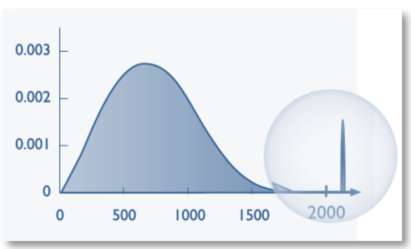
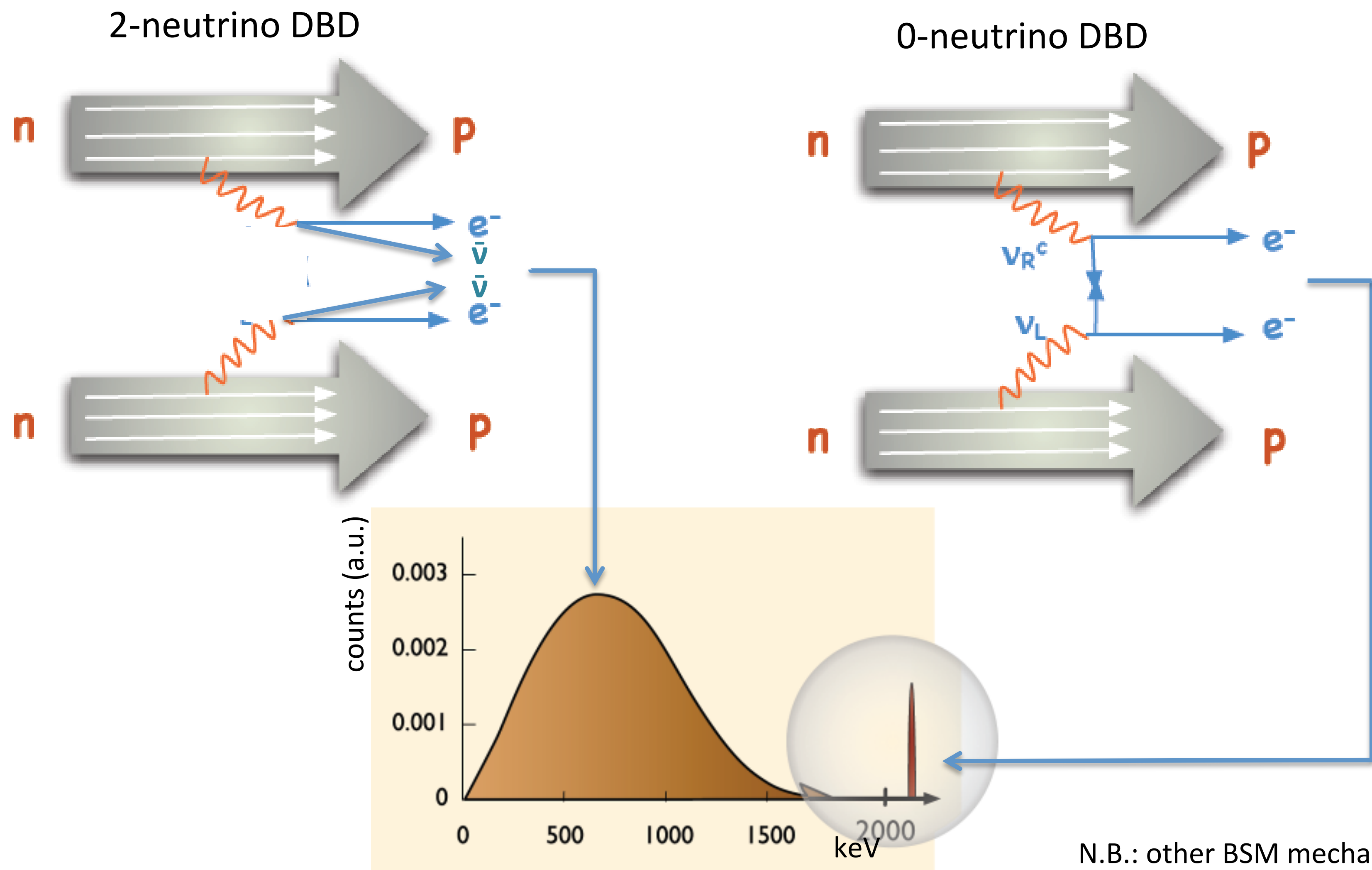
Neutrinoless double beta decay: latest results and future perspectives

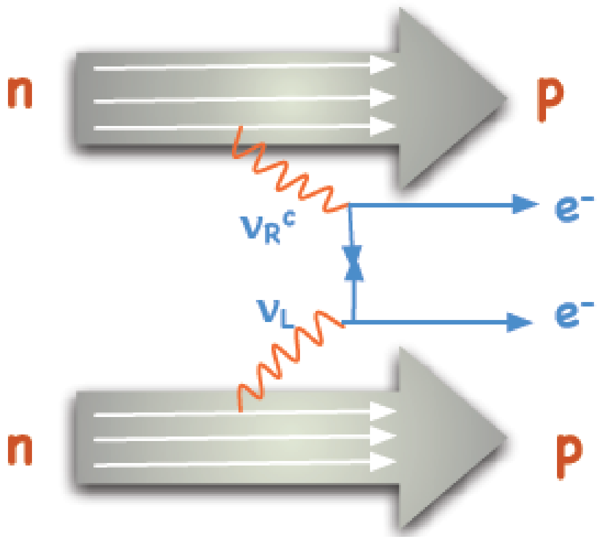


S. Schönert
Technische Universität München (TUM)



2-electron spectra

N.B.: other BSM mechanisms can generate 0νββ decay



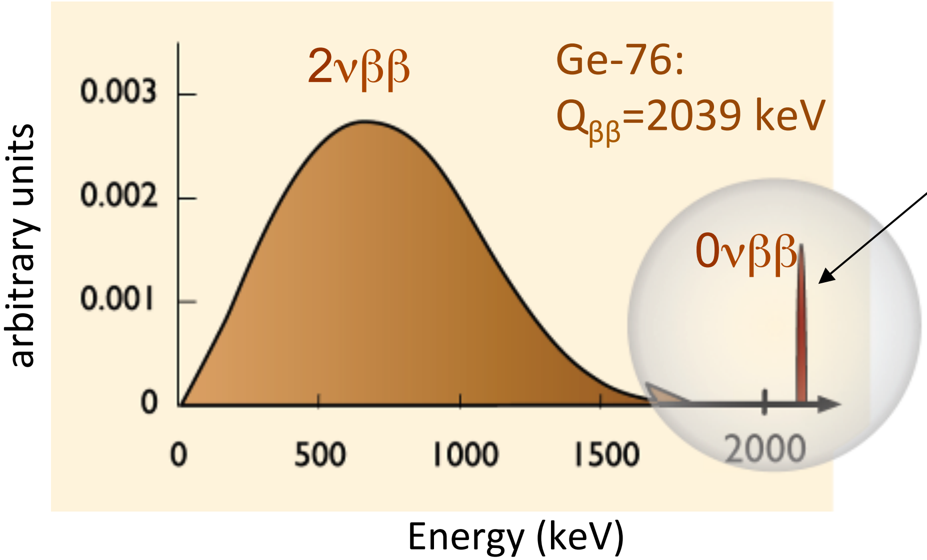
Expected decay rate:

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

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



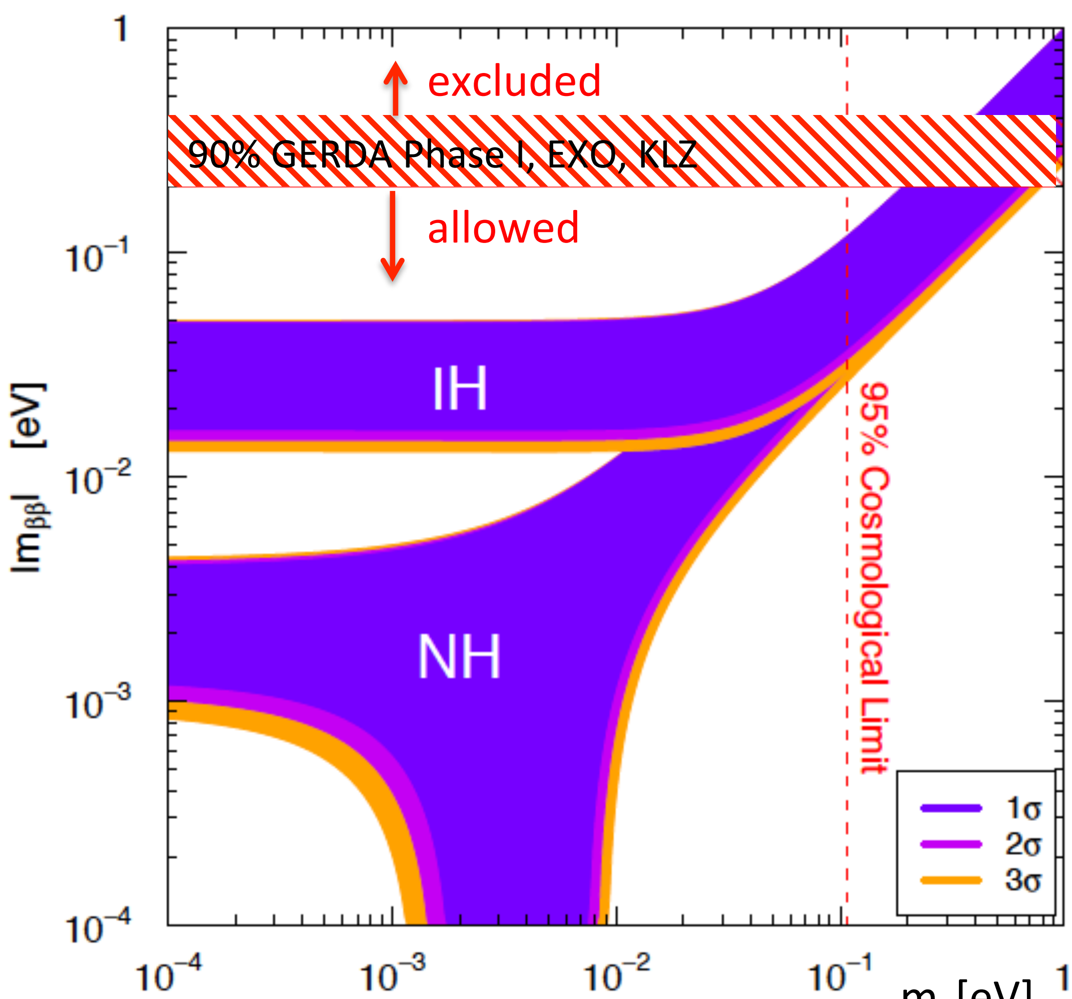
Experimental signatures:

- peak at $Q_{\beta\beta}$ = m(A,Z)-m(A,Z+2)
- two electrons from vertex

Discovery would imply:

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

Which half-lives shall next generation DBD experiments aim for ?



From C. Giunti

<u>3ν-paradigm:</u>

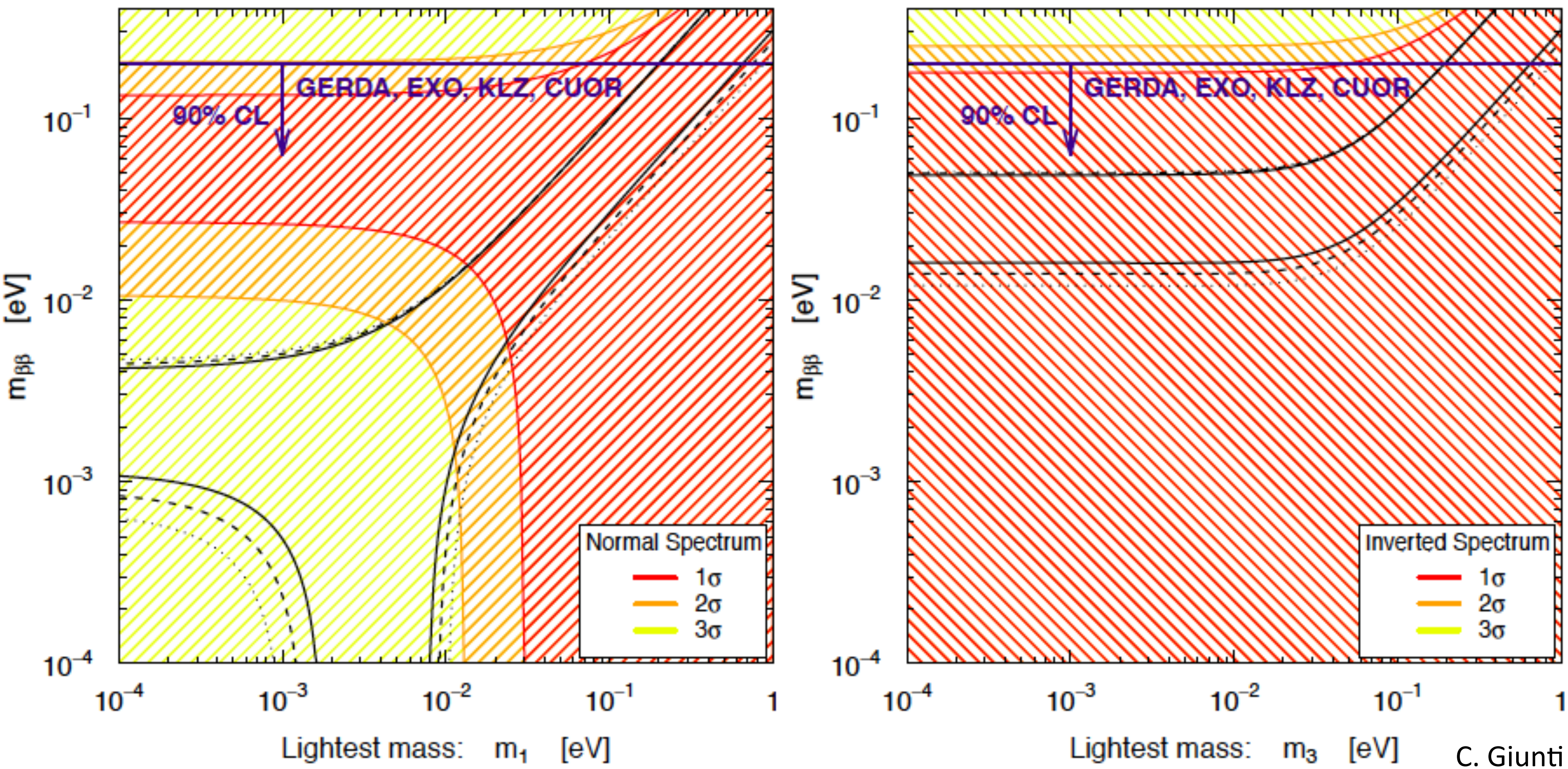
- Next generation of experiments should probe mass range predicted for **IH**
- 10 meV mass range
- **0νββ: $T_{1/2}$ ~ 10^{27} - 10^{28} years**
- **(2νββ: $T_{1/2}$ ~ 10^{19} - 10^{21} years)**

Which half-lives shall next generation DBD experiments aim for ?

<u>3ν + light (eV) sterile neutrino</u>

$$m_{\beta\beta}^{(\text{light})} = \left| \sum_{k=1}^{3} U_{ek}^2 \, m_k \right| \qquad m_{\beta\beta}^{(4)} = |U_{e4}|^2 \sqrt{\Delta m_{41}^2}$$

$$m_{\beta\beta} = m_{\beta\beta}^{(\text{light})} + e^{i\alpha_4} m_{\beta\beta}^{(4)} \qquad m_{\beta\beta}^{(4)} \gtrsim 10^{-2}\,\text{eV}$$



C. Giunti

Which half-lives shall next generation DBD experiments aim for ?

Standard 0νββ-decay with **3 light Majorana** neutrinos => probe 10 meV scale (10^{27} - 10^{28} years)

0νββ-decay including **eV sterile neutrinos** => can be around the corner – or unreachable

0νββ-decay with **driven by other mechanism then light Majorana neutrino exchange** => (nearly) every where

Experimentalist's pragmatic approach: prepare (if possible stage) next-generation experiments to probe $T_{1/2} \sim 10^{27}$ - 10^{28} years, ie. 10 meV scale – and be prepared that things change in the mean time….

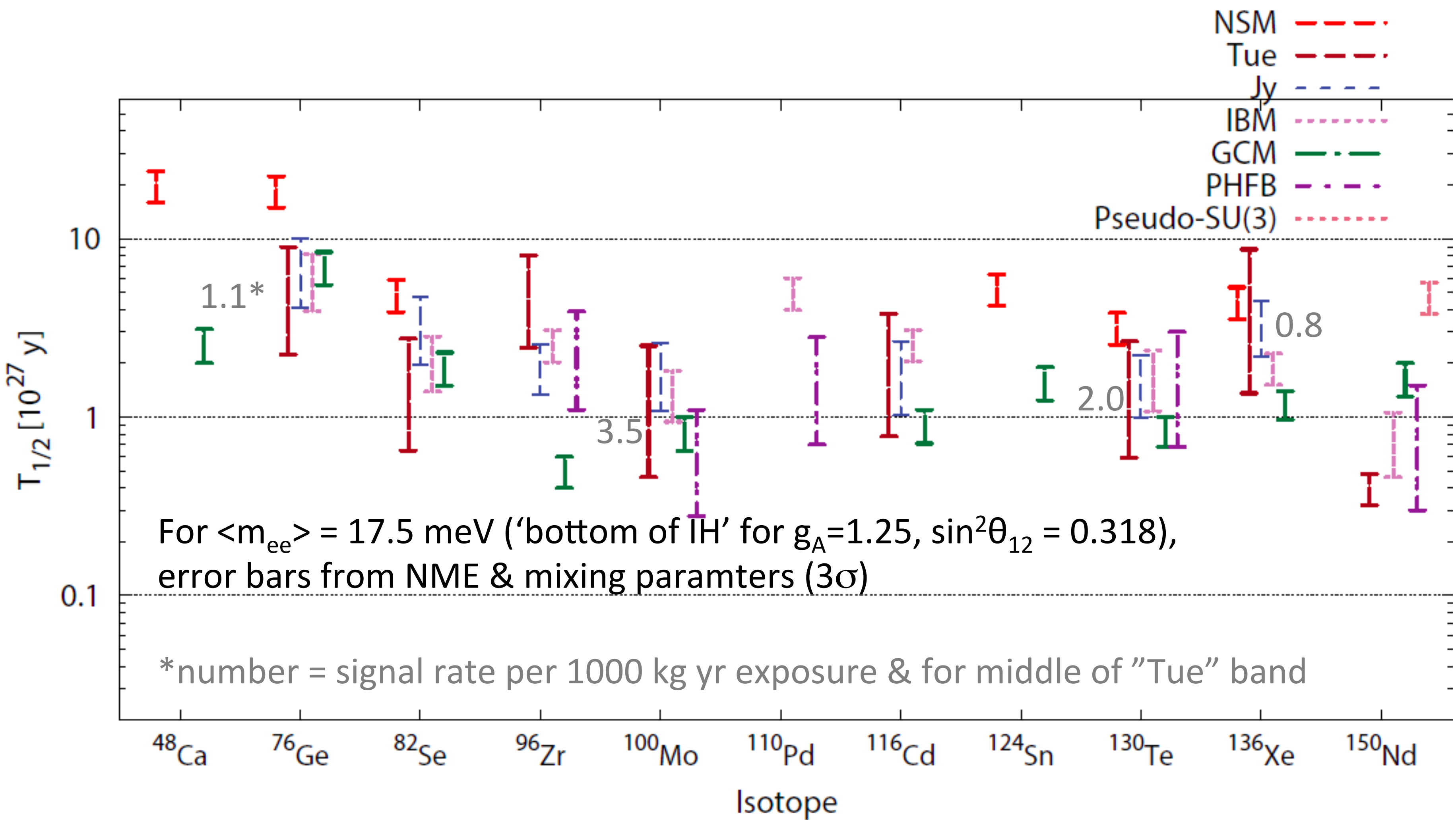
<u>….in the mean time:</u>

eV sterile neutrinos: SOX, Stereo, (and others), SBL will scrutinize eV sterile neutrinos

Mass ordering / hierarchy: Pingu, Juno (2020+), …… glob. analysis & later: LBL acc. Experiments

New data from **direct mass** measurement (KATRIN) & **cosmology**

No isotope significantly preferred by decay rate per mass



DOE NSAC report on 0νββ (24 April 2014), adopted from A. Dueck, W. Rodejohann and K. Zuber, Phys. Rev. D83 (2011) 113010

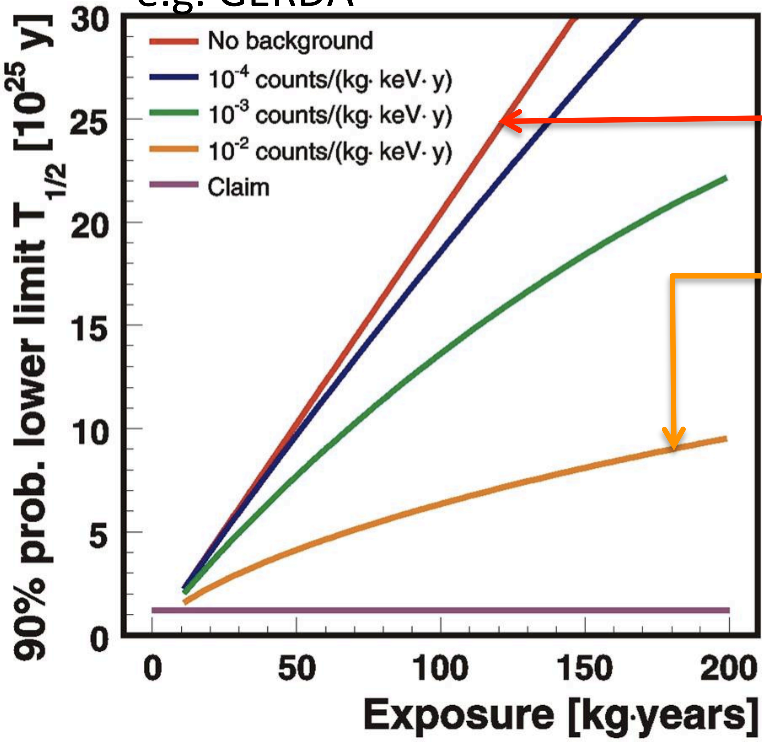
Signal rates & requirements for next generation experiments

Present exp. sensitivities → 10^{25}

Goal next generation → 5×10^{27}

Half life [yr]	approx. signal rate [cts/(ton yr)]
10^{25}	500
5×10^{26}	10
5×10^{27}	**1**
$>10^{29}$	<0.05

e.g. GERDA

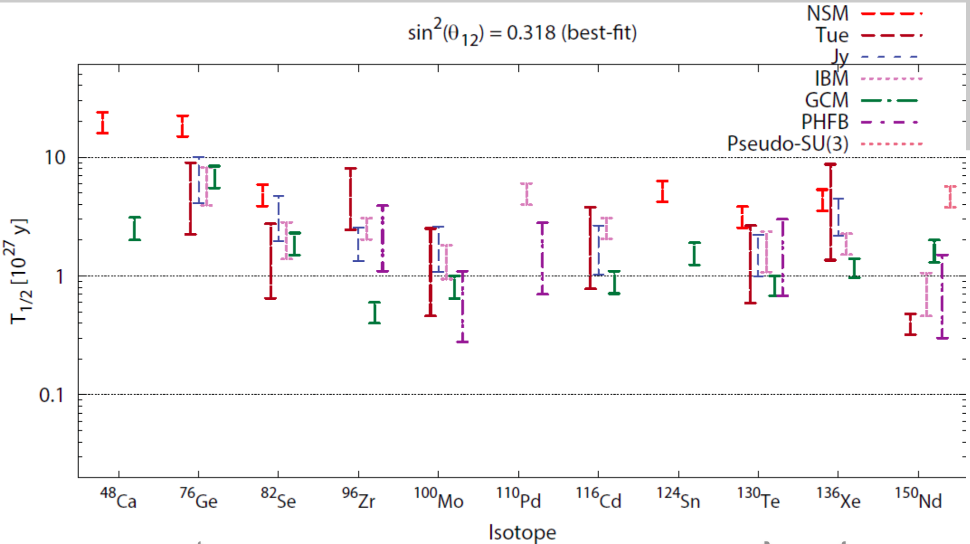


$$(T_{1/2}^{0\nu})^{-1} \propto \varepsilon_{eff}\, f_{enr}\, M\, T$$ Background-free

$$(T_{1/2}^{0\nu})^{-1} \propto \varepsilon_{eff}\, f_{enr} \sqrt{\frac{M\,T}{B\,\Delta E}}$$ Background limited

- Large exposure ($\varepsilon_{eff}\, f_{enr}$ MT) of ββ-isotope
- Bgd-free operation in 0νββ peak region
- Best possible energy resolution to discriminate 0νββ from 2νββ
- Several isotopes

Experimentalist's choice



^{48}Ca, ^{150}Nd currently can not be enriched in large quantities

LXe TPC:	**(n)EXO**
gas-Xe TPC:	**NEXT**
Xe-loaded LS:	**KL-Zen**

Te-loaded LS:	**SNO+**
Te-bolometers:	**Cuore**

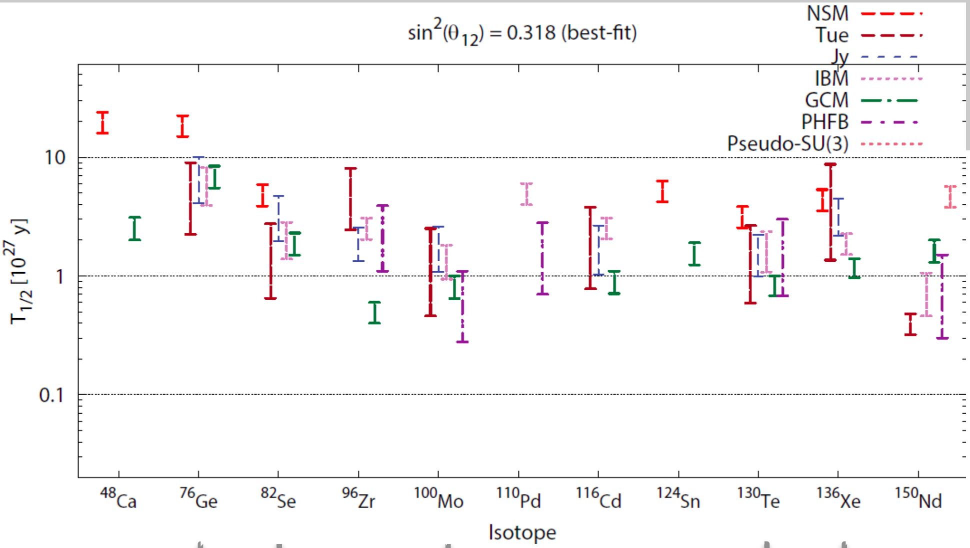
Mo-bolometers: **Lumineu, Amore**

Se-bolometers:	**Lucifer**
Se-calo-tracko:	**SuperNemo**

Ge-semiconductor: **GERDA, MJD**

& other interesting, but less advanced R&D

Experimentalist's choice



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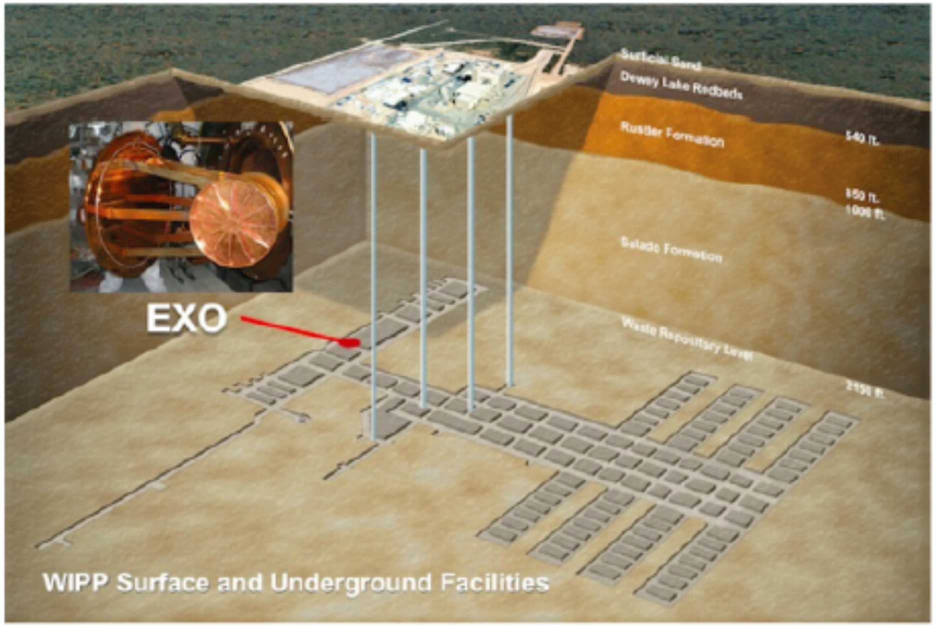
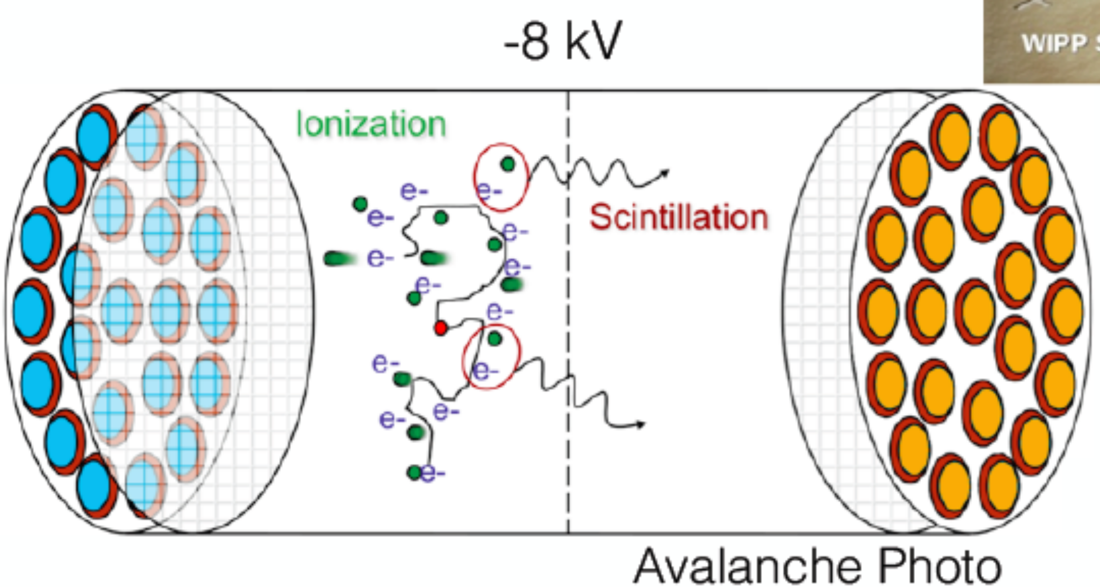
- Liquid Xe Time Projection Chamber (TPC)
- Enriched ^{136}Xe to 80.6%
- Q-value 2458 keV

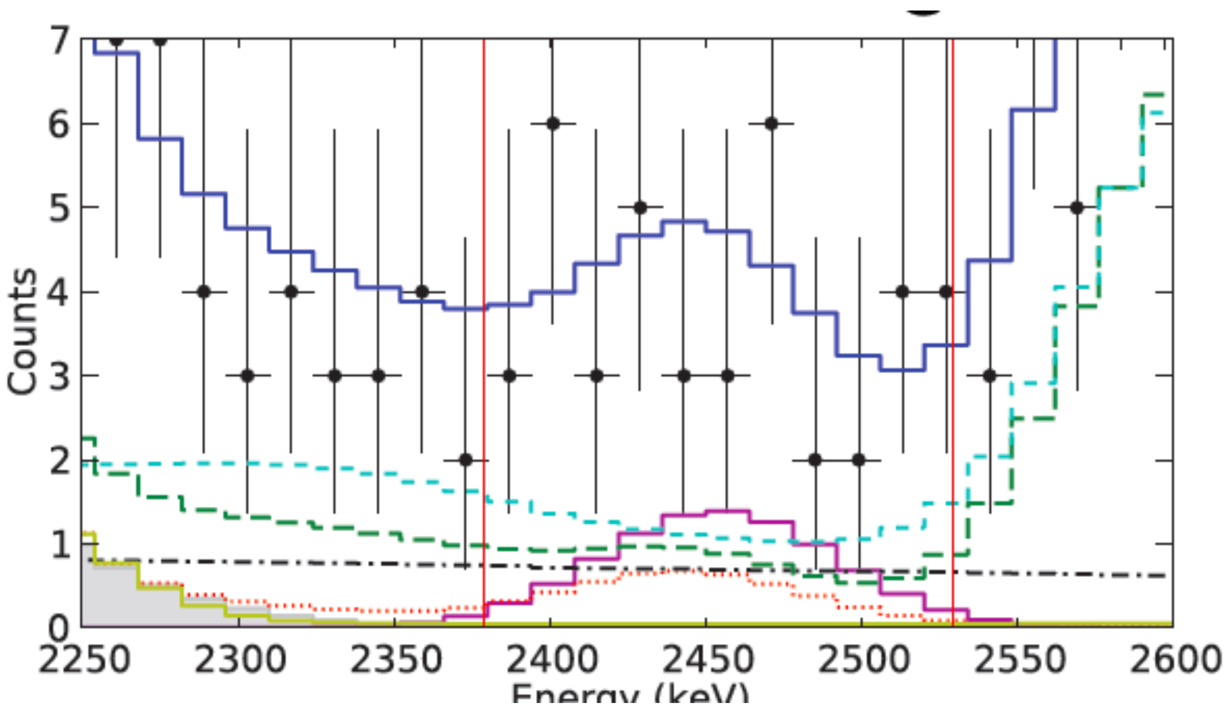




- Located at Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM, USA
- 1585 meters water equivalent

From M. Marino, NIAPP@TUM 2014

The Xenon projects: EXO



$T_{1/2}^{0\nu\beta\beta} > 1.1\cdot10^{25}$ yr

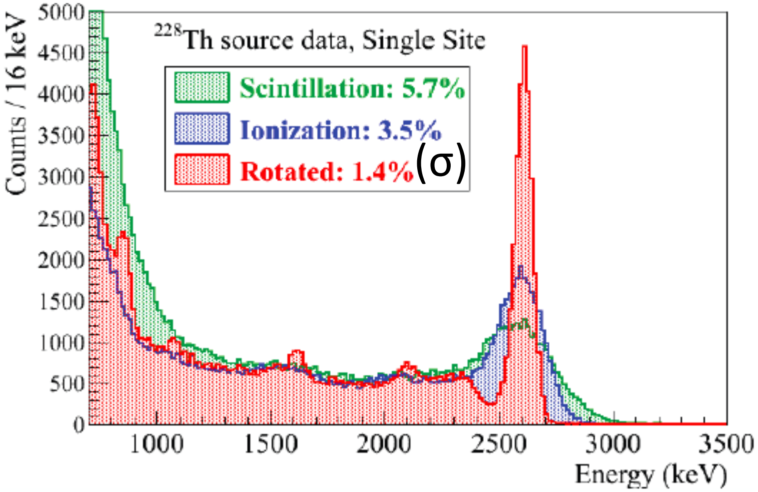
Sensitivity: $1.9\cdot10^{25}$ yr

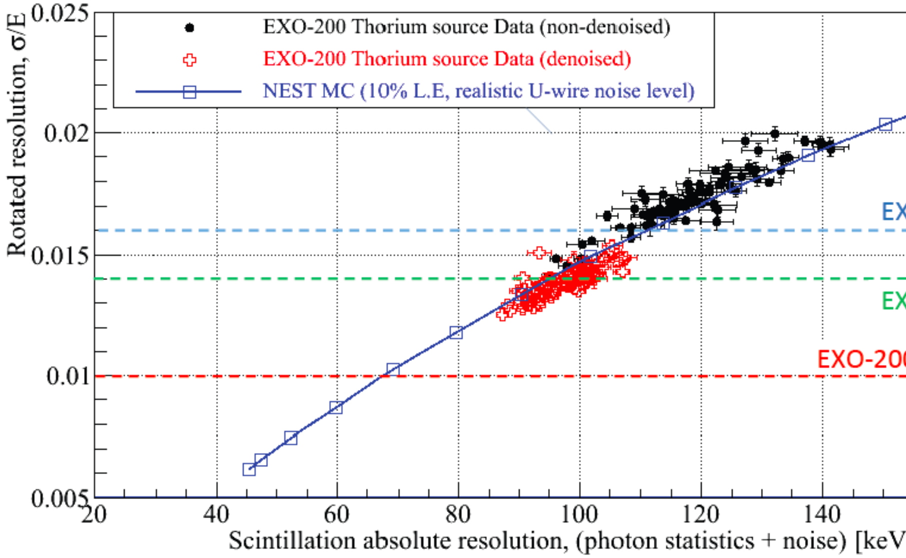
$\langle m_{\beta\beta}\rangle < 190 - 450$ meV (90% C.L.)

Nature **510 (2014) 229-234**

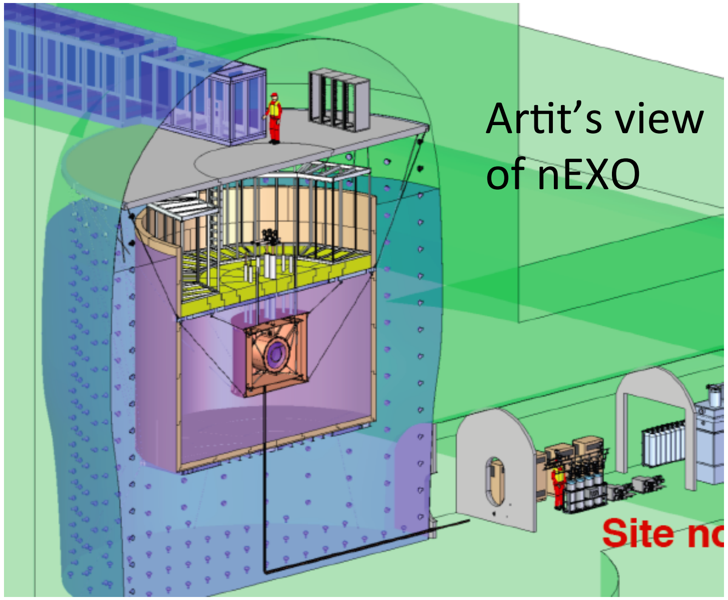
From M. Marino, NIAPP@TUM 2014

The Xenon projects: from EXO to nEXO





Res. @ 2615 keV

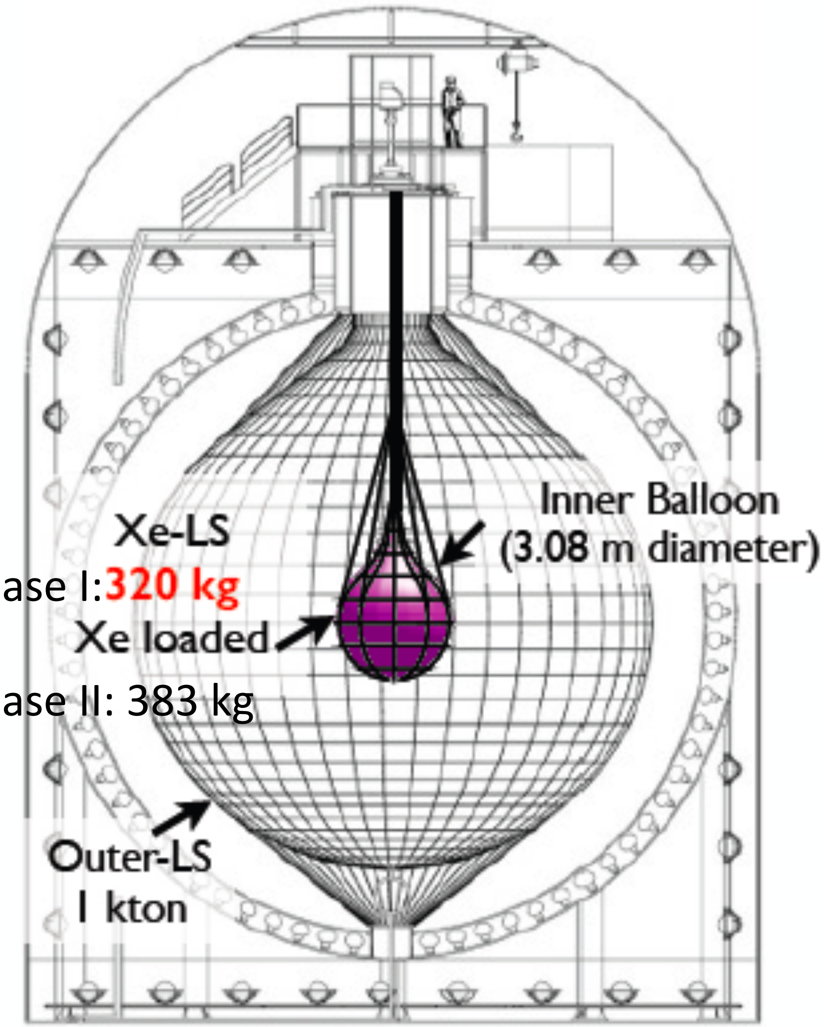


Artit's view of nEXO

Overall Mass: 5 tonnes, 90% enriched ^{136}Xe
Time Projection Chamber (TPC)
Running Time: 10 years
Baseline energy resolution: 1.5%
Preferred site: SNOLAB Cryopit
Final $T_{1/2}$ sensitivity (90% CL): 4.1×10^{27} yrs
With barium tagging: 2.1×10^{28} yrs

From M. Marino, NIAPP@TUM 2014

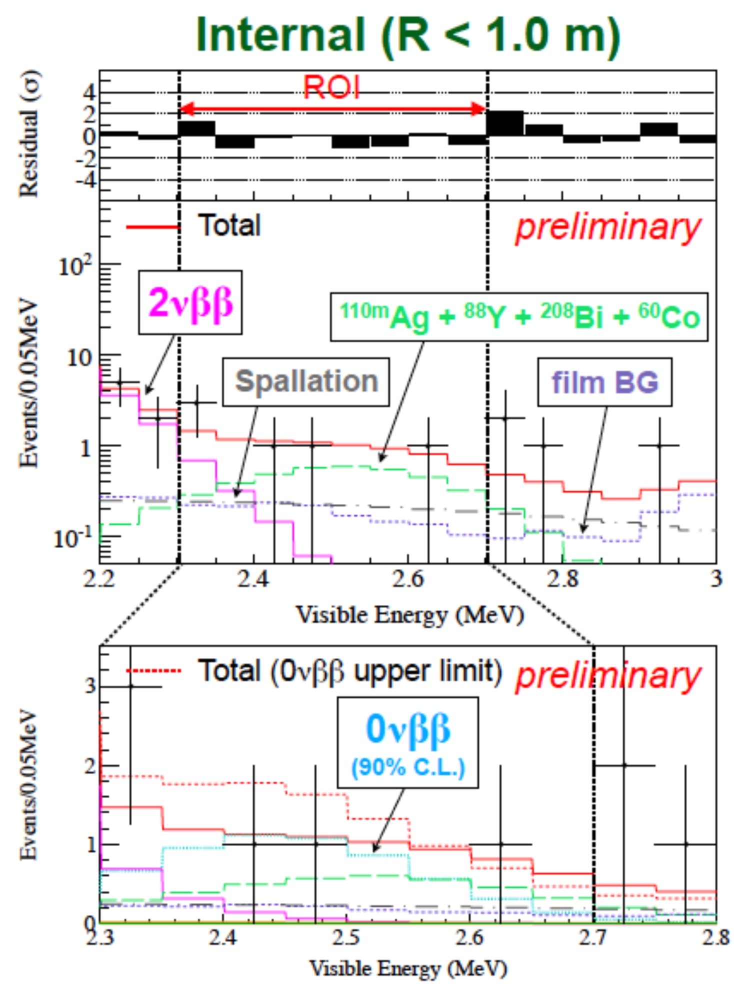
The Xenon projects: KamLAND-Zen



Phase I: 320 kg

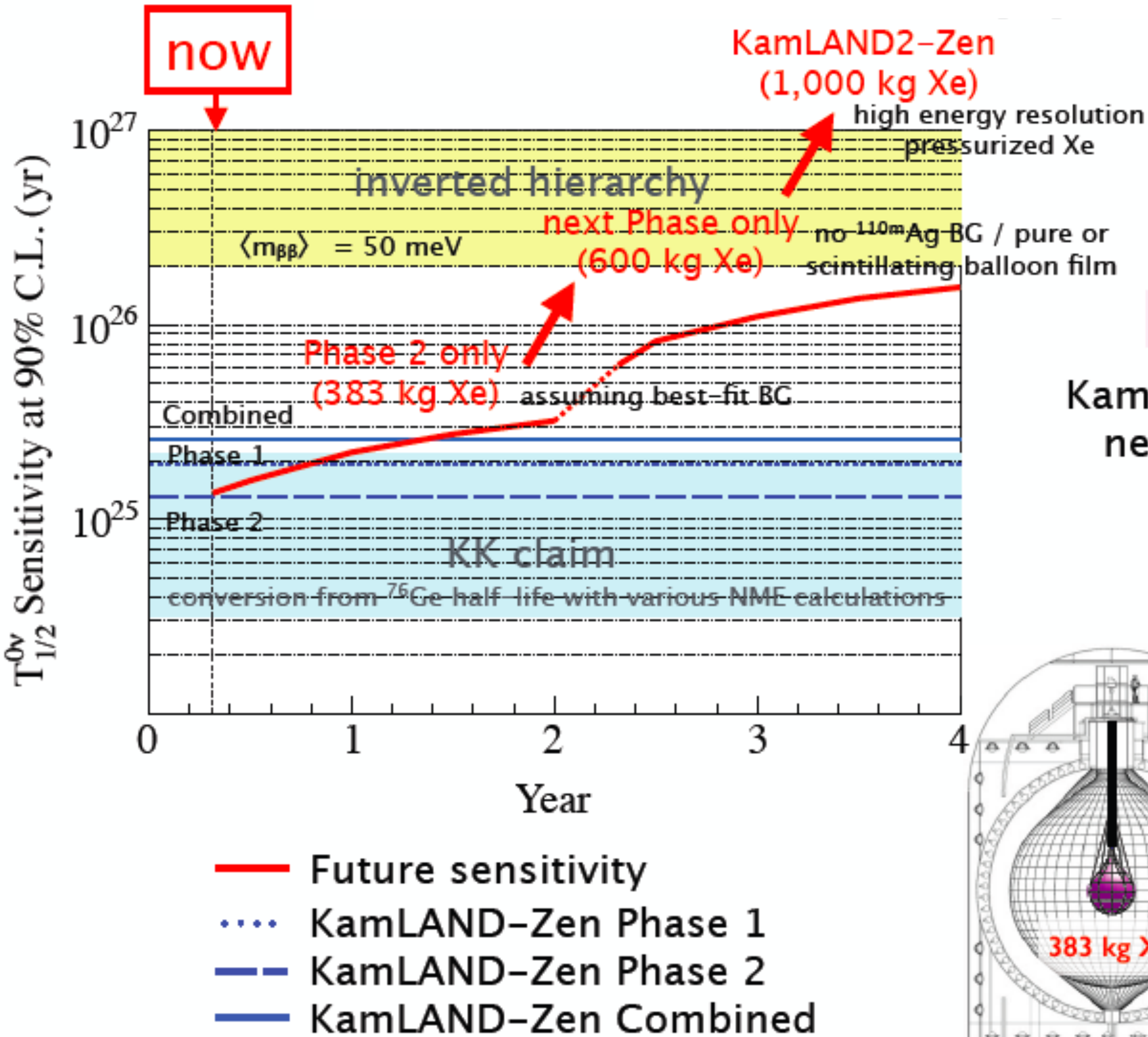
Phase II: 383 kg

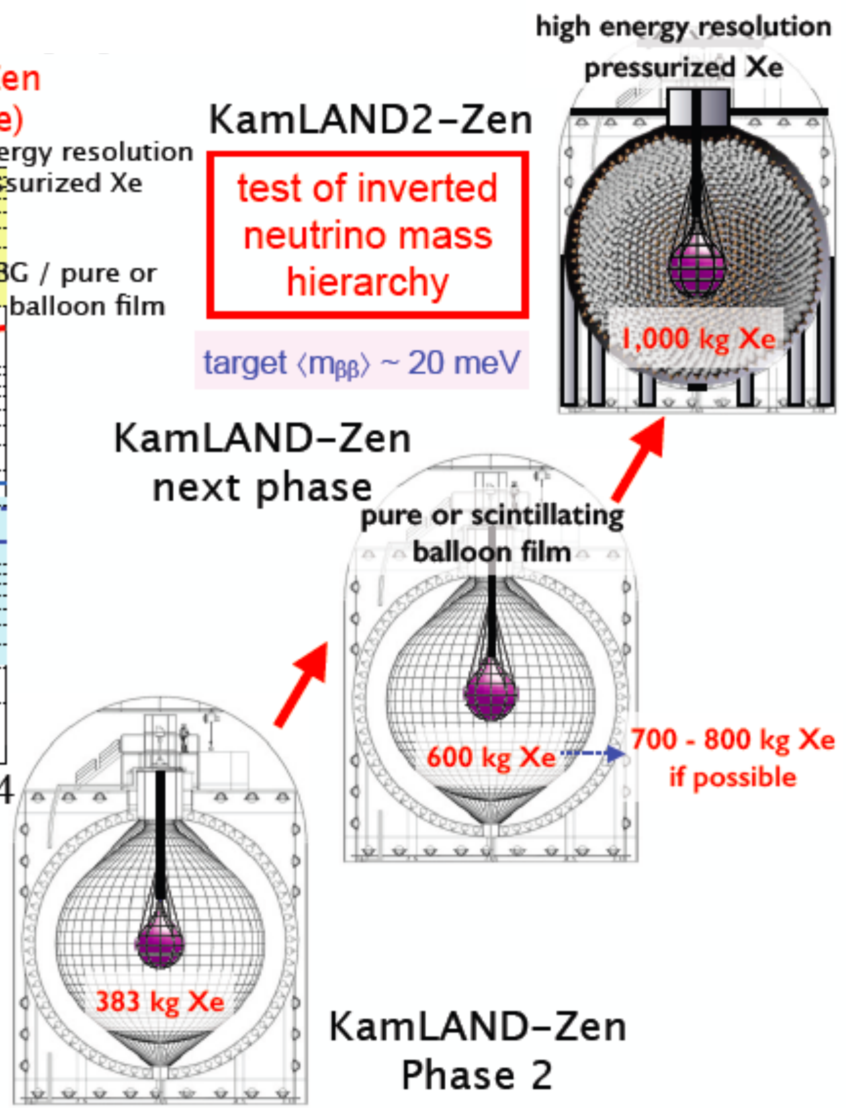
σ_E(2.5MeV) = 4%



I. Shimizu, Neutrino 2014

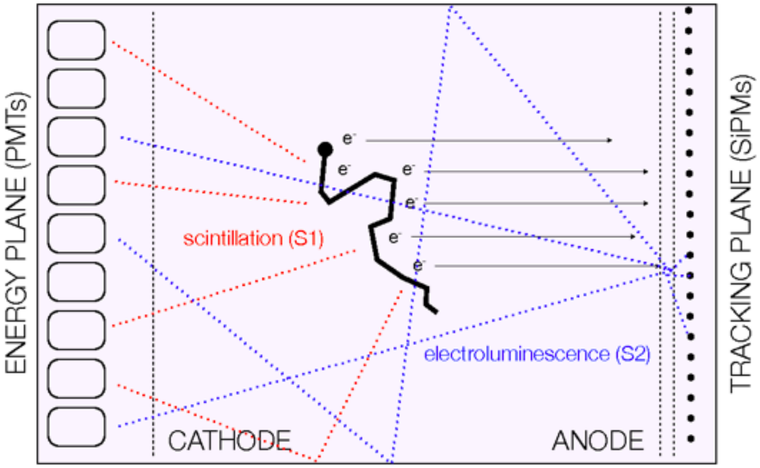
Xe-loaded liquid scintillator



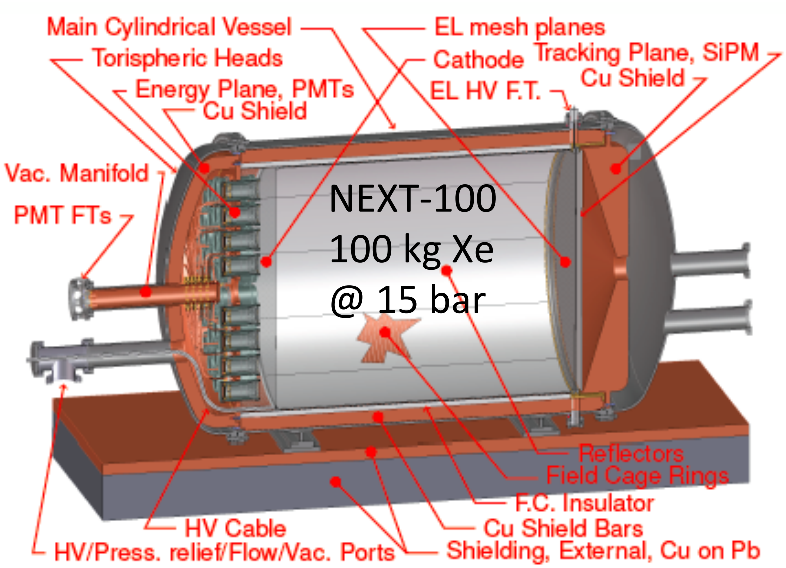


I. Shimizu, Neutrino 2014

The Xenon projects: NEXT-100 @ Canfranc



- Energy resolution: <1% FWHM @ $Q_{\beta\beta}$ =2458 keV
- PID: 2-blob signature

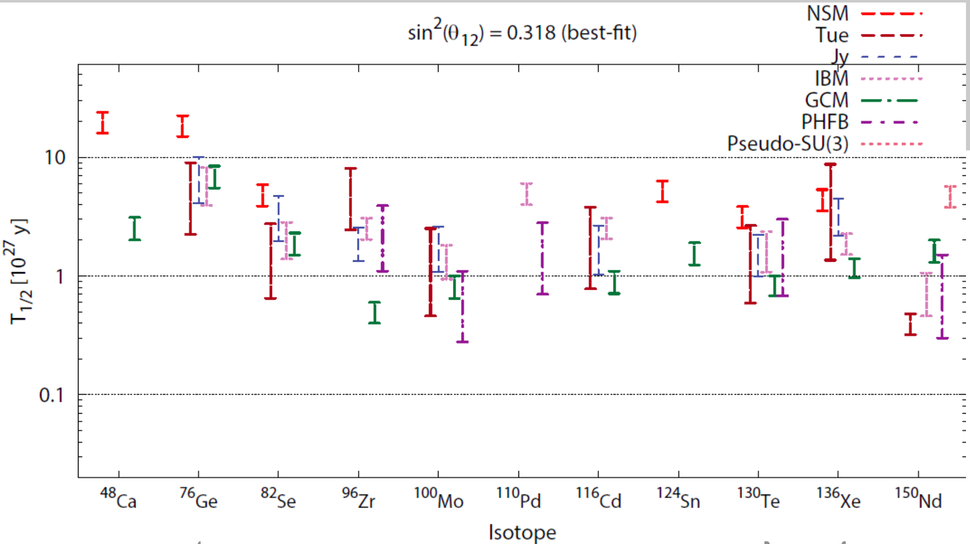


2015: commissioning with non-enriched Xe
2016-2020: physics with 100 kg enr-Xe

$$m_{\beta\beta} \sim 100\, meV$$

D. Lorca, PANIC 2014

Experimentalist's choice



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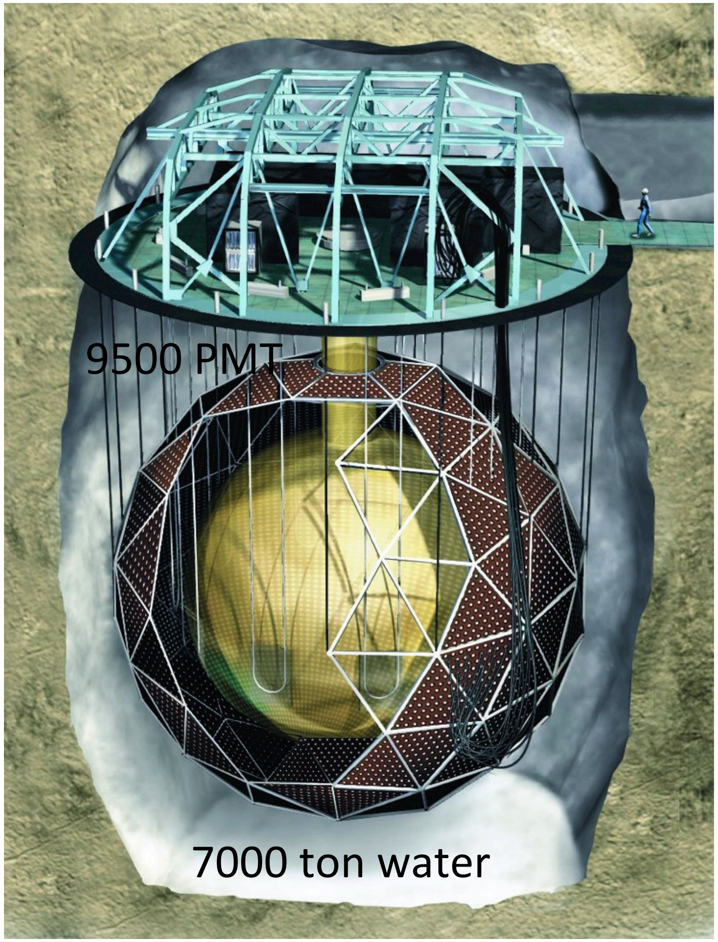
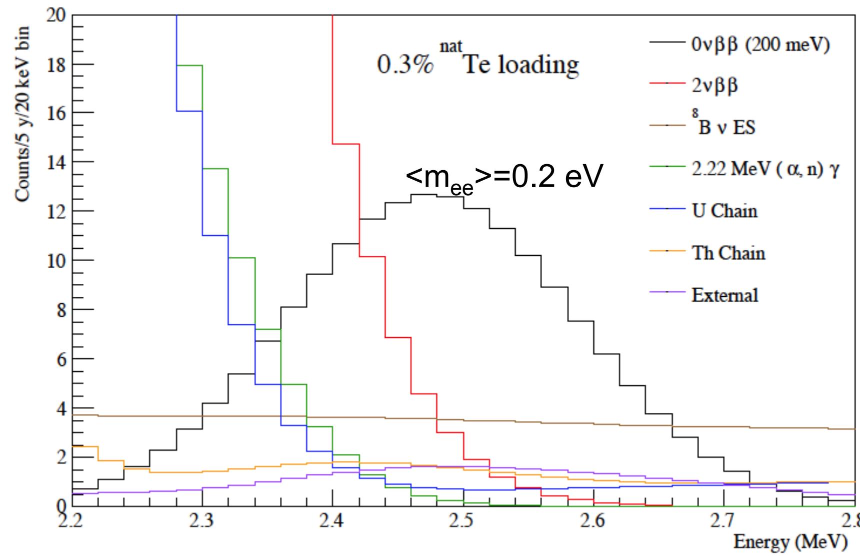
& other interesting, but less advanced R&D

SNO+ with ^{nat}Te



780 ton LAB+PPO in Ø12 m acrylic vessel

0.3% loading → 2340 kg natTe / 800 kg ^{130}Te

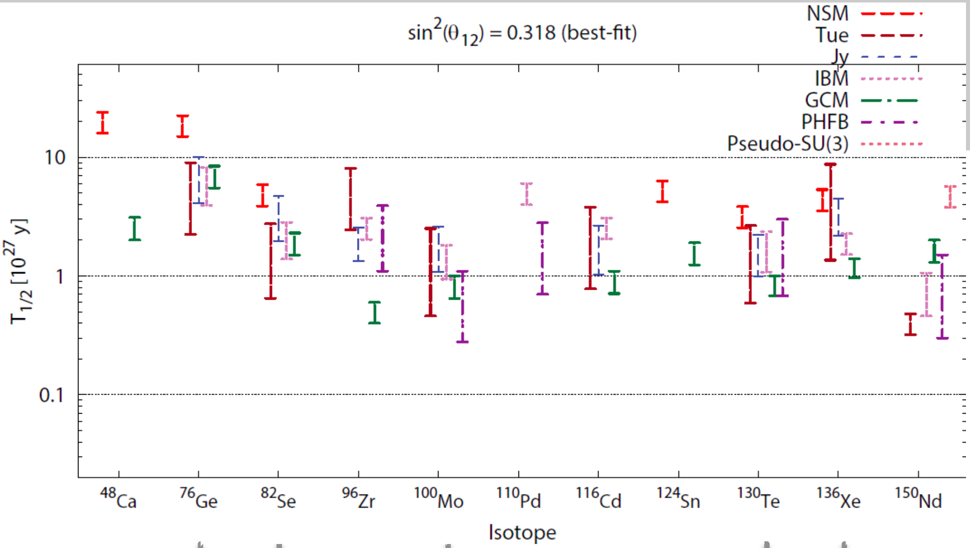


2015: Scintillator filling

2016: physics run

FWHM ~ 270 keV @ $Q_{\beta\beta}$, sensitivity 5 yr $T_{1/2} > 1.0\ 10^{26}$ yr (90% CL)

Experimentalist's choice



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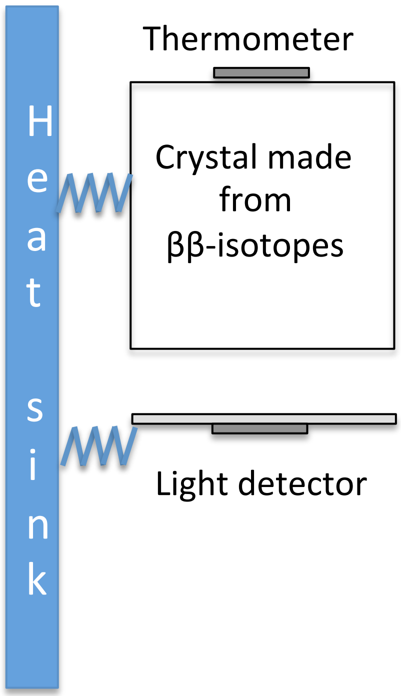


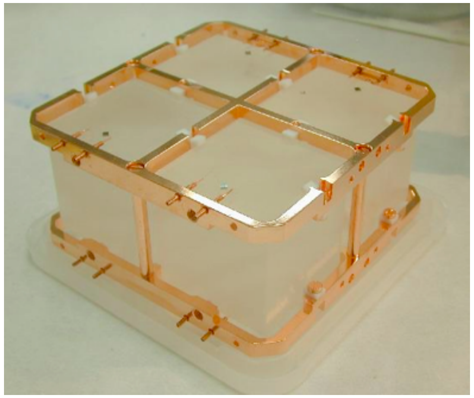
0νββ emitters: ^{130}Te, ^{82}Se, ^{100}Mo & few others

Crystals: TeO_2 , ZnSe, $ZnMoO_4$, $CaMoO_4$

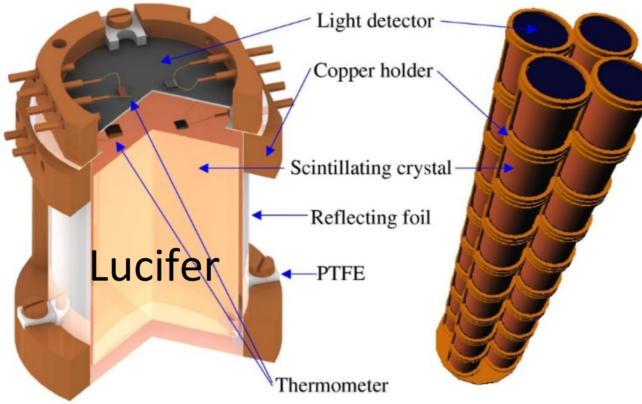
Operation at <20 mK:

$$C \propto T^3$$
$$\Delta T \propto \Delta E / C$$
$$TeO_2: \quad \Delta E \cong 5 keV (FWHM)\, at\, Q_{\beta\beta} = 2528\, keV$$

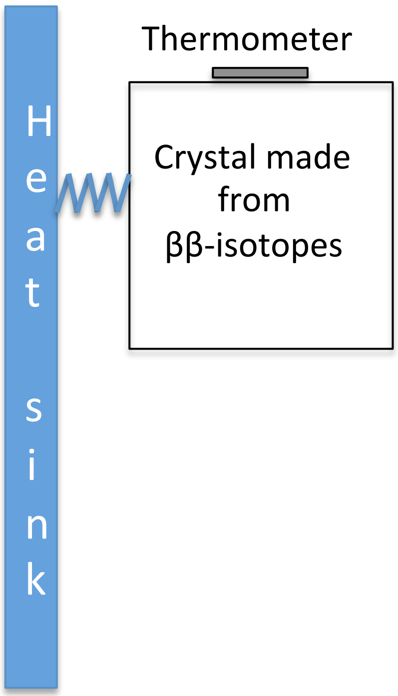
Cuore
(w/o light detection)



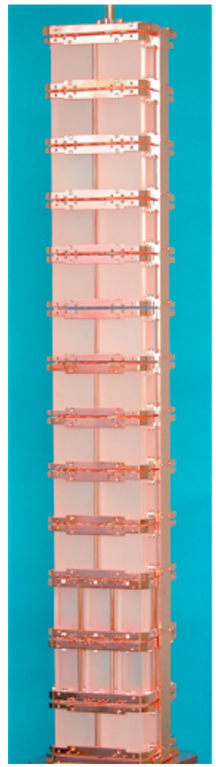
Lucifer, Lumineu, Amore
(with light detection)



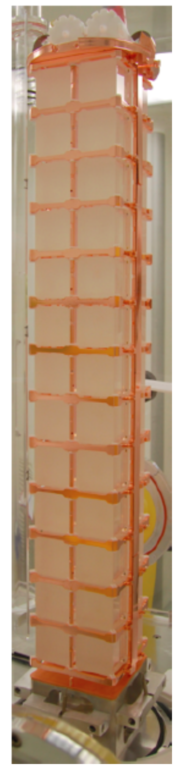
Bolometer experiments: Cuore (^{130}Te)



Cuoricino
2003

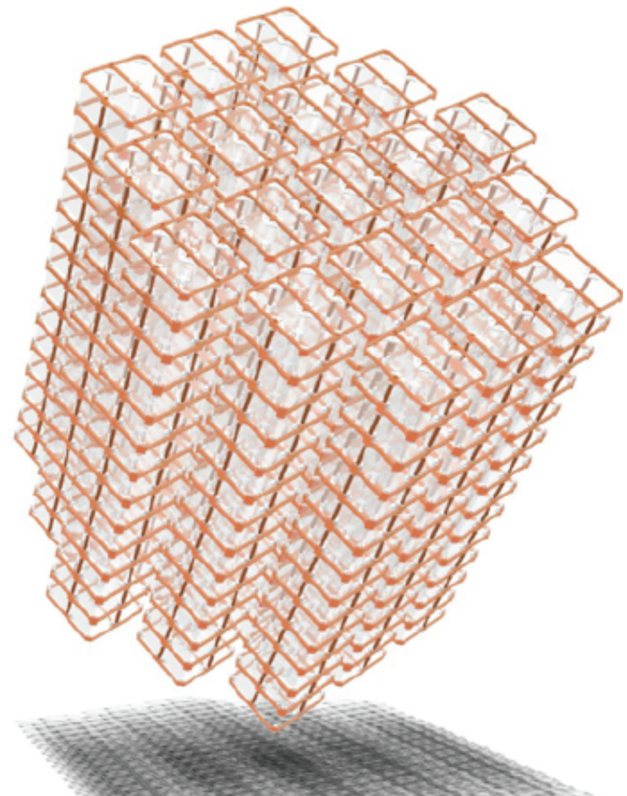


Cuore-0
2012



39 kg
(11 kg ^{130}Te)

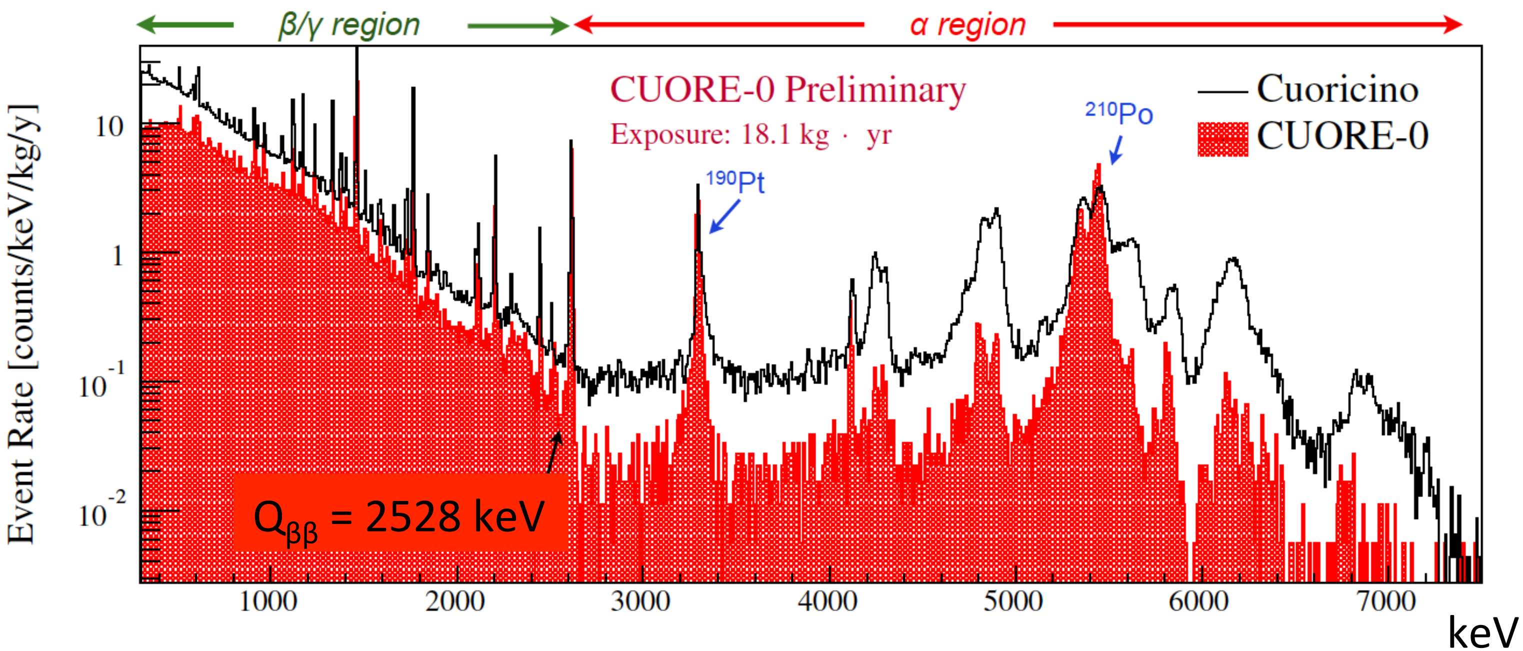
Cuore
2015



741 kg
(206 kg ^{130}Te)

Bolometer experiments: Cuore-0/Cuore (^{130}Te)

Cuore-0: operation of Cuore detector-tower in Couricino cryostat



α-, γ-Backgrounds from nearby surfaces and bulk. Reduction w.r. to Cuoricino:

- 5.5x in alpha energy range
- 2.4x at $Q_{\beta\beta}$

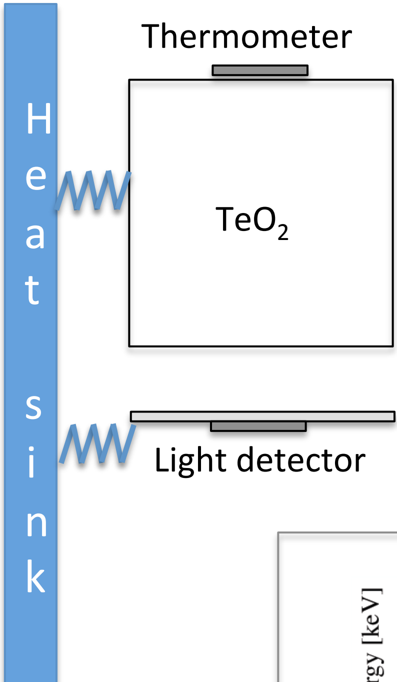
➔ bgd in Cuore ≈0.01 cts/(keV kg y)

➔ Cuore: 9.5 x 10^{25} yr / 40-100 meV

	0vββ region cnts/(keV kg y)	*2700-3900 keV*	*ε(%)*
Cuoricino	0.153 ± 0.006	0.110 ± 0.001	83
CUORE-0	**0.063 ± 0.006**	**0.020 ± 0.001**	78

From O. Cremonesi, Nu2014

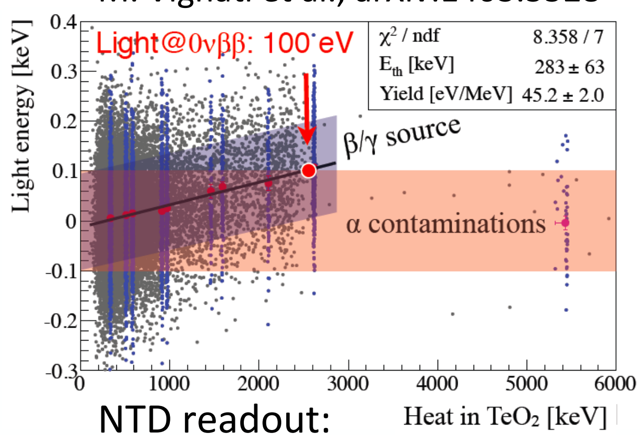
Future bolometer: TeO_2 with coincident Cherenkov detection



Few-MeV α-particles do not generate Cherenkov light while ββ (and γ's) do
➔ Measure Cherenkov light in coinc. with heat

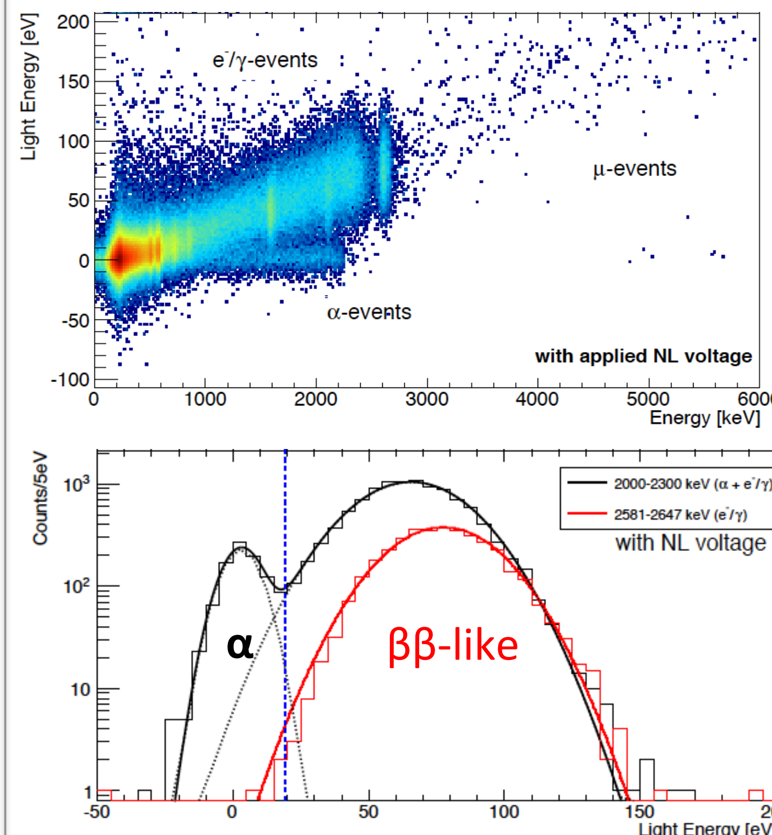
T.Tabarelli de Fatis, EPJ C65, 2010

M. Vignati et al., arXiv:1403.5528



NTD readout: separation on statistical basis

M. Willers et al., arXiv:1407.6516

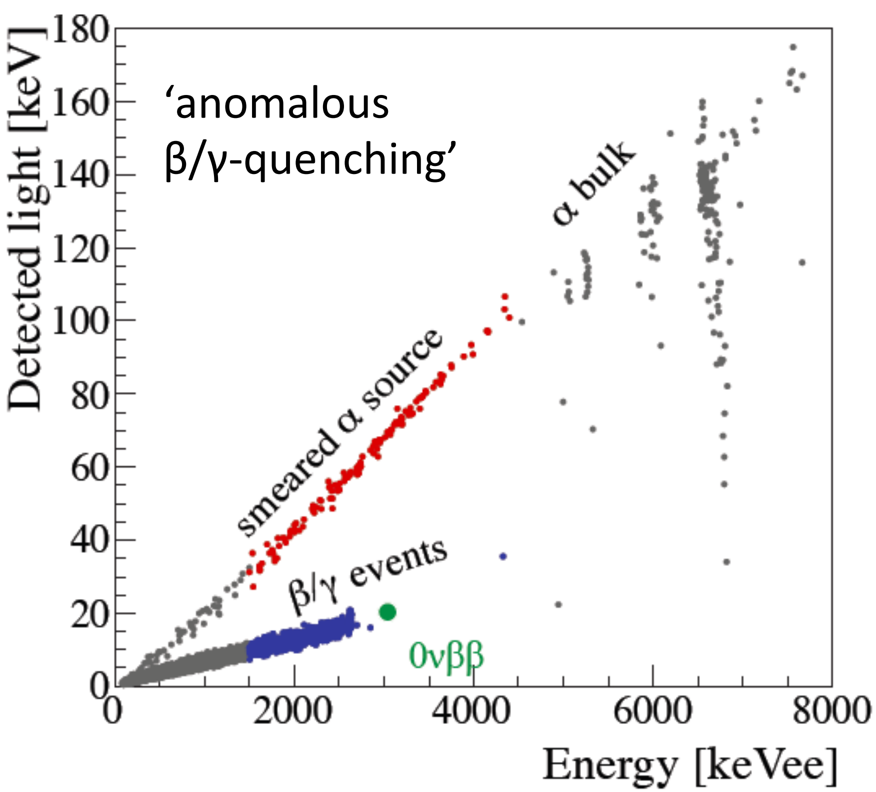


TES/Neganov-Luke light detector: separation event-by-event

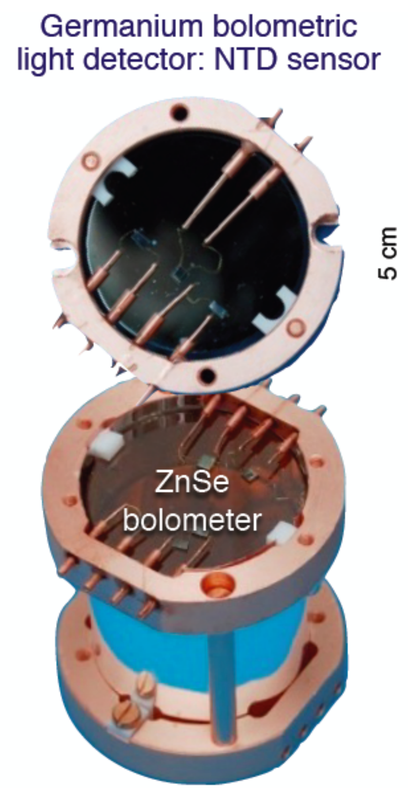
Future bolometer: scintillating crystals – Lucifer (ZnSe)

JINST 1305 (2013)

$Q_{\beta\beta}$ (^{82}Se) = 2995 keV
Array of 32-36 enr. (95%) Zn^{82}Se crystals
Total ^{82}Se nuclei: (6.7-8.0) 10^{25}
Single detector: 460 g
BI (goal): 1-2 x10^{-3} cts / (keV kg yr)
ΔE (FWHM): 10-15 keV



- **Bgd (internal α's):**
  17.2±4.6 μBq/kg (^{232}Th)
  24.6±5.5 μBq/kg (^{238}U)
  Isotope delivery:
  9/15 kg ^{82}Se delivered
  final batch for 02/2015
  Crystal growth:
  Schedule for Jan - June 20
  Current yield: 70%

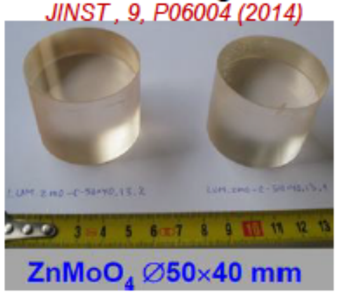


From S. Pirro / M. Vignati

Future bolometer: scintillating crystals – Lumineu ($ZnMoO_4$)

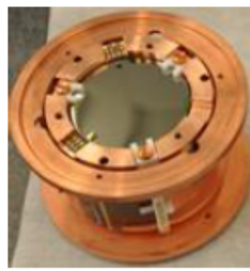
$Q_{\beta\beta}$ (^{100}Mo) = 3034 keV
10 kg ^{enr}Mo

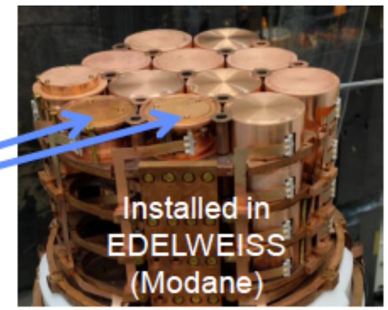
Natural crystals
Regular shape
M ~ 340 g
JINST , 9, P06004 (2014)

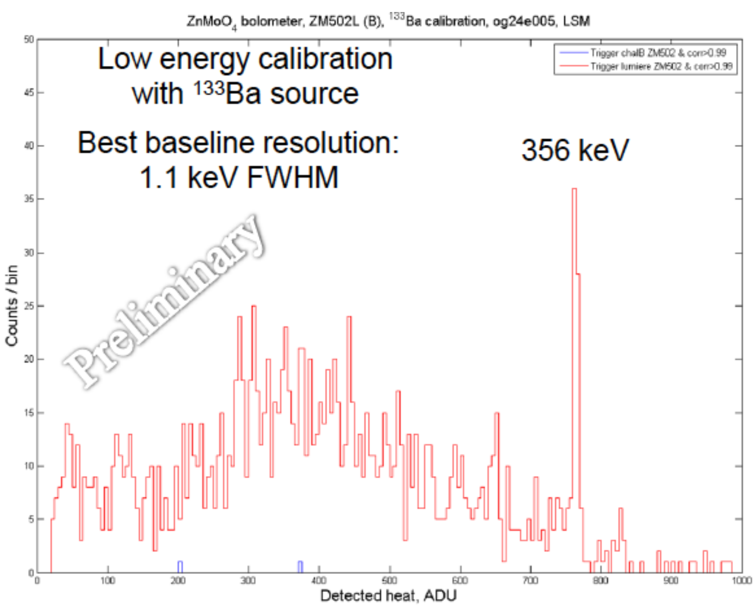


ZMO crystal assembled as bolometer

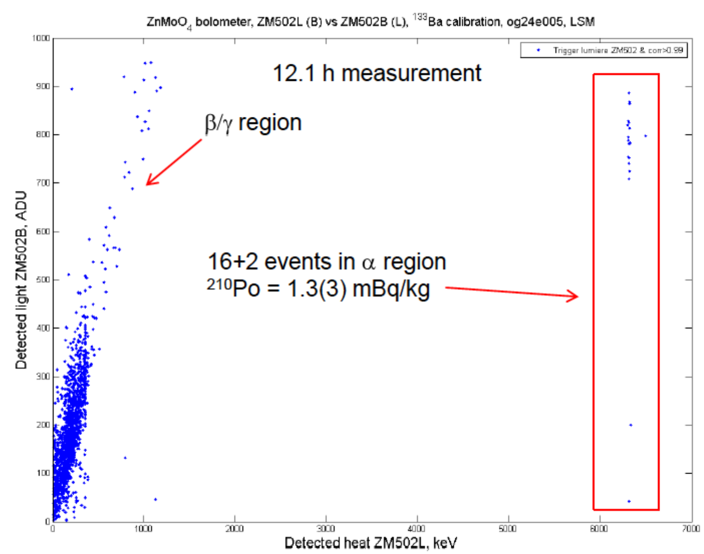
Ge light detector on top





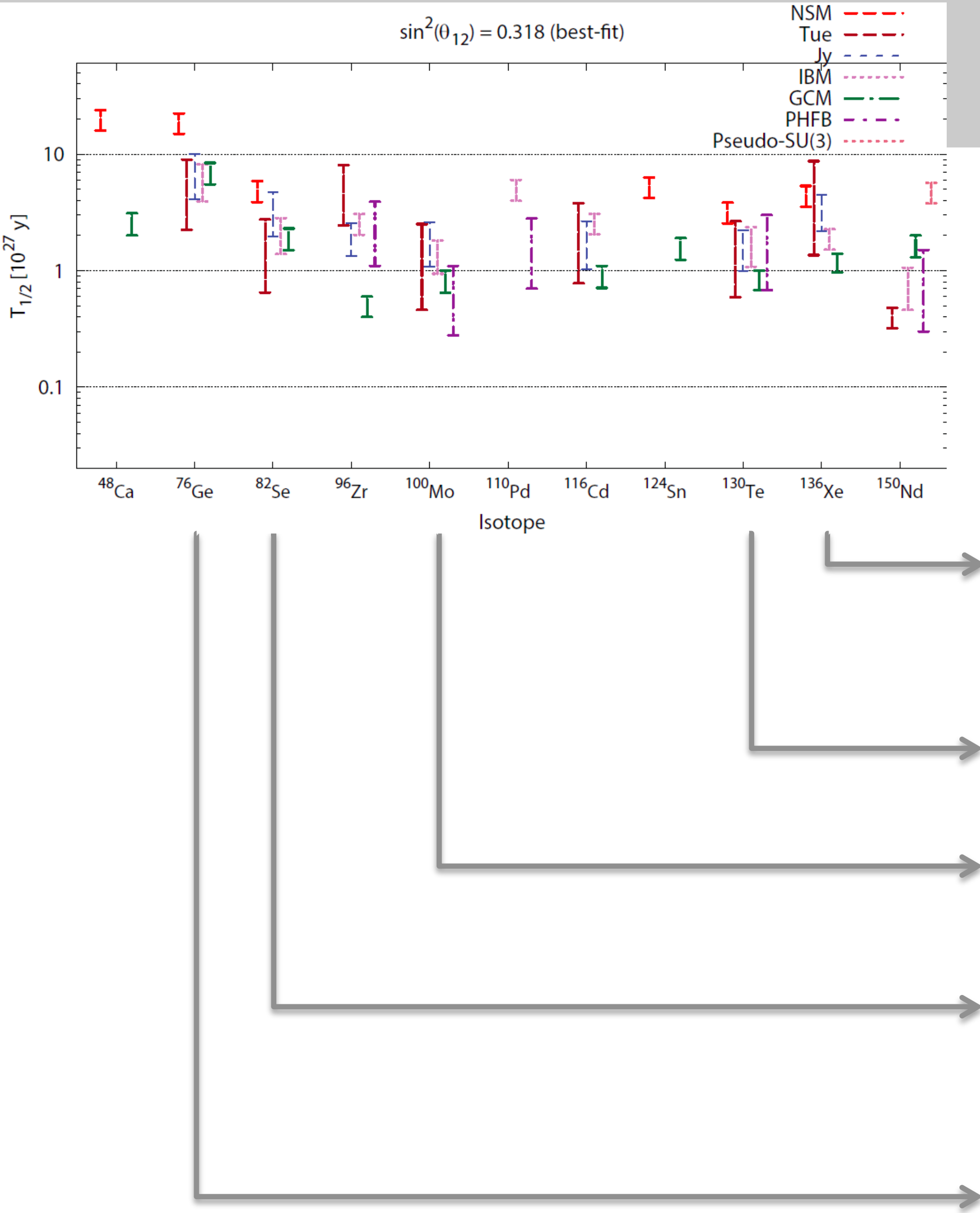


Preliminary data from August LSM run



From A. Giuliani

Experimentalist's choice



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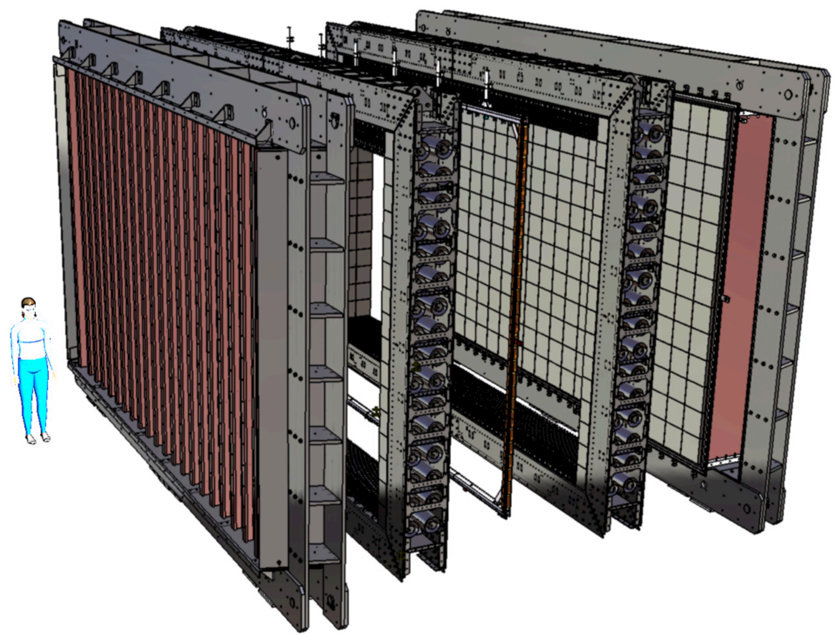
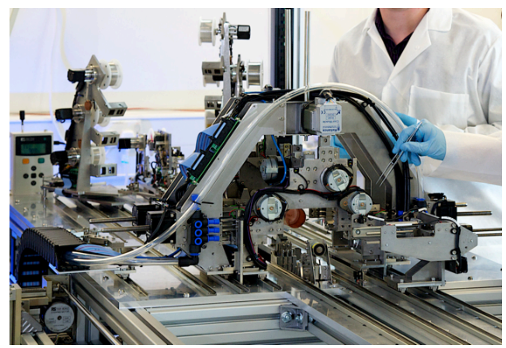
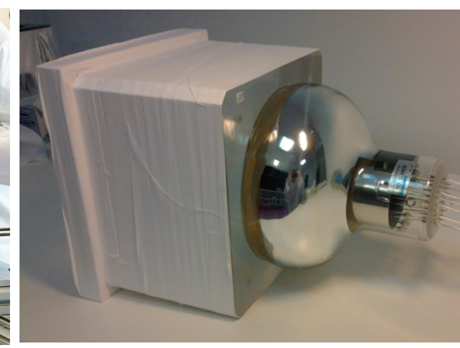
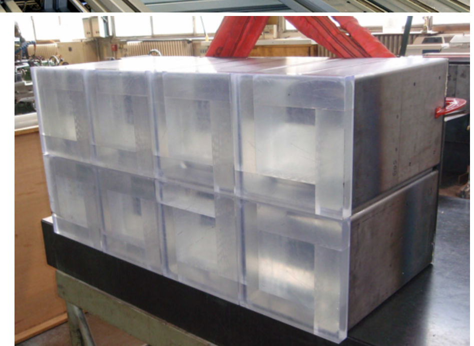
SuperNEMO Demonstrator @ LSM

- 2012: SuperNEMO demonstrator module start construction
- 5.56 kg of enriched ^{82}Se / 4.56 kg puried
- 2015: commissioning
- No background in the ROI in 2.5 years for 7 kg of ^{82}Se expected
- Sensitivity after 17.5 kgy exposure (90 % CL):
  $T_{1/2} > 6.5\ 10^{24}$ yr ($<m_{ee}> < 0.20\text{-}0.40$ eV)

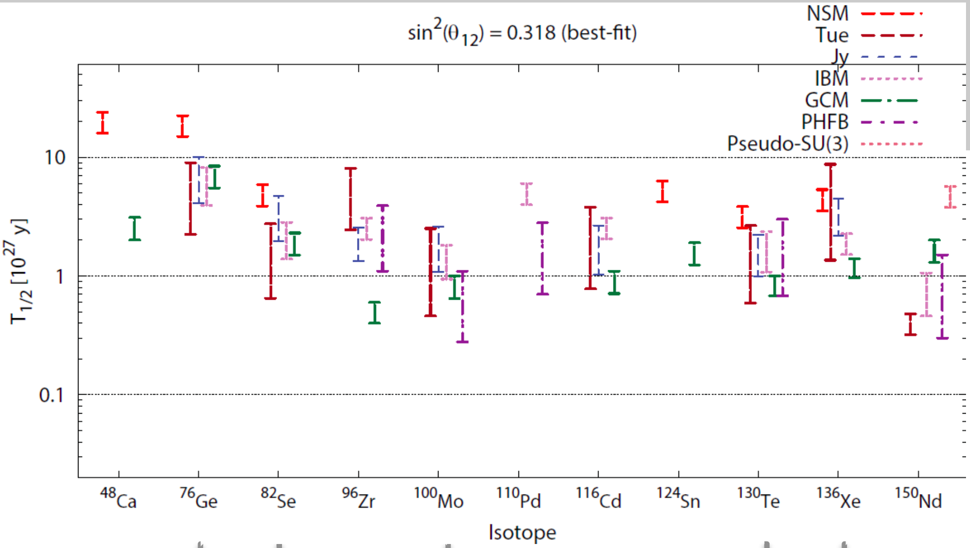








Experimentalist's choice



^{48}Ca, ^{150}Nd currently can not be enriched in large quantities

LXe TPC:	**(n)EXO**
gas-Xe TPC:	**NEXT**
Xe-loaded LS:	**KL-Zen**

Te-loaded LS:	**SNO+**
Te-bolometers:	**Cuore**

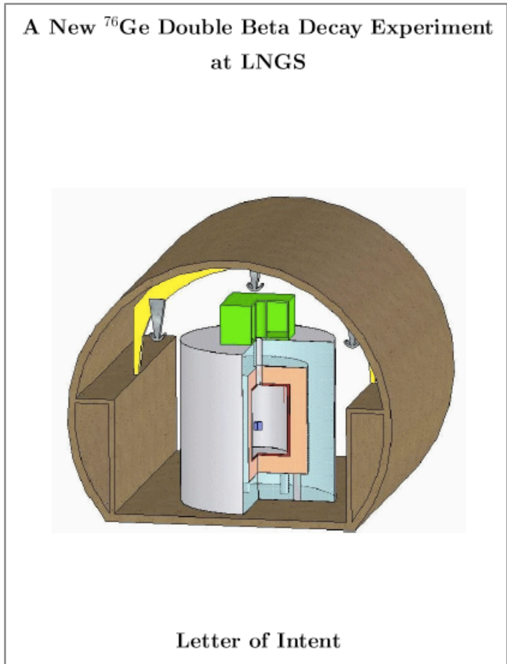
Mo-bolometers:	**Lumineu, Amore**

Se-bolometers:	**Lucifer**
Se-calo-tracko:	**SuperNemo**

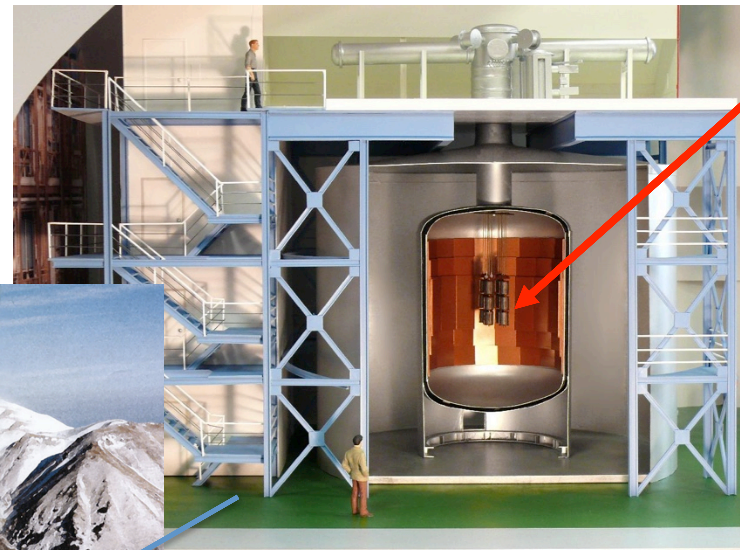
Ge-semiconductor: **GERDA, MJD**

& other interesting, but less advanced R&D

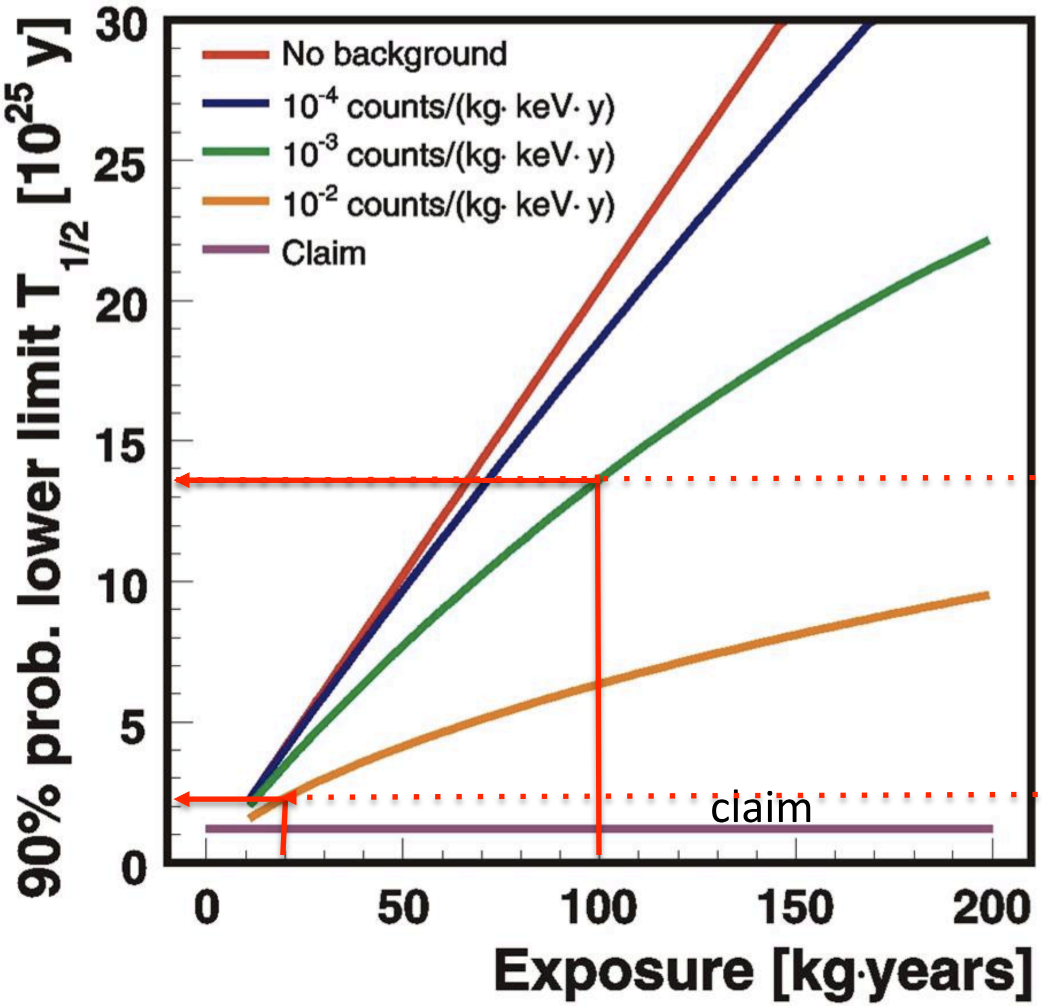
Ge-experiments: GERDA @ LNGS


A New ^{76}Ge Double Beta Decay Experiment at LNGS

Letter of Intent



- ‘Bare’ ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon / H_2O
- <u>Staged approach:</u>
  - Phase I: 18 kg (HdM/IGEX)
  - Phase II: add ~20 kg new enriched BEGe detectors



Phase II:

Add new enr. BEGe detectors (20 kg)

BI ≈ 0.001 cts / (keV kg yr)

Sensitivity after 100 kg yr

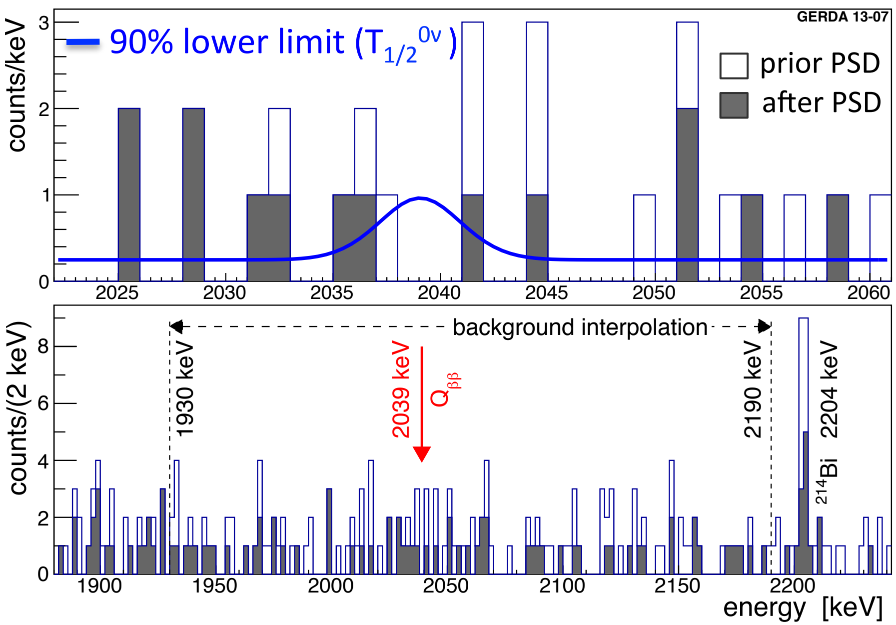
Phase I:

Use refurbished HdM & IGEX (18 kg)

BI ≈ 0.01 cts / (keV kg yr)

Sensitivity after 20 kg yr

PRL 111 (2013) 122503



- **Events ±20 keV blinded**
- After freezing
  - energy calibration
  - data selection
  - statistical analysis method
  - pulse shape cuts

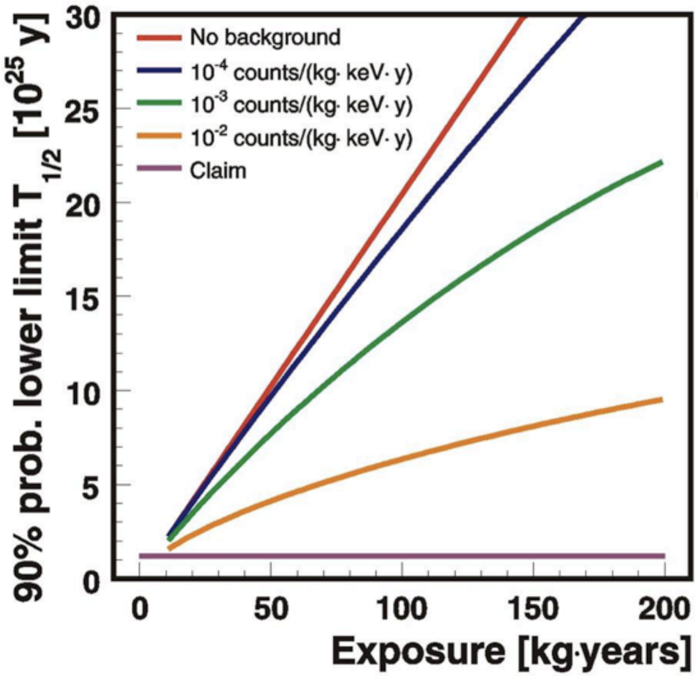
  unblinding June 2013
- Exposure 21.6 kg yr
- Background 0.01 cts/(keV kg yr) after PSD

$$T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}\ \mathrm{yr}$$ 90% C.L.)

- Median sensitivity (90% C.L.): >2.4×10^{25} yr

Past 4.2σ claim: GERDA should see 5.9±1.4 0νββ events in ±2σ interval above bgd of 2.0±0.3
GERDA best fit $N^{0\nu}$ =0: P($N^{0\nu}$ =0|H_1 =signal+bgd) = 1% ➔ claim ruled out @ 99%

Ge-experiments: Reducing background further for GERDA Phase II



Phase II:
10^{-3} cts/(kg keV yr)

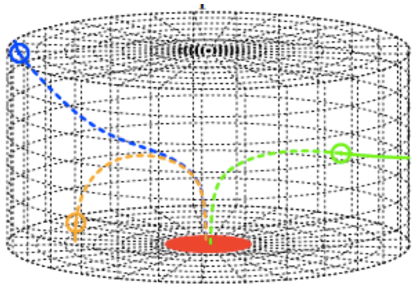
1/10

Phase I:
10^{-2} cts/(kg keV yr)

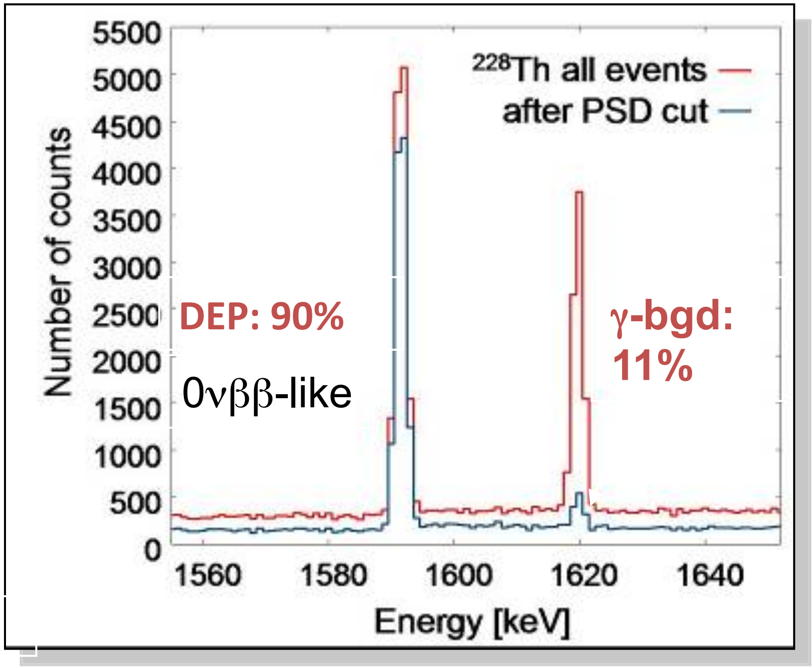
<u>Major hardware upgrade:</u>

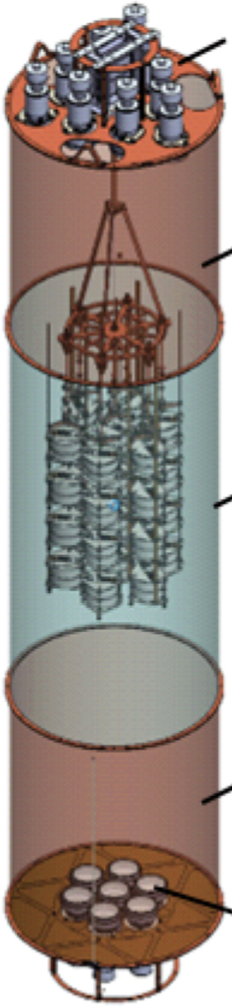
- Novel detectors with advanced pulse shape discrimination (BEGe's)
- Improved detector assembly & electronics
- Liquid argon instrumentation (veto system)
- Integration/commissioning ongoing

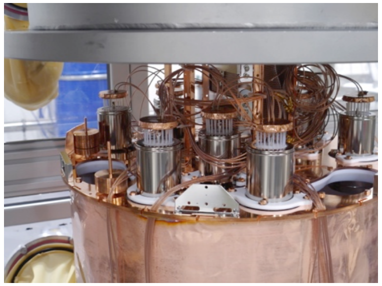
GERDA Phase II: novel Ge-detectors & LAr scintillation veto

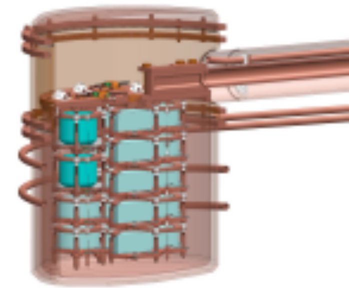


- **SSE/MSE** discrimination
- **Surface** events

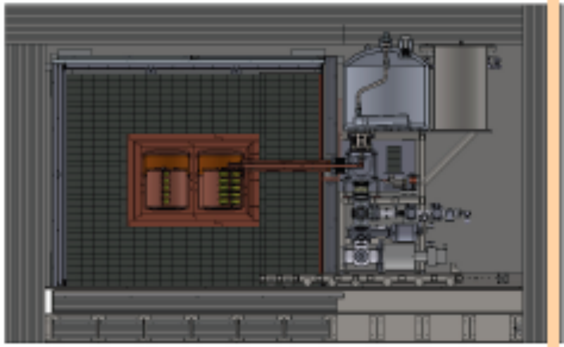








- **40-kg of Ge detectors**
  - 30-kg of 87% enriched ^{76}Ge crystals required for science and background goals
  - Point-contact detectors for DEMONSTRATOR



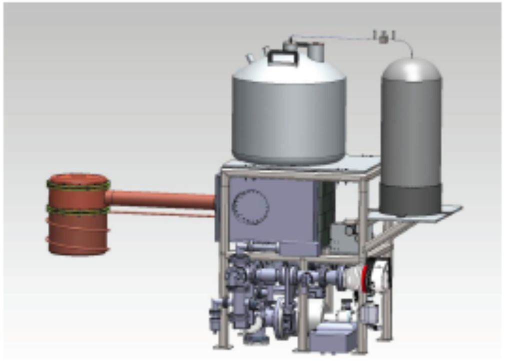
- **Low-background Cryostats & Shield**
  - ultra-clean, electroformed Cu
  - naturally scalable
  - Compact low-background passive Cu and Pb shield with active muon veto
- **Located at 4850' level at Sanford Lab**
- **Background Goal** in the $0\nu\beta\beta$ peak ROI(4 keV at 2039 keV)

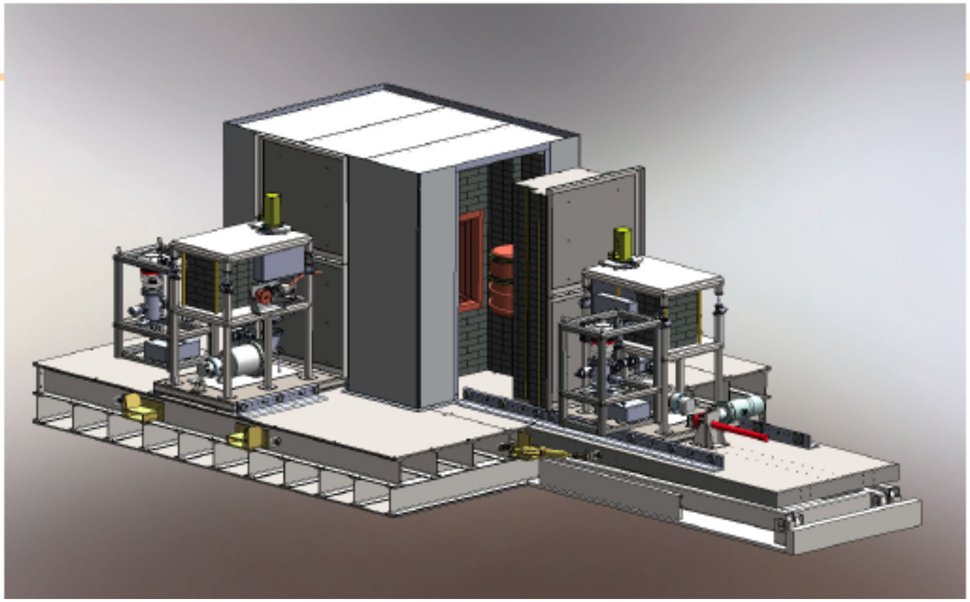
~ 3 count/ROI/t-y (after analysis cuts) (scales to 1 count/ROI/t-y for tonne expt.)

From S. Elliot, NIAPP 2014

MJD Implementation

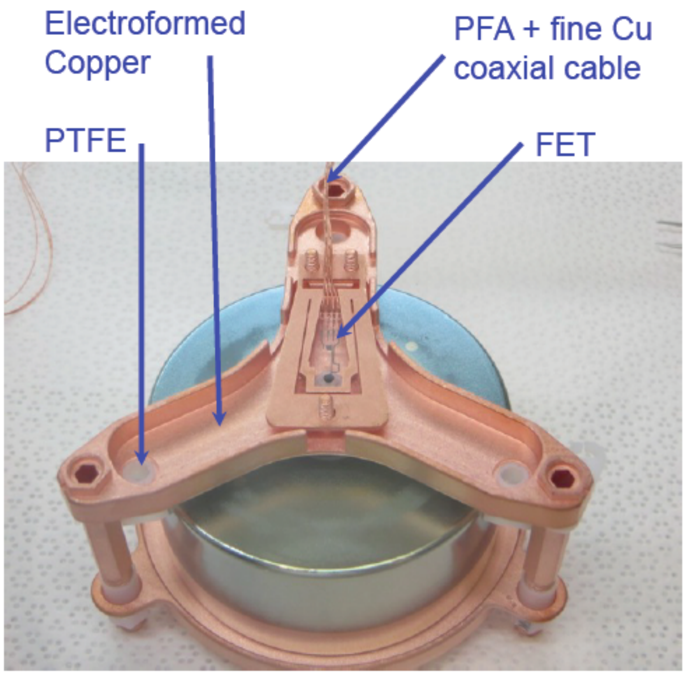
- Three Phases: Commissioning Dates
  - –Prototype cryostat (2 strings, ^{nat}Ge) (In Use)
  - –Module 1 (7 strings ^{enr}Ge) (Winter 2014)
  - –Module 2 (abut half and half ^{enr}Ge-^{nat}Ge) (Late 2015)

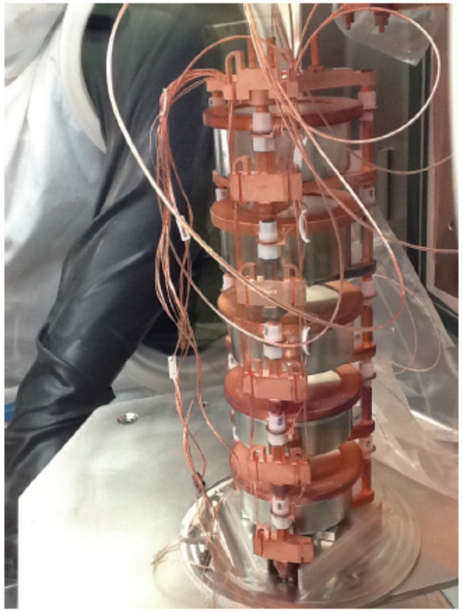




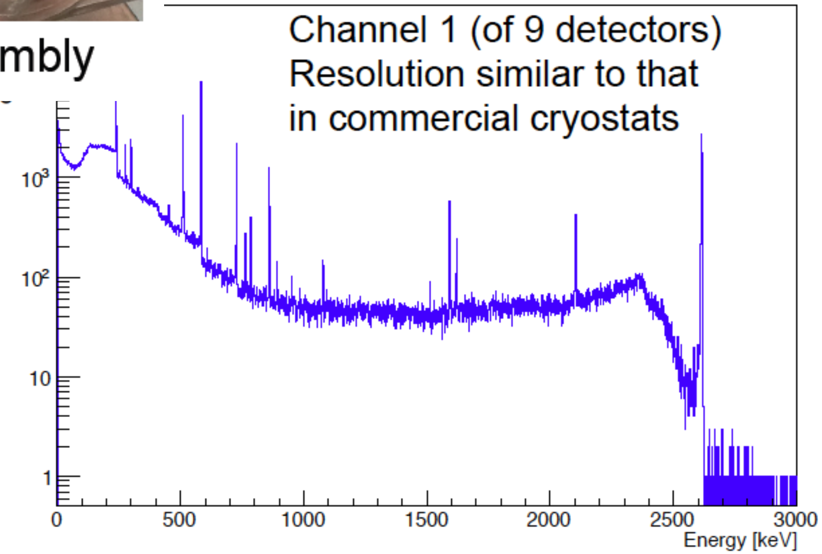
From S. Elliot, NIAPP 2014

Ge-experiments:Majorana Demonstrator (MJD)





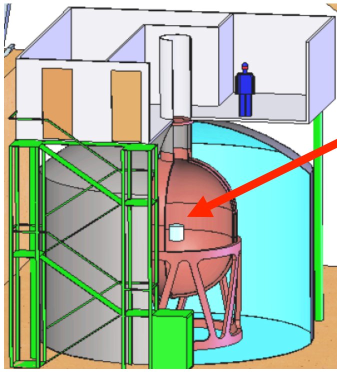
String Assembly



From S. Elliot, NIAPP 2014

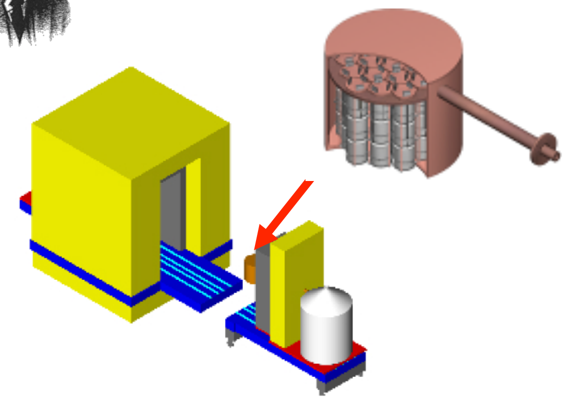
Future Ge-experiments: GERDA & Majorana

GERDA



- ‘Bare’ ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon / H_2O
- Phase I: 18 kg (HdM/IGEX)
- Phase II: add 20 kg new enr. detectors; total ~40 kg

Majorana



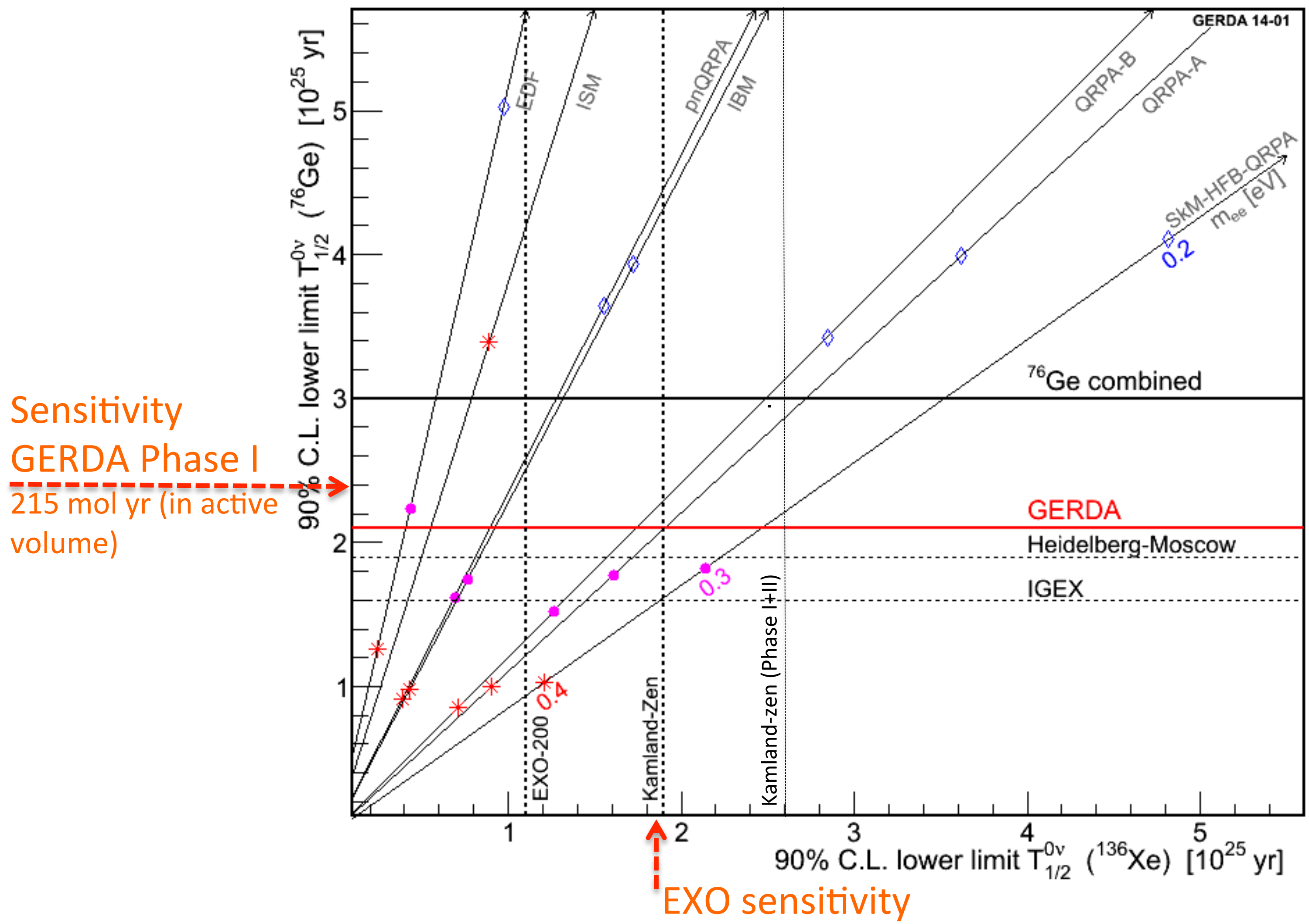
- Array(s) of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Initial phase: R&D demonstrator module: Total 40 kg (30 kg enr.)

Physics goals: degenerate mass range
Technology: study of bgds. and exp. techniques

LoI
- open exchange of knowledge & technologies (e.g. MaGe MC)
- intention to merge for O(1 ton) exp. (inv. Hierarchy) selecting the best technologies tested in GERDA and Majorana

Also interests / discussion in China (Jin Ping)

Comparison of current Ge vs. Xe results



Comparison of sensitivities

Current experiments and future experiments/propsals

		mass [kg]* (total/FV)	FWHM [keV]	background& [cnt/mol yr FWHM]	$T_{1/2}$ limit [10^{25} yr] after 4 yr	<m_{ee}> limit [meV]	date
Gerda II	Ge	35/27	3	0.0004	15	80-190	-2019
MajoranaD	Ge	30/24	3	0.0004	15	80-190	-2019
EXO-200	Xe	170/80	88	0.03	6	80-220	-2019
Kamland-Zen	Xe	383/88 (600/?)	250	0.03	20	44-120	-2018
Cuore	Te	600/206	5	0.02	14	40-160	-2019
SNO+	Te	2340/160	270	0.02	9	50-200	-2020
Kaml.2-Zen	Xe	1100/?	140	?	130	17-50	2020-24
nEXO	Xe	5000/4300	58	0.0007	600 (3000)$	8-22 (4-10)	?

* total= element mass, FV= $0\nu\beta\beta$ isotope mass in fiducial volume (incl enrichment fraction)

& mol of $0\nu\beta\beta$ isotope in active volume and corrected for $0\nu\beta\beta$ efficiency

$ assuming 10 years with Ba tagging

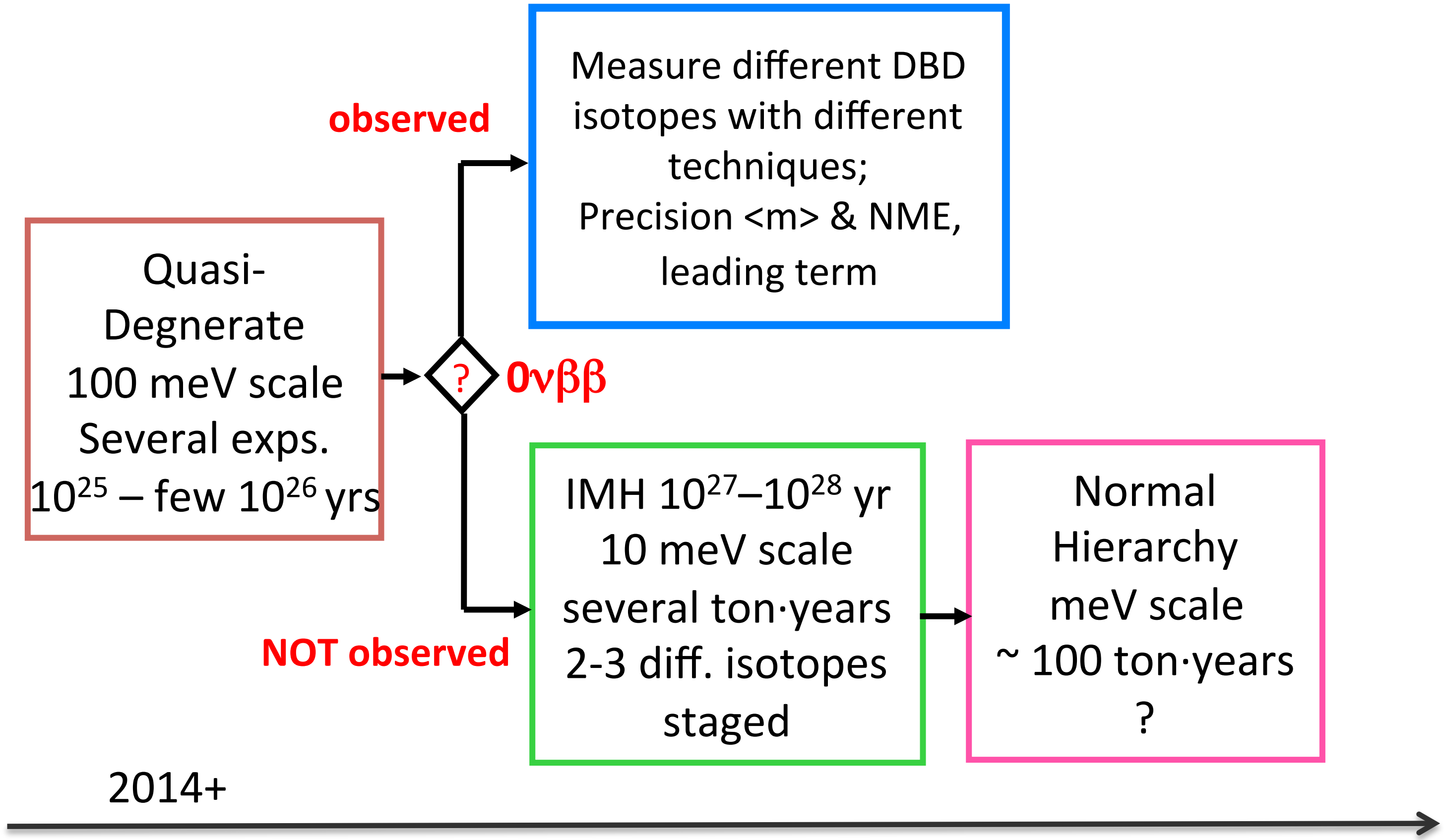
Compilation by B. Schwingenheuer

Conclusions & Remarks

0νββ-signal could be around the corner – or far away….

Goal of next-generation exp’s: **10 meV scale** (IH)

Experimental challenges are, first of all, to reduce **backgrounds** & increase exposure



New world wide collaborations; seeded by present collaborations

Technology down-selection during coming few years

Conclusions & Remarks

0νββ-signal could be around the corner – or far away….
Goal of next-generation exp's: **10 meV scale** (IH)
Experimental challenges are, first of all, to reduce **backgrounds** & increase exposure

Following J.F. Wilkerson @ TUM NIAPP-workshop:

Evidence:

- correct peak energy
- single-site energy deposition
- event distribution in time and space
- signal to background (≥1:1)
- full energy spectrum understood

more direct, but even more difficult:

- observe two-electron nature & kinematics of event
- observe daughter
- observe decay to excited states

Convincing:

- observe 0νββ-signal in several different isotopes
- with different experimental techniques that meet above criteria for evidence