Introduction to Neutrino Physics

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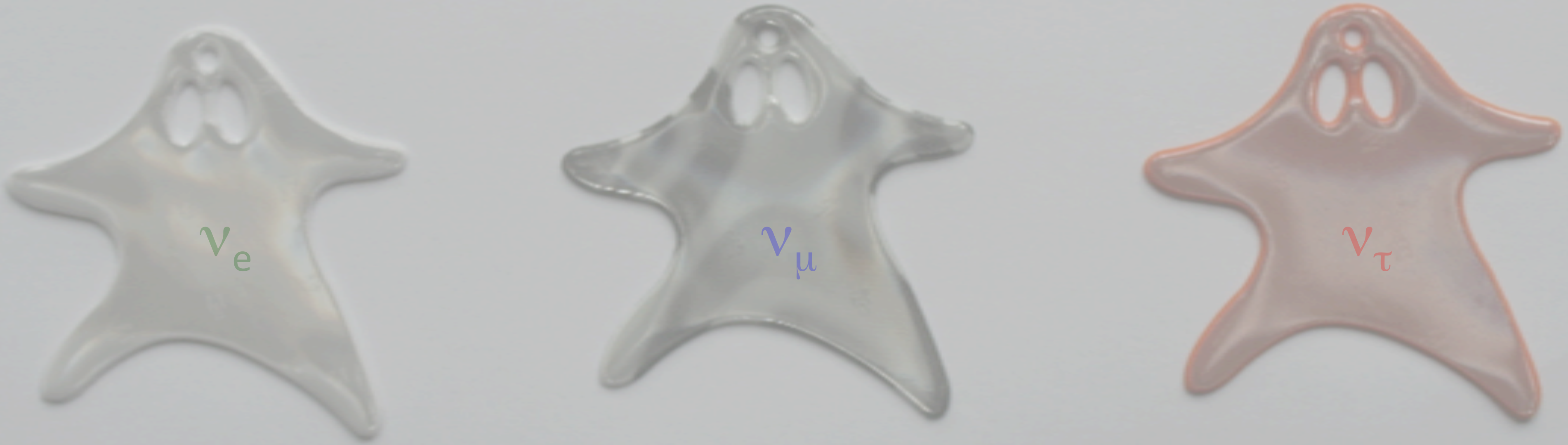


Lecture 4

Neutrinoless double beta decay Part 2

Recap lecture 3 neutrino mass

- Neutrino oscillations don't tell us anything about absolute neutrino masses
- From neutrino oscillations and cosmological observations:

$$50\ \text{meV} < m_\nu < \ \sim 1\ \text{eV}$$

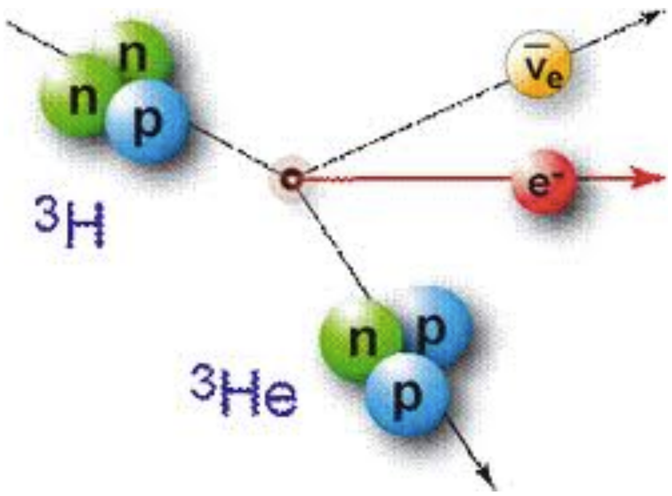
- Straightforward to extend the SM with Dirac masses for neutrinos
  - But this introduces an unnecessary constraint on lepton-number conservation: the neutrino has no electric charge to conserve!
- Can construct a Majorana mass term out of the right-handed field and its charge-conjugate
  - Mixes ν and anti-ν, so no conservation of lepton number
- See-saw mechanism combines Dirac and Majorana to give an extremely light ~left-handed neutrino and an extremely heavy ~right-handed neutrino

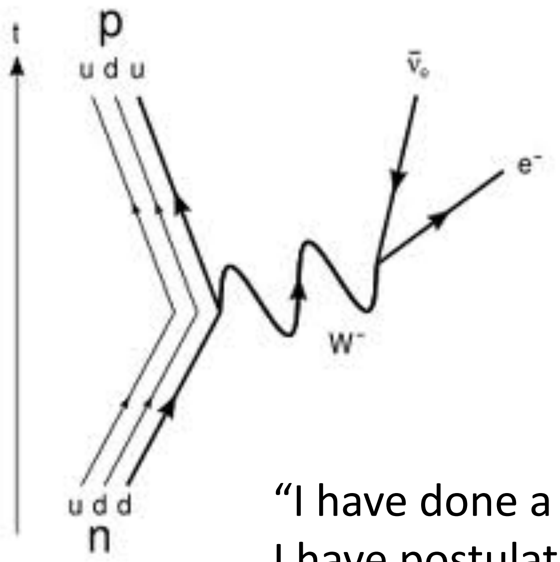
Outline lecture 4

- Beta decay: single and double, with and without neutrinos
- Experimental considerations for a search for neutrinoless double beta decay
- Tour of a few neutrinoless double beta decay experiments

Single beta decay

That’s where it started…

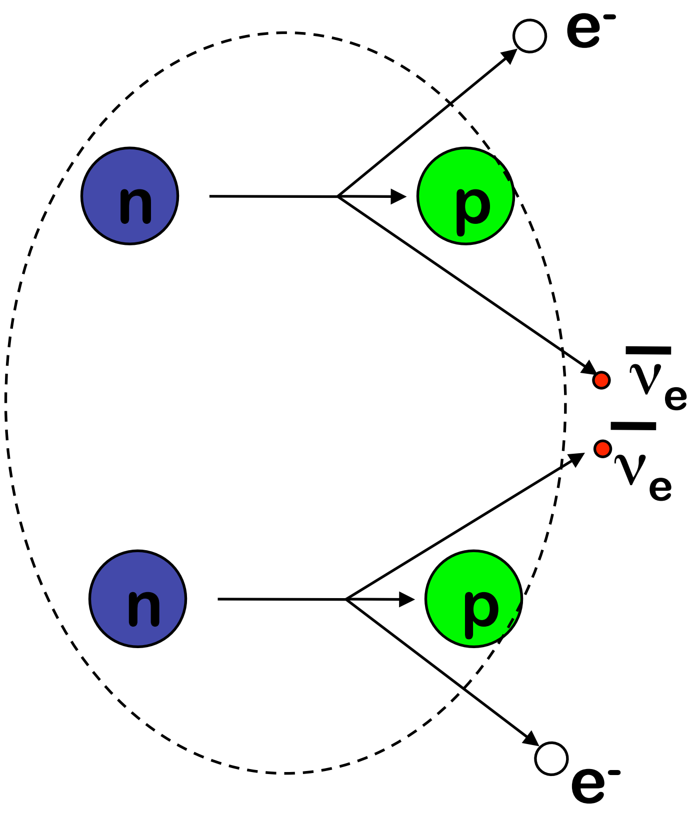




“I have done a terrible thing,
I have postulated a particle
that can not be detected”
(W. Pauli)

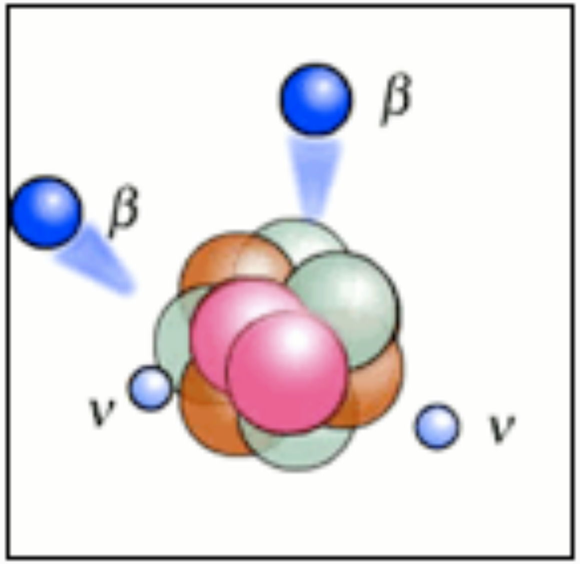
First-order Standard-Model process

Double beta decay



$\mathcal{M}(A,Z) \rightarrow \mathcal{M}(A,Z+2) + 2e^{-} + 2\overline{\nu}_e$

$2\beta^{-}$ process

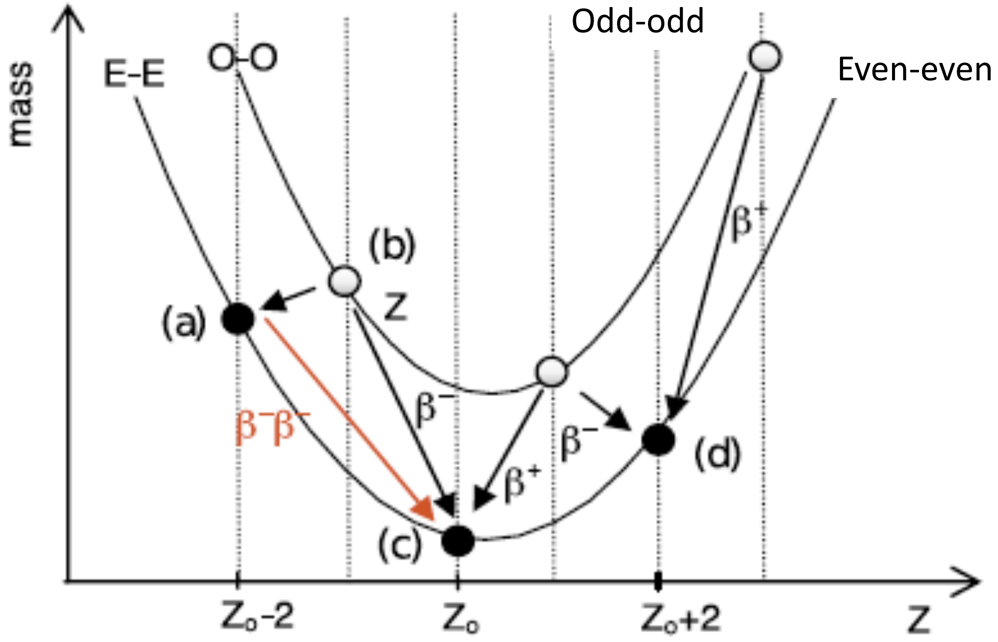


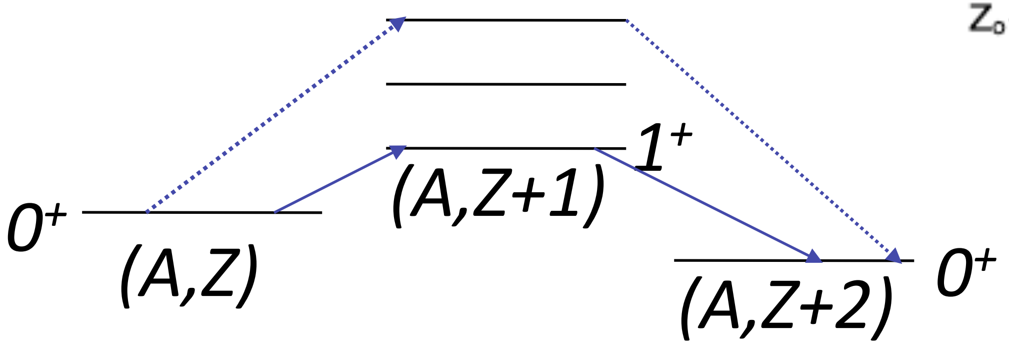
Second-order SM process

Two neutrinos emitted: $2\nu\beta\beta$

Double beta decay

Requires even-even nuclei





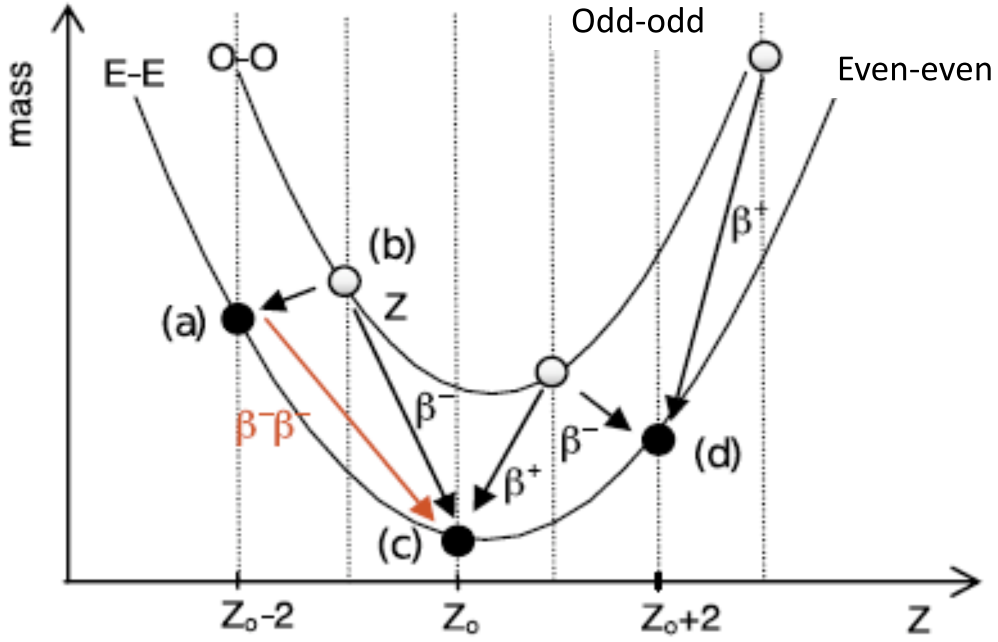
Double beta decay

Rarest kind of radioactive decay:

Only 35 naturally occurring isotopes can decay via $2\beta^-$

Half-lifes of O(10^{16} years) and upwards
C.f. age of the universe O(10^{10} years)

Double beta decay



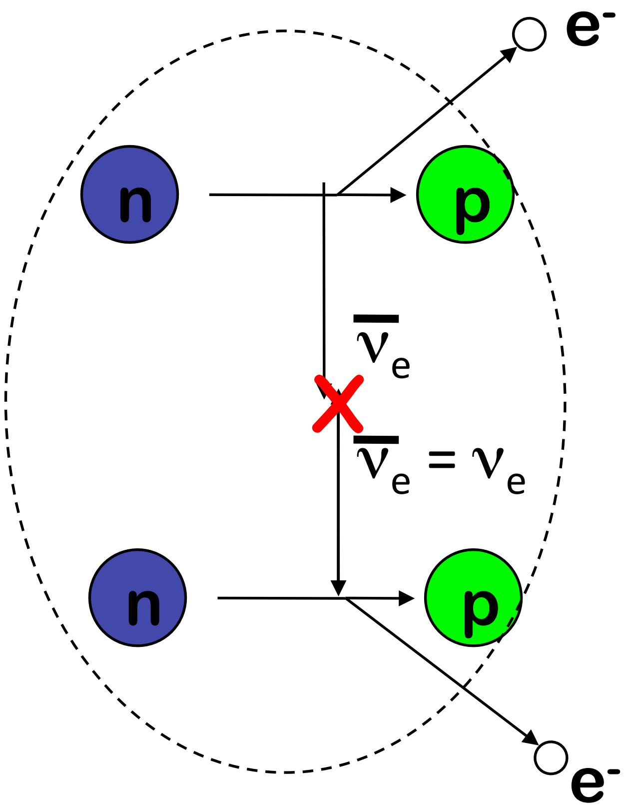
Rarer still:

Can occur also via the $2\beta^+$ process: $\mathcal{N}(A,Z) \rightarrow \mathcal{N}(A,Z-2) + 2e^+ + 2\nu_e$

and via electron capture (EC): $e^- + \mathcal{N}(A,Z) \rightarrow \mathcal{N}(A,Z-2) + e^+ + 2\nu_e$

$2e^- + \mathcal{N}(A,Z) \rightarrow \mathcal{N}(A,Z-2) + 2\nu$

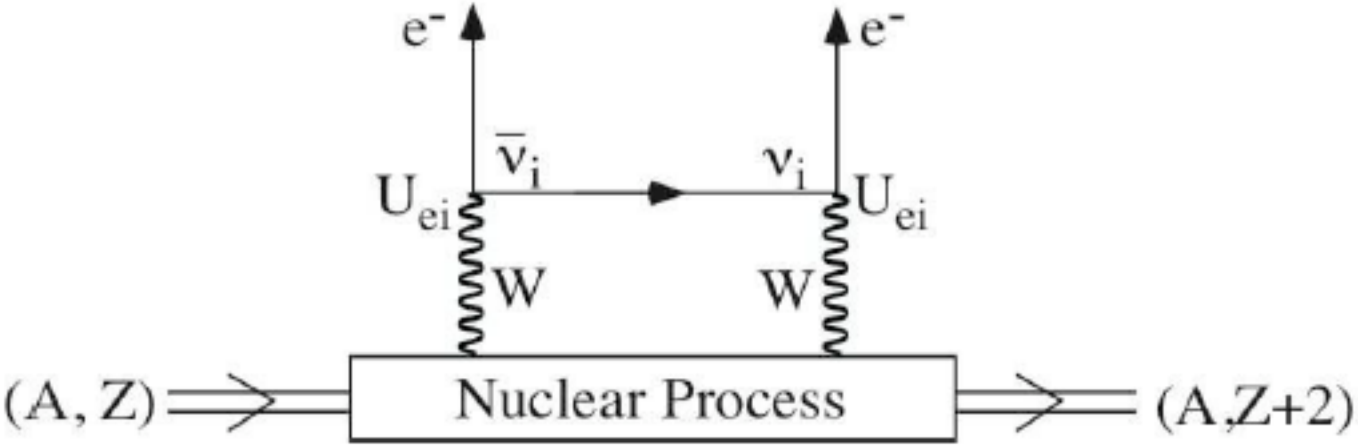
Neutrino-less double beta decay (0νββ)



$\mathcal{N}(A,Z) \rightarrow \mathcal{N}(A,Z+2) + 2e^-$

- Violates lepton number: $\Delta L = 2$
- Forbidden in the Standard Model

0νββ and neutrino mass



Amplitude for 0νββ is proportional to the effective Majorana mass:

$$m_{\beta\beta} = \sum_{k=1}^{3} U_{ek}^2 m_k = |U_{e1}|^2 m_1 + e^{i\alpha} |U_{e2}|^2 m_2 + e^{i\beta} |U_{e3}|^2 m_3$$

$0\nu\beta\beta$ half-life

$$(T_{1/2})^{-1} = G_{0\nu}|M_{0\nu}|^2|m_{\beta\beta}|^2/m_e^2$$

Phase-space factor

Calculable with small uncertainties

Depends on $Q_{\beta\beta}$ and Z

Nuclear Matrix Element

Incorporates knowledge of all nuclear structural effects

Requires accurate nuclear model

Models differ by up to x3

Experimental input could help

The Q value

$$\mathcal{M}(A,Z) \rightarrow \mathcal{N}(A,Z+2) + 2e^-$$

The sum of the kinetic energies of the electrons
is always the same, namely
the mass difference $m_{(A,Z)} - m_{(A,Z+2)}$,
i.e. $Q_{\beta\beta}$ (the “Q value”)

The Q value

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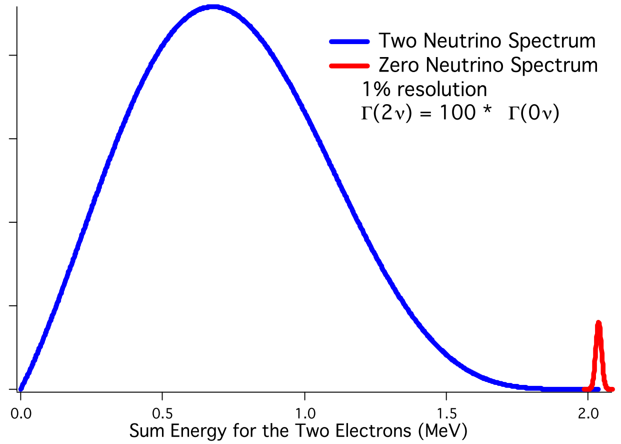


2νββ has a
continuous
spectrum

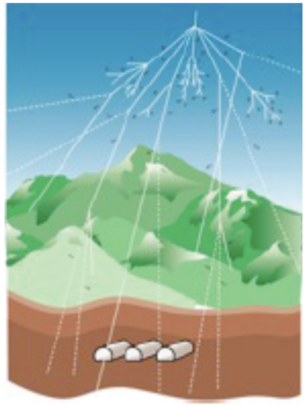
0νββ has a
Discrete spectrum
At the upper end
of the
2νββ spectrum

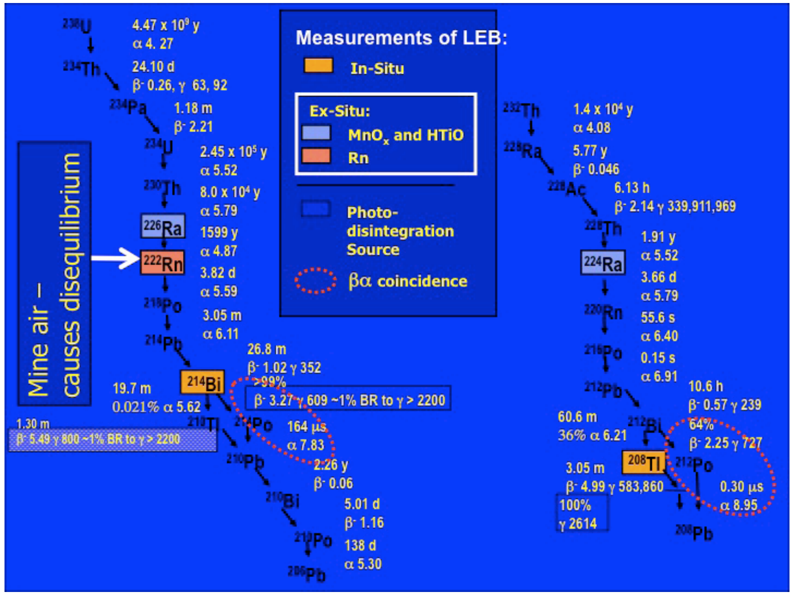
Considerations for a 0νββ experiment

- Which isotope to choose?
  - 35 to choose from…
    - Ex ^{76}Ge, ^{130}Te, ^{82}Se, ^{136}Xe, ^{150}Nd
- Dealing with backgrounds
- Detector techniques
- A few example experiments

Backgrounds

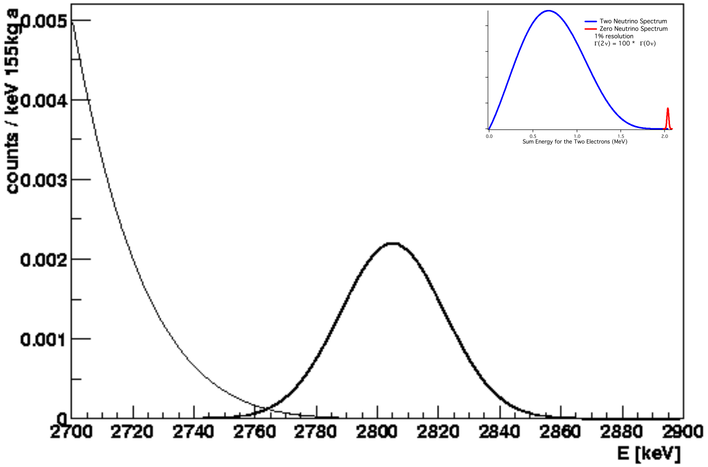
- Cosmic rays





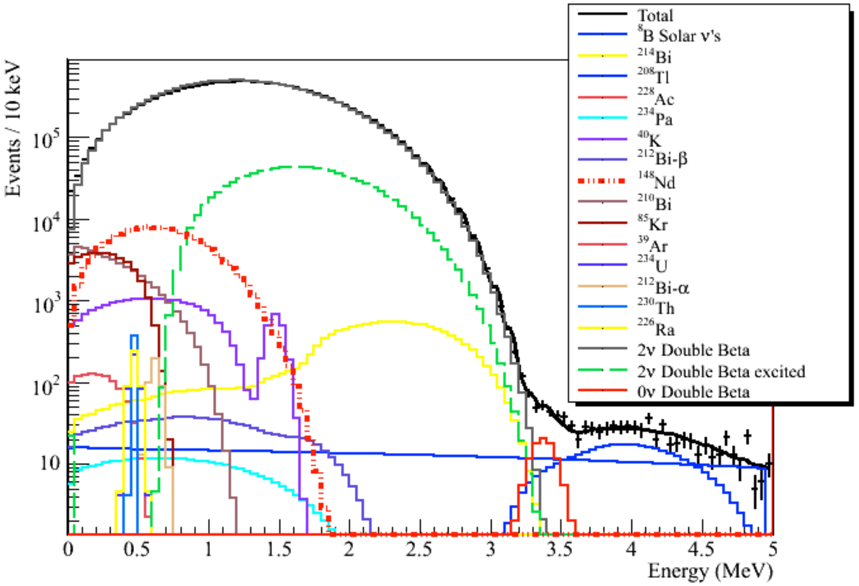
- Natural radioactivity
  - $T_{1/2}(^{238}U, ^{232}Th) \sim 10^{10}$ years
  - $T_{1/2}(0\nu\beta\beta) \sim 10^{25}$ years

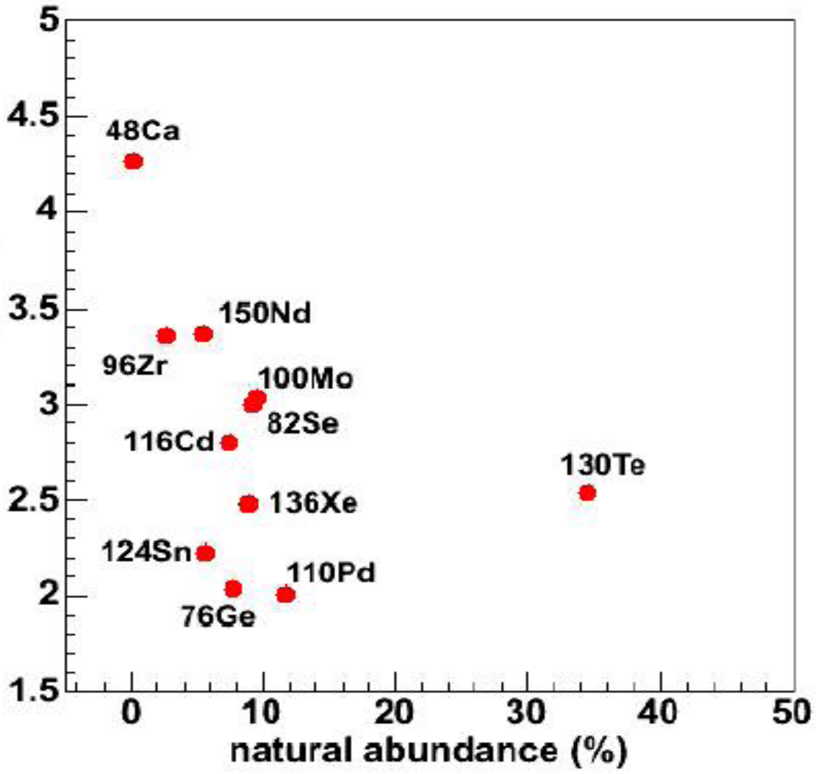
- Standard-Model $2\nu\beta\beta$
  - Irreducible background



Dealing with backgrounds I

- Choose isotope with a high Q value
  - Energy above as much of the background as possible
- Also long $2\nu\beta\beta$ half-life

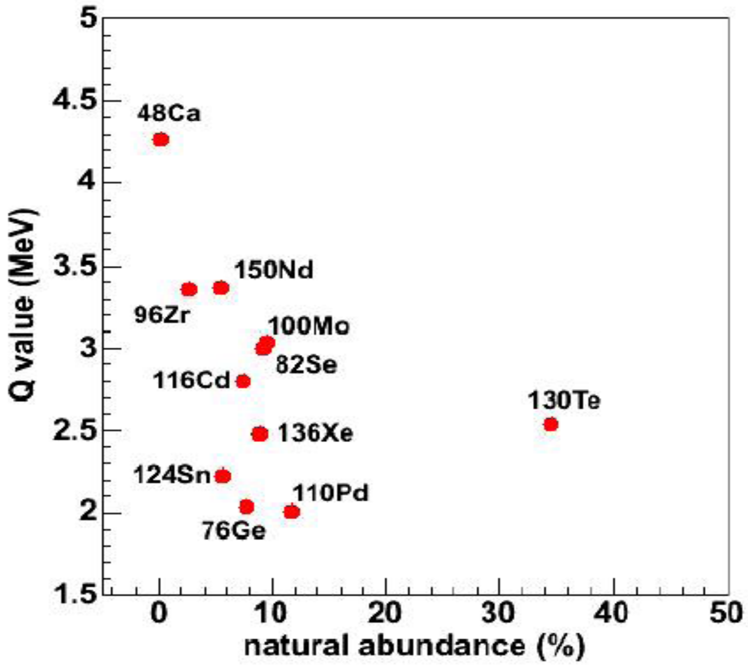




Maximising the decay rate

$$(T_{1/2})^{-1} = G_{0\nu}|M_{0\nu}|^2|m_{\beta\beta}|^2/m_e^2$$

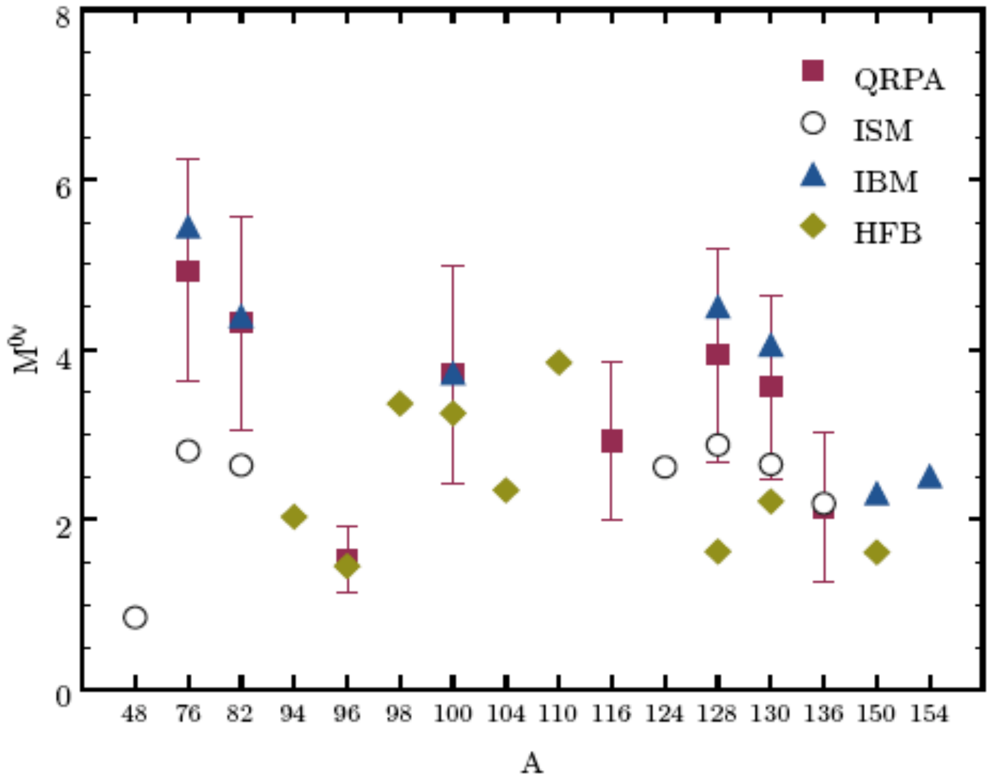
- The more isotope mass you can put in your experiment, the more decays there will be
  - Choose isotope with high natural abundance
  - Choose isotope that is "cheap" per unit mass
  - Consider isotope enrichement



Maximising the decay rate

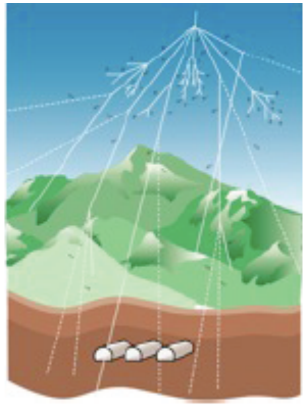
$$(T_{1/2})^{-1} = G_{0\nu}|M_{0\nu}|^2|m_{\beta\beta}|^2/m_e^2$$

- Choose isotope with large phase space
- Choose isotope with small uncertainty on nuclear matrix element

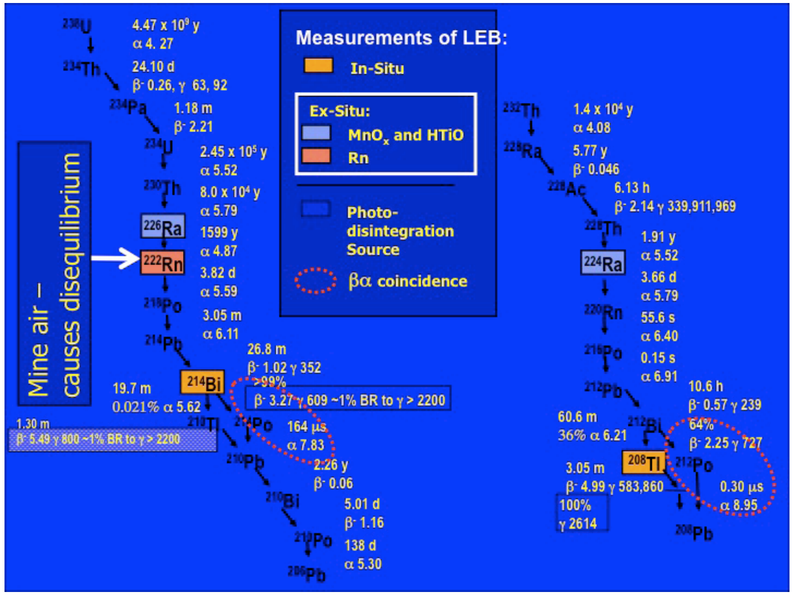


Dealing with backgrounds II

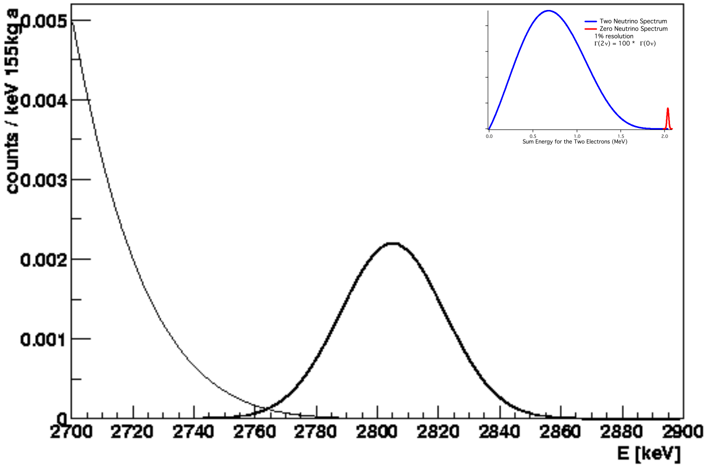
- Cosmic rays
  - Underground lab



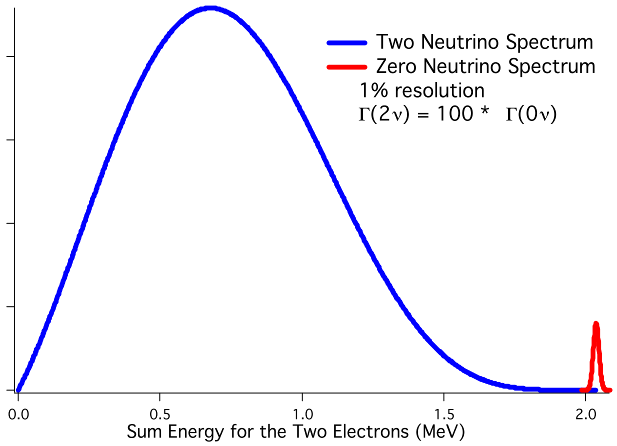
- Natural radioactivity
  - Radiopurity
    - Choice of detector materials
    - Cleanliness
  - Background identification



- Standard-Model 2νββ
  - Irreducible background
  - Good energy resolution

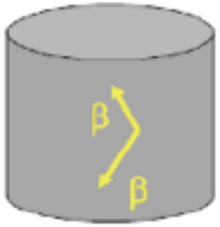


Detector techniques



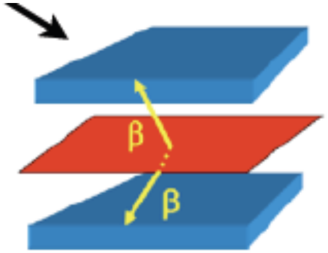
1. Two coincident electrons from the same vertex
2. $E_{e1} + E_{e2} = Q_{\beta\beta}$
3. Angular distribution

Two approaches



Source = detector (calorimeter)

Good E resolution



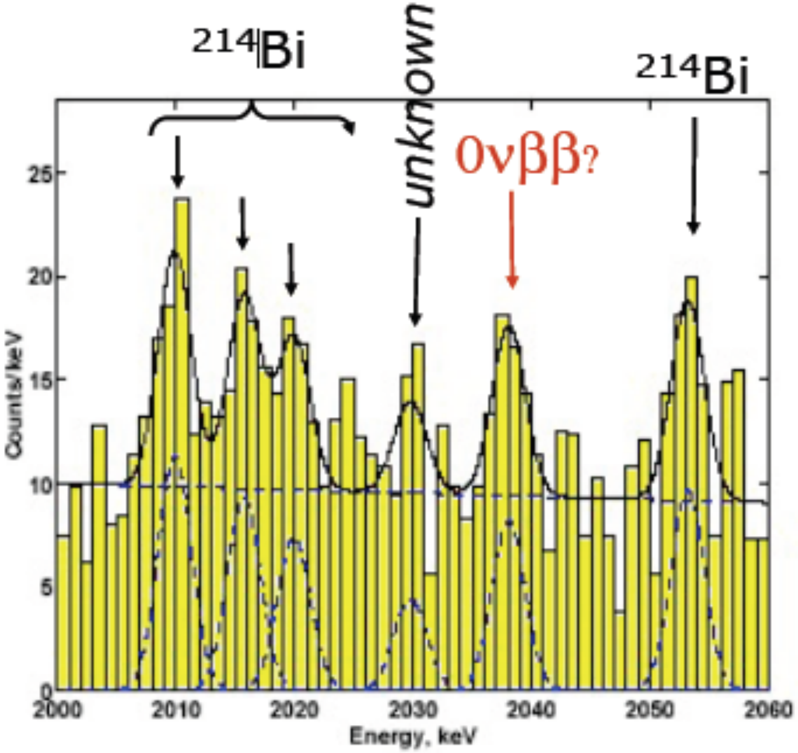
Source ≠ detector (foil + tracking + calorimetry)

Background by topology

- Scintillator calorimeters
- Semiconductors
- Bolometers (energy release via heating)
- Liquid/gas Xe TPC

A controversial claim

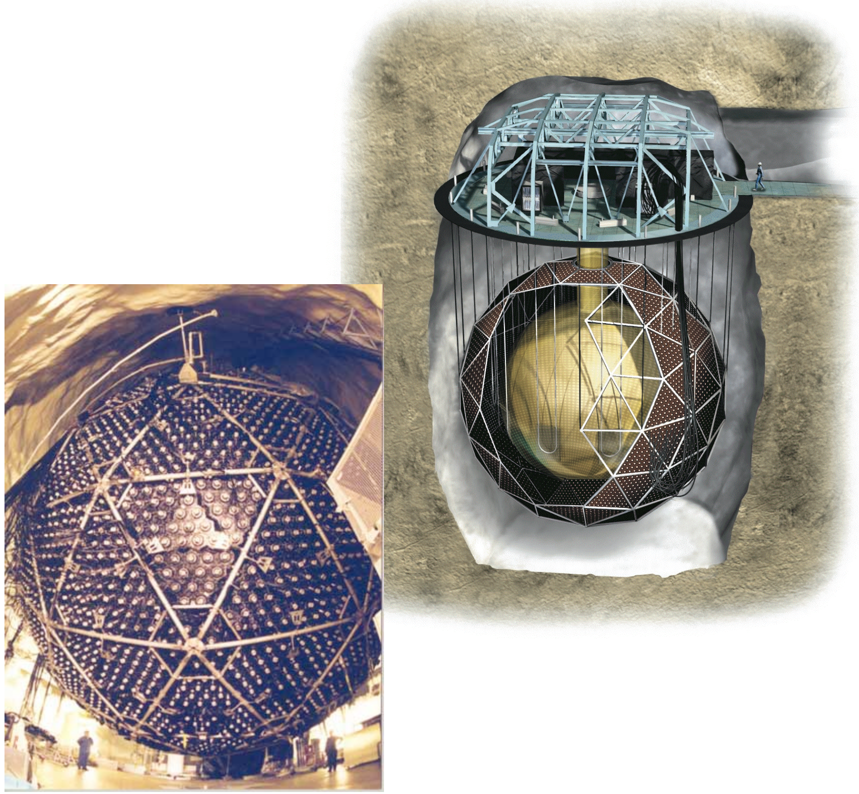
- Klapdor-Kleingrothaus et al., 2004
- High-Purity Ge detector
- Found unknown line at 2038 keV with 4.2σ significance
- $T_{1/2} \sim 10^{25}$ y
- Cannot be dismissed out of hand, but
  - Background underestimated
  - Unknown line in the same region
  - Problem with relative intensities of ^{214}Bi lines



$$< m_\nu > = 0.1 - 0.9\,\mathrm{eV}\ (\mathrm{KKDC},\ 2004)$$

SNO+

- Re-use old SNO (Sudbury Neutrino Observatory) vessel in Creighton nickel mine, Canada
- Candidate isotope ^{150}Nd dissolved in liquid scintillator
  - ^{96}Zr also interesting
- Also other ν sources, e.g.:
  - Low-E solar neutrinos: neutrino-matter interactions; solar composition
  - Reactors: neutrino oscillations
  - Supernova neutrinos
- Data collection to start in 2013



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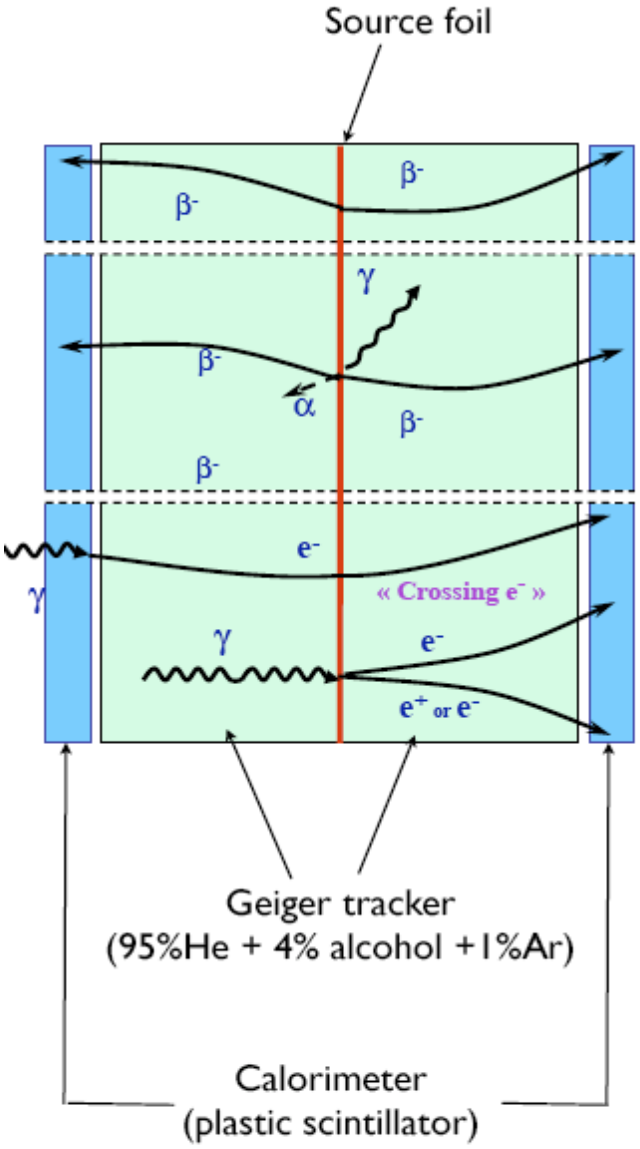
NEMO3: topological signature



Δt ~0 ns Signal

Δt ~0 ns

Internal (e.g. ^{214}Bi)

Δt ≥ 3 ns

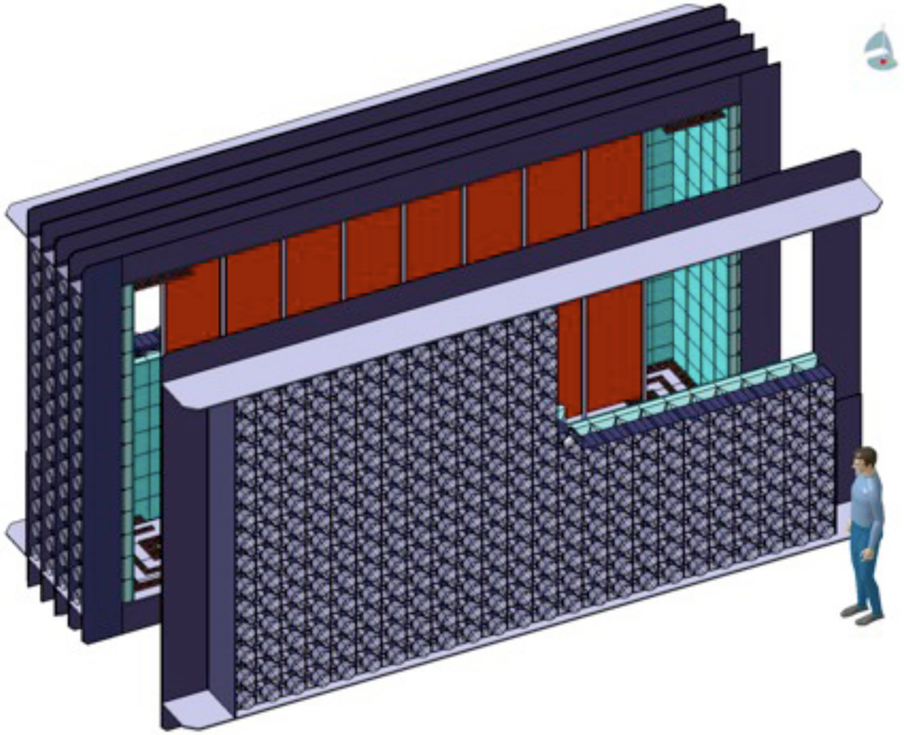
External (e.g. ^{208}Tl, neutrons)

Δt ~0 ns

Nemo3 (Modane lab)

- Measure final-state observables:
  - Individual electron energies ($E_1 + E_2 = Q_{\beta\beta}$)
  - Electron trajectories and vertices
  - Time of flight
  - Angular distribution between electrons
- Background rejection through particle ID: e^-, e^+, α, γ
- Has made many (world-leading) measurements of $2\nu\beta\beta$ half-lives
  - ^{100}Mo, ^{130}Te, ^{82}Se, ^{116}Cd, ^{150}Nd, ^{48}Ca, ^{96}Zr

SuperNEMO

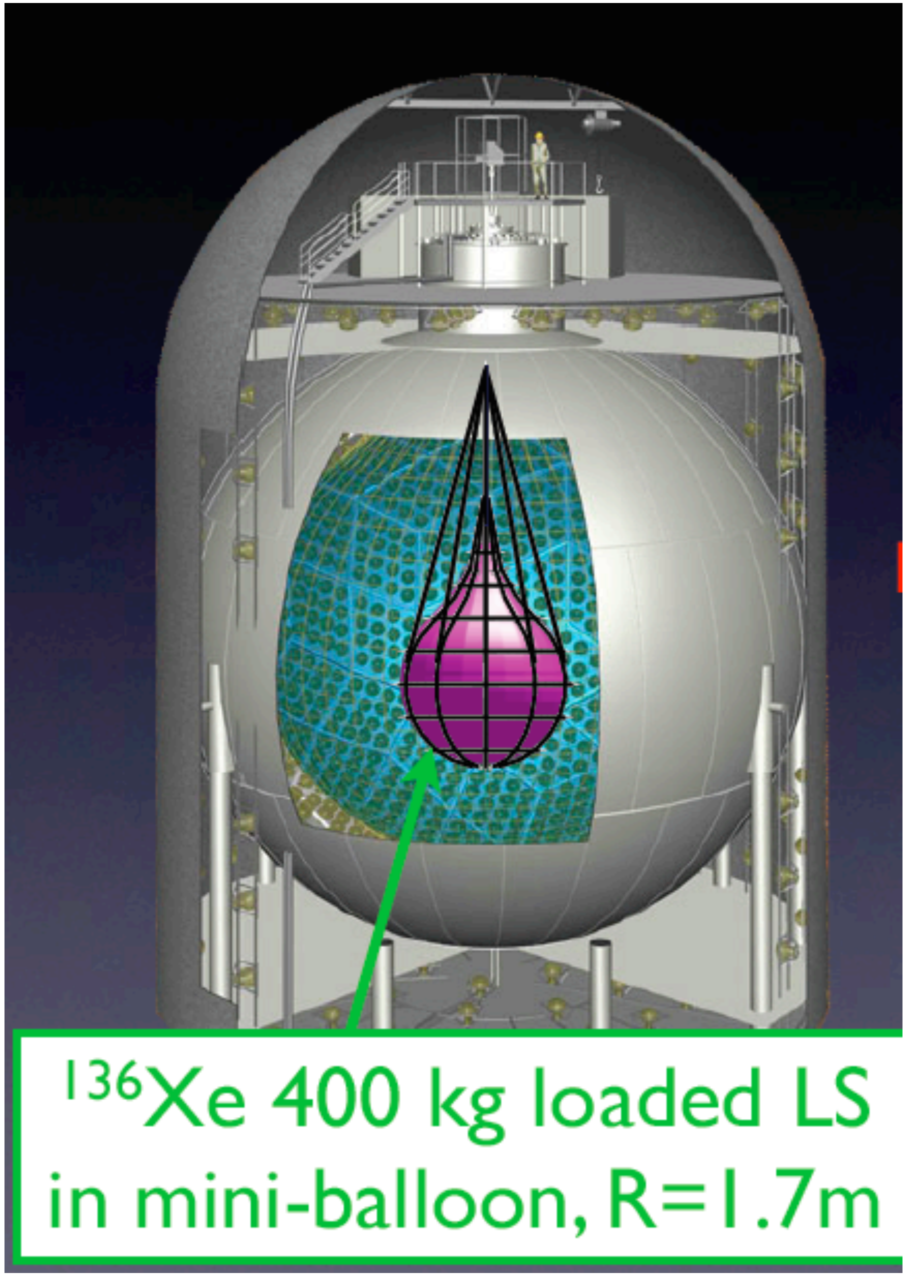


- Successor to NEMO3
  - Again, foils + tracking + calorimetry
- Planar and modular:
  20 modules x 5 kg
  of enriched isotopes
  - 10x NEMO3
- Tracking:
  Drift cells in Geiger mode
- Calorimeter:
  Solid scintillators + PMTs
- Surrounded by water shielding
- Modane lab in France
- Next step: build one “demonstrator” module

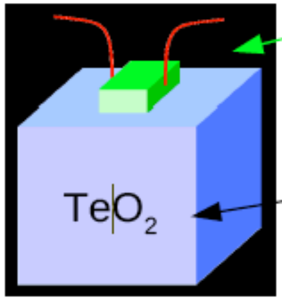
KamLAND-Zen

Reuse old KamLAND detector, with ^{136}Xe as candidate isotope

Balloon to optimise light yield/E resolution vs. amount of ^{136}Xe



CUORE/CUORICINO: the bolometric way

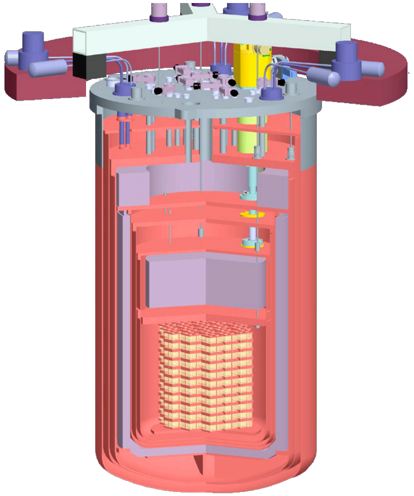


Temperature sensor: $\Delta T \rightarrow \Delta V$

NTD thermistor
$R = R_0 \exp(T/T_0)^\gamma$ → high sensitivity

Absorber: $E \rightarrow \Delta T \sim E/C(T)$

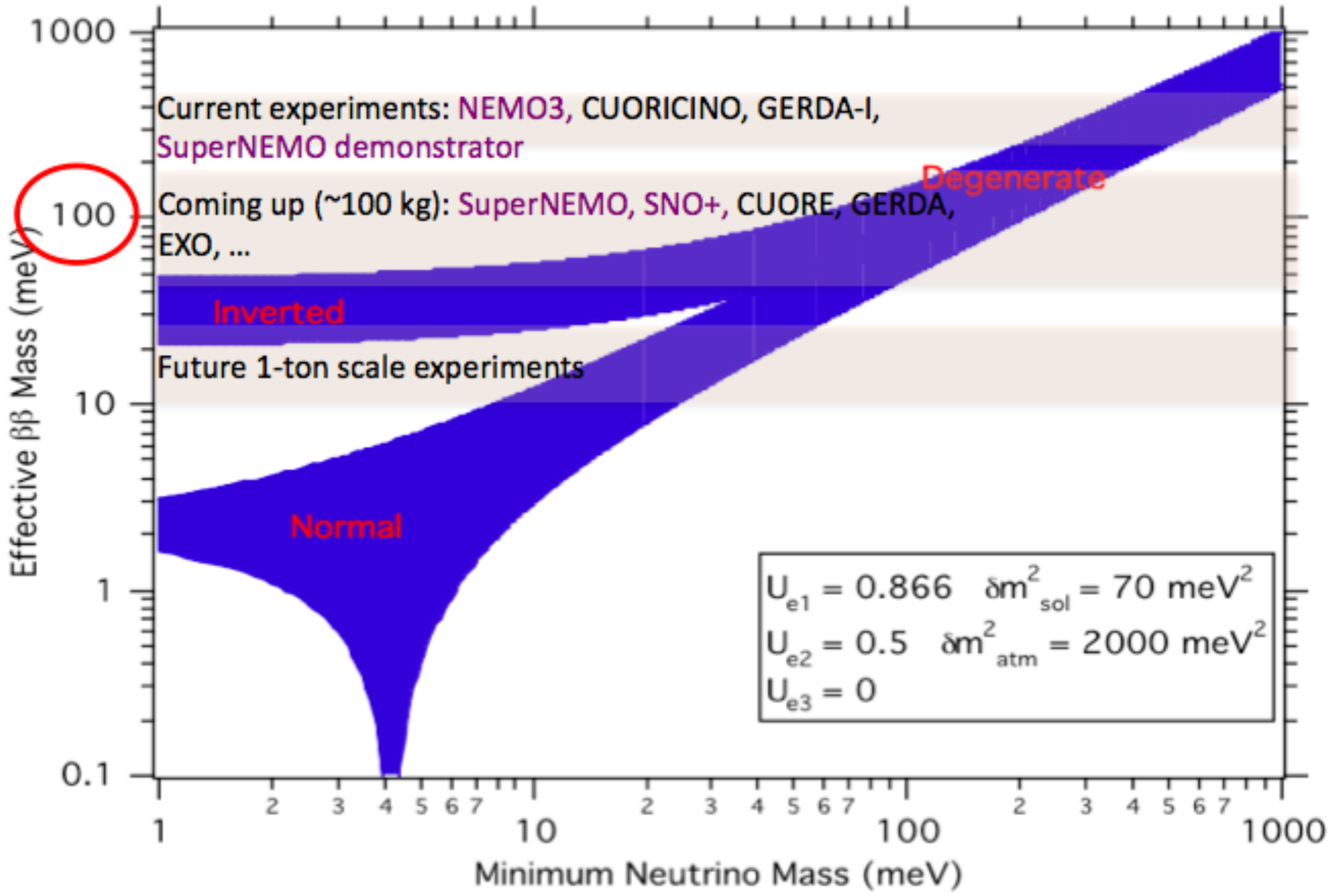
TeO_2 crystals
Low heat capacity
High radio-purity
Large size crystals available



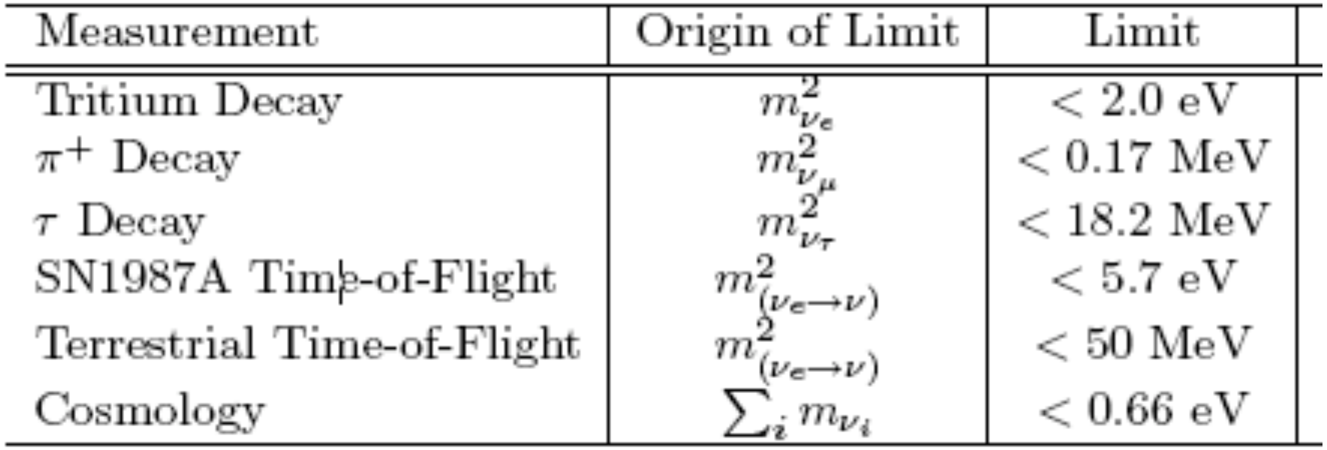
Tower of TeO_2 crystals in cryostat
Plan for ~200 kg of ^{130}Te

Many players lined up

Probing $m_{\beta\beta}$
down to
O(100 meV)



Finally: other limits on neutrino mass



Measurement	Origin of Limit	Limit
Tritium Decay	$m^2_{\nu_e}$	< 2.0 eV
π^+ Decay	$m^2_{\nu_\mu}$	< 0.17 MeV
τ Decay	$m^2_{\nu_\tau}$	< 18.2 MeV
SN1987A Time-of-Flight	$m^2_{(\nu_e \rightarrow \nu)}$	< 5.7 eV
Terrestrial Time-of-Flight	$m^2_{(\nu_e \rightarrow \nu)}$	< 50 MeV
Cosmology	$\sum_i m_{\nu_i}$	< 0.66 eV

From PhD thesis by B. Still, 2009

Recap

- Neutrinoless double beta decay, if it exists, would violate lepton-number conservation by 2
- Half-lives upwards of ~10^{18} years
- Neutrinoless double beta decay is the only experimental technique known to be able to reveal whether the neutrino is Majorana
- Many experiments in the pipeline

Back-ups