INFN PADOVA
Istituto Nazionale di Fisica Nucleare
Sezione di Padova

LEGEND
Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

LEGEND-200: first steps towards the hunt for 0νββ

International Conference on Hight Energy Physics 2024
19 Jul 2024
Mariia Redchuk on behalf of the LEGEND collaboration

What I want you to remember about

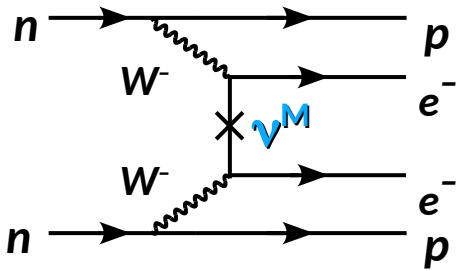
What I want you to remember about LEGEND

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

What I want you to remember about LEGEND

LEGEND = Large Enriched Germanium Experiment for Neutrinoless double beta Decay

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



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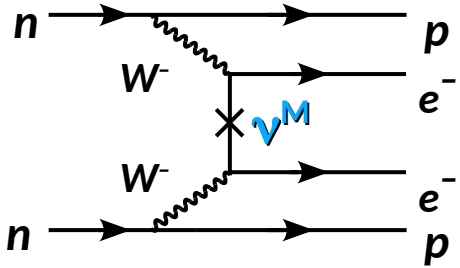
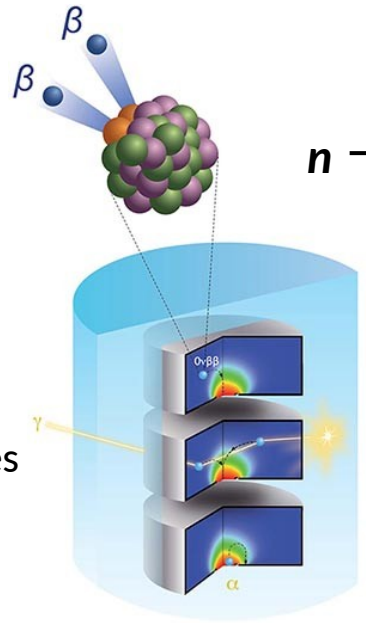


2. **Enriched germanium detectors**
   - excellent energy resolution
   - topological discrimination
   - leading material for 0νββ searches



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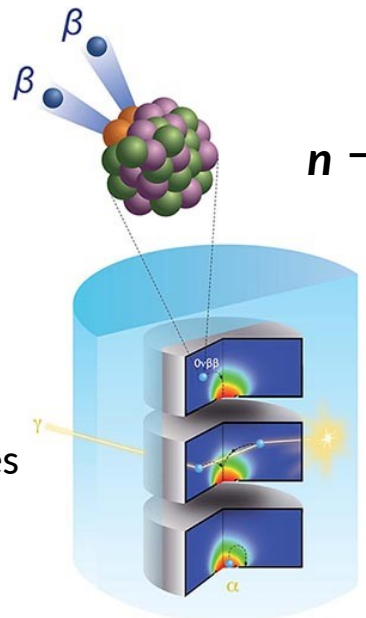
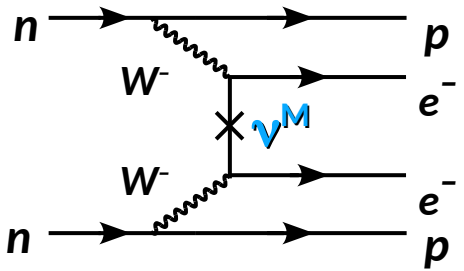
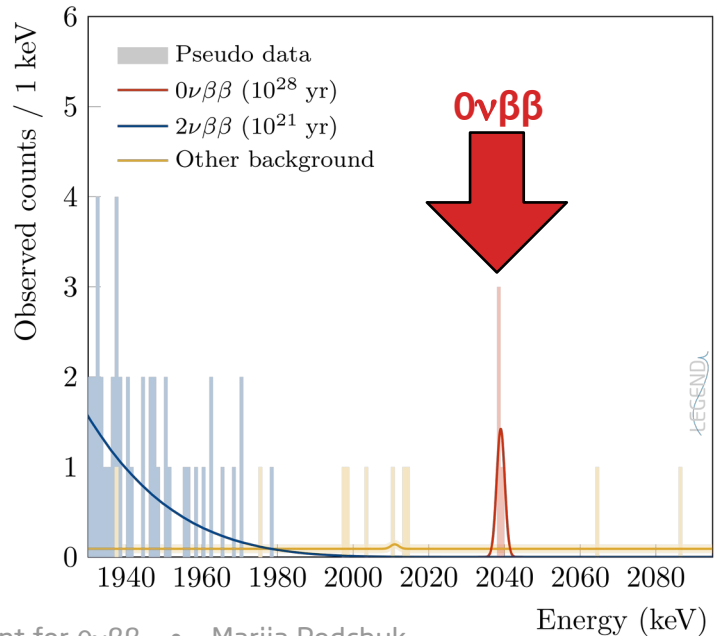


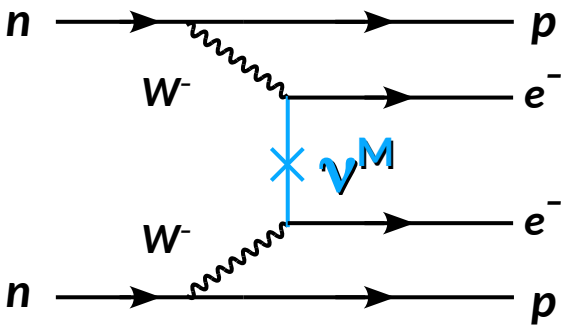


2. **Enriched germanium detectors**
   - excellent energy resolution
   - topological discrimination
   - leading material for 0νββ searches

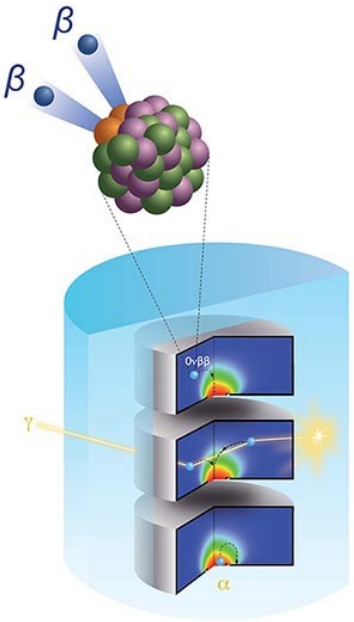
3. **The LEGEND experiment**
   - indeed **large** – 1000 kg of germanium
   - operating in **background free** regime
   - optimized for **0νββ discovery**



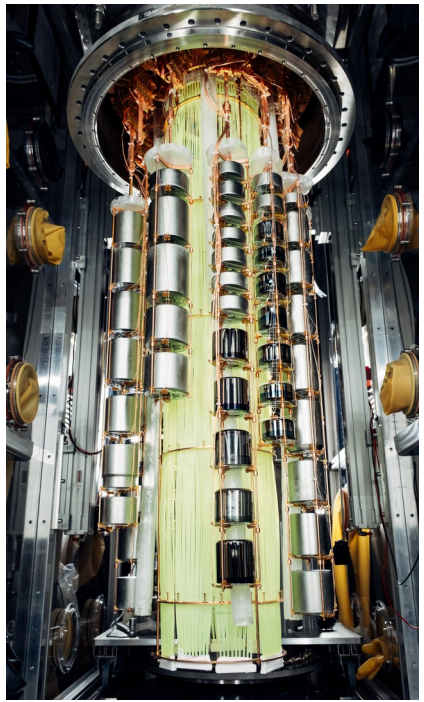
Neutrinoless double beta decay



Germanium experiment technology

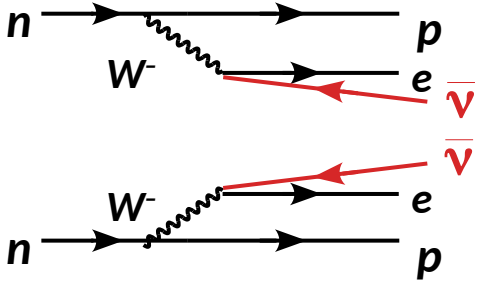


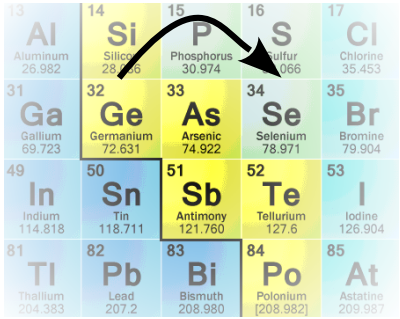
LEGEND-200 first year of data



Neutrinoless double beta decay

Double beta decay (2νββ)

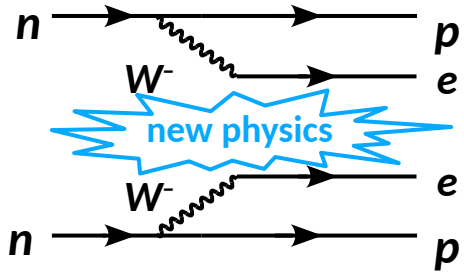




$^{76}Ge \rightarrow {}^{76}Se + 2e^- [+ 2\bar{\nu}_e]$

well-known at this point…

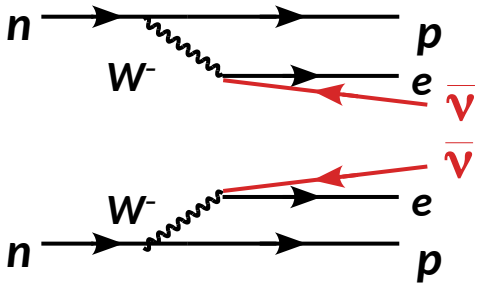
Neutrinoless double beta decay (0νββ)

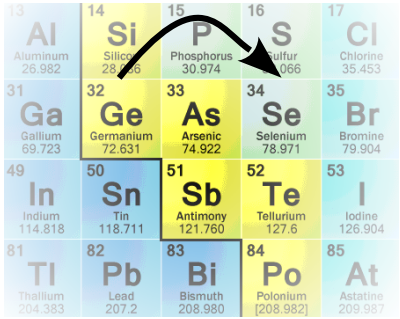


leptogenesis!
matter-antimatter asymmetry!

Neutrinoless double beta decay

Double beta decay (2νββ)





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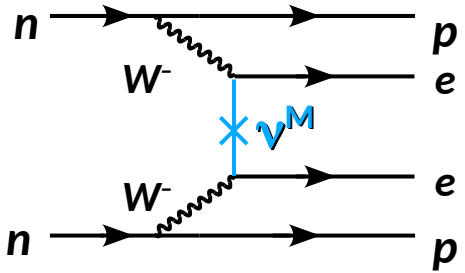


Dirac fermion

ν & $\bar{\nu}$

We only observe

ν_L and $\bar{\nu}_R$

Majorana fermion

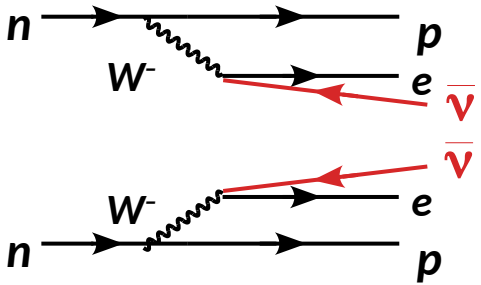
ν

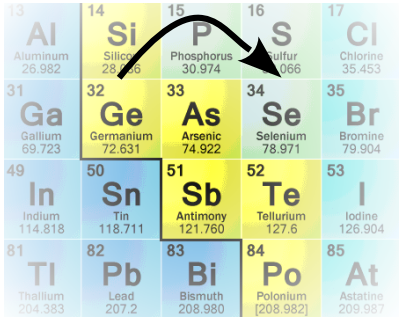
They are simply just

ν_L and ν_R

Neutrinoless double beta decay

Double beta decay (2νββ)





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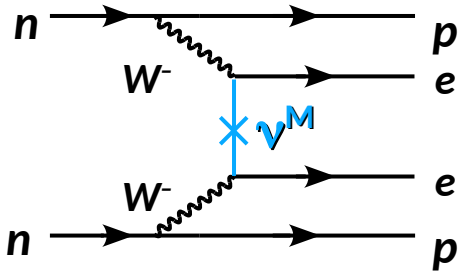
Neutrinoless double beta decay (0νββ)



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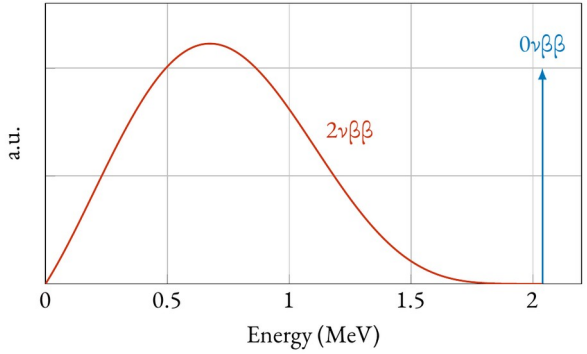

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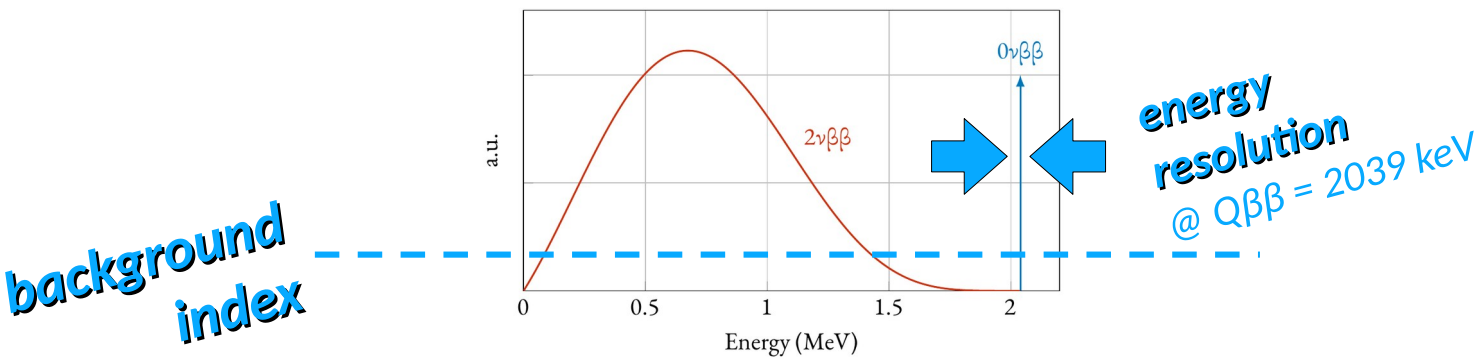
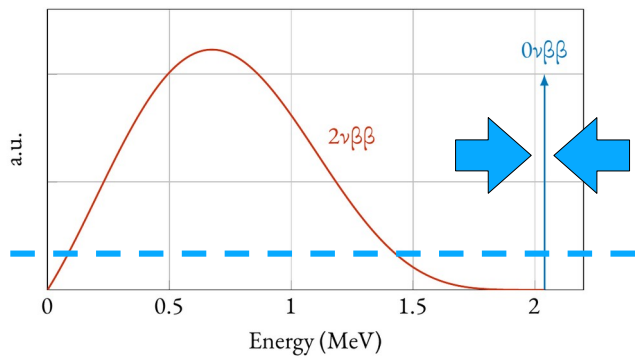
Key experimental parameters



Key experimental parameters

underground lab
shielding
active veto
topological discrimination

background index



energy resolution
@ Qββ = 2039 keV

germanium detectors
low noise electronics

Key experimental parameters

Operating in **background free** regime!

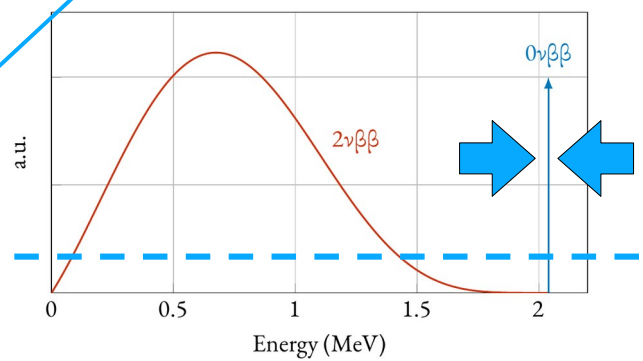
1000kg × 10 yrs

$$M \times t \times B \times \Delta E < 1$$

exposure

underground lab
shielding
active veto
topological discrimination

background index



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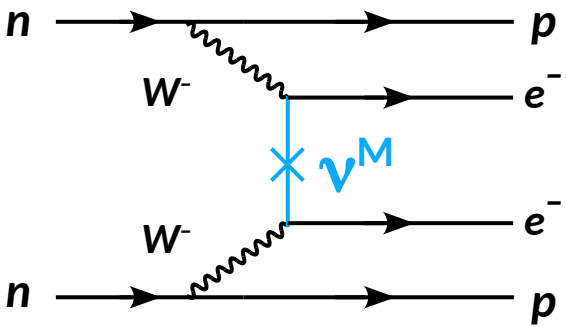
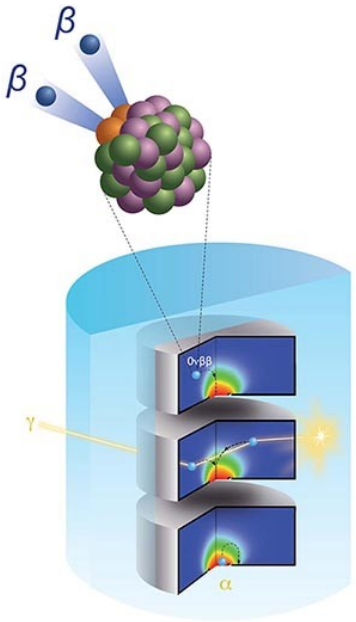


Germanium experiment technology



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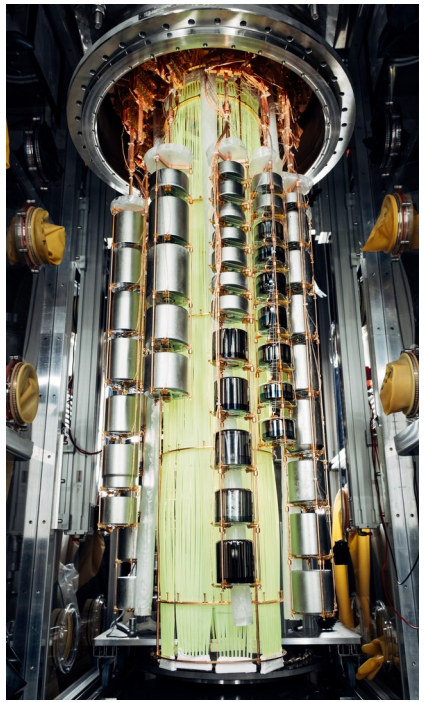
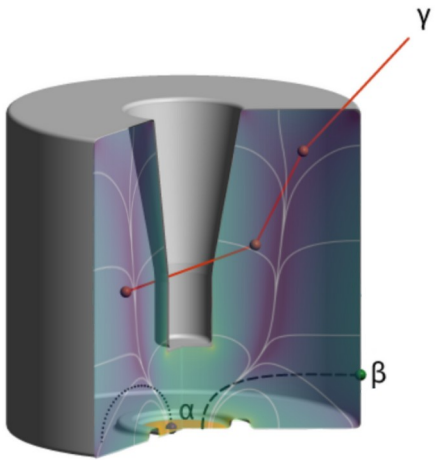
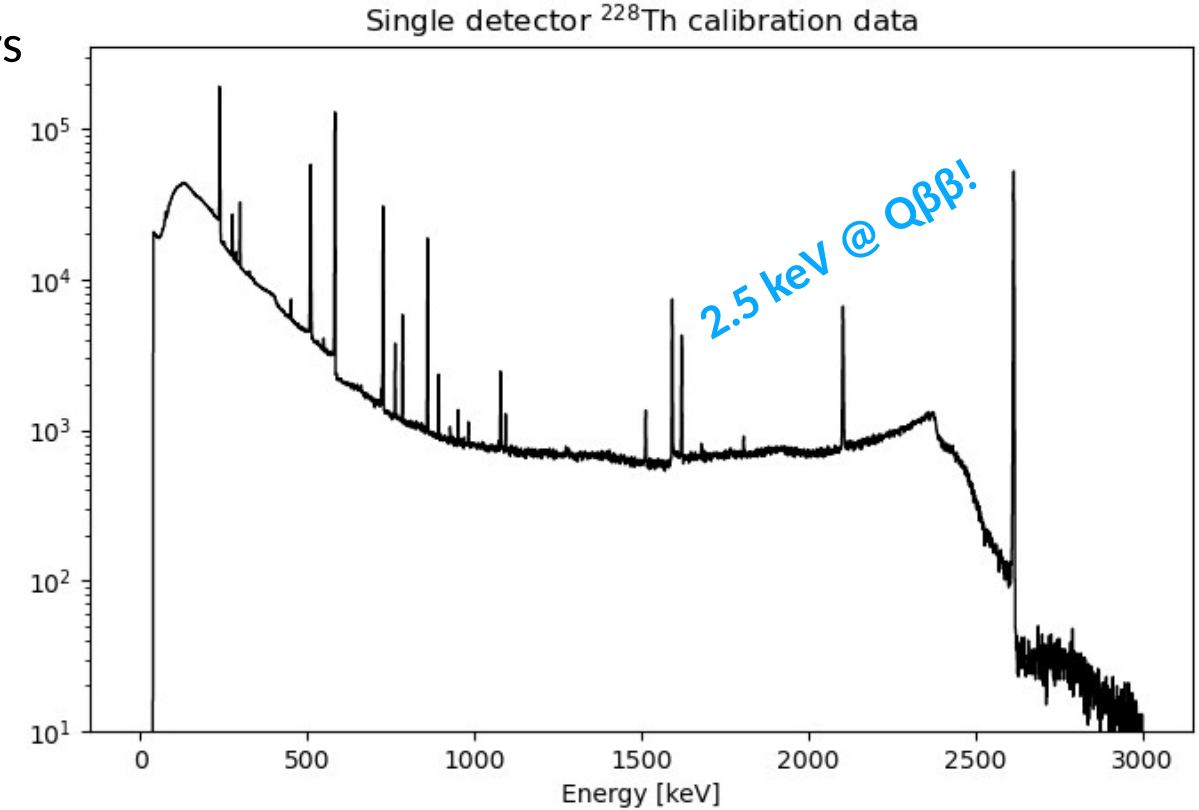


Germanium detectors

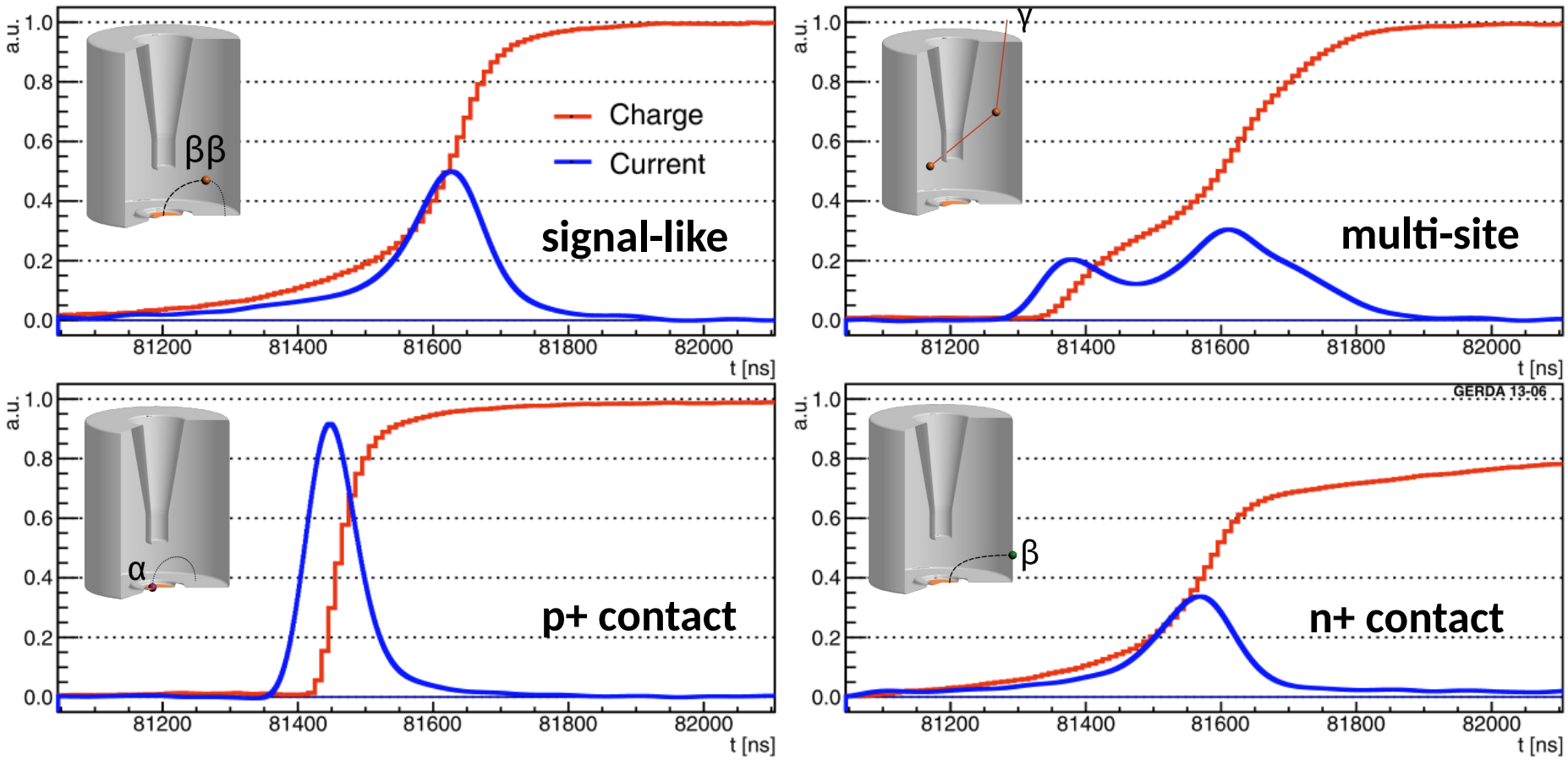
- **high purity** ^{76}Ge enriched detectors
- **detector = source**
- superb **energy resolution**
- **pulse shape discrimination**





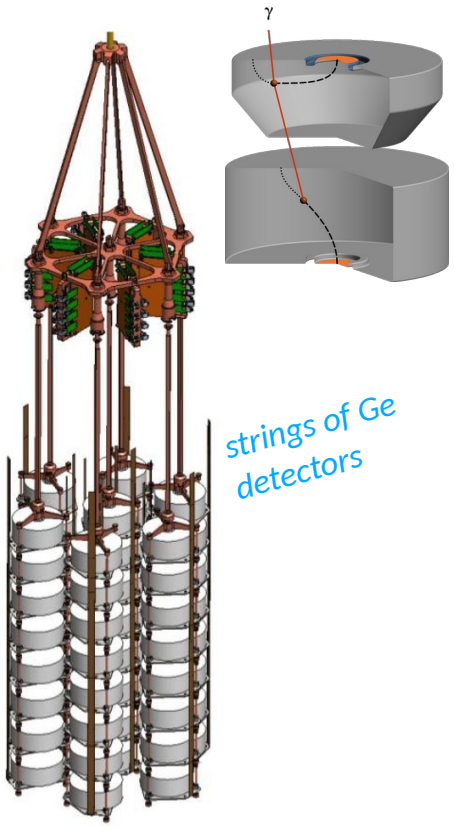
Germanium detectors

Pulse shape discrimination



GERmanium Detector Array (GERDA) technology

Experimental setup



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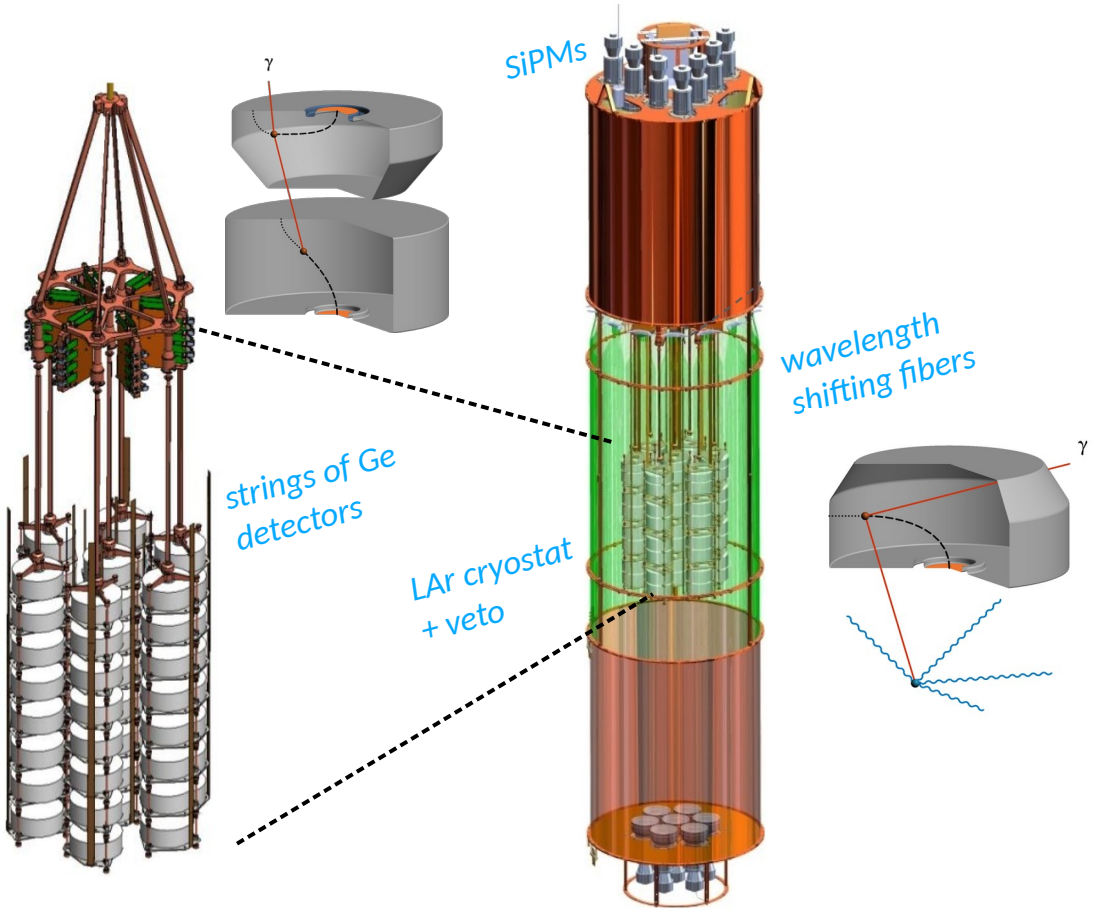

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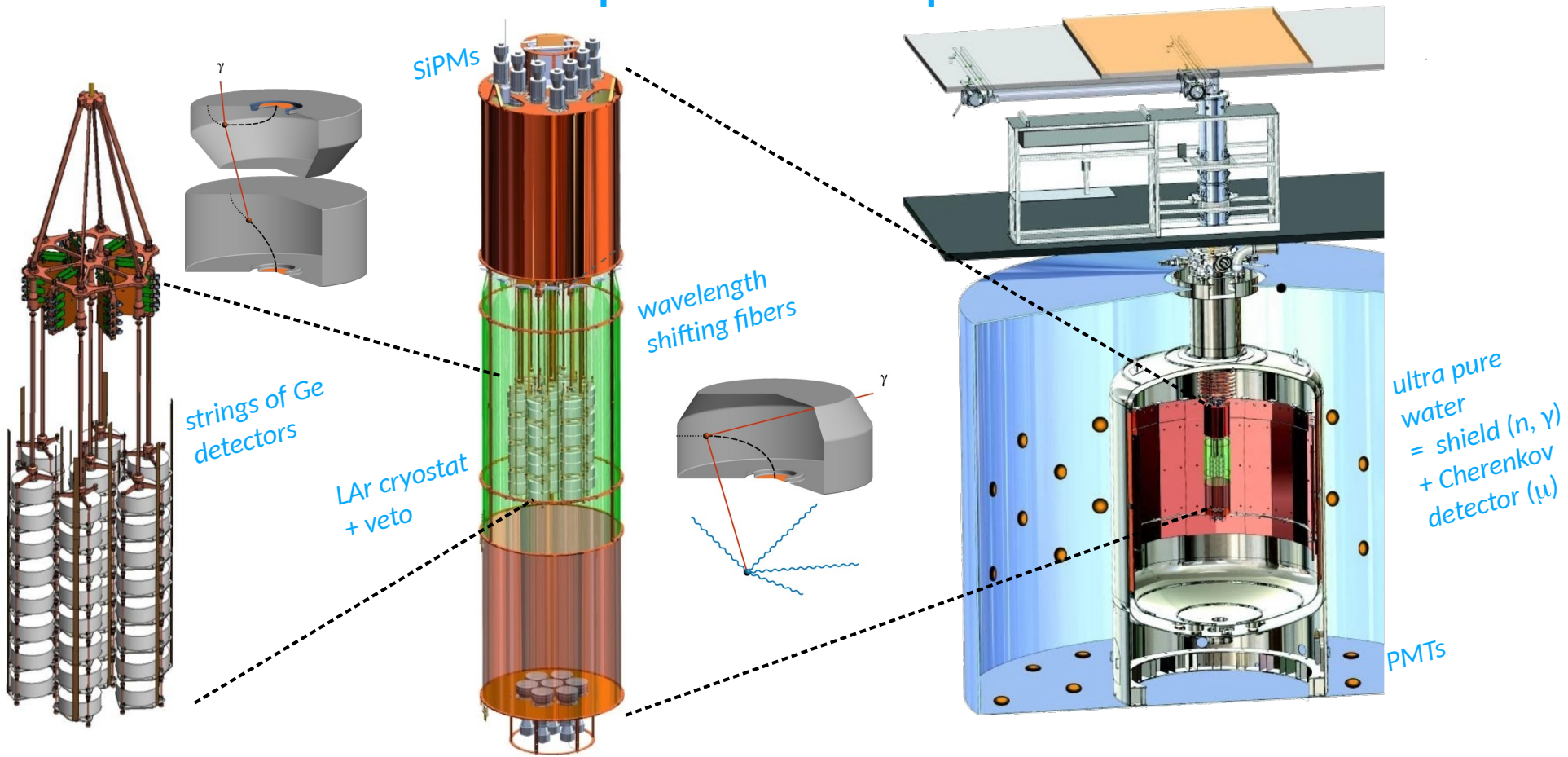
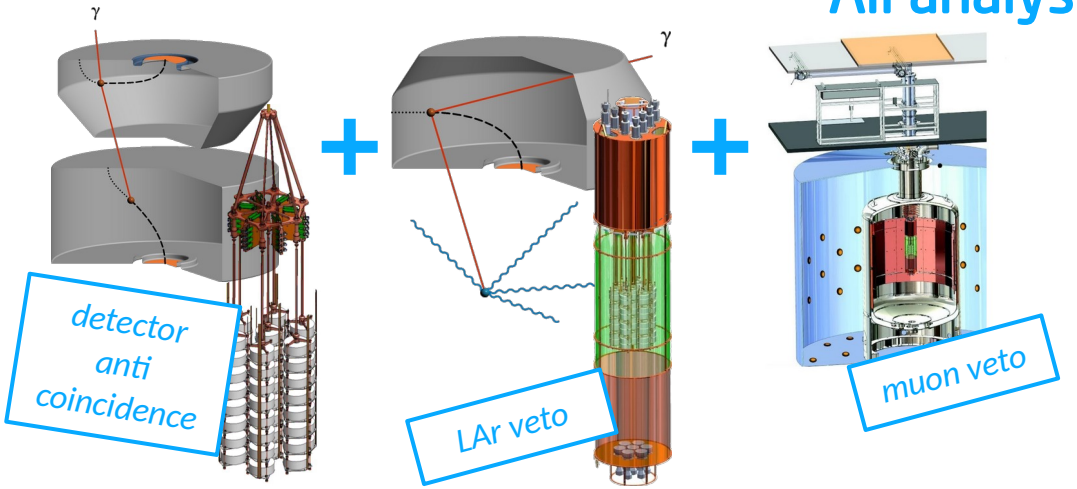


GERmanium Detector Array (GERDA) approach

All analysis cuts



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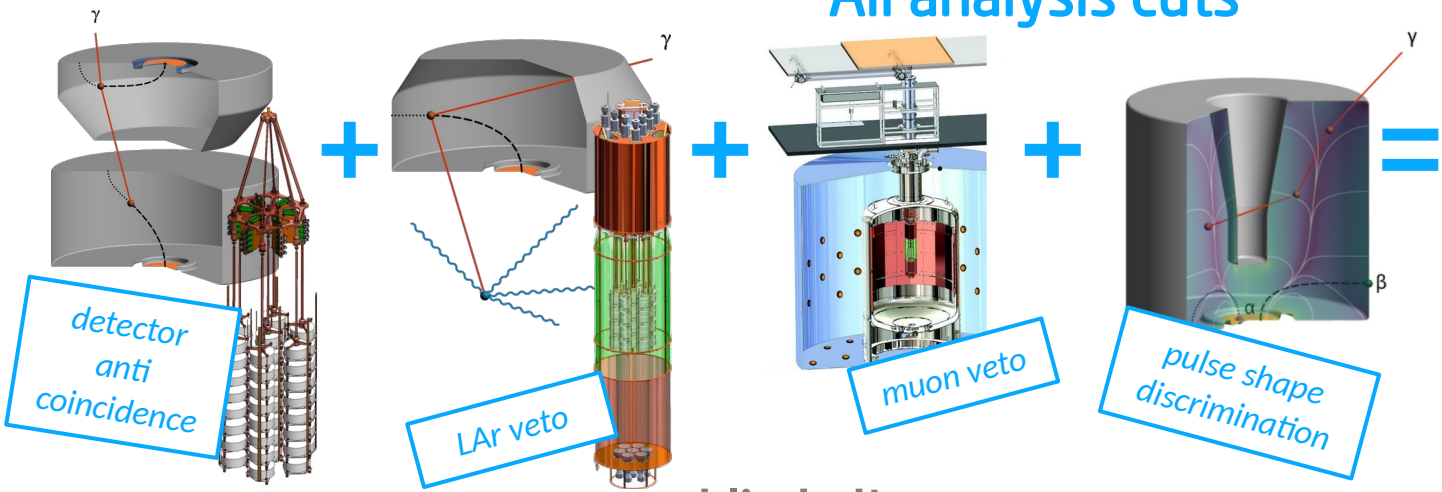


World leading background index

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

&

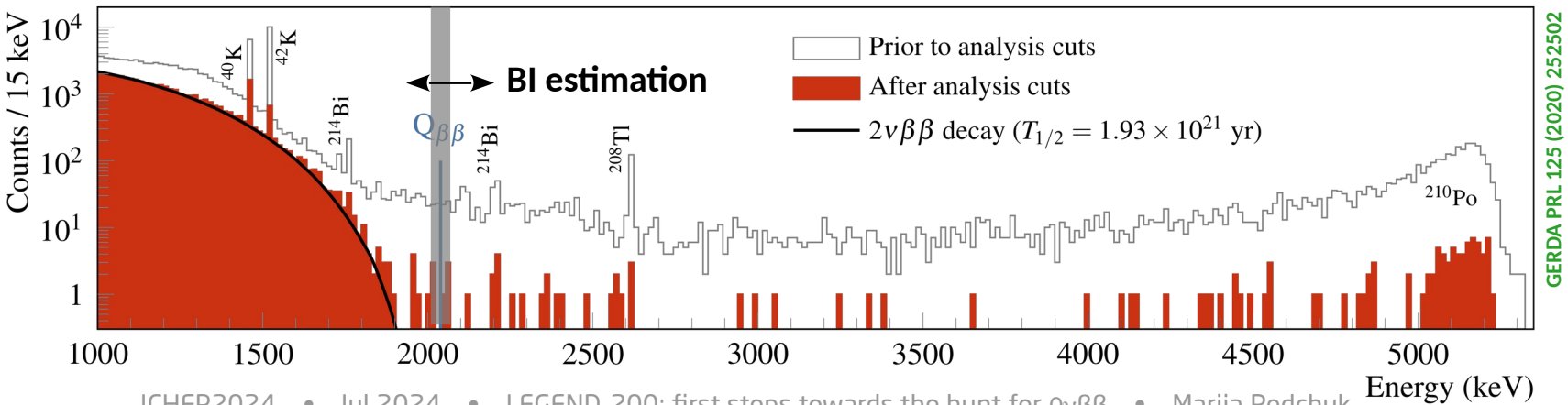
Energy resolution

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

$$M \times t \times B \times \Delta E < 1$$

in **full exposure** → "**background free**"

blinded!



The LEGEND experiment

GERDA	
mass	45 kg
exposure	127 kg yr
bkg idx	$5.2 \cdot 10^{-4}$ cts/(keV kg yr)
resolution	2.6 keV

lowest bkg

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MAJORANA Demonstrator	
mass	30 kg
exposure	65 kg yr
bkg idx	$6.6 \cdot 10^{-3}$ cts/(keV kg yr)
resolution	2.52 keV

lowest bkg

best E reso

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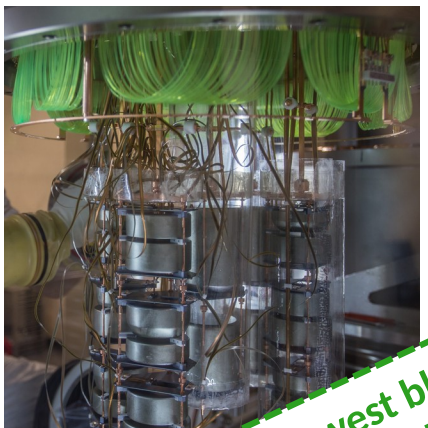

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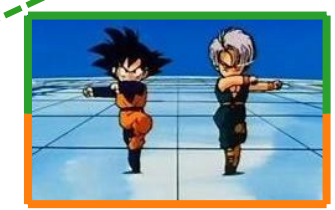

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resolution	2.52 keV

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

lowest bkg

best E reso

The LEGEND experiment

GERDA	
mass	45 kg
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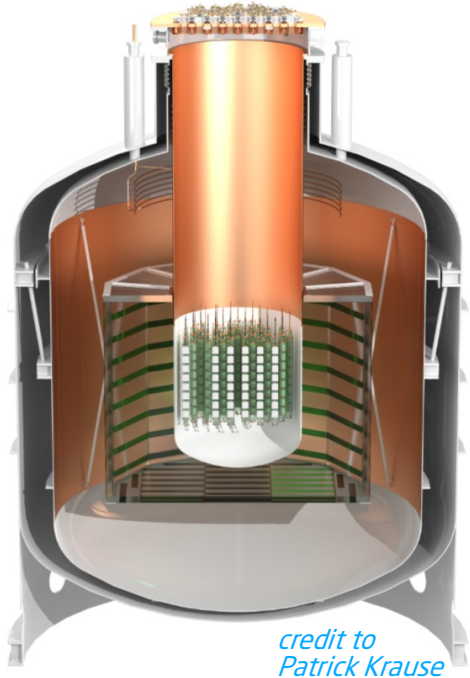
mass	**200 kg**
exposure	**1000 kg yr** x10 ↑
bkg idx	$2 \cdot 10^{-4}$ cts/(keV kg yr) x2.5 ↓
resolution	2.5 keV

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

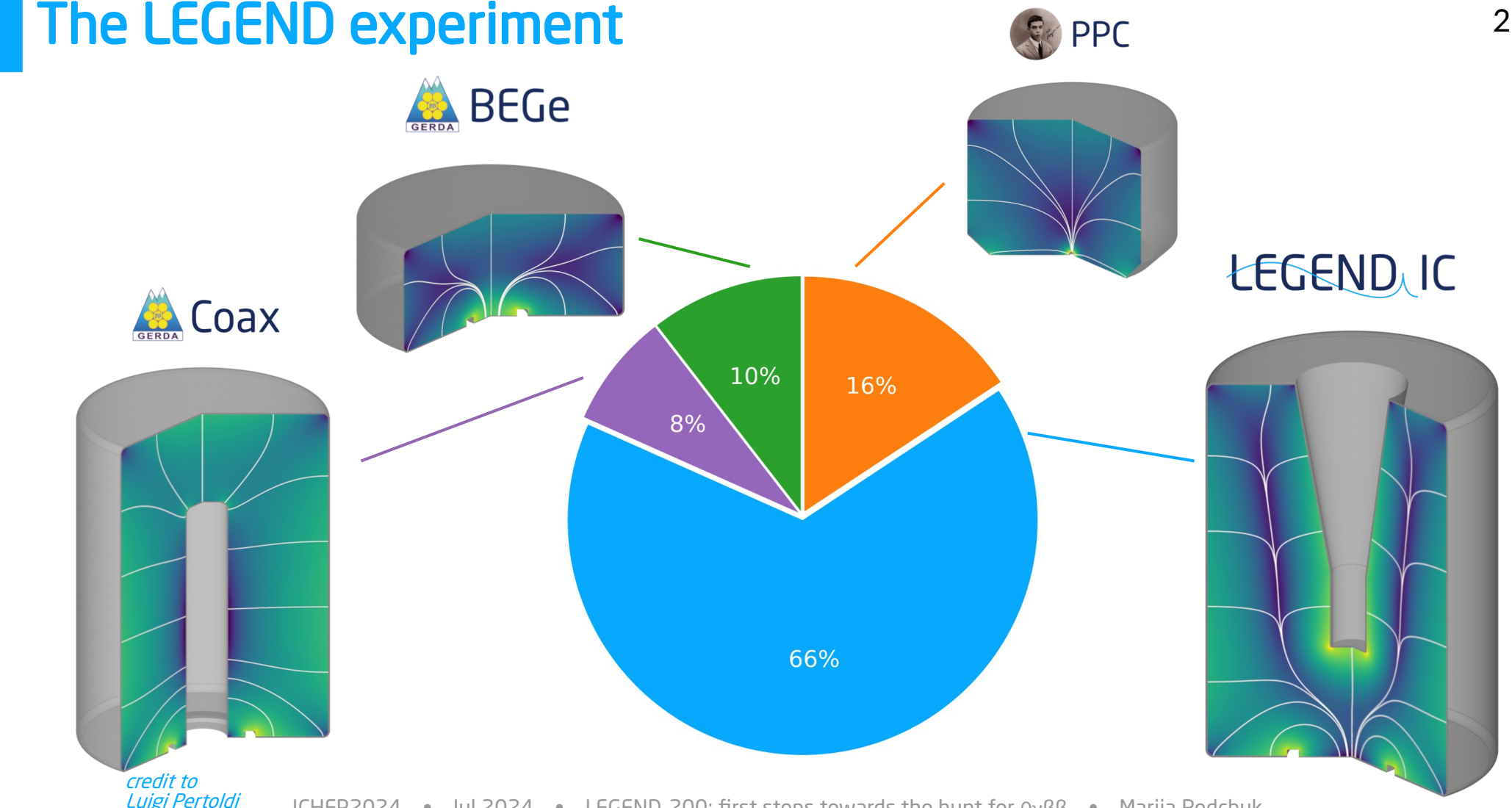
lowest bkg

best E reso



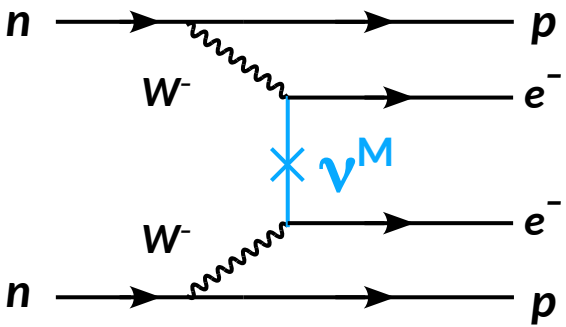
credit to Patrick Krause

The LEGEND experiment



credit to Luigi Pertoldi

Neutrinoless double beta decay



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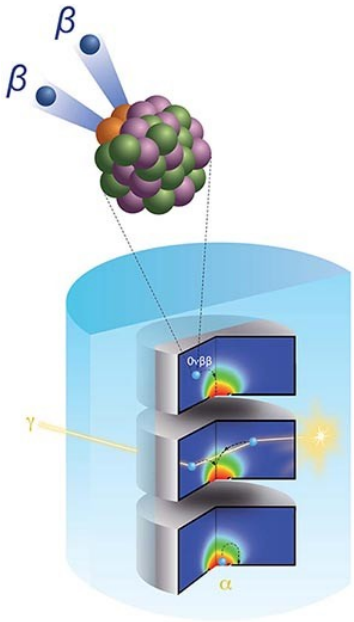

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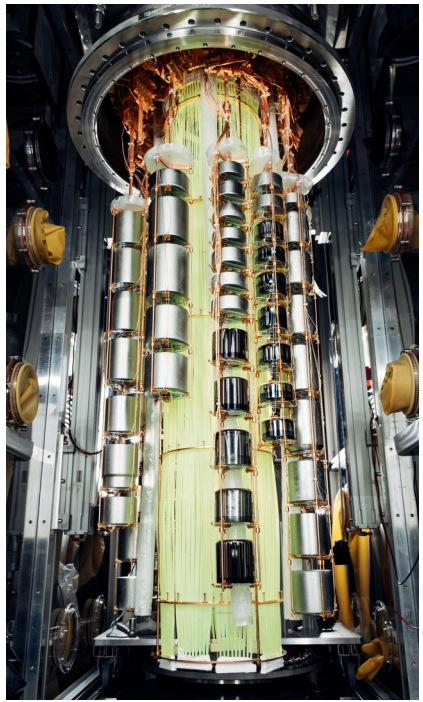
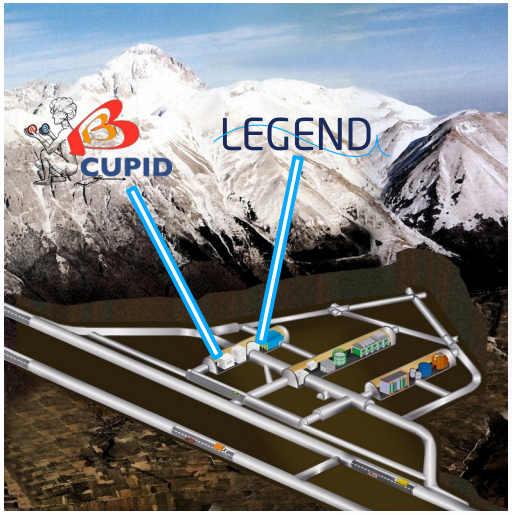


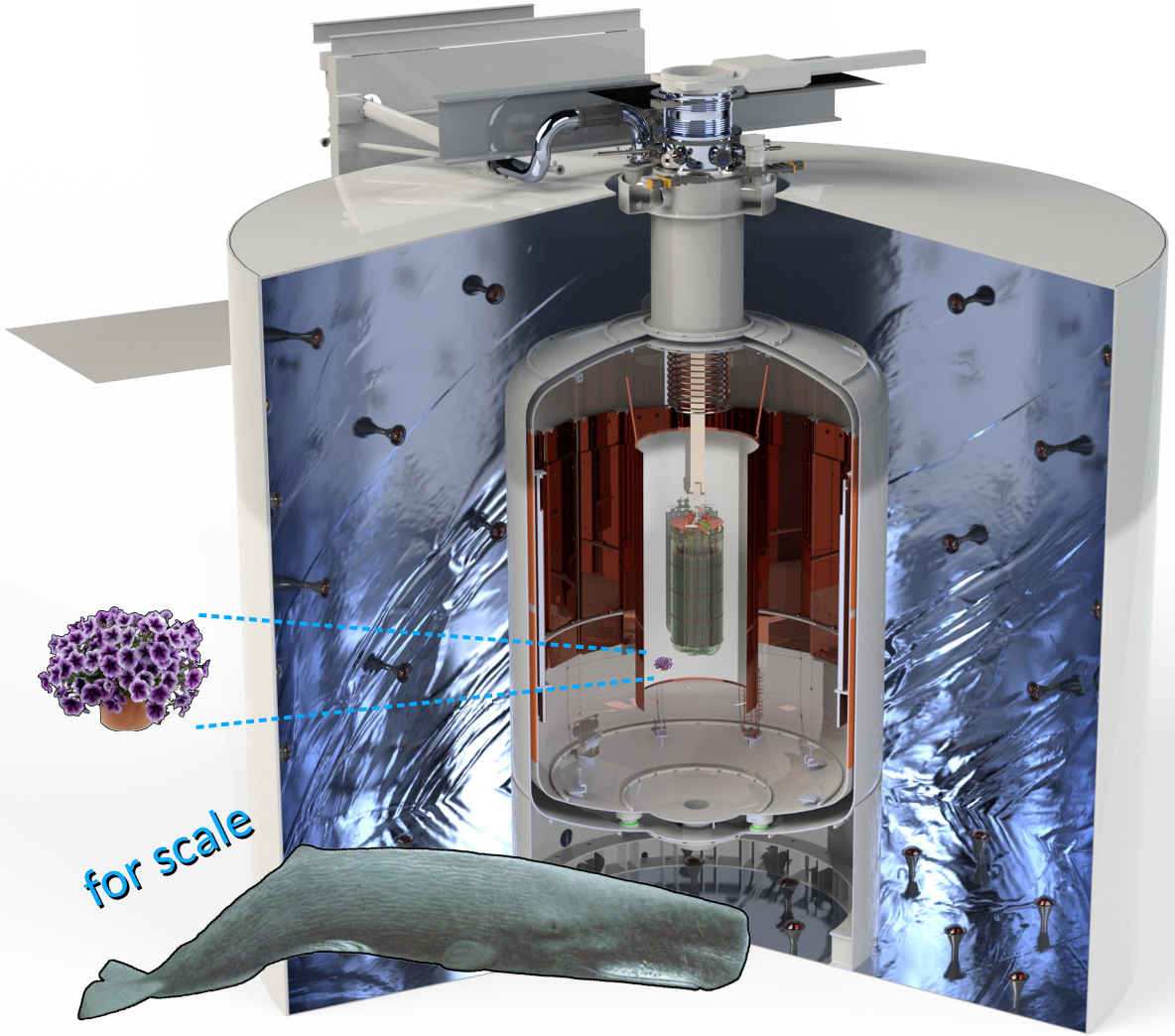
LEGEND-200

INFN

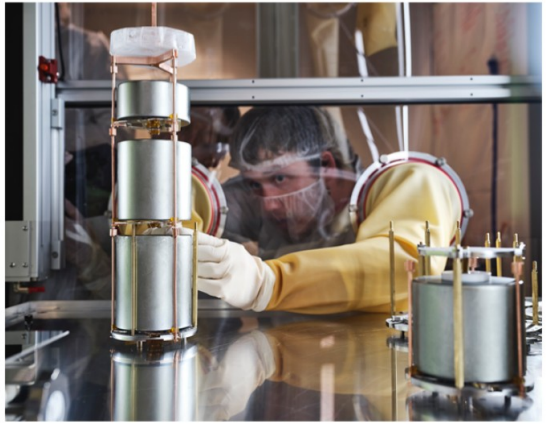
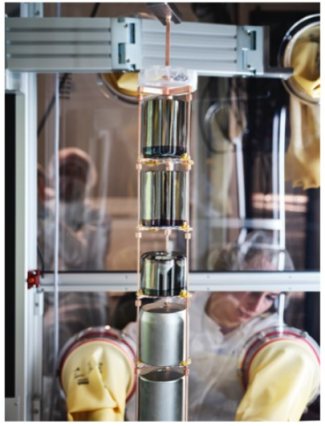
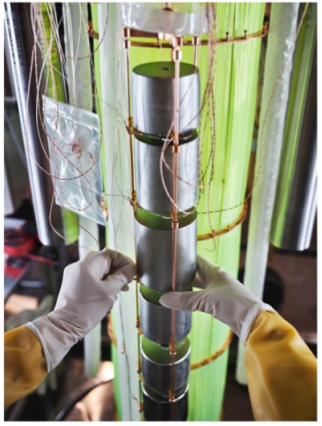
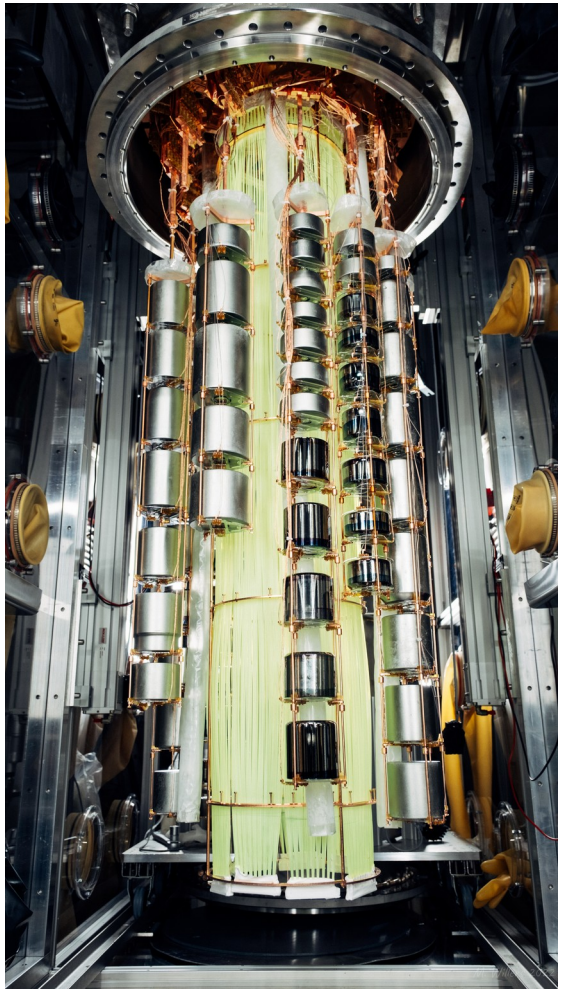
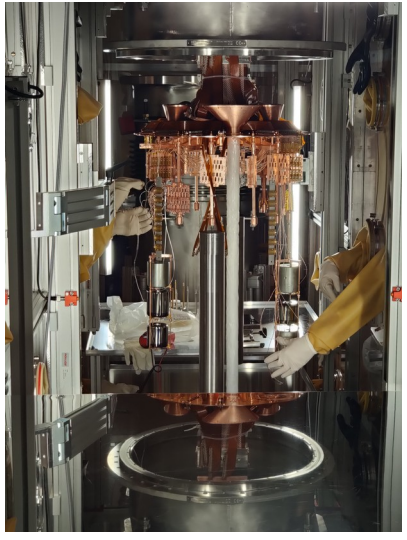
Laboratori Nazionali del Gran Sasso

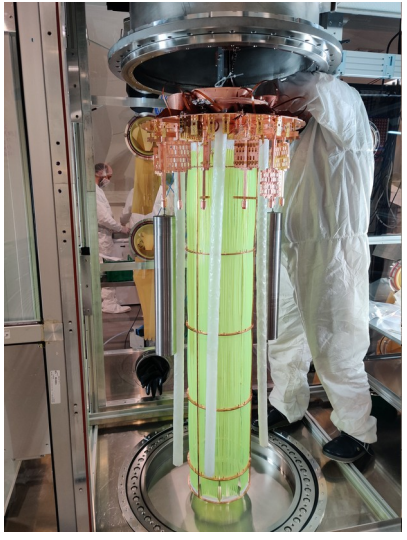


neighbours 👋



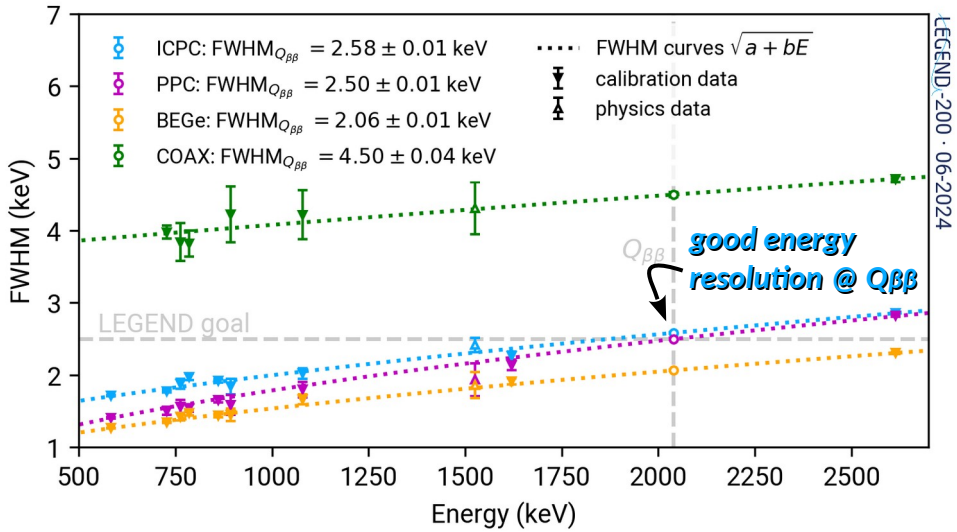
LEGEND-200 commissioning

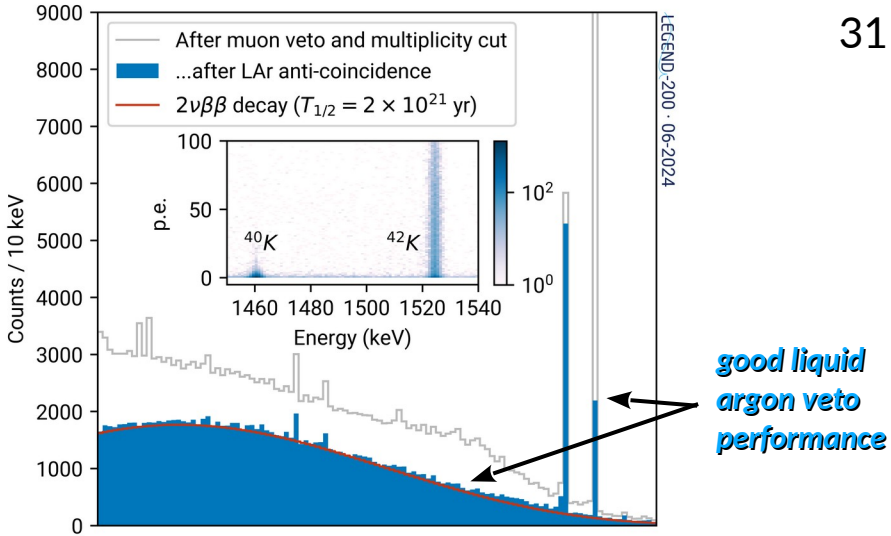






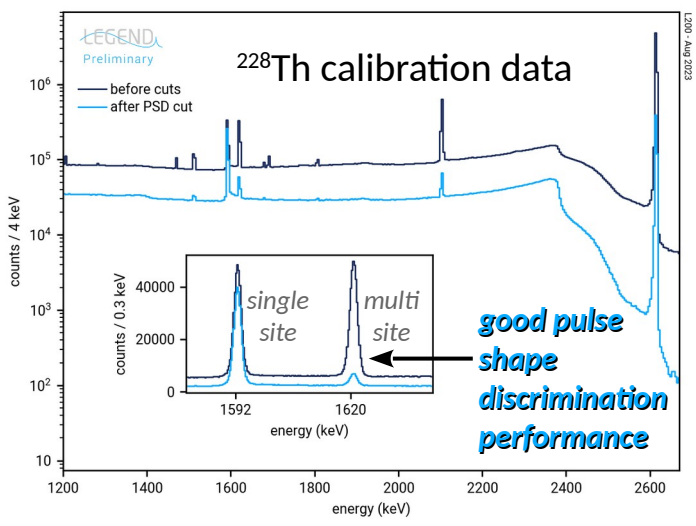


LEGEND-200 performance

- **Commissioning** finished October 2022
- ~142kg **installed** (~100 detectors) on 10 strings
- **Physics data taking** from March 2023
- 1 year **exposure analyzed**
- **Full report on performance @ TAUP2023**

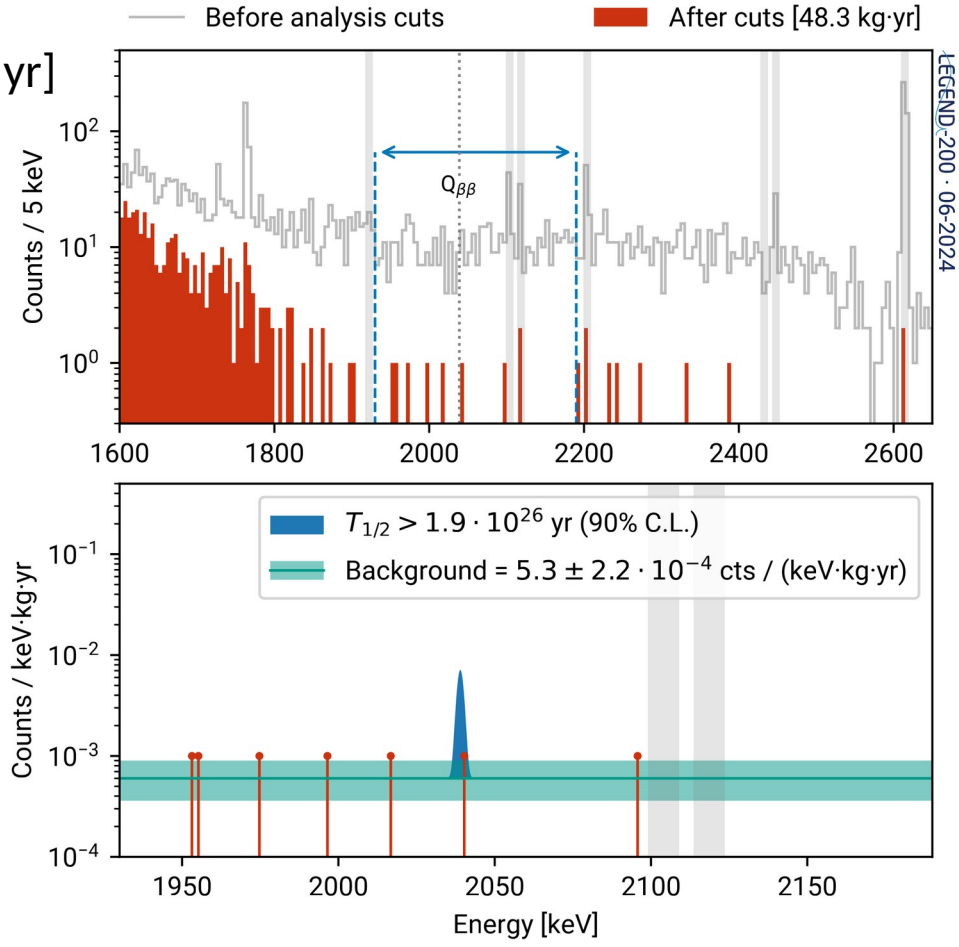






LEGEND-200 first year of physics data

- Silver dataset: **background & performance** [76.2 kg × yr]
- Golden dataset: **0νββ data** with fully vetted pulse shape discrimination parameters [48.3 kg × yr]
- **5 events** in "background estimation window" [1930 – 2190 keV]
- **+ 2 events** in blinding window **after unblinding** [Qbb ± 25 keV]
- **Background index** (5.3 ± 2.2) × 10^{-4} cts/(keV × kg × yr) [GERDA world-leading level]
- **$T_{1/2}$(0νββ)** > 1.9 × 10^{26} yr (combined analysis)
- **Full report @ Neutrino2024**

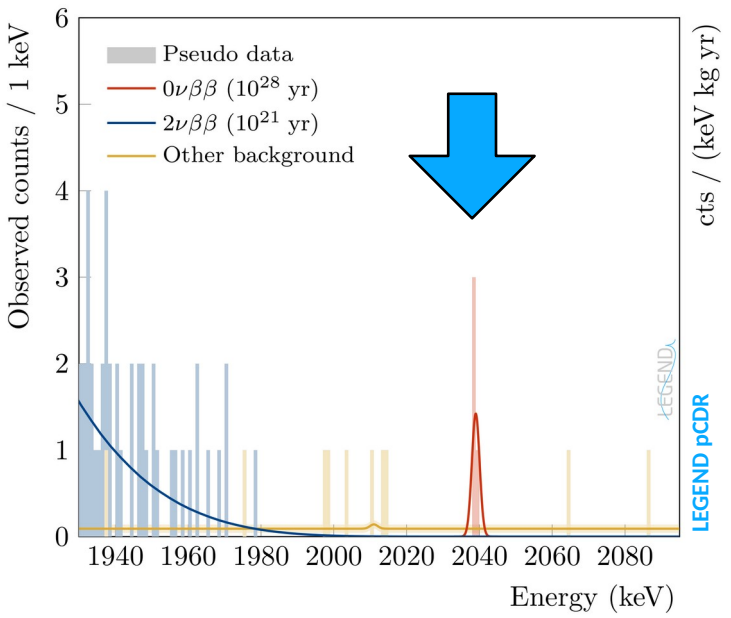


LEGEND-1000 prospects in 0νββ

Poster #023
Sam Watkins / Sofia Calgaro

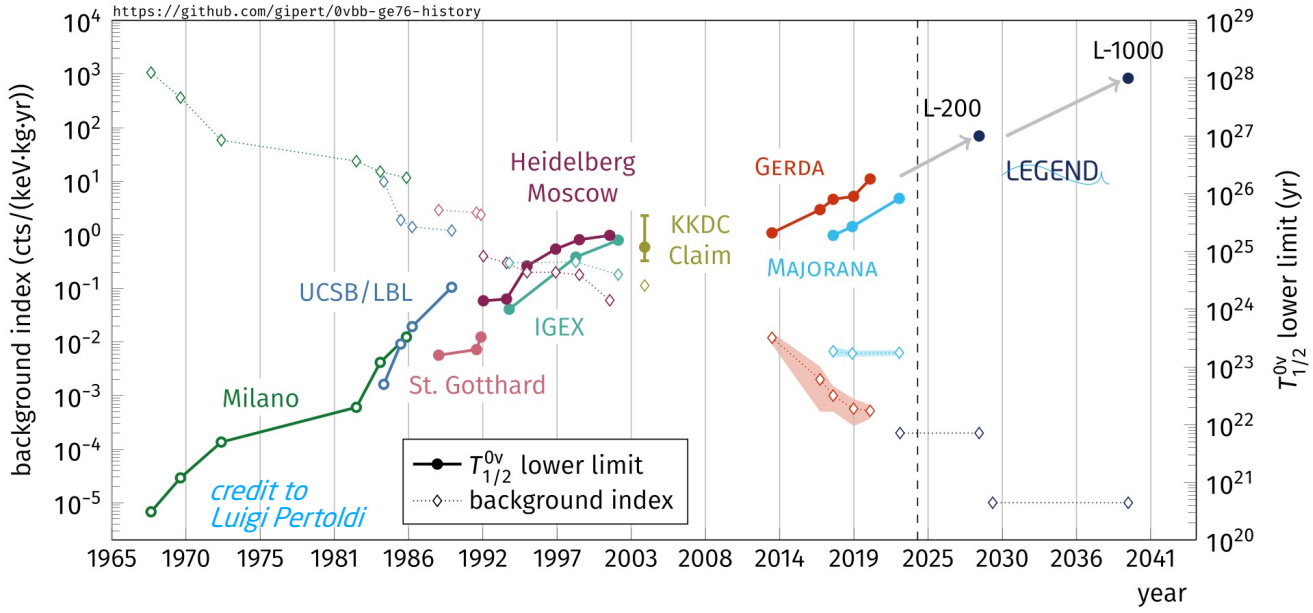
Discovery potential

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



Limit setting

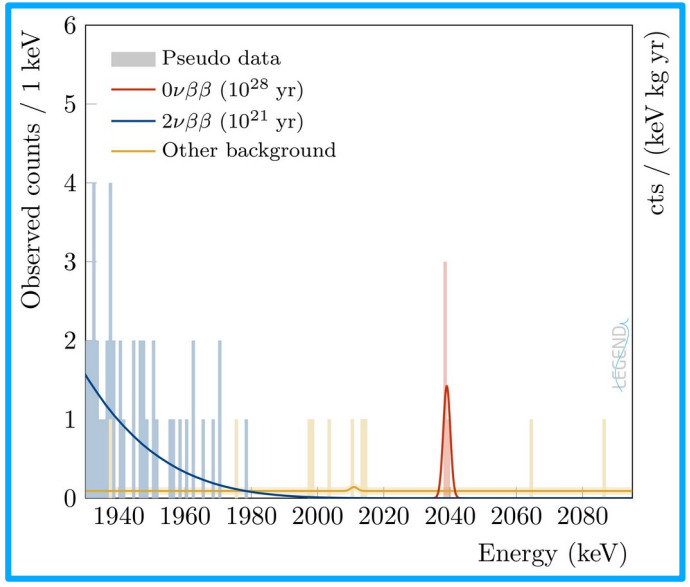
In case of no discovery,
push lower limit
2 orders of magnitude above current best



More about LEGEND

LEGEND Preconceptual Design Report

https://inspirehep.net/literature/1892243



LEGEND website

https://legend-exp.org

Chat with Sofia and me during the coffee breaks

Contact me at

mariia.redchuk@pd.infn.it

INFN PADOVA
Istituto Nazionale di Fisica Nucleare
Sezione di Padova

LEGEND
Large Enriched Germanium Experiment for Neutrinoless ββ Decay

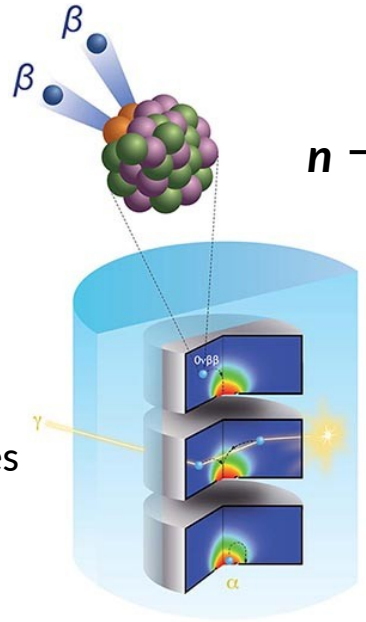
LEGEND Spring collaboration meeting 2024
@ University College London, London, UK

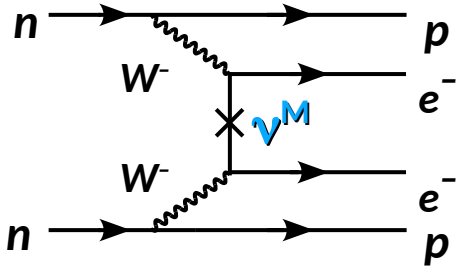
THANK YOU!

What I want you to remember about LEGEND

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

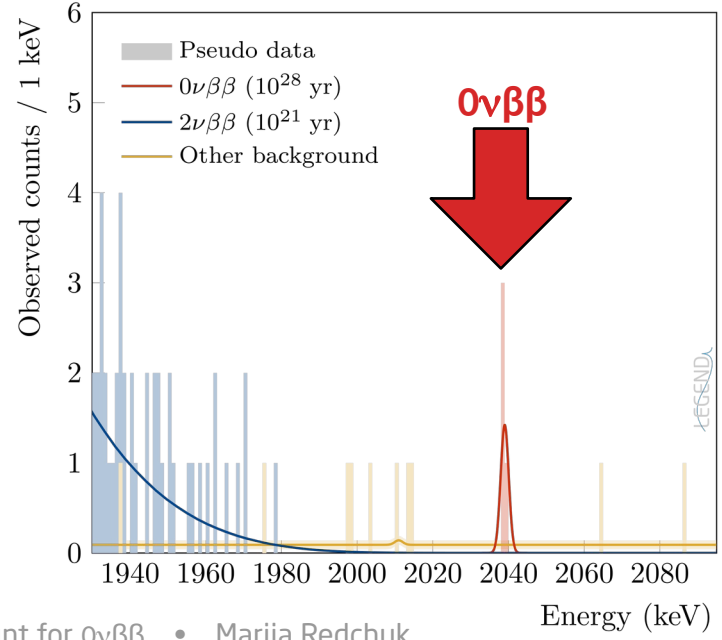
1. **Neutrinoless double beta decay (0νββ)**
   - create matter without antimatter
   - lepton number violation
   - not observed yet





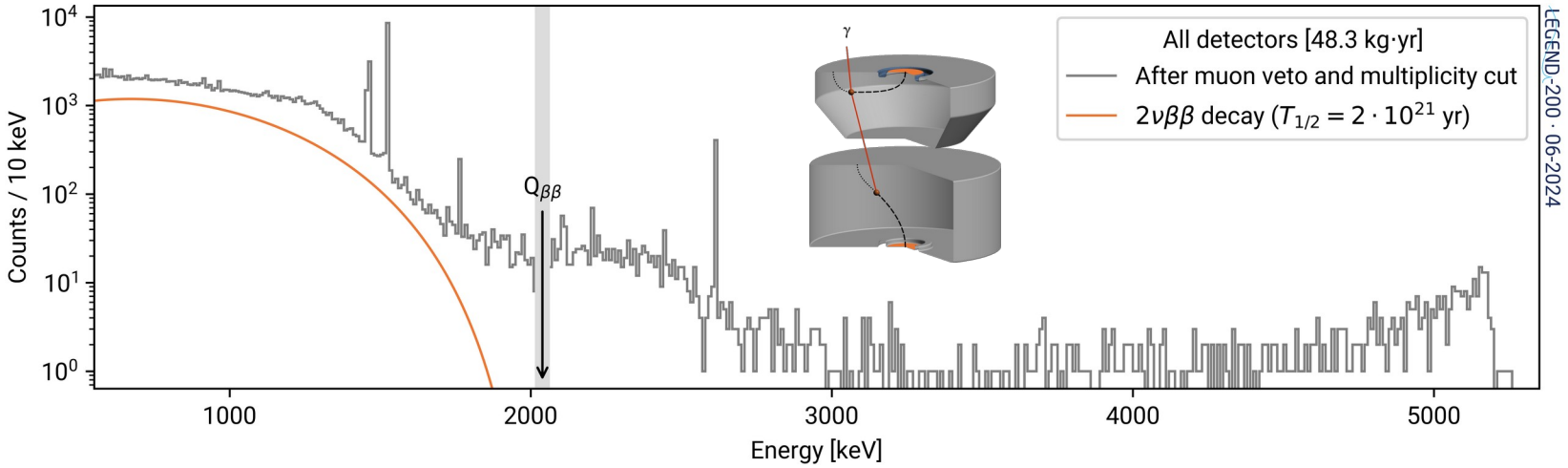
2. **Enriched germanium detectors**
   - excellent energy resolution
   - topological discrimination
   - leading material for 0νββ searches

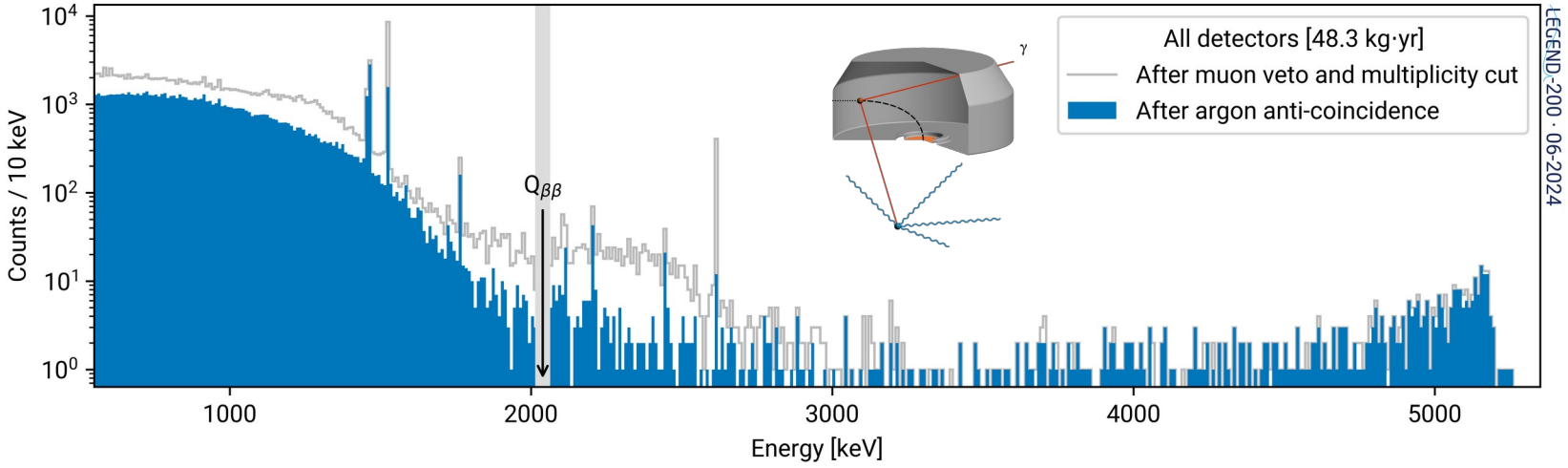
3. **The LEGEND experiment**
   - indeed **large** – 1000 kg of germanium
   - operating in **background free** regime
   - optimized for **0νββ discovery**



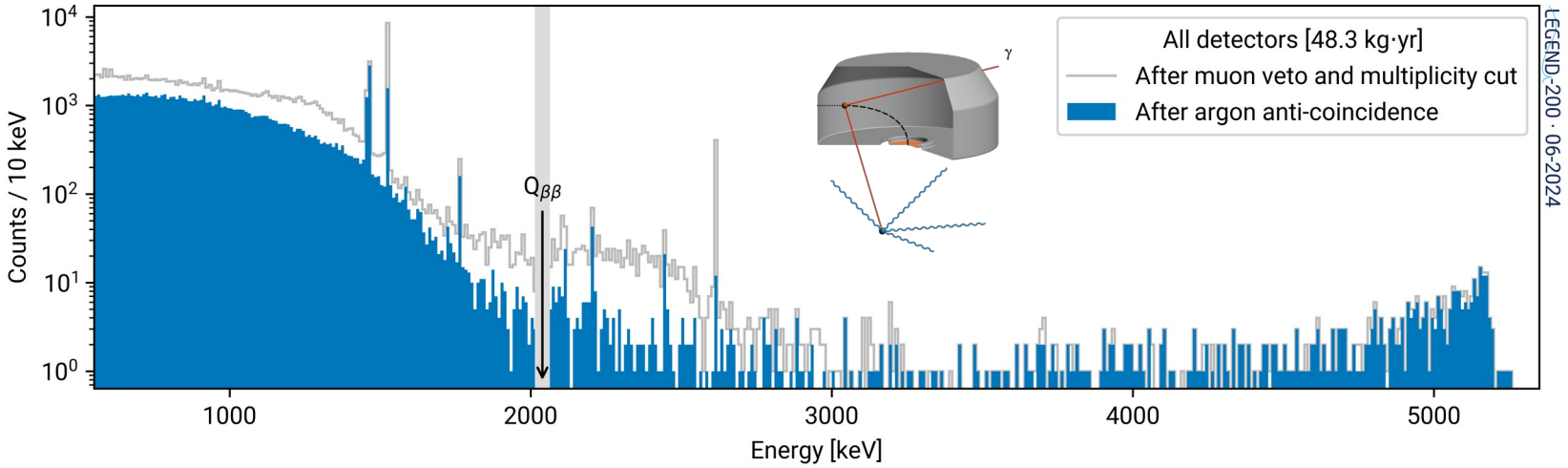
backup

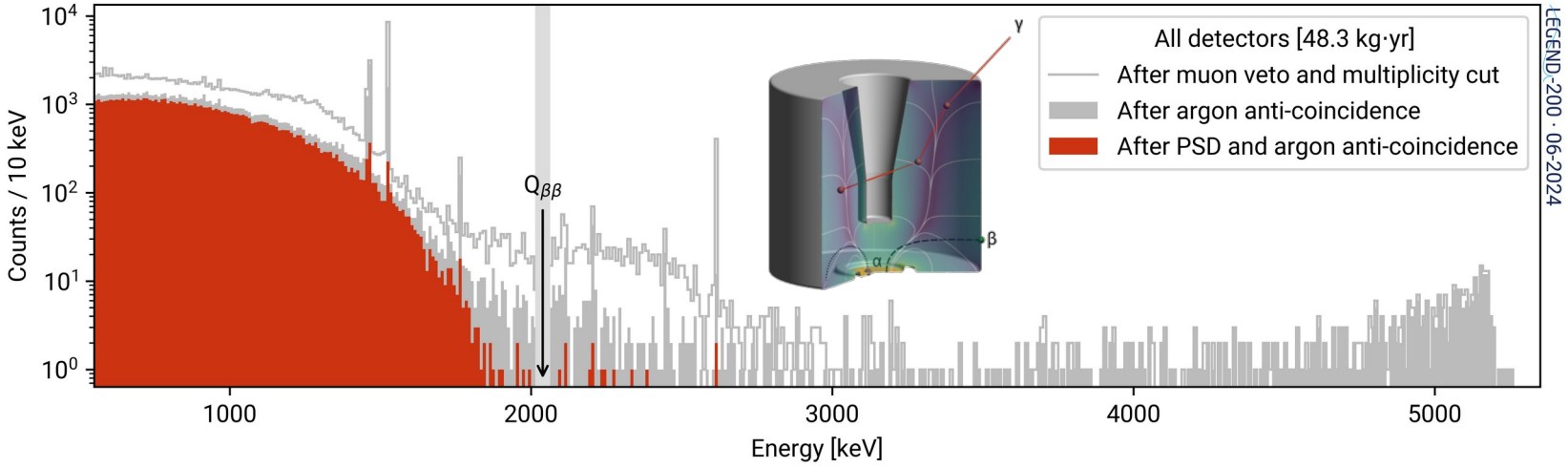
LEGEND-200 first year of physics data



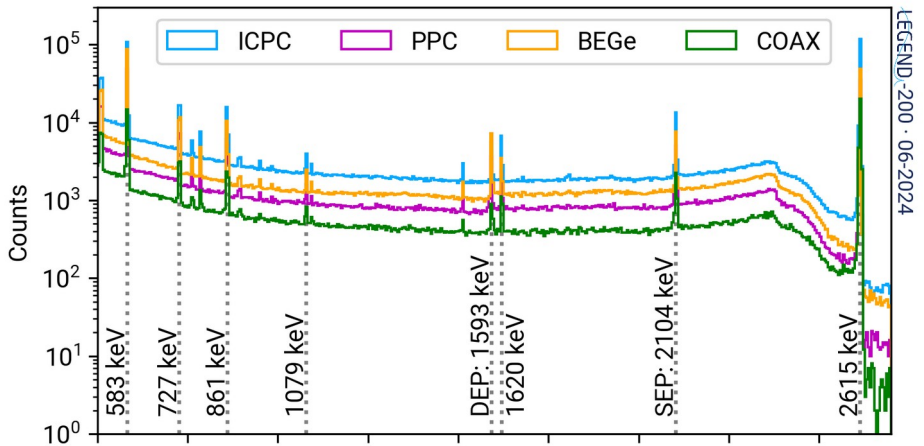


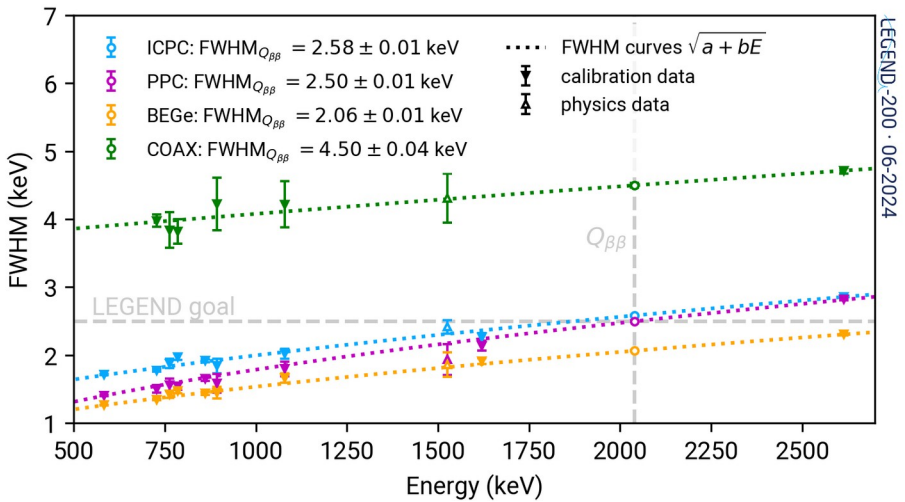
LEGEND-200 first year of physics data

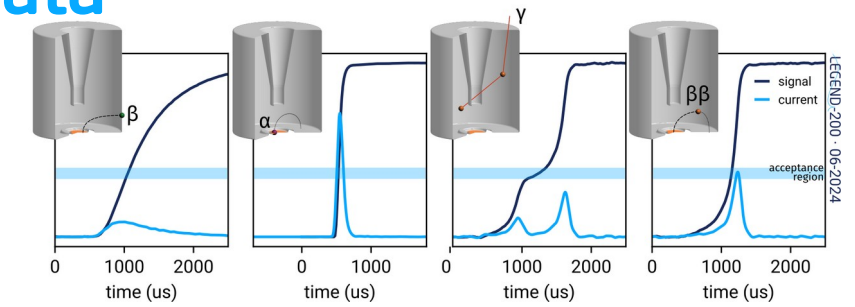


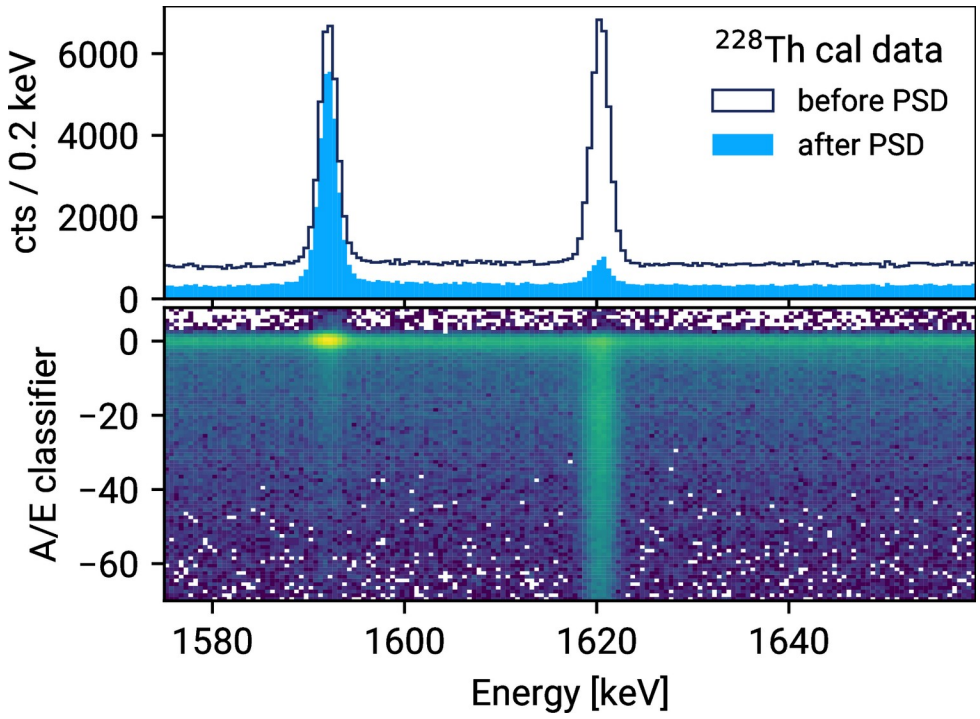


LEGEND-200 first year of physics data









LEGEND timeline

Detector characterization

Transfer of GERDA infrastructure to LEGEND

L1000 Preconceptual Design Report arXiv:2107.11462

US Department of Energy funding

L60 data taking

***L200** data taking*

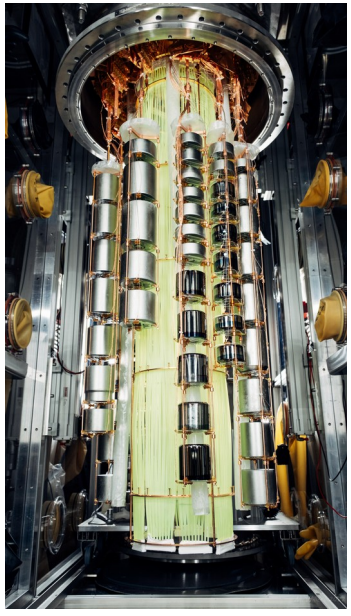
Oct 2019 — Feb 2020 — Aug 2020 — Jul 2021 — Sep 2021 — Jun 2022 — Oct 2022 — Mar 2023

Post-GERDA test @ LNGS

- infrastructure
- GERDA, MAJORANA and new detectors
- readout electronics and DAQ
- 1 month of physics data & calibrations
- ΔE = 2.2 keV @ Qββ

LEGEND-200 commissioning

- **Electronics** & **DAQ**
- **LAr veto** fibers & SiPMs
- **60 kg** of Ge det mounted
- Ge det ^{228}Th **calibration**
- ΔE ~ 2.5 keV @ Qββ
- Data monitoring & analysis tools

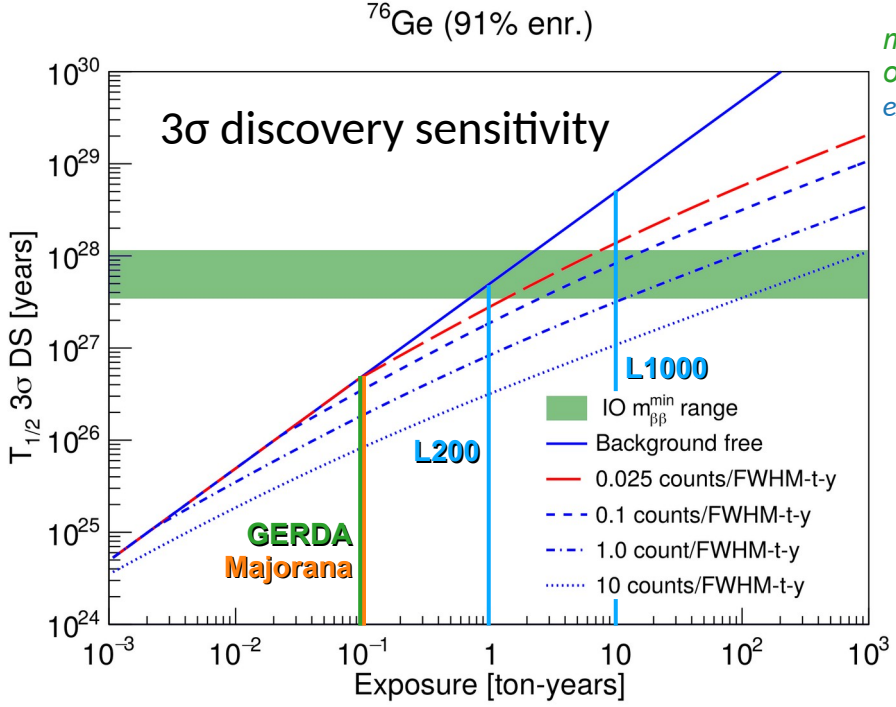


LEGEND-1000 prospects in 0νββ

Nuclear physics: decay half-life

Virtually **background free**!

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

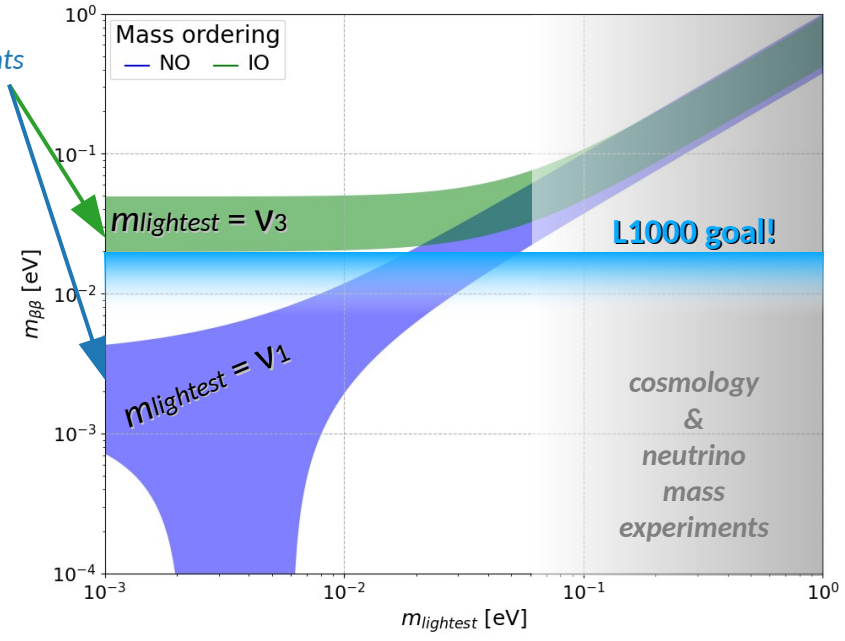


Neutrino physics: Majorana mass

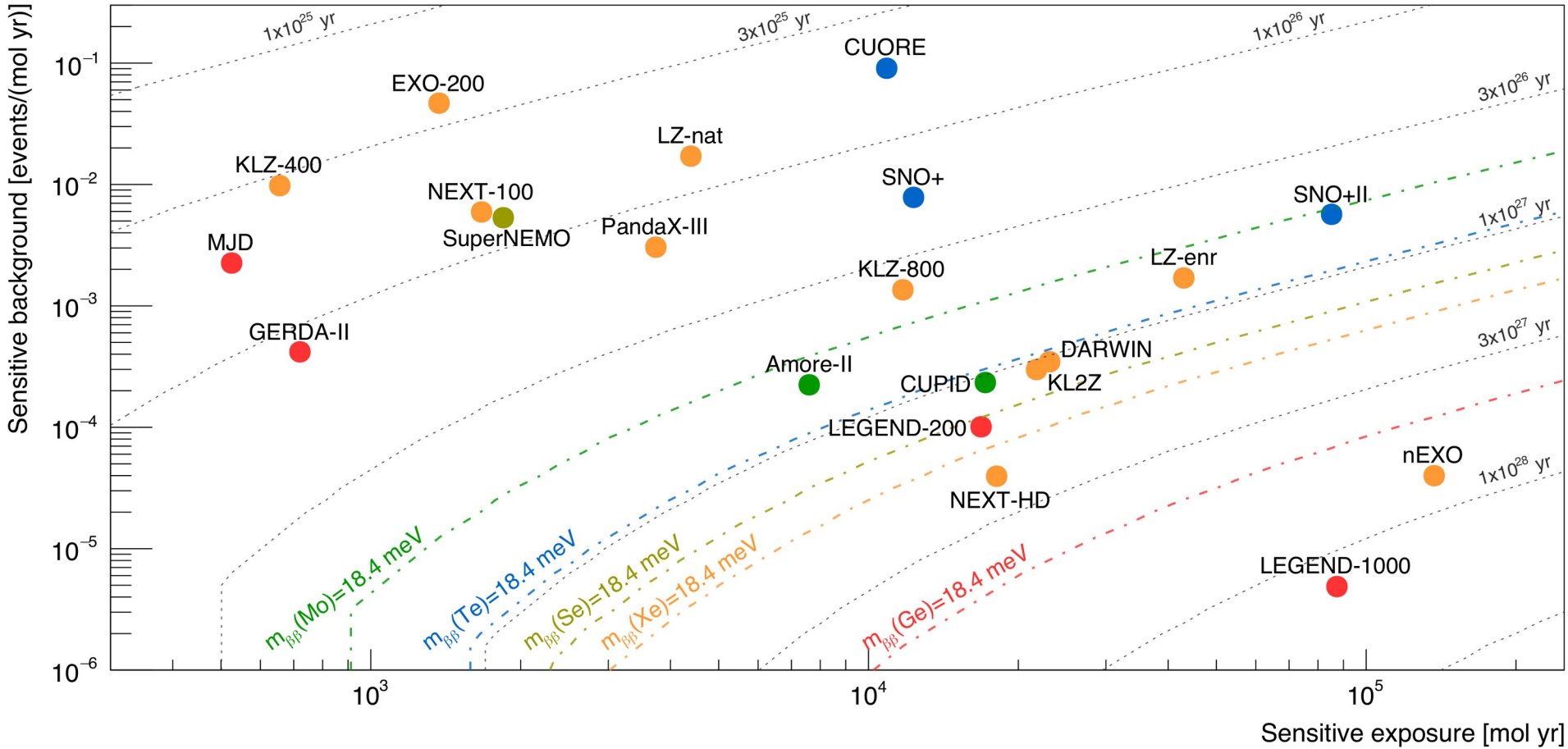
$$m_{\beta\beta}^2 = (F^{0\nu} \cdot |\mathcal{M}^{0\nu}|^2 \cdot T_{1/2}^{0\nu\beta\beta})^{-1}$$

phase space factor — nuclear matrix element

mass ordering experiments



Neutrinoless double beta decay experiments



What else can LEGEND do?

0νββ mechanisms

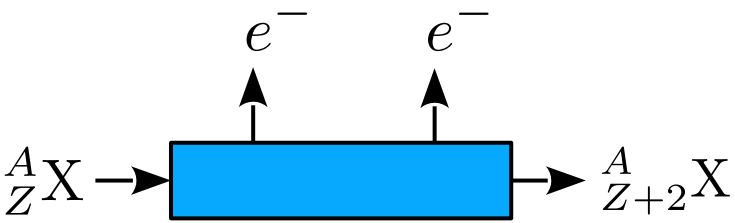
Long-range mechanisms e.g. **light Majorana neutrino**

Short-range mechanisms = **heavy particles**

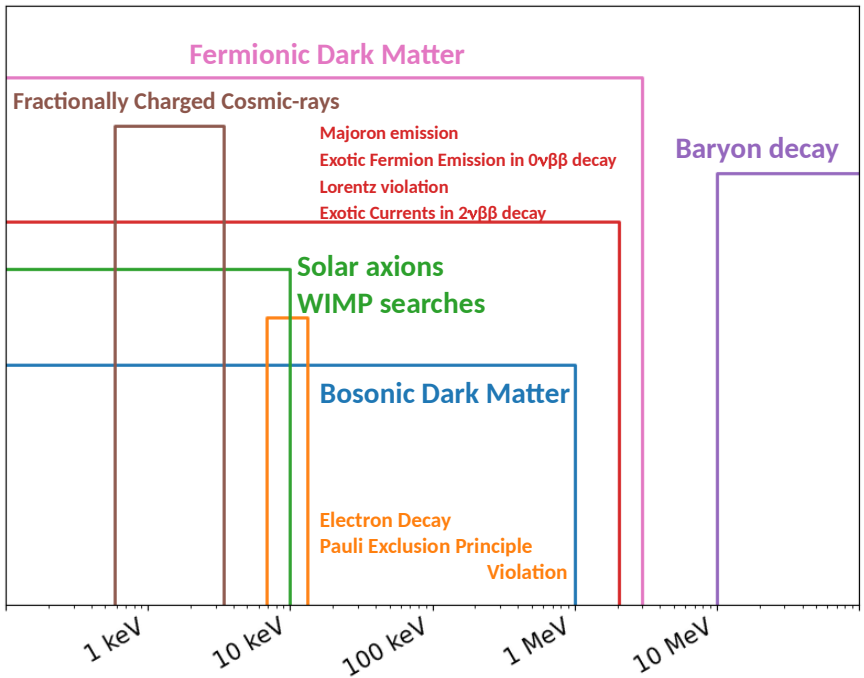
- **SUSY particles** e.g. gluions or squarks
- right-handed currents with **heavy neutrinos** or **scalar fields** e.g. some form of Higgs
- …

Multiple mechanisms at the same time could be possible

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

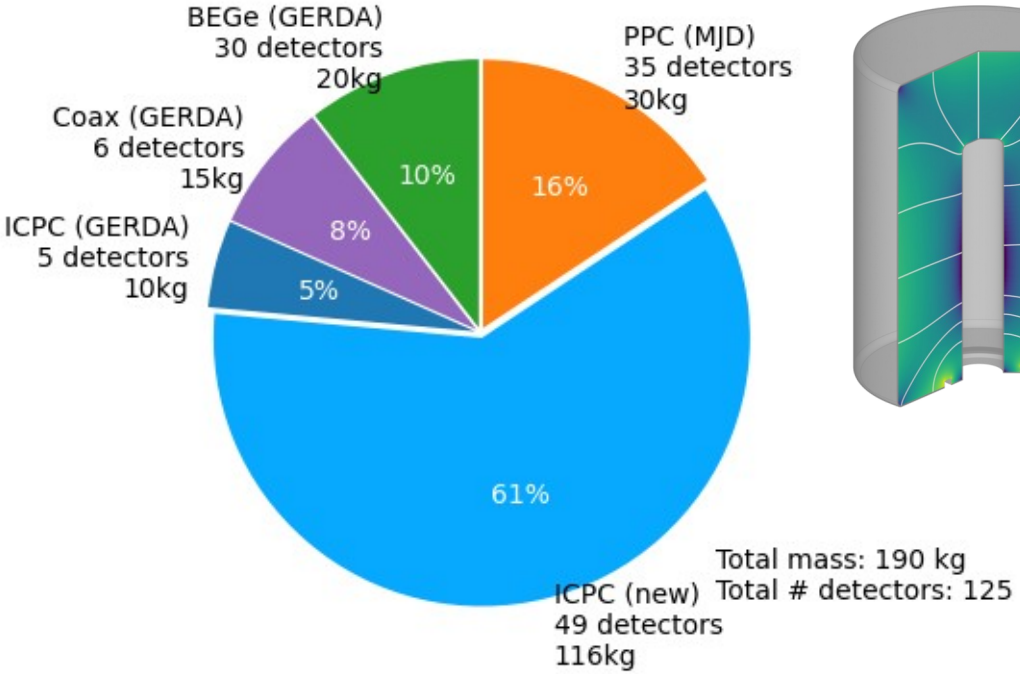


Other Beyond Standard Model searches

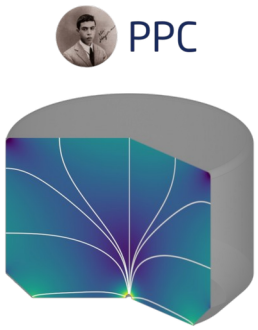


+ BSM physics in ^{36}Ar (ECEC)

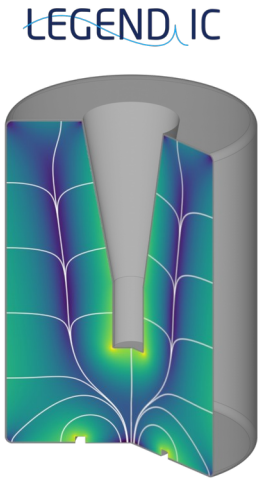
LEGEND-200 detectors



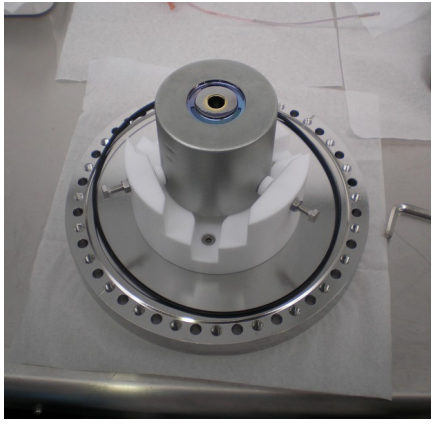
up to 1 kg



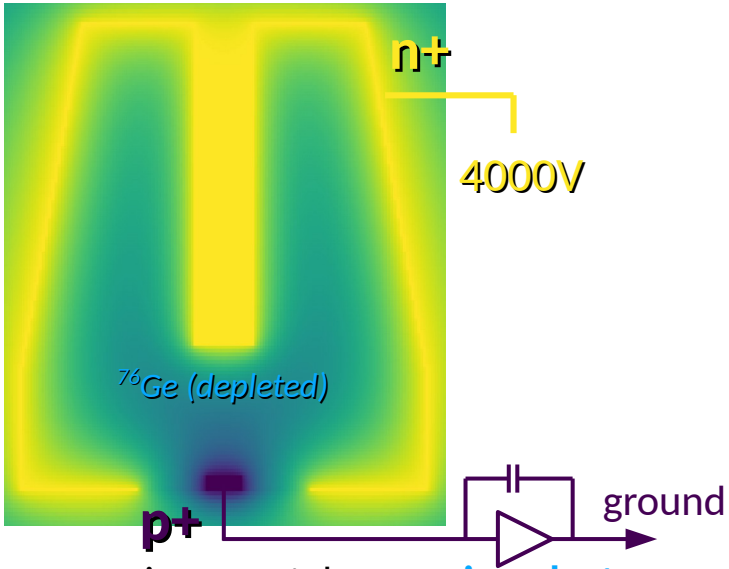
< 1 kg

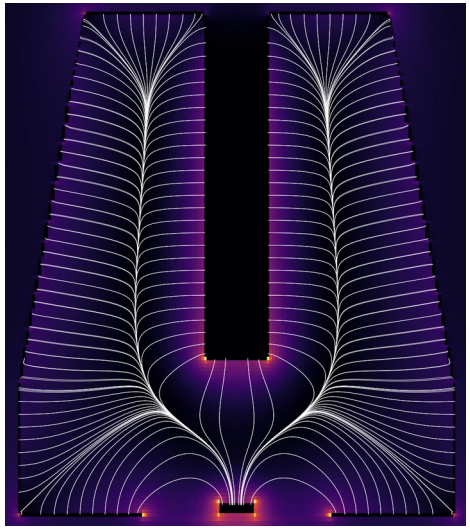


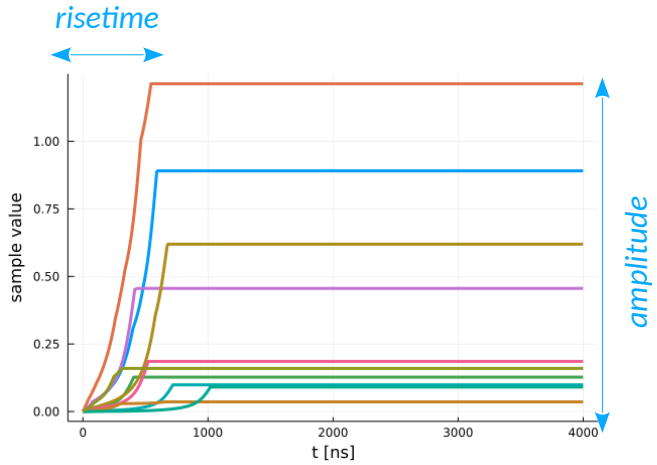
up to 4 kg



Germanium detectors







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

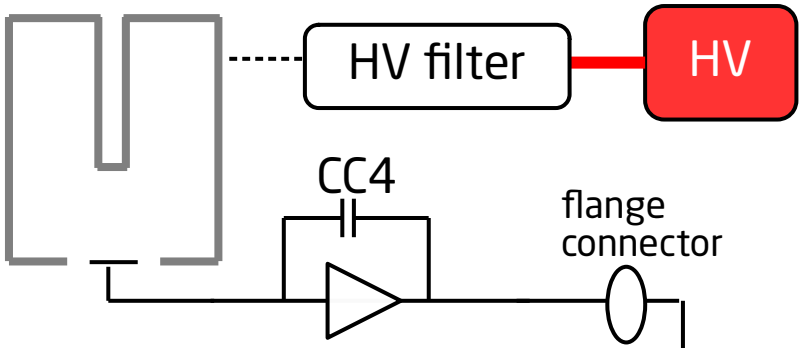
$^{76}Ge \rightarrow {}^{76}Se + 2e^- [+ 2\bar{\nu}_e]$

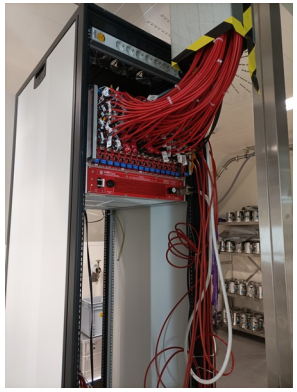
- particles deposit energy in the crystal
- **electron-hole pairs** drift towards respective contacts
- similar trajectories due to ***E field*** profile → **position-independet**

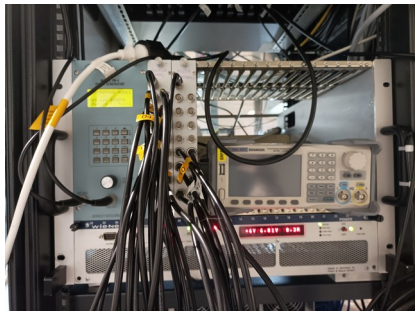
- **energy** based on pulse **risetime** and **amplitude**
- **event topology** based on the **pulse shape**

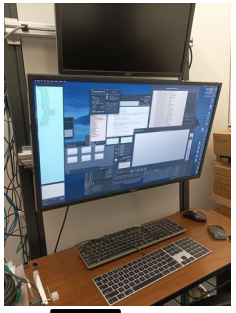
>10^5 *e-h* pairs / MeV

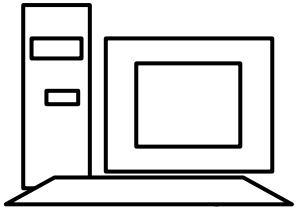
LEGEND-200 DAQ

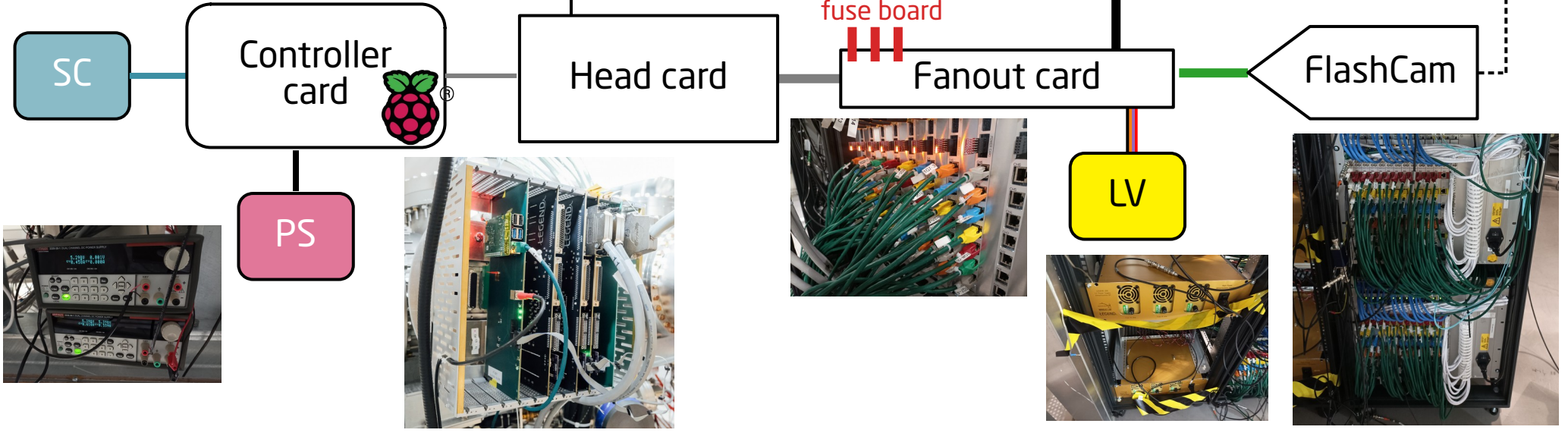








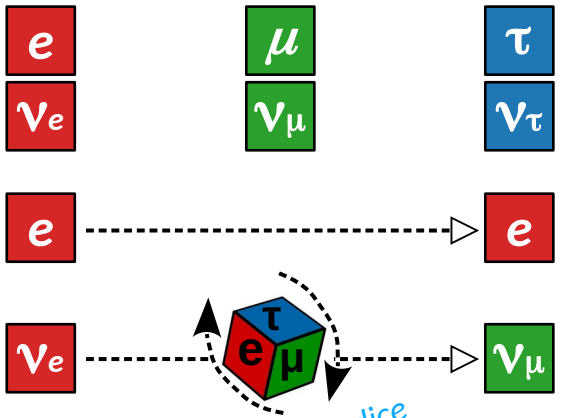


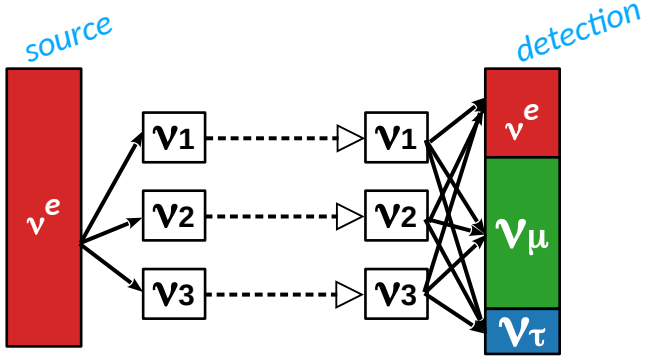


Neutrino physics recap

Neutrino oscillation

flavor change during propagation





Neutrino mixing matrix

mathematical formalism & measurable parameters

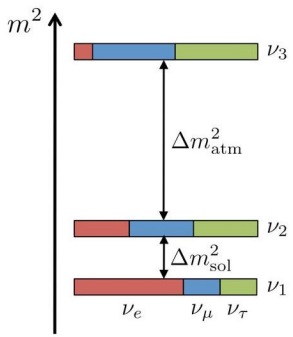
$$\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix} \begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

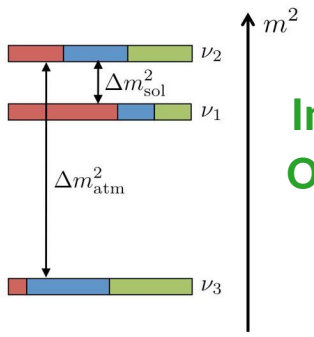
propagate in space — mixing matrix — interact weakly

Neutrino mass ordering

which mass state is the lightest?

Normal Ordering (NO)



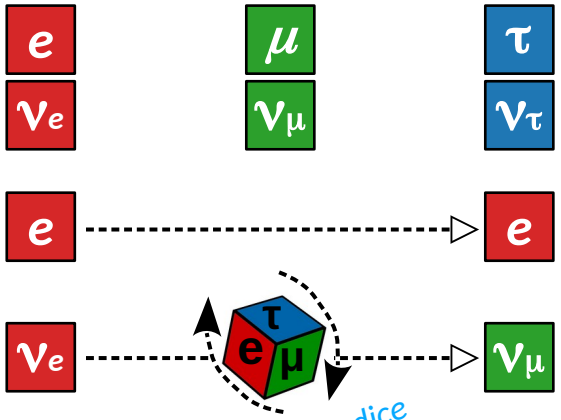


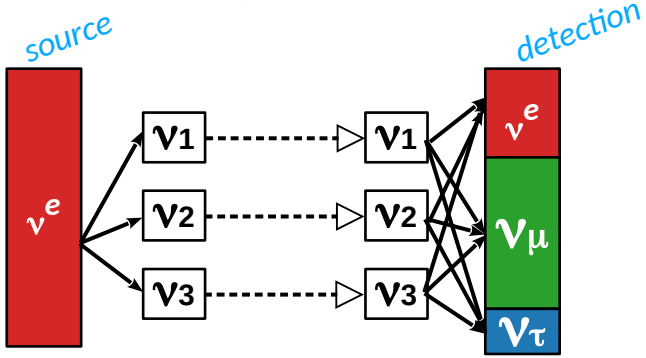
Inverted Ordering (IO)

Neutrino physics recap

Neutrino oscillation

flavor change during propagation





Neutrino mixing matrix

mathematical formalism & measurable parameters

new mixing matrix

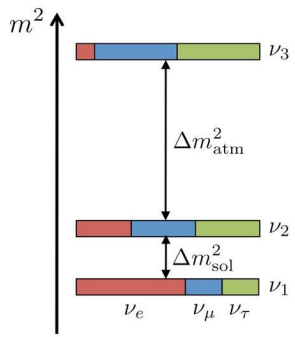
$$\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix} \begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\alpha_1} & 0\\ 0 & 0 & e^{i\alpha_2}\end{pmatrix} \begin{pmatrix}\nu_e\\ \nu_\mu\\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

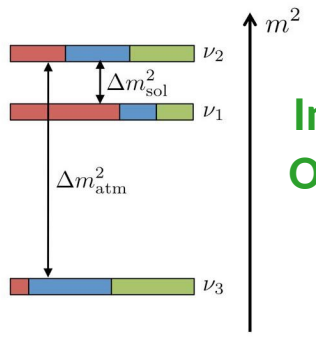
propagate in space — *mixing matrix* — **Majorana phases** — *interact weakly*

Neutrino mass ordering

which mass state is the lightest?

Normal Ordering (NO)





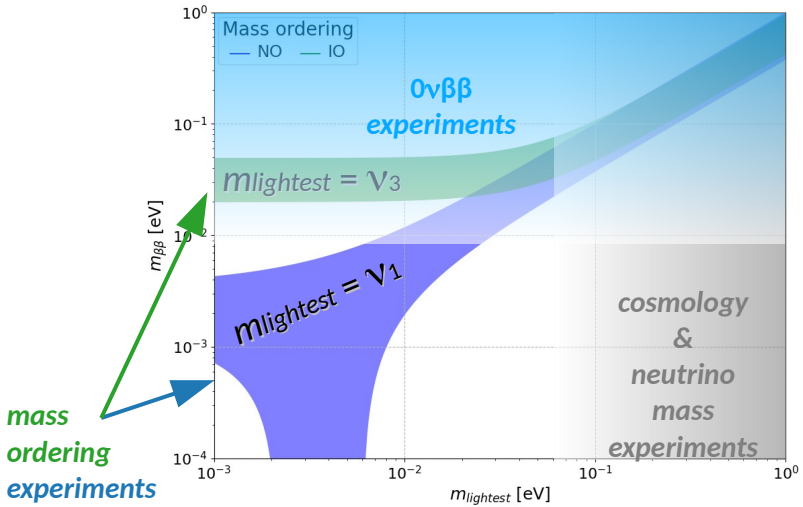
Inverted Ordering (IO)

Back to neutrinoless double beta decay

Neutrino physics

mixing matrix (Majorana phases)

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



Nuclear physics

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 @ Qββ

Connection

phase space factor

nuclear matrix element

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

Neutrino observables

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

Effective Majorana mass

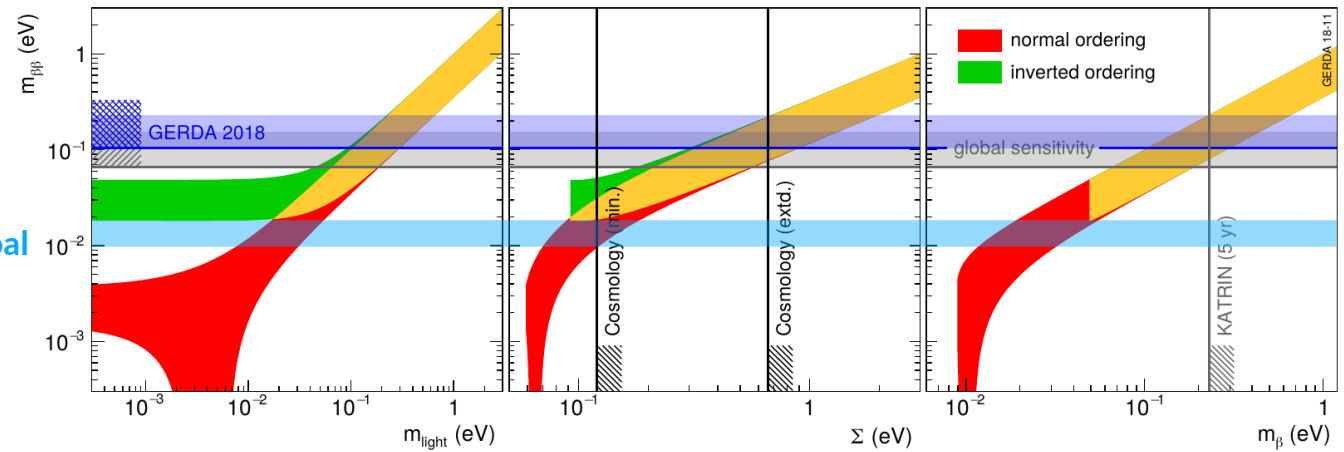
$$m_\beta = \sqrt{\sum m_i^2 |U_{ei}|^2}$$

“Incoherent sum” of νe mass eigenstates
(“mass of electron neutrino”)

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

Sum of neutrino masses
cosmological/astrophysical observable

LEGEND goal



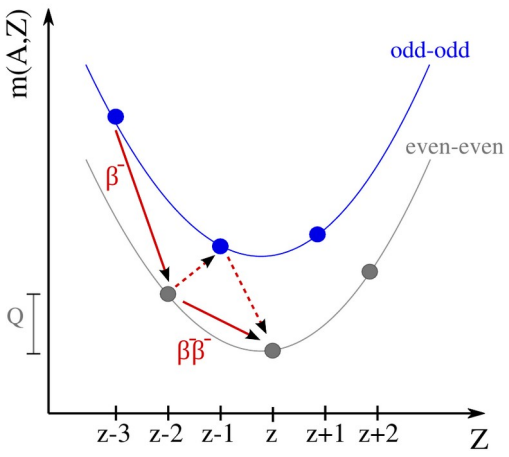
Dirac vs Majorana neutrino

			Probability to produce lepton	
	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	$1-\left(\frac{m_\nu}{2E}\right)^2$	$\left(\frac{m_\nu}{2E}\right)^2 \approx 0$
Majorana $\bar{\nu}$	$\bar{\nu}_R^M = \nu_R^M$	R	$\left(\frac{m_\nu}{2E}\right)^2 \approx 0$	$1-\left(\frac{m_\nu}{2E}\right)^2$

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

Majorana: they are simply just ν_L and ν_R

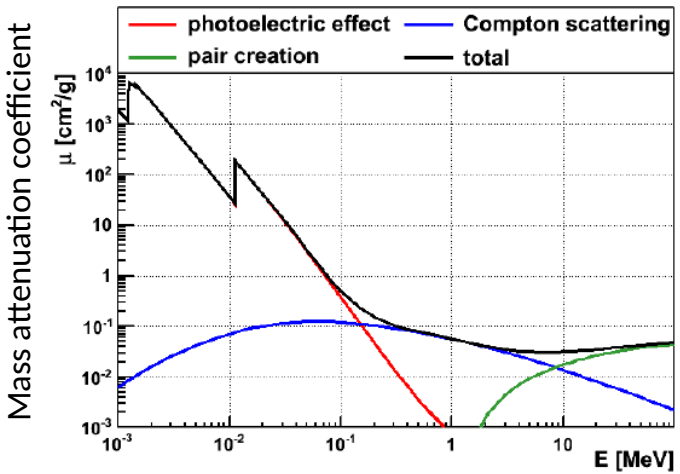
Two-neutrino double beta decay

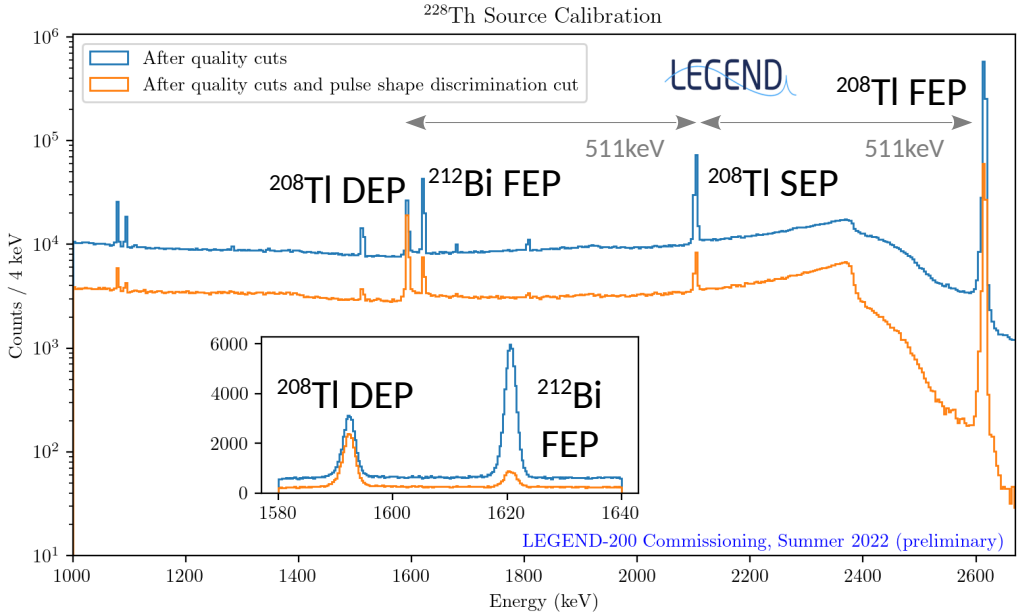


- **35** naturally occurring isotopes which can decay through **2νβ-β-** with forbidden or suppressed β- decay
- Only **6** for **2νβ+β+**, small Q values and much longer livetimes
- Most precise measurement of 2νββ half-life in the world by GERDA

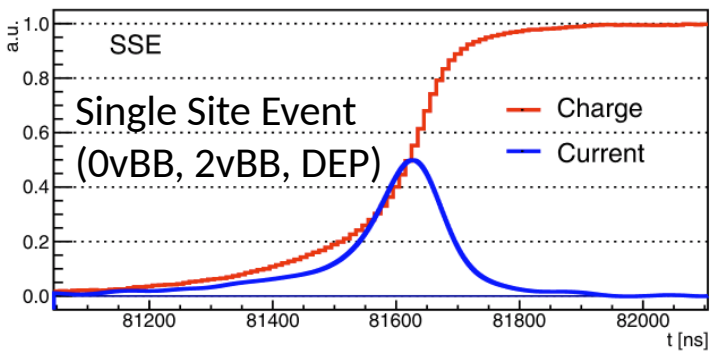
$$T^{2\nu}_{1/2}(^{76}\mathrm{Ge}) = (2.043 \pm 0.033_{stat+sys}) \cdot 10^{21}\mathrm{yr}$$

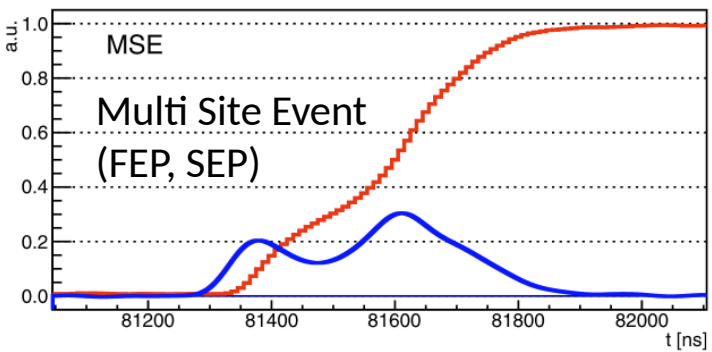
Signal VS background events





FEP = Full energy Peak
SEP = Single Escape Peak
DEP = Double Escape Peak





Pulse shape discrimination