The Quest for Majorana Neutrinos

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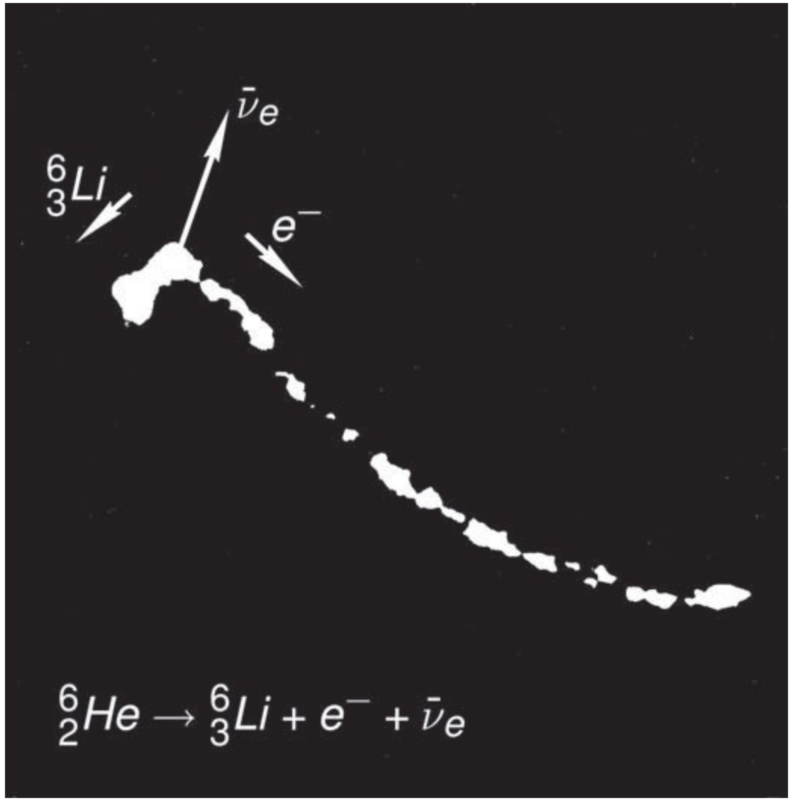
SFB 1258 Neutrinos Dark Matter Messengers
erc
ORIGINS Excellence Cluster
Bundesministerium für Bildung und Forschung

1956: The Neutrino Experiment at Debrecen

by J. Csikai and A. Szalay



discovery of neutrino particle through event-by-event reconstruction of decay kinematics

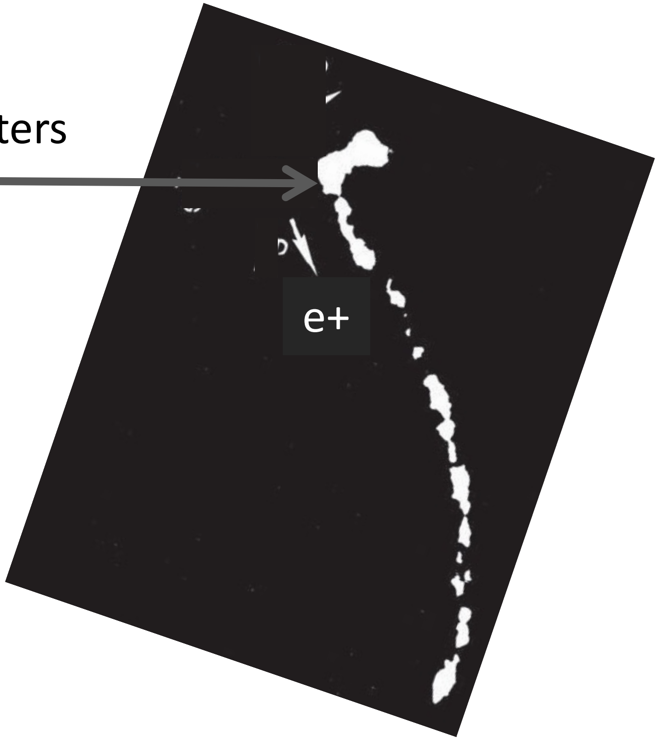
1956: The Reines-Cowan experimental concept

Source: Anti-Neutrinos
from nuclear reactor core

Detection via capture on
protons (H_2O):

$\bar{\nu}_e + p \rightarrow n + e^+$

$\bar{\nu}_e$ travelling of many meters



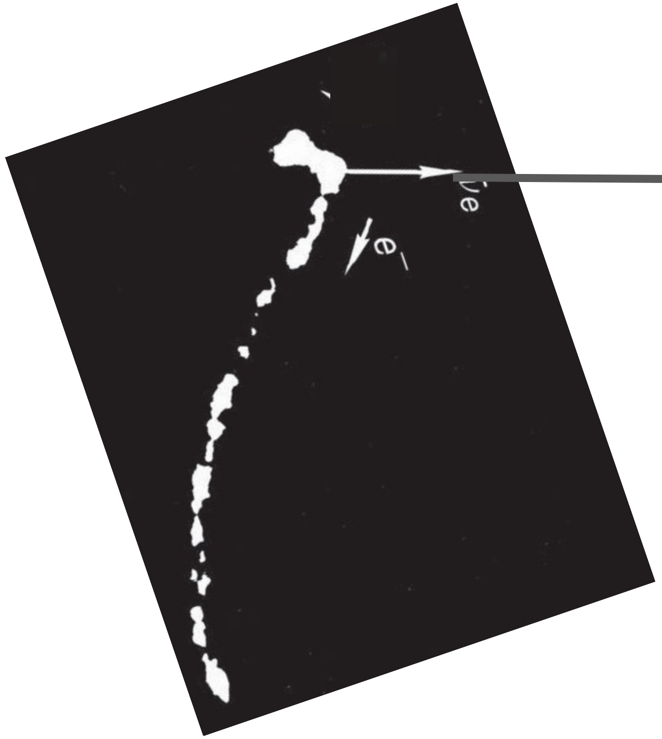
Beta-decays of neutron rich
fission products

1955 Ray Davis: Attempt to detect the antineutrinos from a nuclear neactor by the ^{37}Cl (anti-ν, e^-) ^{37}Ar reaction - are neutrinos and anti-neutrinos identical particles?

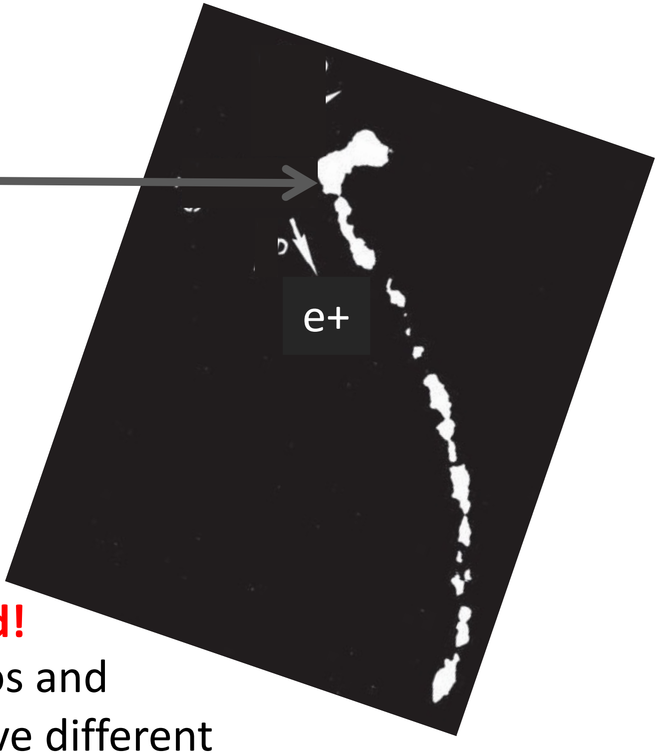
Source: Anti-Neutrinos from nuclear reactor core

Detection via capture on bound **neutrons** (Cl)

ν_e + „**n**“ ➔ „p“ + e^-



if $\overline{\nu}_e$ identical to ν_e

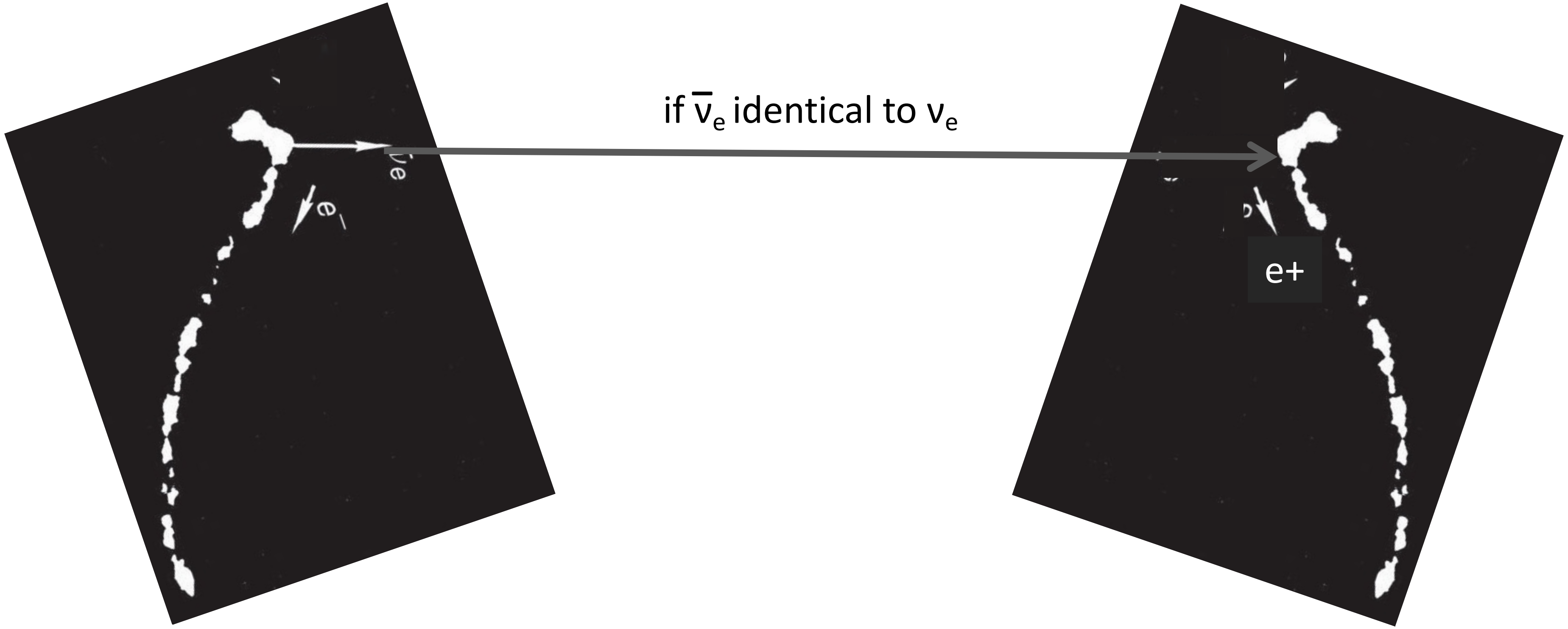


Not observed!
Anti-neutrinos and neutrinos have different helicities

Are neutrinos and anti-neutrinos identical particles?

Today we know that

- neutrinos are massive particles, thus helicity is not a good quantum number
- therefore, emission of anti-neutrinos with „wrong“ helicity state possible (prop. m/E) possible

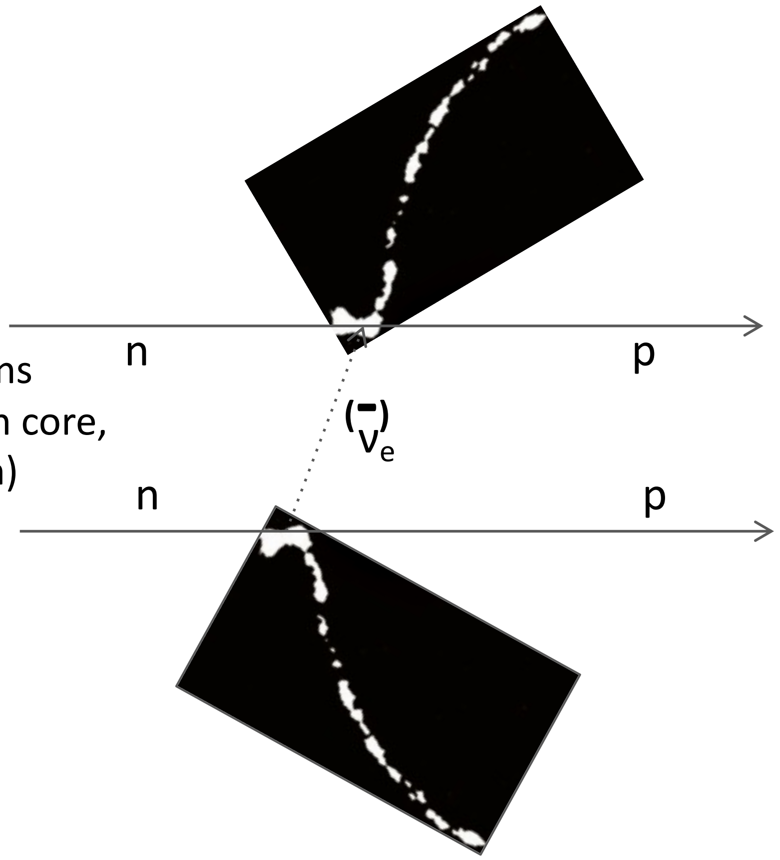


Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

Today we know that

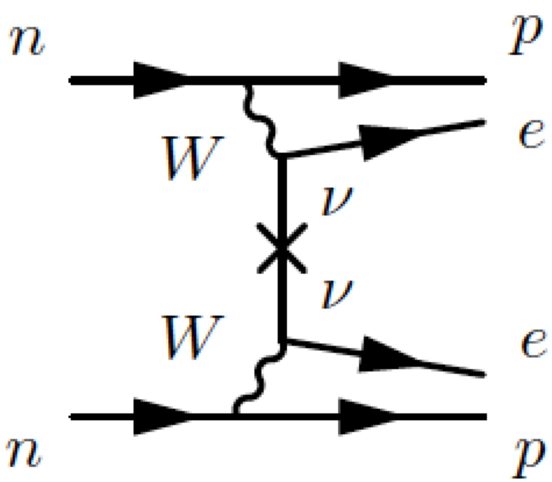
- Neutrinos are massive particles, thus helicity is not a good quantum number
- Therefore, emission of anti-neutrinos with „wrong“ helicity state possible (prop. m/E) possible

(Nukleons bound in core, $\approx 10^{-15}$ m)



$0\nu\beta\beta$-decay would imply that neutrinos are **Majorana particle**

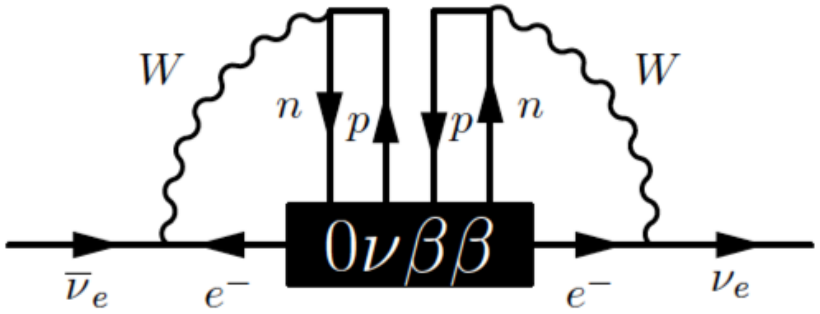
0νββ



Standard paradigm: exchange of
light Majorana neutrinos

$$\left\langle m_{ee} \right\rangle = \left| \sum_i U_{ei}^2 \, m_i \right|$$

PMNS-matrix ν-mass

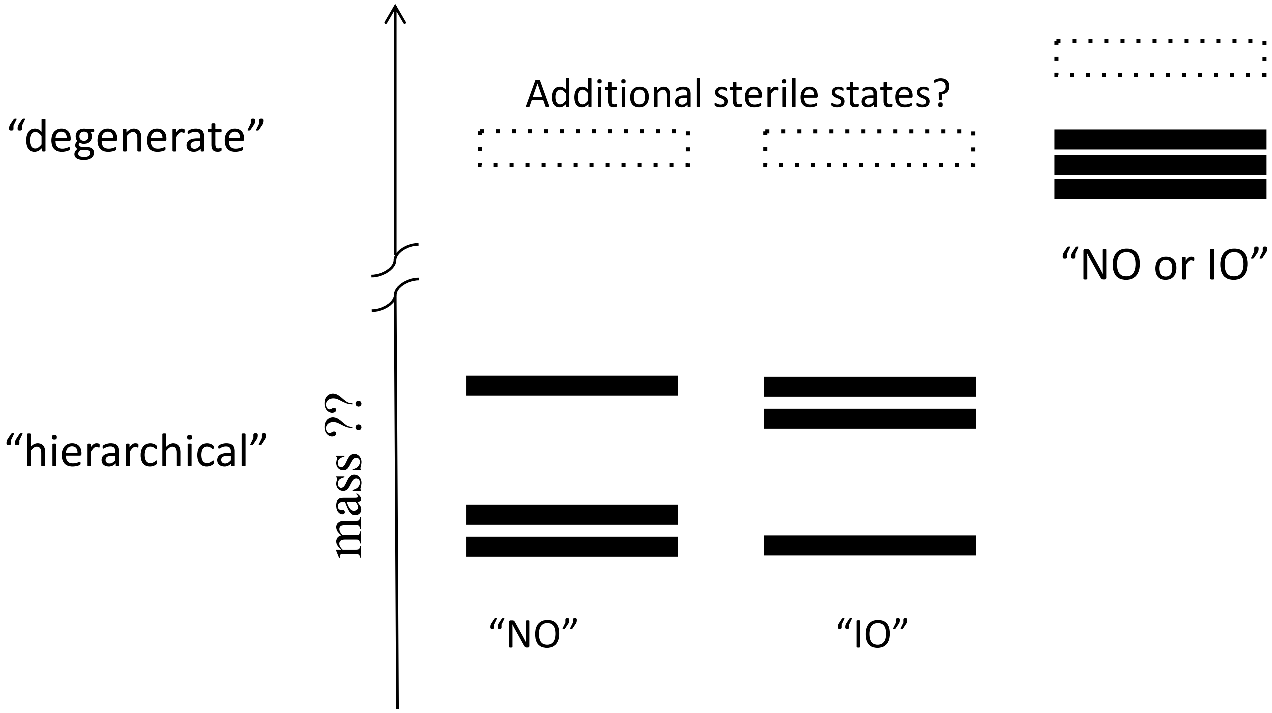


Any 0νββ decay process induces a $\overline{\nu_e}$-ν_e transition, ie. an effective **Majorana mass term**
Schechter, Valle Phys.Rev. D25 (1982)

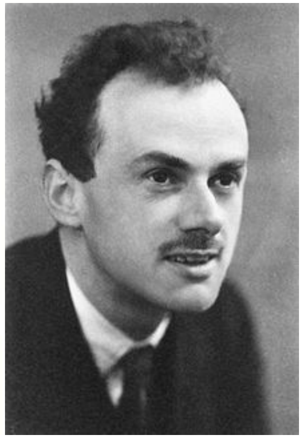
Numerical values tiny; other leading contributions to neutrino mass must exist
Duerr, Merle, Lindner: JHEP 1106 (2011)

The Quests

What is the neutrino mass scale?



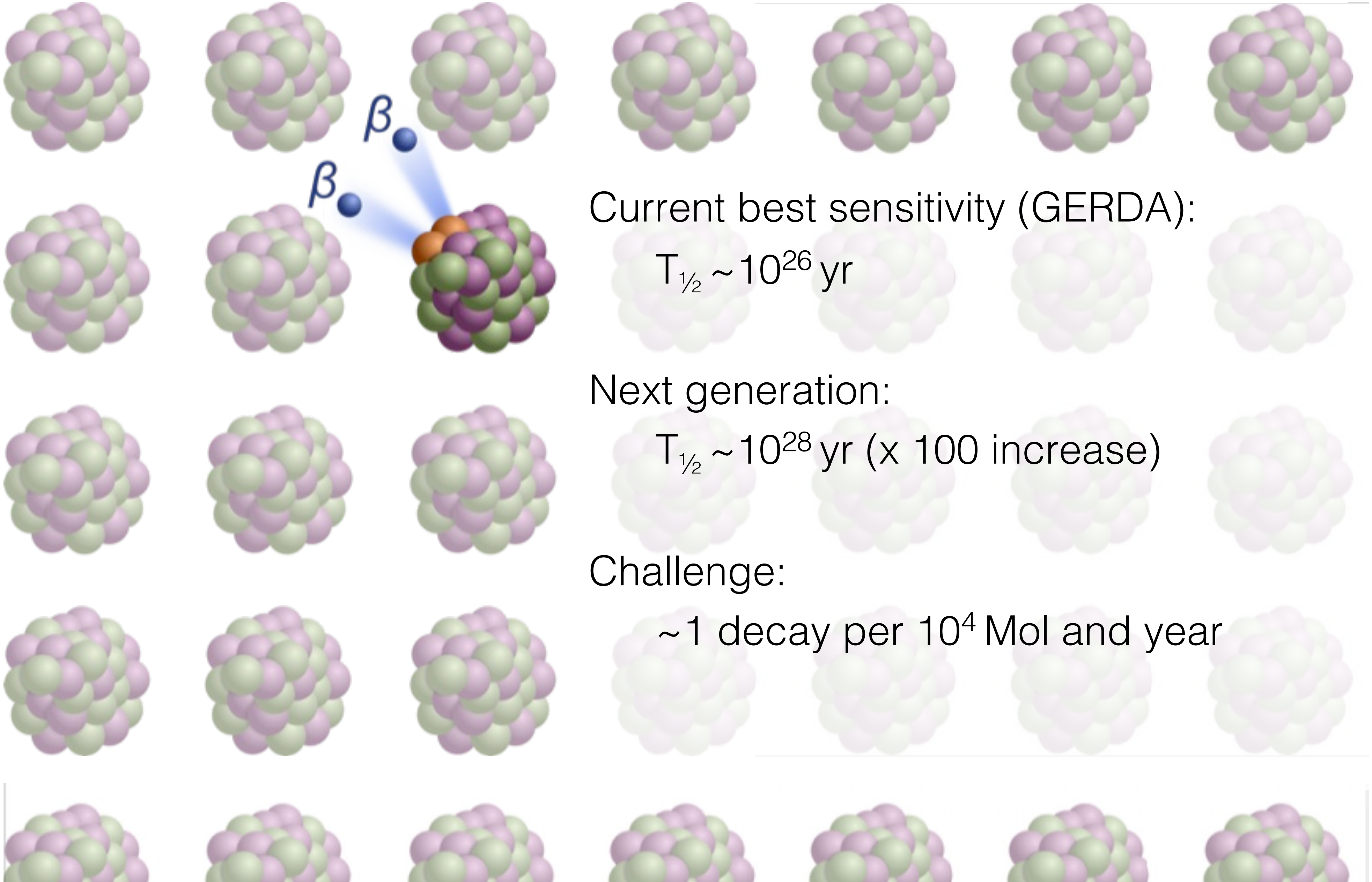
Are neutrinos their own anti-particles?



Is lepton number violated?
No reason for global symmetries to be exact!
[e.g Edward Witten, arXiv:1710.01791]

- Why are neutrinos so much lighter than charged leptons ?
- What is the origin of the matter anti-matter asymmetry ?

$0\nu\beta\beta$ decay: Creation of (leptonic) matter without balancing emission of anti-matter



Current best sensitivity (GERDA):

$T_{1/2} \sim 10^{26}$ yr

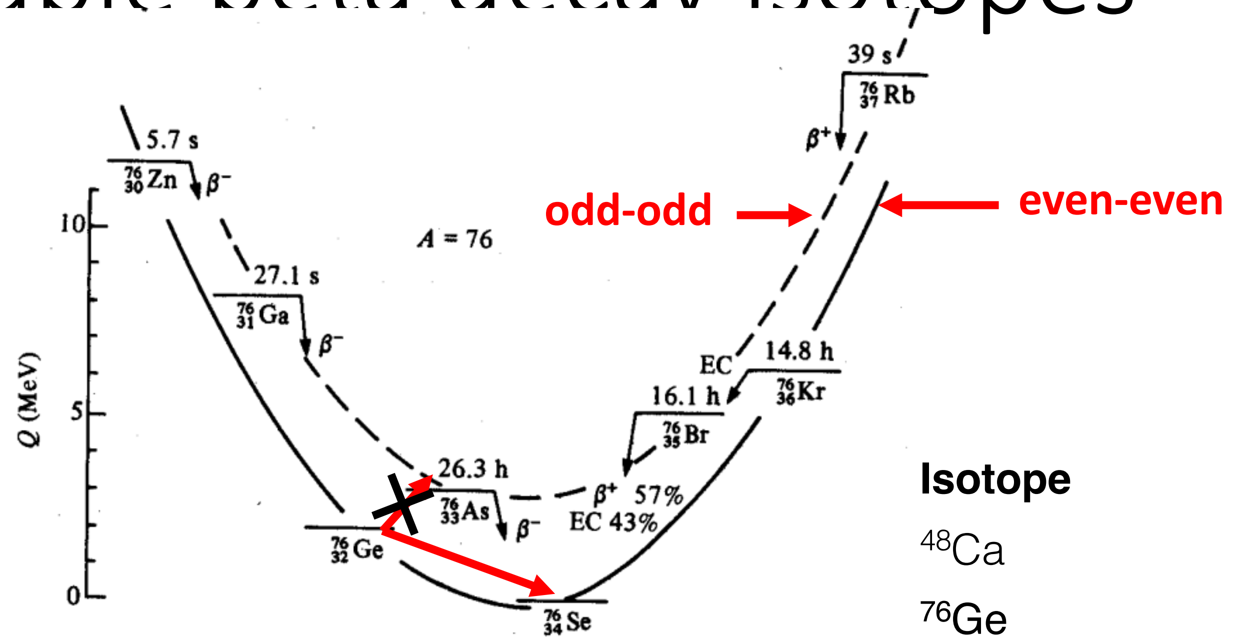
Next generation:

$T_{1/2} \sim 10^{28}$ yr (x 100 increase)

Challenge:

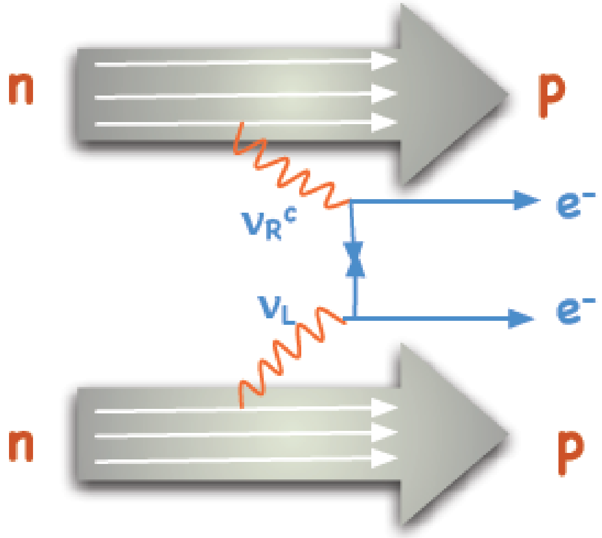
~1 decay per 10^4 Mol and year

Double beta decay isotopes



Isotope	Nat ab.	$Q_{\beta\beta}$
^{48}Ca	0.19 %	4262.96(84) keV
^{76}Ge	**7.6%**	**2039.04(16) keV**
^{82}Se	**8.7%**	**2997.9(3) keV**
^{96}Zr	2.8%	3356.097(86) keV
^{100}Mo	**9.6%**	**3034.40(17) keV**
^{116}Cd	7.5%	2813.50(13) keV
^{130}Te	**34.5%**	**2526.97(23) keV**
^{136}Xe	**8.9%**	**2457.83(37) keV**
^{150}Nd	5.6%	3371.38(20) keV

0νββ decay and neutrino mass



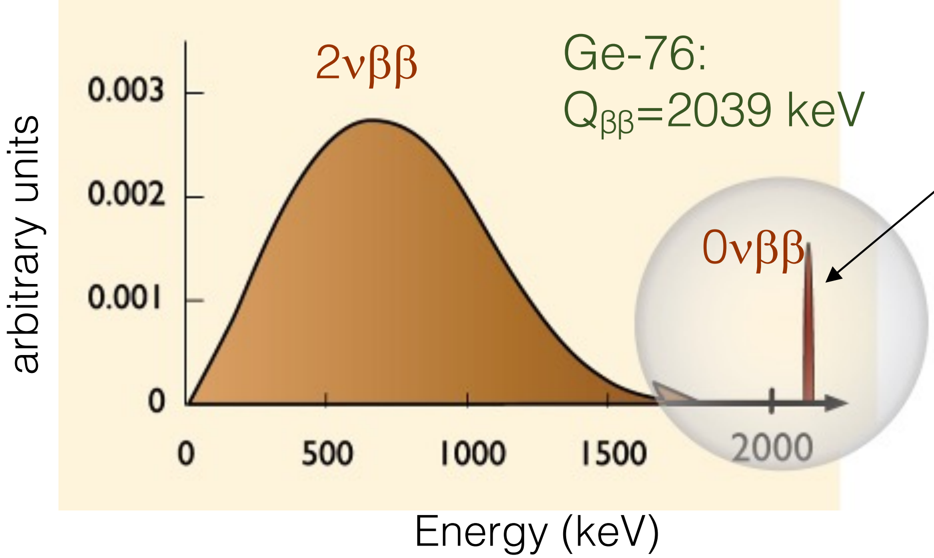
Expected decay rate:

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\langle m_{ee}\rangle^2$$

Phase space integral Nuclear matrix element

$$\langle m_{ee}\rangle = \left|\sum_i U_{ei}^2\, m_i\right|$$ Effective neutrino mass

U_{ei} Elements of (complex) PMNS mixing matrix



<u>Experimental signatures:</u>

- peak at $Q_{\beta\beta}$
- two electrons from vertex

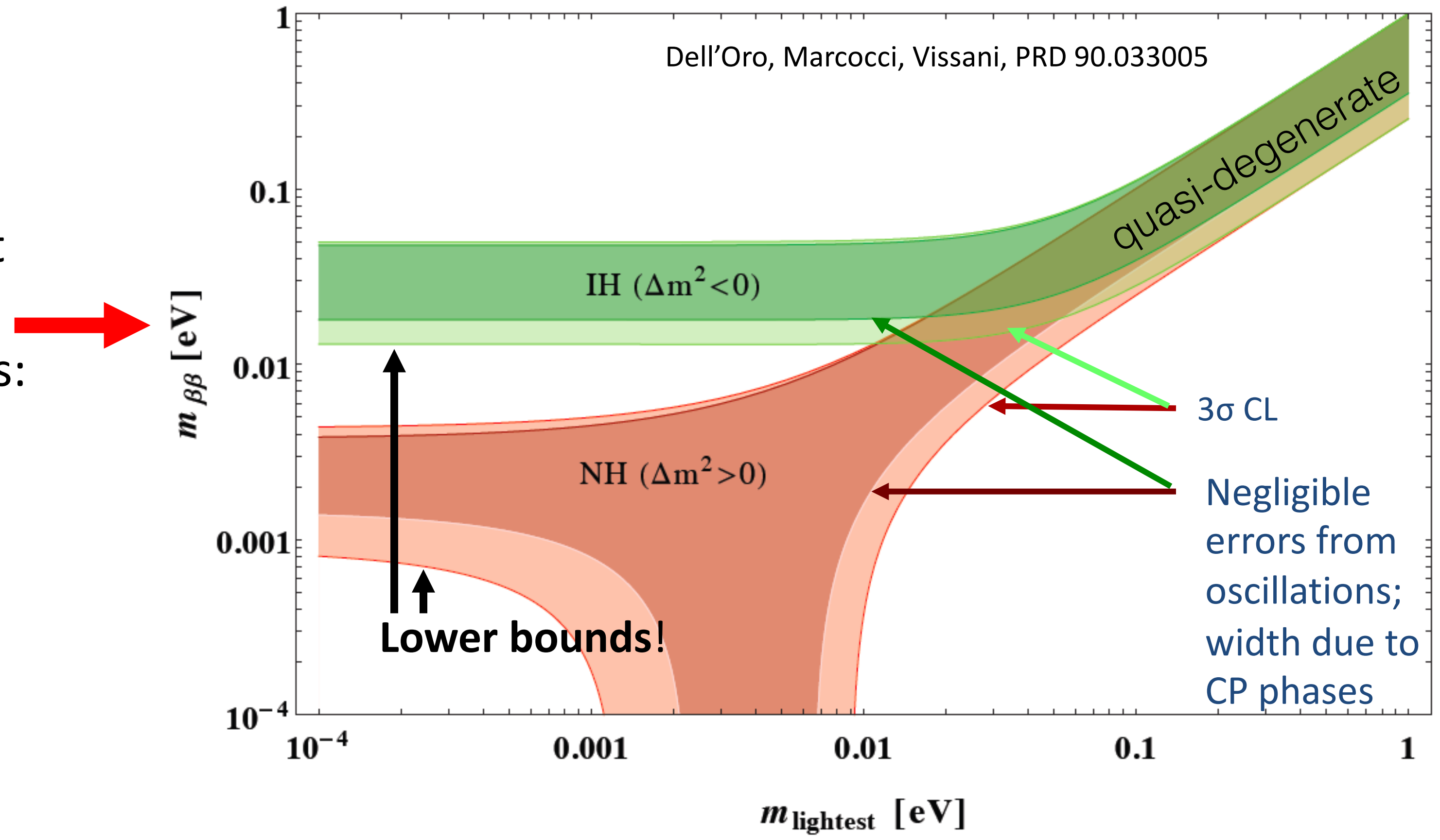
<u>Discovery would imply:</u>

- lepton number violation ΔL = 2
- ν's have Majorana character
- mass scale
- physics beyond the standard model

$0\nu\beta\beta$: Range of m_{ee} from oscillation experiments

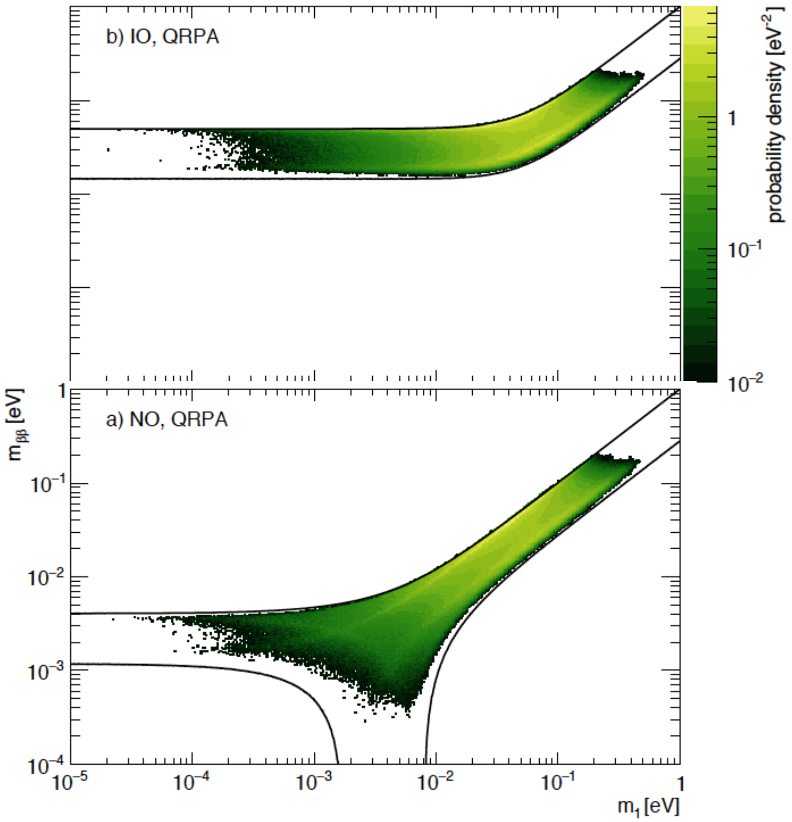
$$m_{ee} = f(m_1, \underbrace{\Delta m^2_{sol}, \Delta m^2_{atm}, \theta_{12}, \theta_{13}}_{\text{from oscillation experiments}}, \alpha\text{-}\beta)$$

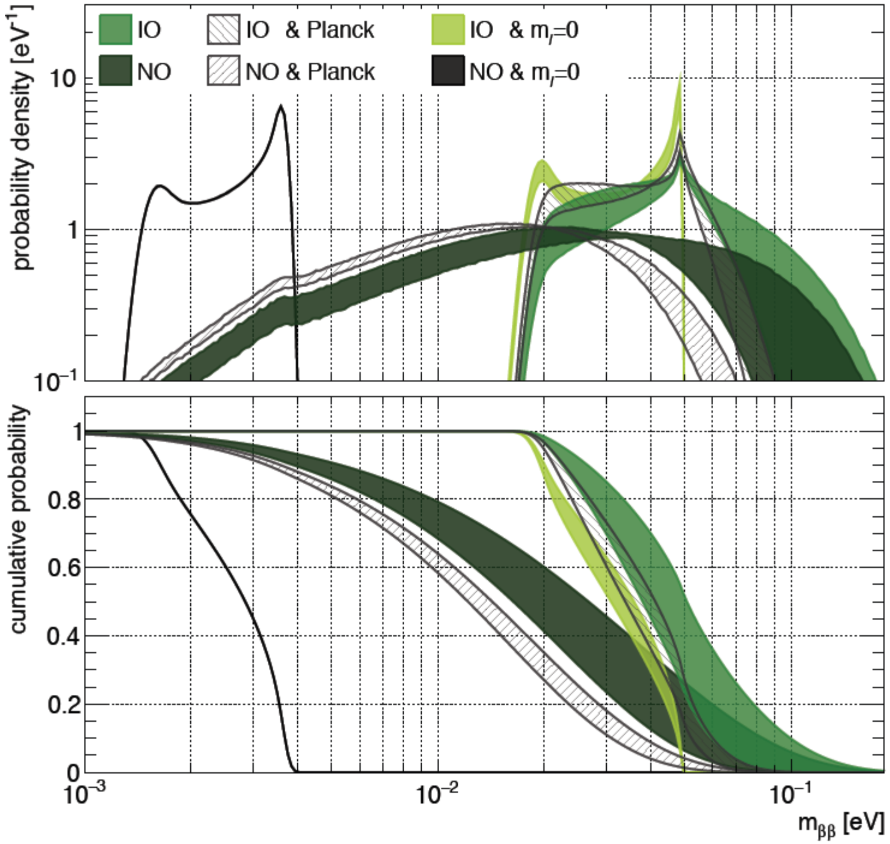
Goal of next generation experiments:



Discovery probabilities

- Global Bayesian analysis including ν-oscillation, m_β $m_{\beta\beta}$, Σ
- Priors:
  - Majorana phases (flat)
  - m_1 (scale invariant)

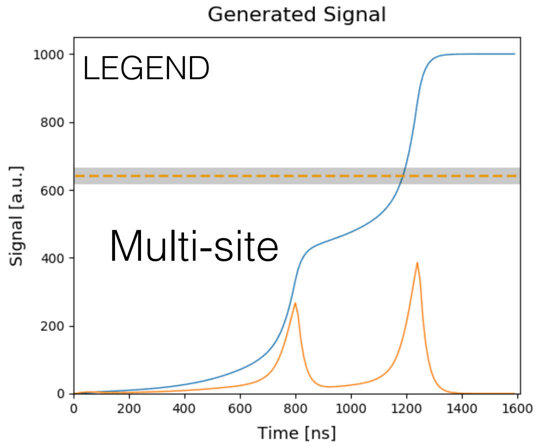


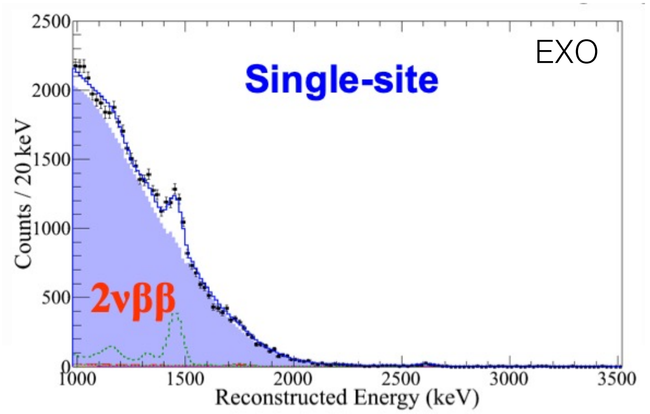


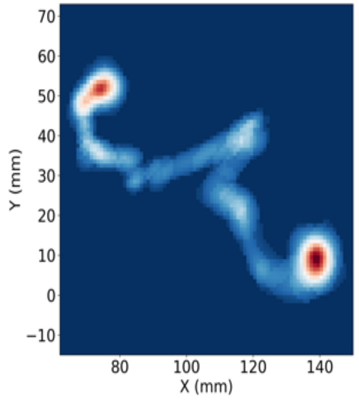
Agostini, Benato, Detwiler arXiv:1705.02996

Ton-scale experiments for discovery

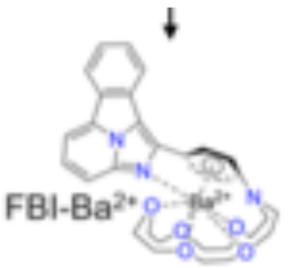
- Need to measure half-lives of up to 10^{28} years
- **One decay** per **ton-year** of material
- Need many **ton-years** of data
- Need extreme **low background rate** and best possible **energy resolution**
- Need to exploit **topology information** of signal and background
- And, if possible, identify **daughter nucleus**







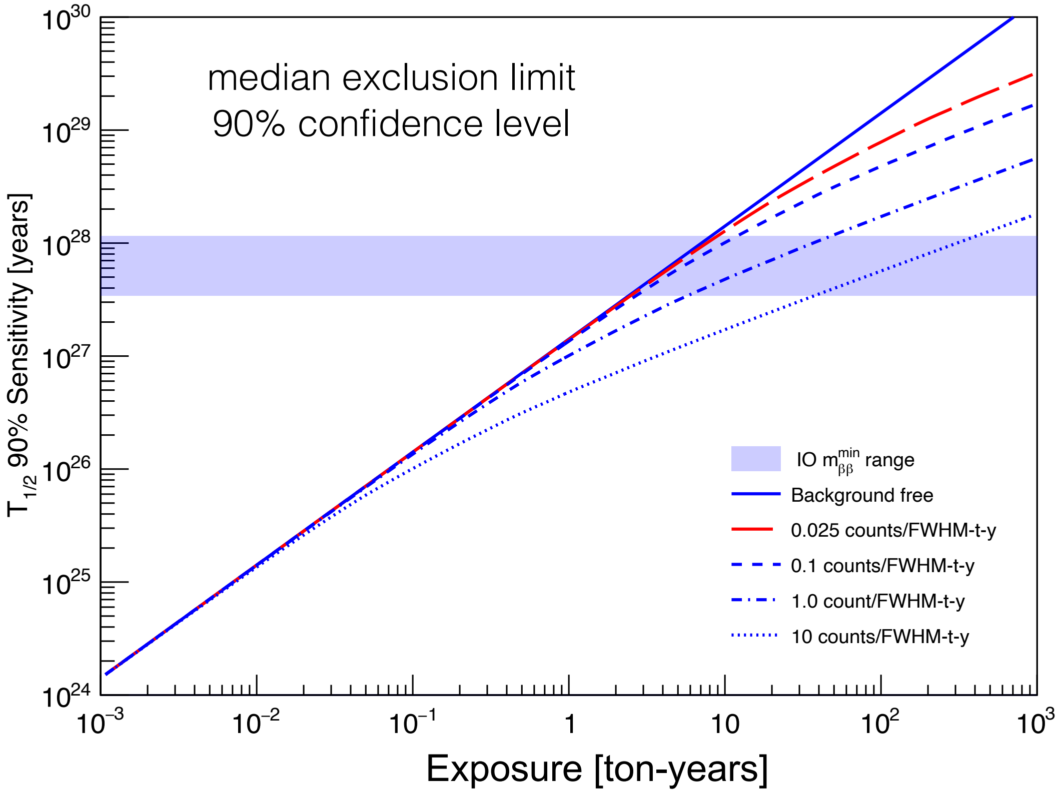
NEXT

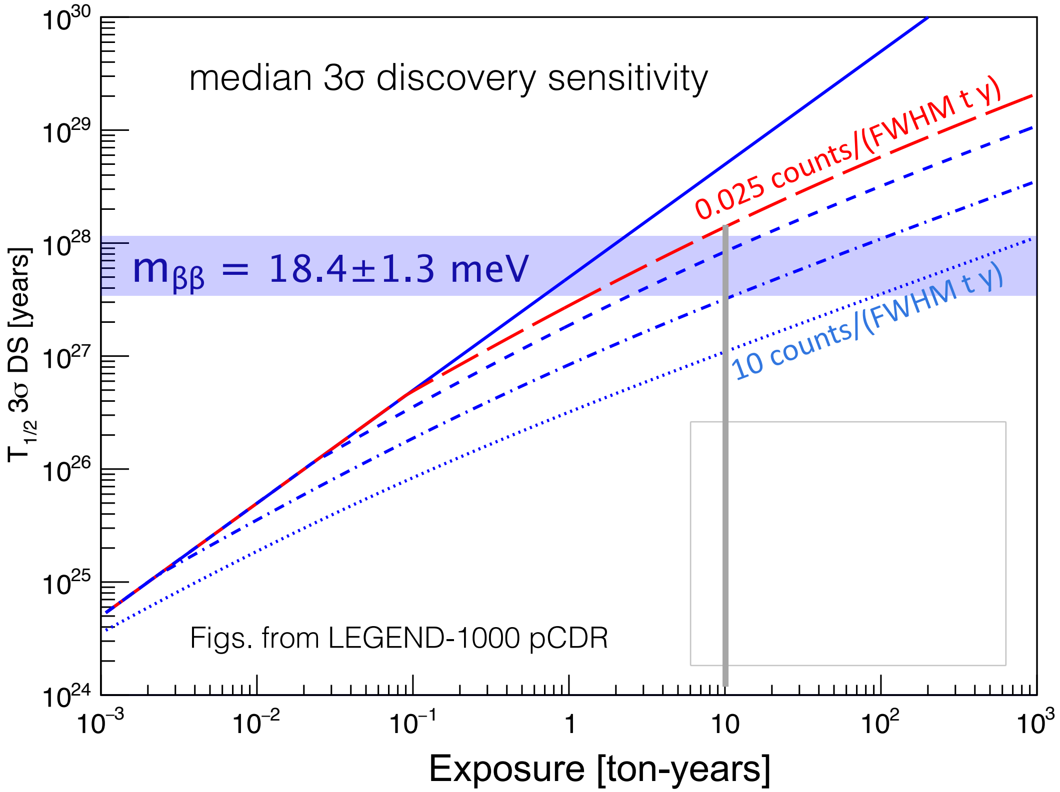


The Effect of Background: Discovery sensitivity vs. exclusion limit

- Ton-scale experiments aim for a **discovery**
- Background-free: Sensitivity rises **linearly with exposure**
- Background-limited: Sensitivity rises as the **square root of exposure**

=> **quasi-background-free**[1] operation makes most efficient use of valuable isotopes





[1] Less than one background count expected in a 4σ Region of Interest (ROI) with 10 t y exposure

Double beta decay isotopes

An isotope production facility at ECP
(Image: TVEL)

Enrichment:

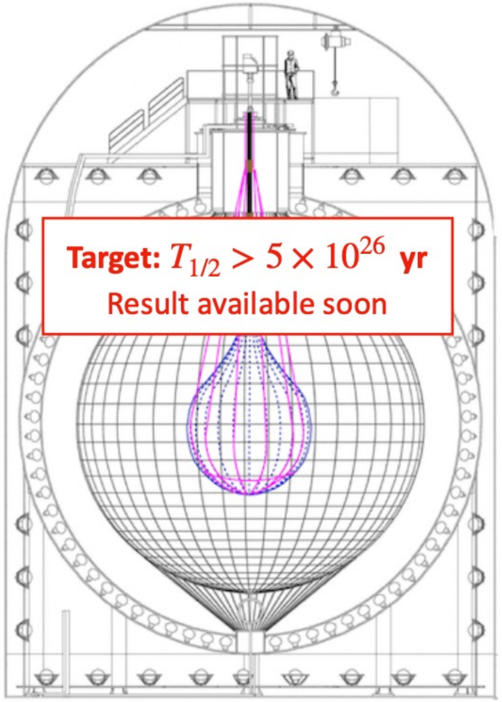
- Current experiments obtain $0\nu\beta\beta$ isotopes largely from **Russia**
- **Reliable** and high-quality supply chain
- Some $0\nu\beta\beta$ isotopes also procured from **European** producer
- Since the **war in Ukraine**, no procurement of $0\nu\beta\beta$ isotopes from Russia possible for **Western countries**
- European producer is **ramping up production capacities** to suffice demands. They state that **sufficient capacities** will be available to fulfill demands by ton-scale experiments (^{76}Ge, ^{100}Mo, ^{136}Xe)
- Additional initiatives are being pursued: e.g. ^{136}Xe extraction from burned nuclear fuel elements
- Projects in China continue to procure $0\nu\beta\beta$ isotopes from Russia

Natural isotopic composition:

- Te (34% ^{130}Te): Cuore, SNO+, JUNO
- Xe (8.9 % ^{136}Xe): Darwin

KamLAND-Zen: ^{136}Xe loaded liquid scintillator

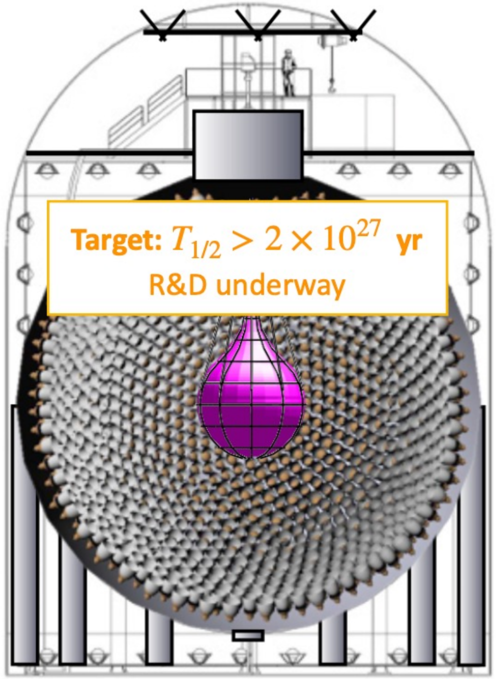
present



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

KLZ-400 (completed):

- **Sensitivity: > 5.6 10^{25} yr (90% C.L.)**
- Unconstraint fit: > 9.2 10^{25} yr (90% C.L.)
- Phase I + II: > 1.07 10^{26} yr (90% C.L.)

KLZ 800 (ongoing):

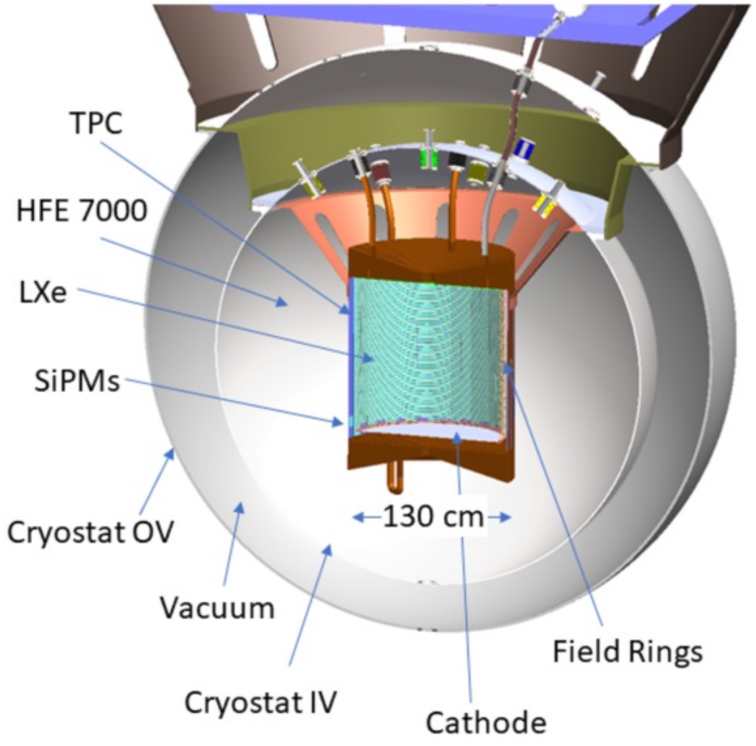
- Since 2019: data taking with 750 kg ^{enr}Xe (new balloon)

KamLAND2-Zen (future) with

- 1000kg+ proposed

Adopted from Aobo Li, TAUP2021

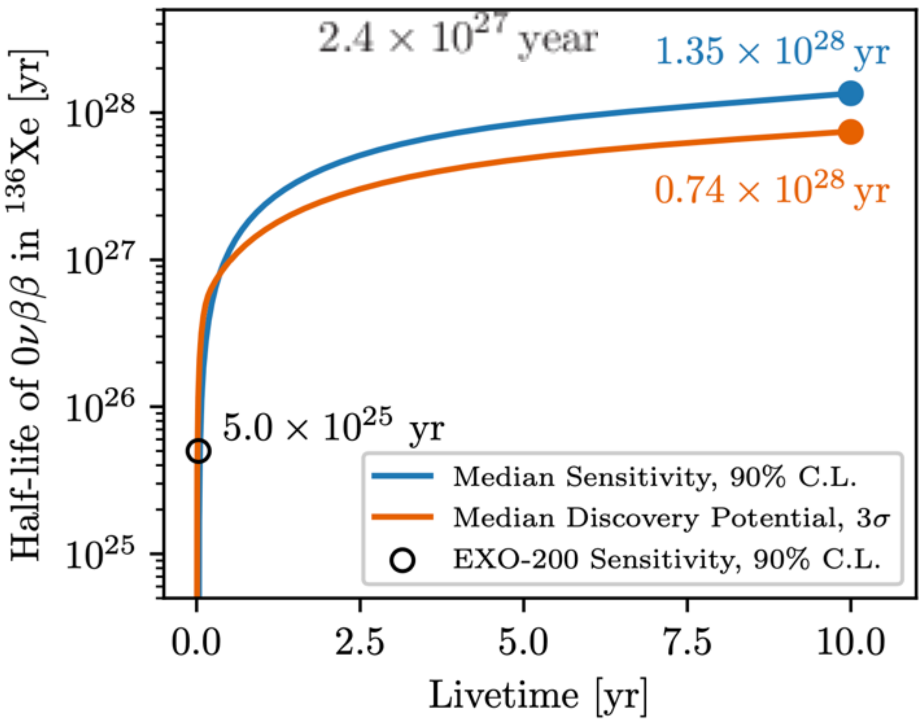
nEXO: ^{136}Xe single phase TPC



Adopted from Ako Jamil, TAUP2021

pCDR: arXiv:1805.11142
Sensitivity: arXiv:2106.16243

- Single Phase Time Projection Chamber (TPC)
- Filled with 5000 kg of liquid xenon Enriched to 90 % in ^{136}Xe
- Monolithic design with single drift volume with 1.2 m drift length
- Energy resolution of $\sigma_E / Q_{\beta\beta} = 0.8$ %
- assuming 6000 m.w.e. overburden (SNOLAB)

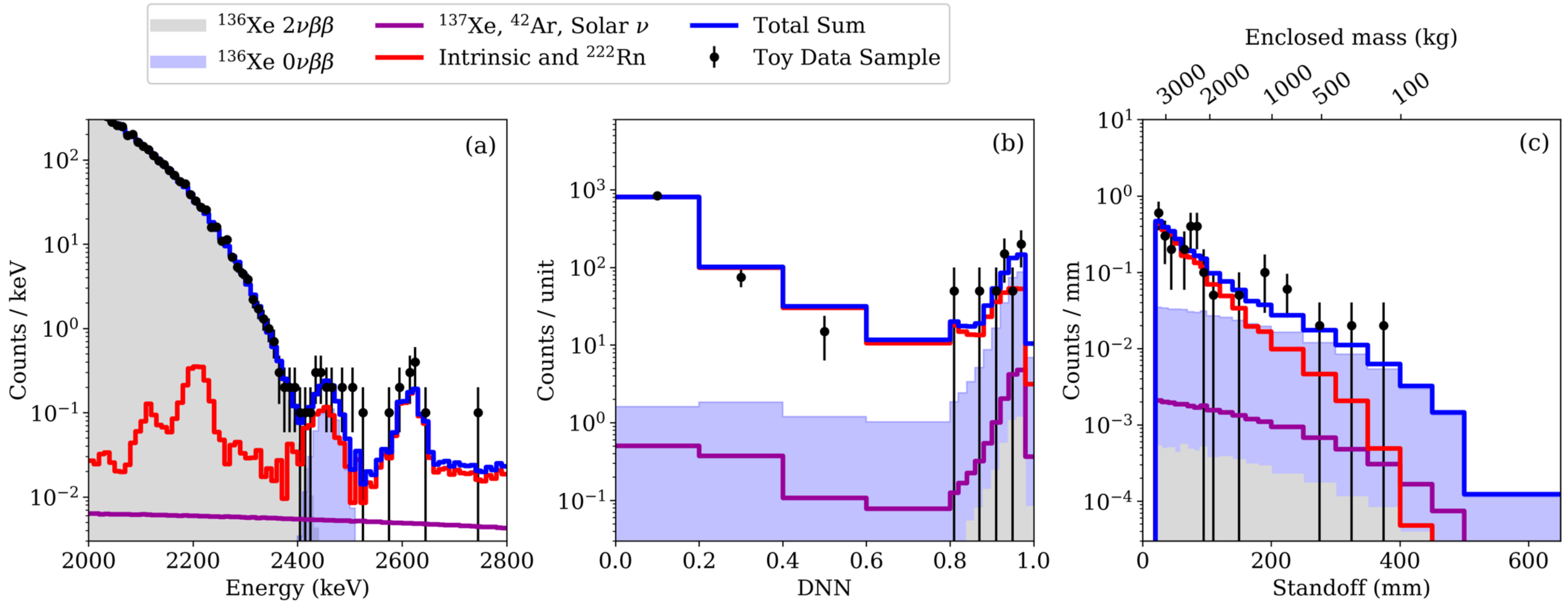


N.B.:
Dual-phase Xe TPCs (DM) with natural Xe also sensitive to $0\nu\beta\beta$

- LZ: $>1.06\times10^{26}$ years at 90% CL (PANIC2021)
- DARWIN: $>2.4\times10^{27}$ (EPJC 80, 808 (2020))

nEXO: topological info for signal and backgrounds

arXiv:2106.16243



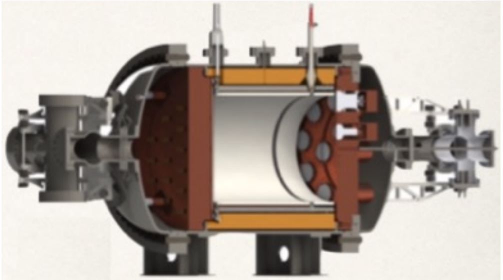
Energy distribution of single-site like events in central 2t of LXe

Topological info between ββ and γ events

Relative distance between a deposit and the nearest surface

^{136}Xe high-pressure gaseous TPC

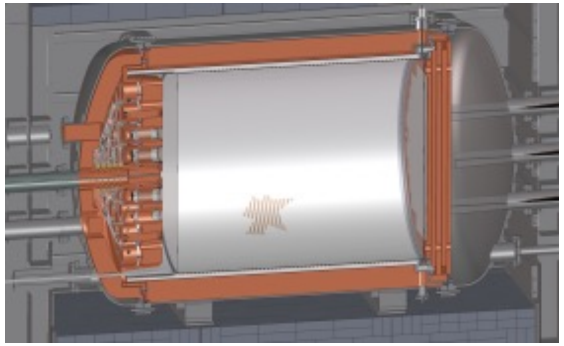
NEXT-NEW (5 kg) 2015-2020



Underground & radio-pure operations, background, $2\nu\beta\beta$

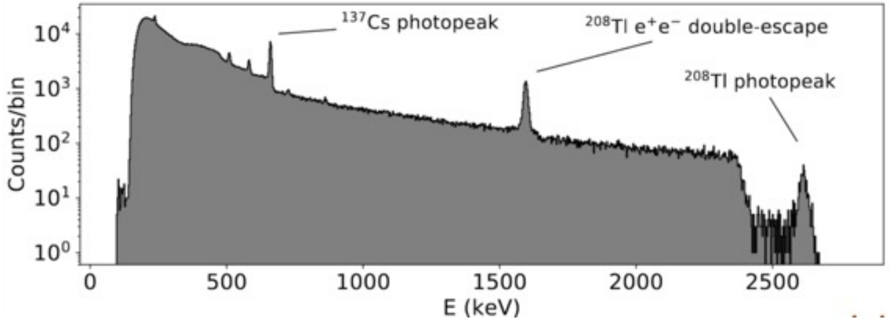
$\Delta E < 1\%$ FWHM
Event topological reconstruction

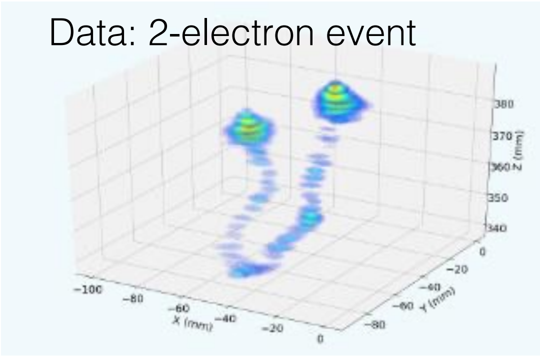
NEXT-100 (100 kg) 2022-2025



$0\nu\beta\beta$ search

400 kg×y sensitivity 1×10^{26}y





<u>HD (High-Definition)</u>

- Up to 1 ton enriched Xe gas @ 20 bar
- Replacement of PMTs by SiPMs
- Xe-He mixture: lower diffusion, better definition
- Target sensitivity: 2×10^{27} y (6 ton yr)

<u>NEXT-BOLD</u> (Barium On Light Detection)

- HD including Ba-tagging by single-molecular-fluorescence imaging
- Background-free operation
- Target sensitivity: 8×10^{27} y (10 ton yr)

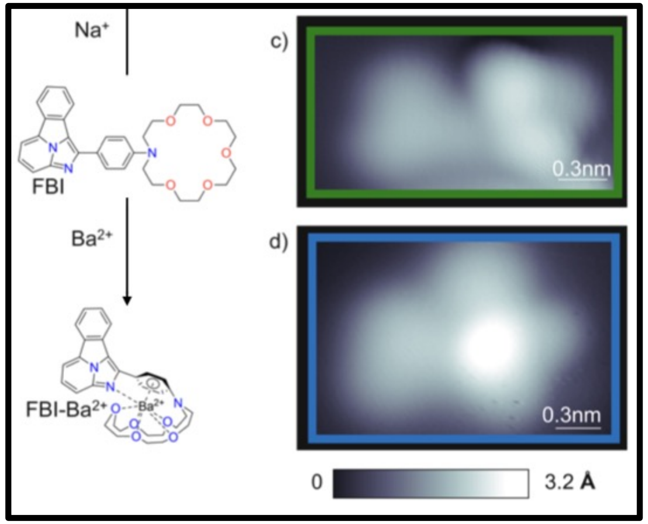
Phys. Rev. Lett. 120, 132504 (2018)

^{136}Xe: Barium tagging next

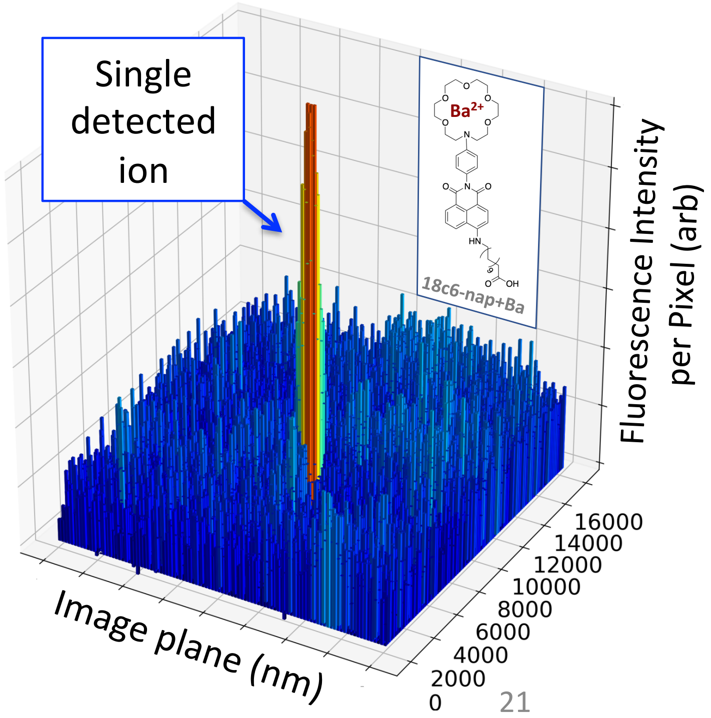
- Detection of **single barium ion** in coincidence with **<1% FWHM energy resolution** and **event topology** essential for background free $0\nu\beta\beta$ search in Xe (NEXT-BOLD)

- NEXT pursues single molecule fluorescent imaging (SMFI) based barium tagging sensors.
- R&D to date has realized molecular ion sensors that:
  - Exhibit barium chelation in vacuum &
  - Enable single ion sensing in xenon gas
  - ON/OFF and Bi-color approaches

STM shows barium location in molecule after chelation



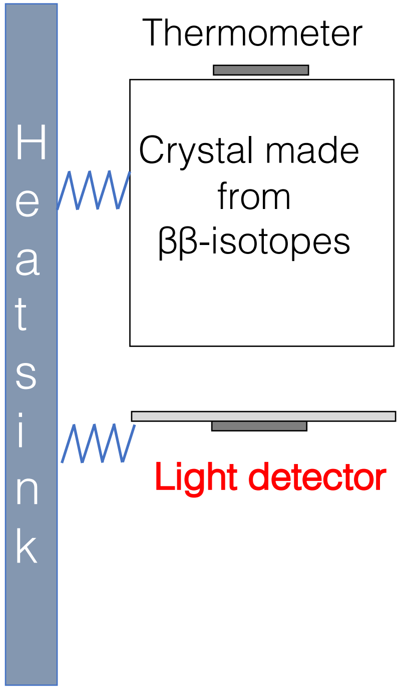
SMFI + high pressure microscopy enables Ba2+ detection in Xe gas



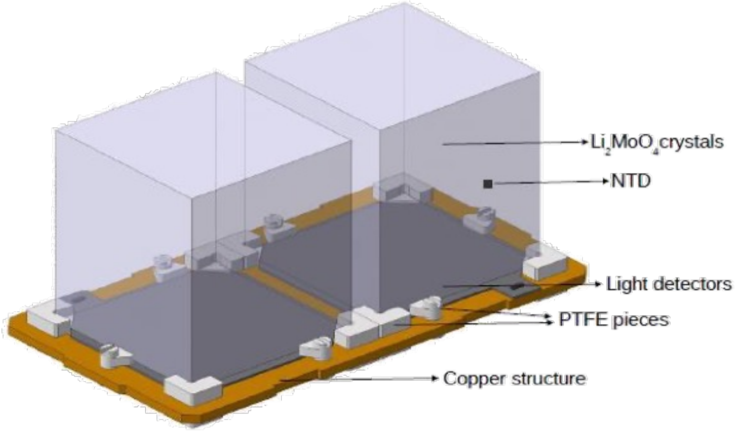
J.Phys.Conf.Ser. 650 (2015) 1, 012002; JINST 11 (2016) 12, P12011; Phys. Rev. Lett. 120 (2018) 13, 132504. Sci.Rep. 9 (2019) 1, 15097; Nature 583 (2020) 7814, 48–54; ACS Sens. (2021) 6, 1, 192–202; arXiv:2201.09099, arXiv:2109.05902

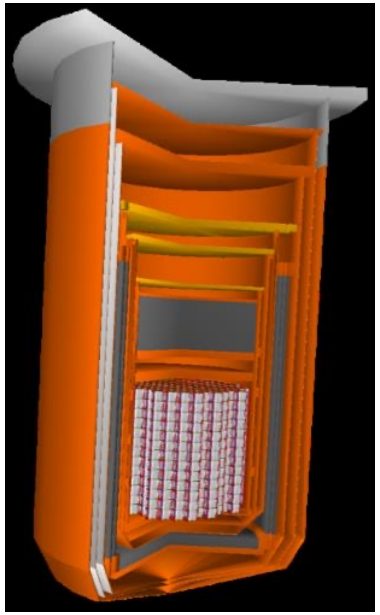
Courtesy M. Sorel, J. Gomez Cadenas

CUPID: ^{100}Mo cryogenic detectors @ LNGS



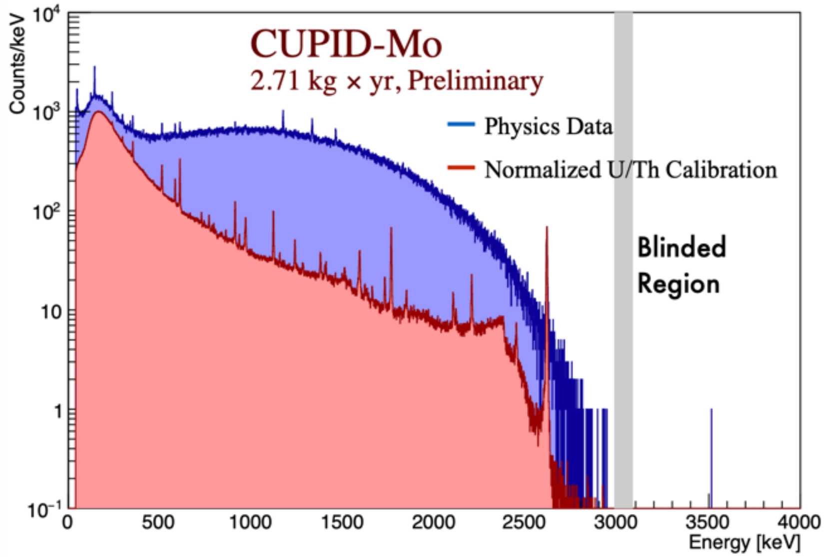
- Simultaneous read out of heat and light: surface alpha rejection
- Single module: $Li_2{}^{100}MoO_4$ 45×45x45 mm –> 280 g
- 57 towers of 14 floors with 2 crystals each -> 1596 crystals
- 240 kg of ^{100}Mo with >95% enrichment
- Bolometric Ge light detectors as in CUPID-Mo, CUPID-0
- Re-use CUORE cryogenic infrastructure and shield @ LNGS
- 10 y discovery sensitivity 1.1×10^{27}



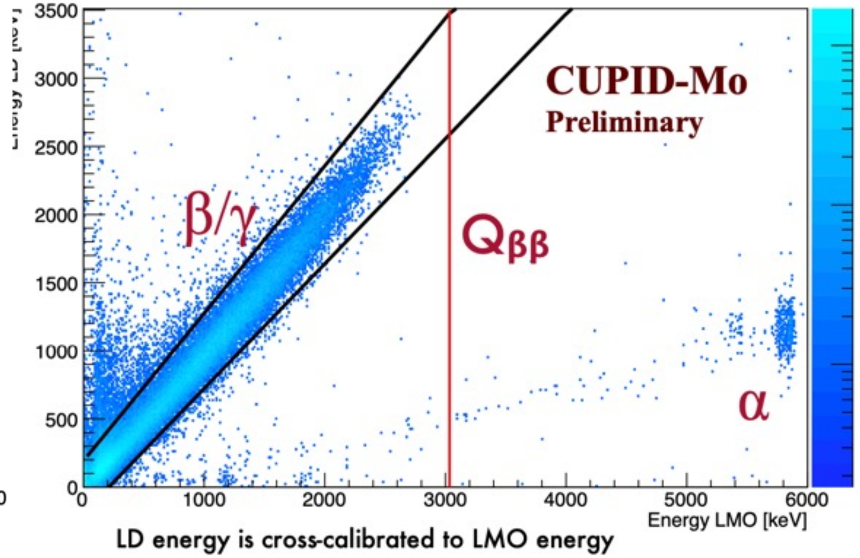


CUPID-Mo: ^{100}Mo cryogenic detectors R&D at LSM

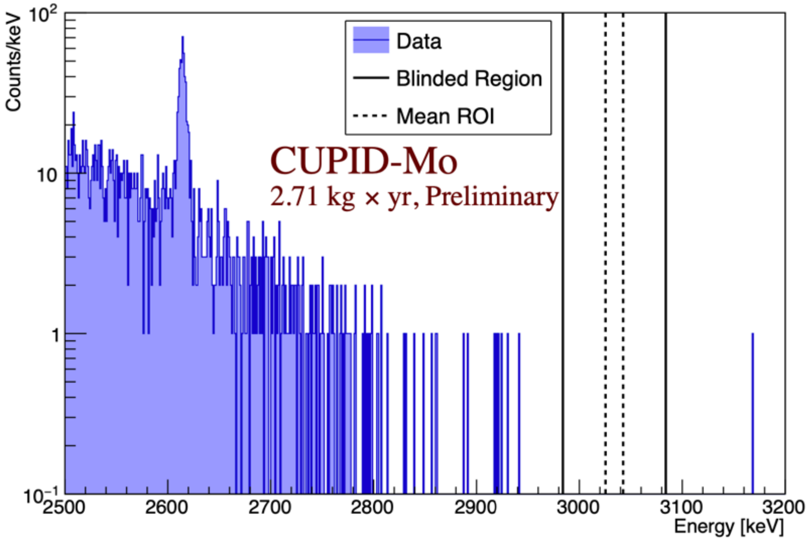
B. Welliver, TAUP2021



ΔE (FWHM): 7.2 keV @ 2.6 MeV



Removal of surface α's



Background-free operation in 2.7 kg yr

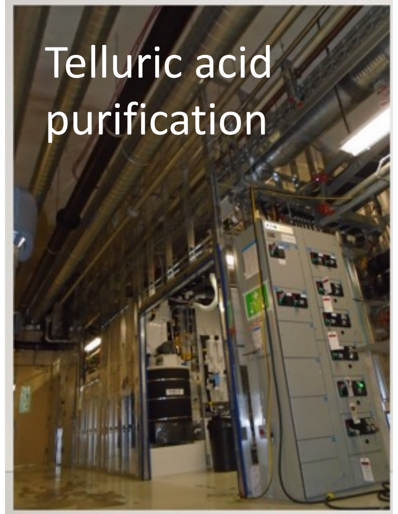
CUPID-Mo Preliminary

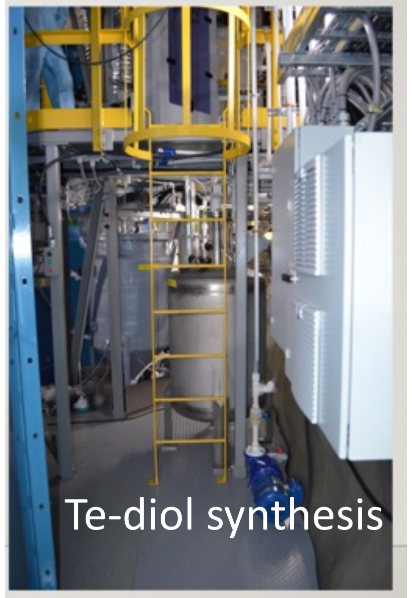
$$T^{0\nu}_{1/2} > 1.8 \times 10^{24}\ \text{yr}\ (90\,\%\ \text{C.I.})$$

$$m_{\beta\beta} < 0.28 - 0.49\ \text{eV}\ (90\,\%\ \text{C.I.})$$

^{nat}Te-loaded liquid scintillator: SNO+

- 780t LS (2.2 g/L PPO in LAB)
- Currently data taking with unloaded LS
  - low energy ^{8}B solar-n, reactor & geo anti-ν_e, Δm^2_{12}, supernova-ν
- $0\nu\beta\beta$ phase: **natural Te** (34% ^{130}Te) loaded as metal organic complex (Te-diol)
- Te-systems ready for operations
- Full-scale Te-diol batches in 2022/23
- Following **demonstration of operations** and **approvals** by SNOLAB, begin **Te-loading in 2024**
- Original plan: load 0.5% (3.9t nat Te): $T_{1/2} > 2\times10^{26}$ yr
- R&D on higher (up to 3%) Te-loading ongoing
- **0.5%** loading phase critical to assess **performance** and Te-related **backgrounds**

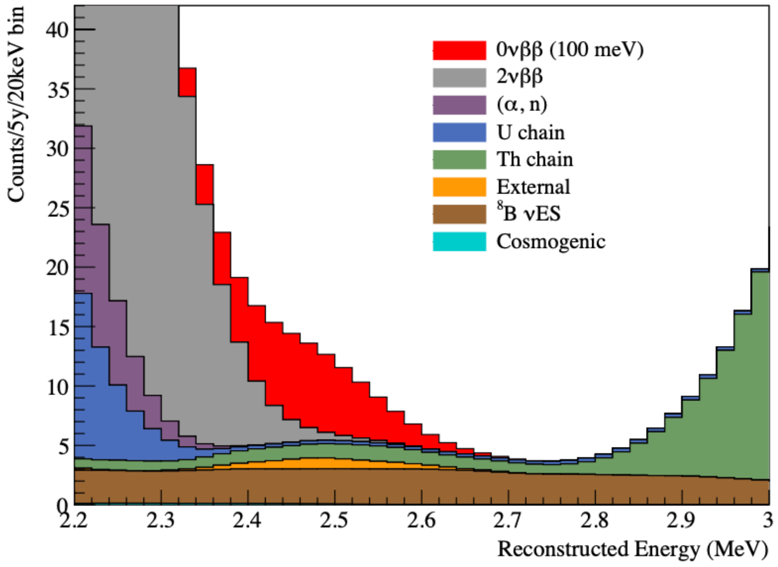


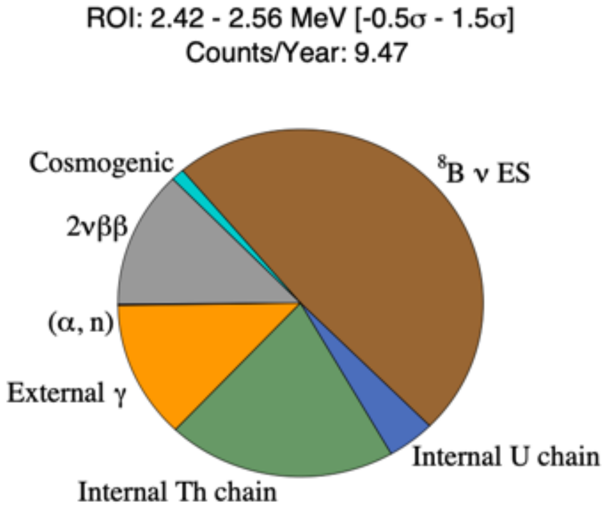


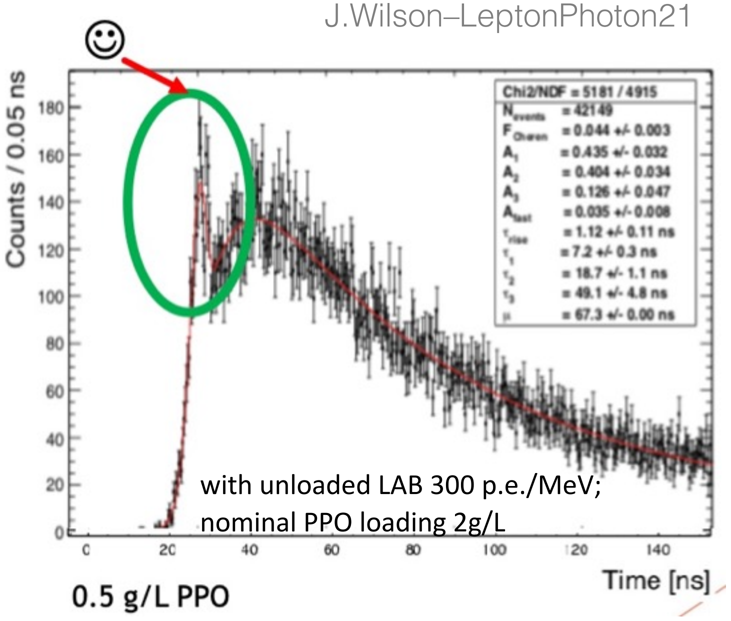
Courtesy M. Chen

^{nat}Te-loaded liquid scintillator: SNO+

J.Wilson–LeptonPhoton21





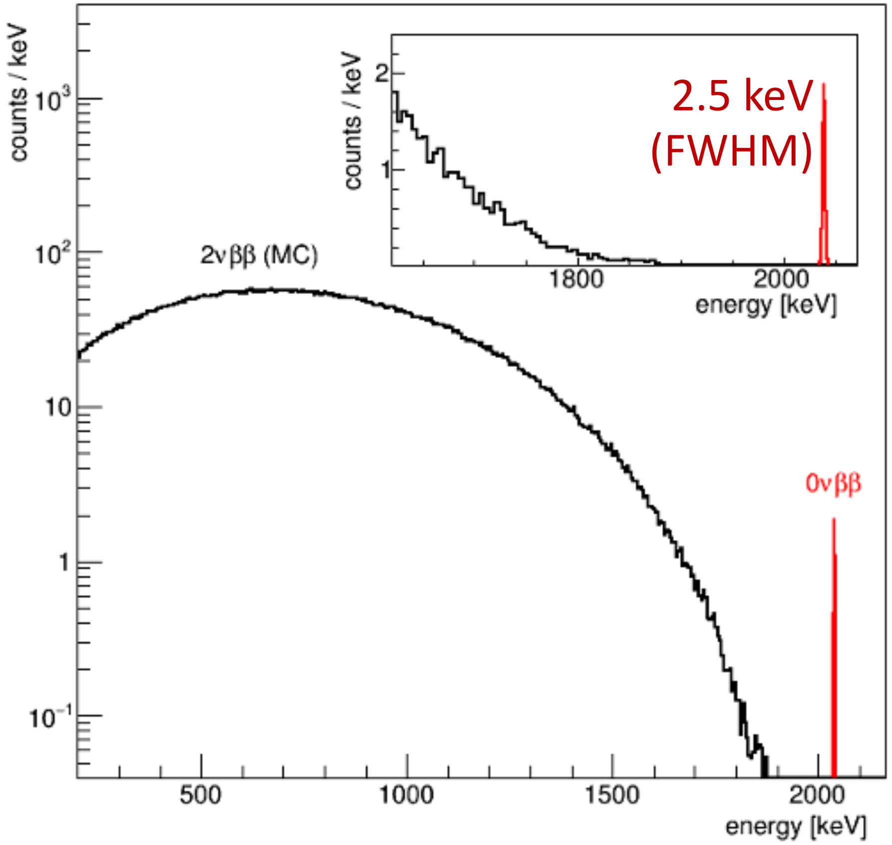


- **Pure scintillator** phase ”Te-out” measurement to test unexpected **backgrounds**
- **Staged Te-loading** to assess remaining Te-backgrounds
- Assess potential of suppression of **solar neutrinos** using **directionality information** arXiv:2001.10825

Courtesy M. Chen

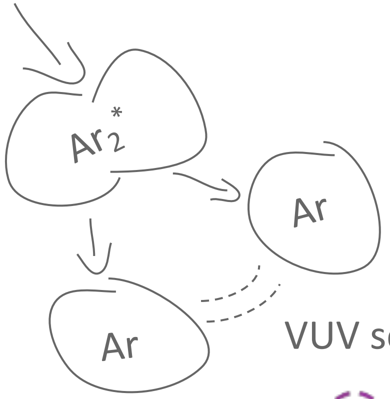
Key features of ^{76}Ge $0\nu\beta\beta$ searches

- $^{76}Ge \rightarrow {}^{76}Se + 2e^-$
- Q-value of ^{76}Ge: $Q_{\beta\beta}$ = 2039 keV
- High purity Ge detectors (>87% ^{76}Ge)
  - source = detector => high detection efficiency
  - high purity => no intrinsic background
  - high density => $0\nu\beta\beta$ point like events
  - semiconductor => ΔE ~0.1% (FWHM) at $Q_{\beta\beta}$
- **$0\nu\beta\beta$ signature:**
  - Point-like energy deposition in detector bulk volume
  - Sharp energy peak at 2039 keV (FWHM ~ 2.5 keV)

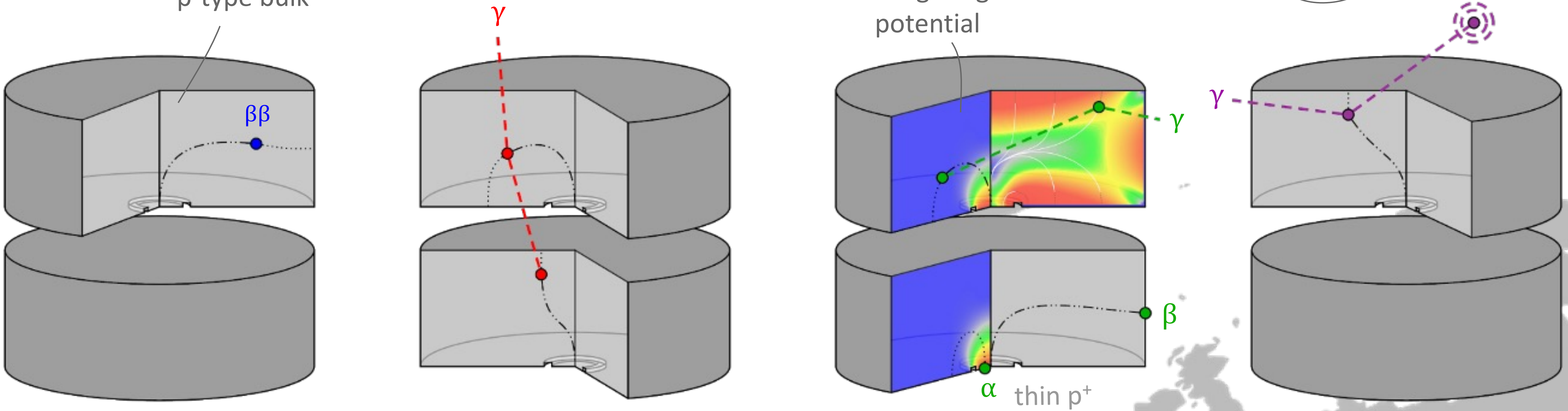


Topology discrimination

excimer creation by
ionization/excitation



VUV scintillation

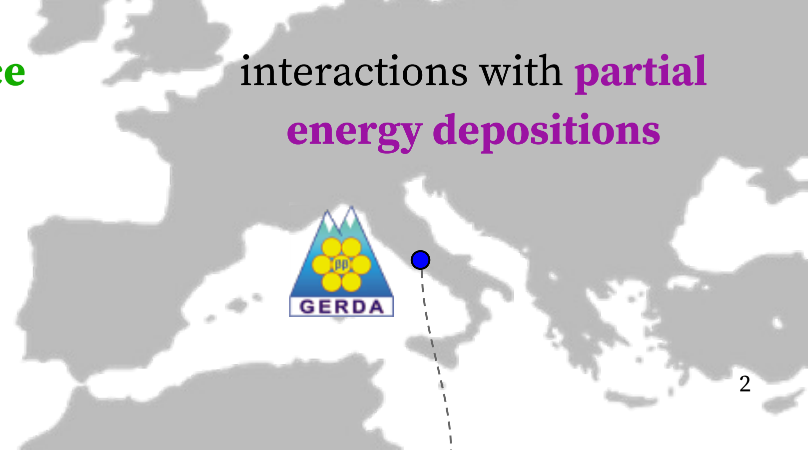


differentiate **point-like** $\beta\beta$ topology from:

multi-detector interactions

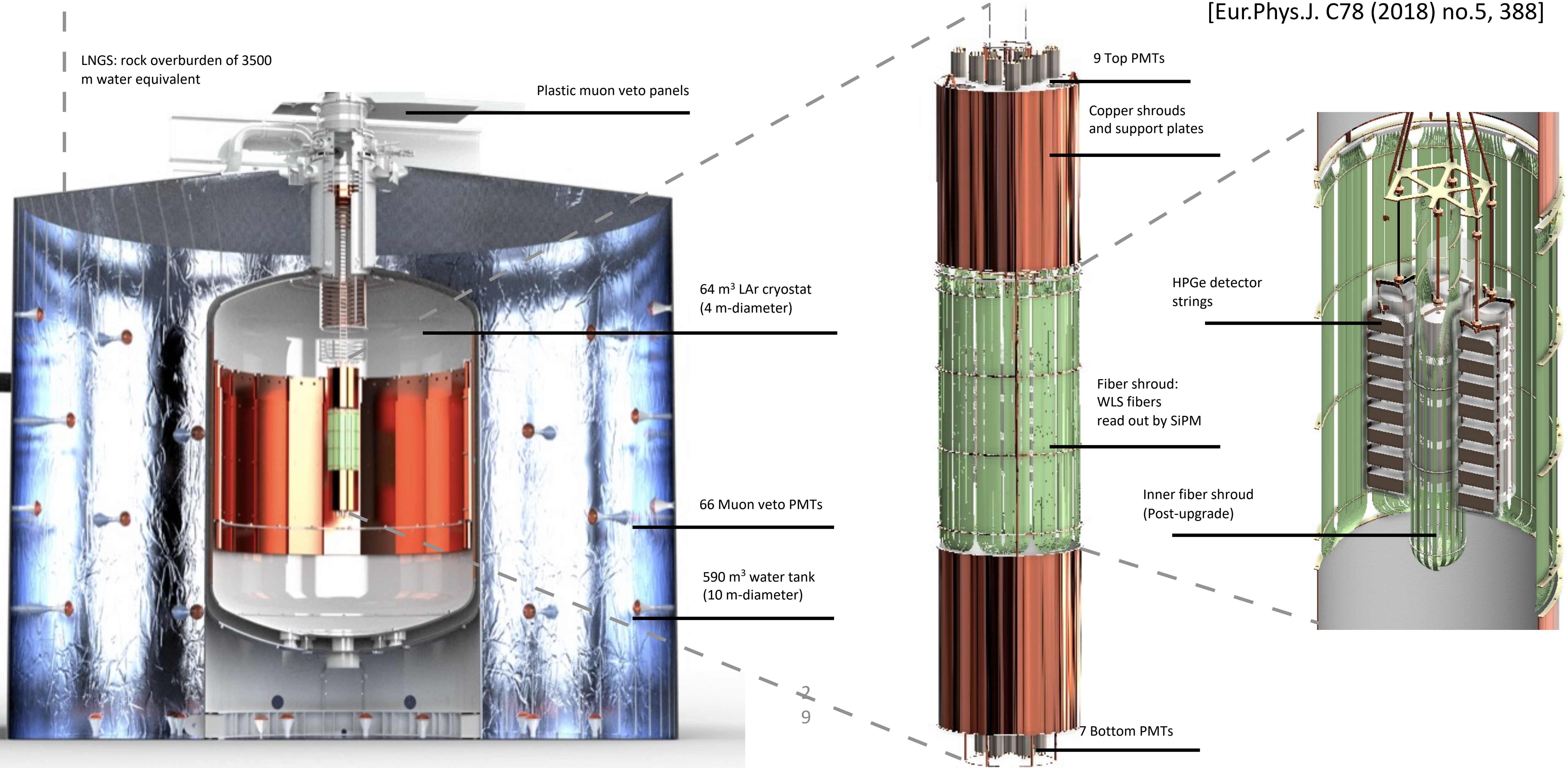
multi-site/surface interactions

interactions with **partial energy depositions**



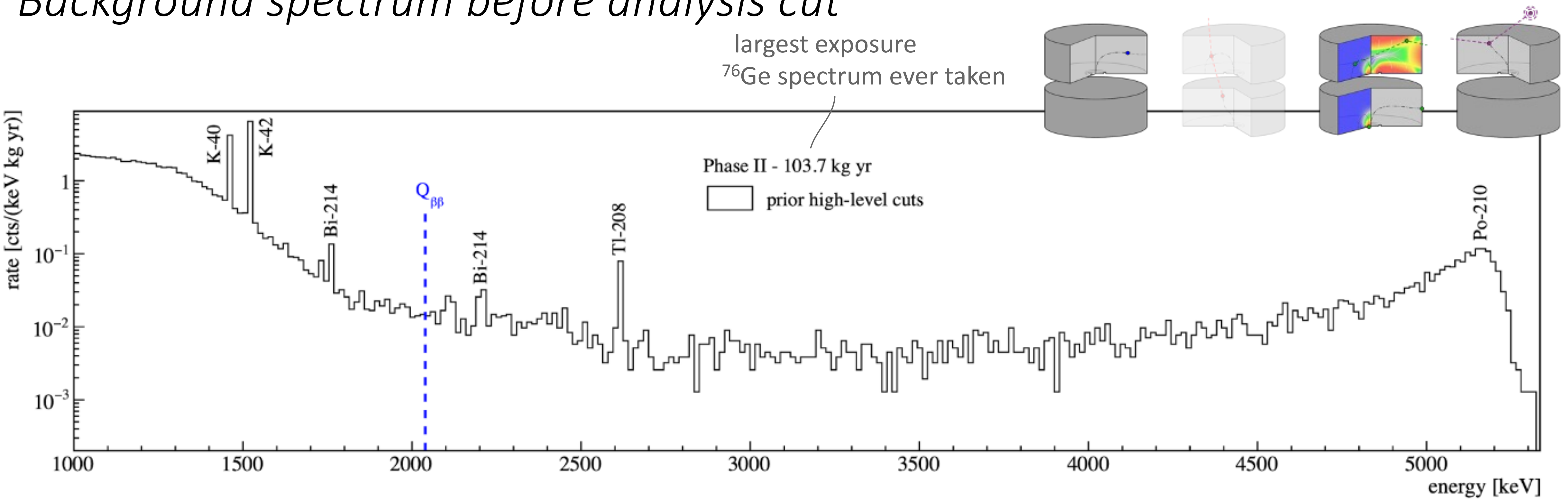
The GERmanium Detector Array experiment at LNGS

[Eur.Phys.J. C78 (2018) no.5, 388]

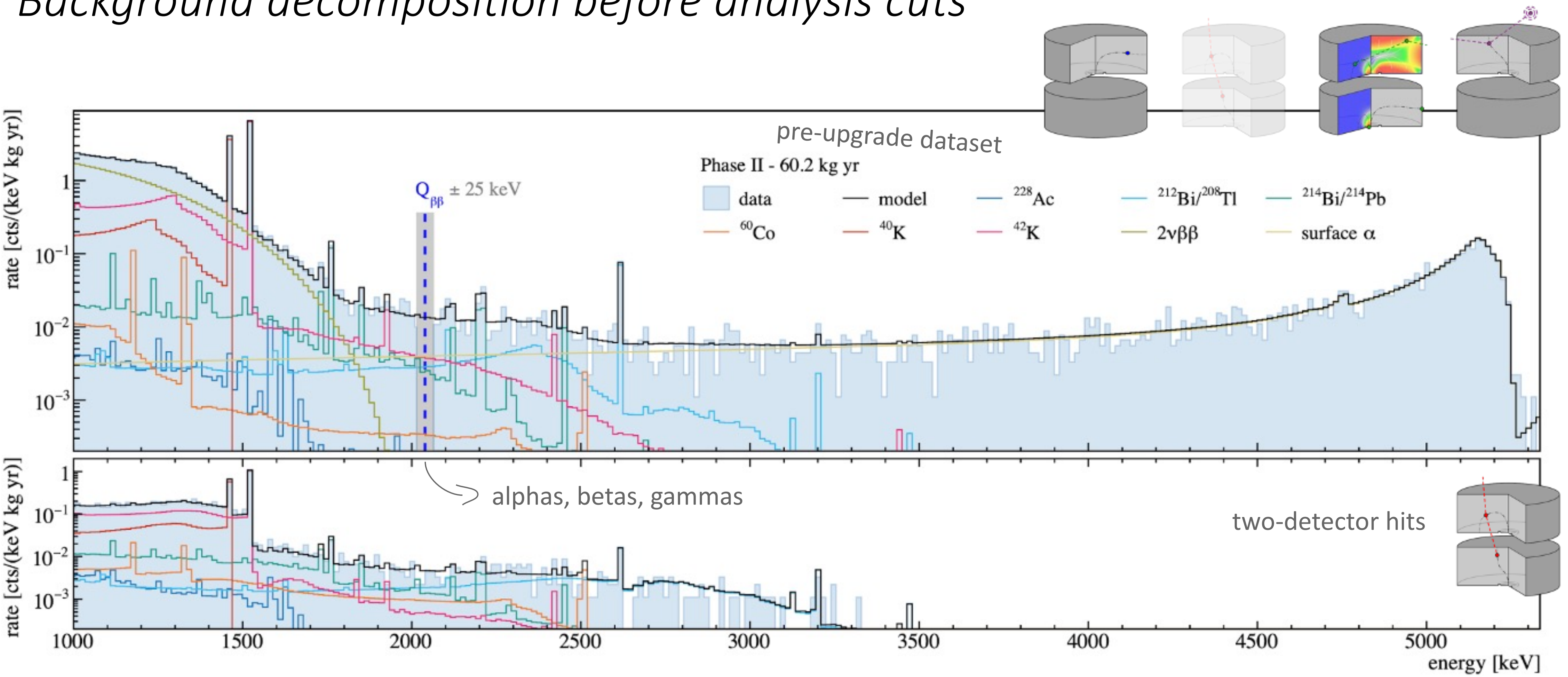


Background spectrum before analysis cut

largest exposure
^{76}Ge spectrum ever taken



Background decomposition before analysis cuts

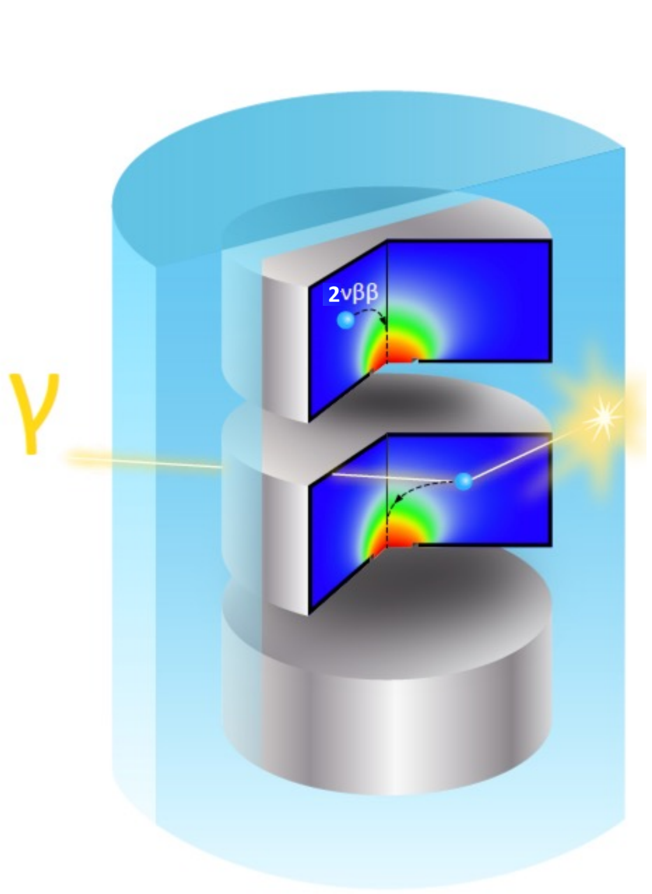


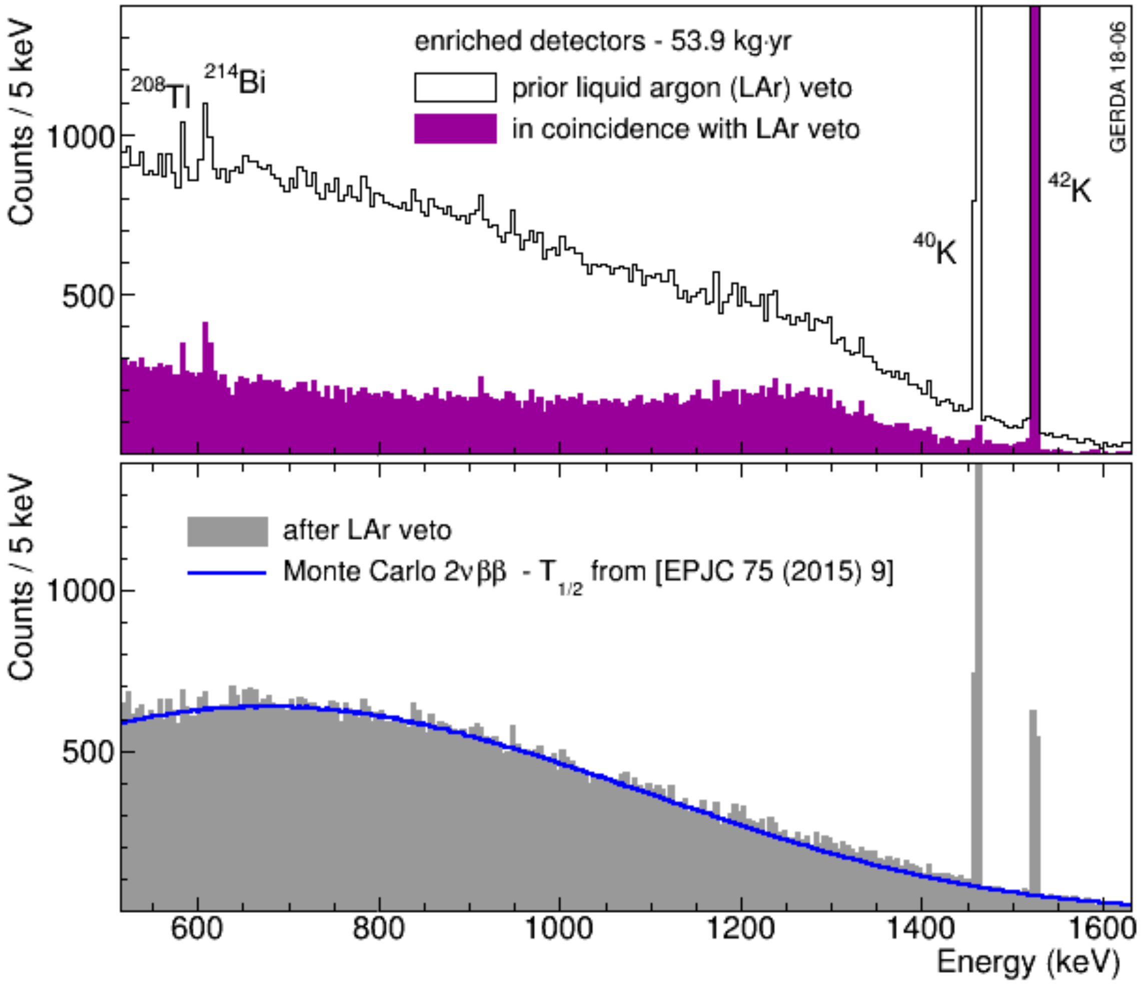
- combined Bayesian fit to multiple datasets with Monte Carlo *pdf*s for **nearby components**

[JHEP 03 (2020) 139]

screening measurements as priors

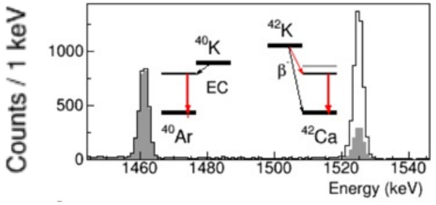
The 2nbb energy range: LAr instrumentation not only a 'veto'





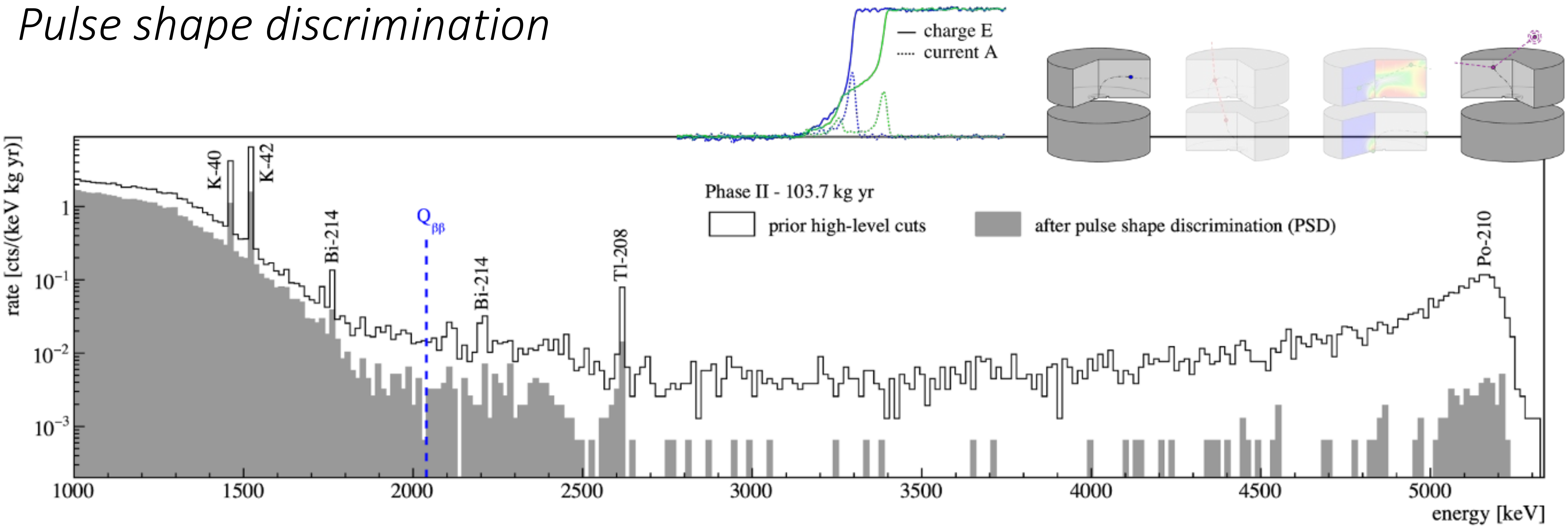
Signal acceptance of LAr veto: 97.7%

In coincidence: spectrum dominated by potassium



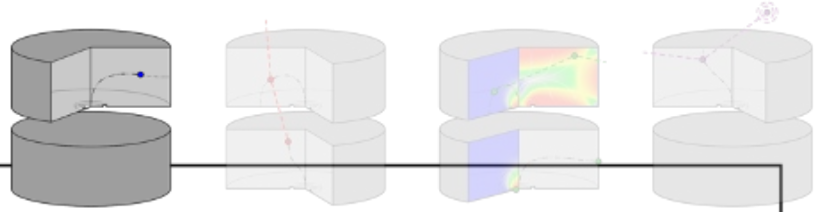
In anti-coincidence: **2νββ spectrum**

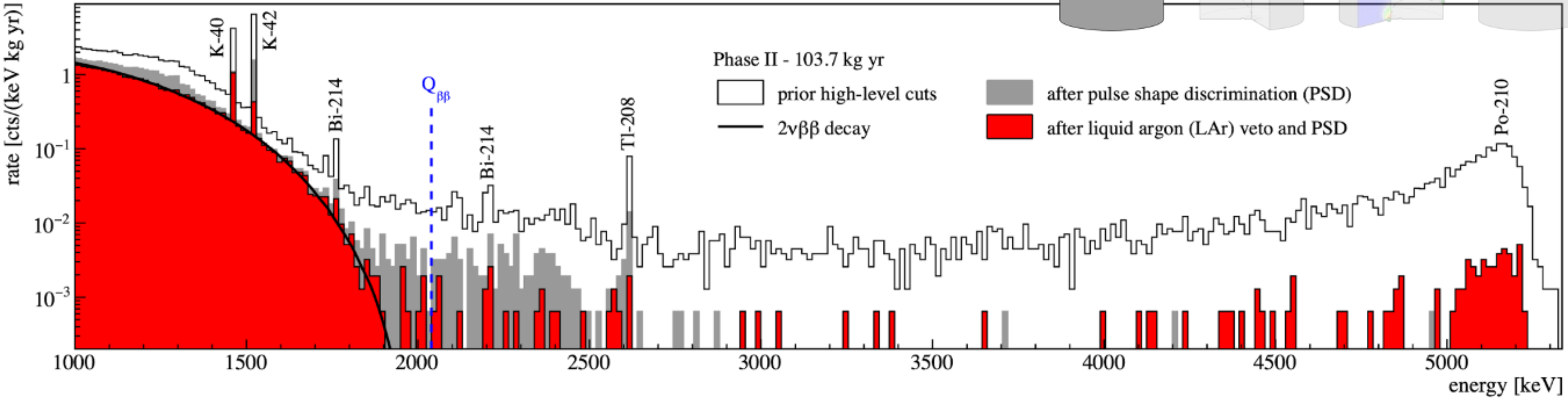
Pulse shape discrimination



- two-sided **mono-parametric** A/E cut for **BEGe / ICPC** detectors
  [Budjas et al., JINST 4 (2009) P10007]
- artificial neural network analysis plus consecutive risetime cut for coaxial detectors
  [Eur. Phys. J. C73 (2013) 2583]
- cut definition / training with ^{228}Th **calibration data** -> ^{208}Tl DEP as signal proxy
- $0\nu\beta\beta$ signal efficiency **~90%** (~70% for coaxials)

Final Phase II spectrum



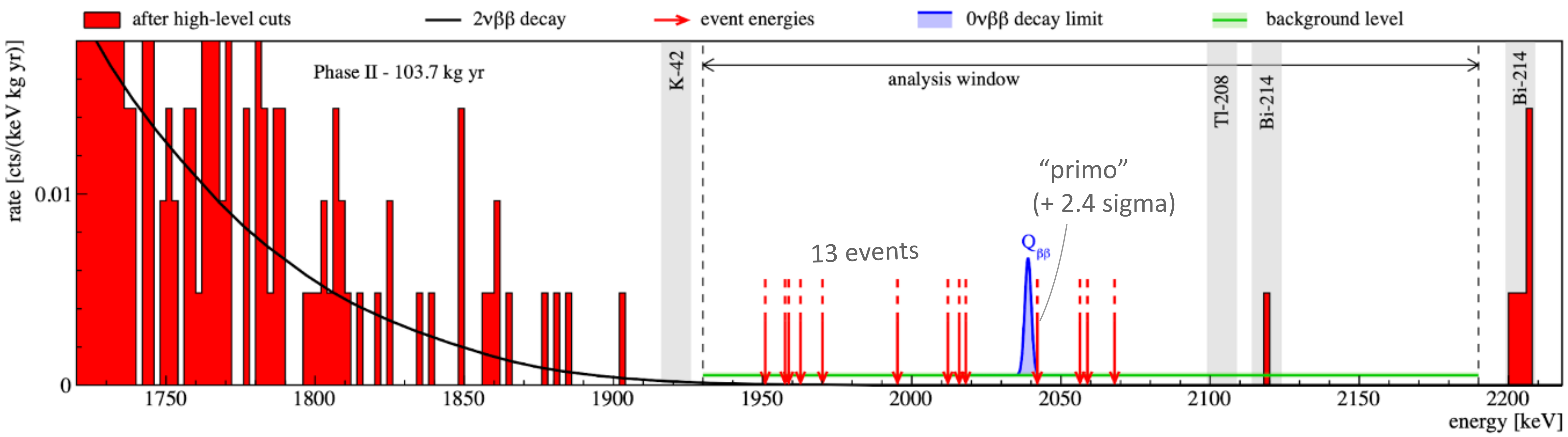


- “clean” **2νββ continuum** shape analysis in preparation
- sparse **single counts at > $Q_{\beta\beta}$**

no alphas in BEGe / ICPC

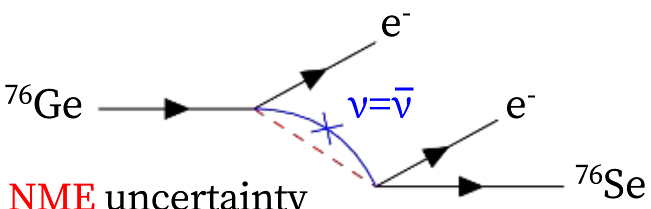
Final GERDA result

< 1 cts in 100 kg yr and 5 keV



- background index **$5.2^{+1.6}_{-1.3}\cdot 10^{-4}$ cts/(keV kg yr)**, energy resolution **~3 keV** (FWHM) resolution tracked per detector/period
- combined (data partitions, Phase I) **unbinned maximum likelihood fit**
  [Nature 544 (2017) 47]
  Gaussian signal on flat background
- **Frequentist:** $N^{0\nu} = 0$ best fit, $\boldsymbol{T_{1/2}}$ **> 1.8·10²⁶ yr** (median sensitivity -"-) at 90% C.L.,
  Bayesian: flat prior on rate, $T_{1/2} > 1.4\cdot 10^{26}$ yr at 90% C.I. $> 2.3\cdot 10^{26}$ yr for flat prior on m_{bb}

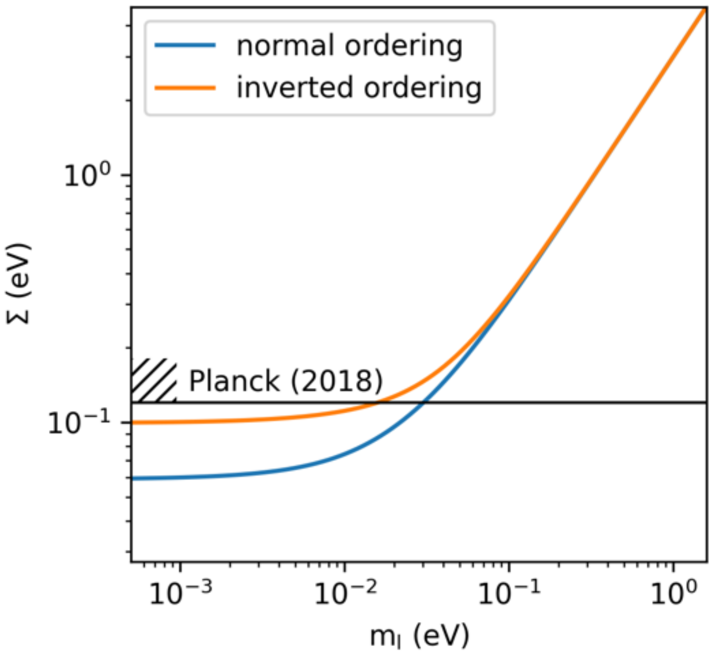
Mass observables



NME uncertainty

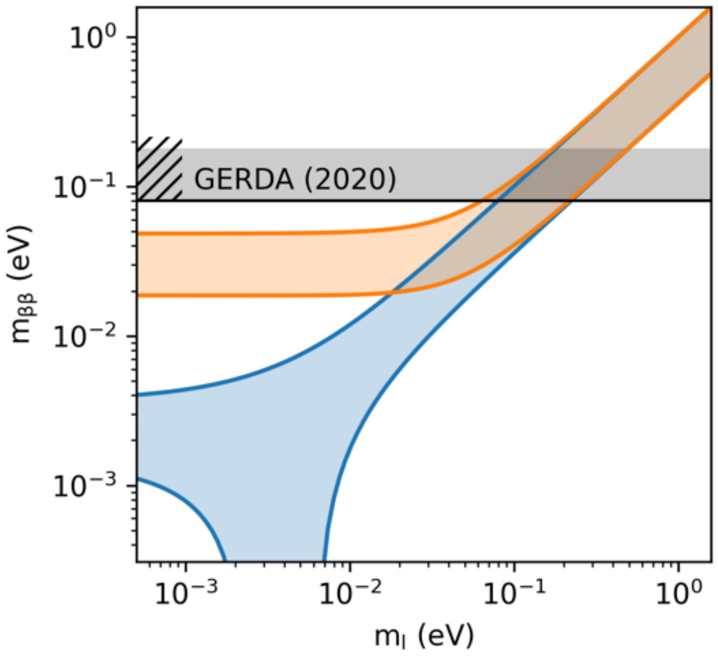
[Engel, Menéndez, Rept.Prog.Phys. 80 (2017) no.4, 046301]

three flavour oscillation parameters from [Esteban et al., JHEP 09 (2020) 178]



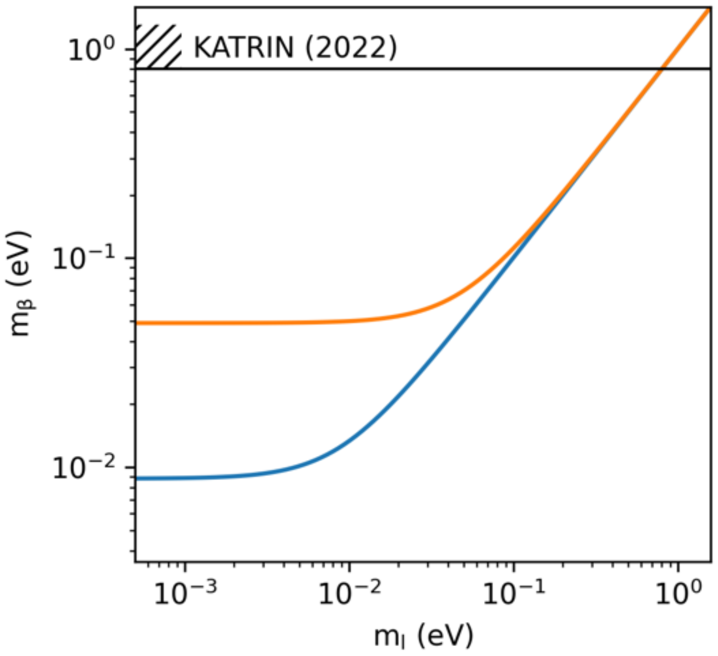
-> Planck+BAO: **Σ < 0.12 eV**

[Aghanim et al., arXiv:1807.06209]



-> GERDA: $\boldsymbol{m_{\beta\beta}}$ **< [0.08,0.18] eV**

KamLAND-Zen: < [0.05,0.23] eV, CUORE:< [0.07,0.34] eV



-> KATRIN: $\boldsymbol{m_\beta}$ **< 0.8 eV** (90% CL)

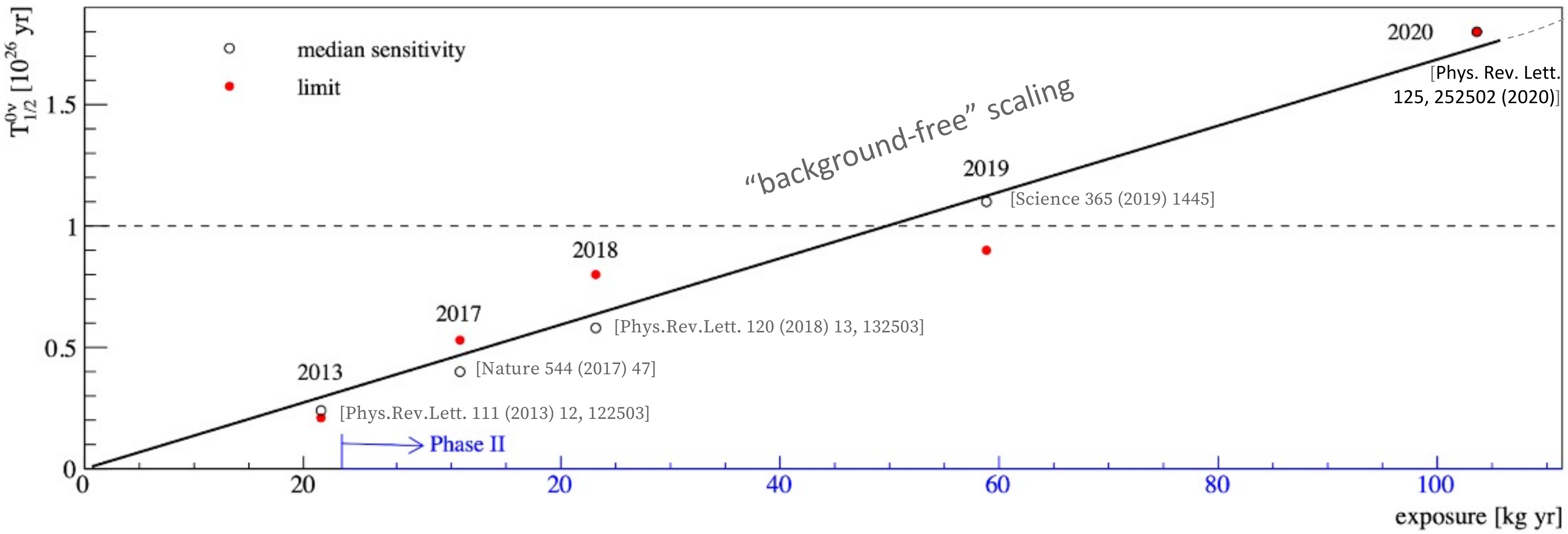
[Aker et al., Nature Phys. 18 (2022) 2, 160-166]

- given “standard” assumptions 0νββ decay searches constrain **neutrino mass**
- **interplay** with cosmology / direct mass measurements -> m_{light} < [0.1,0.5] eV, sum < [0.2,1.5] eV, m_b < [0.1,0.5] eV

[Science 365 (2019) 1445]

GERDA: first quasi background-free experiment

novel Ge detectors & LAr instrumentation



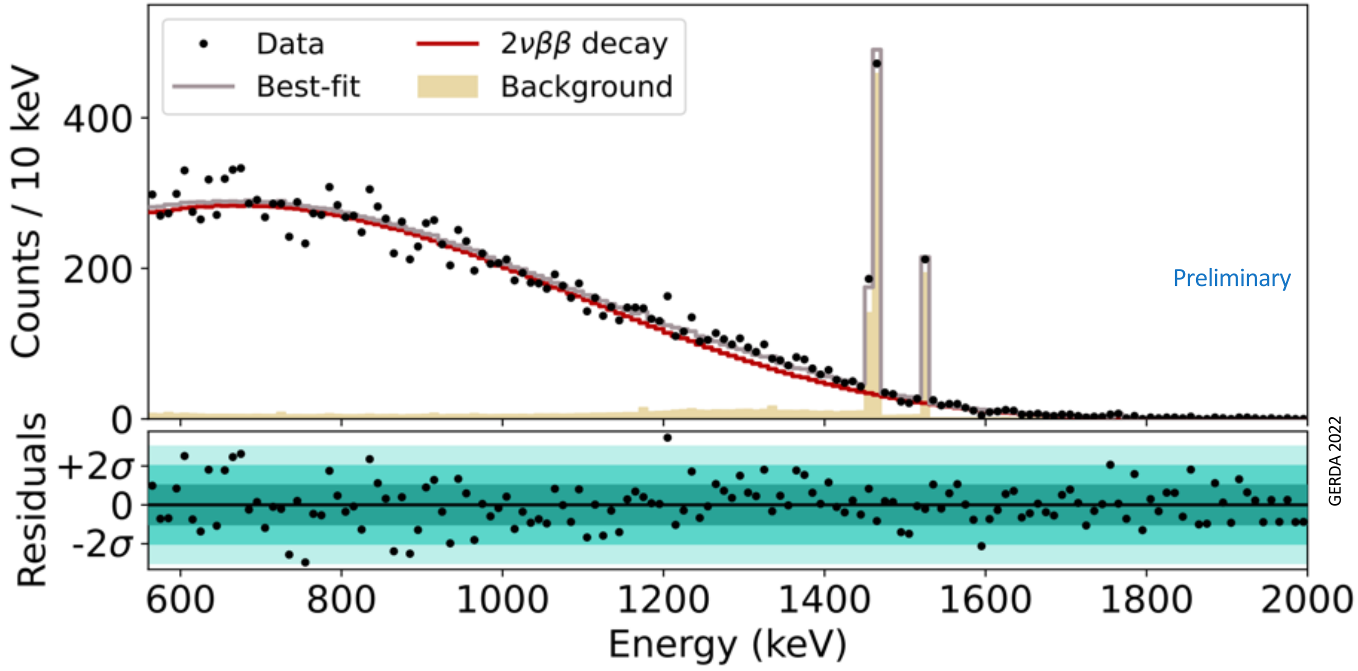
$<10^{-3}$ cts/(keV·kg·yr) ✓
> 100 kg·yr ✓
$> 10^{26}$ yr ✓

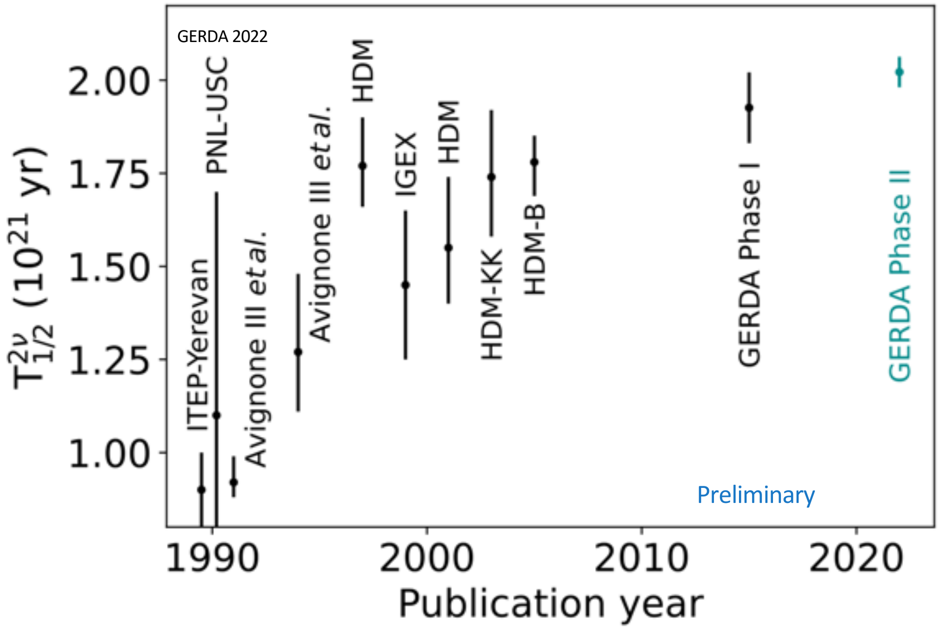
all goals surpassed

- GERDA has finished successfully first experiment with sensitivity beyond 10^{26} yr
- **no signal found** -> "no neutrinos not found"
- further results (2νββ decay, BSM physics)

<u>Recent publications:</u>
Final Results of GERDA on the Search for Neutrinoless Double-β Decay, **Phys. Rev. Lett.** 125, 252502 (2020)
The first search for bosonic super-WIMPs with masses up to 1 MeV/c2 with GERDA , **Phys. Rev. Lett**. 125 (2020) 011801
Modeling of GERDA Phase II data , **J .High Energ. Phys**. 2020, 139 (2020)
Probing Majorana neutrinos with double-β decay, **Science 365**, 1445 (2019);
Improved Limit on Neutrinoless Double-β Decay of 76Ge from GERDA Phase II, **Phys. Rev. Lett.** 120 (2018) 132503
Background-free search for neutrinoless double-β decay of 76Ge with GERDA, **Nature** 544 (2017)
More at https://www.mpi-hd.mpg.de/gerda/public/index-pubgall.html

^{76}Ge $2\nu\beta\beta$ decay: $T_{1/2}^{2\nu}$ = (2.022 $\pm$ 0.041) 10^{21} yr



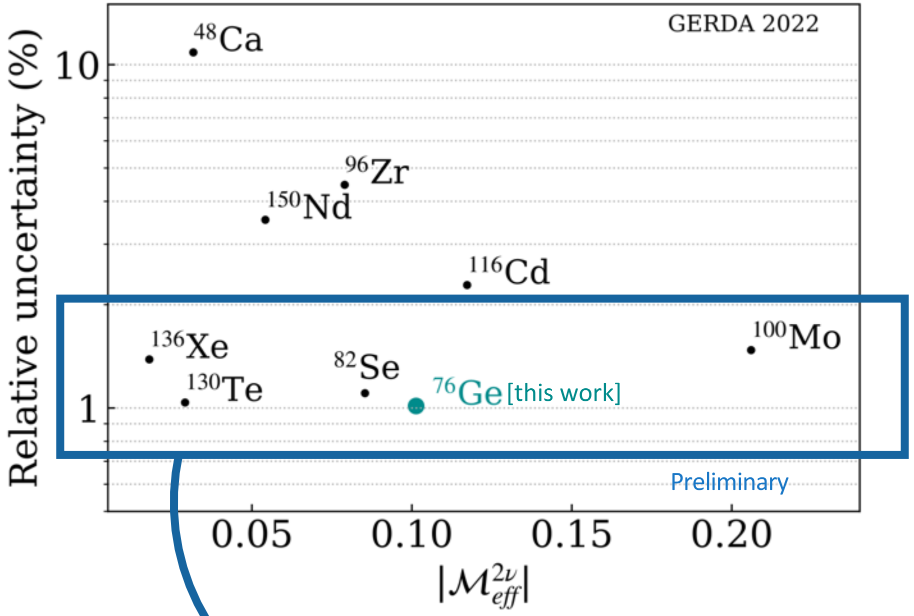


$2\nu\beta\beta$ nuclear matrix element

$$[T^{2\nu}_{1/2}]^{-1} = G^{2\nu} \,|\, \mathcal{M}^{2\nu}_{eff} \,|^2$$

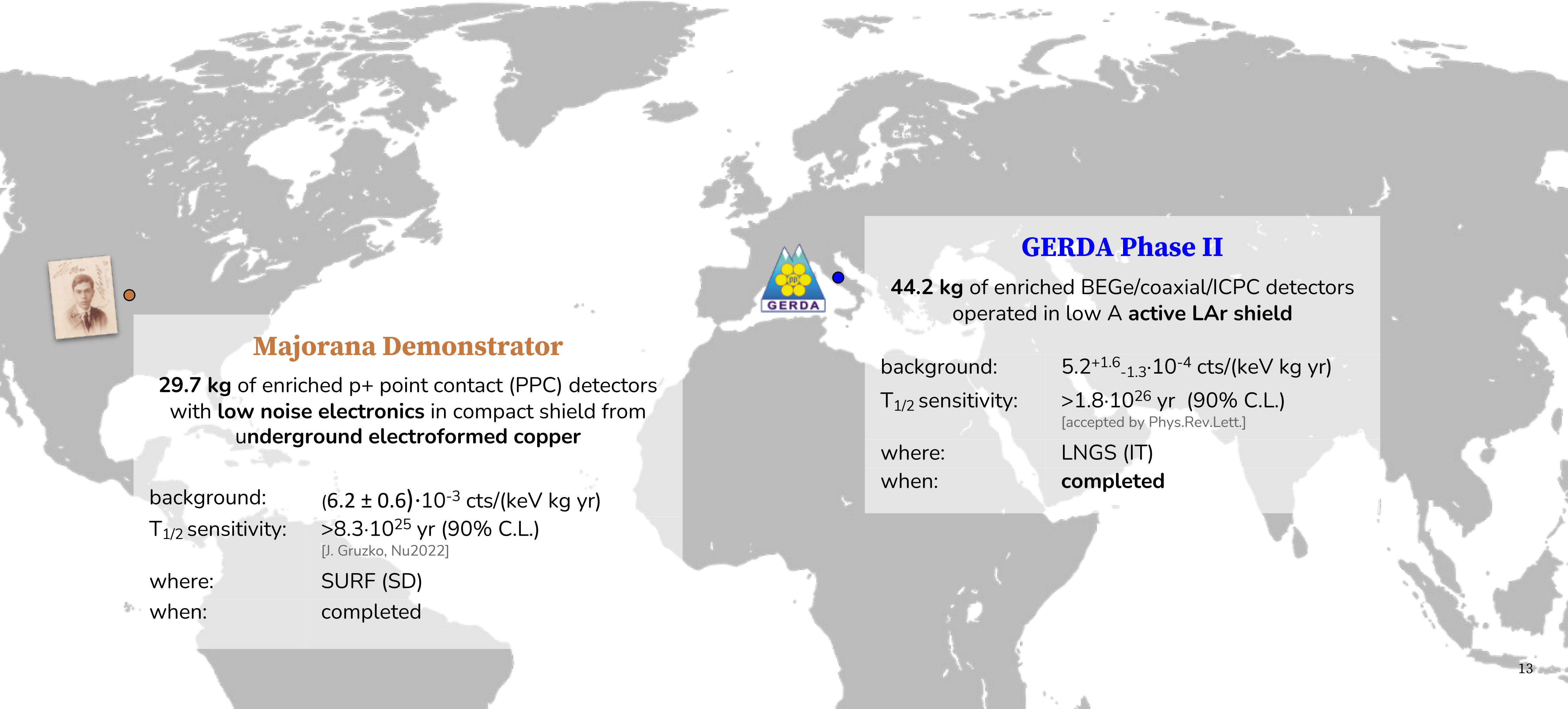
with $G^{2\nu} = 48.17\ 10^{21}\ \mathrm{yr}^{-1}$ [Phys. Rev. C 85, 034316 (2012)]

GERDA result: $|\mathcal{M}^{2\nu}_{eff}| = 0.101(1)$



High precision reached in the last years by several experiments

Combine the best from two worlds



Majorana Demonstrator

29.7 kg of enriched p+ point contact (PPC) detectors with **low noise electronics** in compact shield from **underground electroformed copper**

background:	$(6.2 \pm 0.6) \cdot 10^{-3}$ cts/(keV kg yr)
$T_{1/2}$ sensitivity:	$>8.3 \cdot 10^{25}$ yr (90% C.L.) [J. Gruzko, Nu2022]
where:	SURF (SD)
when:	completed

GERDA Phase II

44.2 kg of enriched BEGe/coaxial/ICPC detectors operated in low A **active LAr shield**

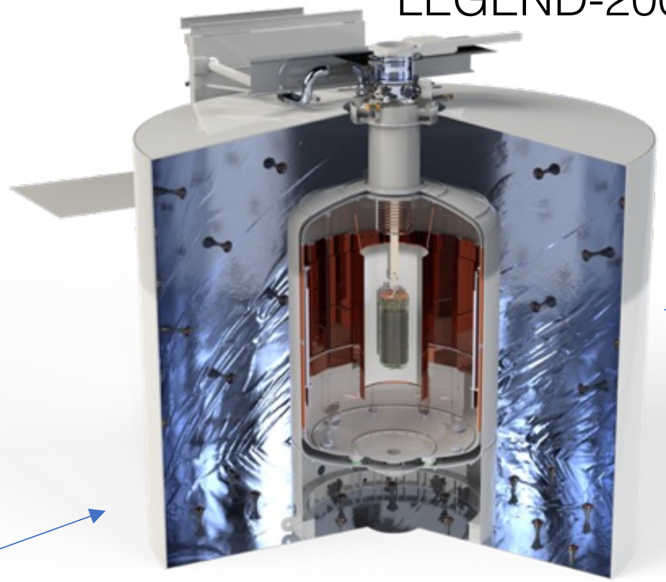
background:	$5.2^{+1.6}_{-1.3} \cdot 10^{-4}$ cts/(keV kg yr)
$T_{1/2}$ sensitivity:	$>1.8 \cdot 10^{26}$ yr (90% C.L.) [accepted by Phys.Rev.Lett.]
where:	LNGS (IT)
when:	**completed**

LEGEND: ^{76}Ge HPGe detectors operated in liquid argon

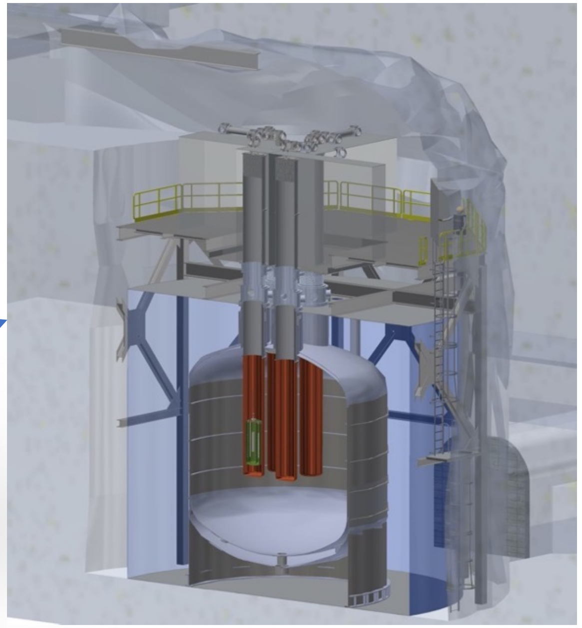
The LEGEND design builds on a track record of breakthrough developments

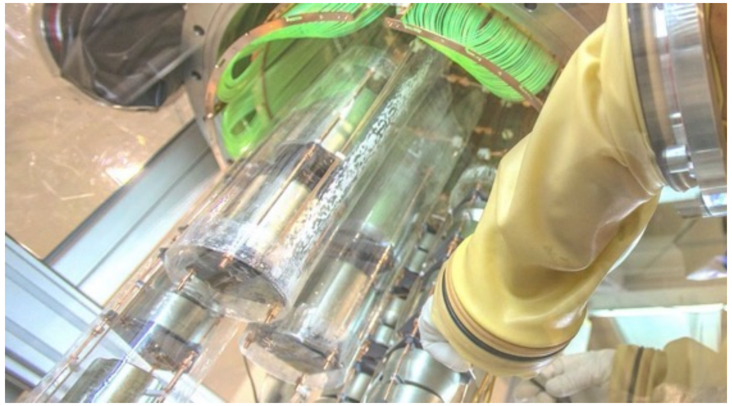
- GERDA : BEGe, LAr instrumentation, cryostat in water shield, fast detector deployment, …
- Majorana Demonstrator (MJD): PPC, EFCu, low-noise front-end electronics,…
- LEGEND-200 (start 2021): Inverted-Coaxial Point Contact (ICPC) detectors, polyethylene naphthalate (PEN)…

LEGEND-200



LEGEND-1000





GERDA

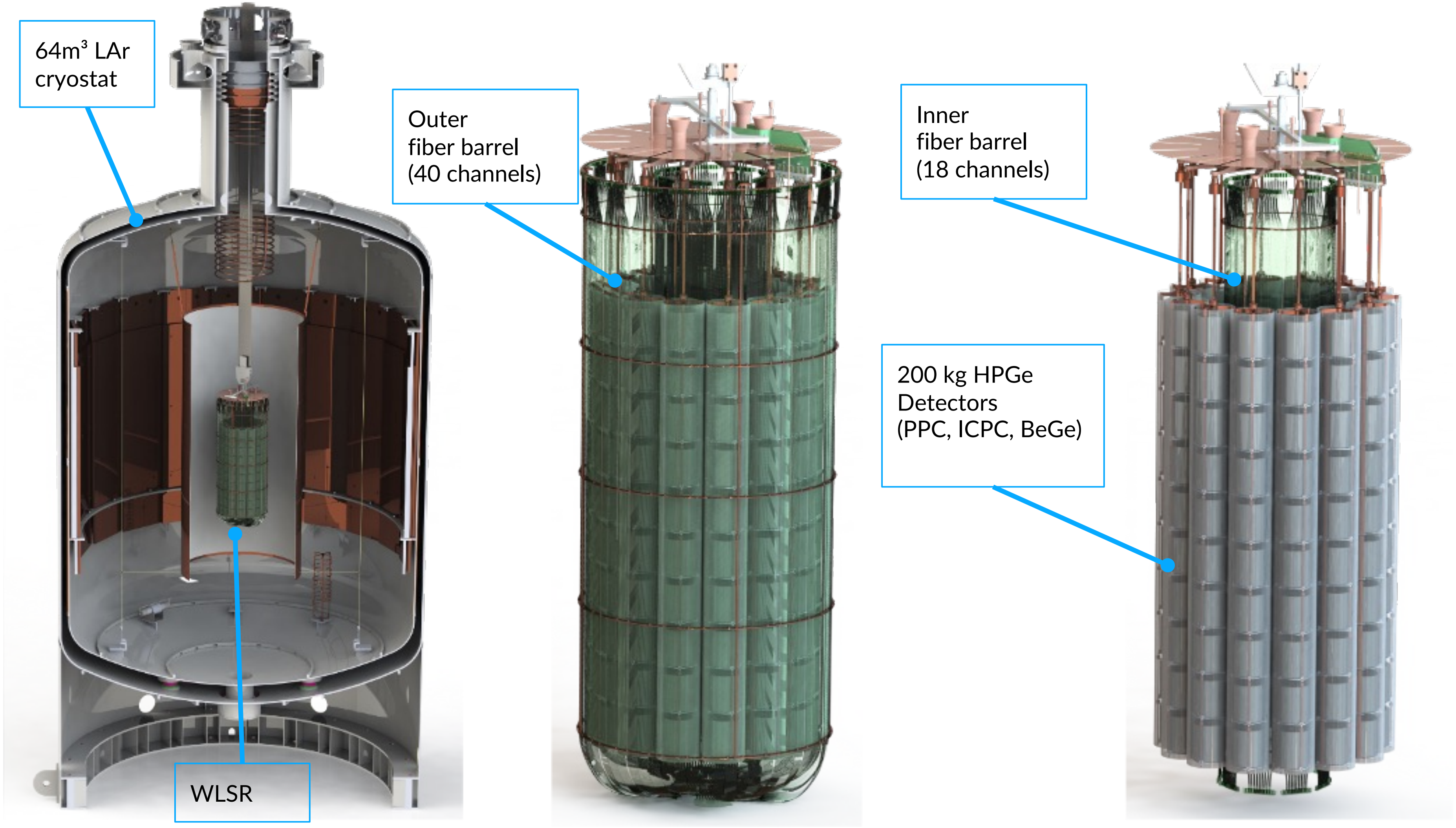
MJD

PPC: p-type Point Contact Ge detectors

BEGe: (modified) Broad Energy Ge detectors

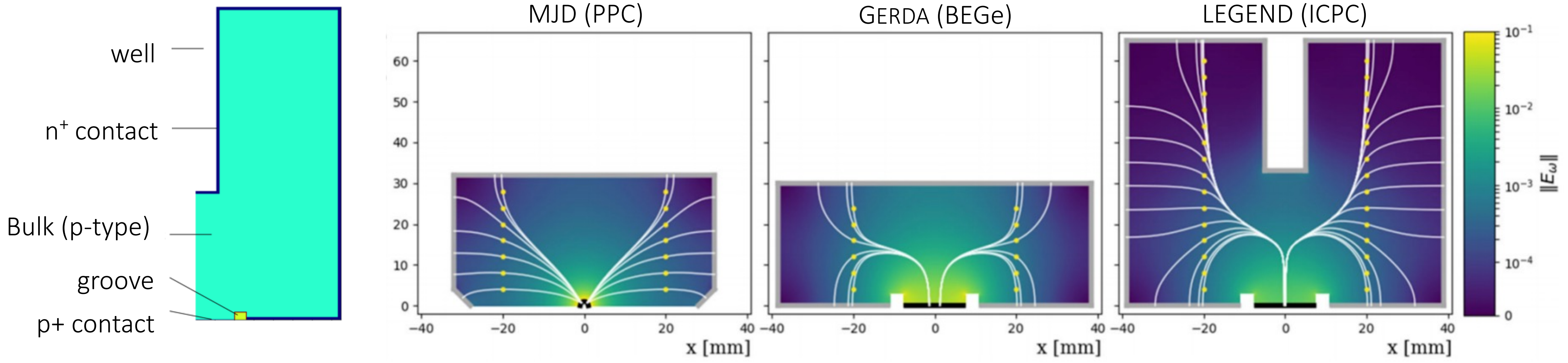
EFCu: Electroformed copper

LEGEND-200



64m³ LAr cryostat
WLSR
Outer fiber barrel (40 channels)
Inner fiber barrel (18 channels)
200 kg HPGe Detectors (PPC, ICPC, BeGe)

Innovation toward LEGEND-1000: ^{enr}Ge Detectors

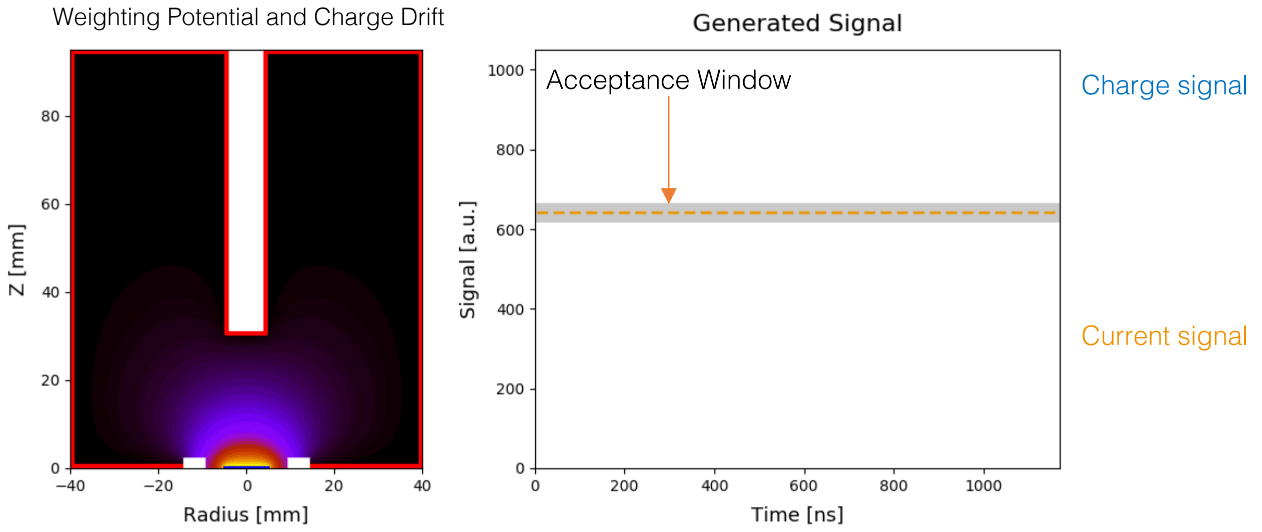


- P-type detectors: Insensitive to alphas on n^+ contact
- Small p^+ contact: Event topology discrimination
- Large-mass ICPC detectors: About 4 times lower backgrounds with respect to BEGe/PPC
- Proven long-term stable operation in liquid argon

Innovation toward LEGEND-1000: Ge Detectors

Event Topologies

0νββ signal candidate (single-site)



Shockley-Ramo Theorem: $Q(t) = -q\phi_w(\boldsymbol{x}_q(t))$

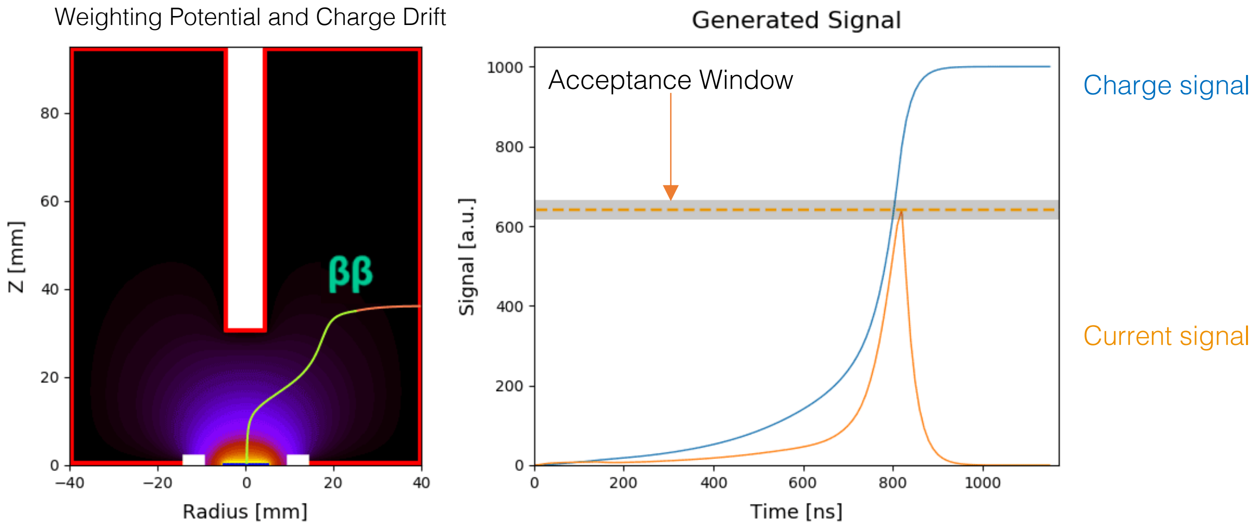
Weighting Potential: ϕ_w

N.B. animation only visible in pptx

Innovation toward LEGEND-1000: Ge Detectors

Event Topologies

0νββ signal candidate (single-site)



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Innovation toward LEGEND-1000: Ge Detectors

Event Topologies

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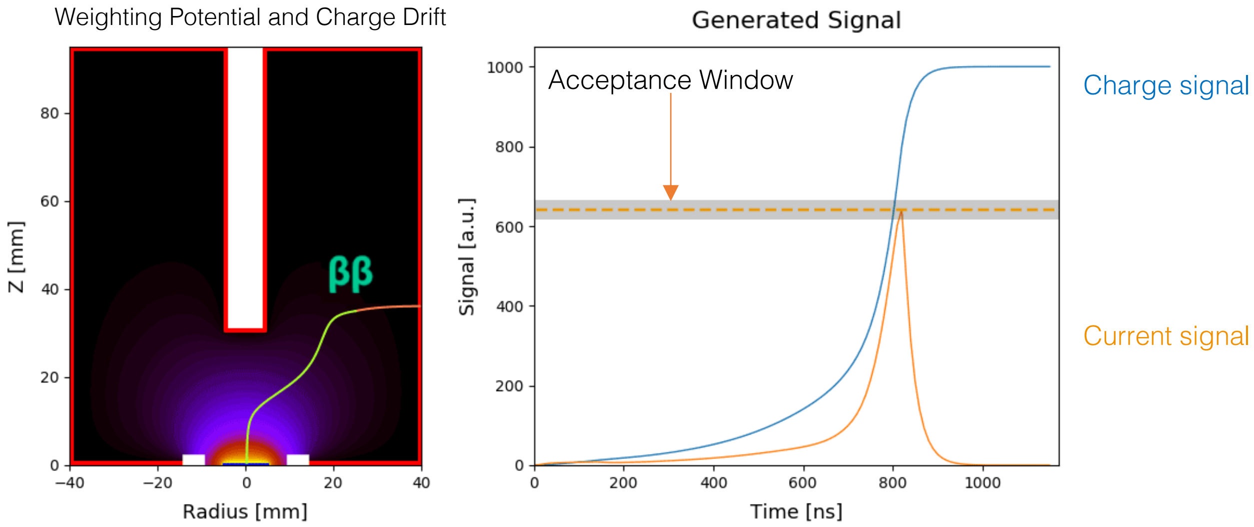
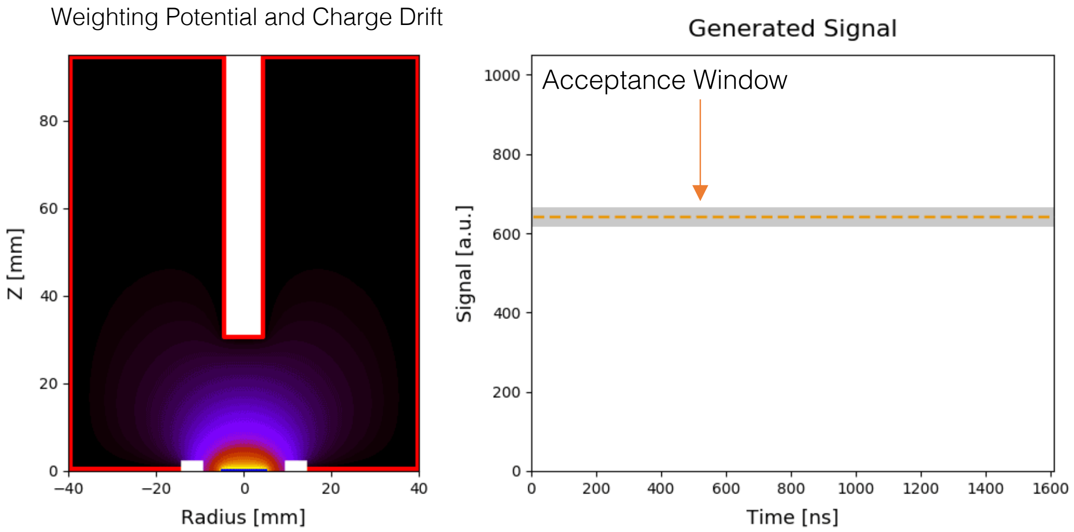


γ-background (multi-site)



Shockley-Ramo Theorem: $Q(t) = -q\phi_w(\boldsymbol{x}_q(t))$

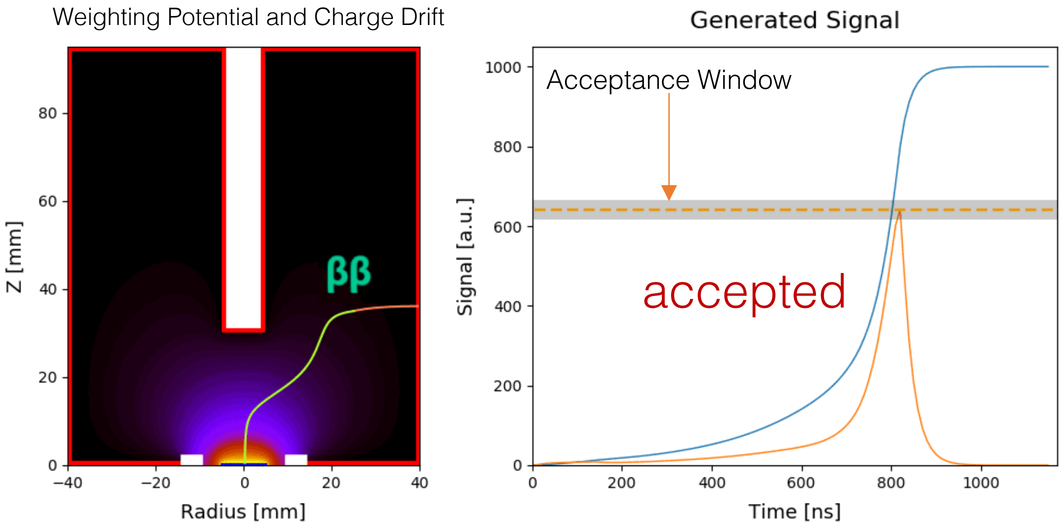
Weighting Potential: ϕ_w

N.B. animation only visible in pptx

Innovation toward LEGEND-1000: Ge Detectors

Event Topologies

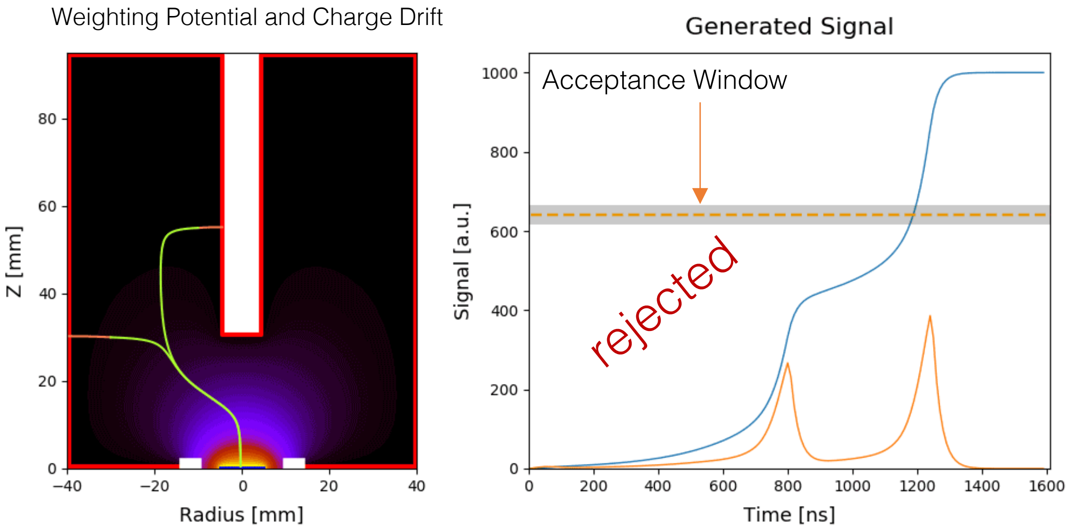
$0\nu\beta\beta$ signal candidate (single-site)



Charge signal

Current signal

γ-background (multi-site)



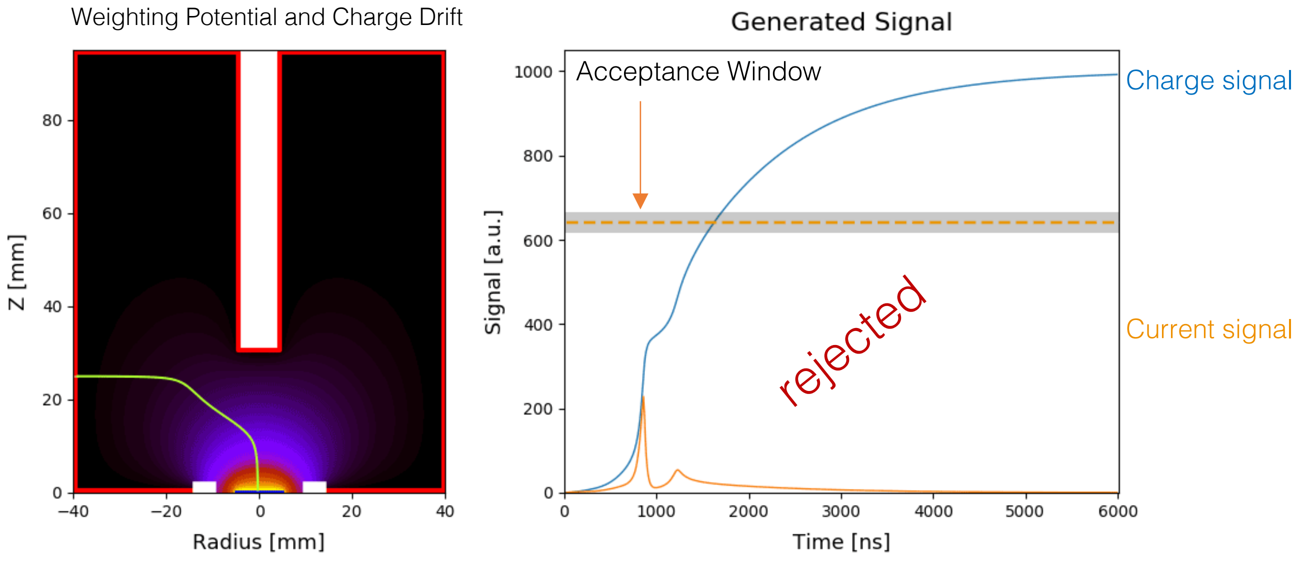
Shockley-Ramo Theorem: $Q(t) = -q\phi_w(\boldsymbol{x}_q(t))$

Weighting Potential: ϕ_w

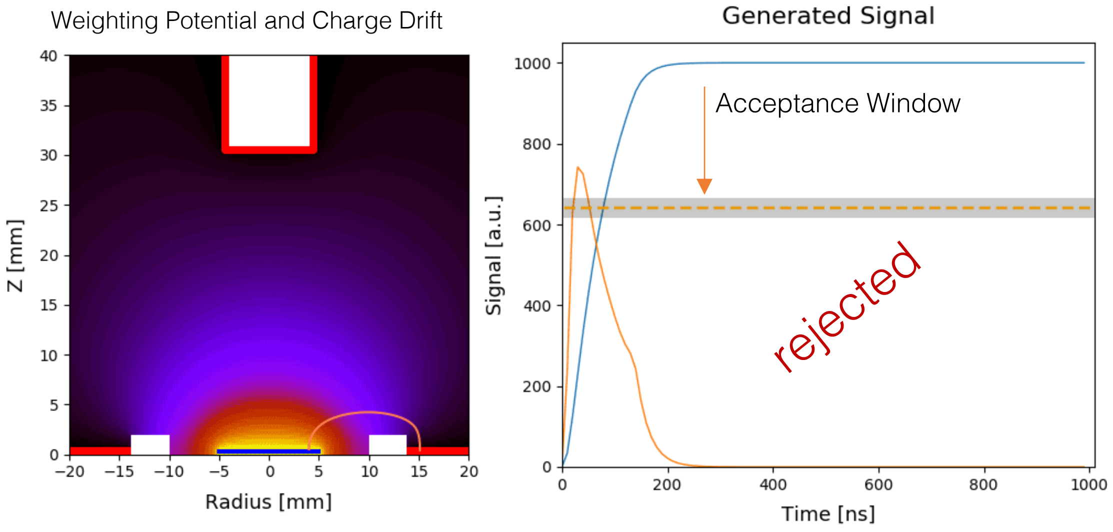
Innovation toward LEGEND-1000: Ge Detectors

Event Topologies

Surface-β-background ^{42}K (^{42}Ar) on n+ contact



α-background on p+ contact



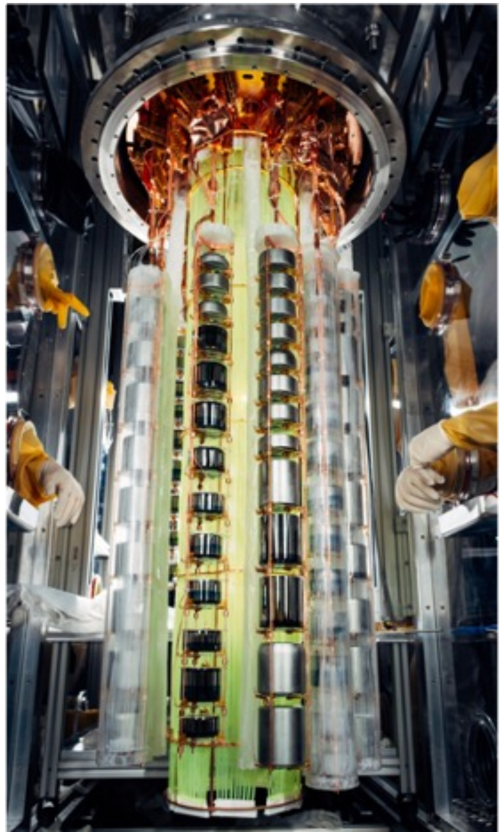
Shockley-Ramo Theorem: $Q(t) = -q\phi_w(\boldsymbol{x}_q(t))$

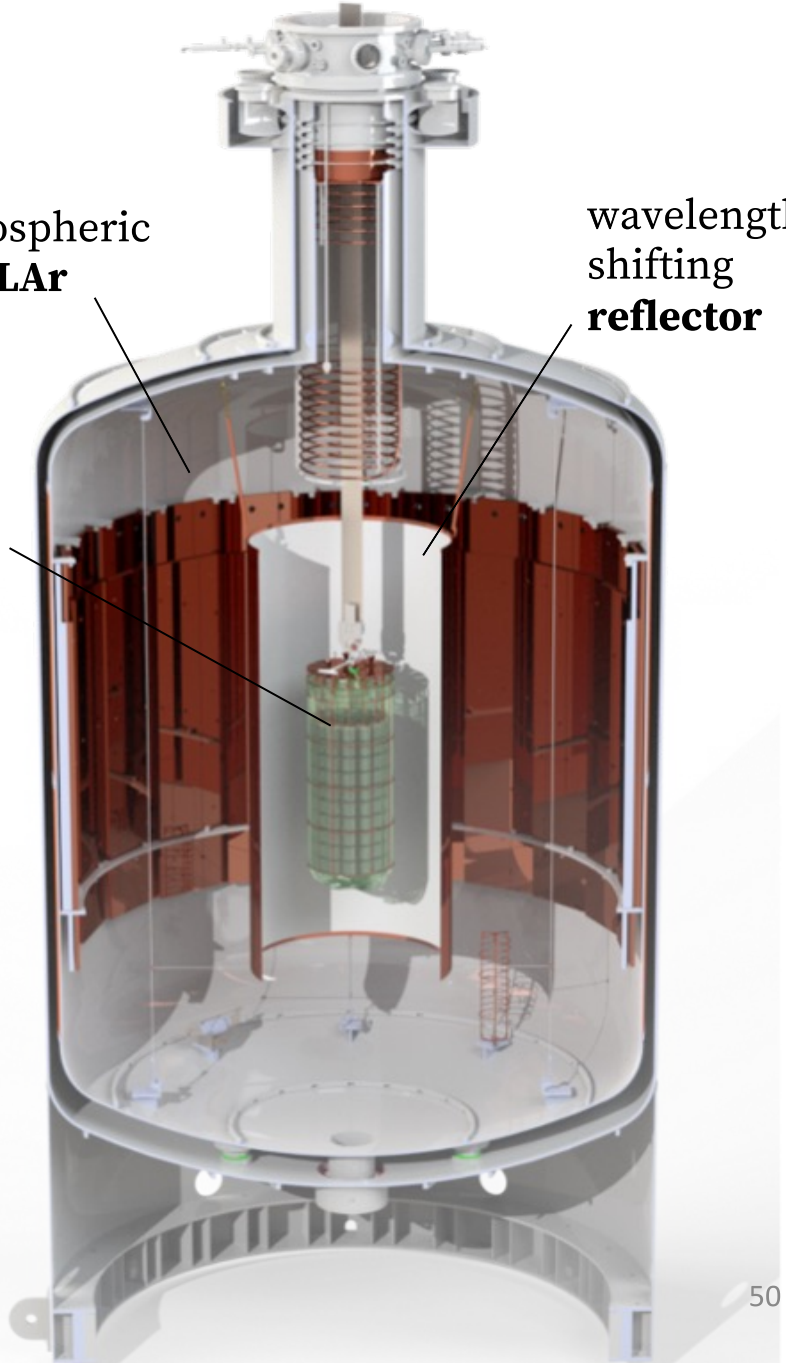
Weighting Potential: ϕ_w

LEGEND-200 status

- **large volume HPGe detectors**, part of isotope material procured from european vendor, improved **electronics**
- improved **light yield** and **photo collection,** optically active materials
- **successful upgrade** of LNGS infrastructure
- commissioning ongoing, **physics data** taking starting

140 kg array





LEGEND-200 status

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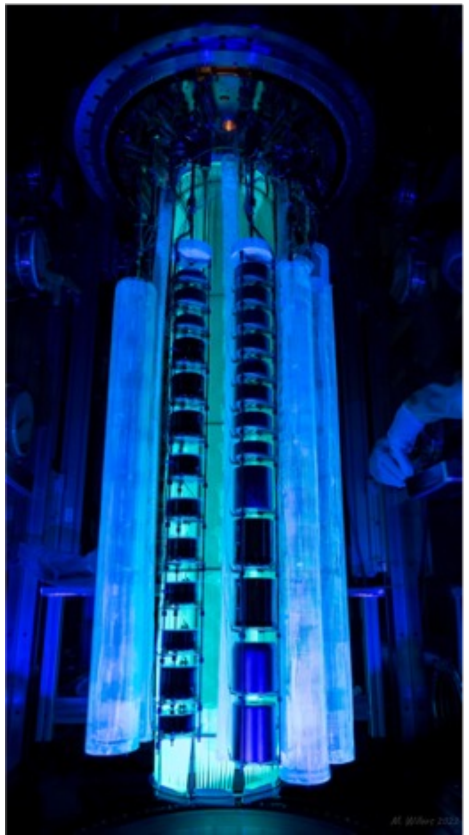
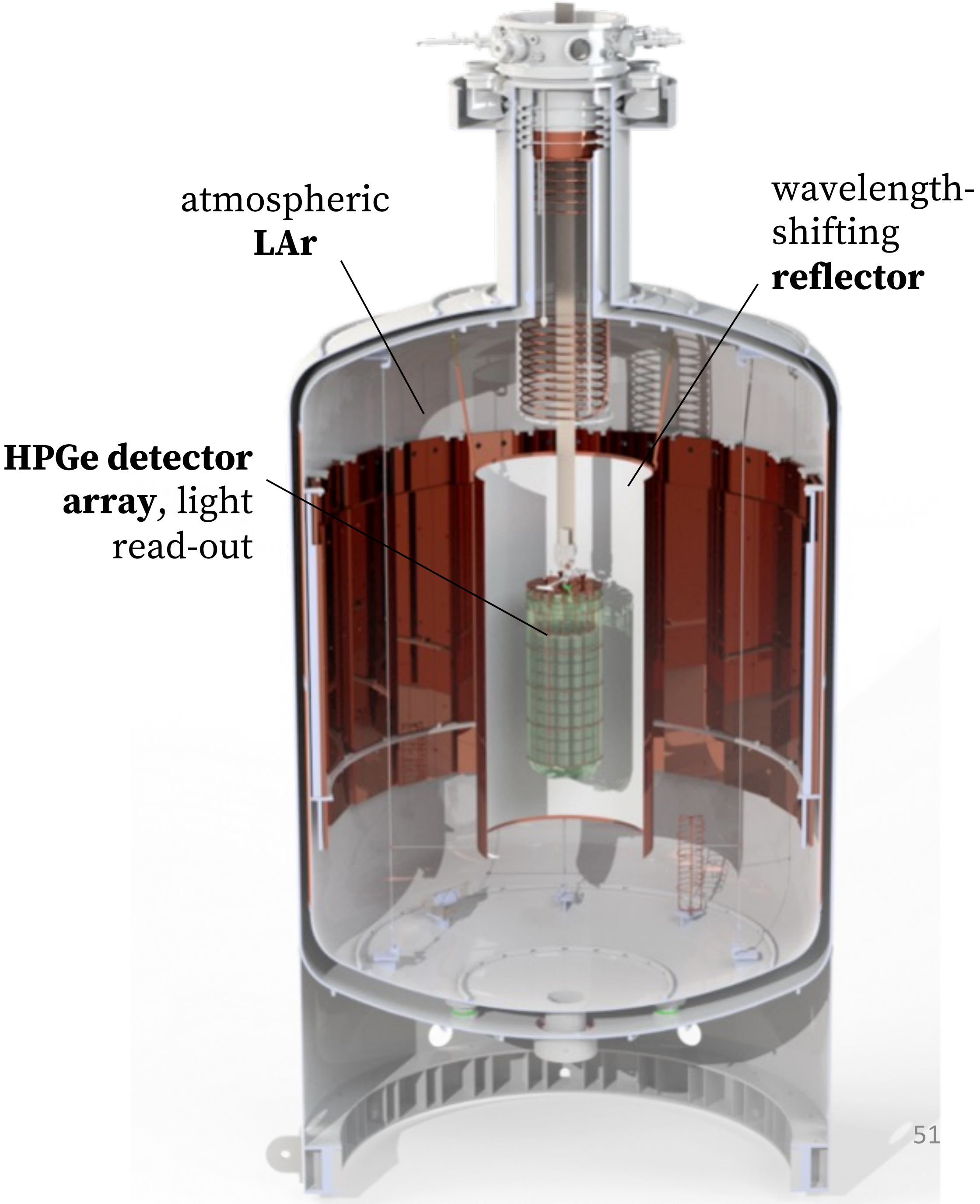
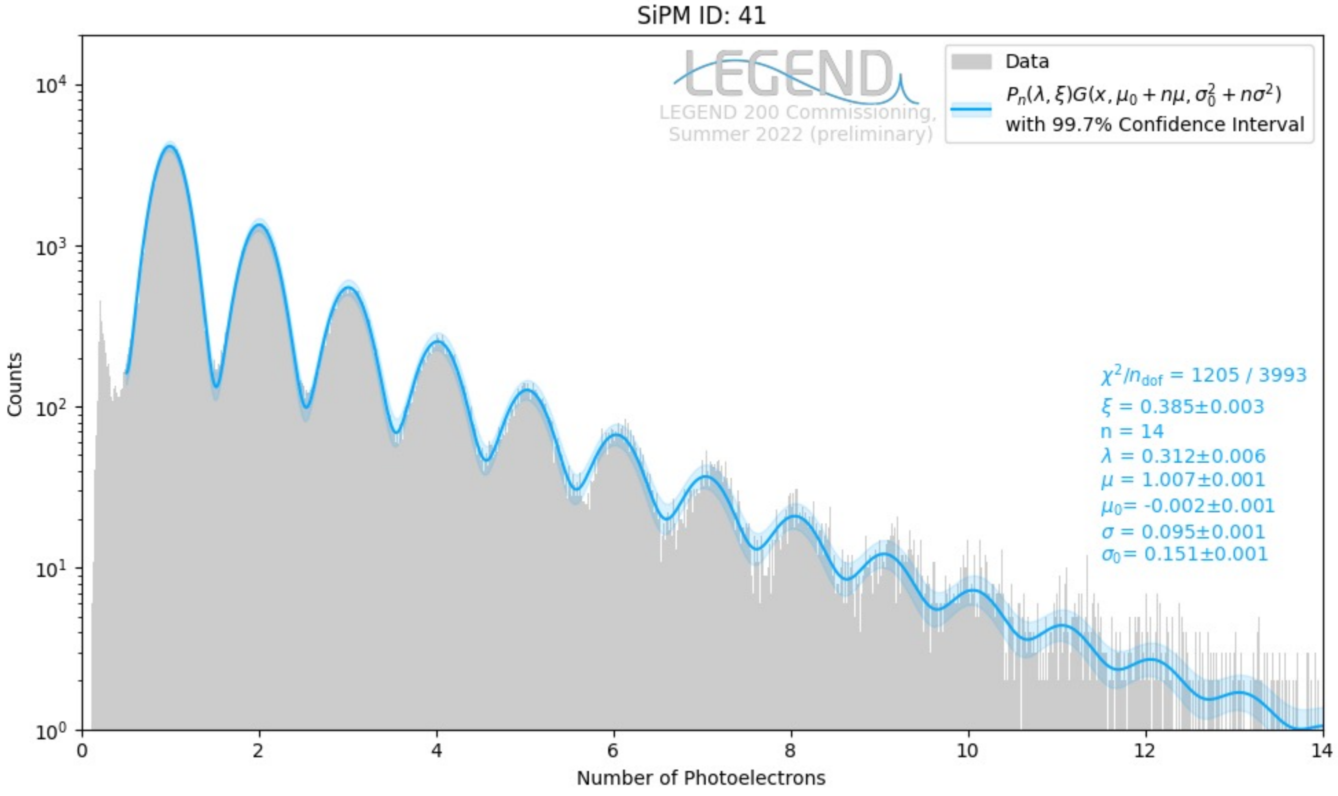
140 kg array





Commissioning performance: LAr instrumentation



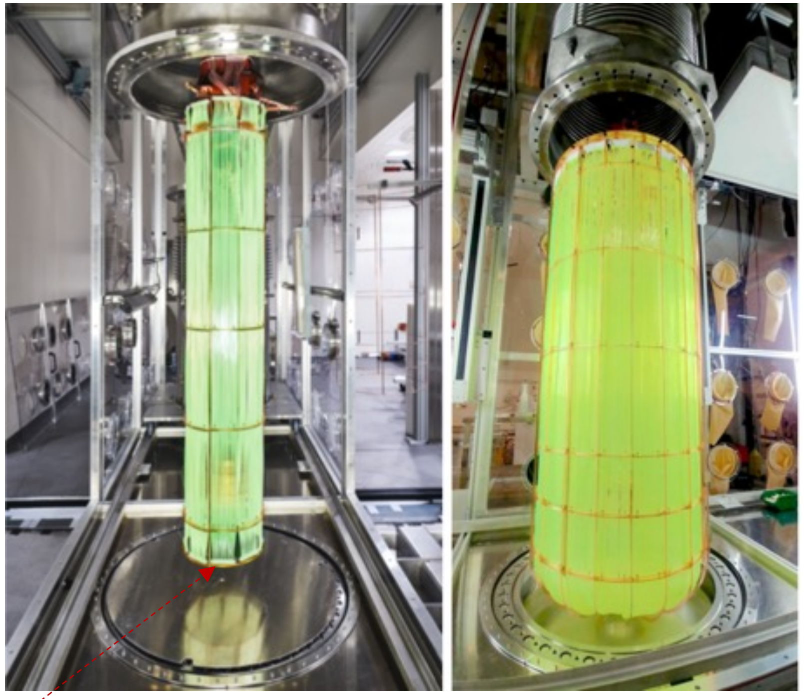
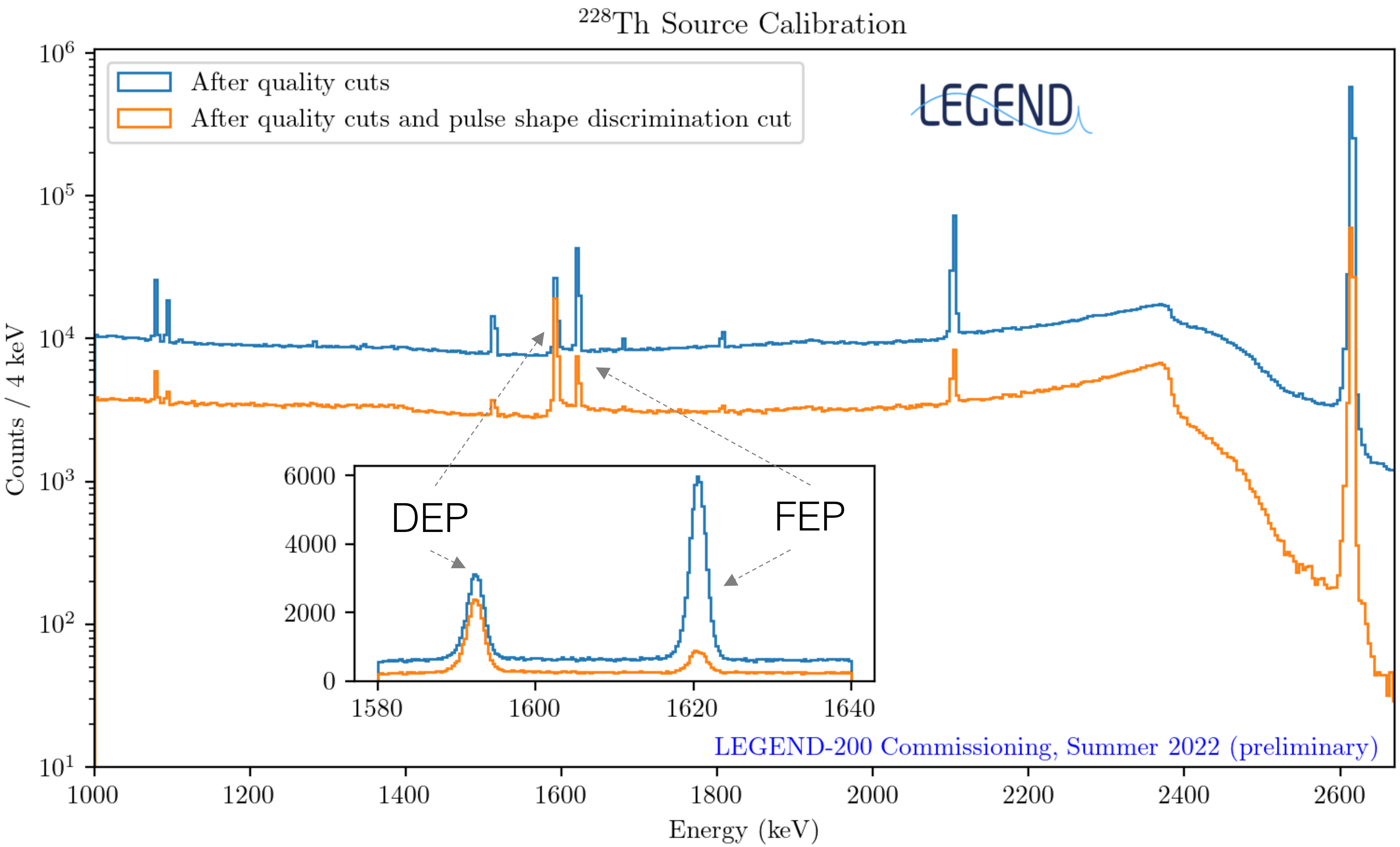


Photo-electron spectrum of single SiPM array (9 SiPM read out in parallel)

Commissioning performance: pulse shape discrimination

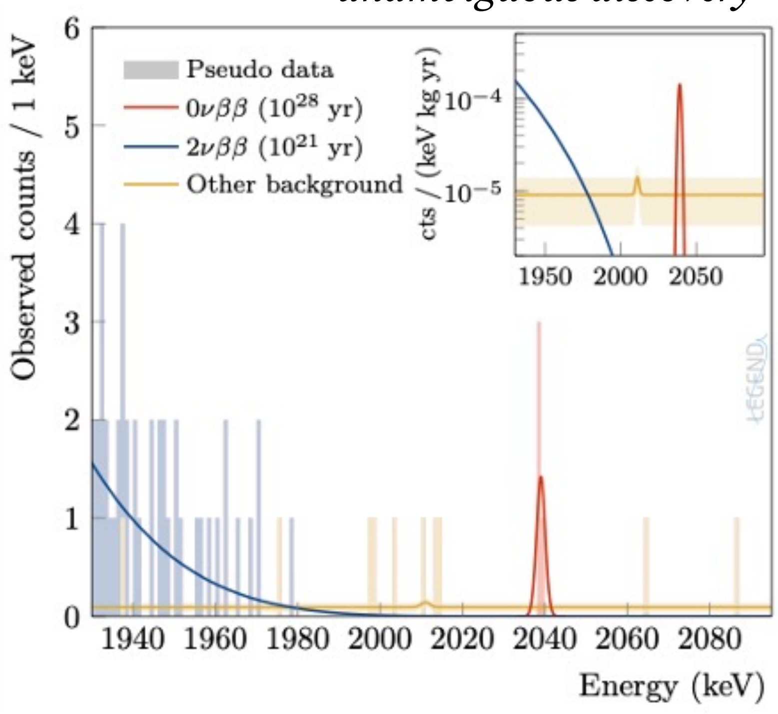


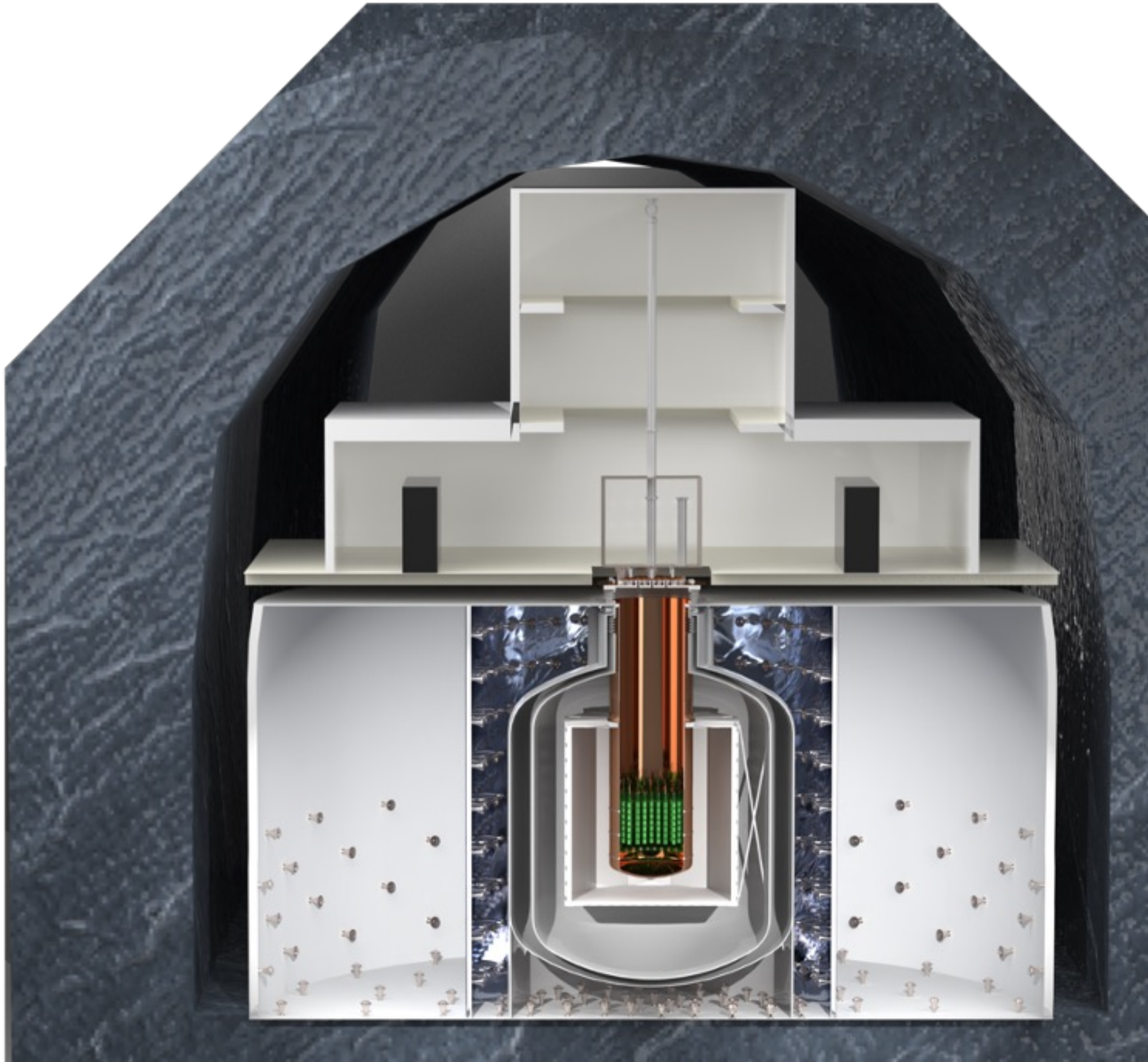
- A/E cut is set to the standard value of 90% DEP (=0ββ proxy) acceptance.

LEGEND-1000

- evaluated as **strongest amongst competitors** in **DOE portfolio review** 2021
- **site selection** (LNGS vs. SNOLAB) **& CD-1/CD-3A in 2023**

unambiguous discovery





concept for LEGEND-1000 at LNGS

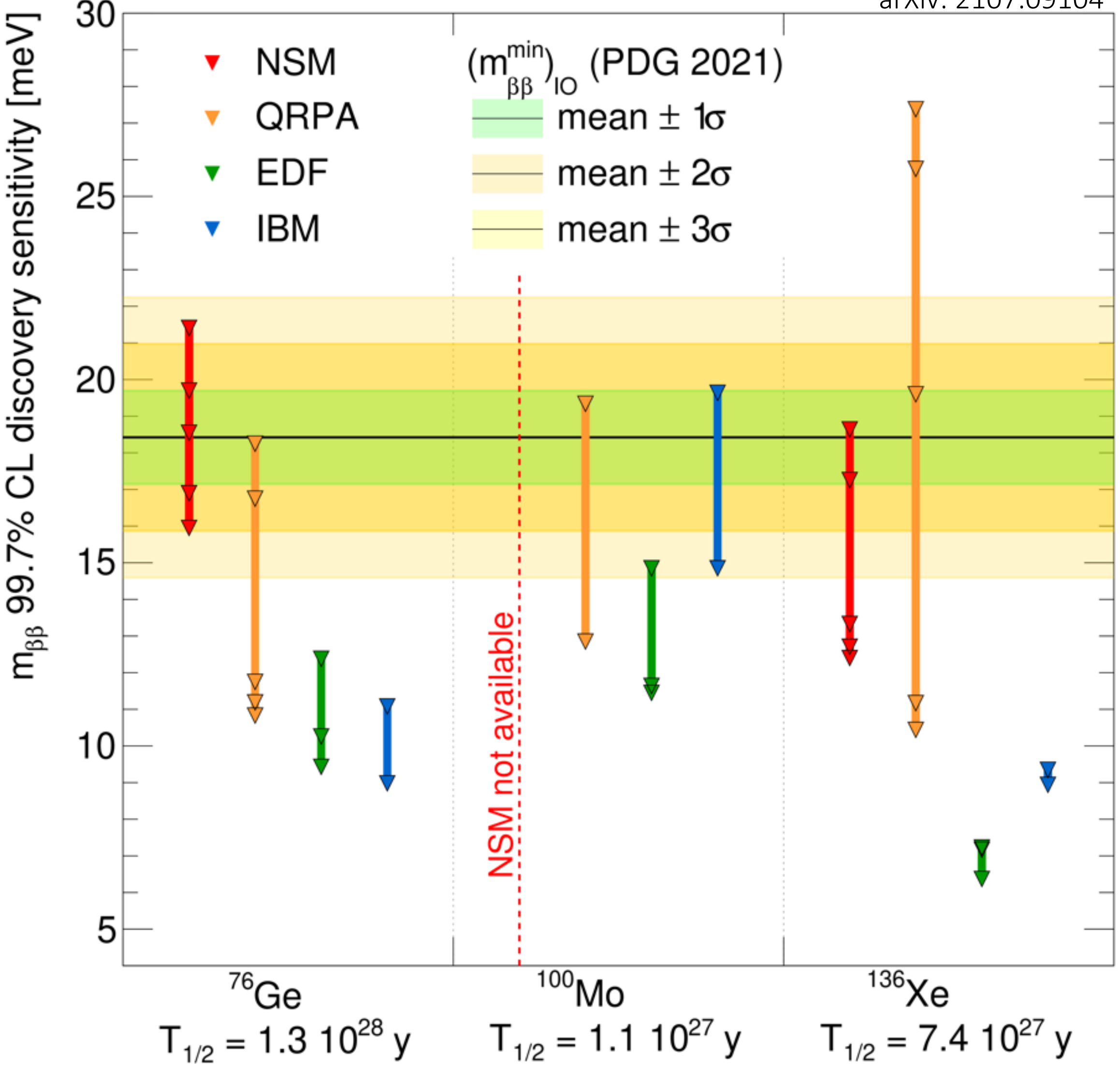
Sensitivity $m_{\beta\beta}$

- $m_{\beta\beta} = m_e / \sqrt{G\ g_A^4\ M^2\ T_{1/2}}$
- Inverted ordering: $m_{\beta\beta}$ > 18.4 ± 1.3 meV
- *M* ➜ 4 many-body methods, each with specific systematics (soon also ab initio)
- Multiple, different set of calculations for each many-body method and isotope

LEGEND will fully test inverted ordering and a large part of the normal ordering space

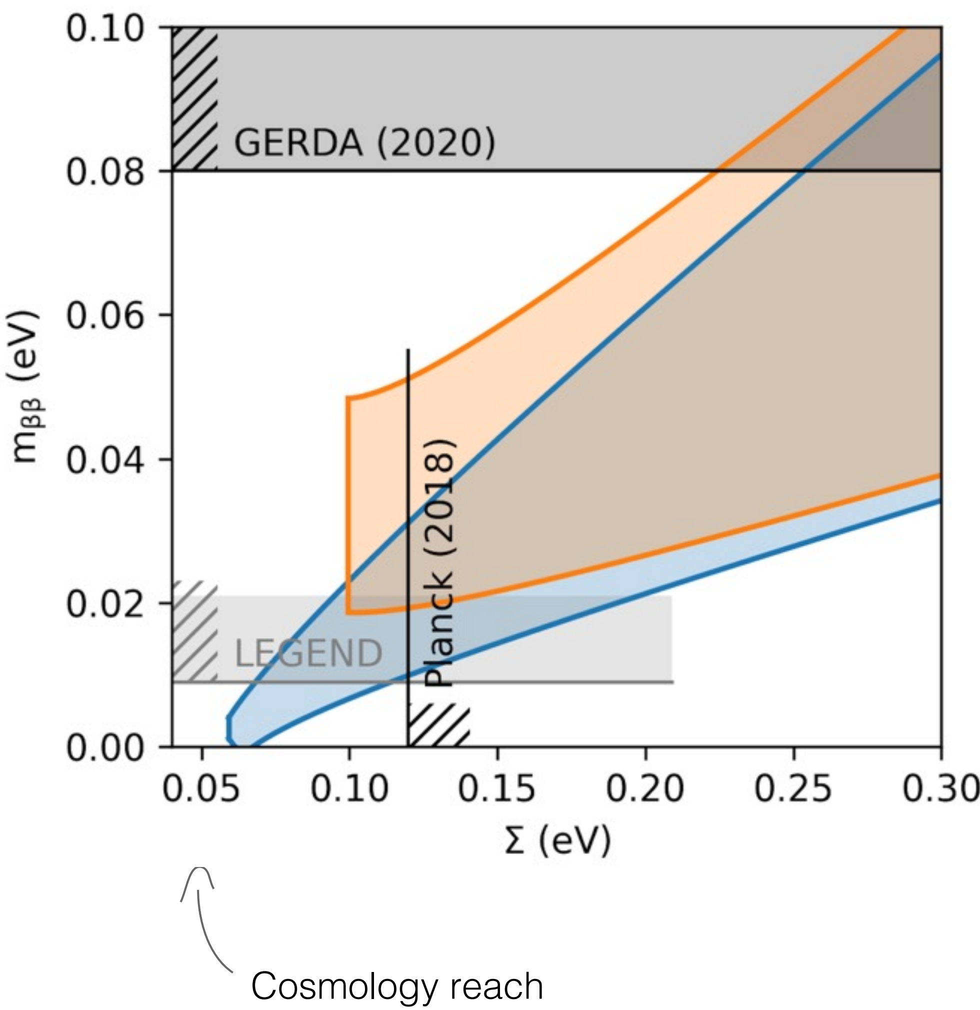
Discovery sensitivity <18.4 meV for 3/4 many-body methods & 12/15 calculations

Agostini, Detwiler, Benato, Menendez, Vissani
"Testing the Inverted Neutrino Mass Ordering with 0νββ Decay"
arXiv: 2107.09104



Summary

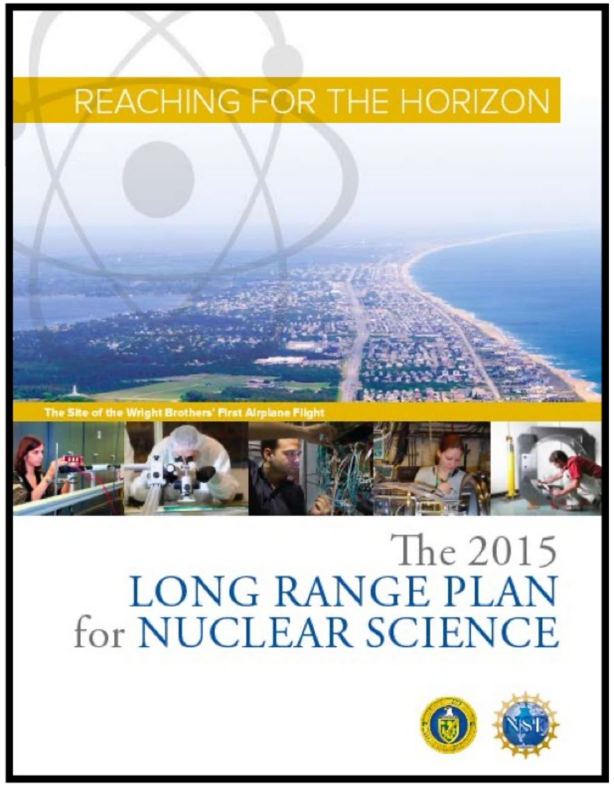
- Major progress in the preparation of **ton-scale** experiments over last few years
- Experiment design for **discovery** (not limit setting)
- Will fully explore **IO** and large part of **NO**
- Several DBD isotopes and techniques are required, given **NME uncertainties** and **confirmation** in case of discovery
- Formidable **experimental challenges** to acquire ton yr exposure quasi **background free – or compensate with huge mass (Te)**
- North-American – European **convergence on portfolio** of experiments(LEGEND, nEXO, CUPID) contingent on funding: **LEGEND** is the current front-runner after DOE portfolio review; breakthrough on Ba-tagging by NEXT
- Asia: KL2Z, Amore, CDEX, JUNO
- **Availability of DBD isotopes** from Western supplier



EXTRA slides

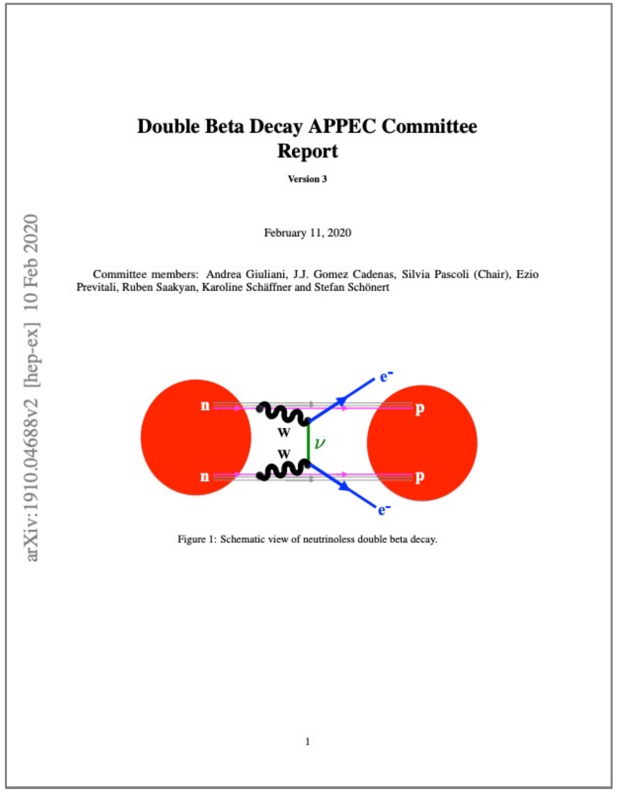
The European and North-American Process

https://science.osti.gov/np/nsac



“We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.”

https://arxiv.org/abs/1910.04688


arXiv:1910.04688v2 [hep-ex] 10 Feb 2020

Double Beta Decay APPEC Committee Report

Version 3

February 11, 2020

Committee members: Andrea Giuliani, J.J. Gomez Cadenas, Silvia Pascoli (Chair), Ezio Previtali, Ruben Saakyan, Karoline Schäffner and Stefan Schönert

Figure 1: Schematic view of neutrinoless double beta decay.

1

- Oct 2019: Roadmap document for the APPEC SAC on the future $0\nu\beta\beta$ decay experimental programme in Europe
- $0\nu\beta\beta$ town meeting London
- Roadmap update 2022, town meeting in Berlin, June 2022

DOE NP Portfolio Review
July 2021
CUPID
LEGEND-1000
nEXO

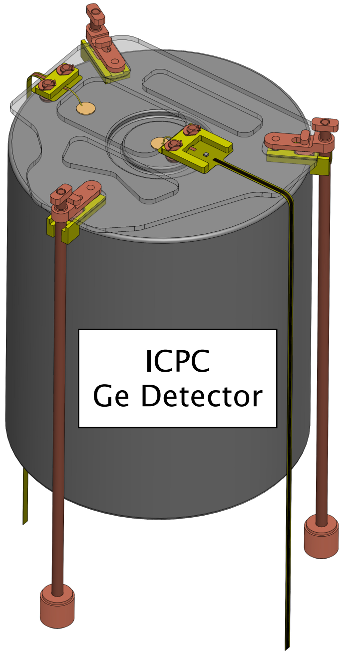
- Outcome: Realize international portfolio LEGEND-1000, nEXO and CUPID with European partners
- LEGEND-1000 was evaluated extremely positively at the Portfolio review. Now being funded by DOE to move to the next step, CD-1

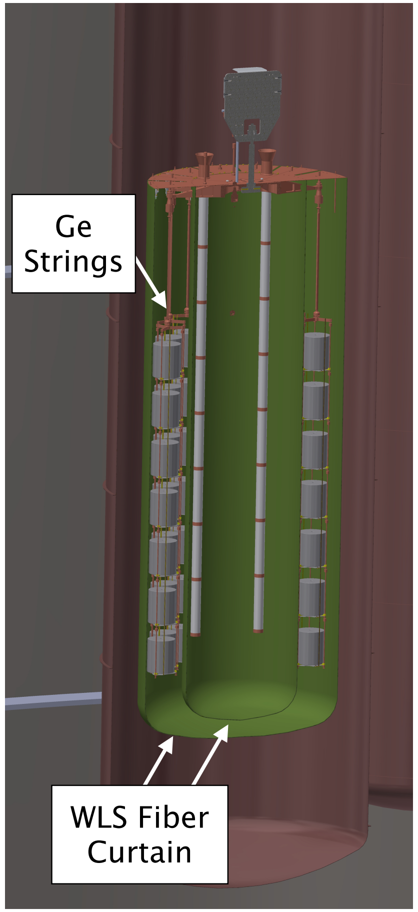
https://agenda.infn.it/event/27143/

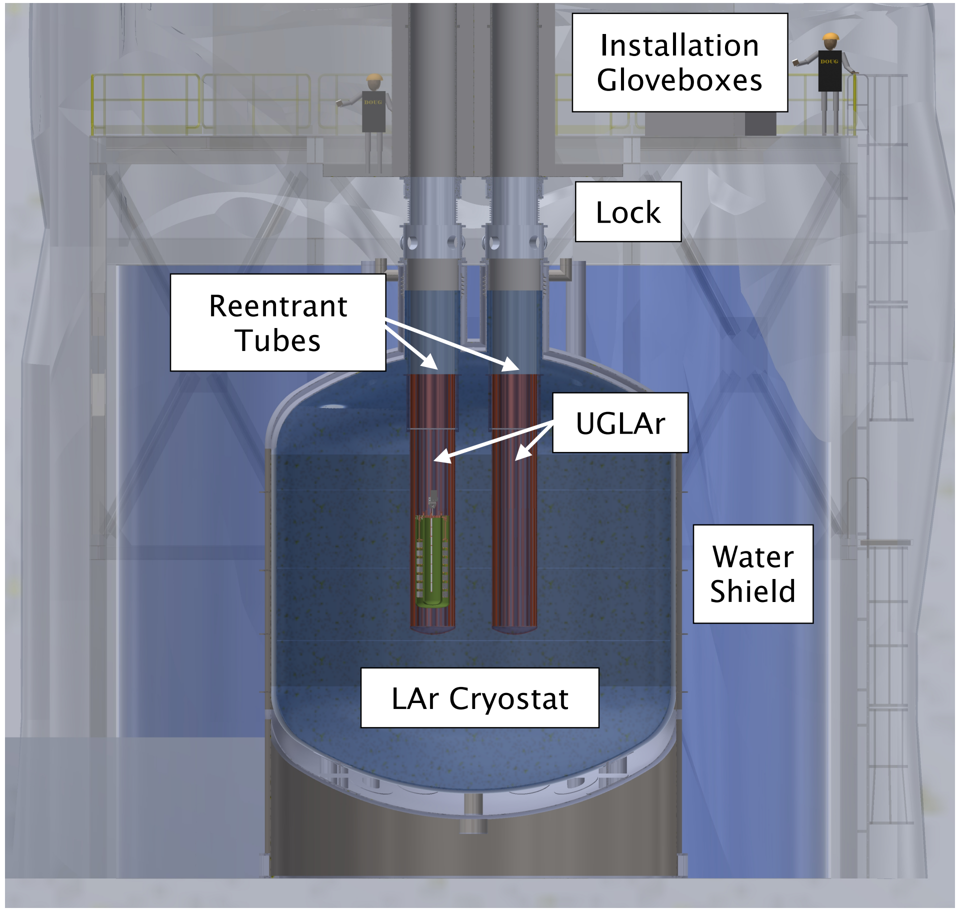
“The international stakeholders in neutrino-less double beta decay research do agree in principle that the best chance for success is an international campaign with more than one large ton-scale experiment implemented in the next decade, with one ton scale experiment in Europe and the other in North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

^{76}Ge: LEGEND-1000 - a discovery experiment for 0νββ of ^{76}Ge

Quasi-background-free[1] search for 0νββ decays of ^{76}Ge at $Q_{\beta\beta}$ = 2039.06 keV



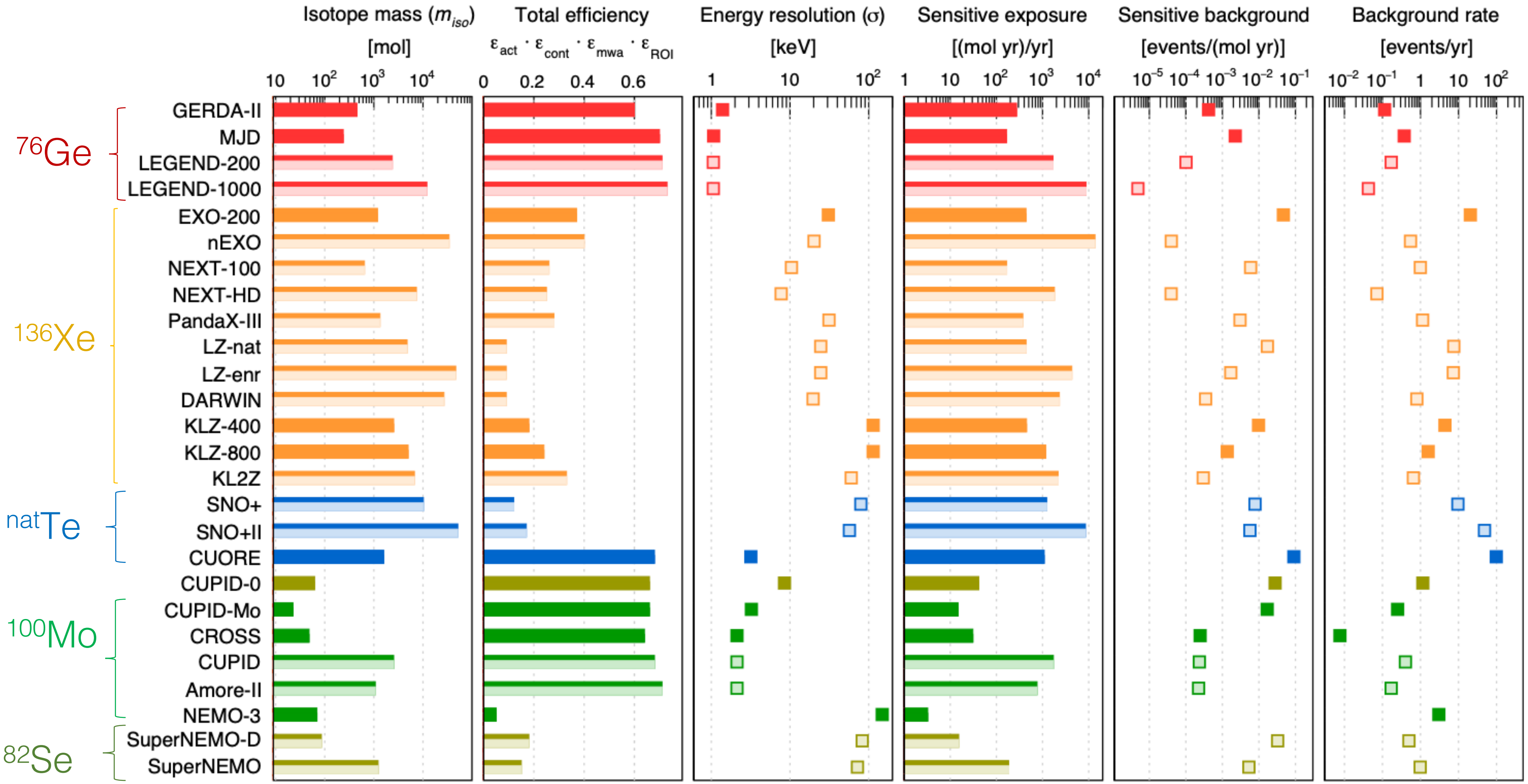




ICPC: Inverted-Coaxial Point Contact
WLS: Wavelength-shifting
UGLAr: Underground Liquid Ar

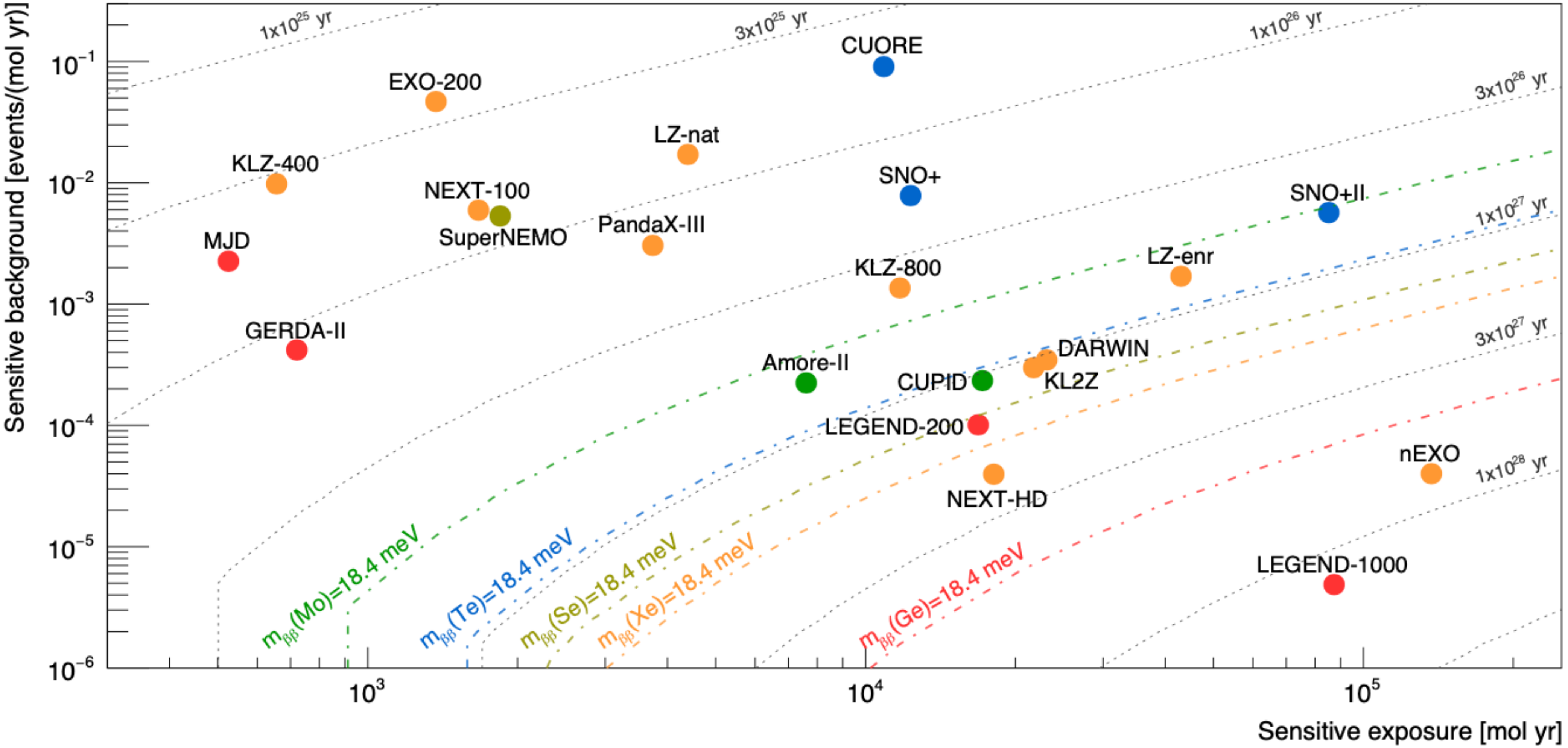
[1] Expected number of background counts is much lower than 1 in the FWHM at full exposure

Isotope masses, efficiencies, sensitive background & exposure and backgrounds



Agostini, Benato, Detwiler, Menendez, Vissani, arXiv:2202.01787

Sensitive background and exposure for recent and future experiments

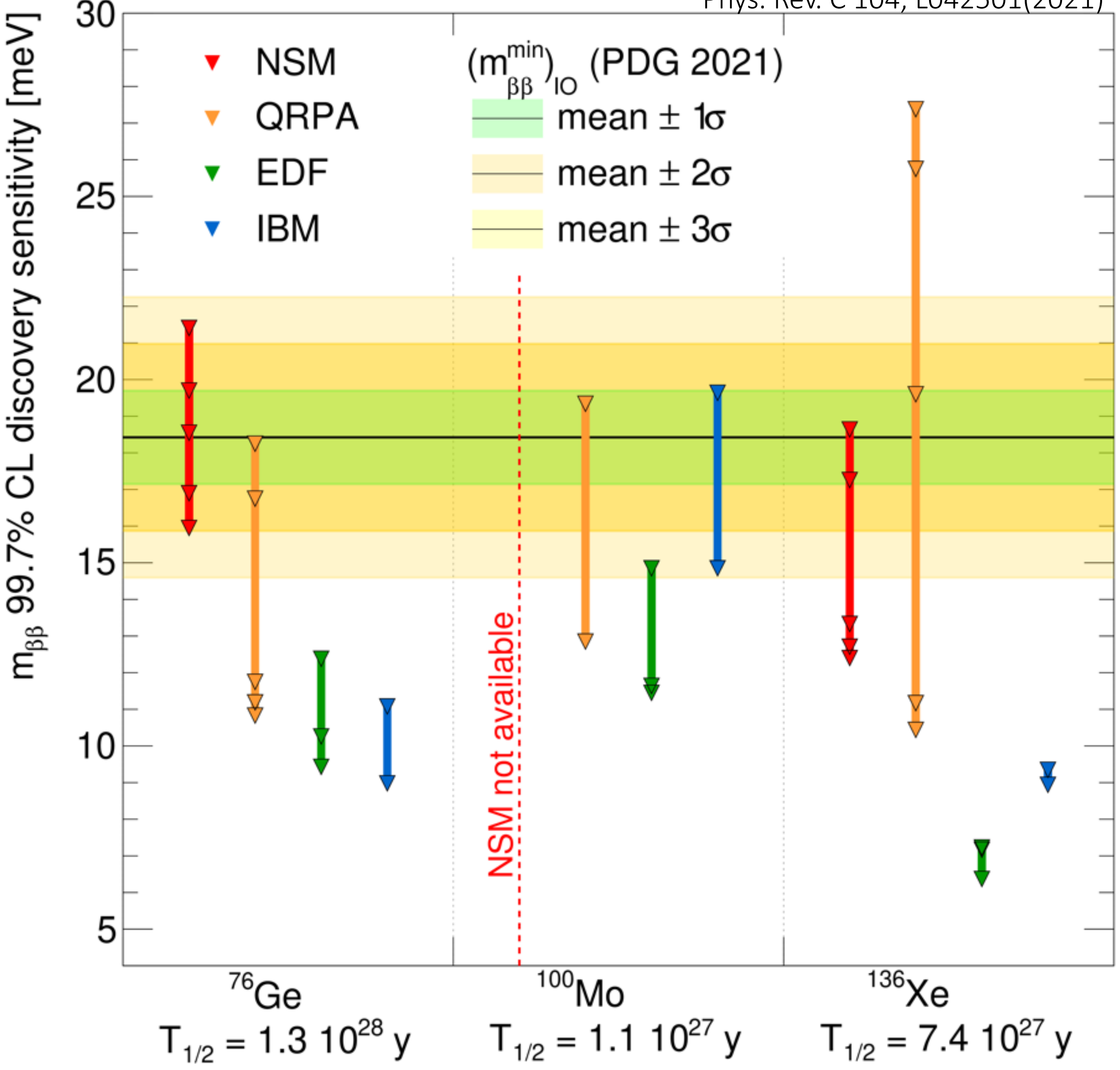


Agostini, Benato, Detwiler, Menendez, Vissani, arXiv:2202.01787

Comparison of $m_{\beta\beta}$ sensitivities

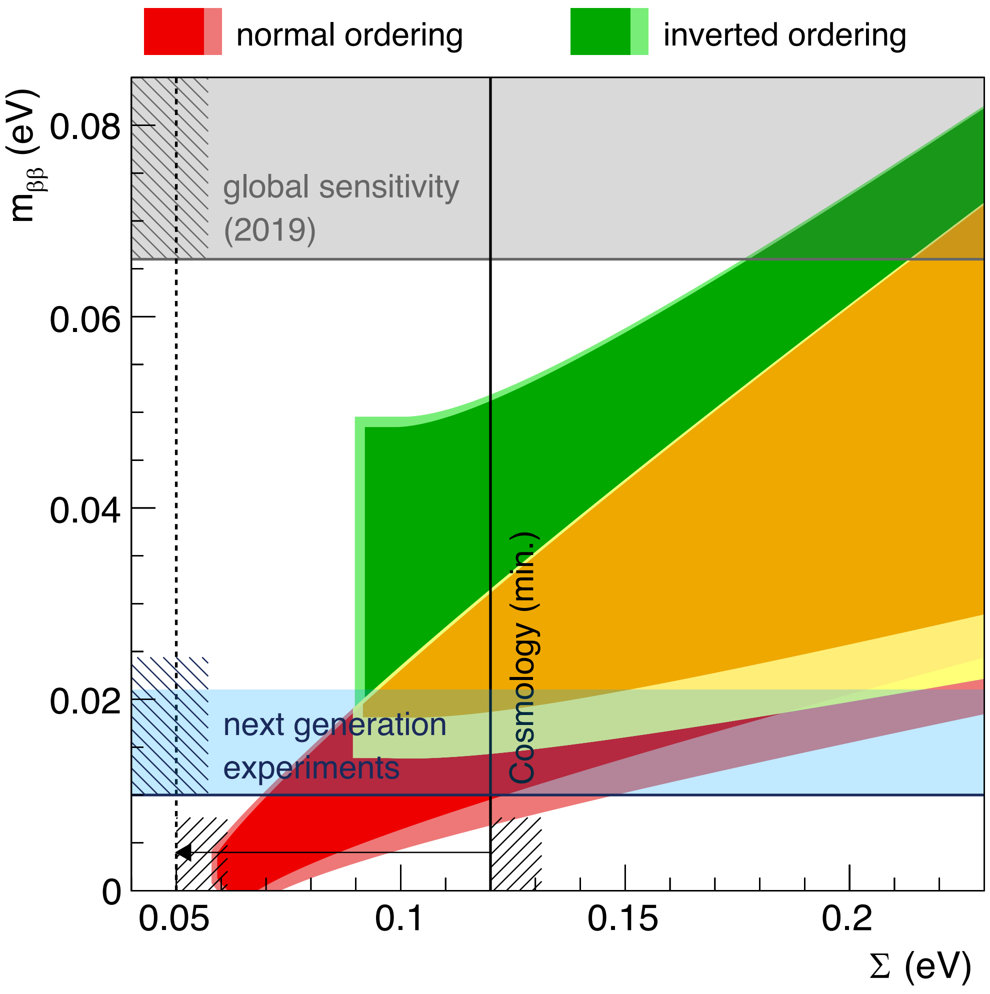
- Inverted ordering: $m_{\beta\beta} > 18.4 \pm 1.3$ meV
- M → 4 many-body methods, each with specific systematics (soon also ab initio)
- Multiple, different set of calculations for each many-body method and isotope

Agostini, Detwiler, Benato, Menendez, Vissani
"Testing the Inverted Neutrino Mass Ordering with 0νββ Decay"
Phys. Rev. C 104, L042501(2021)



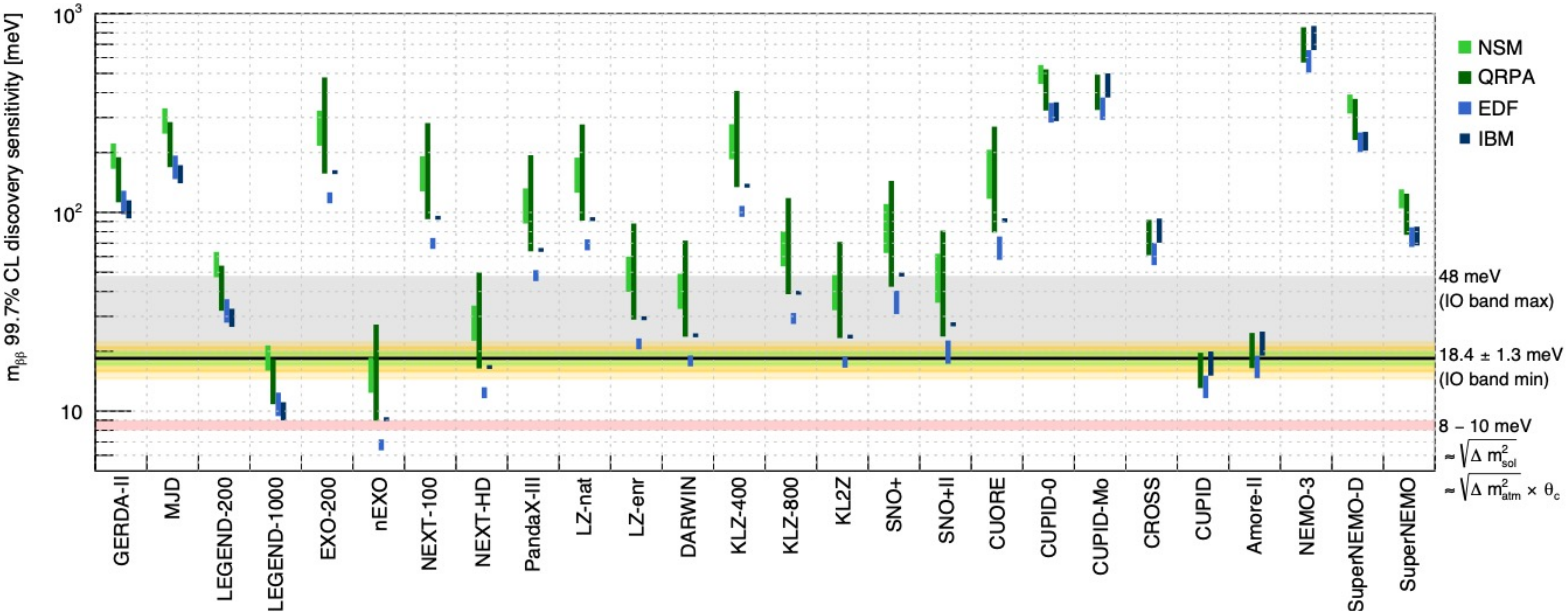
Summary & Outlook

- Major progress for preparation of **ton-scale** experiments over last two years
- Experiment design for **discovery** (not limit setting)
- Will fully explore **IO** and large part of **NO**
- Several DBD isotopes and techniques required, given **NME uncertainties**
- Formidable **experimental challenges** to acquire ton yr exposure quasi **background free – or compensate with huge mass (Te)**
- North-American – European **convergence on portfolio** of experiments contingent on funding: current front-runners are LEGEND-1000, nEXO and CUPID; breakthrough R&D on Ba-tagging by NEXT
- Asia: KL2Z, Amore, PandaX, JUNO
- **Availability of DBD isotopes** from Western supplier
- How to go to **bottom of NO**? Assess **performance** of ton-scale experiments first. All have the potential to **increase exposure** and reduce further **backgrounds**



Courtesy C. Wiesinger

Discovery sensitivities of current- and next-generation 0νββ-decay experiments



Agostini, Benato, Detwiler, Menendez, Vissani, arXiv:2202.01787