invisibles
neutrinos, dark matter & dark energy physics

Universität Zürich[UZH]

The Unbearable Lightness of Neutrinos

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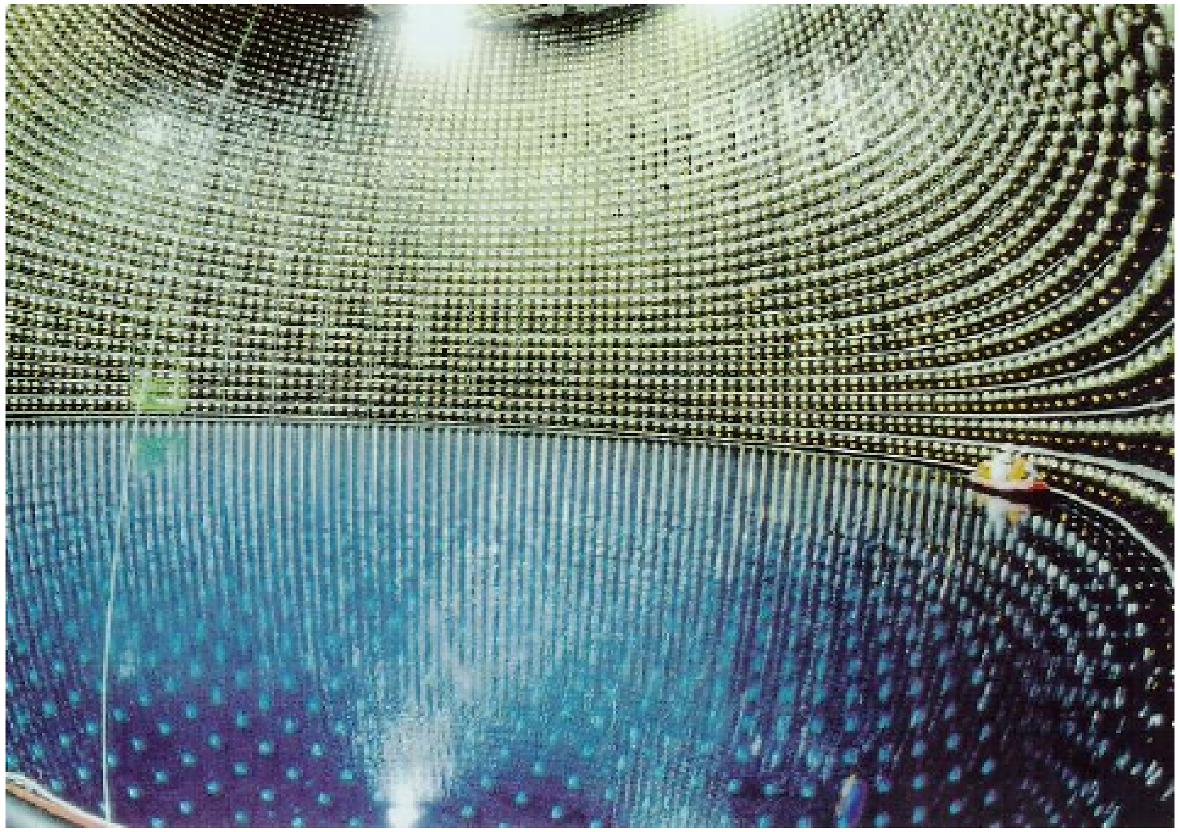
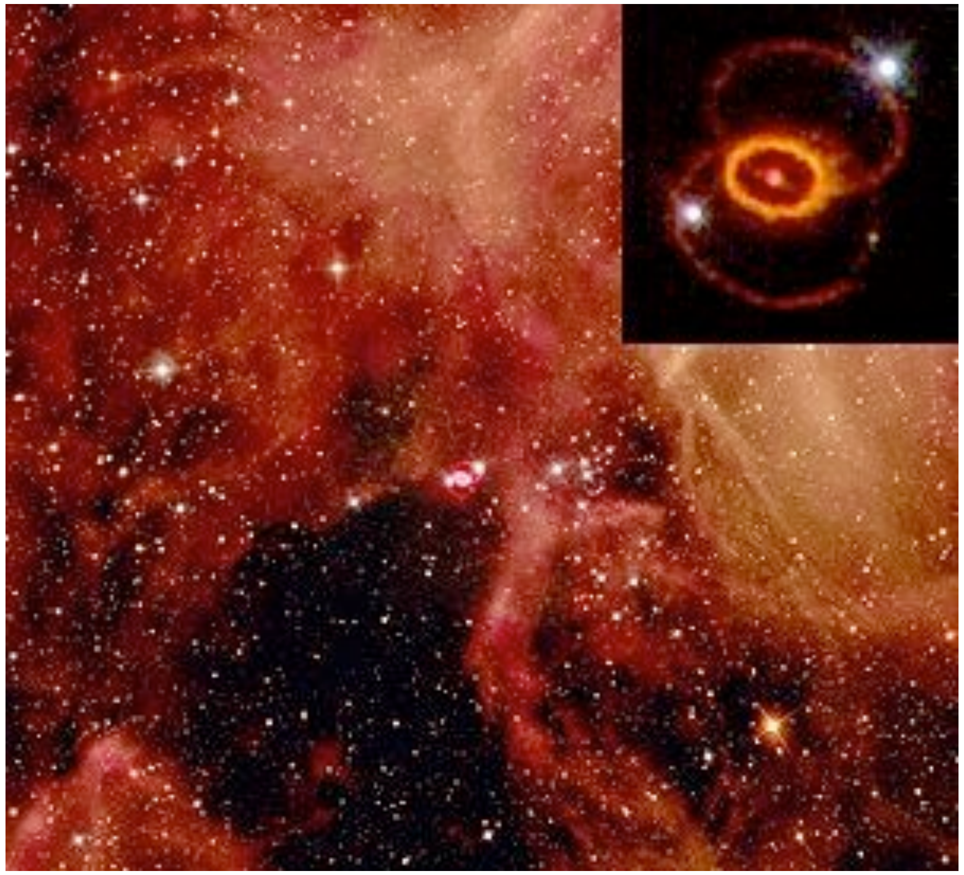
Mysterious Messengers from Outer Space

- February 23, 7:35 universal time, 1987: **a hoard of billions upon billions of extragalactic messengers sweep through the Earth**
- **Only a few of them were stopped.** In fact, 11 left a signal in a large, multi-ton water detector deep in the Kamioka mine in Japan
- **Three hours later, the light from a Supernova explosion in a nearby galaxy reached the Earth**; it was the closest Supernova since the invention of the telescope



The Super-Kamiokande detector in Japan



SN1978A

What had happened?

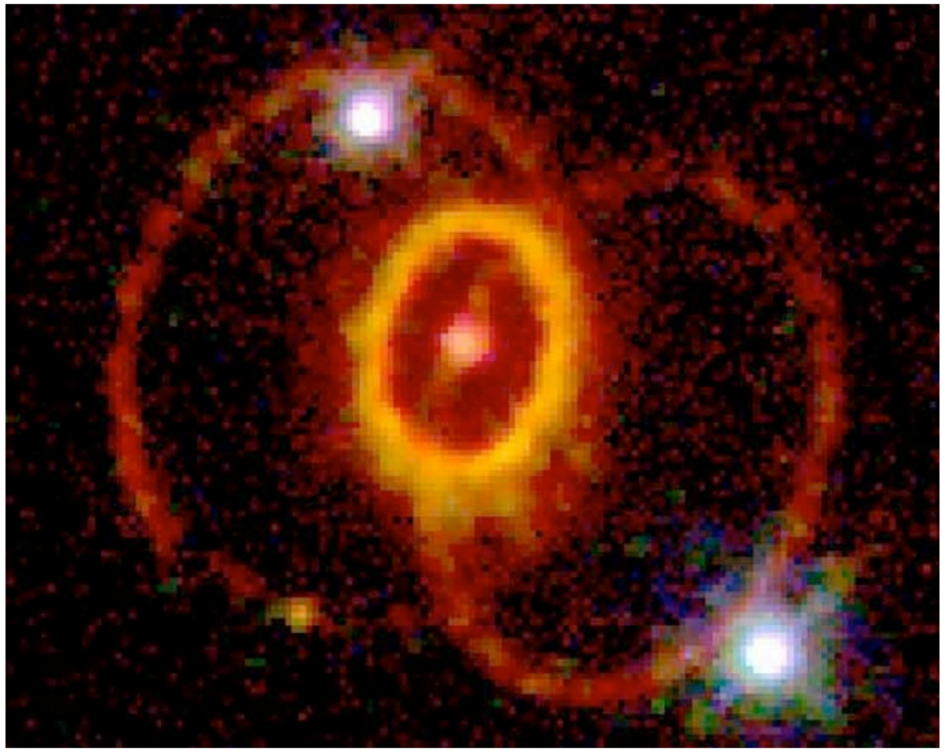
- **A star, 20 times the mass of our Sun, had exploded about 168'000 years ago**

  (this Supernova explosion took place in the Large Magellanic Cloud, one of the 11 dwarf galaxies that orbit the Milky Way)

- **The messengers to reach the Earth first were particles called neutrinos**, ***they had witnessed the death of the star as they zoomed out of the collapsing core***

- It took the photons a few extra hours to reach the surface of the exploding star

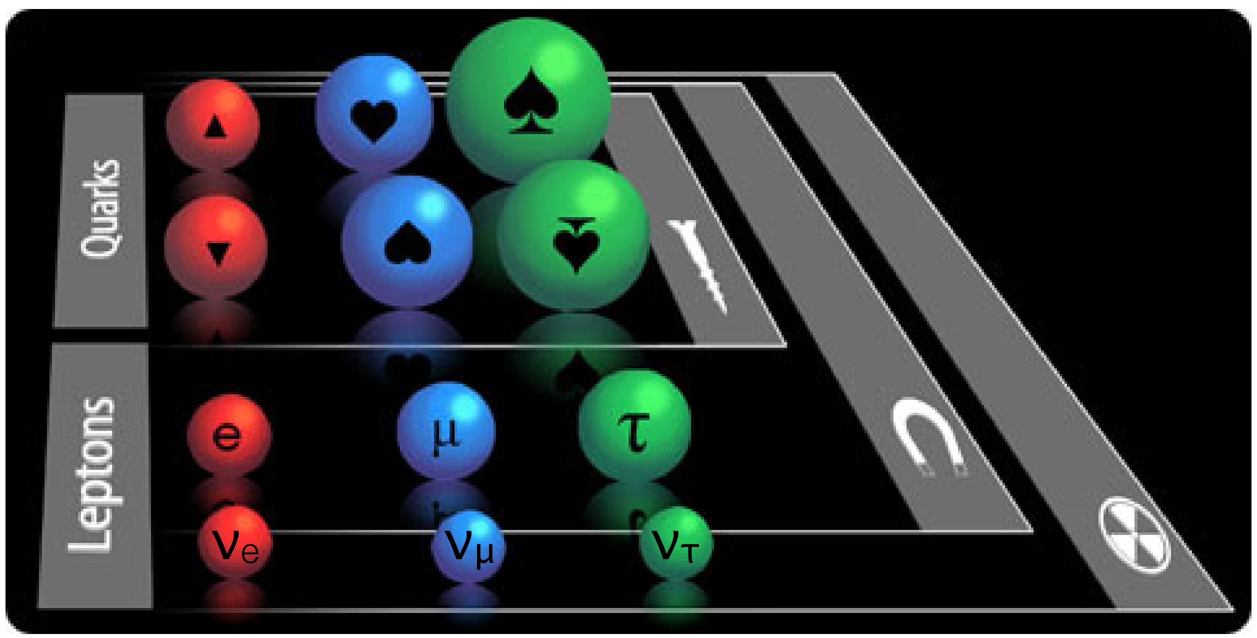
The Large Magellanic Cloud, 168'000 light years away

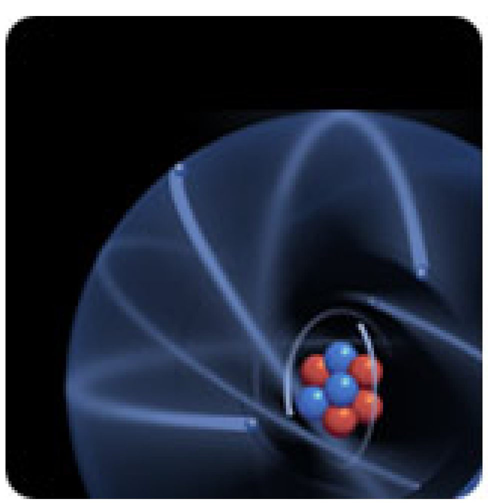


The Supernova remnant

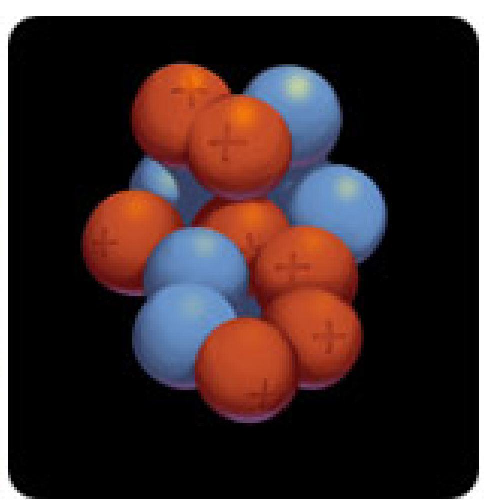
Neutrinos?

- **Particles in the Standard Model of particle physics**
- It deals with the composition of matter on its smallest scales, with symmetries and interactions between the matter constituents

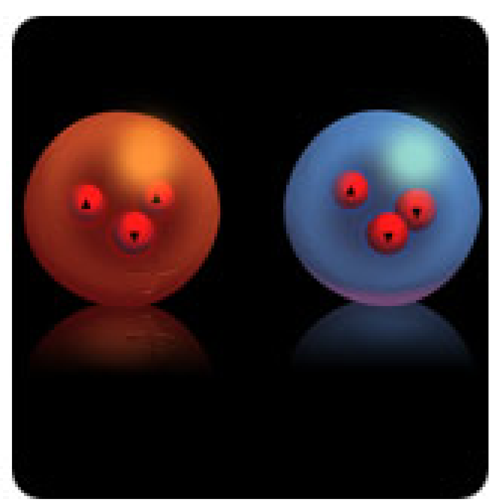




Atoms

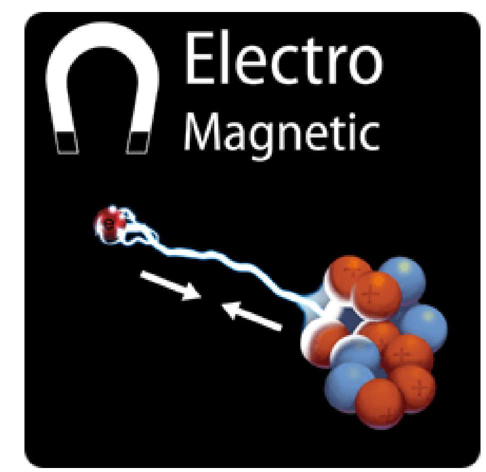


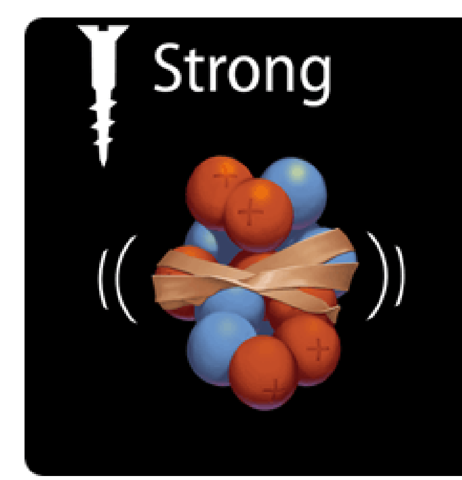
Nuclei



Protons, Neutrons

Forces: particles called bosons mediate the interactions



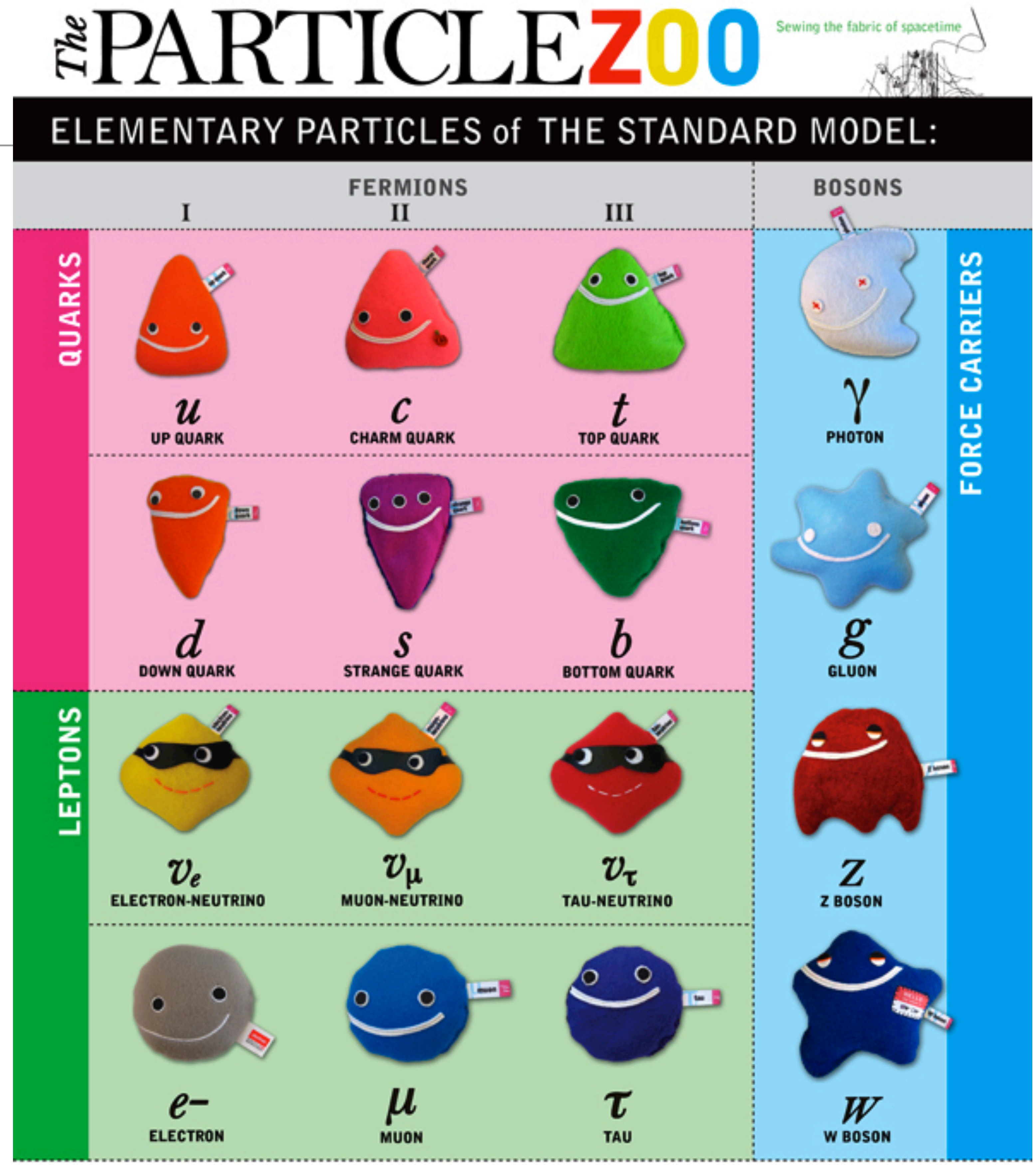


Neutrinos?

- **Neutrinos are electrically neutral and interact only via the weak force**

We know 3 families of quarks and leptons: these are fermions, spin 1/2

Forces between fermions are mediated by gauge bosons, with spin 1



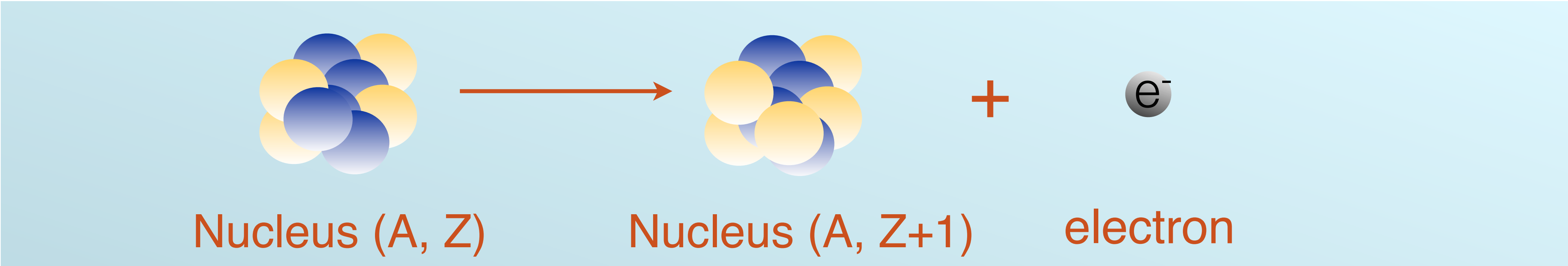
First, some history....

- **Zürich, December 4, 1930:** Wolfgang Pauli, a 30 years old professor at the ETH, writes perhaps one of the most famous letters in modern physics: "Dear radioactive ladies and gentlemen…"
- The letter was addressed mainly to Lise Meitner, who had been working on radioactivity since 1907 and was attending a meeting in Tübingen (Pauli could not attend, because "a ball which takes place in Zürich the night of the sixth to sevenths of December makes my presence here indispensable")

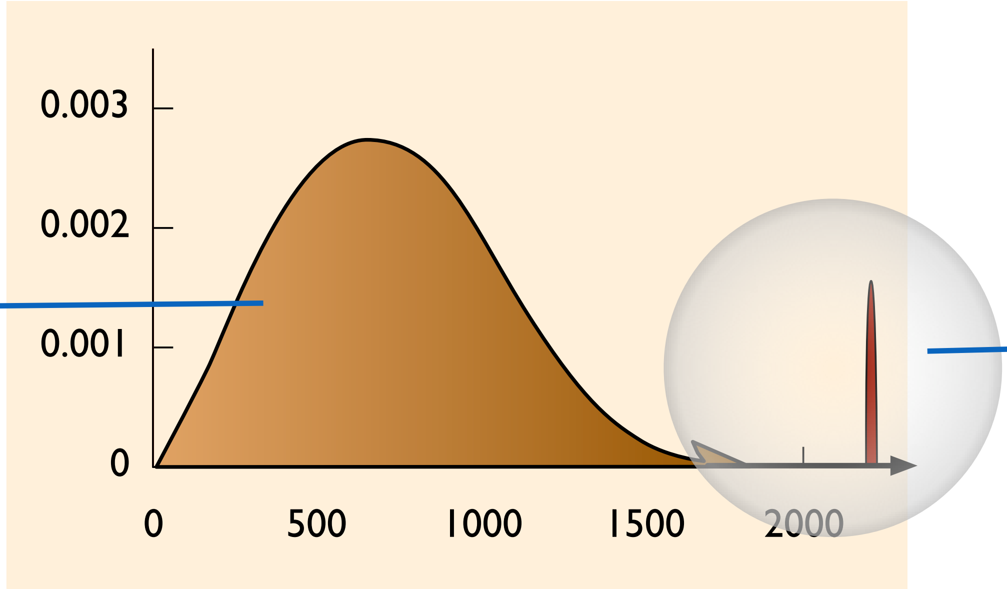
- Pauli was suggesting "a desperate way out" of **some paradox** that had arisen in the nascent field of nuclear physics
- He was proposing "a terrible thing" - a new subatomic particle, **the neutrino,** a particle "which can not be detected"
- In 1930, only the electron, the proton and the photon were known, **and Pauli's idea was quite radical!**

And the Paradox was... the Energy Crisis

- It had been observed (by hard working experimental physicists), that **some nuclei are not stable, but decay under the emission of “beta rays” (electrons)**
- The energy of the emitted electrons could be measured - **the spectrum was continuous**
- **This seemed to violate a well respected law in physics: the conservation of energy!**



Measured energy spectrum



Expected energy of the electron

$mc^2 = E$: the mass difference of the two nuclei is converted into the energy of the electron

Only One Reasonable Way Out...

- **A new particle: the neutrino. It would share the energy with the electron, but would not be observed because of its incredible weak interaction with matter**

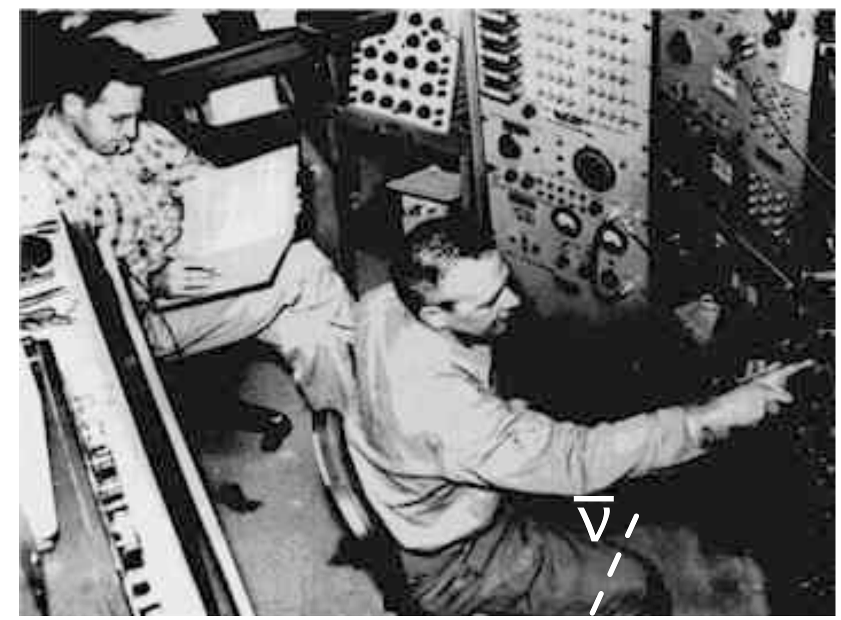
- **Niels Bohr, 1934:** *"I must confess that I don't really feel fully convinced of the physical existence of the neutrino"*

- **Arthur Eddington, 1939:** *"I am not much impressed by the neutrino theory.... Dare I say that physicists will not have sufficient ingenuity to make neutrinos?"*

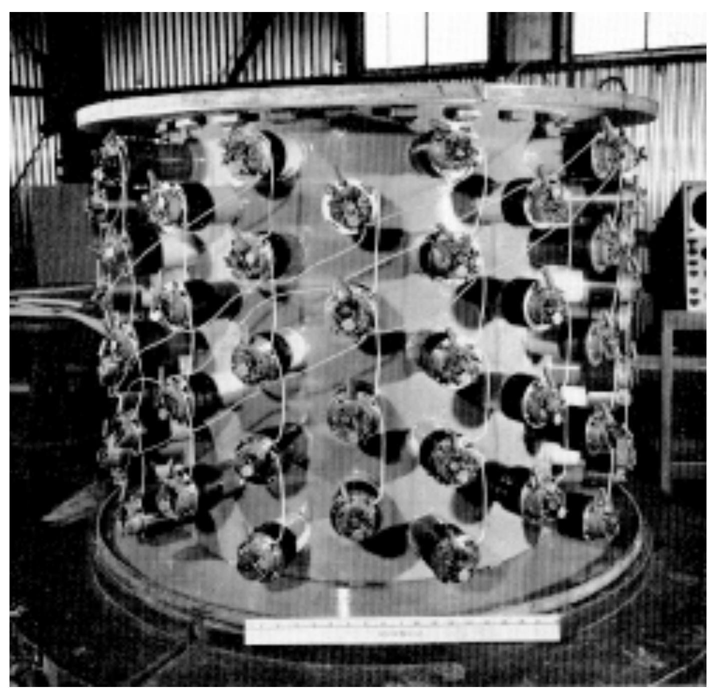
- Thus, while the idea was considered by most as a very useful hypothesis, **few believed it is a real particle,** until...

Neutrinos Galore

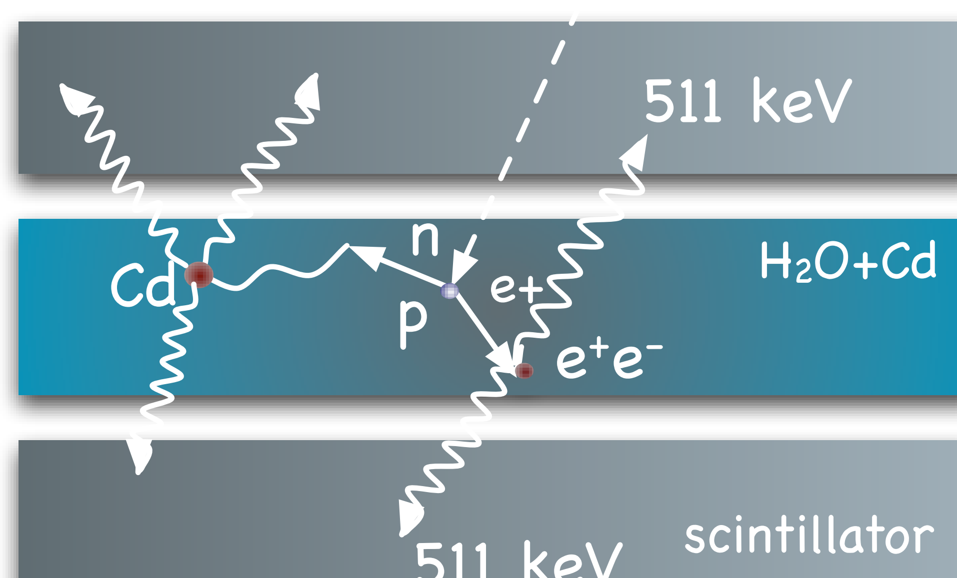
- **Some 30 years later (1956)**, when Clyde Cowan and Fred Reines started the *“Project Poltergeist”* and finally detected (anti)neutrinos at the Savannah River Reactor in South Carolina



Detector: 400 l water + $CdCl_2$ seen by 90 photodetectors



Detection via delayed (a few μs) coincidence reaction:



prompt: $e^+ + e^- \rightarrow \gamma + \gamma$

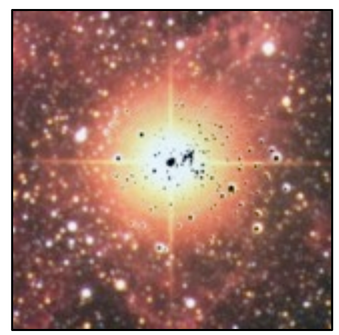
delayed: $n + Cd \rightarrow \gamma' s$

And this was only the beginning of the big adventure...

Neutrino Sources

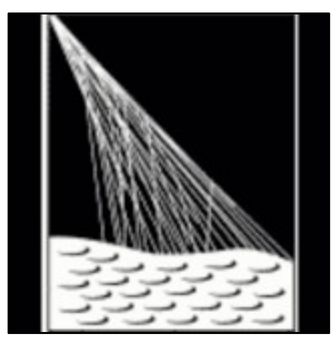
✓ Reactors

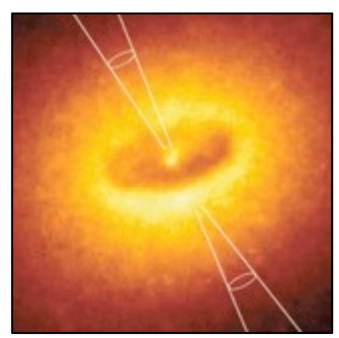
Sun ✓



✓Particle accelerators

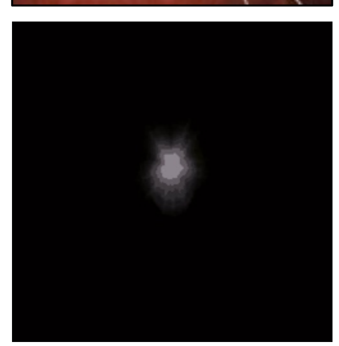
Supernovae
(collapsing stars)
SN 1987A ✓





✓ Earth atmosphere
(from cosmic rays)

Extraterrestrial neutrinos
Recently observed!



✓ Earth crust
(from natural
radioactivity)

Big Bang
(Today ~ 330 ν/cm^3)
Indirect evidence

and people!

Neutrinos dominate our Universe

- The world around us (people, trees, stones, buildings, polenta, the Earth...) **is made of electrons, protons and neutrons**

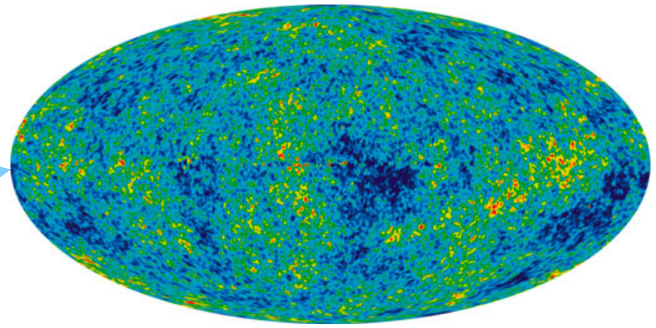



- **Is the whole Universe made of electrons, protons and neutrons?**

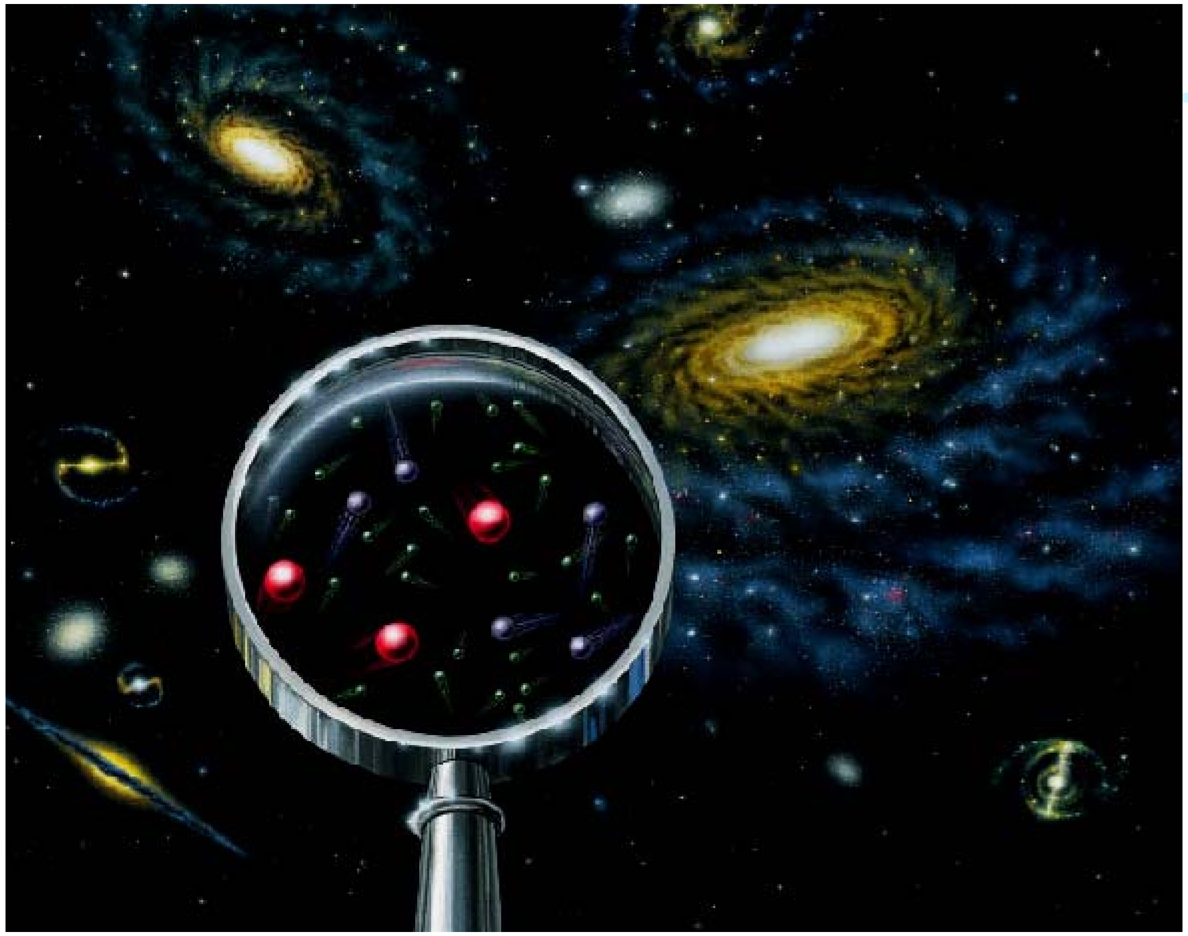
NO

- These are RARITIES; for every one of them, **the Universe contains a billion of neutrinos!**
- **Moreover, our Universe is made of matter, and not of anti-matter**
- **To understand the Universe, we must understand neutrinos!**

Neutrinos from the Big Bang



- As with photons of the **3 Kelvin Cosmic Microwave Background Radiation** (measured very precisely with the WMAP and now with the Planck Satellite)...
- **the Universe is filled with a sea of neutrinos,** that decoupled from the rest of the particles about 10 seconds after the Big Bang



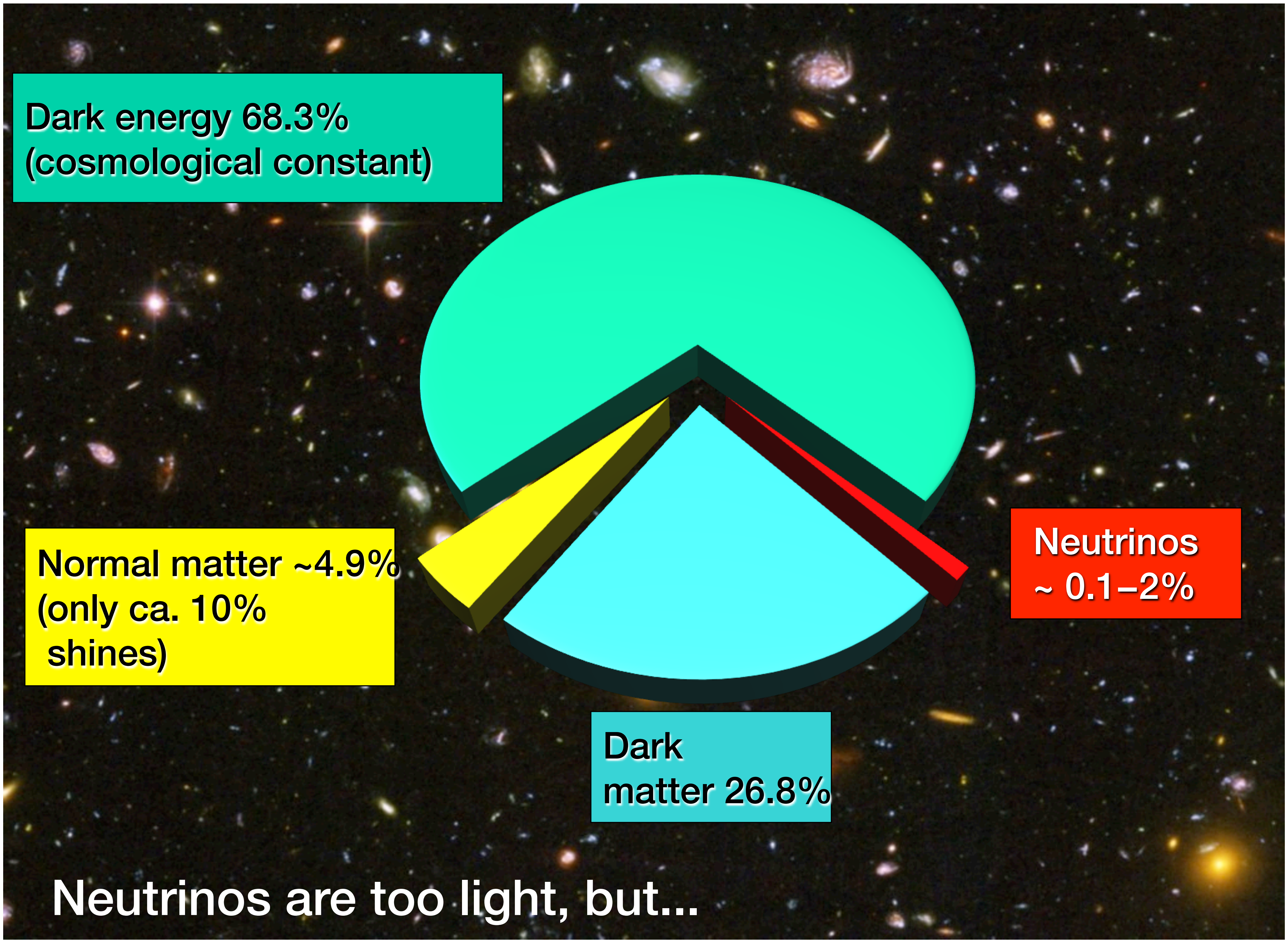
Every cubic meter of space contains about **300 million neutrinos**

Could they make up the DARK MATTER in the Universe?

NO

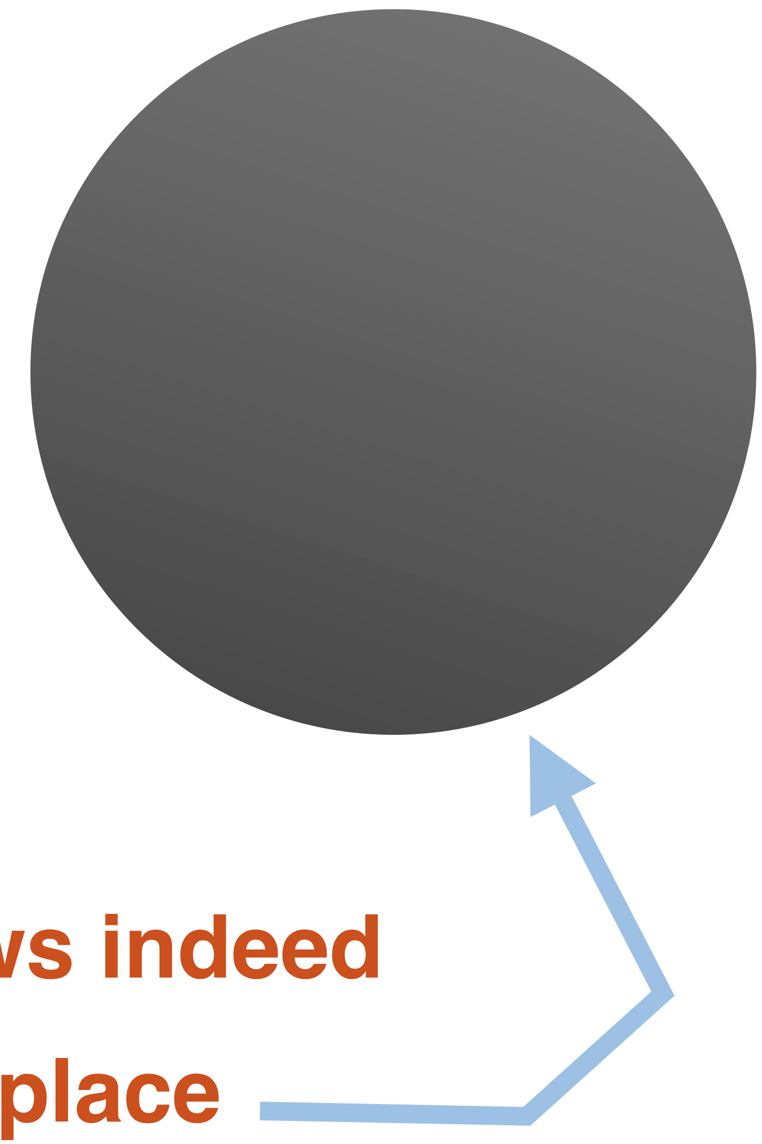
Their mass is much too small!

Neutrinos - too light for the dark matter



Neutrino, the Sun and Us

- Regardless, neutrinos are vital for our life!
- **No neutrinos would mean:**
  - ➡ no energy to keep us warm
  - ➡ no atoms more complicated than hydrogen
  - ➡ no carbon, no oxygen, no water
  - ➡ no Earth, no moon, no us

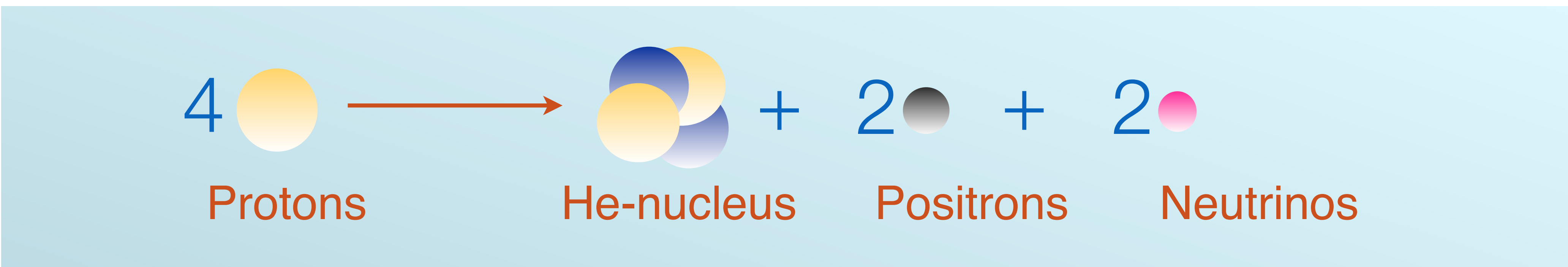


NO neutrinos would be very bad news indeed

The Universe would be a boring place

Solar Neutrinos

- **Our Sun is a gigantic fusion reactor, it shines by converting protons into helium nuclei**
- These reactions are governed by the weak force, hence the Sun shines for *a very long time*

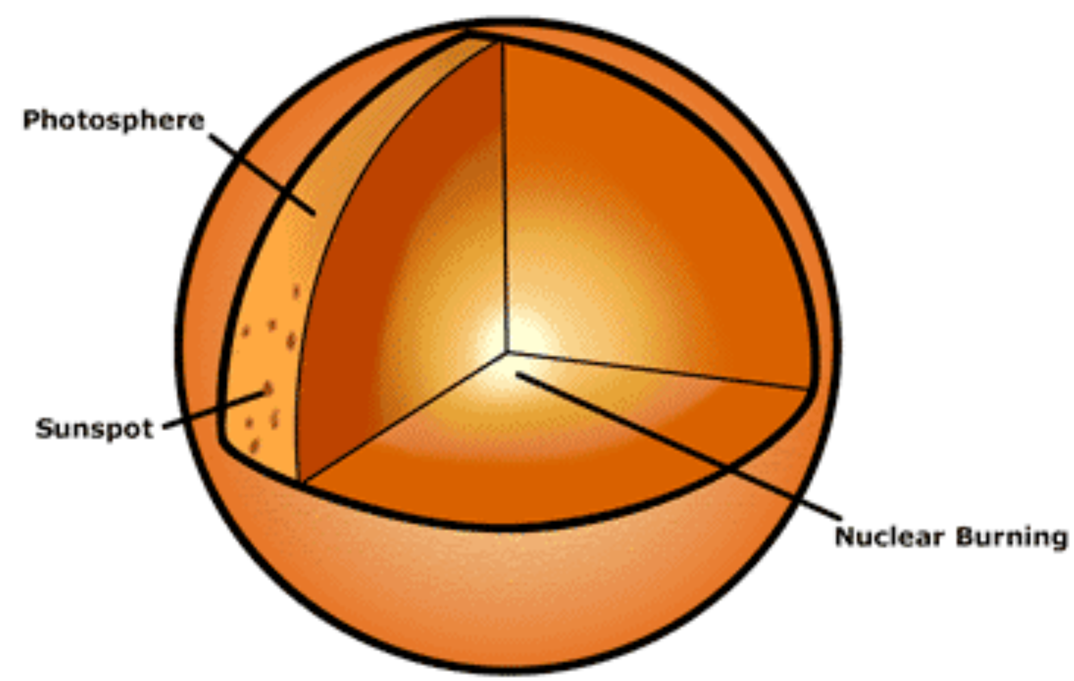


- The neutrino flux on Earth is **65 billion solar neutrinos pro cm^2 and second!**

Almost all of these neutrinos are zipping through the Earth and through us, and do **NOTHING AT ALL**

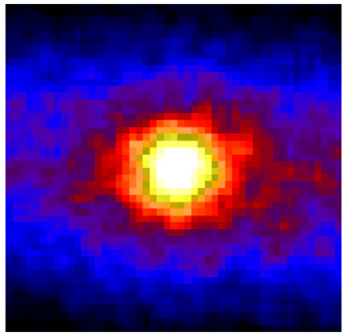
The probability that a particular solar neutrinos will interact as it zips through one of you is **1/10’000’000’000’000’000’000**

Nonetheless...



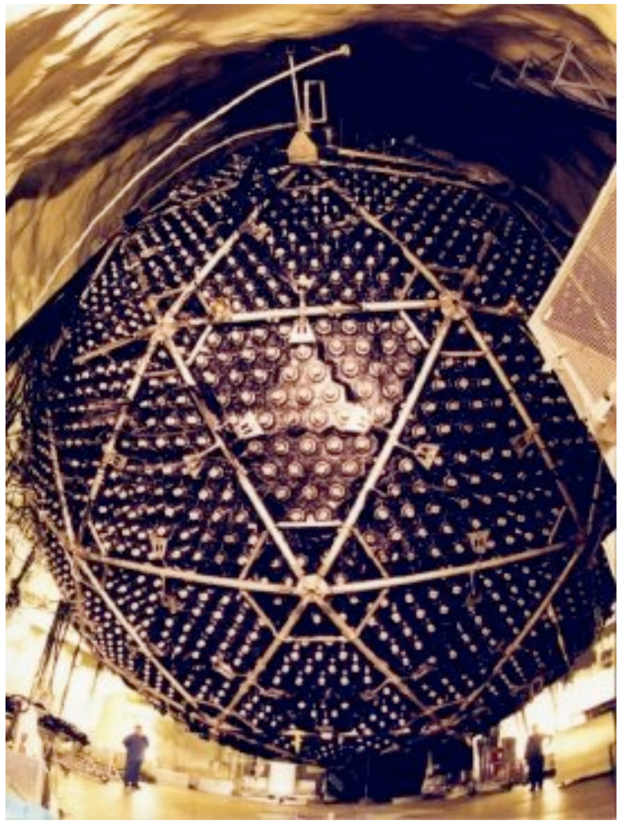
T_{core} = 15‘000‘000 Kelvin

Gigantic Detectors for Solar Neutrinos

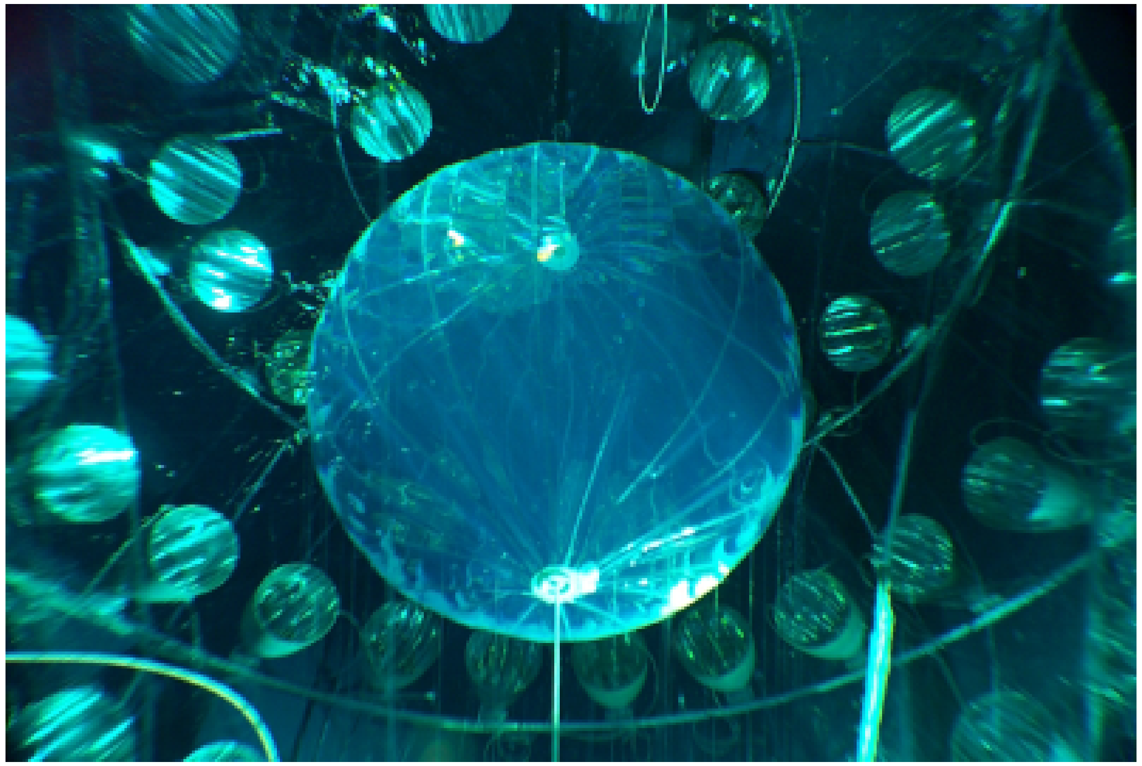


- **We see the Sun in neutrinos!**
- **In fact, solar neutrinos are now routinely detected in gigantic experiments operated in deep underground laboratories around the world**
- From such observations, we learn about **the Sun interior**
- **and about the elusive particles themselves!**

The Chlorine experiment in the US

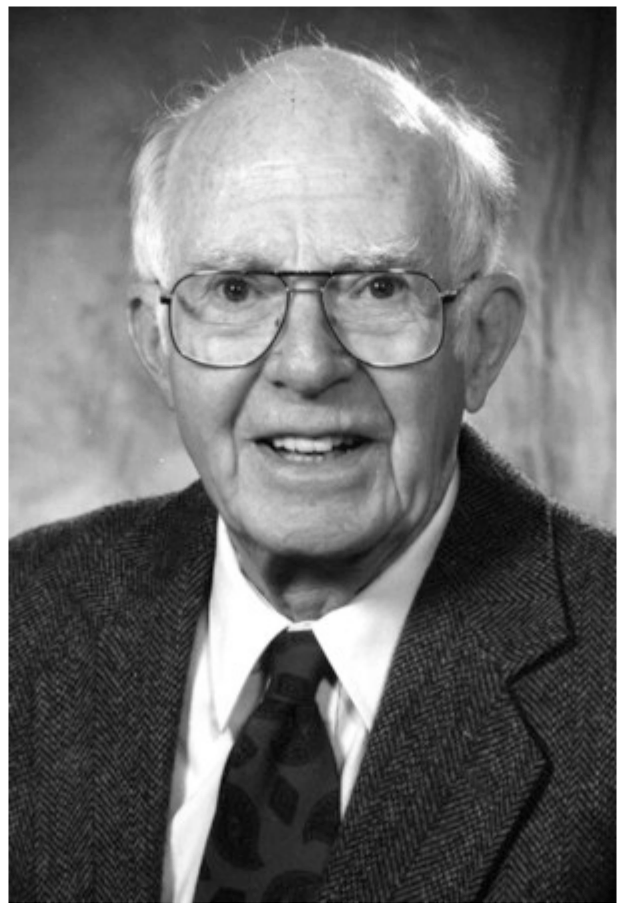


The SNO experiment in Canada



The BOREXINO experiment in Italy

Physics Nobel Prize in 2002 for Neutrino-Astronomy



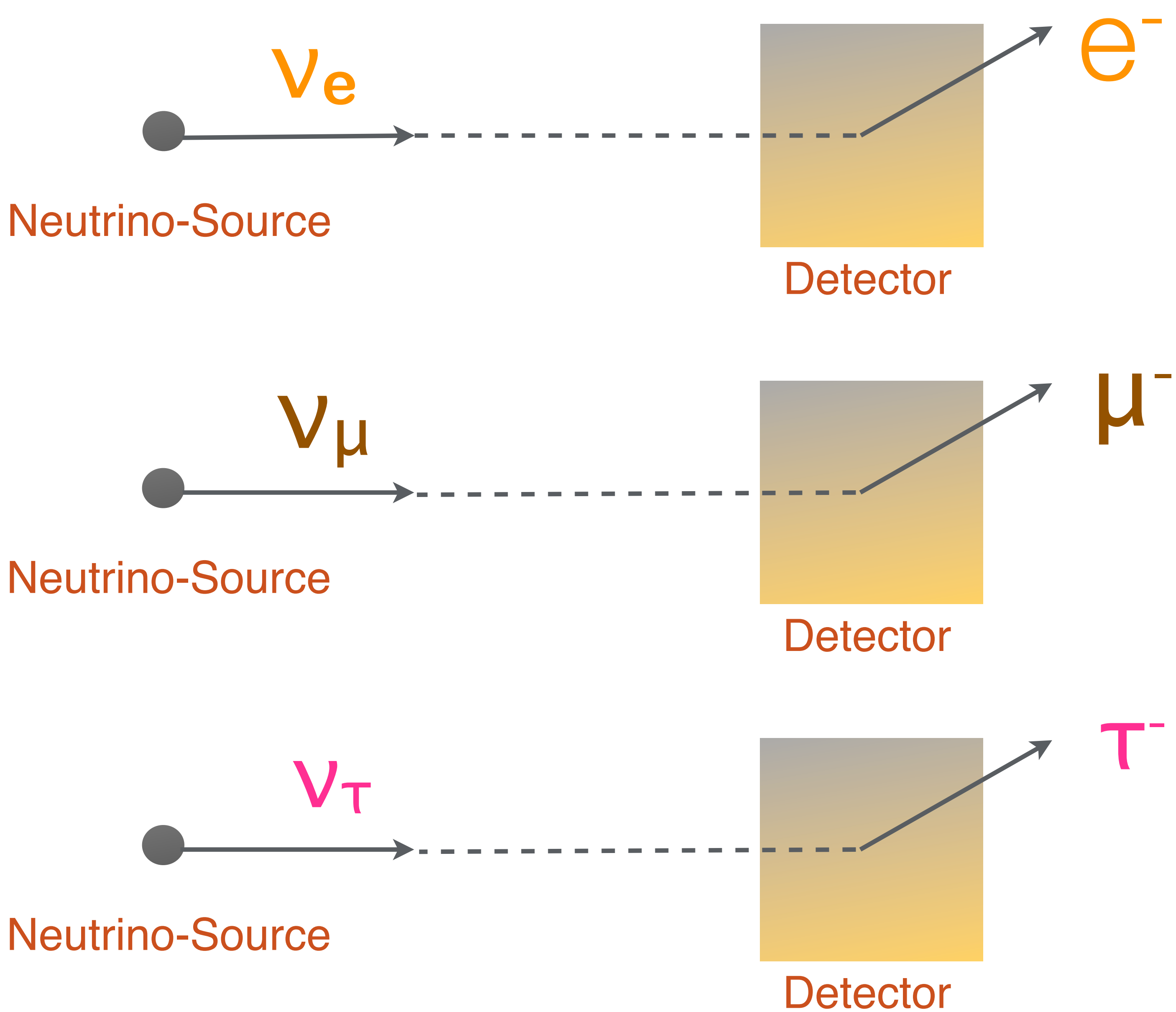
Ray Davis Jr.
(1914–2006)

Masatoshi Koshiba
(*1926)

„for pioneering work in astrophysics, in particular for the detection of cosmic neutrinos ”

What do we know about neutrinos?

- They come in three flavours: ν_e electron, ν_μ muon, ν_τ tau



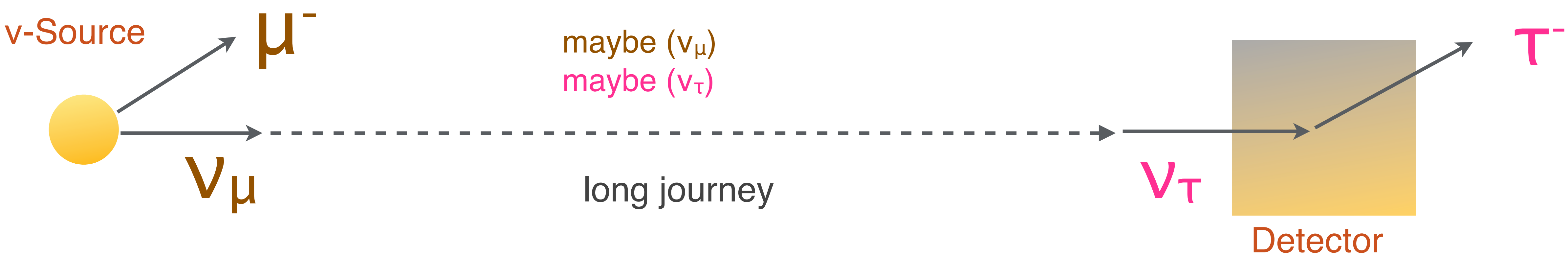
The 3 neutrino flavours participate in charged current (CC) weak interactions together with the corresponding charged lepton

These are of (V-A) type: neutrinos are LH, anti-neutrinos are RH

In the Standard Model, the flavour lepton numbers are conserved, and neutrinos are exactly massless

What do we know about neutrinos?

- However, when neutrinos propagate over macroscopic distances, they oscillate between flavours:



- This is a well studied effect in quantum mechanics
- It means that flavour is not conserved over macroscopic distances, for instance:

$$P(\nu_e \to \nu_e) < 1$$

$$P(\nu_\mu \to \nu_\mu) < 1$$

$$P(\nu_\tau \to \nu_\tau) < 1$$

What do we know about neutrinos?

- A compelling explanation of all the available data comes from the assumption that:
  - ➡ neutrino states with different flavours ν_α mix with neutrino states with different masses ν_i
- The mixing is introduced "a la CKM" in the left-handed fields of the CC interaction Lagrangian:

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i} \nu_i$$

$U_{\alpha i}$ unitary neutrino mixing matrix (PMNS matrix)

ν_α, ν_i quantum fields

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

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{j>i} U_{\alpha i} U_{\beta i} U_{\alpha j} U_{\beta j} sin^2 \frac{\Delta m_{ij}^2 x}{4E}$$

- P: flavor transition probability in the case of CP invariance (U = U*)

Neutrino mixing

- For 3 neutrino flavours, the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix can also be parameterized:

$$c_{ij} = cos\theta_{ij} \qquad s_{ij} = sin\theta_{ij}$$

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

Data from atmospheric ν's and accelerators
$\theta_{23} \approx 45$ deg

Data from reactors and accelerators
$\theta_{13} \approx 9$ deg

Data from solar and reactor neutrinos
$\theta_{12} \approx 34$ deg

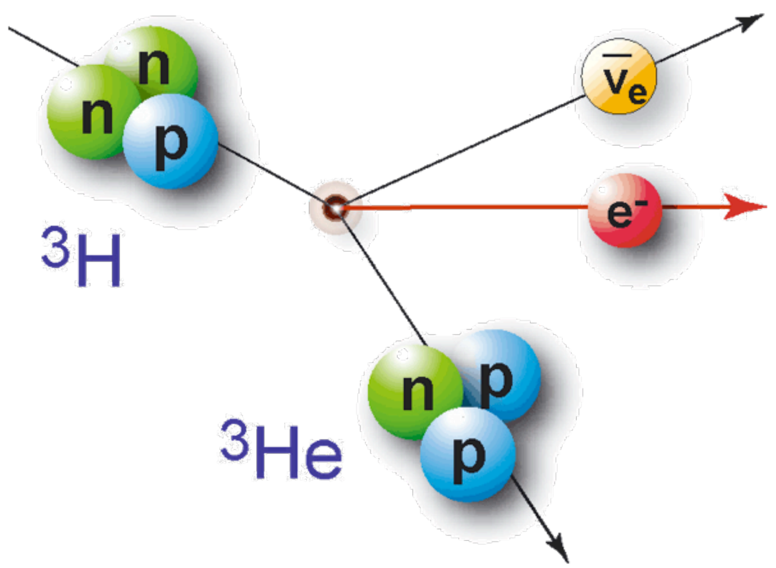
In general, we have 3 mixing angles, 1 CP violating phase, 3 different Δm^2 (only 2 being independent)

=> **no information about the absolute ν-mass scale**

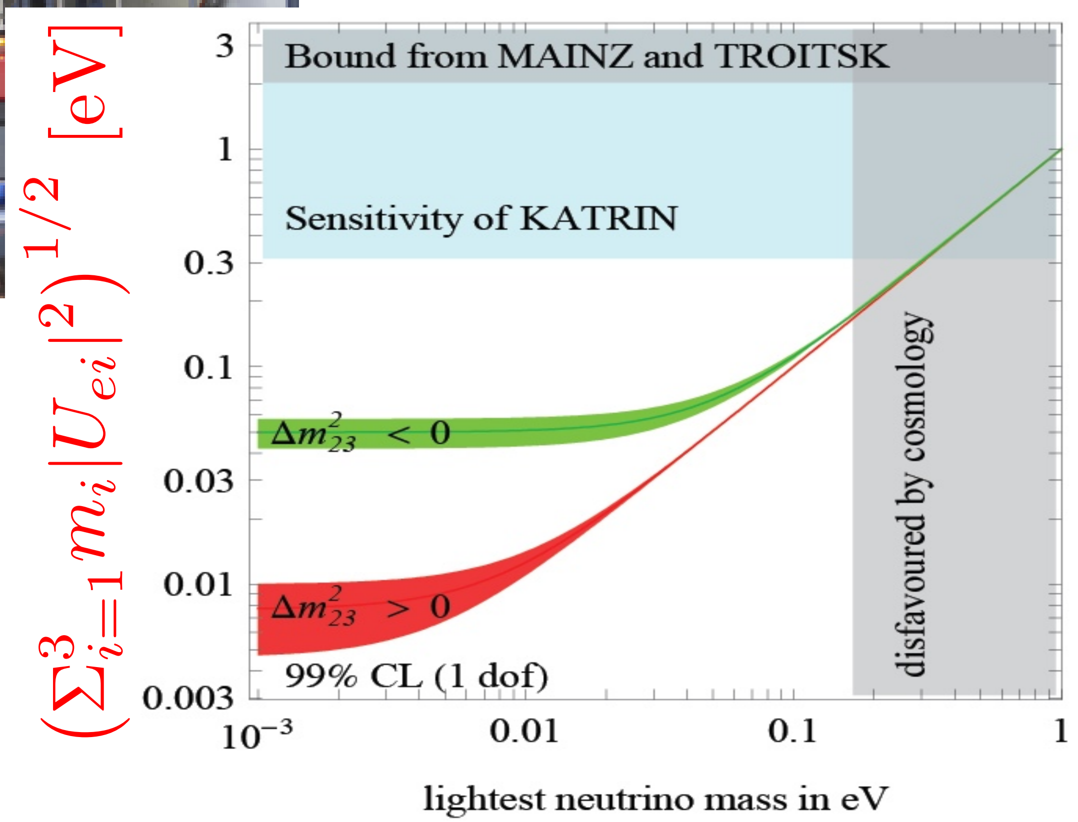
$$\Delta m^2_{sol} \sim 7.5 \times 10^{-5}\ \mathrm{eV}^2 \qquad \Delta m^2_{atm} \sim 2.4 \times 10^{-3}\ \mathrm{eV}^2$$

One Open Question: The Mass of Neutrinos

- **What is the absolute value of the neutrino mass?**
- From experiments that measure the endpoint of the Tritium beta-decay to ^{3}He:



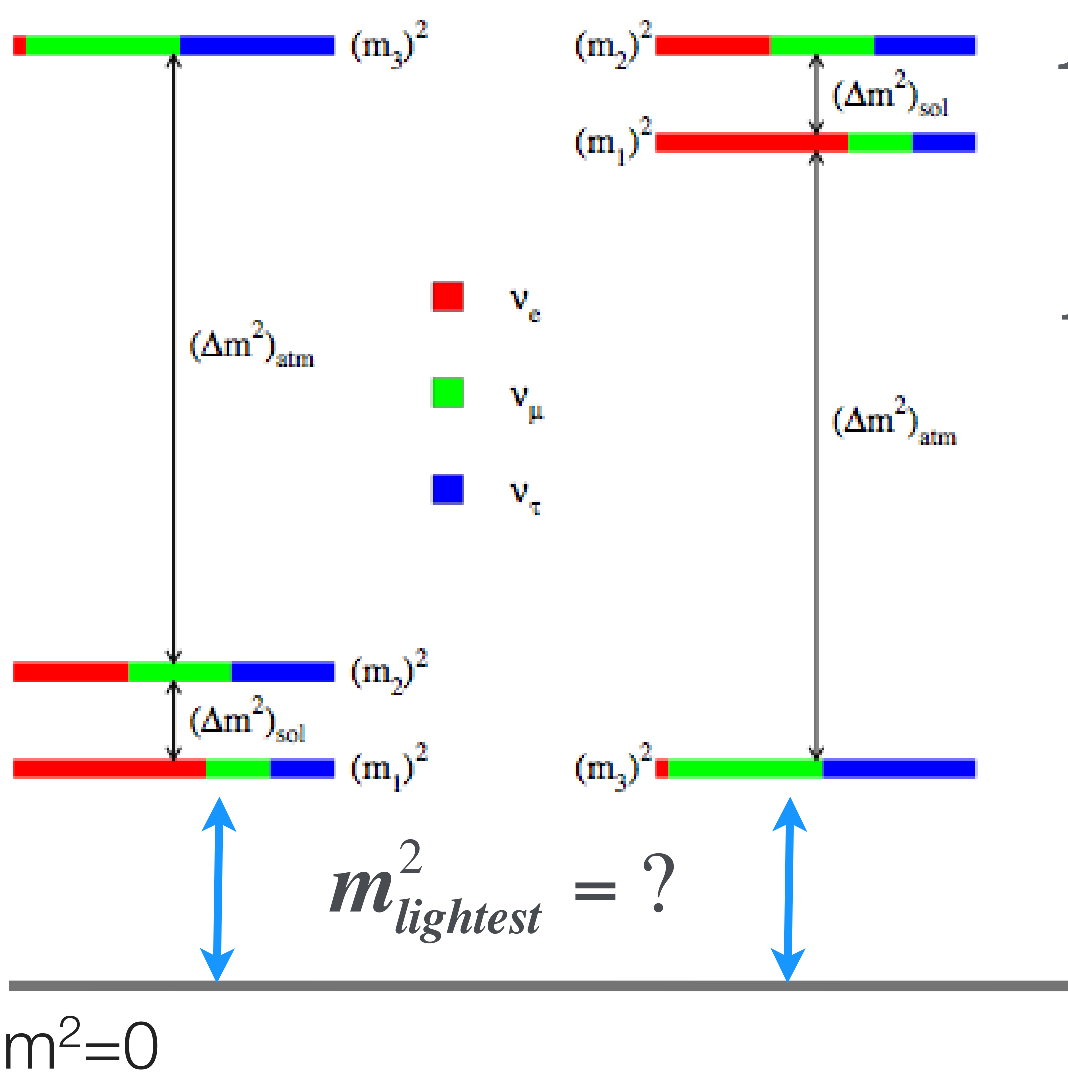
The KATRIN experiment on its long journey to Karlsruhe

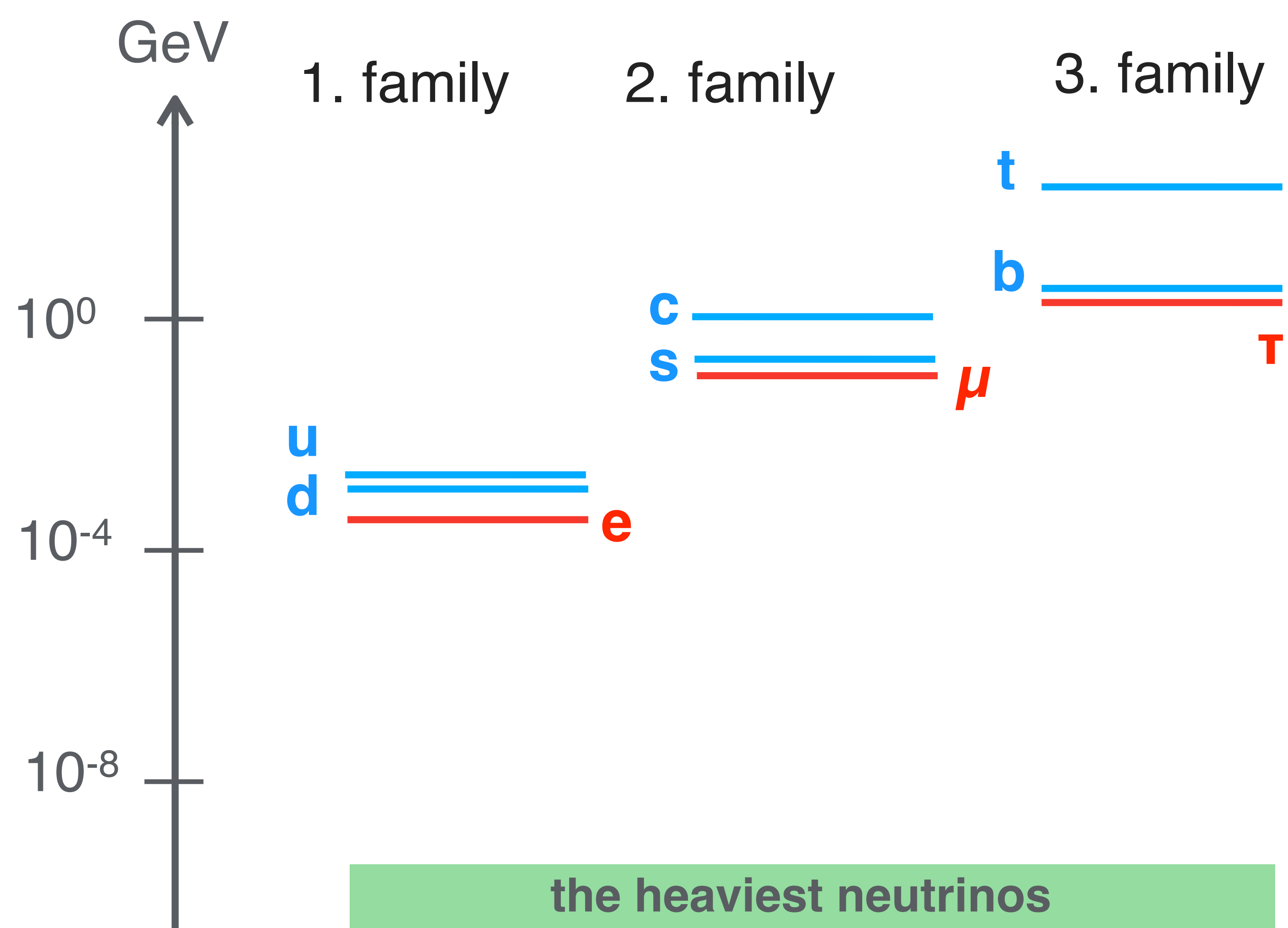


- the neutrino mass **< 2.1 eV**
- BUT HOW SMALL?

One Open Question: The Mass of Neutrinos

- Neutrinos: much lighter than other known particles
  - ➡ Why is their mass so small?
  - ➡ What is their absolute mass scale?





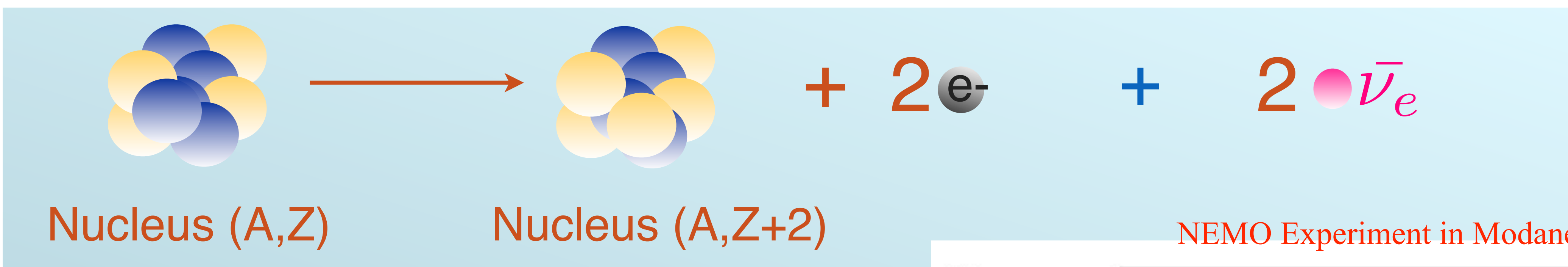
from cosmology:

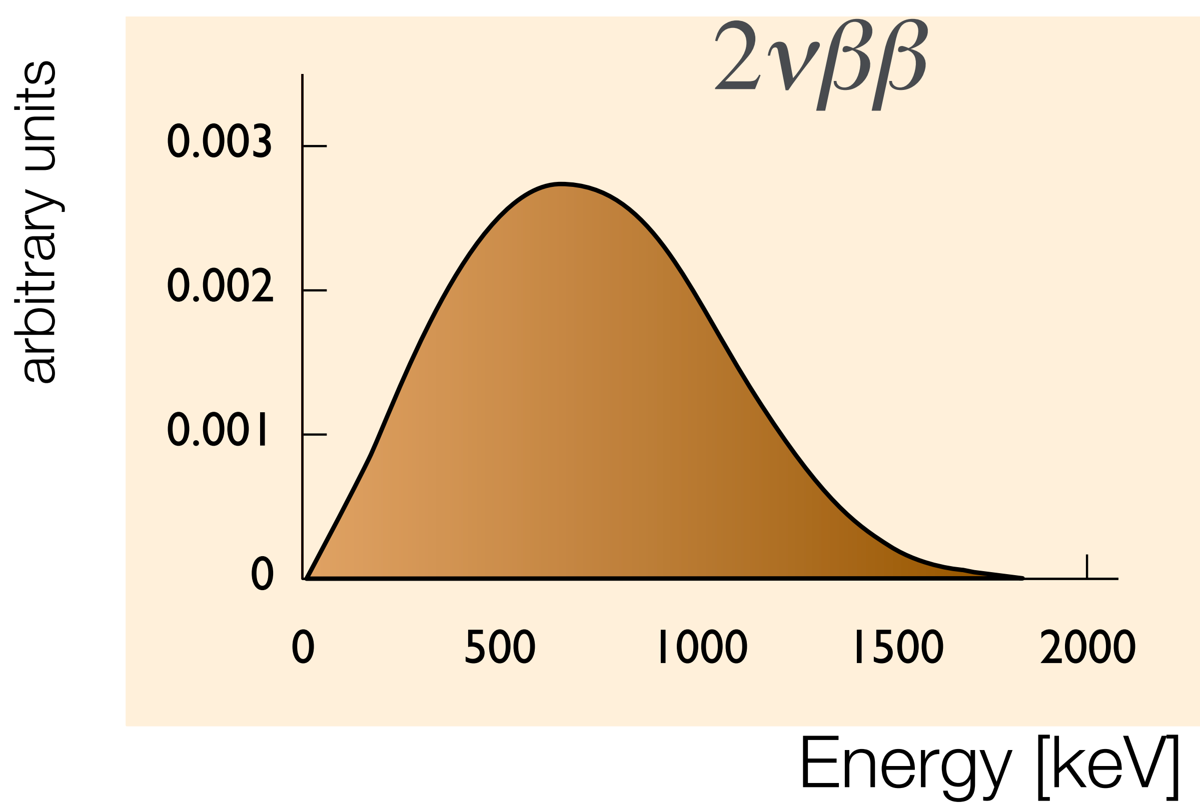
$$\Sigma_i m_i < 230 - 600\,\mathrm{meV}$$

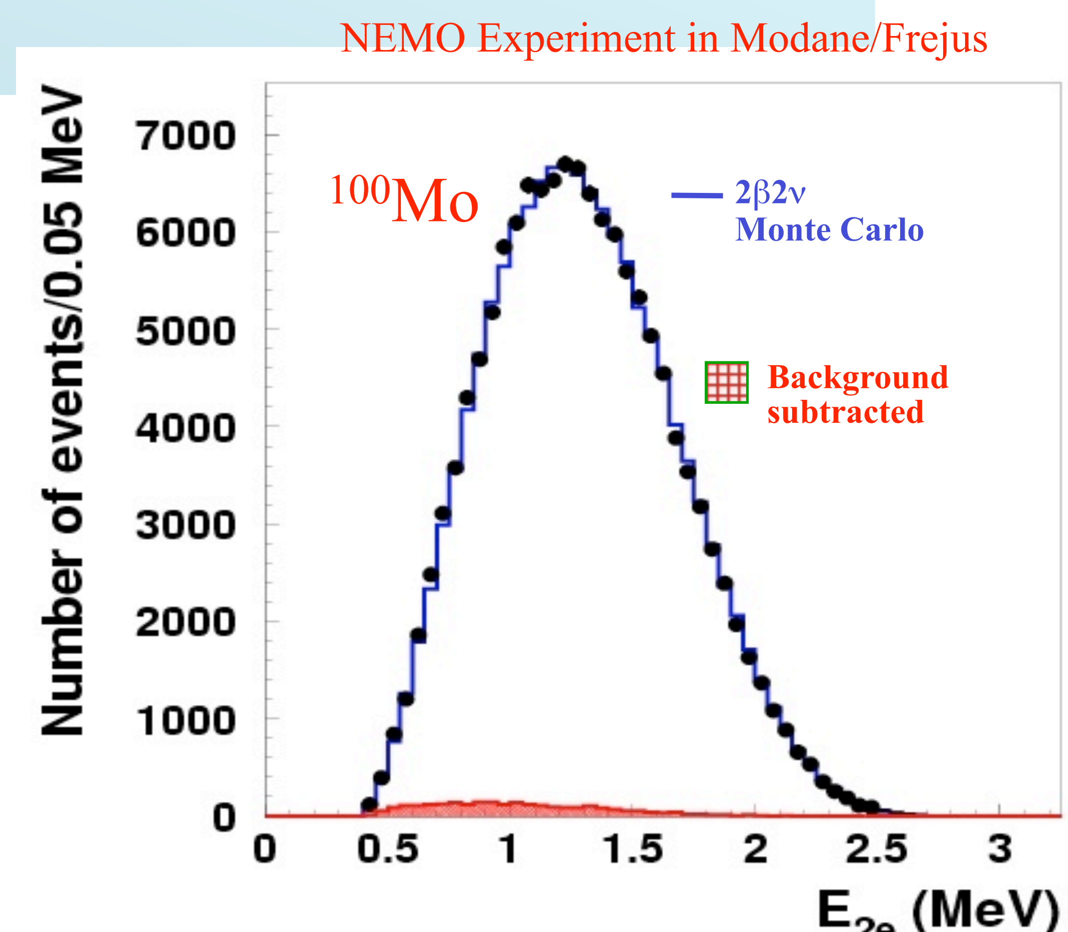
The Double Beta decay

- An ultra-rare nuclear decay, with a half-live > 10 billion times larger than the age of the Universe

- The decay with emission of 2 neutrinos was observed in more than 10 different nuclei: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{238}U

- 





Neutrinoless double beta decay

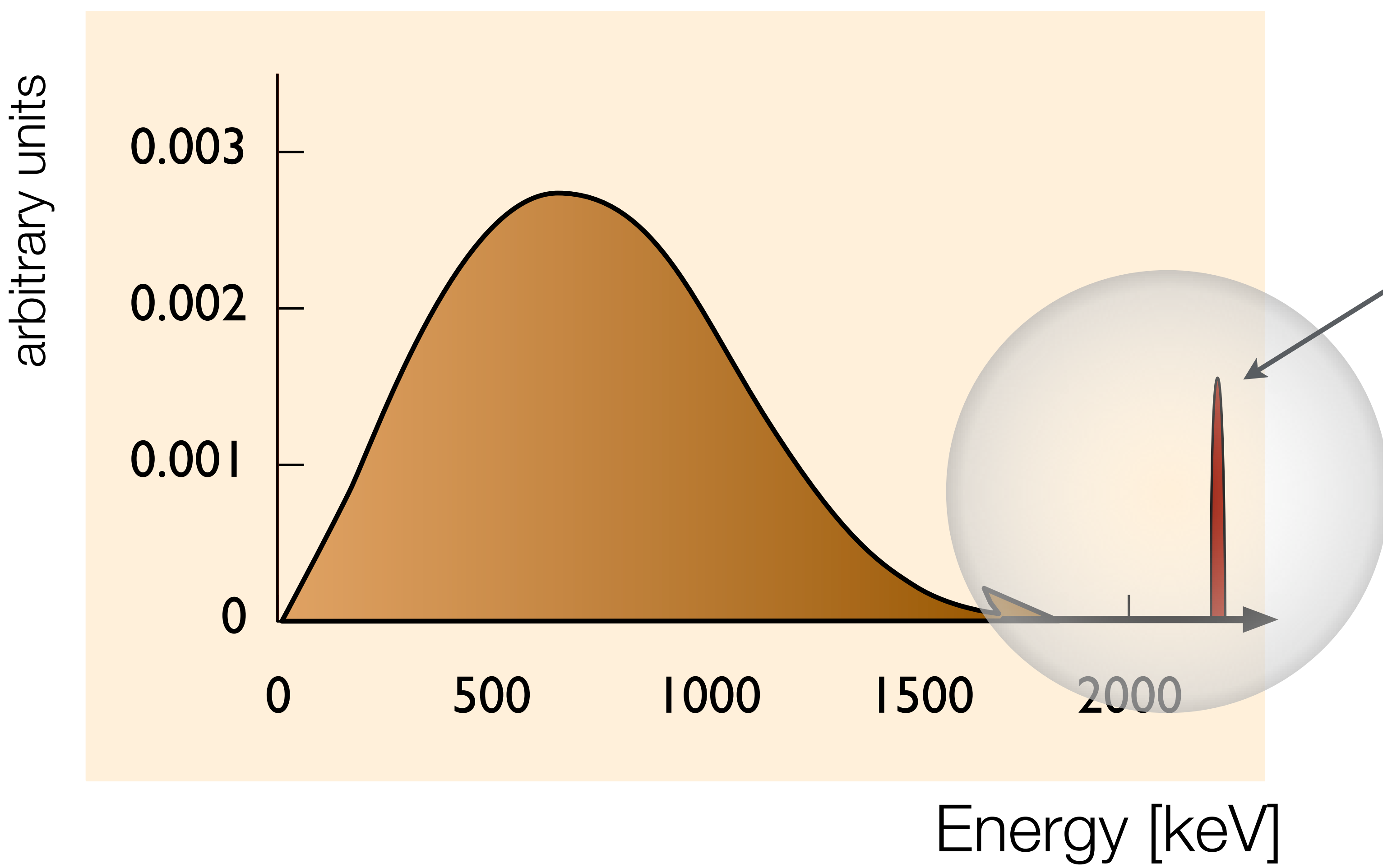
- **More interesting:** the decay mode without emission of neutrinos (“forbidden” in the Standard Model of particle physics, since the lepton number is violated: ΔL = 2)

L = 0

$$2n \rightarrow 2p + 2e^-$$

$$2p \rightarrow 2n + 2e^+$$

L = 2

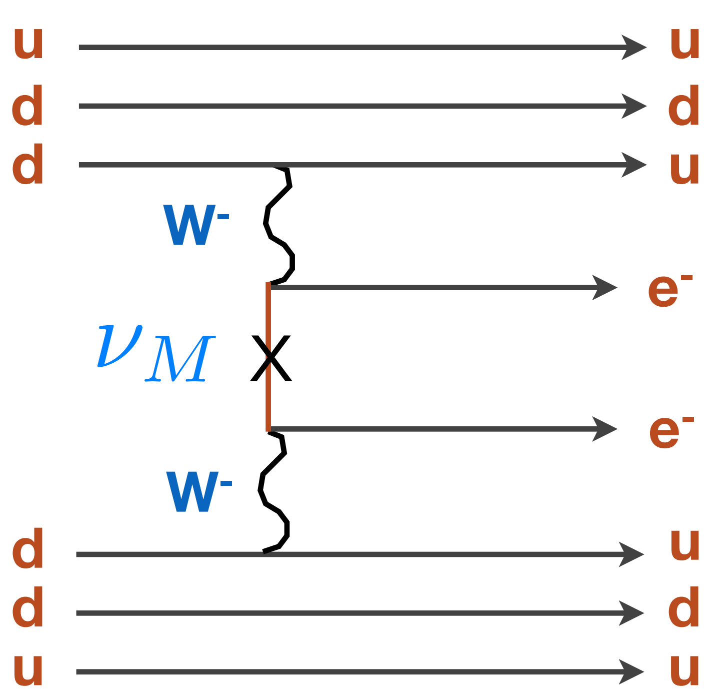


expected:
sharp “peak” at the Q-value of the decay

$$Q = E_{e1} + E_{e2} - 2m_e$$

Neutrinoless double beta decay

- A *virtual neutrino* is exchanged:



Ettore Majorana

➡ the neutron decays under emission of a right handed 'anti-neutrino' $\left|\nu_R\right\rangle^C$

➡ the $\left|\nu_R\right\rangle^C$ has to be absorbed at the second vertex as left handed 'neutrino' $\left|\nu_L\right\rangle$

➡ **neutrinos and anti-neutrinos must be identical: Majorana particles**

➡ **for the helicity to change, we must have $m_\nu > 0$**

Neutrinoless double beta decay

- The decay rate is:

can be calculated

$$\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}$$

- with the ***effective Majorana neutrino mass***:

$$|m_{\beta\beta}| = |m_1|U_{e1}|^2 + m_2|U_{e2}|^2 e^{i(\alpha_1-\alpha_2)} + m_3|U_{e3}|^2 e^{i(-\alpha_1-2\delta)}|$$

➡ a mixture of m_1, m_2, m_3, proportional to the U_{ei}^2, $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$, α_1,α_2 = Majorana phases

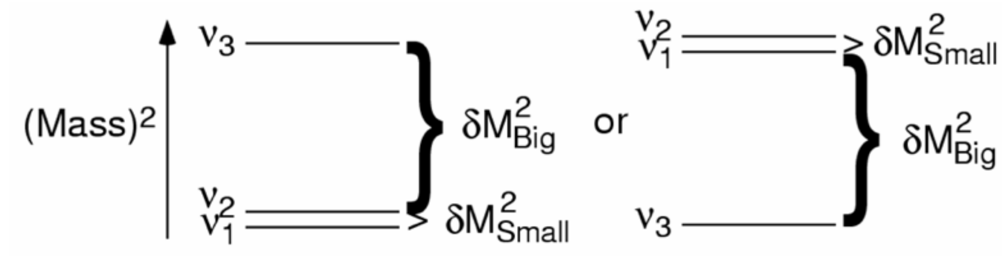
- U_{ei} = matrix elements of the PMNS-Matrix, m_i = eigenvalues of the neutrino mass matrix

Flavor eigenstates $\quad |\nu_e\rangle = \sum_i U_{ei} |\nu_i\rangle \quad$ Eigenstates of the mass operator

Effective Majorana neutrino mass

- Effective neutrino mass as a function of the smallest neutrino mass for the neutrino mass scenarios: “normal” and “inverted” hierarchy, and “degenerate”

neutrino mass hierarchy → **normal**

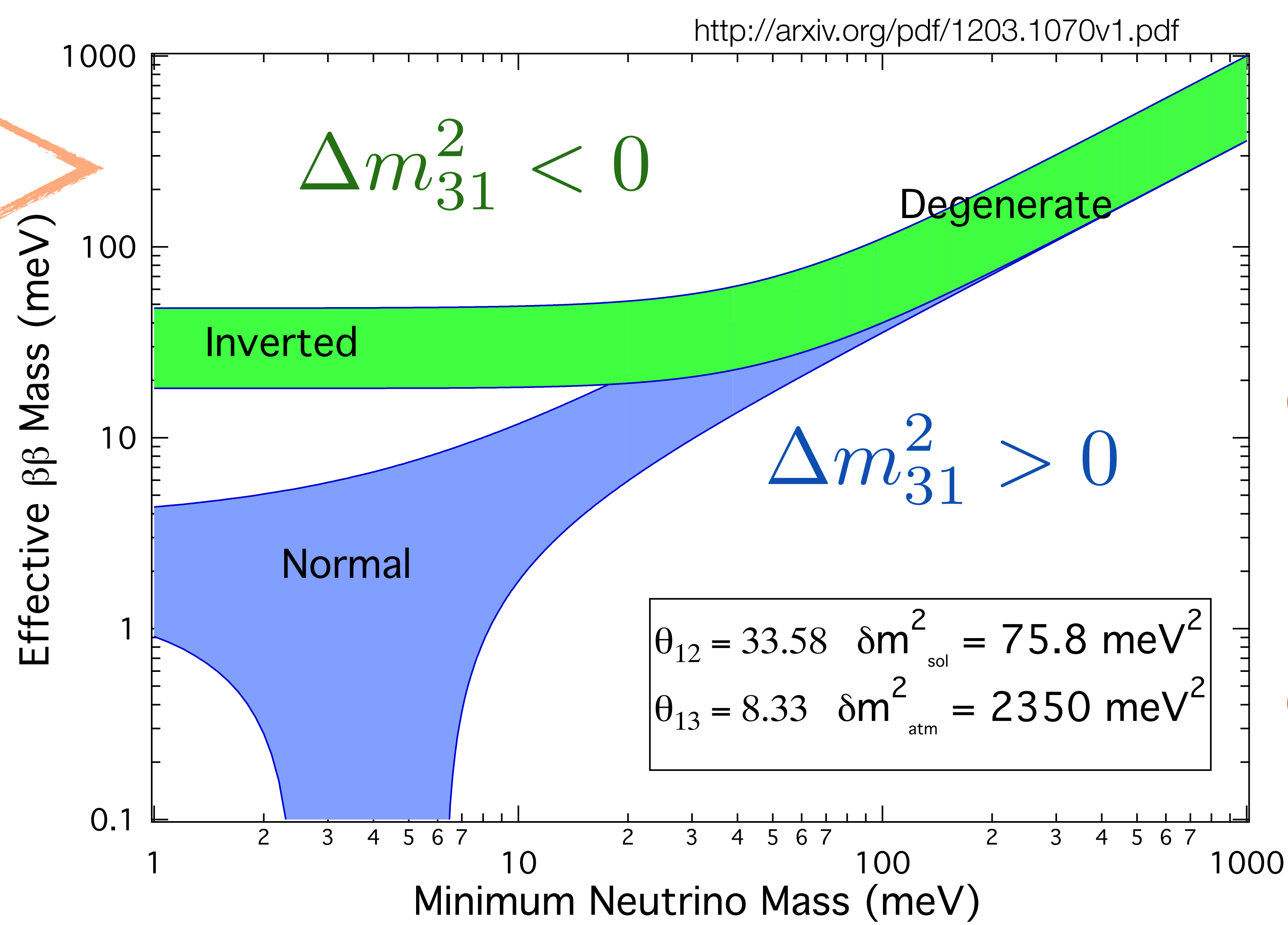


inverted

current sensitivities

$T_{1/2} \sim 10^{27}\,\mathrm{yr}$

$T_{1/2} \sim 10^{29}\,\mathrm{yr}$



100-1000 counts/(y t)

0.5 - 5 counts/(y t)

0.1-1 counts/(y 100 t)

Experimental requirements

- Experiments measure the half life of the decay, $T_{1/2}$

$$T^{0\nu}_{1/2} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

$$\langle m_{\beta\beta} \rangle \propto \frac{1}{\sqrt{T^{0\nu}_{1/2}}}$$

Minimal requirements:

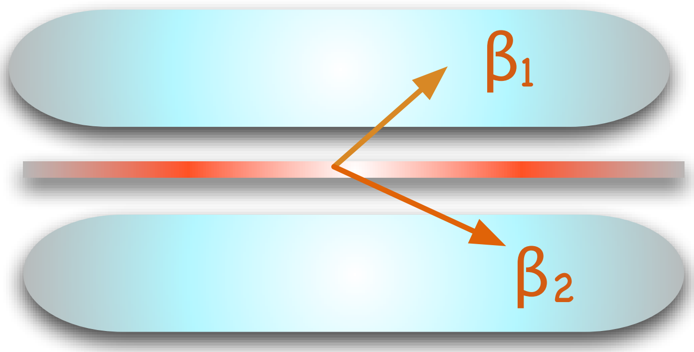
large detector masses
enriched materials
ultra-low background noise
excellent energy resolution

Additional tools to distinguish signal from background:

angular distribution
decay to excited states (gamma-rays)
identification of daughter nucleus

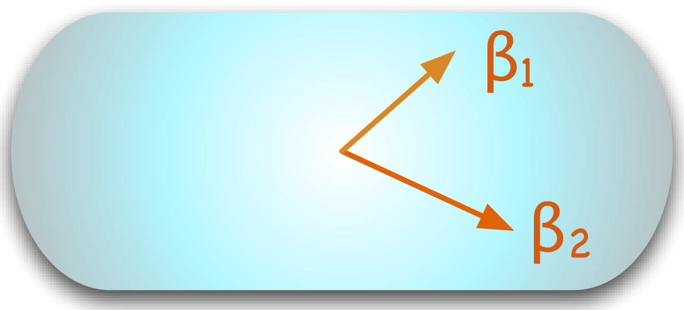
Experiments: Main Approaches

Source ≠ Detector



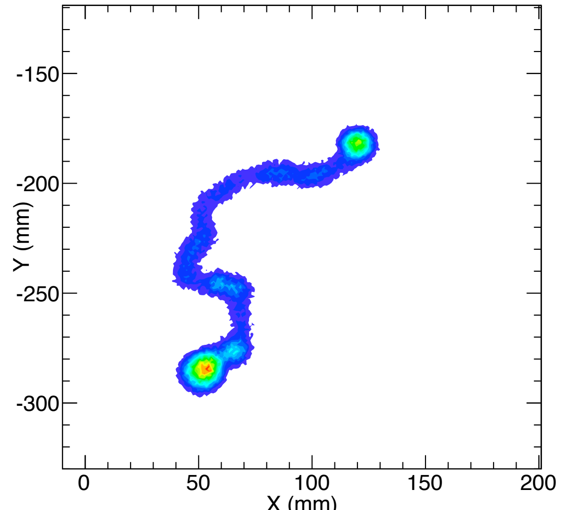
Source as thin foil
Electrons detected with: scintillator, TPC, drift chamber, semiconductor detectors
Event topology
Low energy resolution and detection efficiency

Source = Detector (calorimeters)



The sum of the energy of the two electrons is measured
Signature: peak at the Q-value of the decay
Scintillators, semiconductors, bolometers
High resolution + detection efficiency
No event topology

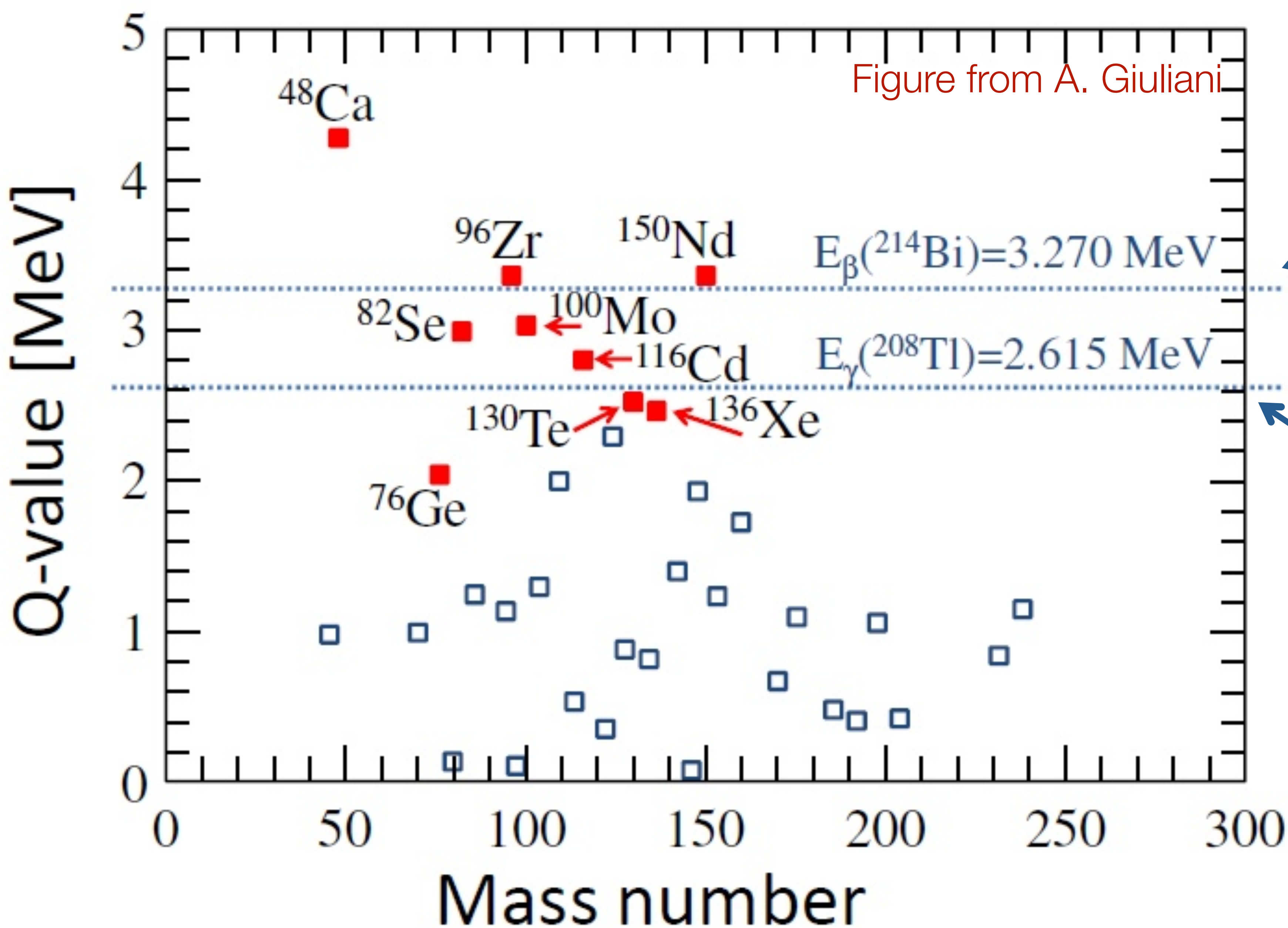
Source = Detector = Tracker



Source is the (high-pressure) gas of a TPC
Charge and light detected with electron multipliers and/or photosensors
Good energy and position resolution, high efficiency
Event topology very helpful in reducing the background and *in identifying the potential signal*

Double Beta Isotopes and Techniques

Phase space factor G ~ Q^5

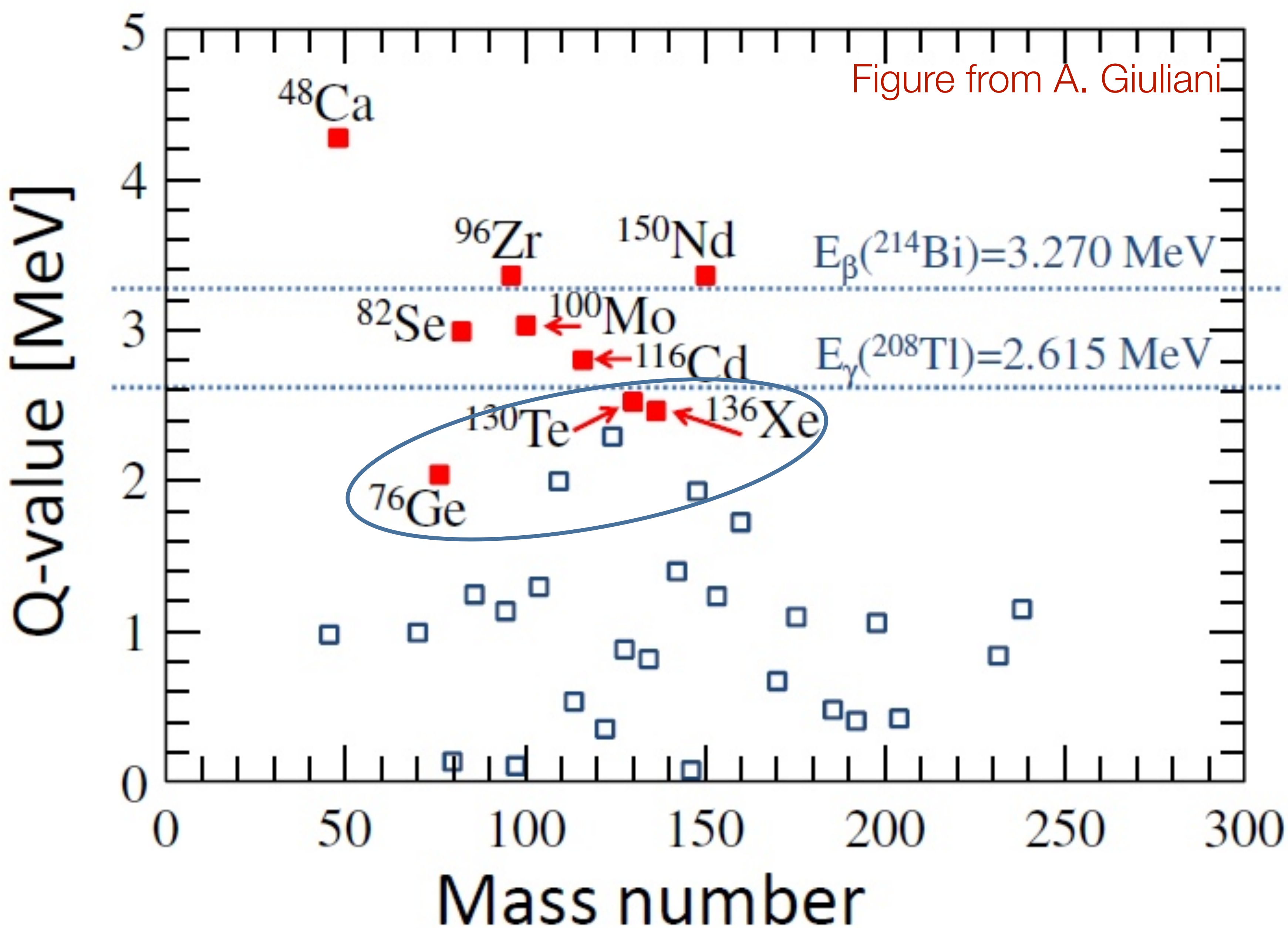


End-point of ^{222}Rn-induced radioactivity

End-point of natural γ radioactivity

Double Beta Isotopes and Techniques

Gamma and beta background, also degraded alphas

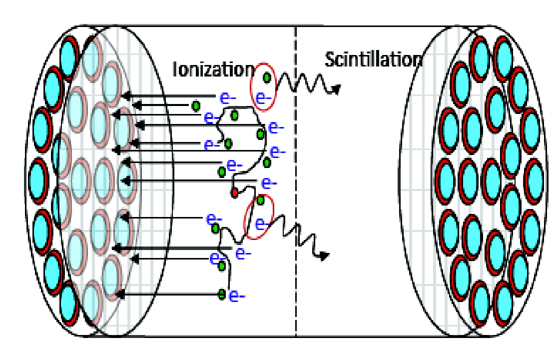


Nonetheless, best current sensitivities!

^{76}Ge: HPGe diodes (GERDA, MAJORANA)

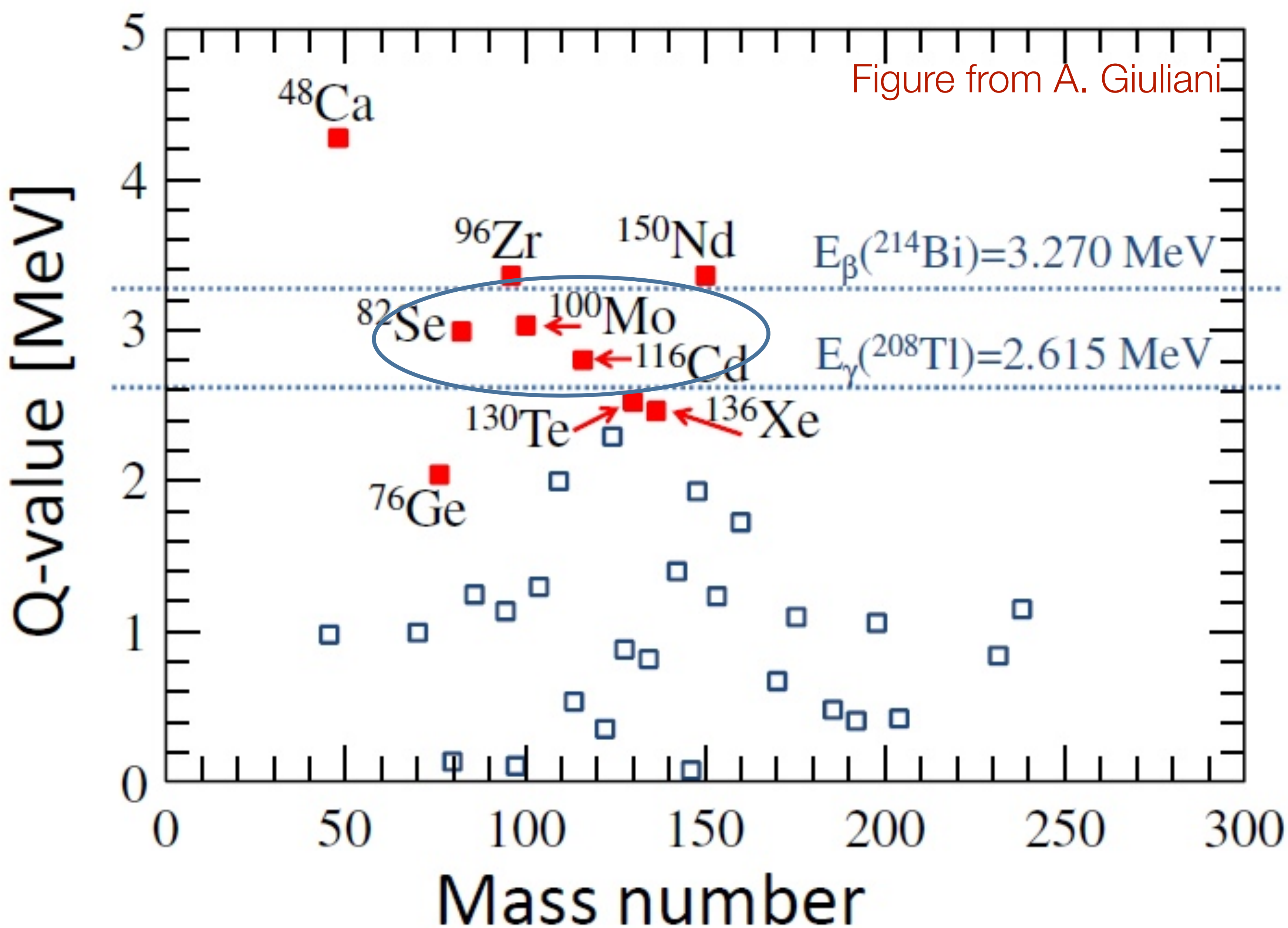
^{130}Te: bolometers, TeO_2 crystals (CUORE) and Te dissolved in large liquid scintillator (SNO+)

^{136}Xe: xenon TPCs (EXO, NEXT) and Xe dissolved in large LS (KamLAND-Zen)

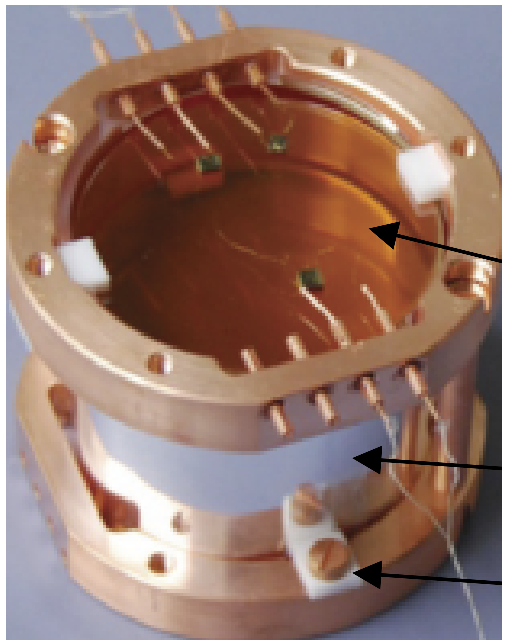


Double Beta Isotopes and Techniques

No gamma background, but degraded alphas

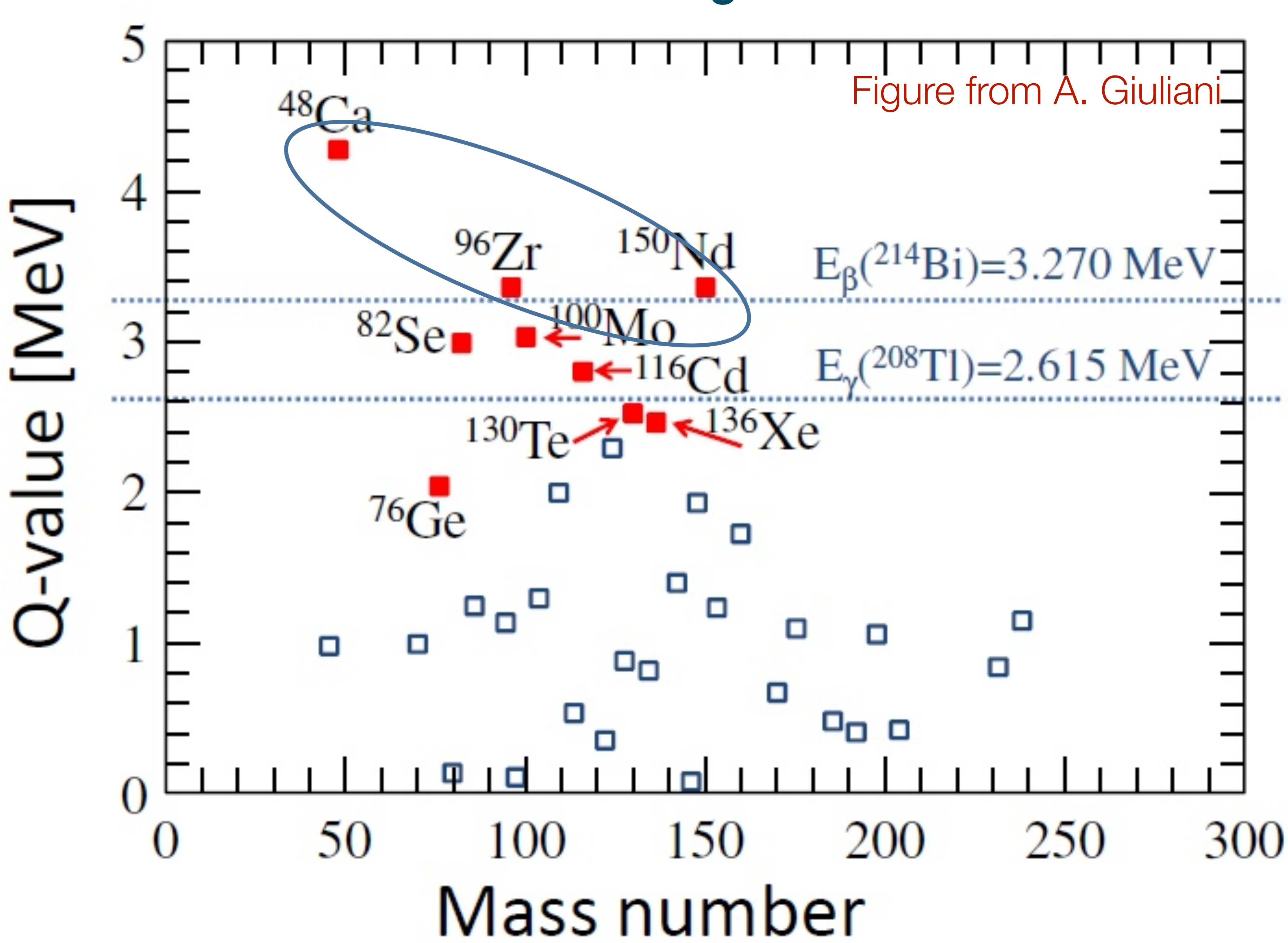


Scintillating bolometers: ZnSe, $ZnMoO_4$, $CdWO_4$ (LUCIFER, LUMINEU, AMORE)



Double Beta Isotopes and Techniques

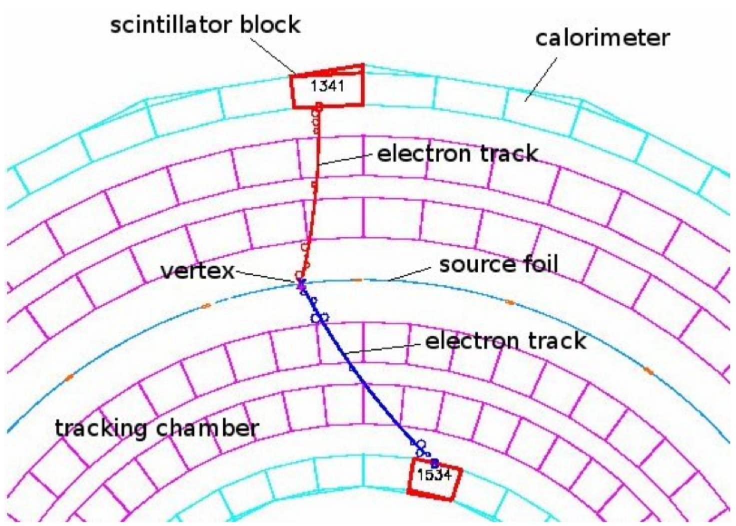
Almost background-free



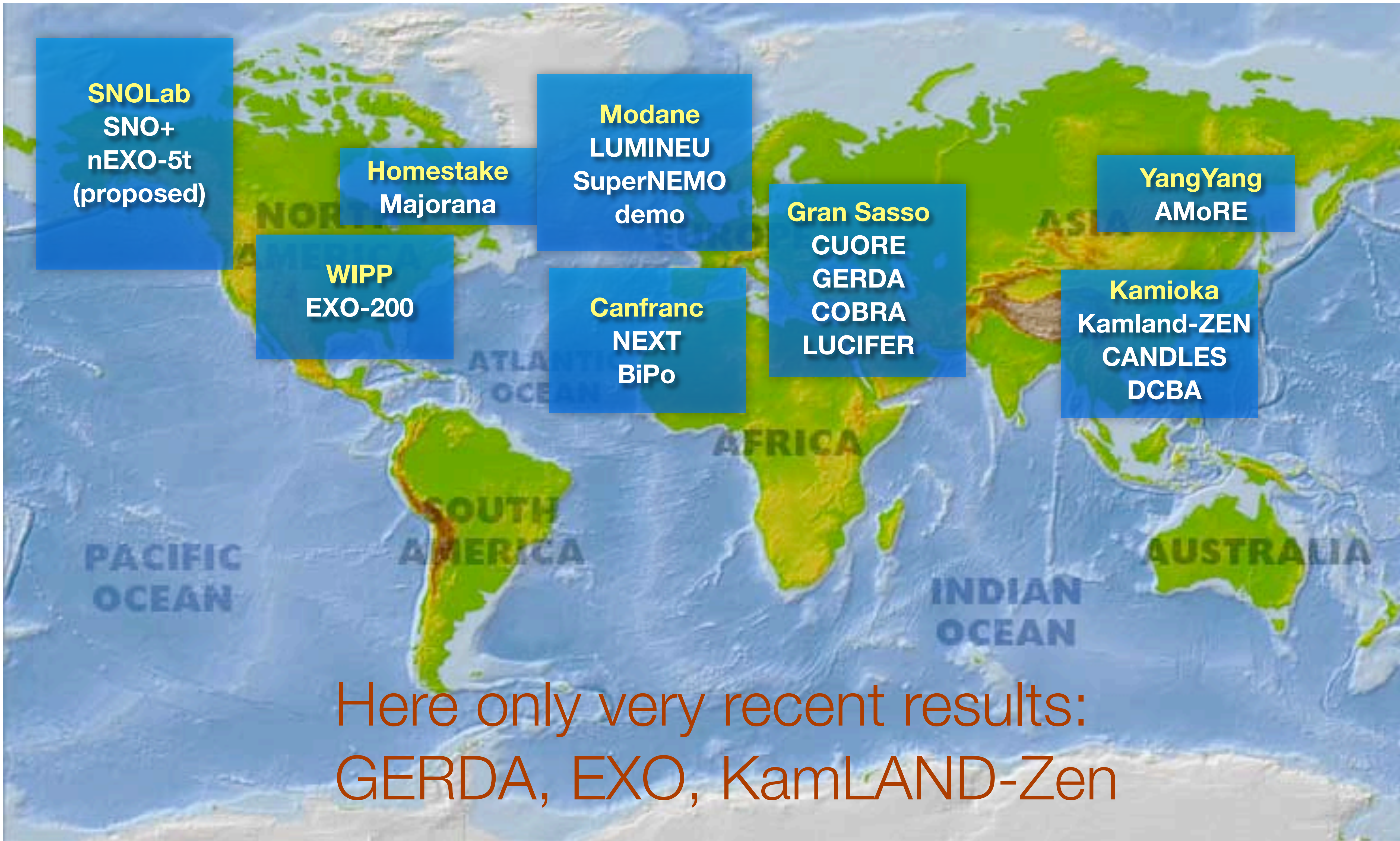
But low isotopic abundance, difficult to enrich

Zr, Nd: Tracking calorimeters with thin foils (SuperNEMO)

CaF_2 scintillators (CANDLES)



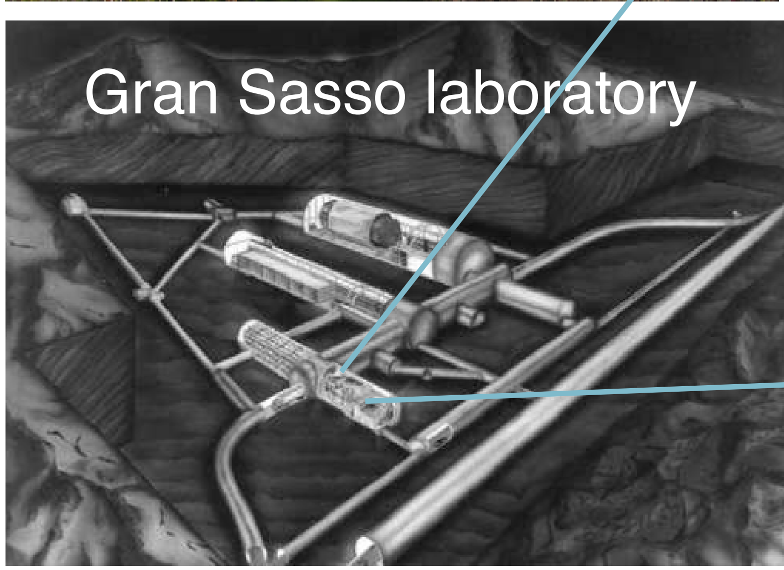
Double beta detectors, world wide



Here only very recent results:
GERDA, EXO, KamLAND-Zen

The GERDA experiment at Gran Sasso

- HPGe detectors, enriched to ~86% in ^{76}Ge, directly submersed in LAr, which is shielded by ~ 10 m x 10 m of water



The LAr cryostat during its installation in Gran Sasso

The GERDA experiment at LNGS

Eur. Phys. J. C (2013) 73:2330

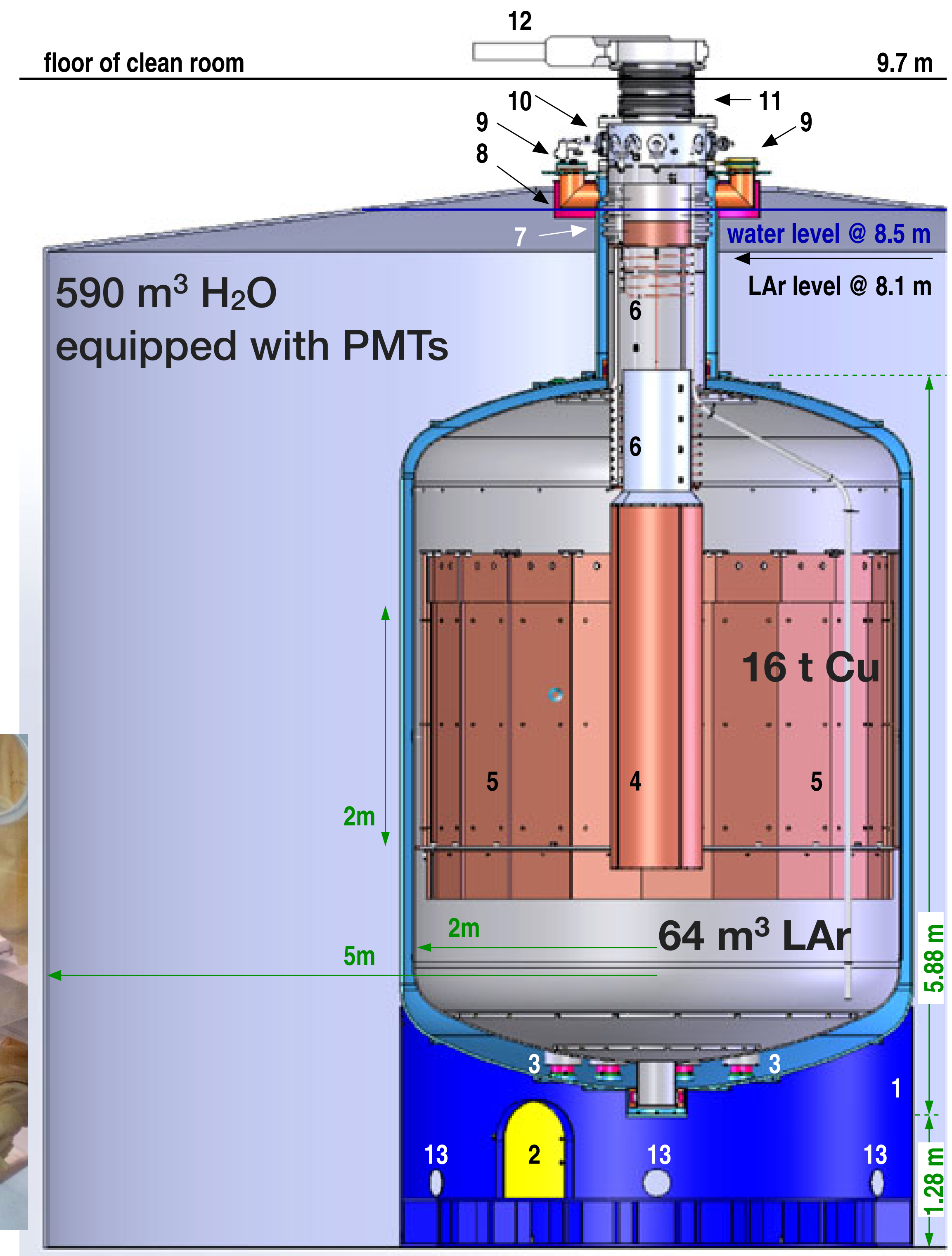
➡ LAr as cooling medium and shielding (U/Th in LAr < 7×10^{-4} μBq/kg)
➡ a minimal amount of surrounding materials

- Phase I (Nov 2011 - May 2013)

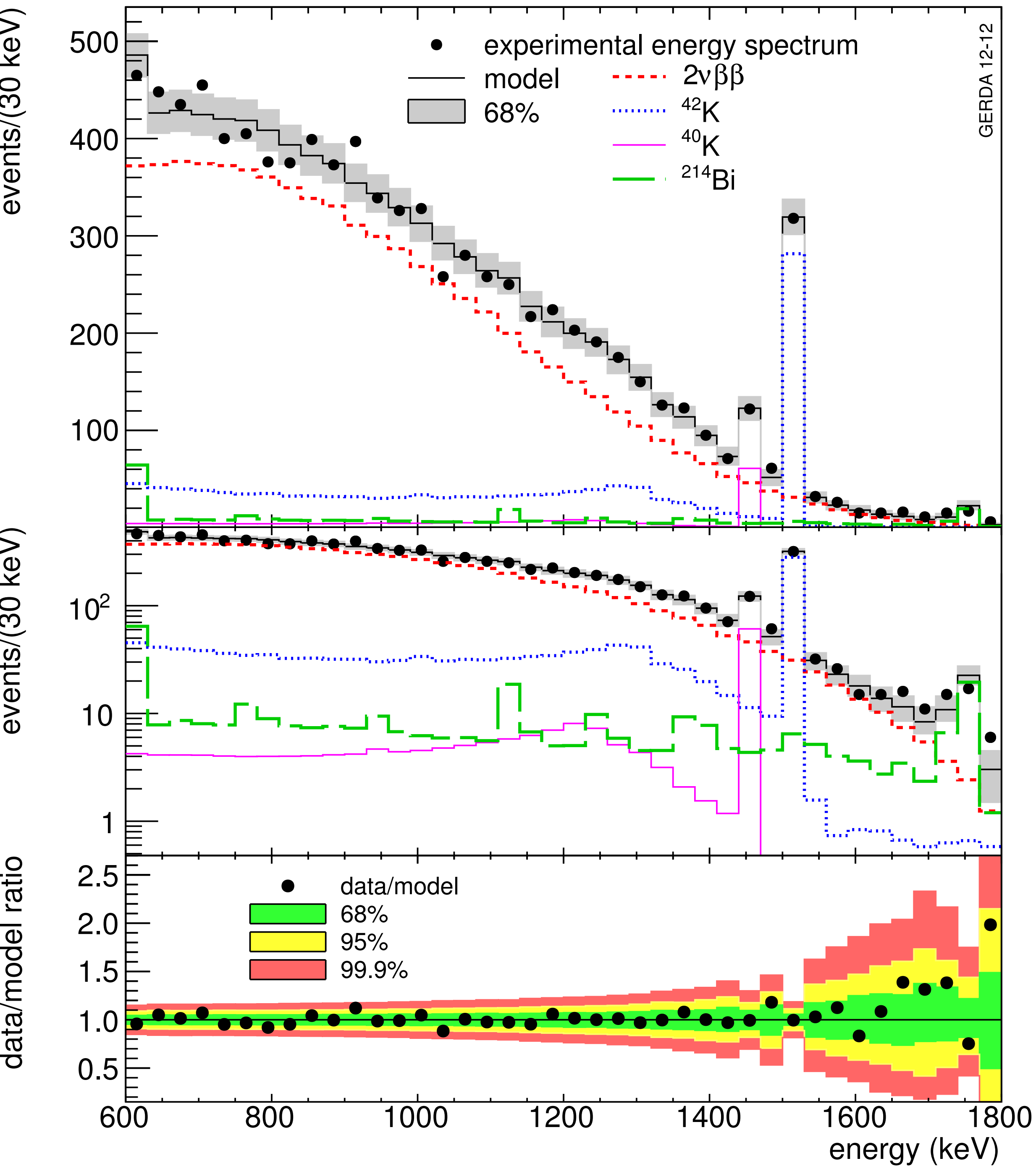
➡ ~18 kg enriched 76Ge detectors

- Phase II (early 2014)

➡ additional 20 kg Ge detectors



Half life of the 2-neutrino decay mode



IOP PUBLISHING — JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **40** (2013) 035110 (13pp) doi:10.1088/0954-3899/40/3/035110

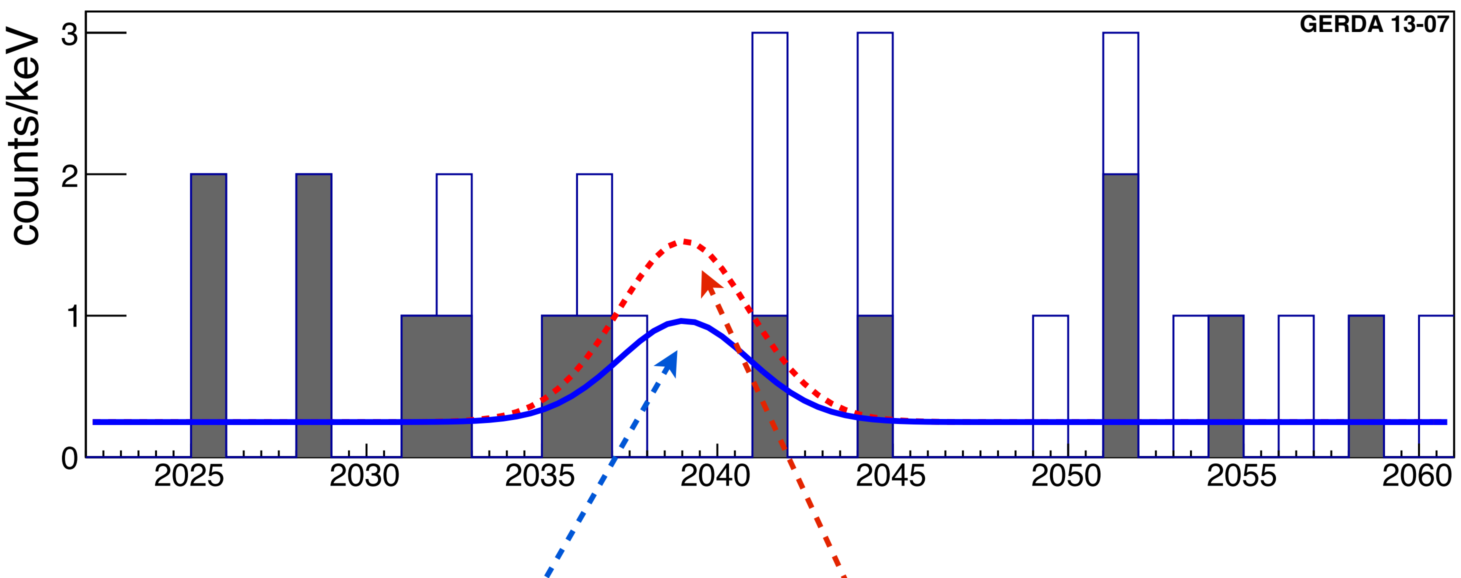
Measurement of the half-life of the two-neutrino double beta decay of ^{76}Ge with the GERDA experiment

$$T_{1/2}^{2\nu} = \left(1.84^{+0.09}_{-0.08}\right) \times 10^{21}\ \mathrm{yr}$$

Item	Uncertainty on $T_{1/2}^{2\nu}$ (%)	
Non-identified background components	+5.3	
Energy spectra from ^{42}K, ^{40}K and ^{214}Bi	±2.1	
Shape of the $2\nu\beta\beta$ decay spectrum	±1	
Subtotal fit model		$^{+5.8}_{-2.3}$
Precision of the Monte Carlo geometry model	±1	
Accuracy of the Monte Carlo tracking	±2	
Subtotal Monte Carlo		±2.2
Data acquisition and selection		±0.5
Grand total		$^{+6.2}_{-3.3}$

The neutrinoless decay mode: no signal

PRL 111, 122503, 2013



"Claim", PLB586 (2004)

$$T^{0\nu}_{1/2} = 1.19 \times 10^{25}\ \mathrm{yr}$$

GERDA lower limit from PL fit of the 3 data sets, with constant term for background (3 parameters for the 3 data sets) and Gaussian term for signal: *best fit is $N_{signal} = 0$*

$$T^{0\nu}_{1/2} > \ 2.1 \times 10^{25}\ \mathrm{yr}\ (90\%\ \mathrm{C.L.})$$

- the limit on the half life corresponds to $N_{signal} < 3.5$ counts

- Observed and predicted number of background events in the energy region $Q_{\beta\beta} \pm 5$ keV

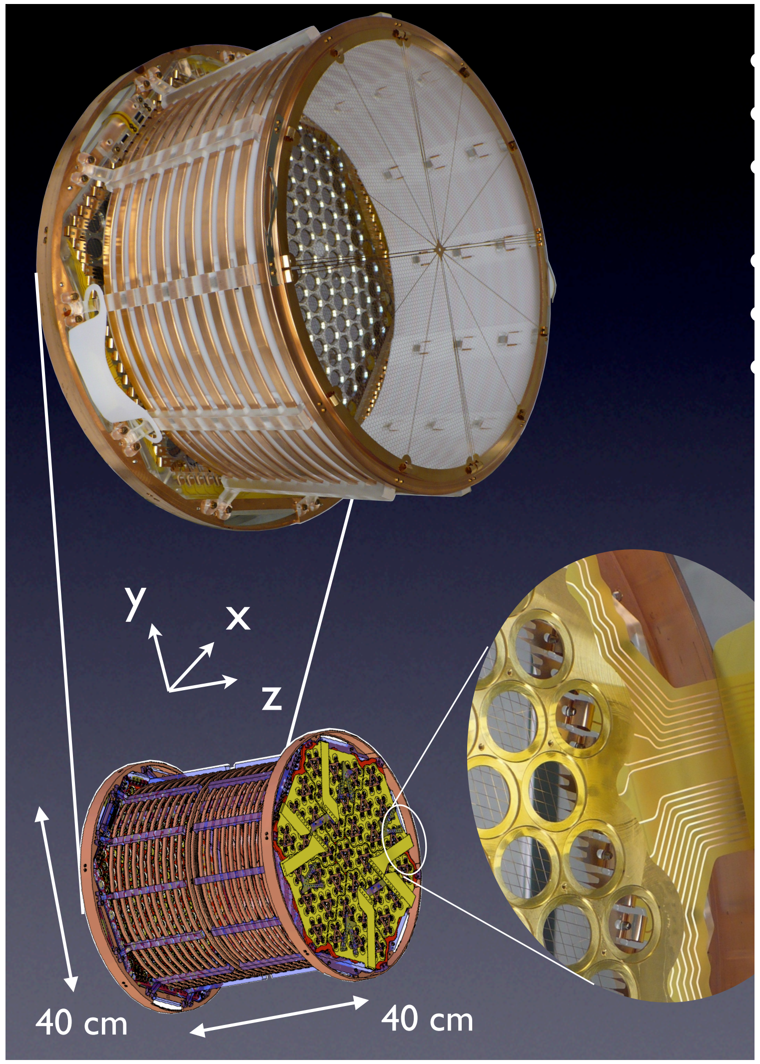
	Observed	Predicted background
No PSD	7	5.1
PSD	3	2.5

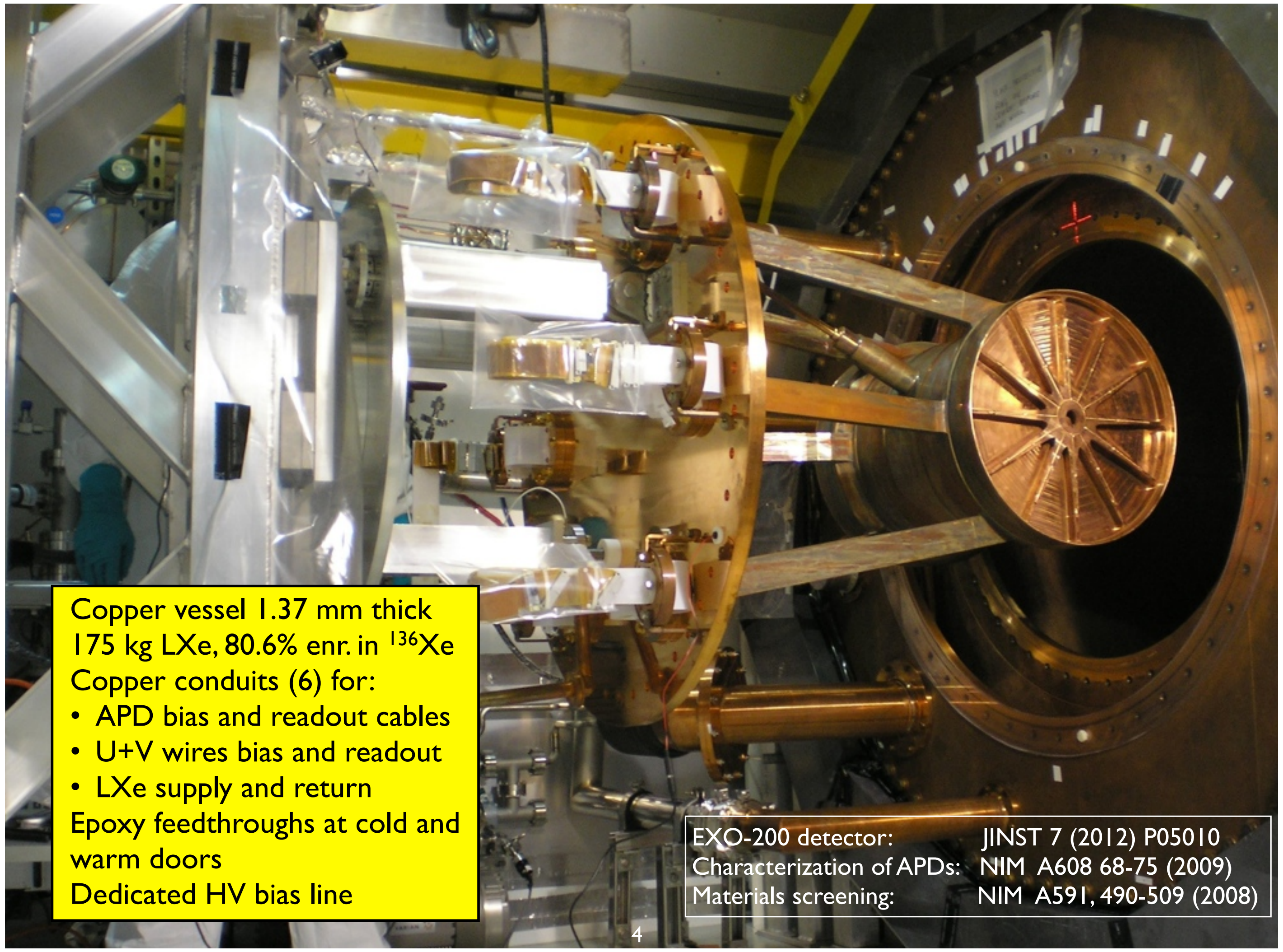
- 5.9 ± 1.4 events are expected for "claim", and 2.0±0.3 signal events

Claim of evidence for 0vbb-decay:
signal: 28.8 ± 6.9 events
BG level: 0.11 counts/(keV kg yr)
HVKK et al., PLB 586 (2004) 198-212

EXO-200 at WIPP (Carlsbad, USA)

- Liquid xenon TPC: 175 kg LXe, 80.6% enriched in ^{136}Xe
- Charge and light readout (triplet wire channels and large area avalanche photodiodes)
- Drift field: 376 V/cm



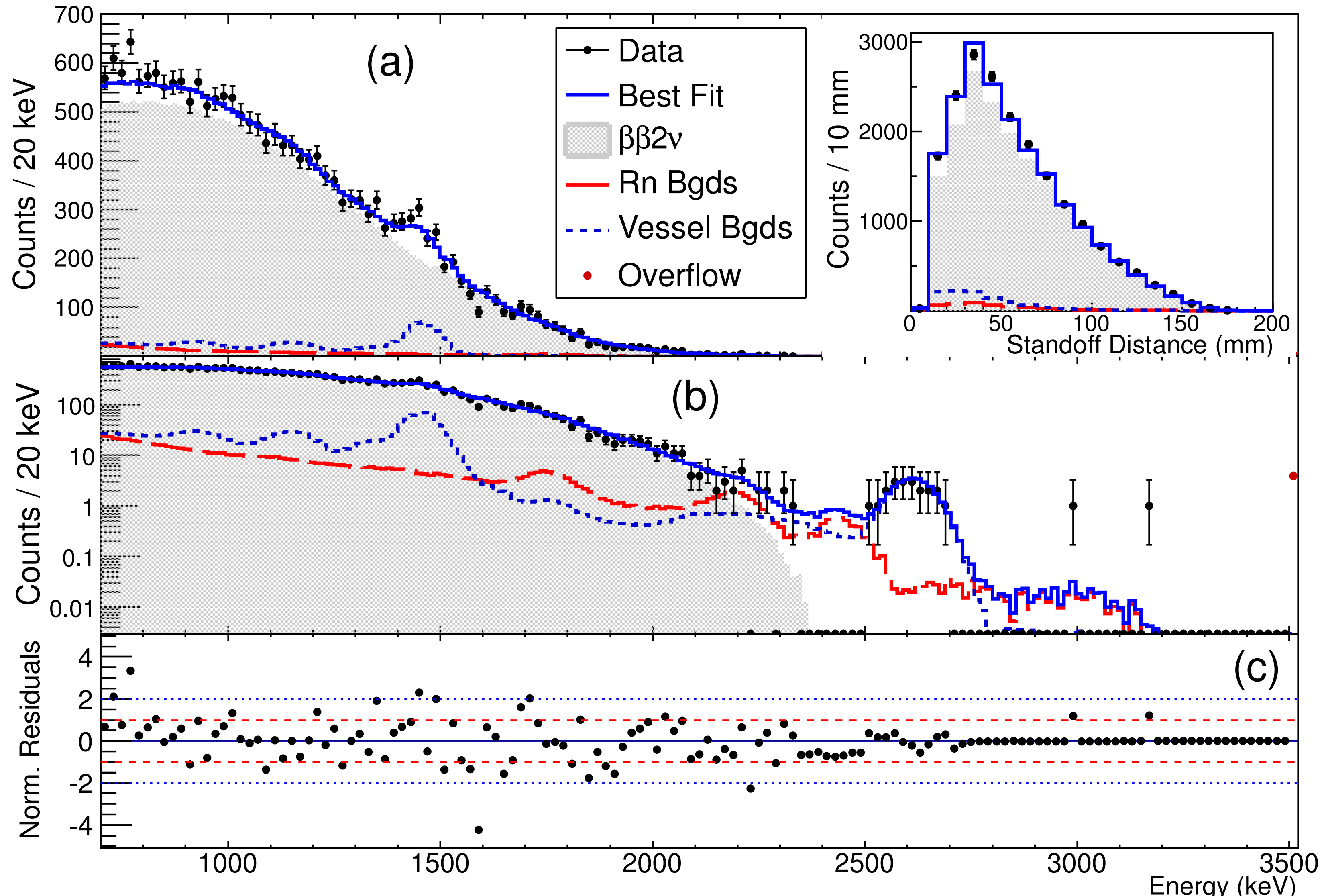


Half life of the 2-neutrino decay mode

- **The first observation of this decay for ^{136}Xe**

- The $T_{1/2}$ corresponds to a matrix element of M = 0.0218±0.0003 MeV-1, the smallest among the isotopes measured so far

PRL 107, 2011 and arXiv:1306.6106, Oct 2013

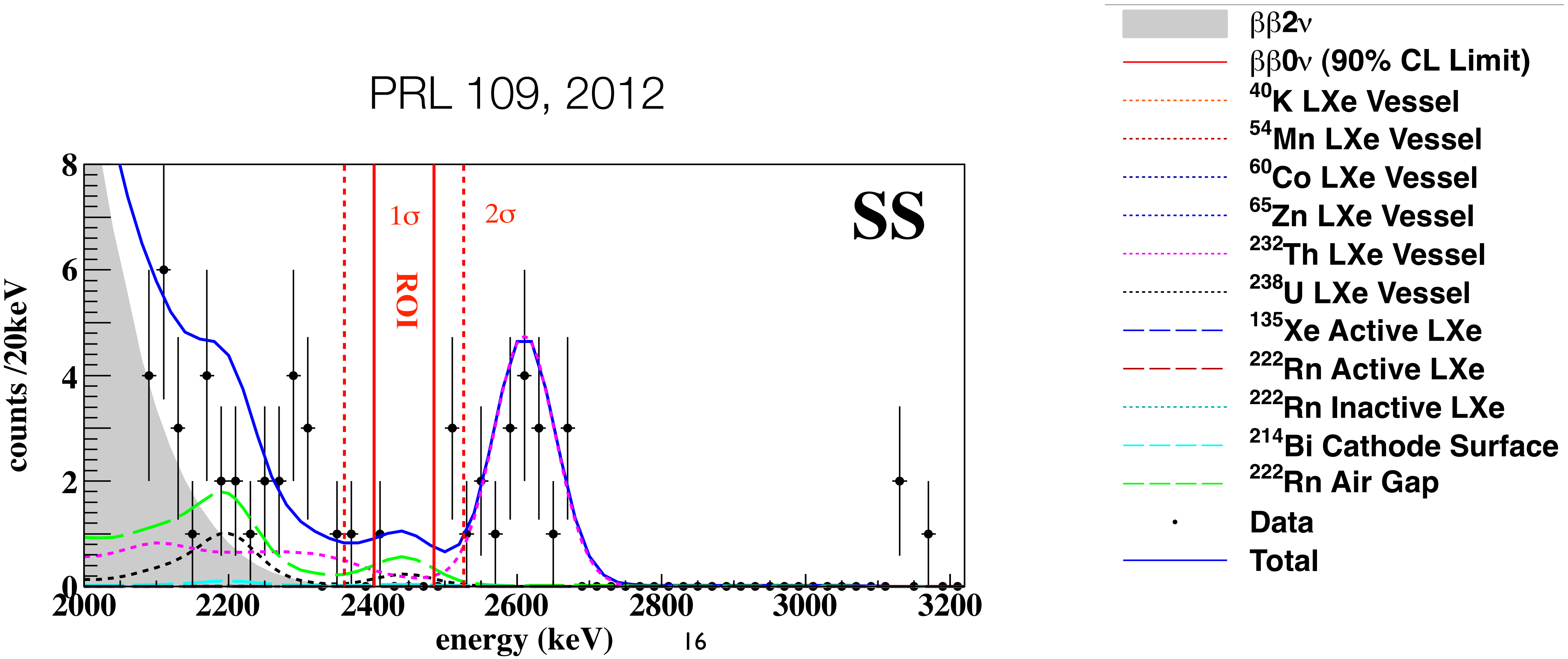


$$T^{2\nu\beta\beta}_{1/2} = 2.165 \pm 0.016(\mathrm{stat}) \pm 0.059(\mathrm{sys}) \cdot 10^{21} \text{ years}$$

The neutrinoless decay mode: no signal

- **No 0-neutrino signal observed => lower limit on $T_{1/2}$**

PRL 109, 2012



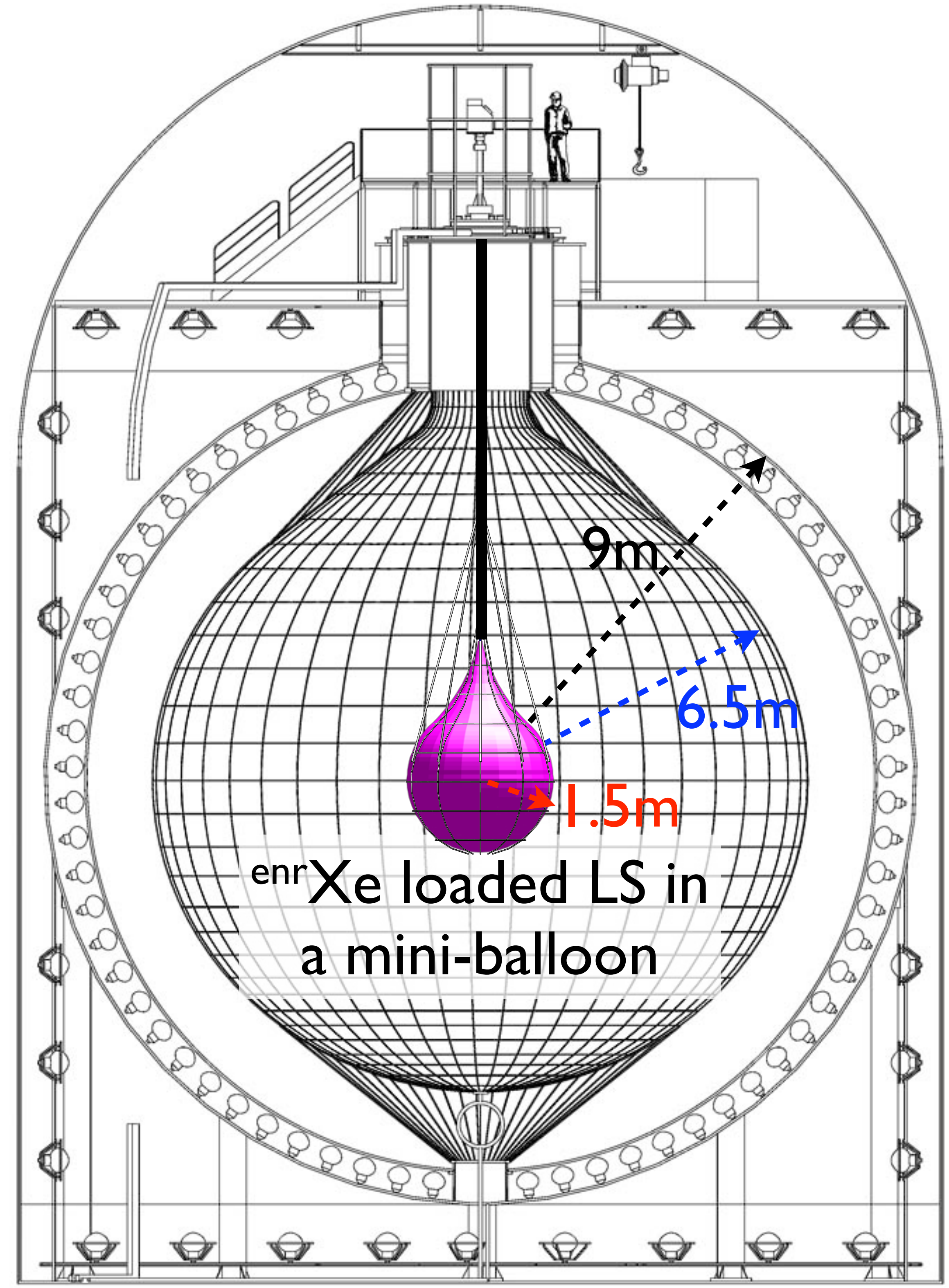
$$T_{1/2}^{0\nu\beta\beta} > 1.6 \times 10^{25}\,\mathrm{yr}\,(90\%\mathrm{C.L.})$$

Exposure: 32.5 kg yr, background: ~ 1.5×10^{-3} $kg^{-1}yr^{-1}keV^{-1}$

KamLAND-Zen

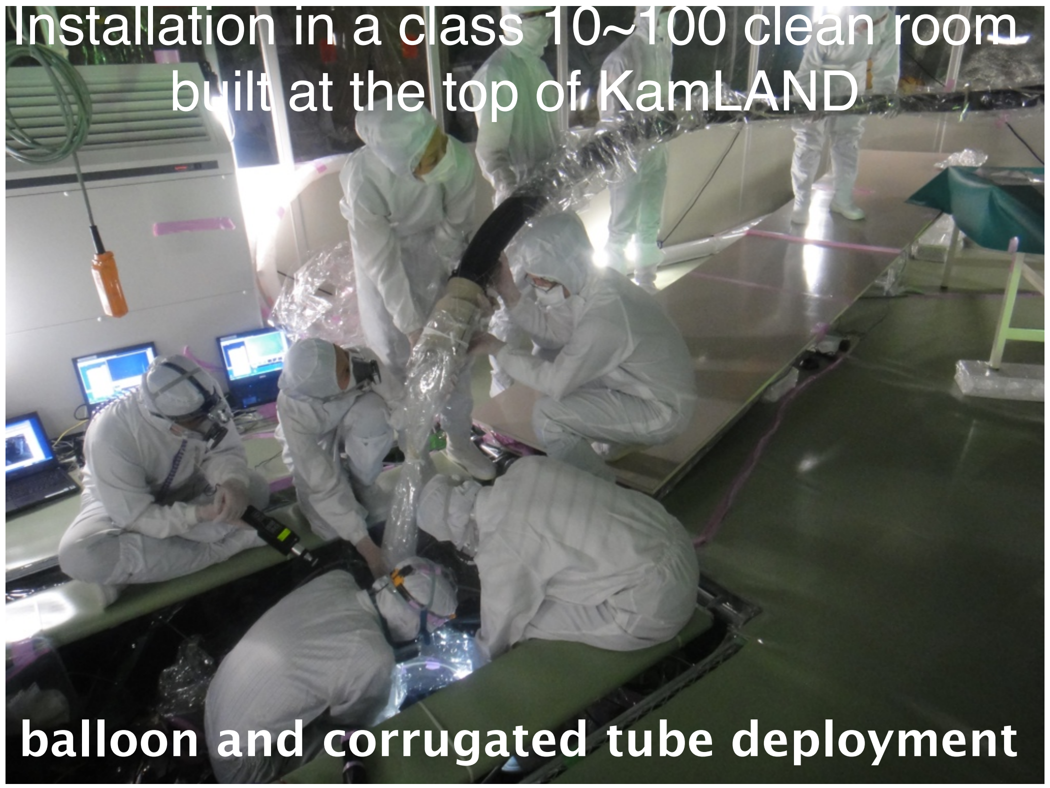
- Scintillator loaded with xenon
- 320 kg 90% enriched ^{136}Xe so far (more than 600 kg in the Kamioka mine)
- Advantages: huge and clean (U: 3.5e-18 g/g, Th: 5.2e-17 g/g) running detector
- Xe + liquid scintillator can be purified, and is highly scalable
- No escape or invisible energy from gammas and beta: good background identification
- Disadvantage: relatively poor energy resolution
- no beta/gamma discrimination
- limited scintillator composition

Zero Neutrino
double beta decay search



KamLAND-Zen: installation

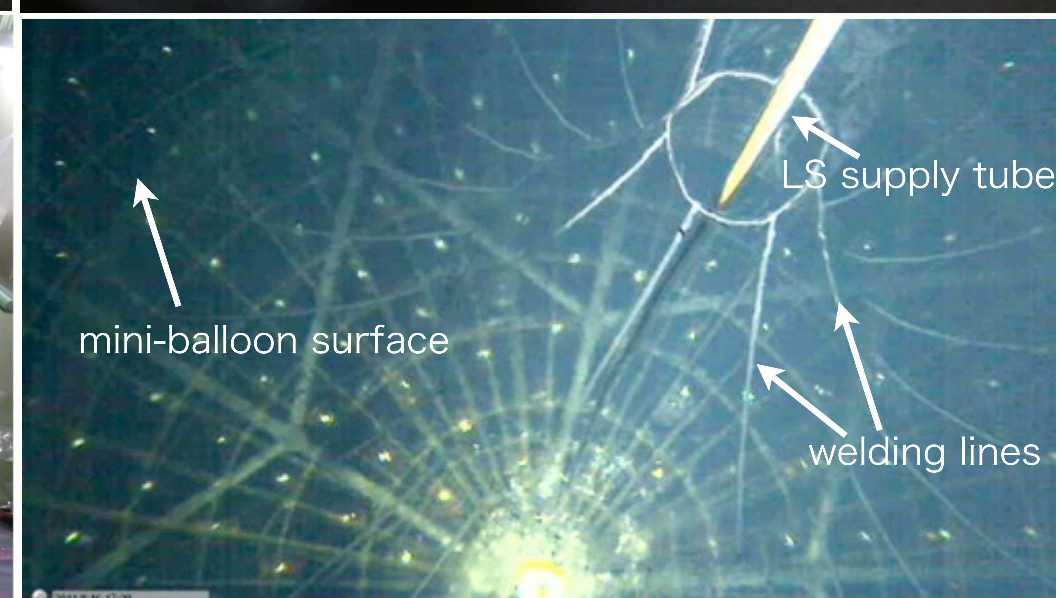
Installation in a class 10~100 clean room built at the top of KamLAND



balloon and corrugated tube deployment

balloon went through the black sheet

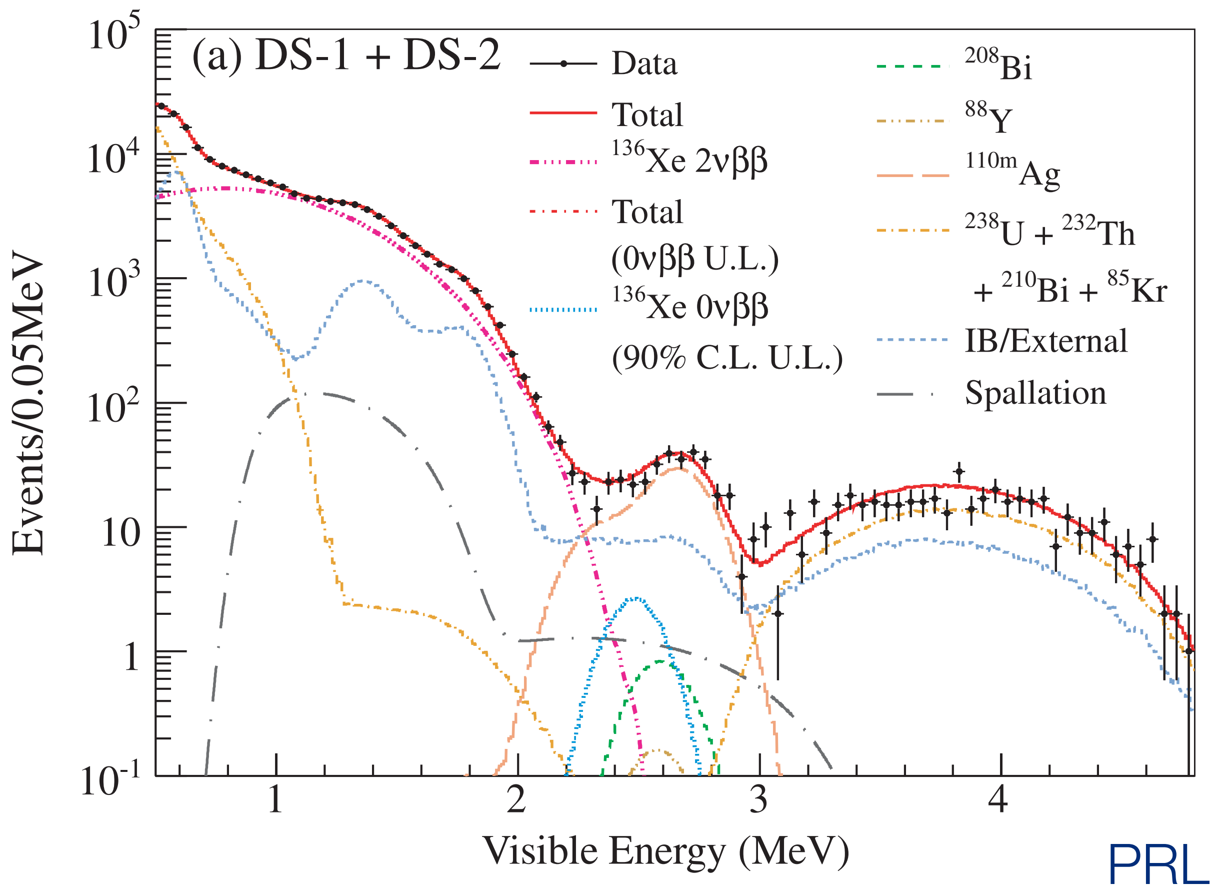
installation completed



mini-balloon inflated with dummy LS and then replaced with Xe-loaded LS
density tuning finished and tubes to be extracted

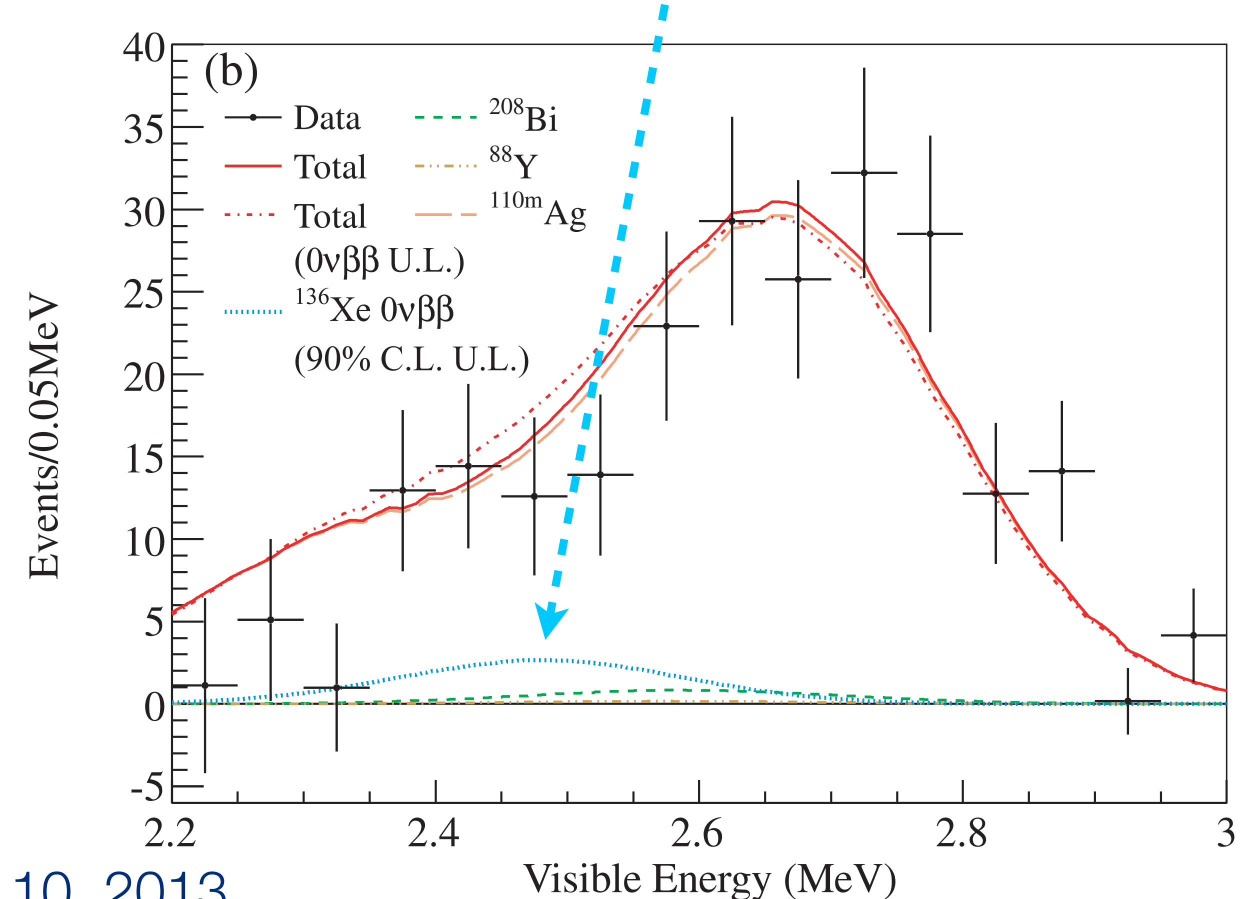
The 2-neutrino and 0-neutrino decay modes

- Resolution at 2.6 MeV: sigma ~ 4.1%; background dominated
- **No evidence for a 0-neutrino signal**



PRL 110, 2013

Q(^{136}Xe) = 2457.8 keV



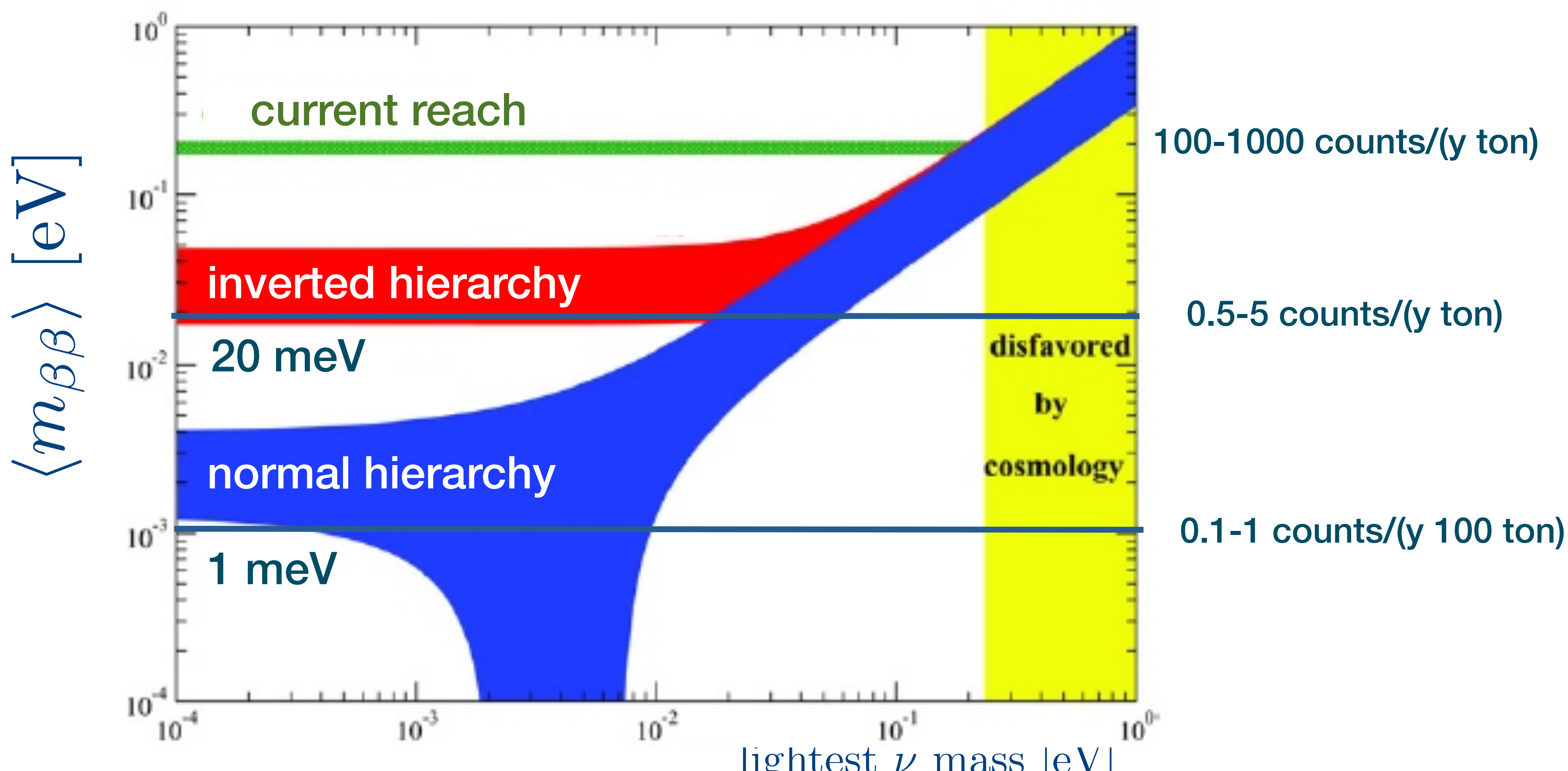
$$T_{1/2}^{2\nu} = 2.38 \pm 0.02(\mathrm{stat}) \pm 0.14(\mathrm{syst}) \times 10^{21} \quad \mathrm{yr.}$$

$$T_{1/2}^{0\nu\beta\beta} > 1.9 \times 10^{25}\ \mathrm{yr}\ (90\%\mathrm{C.L.})$$

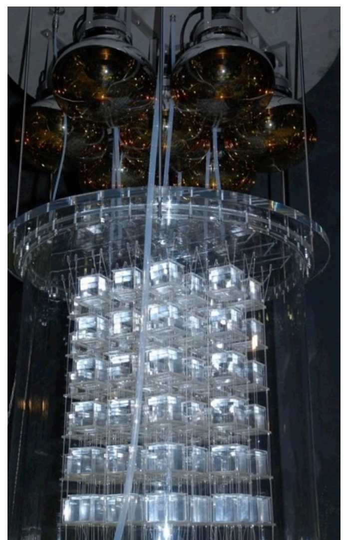
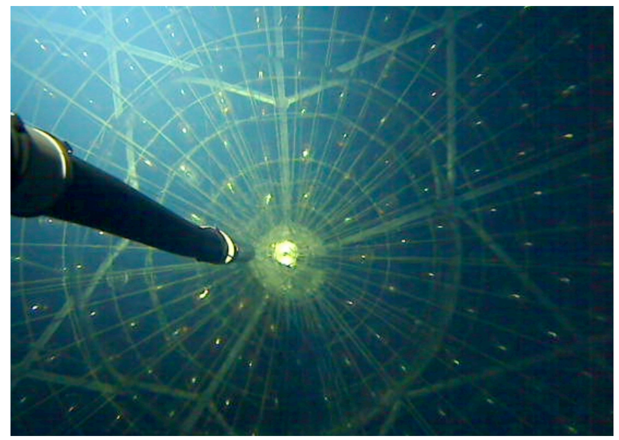
PRC 85, 2012

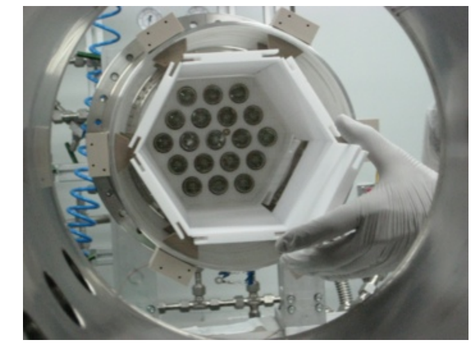
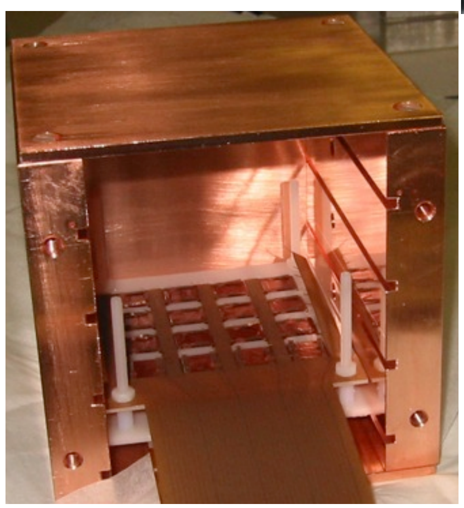
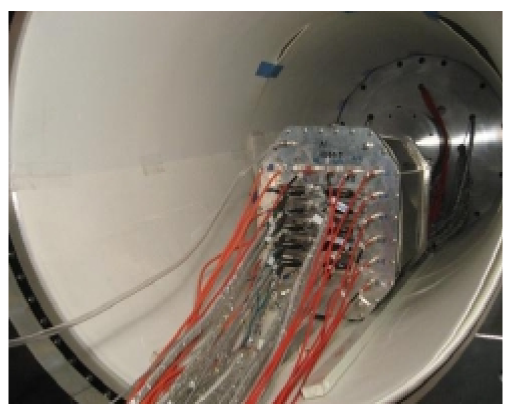
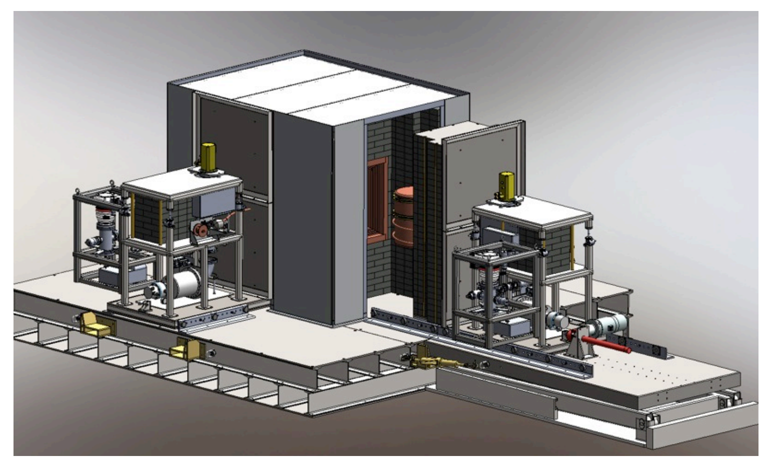
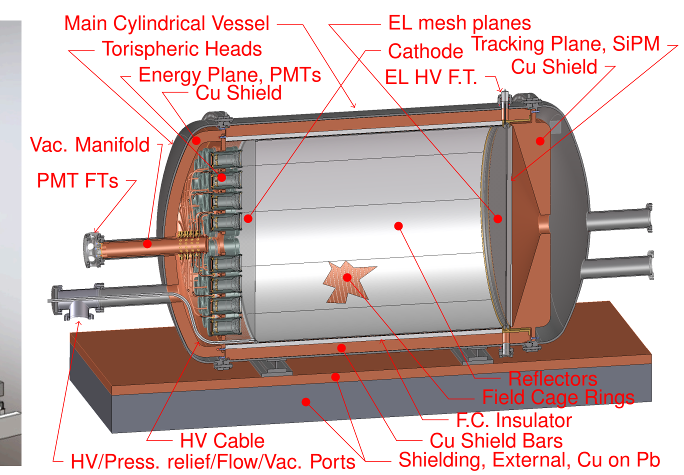
The search continues...

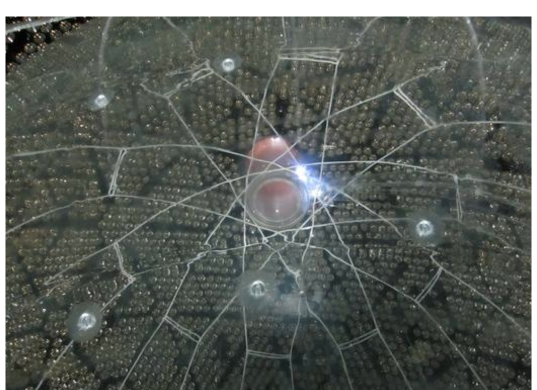
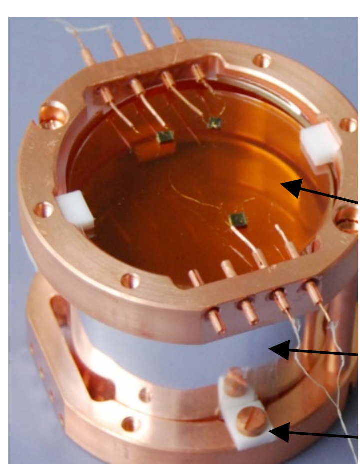
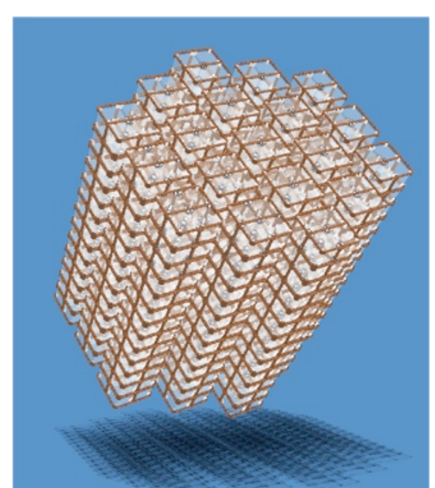
- Ton-scale experiments are needed to explore the *inverted mass hierarchy* scale
- Several technologies are moving towards this scale with ultra-low backgrounds
- It remains to be seen which ones can be upgraded to 10-100 ton scale and explore the *normal hierarchy*

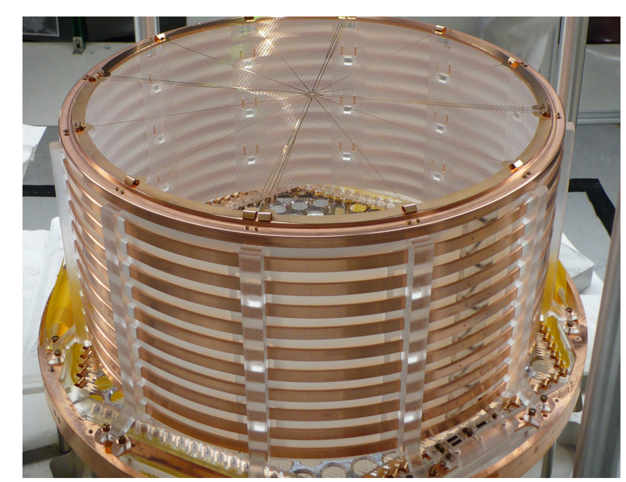


Current and future double beta experiments



Summary

- Neutrinos are *different*!
- Strong evidence for non-zero neutrino masses and non-trivial mixing from oscillation experiments
- Nonetheless, many questions remain unanswered:
  - ➡ absolute mass scale and hierarchy?
  - ➡ Majorana- versus Dirac particles?
  - ➡ is there CP-violation in the neutrino-sector?
  - ➡ what is the origin of small neutrino masses?
  - ➡ what is the origin of the large neutrino mixing?
- The observation of the neutrinoless double beta decay could help in answering some of these questions

End

Matrix elements

$$\Gamma^{0\nu} = \frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}$$

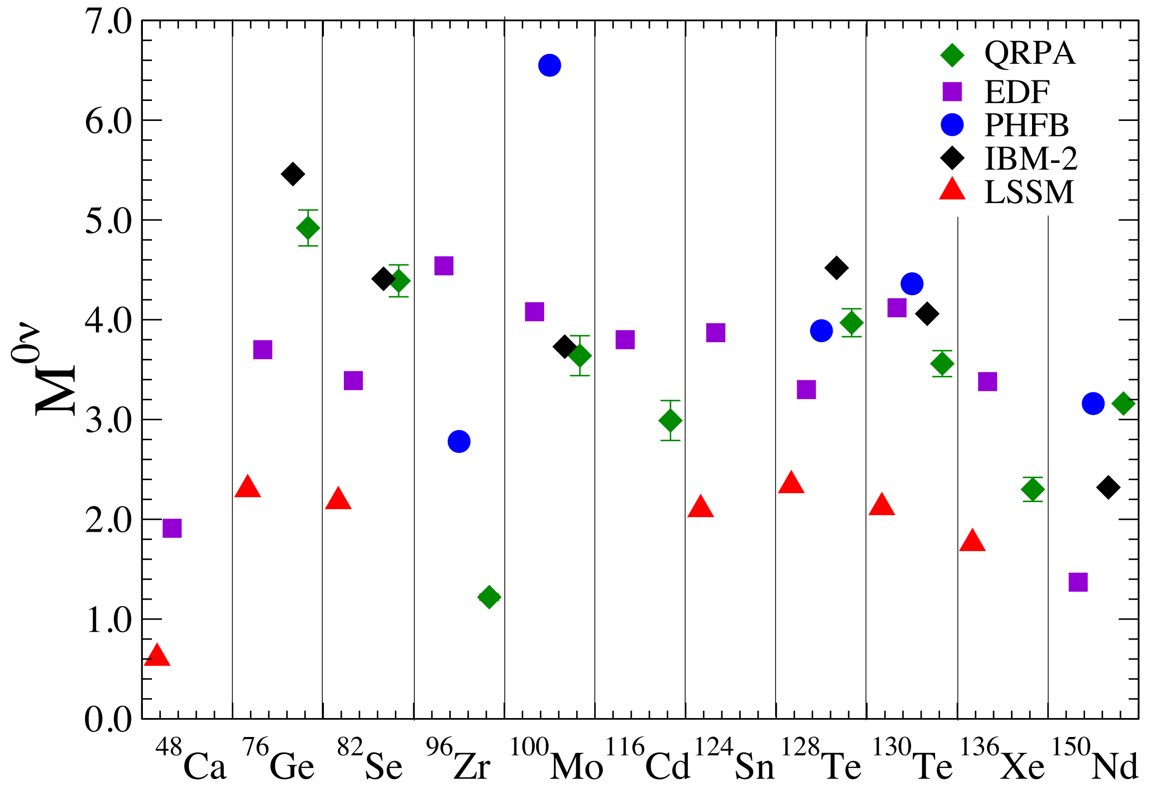


Fig. 3. Values of the NME calculated with the methods in Tab. 2 [74].

Bilenky, Giunti: arXiv:1203.5250v2

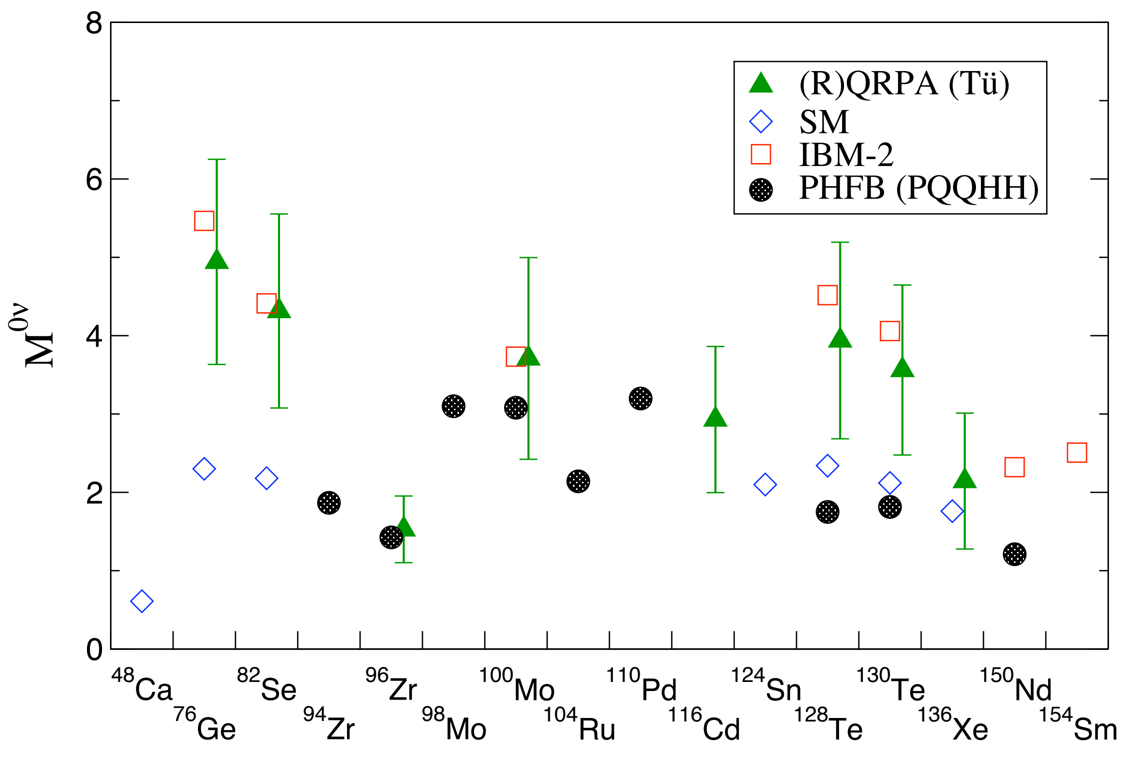


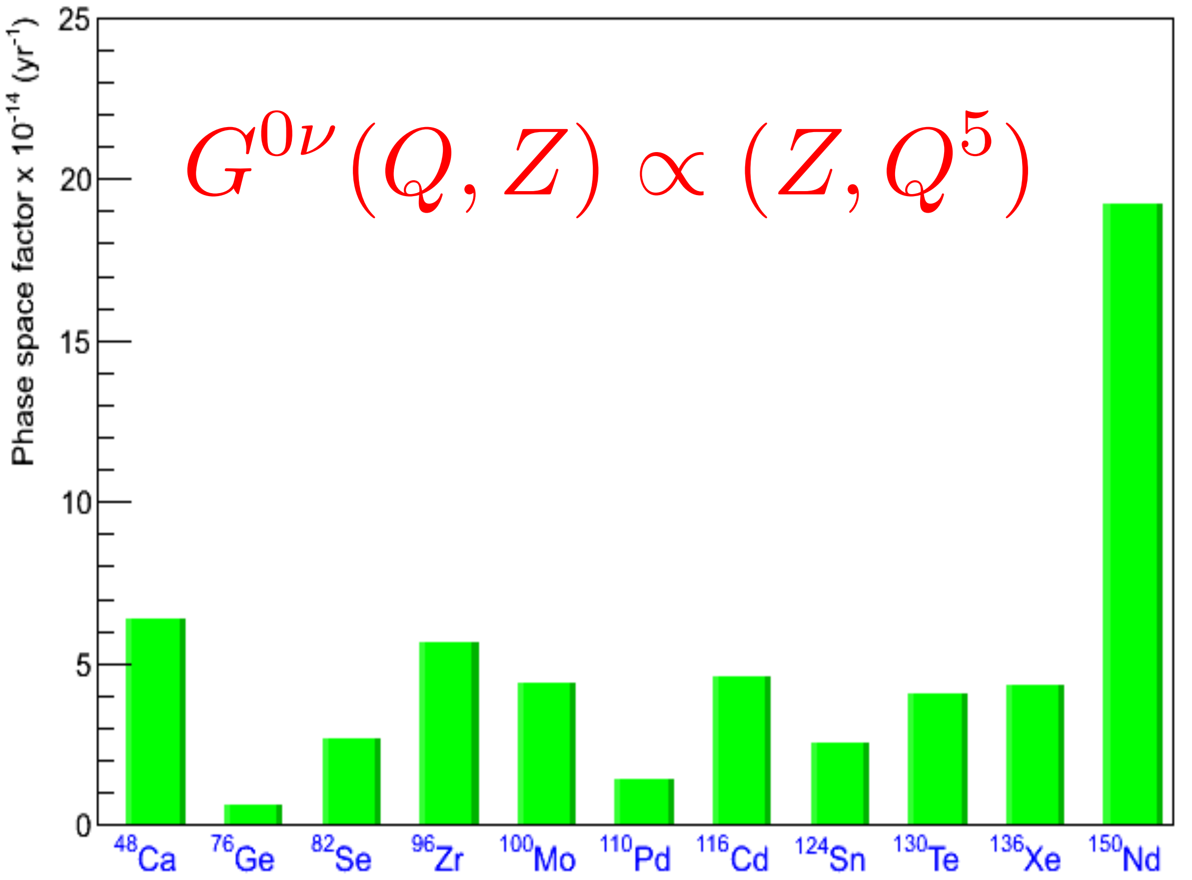
FIG. 7: (Color online) Neutrinoless double beta decay transition matrix elements for the different approaches: QRPA [5, 6], the SM [8–10], the projected HFB method [14] and the IBM [15]. The error bars for the QRPA are calculated as the highest and the lowest values for three different single nucleon basis sets, two different axial charges $g_A = 1.25$ and the quenched value $g_A = 1.00$ and two different treatments of short range correlations (Jastrow-like [25] and the Unitary Correlator Operator Method (UCOM) [26]). The radius parameter is as in this whole work $r_0 = 1.2$ fm.

arXiv:1001.3519

Matrix elements: vary by a factor of 2- 3 for a given A

Phase space

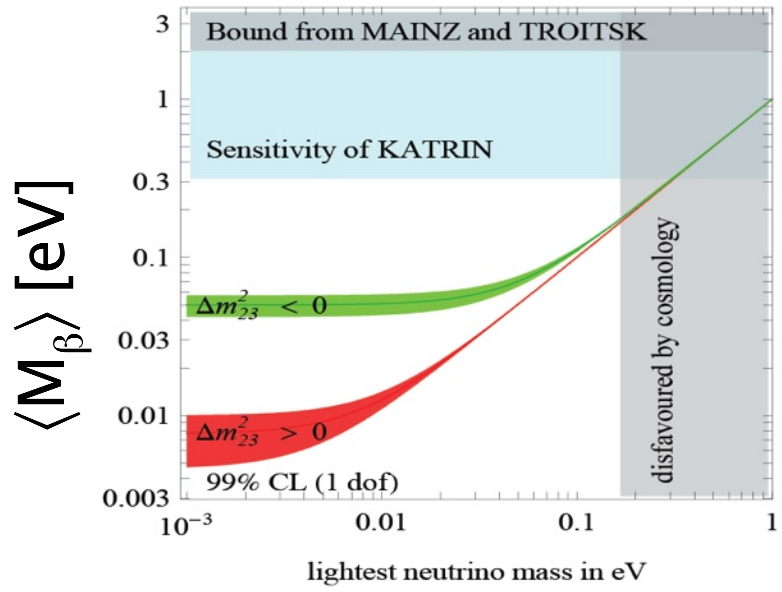
$$\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}$$



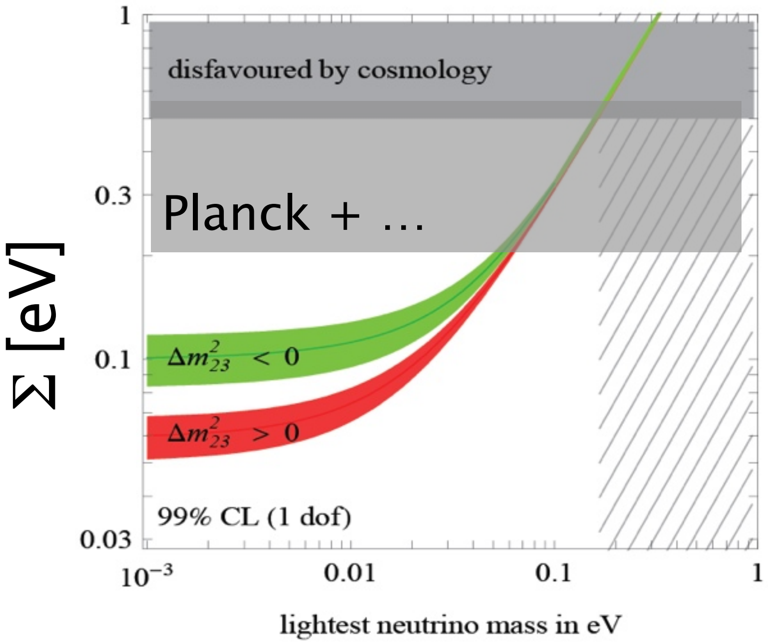
F. Piquemal, Neutrino2012, Kyoto

Transition	G [10^{-14} yr^{-1}]	Q [keV]
$^{48}Ca \rightarrow ^{48}Ti$	6.35	4373.7
$^{76}Ge \rightarrow ^{76}Se$	0.63	2039.1
$^{82}Se \rightarrow ^{82}Kr$	2.70	2995.5
$^{100}Mo \rightarrow ^{100}Ru$	4.36	3035
$^{116}Cd \rightarrow ^{116}Sn$	4.62	2809
$^{130}Te \rightarrow ^{130}Xe$	4.09	2530.3
$^{136}Xe \rightarrow ^{136}Ba$	4.31	2461.9
$^{150}Nd \rightarrow ^{150}Sm$	19.2	3367.3

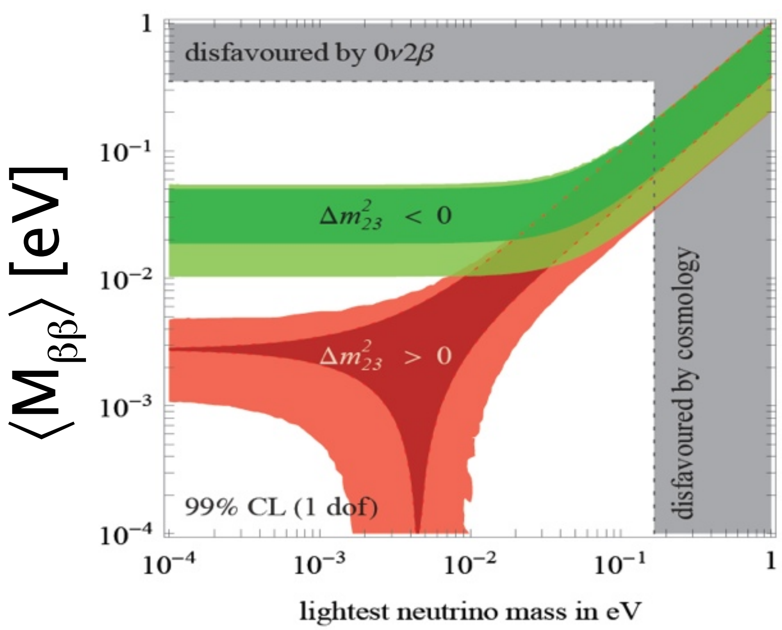
Neutrino masses



b-decay



cosmology



bb-decay