

Neutrino mass and nature

ICHEP Conference 2022 - Bologna

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

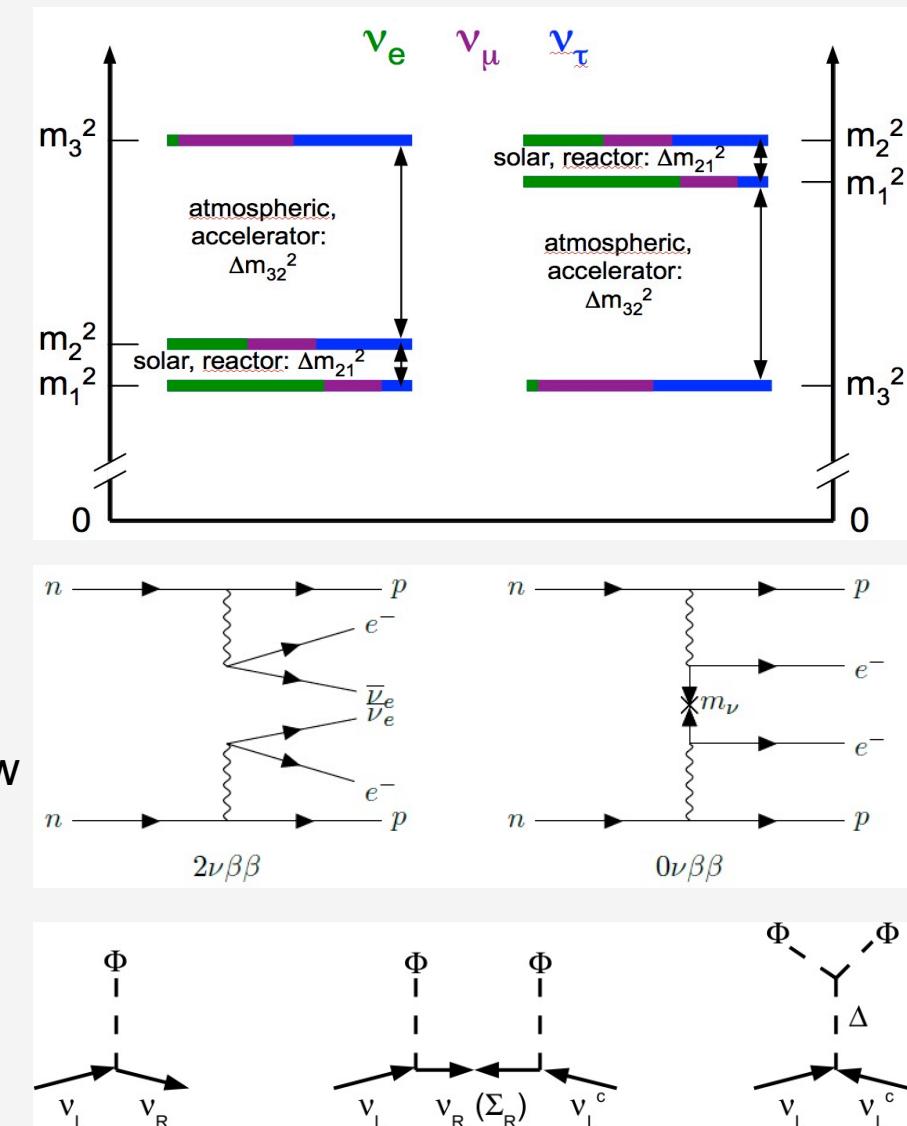


Sorry, I can only be very brief leaving out many experiments, details & results



Current most urgent questions in neutrino physics

- **Hierarchy:** $m(\nu_3) > m(\nu_{2,1})$ or $m(\nu_{2,1}) > m(\nu_3)$?
- **CP violating phase δ_{CP} ?**
3x3 unitary mixing matrix U_{PMNS} :
3 angles and 1 CP violating phase,
connected to baryon asymmetry of universe via leptogenesis ?
- **Is there a 4th or even a 5th light but sterile neutrino ?**
- **Neutrino particle character ?**
are neutrinos their own antiparticles (Majorona)?
leptogenesis might explain baryon asymmetry of universe, Seesaw
- **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

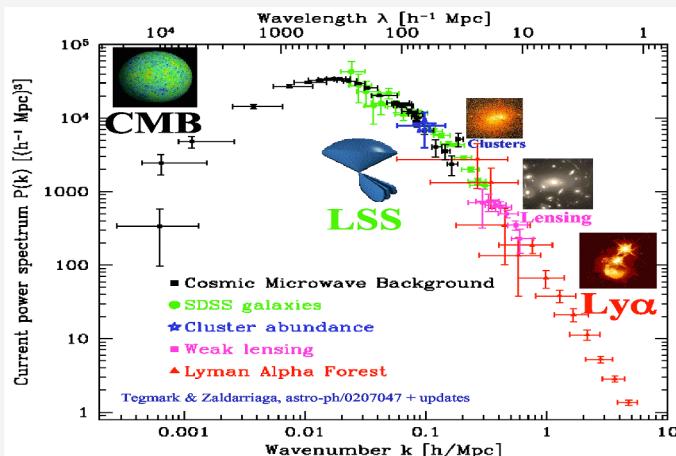


Complementary ways to the neutrino mass

Cosmology

$$\sum_i m(\nu_i) = 3 \cdot \overline{m(\nu_i)}$$

very sensitive, but model dependent
compares power at different scales



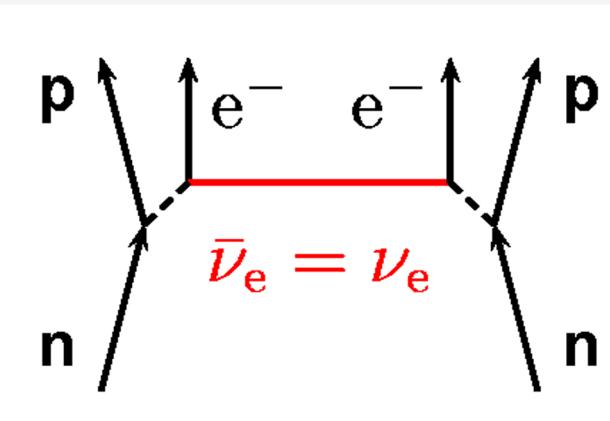
upper limit: $\sum_i m(\nu_i) \approx 0.12 \text{ eV}$
(CMB+BAO)

not far from minimal values for
60 meV (NO), 100 meV (IO)

$0\nu\beta\beta$

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

sensitive to Majorana ν only,
nuclear matrix elements



upper limits by CUORE, EXO-200,
GERDA, KamLAND-Zen, ...

**discovery of $0\nu\beta\beta$ would be BSM:
Majorana ν & lepton number violation**

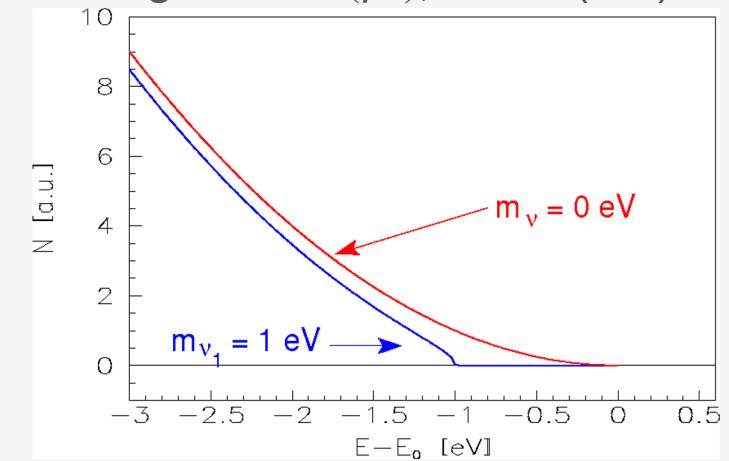
Direct neutrino mass search

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

no further assumptions needed

Time-of-flight measurements
(ν from supernova)

Kinematics of weak decays,
e.g. tritium (β^-), ^{163}Ho (EC)



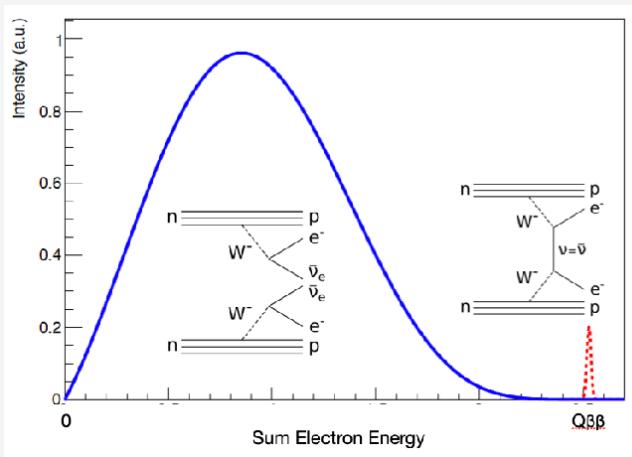
measure charged decay products,
use E -, \vec{p} -conservation

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

0νββ

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

sensitive to Majorana ν only,
nuclear matrix elements



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

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

Exp. sensitivity:

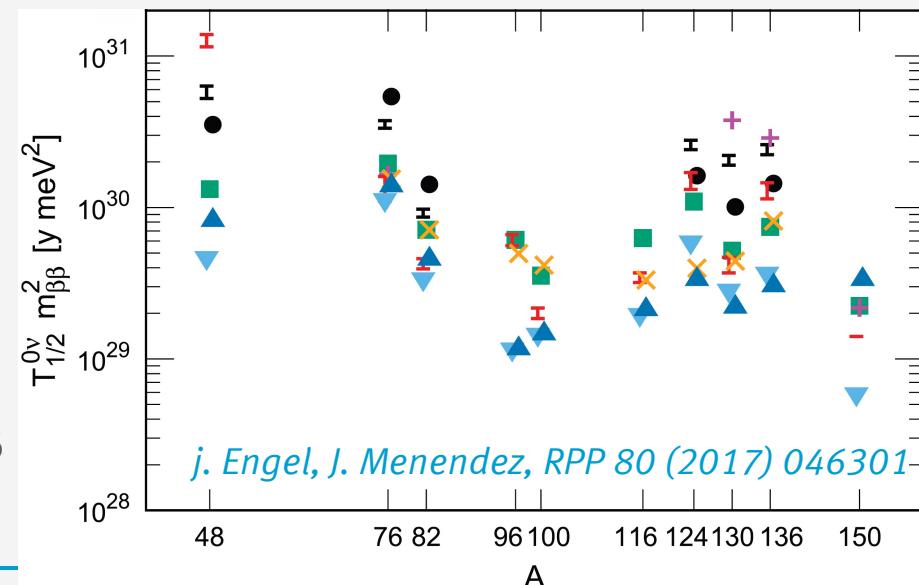
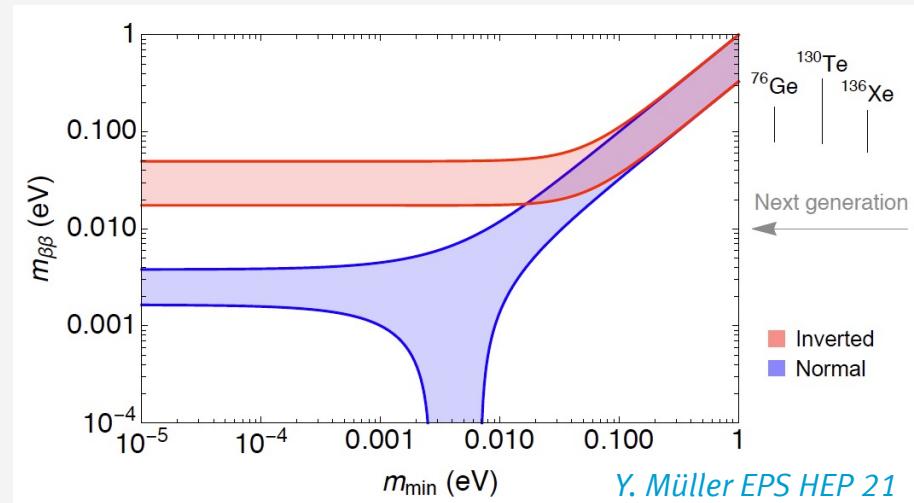
$$T_{1/2}^{0\nu} \propto \begin{cases} a \cdot \varepsilon \cdot M \cdot t & \text{for bg B = 0} \\ a \cdot \varepsilon \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}} & \text{for bg B > 0} \end{cases}$$

Nuclear matrix elements;

$M_{0\nu}(A, Z)$ uncertainty: factor 2-3
here shown is $1/(G_{0\nu} \cdot |M_{0\nu}|^2)$

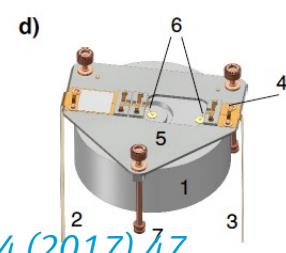
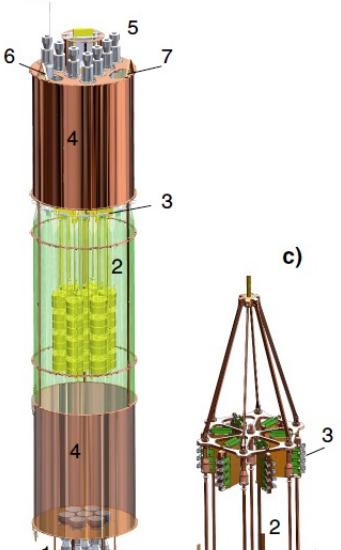
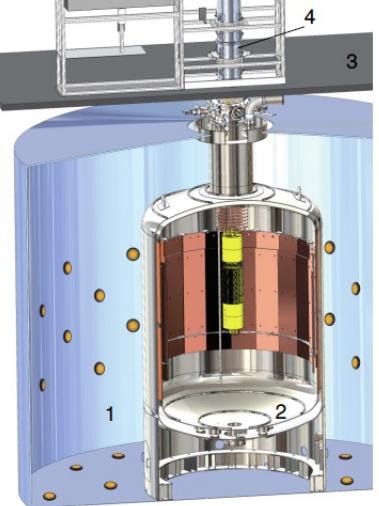
Disclaimer:

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

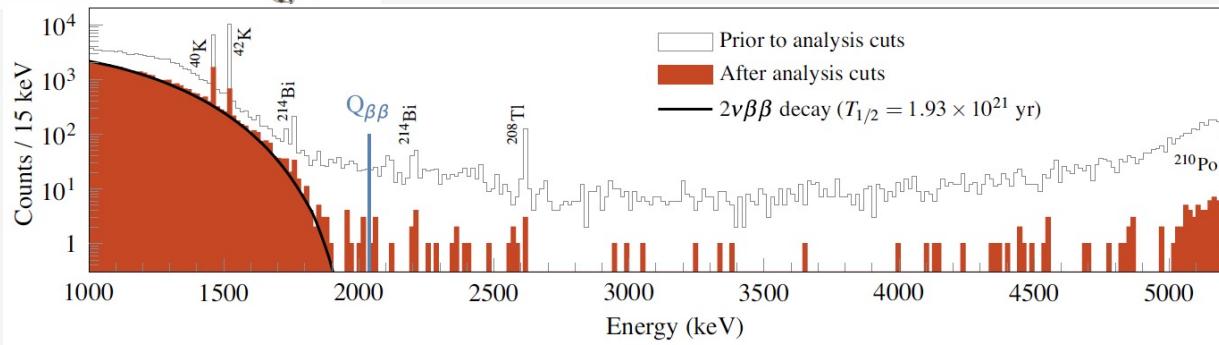


GERDA at LNGS – final result

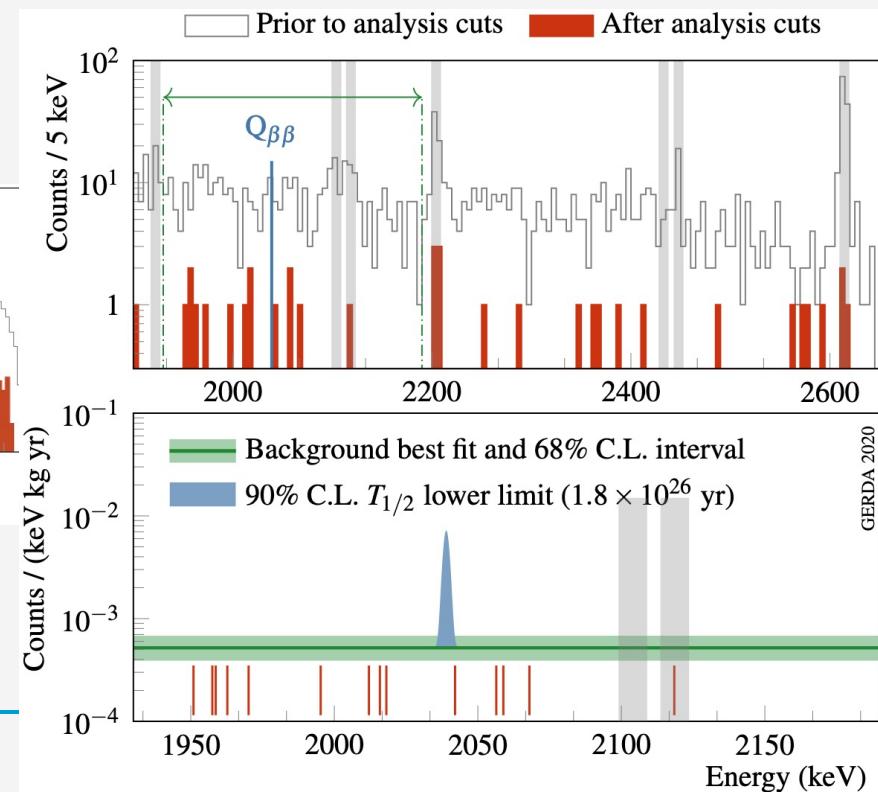
talk by Lolian Shtembari



Nature 544 (2017) 47



PRL 125 (2020) 252502



Majorana Demonstrator @Neutrino 2022 (talk by J. Gruszko, preliminary):

$$B = 6.2 \pm 0.6 \cdot 10^{-3} \text{ counts/(keV kg yr)}$$

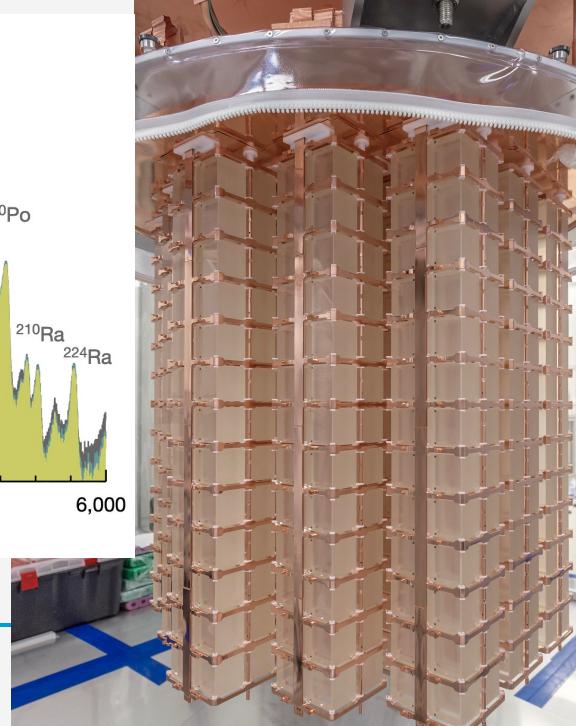
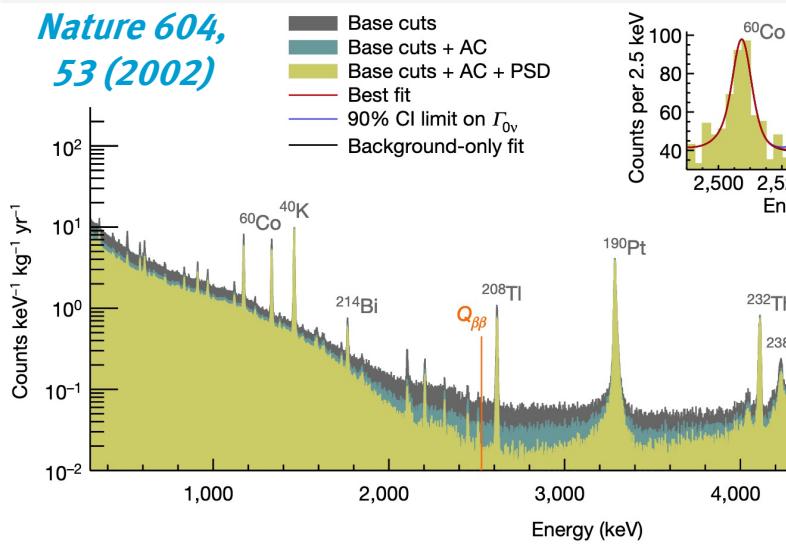
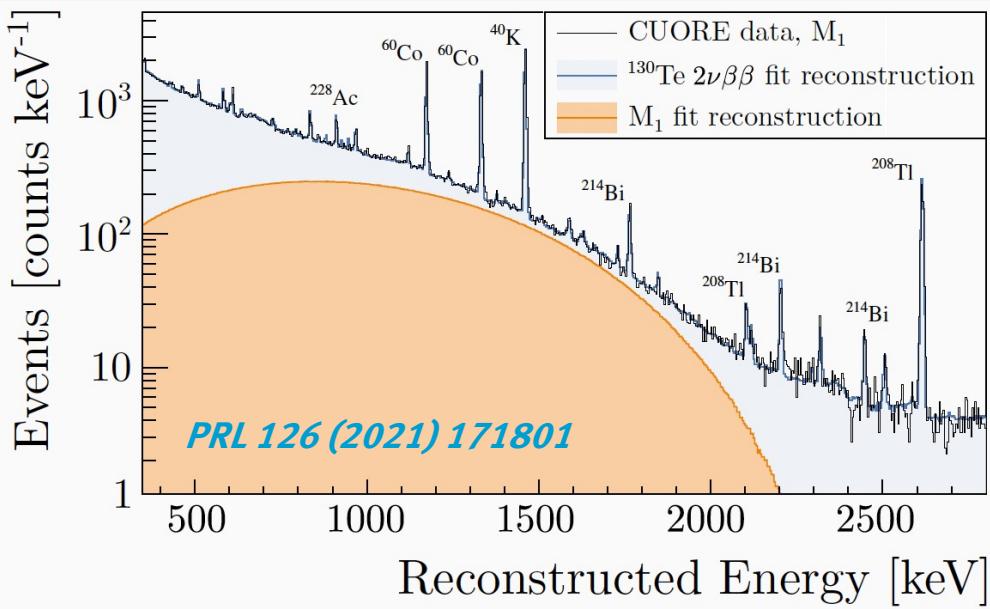
$$T_{1/2}^{0\nu} > 8.8 \cdot 10^{25} \text{ yr}$$

CUORE at LNGS

nat. abundance of ^{130}Te : $\approx 34.2\%$
 exposure (^{130}Te): $288 \text{ kg}^*\text{yr}$
 energy resolution: 7.8 keV (FWHM)
 background index: $B = 1.49(4) \cdot 10^{-2} \text{ counts/(keV kg yr)}$
→ lower limit: $T_{1/2}^{0\nu} > 2.2 \cdot 10^{25} \text{ yr}$ (90% C.L.)
→ upper mass limit: $m_{\beta\beta} < 90 - 305 \text{ meV}$
 2νββ half life: $T_{1/2}^{2\nu} = 7.71^{+0.08}_{-0.06}(\text{stat})^{+0.12}_{-0.15}(\text{sys}) \cdot 10^{20} \text{ yr}$

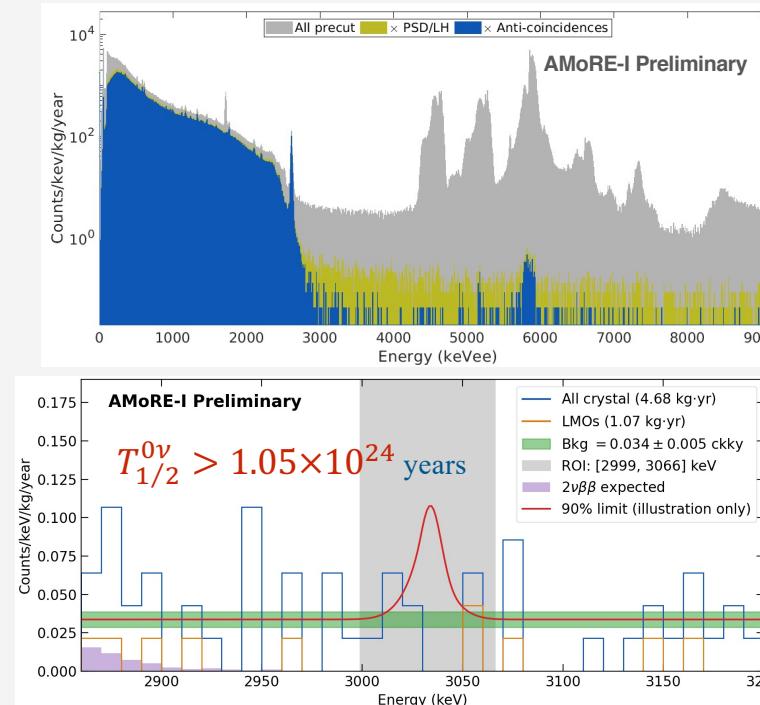
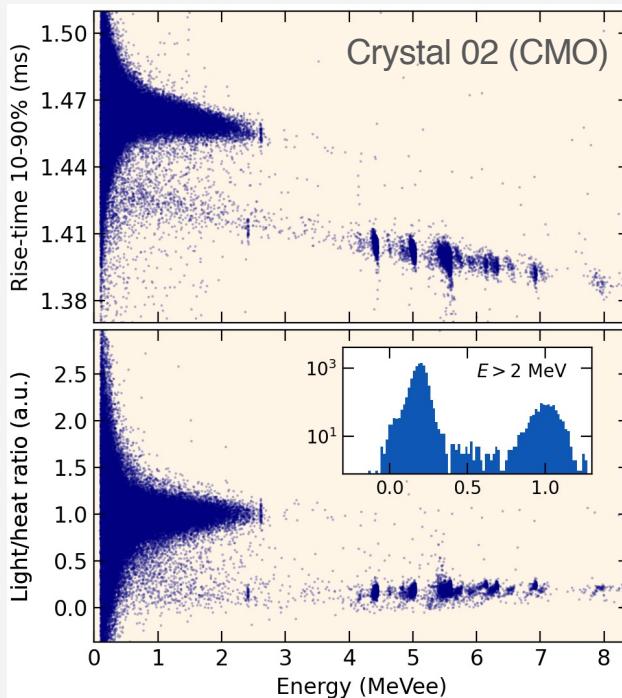
talk by Stefano Dell'Oro

1 t at $T = 10 \text{ mK}$
3 t at $T < 50 \text{ mK}$



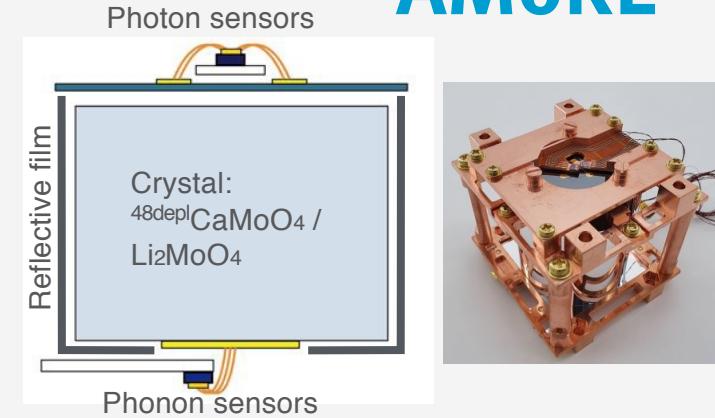
- $\text{Li}_2^{100}\text{MoO}_4$ (LMO), $^{48\text{depl}}\text{Ca}^{100}\text{MoO}_4$ (CMO) scintillation crystal cryogenic bolometers
- Detection of both heat and light signals to discriminate β/a events
- Metallic magnetic calorimeter (MMC) + SQUID for signal readout:
Fast signal (~msec signal rise-time) and a good energy resolution (~10 keV FWHM).

AMoRE-I:



courtesy: Yeongduk Kim

talk by Hanbeom Kim



AMoRE-II in YemiLab (1000 m depth), Civil work done, shielding installation in progress.

Sensitivity goal: $T_{1/2}^{0\nu} \sim 6 \cdot 10^{26} \text{ yr}$
 $m_{\beta\beta} \sim 16 - 30 \text{ meV}$

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

Preparing to start in 2022 with 90 LMO crystals (29.4kg), to be upgraded to 178 kg in 2024.





is an operating neutrino detector at SNOLab with 780 t of liquid scintillator (2.2 g/L PPO in LAB)

Water Phase: completed

- set world-leading limits on invisible nucleon decay
- measured the ${}^8\text{B}$ solar neutrino flux with very low backgrounds

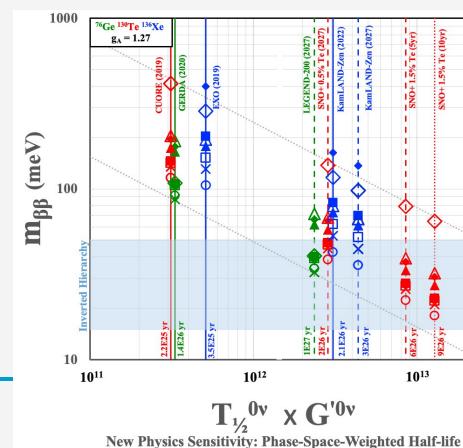
Pure Scintillator Phase: now

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

Double Beta Decay Phase:

- add up to 4,000 kg of ${}^{130}\text{Te}$ 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

courtesy: Christine Kraus



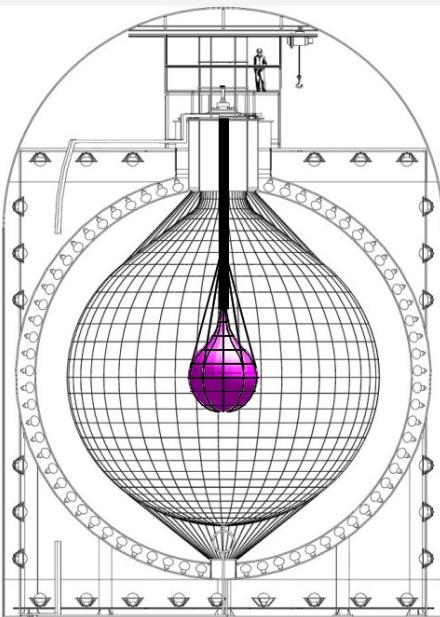
Liquid scintillator detector KamLAND in Kamioka with nylon balloon with LS and DBD isotope ^{136}Xe

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

talk by Azusa Gando

KamLAND-Zen 400: past

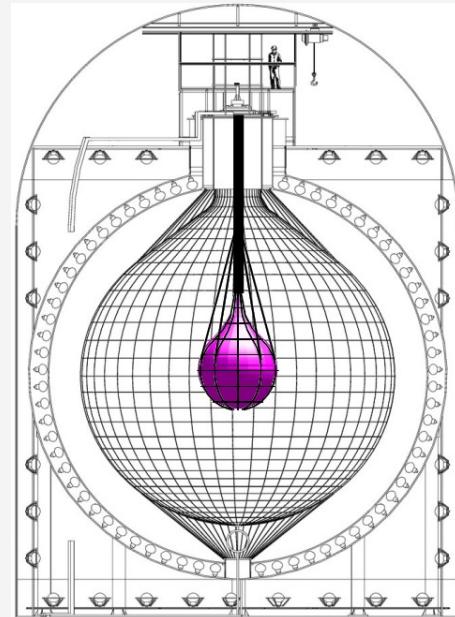
320-380 kg of Xe
Data taking 2011-2015



courtesy: Azusa Gando

KamLAND-Zen 800: present

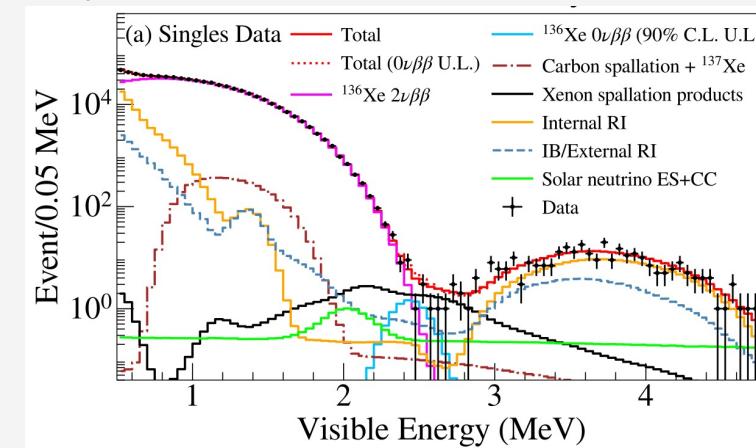
750 kg of Xe, cleaner
DAQ started in 2019



Latest result:

KamLAND-Zen 800 (523.4 d):

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



Combined KamLAND-Zen 400+800:

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

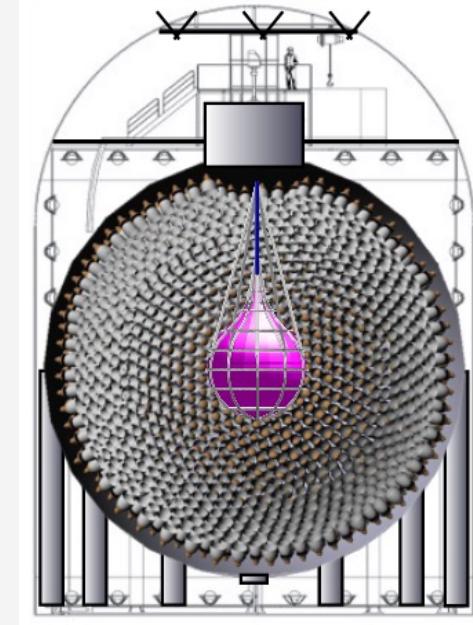
$$m_{\beta\beta} < 36 - 156 \text{ meV}$$

arXiv:2203.02139

KamLAND2-Zen: future

1 t of Xe

Better energy resolution

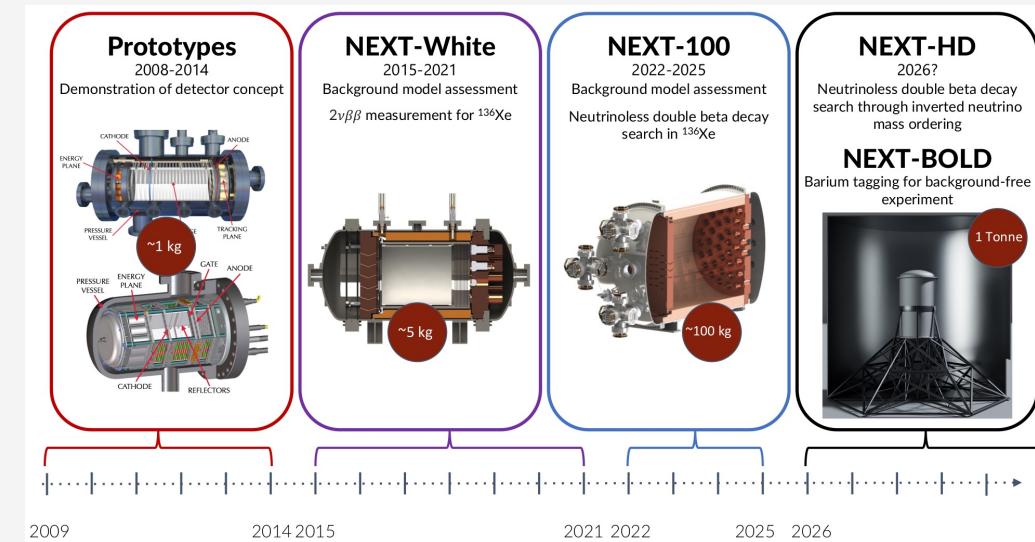
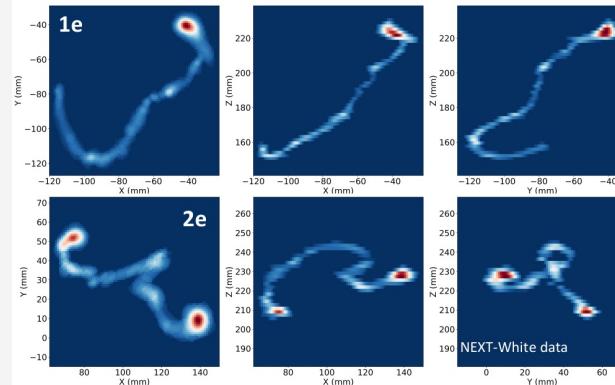


Goal: $\sigma(2.6 \text{ MeV})$: 4% \rightarrow 2%
 $m_{\beta\beta} \approx 20 \text{ meV}$

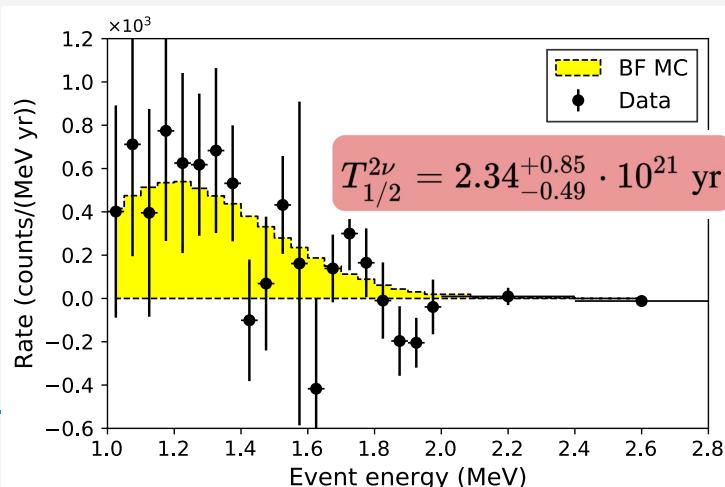
NEXT: a high pressure ^{136}Xe -enriched TPC

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

talks by
Helena Almazan,
Herero Gomez,
Adam Redwine



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)
 NEXT-HD/-BOLD: 1t symmetric TPC with central electrodes, tracking plane with dense SiPMs,..

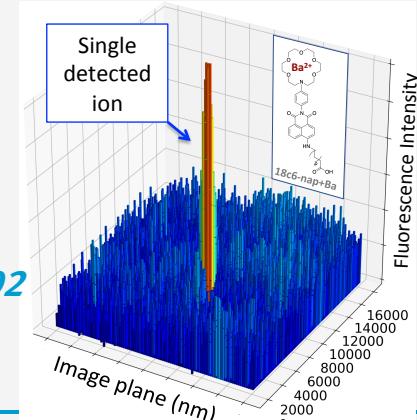


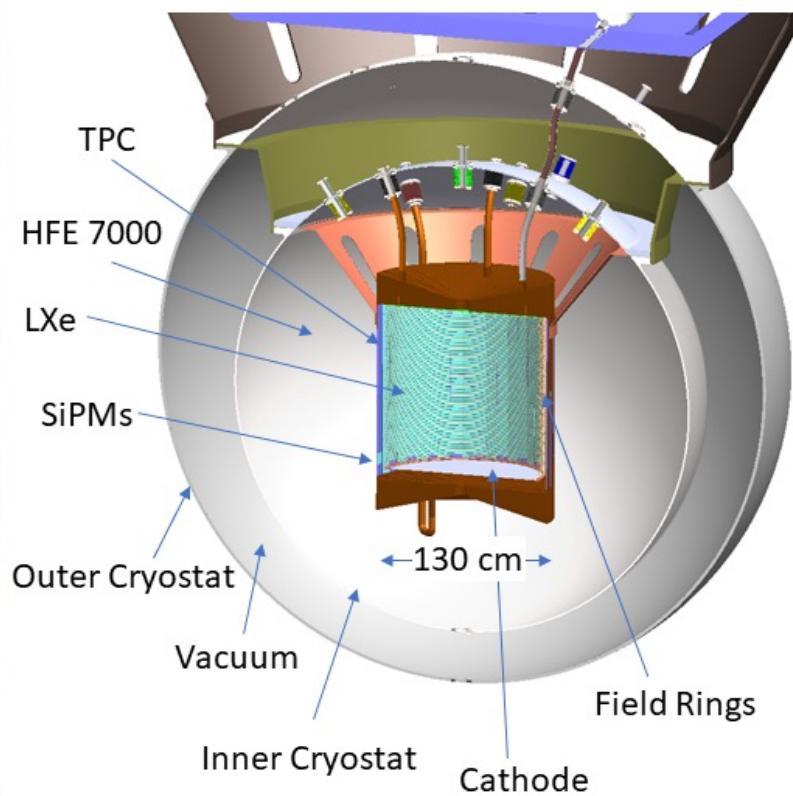
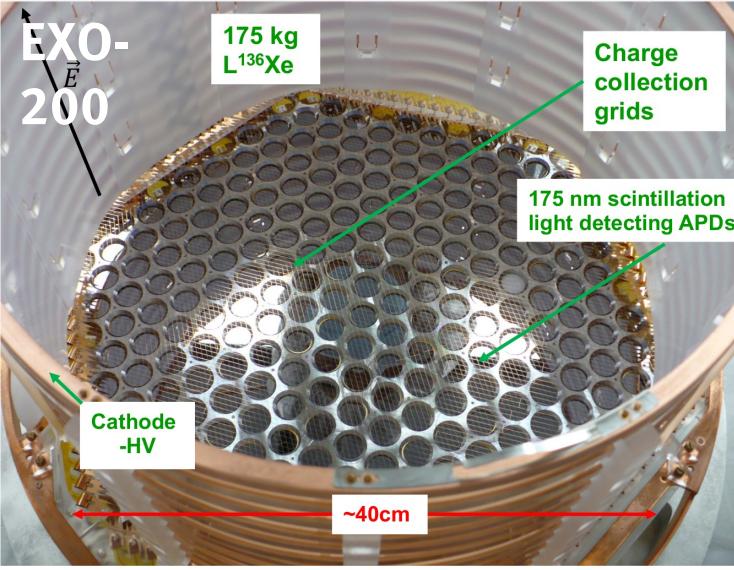
- ICHEP 2022

Tagging of Ba⁺⁺: 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:

$\approx 46 \text{ keV} (\text{FWHM})$

background index:

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

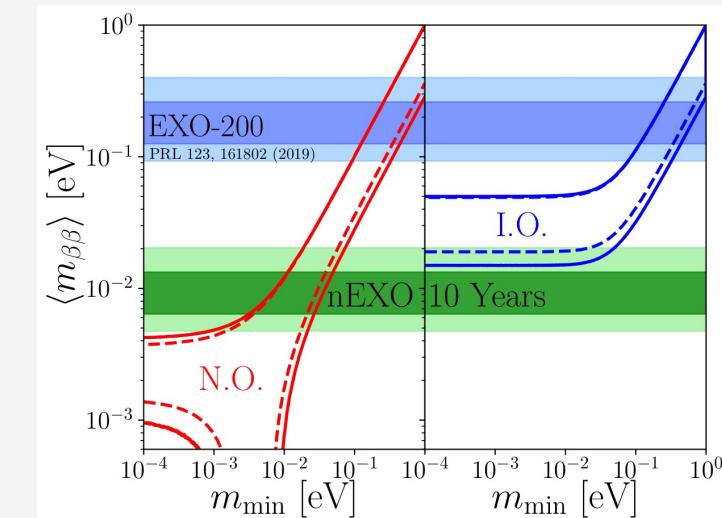
→ **expected sensitivity (10 yr):** $T_{1/2}^{0\nu} > 1.35 \cdot 10^{28} \text{ yr (90\% C.L.)}$

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

talk by Zepeng Li

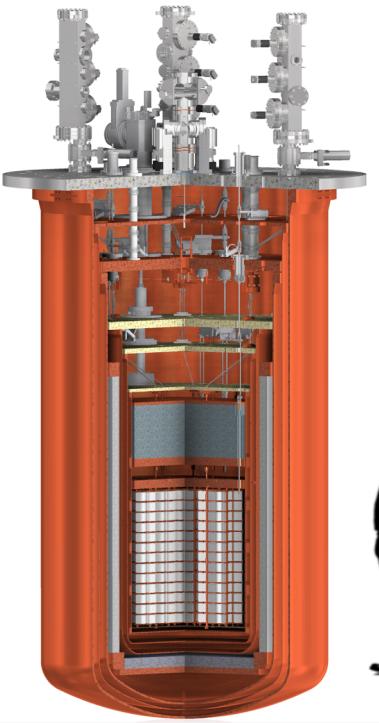
G Adhikari et al. (nEXO Coll.) J. Phys. G: 49 (2022) 015104

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



courtesy Giorgio Gratta

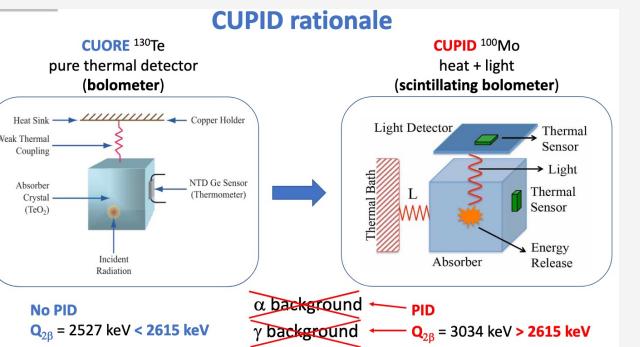
CUPID: CUORE Upgrade With Particle IDentification



Next generation decay $0\nu\beta\beta$: **replace** the CUORE TeO_2 detector with **1596** Li_2MoO_4 scintillating bolometers:

- 450 kg of $\text{Li}_2^{100}\text{MoO}_4$
- 240 kg of ^{100}Mo (high Q)
- 57 towers of 28 crystals, each instrumented with a Light Detector

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): $T_{1/2}^{0\nu} > 1.4 \cdot 10^{27}$ yr (90% C.L.)

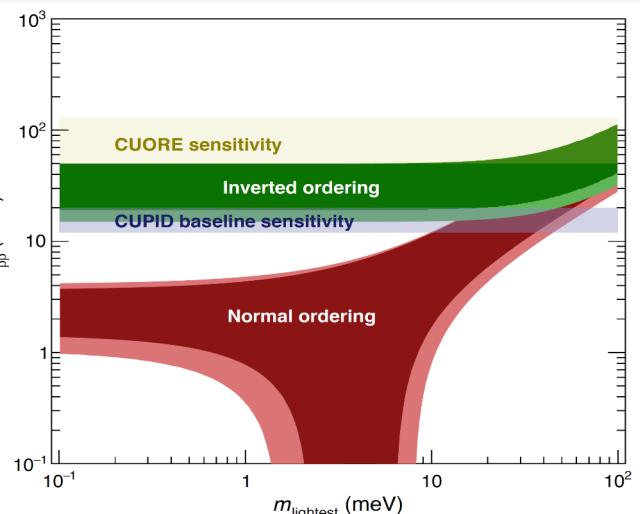
→ exp. sensitivity (10 yr): $m_{\beta\beta} < 10 - 17$ meV

courtesy: Mauran Pavan



talk by Guido Fantini

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



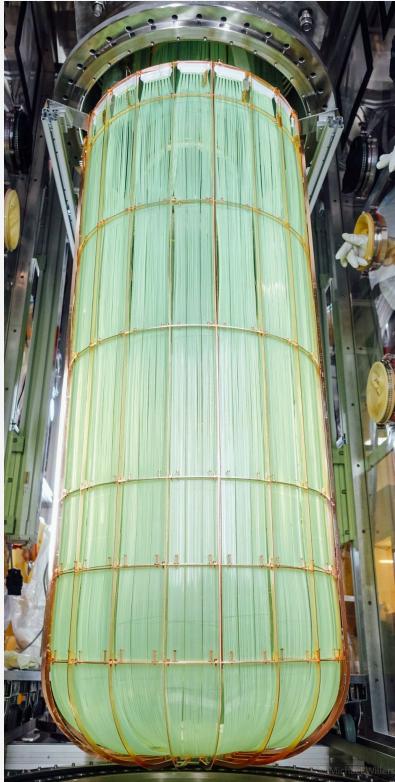
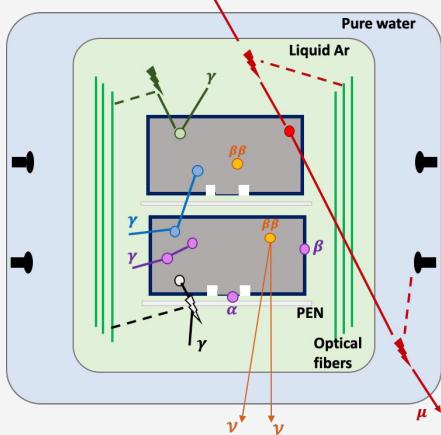
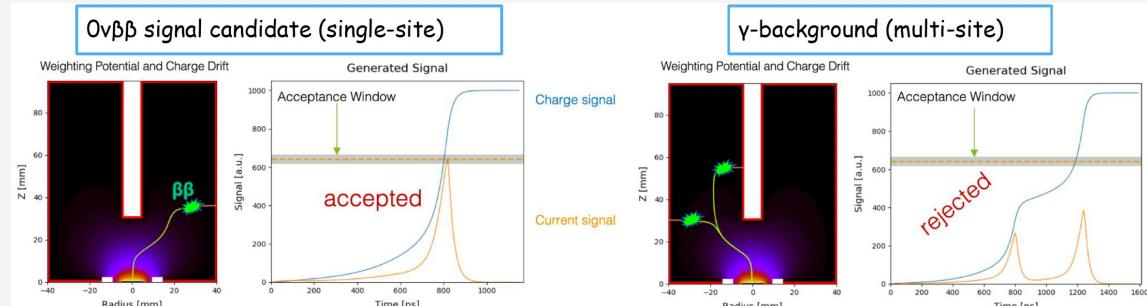


LEGEND-200 at LNGS, future: LEGEND-1000

based on GERDA+Majorana technologies
enriched ^{76}Ge , PPC/BEGe/ICPC detectors (\rightarrow event topology) & active veto

LEGEND-200: commissioning & start data taking with 10 strings in 2022

(≈ 150 kg), goal: 12 strings, goals: $B = 1.0 \cdot 10^{-4}$ cts/(keV kg yr), $T_{1/2}^{0\nu}$ sens.: 10^{27} yr

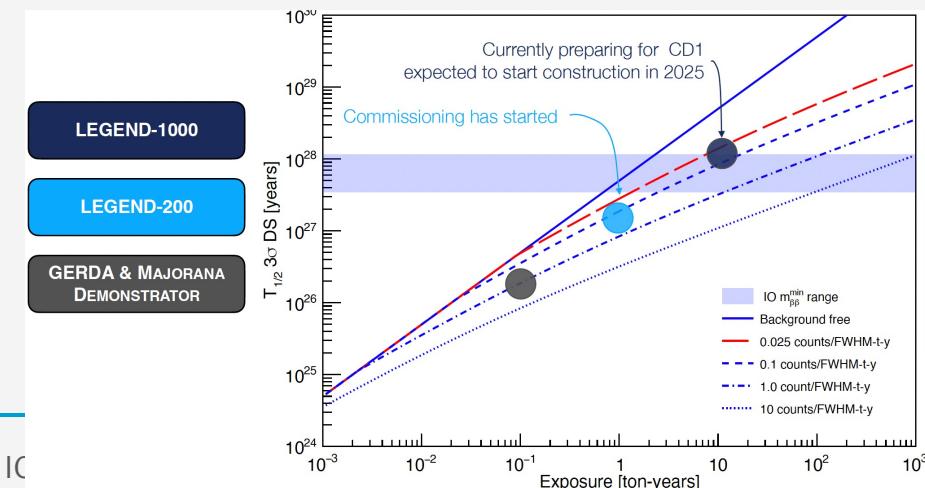


Future plan: LEGEND -1000

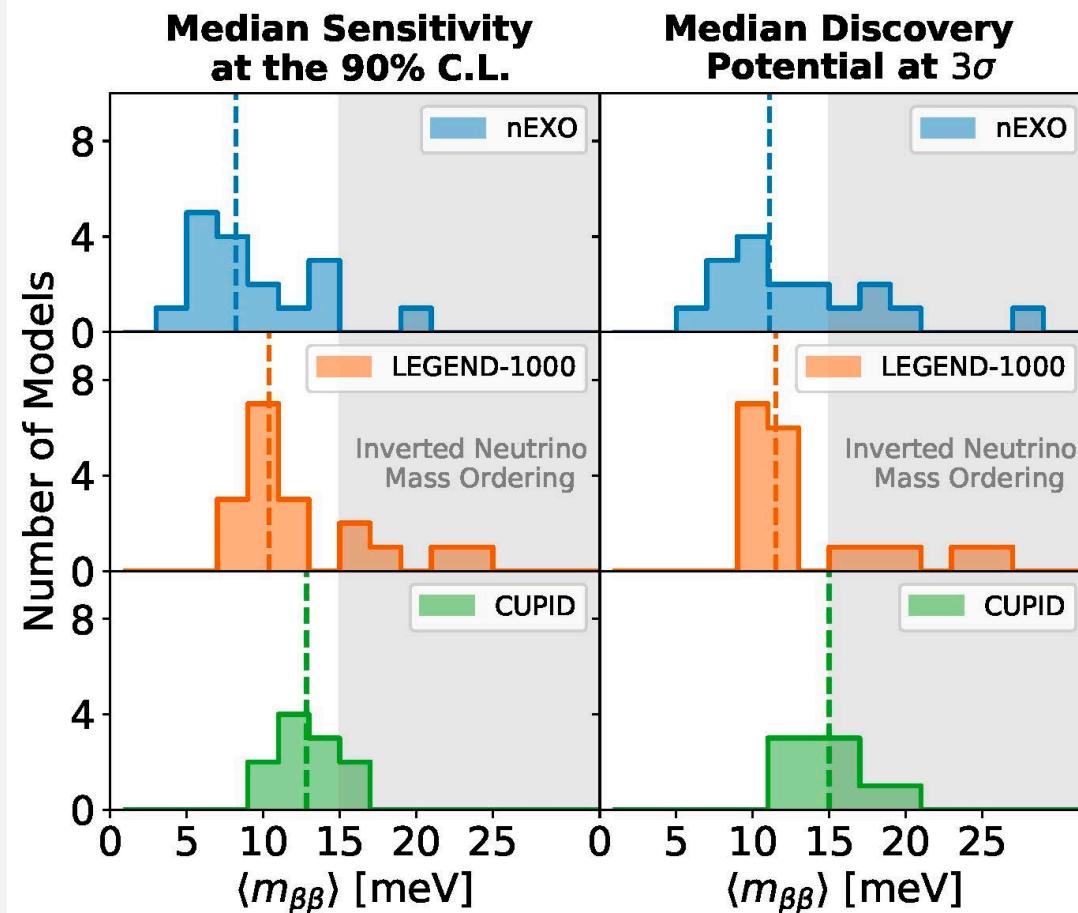
arXiv:2107.11462 (PCDR),
goals: $B = 1.0 \cdot 10^{-5}$ cts/(keV kg yr)

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

talks by Nina Burlac,
Michael Willers



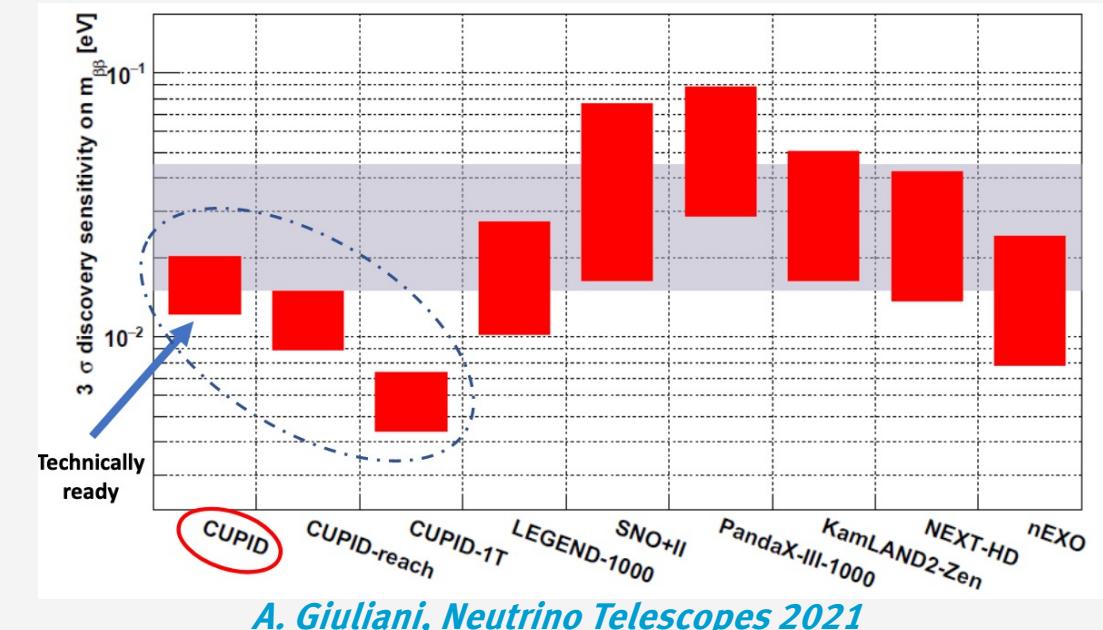
Comparison of DBD experimental sensitivities



courtesy :Giorgio Gratta

$T_{1/2}$ values used [$\times 10^{28}$ 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.)



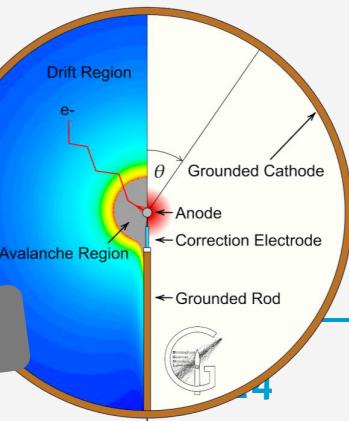
A. Giuliani, Neutrino Telescopes 2021

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, EPJC 80 (2020) 808)
- New proposals:
R2D2, a spherical HP Xenon TPC

talks by Ken Han,
Carla Macolino

talk by Robert Ward



Complementary ways to the neutrino mass

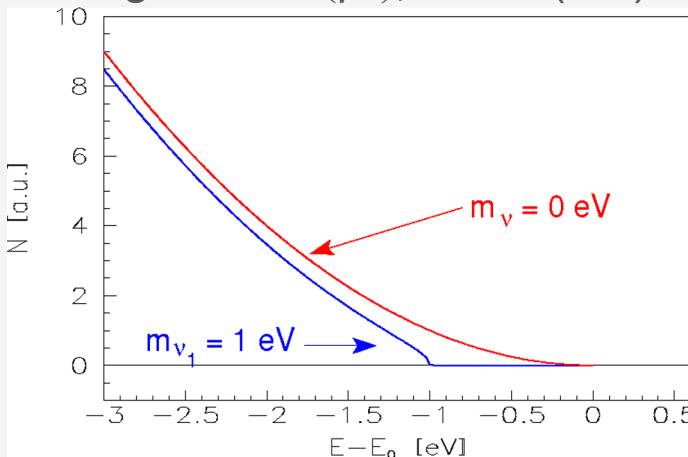
Direct neutrino mass search

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

no further assumptions needed

Time-of-flight measurements
(ν from supernova)

Kinematics of weak decays,
e.g. tritium (β^-), ^{163}Ho (EC)



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

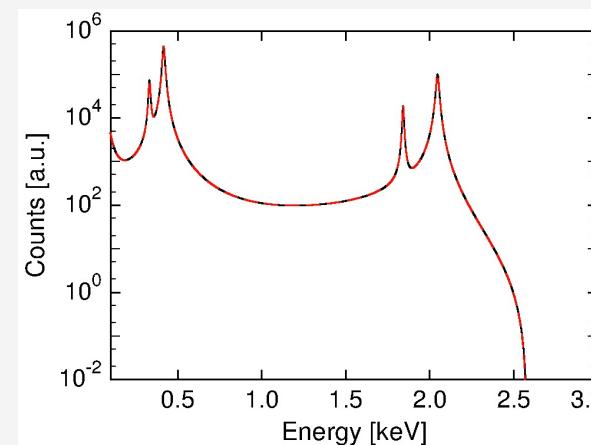
No further assumptions are needed:

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

Determine m_ν^2 from beta electron spectrum

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

phase space: p_e E_e E_ν p_ν

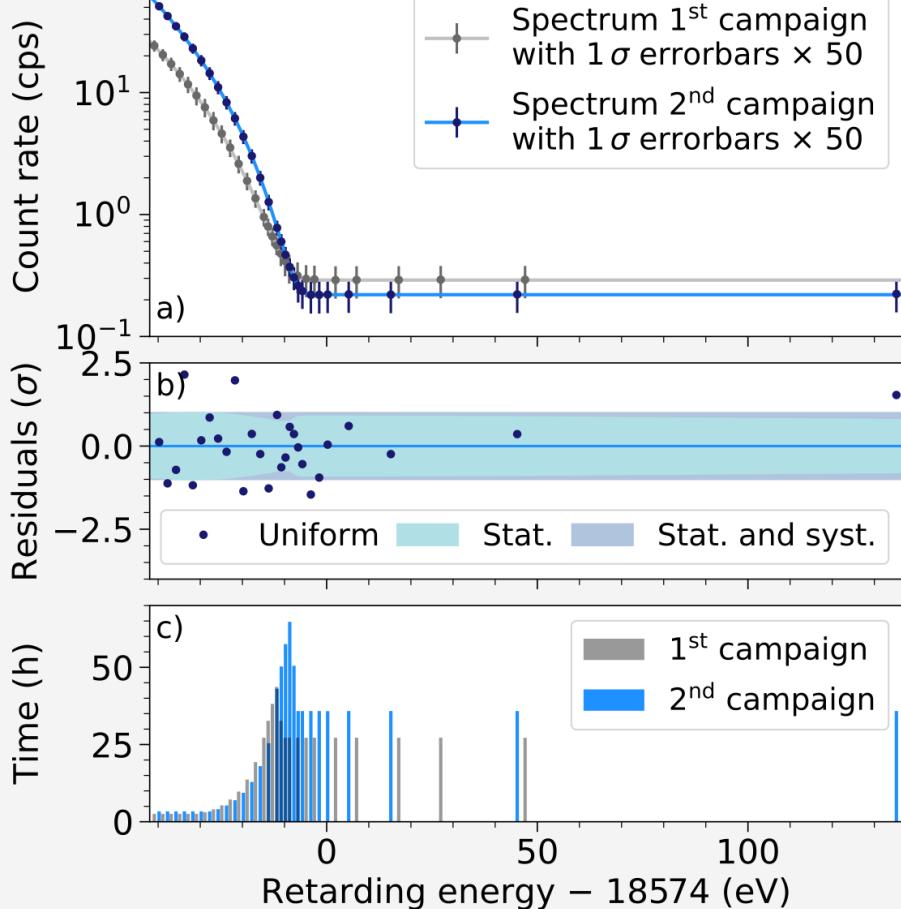
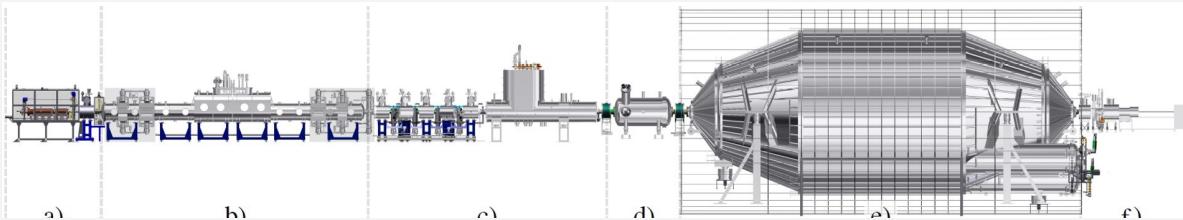


Also phase space $\propto p_\nu \cdot E_\nu$
near endpoint of electron capture deexcitation spectrum, e.g. ^{163}Ho

Time-of-flight: only eV sensitivity for very far away, very strong sources,
e.g. core-collapse supernova, e.g. SN1987a $\rightarrow m_\nu < 5.7$ eV

Karlsruhe Tritium Neutrino experiment KATRIN

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



$$m^2(\nu) = (0.26^{+0.34}_{-0.34}) \text{ eV}^2$$

→ compatible with zero

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

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

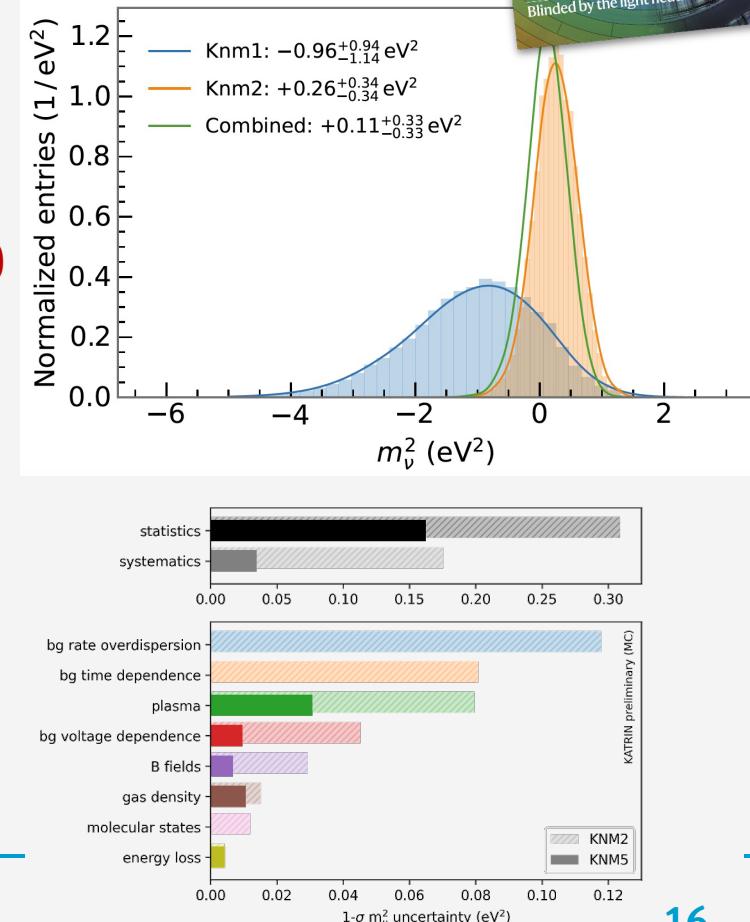
Combine 1st & 2nd campaign:

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

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

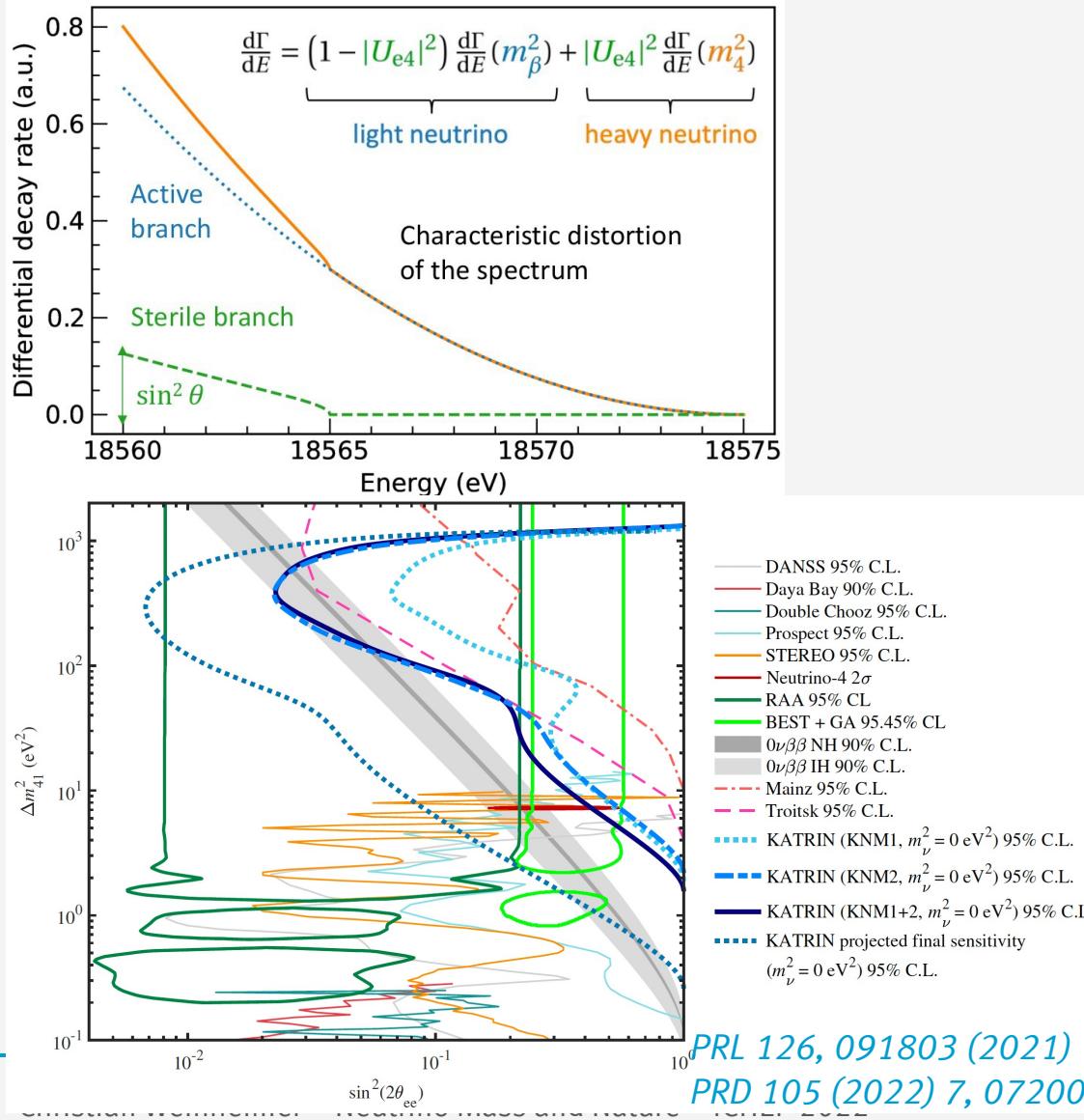
Since 2019, significant improvements
in background rate & systematics
much more data taken ...

Phys. Rev. Lett. 123 (2019) 221802
Nature Physics 18 (2022) 160

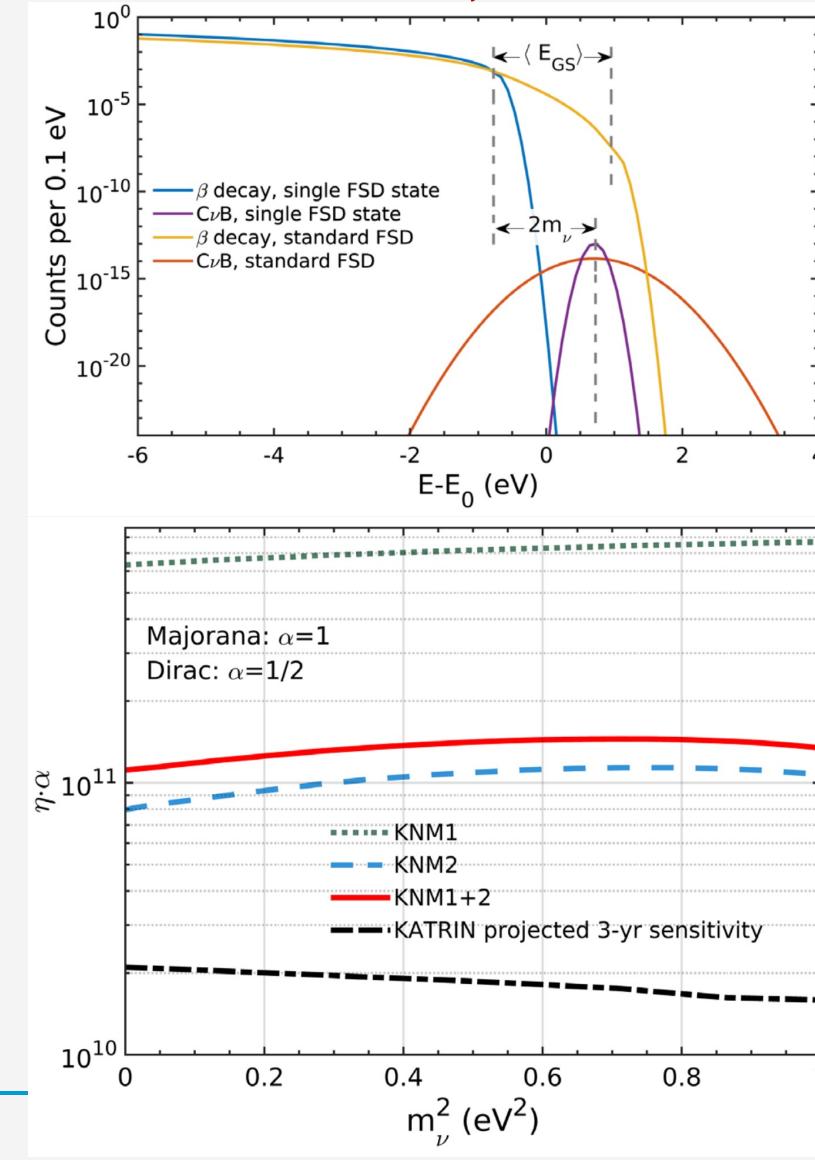


KATRIN's BSM searches near the endpoint

Search for sterile neutrinos:



Search for overdensity of CvB neutrinos



For a T_2 source,
the ro-vibrational
final states
create
an irreducible
background

Future: search for sterile keV neutrinos with KATRIN

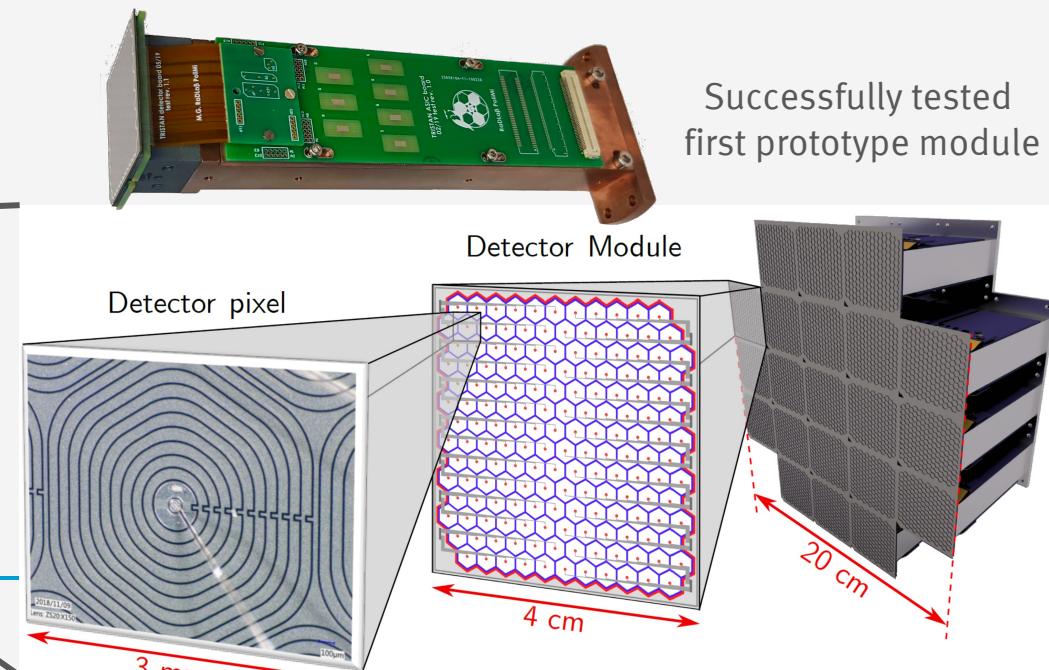
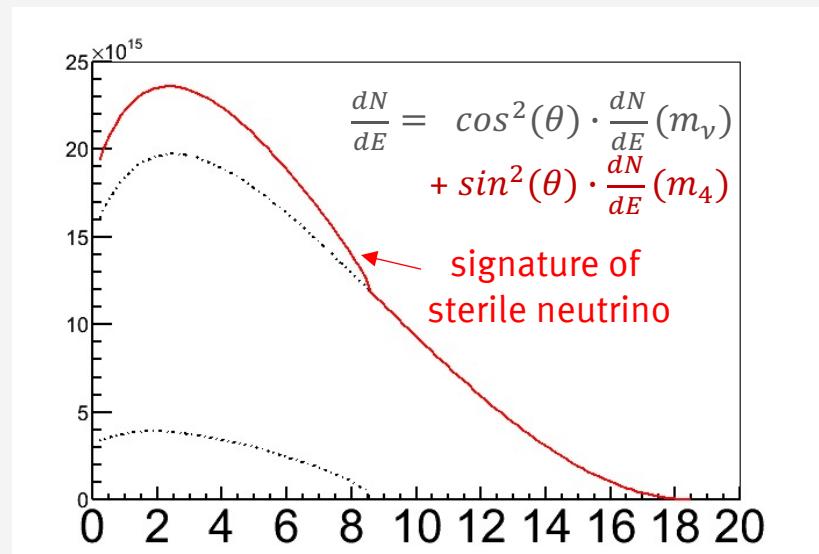
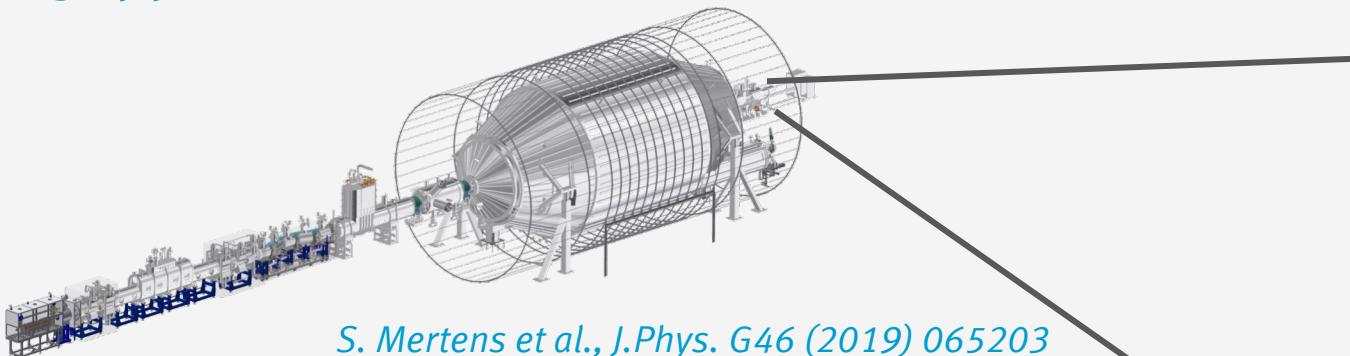
4th mass eigenstate of neutrino mixed with flavour eigenstates
 → BSM particle, dark matter candidate

Look for the kink in the β -spectrum

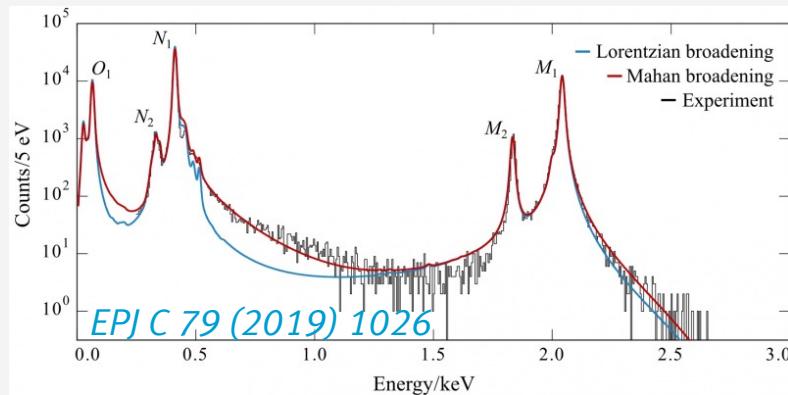
Target sensitivity of $\sin^2 \theta < 10^{-6}$
 → TRISTAN project in KATRIN

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

→ highly pixelized silicon drift detector (SDD)



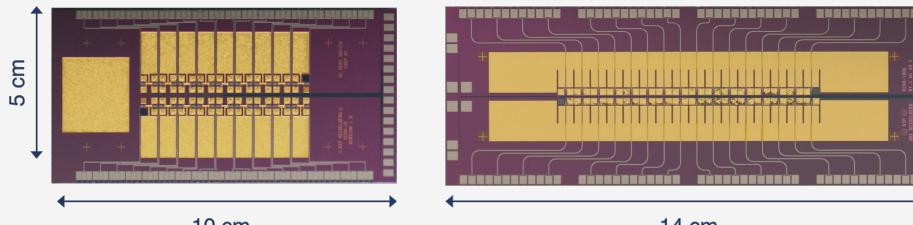
EC with ^{163}Ho cryogenic bolometers: ECHo



ECHo: metallic magnetic calorimeters (MMC):

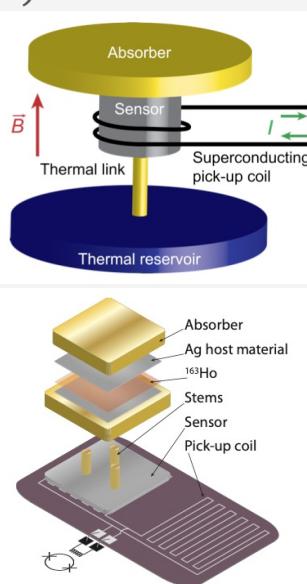
ECHo-1k phase:

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 ($2 \times 10^{12} \text{ }^{163}\text{Ho}$ atoms)

Present status:

High Purity ^{163}Ho source:

- available about 30 MBq

Ion implantation system:

- demonstrated and continuously optimized

Metallic magnetic calorimeters

- reliable fabrication of large MMC array
- successfull characterization of arrays with ^{163}Ho

Multiplexing and data acquisition:

- demonstrated for 8 channels
- development of the SDR electronics
- still to show scaling of the system

courtesy: Loredana Gastaldo

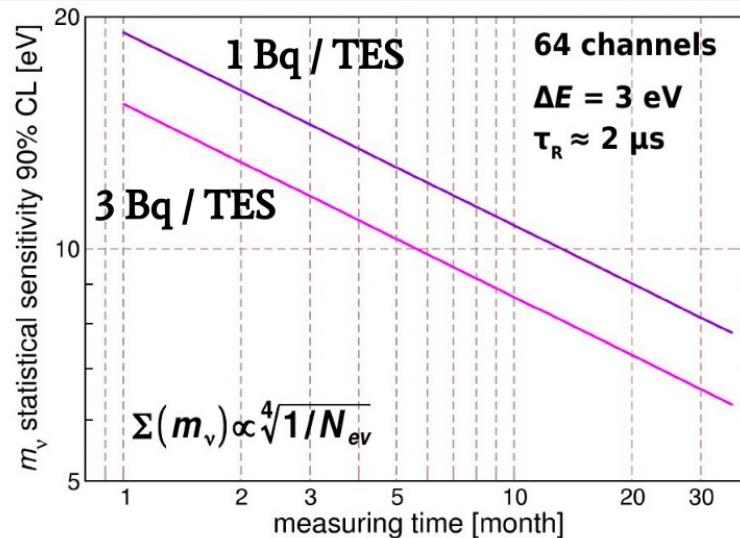
talk by Loredana Gastaldo

EC with ^{163}Ho cryogenic bolometers: HOLMES

HOLMES: superconducting transition edge sensors (TES)

^{163}Ho to be implanted in gold absorber

read-out: frequency multiplexing

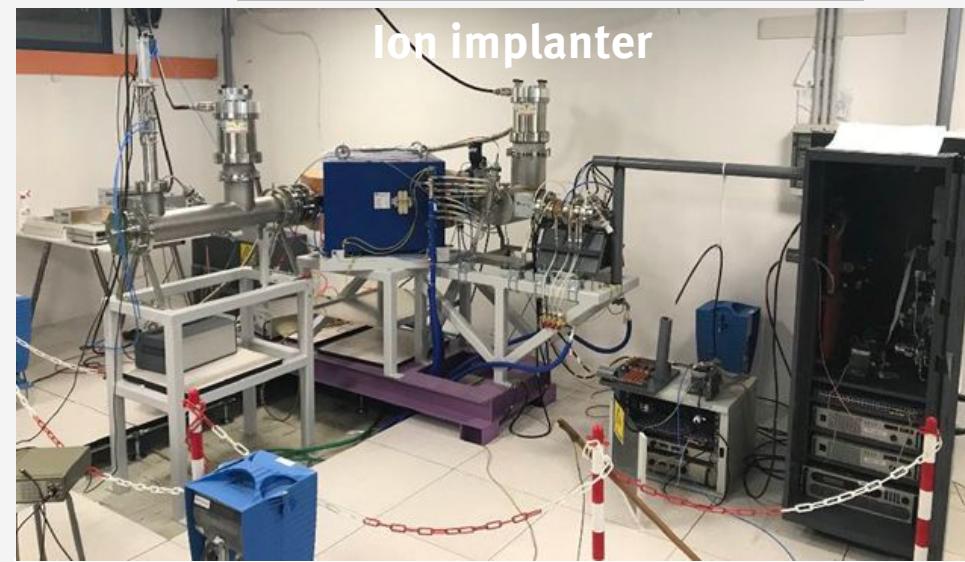


talk by Luca Origo

m_ν sensitivity depends on:

- activity / TES X
 - pile-up fraction (time res.) ✓
 - energy res. ✓
 - # TESs X
 - measuring time ✓
- 300 Bq X → few Bq
 → 10^{-4} ✓
 (1.5 μs) ✓
 → few eV @ few keV ✓
 → 10^3 X → 64
 → → expected 3 years

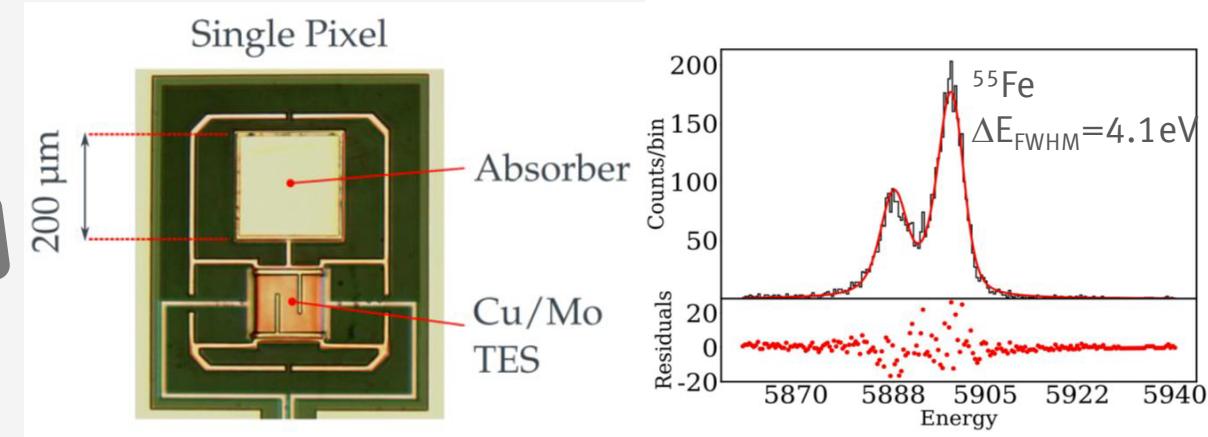
HOLMES status:



Current work:

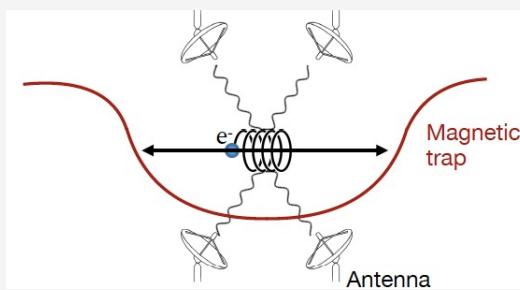
- reliable ^{163}Ho target
- ion-implantation stability
- ^{163}Ho handling procedure

Goal: first measurement still in 2022



courtesy: Luca Origo

Project 8: tritium β spectroscopy with CRES

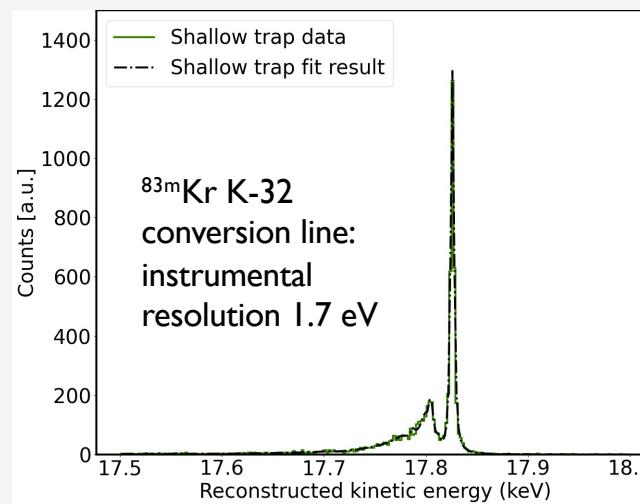
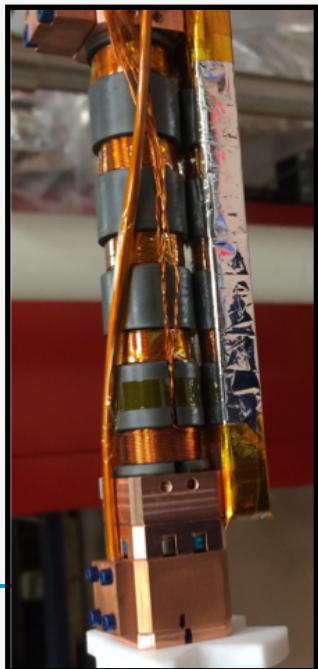


Cyclotron radiation:

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

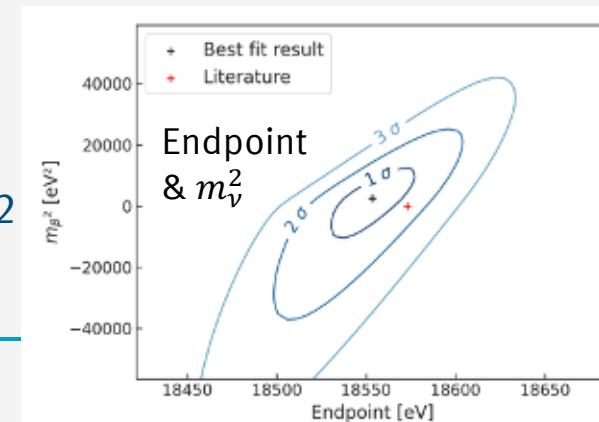
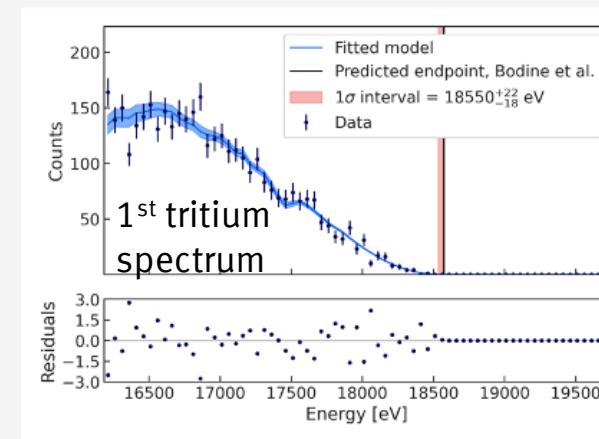
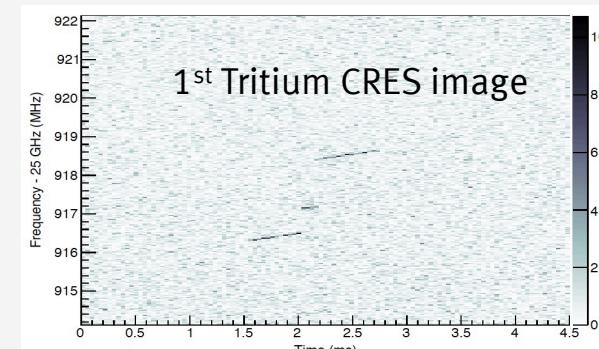
Cyclotron Radiation Emission Spectroscopy (CRES)
to reconstruct kinetic energy of electrons

Phase I & II



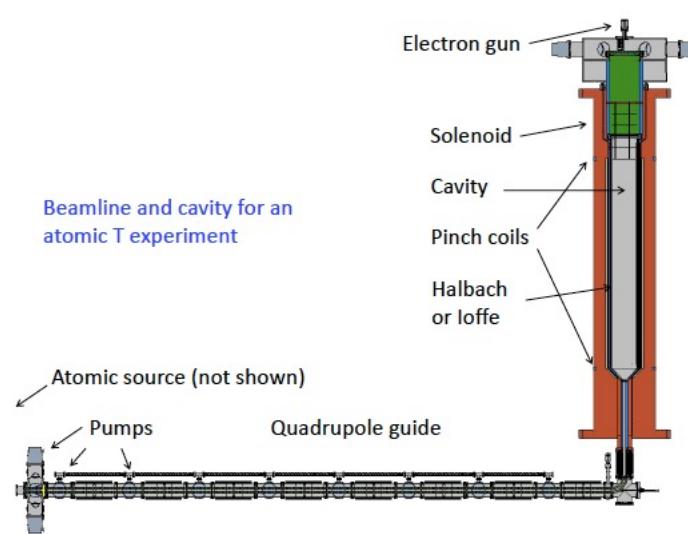
First tritium run using CRES in 2019-2022

Low background observed



Phase III:

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

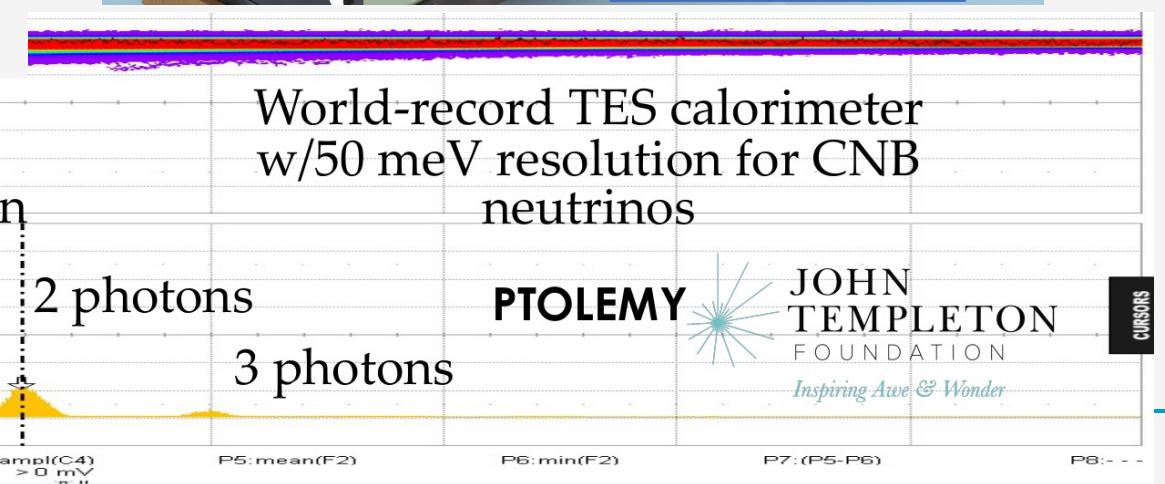
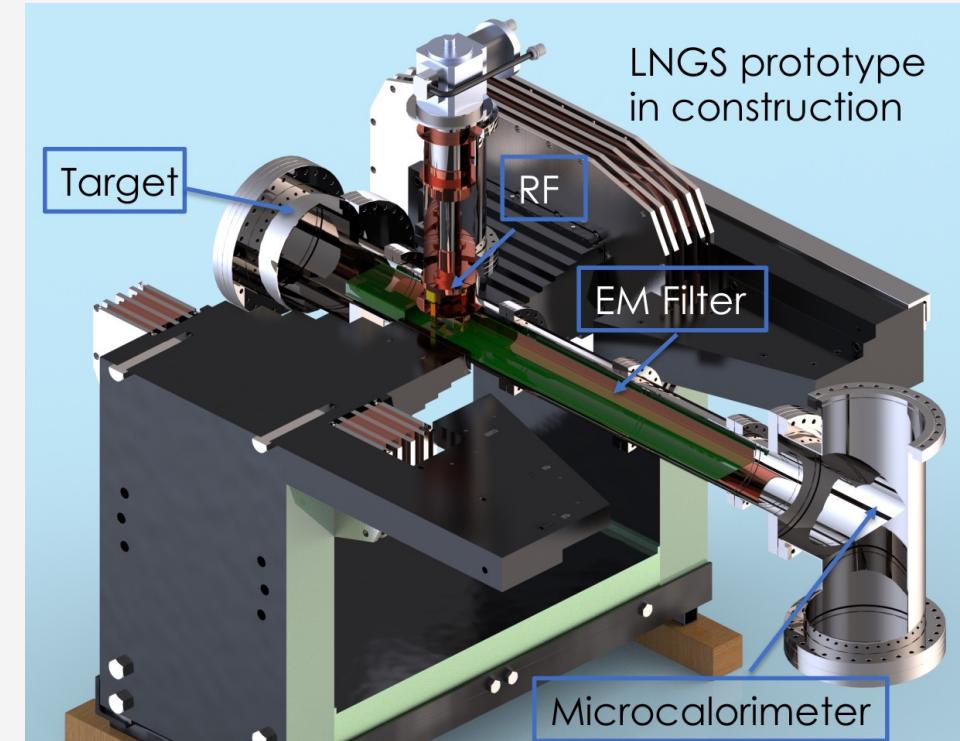
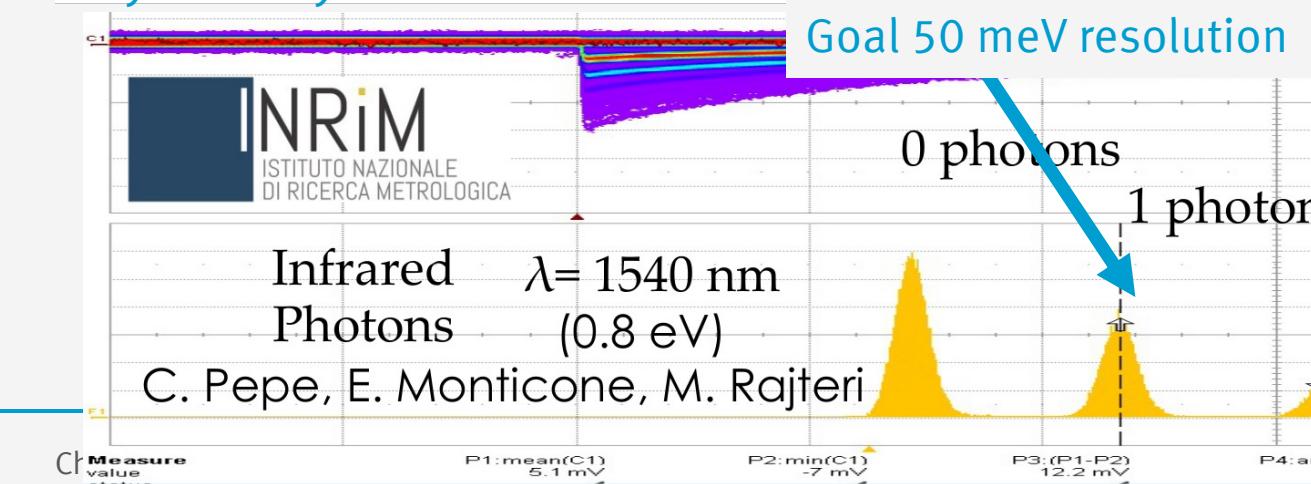
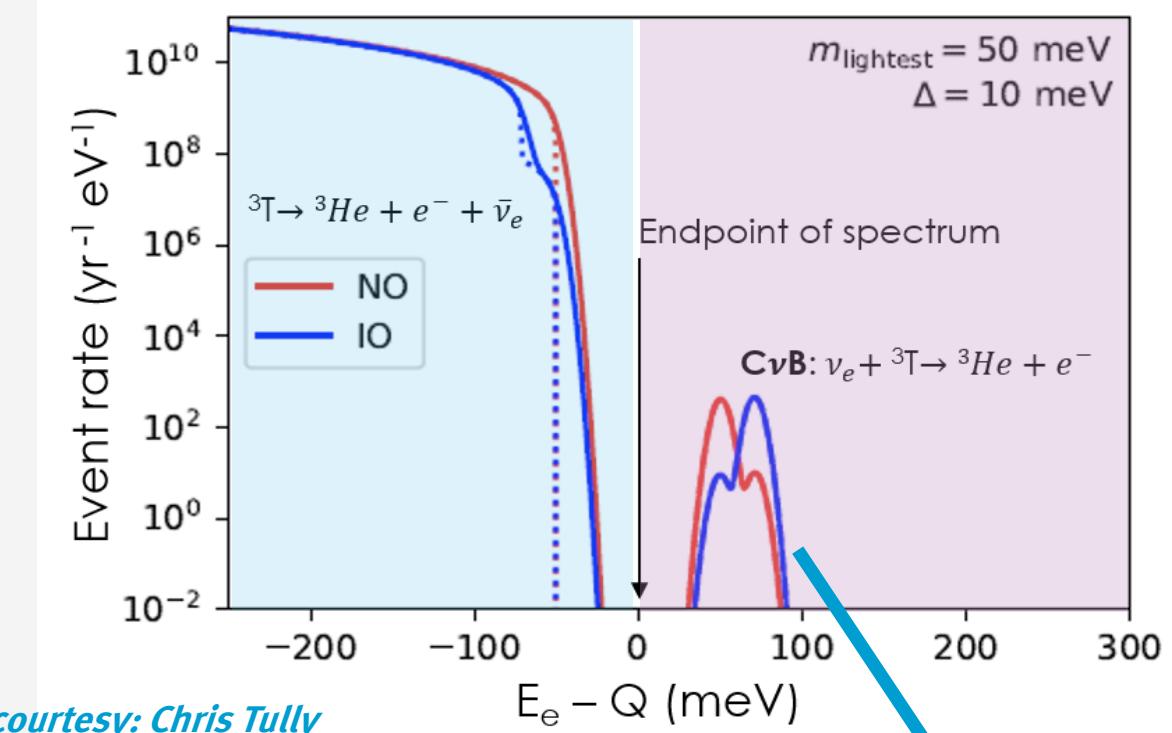


Phase IV:

Eventually, Project 8 wants to build an experiment with sensitivity $O(40 \text{ meV})$:

J. Formaggio, NuMass 2022, Milano

PTOLEMY: R&D towards CvB



- **Neutrino nature** (Dirac \leftrightarrow Majorana \Rightarrow LNV, would allow leptogenesis & BAU, seesaw)
& neutrino mass (cosmology & structure formation, mass generation of super-light fermions)
are leading and timely questions of nuclear and (astro)particle physics as well as of cosmology
- Cosmology, search for $0\nu\beta\beta$ and direct search for neutrino mass provide complementary information
- **Search for $0\nu\beta\beta$ is investigating neutrino nature and mass:**
current sensitivity $T_{1/2}^{0\nu} \approx 2 \cdot 10^{26}$ yr and $m_{\beta\beta} \approx \mathcal{O}(200 \text{ meV})$ by GERDA, KamLAND-ZEN, ...
Next generation experiments (CUPID, LEGEND, KamLAND-ZEN, nEXO, ...) will investigate inverted mass ordering regime with sensitivities of $T_{1/2}^{0\nu} \approx 10^{28}$ yr and $m_{\beta\beta} \approx \mathcal{O}(20 \text{ meV})$
Main challenges: ultra-low background, large mass of DBD isotope (${}^{76}\text{Ge}$, ${}^{100}\text{Mo}$, ${}^{136}\text{Xe}$)
- **Direct search for neutrino mass:**
 - KATRIN reached sub-eV sensitivity and has much more data, provides BSM limits on ν_s , CvB overdensity will search for keV sterile neutrinos
 - Cryo-bolometers (ECHO, HOLMES) with ${}^{163}\text{Ho}$ aim for (sub)eV-sensitivity with large arrays of multiplexed pixels
 - Project 8 (CRES-technology) is opening a new road towards sub-eV neutrino mass sensitivity with tritium
 - Direct neutrino mass search with tritium at the extreme: towards CvB, R&D with PTOLEMY for the (far) future

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- **Searches for neutrinoless double beta decay**

current status

Next steps

regarding

Main issues

- **Direct neutrino mass search**

- KA

W

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

A. Gando, L. Gastaldo, J.J. Gomez, G. Gratta, Y. Kim, C. Kraus, C. Macoloni, S. Mertens, A. Nucciotti, L. Origo,
M. Pavan, F. Pompa, S. Schönert, C. Tully, K. Valerius

Thank you all for your attention

- Cryo-bolometers (ECHO, HOLMES) with ^{163}Ho aim for (sub)eV-sensitivity with large arrays of multiplexed pixels
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