NOW 2022
Neutrino Oscillation Workshop

Rosa Marina (Ostuni, Italy)

September 4 - 11, 2022

September 9th, 2022

Majorana neutrinos and rare decays: where we are going

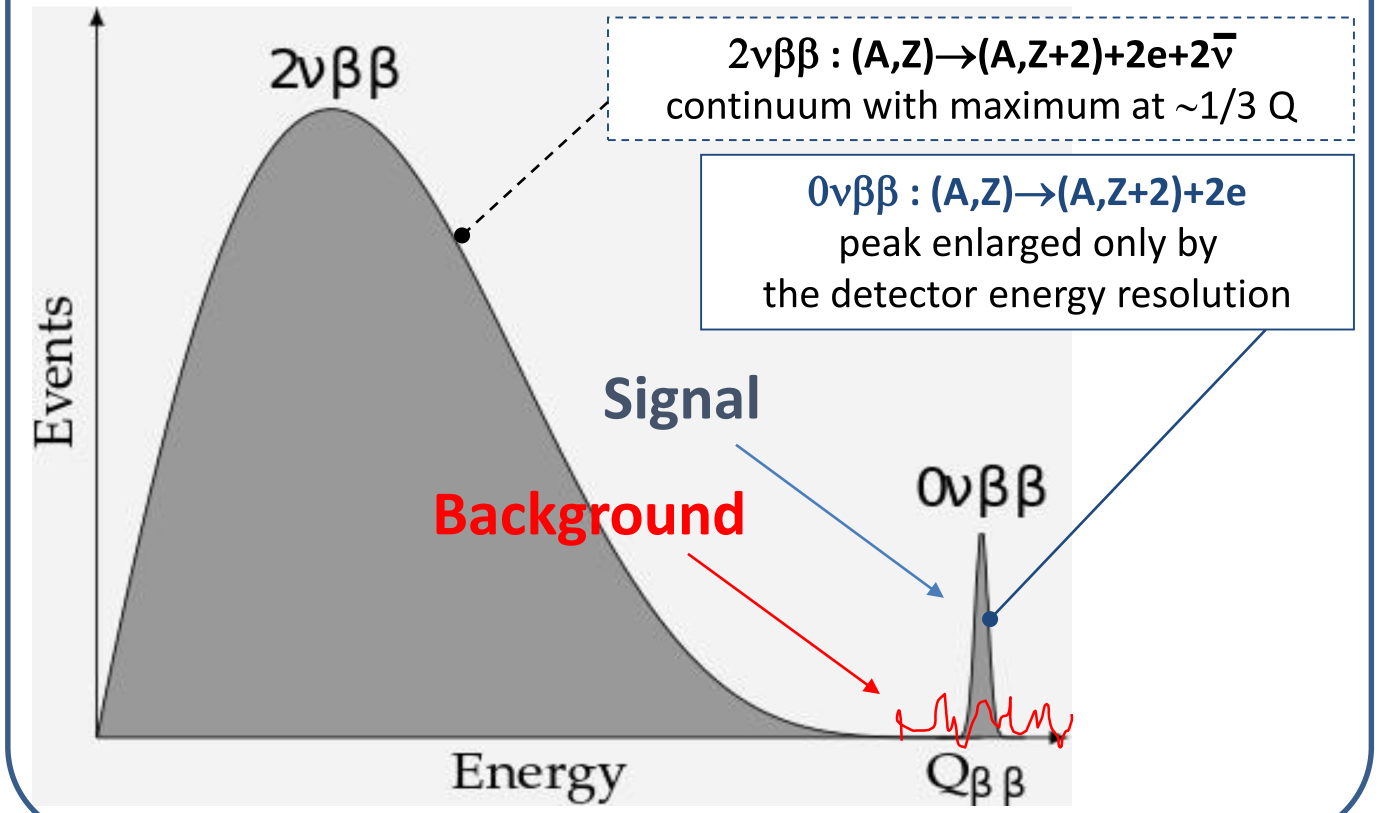
Andrea Giuliani

IJCLab, Orsay, France

Which signature and which nuclei?

Sum energy spectrum of the two electrons

$Q_{\beta\beta}$: energy available for the products



Introduction from

Giovanni Benato, this morning, this conference

In this review, I will consider

- **mass mechanism**
- "Traditional" nuclear matrix elements calculations with **no quenching**

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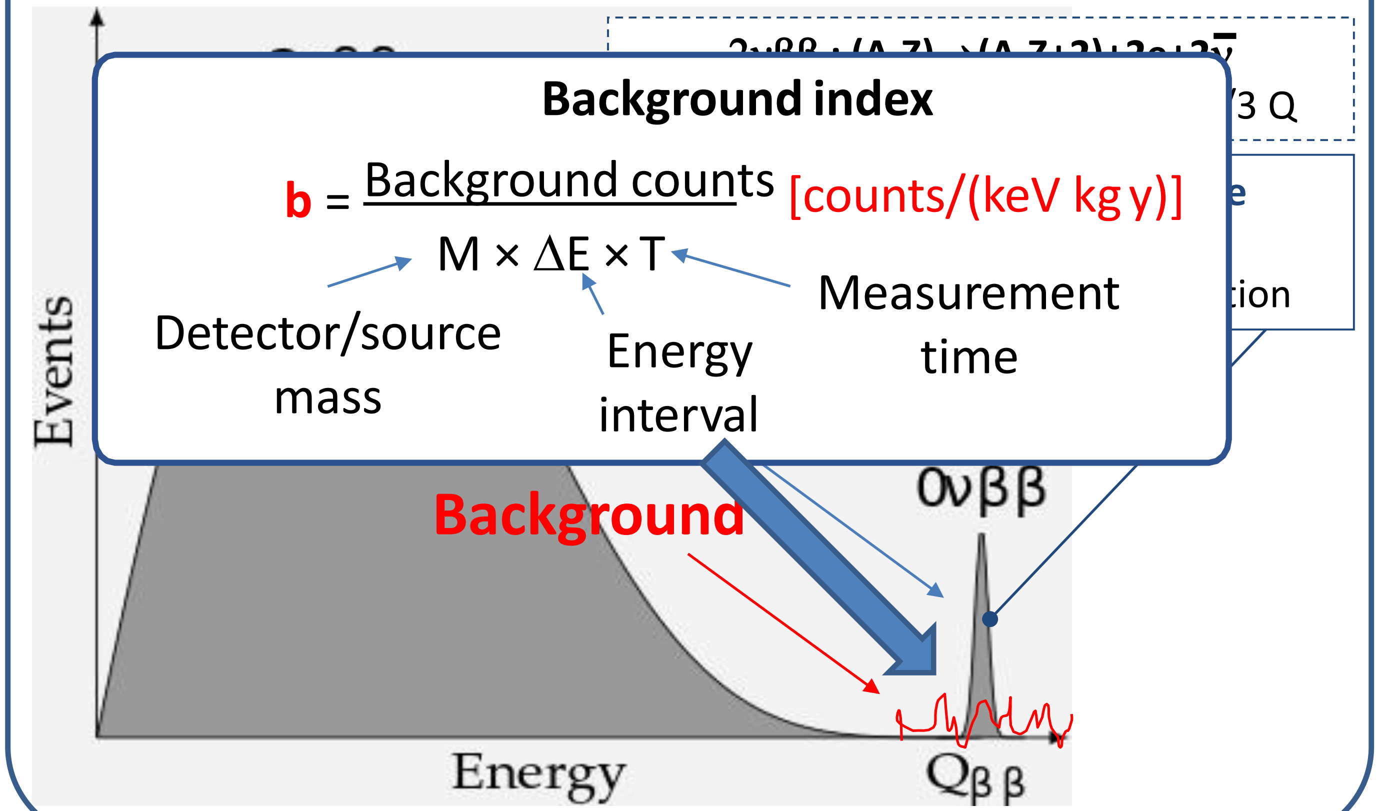

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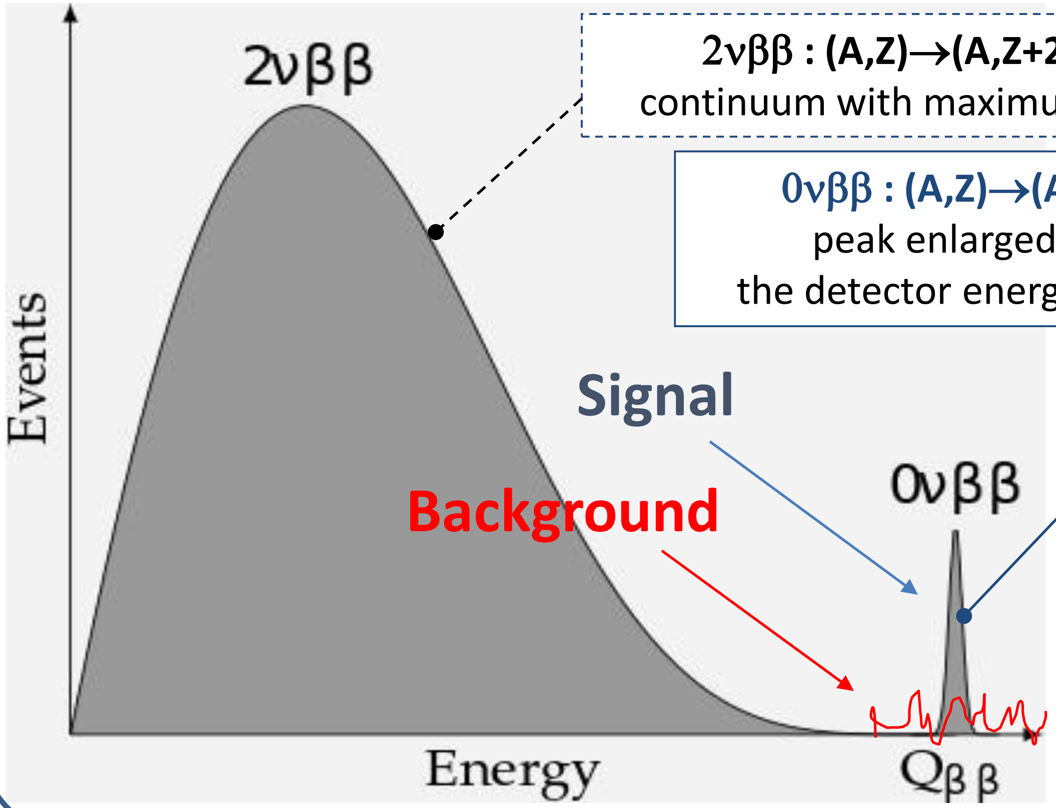


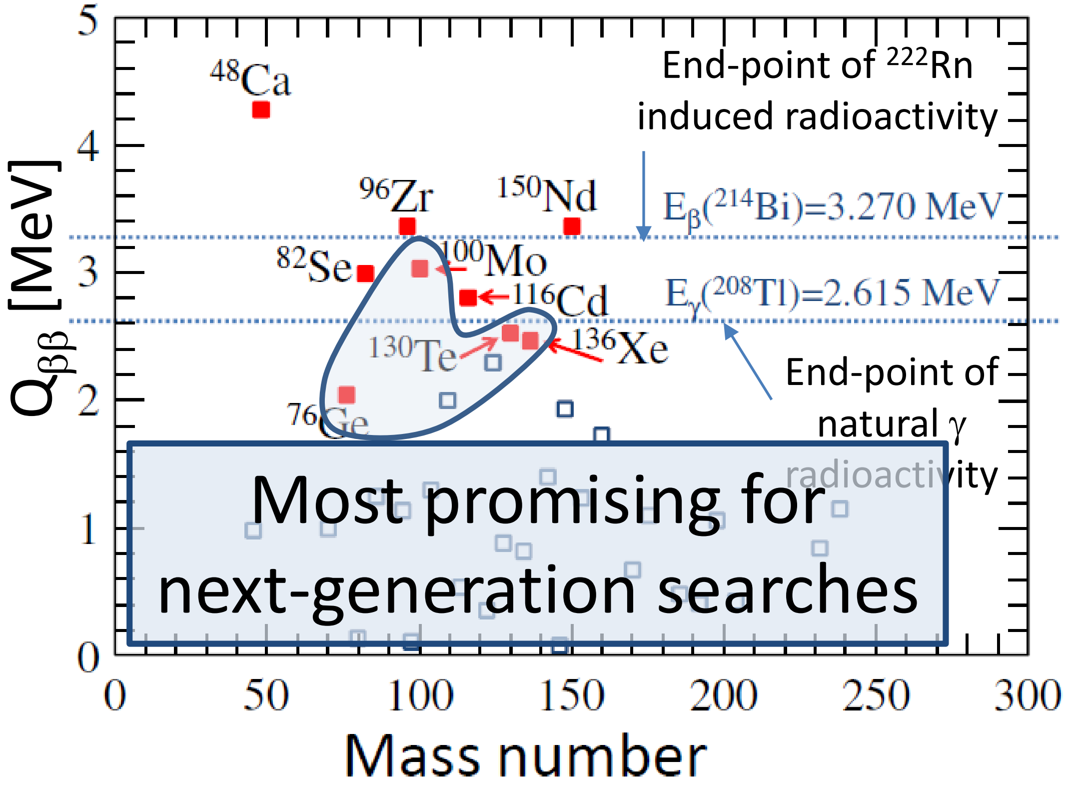
2νββ : (A,Z)→(A,Z+2)+2e+2ν
continuum with maximum at ~1/3 Q

0νββ : (A,Z)→(A,Z+2)+2e
peak enlarged only by
the detector energy resolution

Possible for 35 nuclei

Only **9** are **experimentally relevant**

$Q_{\beta\beta}$ ~ 2-3 MeV for the most promising candidates

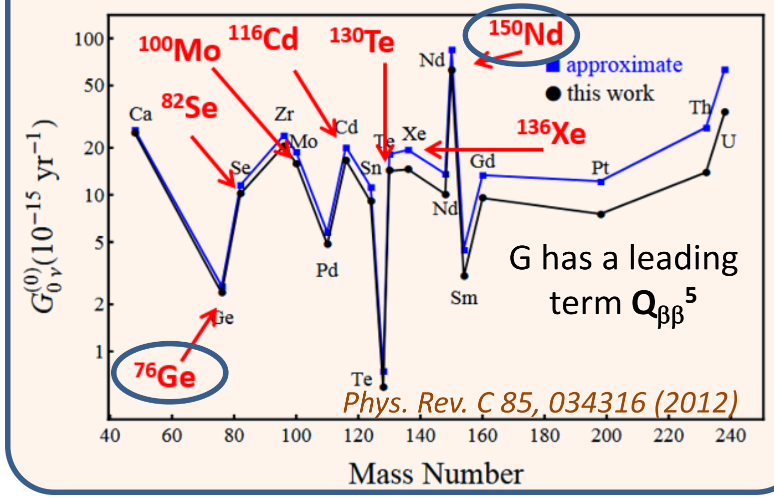


Most promising for
next-generation searches

Which half-lives? (mass mechanism)

Mass mechanism ➡ $1/\tau = G(Q_{\beta\beta},Z)\, g_A^{\,4}\, |M_{nucl}|^2\, m_{\beta\beta}^{\,2}$

Phase space: exactly calculable



G has a leading term $Q_{\beta\beta}^{\,5}$

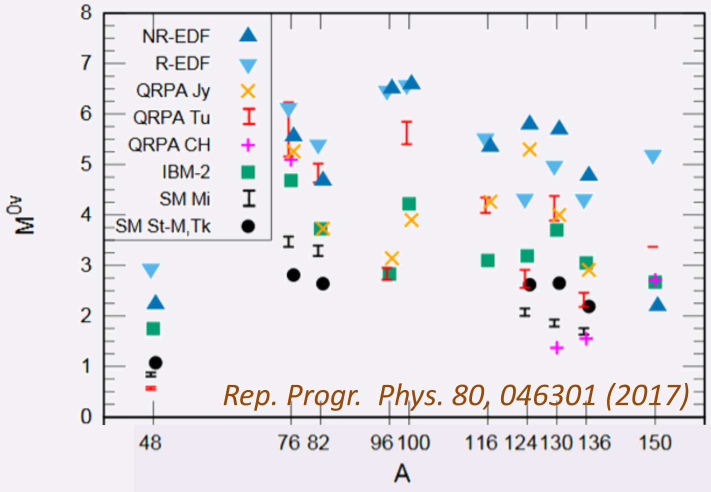
Phys. Rev. C 85, 034316 (2012)

$g_A = \begin{cases} 1.269 & \text{Free nucleon} \\ 1 & \text{Quark} \end{cases}$

$g_{A,eff} \sim$ **0.6 – 0.8** to be taken (« quenching ») to describe β and $2\nu\beta\beta$ rates with current nuclear models

- Controversial
- Ab-initio calculation with unquenched g_A are required
- Progress ongoing

Nuclear matrix elements: several models



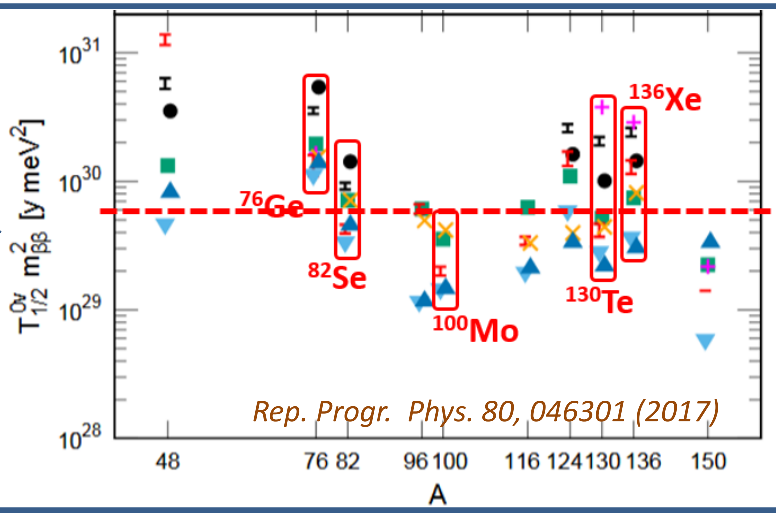
Rep. Progr. Phys. 80, 046301 (2017)

$0\nu\beta\beta$ rate

The $0\nu\beta\beta$ community still assumes **$g_A \approx 1.27$** (no quenching) with «traditional models» for M_{nucl}

This point should be revised in the future, after an expected maturation of ab-initio calculations

arXiv:2108.11805



Rep. Progr. Phys. 80, 046301 (2017)

$$T^{0\nu}_{1/2} \simeq 10^{27-28} \left(\frac{0.01\,\mathrm{eV}}{\langle m_{\beta\beta}\rangle}\right)^2 \mathrm{y}$$

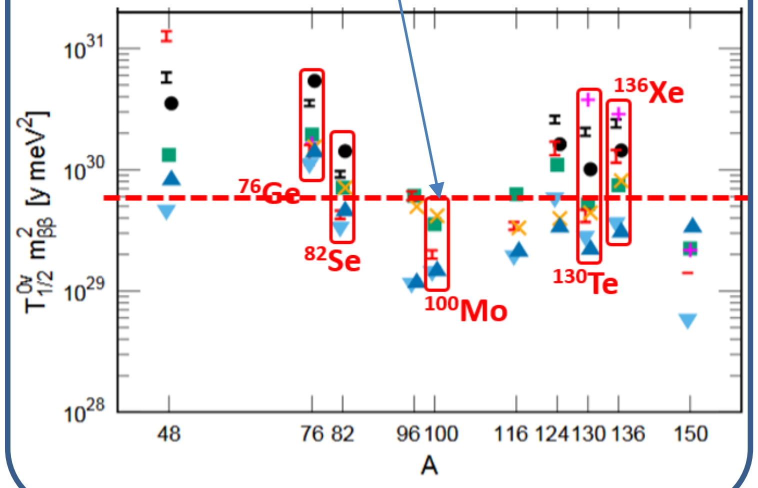
Working formula for general experiment design

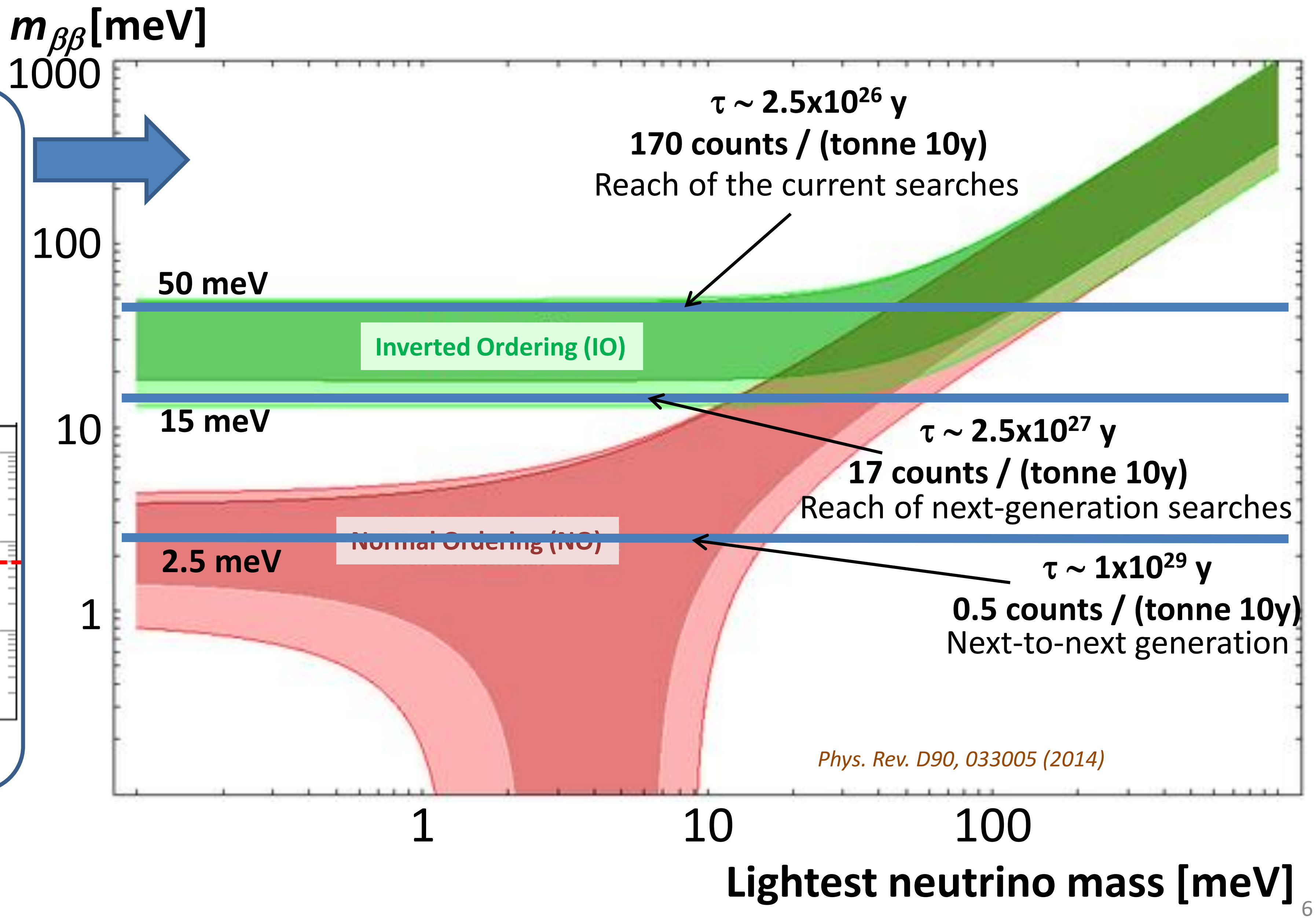
How many counts?

Example: isotope

^{100}Mo

Less favorable Nuclear Matrix Elements





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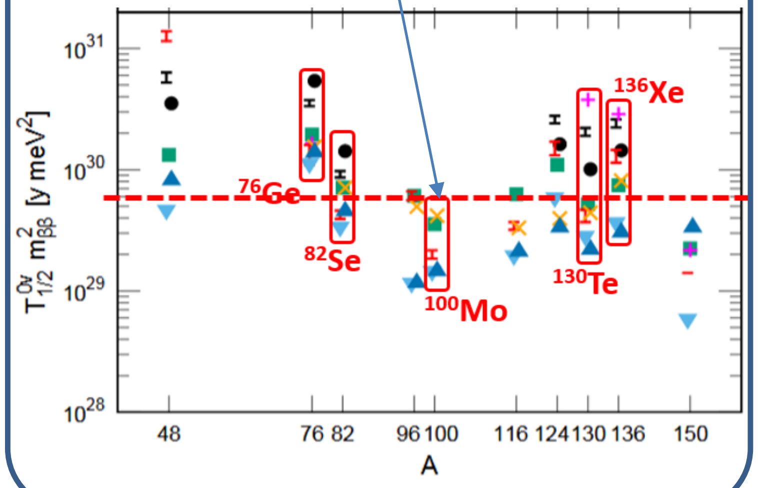
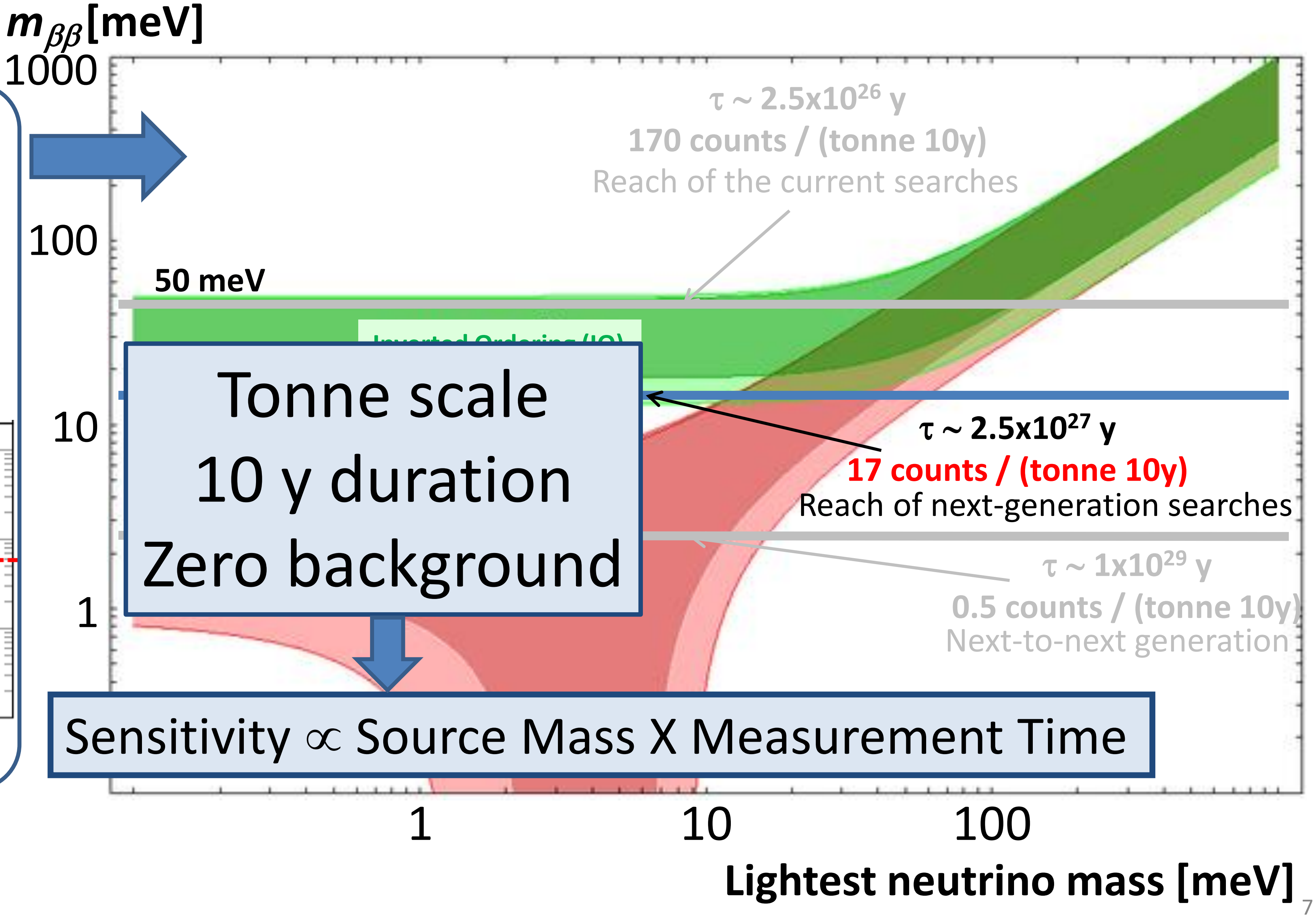


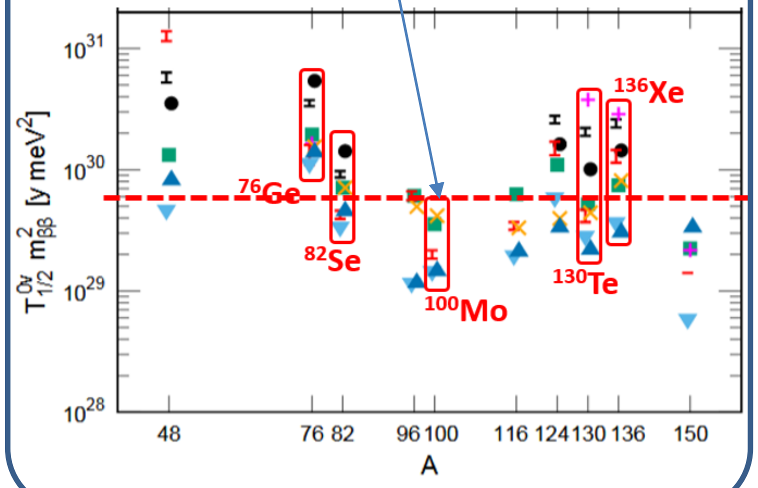


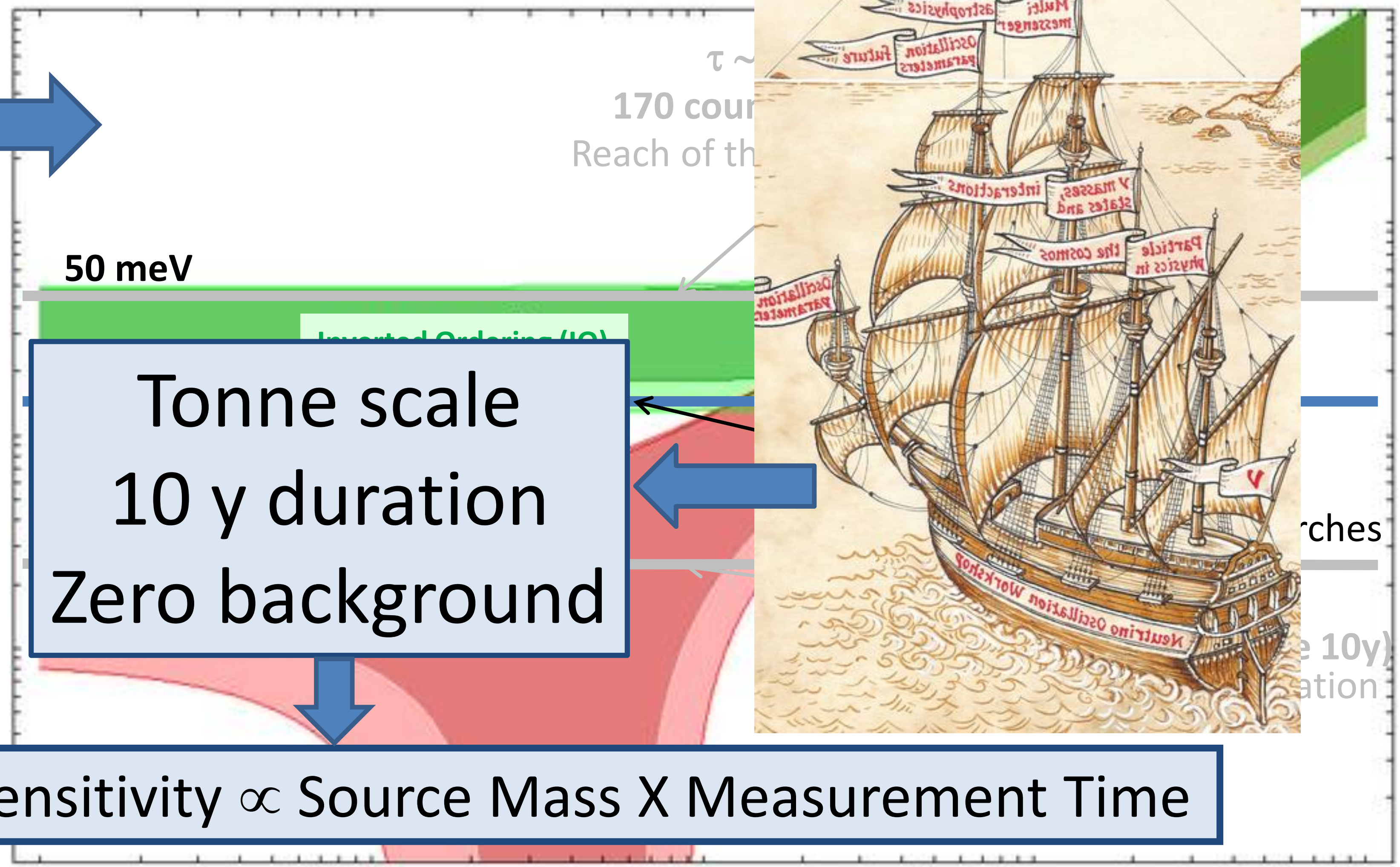
Tonne scale
10 y duration
Zero background

Sensitivity $\propto$ Source Mass X Measurement Time

How many counts?

Example: isotope
^{100}Mo
Less favorable
Nuclear Matrix
Elements





Tonne scale
10 y duration
Zero background

Sensitivity $\propto$ Source Mass X Measurement Time

Expand the source, abate the background

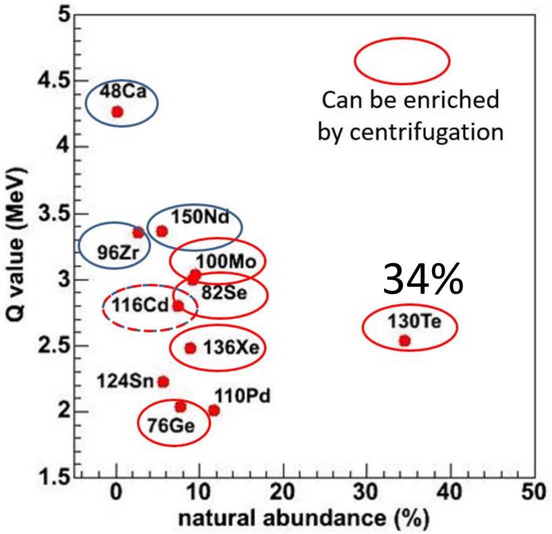
Source

① **Large source** → tonne scale → > 10^{27} nuclei

② **Isotopic enrichment**

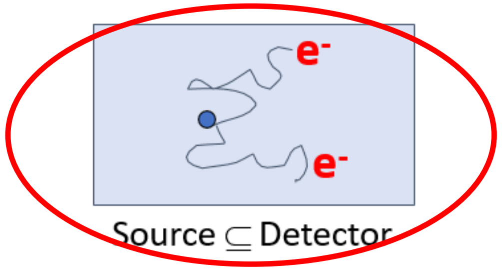
→ the isotopic abundance is artificially increased to > 80%

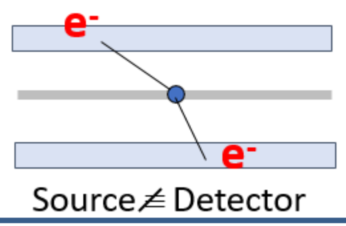
→ Isotope selection



③ **Maximize efficiency**

→ The option in which the source is separated from the detector is abandoned for next-generation experiments





Background

→ **Standard common actions**

① **Natural radioactivity (α, β, γ radiation)**

Levels < 1 μBq/kg are required ⟷ Ordinary material ~ 1-100 Bq/kg

② **Cosmic muons**

Underground laboratory → Muon flux reduction by > 10^6

③ **Neutrons**

Generated by rock radioactivity and muons

Quality and depth of the **underground laboratory**

Dedicated shieldings are often required

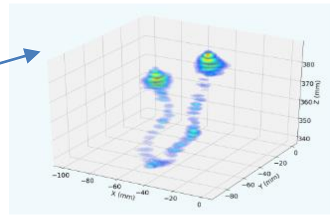
④ **Cosmogenic induced activity (long living)**

Delayed effect of the cosmic radiation (activation)

Choice of detector materials – Storage of material underground

→ **Specific actions depending on the technology**

- High energy resolution
- Particle identification
- Tracking / Event topology
- Multi-site vs. single-site events
- Surface vs. bulk events
- Fiducial volume
- Active shielding
- Final-state nucleus identification



Isotopic enrichment

- **Russia** is by far the main isotope provider for current experiments
  $\rightarrow$ **reliable and high-quality supply chain**
- Some $0\nu\beta\beta$ isotopes procured from a **European producer** (^{82}Se, ^{76}Ge)
- **War against Ukraine** $\rightarrow$ impossible to procure isotopes from Russia for Western countries
- **Intense contacts** with a European producer for a Russia-alternative isotope supply (^{76}Ge,^{100}Mo, ^{136}Xe)
- **Chinese-led projects** could continue to procure $0\nu\beta\beta$ isotopes from Russia
- Experiments using or considering to use **natural isotopic composition** sources:
  Te (34% ^{130}Te): CUORE, SNO+, THEIA, JUNO
  Xe (8.9 % ^{136}Xe): DARWIN

Deployment of an arsenal of technologies

Two main classes of experiment

The source is a fluid or is diluted in a fluid

Scalability – Increase:
- Vessel size
- Source concentration

The source is contained in a crystal

Scalability – Increase:
- Crystal size (marginal)
- Numbers of crystals

Fluid embedded source

Large source mass
Easily scalable

Source dilution in a liquid scintillator
- **Without inner balloon** (SNO+)
- **With inner balloon** (KamLAND-Zen)
- With inner balloon + Cherenkov (Theia)
- Opaque scintillator (LiquidO)

TPCs
- **High pressure gas**
  - **Xe cylindrical** (NEXT-PANDA-X-III-AXEL)
  - Xe spherical (R2D2)
  - SeF_6 (NνDEx)
- **Liquid Xe** (EXO-200-nEXO)
- Double phase Xe (DARWIN-LZ)

Crystal embedded source

High energy resolution / efficiency

Inorganic scintillators (CANDLES-III)

Semiconductor detectors
- **Ge diodes**
  - **Immersed in LAr** (GERDA,LEGEND)
  - Conventional cryostat (MAJORANA dem (MJD))
- Se CCDs (SELENA)
- CdZnTe (COBRA)

Bolometers
- **Pure bolometers** (CUORE)
- **Scintillating bolometers** (CUPID, AMoRE)
- Innovative bolometers (CROSS, BINGO)

Bold red
→ Currently competitive technology

Deployment of an arsenal of technologies

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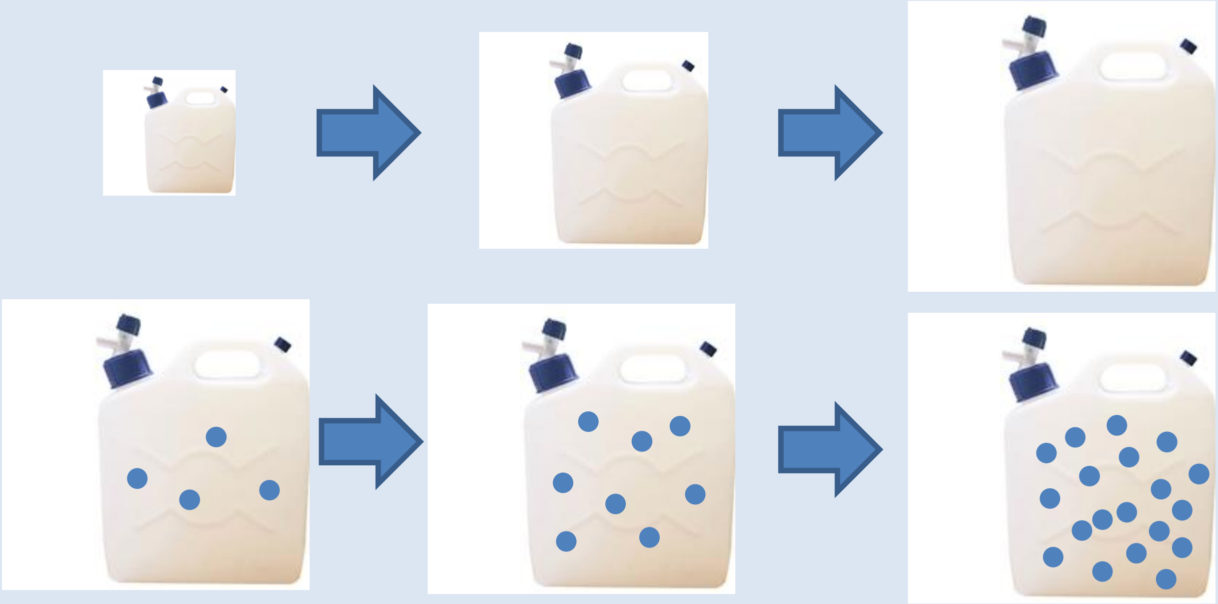
Fluid embedded source



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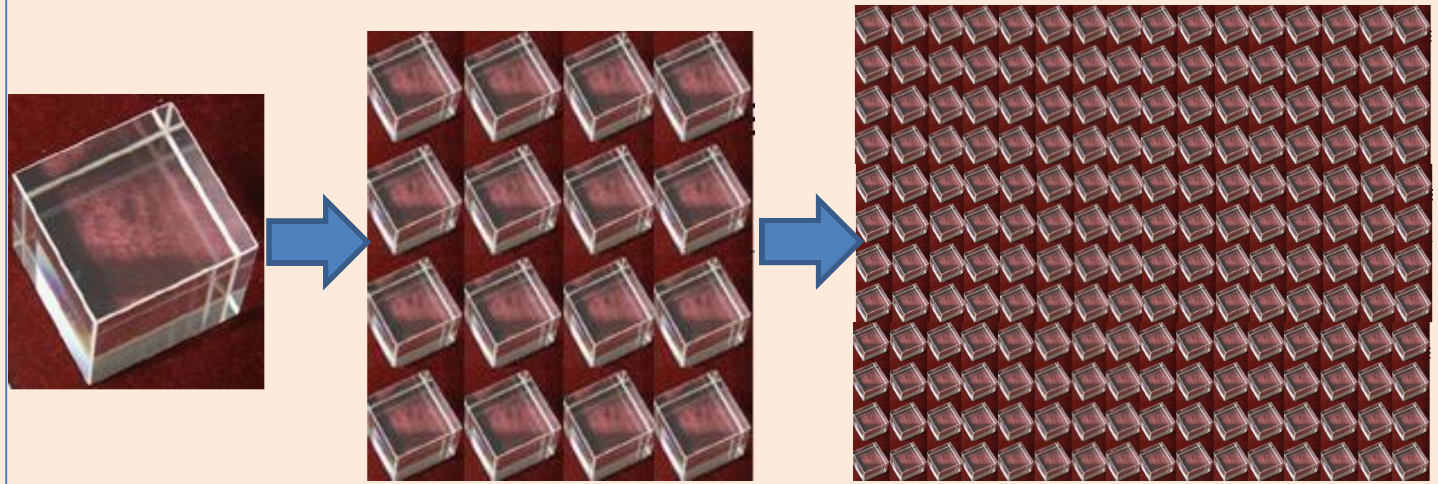

Deployment of an arsenal of technologies

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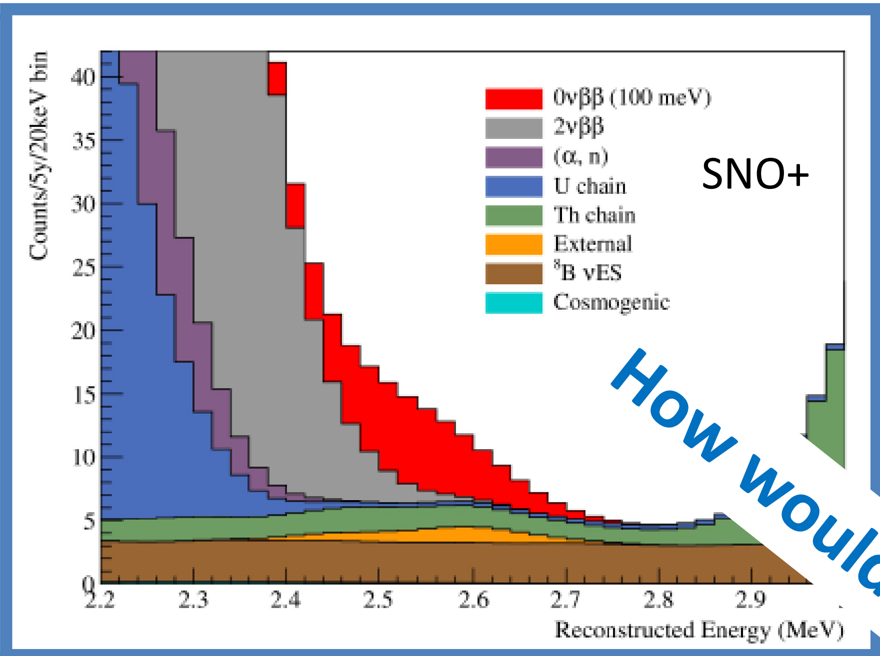


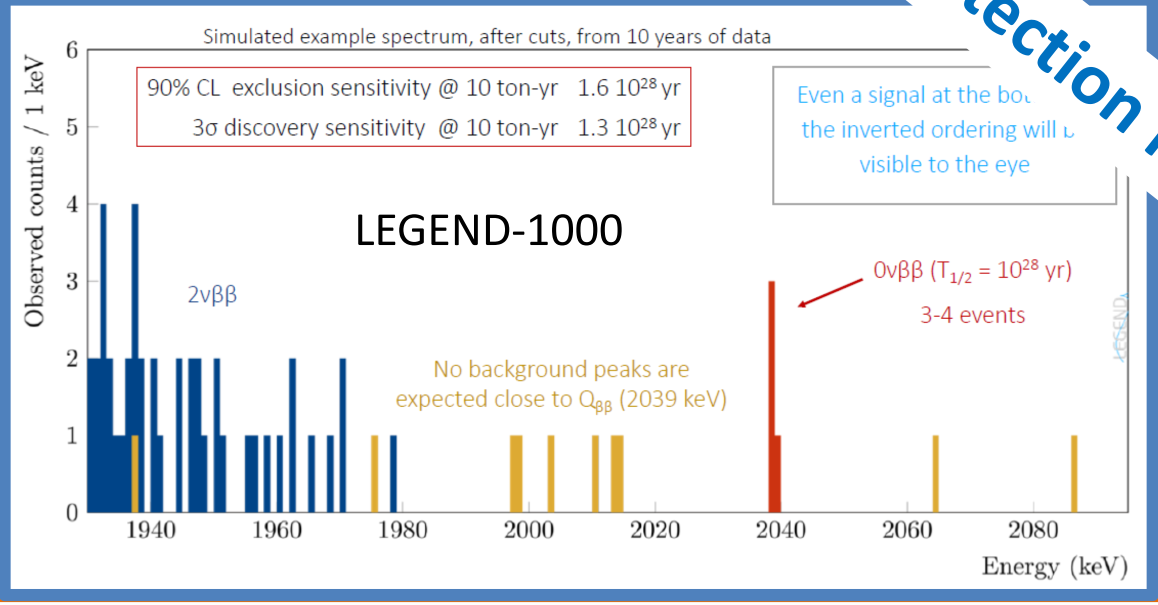
How would detection look like?

The source is contained in a crystal

Scalability – Increase:
- Crystal size (marginal)
- Numbers of crystals

High energy resolution / efficiency

Crystal embedded source

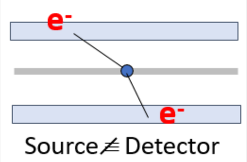


Implementation in tens of experiments

Legenda
(color code)

Completed
Data taking
Construction / Commissioning
Advanced R&D sometimes at CDR/TDR level
R&D

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



TGV-2 EC/EC β^+/EC ^{106}Cd

Large source mass
Easily scalable

Fluid embedded source

NνDEx	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(nat)-^{136}Xe
JUNO	Dilution in liquid scintillator	^{130}Te(nat)
LiquidO	Dilution in opaque liquid scintillator	multi
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(nat)
LZ	Double-phase TPC	^{136}Xe(nat)
R2D2	High pressure TPC	^{136}Xe

High energy resolution / efficiency

Crystal embedded source

CANDLES-III	**Scintillators**	^{48}**Ca**
CANDLES-IV	Scintillating bolometers	^{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**
CDEX-300 / CDEX-1000	**Semiconductor detectors**	^{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/position sensitive bolometers	^{100}Mo-^{130}Te
BINGO	Scintillating / Cherenkov bolometers	^{100}Mo-^{130}Te

Double beta decay: status and prospects

Current generation

(final sensitivity for recently concluded - running - on- commissioning projects)

KamLAND-Zen 400/800 - $T_{1/2} > 2.3\times10^{26}$ y

GERDA - $T_{1/2} > 1.8\times10^{26}$ y

EXO-200 - $T_{1/2} > 3.5\times10^{25}$ y

MAJORANA dem. - $T_{1/2} > 2.7\times10^{25}$ y

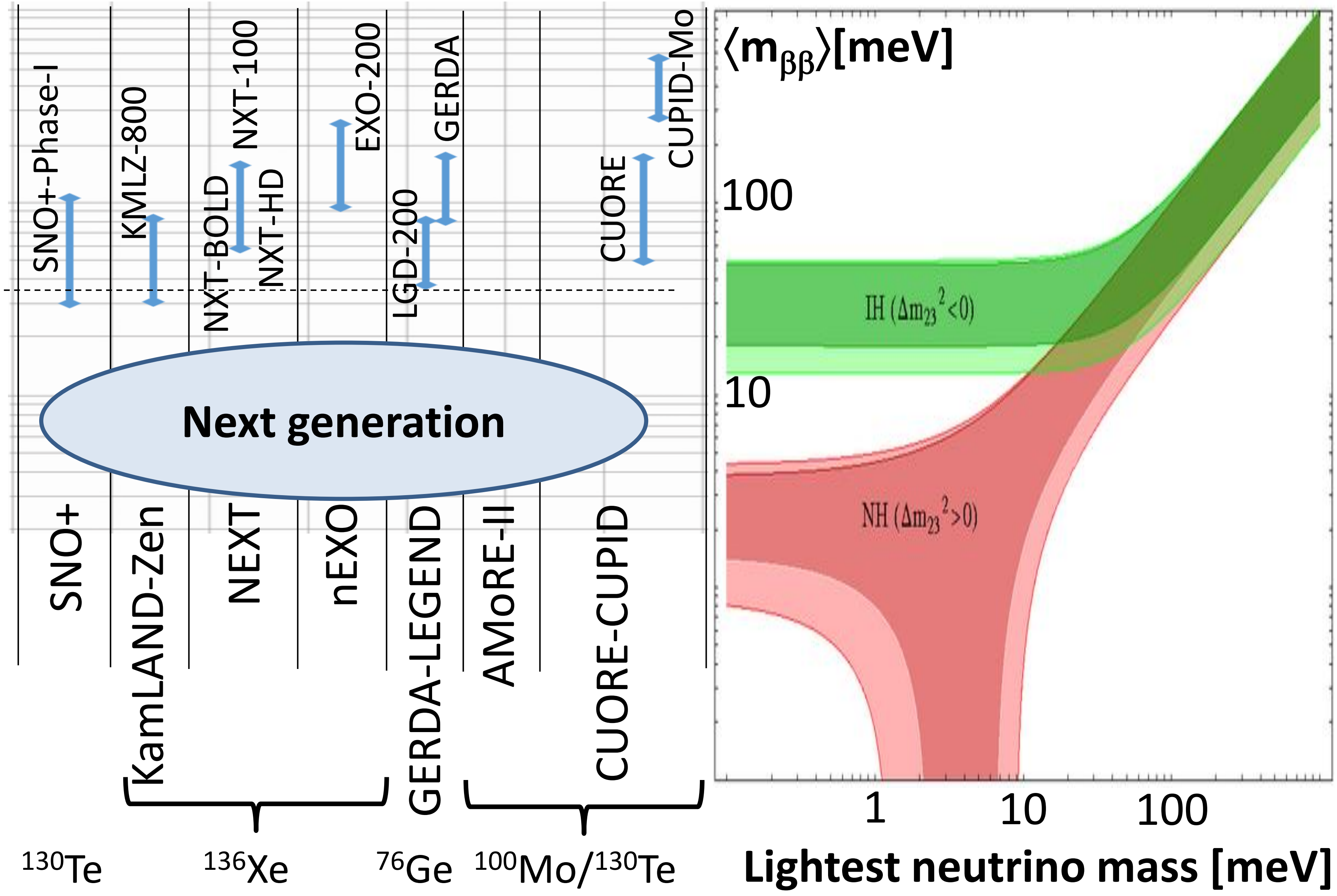
CUORE - $T_{1/2} > 2.2\times10^{25}$ y

CUPID-0 - $T_{1/2} > 4.7\times10^{24}$ y

CUPID-Mo - $T_{1/2} > 1.8\times10^{24}$ y

NEMO-3 - $T_{1/2} > 1.1\times10^{24}$ y

$> 10^{24}$ y club



Most promising next-generation experiments

7 research lines / experiments are more mature:

- 4 fluid embedded
- 3 crystal embedded

Large source mass Easily scalable **Fluid embedded source**	①	KamLAND-Zen 400 → KamLAND-Zen 800 → KamLAND2-Zen
	②	SNO+ → **SNO+-phase II**
	③	EXO-200 → **nEXO**
	④	NEXT-White → NEXT-100 → NEXT-HD / NEXT-BOLD
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**

Completed
Data taking
Construction / Commissioning
Advanced R&D
R&D

Fluid embedded source
Liquid scintillator

Koichi Ichimura, this afternoon, this conference

KamLAND-Zen (400 and 800)

Completed
Data taking
Construction / Commissioning
Advanced R&D
R&D

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

KamLAND-Zen 400/800 – Kamioka, Japan $T_{1/2} > 2.3\times10^{26}$ y
350/745 kg of ^{136}Xe – Leading experiment $m_{\beta\beta} < 36 - 156$ meV

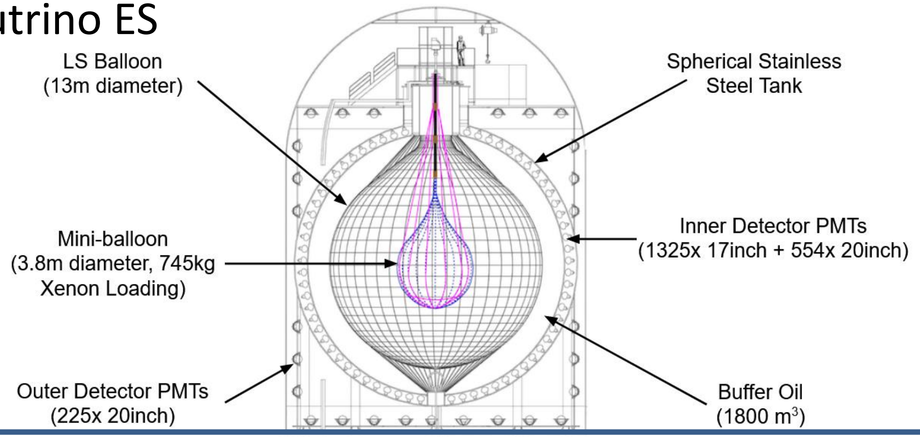
Concept

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: **ΔE(σ) ~7%/√E(MeV) – 4.5%@$Q_{\beta\beta}$**
- Single event position – **Vertex resolution 15 cm/ √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



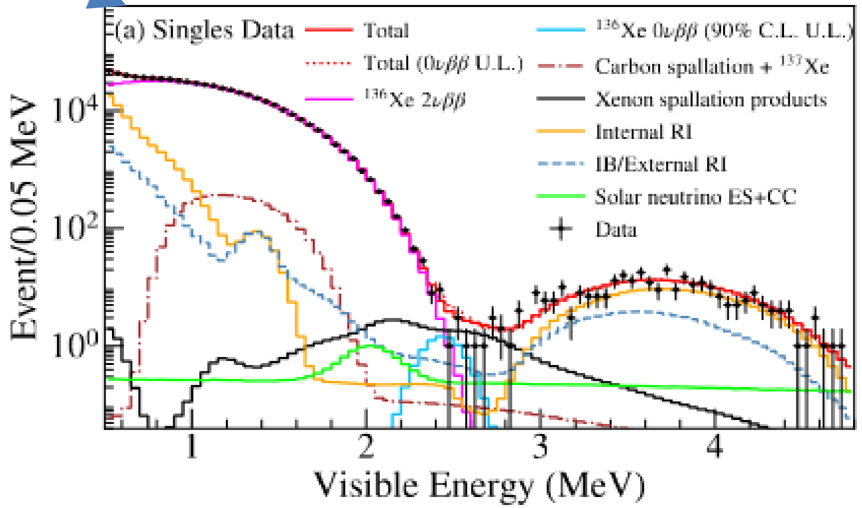
KamLAND-800 (started Jan 2019)

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**

Spectrum with cut of long-lived background events

A. Gando – NEUTRINO 2022
arXiv:2203.02139



Analysed exposure → 970 kg y (^{136}Xe)

$T_{1/2} > 2.0\times10^{26}$ y → Improved limit obtained by combination with KamLAND-Zen 400

KamLAND2-Zen

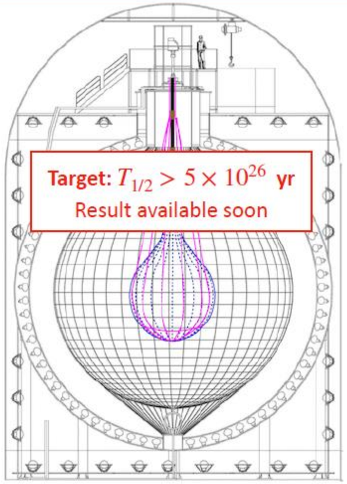
Completed
Data taking
Construction / Commissioning
Advanced R&D
R&D

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

3 neutrinos and beyond, K. Ueshima, 2019

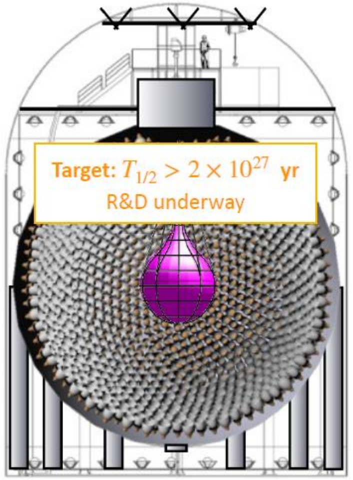
KamLAND2-Zen
- Larger source – 5X brighter → 2X better ΔE
- $m_{\beta\beta} < 20$ meV

Present



KamLAND-Zen 800:
- Mini-balloon Radius = 1.90 m
- Xenon mass = 745 kg
- Data taking starts Jan. 2019

Future



KamLAND2-Zen:
- Xenon mass ~ 1ton
- Aiming at 100% Photocoverage
- PEN scintillation balloon film

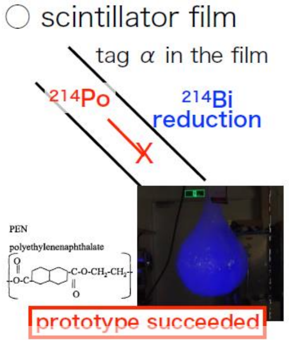
Directions of improvement
- > 1000 kg of ^{136}Xe
- Reduce ^{214}Bi background
- Reduce $2\nu2\beta$ background
- Improve tagging long-lived isotopes (new electronics)

5y sensitivity
$T_{1/2} > 2\times10^{27}$ y
$m_{\beta\beta} <$ ~20 meV

Reduce ^{214}Bi background

Identify BiPo events in balloon

Tag α's with a film on balloon

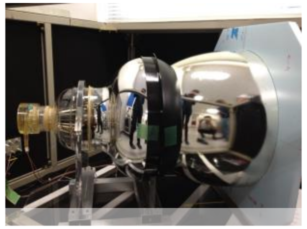


Reduce $2\nu2\beta$ background

Improve energy resolution

Increase light yield

- Brighther scintillator (x 1.4)
- High Q.E. 20'' PMT (22%→30%) (x 1.9)
- Winstone cone for light collection (1.8)



Energy resolution
$\Delta E(\sigma) < 2.5\%@Q_{\beta\beta}$

Ultimate background: elastic scattering of solar ν's on e$^-$

Further evolutions

Possibility to include scintillating inorganic crystals embedding other 2β candidates
Ambitious long-term developments: Super-KamLAND-Zen – a few tens of tons of Xe in a 20 kton detector

SNO+

SNO+ → SNO+-phase II

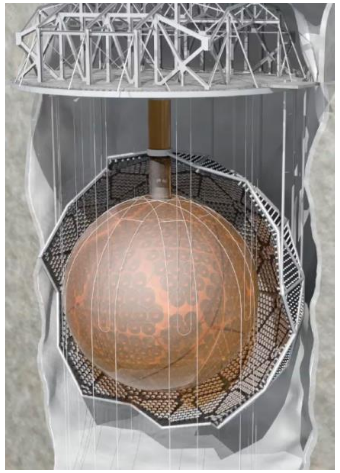
Concept

arXiv:2104.11687v2

Reuse the acrylic vessel, the PMT array and the electronics of the SNO detector at SNOLAB with a new target:

natural-Te-loaded liquid scintillator (LAB + 2g/l PPO "fluor")

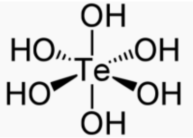
- 780 tons of scintillator
- 3.9 tons of natural tellurium
- → **1.3 tons of ^{130}Te** (34% I.A.)



→ **Scintillator purification system**

→ **Novel metal loading technique**

Telluric acid TeA

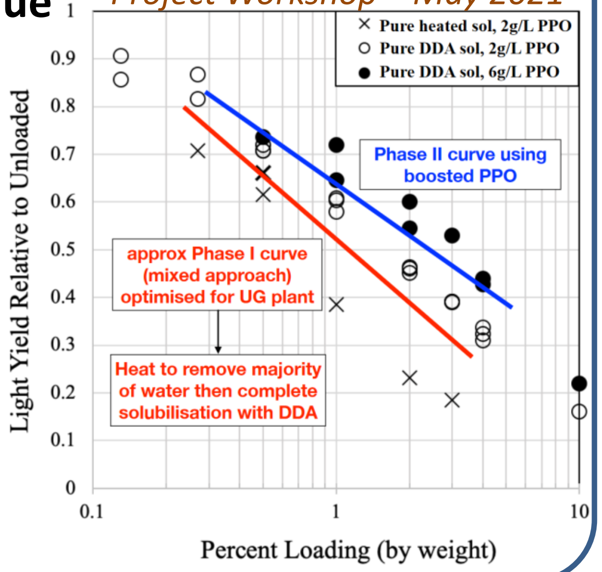


Purification

Reaction with 1.2-butanediol (BD)

Organo-metallic complex (TeBD) soluble in LAB (**0.5% mass loading**)

S.B. Biller – SNOLAB Future Project Workshop – May 2021

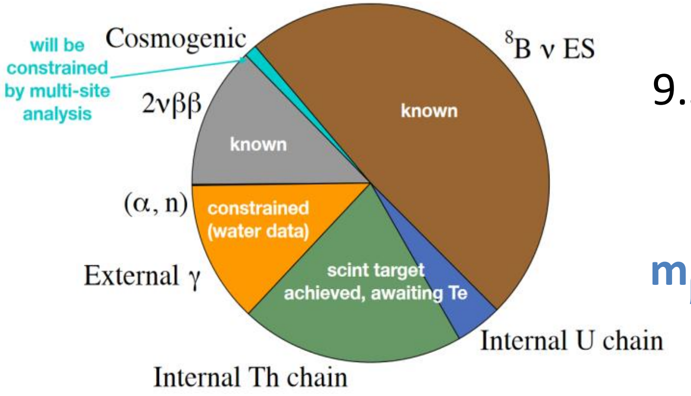


SNO+ consists of **three phases**

- **Pure-water phase** (from May 2017)
  → measurement of the external background
  → physics results (^{8}B ν's, invisible nucleon decays)
- **Liquid scintillator phase** without Te (ongoing)
  → measurement of scintillator background
  → U, Th concentration ~ 5×10^{-17} g/g
  → Background level low enough for $0\nu\beta\beta$
- **Te phase** (from 2024) – Study of $2\nu\beta\beta$ and $0\nu\beta\beta$

ΔE = 190 keV FWHM @$Q_{\beta\beta}$

Background budget and sensitivity



9.5 counts/y in ROI

5 y sensitivity

1.9×10^{26} y

$m_{\beta\beta}$ < 30 - 104 meV

TAUP 2021, M. Chen

SNO+ and evolutions

SNO+ → **SNO+-phase II** → THEIA, ZICOS

SNO+-phase II (start in 2026)

- 0.5% → **3% Te concentration**
- Improve transparency
  - No changes to underground set-up
  - No changes to loading method
  - Increase PPO to ~6g/L
  - Adiabatically increase Te loading towards ~ 3%
  - Loading rate depends on staging and system throughput (project 0.5% per 6-9 months)

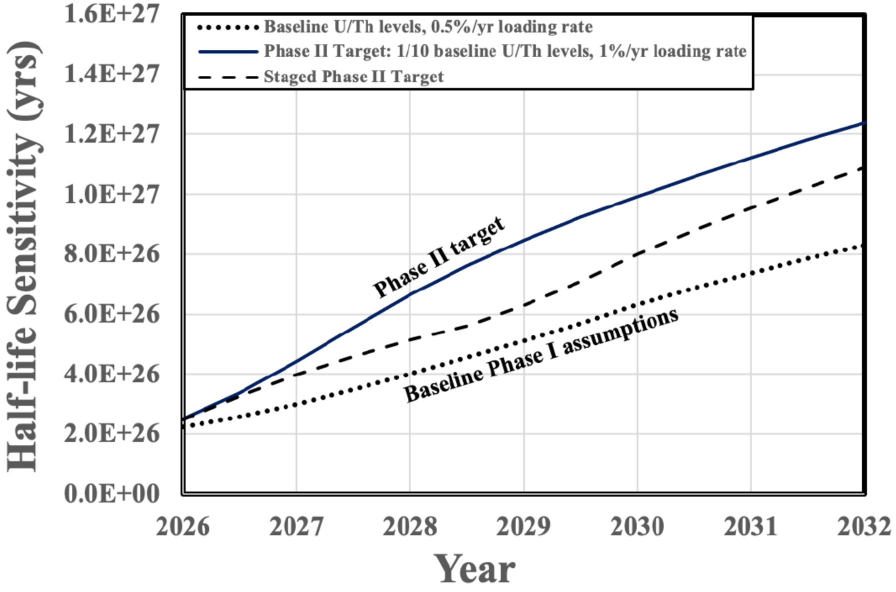
5 y sensitivity

1×10^{27} y

$m_{\beta\beta}$ < 13 – 45 meV

3% Te concentration → 24 t of Te / 8 t of ^{130}Te

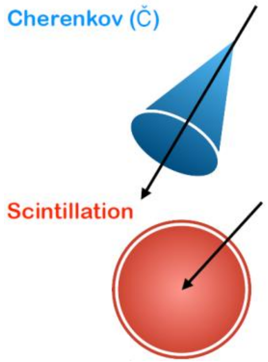
→ 70% "thrown away" by fiducial cuts but still cost effective!

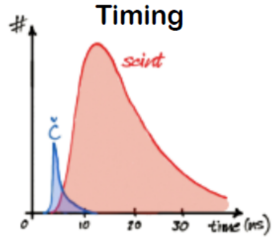


Scaling up towards NO is limited by solar ν's background

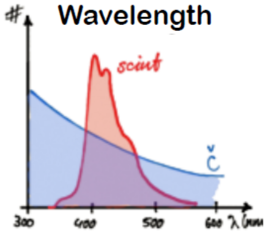
→ Directionality is needed: **Scintillation+ Cherenkov**

Water-based Liquid Scintillator (WBLS)

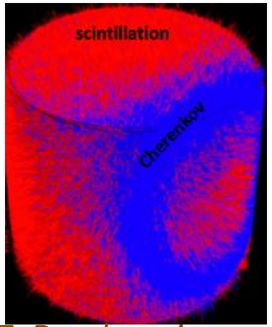




Large area picosecond photodetectors LAPPDs (~70 ps TTS) or other fast photodetectors



- Dichroic filters
- Red-sensitive PMTs
- Filtering



NuSTEC 2021, Z. Bagdasarian

Phys. Rev. Lett. 128, 091803 (2022) ←BOREXINO: proof of concept

M. Wurm, Lisbon 2022 https://indico.lip.pt/event/696/

THEIA – **multipurpose neutrino detector** DUNE cavern

- 50 kt WBLS – 16 m radius balloon with isotope
- 5% natural Te loading – 10 y sensitivity: **1.1×10^{28} y**
- Another option: 3% enriched ^{136}Xe loading

Y. Fukuda, TAUP 2021

ZICOS – **Zr-loaded liquid scintillator detector** KAMIOKA

- 180 t total – 3.5 m radius inner balloon with isotope
- 10 wt.% Zr(iprac)4 loaded in liquid scintillator – 50% ^{96}Zr
- 1.7 t of loaded LS → 865 kg of ^{96}Zr
- Cherenkov+Scintillation demonstrated in protoypes → topological background rejection – Sensitivity: **1×10^{27} y**

Other large liquid-scintillator projects

Completed
Data taking
Construction / Commissioning
Advanced R&D
R&D

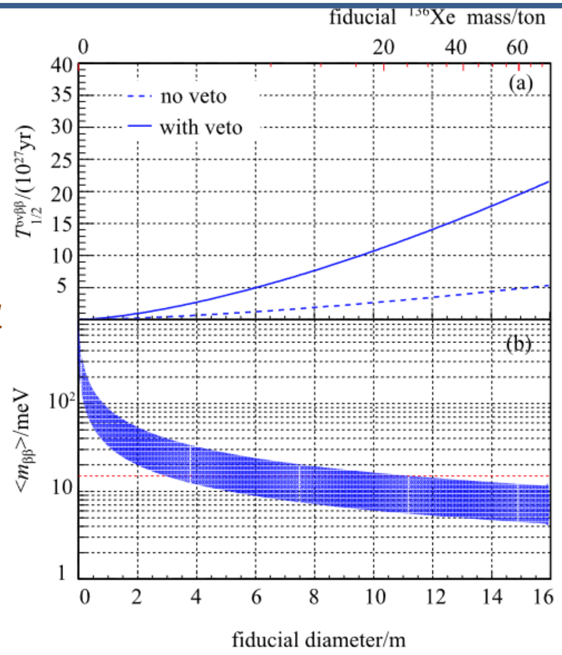
JUNO **- 20 kt LS** (LAB, 2.5 g/L PPO, 3 mg/L Bis-MSB)
After completion of mass-ordering program (~2030)
$\rightarrow$ **upgrade for $0\nu\beta\beta$ search with natural Te or ^{136}Xe**
Huge target mass (**100 t scale**) and aspired low background
High PMT coverage => 1200 p.e./MeV
Reported **R&D results** on TeBD based LS:

- Best performance so far with 0.6% Te-loading
- No measurable difference compared to purified LAB (A.L. > 20m)
- No degradation after 6 months
- Relative light output: 60%~70% w.r.t un-loaded LS

Ambition: towards exploration of normal mass ordering

Monica Sisti, 6/9 this conference

2017 Chinese Phys. C 41 053001



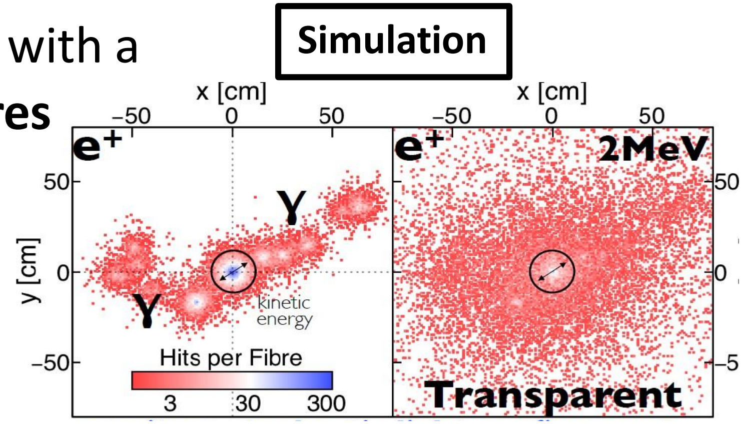
LiquidO *Commun Phys 4, 273 (2021)*

R&D activity based on the well-known liquid scintillator technology with a **radical change of paradigm**: **Opaque scintillator + tight array of fibres**

- conventional paradigm of transparency is abandoned
- scintillation light is confined and collected near its creation point

Target loading fractions: **5-30 %** (vs. current 1-3 %)
Transparency constraint is relaxed
~10 ton isotope (**^{130}Te, ^{82}Se**, **^{100}Mo**, **^{150}Nd**)

Prototype at Bordeaux



Fluid embedded source
Xenon TPCs

Completed
Data taking
Construction / Commissioning
Advanced R&D
R&D

nEXO

EXO-200 → nEXO

nEXO is built on the successful **EXO-200** – **WIPP, US**

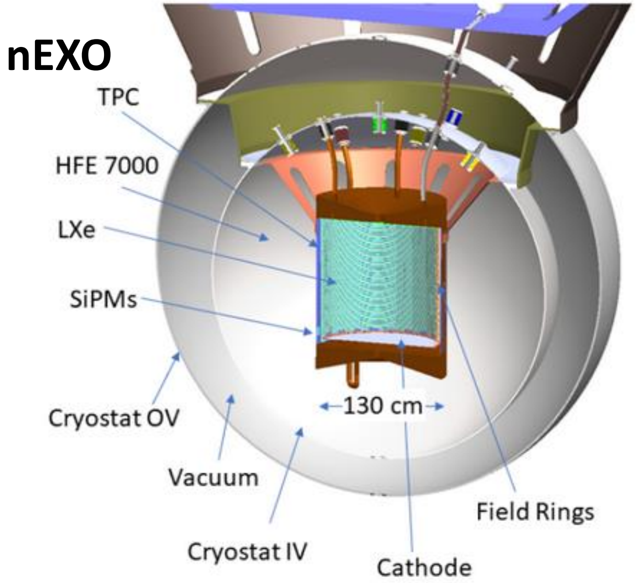
150 kg of ^{136}Xe – $T_{1/2} > 3.5\times10^{25}$ y – $m_{\beta\beta} < 93 - 286$ meV

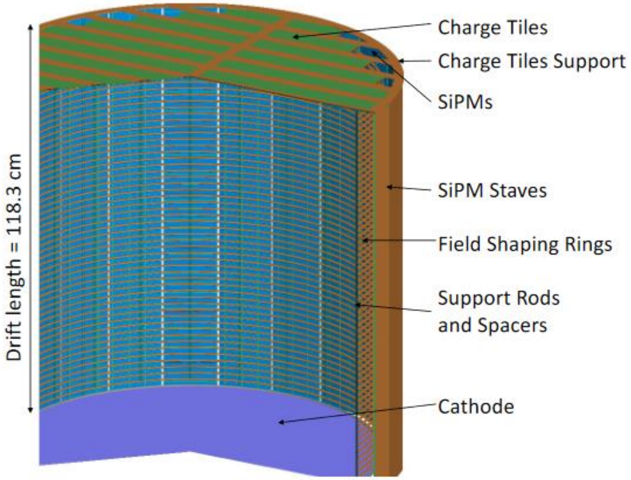
First observation of $2\nu\beta\beta$ of ^{136}Xe (2011) – $T_{1/2} = 2.165\times10^{21}$ y

Concept

Single phase enriched LXe TPC

- Energy resolution **$\Delta E(\sigma) \sim 0.8\%@Q_{\beta\beta} \rightarrow$ 1.9% FWHM**
- Measurement of both charge and scintillation
- **Single site** (including signal) **vs. multi site events** (background)
- Multi-dimensional analysis using energy, 3D position and topology





Main components inside the TPC vessel

nEXO – SNOLab

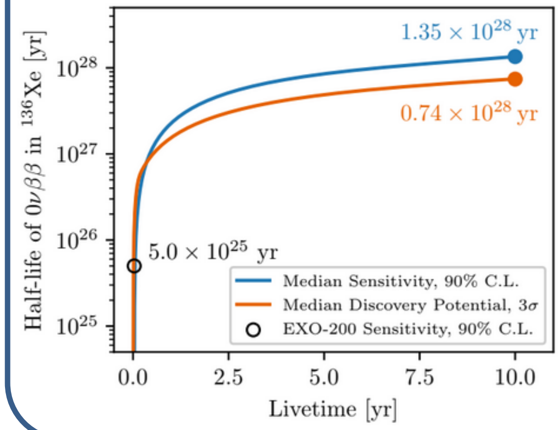
Major upgrades with respect to EXO-200

- More isotope – **~5000 kg of ^{136}Xe**
- Improvement in light sensors (LAAPDs→SiPM)
- Increased light collection
- Improvement in radiopurity (electroformed Cu)
- Cold electronics

	EXO-200	nEXO
Fiducial Mass [kg]	74.7	3281
Energy resolution $\sigma/Q_{\beta\beta}$ [%]	1.2%	0.8%

LXe self shielding

preCDR - arXiv:1805.11142v2
arXiv:2106.16243



Background dominated by Rn outgassing and intrinsic radioactivity

Equivalent background index: 7×10^{-5} c/keV kg y)

10 y sensitivity

1.35×10^{28} y

$m_{\beta\beta} < 5 - 15$ meV

Tagging of individual ^{136}Ba daughter

$^{136}Xe \rightarrow {}^{136}Ba + 2e^-$

Demonstrated by fluorescence in solid Xenon *Nature 569, 203–207 (2019)*

NEXT

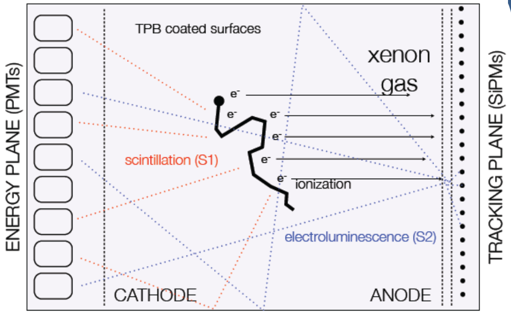
Completed
Data taking
Construction / Commissioning
Advanced R&D
R&D

NEXT-White → NEXT-100 → NEXT-HD / NEXT-BOLD

Concept

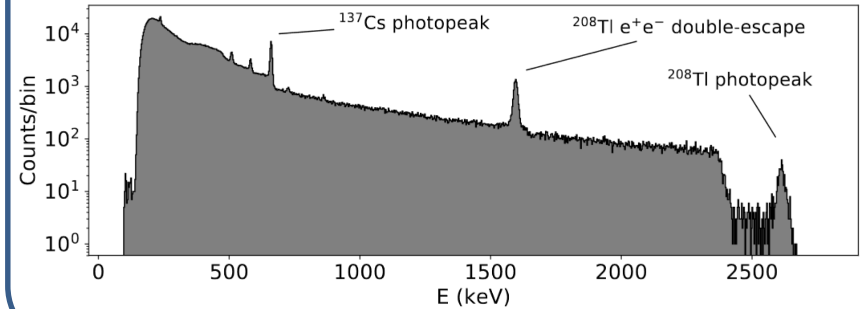
High pressure (10-15 bar) enriched Xe TPC

- Primary scintillation (t_0→ z coordinate)
- Electroluminescence for energy resolution (PMT plane) and for tracking (SiPMs plane) → only light detection, also for the charge readout



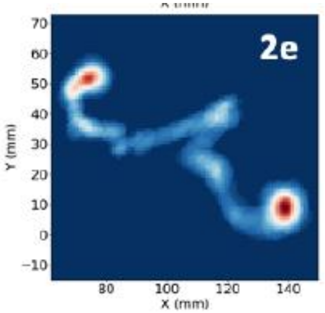
Proof of concept: NEXT-White (2016-2021) – **LSC, Spain**

- 5 kg prototype – enriched Xe from 2019
- Stability
- Long electron lifetime (> 20 ms)
- **ΔE = 0.91% FWHM in the ROI (< 25 keV)**
- **Event topological reconstruction**
- $2\nu\beta\beta$ detected at more than 5σ
- Infrastructure usable for NEXT-100



J. High Energ. Phys. 2019, 230 (2019)

Real ββ event



J. High Energ. Phys. 2019, 52 (2019)

NEXT-100 (funded) – **LSC, Spain** (2022-2025)

Upscaling of NEXT-White

- More isotope – **~97 kg of enr Xe gas (^{136}Xe: 90%)**
- 15 bar operation
- Same structure/technology of NEXT-White
- Larger vessel, 60x PMTs and 5600x SiPMs
- Projected background index: 4×10^{-4} c/keV kg y)

400 kg×y sensitivity **1×10^{26} y** **$m_{\beta\beta}$ < 60 - 160 meV**

Main goal: **prepare future stages** of NEXT technology

NEXT-HD (High Definition) – start in 2026

- Up to 1 ton enriched Xe gas at 20 bar
- Replacement of PMTs by SiPMs
- Xe-He mixture: lower diffusion, better definition
- Projected background index: 5×10^{-5} c/keV kg y)

Target sensitivity: 2×10^{27} y **6 ton×y**

NEXT-BOLD (Barium On Light Detection)

- NEXT-HD-like module with **Ba tagging**
- Ba tagging by **SMFI** (Single Molecule Fluorescence Imaging) was proved *Phys. Rev. Lett. 120, 132504 (2018)*
- R&D to adapt SMFI to the NEXT dry environment
- Background free *Nature 583, 48–54 (2020)*

Target sensitivity: 8×10^{27} y **10 ton×y**

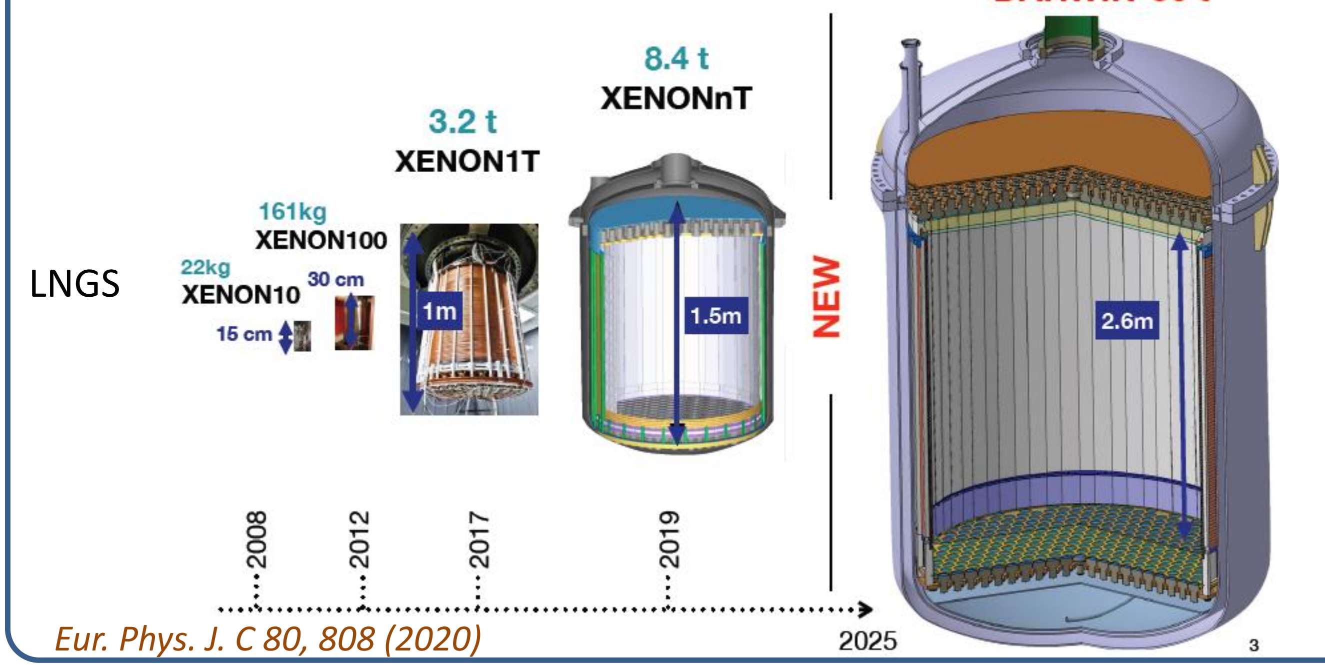
Dual-phase Xe TPC experiments

DARWIN **Dark matter** + **double beta decay** + **other rare event searches**

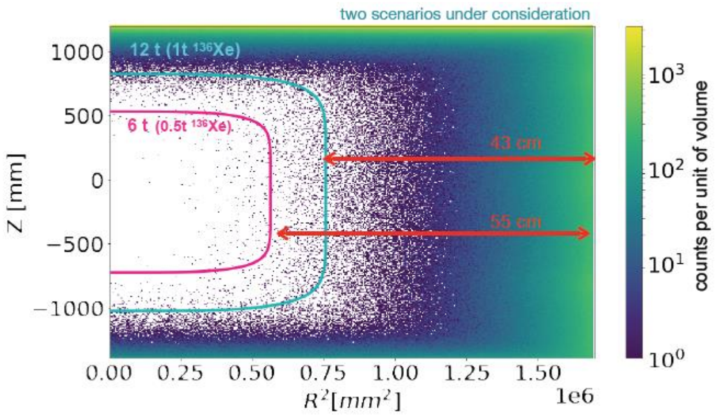
- Dual-phase TPC with natural Xe – the sensitive mass is liquid
- 50 t total (**40 t active**) of **natural liquid xenon** (LXe)
- Energy resolution **1.9 % FWHM** @ 2.5 MeV (XENON 1T)

$\rightarrow$ DARWIN will have more than **3.5 t** of active ^{136}Xe

Carla Macolino, 10/9 this conference



Eur. Phys. J. C 80, 808 (2020)



Main background sources

- ^{222}Rn in LXe
- ^{137}Xe from μ-induced neutrons
- ^{8}B Solar neutrinos

Fiducial volume: 5 t

Background: 0.2 c/(ton y) in ROI

10 y sensitivity: **$T_{1/2} > 2.4\times10^{27}$ y**

$m_{\beta\beta} < 11 – 35$ meV

Similar calculations from PANDAX-4T (3.7 t) and LZ (10 t) with sensitivities two orders of magnitude lower

Ke Han, TAUP 2021 *arXiv:2104.13374*

Crystal embedded source
Semiconductors

Tommaso Comellato, Riccardo Brugnera, this afternoon – this conference

Completed
Data taking
Construction / Commissioning
Advanced R&D
R&D

GERDA → LEGEND

GERDA
MAJORANA dem.
→ LEGEND-200 → LEGEND-1000

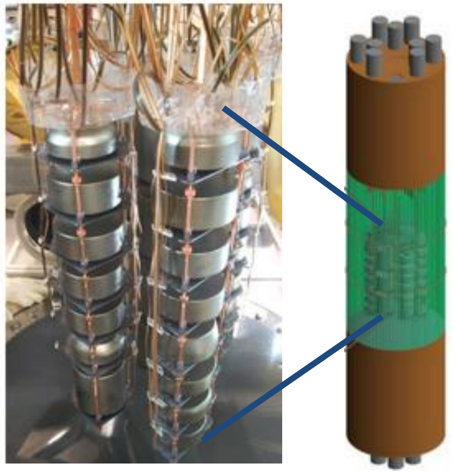
GERDA - LNGS, Italy
35 kg of ^{76}Ge

$T_{1/2} > 1.8\times10^{26}$ y – $m_{\beta\beta} < 79 – 180$ meV

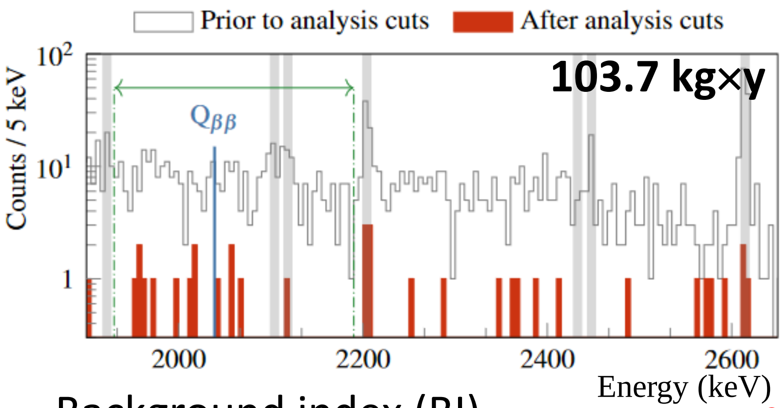
Concept

High purity naked Ge detectors immersed in instrumented LAr

- Energy resolution ΔE ~ 3 keV FWHM @$Q_{\beta\beta}$
- Pulse shape discrimination: **multi site vs. single site events**
- Anticoincidence with **LAr active shield**, instrumented with
  - Wavelength shifting fiber shroud coupled to SiPMs
  - PMTs on top and bottom of the setup



37 HP Ge detectors



Background index (BI)
$5.2^{+1.6}_{-1.3}\times10^{-4}$ c/(keV kg y)

Lowest in all ββ experiments

Phys. Rev. Lett. 125, 252502 (2020)

AIP Conference Proceedings 1894, 020027 (2017)

LEGEND-200 combines the best of GERDA and MJD

- Adopt GERDA detector configuration
- **Reuse GERDA infrastructure at LNGS** (after upgrade)
- Follow MJD selection of radiopure parts
- MJD electronics and low threshold
- ^{76}Ge: **35 kg** from GERDA, **30 kg** from MJD
  140 kg are new material
- **New detector type**, already tested in GERDA
  ICPC detector, **> 2 kg** vs. previous 0.7-0.9 kg
  → same energy resolution and PSD capability

Commissioning: *J. Gruszko – NEUTRINO 2022*

Detector deployment started in Sep 2021
An integrated commissioning run is ongoing

LEGEND-1000

S. Schoenert – NEUTRINO 2022

- Same technology, **new larger infrastructure**
- Phased approach, up to **1000 kg of ^{76}Ge**
- Site to be decided – **SNOLAB / LNGS**

Discovery sensitivity
Background free approach

LEGEND-200	LEGEND-1000
BI: 2× 10^{-4} c/(keV kg y)	BI: 10^{-5} c/(keV kg y)
$T_{1/2} > 10^{27}$ y - 5 y live time	$T_{1/2} > 1.3\times10^{28}$ - 10 y live time
$m_{\beta\beta} < 34 – 78$ meV	$m_{\beta\beta} < 9 – 21$ meV

arXiv:2107.11462v1

Crystal embedded source Bolometers

Stefano Di Lorenzo, this afternoon, this conference

Completed
Data taking
Construction / Commissioning
Advanced R&D
R&D

CUORE → CUPID

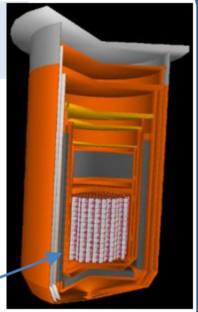
Small scale demonstrators

CUPID-Mo
CUPID-0
CUORE

→ **CUPID** → CUPID Reach / CUPID-1T

CUORE - LNGS, Italy $T_{1/2} > 2.2\times10^{25}$ y – $m_{\beta\beta} < 90 - 305$ meV
Exposure: **1038.4 kg × y –** Pure bolometers (heat signals)
988 TeO_2 crystals (from natural Te), arranged in **19 towers – 206 kg of ^{130}Te**
Nature 604, 53–58 (2022)

CUPID is built on successful CUPID-Mo + CUORE



Li_2MoO_4 scintillating bolometer technology, with demonstration of energy resolution, crystal radiopurity and α rejection

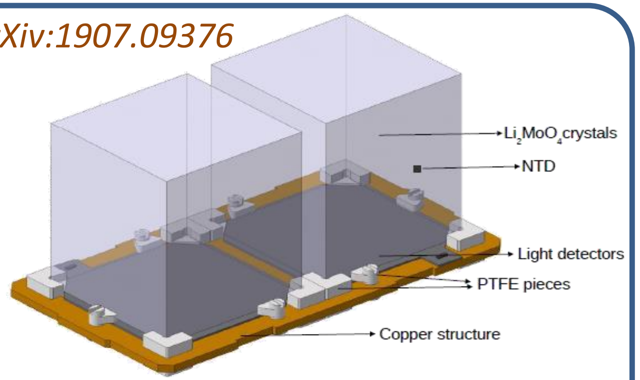
Ton-scale bolometric experiment is possible
- Electronics
- Data analysis tools

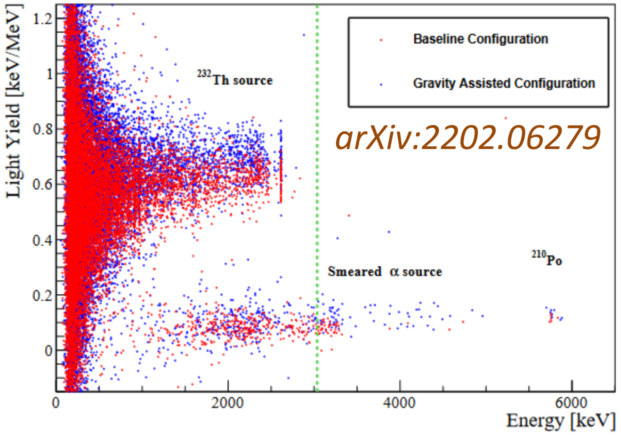
Reuse CUORE infrastructure

CUPID – LNGS – Scintillating bolometers (heat+light signals) *arXiv:1907.09376*

Concept

- Exploit CUORE infrastructure changing isotope and implementing PID
- Single module: $Li_2{}^{100}MoO_4$ **45×45x45 mm – ~280 g**
- 57 towers of 14 floors with 2 crystals each - **1596 crystals**
- **~240 kg of ^{100}Mo** with >95% enrichment
- **~1.6×10^{27}** ^{100}Mo atoms
- **Bolometric Ge light detectors** as in CUPID-Mo, CUPID-0





arXiv:2202.06279

CUPID sensitivity

Data driven background model
- Information from **CUPID-Mo**, **CUPID-0**
- CUORE background model (same infrastructure!)

Projected background index: **1×10^{-4} c/(keV kg y)**
Critical background component: random coincidence of $2\nu\beta\beta$ events (^{100}Mo fastest $2\nu\beta\beta$ emitter: $T_{1/2} = 7.1\times10^{18}$ y)

10 y discovery sensitivity 1.1×10^{27} $m_{\beta\beta} < 12 - 20$ meV

Follow-up of CUPID

CUPID-reach - Same sensitive mass and cryostat as CUPID
Background improvement by factor 5
2.3×10^{27} y → $m_{\beta\beta} < 7.9 - 14$ meV
CUPID-1T - 1 ton isotope → new cryostat
Background improvement by factor 20
9.2×10^{27} y → $m_{\beta\beta} < 4.0 - 6.9$ meV

Criticalities:
- $2\nu\beta\beta$
- Surface events

Beyond CUORE and CUPID: CROSS, BINGO

Techniques for background rejection in future Li_2MoO_4 / TeO_2 based experiments

CROSS Canfranc

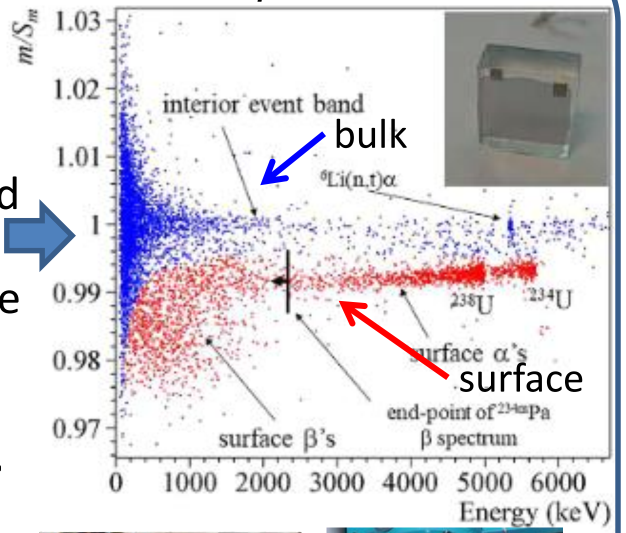
- reject **surface events** by **PSD assisted by metal film coating**

Proof of concept achieved with small prototypes

Both **surface α's and β's** are separated from bulk events

Appl. Phys. Lett. 118, 184105 (2021)

Mixed α/β source



Technology demonstrator
~ 6 kg of ^{100}Mo shared in ~50x Li_2MoO_4 crystals (+ 6x $^{130}TeO_2$ crystals) (Canfranc)

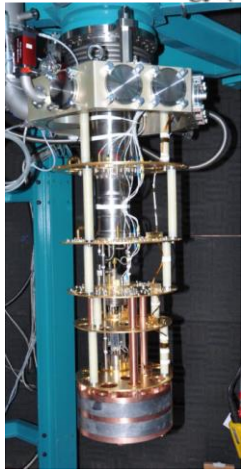
Redundancy

- surface sensitivity
- scintillation light detection

2 y live time

2.0×10^{25} y → **m_{ee} < 90 – 150 meV**

Data taking: late 2023/ early 2024



A. Zolotarova, TAUP 2021

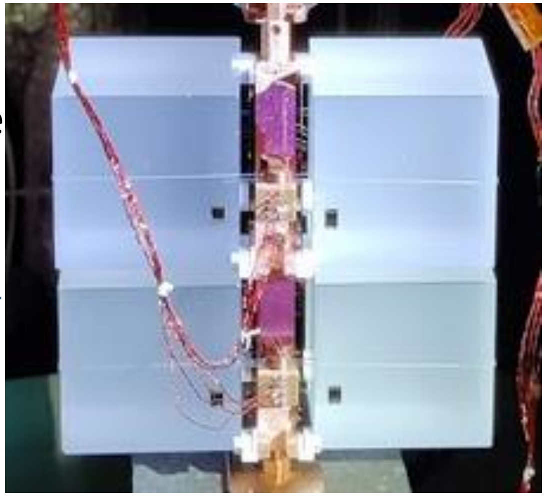
BINGO Modane

Luminescent bolometers

- **Internal active shield** (ultrapure BGO/$ZnWO_4$ scintillators)

→ mitigate γ background in TeO_2

- **Revolutionary assembly** to reject surface background
- **Enhanced-sensitivity** light detectors

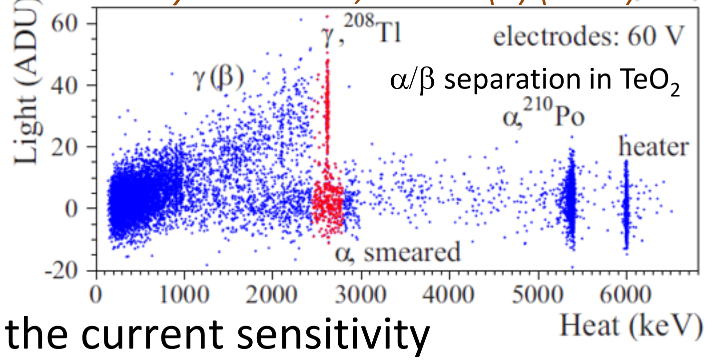


C. Nones, TAUP 2021

Common CROSS/BINGO **development**

Innovative light detectors based on the **Neganov-Trofimov-Luke effect**

Phys. Rev. C 97, 032501(R) (2018)



Increase by a factor 10-20 the current sensitivity reach < 10 eV rms baseline width – Multipurpose :

→ **α/β discrimination in TeO_2 by Cherenkov light**
→ **Read-out scintillator light of the active shield**
→ **Increase S/N to perform pile-up rejection**

CROSS demonstrator Canfranc

AMoRE

Completed
Data taking
Construction / Commissioning
Advanced R&D
R&D

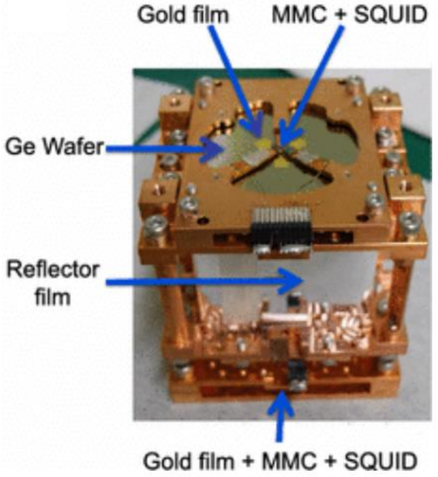
JINST 15 C08010 (2020)
J. Phys.: Conf. Ser. 1468, 012130 (2020)

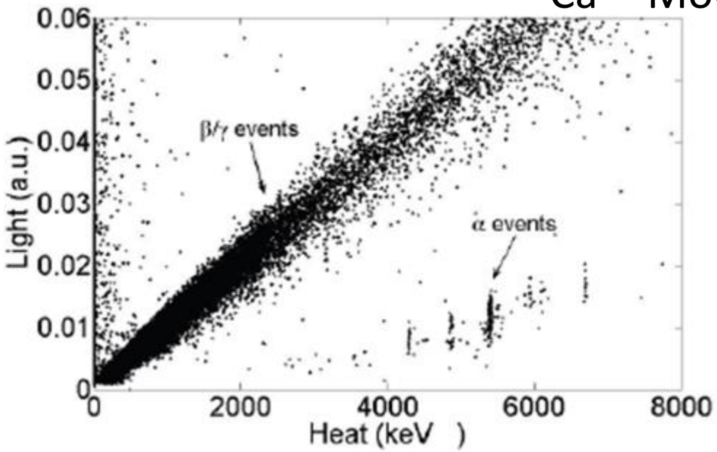
AMORE-I → **AMORE-II**

AMoRE – Y2L Lab (AMORE-I), Yemilab (AMORE-II), Korea

Concept

- **^{100}Mo**-containing scintillating bolometers
- Initially chosen compound (AMoRE pilot – R&D): **$^{48depl}Ca^{100}MoO_4$**
  → high light yield, excellent α/β separation by PSD and light yield
  → **challenging internal contamination** (^{238}U chain)
- $^{48depl}Ca^{100}MoO_4$ has been accompanied by **$Li_2{}^{100}MoO_4$** in **AMORE-I**
- $Li_2{}^{100}MoO_4$ is currently the only compound foreseen in **AMORE-II**
- Heat readout based on **MMC sensors** (faster than CUORE/CUPID)
  → $2\nu\beta\beta$ random coincidences provide negligible background
- Energy resolution **ΔE ~ 10-15 keV FWHM @$Q_{\beta\beta}$**



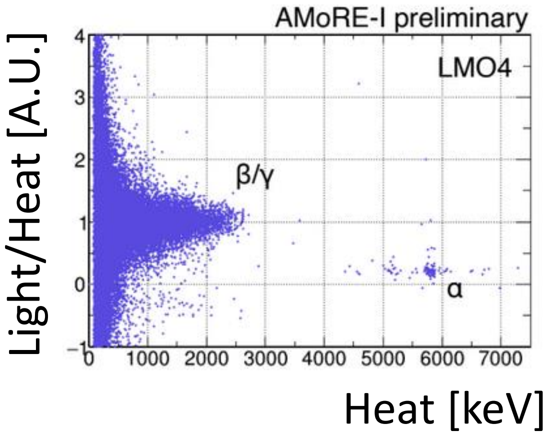


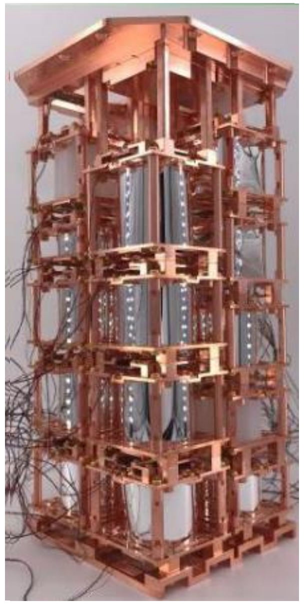
AMORE-I – started in Aug 2020 - stop in 2022

13x $^{48depl}Ca^{100}MoO_4$ (CMO, 4.6 kg)

5x $Li_2{}^{100}MoO_4$ (LMO, 1.6 kg)

→ **3 kg of ^{100}Mo**





Target BI: < 10^{-2} counts/(keV kg y)

Projected sensitivity: 7×10^{24} y **$m_{\beta\beta}$ < 130 – 250 meV**

AMORE-II – 2022 - 2027 *Yoomin Oh – NEUTRINO 2022*

Secured **110 kg of ^{100}Mo** – 596x $Li_2{}^{100}MoO_4$ crystals

New cryostat and underground lab – work in progress

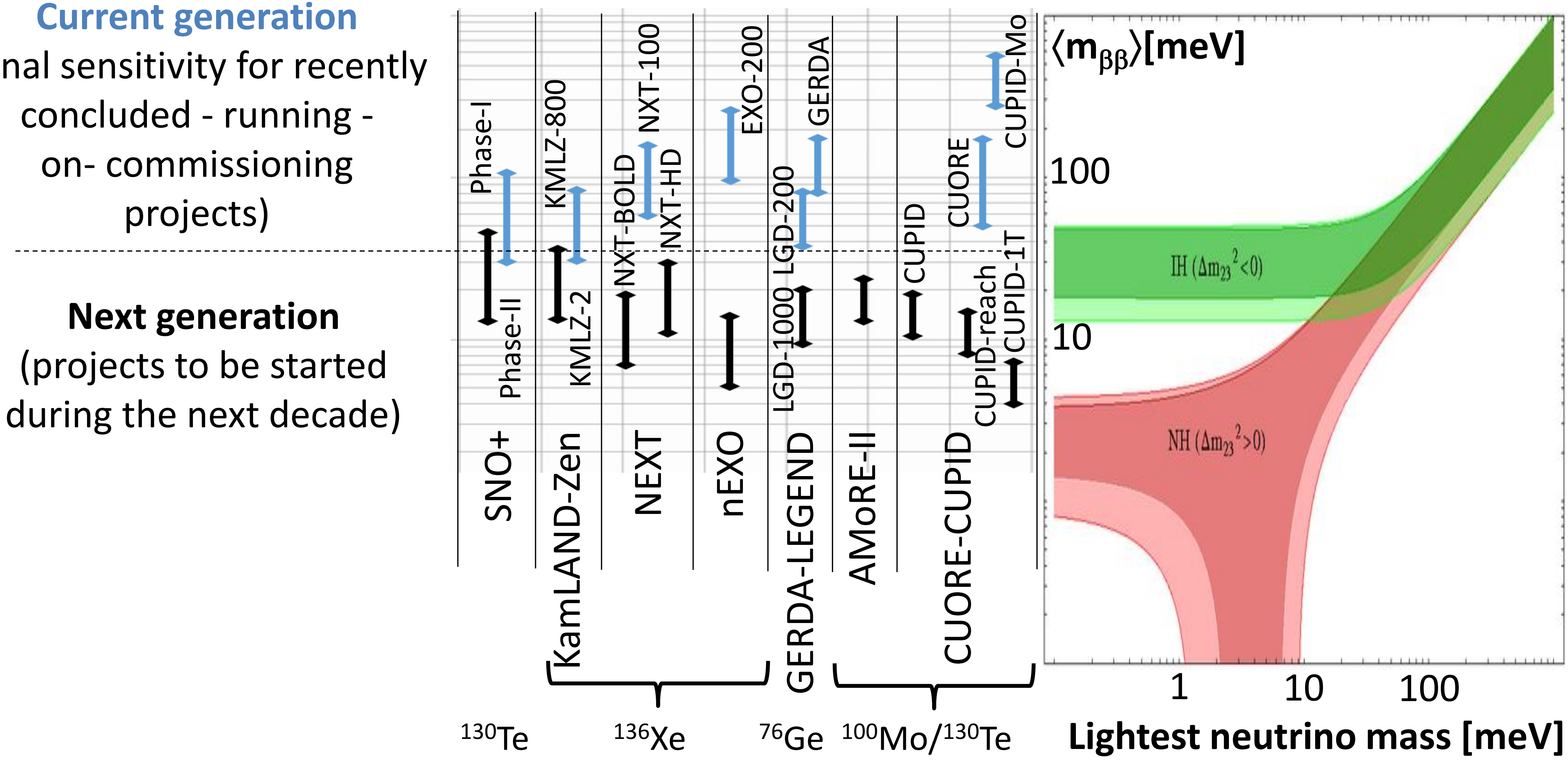
Target BI: < 10^{-4} counts/(keV kg y)

Projected sensitivity: 8×10^{26} y **$m_{\beta\beta}$ < 13 – 25 meV**

Double beta decay: status and prospects

Current generation
(final sensitivity for recently concluded - running - on- commissioning projects)

Next generation
(projects to be started during the next decade)



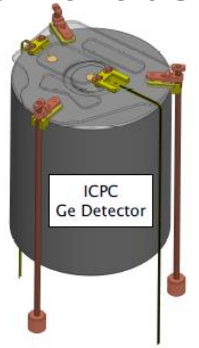
BACK UP

Riccardo Brugnera, tomorrow afternoon – this conference

LEGEND

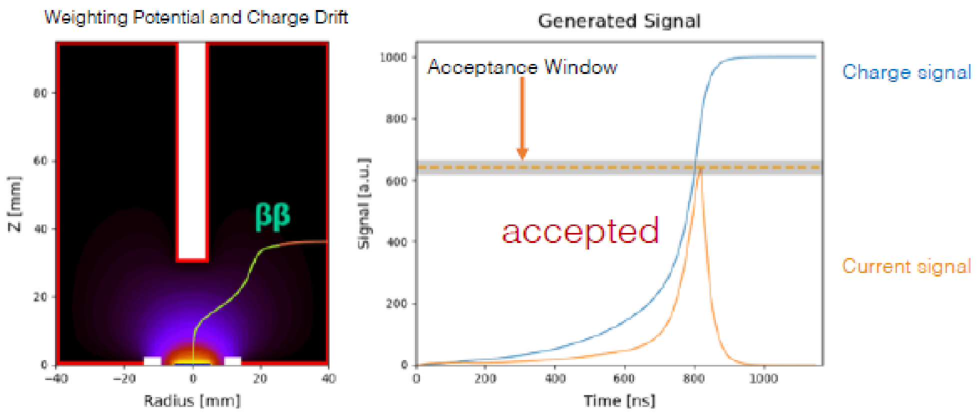
Completed
Data taking
Construction / Commissioning
Advanced R&D
R&D

Pulse shape discrimination with ICPC detectors

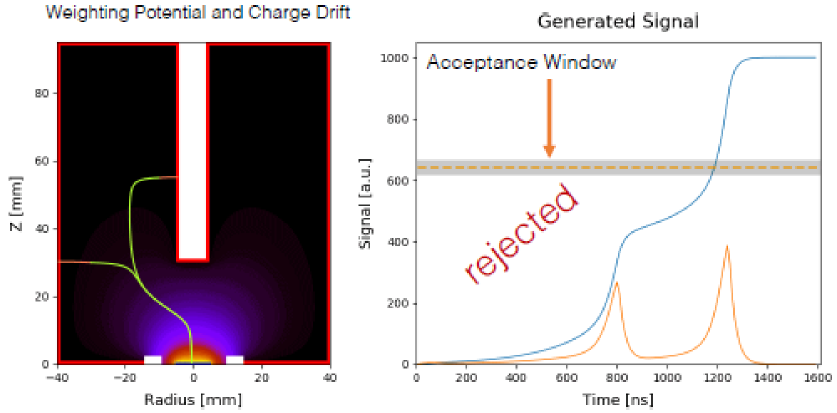


ICPC: Inverted-Coaxial Point Contact
WLS: Wavelength-shifting
UGLAr: Underground Liquid Ar

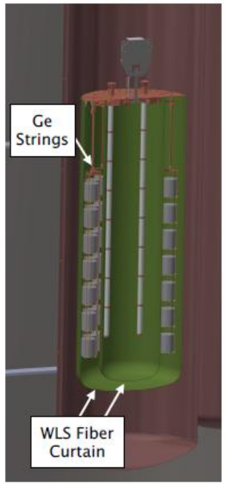
0νββ signal candidate (single-site)

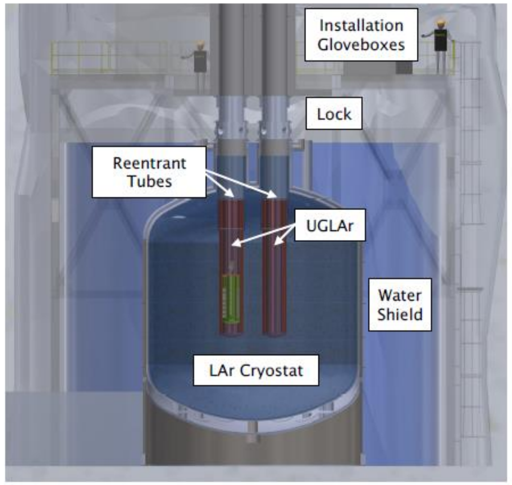


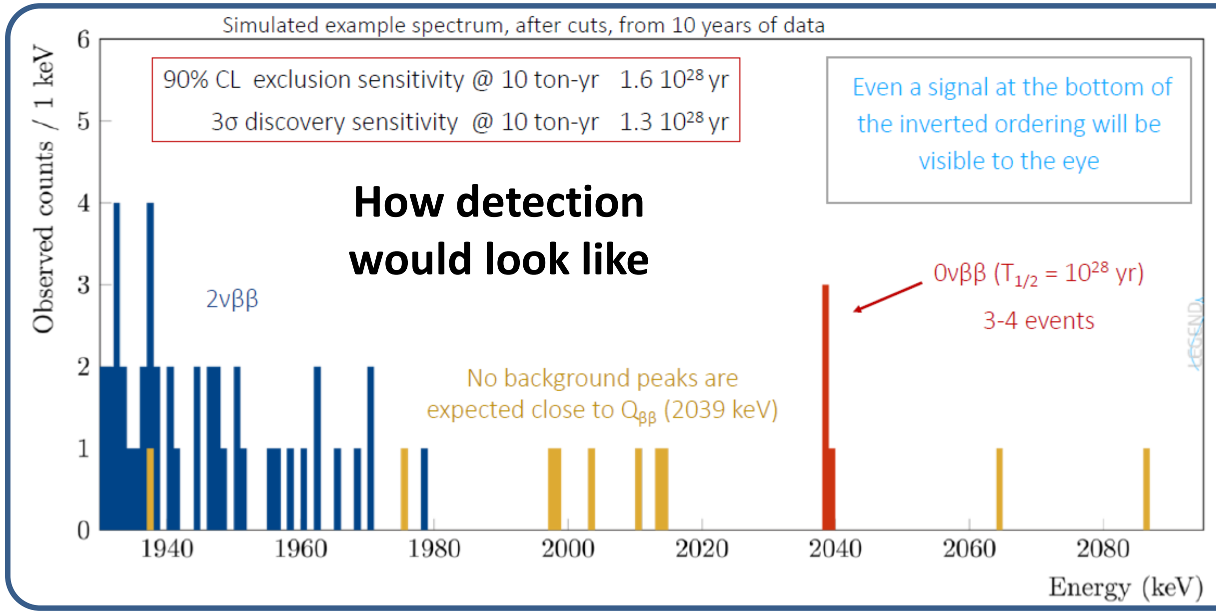
γ-background (multi-site)



Detector arrangement







Other gas TPC experiments

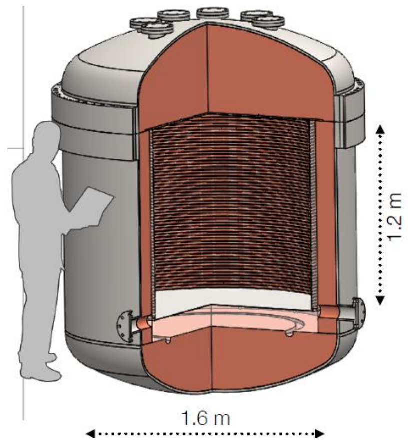
High pressure (10-15 bar) enriched Xe gas TPC

NEXT technology, with variants, is adopted by

- PANDA-X-III – electron collection
- AXEL – electroluminescence (EL)

PANDA-X-III   CJPL

JINST 15 (2020) C03052
M. Sorel – NEUTRINO 2022



One charge readout plane
52x 20x20 cm^2
Microbulk Micromegas modules

Active volume: ∅160x120 cm
Working gas: 99%Xe-1%TMA
140 kg enriched Xe

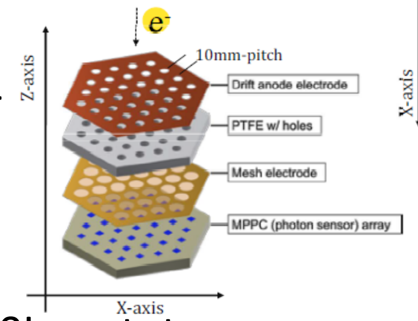
ΔE = 3% FWHM @$Q_{\beta\beta}$ – Signal effiency = 35%
Background index ~10^{-4} c/(keV kg yr)
after topological cuts

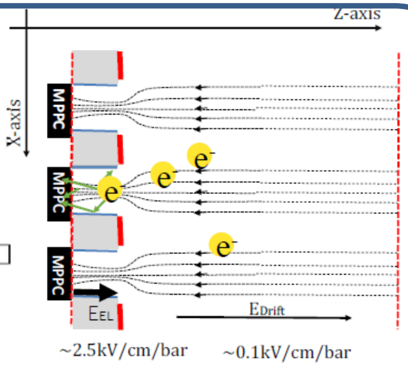
3 y sensitivity: **9×10^{25} y**
$m_{\beta\beta} < 68 – 180$ meV
Further improvement by detailed tracking features

Future extension:
PANDA-X-III 1t
Ton scale detector
Several modules

AXEL   Kyoto

Special readout for EL
Electroluminescence Light Collection Cell
(ELCC)





Proof of principle in 10L prototype
Extrapolated energy resolution: **ΔE = 0.82-1.74 % FWHM @$Q_{\beta\beta}$**
180L set-up under development

NIM A958(2020)162803

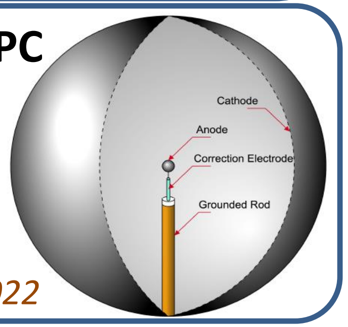
R2D2   **Spherical high pressure (40 bar) Xe gas TPC**

Simple readout and mechanics

Light readout
Primary scintillation
+ EL during avalanche

- ∅40 cm prototype under test
- Prove zero background with ∅74 cm → 50 kg Xe @40 bar

P. Charpentier, NEUTRINO 2022



NvDEX   **High pressure $^{82}SeF_6$ TPC**   CJPL

- Same gas used to enrich Se → in principle extendable to Te, Mo
- SeF_6 does not admit free electrons→ Ion TPC
- Collect and read-out ions without multiplication with CMOS technology
- Topology and good energy resolution
- 100 kg set-up under development

JINST 13(2018)P03015

Other semiconductor-based experiments

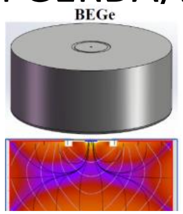
Completed
Data taking
Construction / Commissioning
Advanced R&D
R&D

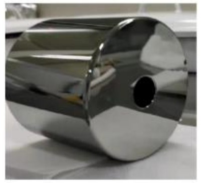
GERDA-MAJORANA-LEGEND are leading
CDEX: similar approach CJPL

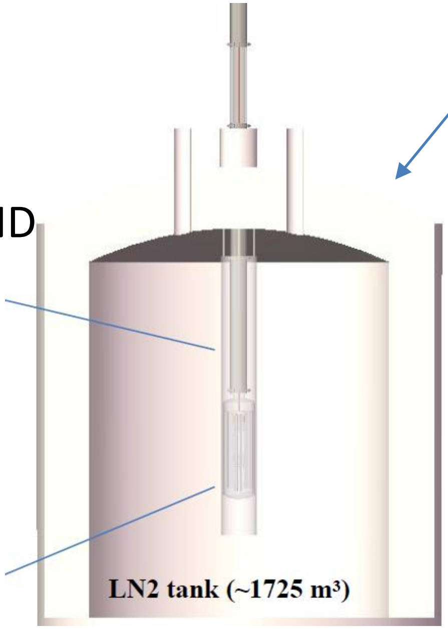
- **Ge diodes** immersed in **instrumented LAr**
- Same type of detectors as in GERDA/LEGEND

Enriched BEGe (baseline)
M ~ 1-1.2 kg

ICPC (option) M ~ 2 kg



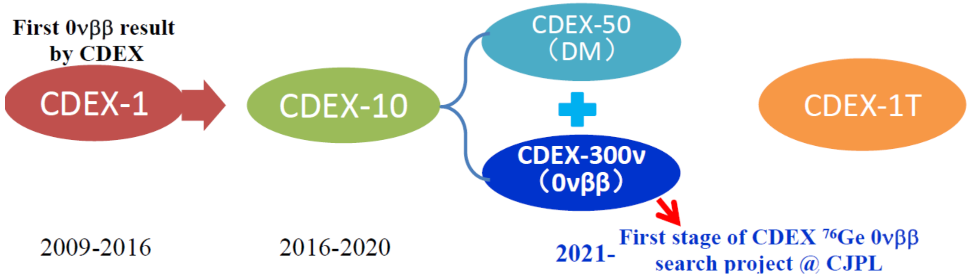




Qian Hue, TAUP 2021
S. Schoenert – NEUTRINO 2022

Set-up: no water tank,
passive LN2 around LAr vessel

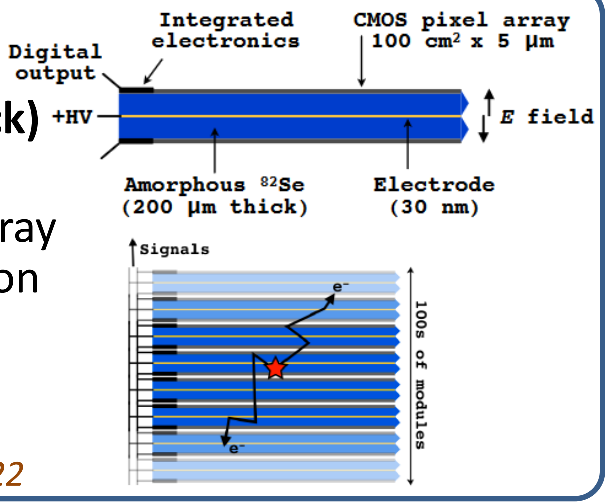
First stage: CDEX-300ν (run from 2024)
~300 kg of ^{76}Ge
Background index <2x10^{-4} c/(keV kg y)
Projected sensitivity: 1×10^{27} y



SELENA Innovative approach
Amorphous ^{82}Se x-ray detectors (0.2 mm thick)
Readout: **CMOS pixel array**

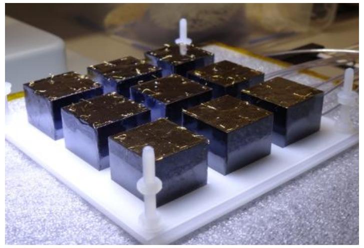
- Stack to achieve high density, high mass array
- 5 μm pixel size gives full track reconstruction
- Industrial production
- Very promising for background control ~0.001 c/(FWHM t y)

JINST 12 (2017) P03022



COBRA **CdZnTe detector technology** LNGS
Several ββ isotopes – ^{116}Cd most promising

- Demonstrator: 64x 1 cm^3 detectors
- Recent upgrade: 9x 2x2x1.5 cm^3 detectors



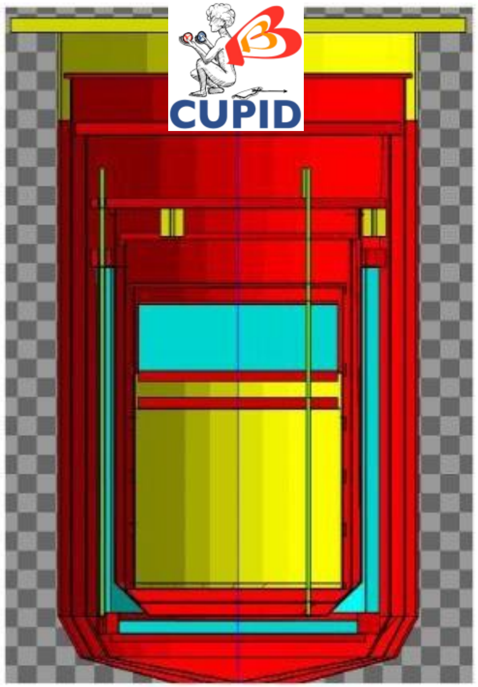
Improvements in energy resolution and background

NIMA 1010 (2021) 165524

Prospects of CUPID

Technically ready

CUPID Baseline



240 kg of ^{100}Mo

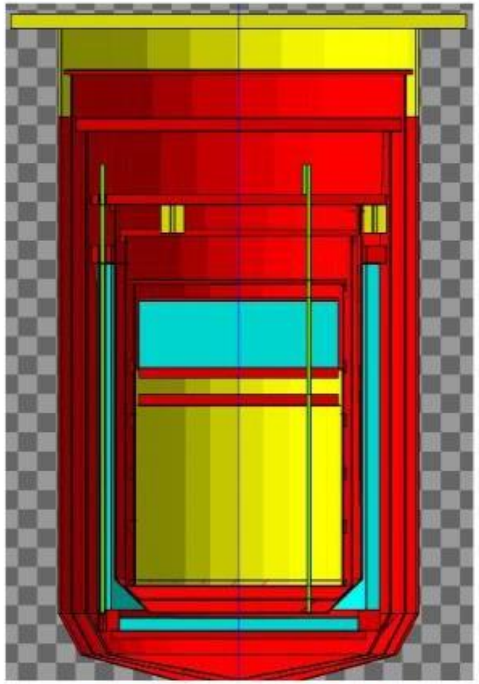
CUORE cryostat

Bkg 1×10^{-4} ckky

Excl. sensitivity:

$T_{1/2} > 1.4 \times 10^{27}$ y

CUPID-reach



240 kg of ^{100}Mo

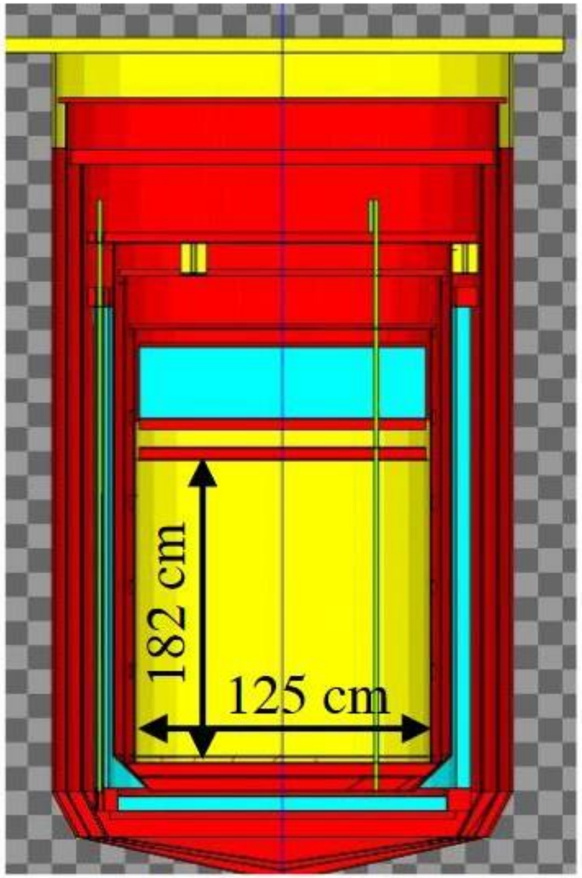
CUORE cryostat

Bkg 2×10^{-5} ckky

Excl. sensitivity:

$T_{1/2} > 2.3 \times 10^{27}$ y

CUPID-1T



1000 kg of ^{100}Mo

New cryostat

Bkg 5×10^{-6} ckky

Excl. sensitivity:

$T_{1/2} > 9.2 \times 10^{27}$ y

Other bolometric efforts

CANDLES

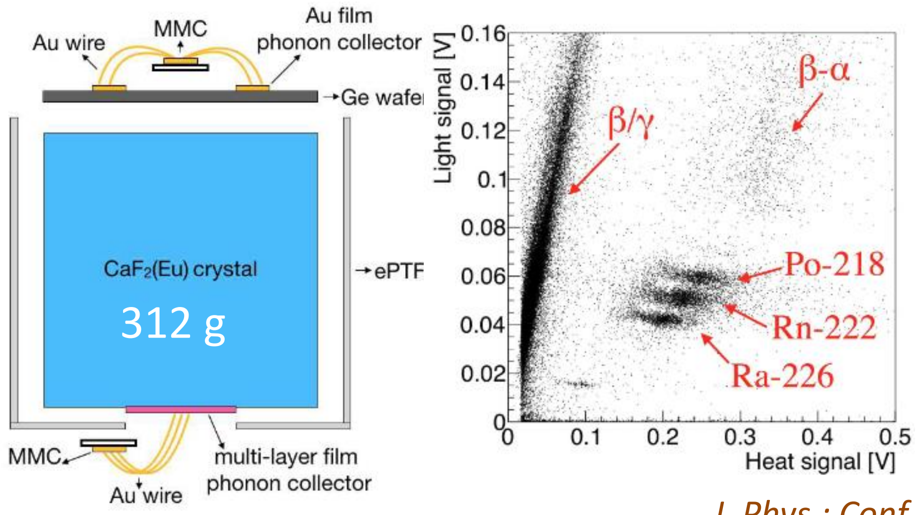
CANDLES-III **Pure scintillation experiment with CaF_2(Eu) crystals**

Natural crystals – 96x 3.2 kg → only **350 g of ^{48}Ca** KAMIOKA

New phase of the experiment → CANDLES-IV

- Study the possibility of enrichment with **Laser Isotopic Separation**
- Move to **scintillating bolometers** (as CUPID, AMoRE)
  - high energy resolution
  - α/β rejection

Preliminary encouraging results with large crystals (**MMC technology**)



Modest energy resolution

σ = 3.2% @ 4.9 MeV

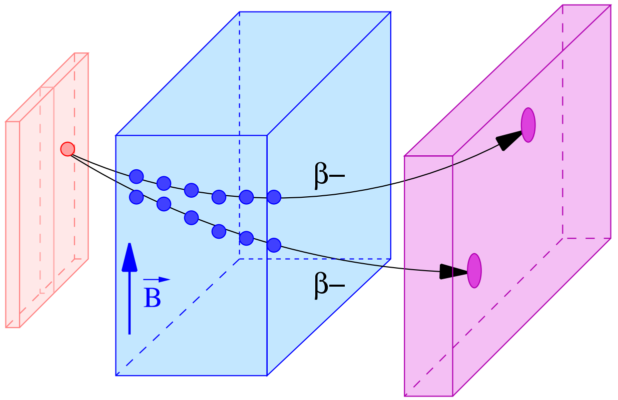
Position dependence

J. Phys.: Conf. Ser. 1468 (2020) 012116

SuperNEMO

Tracker-Calorimeter Technique

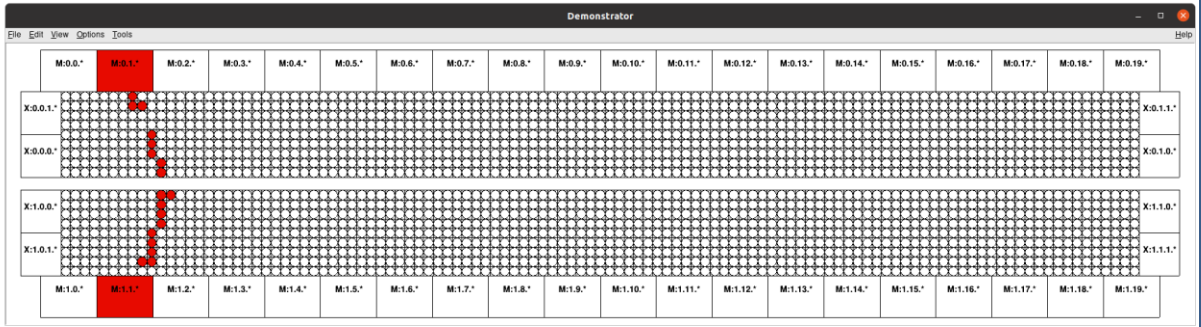
- Foils can be made of any solid $\beta\beta$ isotope (SuperNEMO uses ^{82}Se)
- Identification of e^-, e^+, γ and α → leads to excellent background rejection.
- Event topology reconstruction (energies, angles).
- e-γ separation can probe decays to excited states



SuperNEMO demonstrator status

Modane

- Final commissioning.
- First tracker-calorimeter data September 2021



First ββ-candidate event, 9/9/21

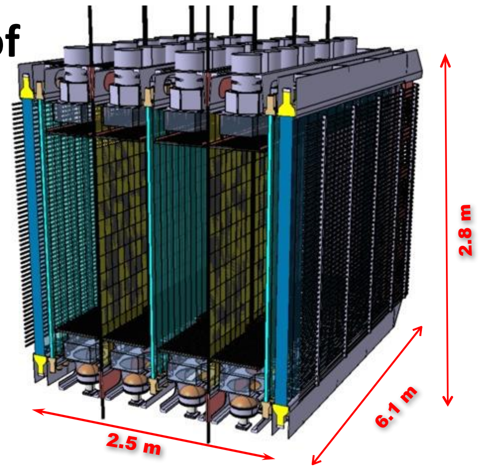
Current role of SuperNEMO

Providing Supporting Measurements

- Precision measurements of 2νββ
- g_A quenching constraints (NEMO-3 analysis in preparation)

Understanding the Ultimate Reach of the Tracker-Calorimeter Technique

- Can the technique be used to confirm & probe a signal found in the next generation of 0νββ experiments?
- Explore different detector technologies & isotopes



Neutrinoless double beta decay in a nutshell

$0\nu\beta\beta$: $(A,Z) \rightarrow (A,Z+2) + 2e^-$

$2n \rightarrow 2p + 2e^-$

Creation of matter without antimatter partners

Beyond Standard Model

Never observed – Best limits $\tau > 10^{24} - 10^{26}$ y

① Standard mechanism: **neutrino physics**

$0\nu2\beta$ is mediated by **light massive Majorana neutrinos**
(exactly those which oscillate)
Sometimes defined "**mass mechanism**"

② Non-standard mechanisms: **Sterile ν, LNV**

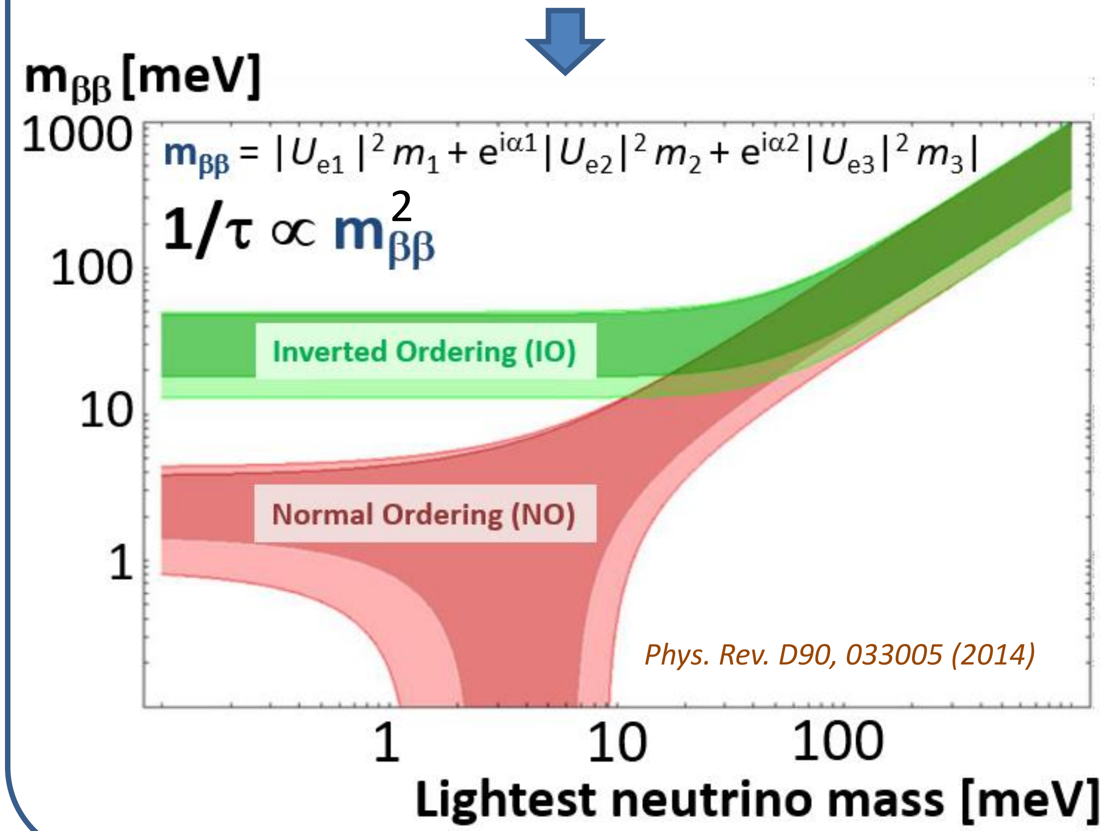
Not necessarily neutrino physics

The only currently viable experimental approach to probe the Majorana nature of neutrino

Francesco Vissani, this workshop

Experiments measure / constrain τ

Assuming mass mechanism, this translates into information on the **effective Majorana mass $m_{\beta\beta}$**



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