Neutrinoless double beta decay & direct neutrino mass measurements

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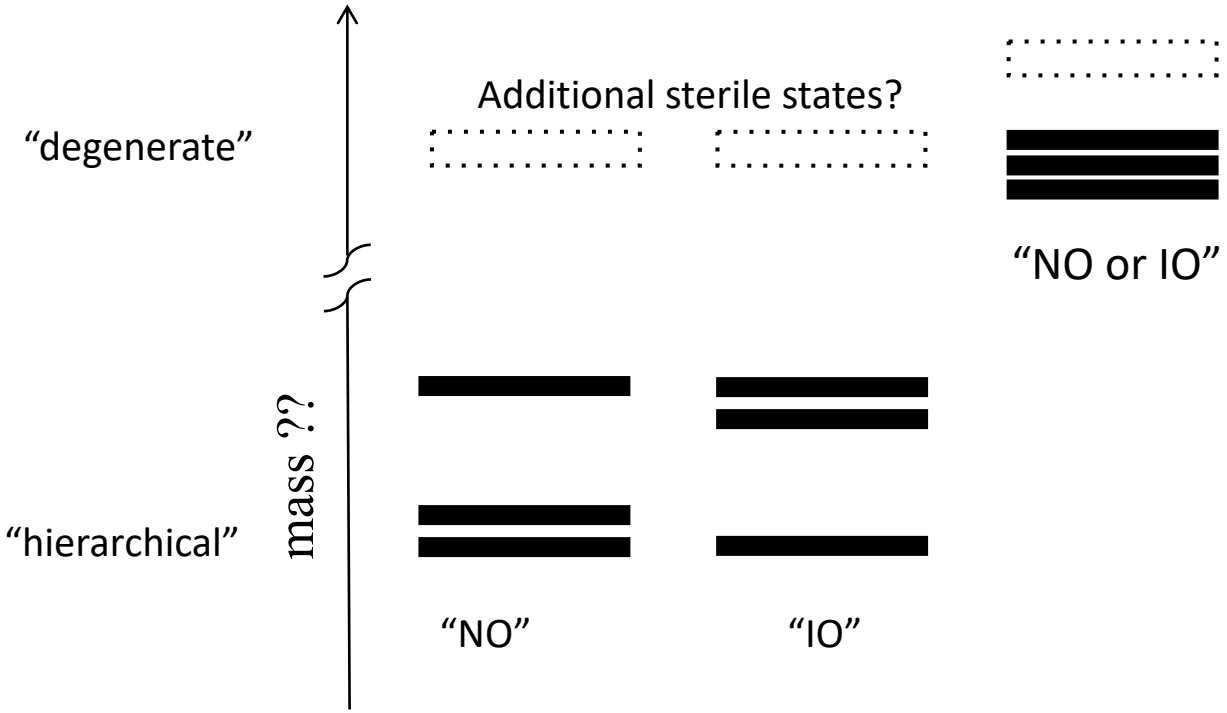
TECHNISCHE UNIVERSITÄT MÜNCHEN

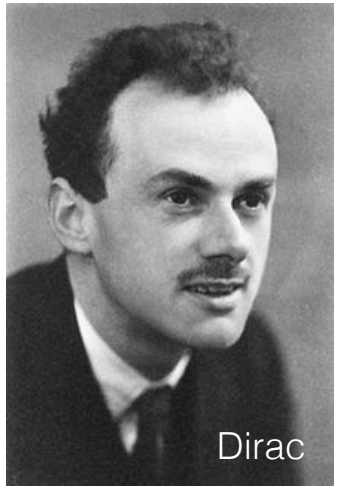
SFB 1258 Neutrinos Dark Matter Messengers

erc

What is the neutrino mass scale?



How are neutrino masses generated ?



- Is lepton number violated?
  No reason for global symmetries to be exact!
  [e.g Edward Witten, arXiv:1710.01791]
- Are neutrinos their own anti-particles?
- Why are neutrinos so much lighter than charged leptons ?
- What is the origin of the matter anti-matter asymmetry ?

Laboratory mass probes

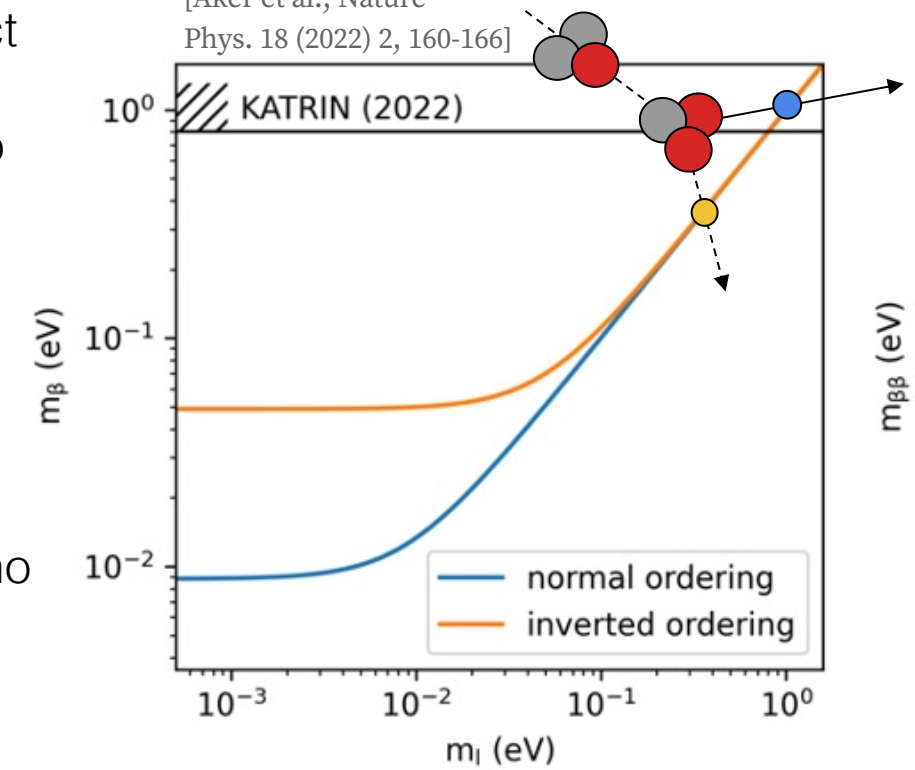
- **β-decay kinematics**, direct mass measurement, effective electron neutrino mass

$$m_\beta = \sqrt{\sum_i |U_{ei}^2| m_i^2}$$

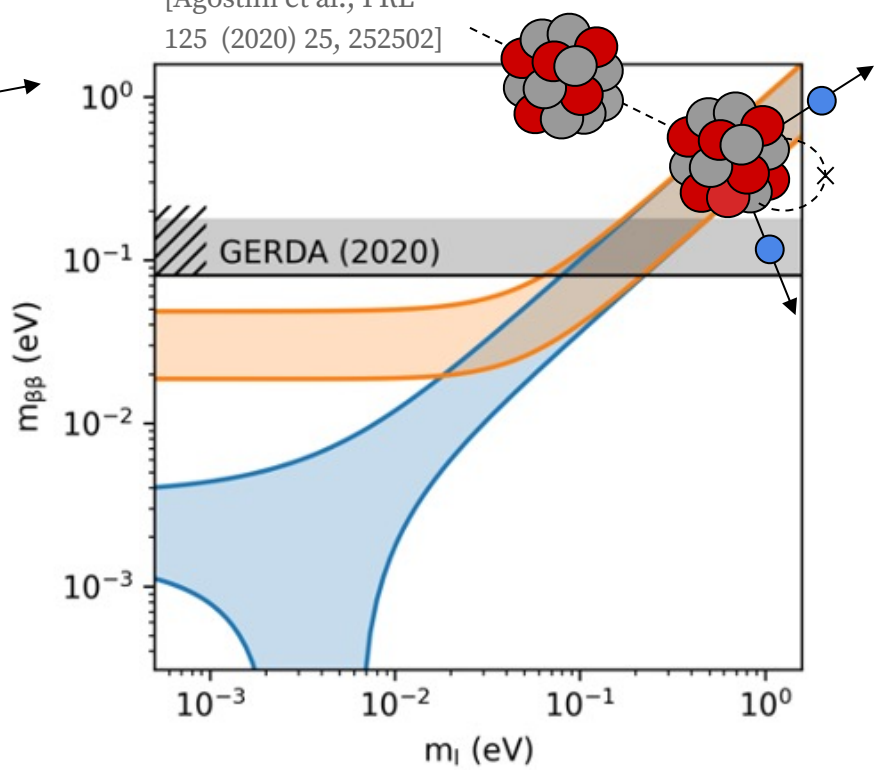
- **neutrinoless ββ-decay**, effective Majorana neutrino mass

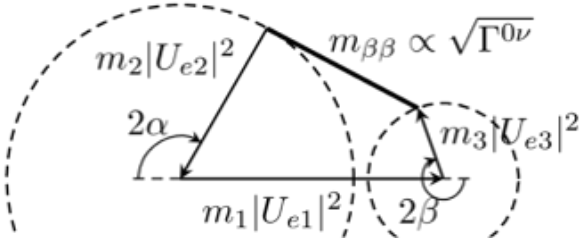
$$m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$$

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



[Agostini et al., PRL 125 (2020) 25, 252502]





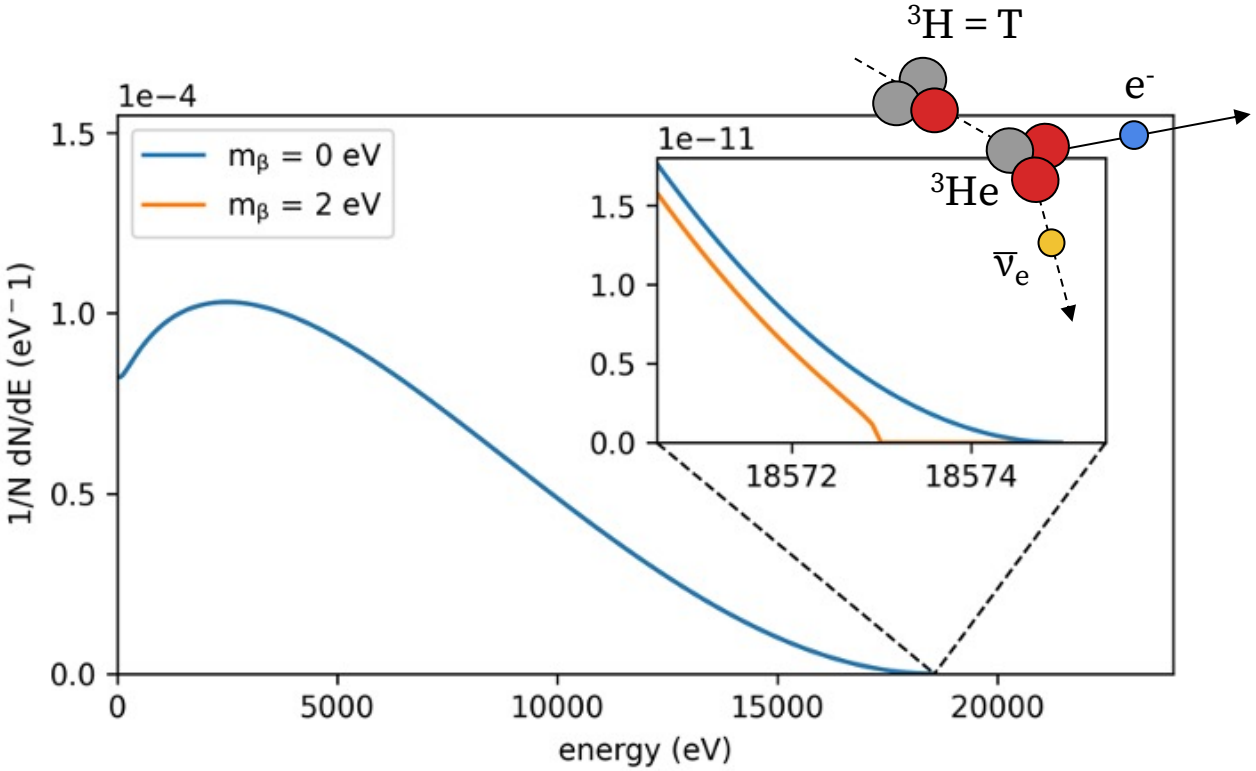
[Bilenky, Pascoli, Petkov, PRD 64 (2001) 053010]

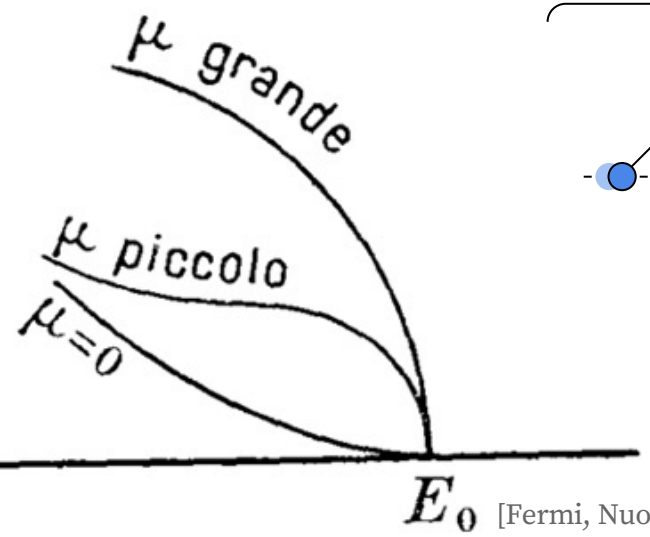
β-decay* kinematics

*or electron capture

measure **spectral distortion**, maximal at endpoint

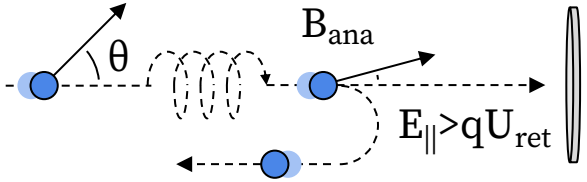
- **high activity** radioactive source, **low Q-value**
- excellent **energy resolution** (eV), low **background** (mcps)
- **high precision** understanding of theoretical spectrum and experimental response



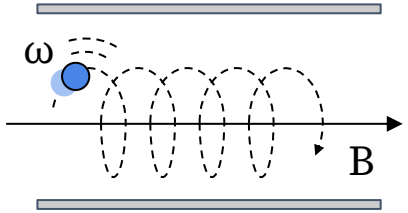


[Fermi, Nuovo Cim. 11 (1934) 1-19]

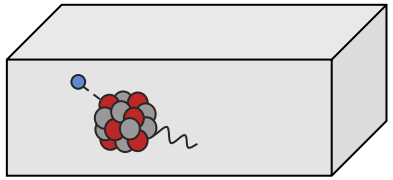
tritium



electrostatic **filter** (MAC-E)



cyclotron radiation emission spectroscopy (CRES)

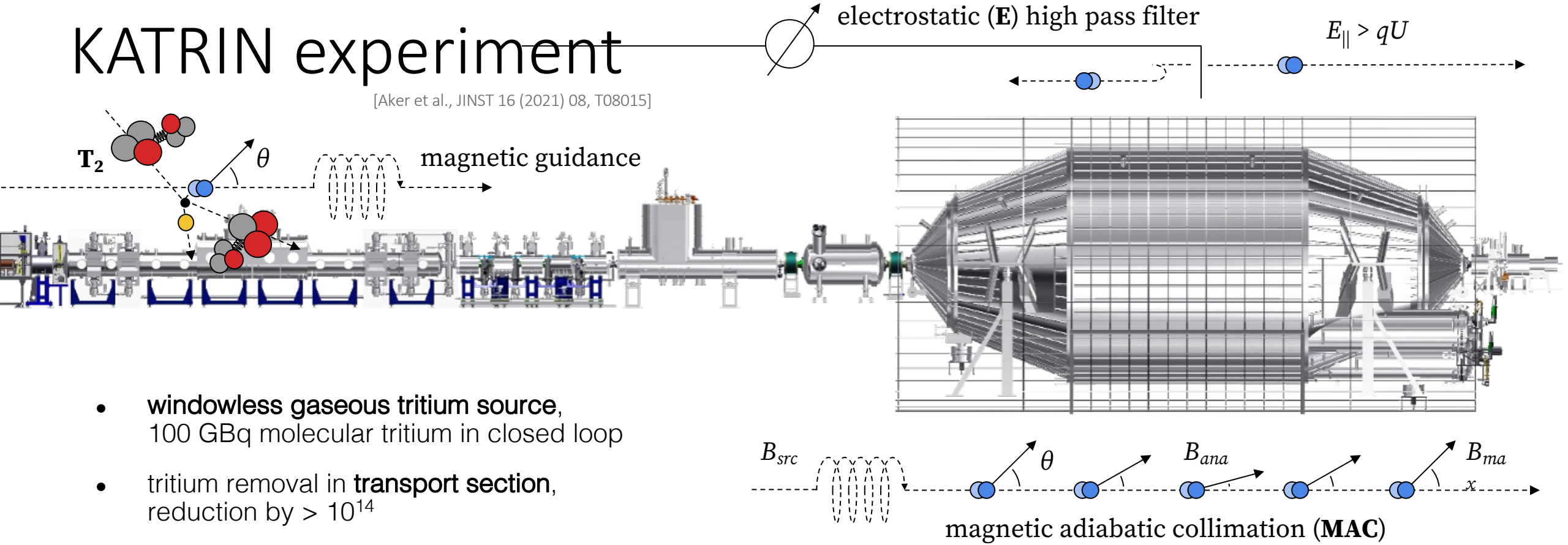


cryogenic **calorimeters**

R & D

KATRIN experiment

[Aker et al., JINST 16 (2021) 08, T08015]



- **windowless gaseous tritium source**, 100 GBq molecular tritium in closed loop
- tritium removal in **transport section**, reduction by > 10^{14}
- high-resolution large-acceptance **angle spectrometer system**
- **focal plane detector**, 148-pixel PIN diode

➔ **integral spectroscopy,** discrete measurement time distribution

KATRIN neutrino mass results

1st campaign, 2 million events (22 days)

[Aker et al., PRL 123 (2019) 22, 221802]

- best fit, **p-value = 0.6**

$$m_\beta^2 = (-1.0^{+0.9}_{-1.1})\ \mathrm{eV}^2$$

→ **upper limit**

$$m_\beta < \mathbf{1.1\ eV}\ (90\%\ \mathrm{CL})$$

2nd campaign, 4 million events (31 days)

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

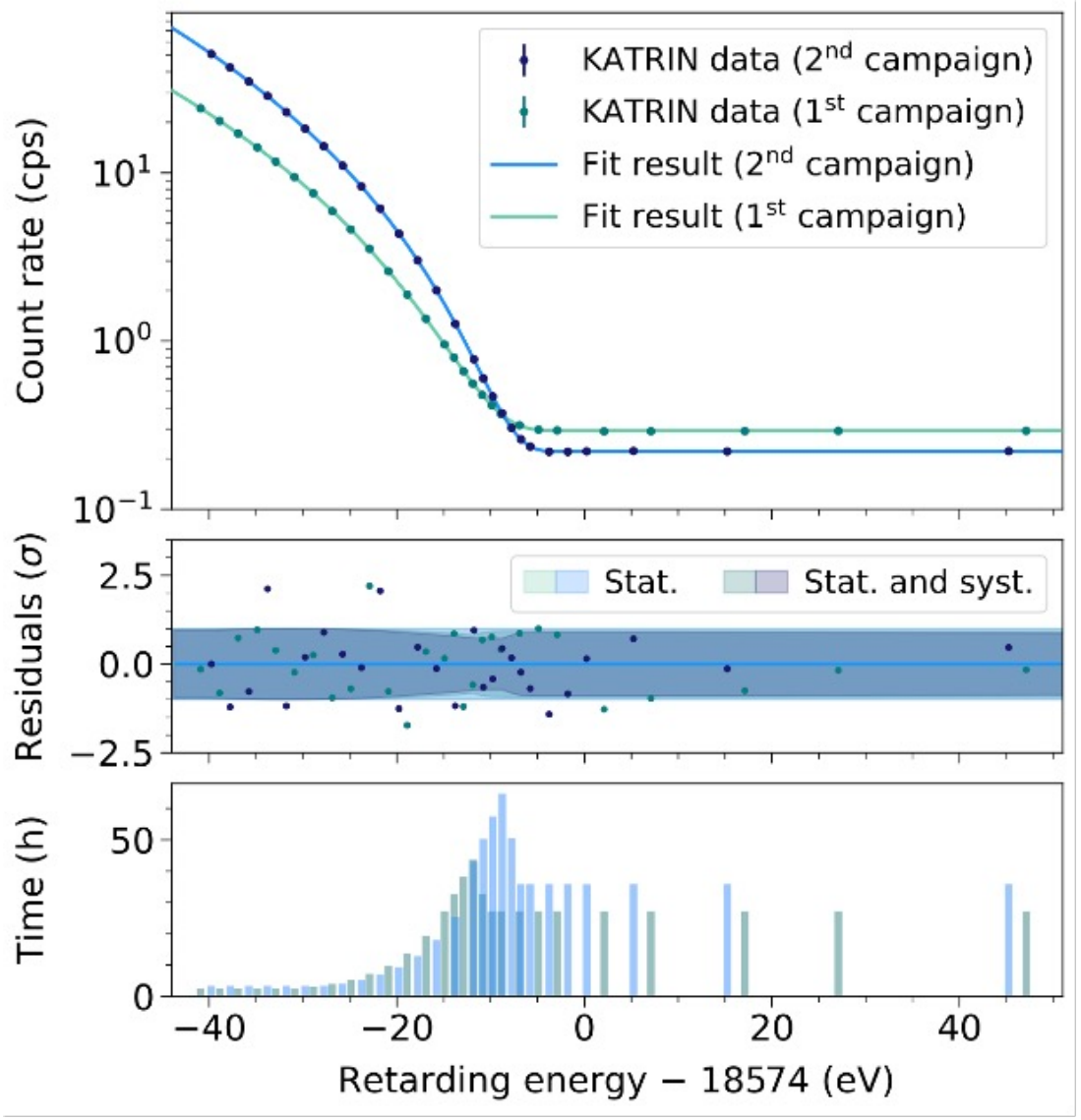
- best fit, **p-value = 0.8**

$$m_\beta^2 = (0.26 \pm 0.34)\ \mathrm{eV}^2$$

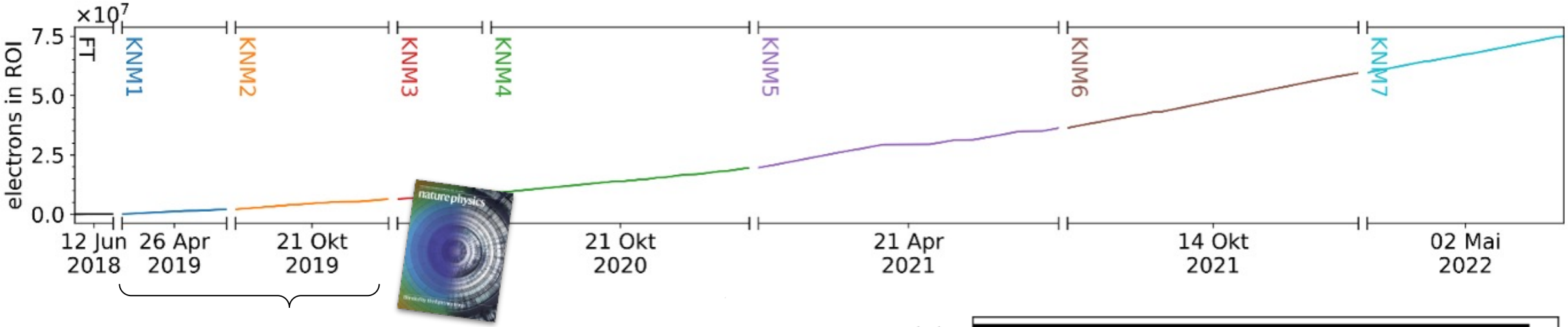
→ **upper limit**

$$m_\beta < \mathbf{0.9\ eV}\ (90\%\ \mathrm{CL})$$

$$m_\beta < \mathbf{0.8\ eV}\ (90\%\ \mathrm{CL})$$

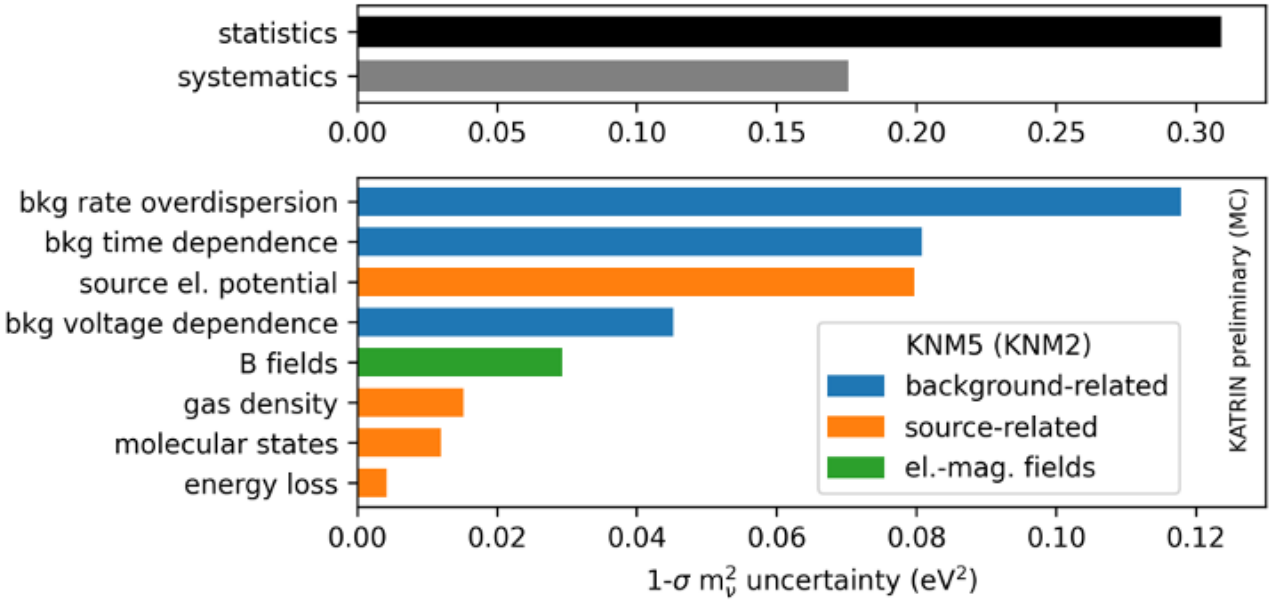


KATRIN status



- first direct **sub-eV** limit, m_β < **0.8 eV** (90% CL)

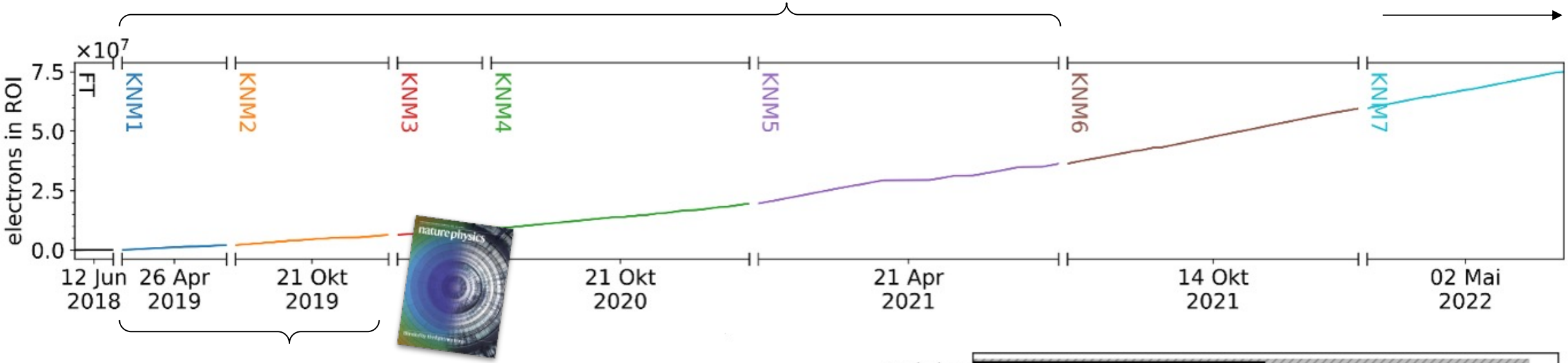
[Aker et al., Nature Phys. 18 (2022) 2, 160-166]



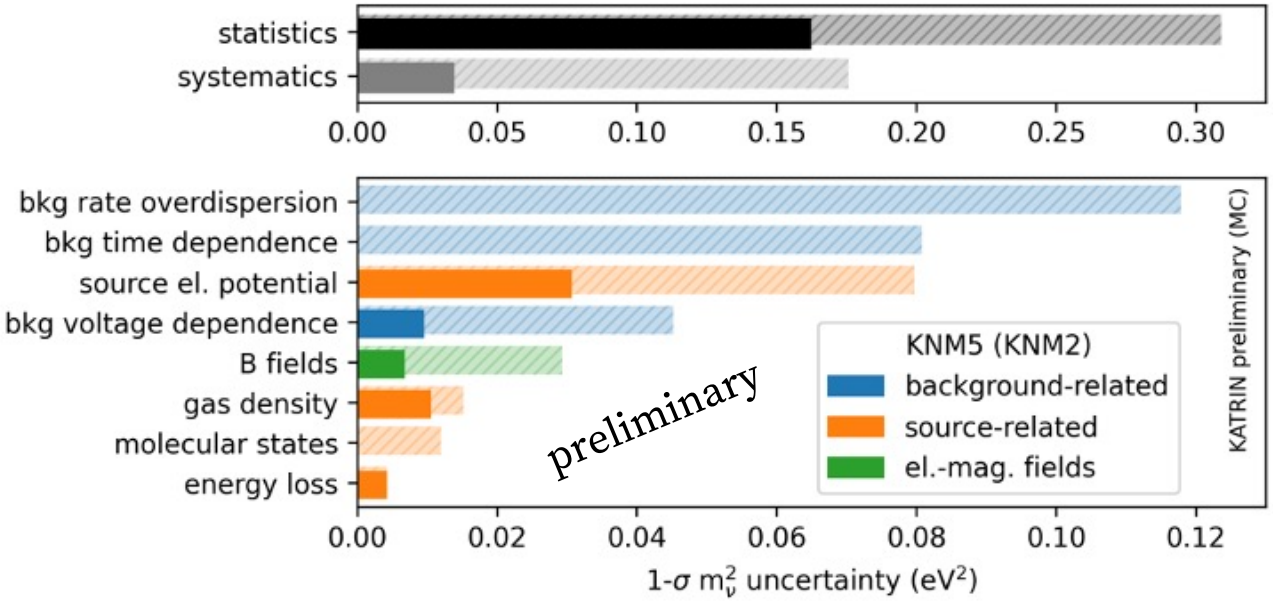
KATRIN status

publication **in preparation,**
projection m_β < **0.5 eV** (90% CL)

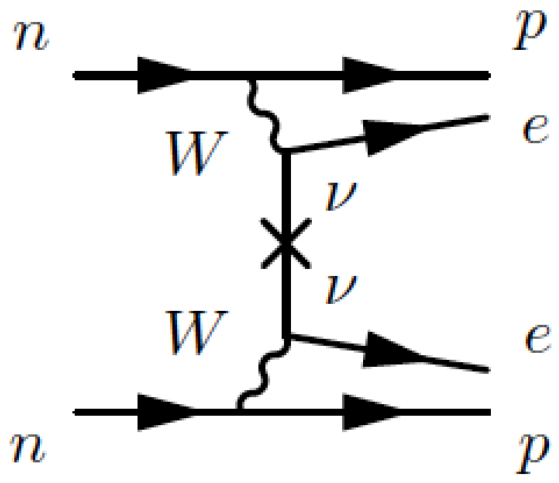
data taking towards
m_β < **0.2 eV** goal



- first direct **sub-eV** limit, m_β < **0.8 eV** (90% CL)
  [Aker et al., Nature Phys. 18 (2022) 2, 160-166]
- **background reduction**, shifted analyzing plane
  [Lokhov et al., EPJ C 82 (2022) 3, 258]
- substantial reduction of **systematic uncertainties**, e.g. high-activity **^{83m}Kr co-filling**
  [Altenmüller et al., J.Phys.G 47 (2020) 6, 065002]
- fast model interpolation with **neural networks**
  [Karl, Eller, Mertens, EPJ C 82 (2022) 5, 439]]



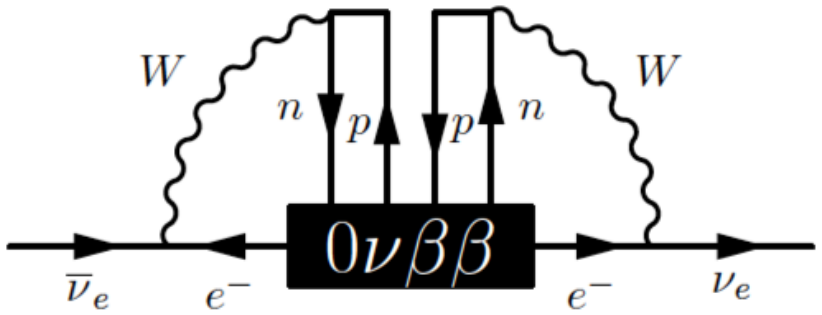
0νββ



Standard paradigm: exchange of **light Majorana neutrinos**

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

PMNS-matrix ν-mass

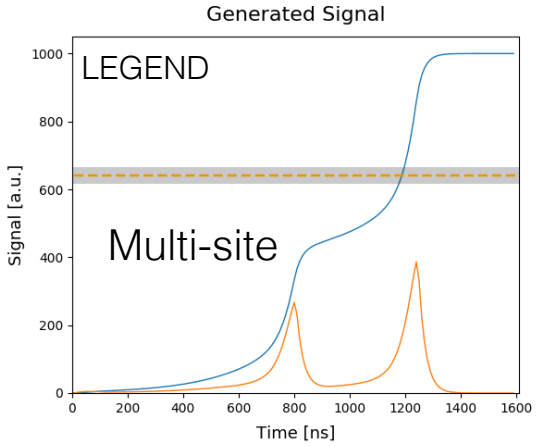


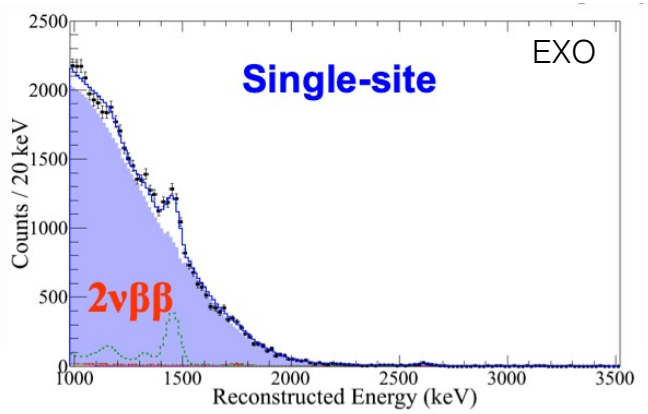
Any 0νββ decay process induces a $\overline{\nu_e}$-ν_e transition, ie. an effective **Majorana mass term**
Schechter, Valle Phys.Rev. D25 (1982)

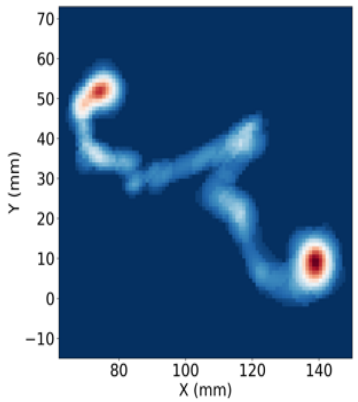
Numerical values tiny; other leading contributions to neutrino mass must exist
Duerr, Merle, Lindner: JHEP 1106 (2011)

Ton-scale experiments for discovery

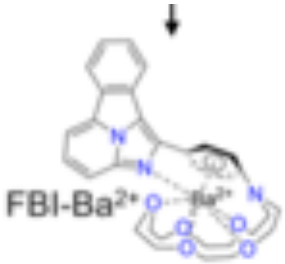
- Need to measure half-lives of up to 10^{28} years
- **One decay** per **ton-year** of material
- Need many **ton-years** of data
- Need extreme **low background rate** and best possible **energy resolution**
- Need to exploit **topology information** of signal and background
- And, if possible, identify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







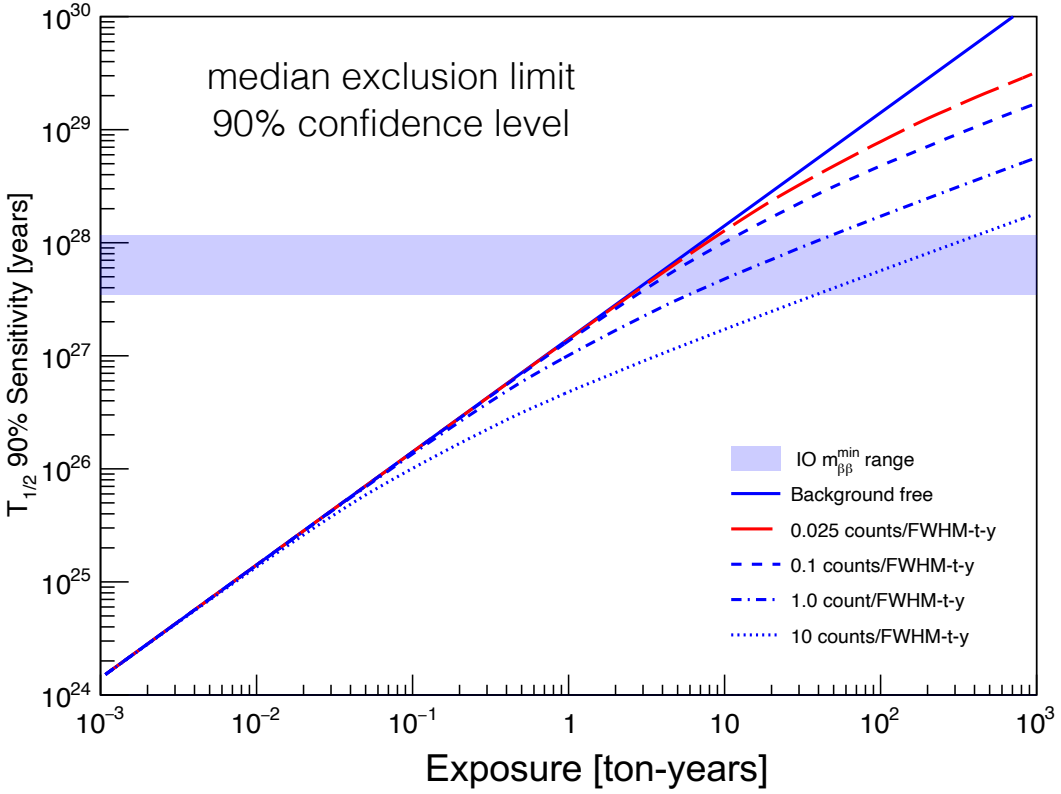
NEXT

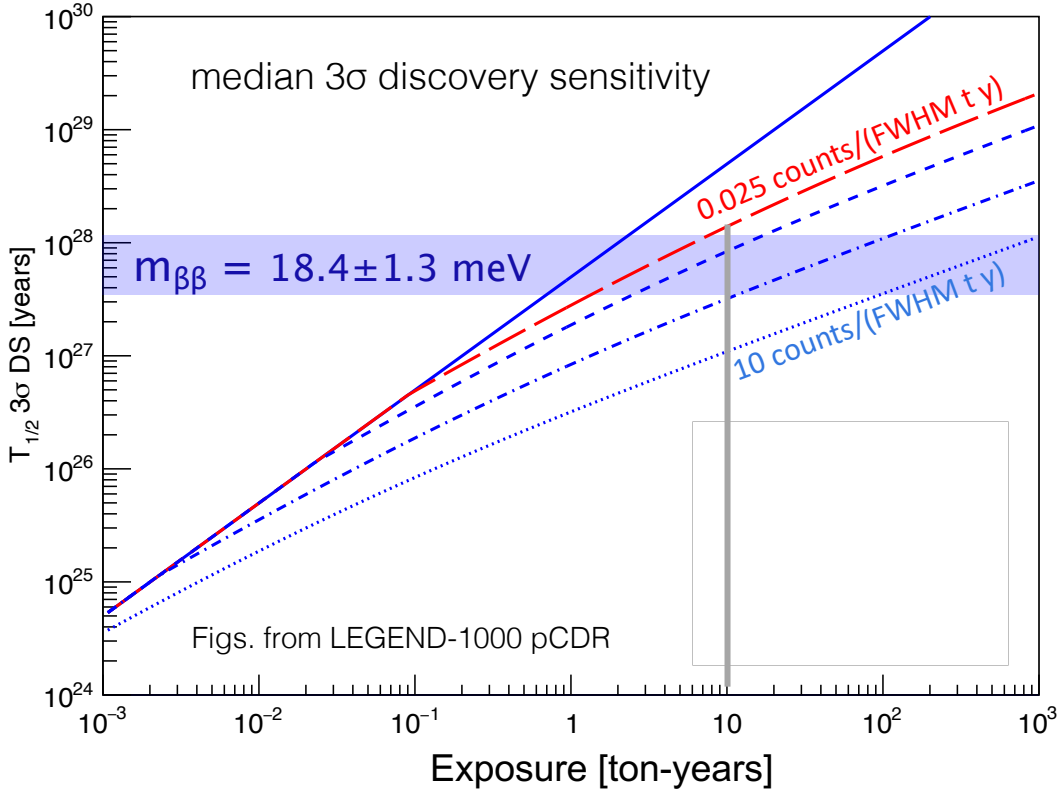


The Effect of Background: Discovery sensitivity vs. exclusion limit

- 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

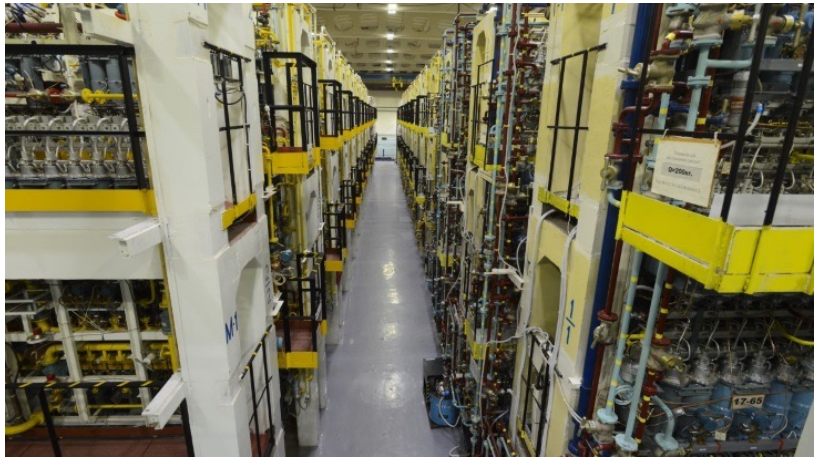




[1] Less than one background count expected in a 4σ Region of Interest (ROI) with 10 t y exposure

Enrichment of double beta decay isotopes

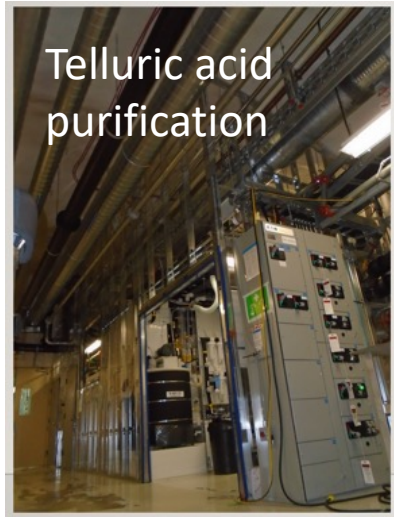
An isotope production facility at ECP (Image: TVEL)

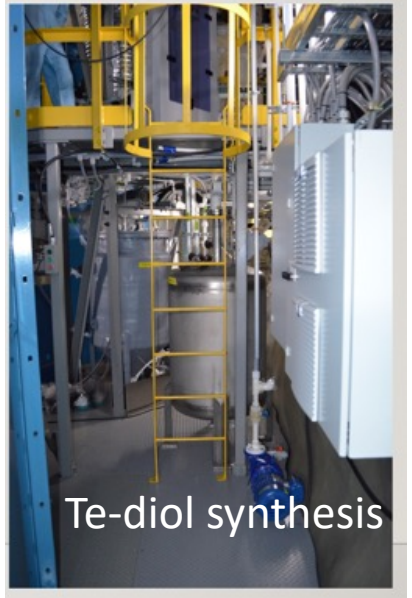


- Current experiments have largely procured **0νββ isotopes from Russia**
- Reliable and high-quality supply chain
- Some 0νββ isotopes also procured from European producer
- Since the Russian invasion of Ukraine, no procurement of 0nbb isotopes from Russia possible for Western countries
- European producer is ramping up production capacities to suffice demands and states that sufficient capacities will be available to fulfill demands by ton-scale experiments
- Additional initiatives are being pursued: e.g. ^{136}Xe extraction from burned nuclear fuel elements
- Projects in China continued procurement of 0νββ isotopes from Russia

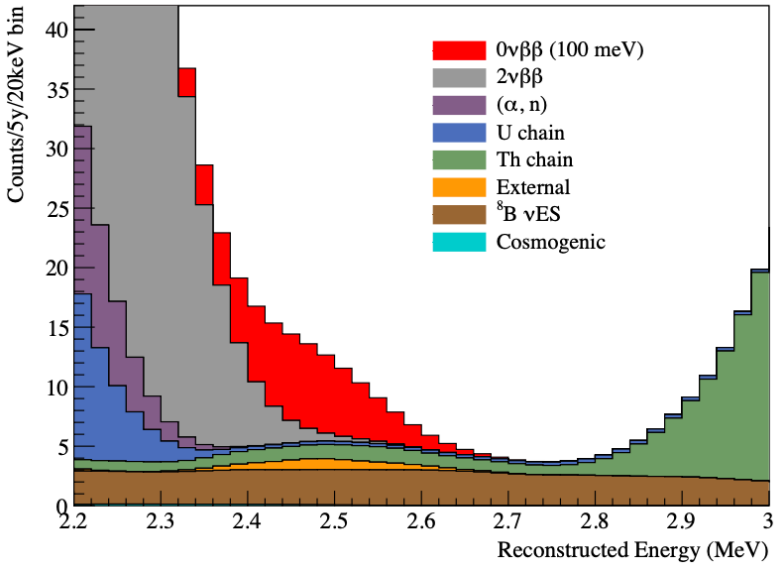
^{nat}Te-loaded liquid scintillator: SNO+

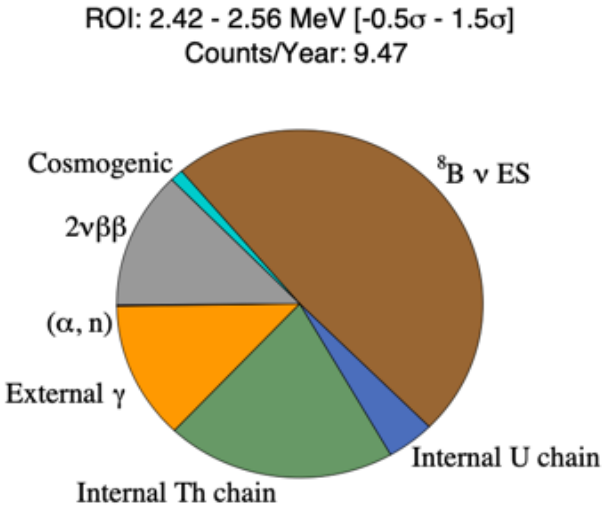
- 780t LS (2.2 g/L PPO in LAB)
- Currently data taking with unloaded LS
  - low energy ^{8}B solar-n, reactor & geo anti-ν_e, Δm^2_{12}, supernova-ν
- $0\nu\beta\beta$ phase: **natural Te** (34% ^{130}Te) loaded as metal organic complex (Te-diol)
- Te-systems ready for operations
- Full-scale Te-diol 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**



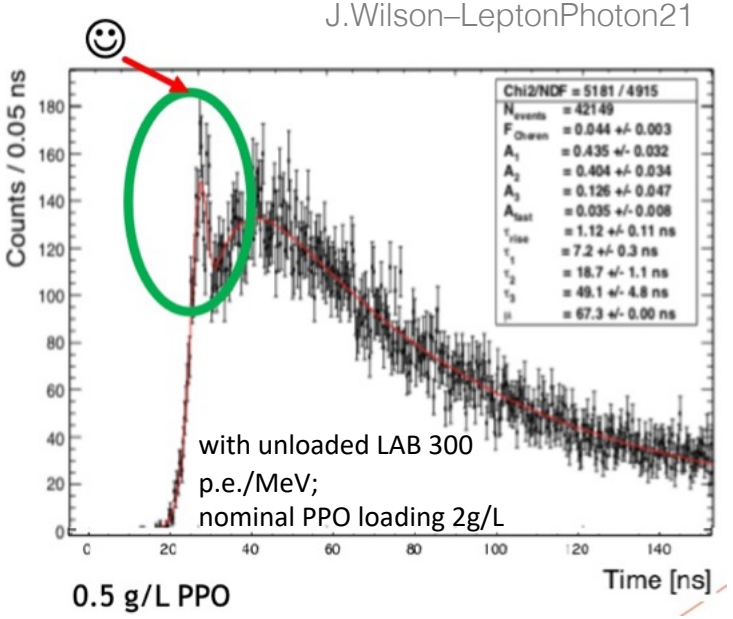


^{nat}Te-loaded liquid scintillator: SNO+



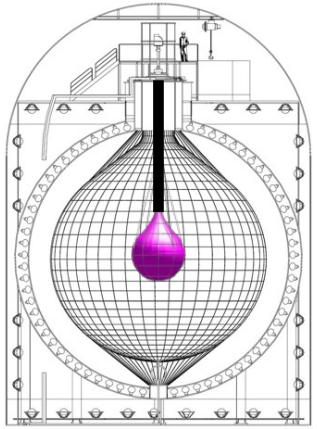


J.Wilson–LeptonPhoton21



- **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

KamLAND-Zen 400

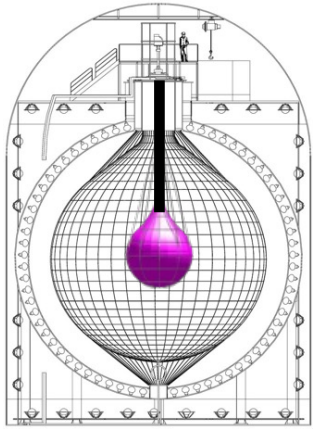


380kg deployed

$$T^{0\nu}_{1/2} > 1.07 \times 10^{26}\,\mathrm{yr}$$

PRL117, 082503 (2016)

KamLAND-Zen 800



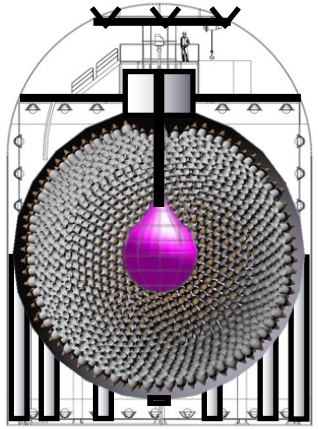
Now, 745kg deployed

$$> 2.3 \times 10^{26}\,\mathrm{yr}$$

PRL130, 051801 (2023)

Further improvements going on;
better neutron tagging
machine learning (ML) for long-lived tagging
ML for beta/gamma discrimination
muon-bundle tracking, and so on

KamLAND2-Zen



Mirror
HQE-PMT } x5 p.e.
new LS
full volume effective
w/ scintillation film

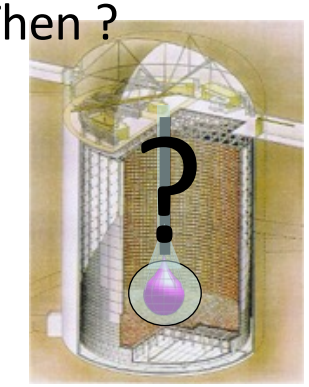
1 ton planned (scalable)

$$> 2 \times 10^{27}\,\mathrm{yr}$$ (target sensitivity)

$$< 12 \sim 53\,\mathrm{meV}$$ (corresponding mass limit)

Further technologies being developed;
imaging sensor (1/10 reduction of long-lived BG)
higher pressure xenon deployment
(2 times more xenon and/or more concentration)

Then ?



It will not be a good choice for the single purpose, but this can be a multi-purpose detector.

$$> 2 \times 10^{28}\,\mathrm{yr}$$

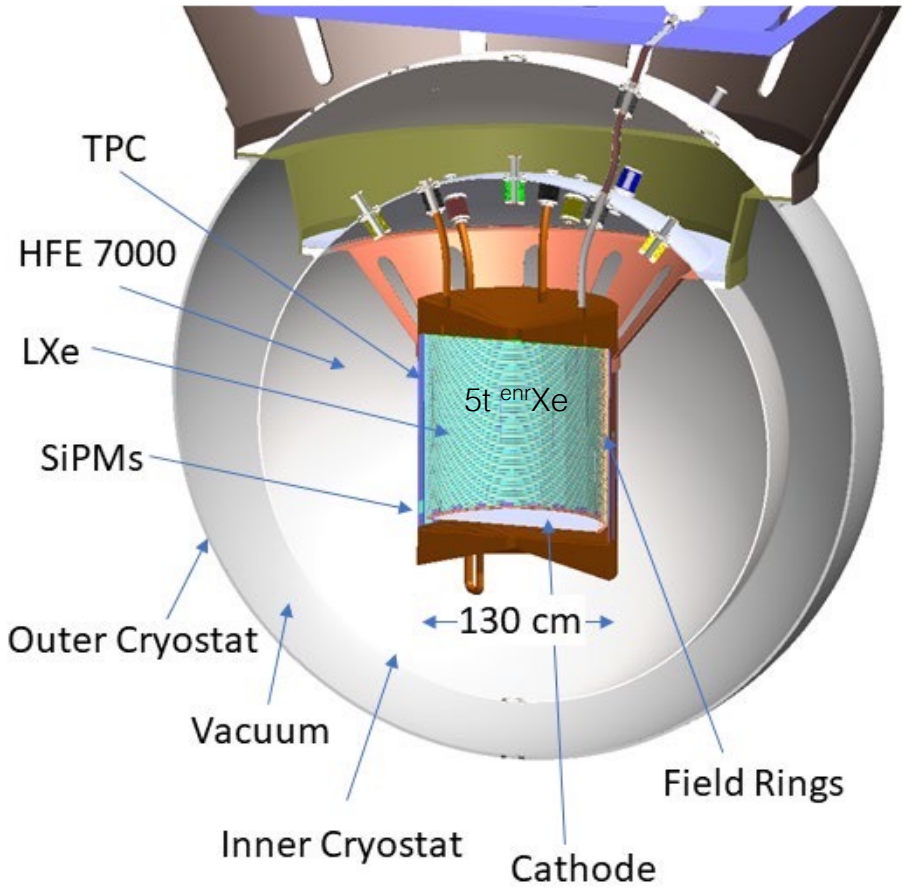
(guesstimated sensitivity)

w/ more than 20 ton xenon
imaging sensor
high-p xenon deployment

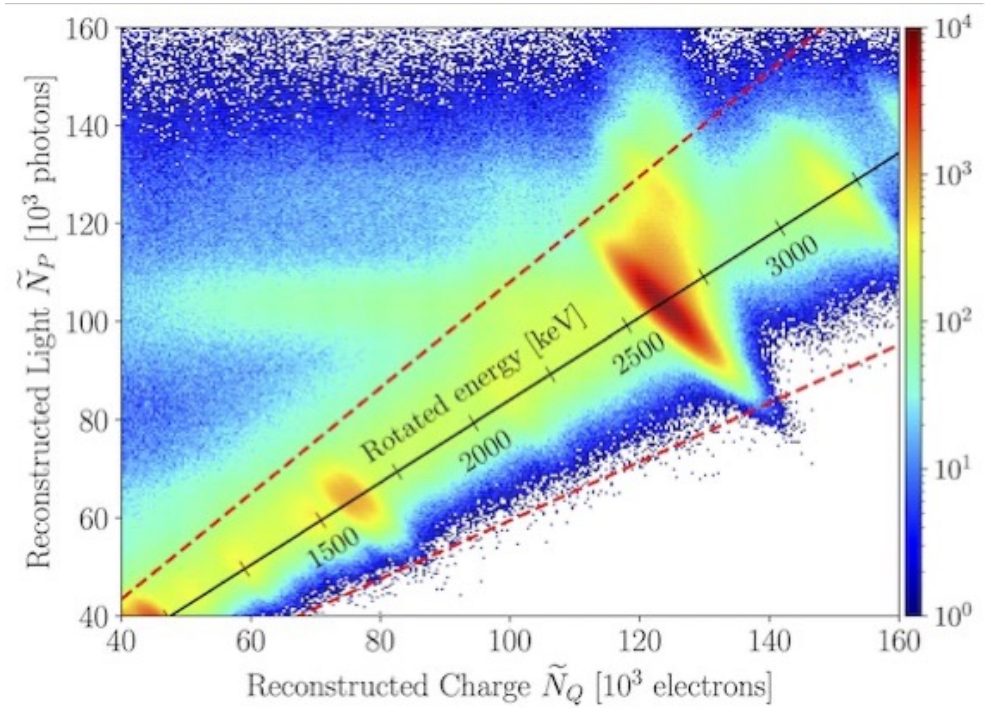
For more xenon (possible source)
Extraction from nuclear spent fuel is considered.
More than 100 ton seems to be possible at 44% concentration of Xe-136 without centrifugal enrichment.

	36 months		atmospheric	
$^{128}Xe/^{132}Xe$	$2.81 \cdot 10^{-3}$		$7.13 \cdot 10^{-2}$	
$^{129}Xe/^{132}Xe$	$4.7 \cdot 10^{-6}$		0.9832	
$^{130}Xe/^{132}Xe$	$3.32 \cdot 10^{-4}$		0.1518	
$^{131}Xe/^{132}Xe$	0.3756		0.7876	
$^{134}Xe/^{132}Xe$	1.3433		0.3883	
$^{136}Xe/^{132}Xe$	2.1176	**44%**	0.3298	**8.9%**

^{136}Xe: nEXO

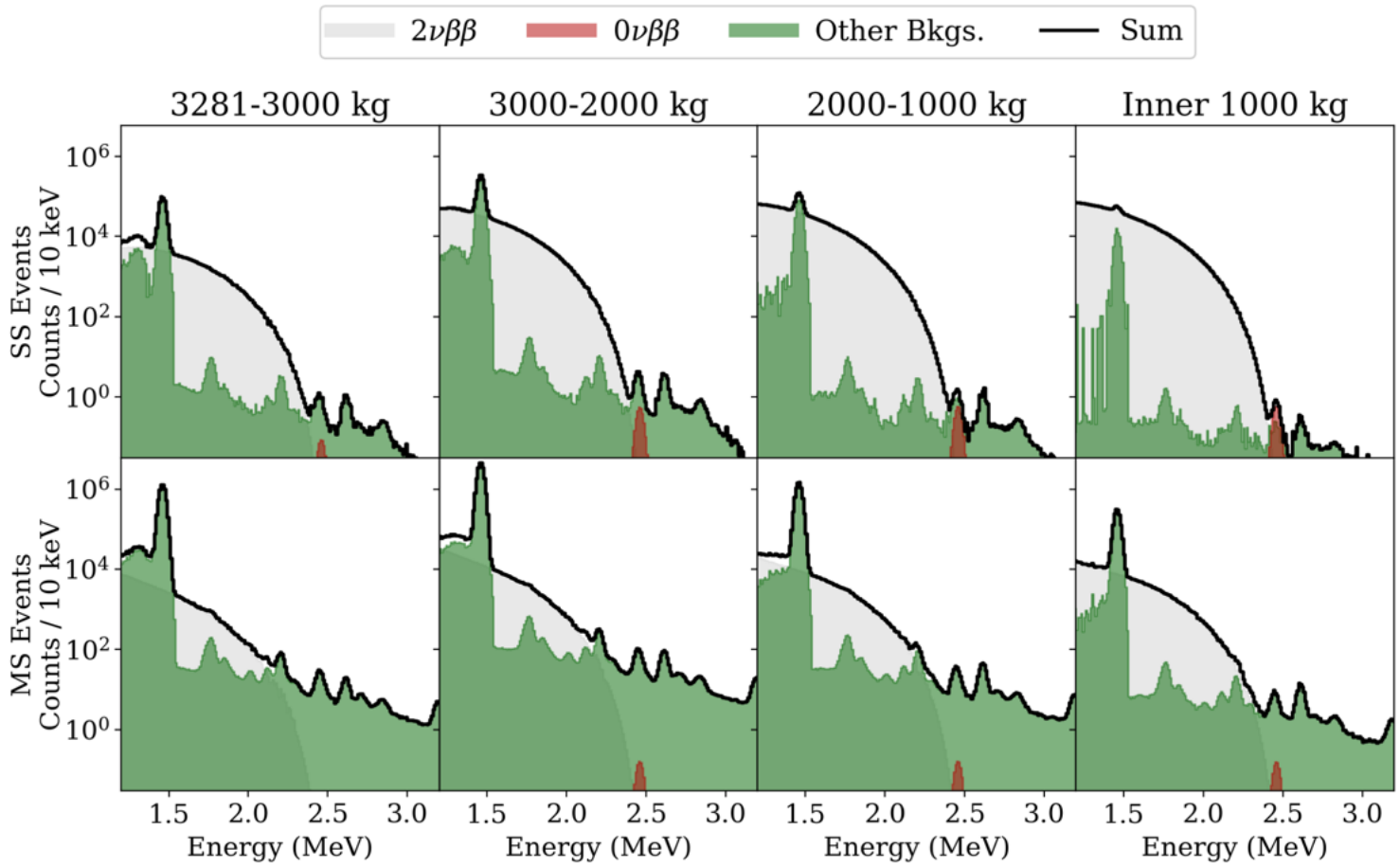


Charge & light readout: ^{232}Th source simulation

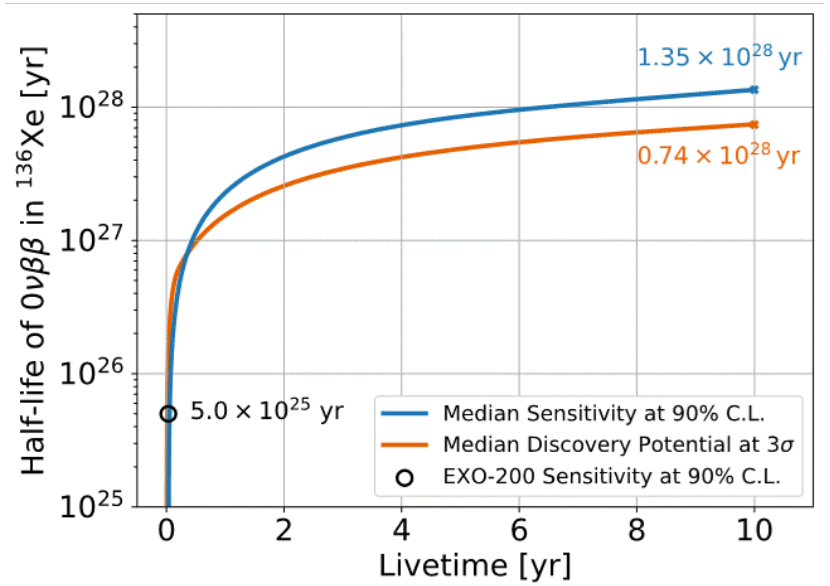


Energy resolution at $Q_{\beta\beta}$ (σ): 1.2% (req.), 0.8% (goal)

^{136}Xe: nEXO



- Advanced topological reconstruction
- γ background identification and rejection.
- Multi-parameter analysis



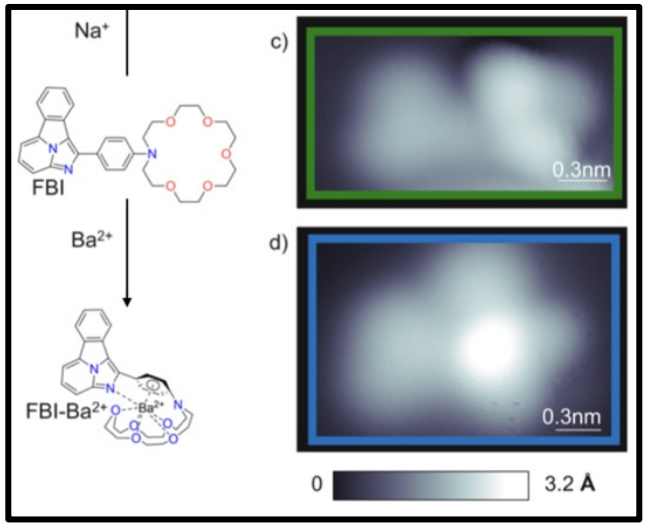
^{136}Xe: Barium tagging

- 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)

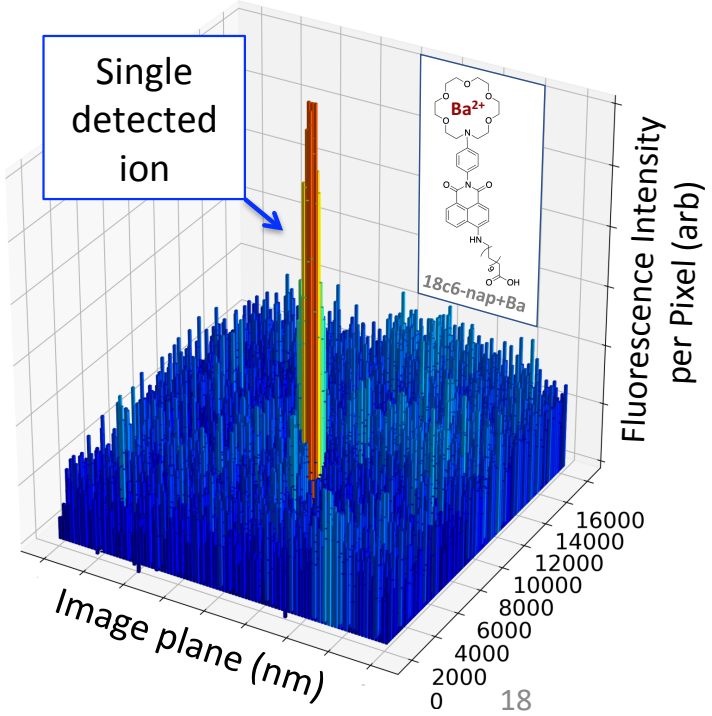
- NEXT pursues single molecule fluorescent imaging (SMFI) based barium tagging sensors.

- 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

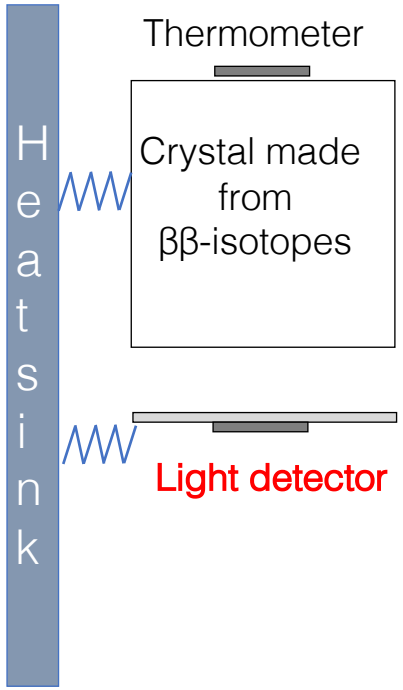


SMFI + high pressure microscopy enables Ba2+ detection in Xe gas

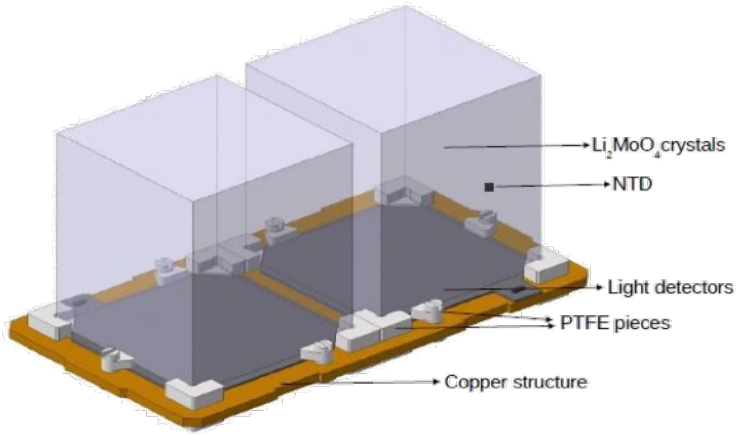


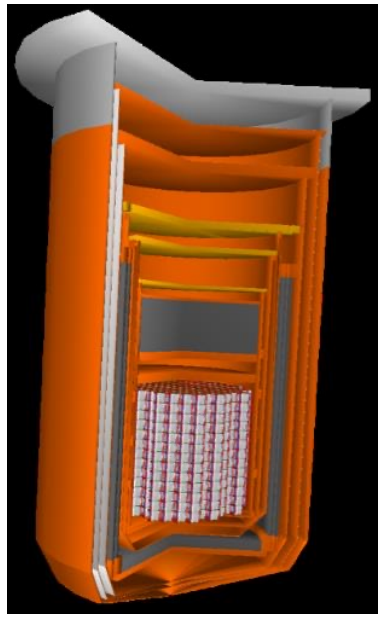
J.Phys.Conf.Ser. 650 (2015) 1, 012002; JINST 11 (2016) 12, P12011; Phys. Rev. Lett. 120 (2018) 13, 132504. Sci.Rep. 9 (2019) 1, 15097; Nature 583 (2020) 7814, 48–54; ACS Sens. (2021) 6, 1, 192–202; arXiv:2201.09099, arXiv:2109.05902

CUPID: ^{100}Mo cryogenic detectors @ LNGS



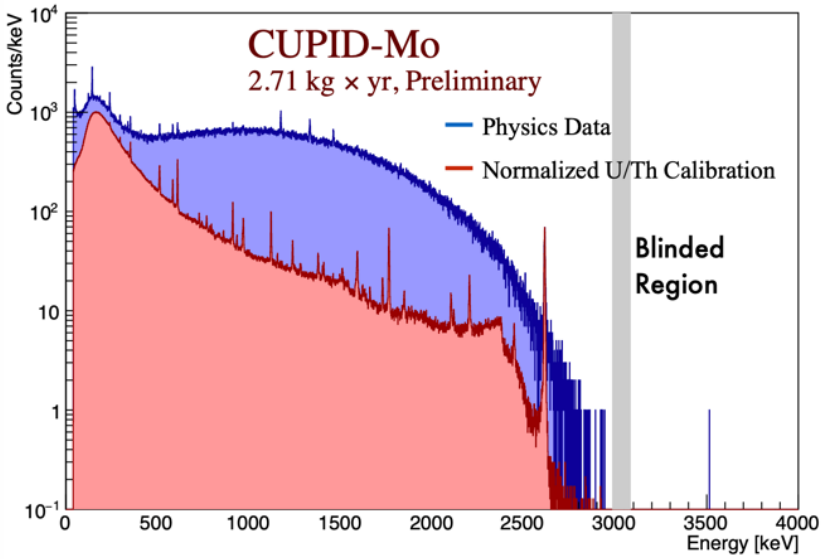
- Simultaneous read out of heat and light: surface alpha rejection
- Single module: $Li_2{}^{100}MoO_4$ 45×45x45 mm –> 280 g
- 57 towers of 14 floors with 2 crystals each -> 1596 crystals
- 240 kg of ^{100}Mo with >95% enrichment
- Bolometric Ge light detectors as in CUPID-Mo, CUPID-0
- Re-use CUORE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



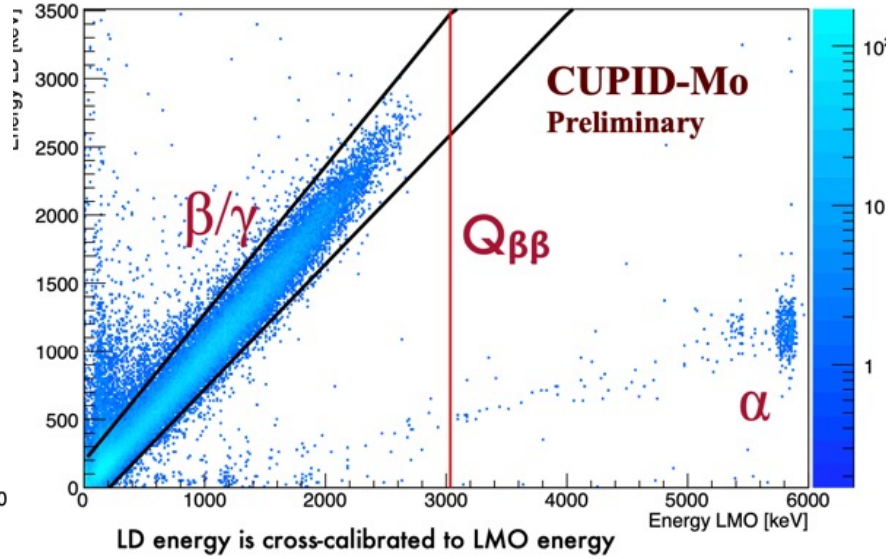


CUPID-Mo: ^{100}Mo cryogenic detectors R&D at LSM

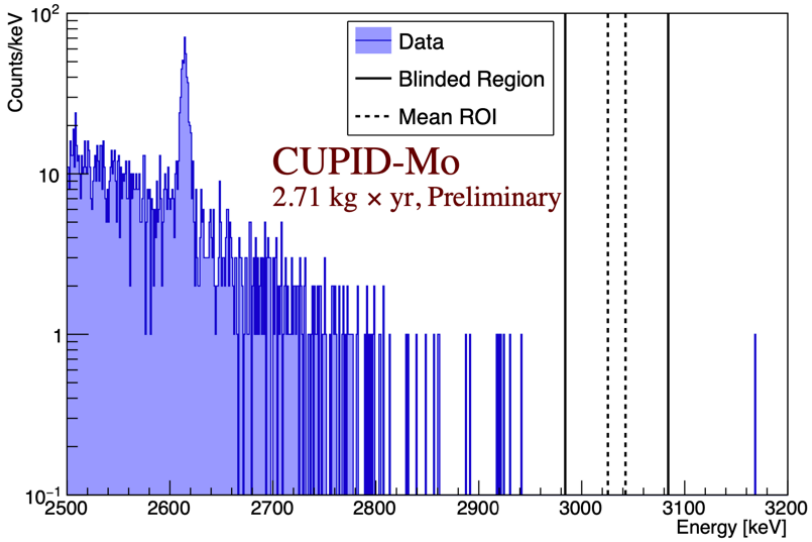
B. Welliver, TAUP2021



ΔE (FWHM): 7.2 keV @ 2.6 MeV



Removal of surface α's



Background-free operation in 2.7 kg yr

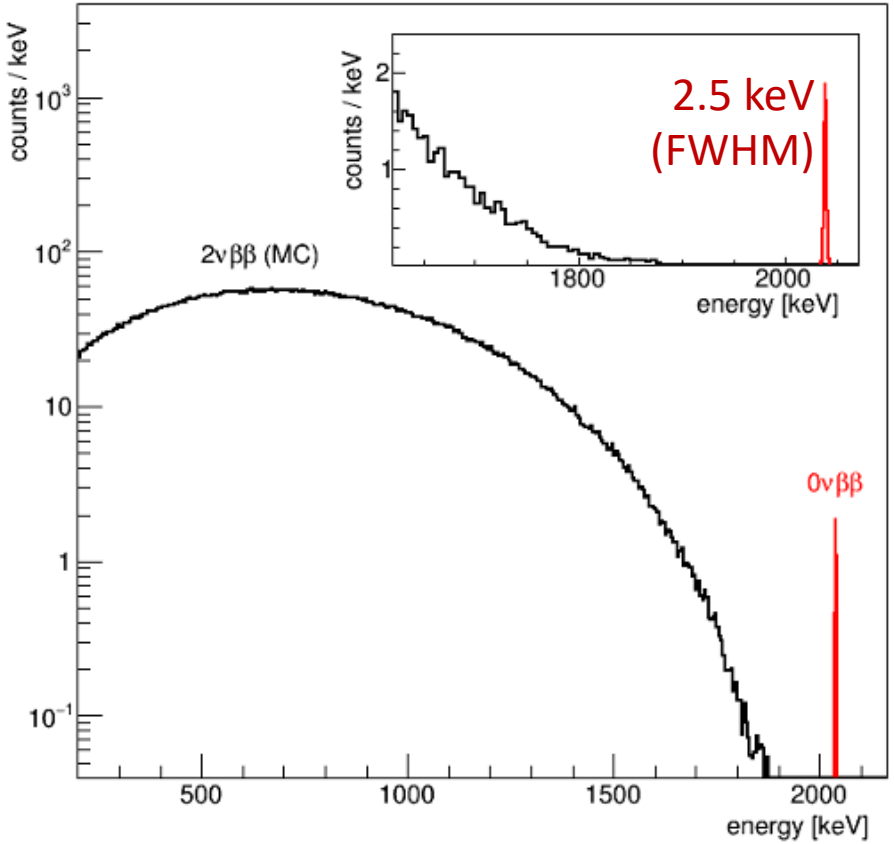
CUPID-Mo Preliminary

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

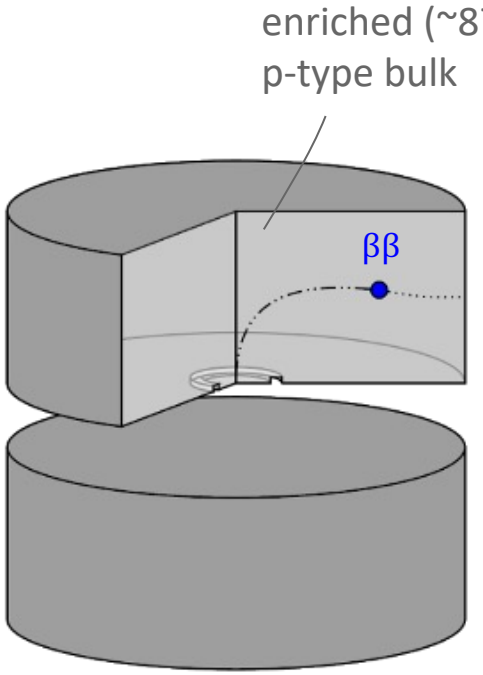
$m_{\beta\beta} < 0.28 - 0.49$ eV (90 % C.I.)

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

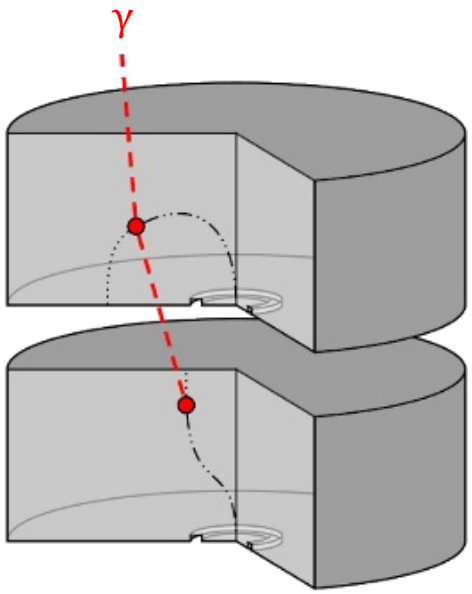
- ^{76}Ge -> ^{76}Se + 2e$^-$
- Q-value of ^{76}Ge: $Q_{\beta\beta}$ = 2039 keV
- High purity Ge detectors (>87% ^{76}Ge)
  - source = detector => high detection efficiency
  - high purity => no intrinsic background
  - high density => $0\nu\beta\beta$ point like events
  - semiconductor => ΔE ~0.1% (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)



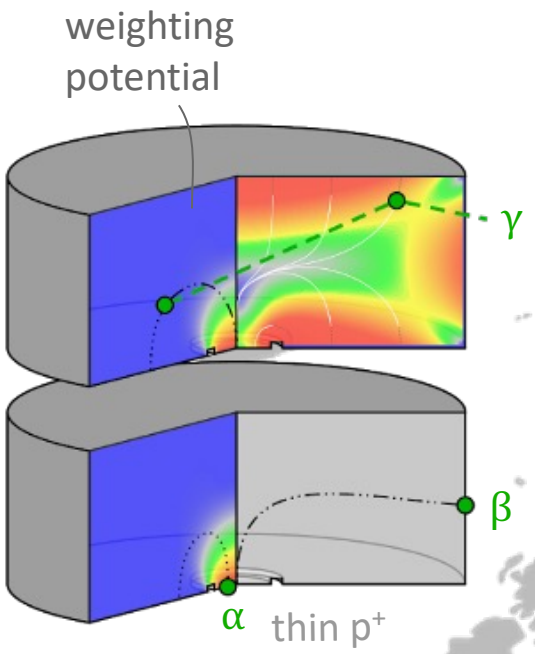
Topology discrimination



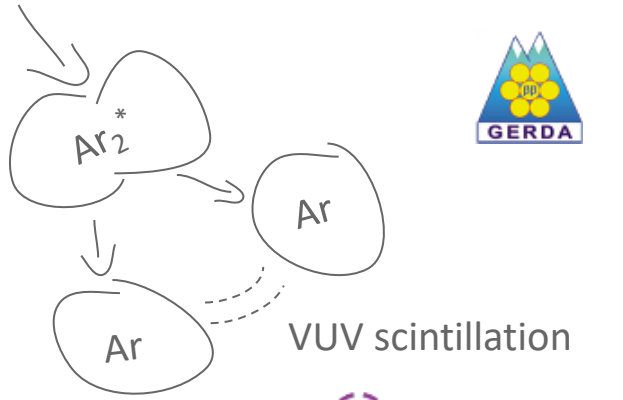
differentiate **point-like** $\beta\beta$ topology from:

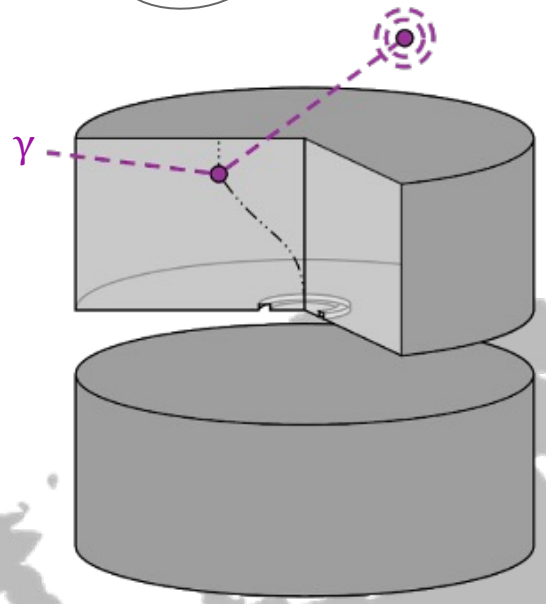


multi-detector interactions



multi-site/surface interactions

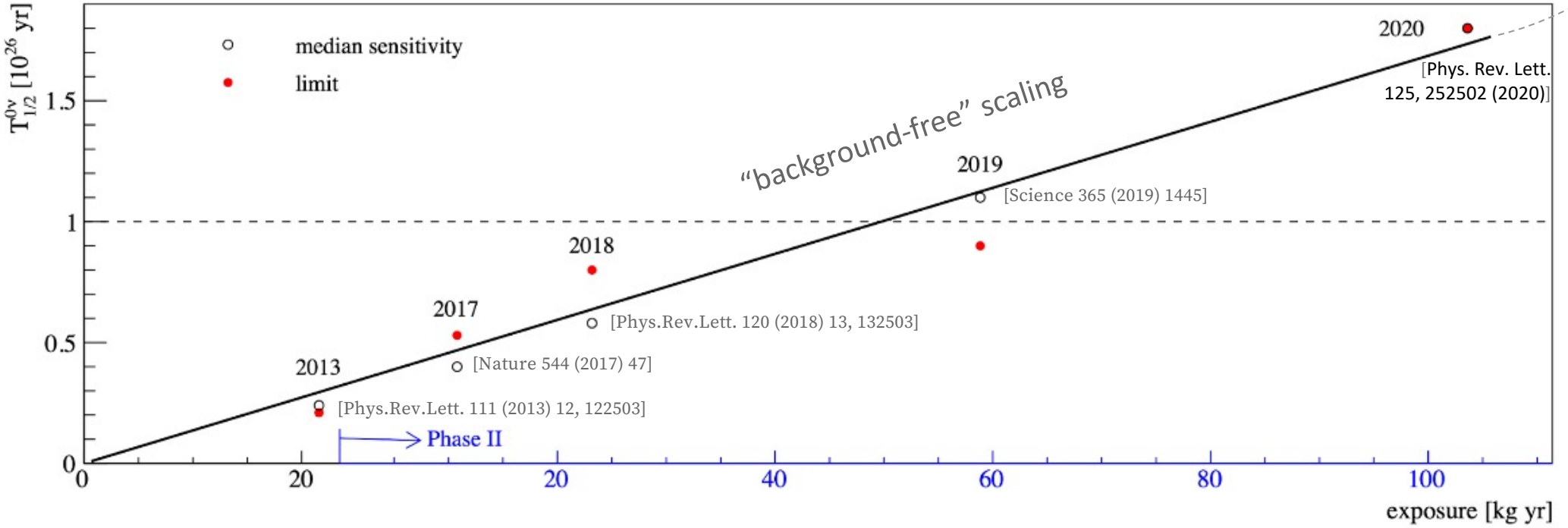




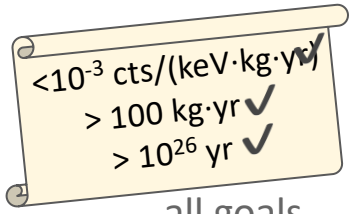
interactions with **partial energy depositions**

GERDA: first quasi background-free experiment

novel Ge detectors & LAr instrumentation



LEGEND



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)

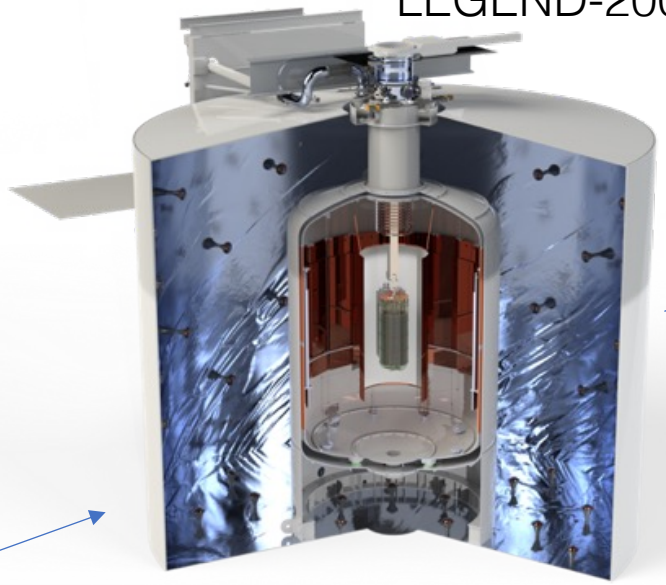
Recent publications:
Final Results of GERDA on the Search for Neutrinoless Double-β Decay, **Phys. Rev. Lett.** 125, 252502 (2020)
The first search for bosonic super-WIMPs with masses up to 1 MeV/c2 with GERDA , **Phys. Rev. Lett**. 125 (2020) 011801
Modeling of GERDA Phase II data , **J .High Energ. 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

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

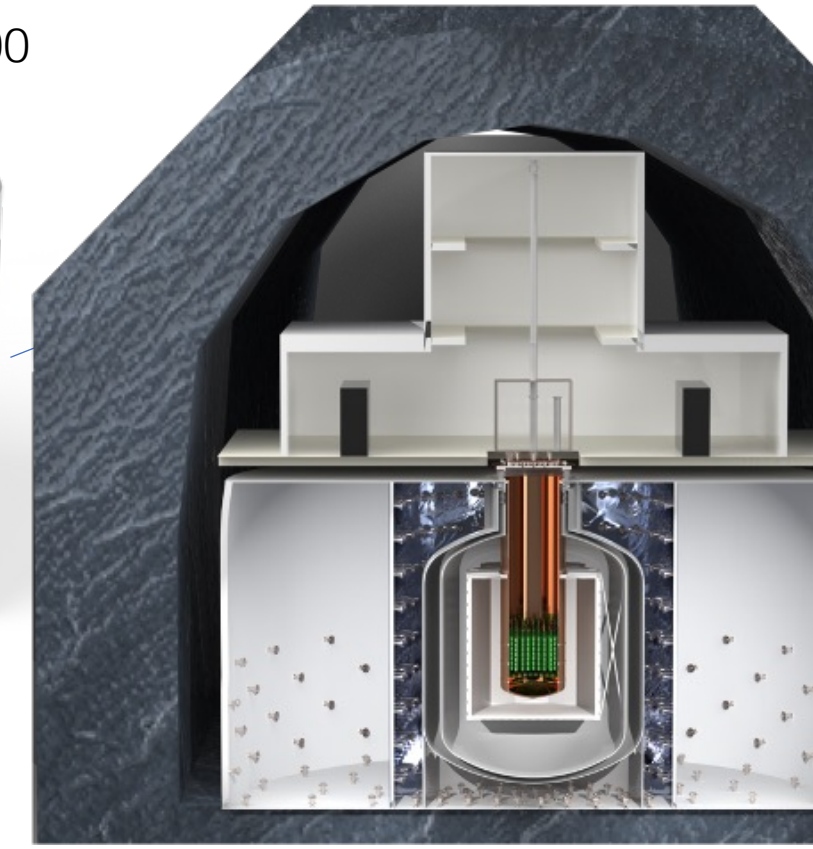
The LEGEND design builds on a track record of breakthrough developments

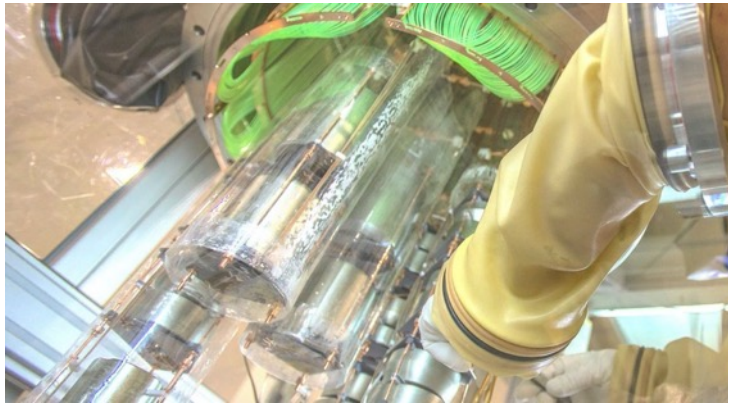
- GERDA : BEGe, LAr instrumentation, cryostat in water shield, fast detector deployment, …
- MAJORANA DEMONSTRATOR (MJD): PPC, EFCu, low-noise front-end electronics,…
- LEGEND-200 (start 2021): Inverted-Coaxial Point Contact (ICPC) detectors, polyethylene naphthalate (PEN)…

LEGEND-200



LEGEND-1000





GERDA

MJD

PPC: p-type Point Contact Ge detectors

BEGe: (modified) Broad Energy Ge detectors

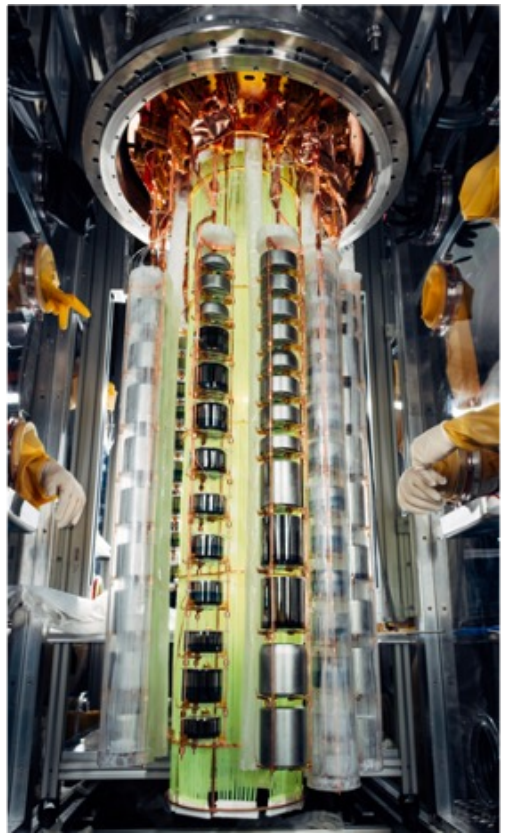
EFCu: Electroformed copper

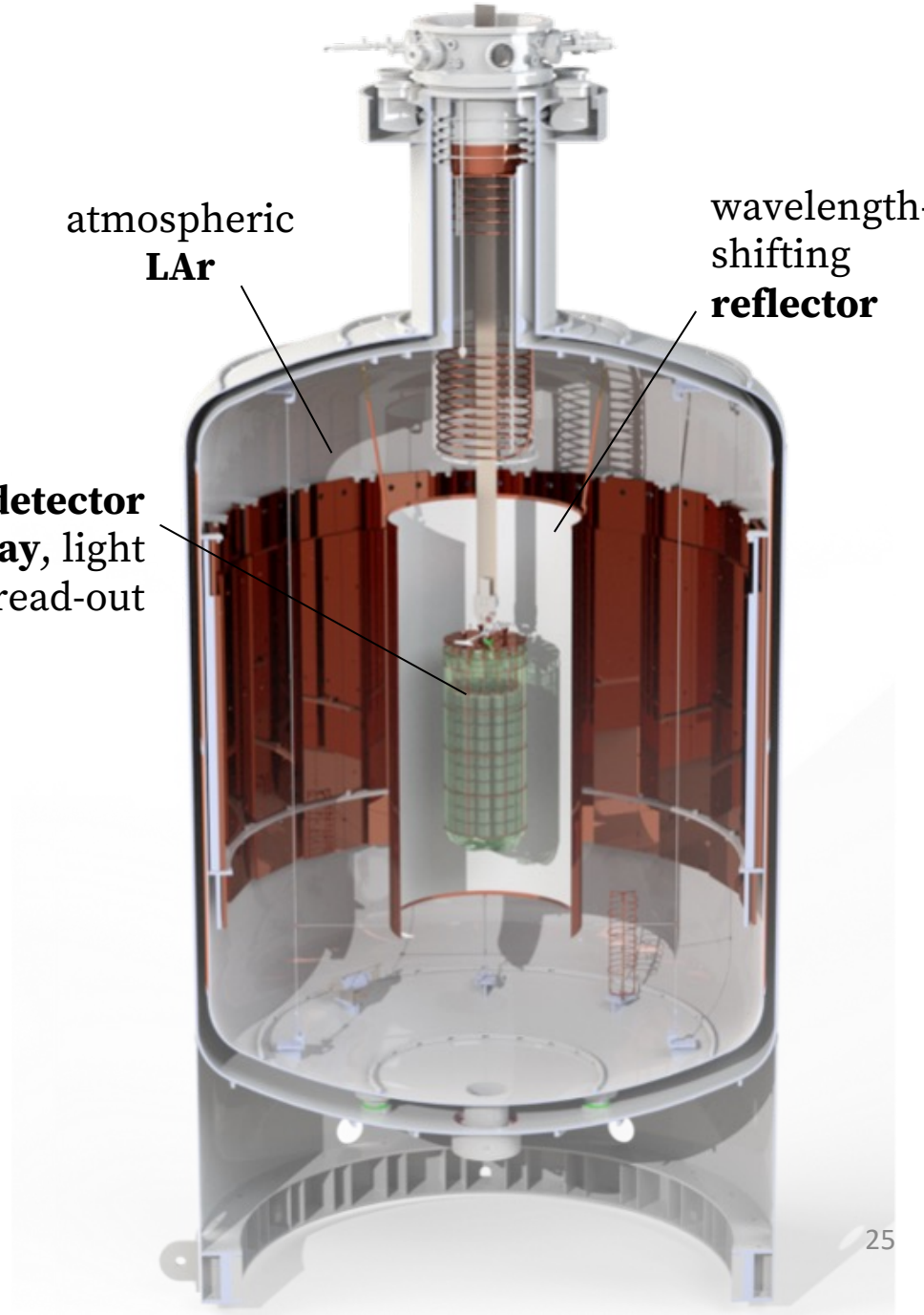
LEGEND-200 status

- **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 will start **this year**

140 kg array





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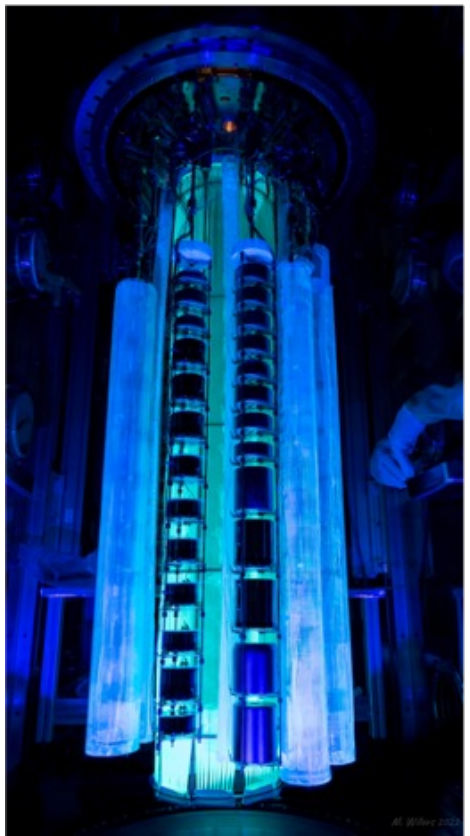
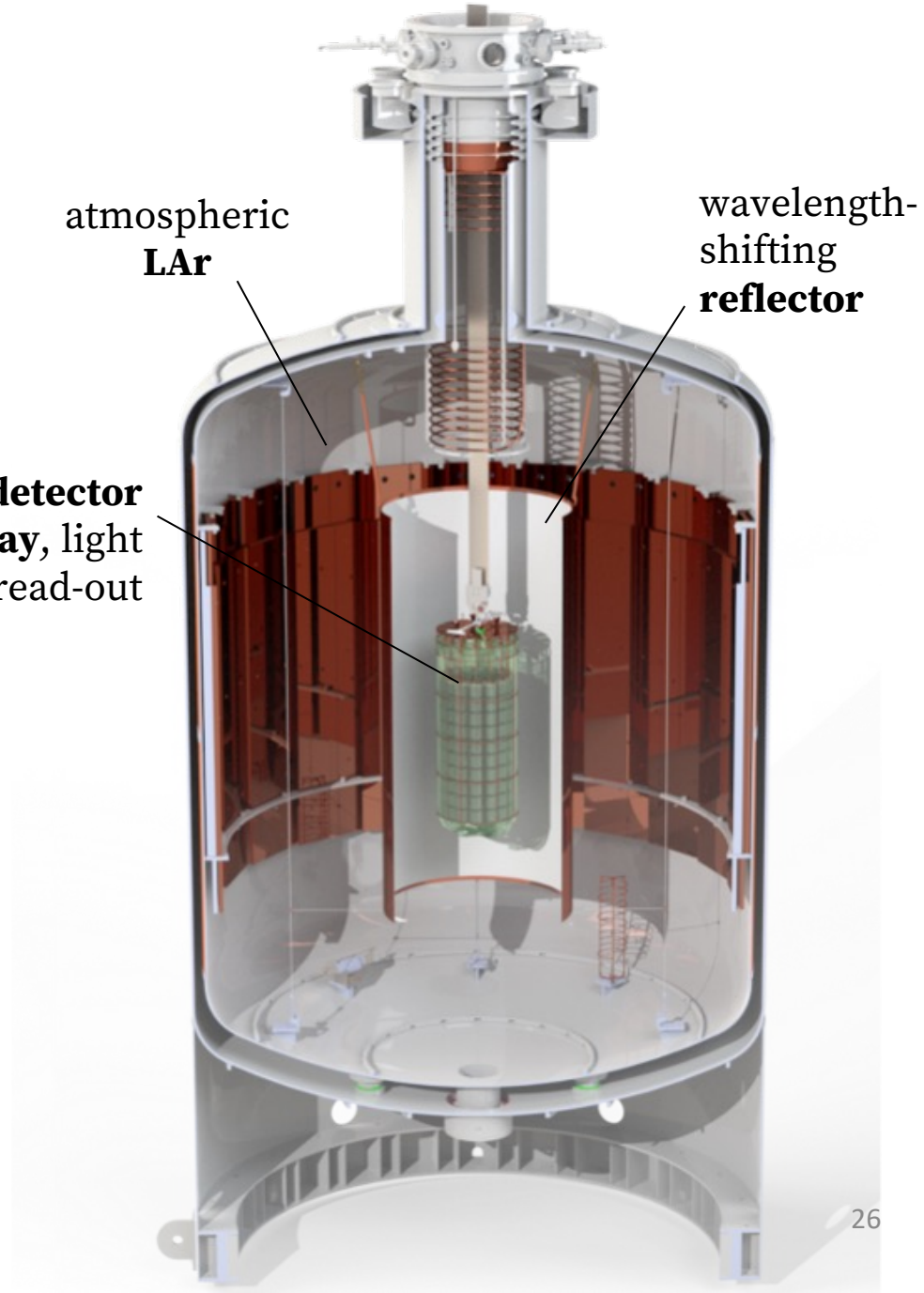
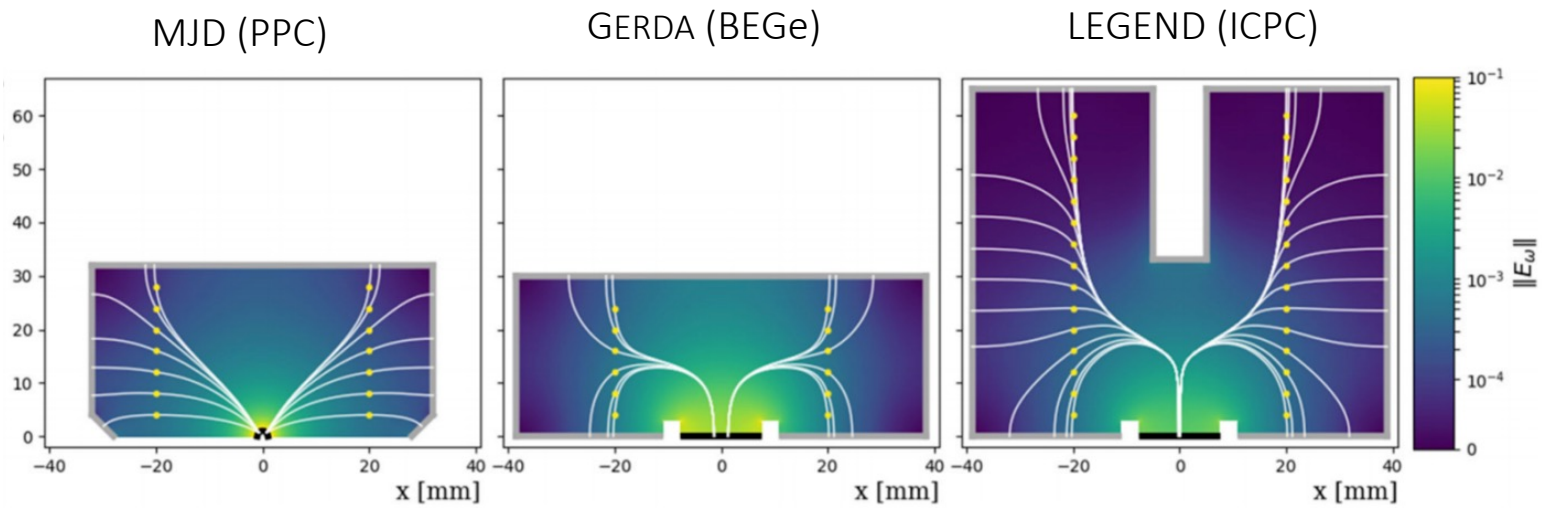
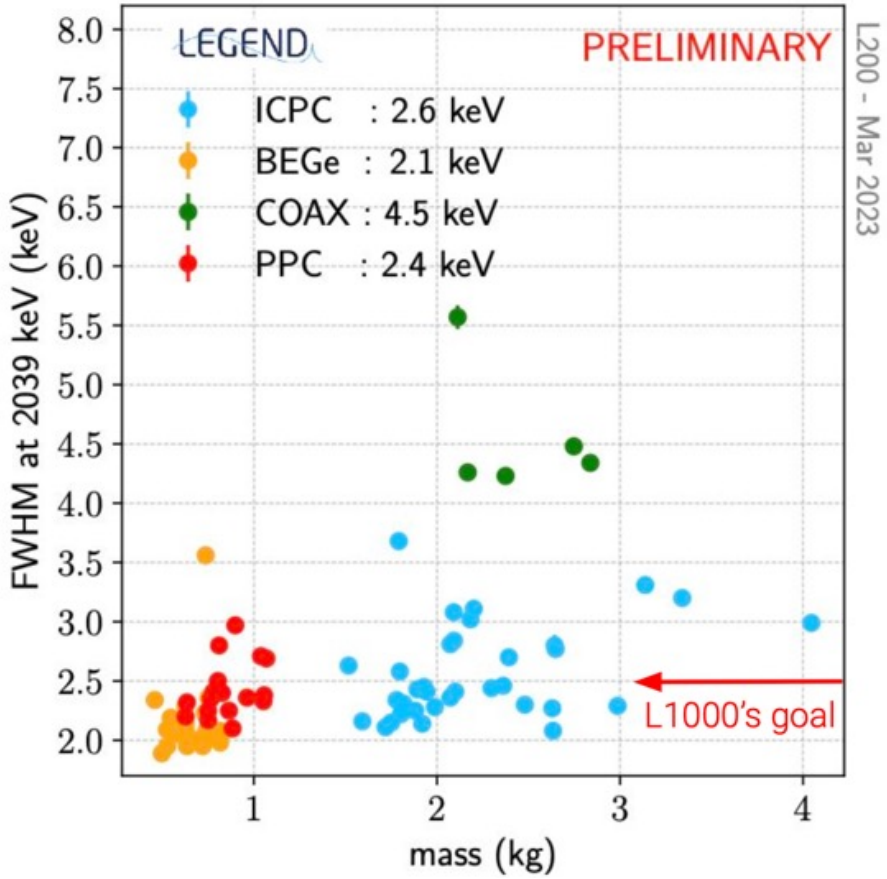




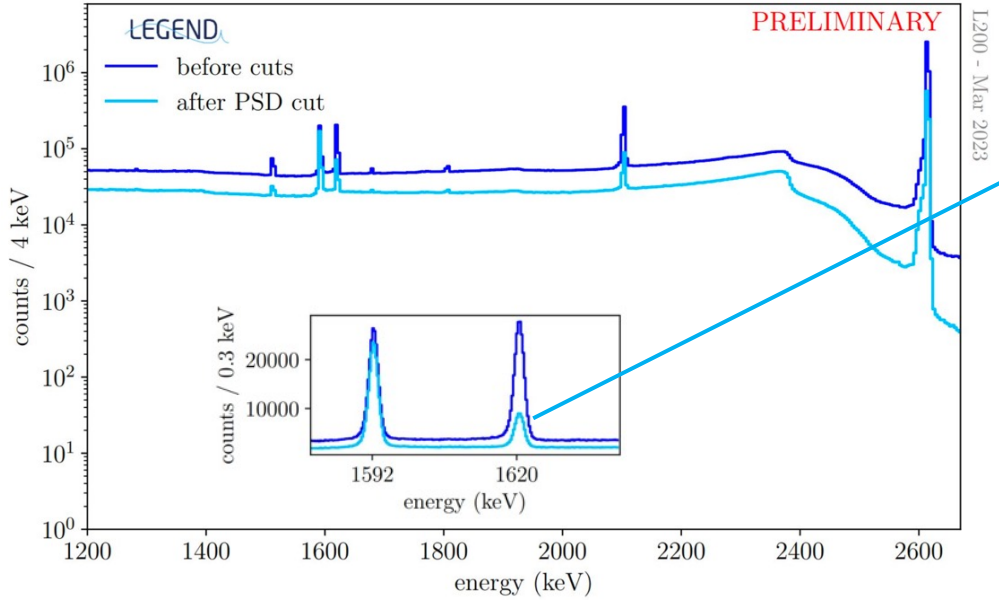
LEGEND-200: Performance of HPGe detectors

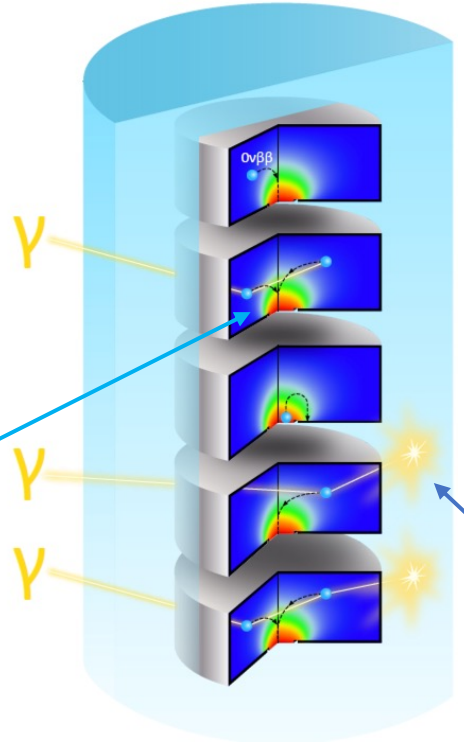




LEGEND-200: event topology discrimination

^{228} Th calibrations





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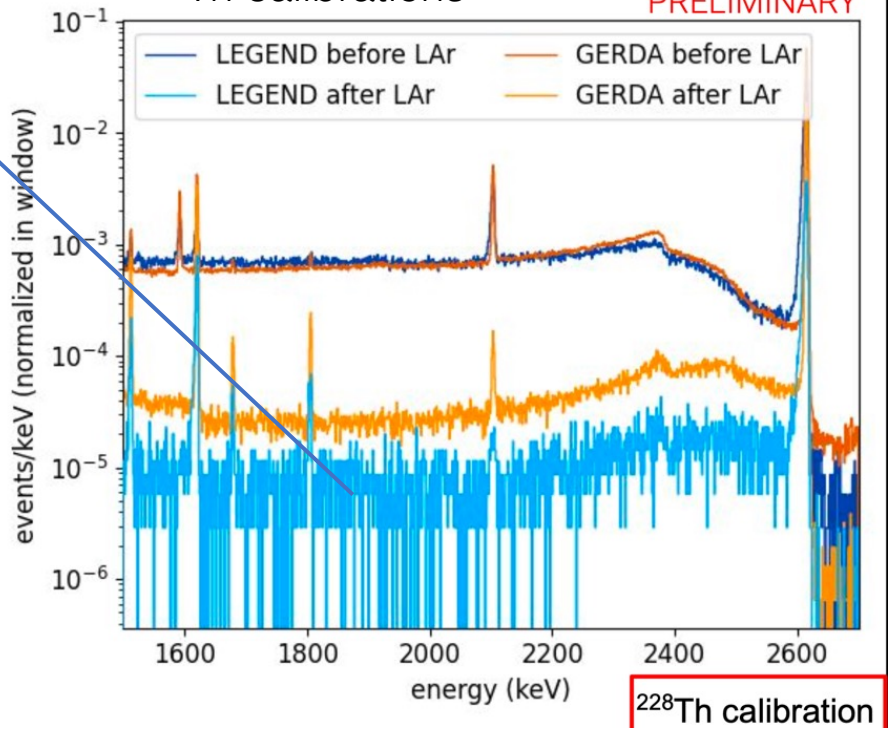
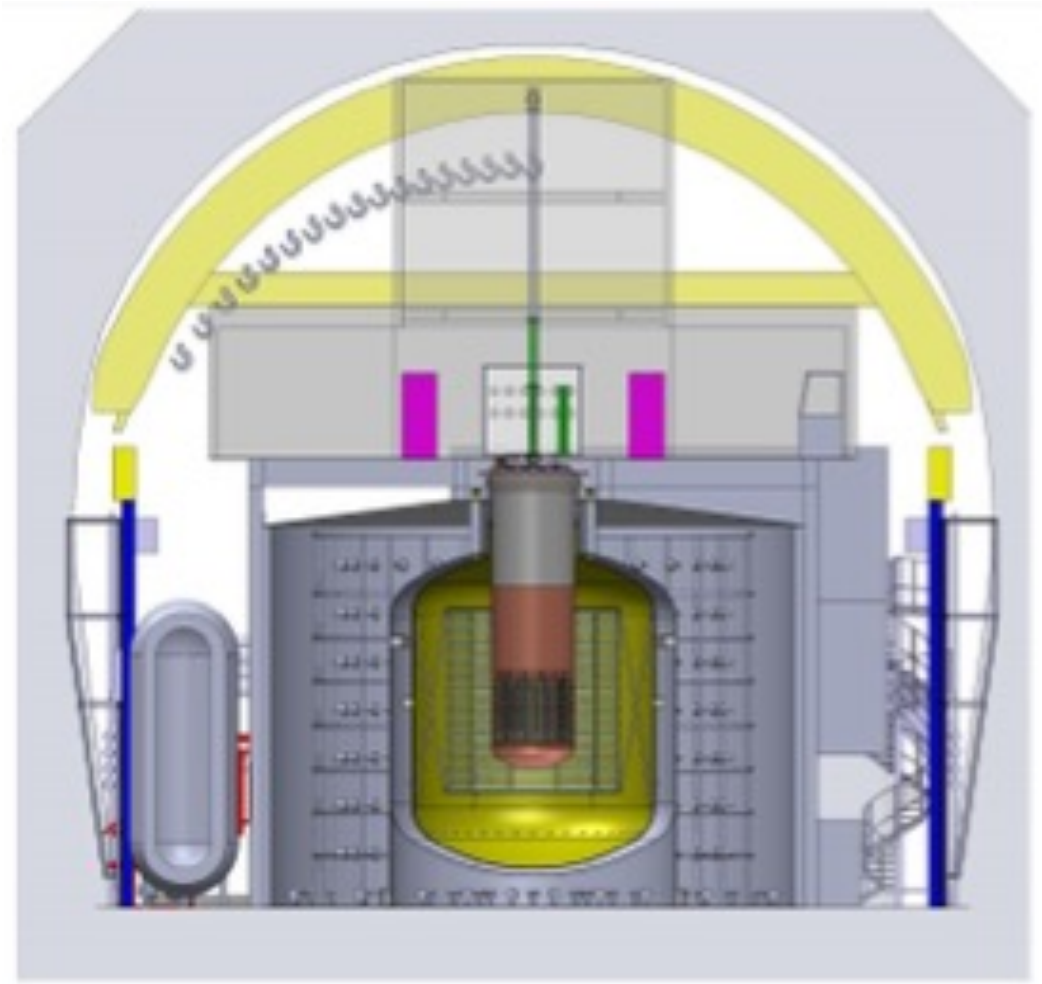
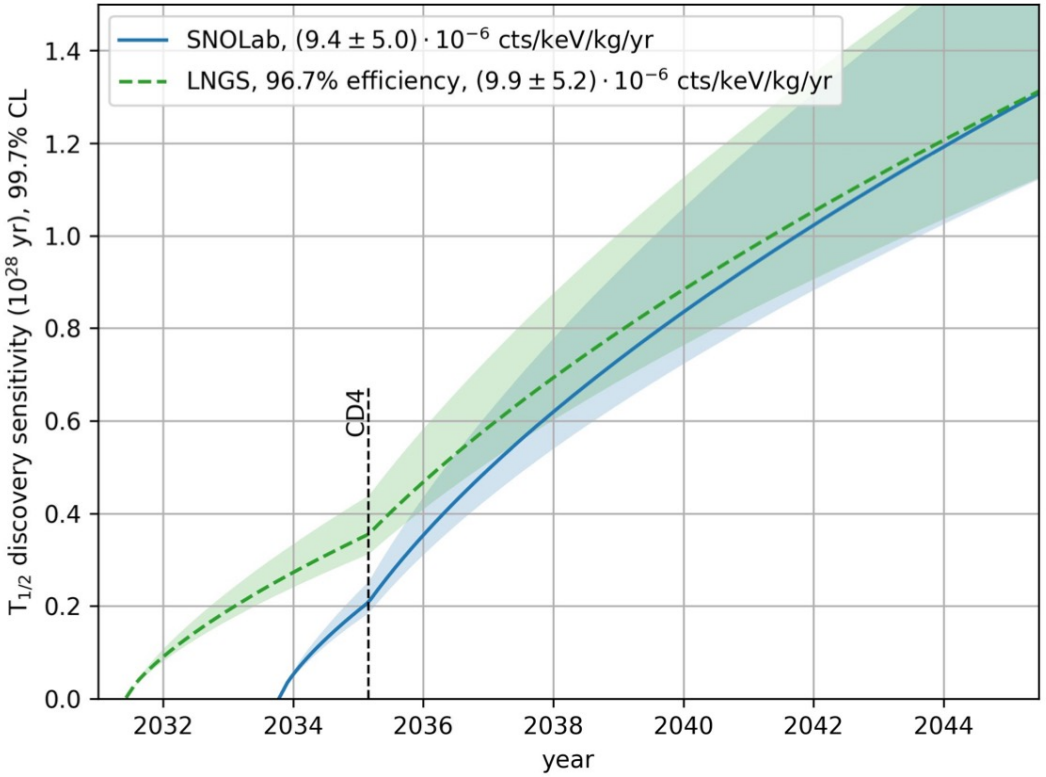


LEGEND-1000



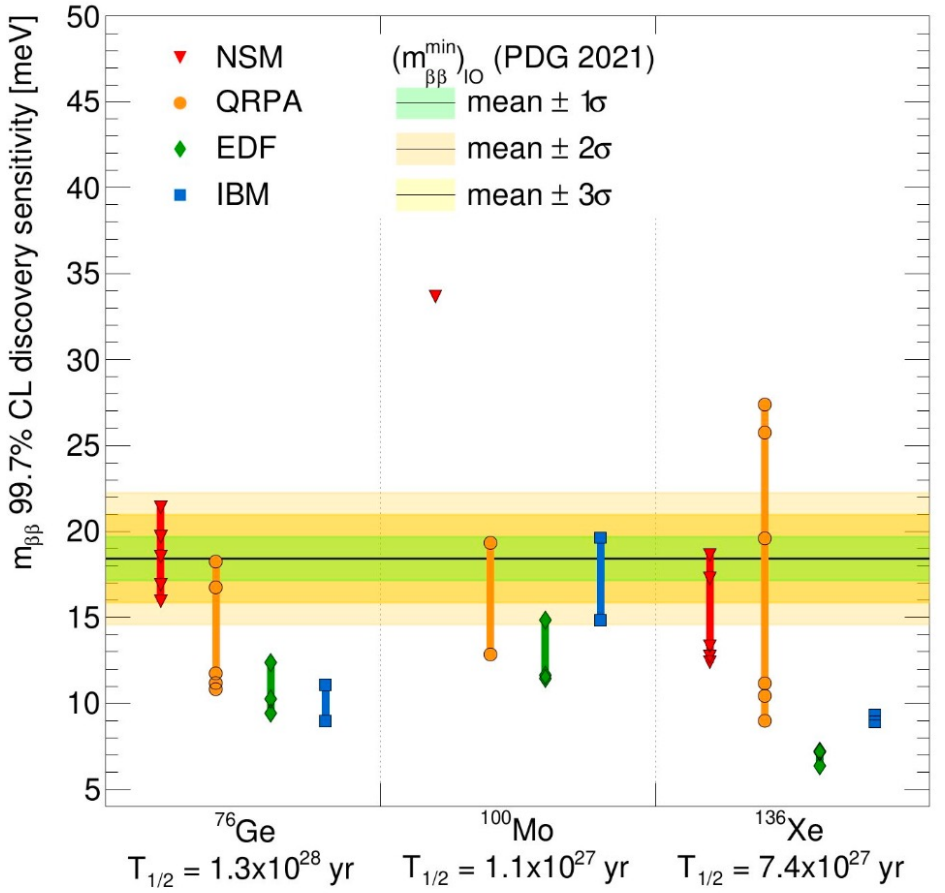
- **CD-1/CD-3A Q1 FY2024**
- Site decision in 2023: LNGS vs. SNOLAB



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
- Multiple, different set of calculations for each many-body method and isotope

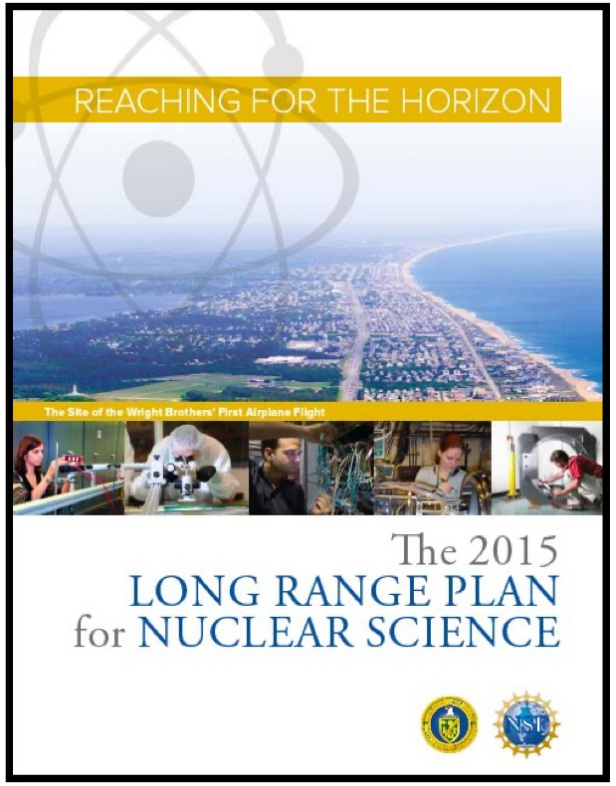
Agostini, Detwiler, Benato, Menendez, Vissani
"Testing the Inverted Neutrino Mass Ordering with 0νββ Decay"
Phys. Rev. C 104, L042501(2021)



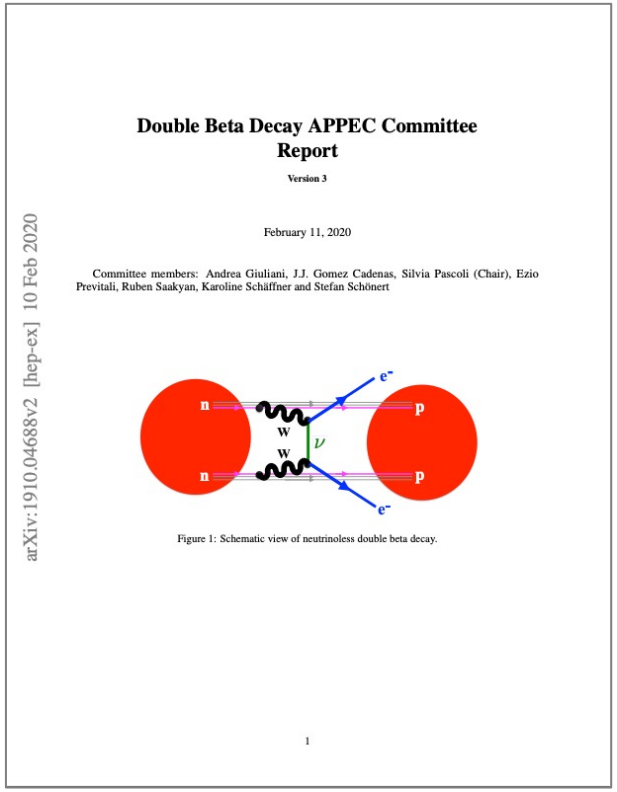
The European and North-American Process

https://agenda.infn.it/event/27143/
https://indico.cern.ch/event/1242655/

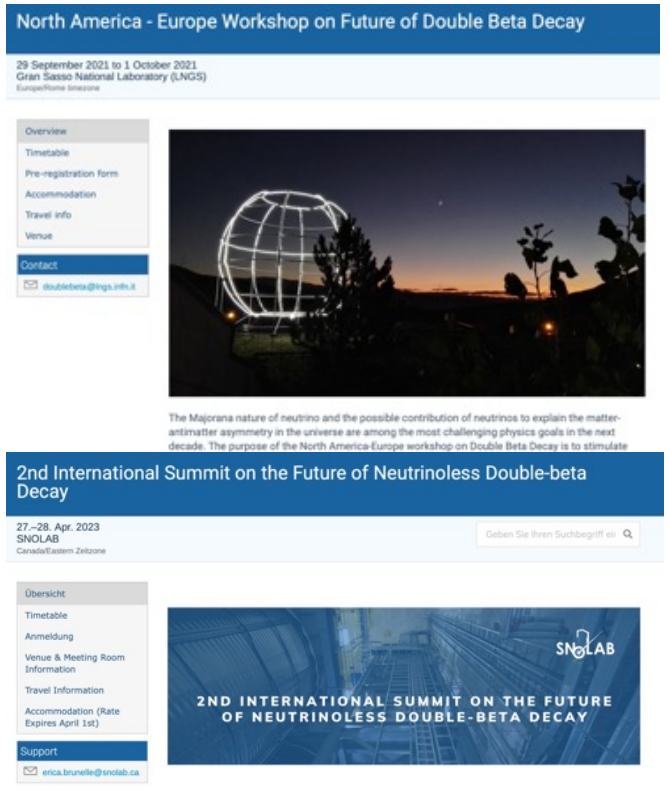
https://science.osti.gov/np/nsac



https://arxiv.org/abs/1910.04688



DOE NP Portfolio Review
July 2021
CUPID
LEGEND-1000
nEXO



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

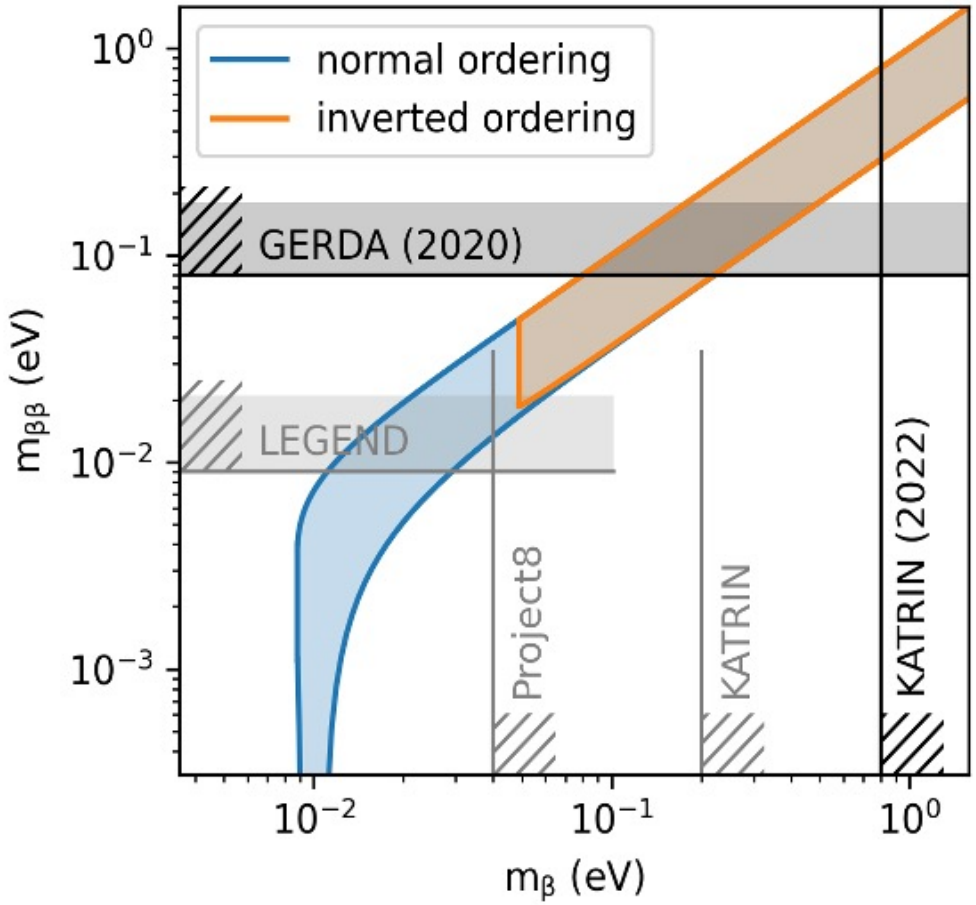
- Oct 2019: Roadmap document for the APPEC SAC on the future $0\nu\beta\beta$ decay experimental programme in Europe
- $0\nu\beta\beta$ town meeting London
- Roadmap update 2022, town meeting in Berlin, June 2022

- Outcome: Realize international portfolio LEGEND-1000, nEXO and CUPID with European partners
- LEGEND-1000 was evaluated top among competitors

"These stakeholders discussed a scenario that could accomplish the goals of the first bullet by deploying CUPID, LEGEND-1000, and nEXO with one tonne-scale experiment in Europe and one tonne-scale experiment in North America."

Summary & Outlook

- Next KATRIN publication in preparation, sensitivity projection $m_\beta < 0.5$ eV
- Data taking towards 0.2 eV sensitivity goal ongoing
- Project8 and ECHO promising technologies to go beyond
- 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**
- North-American – European **convergence on portfolio** of experiments contingent on funding
- **Availability of DBD isotopes** also from Western supplier



EXTRA slides

KLZ dataset is now 970 kg-yr ^{136}Xe exposure!

PRL130, 051801 (2023)

Simultaneous fit has been performed to the entire volume and LL tagged and untagged events.

Binning:
3 time bins
LL tagged/untagged
20 radius bins
upper/lower
86 energy bins

Parameters:
each BG rates
LL efficiency, LL shape
Energy scales (each time, non-linear responses)

BGs
Xe LS: 2ν, Xe-spallation, ν-ES, ^{238}U, ^{232}Th, etc
IB film: ^{238}U, ^{232}Th, ^{40}K, ^{210}Bi, etc
Kam LS: C-spallation, ^{85}Kr, ^{40}K, etc

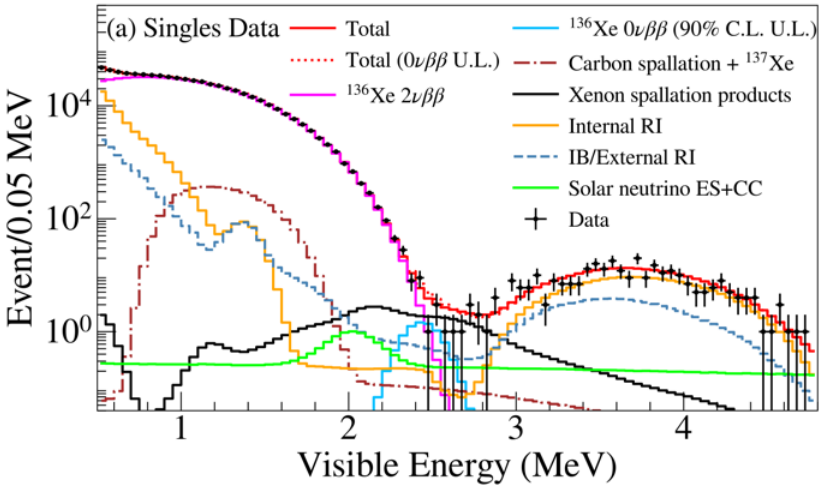
Singles data
(LL untagged, spallation suppressed)

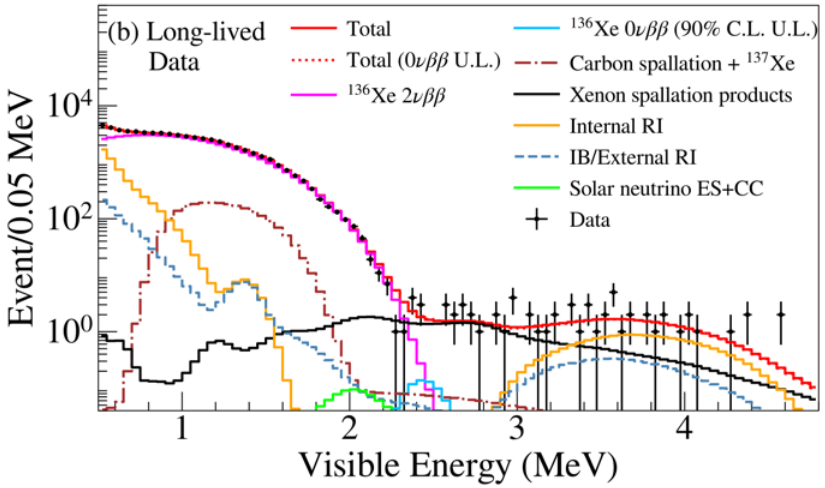
Livetime = 523.4 days

R<1.57m

Long-lived product data
(LL tagged, spallation-rich)

Livetime = 49.3 days



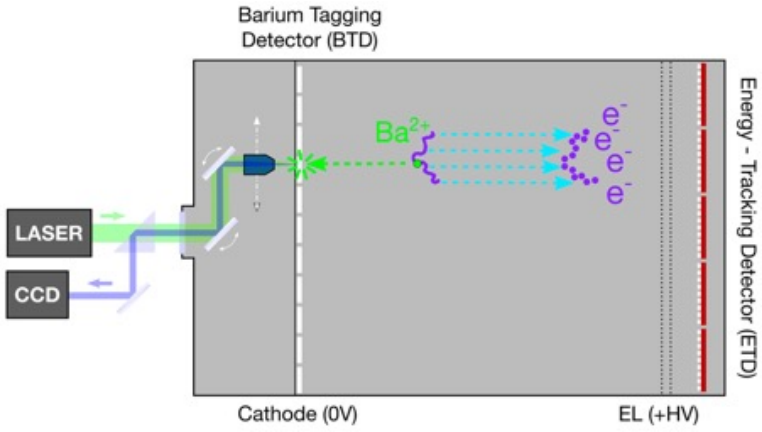


Best fit 0ν2β : 0
90% CL upper limit : <7.9 events/Xe-LS(30.5m^3)

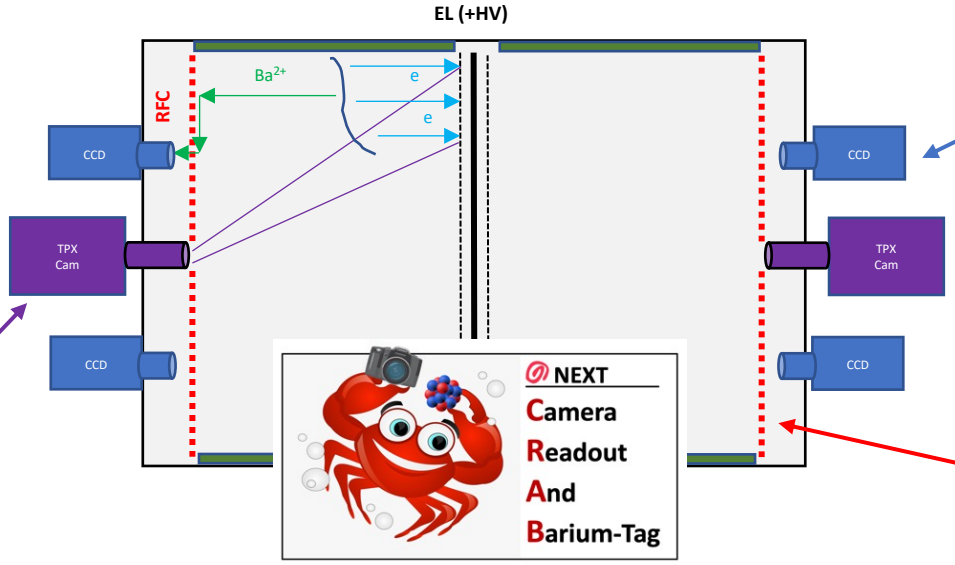
$T^{1/2} > 2.0\times10^{26}$ yr (90% C.L.)

^{136}Xe: Barium tagging demonstrator phases

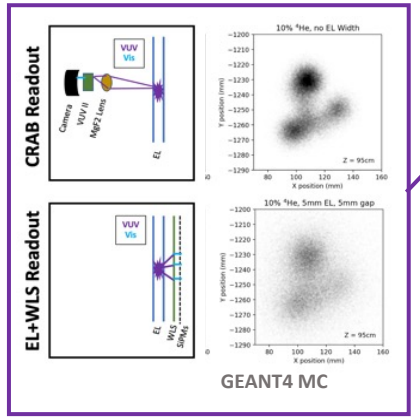
Sensor-to-ion concept (NEXT-BTD)



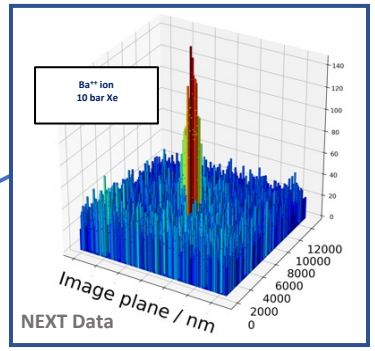
Ion-to-sensor concept (NEXT-CRAB)



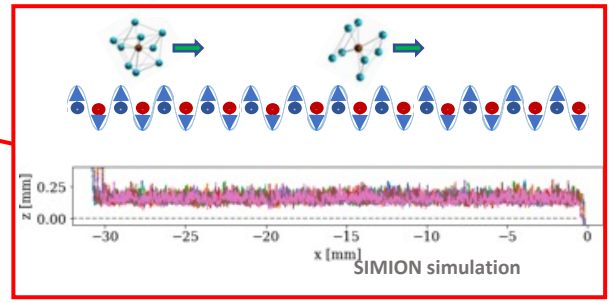
1. Direct VUV camera tracking



2. Single Ba^{2+} ion tagging w/SMFI

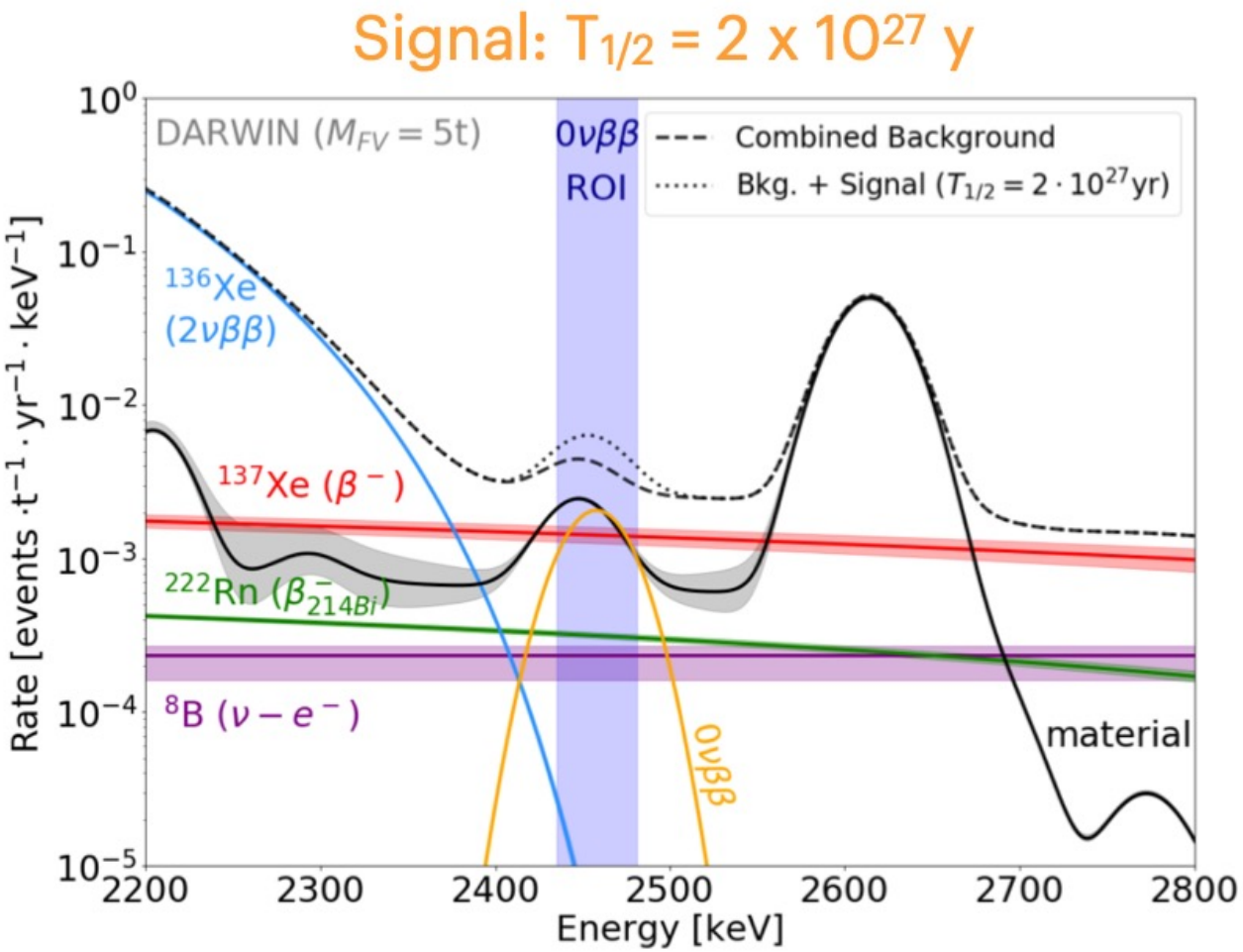


3. RF Carpet ion transport in xenon gas



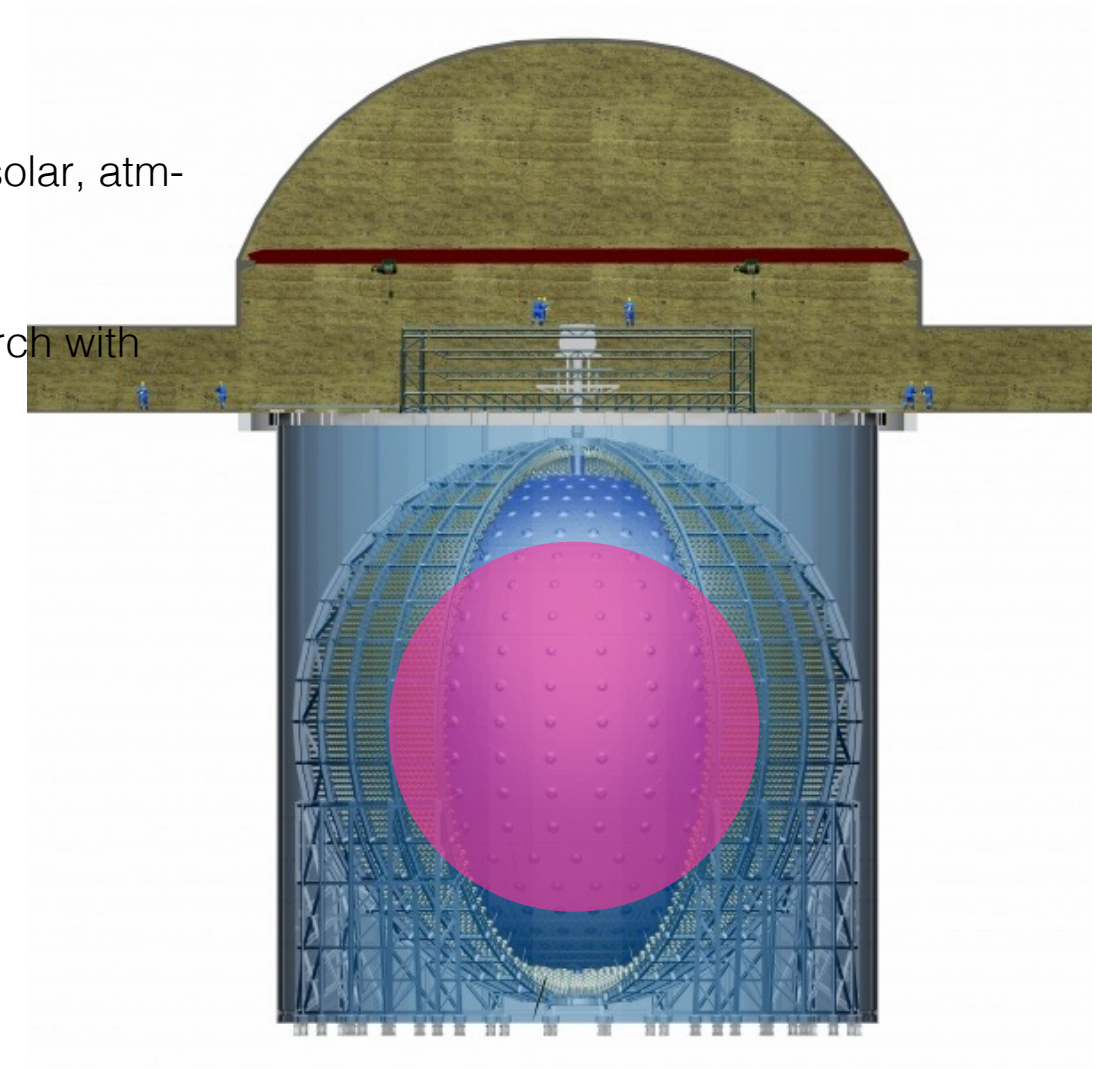
^{nat}Xe: Darwin

- Primary goal: direct dark search
- Large mass of a candidate isotope:
  3.5 t of ^{136}Xe in active target mass (8.9% abundance in natural xenon)
- Excellent energy resolution:
  expect ~0.8% σ at Q-value of 2.5 MeV as demonstrated by XENON1T (Eur. Phys. J. C 80, 785 (2020))
- Main potential backgrounds: ^{222}Rn, ^{8}B neutrinos, ^{137}Xe from cosmogenic activation, 2νββ decays



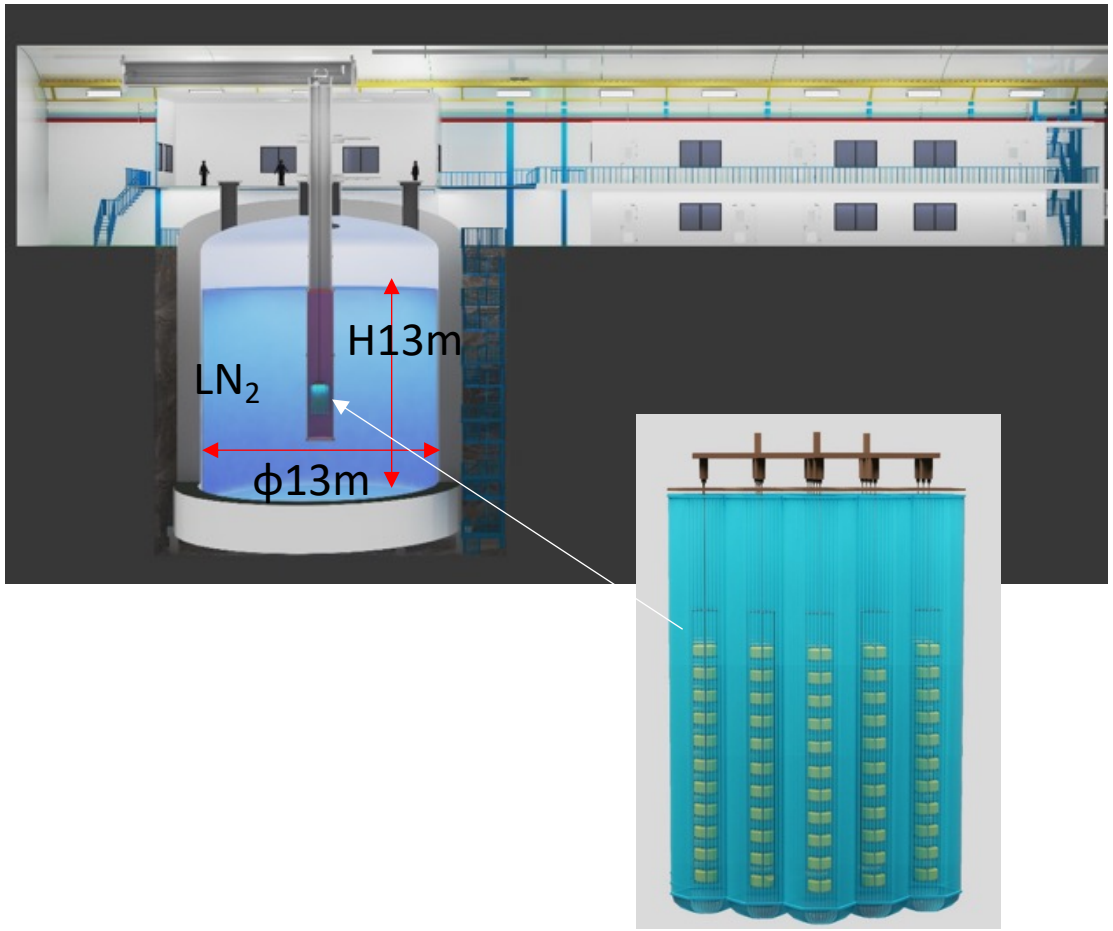
^{nat}Te-loaded liquid scintillator: JUNO

- 20 kt LS (LAB, 2.5 g/L PPO, 3 mg/L Bis-MSB)
- Main goals: neutrino mass ordering with reactor neutrinos, geo-, solar, atm-nu's
- After completion of mass ordering (~2030) upgrade for 0nbb search with ^{nat}Te or ^{136}Xe
- Huge target mass (100 t scale) and aspired low background
- High PMT coverage => 1200 p.e./MeV
- Reported R&D results on Te-diol based LS:
  - Best performance so far with 0.6% Te-loading
  - NO measurable difference compared to purified LAB (A.L. > 20m)
  - NO degradation after 6 months
  - Relative light output: 60%~70% w.r.t un-loaded LS
- Goal: towards exploration of normal mass ordering



^{76}Ge: CDEX-300v @ CJPL

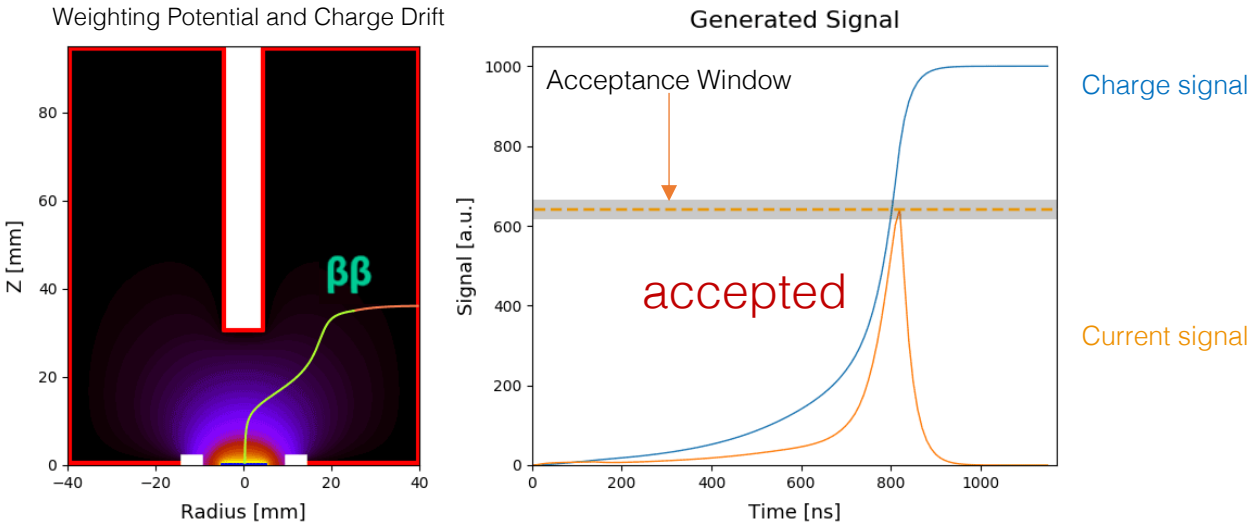
Adoption of LEGEND concept



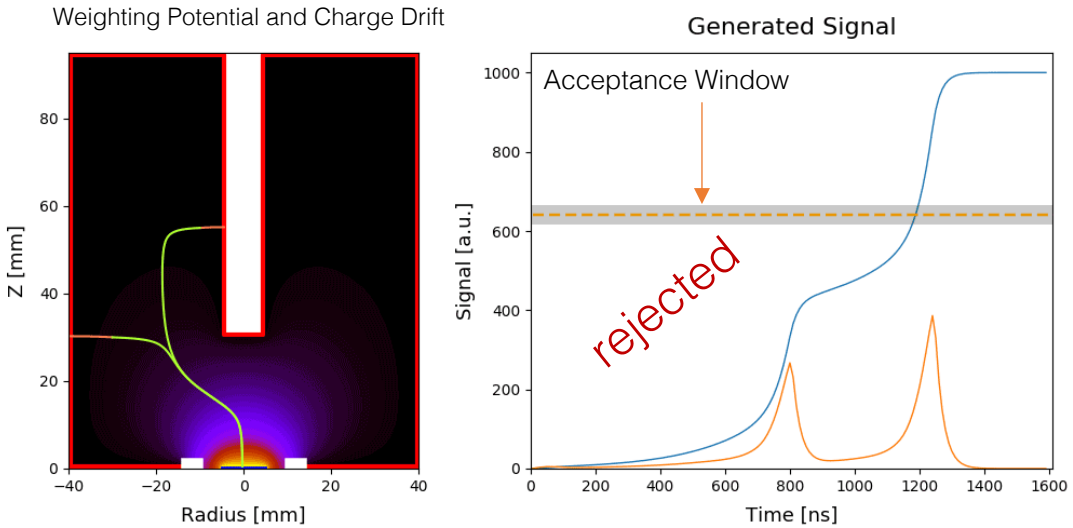
- 1725m³ LN_2 for shielding and Cooling;
- Φ1.5m*8m copper tube filled with LAr and immersed into LN_2 for cooling;
- Enriched Ge array in LAr media for cooling and active LAr shielding.
- 1st 100kg >86% $^{76}GeO_2$ in CJPL, 2nd 100kg ready in the first half of 2023; 3rd 100kg: under preparation;
- Enriched BEGe detectors: First batch (30-40 detectors) at CJPL in 2023

^{76}Ge: LEGEND-1000 - Full event topology reconstruction in novel Ge detectors

0νββ signal candidate (single-site)

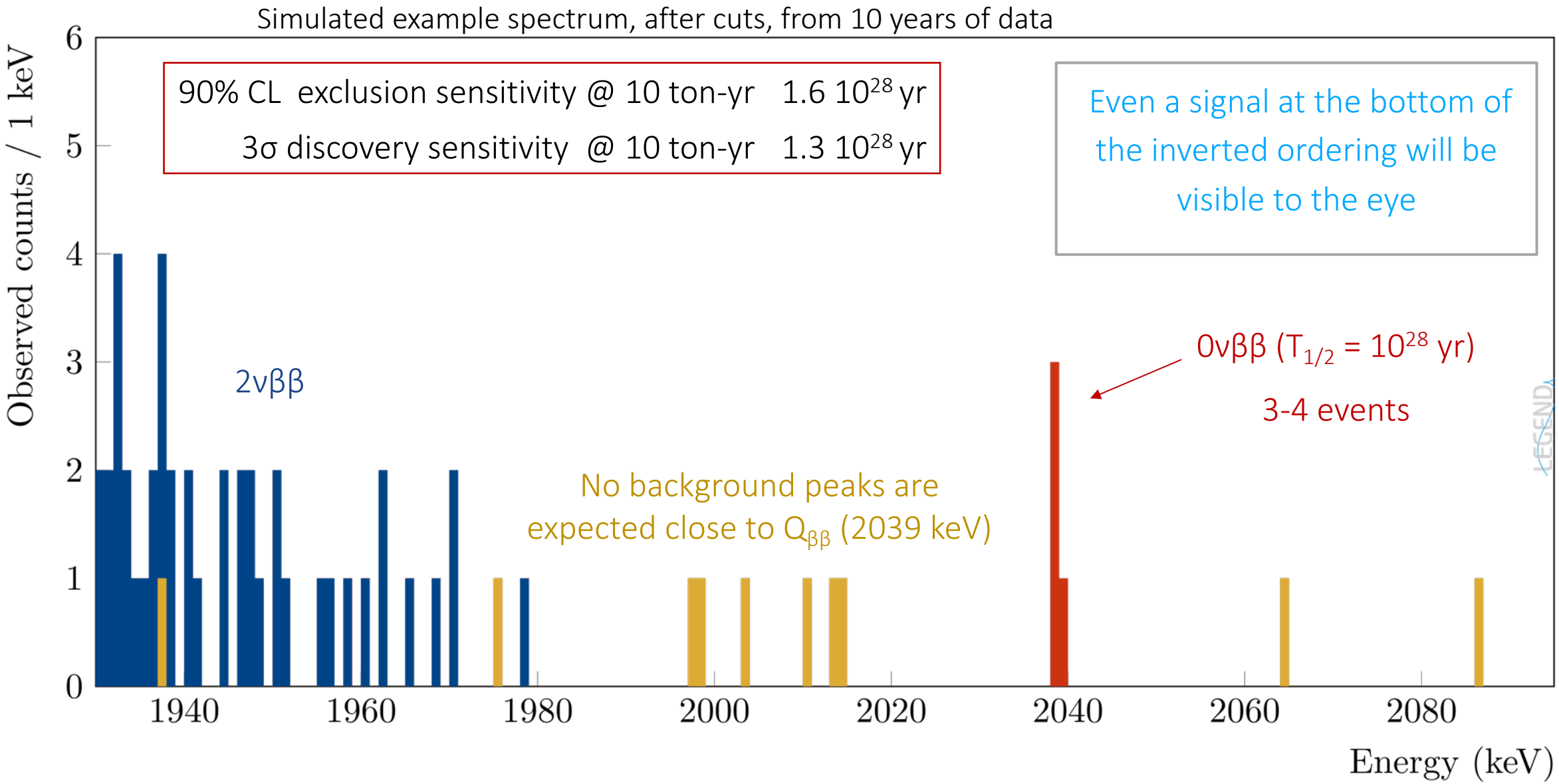


γ-background (multi-site)

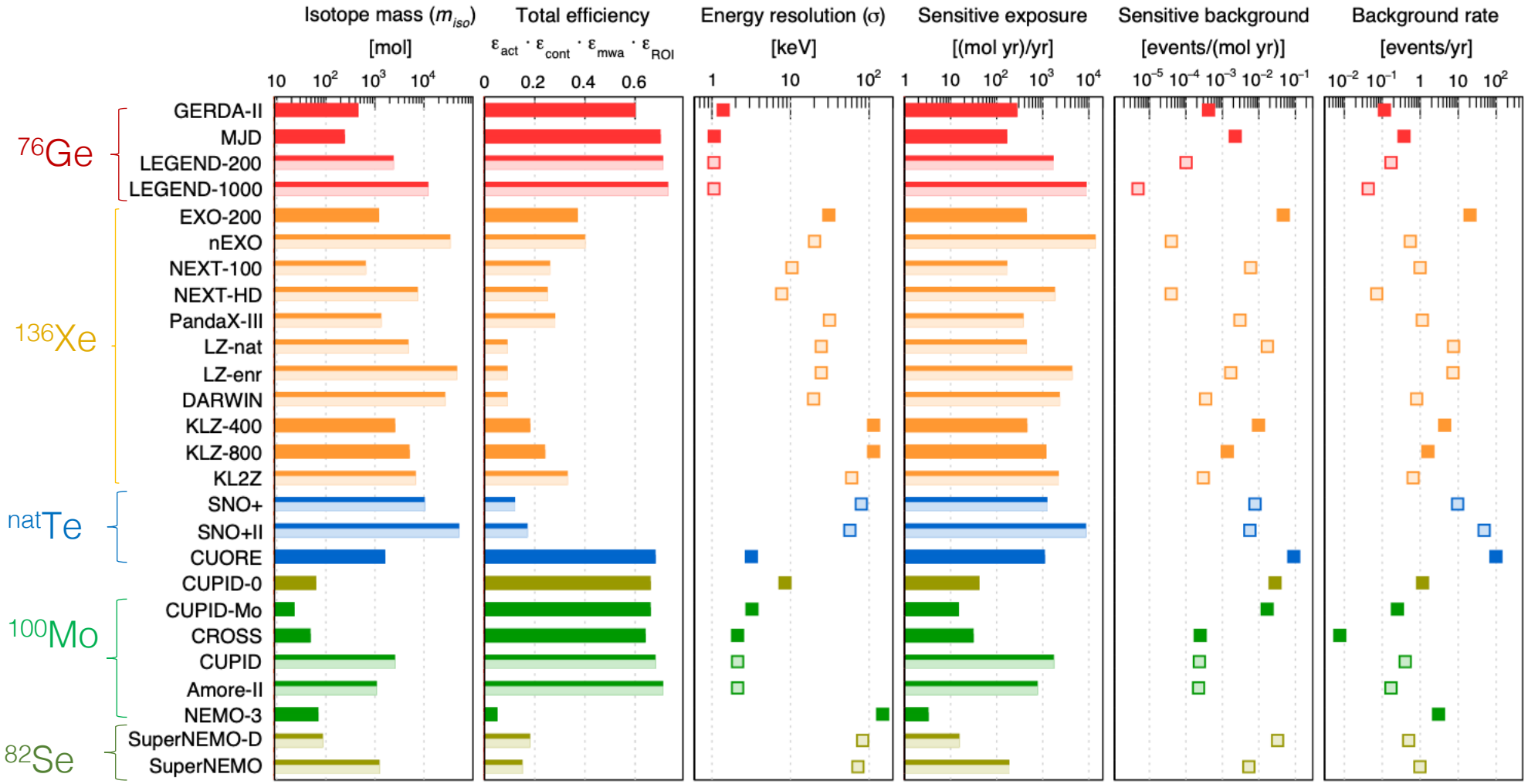


Also highly efficient suppression of surface events

^{76}Ge: LEGEND-1000 designed for an unambiguous discovery

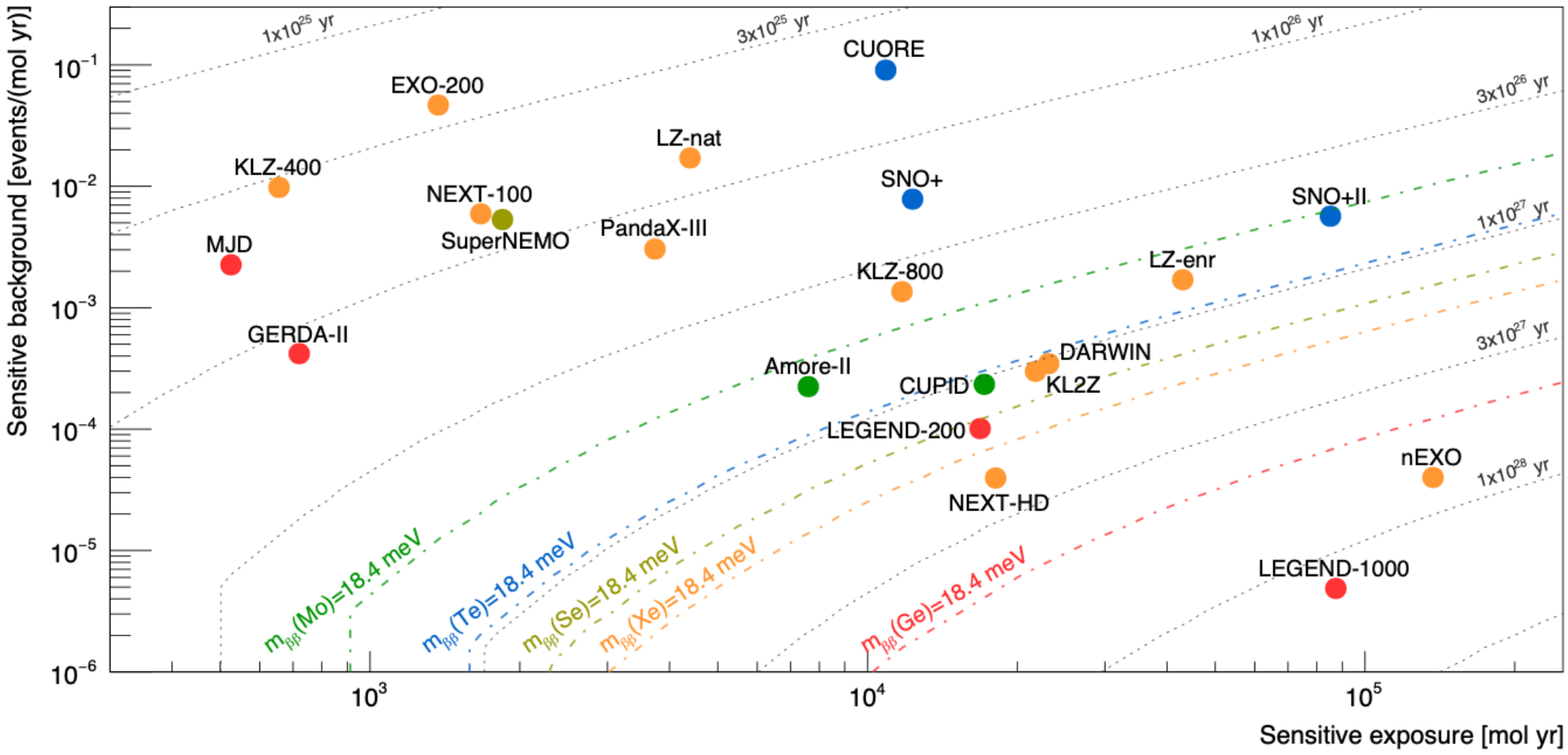


Isotope masses, efficiencies, sensitive background & exposure and backgrounds



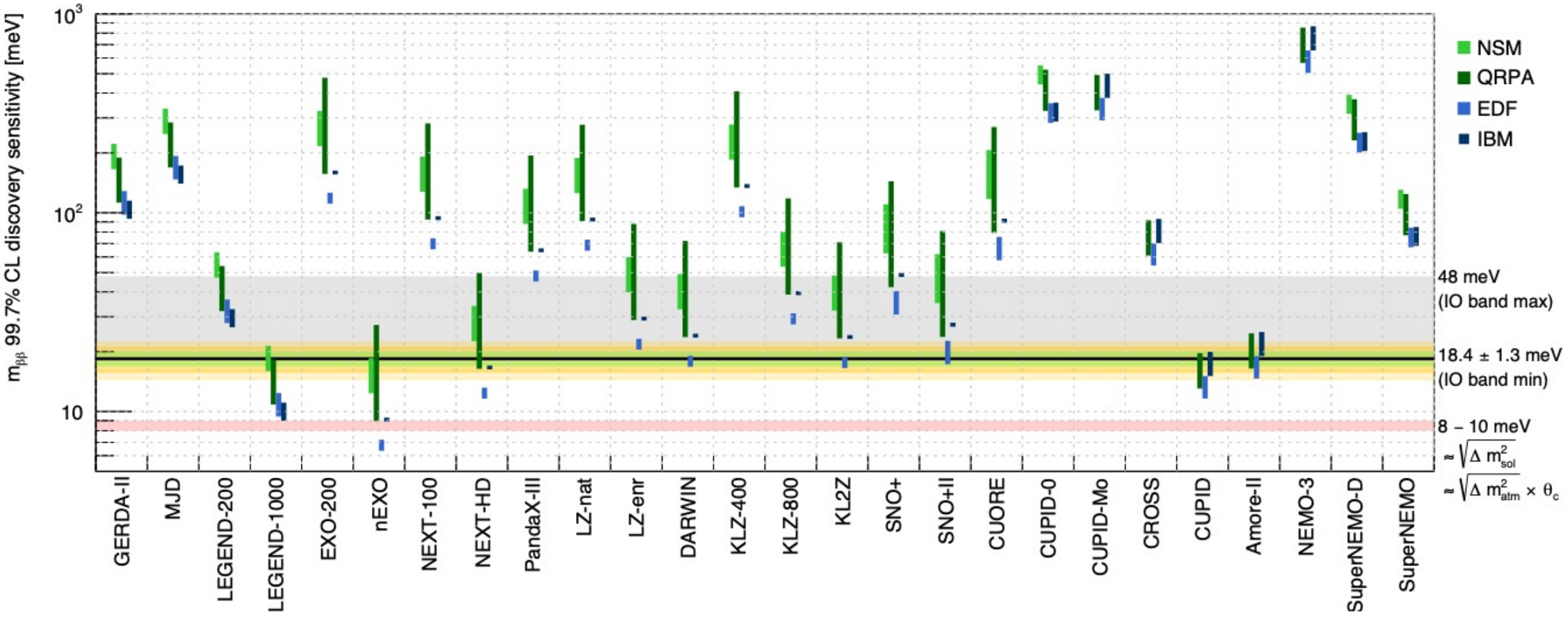
Agostini, Benato, Detwiler, Menendez, Vissani, arXiv:2202.01787

Sensitive background and exposure for recent and future experiments



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

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



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

Neutrino mass observables

Cosmology

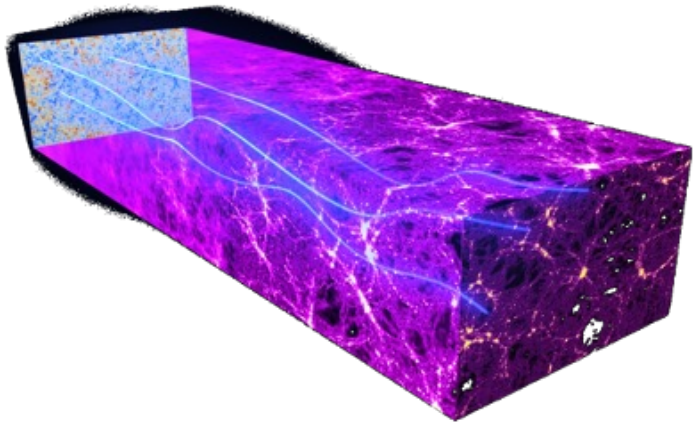
$$\Sigma = \sum_i m_i$$

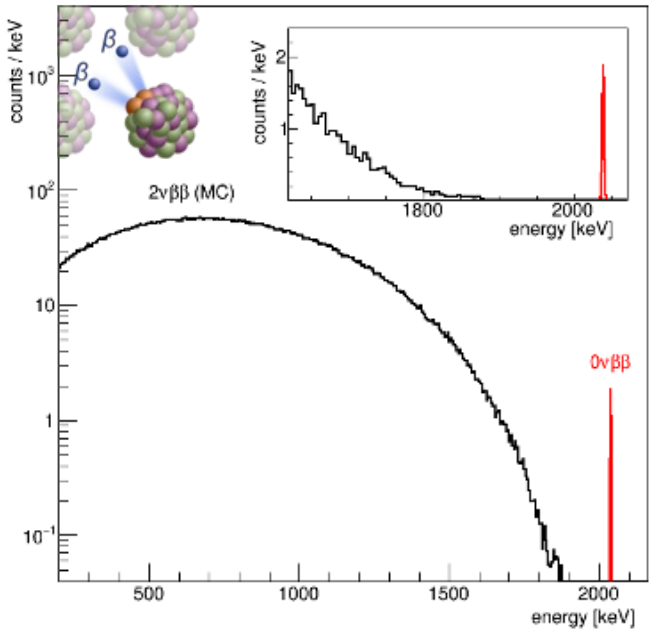
Neutrinoless ßß decay

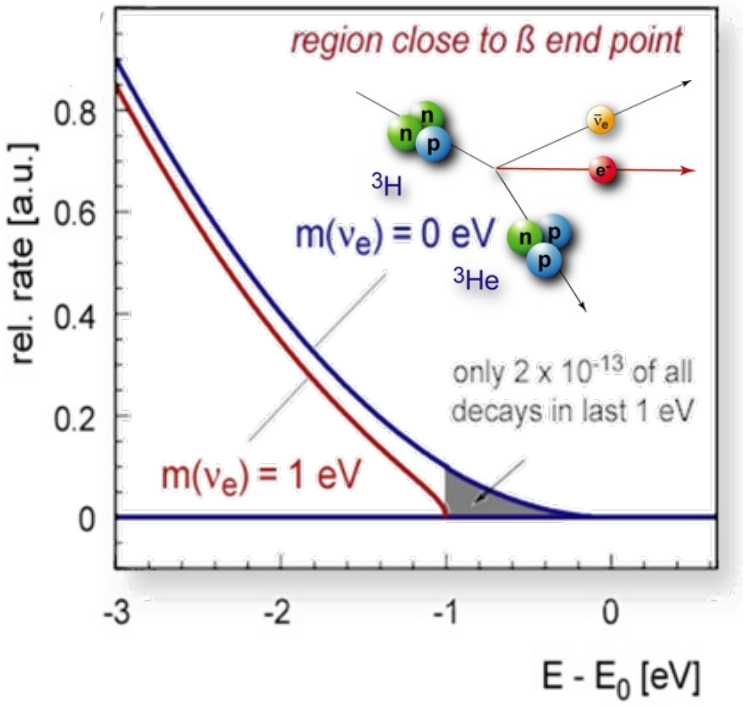
$$m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$$

ß-decay kinematics

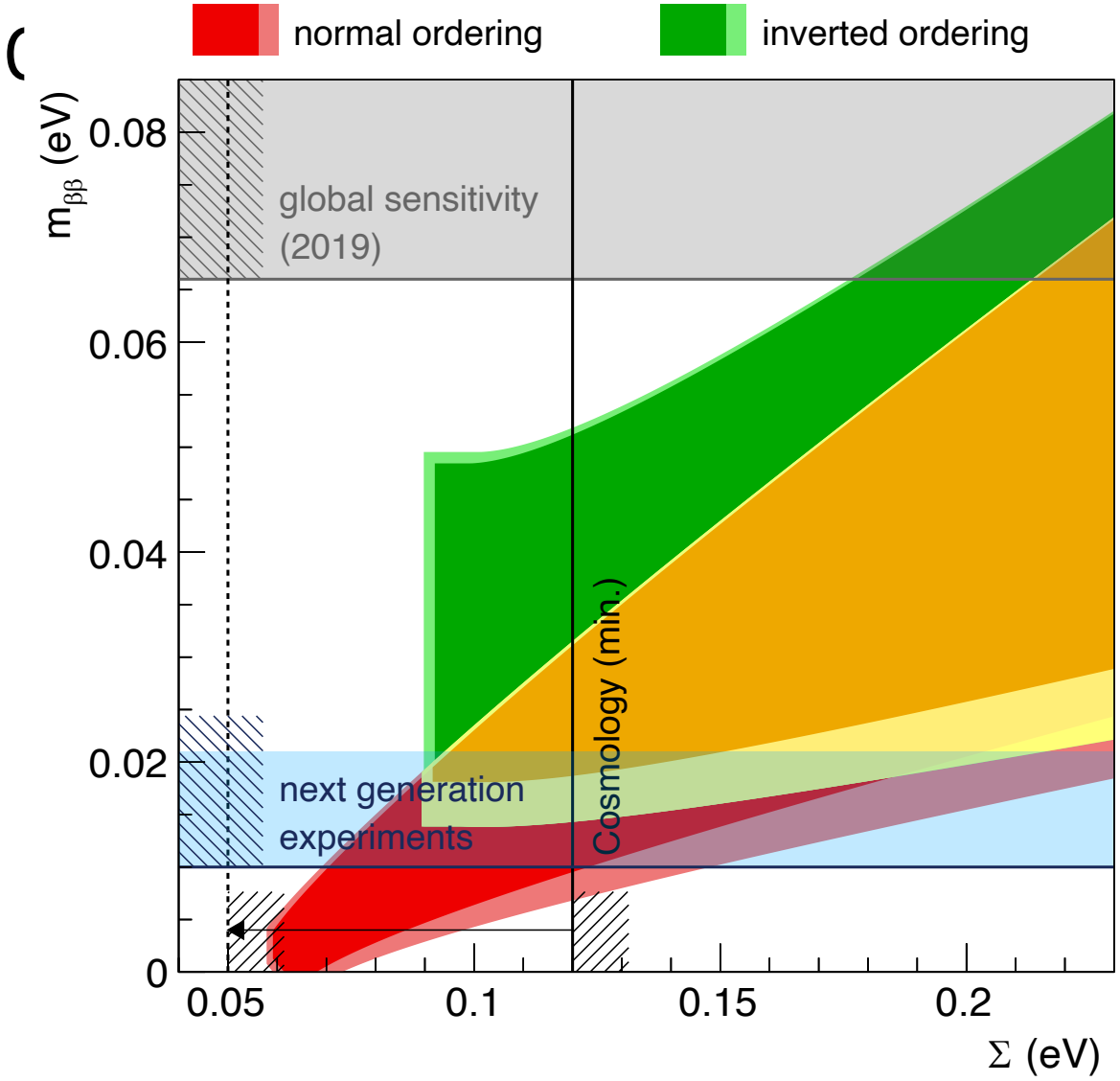
$$m_\beta = \sqrt{\sum_i |U_{ei}^2| m_i^2}$$

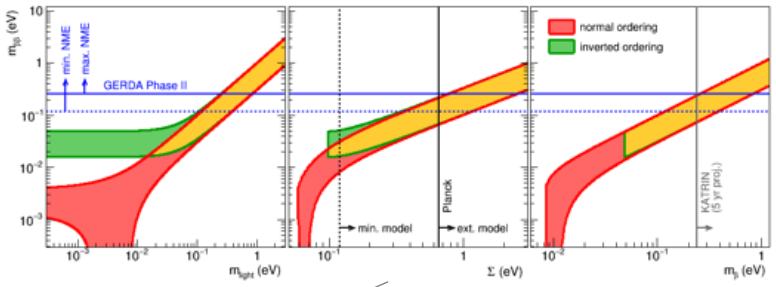






Next decade: large phase space for





Linear projection