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Neutrino mass measurements & neutrinoless double beta decay

- The quest for neutrino mass and nature
- Search for neutrinoless double beta
- Direct search for absolute neutrino mass
- Conclusions

Christian Weinheimer – University of Münster

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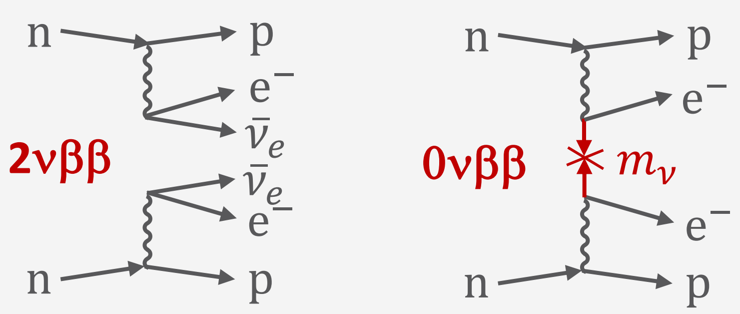
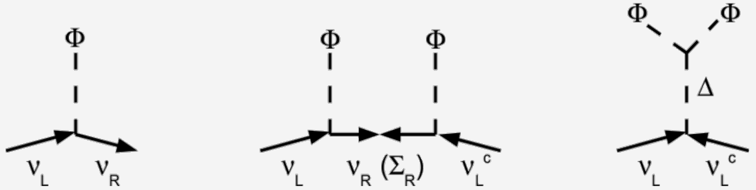
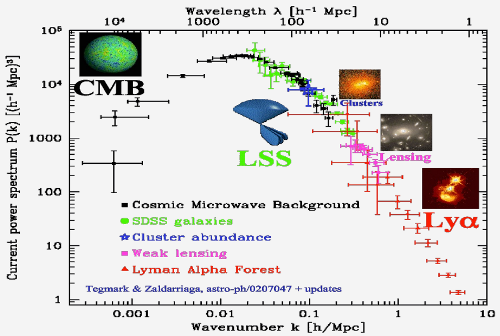
Current most urgent questions in neutrino physics

- **Mass ordering:** m(ν_3) > m($\nu_{2,1}$) or m($\nu_{2,1}$) > m(ν_3) ?
- **CP violating phase δ_{CP} in mixing matrix U_{PMNS}:**
  connected to baryon asymmetry of universe via leptogensis ?
- **Neutrino particle character ?**
  are neutrinos their own antiparticles (Majorona)?
  leptogenesis might explain baryon asymmetry of universe, Seesaw
  → **seach for 0νββ**

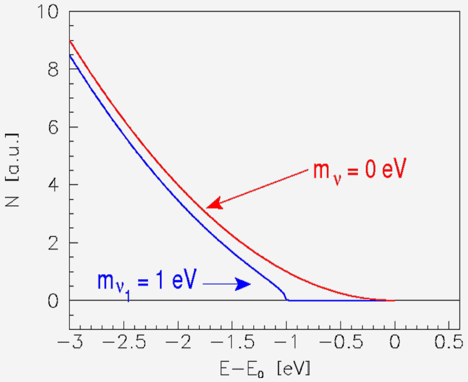




- **Absolute neutrino mass scale ?**
  very important: 10^9 more neutrinos than atoms in the universe
  very important: very small m_ν are probably due to
  more than just the Yukawa coupling to the Higgs
  → **cosmology:** $\sum_i m(\nu_i) \approx$ **0.12 eV** (CMB+BAO)
  → **seach for 0νββ**
  → **direct neutrino mass search**



- **Is there a 4th or even a 5th light but sterile neutrino ?**
  → **also direct neutrino mass search**



Search for neutrinoless double beta decay:
the door to the nature of neutrinos and BSM

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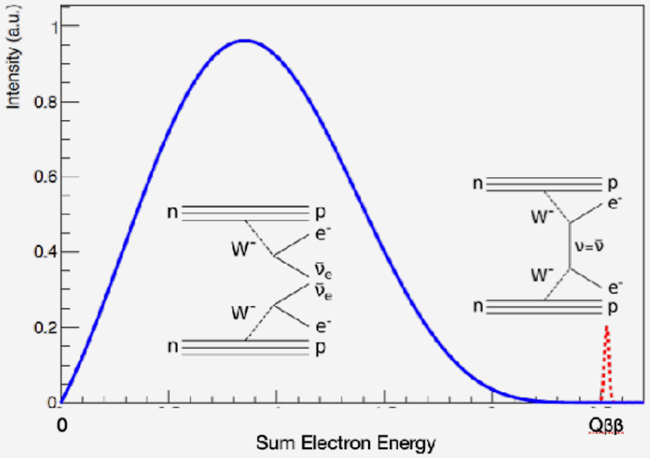
0νββ

$m_{\beta\beta} := \left|\sum_i U_{ei}^2 \cdot m(\nu_i)\right|$

sensitive to Majorana ν only, nuclear matrix elements



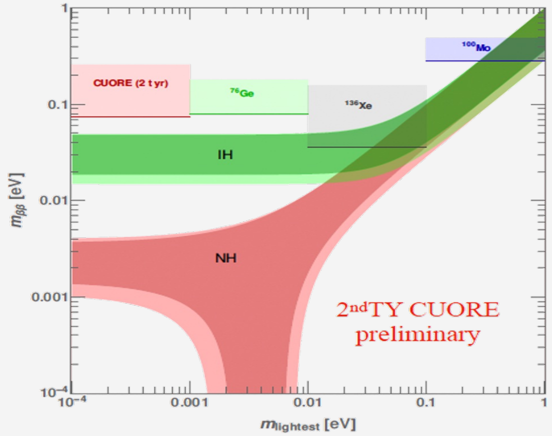
G. Fantini, ICHEP 2022

$$\Gamma^{0\nu} = G_{0\nu}(Q,Z) \cdot |M_{0\nu}(A,Z)|^2 \cdot m_{\beta\beta}^2$$

Discovery of 0νββ would be BSM:
Majorana ν & lepton number violation

Exp. sensitivity:

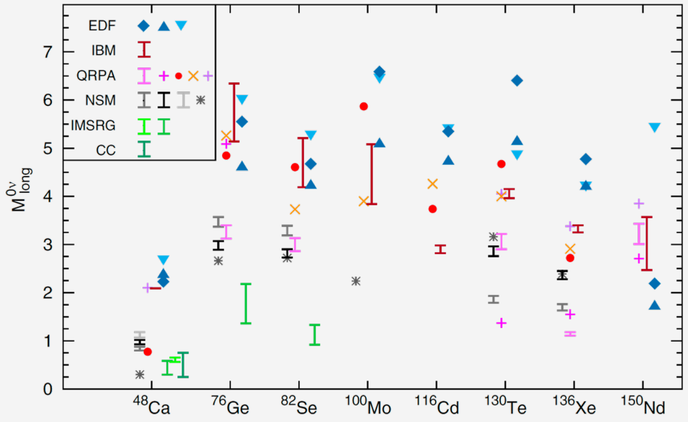
$$T_{1/2}^{0\nu} \propto \begin{cases} a \cdot \varepsilon \cdot M \cdot t & \text{for bg B} = 0 \\ a \cdot \varepsilon \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}} & \text{for bg B} > 0 \end{cases}$$



K. Alfonso TAUP 2023

Nuclear matrix elements;

$M_{0\nu}(A,Z)$ range: factor ≈ 3



M. Agostini, G. Benato, J.A. Detwiler, J. Menéndez, F. Vissani, Rev. Mod. Phys. 95 (2023) 025002

Disclaimer:

$m_{\beta\beta}$ limits are valid only, if 0νββ dominantly via ν exchange

^{76}Ge: GERDA & Majorana (final result) & LEGEND-200

GERDA: enrichment of ^{76}Ge: $\approx$ 87%

exposure: 127.2 kg*yr — *Phys. Rev. Lett. 125, 252502 (2020)*

energy resolution: $\approx$ 3 keV (FWHM)

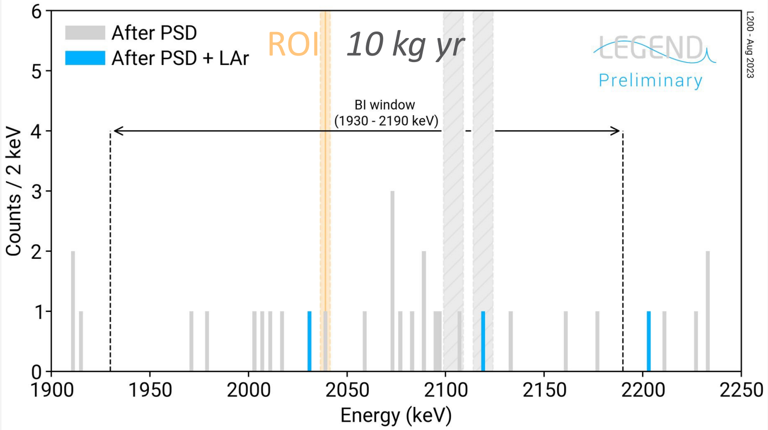
background index: $B = 5.2^{+1.6}_{-1.3} \cdot 10^{-4}$ counts/(keV kg yr)

➞ **lower limit:** $\boldsymbol{T^{0\nu}_{1/2} > 1.8 \cdot 10^{26}}$ **yr** (90% C.L., frequentist)

➞ **upper mass limit:** $\boldsymbol{m_{\beta\beta} < 79 - 180}$ **meV** (without g_A quenching)

Majorana Demonstrator: $B = 15.7^{+1.4}_{-1.3} \cdot 10^{-3}$ counts/(keV kg yr)

➞ **lower limit:** $\boldsymbol{T^{0\nu}_{1/2} > 8.3 \cdot 10^{25}}$ **yr** — *Phys. Rev. Lett. 130, 062501 (2023)*



1st 10 kg yr: $B = 4.1^{+7.3}_{-2.6} \cdot 10^{-4}$ cts/(keV kg yr)

LEGEND-200: enriched ^{76}Ge (>90%)

BEGe/ICPC detectors ➞ event topology & active veto

based on GERDA+Majorana technologies

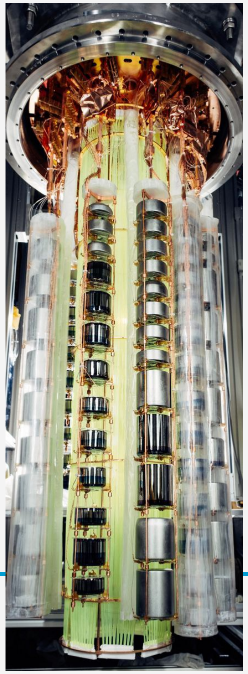
since 03/2023 running: 10 strings with $\approx$ 140 kg

goals: $B = 1.0 \cdot 10^{-4}$ cts/(keV kg yr)

12 strings

sensitivity: $T^{0\nu}_{1/2} = 10^{27}$ yr

M Willers, Kv Sturm TAUP 2023



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CUORE at LNGS

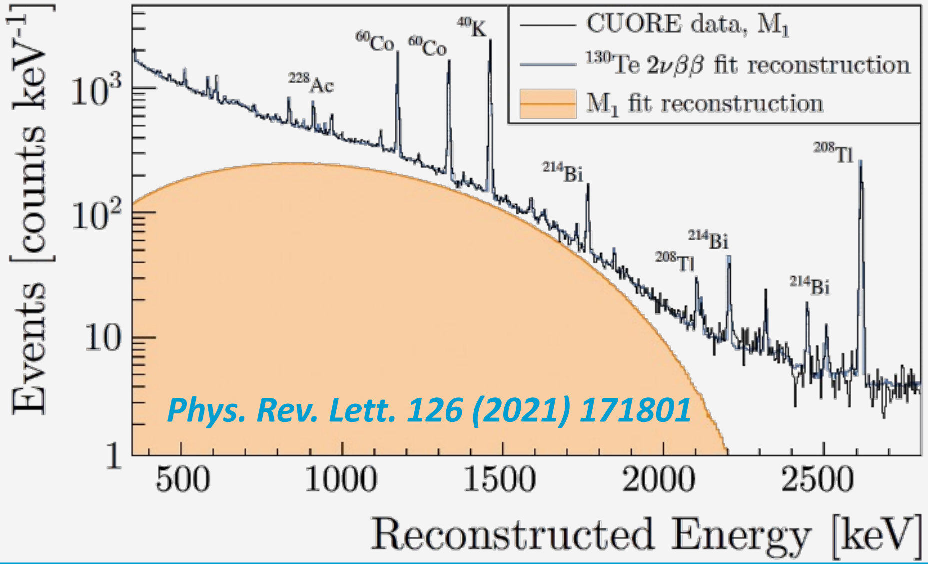
1 t at $T = 10$ mK
3 t at $T < 50$ mK
mK cold since 2019, run until 2025 (3 t yr)
afterwards upgrades towards CUPID

nat. abundance of ^{130}Te: $\approx 34.2\%$
active mass Te_2O (^{130}Te): 742 kg (206 kg)
energy resolution: 7.4 keV (FWHM) by NTD-Ge readout
background index: $B = 1.30(3) \cdot 10^{-2}$ counts/(keV kg yr)

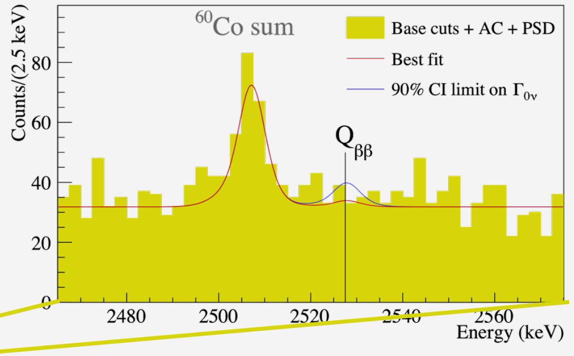
➞ lower limit: $T^{0\nu}_{1/2} > 3.3 \cdot 10^{25}$ **yr** **(90% C.L.)**
➞ upper mass limit: $m_{\beta\beta} < 75 - 255$ **meV**

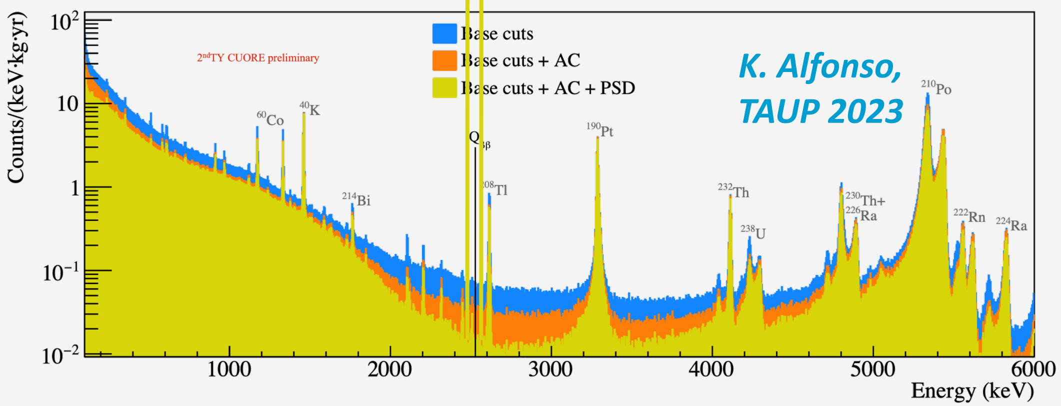
*TAUP 2023 2 t*yr*

2νββ half life: $T^{2\nu}_{1/2} = 7.71^{+0.08}_{-0.06}(stat)^{+0.12}_{-0.15}(sys) \cdot 10^{20}$ yr

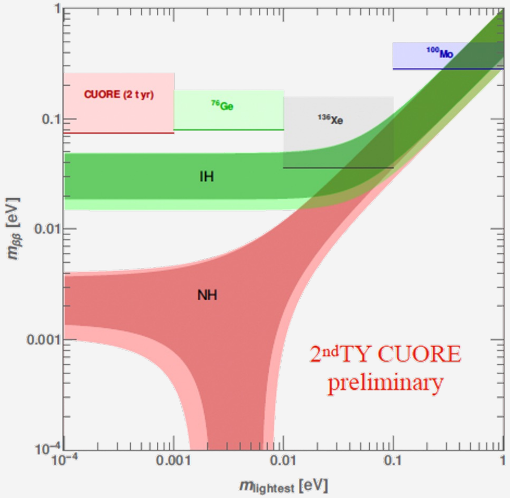


Phys. Rev. Lett. 126 (2021) 171801



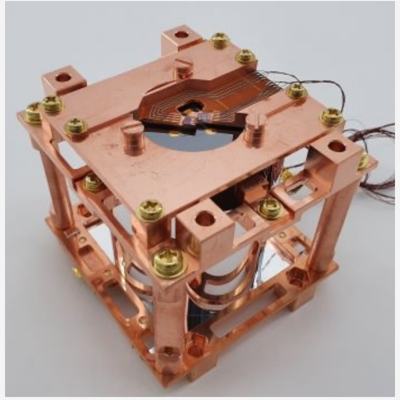


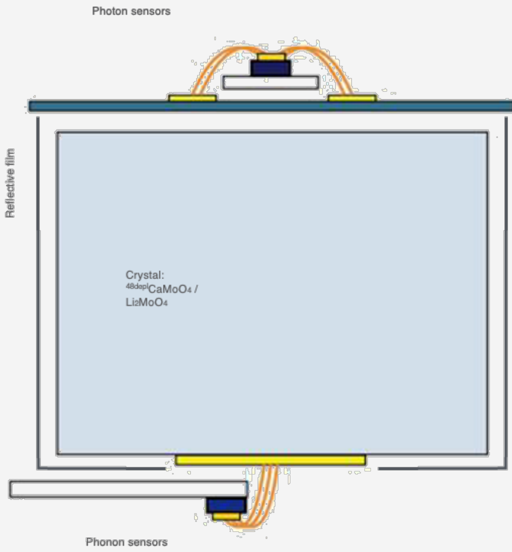
K. Alfonso, TAUP 2023



AMoRE

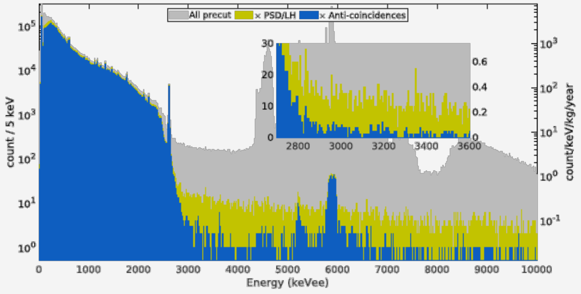
- $Li_2{}^{100}MoO_4$, $^{48depl}Ca^{100}MoO_4$ scintillating crystal cryogenic bolometers
  Detection of both heat and light signals to discriminate β/α events
- Q-value: 3.034 MeV
- Metallic magnetic calorimeter (MMC) + SQUID for signal readout:
  Fast signal (≈ msec rise-time) and a good energy resolution (≈ 10 keV FWHM

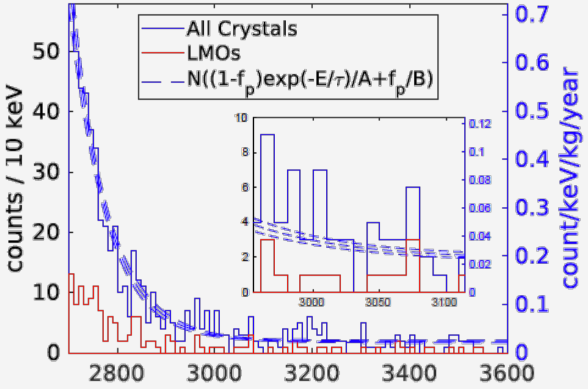




AMoRE-I:

- 6.2 kg (3.0 kg ^{100}Mo), collected 8 kg yr (3.9 kg yr ^{100}Mo)
- Background level: $B \approx 3.2 \cdot 10^{-2}$ count/keV/kg/yr
- $T^{0\nu}_{1/2} > 3.4 \cdot 10^{24}$ yr





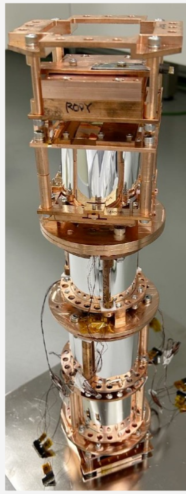
SC Kim TIPP2023

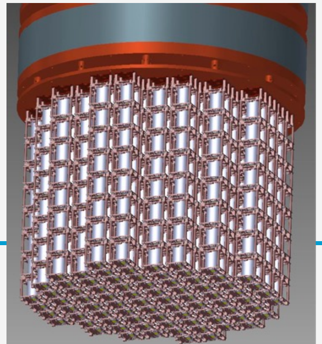
AMoRE-II in YemiLab (1000 m depth), better light det., civil work & shielding installation done

Sensitivity goal: $T^{0\nu}_{1/2} \sim 4 \cdot 10^{26}$ yr
$m_{\beta\beta} \sim 20 - 35$ meV

Background level: $B \sim 10^{-4}$ count/keV/kg/yr

Preparing start with 90 crystals (27kg) in 2024
to be upgraded to 157 kg in 2025





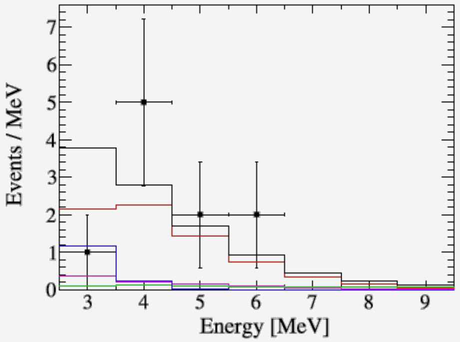
SC Kim TIPP2023 & courtesy: Yeongduk Kim

SNO+

SNO+ at SNOLab with 780 t of liquid scintillator (2.2 g/L PPO in LAB)

Water Phase: completed

- measured the ^8B solar neutrino flux with very low backgrounds
- set world-leading limits on invisible nucleon decay,
  Phys.Rev.D 105 (2022) 11, 112012
- first 3.5σ evidence for reactor antineutrinos through inverse beta decay
  Phys. Rev. Lett. 130, 091801 (2023)



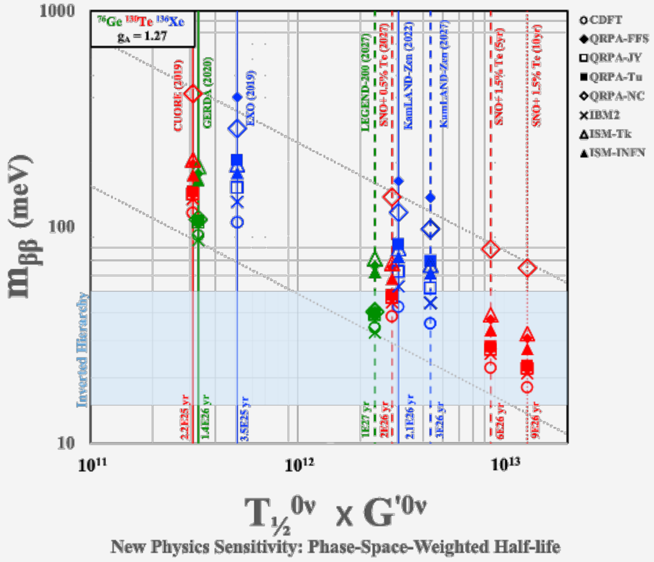
Pure Scintillator Phase:

- detecting low energy ^8B solar neutrinos
- detecting reactor (and geo) antineutrinos to independently measure Δm^2_{12}
- supernova neutrino live

courtesy: Christine Kraus

Double Beta Decay Phase:

- add up to 4,000 kg of ^{130}Te to the detector
- with sensitivity in the IM Ordering parameter space
- Tellurium systems are built ready for operation:
  Full-scale test batches in 2022 and 2023
- Goal: Begin loading Te in the detector in 2024




Telluric acid purification


Te-diol synthesis

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KamLAND-ZEN

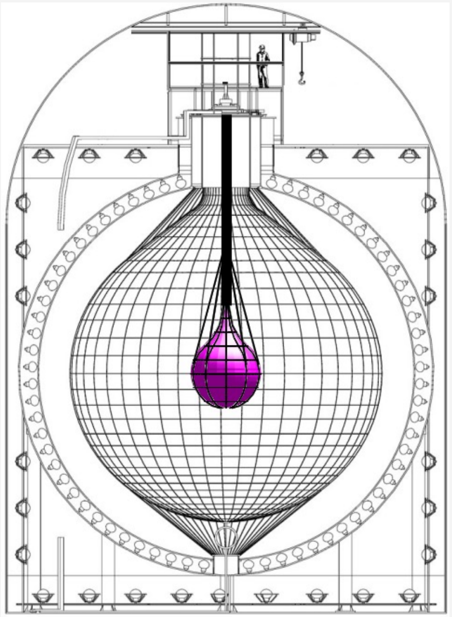
Liquid scintillator detector KamLAND in Kamioka with nylon balloon with LS and DBD isotope ^{136}Xe

- Q-value 2.458 MeV, dissolved into LS ~3% by weight, enrichment ~90%

KamLAND-Zen 400: past

320-380 kg of Xe

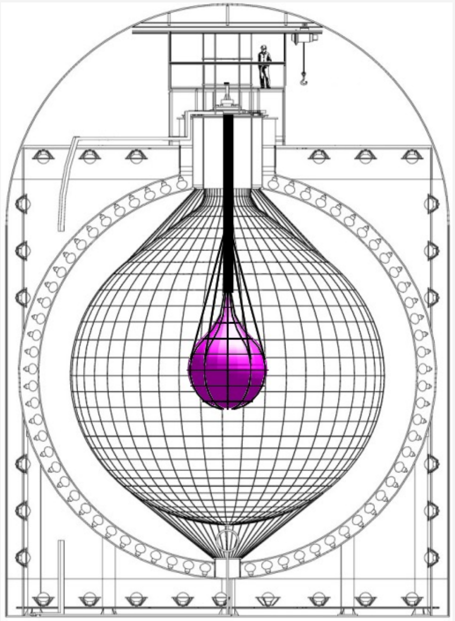
Data taking 2011-2015



KamLAND-Zen 800: present

750 kg of Xe, cleaner

DAQ started in 2019

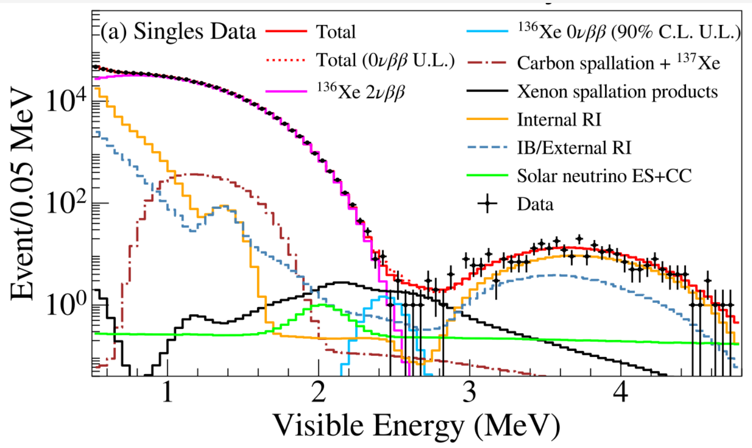


courtesy: Patrick Decowski & Azusa Gando

Latest result:

KamLAND-Zen 800 (523.4 d):

$T^{0\nu}_{1/2} > 2.0 \cdot 10^{26}$ yr



Combined KamLAND-Zen 400+800:

$T^{0\nu}_{1/2} > 2.3 \cdot 10^{26}$ yr

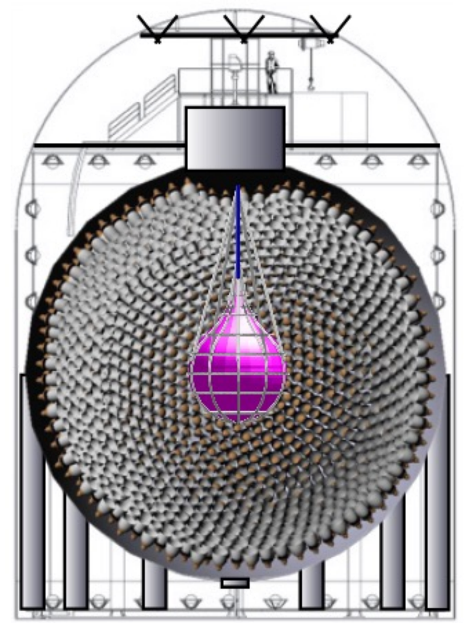
$m_{\beta\beta} < 36 - 156$ meV

Phys. Rev. Lett. 130, 051801 (2023)

KamLAND2-Zen: future

1 t of Xe

Better energy resolution



Goal: $\sigma(2.6\ \text{MeV})$: 4% → 2%

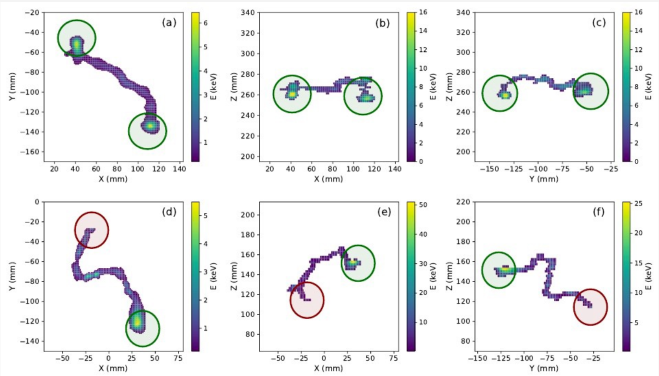
$m_{\beta\beta} \approx 20$ meV

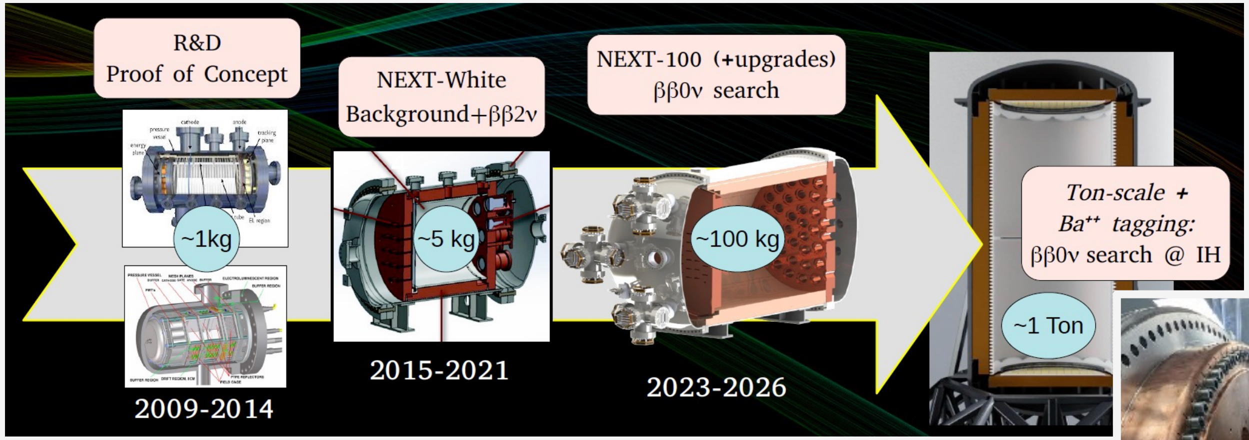
PoS (NOW2022) 067

NEXT: a high pressure ^{136}Xe-enriched TPC

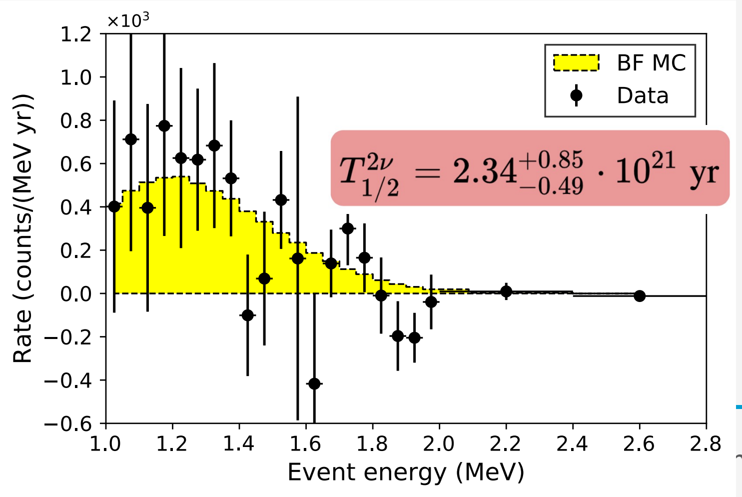
Advantages: High energy resolution (1% FWHM), double electron from vertex ID, goal Ba^{++} tagging

somewhat similar: PandaX-III

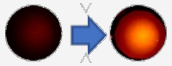


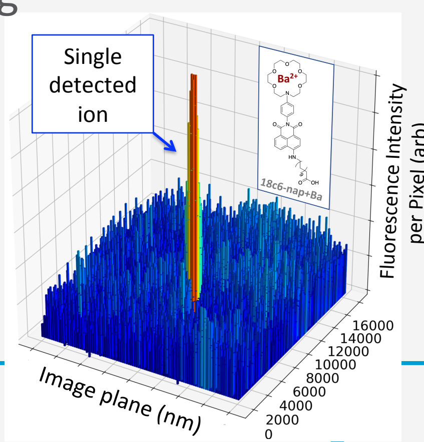


Status: NEXT-White: precision measurement of DBD half-life by measuring with/without enriched xenon
NEXT-100: target background rate: 4×10^{-4} counts/(keV·kg·yr), or ~1 count/(ROI·yr) is being closed
NEXT-HD: 1t symmetric TPC with central electrodes, tracking plane with dense SiPMs,..

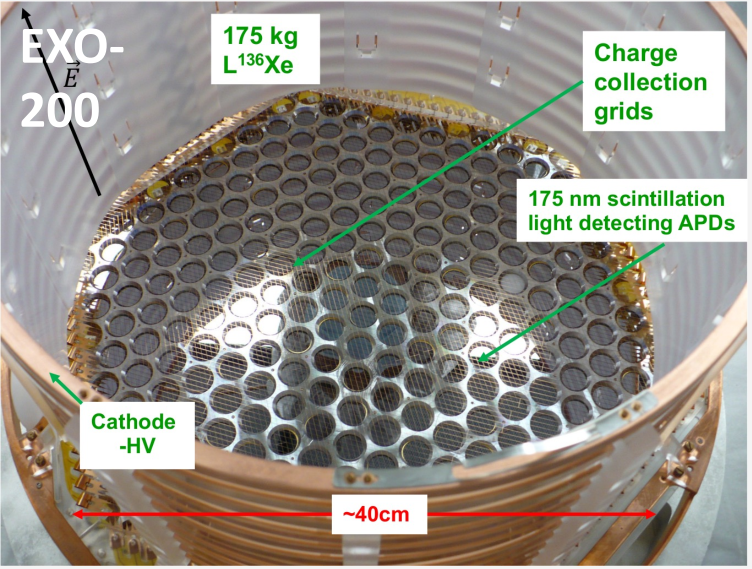


Tagging of Ba^{++} (NEXT-BOLD): Single molecule fluorescent imaging

- developed custom barium chemosensing molecules
  demonstrated single ion response in dry environments:
- Turn-on:  *Phys. Rev. Lett. 120 (2018) 132504, arXiv:2109.05902*
- Bi-color:  *Nature 583 (2020) 7814, 48–54 , arXiv:2201.09099*



courtesy Juan J. Gomez-Cadenas



nEXO: a single phase ^{136}Xe-enriched LXe TPC

nEXO: LXe TPC

enriched ^{136}Xe: 5 t

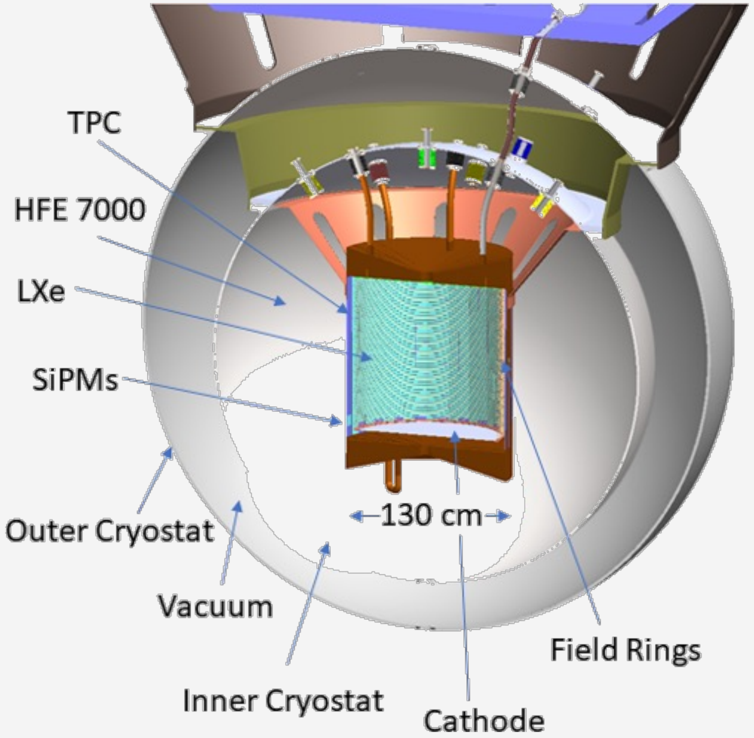
energy resolution: ≈ 46 keV (FWHM)

background index: $B = 7 \cdot 10^{-5}$ counts/(FWHM kg yr)

→ expected sensitivity (10 yr): $T^{0\nu}_{1/2} > 1.35 \cdot 10^{28}$ yr (90% C.L.)

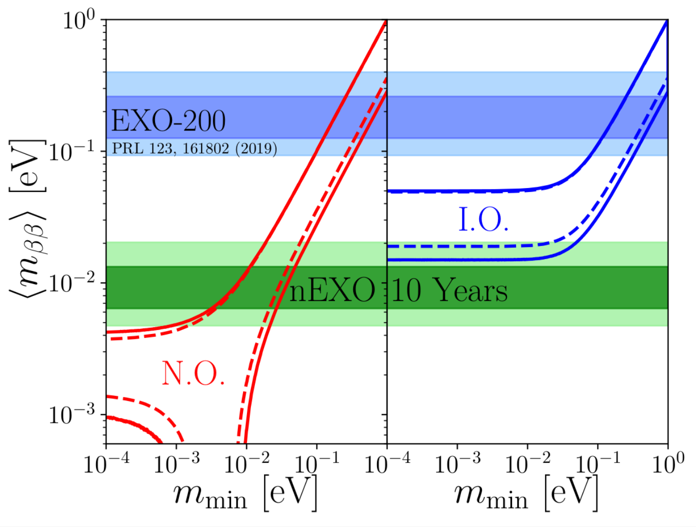
→ expected sensitivity (10 yr): $m_{\beta\beta} < 5 - 20$ meV

G Adhikari et al. (nEXO Coll.) J. Phys. G: 49 (2022) 015104



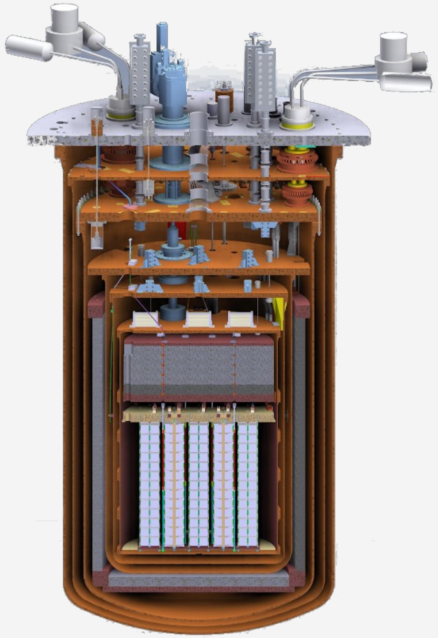
	EXO-200:	*nEXO:*	Improvements:
Vessel and cryostat	Thin-walled commercial Cu w/HFE	*Thin-walled electroformed Cu w/HFE*	Lower background
High voltage	Max voltage: 25 kV (end-of-run)	*Operating voltage: 50 kV*	Full scale parts tested in LXe prior to installation to minimize risk
Cables	Cu clad polyimide (analog)	*Cu clad polyimide (digital)*	Same cable/feedthrough technology, R&D identified 10x lower bkg substrate and demonstrated digital signal transmission
e⁻ lifetime	3-5 ms	*5 ms (req.), 10 ms (goal)*	Minimal plastics (no PTFE reflector), lower surface to volume ratio, detailed materials screening program
Charge collection	Crossed wires	*Gridless modular tiles*	R&D performed to demonstrate charge collection with tiles in LXe, detailed simulation developed
Light collection	APDs + PTFE reflector	*SiPMs around TPC barrel*	SiPMs avoid readout noise, R&D demonstrated prototypes from two vendors
Energy resolution	1.2%	*1.2% (req.), 0.8% (goal)*	Improved resolution due to SiPMs (negligible readout noise in light channels)
Electronics	Conventional room temp.	*In LXe ASIC-based design*	Minimize readout noise for light and charge channels, nEXO prototypes demonstrated in R&D and follow from LAr TPC lineage
Background control	Measurement of all materials	*Measurement of all materials*	RBC program follows successful strategy demonstrated in EXO-200
Larger size	>2 atten. length at center	*>7 atten. length at center*	Exponential attenuation of external gammas and more fully contained Comptons

nEXO ready for being asked to go through DOE CD 1



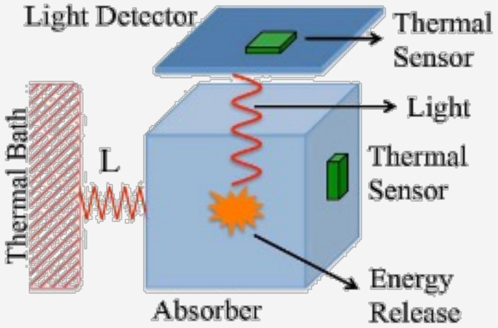
courtesy Giorgio Gratta

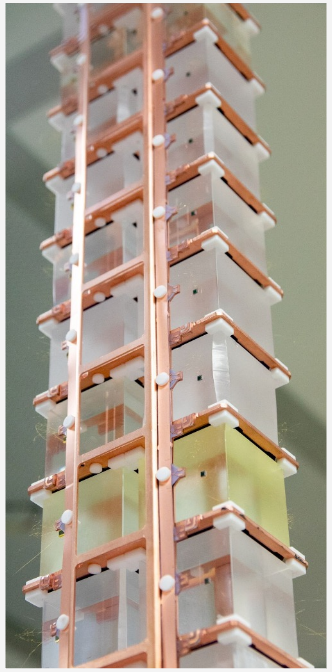
CUPID: CUORE Upgrade With Particle IDentification



Next generation decay 0νββ: **replace** the CUORE TeO_2 detector with 1596 Li_2MoO_4 scintillating bolometers:

- 450 kg of $Li_2{}^{100}MoO_4$
  240 kg of ^{100}Mo, $Q = 3034$ MeV
- 57 towers of 28 crystals, each instrumented with a Light Detector → α-rejection





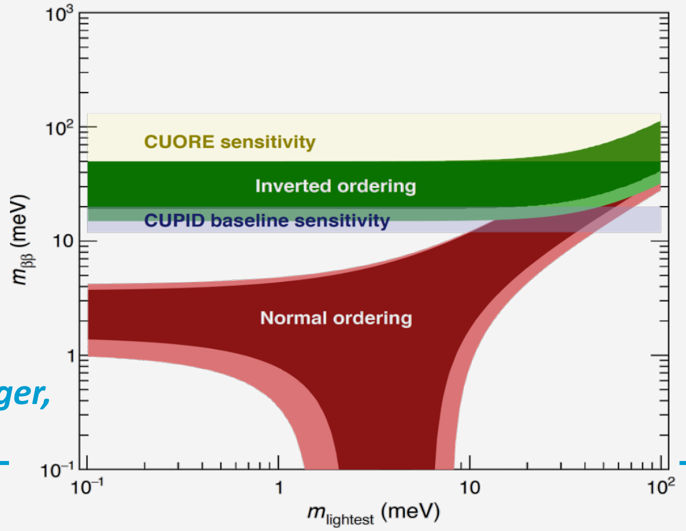
CUPID-like tower (not enriched) Now in operation @LNGS

scintillating bolometer technology: enables PID

Goals: fully probe the "Inverted Hierarchy" region
improve sensitivity to $m_{\beta\beta}$ by factor of ~5 relative to CUORE
energy resolution: $5 - 7$ keV (FWHM)
background index: $B = 1 \cdot 10^{-4}$ counts/(keV kg yr)

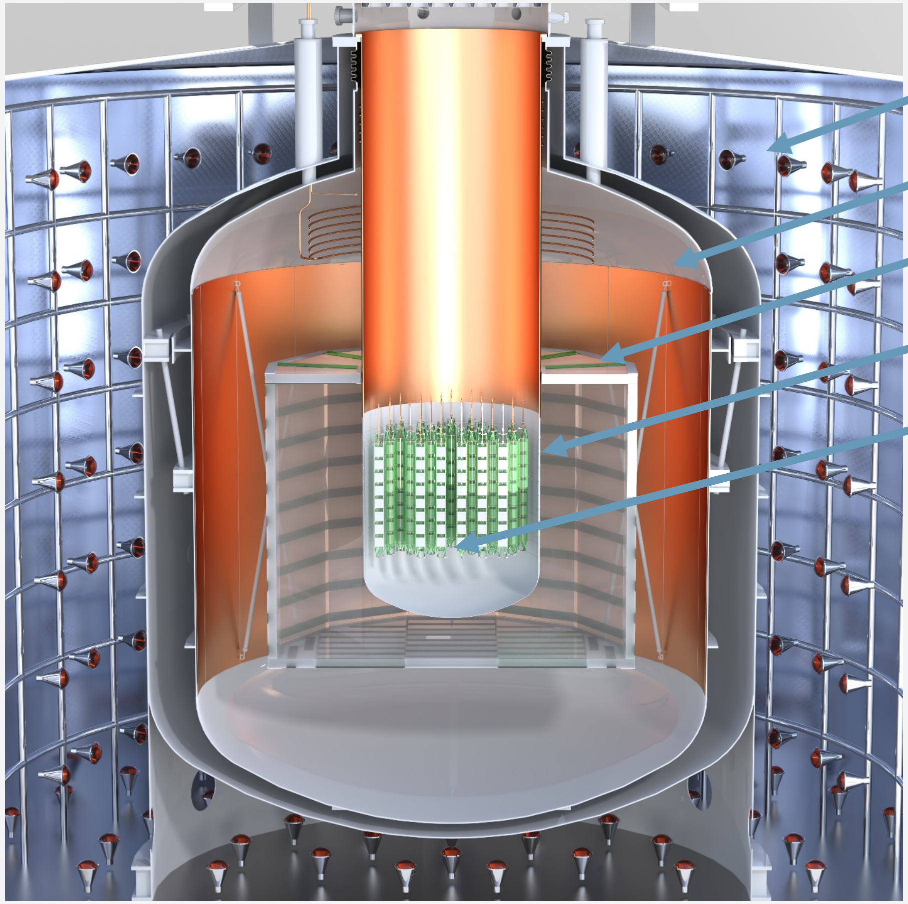
→ exp. sensitivity (10 yr): $T^{0\nu}_{1/2} > 1 \cdot 10^{27}$ yr (90% C.L.)

→ exp. sensitivity (10 yr): $m_{\beta\beta} < 13 - 21$ meV



courtesy: Karsten Heeger, Mauran Pavan

LEGEND-1000



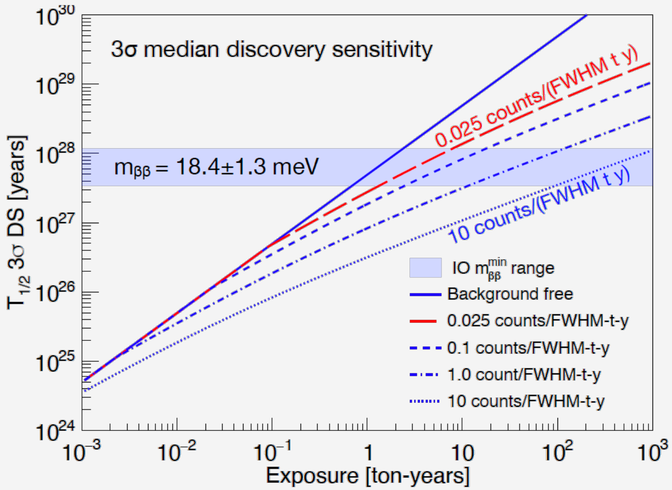
Water tank + PMTs (shielding + muon veto)

Stainless steel cryostat – Xenon doped atmospheric LAr

Neutron moderator + LAr read-out system

Reentrant tube – Underground LAr (UAr)

Ge detector strings and ULAr read-out system

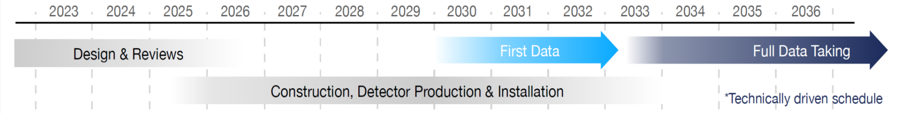


V. Guiseppe, TAUP 2023

- PCDR: arXiv:2107.11462
- goals: $B = 1.0 \cdot 10^{-5}$ cts/(keV kg yr)

$T_{1/2}^{0\nu}$ discovery sensitivity: 10^{28} yr

- DOE-NP: **LNGS Hall C** as site for LEGEND-1000 (former location of Borexino), **site preparation starts in 2024**
- **DOE-NP CD-1** review is scheduled for early summer 2024
- plan to start data taking in 2030



courtesy: S. Schönert

Comparison of DBD experimental sensitivities selected in the Portfolio review process

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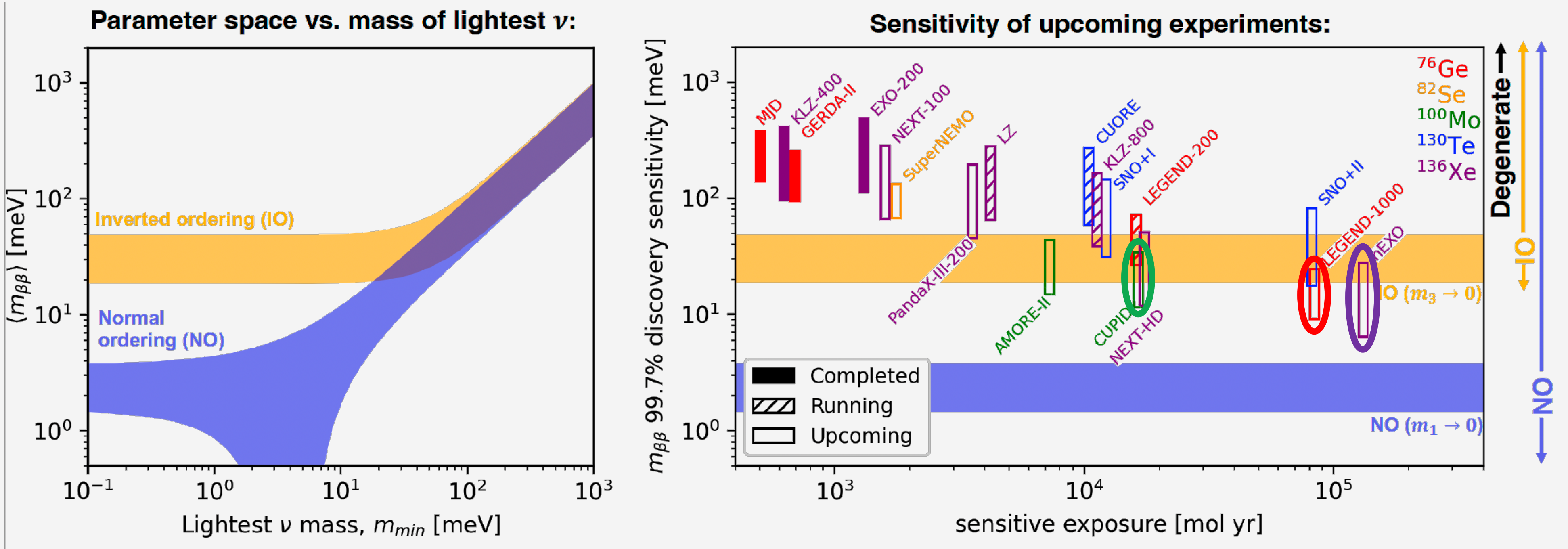
$T_{1/2}$ values used [x10[28] yr]:

nEXO:	1.35 (90% sens.),
	0.74 (3σ discov.)
LEGEND:	1.6 (90% sens.),
	1.3 (3σ discov.)
CUPID:	0.15 (90% sens.),
	0.11 (3σ discov.)

courtesy :Giorgo Gratta



D. Moore, TAUP 2023, adapted from 2212.11099

DOE-Nuclear Physics Portfolio report 2022:

CUPID, **LEGEND-1000**, **nEXO** all successful,

in the Long Range Plan of Nuclear Science in the US 2023 all mentioned on equal footing

In case resources are insufficient to fund all three experiments (CUPID, nEXO, LEGEND-1000), LEGEND-1000 will receive priority

Others:

Xenon dark matter experiments

will also look for $0\nu\beta\beta$:

LZ, PandaX-4T, XENONnT and DARWIN

(sensitivity: $2.4 \cdot 10^{27}$ yr,

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

Complementary ways to the neutrino mass

Direct neutrino mass search

$m^2(\nu_e) := m_\beta^2 := \sum_i |U_{ei}|^2 \cdot m^2(\nu_i)$

no further assumptions needed

a) Time-of-flight measurements

only eV sensitivity for very far away, very strong sources, e.g. core-collapse supernova, e.g. SN1987a

$\rightarrow m_\nu < 5.7$ eV

b) Kinematics of weak decays,

e.g. tritium (β⁻), ^{163}Ho (EC)

measure charged decay products, use E-, $\vec{p}$-conservation

No further assumptions are needed:

use $E_\nu^2 = p_\nu^2 + m_\nu^2 \rightarrow m_\nu^2$

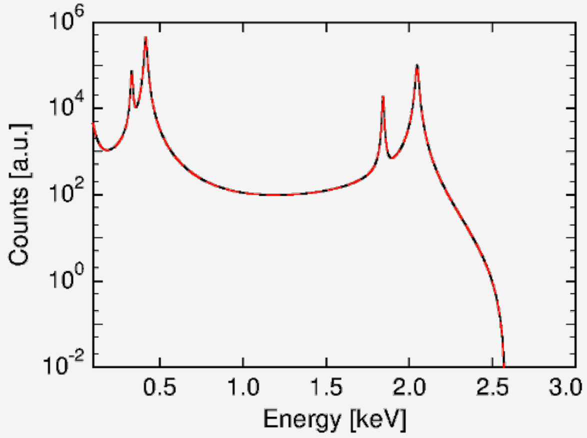
Determine m_ν^2 from beta electron spectrum

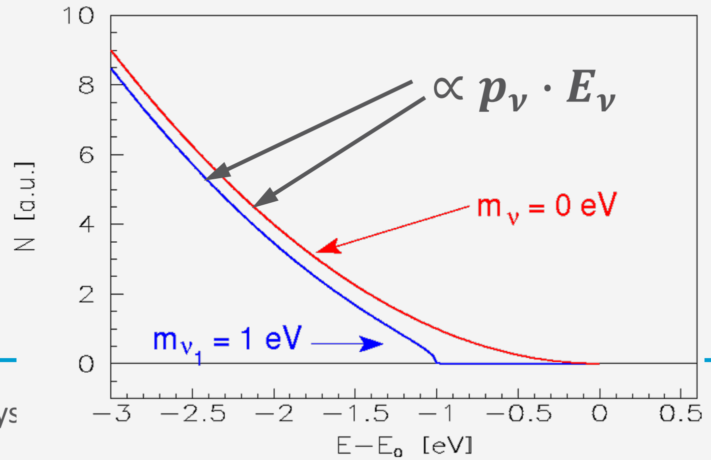
$$\beta^-: \frac{dN}{dE} = K \cdot F(E,Z) \cdot \underbrace{p}_{p_e} \cdot \underbrace{E_{tot}}_{E_e} \cdot \underbrace{(E_0 - Ee)}_{E_\nu} \cdot \sum_i |U_{ei}|^2 \cdot \underbrace{\sqrt{(E_0 - E_e)^2 - m^2(\nu_i)}}_{p_\nu}$$

phase space: p_e E_e E_ν p_ν

EC: Also phase space near endpoint $\propto p_\nu \cdot E_\nu$

deexcitation spectrum, e.g. ^{163}Ho

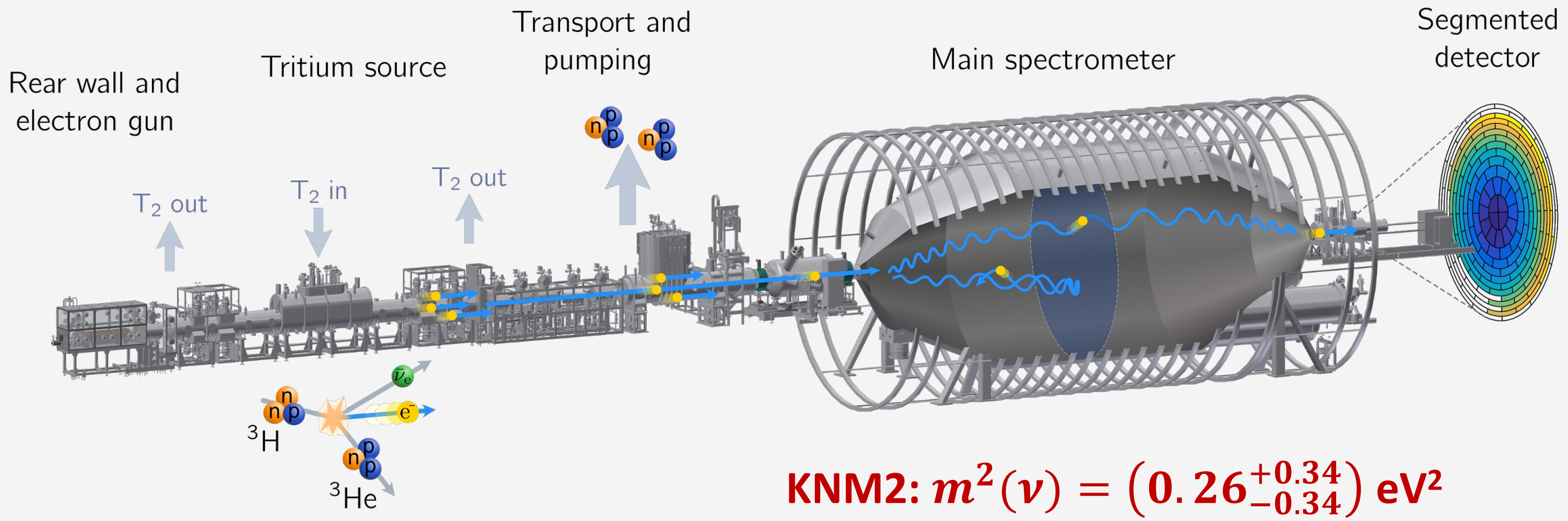




KArlsruhe TRItium Neutrino experiment KATRIN

Universität Münster

A **10^{11} Bq windowless T_2** source with an **high acceptance & eV-resolution integrating spectrometer**



KNM2: $m^2(\nu) = \left(0.26^{+0.34}_{-0.34}\right)$ eV²

→ compatible with zero

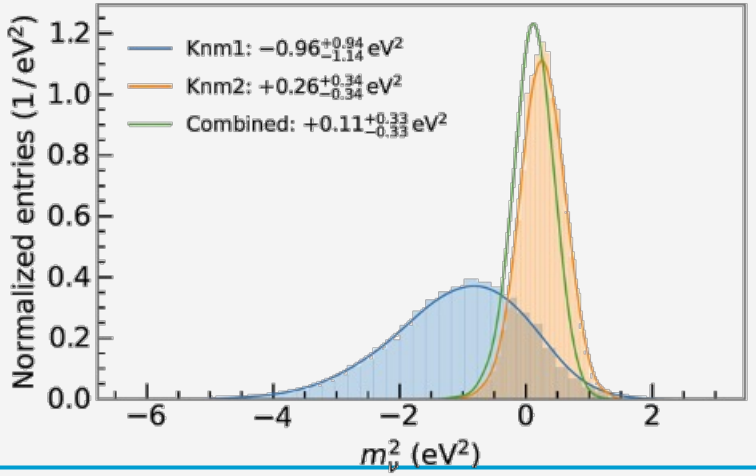
Frequentist limit: $m_\nu < 0.9$ eV (90% CL)

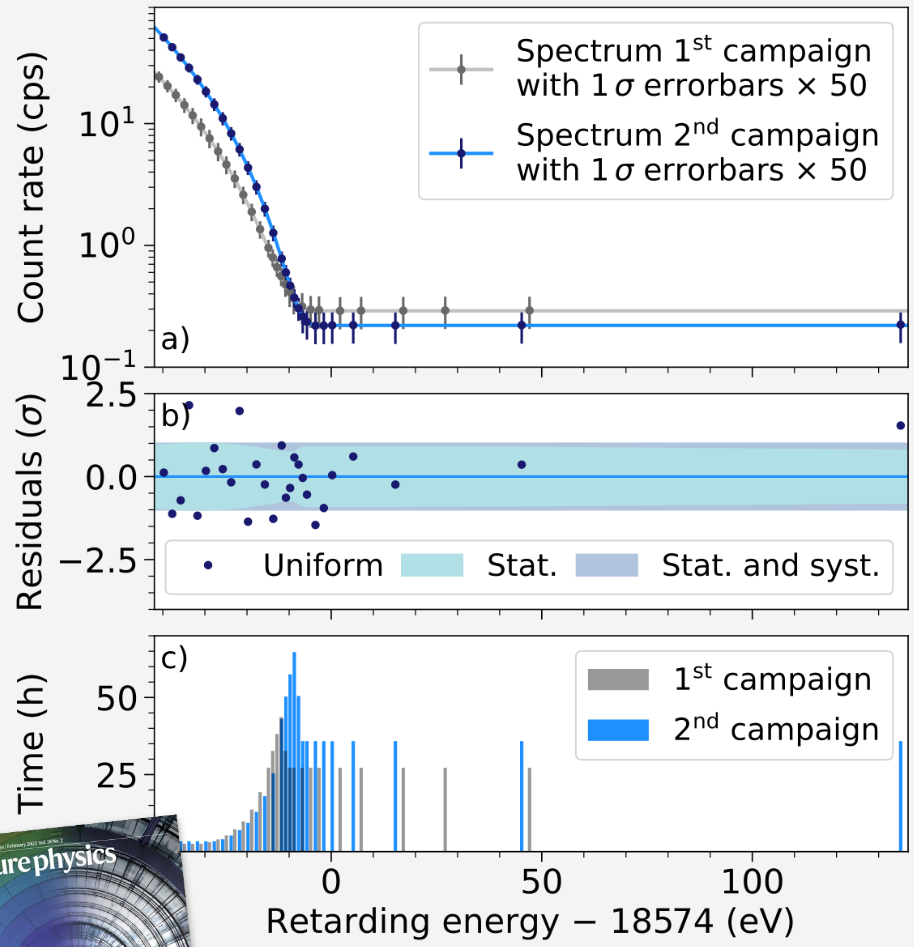
Bayesian: $m_\nu < 0.85$ eV (90% CI)

Combine 1st & 2nd campaign:

Frequentist: $m_\nu < 0.8$ eV (90% CL)

Bayes: $m_\nu < 0.7$ eV (90% CL)

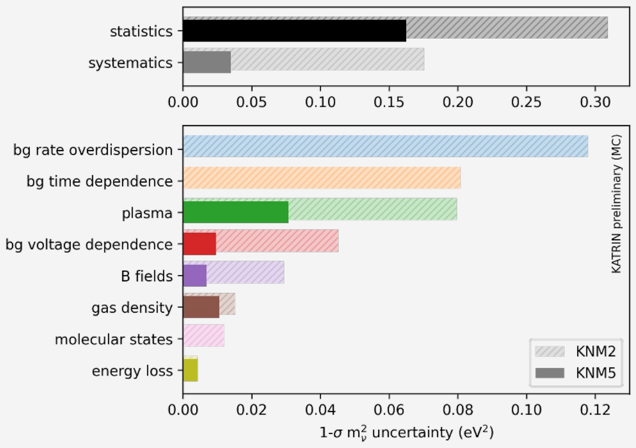




Phys. Rev. Lett. 123 (2019) 221802

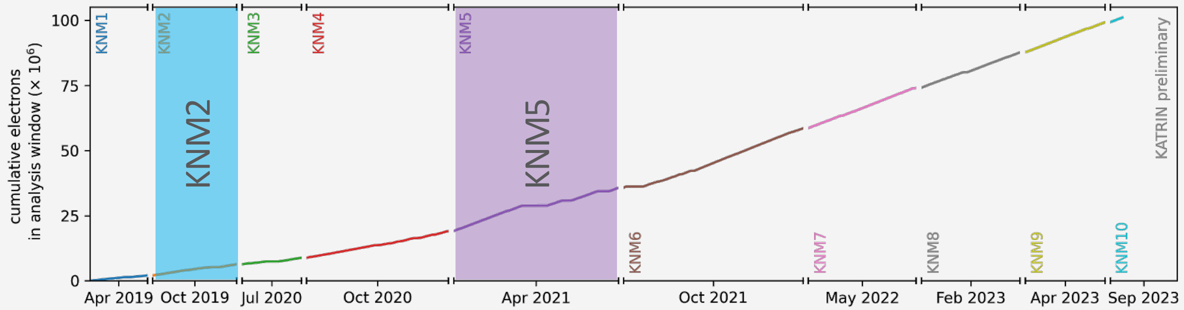
Nature Physics 18 (2022) 160

KATRIN's future sensitivity and sterile ν search



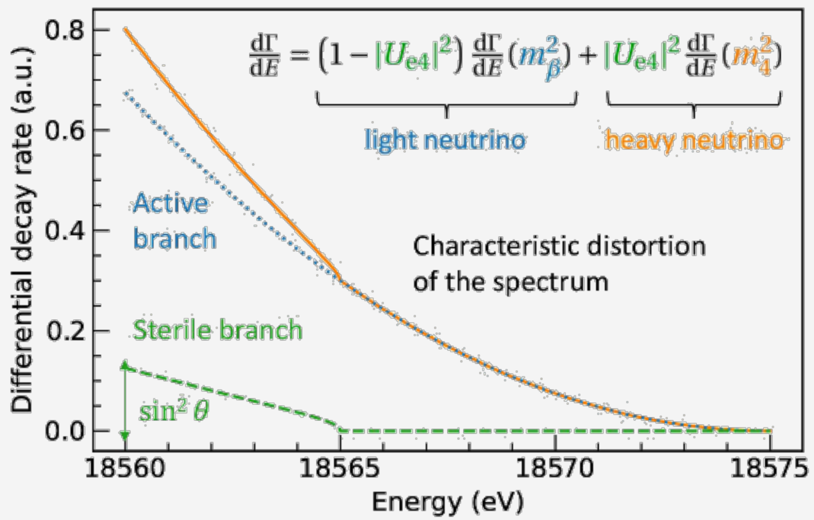
Since 2019
significant improvements

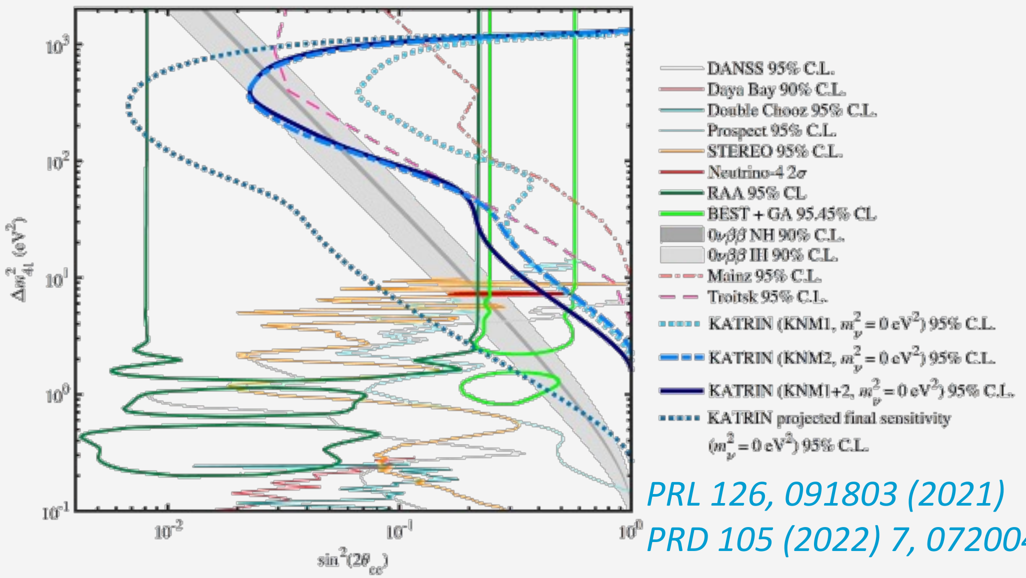
in background rate & systematics
much more data taken …



courtesy : Magnus Schlösser

Search for sterile eV neutrinos:





PRL 126, 091803 (2021)
PRD 105 (2022) 7, 072004

Upcoming result from KNM1-5:

- Statistics ∗6, Systematics ∗ 3
- Sensitivity better than $m_\nu < 0.5$ eV
- Paper (almost) ready for submission

Final result:

- Based on 1000 days of data taking (completed end of 2025)
- Sensitivity better than $m_\nu < 0.3$ eV

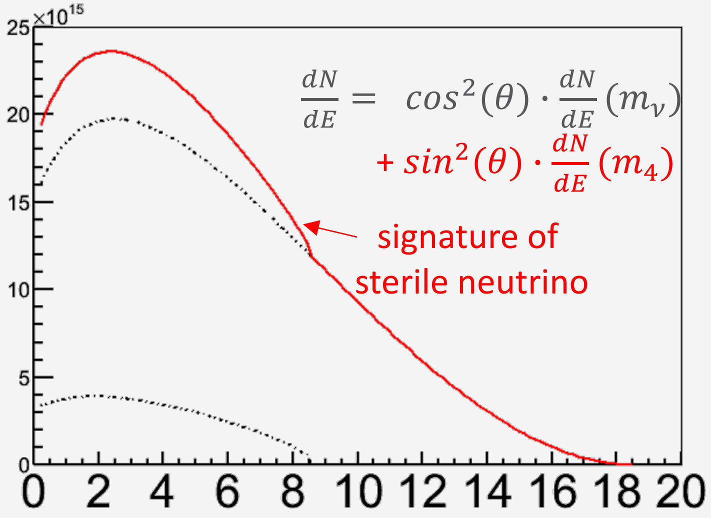
Future: search for sterile keV neutrinos with KATRIN

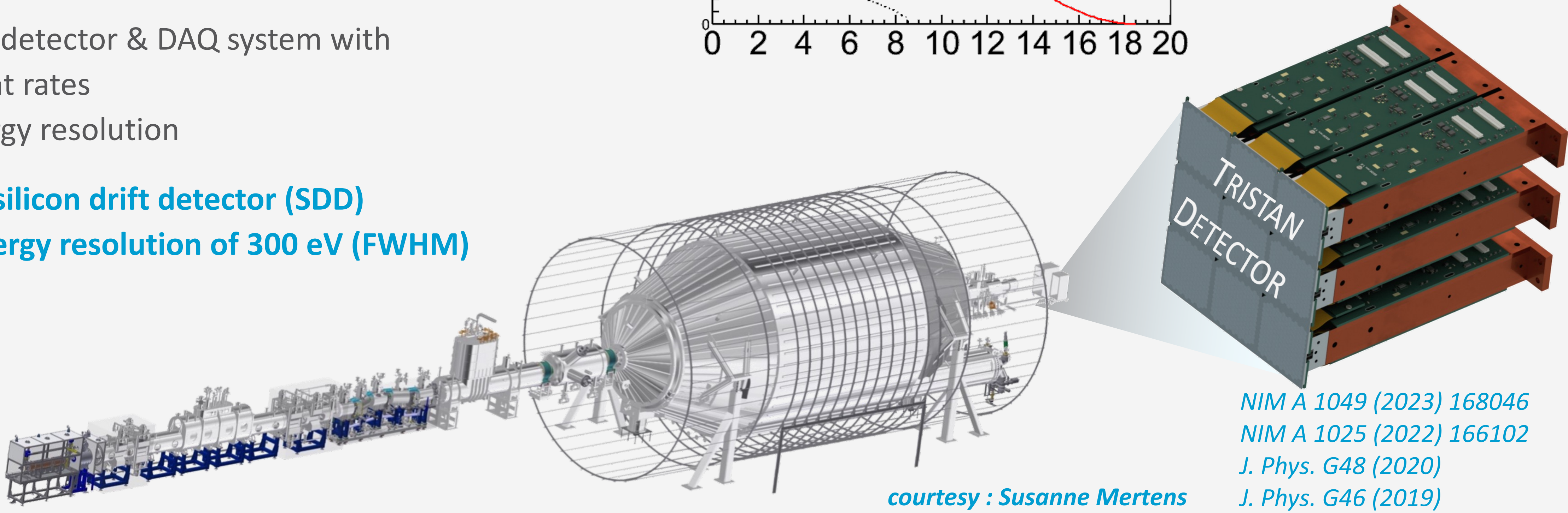
4^{th} mass eigenstate of neutrino mixed with flavour eigenstates
➞ BSM particle, dark matter candidate

Look for the kink in the β-spectrum
Target sensitivity of $sin^2\,\theta < 10^{-6}$
➞ TRISTAN phase of KATRIN in 2026/27

requires a new detector & DAQ system with
- large count rates
- good energy resolution

➞ **1000 pixel silicon drift detector (SDD) with an energy resolution of 300 eV (FWHM)**





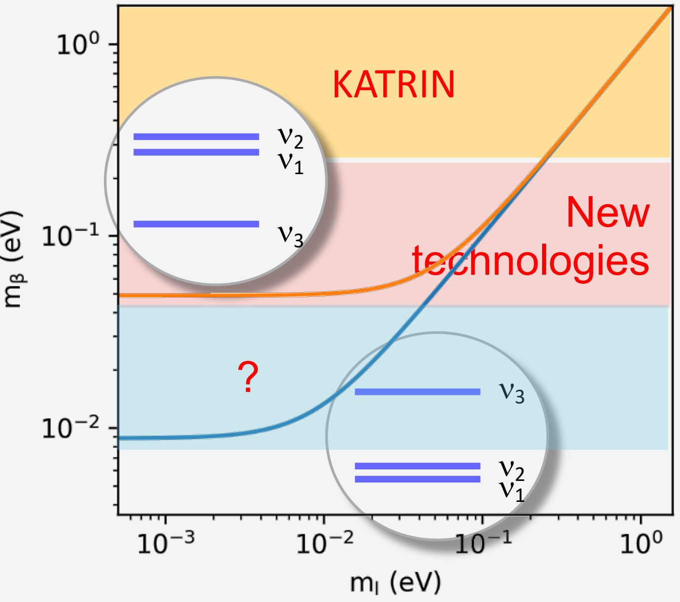
courtesy : Susanne Mertens

NIM A 1049 (2023) 168046
NIM A 1025 (2022) 166102
J. Phys. G48 (2020)
J. Phys. G46 (2019)

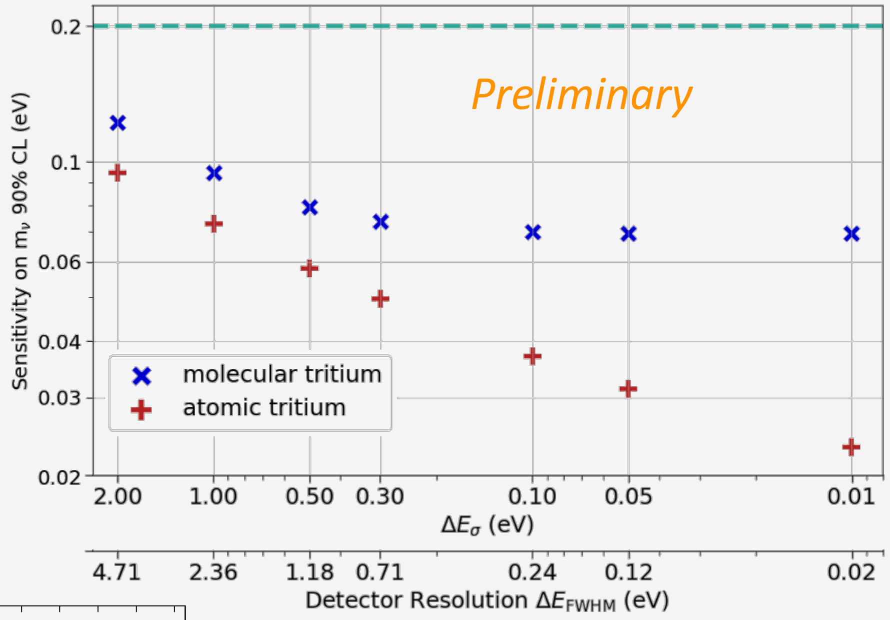
KATRIN^{++} - R&D for the next generation m_ν search

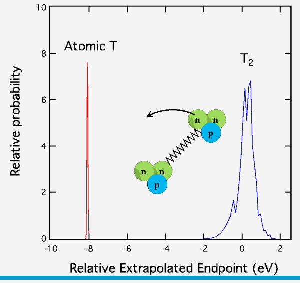
Two major improvements:

- differential measurements, not needing ≈ 30 steps to measure β-spectrum
- improve energy resolution by quantum sensor (MMC detector array, tof) & by atomic T source

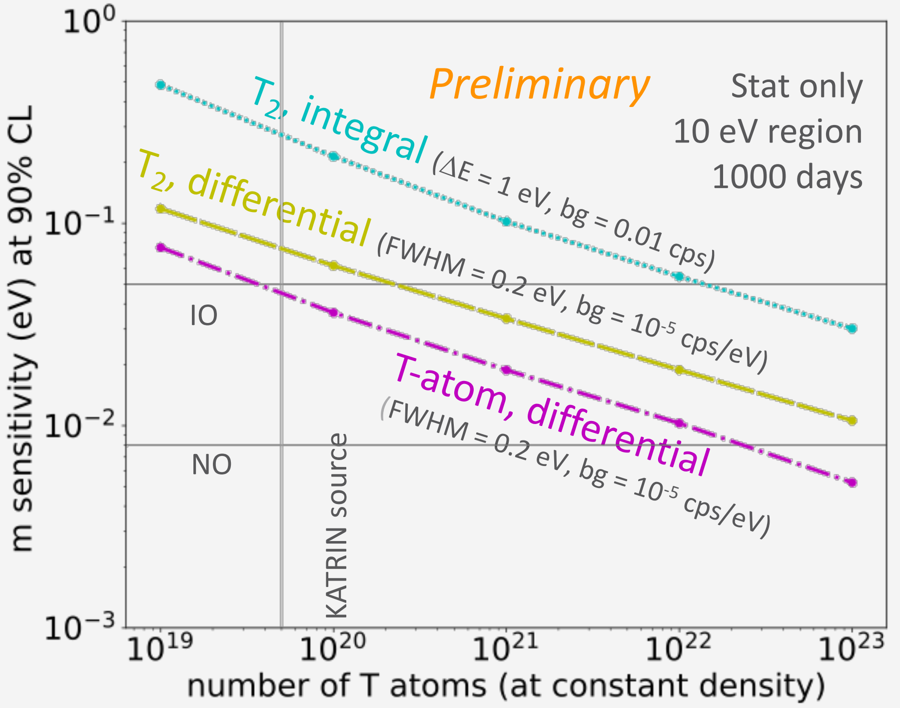


courtesy : Susanne Mertens





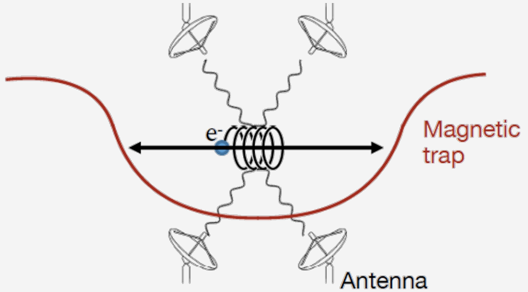
courtesy : Svenja Heyns



courtesy : Susanne Mertens

Project 8: tritium β spectroscopy with CRES

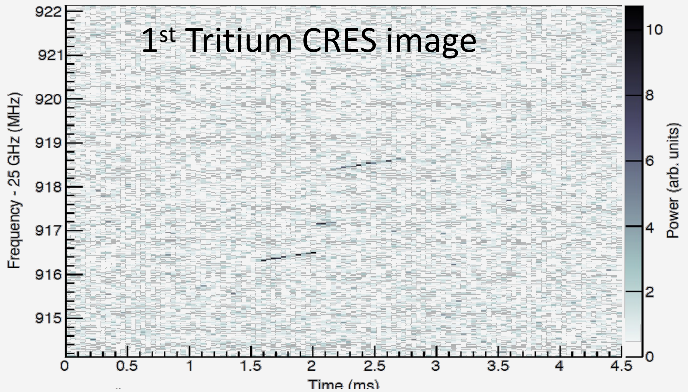
Universität Münster



Cyclotron radiation:

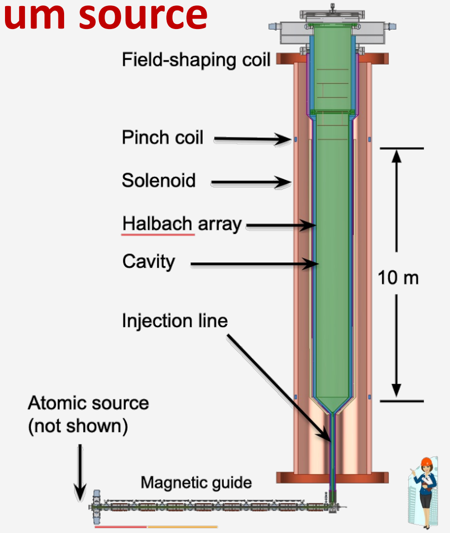
$$\boldsymbol{\omega} = \frac{\omega_0}{\gamma} = \frac{qB}{m_e + \boldsymbol{E_{kin}}}$$

Cyclotron Radiation Emission Spectroscopy (CRES) to reconstruct kinetic energy of electrons

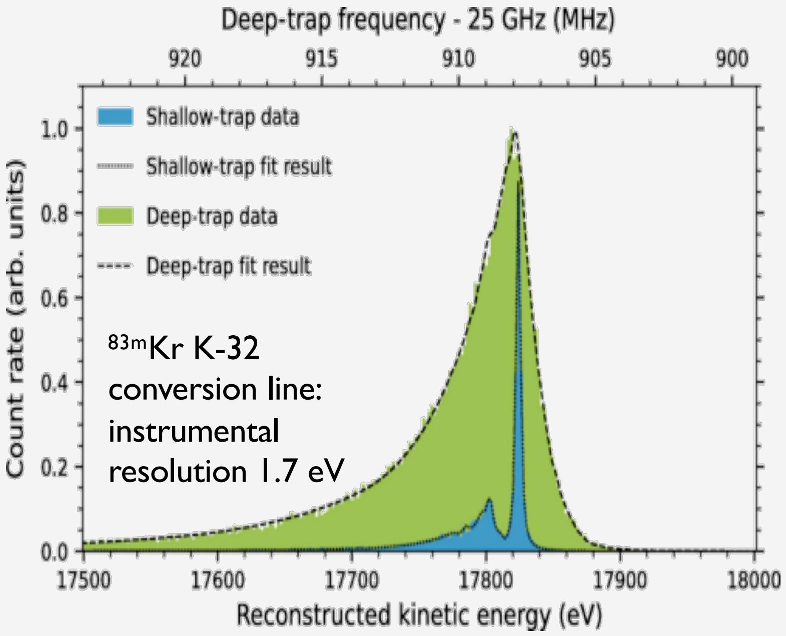


Phase III:

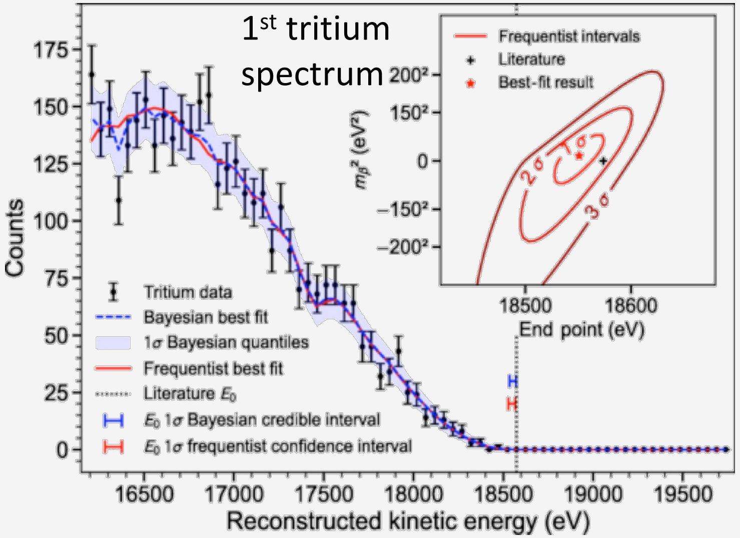
A future CRES experiment will require large volumes and an **atomic tritium source**



Phase I & II

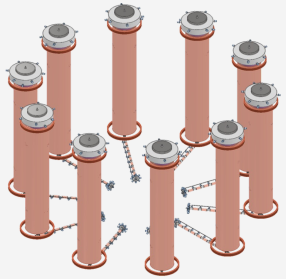


^{83m}Kr K-32 conversion line: instrumental resolution 1.7 eV



First tritium run using CRES, low background observed

PRL 131, 102502 (2023)
Courtesy: M. Fertl



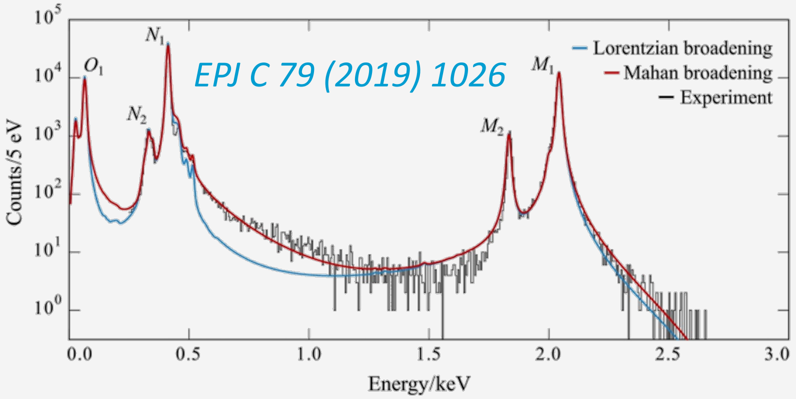
arXiv:2203.07349

Phase IV:

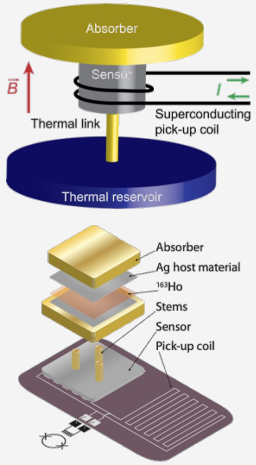
Eventually, Project 8 wants to build an experiment with sensitivity O(40 meV):

EC with ^{163}Ho cryogenic bolometers: ECHo

$^{163}Ho + e^{-} \rightarrow {}^{163}Dy^{*} + \nu_e \rightarrow {}^{163}Dy + \gamma/e^{-} + \nu_e$

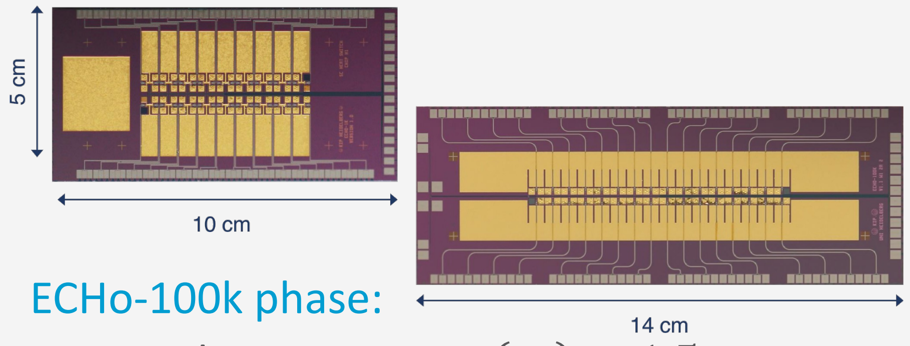


ECHo: metallic magnetic calorimeters (MMC):



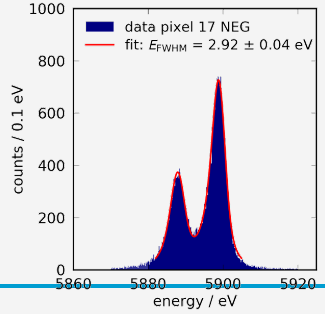
ECHo-1k phase:

sensitivity $m(\nu_e) < 20$ eV



ECHo-100k phase:

expected sensitivity: $m(\nu_e) \approx 1.5$ eV



ECHo-100k baseline: multiplexing to read-out large # MMC

- number of detectors: 12000
- activity per pixel: 10 Bq (2×10^{12} ^{163}Ho atoms)

Present status:

High Purity ^{163}Ho source: available about 30 MBq

Ion implantation system: demonstrated, continuously optimized

Metallic magnetic calorimeters:

- succesfull characterization of arrays with ^{163}Ho

More than 10^8 ^{163}Ho events have been acquired within the ECHo-1k phase:

→ a new neutrino mass limit ≈ 20 eV is on the way

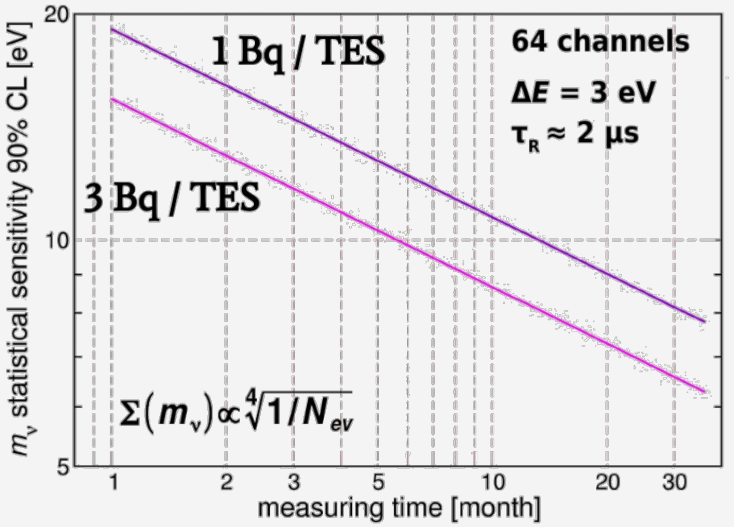
Important steps towards ECHo-100k have been demonstrated:

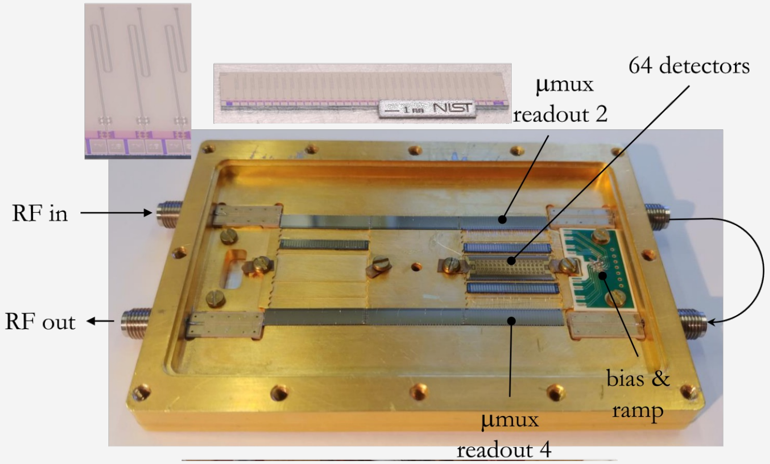
- new ECHo-100k array
- implantation of wafer scale
- multiplexed readout

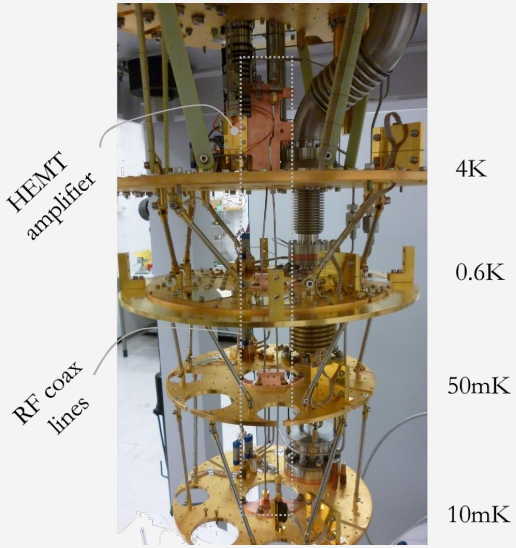
courtesy: Loredana Gastaldo

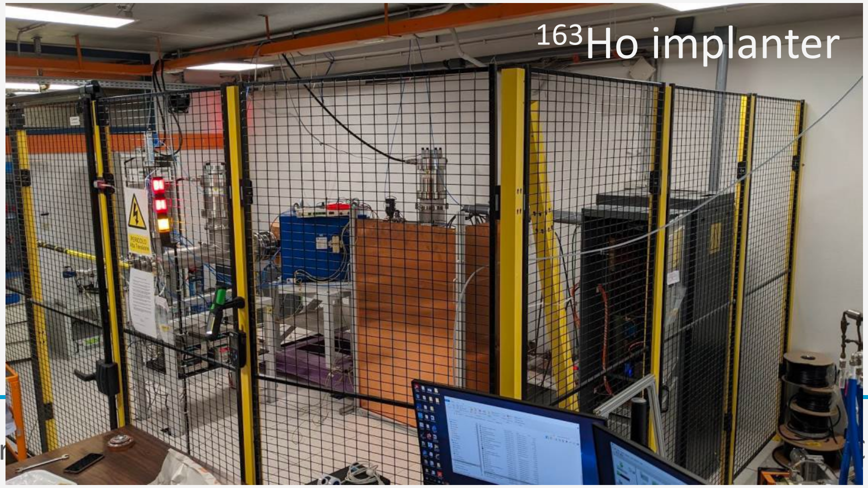
EC with ^{163}Ho cryogenic bolometers: HOLMES

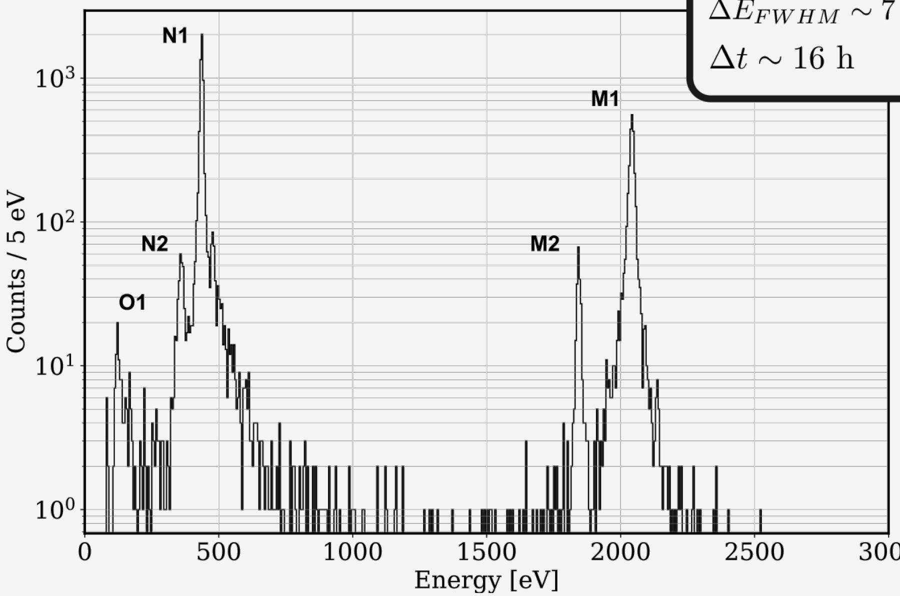
HOLMES: superconducting transition edge sensors (TES)
^{163}Ho being implanted in gold absorber
read-out: frequency multiplexing











First ^{163}Ho spectrum

courtesy: A. Nucciotti

Conclusions

- **Neutrino mass and 0νββ searches are leading and timely questions** of nuclear & (astro)particle physics & cosmology
- Cosmology, search for 0νββ and direct search for neurino mass provide complementary imformation
- **Search for 0νββ is investigating neutrino nature and mass:**
  - Current sensitivity $T^{0\nu}_{1/2} \approx 2 \cdot 10^{26}$ yr and $m_{\beta\beta} \approx \mathcal{O}(200\ \mathrm{meV})$ by GERDA, KamLAND-ZEN 800, EXO-200, CUORE …
  - **LEGEND-200 has started**
  - **Next generation experiments (CUPID, LEGEND-1000, KamLAND2-ZEN, nEXO, …)**: $T^{0\nu}_{1/2} \approx 10^{28}$ yr, $m_{\beta\beta} \approx \mathcal{O}(20\ meV)$
  - Main challenges: ultra-low background, large mass of DBD isotope (^{76}Ge, ^{100}Mo, ^{136}Xe, ^{130}Te)
- **Direct search for neutrino mass:**
  - KATRIN reached sub-eV sensitivity and has much more data, will search for keV sterile neutrinos (TRISTAN-phase)
  - Cryo-bolometers (ECHo, HOLMES) with ^{163}Ho aim for (sub)eV-sensitivity with large arrays of multiplexed pixels
  - Project 8 (CRES-technology, similar QTNM) is opening a new road towards sub-eV neutrino mass sensitivity with tritium planned R&D program (KATRIN^{++l}) with atomic T source and quantum sensors: fully IO regime
  - Direct neutrino mass search with tritium at the extreme: towards CνB, R&D with PTOLEMY for the (far) future

Universität Münster

Conclusions

- **Neutrino mass and 0νββ searches are leading and timely questions** of nuclear & (astro)particle physics & cosmology
- Cosmology, search for 0νββ and direct search for neurino mass provide complementary imformation
- **Search for 0νββ is investigating neutrino nature and mass:**

  - Curr

  - **LE**

  - **Ne**

  - Ma

- **Dire**

  - KA

  - Cry

Many thanks for those who helped me with material & discussions:

C. Bucci, P. Decowski, G. Drexlin, M. Fertl, A. Gando, L Gastaldo, J.J. Gomez, G. Gratta, K. Heeger, Y. Kim, C. Kraus, S. Mertens, A. Nucciotti, M. Pavan, K. Rodenbeck, M. Schlösser, S. Schönert, K. Valerius, ...

Thank you all for your attention

  - Project 8 (CRES-technology, similar QTNM) is opening a new road towards sub-eV neutrino mass sensitivity with tritium
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