Prospects in neutrinoless double beta decay

Stefan Schönert | TU München

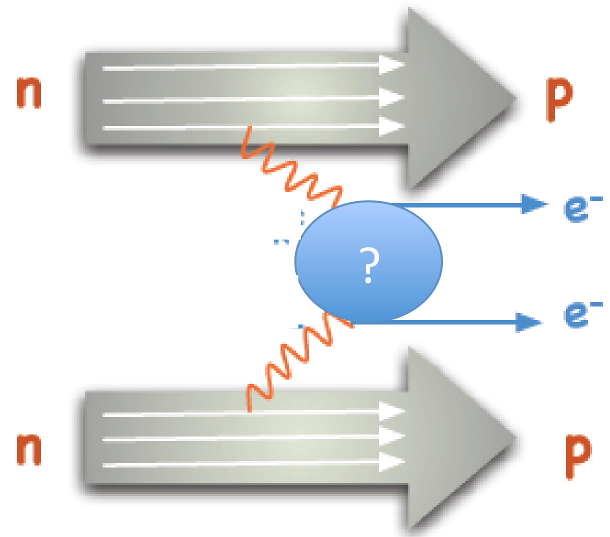
Conference on Neutrino and Nuclear Physics
CNNP2017

15-21 October 2017
Monastero dei Benedettini,
University of Catania, Italy

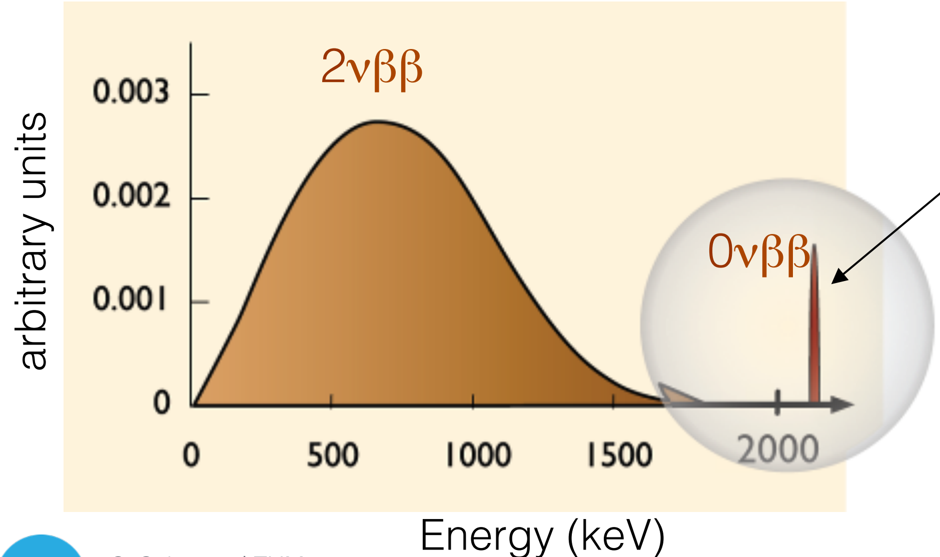
TECHNISCHE UNIVERSITÄT MÜNCHEN

SFB 1258 Neutrinos Dark Matter Messengers

0νββ decay



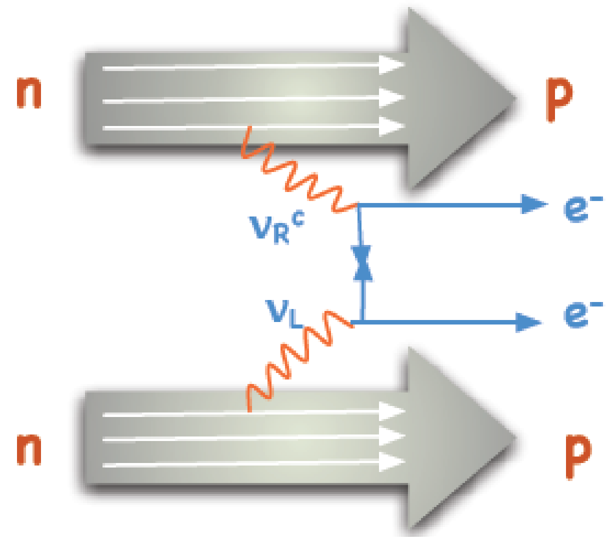
- lepton number violation $\Delta L = 2$
- physics beyond the standard model
- ν's have Majorana character



Experimental signatures:

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

The standard paradigm: 0νββ decay and neutrino mass



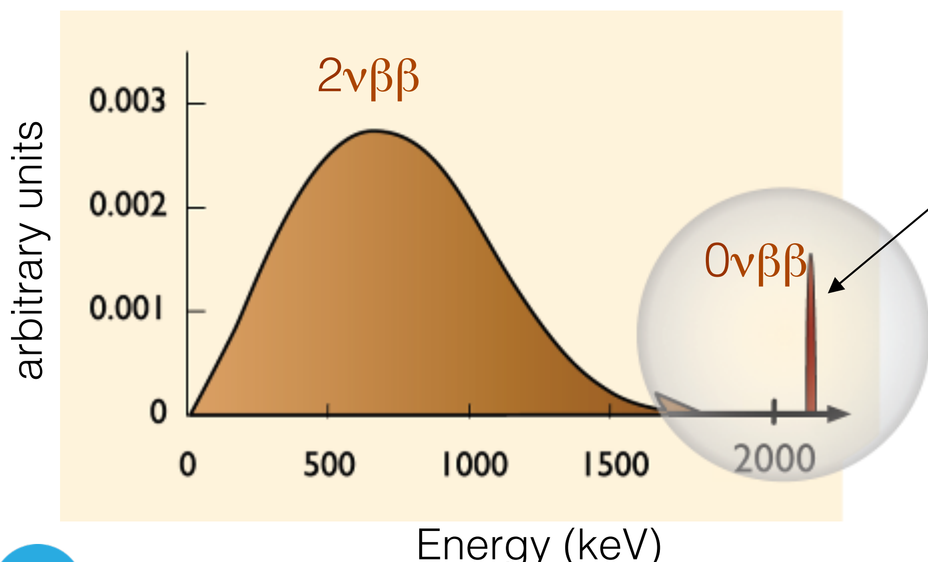
Expected decay rate:

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

Phase space integral   Nuclear matrix element

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

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

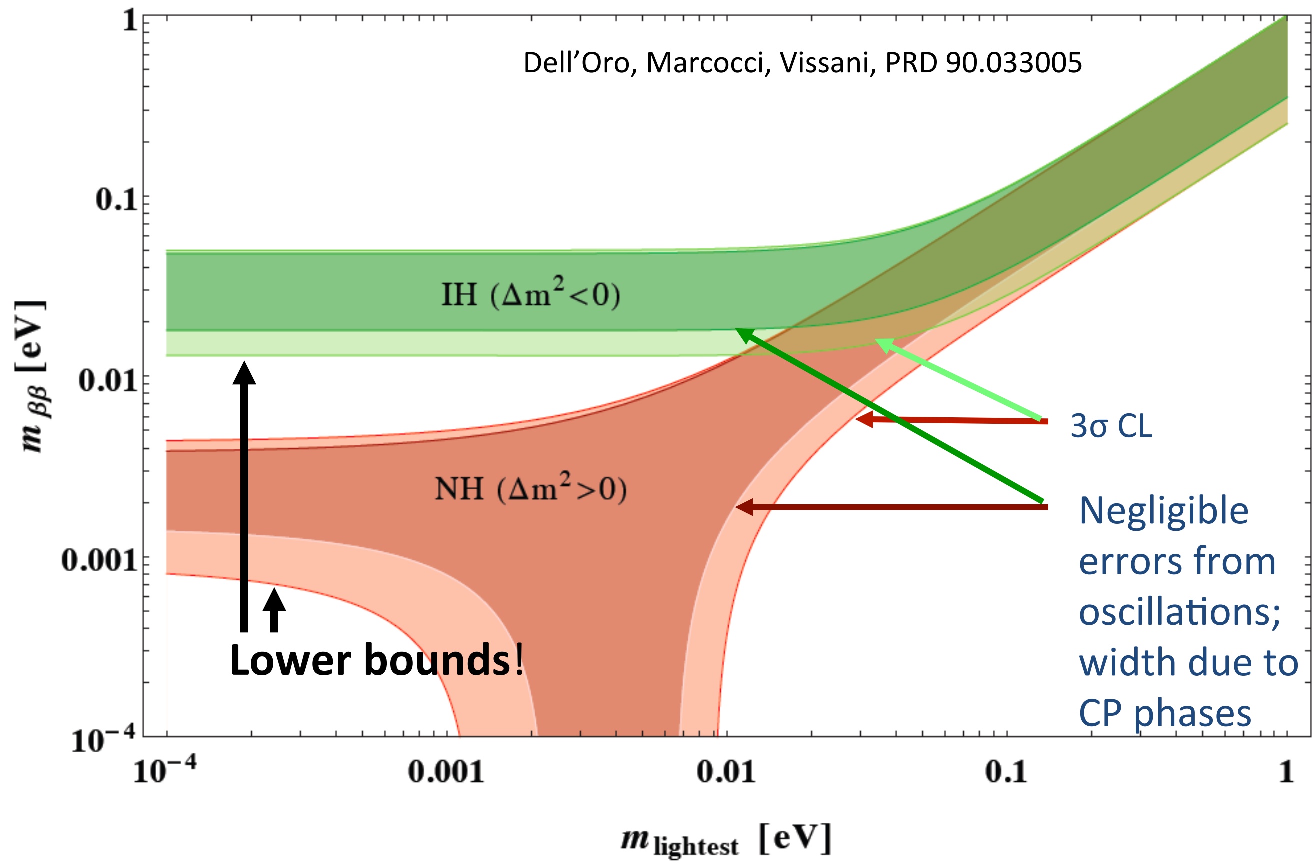


Experimental signatures:
- peak at $Q_{\beta\beta}$
- two electrons from vertex

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

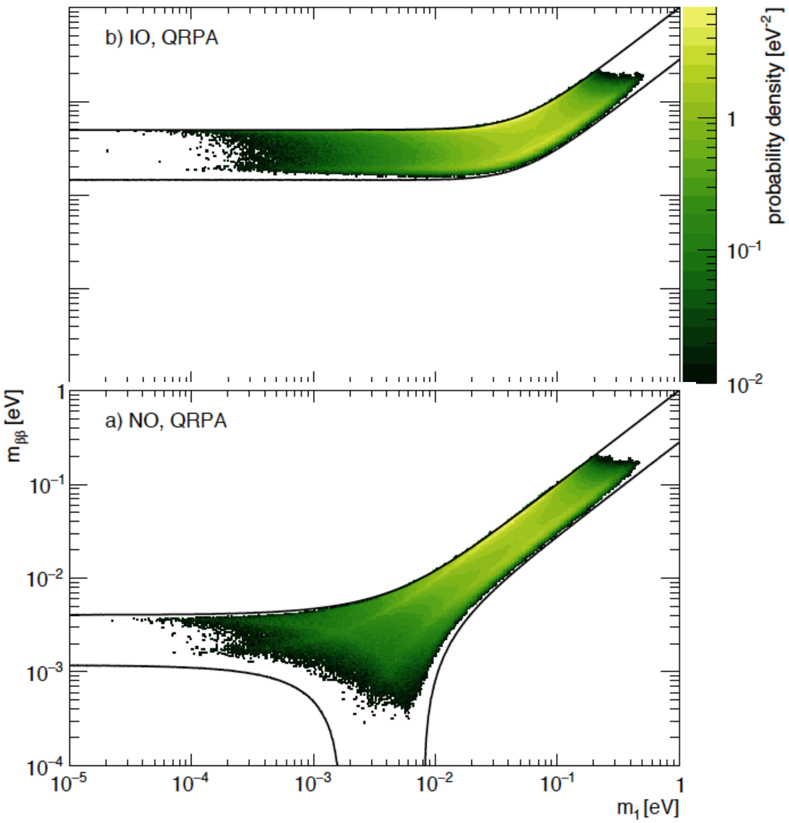
$$m_{ee} = f(m_1, \underbrace{\Delta m^2_{sol}, \Delta m^2_{atm}, \theta_{12}, \theta_{13}}_{\text{from oscillation experiments}}, \alpha\text{-}\beta)$$

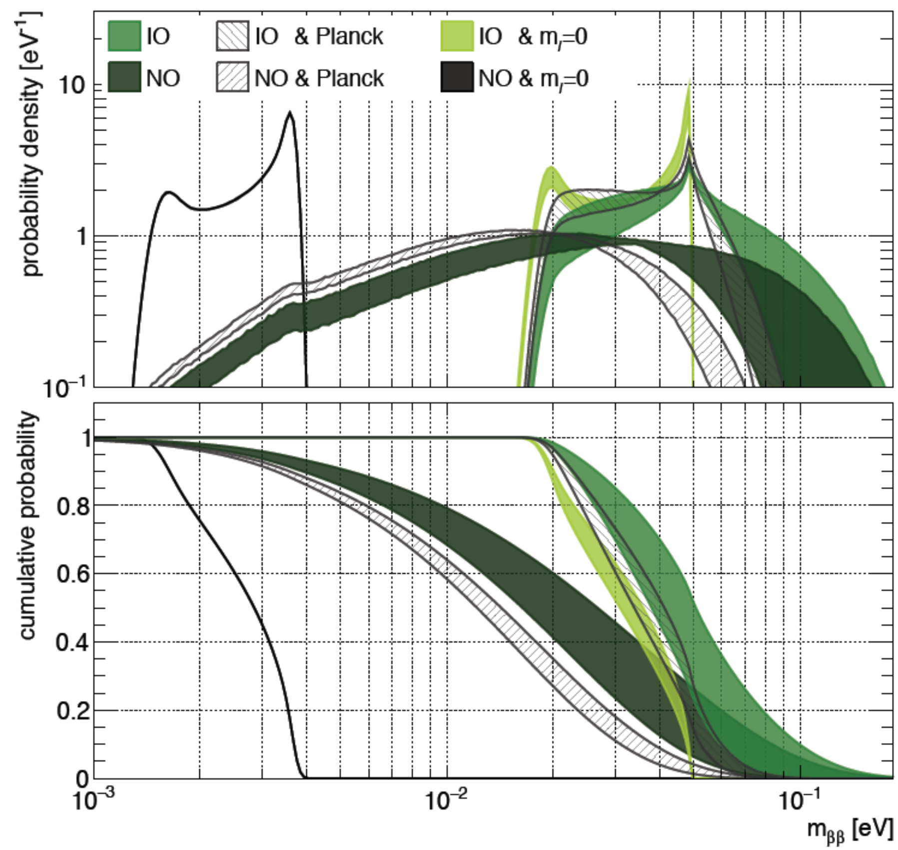
Goal of next generation experiments:



Discovery probabilities

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

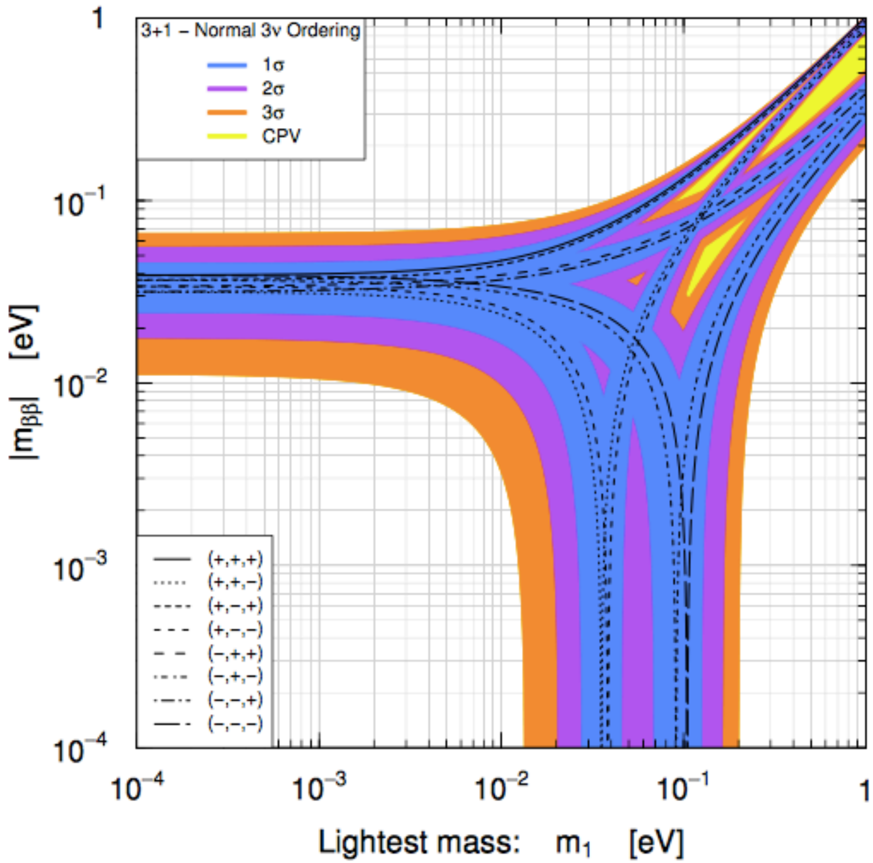




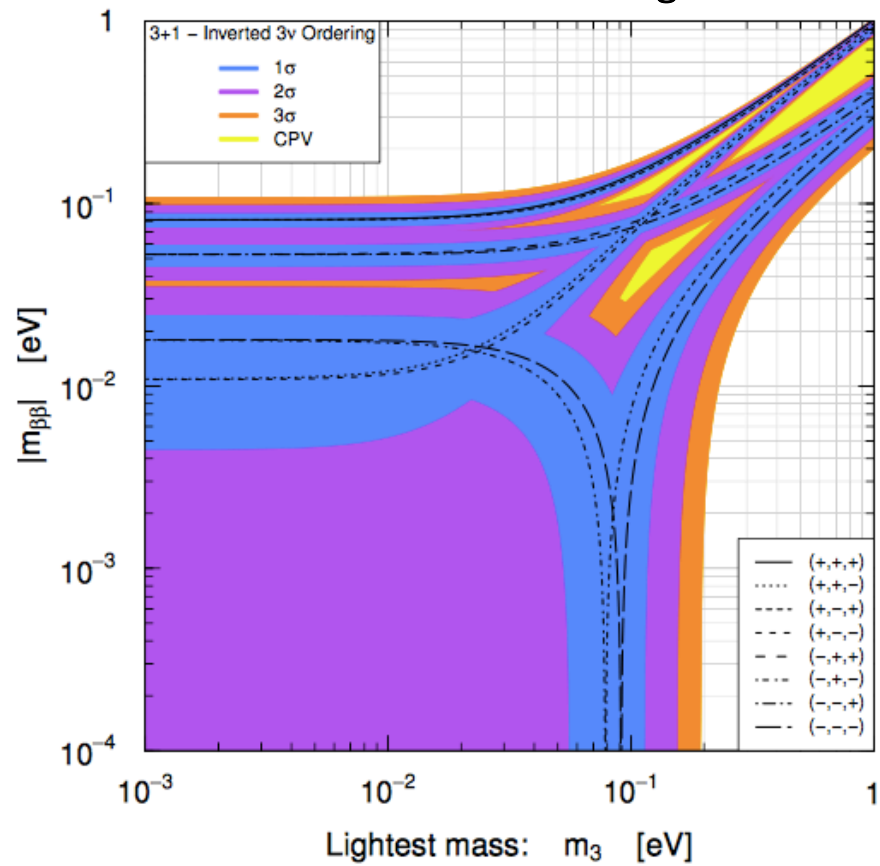
Agostini, Benato, Detwiler arXiv:1705.02996

eV sterile neutrinos

Normal ordering

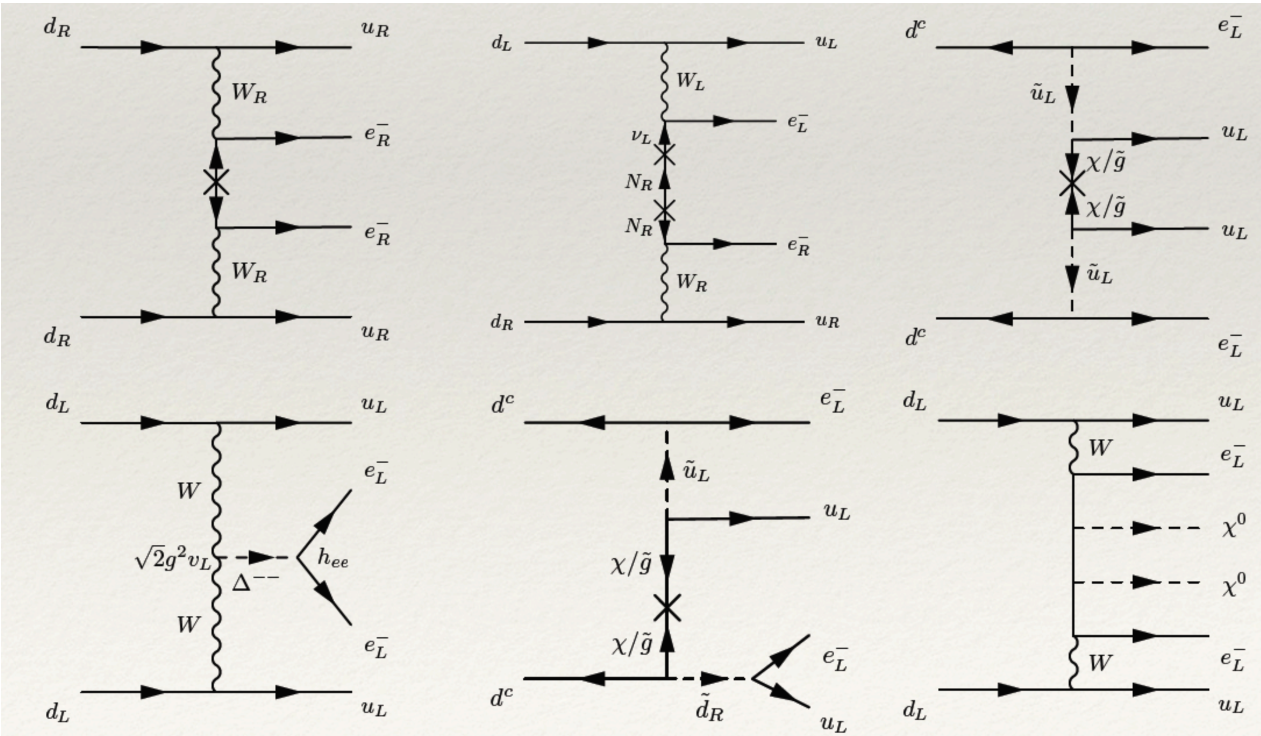


Inverted ordering

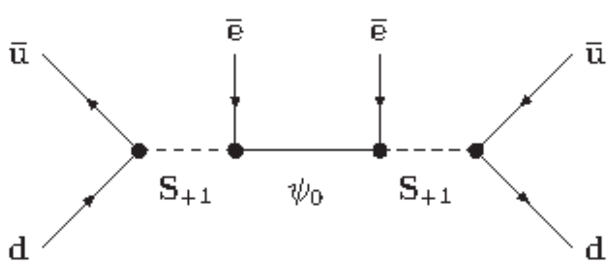


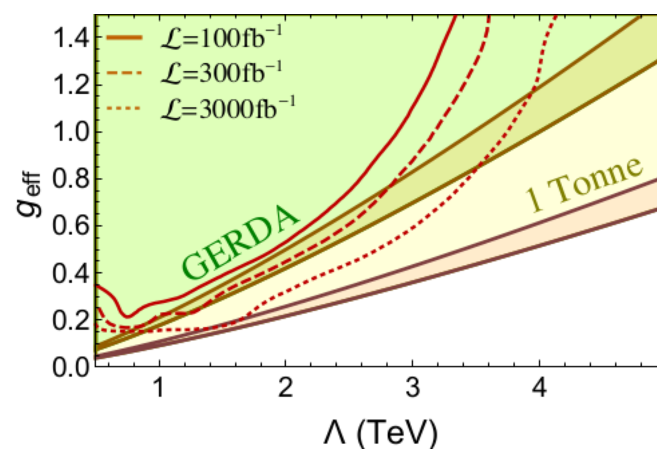
C. Giunti & E.M. Zavanin

L violating interactions

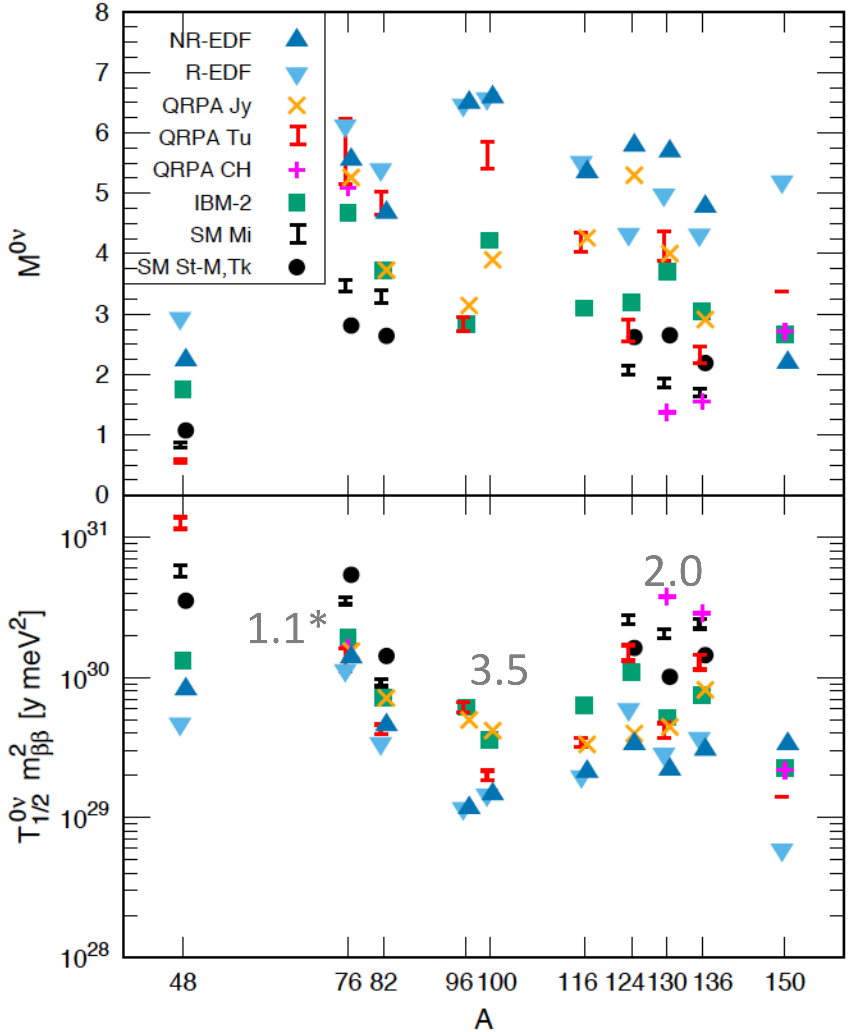


LNV predicted by many BSM theories (LR Symmetry, RPV SUSY, GUTs,…)





Nuclear matrix elements



Spread about x2

No isotope significantly preferred when comparing decay rate per mass

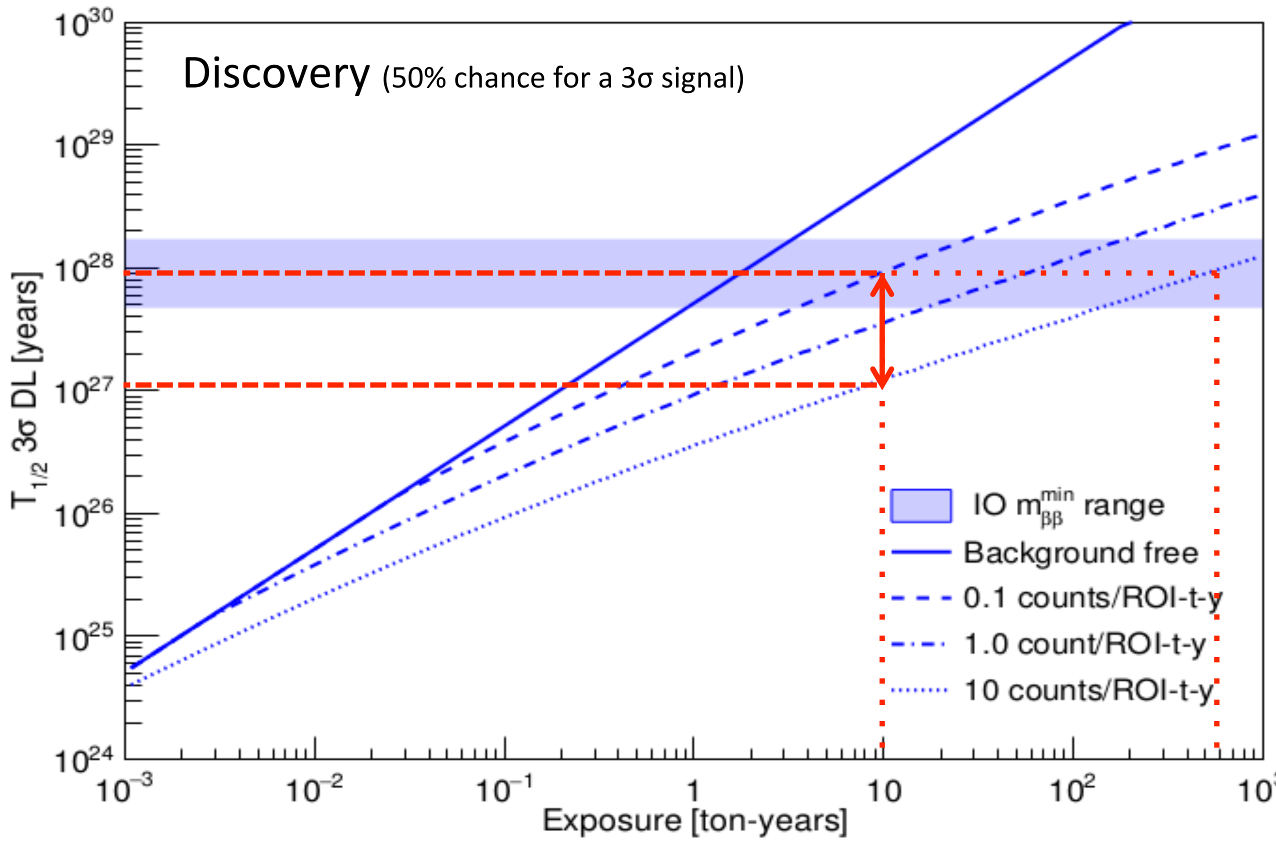
Choice mainly driven by experimental considerations

*number = signal rate per 1000 kg yr exposure & for middle of NME values for For $<m_{ee}>$ = 17.5 meV ('bottom of IH' for g_A=1.25, $\sin^2\theta_{12}$ = 0.318)

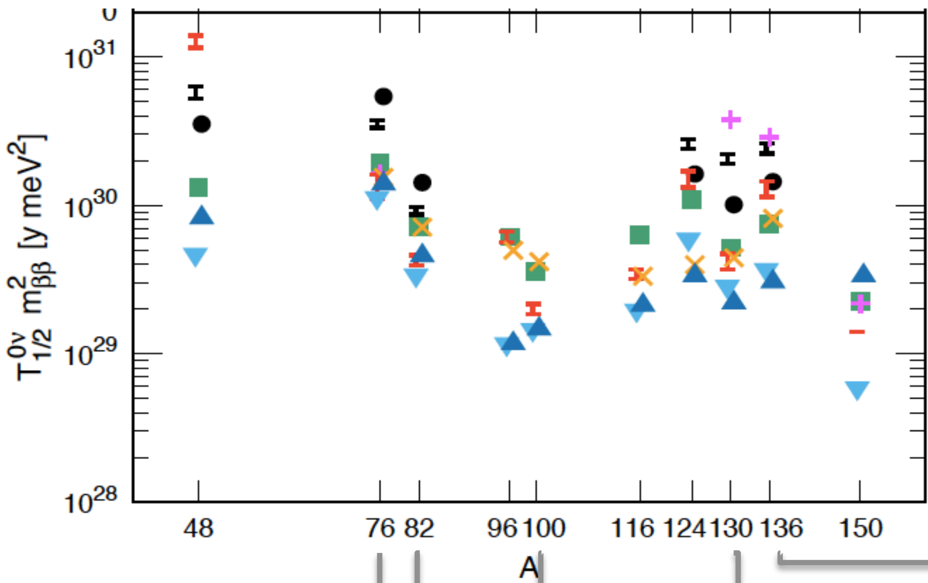
Engel & Menédez

arXiv:1610.06548v2

Discovery sensitivity vs. background



Courtesy J. Detwiler



Experiments

LXe TPC:	EXO-200 / nEXO
gas-Xe TPC:	NEXT, PandaX-III
Xe-loaded LS:	KamLAND-Zen

Te-loaded LS:	SNO+
Te-bolometers:	CUORE / CUPID-Te

Mo-bolometers:	CUPID-Mo (ex Lumineu)
	AMoRE

Se-bolometers:	CUPID-0 (CUPID-Se)
Se-calo-tracko:	SuperNEMO

Ge-semiconductor: GERDA, MJD, LEGEND

& other interesting, but less advanced R&D;
^{48}Ca, ^{150}Nd not available in large quantities

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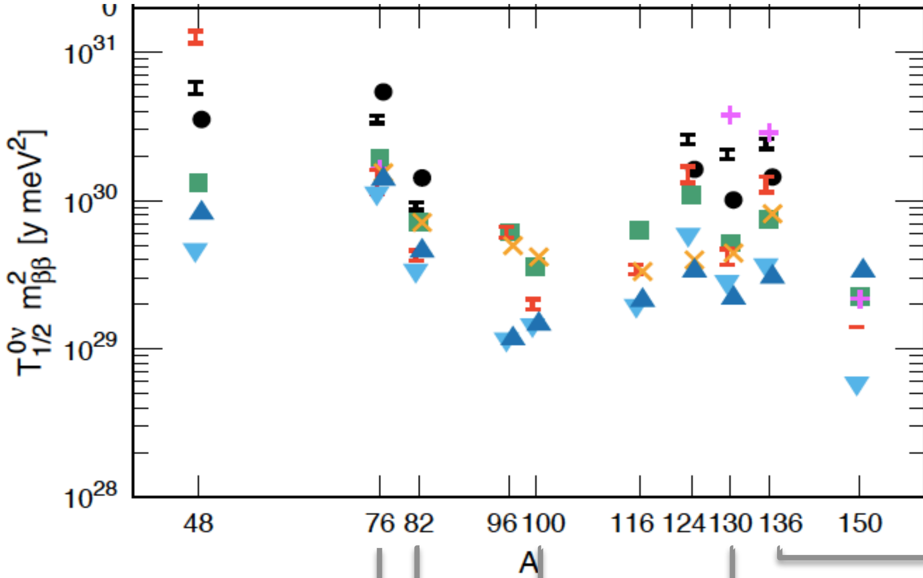

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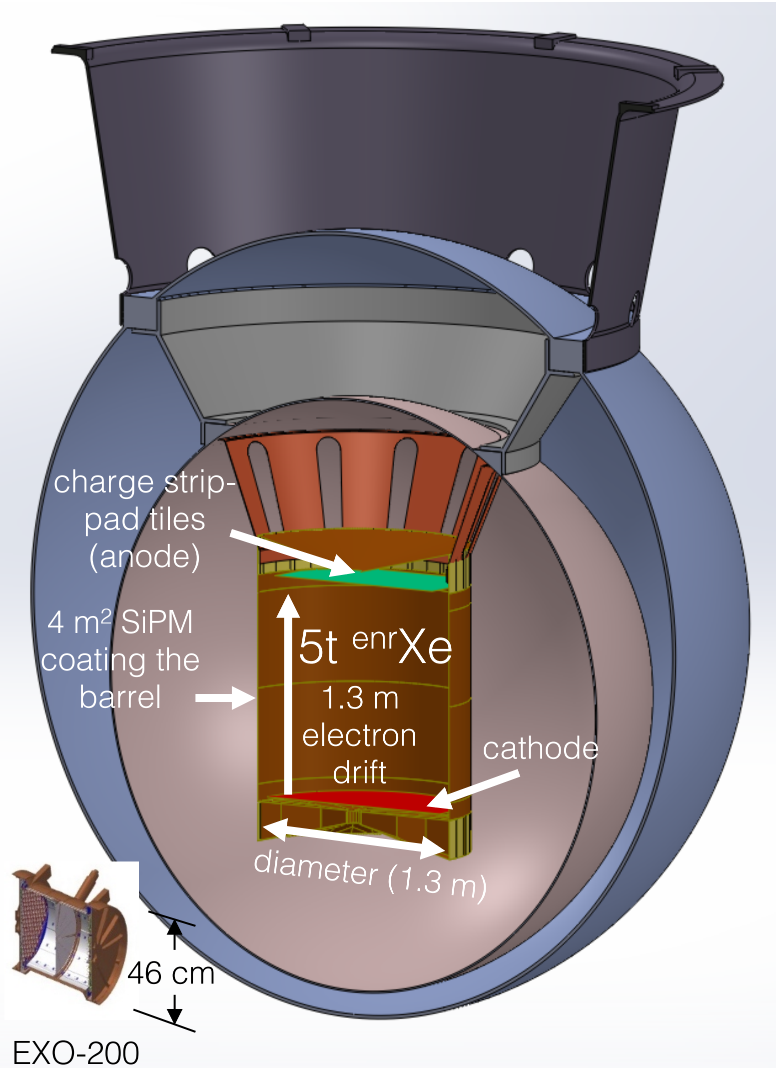
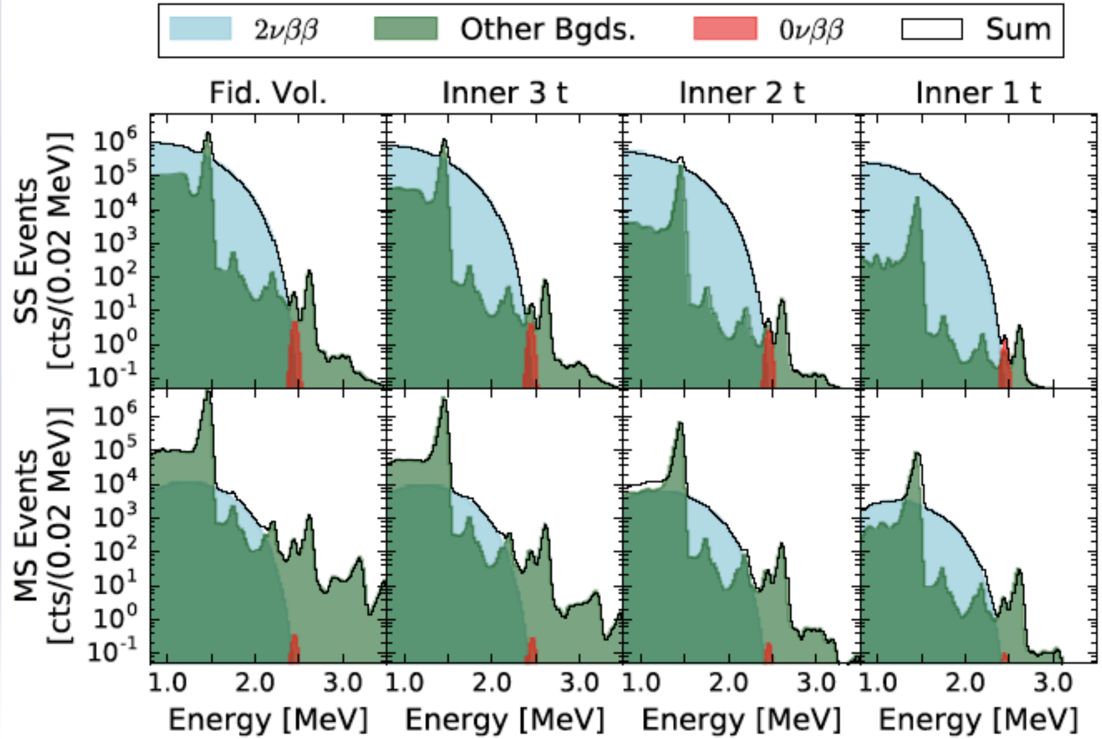
Xenon Experiments: nEXO





Courtesy G. Gratta

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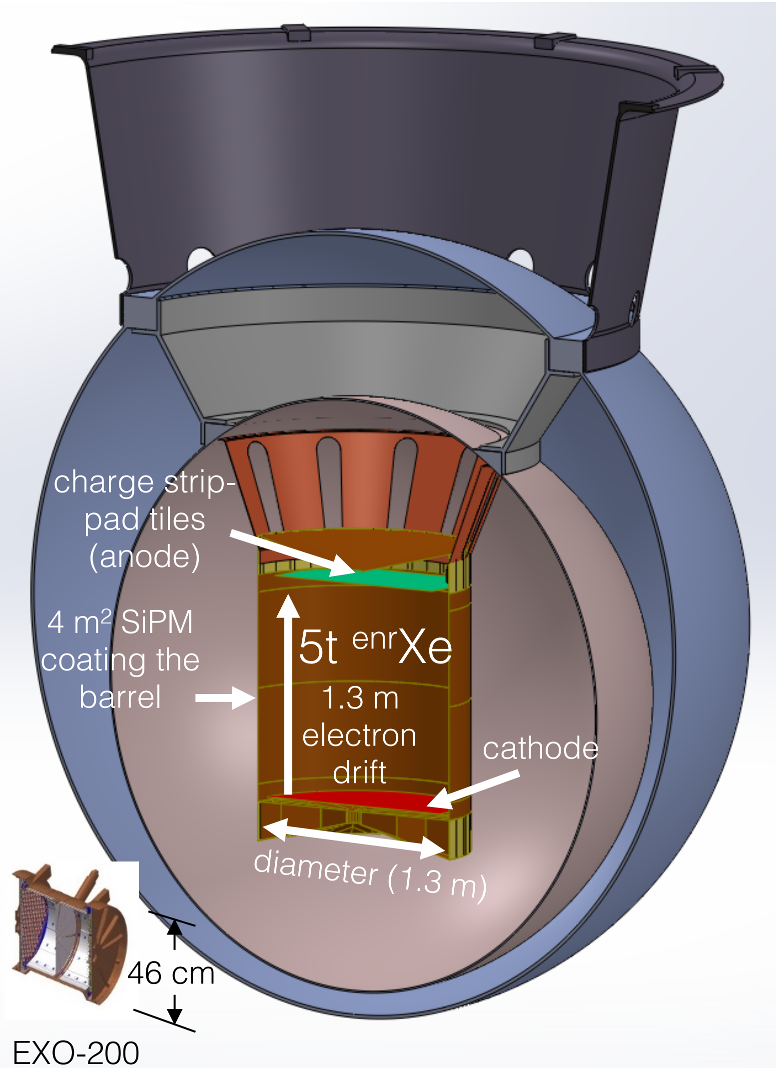
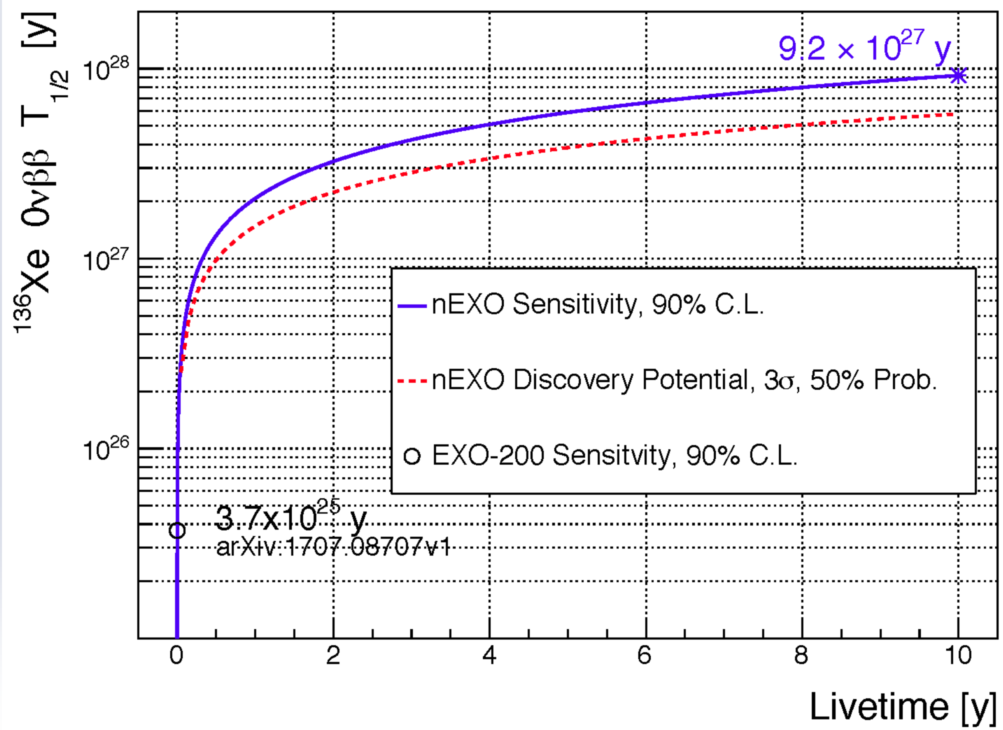


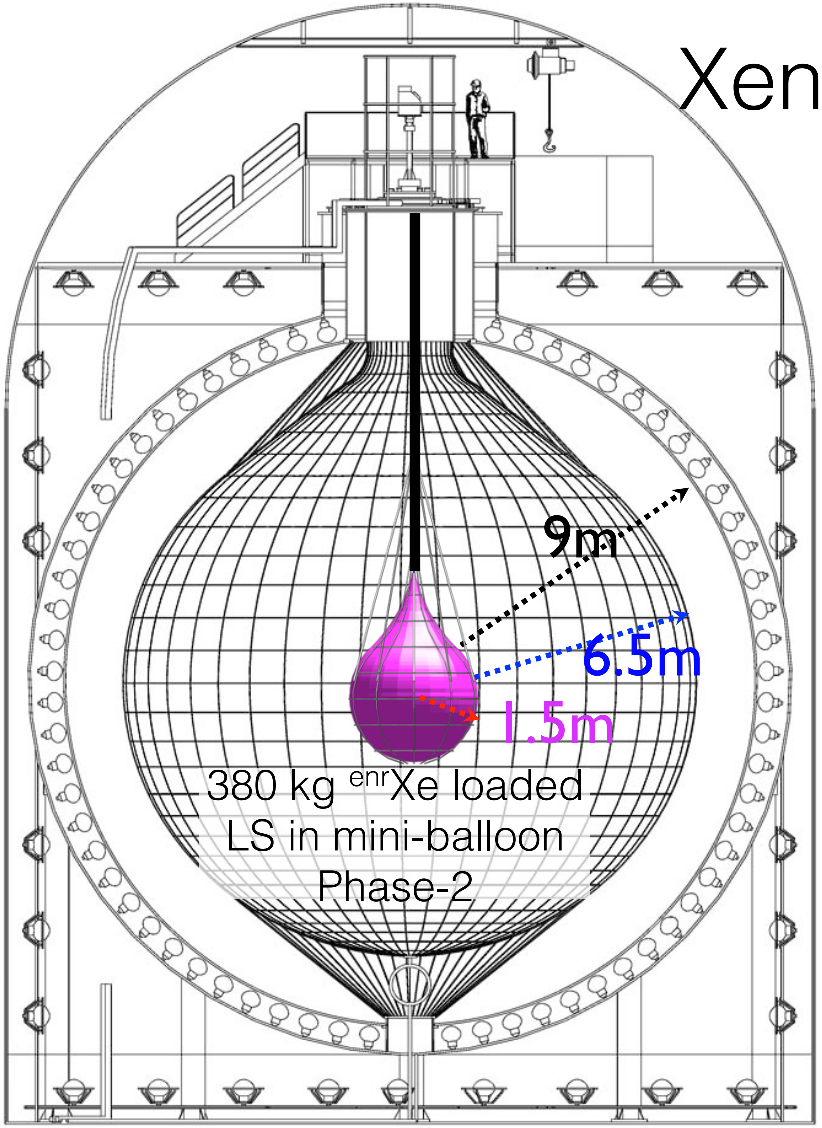


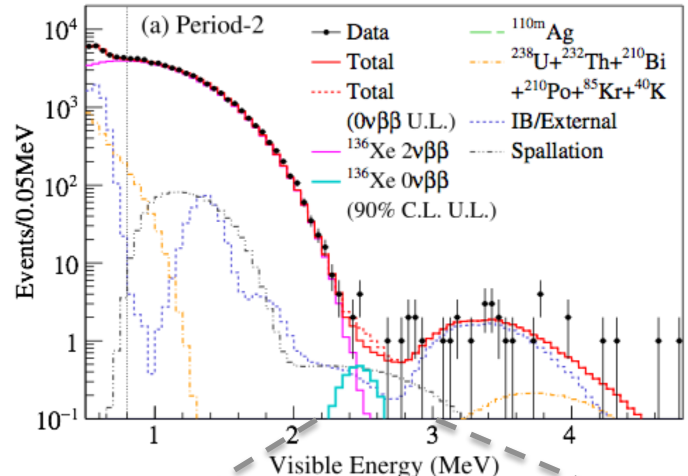
Discovery sensitivity (3σ, 50%) after 10 yr
$T_{1/2}^{0\nu\beta\beta} = 6\text{x}10^{27}$ yr

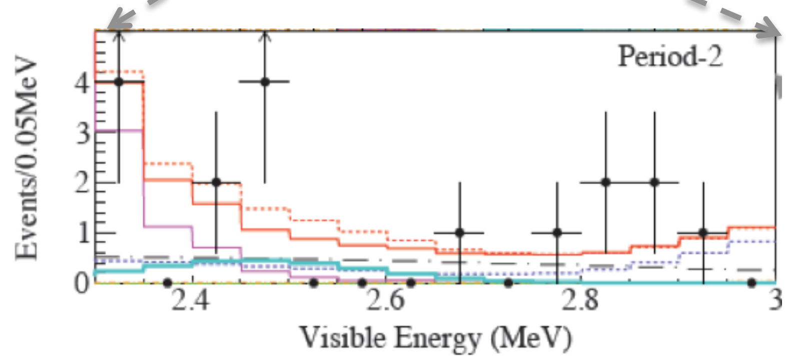
If ^{136}Ba-tagging can be implemented:
$T_{1/2}^{0\nu\beta\beta} = 1.6\text{x}10^{28}$ yr

Courtesy G. Gratta

Xenon Exp's: KamLAND-Zen







Phase-2: 2013/12/11 - 2015/10/27
534.5 days (504 kg-yr)

- Sensitivity: > 5.6 10^{25} yr (90% C.L.)
- Unconstraint fit: > 9.2 10^{25} yr (90% C.L.)
- Phase I + II: > 1.07 10^{26} yr (90% C.L.)
- 2017: data taking with 750 kg ^{enr}Xe (new balloon)
- KamLAND2-Zen with 1000kg+ proposed

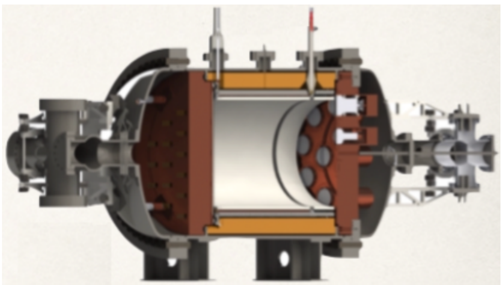
Courtesy K. Inoue

PRL117, 082503 (2016)

Xenon Experiments: NEXT

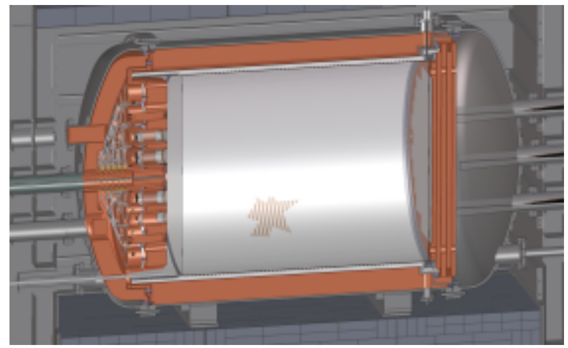
^{136}Xe high-pressure (10-15 bar) TPC

NEXT-NEW (5 kg) 2015-2018



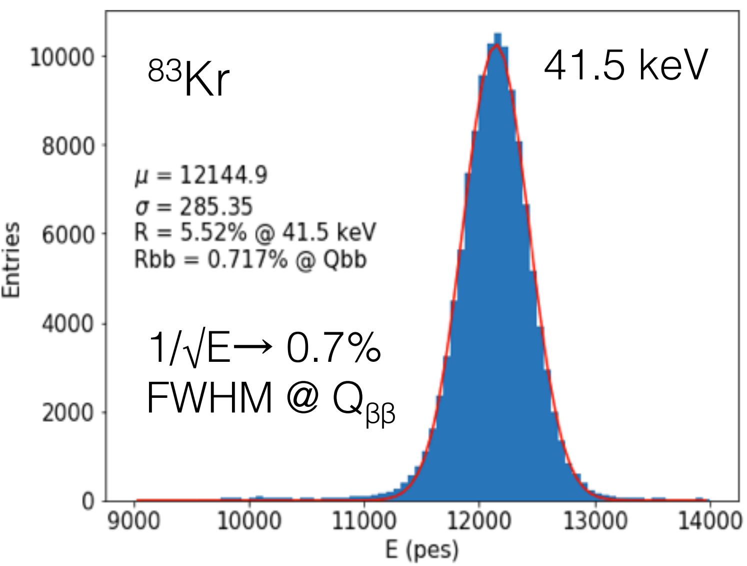
Underground & radio-pure operations, background, 2νββ

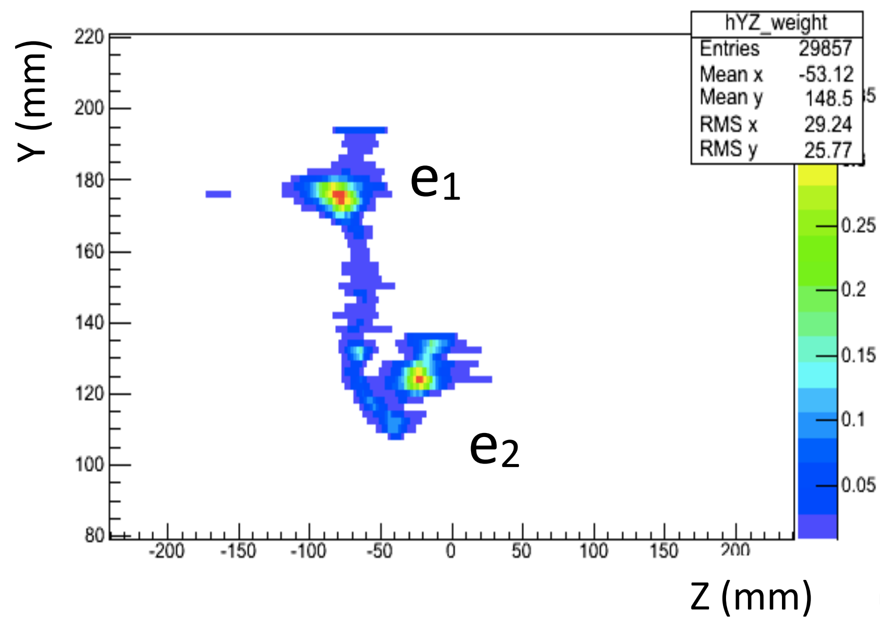
NEXT-100 (100 kg) 2018-2020's



0νββ search

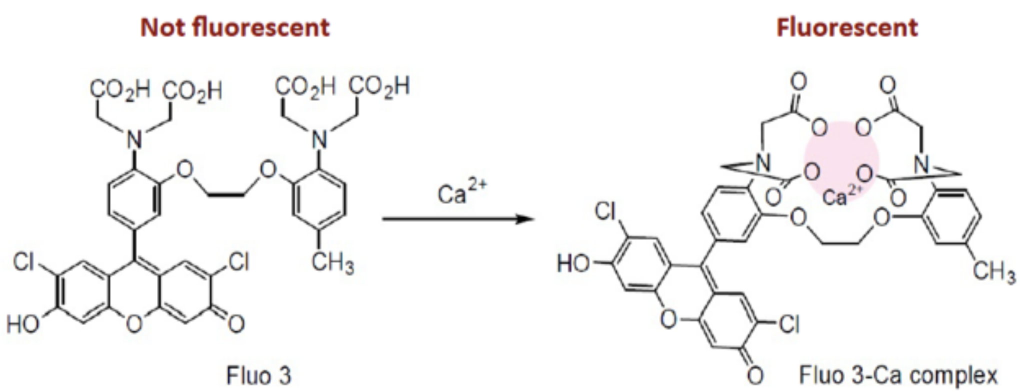
NEXT-ton

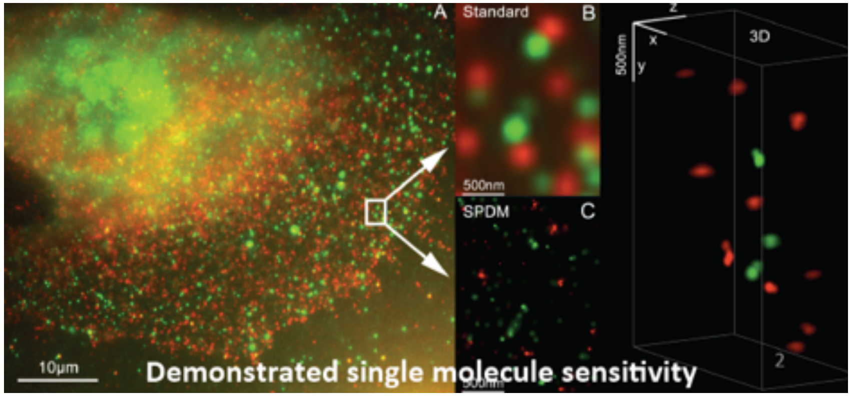


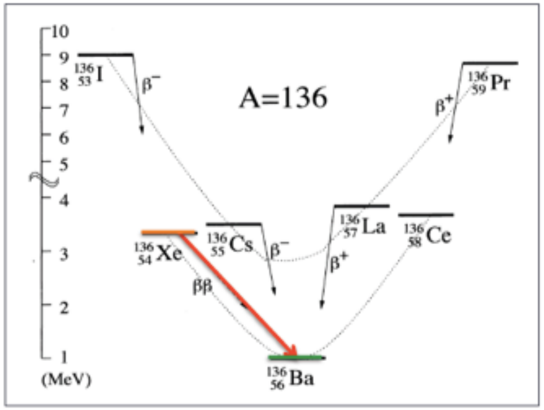


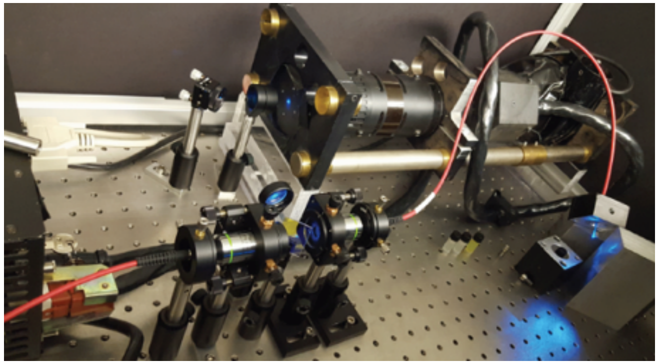
Courtesy JJ Gomez Cadenas

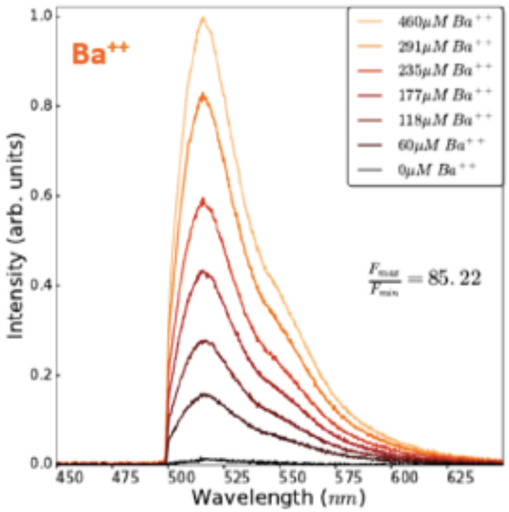
Ba tagging for NEXT





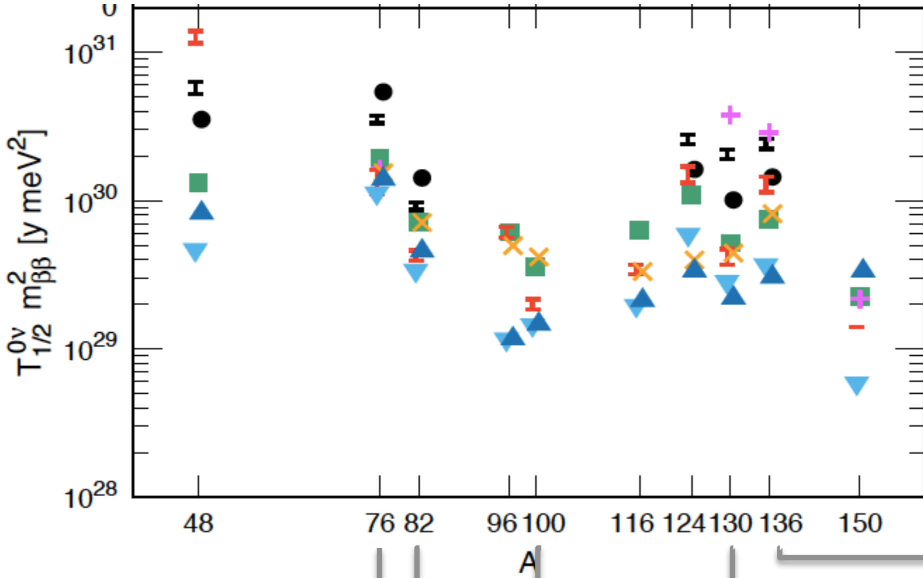






Courtesy Michel Sorel

Experiments



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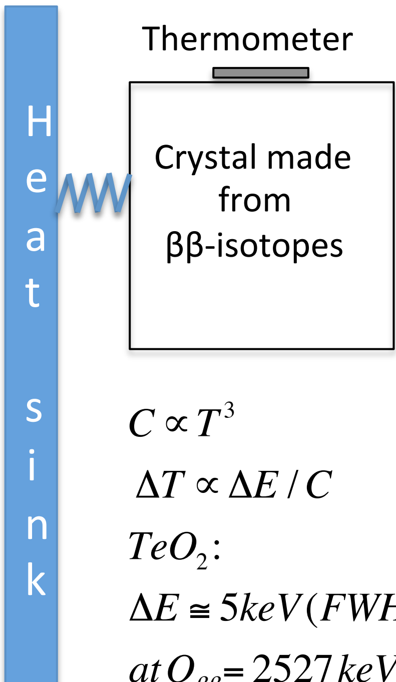
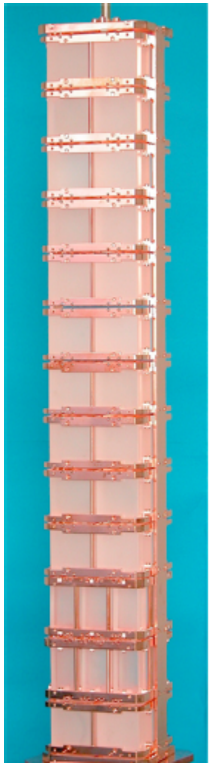
Cryogenic Detectors: CUORE

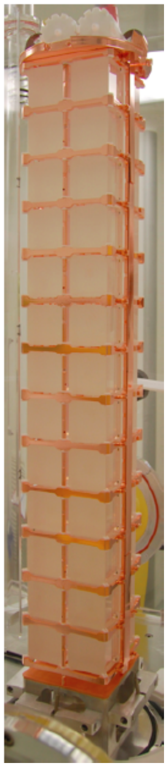


$$C \propto T^3$$
$$\Delta T \propto \Delta E / C$$
$$TeO_2:$$
$$\Delta E \cong 5keV(FWHM)$$
$$at\, Q_{\beta\beta} = 2527\, keV$$

Cuoricino
2003

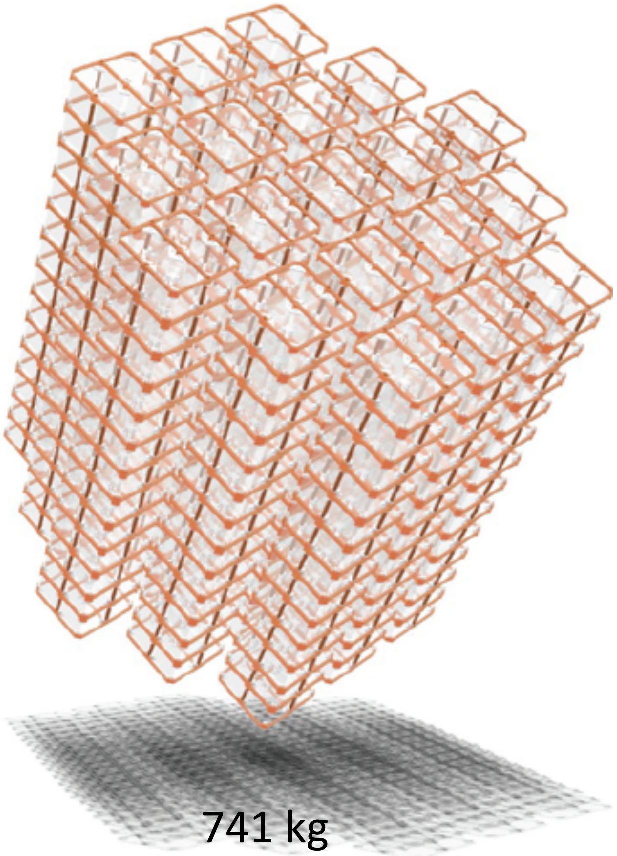


Cuore-0
2012



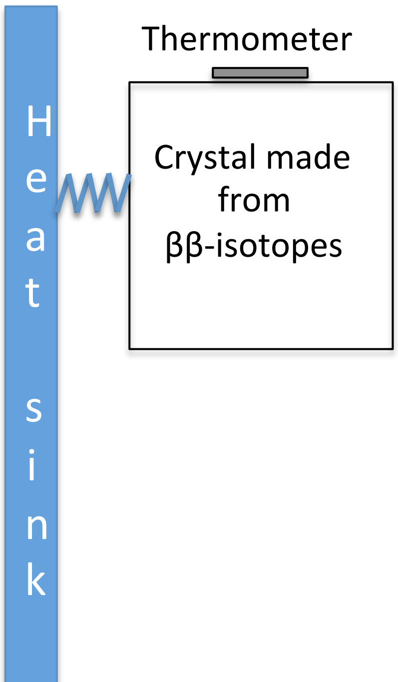
39 kg
(11 kg ^{130}Te)

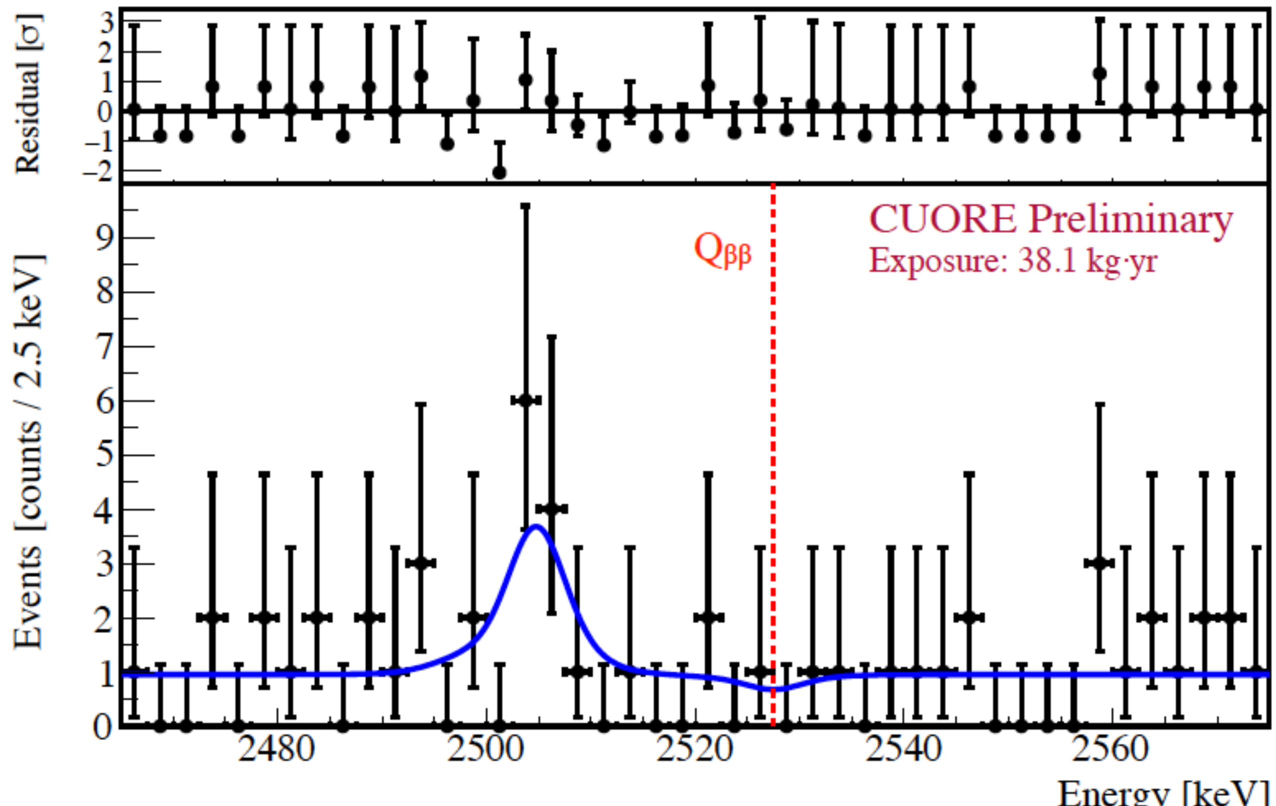
CUORE
2016



741 kg
(206 kg ^{130}Te)

Cryogenic Detectors: CUORE



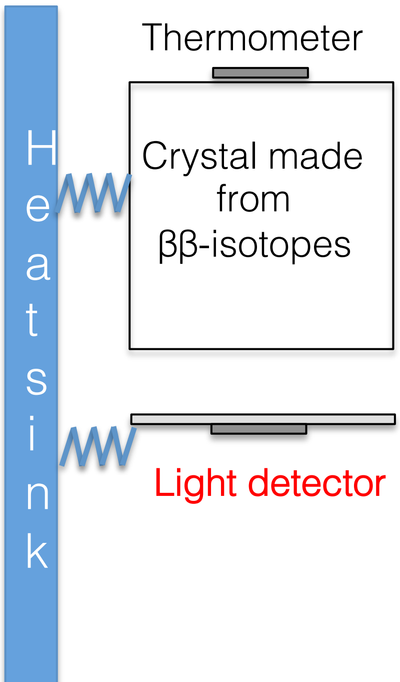


- ROI background index: **$(9.8_{-1.5}^{+1.7}) \times 10^{-3}$ c/(keV·kg·yr)**

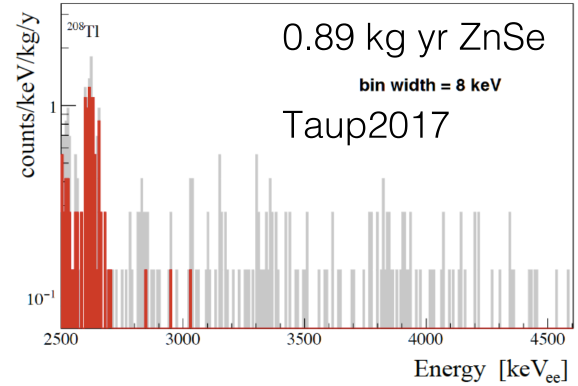
- Half-life limit (90% CL, including systematics): **4.5×10^{24} yr**
- Median expected sensitivity: **3.6×10^{24} yr (arXiv:1705.10816)**

O. Cremonesi, CNNP17

Cryogenic Detectors: CUPID

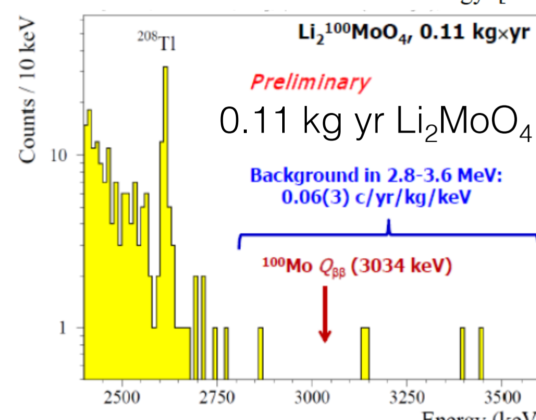


CUPID-0(Se): ZnSe
(ex Lucifer)
Demonstrator @ LNGS
5.2 kg ^{82}Se, 2017



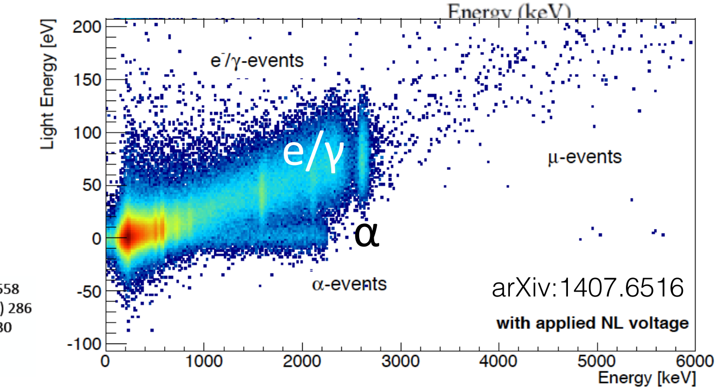
Courtesy
S. Pirro

CUPID-Mo: Li_2MoO_4
(ex Lumineu)
Demonstrator @ LSM
2.34 kg ^{100}Mo, 2018



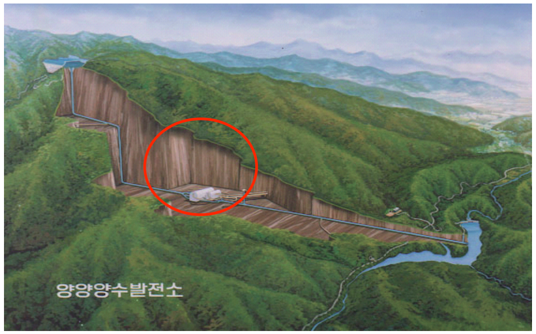
Courtesy
A. Giuliani

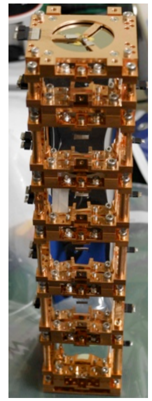
CUPID-Te: TeO_2
(with Cherenkov)
Demonstrator @ LNGS



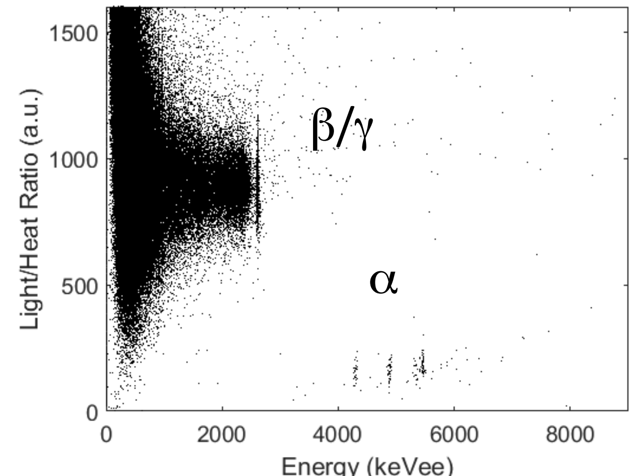
See also:
- J. W. Beeman, et al., Astropart. Phys. 35 (2012) 558
- L. Pattavina, et al., J. Low Temp. Phys. 184 (2016) 286
- K. Scha\¨ffner, et al., Astropart. Phys. 69 (2012) 30
- M. Willers, et al., JINST 10 (2015) P03003
- N.Casali,et al.,Eur. Phys. J. C 75 (12) (2015) 1

Cryogenic Detectors: AMoRE



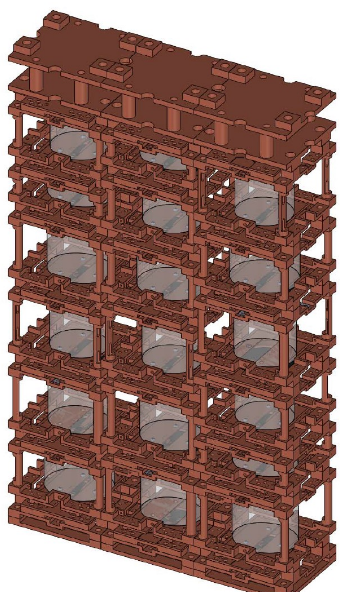


AMoRe-pilot project @ YangYang
6 crystals (1.8 kg)
$^{40}Ca^{100}MoO_4$

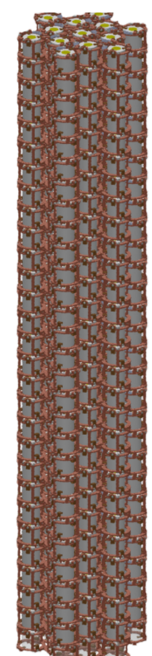


^{100}Mo procurement ongoing (100 kg)

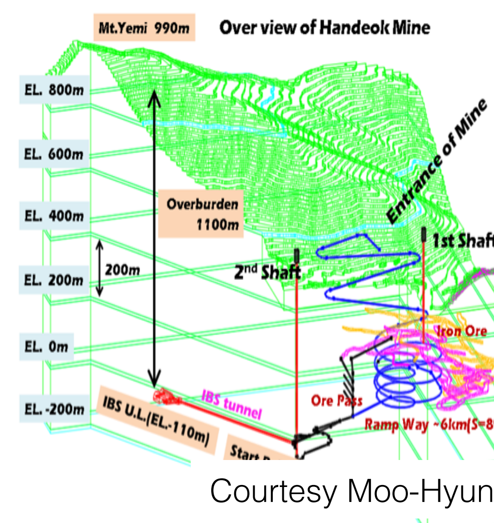
AMoRE-1
5 kg
2018



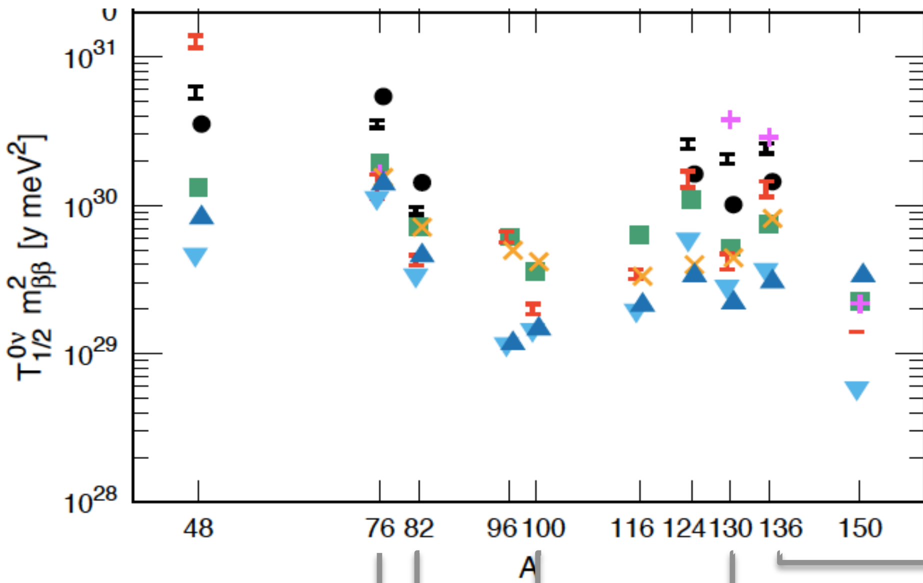
AMoRE-II
200 kg
2020



AMoRE @ Handeok ARF



Courtesy Moo-Hyun Lee



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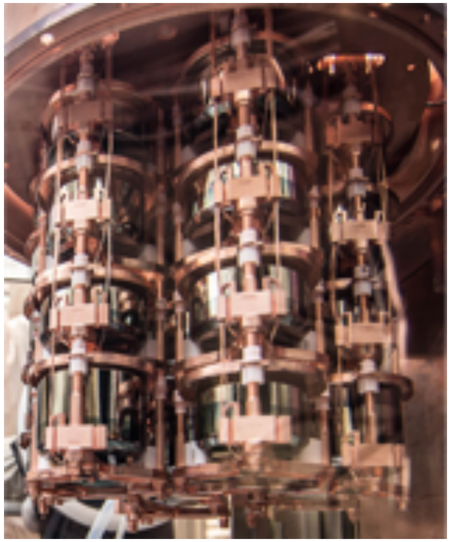
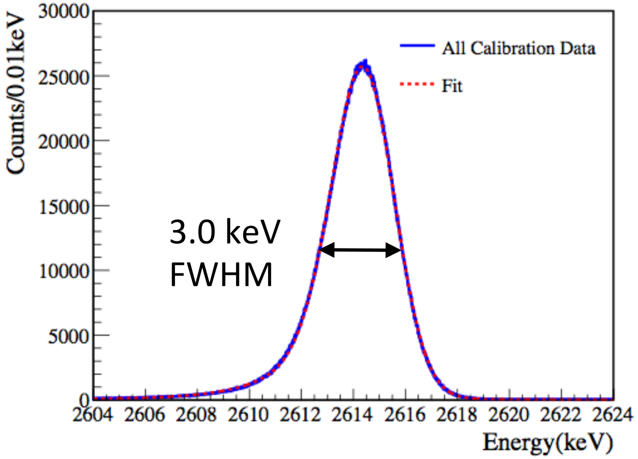
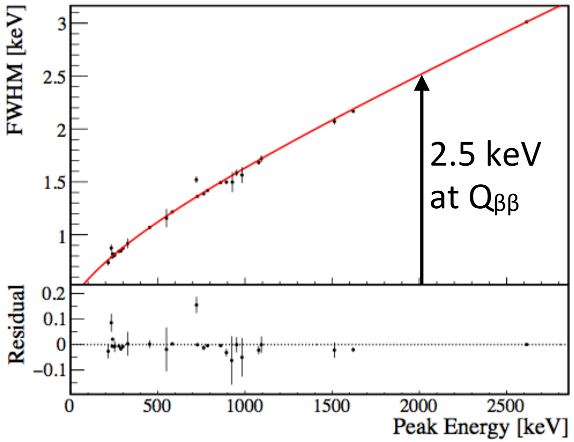
MAJORANA DEMONSTRATOR



^{208}Tl 2615 keV Peak



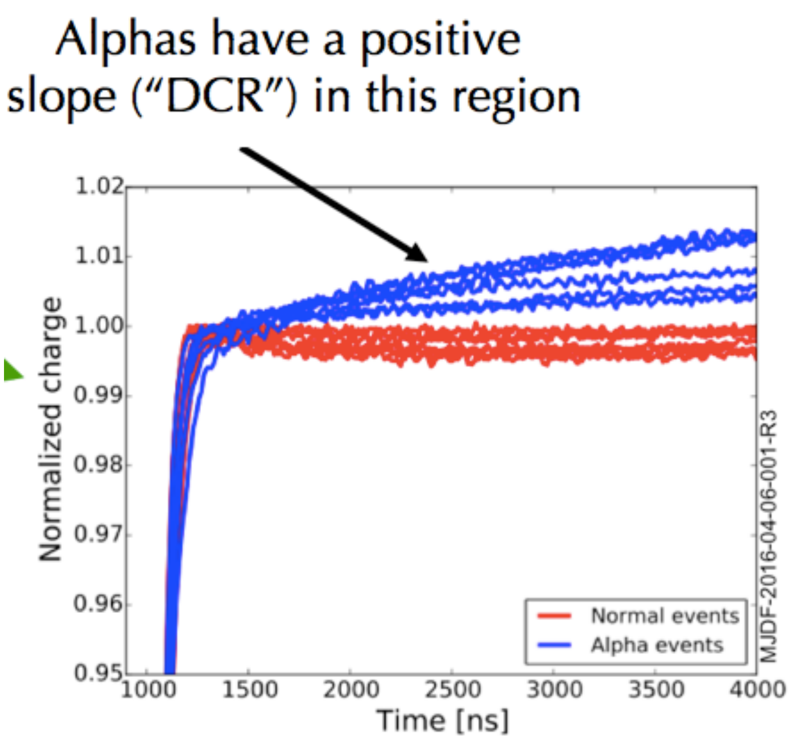
FWHM(E)

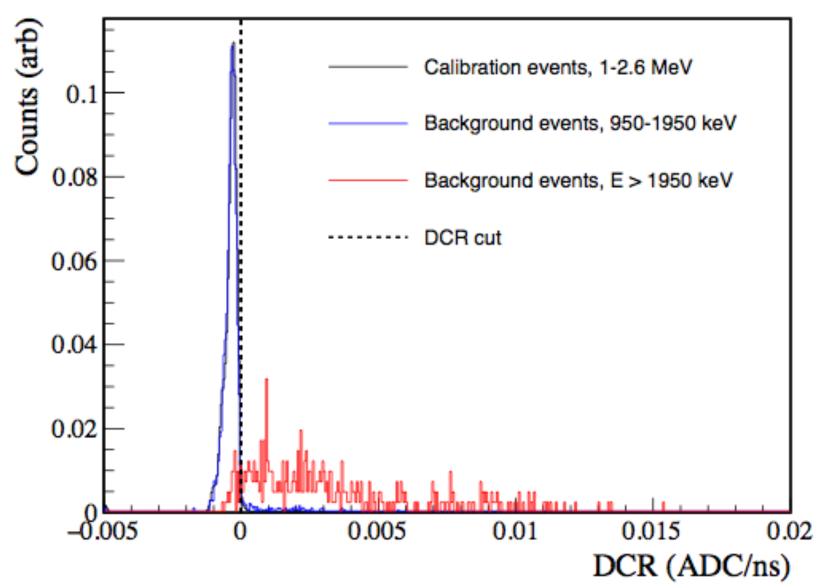


J. Detwiler, CNNP2017

MAJORANA: first background results

- Alpha background with degraded energies observed
- Charge trapped at passivated surface, slowly released into bulk
- Produces a distinctive waveform allowing a high-efficiency cut (99%)

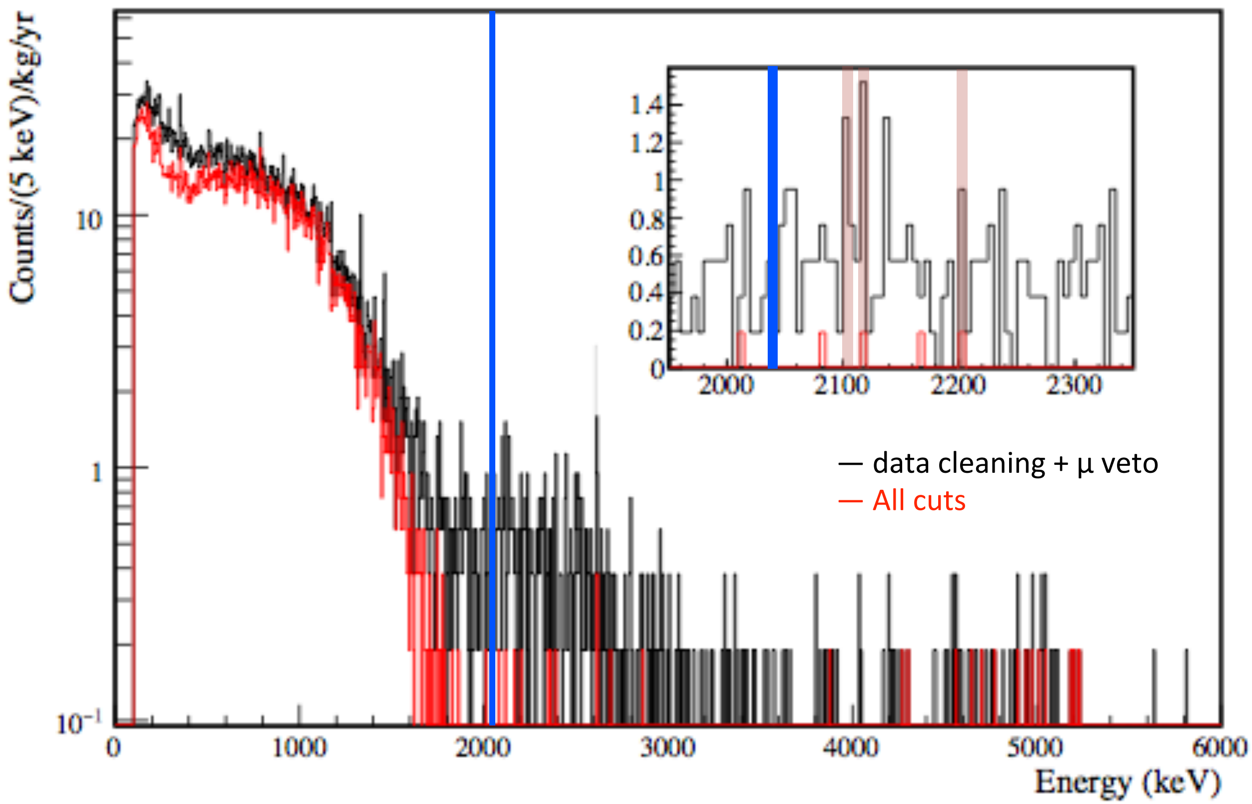




J. Detwiler, CNNP2017

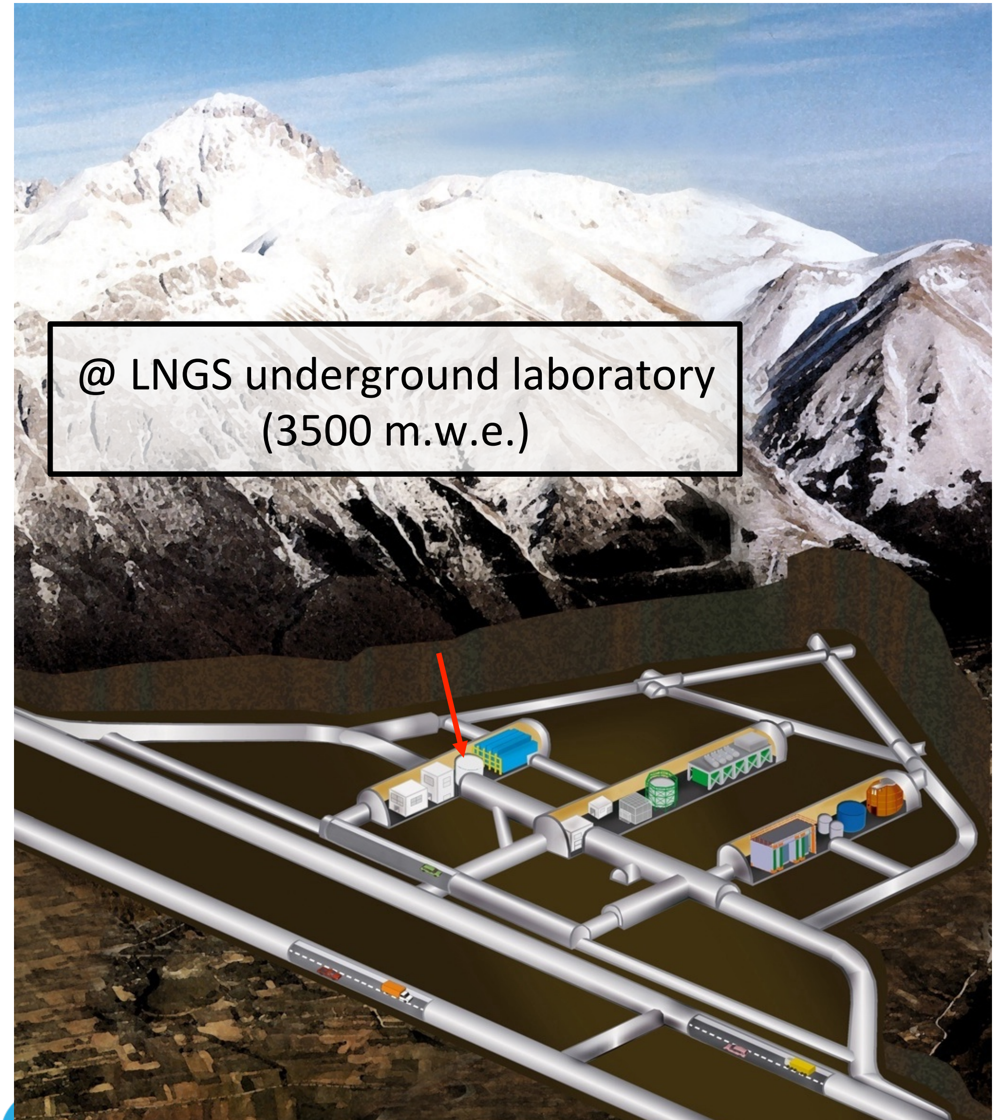
Majorana: first results on backgrounds

- Active Exposure: 5.29 kg y (^{enr}Ge)
- Background after cuts: 3 counts in 360 keV window
- Background rate: $4.0^{+3.0}_{-2.5}$ c/(FWHM t y), $1.6^{+1.2}_{-1.0}$ c/(keV t y)

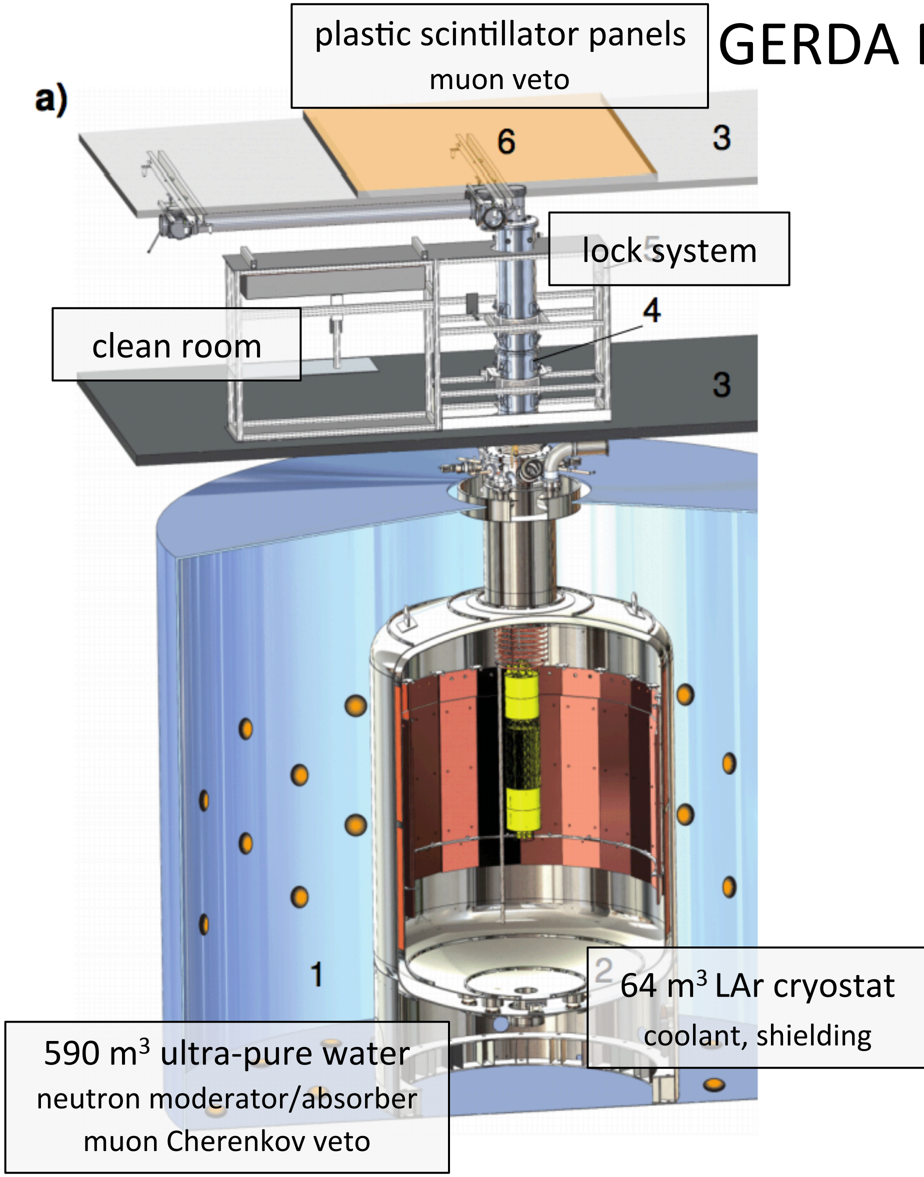


J. Detwiler, CNNP2017

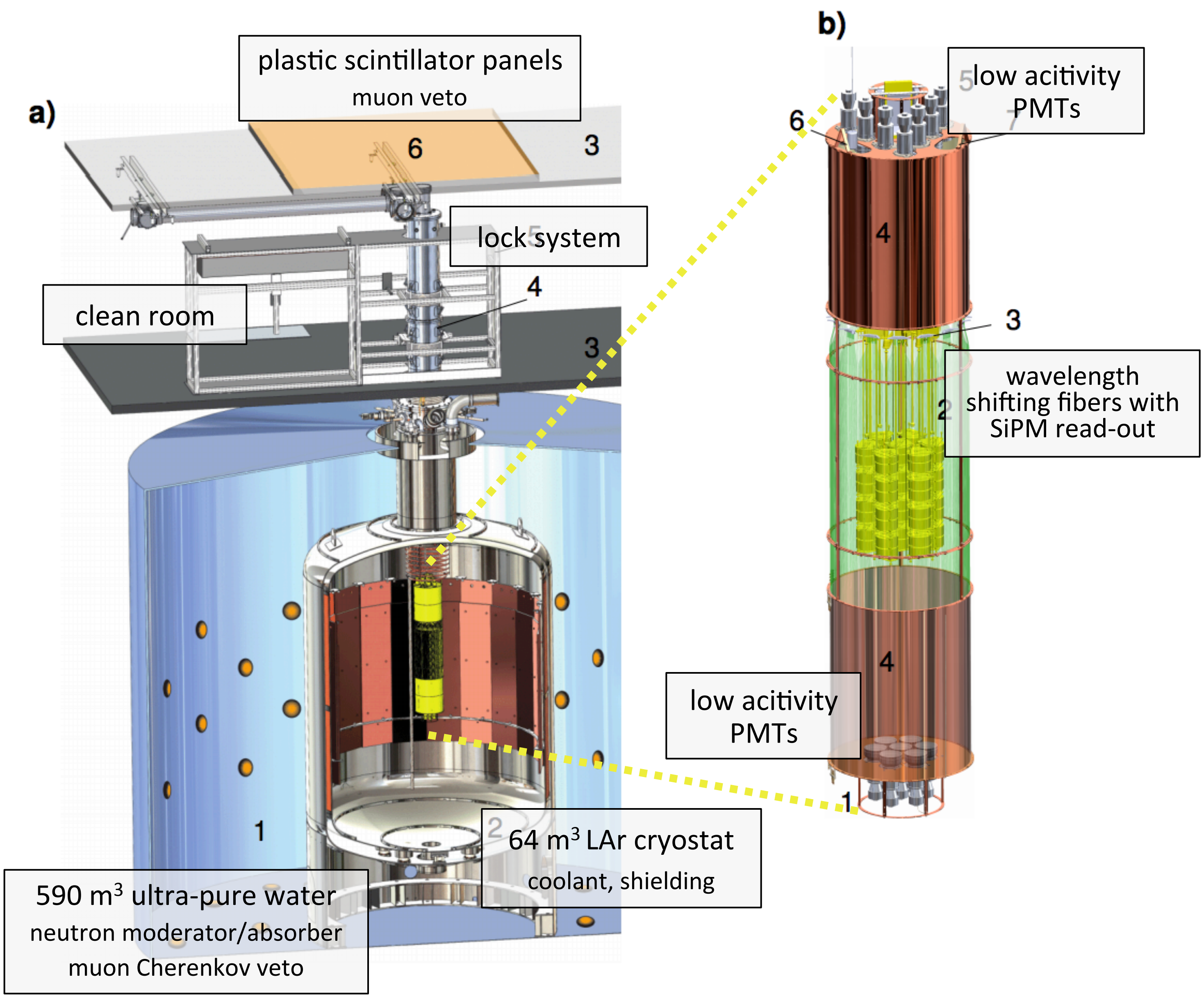
GERDA Phase II experimental setup at LNGS



GERDA Phase II experimental setup at LNGS

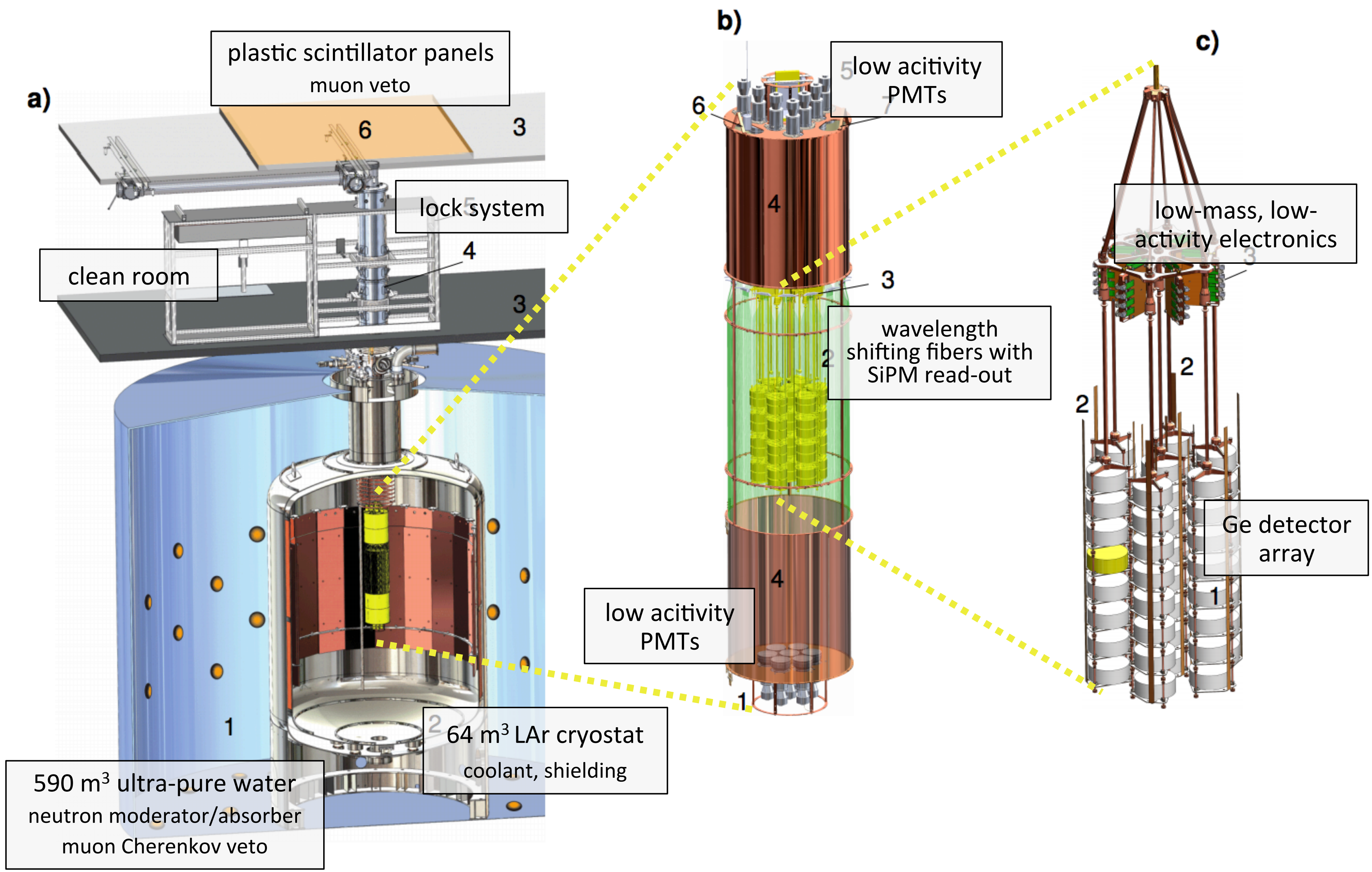


a) overview



a) overview

b) liquid argon (LAr) veto instrumentation

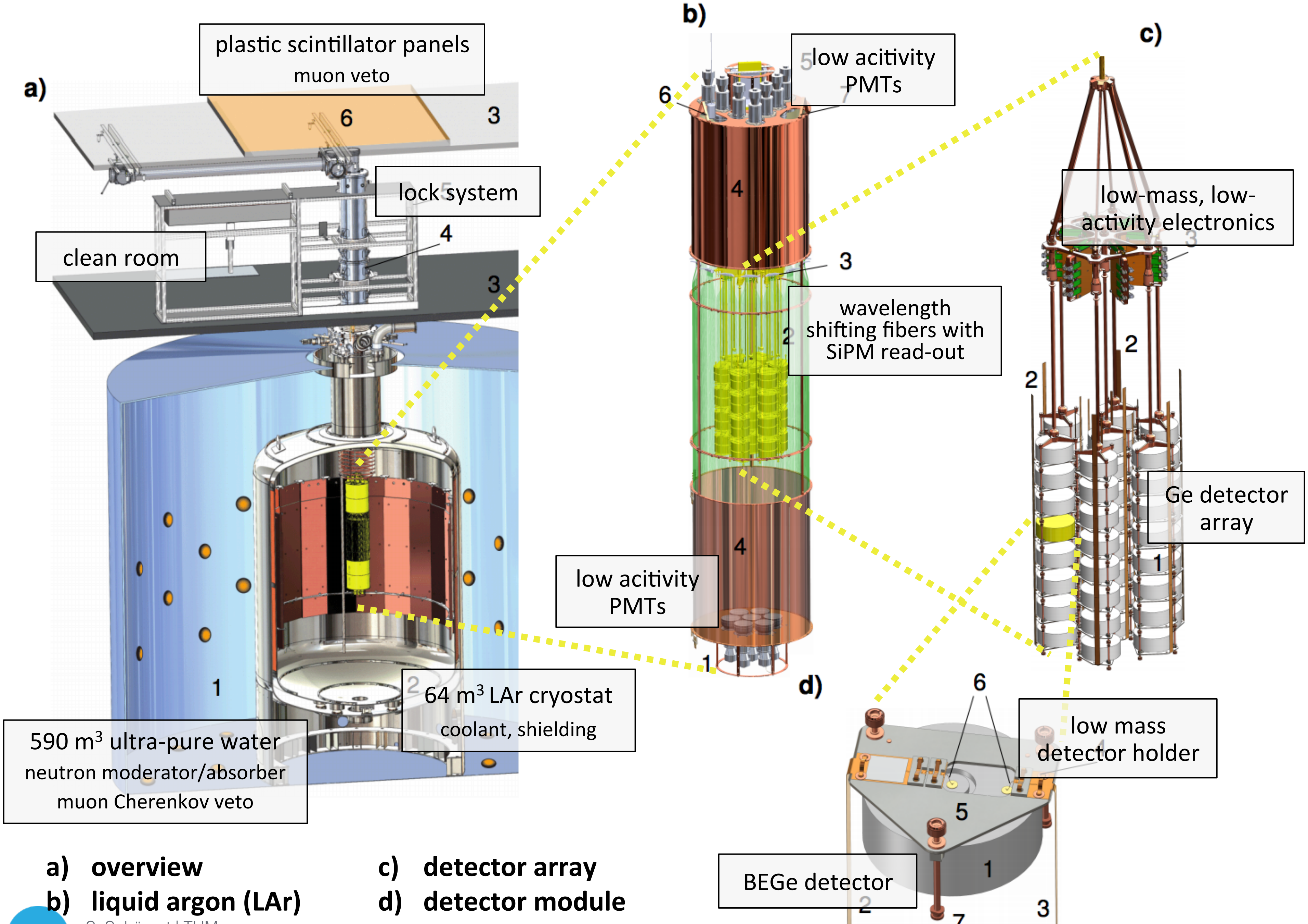


a) overview

veto instrumentation

b) liquid argon (LAr)

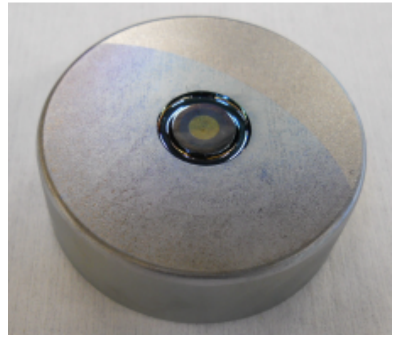
c) detector array



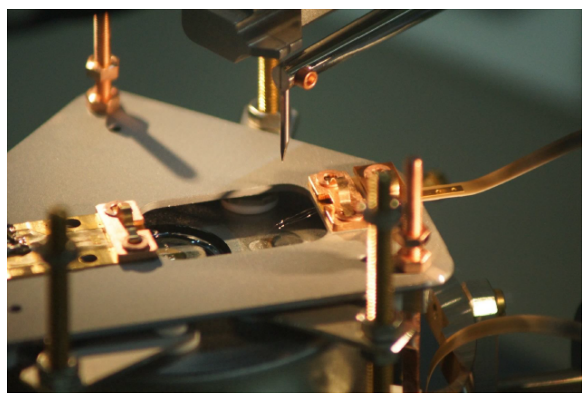
a) overview
b) liquid argon (LAr) veto instrumentation
c) detector array
d) detector module

GERDA Phase II experimental setup at LNGS

New low-mass detector holder (silicon, copper, PTFE)



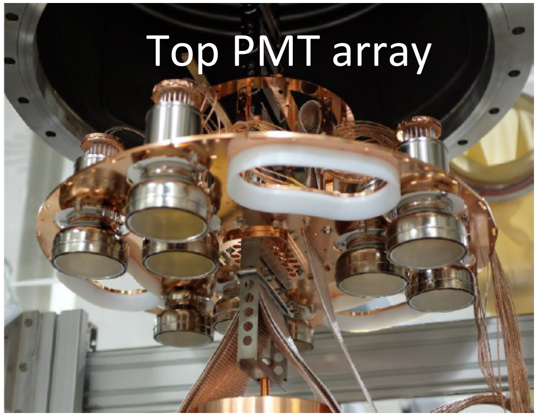
New thick-window BEGe detectors

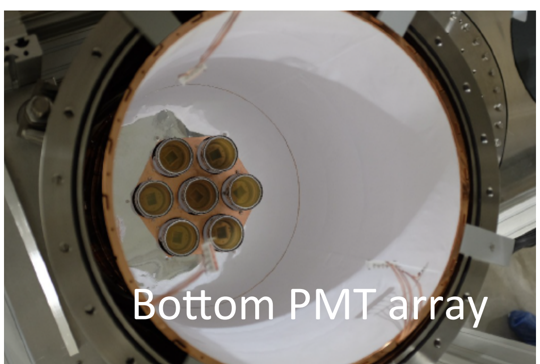


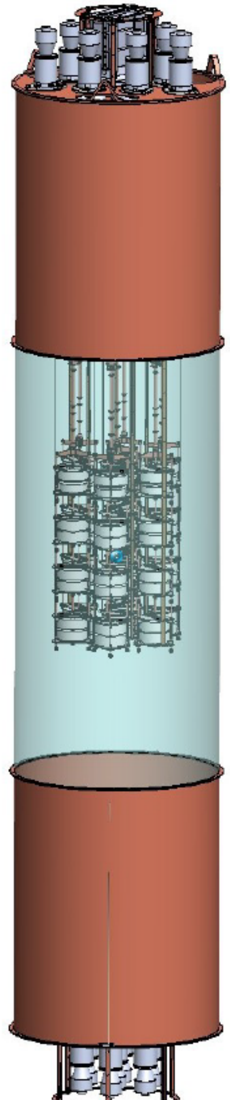
New signal and HV contacting by wire bonding flat ribbon cables

New TBP coated nylon mini-shrouds to reduce attraction K42 ions to n+ surface

Liquid argon instrumentation to identify backgrounds

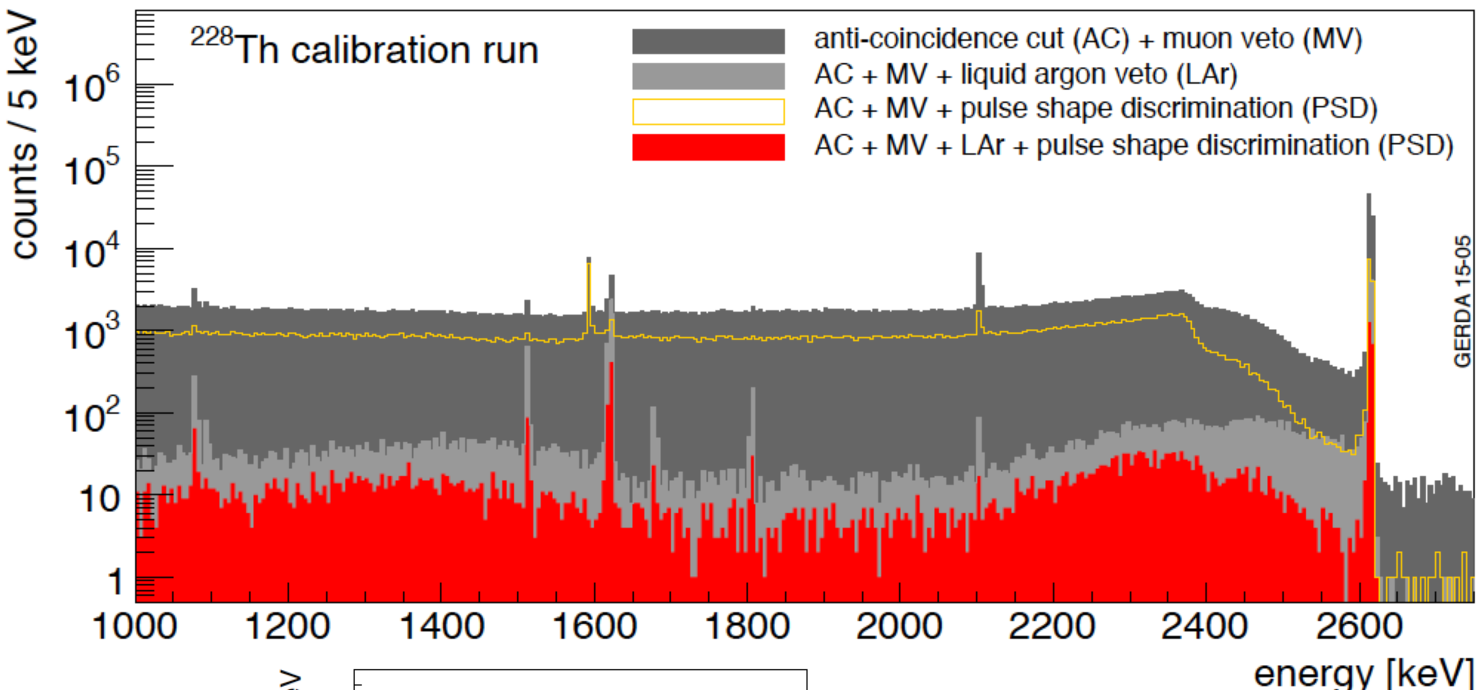


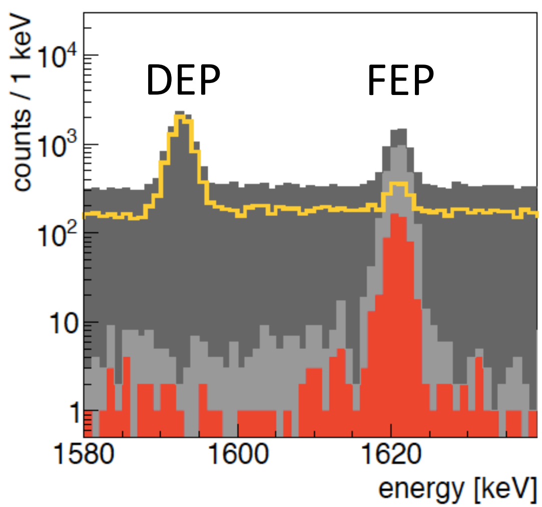




- Event rejection: >0.5 p.e. in any of SiPM or PMT channel (within 5μs of Ge trigger)
- Accidentals (dead time): 2.3±0.1% (Ar-39)

Background suppression (calibration data)

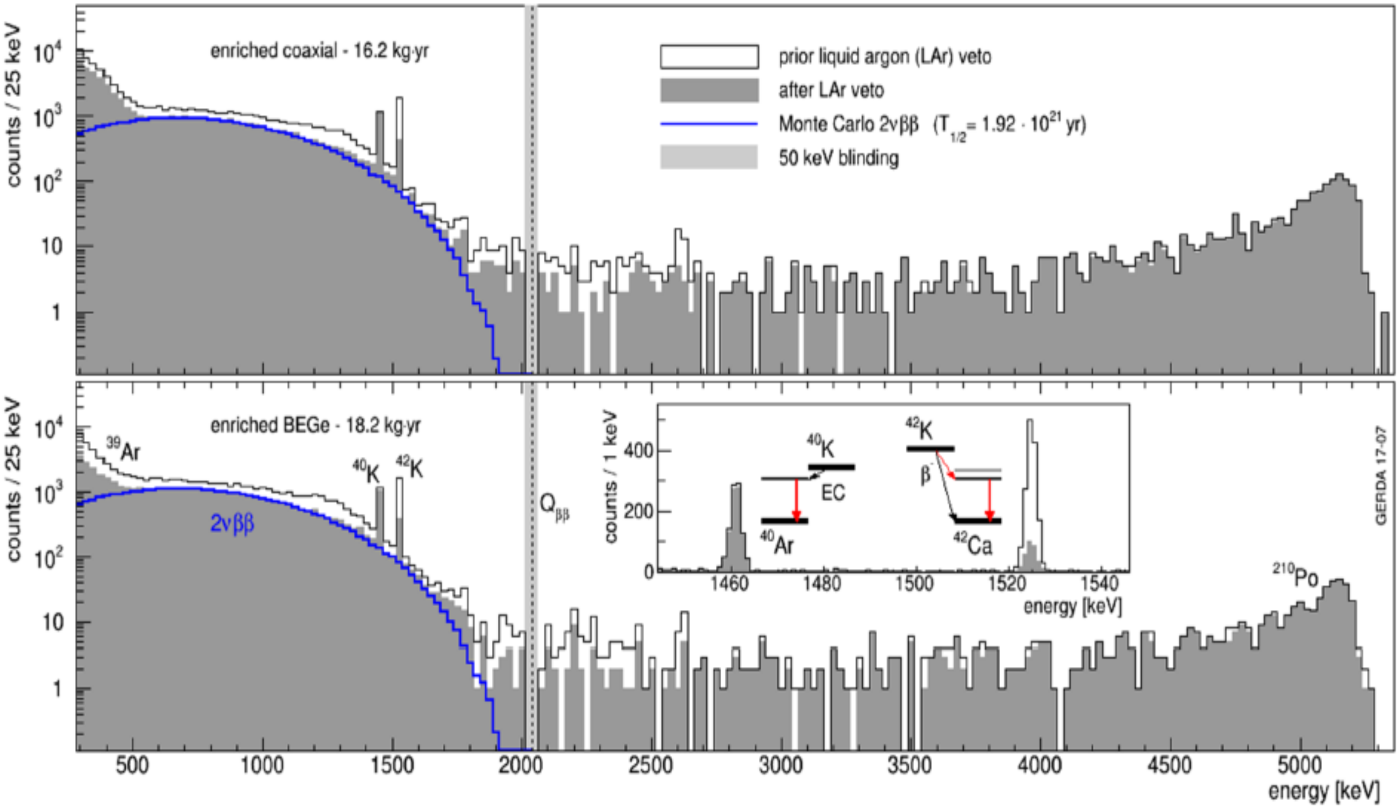




<u>Background suppression by</u>

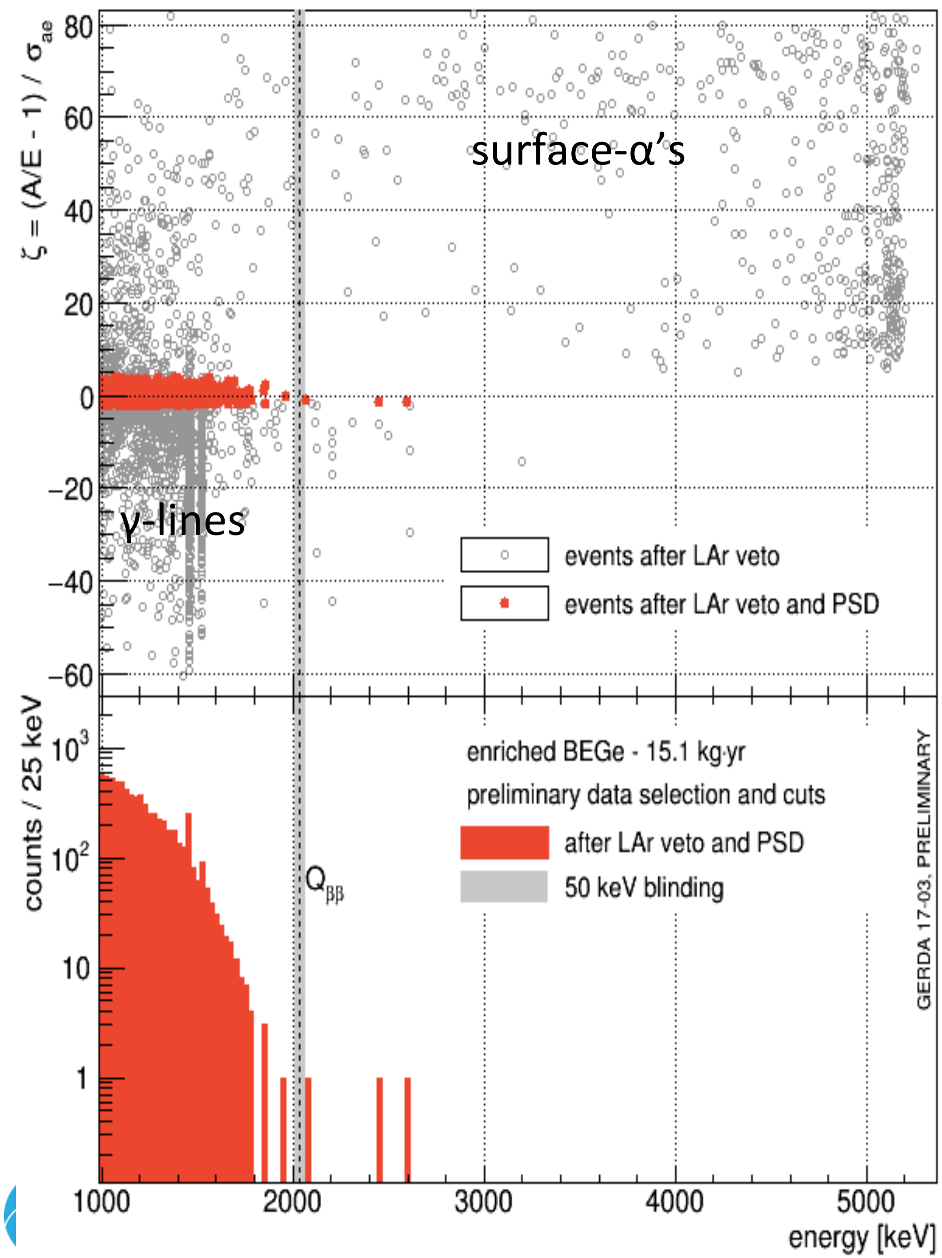
- Muon veto (MV)
- Anti-coincidence detector array (AC)
- Liquid argon veto (LAr)
- Pulse shape discrimination (PSD)

GERDA spectra



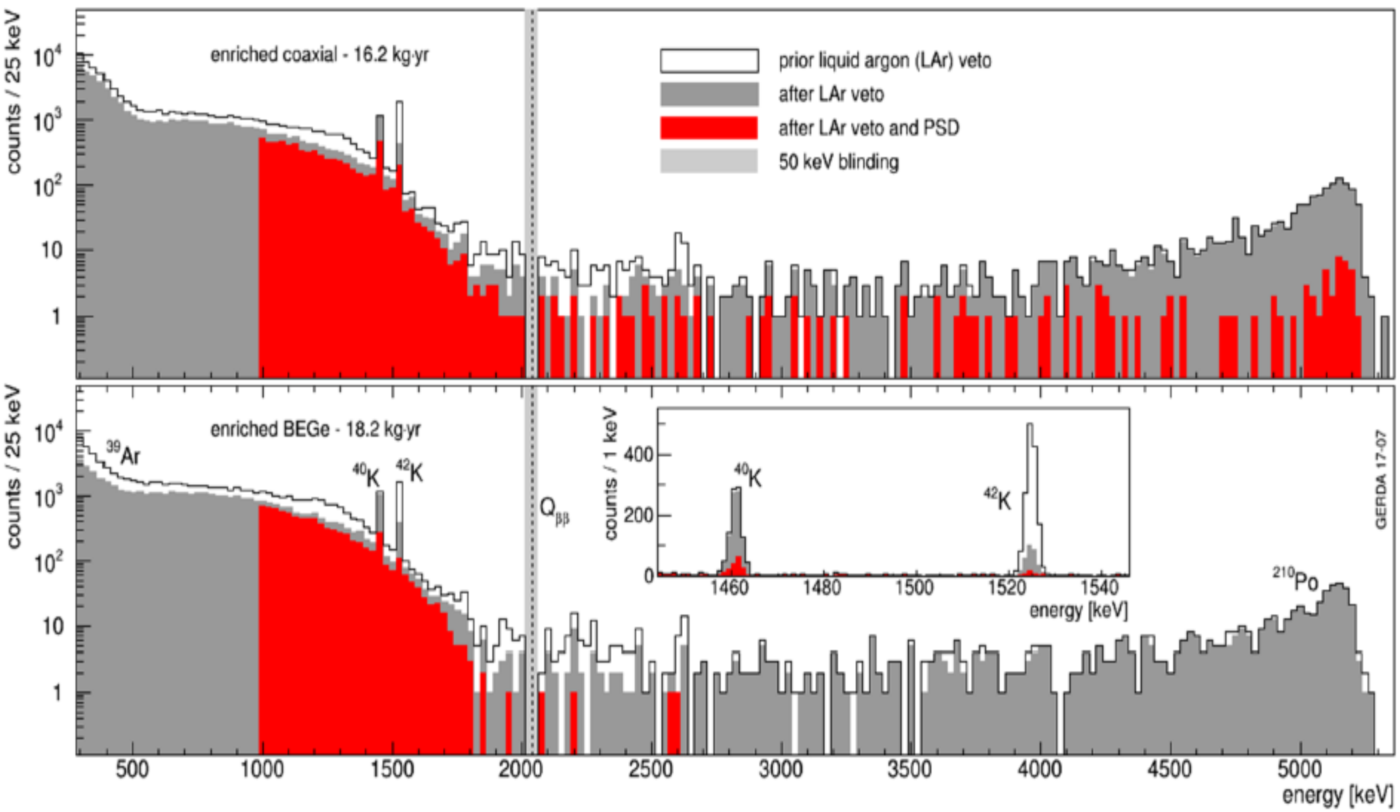
- Most prominent features: ^{39}Ar β (< 500 keV), 2νββ, ^{42}K and ^{40}K γ-rays, α

GERDA: BEGe pulse shape spectra



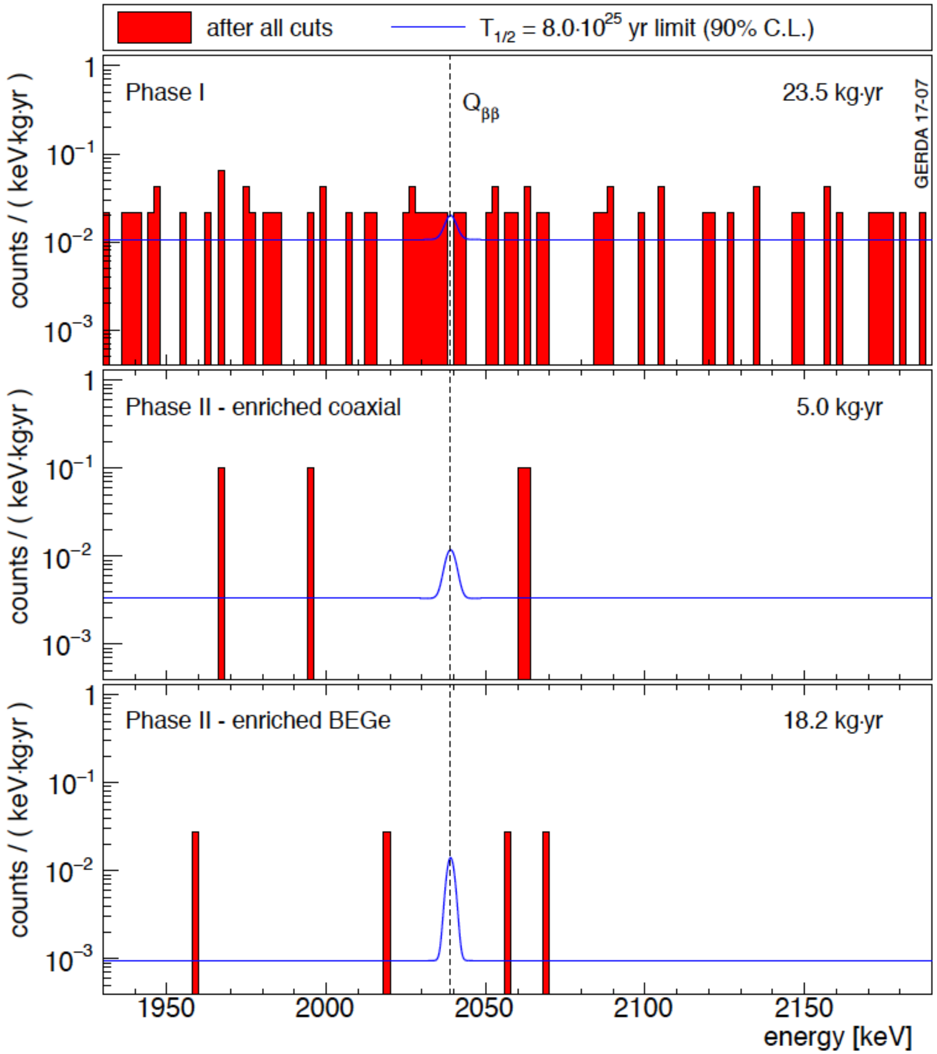
- Mono-parametric cut based on current pulse amplitude *A* and total energy *E*
- Tuned by calibration data DEP of 2615 keV
- Efficiencies:
  - DEP: (87.3±0.2±0.8)%
  - 2νββ: (85.4±0.8±1.7)%
  - 0νββ: (87±2)%
- All surface α's removed
- γ-lines factor 6 suppressed

GERDA spectra



- Most prominent features: ^{39}Ar β (< 500 keV), 2νββ, ^{42}K and ^{40}K γ-rays, α
- PSD clears completely the α region
- LAr and PSD **complementary**
- Final background at $Q_{\beta\beta}$ O(10^{-3} cts/(keV kg yr))

GERDA:



BI: $1.0^{+0.6}_{-0.4} \times 10^{-3}$ cts /(keV kg yr) for enr BEGe's

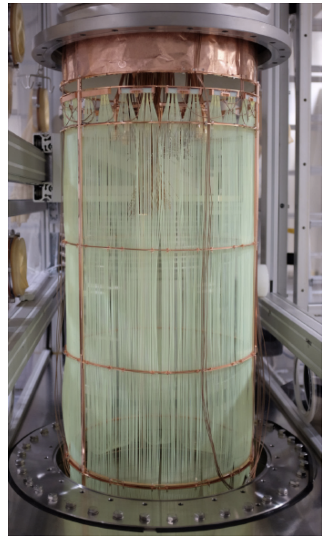
$T_{1/2}^{0\nu} > 8.0 \times 10^{25}$ yr (90% C.L.)
Sensitivity:
$T_{1/2}^{0\nu} > 5.8 \times 10^{25}$ yr

L. Pandola, Taup2017

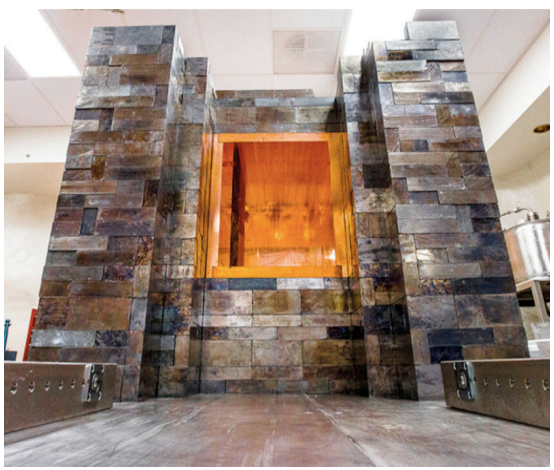
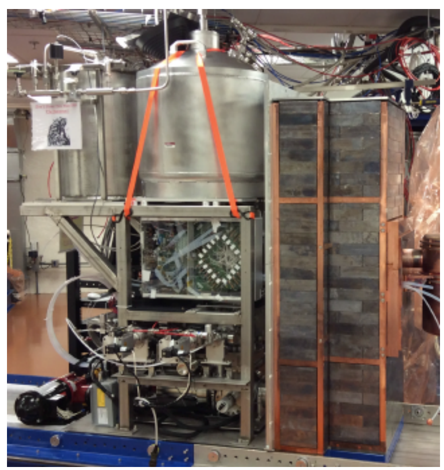
"**Background free search** for neutrinoless double-β decay with GERDA"

The ^{76}Ge future: LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

GERDA
Bare ^{enr}Ge detectors immersed in instrumented LAr shield

MAJORANA DEMONSTRATOR
^{enr}Ge detectors operated in vacuum cryostats in a passive graded shield with ultra-clean copper

LEGEND the collaboration

Univ. New Mexico
L'Aquila Univ. and INFN
Gran Sasso Science Inst.
Lab. Naz. Gran Sasso
Univ. Texas
Tsinghua Univ.
Lawrence Berkeley Natl. Lab.
Leibniz Inst. Crystal Growth
Comenius Univ.
Lab. Naz. Sud
Univ. of North Carolina
Sichuan Univ.
Univ. of South Carolina
Jagiellonian Univ.
Banaras Hindu Univ.
Univ. of Dortmund
Tech. Univ. – Dresden
Joint Inst. Nucl. Res. Inst.
Nucl. Res. Russian Acad. Sci.
Joint Res. Centre, Geel

47 Institutions
219 scientists

Collaboration formed
1st Munich April 2016
2nd Atlanta October 2016
3rd LNGS May 2017
4th Berkeley Dec 2017

Chalmers Univ. Tech.
Max Planck Inst., Heidelberg
Dokuz Eylul Univ
Queens Univ.

Univ. Tennessee
Argonne Natl. lab.
Univ. Liverpool
Univ. College London

Los Alamos Natl. Lab.
Lund Univ.
INFN Milano Bicocca
Milano Univ. and Milano INFN
Natl. Res. Center Kurchatov Inst.
Lab. for Exper. Nucl. Phy. MEPhI
Max Planck Inst., Munich
Technical Univ. Munich
Oak Ridge Natl. Lab.
Padova Univ. and Padova INFN
Czech Tech. Univ. Prague
Princeton Univ.
North Carolina State Univ.
South Dakota School Mines Tech.
Univ. Washington
Academia Sinica
Univ. Tuebingen
Univ. South Dakota
Univ. Zurich

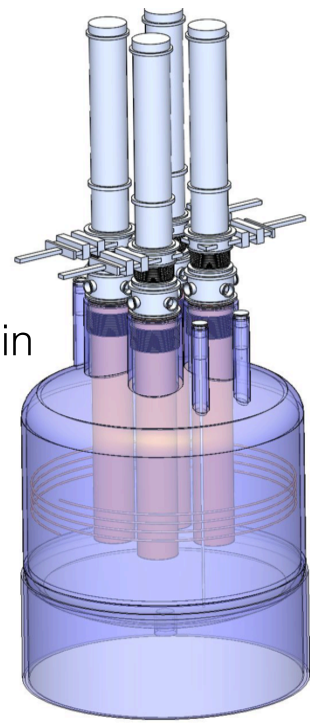
LEGEND program

LEGEND-200 (first phase):

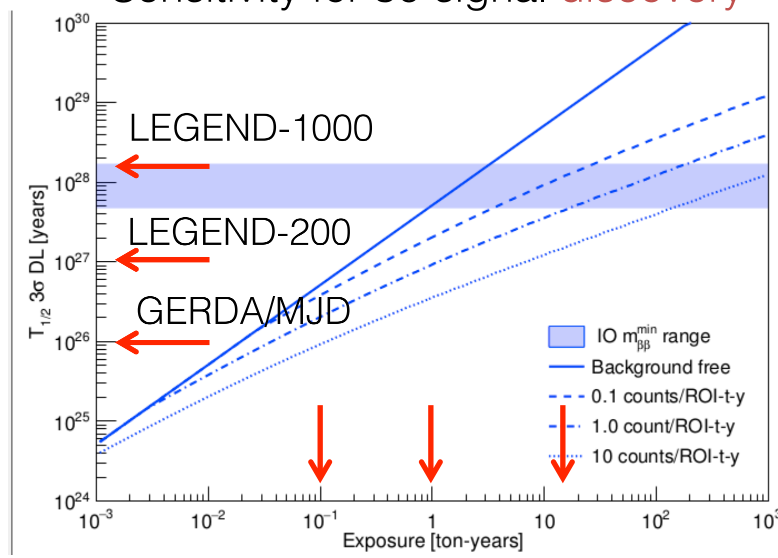
- up to 200 kg of detectors
- BI ~0.6 cts/(FWHM·t·yr)
- use existing GERDA infrastructure at LNGS
- design exposure: 1 t·yr
- Sensitivity 10^{27} yr

LEGEND-1000 (second phase):

- 1000 kg of detectors (deployed in stages)
- BI <0.1 cts/(FWHM·t·yr)
- Location tbd
- Design exposure 12 t·yr
- $1.2 \cdot 10^{28}$ yr



Sensitivity for 3σ signal discovery



17 meV discovery sensitivity for "worst case" NME of 3.5

Summary & Outlook

- Strong activities world-wide for preparation of **ton-scale** experiments
- Search for **LFNV**
- **Very high discovery** potential for IO
- **Reasonable high discovery** potential also for NO (assuming absence of mechanism driving $m_{\beta\beta}$ or m_l to zero)
- **Several DBD isotopes** and techniques required, given NME uncertainties and low signal rates
- Formidable **experimental challenges** to acquire ton yr exposure quasi **background free**
- Community now ready to move to **ton-scale experiments** with **reasonable extrapolations** w.r. to detector performance and background reduction
- **Staging** adopted where possible to produce physics results & minimize (project) risks
- Experimental design for **discovery** (not limit setting!)