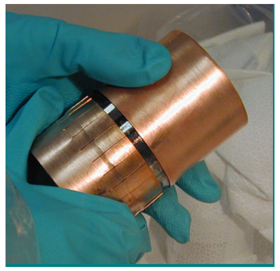
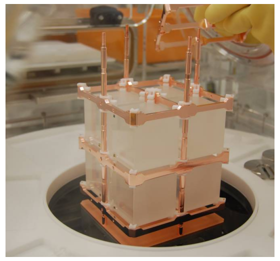
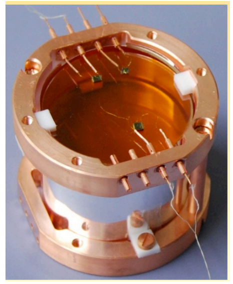
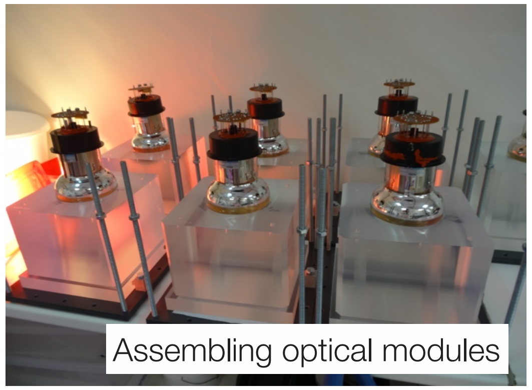
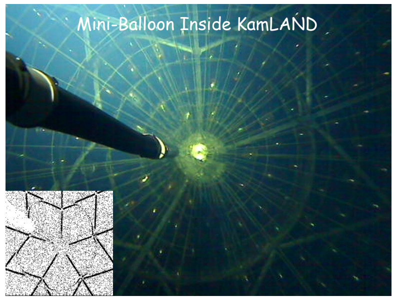
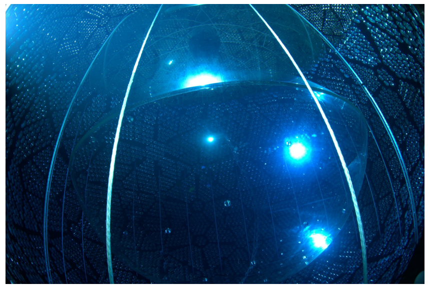
Experimental neutrino physics (SBL, β,ββ0ν)

J.J. Gomez-Cadenas
IFIC (CSIC/UV)
EPS, Vienna, July, 2015



Assembling optical modules



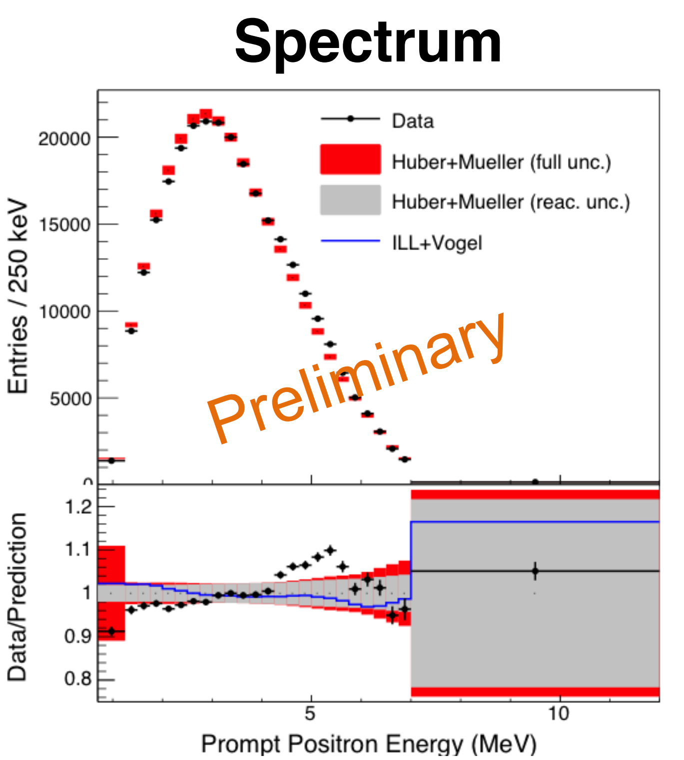


"The only thing that requires more optimism than doing neutrino experiments is to try to summarise them in 30 m"

–Anonymous neutrino experimentalist

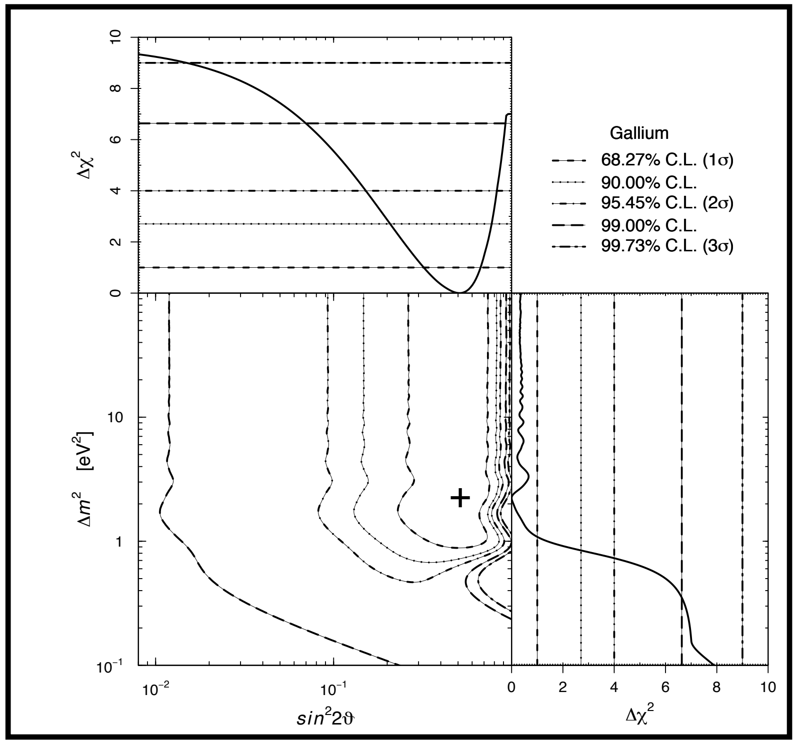
Short base line experiments

The anomalies

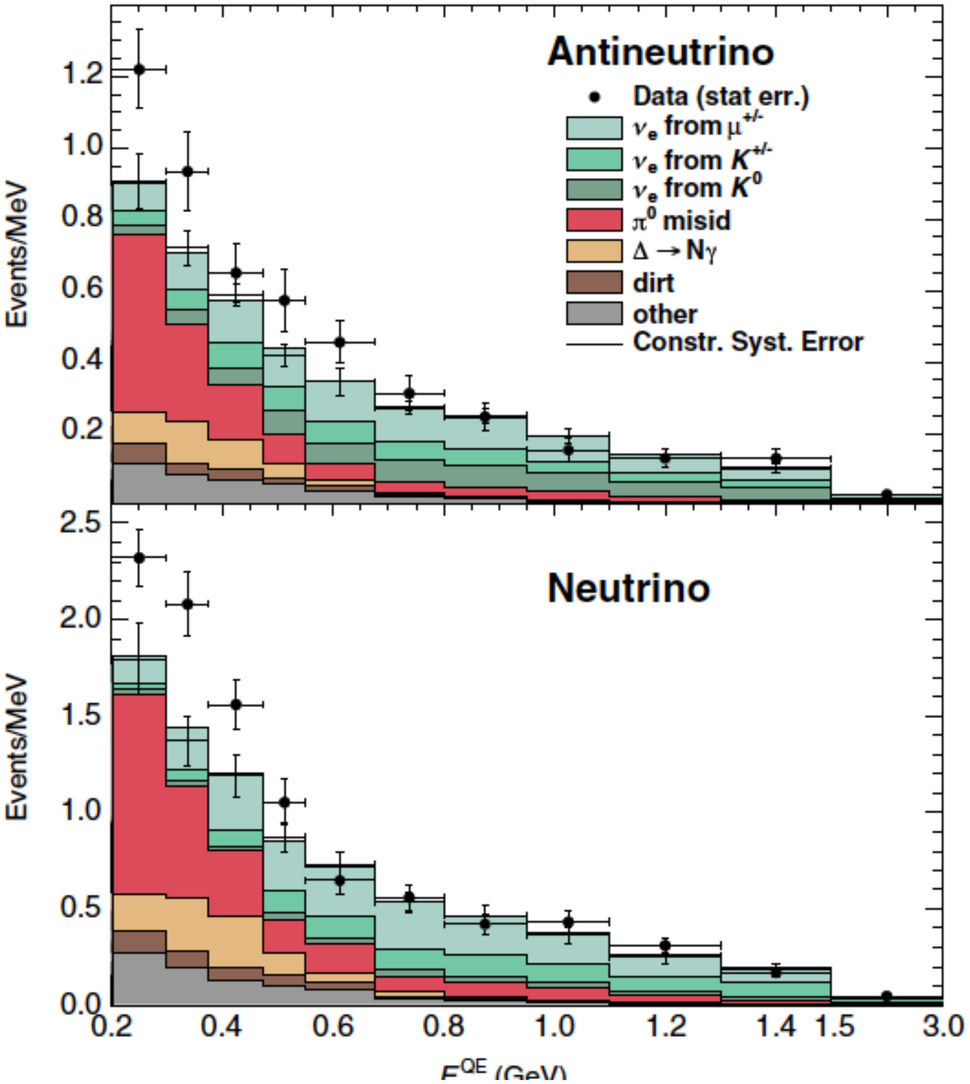


- Spectral shape is not consistent with models, especially between 4-6 MeV.

$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$$



- The number of observed Ge-71 is lower than predicted

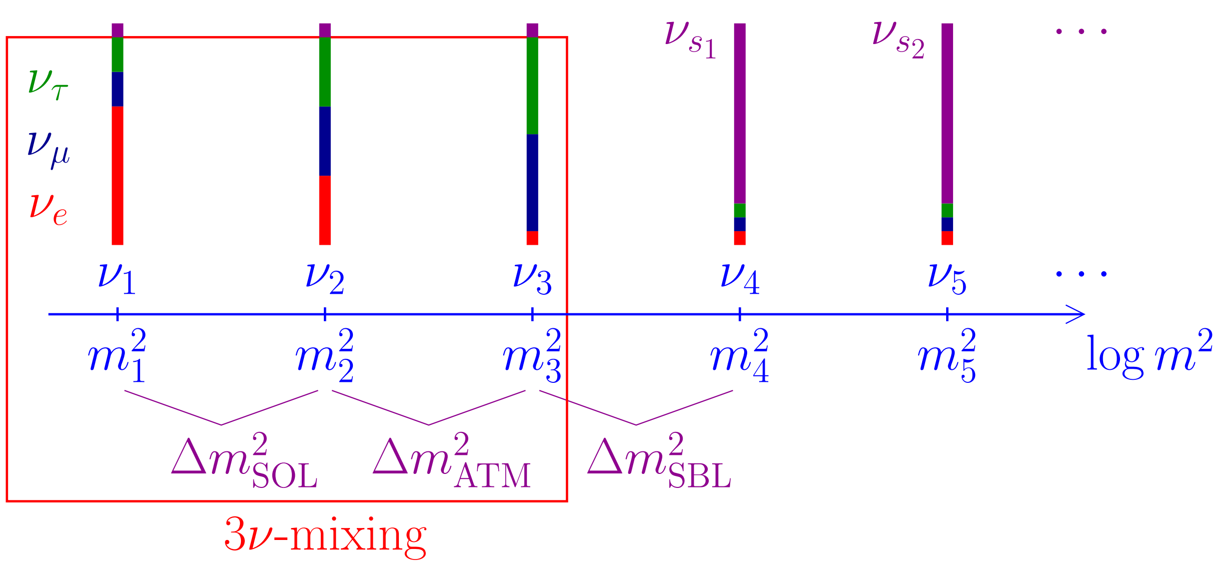


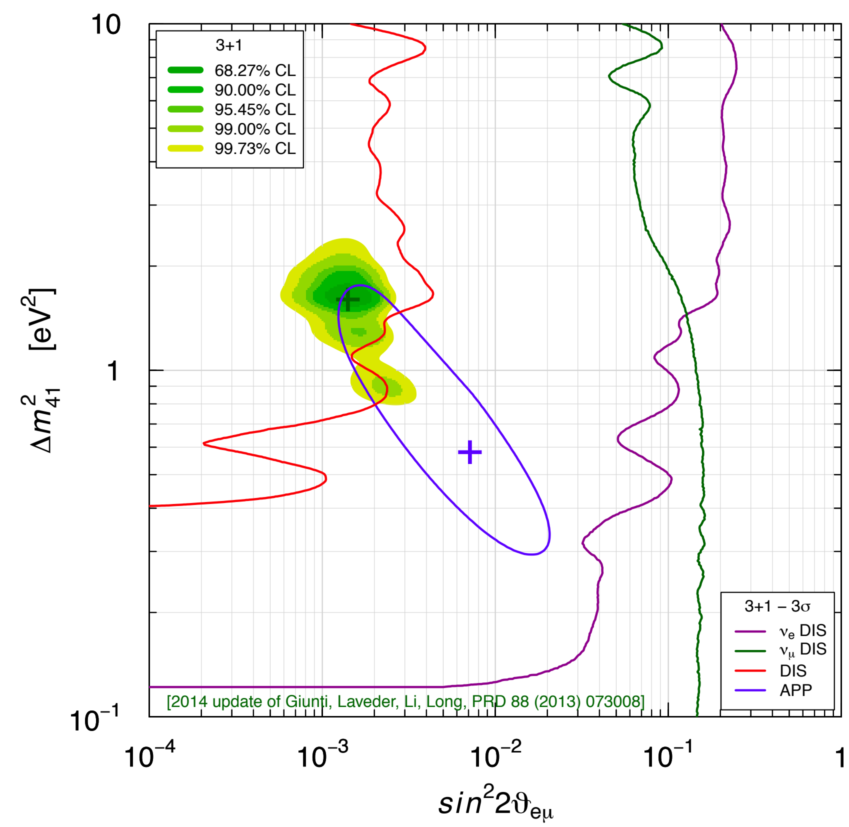
- Excess of events at low E (hard to describe with 3+1 fits)

Short Baseline Experiments

C. Giunti — Status of Light Sterile Neutrinos — EPS-HEP 2015 — 23 July 2015 — 4/15

- The goal of SBL experiments is to test the possible existence of a (new) mass square difference $\Delta m^2 \sim 1\ \mathrm{eV}^2$





Terminology: a eV-scale sterile neutrino
means: a eV-scale massive neutrino which is mainly sterile

GoF = 5%

PGoF = 0.1%

Physics behind the phenomenology: Discussed by PH in previous talk, see also talk by Dimitry Gourbanov

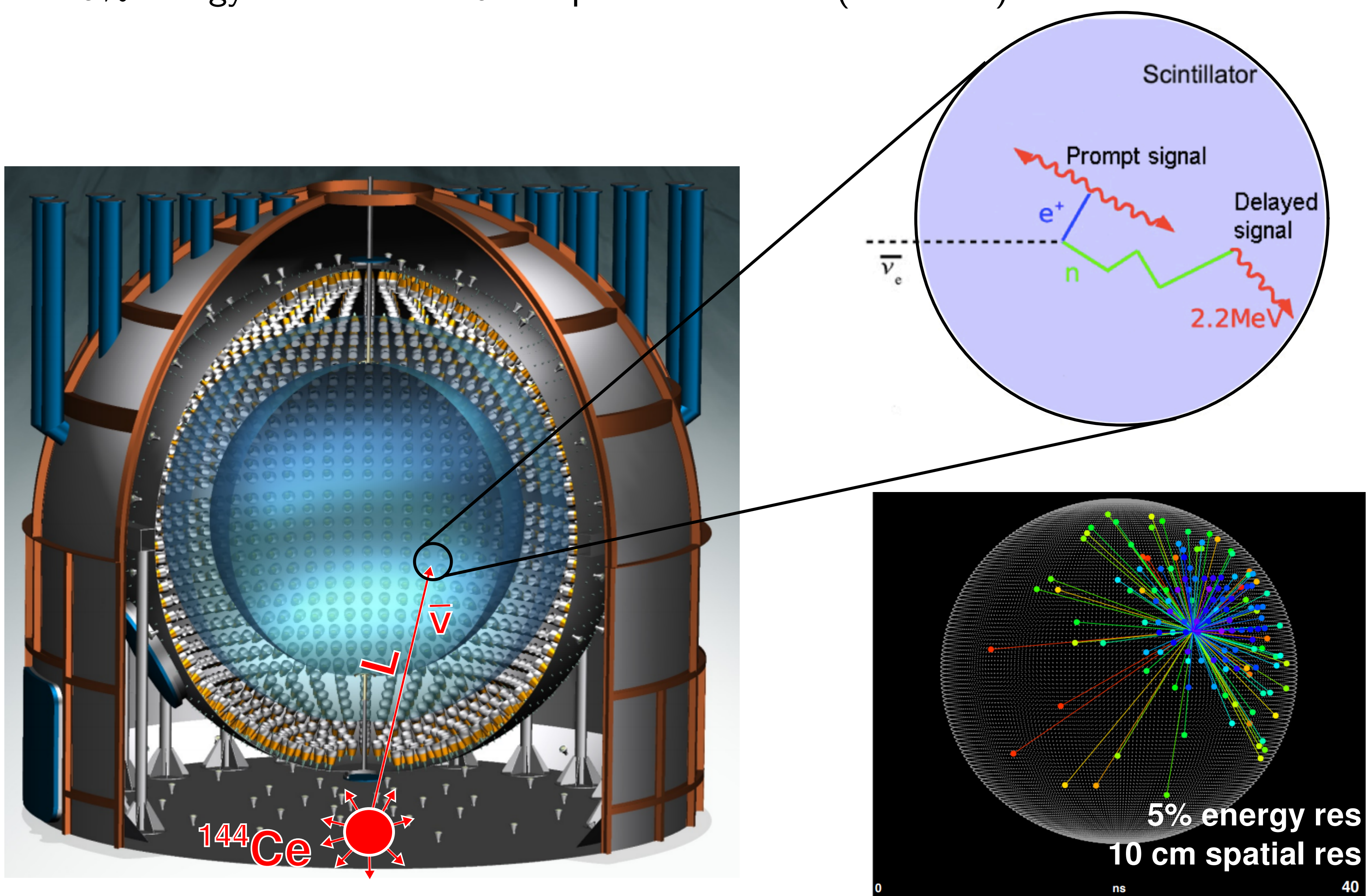
Experimental attack

- Test gallium anomaly with another, high precision, source + solar neutrino detector experiment (SOX)
- Test reactor anomaly with very short baseline experiments capable of measuring the oscillation in the detector itself (SOLID, STEREO)
- Test the MiniBooNE signal with another experiment using the same beam, capable of clarifying the low energy excess (MicroBooNE, ICARUS) —not covered in this talk
- Some existing experiments are also sensitive to 1 eV sterile neutrinos (MINOS, Nova, Opera, IceCube…) —not covered in this talk: se talk by Luca Stanco

Short distance Oscillations with BoreXino (SOX)

Detection concept

1) $\bar{\nu}_e$ interact via inverse beta decay:
   prompt e^+/e^- annihilation + delayed neutron absorption (2.2 MeV)
2) scintillation photons detected by PMTs (energy and time-of-flight)
   5% energy resolution – 10 cm spatial resolution (at 1 MeV)

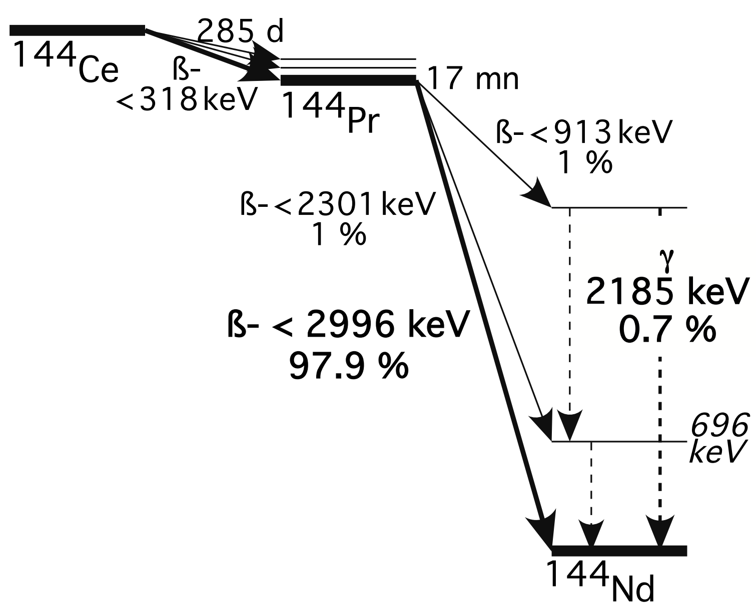


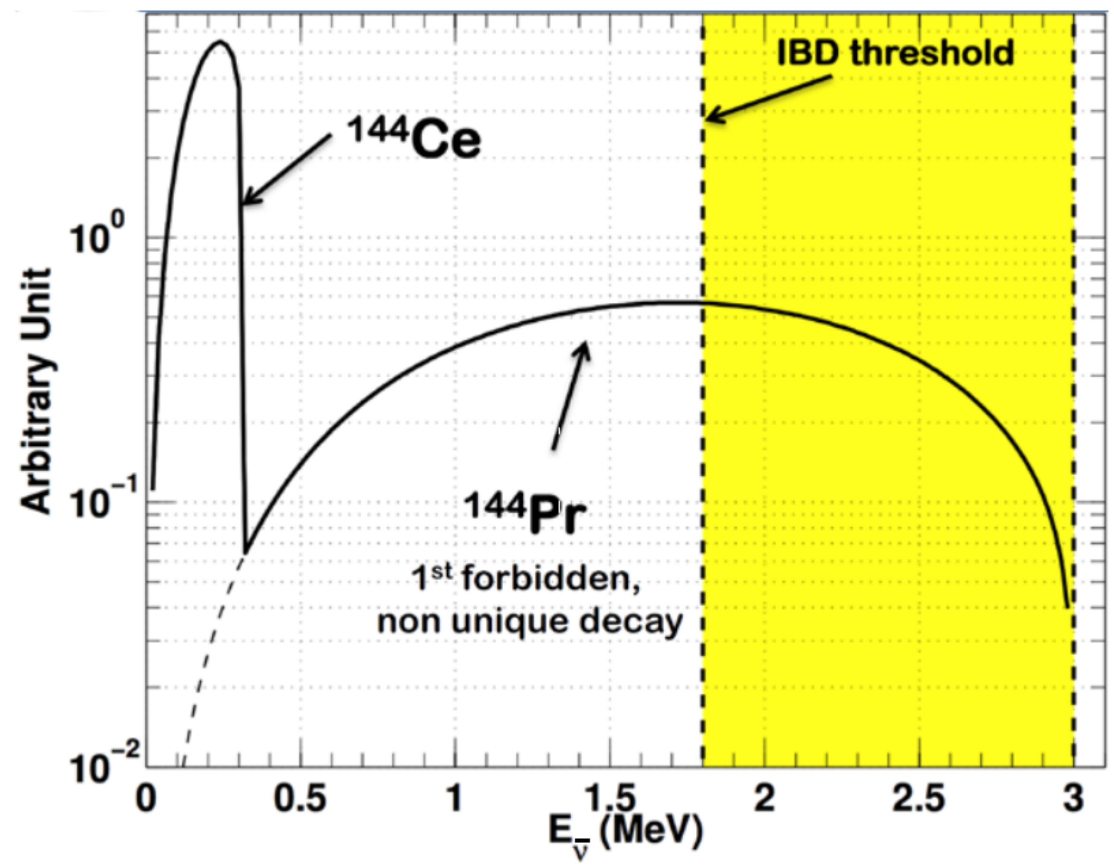
^{144}Ce source – emitted flux

- 100–150 kCi activity **($> 10^{15}\ \bar{\nu}_e$/s)**
- β^- decay chain:

$$^{144}\text{Ce} \rightarrow {}^{144}\text{Pr} + e^- + \bar{\nu}_e$$
$$\searrow {}^{144}\text{Nd} + e^- + \bar{\nu}_e$$

- $T_{1/2}(^{144}\text{Ce}) = 285\,\text{d}$
- $T_{1/2}(^{144}\text{Pr}) = 17\,\text{m}$

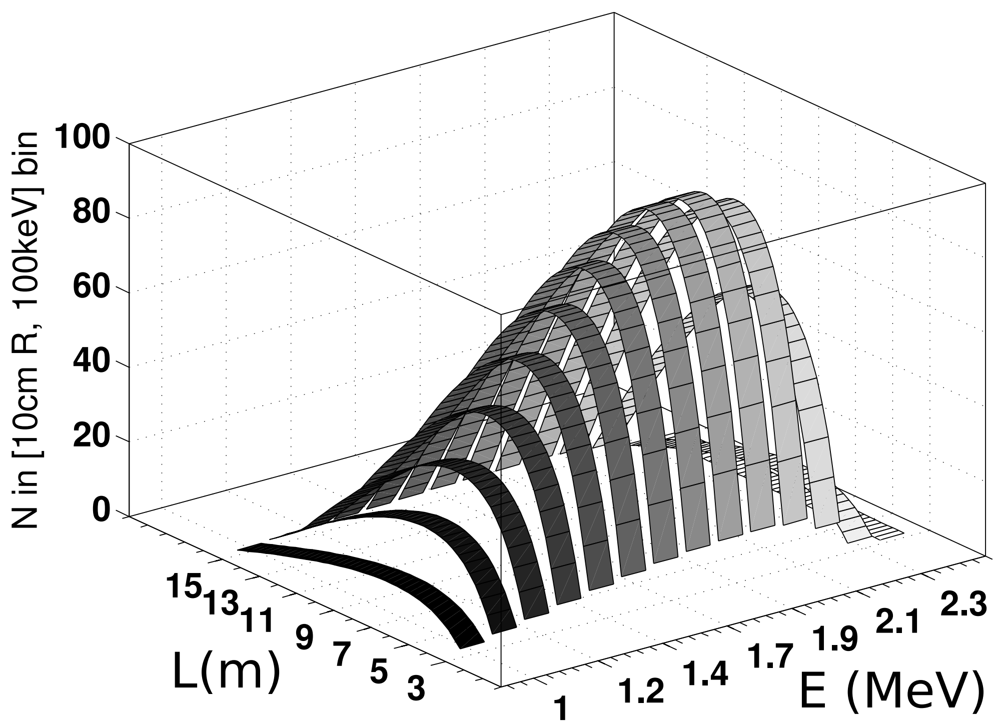




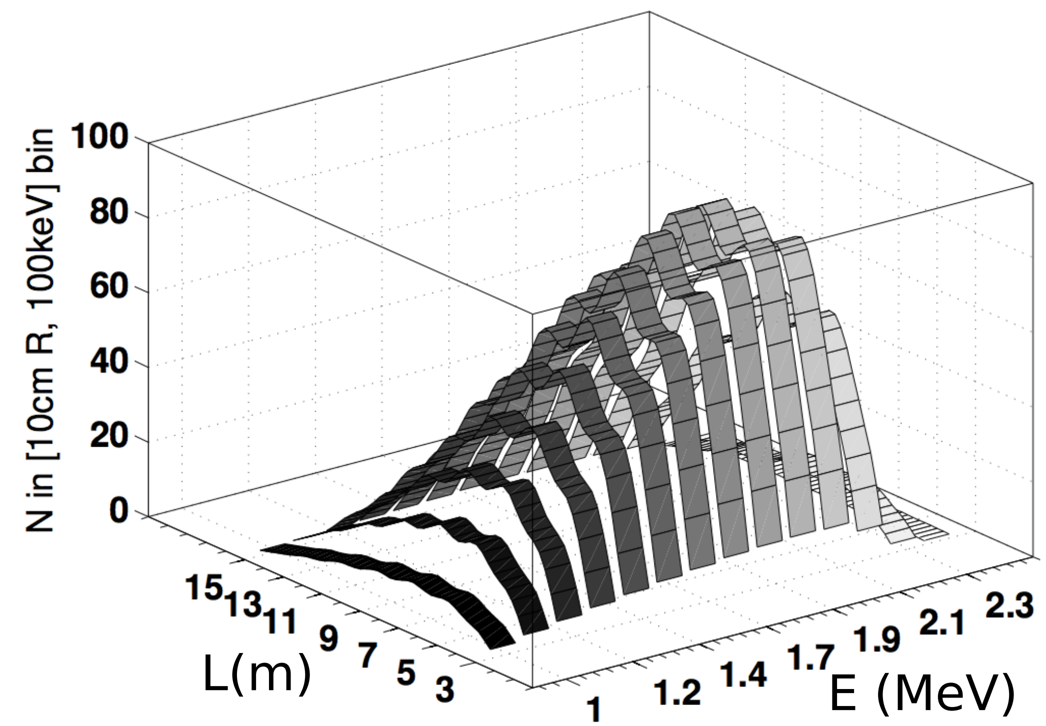
- Q-value(^{144}Ce) = 0.3 MeV
- Q-value(^{144}Pr) = 3 MeV
- detection via inverse beta decay

Sterile neutrino signature

No oscillations



Δm^2_{41}=2 eV^2 $\rightarrow$ oscillations within detector



[Cribier et al., PRL 107, 201801 (2011)]

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{ee}) \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

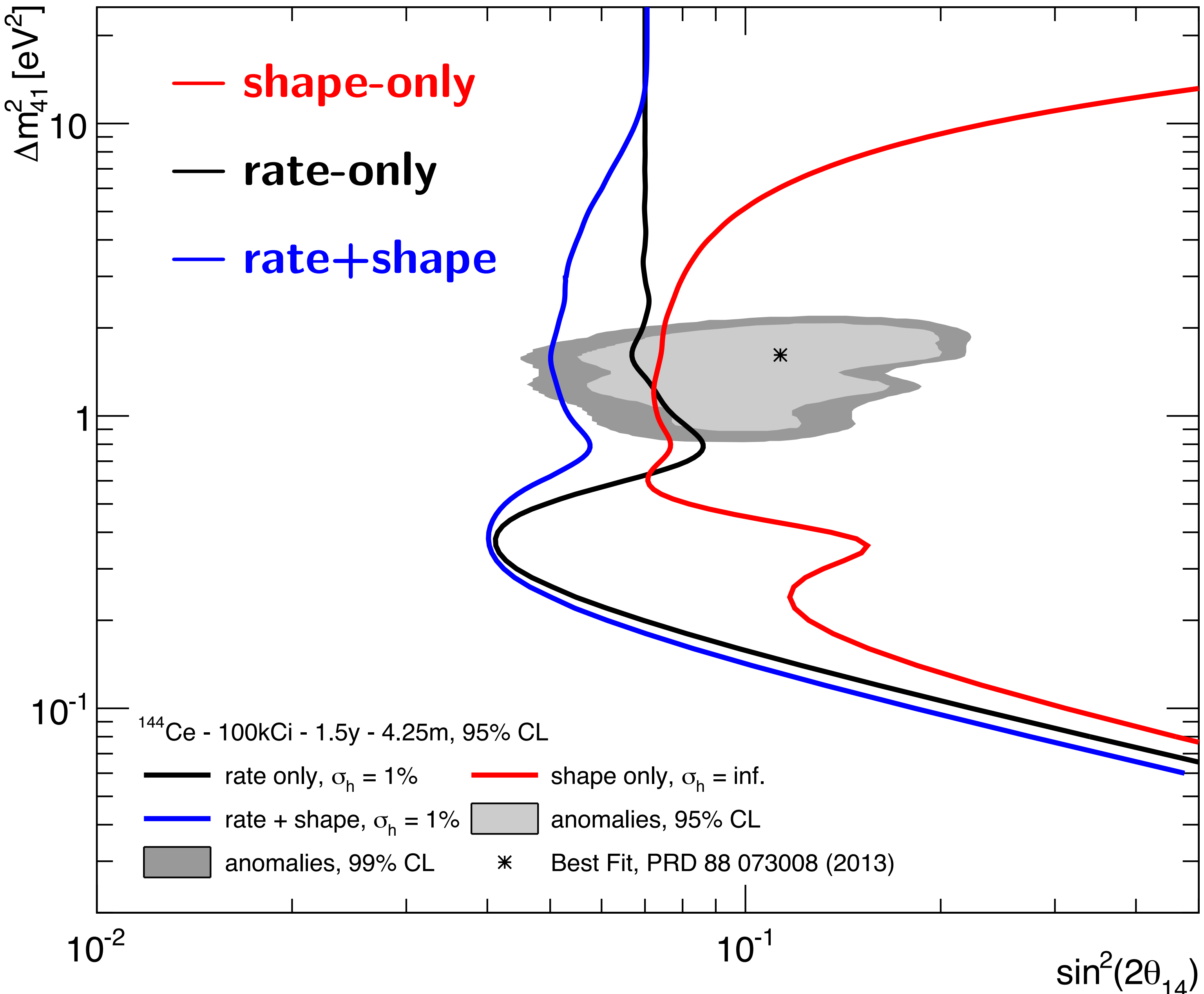
Rate analysis of $\bar{\nu}_e$ events:

- particularly sensitivity for Δm^2_{41} >eV^2
- needed accurate estimate of source activity

Shape analysis (oscillatory pattern):

- very robust for Δm^2_{41} $\sim$eV^2
- smoking gun signature

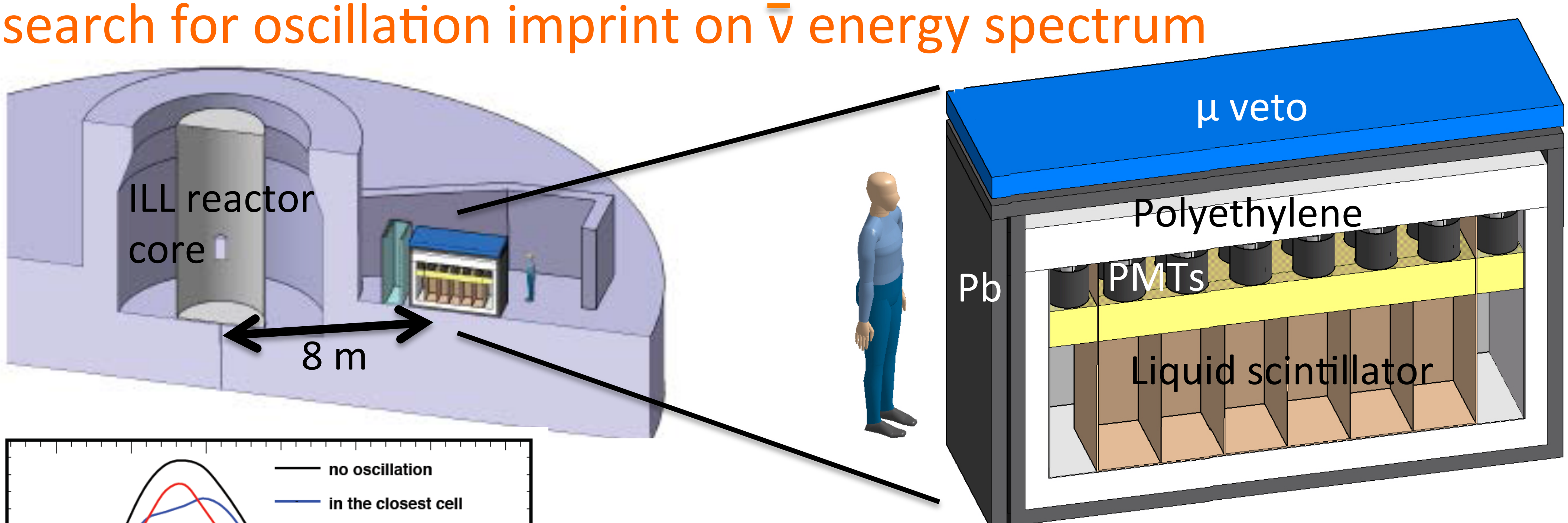
Analysis and sensitivity

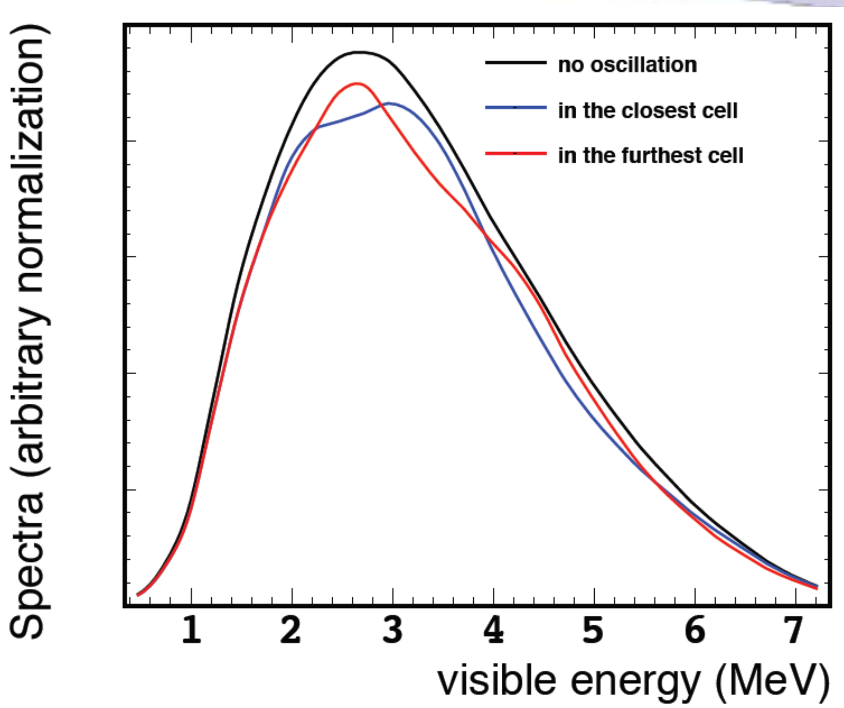


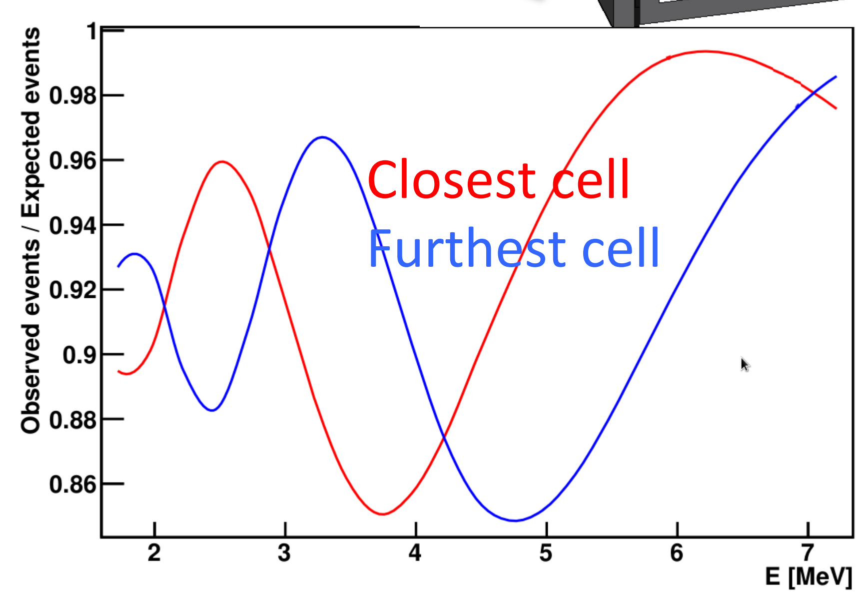
Data taking starts in late 2016

STEREO and SOLID

- Not just another flux measurement: in very short baselines, search for oscillation imprint on $\bar{\nu}$ energy spectrum







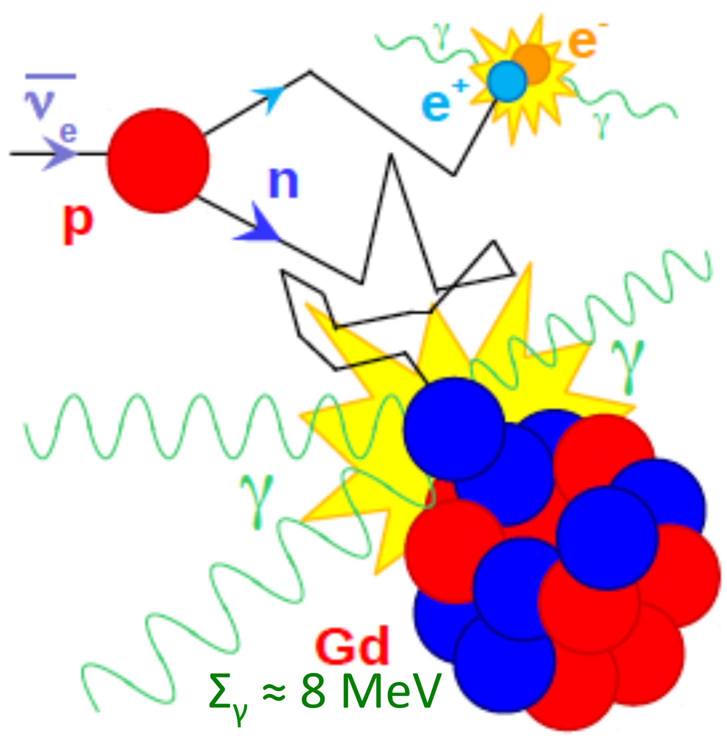
3

Detection concept (STEREO)

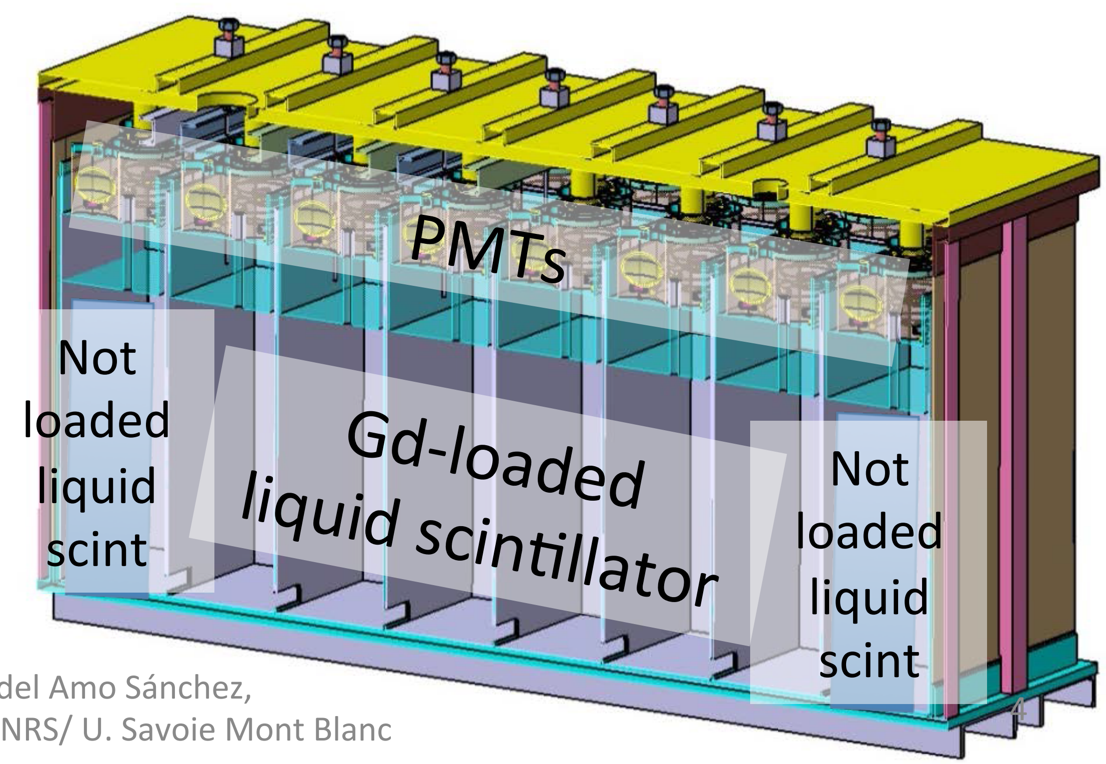
- ν detection via inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$
- Signature: prompt (e+ annihilation)

AND delayed (n capture on Gd) ~ 15 μs later

$$n + Gd \rightarrow Gd + \gamma s$$
$$e^+ + e^- \rightarrow \gamma\gamma$$

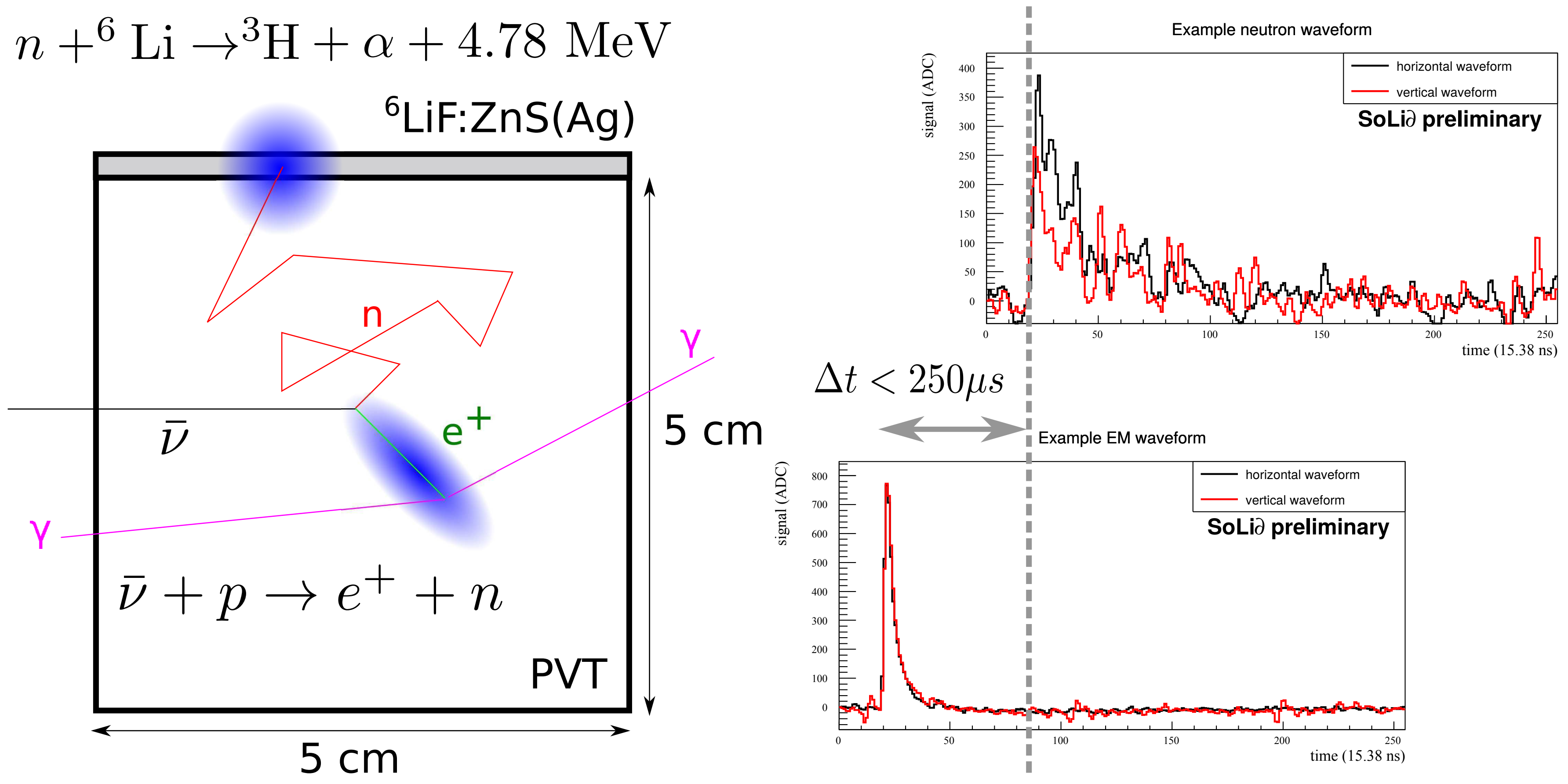


- Segmented detector (6 cells) ➔ L dependence
- 2m^3 Gd-loaded target surrounded by unloaded liquid scintillator to recover escaping γ's



- E(ν) ≈ E(prompt) + 0.78 MeV
- Good energy resolution!

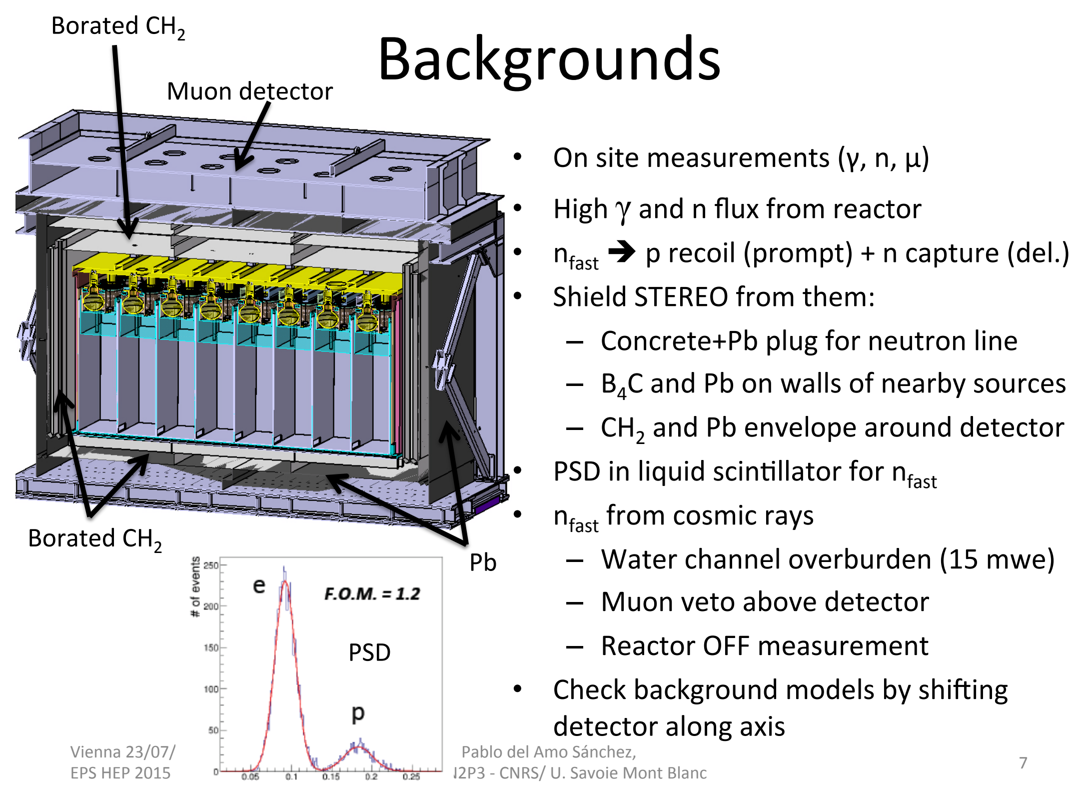
Detection concept (Solid)



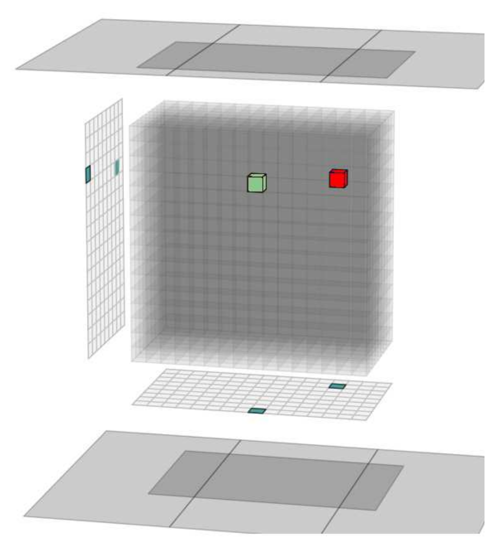
- Both scintillation signals captured in 3×3 mm square wavelength shifting optical fibres
- Scintillation signal detected by 3×3 mm silicon photomultipliers

Backgrounds

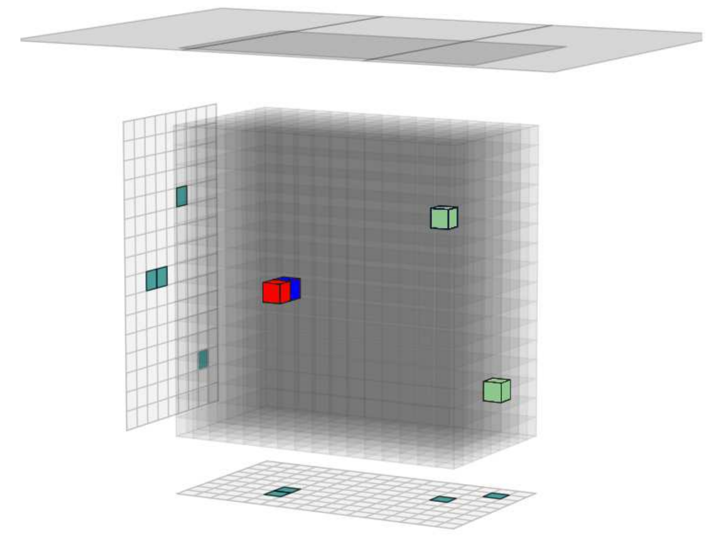
- Dominant backgrounds from neutrons and gammas produced in the reactor(s)
- STEREO approach relies on shielding and PSD
- SOLID approach relies on background characterisation using detector segmentation
- Two different reactors: different backgrounds, systematics. Good!



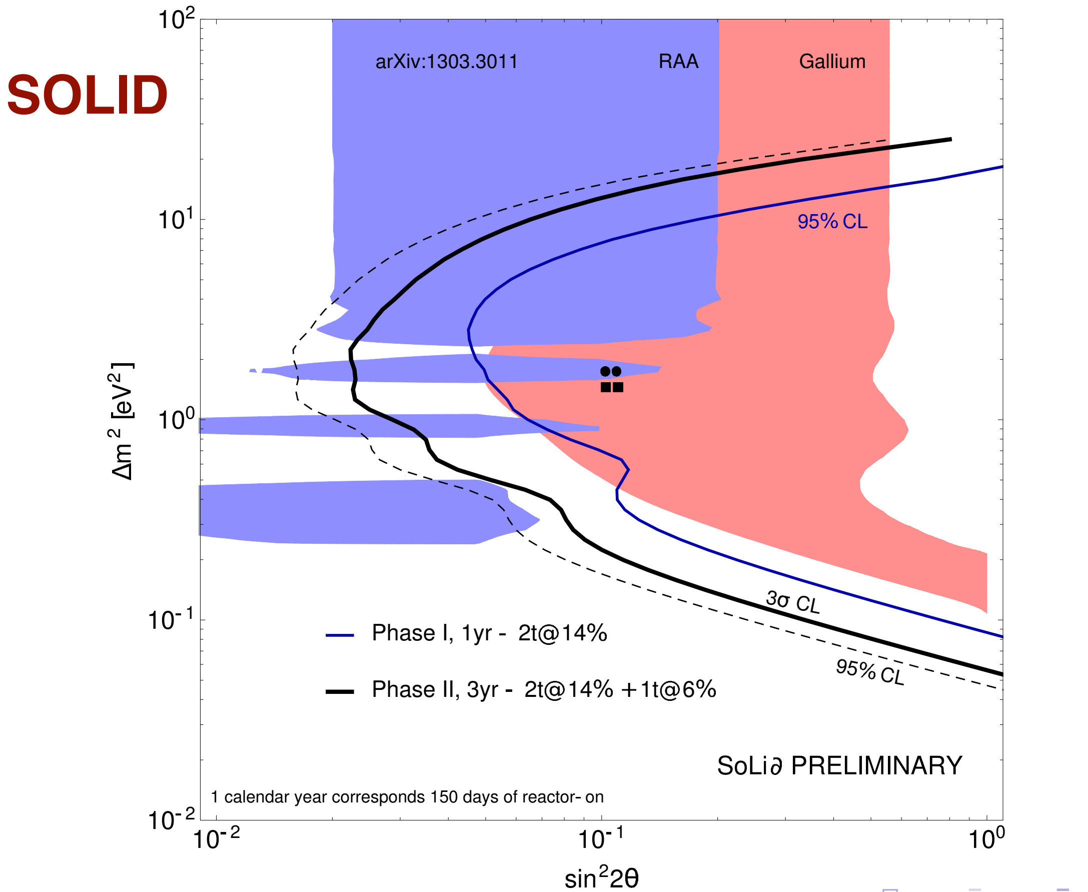
Neutron + gamma

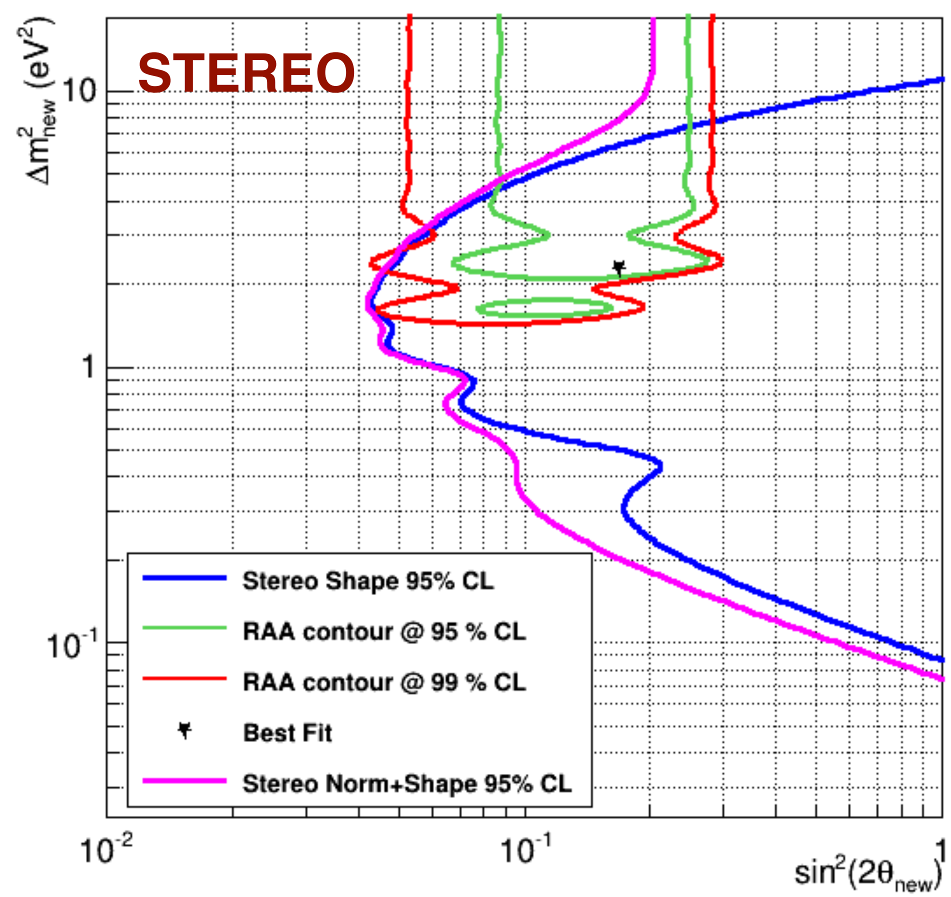


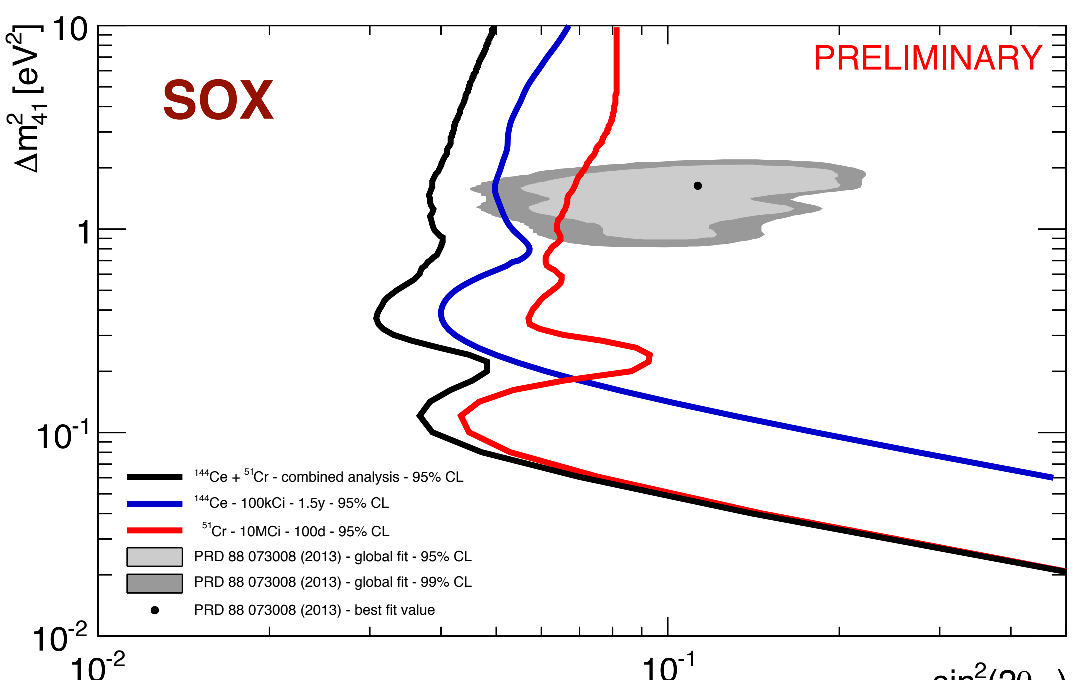
IBD candidate: positron + neutron
(+ accidental gammas)



Sensitivity to 3+1 neutrino oscillations



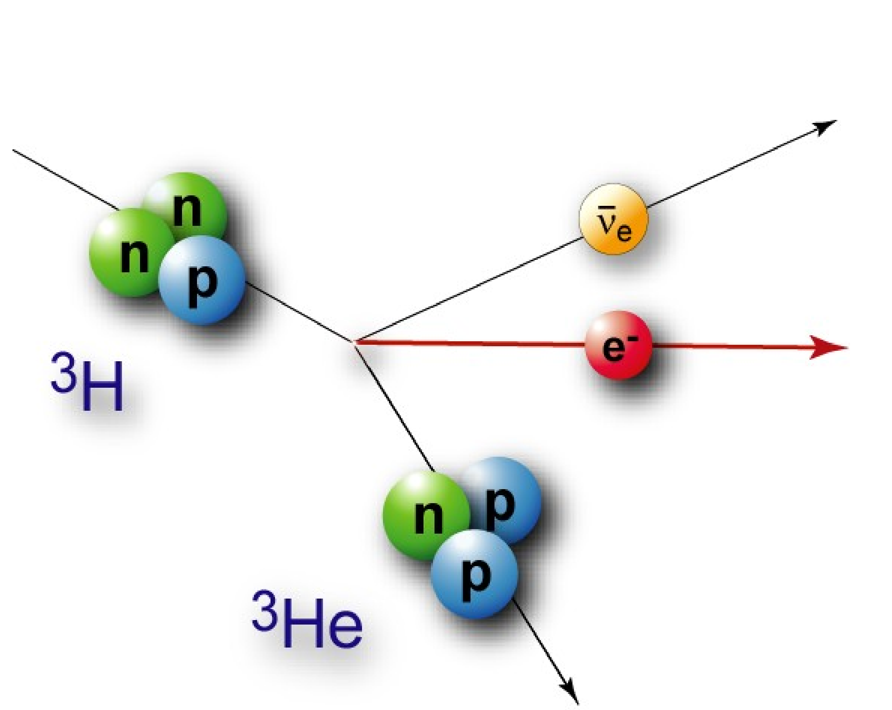




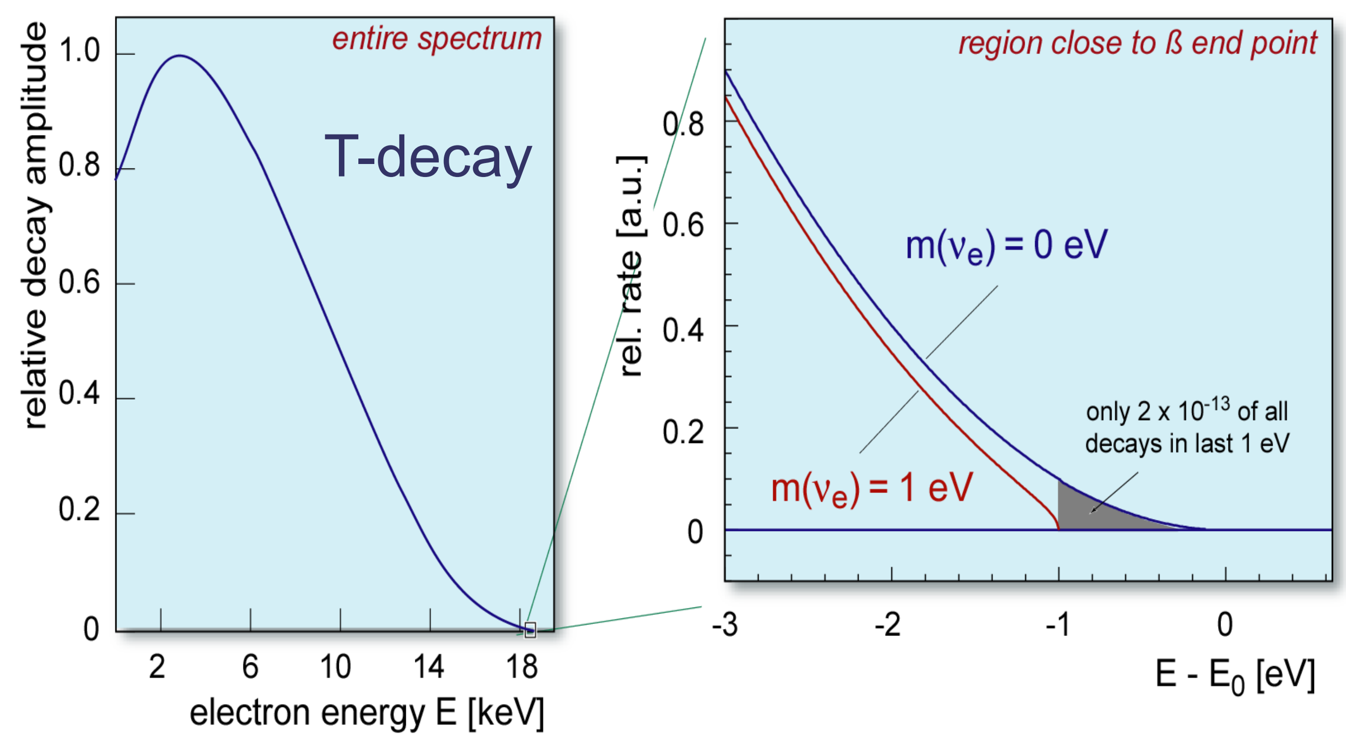
- High discovery potential! The elusive sterile neutrino could very well be catch in the next few years!

β-decay experiments

End-point of β decay



- **The presence of a massive neutrino affects the shape of the electron energy distribution (very) near the end point.**
- **Measurement is “model independent”.**
- **One measures $m_{\nu e}$ (an incoherent sum of mass eigenstates)**

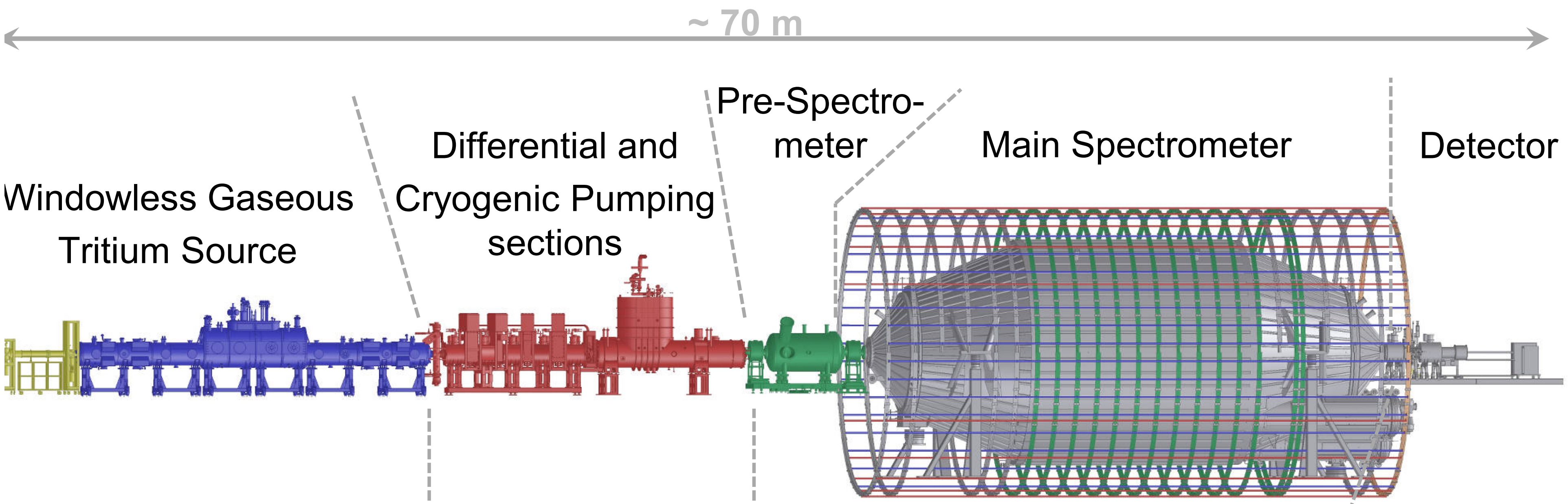


KATRIN

KATRIN experiment

KIT Karlsruhe Institute of Technology

- **KA**rlsruhe **TRI**tium **N**eutrino experiment
- goal: measure neutrino mass with a sensitivity of 200 meV



Windowless Gaseous Tritium Source
- tritium β-decay
- decay rate: 10^{11} 1/s
- T_2 pressure: 10^{-3} to 10^{-6} mbar

Differential and Cryogenic Pumping sections
- β-electron transport
- tritium retention (factor > 10^{12})

Main Spectrometer
- energy analysis of β-electrons
- resolution 0.93 eV @ 18.6 keV
- pressure < 10^{-10} mbar

Detector
- counting of trans-mitted β-electrons

Status

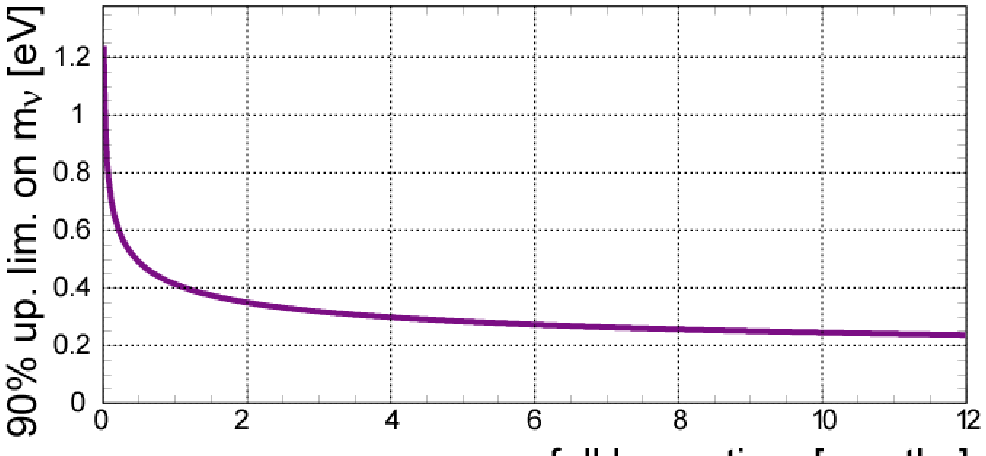
status:

- Main spectrometer commissioning measurements ongoing (focus on backgrounds)

outlook:

- All components placed along the beamline by the end of this year
- Commissioning of beamline in 2016
- First tritium runs end of 2016

Upper limit on $\mathbf{m}_\nu$

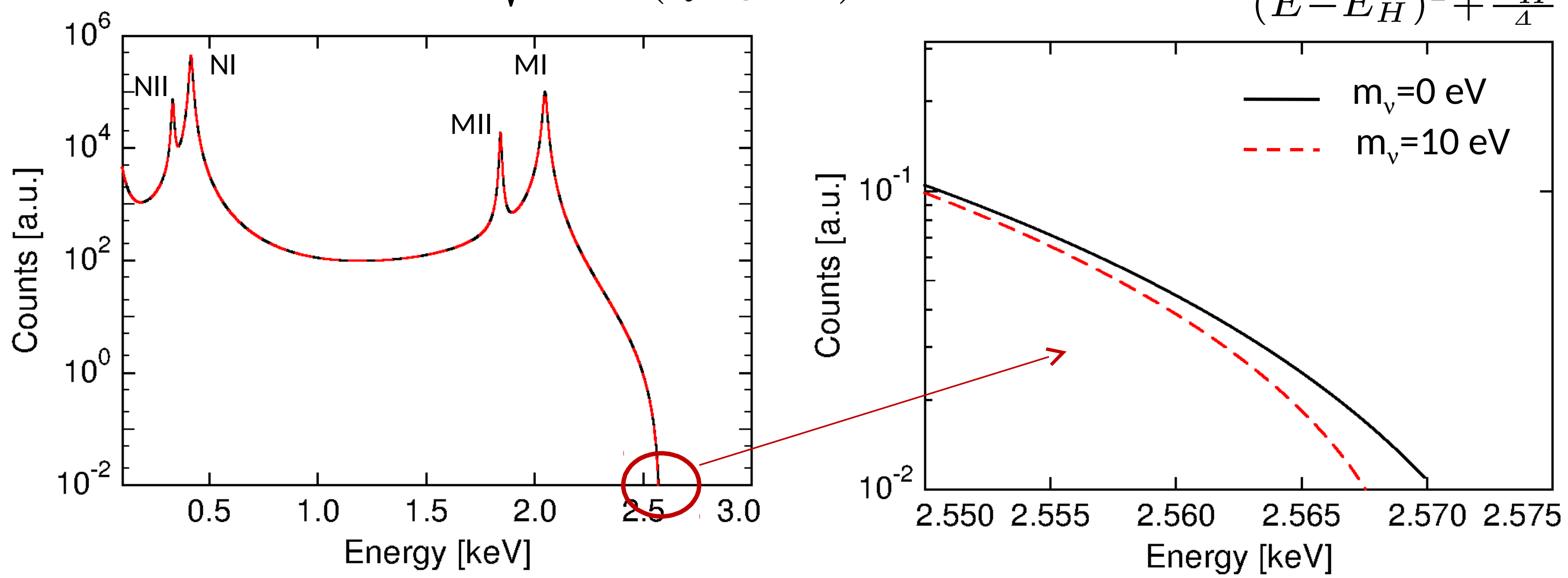


Electron capture and ν mass

$$ {}^{A}_{Z}X + e^{-} \rightarrow {}^{A}_{Z-1} Y^{\star} + \nu $$

The excited atomic shell of daughter nucleus deexcites via X-rays, Auger electrons and/or Coster–Kronig transitions. The energy release can be measured calorimetrically.

$$ \frac{dN}{dE} = A\,(Q_{EC} - E)^2 \sqrt{1 - \frac{m_\nu^2}{(Q_{EC}-E)^2}} \sum_H B_H \phi_H^2(0) \frac{\frac{\Gamma_H}{2\pi}}{(E-E_H)^2 + \frac{\Gamma_H^2}{4}} $$



$$ {}^{163}_{63}Ho + e^{-}(M,N,O) \rightarrow {}^{163}_{62} Dy^{\star} + \nu $$

Halflife of $\tau_{1/2}$ = 4570 a, lowest known Q_{EC} of 2.555(16) keV

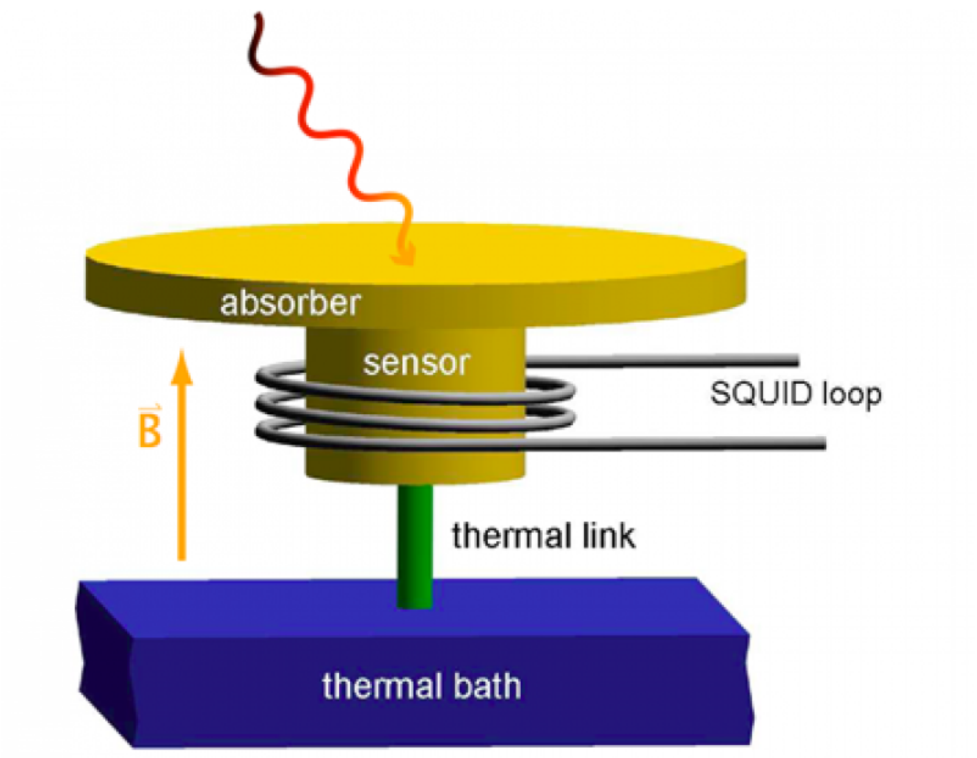
Principle of calorimetric measurement

Example:

Metallic Magnetic Calorimeter

$$\Delta T = \frac{\Delta E}{C}$$

$$\Delta \Phi \propto \frac{\partial M}{\partial T} \Delta T$$



fast coupling phonon–spin

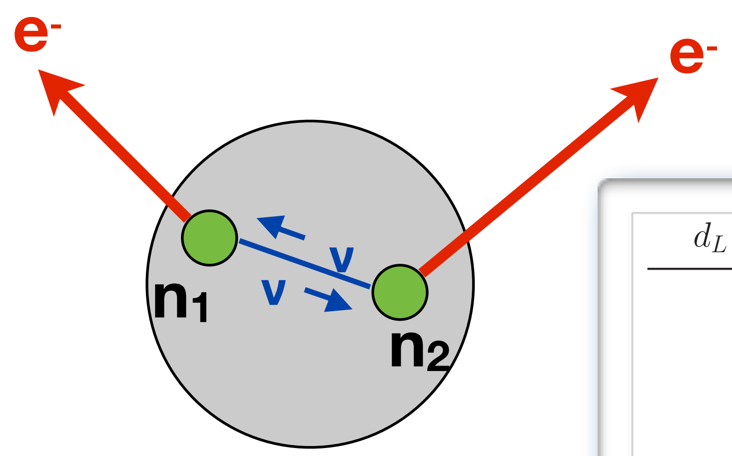
Direct SQUID readout of the change in magnetic flux

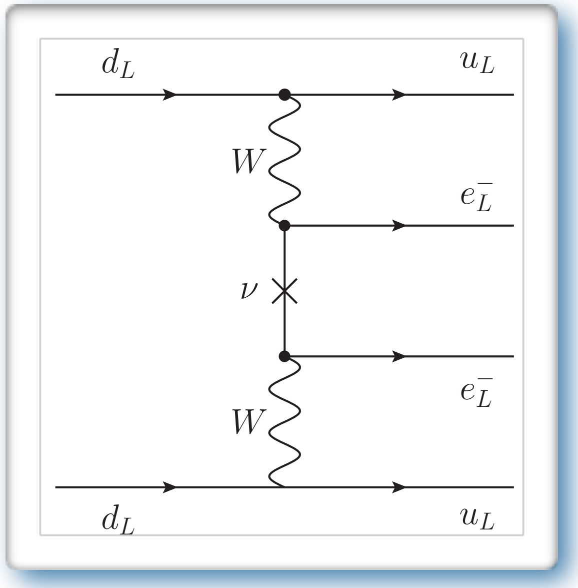
Sensitivity ~10 eV.

ββ0ν-experiments

Neutrinoless double beta decay

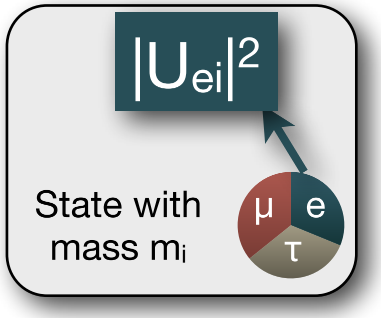
ββ0ν

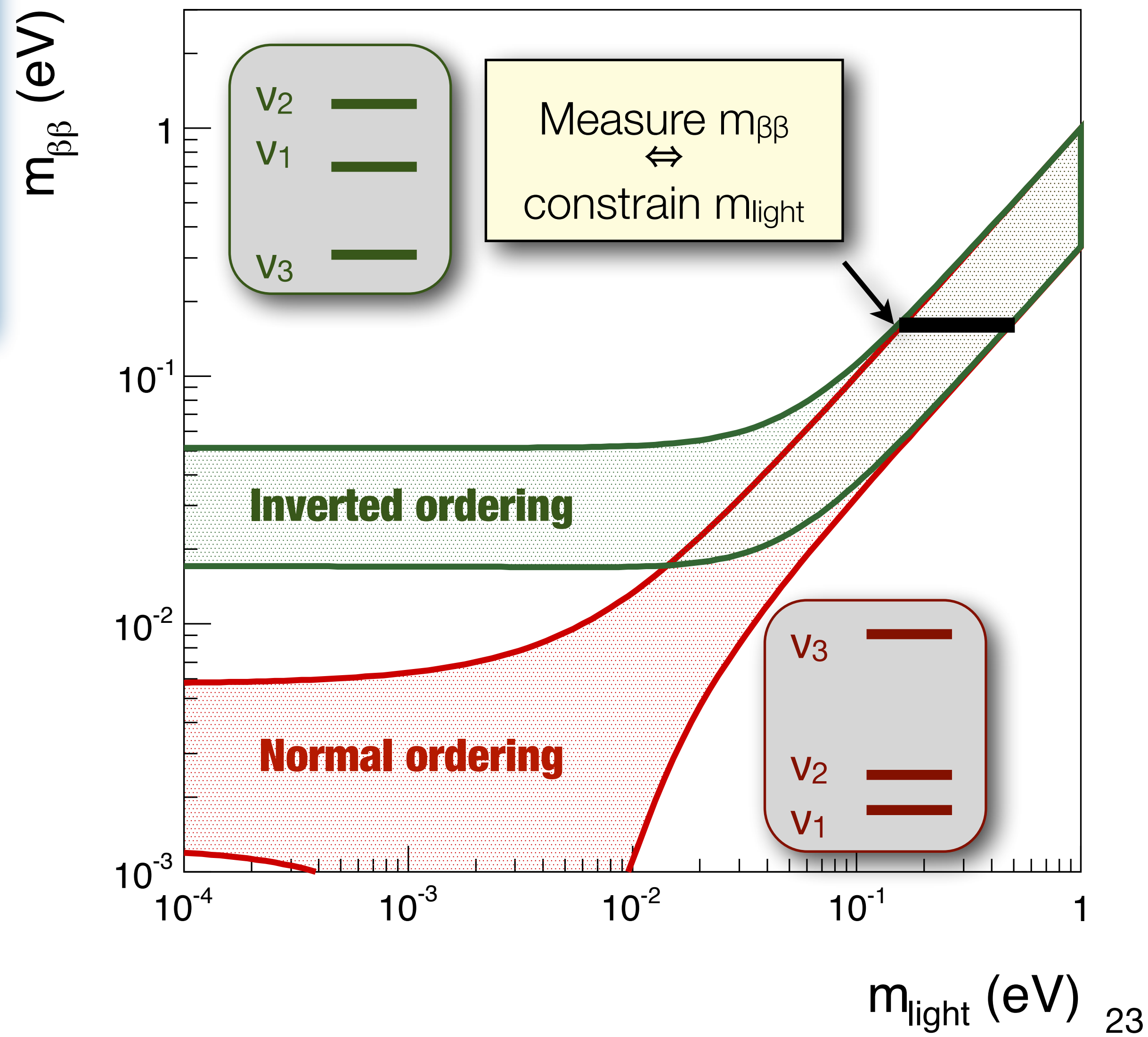




$(\mathrm{Rate})_{\beta\beta0\nu} \propto m_{\beta\beta}^2$

Majorana ν mass:
$m_{\beta\beta} \equiv \left| \sum_i m_i U_{ei}^2 \right|$

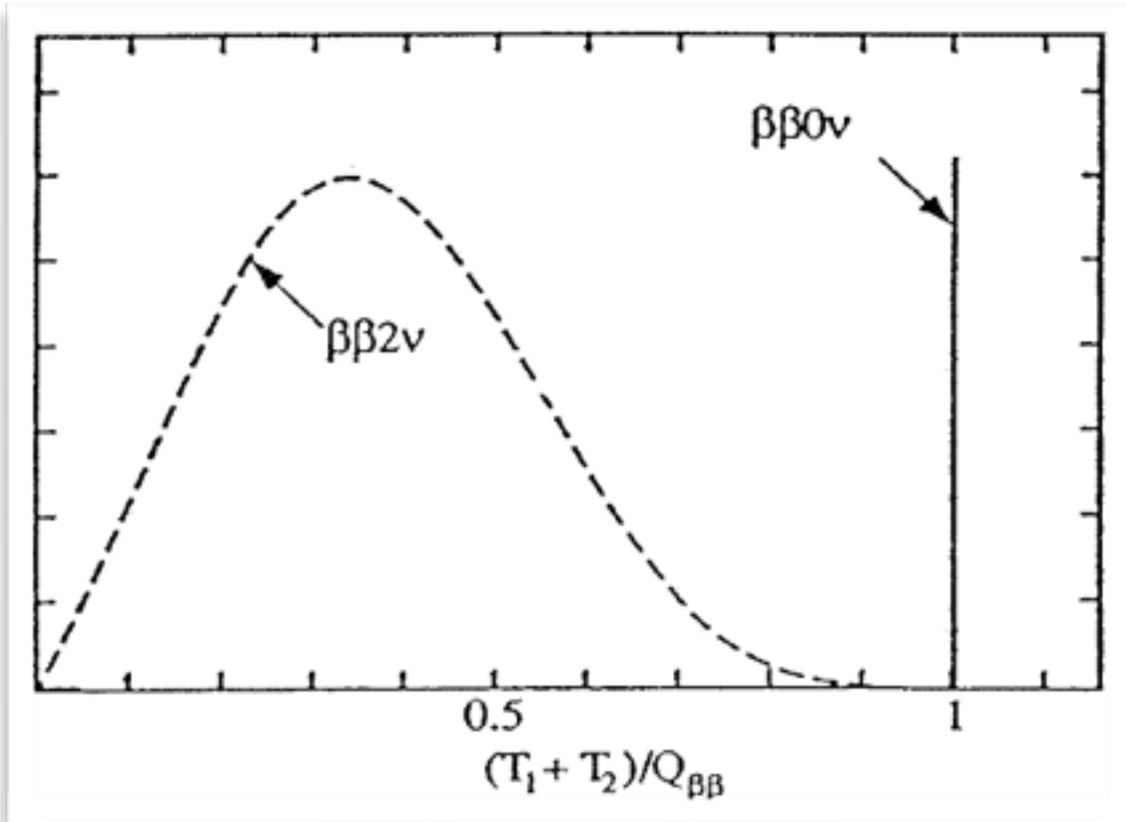




Neutrinoless mode

- Requires Majorana neutrinos
- Not observed yet in Nature
- $>10^{25}$ yr half-lives
- Would signal Beyond-SM physics

Measuring ββ0ν in an ideal experiment



- Get yourself a detector with perfect energy resolution
- Measure the energy of the emitted electrons and select those with (T1+T2)/Q = 1
- Count the number of events and calculate the corresponding half-life.

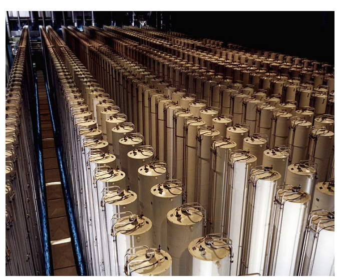
$$N_{0\nu} = \frac{a \cdot N_A}{m_A} \frac{\log 2}{T^{0\nu}_{1/2}} \epsilon \cdot M \cdot t$$

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ m^2_{\beta\beta}$$

Recipe for a ββ0ν experiment

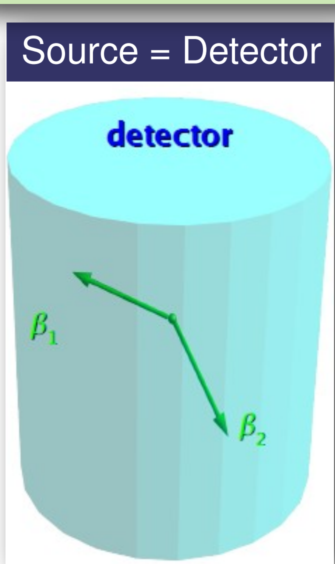
$$T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}}$$

Isotope



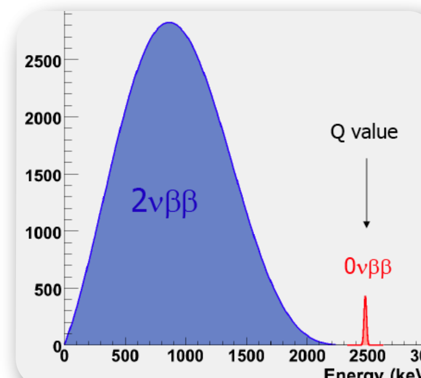
Find an isotope with large Q, no long lived radioactive isotopes, easy to procure and cheap.

Scalability



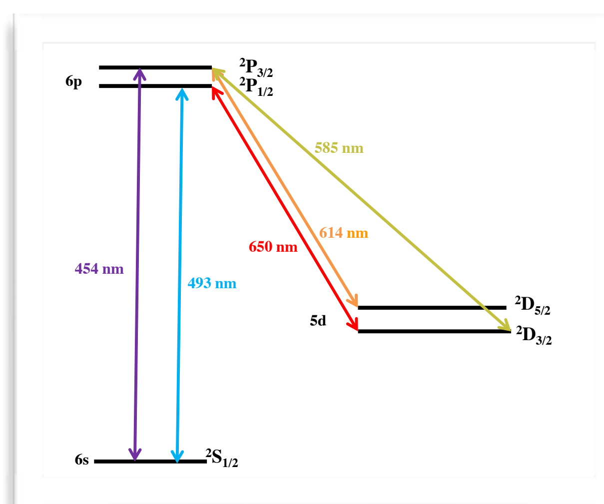
Build a detector with no dead areas, and economy of scale

ΔE



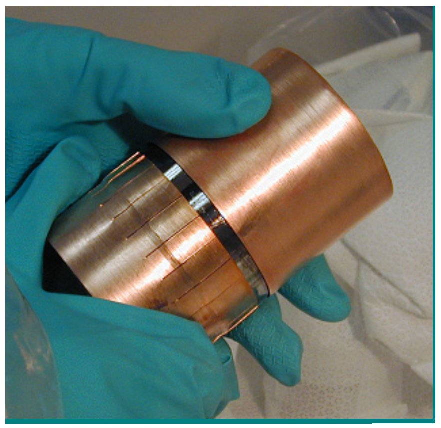
Build a detector with the best possible resolution

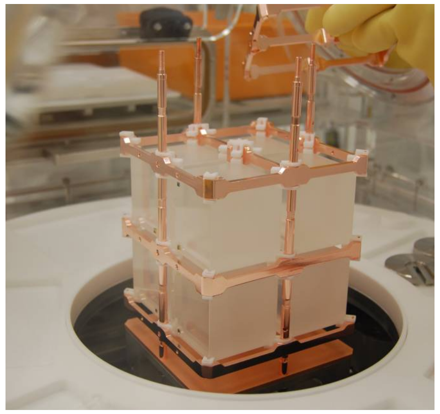
Background

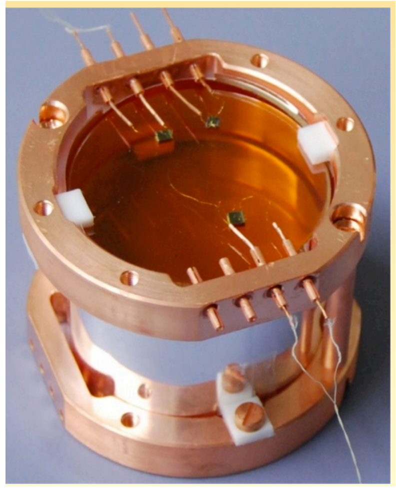


Detector provides extra handles to reduce background

Approaches: Calorimeters

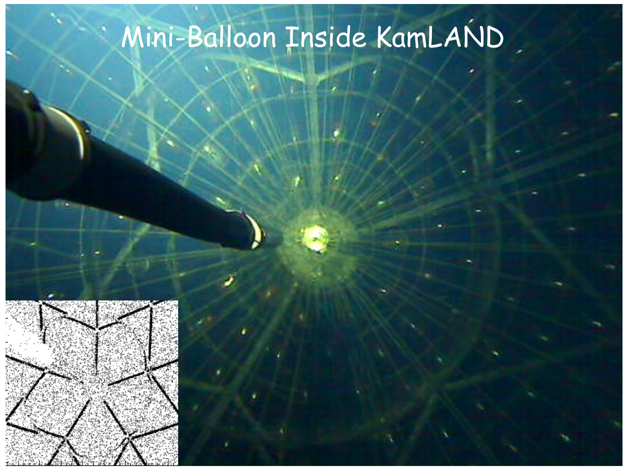


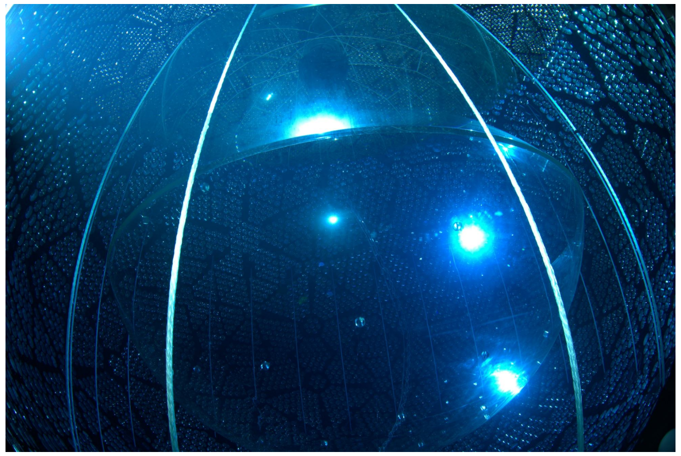




High resolution calorimeters

GERDA (GE-76) **CUORE (TeO2)** **LUCIFER/MINEUX (ZnSE82)**

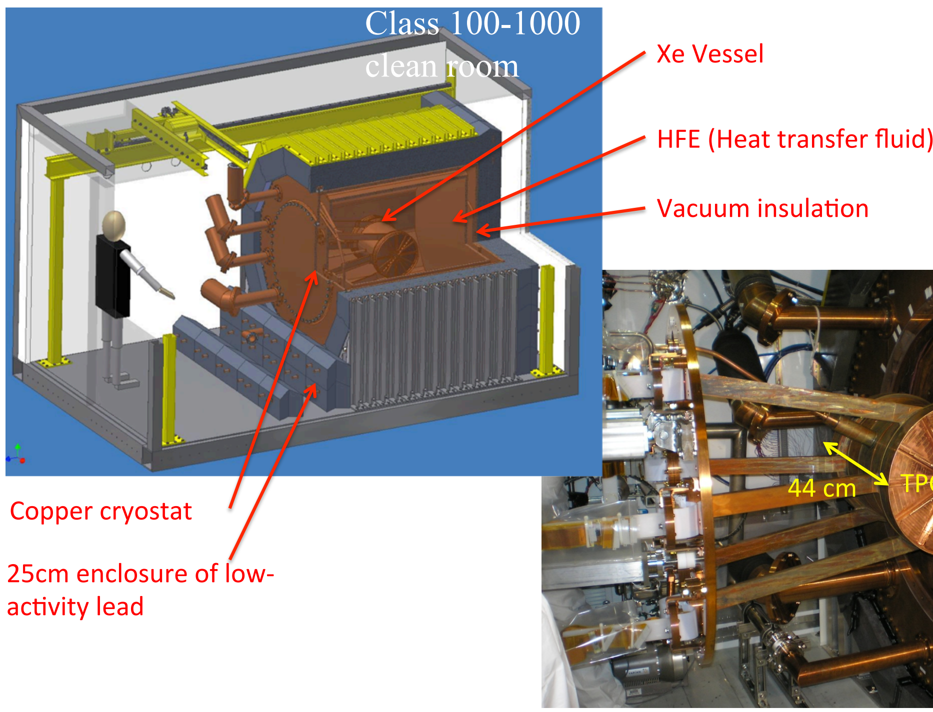




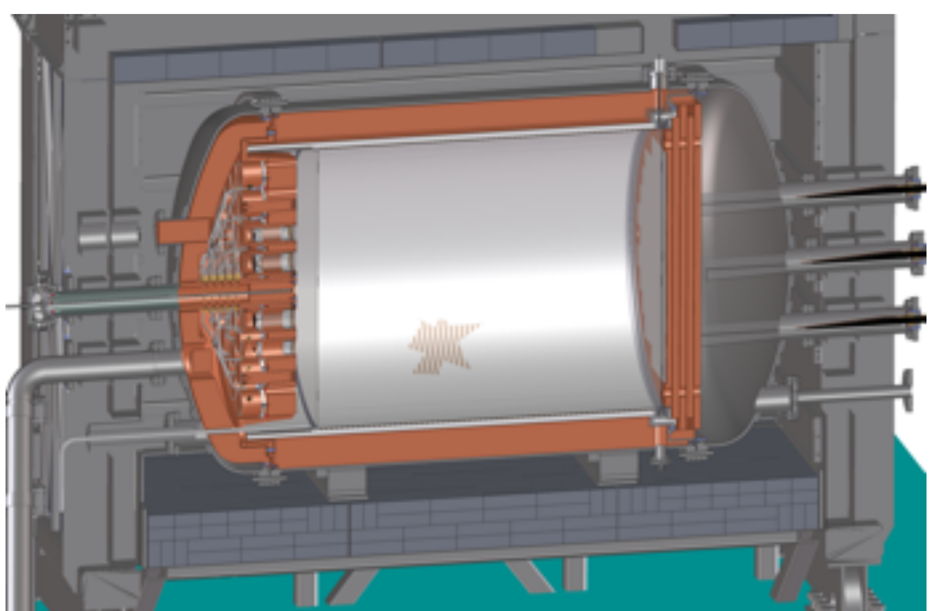
Large calorimeters

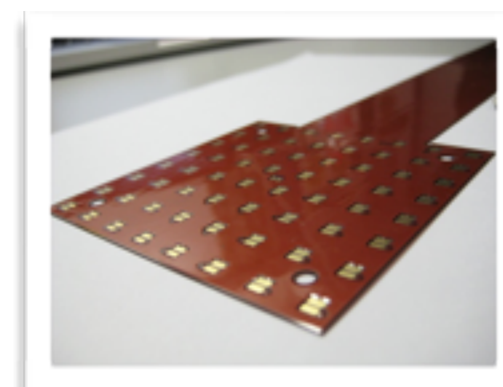
KamLAND-ZEN (Xe-136+LS) **SNO+ (Te + LS)**

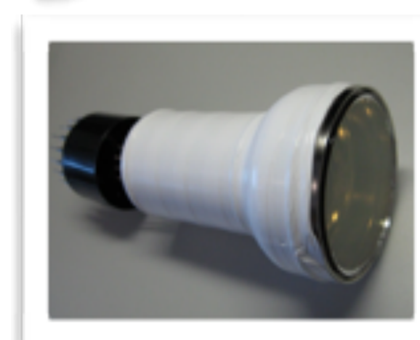
Approaches: Xenon TPCs



EXO
(Xe-136) LXe

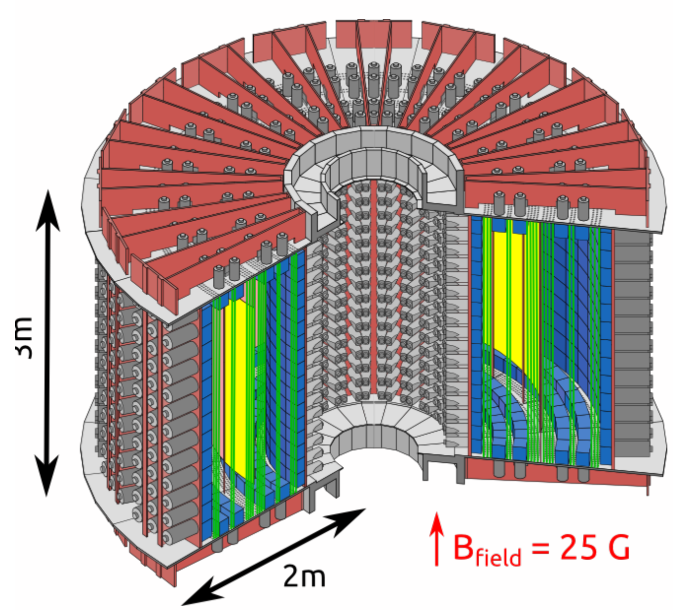




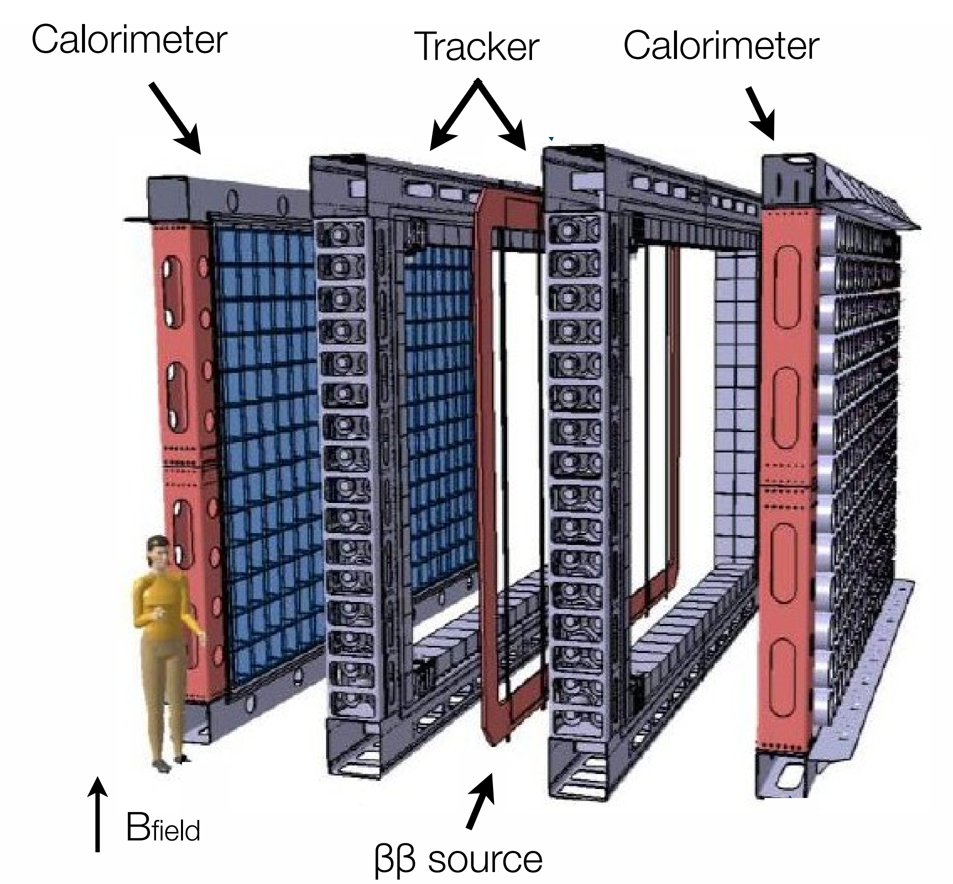


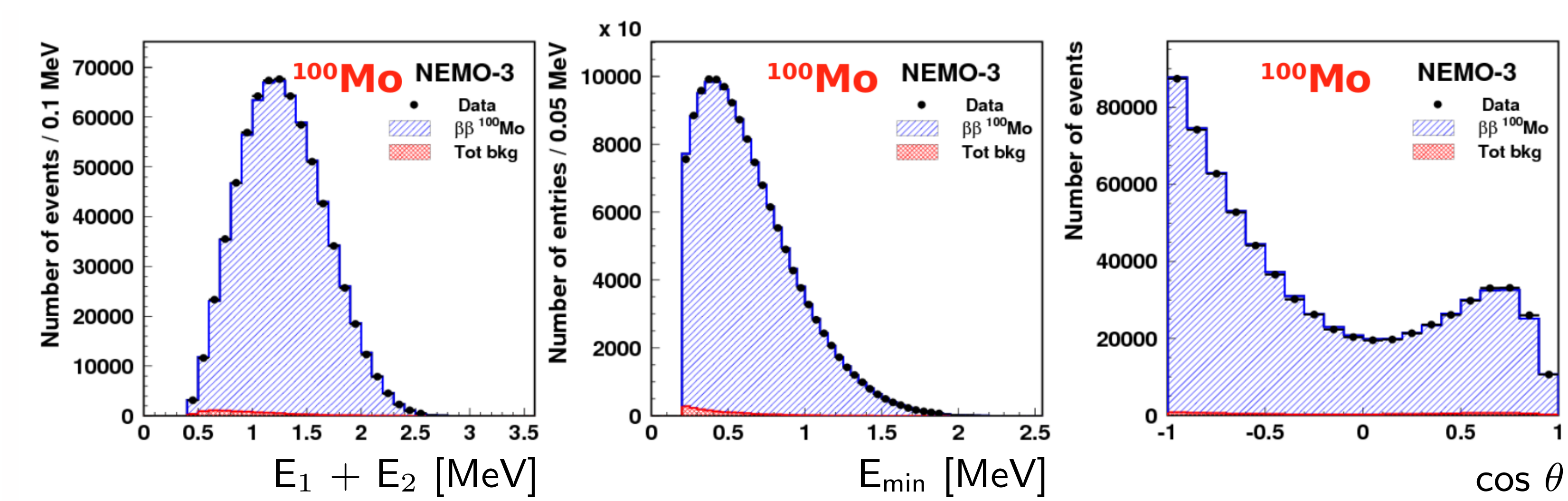
NEXT (Xe-136) HPXe

Approaches: Traco-Calo



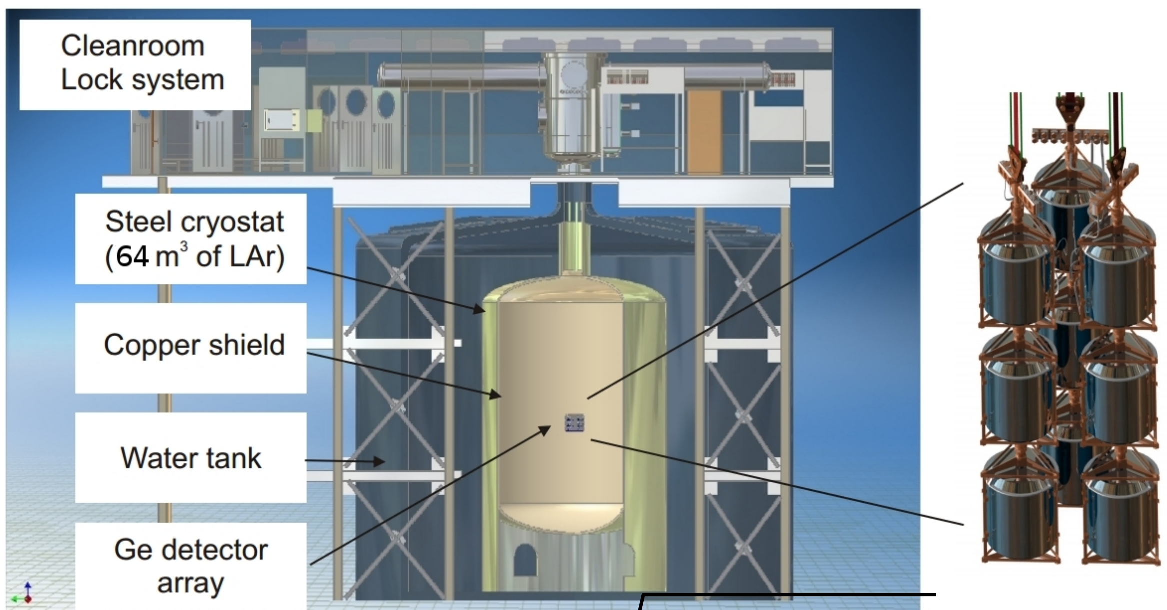
- ββ decay experiment combining tracker and calorimetric measurement
- Allows reconstruction of the final state topology and particle identification
- Located in the Modane underground laboratory (LSM) in the Frejus tunnel at ~4800 m.w.e.
- Measured 10 kg of different ββ isotopes
- Taking data from February 2003 to January 2011





GERDA

- bare Ge detectors in liquid Argon (LAr)
- shield: high-purity LAr/H_2O
- radio-pure material selection
- deep underground (LNGS, 3800 m.w.e.)



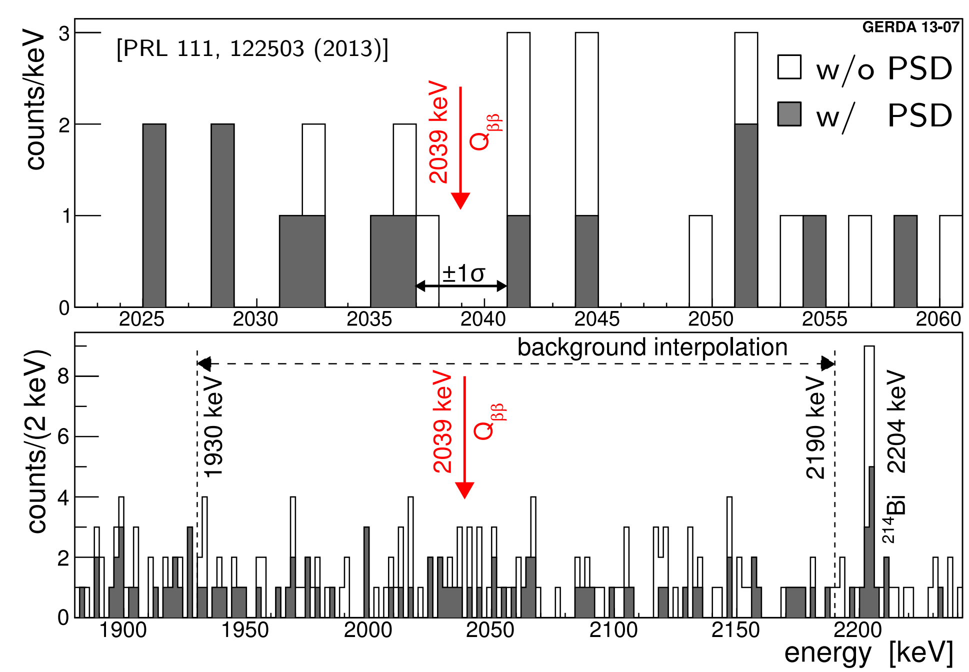
[EPJ C 73 (2013) 2330]

$$T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}}$$

Very mature technique, long operational experience: all parameters demonstrated

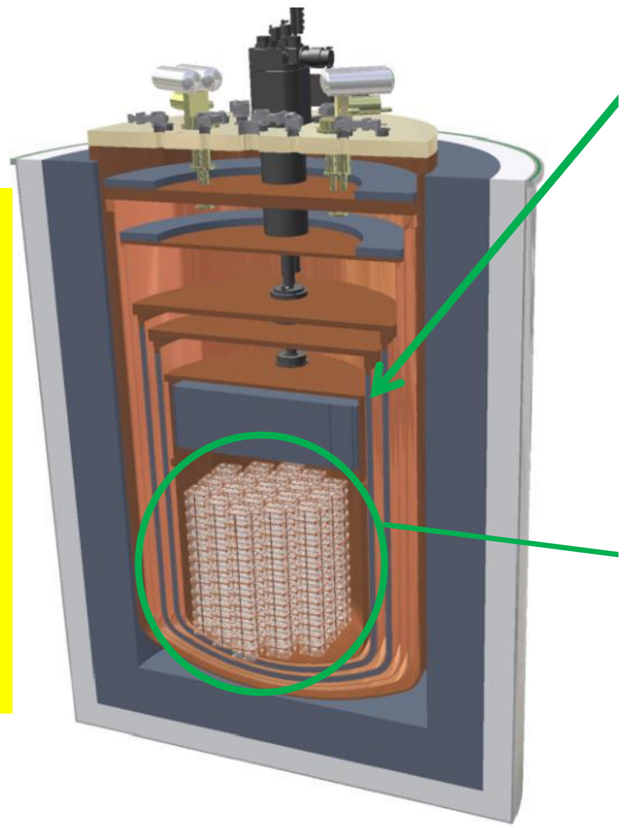
- $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.)

- **a**: expensive
- ε: > 80 %
- **Mt:** no economy of scale
- ΔE Excellent (0.2 % FWHM)
- **b** 10^{-2} (I) - 10^{-3} (II) ckky)



CUORE

988 crystals arranged in 19 towers
741 kg total mass
206 kg of ^{130}Te



- **a**: Uses natural Te
- ε: > 80 %
- **Mt:** Large mass
- ΔE Excellent (0.2 % FWHM)
- **b** (5.8 x10^{-2} ckky (CUORE-0 in ROI

$$T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}}$$

Technique and background well understood thanks to CUORICINO and CUORE0

Background index in ROI: 0.058 ± 0.004(stat.) ± 0.002(syst.) c/keV/kg/y

CUORE-0 90% C.L. lower limit from profile likelihood:

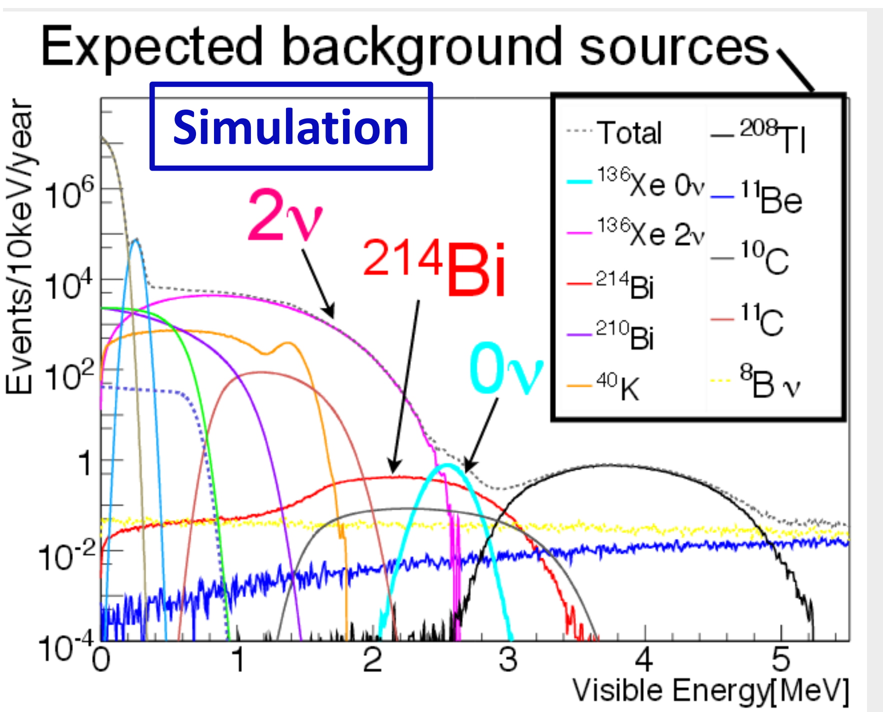
$$T_{1/2}^{0\nu} > 2.7 \cdot 10^{24}\, yr$$

CUORE-0 results combined with the existing 19.75 kg· yr of ^{130}Te exposure from Cuoricino

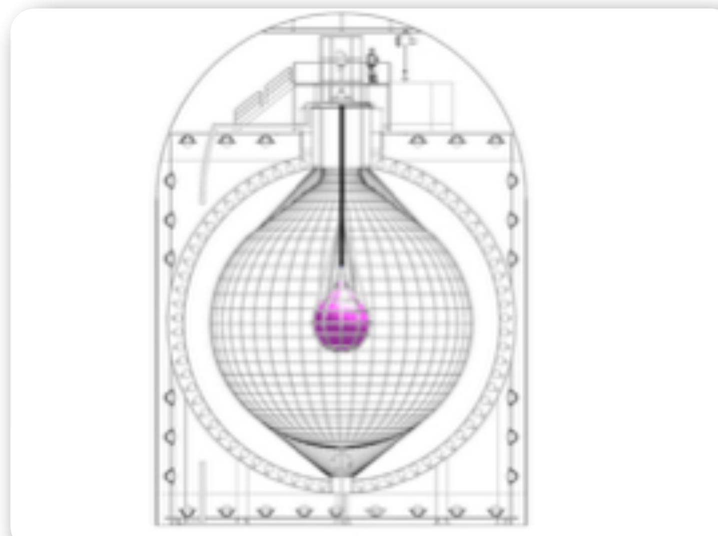
$$T_{1/2}^{0\nu} > 4.0 \cdot 10^{24}\, yr$$

F. Terranova

KamLAND-ZEN/SNO+



$\langle m_\nu \rangle = 150$meV, Xe:400kg



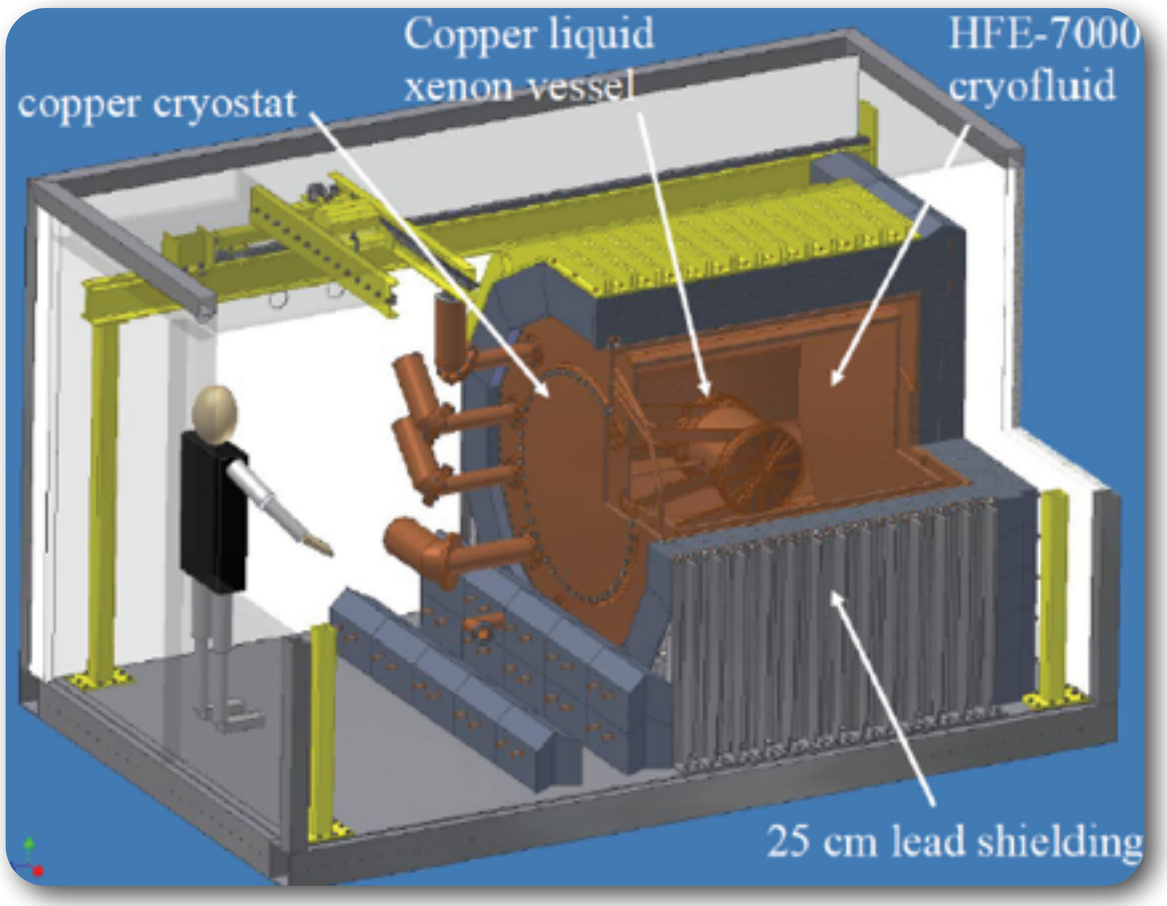
$$T_{1/2} > 1.9 \times 10^{25}\ y$$

- **a**: Xenon-136 is cheap (SNO+ uses natural Te)
- ε: ~50 % (need strict fiducial cuts, relatively poor spacial resolution)
- **Mt**: Large mass
- ΔE Poor (~10 %FWHM)
- **b** 5x10^{-4} ckky

$$T^{-1}_{1/2} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}}$$

KAMLAND: Operational experience
SNO+: Detector very well understood
NEW in the bb0n business (See talk by G. Prior on SNO+)

EXO



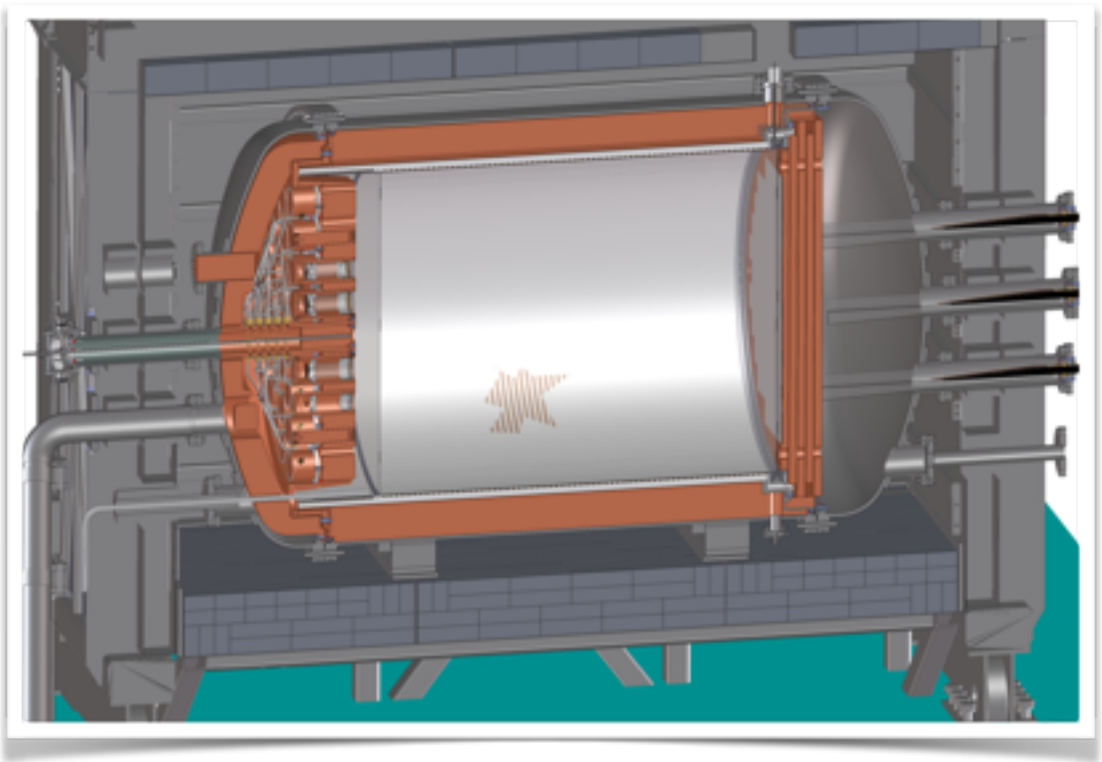
- **a**: Xenon-136 is cheap
- ϵ: > 50 % (self-shielding)
- **Mt:** Economy of scale
- ΔE Moderate (3.6 % FWHM)
- **b** 5×10^{-3} ckky

Detector well understood, operational experience, room to improve technology (e.g, APDs vs SiPMs) all parameters demonstrated

$$T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}}$$

$T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{25}$ yr (90%CL)

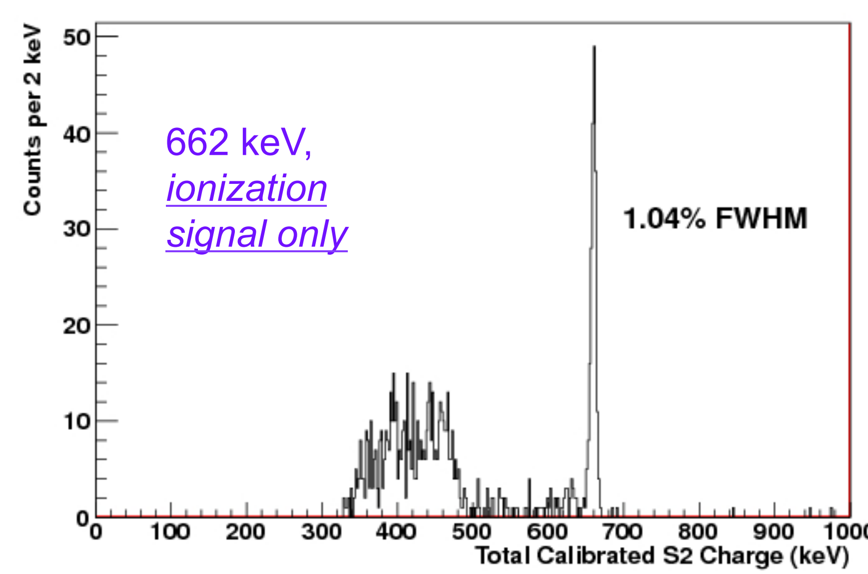
NEXT



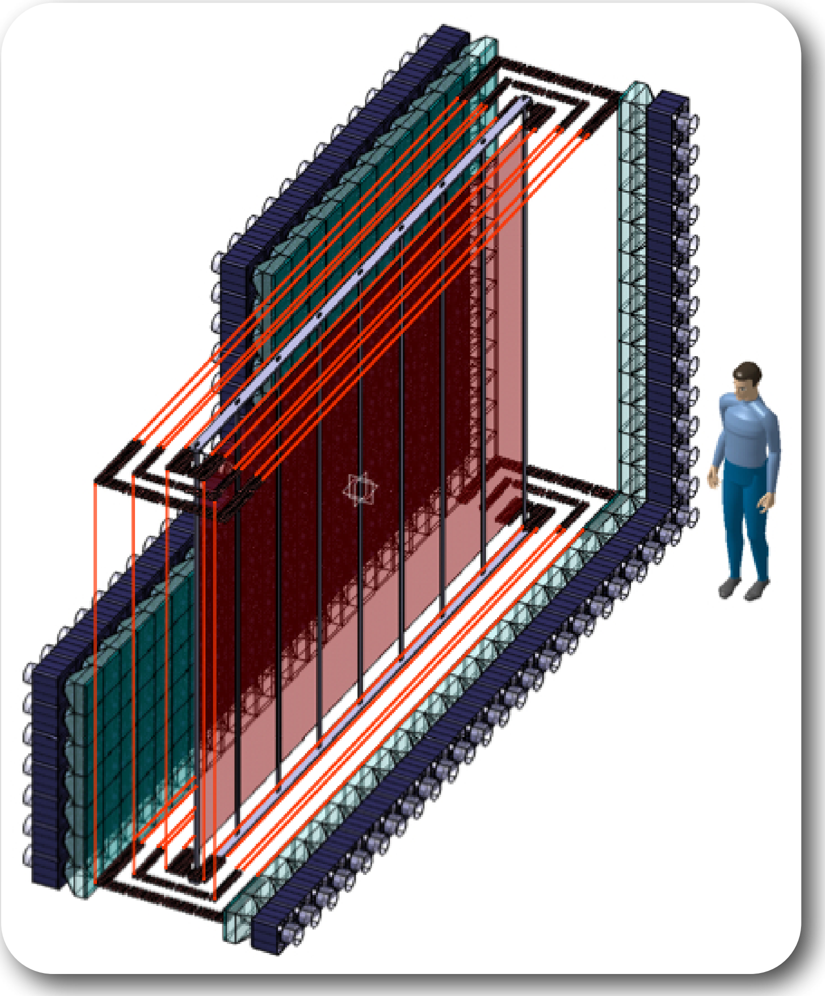
$$T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}}$$

Resolution and topological signature from DEMO and DBDM prototypes, background model pure MC, NEW detector online in 2016 should gain experience (See talk by Pau Novella)

- **a**: Xenon-136 is cheap
- ε: ~ 30 % (Bremss, topology)
- **Mt:** Economy of scale
- ΔE Good (0.5 % FWHM at Qbb)
- **b** Excellent $5x10^{-4}$ ckky



Super-NEMO



- **a**: Se-82 foils, expensive
- ε: ~ 30 %
- **Mt:** Economy of scale
- ΔE Moderate (4 % FWHM)
- **b** Excellent 5x10^{-4} ckky

Experience from NEMO-3, DEMONSTRATOR online in 2016-2017 should gain experience.

$$T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}}$$

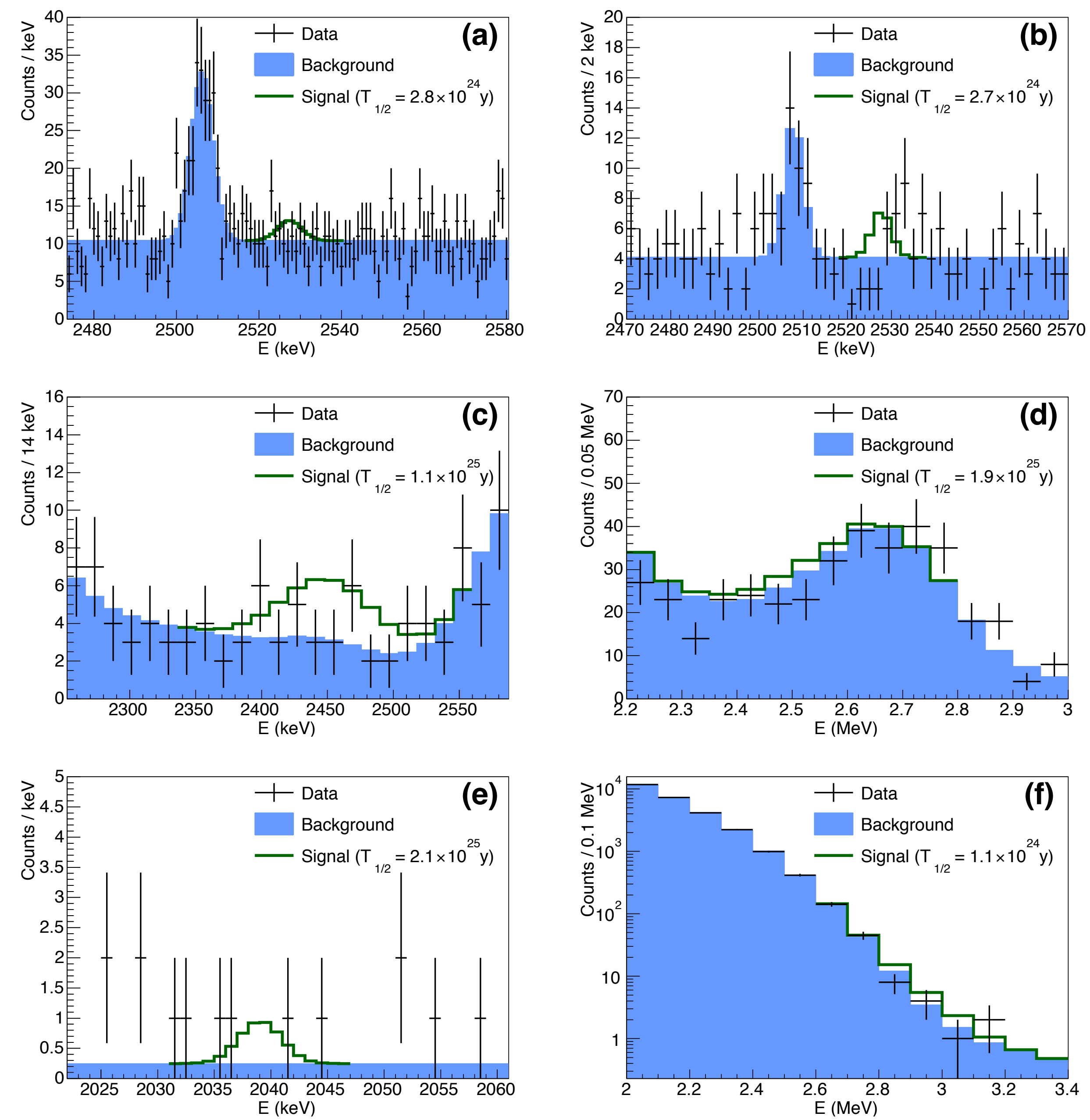
Alberto Remoto

Forerunners

P. Guzowski et al, Phys. Rev. D 92, 012002

	Limit on $T^{0\nu}_{1/2}$ (10^{24} y)				
Experiment	Publ.	Obs.	Exp.	$\pm 1\sigma$ range	$1-CL_b$
^{130}Te:					
CUORICINO	2.8 [8]	2.8	2.9	2.0 – 4.2	0.474
CUORE-0	2.7 [9]	3.0	3.0	2.1 – 4.3	0.520
Combined	4.0 [9]	4.4	4.3	2.9 – 6.2	0.513
^{136}Xe:					
EXO-200	11 [6]	13	21	14 – 30	0.131
KamLAND-Zen	19 [7]	17	11	7 – 15	0.918
Combined	—	21	24	16 – 34	0.360
^{76}Ge:					
GERDA	21 [5]	20	21	14 – 29	0.450
^{100}Mo:					
NEMO-3	1.1 [11]	1.1	0.9	0.6 – 1.4	0.634

TABLE I: The published limits on $T^{0\nu}_{1/2}$ for each experiment are compared to the calculated observed and expected limits. The $\pm 1\sigma$ range around the expected limit and the $1-CL_b$ value of the data are also shown.



Results

Isotope	Phase Space Factor $G^{0\nu}$ (10^{-14}y^{-1}) [24]	Nuclear Matrix Element Models GCM [18]	IBM-2 [19]	NSM [20]	QRPA [21] A-old	A-new	B-old	B-new	pnQRPA [22]	(R)QRPA [23] NME	Rel. Unc.	Correlation Matrix			
^{76}Ge	0.615	4.60	4.68	2.30	5.812	5.157	6.228	5.571	5.26	4.315	0.191	1			
^{100}Mo	4.142	5.08	4.22	—	5.696	5.402	6.148	5.850	3.90	3.184	0.254	0.973	1		
^{130}Te	3.699	5.13	3.70	2.12	4.306	3.888	4.810	4.373	4.00	3.148	0.247	0.899	0.862	1	
^{136}Xe	3.793	4.20	3.05	1.76	2.437	2.177	2.735	2.460	2.91	1.795	0.293	0.805	0.747	0.916	1

TABLE II: Phase space factors for $g_A = 1.27$ for the four isotopes, values of the nuclear matrix elements for the GCM, IBM-2, NSM, QRPA, pnQRPA, and for the (R)QRPA NME calculation, together with the relative uncertainties on the (R)QRPA NMEs and their correlation matrix. The relative uncertainties quoted for the IBM-2 calculation are 0.16 for each isotope.

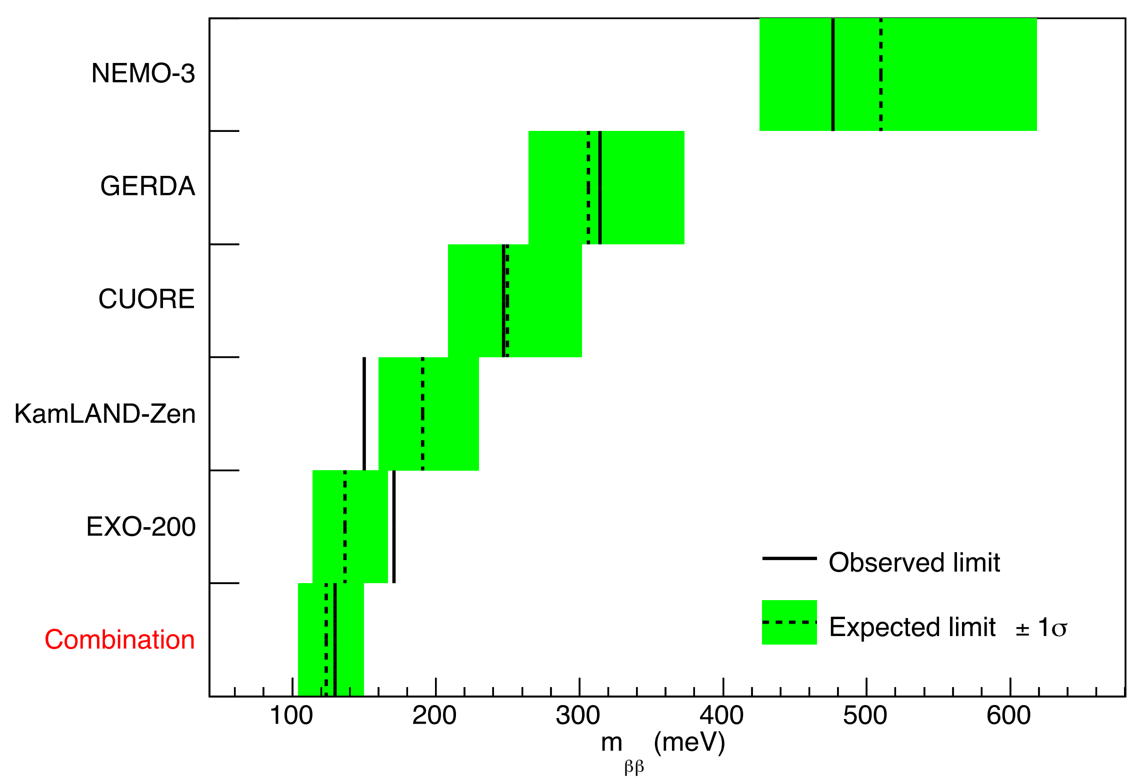


FIG. 2: Individual experiment effective mass limits, and the combined limit, using the GCM model.

Combined limit

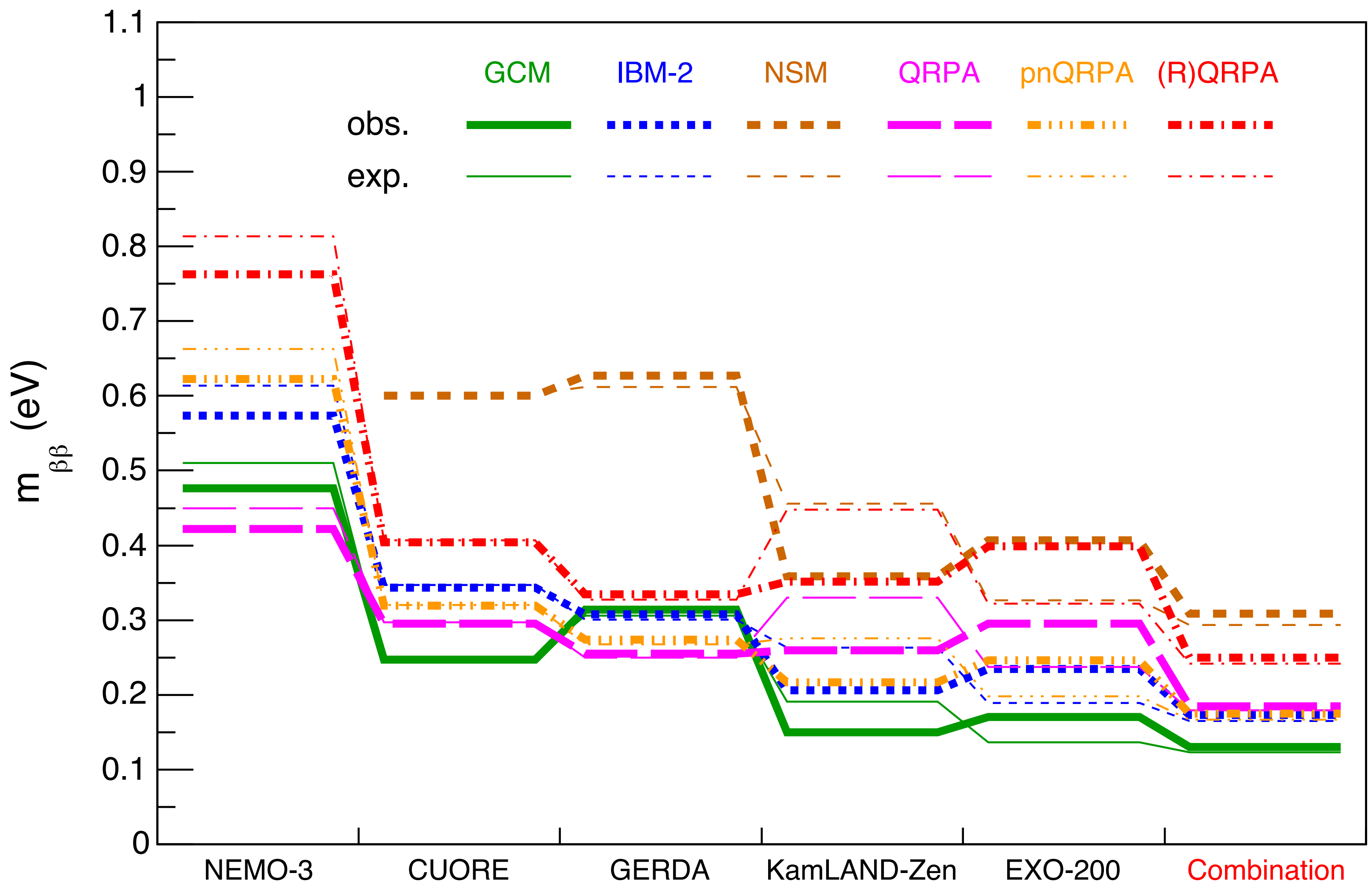
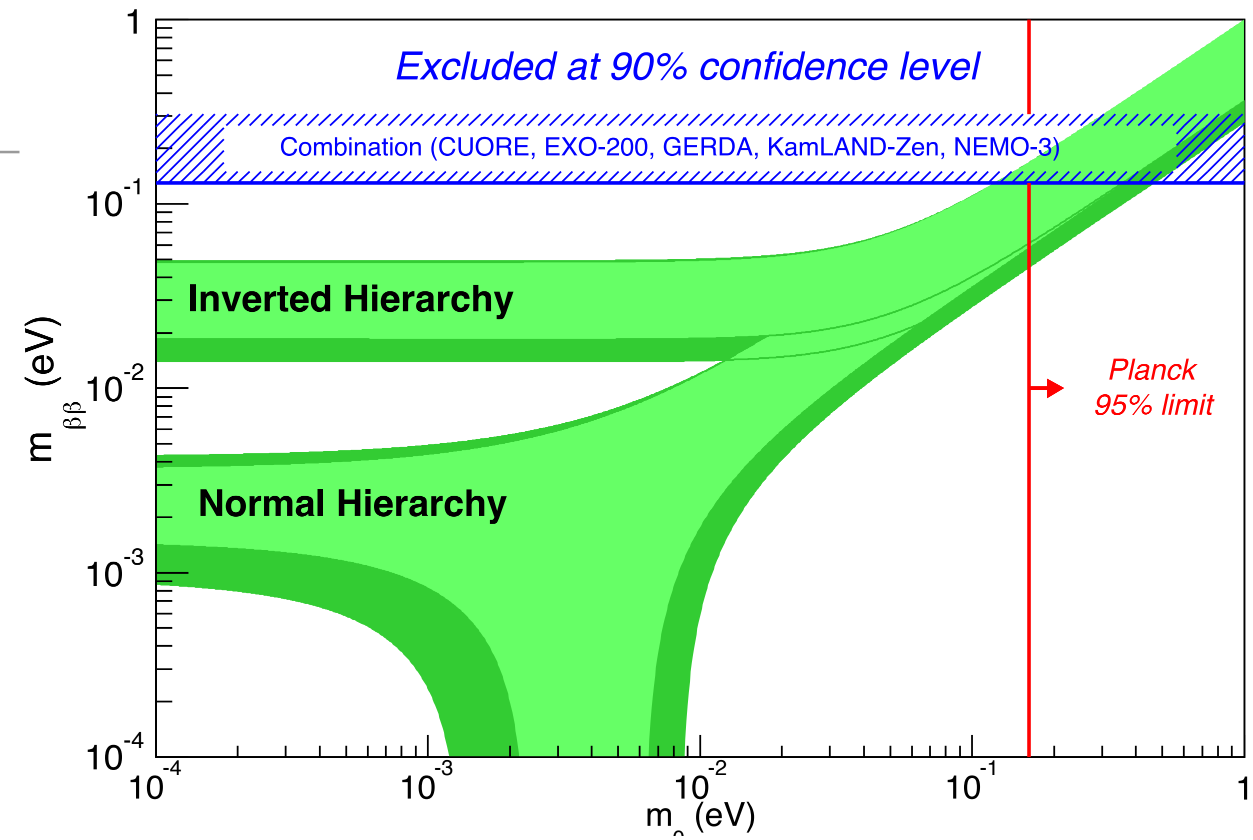


FIG. 3: Observed and expected limit on $m_{\beta\beta}$ for the different experiments and NME models without NME model uncertainties.

Where are we?

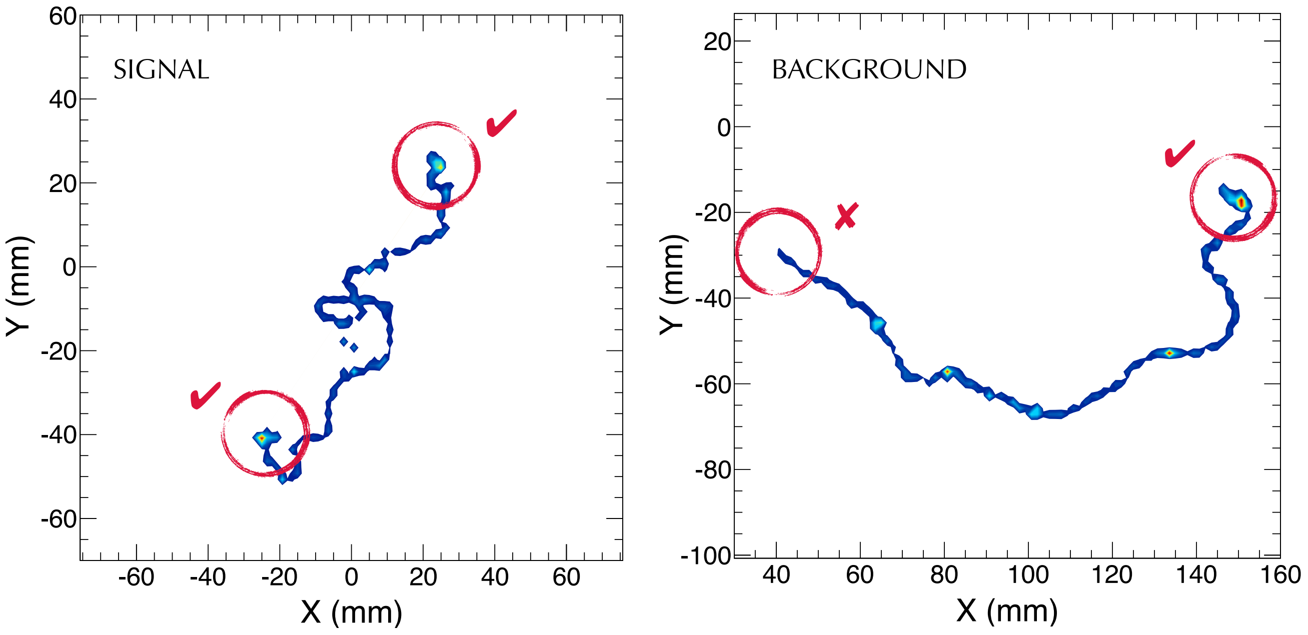
- In spite of the enormous experimental progress over the last decade, ββ0ν experiments are not even getting close to the IH region
- We need to go from ~200 meV to ~20 meV.
- A factor 10 in mββ is a factor 100 in $T_{1/2}$

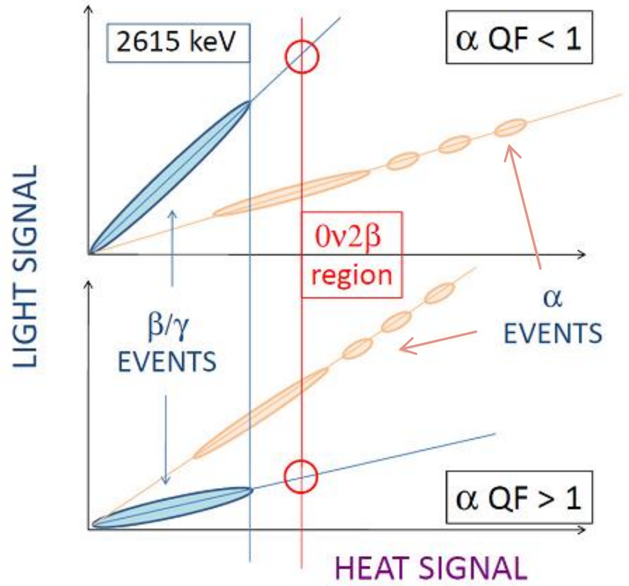


- It appears possible for most of the techniques to reach 10^{26} y (ton scale target mass, improvements in technology)
- Instead reaching 10^{27} y seems very difficult.

How to improve?

- Incremental gains (no revolution but perfect control of technology): GERDA
- New handles (e.g, Scintillating Bolometers, topological signature in NEXT)
- Refine self-shielding and deploy very large masses (need cheap isotope): SNO+ and KamLAND-ZEN.



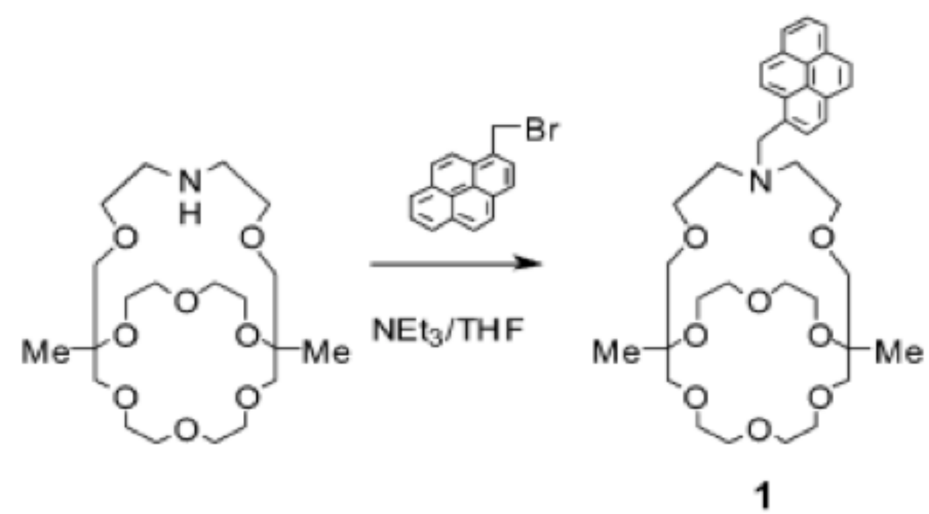


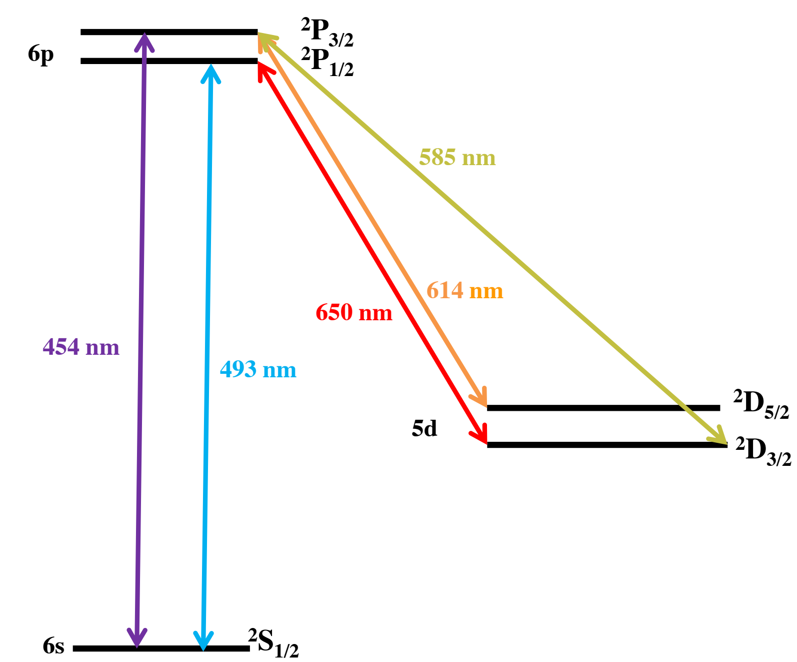
Research Proposal (B1) LUCIFER 2009

Breakthrough in technology

Single Molecule Fluorescente Imaging

- The standard technique for Ba+ tagging (EXO)involves a cycle of excitation/de-excitation with alternating red and blue light. Requires (probably) near-vacuum conditions, which in turn implies extracting a single ion from a large (ton scale) LXe or HPXe TPC. Extremely challenging!
- Dave Nygren's proposal: use SMFI technique (SMFI is based on chelation, capture of an ion in a special molecular cage to form a complex) to can the Ba++ ion and tag it.
- The idea:
  - Ba++ reaches the cathode under the influence of the electric field
  - Ba++ is captured by pyrene-stabilized mono-azacryptand (PSMA). PSMA displays extremely high specificity to Ba++
  - Excitation of PSMA at 342 nm leads to fluorescence in a wide band, 360-430 nm. The interrogation rate in SMFI can exceed 10^5 per second.
  - The arrival of the ion at the TPC cathode reduces the search to a 2-D problem. Diffusion of the ion during drift is small, on the order of 1 mm in any dimension. Conceptually, a coating of SMFI precursors on a non-conductive cathode surface could suffice for capture of the ion





The road ahead

- 2016: GERDA-II, KamLAND-ZEN (600 kg), EXO-200 restarts, CUORE, NEW (first phase of NEXT-100).
- 2017: Super-NEMO demonstrator, NEXT-100
- 2020: Combined limit may be scratching IH, R&D and operational experience may clarify the best techniques
- 2020—? attack the IH.

But a discovery can be around the corner! Keep searching!


THANKS!

backup

Sterile neutrinos and bb0n

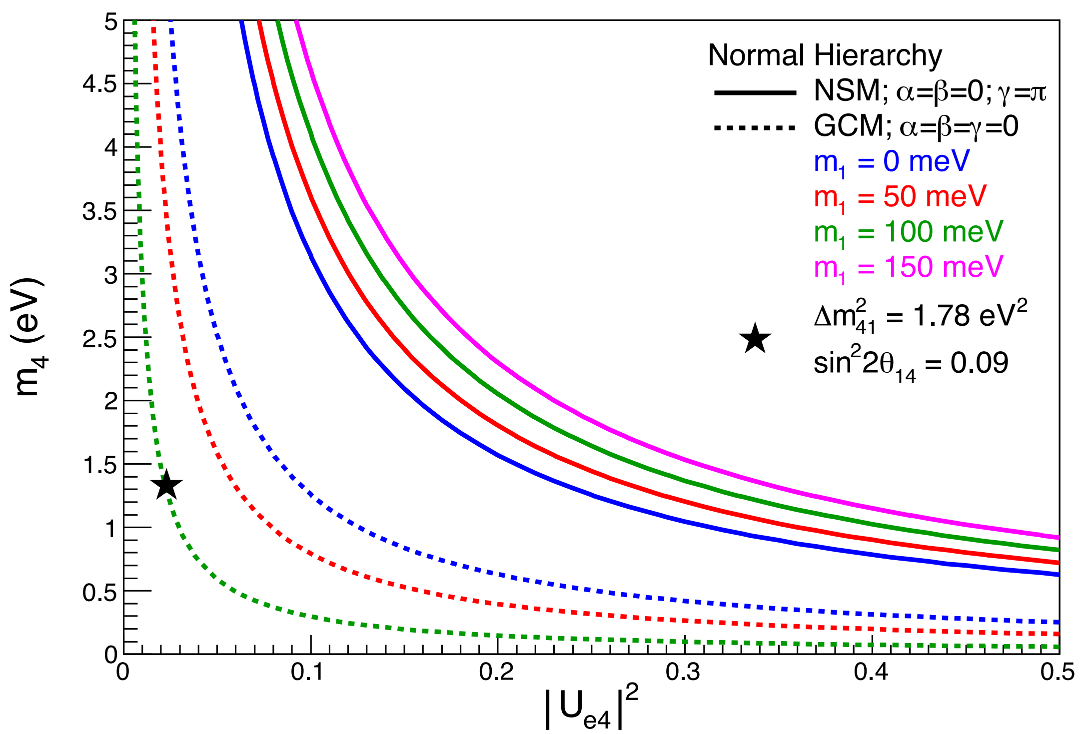


FIG. 7: Limits on $m_{\beta\beta}$ for different NME models translated into a constraint on the sterile neutrino in the $(m_4, |U_{e4}|^2)$ plane in a $(3+1)$ model. Different values of the Majorana phases α, β, γ and of the lightest active neutrino mass m_1 in the NH are shown. The complete region is excluded for $m_1 = 150$ meV with the GCM model and vanishing Majorana phases.

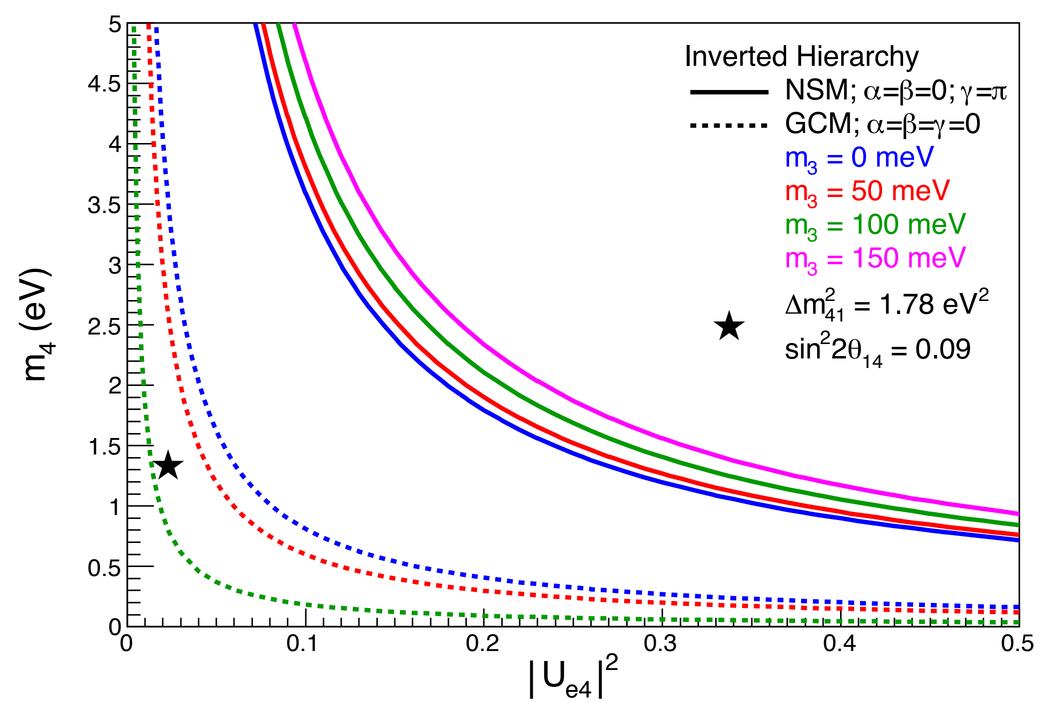


FIG. 8: Limits on $m_{\beta\beta}$ for different NME models translated into a constraint on the sterile neutrino in the $(m_4, |U_{e4}|^2)$ plane in a $(3+1)$ sterile neutrino model. Different values of the Majorana phases α, β, γ and of the lightest active neutrino mass m_3 in the IH are shown. The complete region is excluded for $m_3 = 150$ meV with the GCM model and vanishing Majorana phases.

Ho-163 experiments

ECHo

Au:Er
Metallic magnetic microcalorimeters (MMC)

n irradiation
Er(n,γ)

funding for ECHO–1k demonstrator granted by DFG

HOLMES

MoCu or MoAu
Transition edge sensors (TES)

n irradiation
Er(n,γ)

funding approved

NuMECS

MoCu
Transition edge sensors (TES)

proton irradiation
Dy(p,xn)

Sensitivity ~10 eV. Still not competitive with KATRIN

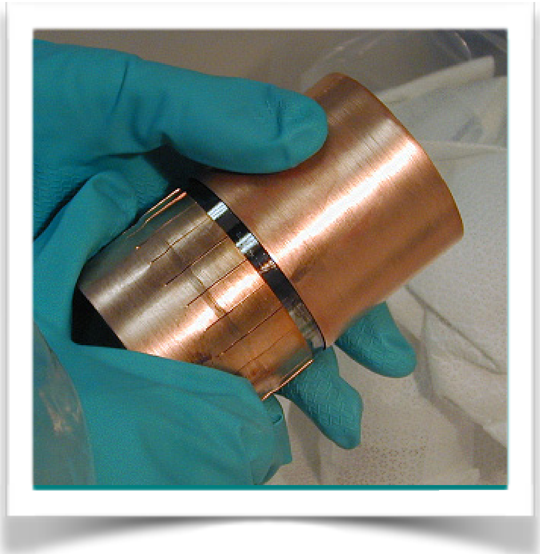
Exploring IH

$$T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}}$$

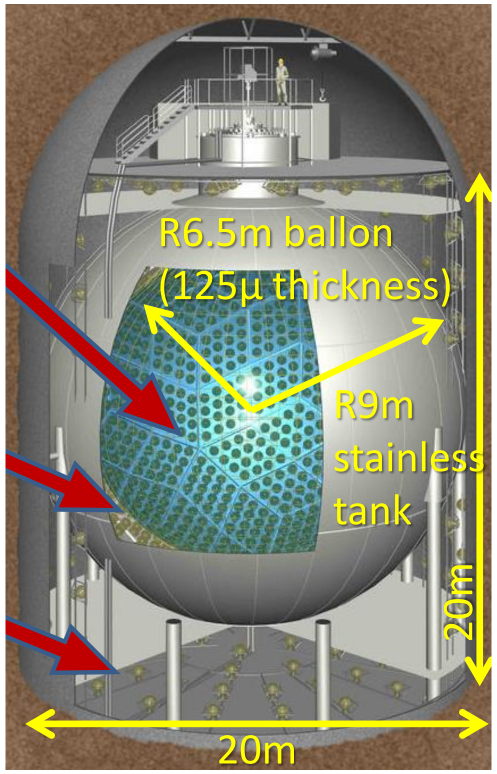
- A factor 10 in mββ is a factor 100 in $T_{1/2}$
- It appears possible for most of the techniques to reach 10^{26} y (ton scale target mass improvements in technology)
- Instead reaching 10^{27} y seems very difficult. It requires that MT/(ΔE×B) improves by 10^4

- Furthermore, the uncertainty in NME advises to run two or more isotopes.
- Exploring the IH is a major experimental challenge that will require a major technological break-through or a very wise combination of experiments

Radiopurity



- Build everything out of extremely radiopure materials.
- Solide state apparatus (GERDA, CUORE), display very low activities in detector material in the range of μBq/kg.



- TPCs (EXO, NEXT), have larger radioactive budget, due to their sensors (PMTs, APDs, SiPMs), but their ability to define a fiducial region away from surfaces, eliminates a whole class of backgrounds (α particles).
- In Super-NEMO the signal is constrained to come from the target, but the background also accumulates in the target and α particle background is relevant.
- LS calorimeters are capable of self-shielding from most backgrounds.