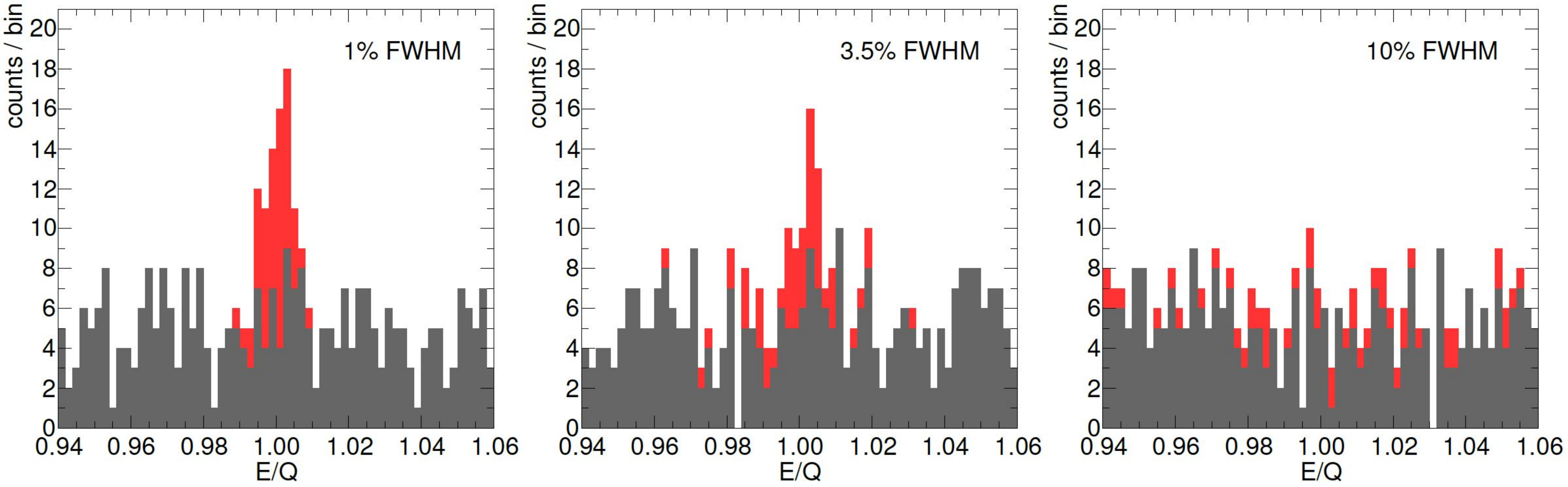
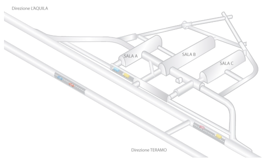
Energy Resolution



Energy resolution is extremely important to disentangle signal from background

Especially on irreducible experimental background

Experimental Background



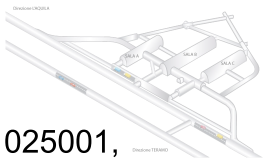
Background sources:

- external (**cosmic rays**, γ from natural chains, Rn, μ, neutrons)
- internal (cosmogenic, material bulk/surface, **2vββ decay**)

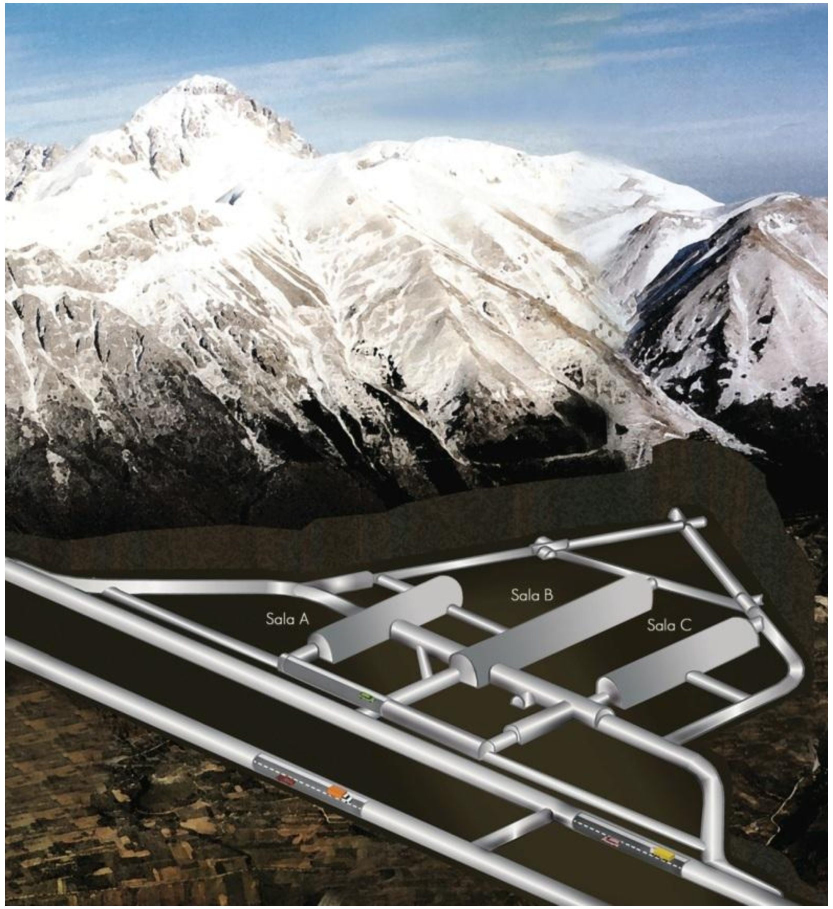
Reduction strategies:

- Select isotope with **high Q-value** (eg. ^{48}Ca, ^{82}Se, ^{100}Mo, ^{150}Nd)
- **Good energy resolution** (for 2vββ bkg a ΔE<2% is needed)
- **Underground operation** to reduce cosmic rays and cosmogenic component (eg. LNGS ~ 3650 m.w.e.)
- **A massive shield** (high radio-purity) against environmental radioactivity (Pb, electro-formed Cu, pure liquids...)
- An active veto against residual cosmic μ's
- **Careful material assay** for detector and set-up construction
- **Particle identification** (tracking, PSA, light/heat...)
- Spectroscopic identification of daughter nucleus ($^{136}Ba^{++}$ tag)

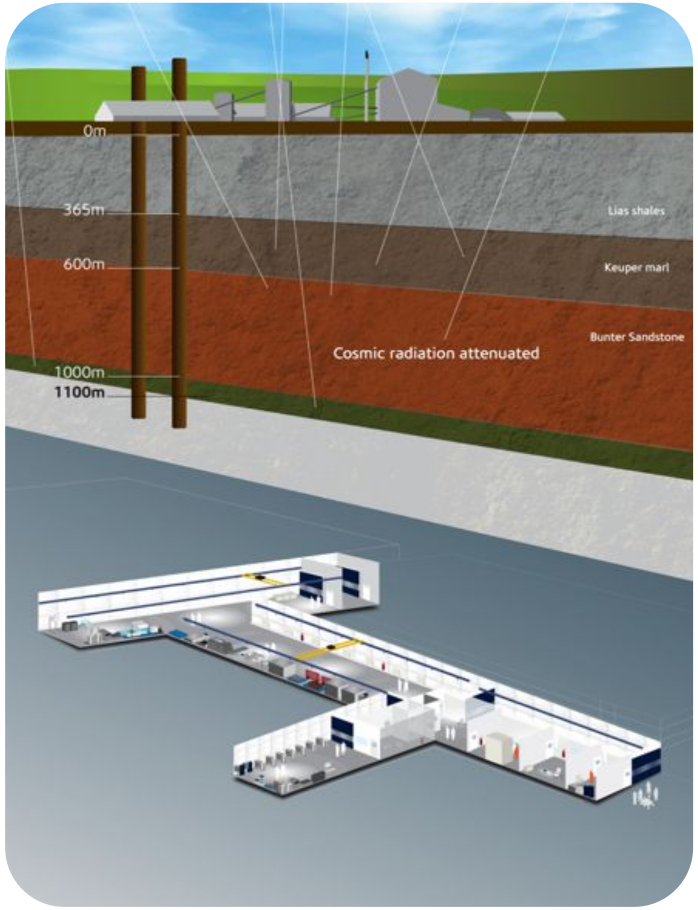
Underground Laboratories



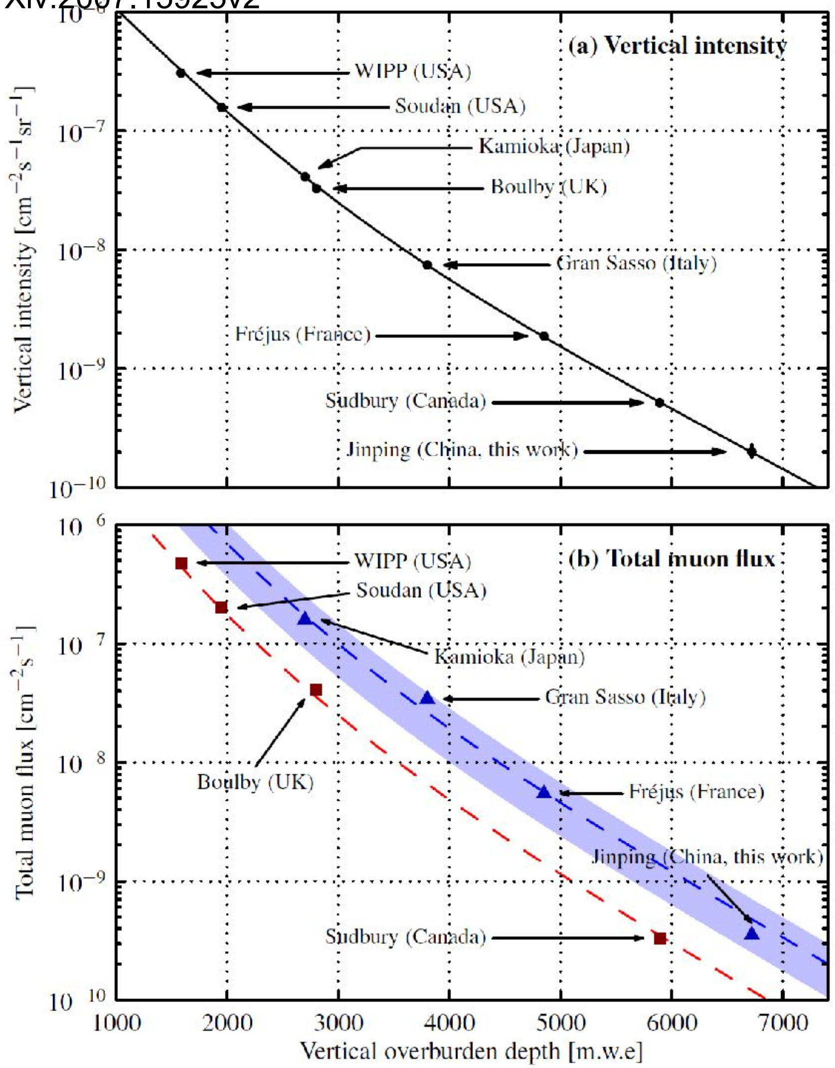
Mountain shielding
Tunnel Access



Flat shielding
Shaft Access

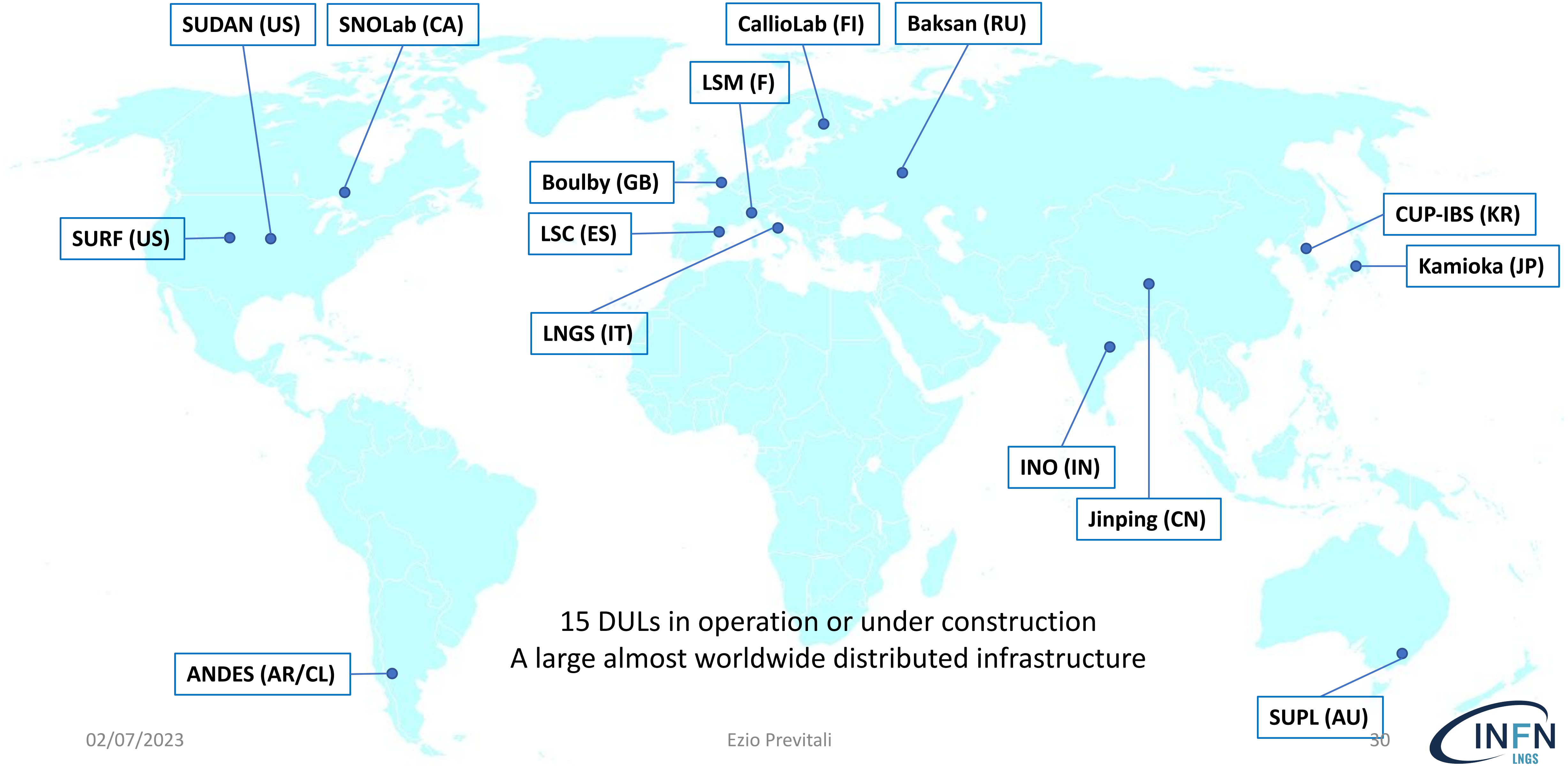


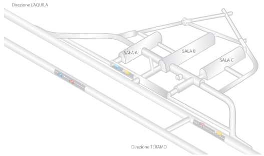
Guo et al., Chinese Physics **C45** (2021) 025001, arXiv:2007.15925v2



INFN LNGS

Underground Laboratories

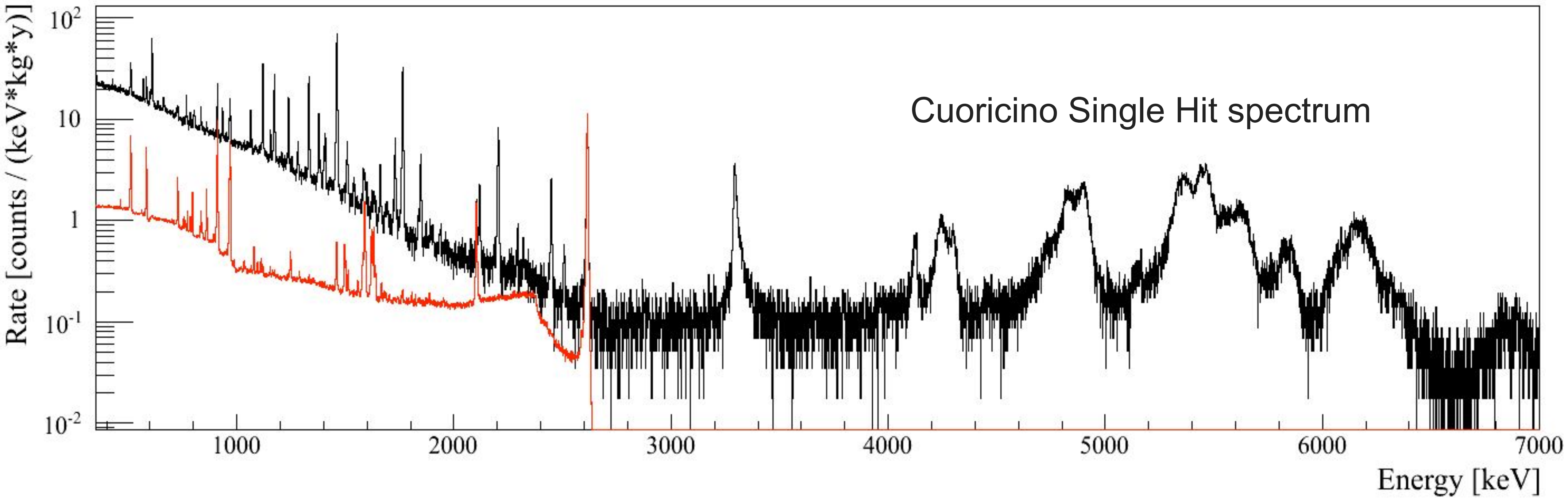




15 DULs in operation or under construction
A large almost worldwide distributed infrastructure

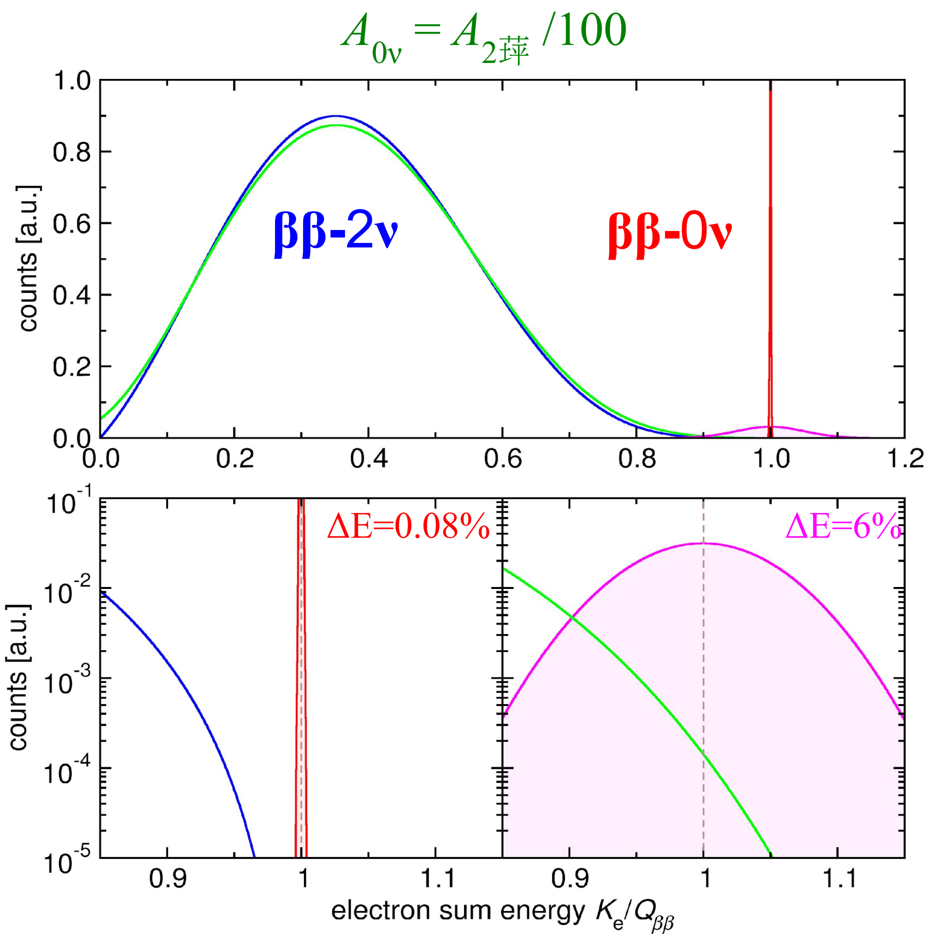
Experimental Background

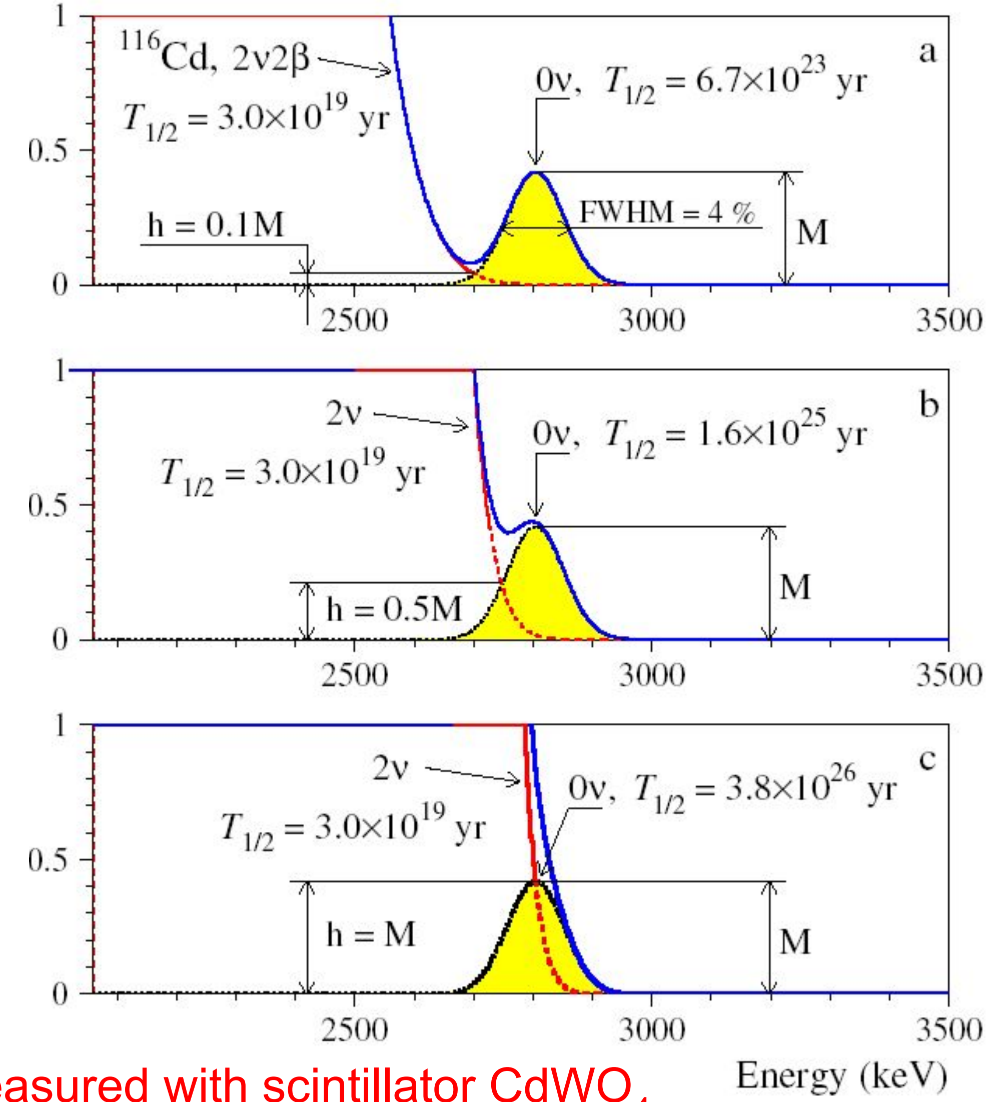
- Material screening with the required sensitivity (less then ppt) is quite difficult
- Required sensitivities could be reached only by the experiments
- An intermediate mass experiment is often required



2νDBD effects on background

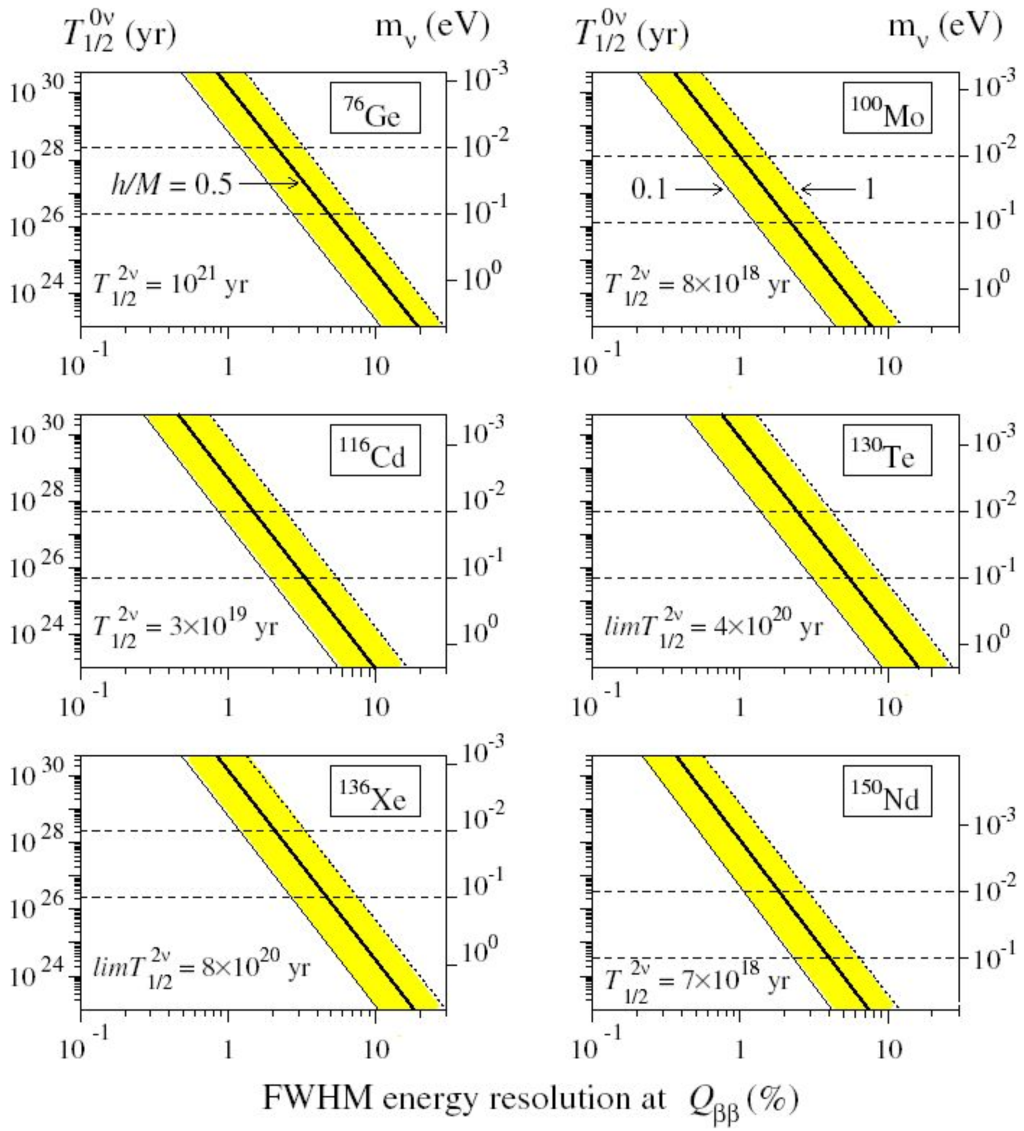
- ββ-2ν is a background source
- detector energy resolution critical





^{116}Cd measured with scintillator $CdWO_4$

2vDBD effects on background



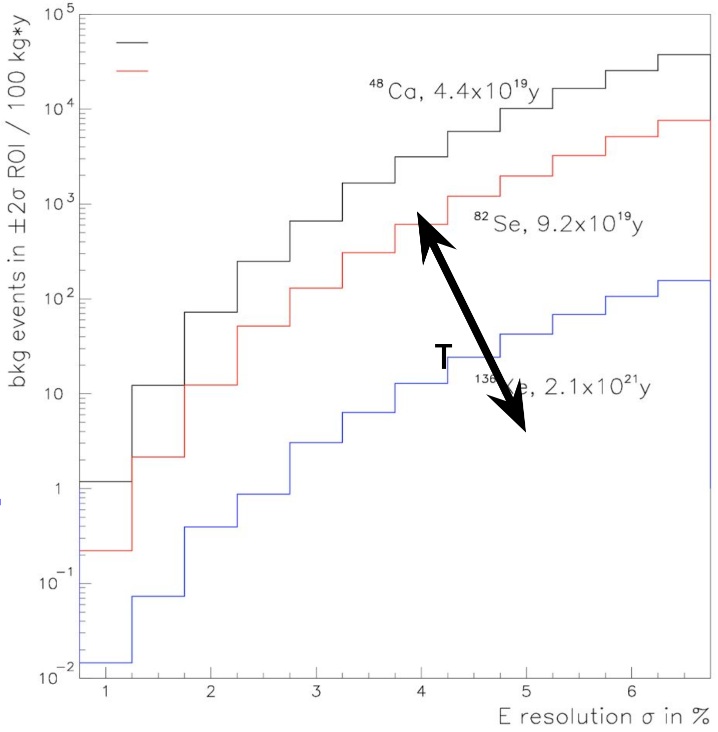
Energy resolution and ββ-2ν lifetime is critical

ββ ^{67}Ge → **HPGe diodes**

ββ ^{116}Cd → **$CdWO_4$ scint.**

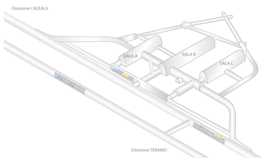
ββ ^{130}Te → **TeO_2 bolometer**

ββ ^{136}Xe → **Xe TPCs**



2vββ fraction in 0vββ ROI

Requested screening facilities



Material selection and screening
- HPGe facilities
- Alpha counting
- ICP-MS

Clean materials production and treatments
- Cu electro-forming
- Advanced additive manufacturing
- Ultra-pure water and gas

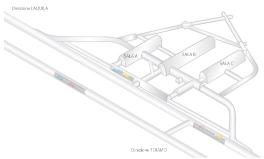
Clean environments for detector constructions
- Radon abatement systems (1000x Rn reduction)
- Clean rooms (ISO5, ISO6)
  Radon-free clean rooms

Environmental monitoring e control
- Sensitive radon detectors (<mBq/m^3)
- Monitoring blanket

Crystal growing facilities

………….

Experimental Approaches



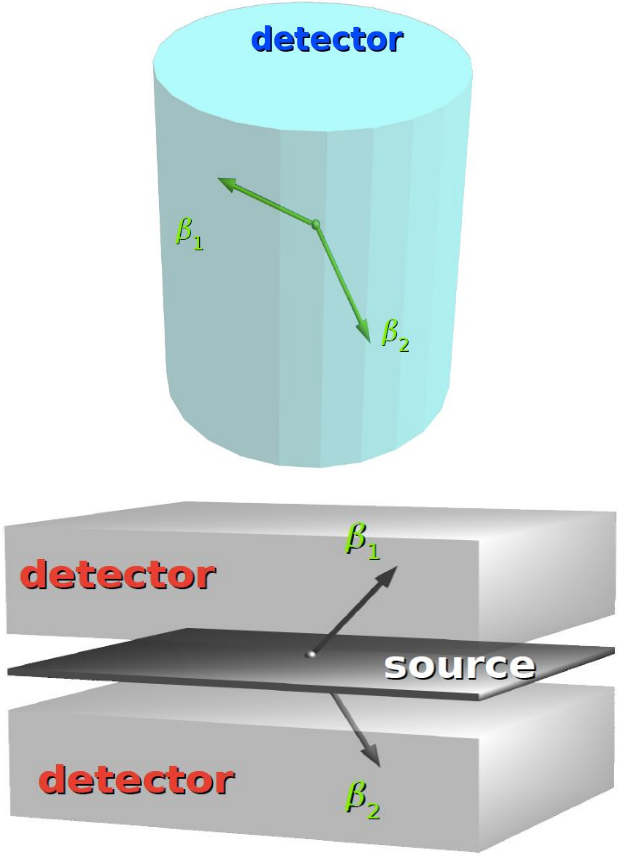
Two main approaches:

- homogeneous (calorimetric or active source)
- inhomogeneous (external-source or passive source)

Calorimeters
Solid-state devices, bolometers, scintillators, gas detectors

+ Very large M possible (~10kg → tons)
+ High efficiency (ε~1)
+ Very high energy resolution (ΔE~0.15% with Ge-diodes, bolometers)
+ Event topology (in gas/liquid Xe detectors or pixellization)
+ Good background levels

- Constraints on detector material (except for bolometers)
- No or partial particle id



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

+ Event topology allowing ¨clean bkg¨ (except $2\nu\beta\beta$)

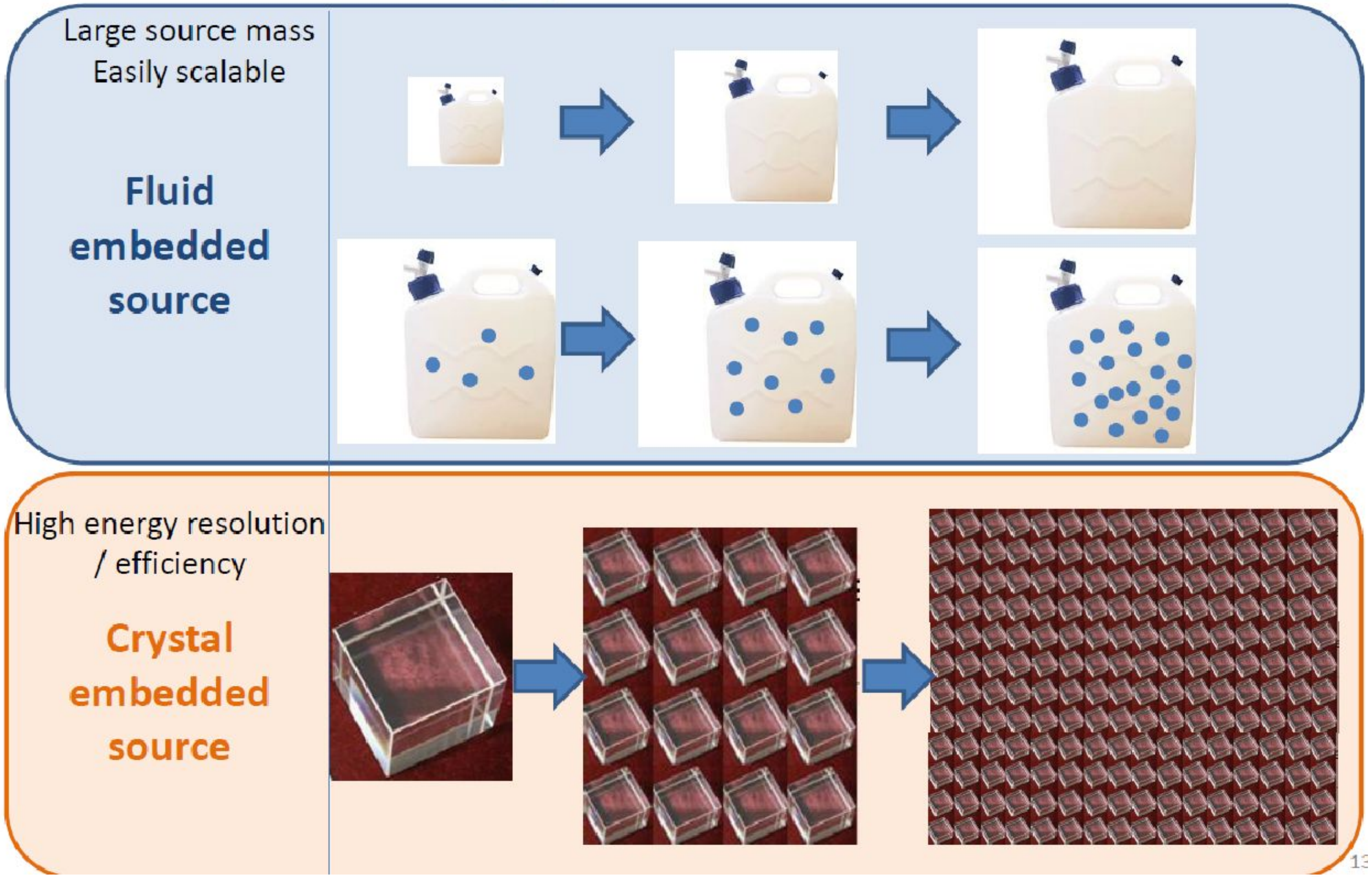
Calorimetric approaches

Fluid sources or sources diluted in a fluid

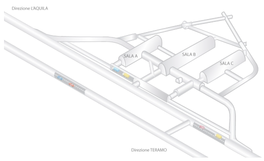
Very good scalability
- increase masses
- increase concentration

Fluid sources or sources diluted in a fluid

Good scalability
- increase single mass
- increase crystal number

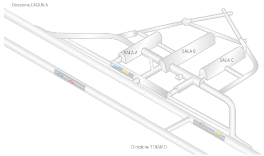


Fluid embedded sources



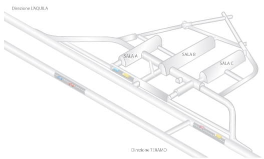
	Helpful	Harmful
Internal Origin	**Strengths** ➢ Source=Detector ➢ Scalability ➢ Large compatibility with isotope ^{136}Xe ➢ Compatibility with isotope ^{130}Te ➢ Possibility of extreme purification of fluids ➢ Fiducialization, delayed coincidence, tracking, single vs multisite events for background reduction (according to technique)	**Weaknesses** ➢ In most of technologies, low energy resolution ➢ No compatibility with high Q-value (> 2615 keV) isotopes ➢ In “dilution approach” (SNO+, KamLAND) low efficiency (isotope mass much smaller than active mass)
External Origin	**Opportunities** ➢ Use of existing facilities (SNO+, KamLAND, Borexino) ➢ Use of well-established technologies (liquid scintillators, TPC)	**Threats**

Crystal embedded sources



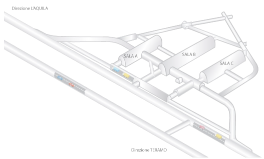
	Helpful	Harmful
Internal Origin	**Strengths** ➢ Source=Detector ➢ Modularity ➢ Compatibility with numerous isotopes (^{76}Ge, ^{100}Mo, ^{82}Se, ^{116}Cd – the last three with Q-values > 2615 keV) ➢ High energy resolution ➢ High efficiency ➢ Particle- or event-type discrimination	**Weaknesses** ➢ No tracking ➢ Scalability possible but costly and complicated ➢ Complicated enrichment-crystallization-purification chain
External Origin	**Opportunities** ➢ Well-studied precursors (Heidelberg Moscow, IGEX, GERDA, Majorana, Cuoricino, CUORE-0, CUORE, CUPID-0, CUPID-Mo)	**Threats**

External sources



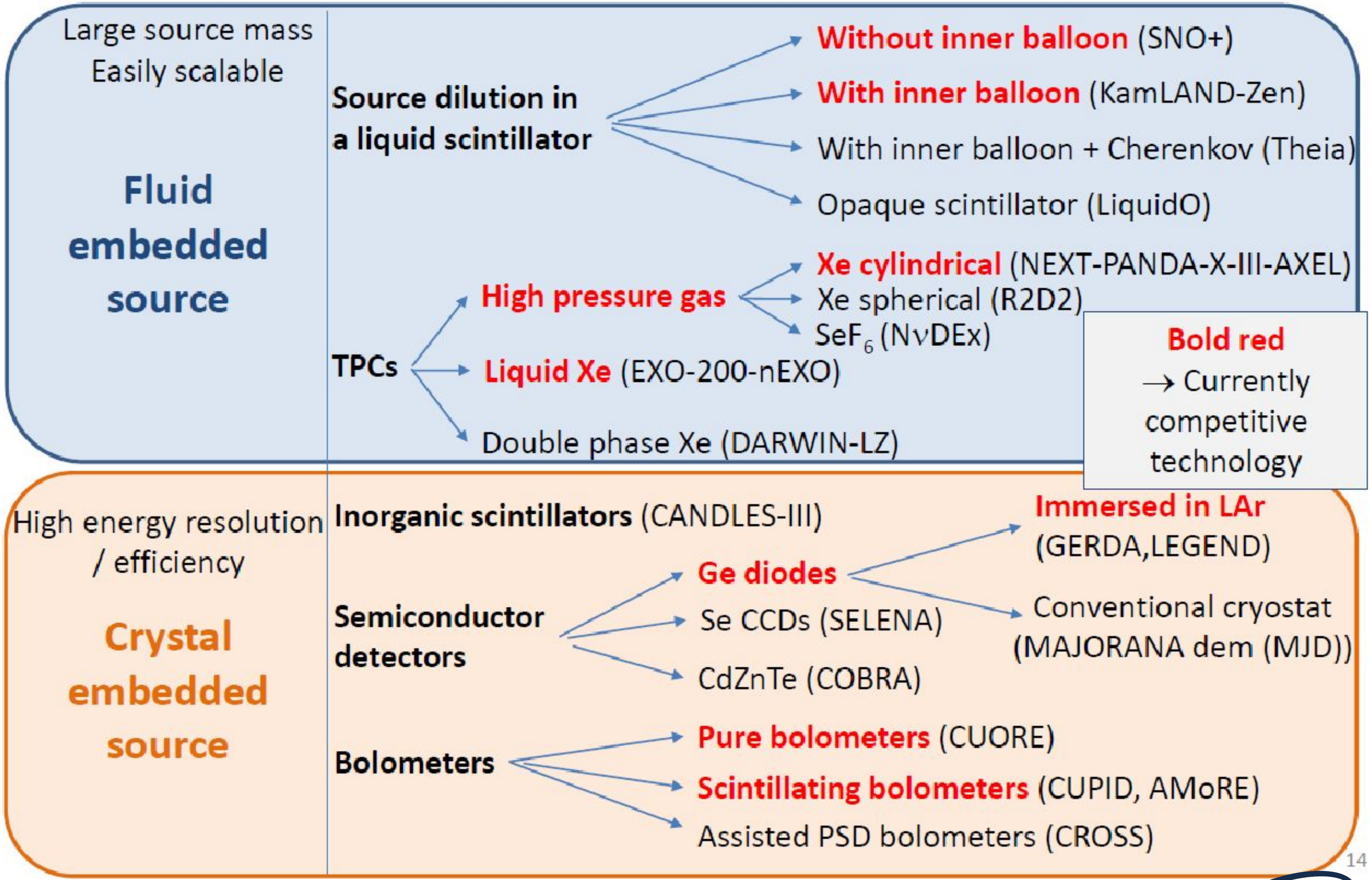
	Helpful	
Internal Origin	**Strengths** ➢ Modularity ➢ Compatibility with all isotopes in principle ➢ Full event reconstruction ➢ Information on the mechanism ➢ Excellent opportunity to study Majoron mode	**Weakness** It will be extremely difficult to scale masses and efficiencies of the sources
External Origin	**Opportunities** ➢ Well-studied precursor (NEMO3)	

Calorimetric strategies



Easy to clean
Pulse shape analysis
Self shielding (fiducial vol.)

Very pure crystals
Pulse shape analysis
(Anti)Coincidence selection



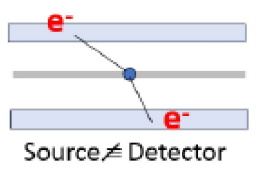
Large number of “possible” experiments

There is a very large number of proposed experiments

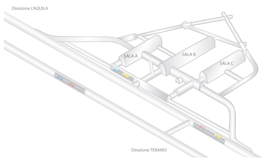
Completed – Red
Ongoing – Green
Commissioning – Blu
R&D - Black

	Experiment	Technique	Isotope
Large source mass Easily scalable	NvDEx	High pressure TPC	^{82}Se
	ZICOS	Dilution in liquid scintillator+Cherenkov	^{96}Zr
	SNO+	Dilution in liquid scintillator	^{130}Te
	SNO+-Phase II	Dilution in liquid scintillator	^{130}Te
	Theia	Dilution in liquid scintillator+Cherenkov	^{130}Te-^{136}Xe
Fluid embedded source	KamLAND-Zen 400	Dilution in liquid scintillator	^{136}Xe
	KamLAND-Zen 800	Dilution in liquid scintillator	^{136}Xe
	KamLAND2-Zen 800	Dilution in liquid scintillator	^{136}Xe
	EXO-200	Liquid TPC	^{136}Xe
	nEXO	Liquid TPC	^{136}Xe
	NEXT-White	High pressure TPC	^{136}Xe
	NEXT-100	High pressure TPC	^{136}Xe
	NEXT-HD / NEXT-BOLD	High pressure TPC	^{136}Xe
	PANDAX-III	High pressure TPC	^{136}Xe
	AXEL	High pressure TPC	^{136}Xe
	DARWIN	Double-phase TPC	^{136}Xe
	LZ	Double-phase TPC	^{136}Xe
	R2D2	High pressure TPC *I. Katsioulas, this conference*	^{136}Xe
	LiquidO	Dilution in opaque liquid scintillator	multi
High energy resolution / efficiency	CANDLES-III	Scintillators	^{48}Ca
	CANDLES-IV	Scintillating bolometers *J. Minami, this conference*	^{48}Ca
	MAJORANA DEM.	Semiconductor detectors	^{76}Ge
	GERDA	Semiconductor detectors	^{76}Ge
	LEGEND-200	Semiconductor detectors	^{76}Ge
	LEGEND-1000	Semiconductor detectors	^{76}Ge
Crystal embedded source	CDEX-300 / CDEX-1000	Semiconductor detectors *Qian Yue, this conference*	^{76}Ge
	SELENA	Semiconductor detectors	^{82}Se
	CUPID-0	Scintillating bolometers	^{82}Se
	CUPID-Mo	Scintillating bolometers	^{100}Mo
	AMORE-I	Scintillating bolometers	^{100}Mo
	AMORE-II	Scintillating bolometers	^{100}Mo
	CUPID	Scintillating bolometers	^{100}Mo
	CUPID Reach / CUPID-1T	Scintillating bolometers	^{100}Mo
	COBRA	Semiconductor detectors	^{116}Cd
	TIN-TIN	Bolometers	^{124}Sn
	CUORE	Bolometers	^{130}Te
	CROSS	Scintillating bolometers	^{100}Mo-^{130}Te
	BINGO	Scintillating / Cherenkov bolometers	^{100}Mo-^{130}Te

SuprNEMO demonstrator | Tracking + Calorimeter | ^{82}Se



Current sensitivities



$T_{1/2} > 10^{24}$ y 90% C.I. restricted club

GERDA $T_{1/2} > 1.8\times10^{26}$ y
Phys. Rev. Lett. 125, 252502 (2020)

KamLAND-Zen 400 $T_{1/2} > 1.07\times10^{26}$ y
Phys. Rev. Lett. 117, 082503 (2016)

EXO-200 $T_{1/2} > 3.5\times10^{25}$ y
Phys. Rev. Lett. 123, 161802 (2019)

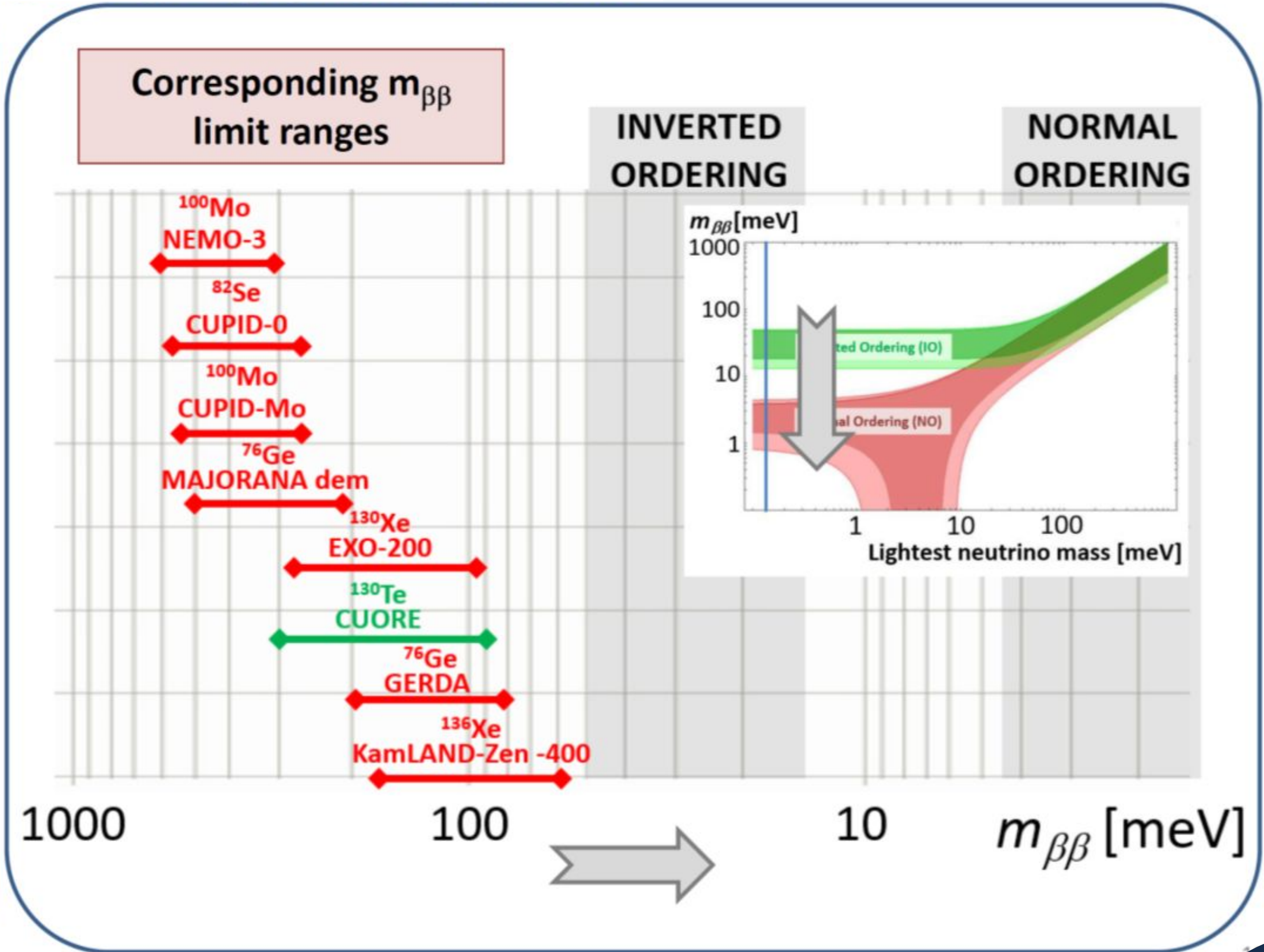
MAJORANA dem. $T_{1/2} > 2.7\times10^{25}$ y
Phys. Rev. C 100, 025501

CUORE $T_{1/2} > 2.2\times10^{25}$ y
arXiv:1907.09376

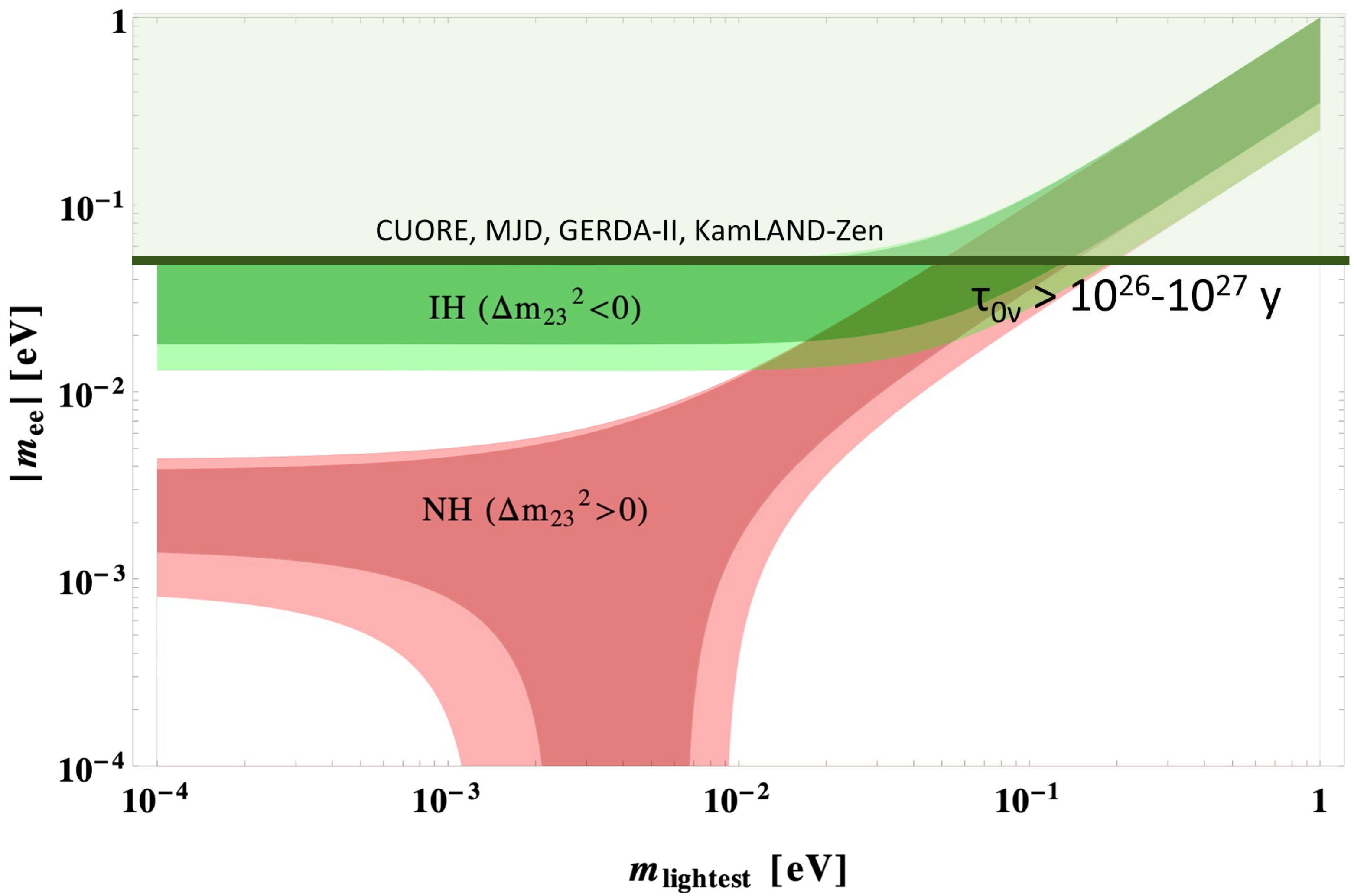
CUPID-0 $T_{1/2} > 4.7\times10^{24}$ y
L. Pagnanini, TAUP 2021

CUPID-Mo $T_{1/2} > 1.8\times10^{24}$ y
B. Welliver, TAUP 2021

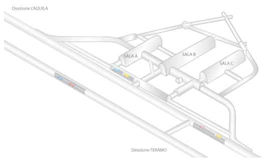
NEMO-3 $T_{1/2} > 1.1\times10^{24}$ y
Phys. Rev. D 92, 072011 (2015)



Reached sensitivity on Majorana mass



Next generation DBD experiments



Large source mass Easily scalable **Fluid embedded source**	① KamLAND-Zen 400 → KamLAND-Zen 800 → KamLAND2-Zen ② EXO-200 → nEXO ③ NEXT-White ›NEXT-100 ›NEXT-HD / NEXT-BOLD ④ SNO+ › SNO+-phase II
High energy resolution/efficiency **Crystal embedded source**	⑤ GERDA, MAJORANA dem. → LEGEND-200 → **LEGEND-1000** ⑥ CUPID-Mo, CUPID-0, CUORE → **CUPID** → CUPID Reach / CUPID 1t ⑦ AMORE-I → **AMORE-II**

KamLAND-Zen

KamLAND-Zen 400 → KamLAND-Zen 800 → KamLAND2-Zen

KamLAND-Zen 400 – Kamioka, Japan
350 kg of ^{136}Xe – Leading experiment

$T_{1/2} > 1.07\times10^{26}$ y
$m_{\beta\beta} < 60 – 160$ meV

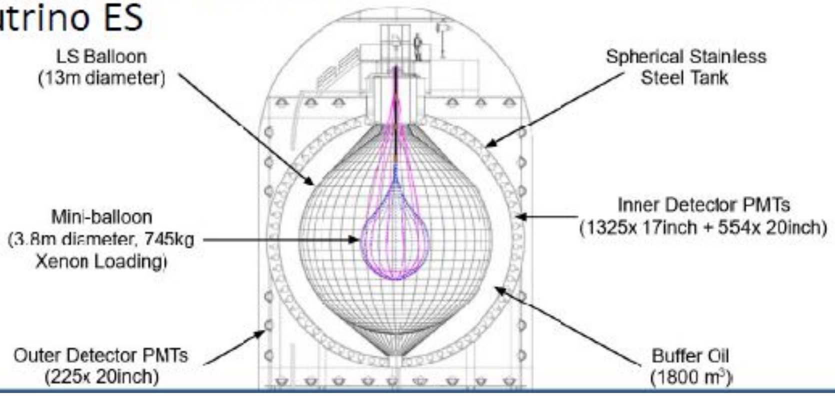
Concept

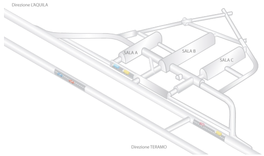
Enriched Xenon diluted (3 wt%) in liquid scintillator exploiting the existing KamLAND detector with the addition of a nylon balloon

- Scalability – increase diameter of nylon inner balloon (IB)
- ^{136}Xe On-off
- Energy resolution: **$\Delta E(\sigma) \sim 7\%/\sqrt{E(MeV)}$ – 4.5%@$Q_{\beta\beta}$**
- Single event position – **Vertex resolution 15 cm/ $\sqrt{E(MeV)}$**

Background:

- $2\nu\beta\beta$ decay of ^{136}Xe
- Xe-LS, IB and outer-LS radioactive impuritities
- Cosmogenic: muon-spallation
- Solar neutrino ES





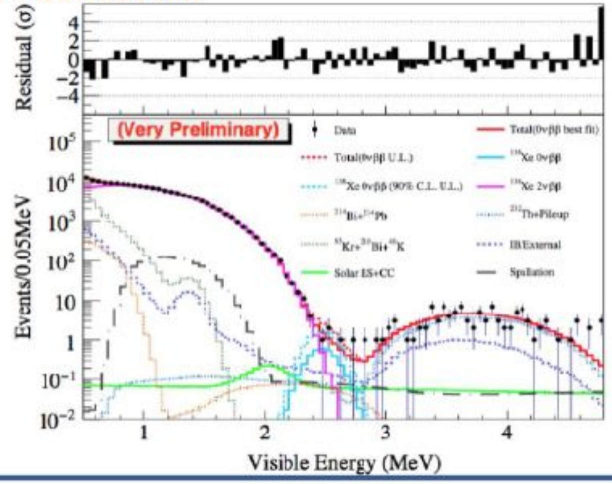
KamLAND-800 (started Jan 2019)

Major new points with respect to KamL-400

- More isotope – **745 kg of ^{136}Xe**
- New balloon (2X larger, more radiopure)
- Reduction of ^{12}C-spallation by analysis
- Characterization of ^{136}Xe spallation
- **Improve KamL-400 results by ~4X in 5 y**

→ $m_{\beta\beta} < 30 – 80$ meV

J. Phys.: Conf. Ser. 1468 012142 (2020)
H. Ozaki - Neutrino Telescope 2021
arXiv:2104.10452

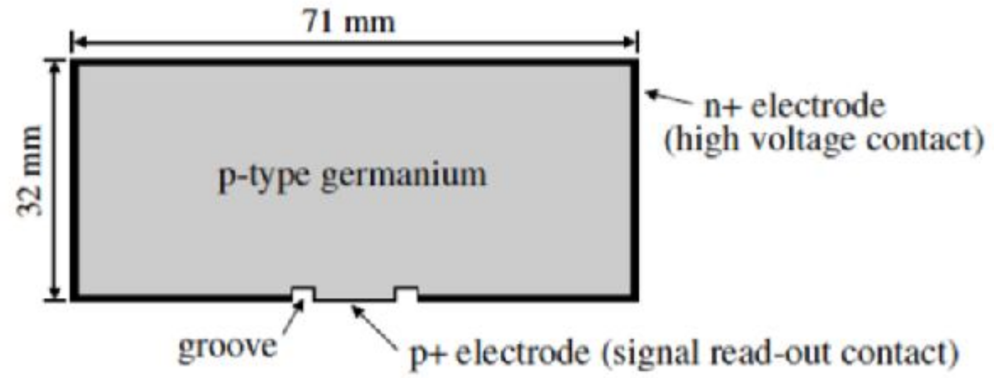


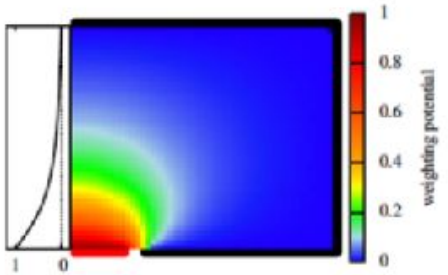
KamLAND2-Zen

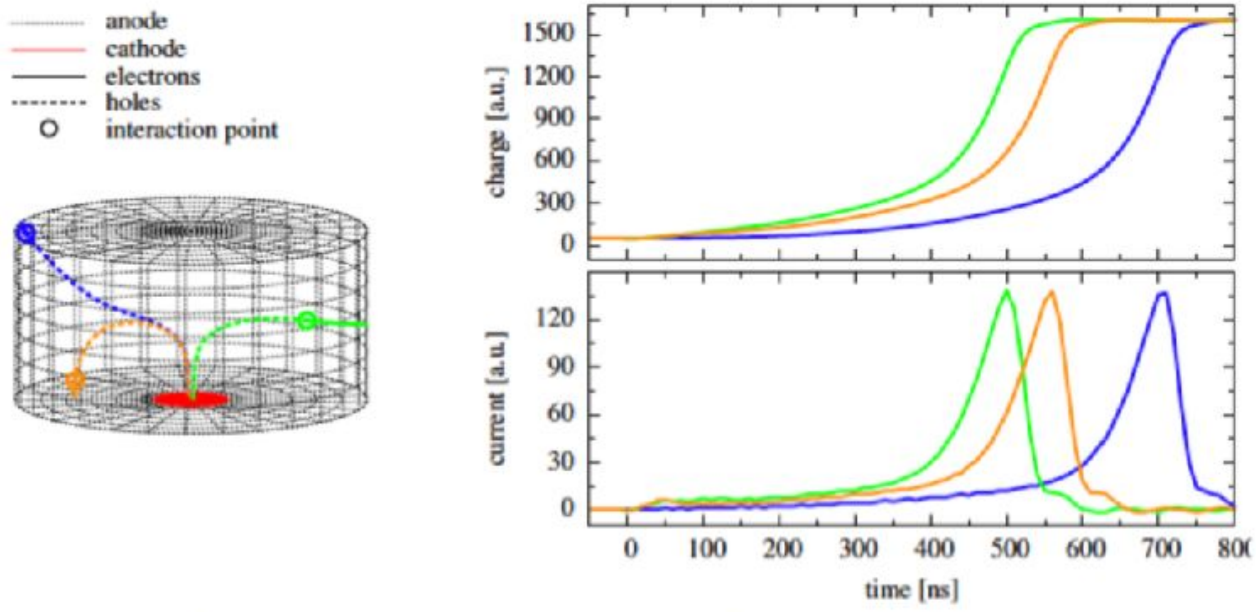
- 1 ton of ^{136}Xe – 5X brighter → 2X better ΔE
- $m_{\beta\beta} < 20$ meV

GERDA, HPGe background rejection

Novel HPGe detectors allow for efficient PID







(a) Trajectories

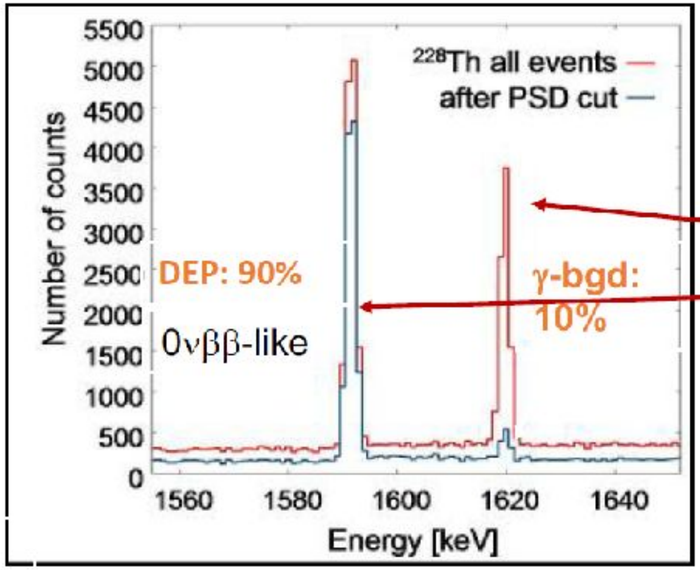
(b) Charge and current pulses

Thanks S. Shoenert

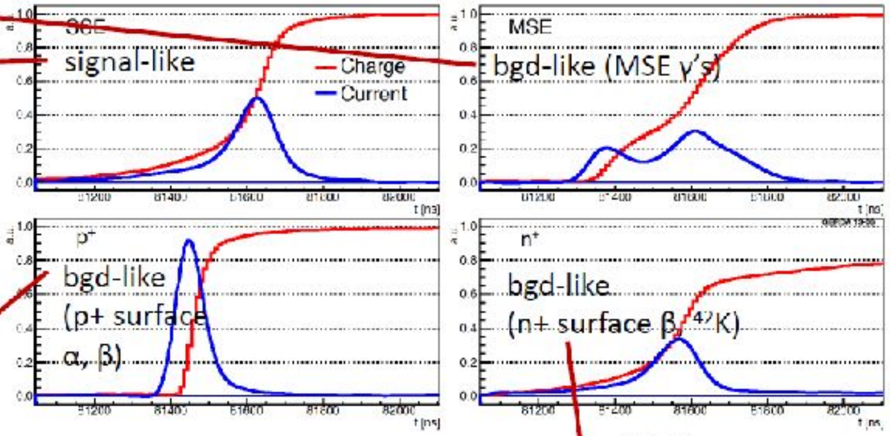
2011 JINST 6 P03005

GERDA, HPGe background rejection

2011 JINST 6 P03005



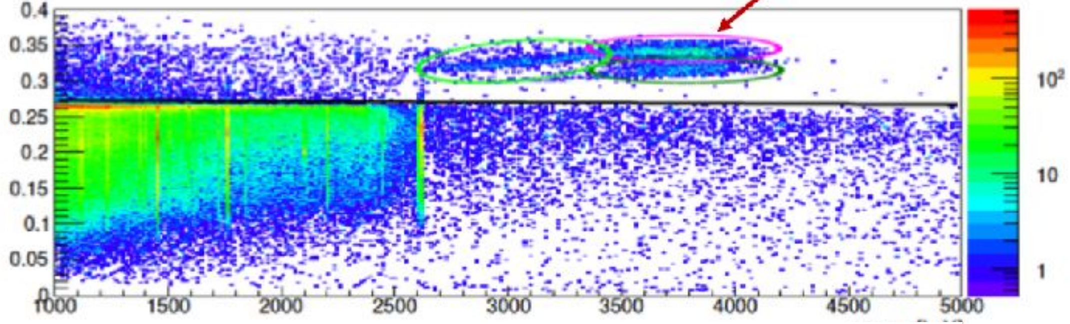
Novel HPGe allow for efficient PID



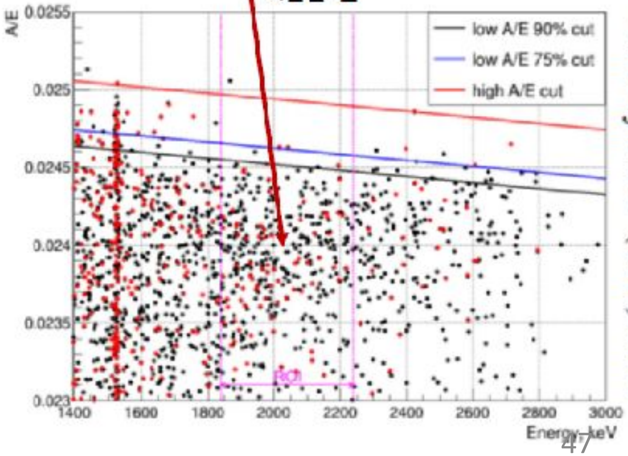
2009 JINST 4 P10007

<1E-4

GSTR-12-002



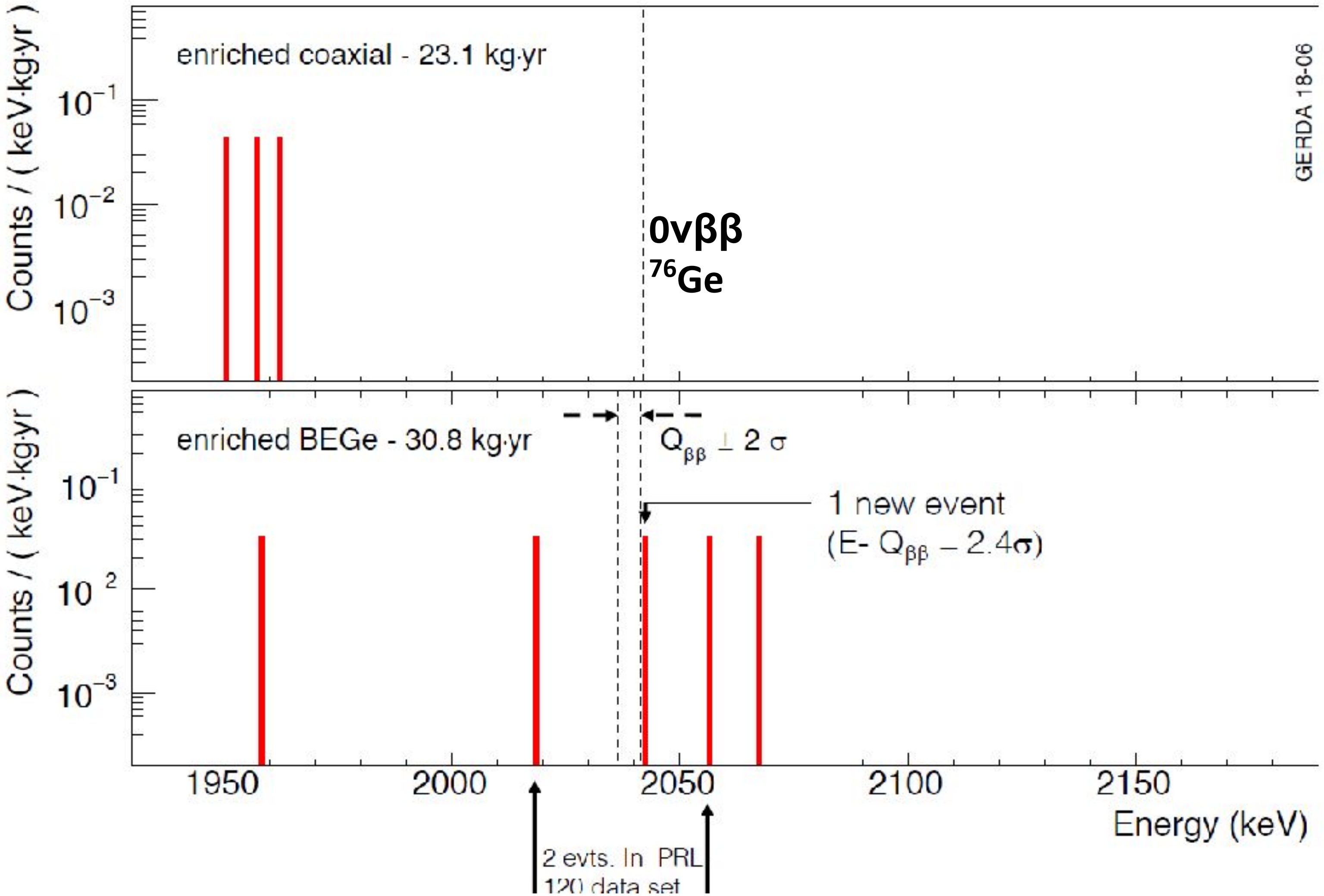
<1E-2



Eur. Phys. J. C (2018) 78:15

Thanks S. Shoenert

GERDA background achivements



Background index*:

$(5.7^{+4.1}_{-2.6} \cdot 10^{-4})$ counts/(keV·kg·yr)

$(5.6^{+3.4}_{-2.4} \cdot 10^{-4})$ counts/(keV·kg·yr)

*: in 1930-2190 keV excluding ±5 keV at $Q_{\beta\beta}$ and lines at 2104 keV and 2119 keV.

GERDA experiment operates in a real **0 background conditions**

Thanks S. Shoenert

From GERDA to LEGEND

LEGEND-200 (first phase):
- up to 200 kg of detectors
- BI <2E-4 cts/(keV kg yr)
- use existing GERDA infrastructure at LNGS
- design exposure: 1 t yr
- Sensitivity 10^{27} yr
- Isotope procurement ongoing
- Start in 2021

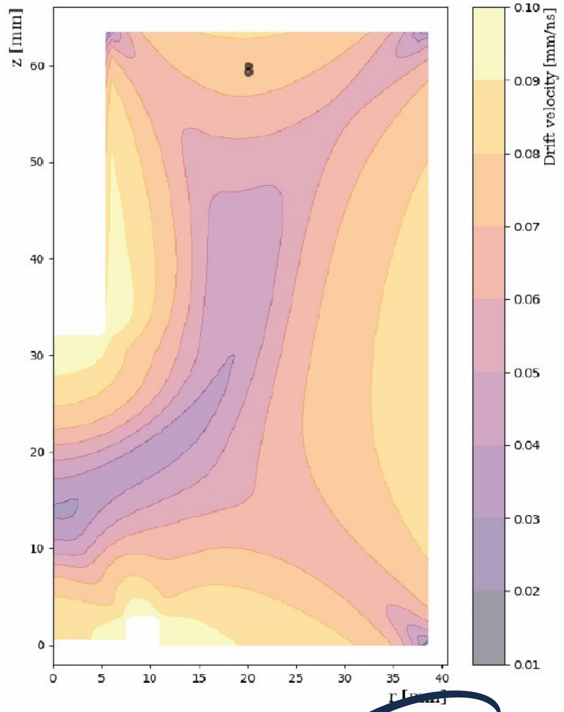
LEGEND-1000 (second phase):
- 1000 kg of detectors (deployed in stages)
- BI <1E-5 cts/(keV kg yr)
- Location tbd
- Design exposure ~10 t yr
- 1.2×10^{28} yr

LEGEND.
To increase the experimental mass a **new HPGe detector configuration** will be adopted

Inverted Coaxial Detector guaranties the same rejection capability as BEGe detector with **a detector mass of 2 kg**

Inverted coaxial detectors:
R. Cooper, D. Radford, P. Hausladen, K. Lagergren
Nucl. Instrum. Methods Phys. Res. Sect. A 665 (2011)

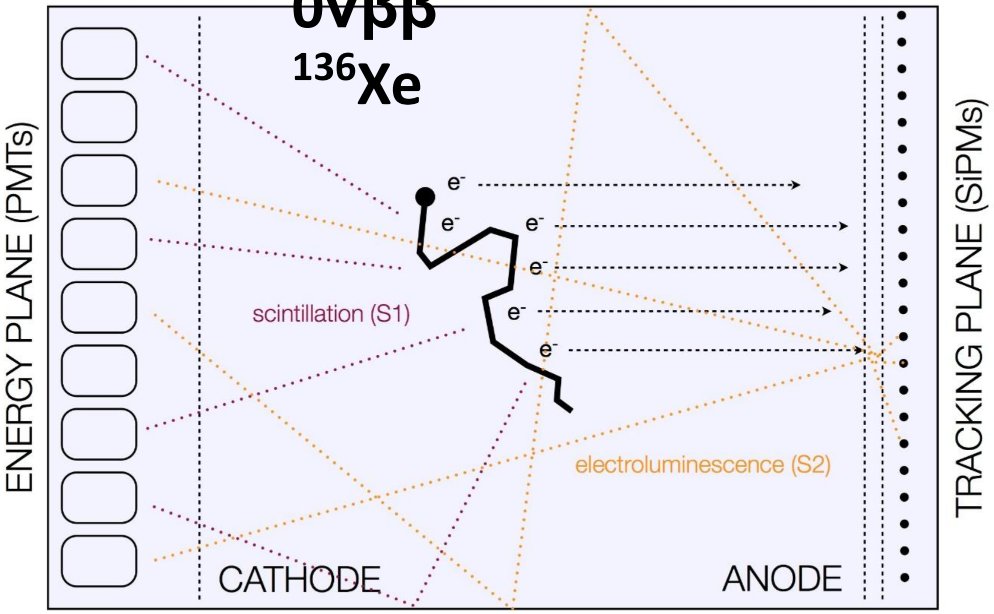
Pulse shape discrimination performance of Inverted Coaxial Ge detectors
A. Domula, M. Hult, Y. Kermaïdicb, G. Marissens, B. Schwingenheuer, T. Wester, K. Zuber; NIMA 891 (2018) 106-110



Thanks S. Shoenert

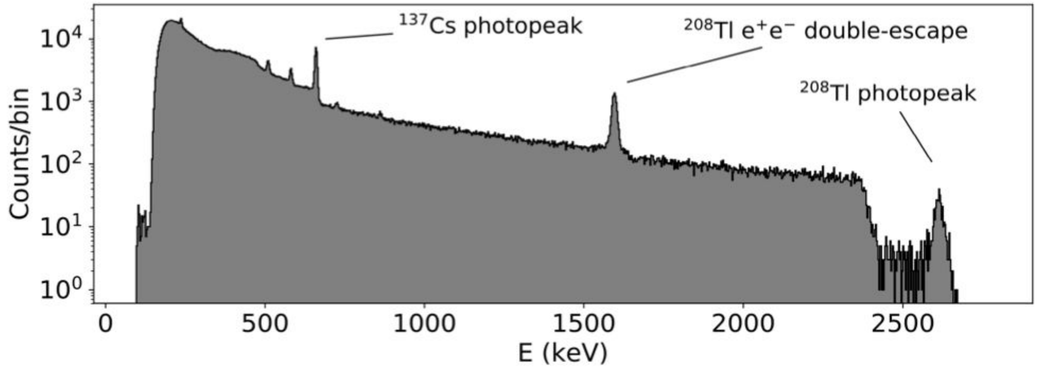
NEXT, High Pressure Gas-Xe TPC

Gas-Xe TPC with two readout planes

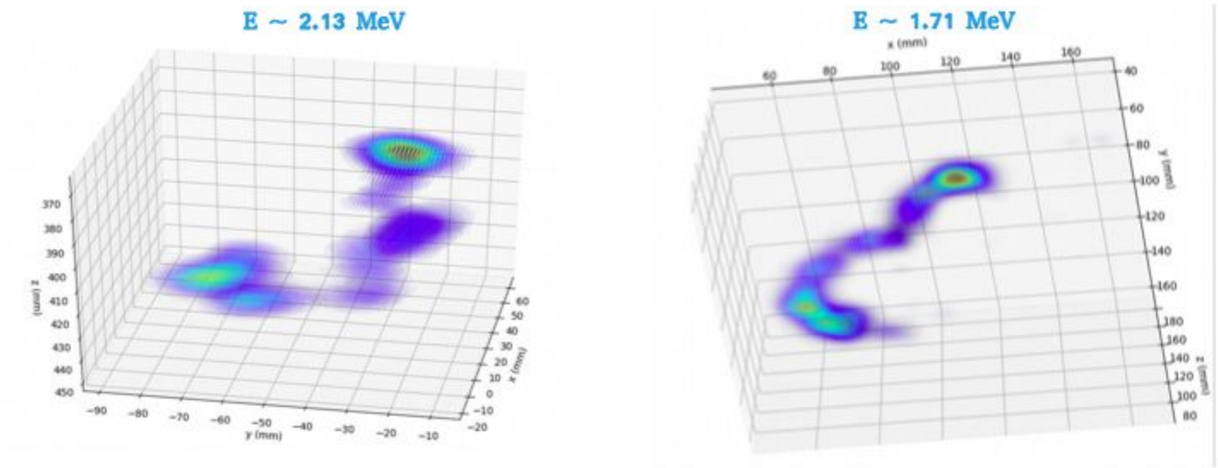


High Energy Resolution
Topological evet reconstruction

Thanks J.J. Gomes Cadenas



Energy resolution at $Q_{\beta\beta}$ < 1 % FWHM

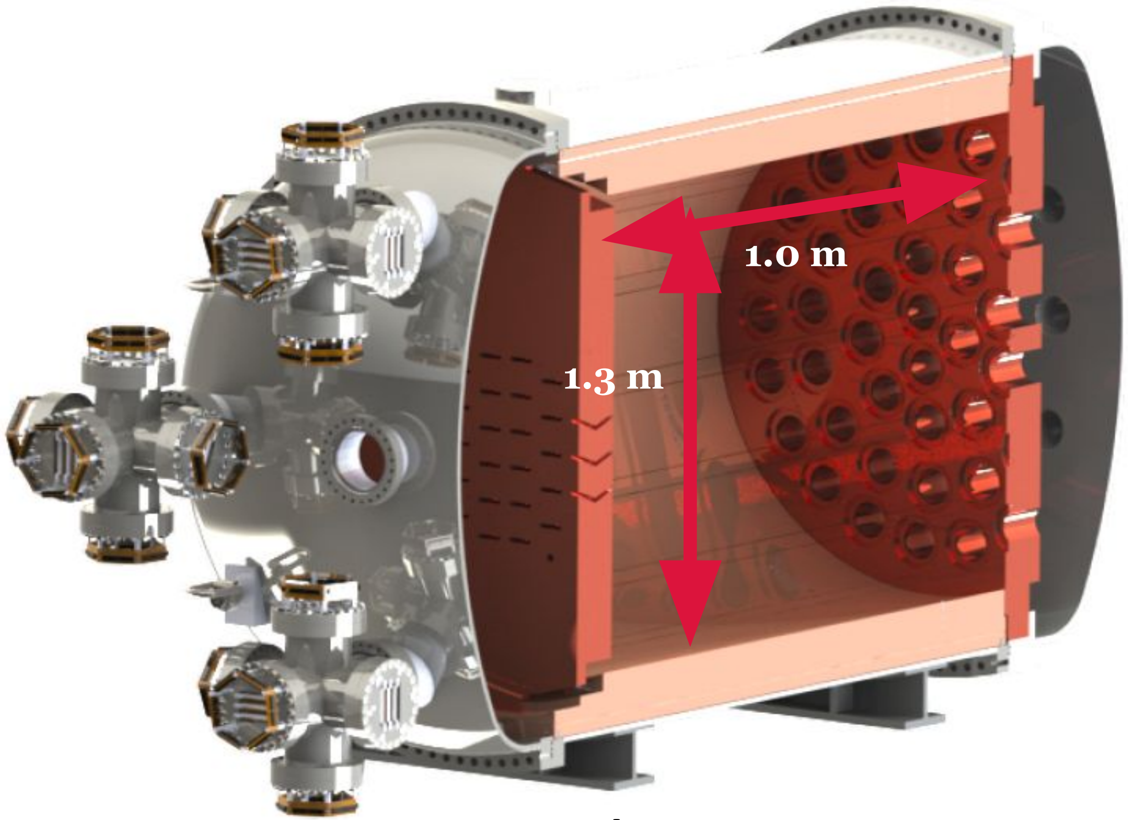


Topological signature: 2nu candidates

Topological signature:
92 % signal efficiency 92 % background rejection

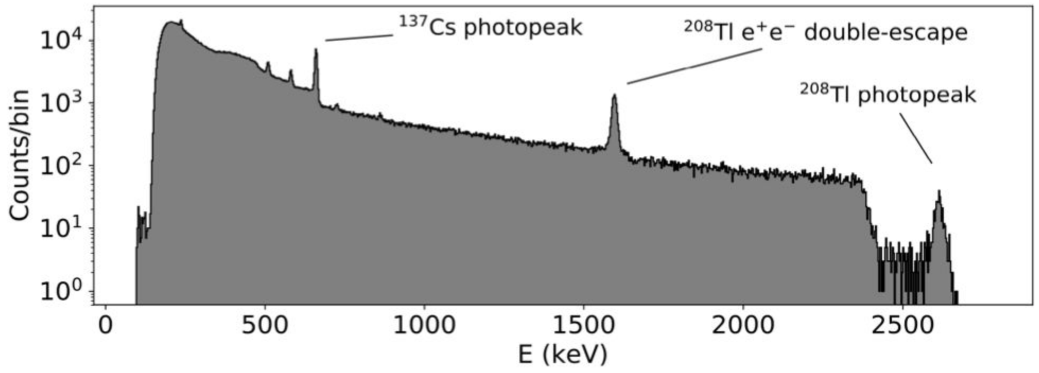
NEXT, High Pressure Gas-Xe TPC

NEXT – 100 detector under preparation

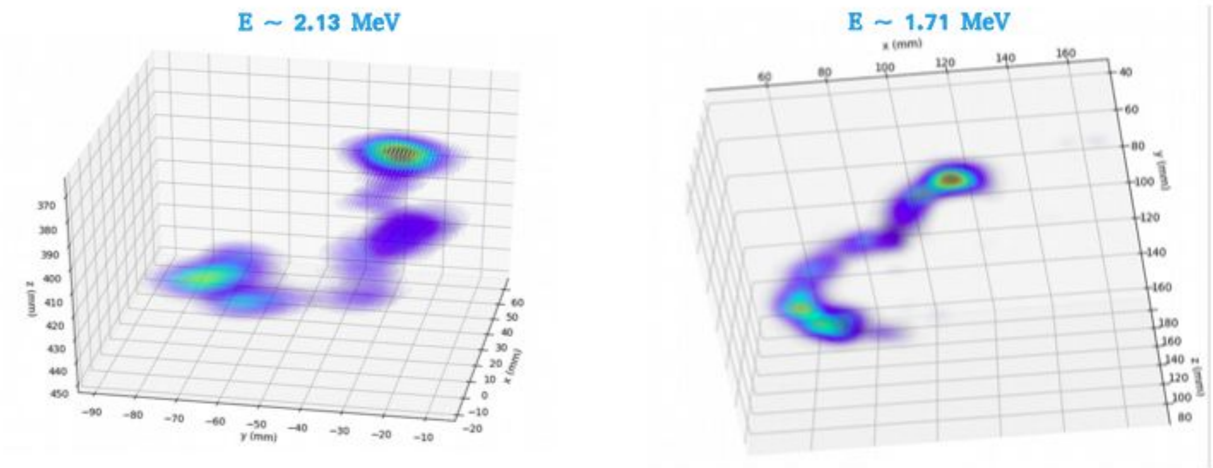


Expected BI: < 4.09 x 10^{-4} cts / (keV kg year)

Thanks J.J. Gomes Cadenas



Energy resolution at Qββ < 1 % FWHM



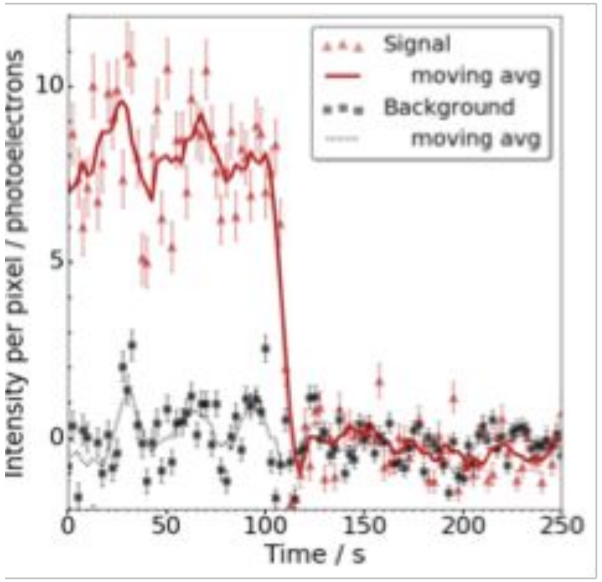
Topological signature: 2nu candidates

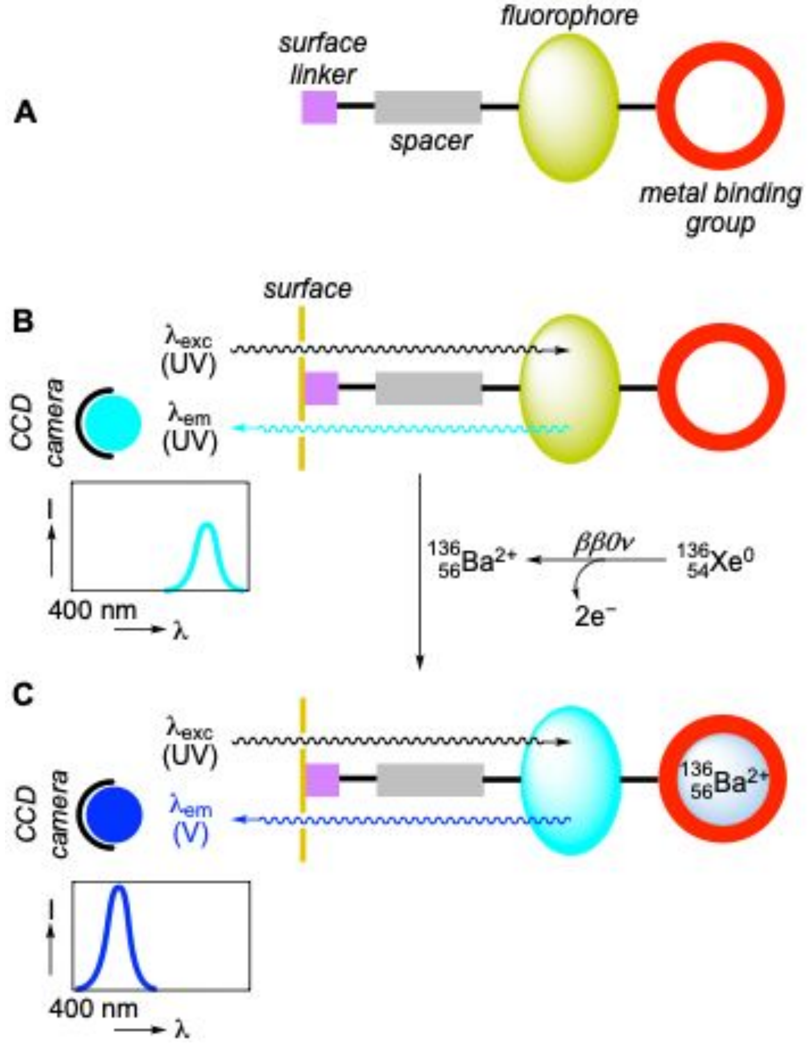
NEXT, Ba++ tagging

0νββ of
^{136}Xe

In the final state there are:
- 2 electrons
- 1 **Ba^{+} ion**

$$^{136}\mathbf{Xe} \;\square\; ^{136}\mathbf{Ba} + 2\,\mathbf{e}^{-}$$





Electrons are detected by the TPC

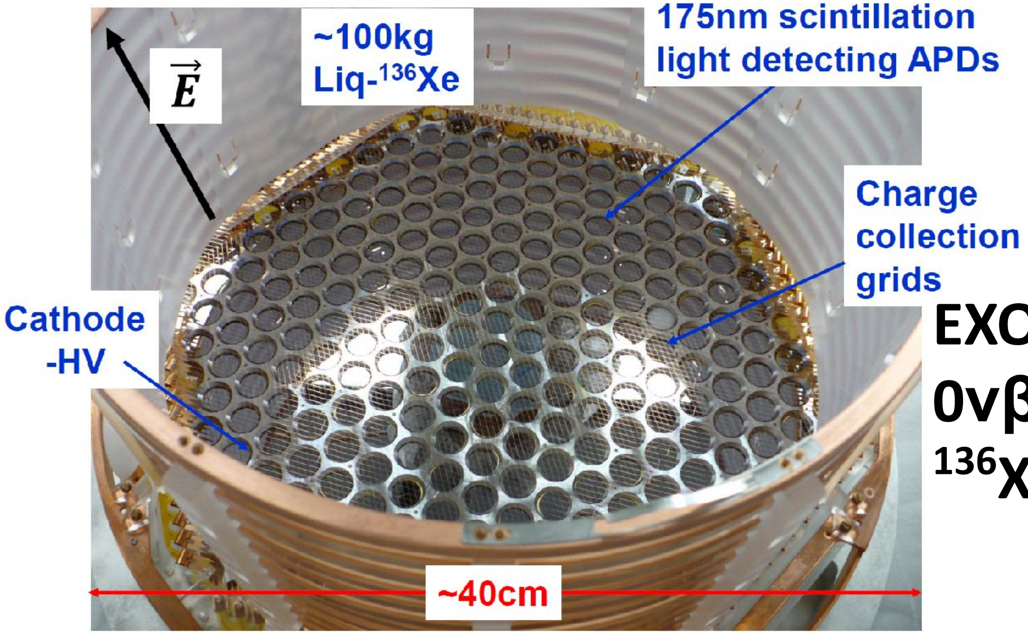
Identification of Ba^{++} ions will strongly suppress the background

A more clear determination of the **Ba detection efficiency** is needed

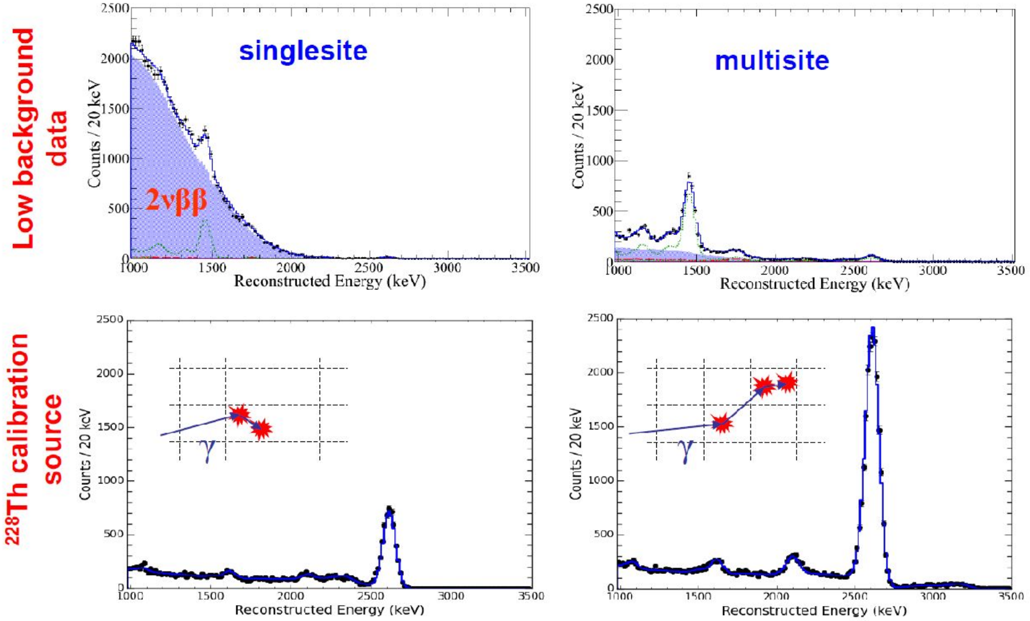
Bi-color molecules developed
R&D is ongoing

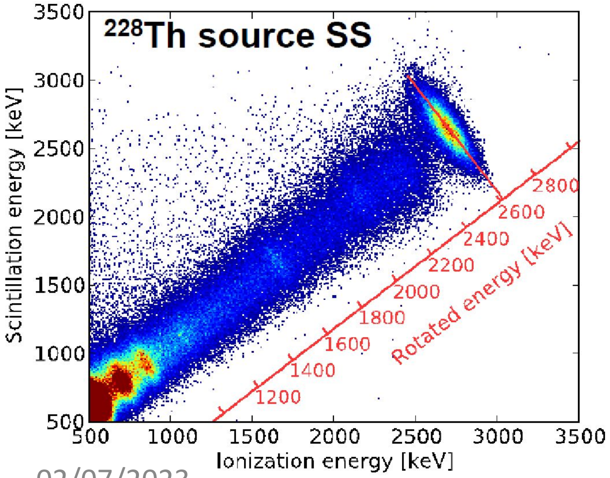
Thanks J.J. Gomes Cadenas

EXO, LXe TPC



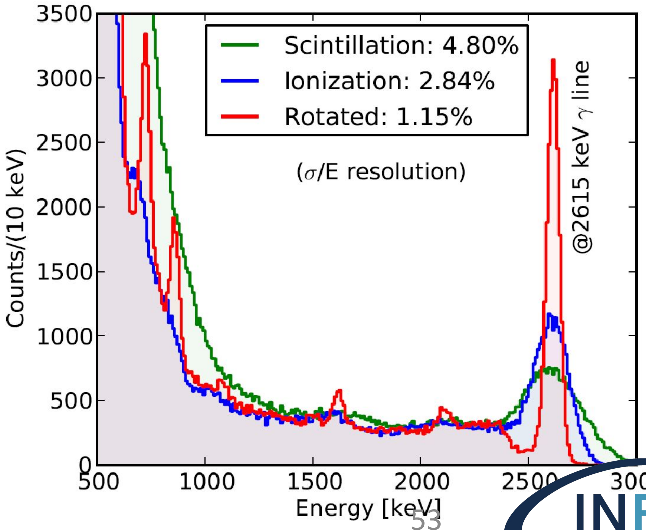
EXO-200
0νββ
^{136}Xe



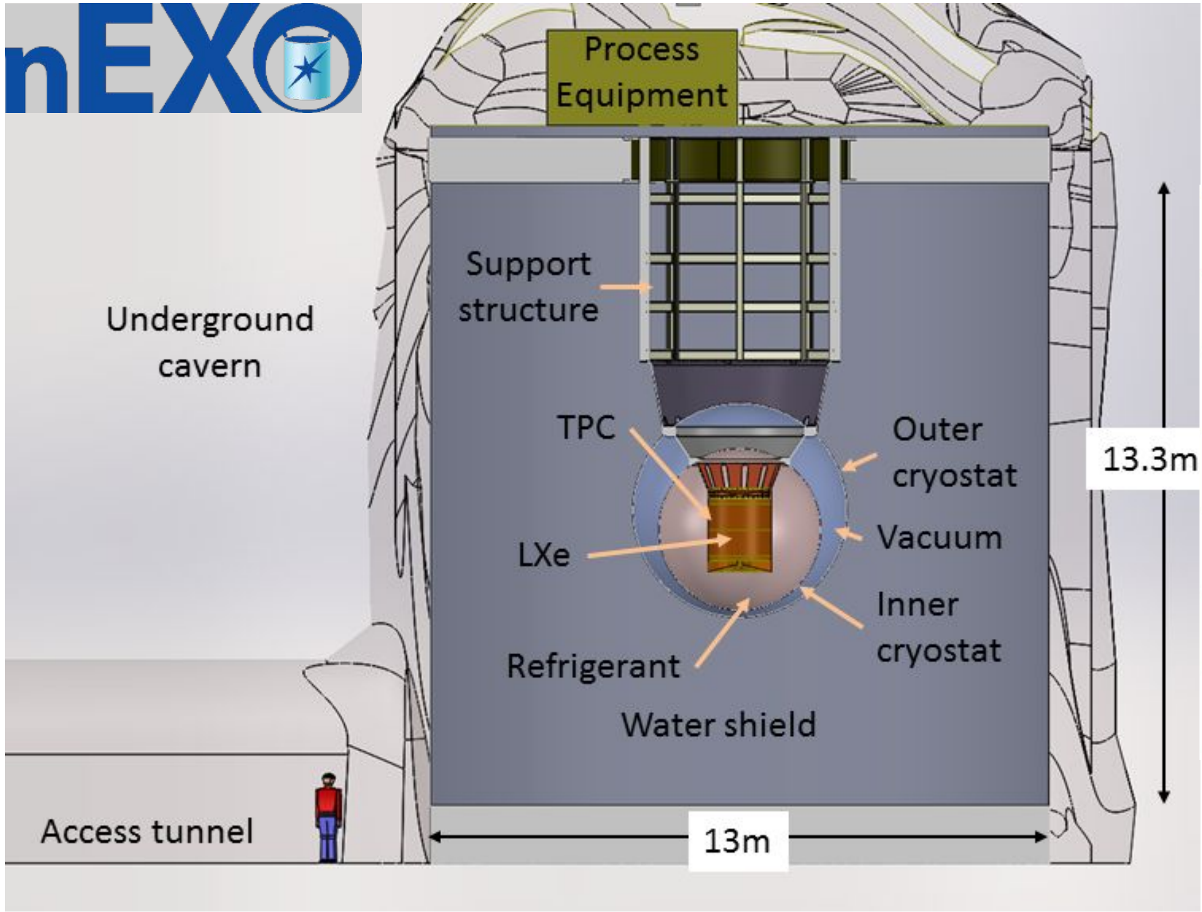


Anticorrelation between scintillation and ionization in LXe known since early EXO R&D

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



From EXO200 to nEXO



5 ton LXe enriched in ^{136}Xe

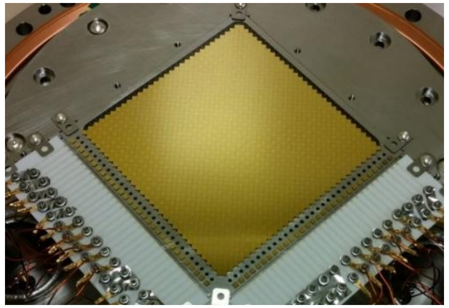
Parameter	nEXO	EXO-200
Fiducial Mass (kg)	4780	98.5
Enrichment (%)	90	80
Data taking time (yr)	5	5
Energy resolution @$Q_{\beta\beta}$ (keV)	58	88 (58)
Background in ROI (ev/yr/mol_{136})	$6.1 \cdot 10^{-4}$	0.022 (0.0073)
Background in ROI inner 3000kg (ev/yr/mol_{136})	$1.6 \cdot 10^{-4}$	-

Thanks G. Gratta

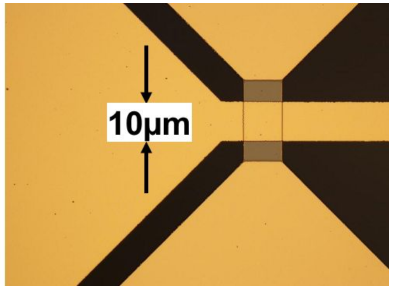
nEXO R&D to finalize detector design

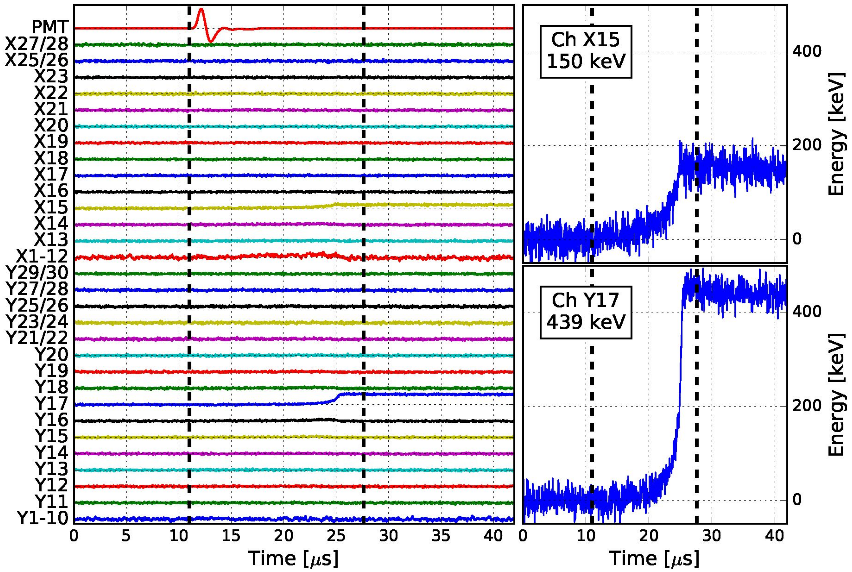
New charge collection tiles

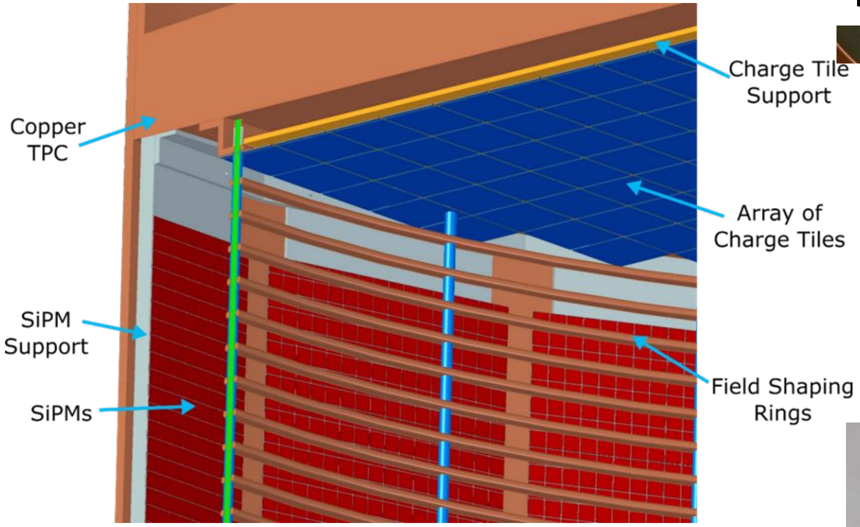
M.Jewell et al., “Characterization of anIonization Readout Tile for nEXO”, J.Inst. 13 P01006 (2018)



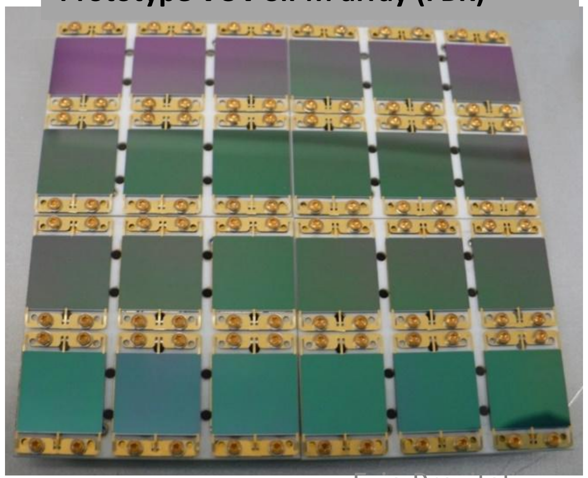
Prototype charge collection tile

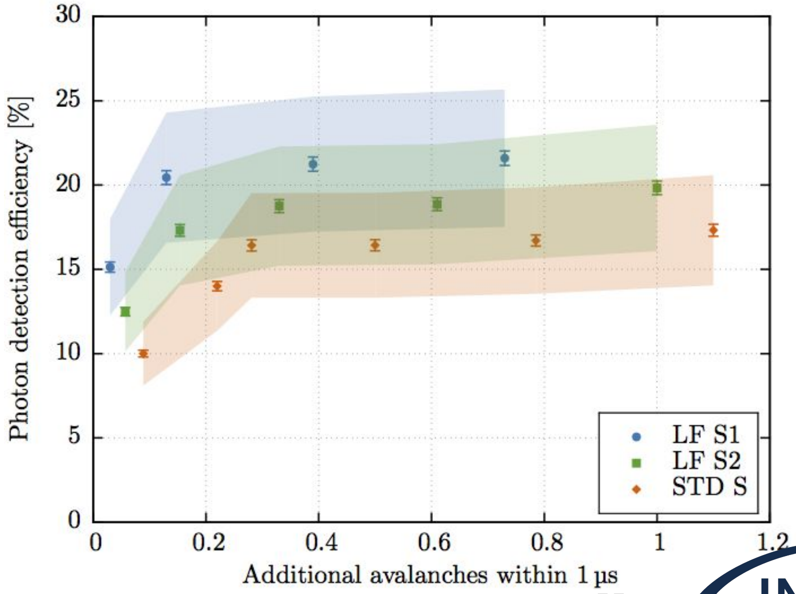






Prototype VUV SiPM array (FBK)





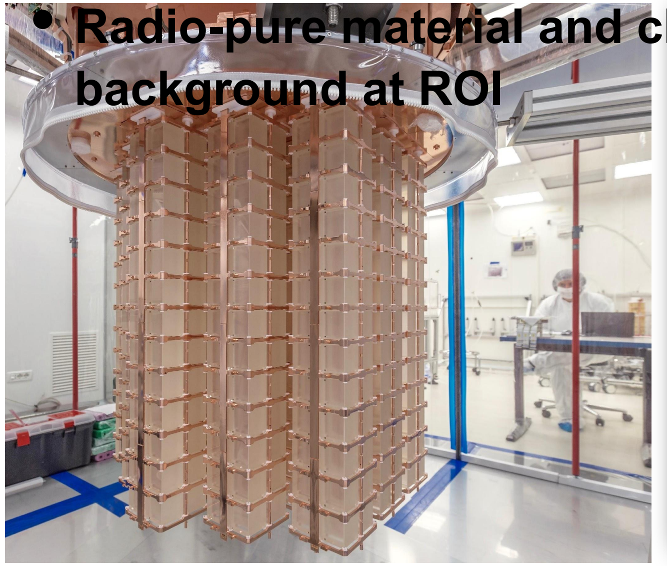
New SiPM

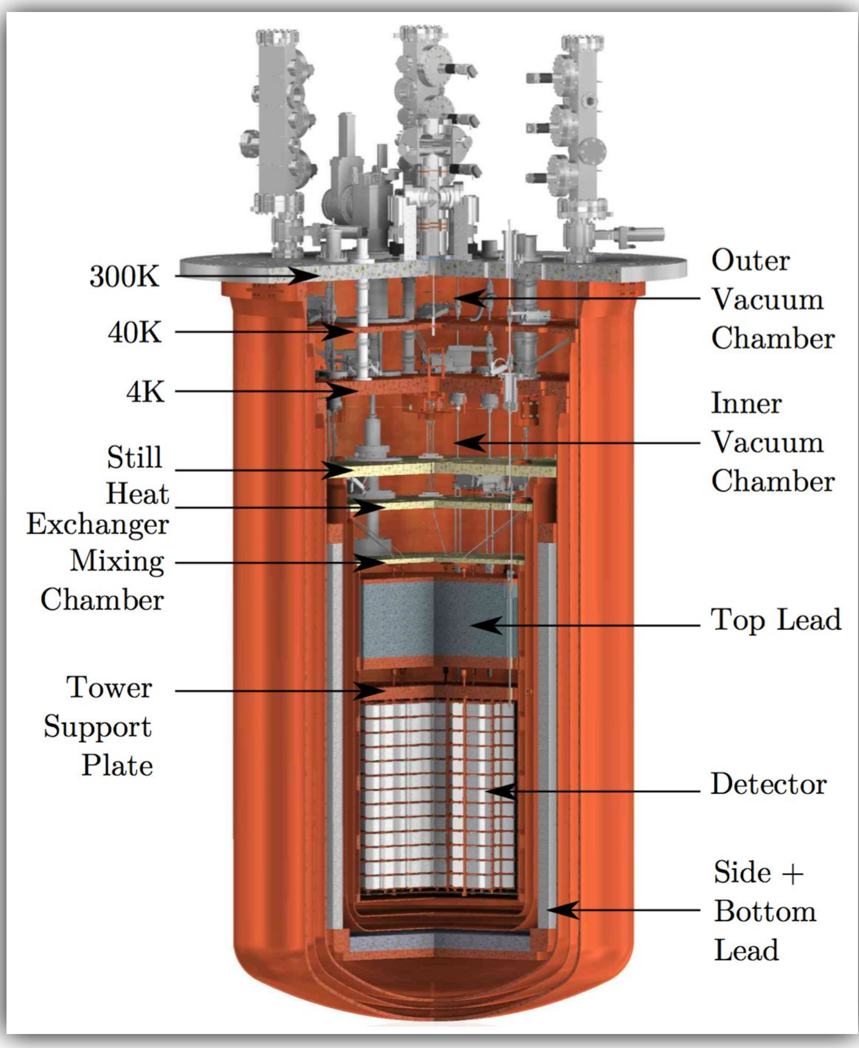
“VUV-sensitive Silicon Photomultipliers for Xenon Scintillation Light Detection in nEXO” IEEE Trans NS 65 (2018) 2823

Thanks G. Gratta

CUORE: Cryogenic Undeground Observatory for Rare events

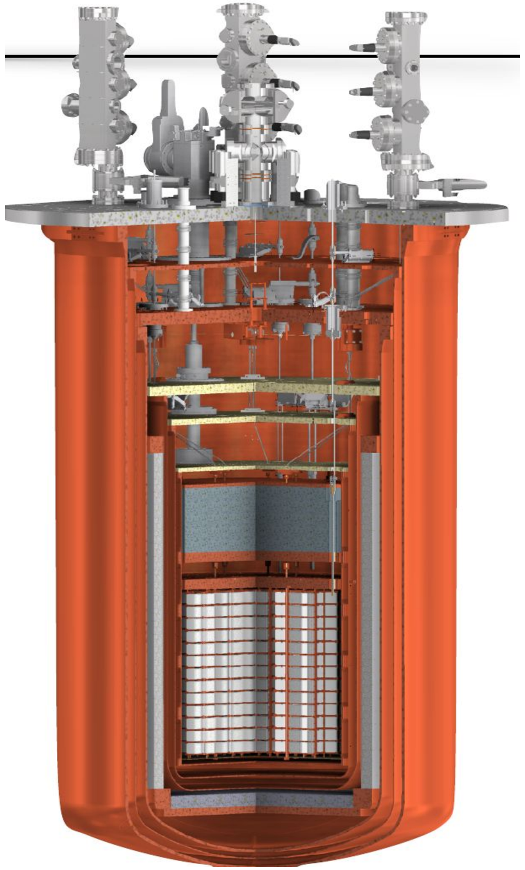
- **988 TeO_2 crystals run as a bolometer array**
  - 5x5x5 cm^3 crystal, 750 g each
- **19 Towers; 13 floors; 4 modules per floor**
  - 741 kg total - 206 kg ^{130}Te
  - 10^{27} ^{130}Te nuclei
- **Excellent energy resolution of bolometers**
- **Radio-pure material and clean assembly to achieve low background at ROI**

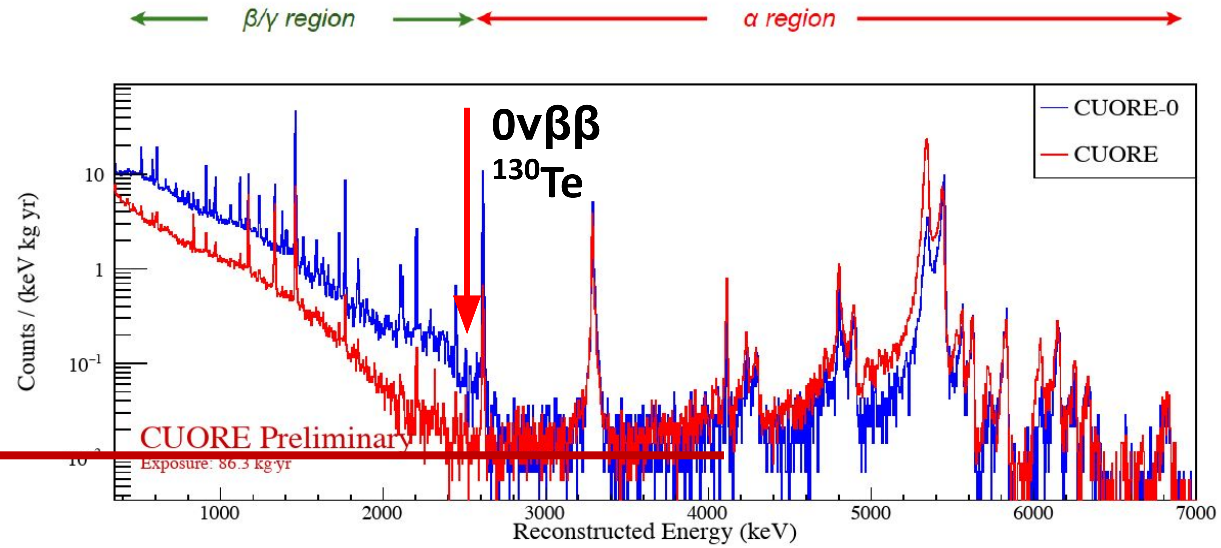




CUPID: CUORE Upgrade with Particle IDentification

- CUORE cryostat: **most powerful cryostat** ever realized
- **Tens of ton of materials** cooled at 10 mK
- Cryogenic detectors are **reliable**



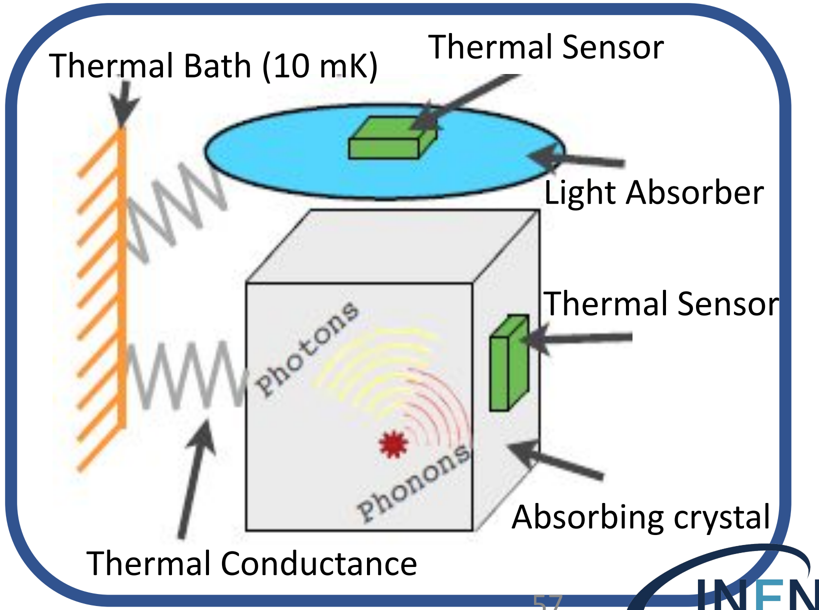


CUORE alpha background
BI ~ 10^{-2} counts/(keV kg years)

CUPID - scintillating bolometers detector

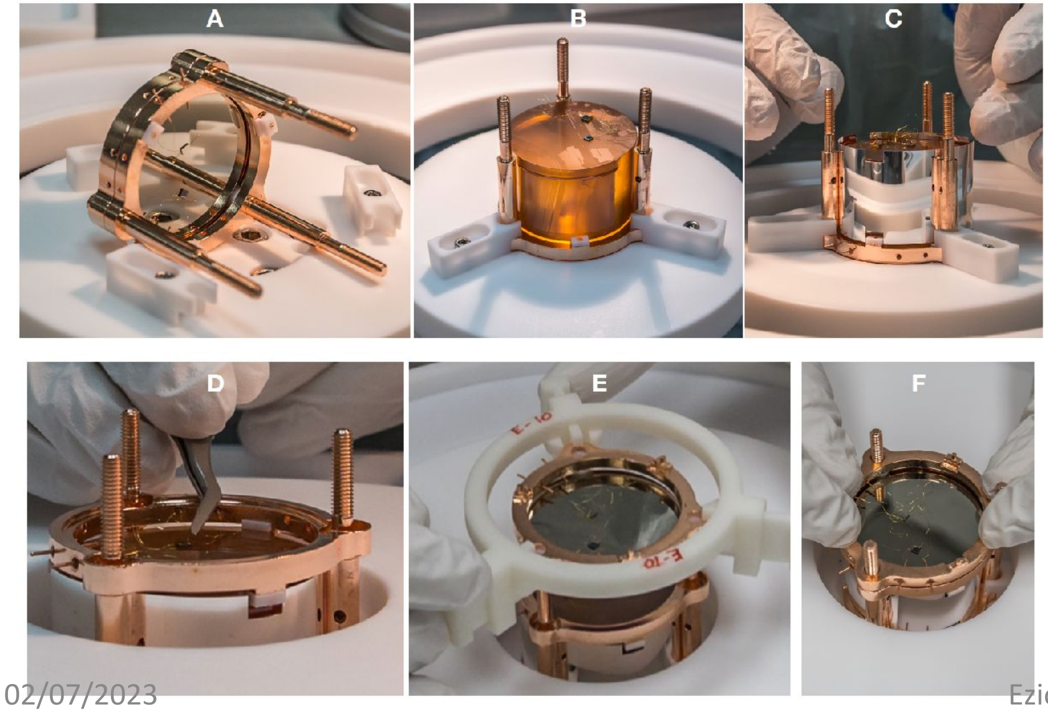
Simultaneous read-out of **Photons and Phonons**

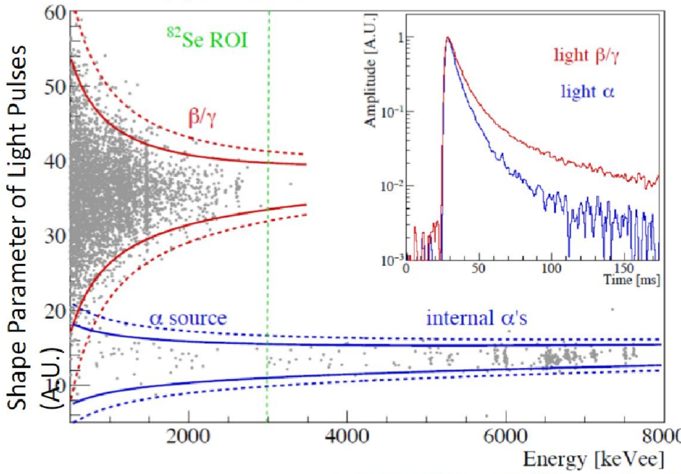
High energy resolution: **as bolometer**
High discrimination capability: **as scintillator**



CUPID scintillating bolometer background rejection

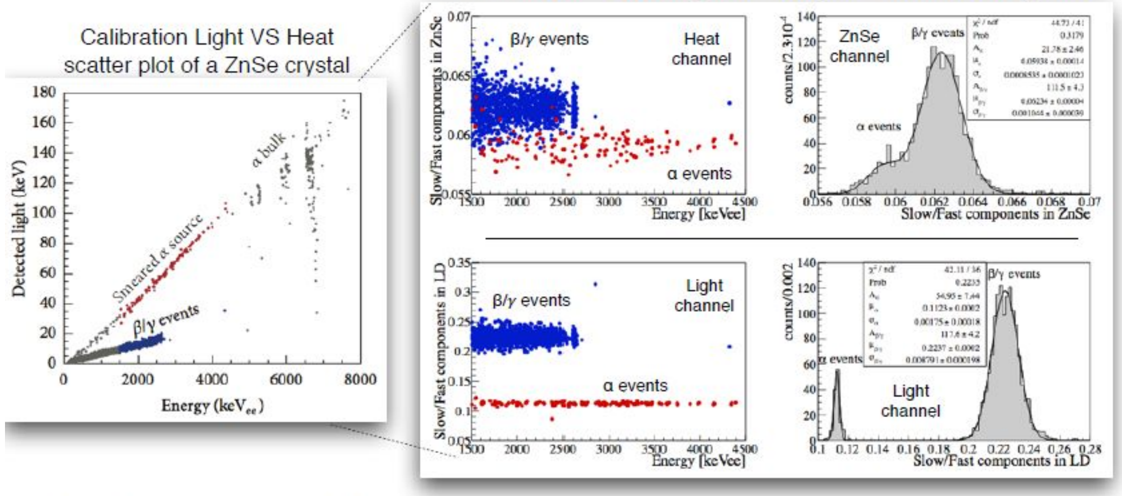
- Scintillating crystals and light detectors operated @ 10 mK
- Grown from **various ββ emitters** (**multi-isotope approach**)
- **Excellent energy resolution** @$Q_{\beta\beta}$ (<1%)
- Possibility to high $Q_{\beta\beta}$ (3 MeV) for **^{82}Se and ^{100}Mo**
- **$LY_\alpha \neq LY_{\beta/\gamma}$** ➜ Particle ID
- **$LShape_\alpha \neq LShape_{\beta/\gamma}$** ➜ Particle ID
- **$HShape_\alpha \neq HShape_{\beta/\gamma}$** ➜ Particle ID





CUPID-0 Data

Particle identification using Pulse Shape Parameters (decay time)



Discrimination potential @ ROI:

$$DP(E) = \frac{|\mu_\alpha(E) - \mu_{\beta\gamma}(E)|}{\sqrt{\sigma_\alpha^2(E) + \sigma_{\beta\gamma}^2(E)}}$$

Heat channel
DP@ROI = 2

Light channel
DP@ROI = 11

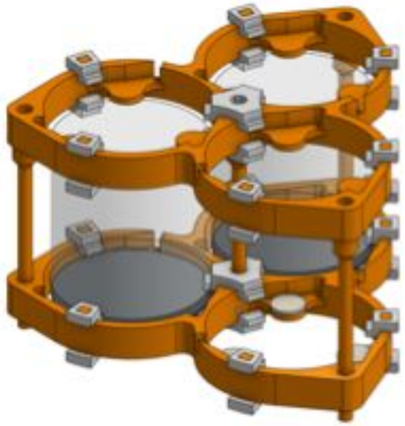
Full rejection of α events shapeHEAT+shapeLIGHT+light

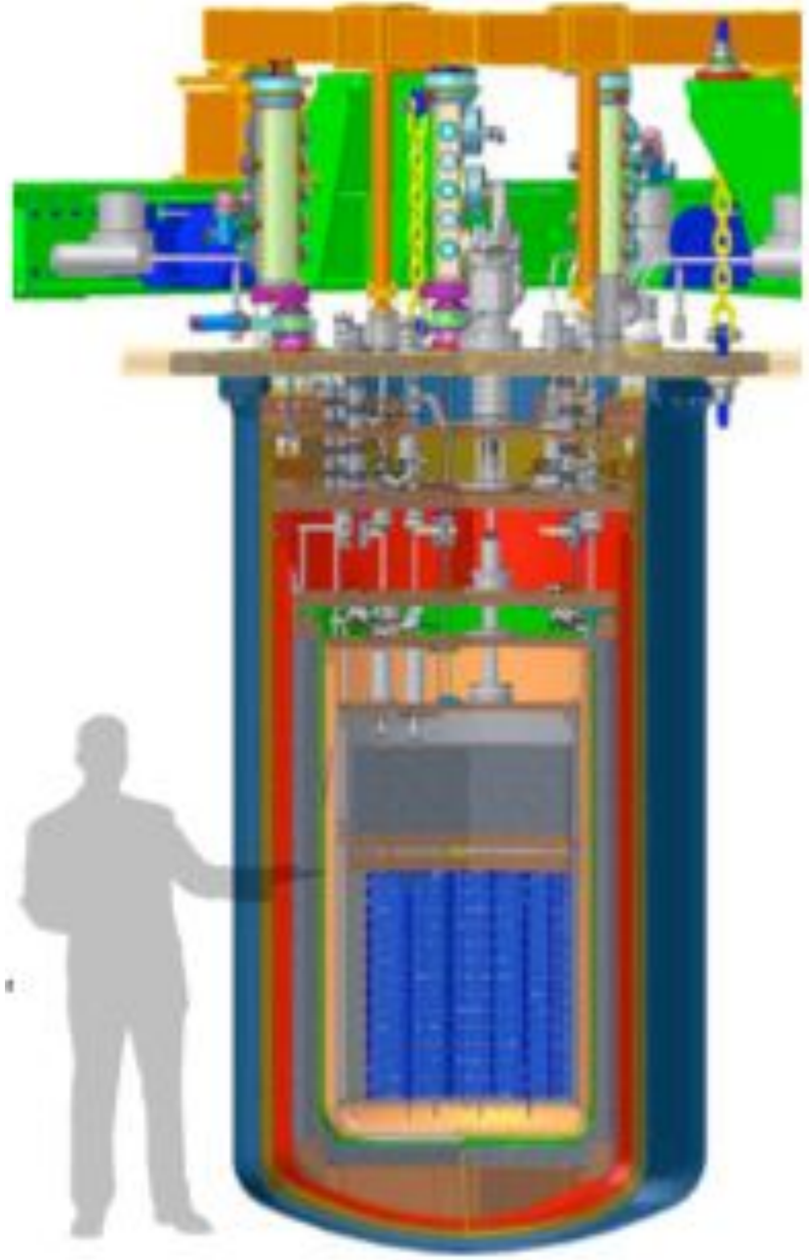
CUPID Conceptual Design

- ~~Re-use *CUORE cryogenic infrastructure*~~ at LNGS
- $Li_2{}^{100}MoO_4$ scintillating crystals
- ~1500 crystals for ***250 kg of ^{100}Mo***
- Active background rejection using light and heat signals
- Options for ***multiple isotopes***.
- TDR and ***construction readiness in 2021***

Expected BI ~ 1 x 10^{-4} cts / (keV kg year)

CUPID CDR available soon





INFN LNGS

CUPID-CROSS surface background rejection

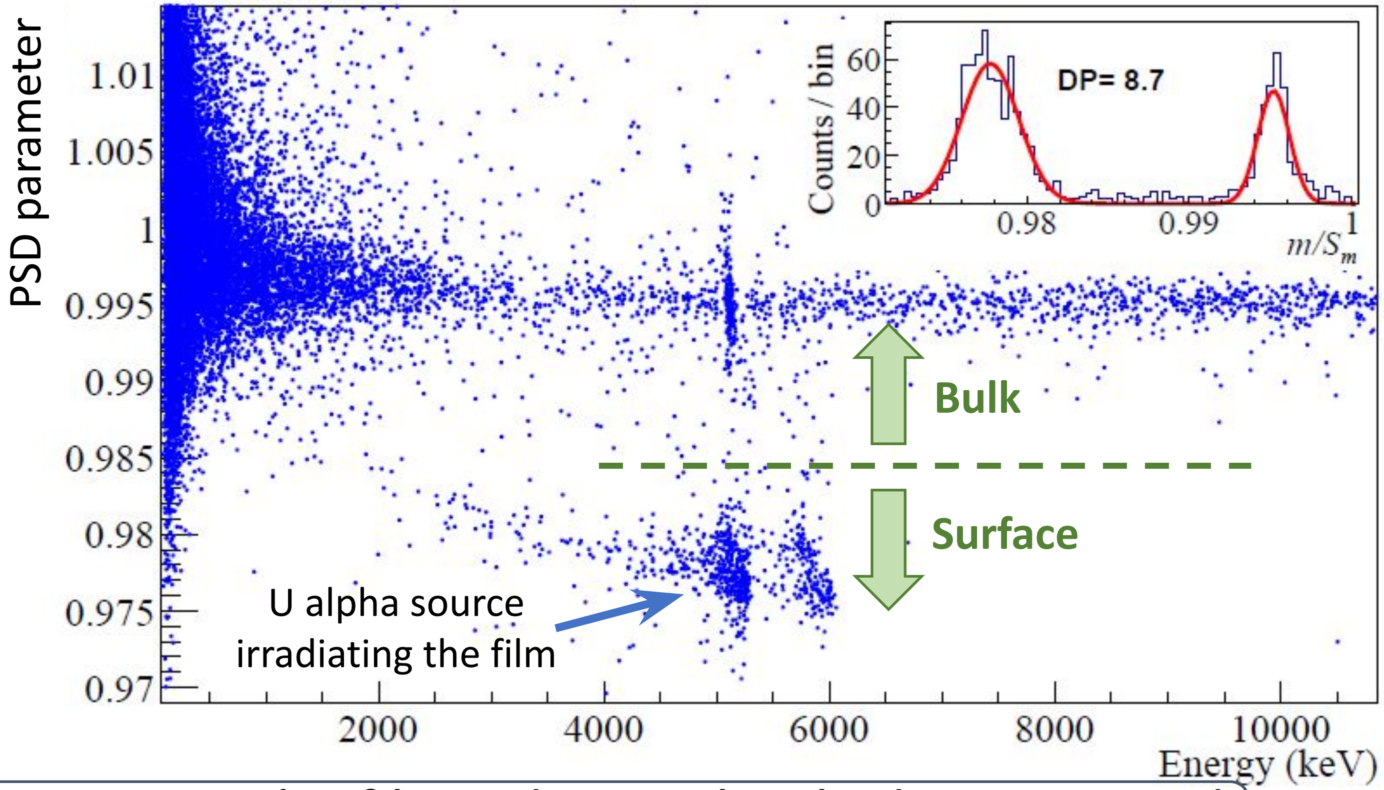
http://arxiv.org/abs/1906.10233

Numerous above-ground tests (CSNSM, Orsay) with **20x20x10 mm Li_2MoO_4** and **TeO_2 crystals** and recently with a **large (75 g) Li_2MoO_4 crystal**

10-µm-thick Al film

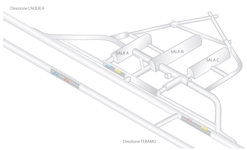
75 g Li_2MoO_4 crystal

Thanks A. Giuliani



Alphas impacting on the film side are clearly discriminated
Next test: **fully coated crystal**

Next generation DBD experiments



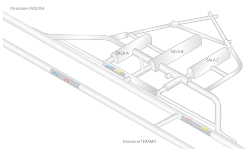
North American and European meeting @ LNGS September 2021 and @ SNOLab April 2023

- Selection of future DBD experiments
  - *Experimental sensitivities*
  - *Budget requested for each experiment*
  - *International collaborations*
- Selection of possible underground laboratories
  - *SNOLab/SURF – North America*
  - *LNGS – Europe (with other European labs)*

	$T_{1/2}$ (10^{28} years)		$m_{\beta\beta}$ (meV) 3σ Discovery	
	Excl. Sens.	3σ Discovery	Median	Range
CUPID	0.14	0.10	15	12 to 20
LEGEND-1k	1.60	1.30	12	9 to 21
nEXO	1.35	0.74	11	7 to 32

← *Prosecutor of CUORE*

Possible near future strategy



Closed session statement

- Neutrino-less double beta decay search is recognised as very compelling science capable of reshaping current understanding of nature

→ **Three experiments supported**

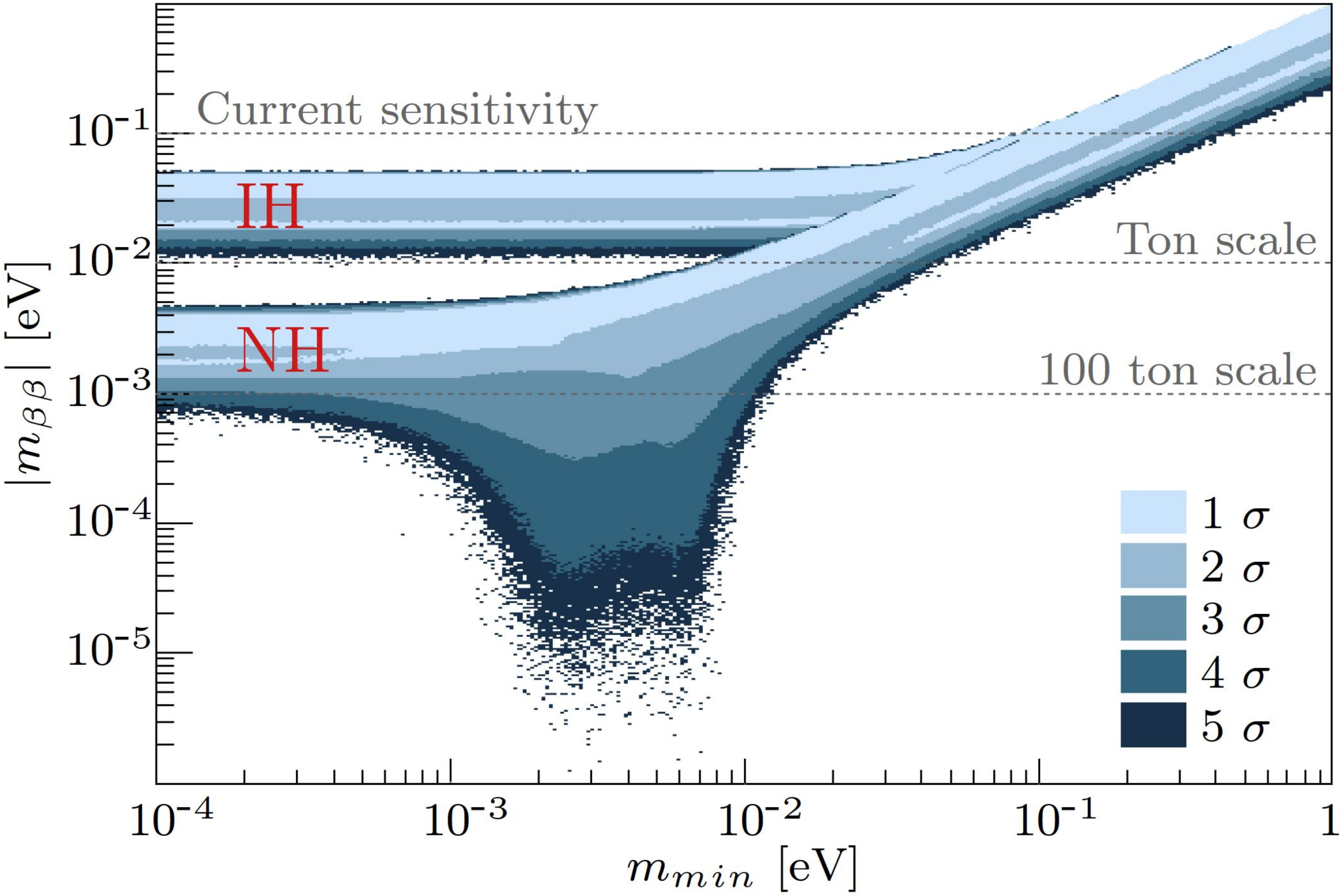
- The international stakeholders in neutrino-less double beta decay research do agree in principle that the best chance for success is an international campaign with more than one large ton-scale experiment implemented in the next decade, with one ton scale experiment in Europe and the other in North America.

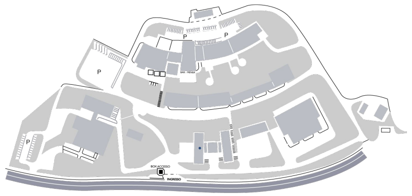
→ Installation site for the two big experiments **must be identified**

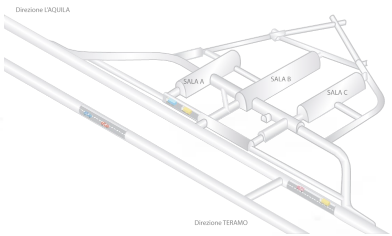
- The international stakeholders in neutrino-less double beta decay are interested in exploring whether a more formal structure for international coordination on this research would be beneficial, not only for experiments of the next decade but also for future multi-ton and/or multi-site experiments.

→ Define international coordination between international stakeholders

What next for neutrinoless DBD?







Thank You