The Quest for Majorana Neutrinos: Future experiments

Stefan Schönert | TU München

22nd edition
Particles and Nuclei International Conference
PANIC 2021

5-10 September 2021
Lissabon - online

TECHNISCHE UNIVERSITÄT MÜNCHEN

SFB 1258 Neutrinos Dark Matter Messengers

Sun 05/09 | Mon 06/09 | Tue 07/09 | **Wed 08/09** | All days

Today's presentations:

Print | PDF | Full screen | Detailed view | Filter

13:00	**Neutrinoless double beta decays** *Online*	*Prof. Manfred Lindner* 13:00 - 13:30
	Final Results of GERDA on the Search for Neutrinoless Double-β Decay *Online*	*Dr Luigi Pertoldi* 13:30 - 13:50
	Latest results from the CUORE experiment *Online*	*Valentina Dompè et al.* 13:50 - 14:10
14:00	**Status and Prospects of the SNO+ Experiment** *Online*	*Ana Sofia Inácio* 14:10 - 14:30

This talk: focus on future ton-scale experiments

Posters not to miss:

^{76}Ge: MJD, LEGEND

https://indico.lip.pt/event/592/contributions/3421/attachments/2506/3807/nruof_mjd_panic.pdf
https://indico.lip.pt/event/592/contributions/3496/attachments/2539/3775/pettus-panic-legend.pdf
https://indico.lip.pt/event/592/contributions/3489/attachments/2499/3611/PANIC%20poster%20final%20-%20pdf.pdf
https://indico.lip.pt/event/592/contributions/3166/attachments/2474/3870/PANIC_LArpurification.pdf

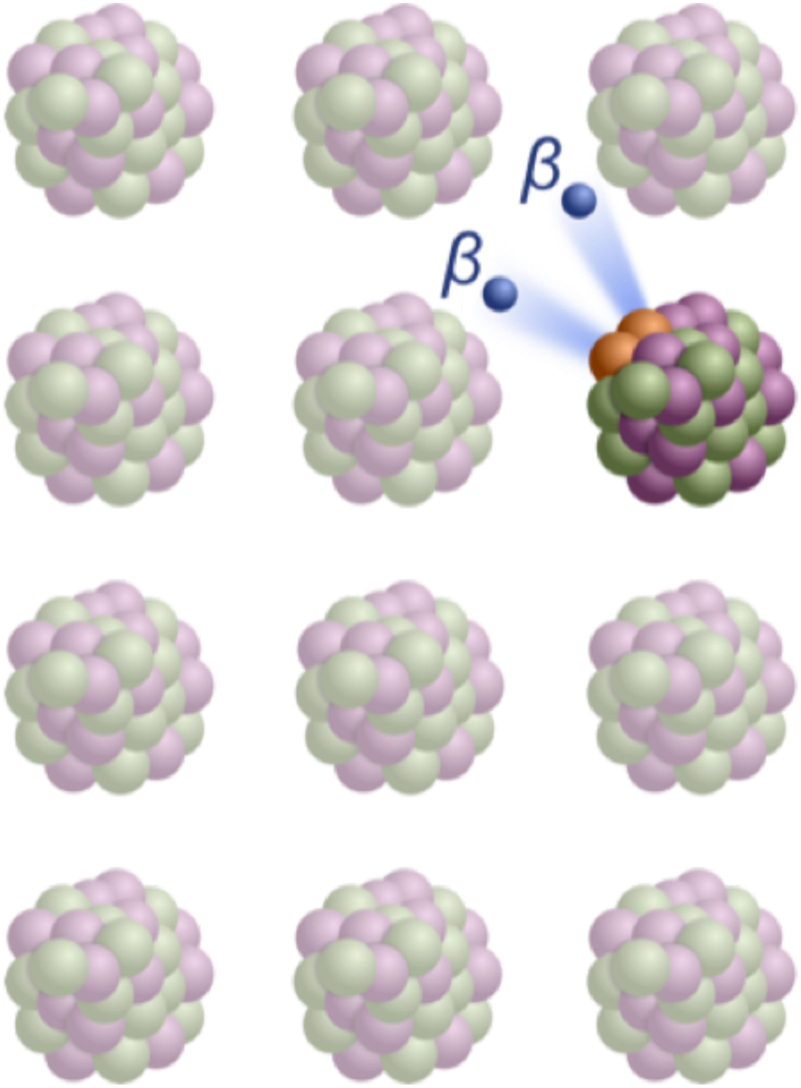
^{48}Ca: Candles

https://indico.lip.pt/event/592/contributions/3490/attachments/2519/3691/2021.09.05_PANIC.pdf

^{136}Xe: NEXT, LZ

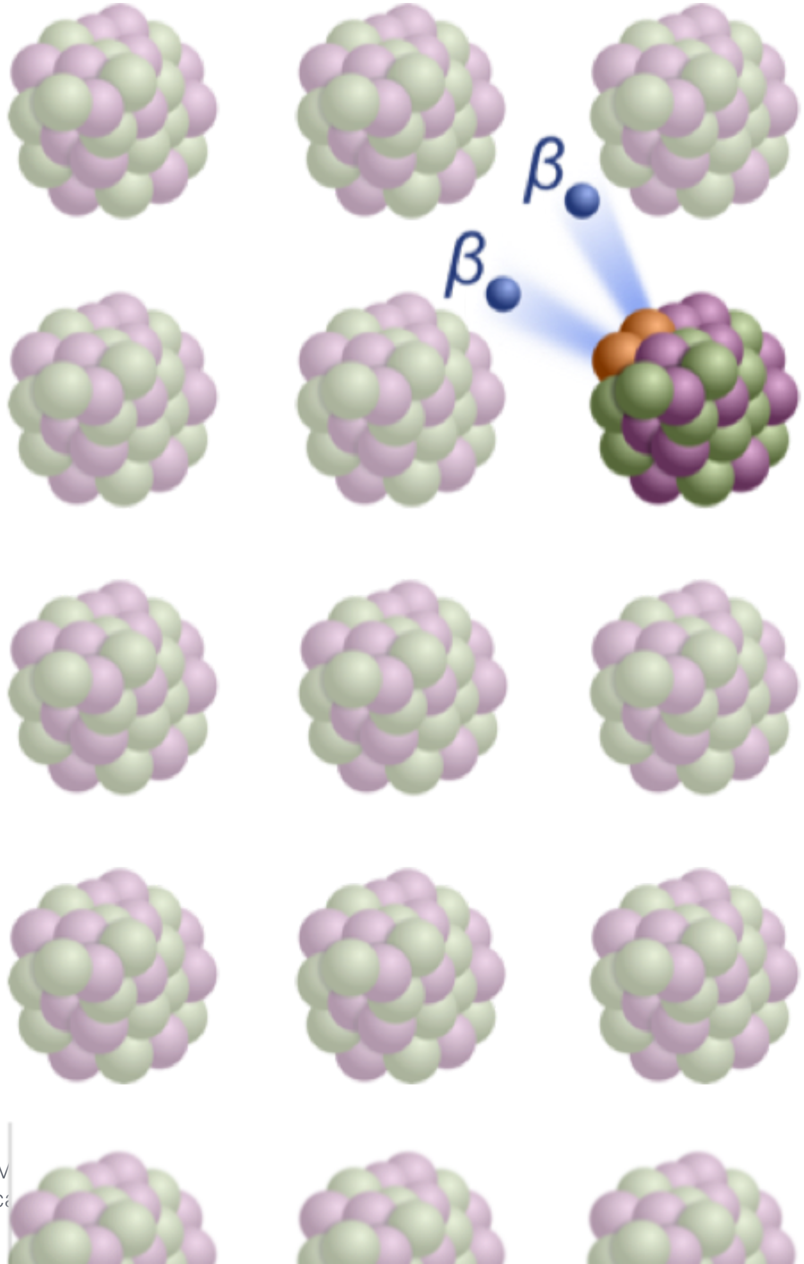
https://indico.lip.pt/event/592/contributions/3500/attachments/2503/3624/MiryamMartinezVaraPANICposterPDF.pdf
https://indico.lip.pt/event/592/contributions/3402/

0νββ decay essiantials



- Creation of (leptonic) matter without balancing emission of anti-matter (Vissani)
- (A,Z)→(A,Z+2) + $2e^-$
- Lepton number violating process (ΔL=2)
- Any ΔL=2 (BSM) operator can generate 0νββ
- Majorana neutrinos generate 0νββ
- Majorana neutrinos would explain small neutrino masses (See-Saw)
- Key ingredient for explanation of matter-antimatter asymmetry
- Discovery of 0νββ always imply new physics

0νββ decay essentials



Current best sensitivity (GERDA):

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

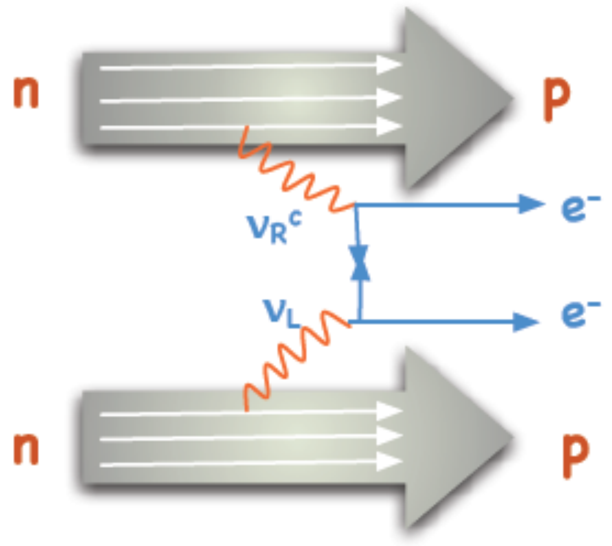
Next generation:

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

Challenge:

~1 decay per 10^4 mol and year

0νββ decay and neutrino mass



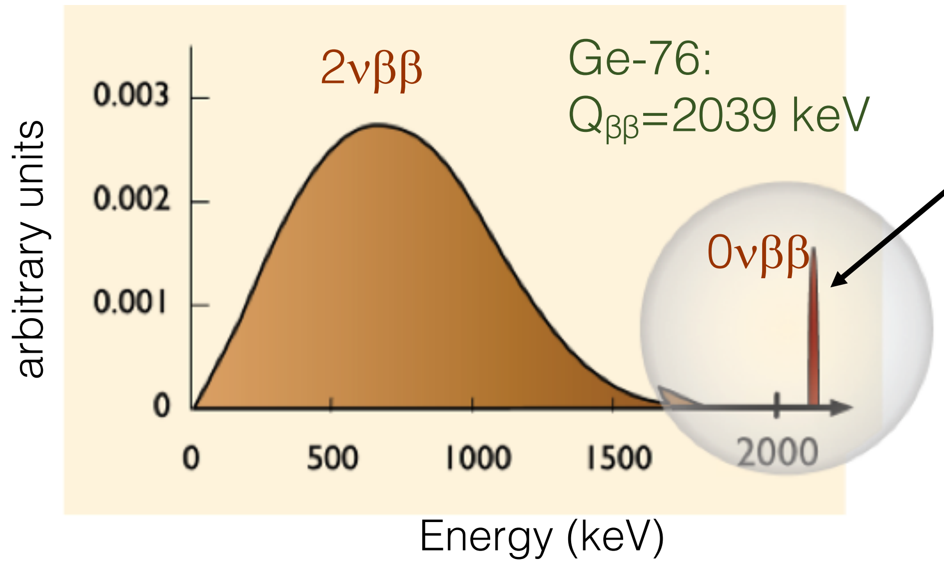
Expected decay rate:

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

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



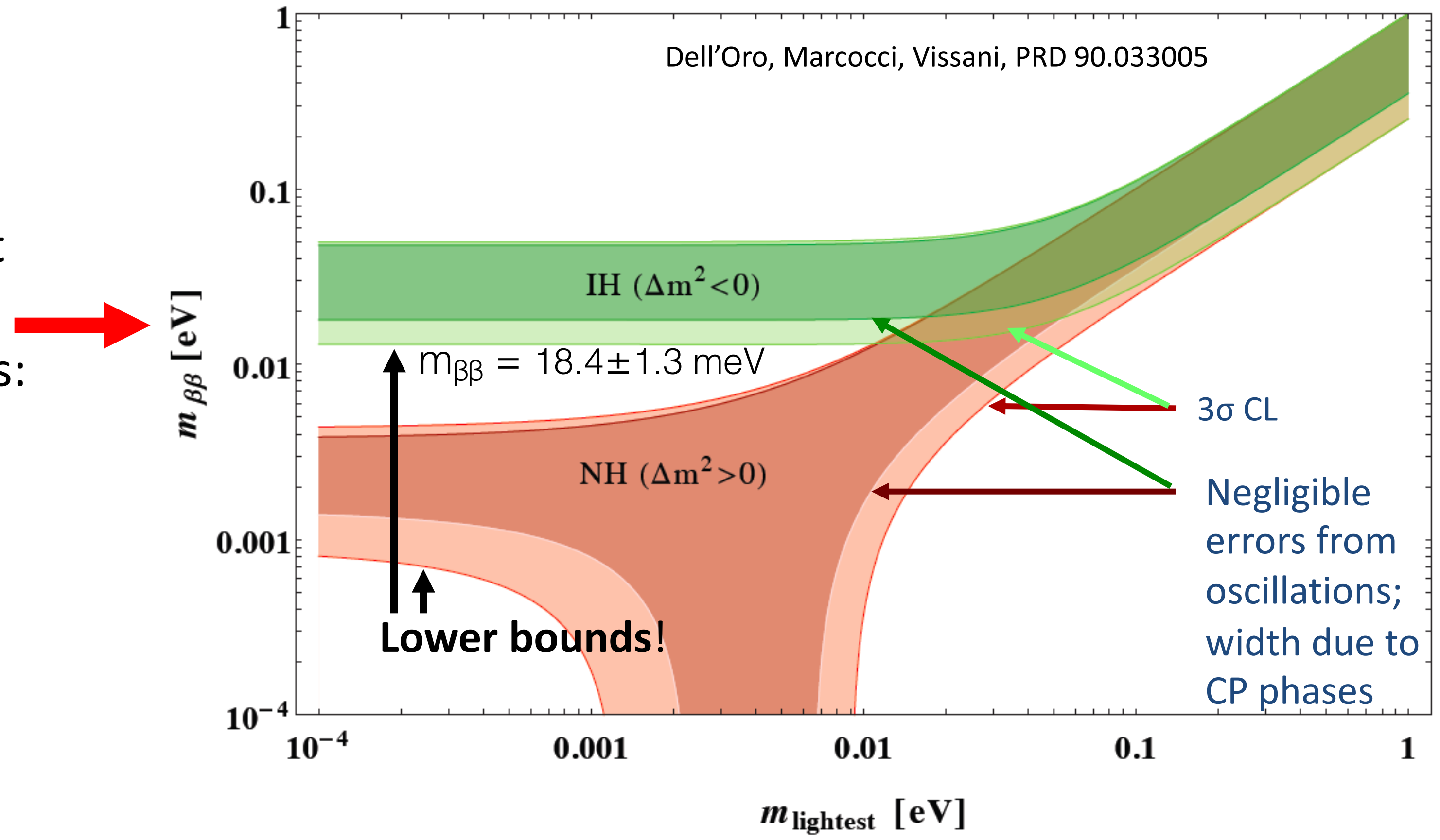
Experimental signatures:
- peak at $Q_{\beta\beta}$
- two electrons from vertex

Discovery would imply:
- 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

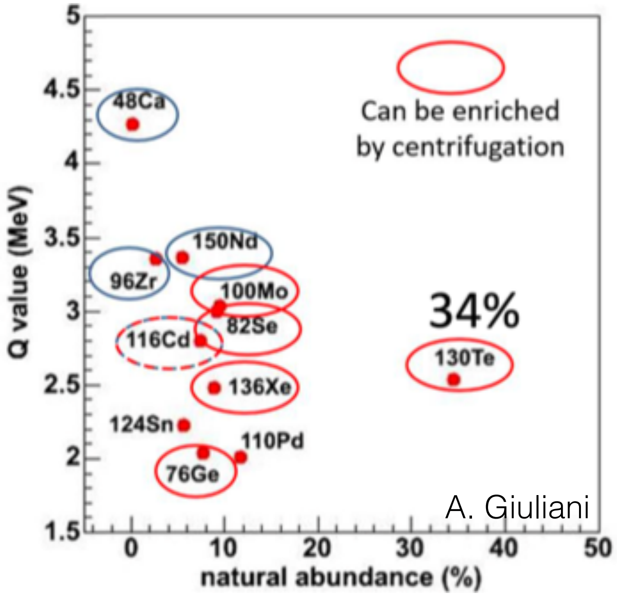
$$m_{\beta\beta} = f(m_1, \underbrace{\Delta m^2_{sol}, \Delta m^2_{atm}, \theta_{12}, \theta_{13}}_{\text{from oscillation experiments}}, \alpha\text{-}\beta)$$

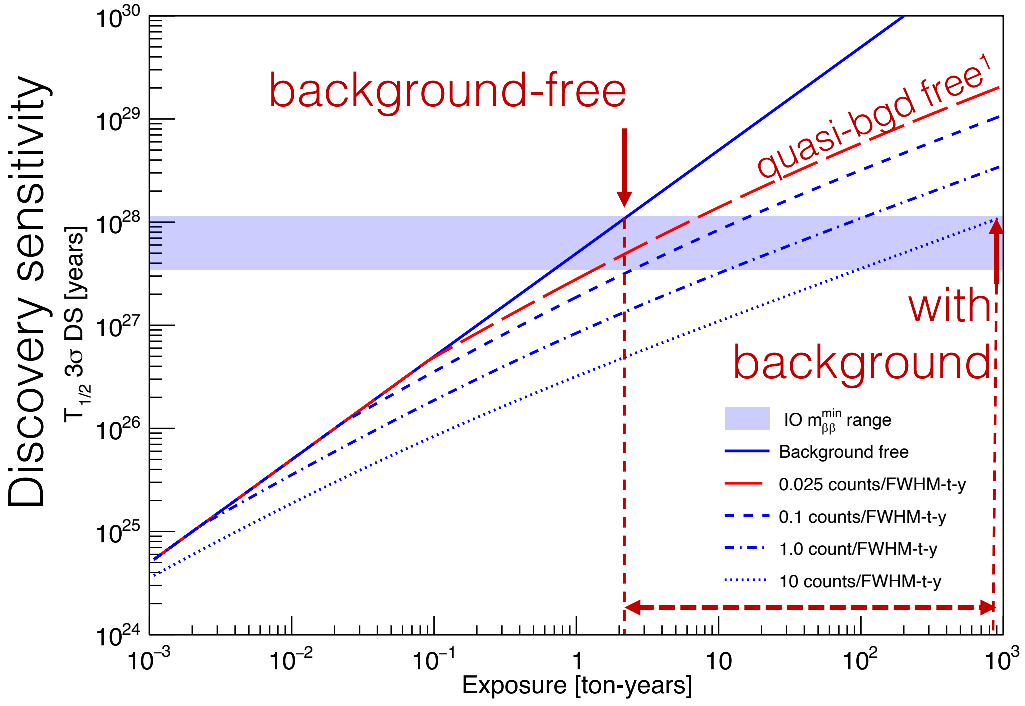
Goal of next generation experiments:



Experimental ingrediencies for next-generation experiments

- Source: ~**10^4 mol** (ton-scale) ββ isotopes
- **Isotopic enrichment** (~ 80 - 90%): reduction of backgrounds and costs
- **Source = detector** for next-gen-exp's to max. detection efficiency
- **Event topology** to identify signal events and discriminate backgrounds (energy resolution, interaction pattern, PID, space-time correlations, daughter isotope tagging, etc.)
- Ideally operate **quasi-free of background**: $t_{1/2}$ sensitivity scales with exposure (M x T)

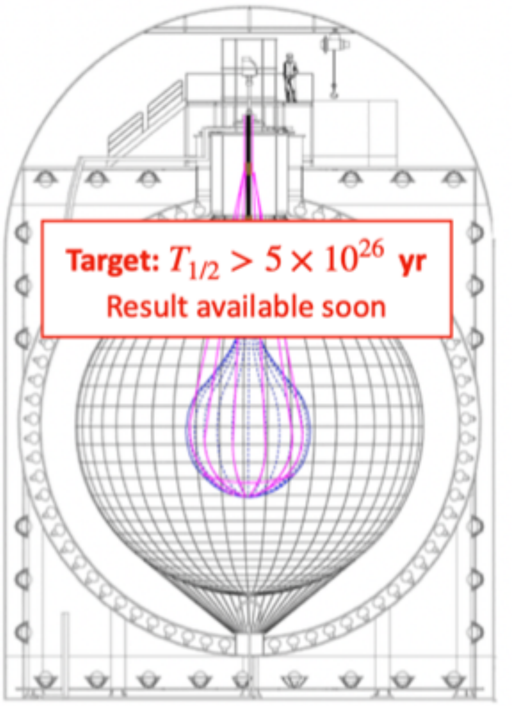




[1] Expected number of background counts is much lower than 1 in the FWHM at full exposure

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

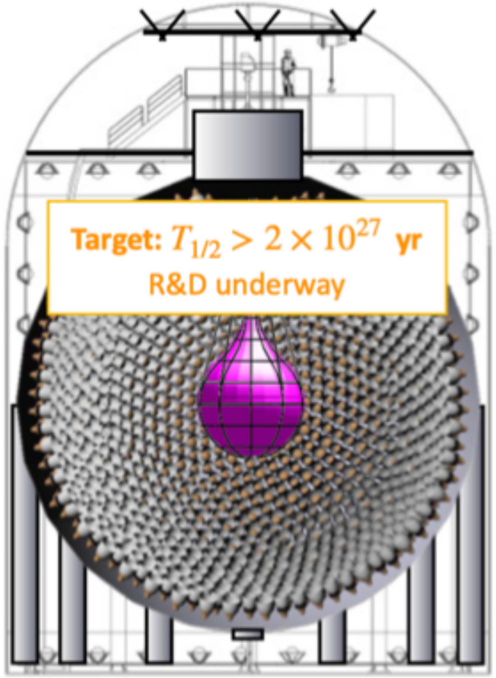
present



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):

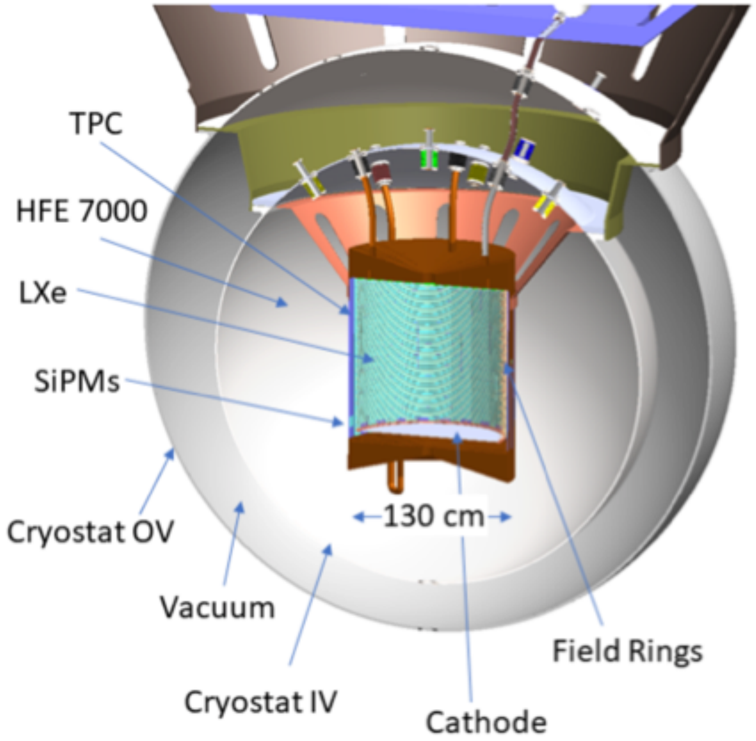
- Since 2019: data taking with 750 kg ^{enr}Xe (new balloon)

KamLAND2-Zen (future) with

- 1000kg+ proposed

Adopted from Aobo Li, TAUP2021

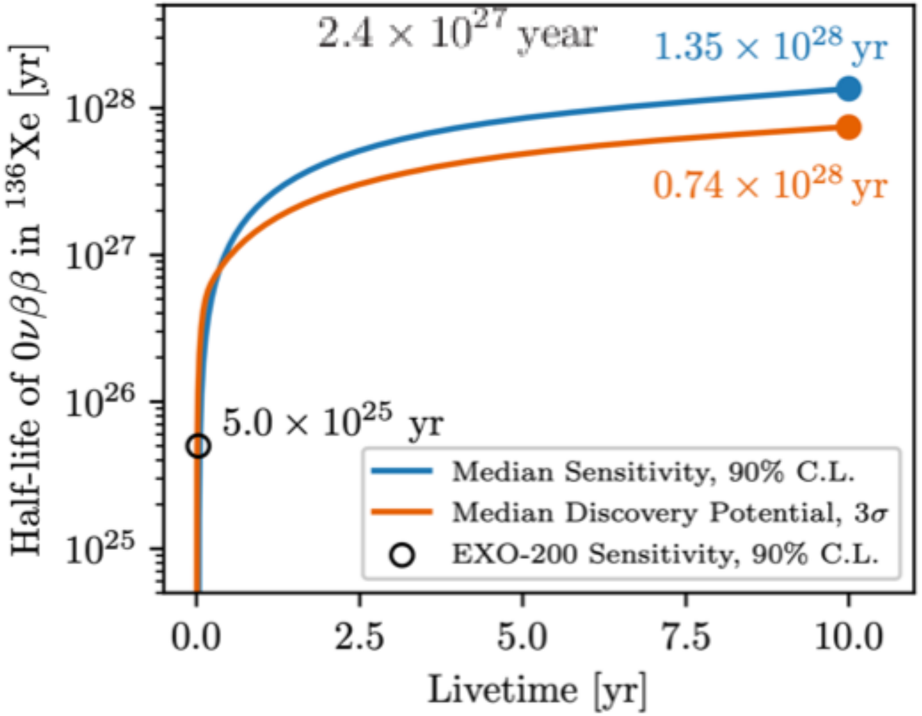
nEXO: ^{136}Xe single phase TPC



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)

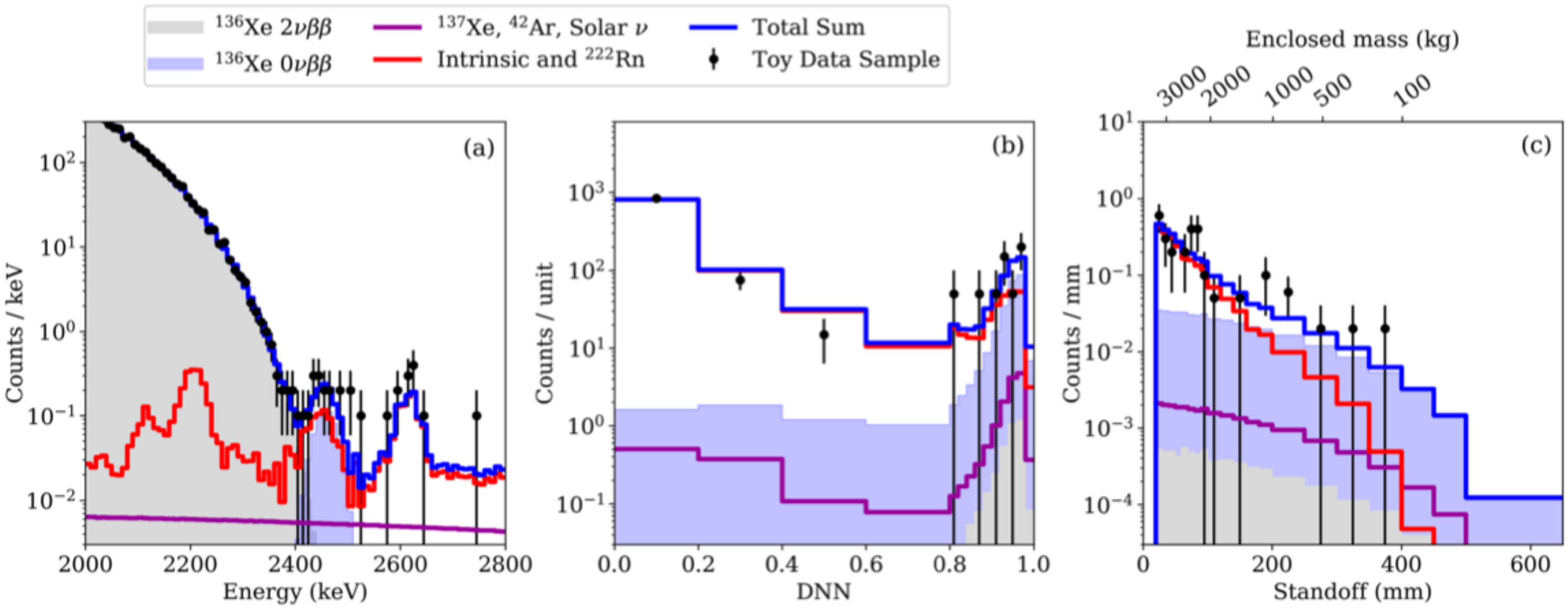


N.B.:
Dual-phase Xe TPCs (DM) with natural Xe also sensitive to $0\nu\beta\beta$

- LZ: >1.06×10^{26} years at 90% CL (PANIC2021)
- DARWIN: >2.4×10^{27} (EPJC 80, 808 (2020))

nEXO: topological info for signal and backgrounds

arXiv:2106.16243



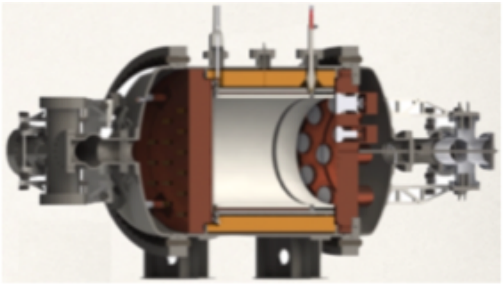
Energy distribution of single-site like events in central 2t of LXe

Topological info between ββ and γ events

Relative distance between a deposit and the nearest surface

^{136}Xe high-pressure gaseous TPC

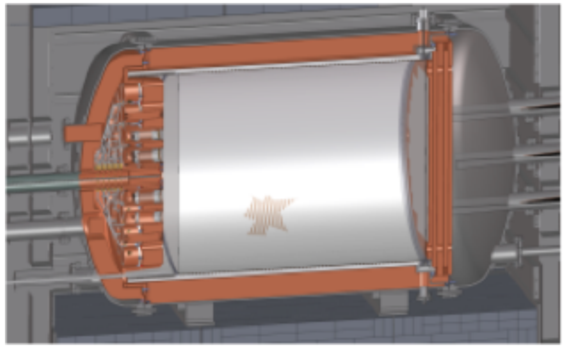
NEXT-NEW (5 kg) 2015-2020



Underground & radio-pure operations, background, 2νββ

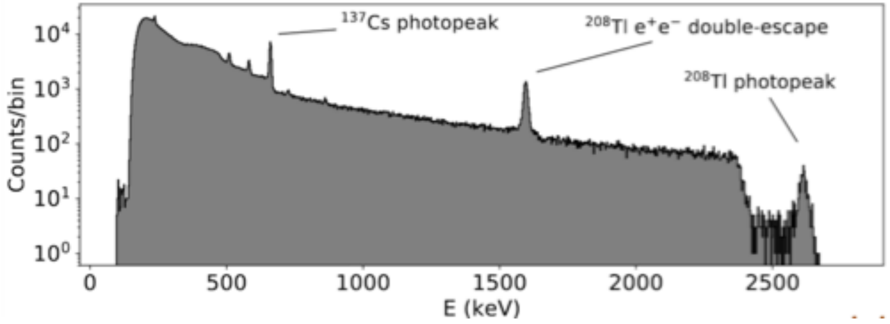
ΔE< 1% FWHM
Event topological reconstruction

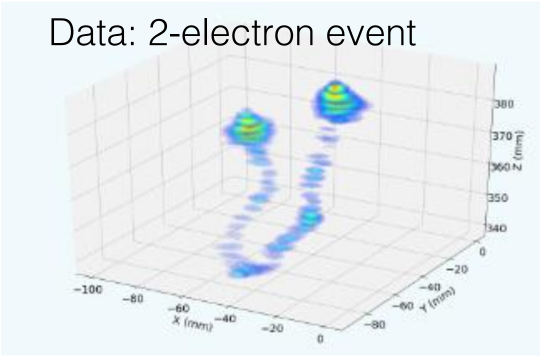
NEXT-100 (100 kg) 2022-2025



0νββ search

400 kg×y sensitivity 1×10^{26}y





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

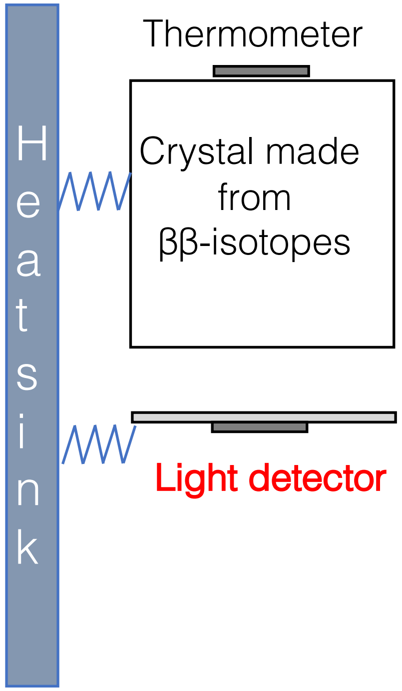
- Up to 1 ton enriched Xe gas @ 20 bar
- Replacement of PMTs by SiPMs
- Xe-He mixture: lower diffusion, better definition
- Target sensitivity: 2×10^{27} y (6 ton yr)

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

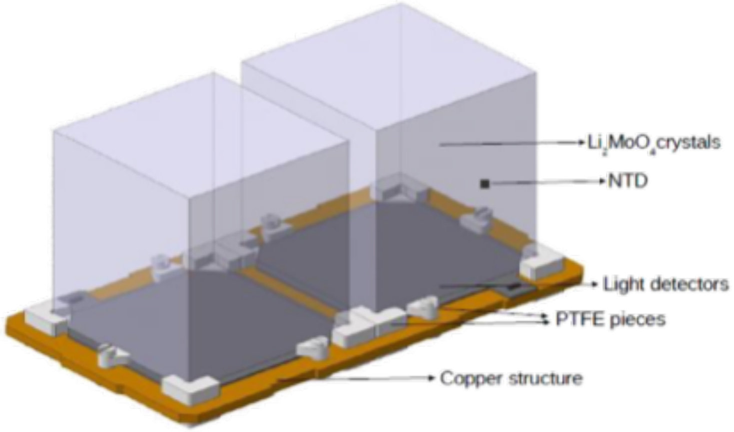
- HD including Ba-tagging by single-molecular-fluorescence imaging
- Background-free operation
- Target sensitivity: 8×10^{27} y (10 ton yr)

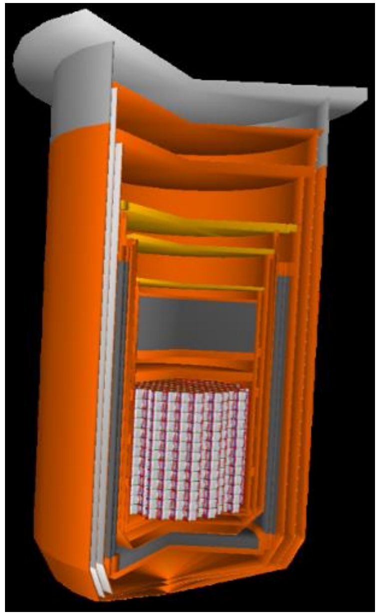
Phys. Rev. Lett. 120, 132504 (2018)

CUPID: ^{100}Mo cryogenic detectors @ LNGS



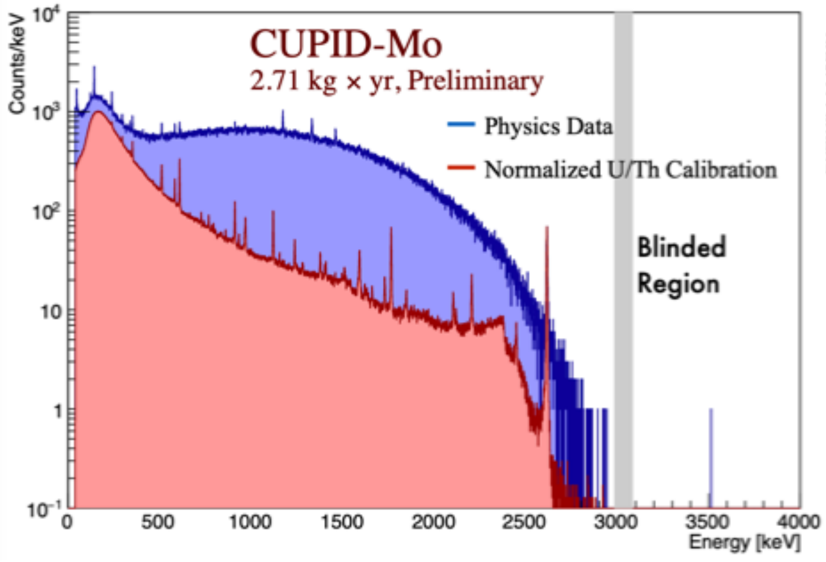
- Simultaneous read out of heat and light: surface alpha rejection
- Single module: $Li_2{}^{100}MoO_4$ 45×45x45 mm –> 280 g
- 57 towers of 14 floors with 2 crystals each -> 1596 crystals
- 240 kg of ^{100}Mo with >95% enrichment
- Bolometric Ge light detectors as in CUPID-Mo, CUPID-0
- Re-use CUORE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



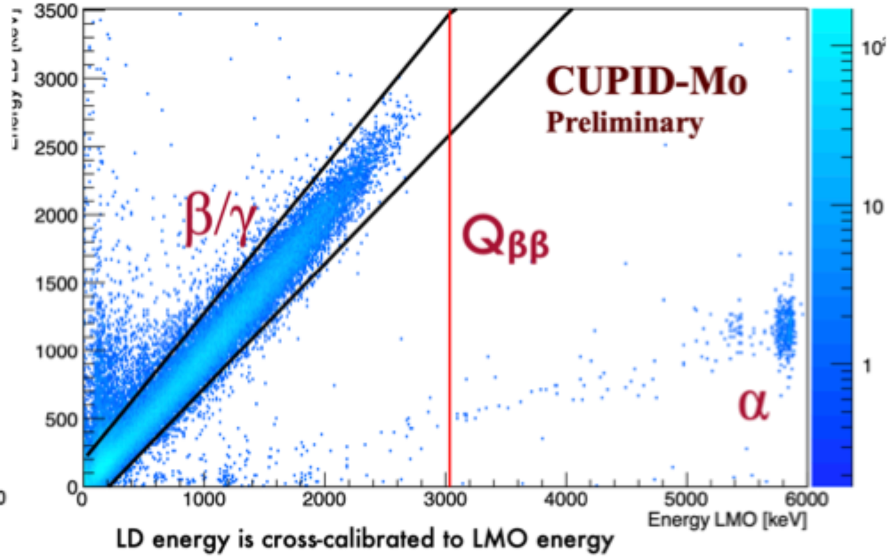


CUPID-Mo: ^{100}Mo cryogenic detectors R&D at LSM

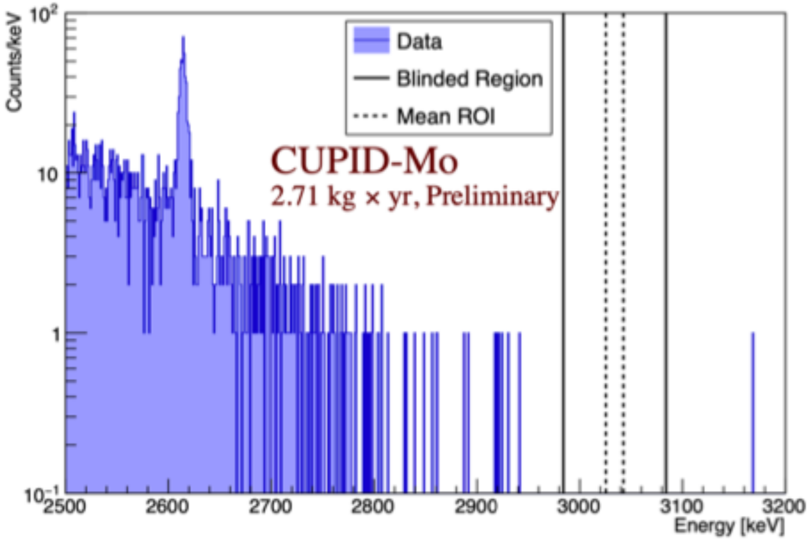
B. Welliver, TAUP2021



ΔE (FWHM): 7.2 keV @ 2.6 MeV



Removal of surface α's



Background-free operation in 2.7 kg yr

CUPID-Mo Preliminary

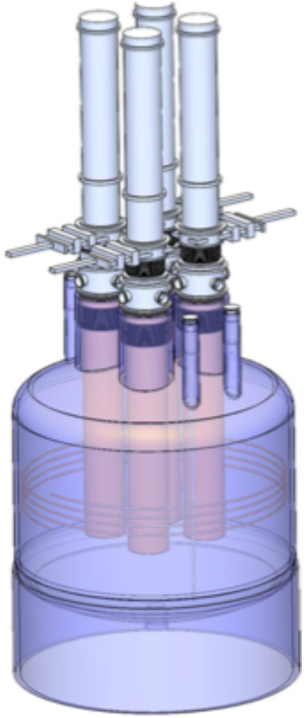
$$T_{1/2}^{0\nu} > 1.8 \times 10^{24} \text{ yr } (90\,\%\text{ C.I.})$$

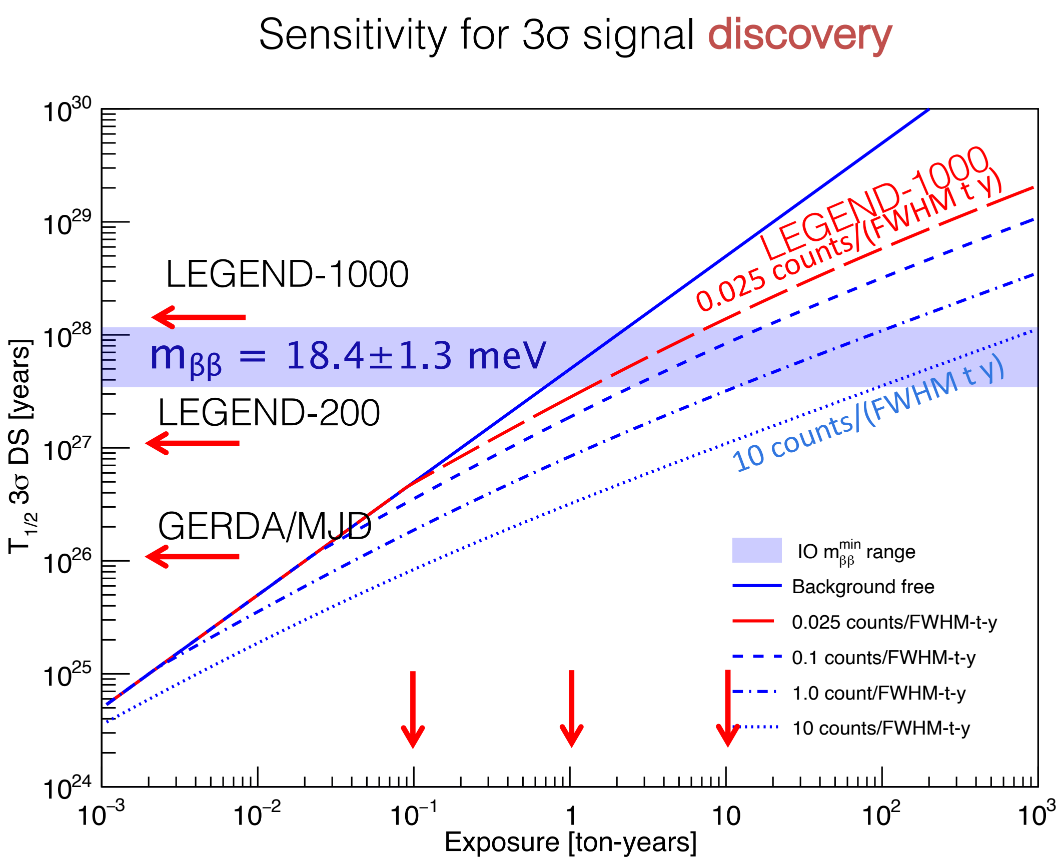
$$m_{\beta\beta} < 0.28 - 0.49 \text{ eV } (90\,\%\text{ C.I.})$$

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

LEGEND-200 (first phase):

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





LEGEND-1000 (second phase):

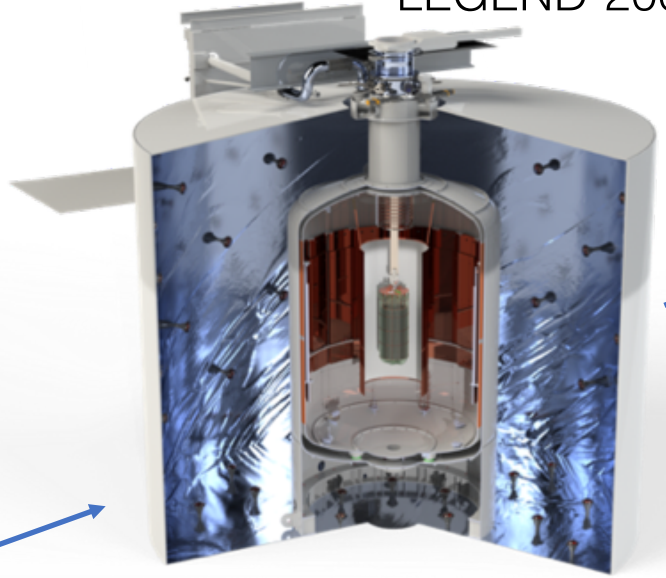
- 1000 kg of detectors (deployed in stages)
- BI <1E-5 cts/(keV kg yr)
- Location: SNOLAB / LNGS
- Design exposure ~10 t yr
- 3σ discovery sensitivity: 1.3 x10^{28} yr
- 90% C.L. excl. sensitivity: 1.6 x10^{28} yr

LEGEND: 76Ge HPGe detectors operated in liquid argon

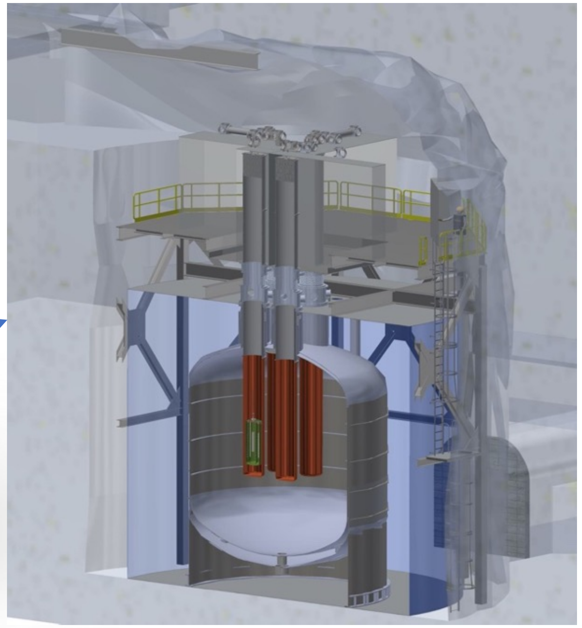
The LEGEND design builds on a track record of breakthrough developments

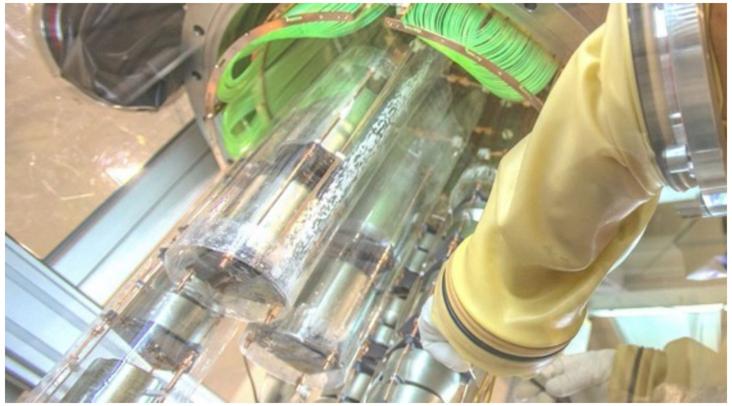
- GERDA : BEGe, LAr instrumentation, cryostat in water shield, fast detector deployment, …
- MAJORANA DEMONSTRATOR (MJD): PPC, EFCu, low-noise front-end electronics,…
- LEGEND-200 (start 2021): Inverted-Coaxial Point Contact (ICPC) detectors, polyethylene naphthalate (PEN)…

LEGEND-200



LEGEND-1000





GERDA

MJD

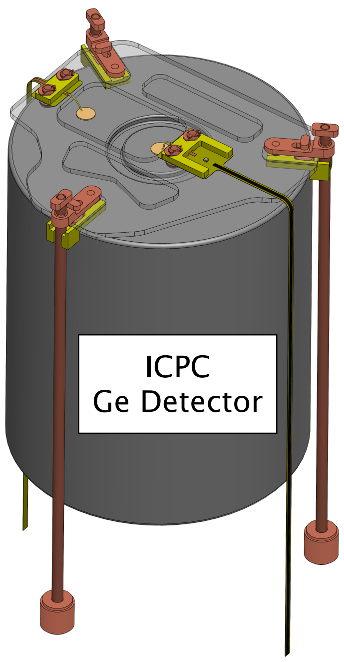
PPC: p-type Point Contact Ge detectors

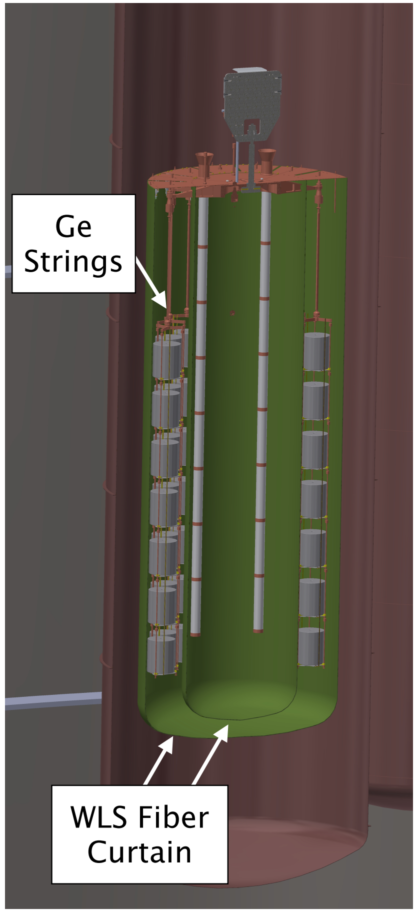
BEGe: (modified) Broad Energy Ge detectors

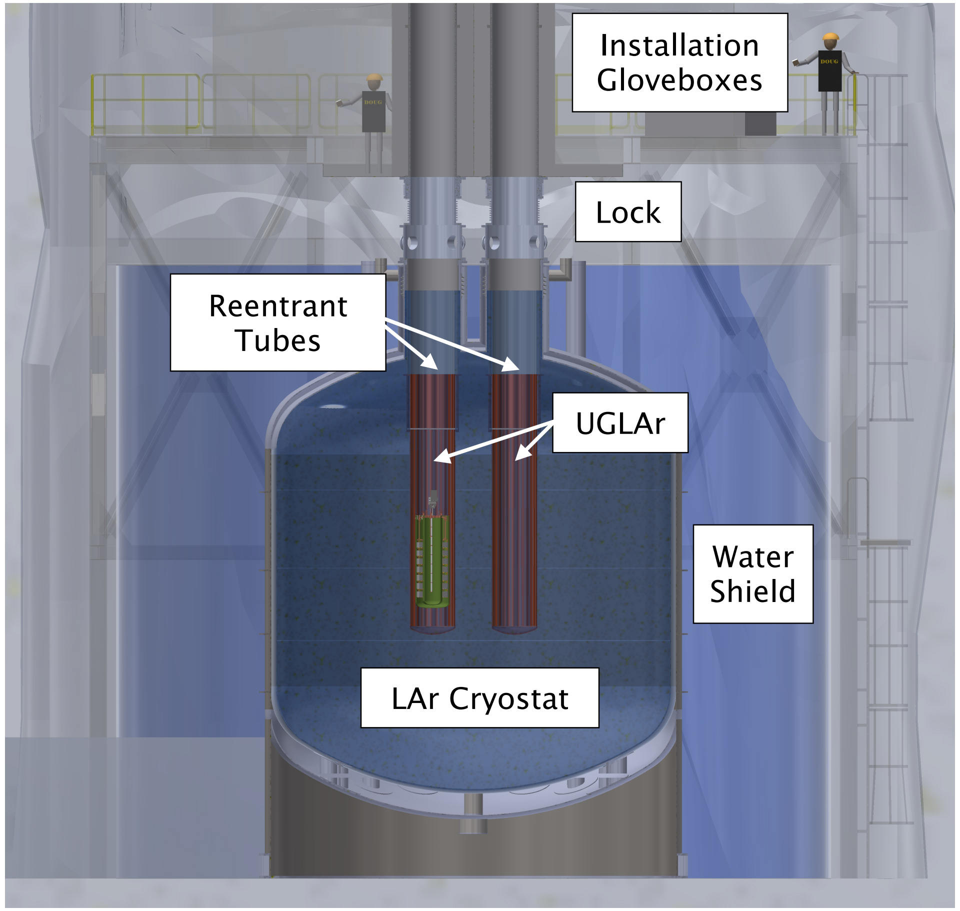
EFCu: Electroformed copper

LEGEND-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







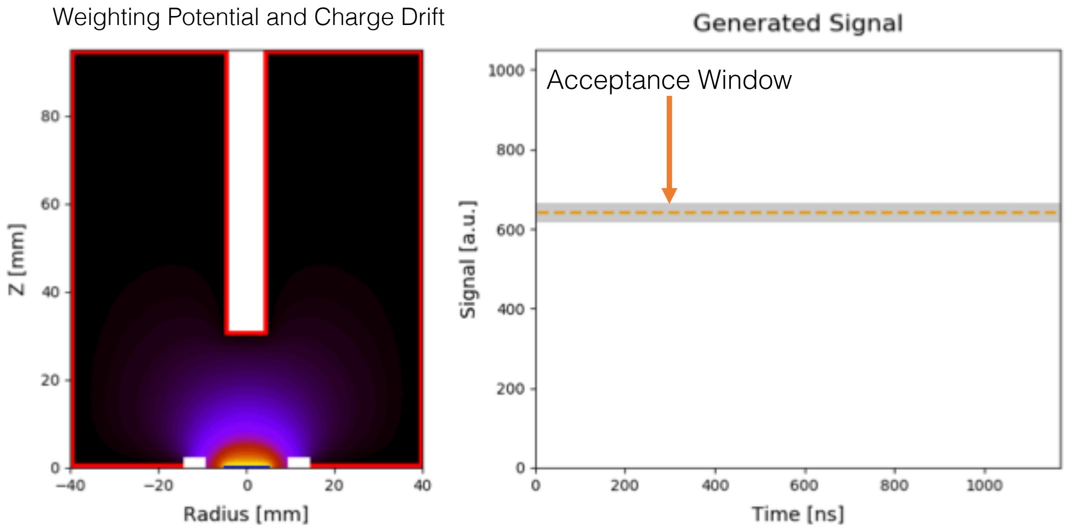
ICPC: Inverted-Coaxial Point Contact
WLS: Wavelength-shifting
UGLAr: Underground Liquid Ar

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

Innovation toward LEGEND-1000: Ge Detectors

Event Topologies

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



Charge signal

Current signal

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

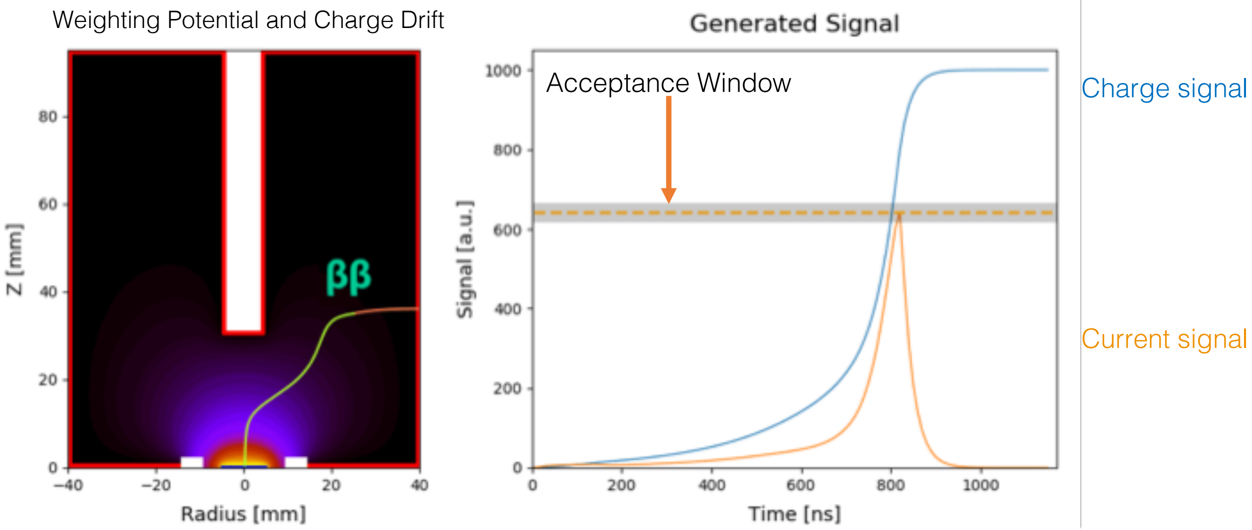
Weighting Potential: ϕ_w

N.B. animation only visible in pptx

Innovation toward LEGEND-1000: Ge Detectors

Event Topologies

0νββ signal candidate (single-site)



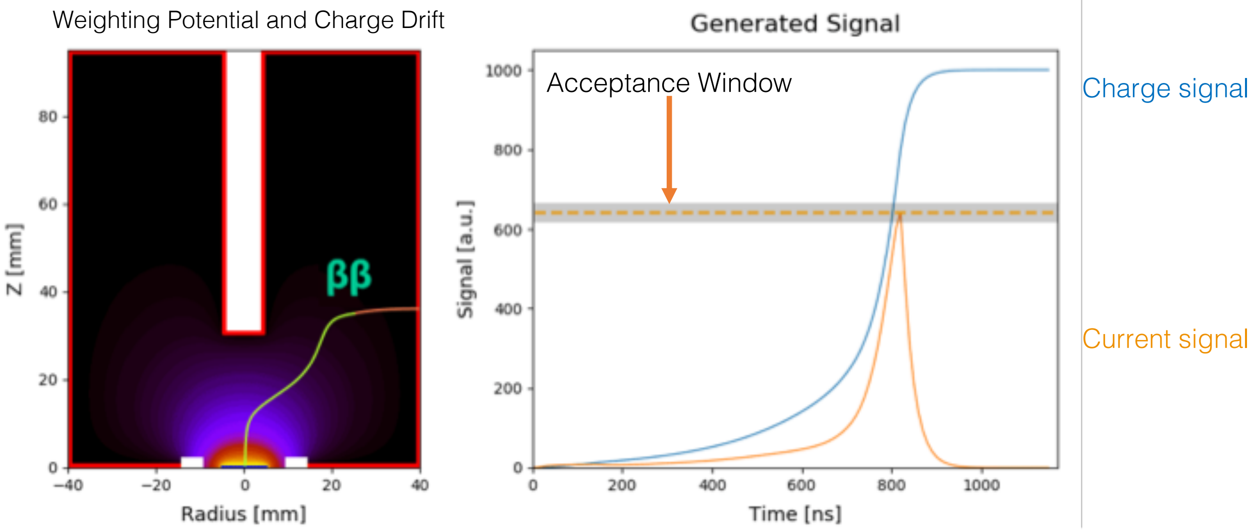
Shockley-Ramo Theorem: $Q(t) = -q\phi_w(\boldsymbol{x}_q(t))$

Weighting Potential: ϕ_w

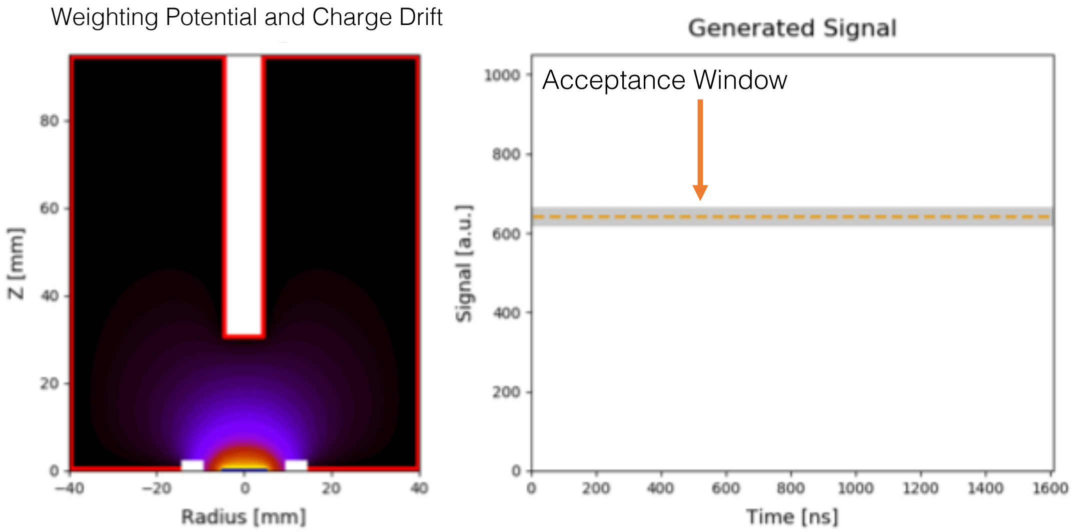
Innovation toward LEGEND-1000: Ge Detectors

Event Topologies

0νββ signal candidate (single-site)



γ-background (multi-site)



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

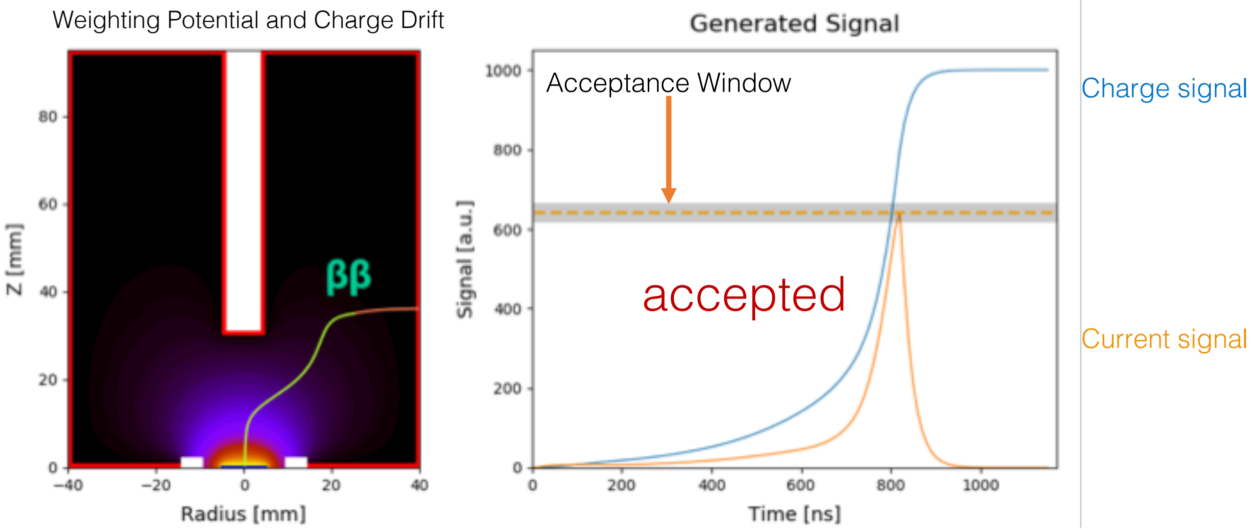
Weighting Potential: ϕ_w

N.B. animation only visible in pptx

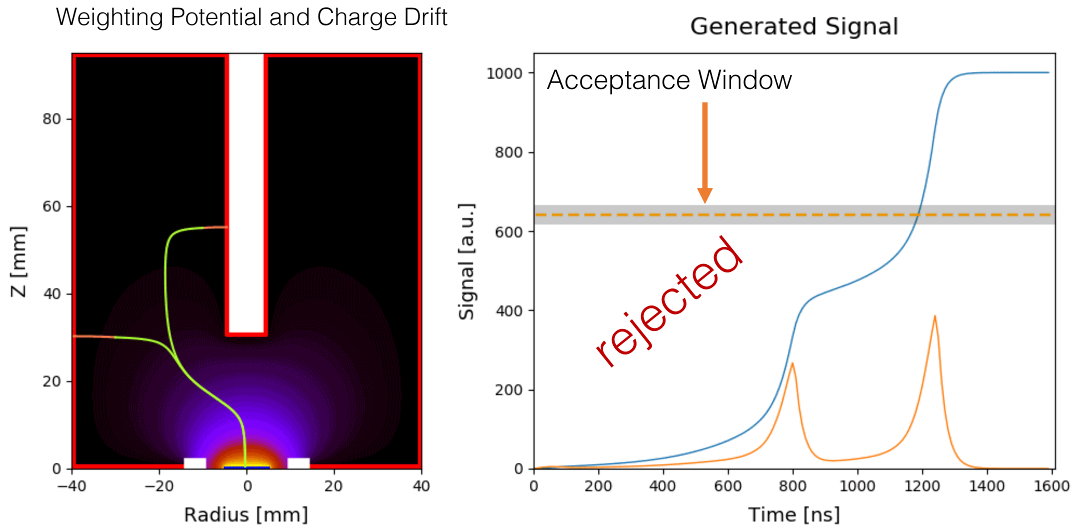
Innovation toward LEGEND-1000: Ge Detectors

Event Topologies

0νββ signal candidate (single-site)



γ-background (multi-site)



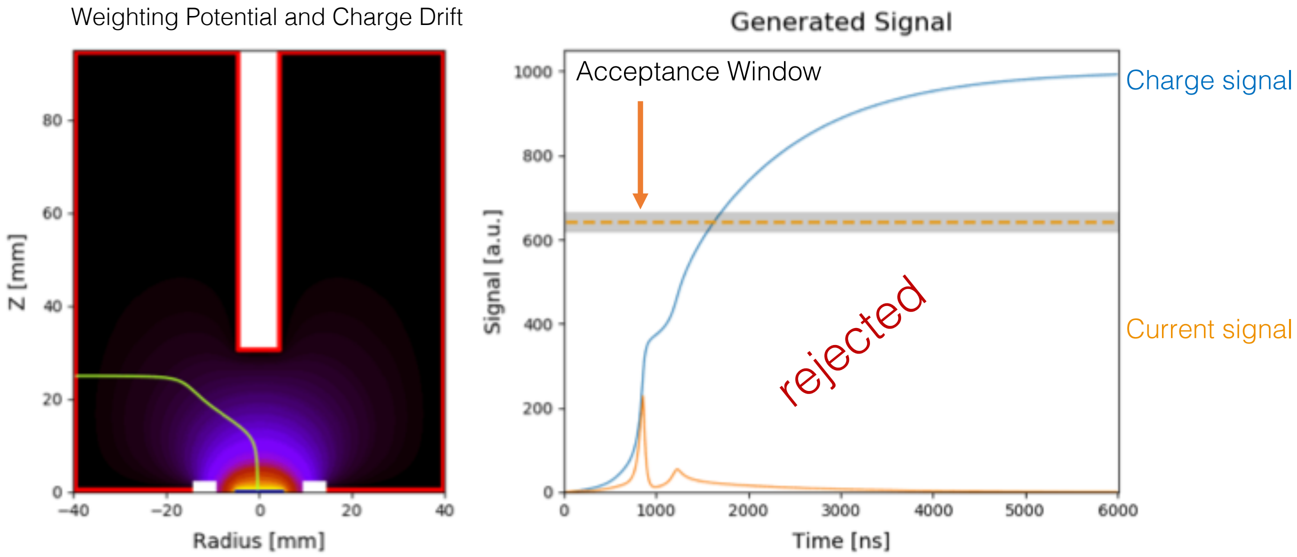
Shockley-Ramo Theorem: $Q(t) = -q\phi_w(\boldsymbol{x}_q(t))$

Weighting Potential: ϕ_w

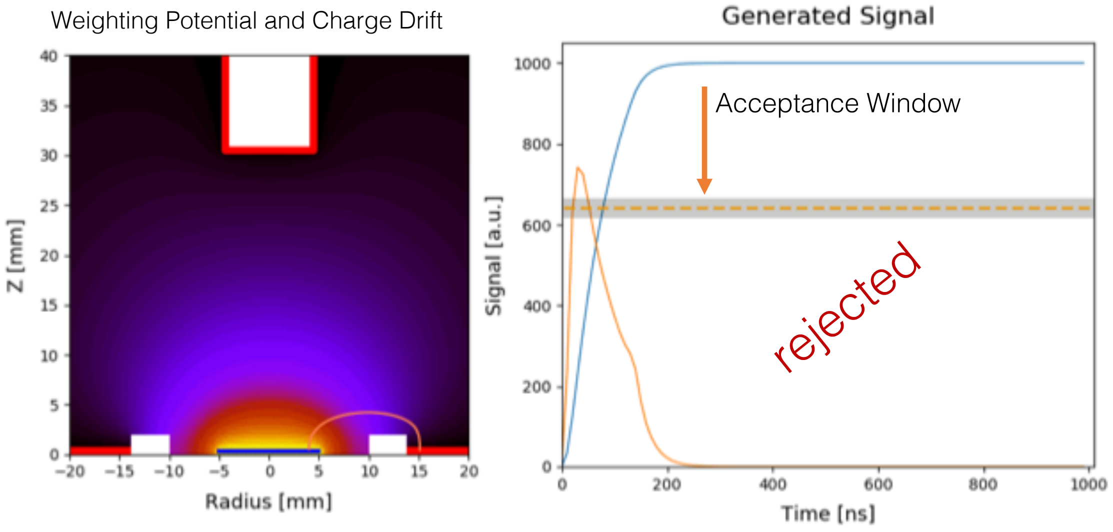
Innovation toward LEGEND-1000: Ge Detectors

Event Topologies

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



α-background on p+ contact



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

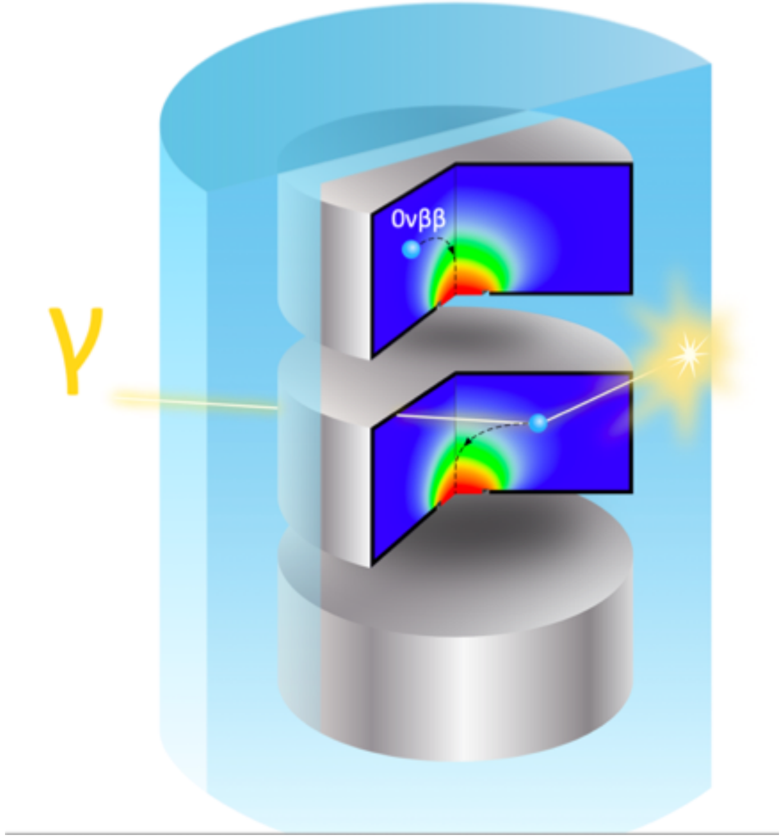
Weighting Potential: ϕ_w

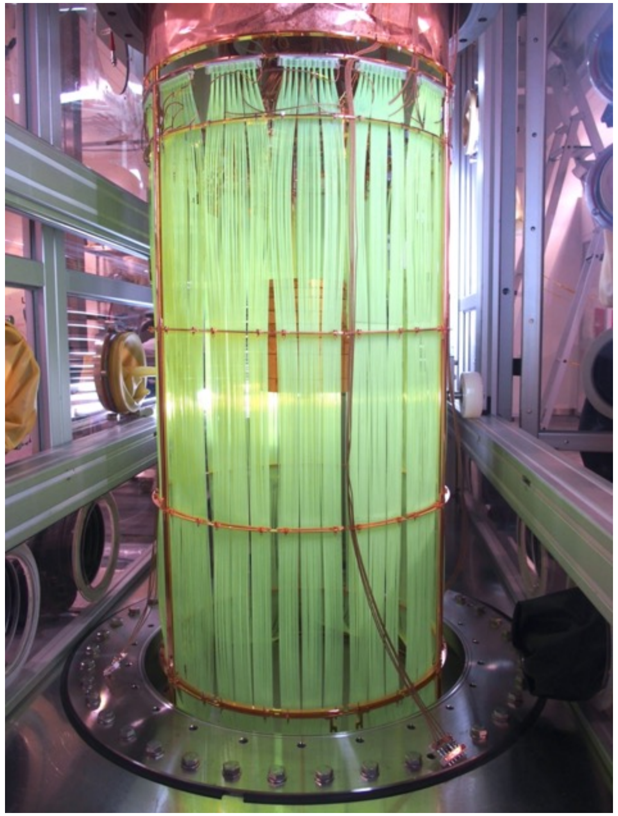
N.B. animation only visible in pptx

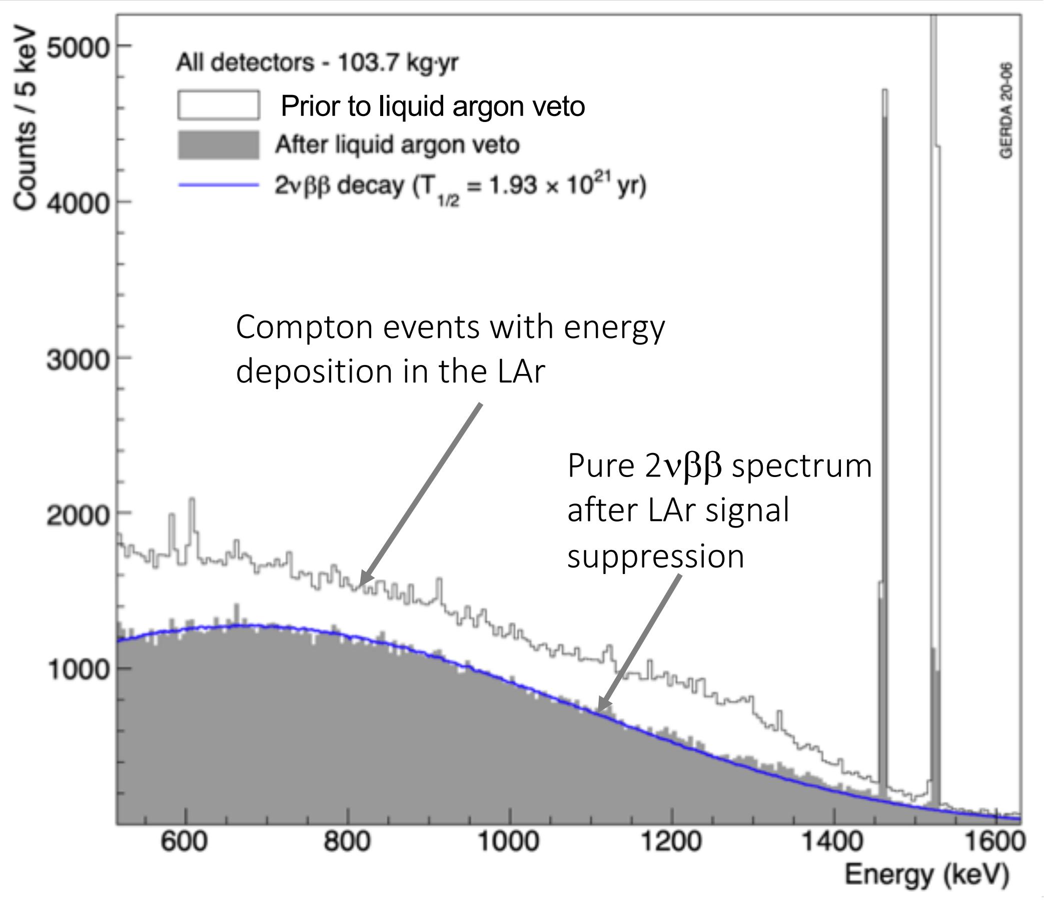
Innovation toward LEGEND-1000: LAr Instrumentation

GERDA: Detection of liquid argon scintillation light

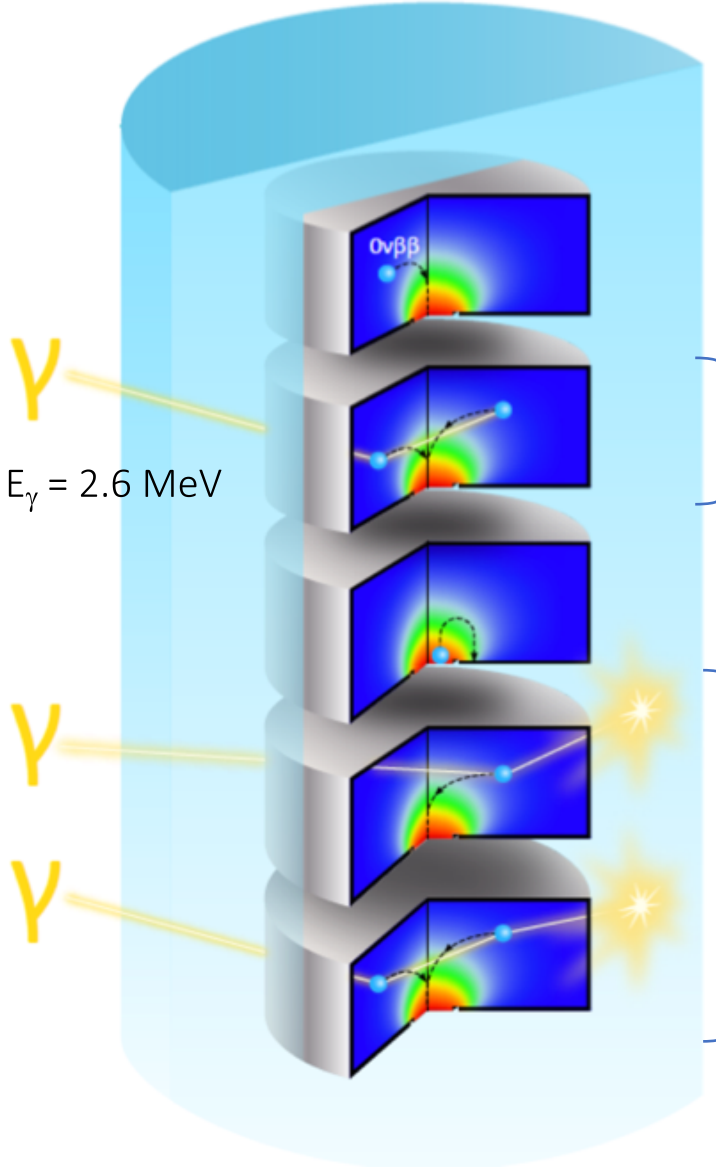
Low-background wavelength-shifting fibers and SiPM arrays for 128 nm single photon detection

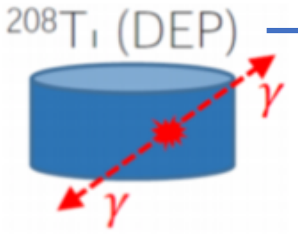


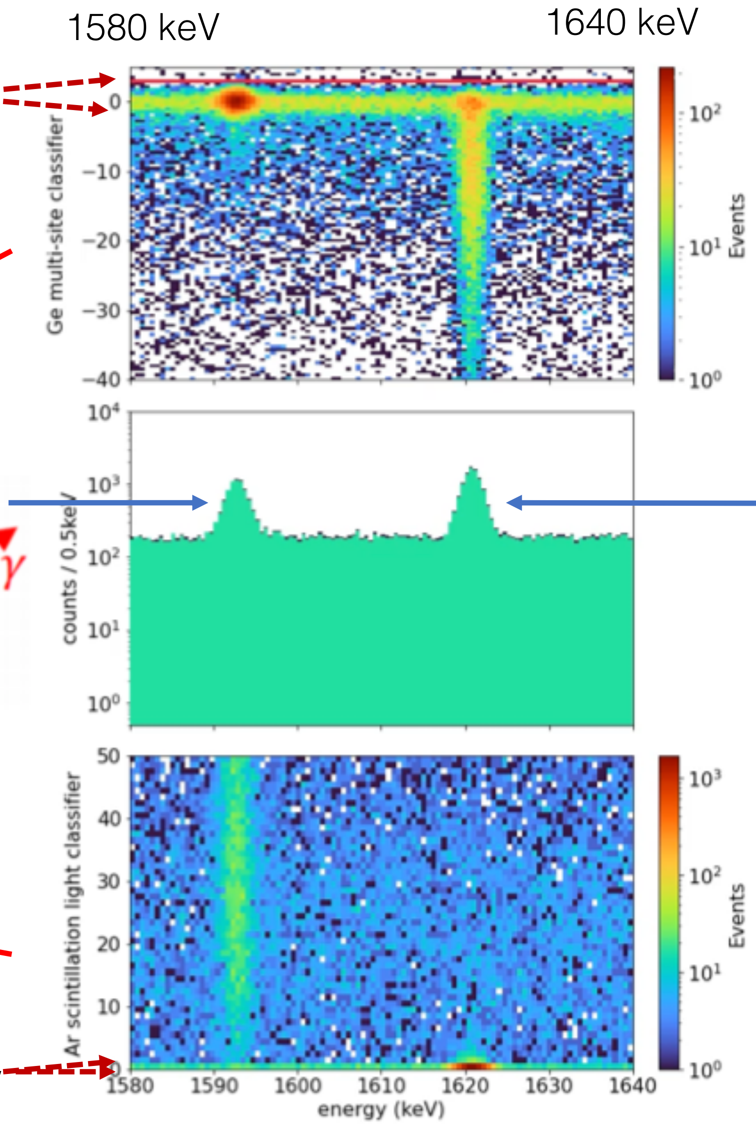


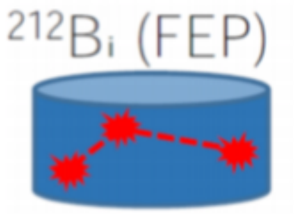


Innovation toward LEGEND-1000: LAr Instrumentation









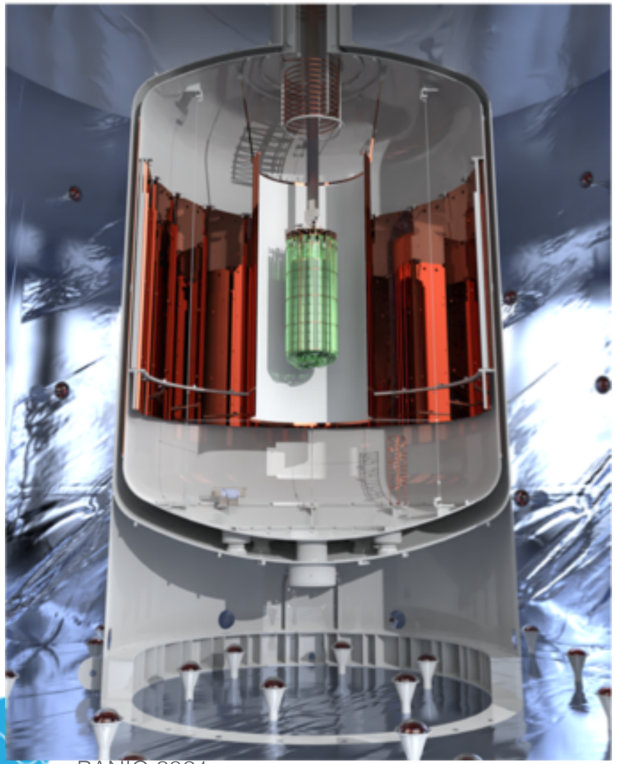
GERDA ^{228}Th calibration data (2.6 MeV γ line)

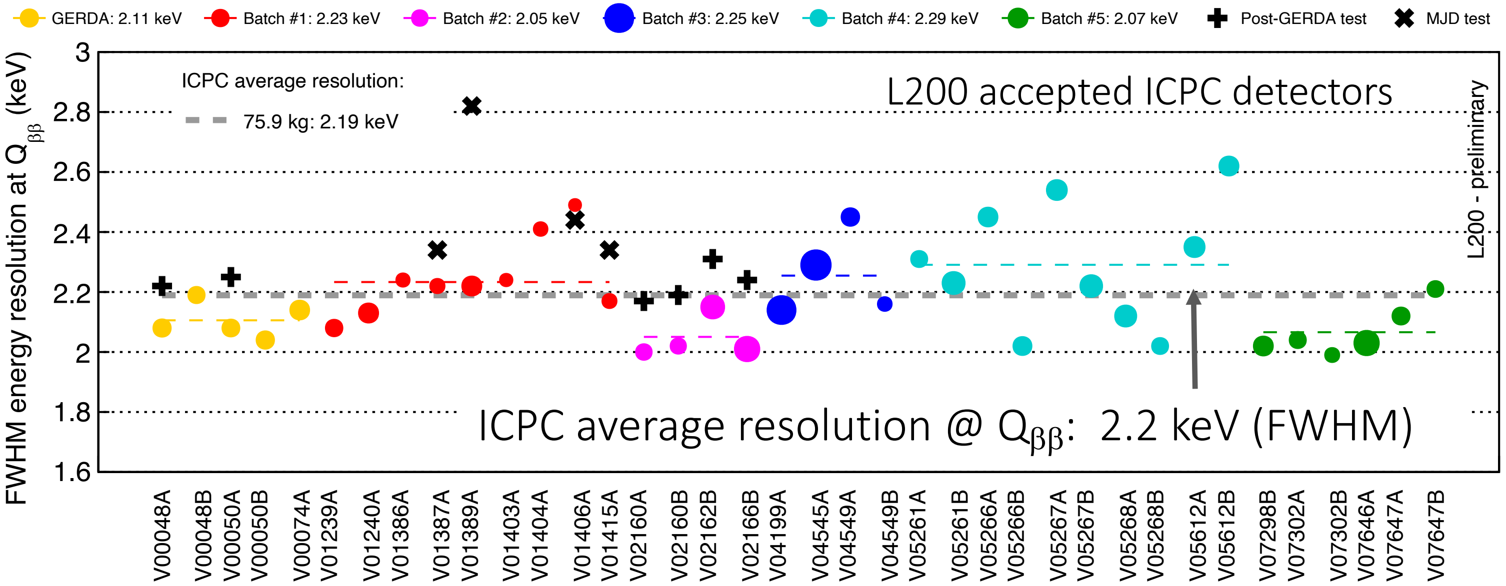
Figure 14, page 24

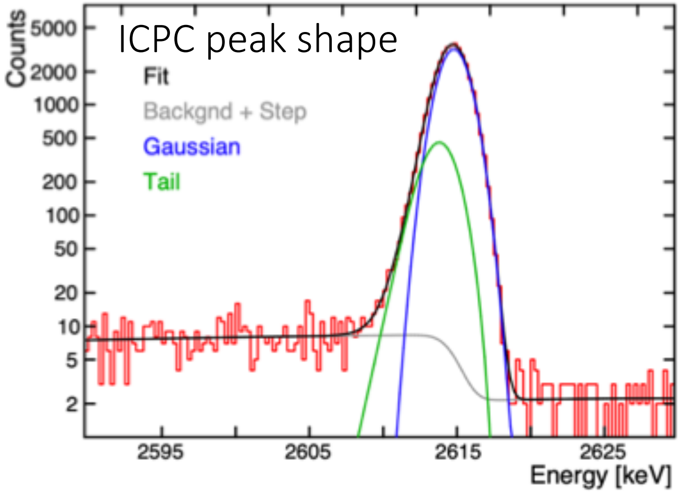
DEP: Double-escape peak
FEP: Full-energy peak
Animation only visible in pptx

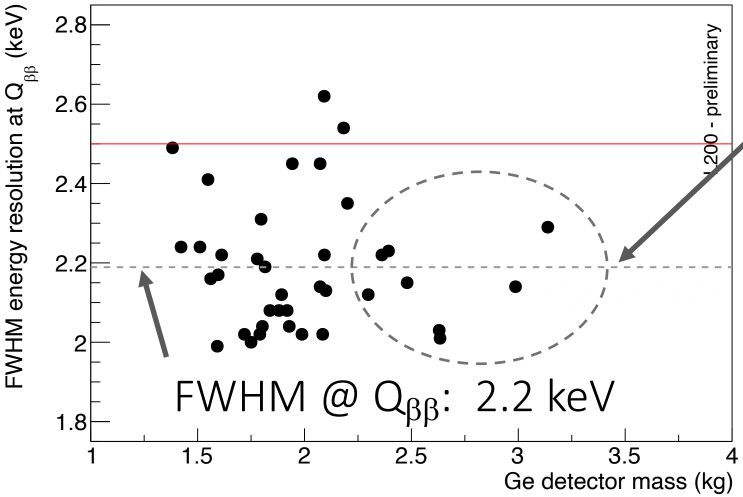
LEGEND-200

- Procurement of ^{76}Ge (92% enr.)
- Novel ICPC detectors
- Improved LAr system
- Low-background materials
- Commissioning 2021



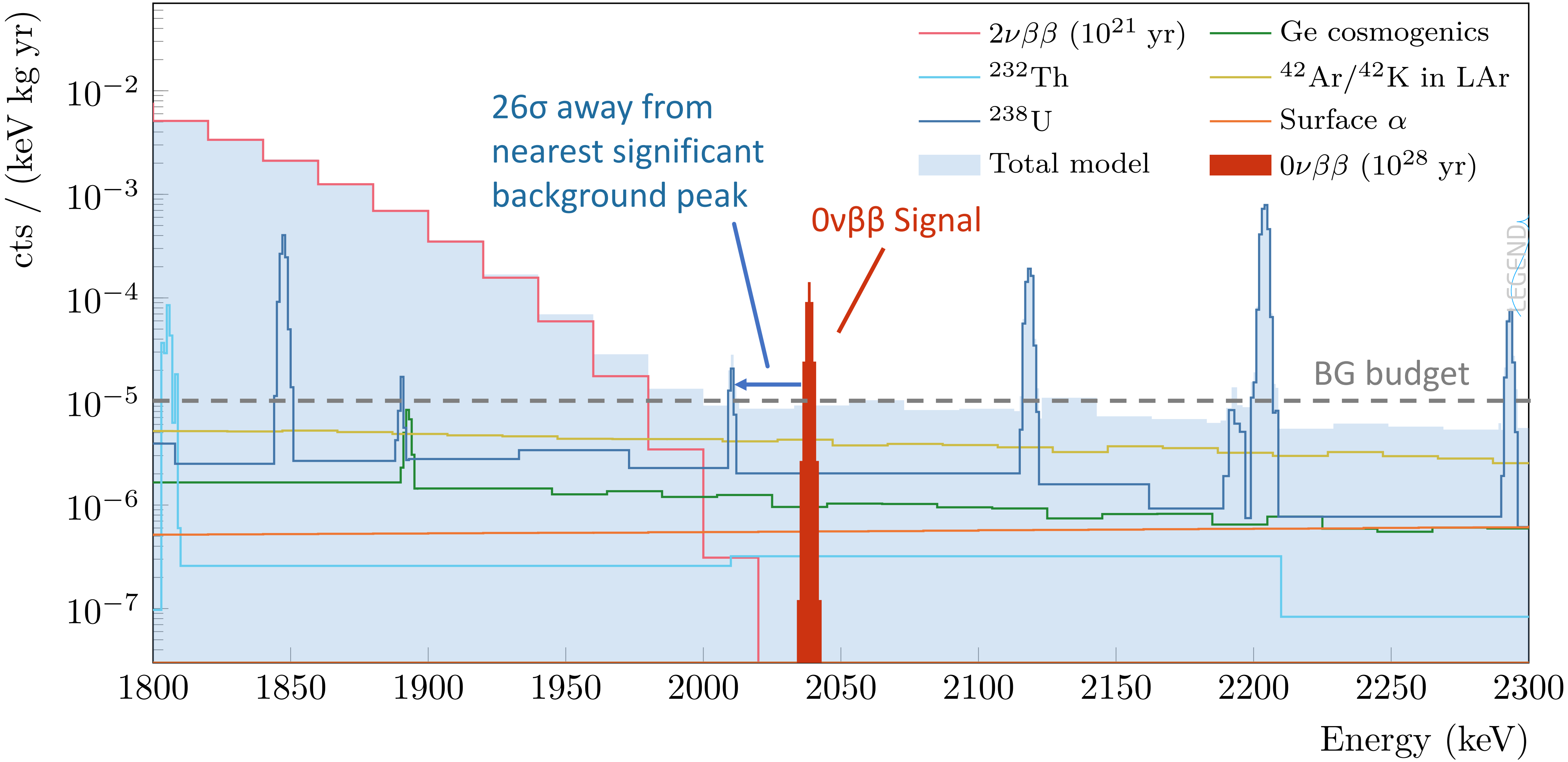






Large mass detectors show excellent energy resolution

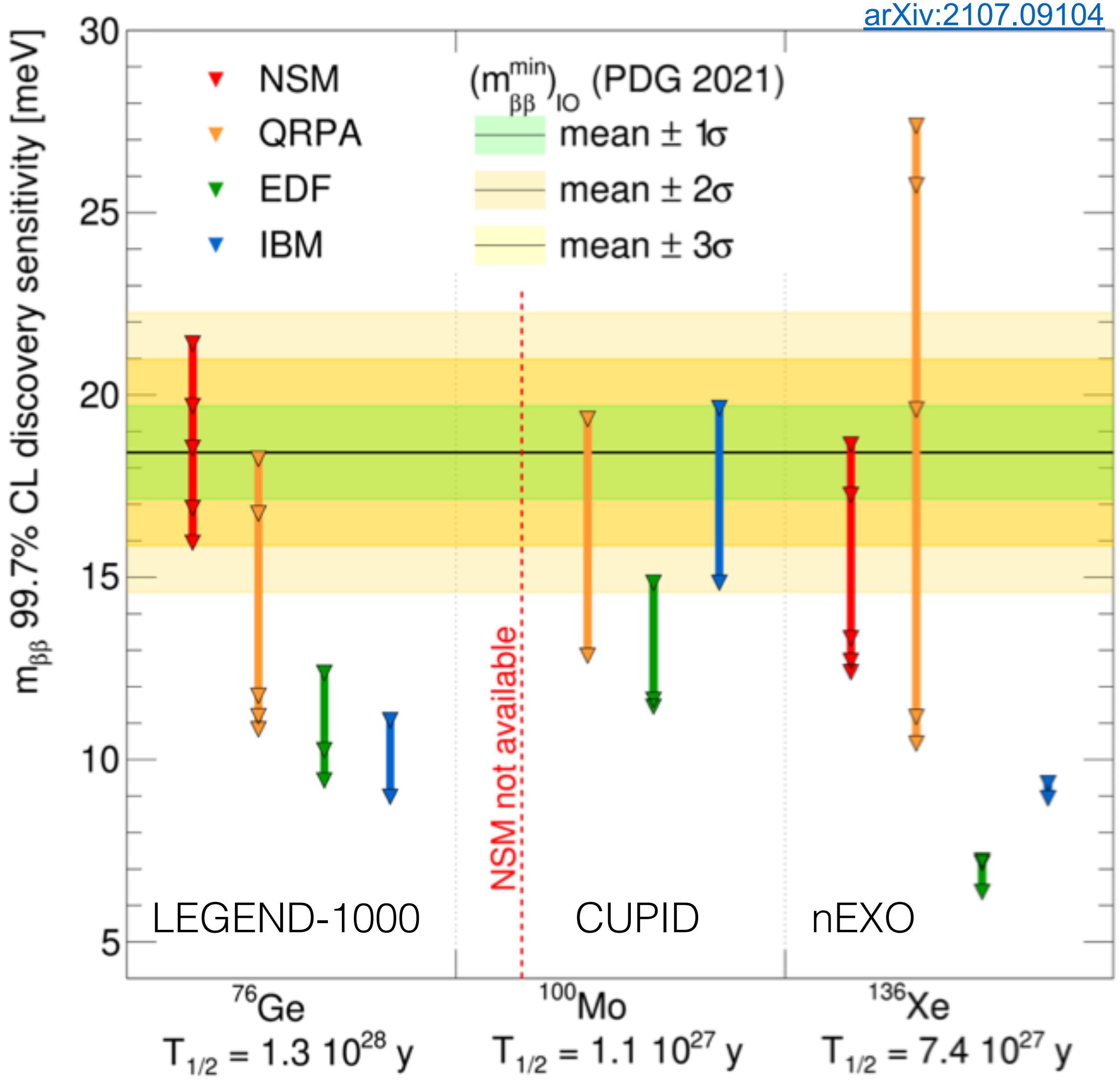
The LEGEND-1000 Background Model



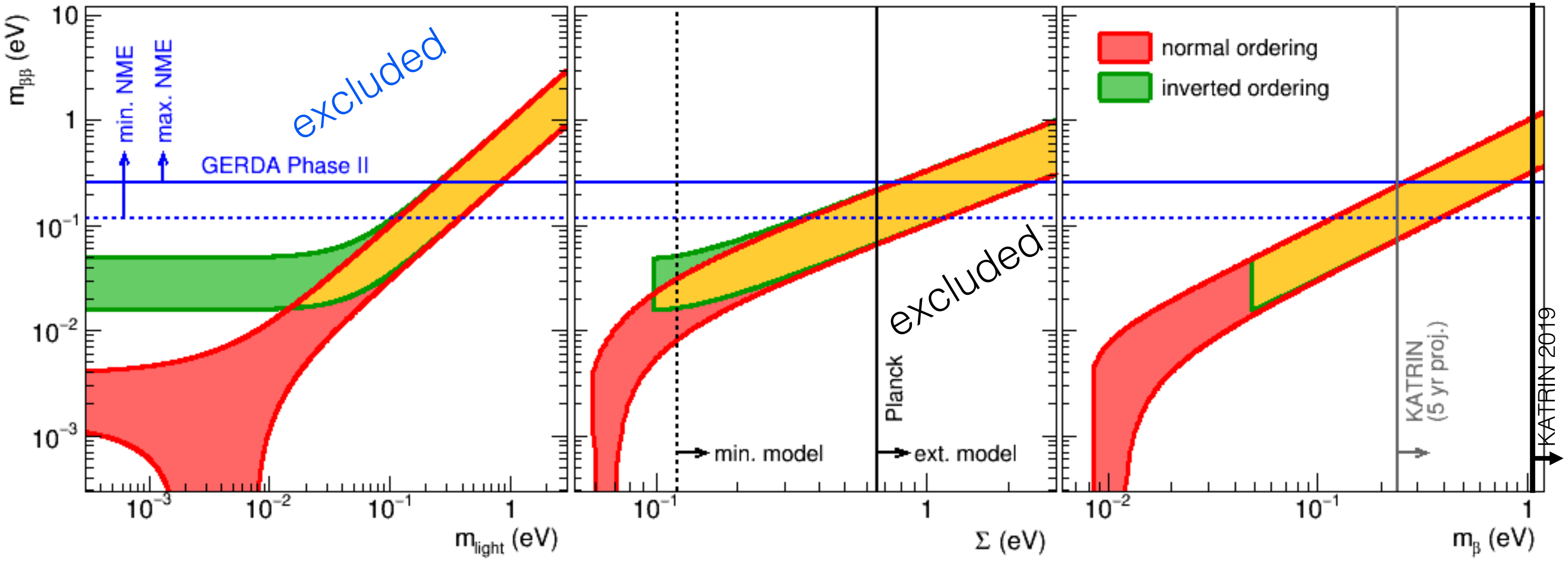
Sensitivity $m_{\beta\beta}$

- $m_{\beta\beta} = m_e / \sqrt{G\, g_A^4\, M^2\, T_{1/2}}$
- Inverted ordering (IO): $m_{\beta\beta} > 18.4 \pm 1.3$ meV
- M ➜ 4 many-body methods, each with specific systematics
- Multiple, different set of calculations for each many-body method and isotope
- All next-generation experiments designed for a discover sensitivity at the IO
- Preliminary Conceptual Design Reports available:
  - nEXO: arXiv:1805.11142, 2106.16243
  - CUPID: arXiv:1907.09376
  - LEGEND-1000: arXiv:2107.11462

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



Current sensitivities probe quasi-degenerate mass spectrum



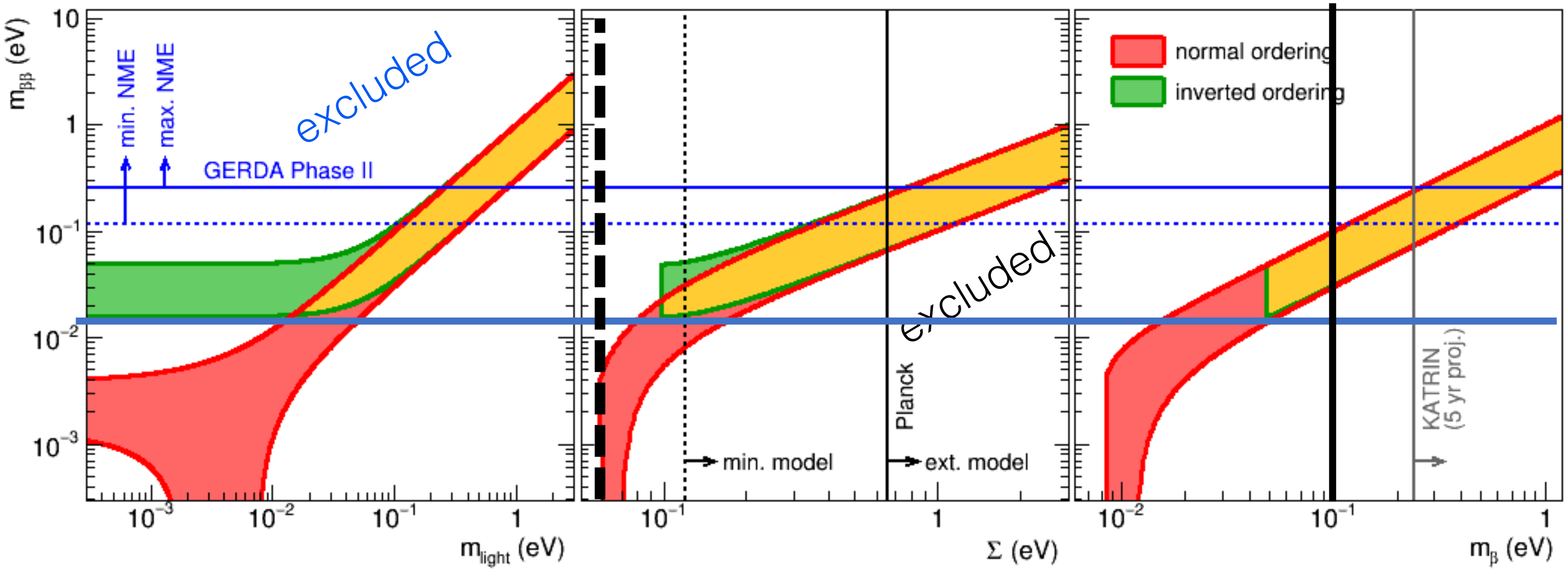
0νββ

cosmology

tritium beta decay

Science, 05 September 2019

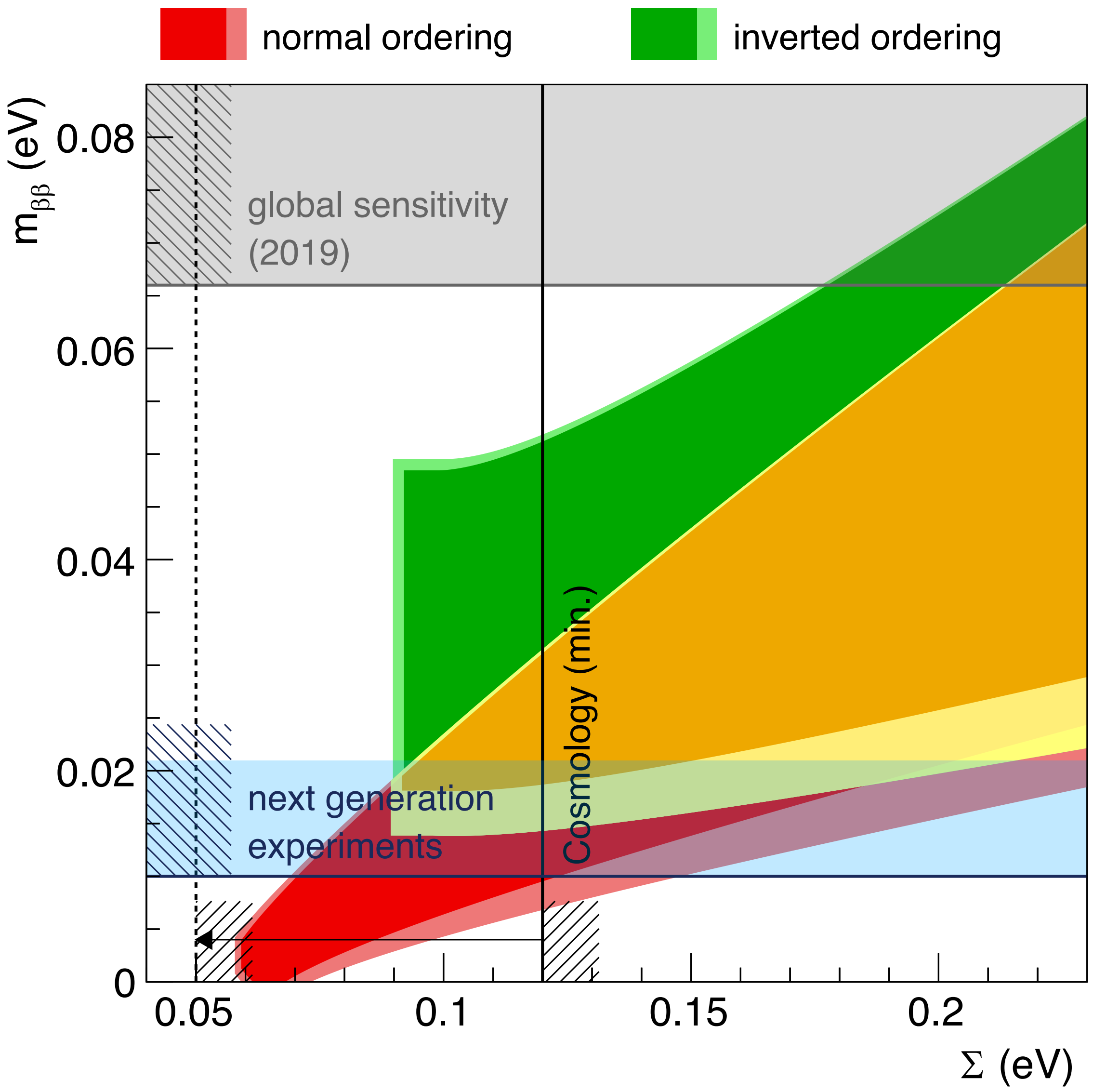
Next decade: large phase space for discoveries

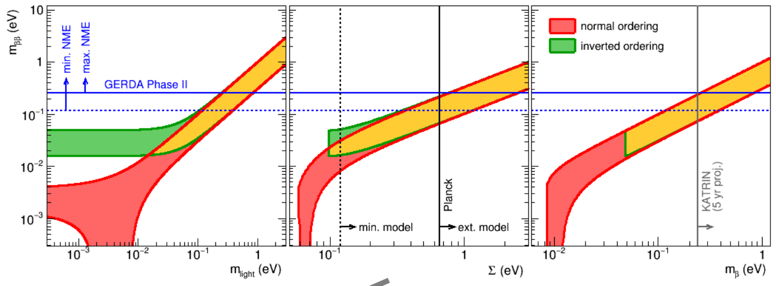


$0\nu\beta\beta$ cosmology tritium beta decay

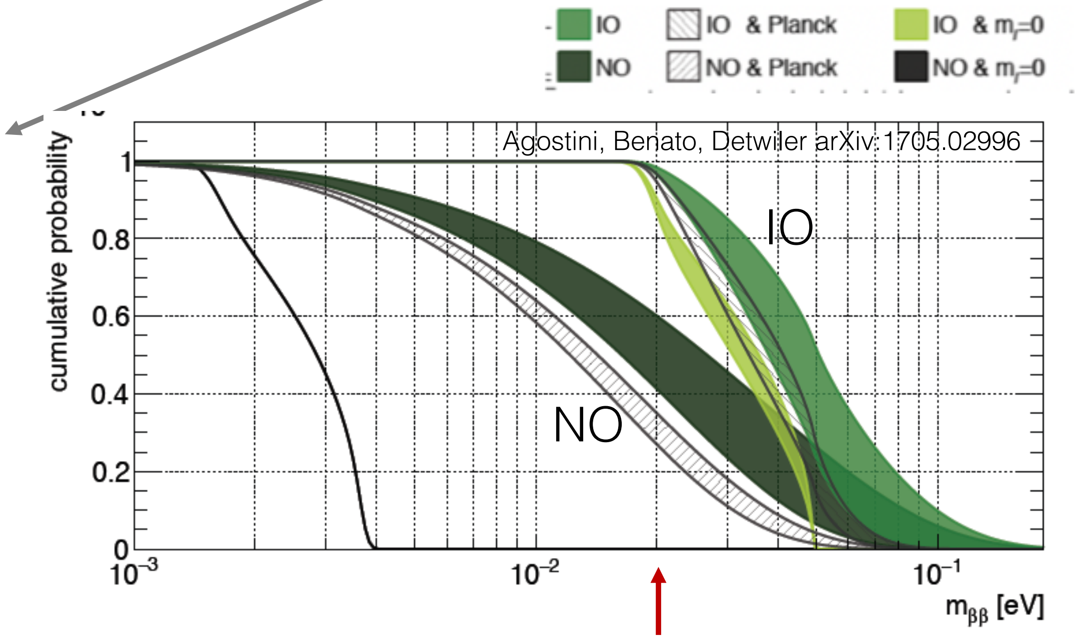
Science, 05 September 2019

Next decade: large phase space for discoveries





Linear projection



~50% of NO parameter space tested

Conclusions & outlook

- Community strives for several ton-scale experiments to increase $t_{1/2}$ discovery sens. by x100 w.r.t. best current limits
- Different isotopes and technologies required
- Technologies are mature (pCDRs available for CUPID, LEGEND-1000, nEXO)
- Next-generation experiments designed for discovery
- North-American European coordination efforts:
    - NSAC Subcommittee on neutrinoless double beta decay, 2015
    - Double Beta Decay APPEC Committee Report 2019 arXiv:1910.04688
    - DOE portfolio review, July 2021 (CUPID, LEGEND, nEXO)
    - North-American European Summit, Sept. 2021 (CUPID, LEGEND, nEXO, NEXT) at LNGS
- Independent programming in Asia (KL2Z, Amore, CDEX, JUNO, …)