Neutrino Masses

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Topics

Neutrino properties

- status
- open questions
- anomalies

Experimental methods

- neutrinoless double beta decay searches
- direct neutrino mass measurements
- cosmology

Status and perspectives

Conclusions

Present status of ν Physics

What we know:

- neutrinos are massive fermions
- there are 3 active neutrino flavors (ν_α)
- neutrino flavor states are mixtures of mass states (ν_k)

$$|\nu_\alpha\rangle = \sum_k U_{\alpha k}|\nu_k\rangle$$

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

Atmospheric / Accelerator — Reactor / Accelerator — Solar / Reactor

Precision measurements of neutrino parameters: available and ongoing

NuFIT 1.1 (2013)

	Free Fluxes + RSBL		Huber Fluxes, no RSBL	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.346$	$0.313^{+0.013}_{-0.012}$	$0.277 \to 0.355$
$\theta_{12}/^\circ$	$33.57^{+0.77}_{-0.75}$	$31.38 \to 36.01$	$34.03^{+0.81}_{-0.77}$	$31.78 \to 36.56$
$\sin^2\theta_{23}$	$0.437^{+0.061}_{-0.031}$	$0.357 \to 0.654$	$0.436^{+0.047}_{-0.032}$	$0.356 \to 0.653$
$\theta_{23}/^\circ$	$41.4^{+3.5}_{-1.8}$	$36.7 \to 54.0$	$41.3^{+2.7}_{-1.8}$	$36.6 \to 53.9$
$\sin^2\theta_{13}$	$0.0231^{+0.0023}_{-0.0022}$	$0.0161 \to 0.0299$	$0.0252^{+0.0022}_{-0.0023}$	$0.0181 \to 0.0320$
$\theta_{13}/^\circ$	$8.75^{+0.42}_{-0.44}$	$7.29 \to 9.96$	$9.13^{+0.40}_{-0.42}$	$7.73 \to 10.31$
$\delta_{CP}/^\circ$	341^{+58}_{-46}	$0 \to 360$	345^{+77}_{-46}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.45^{+0.19}_{-0.16}$	$6.98 \to 8.05$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.08$
$\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$+2.421^{+0.022}_{-0.023}$	$+2.248 \to +2.612$	$+2.429^{+0.029}_{-0.027}$	$+2.256 \to +2.635$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.410^{+0.062}_{-0.063}$	$-2.603 \to -2.226$	$-2.422^{+0.061}_{-0.063}$	$-2.618 \to -2.239$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

Open Questions in ν Physics

What is the absolute neutrino mass scale?
Is the lightest ν massless? Hierarchical or degenerate?

What is the neutrino mass ordering?
Normal ($m_1 < m_2 \ll m_3$) or inverted ($m_3 \ll m_1 < m_2$)?

Are neutrinos Dirac or Majorana particles?
Lepton number violation, neutrinoless double beta decays

Neutrinos could be the only "chargeless" fermions for which Majorana nature and **mass terms** would be possible

What is the origin of neutrino masses and flavor mixing?
See saw mechanisms, flavor symmetries, ...

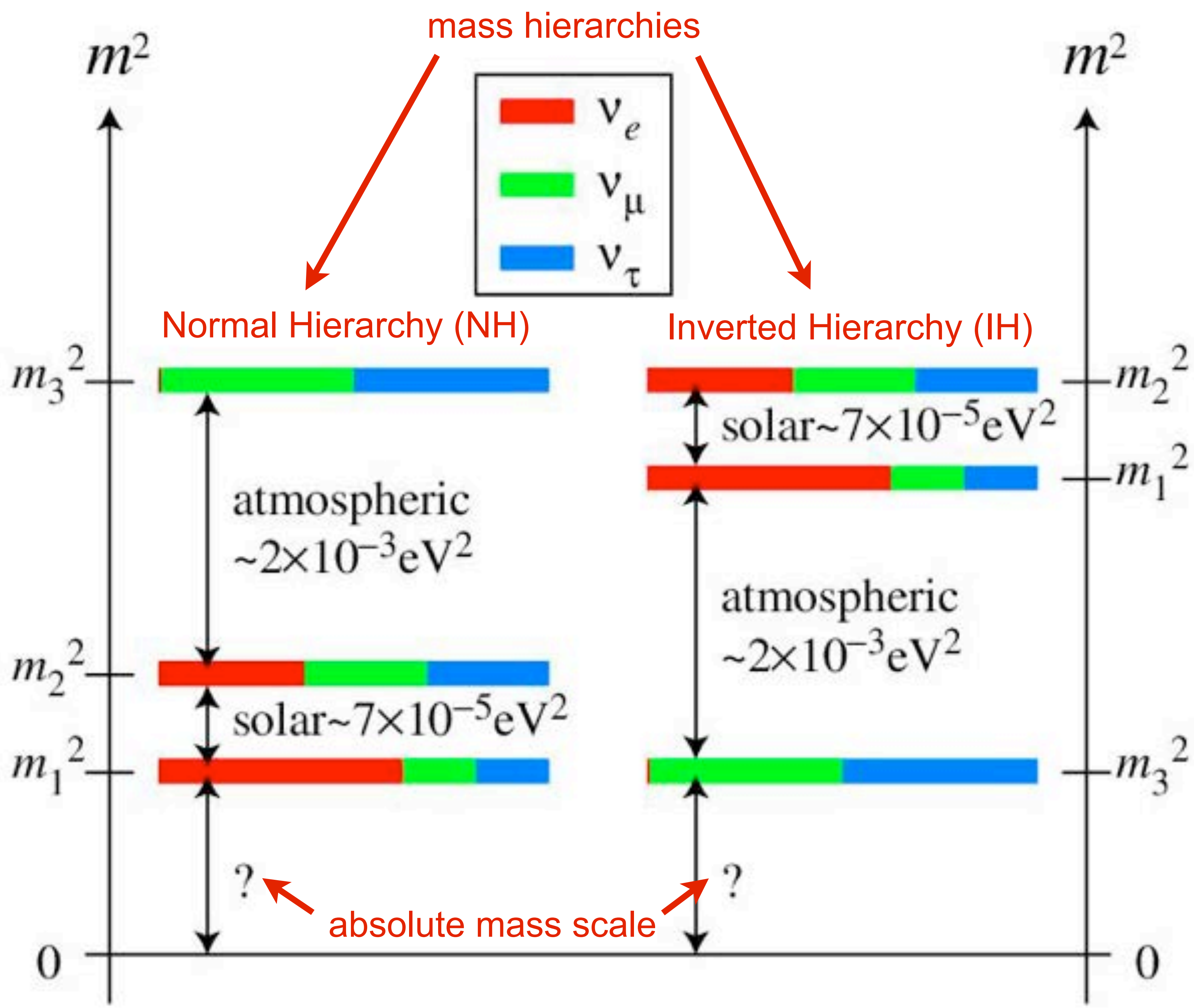
Is there CP violation in the lepton sector?
What is the value of the Dirac CP-violating phase δ?

- **Neutrinos are important probes of the Standard Model limits**
- **Neutrino masses are intimately linked (directly or indirectly) to all the above questions**

Neutrino mass questions

Two main questions are directly related to neutrino masses:

1. absolute mass scale: i.e. mass of the lightest ν
2. degenerate ($m_1 \approx m_2 \approx m_3$) or hierarchical masses ($m_1 < m_2 \ll m_3$ or $m_3 \ll m_1 < m_2$)



- Neutrino oscillation experiments are blind to the first but can solve the second: Daya Bay II, Reno II, T2K, Nova, LBNO, LBNE, PINGU, ORCA, ...

Anomalies and sterile neutrinos

Anomalies are observed in data from

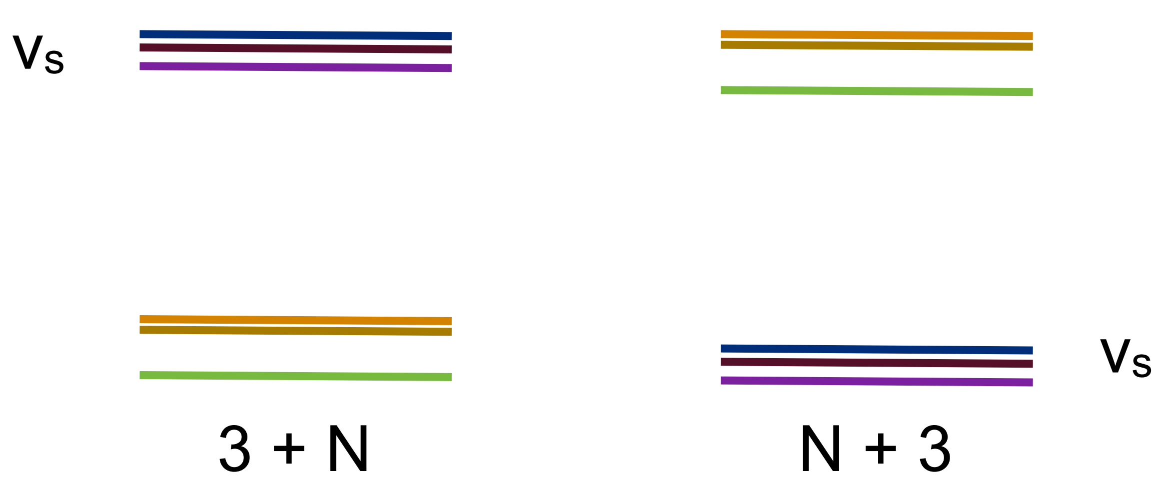
- past reactor oscillation experiments (reanalyzed)
- short baseline accelerator oscillation experiments (LSND, MiniBOONE)
- solar experiment calibration with neutrino sources (GALLEX)

Call for 4th neutrino mass state ν_4

→ sterile neutrino: $\boldsymbol{\Delta m^2 \approx 1}$ eV and $\sin^2 2\theta \gtrsim 0.1$

- Sterile (Right Handed) neutrinos are a natural extension to the Standard Model (νMSM)
- Sterile neutrino in the keV mass range are perfect candidate as Warm Dark Matter (WDM) particles
- Sterile neutrinos are also obvious candidates for extra energy density (J.Hamann et al., PRL 105 (2010) 181301).

Assuming N additional (~ degenerate) sterile states, 2 new hierarchical schemes are possible:

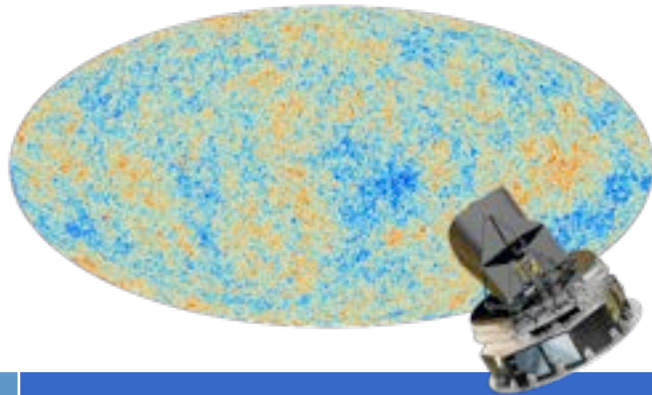


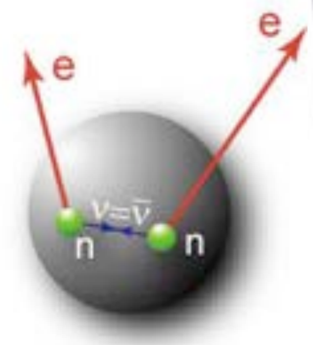
Favored m_s: ~ 1 eV

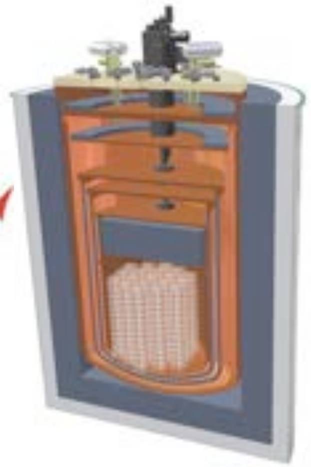
Experimental methods

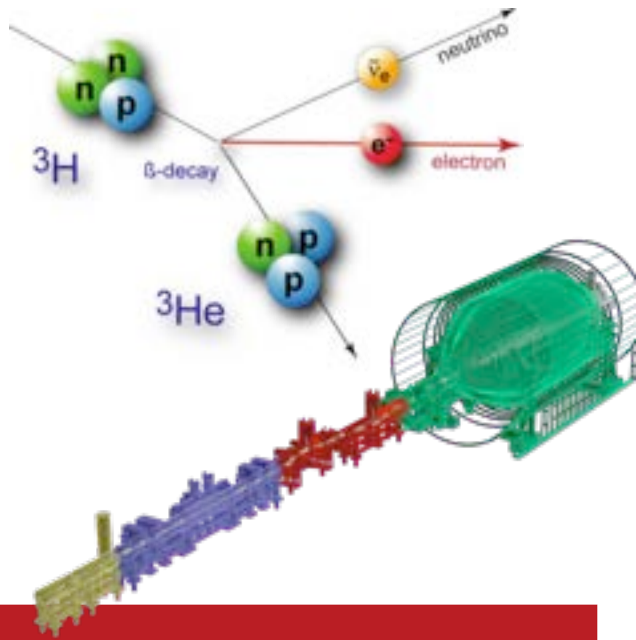
Three complementary tools available

- Different sensitivities
- Complementary pro and cons



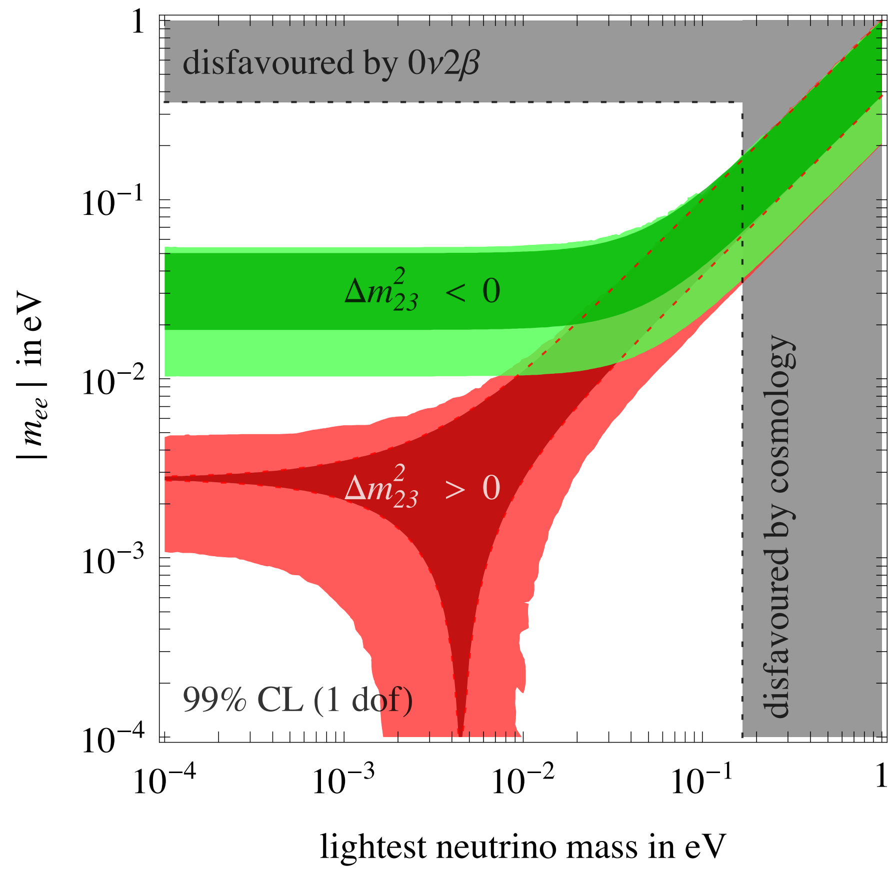






	Cosmology (CMB+LSS+...)	Neutrinoless Double Beta decay	Beta decay end-point
observable	$m_\Sigma=\Sigma_k m_{\nu k}$	$m_{\beta\beta}=\|\Sigma_k m_{\nu k} U_{ek}^2\|$	$m_\beta=(\Sigma_k m_{\nu k}^2 \|U_{ek}\|^2)^{1/2}$
present sensitivity	≈ 0.1 eV	≈ 0.1 eV	2 eV
future sensitivity	0.01 eV	0.01 eV	0.2 eV
model dependency	↓ yes	↓ yes	↑ no
systematics	↓ large	yes	↓ large

Mass hierarchies

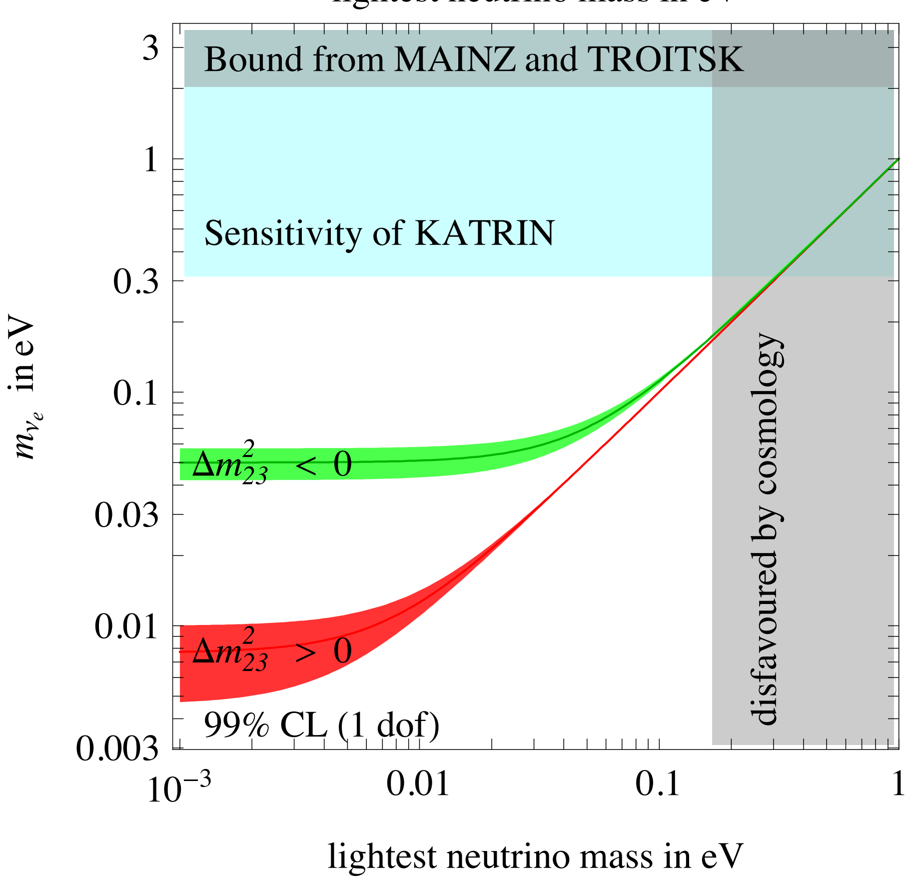


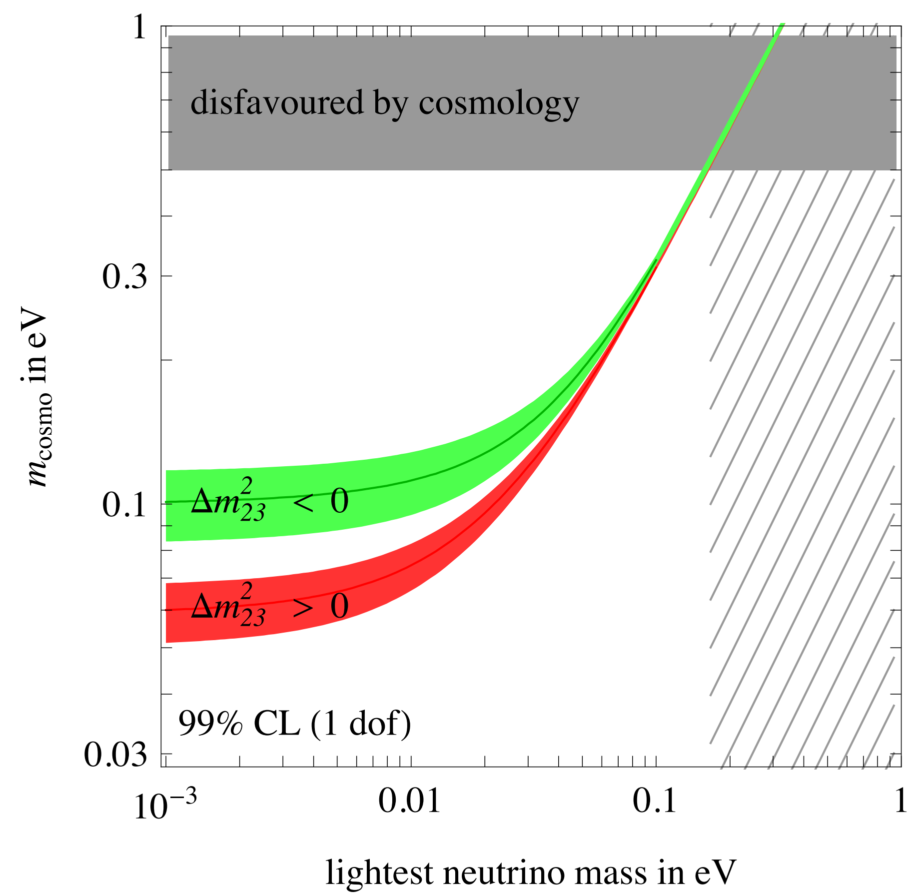
Experimental parameters are pictured as a function of the lightest mass eigenvalue:

--- Normal Hierarchy

--- Inverted Hierarchy

Bands arise from specific experimental and theoretical uncertainties)

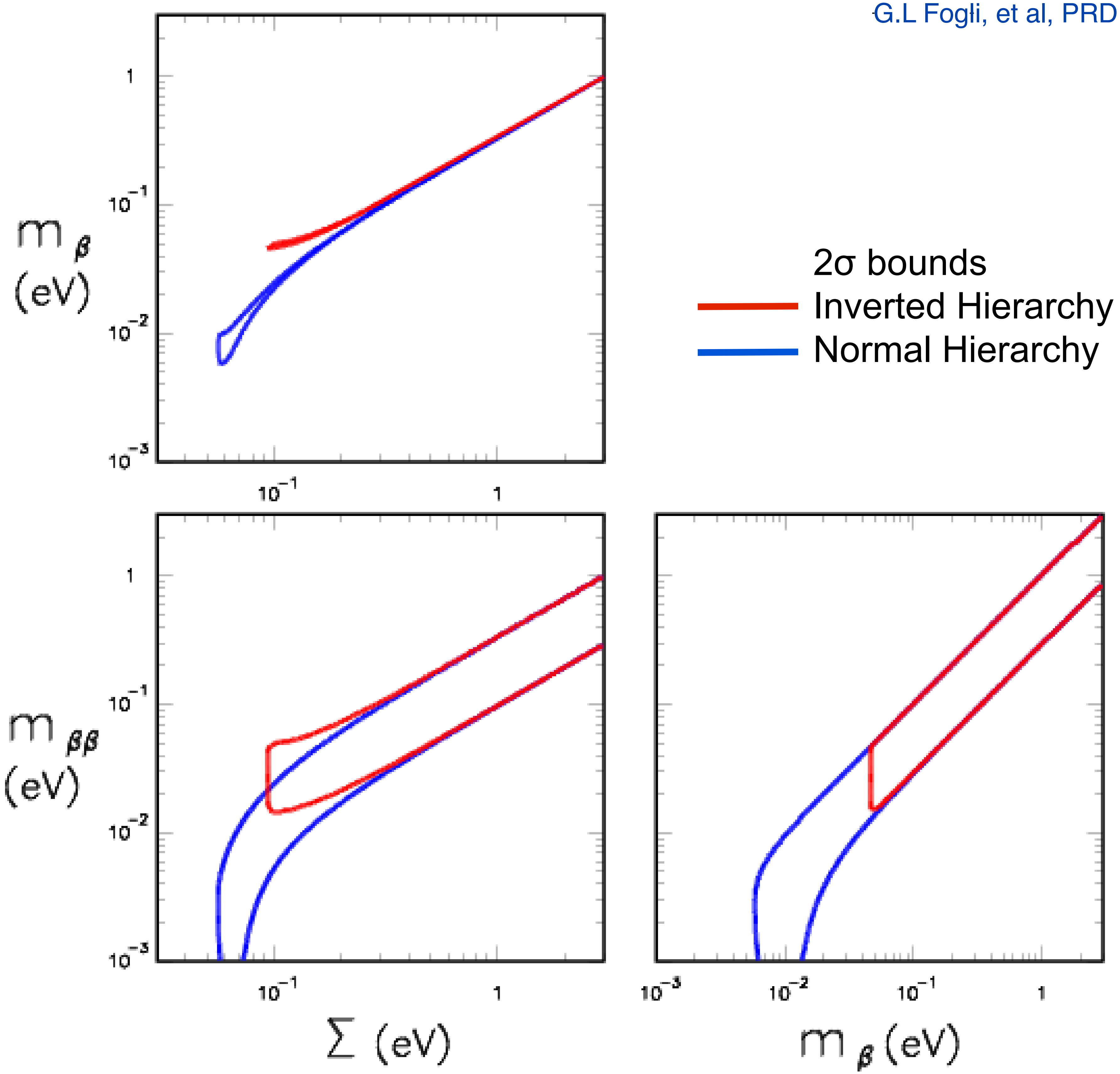




- S.Pascoli et al., arXiv: 0505226
- R.Mohapatra et al., arXiv: 0510213
- A.Strumia and F.Vissani, IFUP-TH/2004-1; arXiv: 0606054

Combining/Comparing results

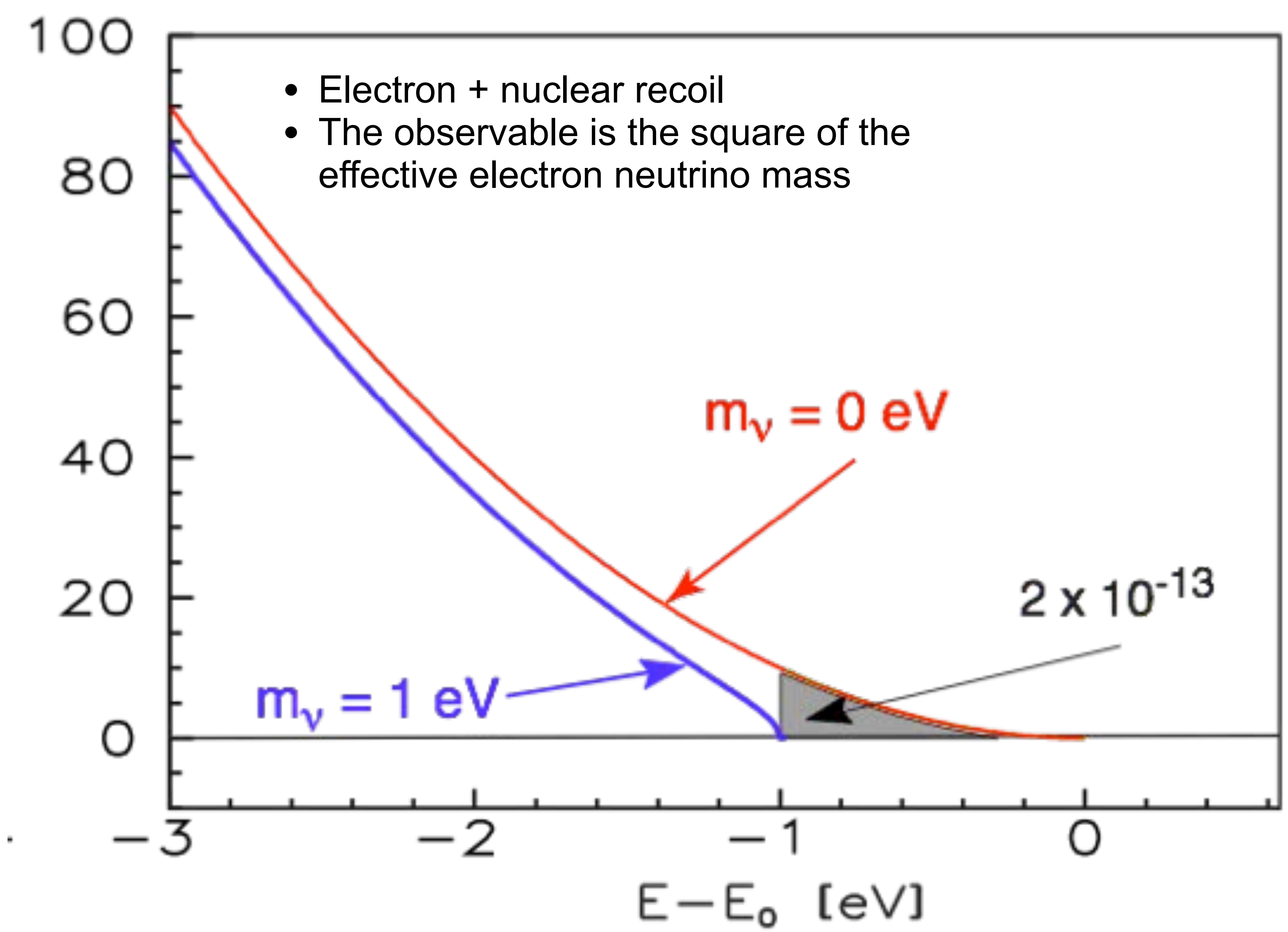
G.L Fogli, et al, PRD 78 033010 (2008), arXiv:hep-ph/0805.2517v3



Direct measurements of neutrino mass

Kinematics of weak decays

- nuclear beta decays
  - single beta (^{3}H, ^{187}Re, ...)
  - EC (^{163}Ho)
- use only energy and momentum conservation
- no further assumptions



Time of flight measurements

- supernovae neutrinos
- use $E^2=p^2c^2+m_\nu^2c^4$
- and hypothesis on emission time distribution
- sensitivity limited to ≈1 eV (SN1987 → $m_\nu \lesssim 6$ eV)

Experimental approaches

Spectrometers: passive source

- **β Source**: ^3H
- **β analyzer**: differential or integral spectrometer: β's from a fraction δE of the ^3H spectrum are magnetically and/or electrostatically selected and transported to the counter
- **β counter**: solid state

↑ high statistics
↑ high energy resolution
↓ large systematics
- source effects
- decays to excited states

↓ background

Calorimeters: active source

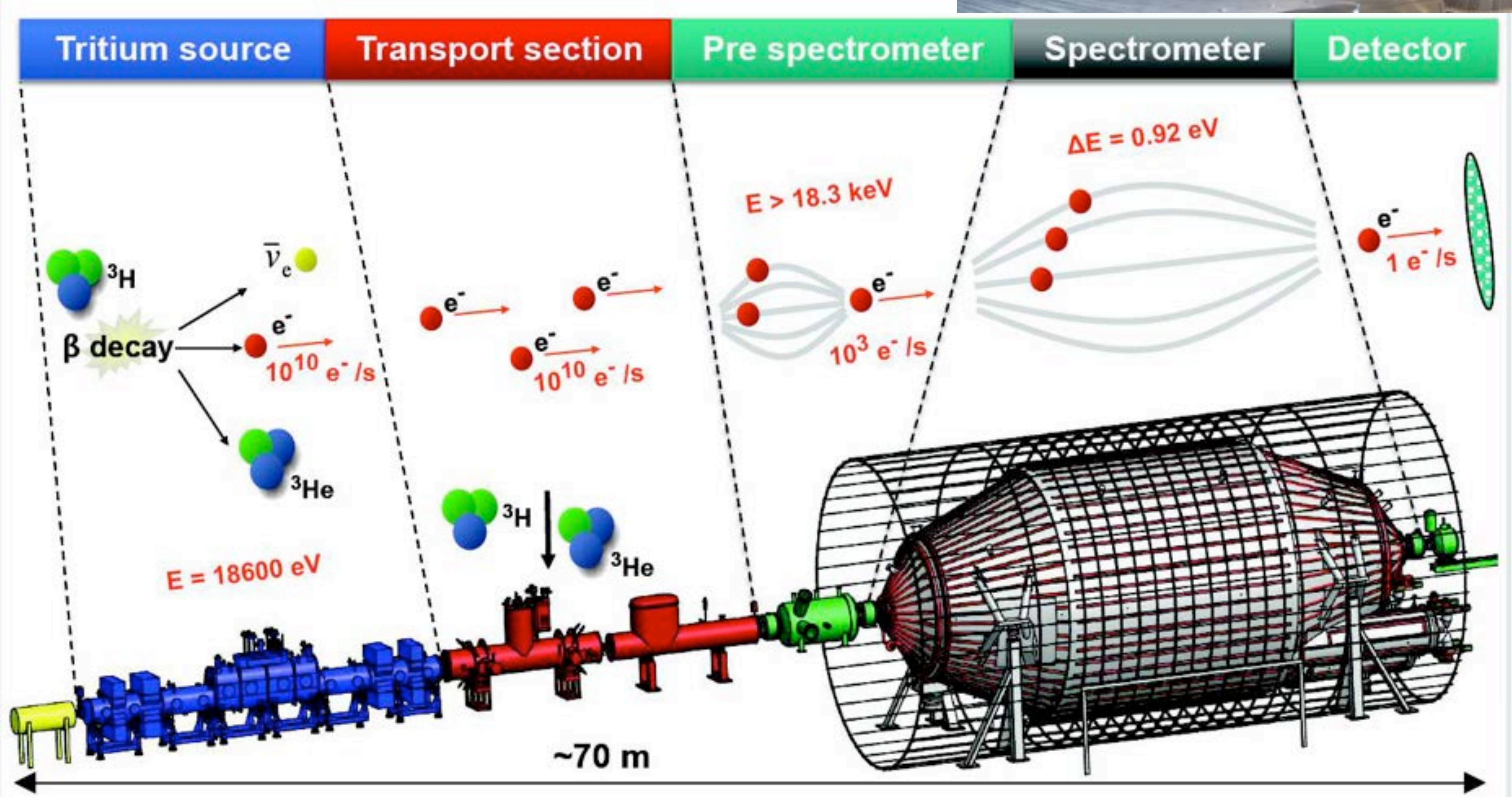
- **β Source**: low Q beta emitters
- **β calorimeter**: ideally all the energy E released in the decay, except for the ν_e energy, can be measured:
  $E = Q - E_\nu$
- **β counter**: solid state

↑ no backscattering
↑ no energy losses in the source
↑ no atomic/molecular final state effects
↑ no solid state excitation
↓ limited statistics
↓ pile-up background
↓ spectrum related systematics

KATRIN

→talk M.Haag

- Large electrostatic spectrometer with gaseous ^{3}H source (Q=18.6keV)
- Expected statistical sensitivity: **m_{ν_e} < 0.2 eV 90% CL**
- Start data taking in **2014/2015**
- Presently under commissioning



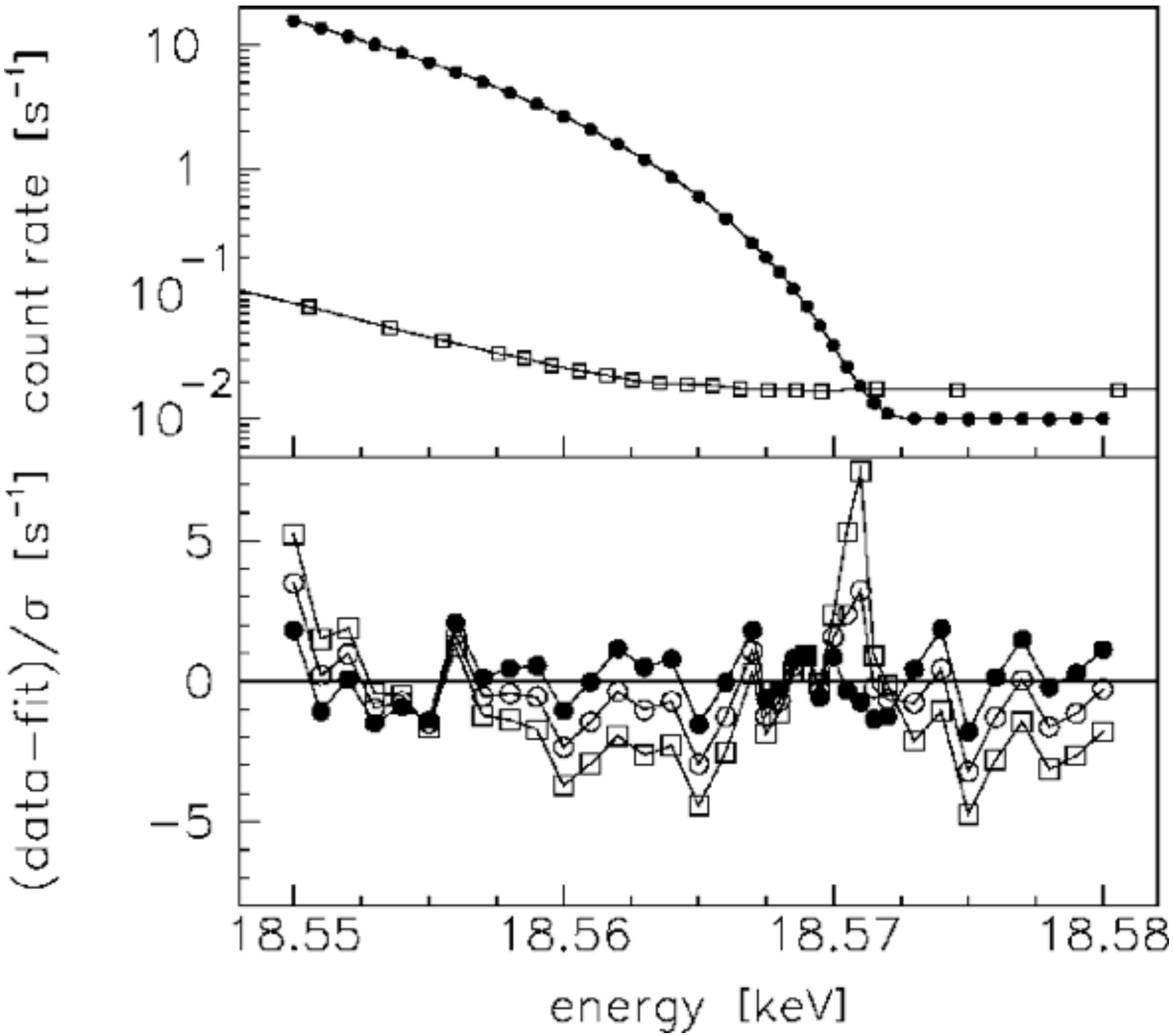
KATRIN sensitivity

sensitivity:
$m_\nu < 0.2$eV (90%CL)

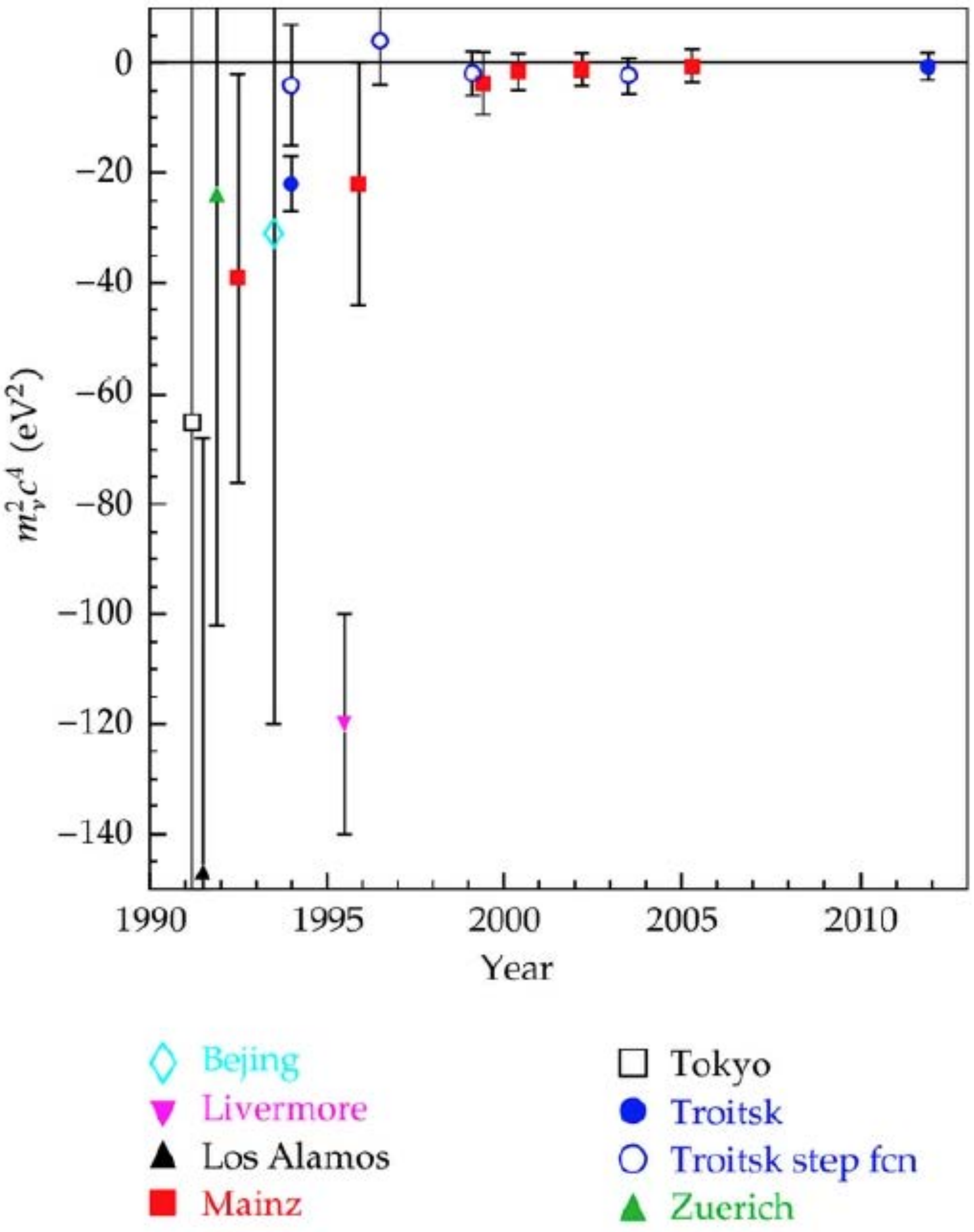
discovery potential:
$m_\nu = 0.3$eV (3σ)
$m_\nu = 0.35$eV (5σ)

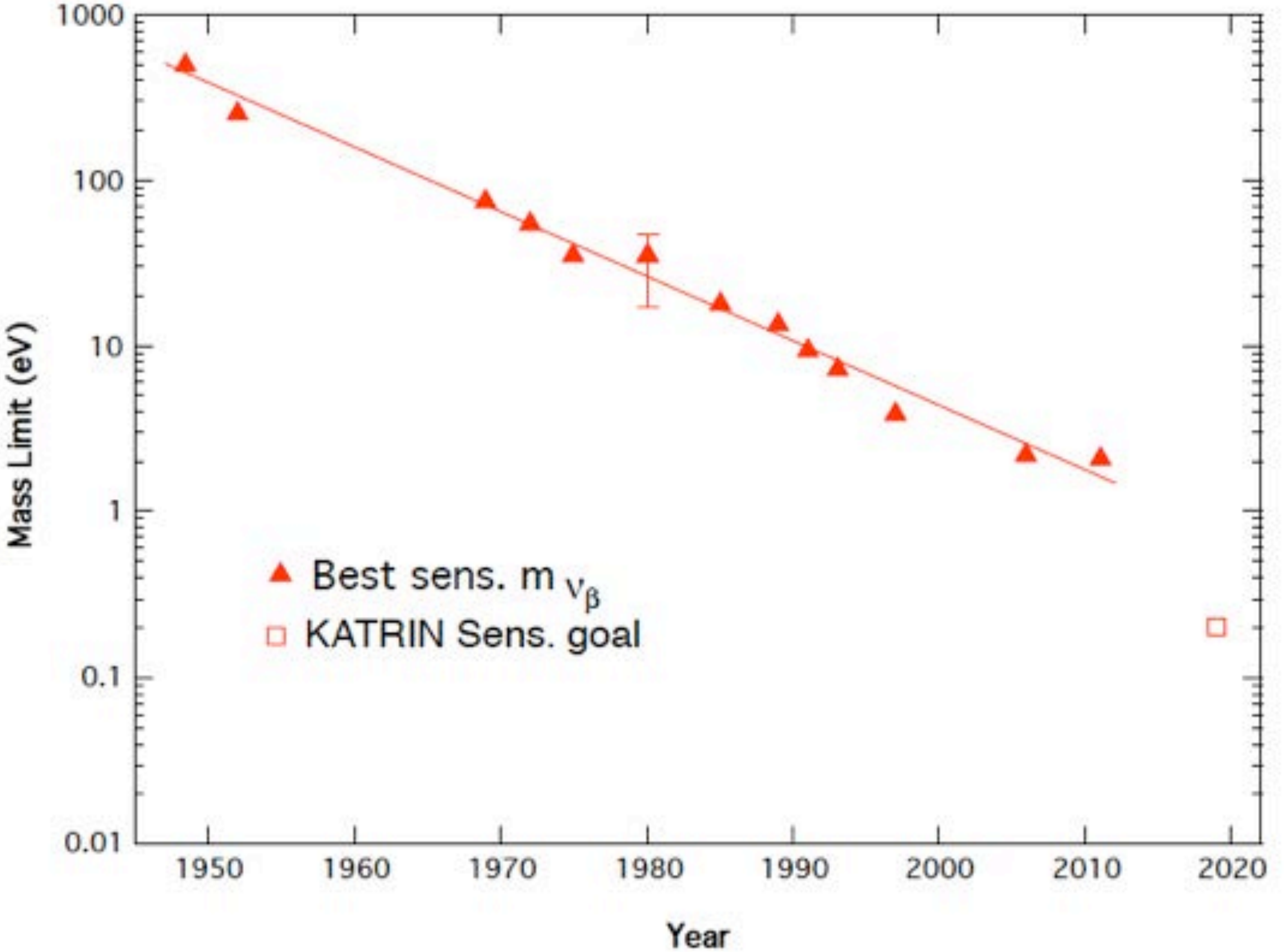
- Expectation for 3 full data taking years: $\sigma_{syst} \sim \sigma_{stat}$
- Sensitivity is still statistically limited,
  - because with more statistics would go closer to the endpoint,
  - where most systematics nearly vanish
- Sensitivity still has to proven, but there might be even some more improvements

Example of KATRIN simulation & fit (last 25eV below endpoint)



Spectrometers progress





^{187}Re Low Temperature Calorimeters

^{187}Re beta decays with very low E_0:

$^{187}Re \rightarrow {}^{187}Os + e^- + \overline{\nu}_e$

- $\tau_{1/2} = 4.16 \times 10^{10}$ y
- First unique forbidden β decay

→

Re and $AgReO_4$
low T μ-calorimeters
O(≲1mg)

→

Almost ideal calorimeter: $\Delta T = \Delta E / C$
- Very good energy resolution
- But slow response

→ important pile-up contribution

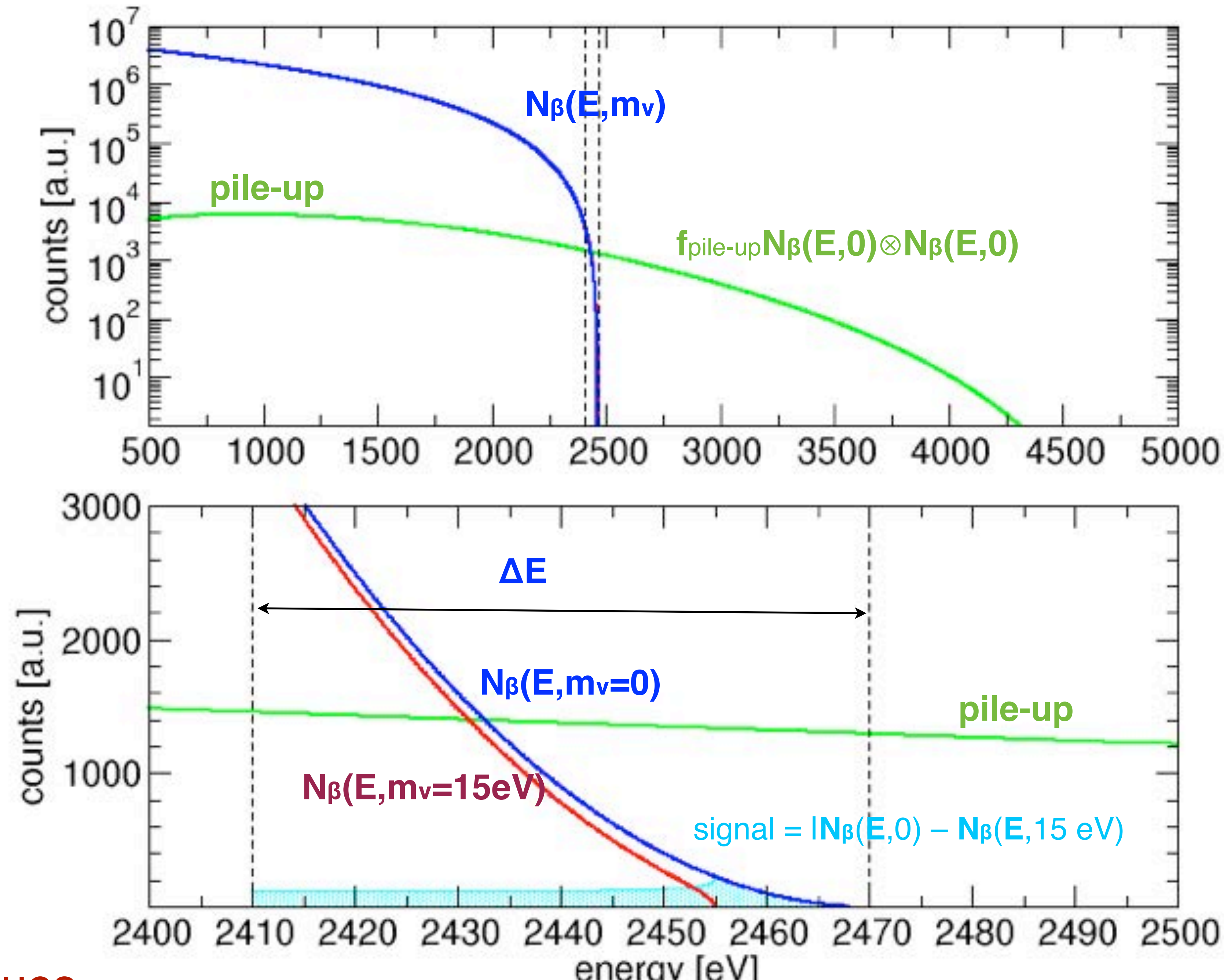
$$F_{\Delta E} \sim A_\beta N_{det} \frac{\Delta E^3}{E_0^3}$$

→ ^{187}Re E_0 = 2.5keV

$$\Sigma_{90}(m_\nu) \sim 0.89 \left(\frac{E_0^3 \Delta E}{A_\beta t_{mea}}\right)^{1/4}$$

Experimental challenges:

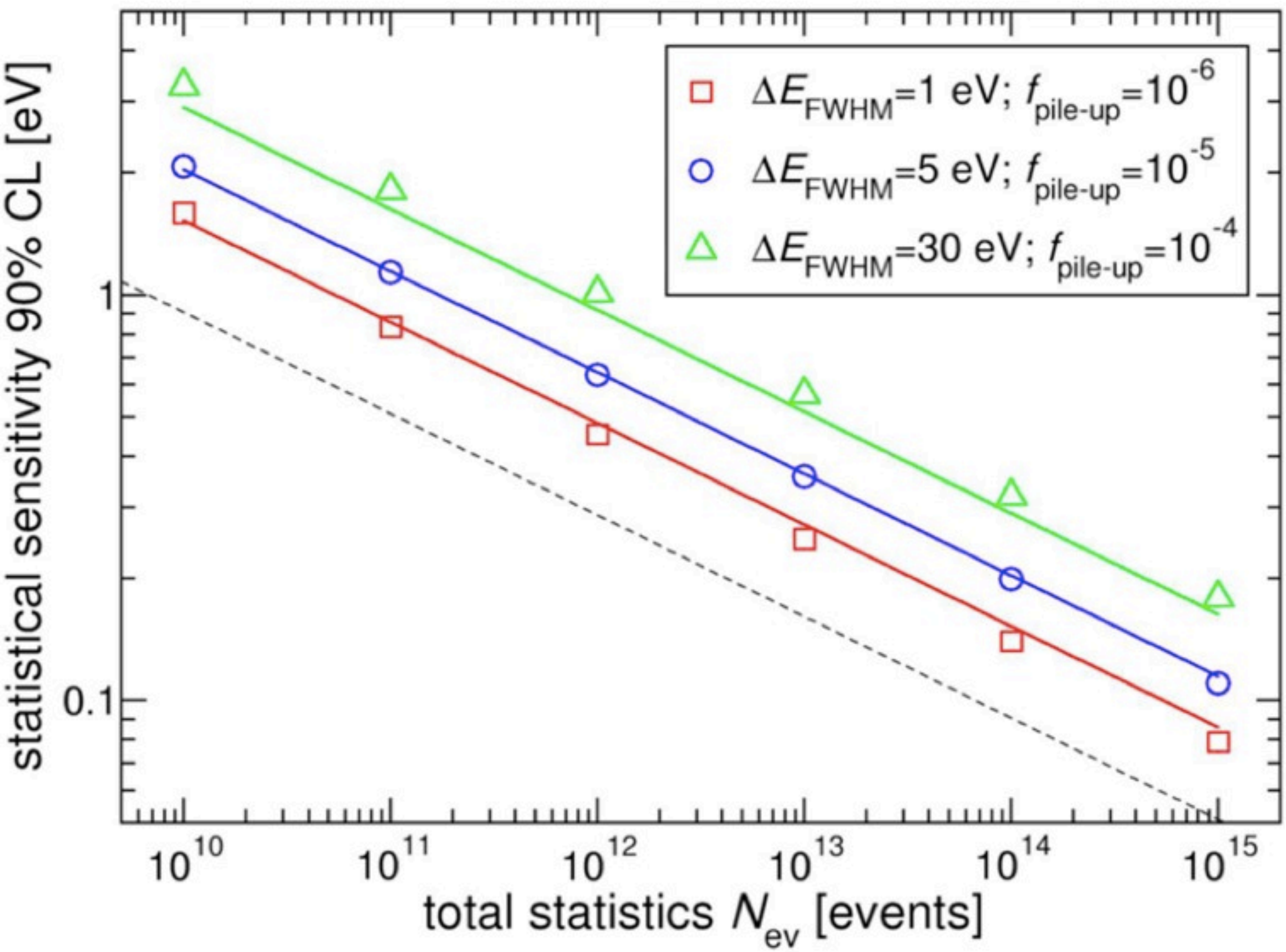
- ► energy resolution ΔE_{FWHM}
- ► time resolution τ_R
- ► exposure $t_{mea} = N_{det} \times T$
- ► single channel activity A_β



many unresolved experimental issues

^{187}Re experimental sensitivity (stat.)

A.Nucciotti et al., Astropart. Phys., 34 (2010) 80 (arXiv:0912.4638v1)



Total statistics so far:
N_{ev} ~ 10^7 events

Perspectives:
- 10-20 arrays
- 5000-10000 pixel/array
- 10 year

very challenging!

Electron capture m_ν measurements

$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$

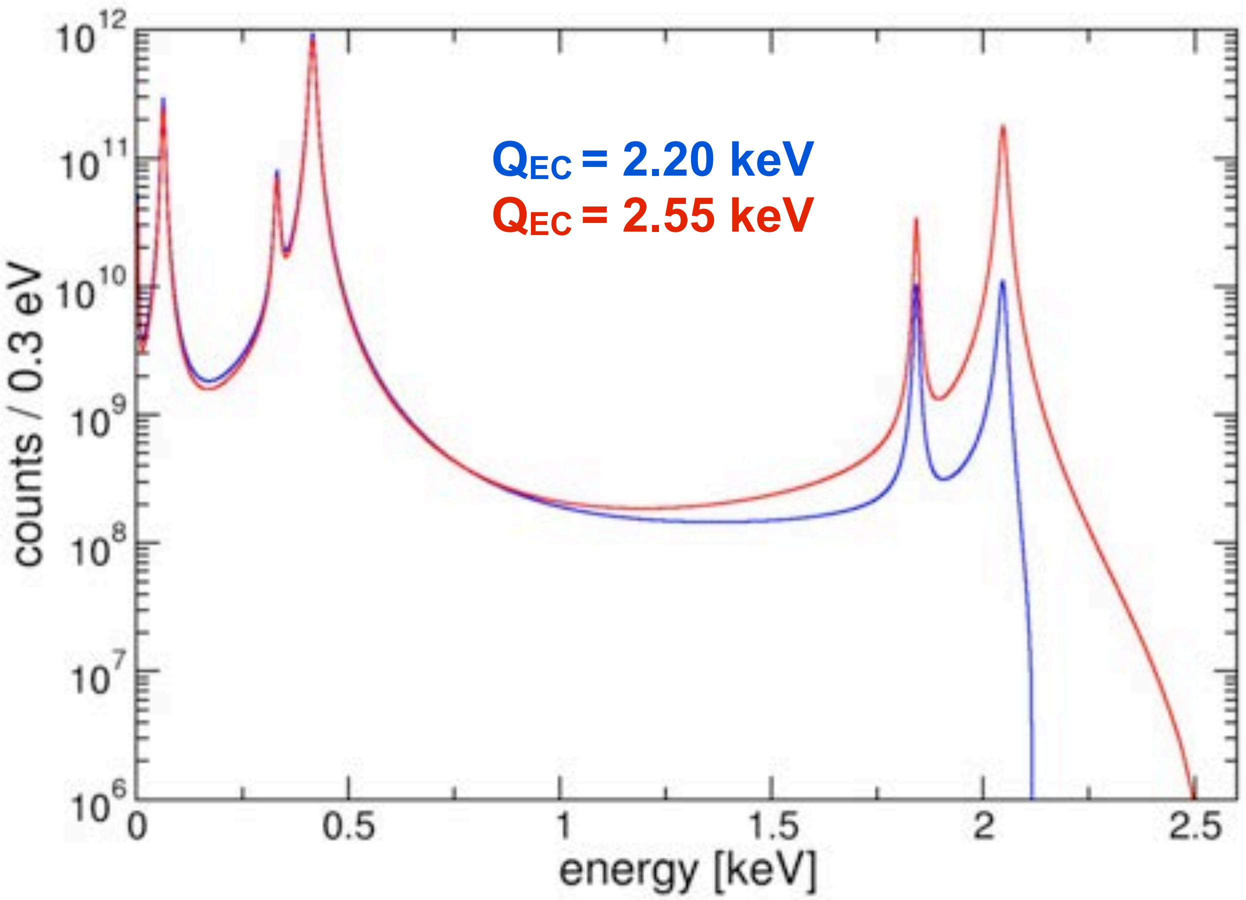
- Calorimetric measurement of Dy atomic de-excitations (mostly non-radiative)
- Rate at end-point and ν mass sensitivity depend on Q

$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2}(Q - E_c)\sqrt{(Q-E_c)^2 - m_\nu^2} \times \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi} \frac{1}{(E_c - E_i)^2 + \Gamma_i^2/4}$$

- Measured: Q_{EC} = 2.2-2.8 keV.
- Recommended: Q_{EC} = 2.555 keV
- $\tau_{1/2}$ ≈ 4570 years: few active nuclei needed

- No direct calorimetric measurement of Q so far
- Q and atomic de-excitation spectrum poorly known
- Complex pile-up spectrum

• A. De Rujula and M. Lusignoli, Phys. Lett. B 118 (1982) 429
• Addendum: arXiv:1305.4857v1



EC sensitivity

EC advantages

- higher specific activity → don't need an Holmium detector
- self calibrating → better systematics control

but

- higher Q → maybe less sensitive
- pile-up spectrum
- chemical effects on Q

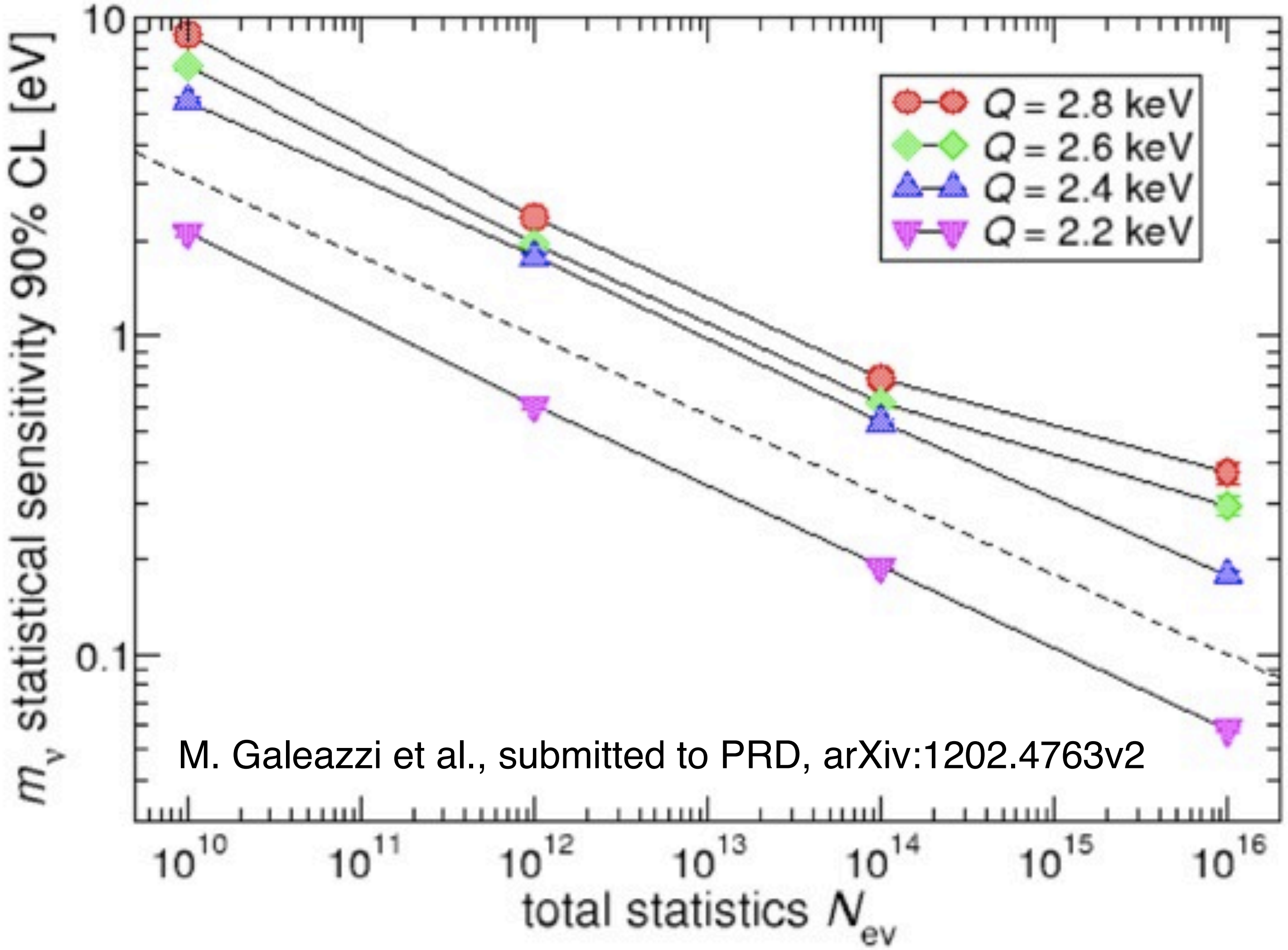
Two (LTD) projects so far

ECHO

MARE

Common technical challenges

- clean ^{163}Ho production
- ^{163}Ho incorporation
- large channel number → high speed MUX
- data handling (processing, storage, ...)



m_ν sensitivity	Number of arrays	Pixels/Array	δE (eV)	Q (eV)	Time scale (y)
0.2	3	5000	1	2200	1
0.1	4	5000	0.3	2200	10
0.3	5	60000	1	2800	5
0.1	100	60000	0.3	2800	10

Double Beta Decay

Very rare nuclear decay

(A,Z) → (A,Z+2) + 2e- (+?)

which can occurr according in different modes

$0\nu\beta\beta$ decay (neutrinoless DBD):

- → violates lepton number by 2 units
- → experimentally not observed
- → $T^{0\nu\beta\beta}_{1/2}$ (^{76}Ge) > ~10^{25} y
- → Current bounds limit neutrino mass scale to $m_\nu \leq O(\mathbf{0.1} - \mathbf{0.5})$ eV
- → Observation implies Physics beyond the standard model of particle physics

$2\nu\beta\beta$ decay:

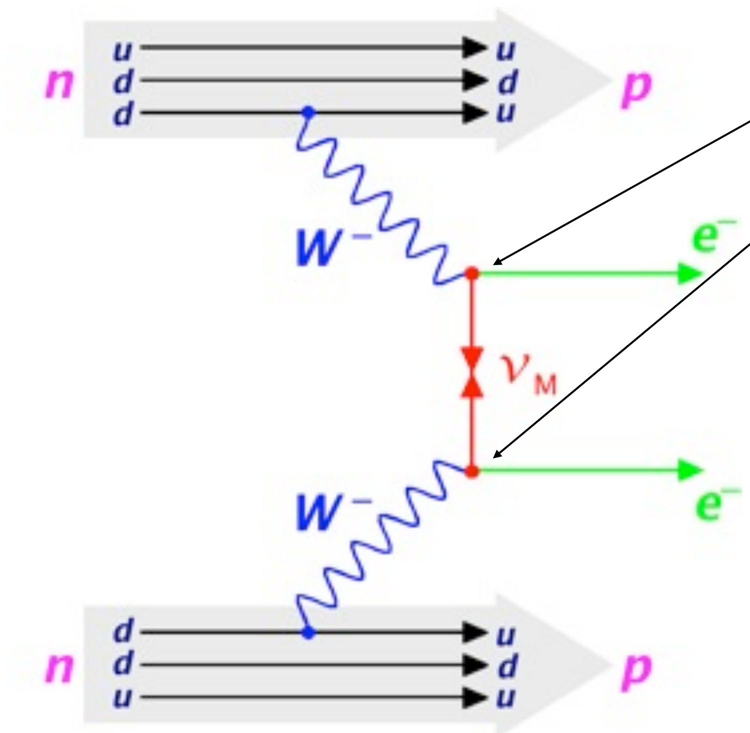
- allowed within Standard model,
  - 2nd order process in Fermi theory
- observed for 12 isotopes:
  - ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128,130}Te, ^{136}Xe, ^{150}Nd and ^{238}U
- First double beta plus decay: ^{130}Ba
- $\mathbf{T^{2\nu\beta\beta}_{1/2} \sim 10^{(19-25)}}$ **y**
- Important constraint for nuclear matrix element calculation

"Exotic" decays:

→ for example X = J, i.e. Majoron
→ experimentally not observed (and no rumours!)
→ Best limit from: $T^{0\nu\beta\beta J}_{1/2}$ (^{128}Te) > ~ few 10^{24} ys

0νββ: mass mechanism

Exchange of a light Majorana neutrino



RH antineutrino (L=1) is emitted at one vertex
LH neutrino (L=-1) is absorbed at the other vertex

- **Majorana particle**
- **Helicity flip (neutrino mass dependence)**

Half lifetime can be expressed as

$$\lambda_{0\nu} = \frac{1}{\tau_{0\nu}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 \frac{\langle m_{ee}\rangle^2}{m_e^2}$$

F_N: Nuclear Factor of merit

PHASE SPACE FACTOR

NME

EFFECTIVE MAJORANA MASS

$$< m_{ee} >= \sum_k U_{ek}^2 m_k$$

NEUTRINO MASS EIGENALUES

NEUTRINO MIXING MATRIX

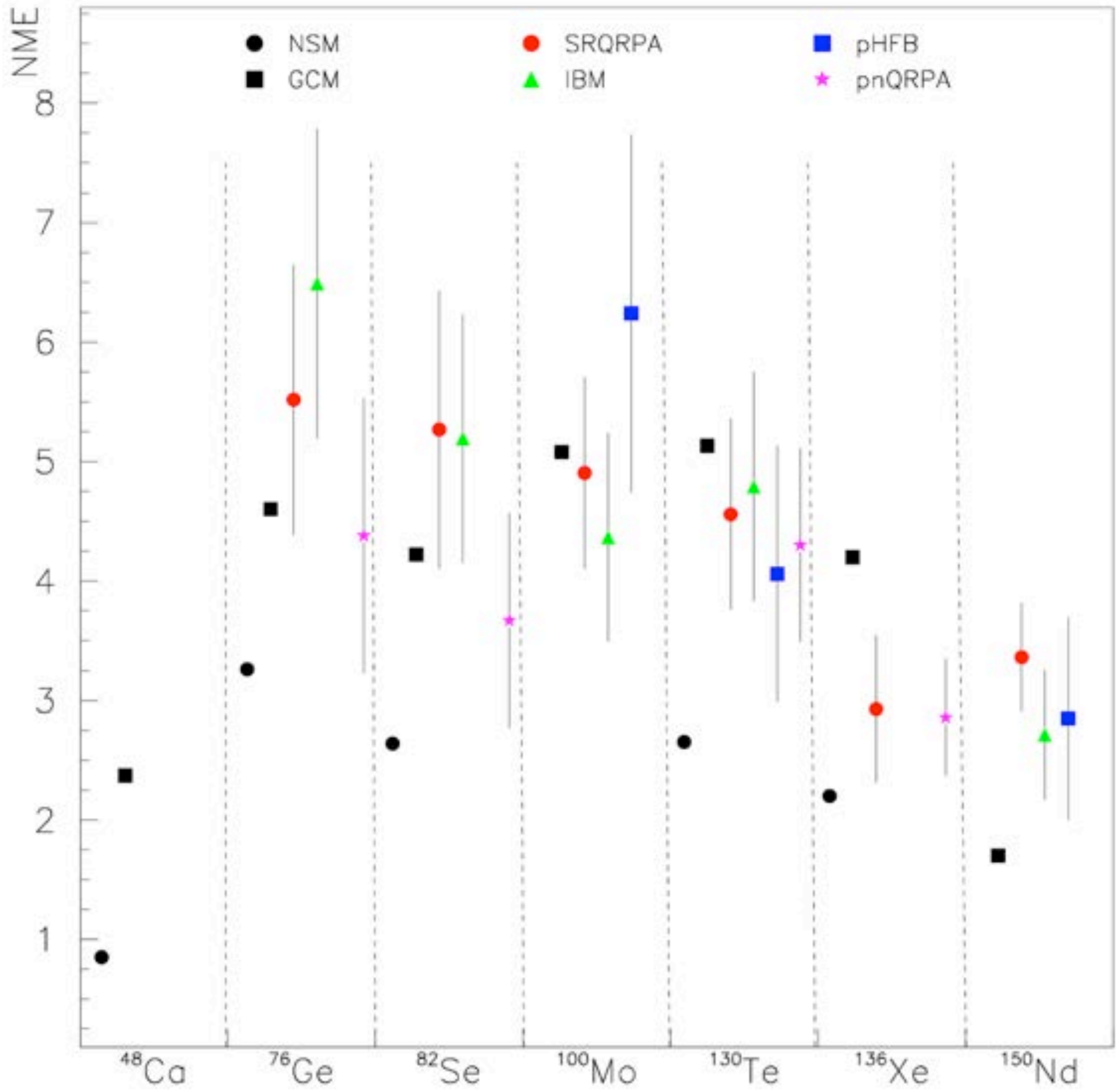
$$= c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3$$

N.B.: Majorana phases make m_{ee} cancellation possible ($\mathbf{m_{ee}}$ could be smaller than any of the $\mathbf{m_i}$).

Nuclear Matrix Elements

Nuclear matrix elements (NME) are calculated according to various models:
QRPA (RQRPA, SQRPA, …….), Shell model, IBM2 ...
Calculation discrepancies are one of the largest sources of uncertainties

NSM nuclear shell model, Nucl. Phys. A 818 (2009) 139.Phys. Rev. C80 (2009) 048501(1)
SRQRPA self-consistent renormalized quasiparticle random phase approx.(2), Phys Rev D83 (2011) 113015, Phys Rev C79 (2009) 055501(1), Phys Rev C83 (2011) 034320
pnQRPA proton-neutron QRPA, Nucl Phys A847 (2010) 207
GCM generating coordinate method Phys. Rev. Lett. 105 (2010) 252503.
IBM interacting boson model(3), Phys Rev C79 (2009) 044301
pHFB projected Hartree-Fock-Bogoliubov Phys Rev C82 (2010) 064310



- more groups calculate NME with different methods
- NSM lower than other calculations
- NME vary by factor 2-3 for a given nucleus
- ”errors” on NME calculations largely correlated for different A
- difference between QRPA calculations small
- **no** ”super” element from NME point-of-view

Experimental signature

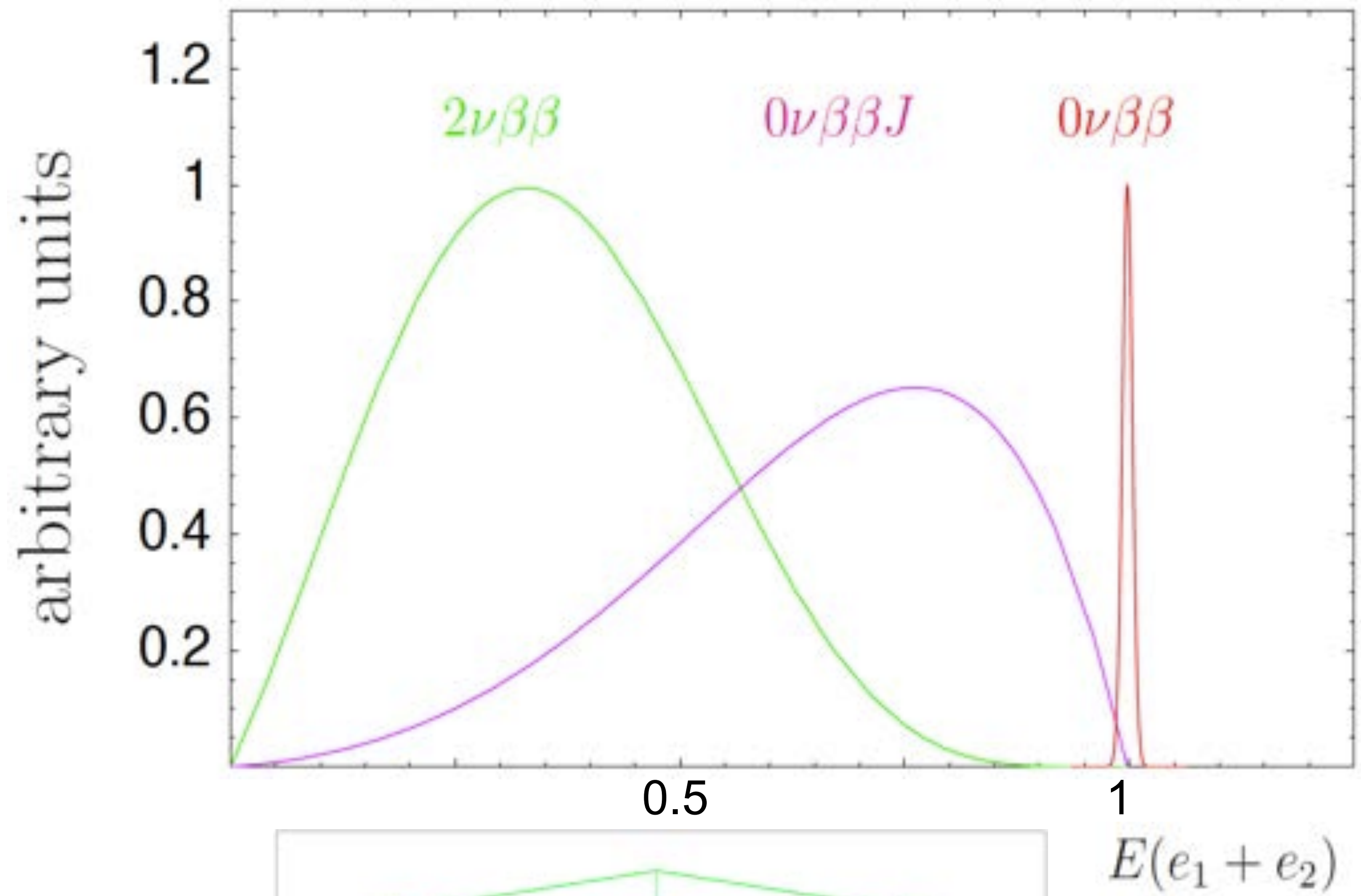
$(A,Z) \rightarrow (A,Z+2)^{++} + 2\ e-$

- A new (ionised) isotope
- Two electrons

Minimal information:

- two e^- energy sum spectrum

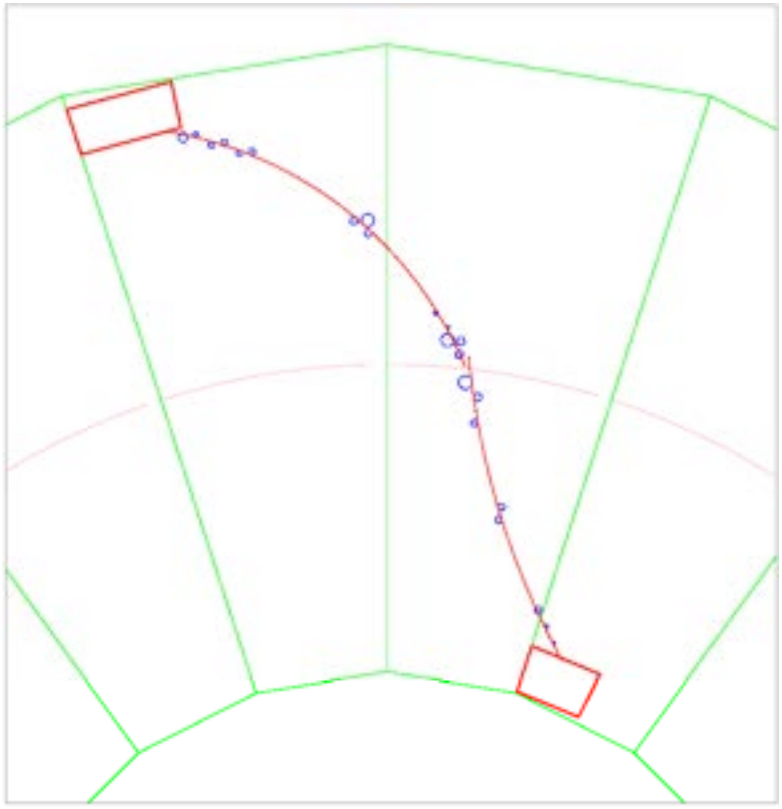
0νββ exhibits a **peak at Q** over 2νββ tail (and background contributions)



Additional signatures:

- Single electron energy spectrum
- Angular correlation between the two electrons
- Daughter nuclear species

Track and event topology
Time Of Flight



Moreover, to cure NME systematics:

- study as many as possible different isotopes

Experimental sensitivity

$$\tau^{0\nu}_{1/2} = ln2\frac{\epsilon N_{nuclei} t_{meas}}{N_{\beta\beta}}$$

Lifetime corresponding to the minimum detectable number of events over background at a given confidence level

$$N_{\beta\beta} \leq \sqrt{bkg \cdot \Delta E \cdot M \cdot t_{meas}}$$

N_{nuclei}	number of active nuclei in the experiment
t_{meas}	measuring time [y]
M	detector mass [kg]
ε	detector efficiency
i.a.	isotopic abundance
A	atomic number
ΔE	energy resolution [keV]
bkg	background [c/keV/y/kg]

N_B = bkg · ΔE · T · M

number of background events expected along the experiment lifetime

N_B >> 1

$$S^{0\nu}_{1/2} \propto \epsilon \frac{i.a.}{A} \sqrt{\frac{M \cdot t_{meas}}{bkg \cdot \Delta E}}$$

N_B ≤ O(1) → "zero background"

$$S^{0\nu}_{1/2} \propto \epsilon \frac{i.a.}{A} M \cdot t_{meas}$$

Performance

Scale

- **Isotopical abundance**
- **Mass**
- **Energy resolution**
- **Background level**

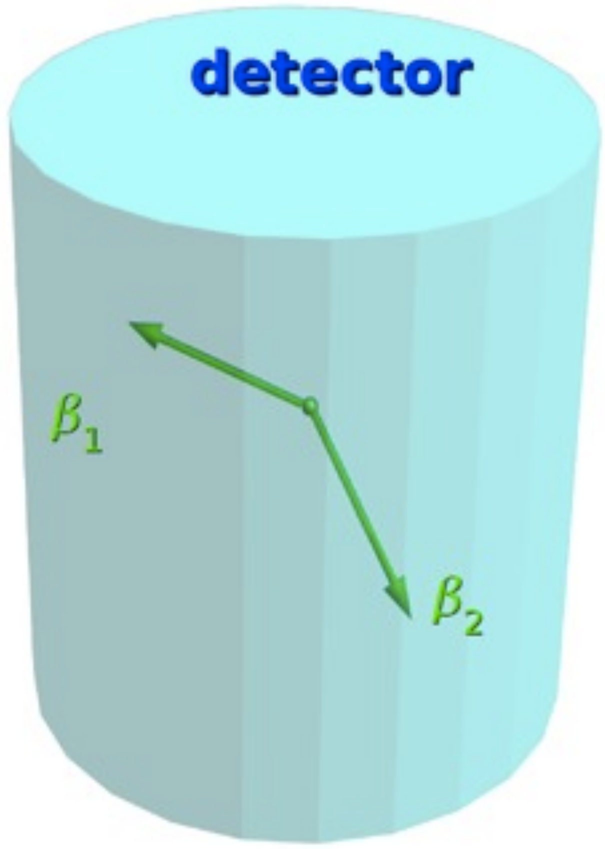
$< m_{ee} >$

$$\frac{1}{S^{0\nu}_{1/2}(m_{ee})} \propto \sqrt{S^{0\nu}_{1/2} \cdot G^{0\nu}} |M^{0\nu}|$$

- **Isotope choice**

Experimental approaches

Two main approaches:
- homogeneous (calorimetric or active source)
- inhomogeneous (external-source or passive source)



Calorimeters

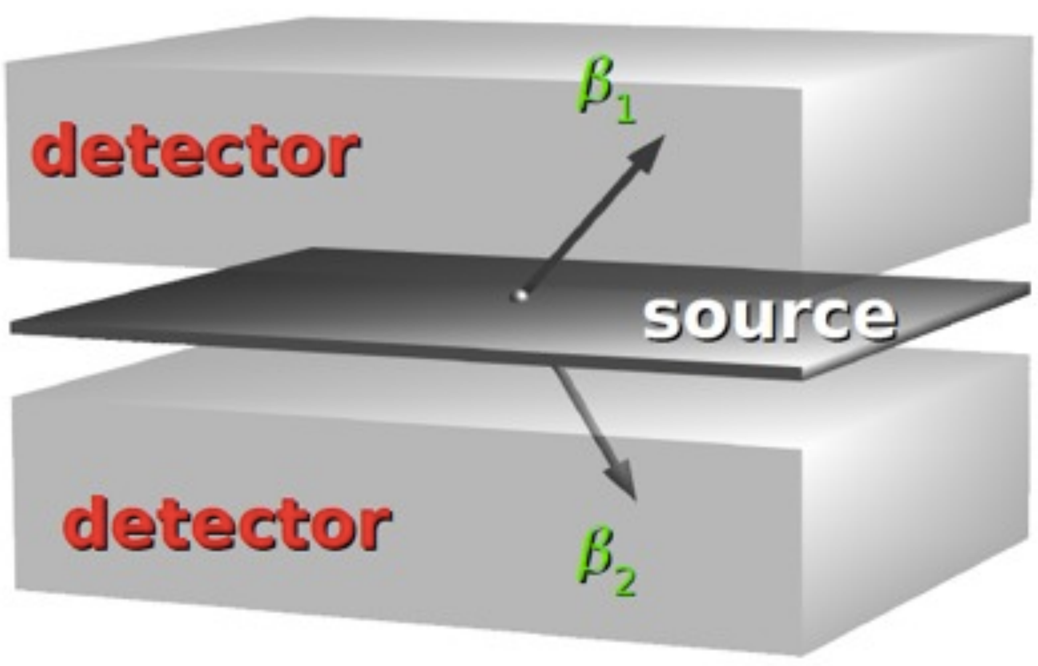
Solid-state devices, bolometers, scintillators, gas detectors

+ Very large M possible (demonstrated ~50kg, proposed ~1t)
+ High efficiency (ε~1)
+ Very high energy resolution (ΔE~0.015% with Ge-diodes, bolometers)
+ Event topology (in gas/liquid Xe detectors or pixellization)
+ Good background levels
- Constraints on detector choice (except for bolometers)
- No or partial particle id

External-source detectors

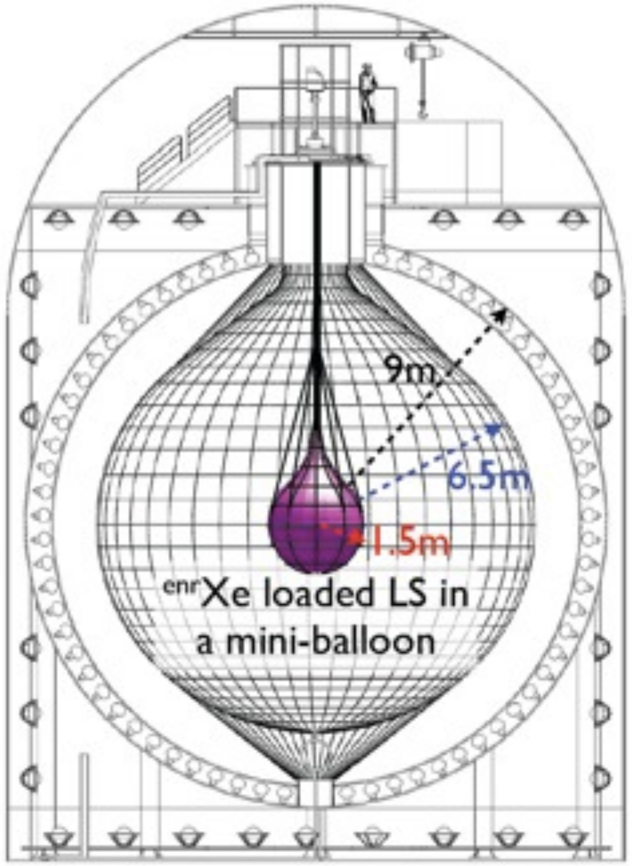
Scintillators, gas TPC, gas DC, magnetic field and TOF

+ Event topology allowing ¨clean bkg¨ (except 2νββ)
+ Several ββ candidates can be studied with same detector
- Difficult to get large source M
- Difficult to get high efficiency
- Difficult to get good resolution



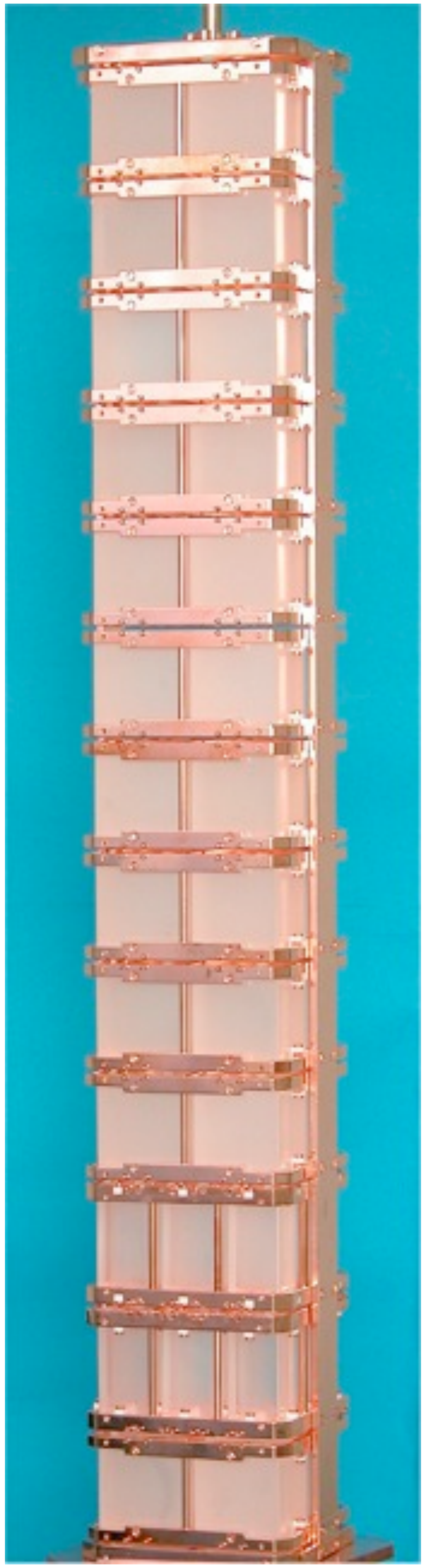
ββ(0ν) present and near past

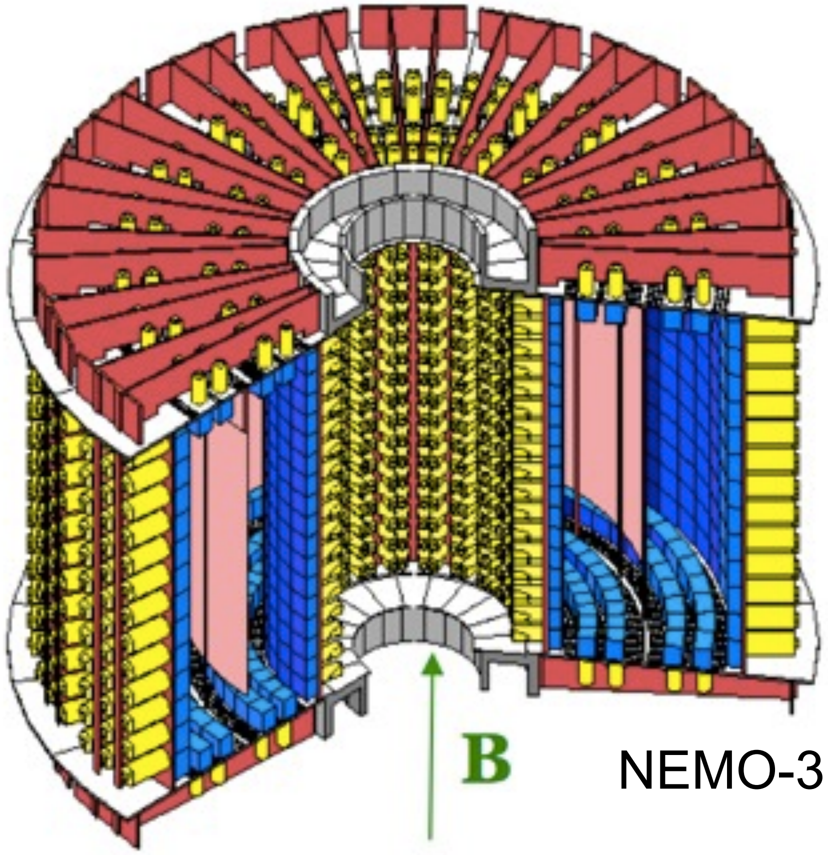
HDM & IGEX
GERDA-I



KamLAND-ZEN

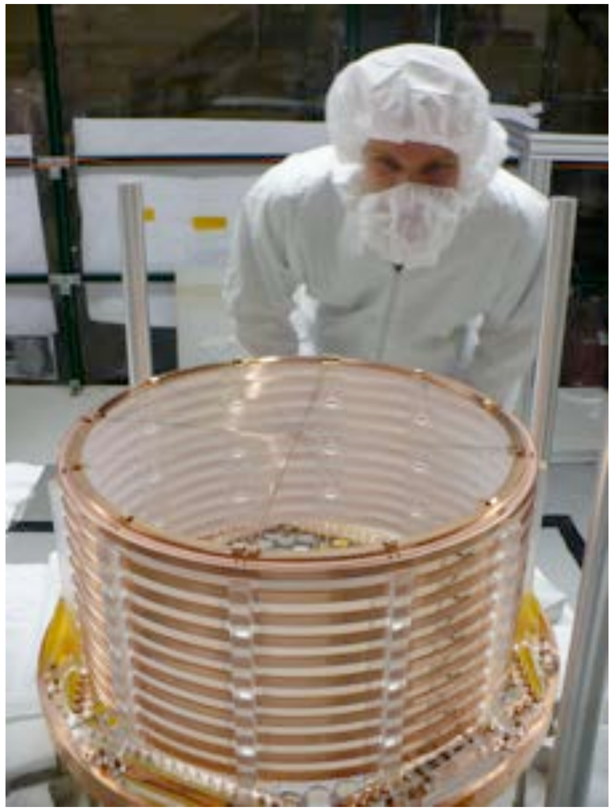
Cuoricino
CUORE0





NEMO-3

EXO-200



Present ββ(0ν) results

Isotope	$T^{2\nu}_{1/2}$ (10^{19} y)	$T^{0\nu}_{1/2}$ (10^{24} y)	$<m_{\beta\beta}>$ (meV)
^{48}Ca	4.4 ± 0.5 (stat) ± 0.4 (syst)	> 0.058	3515-14133
^{76}Ge		**$22.3^{+4.4}_{-3.1}$***	
^{76}Ge	150 ± 10	> 21 (30 comb.)	201-638
^{82}Se	9.6 ± 0.1 (stat) ± 1.0 (syst)	> 0.32	884-2631
^{96}Zr	2.35 ± 0.14 (stat) ± 0.16 (syst)	> 0.0092	4207-15139
^{100}Mo	0.716 ± 0.001 (stat) ± 0.054(syst))	> 1.0	334-946
^{116}Cd	2.88±0.04(stat)±0.16(syst)	> 0.17	1300-2440
^{130}Te	70±9(stat)±11(syst)	> 2.8	296-773
^{136}Xe	217.2 ± 1.7 (stat) ± 6(syst)	> 16	161-385
^{150}Nd	0.911±0.025(stat)±0.063(syst)	> 0.018	2622-5678

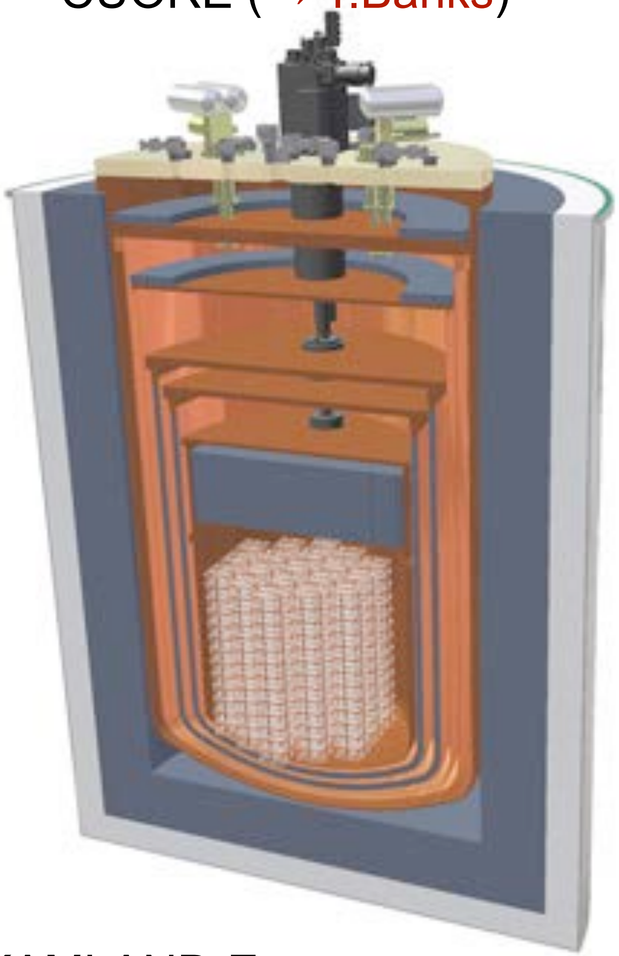
DBD experiments summary

Experiment	Isotope	Technique	Mass ββ(0v) isotope	Status
CANDLES	48Ca	305 kg of CaF2 crystals - liq. scint	0.3 kg	Construction
CARVEL	48Ca	48CaWO4 crystal scint.	~ tonne	R&D
GERDA I	76Ge	Ge diodes in LAr	18 kg	Operating
GERDA II	76Ge	Point contact Ge in LAr	18+21 kg	Construction
Majorana D	76Ge	Point contact Ge	30 kg	Construction
1TGe (GERDA +MJ)	76Ge	Best technology from GERDA and MAJORANA	~ tonne	R&D
NEMO3	100Mo/ 82Se	Foils with tracking	6.9/0.9 kg	Complete
SuperNEMO D	82Se	Foils with tracking	7 kg	Construction
SuperNEMO	82Se	Foils with tracking	100 kg	R&D
LUCIFER	82Se	ZnSe scint. bolometer	18 kg	R&D
AMoRE	100Mo	CaMoO4 scint. bolometer	50 kg	R&D
MOON	100Mo	Mo sheets	200 kg	R&D
COBRA	116Cd	CdZnTe detectors	10 kg/183 kg	R&D
CUORICINO	130Te	TeO2 Bolometer	10 kg	Complete
CUORE-0	130Te	TeO2 Bolometer	11 kg	Operating
CUORE	130Te	TeO2 Bolometer	206 kg	Construction
SNO+	130Te	0.1% natNd suspended in Scint	55 kg	Construction
KamLAND-ZEN	136Xe	2.7% in liquid scint.	380 kg	Operating
NEXT-100	136Xe	High pressure Xe TPC	80 kg	Construction
EXO200	136Xe	Xe liquid TPC	160 kg	Operating
nEXO	136Xe	Xe liquid TPC	~ tonne	R&D
DCBA	150Nd	Nd foils & tracking chambers	20 kg	R&D

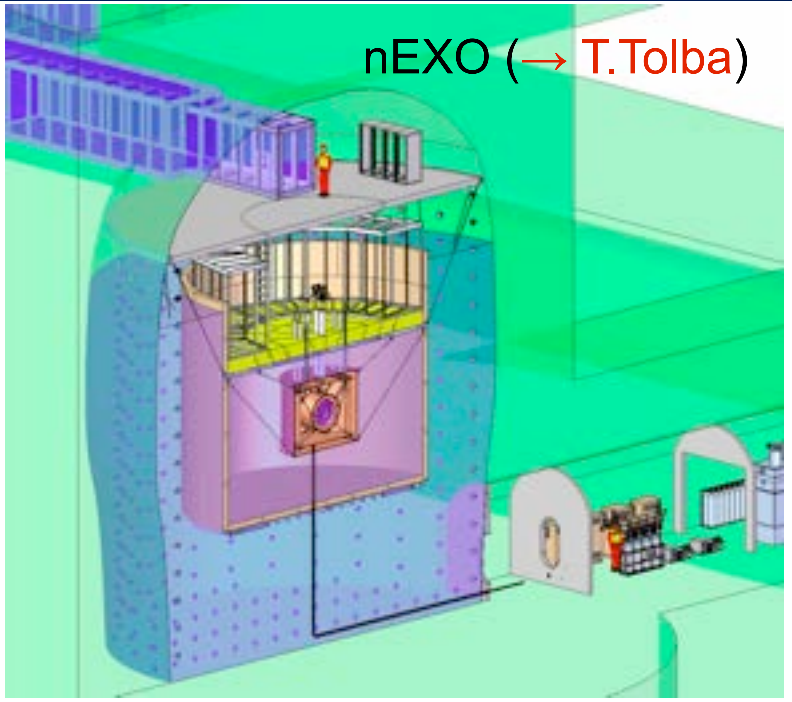
DBD future

GERDA (→ C.Cattadori)

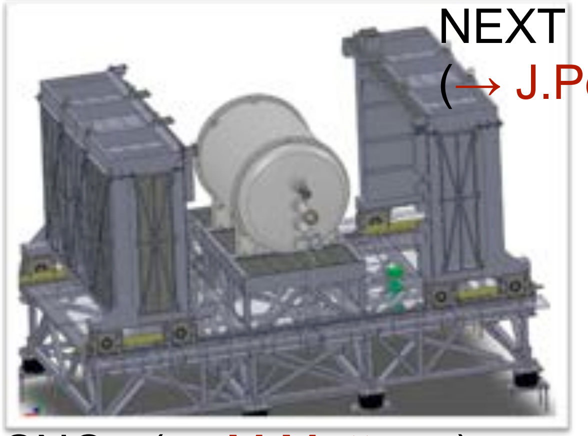
CUORE (→ T.Banks)



nEXO (→ T.Tolba)

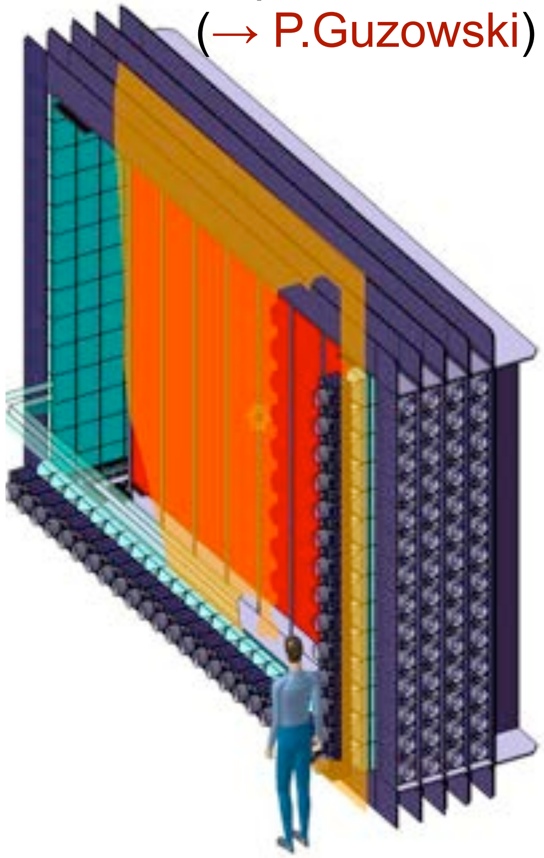


NEXT (→ J.PerezPerez)



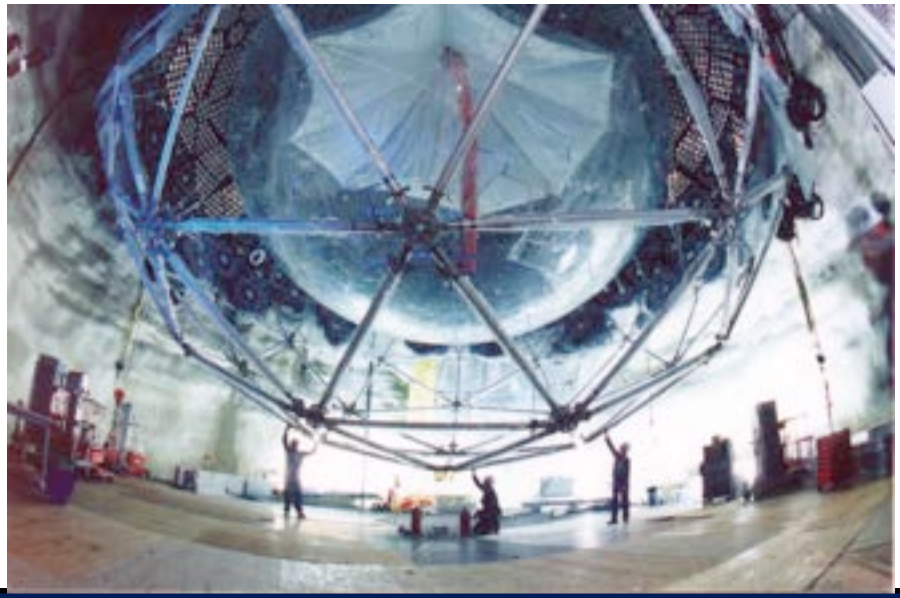
MAJORANA

SuperNEMO (→ P.Guzowski)



KAMLAND-Zen

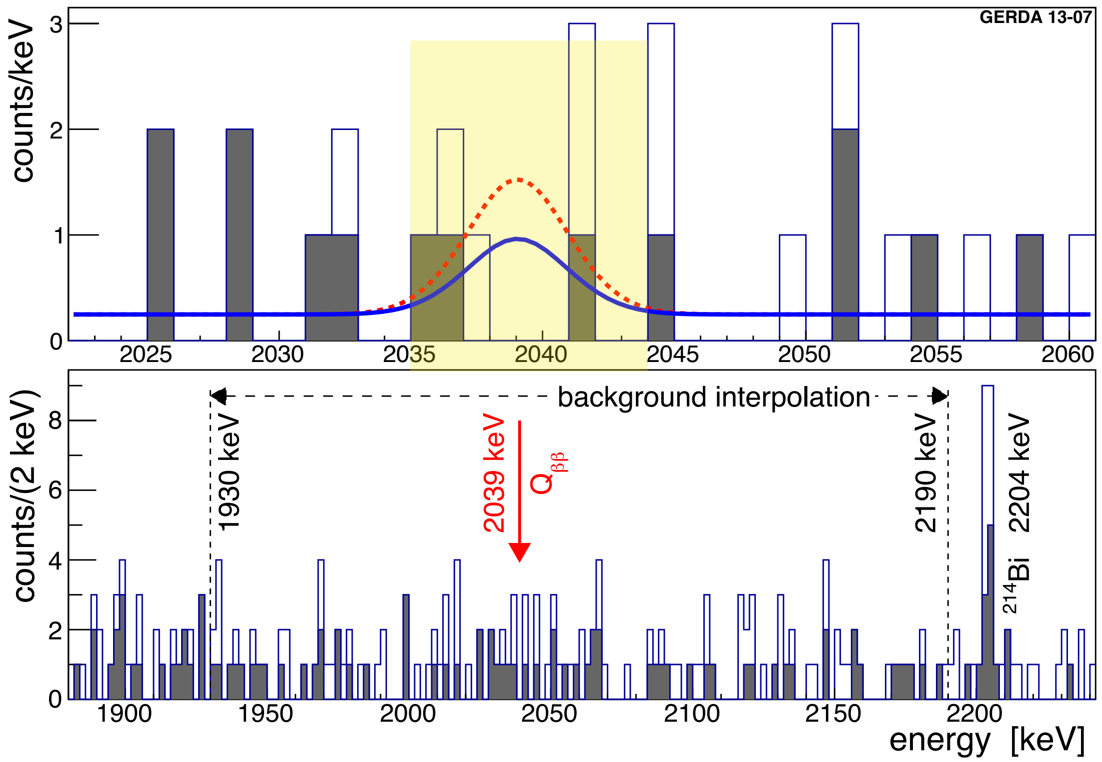
SNO+ (→ M.Mottram)

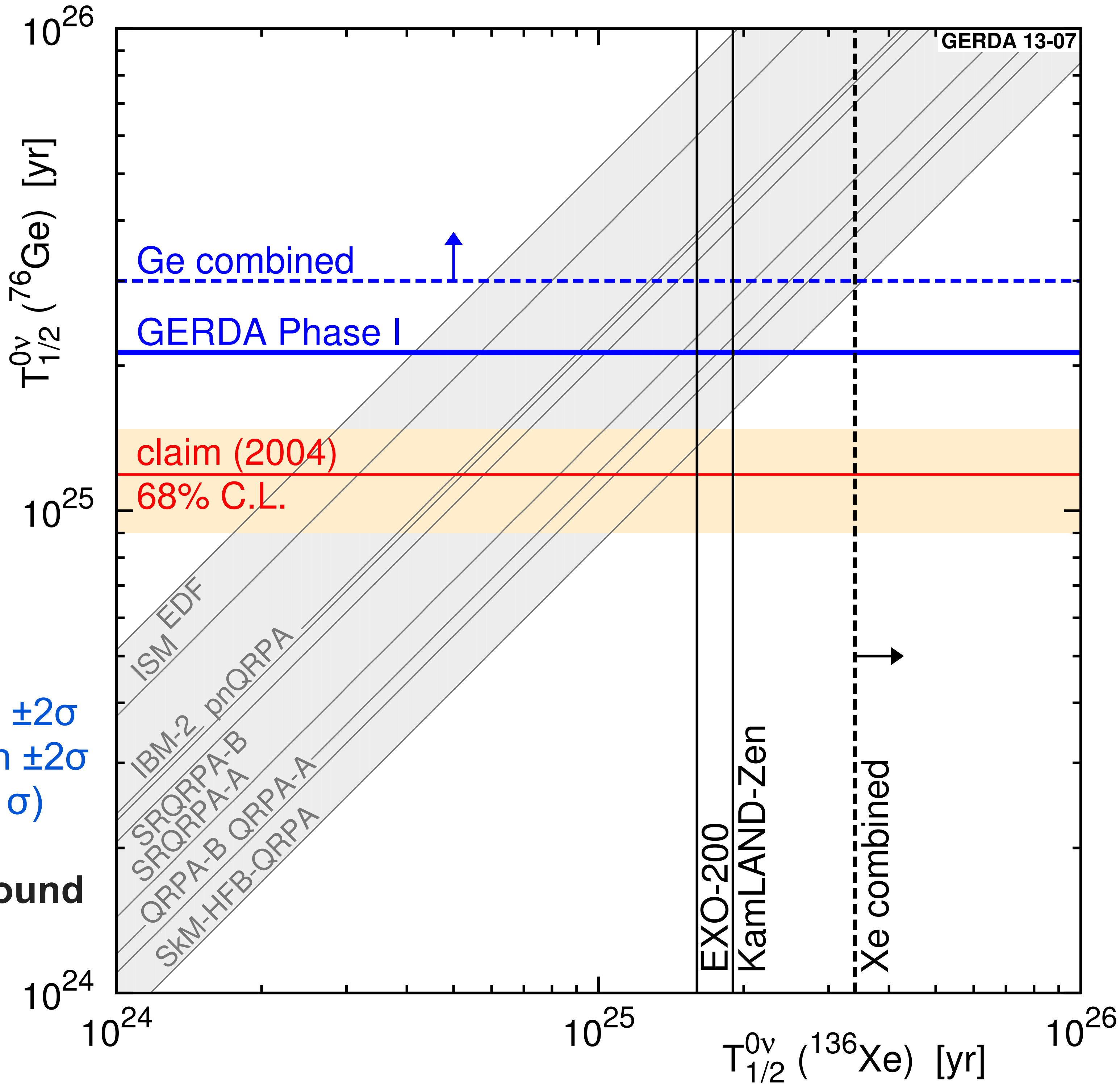


GERDA-I ββ(0ν) results and ^{76}Ge claim

GERDA Coll., arXiv:1307.4720

GERDA : **$T_{1/2}^{0\nu}$ > 2.1 x 10^{25} yr @ 90% CL**
GERDA combined w. IGEX & HdM: **$T_{1/2}^{0\nu}$ > 3.0 x 10^{25} yr @ 90% CL**





Best fit: $N^{0\nu}$ = 0, $N^{0\nu}$ < 3.5 cts @ 90% C.L.

For $T_{1/2}^{0\nu}$ = 1.19 x 10^{25} yr:

- Expected Signal (after PSD): 5.9 ± 1.4 cts in ±2σ
- Expected Bckgd (after PSD): 2.0 ± 0.3 cts in ±2σ
- Observed: 3.0 (0 in ±1σ)

Comparing H1(Claimed signal) to H0(Background only):

- P(H1)/P(H0)=2·10^{-4}
- Assuming H1: P ($N^{0\nu}$=0 | H1)=1%

→ Claim poorly credible

Sensitivity revisited

$z = \eta \cdot \varepsilon / A$

$N_B >> 1$

$$S^{0\nu}_{1/2} \propto \epsilon \frac{i.a.}{A} \sqrt{\frac{M \cdot t_{meas}}{bkg \cdot \Delta E}}$$

$N_B \leq O(1)$ → "zero background"

$$S^{0\nu}_{1/2} \propto \epsilon \frac{i.a.}{A} M \cdot t_{meas}$$

By generalizing:

- $n' = M \cdot z$
- $B' = B/z$

$T \equiv t_{meas}$
$B \equiv bkg$
$\Delta \equiv \Delta E$
$\eta \equiv a.i.$

and re-defining

1. **$x' \equiv n' \cdot T \equiv$ S(cale)**
2. **$y' \equiv B' \cdot \Delta \equiv$ [P(erformance)]$^{-1}$**

we completely get rid of the "z" block and get an effective and objective comparison

The condition

$N_B = (B' \cdot \Delta E) \cdot (n' \cdot T) = x' \cdot y' = P \cdot S$

still holds

Meaning:

n' ≡ number of "effective" moles of ββ isotope
B' ≡ background rate normalized to the number of "effective" moles of ββ isotope

$$S^{0\nu}_{1/2} \propto \sqrt{S \cdot P}$$

$$S^{0\nu}_{1/2} \propto S$$

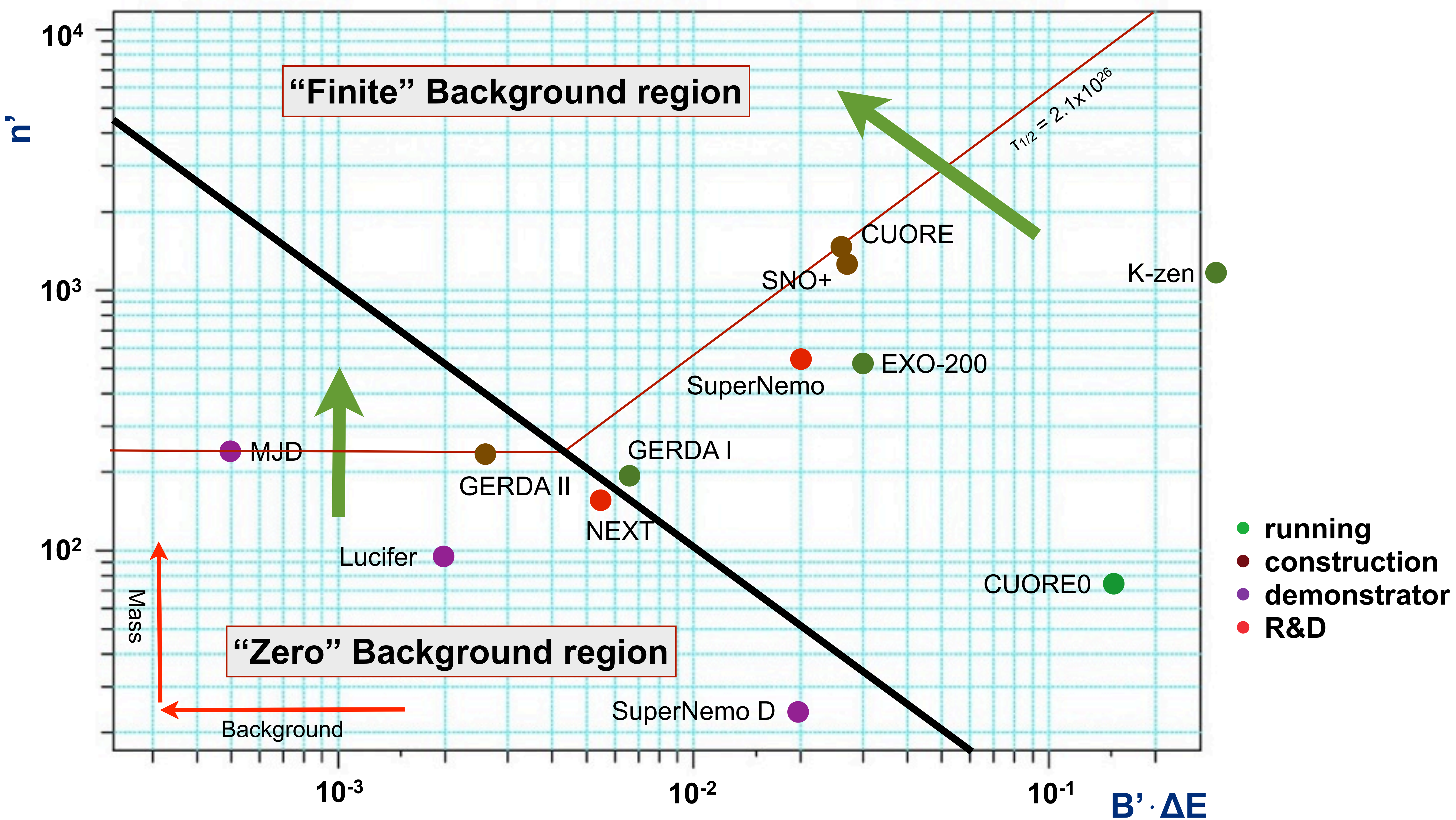
Future ββ(0ν) experiments

IBM2 - Phys. Rev.} C 79 (2009) 044301

	Isotope	B_{iso} (10^{-3} c/keV/kg/y)	FWHM (keV)	$(Performance)^{-1}$ [B'·Δ]	Scale [n'· T]	Status	$F^{0\nu}(1\sigma)$ (10^{26} y)	$<m_\nu>$ (meV)
CUORE	^{130}Te	29	5	2.73E-02	1390	P	**2.1**	60
SNO+	^{130}Te	1.4	240	2.78E-02	1252	D	**2.0**	62
GERDA I	^{76}Ge	21	4.8	6.39E-03	146	R	**1.4**	136
GERDA II	^{76}Ge	7/1	3.2	2.75E-03/3.9E-04	170	D	**2.3/2.4***	105/103
MJD	^{76}Ge	1.2	4	4.91E-04	244	P	**3.5***	86
EXO	^{136}Xe	1.9	97	3.15E-02	463	R	**1.2**	99
NEXT	^{136}Xe	0.8	13	5.44E-03	165	D	**1.6**	82
KamLAND-Zen	^{136}Xe	9.4	243	3.11E-01	1030	R	**0.5**	144
SuperNEMO D	^{82}Se	0.6	120	2.00E-02	23	D	**0.3**	170
SuperNEMO	^{82}Se	0.6	130	2.00E-02	461	D	**1.4**	82
LUCIFER	^{82}Se	1.05	10	1.80E-03	96	D	**1.4***	102

A further generalization

n' = number of "effective" isotope moles B' = counts/keV/n'/yr

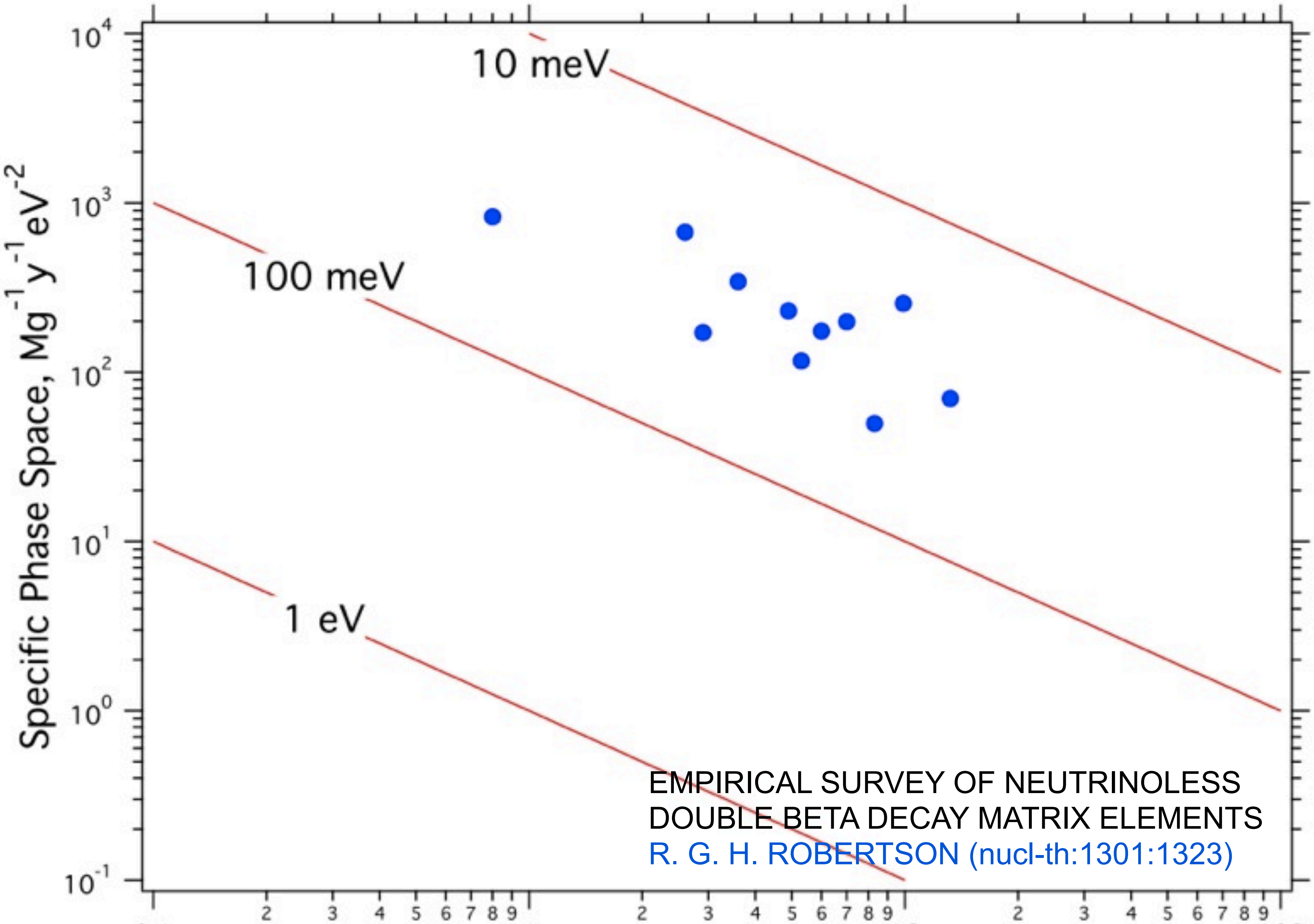


NME revisited

An alternative (stronger) view of the "no super element" statement:

$M^{0v} \rightarrow F^{0v} = G^{0v} |M^{0v}|^2$

If this holds:
conclusions about τ sensitivity translate directly (within a non negligible uncertainty range) on m_{ee} sensitivity



EMPIRICAL SURVEY OF NEUTRINOLESS DOUBLE BETA DECAY MATRIX ELEMENTS
R. G. H. ROBERTSON (nucl-th:1301:1323)

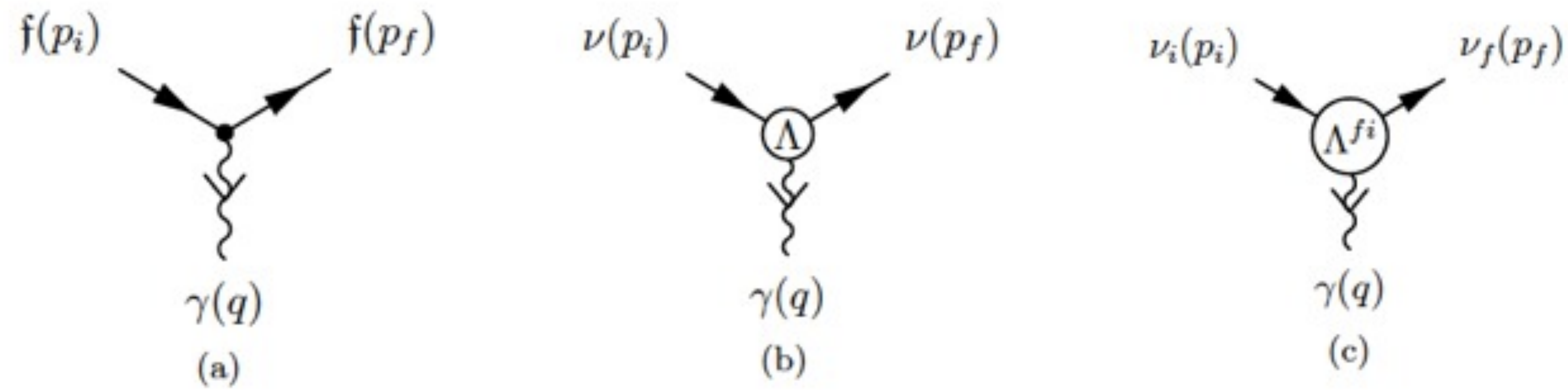
For the sake of ...

→talk A.Studenikin

- Neutrinoless DBD is not the only experimental probe for Majorana neutrinos
- Electromagnetic properties of neutrinos could work as well
- Neutrino magnetic moment and mass are strictly related:

$$\mu^{\nu_e} = \frac{3eG_F}{\sqrt{2}8\pi^2} m_{\nu_e} \sim 3 \cdot 10^{-19} \mu_B \left(\frac{m_{\nu_e}}{1eV}\right)$$

- Couplings:



(a) Tree-level coupling of a charged fermion f with a photon γ
(b) Effective coupling of a neutrino ν with a photon
(c) Effective coupling of neutrinos with a photon including transitions between two different i ν_i and ν_f

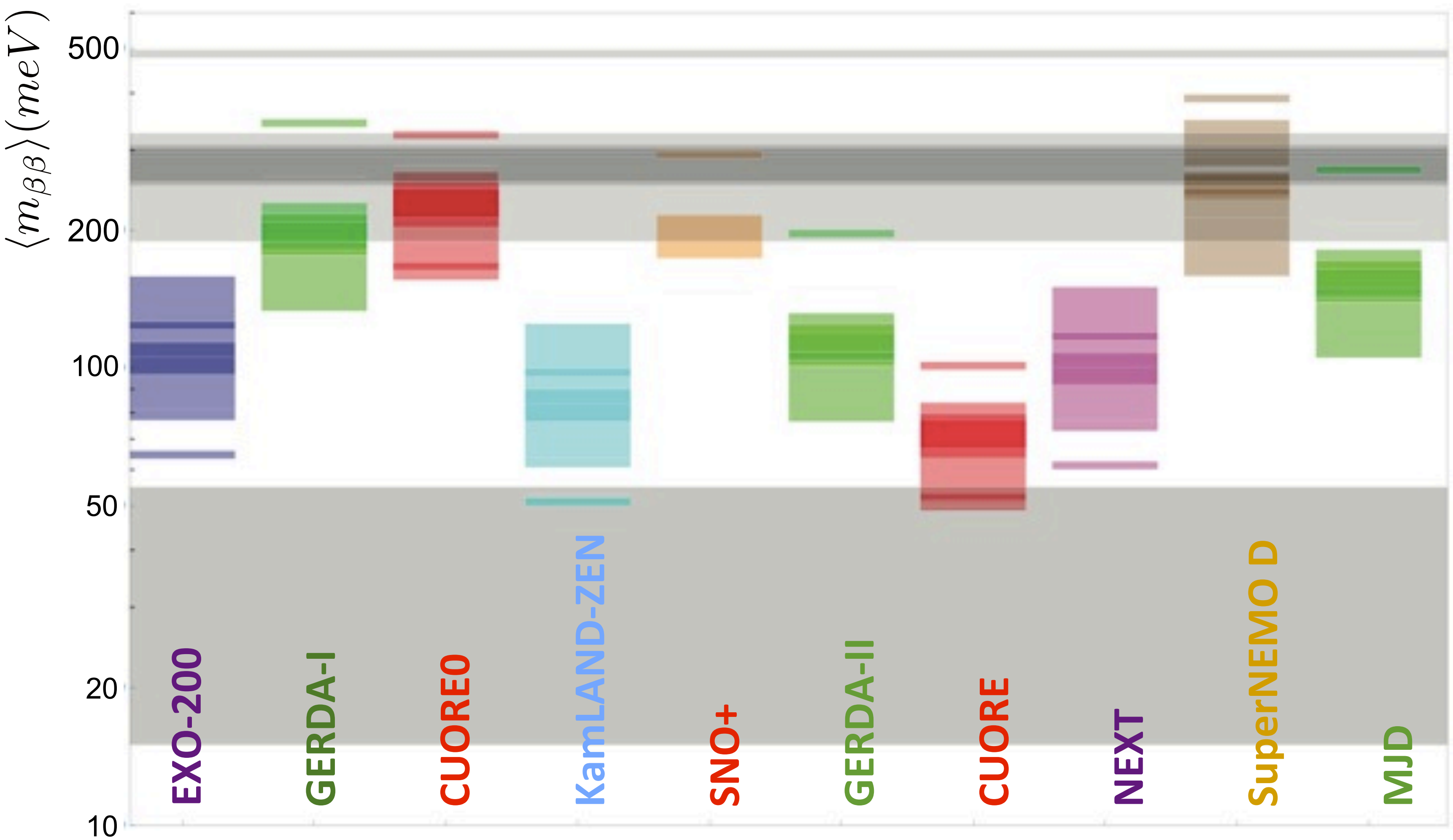
(b) is forbidden for a Majorana ($f_Q=f_M=f_E=0$) neutrino so observation of μ^ν would signal that neutrinos are Dirac particles ($f_E=0$).

Unfortunately, astrophysical or cosmological sensitivities are much worse!

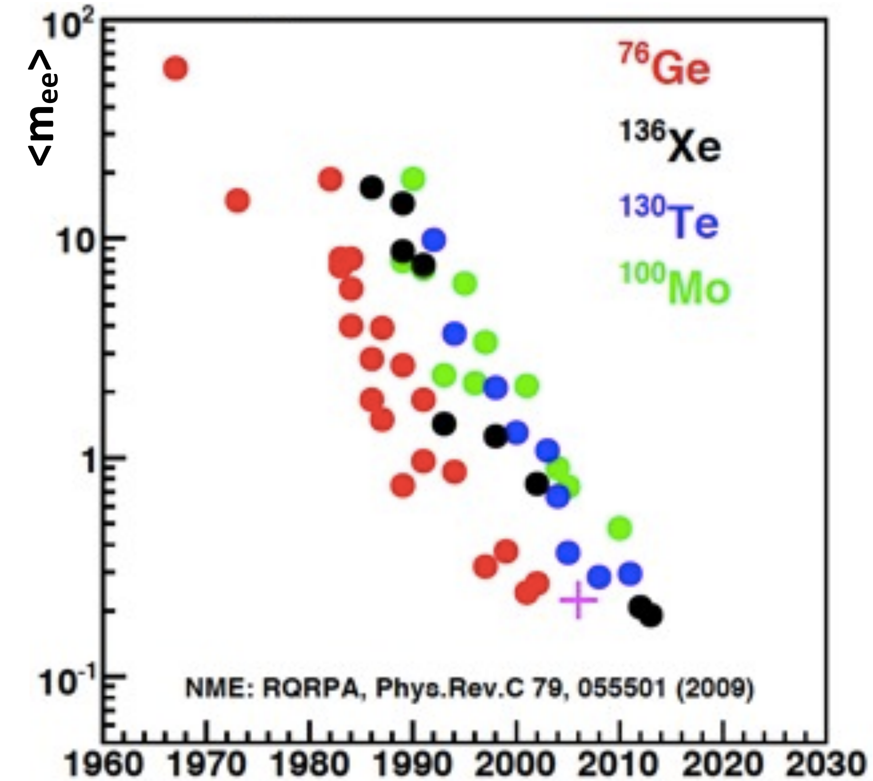
Bounds:

- Astrophysics: $\mu^{\nu_e} \leq 3 \cdot 10^{-12} \mu_B$
- Reactors (Beda et al. (GEMMA Coll.) 2012 $\mu^{\nu_e} \leq 2.9 \cdot 10^{-11} \mu_B$

DBD perspectives

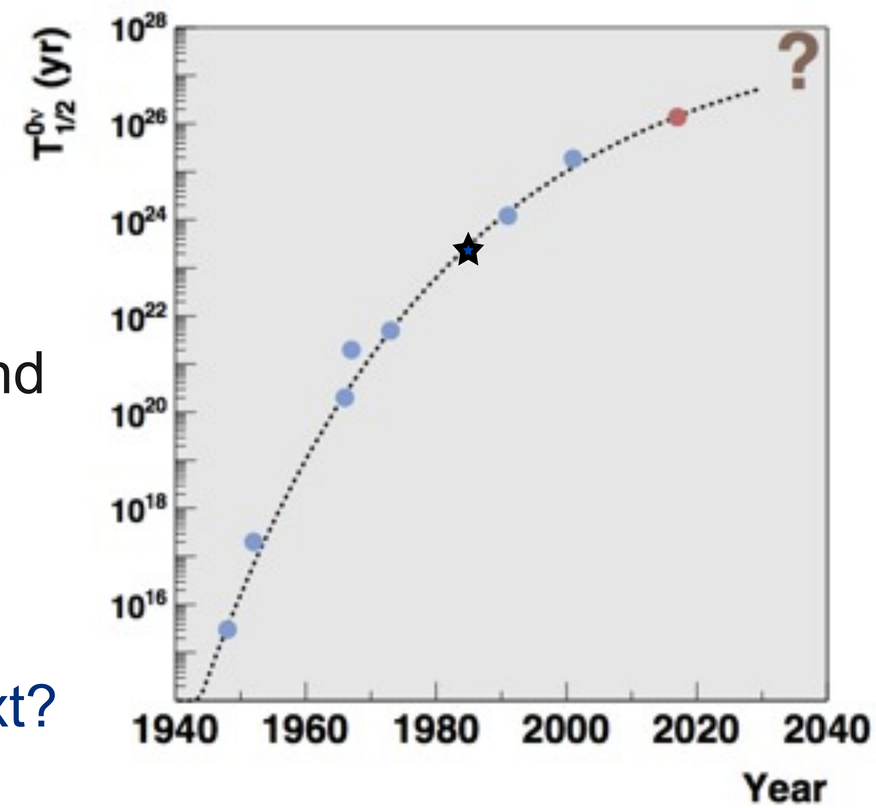


Published results as a function of time



Sensitivity of next generation experiments to the neutrino effective mass m_{ee} under assuming optimistic experimental assumptions and five different frameworks for NME calculations.

What's next?



Cosmological constraints

→talk S.Hannestad

Concept:

- Neutrino number density ~ 112 neutrinos per cm^3 per species.

$$f_\nu = \frac{\Omega_\nu}{\Omega_m} = \frac{\sum_i m_i(\nu)}{93\Omega_m h^2 eV} \approx 0.08 \frac{\sum_i m_i(\nu)}{1(\mathrm{eV})}$$

- Neutrinos disturb the delicate balance between gravity and the Hubble expansion.
- eV neutrinos however stream: d_{FS} ~ 1 Gpc/m_ν(eV)
- Therefore they suppress structure formation for scales smaller than d_{FS} while leaving unaffected larger scales.
- This can be detected in small alterations to the CMB, via gravitational lensing.

Model ingredients:

- General relativity holds at all length scales
- The universe is flat and consists of photons, three neutrinos, baryons, cold dark matter, and dark energy.
- The initial conditions are those of the simplest single-field inflation model (adiabatic perturbations described by a single spectral index).

→ In total: six free parameters + neutrino masses for the simplest model.

Cosmological bounds

- Present bounds on neutrino masses depend on the used data set and model (allowed parameters)
- A variety of data sets and models are available and many analyses can be found in the literature

PLANCK analysys of cosmological parameter (arXiv:1303.5076)

$\Sigma m_\nu < 1.08$ eV @ 95 C.L. (Planck only)

$\Sigma m_\nu < 0.32$ eV @ 95 C.L. (Planck + BAO)

PLANCK

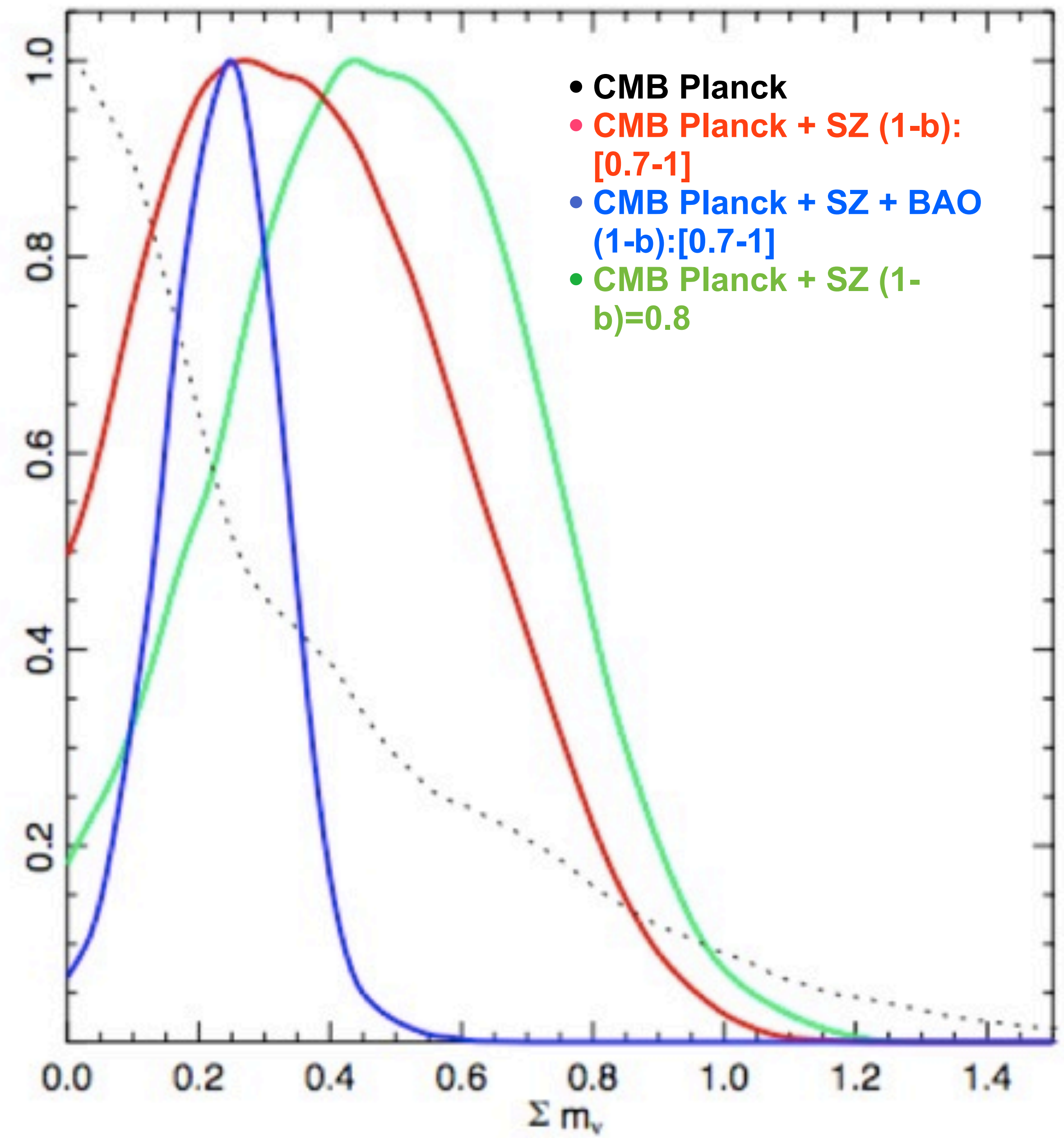
Planck Coll., arXiv:1303.5080

Σm(ν) constraints

- Planck has identified 189 galaxy clusters via the Sunyaev-Zeldovich effect on the CMB.
- These clusters can be used to measure Σm(ν) via its effect on galaxy structure formation.
- CMB data + BAO indicates that more clusters should have been found, indicating some tension in the data.
- One possible solution is to introduce a neutrino mass of magnitude

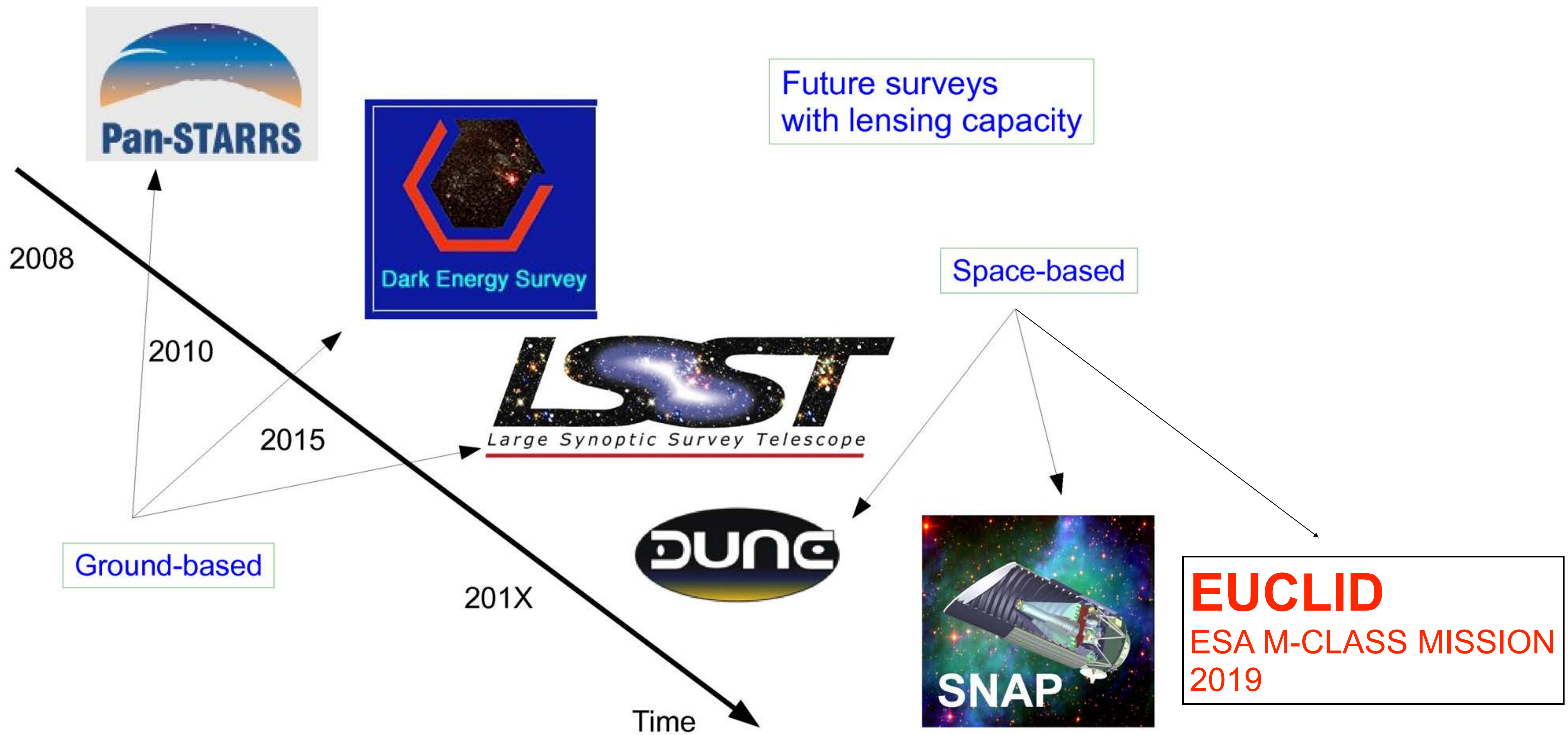
$\Sigma m(\nu) = 0.58 \pm 0.20$ eV

The same effect was seen last year by the SPT (Zou, et al., arXiv:1212:6267)



What's next?

- Improved CMB polarization measurements
- Large scale surveys at higher redshifts and larger volumes
- Weak gravitational lensing on large scales

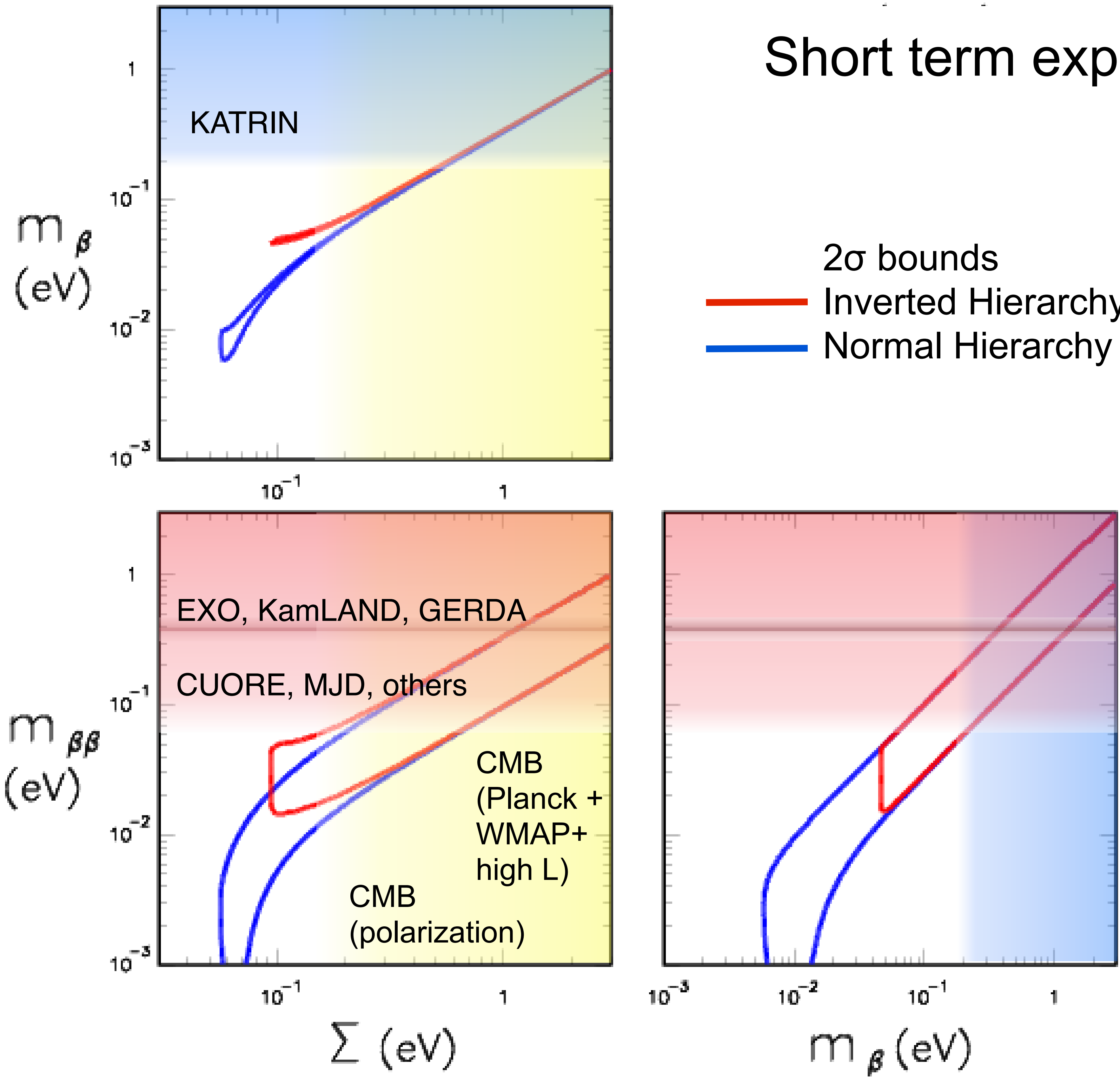


from S.Hannestad talk

Combining results

G.L Fogli, et al, PRD 78 033010 (2008), arXiv:hep-ph/0805.2517v3

Short term expectations: ~ 5 years



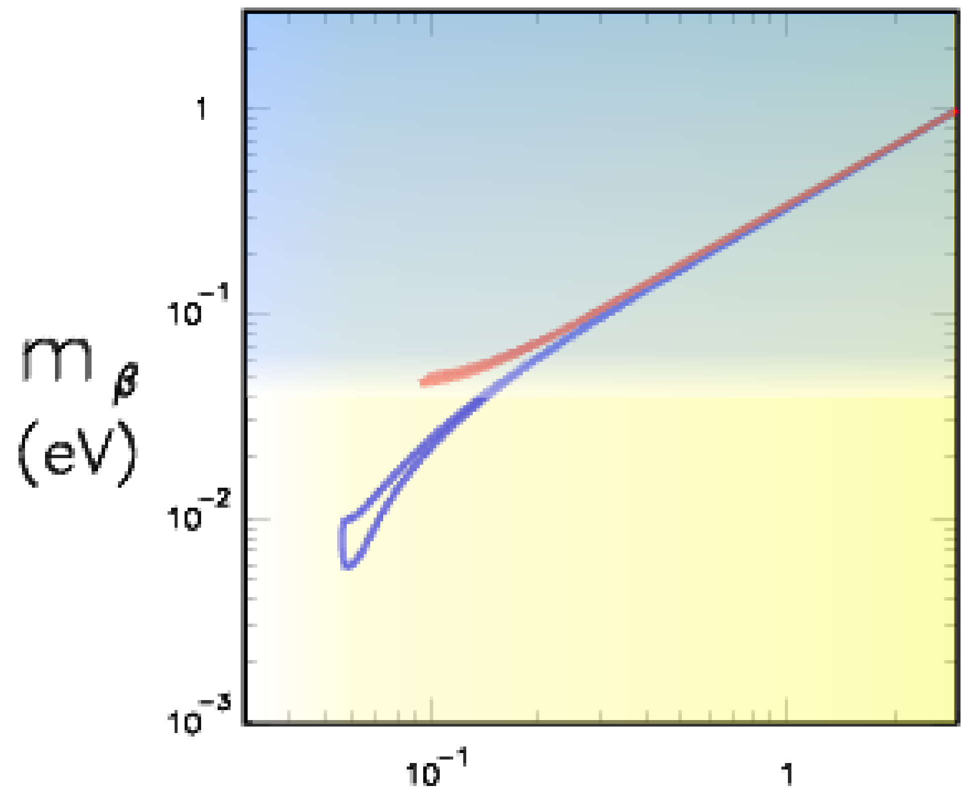
2σ bounds
Inverted Hierarchy
Normal Hierarchy

Claim for ββ-0ν observation in ^{76}Ge
HV. Klapdor-Kleingrothaus et al.Mod. Phys. Lett. A, 21 (2006) 1547

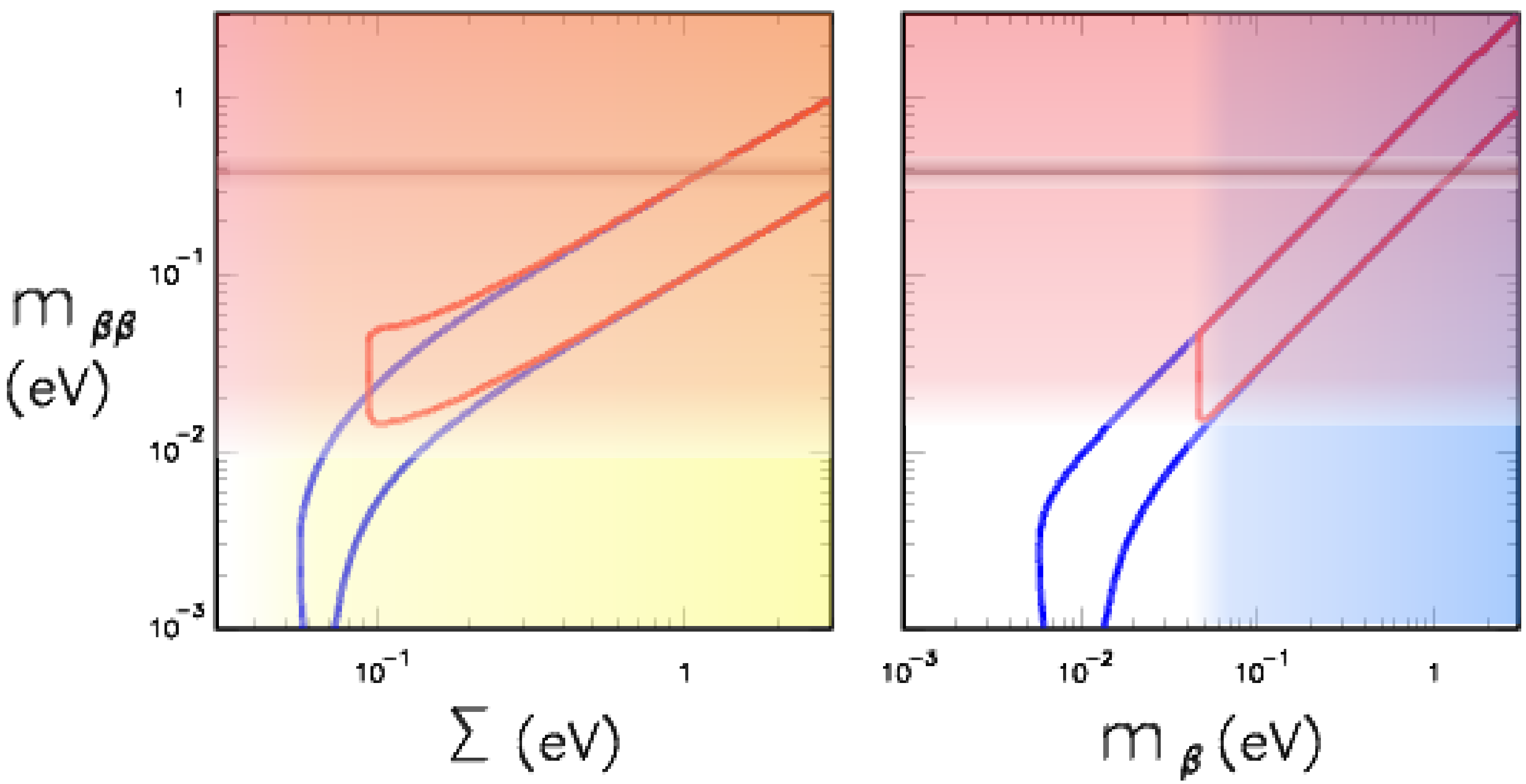
Combining results

G.L Fogli, et al, PRD 78 033010 (2008), arXiv:hep-ph/0805.2517v3

Long term expectations: 10-20 years



2σ bounds
Inverted Hierarchy
Normal Hierarchy



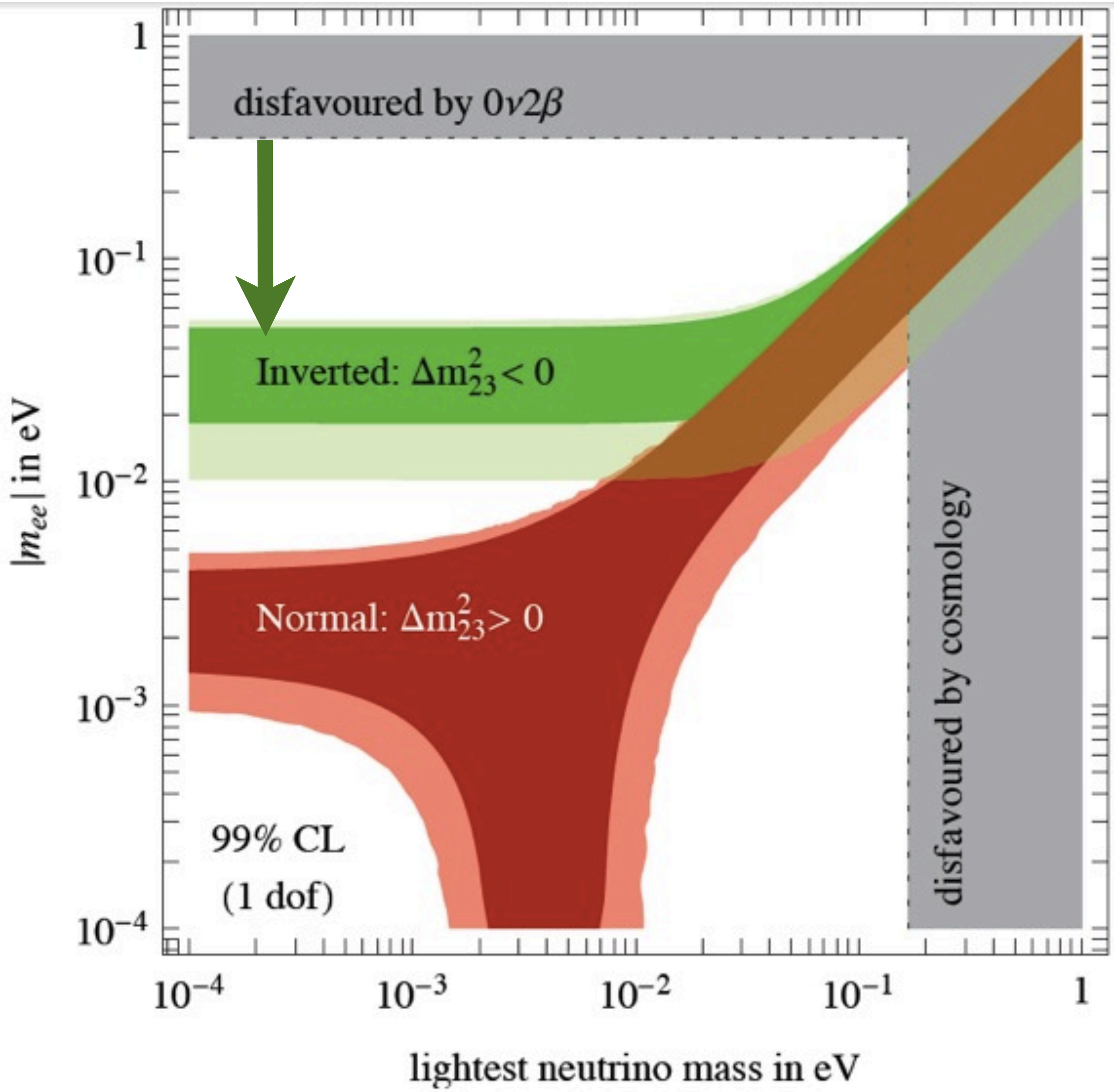
Claim for ββ-0ν observation in ^{76}Ge
HV. Klapdor-Kleingrothaus et al.Mod. Phys. Lett. A, 21 (2006) 1547

Conclusions

- Neutrino physics has still many urgent open questions
- Neutrino masses can get rid of some of them
- All available complementary approaches must be pursued
  - ββ0ν is our only probe of the Majorana/Dirac nature of neutrinos
  - Tritium beta decay is our only model-independent probe
  - Cosmological probes present a good chance to make a observation
- For next generation experiments the technical challenge is becoming daunting
- The effort will require always larger collaborations and presumably few challenging experiments

Backup slides

ββ0ν and neutrino masses

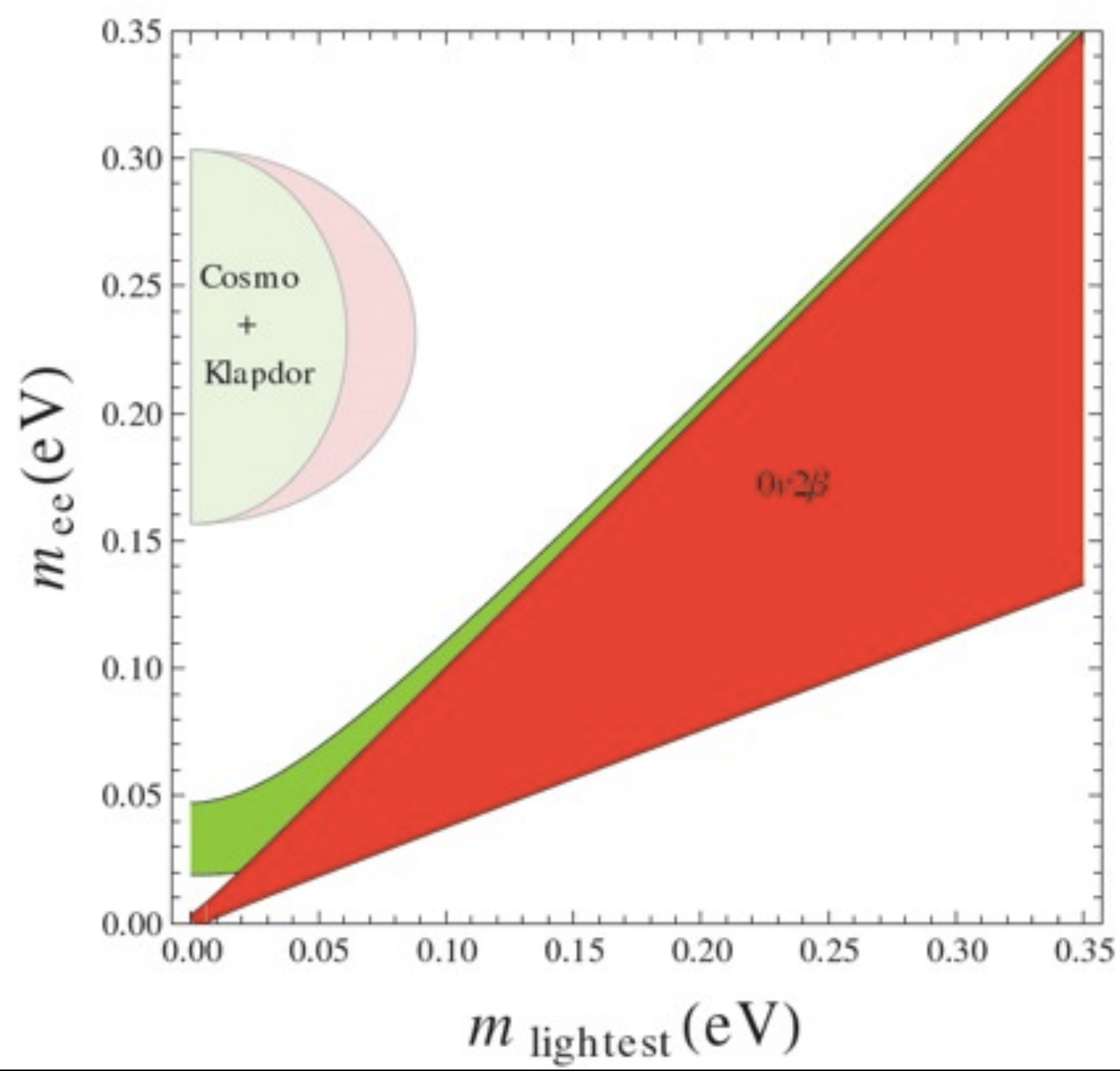


Thanks to the information from oscillations m_{ee} can be expressed in terms of three unknown quantities:

- the mass scale, represented by the mass of the lightest neutrino $\mathbf{m_{min}}$
- the two Majorana phases.

It is then common to distinguish three mass patterns:

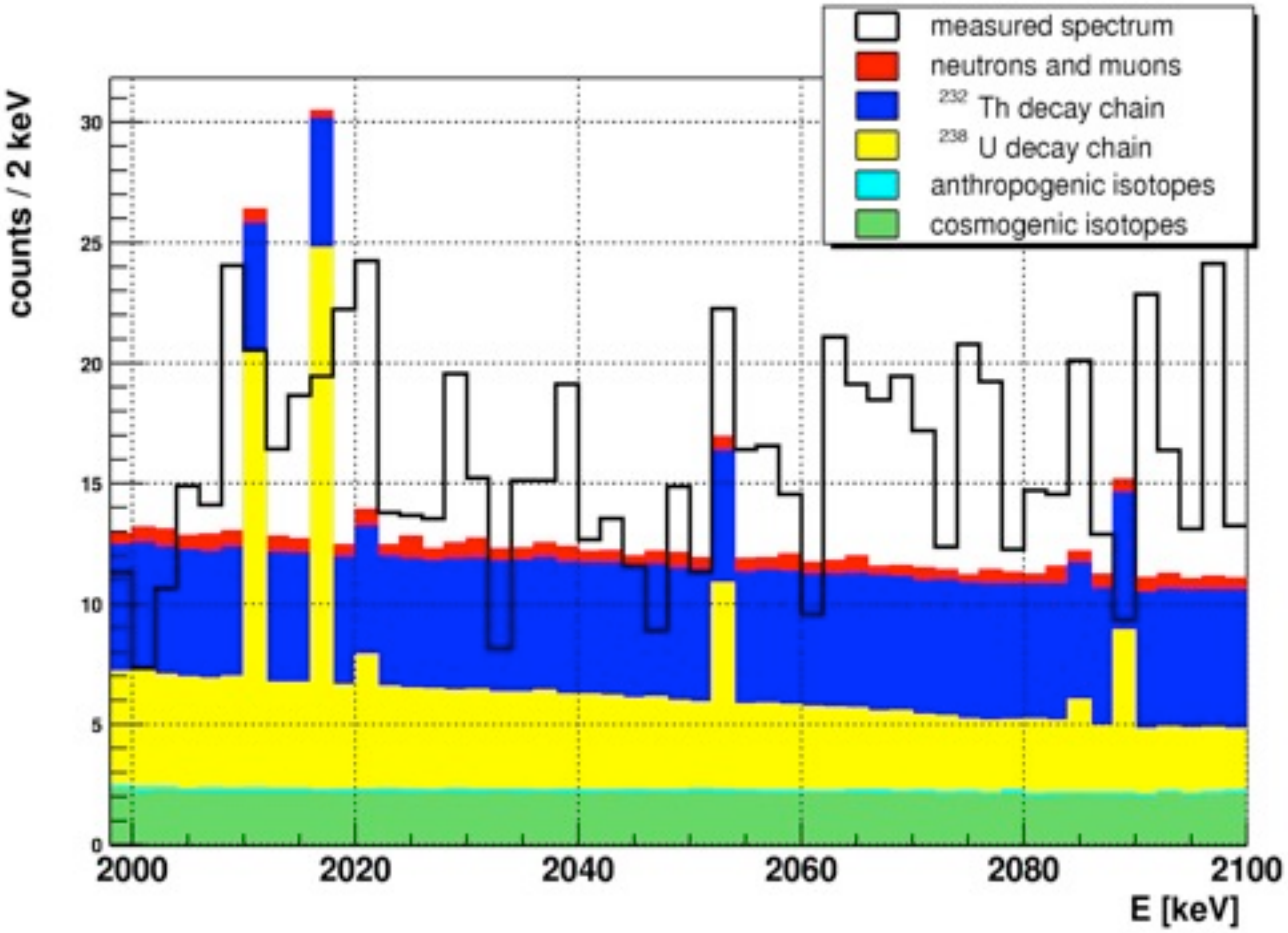
- **normal hierarchy (NH)**, where $\mathbf{m_1 < m_2 < m_3}$
- **inverted hierarchy (IH)** where $\mathbf{m_3 < m_1 < m_2}$
- **quasi-degenerate pattern (QD)**, where the differences between the masses are small with respect to their absolute values

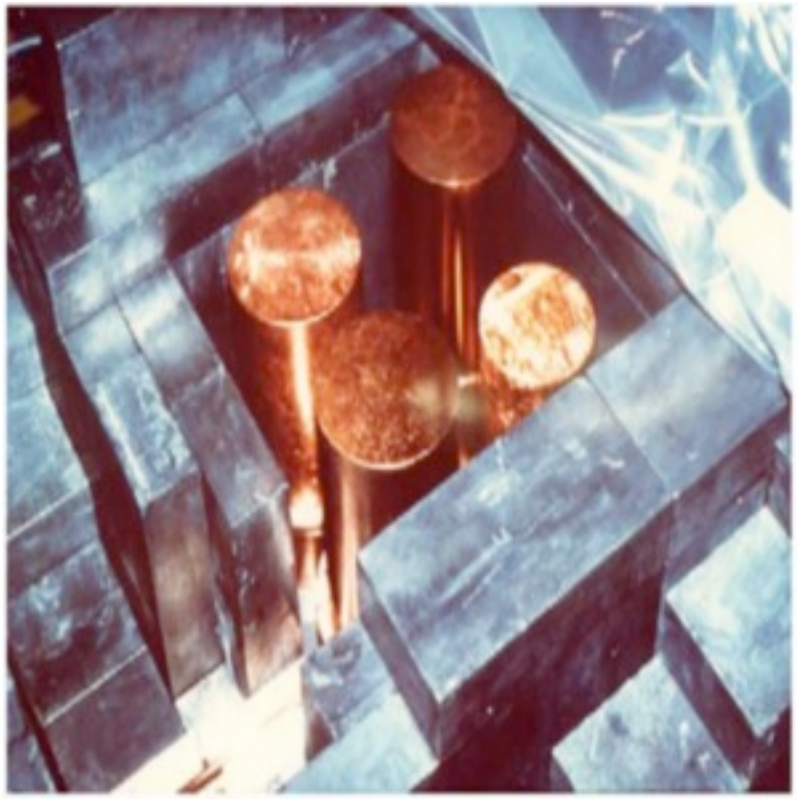


↓ neutrinos must be Majorana particles
↓ uncertainties in $M^{0\nu}$

Heidelberg-Moscow

- 5 HP-Ge crystals, enriched to 87% in ^{76}Ge
  total active mass of 10.96 kg ⇒ 125.5 moles of ^{76}Ge
- run from 1990 to 2003 in Gran Sasso Underground Laboratory
- total statistics 71.7 kg×y
  820 moles×y
- main background from U/Th in the set-up
  $b \approx 0.11$ c/keV/kg/y at $Q_{\beta\beta}$
- lead box and nitrogen flushing ofthe detectors
- digital Pulse ShapeAnalysis(PSA)





1990 – 2001 data
exposure = 35.5 kg×y SSD

$\tau_{1/2}^{0\nu} > 1.9\times10^{25}$ **years**

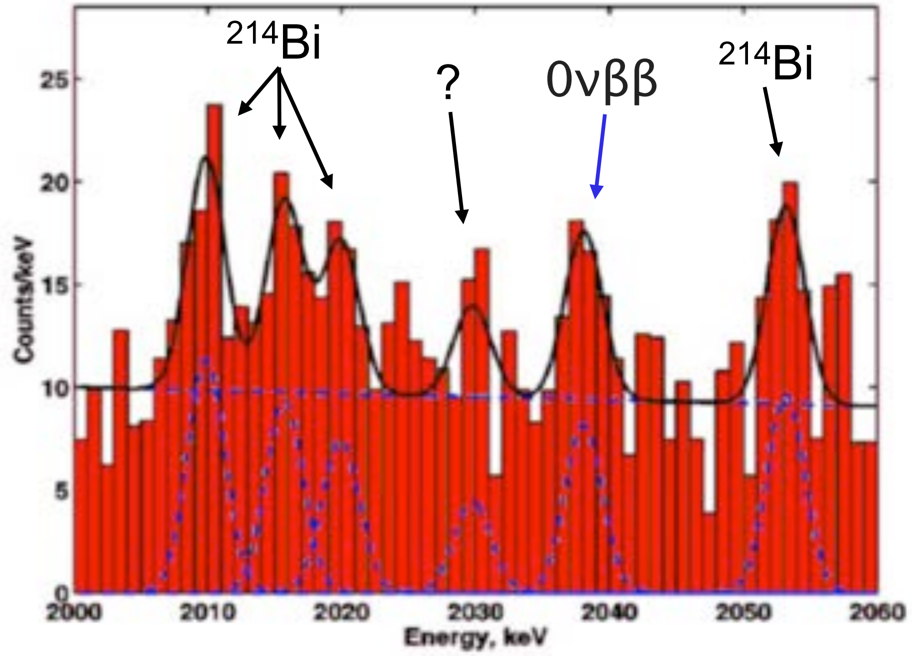
$\langle m_\nu \rangle$ **< 0.35 eV (0.3 – 1.24 eV)**

H.V.Klapdor-Kleingrothaus *et al.*, Eur. Phys. J. A12 (2001) 147

H.V.Klapdor et al.: ^{76}Ge 0νββ evidence

First claim in January 2002 (**Klapdor-Kleingrothaus HV et al. hep-ph/0201231**) with a statistics of 55 kg y and a 2.2-3.1 statistical significance → strong criticism

Claim confirmed in 2004 with the addition of a significant (~1/4) new statistics and improved in the following years



1990 – 2003 data, all 5 detectors
exposure = 71.7 kg×y

$T_{1/2}$ = 1.2×10^{25} years

$\langle m \rangle$ = 0.44 eV

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

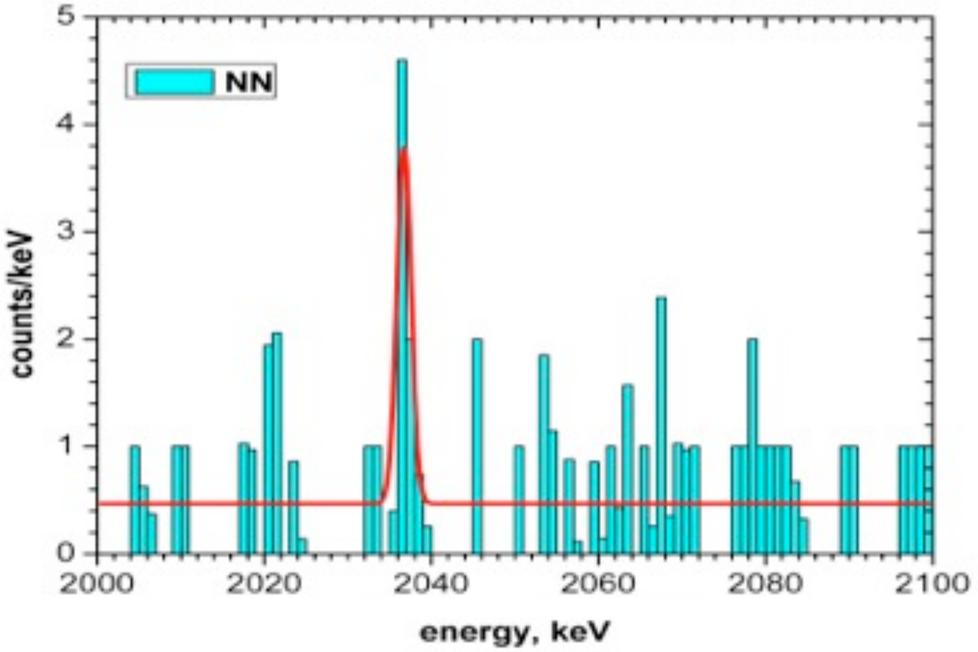
1995-2003 data new re-analysis:
SSE selection by MC & ANN

6.4σ signal

7.05 ± 1.11 events

$2.23^{+0.44}_{-0.31}$ 10^{25} years / 0.32±0.03 eV

H.V.Klapdor-Kleingrothaus *et al*., Phys. Scr. T127 (2006) 40–42

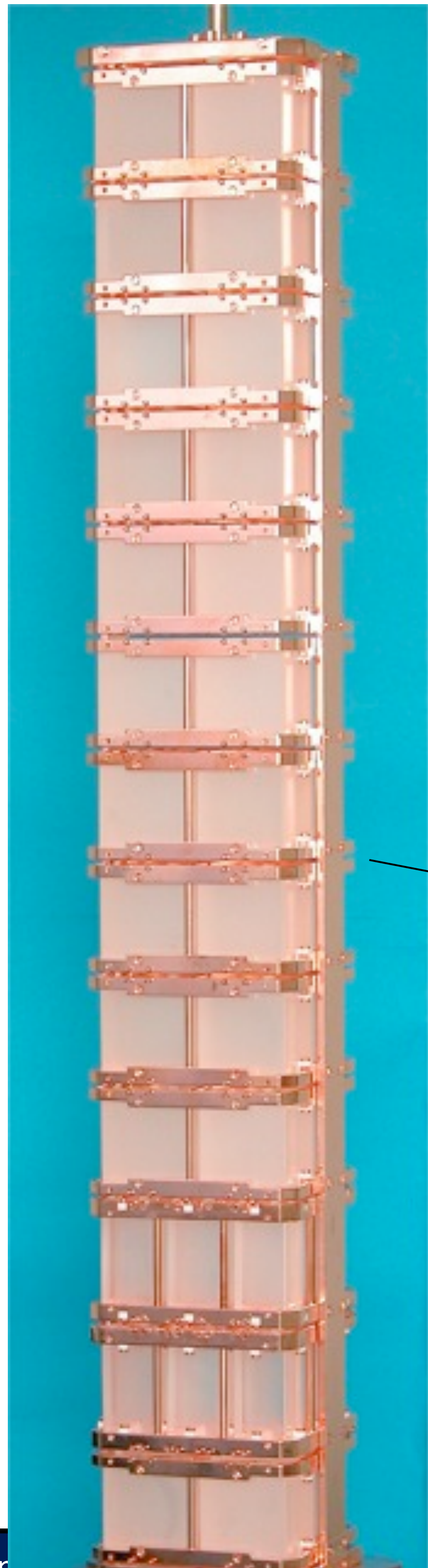


all future experiment will certainly have to cope with this result

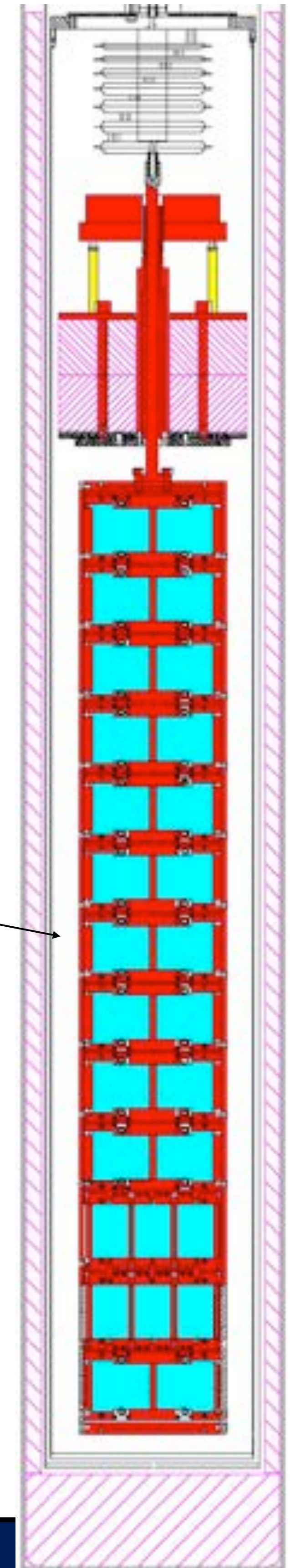
arXiv:1006.2025v1 [hep-ph]: Kirpichnikov alternate interpretation of 2039 keV line

Cuoricino

Cuoricino *tower*: 62 TeO_2 crystals



~85 cm



TeO_2 thermal calorimeters

Active isotope ^{130}Te

natural abundance: a.i. = 33.9%

transition energy: $Q_{\beta\beta}$ = 2529 keV

encouraging predicted half life

$\langle m\nu \rangle \approx 0.3$ eV $\Leftrightarrow$ $T_{1/2}^{0\nu} \approx 10^{25}$ years

Absorber material TeO_2

low heat capacity

large crystals available

radiopure

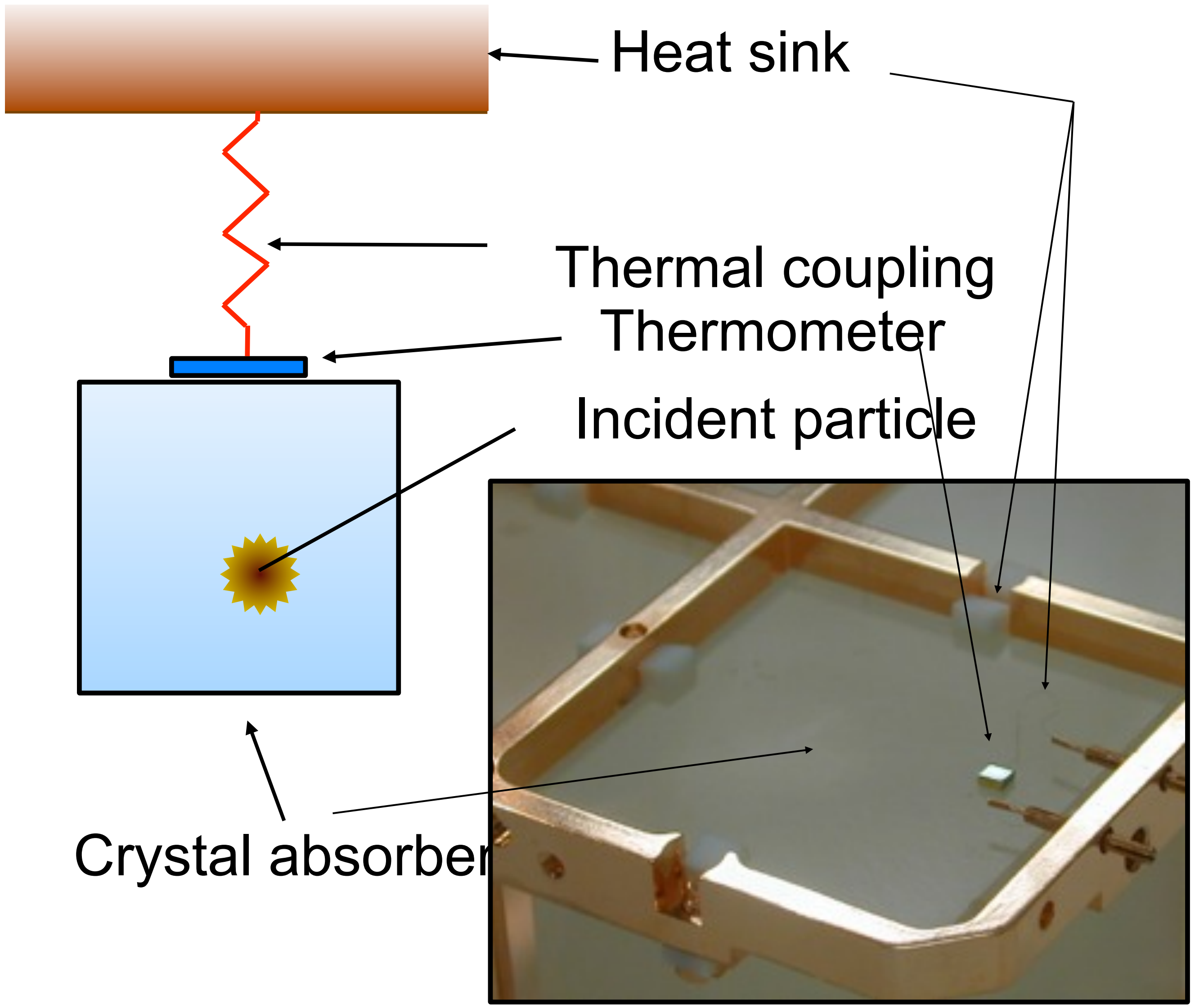
intermediate size ββ experiment

important test for

radioactivity

performance of large LTD arrays

Low Temperature detectors



Detection Principle

$\Delta T = E/C$

C: thermal capacity

low *C*

low *T* (i.e. $T \ll 1K$)

dielectrics, superconductors

ultimate limit to E resolution: statistical fluctuation of internal energy *U*

$\langle \Delta U^2 \rangle = k_B T^2 C$

Thermal Detectors Properties

good energy resolution

wide choice of absorber materials

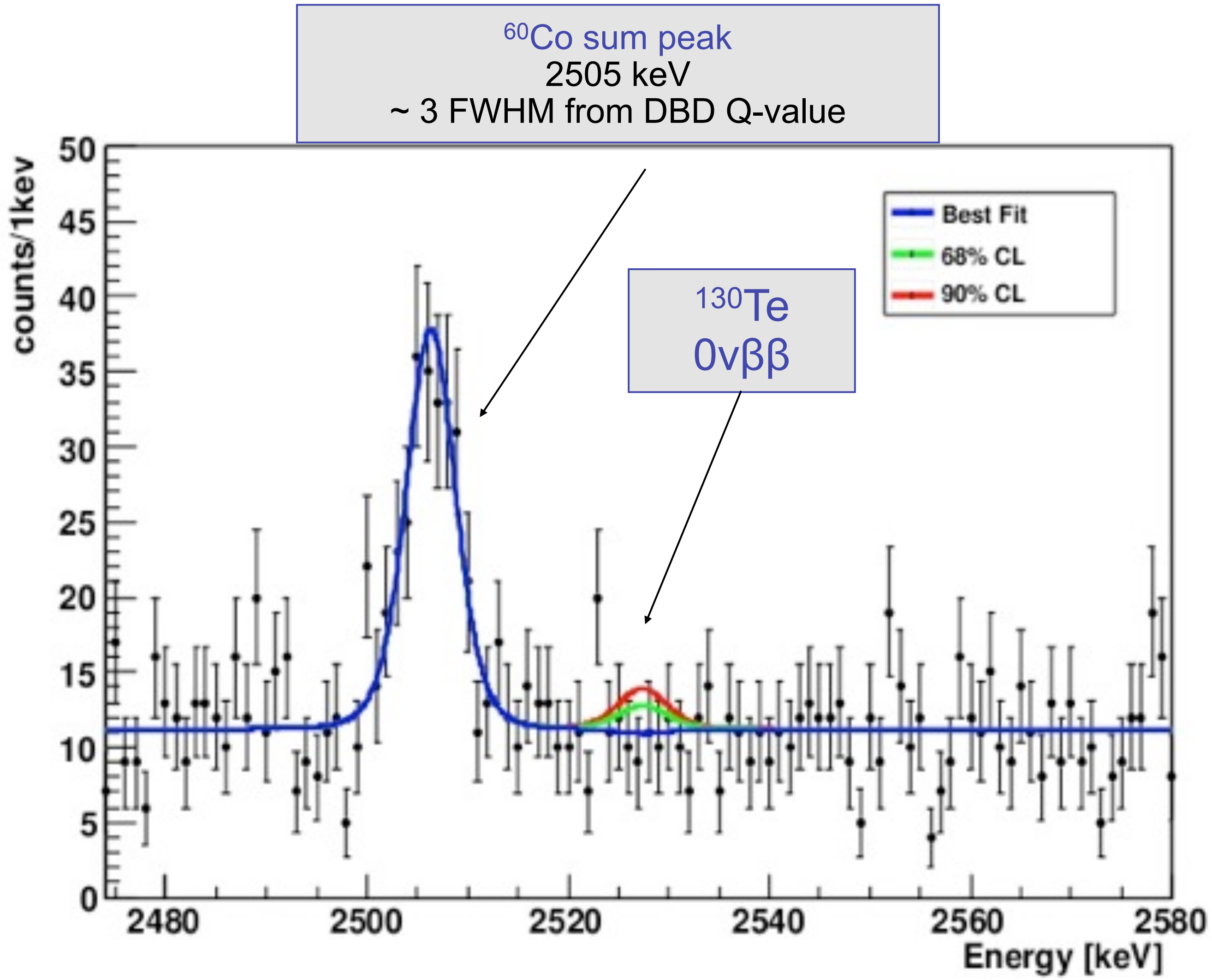
true calorimeters

slow $\tau = C/G \sim 1 \div 10^3$ ms

Cuoricino Results

- total statistics 19.75 kg×y
- average energy resolution FWHM ΔE = 7.5 keV at $Q_{\beta\beta}$
- anticoincidence applied to reduce surface U/Th background and external γ's
- background level: $b \approx 0.18 \pm 0.01$ c/keV/kg/y @ $Q_{\beta\beta}$

30% ± 10% **^{208}Tl (cryostat contamination)**
20% ± 10% **TeO_2 surfaces (α contaminations)**
50% ± 10% **Cu surfaces (α contaminations)**



stopped in June 2008 and disassembled

TOTAL EXPOSURE
19.75 [kg(^{130}Te) yr]

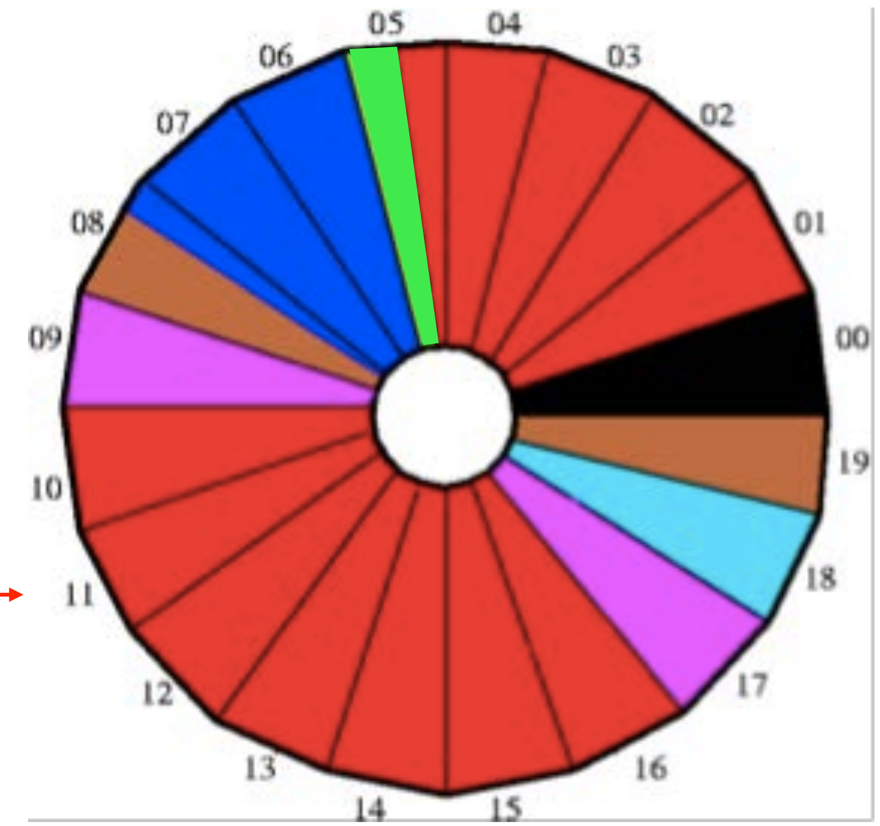
@ 90% C.L.
$t_{1/2} > 2.8\ 10^{24}$ [yr]
$m_{ee} < 0.3 \div 0.7^{1-4}$ eV

1 Šimkovic et al., PRC 77 (2008) 045503
2 Civitarese et al., JoP:Conference series 173 (2009) 012012
3 Menéndez et al., NPA 818 (2009) 139
4 Barea and Iachello, PRC 79 (2009) 044301

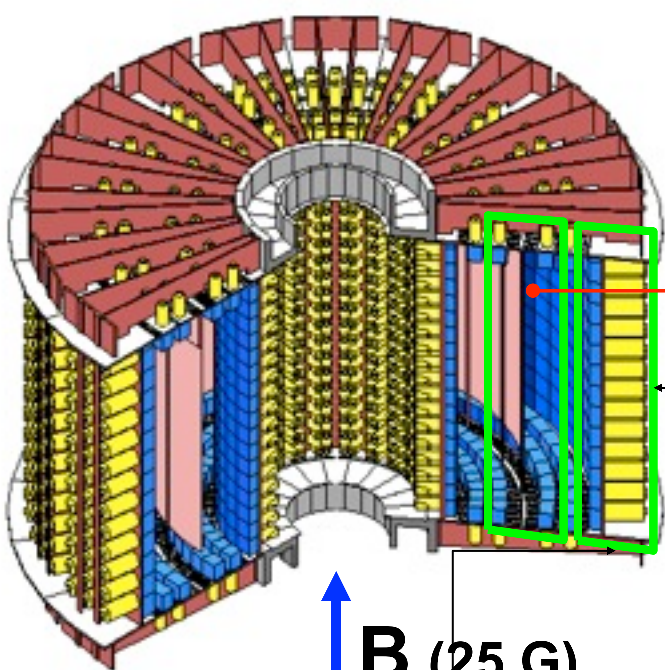
NEMO-3

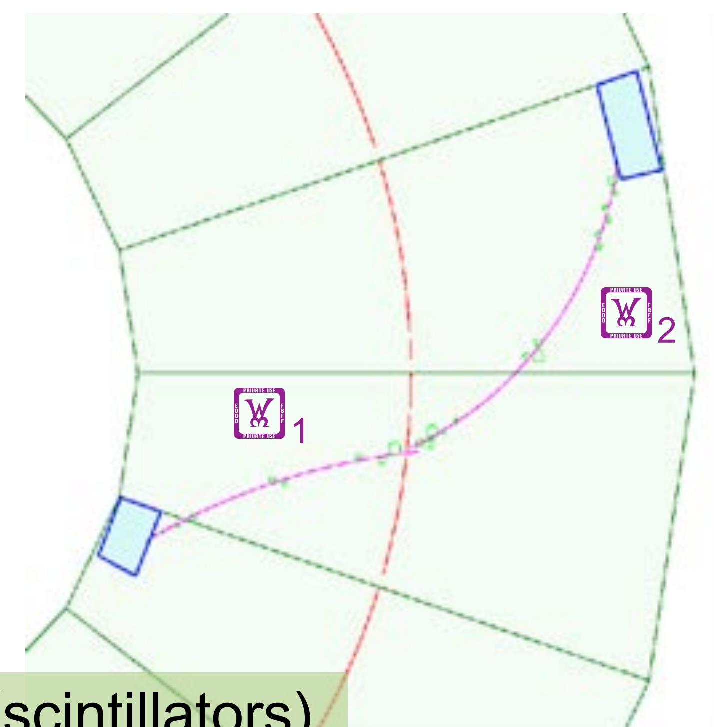
Tracking detector for 2νββ and **0νββ**
at Frejus (4800 m.w.e.)

- 10 kg of enriched material in foils
- 6180 geiger cells ⇒ drift wire chamber
- 1940 plastic scintillators + PMTs
- iron (γ) + water with B (n) shielding + anti-Rn box
- e^-, e^+, α and β identification



sources in foils





calorimeter (scintillators)

tracking volume (drit wire chamber)

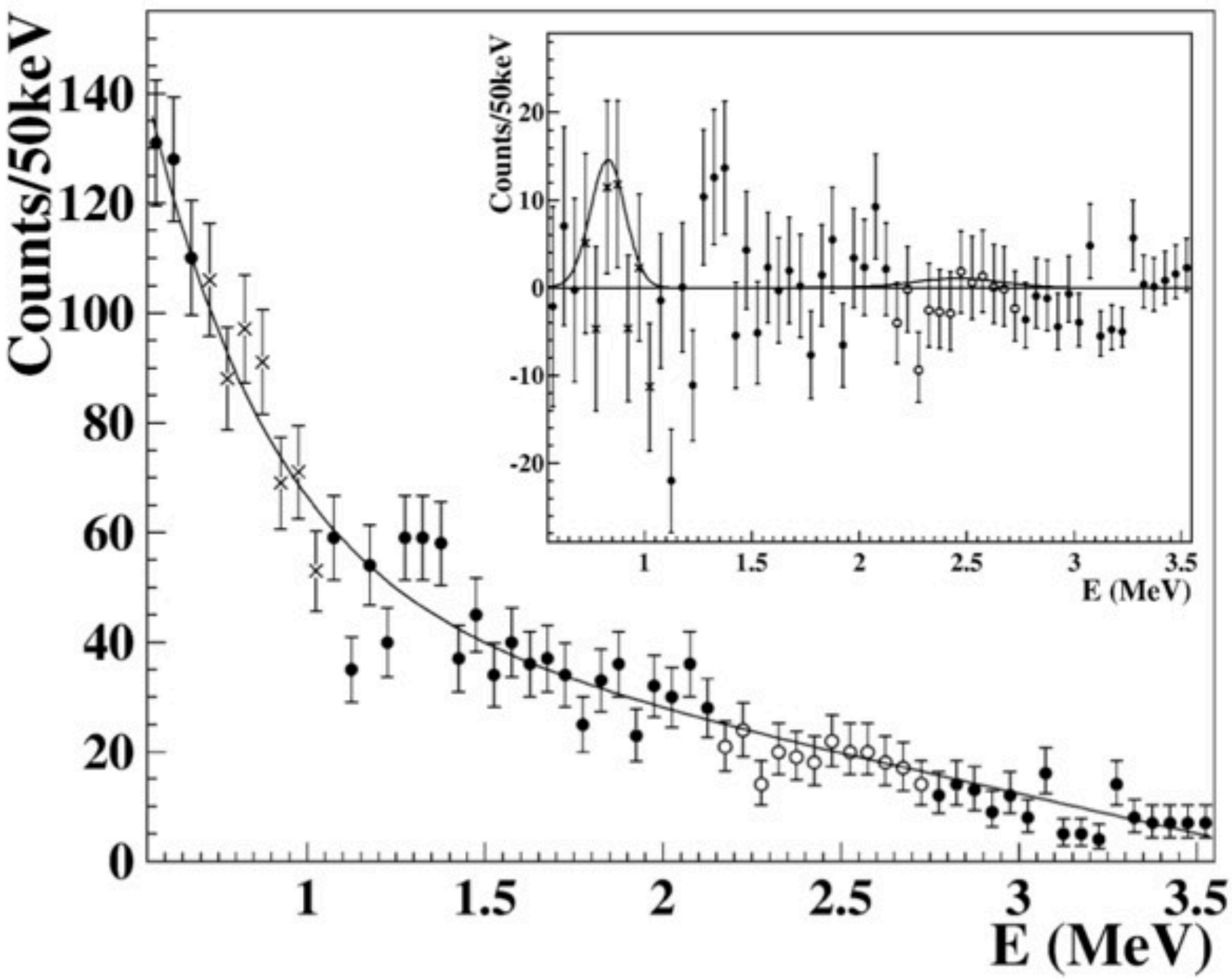
^{100}Mo	(6.9 kg)	➡ **0νββ**
^{82}Se	(0.9 kg)	
^{130}Te	(0.45 kg)	
^{116}Cd	(0.4 kg)	
^{150}Nd	(37g)	
^{96}Zr	(9.4 g)	
^{48}Ca	(7.0g)	
^{nat}Te	(0.5 kg)	
Cu	(0.6 kg)	

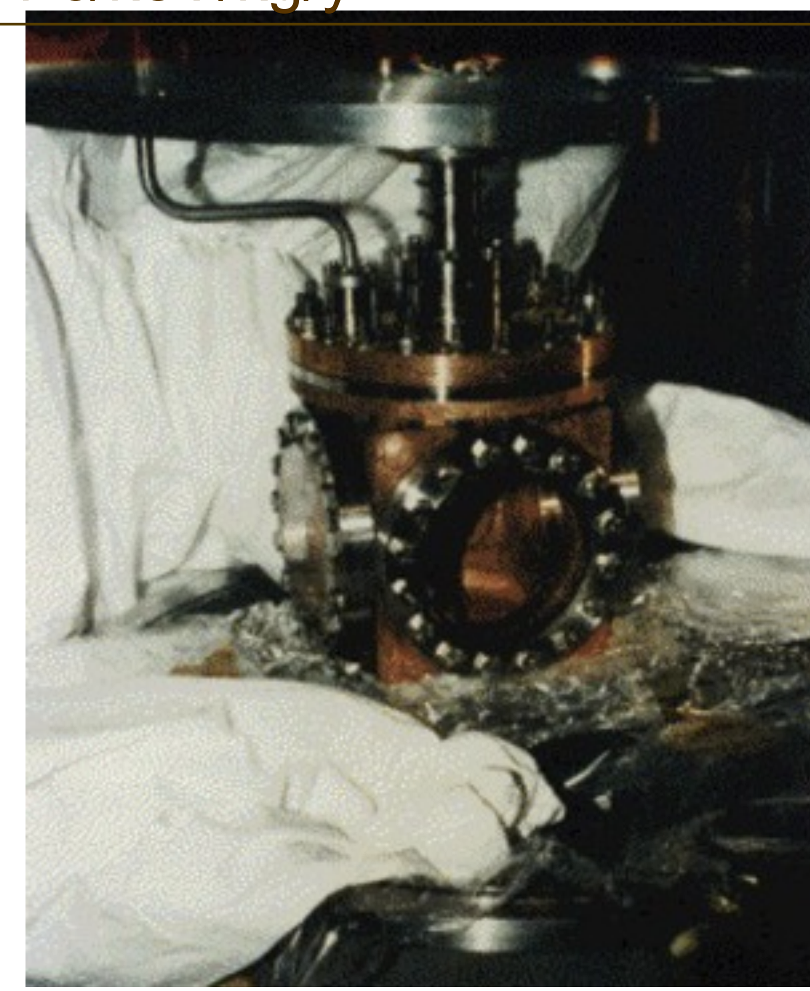
DAMA/LXe

@LNGS since 2000

Liquid Scintillator Detector with LXe - 68.8% enrichment 136Xe – 4.47 kg ^{136}Xe

$N_{\beta\beta}$= 2 x 10^{25} **Δ**E/E (FWHM) ~ 20 % Bkg ~ 0.1 c/keV/kg/y





$T_{1/2}^{0\nu\beta\beta}$ > 1.2 x 10^{24} y @ 90%CL

and "conservative" 2νββ limits

- **$T_{1/2}^{0\nu\beta\beta}$ (0+) > 1 x 10^{22} y @ 90%CL**
- **$T_{1/2}^{0\nu\beta\beta}$ (2+)> 9.4 x 10^{21} y @ 90%CL**

Experimental groups

Homogeneous with high energy resolution

- **CUORE** ^{130}Te
- **GERDA -** ^{76}Ge
- **MAJORANA –** ^{76}Ge
- **LUCIFER -** ^{82}Se – ^{116}Cd – ^{100}Mo

Homogeneous with high energy resolution and tracking

- **NEXT -** ^{136}Xe
- **COBRA -** ^{116}Cd

Homegeneous with low energy resolution

- **KamLAND-ZEN** ^{136}Xe
- **SNO+ –** ^{150}Nd
- **XMASS –** ^{136}Xe
- **CANDLES –** ^{48}Ca

Inhomogeneous with low energy resolution

- **SUPERNEMO -** ^{82}Se or ^{150}Nd
- **MOON -** ^{100}Mo or ^{82}Se or ^{150}Nd
- **DCBA -** ^{150}Nd

GERDA

→talk C.Cattadori

Ge diodes (86% enriched ^{76}Ge) **in LAr cryostat** (active in phase II) **in water tank** (active)
BEGe technology in phase-II**:** better E resolution, Multi/Single interaction discrimination
@LNGS Phase-I ~ end 2011 Phase-II ~ 2014

ββ candidate: ^{76}Ge **– Q** 2039 keV

Source Mass:
Phase-I: 17.7 kg ^{76}Ge – $\mathbf{N_{\beta\beta}}$ 1.4 x10^{26}
Phase-II:+20.8 kg ^{76}Ge – $\mathbf{N_{\beta\beta}}$ 3.0x10^{26}

Projected Bkg:
Phase-I: 0.01 c/keV/kg/y
Phase-II: 0.001 c/keV/kg/y

Sensitivity $T_{1/2}^{0\nu}$:
Phase-I: 2.5x10^{25} y in 1 y
Phase-II: 1.9x10^{26} y in 5 y

Sensitivity <m_{ee}>:
I: Scrutinize KK claim (if true 7 bb cts over 0.5 cts of bkg) in < 2 y
II: <m_{ee}> < 73 ÷ 203 meV in 5 y **> IH**

GERDA-I Background

GERDA is running and taking data

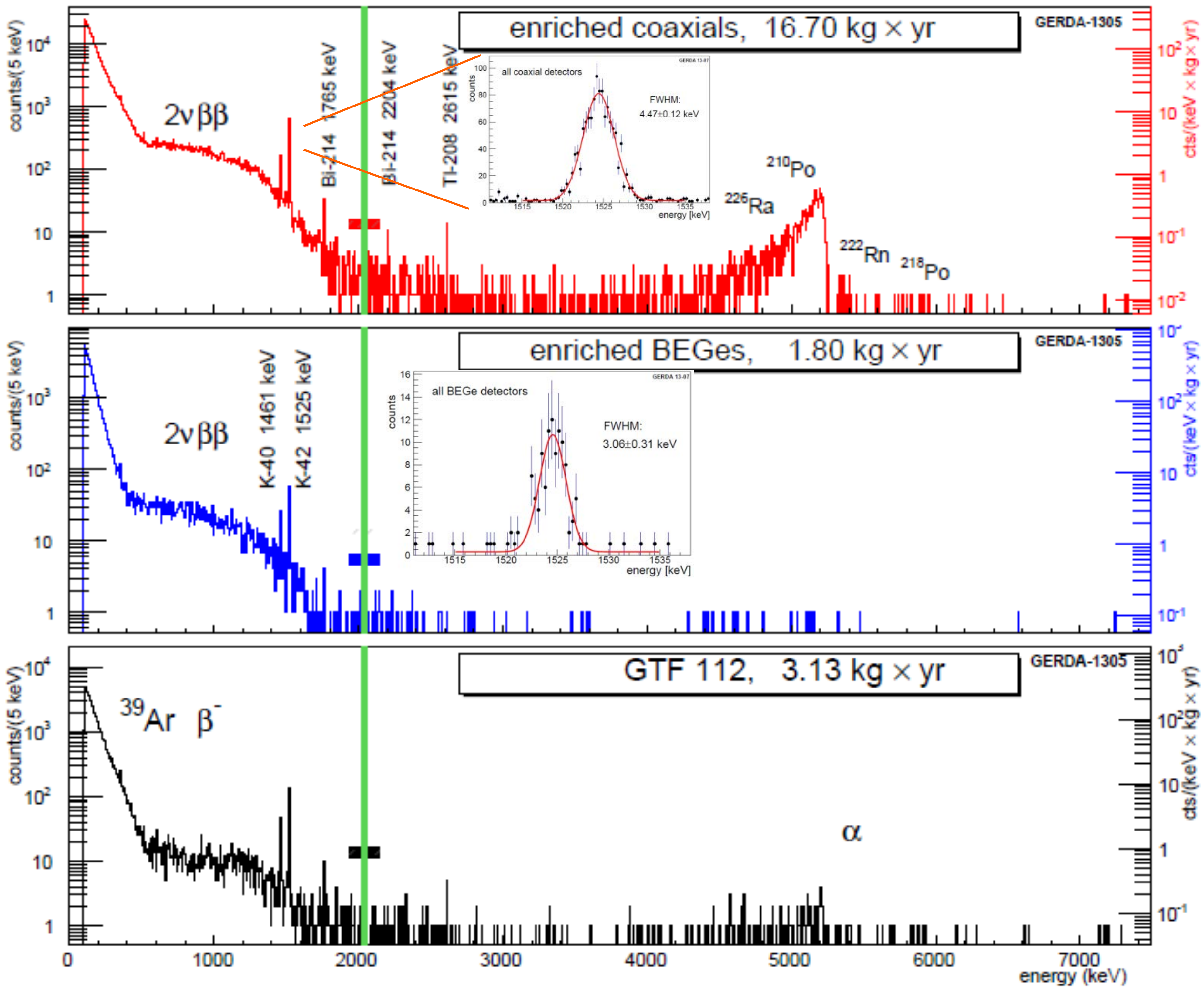
Statistics:
- 19.2(coax) + 2.4 (BeGe) kg·y

Systematics:
- blinding 2019 – 2059 keV

Full background model:
arxiv:1306.5084

Type	Exposure (kg·y)	BI (PSD) (10^{-3} c/kg/keV/y)
coax	16.70	18 ± 2 11 ± 2 (PSD)
BeGe	1.80	40^{+10}_{-8} 5^{+4}_{-3} (PSD)

PSD:
- very effective (mainly on BEGe)
- ε ~85-90%



CUORE

→talk T.Banks

988 TeO_2 (33.8% ai ^{130}Te) **bolometers at ~ 10 mK in a granular structure** (741 kg mass)
@LNGS Phase-I (CUORE0): starts ~ mid 2012 Phase-II: ~ 2014 Future: enr., scintillating bolom.?

ββ candidate: ^{130}Te **– Q** 2527.5 keV

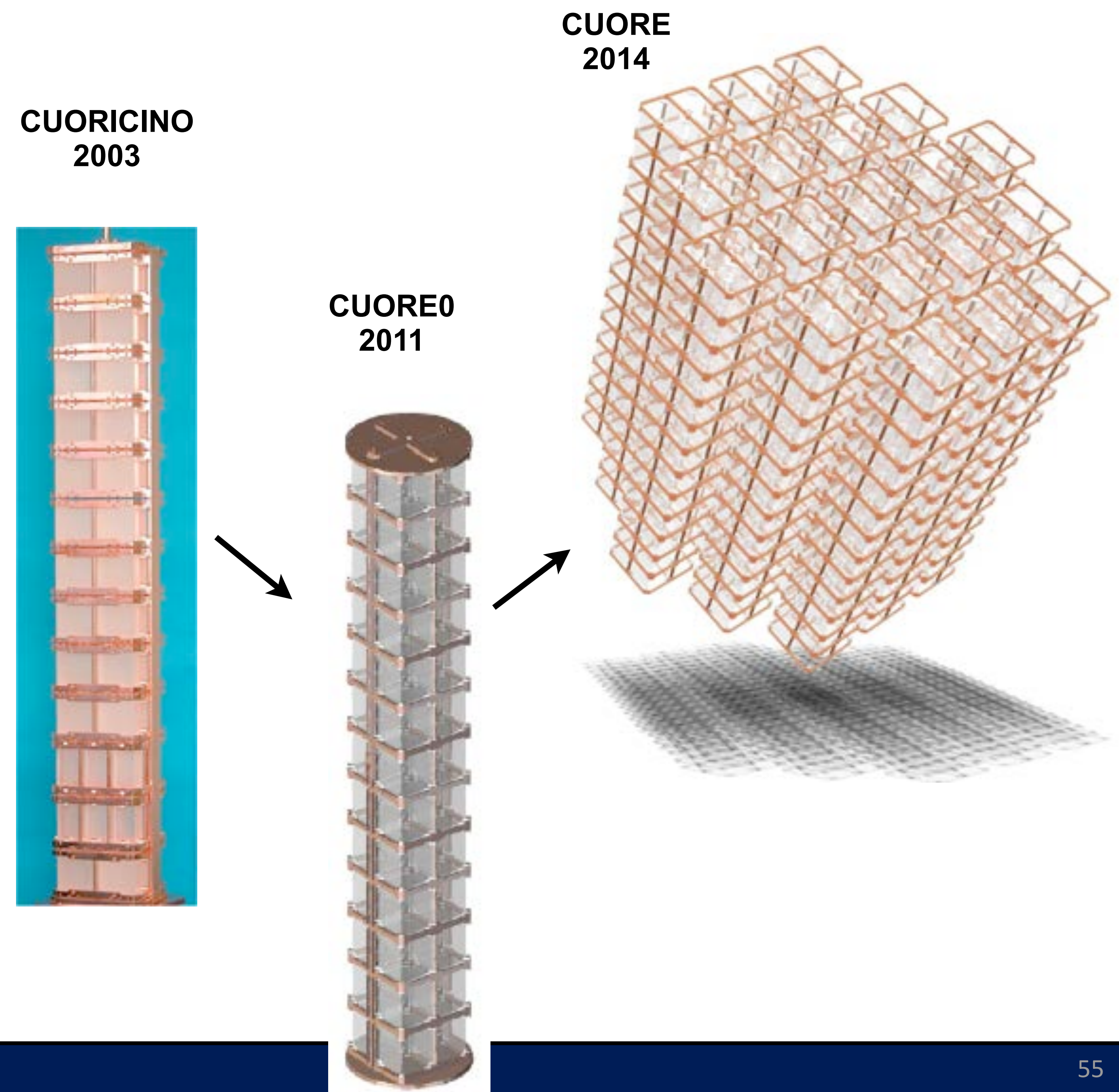
Source Mass:
Phase-I: 10.8 kg ^{130}Te – $\mathbf{N_{\beta\beta}}$ 5.0 x10^{25}
Phase-II: 206 kg ^{130}Te – $\mathbf{N_{\beta\beta}}$ 9.6 x10^{26}

Projected Bkg:
Phase-I : 0.05 c/keV/kg/y
Phase-II: 0.01 c/keV/kg/y

Resolution: ~ 5 keV @ROI

Sensitivity $T_{1/2}^{0\nu}$:
Phase-I: 4.2x10^{24} y in 1 y
Phase-II: 1.6x10^{26} y in 5 y

Sensitivity Phase-II <m_{ee}>:
<m_{ee}> < 40 ÷ 94 meV in 5y (IH)



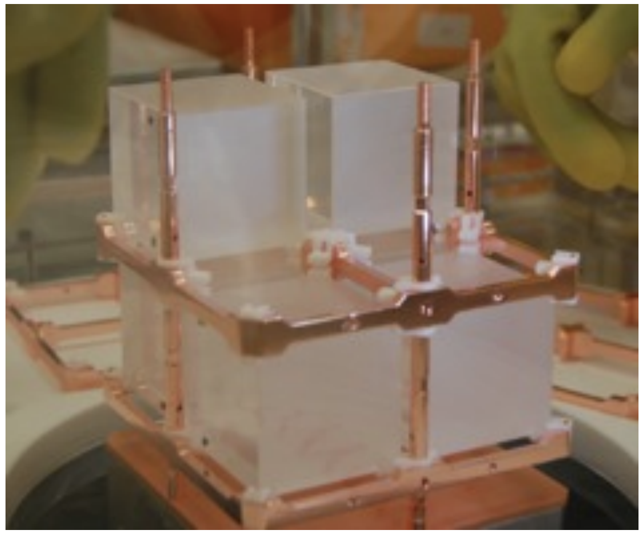
F. Bellini et al., Astrop. Phys. 33 (2010) 169
F. Alessandria et al., nucl-ex:1109.0494v1
C. Arnaboldi et al., Phys. Rev. C 78 (2008) 035502

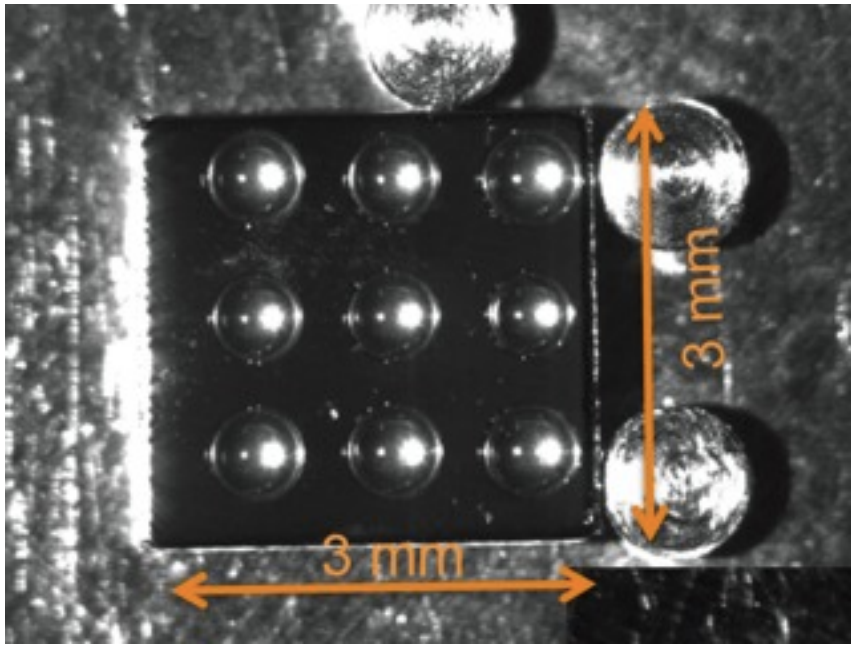
CUORE-0

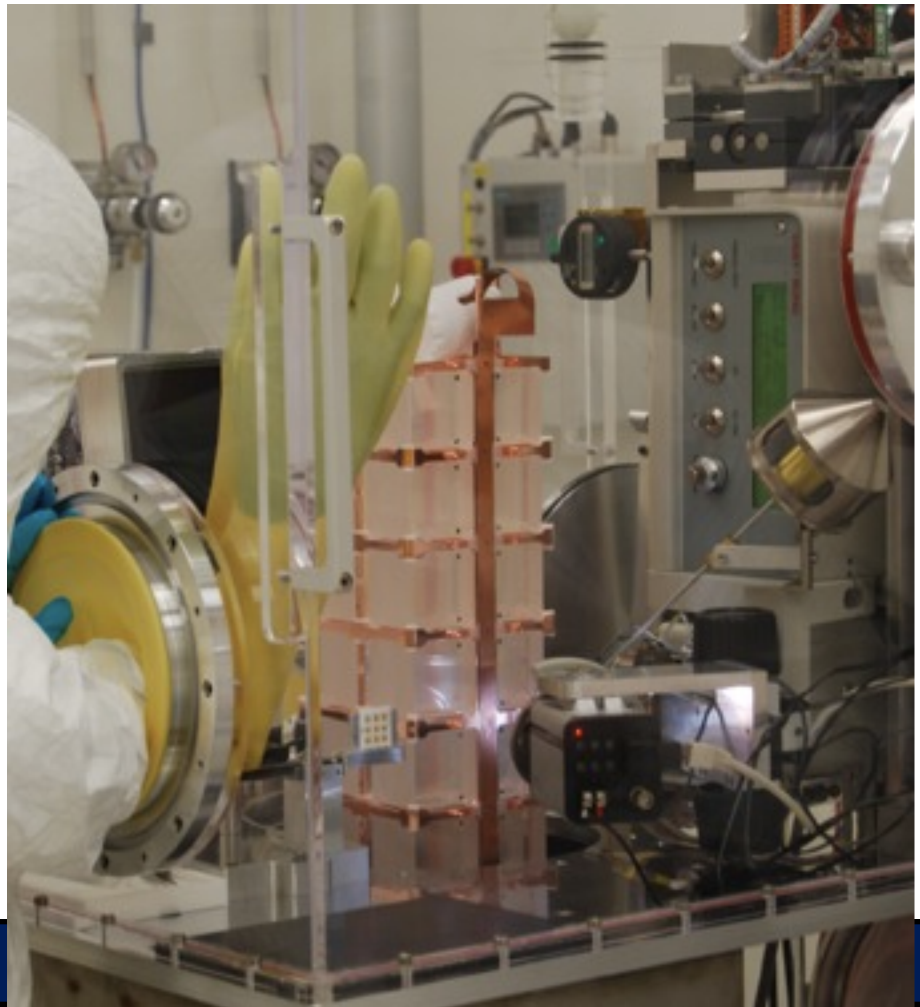
Goals:

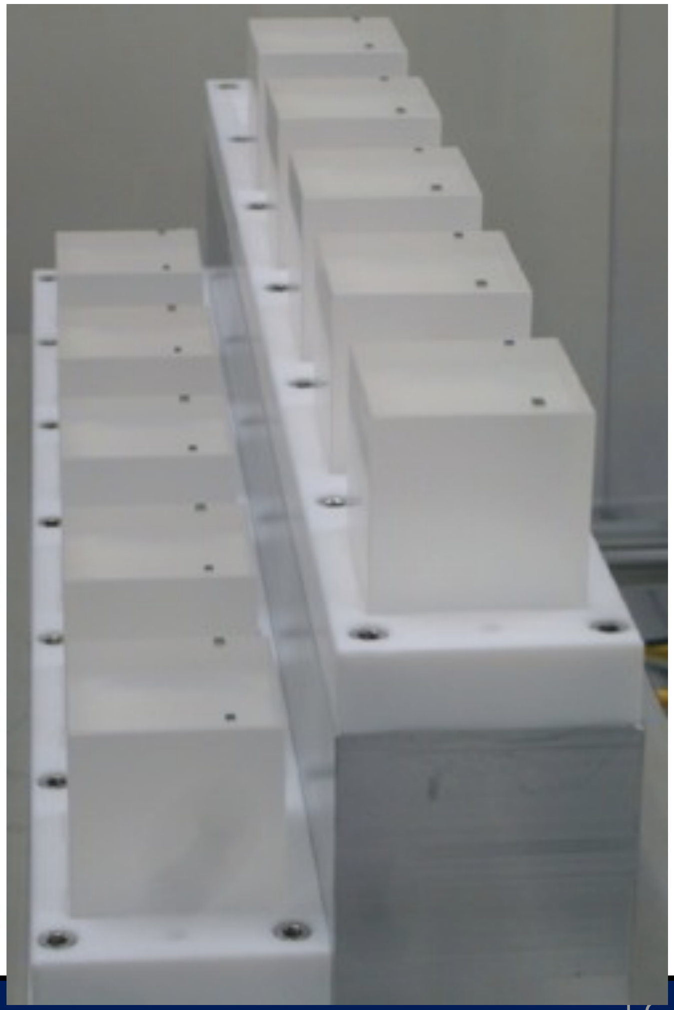
- full test and debug of the new CUORE assembly line
- high statistics check of the improved uniformity of bolometric response

Background measurement started at the beginning of May 2013



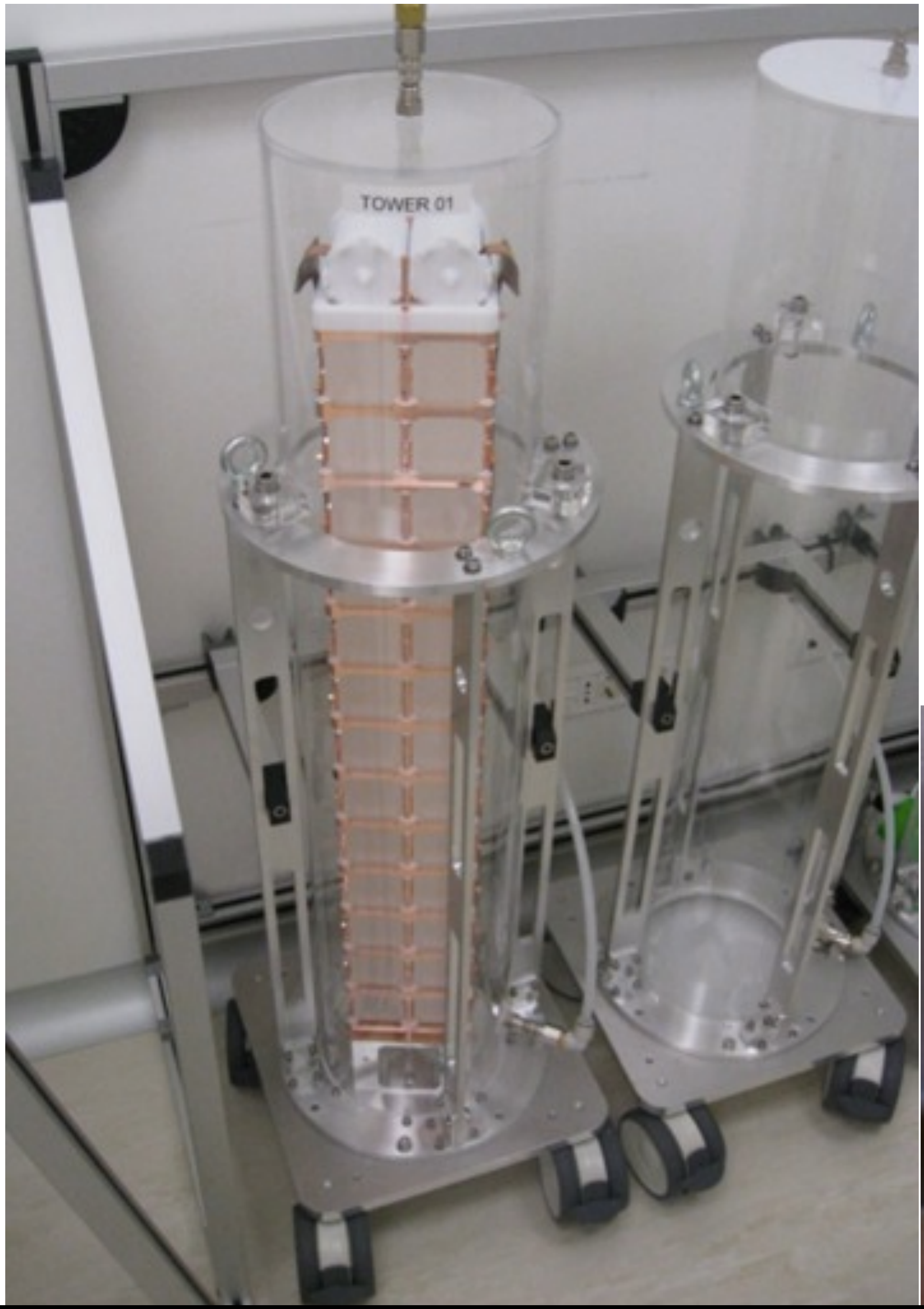


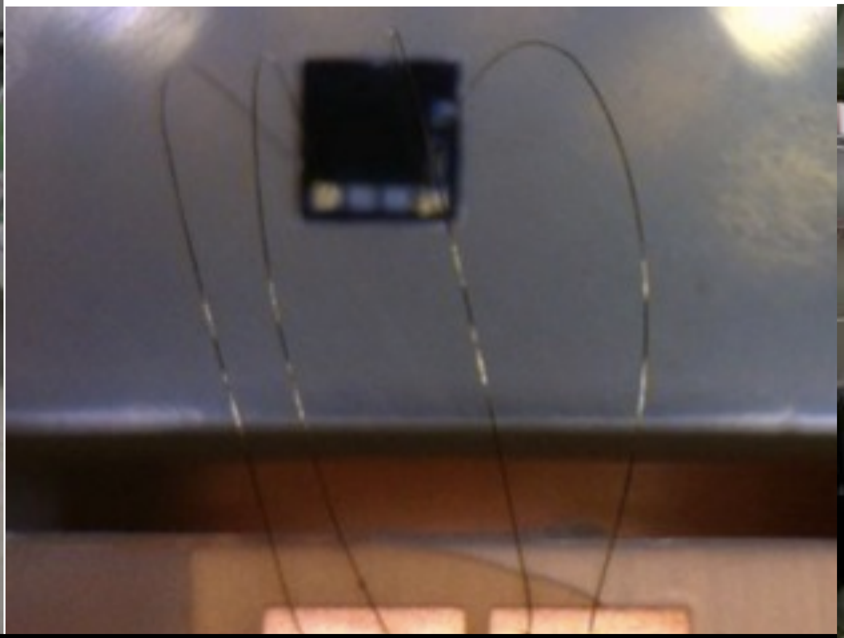




CUORE detector

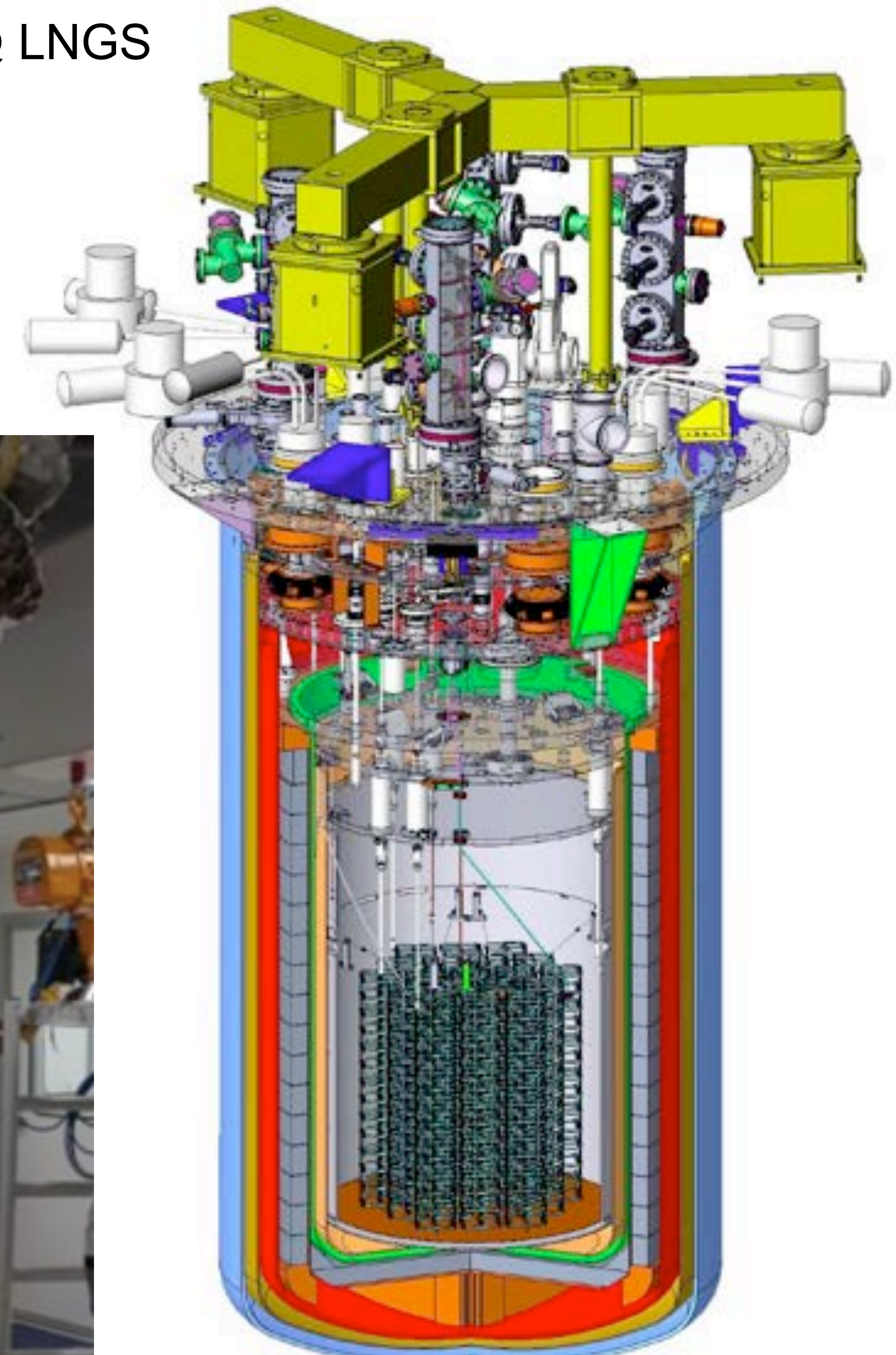
- TeO2 crystals delivery complete
- Parts production almost complete
- Radon abatement system installed
- Assembly program started and well performing
    - 6 CUORE towers built, 2 complete





CUORE setup

- Cryostat construction complete (delivered @ LNGS)
- Dilution unit performance better than expected. Delivered and tested @ LNGS
- CUORE building and infrastructures, ready
- Commissioning of the cryostat started on July 2012
  - 3 (of 6) cryostat chambers tested
  - System cooled to 4K



Kamland-Zen

~16 t (40 t in 2nd phase) **Liquid Scintillator 2.5wt% enrXe loaded** (91% enrichment of ^{136}Xe) in a Ø3.4m Mini Baloon in Kamland detector (1000t LS+Buffer Oil+Water Cherenkov Outer Detector)
@Kamioka mine 1st Phase~ end 2011 2nd Phase >2013

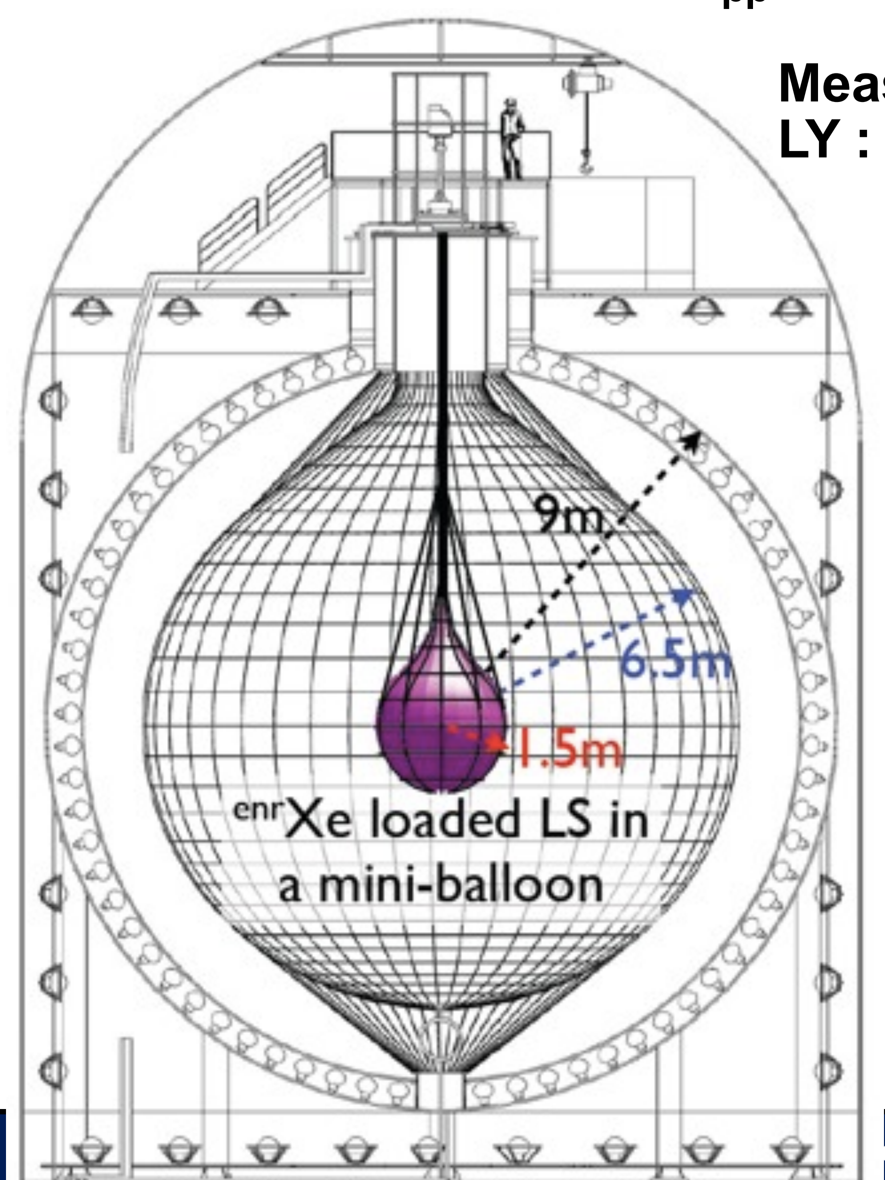
ββ candidate: ^{136}Xe – **Q** 2476 keV

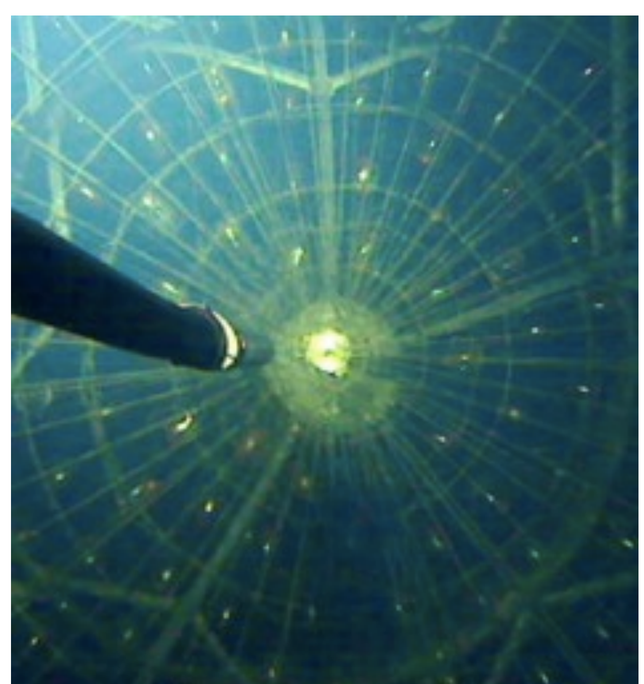
Source Mass:
1st Phase: 140 kg ^{136}Xe – $\mathbf{N_{\beta\beta}}$ 1.6 x1 0^{27} (fiducial)
2nd Phase: 700 kg ^{136}Xe – $\mathbf{N_{\beta\beta}}$ 4.0 x10^{27}

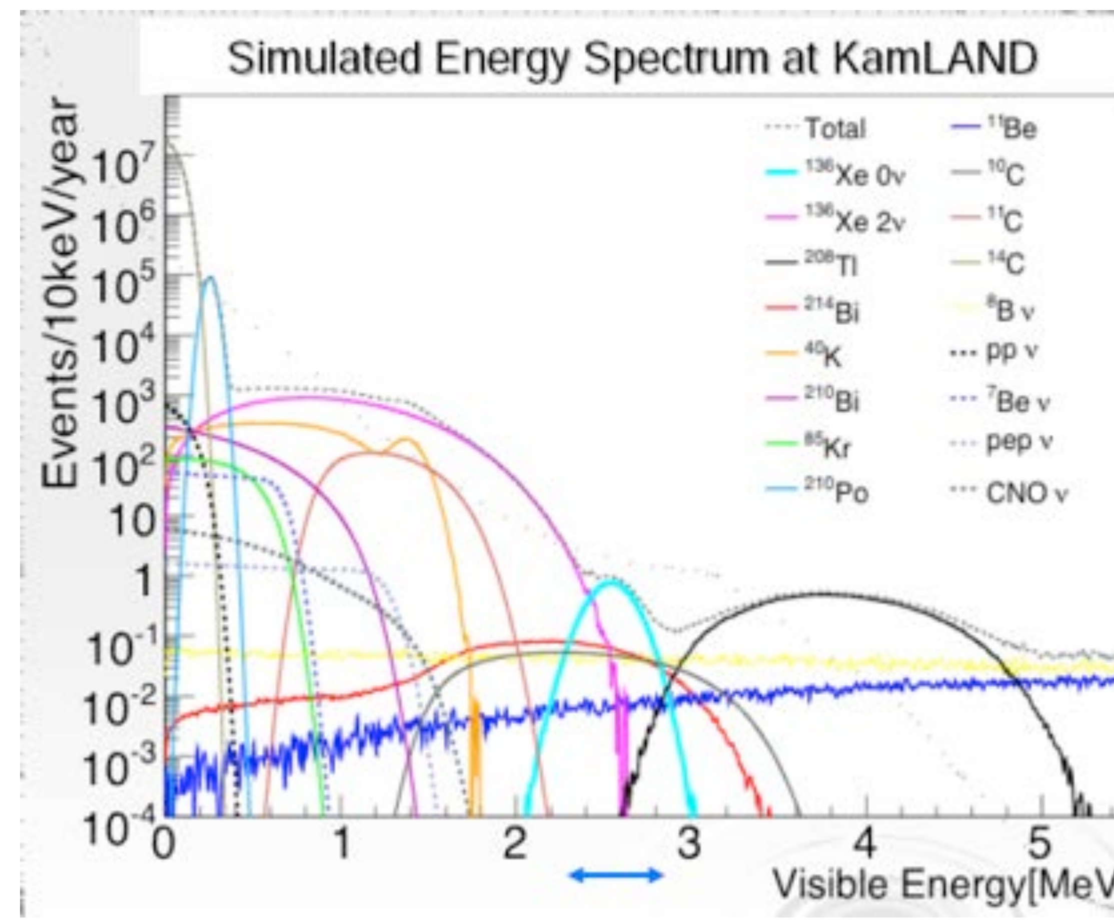
Main Bkg:
- 2νββ ^{136}Xe (slow: $T_{1/2}$~10^{22} y)
- ^{10}C,^{11}Be (1/10 with tag)
- ^{8}B solar ν
- ^{214}Bi, ^{208}Tl from MB (vertex cut)

Measured FWHM: ~ 10% @ROI
LY : 8000 photons/MeV

=> expected S/Bkg ~ 2

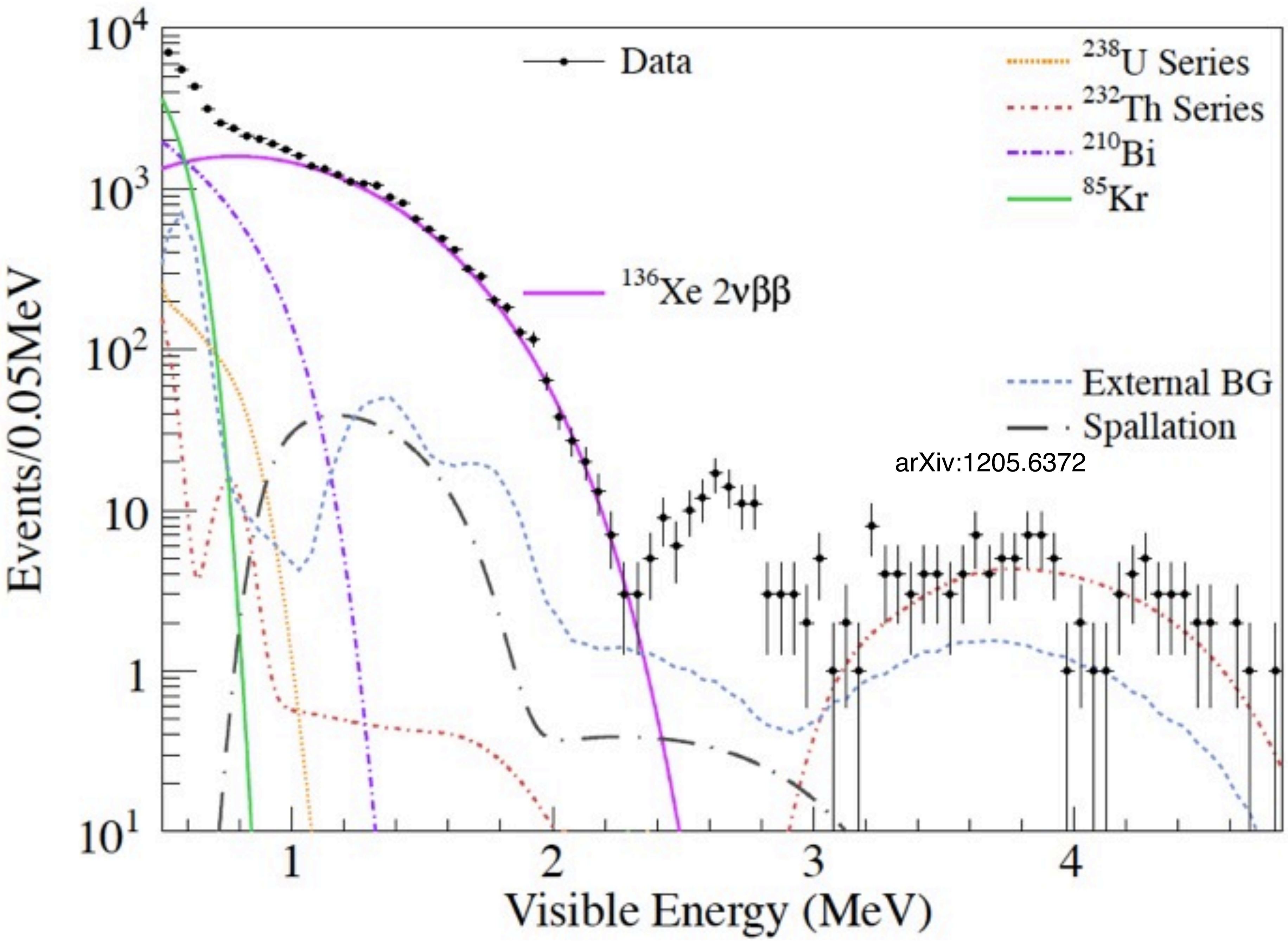


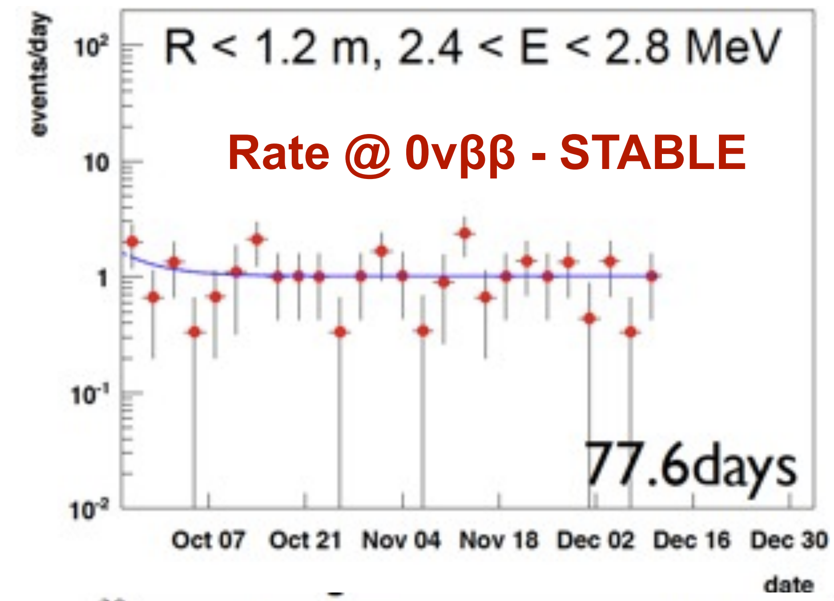


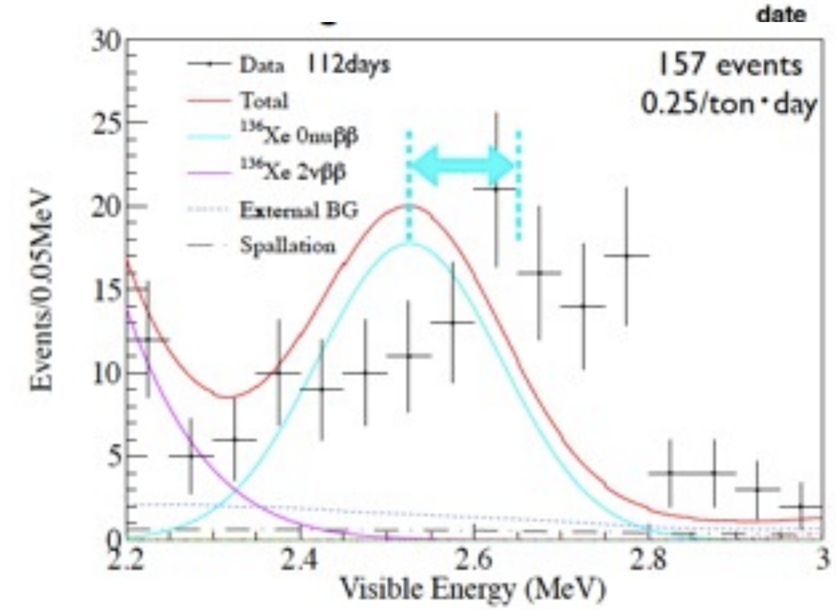


Target Sensitivity:
1st phase: <m_{ee}> ~ 60 meV @1 y
2nd phase: <m_{ee}> ~ 25 meV @5 y (IH)

Kamland-Zen 2νββ





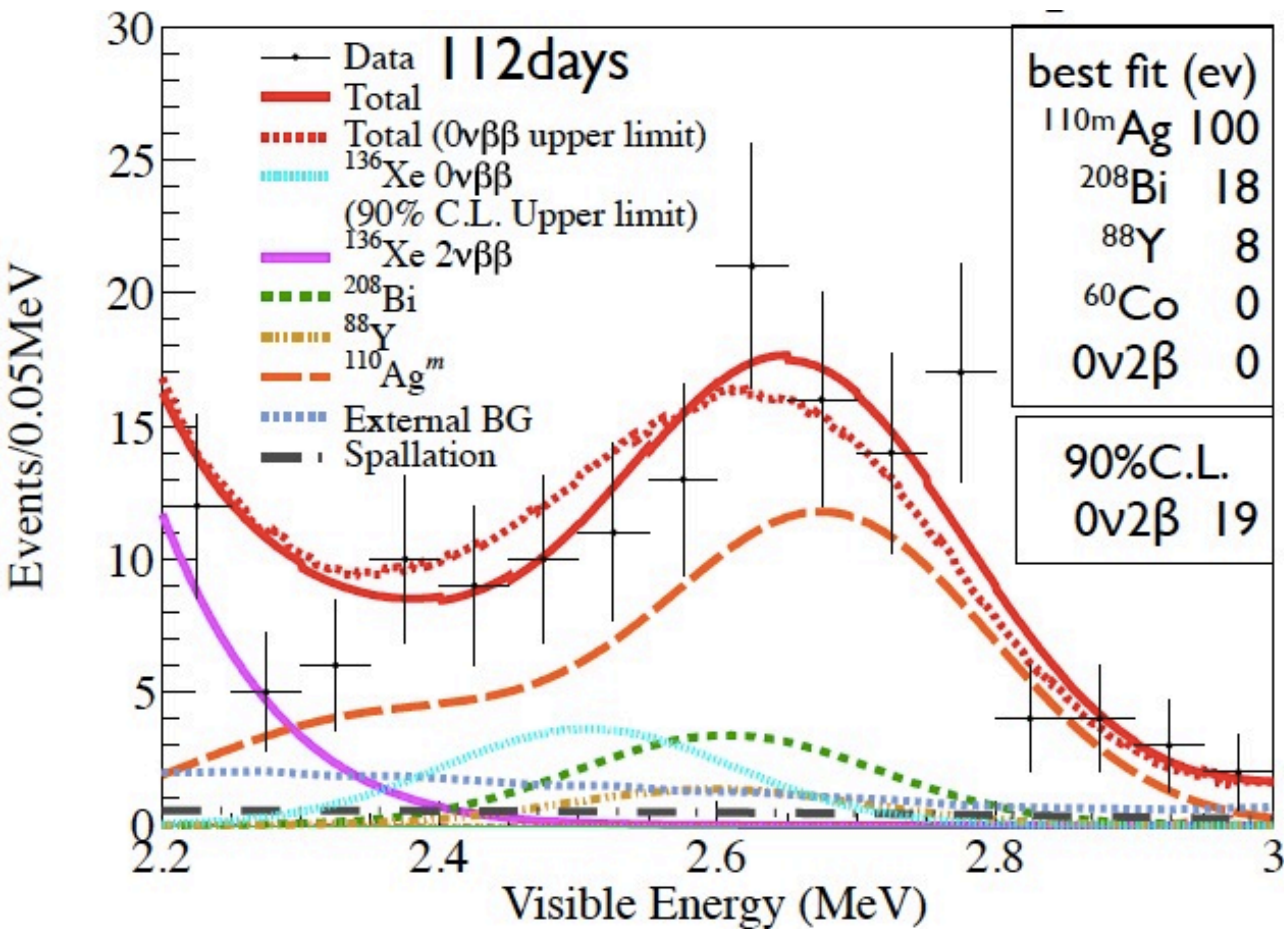


precise measurement of the 2νββ half-life:

$\tau_{1/2}^{2\nu\beta\beta}$ (^{136}Xe) = (2.30 ± 0.02 stat ± 0.12 sys)·10^{21} yr

Kamland-Zen 0νββ

arXiv:1205.6372



- KL-Zen: 112 days
- ^{110}Ag + ^{208}Bi fit

$\tau_{1/2}^{0\nu\beta\beta}$ (^{136}Xe) > $6.2\cdot10^{24}$ y

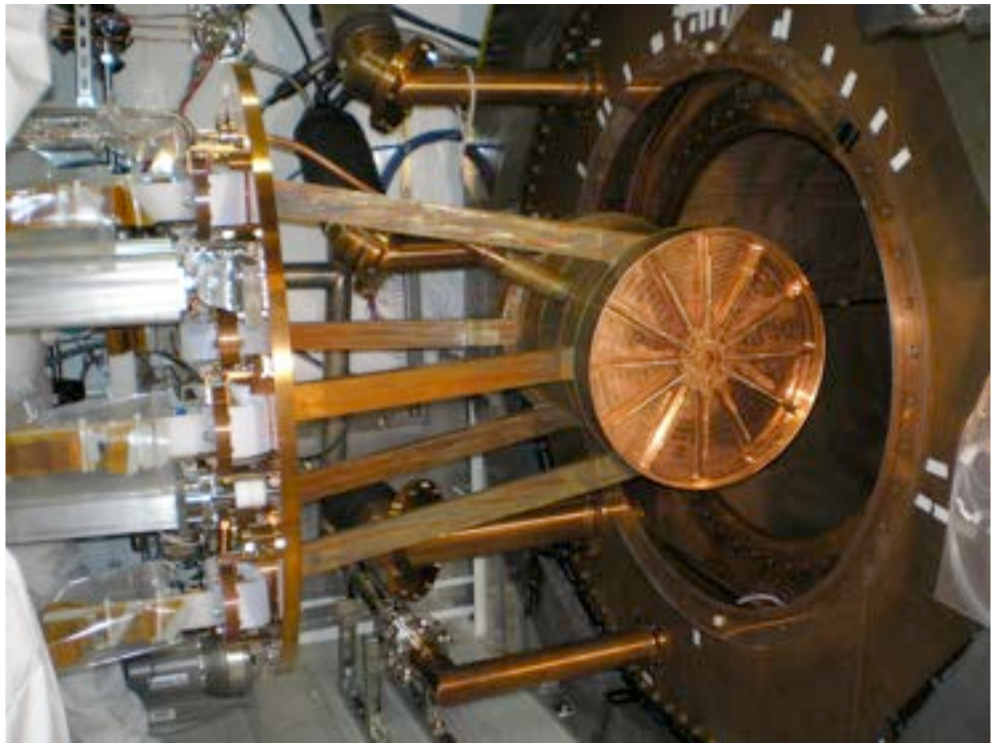
Results and perspectives:

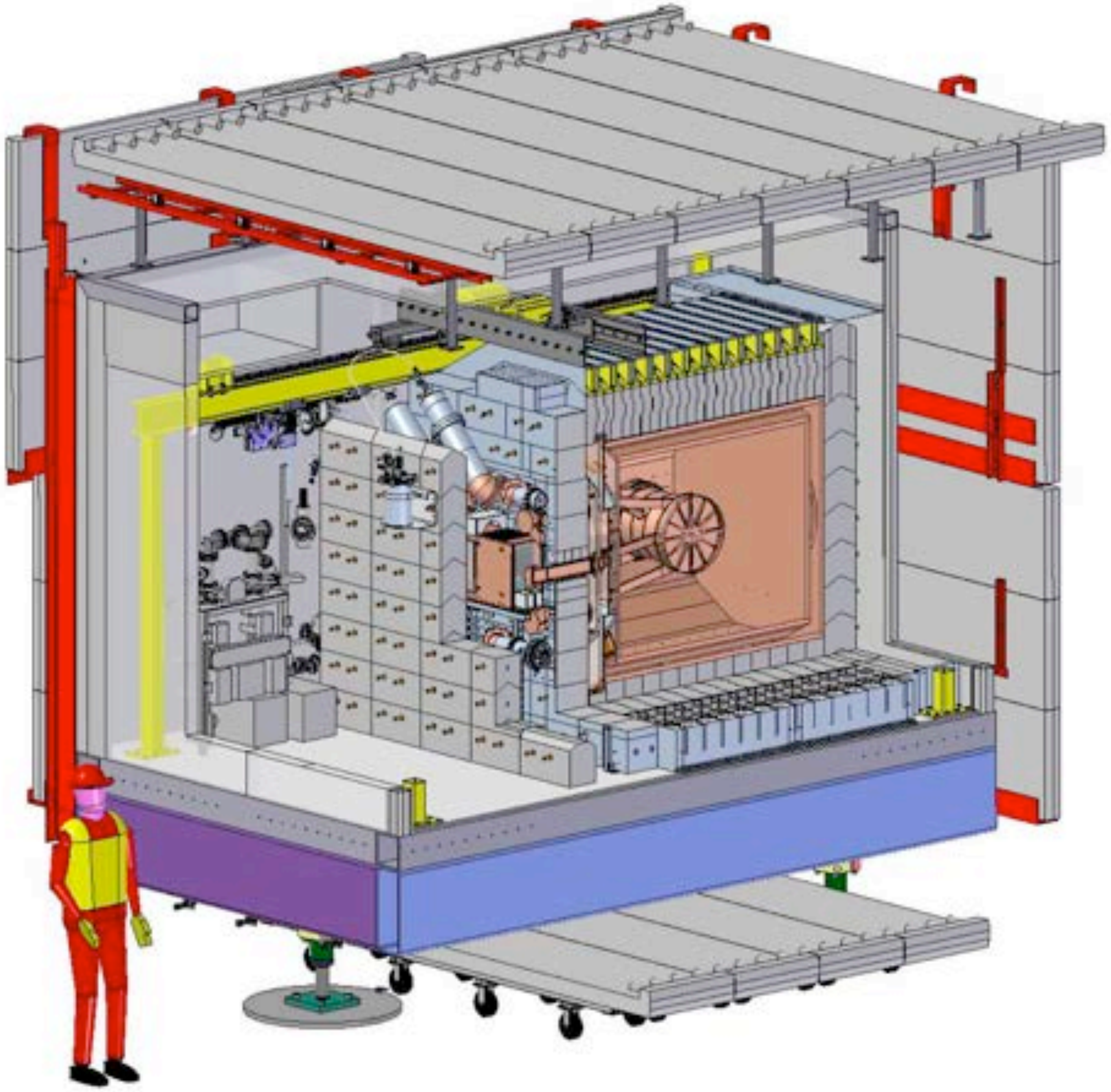
- validity of using the low radioacivity environment of neutrino detector for a rare phenomena study
- better understanding of background → effective purification is about to start (reduction factor 100)
- R&D for larger Xe concentration and better light yield

EXO-200

→talk T.Tolba

~ 1 ton TPC of liquid ^{enr}Xe (80.6% of ^{136}Xe) at 167 K with double read-out **(ion+scint)** allowing event **3D tracking** and **α/β discrimination + Ba^+ daughter tag** for **free bkg exp**.
GOAL of EXO-200: 1st step with 175 kg LXe without Ba^+ tag for QD region @WIPP
Exo-200: Started 2011 – 2νββ result: $T_{1/2}$ ~ 2.1x10^{21} y
Start nEXO?





ββ candidate: ^{136}Xe **– Q** 2458 keV

Source Mass:
- Exo-200: ~ 90 kg FMass ^{136}Xe – $\mathbf{N_{\beta\beta}}$ 4 x10^{26}

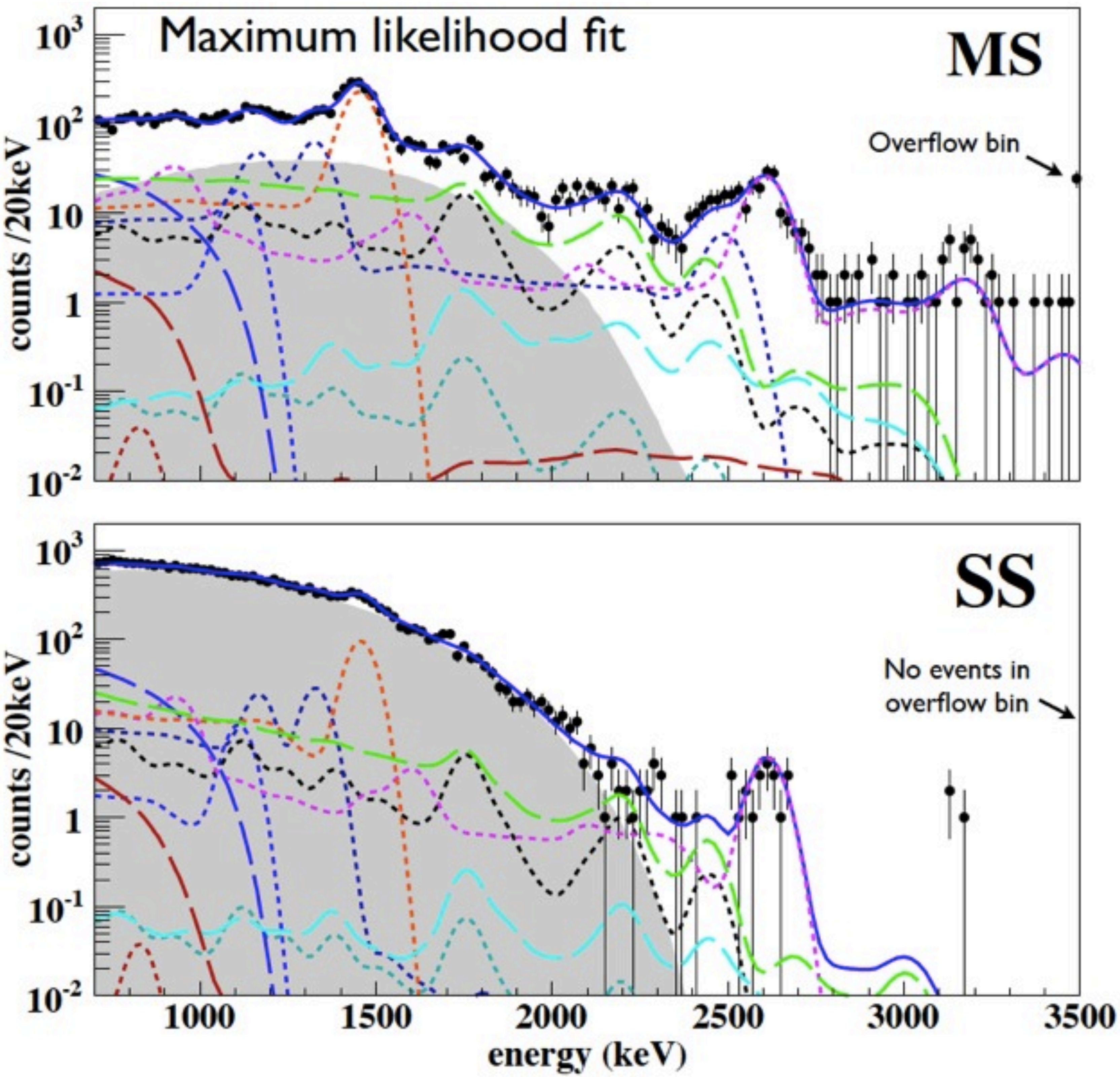
Bkg Strategy:
- low activity materials / LXe purity check
- conventional screening techniques+ FV cut
- 3D track (double grid (xy) + Avalanche Photo Diodes (t_0->z))
- α/**β** discrimination through ion. vs. light
- Ba^+ tag with Resonant Ionization Spectrosc.

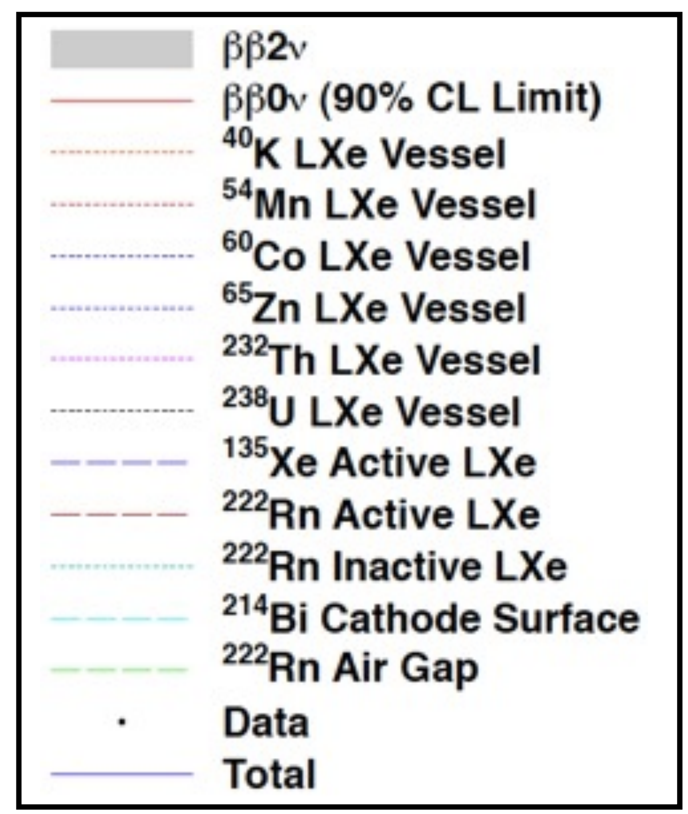
Projected Bkg: ~ 10^{-4} c/keV/kg/y

Projected FWHM: ~ 3.7% @ROI (maybe better if gas Xe)

Target Sensitivity:
- Exo-200: $T_{1/2}$ ~ 6.4x10^{25} y @2y <m_{ee}> < 87 ÷ 224 meV in 2y
- Exo-full: $T_{1/2}$ ~ 2.0x10^{27} y @ 5y <m_{ee}> < 16 ÷ 40 meV in 5y

EXO: 2νββ





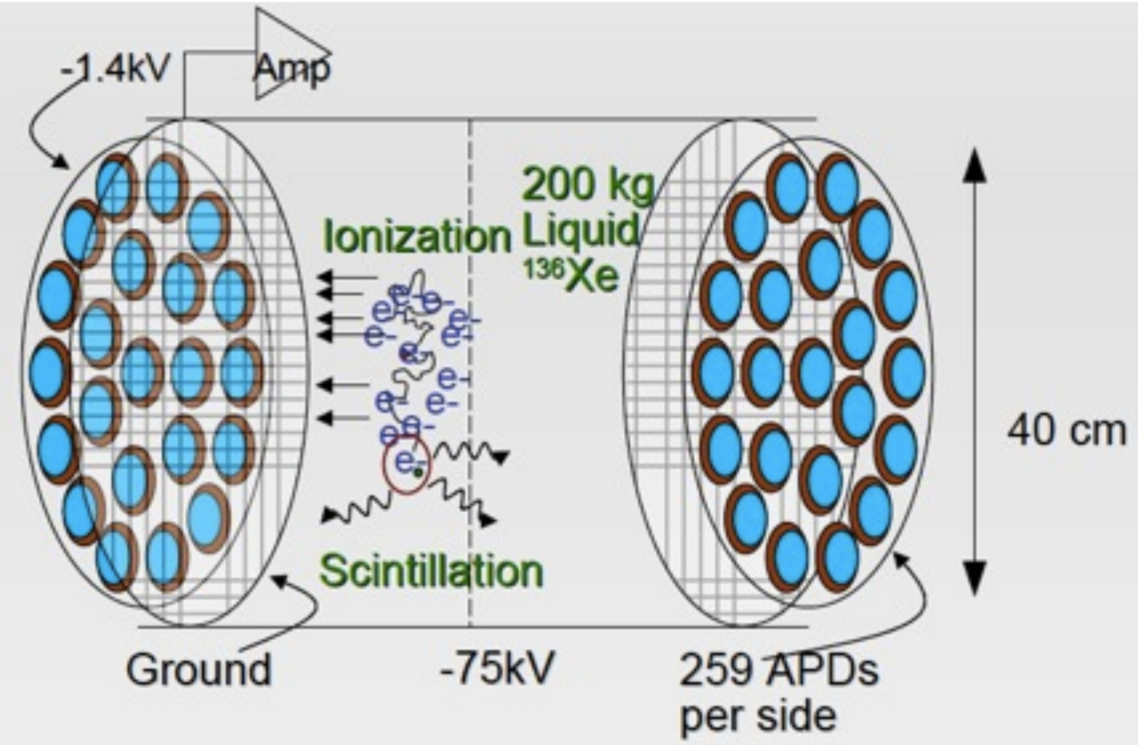
- Trigger fully efficient above 700 keV
- Low background run livetime: 120.7 days
- Active mass: 98.5 kg LXe (79.4 kg 136LXe)
- Exposure: 32.5 kg.yr
- Total dead time from vetos: 8.6%

- ~22,000 2νββ events !
- Also populate MS spectrum, partly due to bremsstrahlung
- MC predicts that 82.5% of 2νββ are SS

$\tau_{1/2}^{2\nu\beta\beta}$ (^{136}Xe) = (2.23 ± 0.017 stat ± 0.22 sys)·10^{21} yr

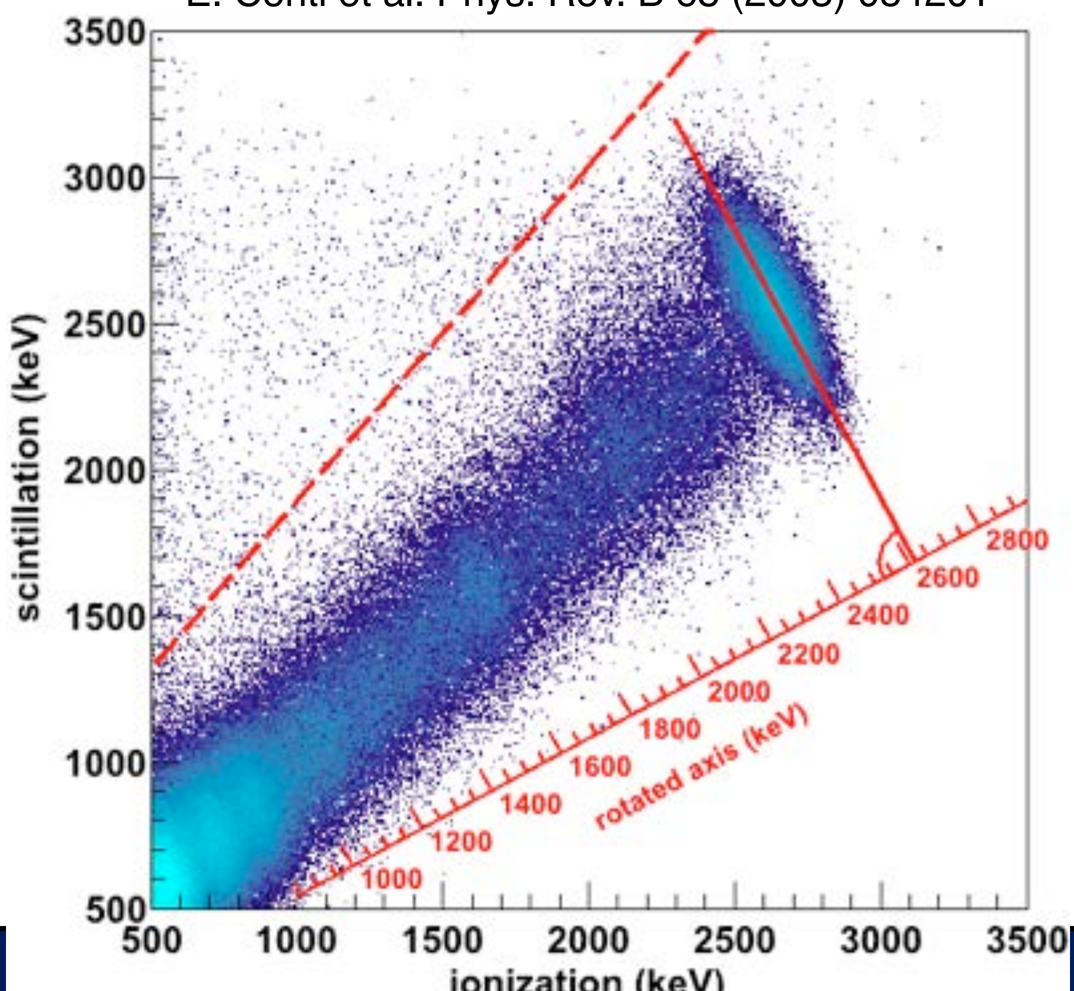
5 times faster than previous limit

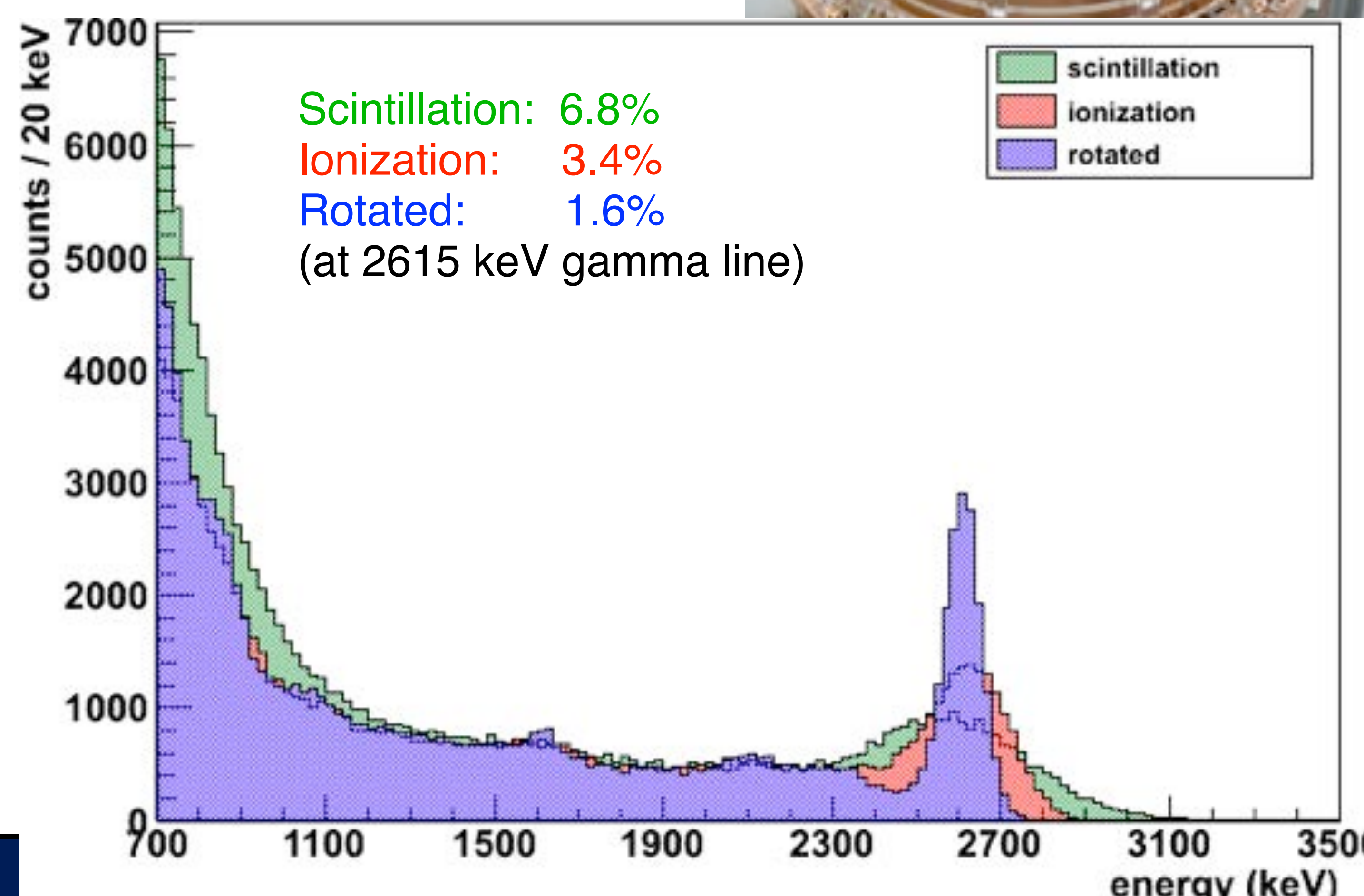
Resolution: scintillation vs charge



- Properties of xenon cause increased scintillation to be associated with decreased ionization (and vice-versa).
- Use projection onto a rotated axis to determine event energy

E. Conti et al. Phys. Rev. B 68 (2003) 054201





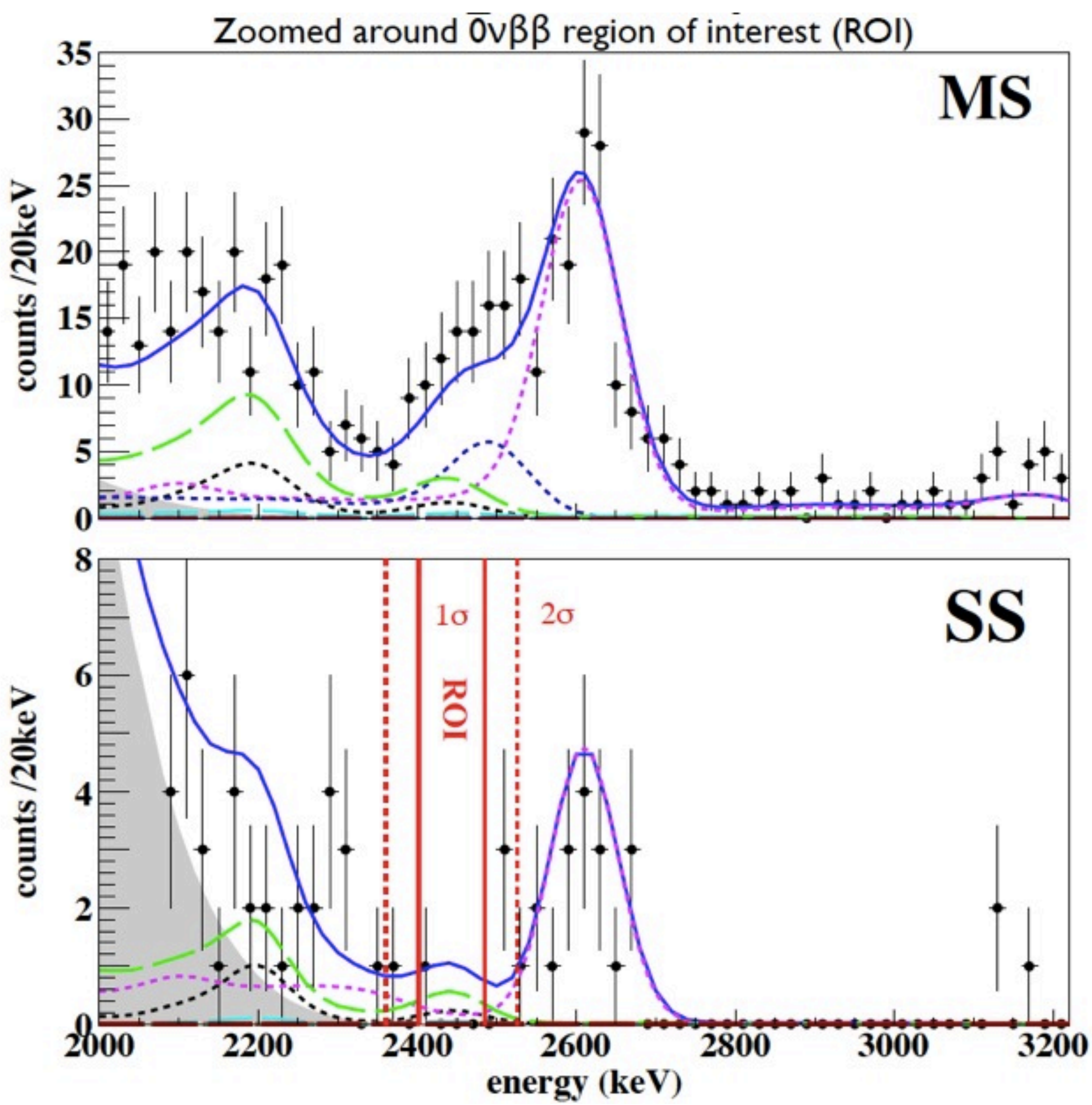
EXO-200 0νββ

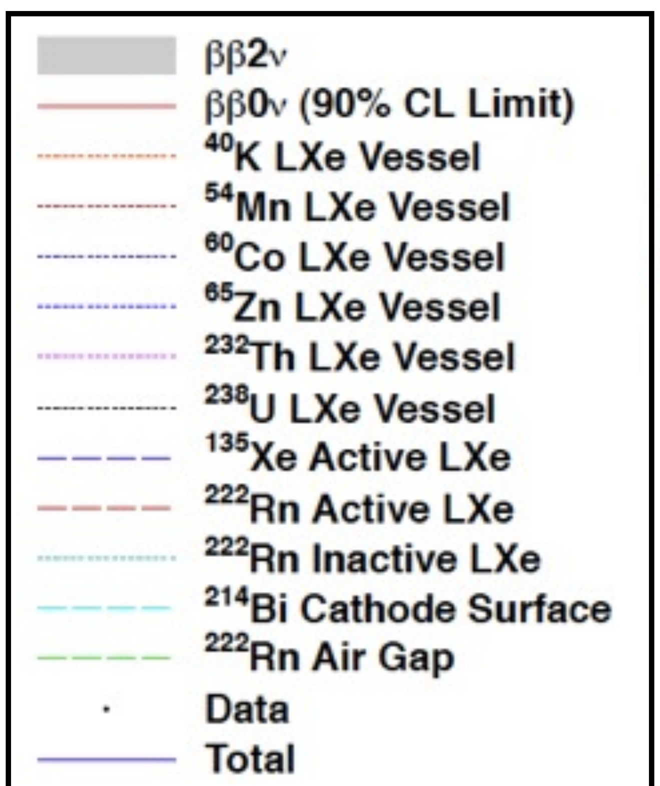
M. Auger et al., PRL 109 (2012) 032505; arXiv:hep-ex/1205.5608v2

EXO-200 is taking low background data. Detector works well:

- Energy resolution: 1.67% at Qββ
- Background: 1.5×10^{-3} (kg keV yr)$^{-1}$
- 1 (5) counts in 1σ (2σ) 0νββ ROI
- Background within expectation

- Improvements on resolution and b in progress
- EXO-200 approved to run for 4 more years

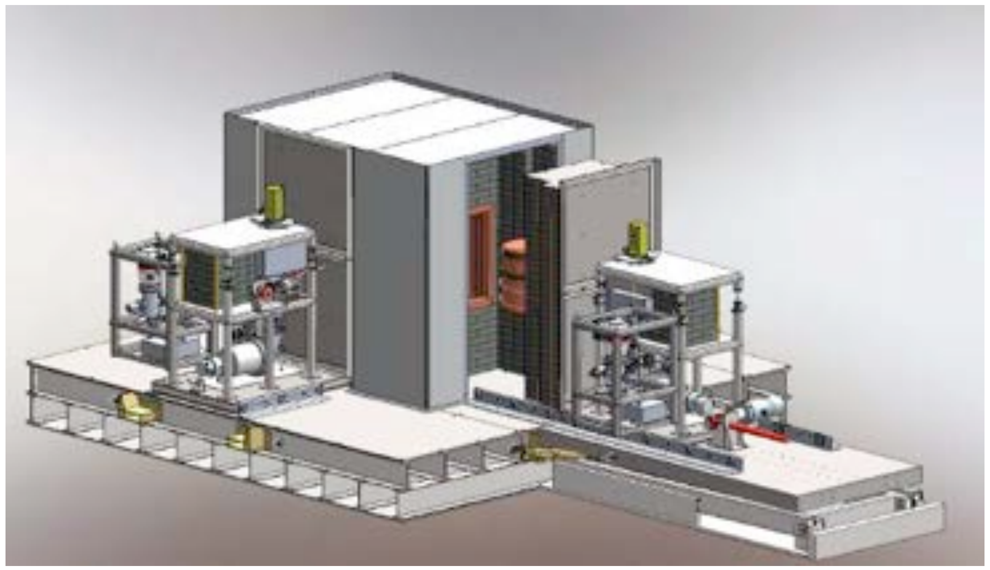


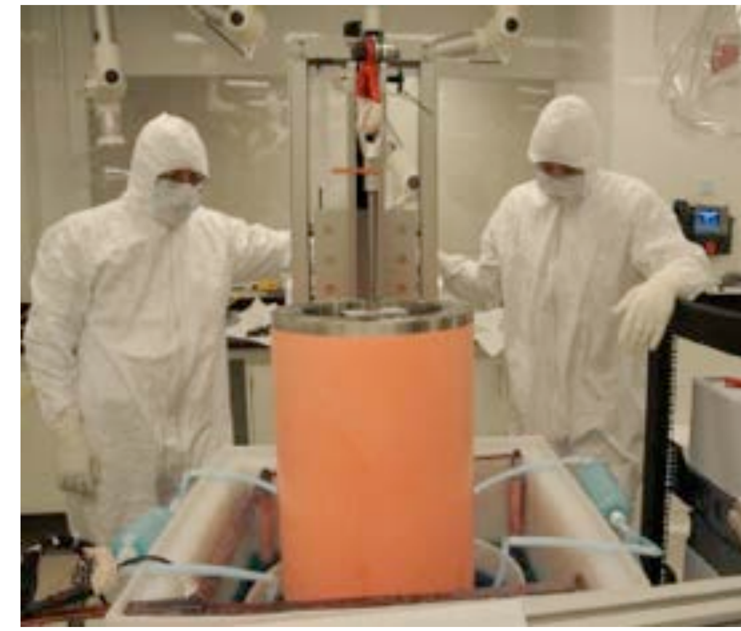


$\tau_{1/2}^{0\nu\beta\beta}$ (^{136}Xe) > $1.6 \cdot 10^{25}$ yr (<m_{ee}>140-380 meV) arXiv:1205.5608

Majorana Demonstrator

BEGe detectors (20 kg ^{nat}Ge + 20 kg 86% enriched ^{76}Ge) **in 2 conventional cryostats** made of electro-formed Cu + Pb/Cu passive shields + m active veto
GOAL: **demonstrate bkg and feasibility, test KK claim** @Sanford UL Start ~ 2014





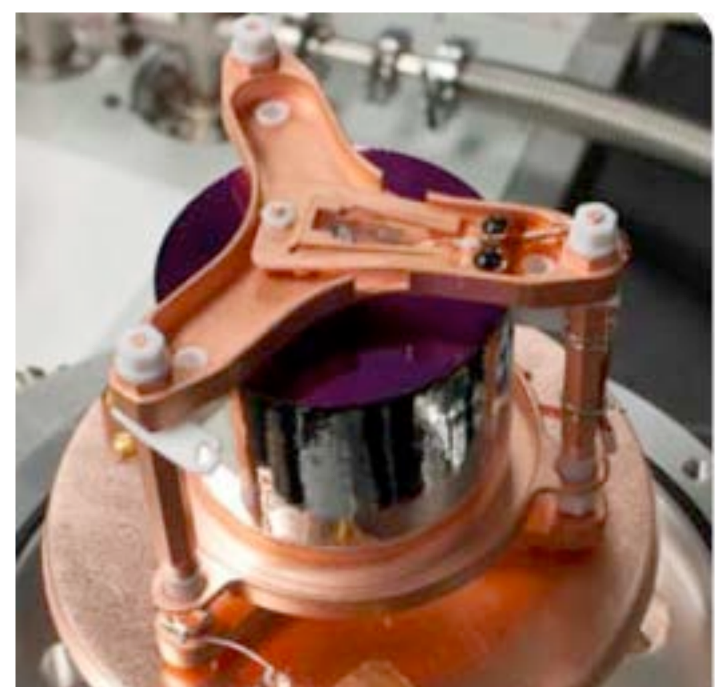
ββ candidate: ^{76}Ge **– Q** 2039 keV

Source Mass:
30 kg ^{76}Ge – $\mathbf{N_{bb}}$ 2.4 x10^{26}

Projected Bkg:
0.001 c/keV/kg/y (shields + BEGe techn.)

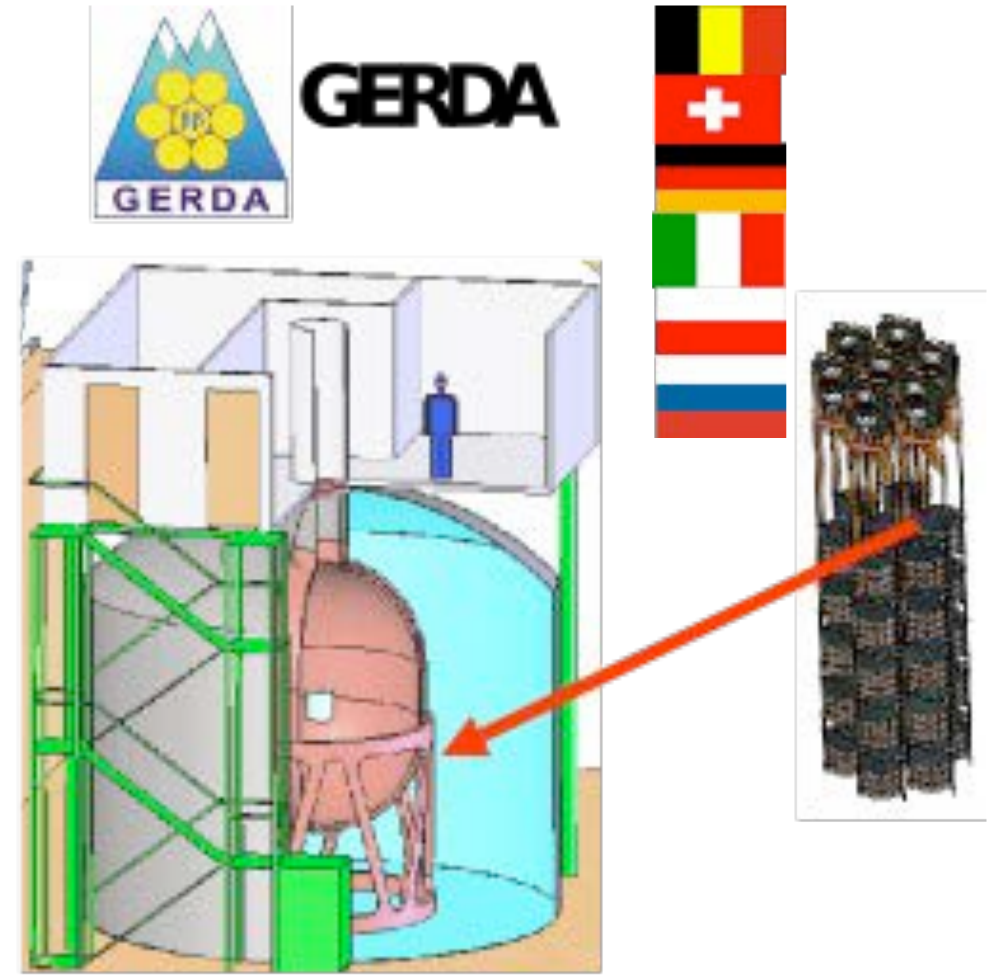
Sensitivity $T_{1/2}^{0\nu}$:
9×10^{25} y in 5 y

Sensitivity $\langle m_{ee} \rangle$:
Scrutinize KK claim in < 2 y
$\langle m_{ee} \rangle$ < 106 ÷ 295 meV in 5y **> IH**



Schedule: 2012: 2-3 ^{nat}Ge strings in prototype cryostat above ground (19 ^{nat}Ge diodes in hand)
2013: 3 strings ^{nat}Ge + 4 strings ^{enr}Ge below ground (1st cryostat)
2014: full experiment

MAjorana-GErda



Joint Cooperative Agreement:

Open exchange of knowledge and technologies

Select best technique developed and tested in GERDA and Majorana

Intention to merge for 1 ton exp. (~ 2020)

=> factor ~ 2.5 on $<m_{ee}>$: 43 ÷ 120 meV in 5 y (enter IH region)

AMORE

100 kg $^{40}Ca^{100}MoO_4$ scintillating bolometers (96% ^{100}Mo enriched, <0.001% ^{48}Ca depletion) at low T with double read-out **(heat/light) or shape analysis** for **alpha bkg** suppression
@YangYangUL R&D phase

ββ candidate: ^{100}Mo **– Q** 3034 keV

Source Mass:
50 kg ^{100}Mo – $\mathbf{N_{bb}}$ 3.0 x10^{26}

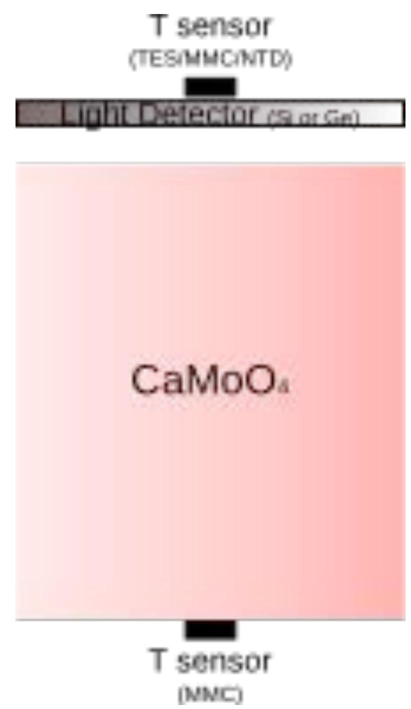
Projected Bkg:
0.001 c/keV/kg/y

Projected FWHM: ~ 0.07% @ROI
Measured FWHM: ~ 0.2% @ 5 MeV

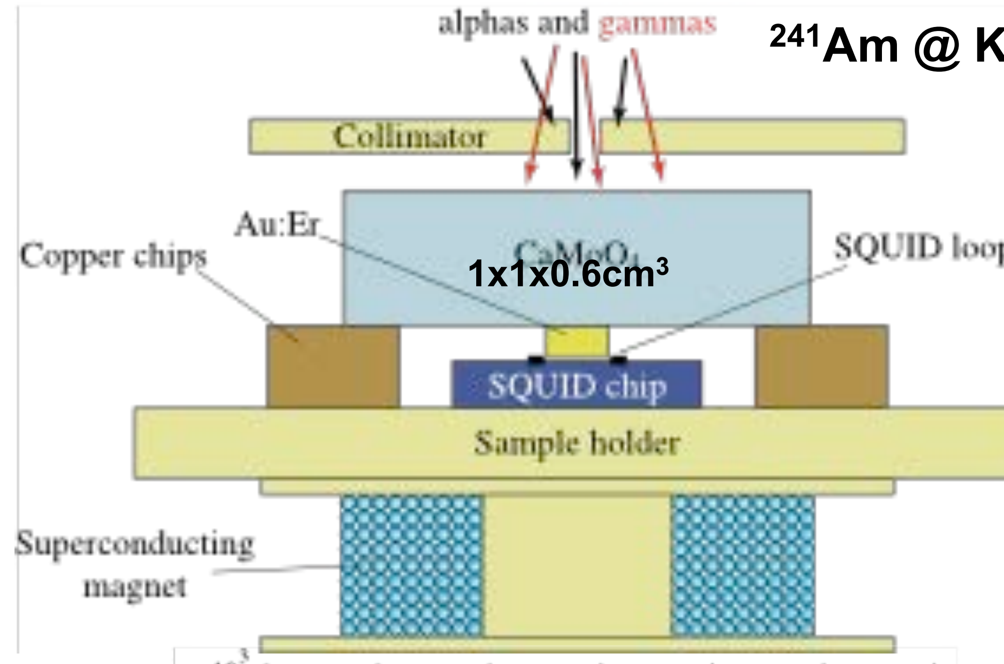
LY (RoomT): ~9300 phot/MeV

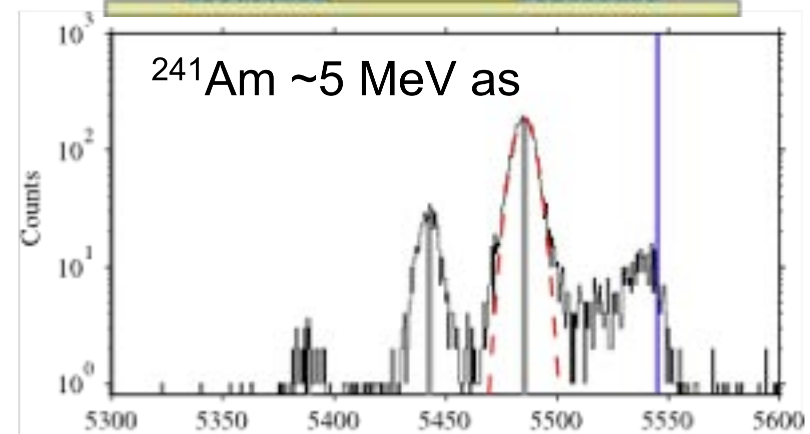
Sensitivity $T_{1/2}^{0n}$:
$3x10^{26}$ y in 5 y

Sensitivity <m$_{ee}$>:
<m$_{ee}$> < 27 ÷ 63 meV in 5y (IH)

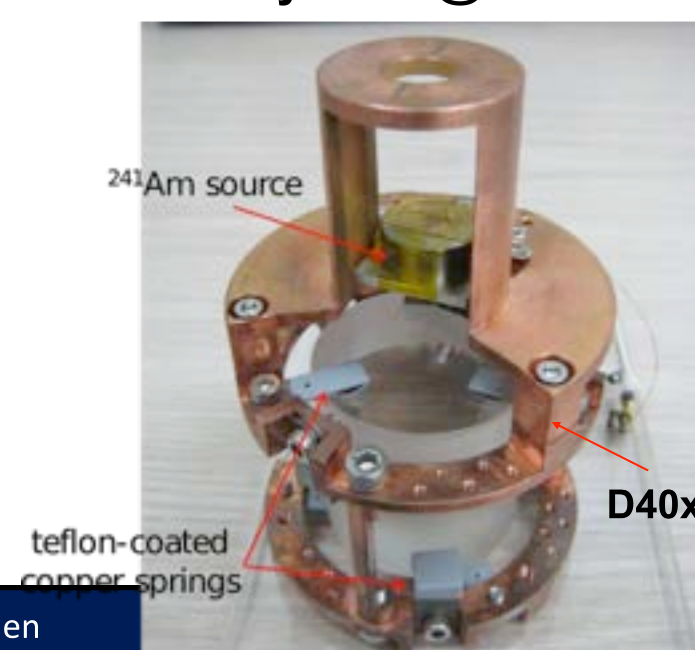


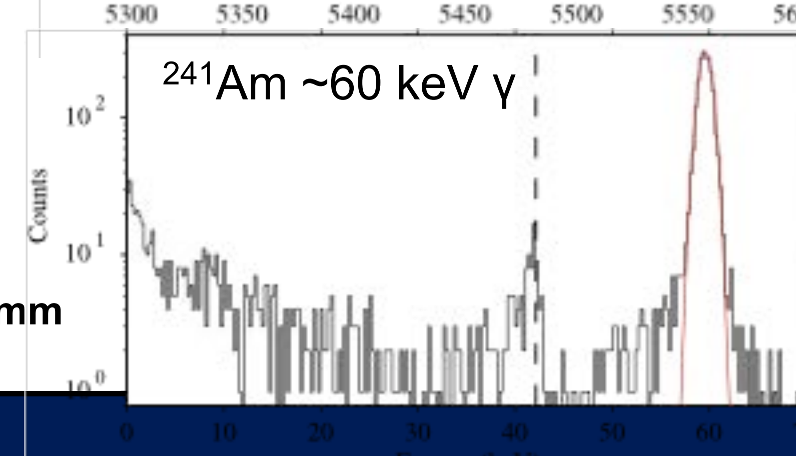
^{241}Am @ KRISS





July 2011 @KRISS





Candles

CANDLES-III: 96 CaF_2 scintillators (0.187% ai of ^{48}Ca) **in a granular structure (~305 kg)**
with 4p Liquid Scintillator active shield and H_2O buffer passive shield + 62 PMTs
GOAL: 1^{st} step towards a ~tons CaF_2 experiment for IH
@Kamioka mine 1st phase: commissioning started in June 2011 Start 2nd phase?

ββ candidate: ^{48}Ca **– Q** 4270 keV !!

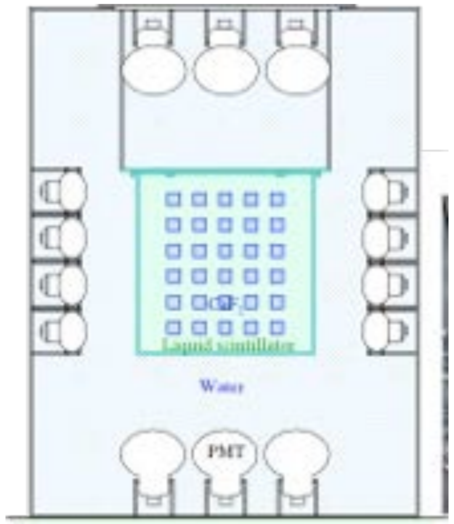
Source Mass:
1^{st} phase: 350 g ^{48}Ca – $\mathbf{N_{bb}}$ 4.4 x10^{24}
2^{nd} phase: $\mathbf{N_{bb}}$ ~10^{26}

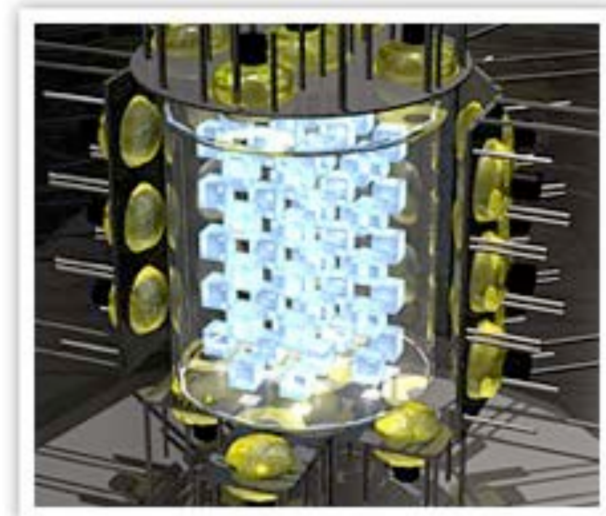
Bkg Strategy:
- 2nbb negligible if DE 4% FWHM
- 4p LS shield for external g
- PSD + time/position (internal Bi-Po,Bi-Tl)

=> ~ bkg free experiment

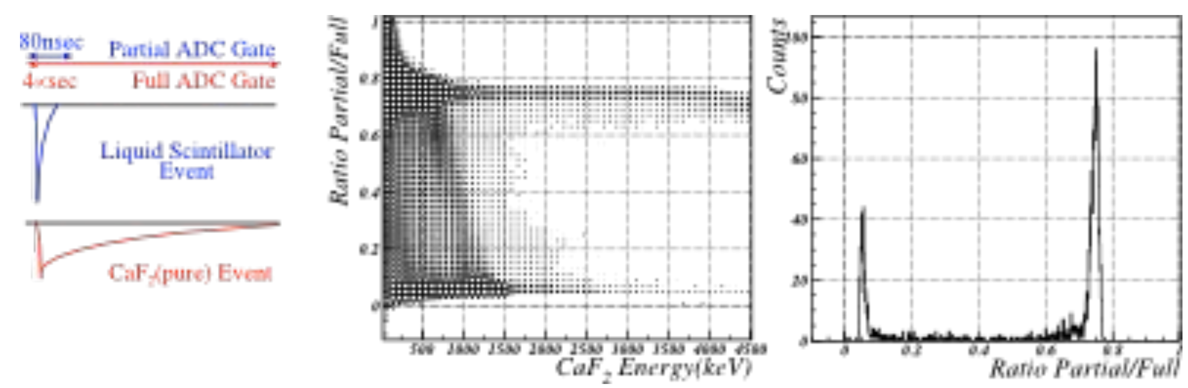
Measured FWHM: ~ 3.4% @ROI

Target Sensitivity:
1^{st} phase: $<m_{ee}>$ ~ 500 meV @3 y
2^{nd} phase: IH region

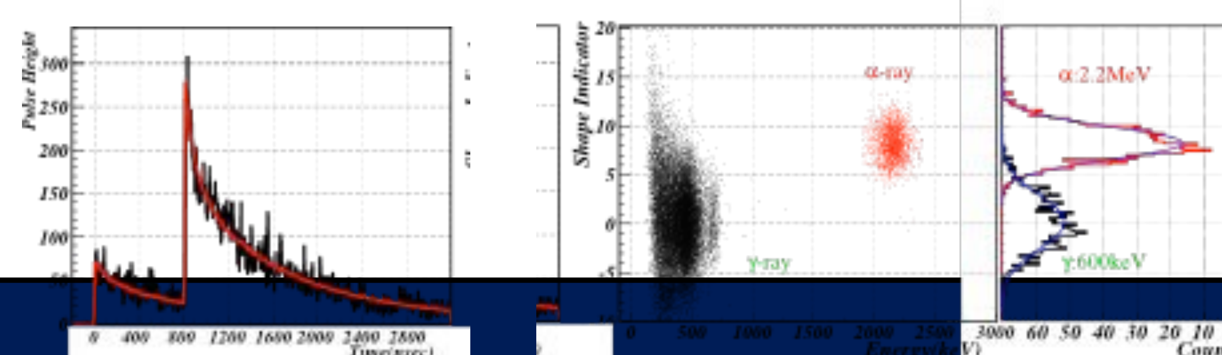




External (LS) vs internal events (with 2 ADC gates)



Bi-Po and Bi-Tl events (Pup + a/b different shape)

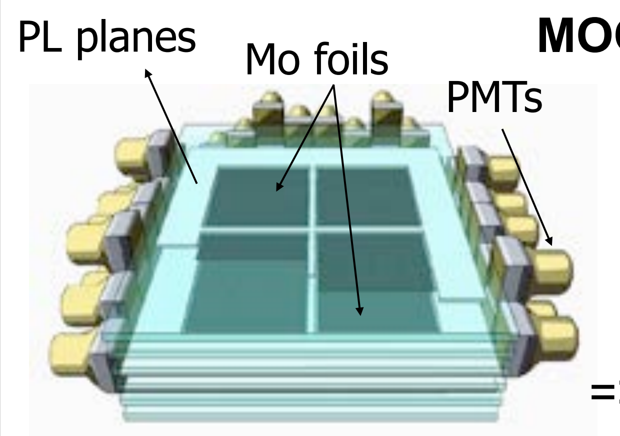


MOON

Multi-layer detector modules: **PL scint. planes** (E+t) / **PL-fibers** (V,j) / 50mg/cm^2 **source** foils
@Oto U.L. MOON-1: prototype ~ 2006 3 Phases of increasing mass (start Phase-III ?)

ββ candidate: ^{82}Se – **Q** 2995 keV
^{100}Mo – **Q** 3134 keV

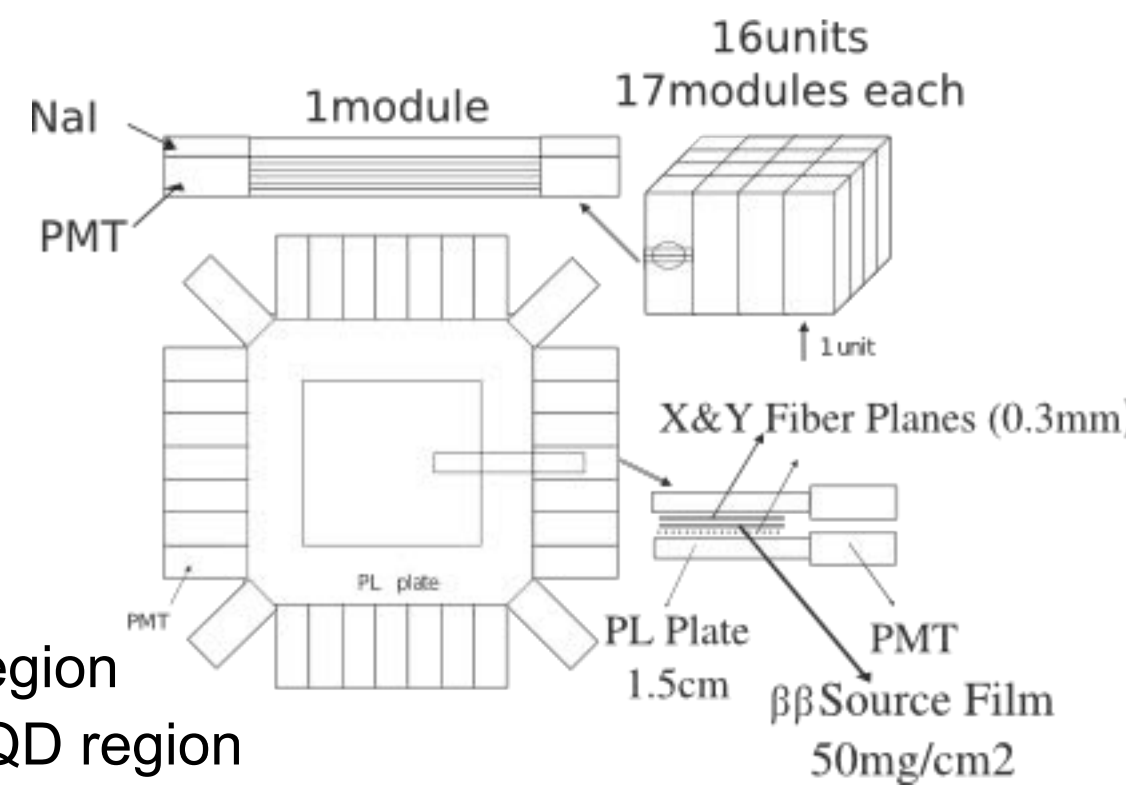
Source mass:
Phase-I: 0.03 t isotope
Phase-II: 0.12 t isotope
Phase-III: 0.48 t isotope



MOON-1

6 layers PL scintill.
5 Mo films (94.5 % enr)
(40mg/cm2 each)
56 PMTs
ELEGANT-V shields
=> **Proved s~2.9%@3MeV**

Bkg Strategy:
- Standard shieldings+active veto from M-layer
- Low ^{208}Tl/^{214}Bi contam. in source foils
- M=2 event with same V
- E1+E2 @ROI (Q-DE$_{source}$ within 3s)
- no delayed coincidence (Dt~h)
- 2nbb reduced with good DE



Measured DE: s~2.2 % @ROI (Foreseen s ~1.7 %)

Target Sensitivity:
Phase-I: $\mathbf{T_{1/2}}^{0n}$~ 0.32(0.15) x10^{26} @ 1y for Se(Mo) -QD region
Phase-II: $\mathbf{T_{1/2}}^{0n}$~ 1.12(0.41) x10^{26} @ 1y for Se(Mo) - LowQD region
Phase-III: $\mathbf{T_{1/2}}^{0n}$~ 5.90(2.00) x10^{26} @ 1y for Se(Mo) -IH region

DCBA

Momentum analyzer consisting of tracking detectors (DC) with solenoid magnet for uniform B @KEK **DCBA-T2**: prototype~ 2009 **DCBA-T3** in construction for DE improvements
Future: MTD-full ~200 mol ^{150}Nd source Start ?

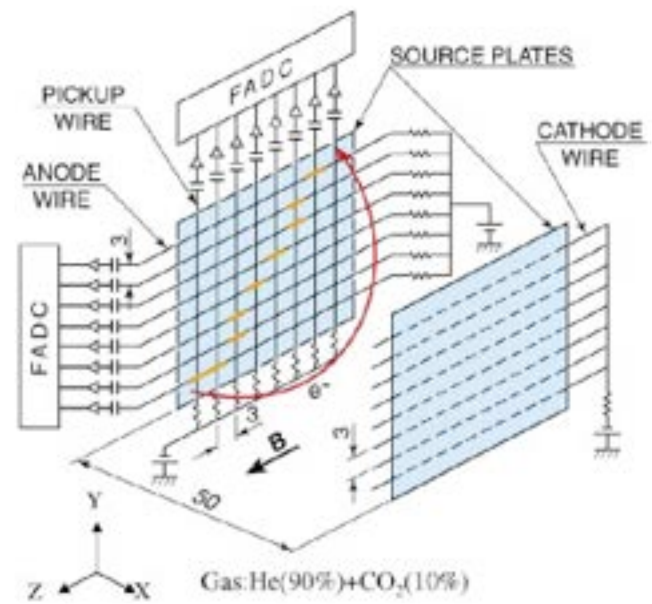
ββ candidate: ^{150}Nd **– Q** 3370 keV

Source mass:
DCBA-T2: 0.03 mol ^{100}Mo for test with 2nbb
DCBA-T3: 0.18 mol ^{150}Nd ($Nd_2{}^{nat}O_3$)
MTD-1: 1.3x10^{26} ^{150}Nd ($Nd_2{}^{enr}O_3$ – 60% enr)
MTD-full: 10 x MTD-1

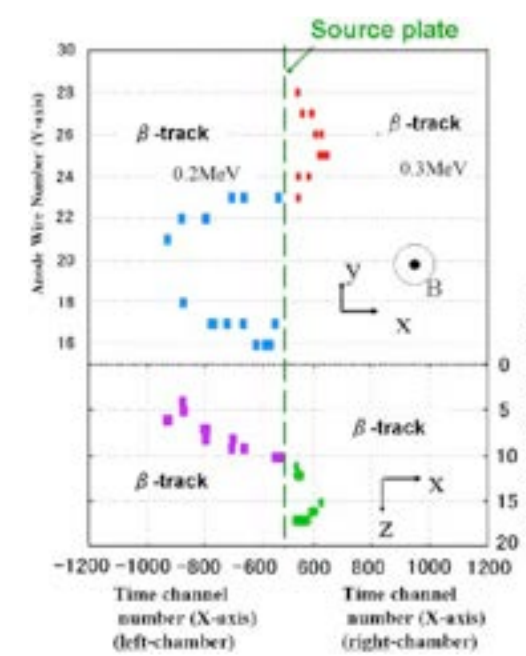
Bkg Strategy:
-Vetoes for cosmic rays
-3D track in uniform B
(search for 2 circled curves in X,Y + sin in Z)
-p and T from track

DCBA-T2 DE FWHM: ~6.2 % @ROI
DCBA-T3 foreseen ~3.4 % (>B)

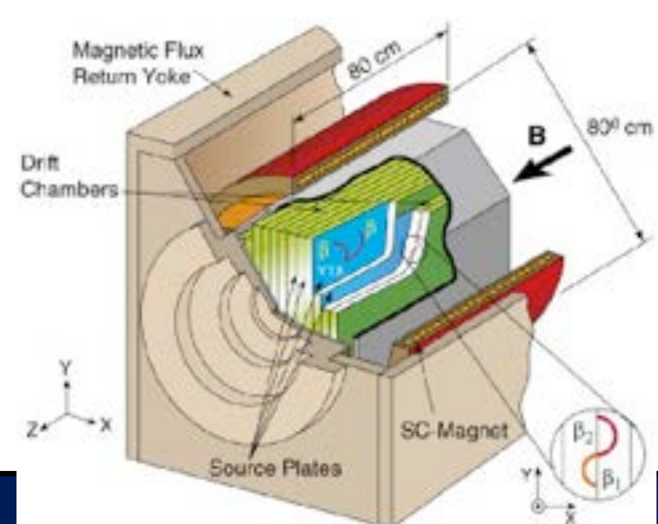
Target Sensitivity:
DCBA-T3: **$<m_{ee}>$ ~ 4 eV**
MTD-1: **$<m_{ee}>$ ~ 100 meV**
MTD-full: $<m_{ee}>$ ~ 30 meV

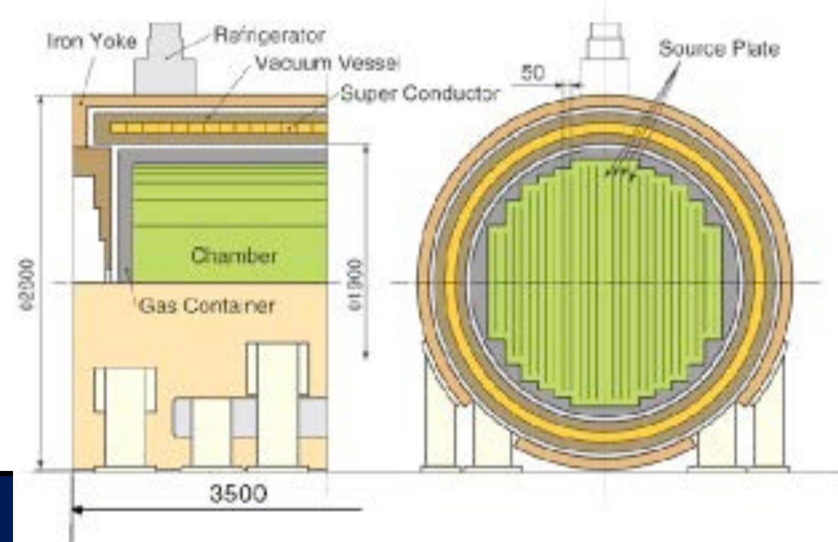


2νββ track with ^{100}Mo source



DCBA-T3 and MTD (vs. DCBA-T2):
12 Drift Chambers (vs. 2)
3 mm wire pitch (vs. 6 mm)
B=3 kG (vs. 0.8 kG) with Sup. Sol. Magn. (vs. conventional S.M.)
^{150}Nd in Nd_2O_3 plates -^{nat}Nd @T3, ^{enr}Nd @MTD (vs. ^{100}Mo in ^{nat}Mo)





SuperNEMO

20 modules of **tracker-calorimeter** with 40 mg/cm^2 source foil each (~5 kg ^{82}Se each).
@LSM Demonstrator (1 module) start-up ~ 2013 Full: start-up ~2014

ββ candidate: ^{82}Se **– Q** 2995 keV

Source mass:
Demonstrator**:** 5 kg ^{82}Se - **N$_{\beta\beta}$** 1.8 x10^{25}
Full**:** 100 kg ^{82}Se - **N$_{\beta\beta}$** 7.3 x10^{25}

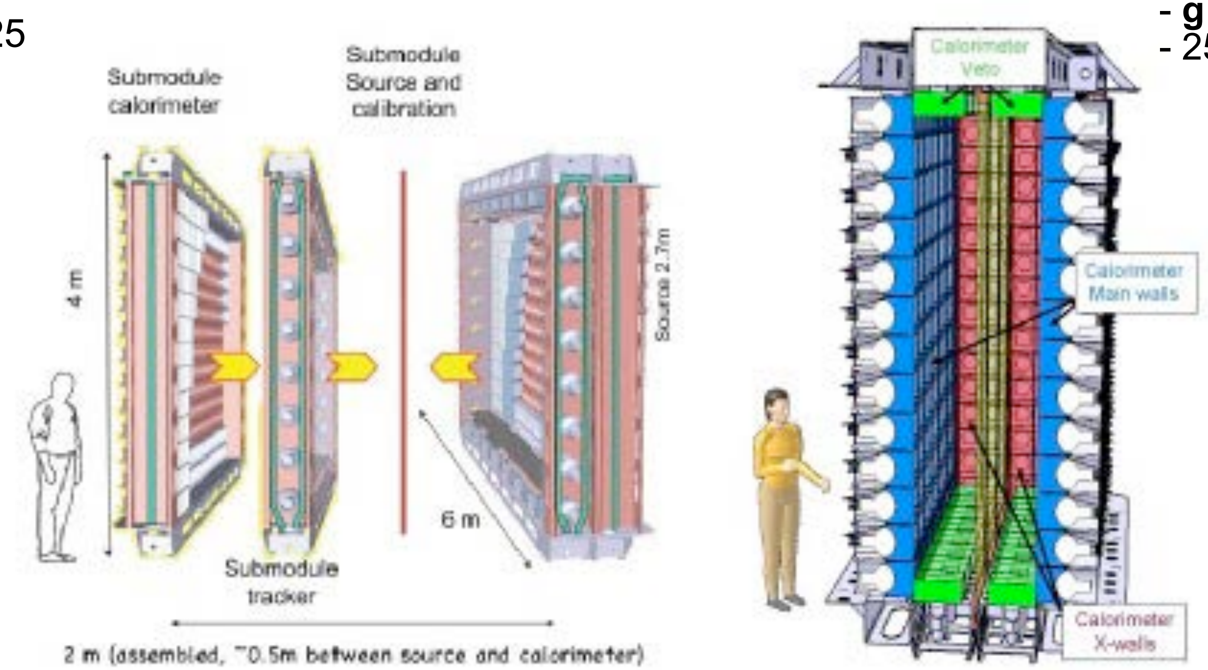
Bkg Strategy:
- Standard shieldings
- Low ^{208}Tl/^{214}Bi contam. in source foils
- tracking
- 2nbb reduced with better DE

Measured ΔE: ~4 % @ ROI
with best calorimeter/PMT choice

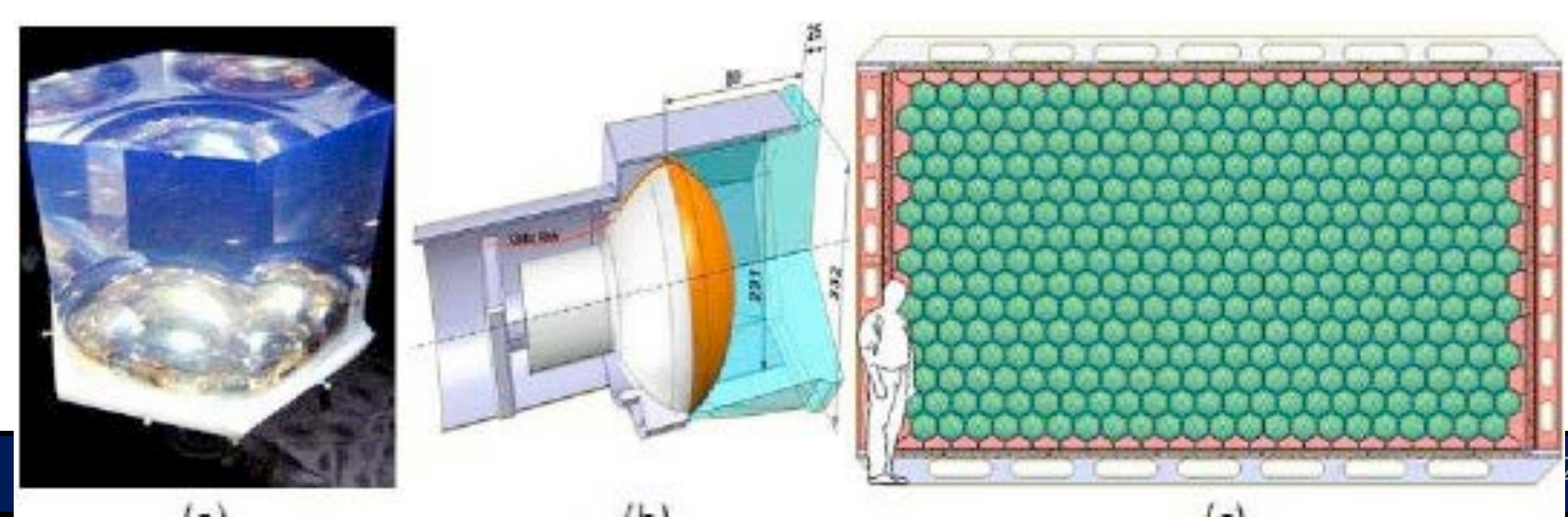
Target Sensitivity:
Demonstrator**:** KK claim within 2015
Full**:** **$T_{1/2}^{0\nu}$**~ 1.2 x10^{26} 90%CL @ 5y
<m$_{ee}$> ~ 40-105 meV @ 5y

Single-Module: 5x4x1 m^3

- **track** (2000 wire Drift Cells in Geiger Mode)
- **calorimeter wall** (550 PVT +PMTs)
- **g veto**
- 25 Gauss B



Calorimeter: PVT (plastic scintillator) + PMT (~550/module)



SNO+

~ 780 t Liquid Scintillator 0.1% ^{nat}Nd loaded (5.6% a.i. of ^{150}Nd) in a Ø 6m Acrylic Vessel surrounded by 7000 t ultrapure H_2O and ~9000 PMT.
@SNO Lab **Start ~ 2014**

ββ candidate: ^{150}Nd **– Q** 3370 keV

Source Mass:
43.7 kg ^{150}Nd – **N**$_{\beta\beta}$ 1.8 x10^{26}

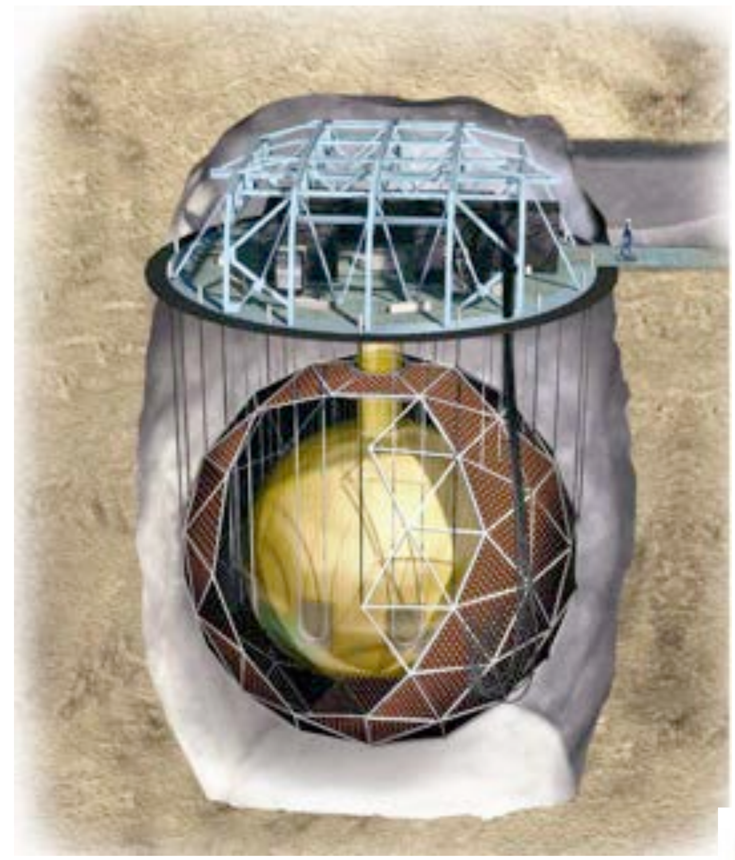
Trade off ΔE / Nd loading

Main Bkg:
- Th/U in LS and Nd negligible/tagged
- 2νββ → fit at End Point
- ^{8}B solar ν

Projected FWHM: ~ 6.4% @ROI

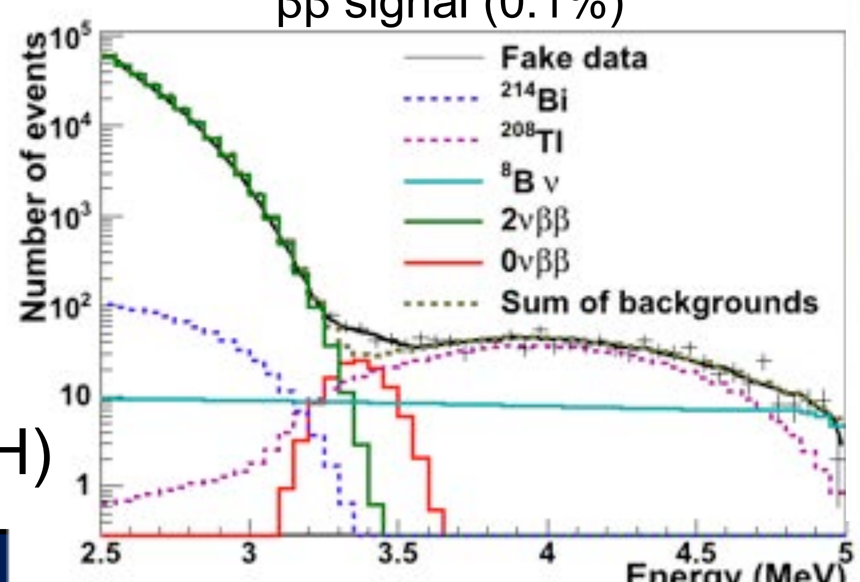
Sensitivity $T_{1/2}^{0\nu}$:
7.7x10^{24} in 5 y

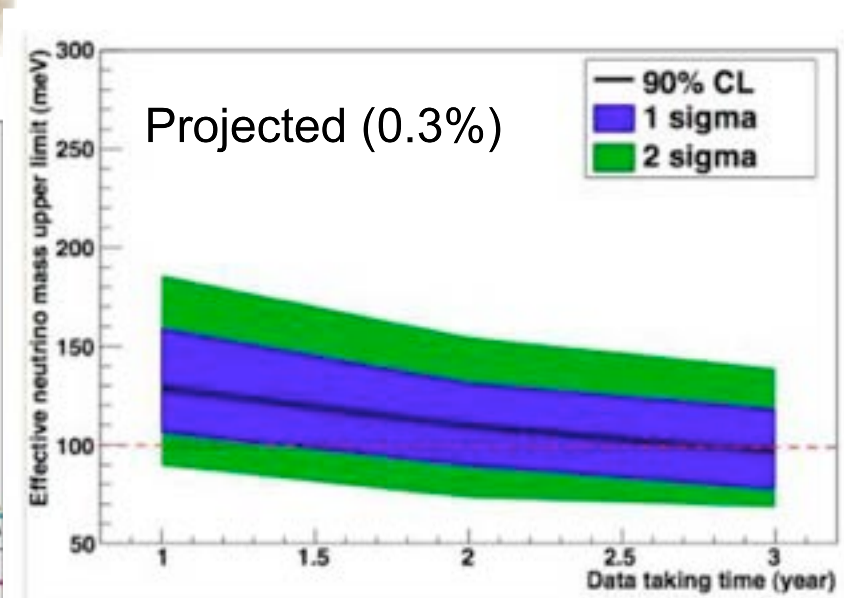
Sensitivity <m$_{ee}$>:
<m$_{ee}$> < 172 ÷ 180 meV in 5 y (> IH)



Schedule:
2011: - Finish cavity
- AV hold-down-net
- Sand in AV
2012: - LS process system
- Water fill: cal runs
2013: - Pure LS phase
2014: - Nd-loaded phase
Then: - 0.3% Nd loading?
- ^{150}Nd enrichment?

ββ signal (0.1%)



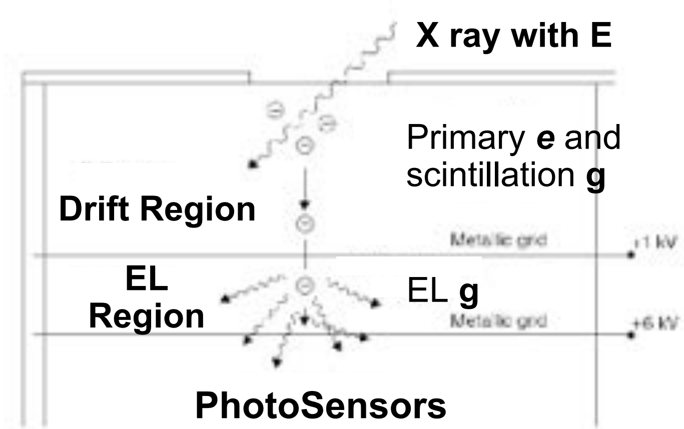


NEXT-100

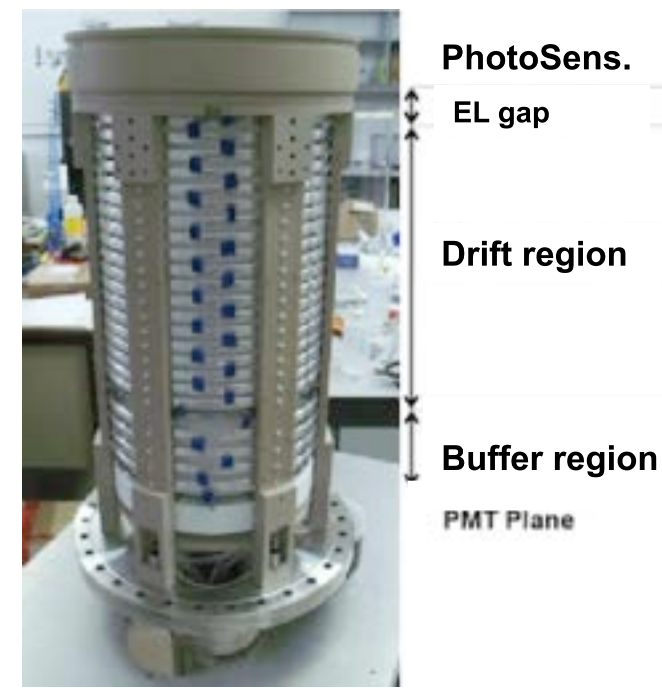
119 kg High Pressure Gas- ^{enr}Xe EL TPC (~ 90% of ^{136}Xe) with double read-out **(ion +scint/EL)** allowing **good DE** + event **3D tracking** and **topology** for a **free bkg exp**.
@SLC Next-1: on-going Next-100: ~ 2015 Future 1t?

ββ candidate: ^{136}Xe **– Q** 2458 keV

Source Mass:
~ 90 kg FMass ^{136}Xe – $\mathbf{N}_{\beta\beta}$ 4.0 x10^{26}

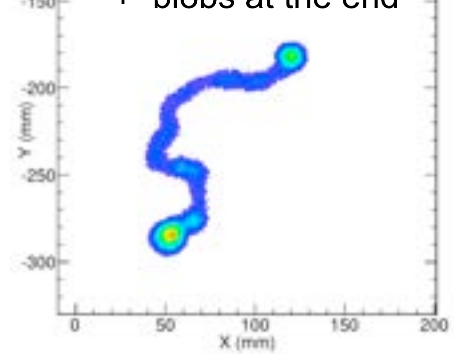


Bkg Strategy:
- low activity materials / GasXe purity monitor
- conventional screening techniques
- 3 cuts: FV + ROI + topology



Projected Bkg: ~ $2\cdot10^{-4}$ c/keV/kg/y

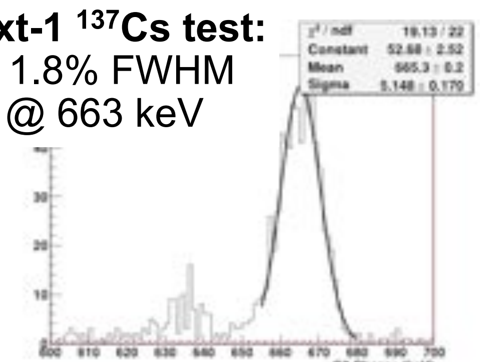
ββ event simulation:
~ 20 cm ioniz. track
+ blobs at the end



Projected FWHM: ~ 0.5-1% @ROI

Target Sensitivity:
Next-100: <m_{ee} > ~ 89 meV @ 6y
Next-100+Next-1t: <m_{ee} > ~ 38 meV @ 6y (3+3)

Next-1 ^{137}Cs test:
~ 1.8% FWHM
@ 663 keV



COBRA

Large Array (total 420 kg) **CdZnTe smc detectors** (^{116}Cd enr.) **– solid state TPC** at room temperature with **tracking capability**.

@LNGS R&D: on-going with 2 types of det. COBRA: technical design report ~2013

ββ candidate: 9 candidates
Most promising (high Q) ^{116}Cd **– Q** 2809 keV

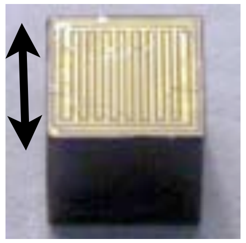
2 types of detectors under consideration:
- CoPlanar Grid Detectors (CPG)
  - ✳ little ¨location¨ info (with PSA)
  - ✳ simple read-out
- Pixelated Detectors
  - ✳ 3D ¨location¨ + Particle ID if small pixels.
  - ✳ Complex read-out

Bkg Strategy:
- low activity materials
- conventional screening techniques
- Multi/Single hit event with both types
- Tracking with Pixelated

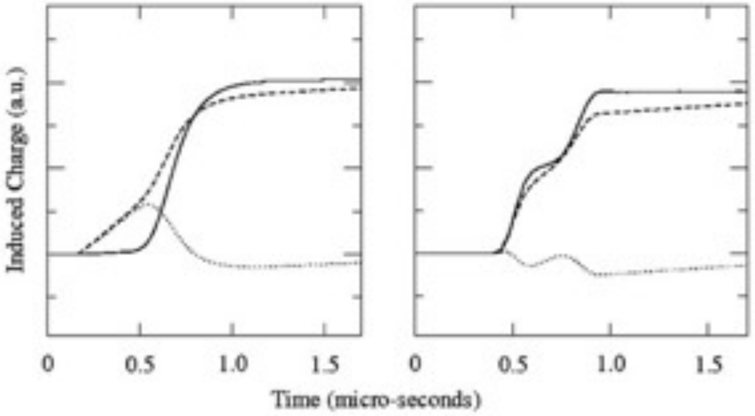
Projected DE: < 2 (1) % @ROI with CGD(Pix)

Target Sensitivity:
COBRA: $\langle m_\nu \rangle$ ~ 50 meV

1 cm



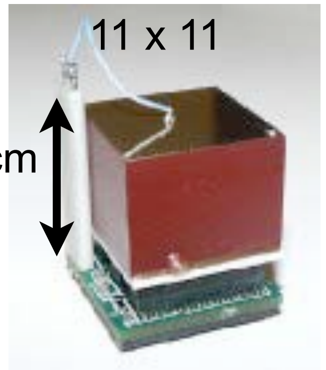
CPG results:
- 18kg·d data with 4x4 array
- 2011 new setup: 8 det -> 64 soon

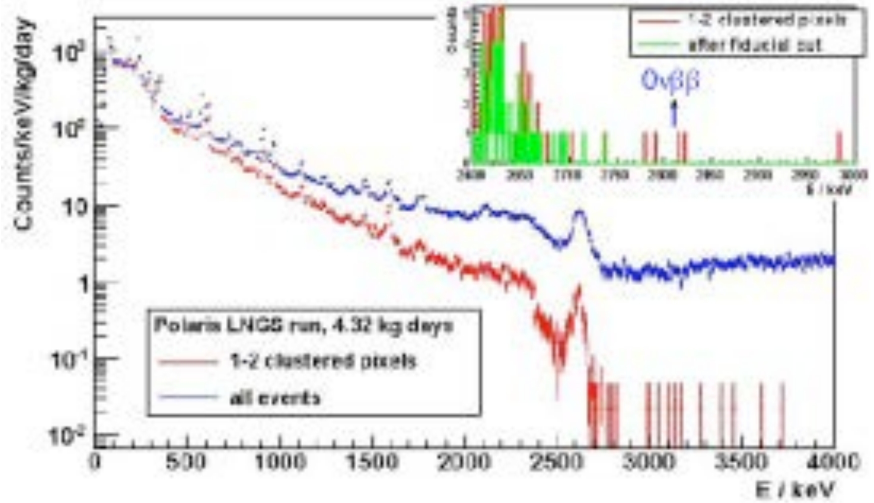


LARGE PIXELS

11 x 11

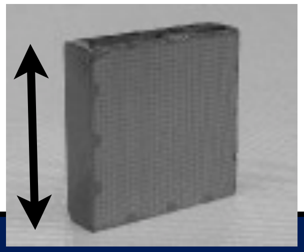
1.5 cm

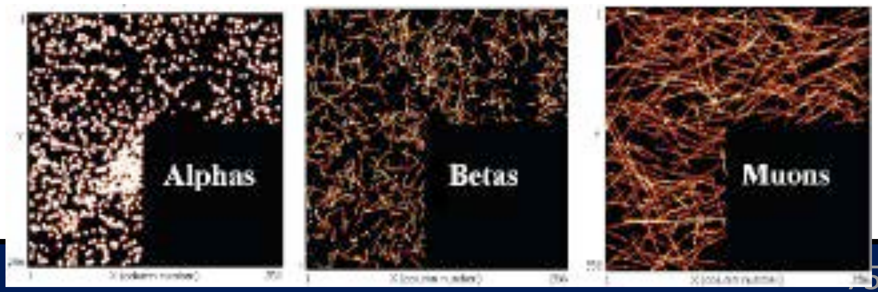




SMALL PIXELS

1.4 cm





Lucifer

ZnSe scintillating bolometers (95% enriched ^{82}Se) at ~ 10 mK
with double read-out **(heat/light)** for **alpha bkg** suppression
GOAL: demonstrate feasibility of large M exp with this technique
@LNGS Cuoricino/CUORE-0 cryostat start ~ 2014

ββ candidate: ^{82}Se **– Q** 2995 keV

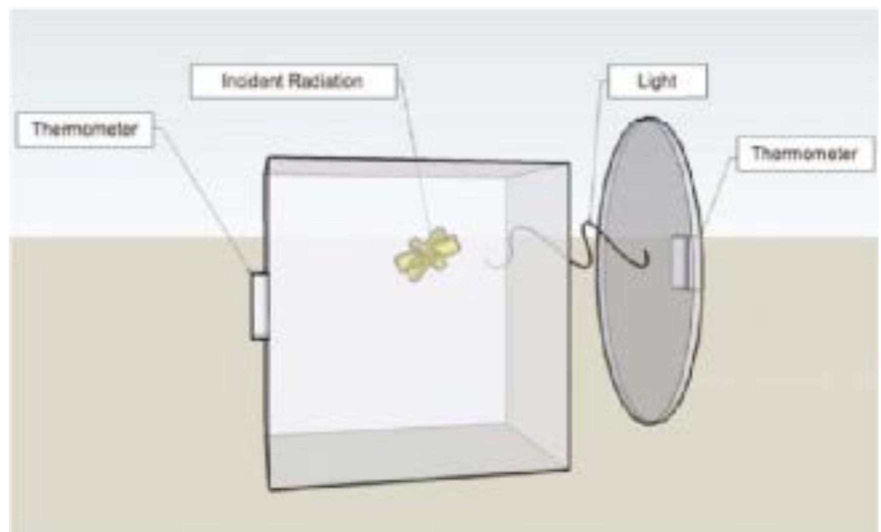
Source Mass:
17.6 kg ^{82}Se – $\mathbf{N_{\beta\beta}}$ 1.3 x10^{26}

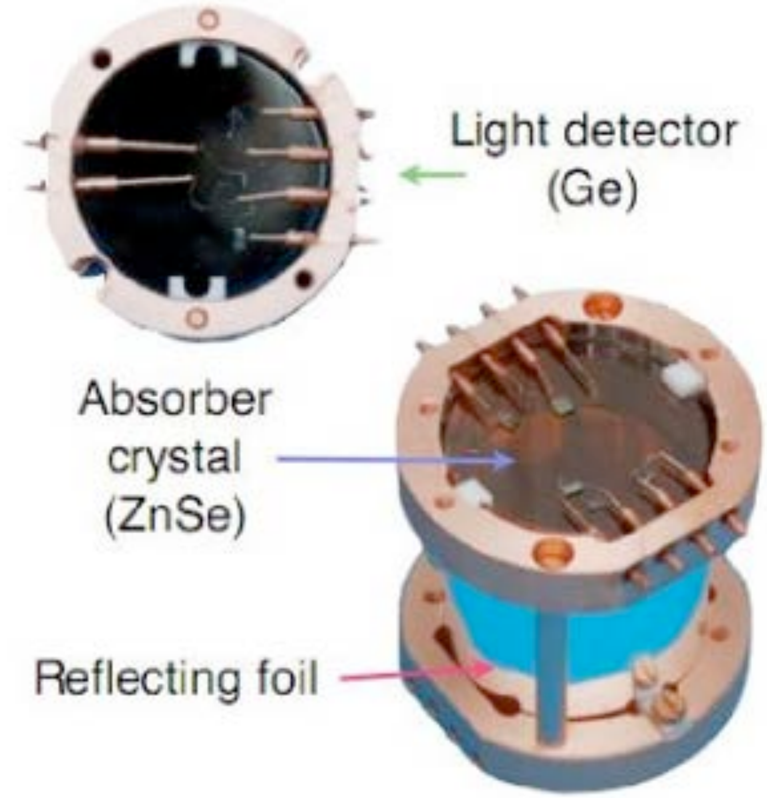
Projected Bkg:
0.001 c/keV/kg/y

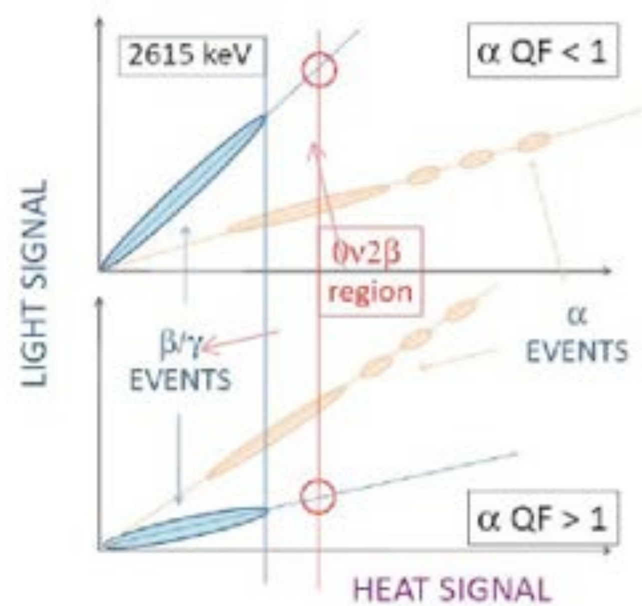
Projected FWHM: ~ 0.17% @ROI
Measured FWHM: ~ 0.34% @2615 keV

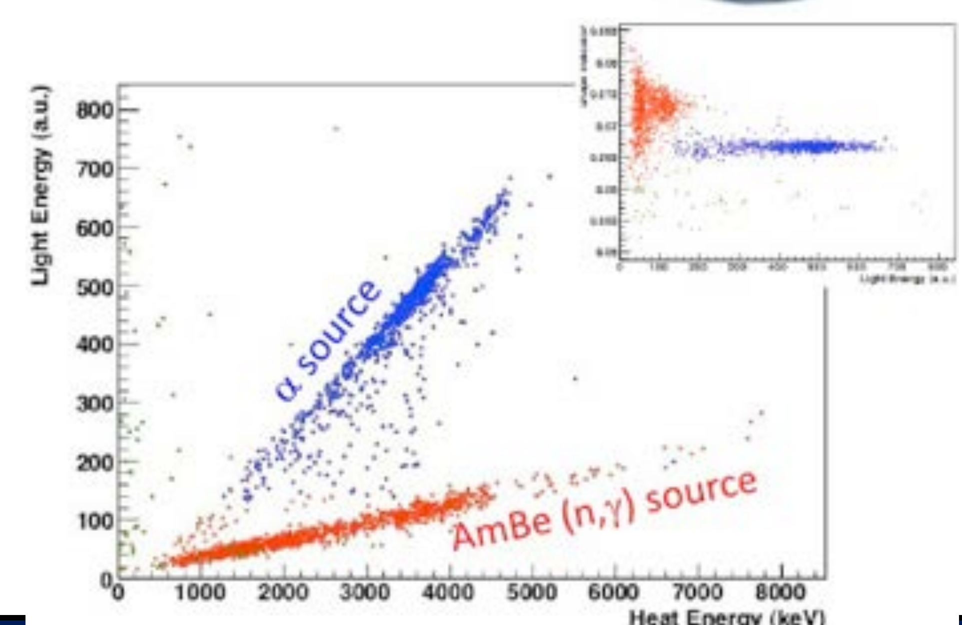
LY: 17.6 keV/MeV (~8800 phot/MeV)

PSA: α/β separation (both heat & light)









A. Alessandrello et al., Nucl. Phys. B Proc. Suppl. 28 (1992) 233-235
S. Pirro et al., Phys. Atom. Nucl. 69 (2006) 2109-2116
C. Arnaboldi et al., Astrop. Phys. 34 (2010) 143-150

Constraints on Σm(ν)

Method	Current Σm(ν) bound (eV)	Future Σm(ν) sensitivity (eV)	Datasets
CMB primordial (ISW, lensing, polarization)	0.66	0.2	Planck, WMAP, SPT, ACT
CMB primoridial + distance scale	0.23		Planck, WMAP, SPT, ACT + BAO & H0
Galaxy distributions	0.6	0.1	SDSS, BOSS (DES, BigBOSS, LSST)
Lensing of galaxies	0.6	0.07	CFHT-LS, COSMOS (WFIRST, DES, LSST, EUCLID)
Lyman α	0.2	0.1	SDSS, BOSS, KECK
21 cm mapping	-0.1	– 0.006	SKA, FFTT
Galaxy clusters	0.3	0.1	Planck, SPT, SDSS