Neutrinoless double beta decay

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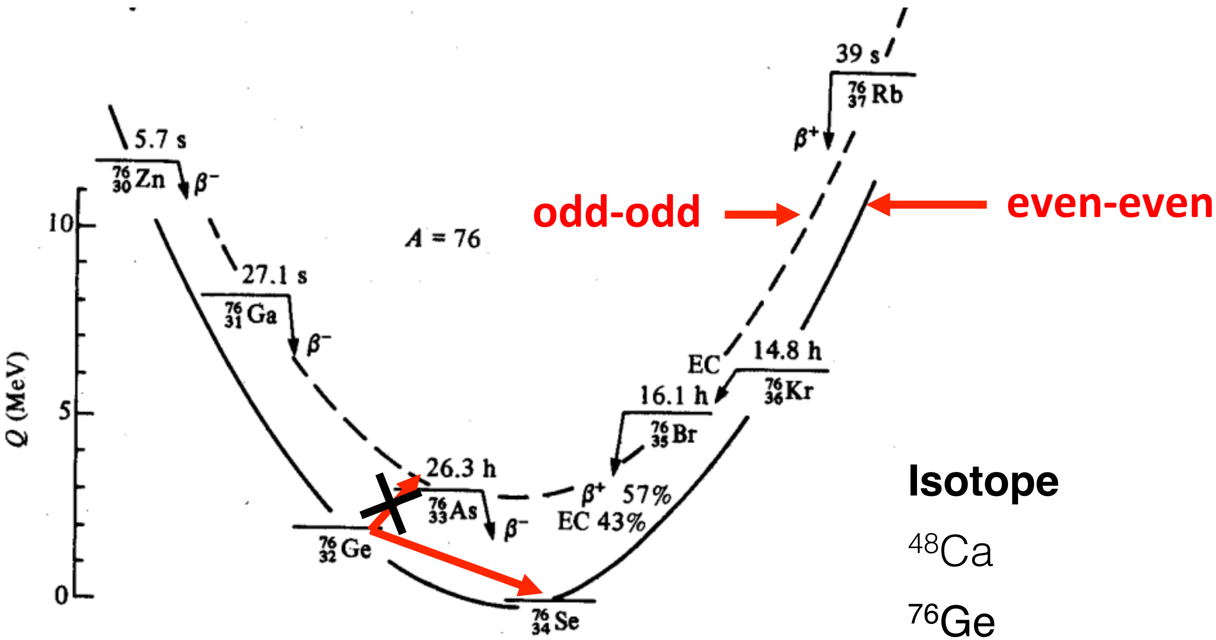
TECHNISCHE UNIVERSITÄT MÜNCHEN

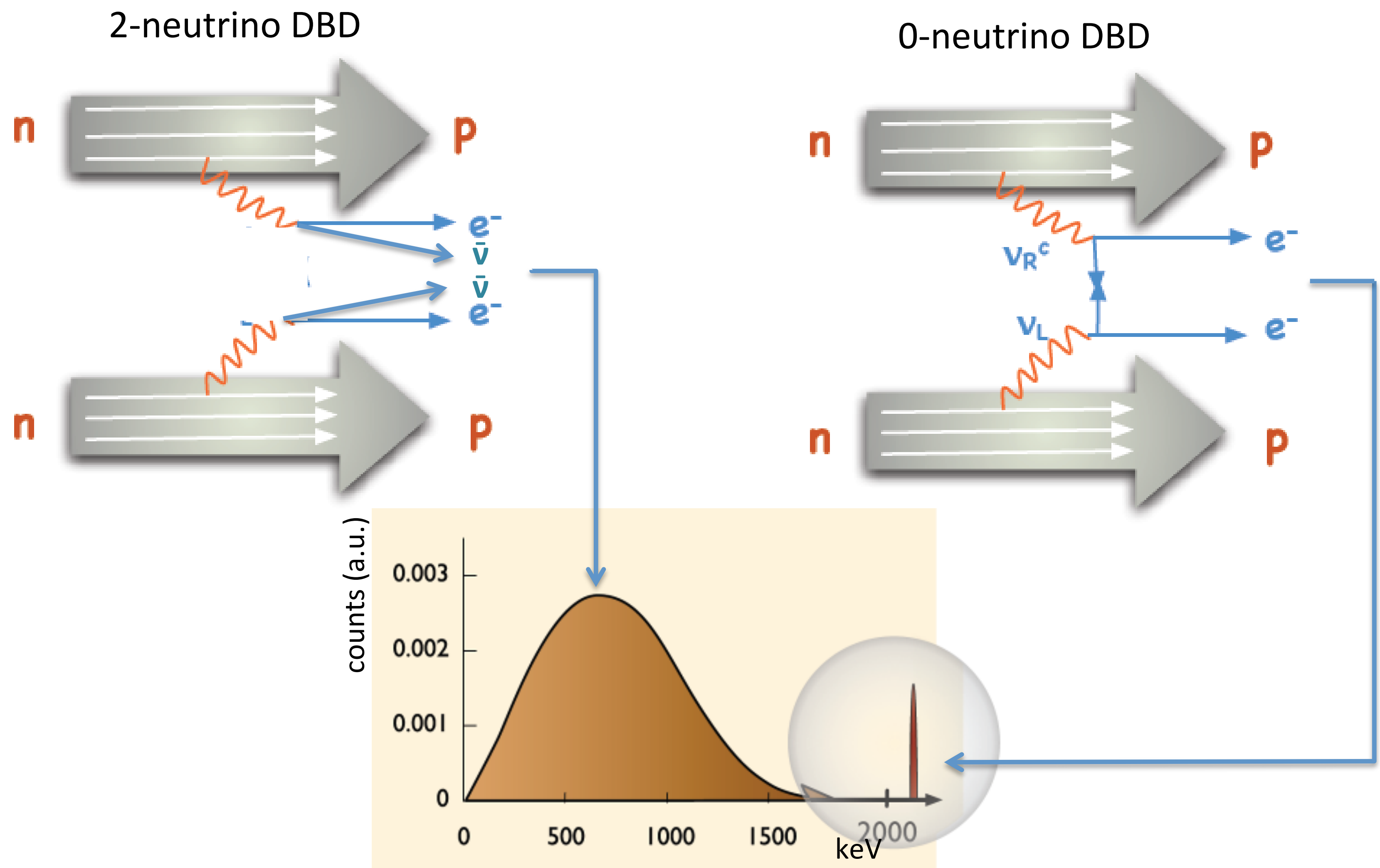
SFB 1258 Neutrinos Dark Matter Messengers

Double beta decay isotopes



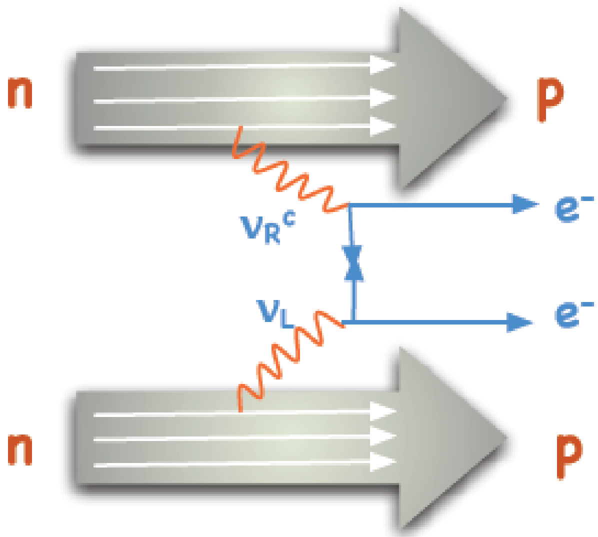
Isotope	Nat ab.	$Q_{\beta\beta}$
^{48}Ca	0.19 %	4262.96(84) keV
^{76}Ge	**7.6%**	**2039.04(16) keV**
^{82}Se	**8.7%**	**2997.9(3) keV**
^{96}Zr	2.8%	3356.097(86) keV
^{100}Mo	**9.6%**	**3034.40(17) keV**
^{116}Cd	7.5%	2813.50(13) keV
^{130}Te	**34.5%**	**2526.97(23) keV**
^{136}Xe	**8.9%**	**2457.83(37)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

2νββ and 0νββ decay



2-electron spectra

0νββ decay and neutrino mass



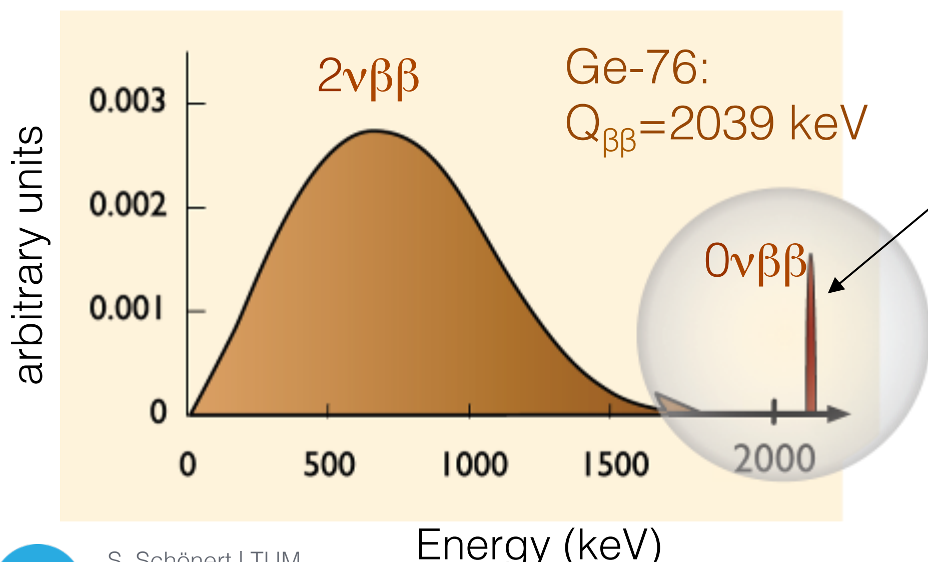
Expected decay rate:

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

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



<u>Experimental signatures:</u>

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

<u>Discovery would imply:</u>

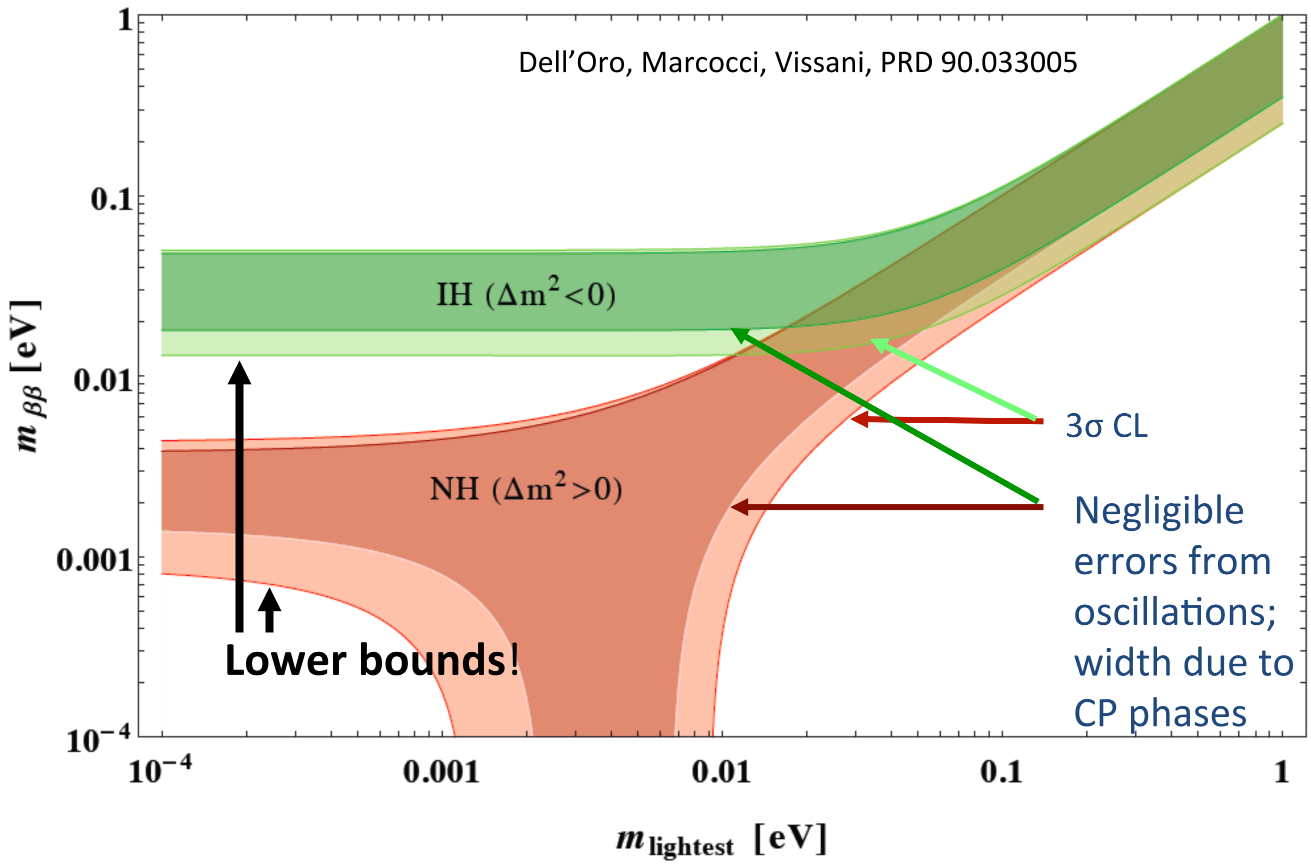
- lepton number violation ΔL = 2
- ν's have Majorana character
- mass scale
- physics beyond the standard model

0νββ: Range of m_{ee} from oscillation experiments

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

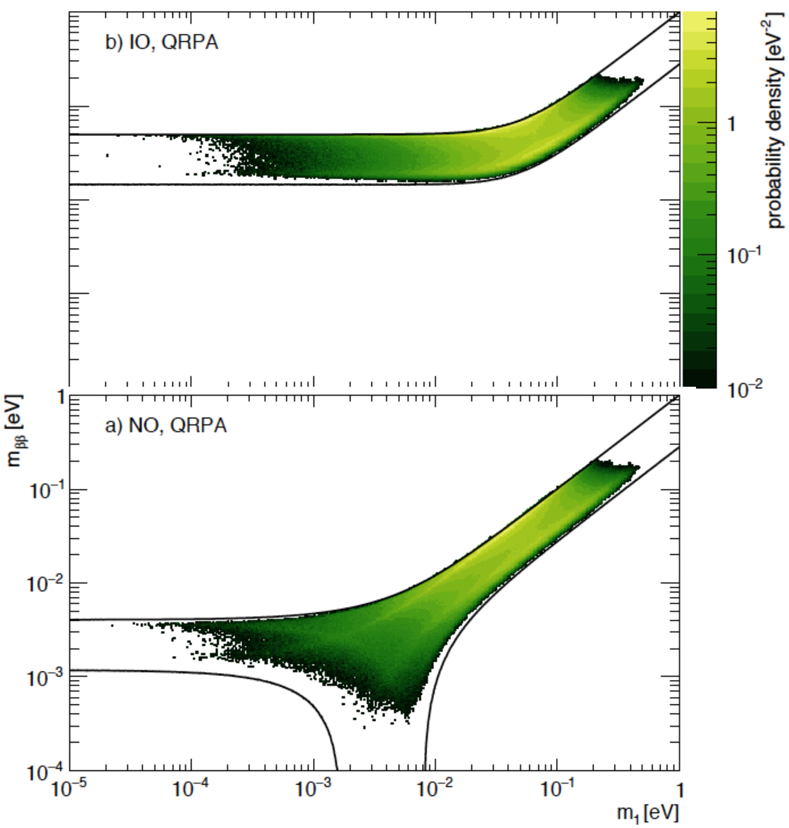
from oscillation experiments

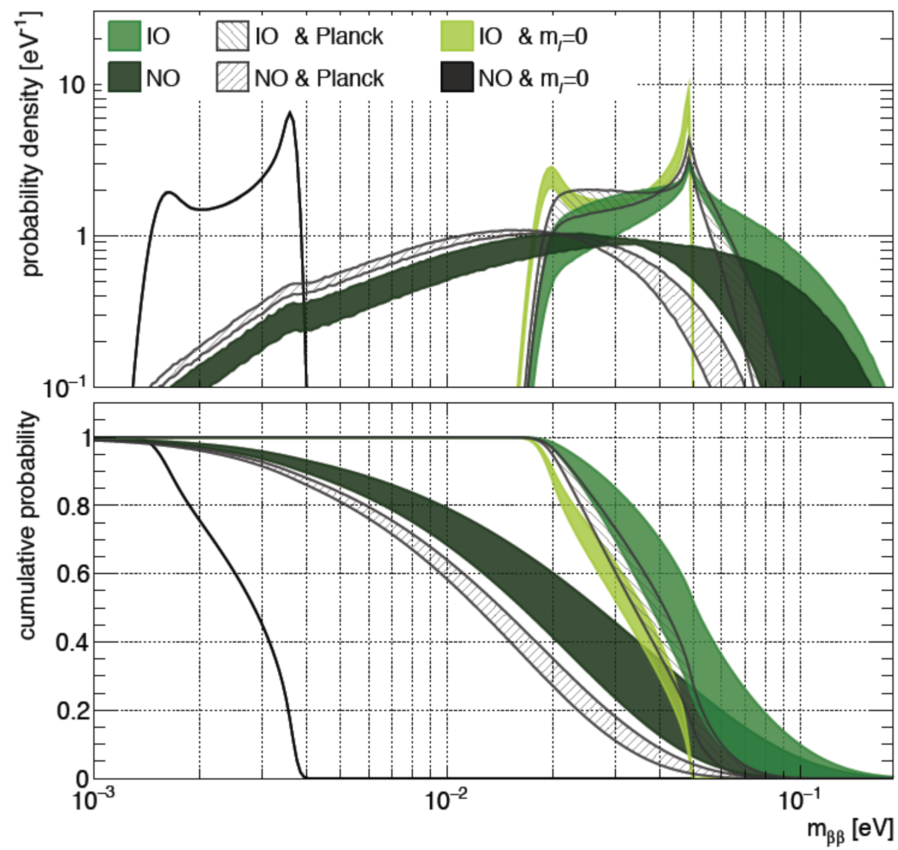
Goal of next generation experiments:



Discovery probabilities

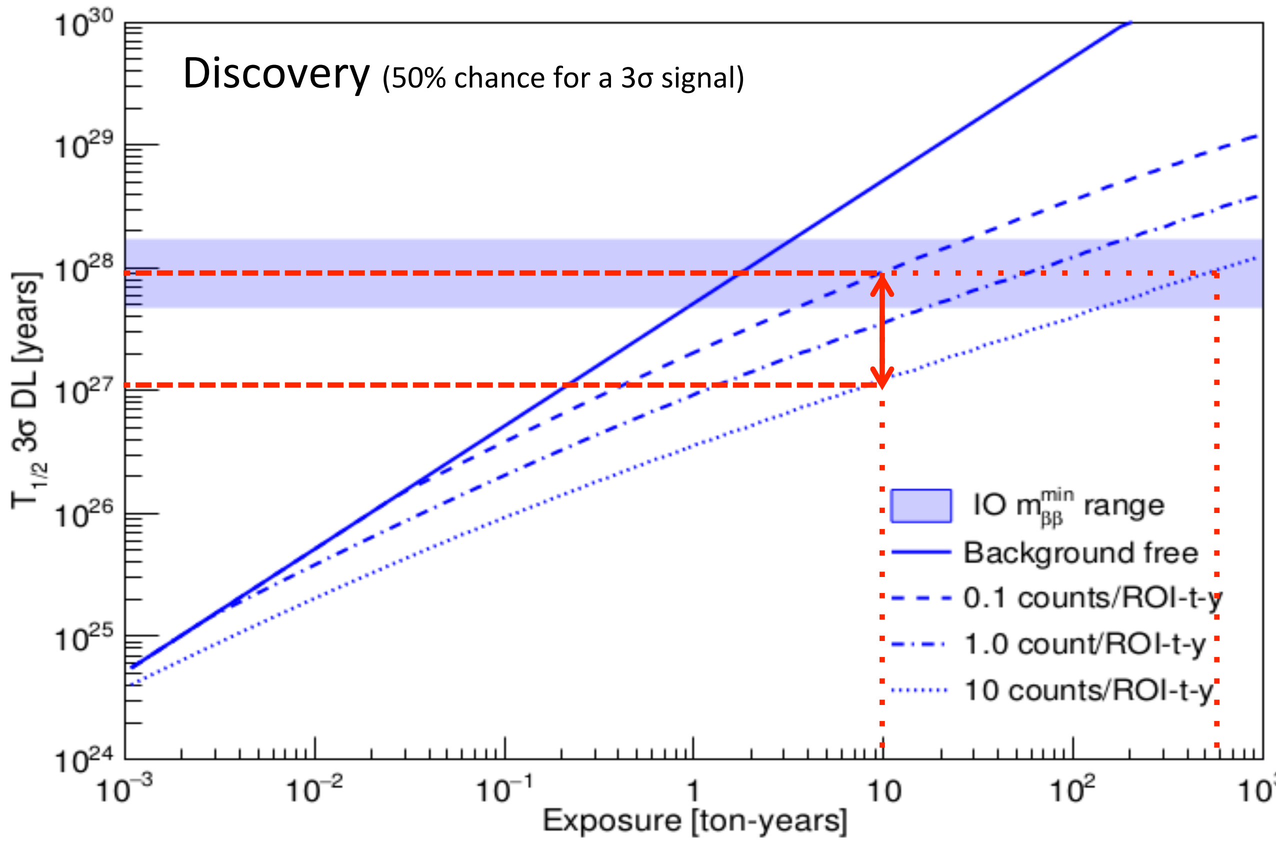
- Global Bayesian analysis including ν-oscillation, m_β $m_{\beta\beta}$, Σ
- Priors:
  - Majorana phases (flat)
  - m_1 (scale invariant)





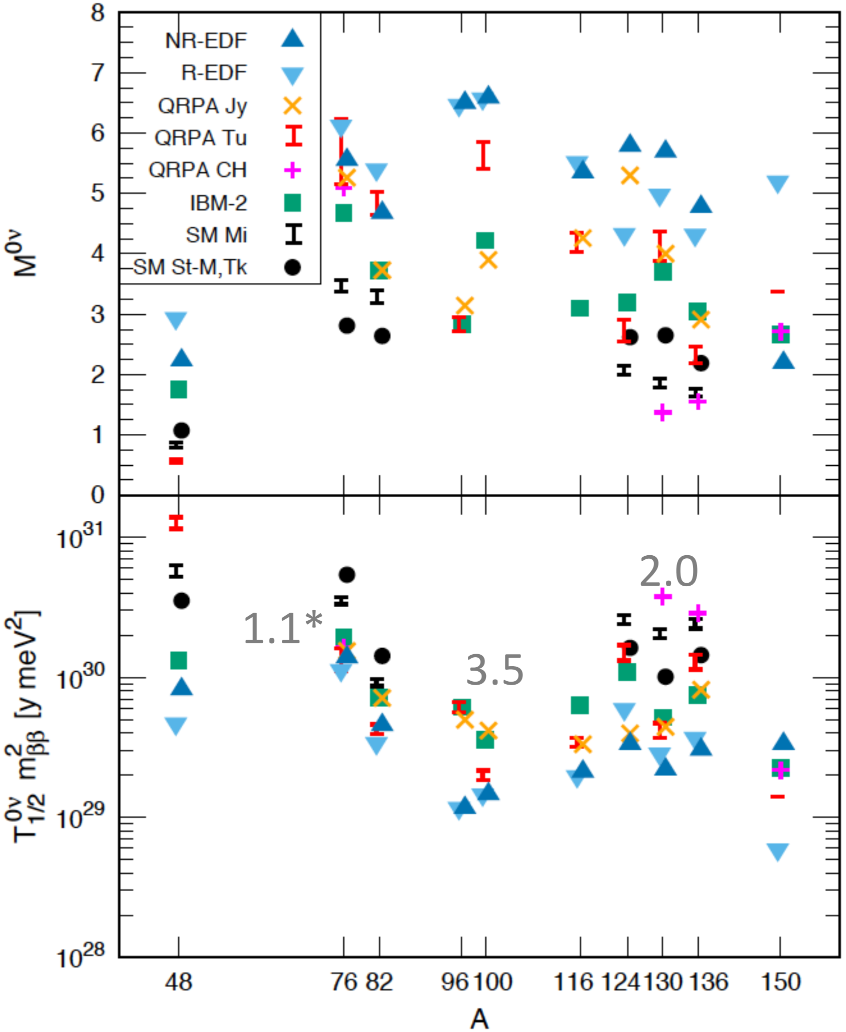
Agostini, Benato, Detwiler arXiv:1705.02996

Discovery sensitivity vs. background



Courtesy J. Detwiler

Nuclear matrix elements



Spread about x2

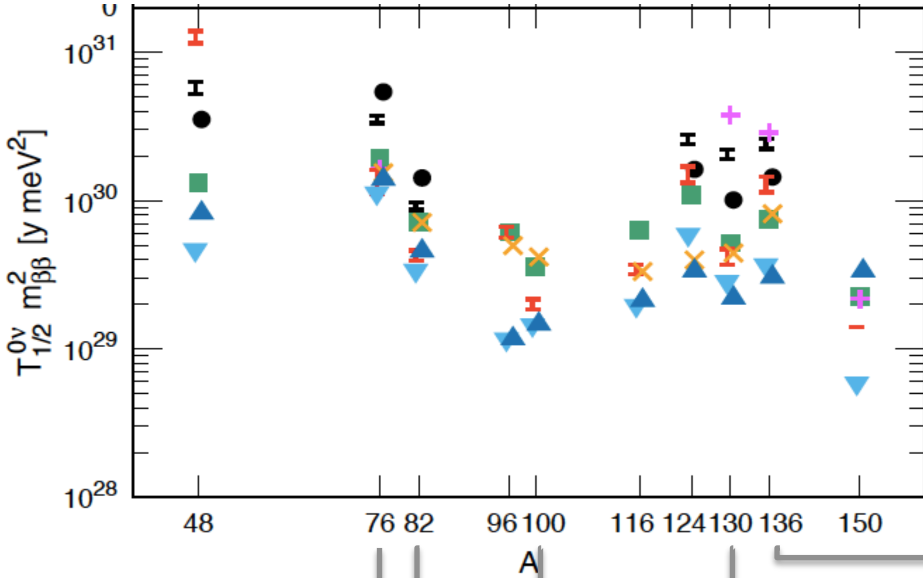
No isotope significantly preferred when comparing decay rate per mass

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

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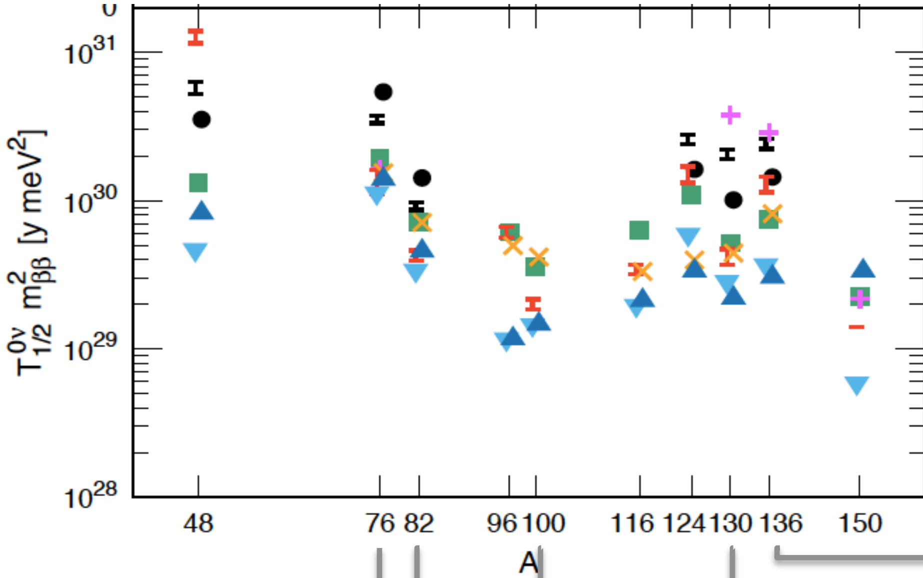

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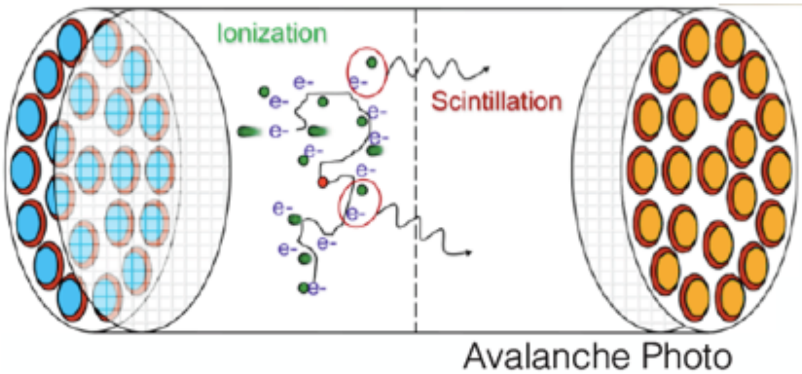
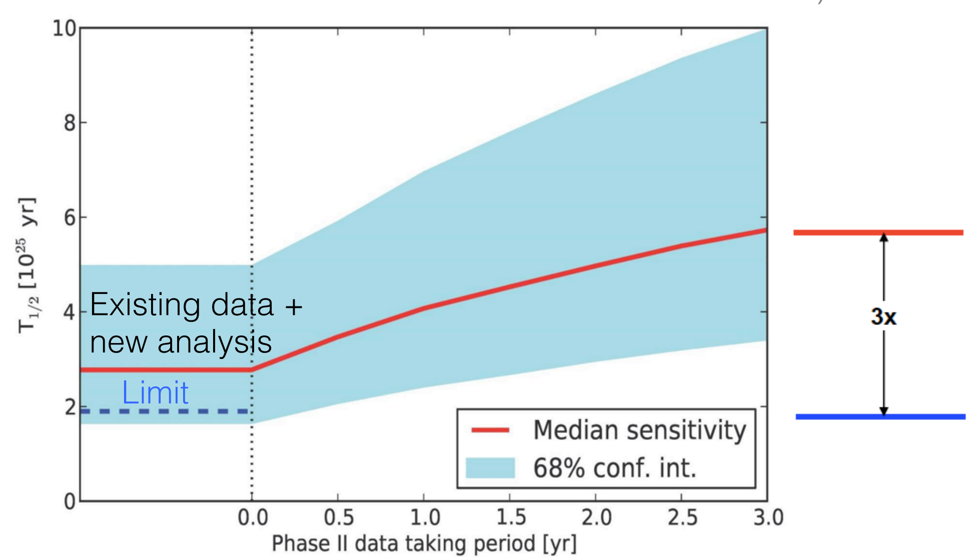
Xenon Experiments: EXO-200



- ^{136}Xe: $Q_{\beta\beta}$ = 2458 keV
- Liquid Xe TPC (80.6% ^{136}Xe)
- 75 kg ^{136}Xe in FV
- Phase I completed: 122 kg yr
- $T_{1/2}^{0\nu\beta\beta}$>1.1×10^{25} yr
- Sensitivity: 1.9×10^{25} yr

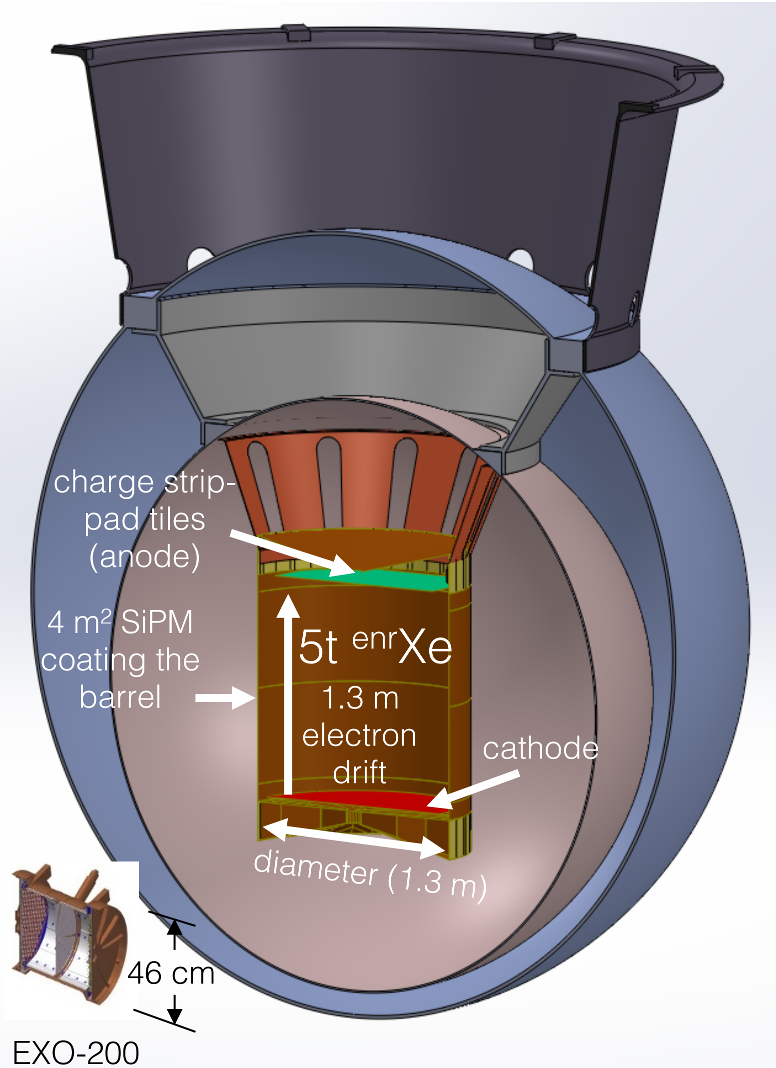
Nature 510 (2014)

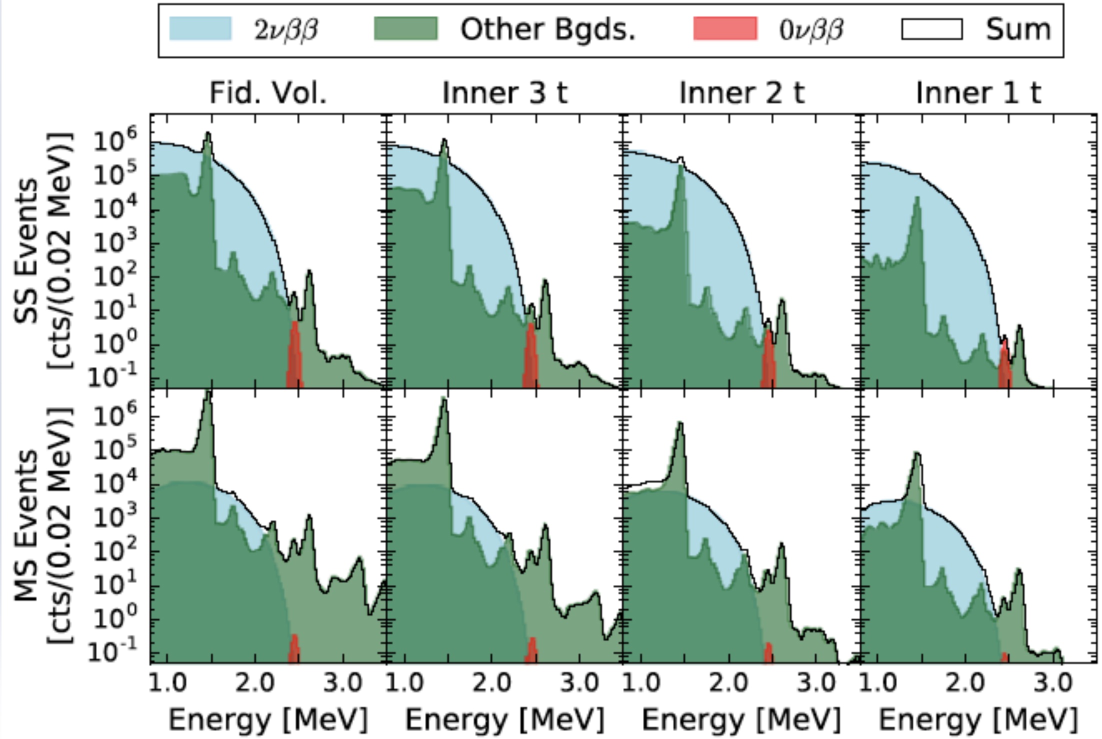
- Phase II: Jan 2016 with improved detector performance: e.g. σ/E: 1.6% (Phase I) => 1.3% (Phase II); Rn reduction
- New results by Caio Licciardo on Friday



Courtesy G. Gratta

Xenon Experiments: nEXO



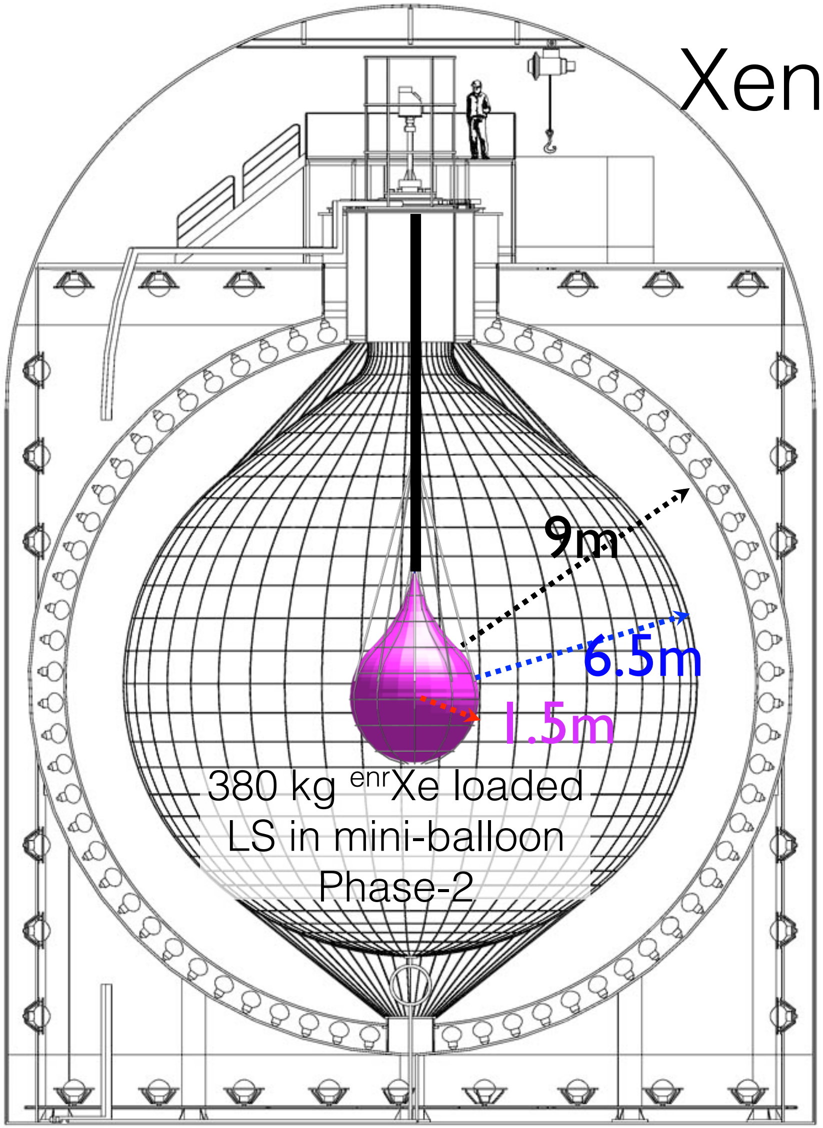


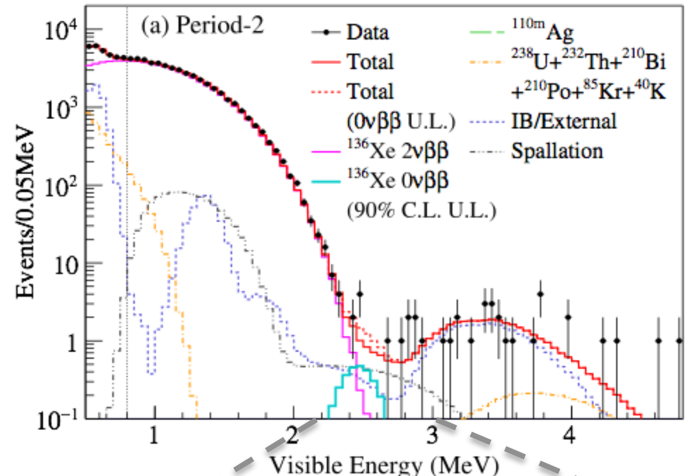
Discovery sensitivity (3σ, 50%) after 10 yr
$T_{1/2}^{0\nu\beta\beta}$ = 5.5x10^{27} yr

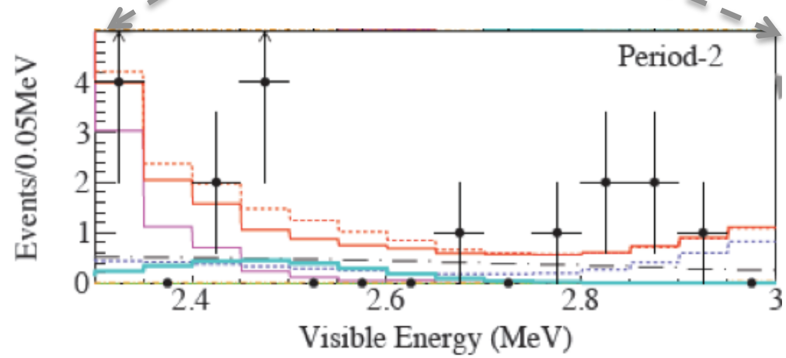
If ^{136}Ba-tagging can be implemented:
$T_{1/2}^{0\nu\beta\beta}$ = 1.6x10^{28} yr

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

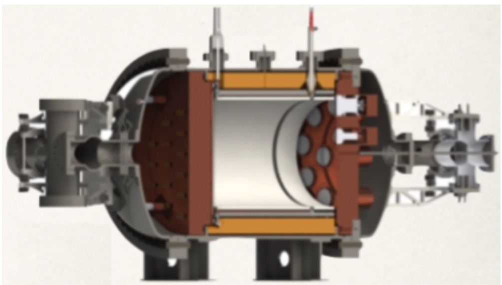
Courtesy K. Inoue

PRL117, 082503 (2016)

Xenon Experiments: next

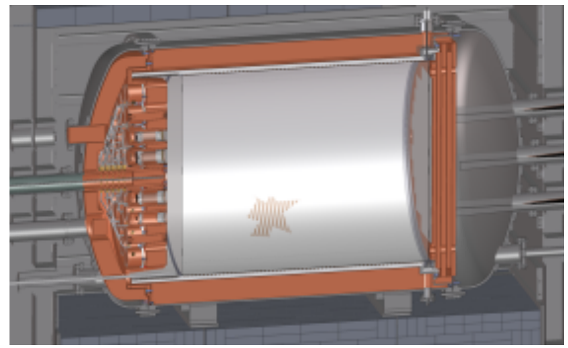
^{136}Xe high-pressure (10-15 bar) TPC

NEXT-NEW (5 kg) 2015-2018



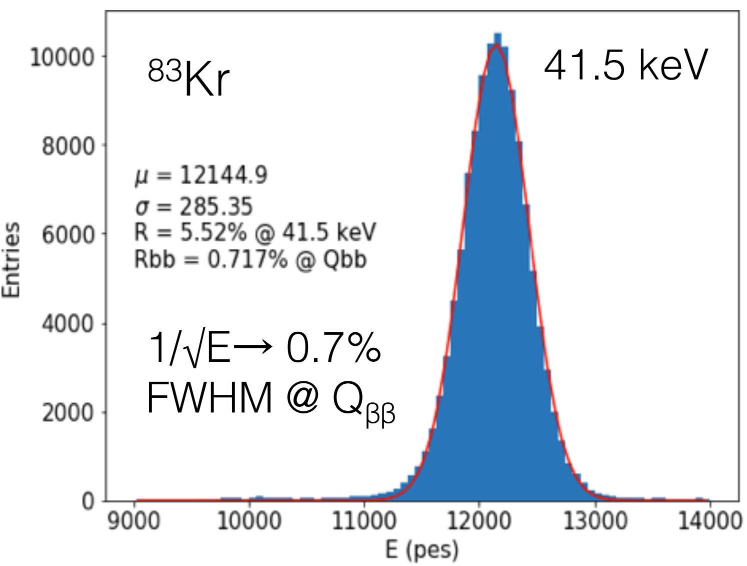
Underground & radio-pure operations, background, 2νββ

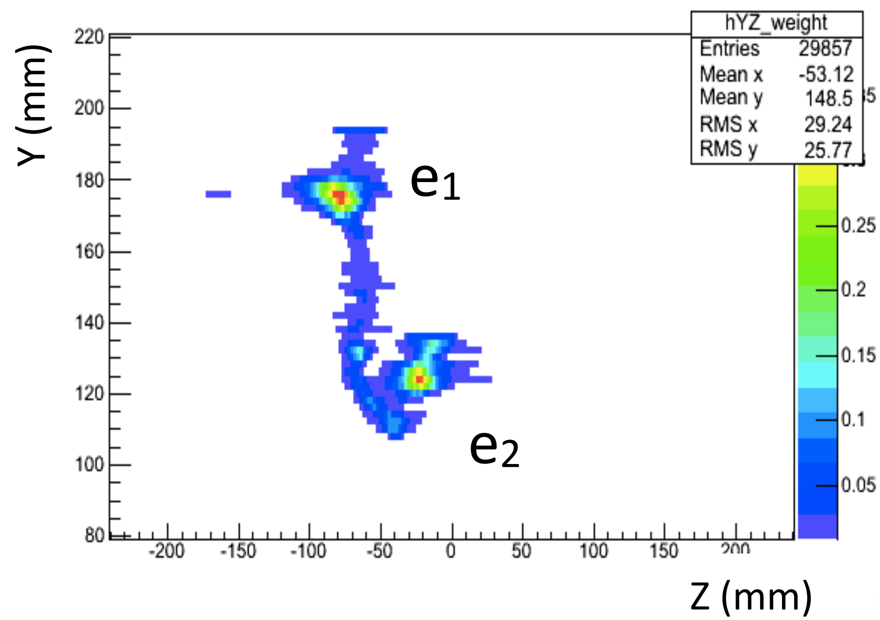
NEXT-100 (100 kg) 2018-2020's



0νββ search

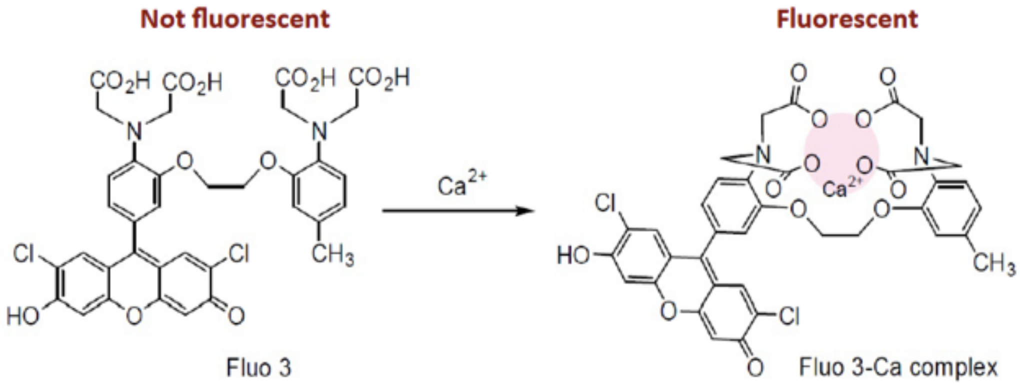
→ NEXT-ton

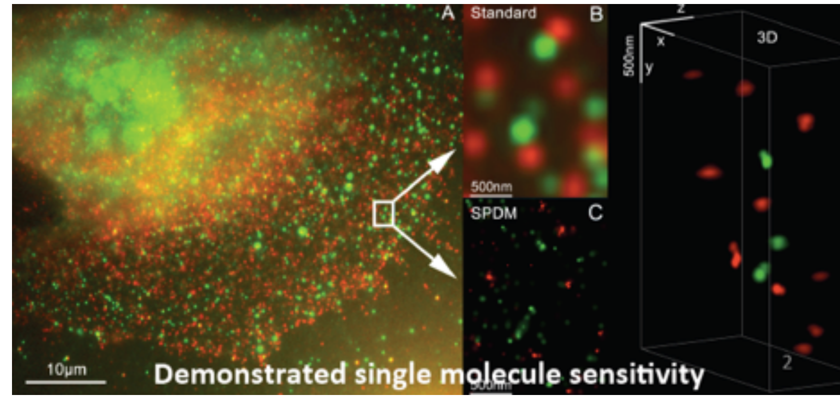


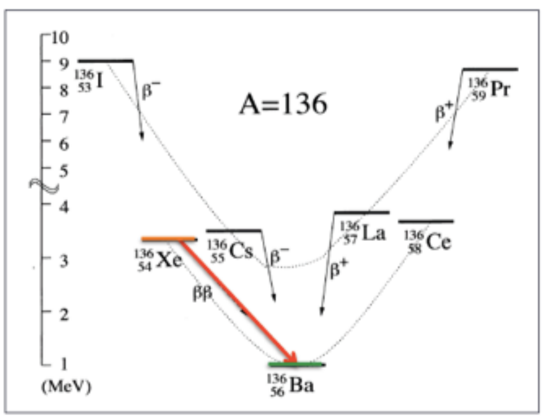


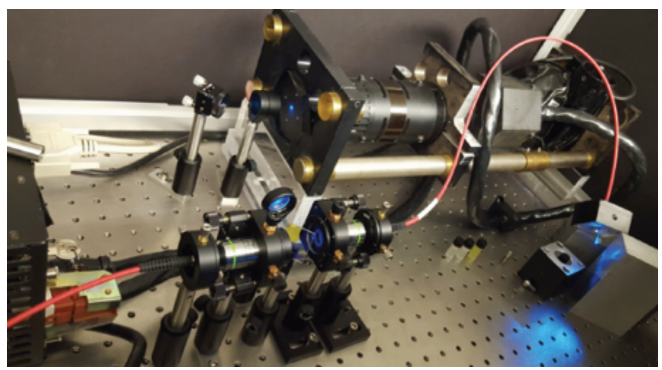
Courtesy JJ Gomez Cadenas

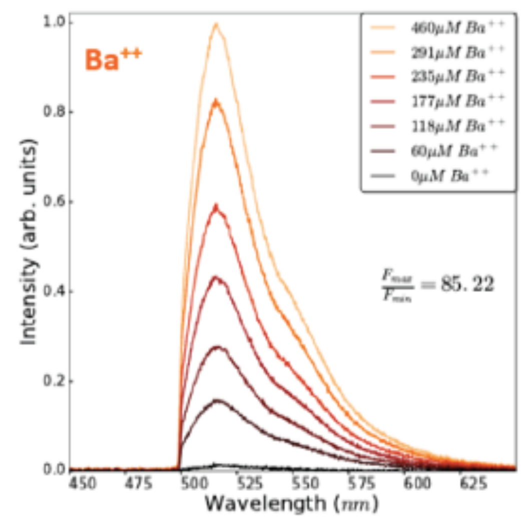
Ba tagging for NEXT





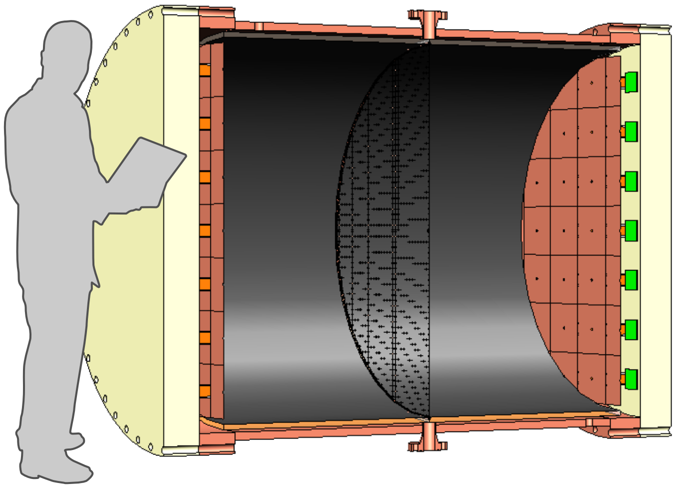


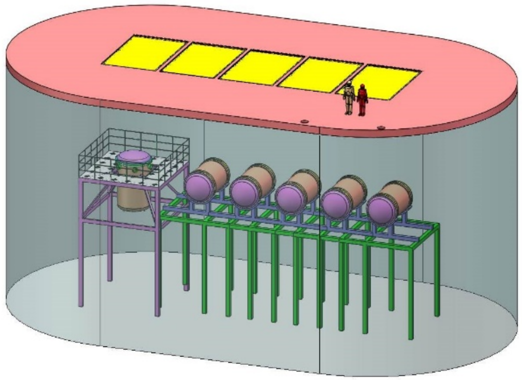




Courtesy Michel Sorel

Xenon Experiments: PandaX-III

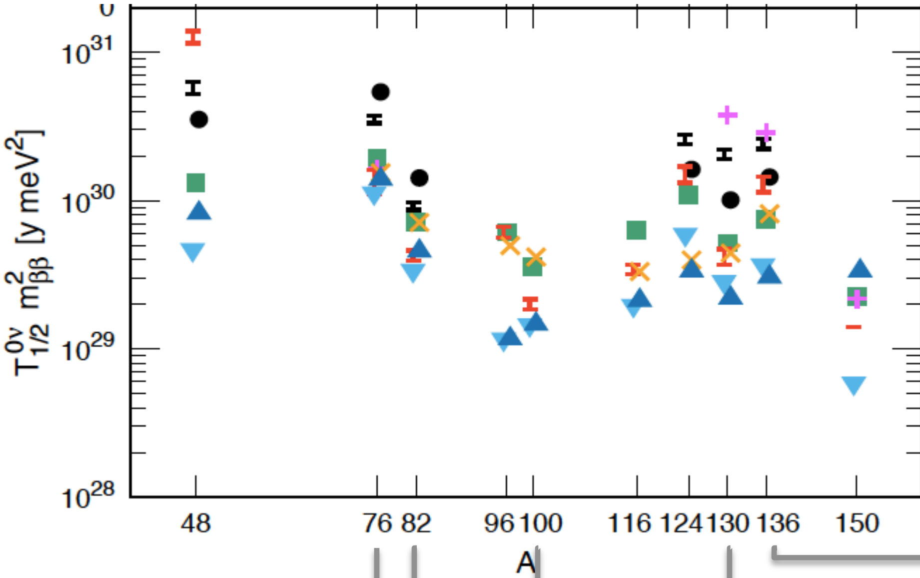




- First 200-kg module:
  - Microbulk Micromegas for charge readout
  - 3% FWHM, 1 x 10^{-4} c/keV/kg/y in the ROI
- Ton-scale:
  - Four more modules with upgraded charge readout and better low-background material screening.
  - 1% FWHM, 1 x 10^{-5} c/keV/kg/y in the ROI

Courtesy Ke Han

Experiments



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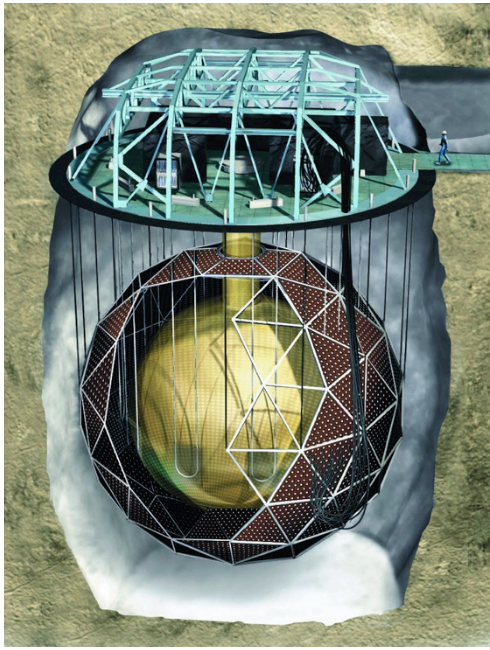
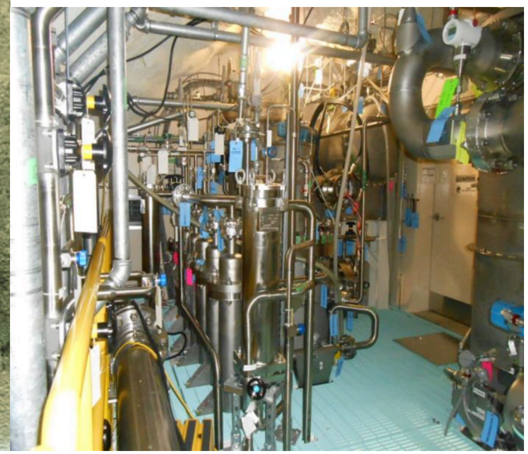
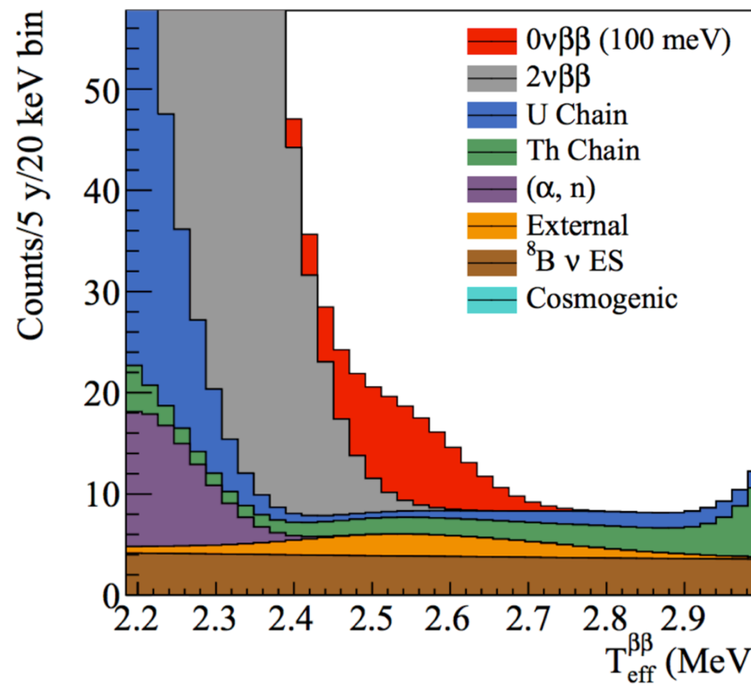
SNO+





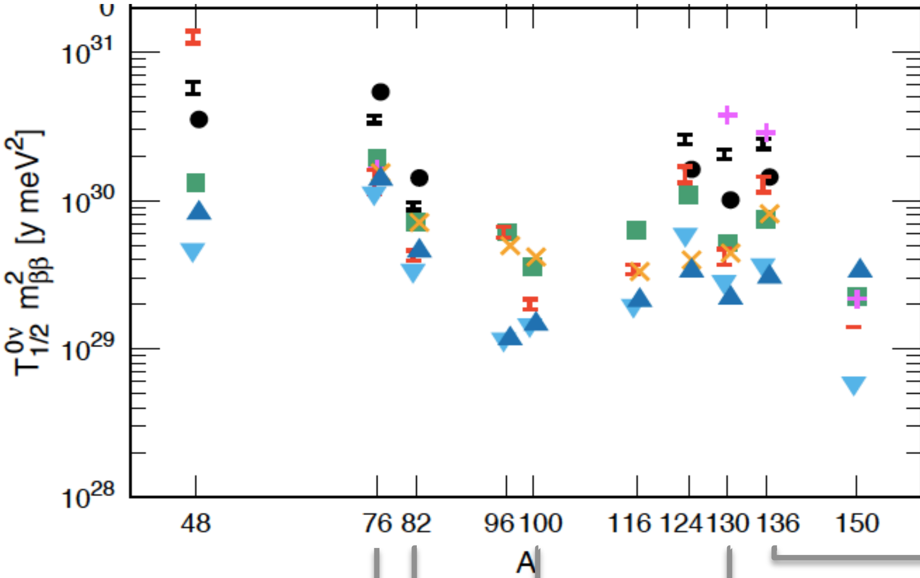
Filling with unloaded liquid scintillator later this year

- 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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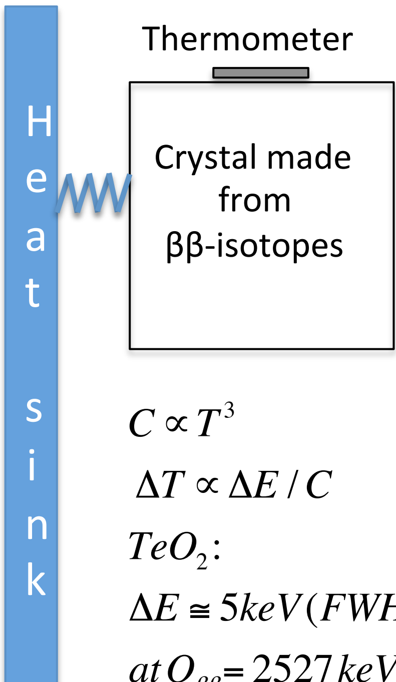
Cryogenic Detectors: CUORE



$C \propto T^3$

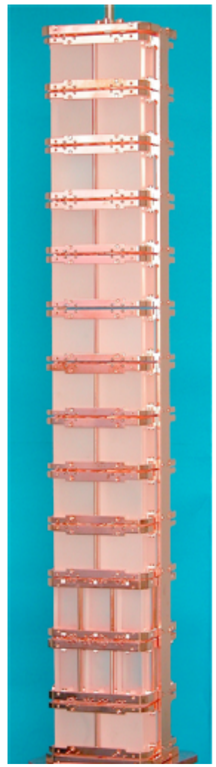
$\Delta T \propto \Delta E / C$

TeO_2:

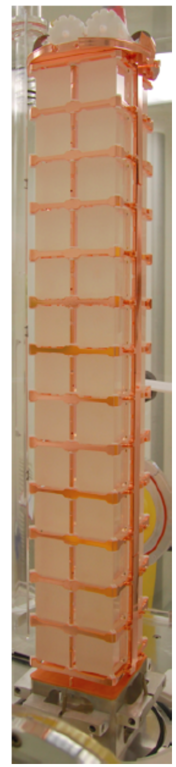
$\Delta E \cong 5 keV (FWHM)$

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

Cuoricino
2003

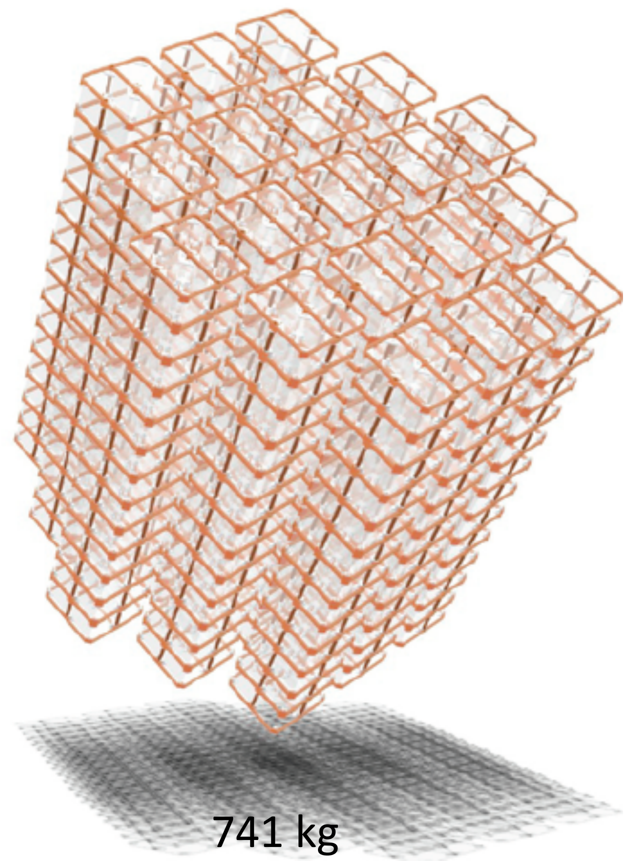


Cuore-0
2012



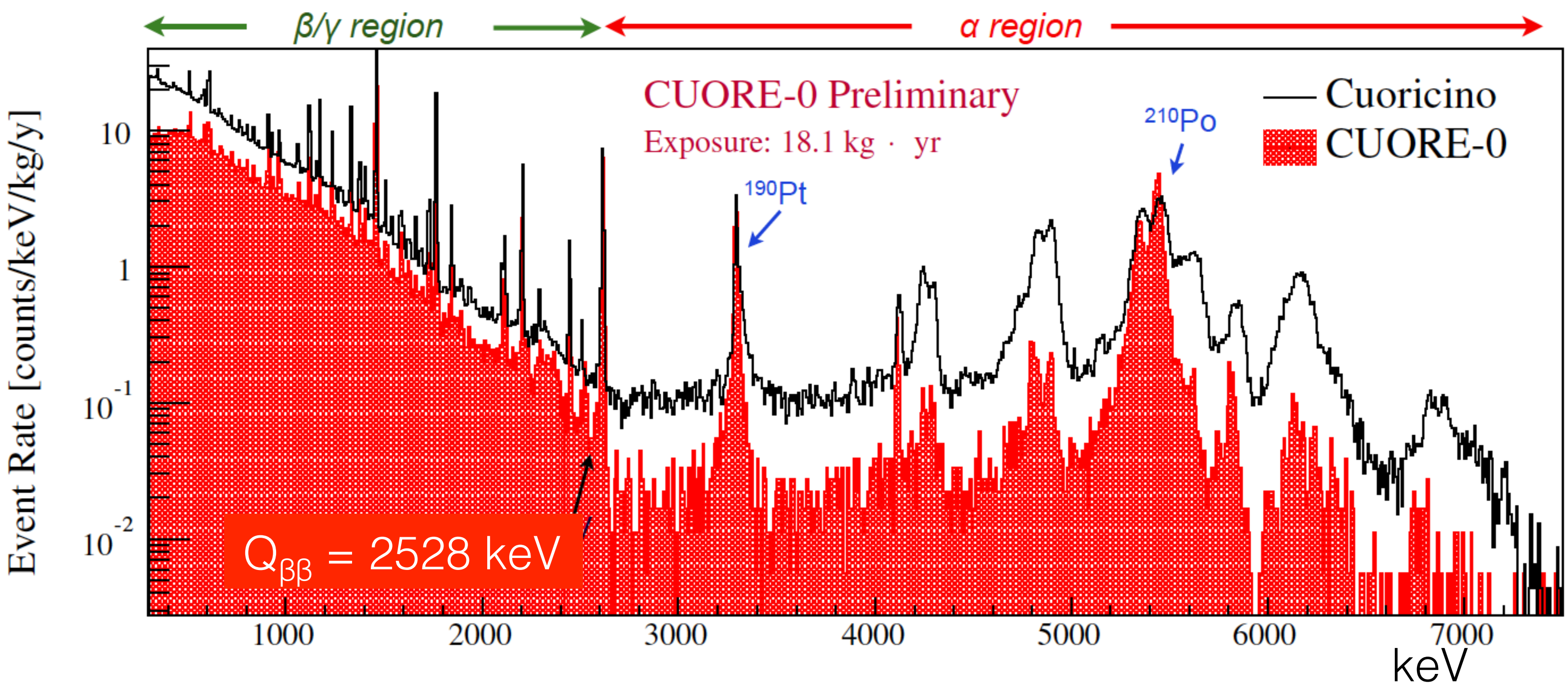
39 kg
(11 kg ^{130}Te)

CUORE
2016



741 kg
(206 kg ^{130}Te)

Cryogenic Detectors: CUORE

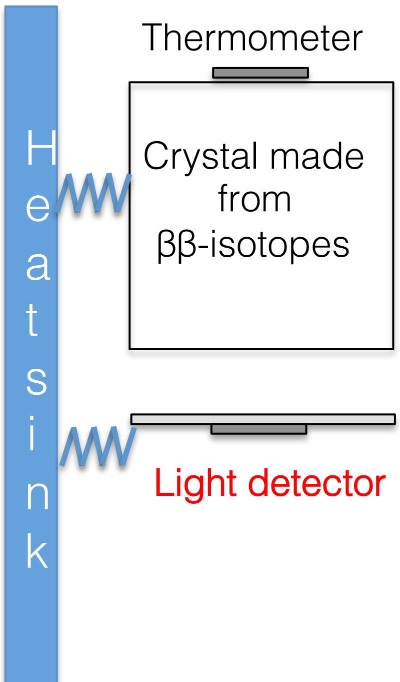


CUORE-0: 0.06 cts/(keV kg yr) => Cuore expectation ≈0.01 cts/(keV kg y)

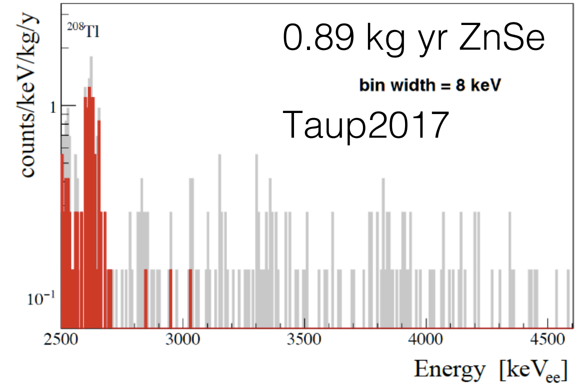
First **CUORE results** on Friday by O. Cremonesi

Courtesy O. Cremonesi

Cryogenic Detectors: CUPID

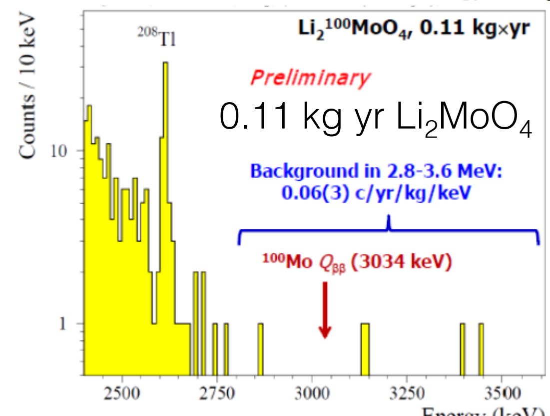


CUPID-0: ZnSe
(ex Lucifer)
Demonstrator @ LNGS
5.2 kg ^{82}Se, 2017



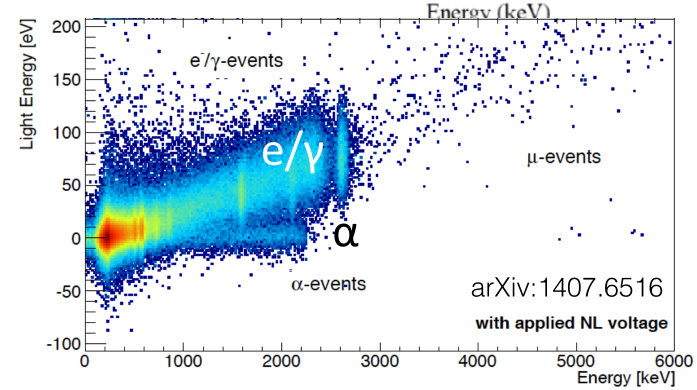
Courtesy
S. Pirro

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

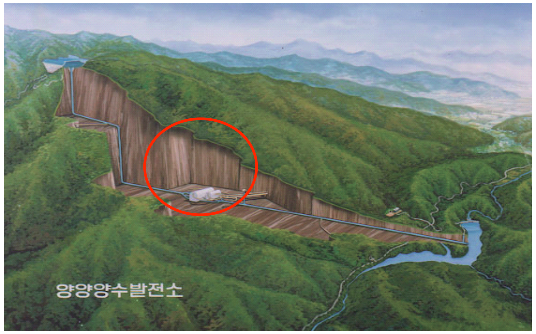


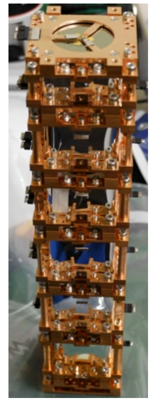
Courtesy
A. Giuliani

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

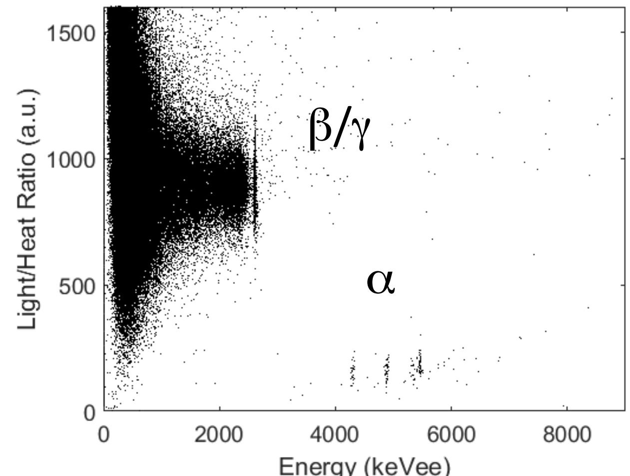


Cryogenic Detectors: AMoRE



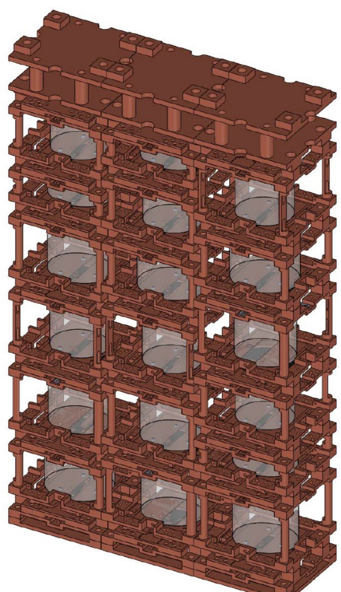


AMoRe-pilot project @ YangYang
6 crystals (1.8 kg)
$^{40}Ca^{100}MoO_4$

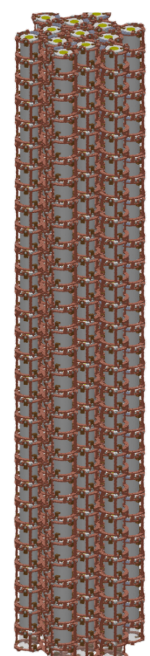


^{100}Mo procurement ongoing (100 kg)

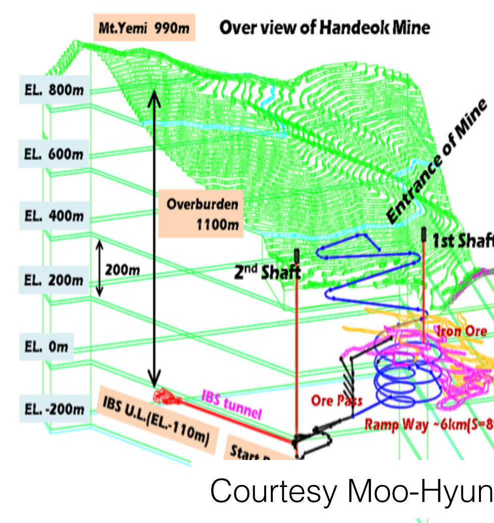
AMoRE-1
5 kg
2018



AMoRE-II
200 kg
2020

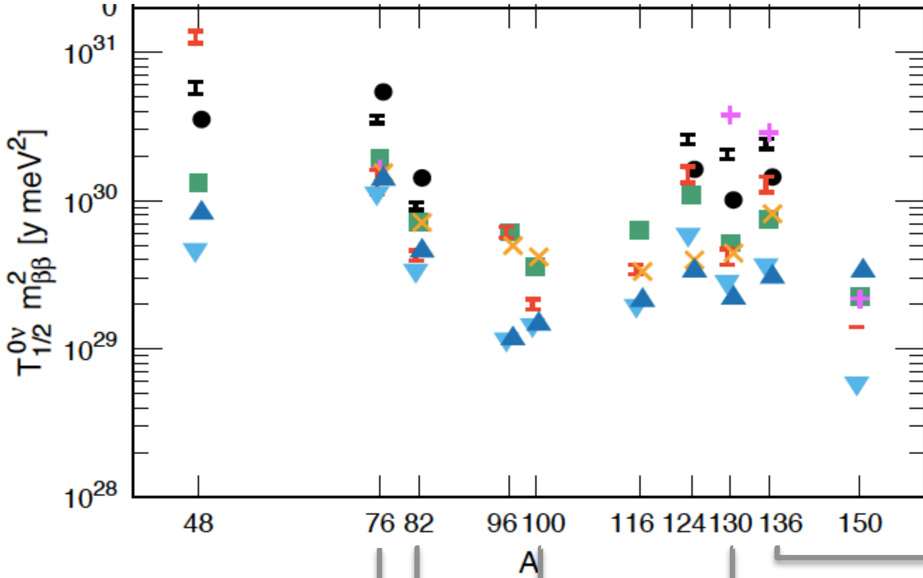


AMoRE @ Handeok ARF



Courtesy Moo-Hyun Lee

Experiments



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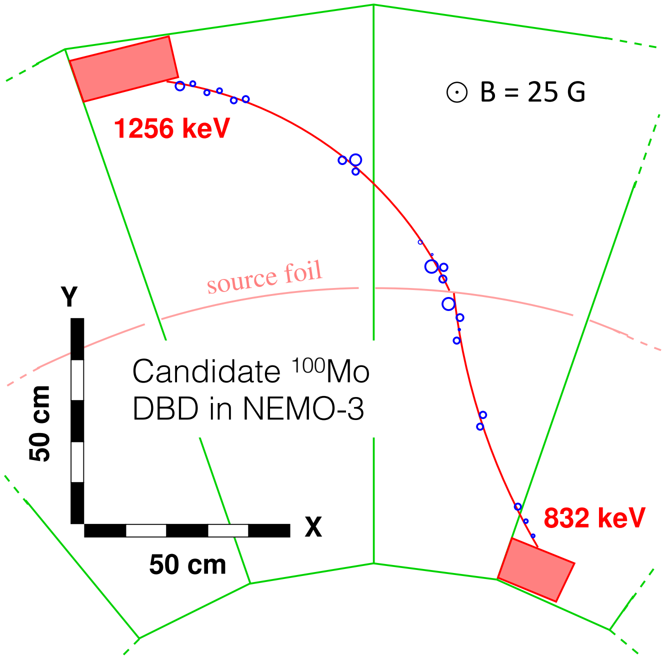
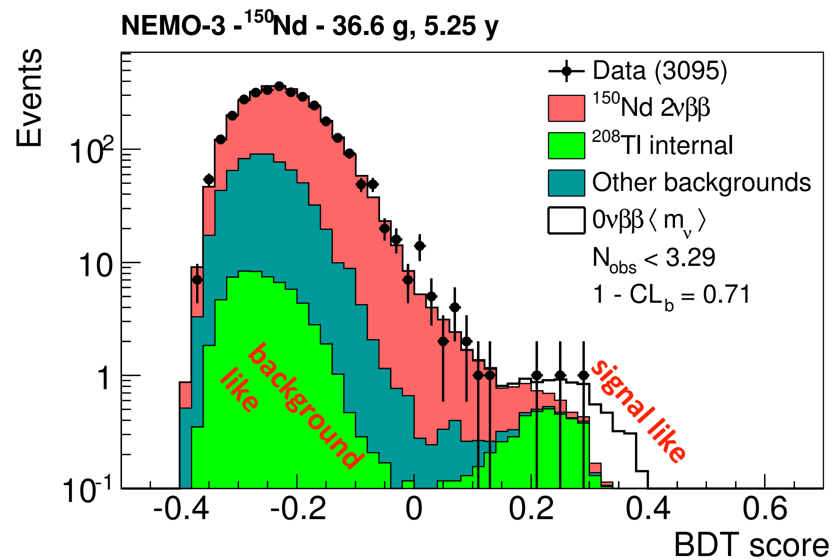
NEMO-3



Recent results from ^{150}Nd



$$T_{1/2}^{0\nu\beta\beta} > 2.0 \times 10^{22}\,\mathrm{yr}\ (90\%\ \mathrm{C.L.})$$

PRD 94, 072003 (2016)

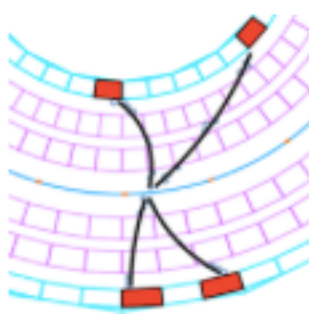
NEMO-3: 2003 – 2011 @ LSM

^{100}Mo (7kg) ; ^{82}Se (1kg)

^{150}Nd, ^{96}Zr, , ^{130}Te

^{48}Ca: PRD 93, 112008 (2016)

^{116}Cd: PRD 95, 012007 (2017)



Search for 0νββββ (Quadruple beta decay)

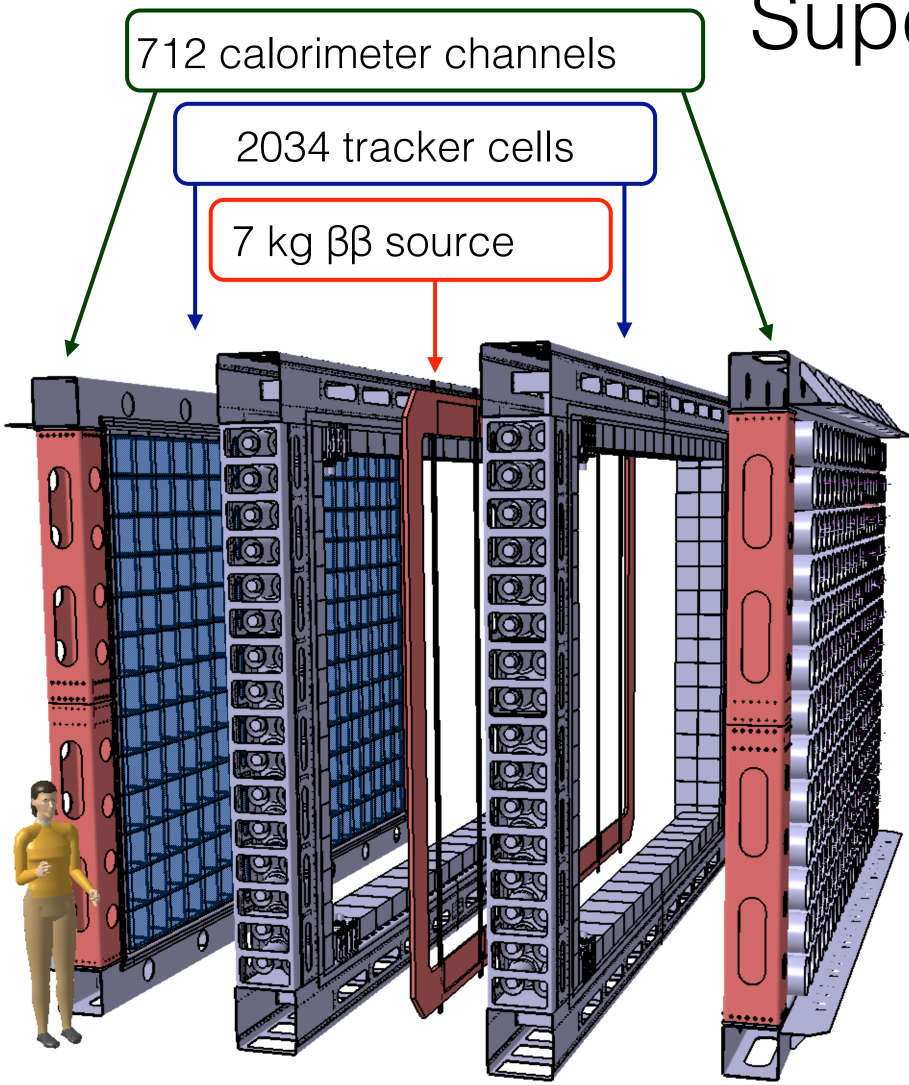
$$^{150}\mathrm{Nd} \xrightarrow{2.079\ \mathrm{MeV}} {}^{150}\mathrm{Gd} + 4e^-$$

$$T_{1/2}^{0\nu4\beta} > (1.1 - 3.2) \times 10^{21}\ \mathrm{yr}\ (90\%\ \mathrm{C.L.})$$

arXiv:1705.08847, PRL 119, 041801 (2017) Editor's suggestion

Courtesy D. Waters

SuperNemo Demonstrator



Demonstrator Module

Status:

All detector parts underground at LSM

Half-detector fully assembled and undergoing testing/commissioning

Source foil fabrication (7kg of ^{82}Se) complete within next few months

SuperNEMO Demonstrator Module fully assembled by end-2017

Physics data-taking starts in 2018

Expected sensitivity:

17.5 kg×yr initial exposure (2.5 yr):

$T^{0\nu}_{1/2} > 6.5 \times 10^{24}$ yr $\quad \langle m_\nu \rangle < 0.20 - 0.40$ eV

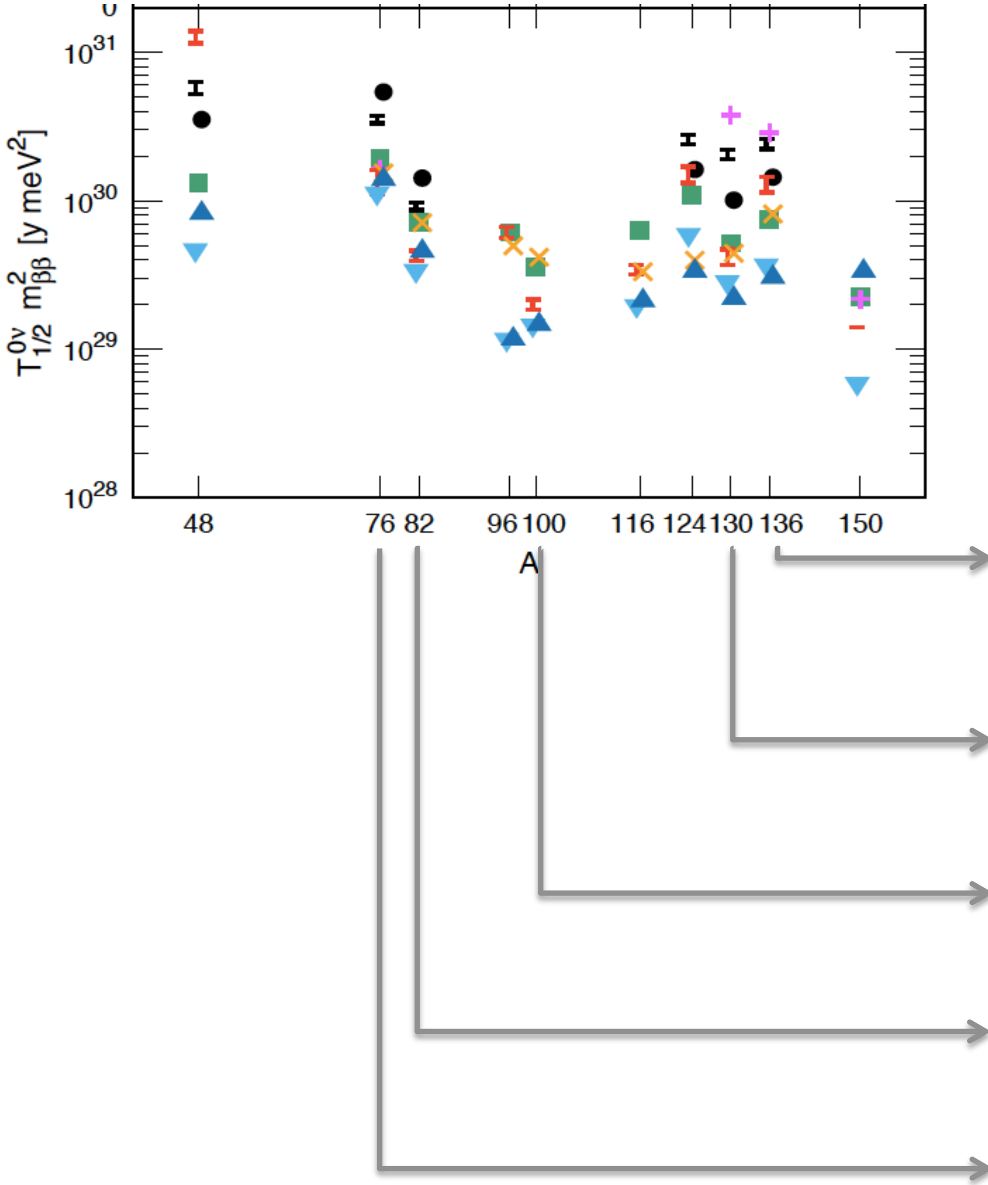
SuperNEMO (100 kg ^{82}Se, 20 mod., 500 kgxyr)

500 kg×yr :

$T^{0\nu}_{1/2} > 10^{26}$ yr $\quad \langle m_\nu \rangle < 50 - 100$ meV

Courtesy D. Waters

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

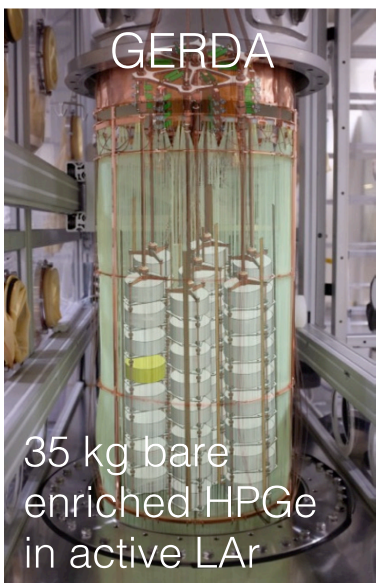
Se-bolometers:	CUPID-0 (ex Lucifer)
Se-calo-tracko:	SuperNEMO

Ge-semiconductor: GERDA, MJD, LEGEND

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

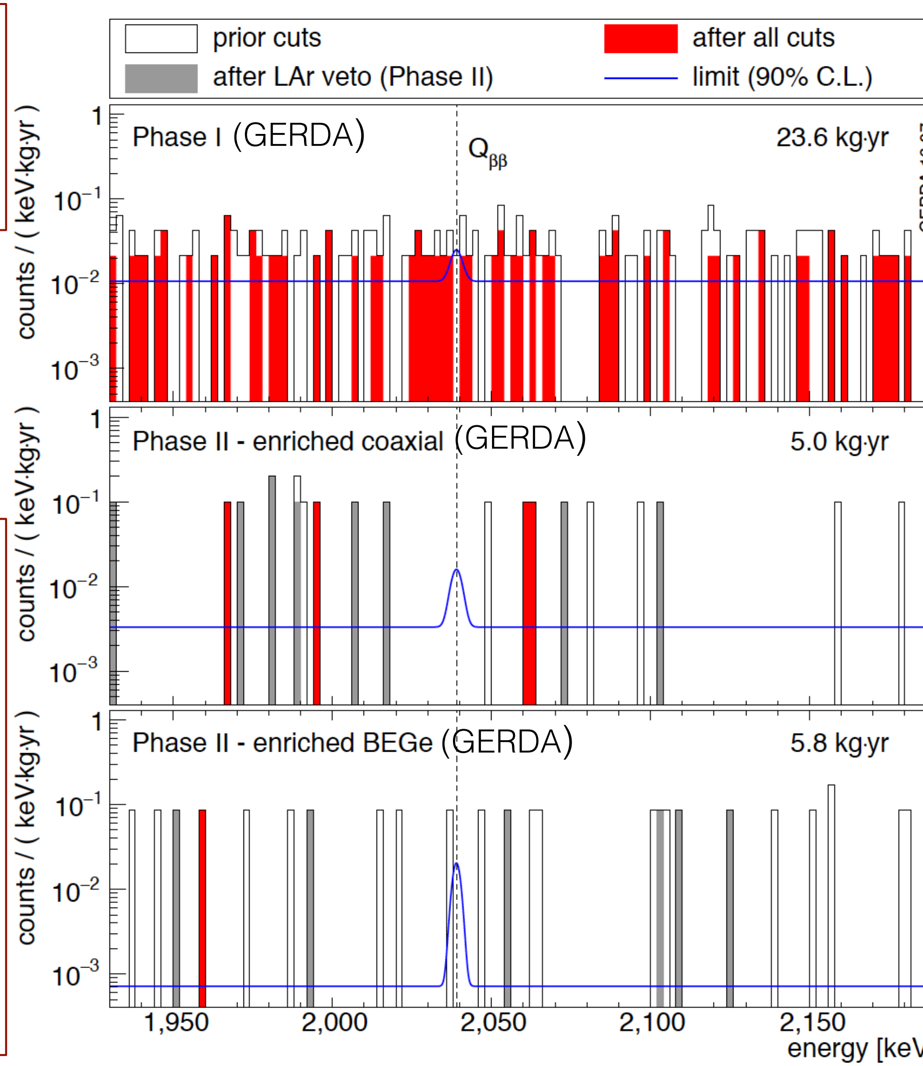
Ge-Experiments: MJD & GERDA

TAUP 2017
BI: $1.8^{+3.2}_{-1.1} \times 10^{-3}$ cts /(keV kg yr)
ROI: 2.8 keV



Nature 554 (2017) 47-52
BI: $0.7^{+1.1}_{-0.5} \times 10^{-3}$ cts /(keV kg yr) for enr BEGe's

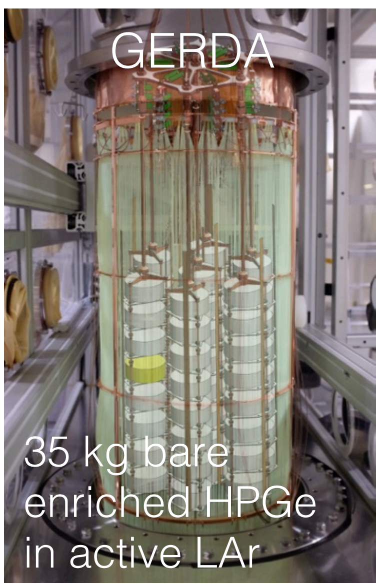
$T_{1/2}^{0\nu} > 5.3 \times 10^{25}$ yr (90% C.L.)
Sensitivity:
$T_{1/2}^{0\nu} > 4.0 \times 10^{25}$ yr



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

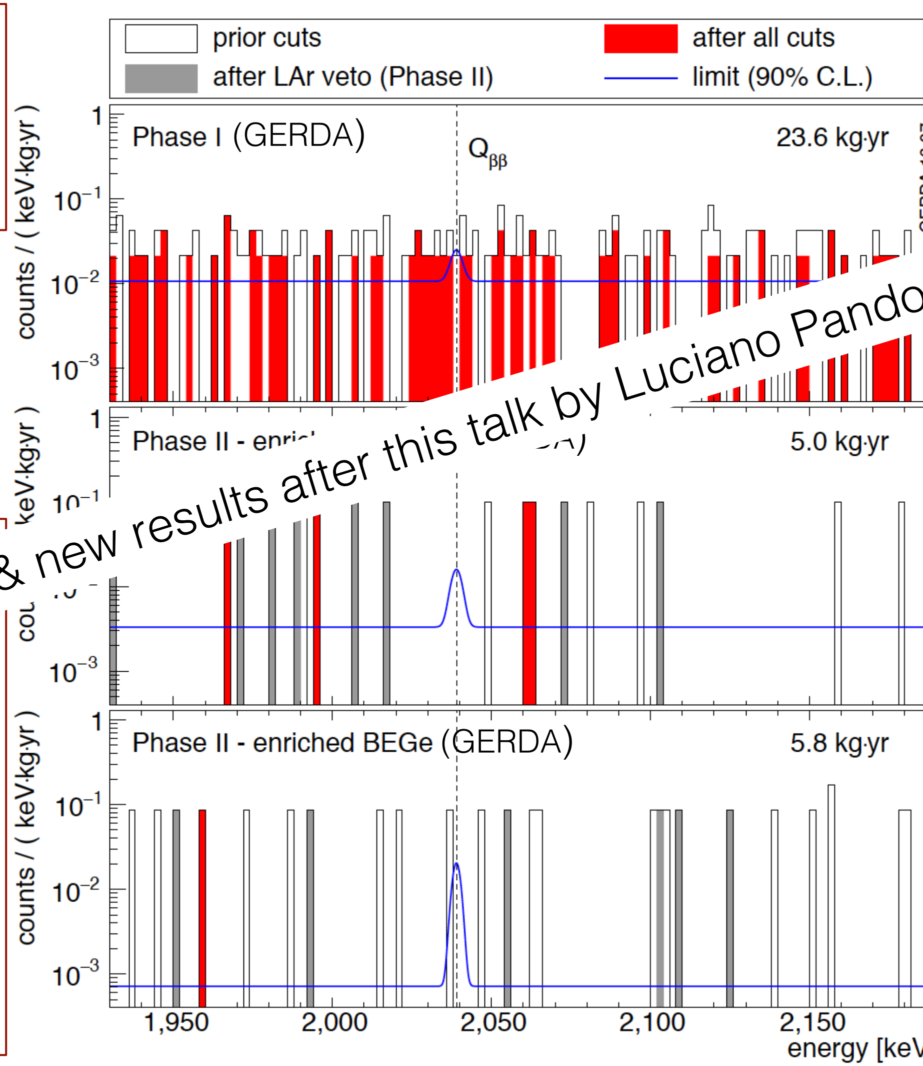
Ge-Experiments: MJD & GERDA

TAUP 2017
BI: $1.8^{+3.2}_{-1.1} \times 10^{-3}$ cts /(keV kg yr)
ROI: 2.8 keV



Nature 554 (201[illegible]) 47-52
BI: 0.[illegible] $_{-0.5} \times 10^{-3}$ cts /(keV kg yr) for enr BEGe's

$T_{1/2}^{0\nu} > 5.3 \times 10^{25}$ yr (90% C.L.)
Sensitivity: $T_{1/2}^{0\nu} > 4.0 \times 10^{25}$ yr



More details & new results after this talk by Luciano Pandola

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

Ge-Experiments: LEGEND

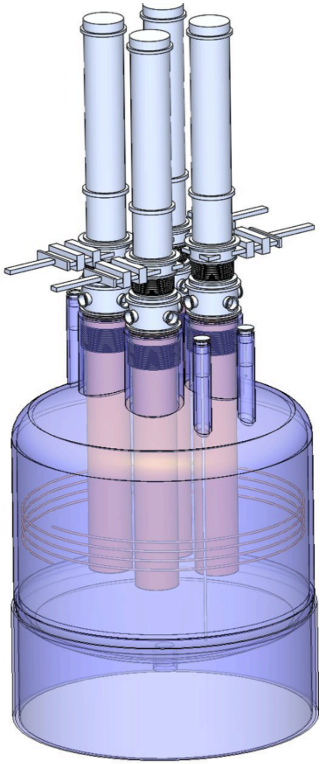
Large **E**nriched **Ge**rmanium **E**xperiment for **N**eutrinoless ββ **D**ecay

<u>First phase:</u>

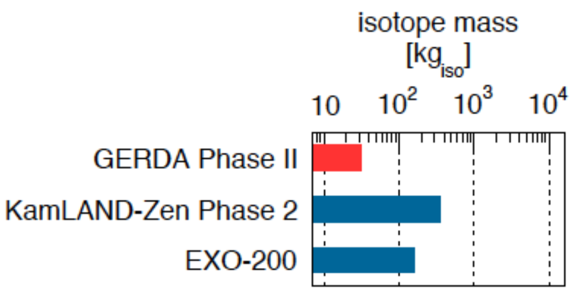
- (up to) 200 kg
- modification of existing GERDA infrastructure at LNGS
- BG goal (x5 lower) 0.6 c /(FWMH t y)
- start by 2021

<u>Subsequent stages:</u>

- 1000 kg (staged)
- timeline connected to U.S. DOE down select process
- BG: goal (x30 lower) 0.1 c /(FWHM t y)
- Location: TBD
- Required depth (Ge-77m) under investigation

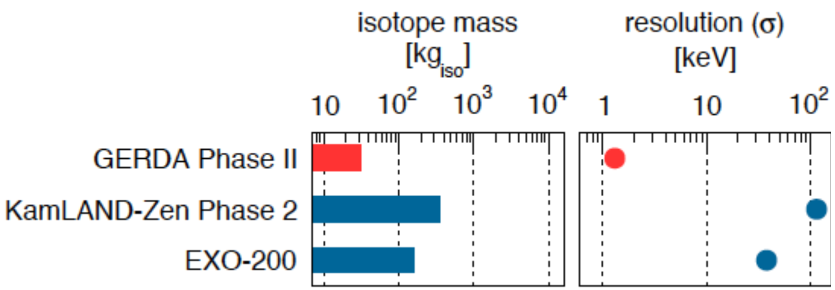


Comparison of Experiments



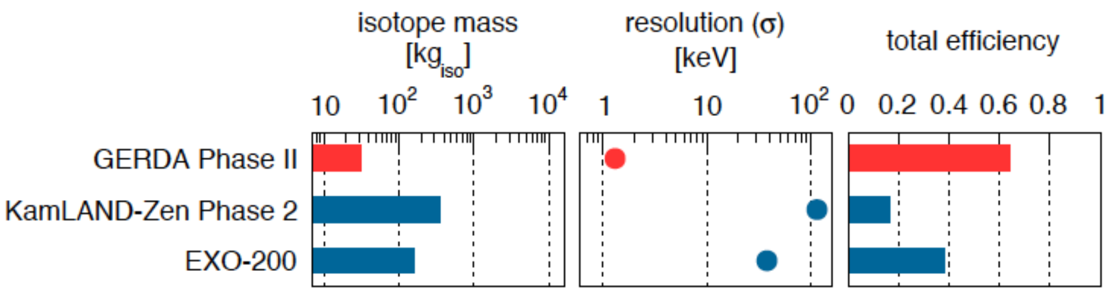
Adopted from Agostini, Benato, Detwiler arXiv:1705.02996

Comparison of Experiments



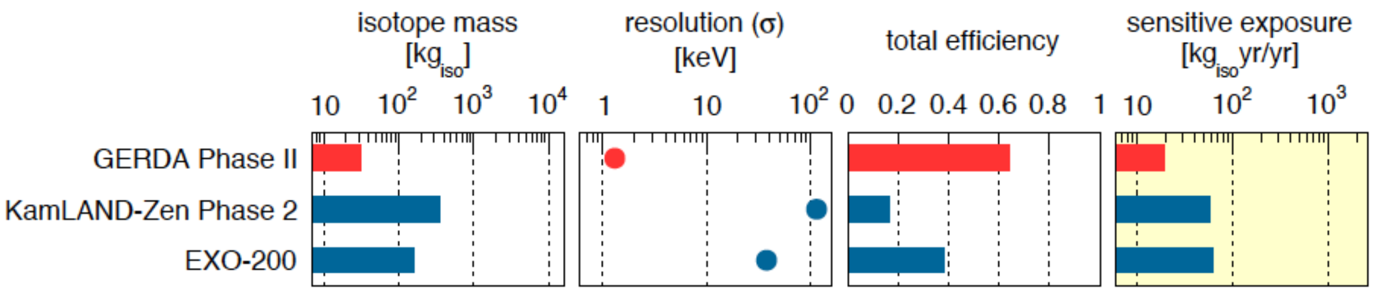
Adopted from Agostini, Benato, Detwiler arXiv:1705.02996

Comparison of Experiments



Adopted from Agostini, Benato, Detwiler arXiv:1705.02996

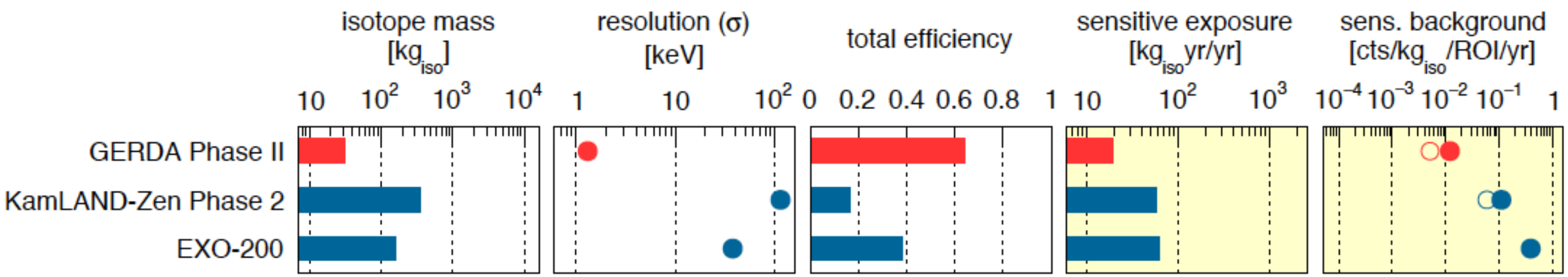
Comparison of Experiments



$M \cdot t \cdot \varepsilon_{tot}$

Adopted from Agostini, Benato, Detwiler arXiv:1705.02996

Comparison of Experiments

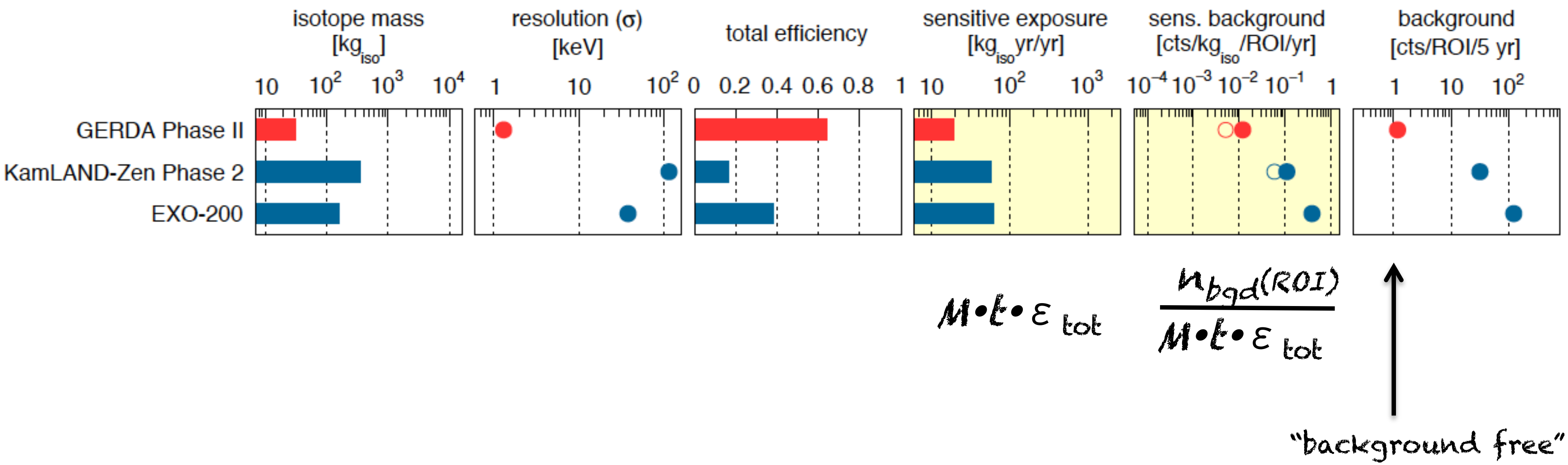


$M \cdot t \cdot \varepsilon_{tot}$

$\frac{n_{bgd}(ROI)}{M \cdot t \cdot \varepsilon_{tot}}$

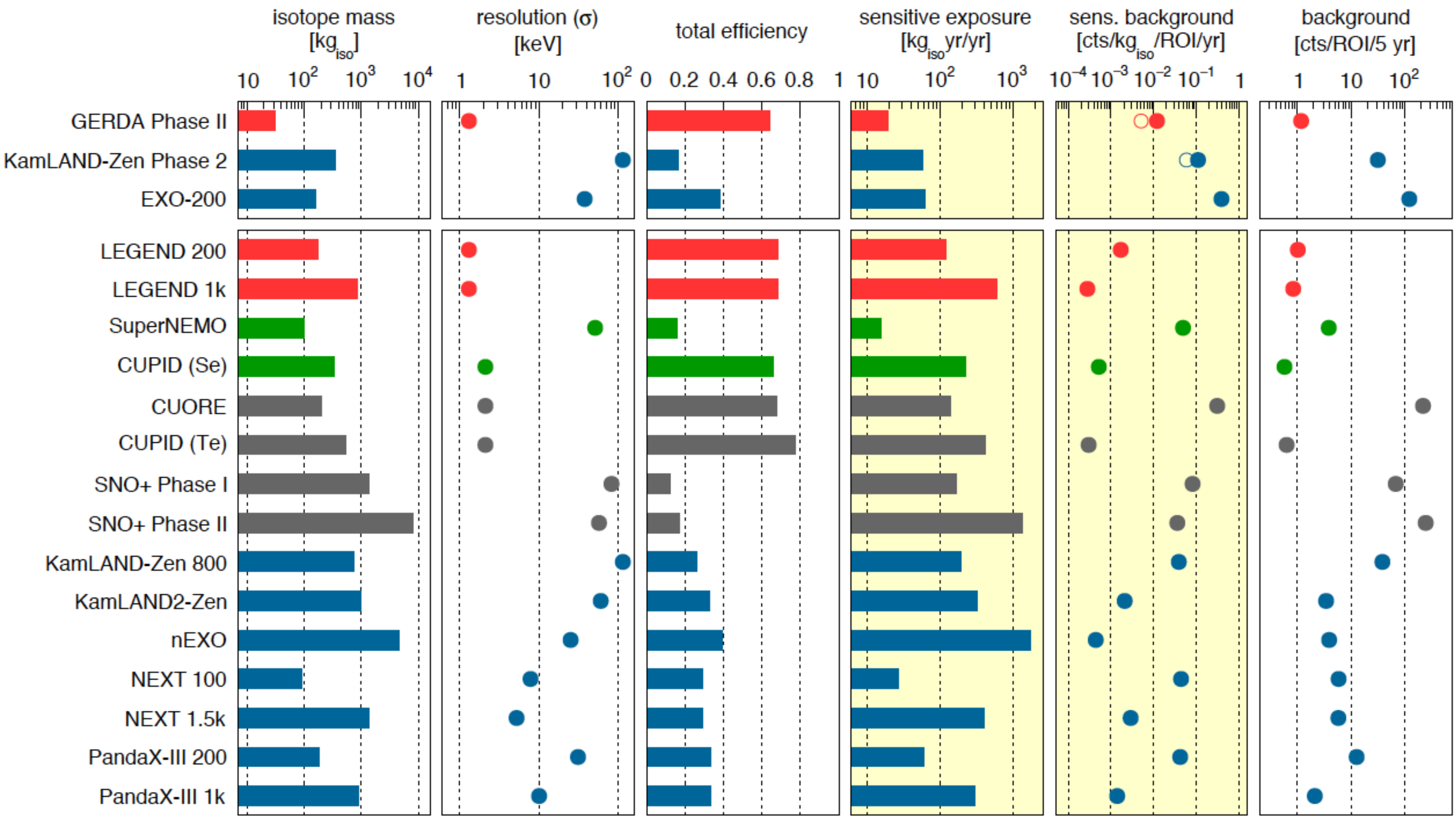
Adopted from Agostini, Benato, Detwiler arXiv:1705.02996

Comparison of Experiments



Adopted from Agostini, Benato, Detwiler arXiv:1705.02996

Comparison of Experiments



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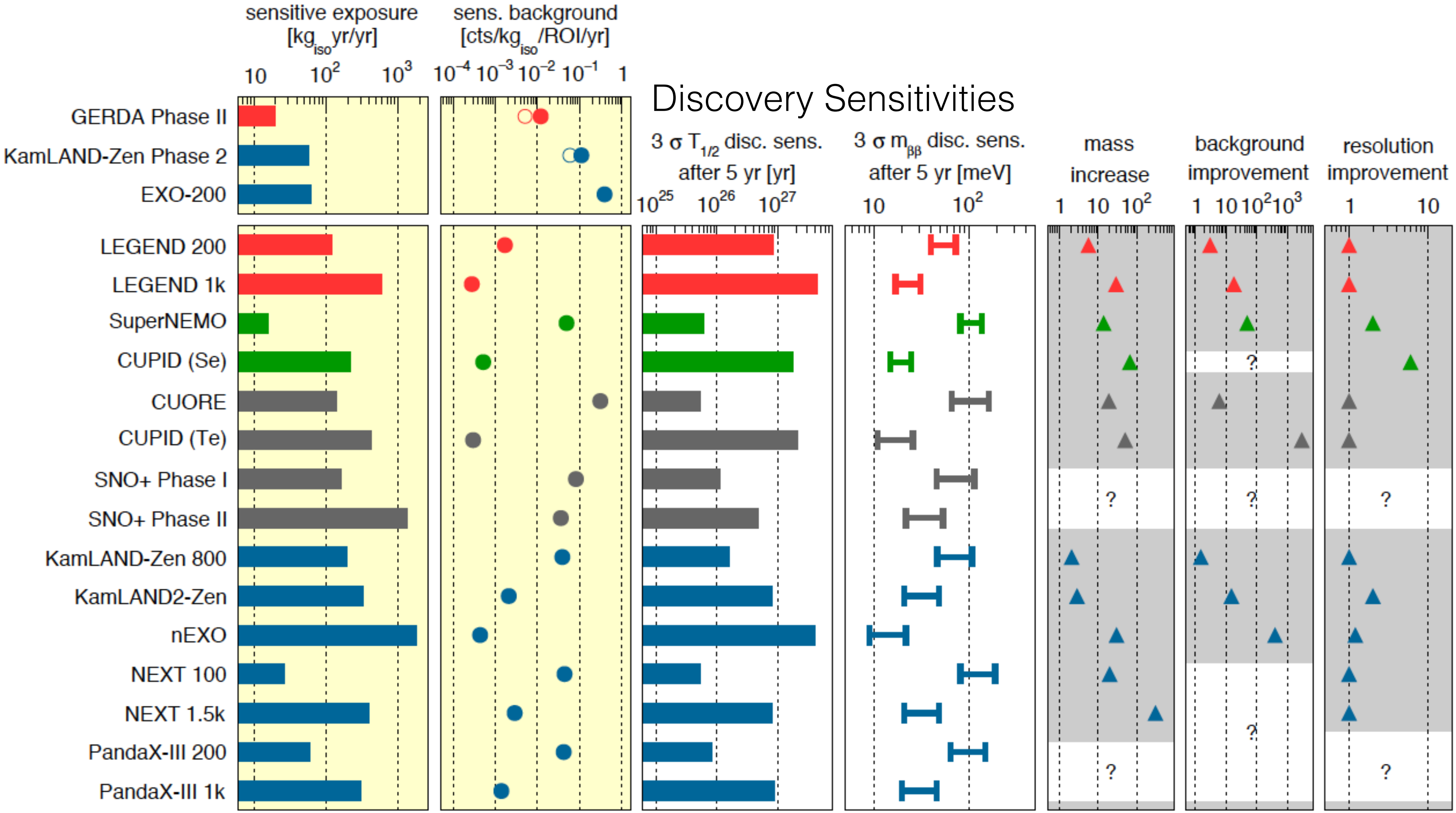
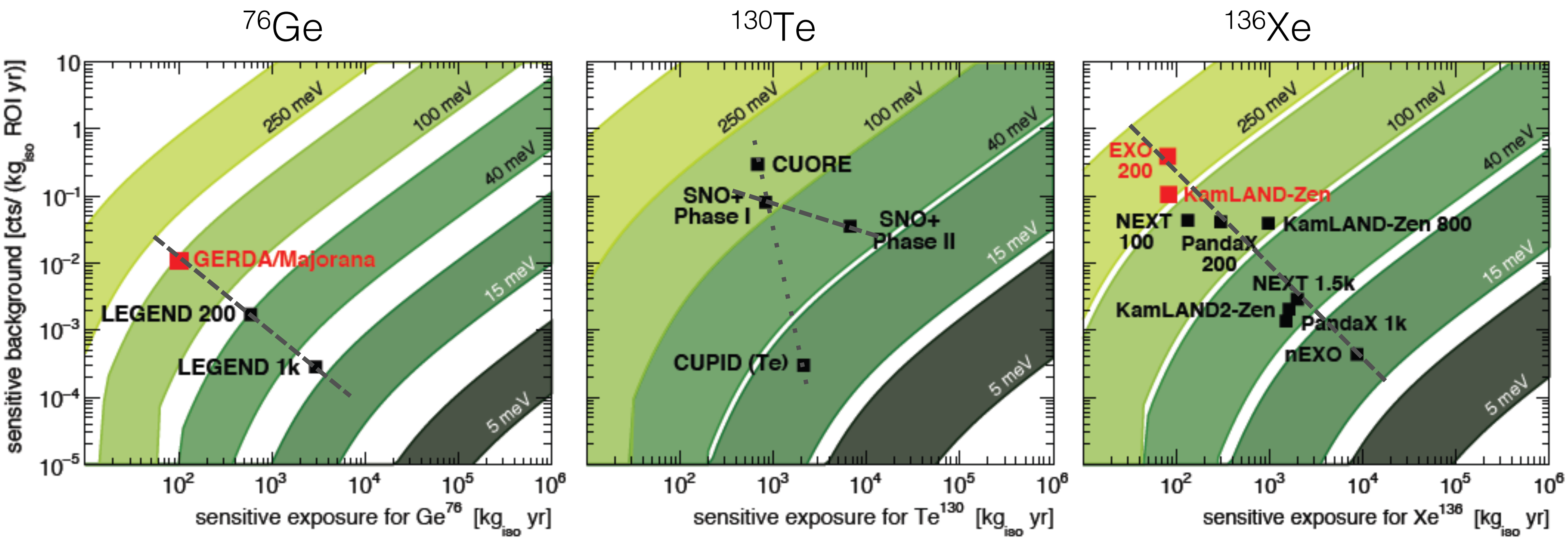
Comparison of Experiments



Adopted from Agostini, Benato, Detwiler arXiv:1705.02996

Discovery sensitivities

(5 yr live time)



Agostini, Benato, Detwiler arXiv:1705.02996

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 mostly **reasonable extrapolations** w.r. to detector performance and background reduction
- **Staging** largely adopted to produce physics results & minimize (project) risks
- Experimental design for **discovery** (not limit setting!)

- **Taup 2017:**
  - New results by **GERDA** – after this talk by L. Pandola
  - First results from **CUORE** – Friday by O. Cremonesi
  - New Results by **EXO** – Friday by C. Licciardi

Extra Slides

Experiment	Iso.	Iso. Mass [kg_{iso}]	σ [keV]	ROI [σ]	ϵ_{FV} [%]	ϵ_{sig} [%]	$\mathcal{E}$ $\left[\frac{kg_{iso}\,yr}{yr}\right]$	$\mathcal{B}$ $\left[\frac{cts}{kg_{iso}\,ROI\,yr}\right]$	3σ disc. sens. $\hat{T}_{1/2}$ [yr]	3σ disc. sens. $\hat{m}_{\beta\beta}$ [meV]	Required Improvement Bkg	Required Improvement σ	Required Improvement Iso. Mass
LEGEND 200 [61, 62]	^{76}Ge	175	1.3	[-2, 2]	93	77	119	$1.7 \cdot 10^{-3}$	$8.4 \cdot 10^{26}$	40–73	3	1	5.7
LEGEND 1k [61, 62]	^{76}Ge	873	1.3	[-2, 2]	93	77	593	$2.8 \cdot 10^{-4}$	$4.5 \cdot 10^{27}$	17–31	18	1	29
SuperNEMO [68, 69]	^{82}Se	100	51	[-4, 2]	100	16	16.5	$4.9 \cdot 10^{-2}$	$6.1 \cdot 10^{25}$	82–138	49	2	14
CUPID [58, 59, 70]	^{82}Se	336	2.1	[-2, 2]	100	69	221	$5.2 \cdot 10^{-4}$	$1.8 \cdot 10^{27}$	15–25	n/a	6	n/a
CUORE [52, 53]	^{130}Te	206	2.1	[-1.4, 1.4]	100	81	141	$3.1 \cdot 10^{-1}$	$5.4 \cdot 10^{25}$	66–164	6	1	19
CUPID [58, 59, 70]	^{130}Te	543	2.1	[-2, 2]	100	81	422	$3.0 \cdot 10^{-4}$	$2.1 \cdot 10^{27}$	11–26	3000	1	50
SNO+ Phase I [66, 71]	^{130}Te	1357	82	[-0.5, 1.5]	20	97	164	$8.2 \cdot 10^{-2}$	$1.1 \cdot 10^{26}$	46–115	n/a	n/a	n/a
SNO+ Phase II [67]	^{130}Te	7960	57	[-0.5, 1.5]	28	97	1326	$3.6 \cdot 10^{-2}$	$4.8 \cdot 10^{26}$	22–54	n/a	n/a	n/a
KamLAND-Zen 800 [60]	^{136}Xe	750	114	[0, 1.4]	64	97	194	$3.9 \cdot 10^{-2}$	$1.6 \cdot 10^{26}$	47–108	1.5	1	2.1
KamLAND2-Zen [60]	^{136}Xe	1000	60	[0, 1.4]	80	97	325	$2.1 \cdot 10^{-3}$	$8.0 \cdot 10^{26}$	21–49	15	2	2.9
nEXO [72]	^{136}Xe	4507	25	[-1.2, 1.2]	60	85	1741	$4.4 \cdot 10^{-4}$	$4.1 \cdot 10^{27}$	9–22	400	1.2	30
NEXT 100 [64, 73]	^{136}Xe	91	7.8	[-1.3, 2.4]	88	37	26.5	$4.4 \cdot 10^{-2}$	$5.3 \cdot 10^{25}$	82–189	n/a	1	20
NEXT 1.5k [74]	^{136}Xe	1367	5.2	[-1.3, 2.4]	88	37	398	$2.9 \cdot 10^{-3}$	$7.9 \cdot 10^{26}$	21–49	n/a	1	300
PandaX-III 200 [65]	^{136}Xe	180	31	[-2, 2]	100	35	60.2	$4.2 \cdot 10^{-2}$	$8.3 \cdot 10^{25}$	65–150	n/a	n/a	n/a
PandaX-III 1k [65]	^{136}Xe	901	10	[-2, 2]	100	35	301	$1.4 \cdot 10^{-3}$	$9.0 \cdot 10^{26}$	20–46	n/a	n/a	n/a

Agostini, Benato, Detwiler arXiv:1705.02996