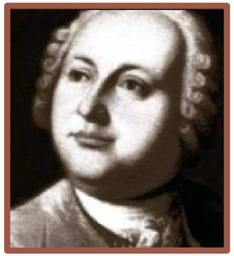
Università degli Studi di Padova

INFN Padova
Istituto Nazionale di Fisica Nucleare
Sezione di Padova

LEGEND
Large Enriched Germanium Experiment for Neutrinoless ββ Decay

Status of the LEGEND experiment



Lomonosov conference
20 Aug 2021

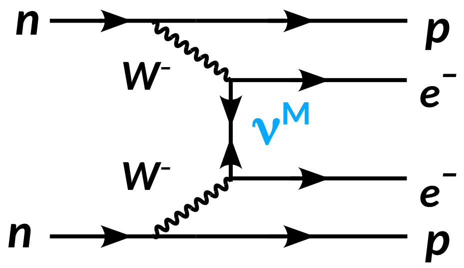
Mariia Redchuk on behalf of the **LEGEND collaboration**

What I want you to remember about

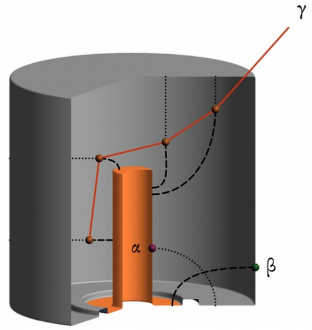
LEGEND

What I want you to remember about LEGEND

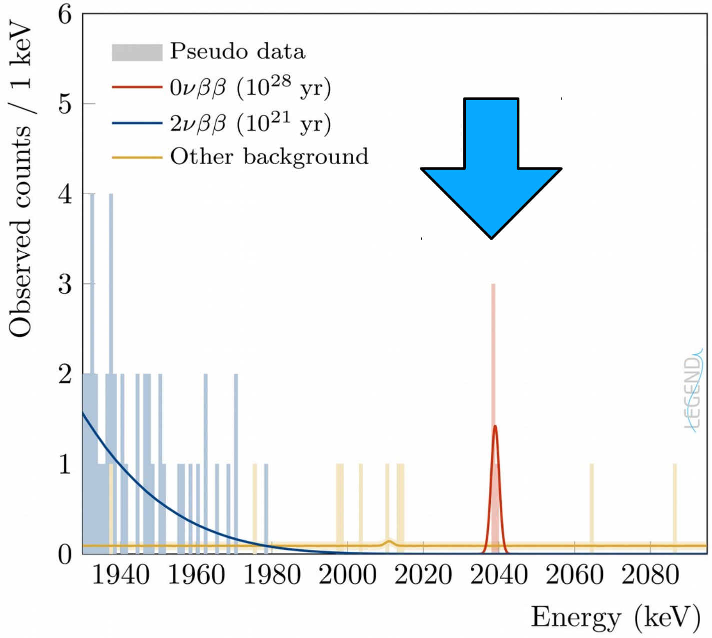
LEGEND = Large Enriched Germanium Experiment for Neutrinoless double beta Decay



1. **Neutrinoless double beta decay (0νββ)**
   - create matter without antimatter
   - lepton number violation
   - not observed yet

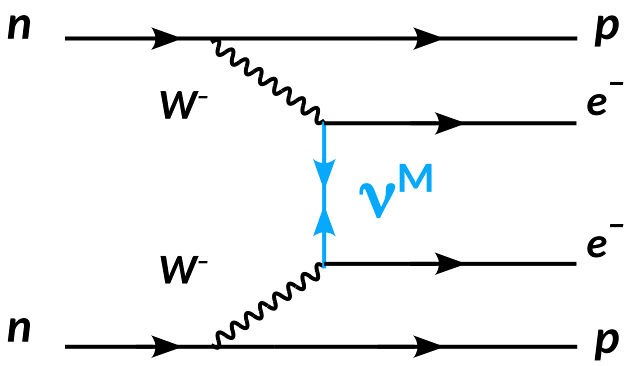


2. **Enriched germanium detectors**
   - leading material for 0νββ searches
   - excellent energy resolution
   - topological discrimination



3. **The LEGEND experiment**
   - indeed large
   - aims to observe 0νββ in germanium
   - or push the lower limit on decay half-life
   - synergy with other neutrino physics experiments

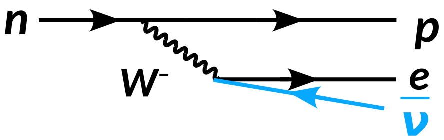
Neutrinoless double beta decay



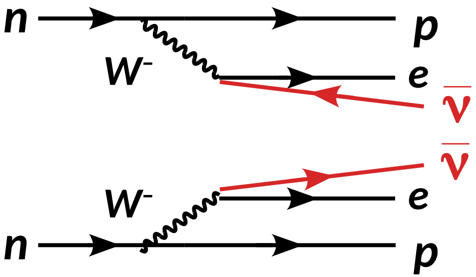
Neutrinoless double beta decay

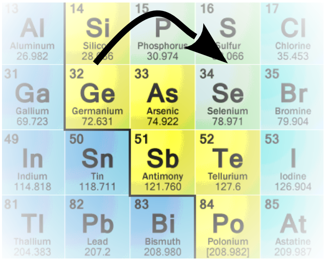
lepton number not conserved!
matter-antimatter asymmetry!

Beta decay



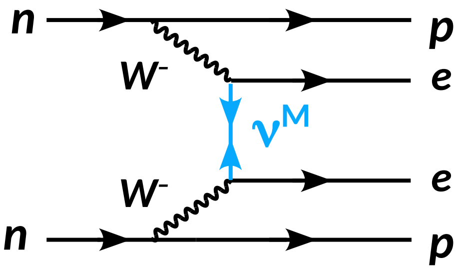
Double beta decay (2νββ)





^{76}Ge → ^{76}Se + 2e$^-$ [+ 2$\bar{\nu}_e$]

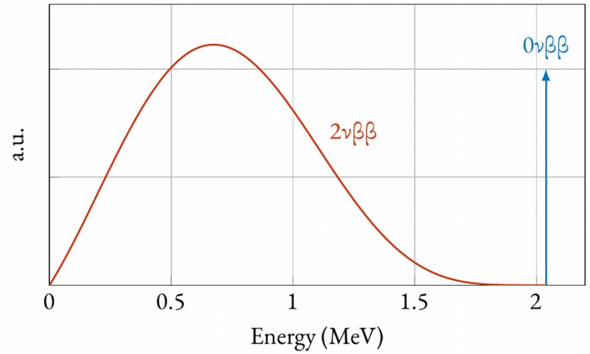
Neutrinoless double beta decay (0νββ)



Dirac neutrino

$\nu \neq \bar{\nu}$

In nature
we only observe
ν_L and $\bar{\nu}_R$



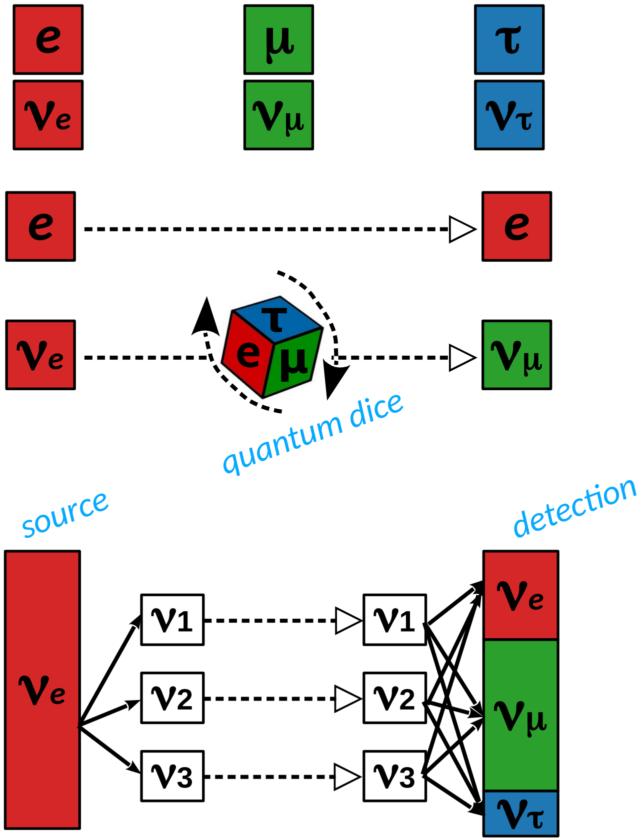
Majorana neutrino

$\nu = \bar{\nu}$

That's because
they are simply just
ν_L and ν_R

Some neutrino physics

Neutrino oscillation
flavor change during propagation



Neutrino mixing matrix
mathematical formalism & measurable parameters

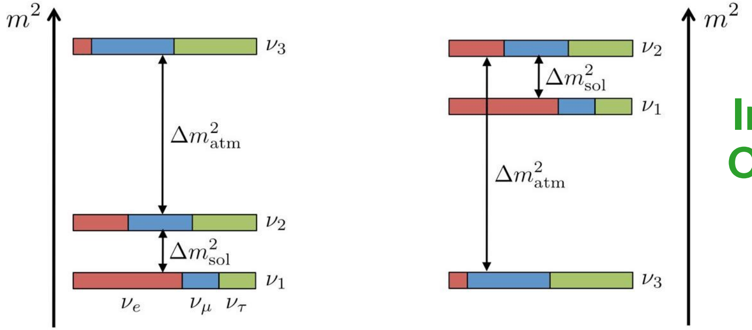
new mixing matrix

$$\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix} \begin{pmatrix} 1 & 0 & 0\\ 0 & e^{i\alpha_1} & 0\\ 0 & 0 & e^{i\alpha_2}\end{pmatrix} \begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

propagate in space — *mixing matrix* — *Majorana phases* — *interact weakly*

Neutrino mass ordering
which mass state is the lightest?

Normal Ordering (NO)



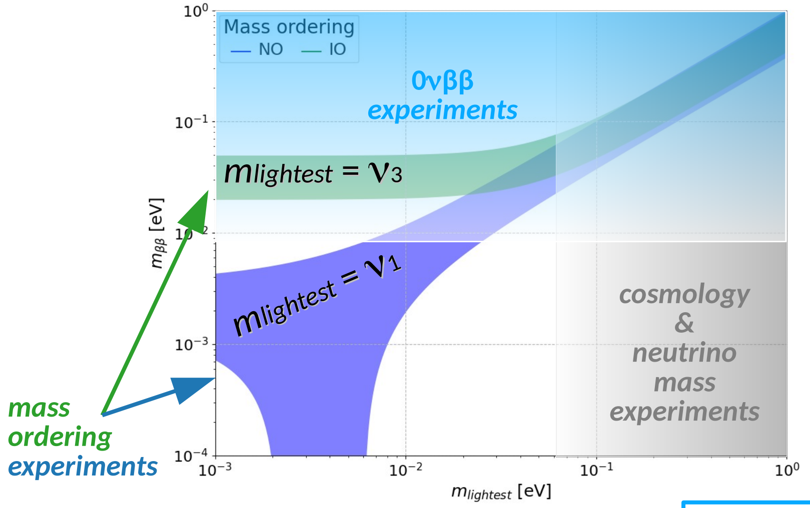
Inverted Ordering (IO)

Back to neutrinoless double beta decay

Neutrino physics point of view

mixing matrix
(Majorana phases)

Majorana mass $m_{\beta\beta} = |\sum U_{ei}^2 m_i|$



Experimental point of view

0νββ signature $Q_{\beta\beta} = M_{init} - M_{final} - 2m_e$

Decay half-life
zero background regime

$$T_{1/2}^{0\nu\beta\beta} \sim \frac{Mt}{N^{0\nu\beta\beta}}$$

exposure; observed events

1σ sensitivity
in presence of background

$$T_{1/2}^{0\nu\beta\beta} \sim \sqrt{\frac{Mt}{\mathrm{BI} \cdot \Delta E}}$$

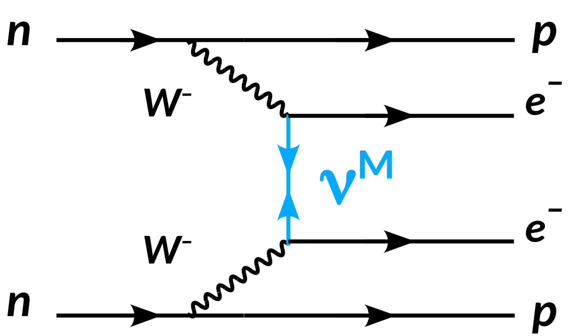
background index; energy resolution

Connection

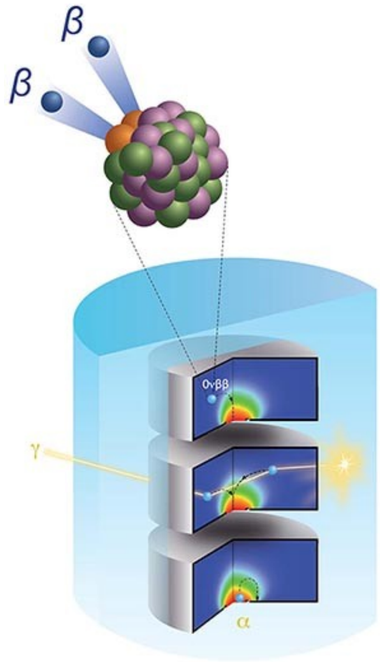
phase space factor; nuclear matrix element

$$m_{\beta\beta}^2 = (F^{0\nu} \cdot |\mathcal{M}^{0\nu}|^2 \cdot T_{1/2}^{0\nu\beta\beta})^{-1}$$

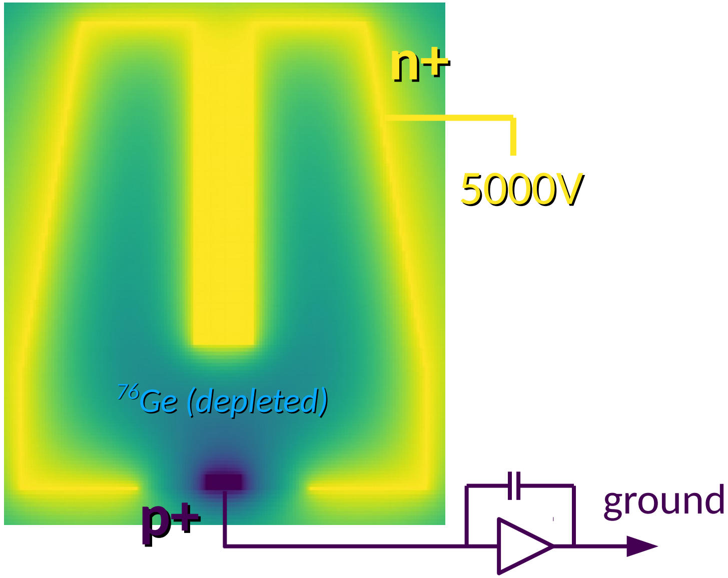
Neutrinoless double beta decay

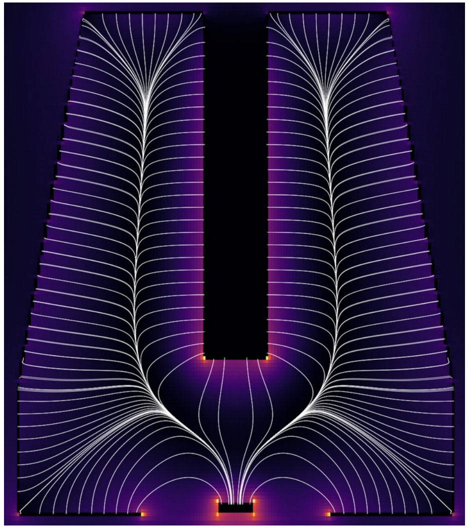


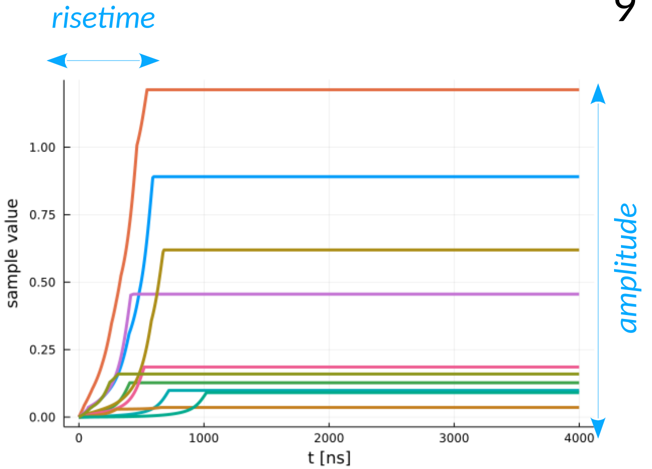
Germanium experiment technology



Germanium detectors







- germanium crystal → **semiconductor**
- implanted **p+** and **n+** contacts → **diode**
- crystal fully **depleted**
- germanium serves as both **detector** and **source of 2νββ/0νββ**

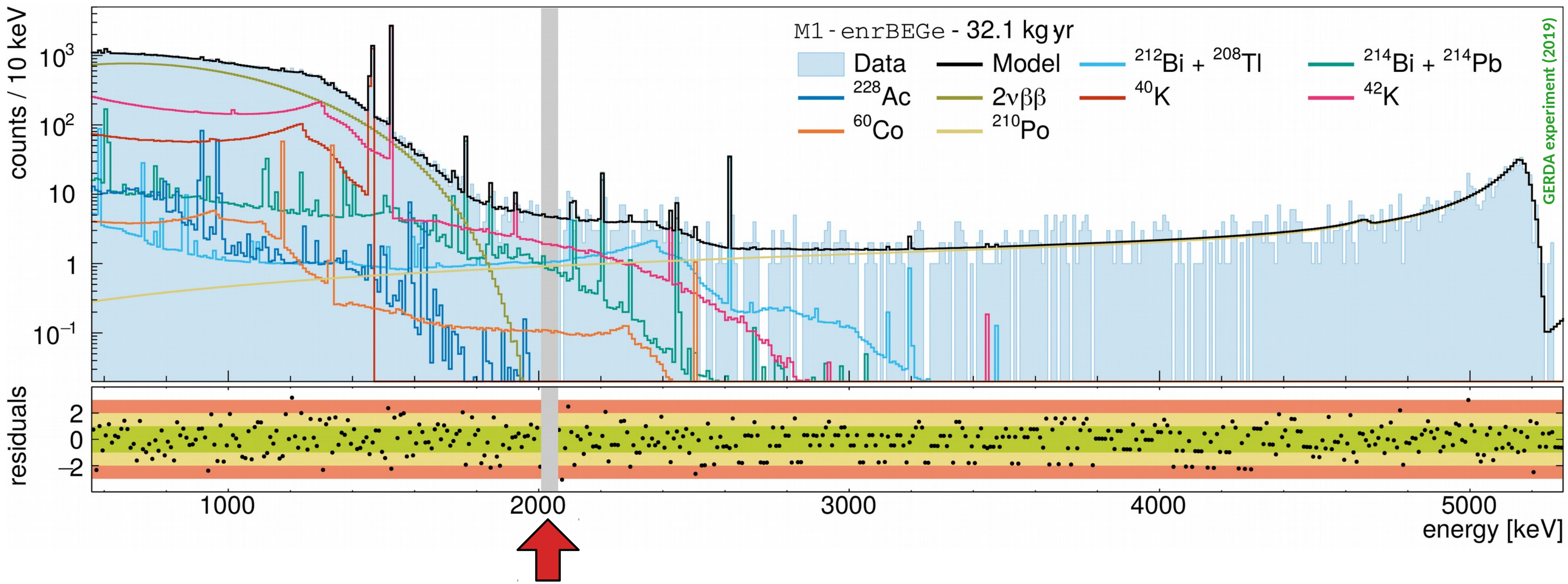
$$^{76}Ge \rightarrow {}^{76}Se + 2e^{-} \; [\, + 2\bar{\nu}_e \,]$$

- particles deposit energy in the crystal
- **electron-hole pairs** drift towards respective contacts
- similar trajectories due to ***E field*** profile → **position-independet**

- mirror charge on the p+ contact → **signal**
- reconstruct energy based on the pulse **risetime** and **amplitude**

Germanium detectors

Spectrum before analysis cuts



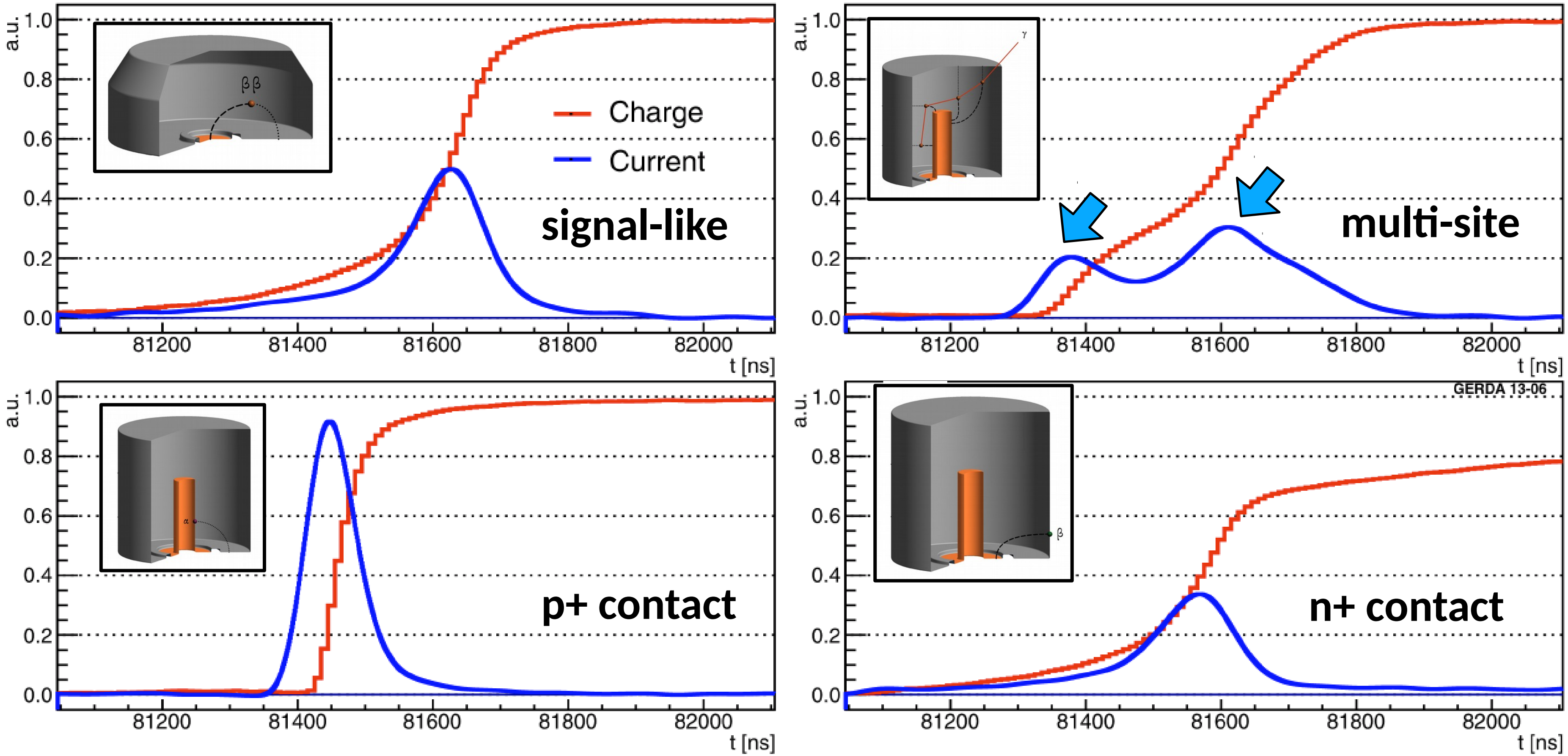
Window around Qββ is blinded!

$Q_{\beta\beta}(^{76}Ge) = 2039.061 \pm 0.007$ keV

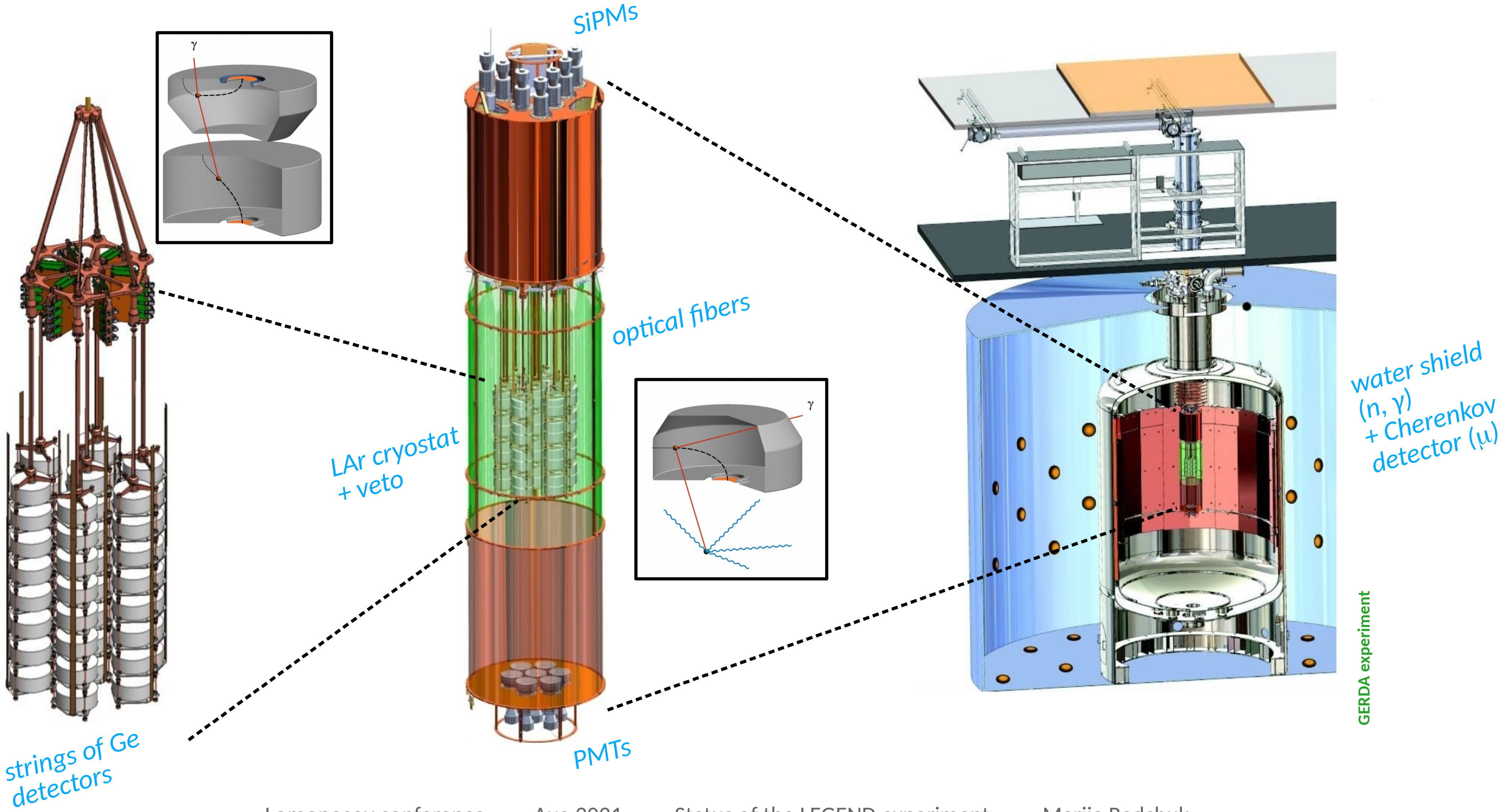
Background index is computed based on the rest of the spectrum

Germanium detectors

Pulse shape discrimination



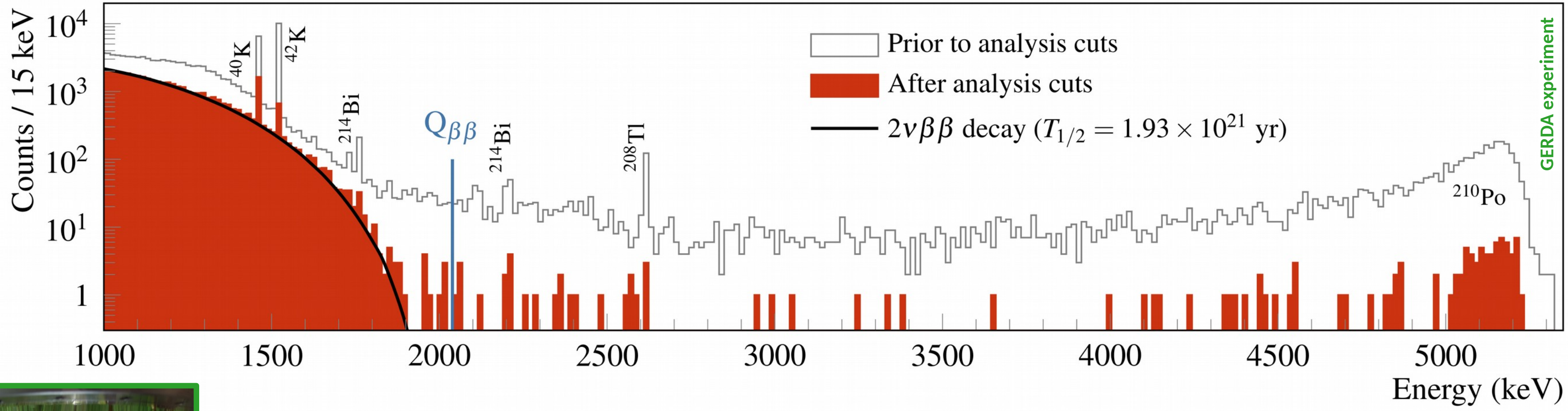
Germanium experiments

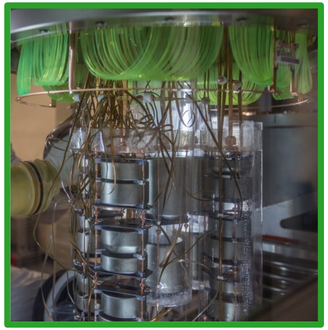


Germanium experiments

All analysis cuts

- Quality cuts
- Muon veto
- LAr veto
- Detector anti-coincidence
- Pulse shape discrimination





GERDA experiment

World leading background index

$$\mathrm{BI} = 5.2^{+1.6}_{-1.3} \times 10^{-4} \frac{\mathrm{counts}}{\mathrm{keV\ kg\ yr}}$$

Energy resolution

$$\Delta E = (2.6 \pm 0.2)\mathrm{keV}$$

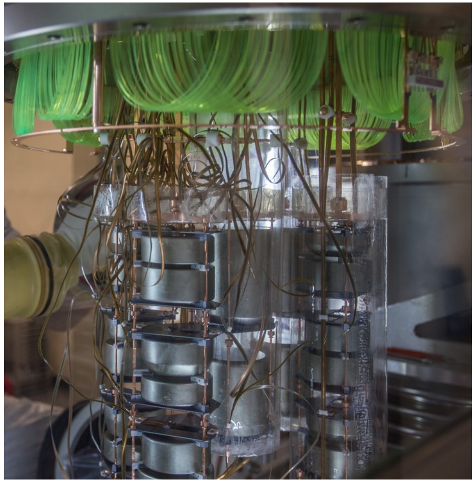
Germanium experiments

GERDA	
mass	44.2 kg
exposure	100 kg yr
bkg idx	$(5.2 \pm 1.6) \cdot 10^{-4}$ cts/(keV kg yr)
resolution	(2.6 ± 0.2) keV

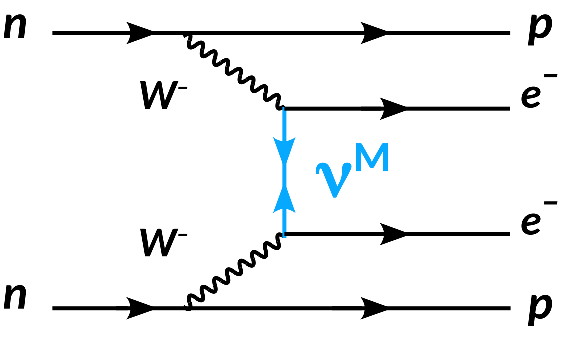
MAJORANA Demonstrator	
mass	29.7 kg
exposure	75 kg yr
bkg idx	$(4.7 \pm 0.8) \cdot 10^{-3}$ cts/(keV kg yr)
resolution	(2.53 ± 0.08) keV

LEGEND-200 goal	
mass	**200 kg**
exposure	1000 kg yr x10 ↑
bkg idx	$2 \cdot 10^{-4}$ cts/(keV kg yr) x2.5 ↓
resolution	2.5 keV

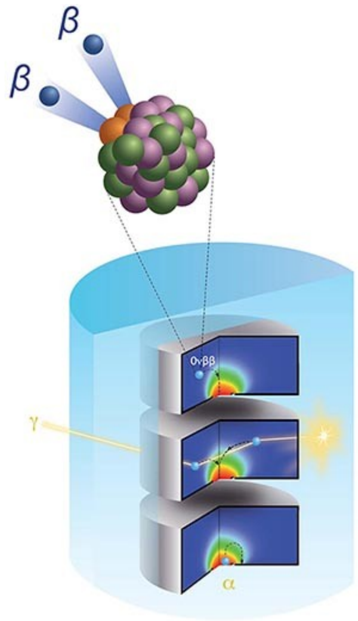
LEGEND-1000 goal	
mass	**1000 kg**
exposure	10 000 kg yr x100 ↑
bkg idx	10^{-5} cts/(keV kg yr) x50 ↓
resolution	2.5 keV



Neutrinoless double beta decay



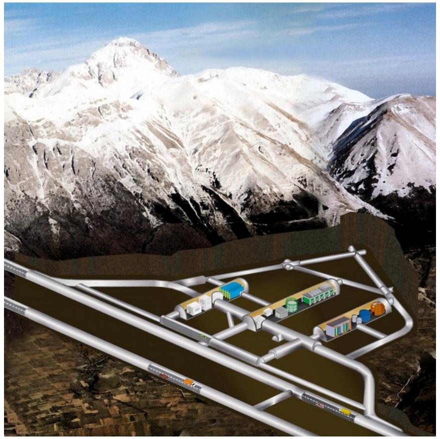
Germanium experiment technology



Status of the LEGEND experiment

LEGEND baseline design

INFN
Laboratori Nazionali del Gran Sasso

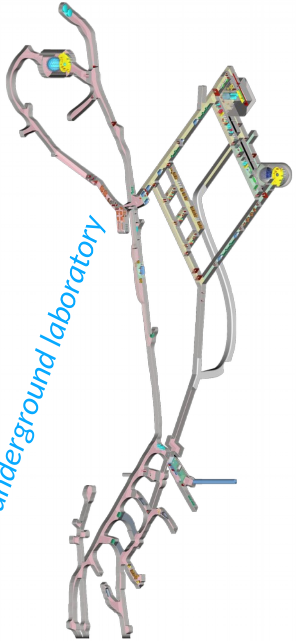


largest underground research center

LEGEND-200

LEGEND-1000

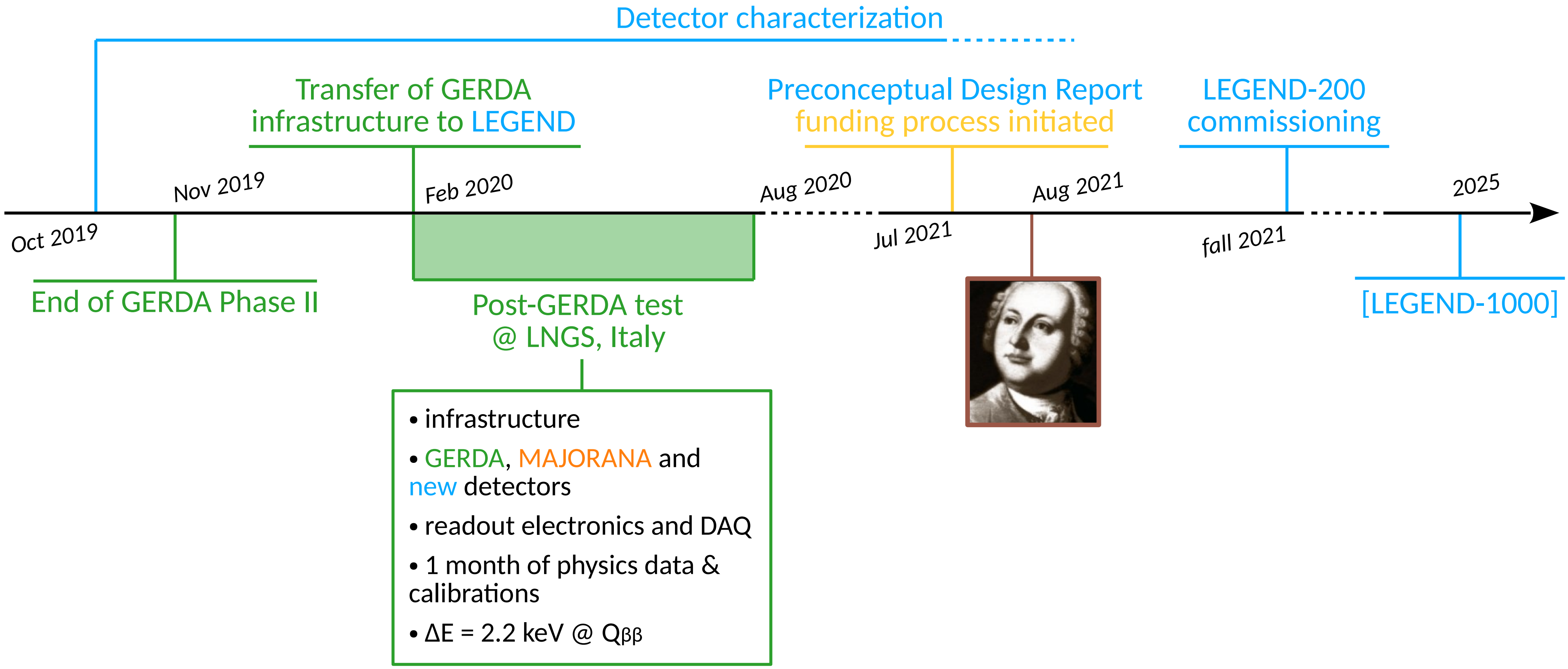
SNOLAB



deepest underground laboratory

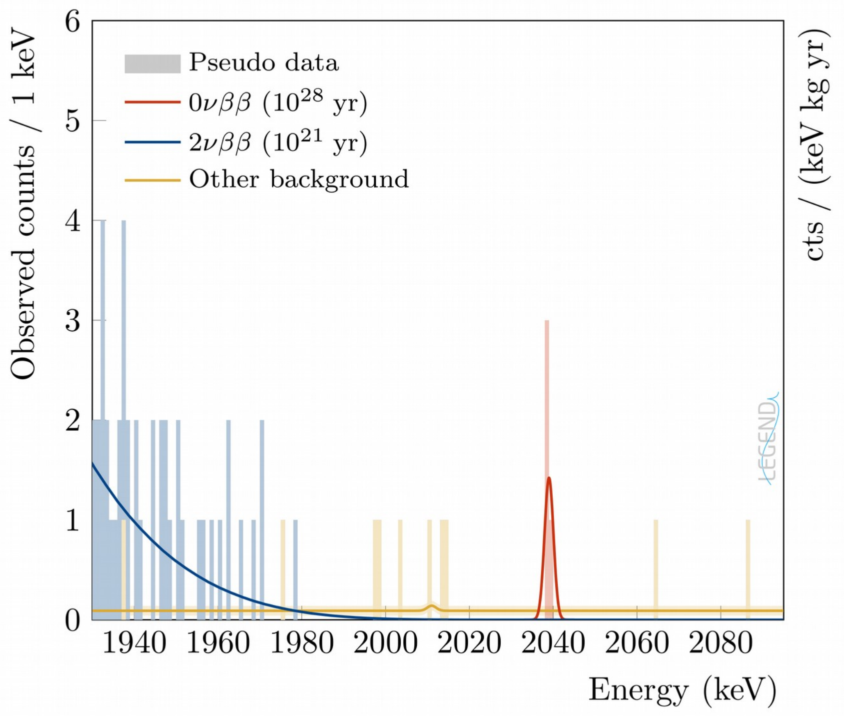
LEGEND timeline

LEGEND timeline and status

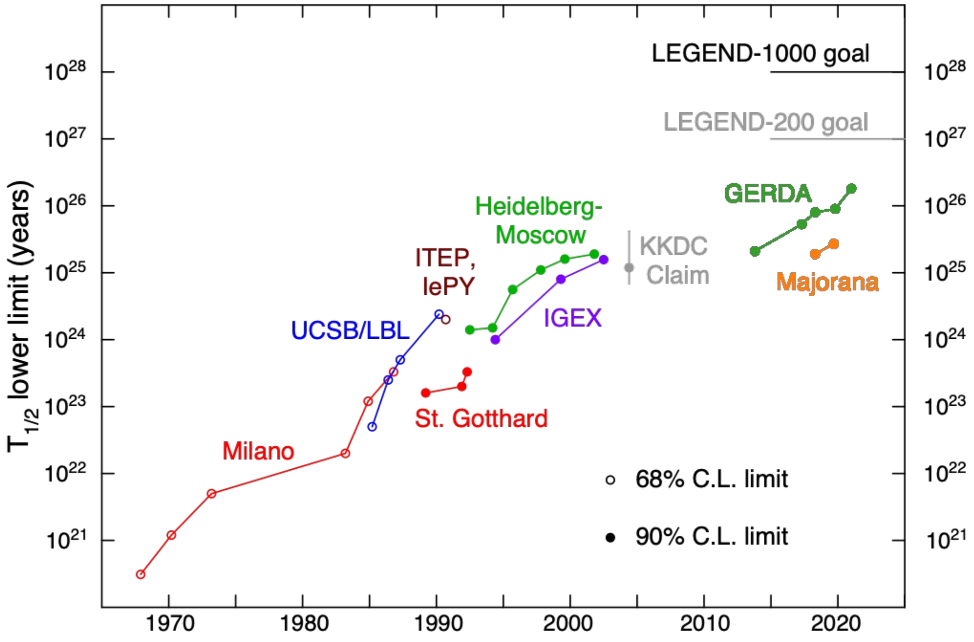


LEGEND prospects in 0νββ

Virtually **background free**!
Unambiguous discovery
even with a **handful of counts**



In case of no discovery,
push lower limit
2 orders of magnitude above current best



LEGEND prospects in 0νββ

Discovery potential

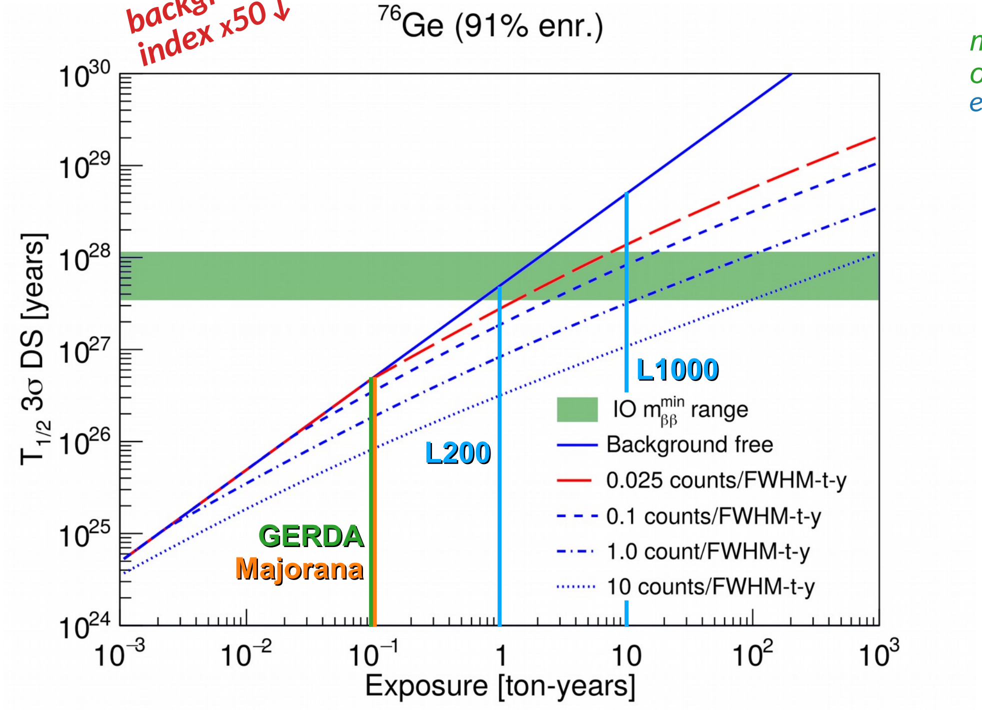
$$T_{1/2}^{0\nu\beta\beta} \sim \sqrt{\frac{Mt}{\mathrm{BI}\cdot\Delta E}}$$

exposure x100 ↑

background index x50 ↓

$$\Rightarrow T_{1/2}^{0\nu\beta\beta} \sim \frac{Mt}{N^{0\nu\beta\beta}}$$

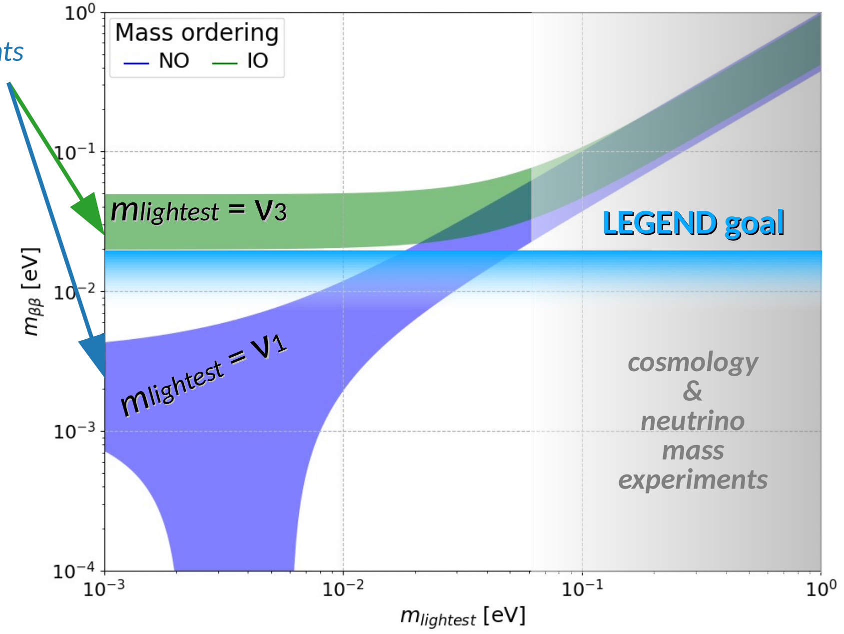
background free regime



Limit setting

$$m_{\beta\beta}^2 = (F^{0\nu}\cdot|\mathcal{M}^{0\nu}|^2\cdot T_{1/2}^{0\nu\beta\beta})^{-1}$$

mass ordering experiments



What else can LEGEND do?

Alternative 0νββ mechanisms

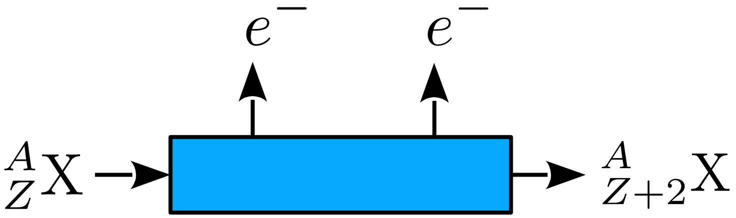
Long-range mechanisms e.g. **light Majorana neutrino**

Short-range mechanisms = **heavy particles**

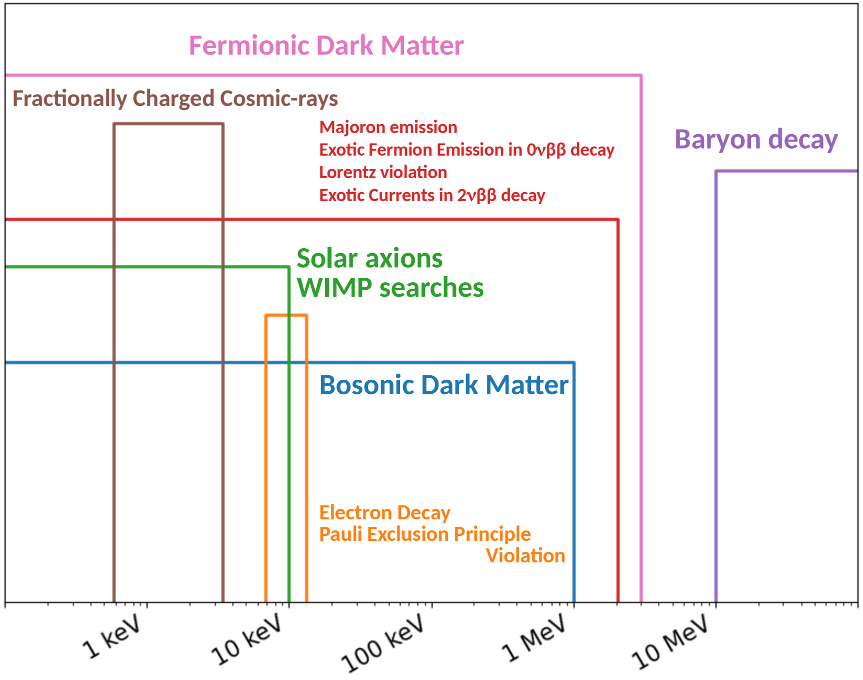
- **SUSY particles** e.g. gluions or squarks
- right-handed currents with **heavy neutrinos** or **scalar fields** e.g. Higgs
- …

Multiple mechanisms at the same time could be possible

LEGEND can probe short-range mechanisms beyond what other experiments can do



Other Beyond Standard Model searches

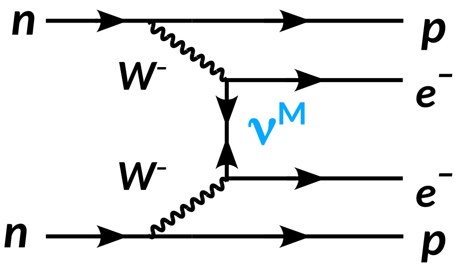


+ BSM physics in ^{36}Ar (ECEC)

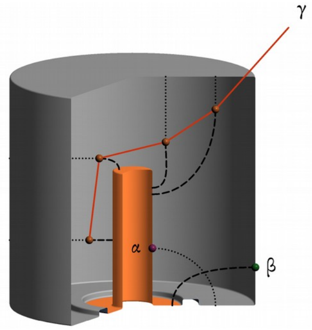
What I want you to remember about LEGEND

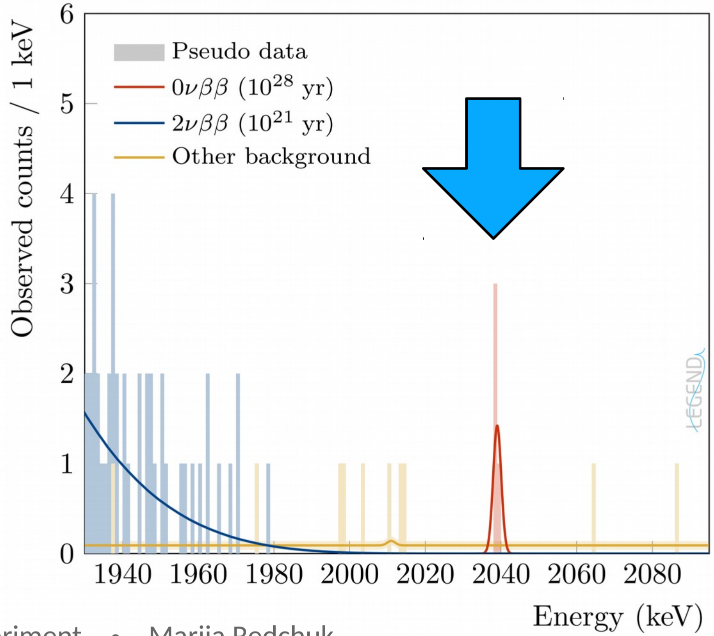
LEGEND = **L**arge **E**nriched **G**ermanium **E**xperiment for **N**eutrinoless double beta **D**ecay

1. **Neutrinoless double beta decay (0νββ)**
   - create matter without antimatter
   - lepton number violation
   - not observed yet



2. **Enriched germanium detectors**
   - leading material for 0νββ searches
   - excellent energy resolution
   - topological discrimination



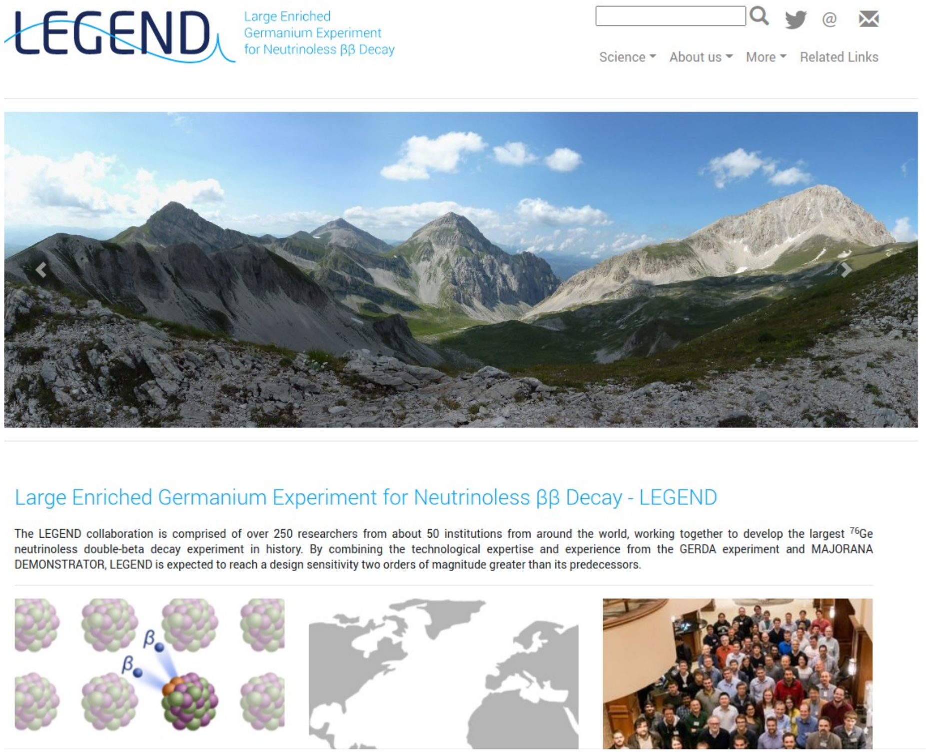


3. **The LEGEND experiment**
   - indeed large
   - aims to observe 0νββ in germanium
   - or push the lower limit on decay half-life
   - synergy with other neutrino physics experiments

More about LEGEND

LEGEND website

https://legend-exp.org



LEGEND Preconceptual Design Report

https://inspirehep.net/literature/1892243

LEGEND-1000 Preconceptual Design Report

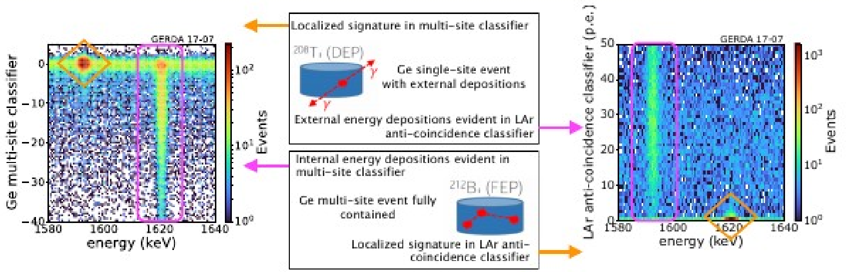


FIG. 15. An example of the clear separation of signal and background in the complementary PSD and anti-coincidence classifiers from GERDA calibration data. Two types of events are considered: a ^{208}Tl double-escape peak (DEP) event and a ^{212}Bi full-energy peak (FEP) event. Both of these are characteristic of backgrounds that cause peaks in the Ge spectrum. The orange diamonds indicate the classification of events as signal-like in one of the two parameter spaces, the magenta rectangles highlight the distribution in each parameter for background like events. Unlike the two cases here, a $0\nu\beta\beta$ decay event would be classified as a signal in both observable parameters.

~~Chat with me during the coffee break~~

Contact me if you have questions

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1222·2022 800 ANNI

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INFN PADOVA
Istituto Nazionale di Fisica Nucleare
Sezione di Padova

LEGEND
Large Enriched Germanium Experiment for Neutrinoless ββ Decay

THANK YOU!

9 countries • 47 institutions • 260 members

Backup

Dirac vs Majorana neutrino

"But if $\nu = \bar{\nu}$, does that mean ν can participate in inverse beta decay?"

For Majorana, there is no such thing as $\bar{\nu}$, just ν, what matters is **helicity**

Dirac		Majorana	
$\bar{\nu}_e^R + p \rightarrow n + e^+$	yes	$\nu_e^R + p \rightarrow n + e^+$	yes
$\nu_e^L + p \rightarrow n + e^+$	never	$\nu_e^L + p \rightarrow n + e^+$	yes but ~0% chance
$\nu_e^R + p \rightarrow n + e^+$	never		- - - - -
$\bar{\nu}_e^L + p \rightarrow n + e^+$	yes but ~0% chance		

Dirac: so far, we have only observed ν_L and $\bar{\nu}_R$

Majorana: they are simply just ν_L and ν_R

Dirac vs Majorana neutrino

	notation	chirality	$p(l^-)$	$p(l^+)$
Dirac ν	ν_L^D	L	$1-\left(\frac{m_\nu}{2E}\right)^2$	0
	ν_R^D	R	$\left(\frac{m_\nu}{2E}\right)^2$	0
Dirac $\bar{\nu}$	$\bar{\nu}_L^D$	L	0	$\left(\frac{m_\nu}{2E}\right)^2$
	$\bar{\nu}_R^D$	R	0	$1-\left(\frac{m_\nu}{2E}\right)^2$
Majorana ν	$\nu_L^M = \bar{\nu}_L^M$	L	$1-\left(\frac{m_\nu}{2E}\right)^2$	$\left(\frac{m_\nu}{2E}\right)^2$
Majorana $\bar{\nu}$	$\bar{\nu}_R^M = \nu_R^M$	R	$\left(\frac{m_\nu}{2E}\right)^2$	$1-\left(\frac{m_\nu}{2E}\right)^2$

Dirac: so far, we have only observed ν_L and $\bar{\nu}_R$

Majorana: they are simply just ν_L and ν_R

Neutrino observables

$$m_{\beta\beta} = |\sum U_{ei}^2 m_i|$$

Effective Majorana mass

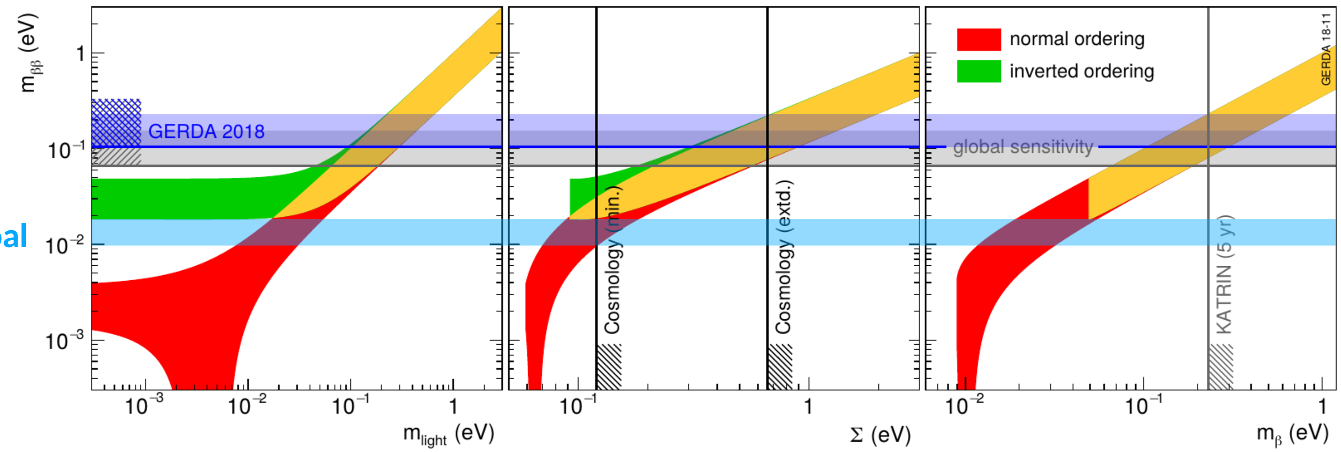
$$m_\beta = \sqrt{\sum m_i^2 |U_{ei}|^2}$$

"Incoherent sum" of ν_e mass eigenstates
("mass of electron neutrino")

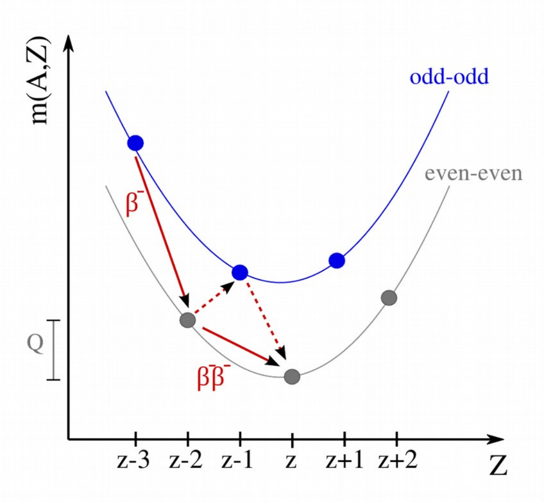
$$\Sigma \text{ or } m_{cosm} = \sum m_i$$

Sum of neutrino masses
cosmological/astrophysical observable

LEGEND goal



Two-neutrino and neutrinoless double beta decay



- **35** naturally occurring isotopes which can decay through **2νβ-β-** with forbidden or suppressed β-decay
- Only **6** for **2νβ+β+**, small Q values and much longer livetimes

Limits by present-generation experiments

Experiment	Isotope	Exposure [kg-yr]	$T^{0\nu}_{1/2}[10^{25}$ yr]	$m_{\beta\beta}$[meV]
GERDA [77]	^{76}Ge	127.2	18	79 – 180
MAJORANA [78]	^{76}Ge	26	2.7	200 – 433
KamLAND-Zen [79]	^{136}Xe	594	10.7	61 – 165
EXO-200 [80]	^{136}Xe	234.1	3.5	93 – 286
CUORE [81]	^{130}Te	1038.4	2.2	90 – 305

Alternative mechanisms for 0νββ

Long-range mechanisms e.g. **light Majorana neutrino** $T_{1/2}^{0\nu\beta\beta} \sim m_{\beta\beta}$

Short-range mechanisms = **heavy particles**

- **SUSY particles** e.g. gluions or squarks
- Right-handed currents with **heavy neutrinos** or **scalar fields** e.g. Higgs
- …

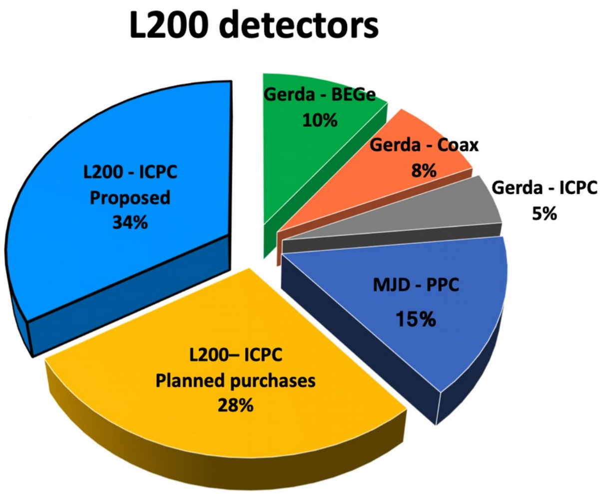
Multiple mechanisms at the same time could be possible

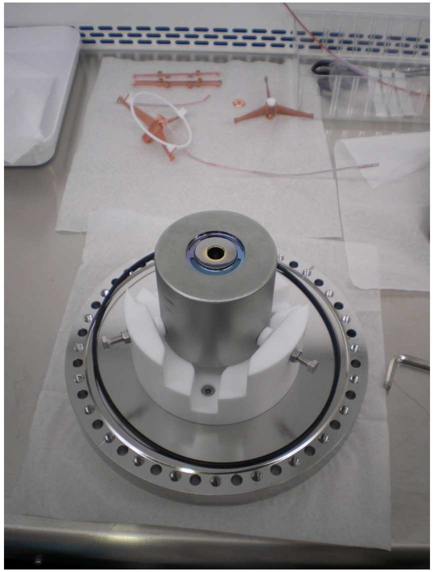
Let's see if we observe **0νββ**!

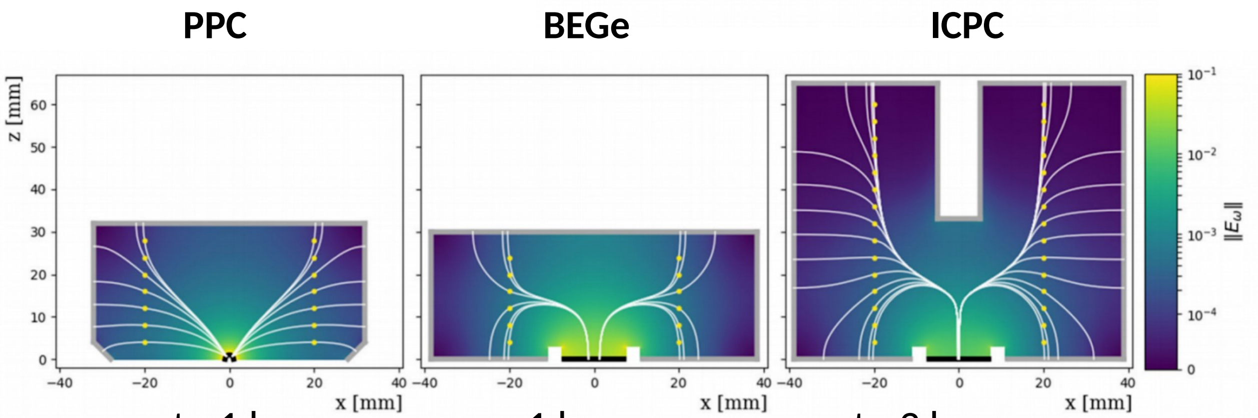
$T_{1/2}^{0\nu\beta\beta} \sim 10^{26-27}\text{yr}$ ⇒ Possible to see in LHC and determine dominant (short-range) mechanism

Germanium detectors

- e- do not contribute much since they drift through a volume of low field strength
- n+ → diffused lithium, p+ → ion-implanted boron
- >10^5 *e-h* pairs / MeV





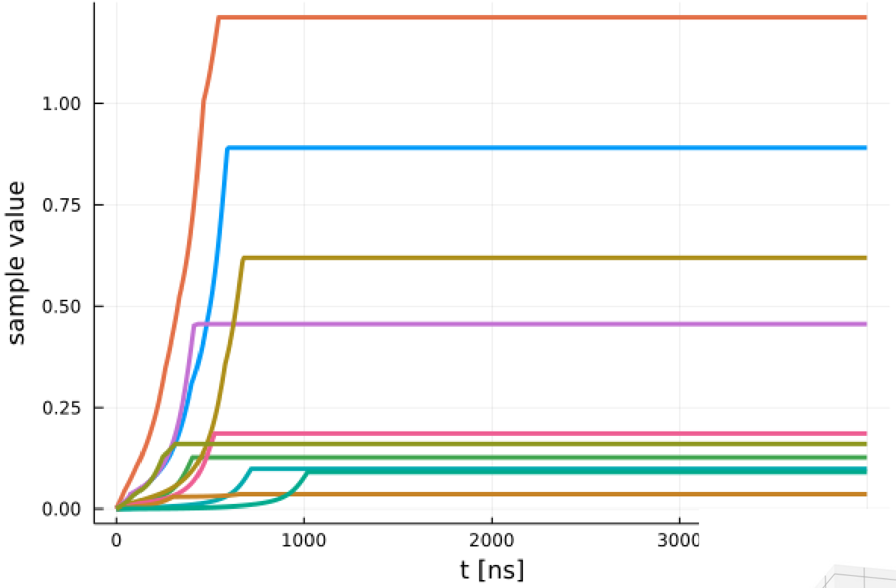


up to 1 kg

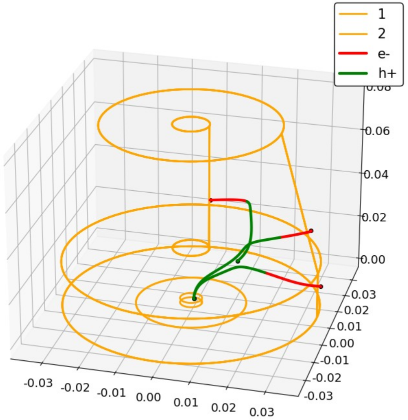
< 1 kg

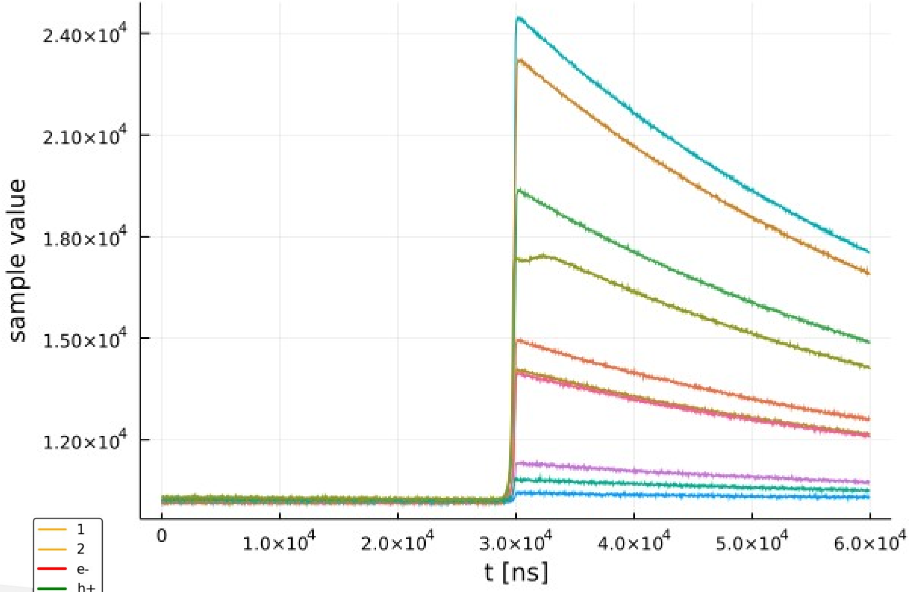
up to 3 kg
Longer drift times
→ optimal PSD

Waveforms



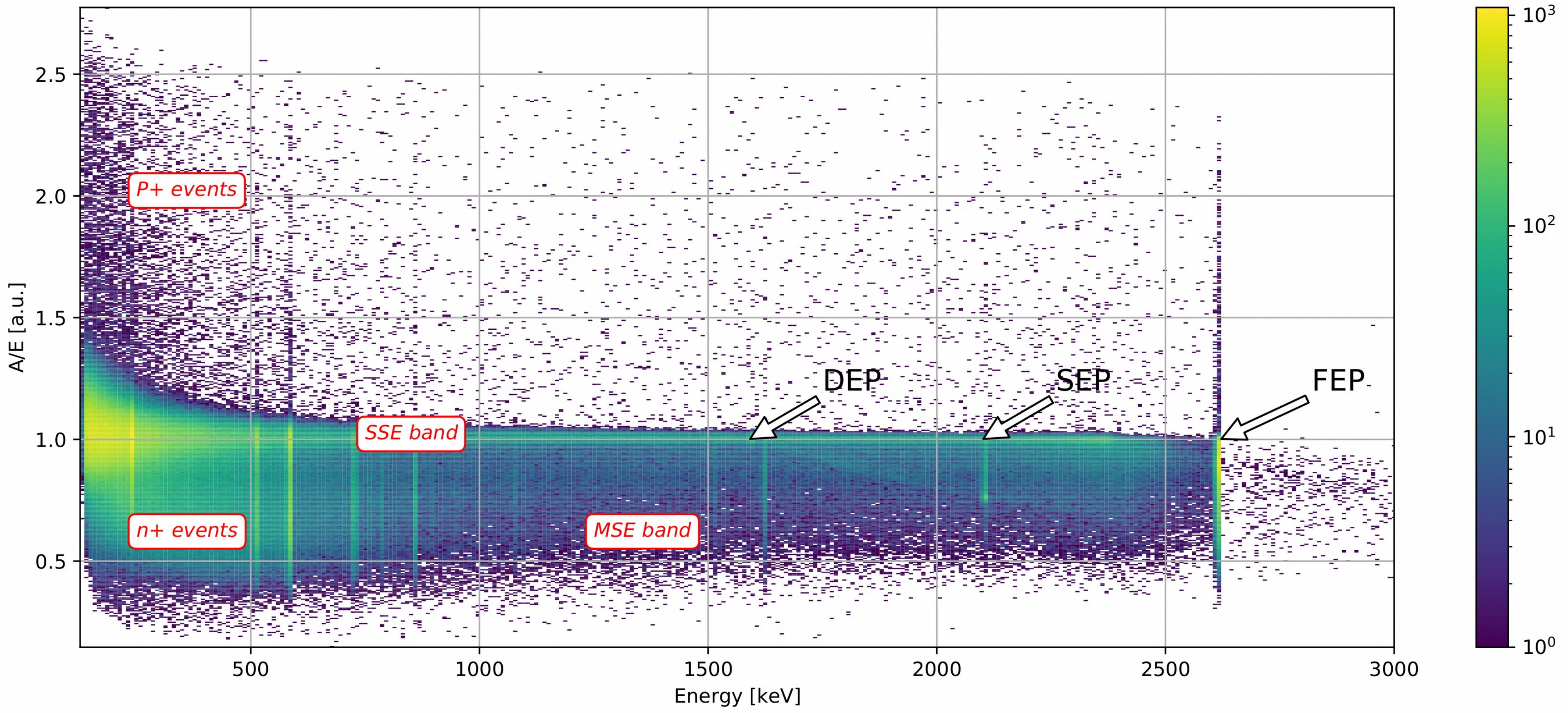
Pulse on the p+ contac
(simulation)





DAQ waveform
(characterization data)

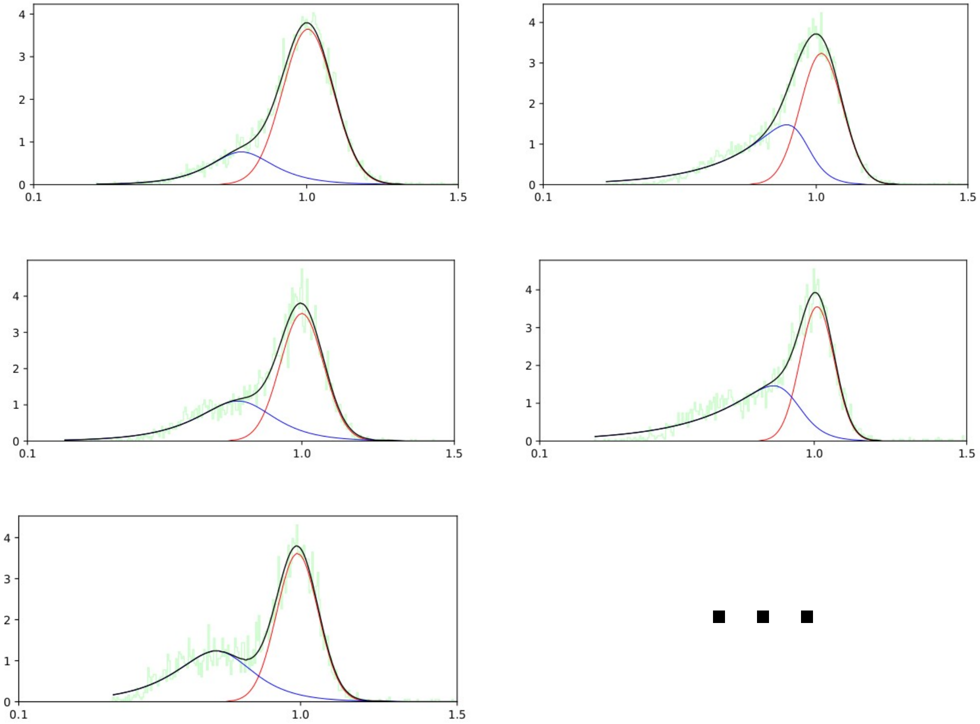
Pulse shape analysis



Pulse shape discrimination

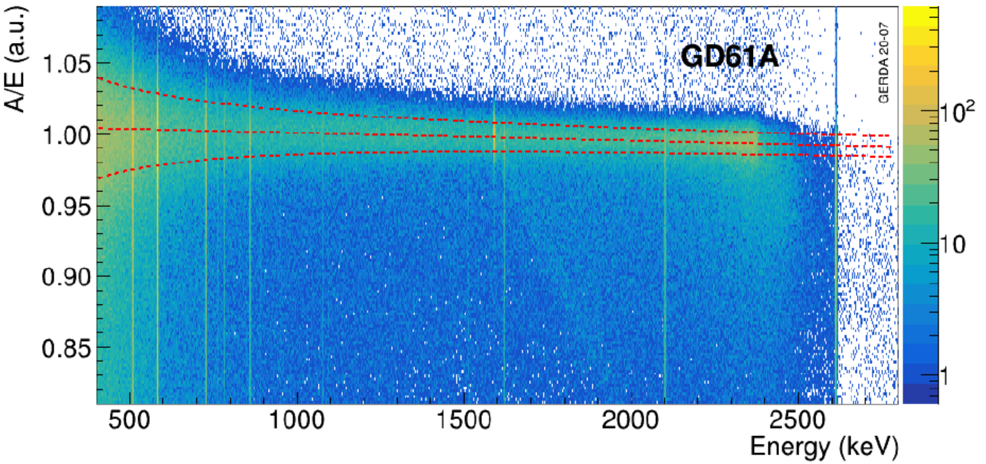
Fits in 30-keV slices

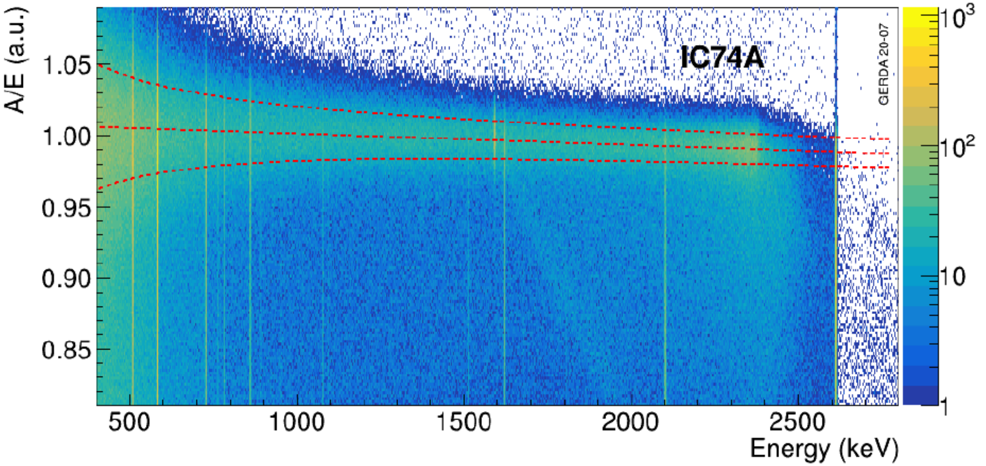
– SSE – MSE – total



. . .

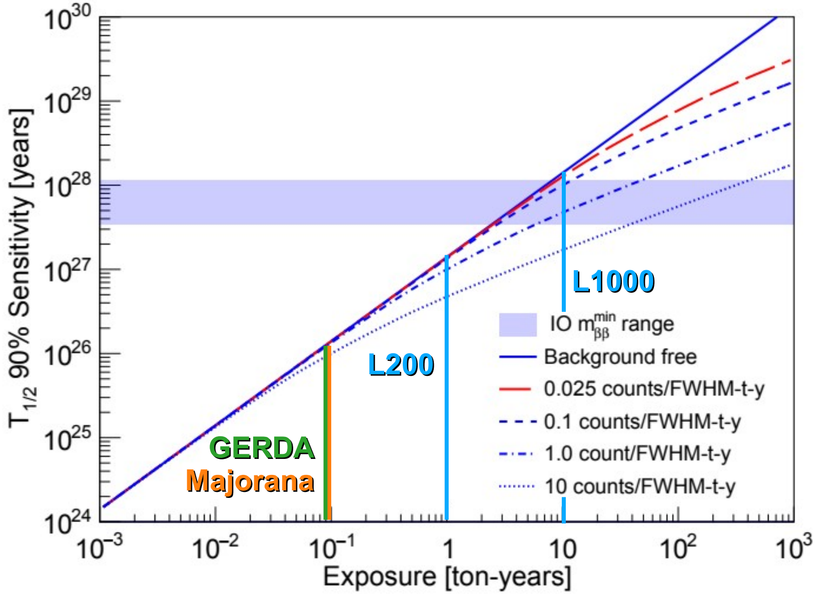
→ obtain μ and σ for each slice for each detector





The LEGEND experiment

limit setting



signal discovery