North America - Europe Workshop on Future of Double Beta Decay
29 September 2021 to 1 October 2021
Gran Sasso National Laboratory (LNGS)

September 29th, 2021

Survey on other next generation Double Beta experiments

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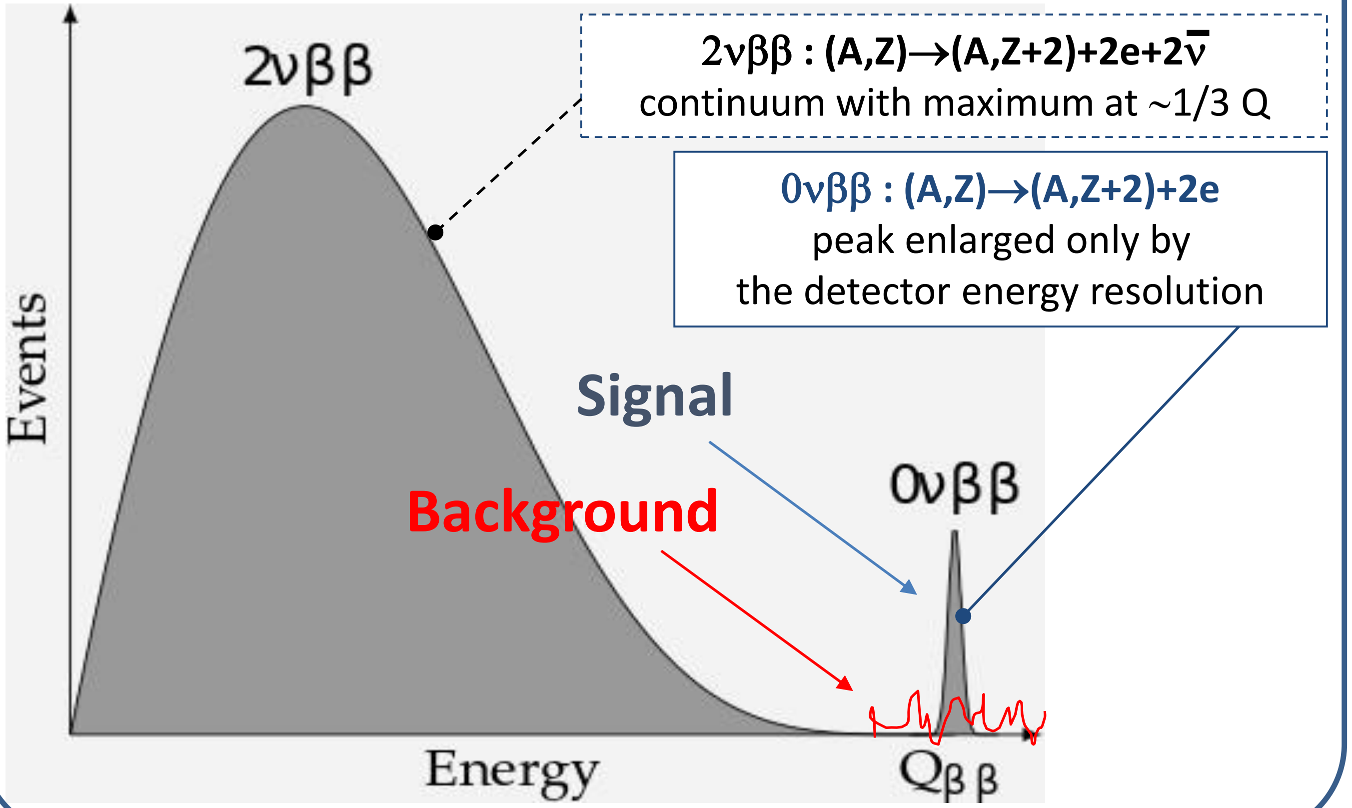
Which signature and which nuclei?

Sum energy spectrum of the two electrons

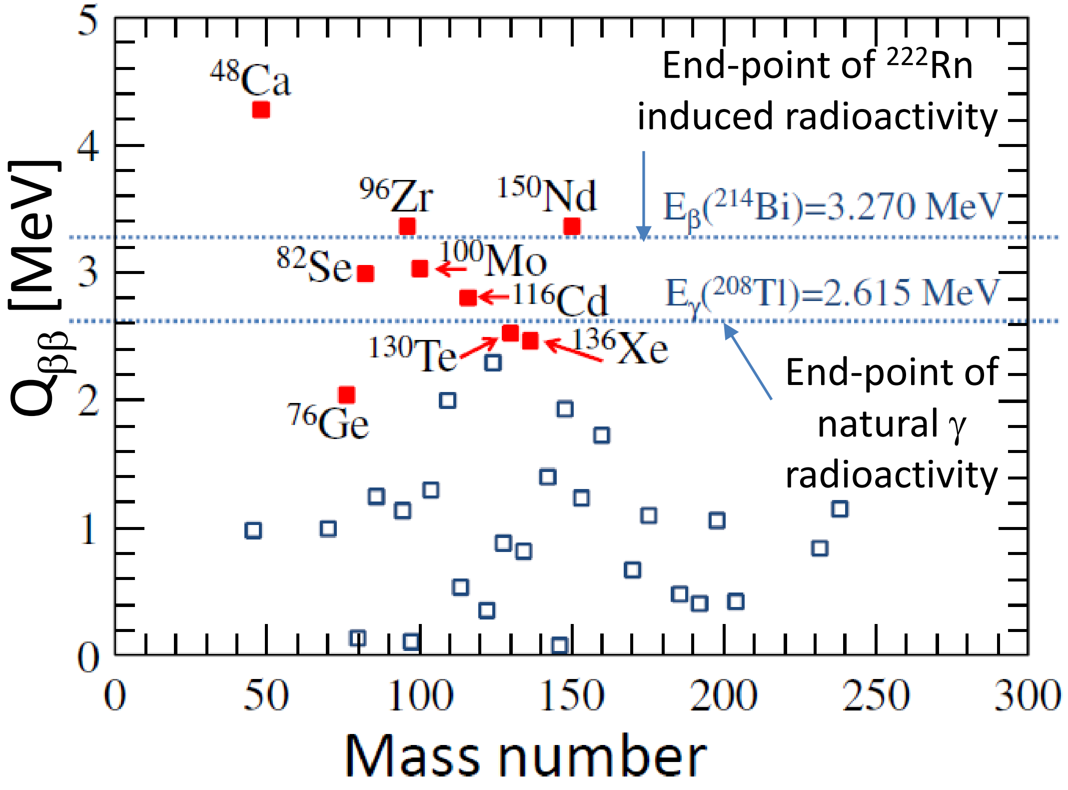
$\mathbf{Q_{\beta\beta}}$: energy available for the products



Possible for 35 nuclei

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

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



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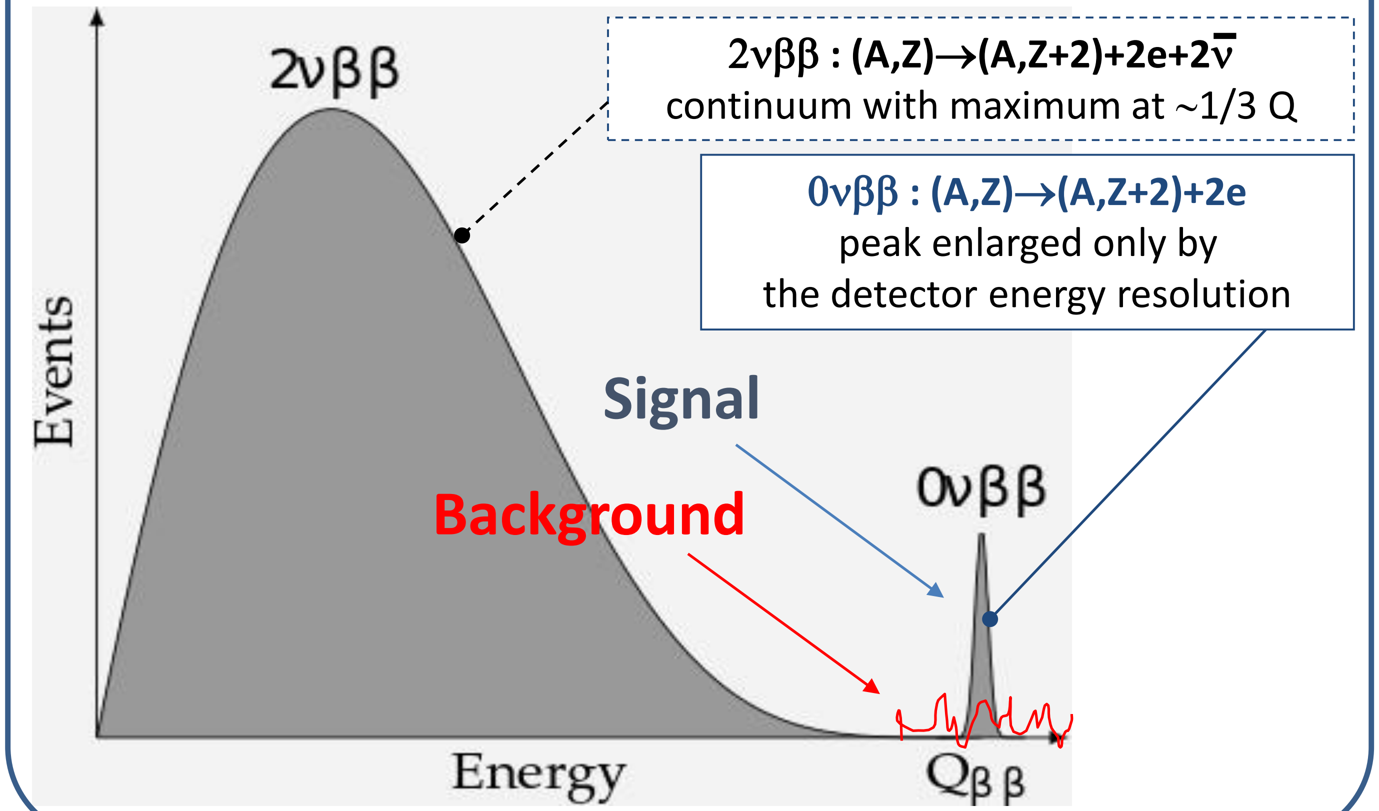

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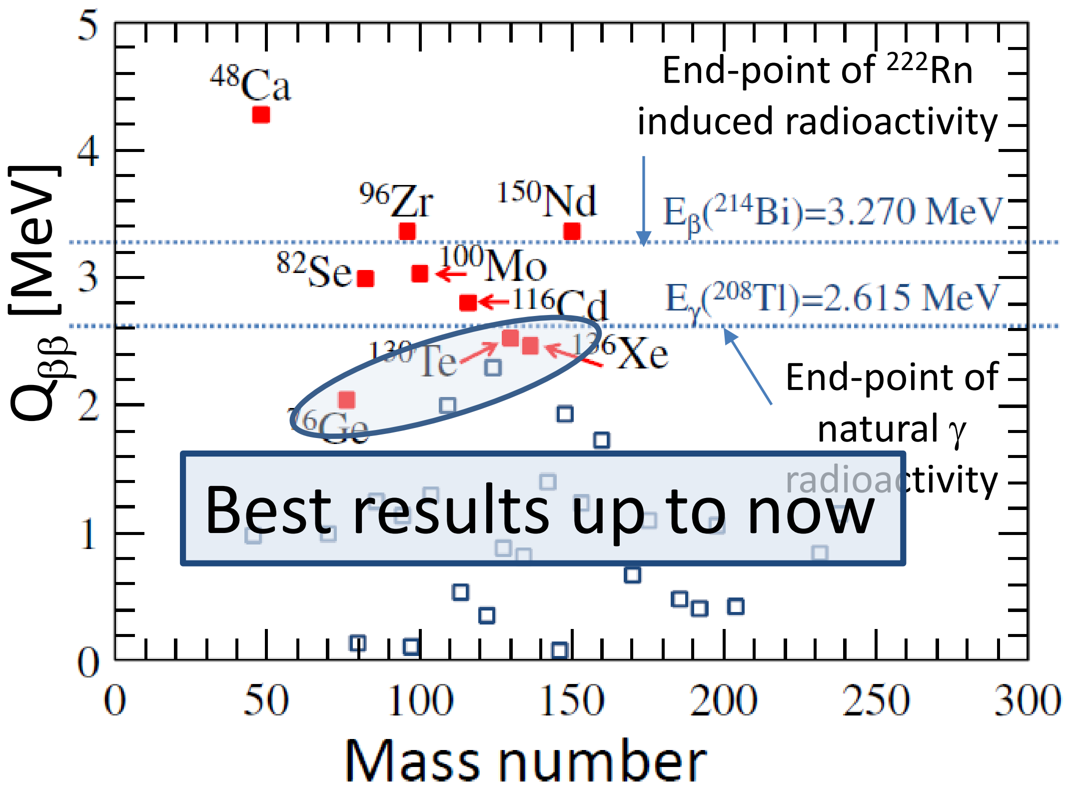

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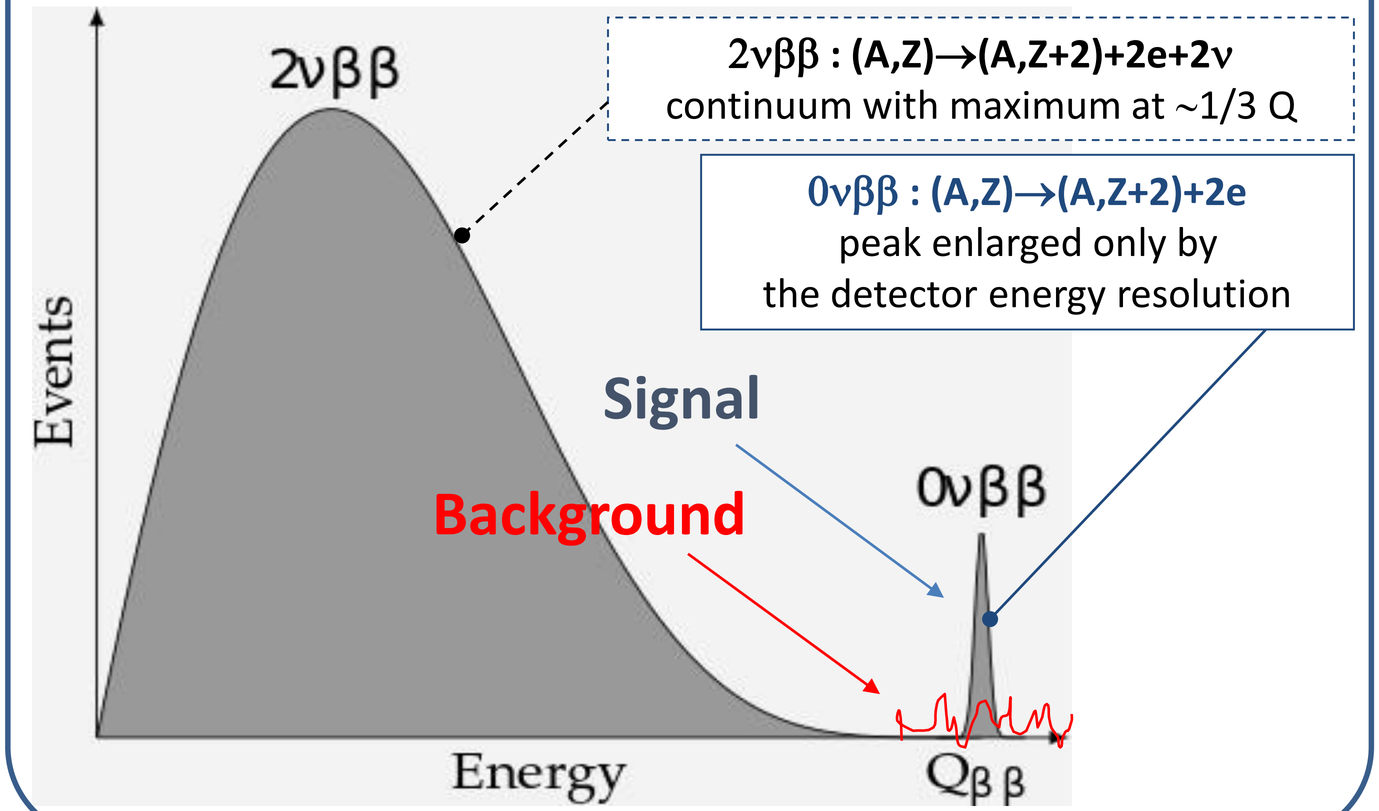

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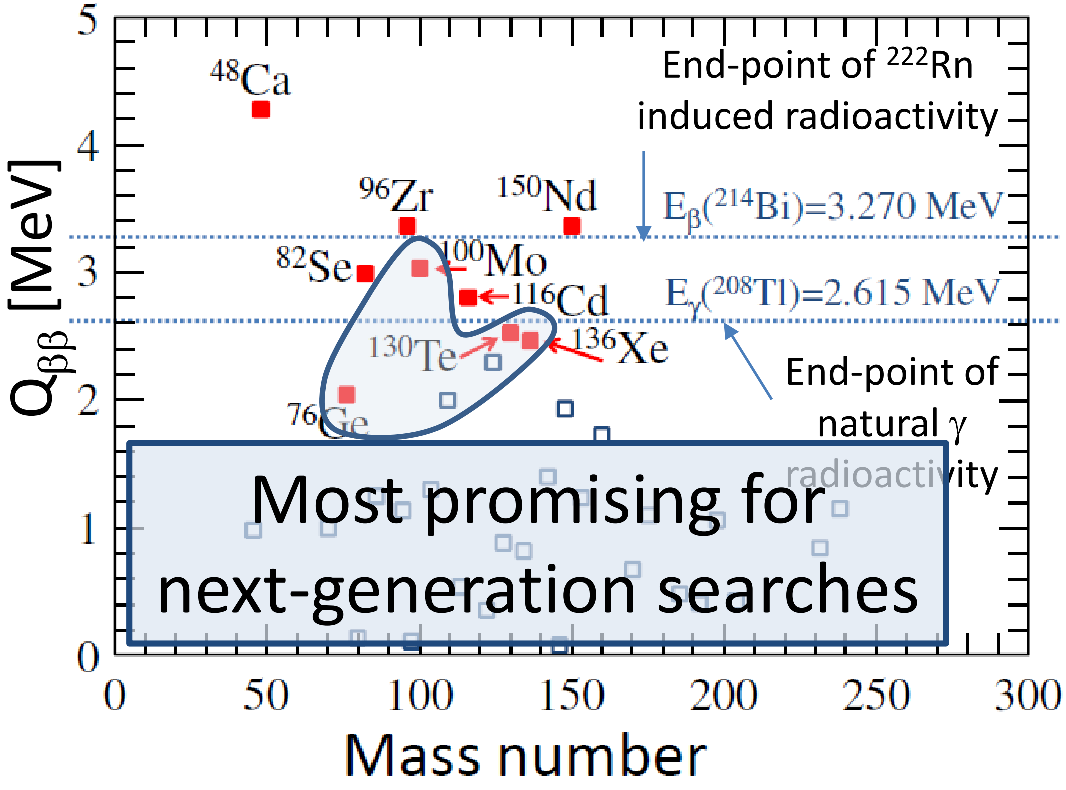
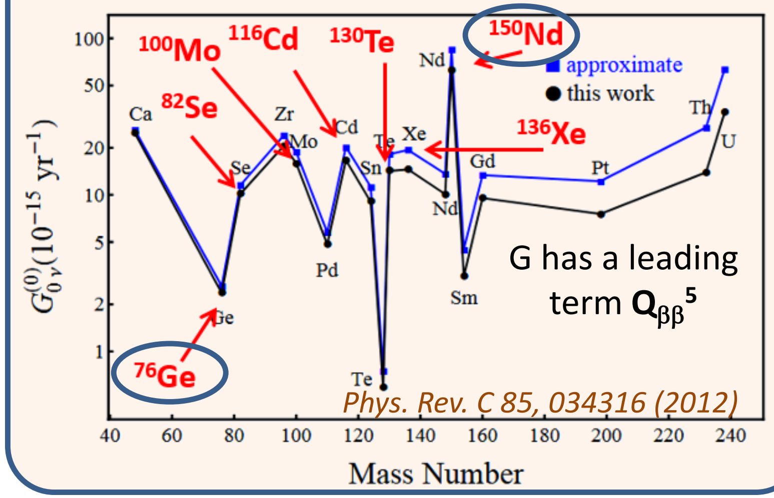


Which half-lives?

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

Phase space: exactly calculable

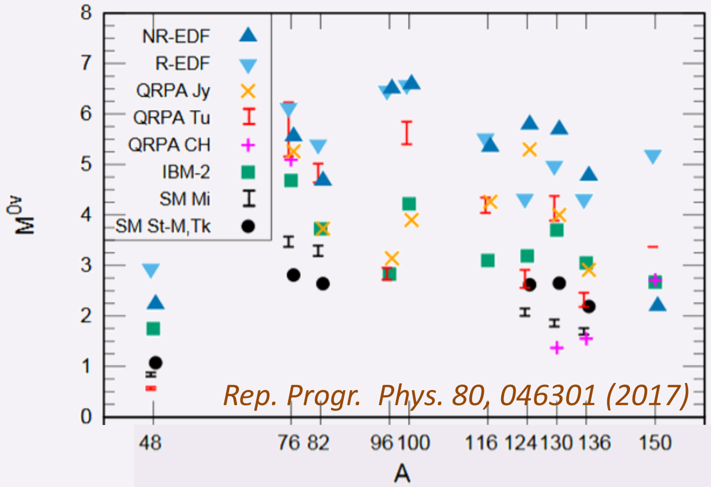


g_A = { 1.269 Free nucleon; 1 Quark }

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

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

Nuclear matrix elements: several models

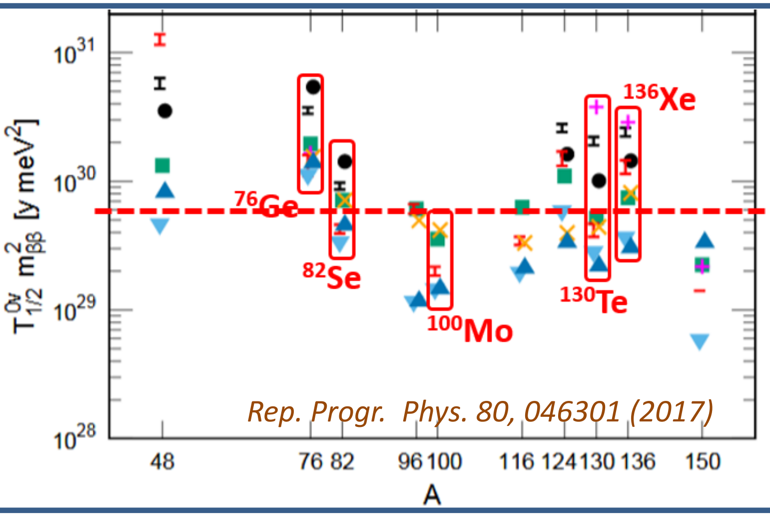


0νββ rate

The 0νββ community still assumes **g_A≈ 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

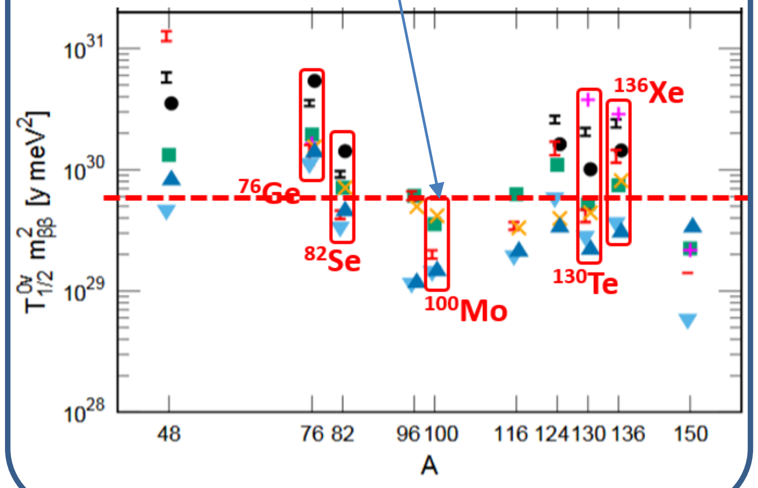


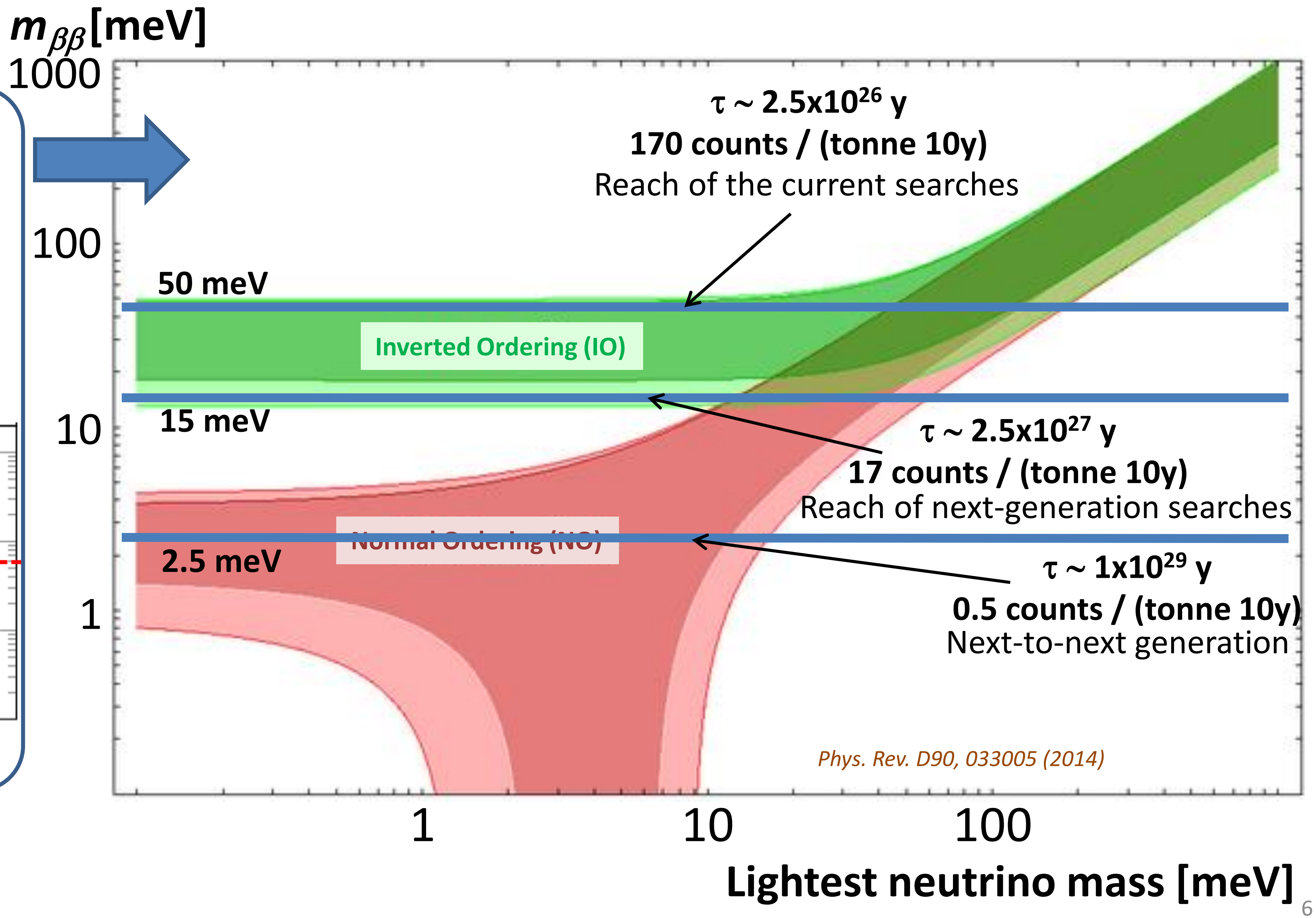
$$T^{0\nu}_{1/2} \simeq 10^{27-28} \left(\frac{0.01\,\text{eV}}{\langle m_{\beta\beta} \rangle} \right)^2 \text{y}$$

Working formula for general experiment design

How many counts?

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



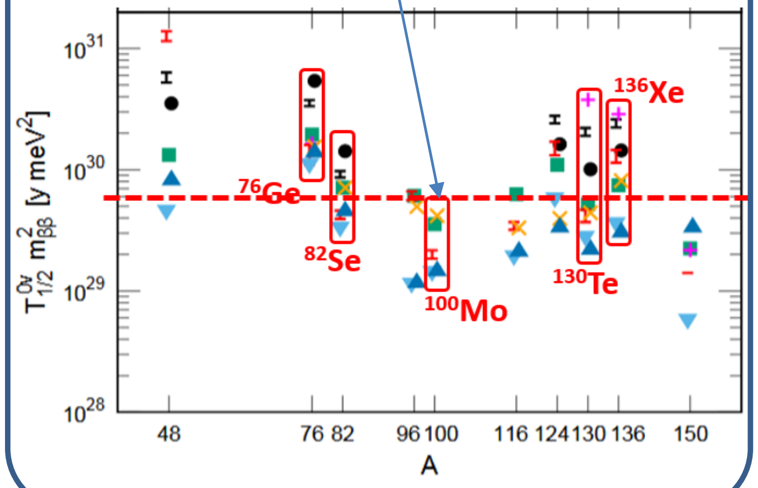


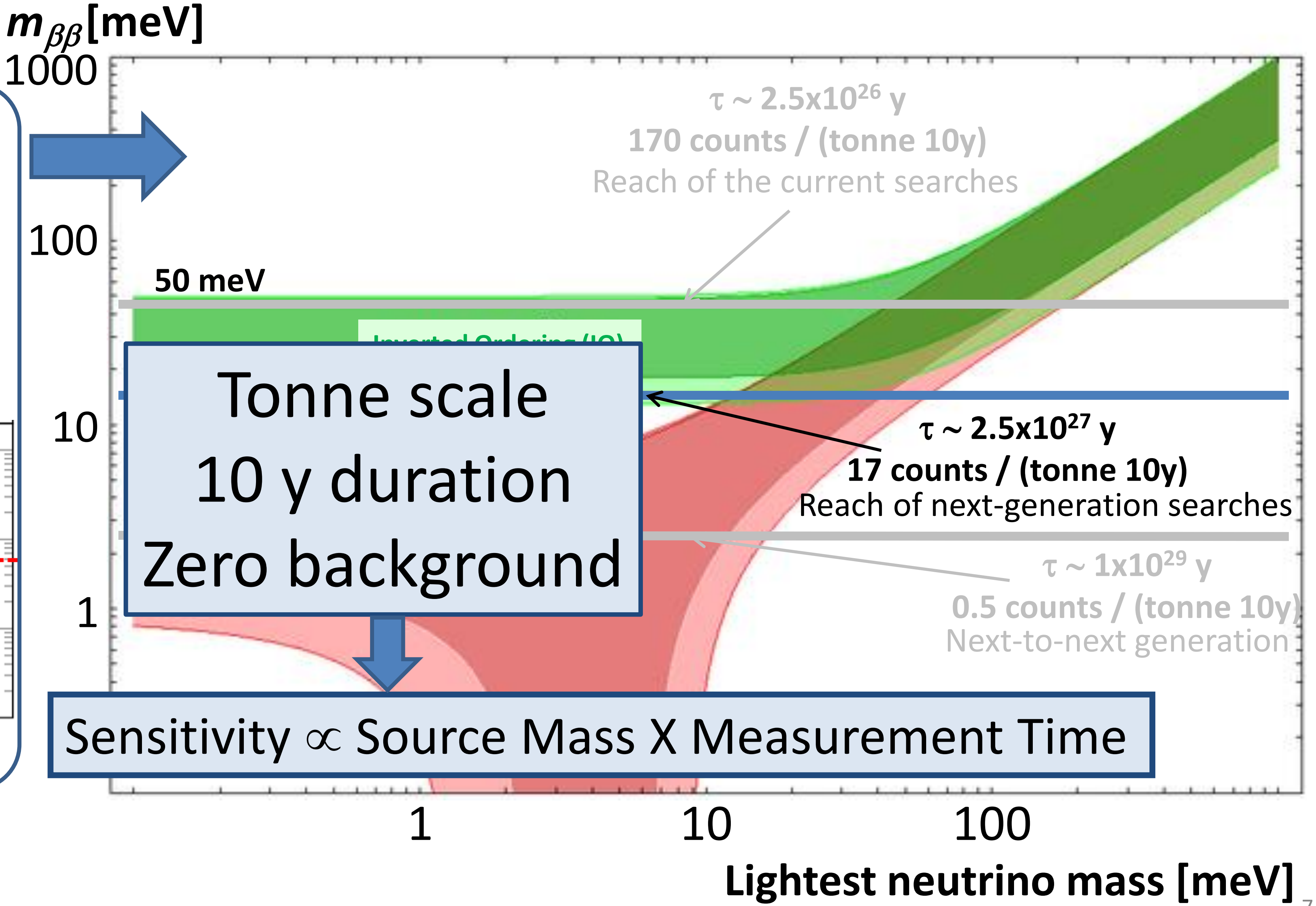
How many counts?

Example: isotope

^{100}**Mo**

Less favorable Nuclear Matrix Elements





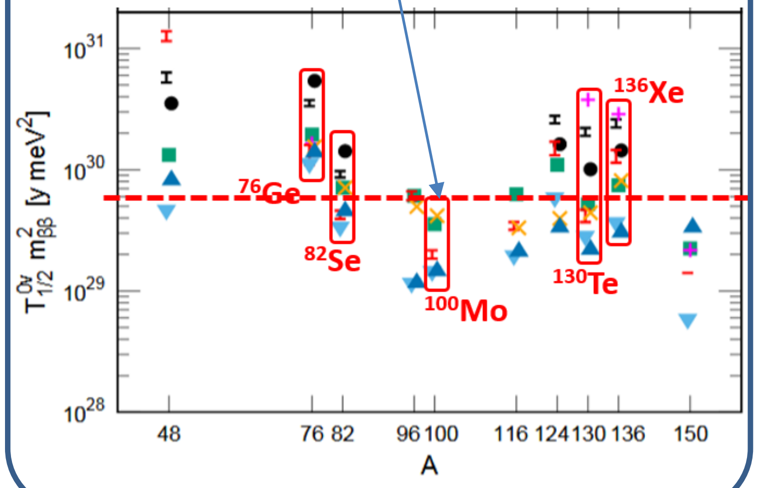
Tonne scale
10 y duration
Zero background

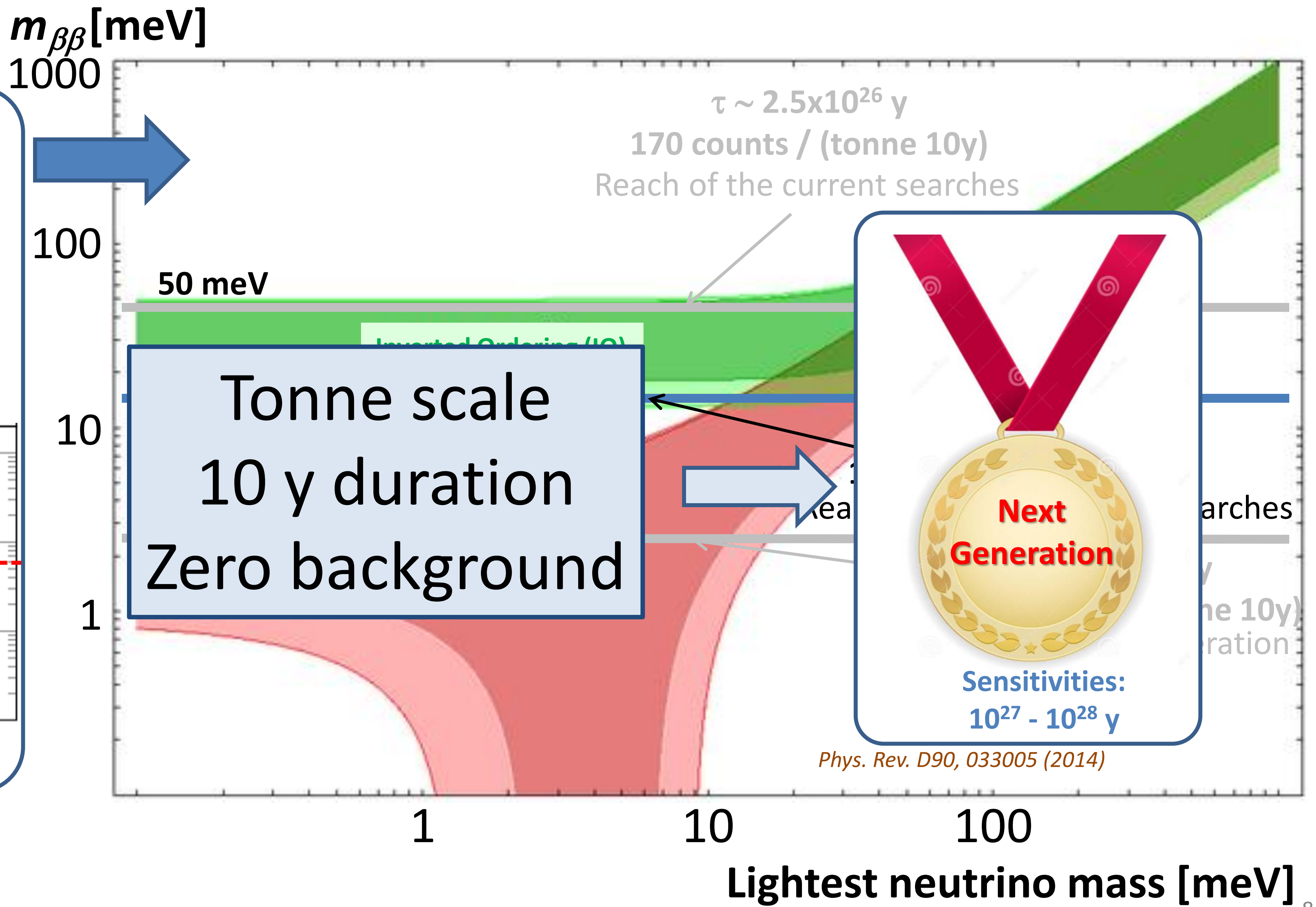
Sensitivity ∝ Source Mass X Measurement Time

How many counts?

Example: isotope ^{100}Mo

Less favorable Nuclear Matrix Elements





Tonne scale
10 y duration
Zero background

Next Generation

Expand the source, abate the background

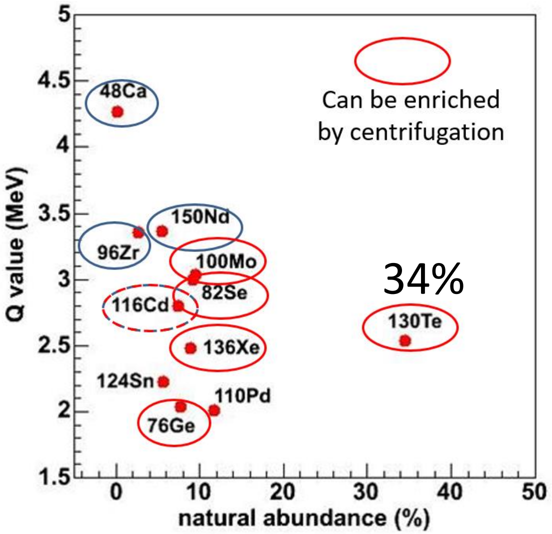
Source

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

② **Isotopic enrichment**

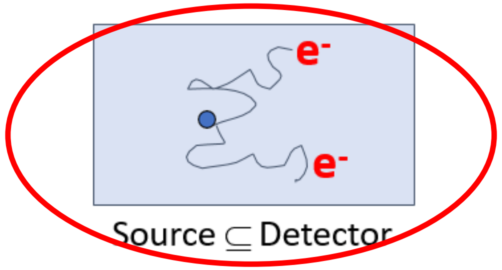
→ the isotopic abundance is artificially increased to > 80%

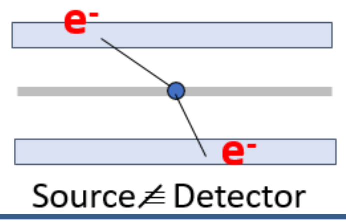
→ Isotope selection



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

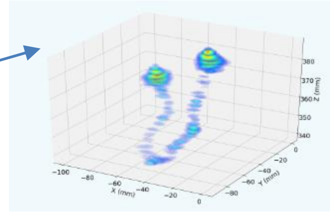
④ **Cosmogenic induced activity (long living)**

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



background index b

$$b = \frac{\text{background counts } @Q_{\beta\beta}}{M \times \Delta E \times T}$$

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)
- → Assisted PSD bolometers (CROSS)

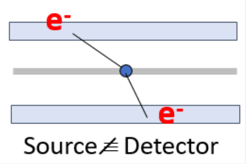
Bold red
→ Currently competitive technology

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-^{136}Xe
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	^{136}Xe
LiquidO	Dilution in opaque liquid scintillator	multi

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 bolometers	^{100}Mo-^{130}Te
BINGO	Scintillating / Cherenkov bolometers	^{100}Mo-^{130}Te

Completed
Data taking

Current situation

$T_{1/2}$ > 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

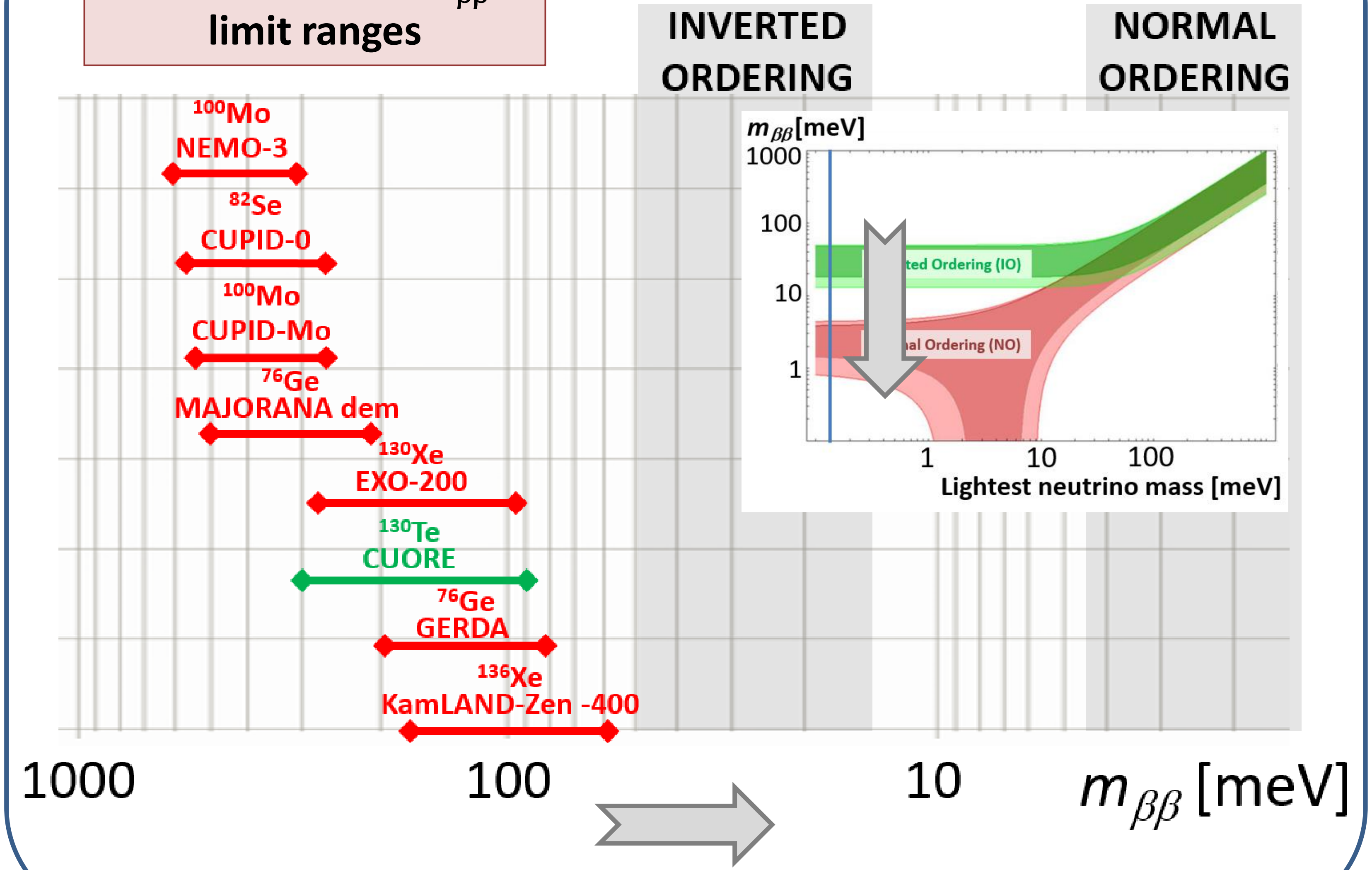
CUORE $T_{1/2} > 2.2\times10^{25}$ y
arXiv:1907.09376

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)

Corresponding $m_{\beta\beta}$ limit ranges



Most promising next-generation experiments

7 research lines / experiments are more mature:
- 4 fluid embedded
- 3 crystal embedded

In my view, **these experiments are in the best position for actual construction and data taking** on a-few-year time scale, for several reasons:
- Technology maturity
- Solid collaboration
- Funding prospects

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**

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

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High energy res...
/ effi...

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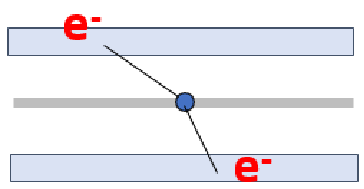
⑦ AMORE-I → AMORE-II

nEXO, NEXT, LEGEND, CUPID → this workshop

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

Other promising developments

SuperNEMO
(Tracking+Calorimetry)



Source≠Detector

Large source mass
Easily scalable

Fluid embedded source

Source dilution in a liquid scintillator
- Without inner balloon (**SNO+**)
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- With inner balloon + Cherenkov (Theia, ZICOS)
- 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, PANDAX-4T)

High energy resolution / efficiency

Crystal embedded source

Inorganic scintillators (CANDLES-III)

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

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

KamLAND-Zen (400 and 800)

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

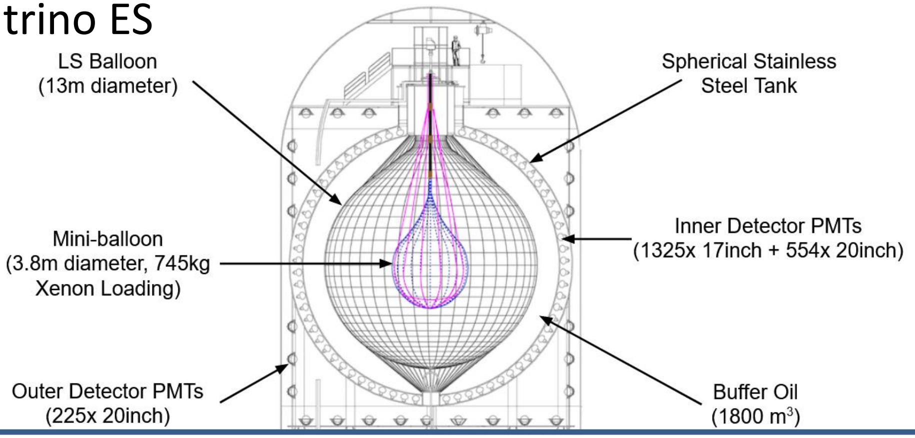
Concept

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: **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



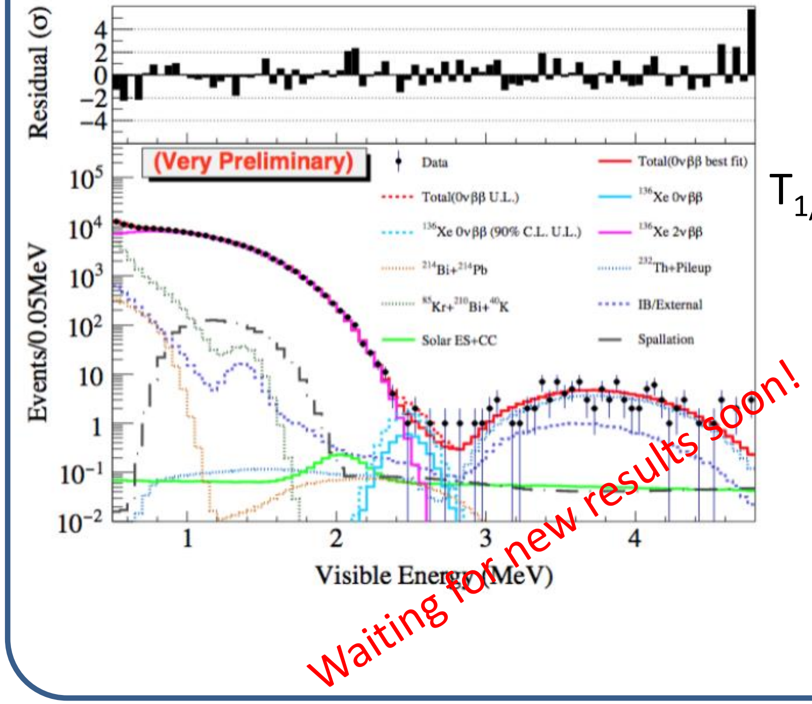
KamLAND-800 (started Jan 2019)

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**

→ $m_{\beta\beta} < 30 – 80$ meV

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



Analysed exposure

246.1 kg y

$T_{1/2} > 4\times10^{25}$ y

Available exposure (under analysis)

419 kg y

KamLAND2-Zen

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

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

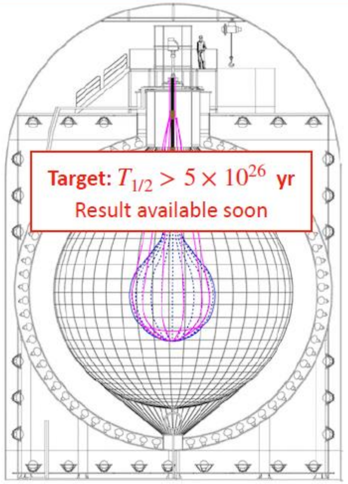
3 neutrinos and beyond, K. Ueshima, 2019

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

Directions of improvement
- > 1000 kg of ^{136}Xe
- Reduce ^{214}Bi background
- Reduce $2\nu2\beta$ background

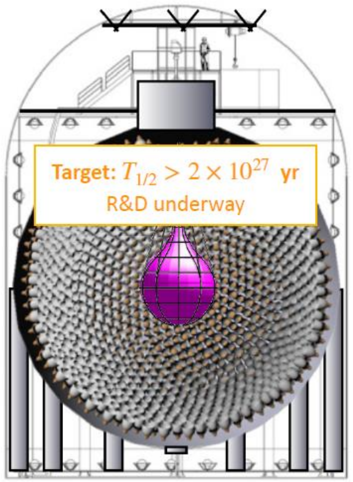
5y sensitivity
$T_{1/2} > 2\times10^{27}$ y
$m_{\beta\beta} < 14 – 37$ meV

Present



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

Future



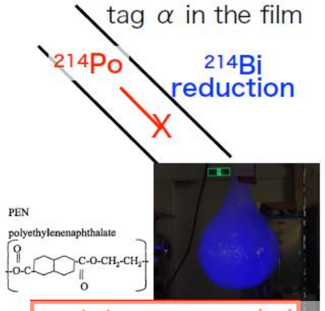
KamLAND2-Zen:
- Xenon mass ~ 1ton
- Aiming at 100% Photocoverage
- PEN scintillation balloon film

Reduce ^{214}Bi background

Identify BiPo events in balloon

Tag α's with a film on balloon

○ scintillator film

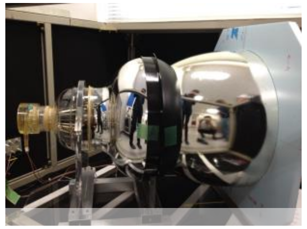


Reduce $2\nu2\beta$ background

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
ΔE(σ) < 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

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

SNO+

SNO+ $\rightarrow$ SNO+-phase II

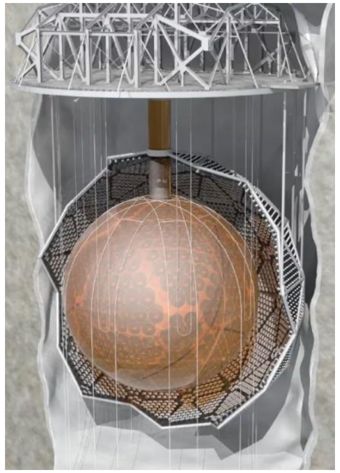
Concept

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")

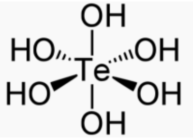
- 780 tons of scintillator
- 3.9 tons of natural tellurium
- $\rightarrow$ **1.3 tons of ^{130}Te** (34% I.A.)



$\rightarrow$ Scintillator purification system

$\rightarrow$ Novel metal loading technique

Telluric acid TeA

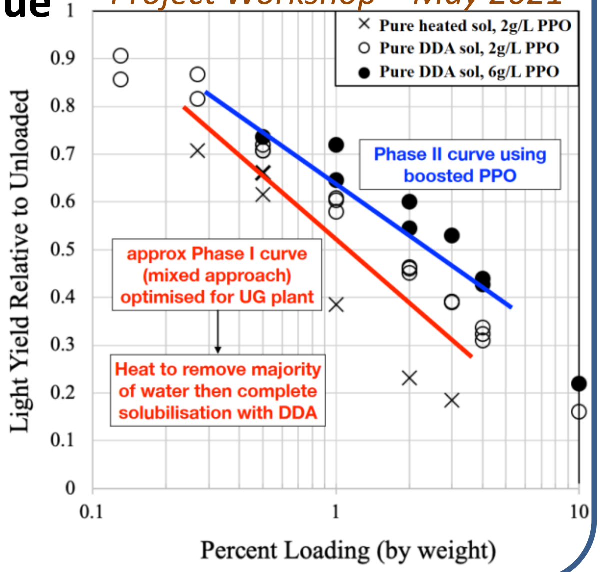


Purification

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

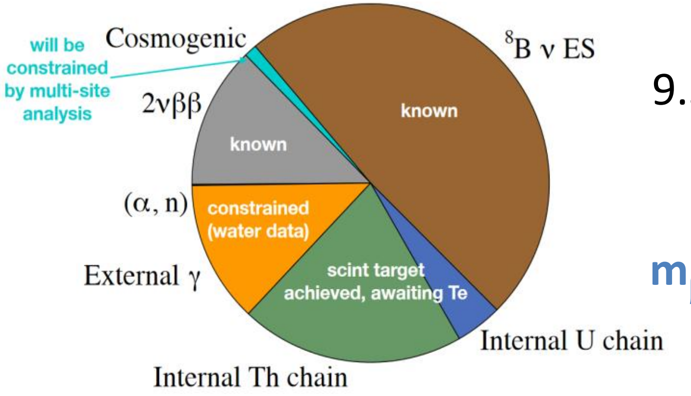


SNO+ consists of **three phases**

- **Pure-water phase** (from May 2017)
  $\rightarrow$ measurement of the external background
  $\rightarrow$ physics results (^{8}B ν's, invisible nucleon decays)
- **Liquid scintillator phase** without Te (ongoing)
  $\rightarrow$ measurement of scintillator background
  $\rightarrow$ U, Th concentration ~ 5×10^{-17} g/g
  $\rightarrow$ Background level low enough for $0\nu\beta\beta$
- **Te phase** (from 2022) – 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

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

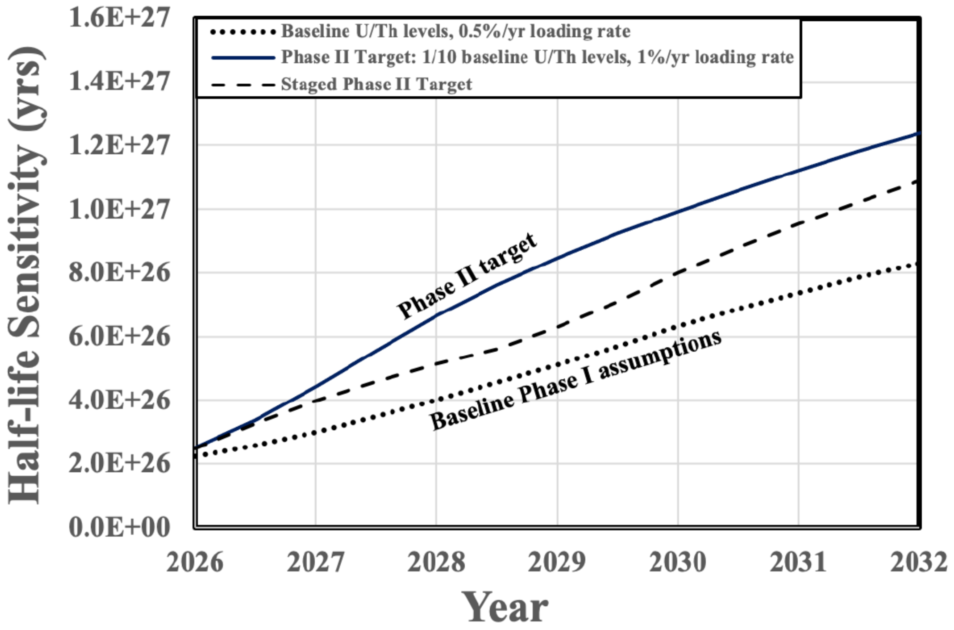
SNO+ → **SNO+-phase II** → THEIA, ZICOS

SNO+-phase II (start in 2026) **5 y sensitivity**

- 0.5% → **3% Te concentration** **1×10^{27} y**
- Improve transparency **$m_{\beta\beta}$ < 13 – 45 meV**

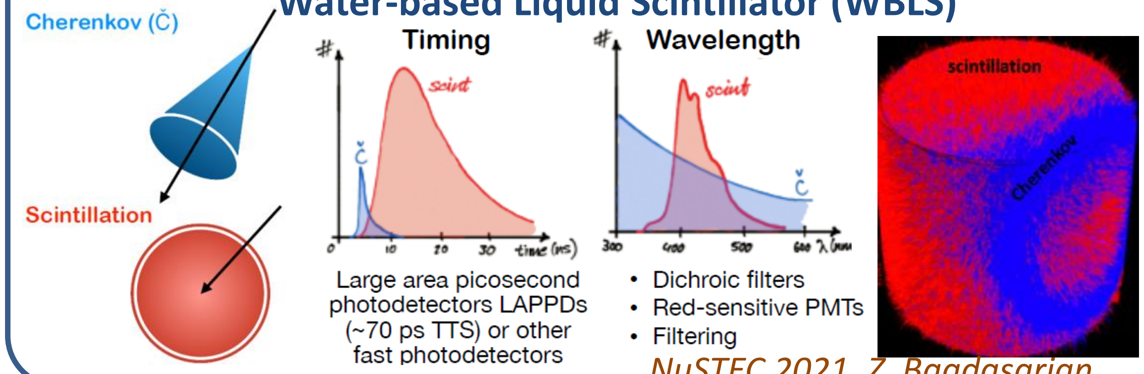
  No changes to underground set-up
  No changes to loading method
  Increase PPO to ~6g/L
  Adiabatically increase Te loading towards ~ 3%
  Loading rate depends on staging and system throughput
  (project 0.5% per 6-9 months)

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)



NuSTEC 2021, Z. Bagdasarian

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

TAUP 2021, Y. Fukuda

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**

SNO+ and evolutions

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

SNO+-phase II (start in 2026)

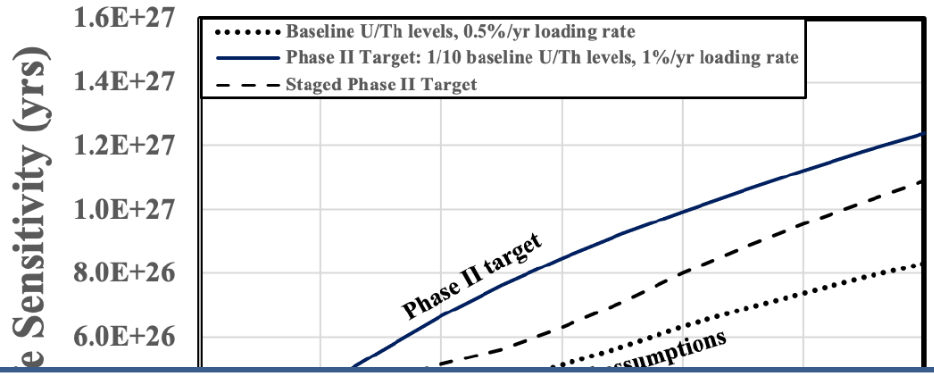
- 0.5% → **3% Te concentration**
- Improve transparency

No changes to underground set-up
No changes to loading method
Increase PPO to ~6g/L
Adiabatically increase Te loading towards ~ 3%

5 y sensitivity

1×10^{27} y

$m_{\beta\beta}$ < 13 – 45 meV



LiquidO

R&D activity based on the **well-known liquid scintillator technology**

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

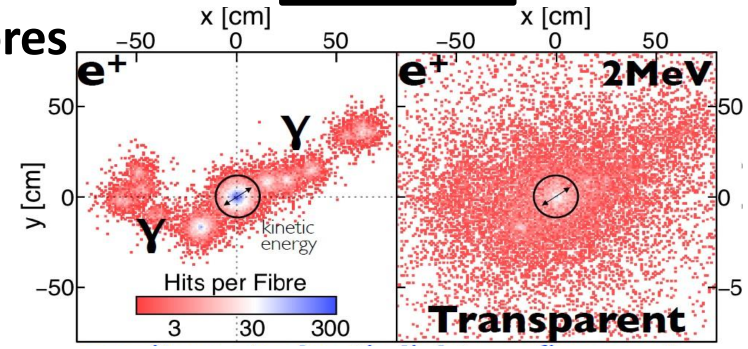
Target loading fractions: **5-30 %** (vs. current 1-3 %)

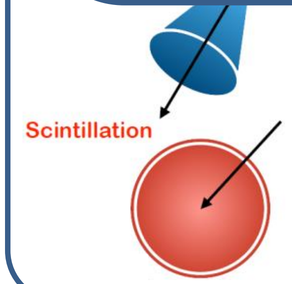
Transparency constraint is relaxed

~10 ton isotope (**^{130}Te**, **^{82}Se**, **^{100}Mo**, **^{150}Nd**)

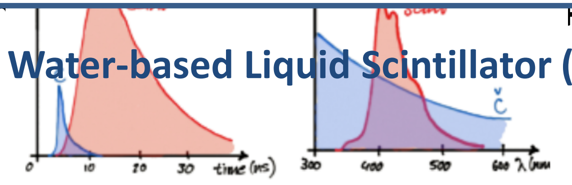
Prototype at Bordeaux

Simulation



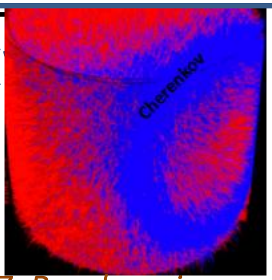


Water-based Liquid Scintillator (



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

- Dichroic filters
- Red-sensitive PMTs
- Filtering



NuSTEC 2021, Z. Bagdasarian

TAUP 2021, Y. Fukuda

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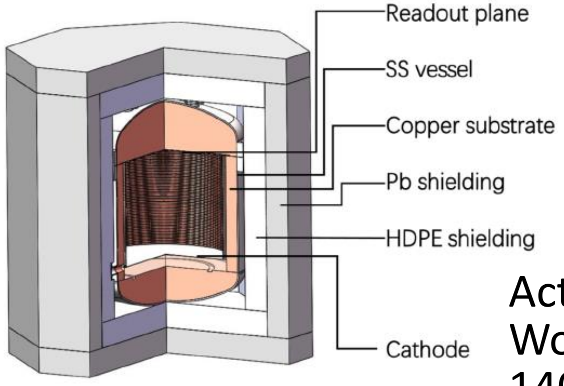
- 10 wt.% Zr(iprac)4 loaded in liquid scintillator – 50% ^{96}Zr
- 1.7 t of loaded LS → 865 kg of ^{96}Zr
- Cherenkov+Scintillation demonstrated in protoypes
→ topological background rejection – Sensitivity: **1×10^{27} y**

Other 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*



Charge readout:
52x 20x20 cm^2
Microbulk Micromegas modules

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

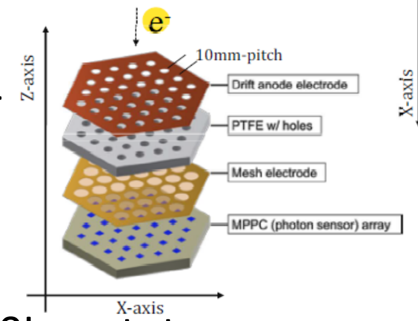
ΔE = 3% FWHM @$Q_{\beta\beta}$ – Signal efficency = 35%
Background index ~10^{-4} c/(keV kg yr)
after topological cuts

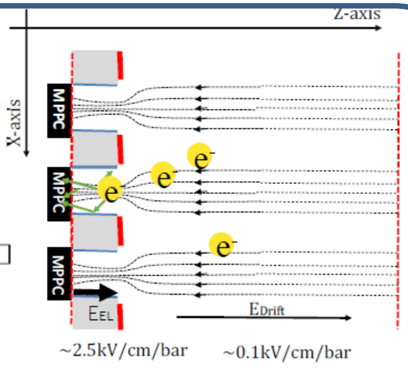
3 y sensitivity: **8.5×10^{25} y**
$m_{\beta\beta}$ < 68 – 180 meV

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

AXEL Kyoto

Special readout for EL
Electroluminescence Light Collection Cell
(ELCC)





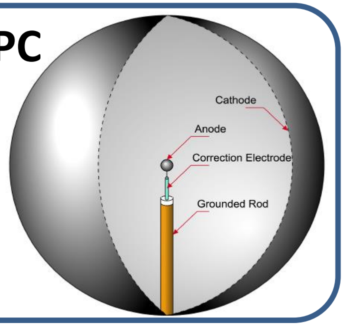
Proof of principle in 10L prototype
Extrapolated energy resolution: **ΔE = 0.82-1.74 % FWHM @$Q_{\beta\beta}$**
180L set-up under development

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

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

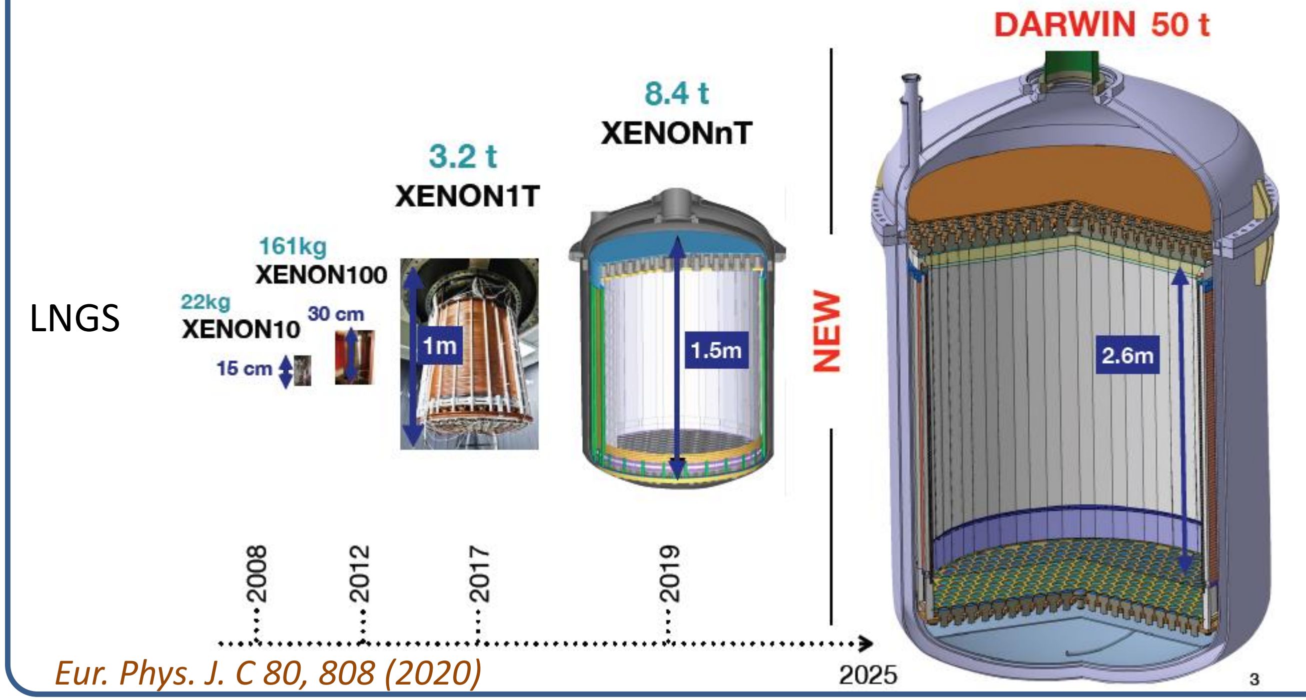


Dual-phase Xe TPC experiments

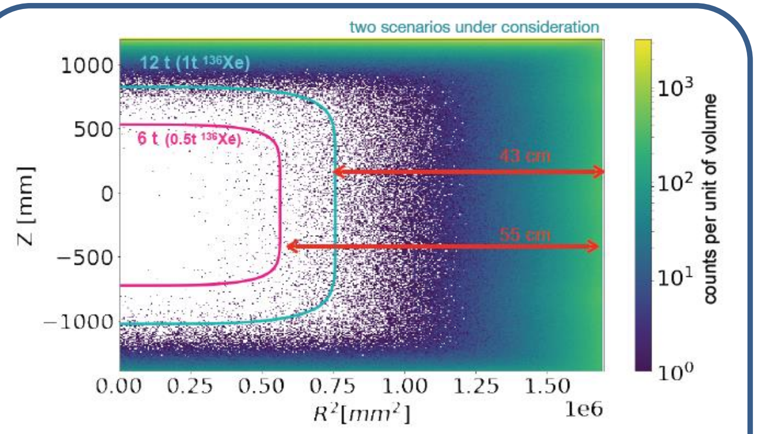
DARWIN **Dark matter** + **double beta decay** + **other rare event searches**

- Dual-phase TPC with natural Xe – the sensitive mass is liquid
- 50 t total (**40 t active**) of **natural liquid xenon** (LXe)

→ DARWIN will have more than **3.5 t** of active ^{136}Xe



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*

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

AMoRE

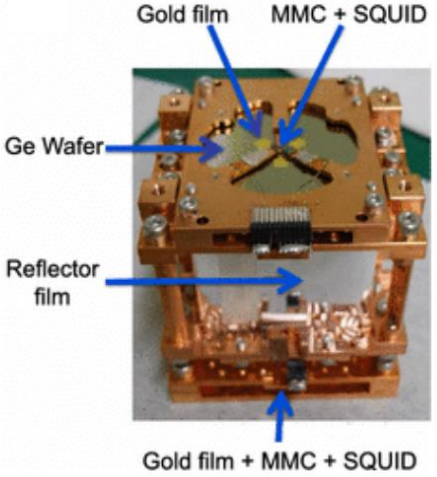
JINST 15 C08010 (2020)
J. Phys.: Conf. Ser. 1468, 012130 (2020)

AMORE-I $\rightarrow$ **AMORE-II**

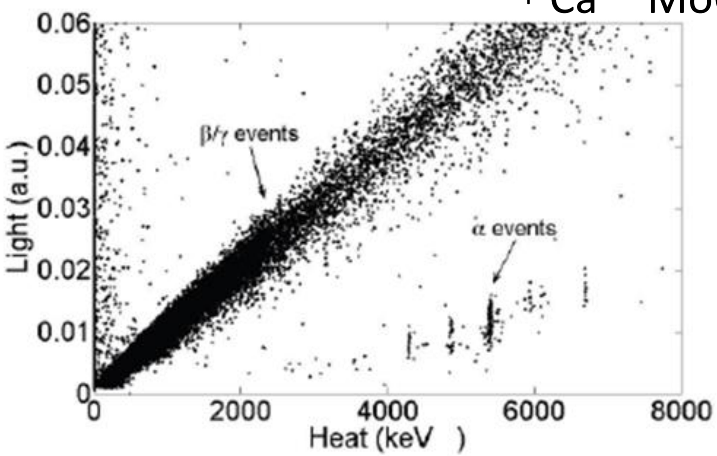
AMoRE – Y2L Lab (AMORE-I), Yemilab (AMORE-II), Korea

Concept

- ^{100}**Mo**-containing scintillating bolometers
- Initially chosen compound (AMoRE pilot – R&D): $^{48depl}Ca^{100}MoO_4$
  $\rightarrow$ high light yield, excellent α/β separation by PSD and light yield
  $\rightarrow$ **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)
  $\rightarrow$ $2\nu\beta\beta$ random coincidences provide negligible background
- Energy resolution **ΔE ~ 10-15 keV FWHM @$Q_{\beta\beta}$**

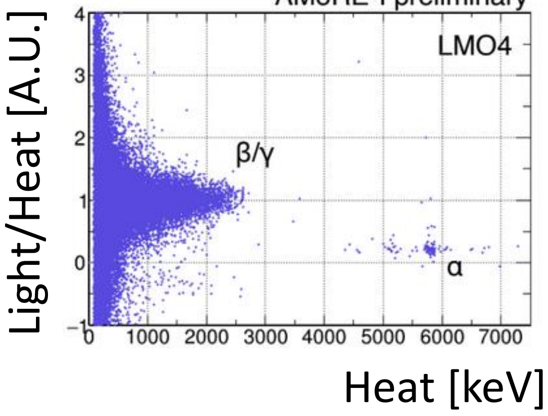


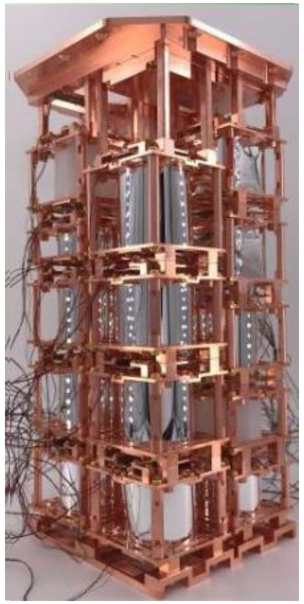
$^{48depl}Ca^{100}MoO_4$



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)
$\rightarrow$ **3 kg of ^{100}Mo**

AMoRE-I preliminary





Target BI: < 10^{-2} counts/(keV kg y)
Projected sensitivity: 7×10^{24} y $m_{\beta\beta}$ **< 130 – 250 meV**

AMORE-II – 2022 - 2027
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**

Other bolometric experiments

CANDLES

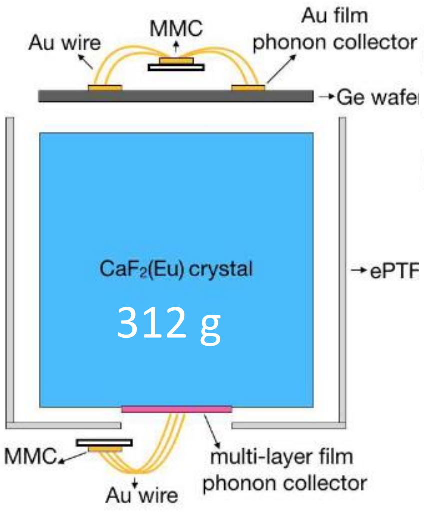
CANDLES-III **Pure scintillation experiment with CaF_2(Eu) crystals**

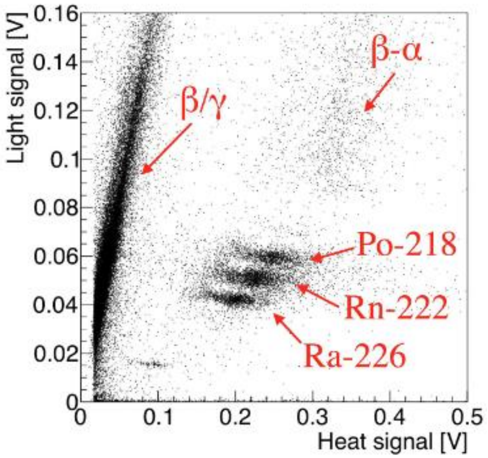
Natural crystals – 96x 3.2 kg → only **350 g of ^{48}Ca** KAMIOKA

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

Techniques for background rejection in future TeO_2 / Li_2MoO_4 based experiments

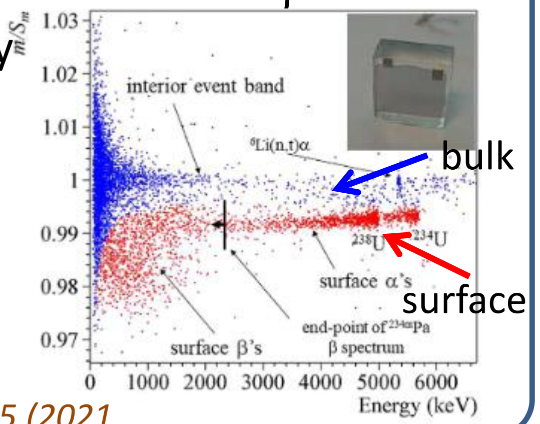
CROSS Canfranc

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

Proof of concept with small prototypes

^{100}Mo 6 kg demonstrator

Mixed α/β source



Appl. Phys. Lett. 118, 184105 (2021

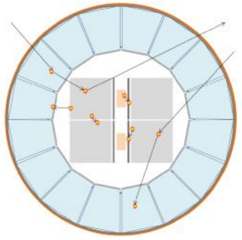
BINGO Modane

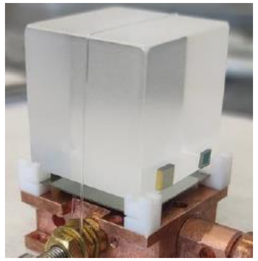
Luminescent bolometers

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

→ mitigate γ background in TeO_2

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





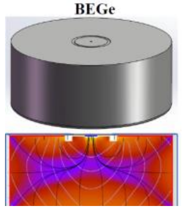
C, Nones, TAUP 2021

Other semiconductor-based experiments

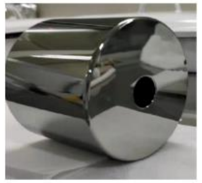
GERDA-MAJORANA-LEGEND are leading

CDEX: similar approach CJPL

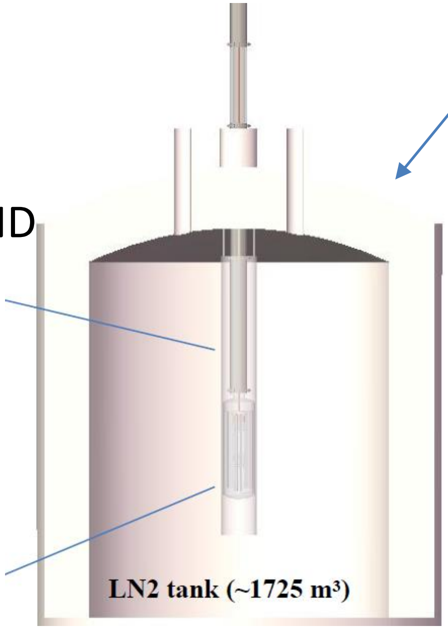
- **Ge diodes** immersed in **instrumented LAr**
- Same type of detectors as in GERDA/LEGEND



Enriched BEGe (baseline)
M ~ 1-1.2 kg

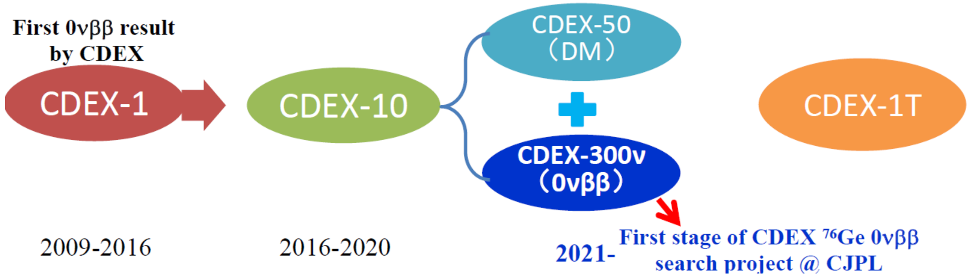


ICPC (option) M ~ 2 kg



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**



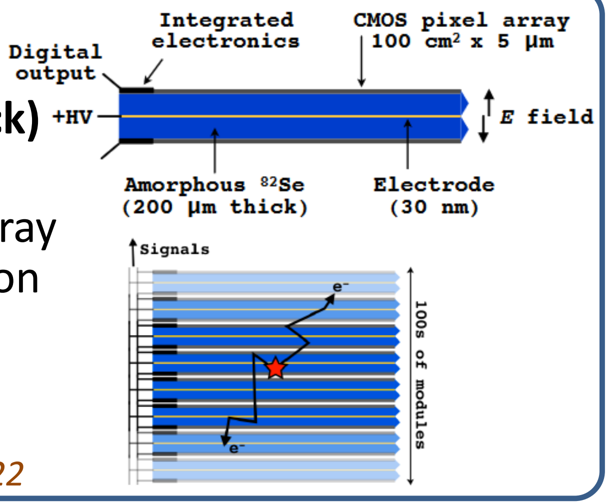
Qian Hue, TAUP 2021

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)

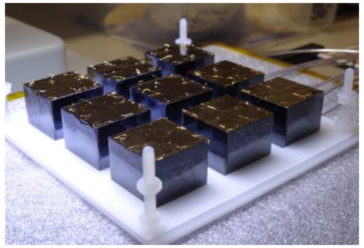


JINST 12 (2017) P03022

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



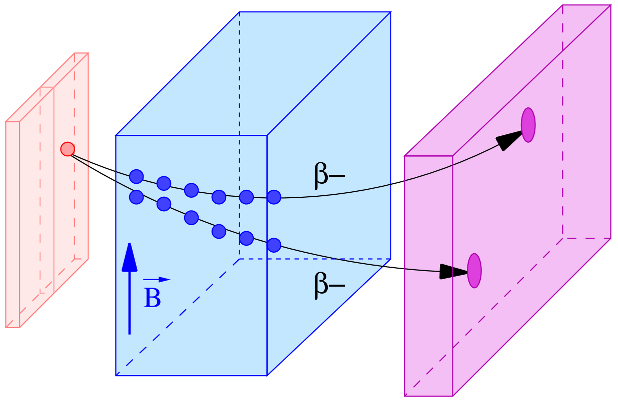
Improvements in energy resolution and background

NIMA 1010 (2021) 165524

SuperNEMO

Tracker-Calorimeter Technique

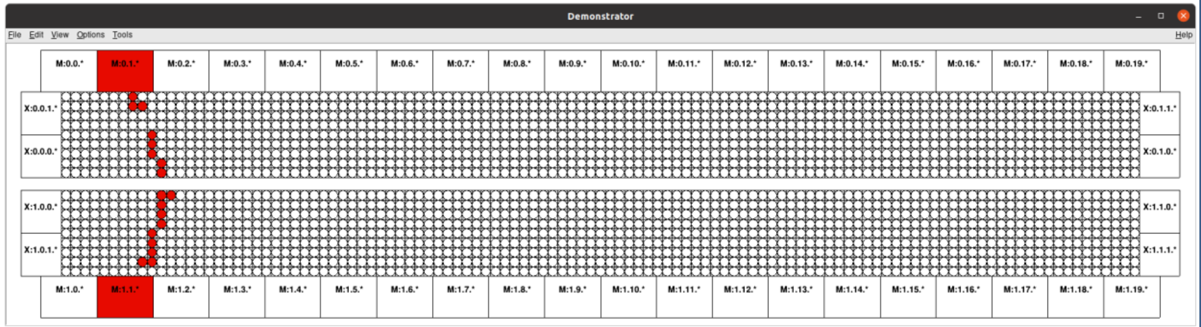
- Foils can be made of any solid $\beta\beta$ isotope (SuperNEMO uses ^{82}Se)
- Identification of e^-, e^+, γ and α → leads to excellent background rejection.
- Event topology reconstruction (energies, angles).
- e-γ separation can probe decays to excited states



SuperNEMO demonstrator status

Modane

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



First ββ-candidate event, 9/9/21

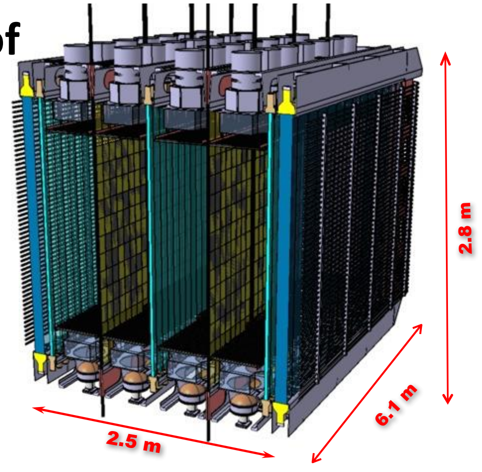
Current role of SuperNEMO

Providing Supporting Measurements

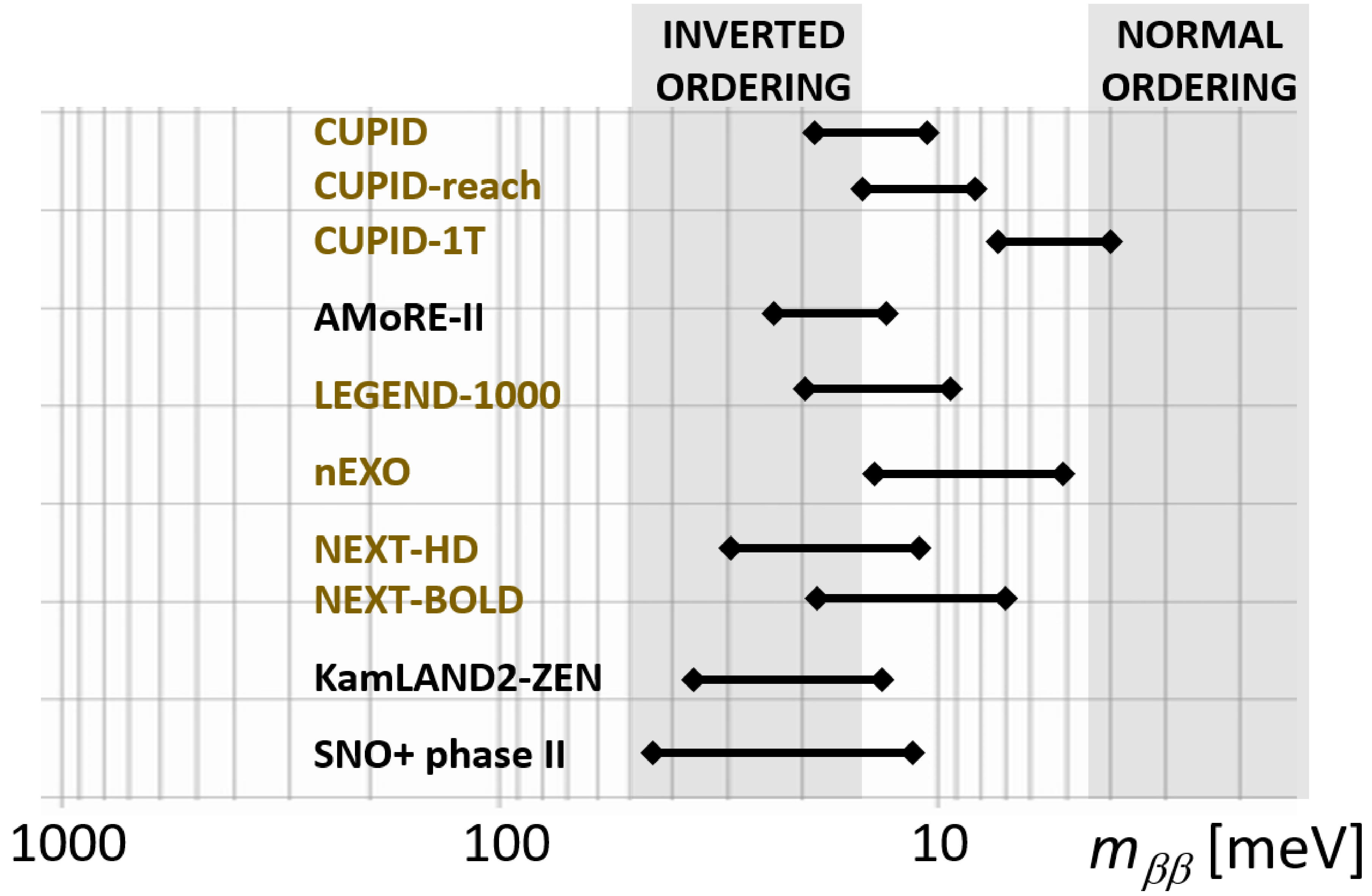
- Precision measurements of 2νββ
- g_A quenching constraints (NEMO-3 analysis in preparation)

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



Promising next-generation projects



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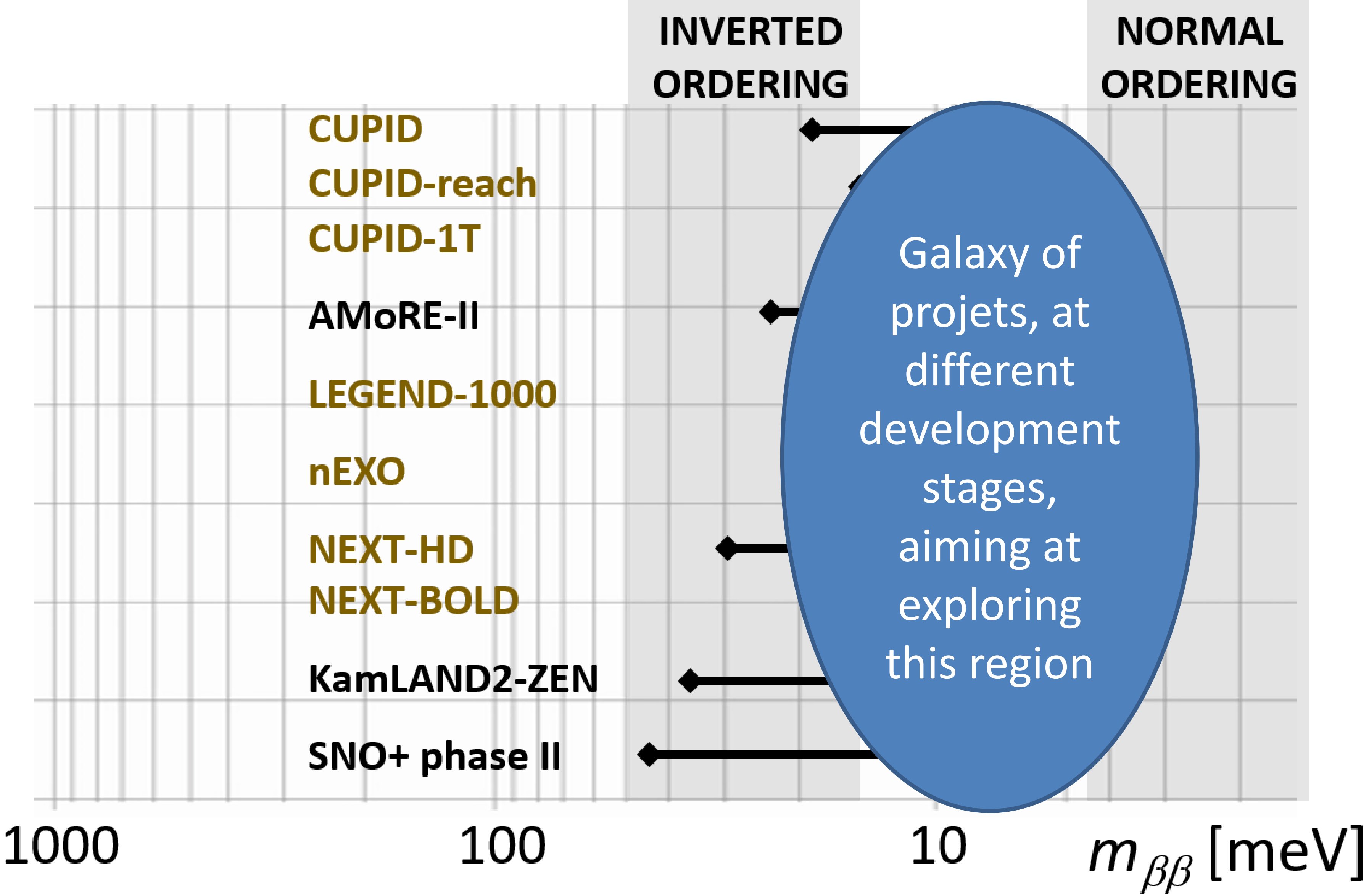


BACK UP

Neutrinoless double beta decay in a nutshell

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

2n → 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**

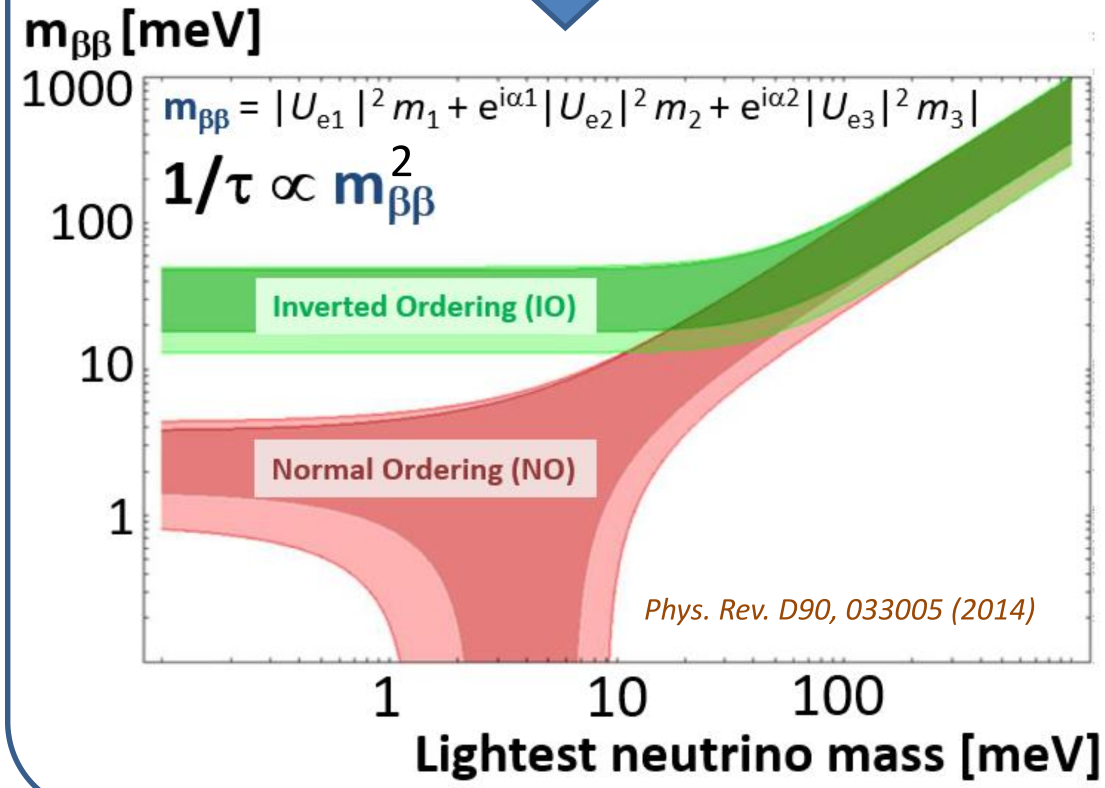
Not necessarily neutrino physics

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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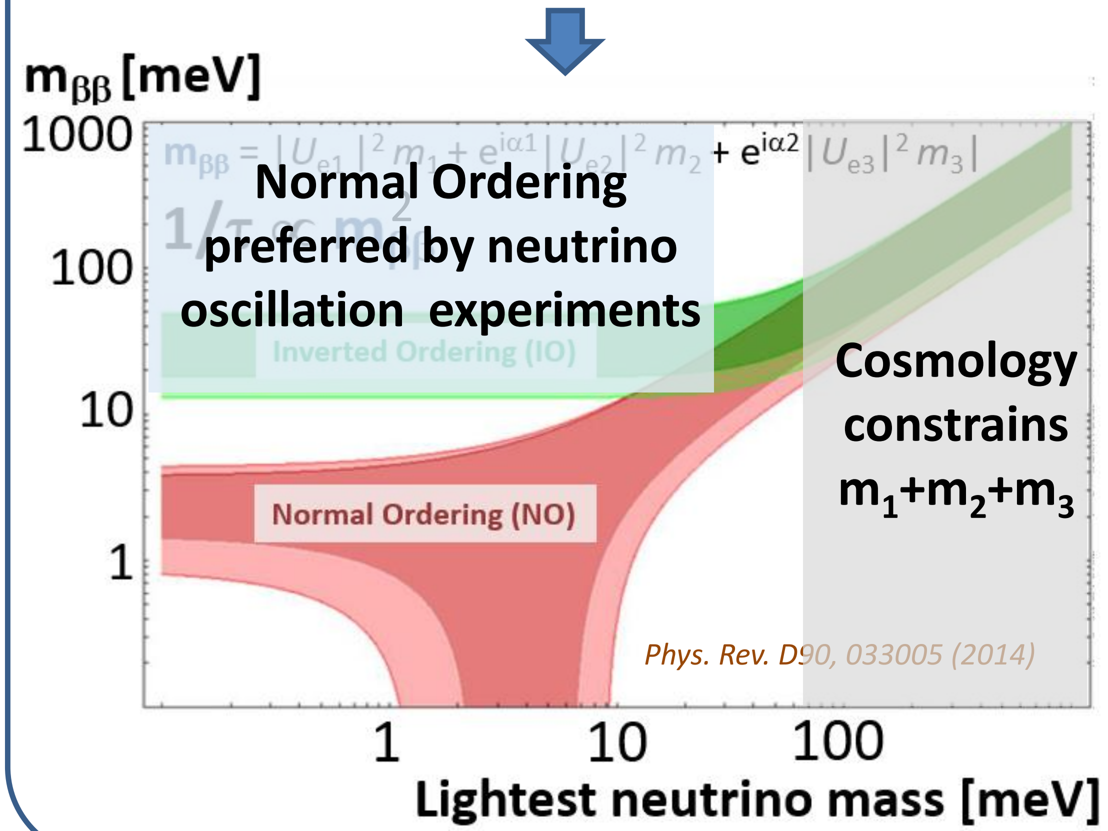


Completed
Data taking
Construction / Commissioning
Advanced R&D
R&D

nEXO

EXO-200 → **nEXO**

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

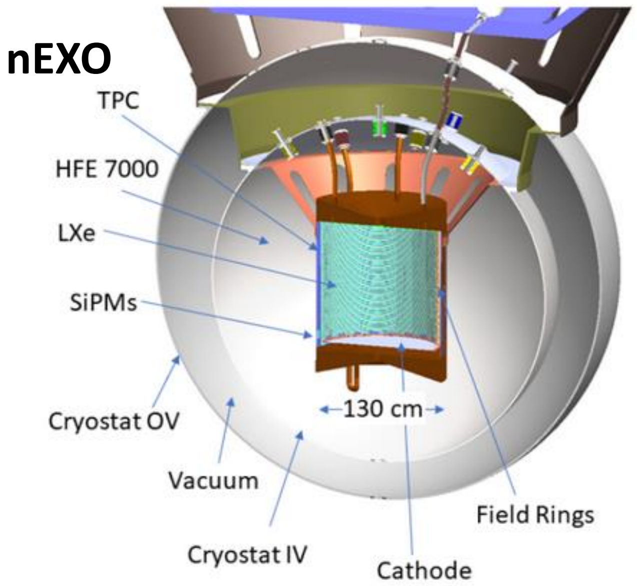
150 kg of ^{136}Xe – $T_{1/2}$ > 3.5×10^{25} y – $m_{\beta\beta}$ < 93 – 286 meV

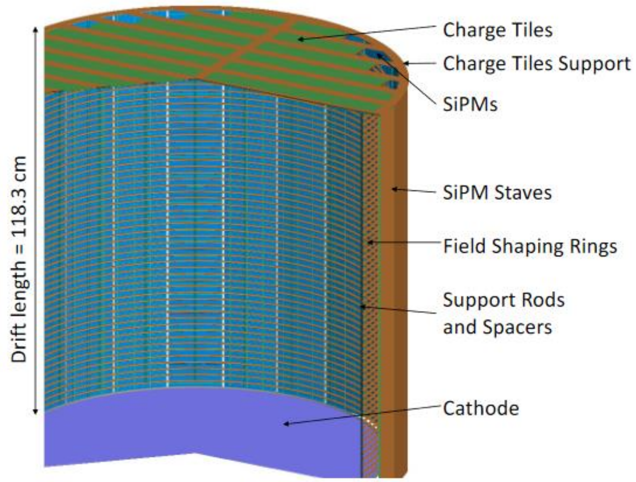
First observation of 2νββ of ^{136}Xe (2011) – **$T_{1/2}$ = 2.165×10^{21} y**

Concept

Single phase enriched LXe TPC

- Energy resolution **ΔE(σ) ~ 0.8%@$Q_{\beta\beta}$**
- 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 (under DoE Portfolio Review) – SNOLab

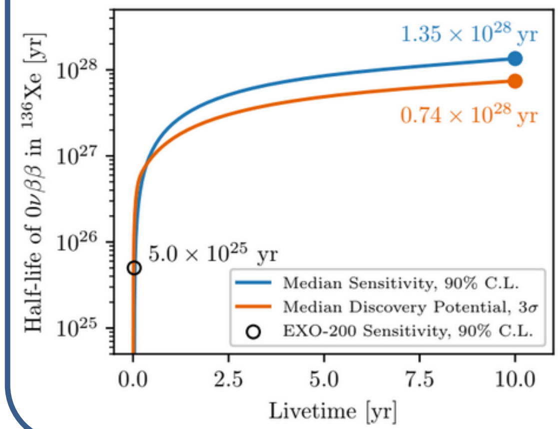
Major upgrades with respect to EXO-200

- 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 σ/$Q_{\beta\beta}$ [%]	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 → ^{136}Ba + 2e$^-$

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

GERDA → LEGEND

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

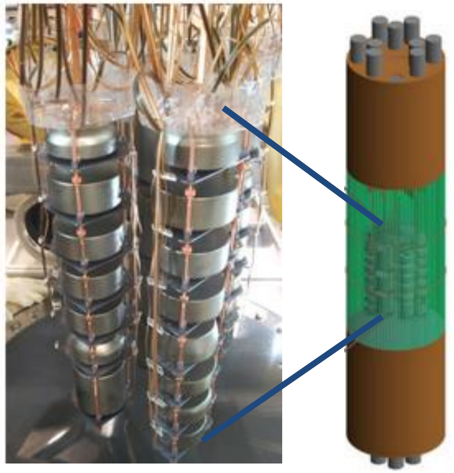
GERDA
MAJORANA dem.
} → LEGEND-200 → LEGEND-1000

GERDA - LNGS, Italy $T_{1/2} > 1.8\times10^{26}$ y – $m_{\beta\beta} < 79 - 180$ meV
35 kg of ^{76}Ge – Leading experiment in terms of half-life

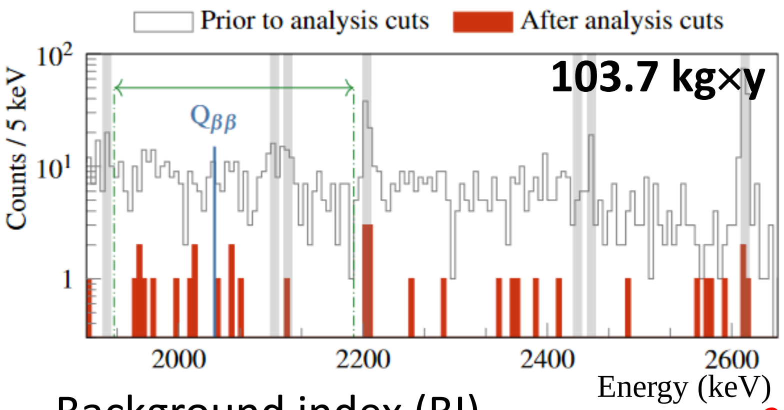
Concept

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)
$5.2^{+1.6}_{-1.3} \times 10^{-4}$ c/(keV kg y)
Lowest in all ββ experiments

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

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:
Detector deployment starts in Sep 2021
Data taking: end 2021 / beginning 2022

AIP Conference Proceedings 1894, 020027 (2017)

LEGEND-1000 (under DoE Portfolio Review)

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

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

CUORE → CUPID

Small scale demonstrators

CUPID-Mo
CUPID-0
CUORE

→ **CUPID** → CUPID Reach / CUPID-1T

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

CUORE - LNGS, Italy $T_{1/2} > 2.2 \times 10^{25}$ y – $m_{\beta\beta} < 90 – 305$ meV
Exposure: **1038.4 kg × y –** Record for a bolometric experiment

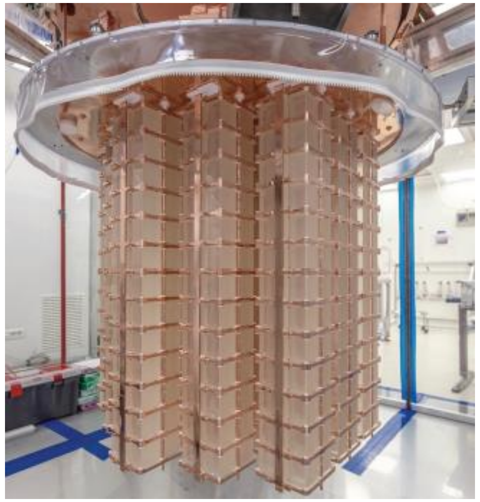
Concept

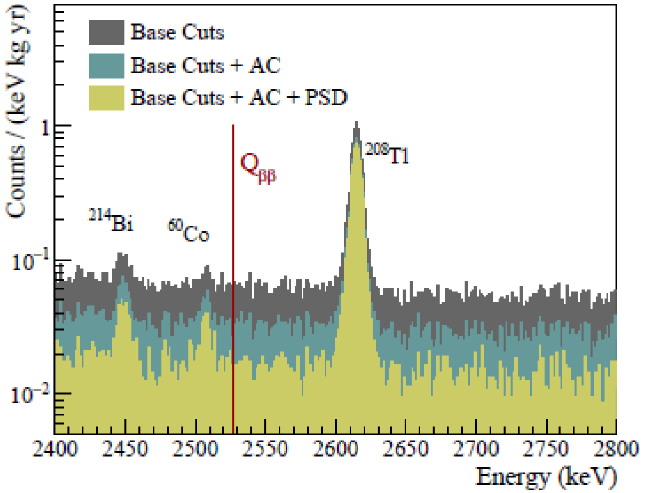
arXiv:1907.09376

Array of natural TeO_2 crystals operated as bolometers at 10 mK

- Built on the precursor CUORICINO experiment
- **988 TeO_2 crystals**, arranged in **19 towers – 206 kg of ^{130}Te**
- Energy resolution ΔE ~ 7.8 keV FWHM @$Q_{\beta\beta}$ – $Q_{\beta\beta}$=2527 keV
- Background index **1.49×10^{-2} c/(keV·kg·y)**

Dominated by **energy-degraded surface α's**





Target half-life sensitivity: **9×10^{25} y** $m_{\beta\beta} < 50 – 130$ meV

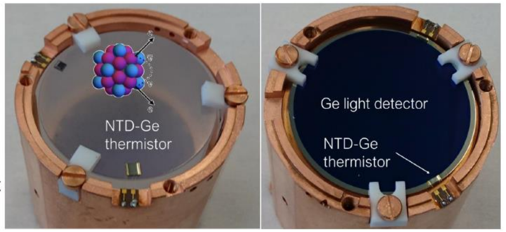
CUPID-Mo - LSM, France
Exposure: **2.71 kg × y**
Preliminary
$T_{1/2} > 1.8 \times 10^{24}$ y
$m_{\beta\beta} < 280 – 490$ meV
NEW

Concept ← LUMINEU R&D

Phys. Rev. Lett. 126, 181802 (2021)

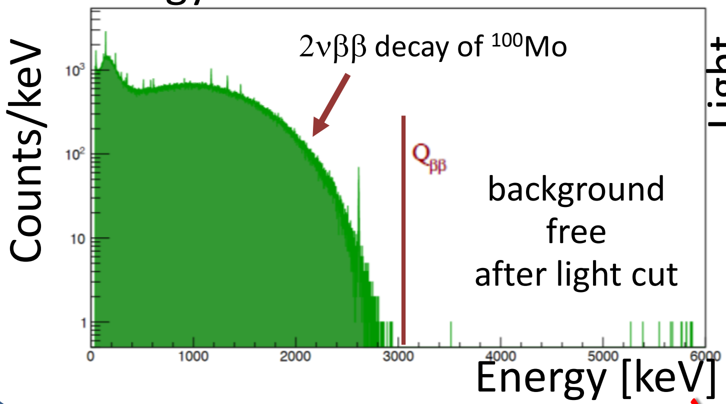
2 changes wrt CUORE:

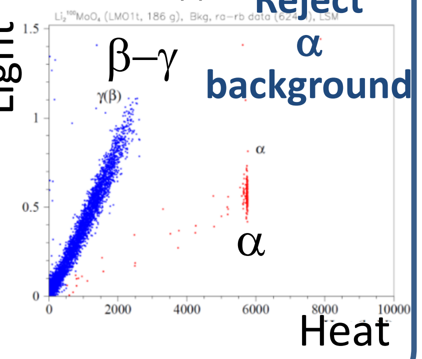
① **Pure bolometers → Scintillating bolometers**



② **^{130}Te (TeO_2) → ^{100}Mo (enriched Li_2MoO_4)**
$Q_{\beta\beta}$=3034 keV > 2.6 MeV (**reject external γ background**)

- **20 Li_2MoO_4 crystals – 2.26 kg of ^{100}Mo**
- Energy resolution ΔE ~ 7.8 keV FWHM @$Q_{\beta\beta}$





Reject α background

CUPID-0 - LNGS, Italy $Zn^{82}Se$
First scintillating bolometer demonstrator
NEW
Preliminary
L. Pagnanini, this conference
$T_{1/2} > 4.7 \times 10^{24}$ y
$m_{\beta\beta} < 276 – 570$ meV

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

CUORE → CUPID

Small scale demonstrators

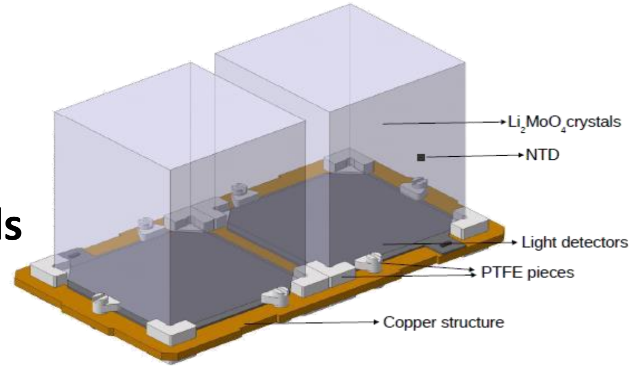
CUPID-Mo
CUPID-0
CUORE

→ **CUPID** → CUPID Reach / CUPID-1T

CUPID (under DoE Portfolio Review) – **LNGS, Italy**

Concept

- 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

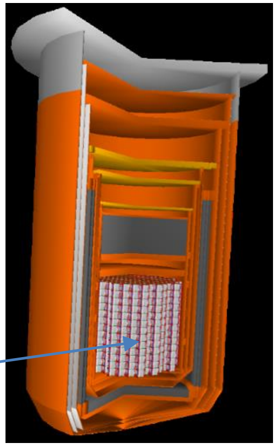


arXiv:1907.09376

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 and data analysis tools
Reuse CUORE infrastructure



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

Possible follow-up of CUPID

CUPID-reach - Same sensitive mass and cryostat as CUPID
Background improvement by factor 5
2.3×10^{27} y → $m_{ee} < 7.9 – 14$ meV

CUPID-1T - 1 ton isotope → new cryostat
Background improvement by factor 20
9.2×10^{27} y → $m_{ee} < 4.0 – 6.9$ meV

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

Intense R&D to improve background in Li_2MoO_4 and TeO_2 based bolometric experiments

CROSS → reject **surface events** by **PSD assisted by metal film coating**

BINGO →
- Internal active shield ($ZnWO_4$ scintillators)
- Enhanced-sensitivity light detectors
- Revolutionary detector assembly