Neutrinoless double beta decay

Stefan Schönert | TU München

25th Anniversary of the Rencontres du Vietnam
Windows to the Universe

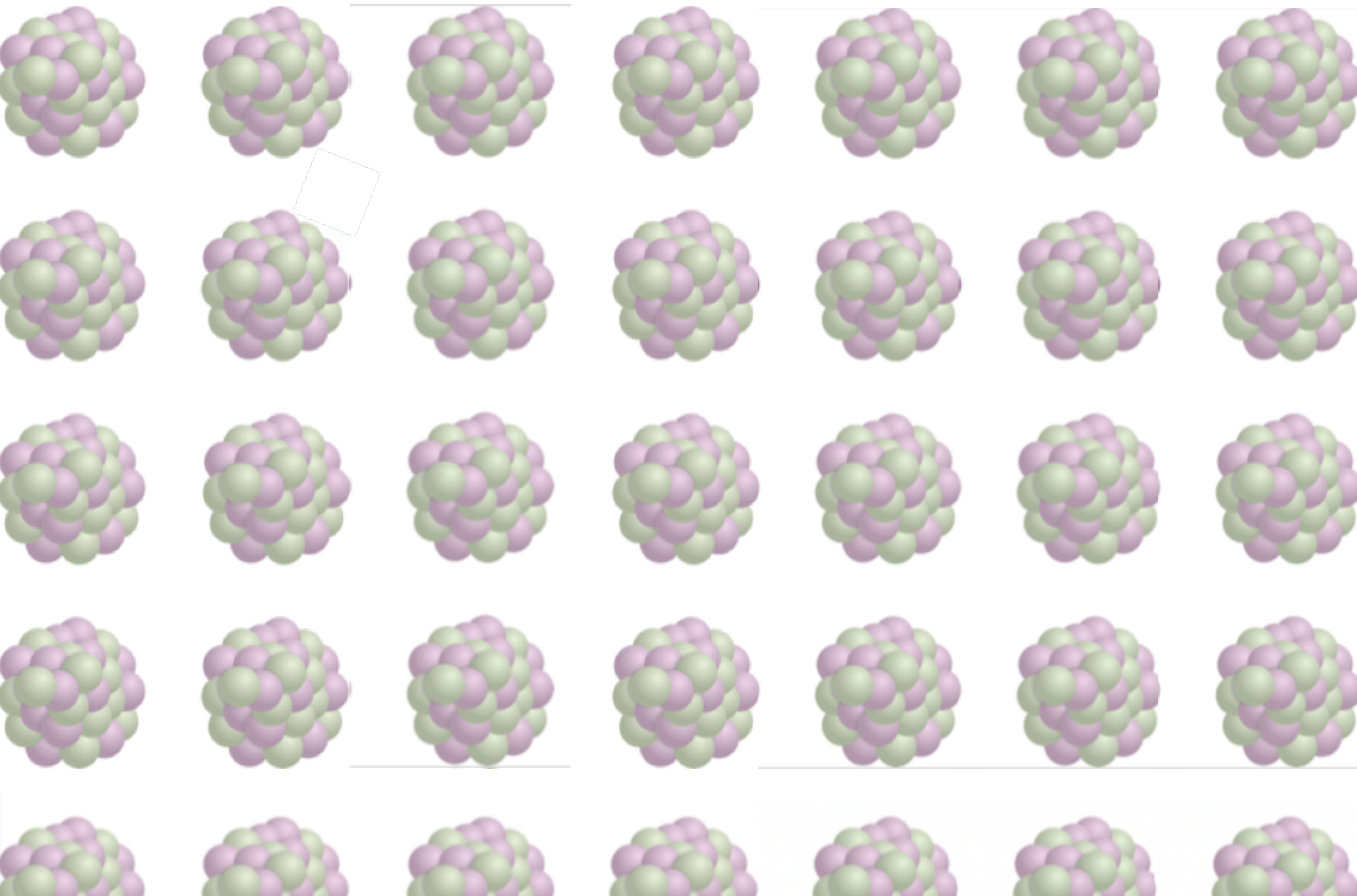
6-11 August 2018
ICISE, Quy Nhon, Vietnam

TECHNISCHE UNIVERSITÄT MÜNCHEN

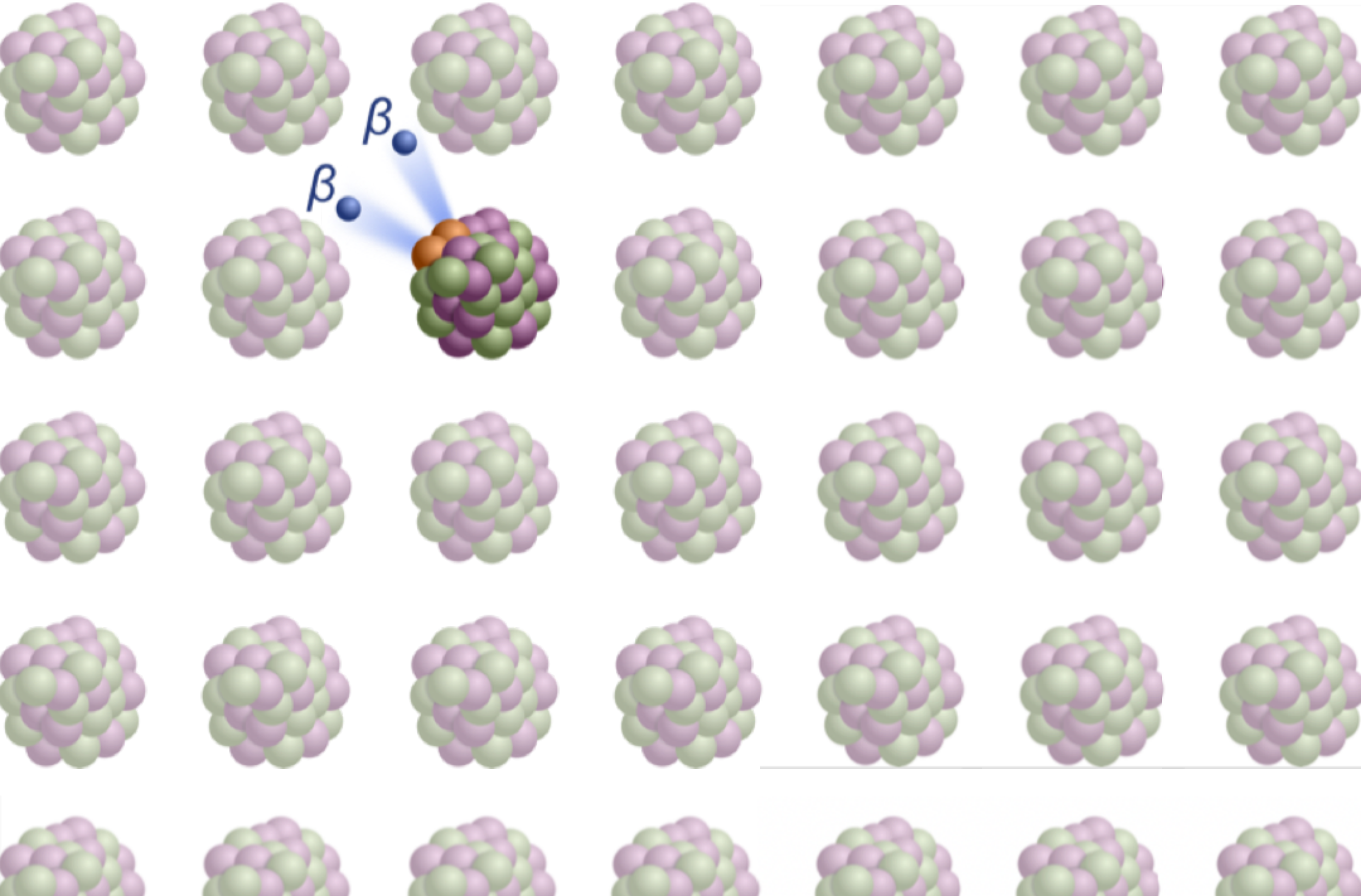
SFB 1258 | Neutrinos Dark Matter Messengers

du Vietnam

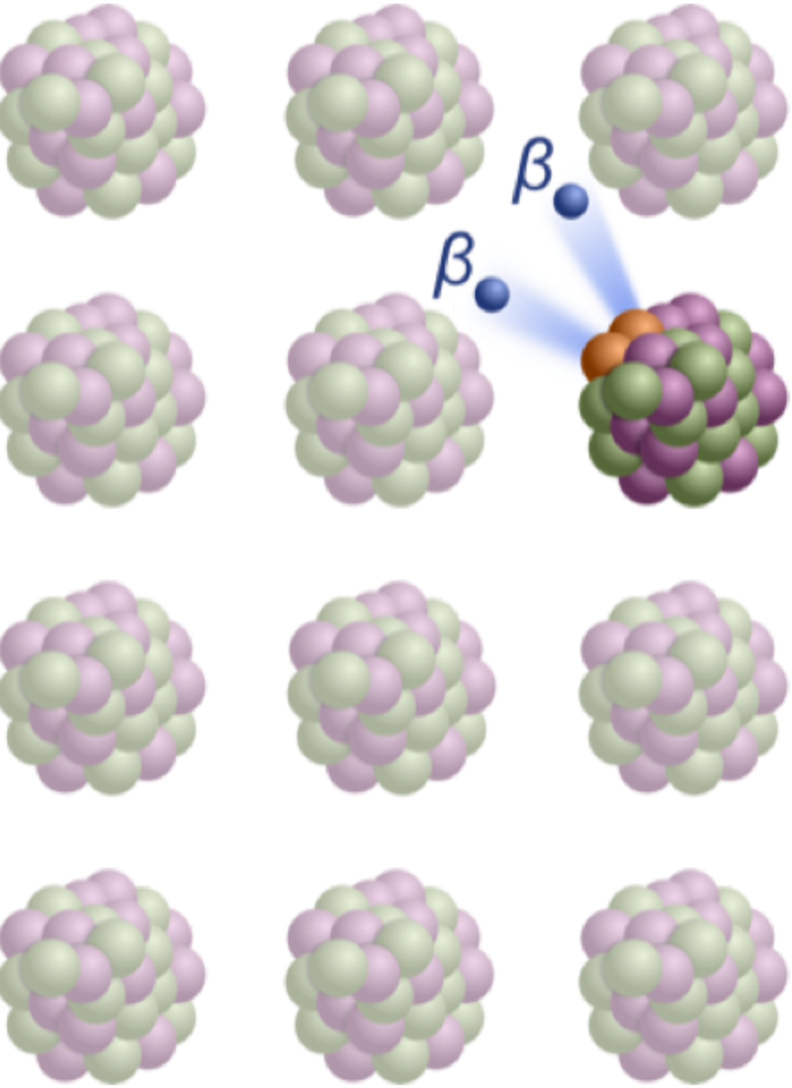
0νββ decay



0νββ decay

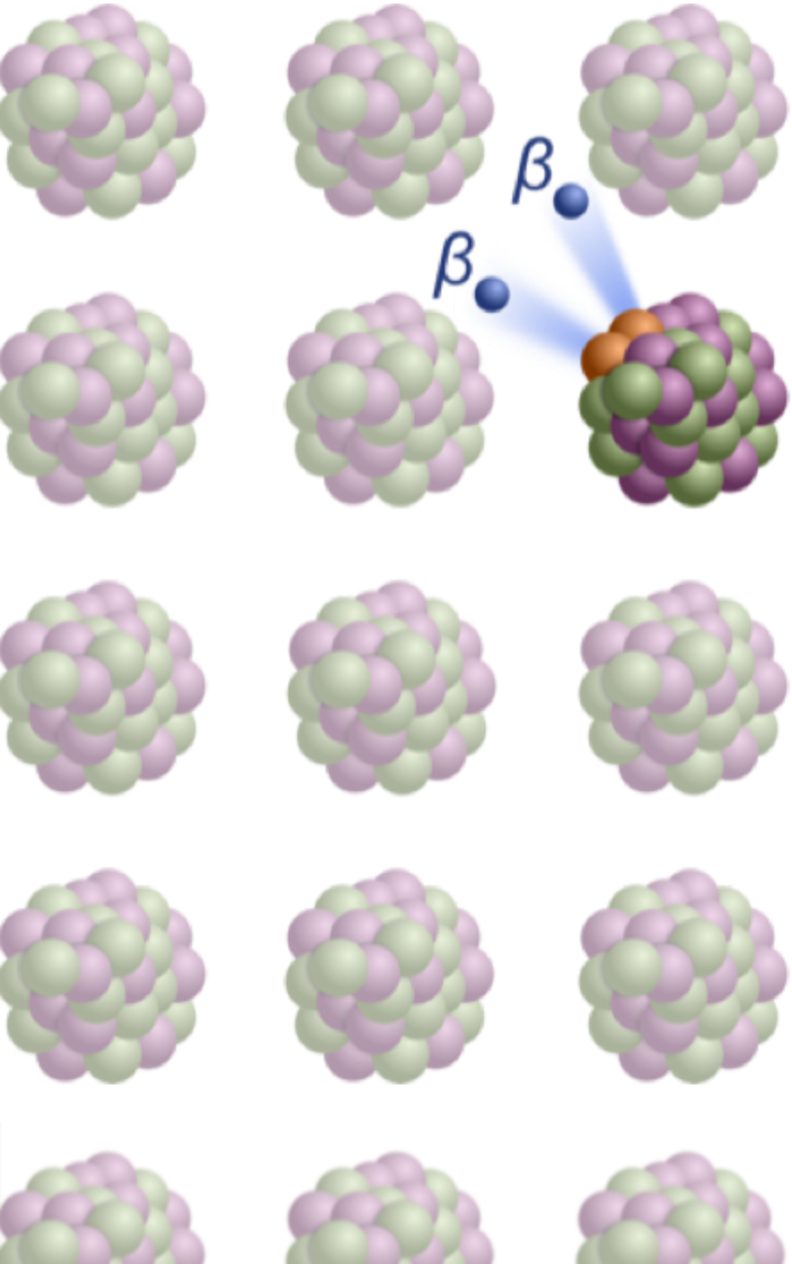


$0\nu\beta\beta$ decay



- Creation of matter without balancing emission of anti-matter (Vissani)
- $(A,Z)\rightarrow(A,Z+2) + 2e^-$
- Lepton number violating process ($\Delta L=2$)
- Majorana neutrinos generate $0\nu\beta\beta$
- Majorana neutrinos would explain small neutrino masses (See-Saw)
- Key ingredient for explanation of matter-antimatter asymmetry
- In general: $\Delta L=2$ (BSM) operators can generate $0\nu\beta\beta$
- Discovery of $0\nu\beta\beta$ always imply new

0νββ decay



Current best sensitivity:

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

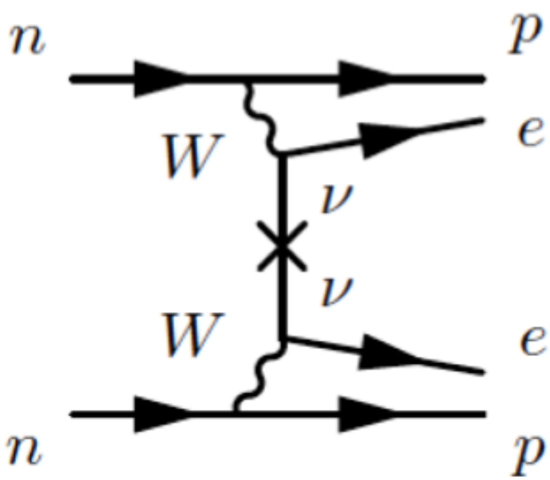
Next generation:

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

Challenge:

~1 decay per 10^4 Mol and year

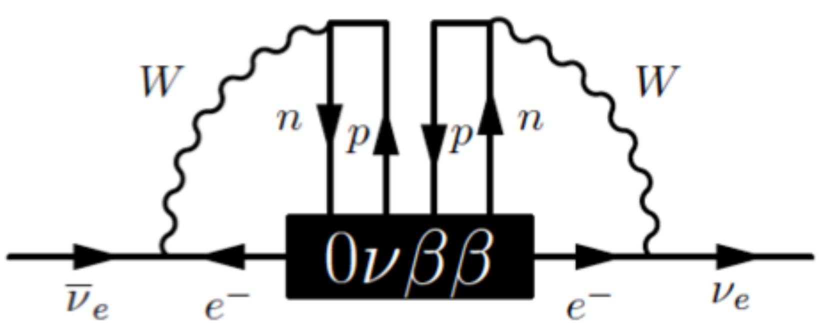
0νββ



Standard paradigm: exchange of
light Majorana neutrinos

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

PMNS-matrix ν-mass

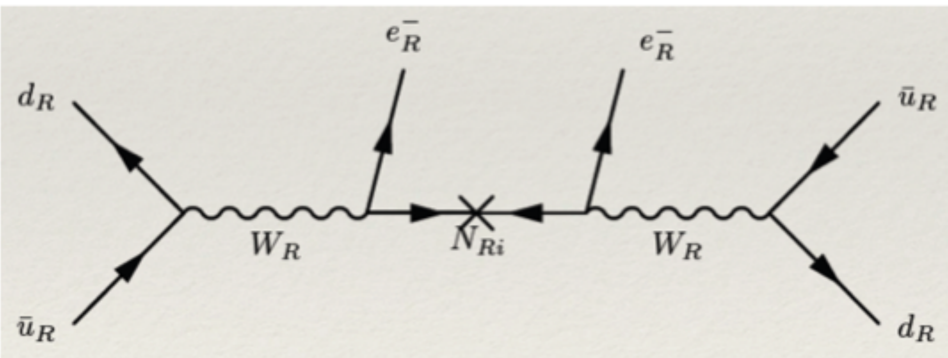


Any 0νββ decay process induces a $\overline{\nu_e}$-ν_e transition, ie. an effective **Majorana mass term**
Schechter, Valle Phys.Rev. D25 (1982)

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

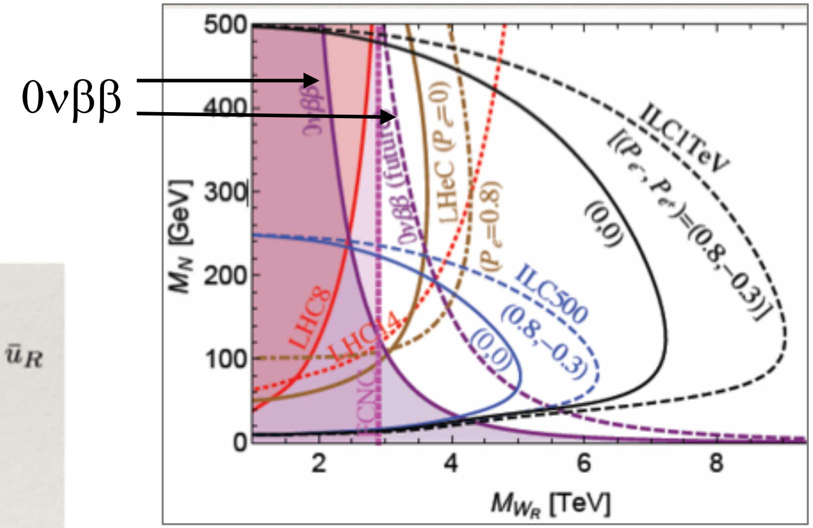
Complementarity of LHC and 0νββ decay

Probing the TeV scale with same-sign di-leptons in 0νββ and LHC:

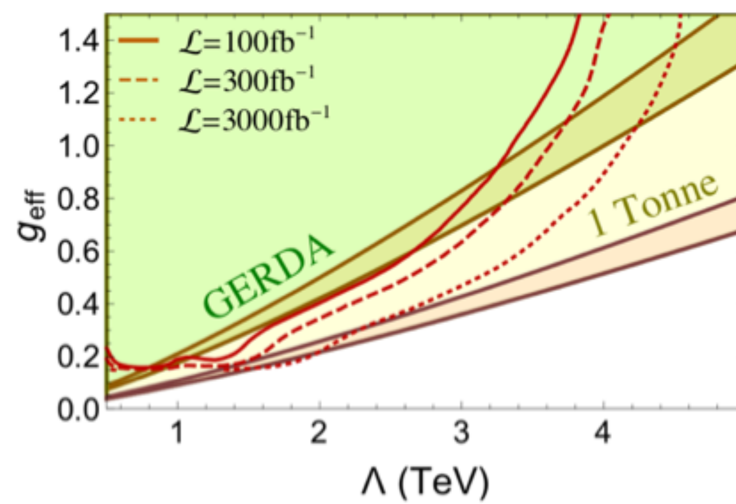


$$G_F^2 \frac{|m_{ee}|^2}{q^2} = \frac{1}{\Lambda^5} \text{ for } |m_{ee}| \sim \text{eV and } \Lambda \sim \text{TeV}$$

"eV = TeV"



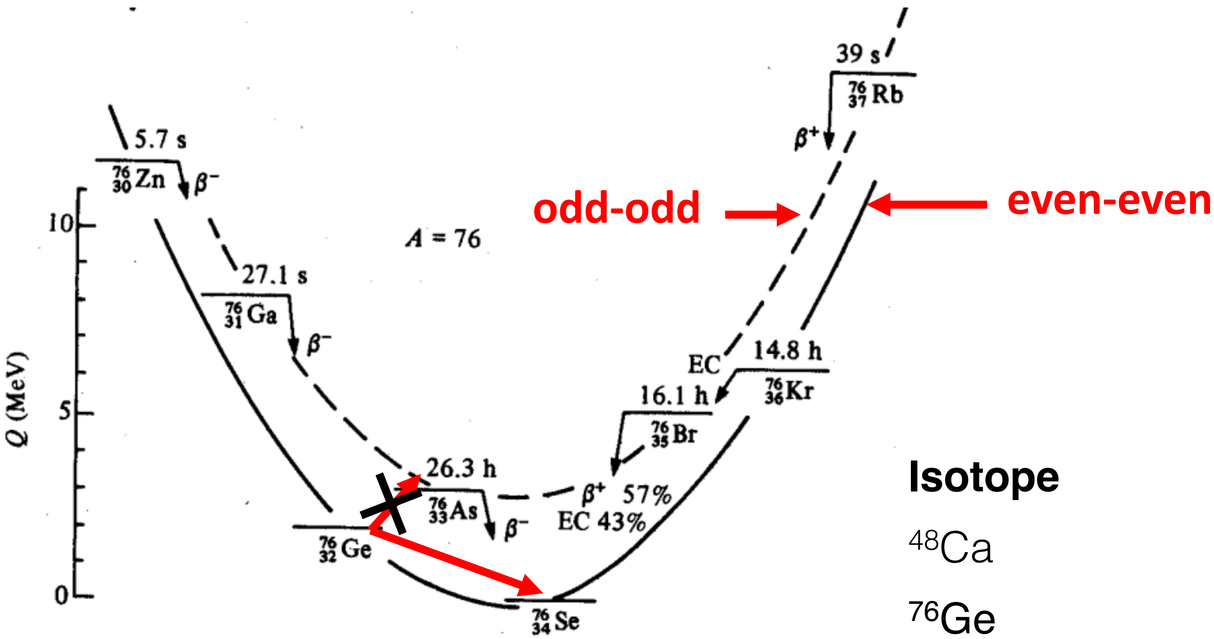
Biswal, Dev, 1701.08751



Ramsey-Musolf et al., 1508.04444

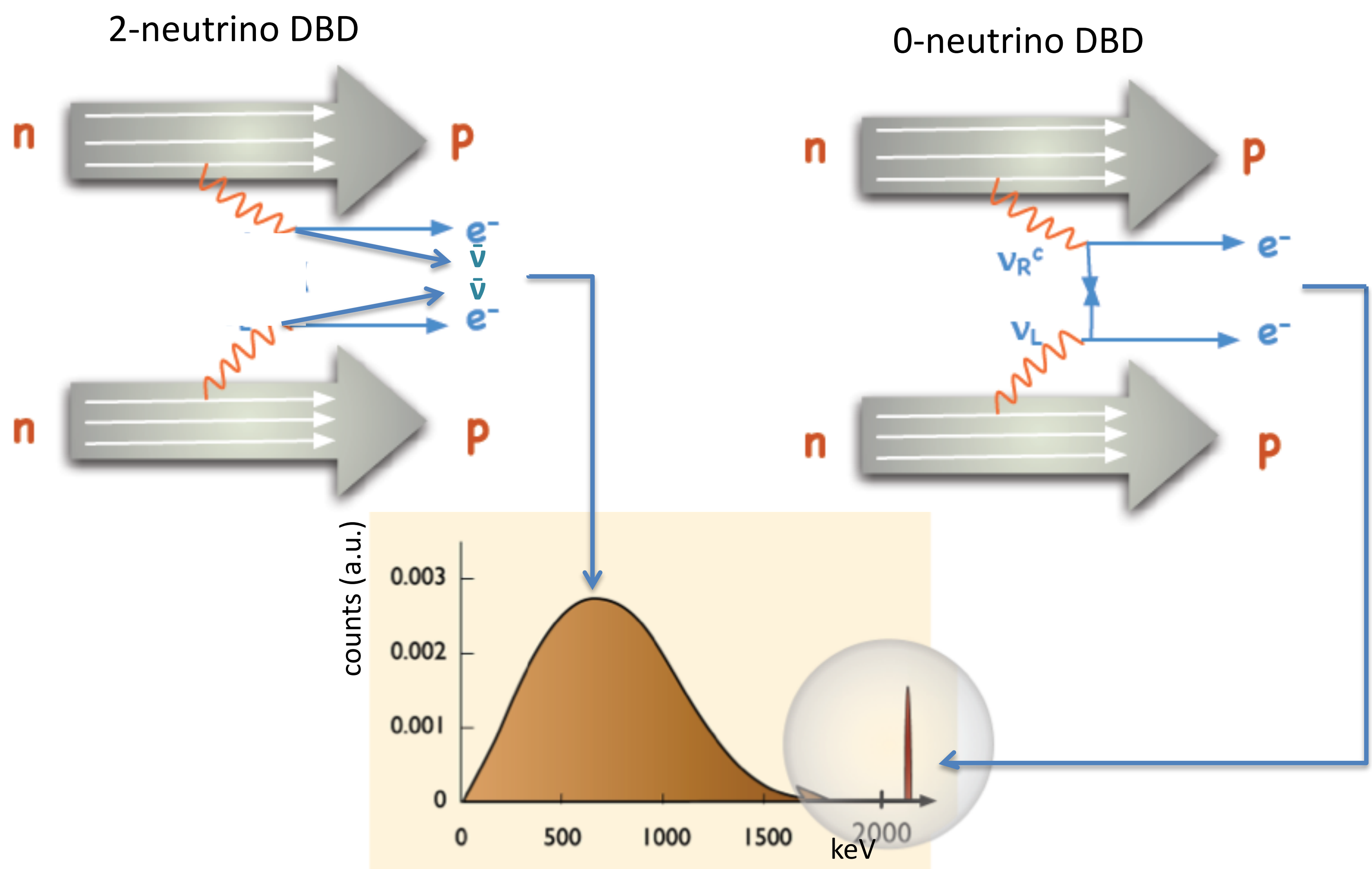
See also: Hirsch et al., 1511.03945

Double beta decay isotopes



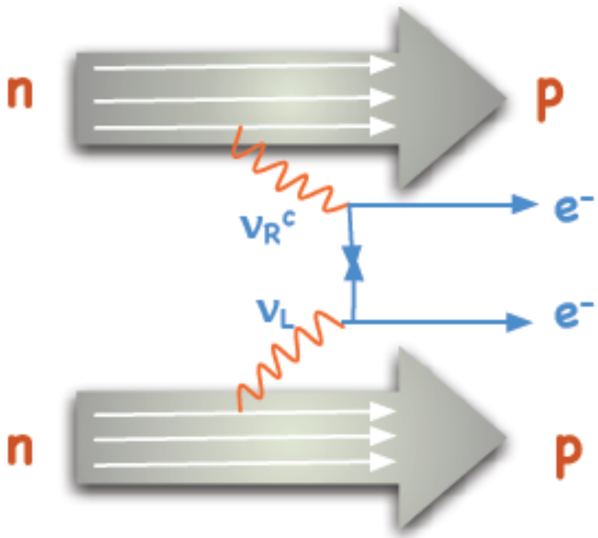
Isotope	Nat ab.	$Q_{\beta\beta}$
^{48}Ca	0.19 %	4262.96(84) keV
^{76}Ge	**7.6%**	**2039.04(16) keV**
^{82}Se	**8.7%**	**2997.9(3) keV**
^{96}Zr	2.8%	3356.097(86) keV
^{100}Mo	**9.6%**	**3034.40(17) keV**
^{116}Cd	7.5%	2813.50(13) keV
^{130}Te	**34.5%**	**2526.97(23) keV**
^{136}Xe	**8.9%**	**2457.83(37) keV**
^{150}Nd	5.6%	3371.38(20) keV

2νββ and 0νββ decay



2-electron spectra

0νββ decay and neutrino mass



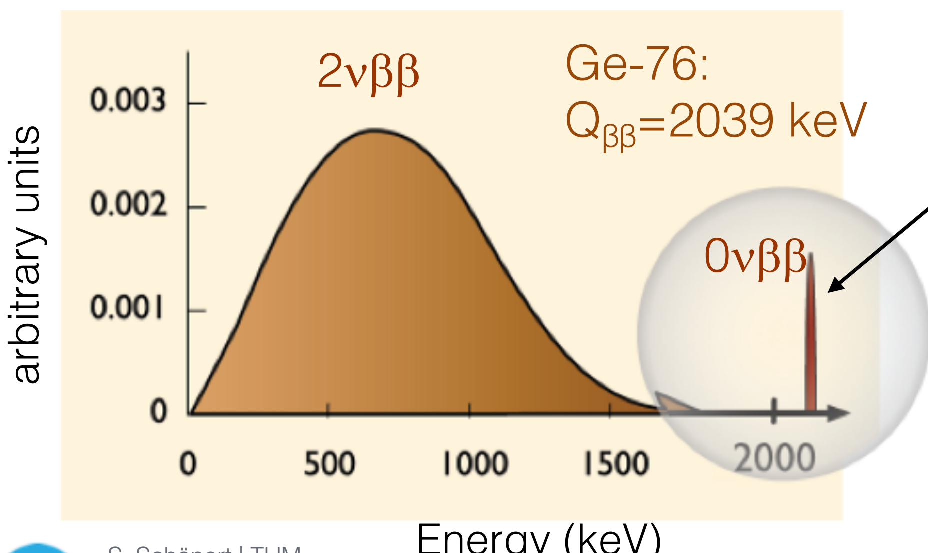
Expected decay rate:

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

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

Discovery would imply:

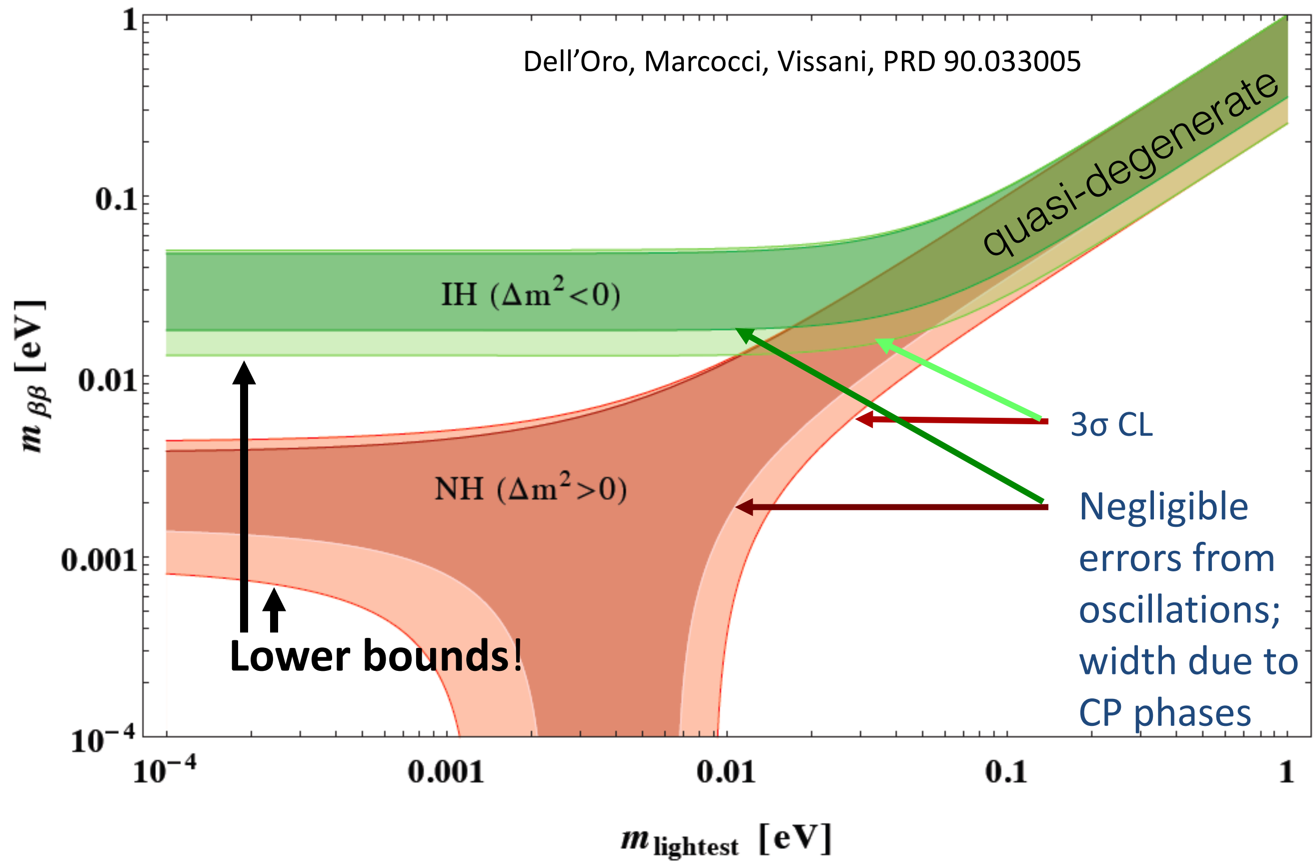
- lepton number violation ΔL = 2
- ν's have Majorana character
- mass scale
- physics beyond the standard model

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

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

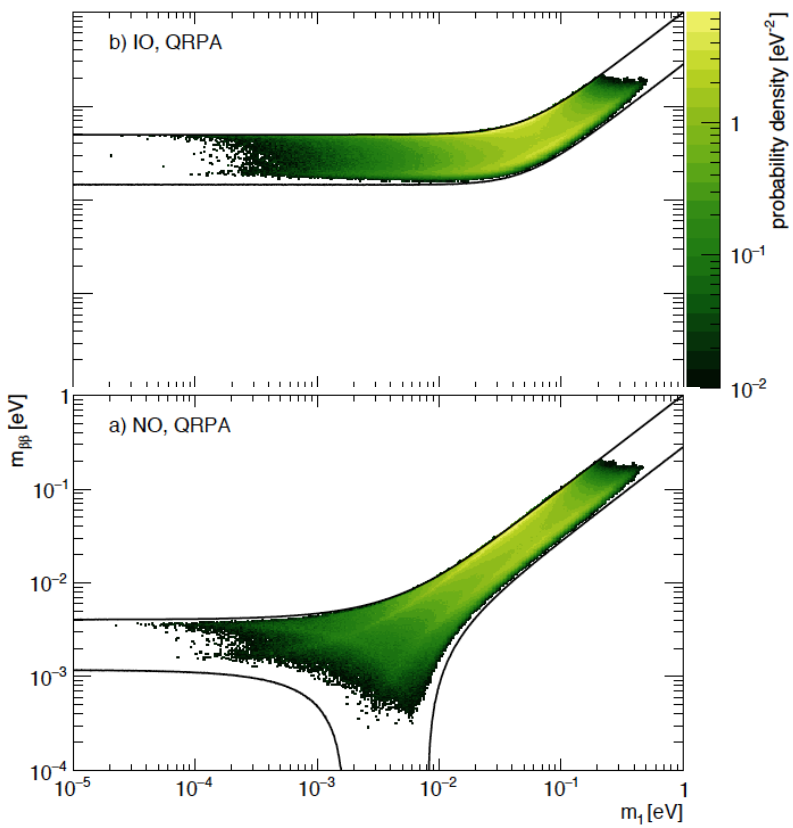
from oscillation experiments

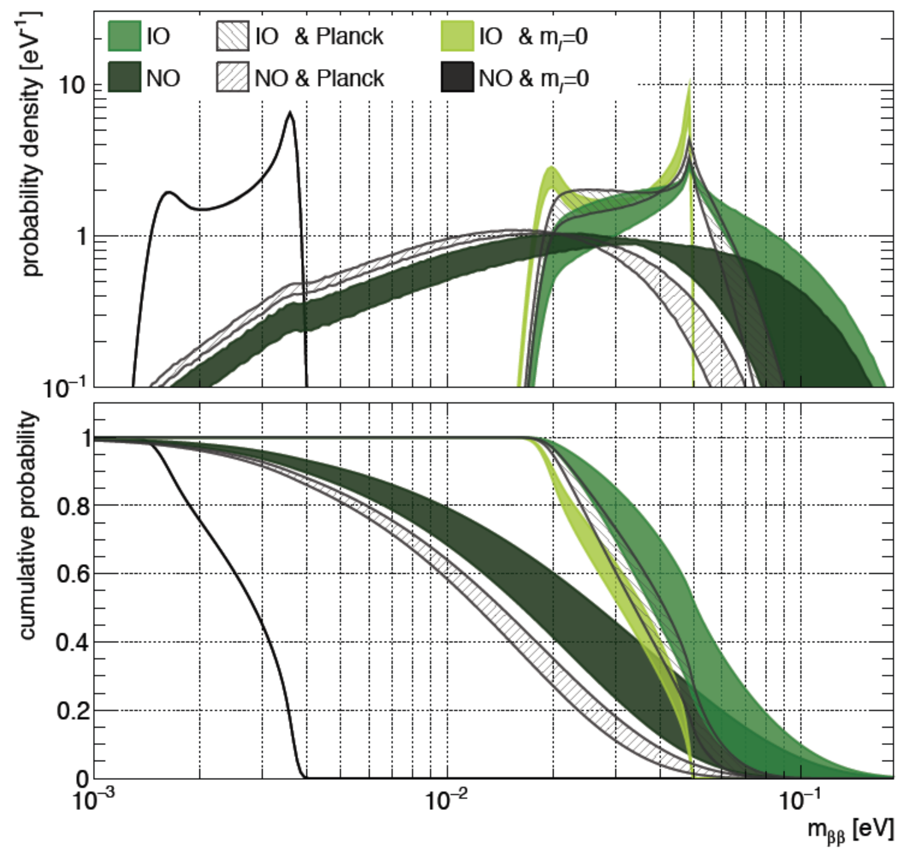
Goal of next generation experiments:



Discovery probabilities

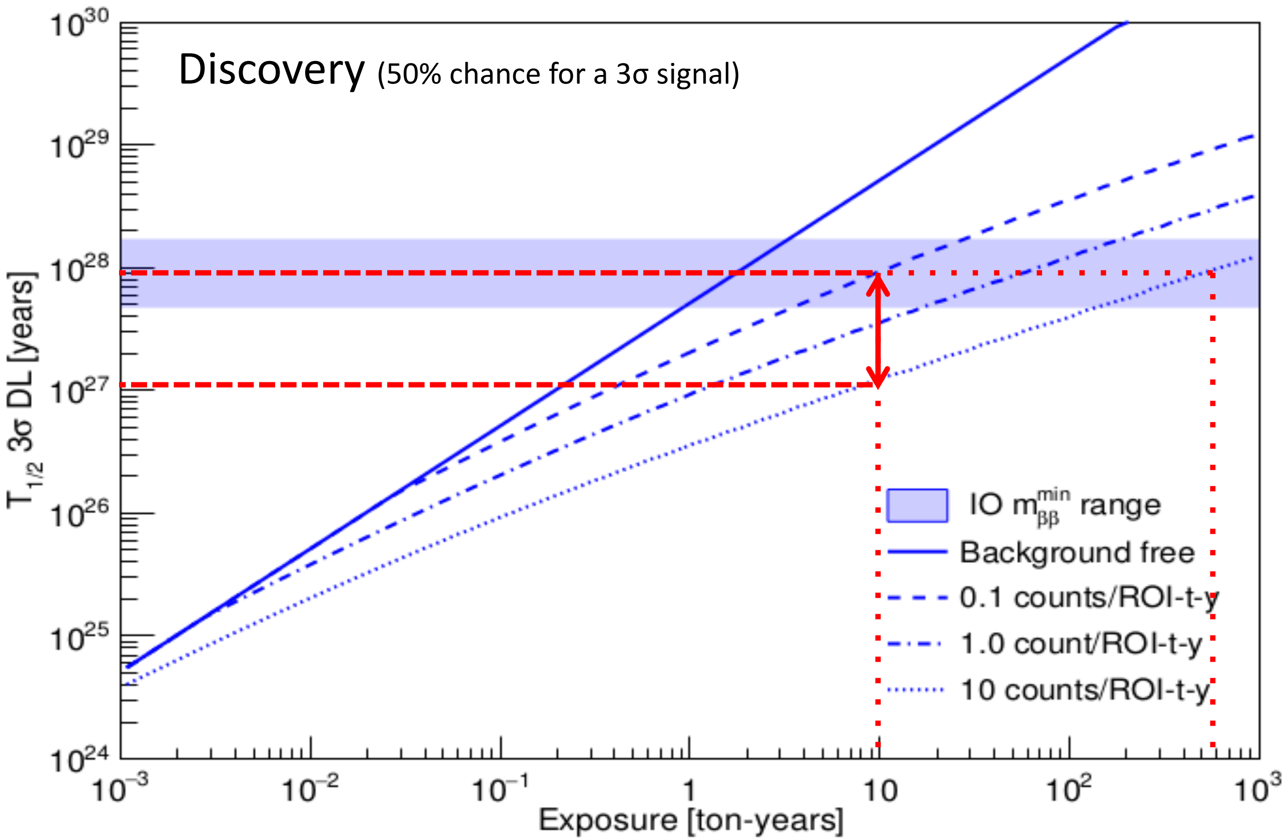
- Global Bayesian analysis including ν-oscillation, m_β $m_{\beta\beta}$, Σ
- Priors:
  - Majorana phases (flat)
  - m_1 (scale invariant)





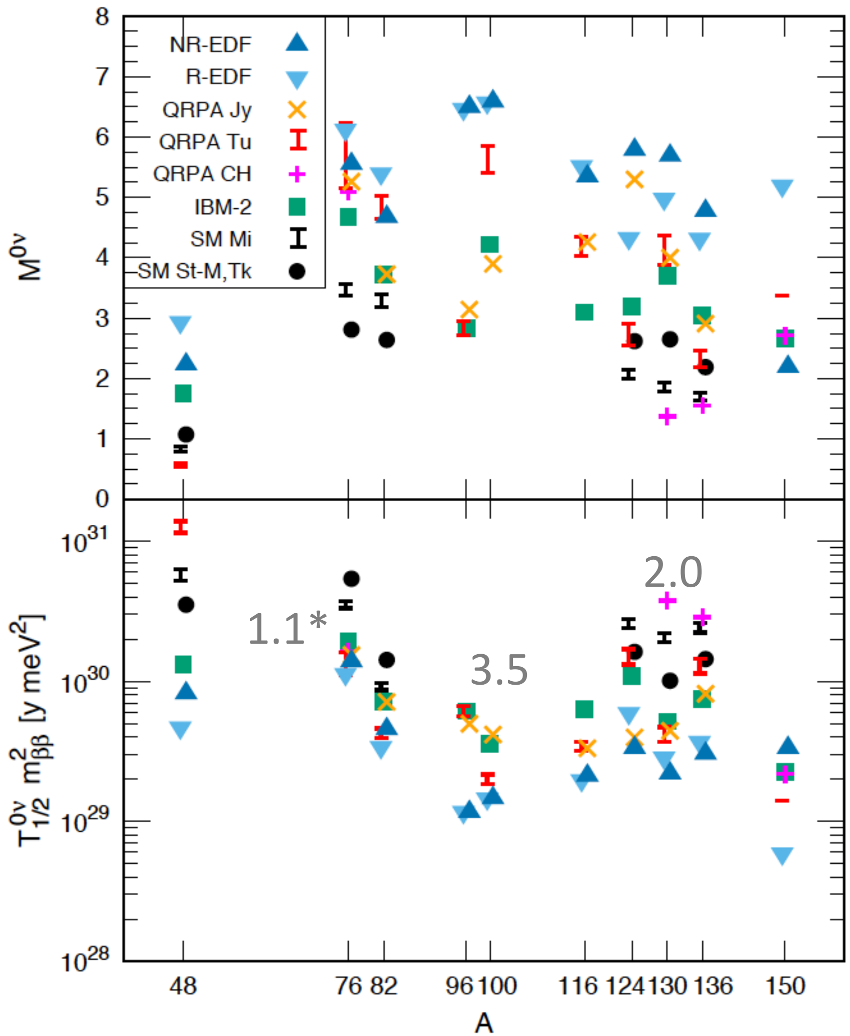
Agostini, Benato, Detwiler arXiv:1705.02996

Discovery sensitivity vs. background



Courtesy J. Detwiler

Nuclear matrix elements



Spread about x2

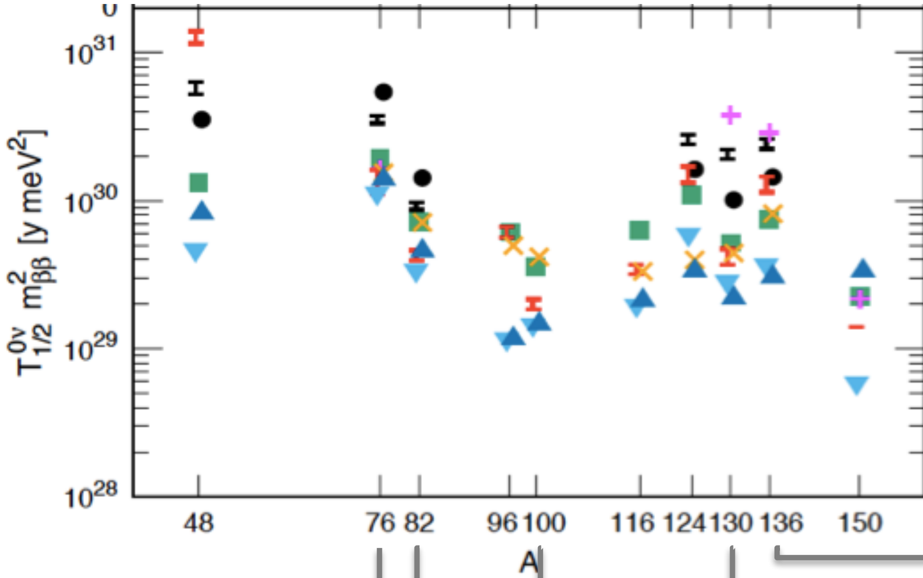
No isotope significantly preferred when comparing decay rate per mass

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



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

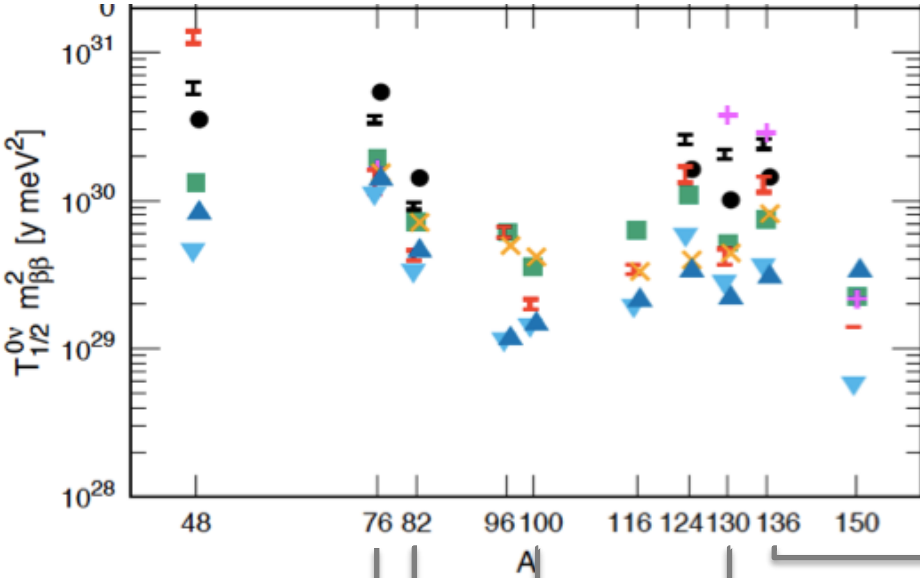
Mo-bolometers: CUPID-Mo (ex Lumineu)
AMoRE

Se-bolometers: CUPID-0 (ex Lucifer)
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

Experiments



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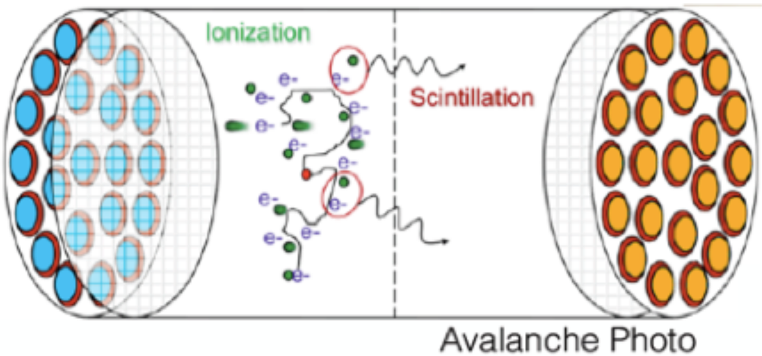
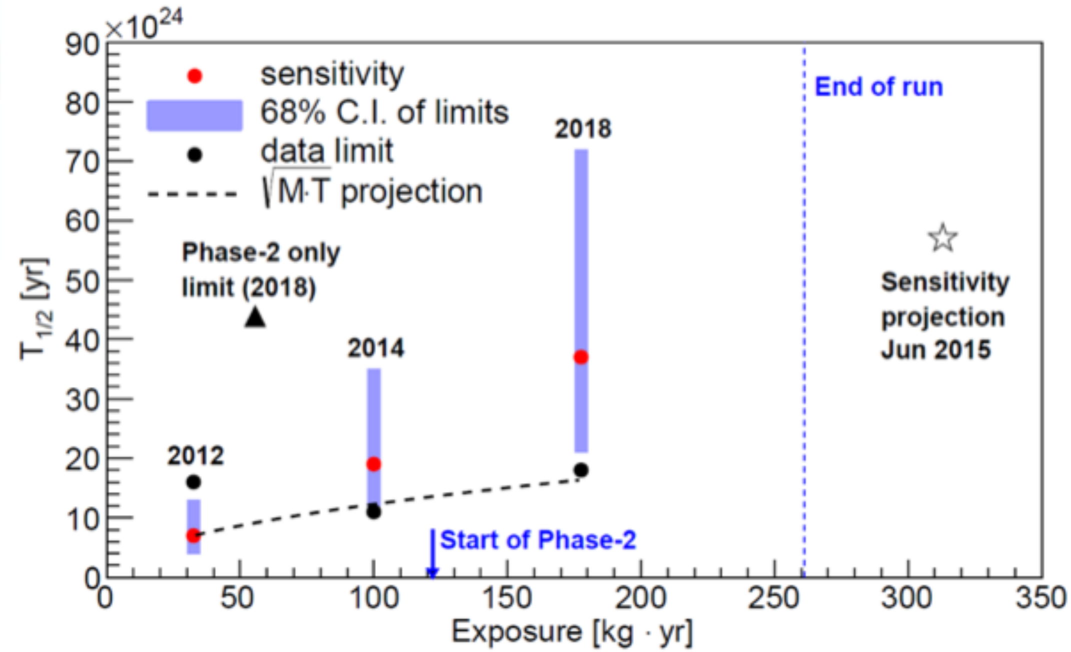
Xenon Experiments: EXO-200



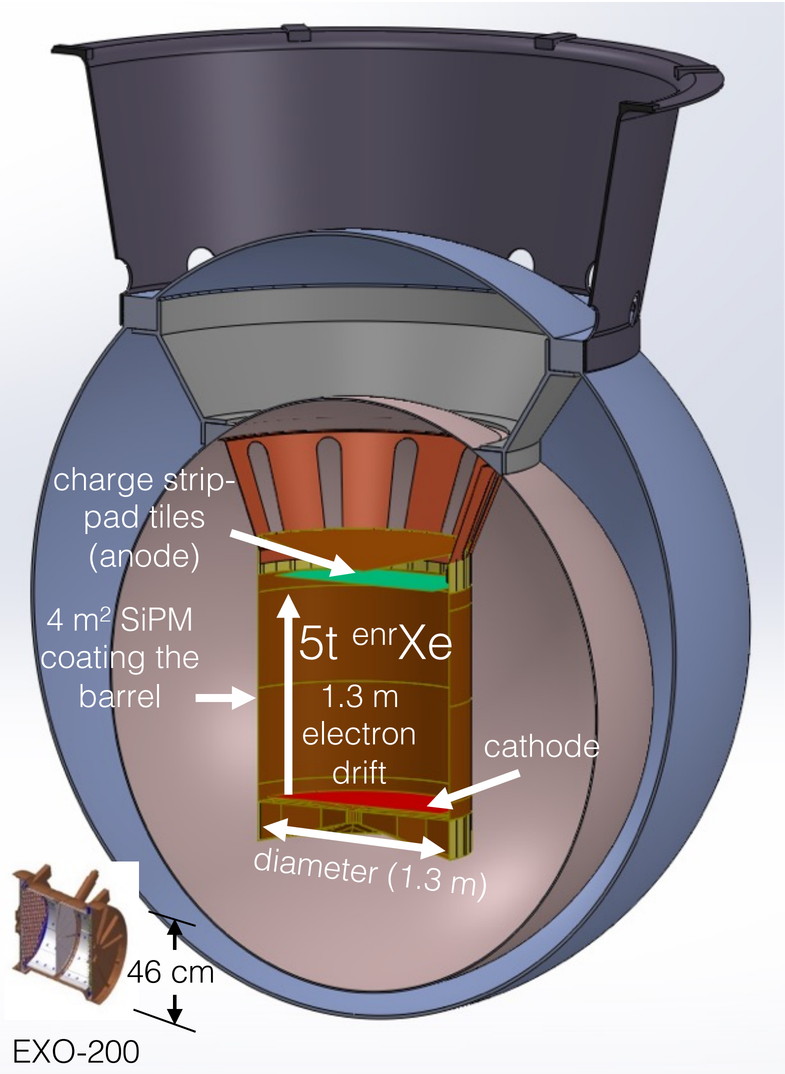
- ^{136}Xe: $Q_{\beta\beta}$ = 2458 keV
- Liquid Xe TPC (80.6% ^{136}Xe)
- 75 kg ^{136}Xe in FV

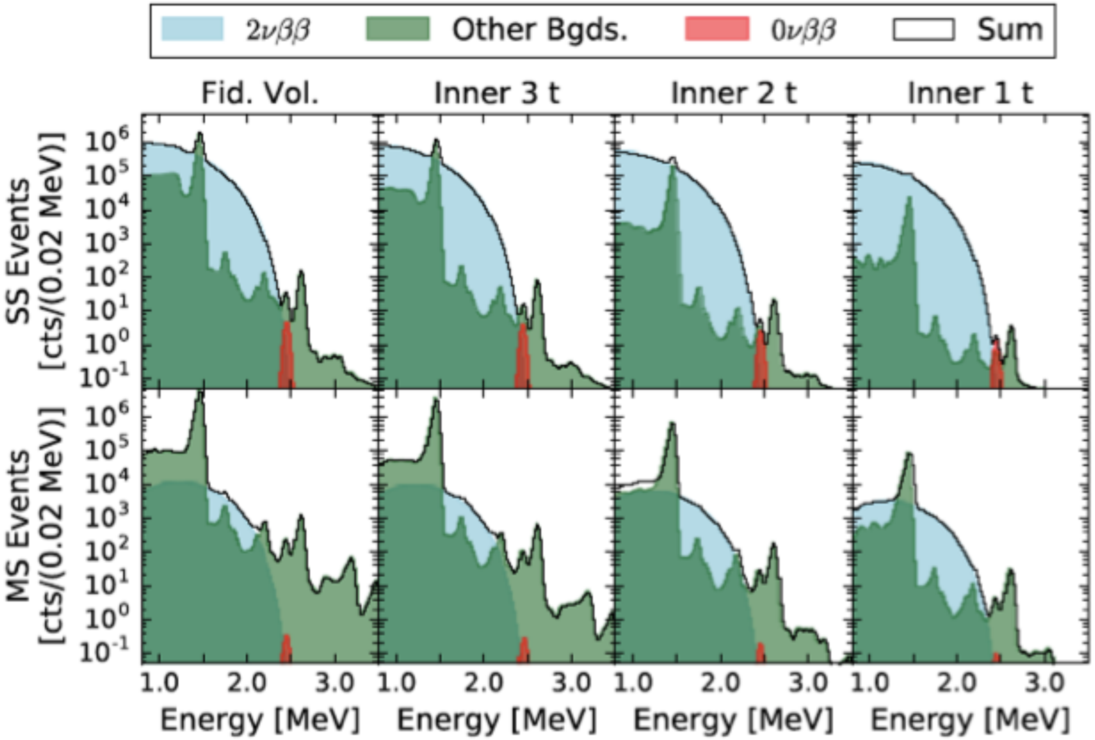


	Sensitivity (yr)	90% CL Limit (yr)	$\langle m_{\beta\beta} \rangle$ (meV)
PRL 109, 032505 (2012)	0.7×10^{25}	1.6×10^{25}	
Nature 510, 229 (2014)	1.9×10^{25}	1.1×10^{25}	
PRL 120 072701 (2018)	3.8×10^{25}	1.8×10^{25}	147-398

Courtesy G. Gratta

Xenon Experiments: nEXO



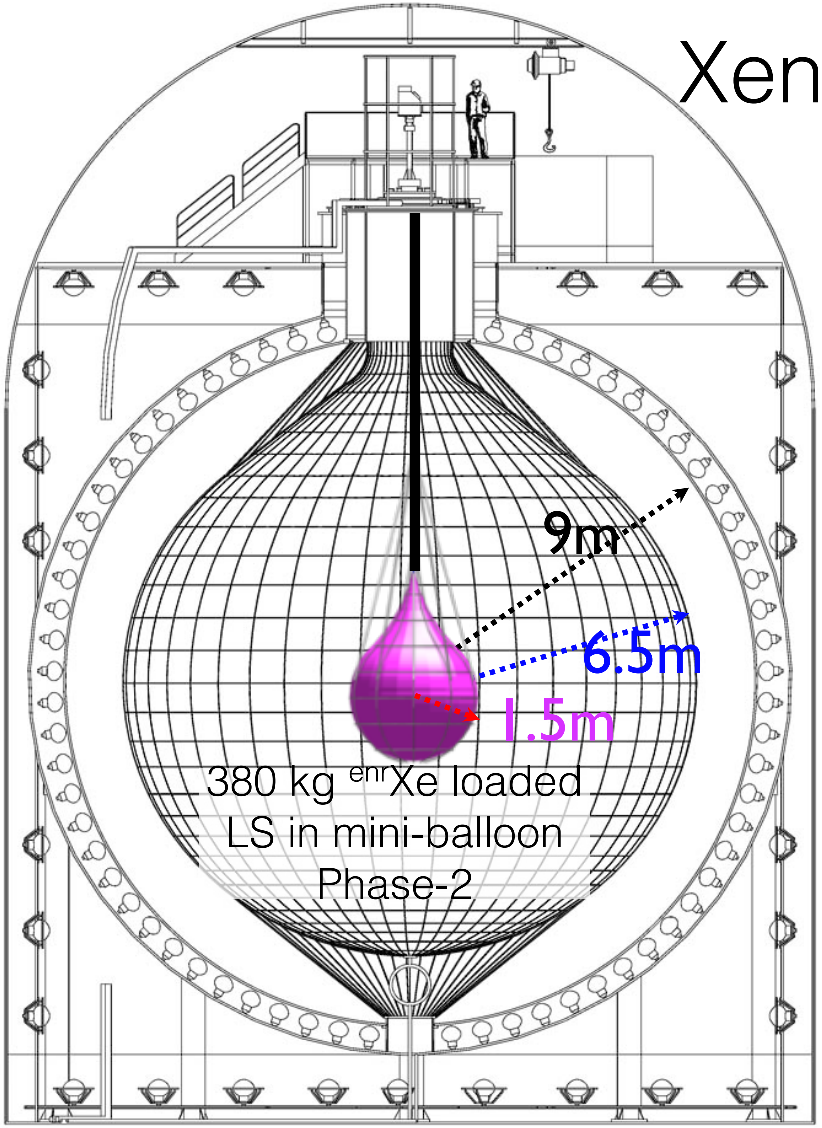


Discovery sensitivity (3σ, 50%) after 10 yr
$T_{1/2}^{0\nu\beta\beta} = 5.5\text{x}10^{27}$ yr

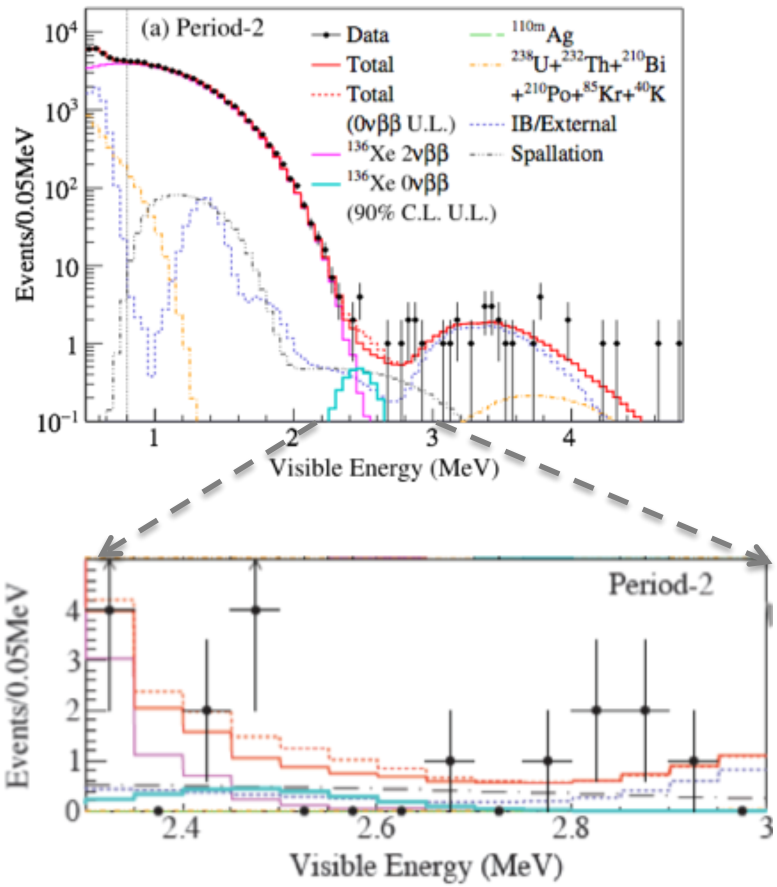
If ^{136}Ba-tagging can be implemented:
$T_{1/2}^{0\nu\beta\beta} = 1.6\text{x}10^{28}$ yr

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

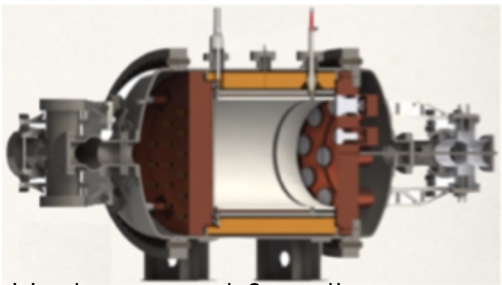
Courtesy K. Inoue

PRL117, 082503 (2016)

Xenon Experiments: next

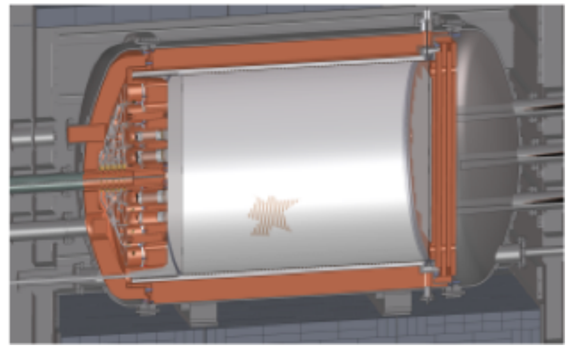
^{136}Xe high-pressure (10-15 bar) TPC

NEXT-NEW (5 kg) 2015-2018



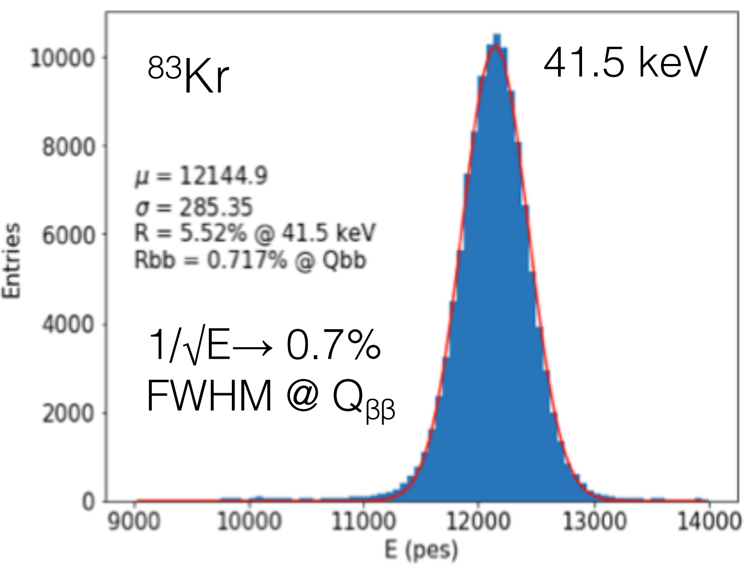
Underground & radio-pure operations, background, 2νββ

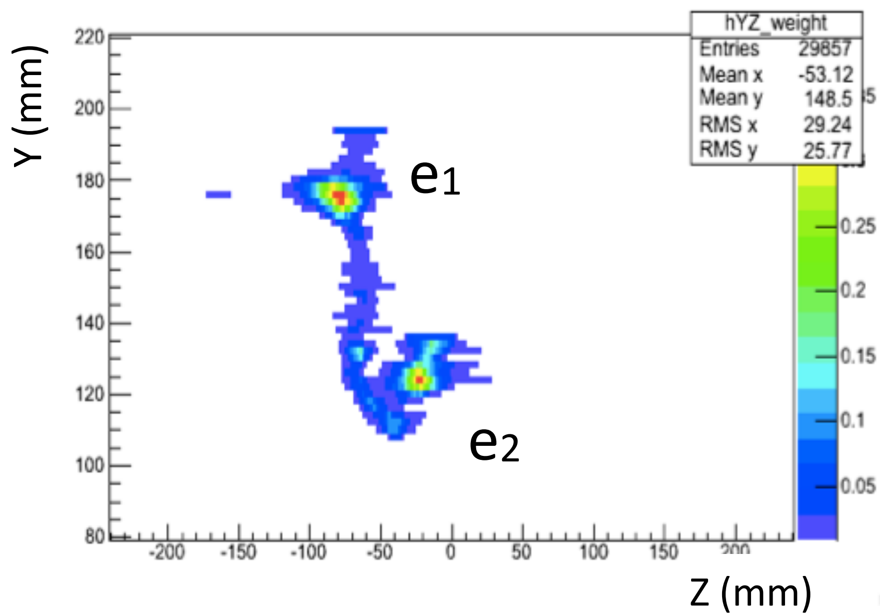
→ NEXT-100 (100 kg) 2018-2020's



0νββ search

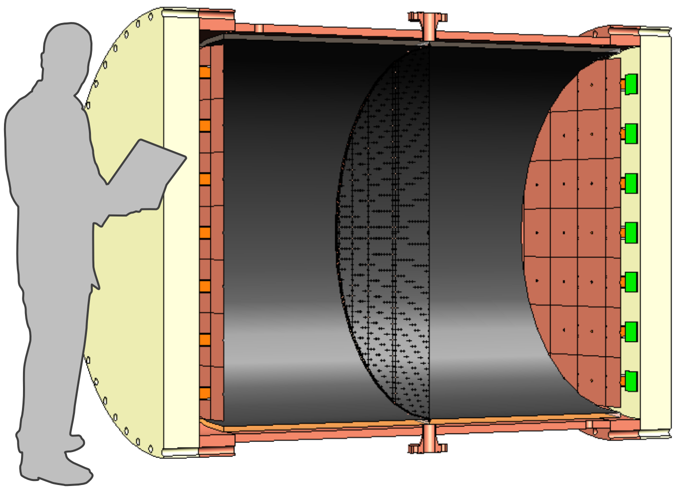
→ NEXT-ton

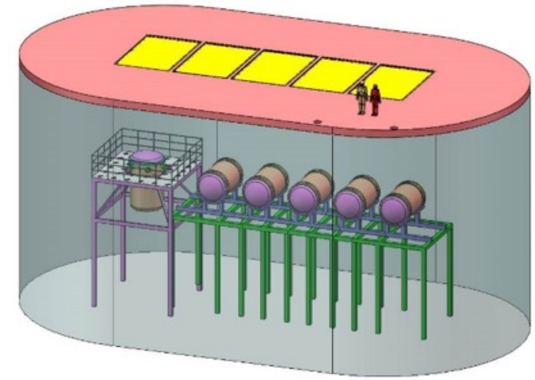




Courtesy JJ Gomez Cadenas

Xenon Experiments: PandaX-III

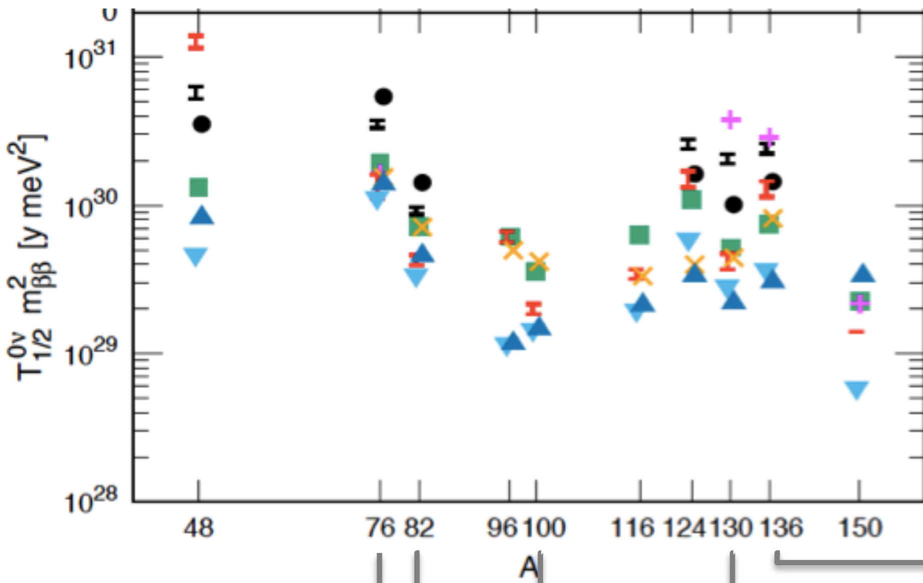




- First 200-kg module:
  - Microbulk Micromegas for charge readout
  - 3% FWHM, 1 x 10^{-4} c/keV/kg/y in the ROI
- Ton-scale:
  - Four more modules with upgraded charge readout and better low-background material screening.
  - 1% FWHM, 1 x 10^{-5} c/keV/kg/y in the ROI

Courtesy Ke Han

Experiments



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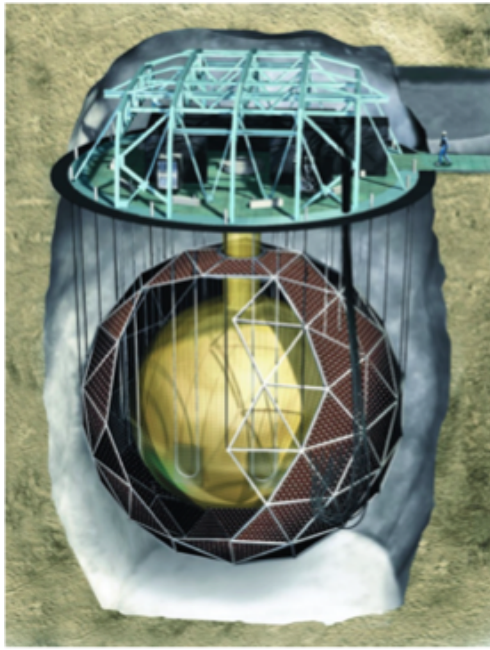
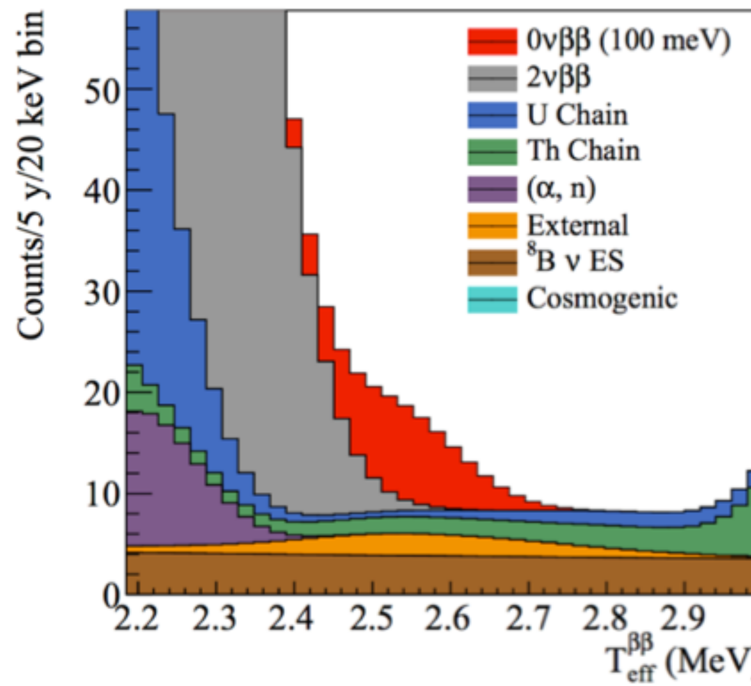
& other interesting, but less advanced R&D; ^{48}Ca, ^{150}Nd not available in large quantities

SNO+



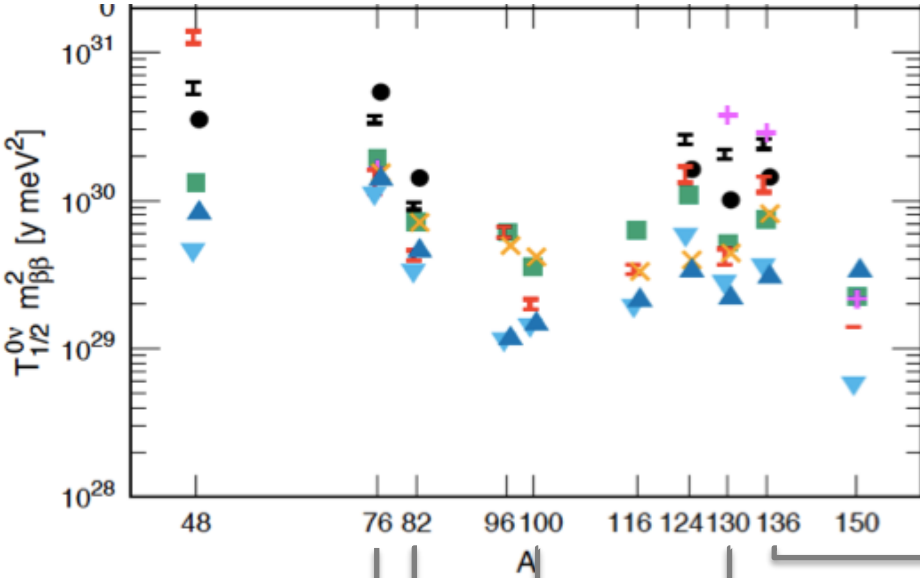
Filling with unloaded liquid scintillator 2018

- 3.9 t Te
- 780 t LAB(+PPO+Te-ButaneDiol)
- 0.5% loading → 1300 kg ^{130}Te



Sensitivity:
5 yr $T_{1/2} > 2\times10^{26}$ yr (90% CL)

Experiments



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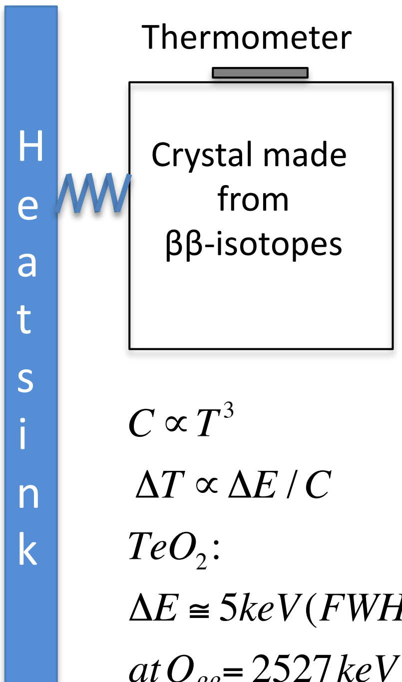
Cryogenic Detectors: CUORE



$$C \propto T^3$$

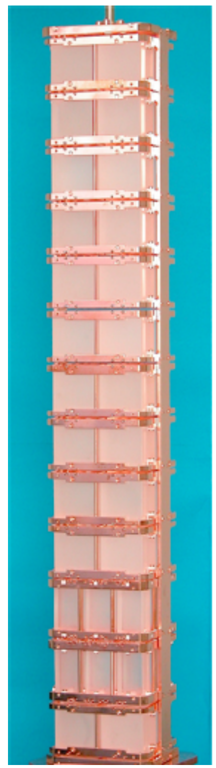
$$\Delta T \propto \Delta E / C$$

$$TeO_2:$$

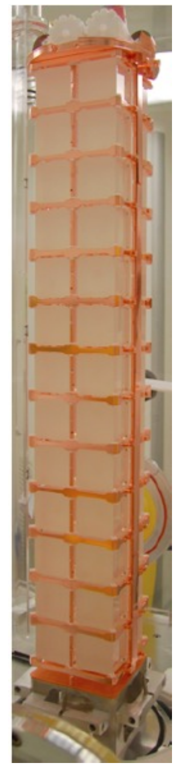
$$\Delta E \cong 5 keV (FWHM)$$

$$at\, Q_{\beta\beta} = 2527\, keV$$

Cuoricino
2003

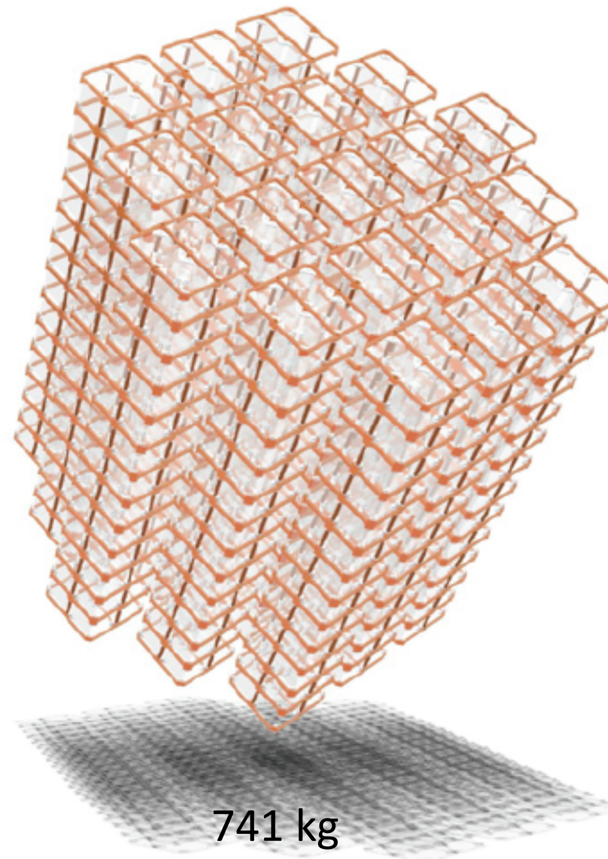


Cuore-0
2012



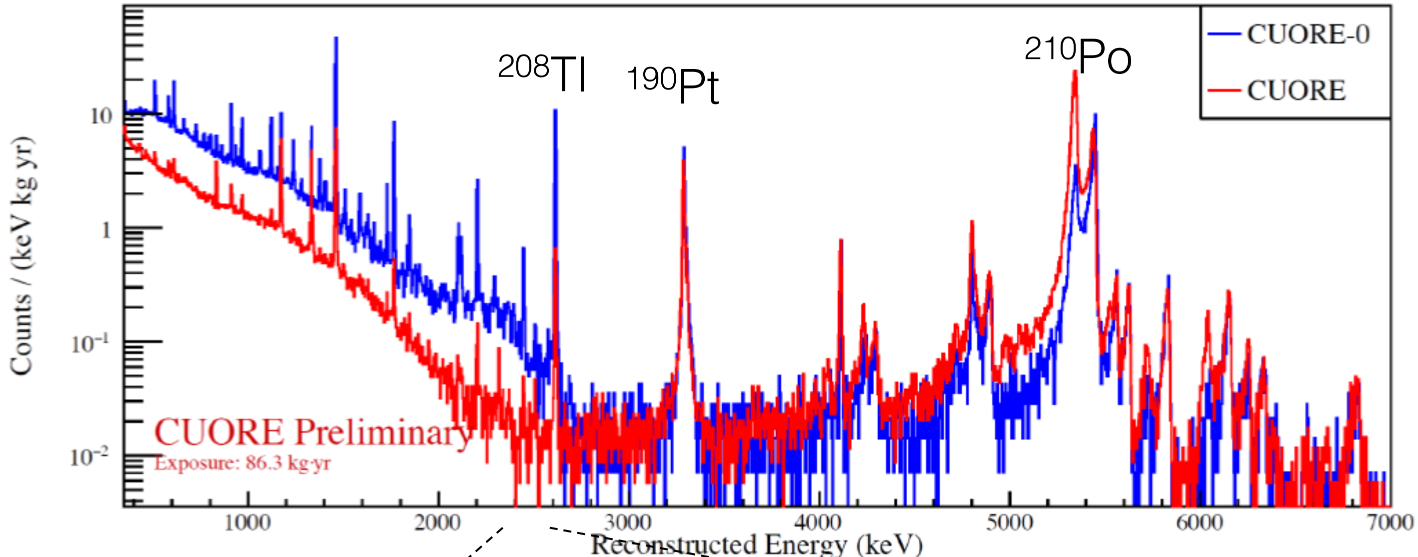
39 kg
(11 kg ^{130}Te)

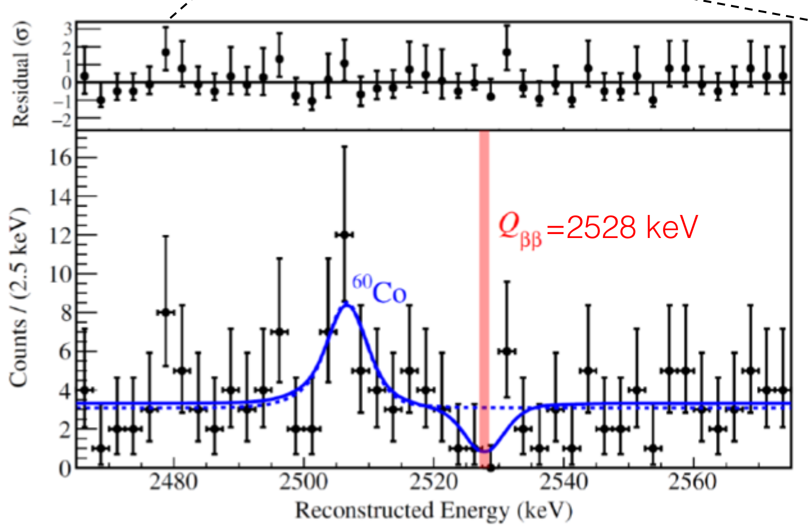
CUORE
2016



741 kg
(206 kg ^{130}Te)

Cryogenic Detectors: CUORE





BI: 1.4 x10^{-2} cts/(keV kg y)

Sensitivity (90% C.L): 7.0 x 10^{24} yr

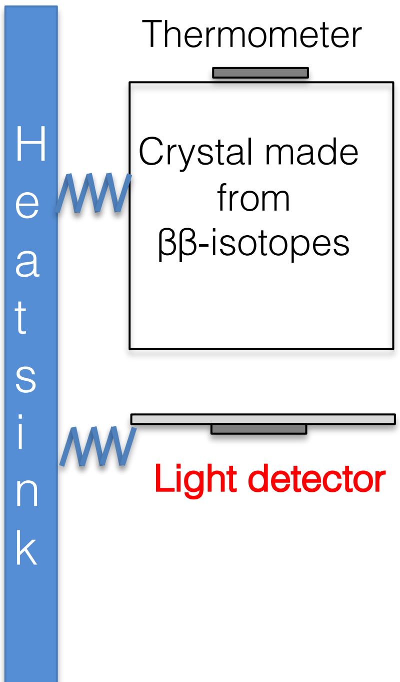
Limit (90% C.L): 1.3 x 10^{25} yr

^{130}Te-combined: 1.5 x 10^{25} yr

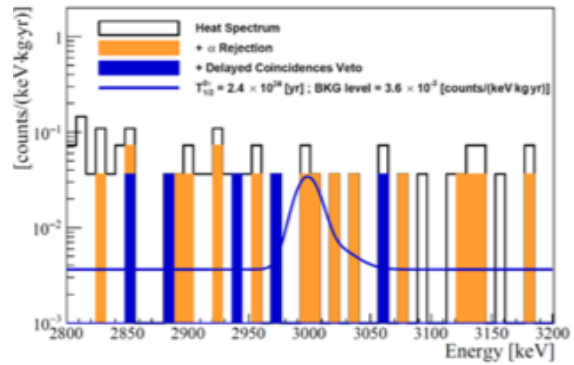
$m_{\beta\beta}$ < 110 – 520 meV

J. Ouellet, Neutrino 2018

Cryogenic Detectors: CUPID



CUPID-0: ZnSe
@ LNGS
5.2 kg ^{82}Se

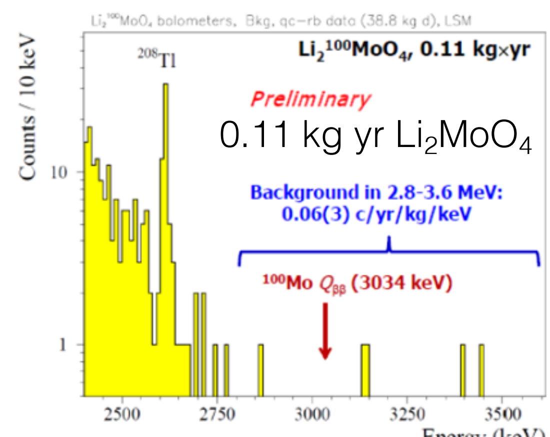


$T_{1/2}$> 2.4x10^{24} y (90%C.I.)

BI = 3.6x10^{-3} cts/(keV kg y)

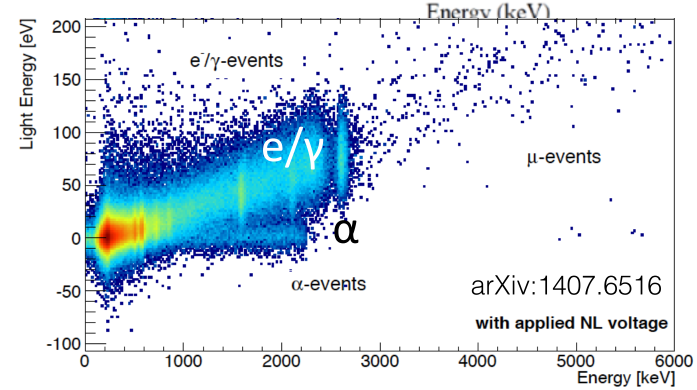
S. Pirro, NDM2018

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

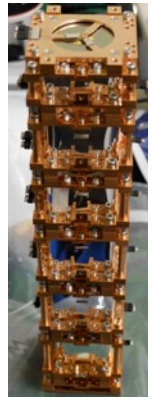


Courtesy
A. Giuliani

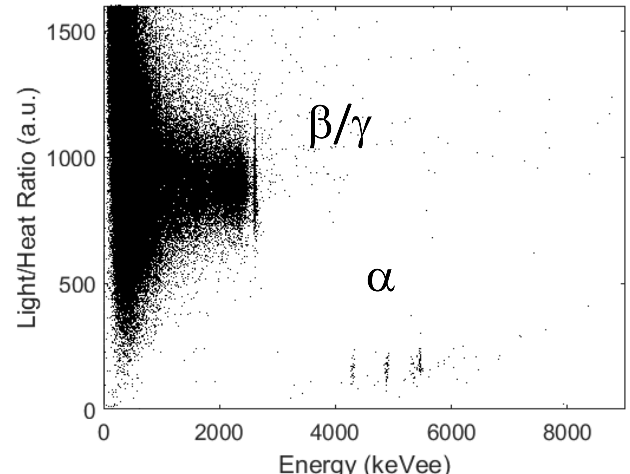
CUPID-Te:TeO_2
(with Cherenkov)
Demonstrator @ LNGS



Cryogenic Detectors: AMoRE

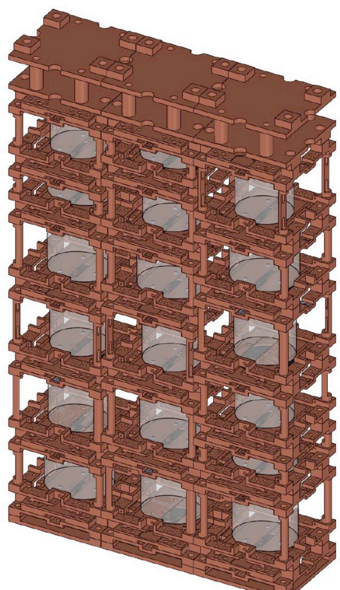


AMoRe-pilot project @ YangYang
6 crystals (1.8 kg)
$^{40}Ca^{100}MoO_4$



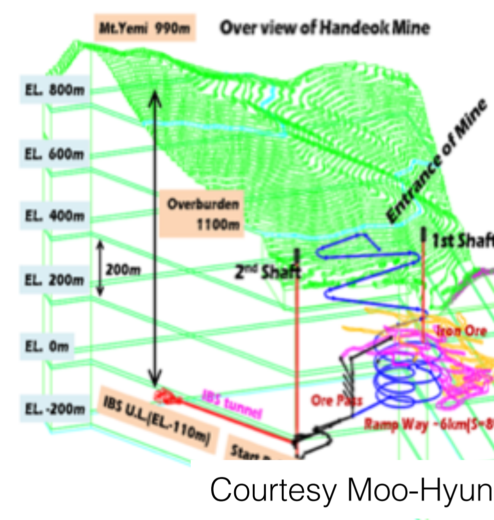
^{100}Mo procurement ongoing (100 kg)

AMoRE-1
5 kg
2018



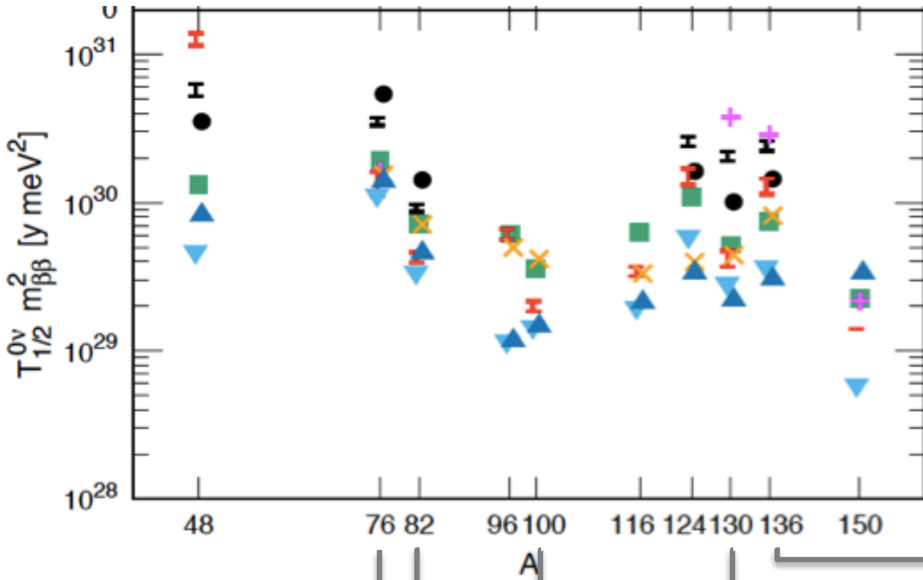
AMoRE-II
200 kg
2020

AMoRE @ Handeok ARF



Courtesy Moo-Hyun Lee

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

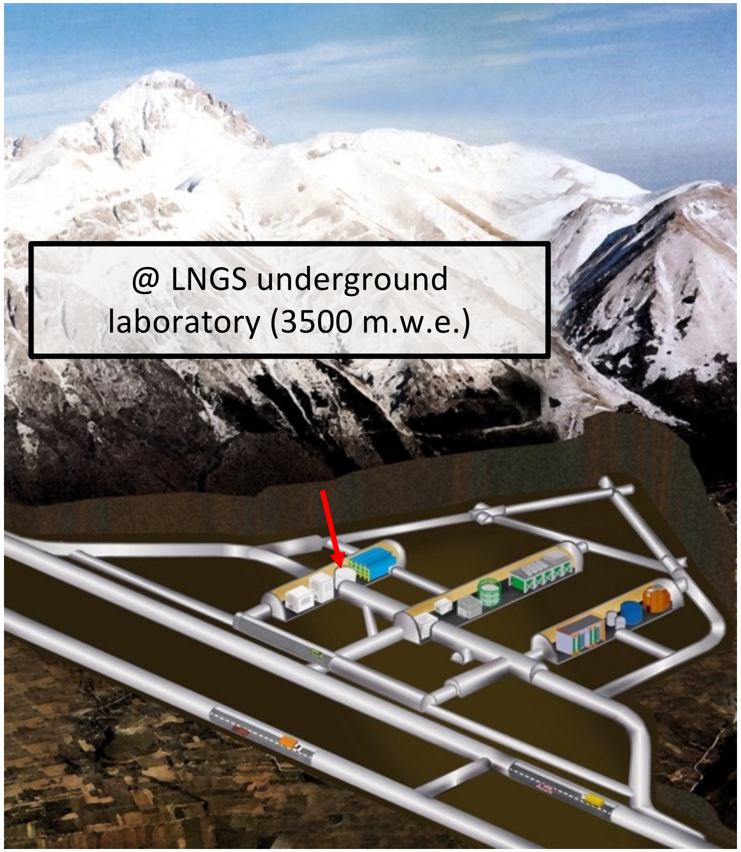
Mo-bolometers:	CUPID-Mo (ex Lumineu) AMoRE

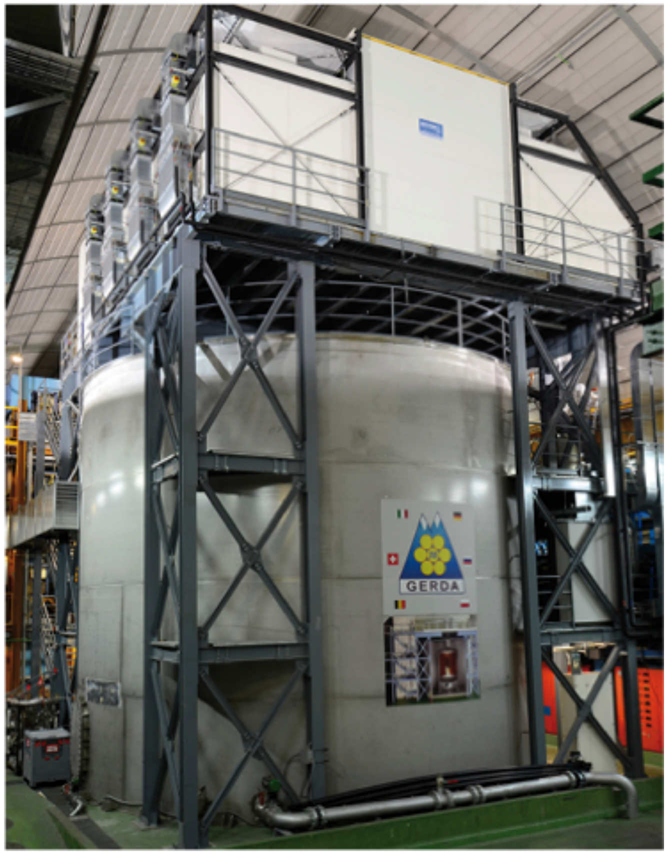
Se-bolometers:	CUPID-0 (ex Lucifer)
Se-calo-tracko:	SuperNEMO

Ge-semiconductor: GERDA, MJD, LEGEND

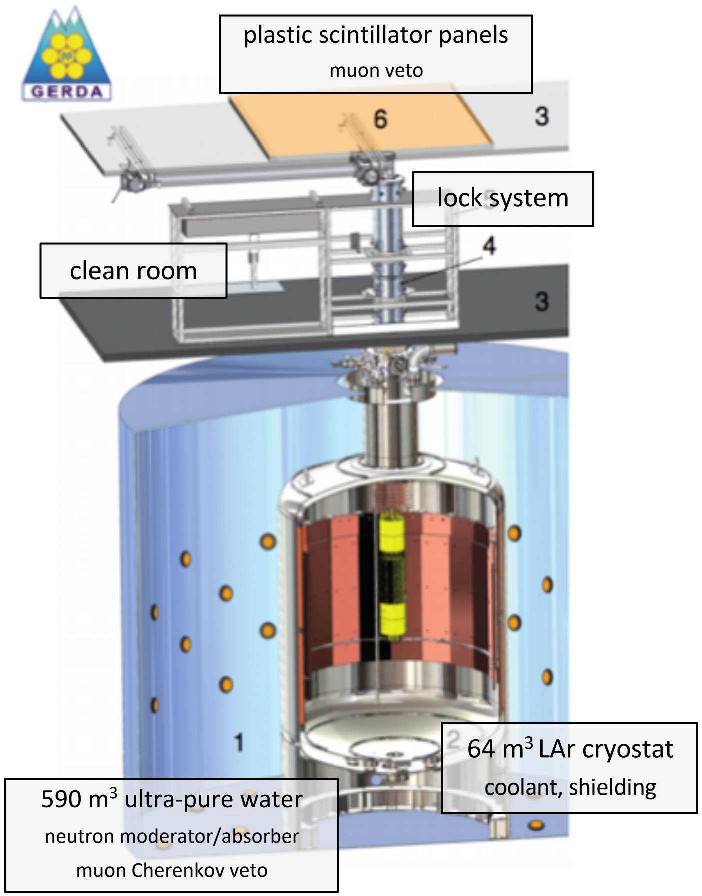
& other interesting, but less advanced R&D; ^{48}Ca, ^{150}Nd not available in large quantities

GERDA experimental setup at LNGS

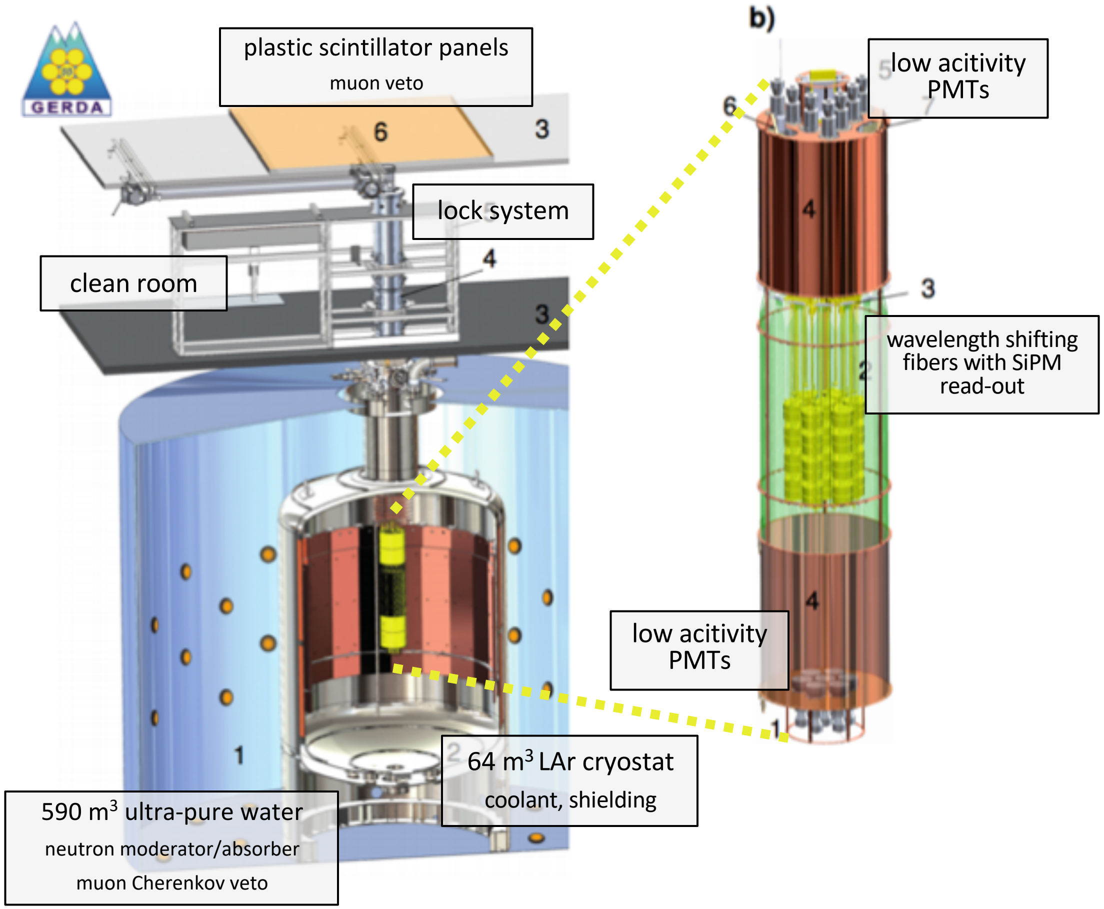




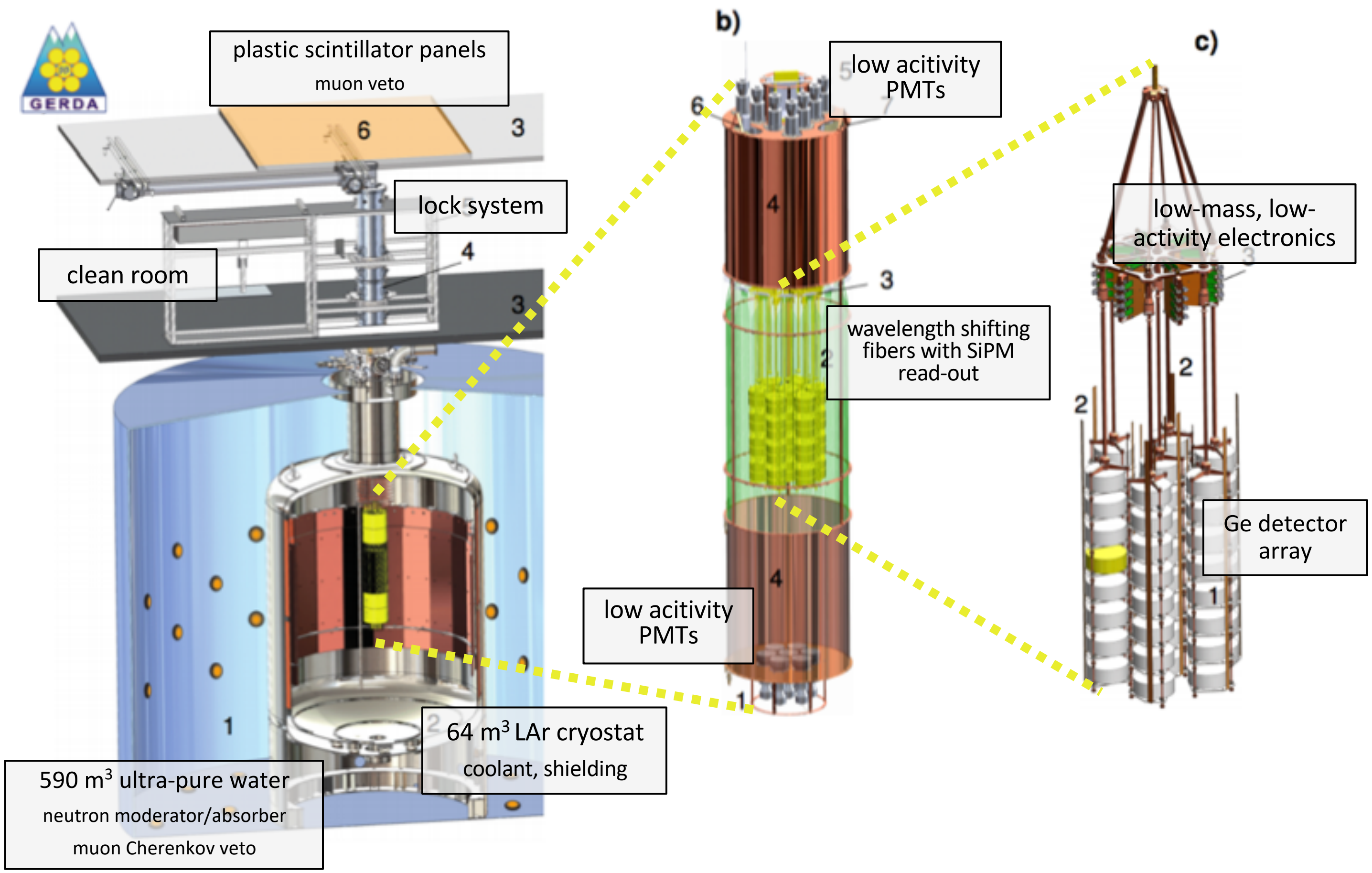
GERDA experimental setup at LNGS



a) overview



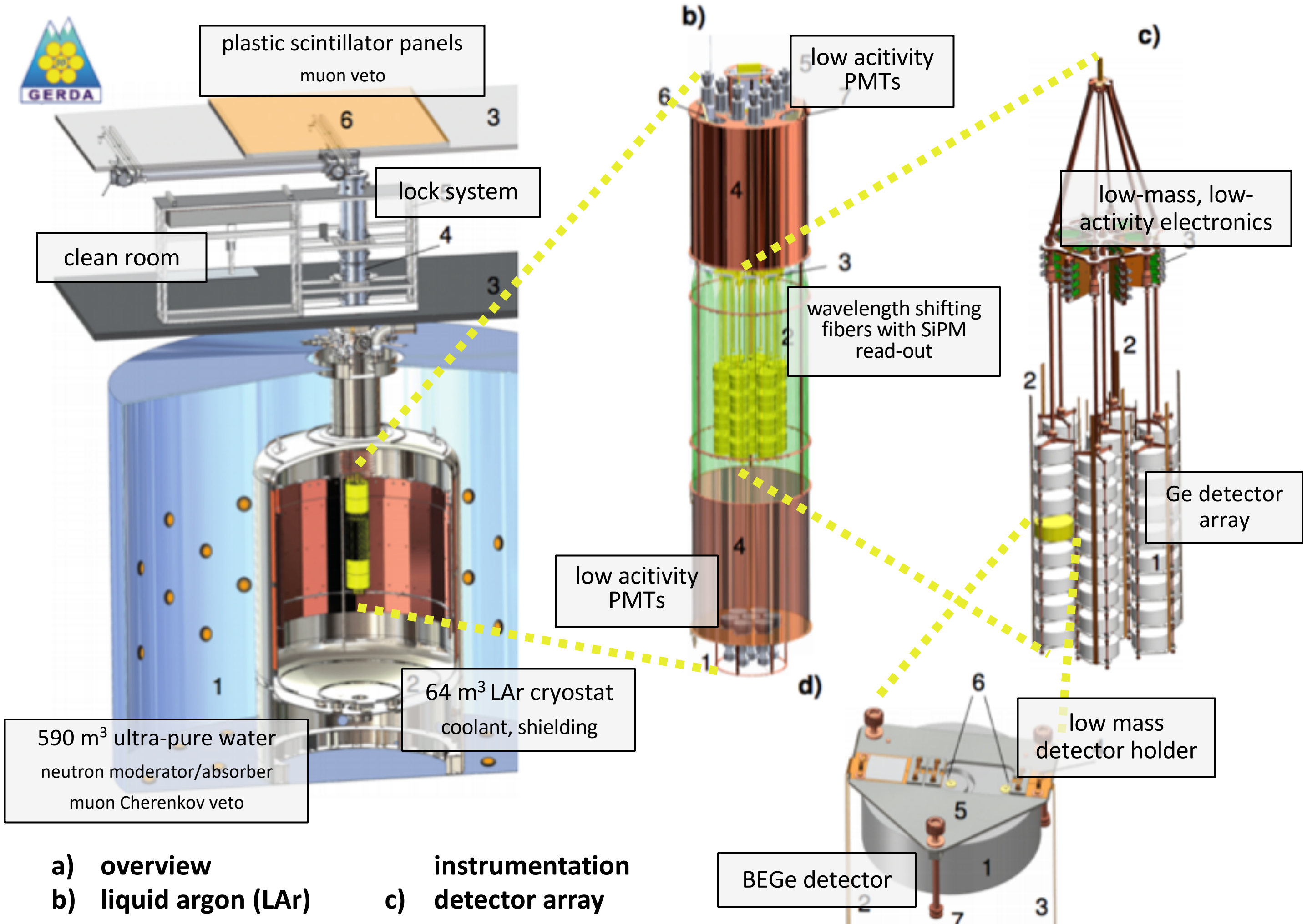
a) overview veto
b) liquid argon (LAr) instrumentation



a) overview

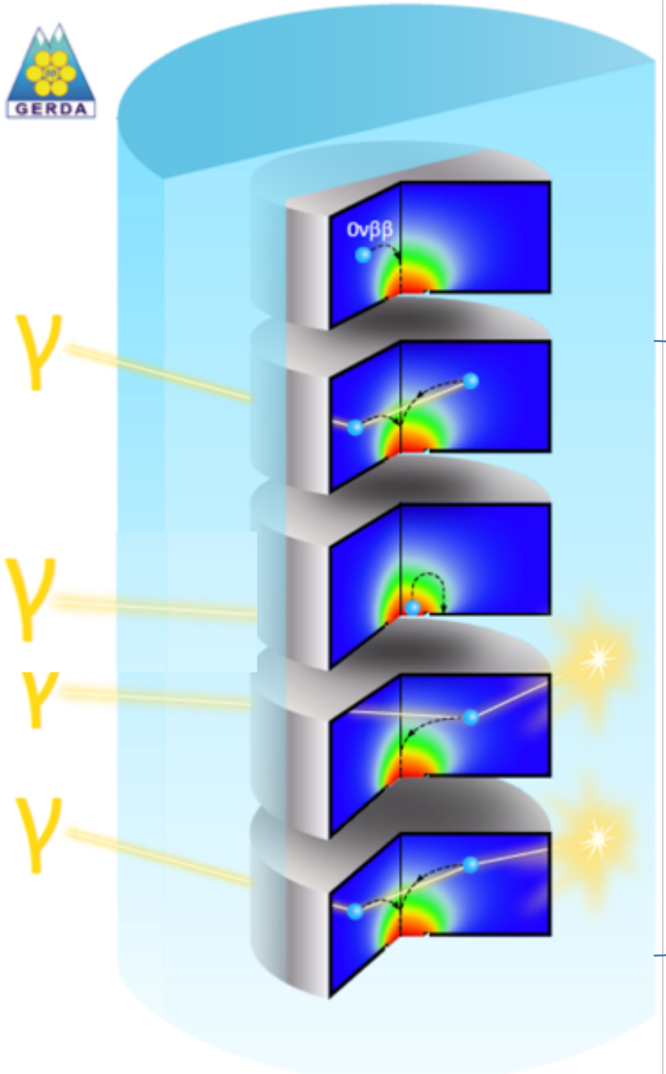
b) liquid argon (LAr) veto instrumentation

c) detector array

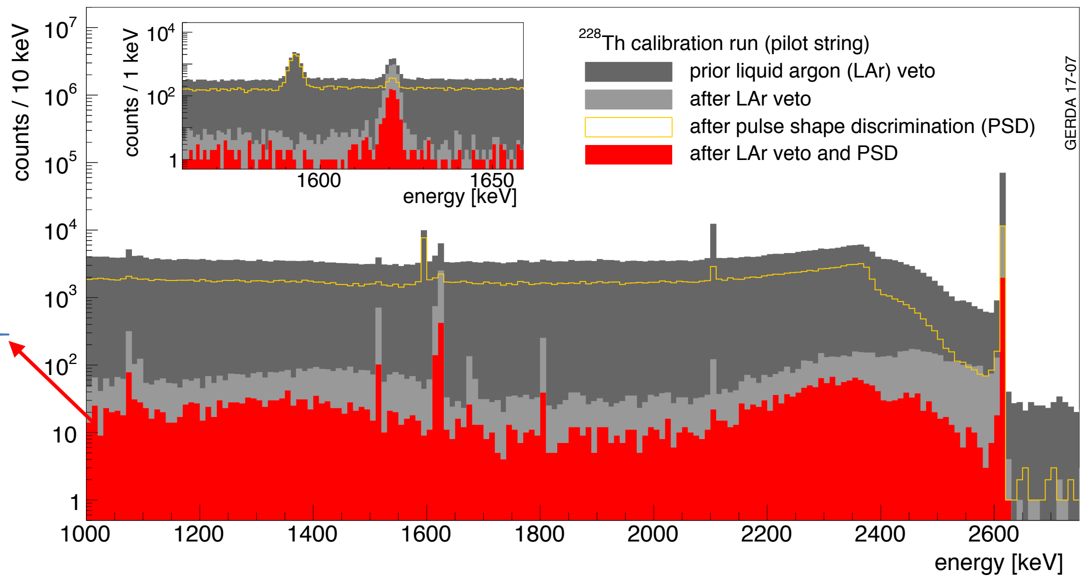


a) overview
b) liquid argon (LAr) veto instrumentation
c) detector array
d) detector module

Interplay between PSD and LAr Veto



^{228}Th calibration source



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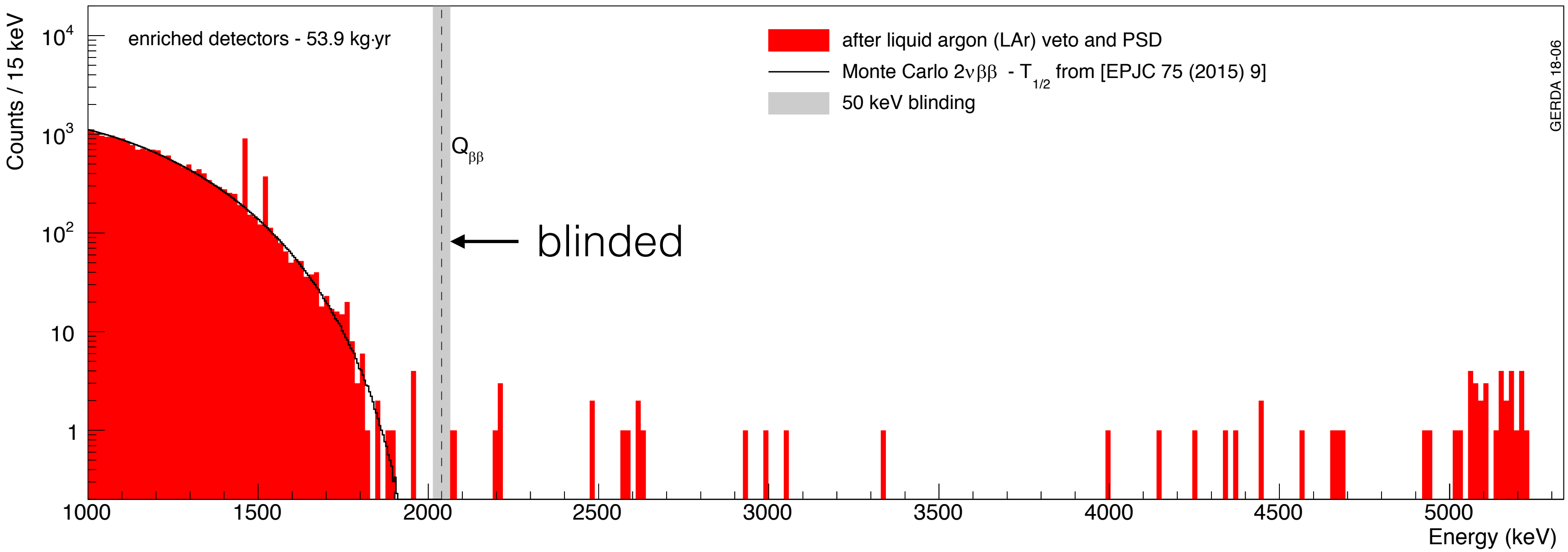
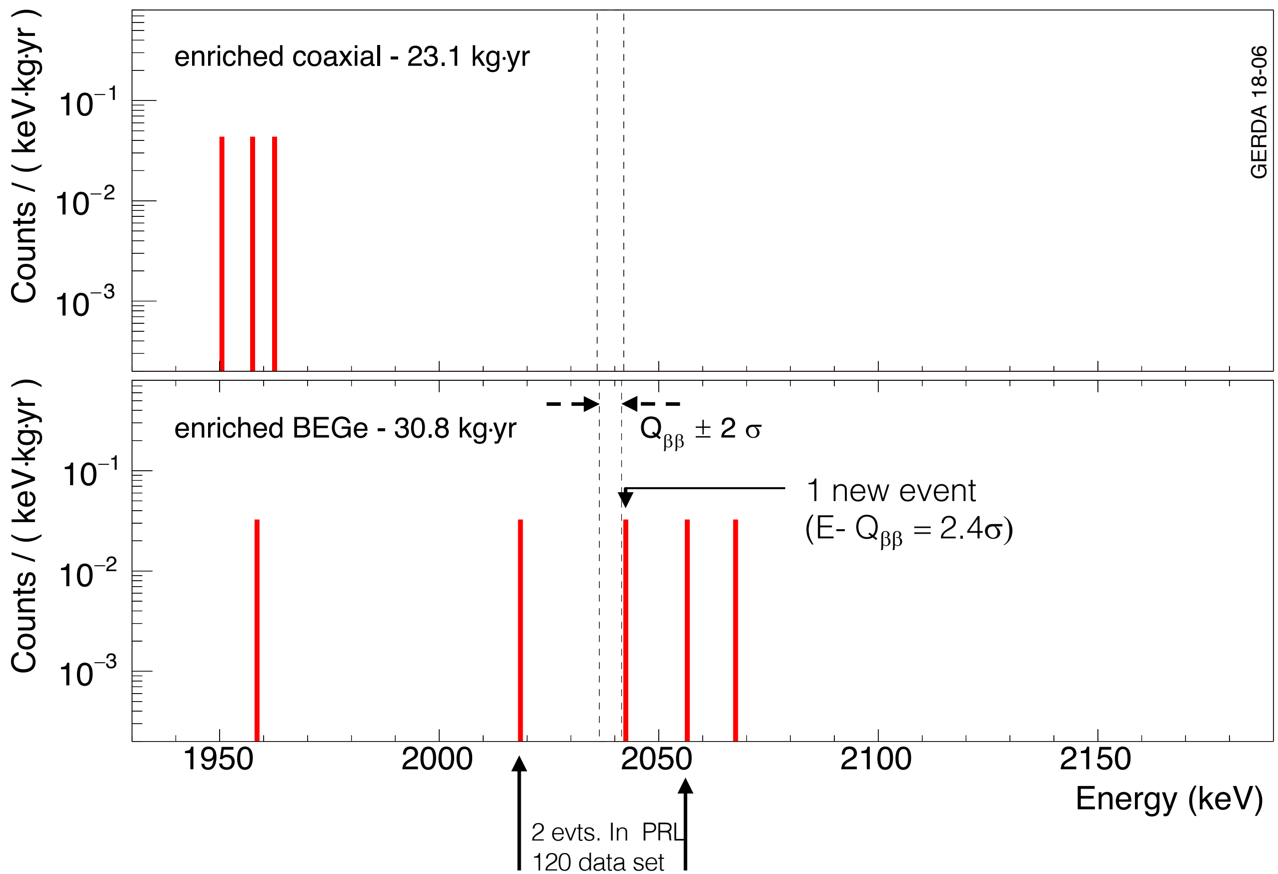
The full energy range – after PSD and LAr



Unblinded data



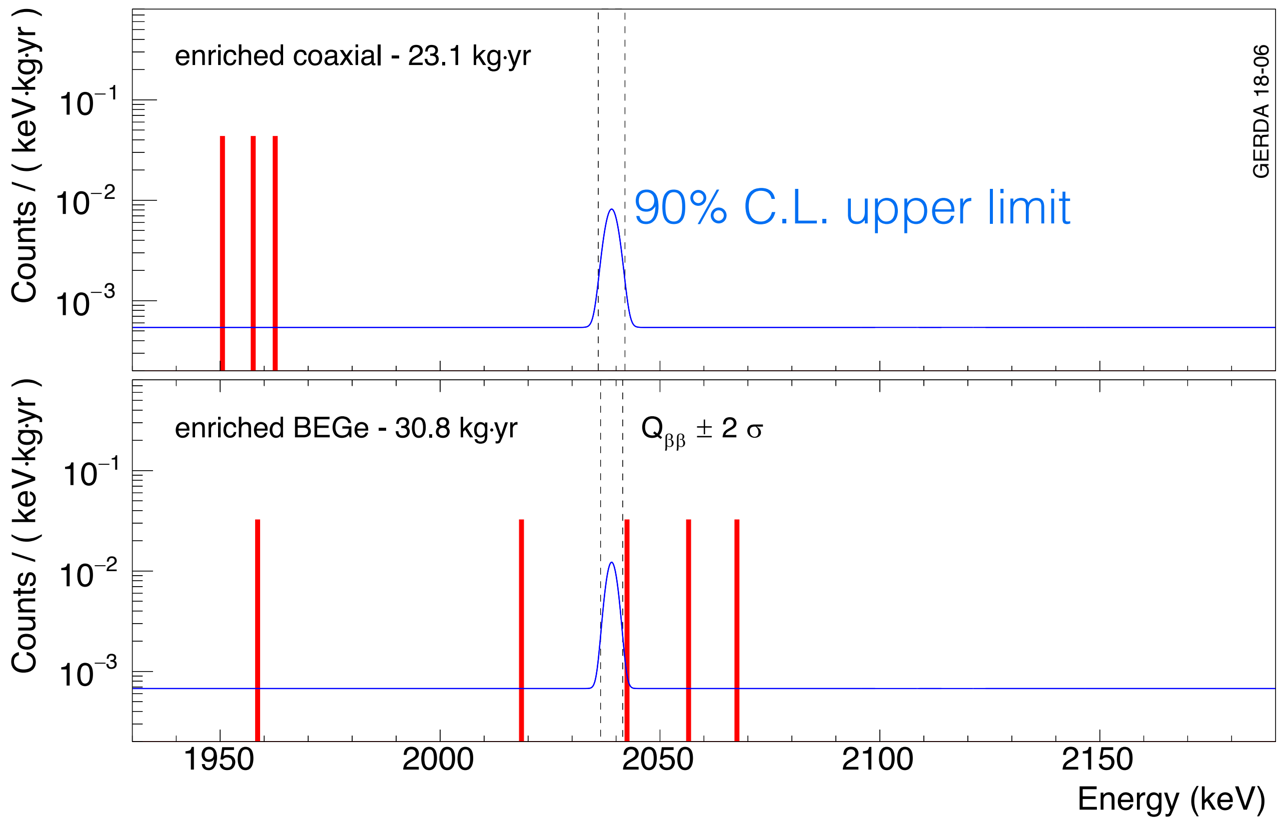
Background index*:

$(5.7^{+4.1}_{-2.6} \cdot 10^{-4})$ counts/(keV·kg·yr)

$(5.6^{+3.4}_{-2.4} \cdot 10^{-4})$ counts/(keV·kg·yr)

*: in 1930-2190 keV excluding ±5 keV at $Q_{\beta\beta}$ and lines at 2104 keV and 2119 keV.

Fit to full GERDA data sets



Frequentist:
Best fit $N^{0\nu} = 0$
$T^{0\nu}_{1/2} > 0.9 \cdot 10^{26}$ yr (90% C.L.)
Median sensitivity (NO Signal)
$T^{0\nu}_{1/2} > 1.1 \cdot 10^{26}$ yr (90% C.L.)
63% of MC realizations yield limit stronger than data

$m_{\beta\beta} < 0.11 - 0.25$ eV,
with NME: 2.8–6.1, $g_A = 1.27$

Bayesian:
$T^{0\nu}_{1/2} > 0.8 \cdot 10^{26}$ yr (90% C.I.)
Median sensitivity:
$T^{0\nu}_{1/2} > 0.8 \cdot 10^{26}$ yr (90% C.I.)
59% of MC realizations yield limit stronger than data

Bayes factor: P(H1)/P(H0) = 0.054
where:
H1:signal+background hypothesis
H0: background only hypothesis

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

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

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

Foundations: GERDA & MAJORANA

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

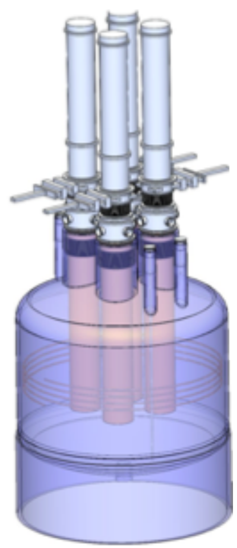
The LEGEND program

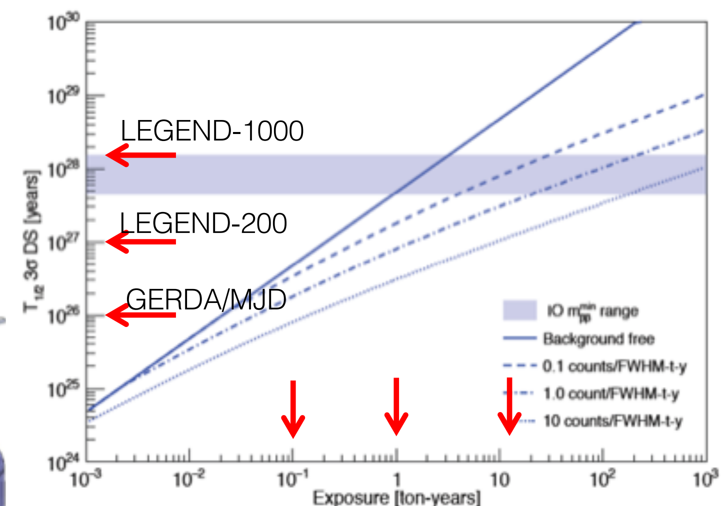
LEGEND-200 (first phase):

- 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
- Isotope procurement ongoing
- Start in 2021

LEGEND-1000 (second phase):

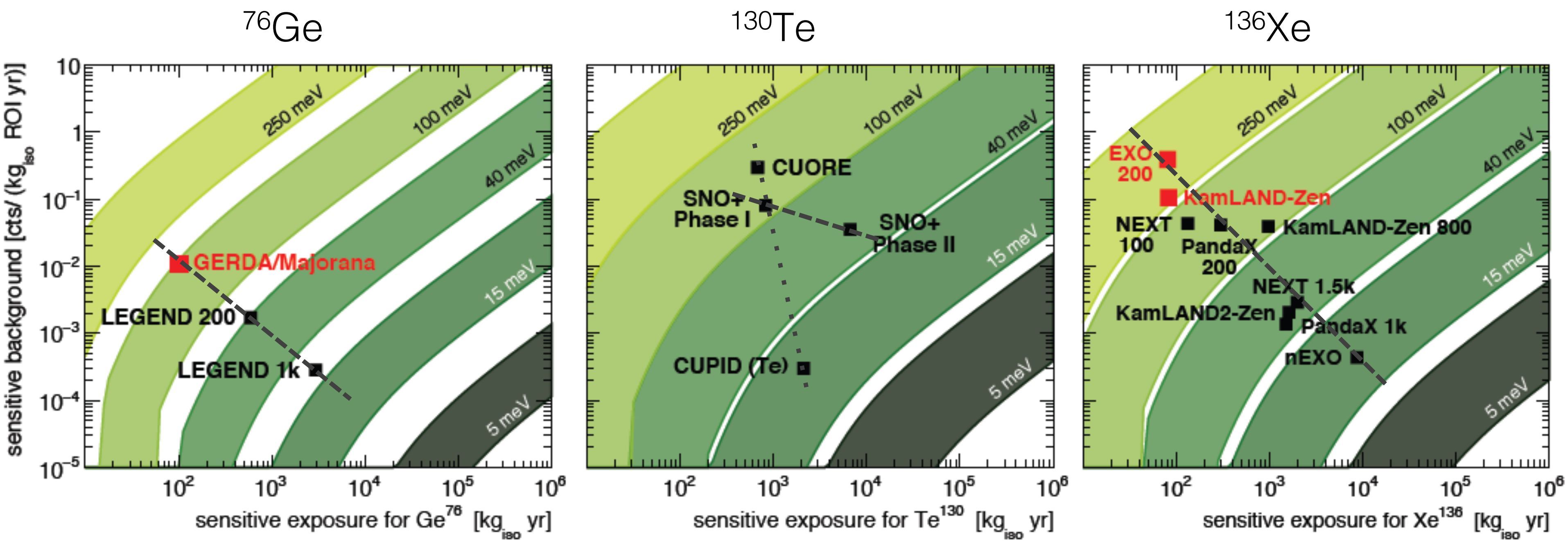
- 1000 kg of detectors (deployed in stages)
- BI <0.1 cts/(FWHM t yr)
- Location tbd
- Design exposure 12 t yr
- 1.2×10^{28} yr





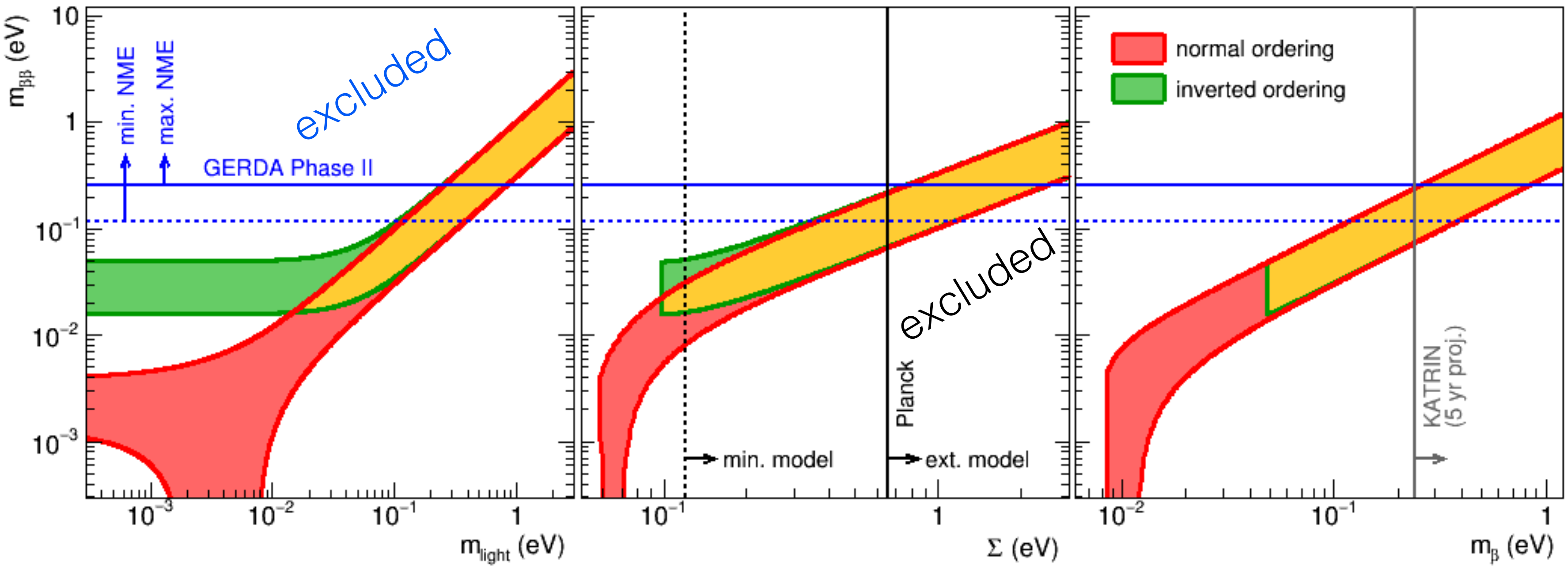
Discovery sensitivities

(5 yr live time)



Agostini, Benato, Detwiler arXiv:1705.02996

Probing quasi-degenerate Majorana masses



0νββ cosmology tritium beta decay

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25th anniversary Rencontres du Vietnam

Summary & Outlook

- Strong activities world-wide for preparation of **ton-scale** experiments
- **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 most **reasonable extrapolations** w.r.t. to detector performance and background reduction
- **Staging** largely adopted to produce physics results & minimize (project) risks
- Experimental design for **discovery** (not limit setting!)