Present and future strategies for Neutrinoless Double Beta Decay

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Open questions in ν physics

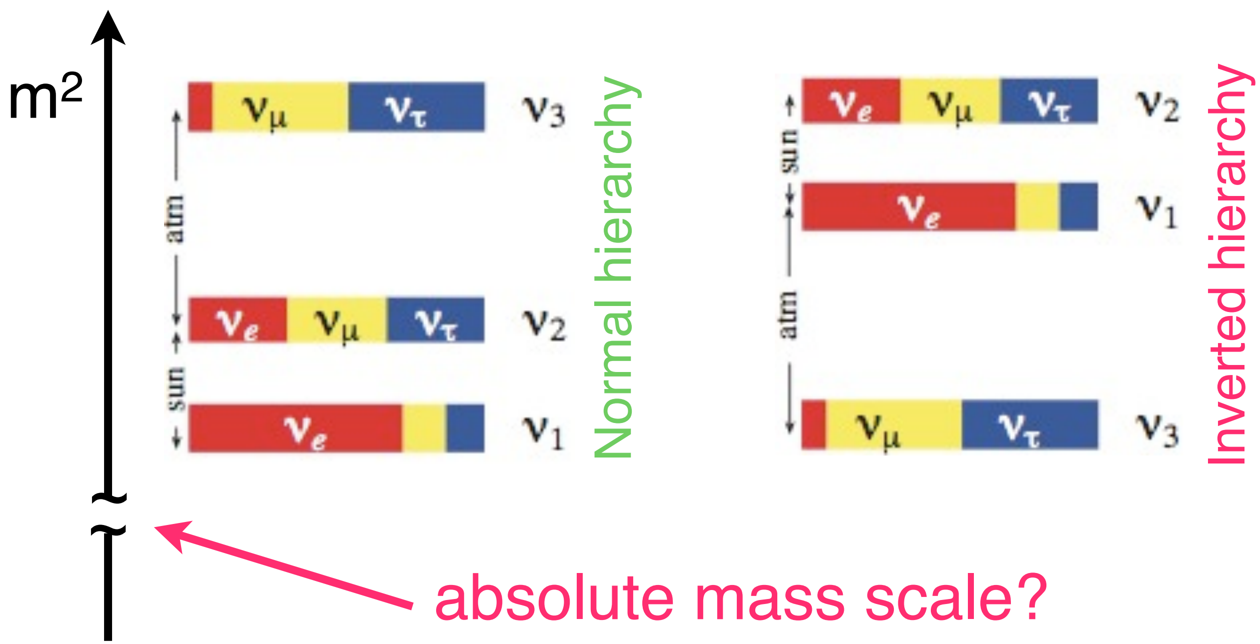
- ~~What is the size of the θ_{13} mixing angle?~~
  - Is there CP violation?
- Are there sterile neutrinos?
- Is the total Lepton Number conserved?
  - Is the neutrino a Majorana particle?
- What is value of the neutrino mass?
- What is the hierarchy of neutrino masses?

Oscillation Results

- Almost all oscillation parameters have been measured (arXiv:1205.5254)

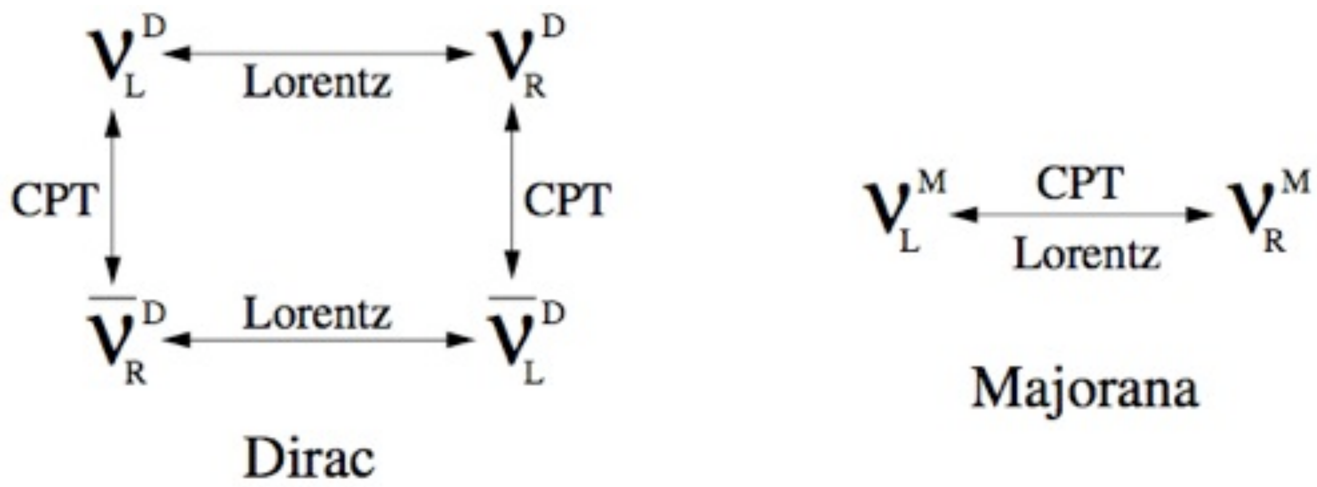
Oscillation Parameter			Value	Precision
solar mass splitting	Δm^2_{21}	$=$	$7.54\,^{+0.26}_{-0.22} \times 10^{-5}\,\mathrm{eV}^2$	3%
atmospheric mass splitting	$\lvert\Delta m^2_{23}\rvert$	$=$	$2.43^{+0.07}_{-0.09} \times 10^{-3}\,\mathrm{eV}^2$	3%
solar mixing angle	$\sin^2\theta_{12}$	$=$	$0.307^{+0.018}_{-0.016}$	6%
atmospheric mixing angle	$\sin^2\theta_{23}$	$=$	$0.398^{+0.030}_{-0.026}$	7%
'CHOOZ' mixing angle	$\sin^2\theta_{13}$	$=$	0.025 ± 0.003	12%

- The sign of Δm^2_{23} is still unknown, thus allowing two configurations:



Neutrino nature

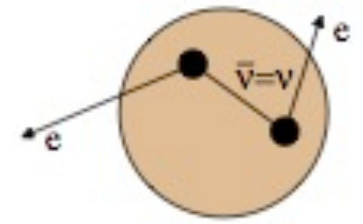
- Except for the total leptonic number the neutrino is a neutral fermion.
- So if the total leptonic number is not conserved neutrinos can be Majorana particles:
  - particle and antiparticle are the same. Chirality determines the charge of the lepton produced in interactions:

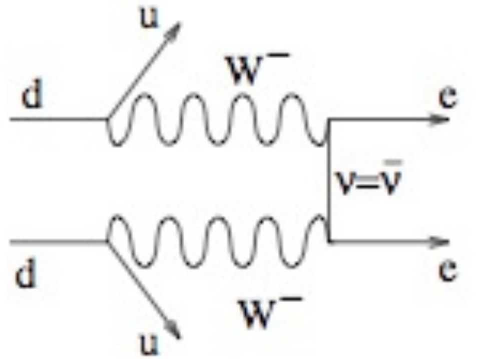


- It is still not clear today whether neutrinos are Dirac or Majorana particles. The distinction make sense only because they are massive.

Neutrinoless double beta decay

- Nuclear process: (A,Z) → (A,Z+2) + 2 e$^-$
- Can only happen if lepton number is not conserved, unlike the Standard Model allowed 2ν mode: (A,Z) → (A,Z+2) + 2 e$^-$ + 2 $\overline{\nu}$
- The decay probability depends on the effective Majorana mass $m_{\beta\beta}$ of the neutrino exchanged between the two electron vertexes.





- The measurable quantity is the half-life ($\tau^{0\nu}_{1/2}$) of the decay:

Phase space factor: ~ Q^5

Effective neutrino mass

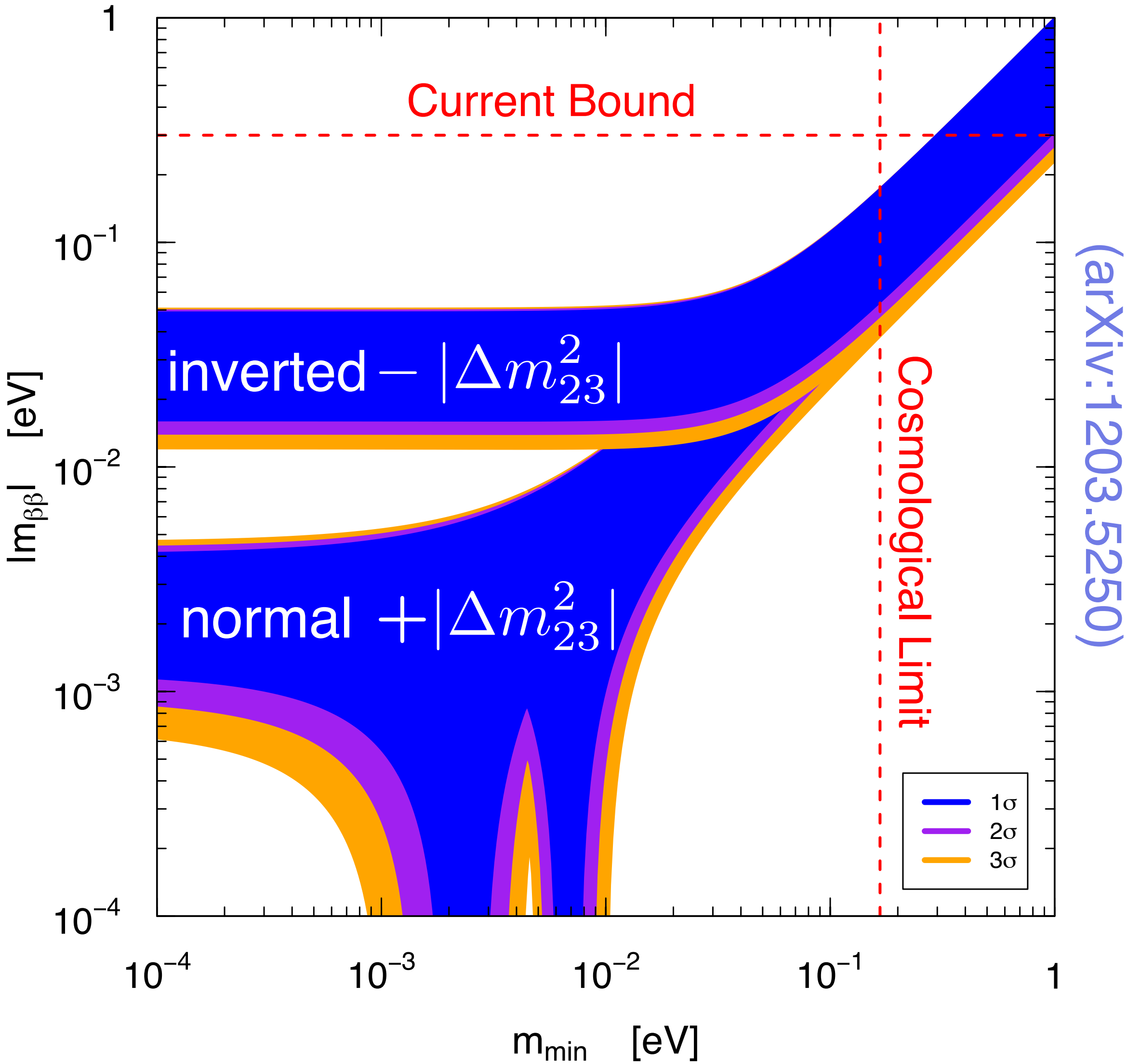
$$\frac{1}{(\tau^{0\nu}_{1/2})} = G(Q,Z)|M_{nucl}|^2|m_{\beta\beta}|^2 = F_N\frac{|m_{\beta\beta}|^2}{m_e^2}$$

Nuclear Matrix element

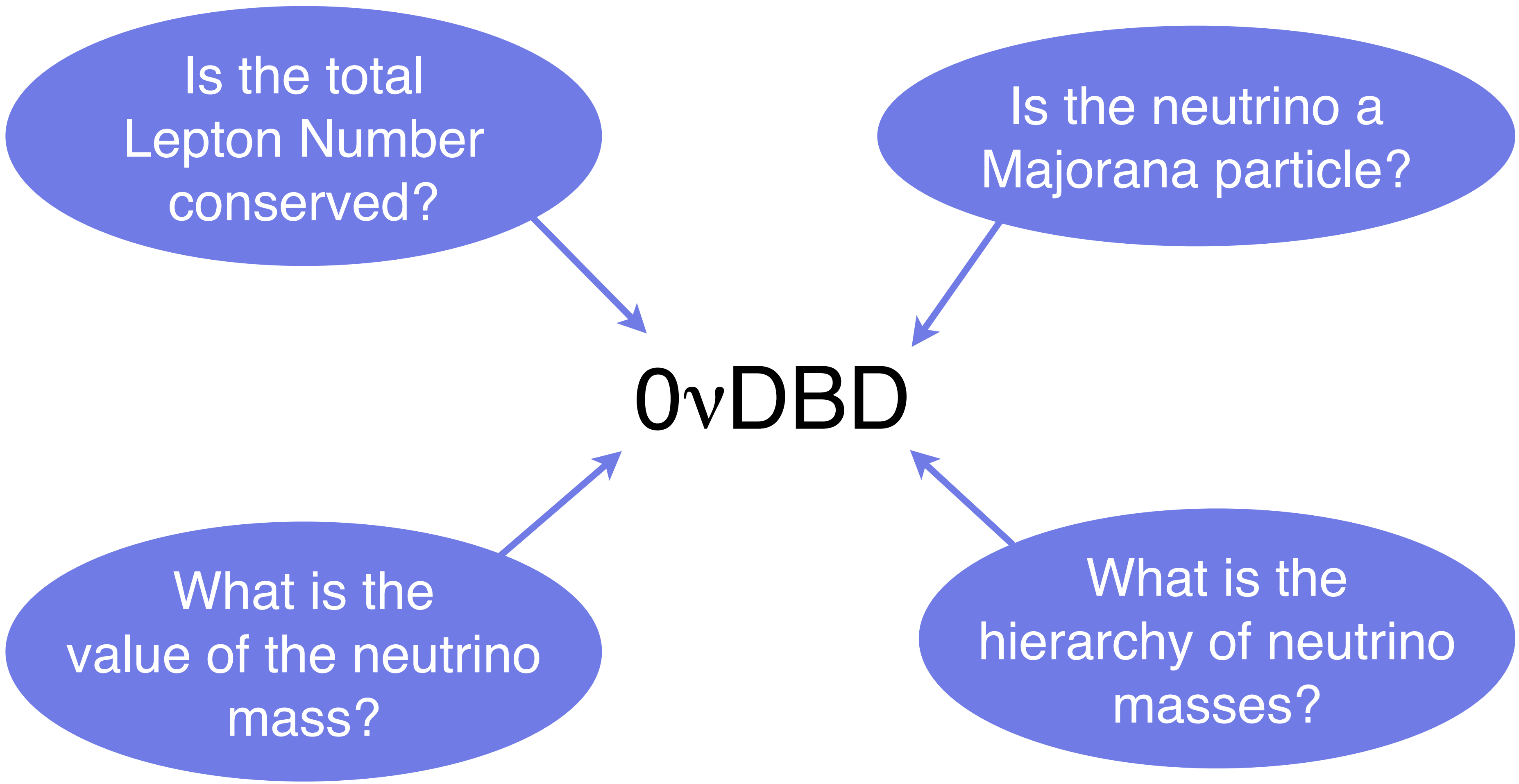
Effective Majorana mass

- Effective neutrino Majorana mass in terms of the measured oscillation parameters and the unknown lightest neutrino mass:

$$m_{\beta\beta} = f(\theta_{12}, \theta_{13}, \theta_{23}, \Delta m^2_{12}, \pm|\Delta m^2_{23}|, m_{\min})$$



Summary so far

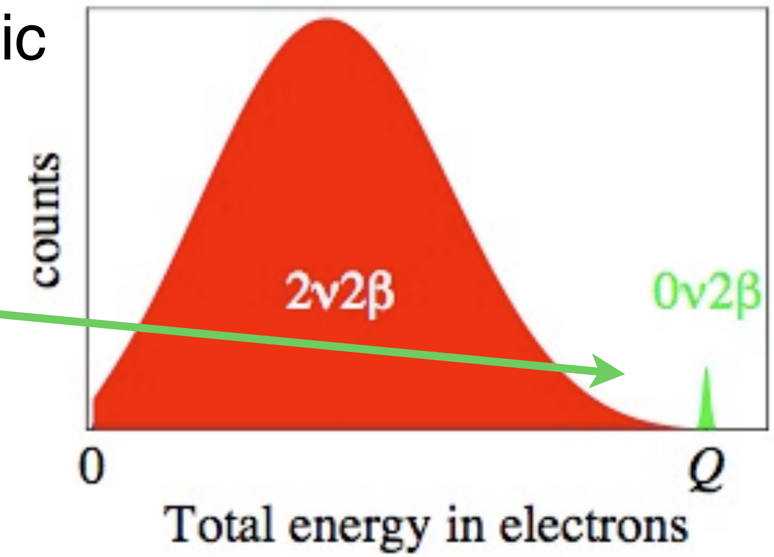


1 measure → many answers...

...extremely challenging though.

0νDBD in Experiments

- Experiments measure the sum of the kinetic energies of the two emitted electrons.
  - Signature: monochromatic line at the Q-value of the decay.



- Sensitivity ($S^{0\nu}$): lifetime corresponding to the minimum number of detectable events above background at a given C.L.:

$$S^{0\nu} = \ln 2 N_A \cdot \frac{a}{A} \left(\frac{Mt}{B \Delta E} \right)^{1/2} \cdot \epsilon$$

Isotopic abundance (%) → a

Detector mass (kg) → M

Measurement time (y) → t

detection efficiency → ϵ

Atomic mass → A

Background (counts/keV/kg/y) → B

Energy Resolution (keV) → ΔE

Isotope choice

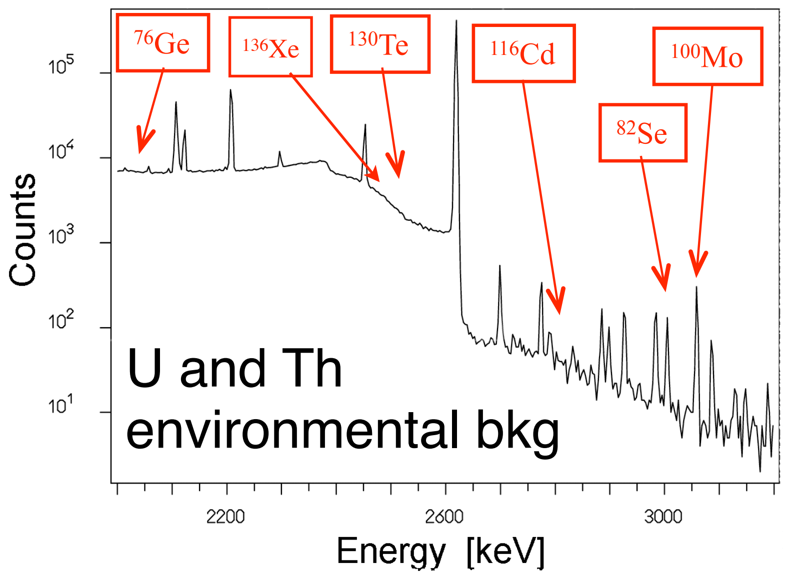
$$|m_{\beta\beta}|^2 = 1 / \left[G(Q,Z)\, |M^{0\nu}|^2\, \tau^{0\nu}_{1/2} \right]$$

- 0νDBD candidates of experimental interest: (arXiv:1201.4916)

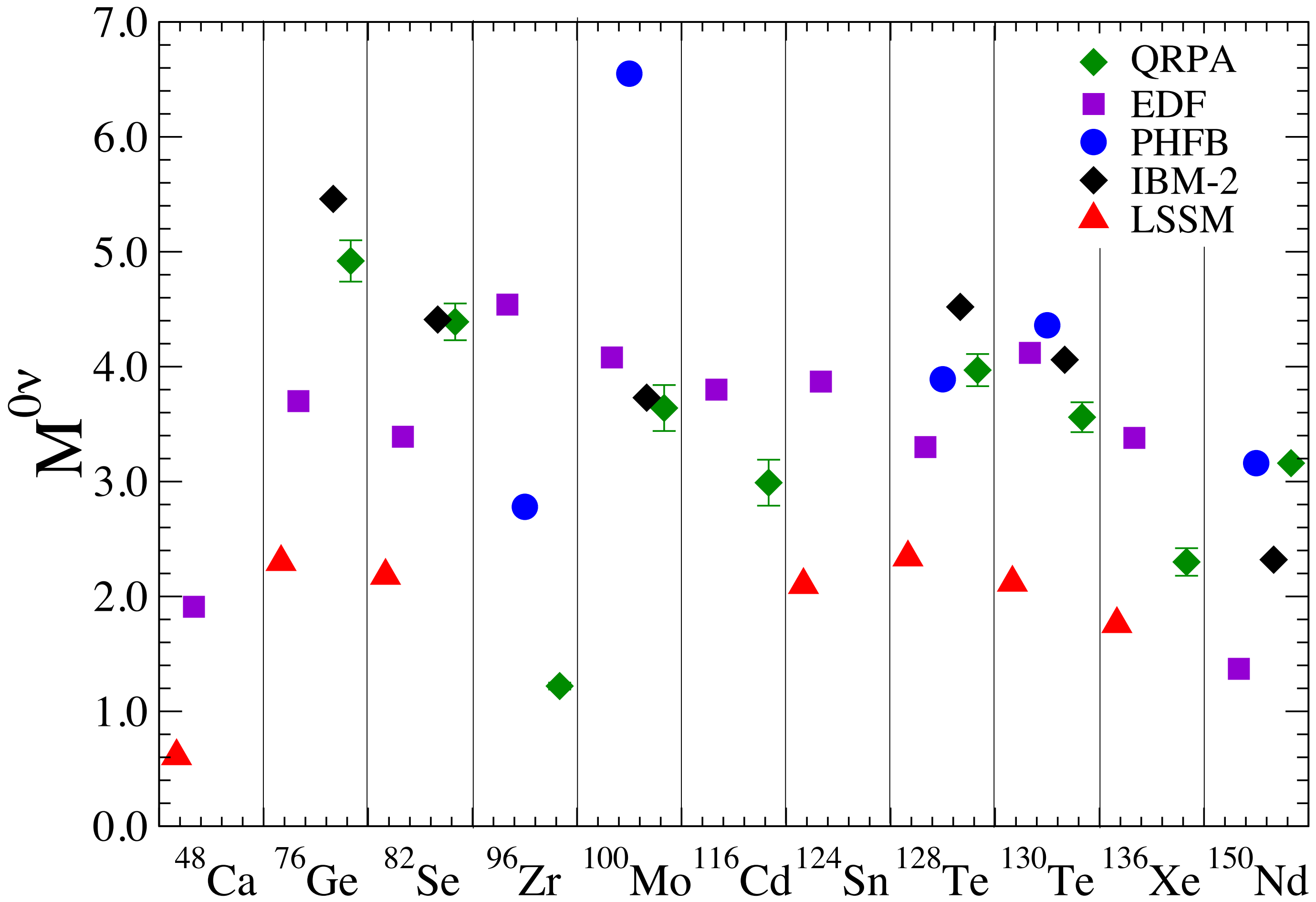
isotope	$G^{0\nu}$ $[10^{-14} y^{-1}]$	$Q_{\beta\beta}$ [keV]	nat. abund. [%]	$T^{2\nu}_{1/2}$ $[10^{20}$ y]
^{48}Ca	6.3	4273.7	0.187	0.44
^{76}Ge	0.63	2039.1	7.8	15
^{82}Se	2.7	2995.5	9.2	0.92
^{100}Mo	4.4	3035.0	9.6	0.07
^{116}Cd	4.6	2809	7.6	0.29
^{130}Te	4.1	2528	34.2	9.1
^{136}Xe	4.3	2461.9	8.9	21
^{150}Nd	19.2	3367.3	5.6	0.08

- In general, Q > 2615 keV isotopes are preferred because they lie above the natural radioactivity edge.

- However the choice has been dominated so far by technology compromises.



Nuclear amplitude $|m_{\beta\beta}|^2 = 1 / \left[G(Q,Z)\,|M^{0\nu}|^2\,\tau^{0\nu}_{1/2}\right]$

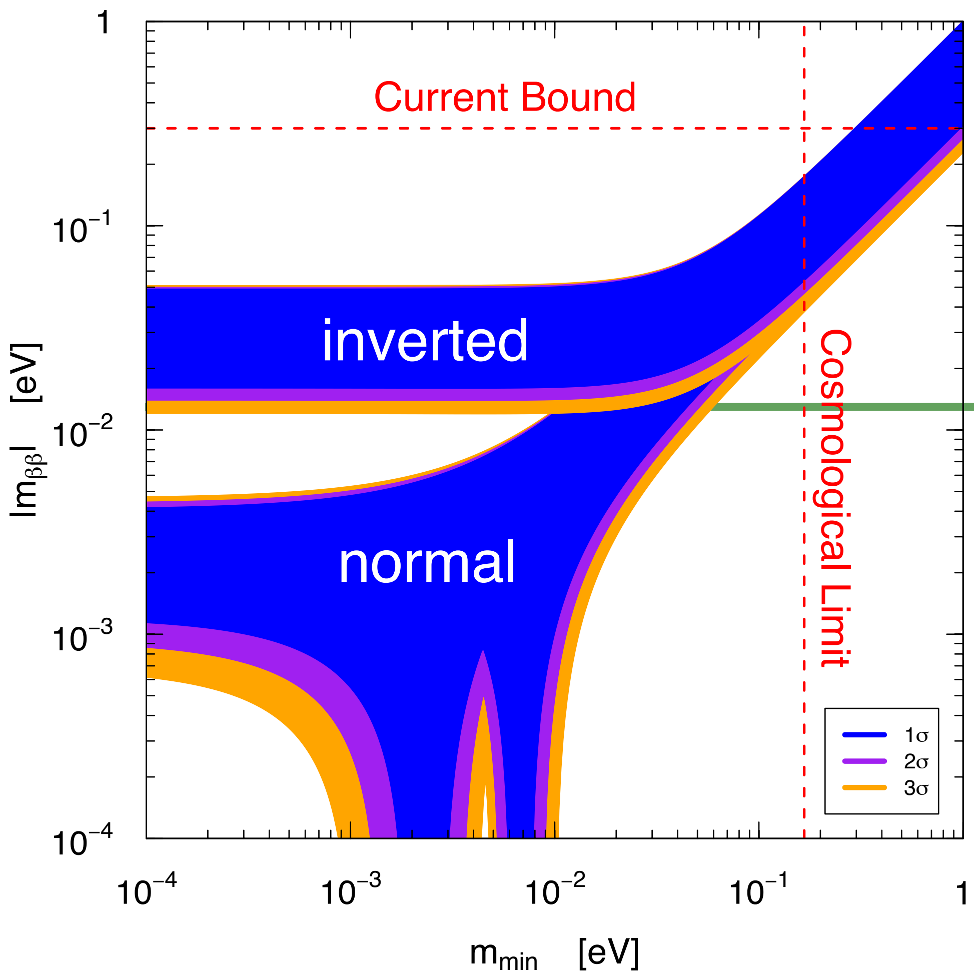


arXiv:1201.4916

- The spread in the values does not influence the isotope choice.
- Generate problems when comparing exclusions and evidences from experiments running different isotopes.

Experimental race

$$S^{0\nu} = \ln 2 N_A \cdot \frac{a}{A} \left(\frac{Mt}{B \Delta E} \right)^{1/2} \cdot \epsilon$$



Entire inverted hierarchy:

M ~ 1 ton

a ~ 90%

B ΔE ~ 1 count/ton/year

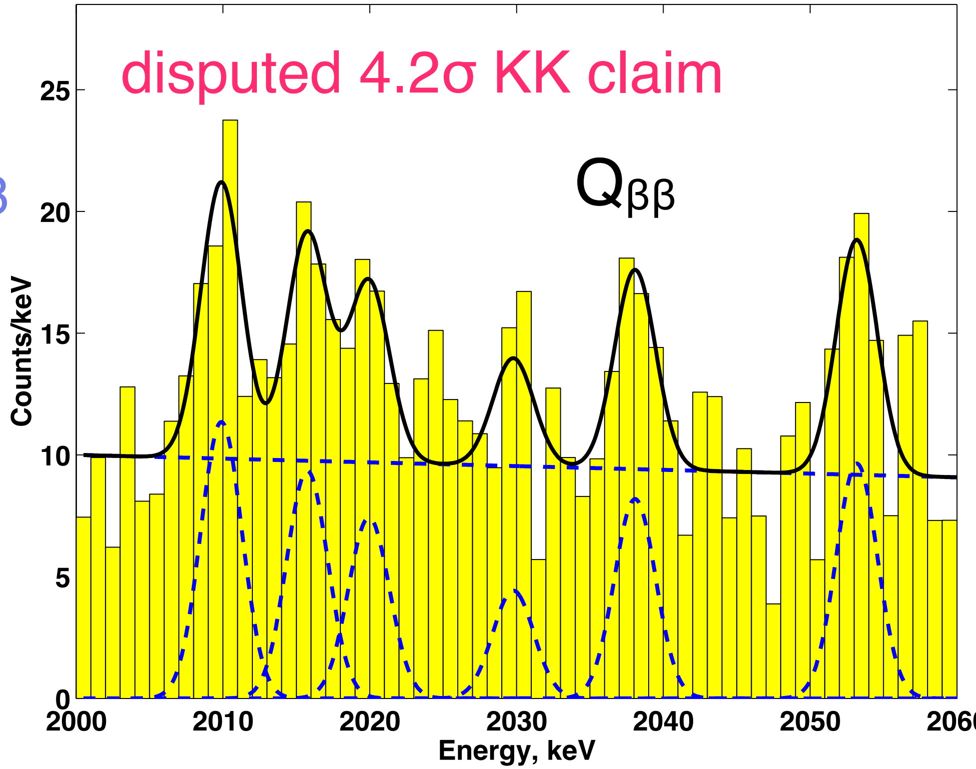
Normal hierarchy:

Dream

Germanium diodes

The Klapdor-Kleingrothaus claim

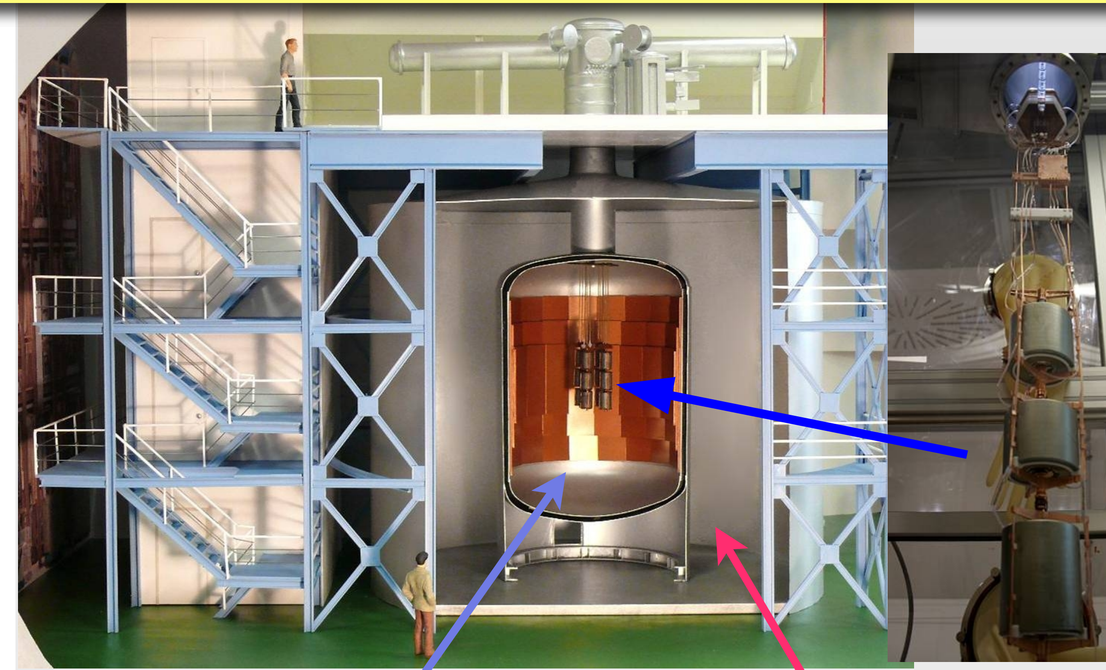
- Past Germanium-diodes-based experiment: Heidelberg-Moscow
  - background 0.12 cpy/keV/kg
  - no evidence in 10 kg(^{76}Ge)×3.5y
- A small group departed from the collaboration and published their own (improved) analysis of the data.
- The group claimed for the peak observation: Phys.Lett.B 586(2004)198
  - $T^{0\nu}_{1/2} = (2.23+0.44)\times10^{25}$ yr
  - $\langle m_{\beta\beta} \rangle = 0.32 \pm 0.03$ eV

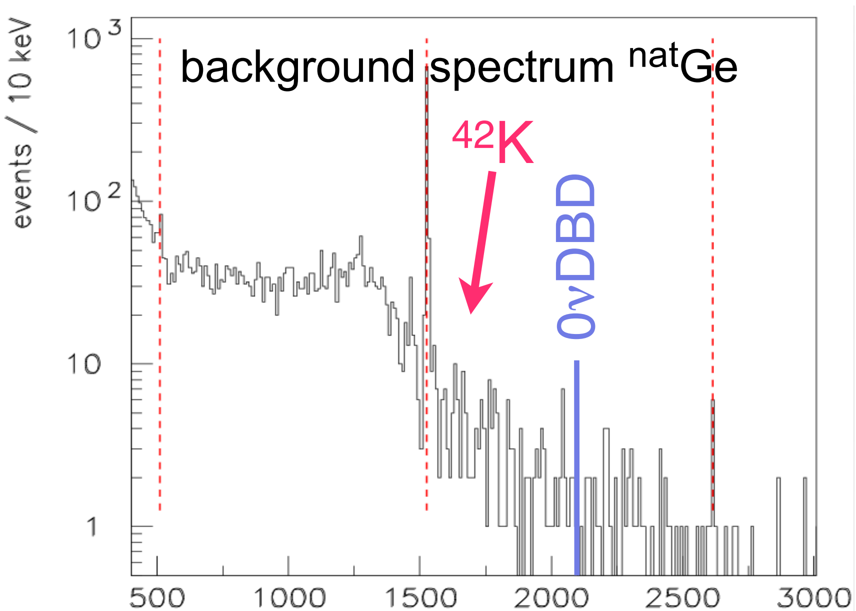


Gerda - @LNGS

- Present: Gerda phase I
  3 ^{nat}Ge diodes: 7.6 kg
  6 ^{enr}Ge diodes 14.6 kg
- ΔE = 3 keV FWHM
- Data taking delayed by an unexpected ^{42}Ar contamination in the LAr

$^{42}Ar(\beta^-) \longrightarrow {}^{42}K$ (β^-, Q=3.52 MeV)

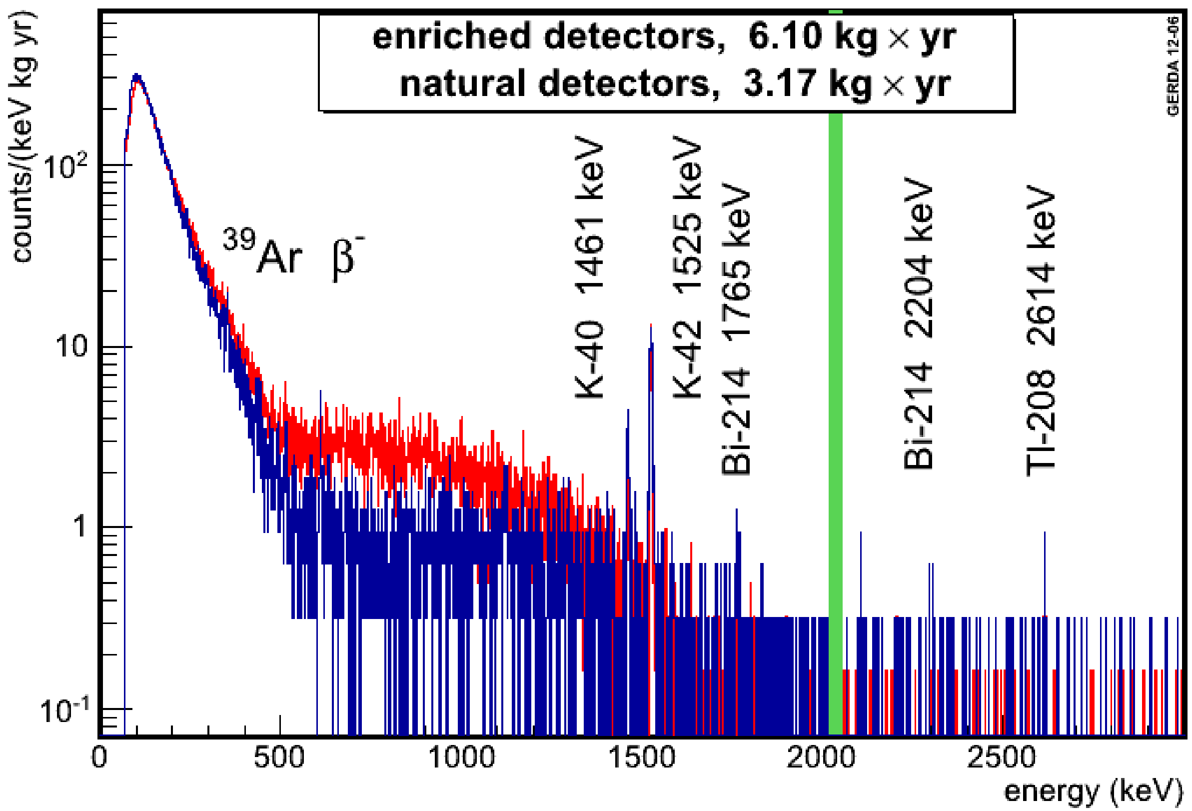


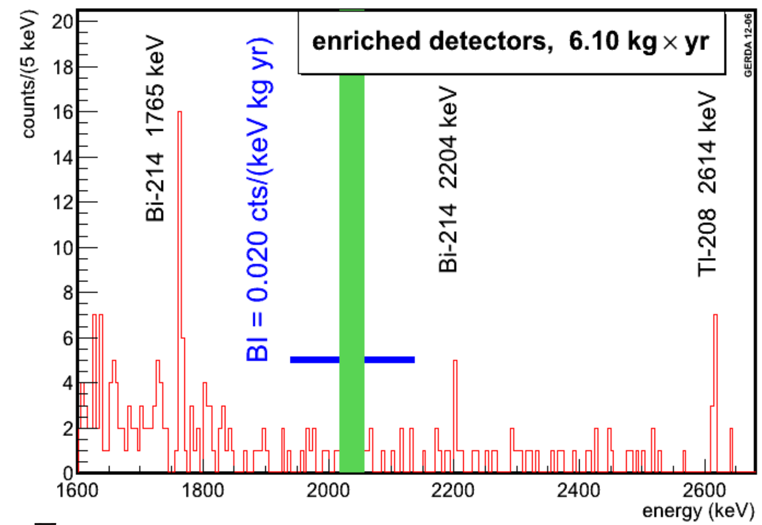


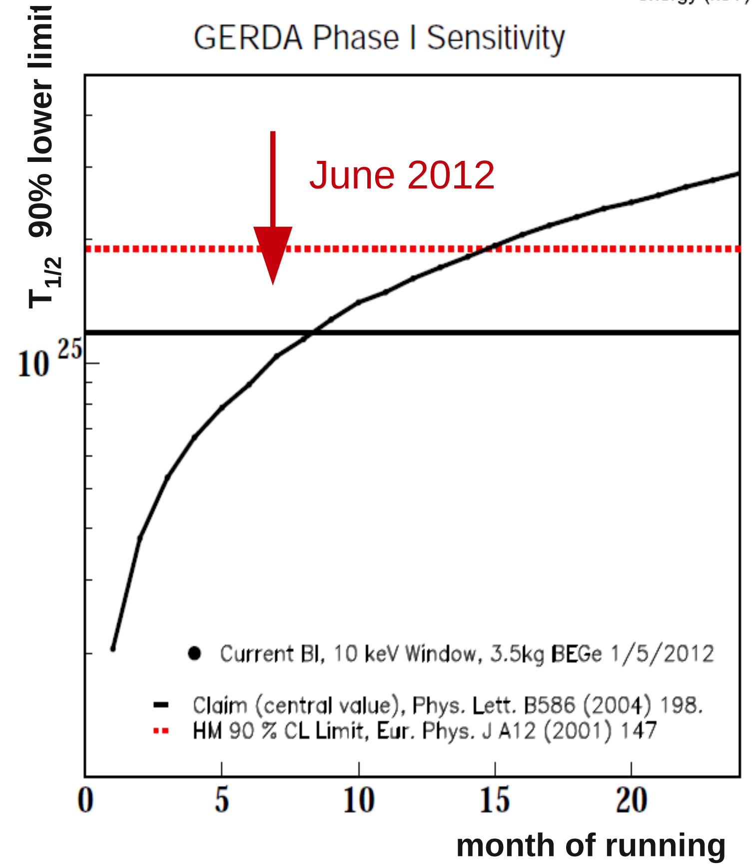
- Diodes p-contact attracts the ^{42}K ions which then decay in the detector: bkg 6x higher than the design.
- Bkg successfully reduced by catching the ^{42}K ions with electric fields inside the LAr.

Gerda: good data from 11/11

P. Grabmayr at Neutrino 2012



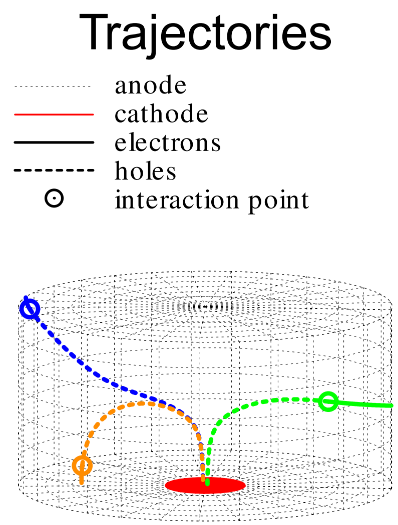


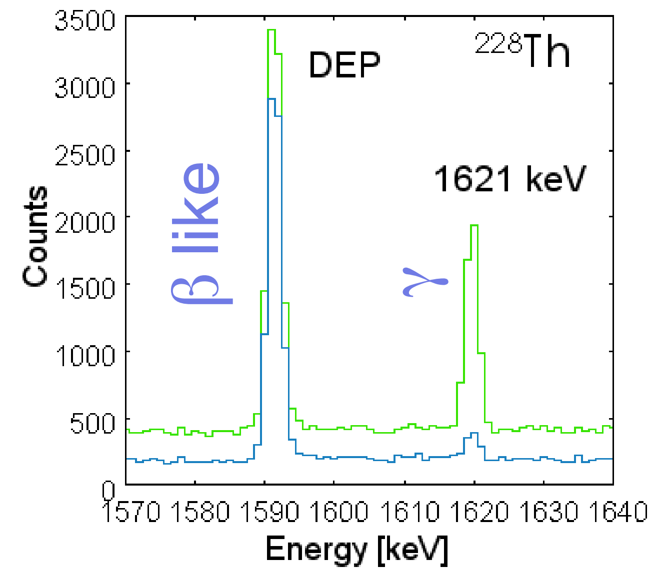


- 0νDBD region blinded.
- Should check KK claim in ~1.5 y.

Germanium diodes: future

- Gerda phase II (2013)
  - Increase mass to ~25 kg
  - New detectors: BEGe, Allow γ/β discrimination via Multi/Single site identification



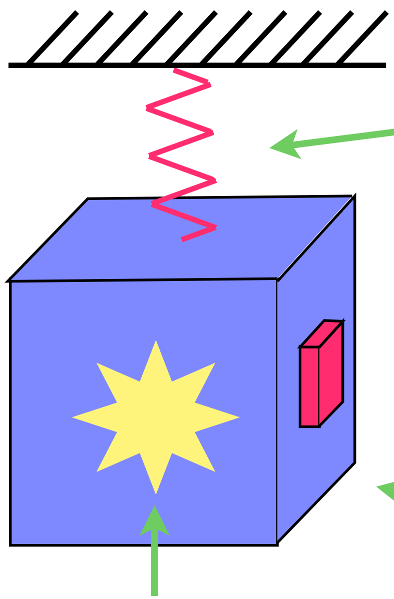


  - Veto external gammas with readout of scintillation light of LAr
  - New bkg. lower by 1 order of mag.: 10^{-3} counts/keV/kg/y
- Majorana Demonstrator (2013)
  - Deploy 40 kg of ^{enr}Ge
  - Determine the best technology for a 1 ton Ge experiment to be pursued together with the Gerda collaboration.

Bolometers

Bolometric technique

- Particle energy converted into phonons → temperature variation.
- Crystals embedding 0νDBD source.
- Low crystal heat capacitance and low base temperature to see small temperature variations → $\Delta T \sim E/C$



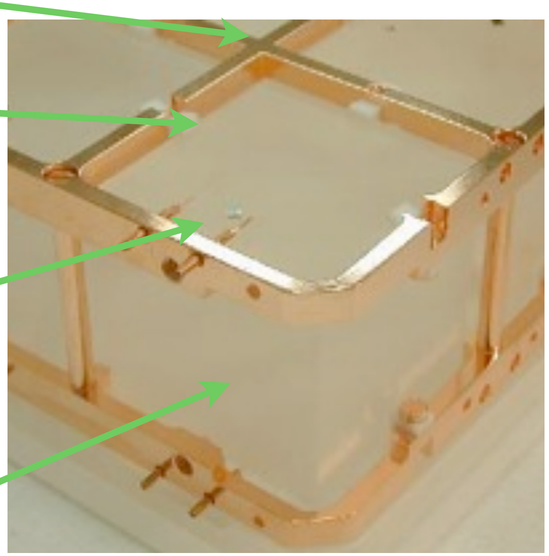
Heat bath ~ 10 mK

Weak thermal coupling

Thermometer:
NTD Ge thermistor
R ~ 100 MΩ

Absorber Crystal
C ~ 2 10^{-9} J/K

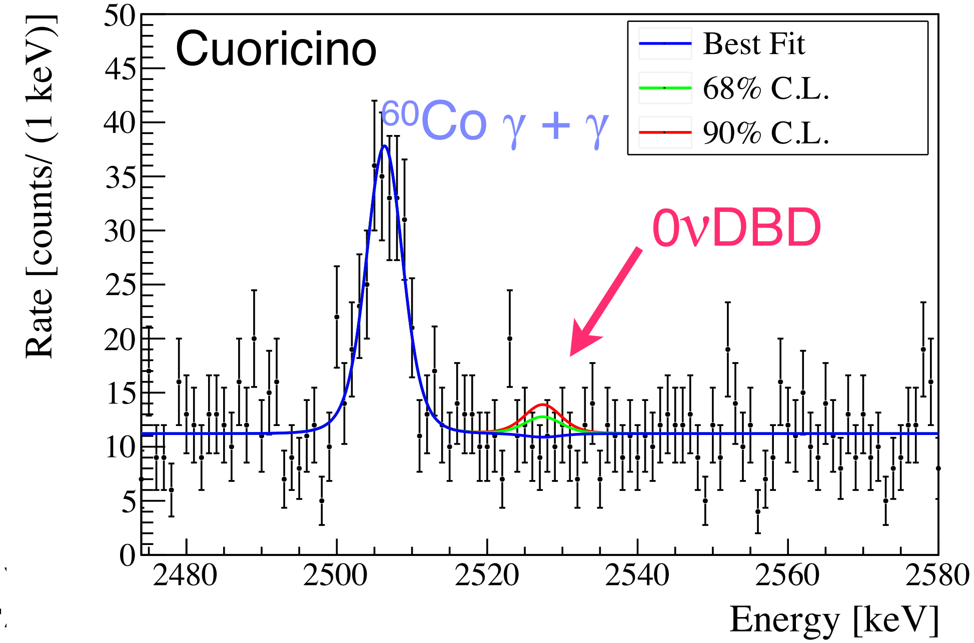
Energy release

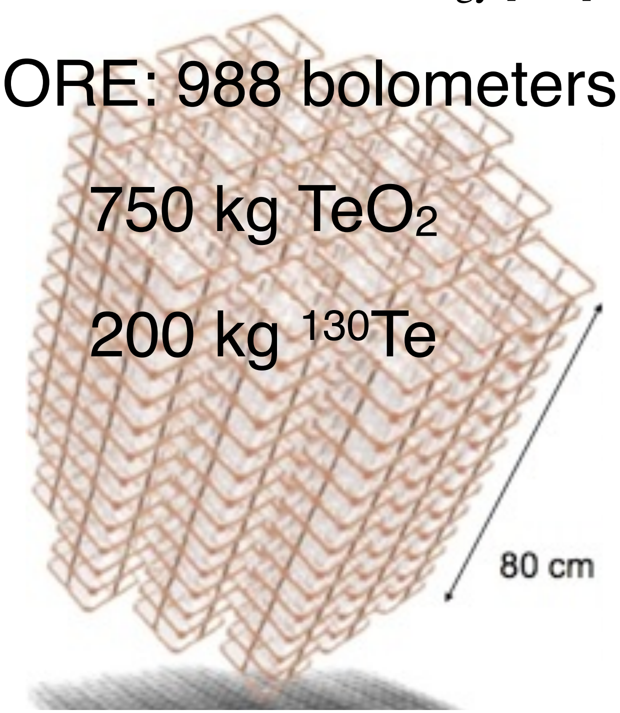


- Detector response in this configuration: ~ 0.1 mK / MeV
- Resolution @0νDBD ~ few keV

CUORE - @LNGS

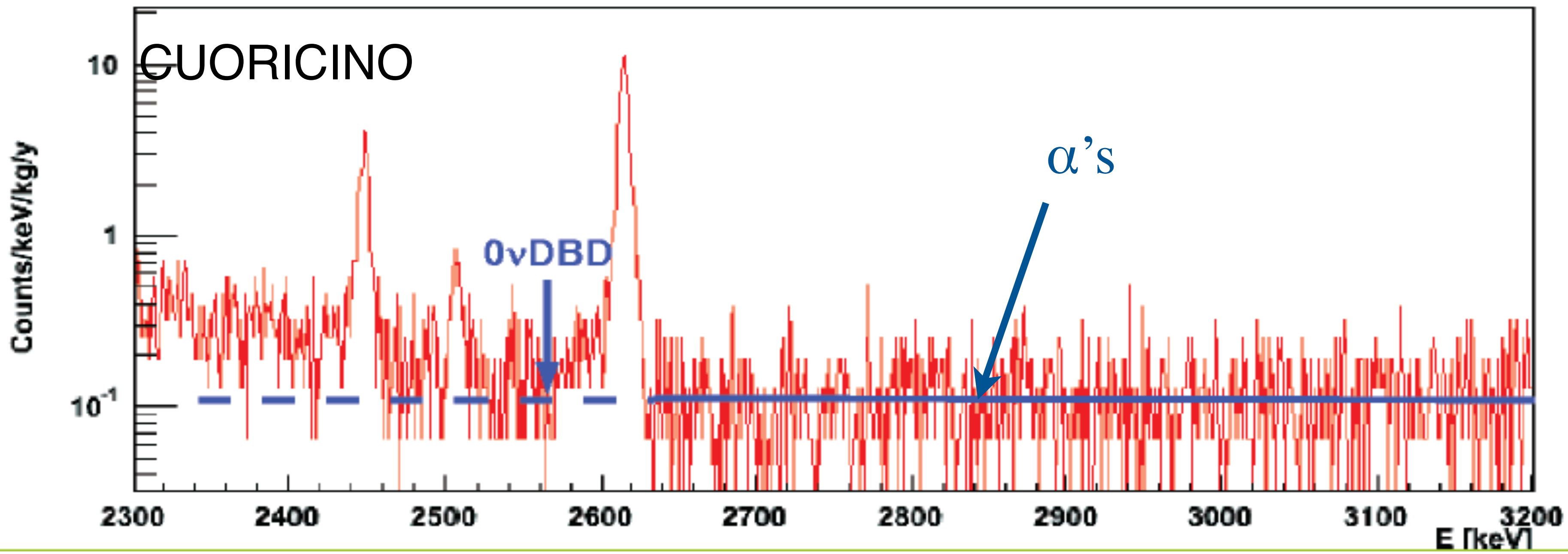
- $^{nat}TeO_2$ bolometers (34% ^{130}Te), 750g each (ΔE =5 keV FWHM)
- Past: Cuoricino
  - 62 bolometers
    11 kg (^{130}Te)×2y,
    Bkg: 0.16 cpy/keV/kg
  - $T^{0\nu}_{1/2} > 2.8\times10^{24}$ years (90% CL)
    $\langle m_{\beta\beta}\rangle < 300\sim700$ meV
- Future: Cuore (data taking in 2015)
  - Expected bkg: 0.01~0.04 cpy/keV/kg
  - Exp. $T^{0\nu}_{1/2} > 1.6\times10^{26}$ years
    $\langle m_{\beta\beta}\rangle < 40\sim94$ meV
- Present: Cuore-0, a CUORE-like tower.
  - same mass of Cuoricino, 0.05 cpy/keV/kg.





CUORE: the α nightmare

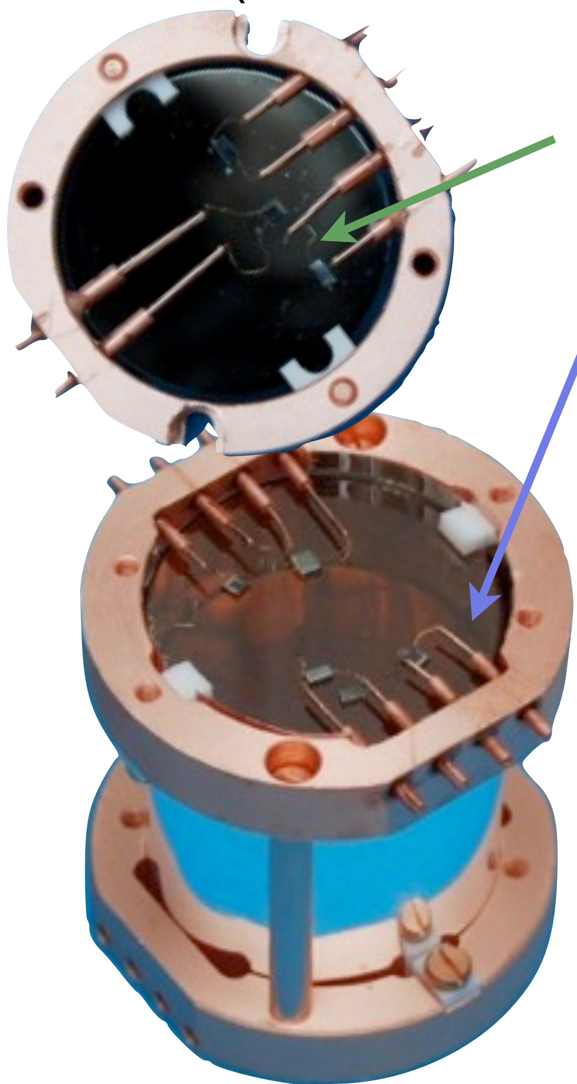
- MC: the background in CUORICINO is due to degraded α particles which release only a part of their energy in the detector (surface contaminations, mainly in copper).



- TeO_2 bolometers, per se, do not allow to discriminate β and α particles.
    - α bkg partially reduced by cleaning the detector parts.

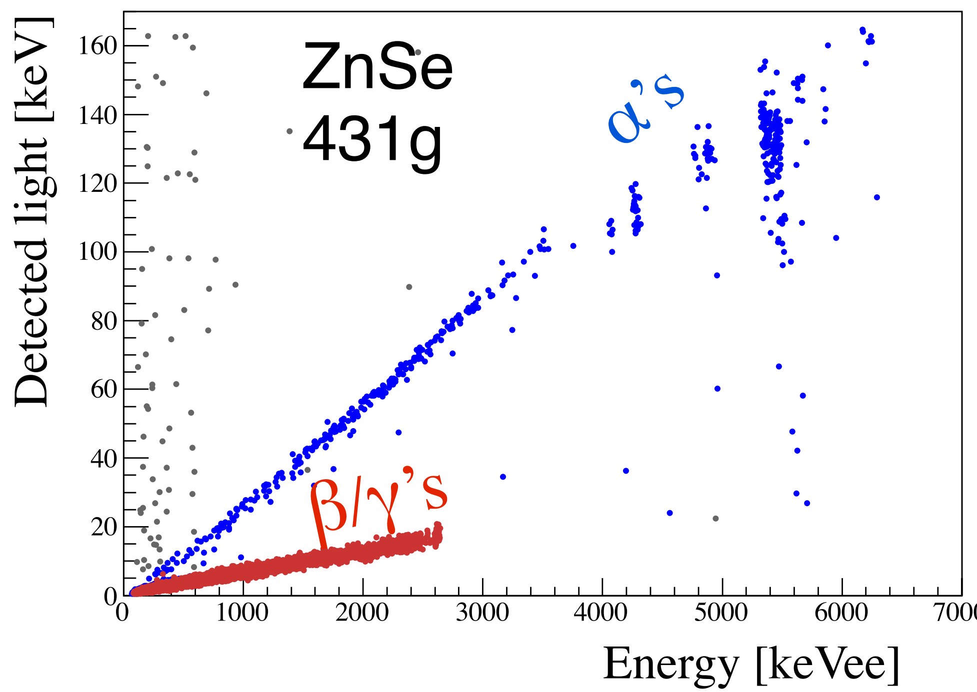
LUCIFER - @LNGS

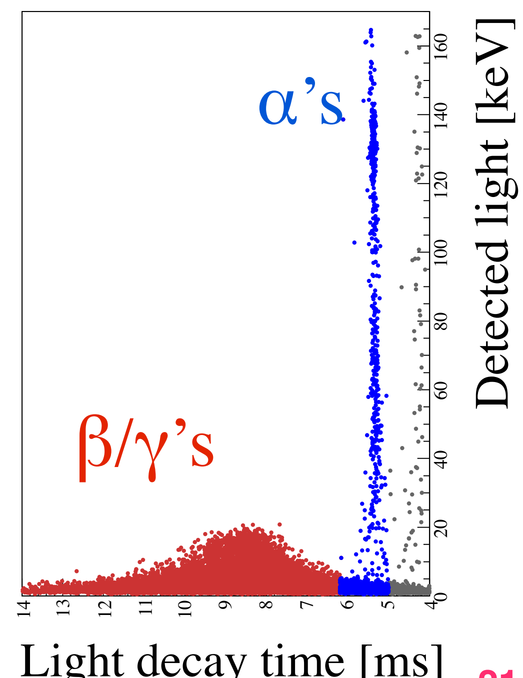
- Scintillating bolometers to discriminate the α background, enriched in ^{82}Se or ^{100}Mo.
  - Target: define the technology for a ZERO background (<1 count/ton/year), ~1-ton isotope experiment after CUORE.



Light detector: Ge bolometer

Absorber bolometer: $Zn^{82}Se$ or $Zn^{100}MoO_4$

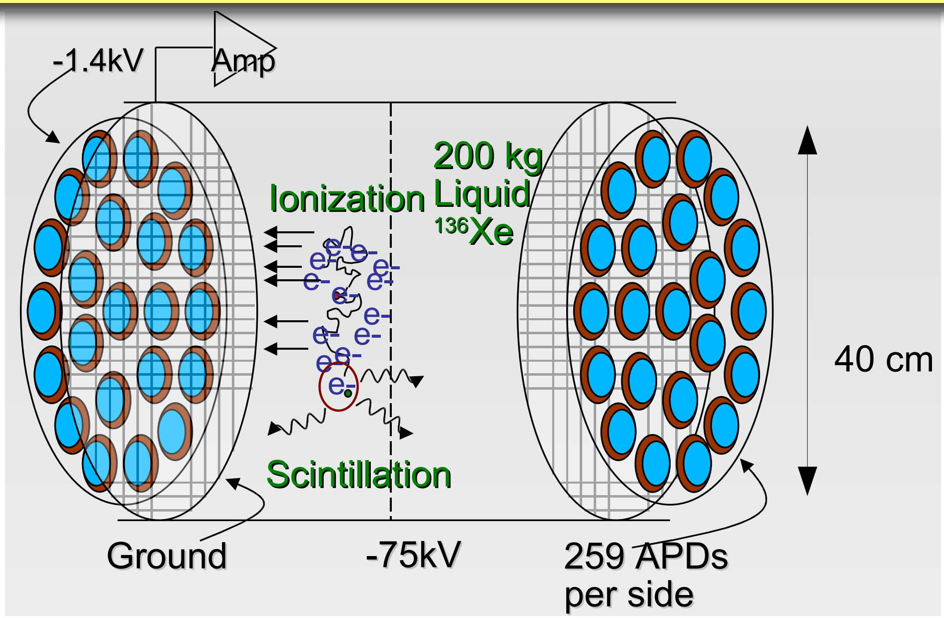


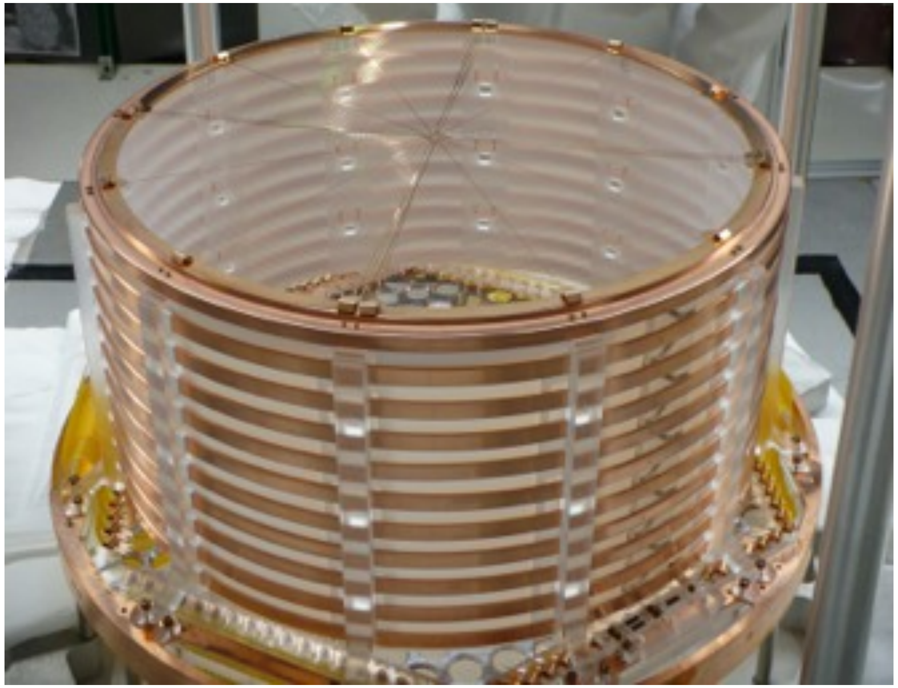


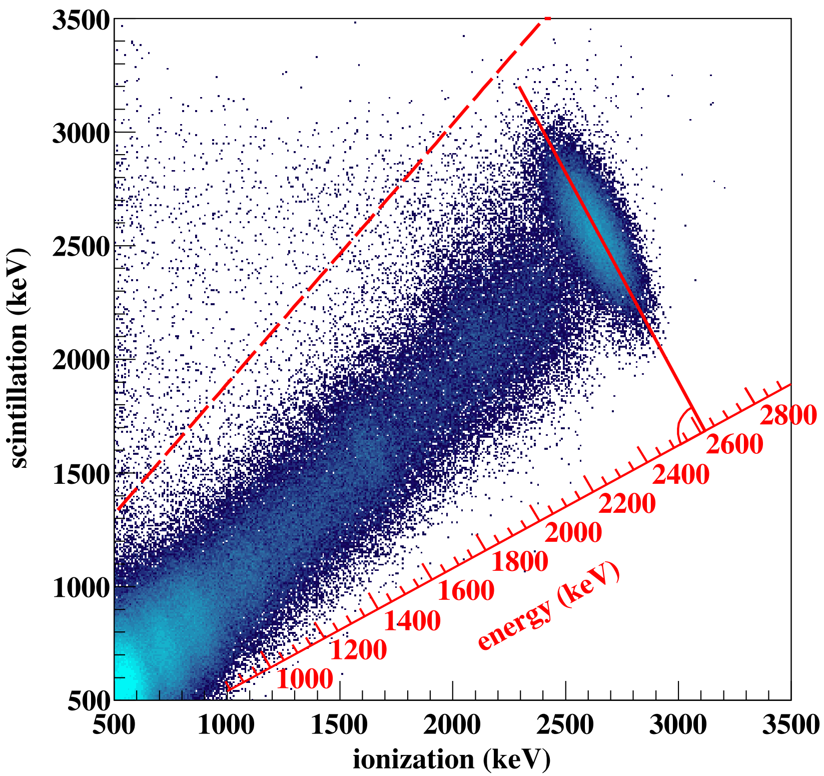
Liquid scintillators

Exo-200 - @WIPP

- Double sided TPC
- 200 kg Liquid ^{136}Xe
- ΔE = 100 keV FWHM
- Multi/Single site discrimination
- Bkg: 0.0015 cpy/keV/kg
- Data taking started in Spring 2011

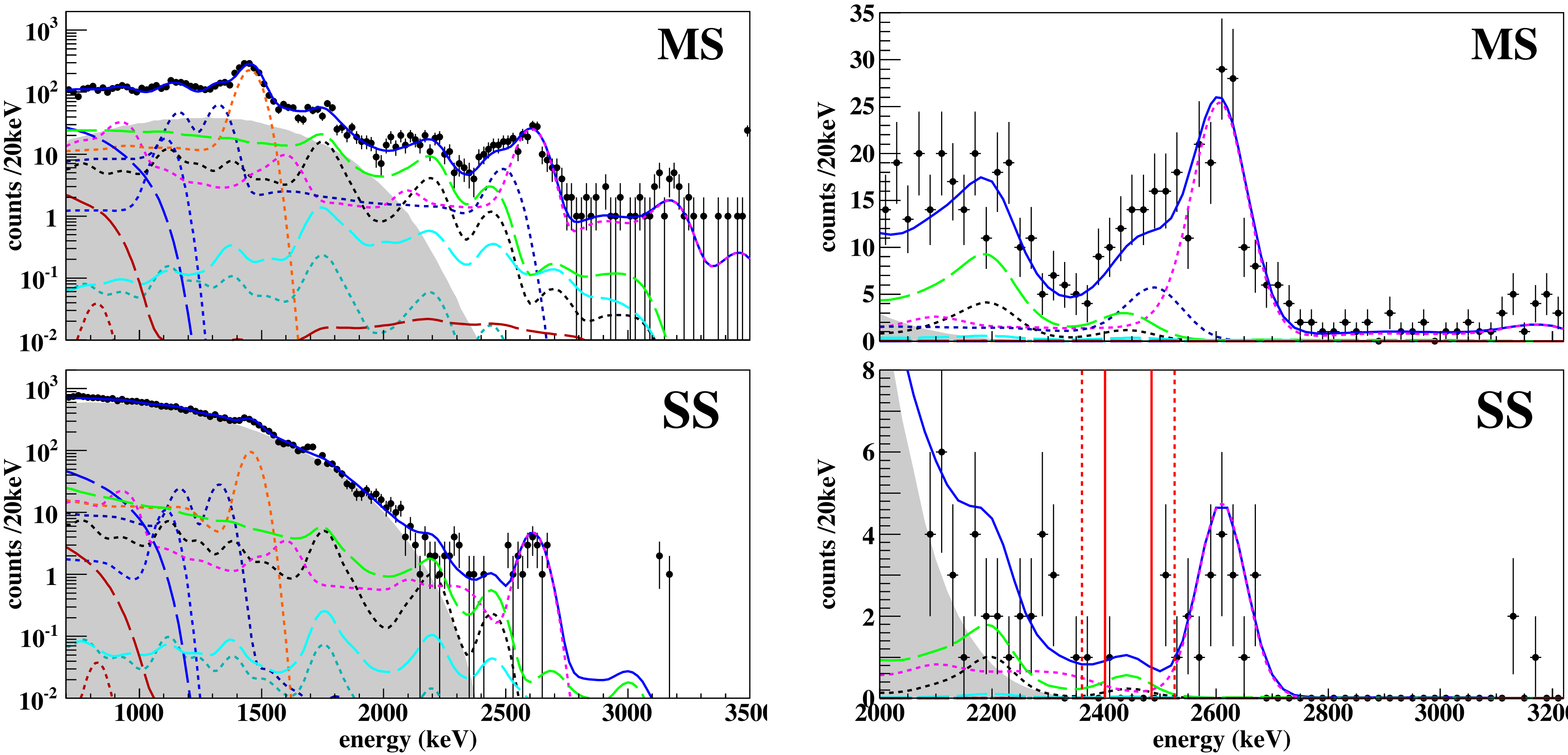




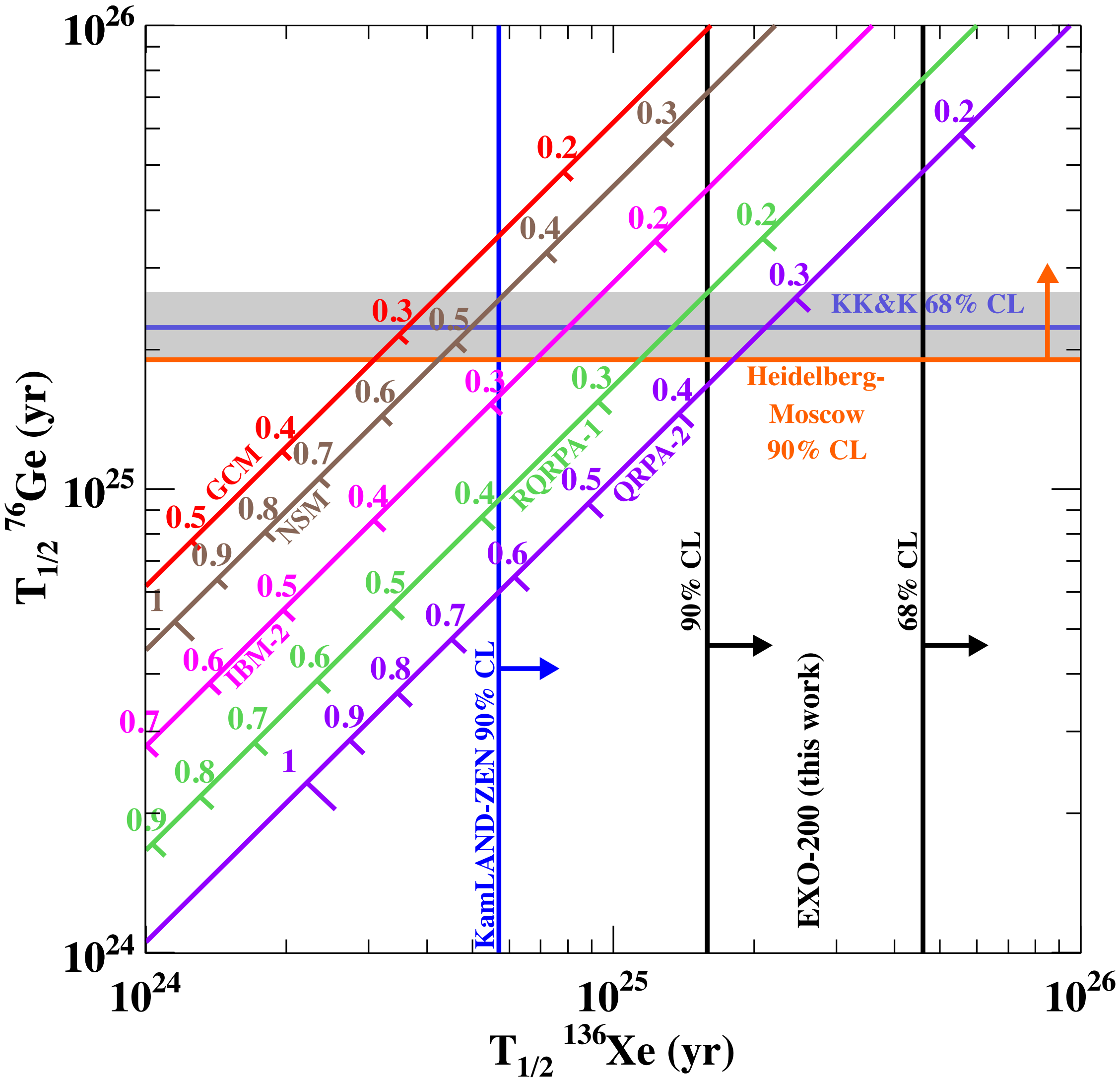


Exo-200 results (32.5 kg×yr)

- First observation of 2νββ decay of ^{136}Xe
  - $T^{2\nu}_{1/2}$ = (2.23 ± 0.017 stat ± 0.22 sys)·10^{21} yr (6x faster than previous limit)
- $T^{0\nu}_{1/2} > 1.6\cdot10^{25}$ yr ⟶ ⟨mββ⟩ < 140–380 meV (90% C.L.) arXiv:1205.5608

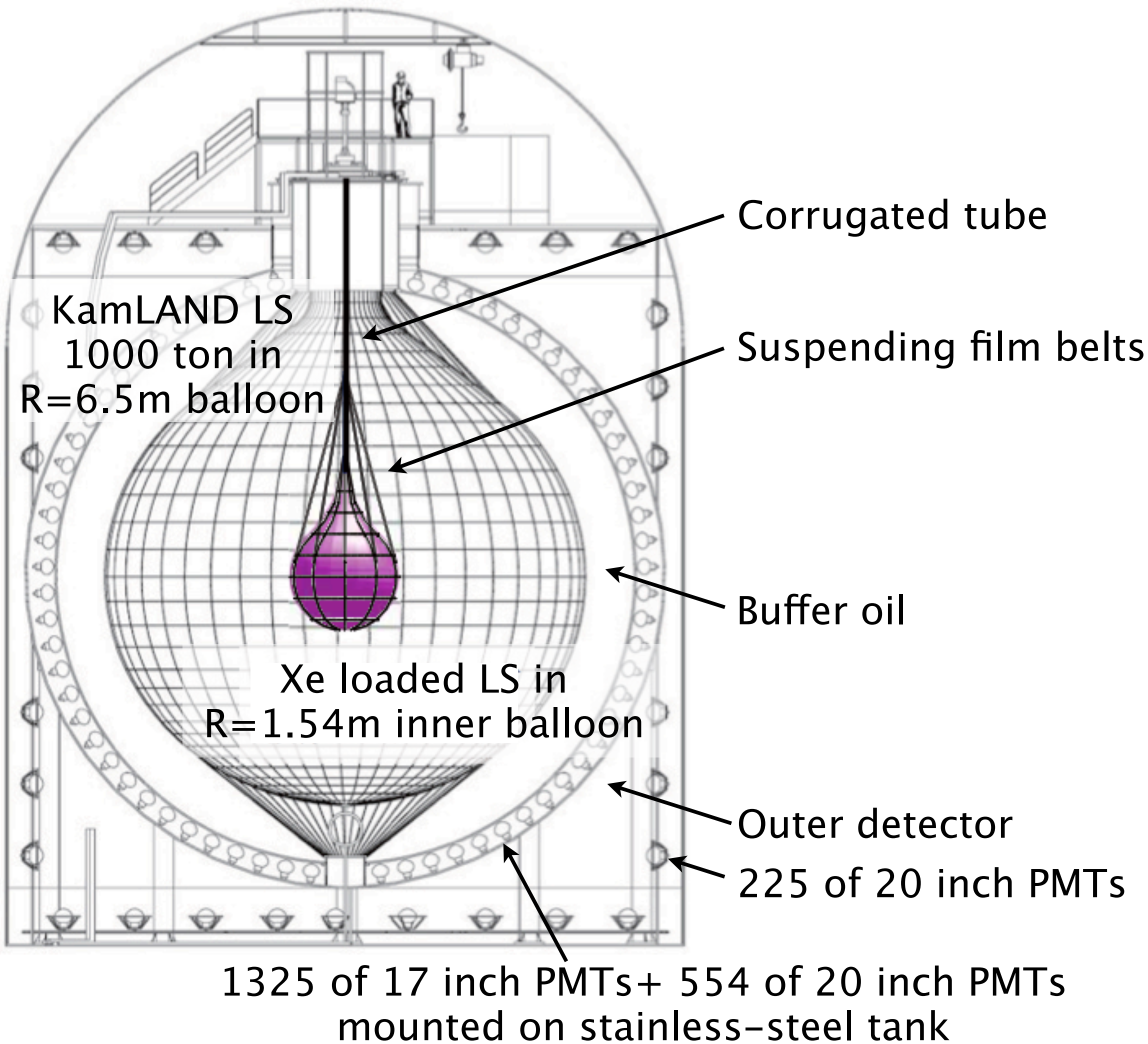


Exo vs KK claim



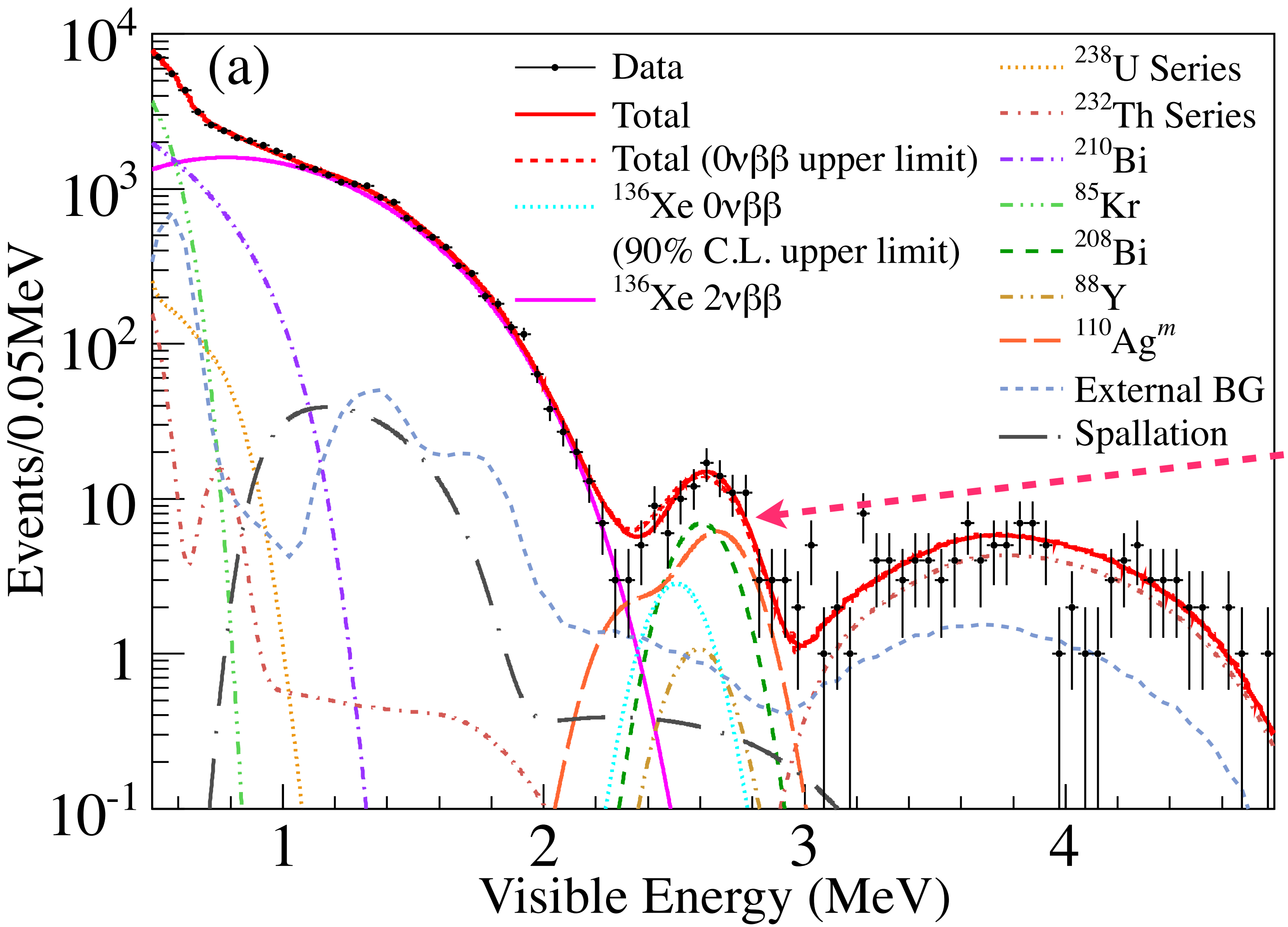
- Now: Improving energy resolution and pattern recognition
- Future: 1T with tagging of $^{136}Ba^{++}$ ion (^{136}Xe daughter).

Kamland-Zen



- Total: ~320 kg 90% enriched ^{136}Xe (2.4 wt%)
- Fiducial (~R/2): 125±7 kg ^{136}Xe
- U : 3.5×10^{-18} g/g
  Th: 5.2×10^{-17} g/g
- Res@2615 keV: 250 keV FWHM
- Taking data since September 24, 2011

Kamland-Zen: results (112 days)



Background peak very close to the 0νDBD: ^{110m}Ag or ^{208}Bi, ^{88}Y from Spallation or from Fukushima.

0νDBD hypothesis rejected at 8σ

- $T^{0\nu}_{1/2} > 6.2\times10^{24}$ yr (90% CL) ⟶ $\langle m_{\beta\beta}\rangle$ < 260~540 meV
- $T^{2\nu}_{1/2}$=2.30±0.02(stat)±0.12(syst) ×10^{21} yr (arXiv:1205.6372)

Kamland-Zen future

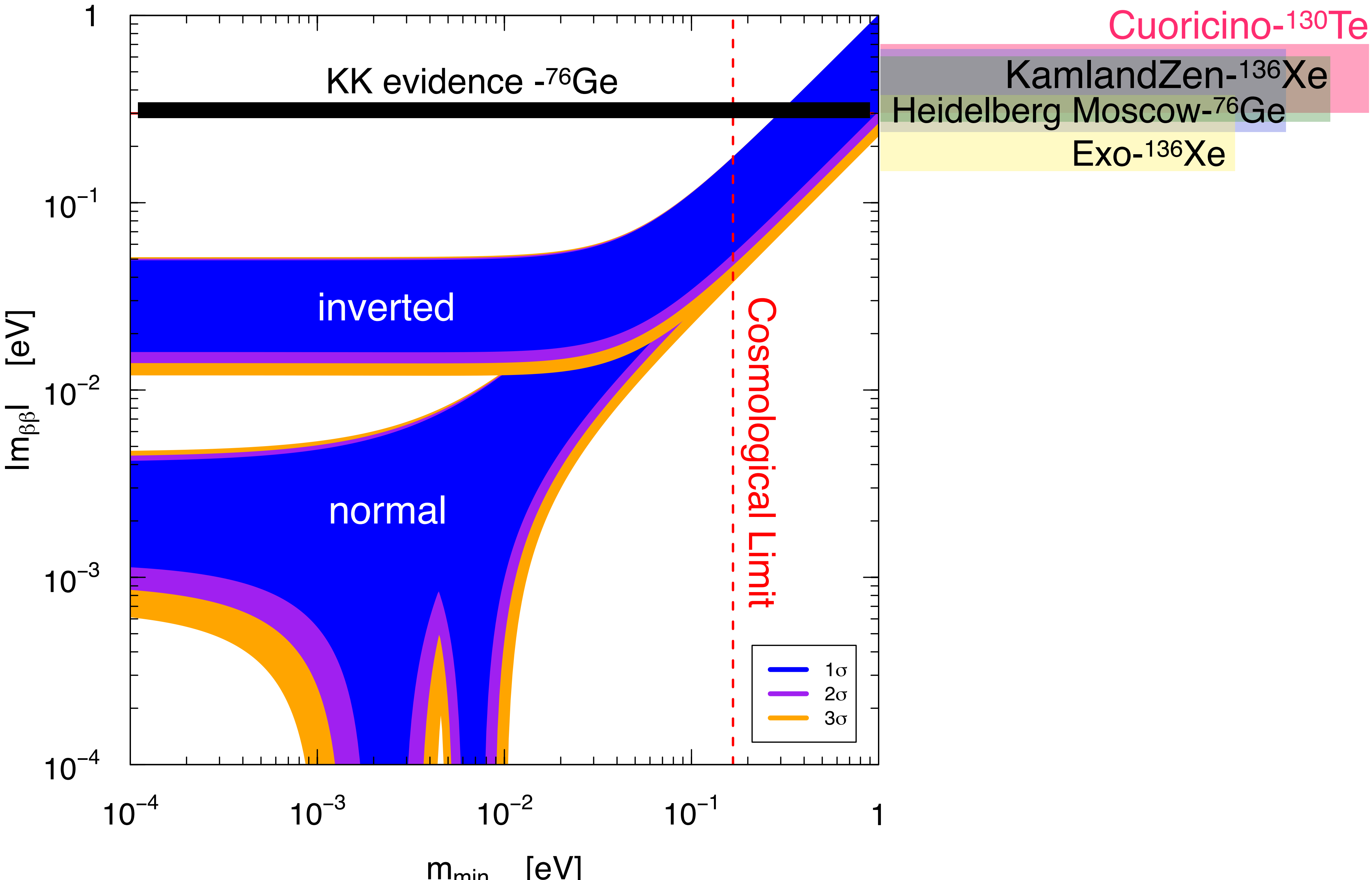
K. Inoue at Neutrino 2012

- Soon (target sensitivity: ~80 meV):
    - improved purification of Xe-LS to remove peaking contaminants ^{110m}Ag, ^{208}Bi,^{88}Y -> Target: more than a factor 100 reduction.
- Near future (target sensitivity ~40 meV):
    - increased Xe amount and cleaner baloon
- Future (target sensitivity ~20 meV):
    - improve resolution with new LS and more efficient light collection.

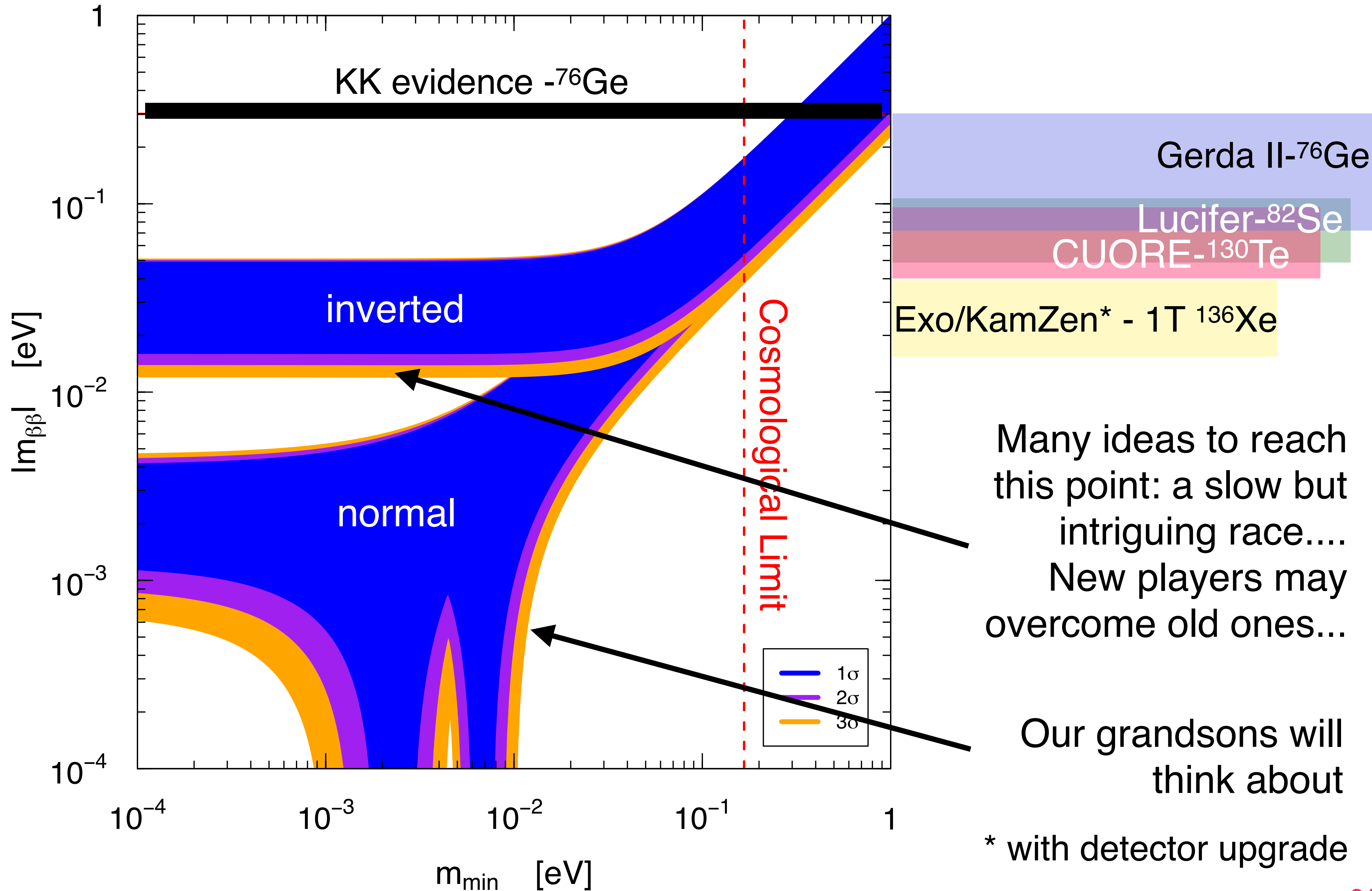
Other projects

- Amore: $Ca^{100}MoO_4$ bolometers (development)
- Next: 100kg, high pressure, ^{136}Xe-gas TPC (development)
- Sno+: 44kg ^{150}Nd in liquid scintillator (development)
- SuperNemo: 100 kg of various isotopes, tracking (development)
- ... and others.

Conclusion: present limits



Conclusion: next reaches



Many ideas to reach this point: a slow but intriguing race.... New players may overcome old ones...

Our grandsons will think about

* with detector upgrade