



DBD Searches Status & Perspectives

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Present knowledge in ν Physics

- From Oscillation experiments:
 - Neutrinos are massive fermions (massless in SM!)
- There are 3 active neutrino flavors ν_α
- Neutrino Flavor states
 - Are *not* mass eigenstates
 - Are mixture of mass eigenstates ν_k

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

CP violating Phase

Majorana Phases

$$U_{MNSP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta} & c_{13} & \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\beta/2} \end{pmatrix}$$

Neutrinos

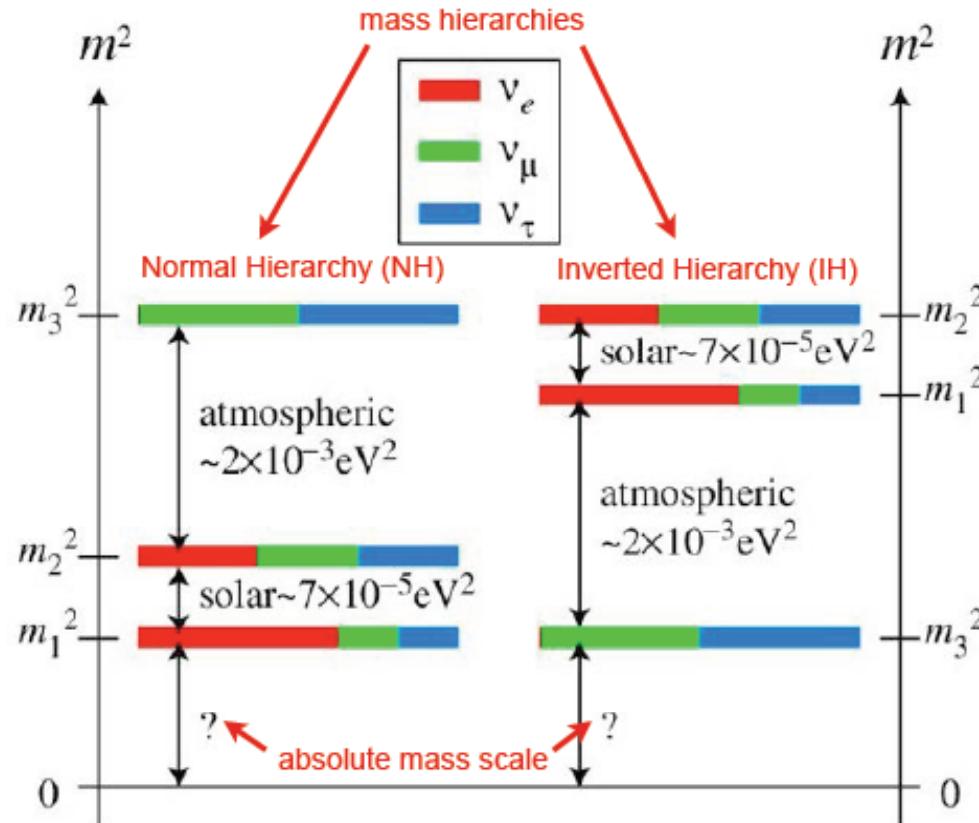
$$U_{MNSP} = \begin{pmatrix} 0.8 & 0.5 & 0.026 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Quarks

$$V_{CKM} = \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.1 \\ 0.001 & 0.1 & 1 \end{pmatrix}$$

Open question in ν Physics

1. Mass of the lightest ν_i \longleftrightarrow Absolute mass scale: i.e.
2. Hierarchy ($m_1 \ll m_2 < m_3$ or $m_3 \ll m_1 < m_2$) or degeneracy ($m_1 \approx m_2 \approx m_3$)



Forthcoming Neutrino Oscillation Experiment (Daya Bay II, JUNO, Reno II, T2K, Nova, LBNO, LBNE, Pingu, ORCA), cannot address point 1, but **can solve point 2**.

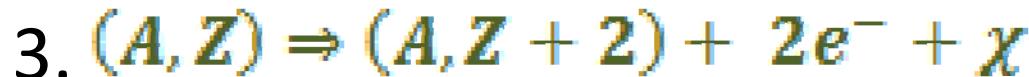
DECAY Modes of $\beta\beta$ decay



$2\nu\beta\beta$; Allowed in SM; Observed in 12 Nuclei ; $T_{1/2} 10^{19} - 10^{21}$ y



$0\nu\beta\beta$; NOT Allowed in SM; Not observed apart 1 discussed claim ; $T_{1/2} > 10^{25}$ y



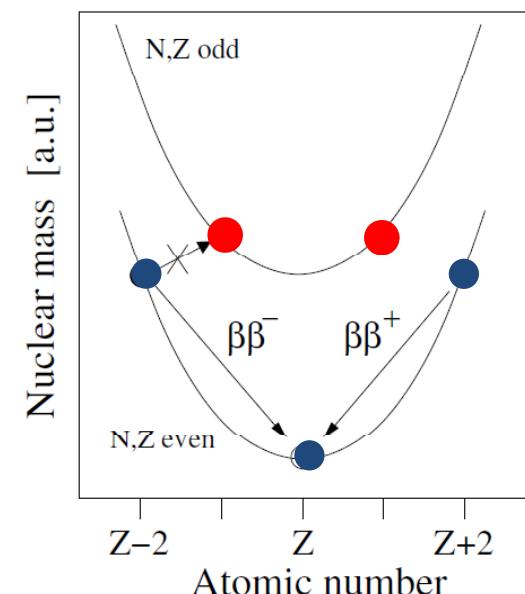
$\beta\beta$ w. Majoron Emission; NOT foreseen in SM; NOT observed; $T_{1/2} > 10^{22}$ y

❑ Process 2. and 3. would imply new physics beyond SM

❑ Very sensitive to new physics as Phase Space factor very favorable especially for 2.

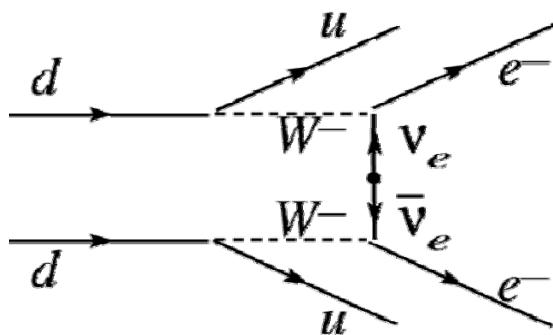
❑ $2\nu\beta\beta$ proposed by Goeppert-Meyer in 1935

❑ $0\nu\beta\beta$ proposed by Racah in 1937



$0\nu\beta\beta$: the mass mechanism

$$(A, Z) \Rightarrow (A, Z + 2) + 2e^-$$



Proposed by Majorana (and Racah) in 1937:

- A **RH anti- ν ($L=1$)** is emitted at one vertex (1st n)
- A **LH ν ($L= -1$)** is absorbed at second vertex (2nd n)

It is a forbidden process in SM and requires

- Lepton number violation by two units $\Delta L = 2$
- Majorana ν of finite mass $\nu_e = \bar{\nu}_e \quad \langle m_\nu \rangle \neq 0$

➤ **IF neutrinos are massive DIRAC particles:**

Helicity flip can be accommodated by the finite mass,
BUT Lepton number is rigorously conserved



**0ν DBD is
forbidden**

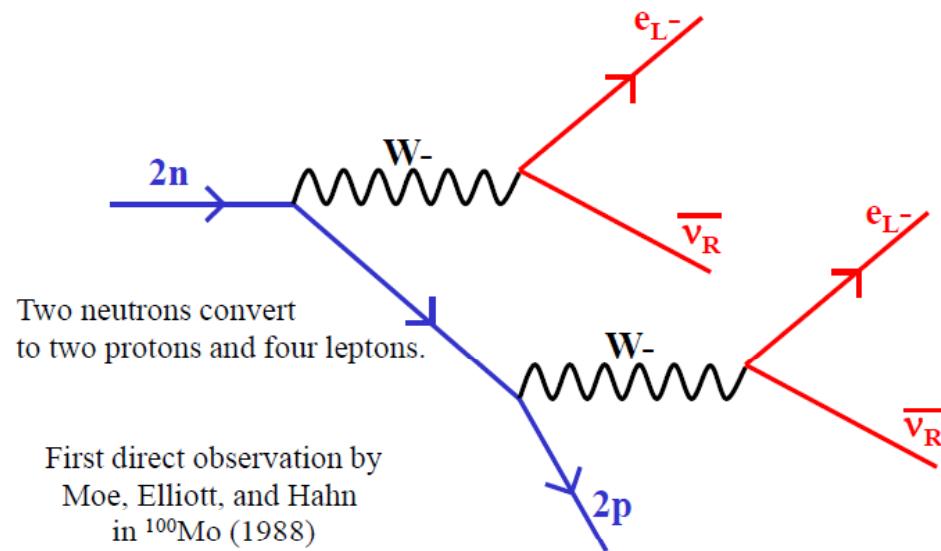
➤ **IF neutrinos are massive MAJORANA particles:**

Helicity flip can be accommodated by the finite mass,
AND Lepton number is not relevant



**0ν DBD is
allowed**

$2\nu\beta\beta$



No Direct Implications for neutrino physics, but useful for checking the Nuclear Matrix Element Calculations

Experimental Survey of $2\nu\beta\beta$ half-lives

Isotope	$T^{2\nu} \frac{1}{2} (10^{19} \text{ y})$
^{48}Ca	$4.4 \pm 0.5(\text{stat}) \pm 0.4(\text{syst})$
^{76}Ge	178^{+7}_{-9}
^{76}Ge	$184 \pm 9 (\text{stat}) \pm 11 (\text{syst})$
^{82}Se	$9.6 \pm 0.1 (\text{stat}) \pm 1.0 (\text{syst})$
^{96}Zr	$2.35 \pm 0.14 (\text{stat}) \pm 0.16 (\text{syst})$
^{100}Mo	$0.716 \pm 0.001 (\text{stat}) \pm 0.054 (\text{syst})$
^{116}Cd	$2.88 \pm 0.04 (\text{stat}) \pm 0.16 (\text{syst})$
^{130}Te	$76 \pm 15 \pm (\text{stat}) 8 (\text{syst})$
^{136}Xe	$217.2 \pm 1.7 (\text{stat}) \pm 6 (\text{syst})$
^{150}Nd	$0.92 \pm 0.025 (\text{stat}) \pm 0.063 (\text{syst})$

$0\nu\beta\beta$ rate and the effective neutrino mass

DBD can address, although in a Nuclear Model Dependent way

1. Absolute mass scale: i.e. mass of the lightest ν
2. Hierarchy ($m_1 \ll m_2 < m_3$ or $m_3 \ll m_1 < m_2$) or degeneracy ($m_1 \approx m_2 \approx m_3$)

$$0\nu\beta\beta \text{ rate} \sim (\text{effective Majorana neutrino mass})^2$$

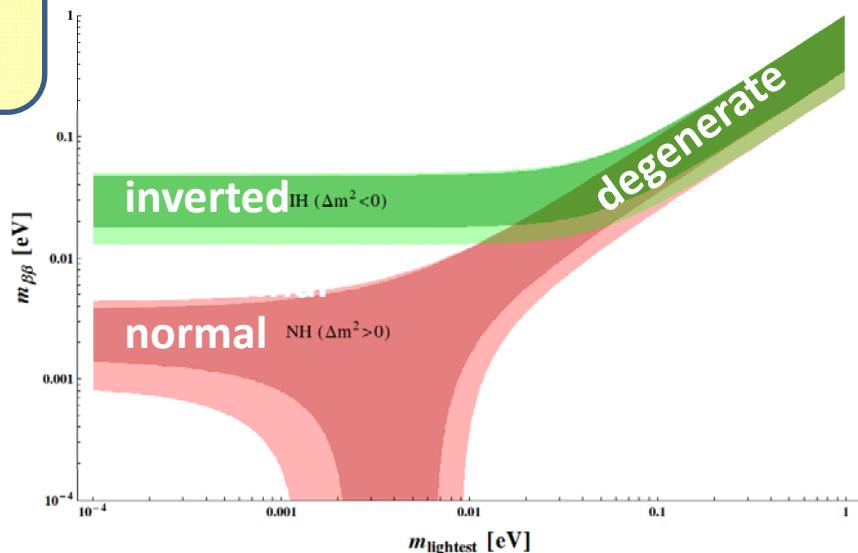
0v $\beta\beta$ half-life $(T_{1/2}^{0\nu})^{-1} \sim F_{0\nu}(Q, Z) |M_{0\nu}|^2 \langle m_{ee} \rangle^2 / m_e^2$

Phase space... Nuclear Matrix Elements

$$\begin{aligned} \langle m_{ee} \rangle &= \left| \sum_k m_k |U|^2_{ek} |e^{ia_i}| \right| \\ &= c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3 \end{aligned}$$

N.B. m_{ee} could be $<$ any m_i due to possible Majorana Phases cancellation

- Plotting m_{ee} vs. the lightest neutrino eigenstates & constraining by oscillation experiments data, one gets 3 allowed bands



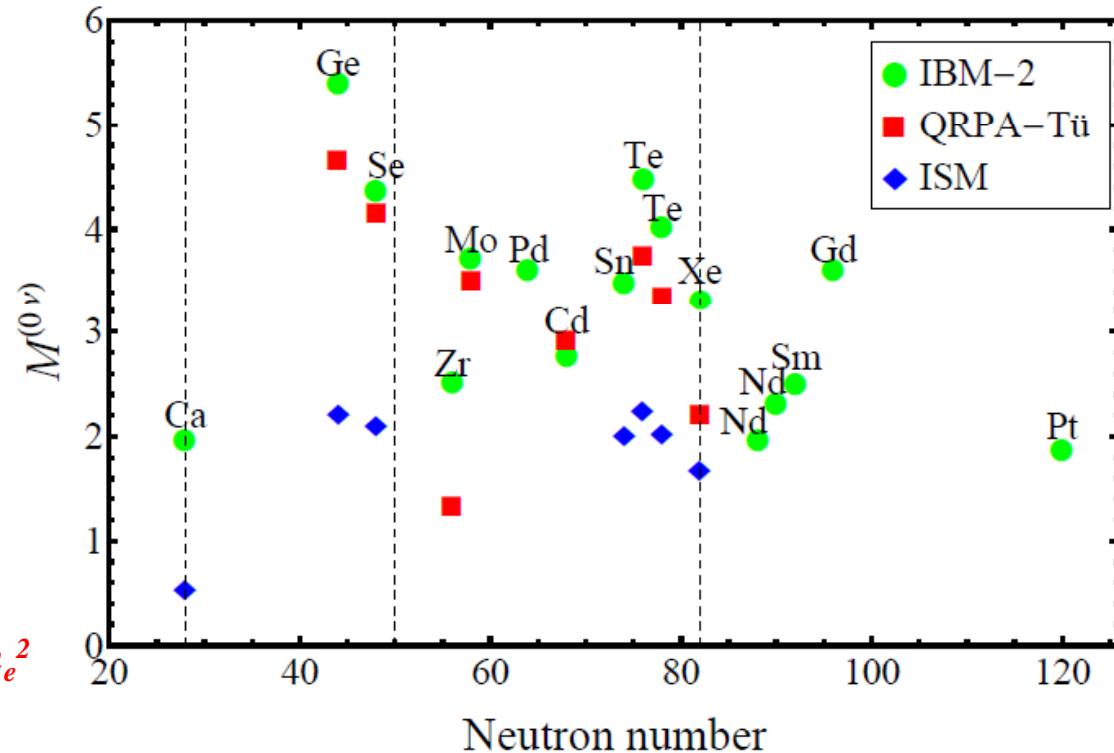
The Nuclear Matrix Elements

IBM: Interacting Boson Model,
Phys. Rev. Lett. 1055(2010) 252503

QRPA-Tü: Quasiparticle Random
Phase Approach

ISM: Shell Model

$$(T_{1/2}^{0\nu})^{-1} \sim F_{0\nu}(Q, Z) |M_{0\nu}|^2 \langle m_{ee}^2 / m_e^2 \rangle$$



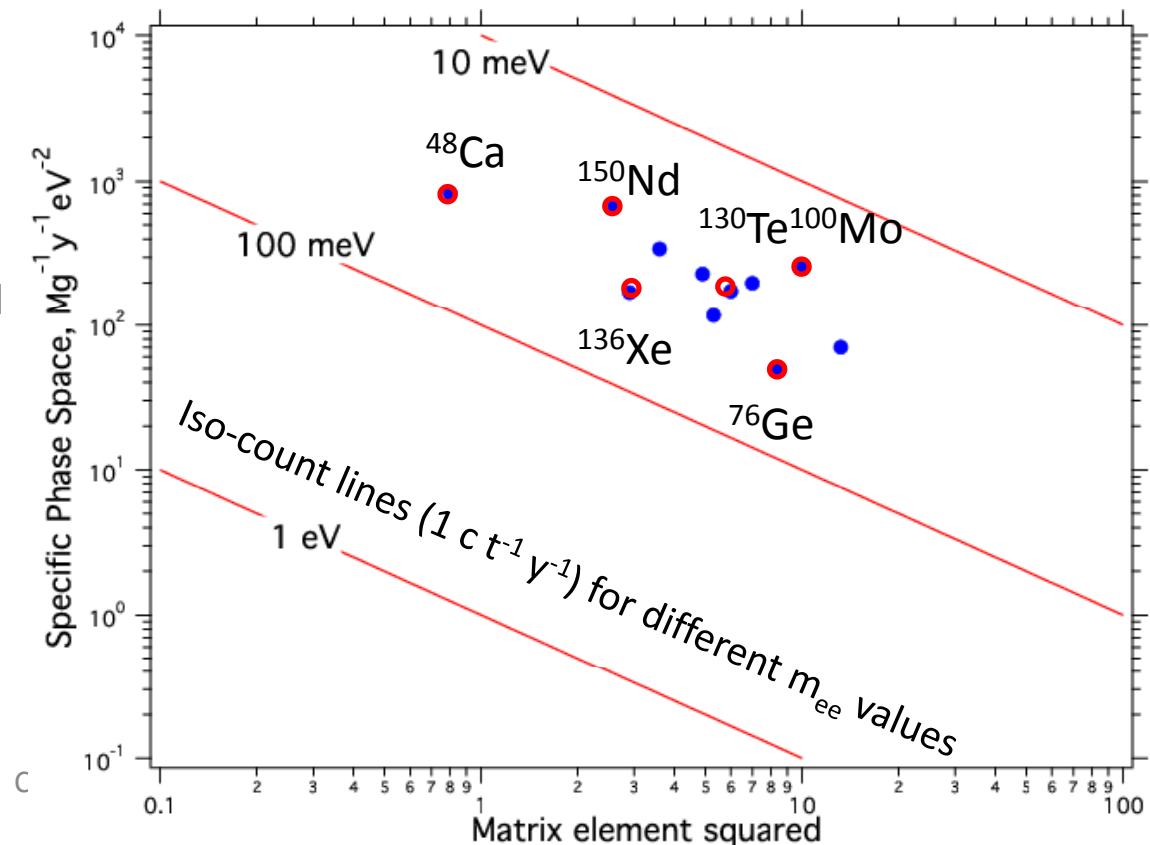
Conclusions:

- NME vary by factor 2-3 for a given nucleus depending on the model
- NME depends on g_A quenching value (1.269, 1.0,)
- Calculation discrepancies are one of the largest source of uncertainties in the $0\nu\beta\beta$ half-life computation
- No super element from NME

Does it exist a $0\nu\beta\beta$ Super-Element to investigate?

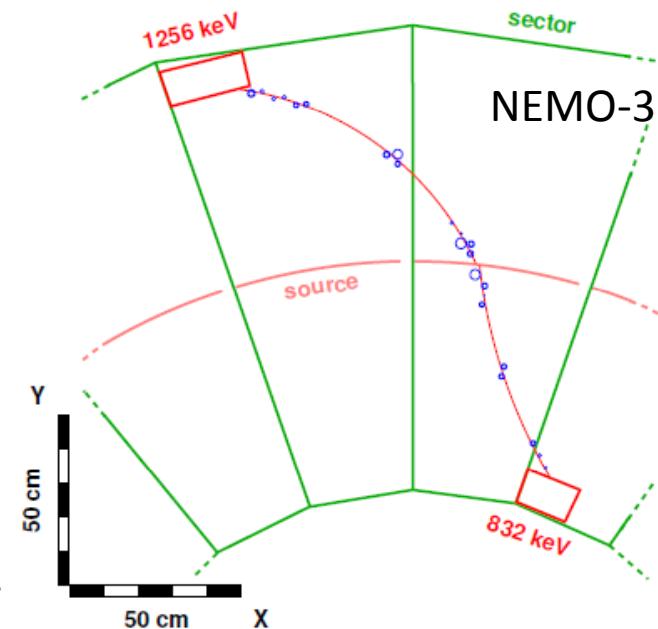
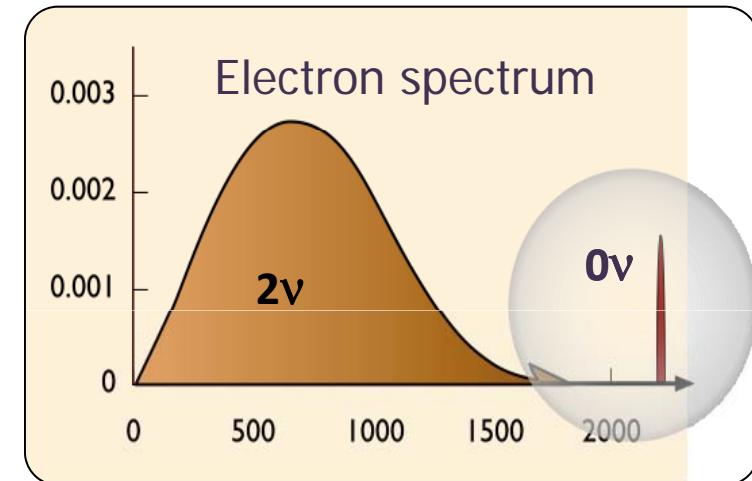
- Anticorrelation between Phase Space Factors and NME^2 pointed out by Robertson Mod.Phys.Lett. A28 (2013) 1350021
- No DBD Super-Element

Phase-space factor evaluated at $gA=1$ vs Geometric mean of the squared matrix element range and the. The points in order of increasing abscissa value are: ^{48}Ca , ^{150}Nd , ^{136}Xe , ^{96}Zr , ^{116}Cd , ^{124}Sn , ^{130}Te , ^{82}Se , ^{76}Ge , ^{100}Mo , and ^{110}Pd .



$\beta\beta$: Experimental Signatures

- Minimal signature:
Sum energy spectrum of the two e^-
 - $0\nu\beta\beta$ exhibits a peak at $Q_{\beta\beta}$
 - $2\nu\beta\beta$ exhibit a continuum spectrum
- Additional signatures:
 - Single electron spectrum
 - Angular correlation between the two e^-
 - Identification of Daughter nuclear species



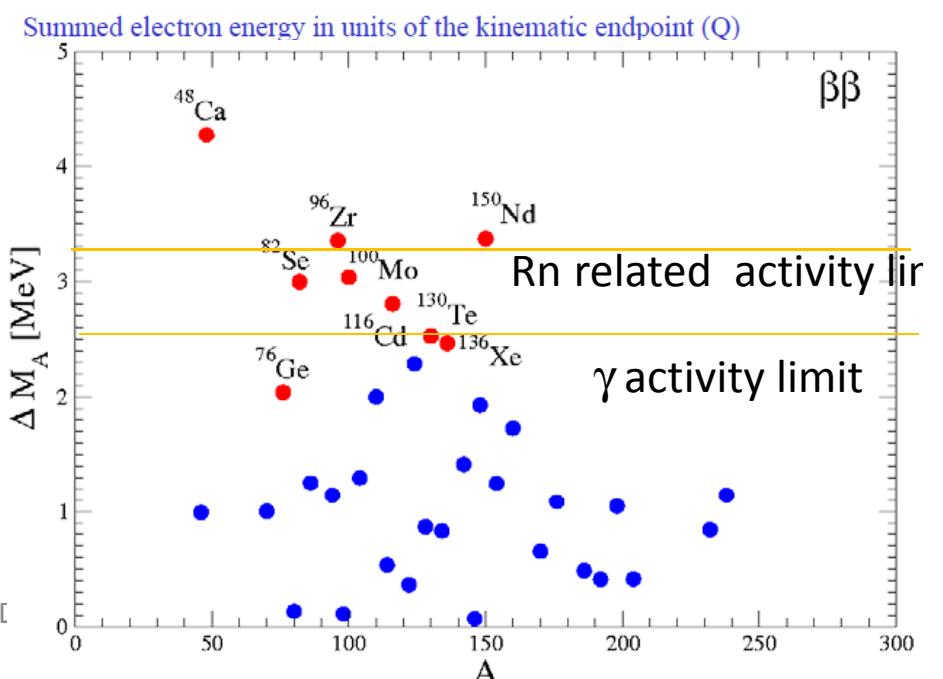
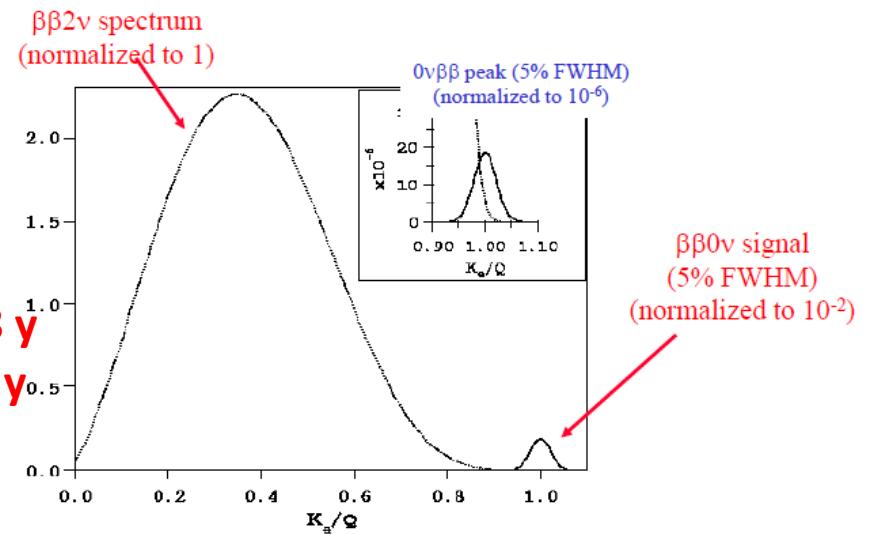
Backgrounds to $0\nu\beta\beta$

- $2\nu\beta\beta$ depending on 2ν decay rate and on setup Energy Resolution, and event topology discrimination

$$\frac{S}{B} = \frac{m_{ee}}{7Q\delta^6} \frac{\Gamma^{0\nu}}{\Gamma^{2\nu}} = \frac{m_{ee}}{7Q\delta^6} \frac{T_{1/2}^{2\nu}}{T_{1/2}^{0\nu}}$$

^{100}Mo : $7.2 \times 10^{18} \text{ y}$
 ^{136}Xe : $2.2 \times 10^{21} \text{ y}$
 $\delta = \Delta E/Q$

- Natural radioactivity of source itself and construction materials γ , β , α , n emitters
- Fallout Radioisotopes (^{137}Cs , ^{110}Ag)
- Long living Cosmogenic isotopes (^{68}Ge , ^{60}Co)
- Spallation n



Experimental sensitivity

Lifetime corresponding to the **minimum detectable n. of events ($N_{\beta\beta}$) over bkg** at a given CL

ε = detection efficiency
 A= Atomic weight
 i.a.= isotopic abundance
 M = mass of detector [kg]
 T = data taking time [y]
 BI = **background index**
 [cts/(keV kg y)]
 ΔE = FWHM @ $Q_{\beta\beta}$ [keV]

$$T_{1/2}^{0\nu} = \ln 2 \frac{\varepsilon N_{nuclei} T_{meas}}{N_{\beta\beta}}$$

$$N_{\beta\beta} \geq \sqrt{BI \cdot \Delta E \cdot M \cdot T_{meas}}$$

N_{bkg}>1

Scale Performances

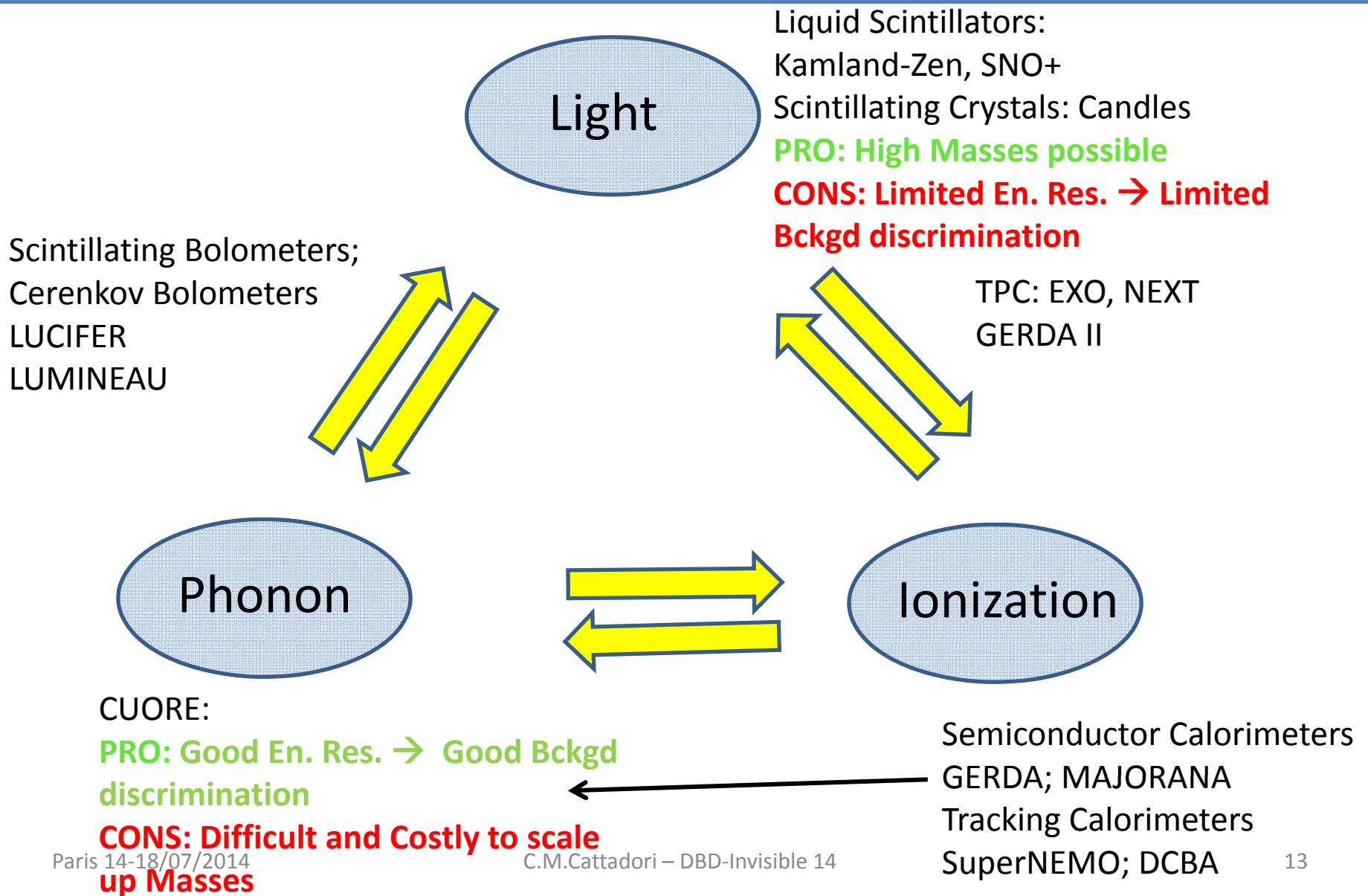
$$T_{1/2}^{0\nu} \propto \varepsilon \frac{i.a.}{A} \sqrt{\frac{M \cdot T_{meas}}{BI \cdot \Delta E}}$$

$$m_{ee} \propto \frac{1}{Q^{1/2} \cdot M_{0\nu}} \left(\frac{BI \cdot \Delta E}{M \cdot T_{meas}} \right)^{1/4}$$

$$T_{1/2}^{0\nu} \propto \varepsilon \frac{i.a.}{A} M T_{meas}$$

Bck free
N_{bkg}<1

Choosing the technique: Better multiple event reconstruction



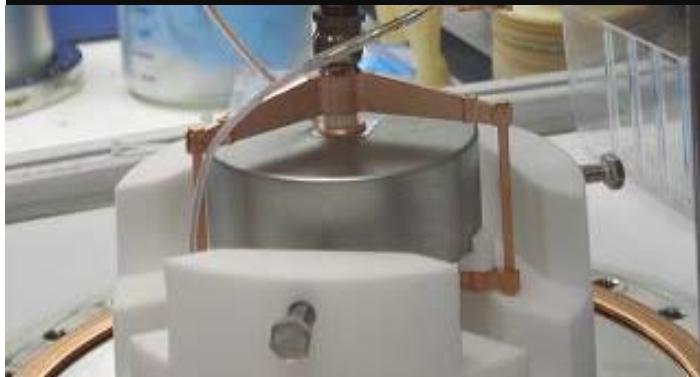


GERDA - I



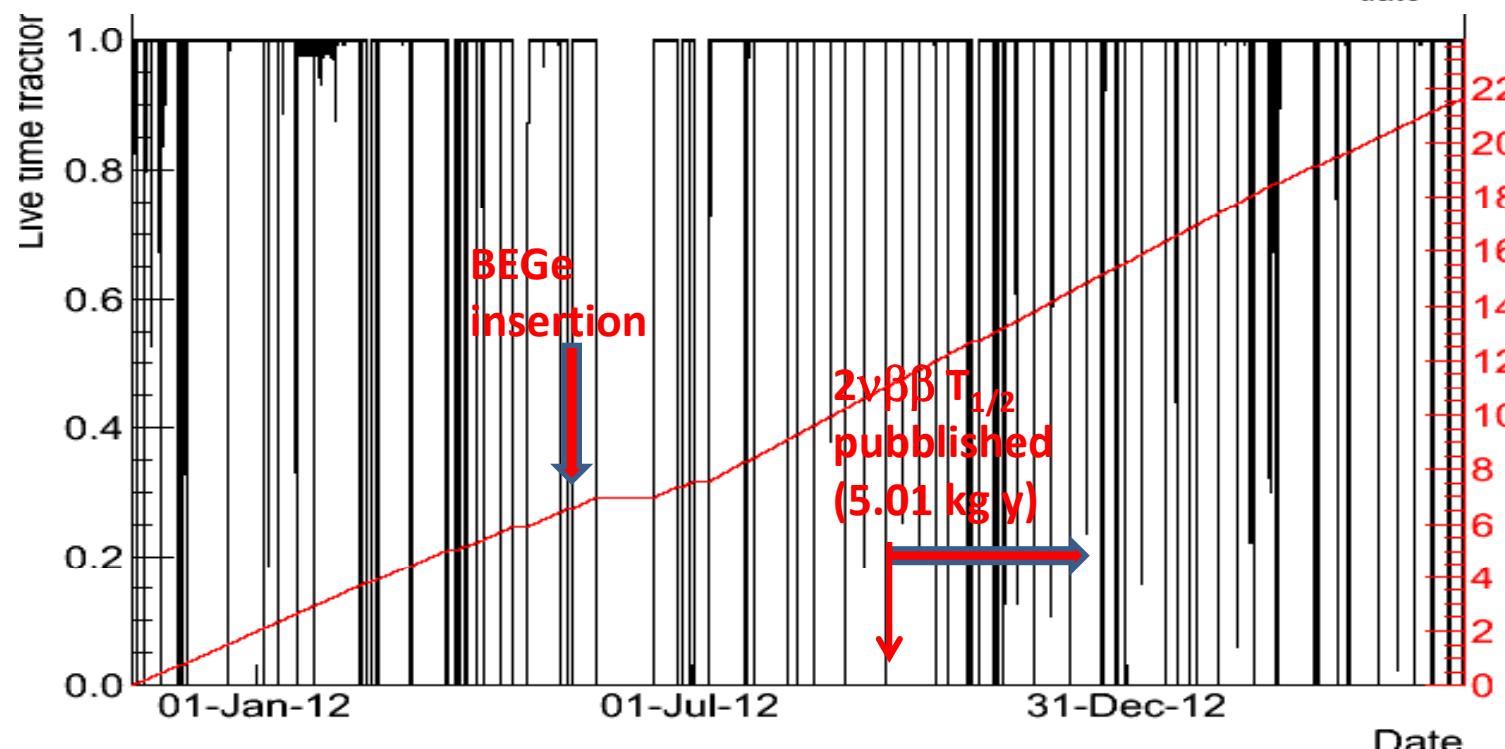
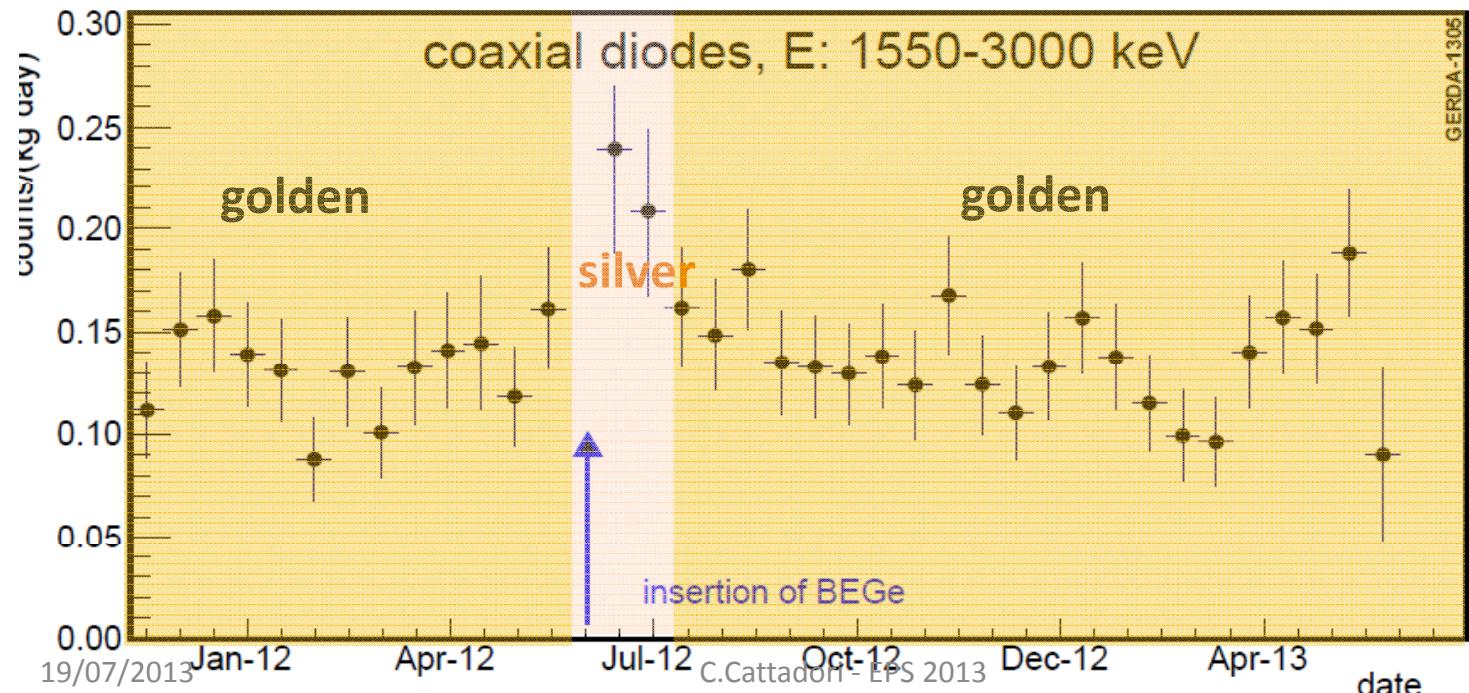


Pictures from GERDA



26/11/2013

C.Cattadori - CPAN 2013



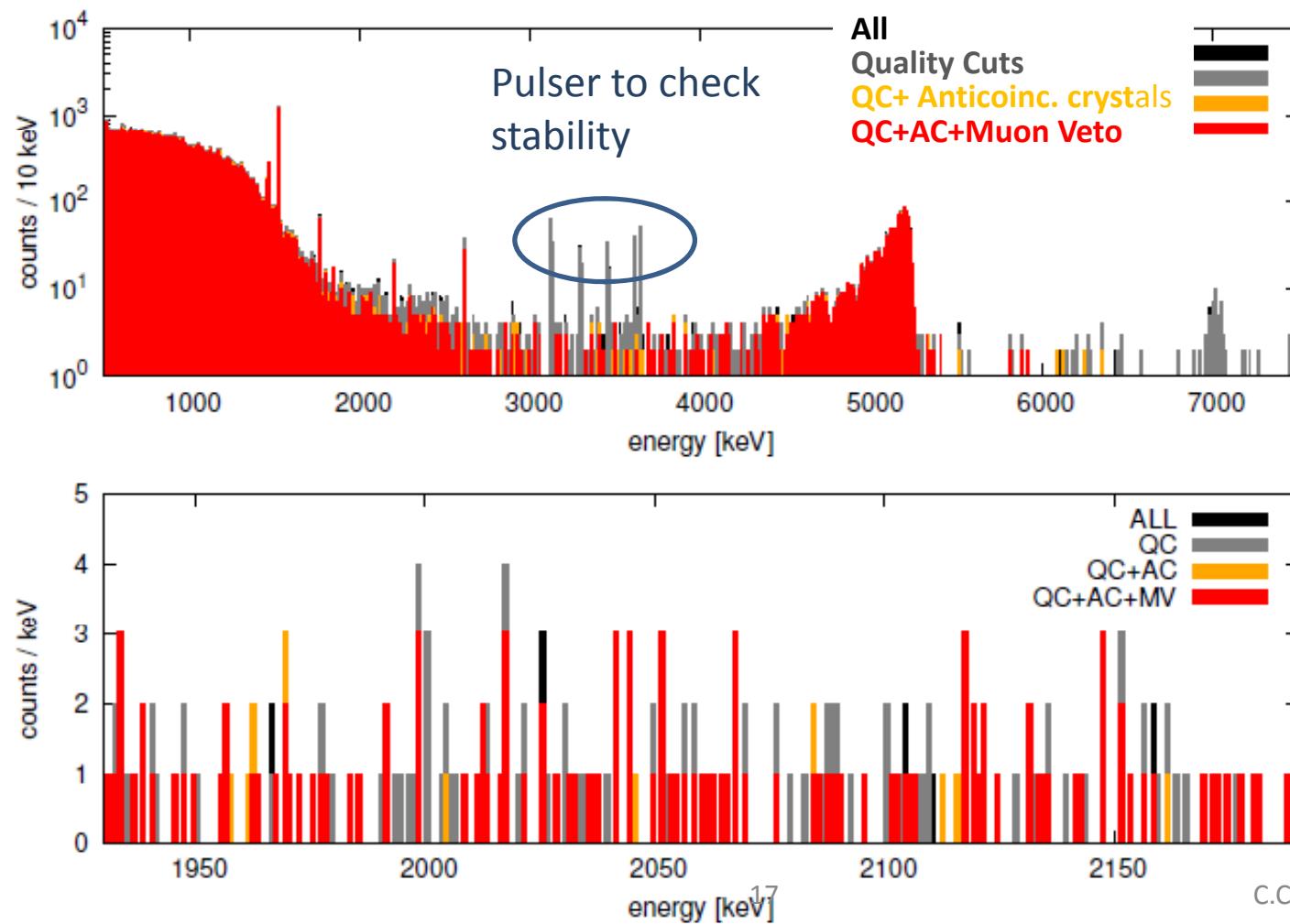
GERDA

Data taking:
Nov 2011-
June 2013



GERDA Cuts:

Events accepted by the analysis cut

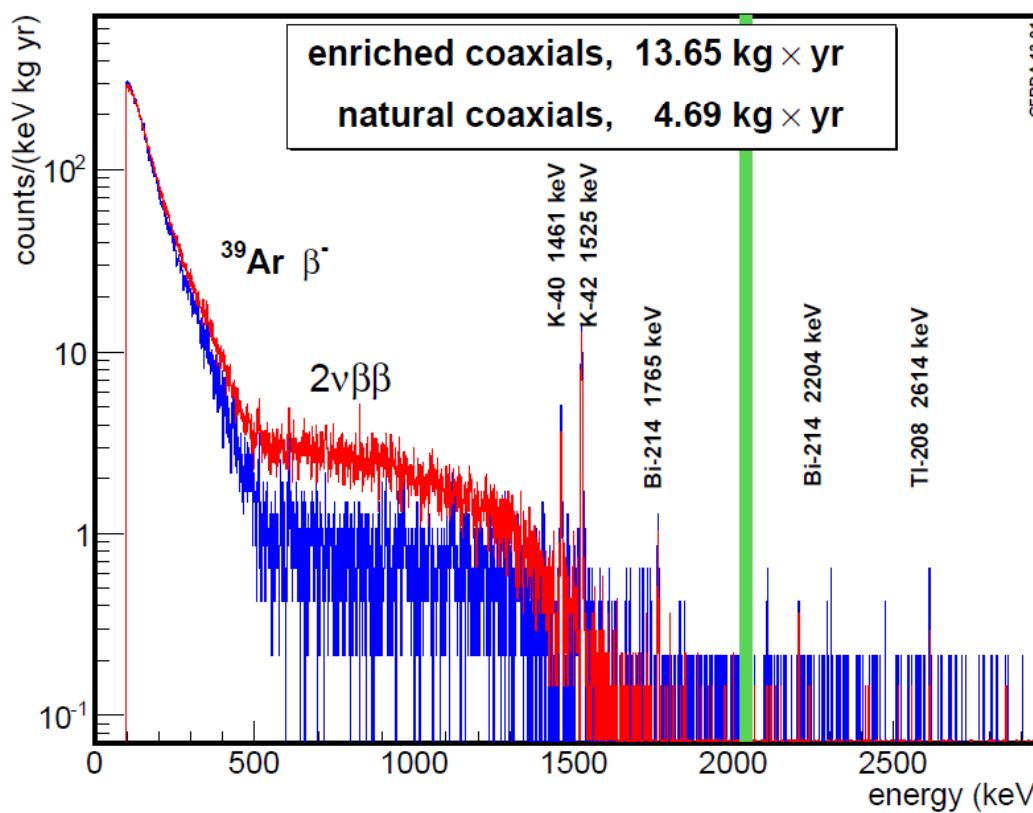
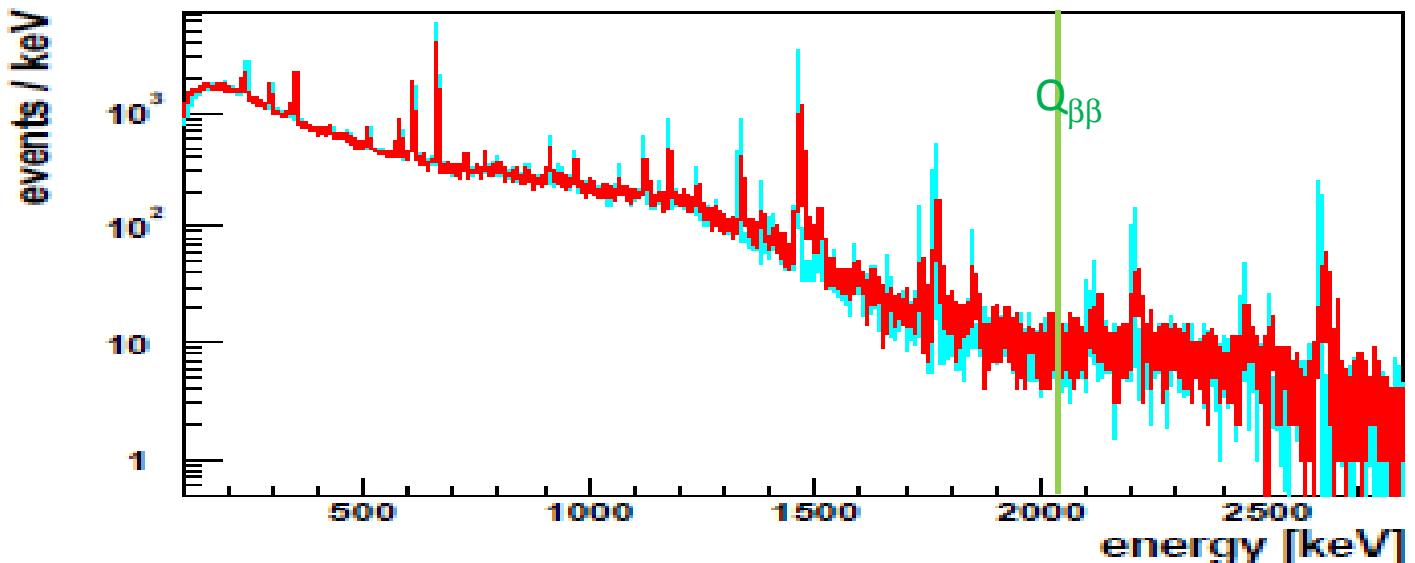


Very high quality:
•more than 90% of events accepted

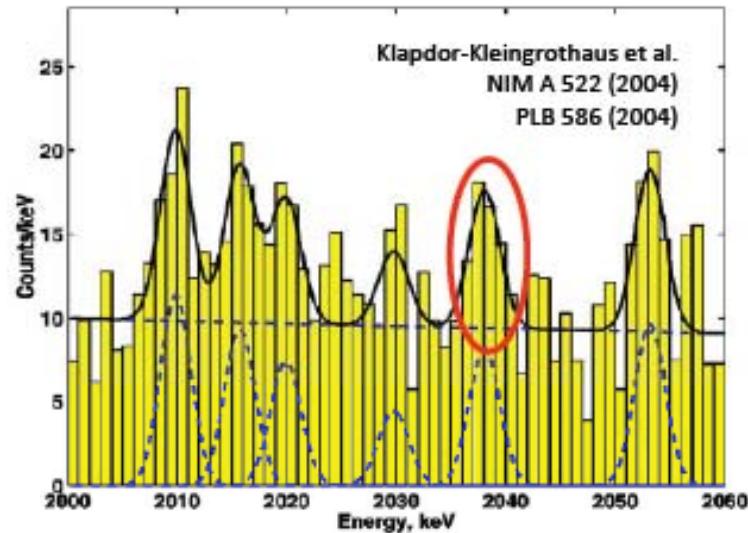
Thanks to superior setup
•Ultra- low background
•Low Electronic noise



GERDA BI
vs. HdM
(both no
PSA)
BI Reduction
factor ~ 10



The ${}^0\nu\beta\beta$ observation claim



Klapdor-Kleingrothaus et al., NIM A 522 (2004), PLB 586 (2004):

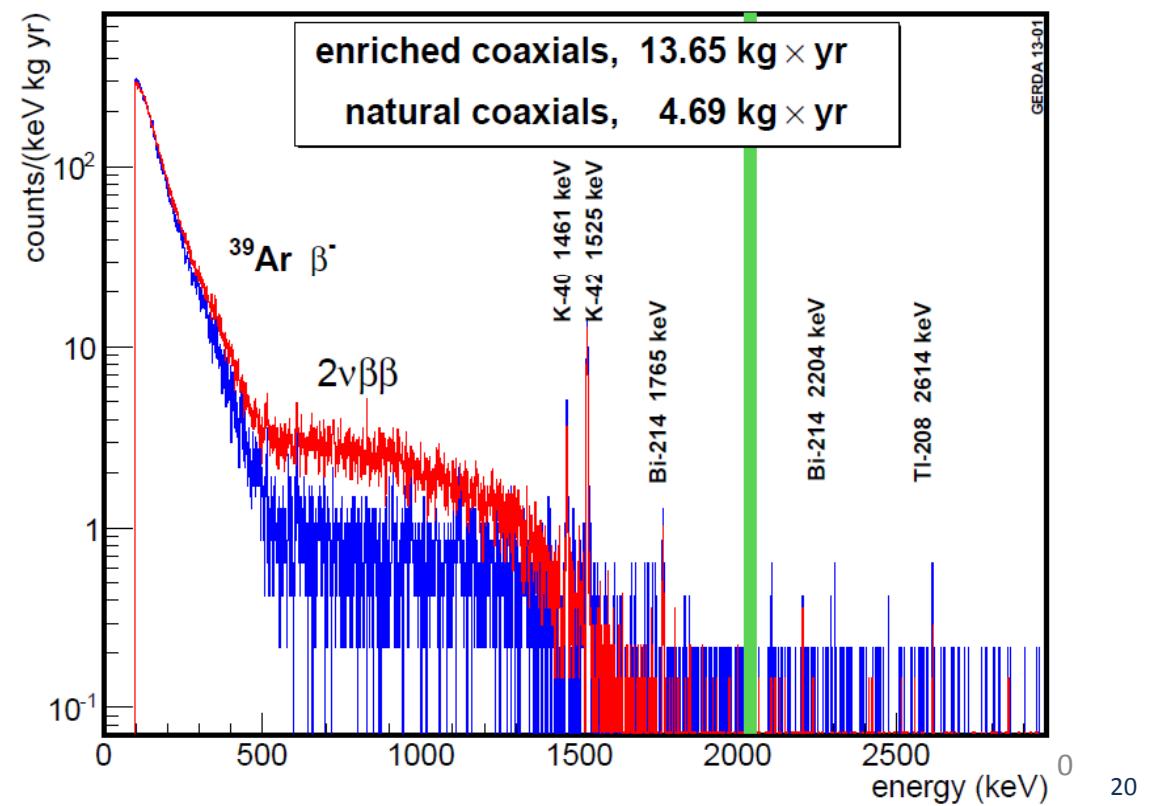
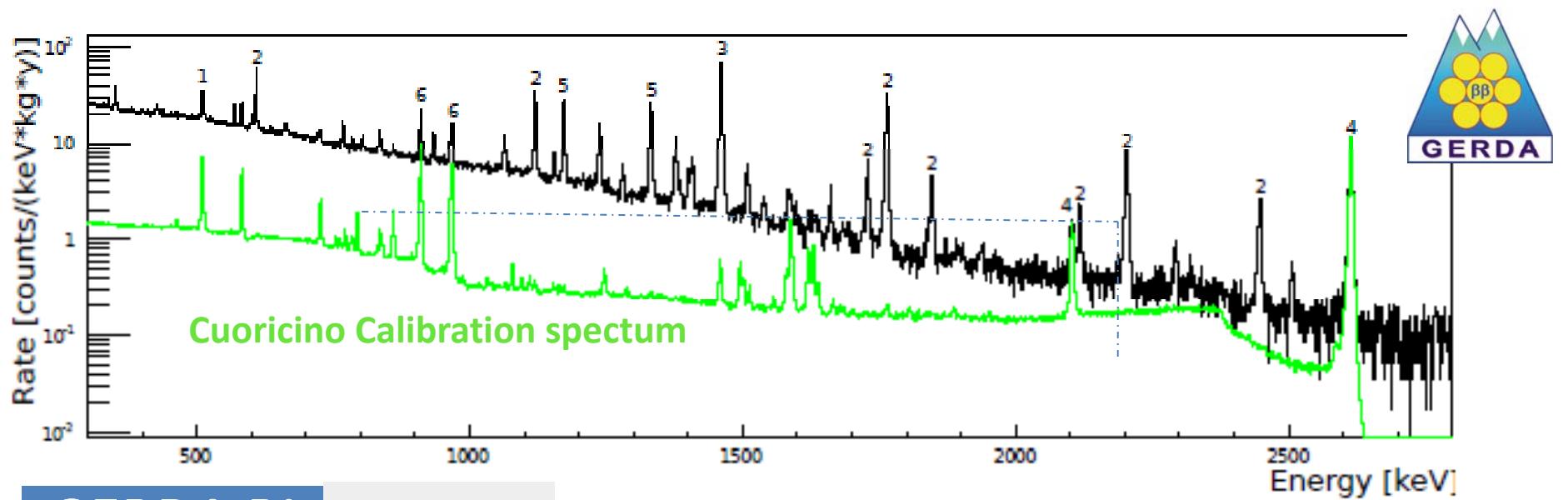
- 71.7 kg year - Bgd 0.17 / (kg yr keV)
- 28.75 ± 6.87 events (bgd: ~ 60)
- Claim: 4.2σ evidence for ${}^0\nu\beta\beta$
- reported $T_{1/2}{}^{0\nu} = 1.19 \times 10^{25}$ yr

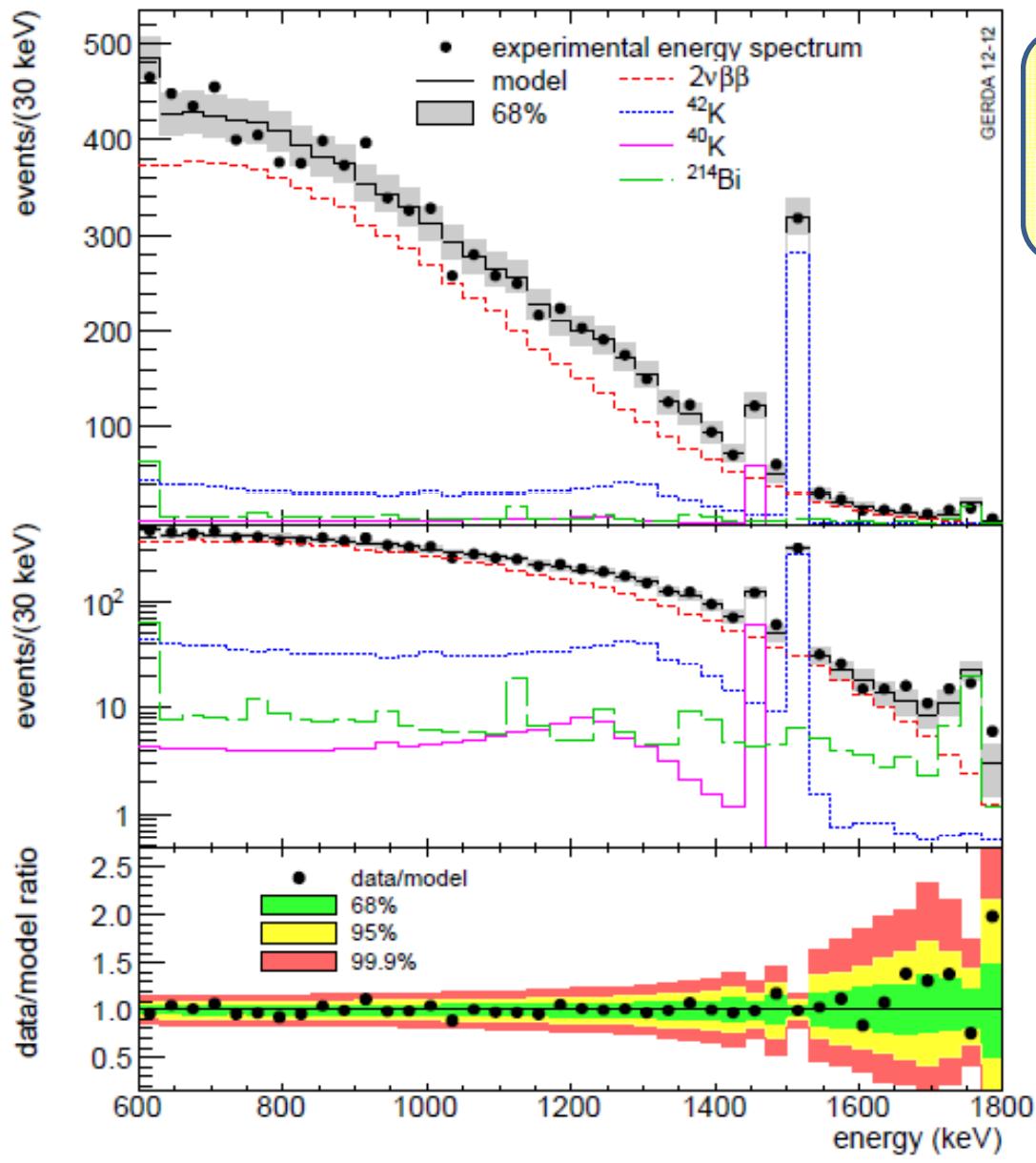


N.B. Half-life $T_{1/2}{}^{0\nu} = 2.23 \times 10^{25}$ yr $T_{1/2}$ after PSD analysis (Mod. Phys. Lett. A 21, 1547 (2006).) is not considered because:

- reported half-life can be reconstructed only (Ref. 1) with $\epsilon_{psd} = 1$ (previous similar analysis $\epsilon_{psd} \approx 0.6$)
- $\epsilon_{fep} = 1$ (also in NIM A 522, PLB 586 (2004) (GERDA value for same detectors: $\epsilon_{fep} = 0.9$)

(1) B. Schwingenheuer in Ann. Phys. 525, 269 (2013):





GERDA Result on 2ν $\beta\beta$

$$T_{1/2}^{0\nu} = (1.84^{+0.09}_{-0.08} \text{ (stat)} \pm 0.11 \text{ (syst)})$$

arXiv:1212.4067;
J. Phys. G: NPP 40 (2013) 035110

- 6 independent models for the 6 detectors ($5 \times 6 = 30$ detector parameters)
- $T^{2\nu}_{1/2}$ common in 6 detectors
- Background from 3 sources: ^{42}K , ^{40}K , ^{214}Bi (γ -lines used for normalization)
 - ^{42}K : homogeneously distributed
 - ^{40}K & ^{214}Bi : close sources
- Detectors active masses and enr. factors are nuisance parameters in the fit.
- $T^{2\nu}_{1/2}$ pdf is quasi-gaussian

$\beta\beta$ spectrum: 8796 events:

Model of the residual background: 80% 2ν $\beta\beta$, 14% ^{42}K , 3.8% ^{214}Bi , 2% ^{40}K ,

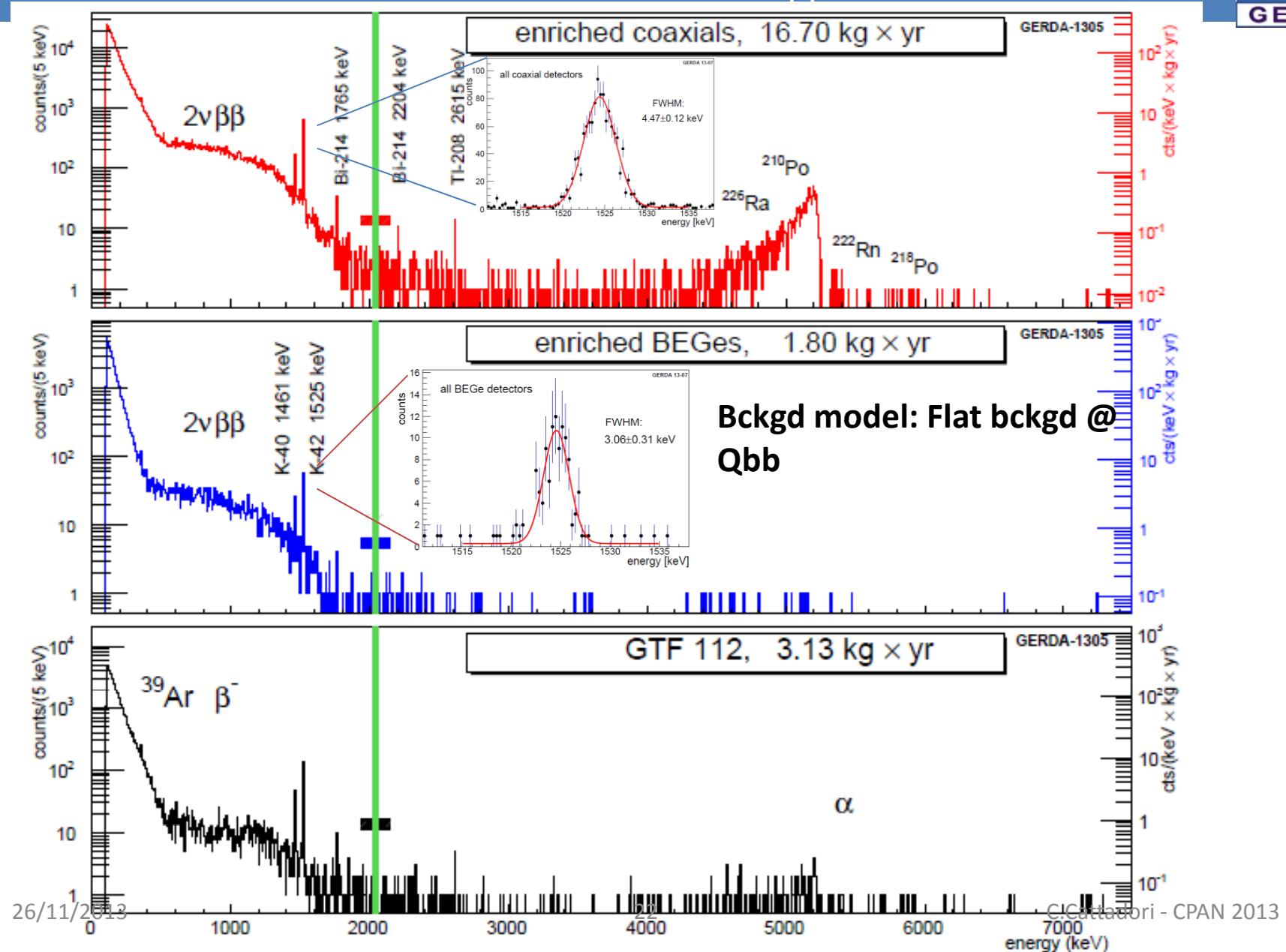
NuMass - Milan 4-8 Feb 2013

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The blinded energy spectra: events falling in ± 20 keV around $Q_{\beta\beta}$ not reconstructed



From unblinded counts to $T_{1/2}^{0\nu}$

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$$T_{1/2}^{0\nu} = \frac{\ln 2 \cdot N_A}{m_{enr} \cdot N^{0\nu}} \cdot \mathcal{E} \cdot \epsilon$$

$$\epsilon = f_{76} \cdot f_{av} \cdot \epsilon_{fep} \cdot \epsilon_{psd}$$

In 230 keV
@ $Q_{\beta\beta}$

In ROI
 ± 5 keV

Expected
bckgd only

data set	$\mathcal{E} [\text{kg}\cdot\text{yr}]$	$\langle \epsilon \rangle$	bkg	BI ^{†)}	cts
without Pulse Shape Discrimination					
<i>golden</i>	17.9	0.688 ± 0.031	76	18 ± 2	5
<i>silver</i>	1.3	0.688 ± 0.031	19	63^{+16}_{-14}	1
<i>BEGe</i>	2.4	0.720 ± 0.018	23	42^{+10}_{-8}	1
with Pulse Shape Discrimination					
<i>golden</i>	17.9	$0.619^{+0.044}_{-0.070}$	45	11 ± 2	2
<i>silver</i>	1.3	$0.619^{+0.044}_{-0.070}$	9	30^{+11}_{-9}	1
<i>BEGe</i>	2.4	0.663 ± 0.022	3	5^{+4}_{-3}	0

^{†)} in units of $10^{-3} \text{ cts}/(\text{keV}\cdot\text{kg}\cdot\text{yr})$.

BI Rej _{PSD} $\text{Coax} \sim 43\%$

BI Rej _{PSD} $\text{BEGe} \sim 87\%$

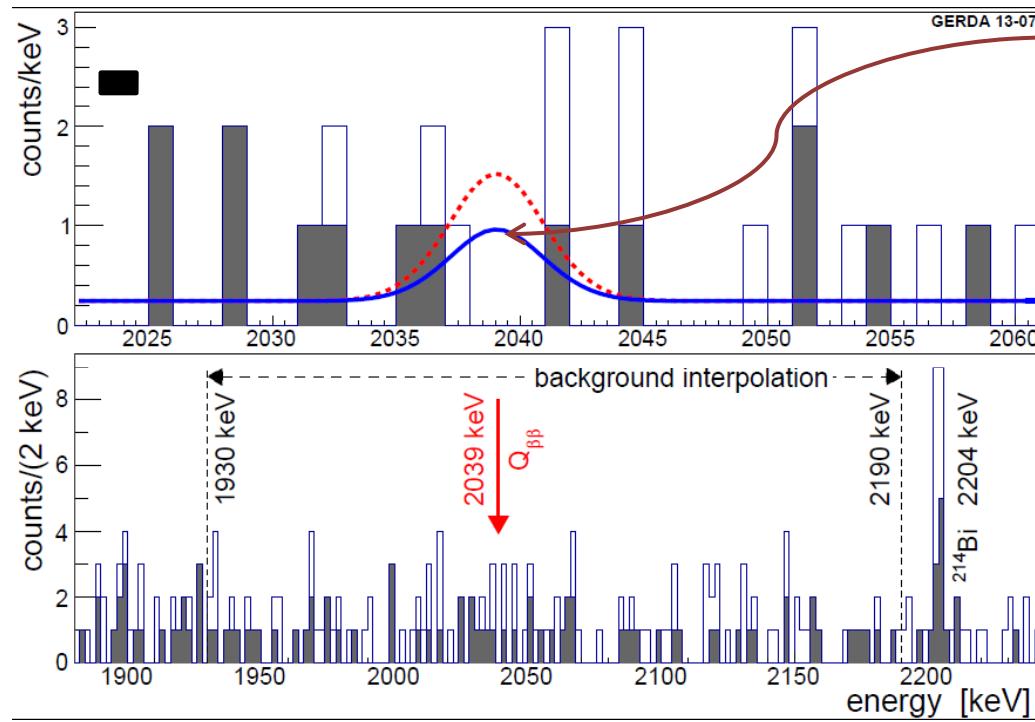
$T_{1/2}^{0\nu}$ from GERDA data sets

PRL111(2013)122503



Performed Profile Likelihood fit of the 3 data sets

- B+S: described by constant term + $\text{Gaus}(Q_{\beta\beta}, \sigma_E)$
- 4 free parameters in the fit $B_{\text{gold}}, B_{\text{silv}}, B_{\text{BEGe}}, 1/T_{1/2}^{0\nu}$
- Systematics folded in



Frequentist approach

Best fit: $N^{0\nu} = 0$

$N^{0\nu} < 3.5$ cts @ 90% C.L.

$T_{1/2}^{0\nu} > 2.1 \times 10^{25}$ yr @ 90% CL

Bayesian approach

Flat prior for $1/T_{1/2}^{0\nu}$

Best fit: $N^{0\nu} = 0$

$T_{1/2}^{0\nu} > 1.9 \times 10^{25}$ yr @ 90% CI

Median sensitivity:

$T_{1/2}^{0\nu} > 2.1 \times 10^{25}$ yr

GERDA (all data sets) vs KK (2004) claim

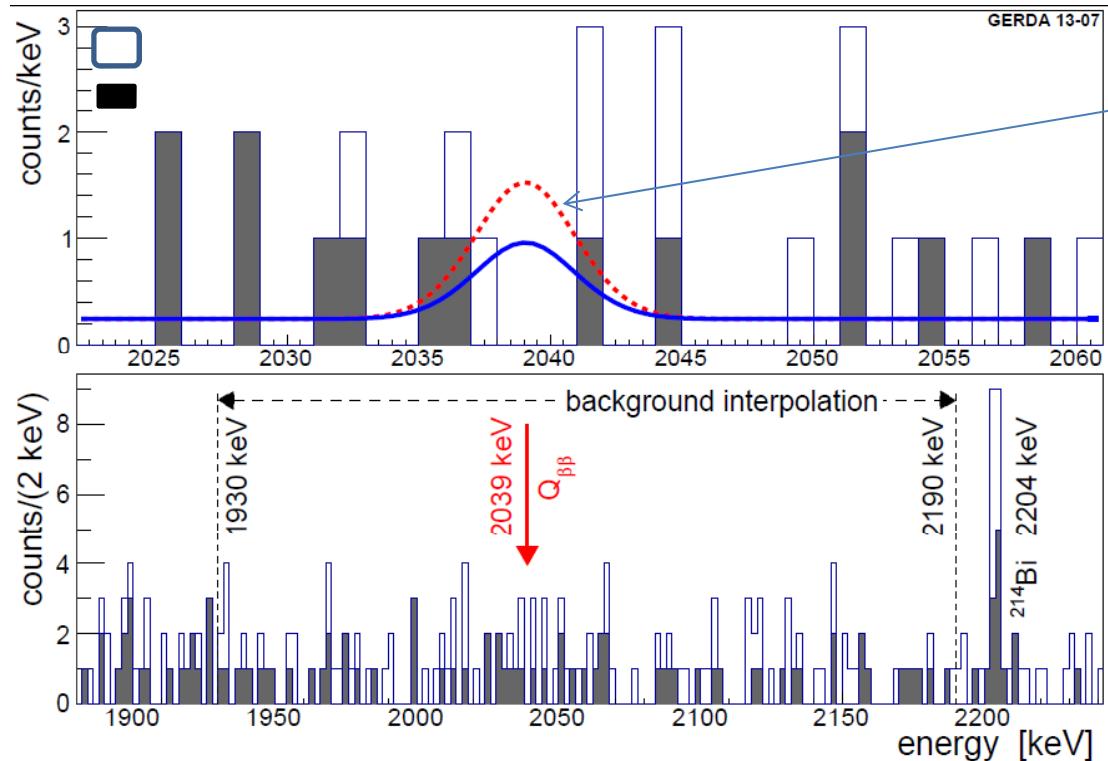
PRL111(2013)122503

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

Expected Signal (after PSD): 5.9 ± 1.4 cts in $\pm 2\sigma$

Expected Bckgd (after PSD): 2.0 ± 0.3 cts in $\pm 2\sigma$

Observed: 3.0 (0 in $\pm 1\sigma$)



From profile likelihood
Assuming H1,
 $P(N^{0\nu}=0 \text{ for H1})=1\%$

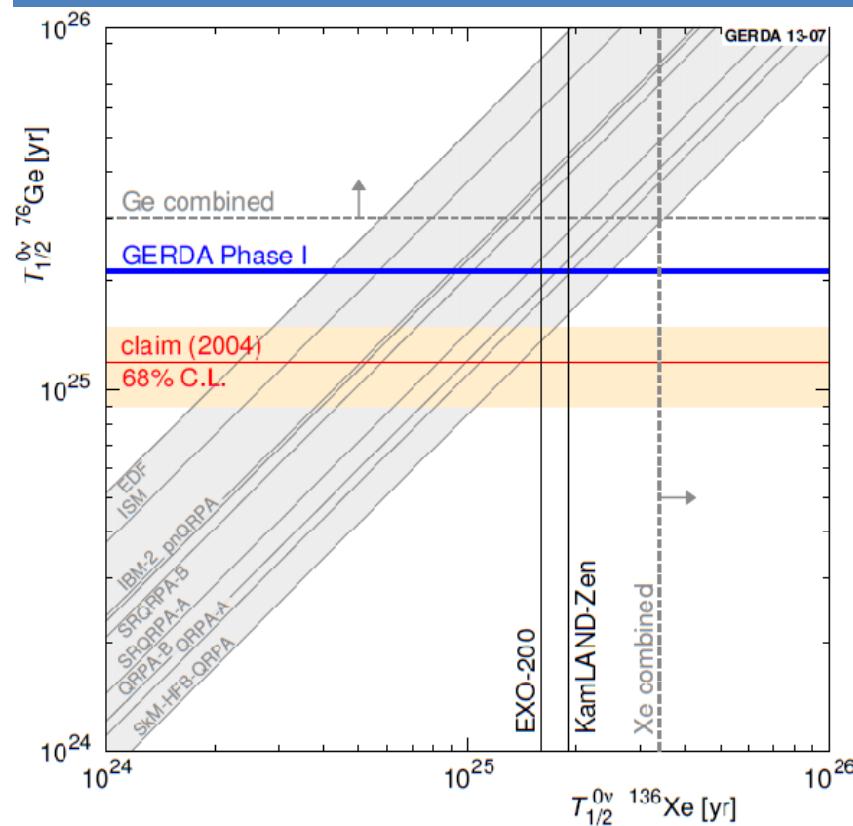
Comparing
H1: Claimed signal
H0: Background only
Bayes factor
 $P(H1)/P(H0)=0.024$
(uncertainties on claim included)

Claim poorly credible

Combining GERDA, HdM, IGEX & Xe



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H1: signal with $T_{1/2}^{0\nu} = 1.19 \times 10^{25}$ yr
H0: background only

	Isotope	$P(H_1)/P(H_0)$	Comment
GERDA	^{76}Ge	0.024	Model independent
GERDA +HdM+IGEX	^{76}Ge	0.0002	Model independent
KamLAND-Zen*	^{136}Xe	0.40	Model dependent: NME, leading term
EXO-200*	^{136}Xe	0.23	Model dependent: NME, leading term
GERDA+KLZ* +EXO*	$^{76}\text{Ge} + ^{136}\text{Xe}$	0.002	Model dependent: NME, leading term

*:with conservative NME ratio $M_{0\nu}(^{136}\text{Xe})/M_{0\nu}(^{76}\text{Ge}) \approx 0.4$ from:

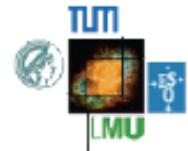
NME from
 P.S. Bhupal Dev et
 al (2103),
 arXiv:1305.0056

Combining GERDA, HdM, IGEX
3 GERDA Data sets, 1 HdM, 1 IGEX
Profile likelihood function w. 5 independent bckgds

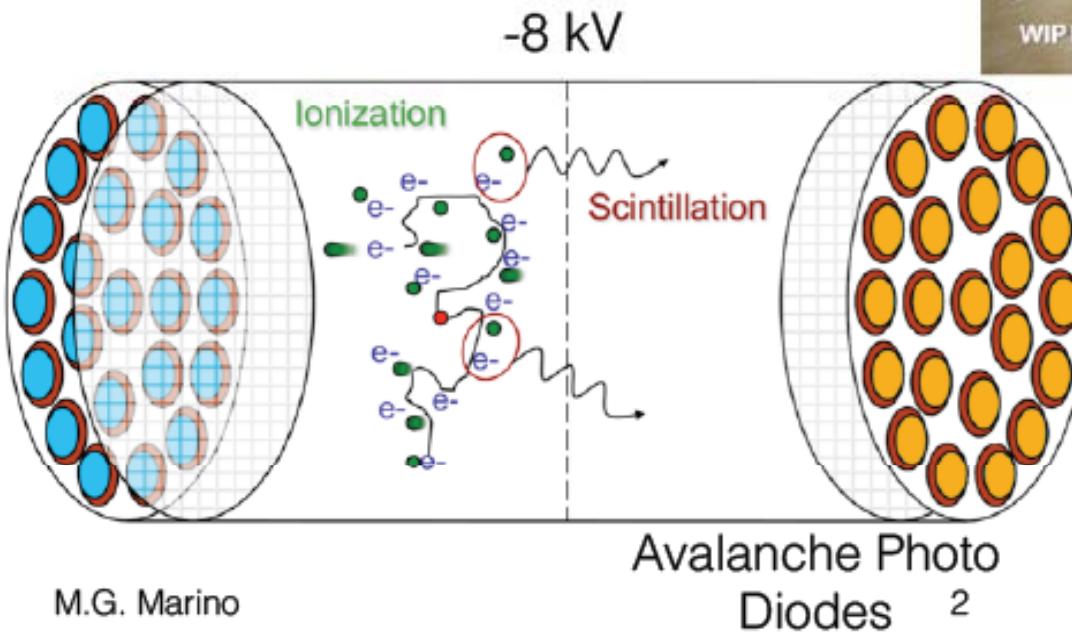
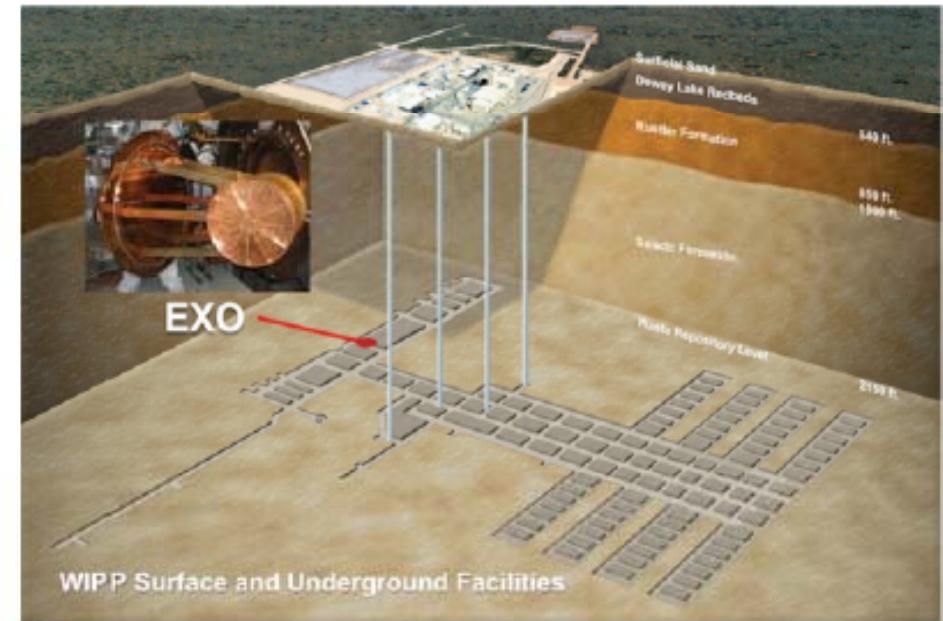
$T_{1/2}^{0\nu} > 3.0 \times 10^{25}$ yr @ 90% CL

EXO

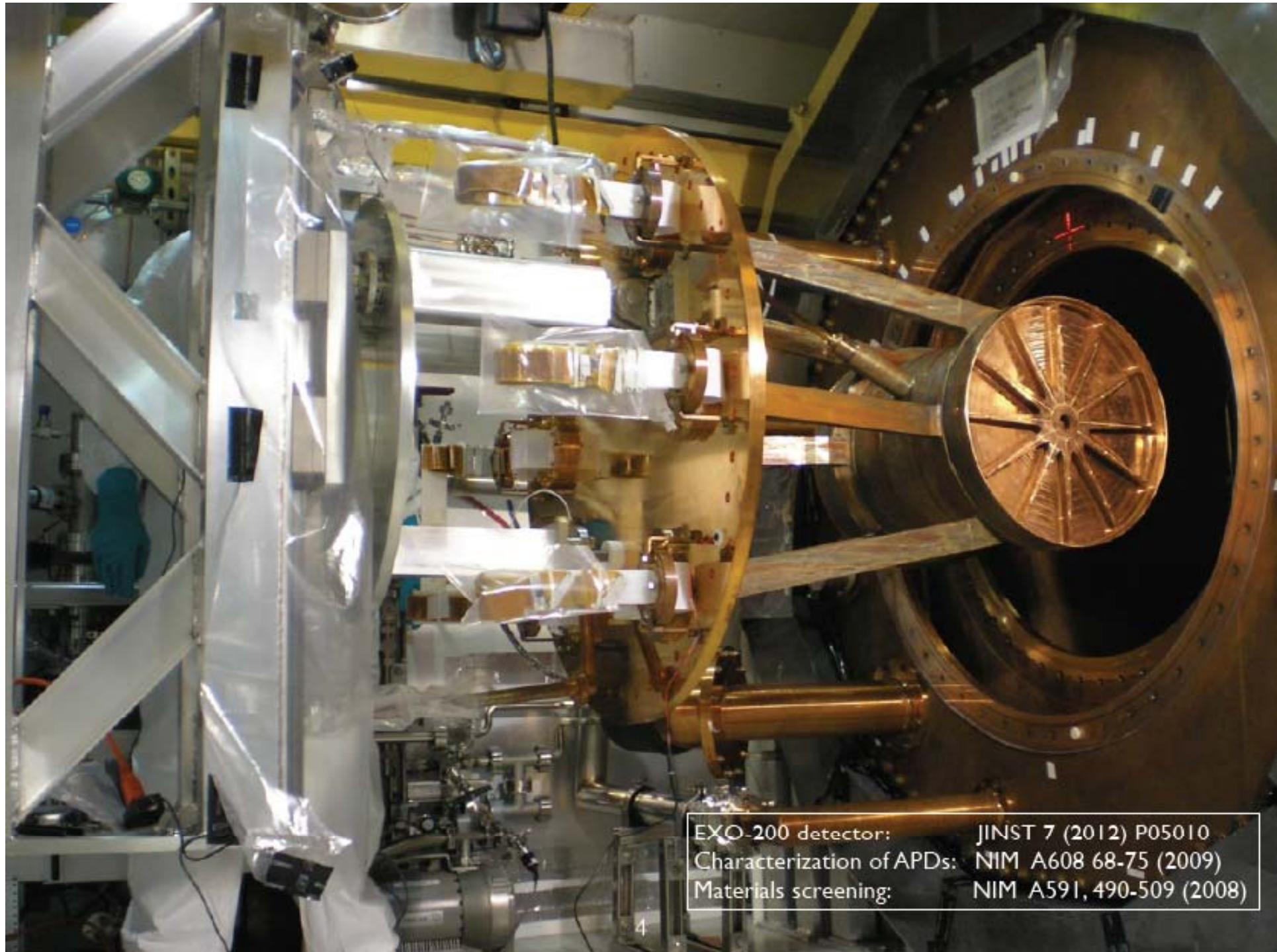
Enriched Xenon Observatory



- Liquid Xe Time Projection Chamber (TPC)
- Enriched ^{136}Xe to 80.6%
- Q-value 2458 keV

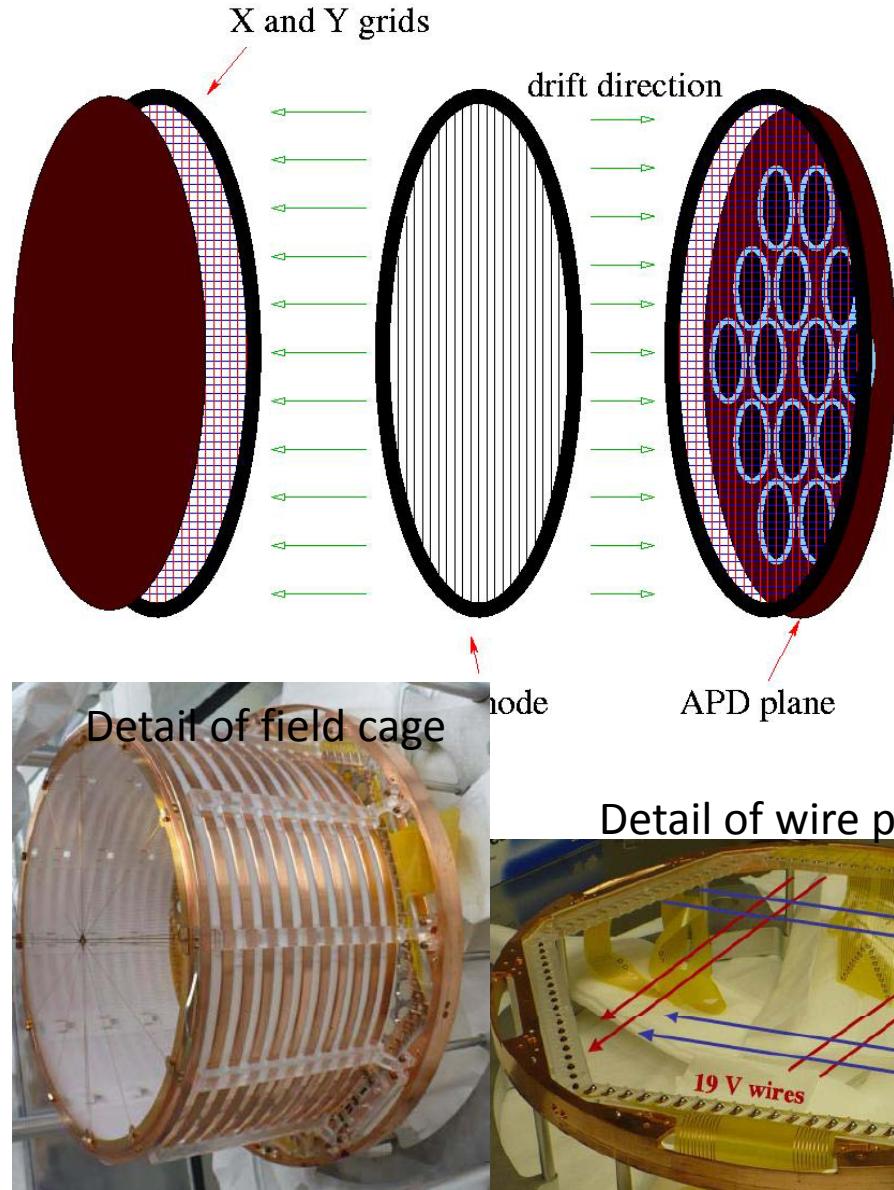


- Located at Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM, USA
- 1585 meters water equivalent



EXO-200 detector: JINST 7 (2012) P05010
Characterization of APDs: NIM A608 68-75 (2009)
Materials screening: NIM A591, 490-509 (2008)

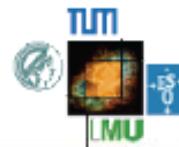
The EXO Operating principle



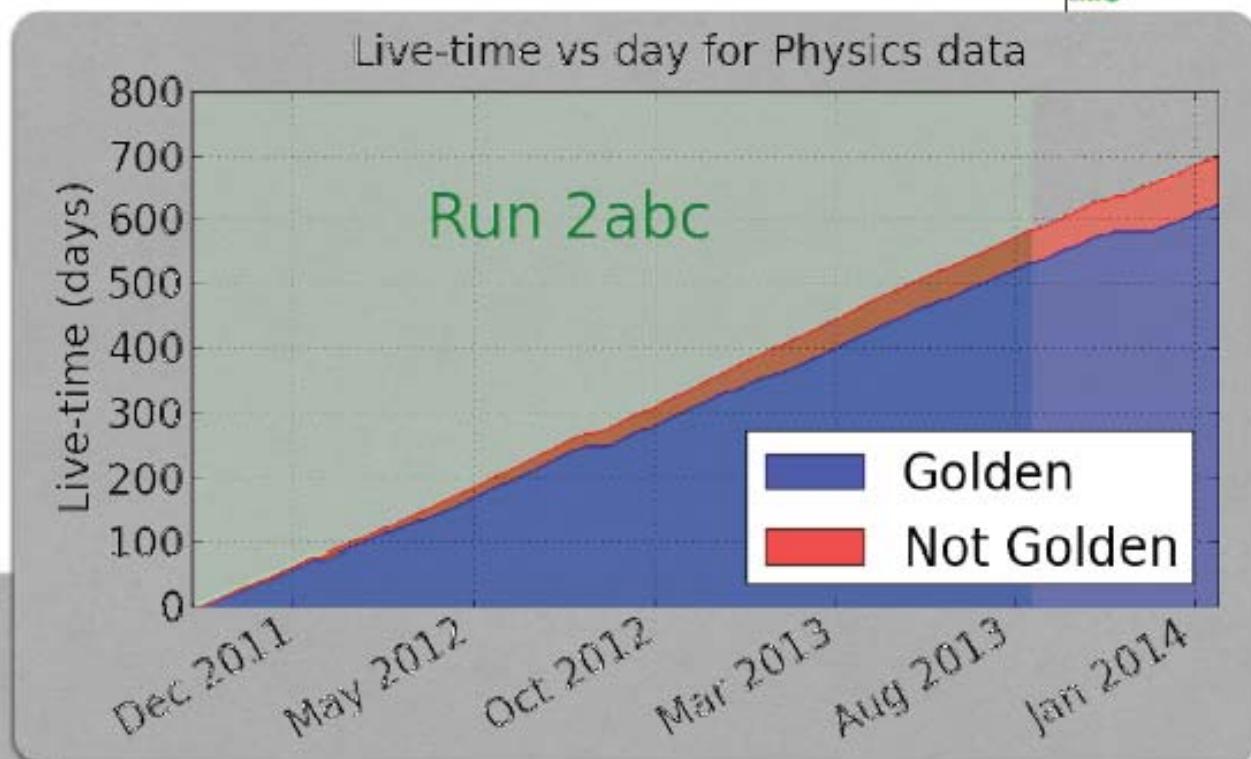
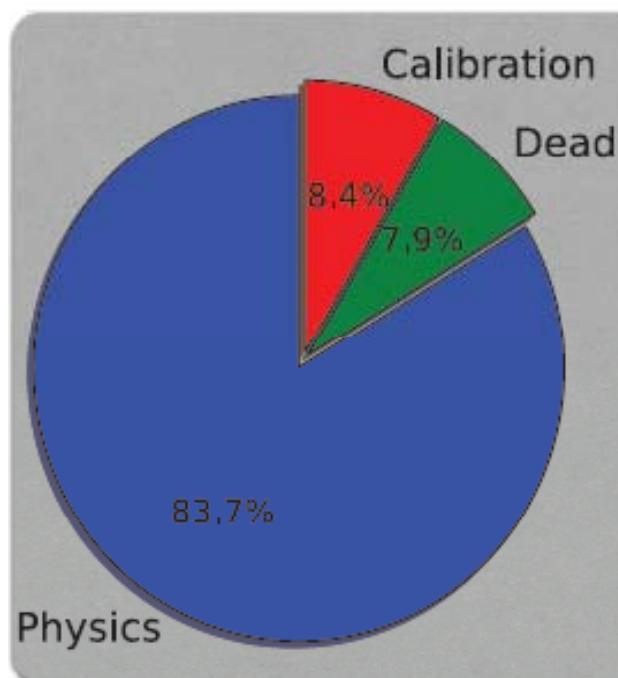
The principle:
**Simultaneous readout of
charge and scintillation in
a large and homogeneous
Liquid Xe TPC**



Recent results (Run 2)



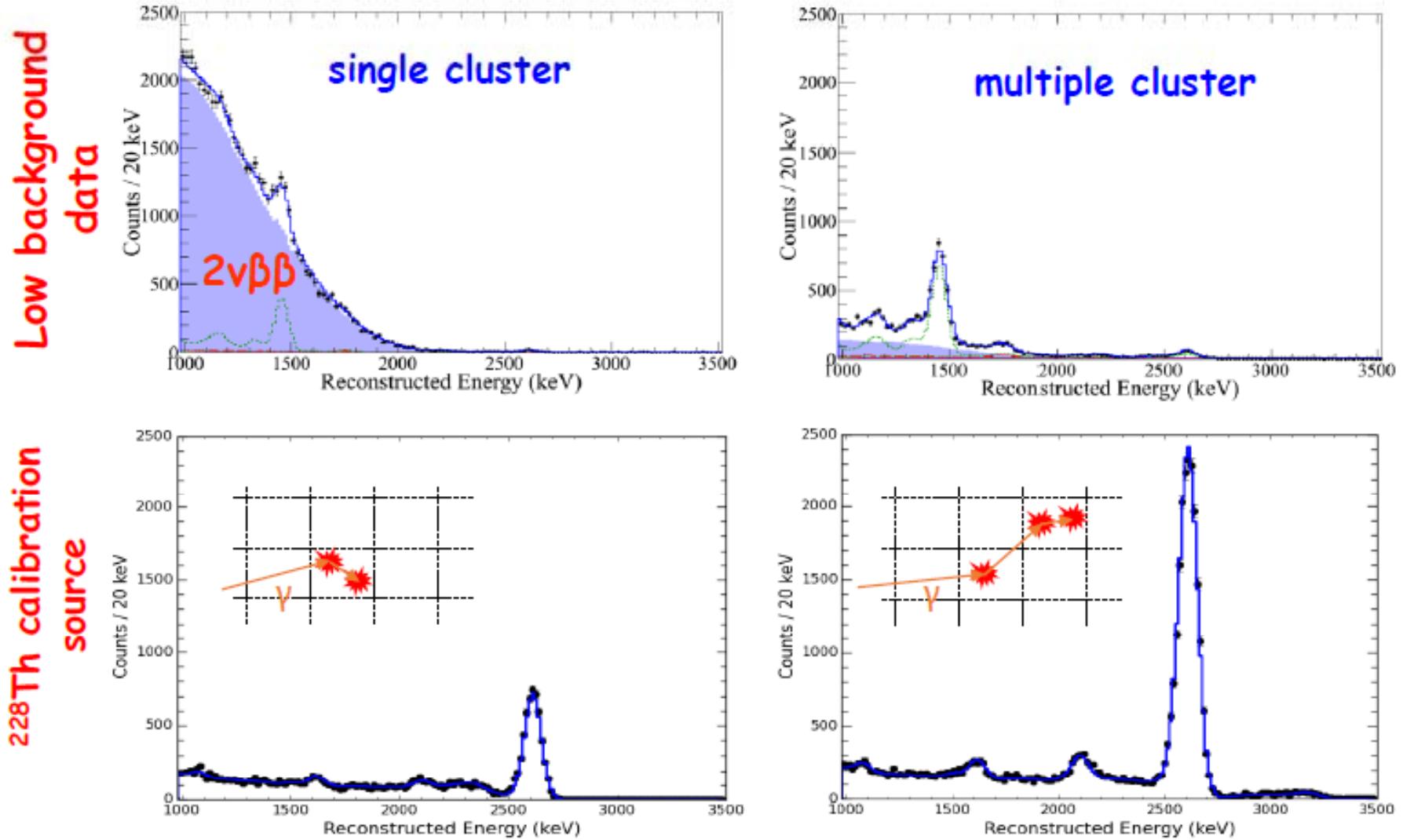
nature
(12 June 2014, online 4 June)
doi:10.1038/nature13432



Accumulation of “Golden” data
 447.60 ± 0.01 days livetime
($100 \text{ kg}\cdot\text{yr}$, $736 \text{ mol}\cdot\text{yr}$ ^{136}Xe
exposure)

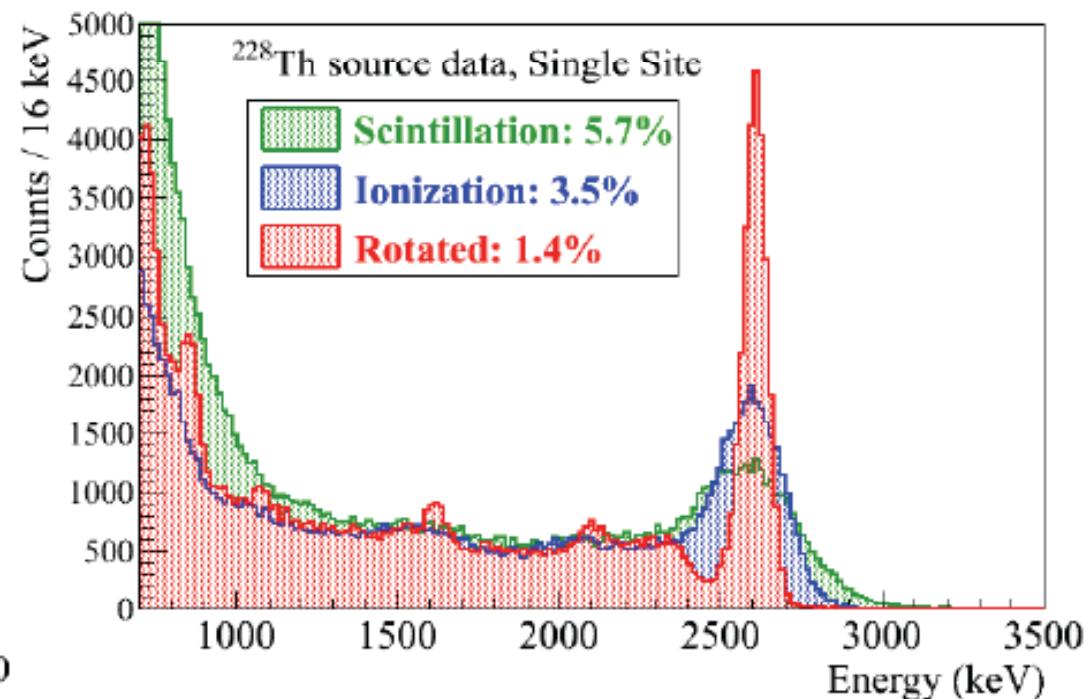
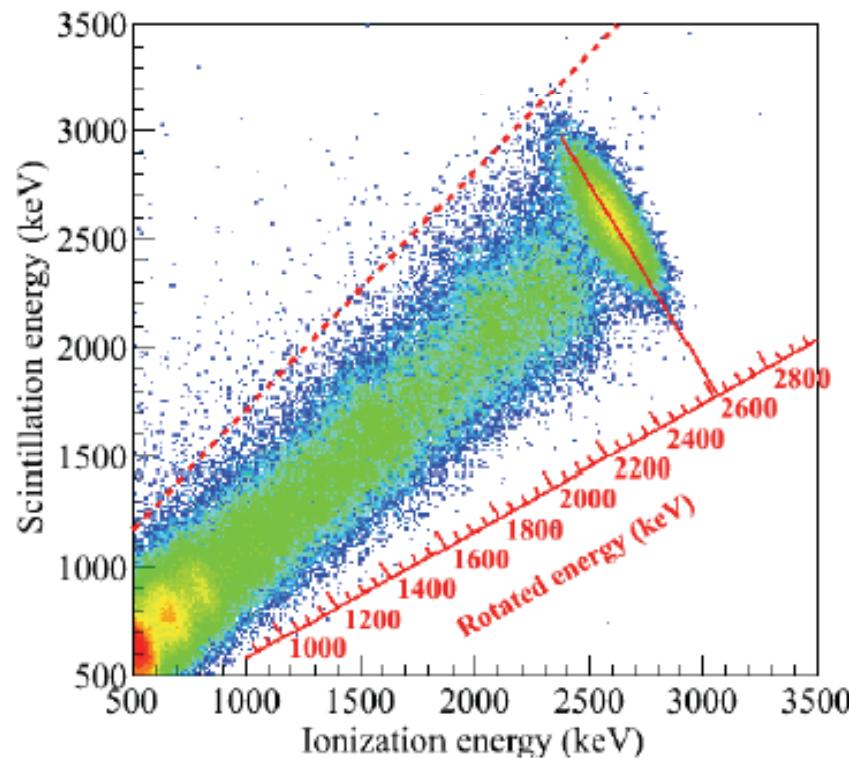
(6 Oct 2011- 1 Sep 2013)

Tracking: an essential tool to identify and suppress backgrounds



Energy measurement

Combination of charge and light

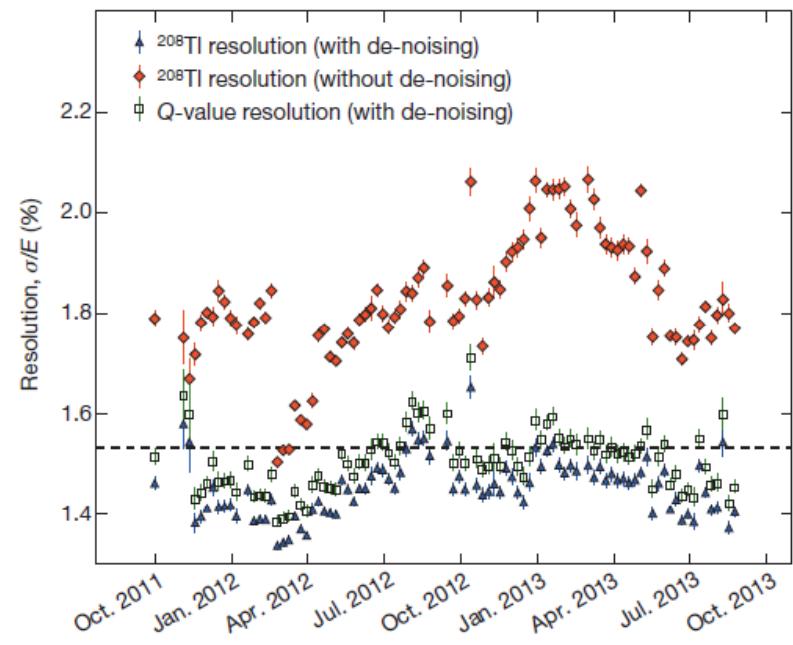
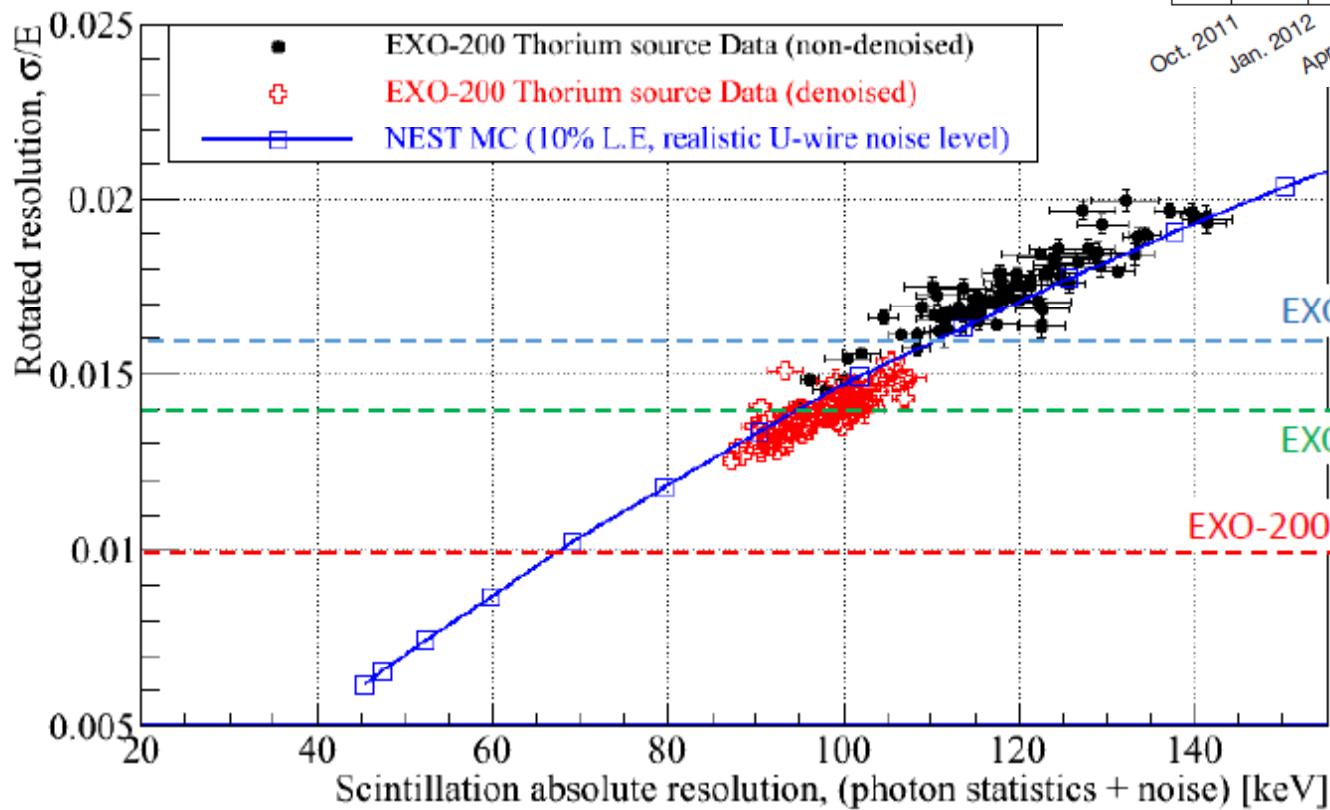


'Rotation angle' determined weekly using ^{228}Th source data, defined as angle which gives best 'rotated' resolution

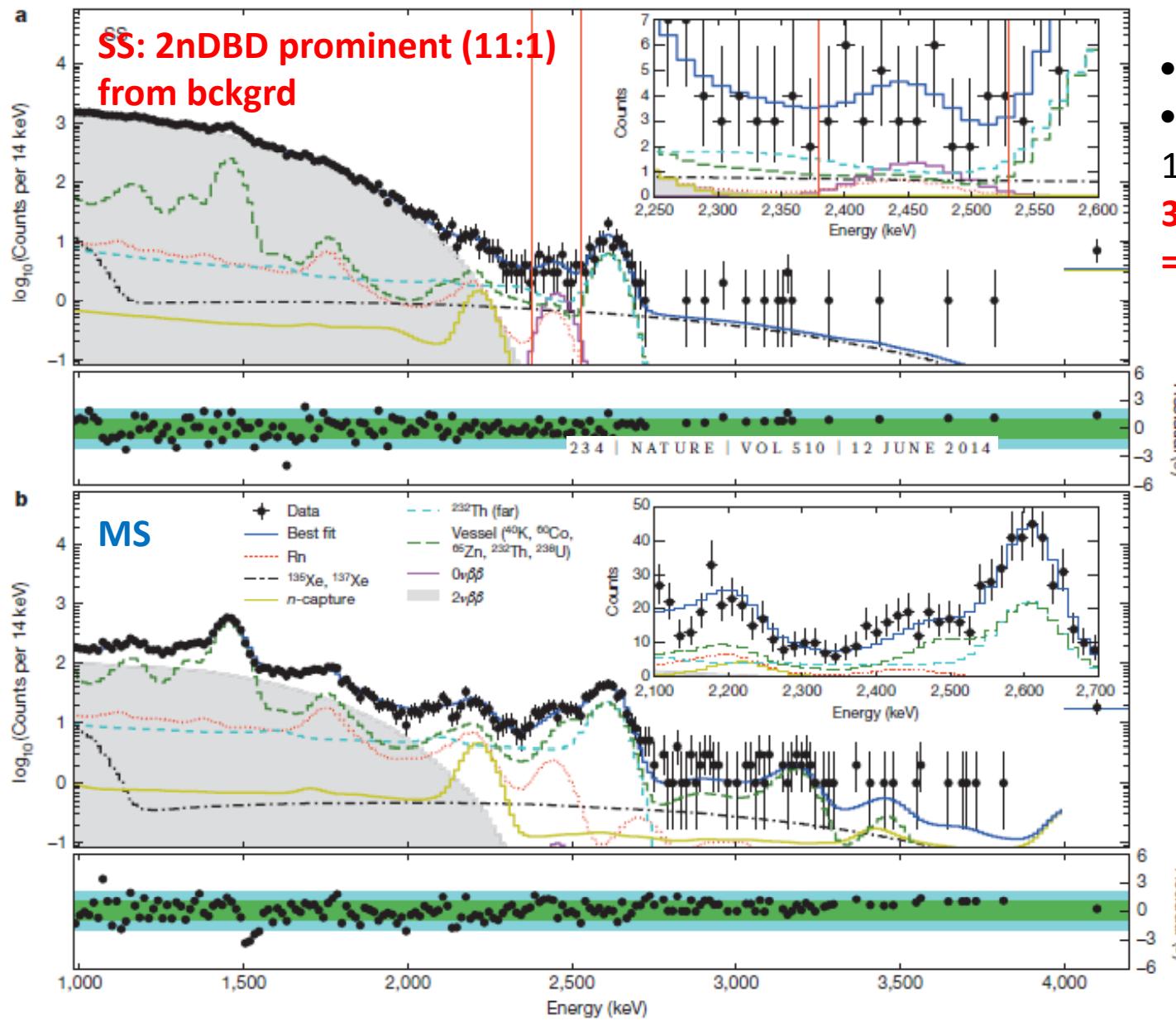
Energy resolution is dominated by APD noise (more on this later)

Significant IMPROVEMENTS in En. Res. by APD Denoising

EXO-200 and nEXO resolution



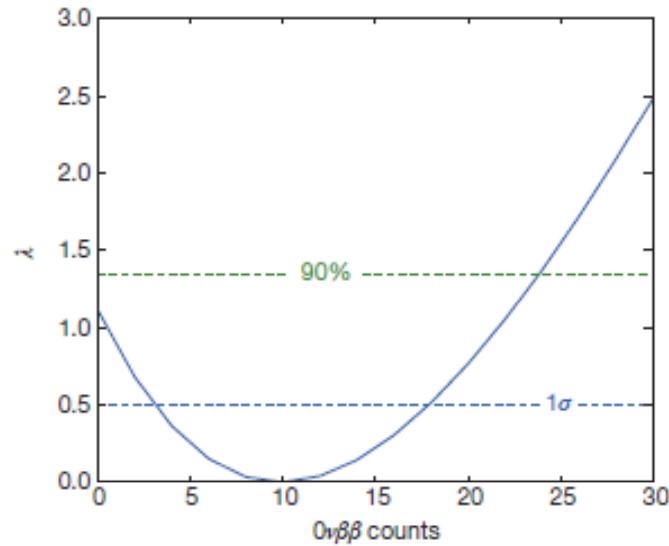
EXO Total Spectrum: 234 | NATURE | Vol 510 | 12 june 2014



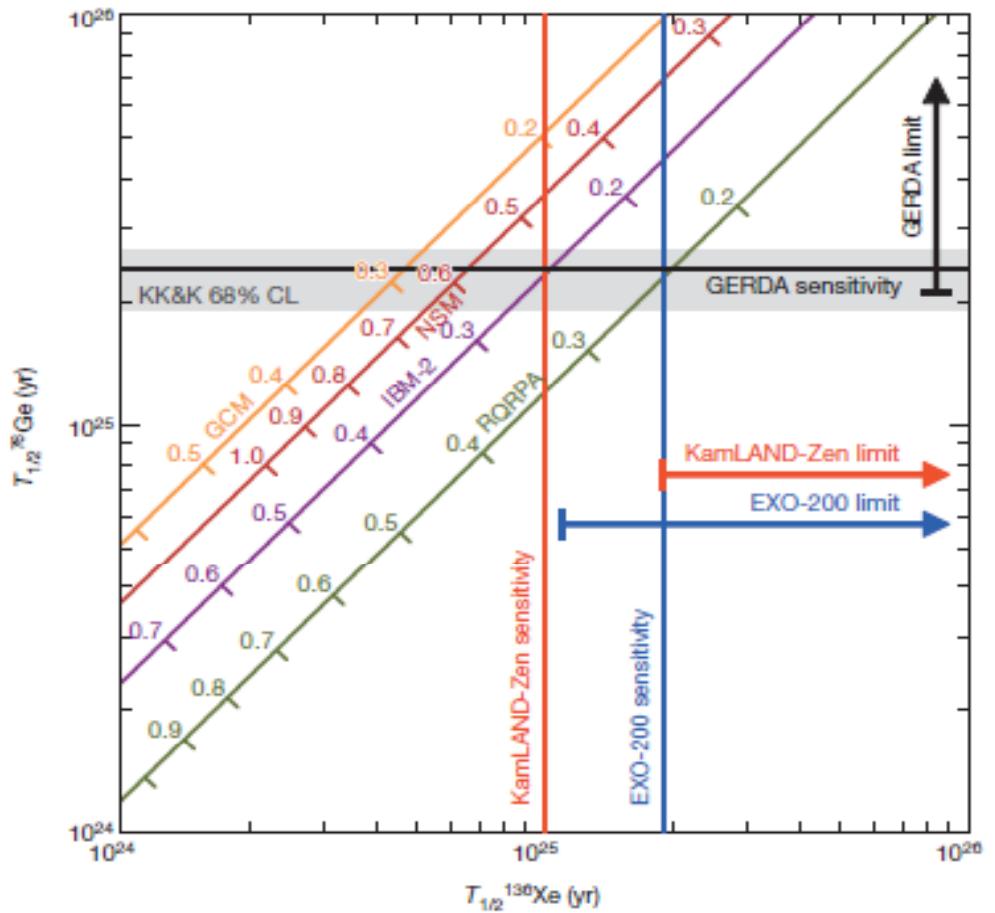
- Energy bins: 14 keV
 - Exposure (GOLDEN): 100. kgy
- 39 cts found in $\pm 2\sigma$ ROI**
 $= 2.5 \text{ E-2 cts/kky}$

	Cts
$2\nu\beta\beta$	0.017 ± 0.002
232Th	16
137Xe	7
238U	8.1
other	
Tot expected	$31.1 \pm 1.8 \text{ (stat)} + 3.3 \text{ (syst)}$

EXO results on $0\nu\beta\beta$: 234 | NATURE | Vol 510 | 12 june 2014



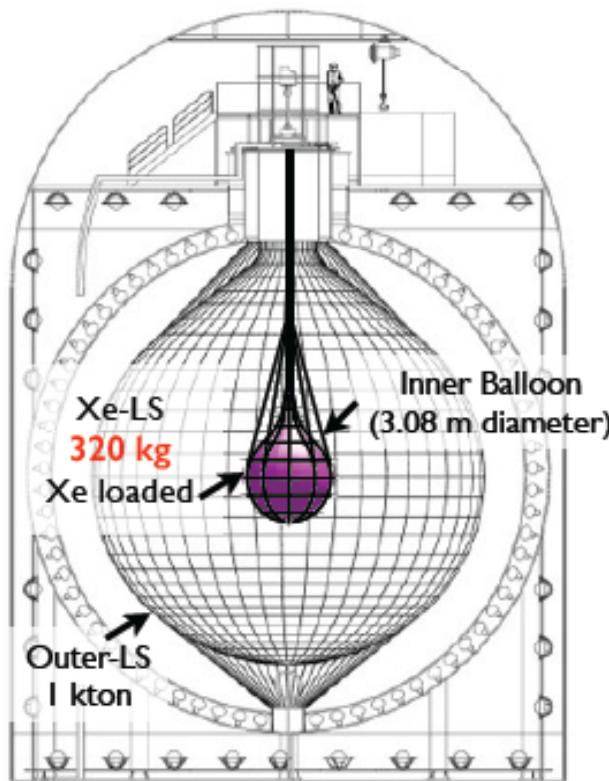
- From PL 9.9 cts → consistent at 1.2σ with null Hypothesys (bkgd only)
- $T_{0\nu}^{1/2} > 1.1 \times 10^{25} \text{ yr}$ @ 90% C.L.
- Sensitivity: $1.9 \times 10^{25} \text{ yr}$
- $190 \text{ meV} < m_{ee} < 450 \text{ meV}$



KamLAND-Zen

Kamioka Liquid Scintillator Anti-Neutrino Detector
Zero Neutrino Double Beta

KamLAND-Zen
Phase I



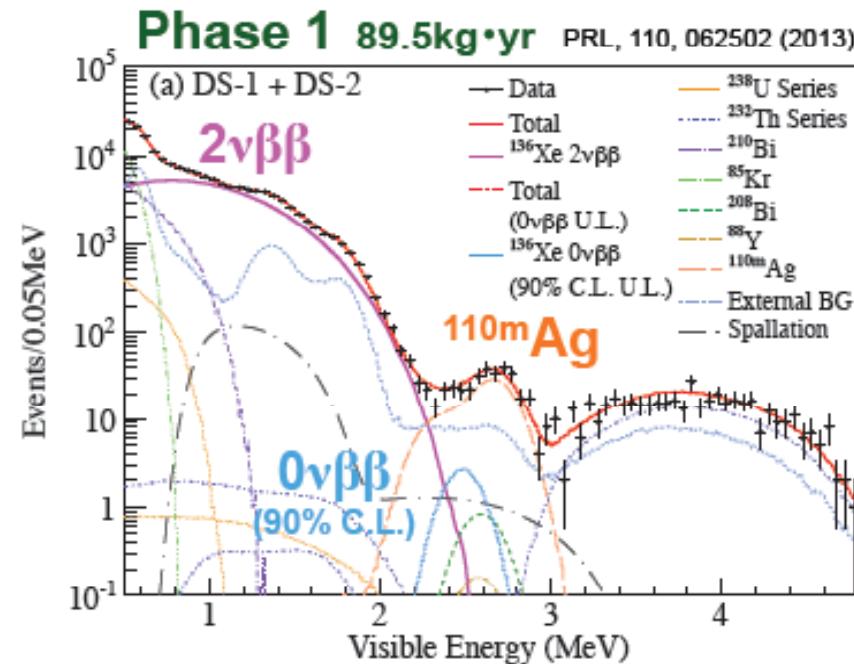
Xenon loaded LS (Xe-LS)	
decane	82%
pseudo-cumene	18%
PPO	2.7 g/liter
xenon	2.44 wt%

$$\sigma_E(2.5\text{MeV}) = 4\%$$

Advantage of KamLAND

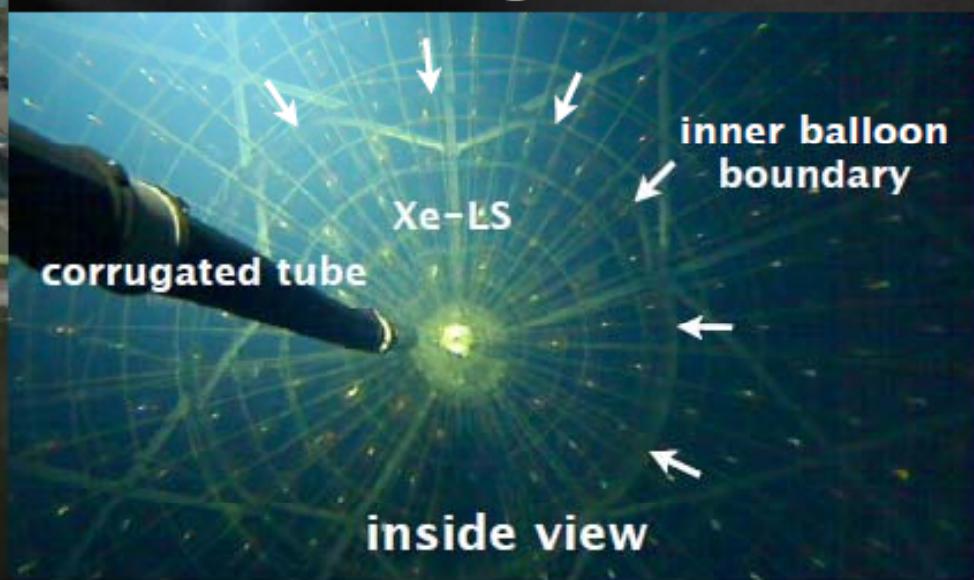
- running detector : start quickly with relatively low cost
 - big and pure : no BG from external gamma-rays
 - purification of LS, replacement of mini-balloon are possible
- **high scalability** (a few ton of Xe)

realize double beta-decay search with **low background**



$$T^{0\nu}_{1/2} > 1.9 \times 10^{25} \text{ yr (90\% C.L.)}$$

Construction in 2011



Improvement Efforts after Phase 1

1. Remove radioactive impurities by Xe-LS purification

candidates of ~2.6 MeV peak

→ only 4 nuclei ^{110m}Ag (250 d), ^{208}Bi (3.68×10^5 yr), ^{88}Y (107 d), ^{60}Co (5.27 yr)
lifetime longer than 30 days detected in Fukushima fallout

Two possible sources:

- (1) contamination by Fukushima-I reactor fallout
 - (2) cosmogenic Xe spallation while above ground

"primary" background source (^{110m}Ag)
can be removed by Xe-LS purification

2. Increase amount of Xenon

phase 1

phase 2

Xe concentration (2.44 ± 0.01) wt% → (2.96 ± 0.01) wt%

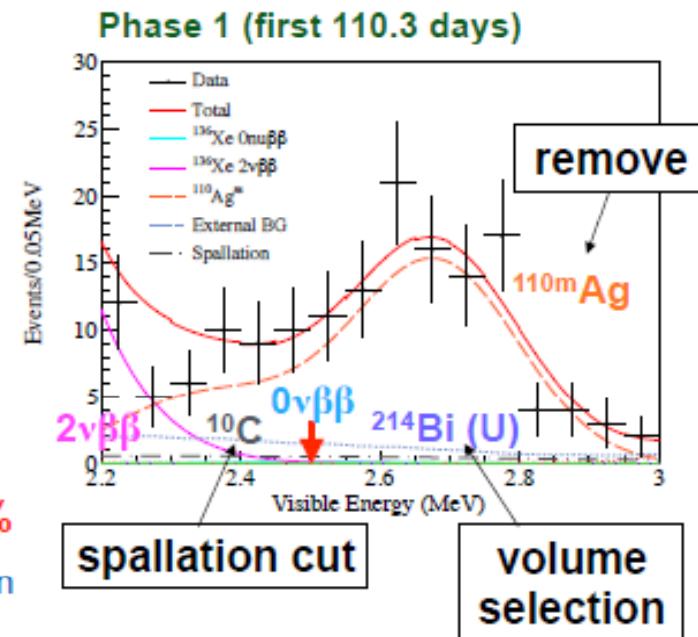
increase of S/N ~ 1.2 Xe-pressurized phase is a future option

3. Spallation cut after muon

muon-neutron- ^{10}C ($\tau = 27.8$ s) triple coincidence \rightarrow ^{10}C background rejection

4. Optimization of volume selection

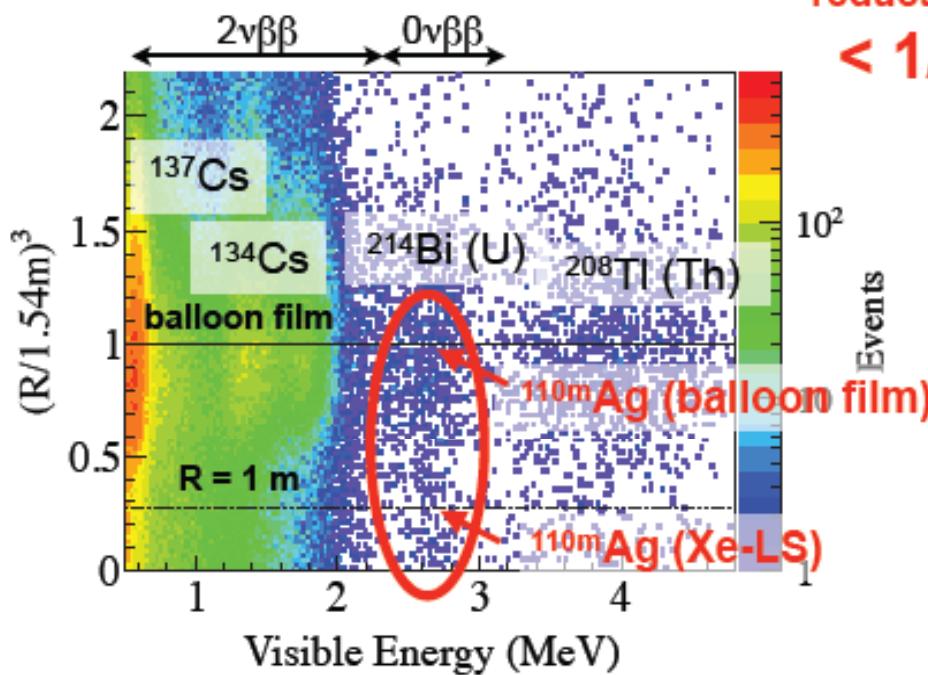
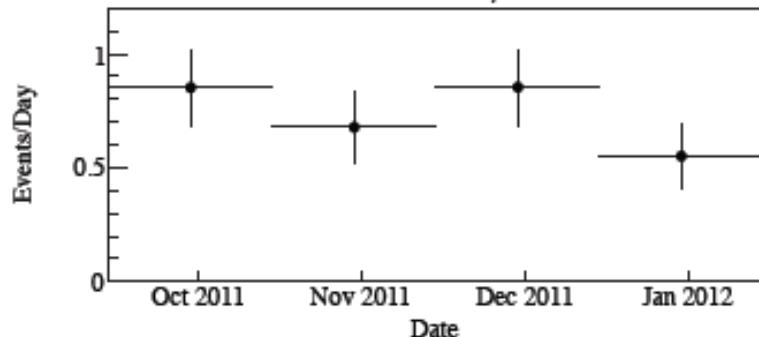
fiducial volume limitation by ^{214}Bi (U) on the balloon film → **multi-volume selection**



^{110m}Ag Background Reduction

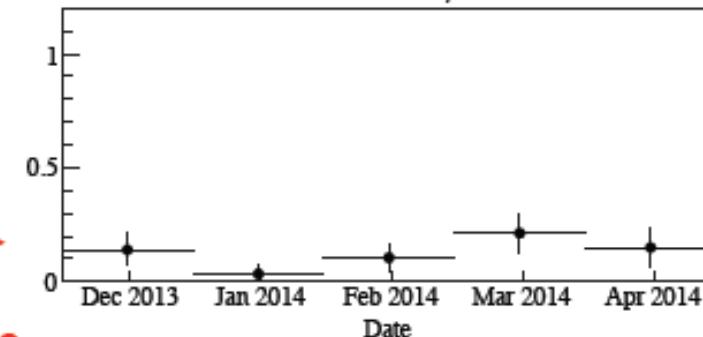
Phase 1 (first 112.3 days)

$2.2 < E < 3.0 \text{ MeV}, R < 1 \text{ m}$

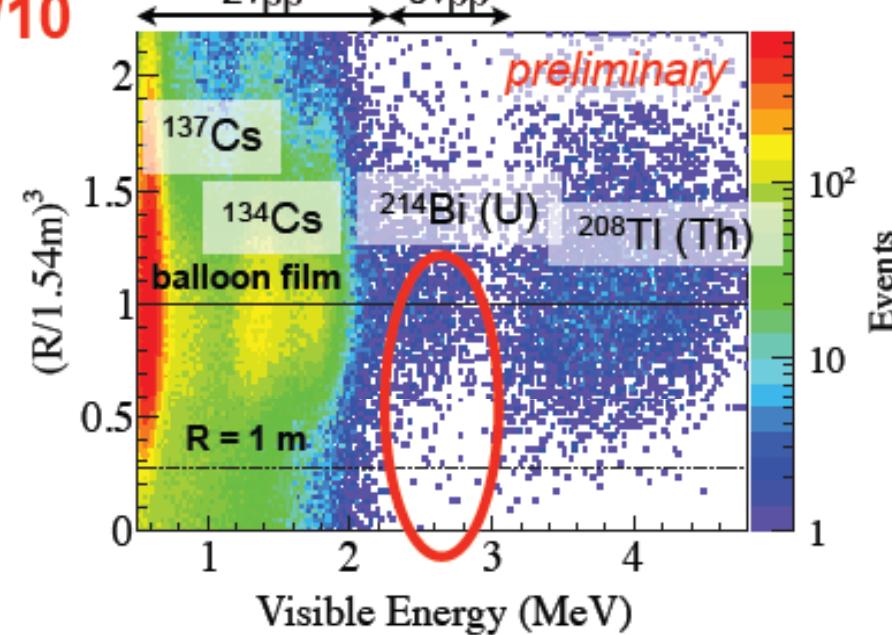


Phase 2 (first 114.8 days)

$2.2 < E < 3.0 \text{ MeV}, R < 1 \text{ m}$



^{110m}Ag BG reduction to
 $< 1/10$



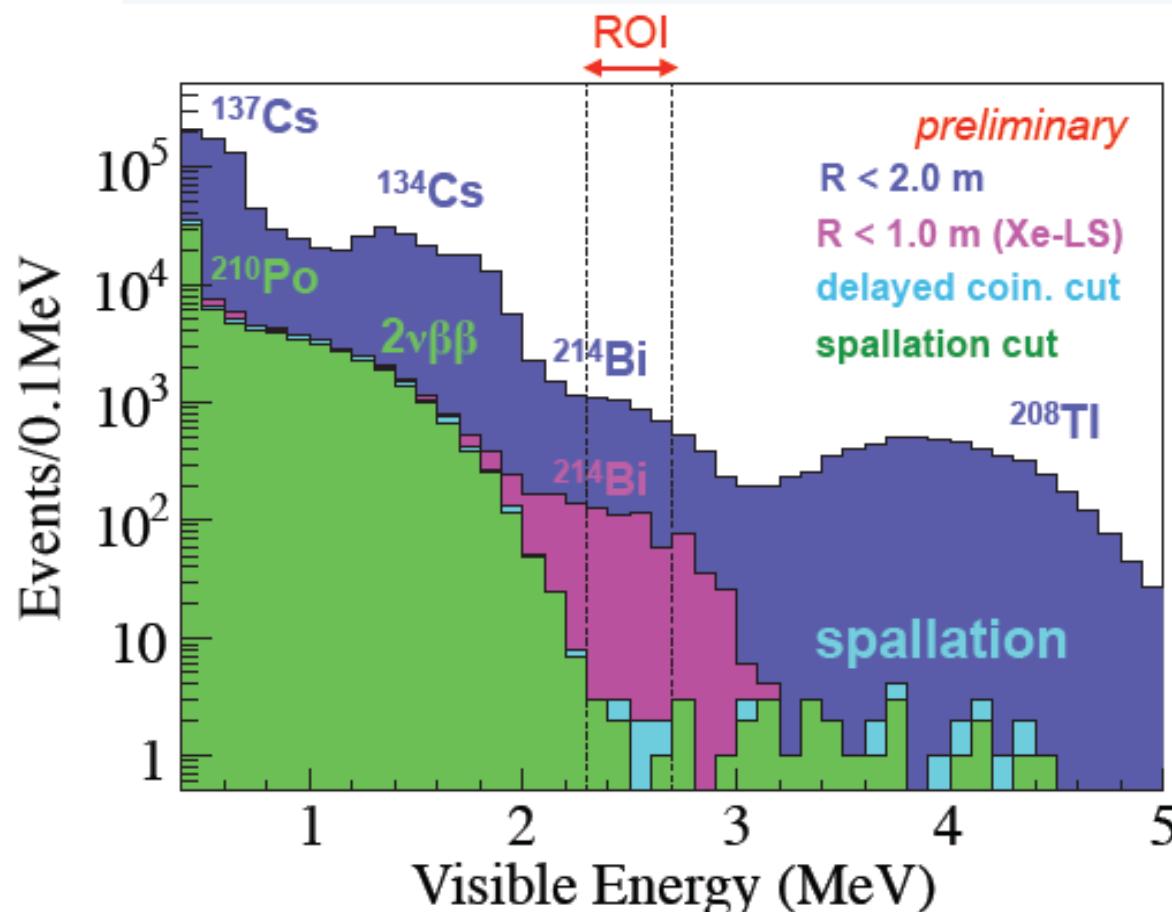
Primary BG : ^{214}Bi (U) at balloon / spallation ^{10}C / remaining ^{110m}Ag ?

Event Reduction

Phase 2 114.8 days

$\beta\beta$ isotope ^{136}Xe 90.77% enriched $Q_{\beta\beta} = 2458 \text{ keV}$

348 kg ^{136}Xe in all volume Dec. 11, 2013 - May 1, 2014



number of event
in ROI
($2.3 < E < 2.7 \text{ MeV}$)

Dec. 11, 2013 - May. 1, 2014

around mini-balloon
($R < 2.0 \text{ m}$)
&
muon veto

3756 events

volume cut
 $R < 1.0 \text{ m}$
($V = 4.2 \text{ m}^3$) **27% of whole balloon Vol**

413 events

delayed coincidence cut
($^{214}\text{Bi-Po}$, $^{212}\text{Bi-Po}$, anti- ν)

10 events

Spallation cut

6 events

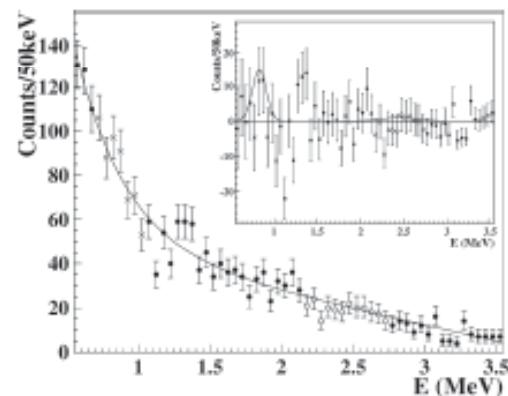
(Livetime 114.8 days)

Exposure: 29.6 kgy

Volume selection and spallation cut distinguish backgrounds

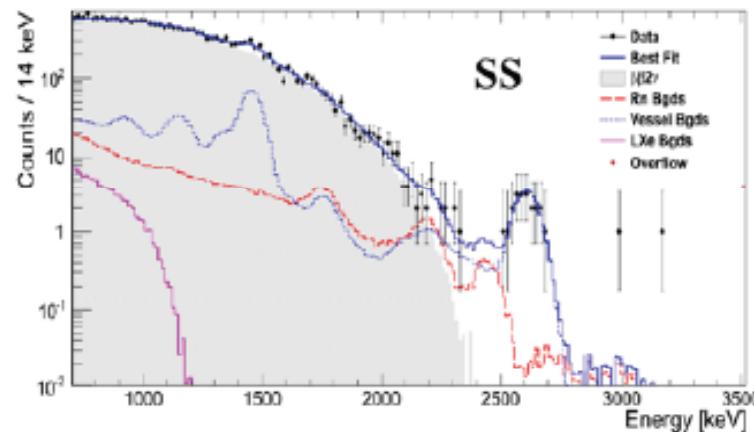
Fit to Energy Spectrum for $2\nu\beta\beta$

DAMA (2002) Liquid Xe scintillator



$T^{2\nu} \frac{1}{2} > 1.0 \times 10^{22} \text{ yr at 90\% C.L.}$

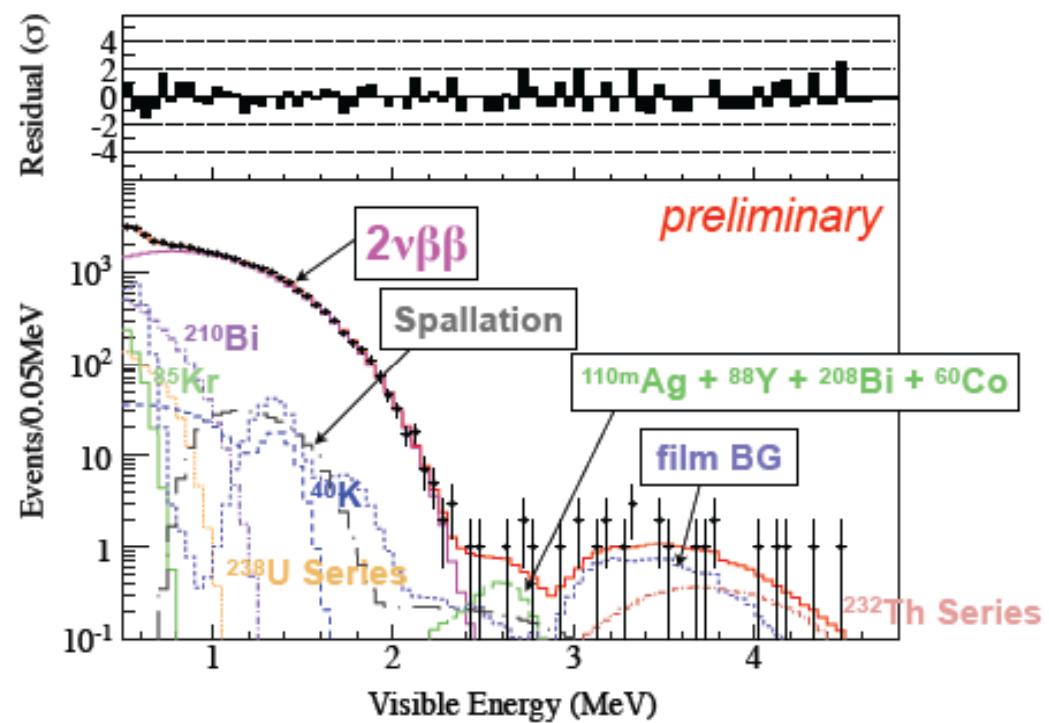
EXO-200 (2013) Liquid Xe TPC + scintillator



$T^{2\nu} \frac{1}{2} = 2.165 \pm 0.016(\text{stat}) \pm 0.059(\text{syst}) \times 10^{21} \text{ yr}$

KamLAND-Zen (2014) Xe loaded liquid scintillator

Phase 2 Internal ($R < 1.0 \text{ m}$)



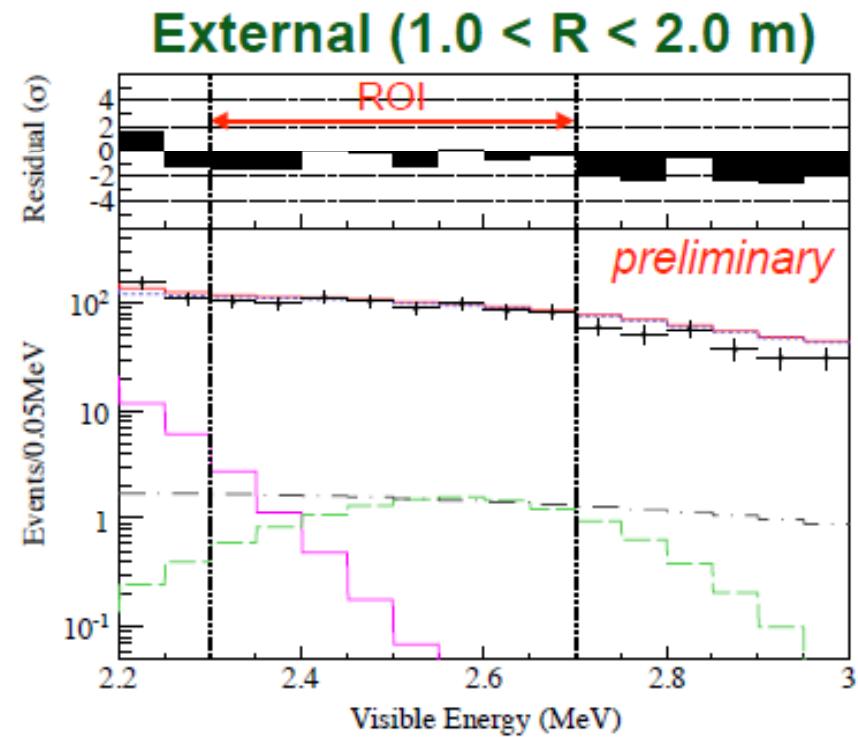
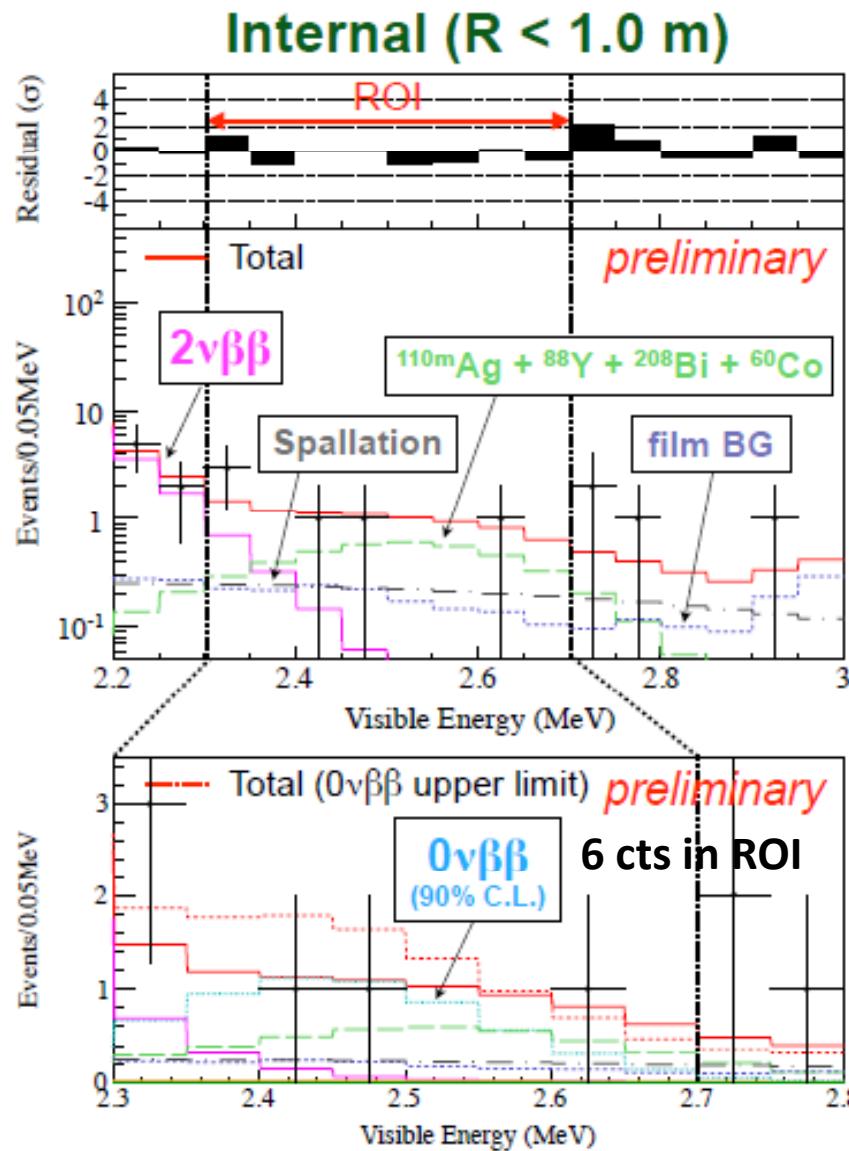
$T^{2\nu} \frac{1}{2} = 2.32 \pm 0.05(\text{stat}) \pm 0.08(\text{syst}) \times 10^{21} \text{ yr}$

consistent with KamLAND-Zen Phase 1

\downarrow
 $T^{2\nu} \frac{1}{2} = 2.30 \pm 0.02(\text{stat}) \pm 0.12(\text{syst}) \times 10^{21} \text{ yr}$

← consistent with EXO-200

Fit to Energy Spectra for $0\nu\beta\beta$



Fit to Energy-Volume 2D spectra

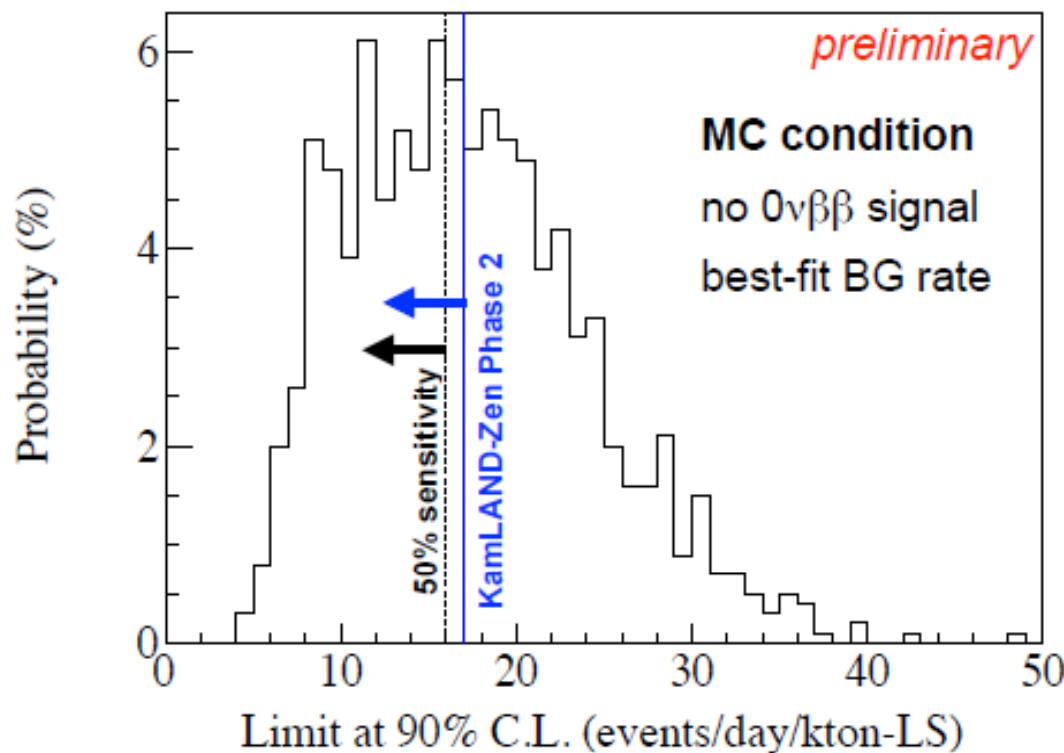
Limits on $0\nu\beta\beta$ at 90% C.L.

< 17.0 events/day/kton-LS

$T^{0\nu}_{1/2} > 1.3 \times 10^{25}$ yr

Upper Limits from Toy MC

distribution of $0\nu\beta\beta$ limits from Toy MC



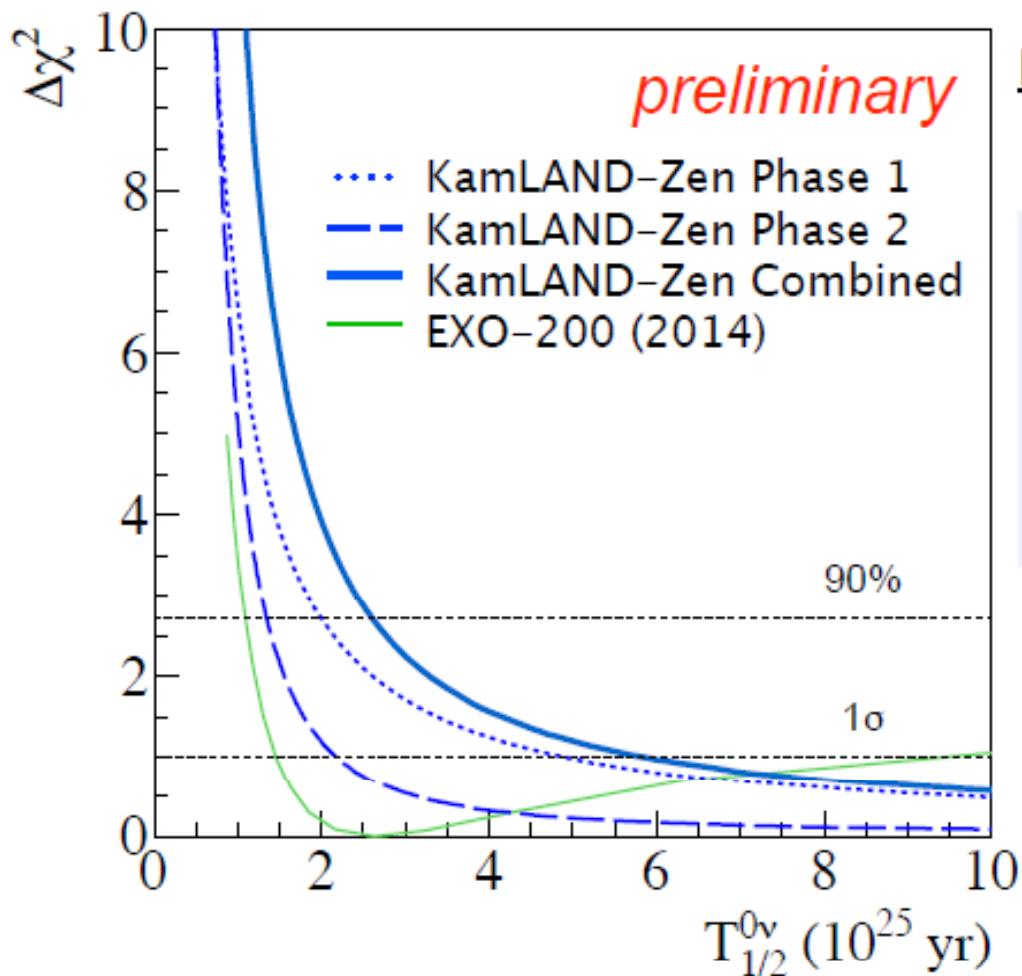
< 17 events/day/kton-LS 52% of the time

< 16 events/day/kton-LS 50% of the time

Sensitivity is checked by MC assuming best-fit BG rate

^{136}Xe $0\nu\beta\beta$ Decay Half-life

combined result (Phase 1 + 2)



Half-life limit at 90% C.L.

KamLAND-Zen

Phase 1 $T^{0\nu}_{1/2} > 1.9 \times 10^{25} \text{ yr}$

Phase 2 $T^{0\nu}_{1/2} > 1.3 \times 10^{25} \text{ yr}$

Combined $T^{0\nu}_{1/2} > 2.6 \times 10^{25} \text{ yr}$

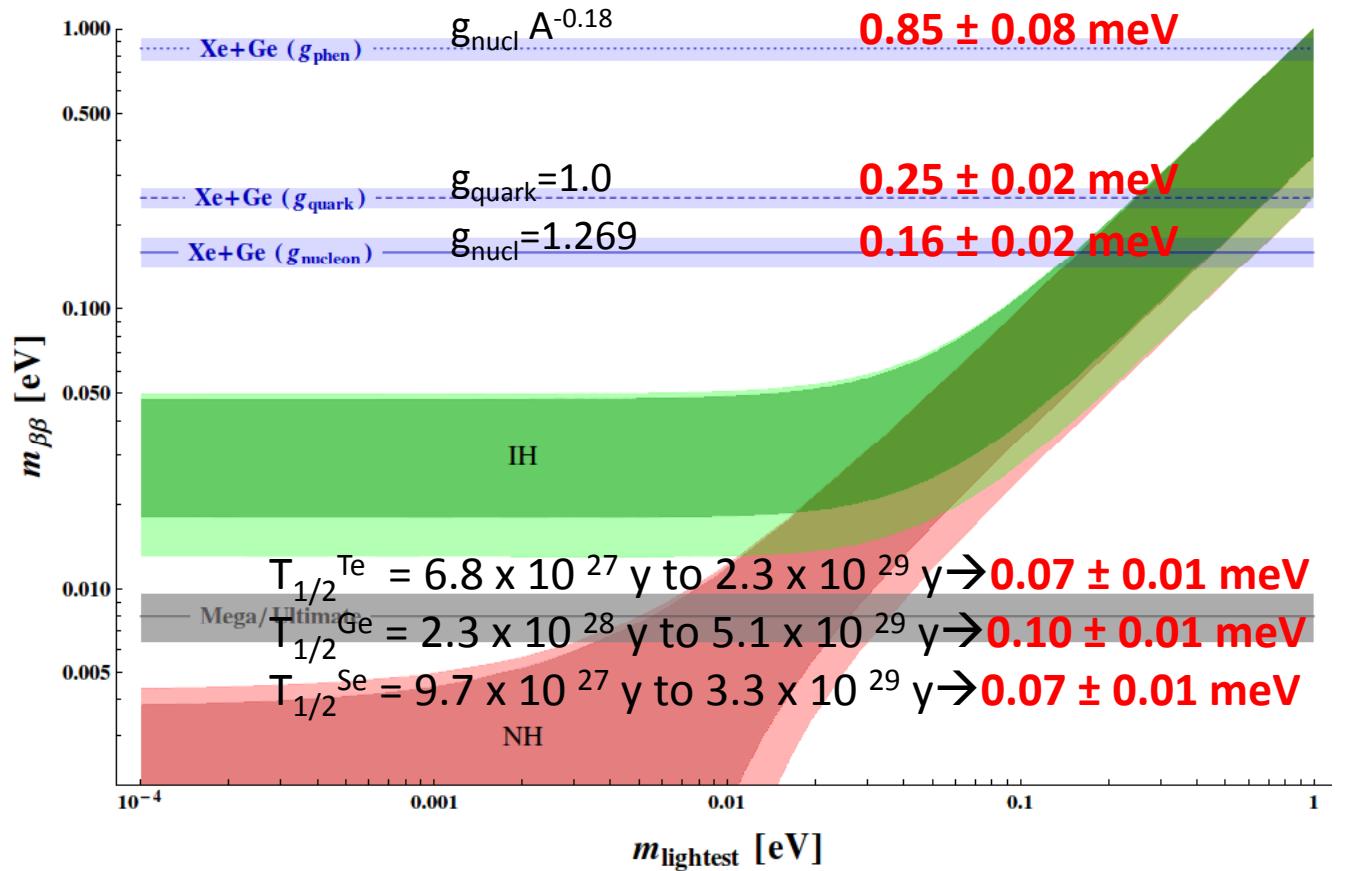
QRPA NME model
J. Phys. G 39 124006 (2012)

$\langle m_{\beta\beta} \rangle < 0.14\text{--}0.28 \text{ eV}$

Limits on ^{136}Xe half-life and effective neutrino mass are improved

Conclusion on Ge+Xe

- Present Sensitivity on m_{ee} according to the Ge+Xe combined limit for
 - different quenching scenarios for g_A)
 - NME from QRPA. No error on relative ratio of $\text{NME}_{\text{Xe}}/\text{NME}_{\text{Ge}}$
- Bands from phase space & NME uncertainties



From Dell'Oro, Marcocci, Vissani, hep-ph/1404.2616v1

Status of experimental searches

Isotope	$T^{2\nu} \frac{1}{2}$ (10^{19} y)	$T^{0\nu} \frac{1}{2}$ (10^{24} y)	$\langle m_{\beta\beta} \rangle$ (meV)
^{48}Ca	$4.4 \pm 0.5(\text{stat}) \pm 0.4(\text{syst})$	>0.058	3515-14133
^{76}Ge	$1.78^{+0.07}_{-0.09}$	$22.3^{+4.4}_{-3.1}$	400
^{76}Ge	$184 \pm 90 \text{ (stat)} \pm 11 \text{ (syst)}$	>21.0 > 30 GERDA&IGEX&HdM	201-638
^{82}Se	$9.6 \pm 0.1(\text{stat}) \pm 1.0(\text{syst})$	>0.32	884-2631
^{96}Zr	$2.35 \pm 0.14 \text{ (stat)} \pm 0.16 \text{ (syst)}$	>0.0092	4207-15139
^{100}Mo	$0.716 \pm 0.001 \text{ (stat)} \pm 0.054 \text{ (syst)}$	> 1.0	334-946
^{116}Cd	$2.88 \pm 0.04 \text{ (stat)} \pm 0.16 \text{ (syst)}$	> 0.17	1300-2440
^{130}Te	$70 \pm 9 \pm (\text{stat}) 11 \text{ (syst)}$	> 2.8	296 – 773
^{136}Xe	$217.2 \pm 1.7 \text{ (stat)} \pm 6 \text{ (syst)}$	>26	140-280
^{150}Nd	$0.911 \pm 0.025 \text{ (stat)} \pm 0.063 \text{ (syst)}$	> 0.018	2622-5678



^{130}Te $\beta\beta0\nu$ search with TeO_2 bolometers

MiDBD
1.8 kg ^{130}Te



1997-2001

$\tau_{1/2}^{0\nu} > 2.1 \times 10^{23} \text{ y}$ [1]
(90% C.L.)

Cuoricino
11.3 kg ^{130}Te



2003-2009

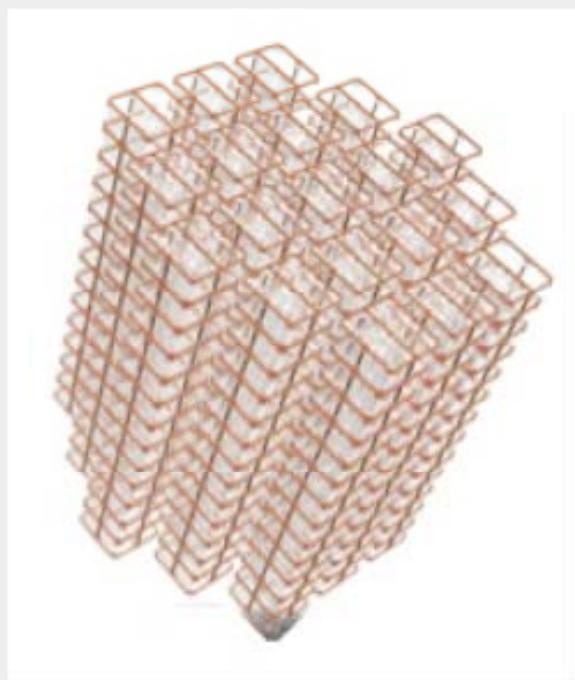
$\tau_{1/2}^{0\nu} > 2.8 \times 10^{24} \text{ y}$ [2]
(90% C.L.)

CUORE-0
10.9 kg ^{130}Te



2013...2015

CUORE
 $\sim 206 \text{ kg } ^{130}\text{Te}$



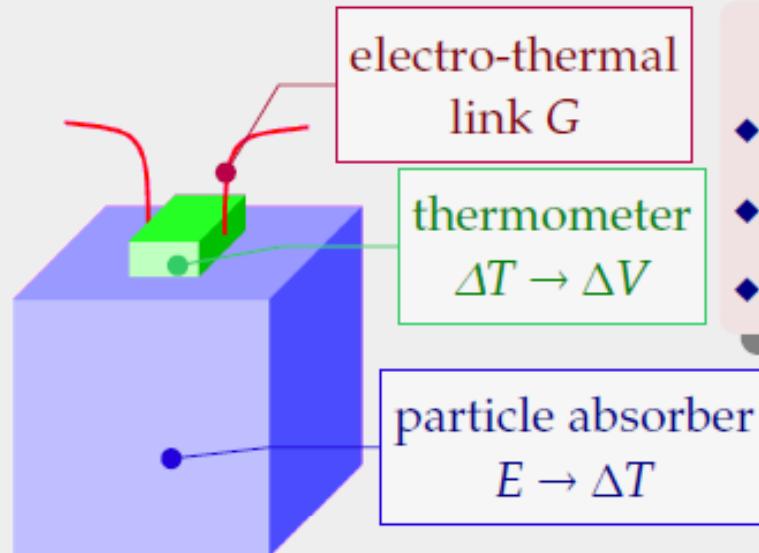
2015...

[1] C. Arnaboldi et al., Phys. Lett. B557 (2003) 167

[2] E. Andreotti et al., Astrop. Phys. 34 (2011) 822



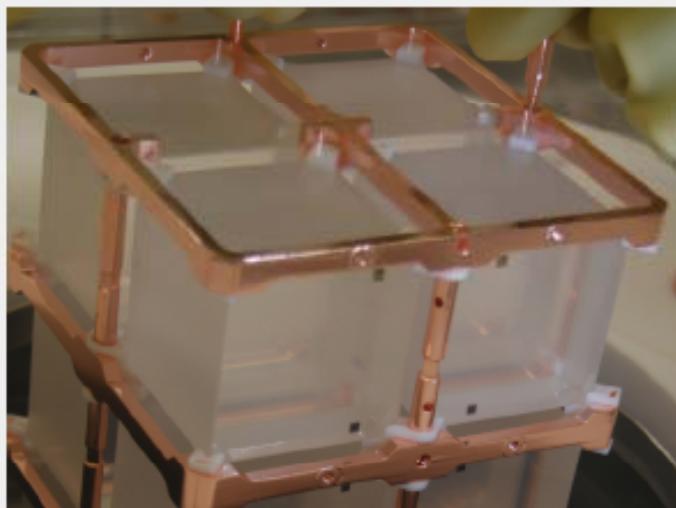
TeO₂ cryogenic detectors or bolometers



electro-thermal
link G

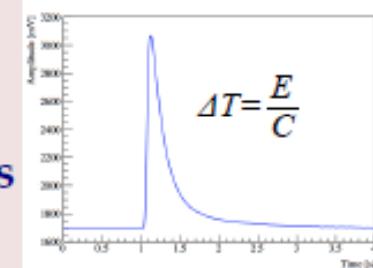
thermometer
 $\Delta T \rightarrow \Delta V$

particle absorber
 $E \rightarrow \Delta T$



Properties of bolometers

- ◆ high energy resolution: $(k_B C T^2)^{1/2}$
- ◆ large choice of absorber materials
- ◆ true calorimeters



TeO₂ Absorbers

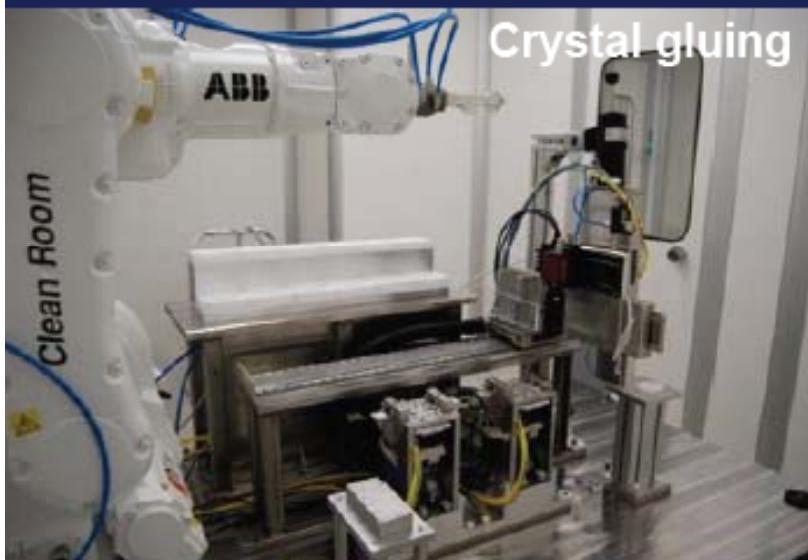
- ◆ low specific heat
- ◆ large crystals available
- ◆ radiopure
- ◆ 5×5×5 cm³ crystals have high detection efficiency for ββ0ν events: ~87%

$T \sim 10 \text{ mK}$
 $\Delta T / \Delta E \sim 0.1 \text{ mK/MeV}$
 $\Delta V / \Delta E \sim 0.3 \text{ mV/MeV}$
 $\tau = C/G \sim 1 \text{ s}$
 $C \sim 2 \times 10^{-9} \text{ J/K}$

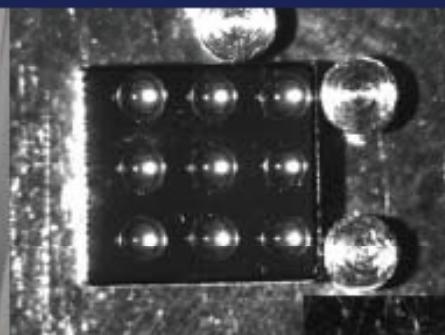
¹³⁰Te as ββ0ν candidate

- * high natural isotopic abundance: 34.2 %
- * transition energy: $Q = 2528 \text{ keV}$
- * encouraging nuclear matrix element calculations

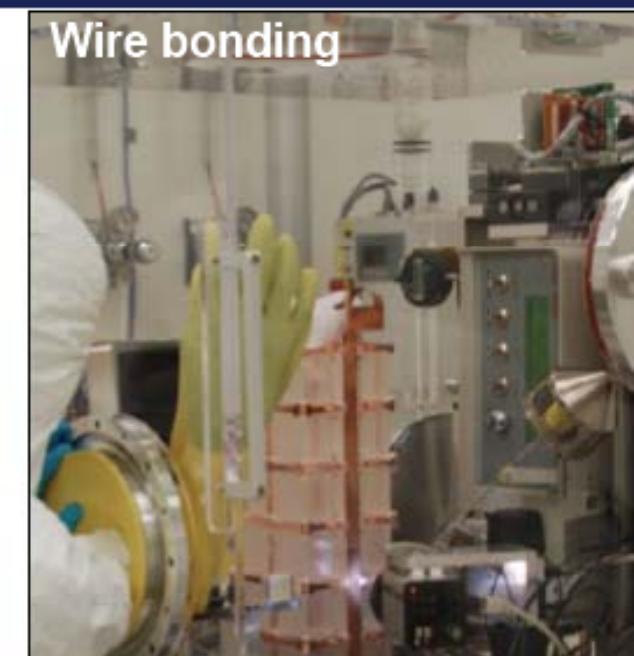
Tower assembly



Crystal gluing



Wire bonding



Mechanical assembly

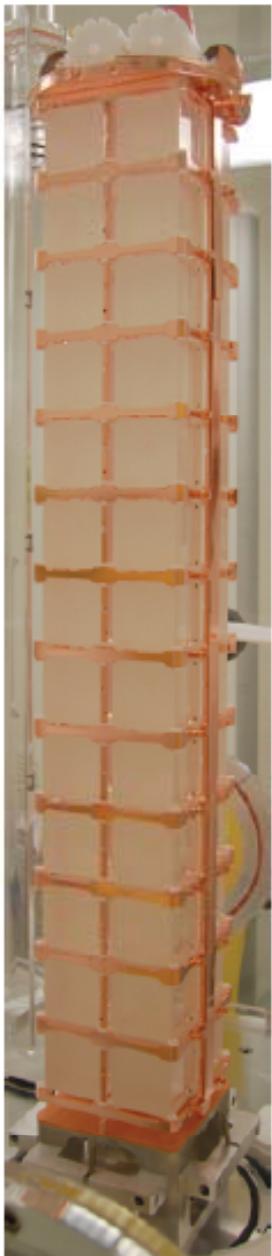


Cabling



Clean room

CUORE-0

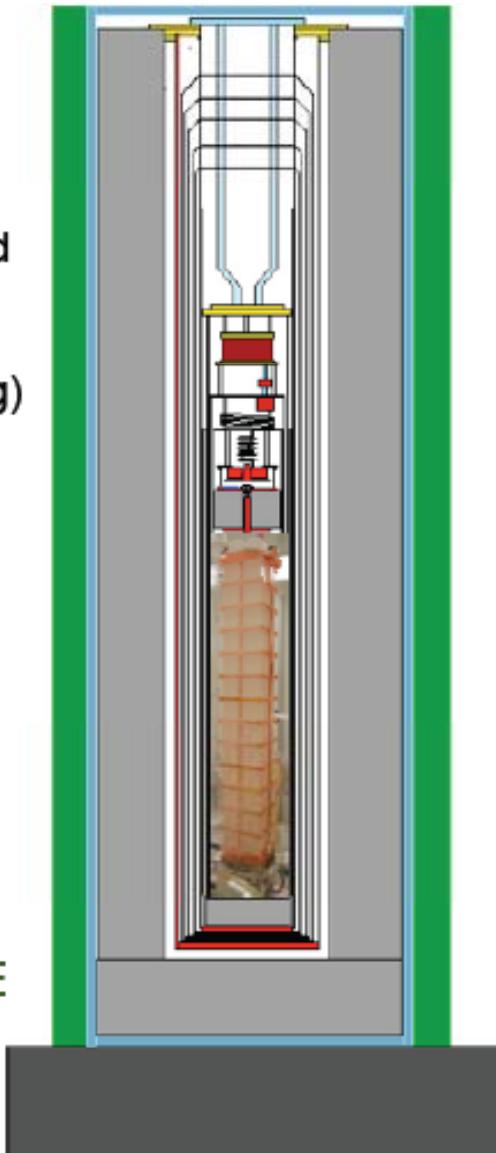


1 CUORE tower

- 52 TeO₂ 5x5x5 cm³ bolometers
- 13 floors of 4 crystals each
- total mass: 39 kg (11 kg of ¹³⁰Te)
- All detector components manufactured, cleaned and stored with same protocols defined for CUORE
- Assembled with the same procedures of CUORE:
 - dedicated class 1000 clean room (underground building)
 - all steps of the assembly (crystal gluing, mounting, cabling, bonding) performed under nitrogen inside special glove boxes.
- Operated inside the 25-year-old Cuoricino cryostat at LNGS.
- Low temperature roman lead shield

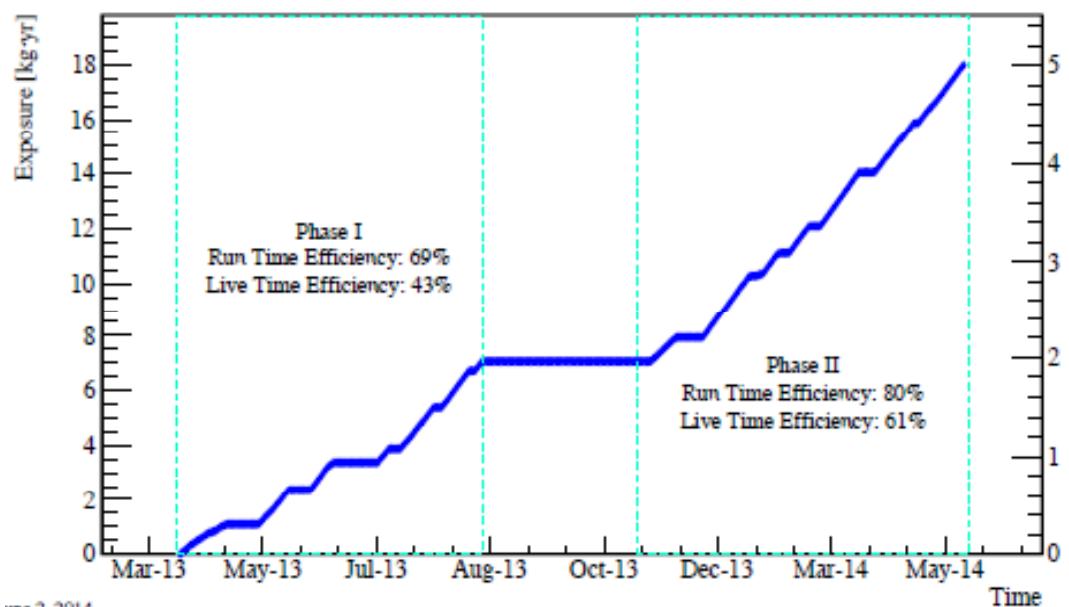
Goals:

- Proof of concept of CUORE detector in all stages
- Test and debug of the CUORE tower assembly line
- Test of the CUORE DAQ and analysis framework
- Operating as independent experiment while CUORE is under construction
- Demonstrate potential for DM detection

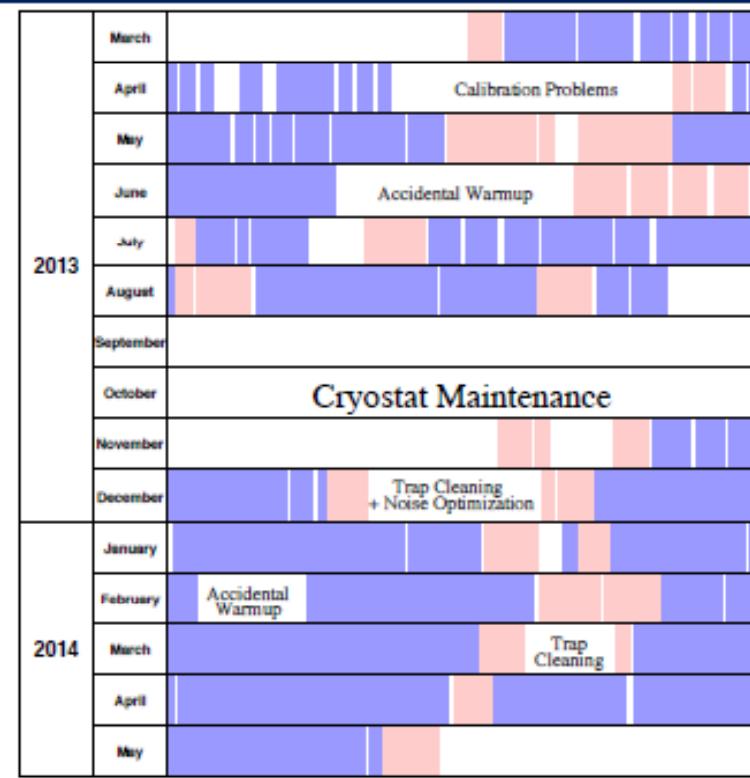


CUORE-0 data taking

- August 2012: base T reached
... problems with old Cuoricino cryostat
- March 2013: start data taking (Phase I)
- September 2013: first results are released (\rightarrow arXiv:1402.0922)
- October 2013: long maintenance stop
- November 2013: background data taking restarted (Phase II)
 \rightarrow improved conditions
 - Longer system lifetime (no warm-up required so far)
 - Better noise conditions
 - Improved energy resolution
 - Lower Threshold
 - Data analysis tools optimization
 - Stable background values

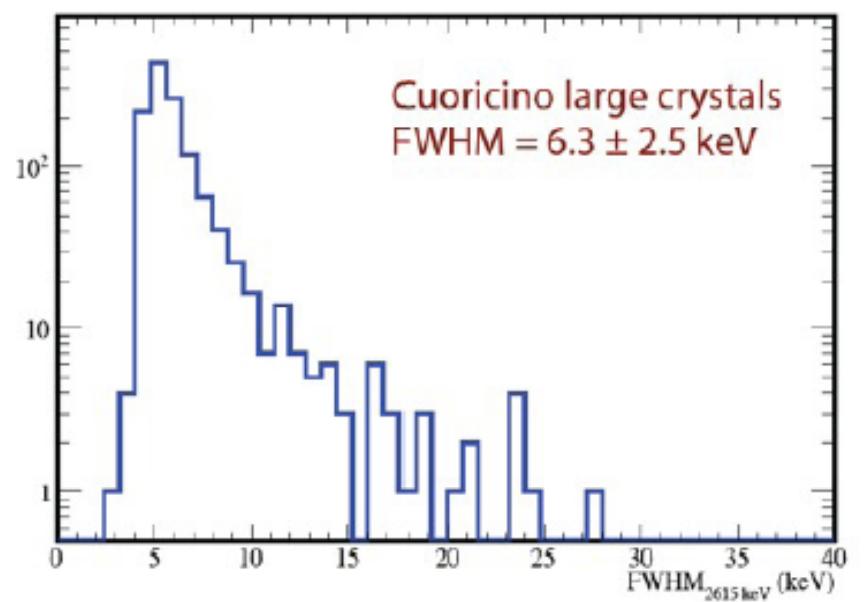
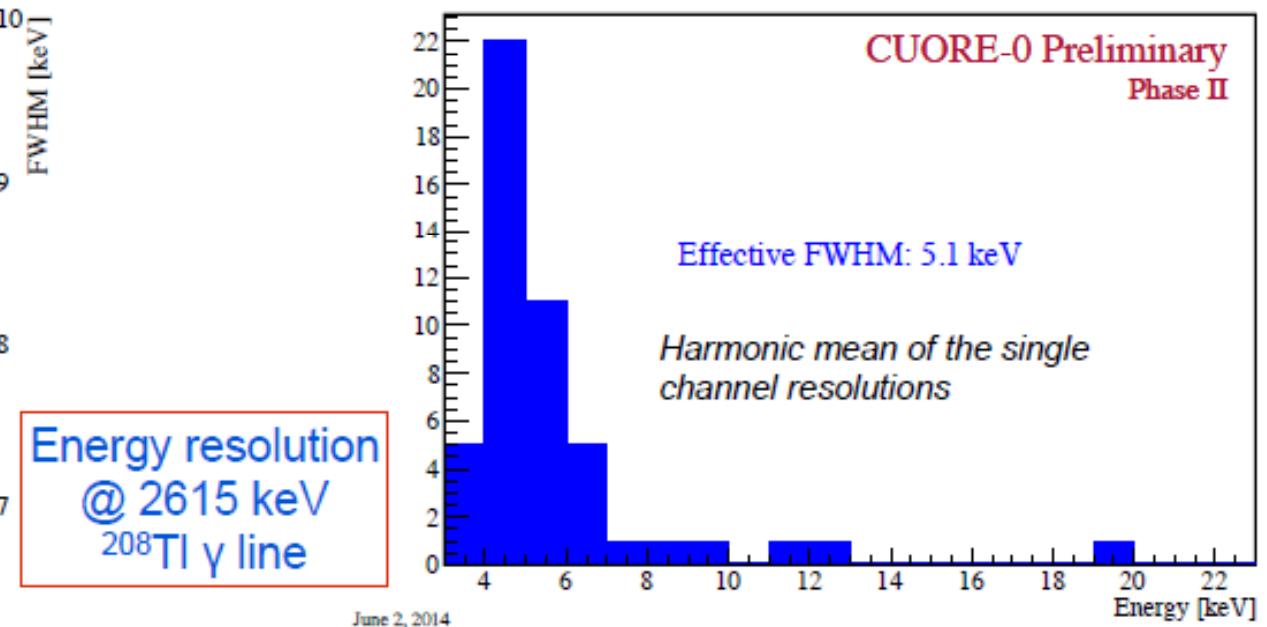
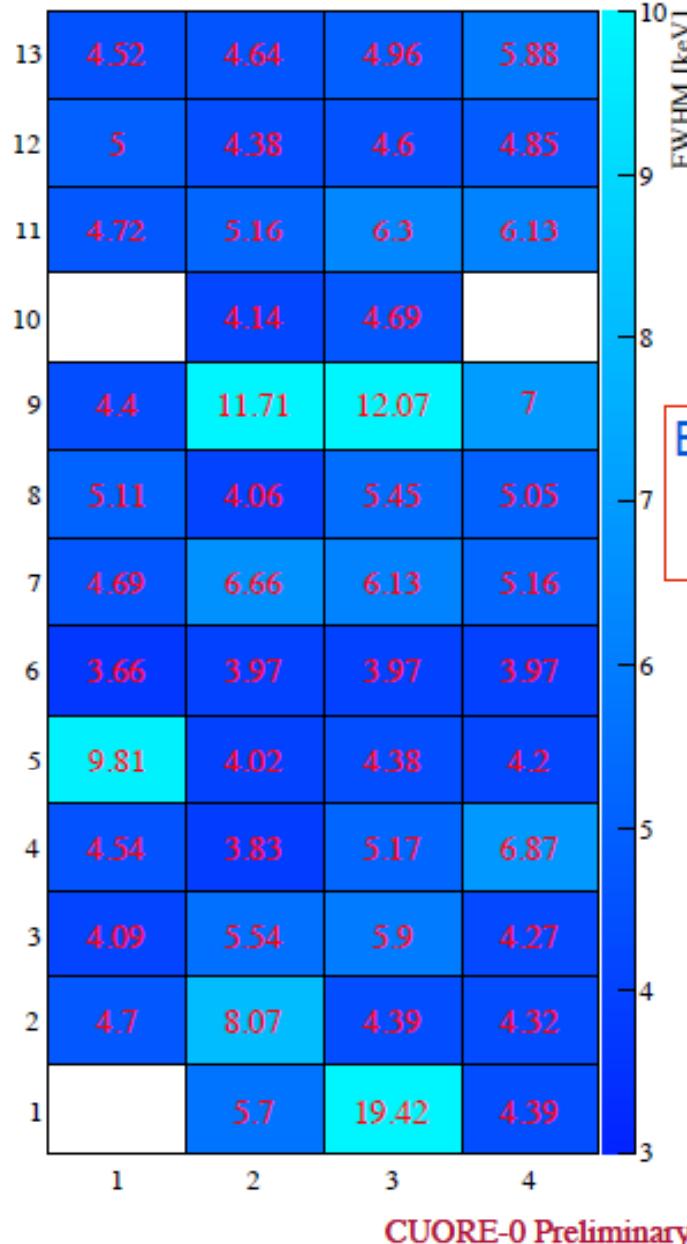


June 2, 2014

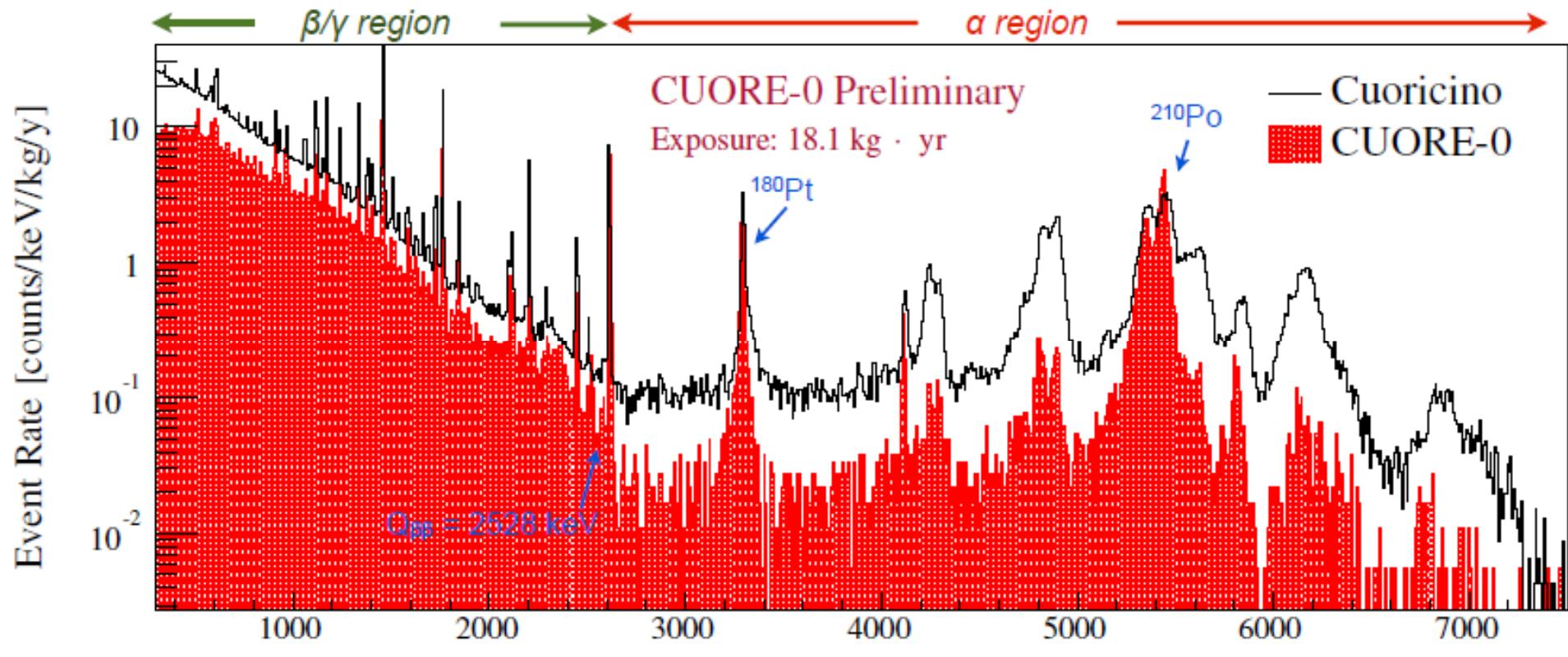


- Background measurements
- Calibration runs

CUORE-0 energy resolution: phase II



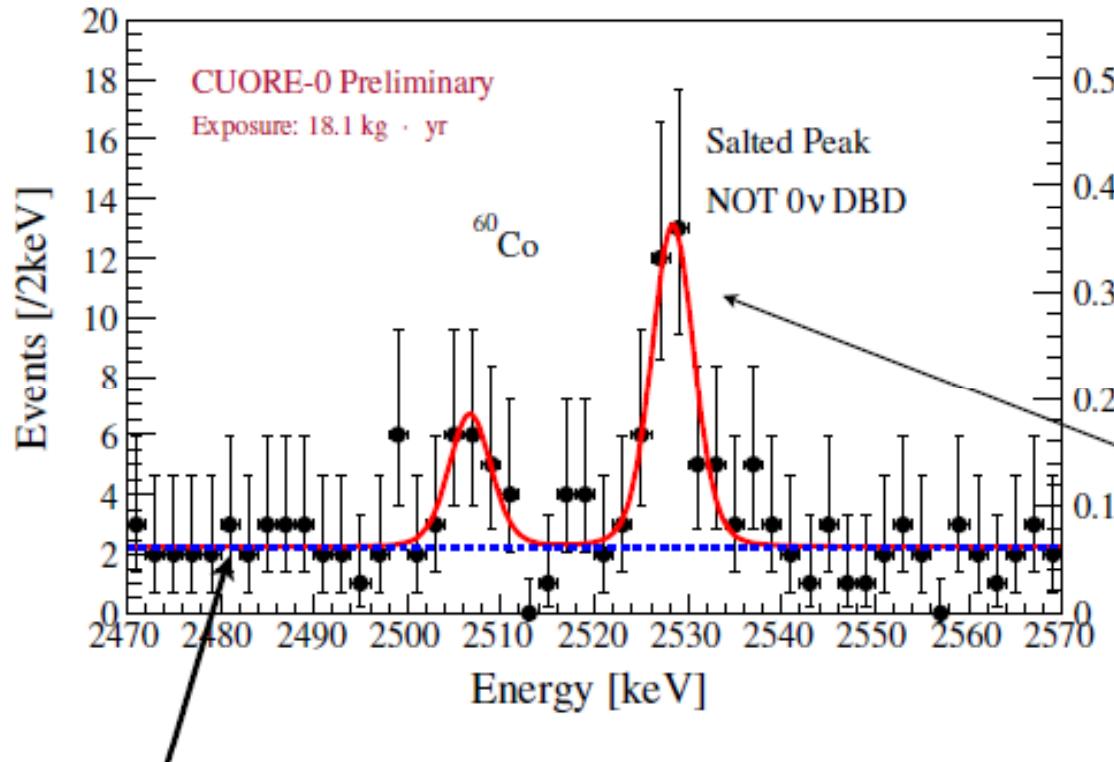
CUORE-0 background



- Cuoricino background model confirmed:
 - environmental gamma's from material bulk contaminations
 - surface radioactive contaminations of close materials
- Evident reduction with respect to Cuoricino
 - factor of 6 for surface contaminations
 - factor ~ 2.5 in the ROI

	$0\nu\beta\beta$ region cnts/(keV kg y)	2700-3900 keV	$\varepsilon(\%)$
Cuoricino	0.153 ± 0.006	0.110 ± 0.001	83
CUORE-0	0.063 ± 0.006	0.020 ± 0.001	78

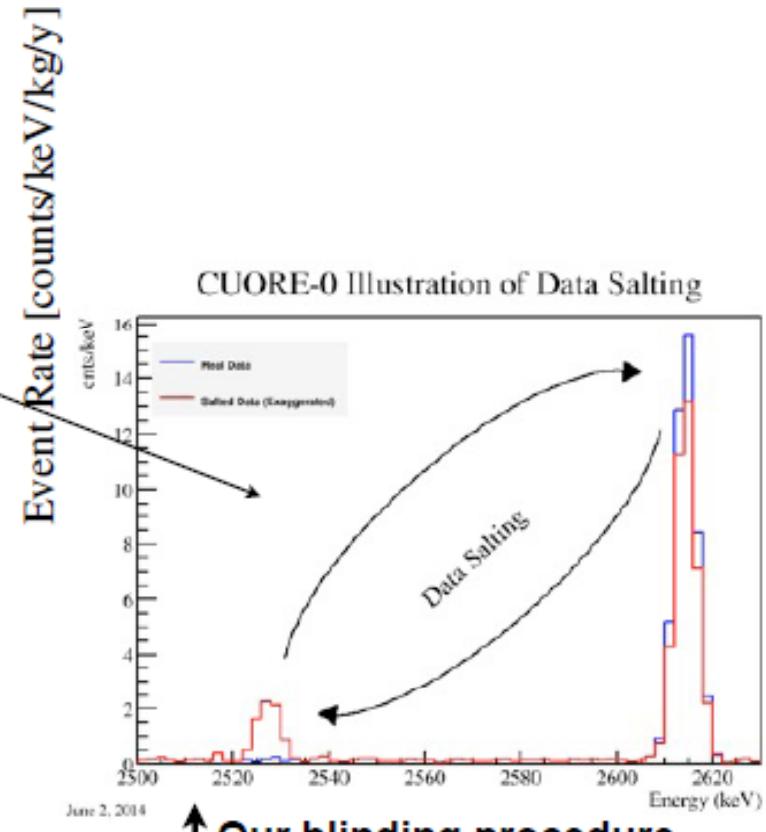
CUORE-0: $\beta\beta 0\nu$ ROI



Background consistent with Cuoricino model:

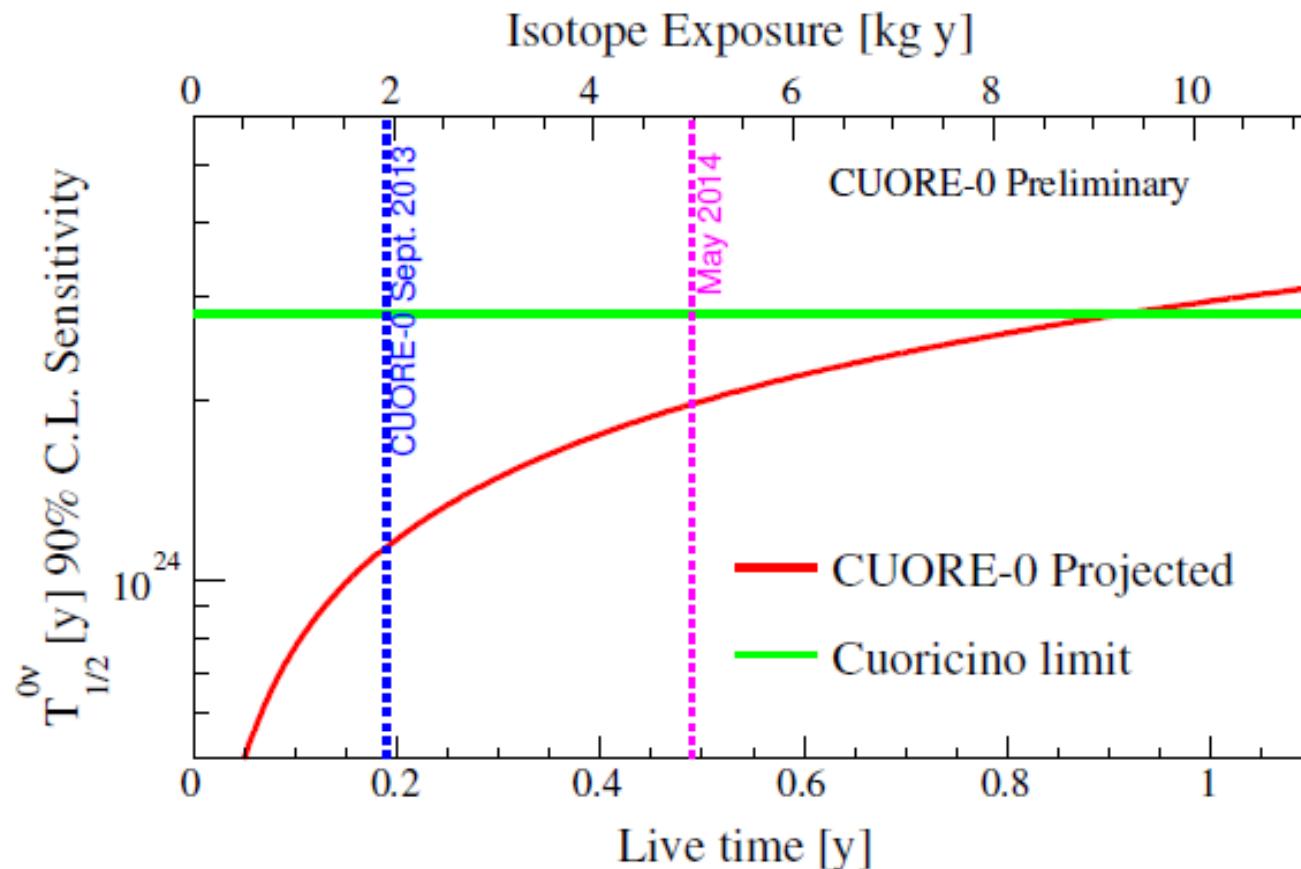
- dominated by ^{228}Ac γ 's from the environmental materials (mainly cryostat).

Unblinding: early 2015



↑ Our blinding procedure produces an artificial peak in the ROI:

a small (blinded) fraction of the events within ± 10 keV of the 2615 keV peak from ^{200}Tl is exchanged with the events within ± 10 keV of the Q-value



CUORE-0 expected to surpass Cuoricino sensitivity with ~1 year of livetime.

Energy resolution:

$\Delta E \sim 5.2 \text{ keV FWHM @ } 2615 \text{ keV}$

Background index (in the $\beta\beta$ ROI):

$b = 0.063 \pm 0.006 \text{ cnts/(keV} \cdot \text{kg} \cdot \text{yr)}$

- Improvements to noise still in progress
 - Pulse shape cuts are still being optimized
- CUORE-0 sensitivity may still improve in the future.

Coming soon

- GERDA II
- Majorana Demonstrator
- CUORE

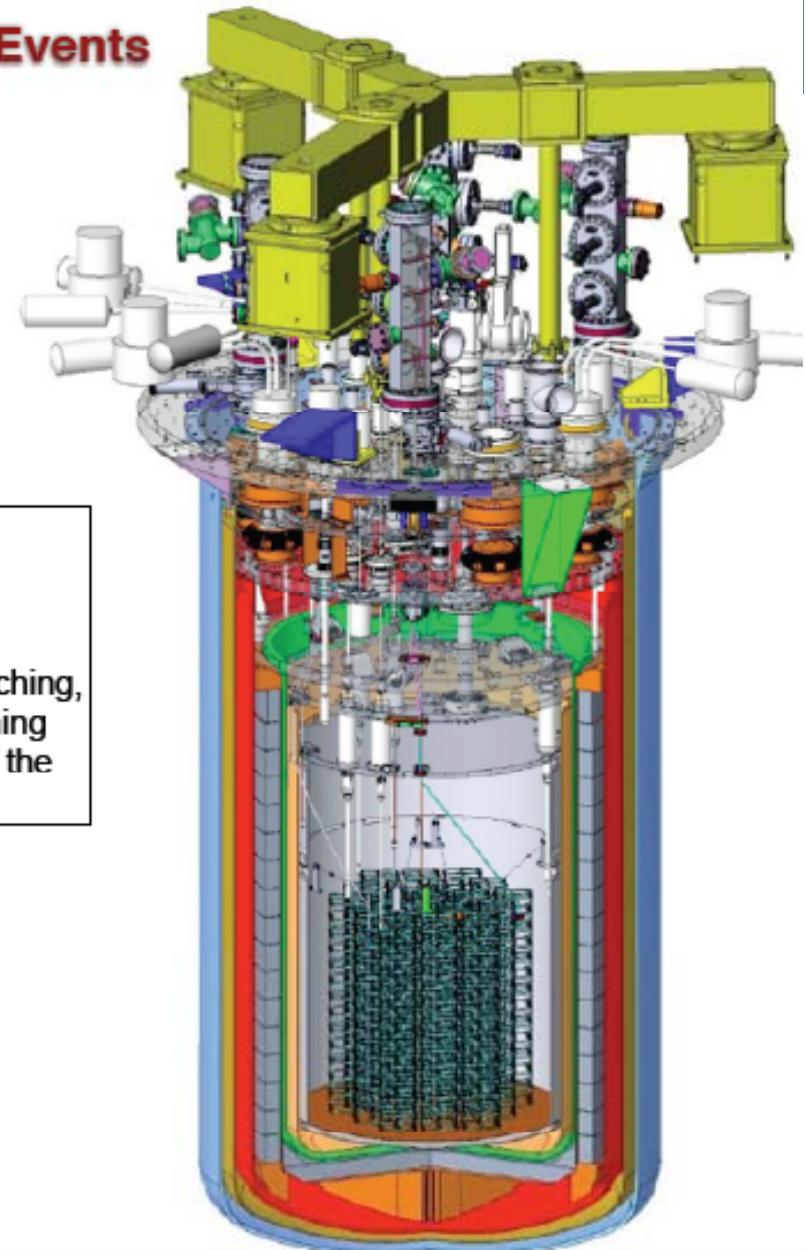
CUORE @ LNGS

Cryogenic Underground Observatory for Rare Events

CUORE detector

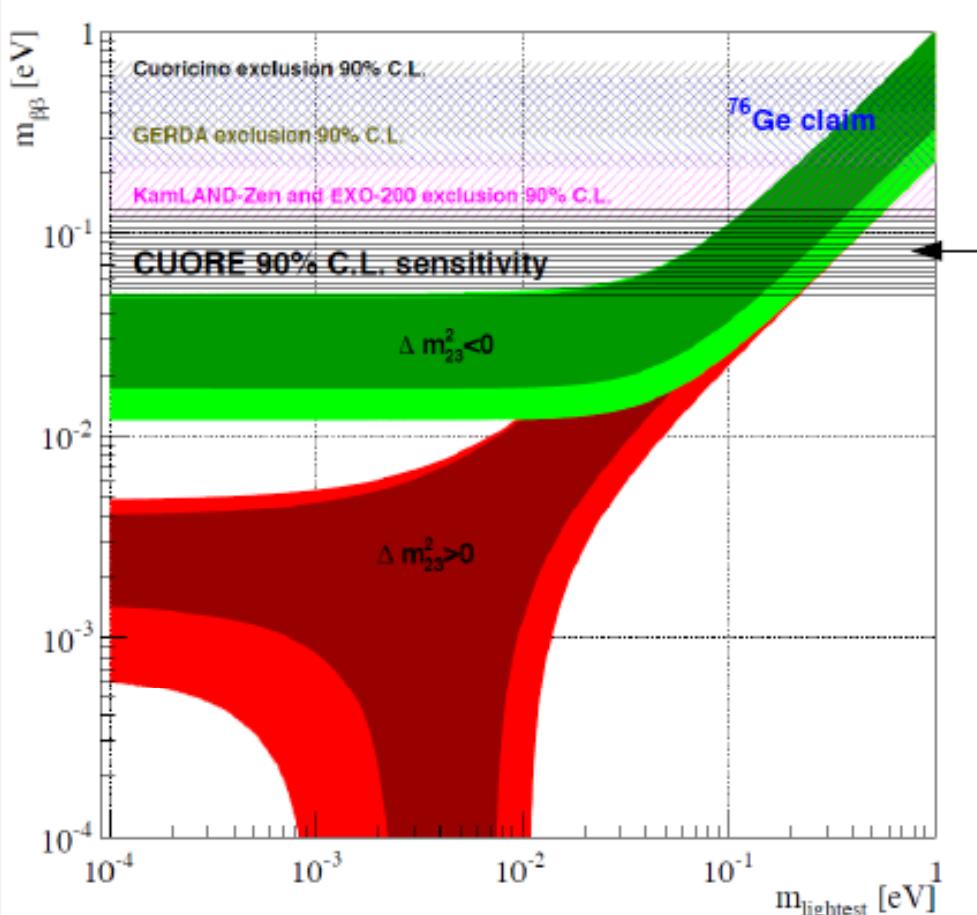
- 988 TeO₂ crystals run as a bolometer array
 - 5x5x5 cm³ crystal, 750 g each
- 19 Towers; 13 floors; 4 modules per floor
 - 741 kg total - 206 kg ¹³⁰Te
 - 10^{27} ¹³⁰Te nuclei
- Excellent energy resolution of bolometers
- Radio-pure material and clean assembly to achieve low background at ROI

- strict radiopurity control protocol to limit bulk and surface contaminations in crystal production
- transportation at sea level to LNGS
- bolometric test to check performances and radio-purity
- TECM protocol (Tumbling, Electropolishing, Chemical etching, and Magnetron plasma etching) for copper surface cleaning
- limited exposure to cosmic rays: underground storage of the copper parts in between production and cleaning



Complex cryogenic set-up

- Fully cryogen-free system:
 - custom cryostat
 - 5 pulse tubes
 - a powerful dilution refrigerator and
- ~10 mK operating temperature
- Independent suspension of the detector array
- An embedded detector calibration system
- Radio-pure materials
- Heavy low temperature shield



Design goal:

- ♦ bkg: 0.01 counts/(keV·kg·y)
- ♦ ΔE : 5 keV FWHM
- ♦ t_{meas} : 5 years



- Sensitivity $S^{0\nu}(\tau_{1/2})$:
 - $1.6 \times 10^{26} \text{ y}$ (1σ)
 - $9.5 \times 10^{25} \text{ y}$ (90% C.L.)
- effective Majorana mass:
 $m_{\beta\beta} : 51 - 133 \text{ meV}$ (90% C.L.)

$$S^{0\nu}(\tau_{1/2}) \propto \epsilon \cdot \frac{i \cdot a}{A} \sqrt{\frac{M t_{\text{meas}}}{\Delta E \cdot bkg}} \quad bkg \neq 0$$

ϵ	detector efficiency	ΔE	FWHM resolution
i.a.	$\beta\beta 0\nu$ isotope abundance	M	total active mass
A	atomic mass	t_{meas}	measuring time
bkg	background @ ROI in counts/keV/kg/y		

GERDA Phase II



Phase I



Phase II

Phase I: 13 kg of ^{enr}Ge COAX Detectors
3 kg of ^{enr}Ge BEGe Detectors
w. enhanced PSD

15/07/2014

Phase II: 18 kg of ^{enr}Ge COAX Detectors
21 kg of ^{enr}Ge BEGe Detectors
w. enhanced PSD

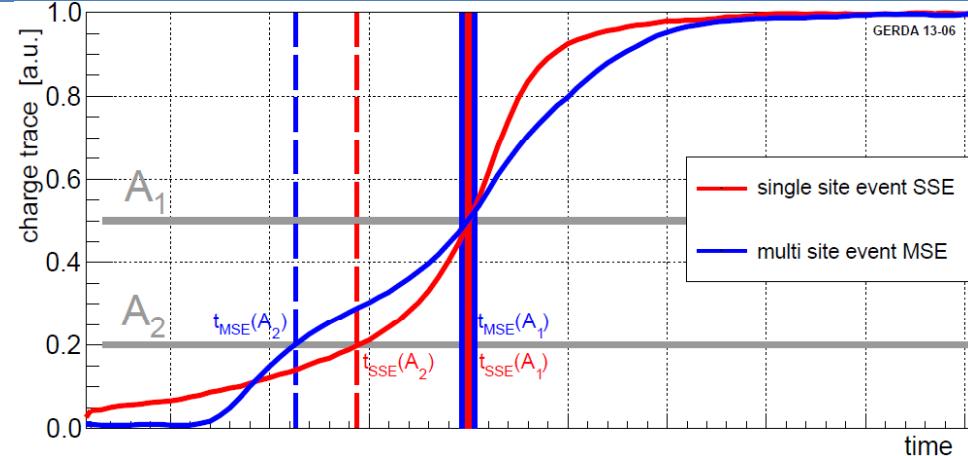
GERDA CdS MiB 30/06/2014

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GERDA Strategy to improve $T_{1/2}$ limits



- Increase ^{enr}Ge mass (40 kg in total) 21 kg in form of Ge-BEGe type with enhanced PSD to pinpoint $\beta\beta$ events (Single Site) vs residual γ events (Multi Site)
- Reduce radioactivity of Ge holders and mechanical structures
- New Ge readout electronics with closer FE devices in die for improved FWHM
- Transparent Shroud (instead of Cu opaque MS) surrounding each Ge detector string to mitigate ^{42}Ar bkgd.
-





top plate with
9 PMTs



Cu shroud 1, h~ 60 cm

flange

Ø49 cm central window, h~100 cm,
covered by dense curtain of $1 \times 1 \text{ mm}^2$
scintillating fibers on radius of 23.25 cm;
readout by KETEK SIPMs 3x3 arrays

flange

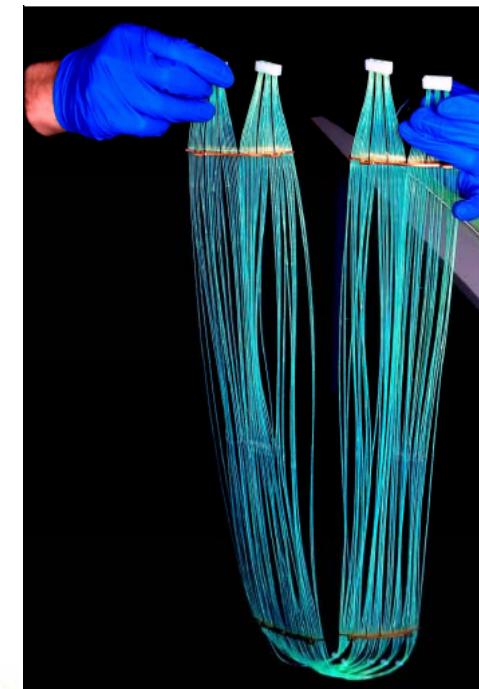
Cu shroud 2 Ø49 cm, h~60cm, t=0.1mm
coated with tetratex & WLS (TPB)

bottom plate with 7 PMTs

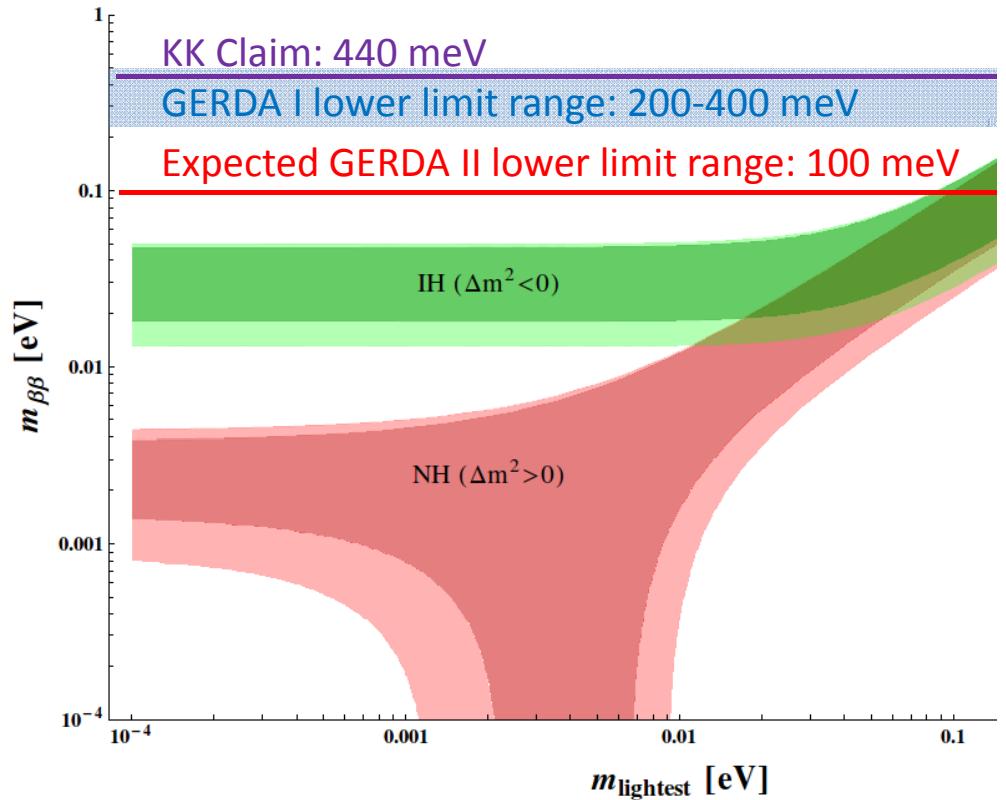
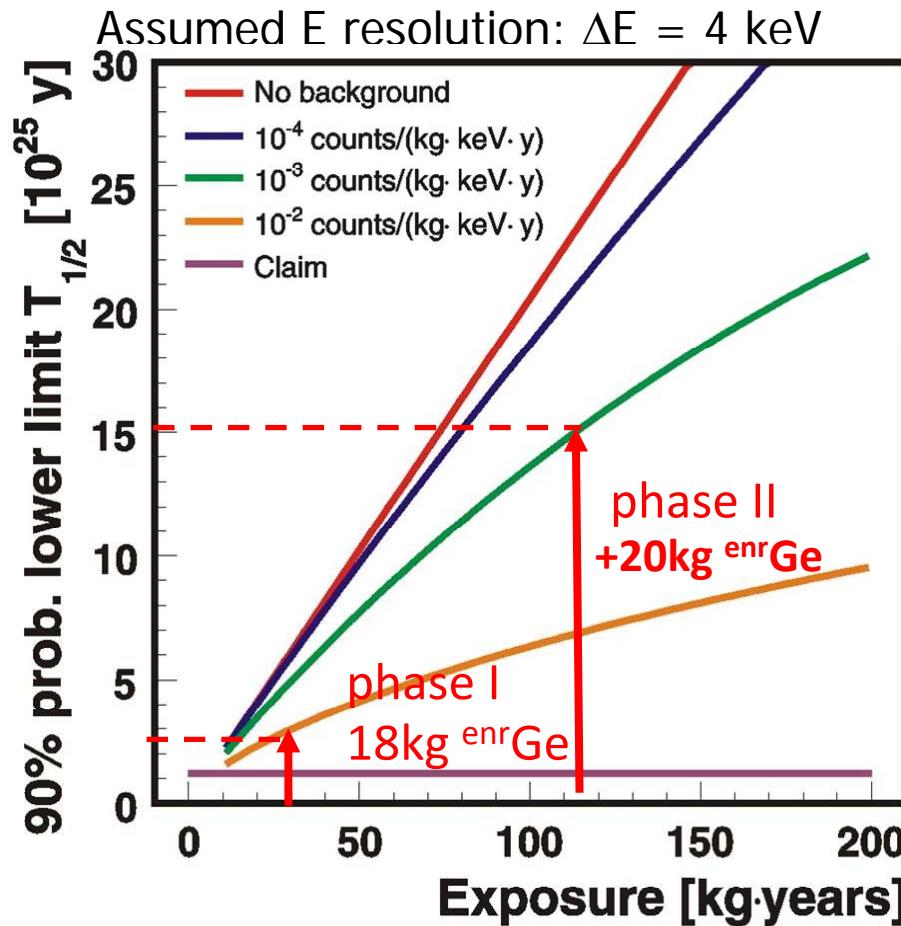
15/07/2014

hybrid LAr veto system

PMTs and SIPMs & fibers are deployed together with detector array through Phase II lock w/o LAr drainage



GERDA II Expected Sensitivity

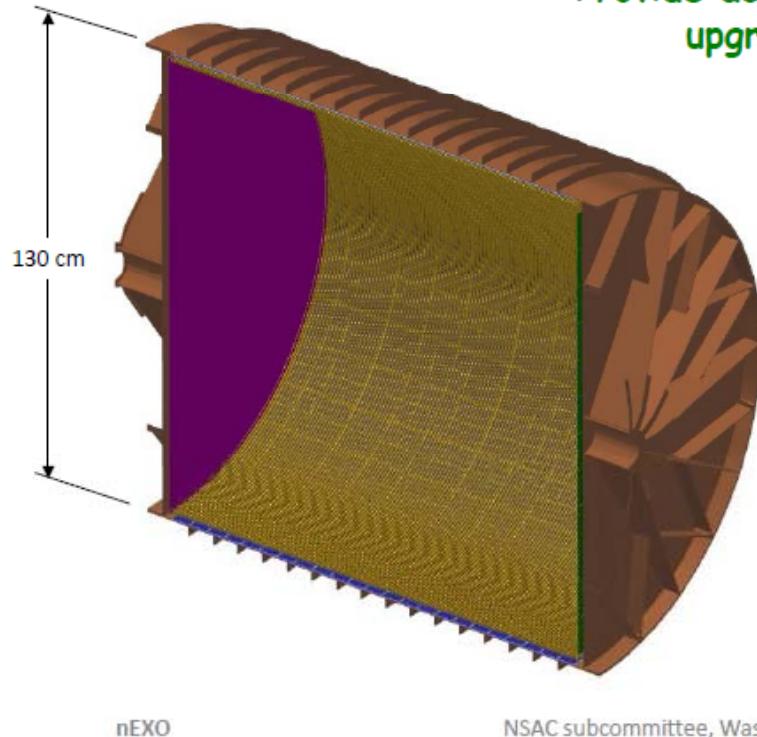


From Dell'Oro, Marcocci, Vissani, hep-ph/1404.2616v1

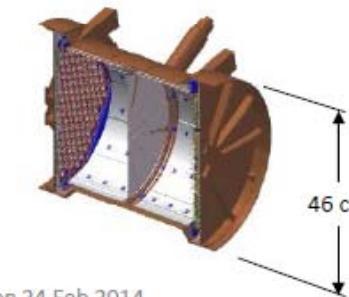
nEXO

- 5 tonnes of ${}^{enr}Xe$: entirely cover inverted hierarchy (more later)

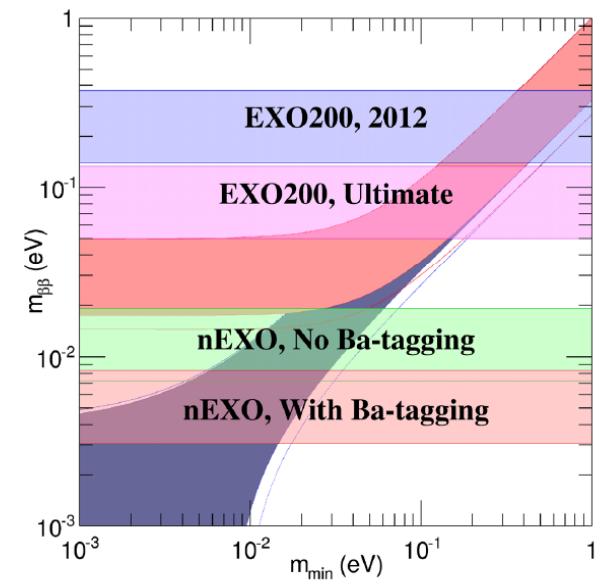
- LXe TPC "as similar to EXO-200 as possible"
- Provide access ports for a possible later upgrade to Ba tagging



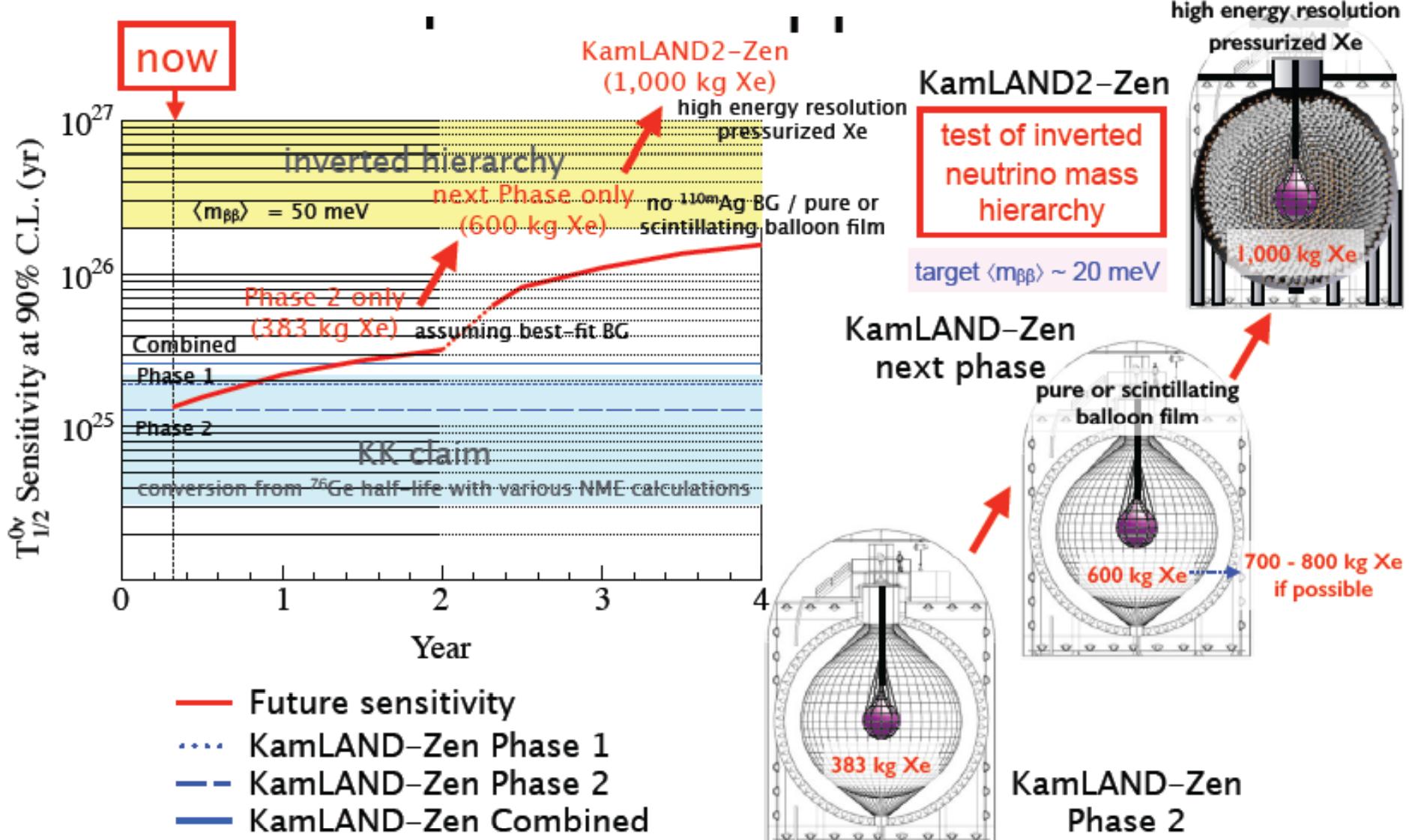
NSAC subcommittee, Washington 24 Feb 2014



→ A unique combination of conservative and aggressive design with important upgrade paths as desirable for a large experiment



KAMLAND-ZEN: Perspectives of $0\nu\beta\beta$ Searches



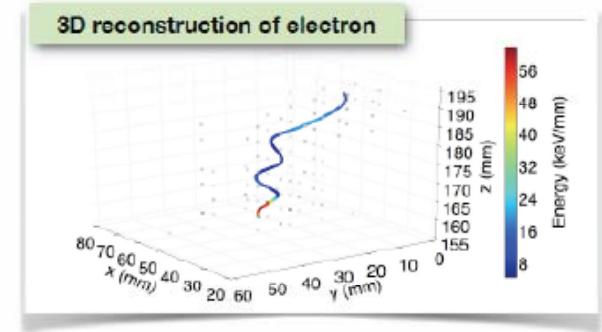
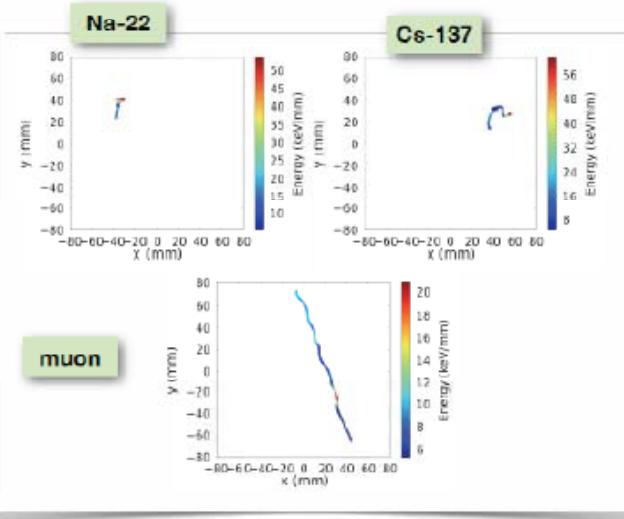
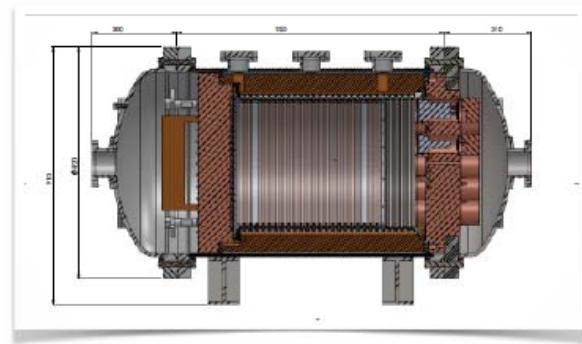
Detector improvements are planned in the near future

Projects in R&D Stage

- MAJORANA Demonstrator: 30kg ^{enr}Ge + 10kg ^{nat}Ge in form of BEGe detectors. Sanford Ugd. Lab
- NEXT: Advanced; 10 kg of high pressure gas ^{enr}Xe TPC prototype almost ready to go at Canfranc Ugd. Lab
- Lucifer/Lumineau (still R&D)

NEXT: High Pressure Xe TPC at Canfranc

High Pressure Gas TPC



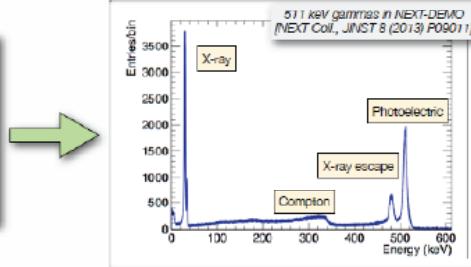
Events Topology in NEXT

- Higher energy deposition clearly visible at electron track end-point.

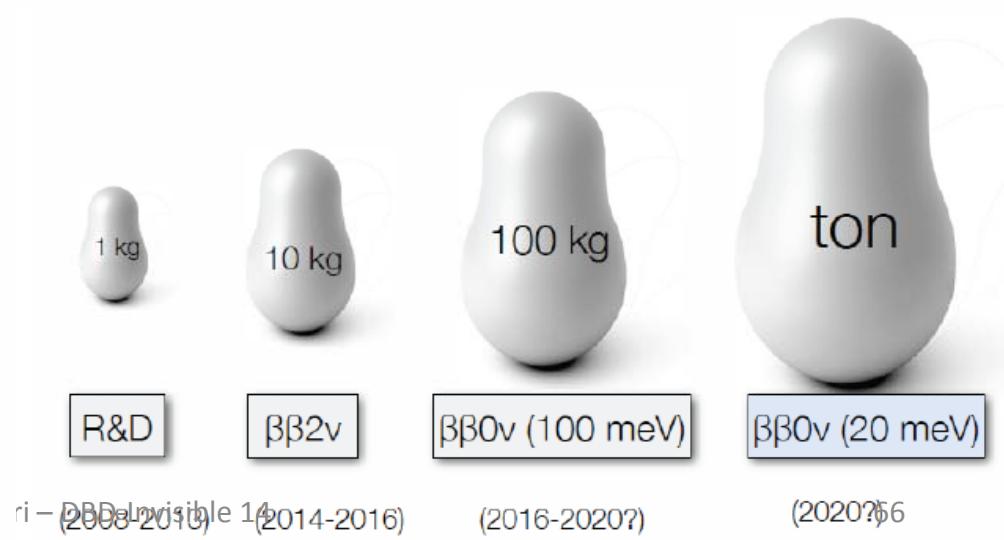
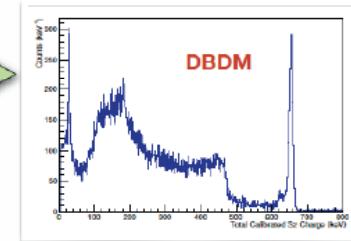
tracks reconstructed using SiPMs + PMTs

NEXT R&D: detector performance achievements

- 1.8% FWHM energy resolution for 511 keV electrons over large fiducial volume
- Extrapolates to 0.75% FWHM at $Q_{\beta\beta}$ energy of 136Xe decay



- The DBDM prototype at LBNL extrapolates to **0.5 % FWHM** at $Q_{\beta\beta}$ using 660 Cs-137 electrons



Current activity on new regular-shape natural crystals and enriched crystals

New ZnMoO_4 LUMINEU crystals have been grown in NIIC (Russia) by using LTG Cz

- Improved ZnMoO_4 (2×338 g) were produced. A boule was grown, melted and then crystallized again. Molybdenum was purified by using double recrystallization from solutions [1]
- First $\text{Zn}^{100}\text{MoO}_4$ boule was developed from deeply purified ^{100}Mo and two samples (64 and 61 g) were produced [2]

New bolometers based on two improved ZnMoO_4 and first $\text{Zn}^{100}\text{MoO}_4$ crystals will be tested soon at the LSM

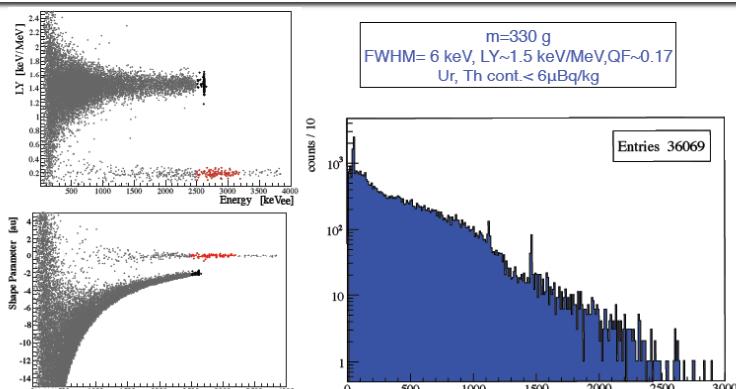
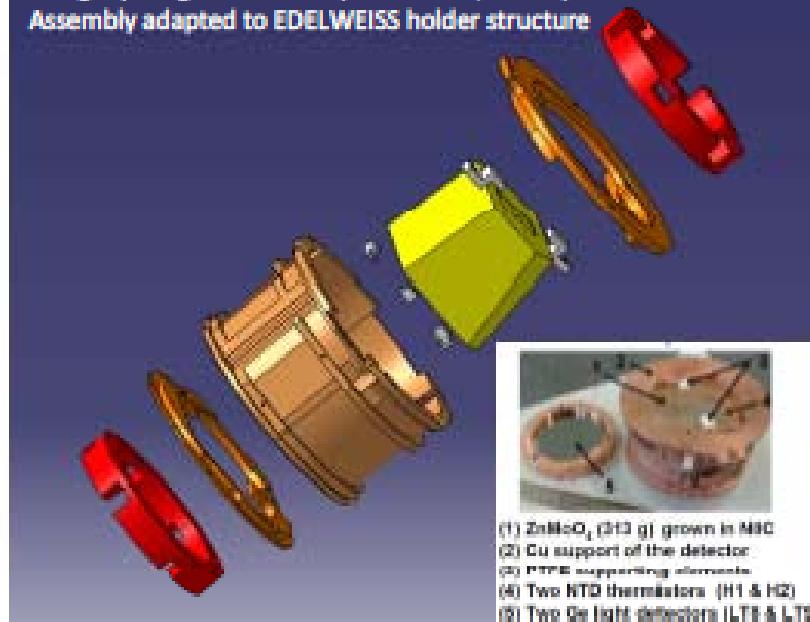
[arXiv:1405.6937v1](https://arxiv.org/abs/1405.6937v1) [physics.ins-det]



Assembly of a 313 g natural ZMO detector

313 g crystal grown at NIIC (Novosibirsk, Russia)

Assembly adapted to EDELWEISS holder structure



- First measurement of $2\nu\beta\beta$ decay published *J. Phys. G: Nucl. Part. Phys.* 41 075204.
- MOU between INFN, IN2P3, ITEP: common interest for an experiment based on ~10 kg of ZnMoO_4 with 95% enriched ^{100}Mo .

LUMINEU summary

Luminescent Underground Molybdenum Investigation for NEUtino mass and nature

Funded by Agence Nationale de la Recherche (France)

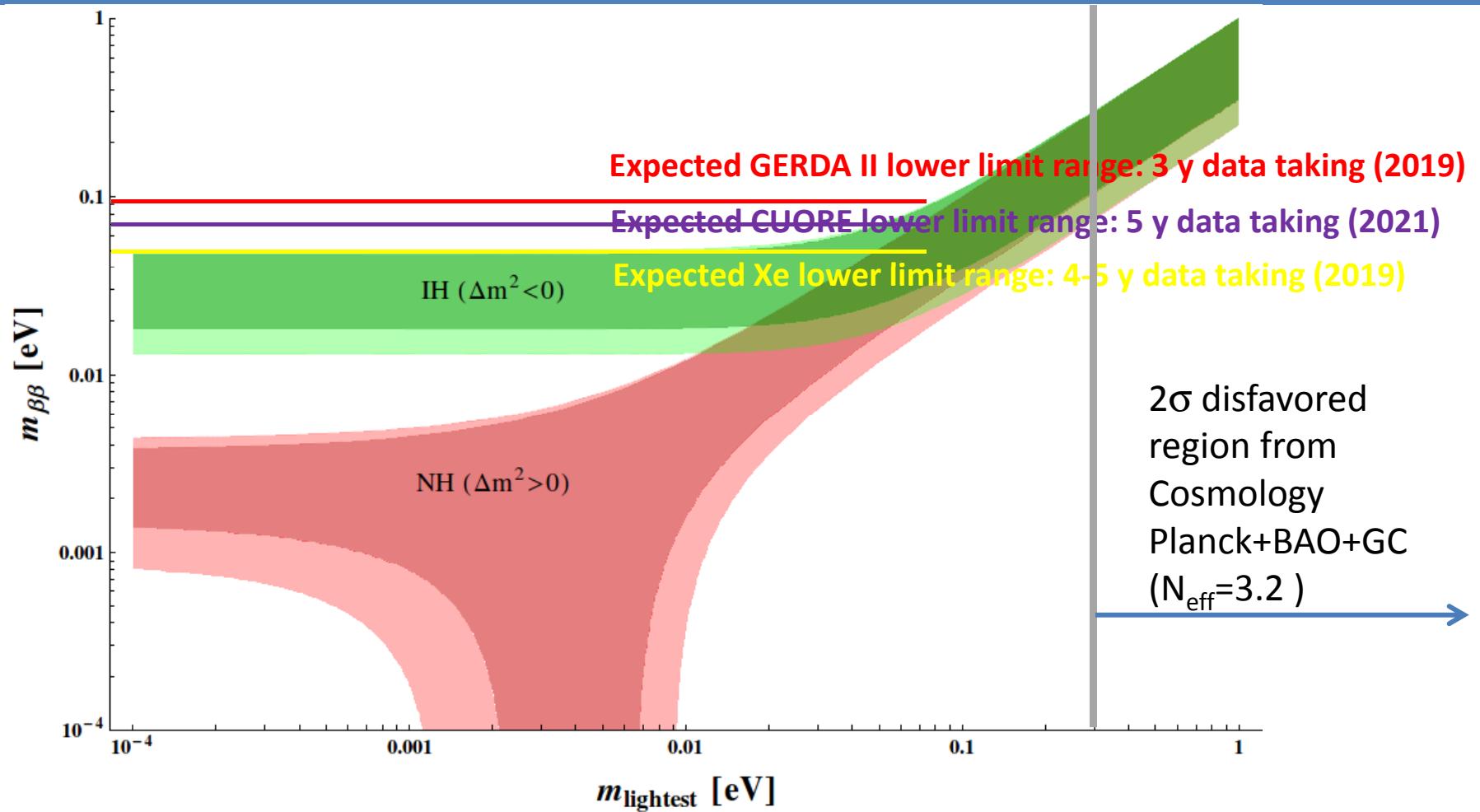
Collaboration: France (Orsay, Saclay, ICMCB Bordeaux), Ukraine (KINR Kiev), Russia (NIIC Novosibirsk), Germany (Heidelberg); about 40 physicists - engineers

Aim: Set the bases for a next-generation neutrinoless double-beta decay experiment for the study of the isotope ^{100}Mo embedded in ZnMoO_4 scintillating bolometers

Future Perspectives

- Each project aims to Increase Mass to $O(1 \text{ ton})$
 - nEXO
 - Kamland-Zen
 - Cuore
 - GERDA – Majorana (joint project)
- Improve event tagging to reach the 0-bckgd condition.
Intense R&D on
 - Bolometer → Scintillating/Cerenkov Bolometers (LUCIFER, LUMINEAU, CANDLES)
 - Solid State Detectors: PSD
- EVERYBODY: Reduce background, aiming to Bckgd free regime.
 - Improve setups, de-Rn atmospheres in clean rooms.....

Expected sensitivities from sensitivities stated by Collaborations



From Dell'Oro, Marcocci,Vissani, hep-ph/1404.2616v1

Conclusions

- In the next 3-5 years experiments will reach the “top” of the IH region (70 meV)
- What if $0\nu\beta\beta$ is not found?
 - Neutrinos are Dirac particles
 - Neutrinos are Majorana Particles but Majorana Phases Cancellations (or else) make m_{ee} very small and so $0\nu\beta\beta$ is very suppressed or absent
 - The Majorana mass mechanism is not the leading one. Other possible mechanisms are
 - Left-Right symmetric models
 - Heavy Right Handed Neutrinos
 -

CUORE Collaboration

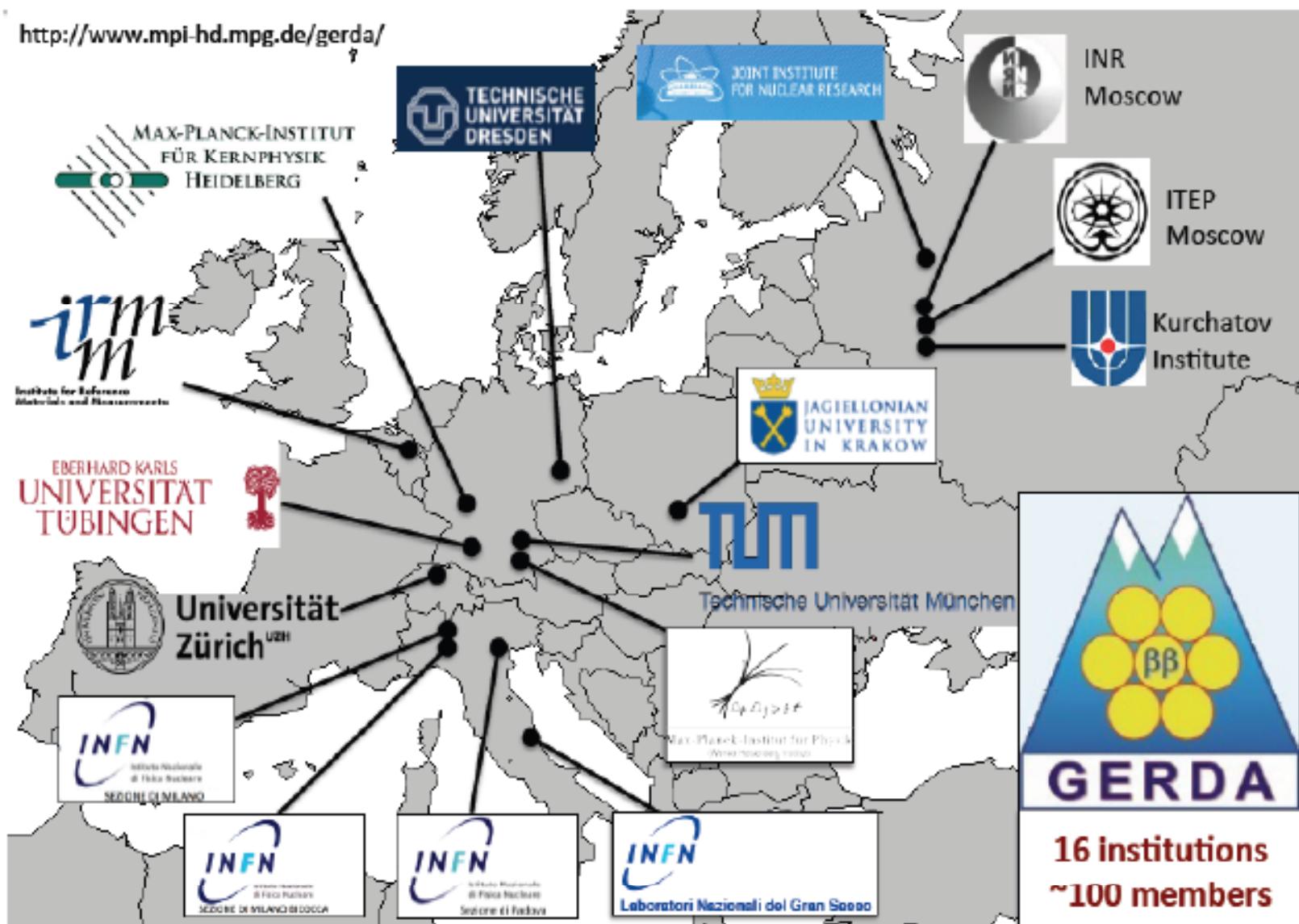


- 19 groups
 - Italy
 - USA
 - China
 - France
- 148 collaborators
- 117 researchers



GERDA

collaboration



Experiments and techniques

Calorimeters: Solid State, Bolometers

- Intermediate mass possible ($O(50 \text{ kg})$ done), $O(100 \text{ kg})$ ready to go, $O(1 \text{ t})$ proposed)
- High En. Res (FWHM: 0.15% for Ge diodes & Bolometers)
- High Efficiency (~ 1)
- BKG can be reduced (done)
- Limited particle ID
- Non monolithic volumes

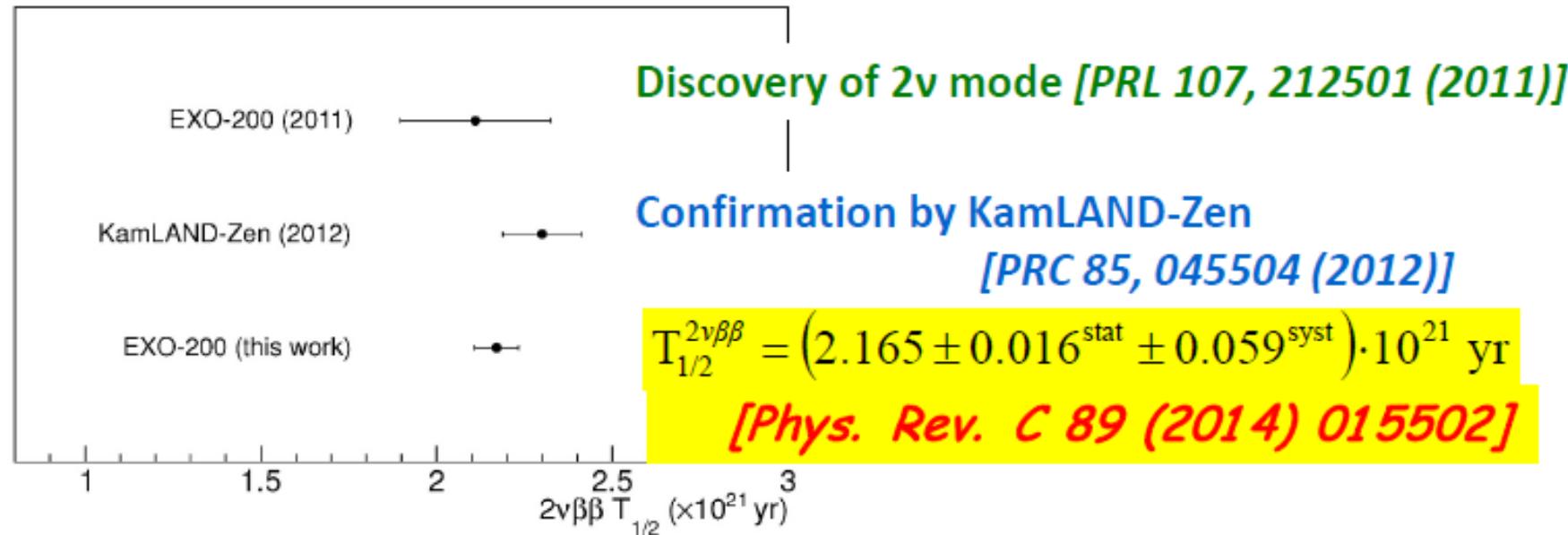
Calorimeters: Liquid Scintillators - Gas Detectors

- (Large masses feasible $O(100 \text{ kg})$ done), $O(1 \text{ t})$ proposed)
- Intermediate En. Res (FWHM: O(3-10%)) → bkg from 2ν
- High Efficiency
- Monolithic volumes (self shielding, definition of fiducial volume)

External-source detectors: gas TPC/DC, magnetic field and TOF

- Difficult to scale up masses
- Intermediate efficiency
- Low energy res
- Event topology → handle to abate bkgd, but $2\nu\beta\beta$
- Address different isotopes

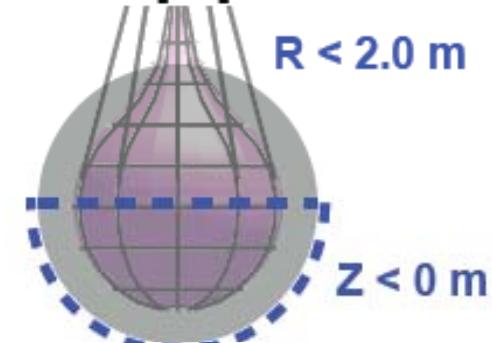
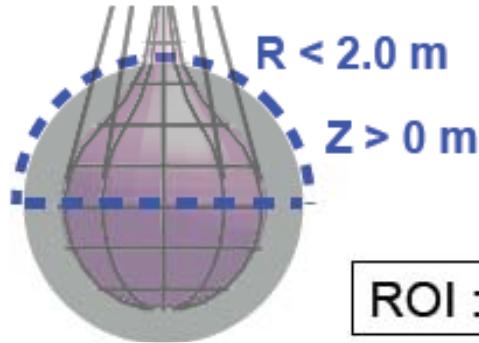
...since the start of EXO-200 data taking in Jun 2011...



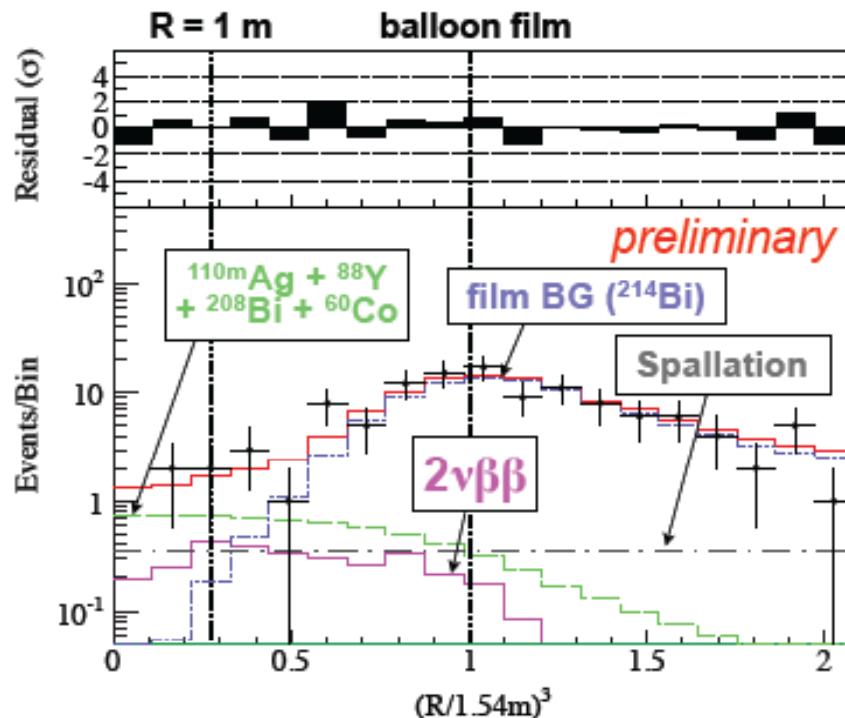
Nuclide	$T_{1/2}^{2\nu\beta\beta} \pm \text{stat} \pm \text{sys}$ [y]	rel. uncert. [%]	$G^{2\nu}$ $[10^{-21} \text{ y}^{-1}]$	$M^{2\nu}$ $[\text{MeV}^{-1}]$	rel. uncert. [%]	Experiment (year)
^{136}Xe	$2.165 \pm 0.016 \pm 0.059 \cdot 10^{21}$	± 2.83	1433	0.0218	± 1.4	EXO-200 (this work)
^{76}Ge	$1.84^{+0.09+0.11}_{-0.08-0.06} \cdot 10^{21}$	± 7.7 ± 5.4	48.17	0.129	± 3.9 ± 2.8	GERDA [39] (2013)
^{130}Te	$7.0 \pm 0.9 \pm 1.1 \cdot 10^{20}$	± 20.3	1529	0.0371	± 10.2	NEMO-3 [40] (2011)
^{116}Cd	$2.8 \pm 0.1 \pm 0.3 \cdot 10^{19}$	± 11.3	2764	0.138	± 5.7	NEMO-3 [41] (2010)
^{48}Ca	$4.4^{+0.5}_{-0.4} \pm 0.4 \cdot 10^{19}$	± 14.6 ± 12.9	15550	0.0464	± 7.3 ± 6.4	NEMO-3 [41] (2010)
^{96}Zr	$2.35 \pm 0.14 \pm 0.16 \cdot 10^{19}$	± 9.1	6816	0.0959	± 4.5	NEMO-3 [42] (2010)
^{150}Nd	$9.11^{+0.25}_{-0.22} \pm 0.63 \cdot 10^{18}$	± 7.4 ± 7.3	36430	0.0666	± 3.7 ± 3.7	NEMO-3 [43] (2009)
^{100}Mo	$7.11 \pm 0.02 \pm 0.54 \cdot 10^{18}$	± 7.6	3308	0.250	± 3.8	NEMO-3 [44] (2005)
^{82}Se nEXO	$9.6 \pm 0.3 \pm 1.0 \cdot 10^{18}$	± 10.9	1596	0.0980	± 5.4	NEMO-3 [44] (2005)

NSAC subcommittee, Washington 24 Feb 2014

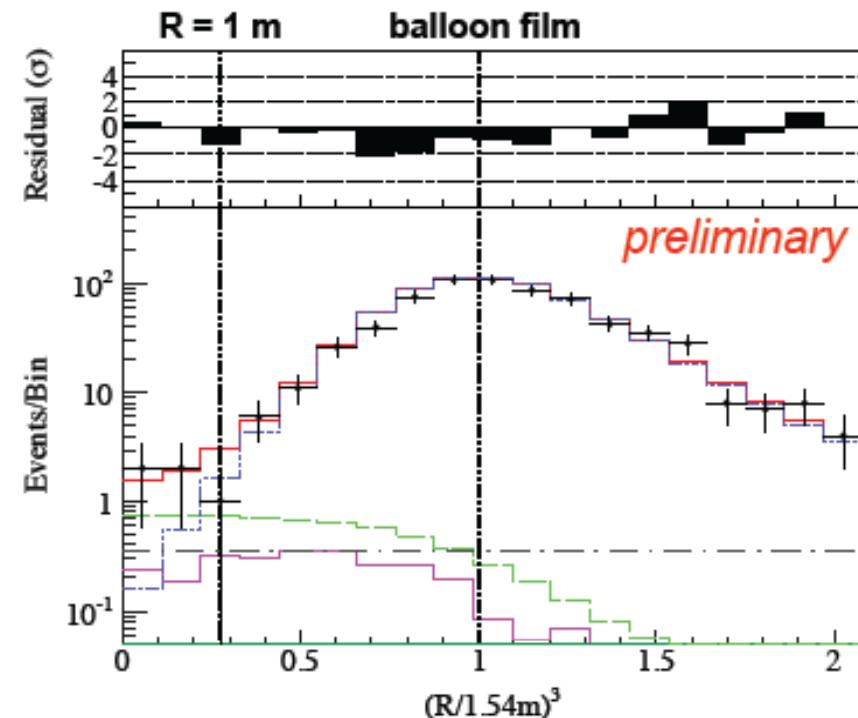
Fit to R^3 Spectra for $0\nu\beta\beta$



Upper hemisphere ($Z > 0 \text{ m}$)



Lower hemisphere ($Z < 0 \text{ m}$)



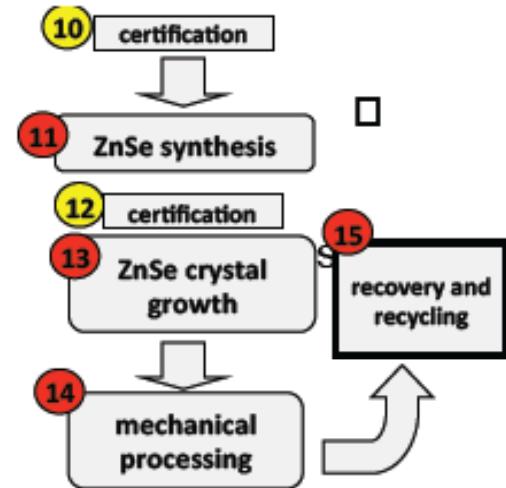
^{214}Bi vertex dispersion is consistent with data

LUCIFER

- ERC Advanced Grant n. 247115
 - ▶ Budget: 3.2 M€
 - ▶ Project duration: 01.03.2010-01.03.2015
- Goal: demonstrator of an experiment with bkg. \sim 1cts/ton/y/keV **with sensitivity comparable** to next generation experiment.
- Scintillating bolometers technique
 - ▶ Alfa background rejection thanks to the scintillation light
- Crystals:
 - ▶ Primary choice: ZnSe with enriched Se at 95% in ^{82}Se ($Q=2997\text{ keV}$, i.a.=8.7%)
 - ▶ Secondary choice: ZnMoO₄ ($Q=3034\text{ keV}$, i.a.=9.6%)

Synthesis & Crystal growth

- cylinder Ø=45mm, h=55mm, w=460.7g(nat Se),
- SmiLab Ltd(Ukraine): only supplier able to perform synthesis and crystal growth
- Crystals growth is difficult:
 - ▶ High melting point(1525°C) & total vapor pressure(~2Bar) deviation from stoichiometry
 - ▶ Very difficult control of local temperature defects
- Required **efficiency** of growth and processing **> 65%**
- Smilab not able to reach such efficiency: **TPY ~22%**
- Alternative supplier ISMA Kharkov is being tested.



ZnSe

- 430 g ZnSe crystal **JINST 1305 (2013) P05021**
- LY ~6.5 keV/MeV for β/γ , QFa ~4, poor light collection □ pulse shape discrimination on light detector

