TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Mathematik und Naturwissenschaften, Institut für Kern- und Teilchenphysik

Non-accelerator neutrino physics

Nobel price of physics 2015

22.3. 2016, IOP HEPP Meeting Brighton

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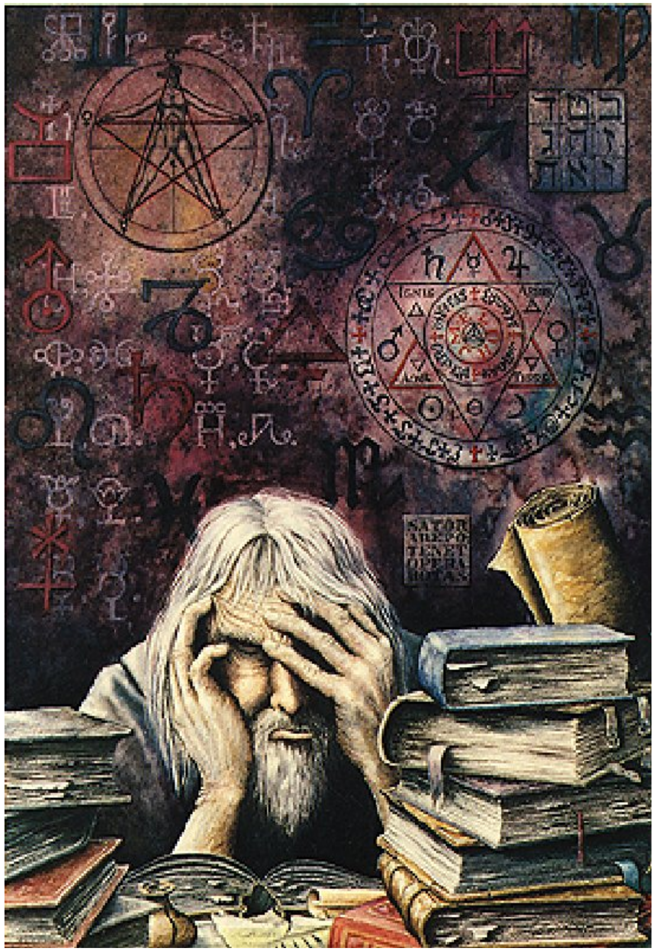
Institut für Kern- und Teilchenphysik

DRESDEN concept

How to explain everything about neutrinos in 30 mins

Contents



❖ General remarks

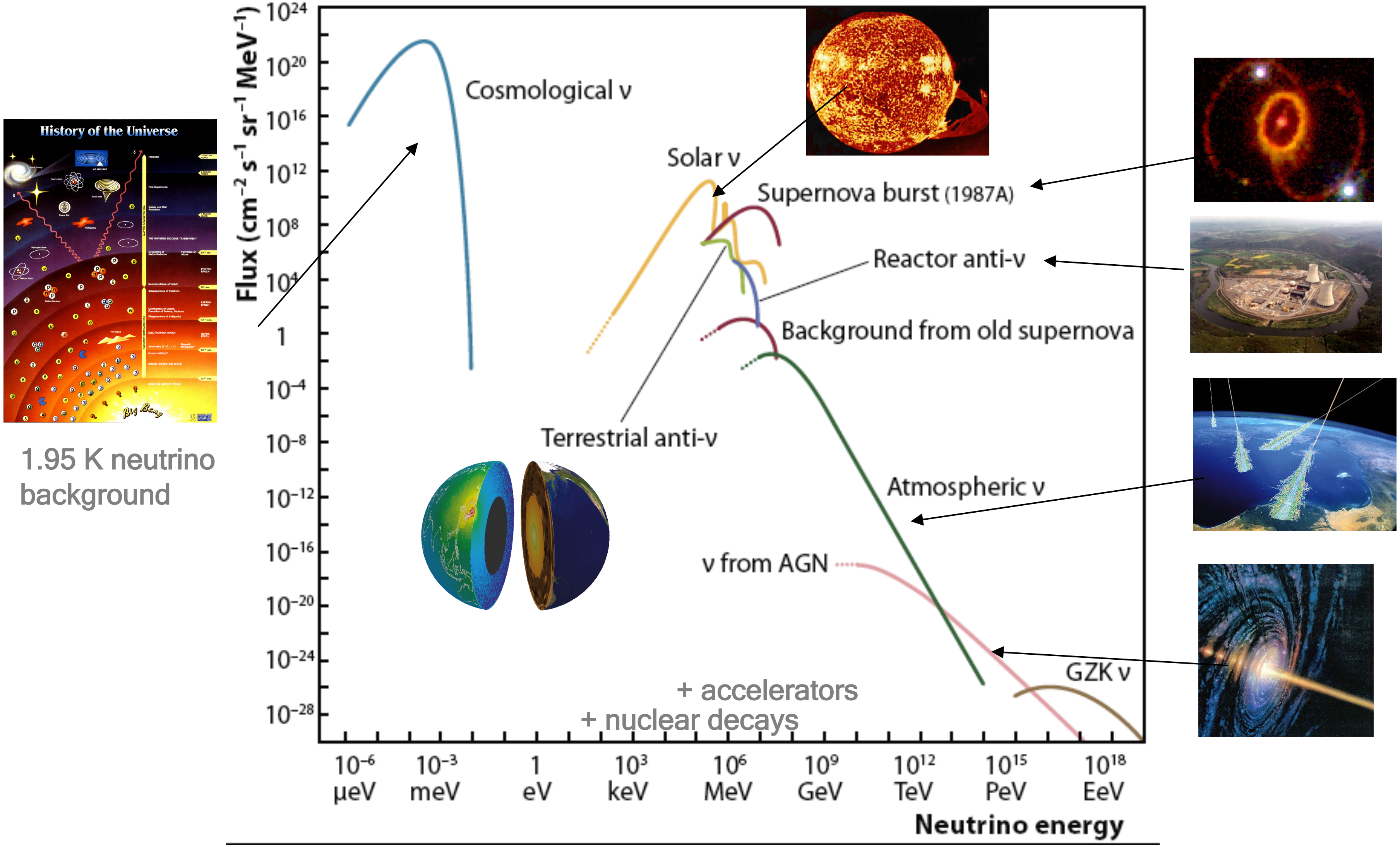
❖ Absolute mass measurements

- Beta decay
- Double beta decay
- Cosmology

❖ Astrophysical neutrinos

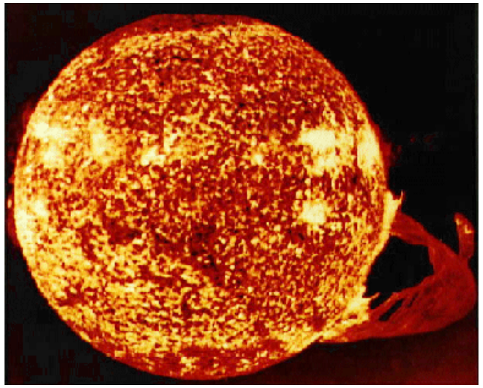
❖ Summary and outlook

Universal neutrino spectrum

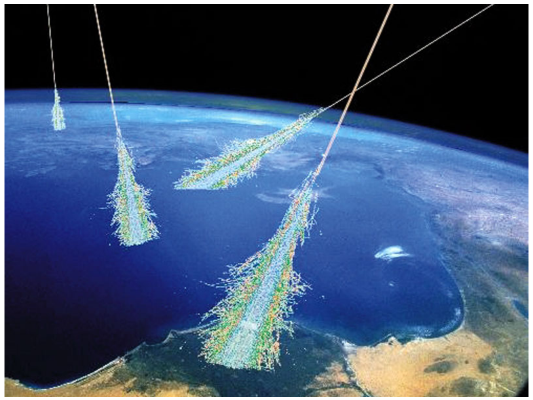


Search for oscillations

Appearance searches : New flavour appears not produced at source
Disappearance searches: Less neutrinos than expected from source



$$\theta_{12}, \theta_{13}, \Delta m_{12}^2$$



$$\theta_{23}, \Delta m_{23}^2$$

Neutrino mixing

www.nu-fit.org

NuFIT 2.0 (2014)

Leptons :

$$|U|_{3\sigma} = \begin{pmatrix} 0.801 \to 0.845 & 0.514 \to 0.580 & 0.137 \to 0.158 \\ 0.225 \to 0.517 & 0.441 \to 0.699 & 0.614 \to 0.793 \\ 0.246 \to 0.529 & 0.464 \to 0.713 & 0.590 \to 0.776 \end{pmatrix}$$

Compare to

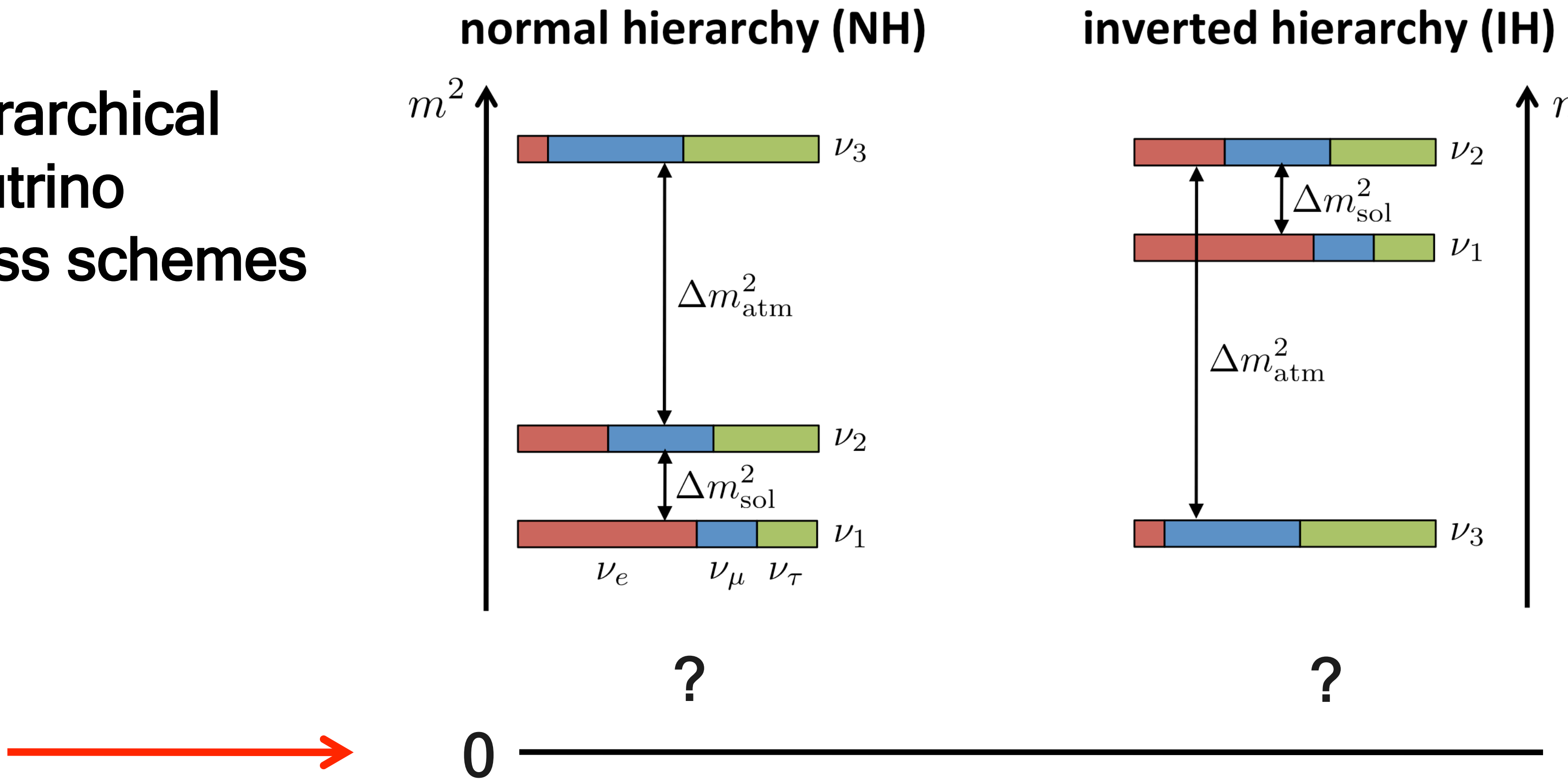
Quarks:

$$|V_{\mathrm{CKM}}| \simeq \begin{pmatrix} 0.97419 & 0.2257 & 0.00359 \\ 0.2256 & 0.97334 & 0.0415 \\ 0.00874 & 0.0407 & 0.999133 \end{pmatrix}$$

Neutrino mass schemes

• almost degenerate neutrinos $m_1 \approx m_2 \approx m_3$

• hierarchical neutrino mass schemes



What is the absolute neutrino mass?

The twofold way....

- ★ Precision determination of mixing matrix elements (PMNS), CP violation in lepton sector
- ★ Absolute neutrino mass measurement

Fermi theory of weak interaction

E. Fermi (1934)

101

:

Versuch einer Theorie der β-Strahlen. I[1]).

Von **E. Fermi** in Rom.

Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

Eine quantitative Theorie des β-Zerfalls wird vorgeschlagen, in welcher man die Existenz des Neutrinos annimmt, und die Emission der Elektronen und Neutrinos aus einem Kern beim β-Zerfall mit einer ähnlichen Methode behandelt, wie die Emission eines Lichtquants aus einem angeregten Atom in der Strahlungstheorie. Formeln für die Lebensdauer und für die Form des emittierten kontinuierlichen β-Strahlenspektrums werden abgeleitet und mit der Erfahrung verglichen.

7. Die Masse des Neutrinos.

Durch die Übergangswahrscheinlichkeit (32) ist die Form des kontinuierlichen β-Spektrums bestimmt. Wir wollen zuerst diskutieren, wie diese Form von der Ruhemasse μ des Neutrinos abhängt, um von einem Vergleich mit den empirischen Kurven diese Konstante zu bestimmen. Die Masse μ ist in dem Faktor p_σ^2/v_σ enthalten. Die Abhängigkeit der Form der Energieverteilungskurve von μ ist am meisten ausgeprägt in der Nähe des Endpunktes der Verteilungskurve. Ist E_0 die Grenzenergie der β-Strahlen, so sieht man ohne Schwierigkeit, daß die Verteilungskurve für Energien E in der Nähe von E_0 bis auf einen von E unabhängigen Faktor sich wie

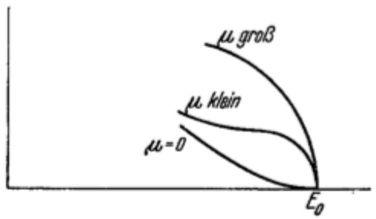
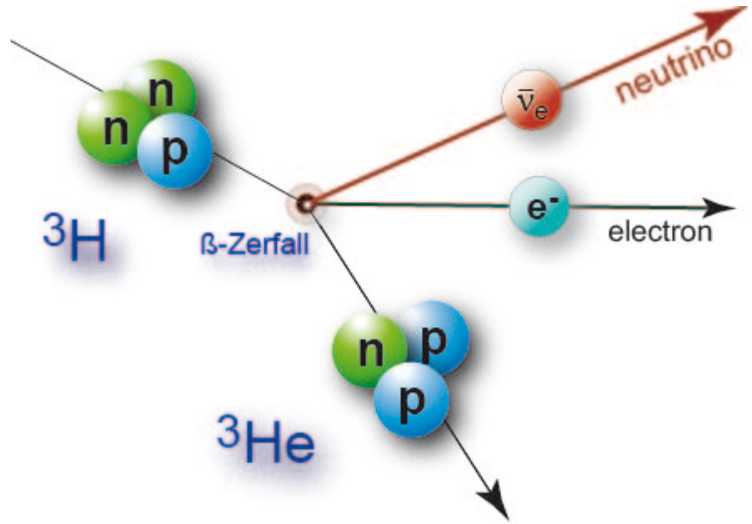
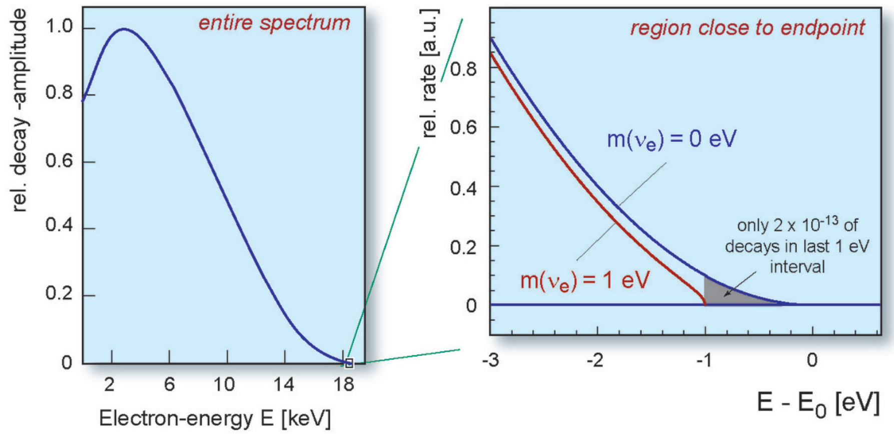


Fig. 1.

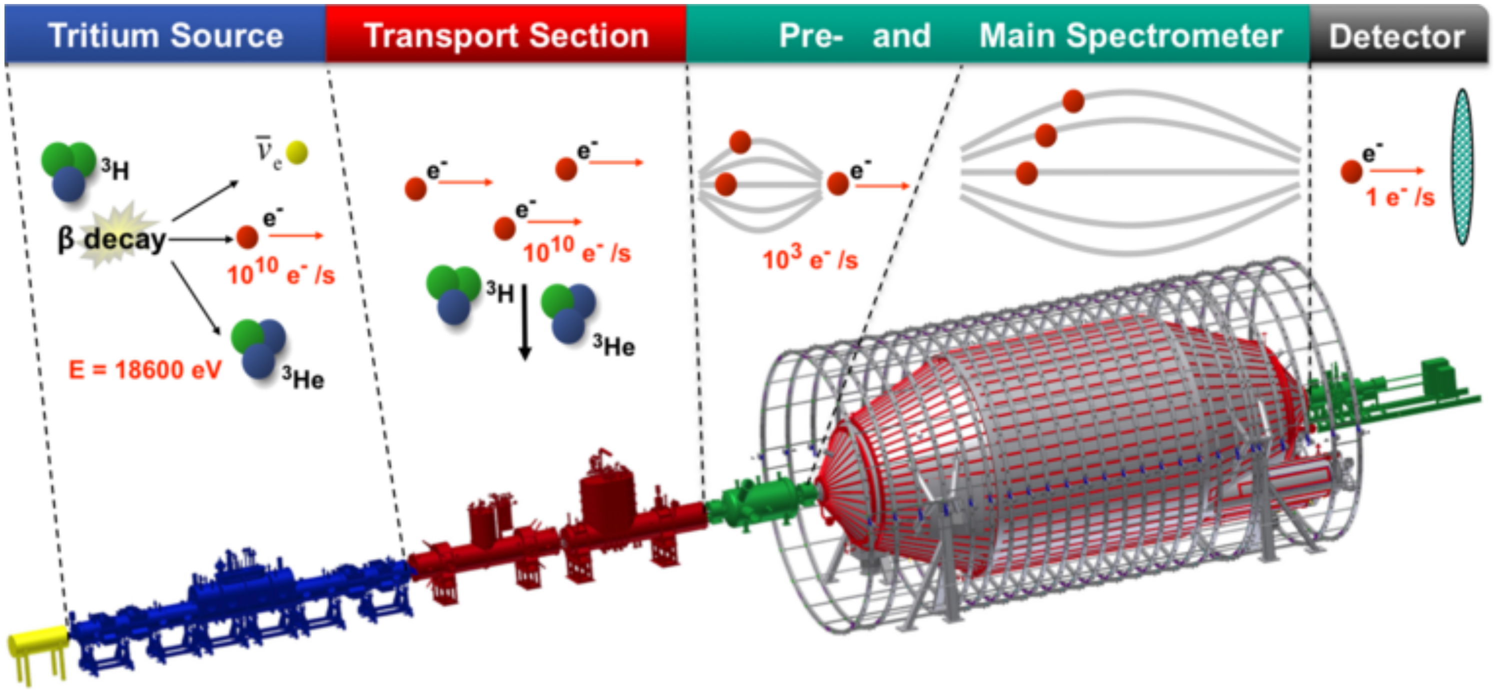
$$\frac{p_\sigma^2}{v_\sigma} = \frac{1}{c^3}(\mu c^2 + E_0 - E)\sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)} \qquad (36)$$





KATRIN

The next generation (ultimate spectrometer?): Aimed sensitivity of 0.2 eV



Tritium decays, releasing an electron and an anti-electron-neutrino. While the neutrino escapes undetected, the electron starts its journey to the detector.

Electrons are guided towards the spectrometer by magnetic fields. Tritium has to be pumped out to provide tritium free spectrometers.

The electron energy is analyzed by applying an electrostatic retarding potential. Electrons are only transmitted if their kinetic energy is sufficiently high.

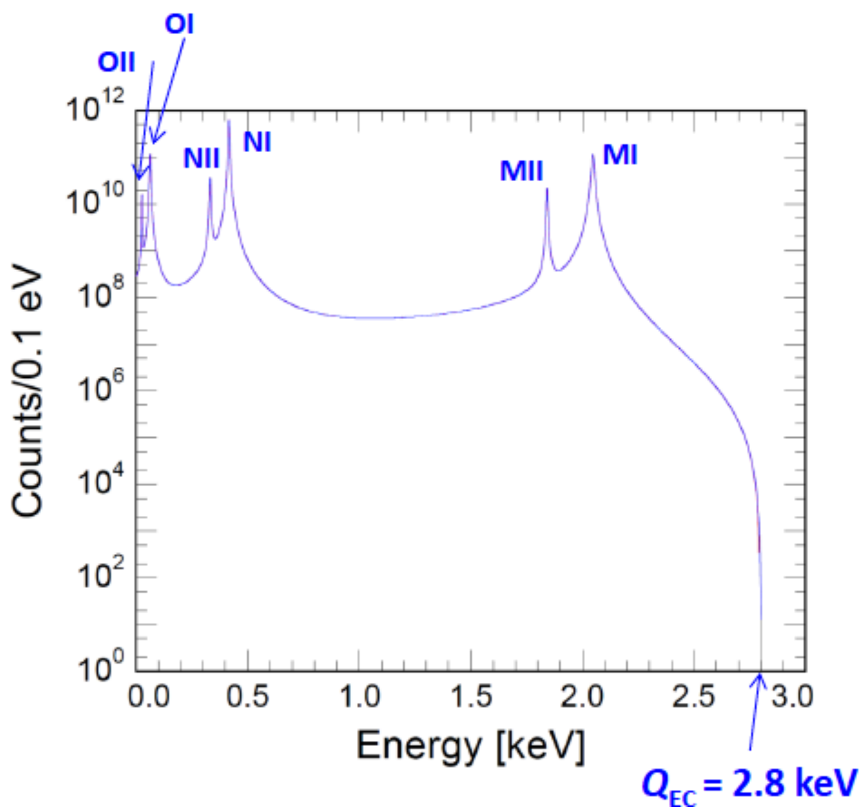
At the end of their journey, the electrons are counted at the detector. Their rate varies with the spectrometer potential and hence gives an integrated β-spectrum.

KATRIN- The next step

Take the long way home...

The case of Ho-163

$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^{*} + \nu_e$$



$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow ^{163}_{66}\mathrm{Dy} + E_C$$

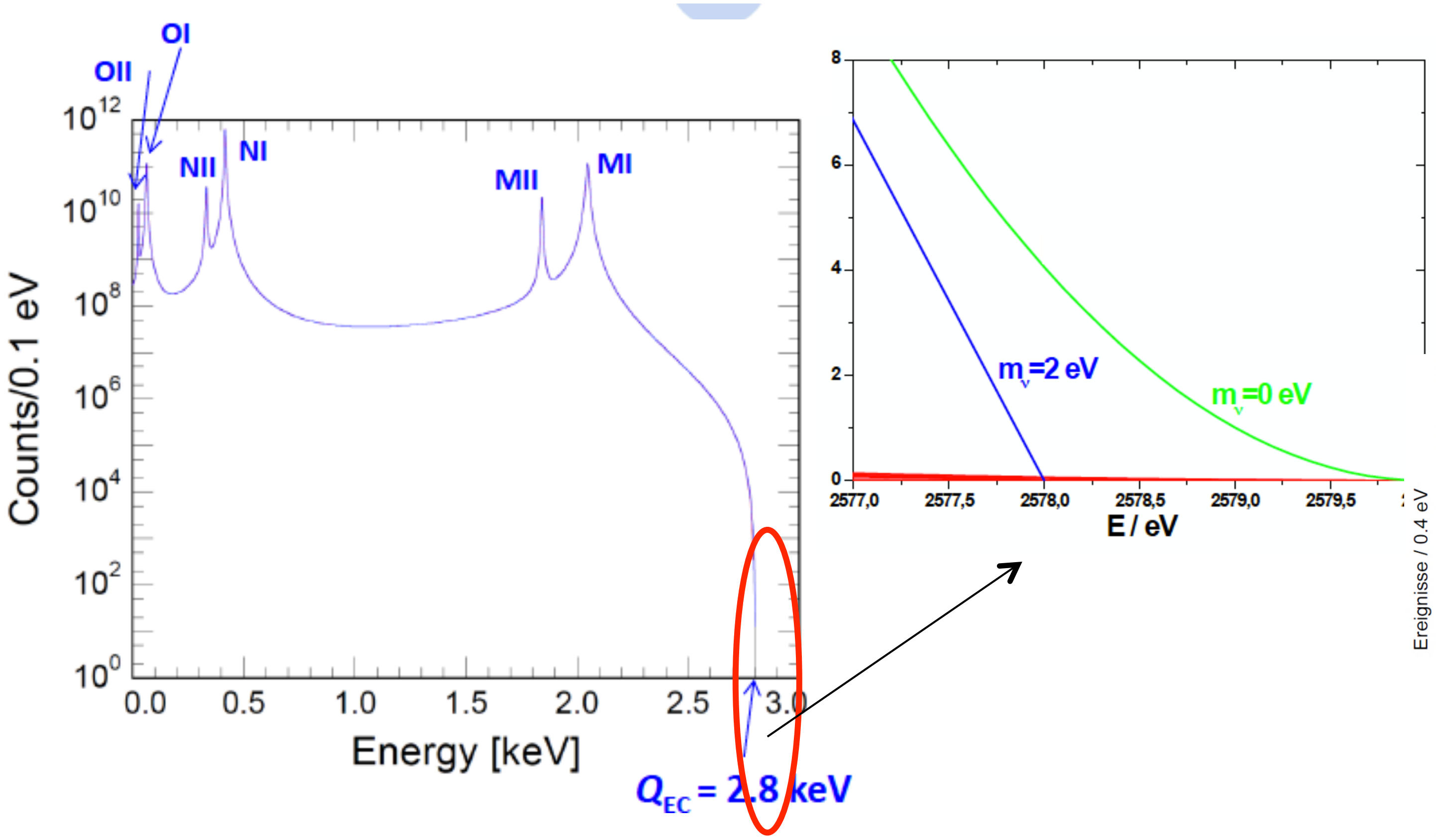
Endpoint of internal bremsstrahlungs spectrum

Current bound : m < 225 eV

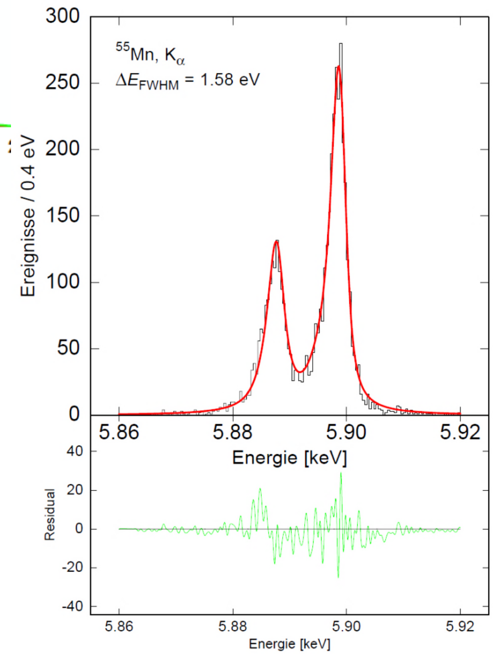
P.F. Springer et al., Phys. Rev. A 35 (1987)

EC signal

Very low Q-value allows only M-capture and higher shells



ECHO



Usage af cryobolometers (ECHO, Holmes)

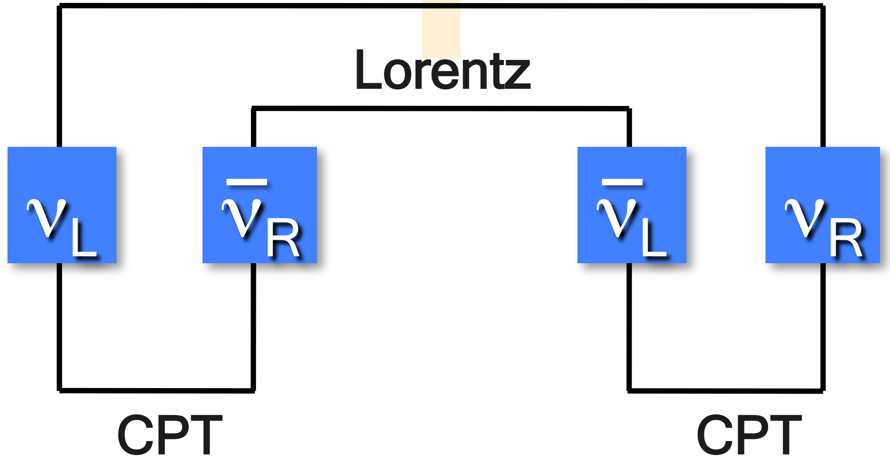
Are neutrinos (very) special?

intrinsic particle-antiparticle symmetry of neutrinos?

Dirac neutrino

4 ν states
lepton number conservation $\Delta L = 0$
neutrino ≠ antineutrino

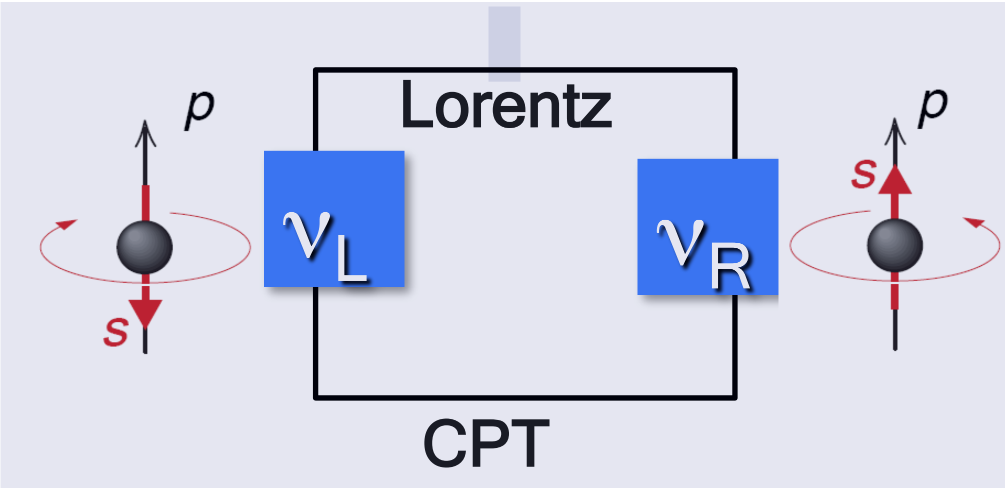
ν^D



Majorana neutrino

2 ν states
lepton number violation $\Delta L = 2$

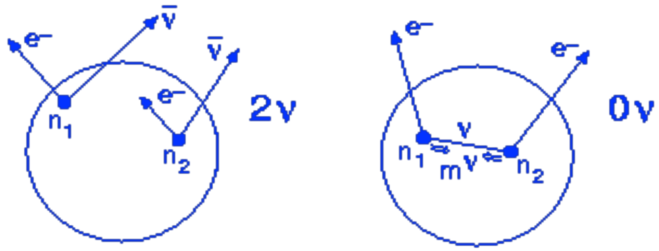
ν^M



ν^D and ν^M only distinguishable if $m_\nu \neq 0$

Double beta decay

- $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$ 2νββ
- $(A,Z) \rightarrow (A,Z+2) + 2e^-$ 0νββ



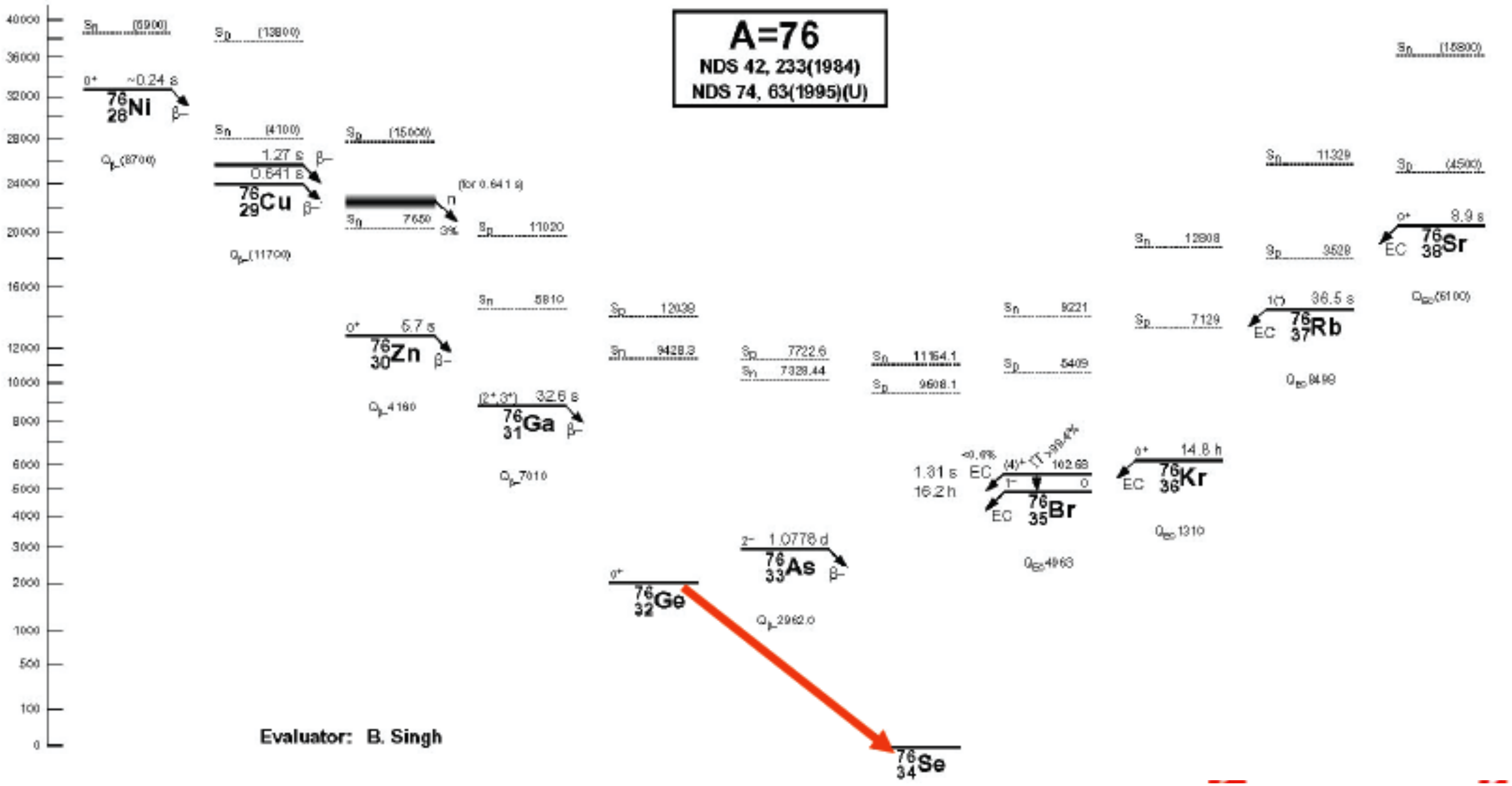
Unique process to measure character of neutrino

The smaller the neutrino mass the longer the half-life

Neutrino mass measurement via half-life measurement

Requires half-life measurements well beyond 10^{20} yrs!!!!

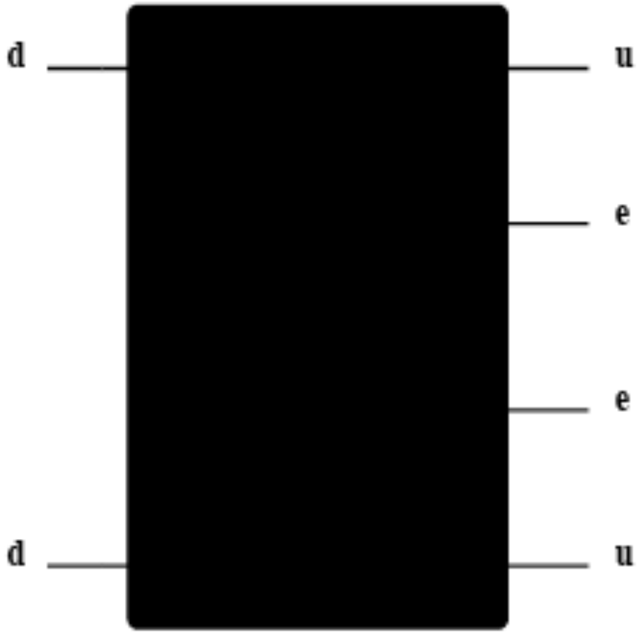
Example - Ge76



Only 35 isotopes in nature are able to do that!

$0\nu\beta\beta$

Any $\Delta L=2$ process can contribute to $0\nu\beta\beta$

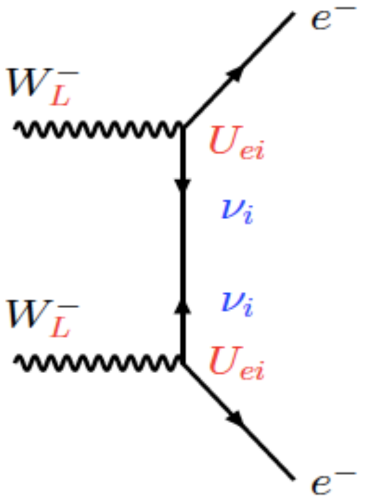


- R_p violating SUSY
- V+A interactions
- Extra dimensions (KK- states)
- Leptoquarks
- Double charged Higgs bosons
- Compositeness
- Heavy Majorana neutrino exchange
- Light Majorana neutrino exchange
- ...

$$1 / T_{1/2} = PS * NME^2 * \varepsilon^2$$

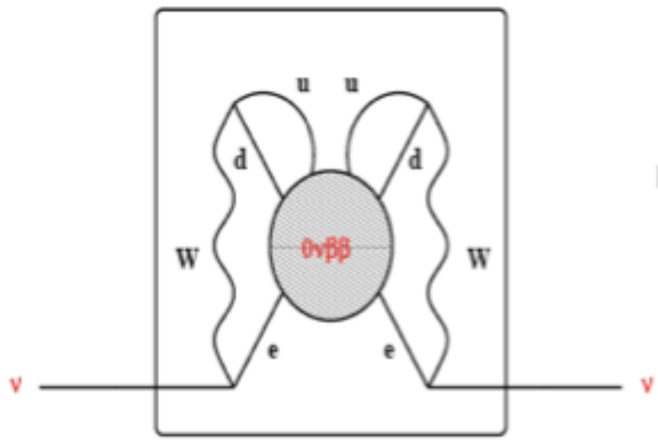
Nice interplay with LHC

Light Majorana neutrinos



$$\varepsilon \equiv \langle m_\nu \rangle = \left| \sum_i U_{ei}^2 m_{\nu_i} \right|$$

$$1 / T_{1/2} = PS * NME^2 * (\langle m_\nu \rangle / m_e)^2$$



Schechter and Valle 1982:

Independent of mechanism for neutrinoless DBD
Majorana neutrino mass will appear in higher order!

Observe $0\nu\beta\beta$ decay

$\equiv$

Neutrinos are Majorana particles

3 Flavour mixing (PMNS)

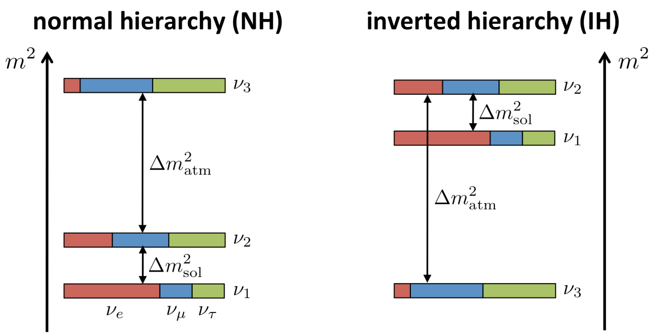
Neutrinos mix as oscillation experiments have shown, hence

Leptonic mixing (PMNS) matrix (including Majorana character)

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

solar reactor atmospheric

$$\langle m_\nu \rangle = \left| \sum_i U_{ei}^2 m_{\nu_i} \right| = \left| c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i2\alpha_1} m_2 + s_{13}^2 e^{i2(\alpha_2 - \delta)} m_3 \right|$$



normal **inverted**

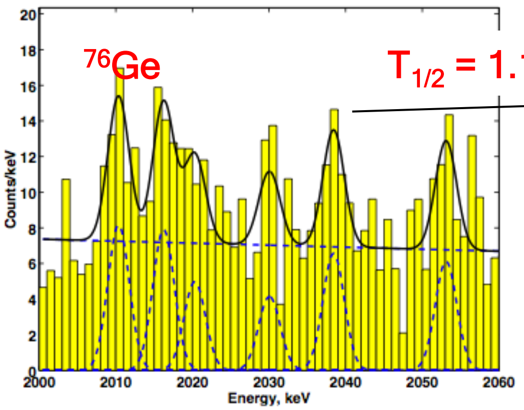
From oscillation experiments

$\sin^2 2\theta_{23} > 0.9$ (90%CL), best fit $\theta_{23} = 45°$

$\sin^2 2\theta_{13} = 0.09$ (90%CL), $\theta_{13} = 9°$

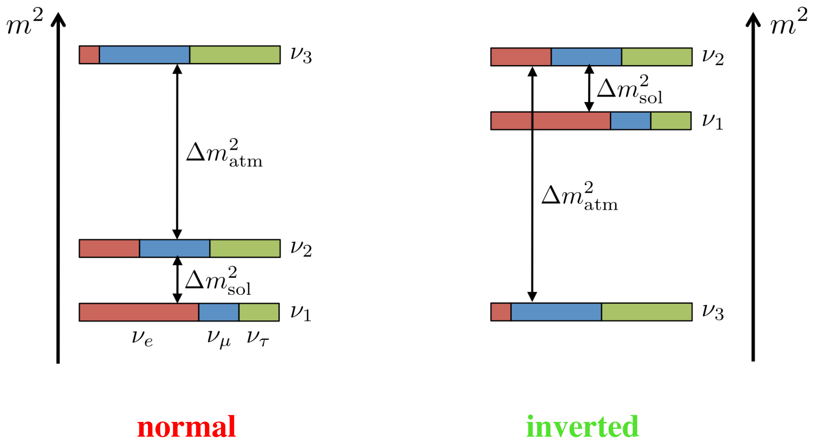
$\sin^2 \theta_{12} = 0.32, \theta_{12} = 34^\circ.06^{+1.16}_{-0.84}$

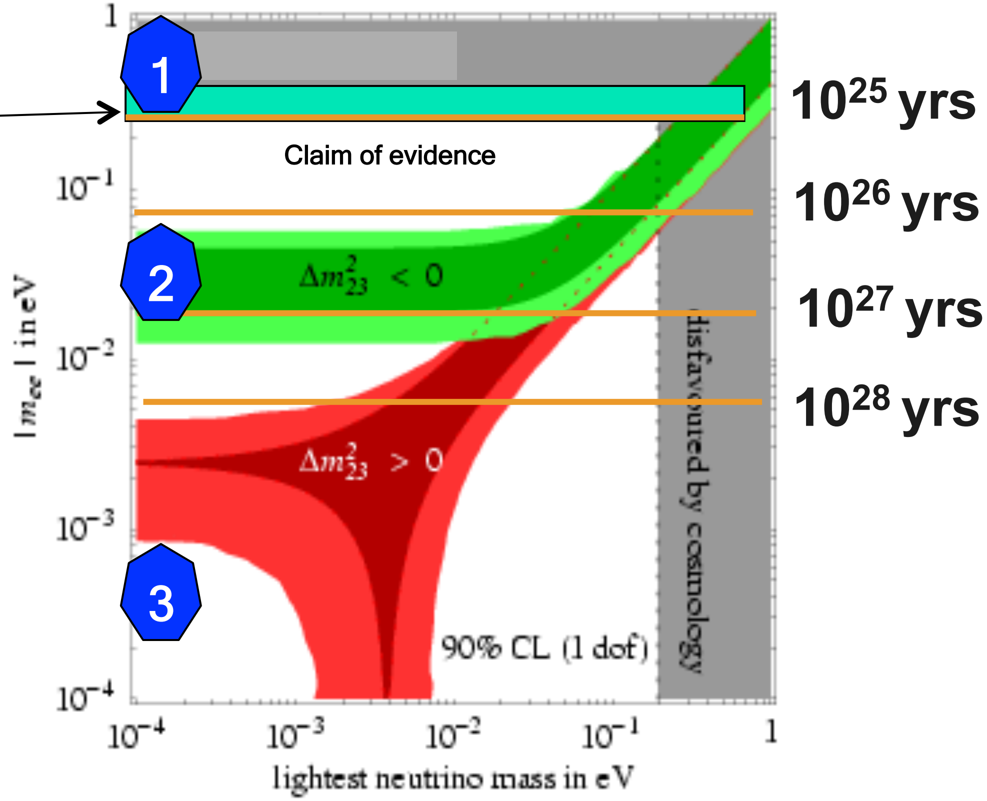
Mass hierarchies and DBD



H.V. Klapdor-Kleingrothaus et al.
Phys. Lett. B 586, 198 (2004)

normal hierarchy (NH) **inverted hierarchy (IH)**





1.) Is the claimed evidence correct?
GERDA phase I, Xe-experiments

2.) Can we probe the inverted hierarchy?

3.) What about the normal hierarchy?

or

Back of an envelope

This is the 50 meV option, just add 0's to moles and kgs if you want smaller neutrino masses

$$T_{1/2} = \ln 2 \cdot a \cdot N_A \cdot M \cdot t \,/\, N_{\beta\beta} \quad (\tau \gg T) \quad \text{(Background free)}$$

For half-life measurements of 10^{26-27} yrs

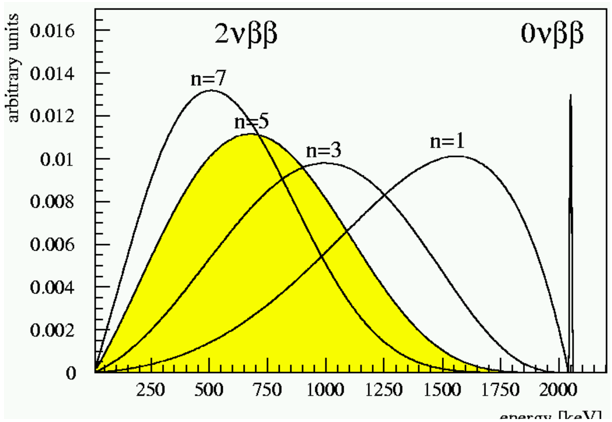
1 event/yr you need 10^{26-27} source atoms

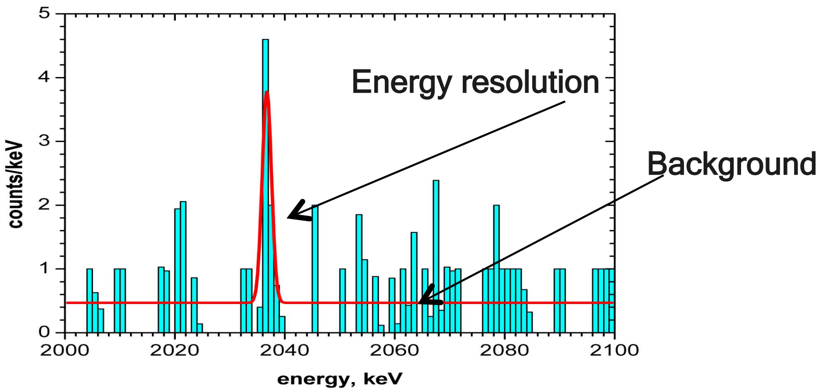
This is about 1000 moles of isotope, implying about 100 kg

Now you only can loose: nat. abundance, efficiency, background, ...

0νββ: Peak at Q-value of nuclear transition

Sum energy spectrum of both electrons





Measured quantity: Half-life

$1 / T_{1/2} = PS * NME^2 * (<m_\nu> / m_e)^2$

Experimental sensitivity depends on

$$T_{1/2}^{-1} \propto a\varepsilon\sqrt{\frac{Mt}{\Delta EB}}$$ (BG limited)

$$T_{1/2}^{-1} \propto a\varepsilon Mt$$ (BG free)

If background limited $m_\nu \propto \sqrt[4]{\frac{\Delta EB}{Mt}}$

Perfect world experiment

- No background
- δ function as peak
- 100 % abundance
- 100% detection efficiency
- Infinite measuring time
- Infinite mass

$$T_{1/2}^{-1} \propto a\varepsilon\sqrt{\frac{Mt}{\Delta EB}}$$

Life is easy, the rest is just details

Experimental approaches

$0\nu\beta\beta$ decay rate scales with Q^5 → only those with Q>2000 keV

11 isotopes of interest

Isotope	Nat. abund. (%)	Q-values 2016
Ca-48	0.187	4262.96 ± 0.84
Ge-76	7.44	2039.006 ± 0.050
Se-82	8.73	2997.9 ± 0.3
Zr-96	2.80	3356.097 ± 0.086
Mo-100	9.63	3034.40 ± 0.17
Pd-110	11.72	2017.85 ± 0.64
Cd-116	7.49	2813.50 ± 0.13
Sn-124	5.79	2292.64 ± 0.39
Te-130	33.80	2527.518 ± 0.013
Xe-136	8.9	2457.83 ± 0.37
Nd-150	5.64	3371.38 ± 0.20

Candles

GERDA, Majorana

SuperNEMO, LUCIFER

MOON, AMore

COBRA

Tin.Tin

CUORE, SNO+

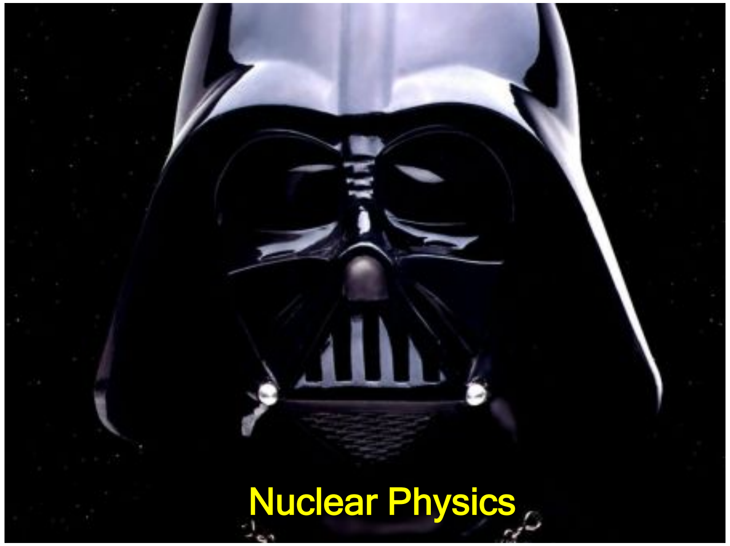
nEXO, KamLAND-Zen, NEXT, XMASS

MCT, SuperNEMO(?)

There is no super-isotope!

Master equation

$$1 / T_{1/2} = PS * NME^2 * (<m_\nu> / m_e)^2$$



Measurement

Exact calculation

Complex calculations

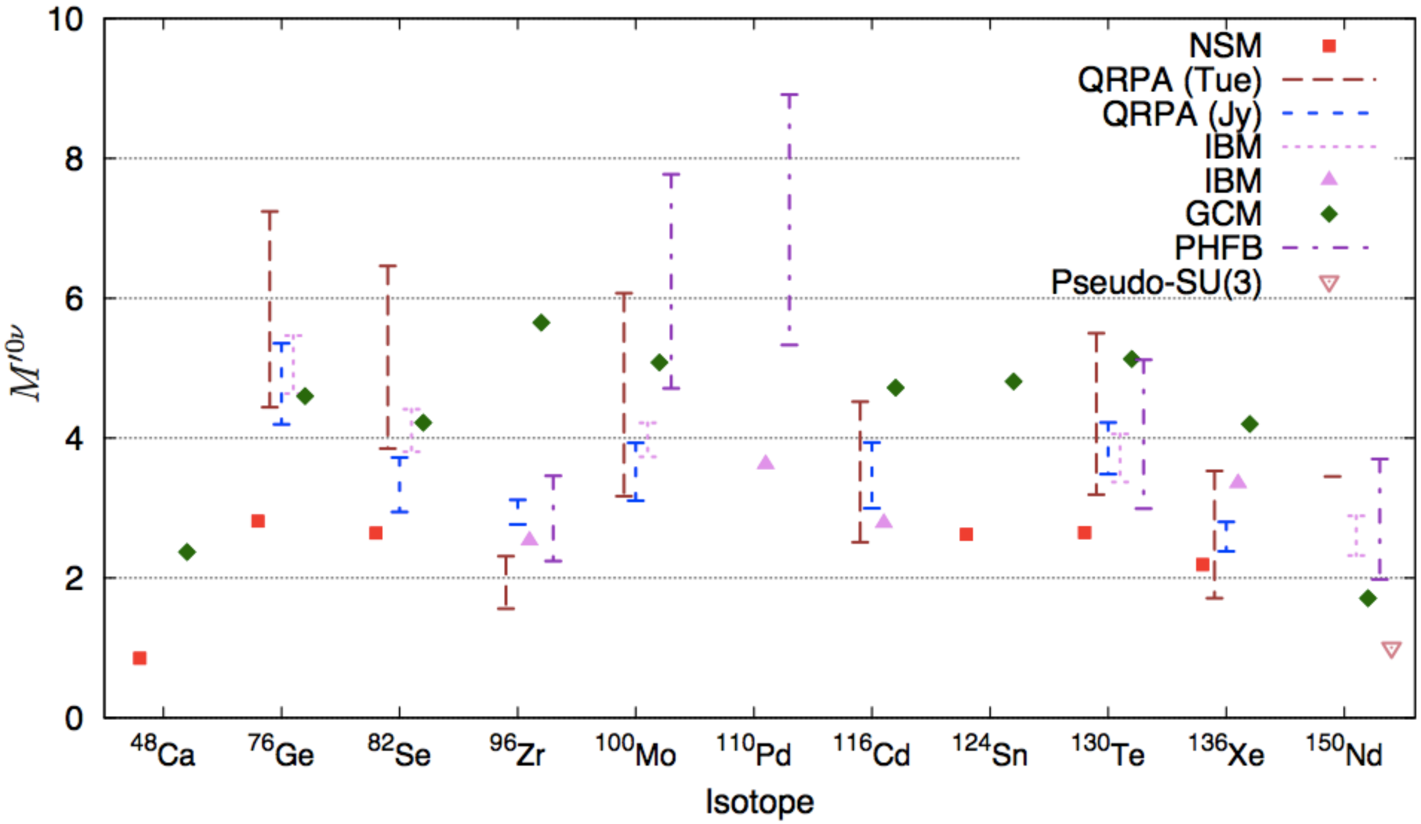
Quantity of interest

J. Kotila, F. Iachello, PRC 034316 (2012)
S. Stoica, M. Mirea, arXiv:1307.0290

Severe nuclear structure issue

Matrix element

Rescaled as people use different g_A (1-1.25) and R_0 (1.0-1.3 fm)



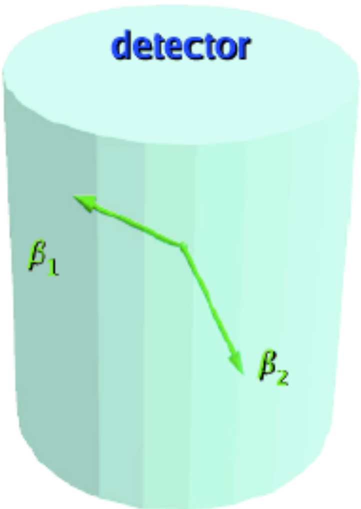
A. Dueck, W. Rodejohann, K. Zuber, arXiv:1103.4152, PRD 83, 113010 (2011)

Several new techniques applied in last years

Signatures and approaches

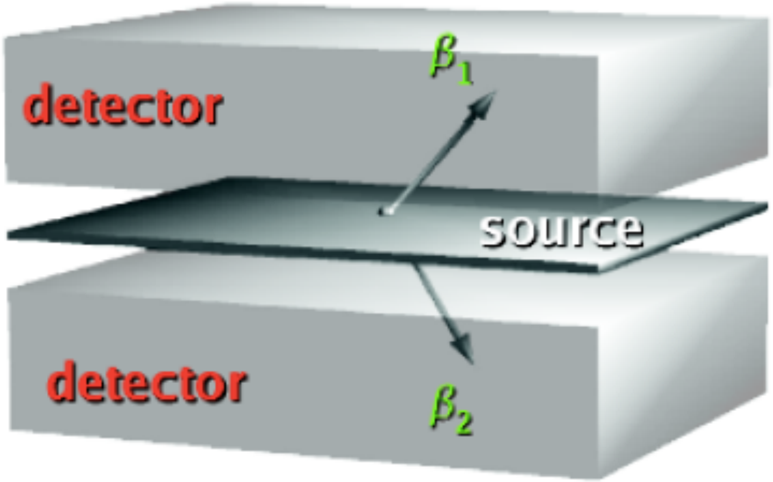
- Sum energy of both electrons
- Single electron spectra and opening angle
- Detection of daughter ion

Source = detector



- Semiconductors
- Cryogenic bolometers
- Scintillators
- Liquid Noble gases

Source ≠ detector



- TPCs (foils)
- Scintillators (foils)

All low background

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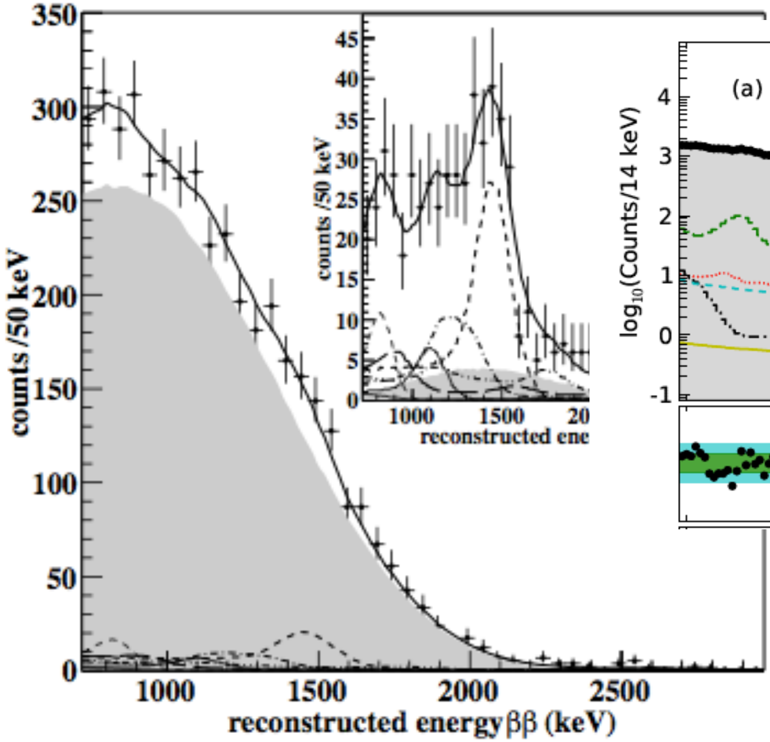
The fantastic 4

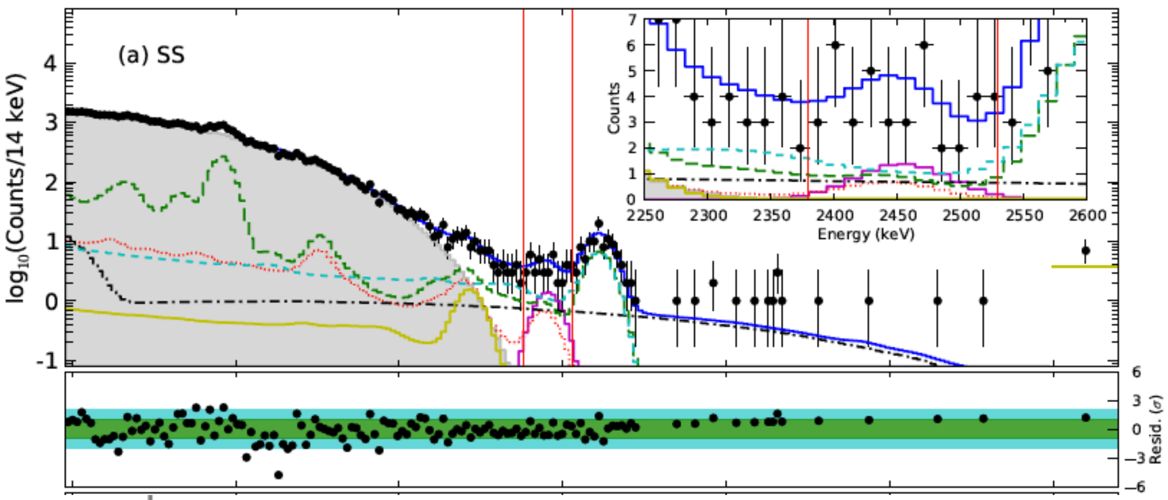
Because they've started

EXO-200

200 kg of enriched (80%) Xe-136 at hand

Current half-life limit on 0nu decay :
$T_{1/2} > 1.1 \times 10^{25}$ years (90%CL)
J. B. Albert et al., Nature 510,229 (2014)





In conflict with positive claim for almost all matrix element calculations

Uncertainties due to conversion

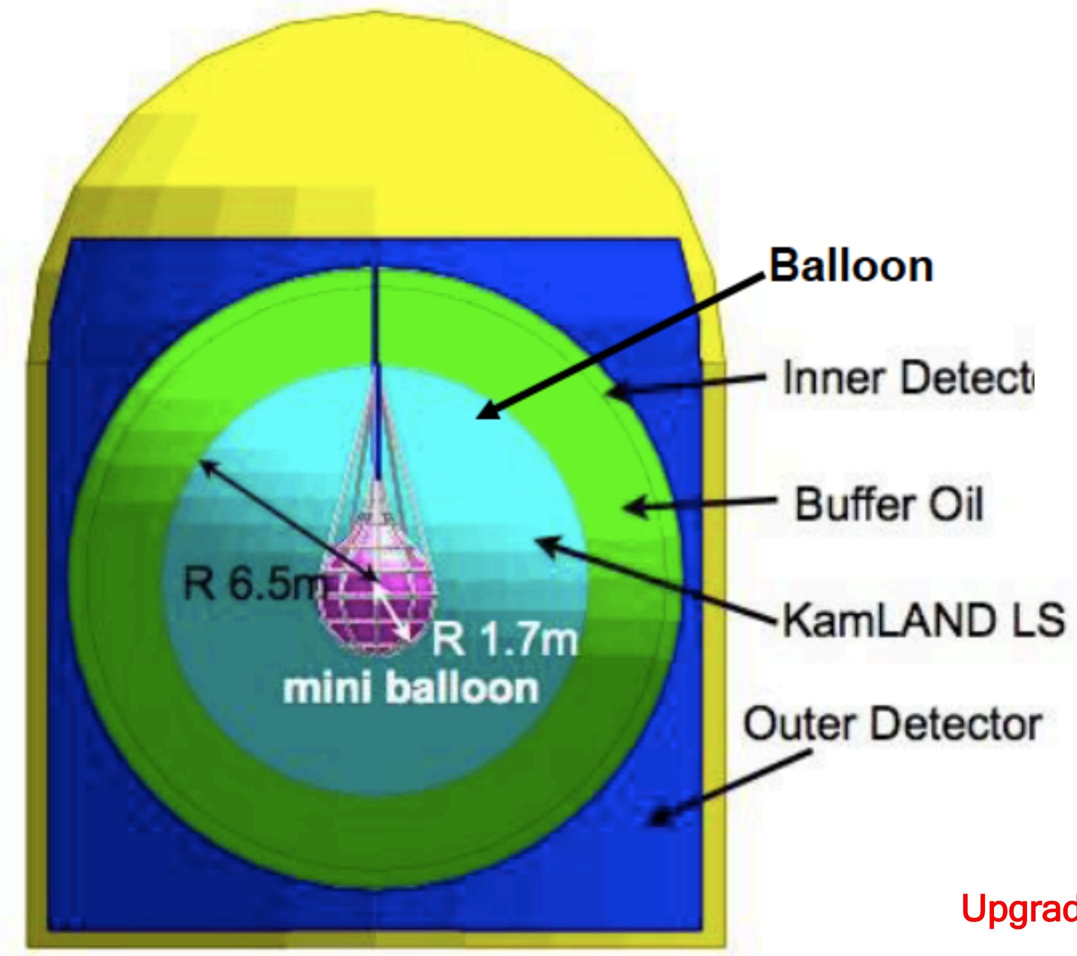
First observation of 2nu decay of Xe-136,
N. Ackerman et al., PRL 107, 212501 (2011)

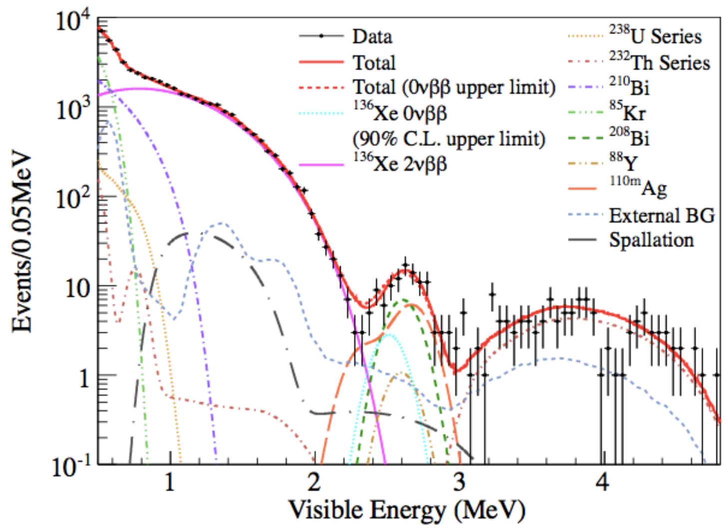
Future option: Barium tagging

DRESDEN concept
Exzellenz aus Wissenschaft und Kultur

KamLAND - Zen

Using 400 kg of Xe (91.7% enriched in Xe-136)





$$T^{0\nu}_{1/2} > 5.7 \times 10^{24} \text{ yr (90\% C.L.)}$$

A Gando et al., PRC 85,045504 (2012)

$T_{1/2} > 1.9 \times 10^{25}$ years (90%CL)
A. Gando, PRL 110, 062502 (2013)

Upgrade to 1 ton enriched Xe planned soon

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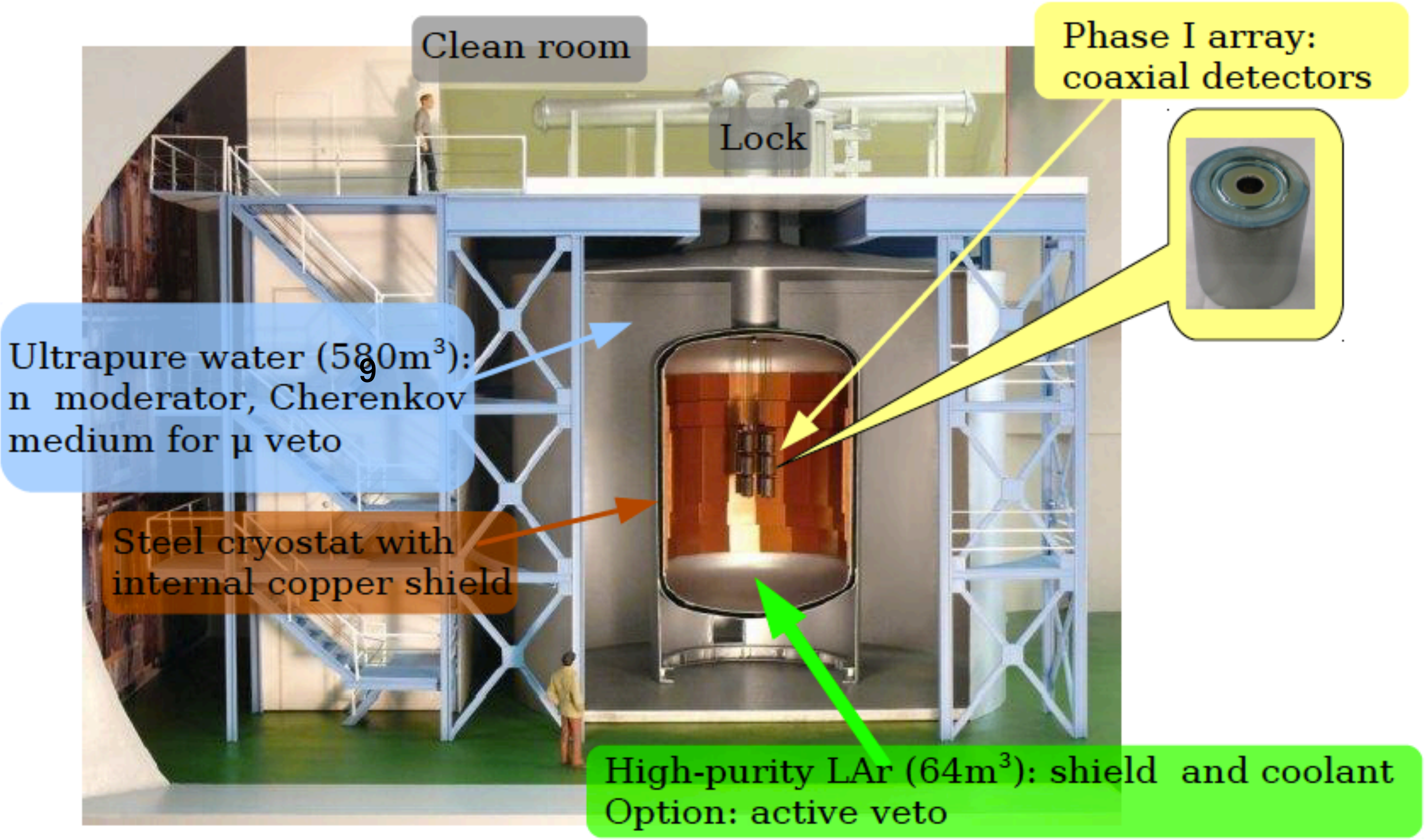
GERDA-Principal Setup

Talk A. Kirch

GERDA

Idea : Running bare Ge crystals in LAr



The Gerda experiment for the search of $0\nu\beta\beta$ decay in ⁷⁶Ge
Eur. Phys. J. C (2013) 73:2330

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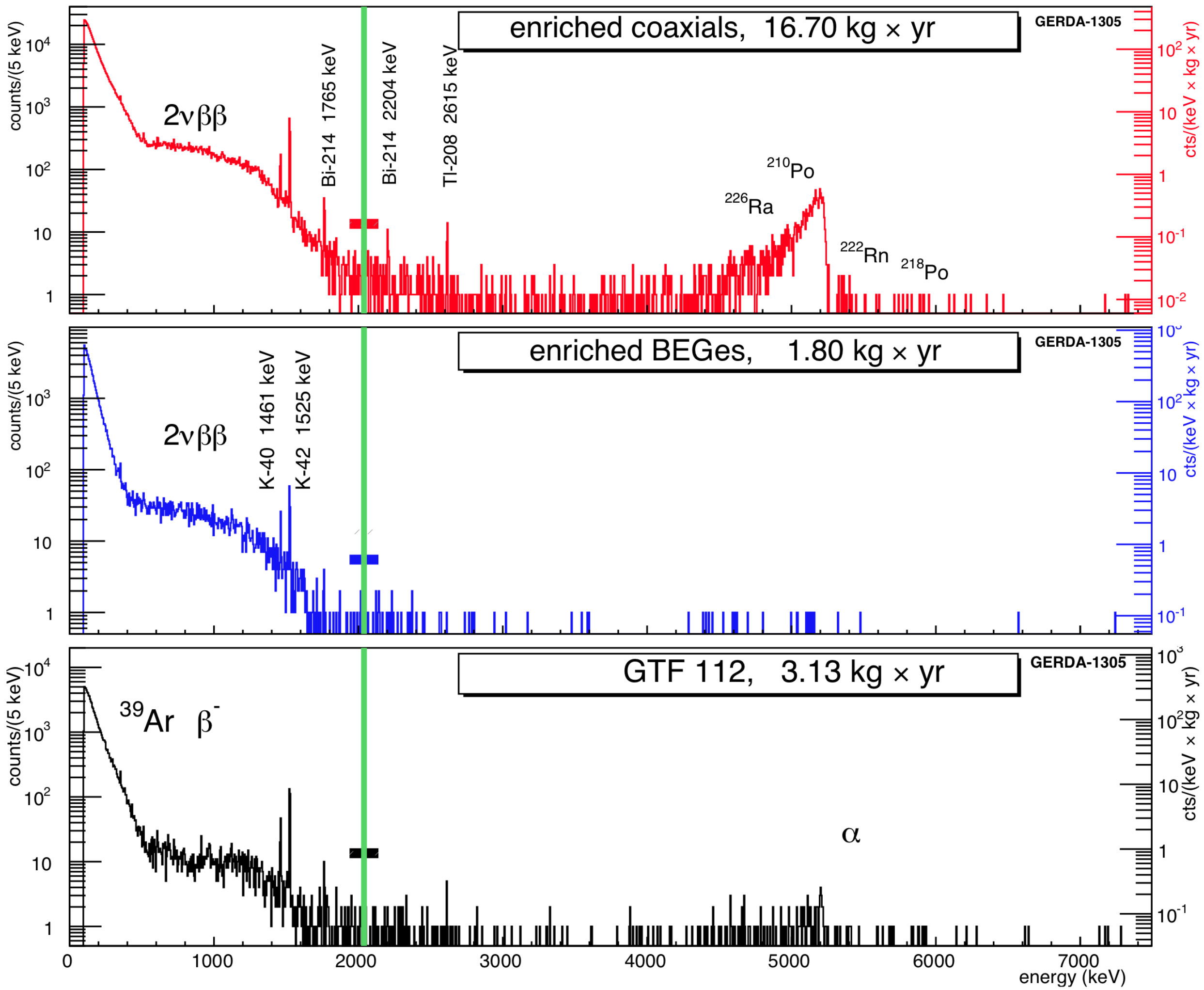
Phase I data taking

iktp



K. Zuber

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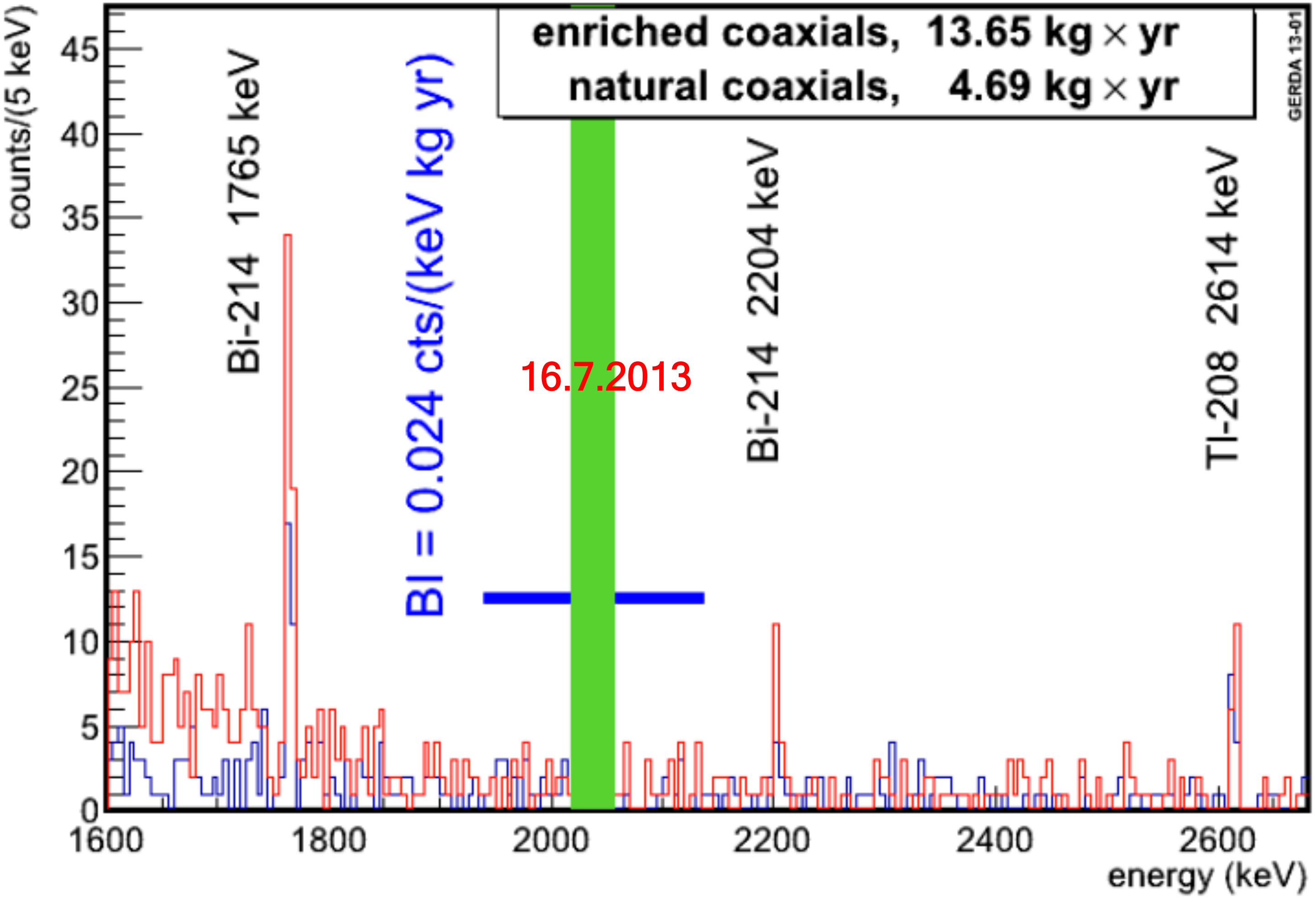
Phase I data taking

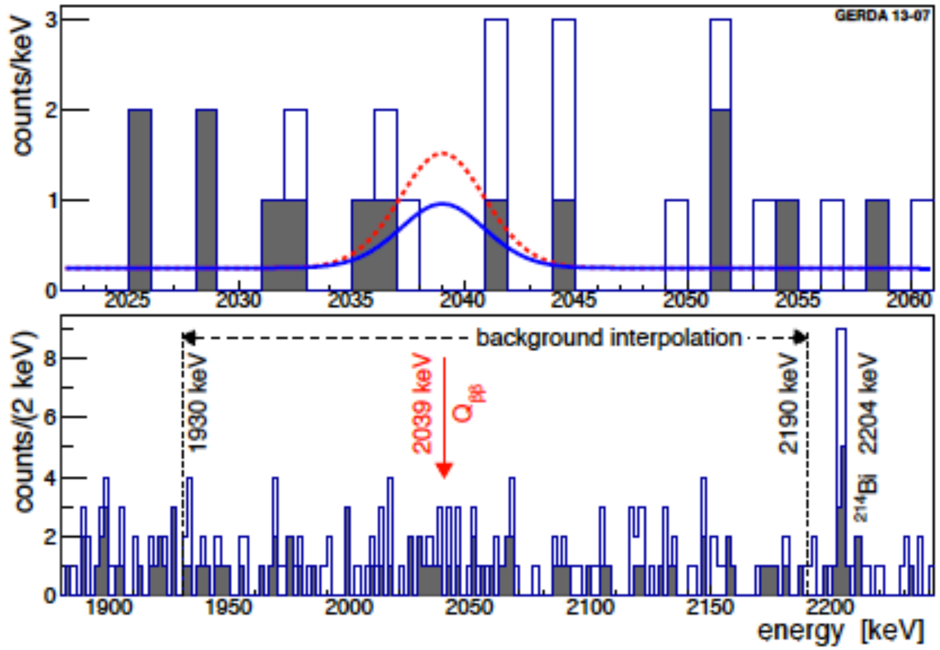
iktp

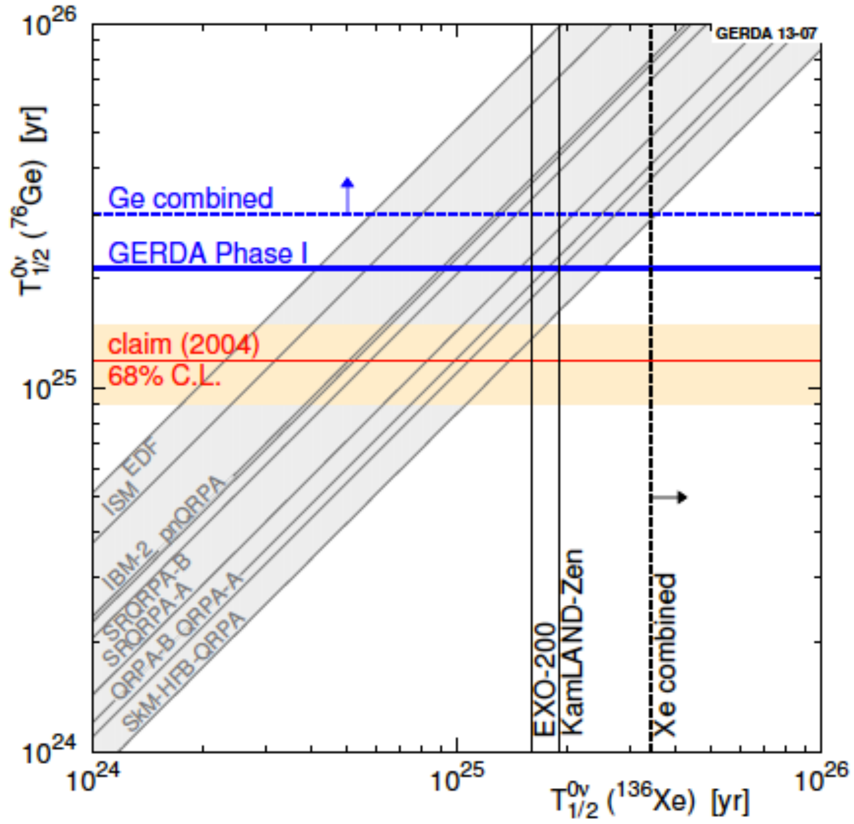


Phase I results

Pulse shape discrimination: M. Agostini et al. Eur. Phys. J. C 71,2583 (2013)

Result Phase 1: M. Agostini et al., PRL 111, 122503 (2013)

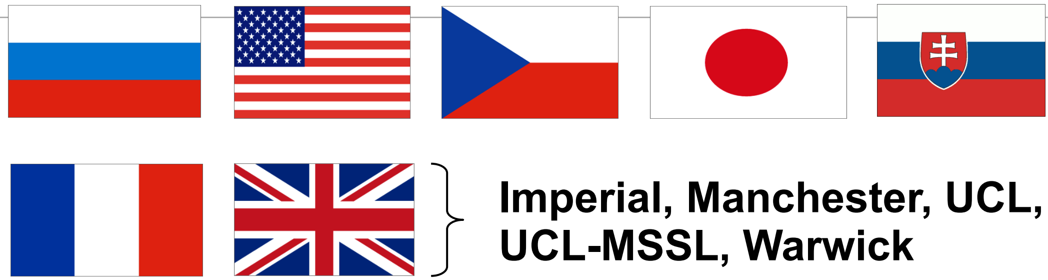




Overview of SuperNEMO

Talk by X. Liu

supernemo collaboration



Imperial, Manchester, UCL, UCL-MSSL, Warwick

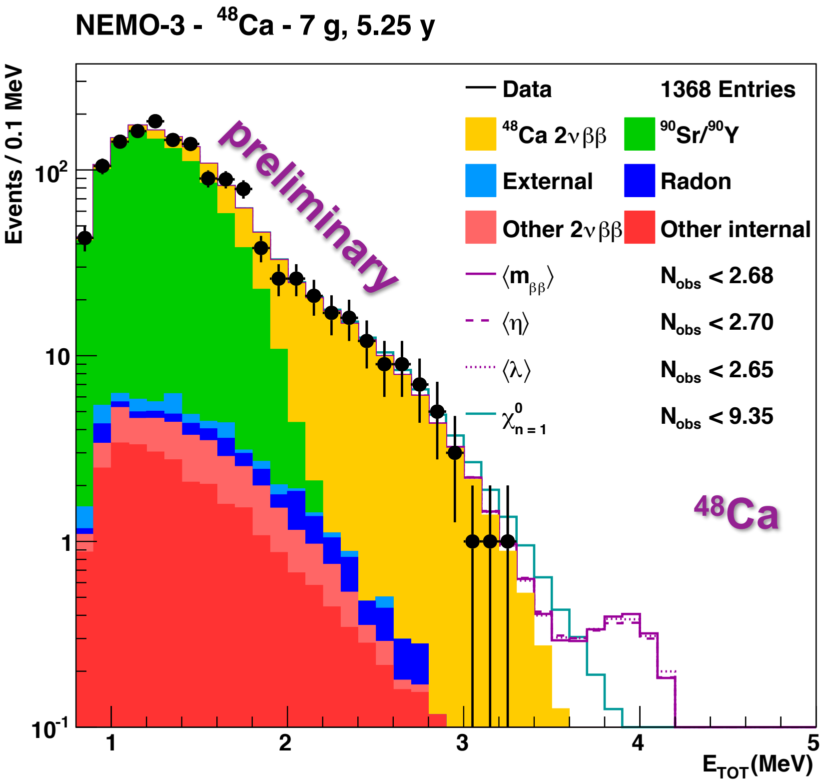
The goals of SuperNEMO :

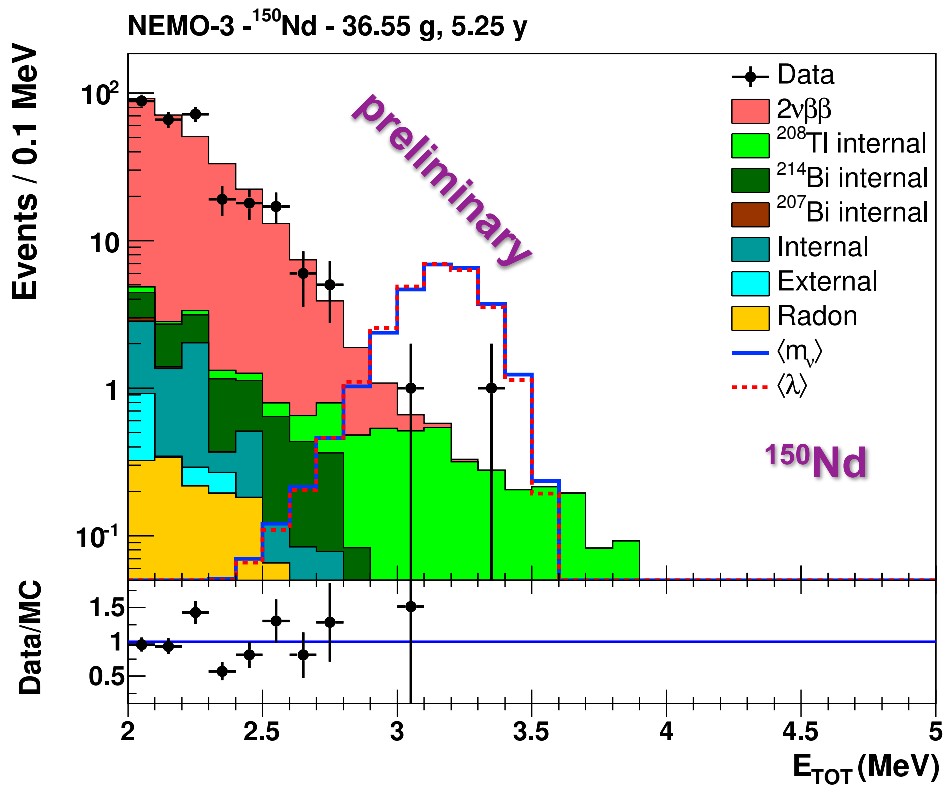
1. **Build on the experience of the extremely successful NEMO-3 experiment.**
2. **Use the power of the tracking-calorimeter approach to identify and suppress backgrounds. This will yield a zero-background experiment in the first (Demonstrator Module) phase.**
3. **Prove that a 100 kg scale experiment can reach the inverted mass hierarchy (~50 meV) domain.**
4. **In the event of a discovery by any of the next-generation experiments, demonstrate that the tracking-calorimeter approach is by far the best one for characterising the mechanism of $0\nu\beta\beta$ decay.**

K. Zuber

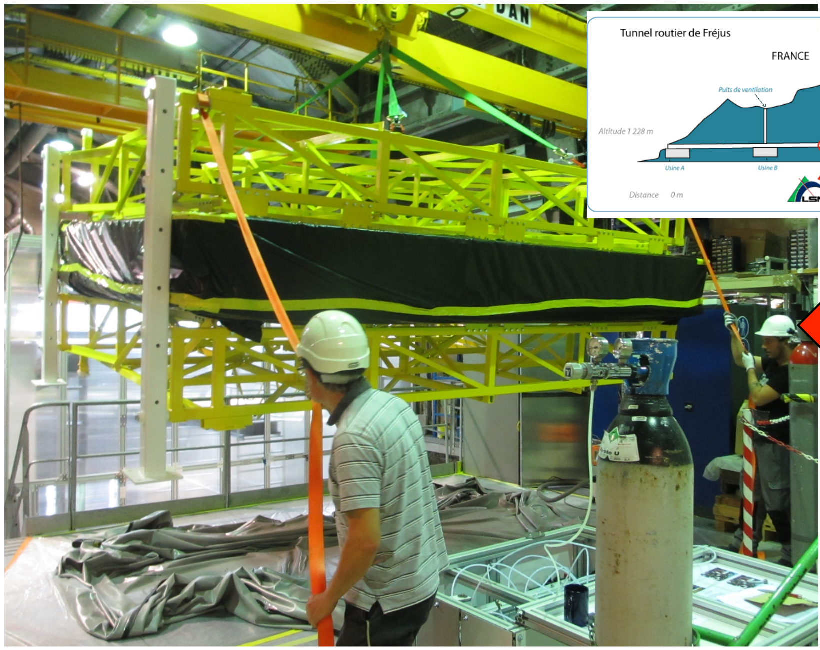
NEMO-3 2νββ

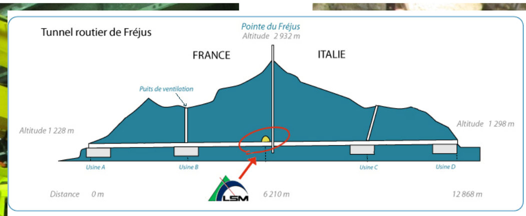
- **World's best and/or first measurement of 2-neutrino half-lives for 7 isotopes !**
- **Publication of 2 of the most interesting isotopes (^{48}Ca, ^{150}Nd) is imminent.**
  - ***Both are these measurements are UK PhD theses.***

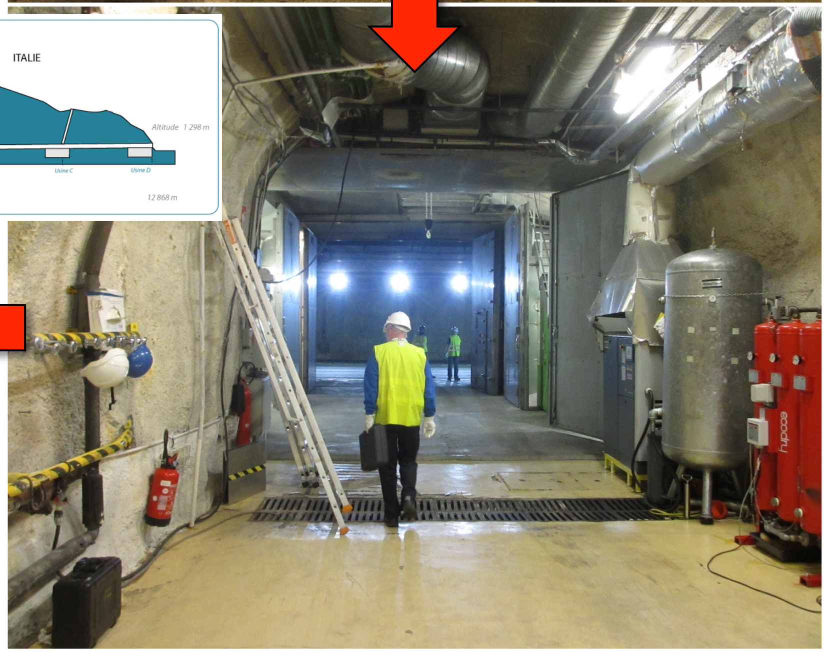





SOFITRANS
2951

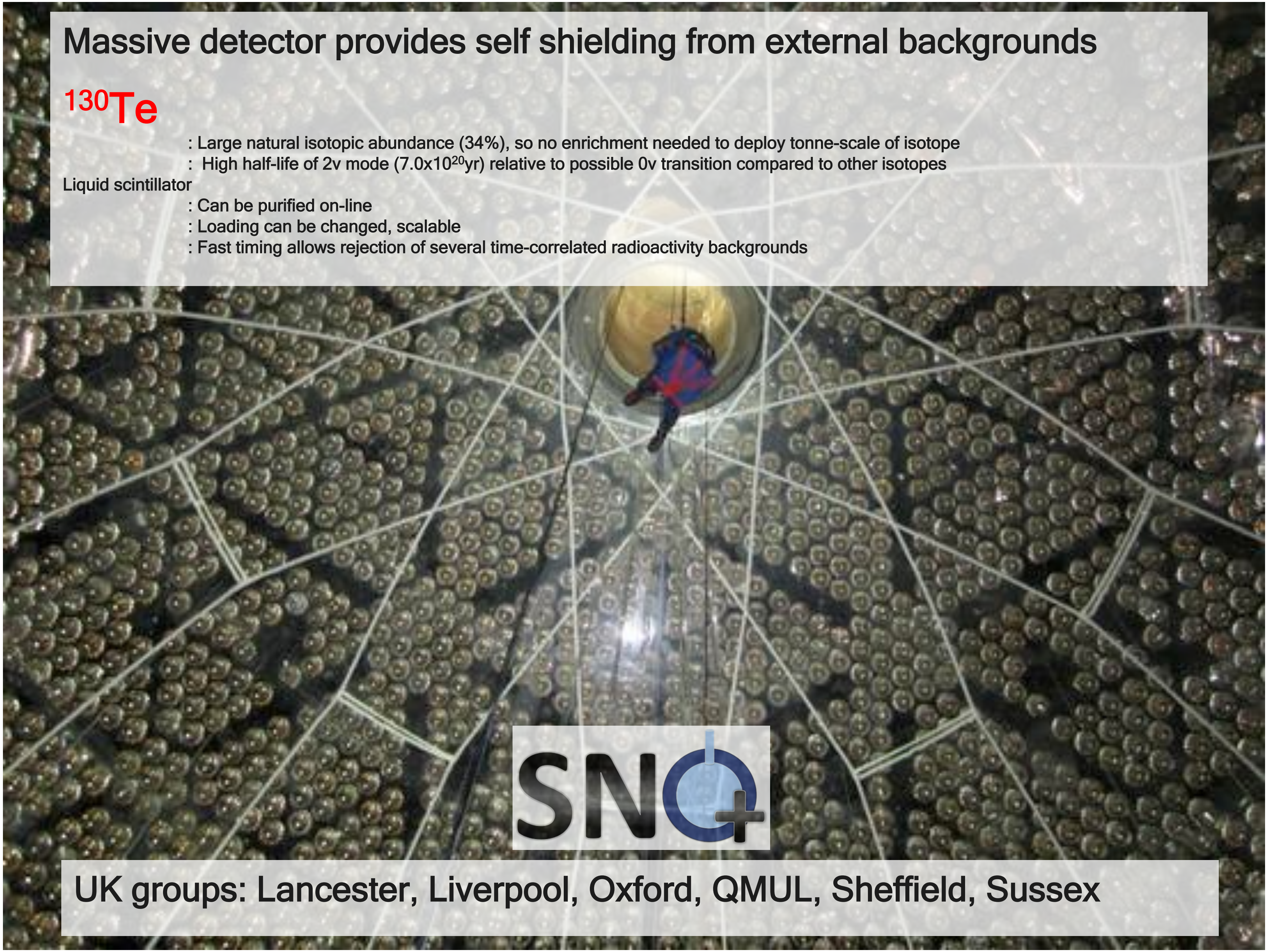



Tunnel routier de Fréjus
Pointe du Fréjus
Altitude 2 932 m
FRANCE
ITALIE
Puits de ventilation
Altitude 1 228 m
Altitude 1 298 m
Usine A
Usine B
Usine C
Usine D
LSM
Distance 0 m
6 210 m
12 868 m



perN

SNO+ @ SNOLAB



Massive detector provides self shielding from external backgrounds

^{130}Te

: Large natural isotopic abundance (34%), so no enrichment needed to deploy tonne-scale of isotope
: High half-life of 2v mode ($7.0\text{x}10^{20}$yr) relative to possible 0v transition compared to other isotopes

Liquid scintillator

: Can be purified on-line
: Loading can be changed, scalable
: Fast timing allows rejection of several time-correlated radioactivity backgrounds

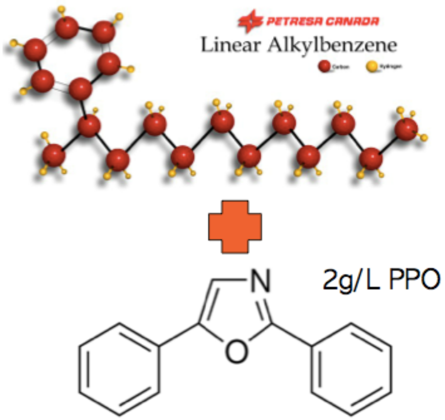
SNO+

UK groups: Lancester, Liverpool, Oxford, QMUL, Sheffield, Sussex

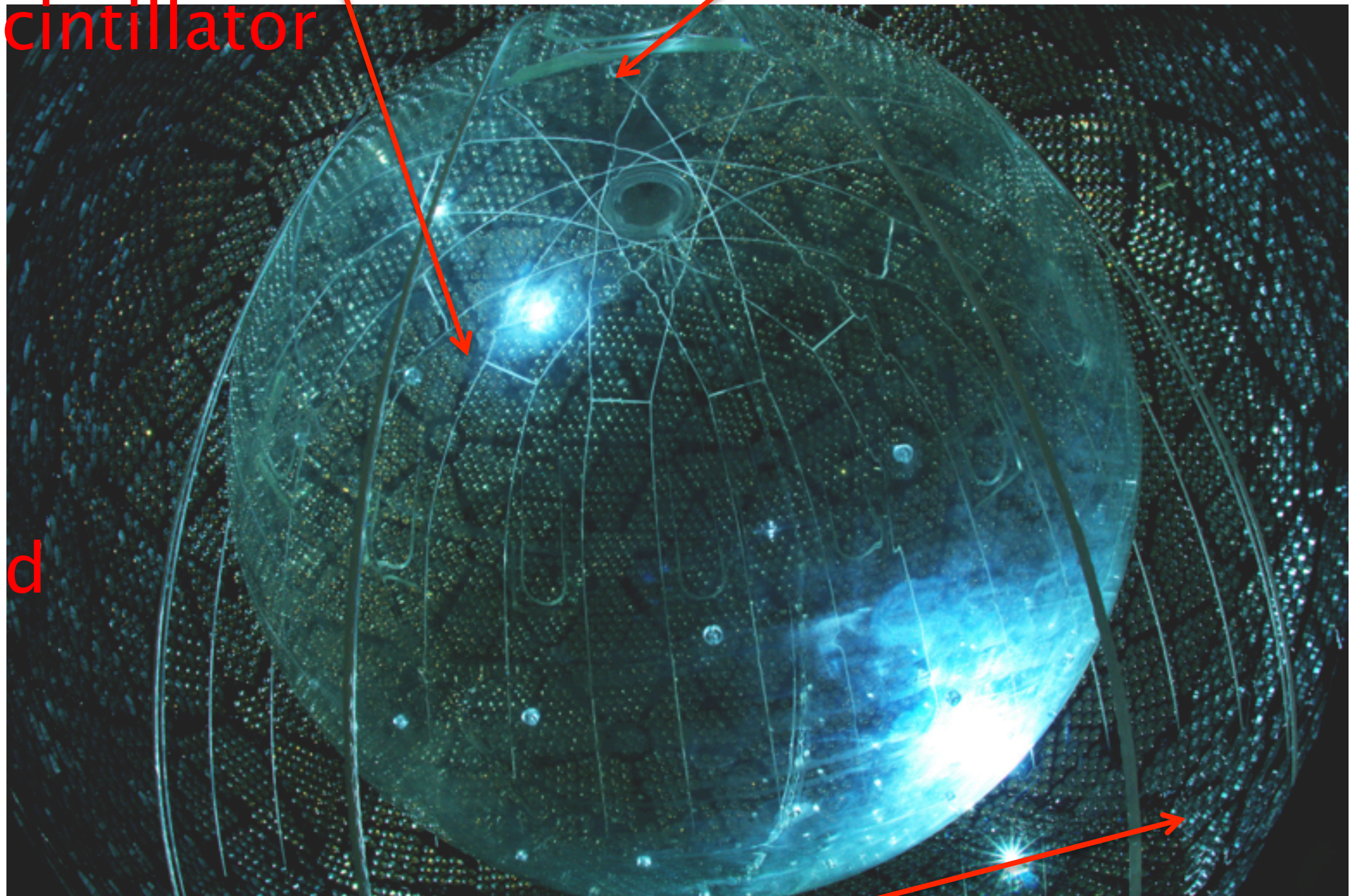
SNO+ Detector

★ 12m diameter Acrylic Vessel Hold down rope net

★ 780 tonnes scintillator



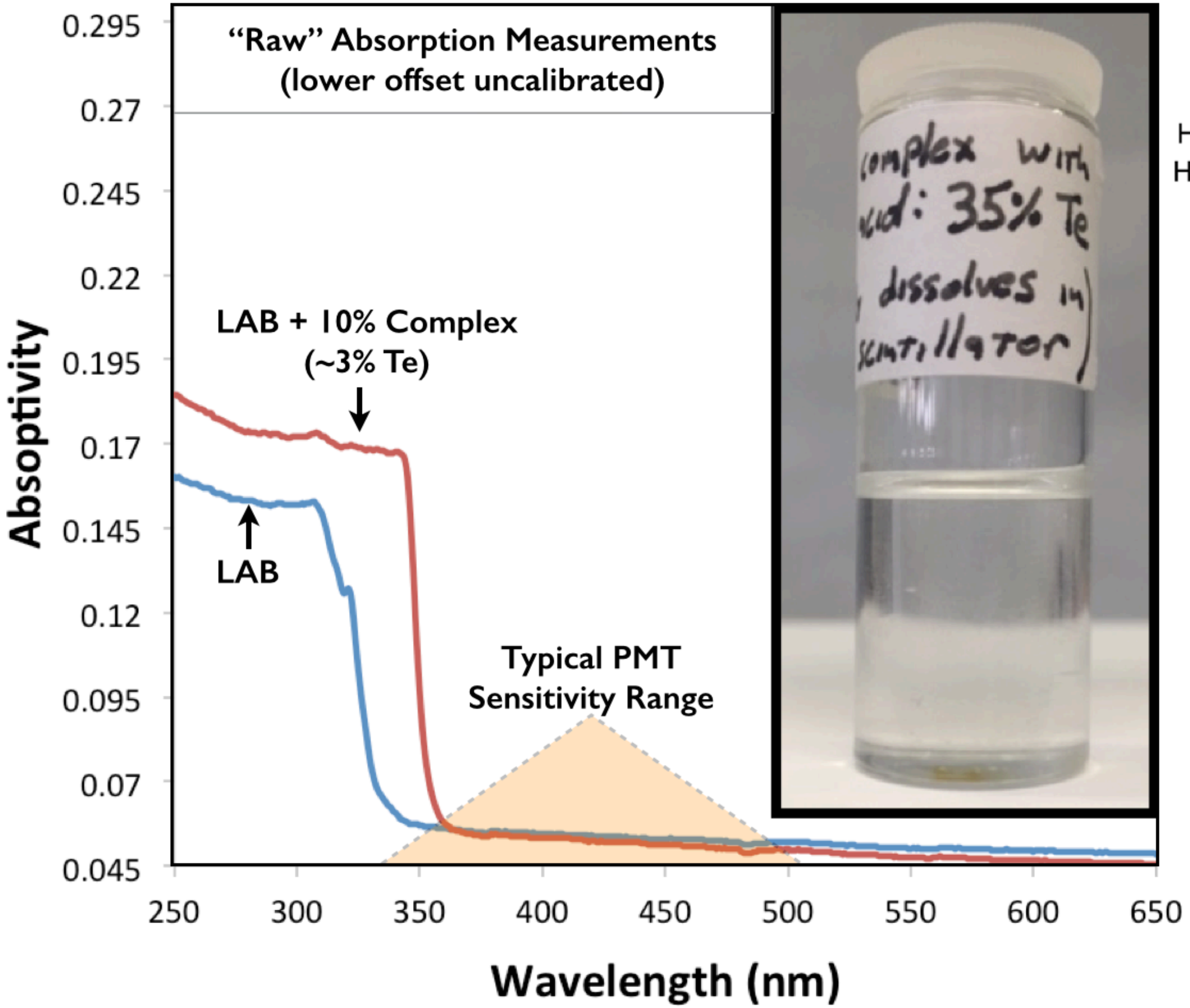
★ + Telluric acid

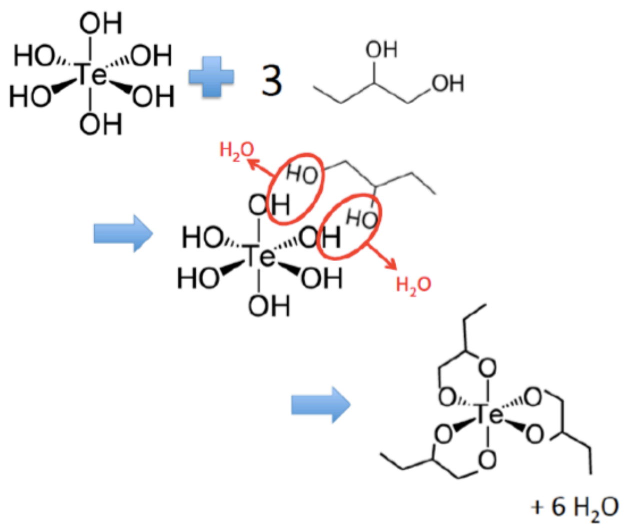


★ 7ktonnes water shielding

★ ~9300 8inch PMT array

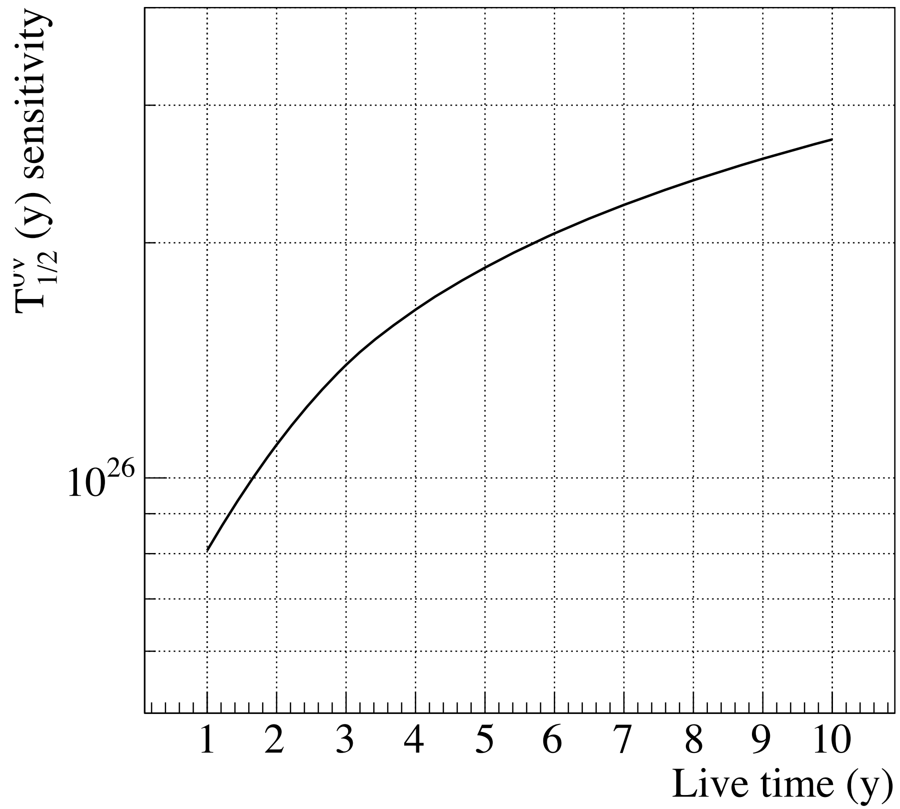
Diol Complexes





New method to load Te with higher light yield, lower backgrounds, easier to implement.

SNO+ 0νββ Sensitivity



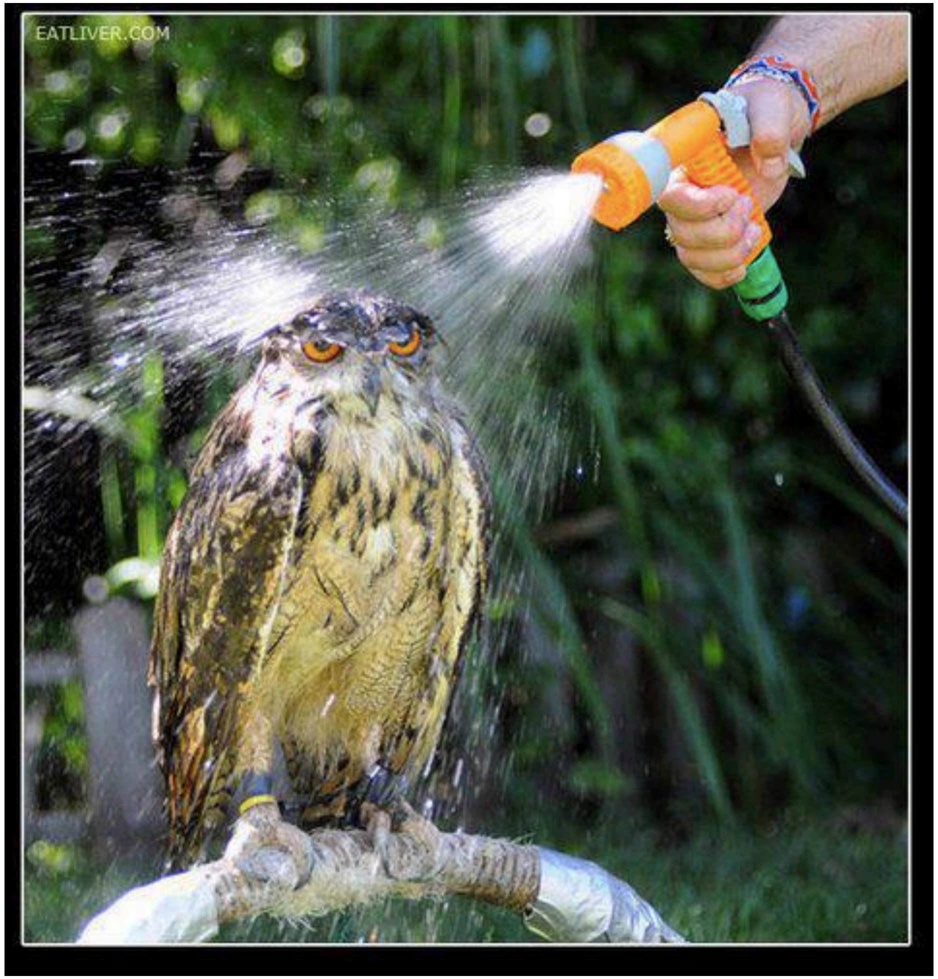
$T_{½} > 1.9 \times 10^{26}$ years with 5 years data, 0.5% loading

Immediately competitive with 1 year of data

For more info see talk by E. Leming

The future...

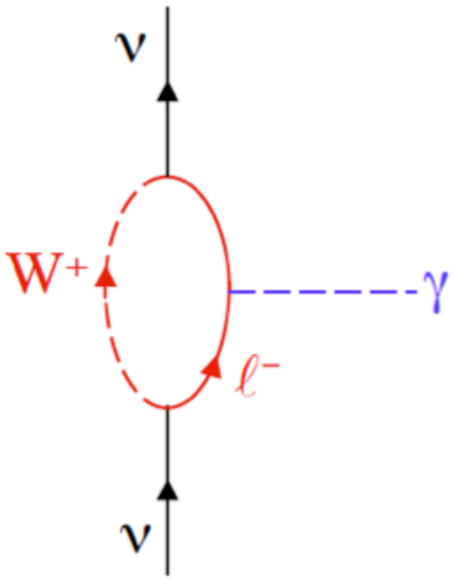
or



Magnetic moment of neutrino

- Can exist if neutrinos have a non-vanishing mass
- Should be Dirac neutrino

$$\mu_\nu = \frac{3eG_F m_\nu}{8\pi^2\sqrt{2}} = \frac{3G_F m_e m_\nu}{4\pi^2\sqrt{2}}\mu_B$$



$$\mu_\nu = 3 \times 10^{-19}\,(m_\nu/1\text{eV})\,\mu_B$$

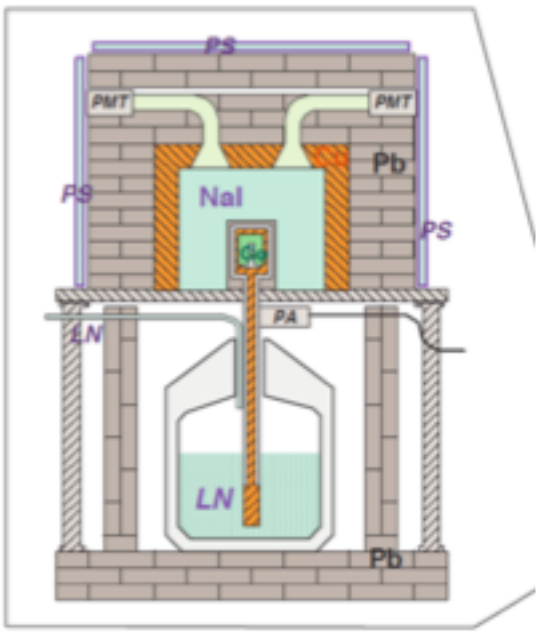
Marciano, Shrock, Lee, Fujikawa,Sanda

$$-\mu\langle s\cdot\vec{B}\rangle - d\langle s\cdot\vec{E}\rangle$$

Under CPT $\vec{E}$ *and* $\vec{B}$ *are unchanged while s changes sign (L to R) for Majorana neutrinos, so for CPT to be conserved* **μ** *and* **d** *must vanish.*

Magnetic moment searches GEMMA vs. astrophysics

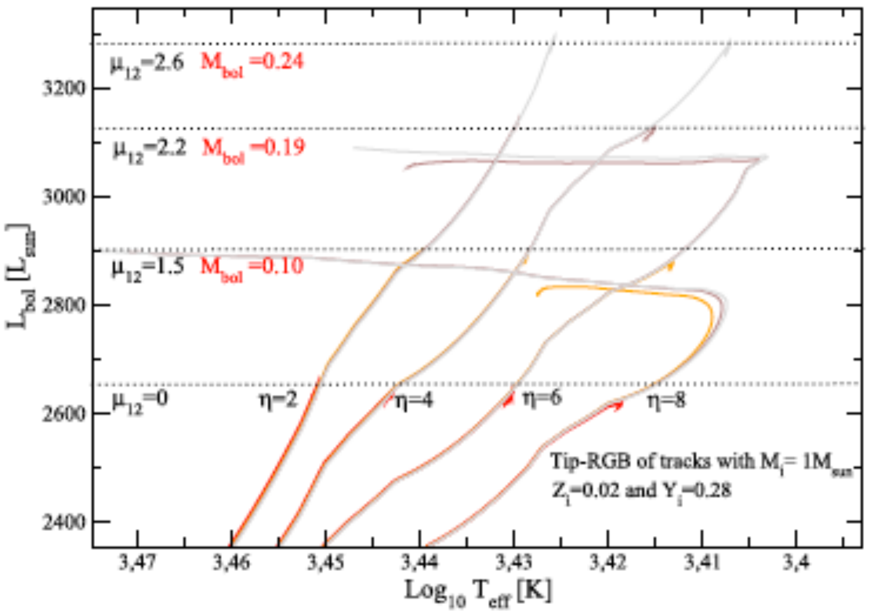
Idea: Increases cross section at low E



$$\mu_\nu < 2.9 \times 10^{-11} \mu_B (90\% CL)$$

Beda et al. 2013

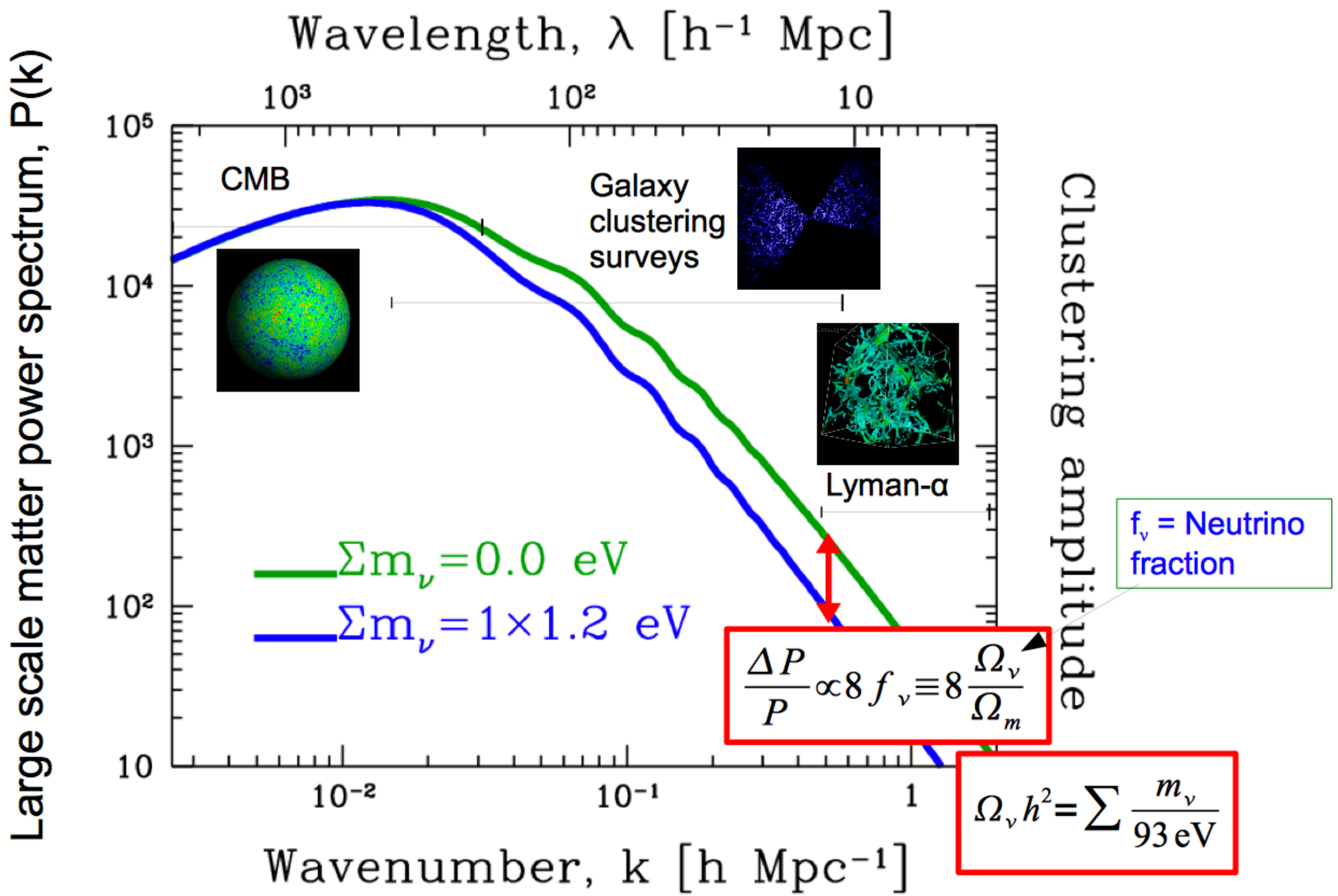
Idea: Increases energy loss of stars (tip-RGB stars, He-flash)



$$\mu_\nu < 2.2 \times 10^{-12} \mu_B (90\% CL)$$

Arceo-Diaz et al. 2015

Power Spectrum



Now you see me...
Now you don‘t

$$\Sigma = m_1 + m_2 + m_3$$

$m_\nu = 0$

Planck mission15,
Lesgourges,
Pastor14,
Palanque14
...

$m_\nu > 0$

Beutler14,
Battye14,
Sanchez13,
....

Correlation with other cosmological parameters, model dependent

Summary

There are basically 3 ways to learn about the absolute neutrino masses:

Beta decay: (most secure)

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

Double beta decay: (only if neutrnos are Majorana particles)

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

Cosmology: (model dependent, corrrelations)

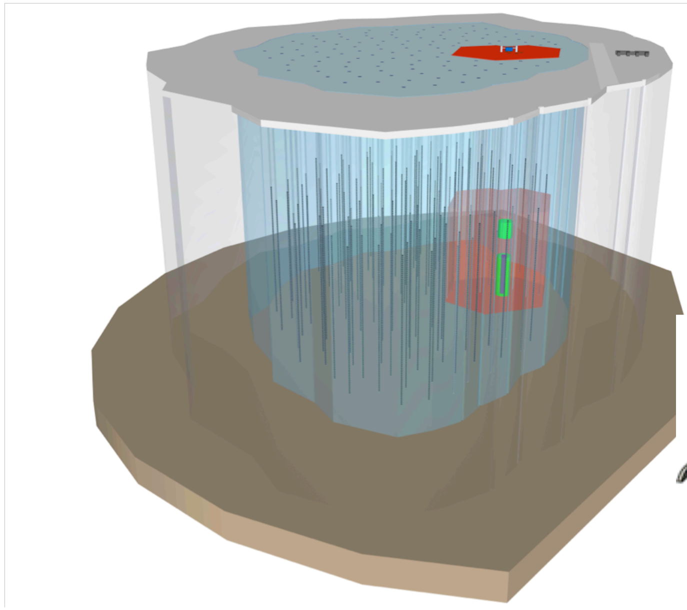
$$\Sigma = m_1 + m_2 + m_3$$

Phenomenon	Measure	Sensitivity	Dirac vs Majorana
Flavor oscillations	$\Delta m_{ij}{}^2 = m_i{}^2 - m_j{}^2$		No
β-decay	$< m_\beta >^2 = \sum_i m_i{}^2 \lvert U_{ei}\rvert^2$	0.2 eV	No
Cosmology	$M = \sum_i m_i$	0.1 eV	No
0νββ	$< m_\beta > = \sum_i m_i \lvert U_{ei}\rvert^2 e^{i\alpha}$	0.01eV	Yes

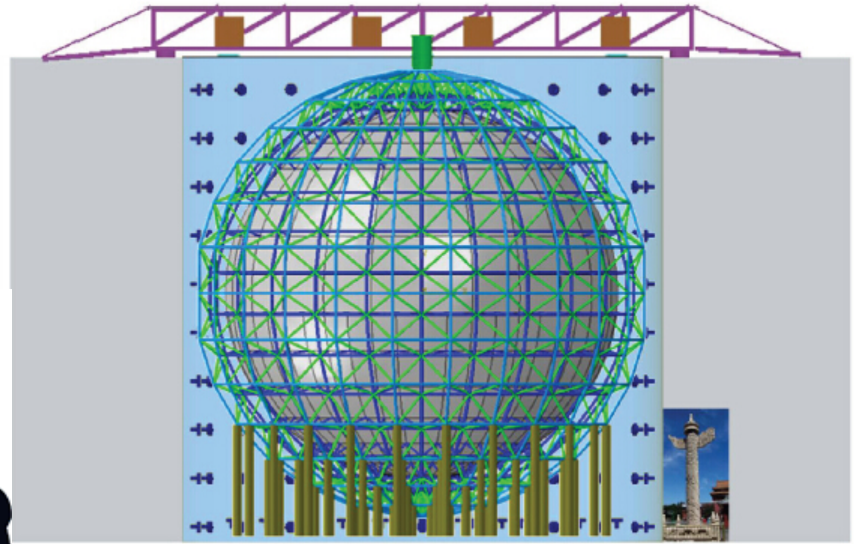
No value yet, but masses seem to be below 1 eV (electron: 511000 eV)

New future infrastructures

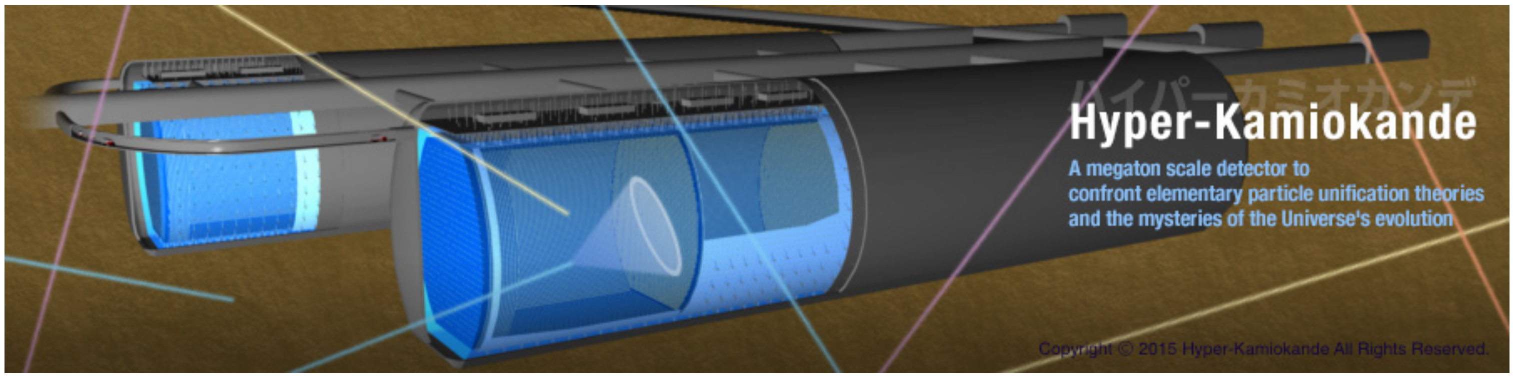
10 km^3 detector at Antarctica



20 kton liquid scintillator in China



1 Megaton water detector in Japan



The future

- ★ Absolute neutrino mass measurement
- ★ Which mass scheme?
- ★ Understanding mixing pattern
- ★ Three flavour analysis
- ★ Is there CP-violation in the lepton sector (is it observable)?
- ★ Neutrino astronomy
- ★ Supernova neutrinos
- ★ Geoneutrinos
- ★ Are there sterile neutrinos?
- ★ Unexpected things?

Always expect the unexpected