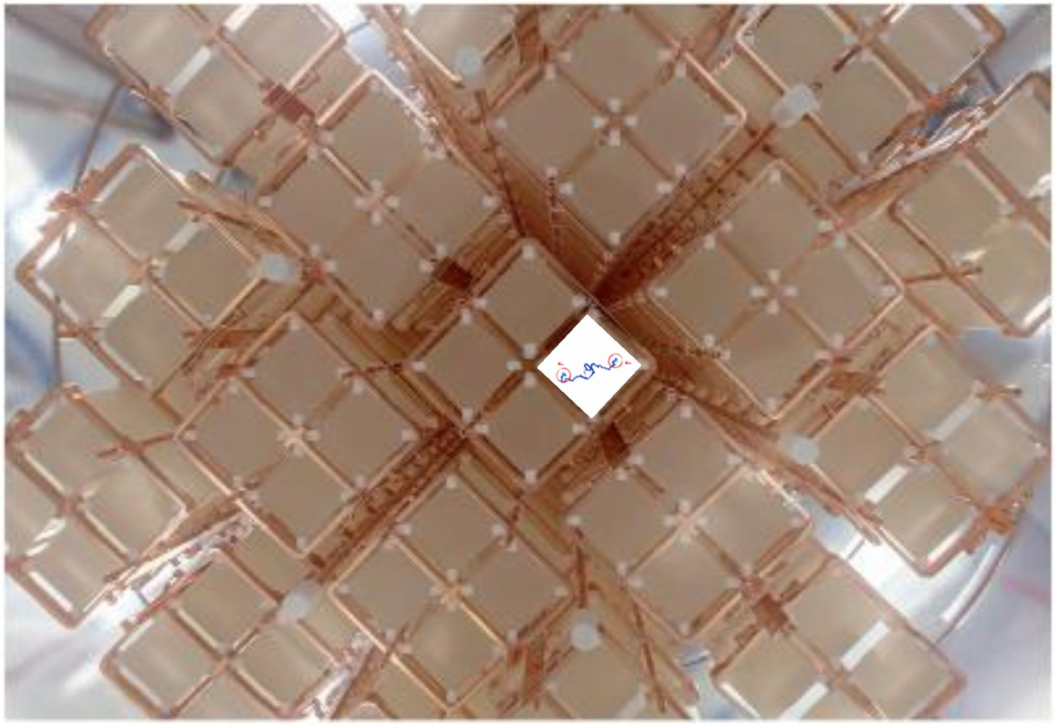
The search for neutrino-less double beta decay

A (Europe-focused) review of current **experiments** and of the impressive results achieved in the last two years

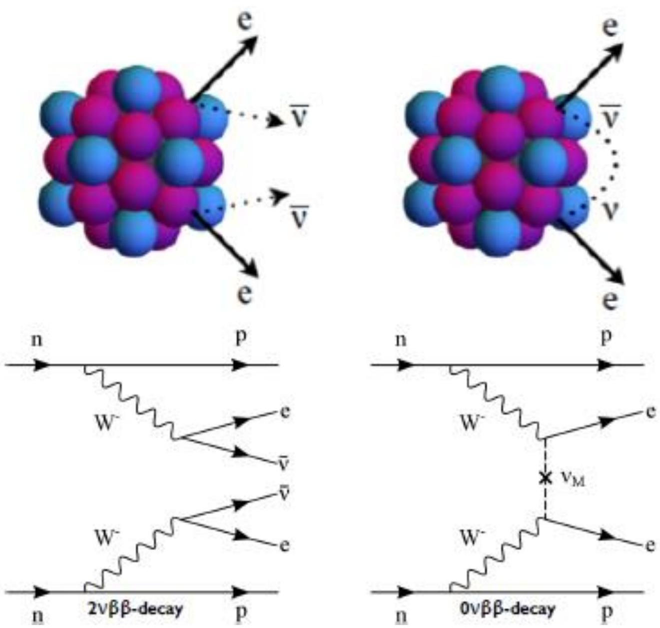
Experimental strategies for the **next generation**

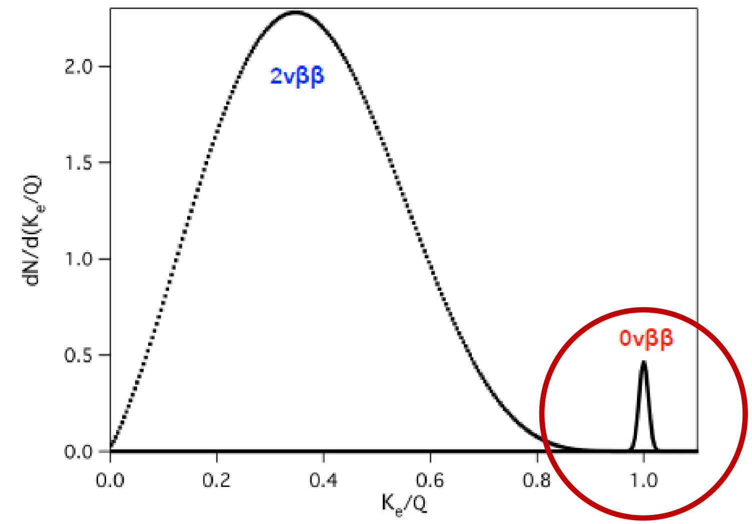
Why such a growth of interest in this field, **right now**?



F. Terranova, Univ. of Milano Bicocca and INFN

Neutrino-less double beta decay (NLDBD)





To date, NLDBD is the only viable option to show that neutrinos are Majorana particles $(\nu = \bar{\nu})$

Experimental observation of neutrino-less double beta decay

It will establish **violation of lepton number** in particle physics

Shed light on **mass generation mechanisms** and the smallness of neutrino masses

Open a window to understand **matter dominance** in the universe

Provide information on the **size and pattern** of neutrino masses

NLDBD and neutrino masses

The decay half-life is connected in a non trivial manner to the neutrino masses

Half-life Phase space factor

$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}|M^{0\nu}|^2|\langle m_{\beta\beta}\rangle|^2$$

Nuclear matrix element

Effective Majorana neutrino mass:

(exact form depends on the lepton flavor violating mechanism!)

$$m_{\beta\beta} \equiv \left|\sum_{i=1}^{3} U_{ei}^2\, m_i\right|$$

[See also talk from E. Lisi]

$$< m_{\beta\beta} >= \left|U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i(\alpha_1-\alpha_2)} + U_{e3}^2 m_3 e^{i(-\alpha_1-2\delta)}\right|$$

Phase space: known with good precision
Nuclear matrix element: major challenge
in nuclear physics

$$M_{(0\nu)} = g_A^2 M^{(0\nu)}$$

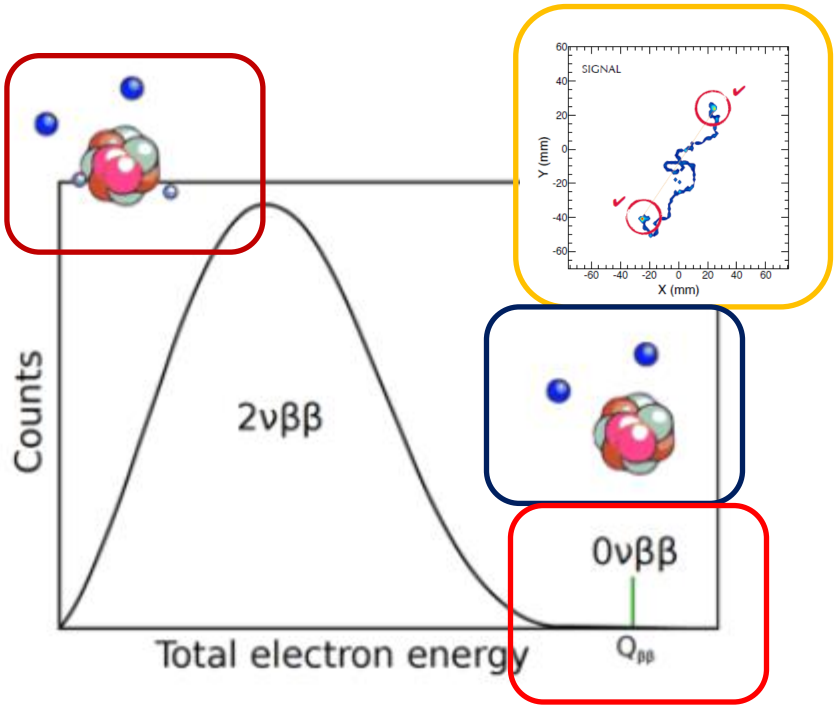
$$g_A^{\mathrm{quark}} = 1$$
$$g_A^{\mathrm{nucleon}} = 1.27$$
$$g_A^{2\nu\beta\beta} = 1.27 \cdot A^{-0.18}$$
$$g_A^{0\nu\beta\beta} = \;??$$

$m_{\beta\beta}$ Linked to neutrino eigenstate (as cosmology), mixing angles (as oscillations) and Majorana CP violating phases (unique!)

If neutrino are Majorana particles, oscillation data provide guidance for the NLDBD half time. Still, the constraints are loose and a lot of work is needed to reduce the uncertainties on M and g_A.

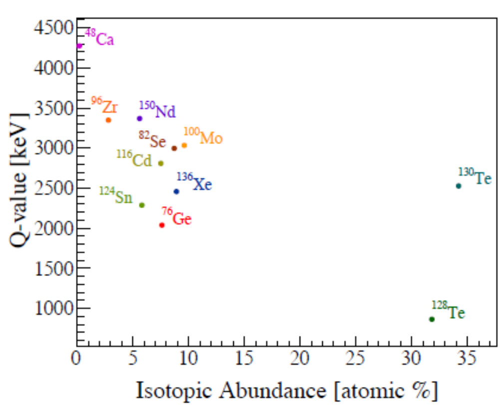
The perfect experiment

The experimental signature of NLDBD is extremely simple: two electrons whose energy sum (Q-value) is known in advance with very high precision (Penning traps). "Intrinsic" background: $(A,Z) \rightarrow (A,Z+2)\ 2e^-\ 2\nu$



Track the out-coming electrons to separate α, β, γ from ββ

Choose the detector with the best energy resolution (<1% FWHM) to reduce the "intrinsic" 2ν background



Select isotopes with high Q-value against natural radioactivity and high isotopic abundance

ββ Decay Reaction	Isotopic Abundance [atomic %]	Q-value [keV]
$^{48}Ca \rightarrow ^{48}Ti$	0.2	4274
$^{76}Ge \rightarrow ^{76}Se$	7.6	2039
$^{82}Se \rightarrow ^{82}Kr$	8.7	2996
$^{96}Zr \rightarrow ^{96}Mo$	2.8	3348
$^{100}Mo \rightarrow ^{100}Ru$	9.6	3034
$^{116}Cd \rightarrow ^{116}Sn$	7.5	2814
$^{124}Sn \rightarrow ^{124}Te$	5.8	2288
$^{128}Te \rightarrow ^{128}Xe$	31.8	866
$^{130}Te \rightarrow ^{130}Xe$	34.2	2528
$^{136}Xe \rightarrow ^{136}Ba$	8.9	2458
$^{150}Nd \rightarrow ^{150}Sm$	5.6	3368

Back to earth….

The number of candidate isotopes is rather small and we often end up choosing among alternative options:

Superior energy resolution (0.1%)

Germanium detectors	**Gerda**, Majorana
Bolometers	**CUORE**, CUPID-0, AMORE

Compromise:

Superior tracking capability

Compromise:

Source not in detector	**SuperNemo**
TPC with source in detector	EXO-200, **Next**, PandaX-III

Huge isotope masses (1 ton)

Loaded scintillators	**Kamland-Zen**, SNO+

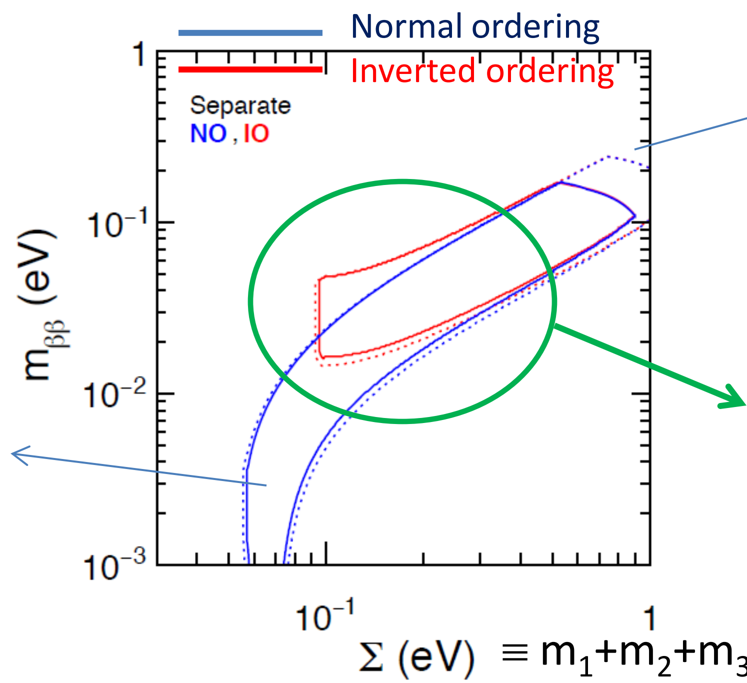
Compromise:

energy resolution
restricted isotope list
tracking capability
mass scalability

From the “perfect” to the “best” experiment

After 2012 (high precision measurement of all mixing angles), $m_{\beta\beta}$ is well constrained from neutrino (and cosmology) data. Now we know where to look for.

See also talks of E. Lisi and S. Schoenert



Nearly degenerate mass eigenstate. Best case scenario: possible but unlikely (cosmology)

Accidental cancellation among CP phases. Worst case scenario: possible but unlikely

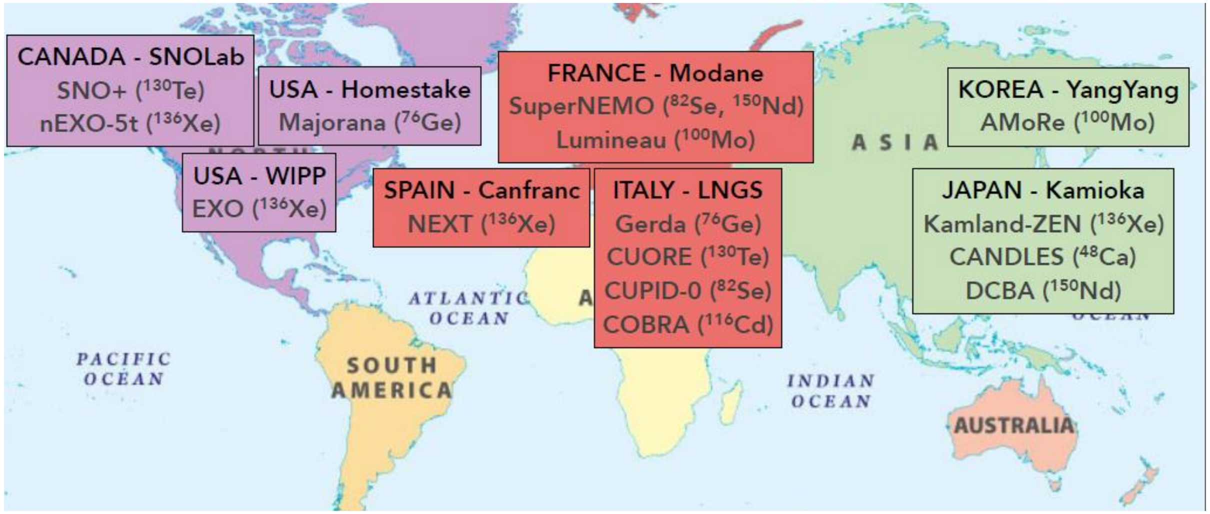
We want to be here: possible and likely

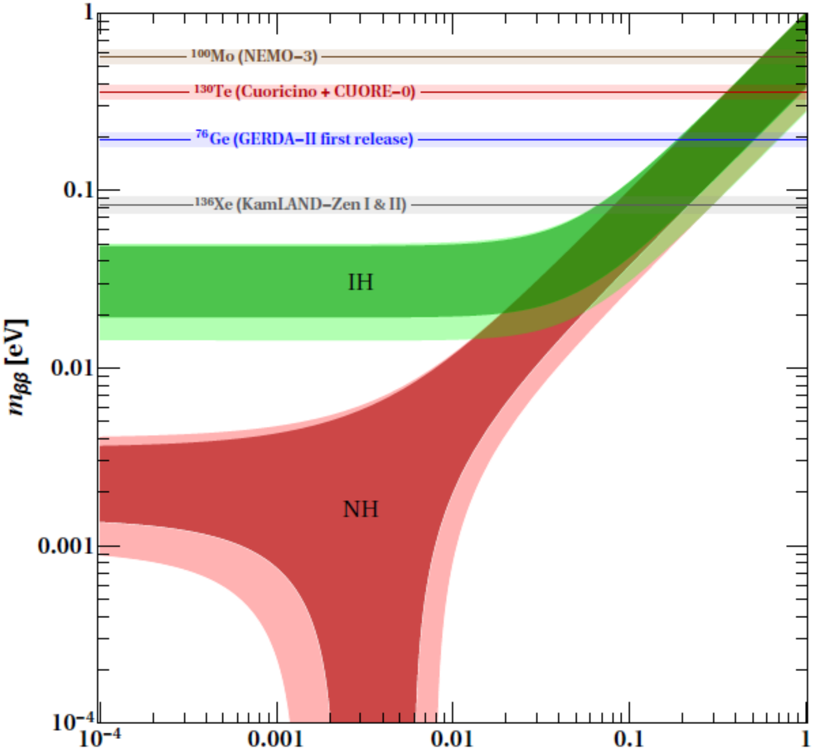
We are developing technologies that are able to explore NLDBD half-lifes at the level of 10^{26} y and that are potentially scalable up to 10^{28} y.

For “zero background experiments”, sensitivity ~ exposure

For finite background: sensitivity ~ $(\text{exposure})^{1/2}$

The present generation of NLDBD experiment





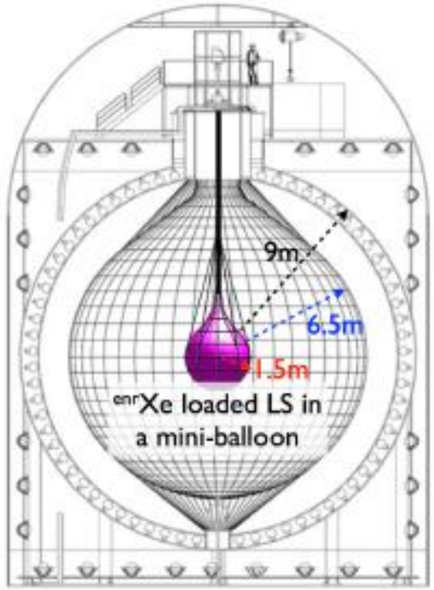
Osc. par.: F. Capozzi *et al.*, **Nucl. Phys. B 908, 218 (2016)**
NMEs (IBM-2): J. Barea *et al.*, **Phys. Rev. C 91, 034304 (2015)**
PSFs: J. Kotila, F. Iachello, **Phys. Rev. C 85, 034316 (2012)**
$g_A = 1.269$

Experiment sensitivities:
^{100}Mo: R. Arnold *et al.*, **Phys. Rev. D 92, 072011 (2015)**
^{130}Te: K. Alfonso *et al.*, **Phys. Rev. Lett. 115, 102502 (2015)**
^{76}Ge: M. Agostini, Presentation at Neutrino 2016
^{136}Xe: A. Gando *et al.*, **Phys. Rev. Lett. 117, 082503 (2016)**

Courtesy of S. Dell'Oro

Kamland-Zen (Japan)

The world leader in the field and the paradigm of a scalable, finite-background experiment



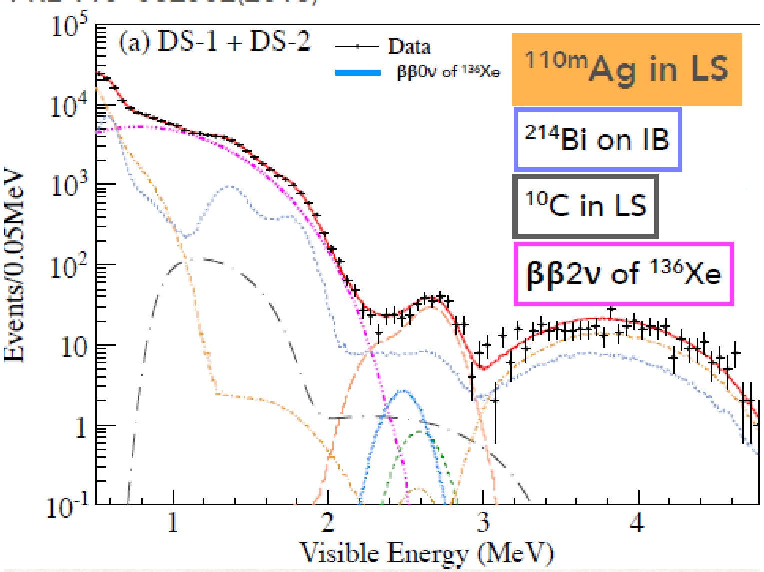
Isotope: ^{136}Xe, Q-value = 2458 keV

$T_{1/2} > 1.07 \times 10^{26}$ y (90 % CL)

- ✓ Active target 350 kg
- ✓ Energy resolution 4% at Q-value
- ✓ Position reconstruction: bkg rejection
- ✓ Bi-Po for ^{214}Bi, 3-fold coincidence for ^{10}C

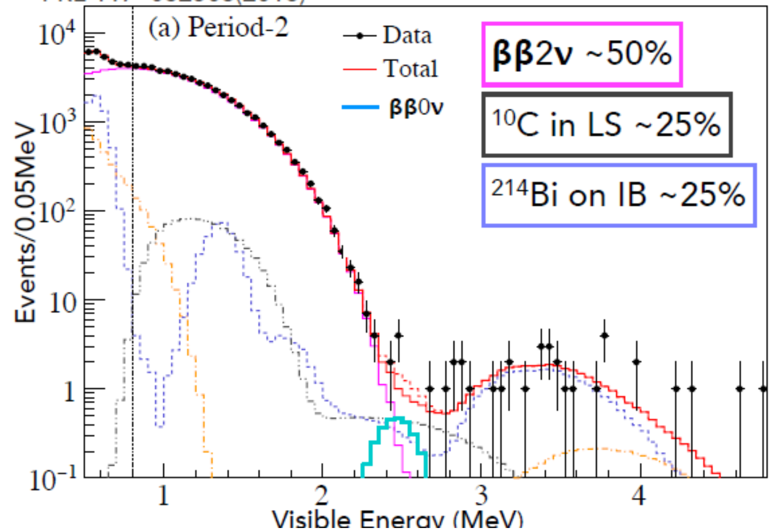
Unexpected background: ^{110m}Ag

PRL 110 062502(2013)



→ 18 months purification campaign

PRL 117 082503(2016)



The scalability of Kamland-Zen

Phase III (Kamland-Zen 800) : 750 kg of enriched Xe.

- ✓ New clean Inner Balloon to reduce ^{214}Bi
- ✓ Improve ^{10}C tag

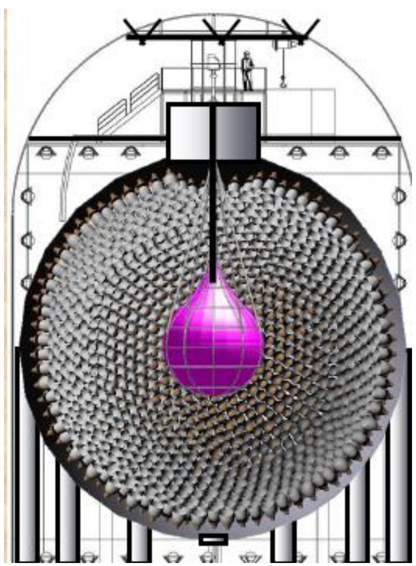
In progress. Slowed down by a leak in the balloon (see Y. Efremenko at MEDEX 2017)

Improvement in energy resolution steers the long-term plans of Kamland2-Zen

Winston cone	light collection ×1.8
high q.e. PMT 17"φ→20"φ ε=22→30+%	light collection ×1.9
New LAB LS (better transparency)	light collection ×1.4

expected σ(2.6MeV)= 4% → ~2%

target sensitivity 20 meV



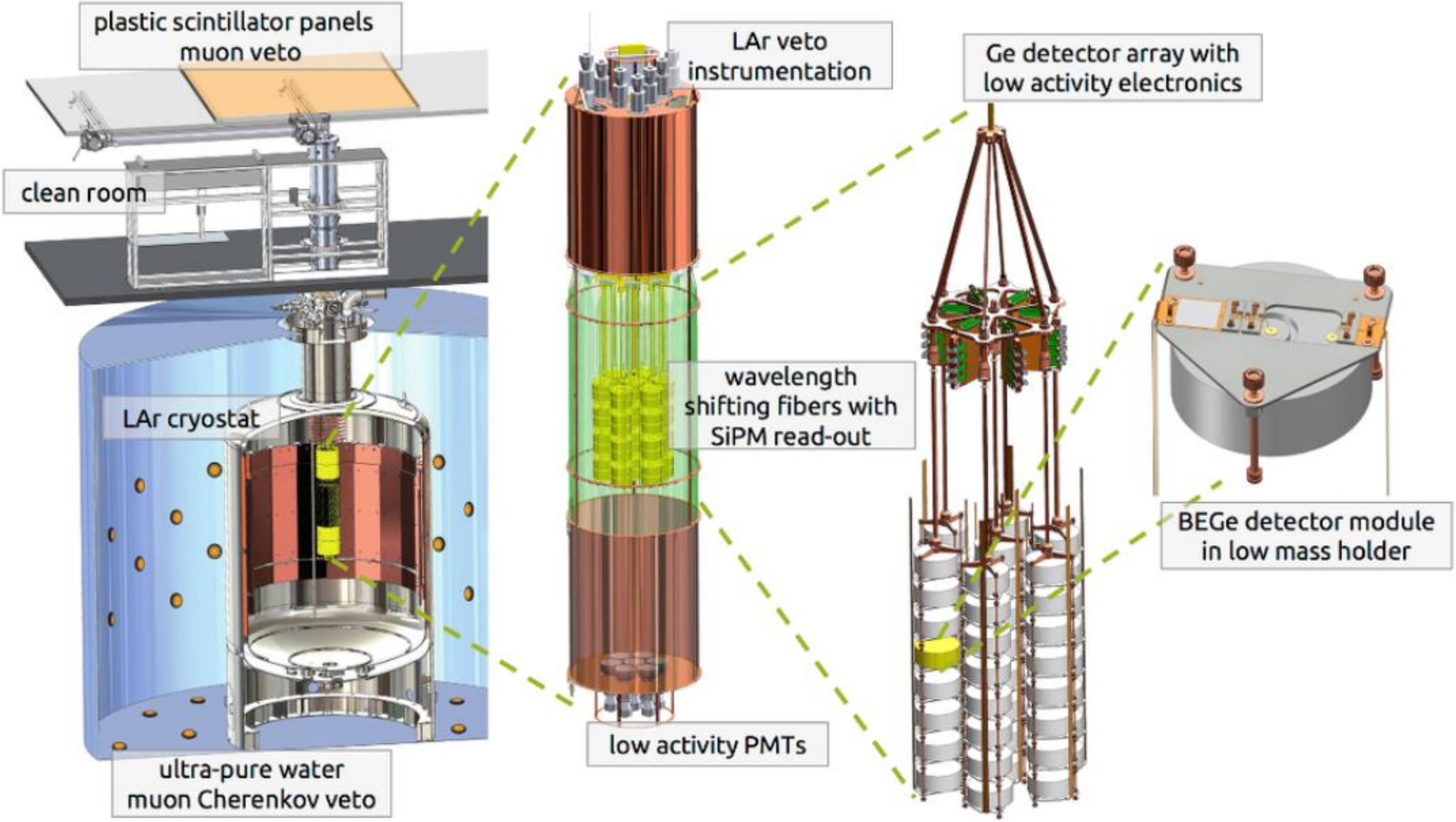
Ultimate facility:

SuperKamland-ZEN in parallel with HyperKamiokande ?

Similar consideraton apply to SNO+ (Canada)
Not covered in this review

GERDA (Gran Sasso, Italy)

The paradigm of a scalable, zero background experiment



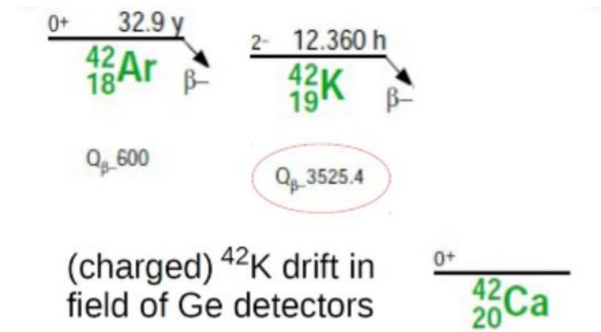
Isotope: ^{76}Ge, Q-value = 2039 keV

$T_{1/2}$ = 5.3 10^{25} y (90 % CL)

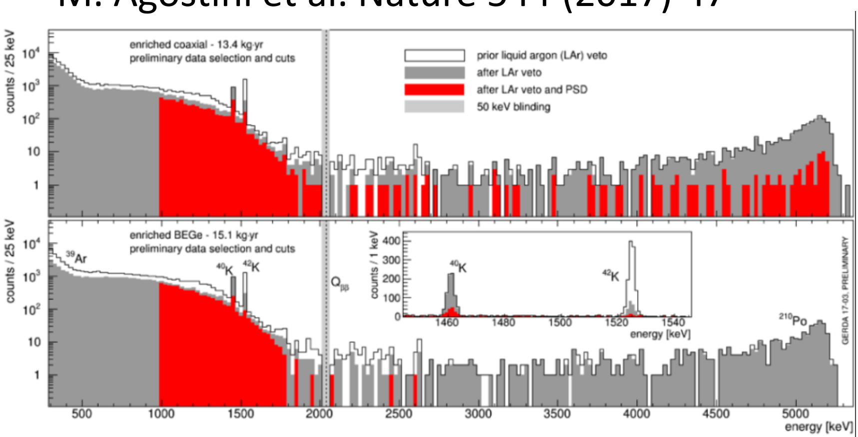
Both **GERDA** and **Majorana (US)** employ high-purity Germanium detector with 3 keV energy resolution at the ^{76}Ge Q-value. The 2ν "intrinsic" background is not an issue neither for the current nor for the next generation of experiment

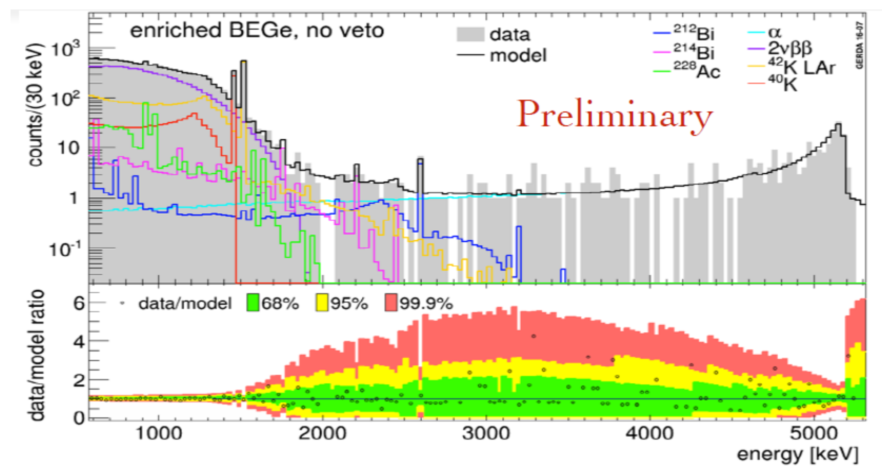
Unexpected background: ^{42}K

"Zero background" has been achieved in Gerda employing a liquid argon veto system and pulse shape analysis



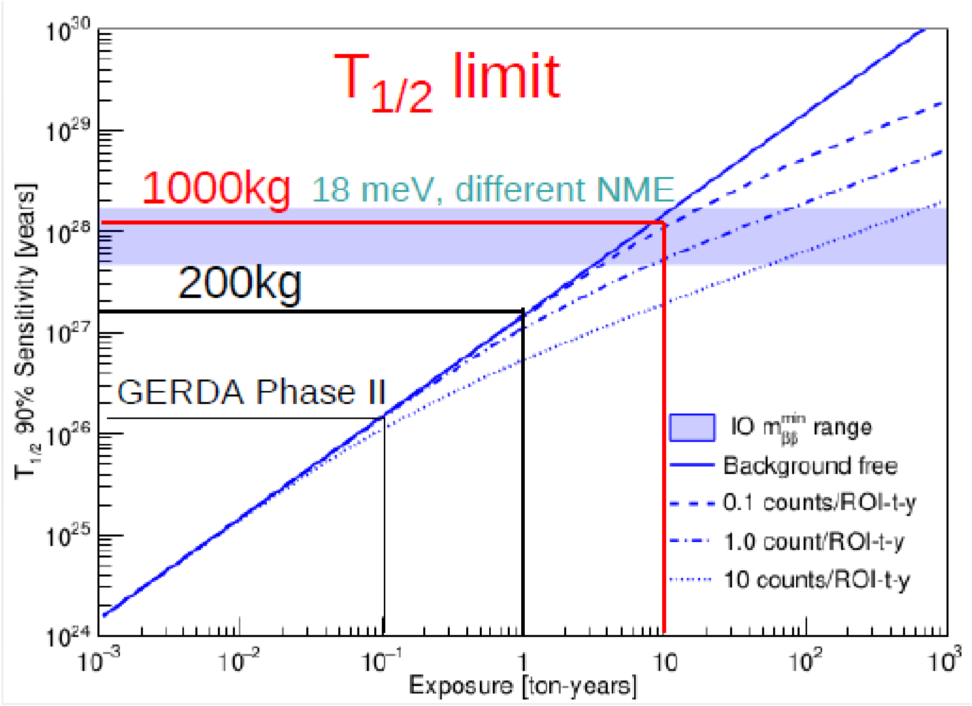
M. Agostini et al. Nature 544 (2017) 47





Background index: 0.6 10^{-3} counts/keV kg y

The scalability of GERDA and Majorana



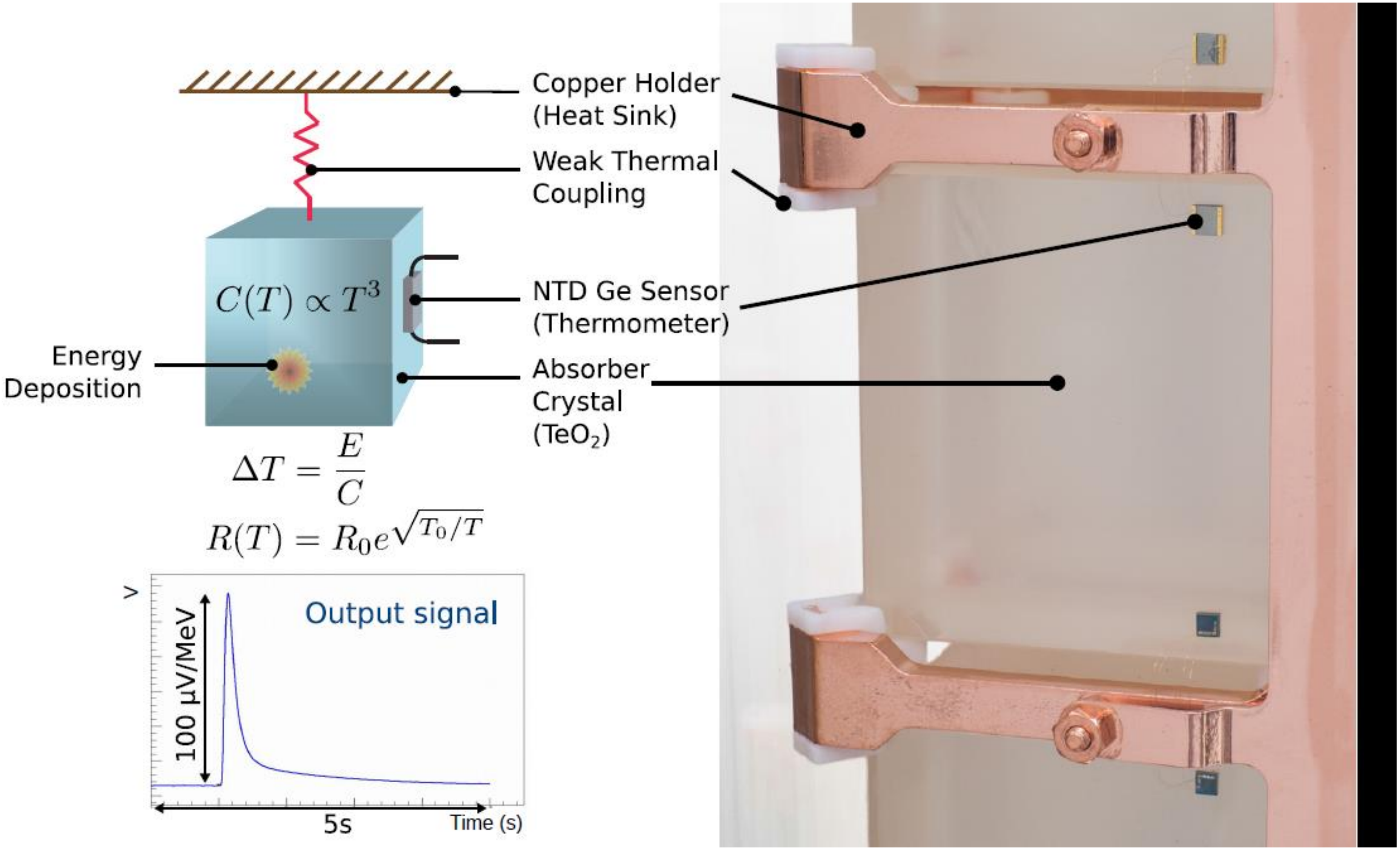
LEGEND (a new collaboration merging the expertise of GERDA and Majorana):

- up to 200 kg of ^{76}Ge in the present LNGS cryostat. Assume a reduction of 5 in background with respect to GERDA
- 1000 kg of ^{76}Ge in a new installation if Ge is chosen by the US down-select process. Further background reduction (1/30 of GERDA to stay in "zero background mode") is needed to fully exploit this facility.

See Talk of S. Schoenert

CUORE (Gran Sasso, Italy)

The largest bolometric experiment ever



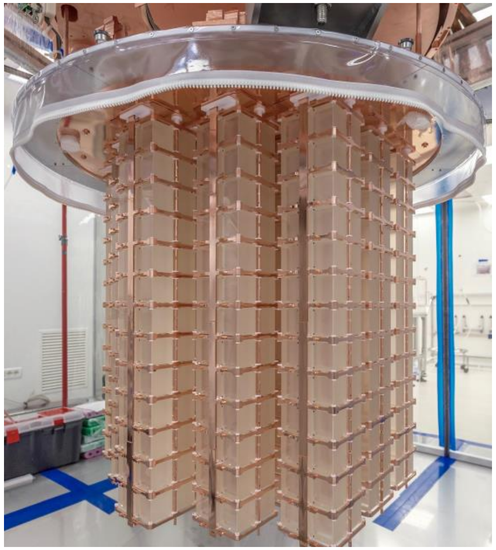
Isotope: ^{130}Te, Q-value = 2528 keV

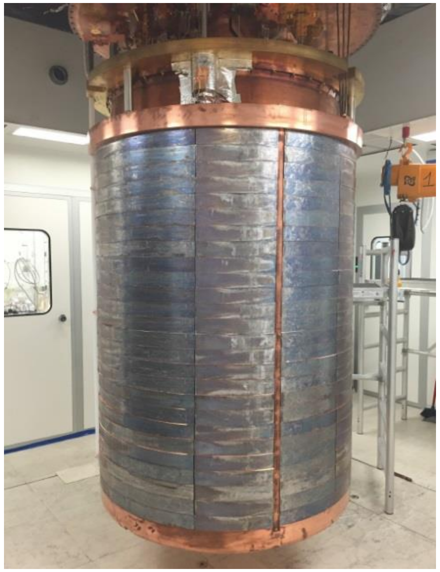
Mass: 206 kg of ^{130}Te (742 kg of TeO_2)
Detectors: 988 TeO_2 bolometers (5x5x5 cm^3)
working at **a temperature of about 10 mK**

$T_{1/2} > 4$~10^{24} y (90 % CL)
(combined CUORE-0 + Cuoricino)

K. Alfonso et al., Phys. Rev. Lett. 115, 102502 (2015)

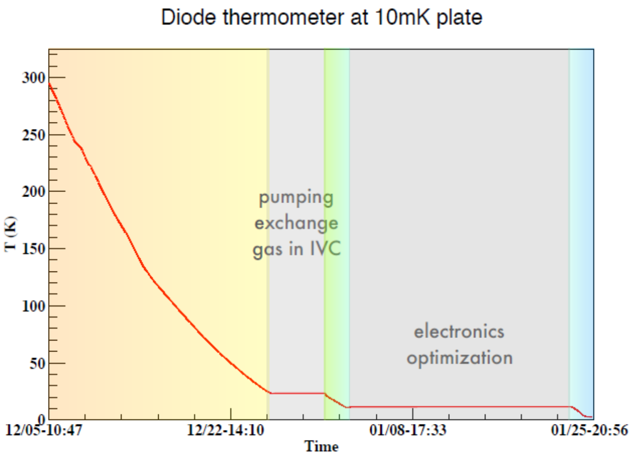
A very special year for CUORE



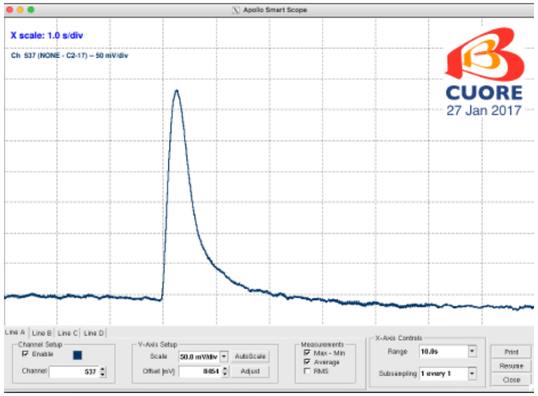


End of detector installation: Aug 2016

Shields, and electronics installed: Sep – Nov 2016



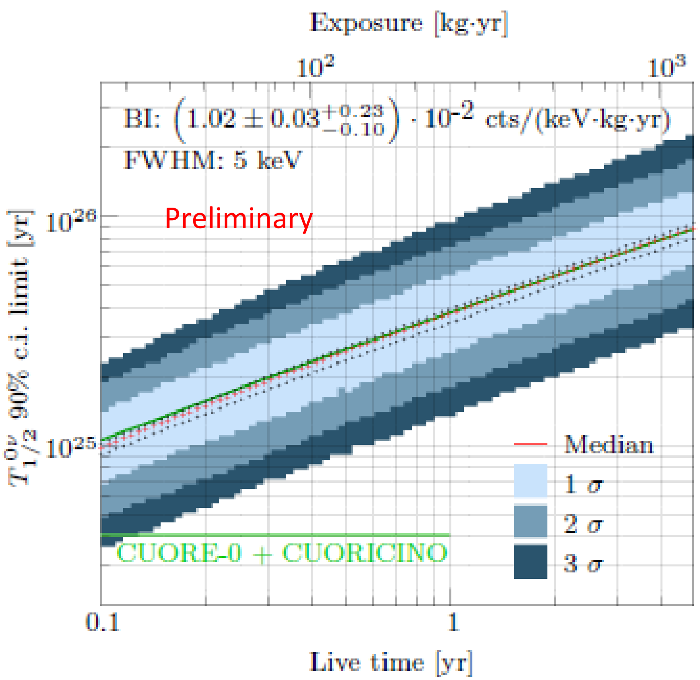
Detector cooled down to base temperature (7 mK)



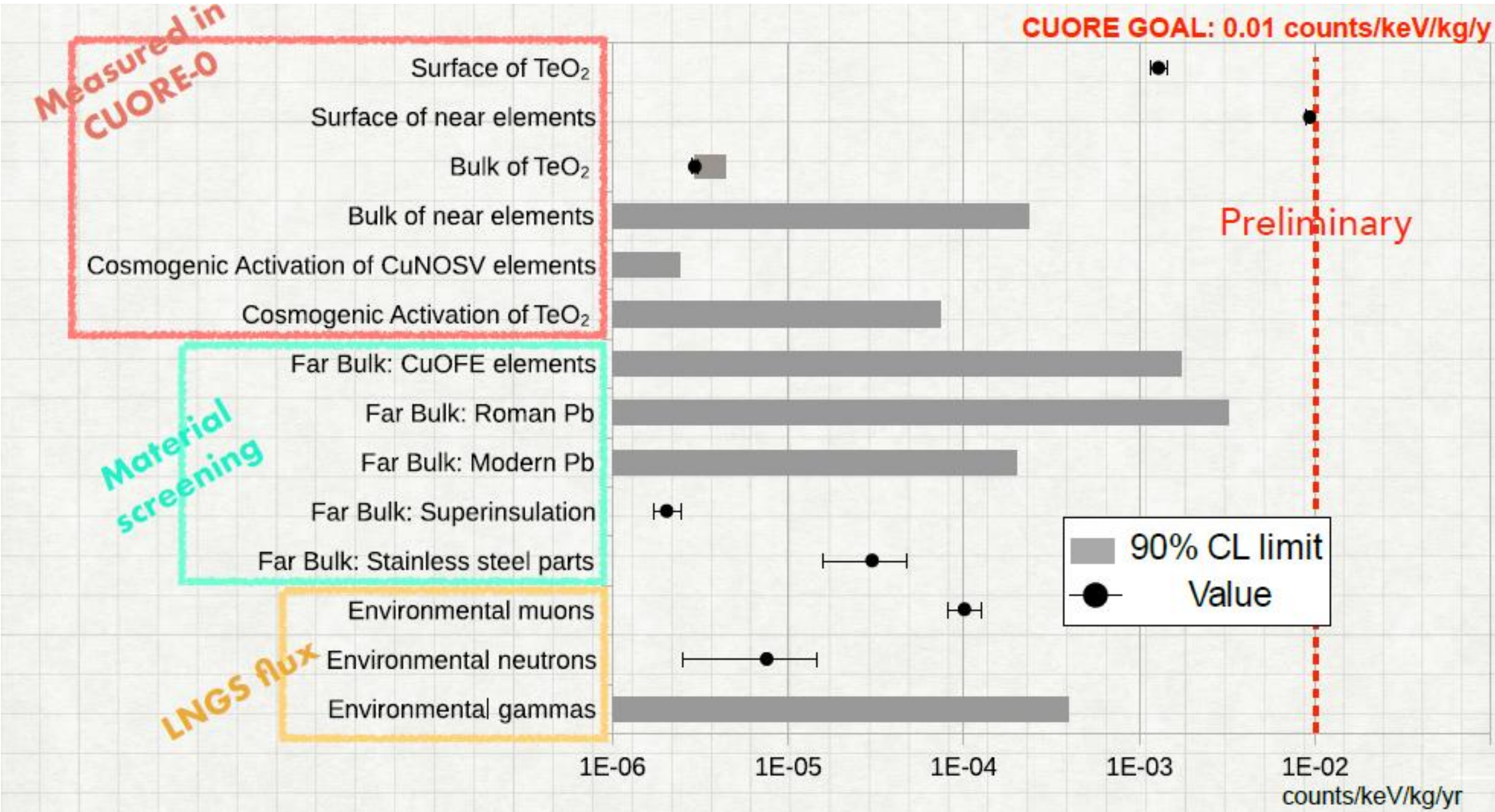
The first CUORE pulse (27 Jan)

End of commissioning and start of data taking: April 2017

Expected sensitivity:
C. Alduino et al.
arXiv:1705.10816



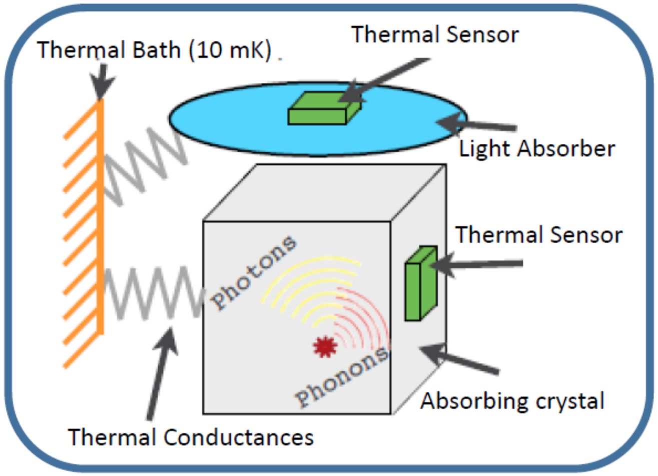
Background budget of CUORE



Background rejection in CUORE is achieved by the measurement of the energy deposited in the crystals, pulse-shape analysis and detector coincidences but…

Scalability of the bolometric technique

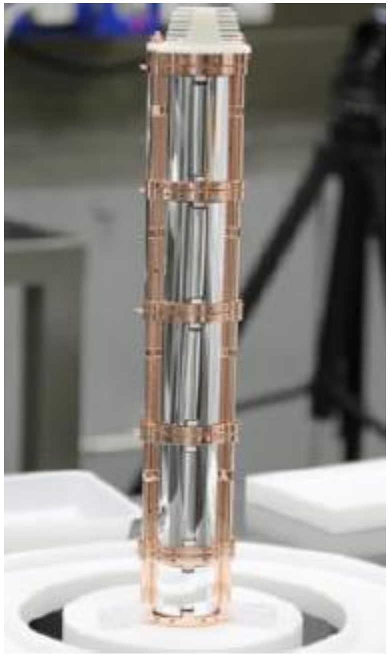
Bolometers offer additional opportunities to reach the 10^{-4} counts/kg keV y regime



Observation of photons in scintillating bolometers (CUPID-0)

Observation of Cherenkov photons or surface effects in TeO_2 crystals

G. Wang et al. [CUPID Coll.] arXiv:1504.03599



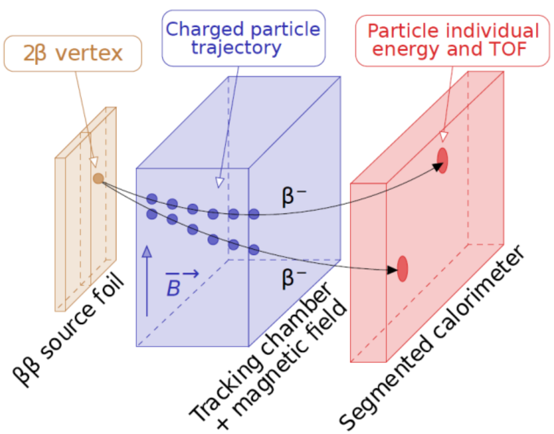
CUPID-0 (^{82}Se, SeZn bolometers) expected background

Eur. Phys. J. C76 (2016) 7, 364.

Background at ^{82}Se $Q_{\beta\beta}$ (counts/keV/kg/y)	
after α discrimination	4×10^{-3}
coincidences rejection	2.3×10^{-3}
^{208}Tl – ^{212}Bi time delay rejection	1×10^{-3}
+ cryostat γ contamination	$< 1.5 \times 10^{-3}$

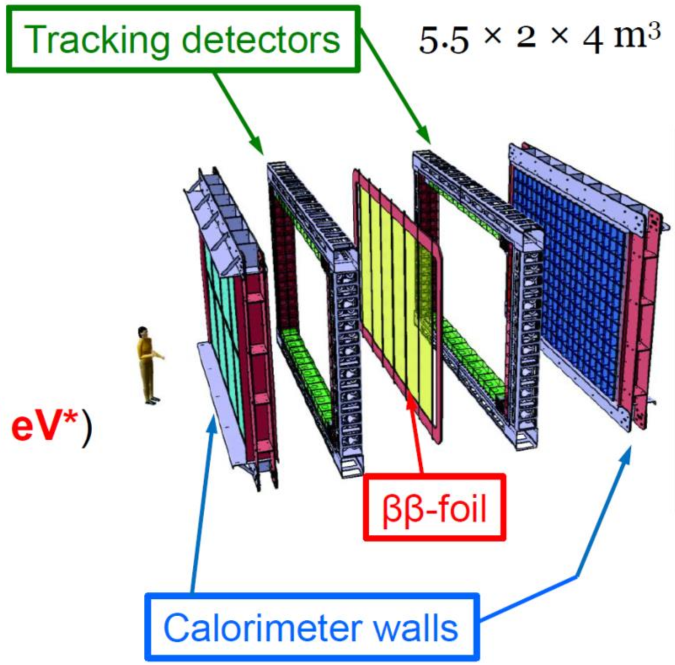
SuperNEMO (Modane, France)

- Modular geometry (20 modules)
- Planned start: **2017**
- Placed in **LSM** (Modane, FRA)
- Studied isotope: **^{82}Se**



7 kg of isotope (**100+ kg***)
$0\nu\beta\beta$: $T_{1/2} > 6\text{x}10^{24}$ yr (**10^{26} yr***).
Limit $m_{\beta\beta}$: 0,2-0,4 eV (**0,04 -0,11 eV***)

* Full SuperNEMO design = 20 modules



Maximum flexibility in the choice of the isotope: **source outside detector** (^{82}Se, ^{150}Nd, ^{100}Mo) and outstanding precision in the **topology reconstruction**.
It comes at the expenses of scalability and energy resolution

NEMO 2,3

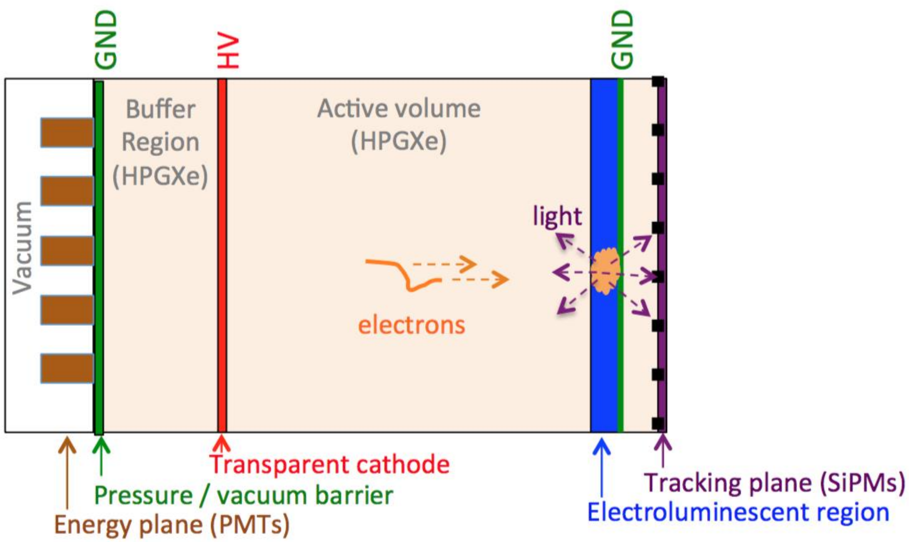
Isotope	$T_{1/2}$ (yr)
^{82}Se	2.1×10^{23}
^{100}Mo	1.1×10^{24}
^{116}Cd	1.6×10^{22}
^{96}Zr	8.6×10^{21}
^{150}Nd	1.8×10^{22}
^{48}Ca	1.3×10^{22}

NEXT (Canfranc, Spain) and (n)EXO (US)

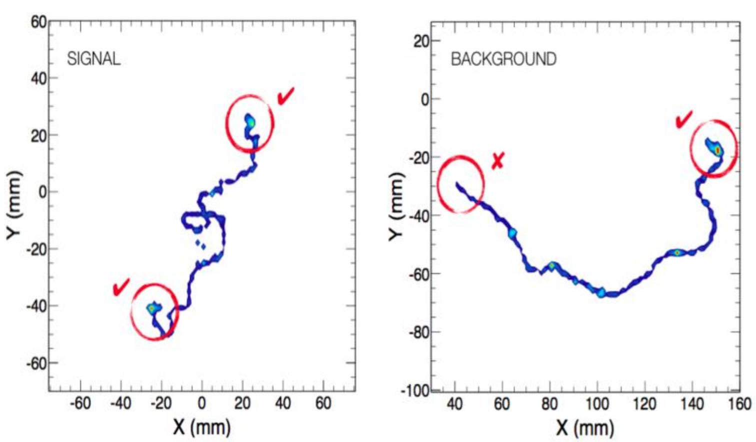
It is fortunate that ^{136}Xe is both a NLDBD candidate and a noble gas!

Isotope: ^{136}Xe, Q-value = 2458 keV

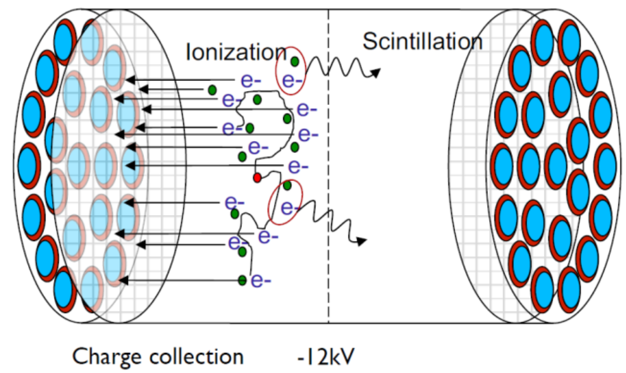
$T_{1/2} = 1.1\ 10^{25}$ y (90 % CL) (EXO-200)

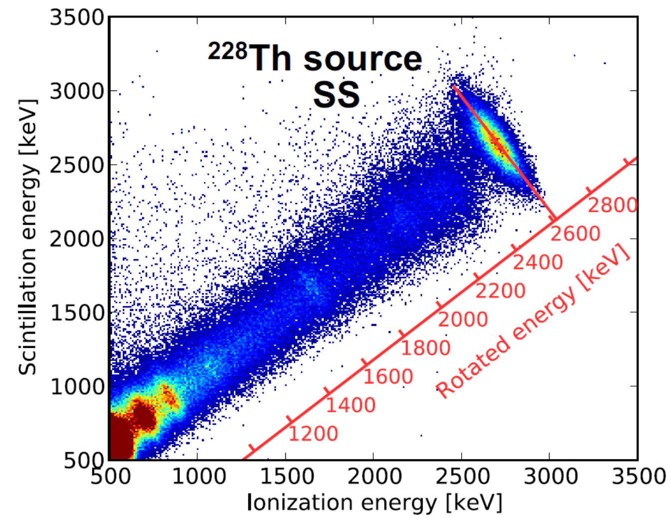


High pressure gas TPC



Liquid Xe TPC





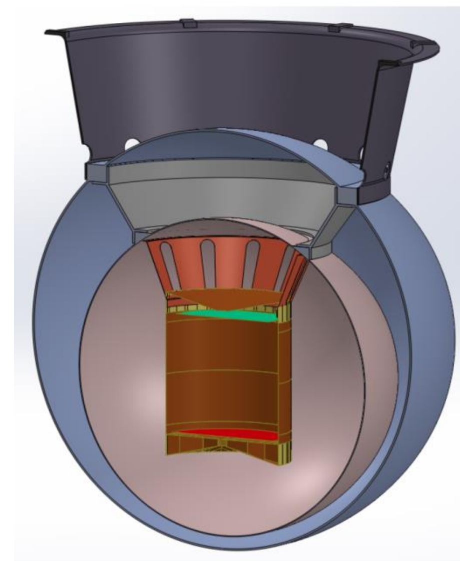
V. Alvarez et al, JINST 7 (2012) T06001

J.B. Albert et al, Nature 510 (2014) 229

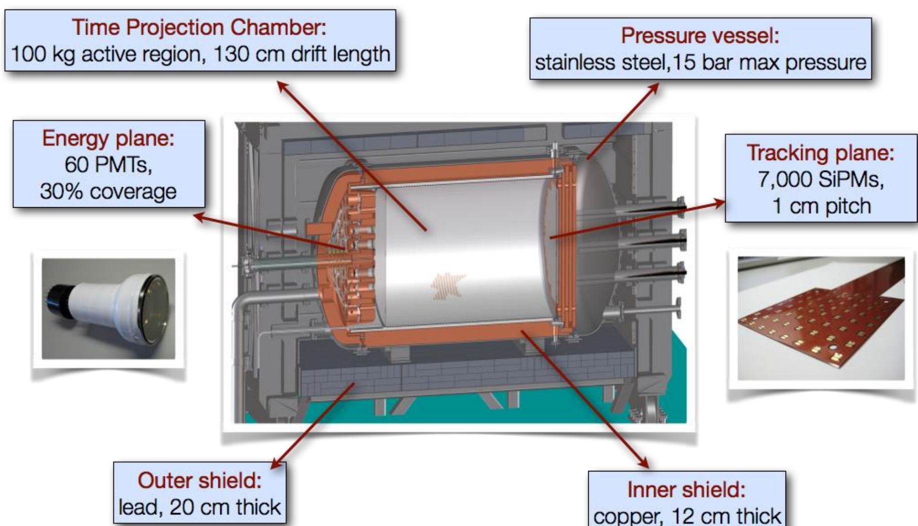
Scalability of the Xe-TPC techniques

Both options have still large scalability potential using conventional techniques (**self shielding**, radio-purity assessment, background mitigation). Non conventional options (Ba tagging, diffusion reduction with dopants) under study.

nEXO (ton scale) at SNOLAB



NEXT-100 (100 kg scale)



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Improvement	Reason
About 30× mass	Sensitivity to cover inverted hierarchy
Remove cathode from middle	Provide larger LXe-only volume in the middle with lower backgrounds.
6× high voltage	Required to enable a longer drift length
$>3\times$ electron lifetime	Required to enable a longer drift length
Increased photo-coverage	Energy resolution (to 1% σ/E), lower scintillation threshold
SiPMs instead of APDs	Higher gain, lower bias, better energy resolution, lower scintillation threshold, less material, lower radioactivity.
In LXe front end electronics	Lower noise, fewer cables, lower threshold to ID Compton
Low outgassing materials	Longer electron lifetime from higher purity LXe
New calibration methods	Required to calibrate “deep” detector
Deeper site	Reduced cosmogenic activation
Charge tiles instead of wires	3mm position resolution, simpler/smaller mechanical supports, lower radioactivity

Conclusions

Why **interest in NLDBD is growing** even if experimental searches started more than 70 years ago?

- ✓ Because the physics case became very strong after the discovery of neutrino oscillations
- ✓ Because the precise knowledge of mixing parameters drives our efforts toward the $T_{1/2} = 10^{26} - 10^{28}$ y half life range

Are the experimental techniques **mature enough**?

- ✓ $T = 10^{26}$ y is the present of NLDBD and major results are coming at very high speed:

  EXO-200 (Nature, 2014), Kamland-Zen (PRL 2016), Gerda (Nature 2017) …. easy to predict that others will come soon (CUORE, e.g., is in data taking)

- ✓ Most of the technologies are **scalable**. The most promising remains: liquid scintillators, germanium, bolometers, tracking (e.g. with TPC) but we should keep an eye on **ongoing R&D's** (not covered in this talk)

Can a PhD student make a **breakthrough** in this field?

- ✓ Yes. No clear path to reach the $T = 10^{29}$ y, which remains very interesting from the point of view of parameter spaces.