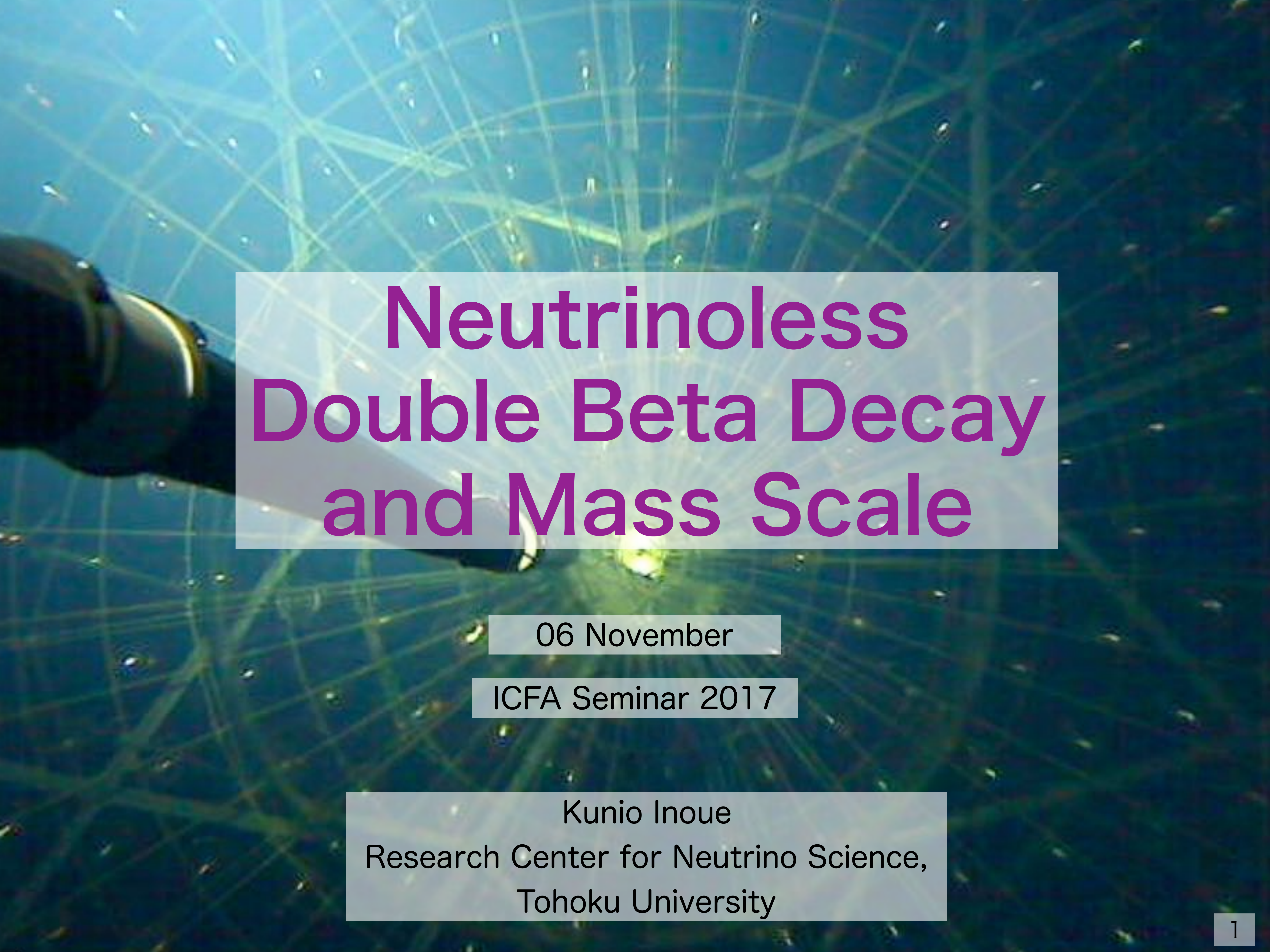


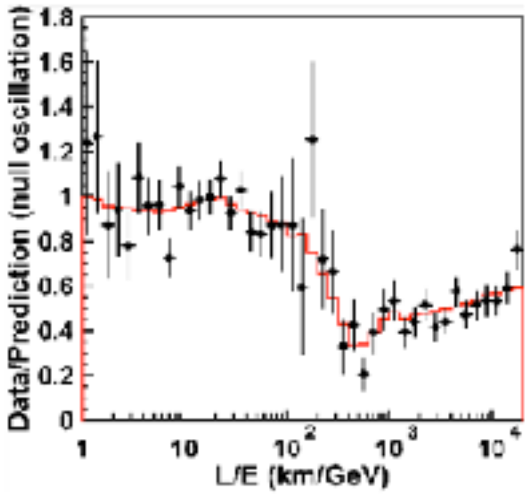
Neutrinoless Double Beta Decay and Mass Scale

06 November

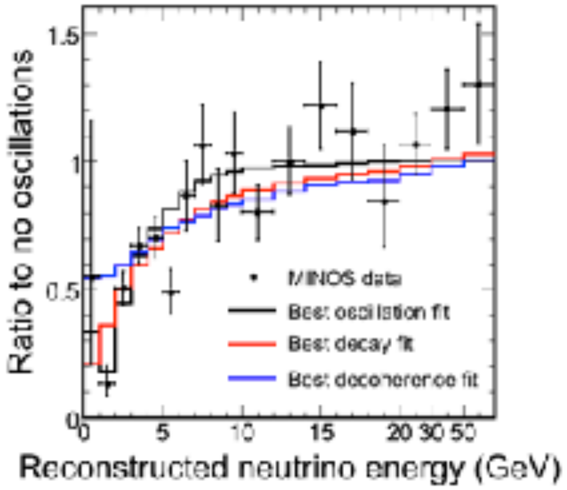
ICFA Seminar 2017

Kunio Inoue
Research Center for Neutrino Science,
Tohoku University

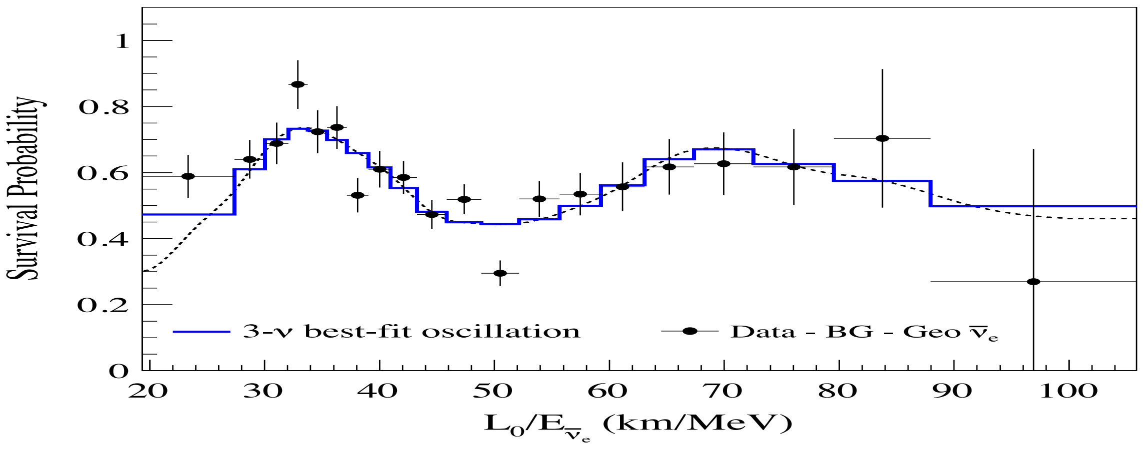
SK atm.



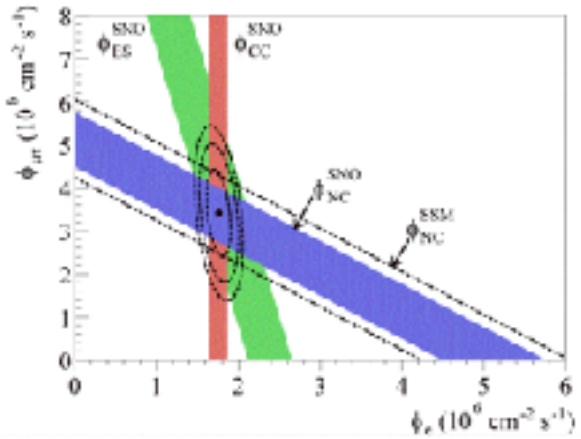
MINOS



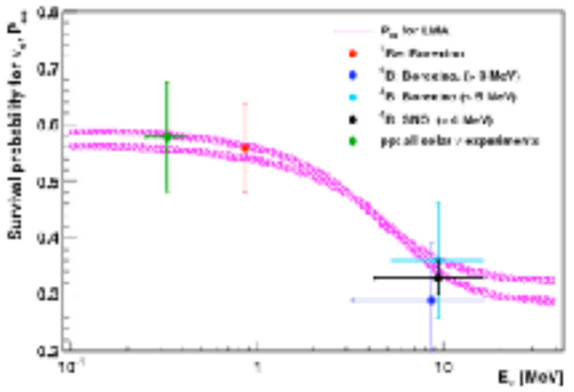
KamLAND 2 cycles



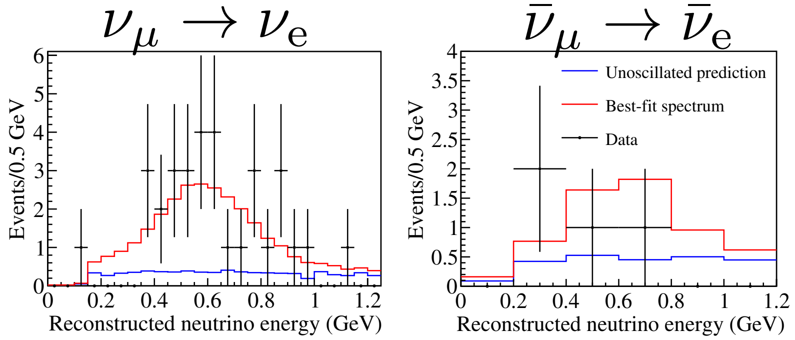
SNO CC/NC



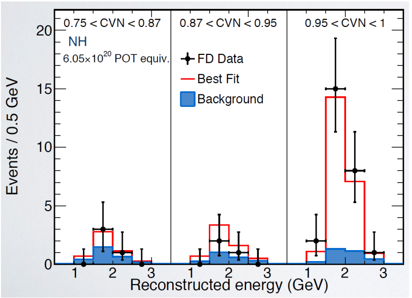
Borexino MSW



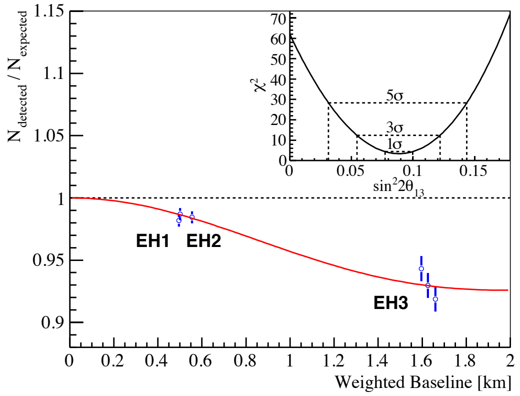
T2K



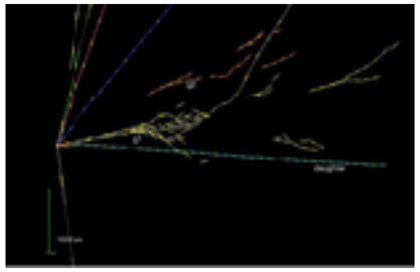
NOvA



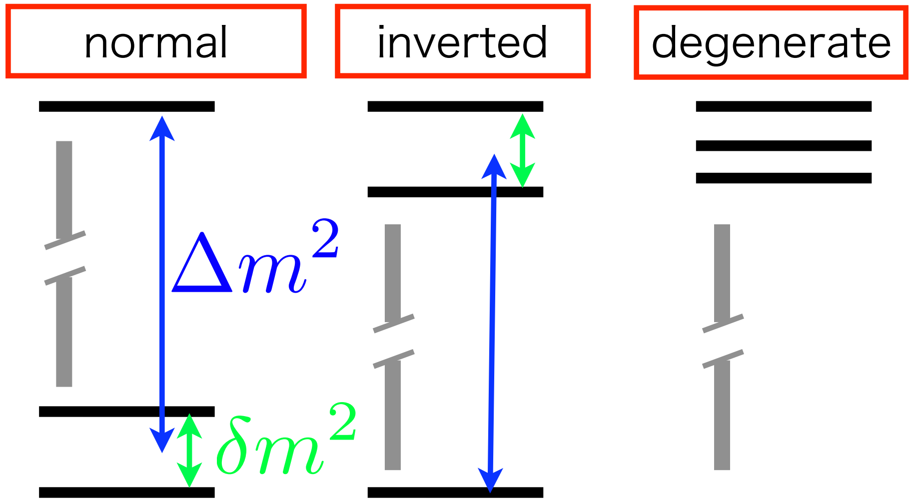
SBL reactor



OPERA $\nu_\mu \to \nu_\tau$



mass hierarchy



normal

inverted

degenerate

Δm^2

δm^2

arXiv:1708.01186

δm^2 $(7.56 \pm 0.19) \times 10^{-5}\,\mathrm{eV}^2$ **2.5%**

Δm^2 $(2.55 \pm 0.04) \times 10^{-3}\,\mathrm{eV}^2$ (normal)
$(2.49 \pm 0.04) \times 10^{-3}\,\mathrm{eV}^2$ (inverted) **1.6%**

$\sin^2\theta_{12}$ $0.321^{+0.018}_{-0.016}$

$\sin^2\theta_{23}$ $0.430^{+0.020}_{-0.018}$ (normal)
$0.596^{+0.017}_{-0.018}$ (inverted)

$\sin^2\theta_{13}$ $0.02155^{+0.00090}_{-0.00075}$ (normal)
$0.02140^{+0.00082}_{-0.00085}$ (inverted)

δ_{CP} $4.40^{+0.97}_{-0.63}$ (normal)
$4.52^{+0.82}_{-0.72}$ (inverted)

Yet Unknown

○ one or three CP phases

○ mass (absolute value and hierarchy)

● Majorana？ Dirac？

○ # of generations

measurable with oscillation

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

oscillation	$\Delta m_{ij}^2 = m_i^2 - m_j^2$
neutrinoless double beta	$\langle m_{\beta\beta}\rangle = \lvert \Sigma\, m_i \lvert U_{ei}\rvert^2 \varepsilon_i \rvert$
cosmology	$M = \Sigma\, m_i$
single beta	$\langle m_\beta\rangle^2 = \Sigma\, m_i^2 \lvert U_{ei}\rvert^2$

indispensable

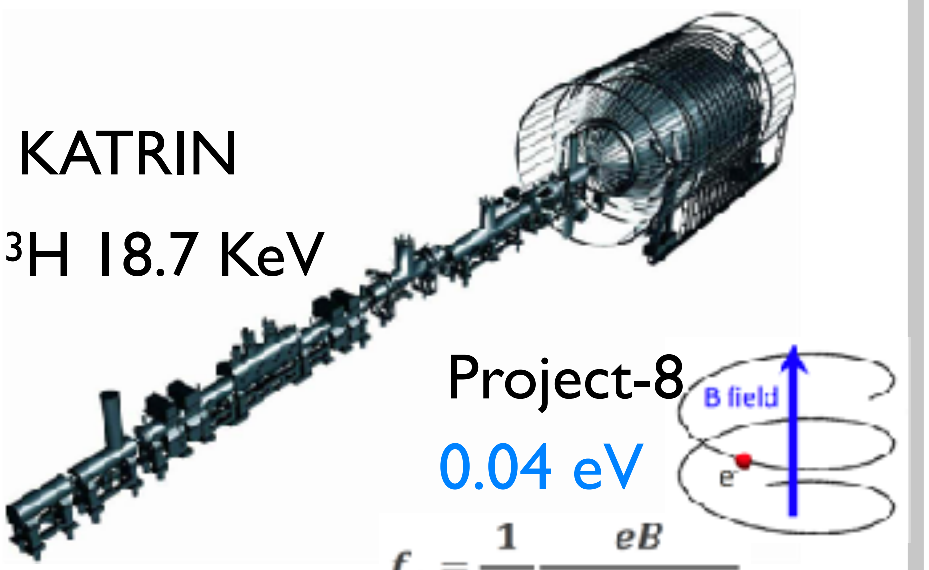
double beta

realistic test of Majorana nature

sensitive to absolute mass

opens Majorana CP measurement

Single beta decay



KATRIN

^{3}H 18.7 KeV

Project-8

0.04 eV

$$f_c = \frac{1}{2\pi}\frac{eB}{(m+E_{kin})}$$

$$\langle m_\beta \rangle^2 = \Sigma\, m_i^2\, |U_{ei}|^2$$

current limit

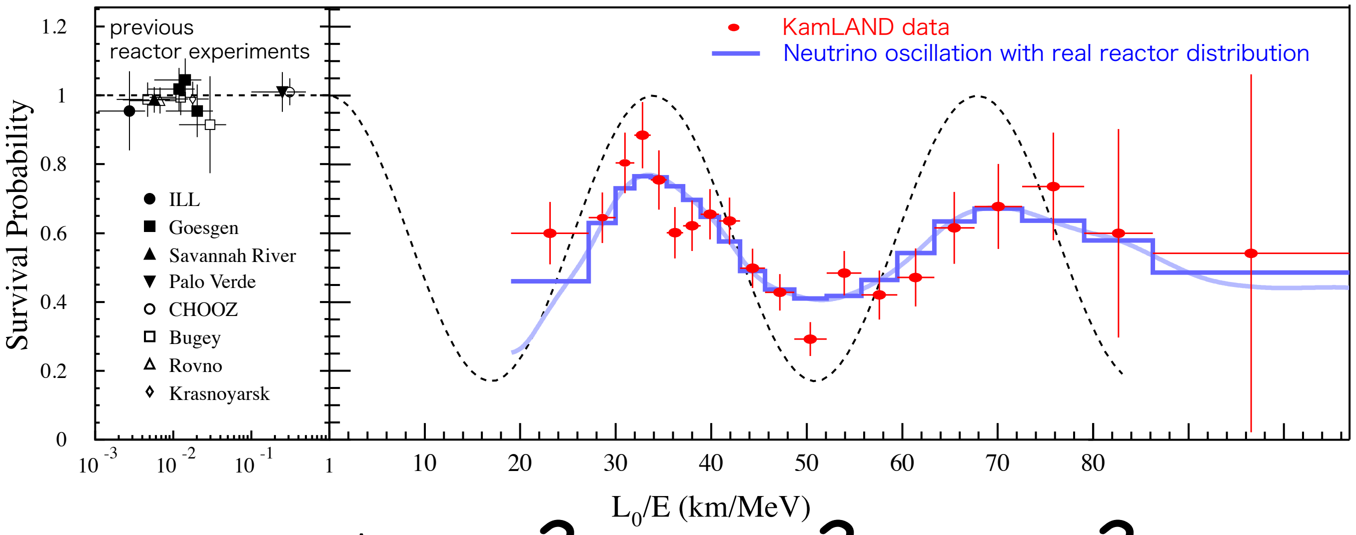
< 2.2 eV (95%)

future sensitivity

0.2 eV

Neutrino oscillation

solar, reactor, atmospheric, accelerator



$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

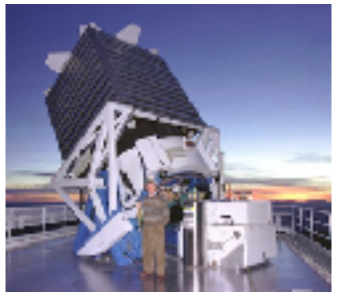
normal

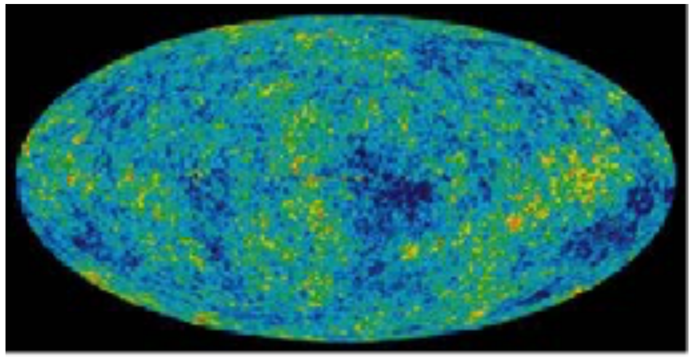
$$\Delta m^2_{31} = \Delta m^2 = (2.55 \pm 0.04) \times 10^{-3}\,\mathrm{eV}^2$$
$$\Delta m^2_{21} = \delta m^2 = (7.56 \pm 0.19) \times 10^{-5}\,\mathrm{eV}^2$$

$$m_\nu$$

Cosmology

CMB satellite, galaxy survey, weak gravitational lensing,...





$$M = \Sigma\, m_i$$

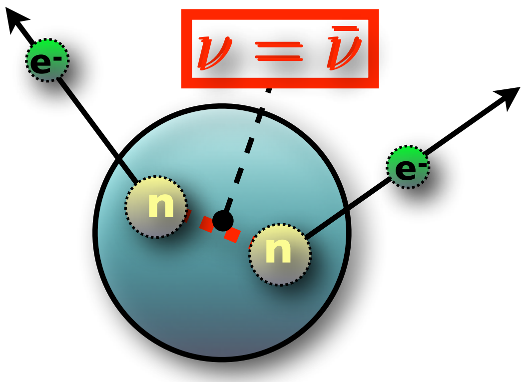
IH: $\Sigma m_i > 0.1$eV

< 0.2 ~ 0.7 eV

0.01 eV ?

Double beta decay

Ge, Te, Mo, Cd, Ca, Xe, Se, ...



$$\langle m_{\beta\beta} \rangle = |\Sigma\, m_i\, |U_{ei}|^2\, \varepsilon_i|$$

< ~0.1 eV

0.01~0.03 eV

Neutrino in the universe

visible radius	46.5 billion light years
visible volume	~3×10^{80} m^3
density	10^{-26} kg/m^3
matter fraction	5%
hydrogen mass	1.6×10^{-27} kg
# of electrons	~10^{80}
	(3×10^{-7}/cm^3)
# of neutrinos	~10^{89}
	(300/cm^3)

what rest ?

neutrino dominates in the universe!

What happened at 13.8 billion years ago when the universe started.

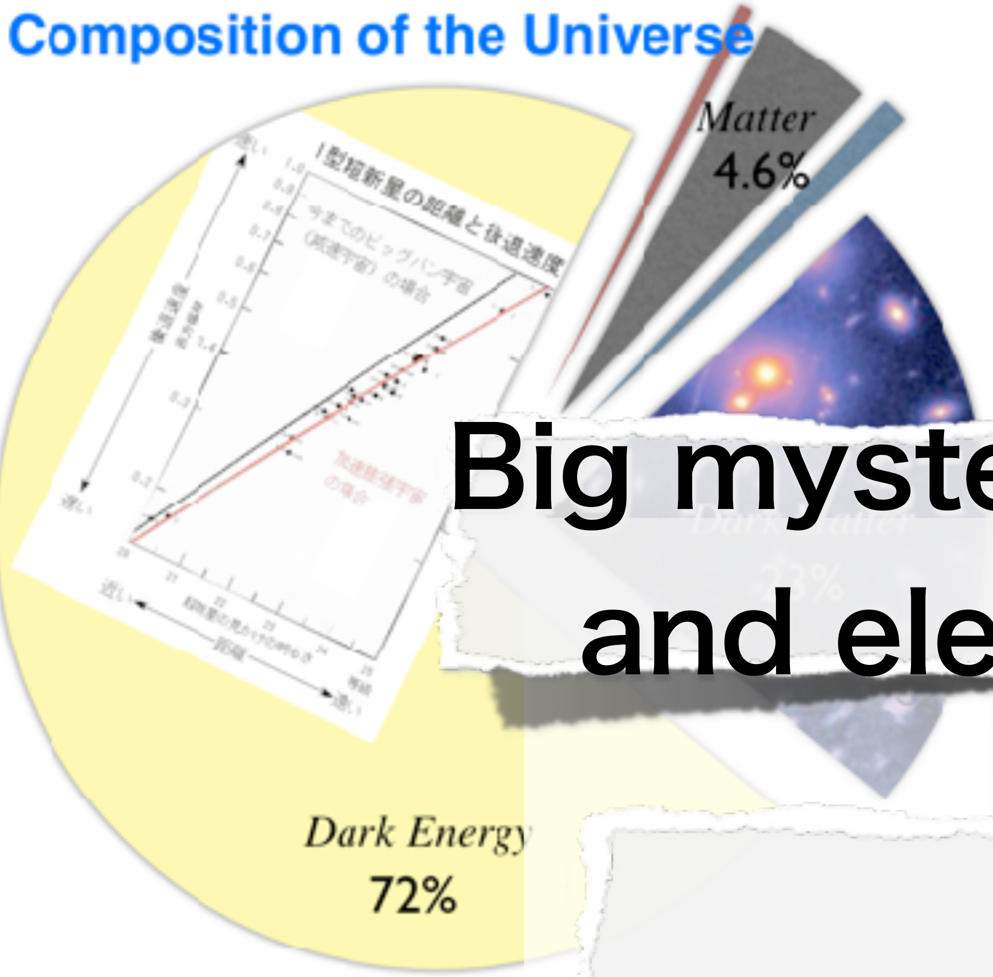
1. “Inflation” generated energy. (details yet unknown)
2. Energy transformed into matter ($E=mc^2$) as “Big Bang”.

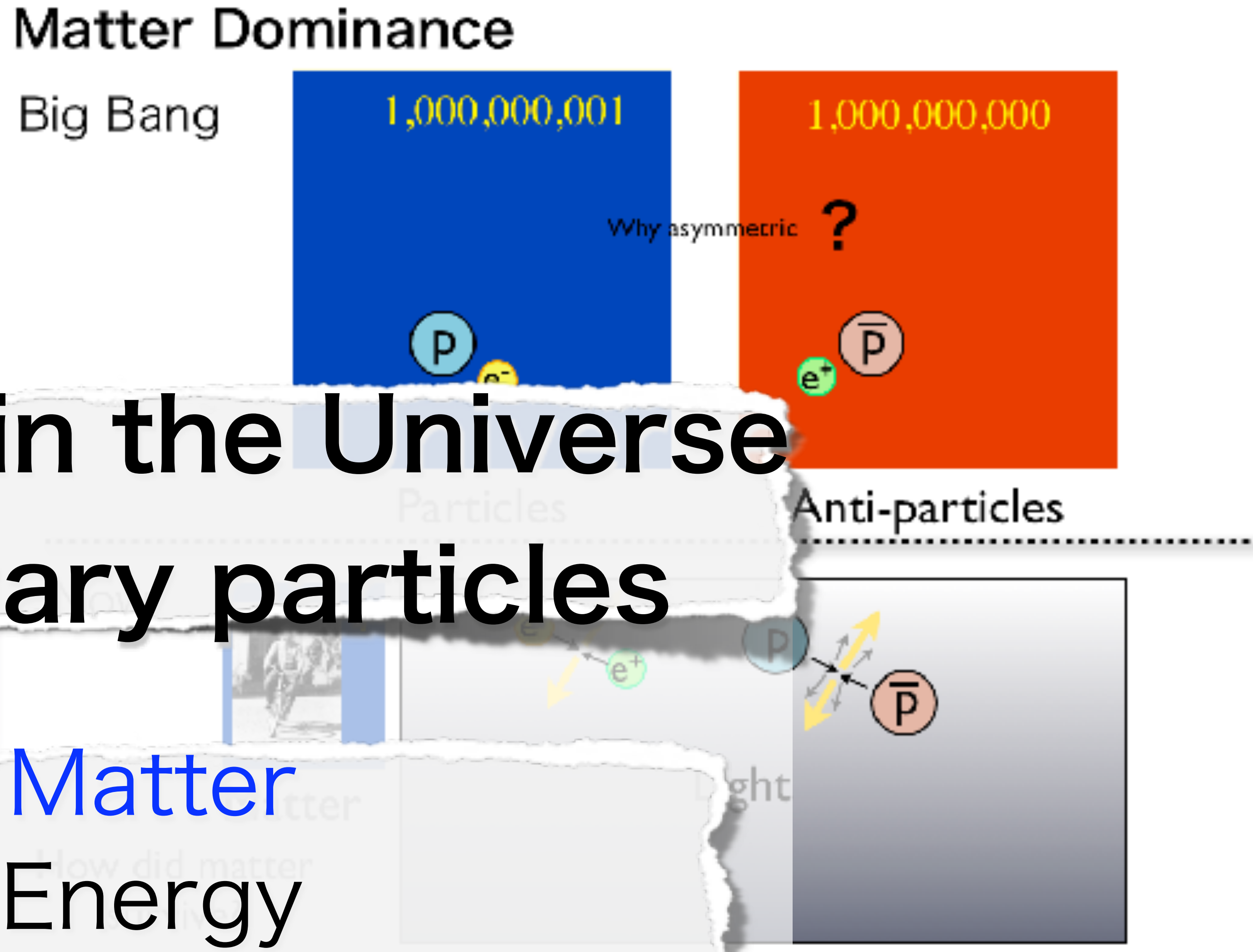
Particle theory creates pair of particle and anti-particle from vacuum, but annihilates them when they met.

In the end, anything including us cannot remain.

But we are here?

Mystery of Matter Dominance in the universe





Big mysteries in the Universe and elementary particles

Dark Matter

Dark Energy

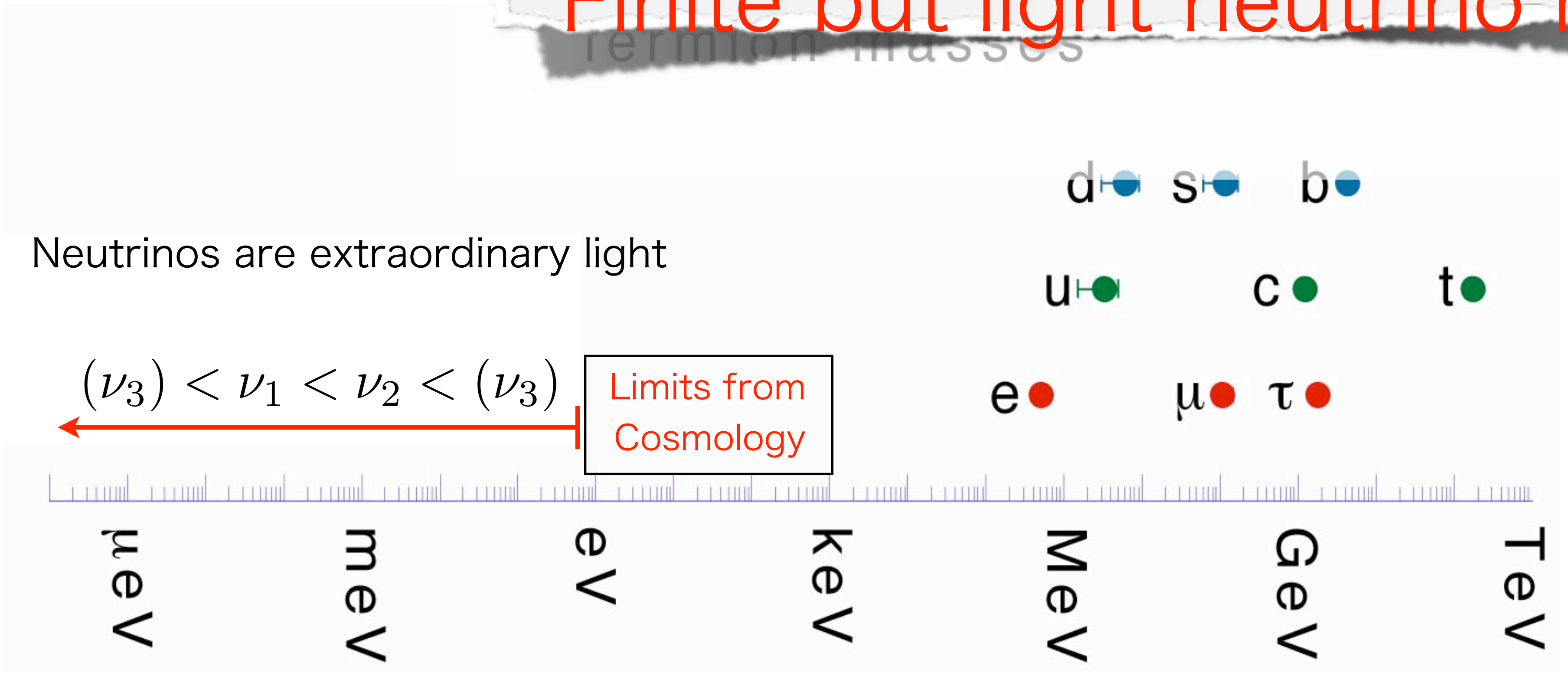
Matter Dominance

Finite but light neutrino mass

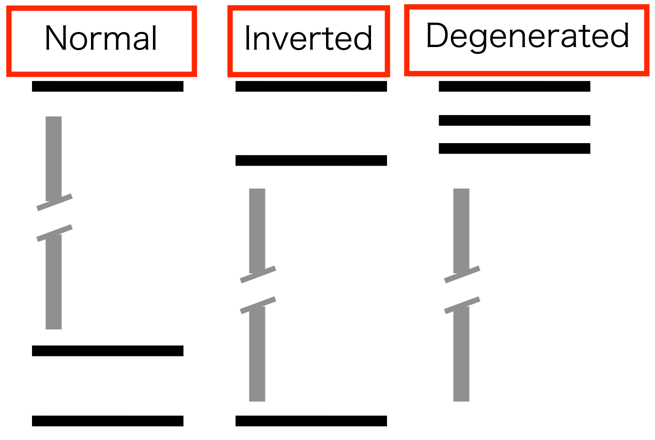
Neutrinos are extraordinary light

$(\nu_3) < \nu_1 < \nu_2 < (\nu_3)$

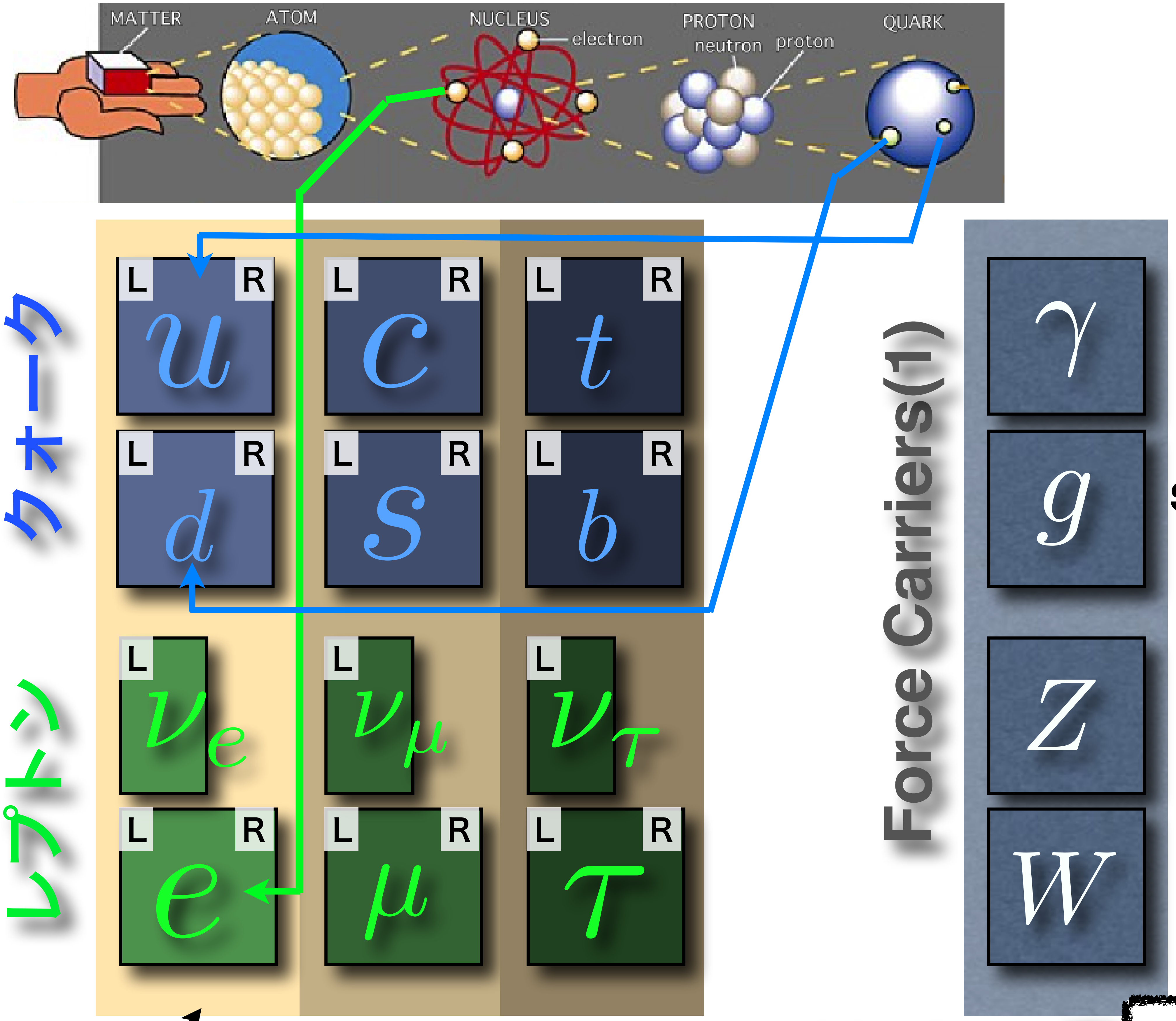
Limits from Cosmology



Mass hierarchy and Absolute masses are yet unknown



Matter Particles（1/2）



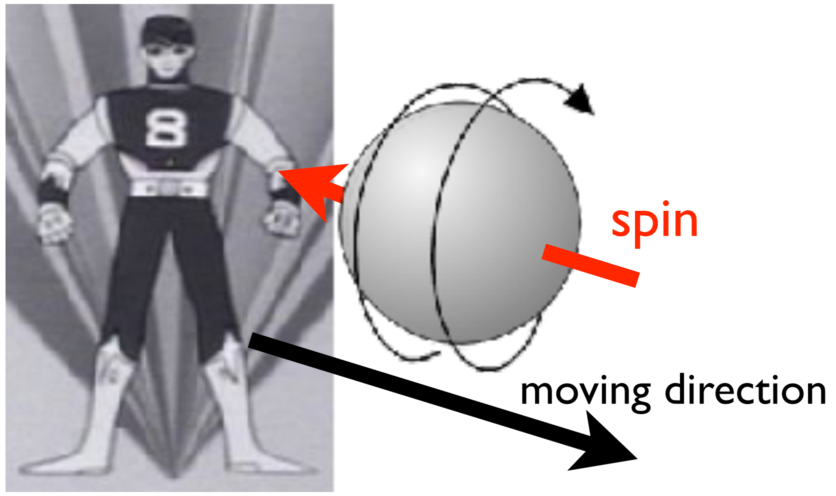
This generation constitute ordinary matter.

origin of mass(0) H^0

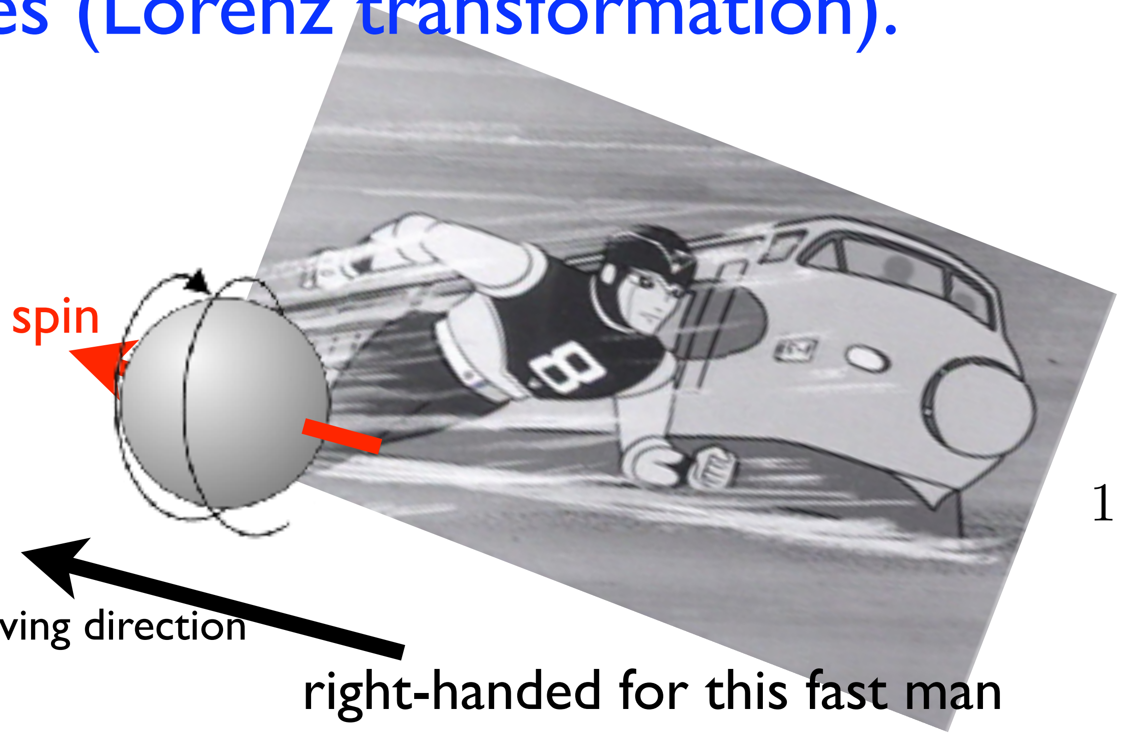
explains only 1% of ordinary matter!

Neutrino has mass and is slower than light.

Helicity (rotating direction wrt moving direction) changes in coordinates (Lorenz transformation).



left-handed for him



right-handed for this fast man

probability of helicity flip

$$1-\frac{p}{E}\sim\frac{1}{2}\left(\frac{m}{E}\right)^2$$

What is right-handed neutrino?

Discovery of neutrino mass

modification of ST
indication of GUT

right-handed neutrino?
Dirac vs Majorana

If Majorana,
Big leap toward the resolution of Big Mysteries of the universe!

Dirac vs. **Majorana**

e

LH electron (e^-_L)   RH electron (e^-_R)

LH positron (e^+_L)   RH positron (e^+_R)

Matter particle (Fermion) has at least 4 components.

It is naturally derived from quantum mechanics and special relativity (Dirac equation).

ν

LH ν_L RH ν_R (N_R)
not discovered

LH $\bar{\nu}_L$ ($\bar{N}_L$)
not discovered
RH $\bar{\nu}_R$

Dirac neutrino

$$\nu_L \quad \underbrace{\nu_R \quad \bar{\nu}_L}_{\text{unobservable}} \quad \bar{\nu}_R$$

$$\nu \neq \bar{\nu}$$

Majorana neutrino

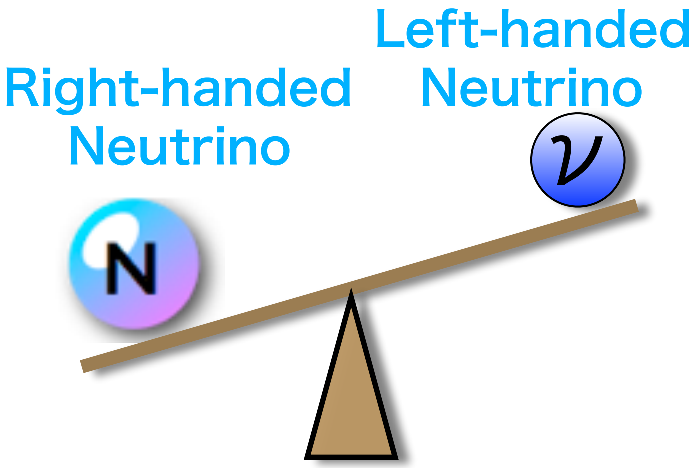
(1937)

$$\nu_L \quad \bar{\nu}_R \quad \underbrace{\bar{N}_L \quad N_R}_{\text{just heavy}}$$

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

Majorana neutrino violates Lepton #.

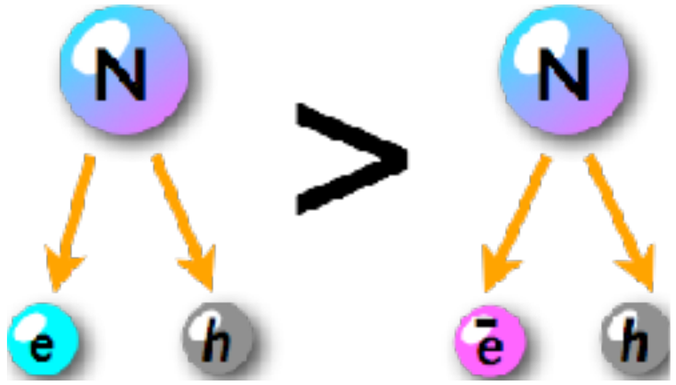
Seesaw Mechanism and Light neutrino mass



(Neutrino Mass) ~ m^2/M

Light neutrino mass

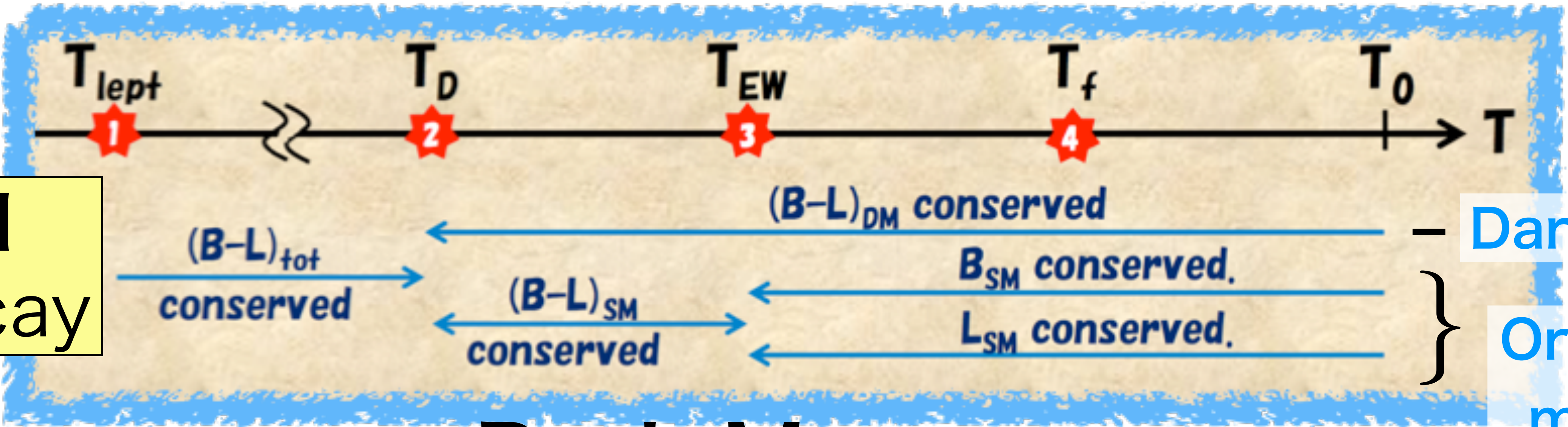
Matter dominance through Leptogenesis



Lepton number generated by right-handed neutrino decay transfers to Baryon number.

Matter dominance

Asymmetric Dark Matter (Dark Matter through Leptogenesis)



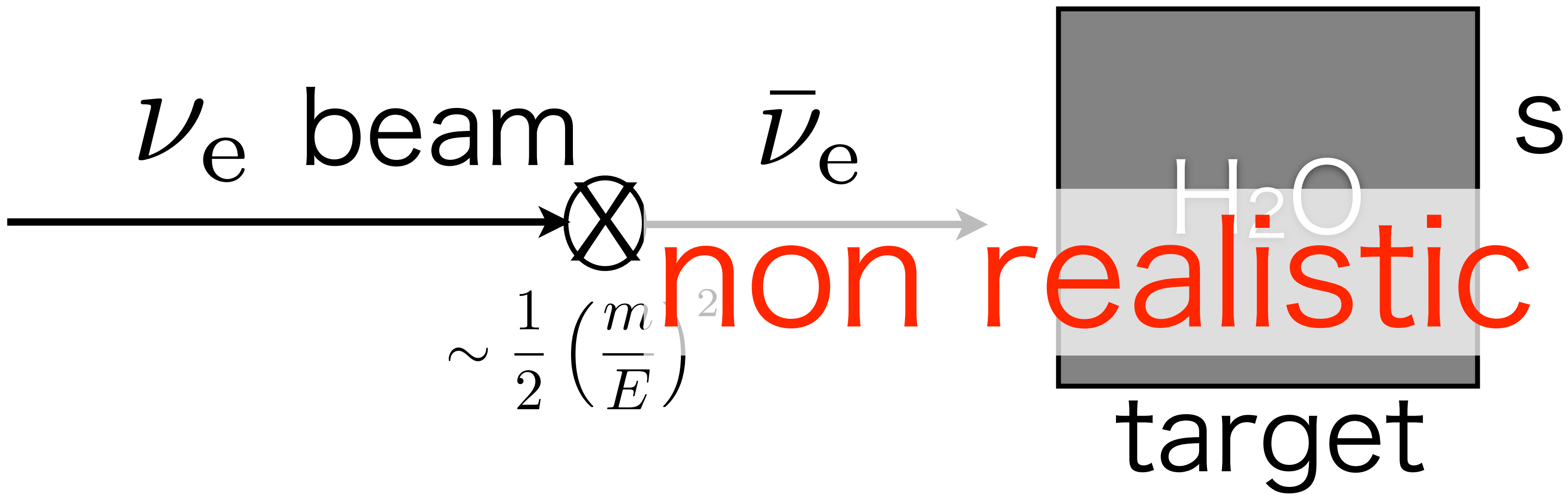
N decay

– Dark matter

} Ordinary matter

Dark Matter

Simple test for Majorana nature; $\nu = \bar{\nu}$



ν_e beam

$\bar{\nu}_e$

$\sim \frac{1}{2}\left(\frac{m}{E}\right)^2$

H_2O

non realistic

target

search for

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

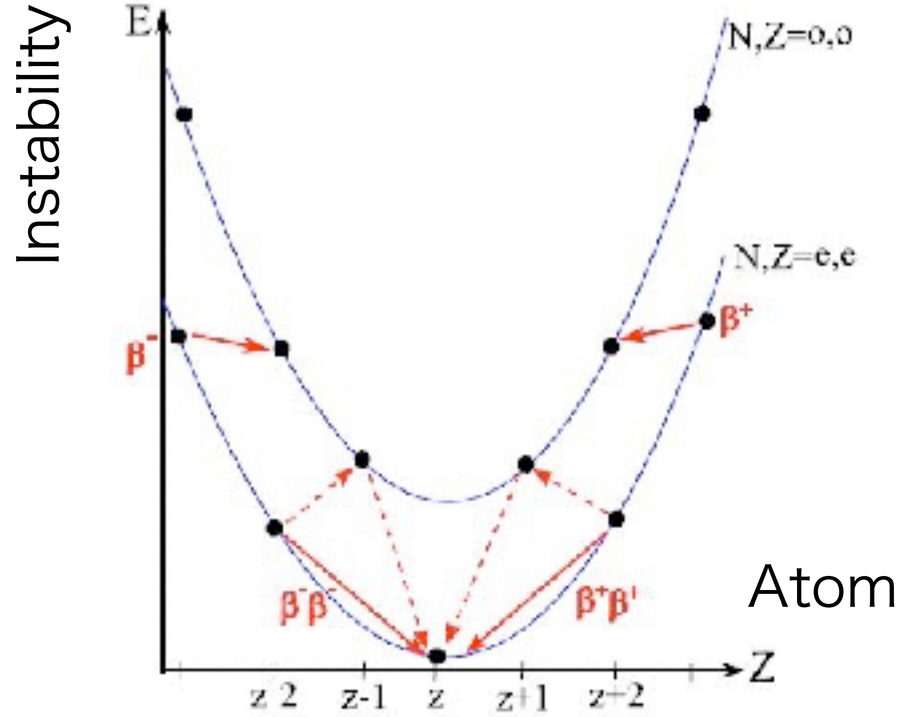
$$\sigma \propto E^2$$

Small mass(less than eV), high energy (MeV) prohibits helicity flip.

Cross section is also small.

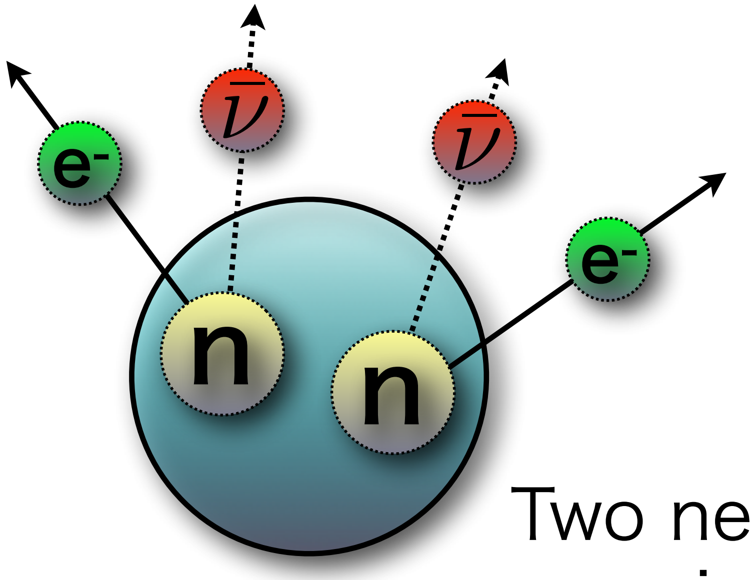
Fortunately, Nature is kind,

Several tens nuclei undergo “Double Beta Decay”.



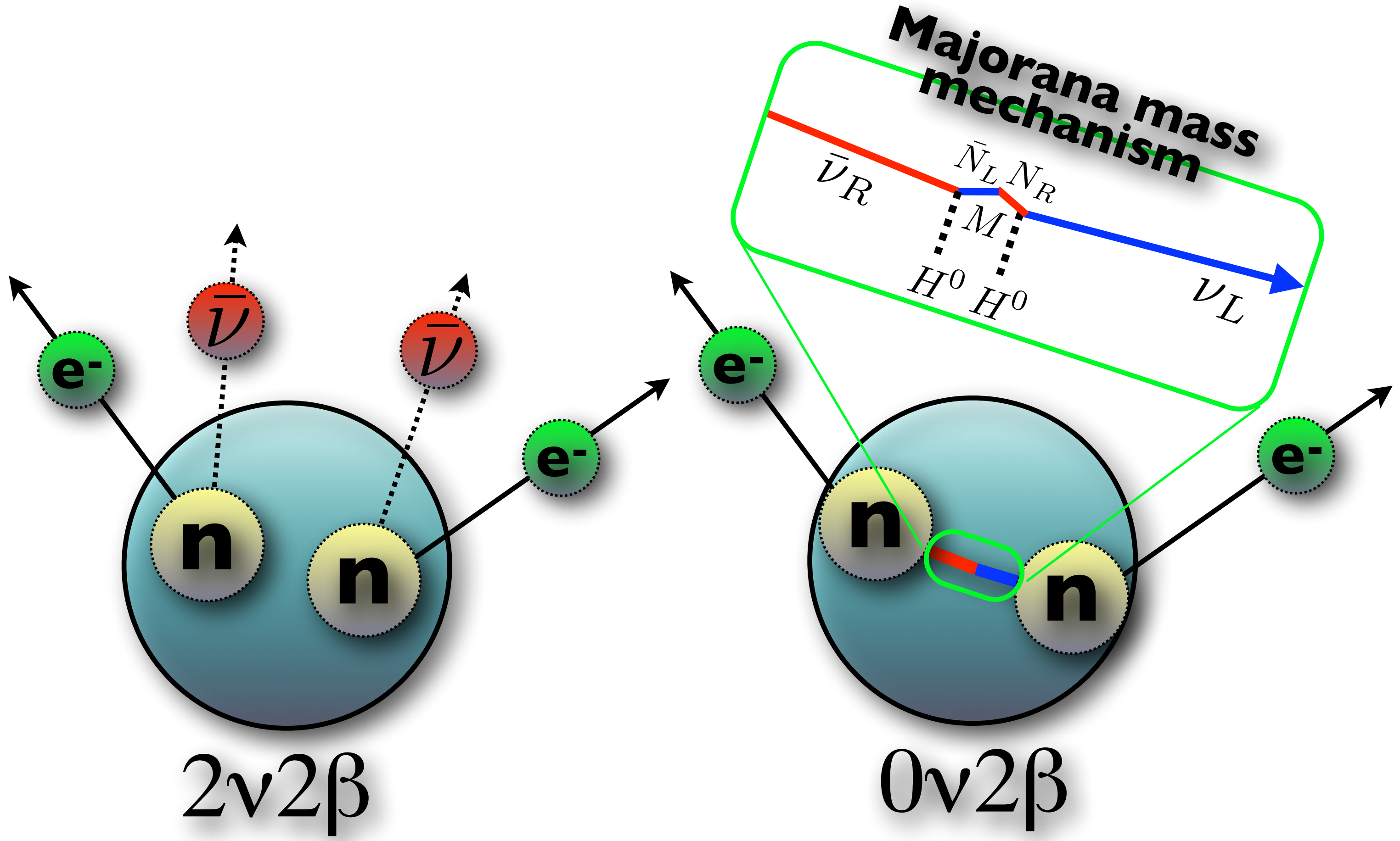
Atomic number

Two neutrinos are created simultaneously in the volume of nucleus size.



Two neutrinos may interact.

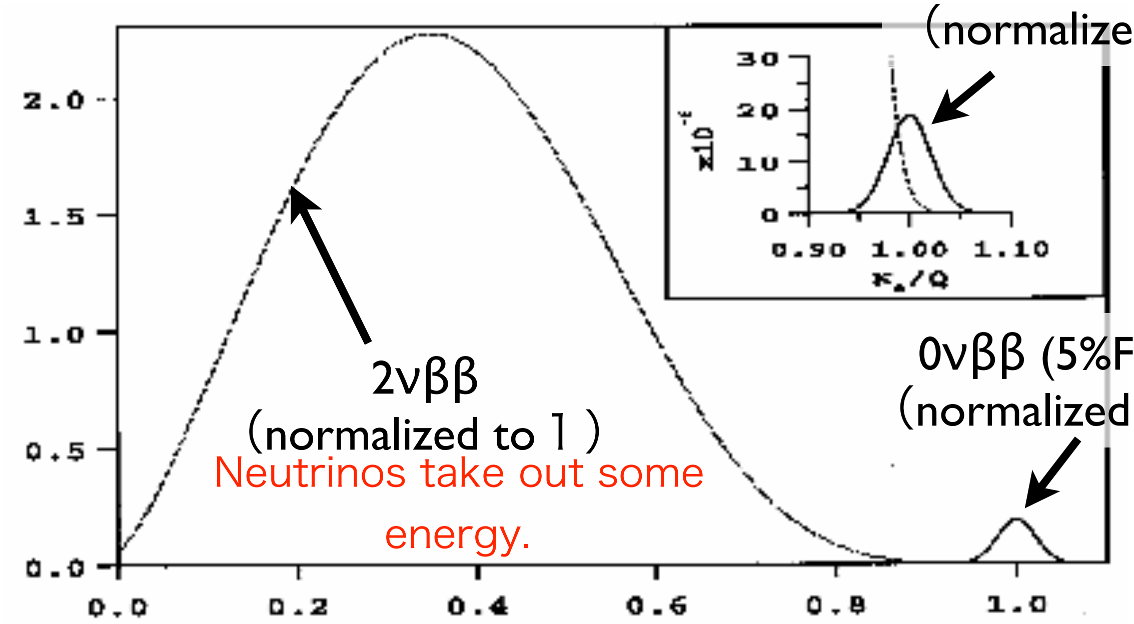
If neutrinos are Majorana, neutrino less double beta decay（0ν2β）can happen.



theoretical history

1930 light neutral particle (W.Pauli)
1933 β decay theory (E.Fermi)
1935 $2\nu2\beta$ (M.Goeppert-Mayer)
1937 Majorana neutrino (E.Majorana)
1939 $0\nu2\beta$ (W.Farry)


W.Furry



0νββ (5%FWHM)
（normalized to 10^{-6}）

2νββ
（normalized to 1）

Neutrinos take out some energy.

0νββ (5%FWHM)
（normalized to 10^{-2}）

Total energy is observed.

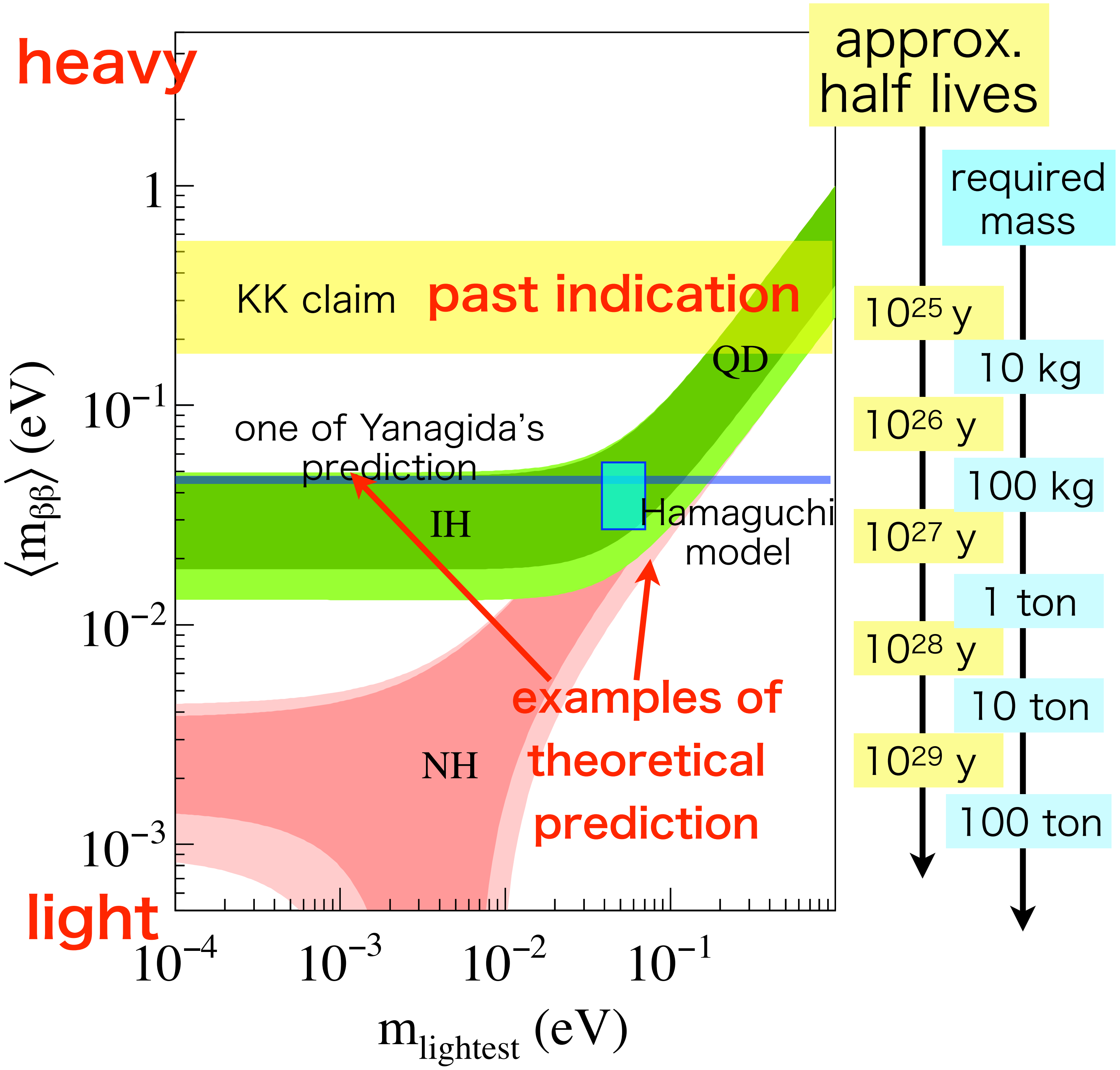
Larger the mass, easier to observe $0\nu2\beta$

Majorana CP

$$\langle m_{\beta\beta}\rangle = |\Sigma m_i |U_{ei}|^2 \varepsilon_i|$$

$$\frac{1}{T_{1/2}} = G_{0\nu}|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

Milestones of $0\nu2\beta$ search



✓ KK claim is refuted

KamLAND-Zen, EXO-200, GERDA

What's next?

✓ covering QD hierarchy

KamLAND-Zen has almost achieved.

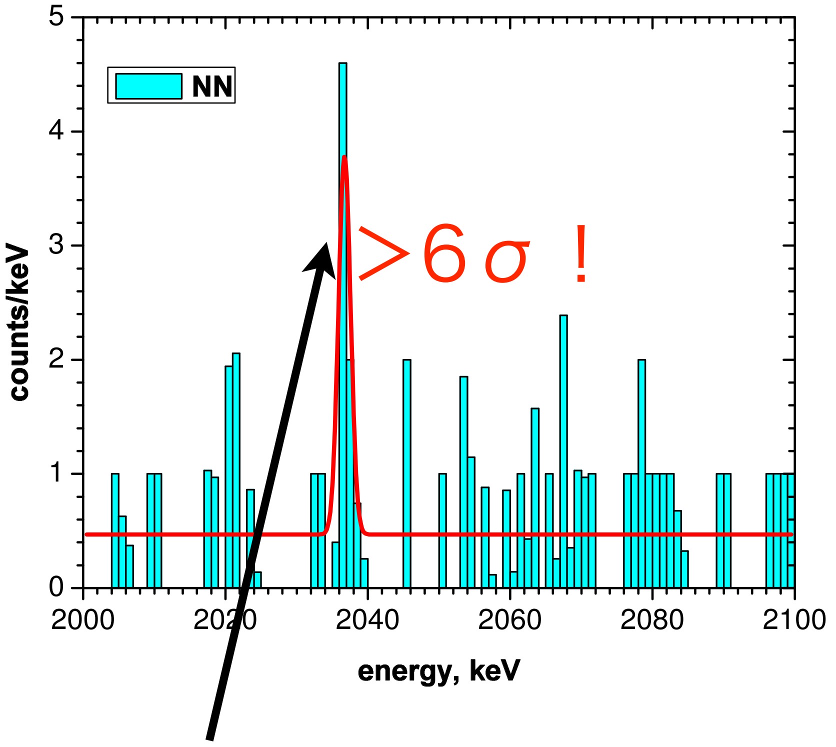
- Yanagida's prediction
  47±1 meV PRD86,013002(2012)
- Hamaguchi model
  24-55 meV (1 σ) arXiv:1705.00419
- covering IH
  ~20 meV next generation
- covering NH
  <1 meV very difficult

past big argument in $0\nu 2\beta$ search

KK claim

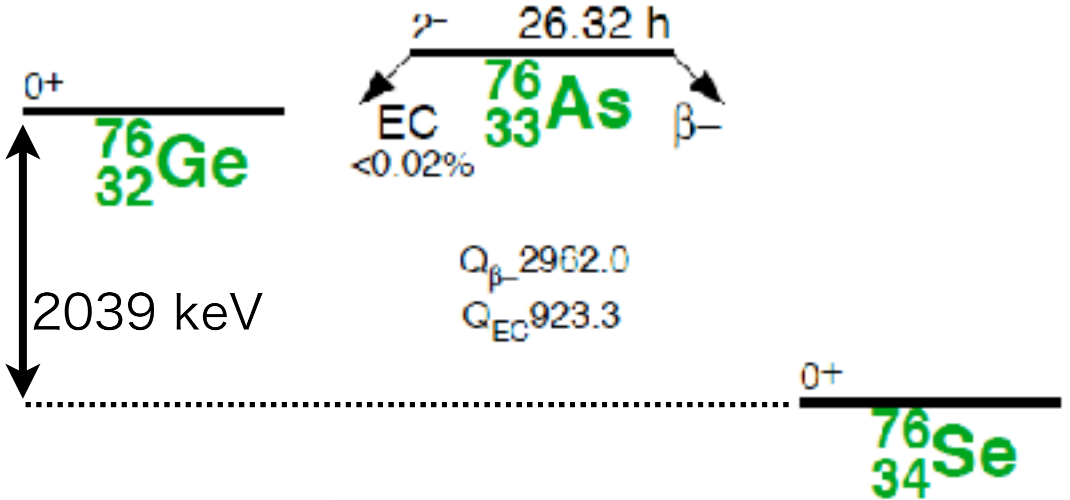
Part of Heidelberg Moscow experiment

Klapdor et al. Mod.Phys.Lett.A21(2006)1547



Evidence of $0\nu 2\beta$?

11 kg ^{76}Ge



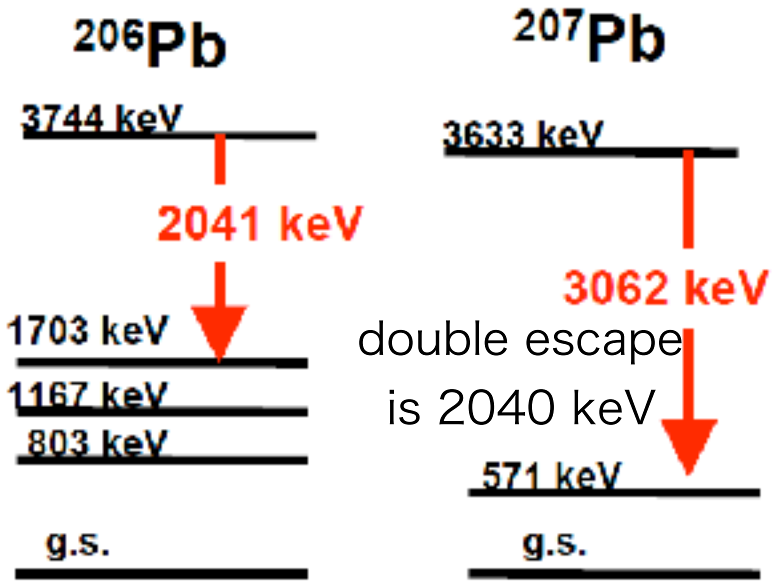
exposure 71 kg·year

$T_{1/2}=2.23^{+0.44}_{-0.31}\times 10^{25}$ years

$m_\nu = 320 \pm 30$ meV

NME uncertainty not included

BG candidates



double escape is 2040 keV

Statistical significance is high but there are many **BGs**, and not very convincing

Lesson:
"High resolution only" may suffer from unknown lines.

Strategy

Discovery may be close.

● Important to run with the best sensitivity and aim at the first discovery

  ○ Priority on **Scalability** with conventional and established technology

● In case $0\nu 2\beta$ is not found,

  ○ **Full coverage of inverted hierarchy is important**

  - if contradict with cosmology or neutrino oscillation → can say “Neutrino is Dirac”
  - if believing Majorana neutrino → can say “Normal hierarchy” by a process of elimination

  ○ **to be multi-purpose**

  for example, Geo-neutrino observation, 4th generation neutrino search, Solar neutrino observation, Dark matter search

● In case $0\nu 2\beta$ is discovered,

  ○ precision measurement

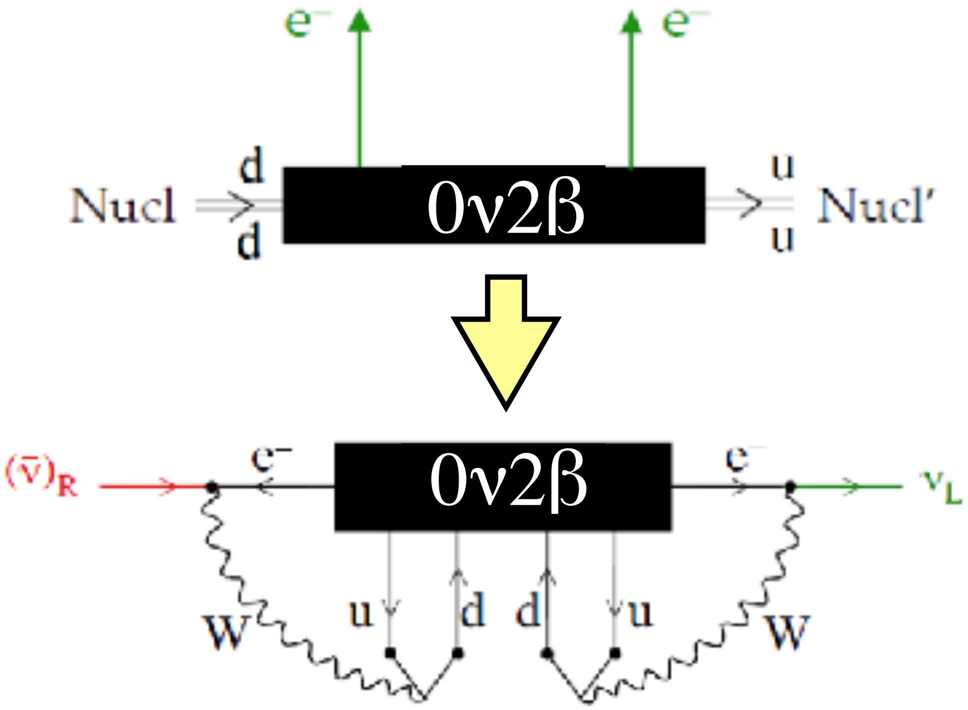
  ○ **various nuclei** → reduce error from NME, identify physics background diverse technology

  ○ **tracking measurement** → identify physics background diverse technology

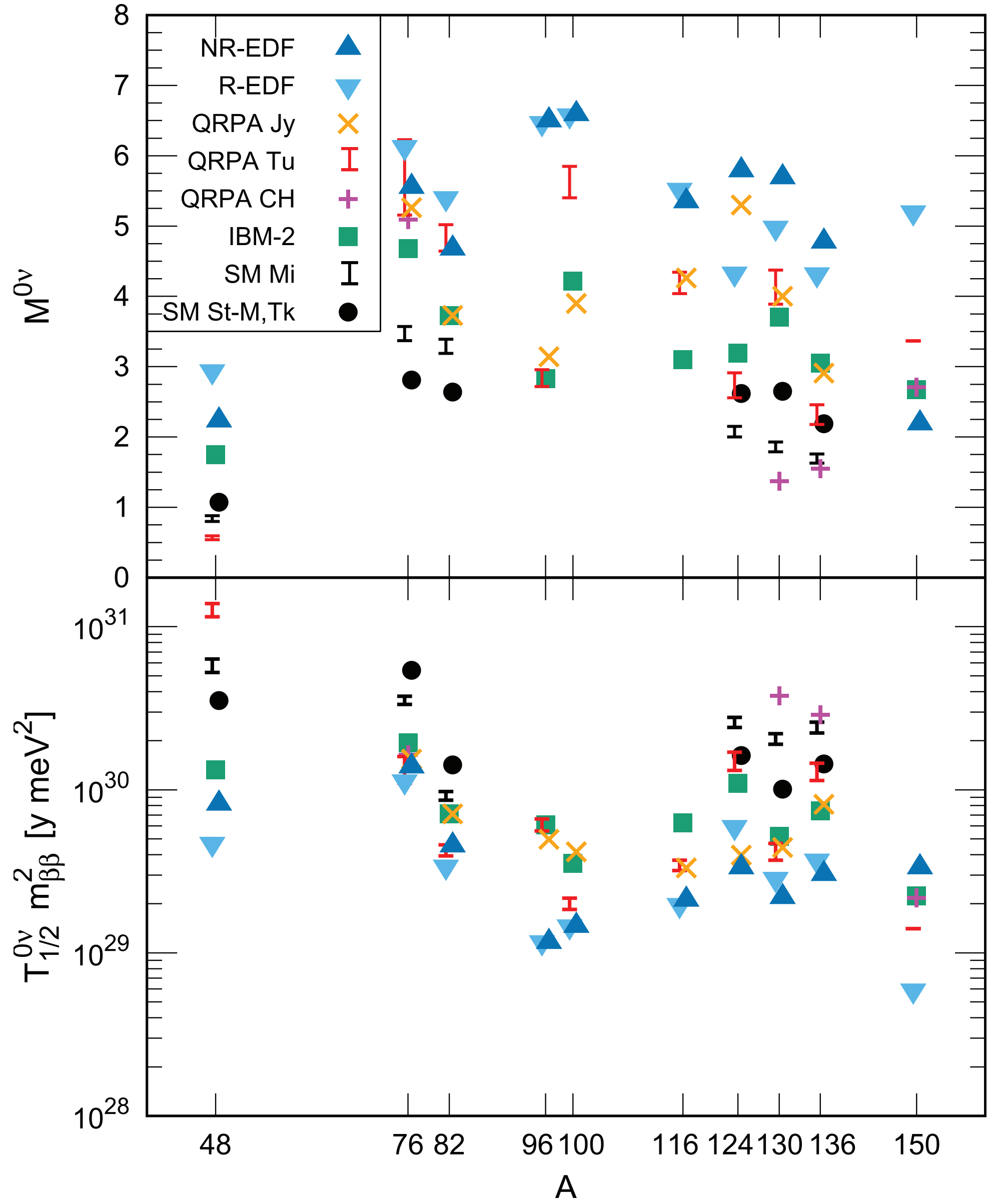
  ○ combine with cosmology, β decay → identify physics, possibility of Majorana CP measurement

Regardless of physics background 0ν2β is evidence of Majorana neutrino

(Schechter-Valle theorem)



$$\frac{1}{T_{1/2}} = G_{0\nu}|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$



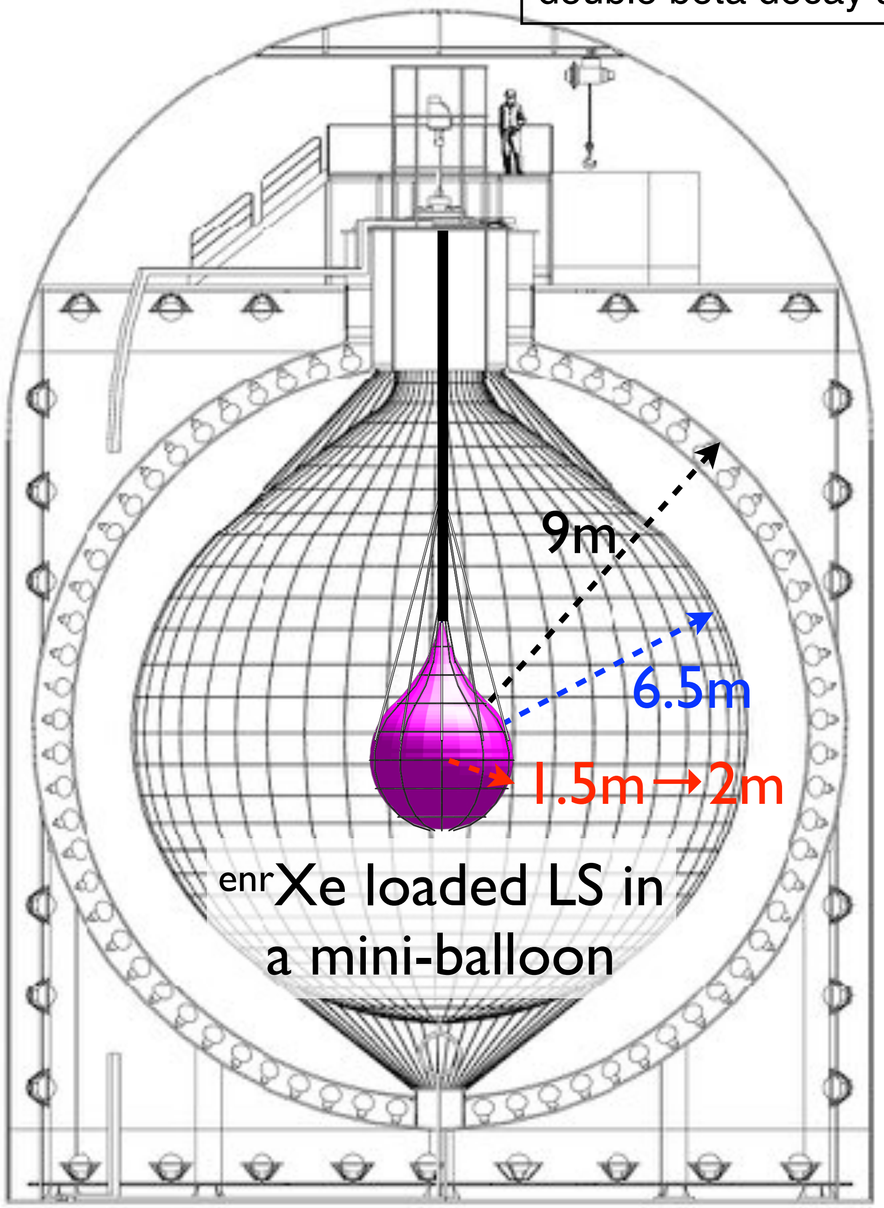
Rep. Prog. Phys. 80 (2017) 046301

recent arguments : effective g_A

It may suppress $0\nu2\beta$ by another factor 50.

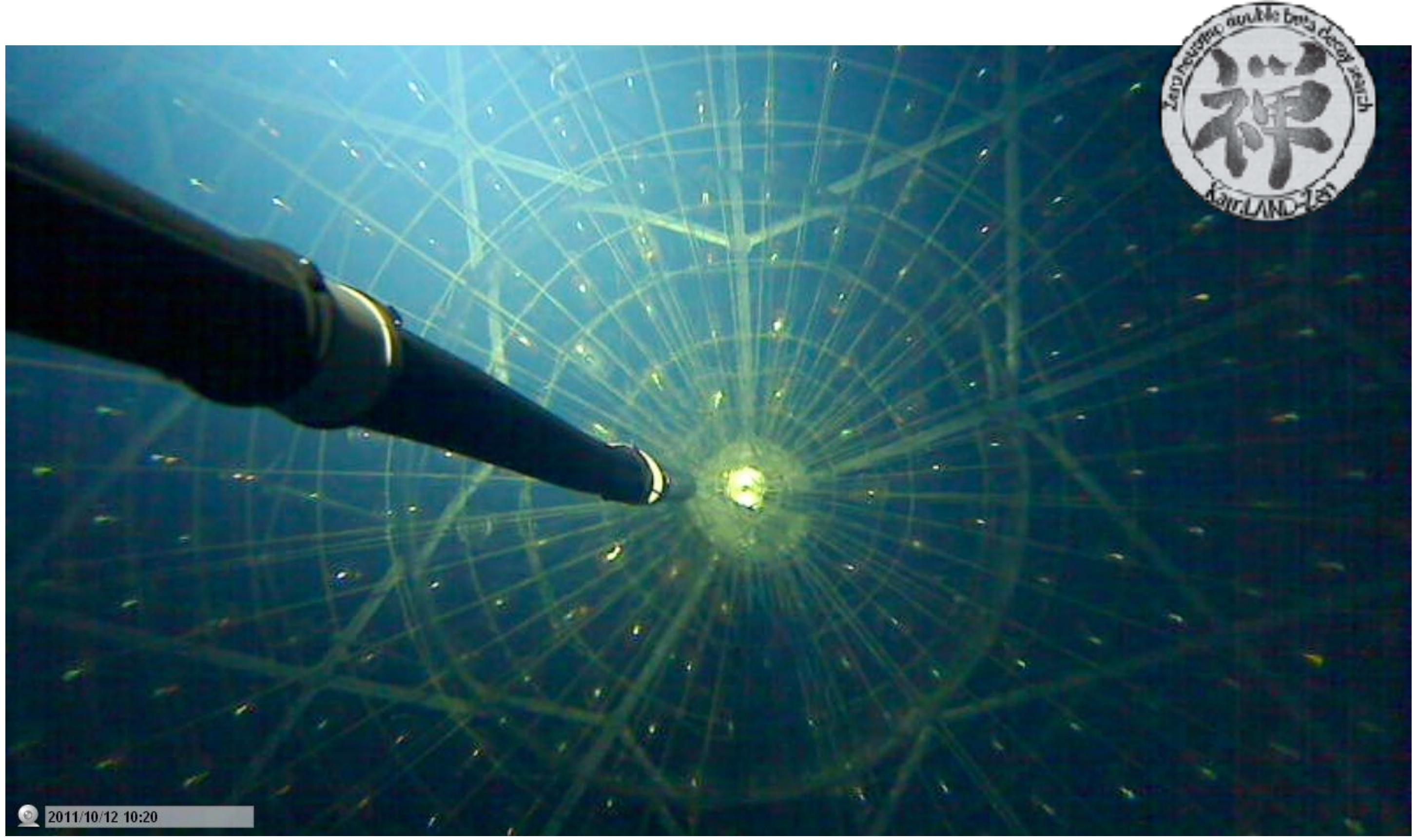
Current world best limit from
KamLAND-Zen

Zero Neutrino
double beta decay search



90% enriched ^{136}Xe
320kg for phase-I
380kg for phase-II
750kg for Zen 800 (to start in months)

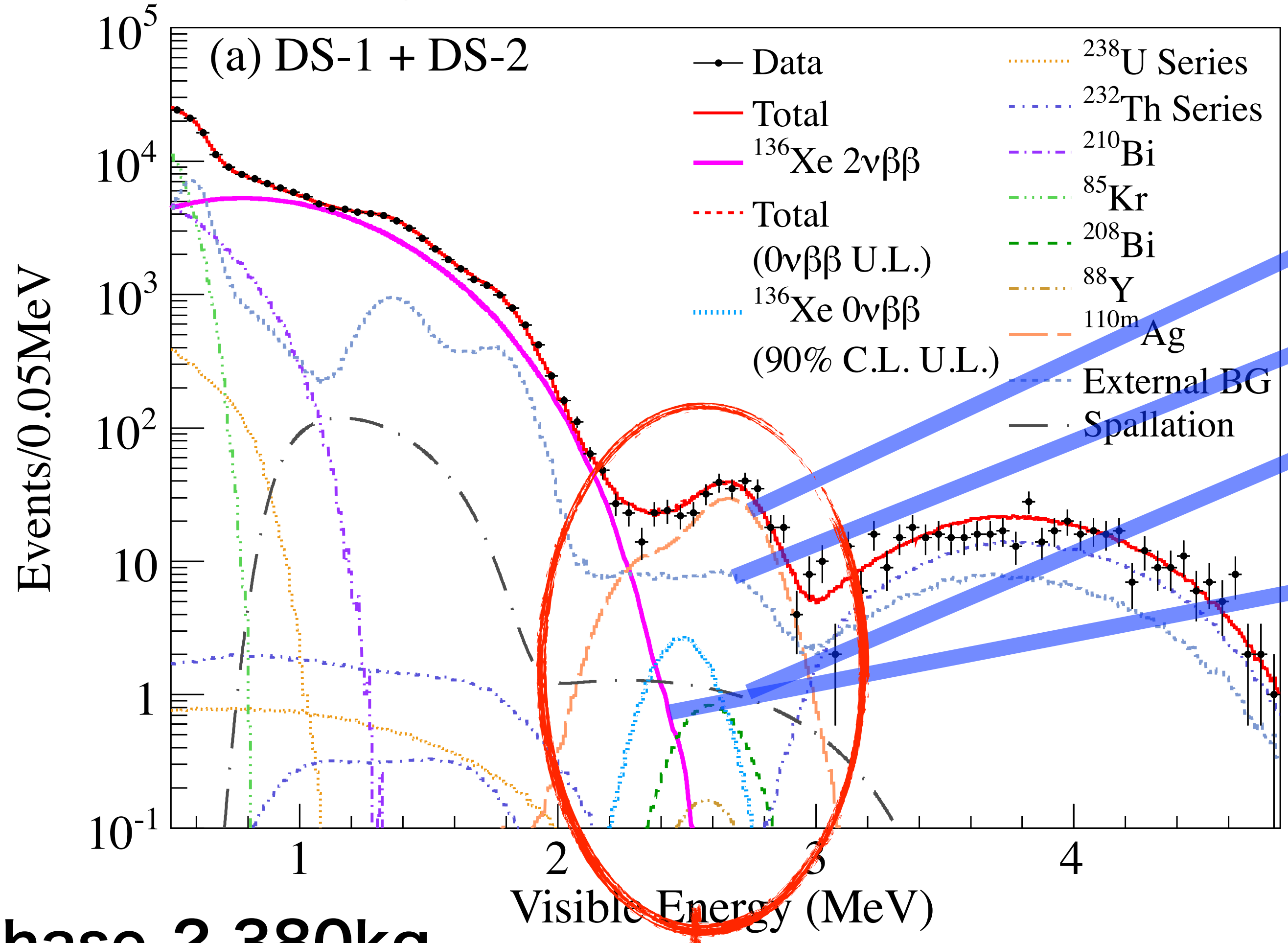
largest
amount
so far



Advantages of using KamLAND

- running detector
  → relatively low cost and quick start
- huge and clean (1200m^3, U: 3.5x10^{-18} g/g, Th: 5.2x10^{-17})
  → negligible external gamma
  (Xe and mini-balloon need to be clean)
- Xe-LS can be purified, mini-balloon replaceable if necessary, with relatively low cost
  → highly scalable (up to several tons of Xe)
- No escape or invisible energy from β, γ
  → BG identification relatively easy
- **anti-neutrino observation continues**
  → geo-neutrino w/o Japanese reactors

Phase-1 320kg



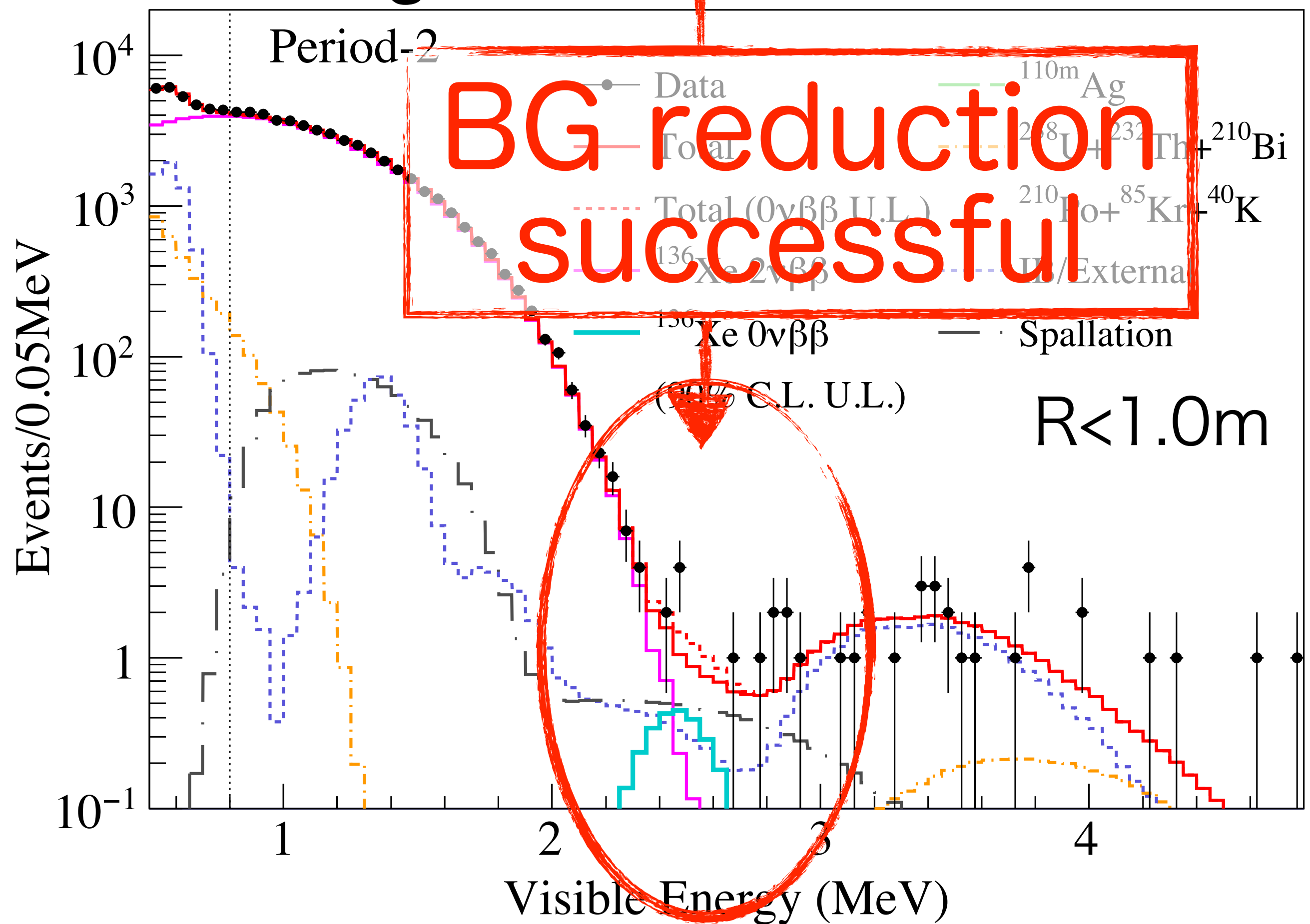
^{110m}Ag LS

^{214}Bi balloon

^{10}C LS

2ν2β LS

Phase-2 380kg



BG reduction successful

Phase-1,2 combined results

!!!

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

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

What KLZ has demonstrated;

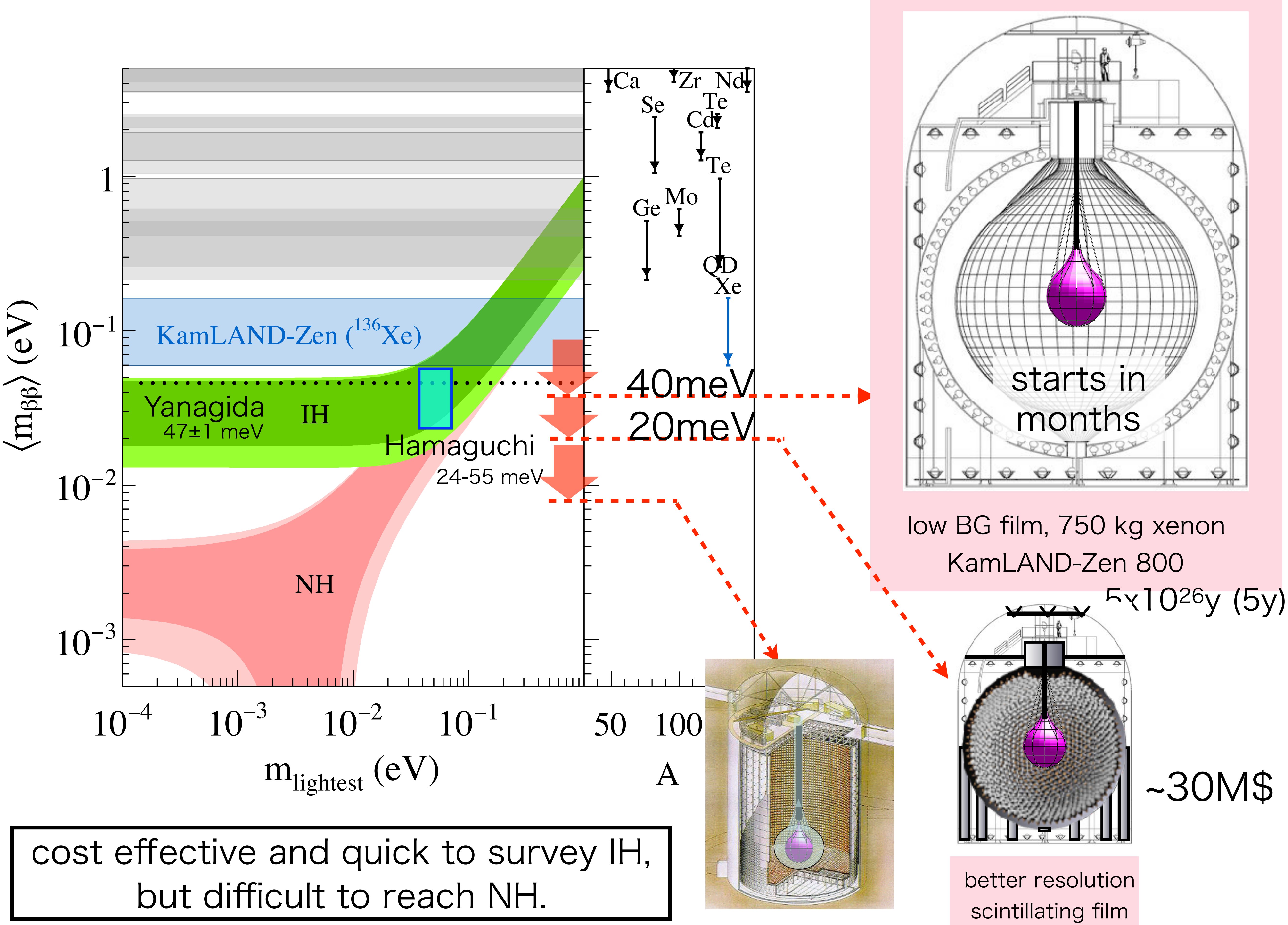
① BG can be identified (full active)

② In-situ purification possible (liquid media)

③ On/Off measurement possible (xenon is gas)

④ multi-purpose (geo-neutrino)

⑤ easily scalable (mini-balloon)



40meV

20meV

starts in months

low BG film, 750 kg xenon

KamLAND-Zen 800

5×10^{26}y (5y)

~30M$

better resolution

scintillating film

KamLAND2-Zen

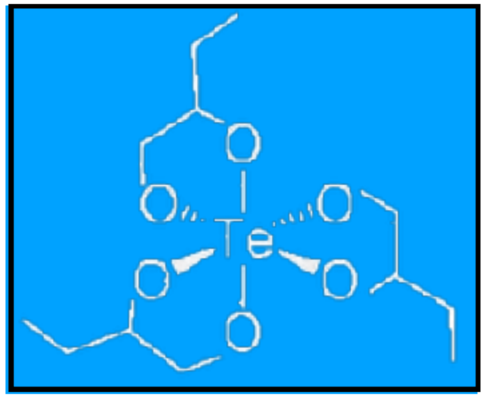
2×10^{27}y (5y)

cost effective and quick to survey IH,
but difficult to reach NH.

poor resolution / BG discrimination

SNO+

uniformly dissolved
Tellurium-ButaneDiol



natural abundance of ^{130}Te: **34%**

phase I, 0.5 wt% loading
(1.3t, 260kg fiducial)
sensitivity: 2×10^{26} yr, 38~92 meV (5y)

phase II, 2wt% loading + HQE PMTs
target sensitivity: 10^{27} yr, 17~41 meV

Enrichment is not necessary.

Negligible spallation BGs. (deep site)

Toward High resolution & BG discrimination

poor resolution

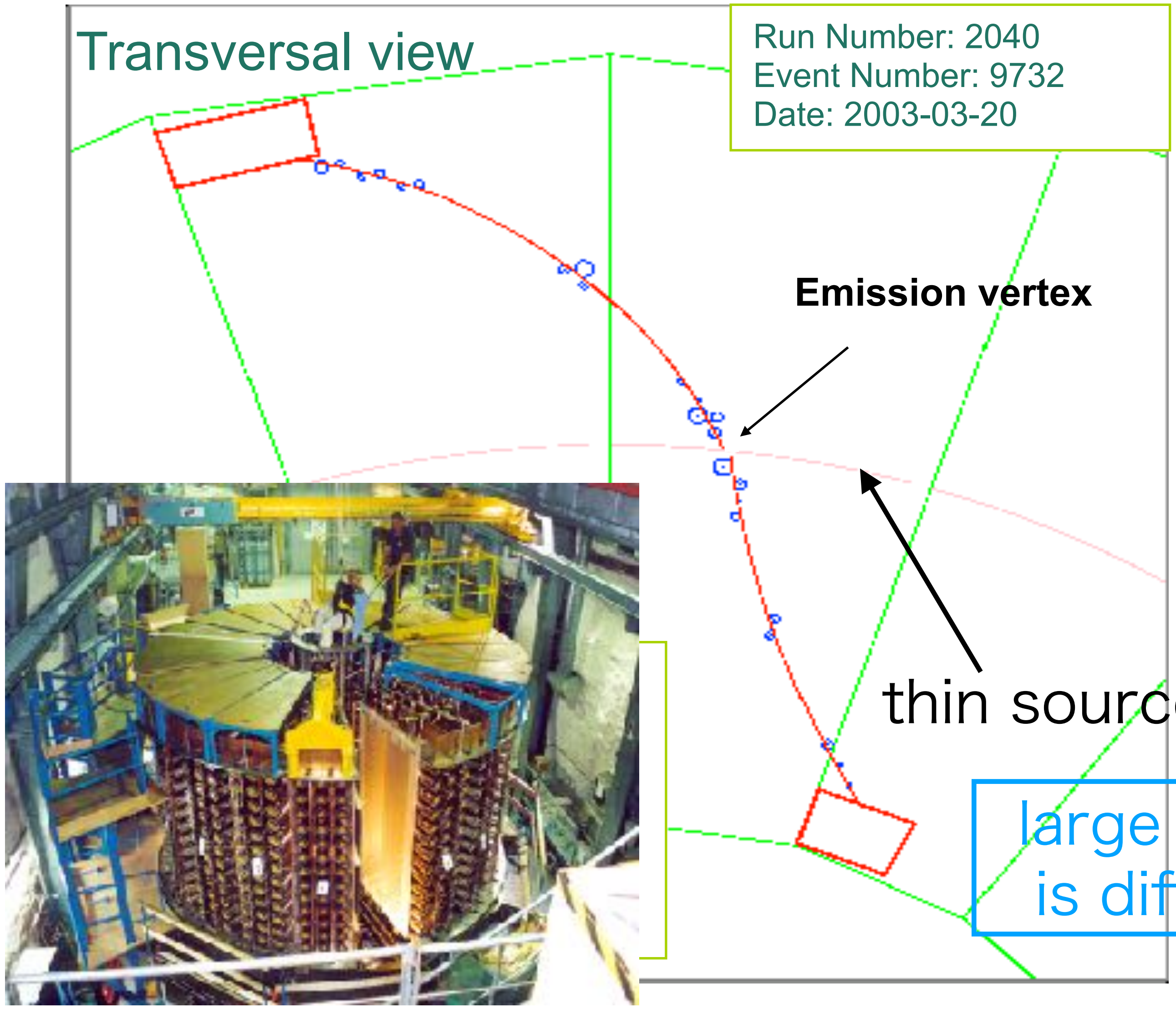
↕

good resolution

projects listed in
“report to NSAC, NLDBD2015”

LS	KamLAND-Zen → KLZ 800 → KL2Z
	→ SNO+ phase I → SNO+ phase II
Track-Calo	NEMO-3 → SuperNEMO
Xe TPC	→ NEXT-100 → NEXT-1.5k
	→ PandaX-III 200 → PandaX-III 1k
liq.Xe TPC	EXO-200 → nEXO
Bolometer	CUORE → CUPID
Germanium	GERDA → LEGNED 200 → LEGEND 1k
	Majorana ↗

NEMO-3 → SuperNEMO



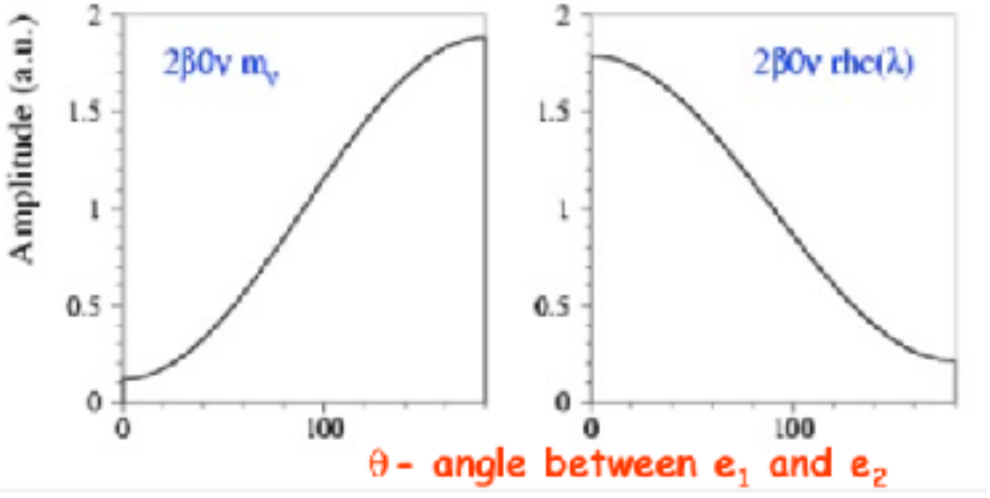
large mass is difficult

Many different nuclei have been measured.

^{100}Mo, ^{82}Se, ^{150}Nd, ^{130}Te, ^{96}Zr, ^{48}Ca, ^{116}Cd

$T_{1/2}>1\times10^{24}$ y (7kg)
m > 0.47~0.96 eV

Angular distribution is important to understand physics behind.

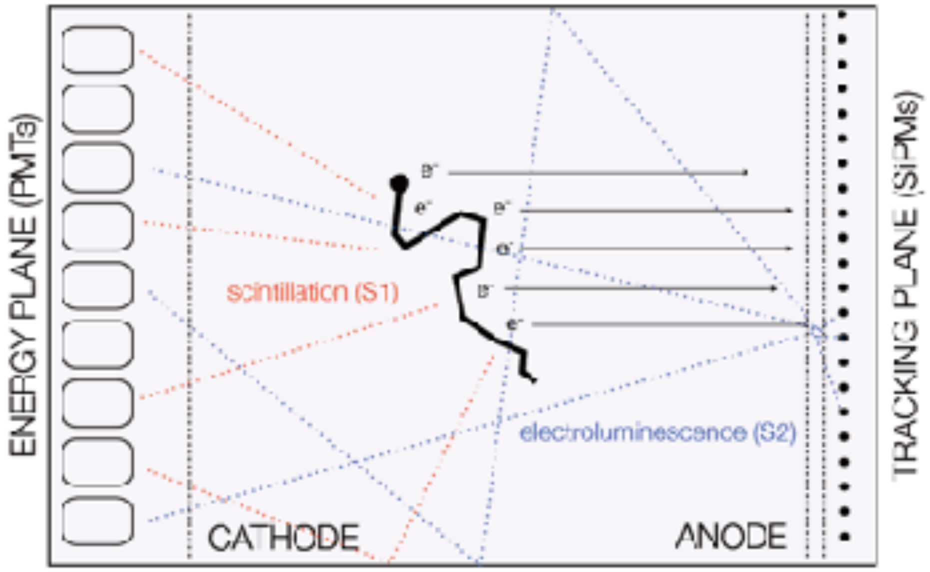


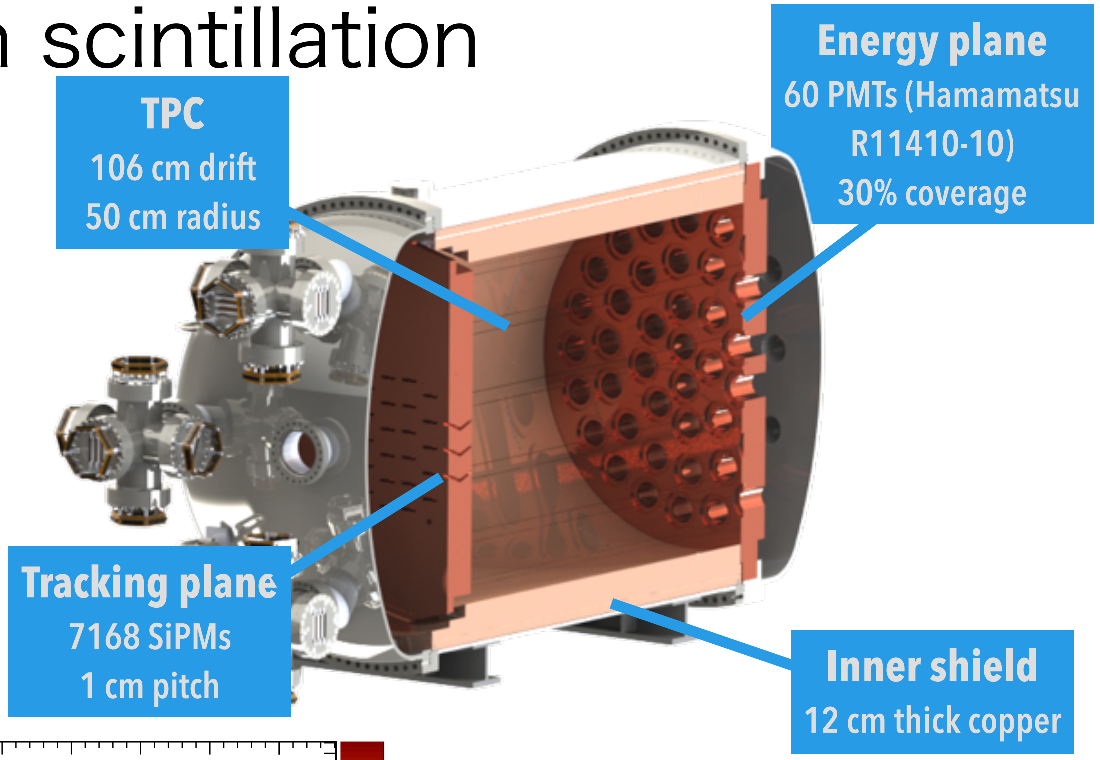
Expected sensitivity of SuperNEMO
50~100 meV (5 y, 100 kg ^{82}Se)

Once $0\nu2\beta$ is found, this type of experiment becomes very important.

NEXT-100 → NEXT-1.5k

High pressure xenon gas TPC with scintillation

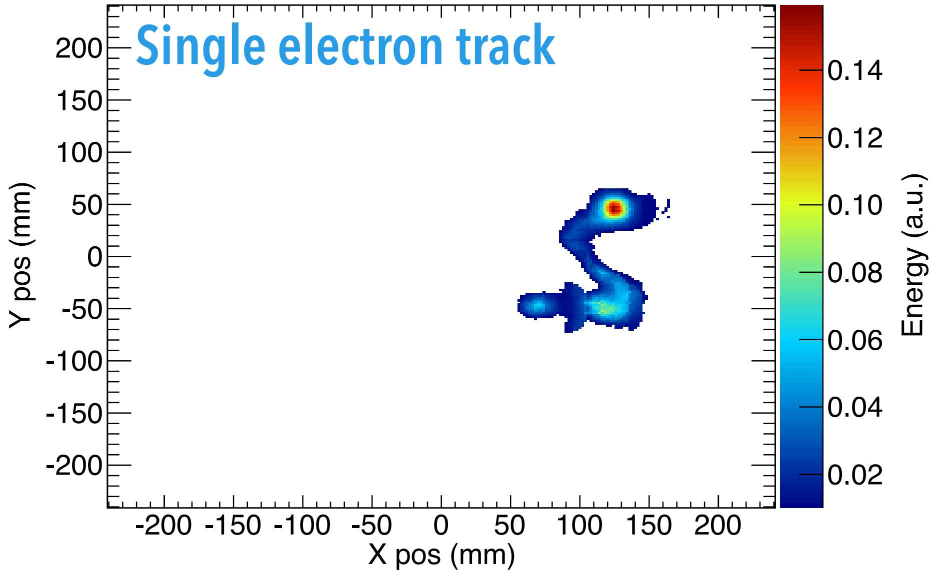


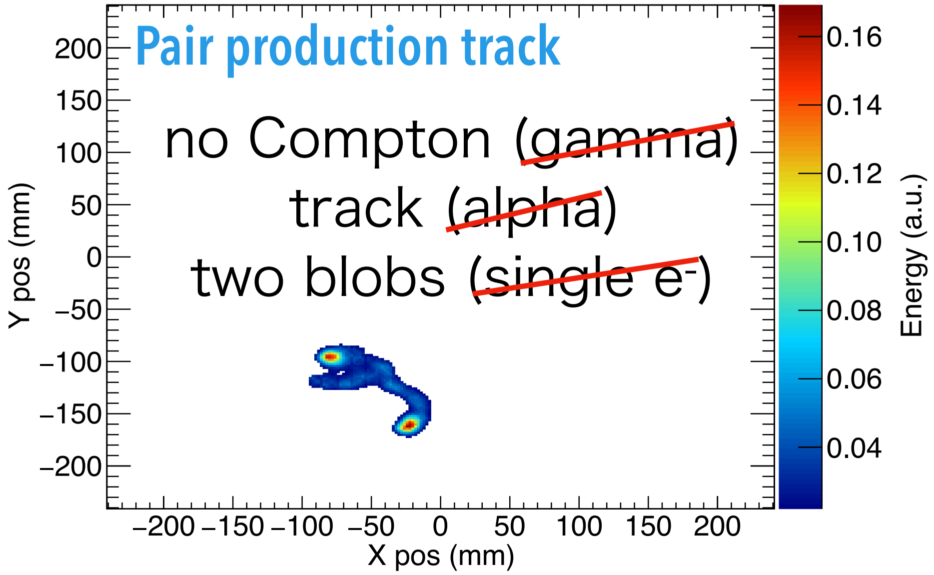

TPC
106 cm drift
50 cm radius

Energy plane
60 PMTs (Hamamatsu R11410-10)
30% coverage

Tracking plane
7168 SiPMs
1 cm pitch

Inner shield
12 cm thick copper


Single electron track


Pair production track

no Compton (~~gamma~~)
track (~~alpha~~)
two blobs (~~single e⁻~~)

Single electron/ gamma / alpha can be discriminated.

External gamma need to be suppressed.
Large mass requires huge detector.
Angular distribution will be difficult.

NEXT-100 will starts by the end of 2018 with sensitivity of 5x10^{25} yrs in 3yrs, 90-180 meV.

EXO-200 → nEXO

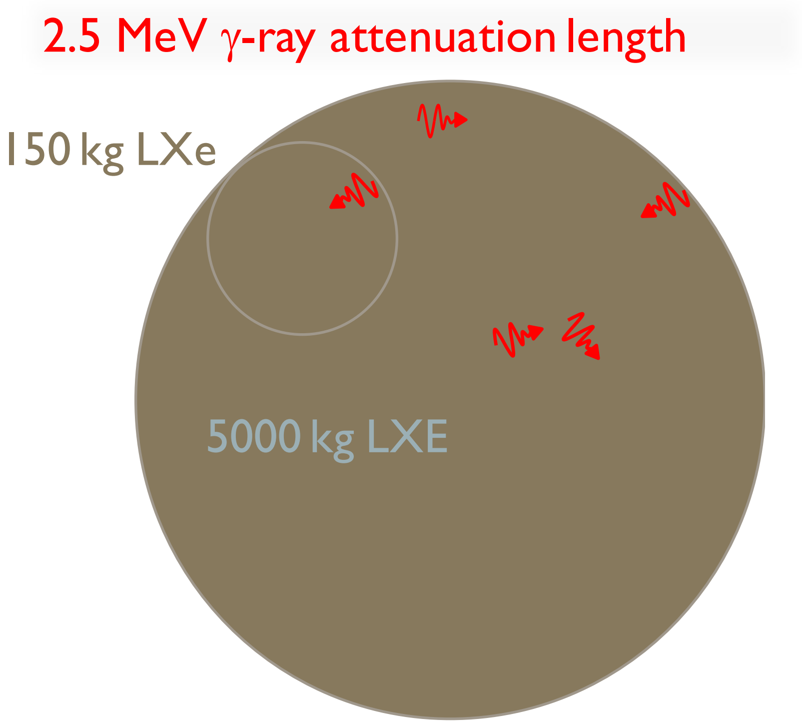
liquid xenon TPC with scintillation

Xenon amount 200 kg (80% enrichment)
→ 5t in nEXO

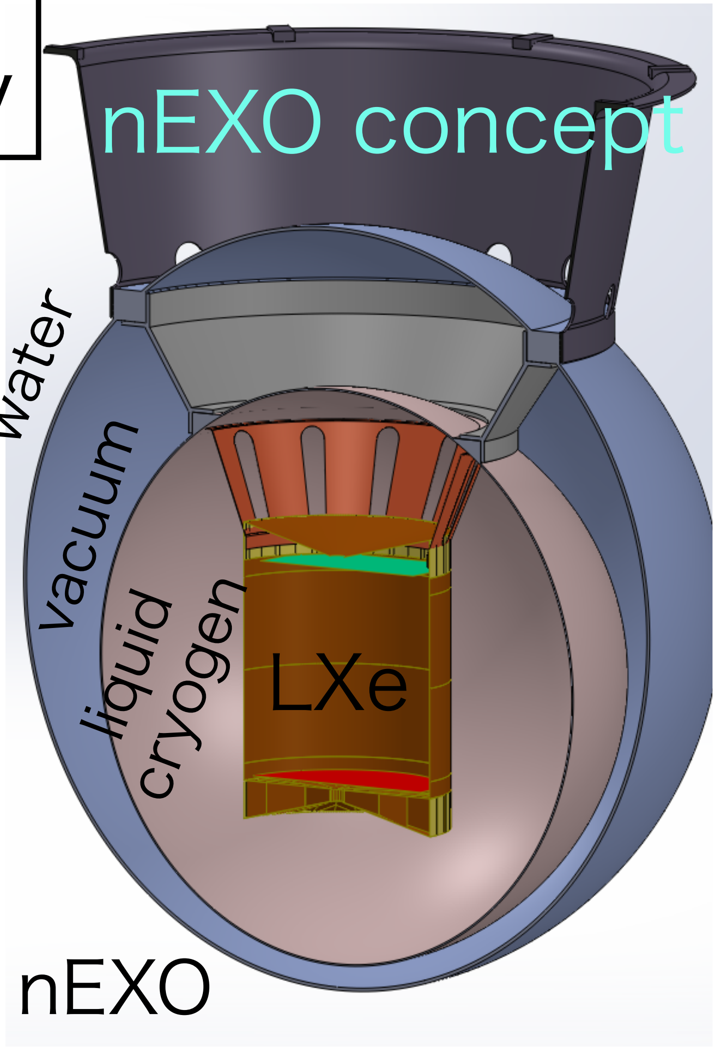
No track information, but multi-site vs single-site separation very efficient to reduce Compton BG.

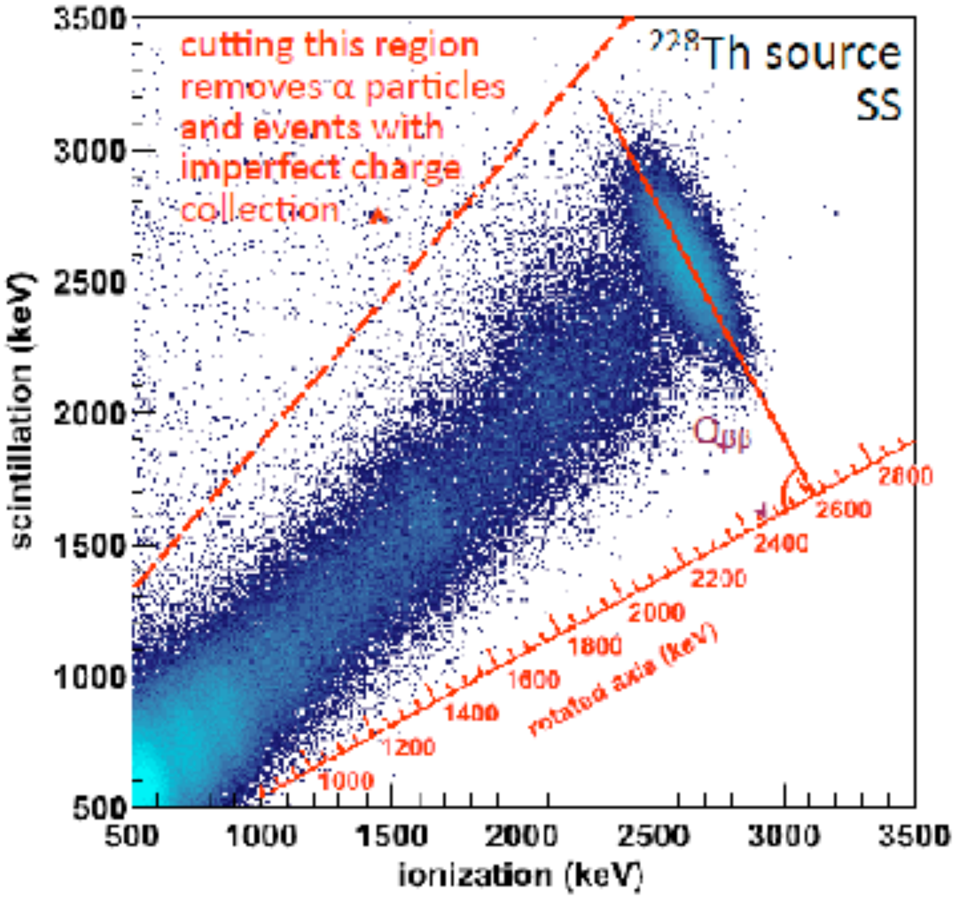
arXiv:1707.08707

current EXO-200 result
$T_{1/2}>1.8\times10^{25}$ y
m > 147~398 meV



powerful self-shielding in nEXO



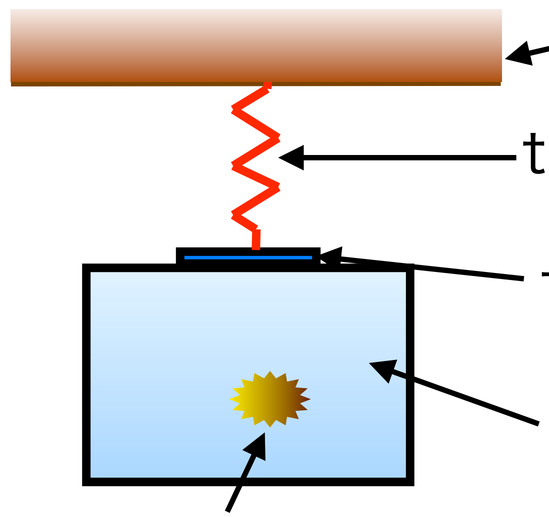


Correlation of ionization & scintillation provides good enough energy resolution.

~1.2%/√E (200 phase II)

nEXO target
9.2×10^{27}y (10y)
6~18 meV

CUORE → CUPID (CUORE Upgrade with Particle Identification)



heat sink (Cu)
C∝T^3, **~10mK**

thermal coupling (PTFE)

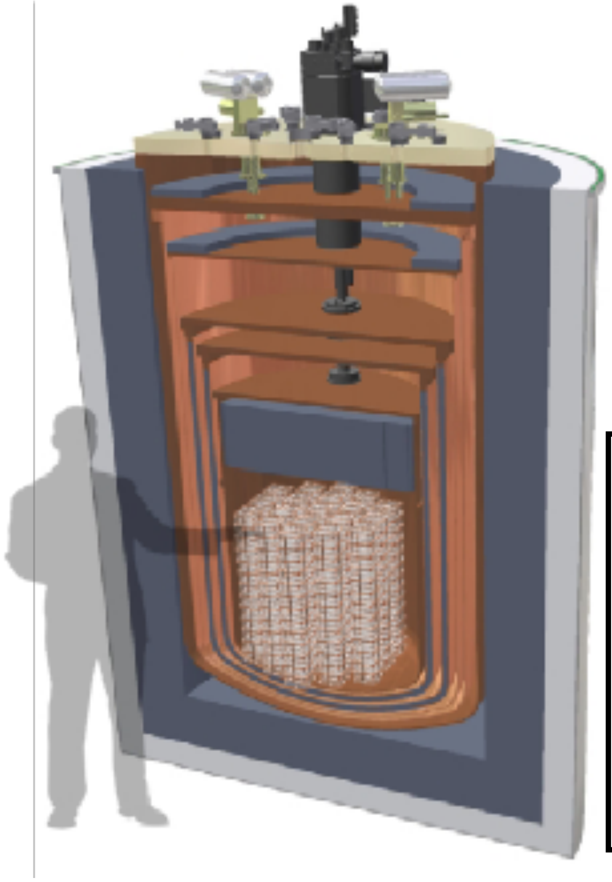
thermistor (NTD-Ge)

absorber (TeO_2)

energy deposit

ΔT=~0.1mK/MeV

effective resolution
7.7keV FWHM@2527keV



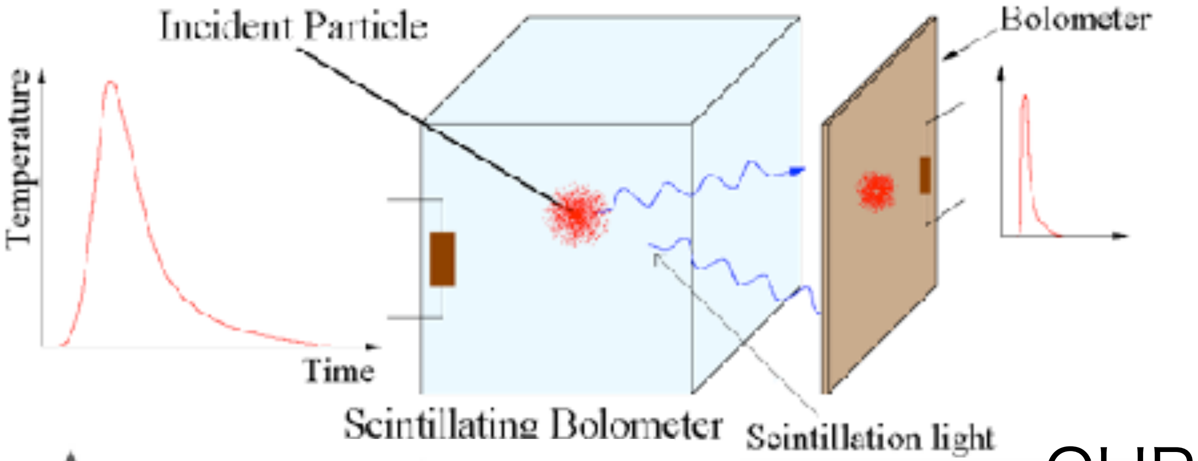
988 detectors
741 kg of TeO_2
204 kg of ^{130}Te

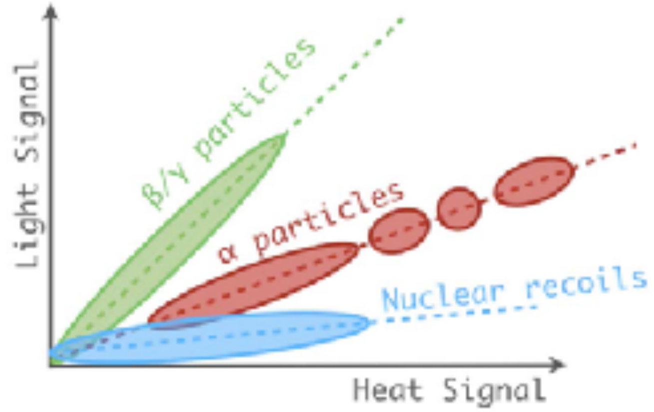
current CUORE result
(arXiv:1710.07988)

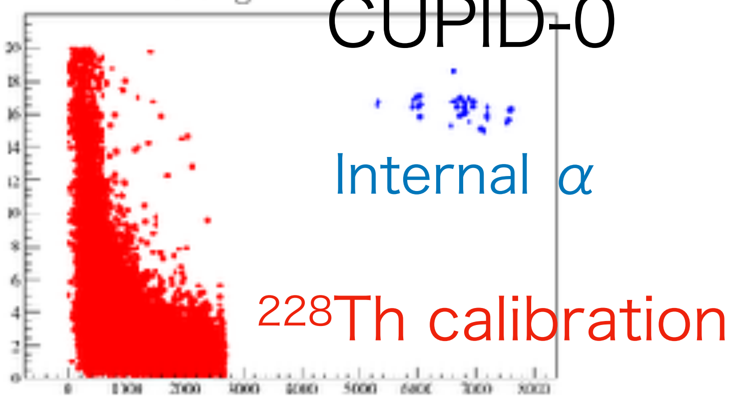
$T_{1/2} > 2.8 \times 10^{24}$ yr (90%)

$m_{ee} < 0.3 \sim 0.7$ eV

Scintillating bolometer brings PID







Unfortunately,
TeO_2 doesn't scintillate.
There are other candidates;
$Zn^{82}Se$, $Zn^{100}MoO_4$, $^{116}CdWO_4$

Target sensitivity

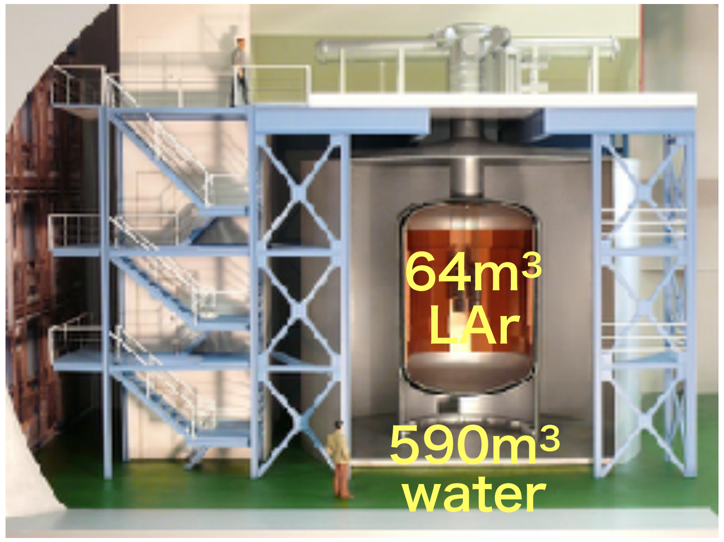
$Zn^{82}Se$ case (335kg ^{82}Se)

$T_{1/2} > 4.2 \times 10^{27}$ yrs (10y)

$m_{ee} < 6\text{-}19$ meV

GERDA, Majorana → LEGEND

Large Enriched Germanium Experiment
for Neutrinoless Double-Beta Decay



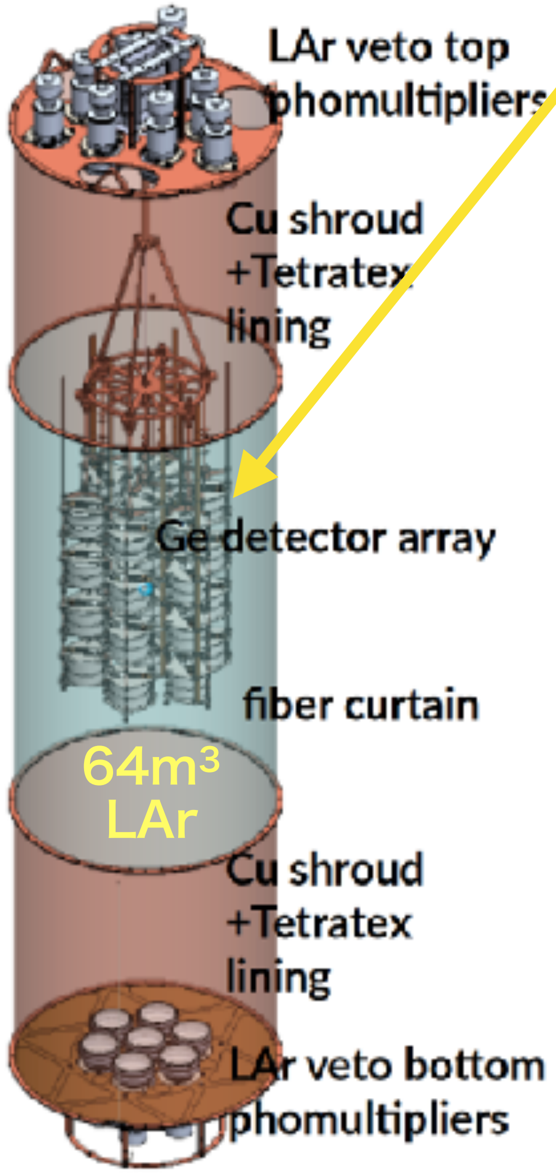
810
scintillator
fibers coupled
to 90 SiPMs

GERDA Phase II result

Nature 544, 47-52 (2017)

$T_{1/2} > 5.3\text{x}10^{25}$ yrs (90%)

mee < 150~330meV

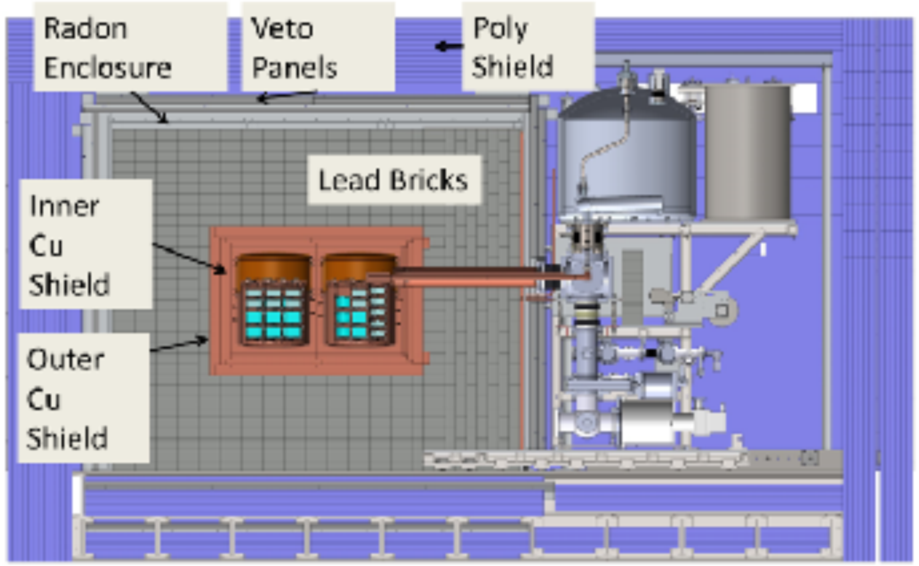


GERDA uses liquid argon active veto.

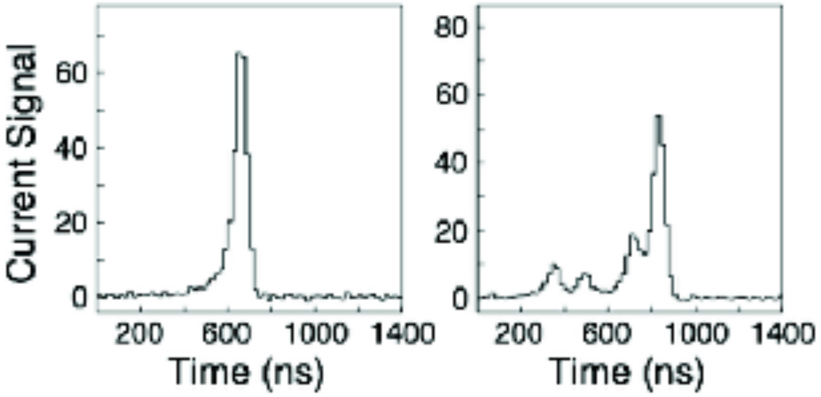
35.8kg enriched + 7.6 kg natural Ge **3keV FWHM@2039keV**

Majorana (demo.) uses better signal processing.

12.9kg enriched + 8.8 kg natural Ge



single-site vs multi-site



LEGEND combines them.

Phase I (200kg) starts by 2021 using GERDA infrastructure.

Phase I target sensitivity, $T_{1/2} > 10^{28}$ yrs, $m_{ee} < 10\text{~}20$meV

Conclusion

- $0\nu2\beta$ searches are connected with big mysteries of the Universe and elementary particles.
- Those searches may be very close to the discovery and their experiments are in keen competition over the world.
- Higher sensitivity can be realized by various approaches and full coverage of IH seems to be secured.
- Reaching NH (below 5meV) is still very difficult. Required hundreds tons of DBD nuclei may be achieved by ^{136}Xe (centrifugal) or ^{130}Te (natural). Homogeneous self-shielding detector without inactive region and with high energy resolution will be preferred.
    - nEXO is such structure (but small).
    - DARWIN (dark matter search) plans 40t LXe TPC.
    - DUNE (LBNE) plans 70kt LAr TPC.

Maybe, super-nEXO reaches NH?   Let's dream!