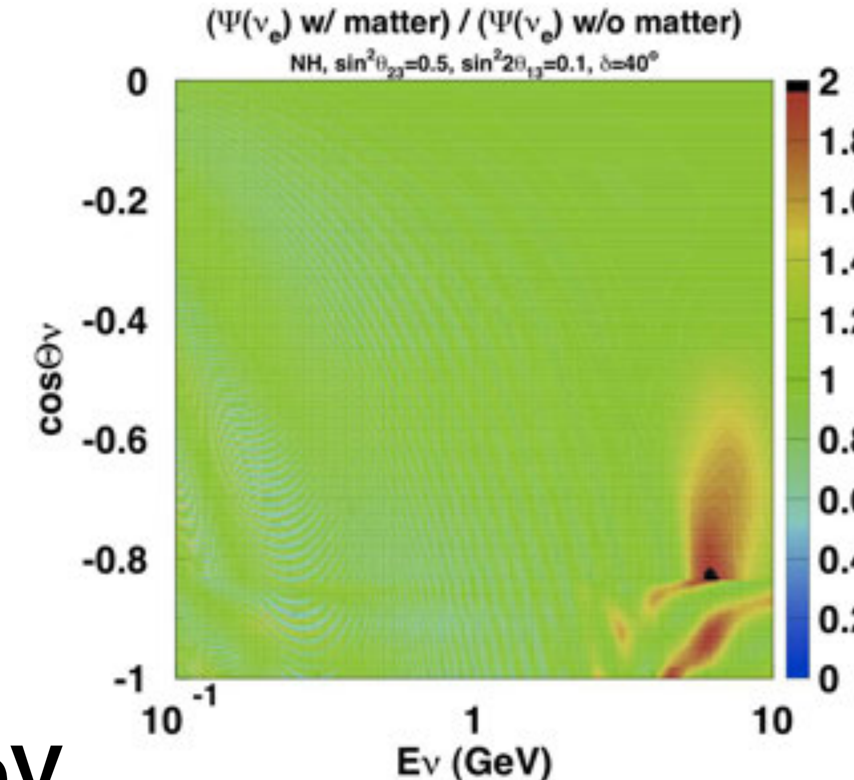
Detector



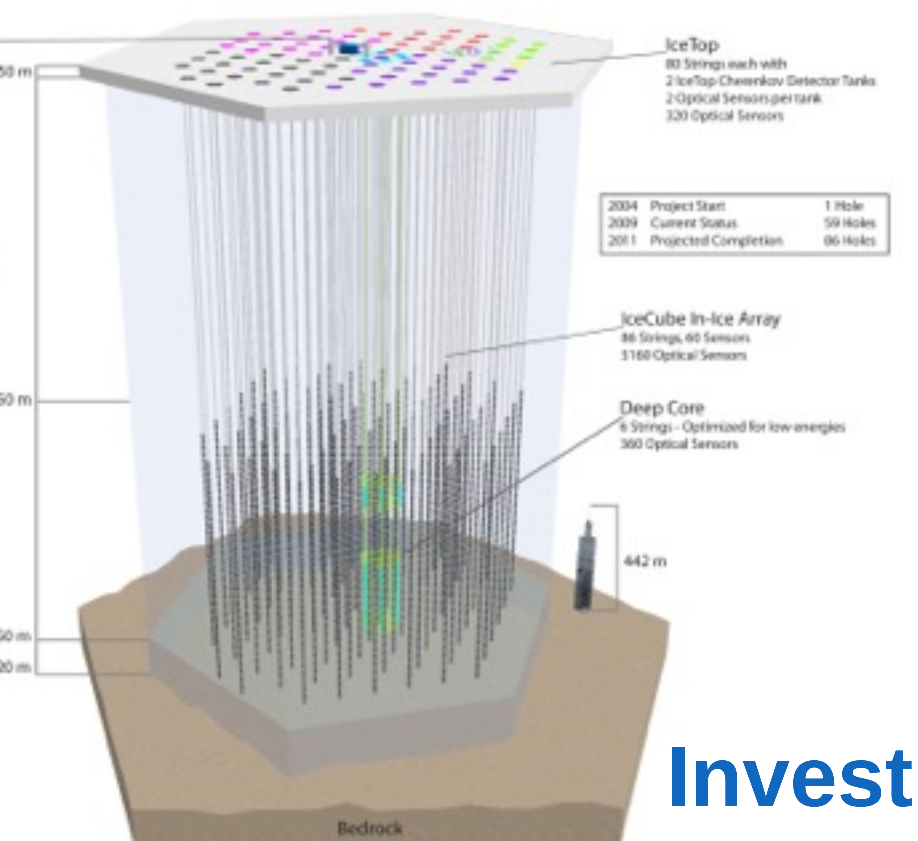
ν ~ TeV

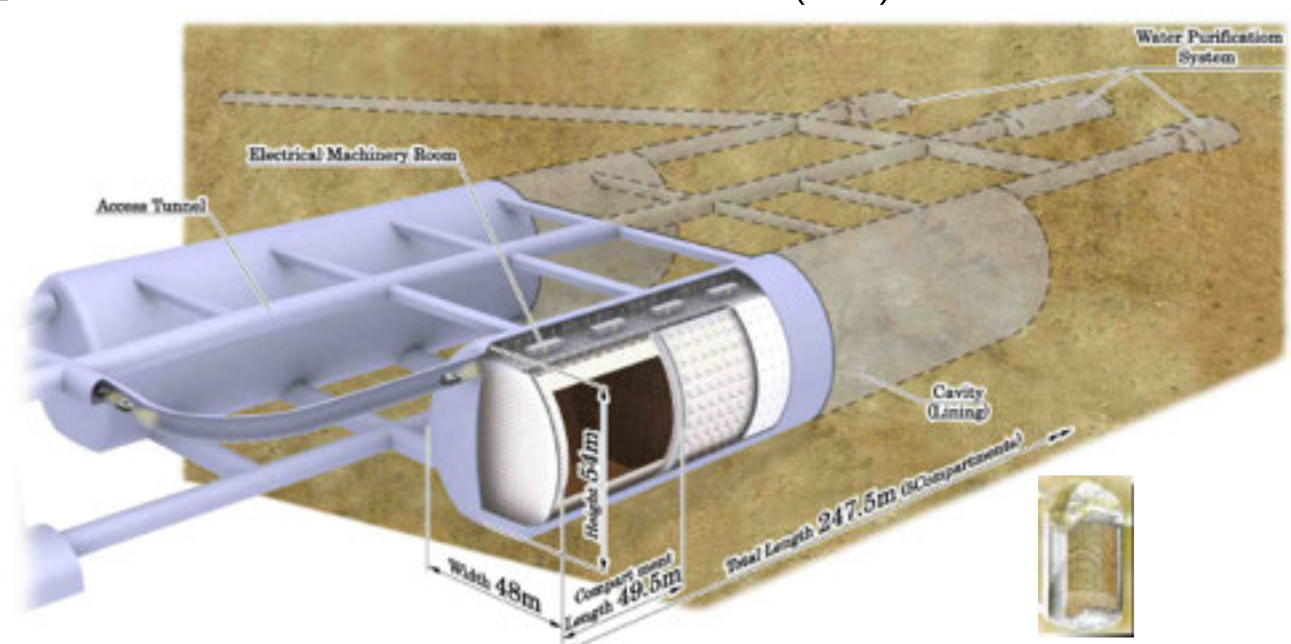
ν ~ GeV

Hyper-K



Letter of Intent (2011)





Size of Super-K

Investigation of density and chemical composition of the Earth's core

Summary

- Neutrinos have been played a key role to develop particle physics so far.

- Discovery of the neutrino mass and mixing from the studies for the last few decades is a revolution.

- Future prospects of neutrino physics are very exciting!

- Furthermore, neutrinos will be essential to reveal the history of the Universe and the Earth.

Let's pay great attention to the next geo neutrino talk!