Neutrinoless double beta decay: Experimental challenges

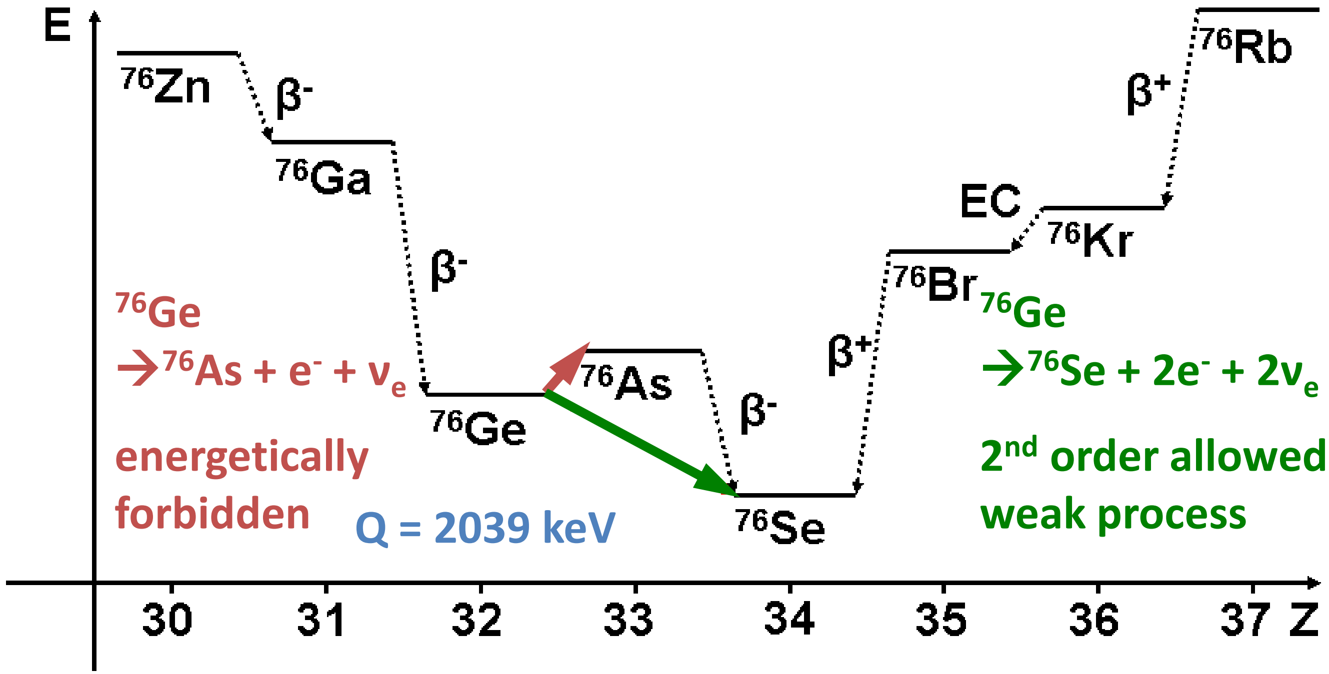
Konstantin Gusev

JINR, Dubna

NOW 2018

September 2018 – Rosa Marina (Ostuni, Italy)

Short intro in 0νββ-decay

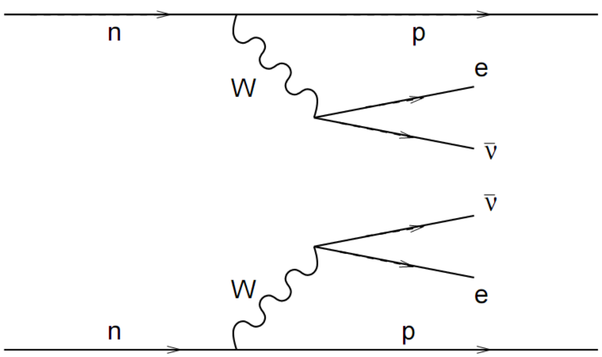


✓ In 1936 Maria Göppert-Mayer noted, that in some even-even nuclei the single β-decay is energetically forbidden whereas the simultaneous but independent β-decay of two nucleons (so-called double beta decay) is allowed

Short intro

Why (0ν)ββ-decay?

2νββ

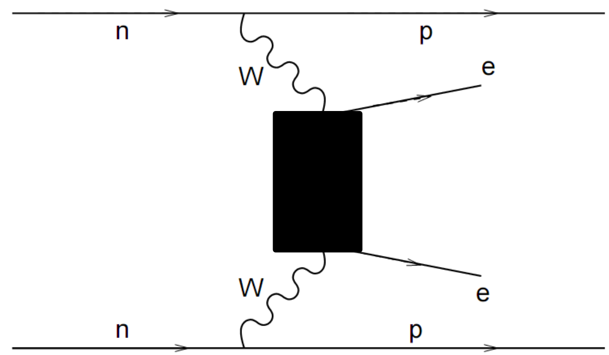


- violates lepton number? **NO**
- forbidden in SM? **NO**

- but half life is 10^{10} longer than the age of the universe, however already observed!

^{76}Ge: $T^{2\nu}_{1/2} = 1.92 \times 10^{21}\text{yr}$

0νββ



- violates lepton number? **YES!**
- forbidden in SM? **YES!**

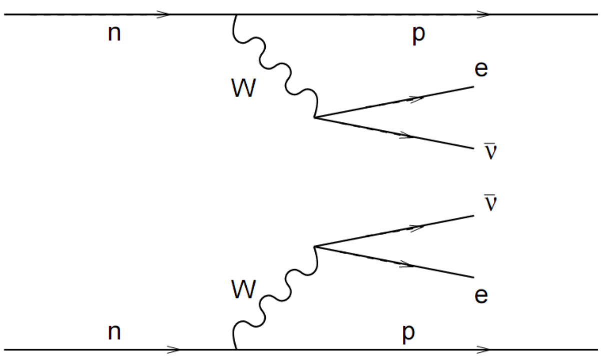
New Physics!

- **ν** has **Majorana** mass component

Short intro

Why (0ν)ββ-decay?

2νββ

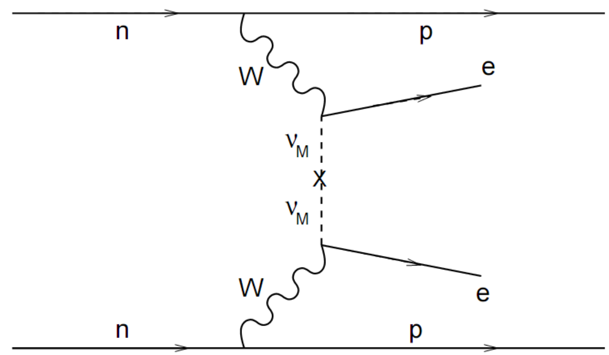


- violates lepton number? **NO**
- forbidden in SM? **NO**

- but half life is 10^{10} longer than the age of the universe, however already observed!

^{76}Ge: $T_{1/2}^{2\nu} = 1.92 \times 10^{21}\mathrm{yr}$

0νββ



- violates lepton number? **YES!**
- forbidden in SM? **YES!**

New Physics!

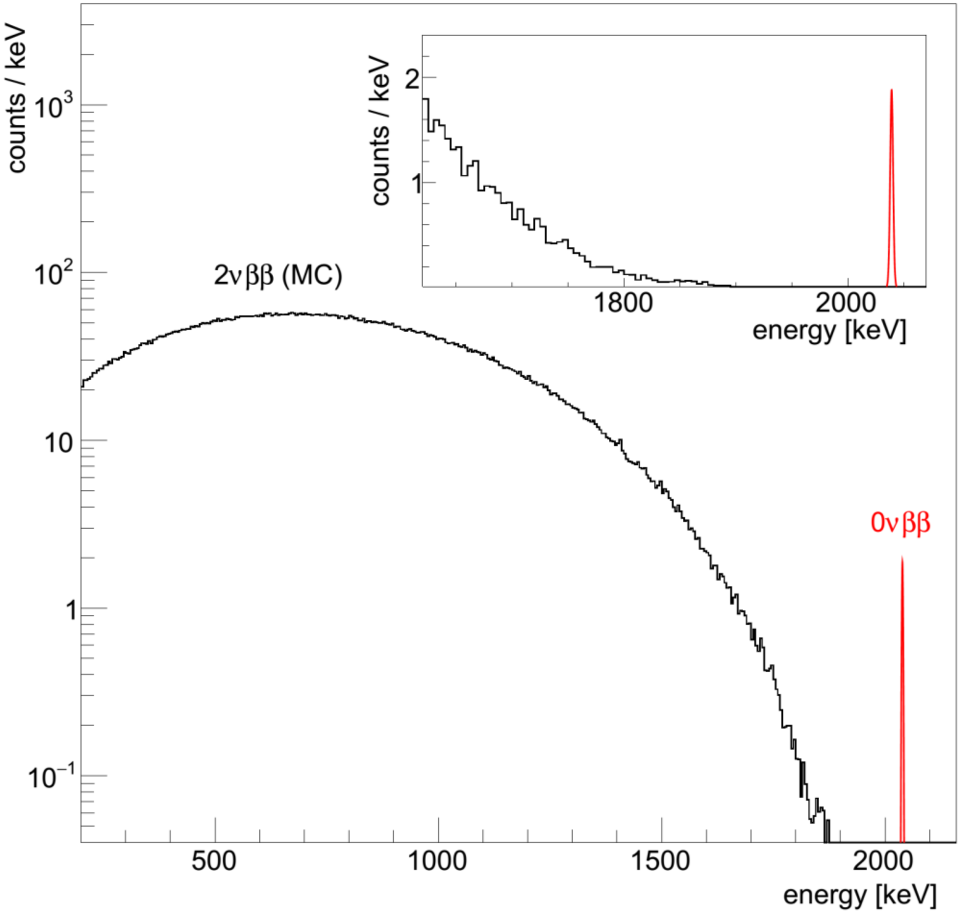
- **ν** has **Majorana** mass component
- **IF** light neutrino exchange

Access to ν mass scale

Short intro

What are we measuring?

Summed electron spectrum (^{76}Ge):



0νββ:
Sharp peak at Q-value of the decay

$T_{1/2}^{0\nu} > 10^{25}\mathrm{yr}$

2νββ:
Continuous spectrum

$T_{1/2}^{2\nu} \sim 10^{21}\mathrm{yr}$

→ **Background for 0νββ**

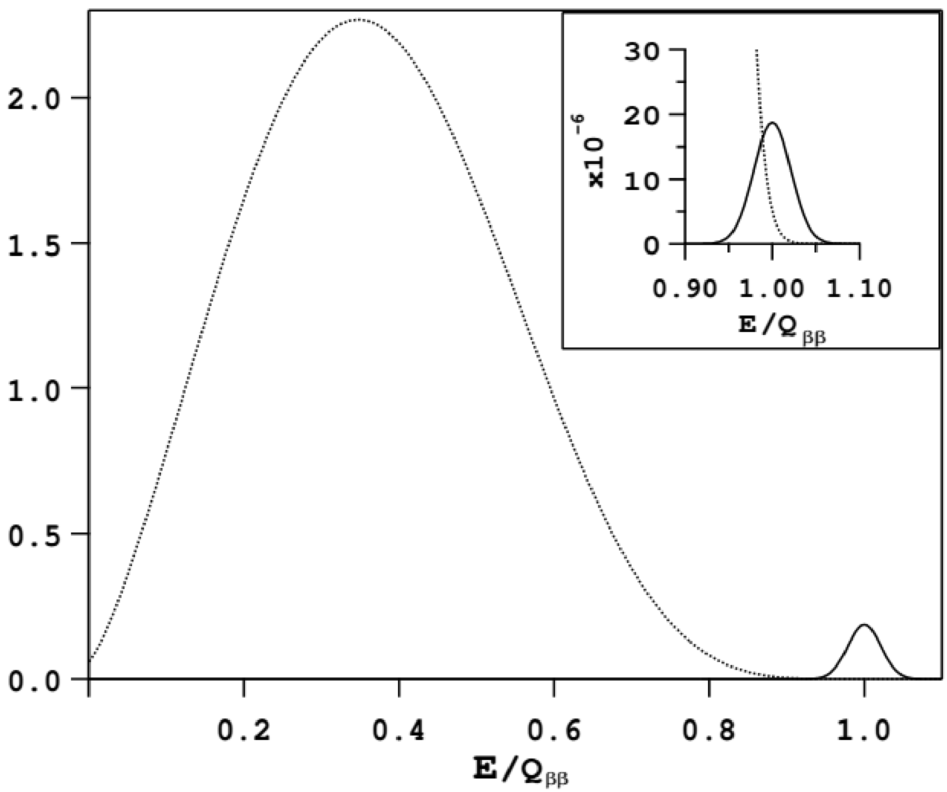
↓

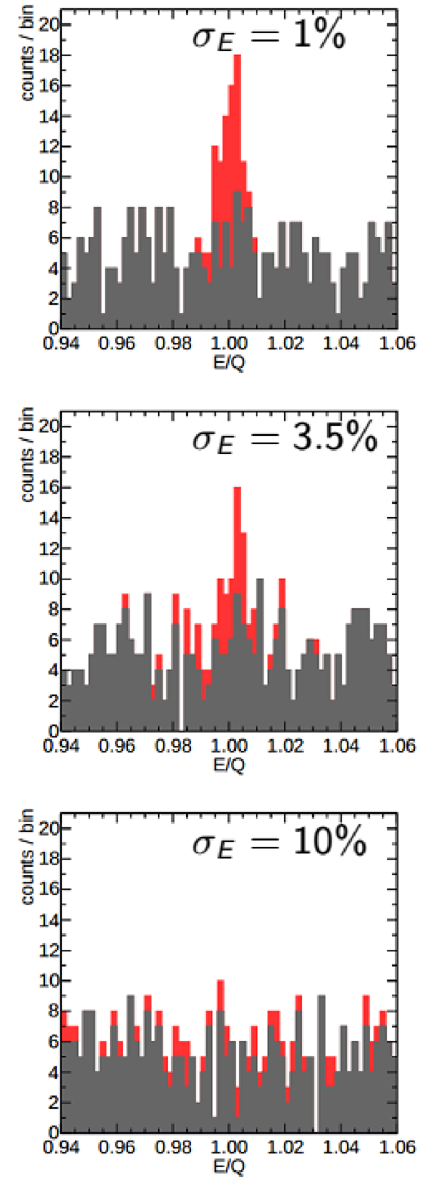
Energy resolution essential

Short intro

What are we measuring?

✓ Resolution remains essential due to 2νββ





Short intro

How to measure?

Experimental sensitivity:

- **Zero** background:

$$T^{0\nu}_{1/2} \propto M\,t$$

- Non-zero background:

$$T^{0\nu}_{1/2} \propto \sqrt{\frac{M\,t}{\Delta E\;BI}}$$

$M\,t$ – exposure (kg yr)

ΔE – energy resolution (keV)

BI – background index (counts/keV kg yr)

Isotope	$G^{0\nu}$ $(10^{-14}\mathrm{yr})$	$Q(\mathrm{keV})$	Nat. ab. (%)
^{48}Ca	6.3	4273.7	0.187
^{76}Ge	0.63	2039.1	7.8
^{82}Se	2.7	2995.5	9.2
^{100}Mo	4.4	3035.0	9.6
^{130}Te	4.1	2530.3	34.5
^{136}Xe	4.3	2461.9	8.9
^{150}Nd	19.2	3367.3	5.6

enrichment required except for ^{130}Te, not (yet) possible for all, costs differ

✓ Target mass and detector efficiency as high as possible
✓ "**Zero-background**" to have linear increase of sensitivity vs exposure

Short intro

What about mass?

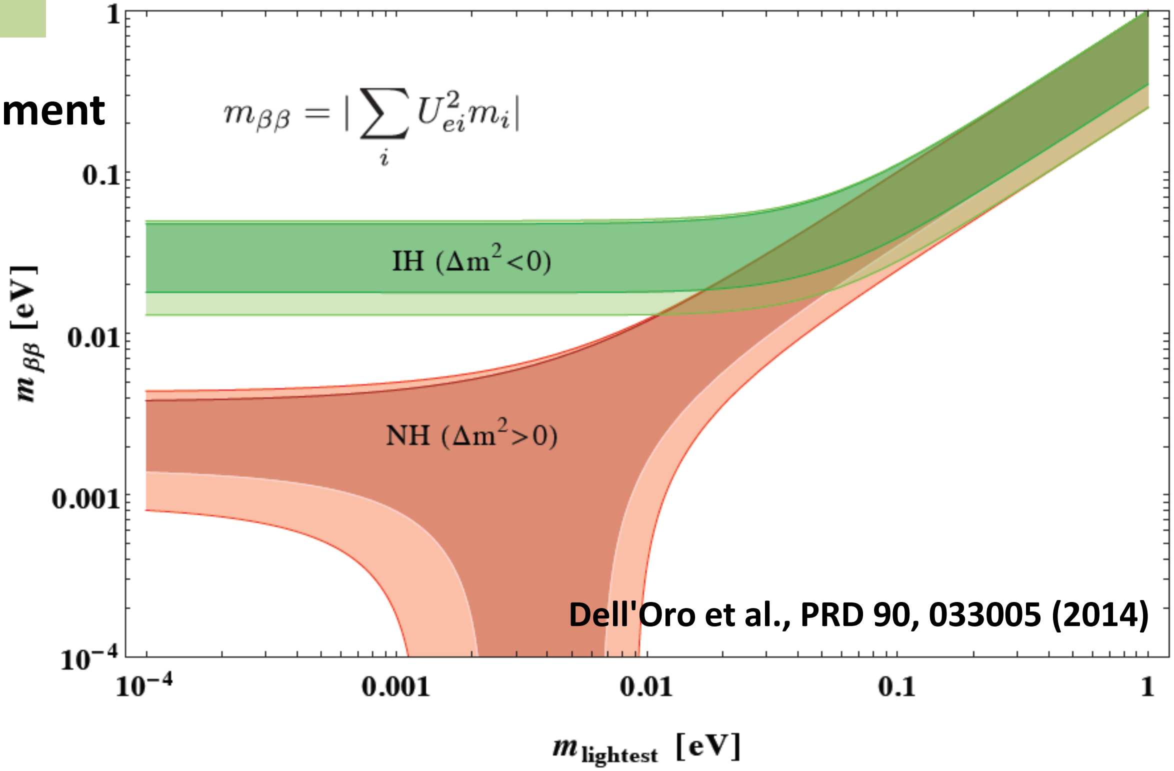
Effective Majorana neutrino mass contributes in the decay rate:

Phase space factor ⬇ | **Effective Majorana neutrino mass**

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

0νββ decay rate | **Matrix element (NME)**

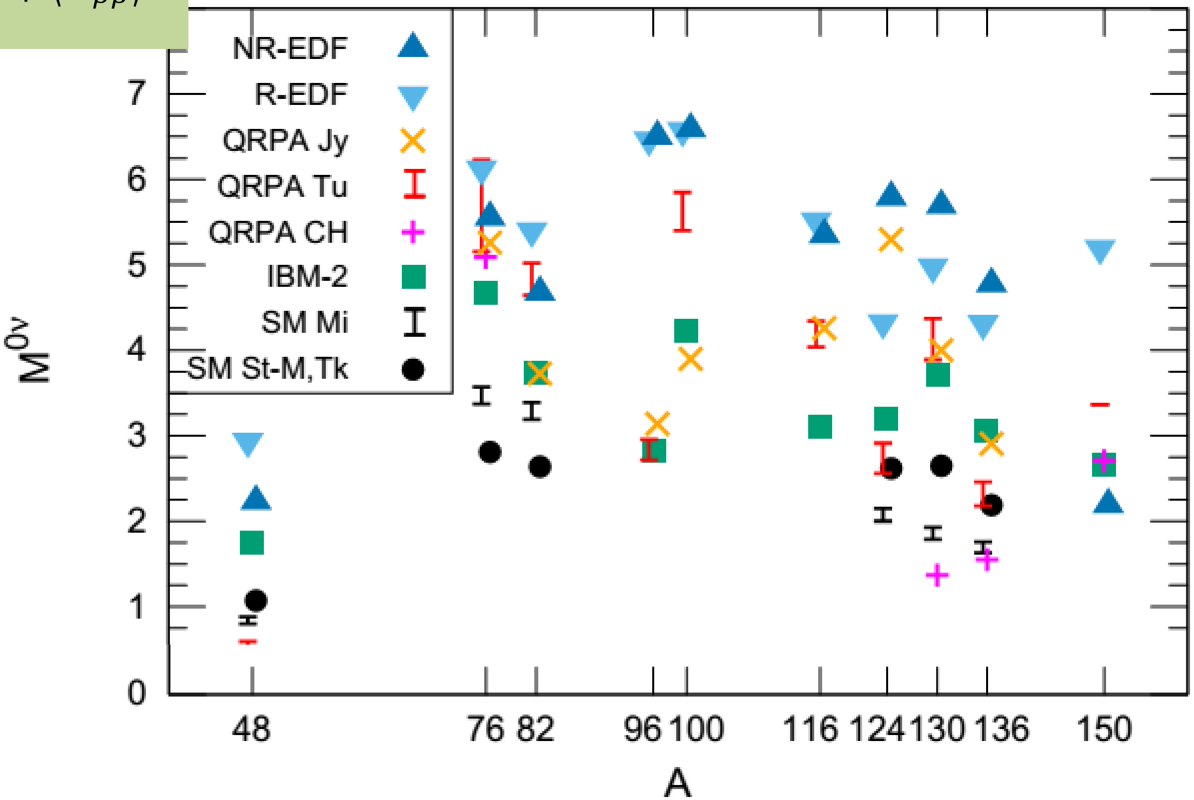
$$\langle m_{\beta\beta}\rangle = \left|\sum_i U_{ei}^2\, m_i\right|$$



Short intro

NME

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$



Engel & Menéndez arXiv: 1610.06548v2

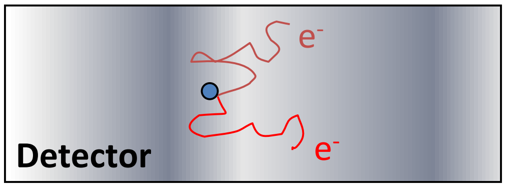
✓ No preferred isotope from Nuclear Physics (G*M)

See today's talk by **Fedor Simkovic**

Short intro

Two experimental approaches

Source = Detector



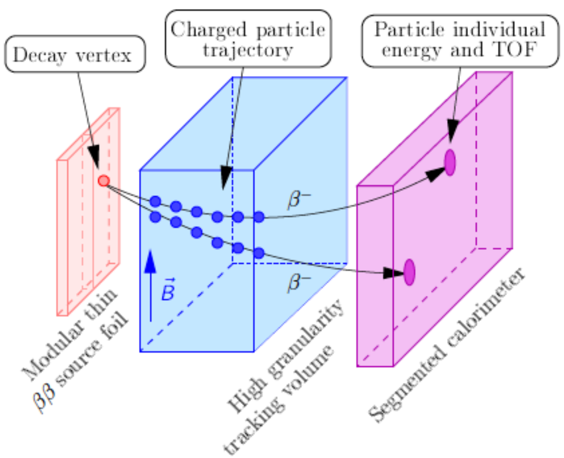
GERDA, MJD, CUORE, EXO, Kamland-Zen, SNO+, ...

+ High detection efficiency
+ Large target mass possible

± Reconstruction of event topologies

– Restricted number of isotopes

Source ≠ Detector



SuperNEMO

+ Reconstruction of event topologies
+ Coincidence scheme
  → zero background
+ No restriction on isotopes

– Difficult to obtain large masses

0νββ-experiments

Now

Gas or liquid *Easy to get huge mass*	TPCs	EXO-200 NEXT-10
	Liquid scintillators	KamLAND-Zen
Crystal *Energy resolution*	Bolometers	CUORE CUPID-0,-Mo AMoRE
	Ge-detectors	GERDA MJD
Source ≠ Detector		

Adapted from A. Giuliani, Neutrino2018

0νββ-experiments
Soon

Now

Gas or liquid	TPCs	EXO-200 NEXT-10	NEXT-100 PANDA-X-III
Easy to get huge mass	Liquid scintillators	KamLAND-Zen	KZ-800 SNO+ phase I
Crystal	Bolometers	CUORE CUPID-0,-Mo AMoRE	AMoRe II
Energy resolution	Ge-detectors	GERDA MJD	LEGEND-200
Source ≠ Detector			SuperNEMO

Adapted from A. Giuliani, Neutrino2018

0νββ-experiments

Future

		Now	Soon	
Gas or liquid *Easy to get huge mass*	TPCs	EXO-200 NEXT-10	NEXT-100 PANDA-X-III	nEXO NEXT-2.0 PANDAX-III 1t
	Liquid scintillators	KamLAND-Zen	KZ-800 SNO+ phase I	KamLAND2-Zen SNO+ phase II
Crystal *Energy resolution*	Bolometers	CUORE CUPID-0,-Mo AMoRE	AMoRe II	CUPID
	Ge-detectors	GERDA MJD	LEGEND-200	LEGEND-1000
Source ≠ Detector			SuperNEMO	

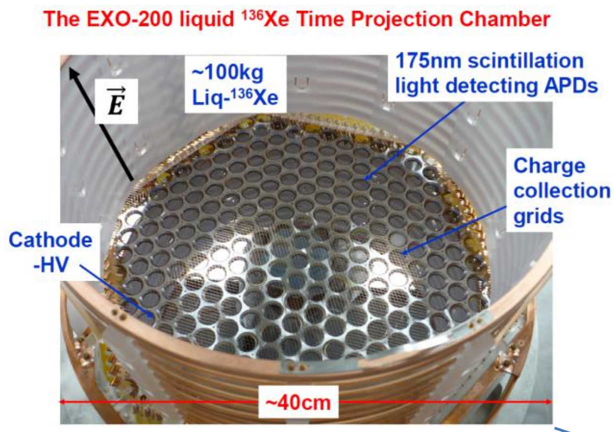
Adapted from A. Giuliani, Neutrino2018

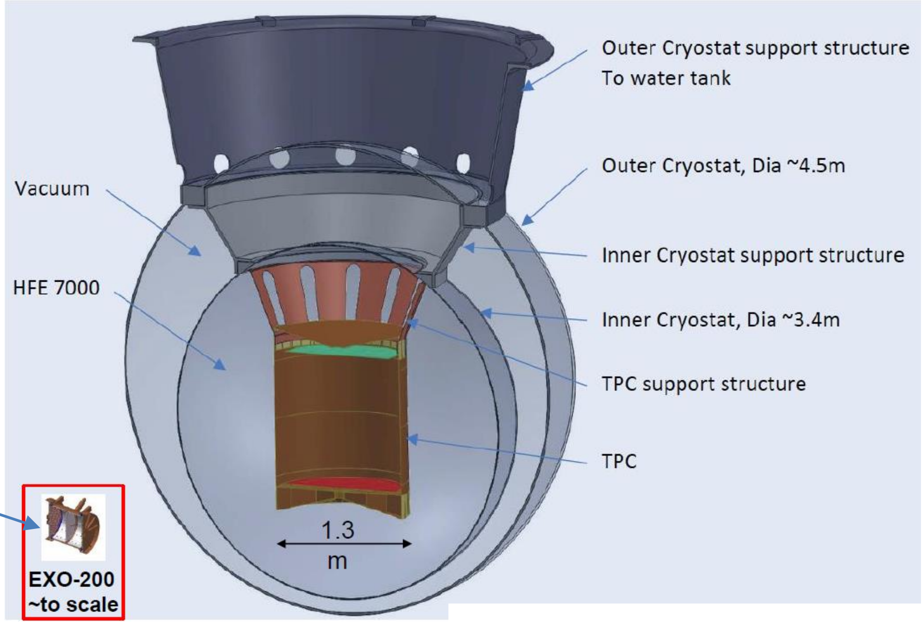
0νββ-experiments

Now 2018

		Now	Soon	Future
Gas or liquid	TPCs		See today's talk by **Yoshihito Gando**	
Easy to get huge mass	Liquid scintillators	**KamLAND-Zen**	**KZ-800** **SNO+ phase I**	**KamLAND2-Zen** **SNO+ phase II**
			See talk on Sept 11 by **Edward Leming**	
Crystal	Bolometers	**CUORE** **CUPID-0,-Mo**	See today's talk by **Paolo Gorla**	**CUPID** See today's talk by **Nicola Casali**
Energy resolution	Ge-detectors	**GERDA**	See today's talk by **Christoph Wiesinger**	
Source ≠ Detector				

0νββ-decay with TPCs
EXO-200 and nEXO

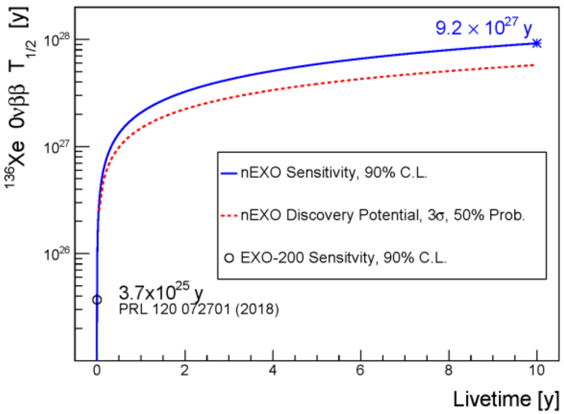




Method	Liquid TPC
Location	WIPP, USA
Isotope	^{136}Xe
$T_{1/2}$ sensitivity	> $3.7\cdot10^{25}$ yr (90% CL)
Limit	> $1.8\cdot10^{25}$ yr (90% CL)

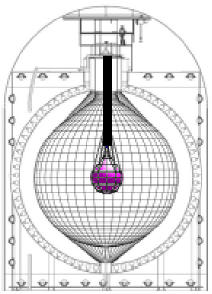
PRL 120 072701 (2018)

From **EXO-200** to **nEXO**:
- ✓ 150 kg → 5000 kg
- ✓ WIPP → SNOLAB
- ✓ 3.7 → 920 (× 10^{25}) yr



EXO-200 will finish data taking in 2018

0νββ-decay with liquid scintillators
KamLAND-Zen, 800, 2-Zen



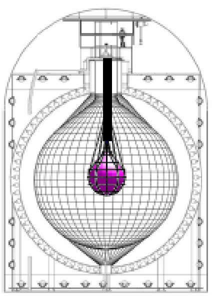
Past

KamLAND-Zen 400

320-380 kg of Xenon
Data taking 2011 ~ 2015

Method	Xe-loaded LS
Location	Kamioka, JAPAN
Isotope	^{136}Xe
$T_{1/2}$ sensitivity	> $5.6 \cdot 10^{25}$ yr (90% CL)
Limit	> $1.1 \cdot 10^{26}$ yr (90% CL)

PRL 117 109903 (2016)

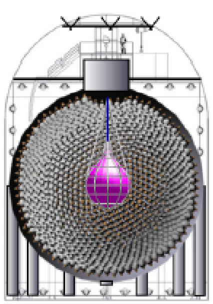


Present

KamLAND-Zen 800

~750 kg of Xenon
DAQ to start in this year

Status 2018:
- ✓ New ballon installed
- ✓ Filled in May 2018 with dummy LS
- ✓ Will be replaced with Xe-loaded LS



Future

KamLAND2-Zen

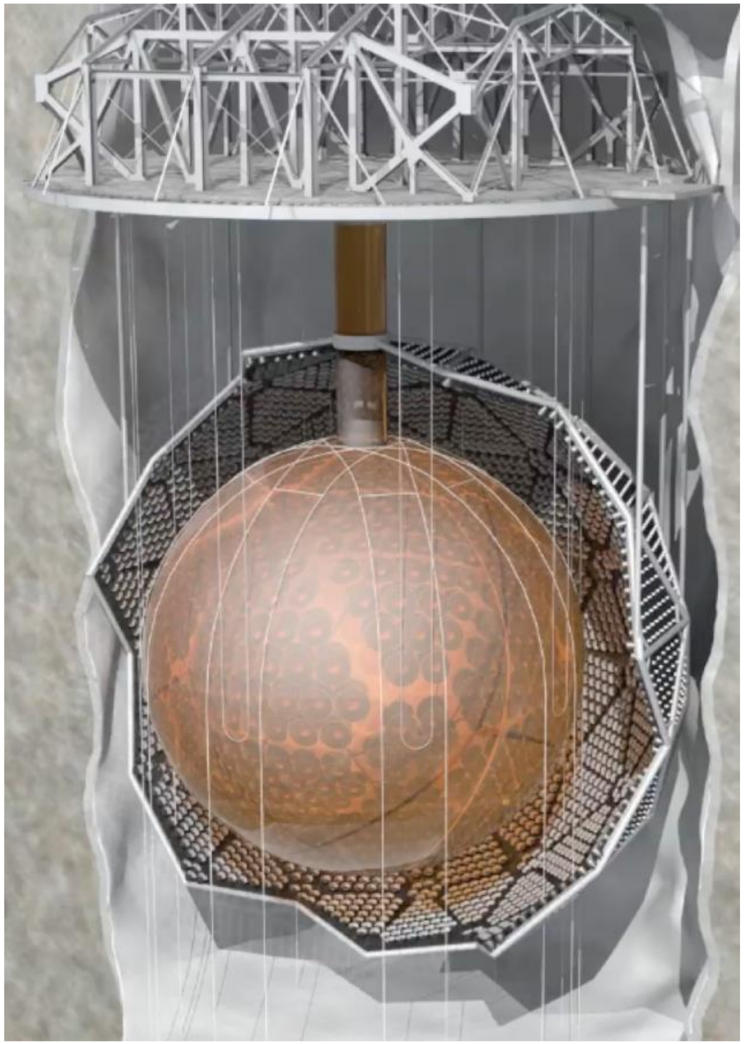
~1 ton of ^{136}Xe
Better energy resolution

- ✓ Brigther LS
- ✓ New PMTs
- → Better energy resolution

See today's talk
by **Yoshihito Gando**

$0\nu\beta\beta$-decay with liquid scintillators

SNO+

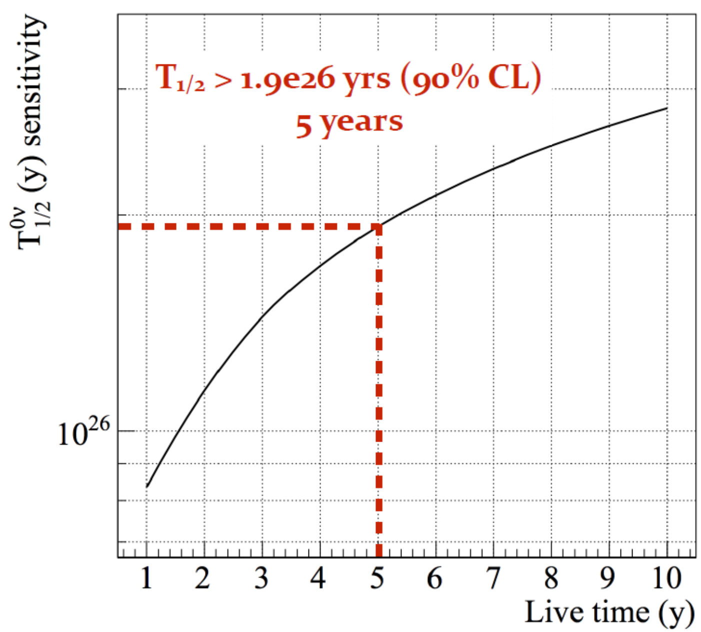


- ✓ SNOLAB, Ontario
- ✓ 780 ton LAB/PPO (2g/L) in 6m radius acrylic vessel
- ✓ ~9400 PMTs at 8.5m

Phased implementation:

- ✓ Water phase → ongoing
- ✓ Pure scintillator phase → LS fill in July 2018
- ✓ Loaded scintillator phase → 0.5% ^{130}Te loading in 2019

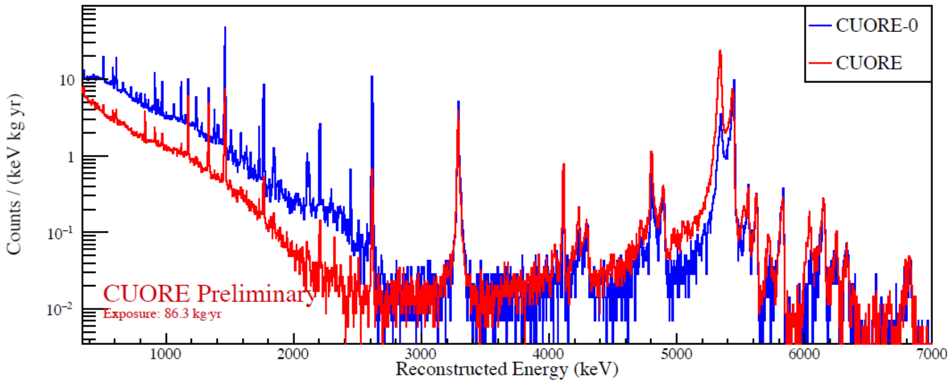
1300 kg of ^{130}Te



See talk on Sept 11 by **Edward Leming**

0νββ-decay with bolometers

CUORE and CUPID



Status 2018:

- ✓ CUORE is taking data
- ✓ 5 y projected half-life sensitivity: ~10^{26} y

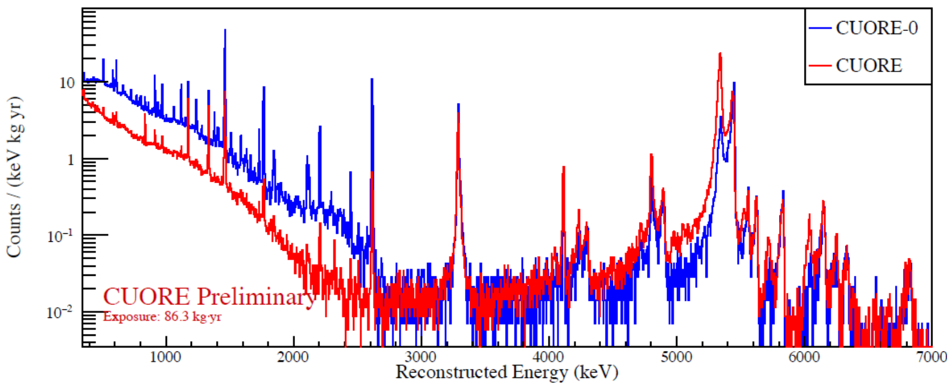
Method	Bolometers
Location	LNGS, Italy
Isotope	^{130}Te
$T_{1/2}$ sensitivity	> $0.7\cdot10^{25}$ yr (90% CL)
Limit (latest)	> $1.5\cdot10^{25}$ yr (90% CL)

PRL 120 132501 (2018)

See today's talk by **Paolo Gorla**

0νββ-decay with bolometers

CUORE and CUPID



Method	Bolometers
Location	LNGS, Italy
Isotope	^{130}Te
$T_{1/2}$ sensitivity	> $0.7 \cdot 10^{25}$ yr (90% CL)
Limit (latest)	> $1.5 \cdot 10^{25}$ yr (90% CL)

PRL 120 132501 (2018)

Status 2018:

✓ CUORE is taking data

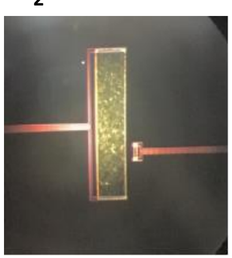
✓ 5 y projected half-life sensitivity: ~10^{26} y

See today's talk by **Paolo Gorla**

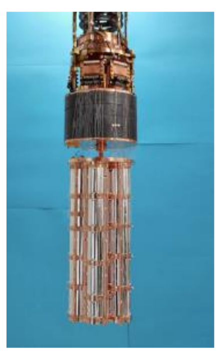
CUORE Upgrade with Particle ID (CUPID)

New detector technology – luminescent bolometers:

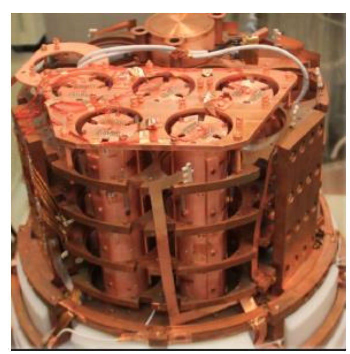
$^{130}TeO_2$ + Cherenkov light



CUPID-0 – $Zn^{82}Se$



CUPID-Mo – $Li_2{}^{100}MoO_4$ – baseline option for CUPID



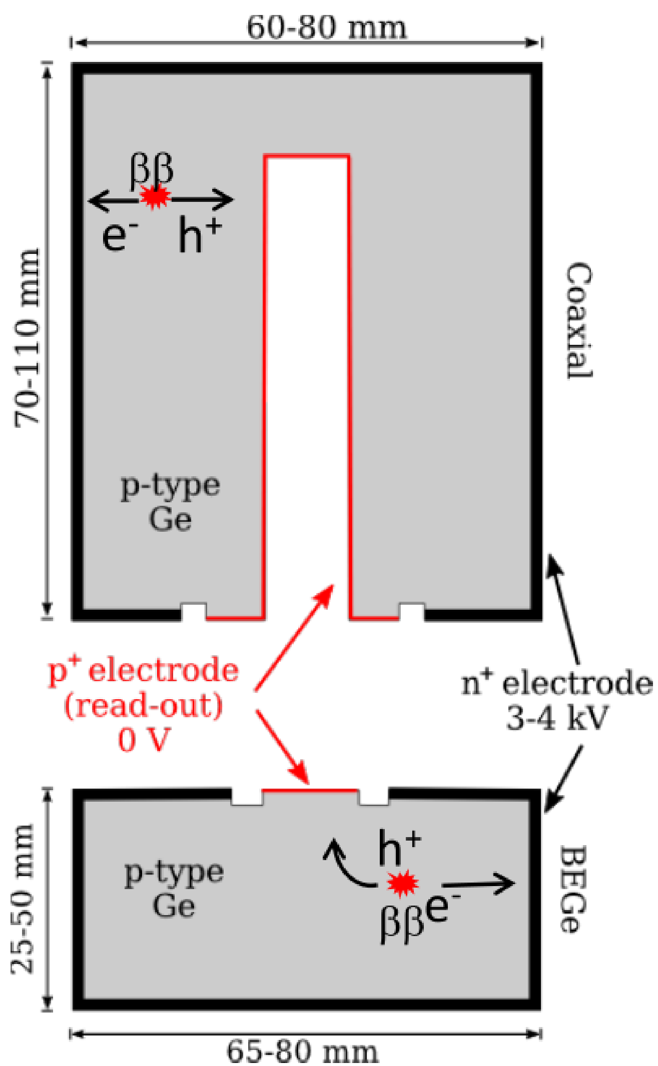
Mission:

half-life sensitivity higher than 10^{27} y

See today's talk by **Nicola Casali**

0νββ-decay with Ge detectors

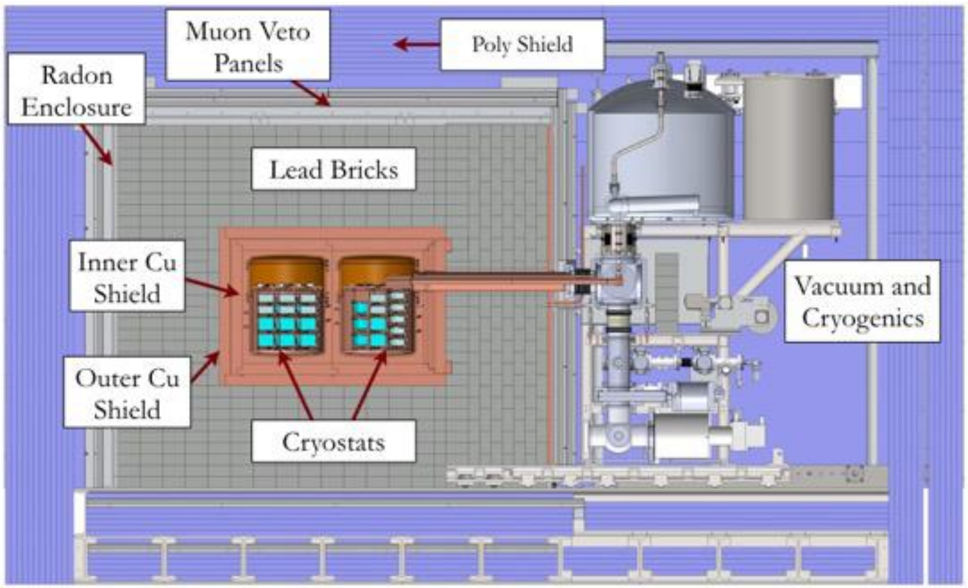
HPGe detectors enriched in ^{76}Ge



- ✓ detector-grade germanium is high-purity material
  ⇒ low background
- ✓ established detector technology
  ⇒ industrial support
- ✓ very good energy resolution
  ~0.1% at $Q_{\beta\beta}$
- ✓ high detection efficiency
  source = detector

0νββ-decay with Ge detectors

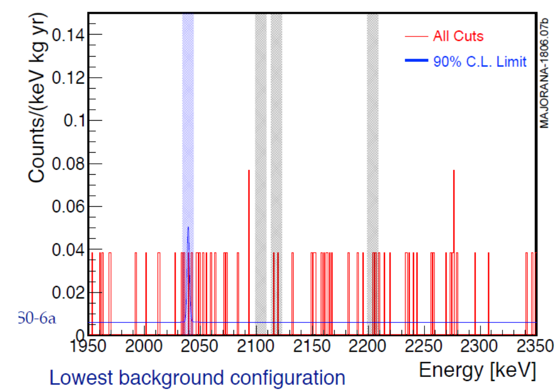
MJD



Method	Ge detectors
Location	SURF, USA
Isotope	^{76}Ge
$T_{1/2}$ sensitivity	> $4.8 \cdot 10^{25}$ yr (90% CL)
Limit (latest)	> $2.7 \cdot 10^{25}$ yr (90% CL)

V. Guiseppe, Neutrino2018

✓ Arrays of Ge-diodes in high purity electroformed Cu cryostat



Features:

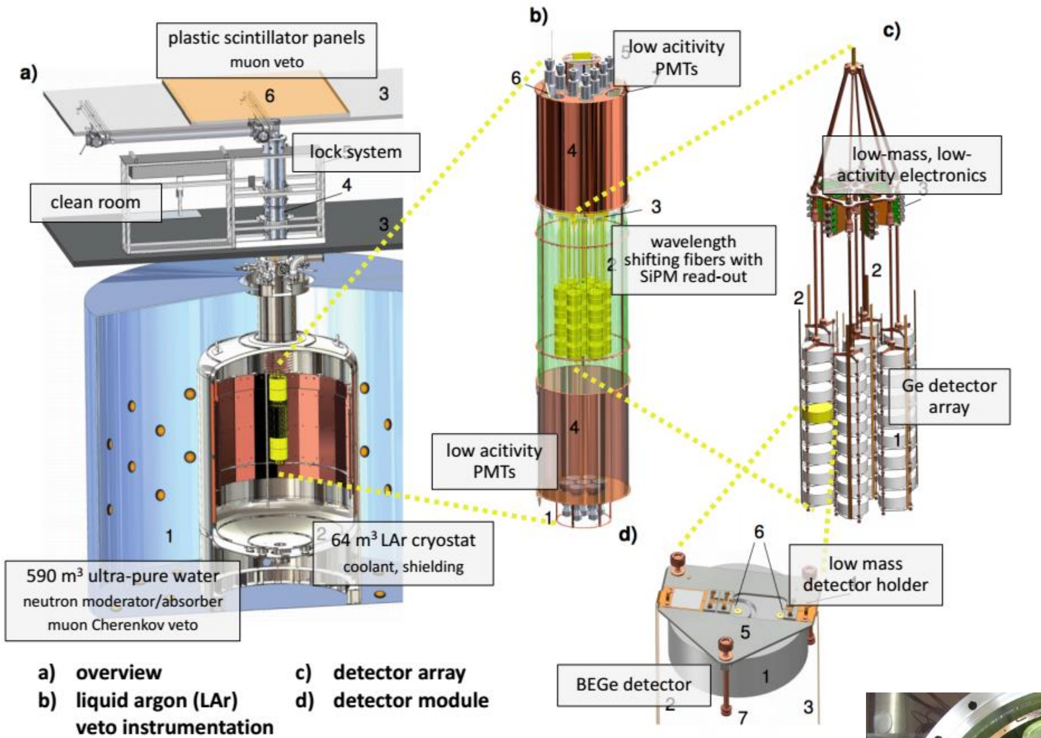
- ✓ Radiopurity of nearby parts (FETs, cables, Cu mounts, etc.)
- ✓ Low noise electronics yields better PSD
- ✓ Low energy threshold (cosmogenic and low-E background)

Status 2018:

- ✓ Data taking ongoing
- ✓ Planning an upgrade to improve channel reliability and background

Expect to reach 50-70 kg yr exposure with sensitivity in the range of 10^{26} yr

0νββ-decay with Ge detectors
GERDA



Method	Ge detectors
Location	LNGS, Italy
Isotope	^{76}Ge
$T_{1/2}$ sensitivity	> **$1.1 \cdot 10^{26}$ yr** (90% CL)
Limit (latest)	> $0.9 \cdot 10^{26}$ yr (90% CL)

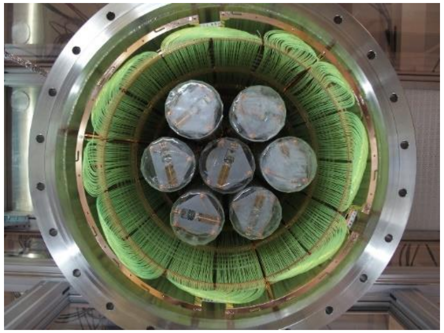
A.J. Zsigmond, Neutrino2018

✓ Bare Ge-diodes array in liquid Ar

Features:

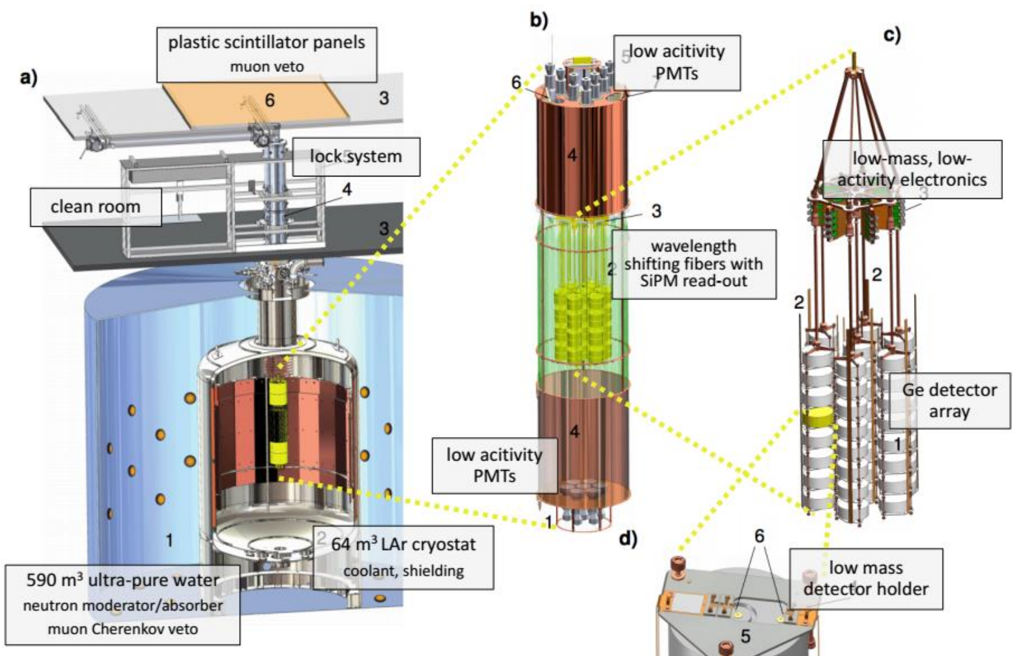
✓ LAr active veto

✓ Low-A shield, no Pb



GERDA will collect data until the end of 2019

0νββ-decay with Ge detectors
GERDA



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

Method	Ge detectors
Location	LNGS, Italy
Isotope	^{76}Ge
$T_{1/2}$ sensitivity	> **$1.1 \cdot 10^{26}$ yr** (90% CL)
Limit (latest)	> $0.9 \cdot 10^{26}$ yr (90% CL)

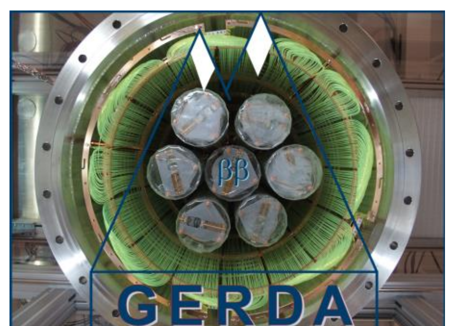
A.J. Zsigmond, Neutrino2018

✓ Bare Ge-diodes array in liquid Ar

Features:

✓ LAr active veto

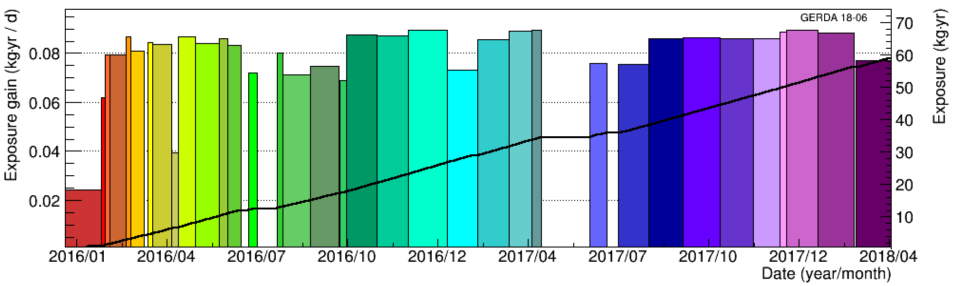
✓ Low-A shield, no Pb



GERDA will collect data until the end of 2019

0νββ-decay with Ge detectors

GERDA: results 2018

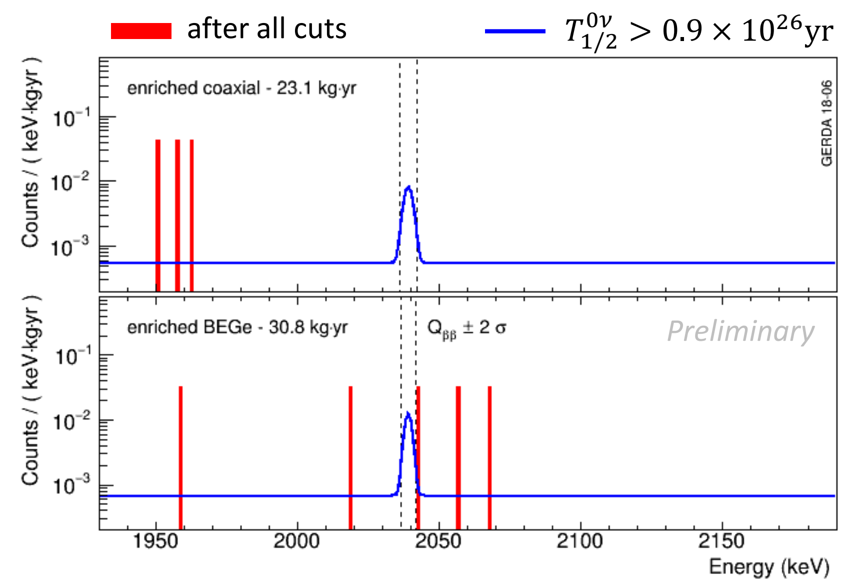


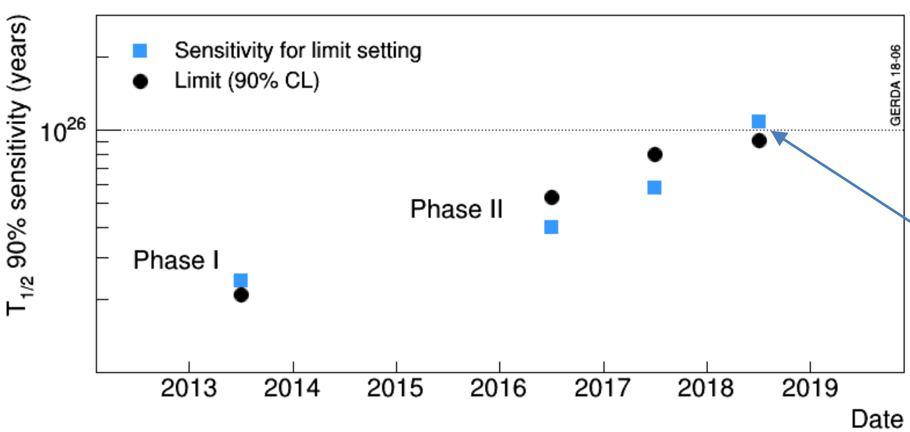
- ✓ 60 kg yr of data collected in Phase II by April 2018
- ✓ 82.4 kg yr in total (Phase I + II)

- ✓ **Unique** background indices achieved:
  Coax: $5.7^{+4.1}_{-2.6} \times 10^{-4}$ cts/(keV·kg·yr)
  BEGe: $5.6^{+3.4}_{-2.4} \times 10^{-4}$ cts/(keV·kg·yr)
  best *in the field when normalized to FWHM!*

New 2018 limits:

- ✓ Median sensitivity for limit setting:
  1.1×10^{26} yr (world best!)
- ✓ Best fit → no signal
  $T^{0\nu}_{1/2} > 0.9 \times 10^{26}$ yr (90% CL)
- ✓ Probability to have stronger limit 63%





GERDA reached important milestone for 0νββ search!

See today's talk
by **Christoph Wiesinger**

$0\nu\beta\beta$-decay with Ge detectors
GERDA: upgrade 2018

Upgrade of the GERDA experiment aims to:

- ✓ Test the novel detectors + increase the mass of ^{76}Ge
- ✓ Show the possibility to improve the background index
- ✓ Prove the robustness and reproducibility of the GERDA approach

Upgrade includes:

- New LAr veto:
  - ✓ new fiber curtain (improved light collection) + central module to read out hidden Ar volume
- Installation of 5 novel **inverted coaxial detectors** made from **^{76}Ge**
  - ✓ Total increase of ^{76}Ge mass ~ 6 kg!
- Exchange of all signal and HV cables by new ones with better radiopurity
- New signal cable routing to reduce the cross-talk and improve resolution
- Repairing of broken electronic channels and installation of protective diodes

old curtain

810 fiber ends, 90 SiPMs

new curtain

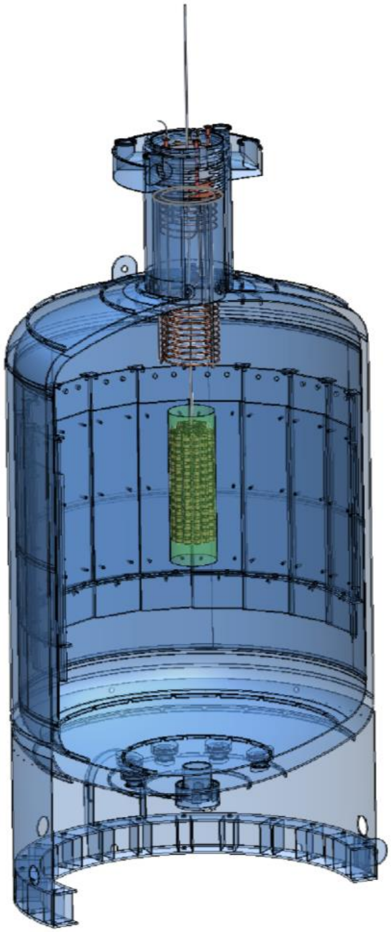
1215 fiber ends, 135 SiPMs

Central module

0νββ-decay with Ge detectors

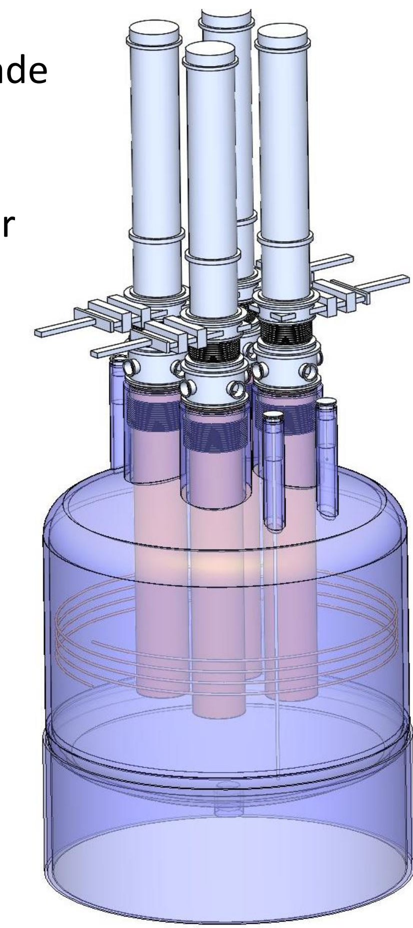
LEGEND: the best from GERDA and MJD

Large **E**nriched **G**ermanium **E**xperiment for **N**eutrinoless ββ **D**ecay



First stage (**L200**):

- ✓ (up to) 200 kg in upgrade of existing GERDA infrastructure at LNGS
- ✓ bkg reduction by factor 3-5 w.r.t GERDA
- ✓ Sensitivity **10^{27}** yr



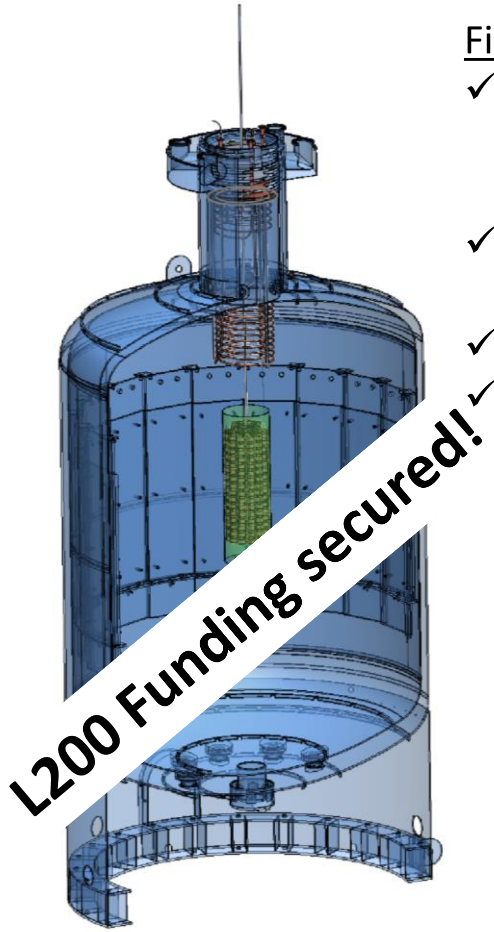
Subsequent stages:

- ✓ 1000 kg (staged)
- ✓ timeline connected to DOE down select process
- ✓ bkg factor 30 w.r.t GERDA
- ✓ Location tbd
- ✓ Sensitivity **10^{28}** yr

0νββ-decay with Ge detectors

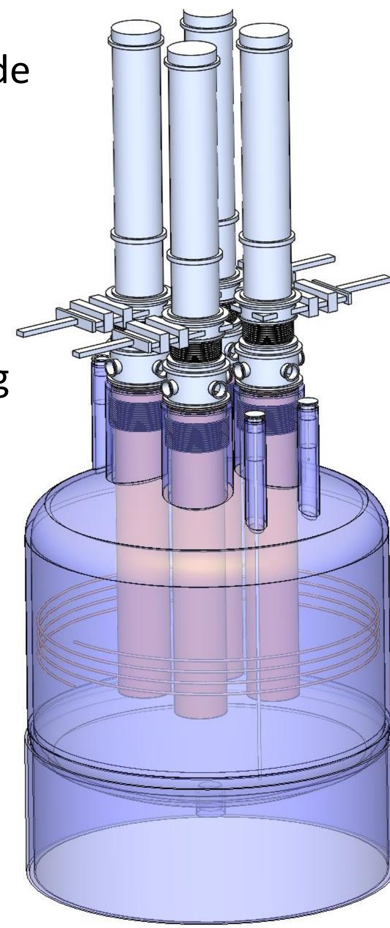
LEGEND: the best from GERDA and MJD

Large **E**nriched **G**ermanium **E**xperiment for **N**eutrinoless ββ **D**ecay



First stage (**L200**):

- ✓ (up to) 200 kg in upgrade of existing GERDA infrastructure at LNGS
- ✓ bkg reduction by factor 3-5 w.r.t GERDA
- ✓ Sensitivity **10^{27}** yr
- ✓ Plan to **start** data taking in **2019**

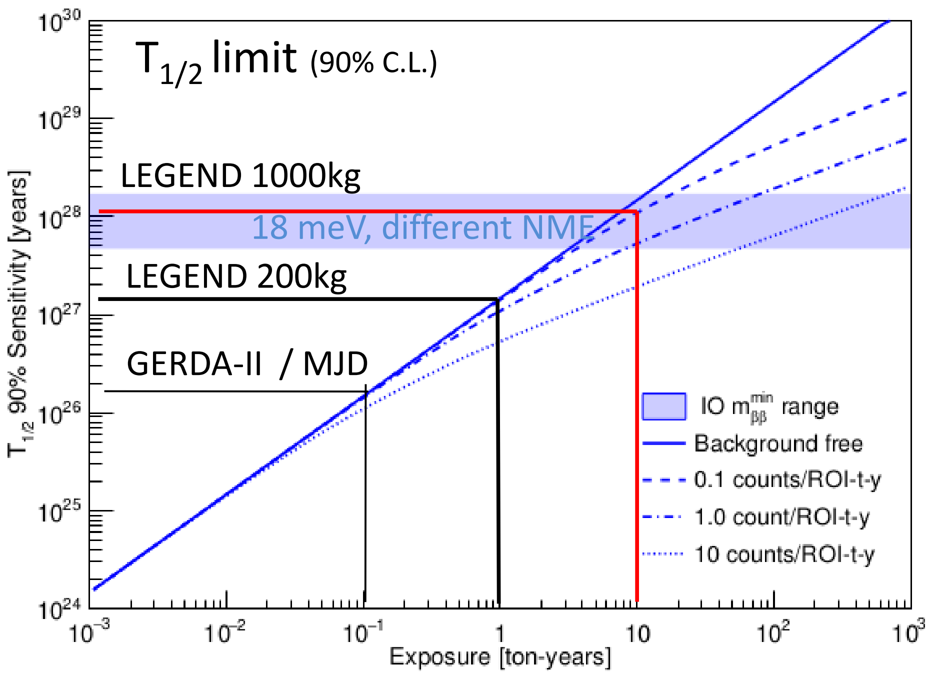


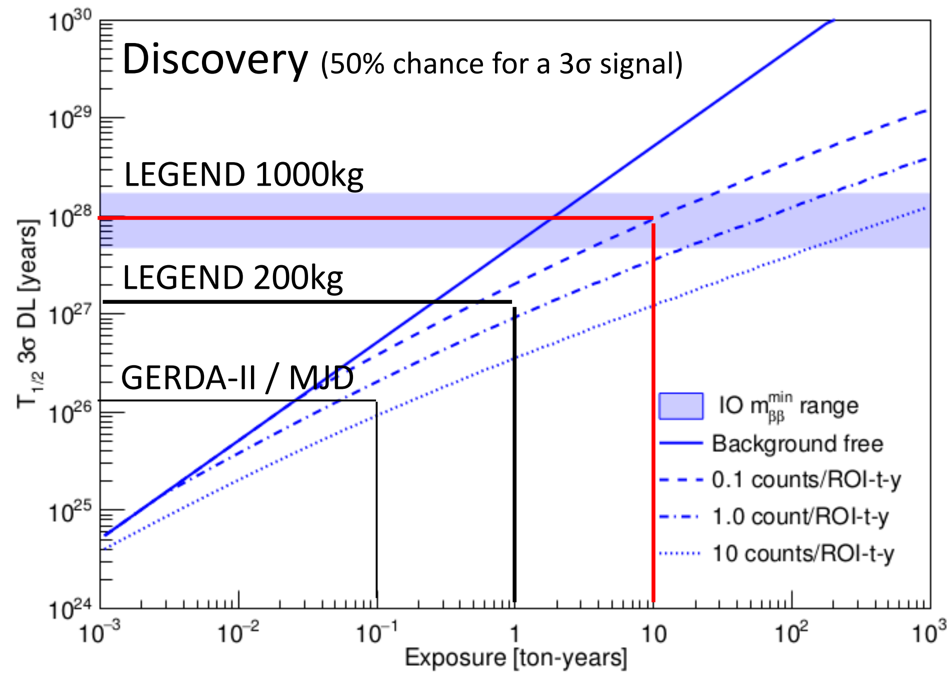
Subsequent stages:

- ✓ 1000 kg (staged)
- ✓ timeline connected to DOE down select process
- ✓ bkg factor 30 w.r.t GERDA
- ✓ Location tbd
- ✓ Sensitivity **10^{28}** yr

0νββ-decay with Ge detectors

LEGEND: sensitivity



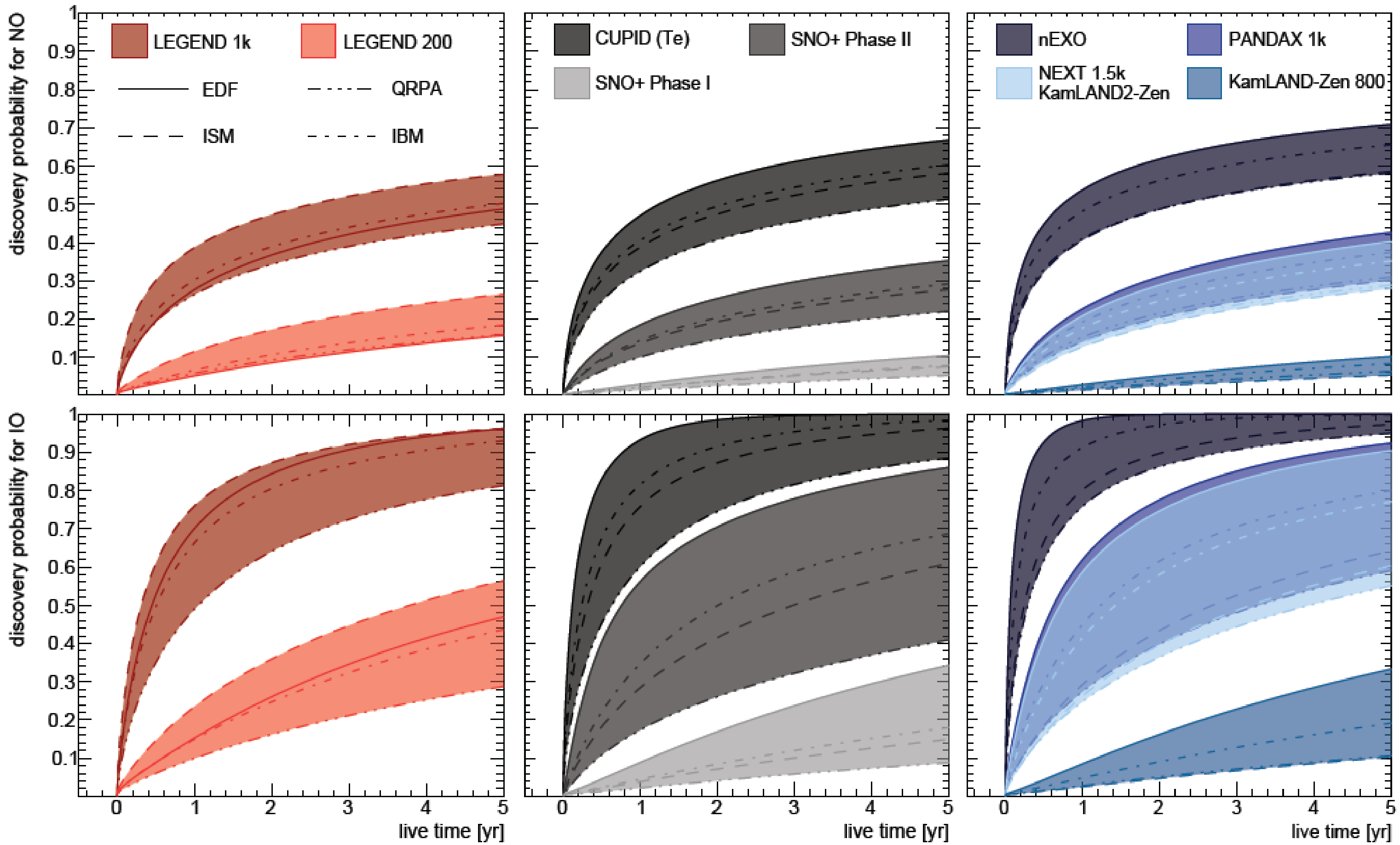


- ✓ $T_{1/2}$ unknown, BSM → 'around corner'
- ✓ background reduction in steps → phased approach

- ✓ inputs: 60% efficiency (GERDA number)
- ✓ Background: GERDA/MJD ~ 3 cts/(FWHM t yr)
  200 kg ~ 0.6 cts/(FWHM t yr)
  1000 kg ~ 0.1 cts/(FWHM t yr)

N.B.: background-free operation is a prerequisite for a discovery

0νββ-decay experiments
Discovery probability



Discovery probability of next-generation neutrinoless double-β decay experiments
M. Agostini, G. Benato and J. A. Detwiler Phys. Rev. D 96, 053001 (2017)

$0\nu\beta\beta$-decay experiments
Summary

- ✓ $0\nu\beta\beta$ decay is a crucial process, New Physics maybe around the corner
- ✓ Very active field: several ton-scale experiments are in preparation
- ✓ Huge experimental effort: tons of material, but “zero” background
- ✓ The discovery probability for the next generation projects is pretty high
- ✓ We need to observe the signal with multiple isotopes using various experimental methods