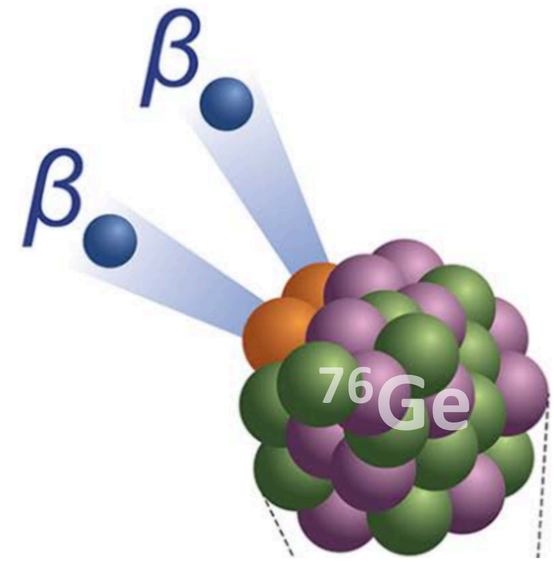
# Probing new physics via extremely rare decay search with GERDA and LEGEND

**Yoann KERMAÏDIC**

LPSC seminar
Grenoble

23 January 2020



# Crucial open issues in particle physics

**Number of baryons / antibaryons**
*(matter) / (antimatter)*

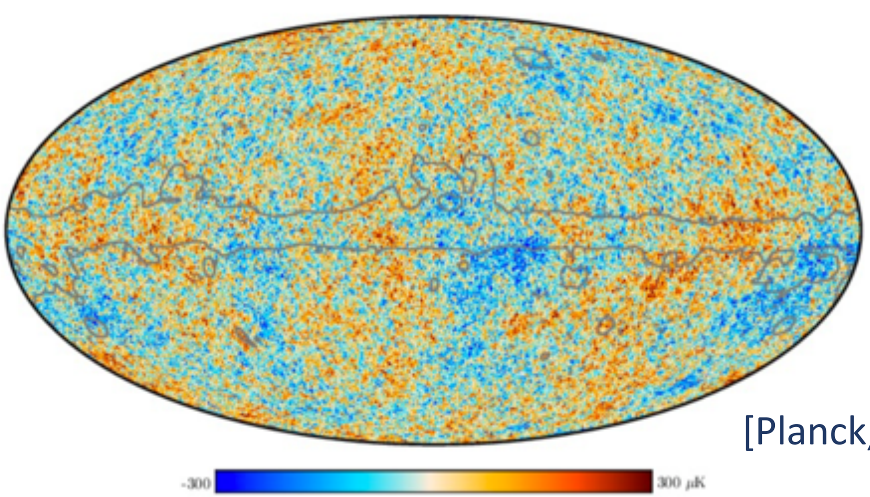
**Baryonic asymmetry of the Universe**

$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} = \begin{array}{ll} (6.122 \pm 0.063)\times 10^{-10} & \text{[Planck, 2018]} \\ (6.119 \pm 0.100)\times 10^{-10} & \text{[Cooke, 2018]} \end{array}$$

**Number of photons**
*(light)*

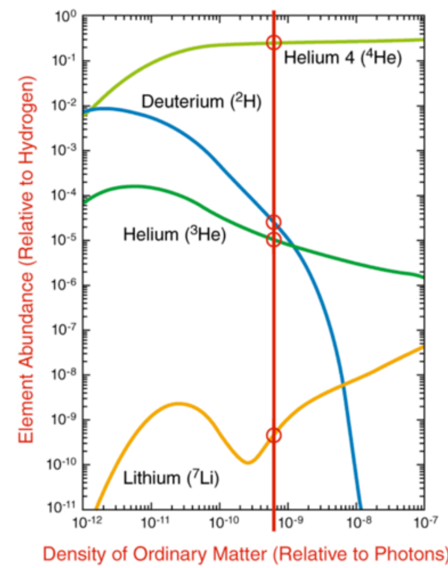
Among many theoretical BSM models: the **leptogenesis!?**

**Cosmic Microwave Background**




[Planck, 2018]

**Element abundance of the Universe**




[Cooke, 2014]

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**Non-zero but tiny neutrino masses**

**See-saw** mechanism?

- requires neutrinos to be **Majorana** - **Lepton Number is violated** in general
- new mass term in the Lagrangian **explaining the smallness of masses**
- provides a mechanism for **effective leptogenesis**

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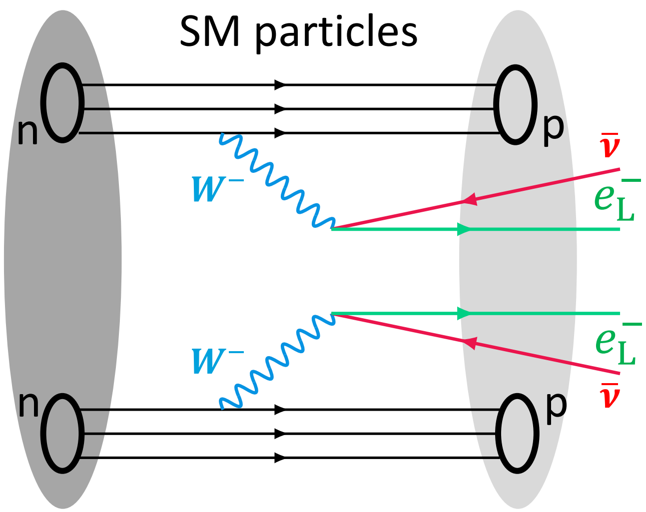
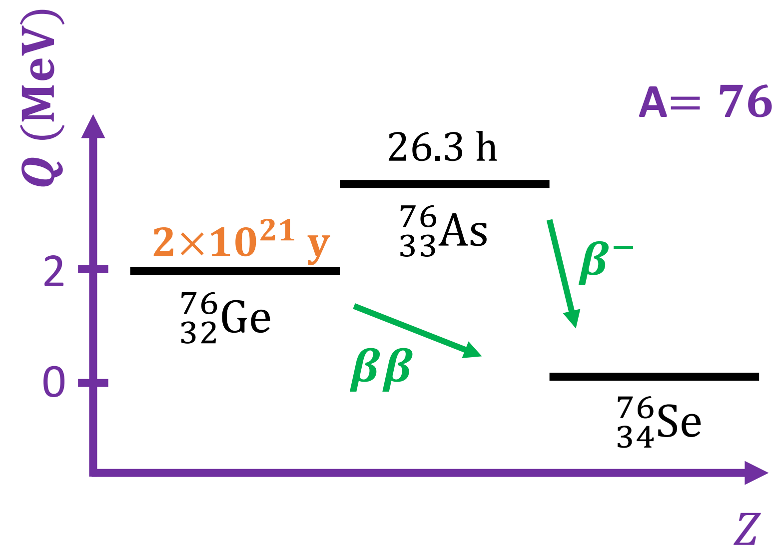
**HOW TO RELATE THIS TO $^{76}$Ge?**

# Two neutrinos double beta decay - $2\nu\beta\beta$



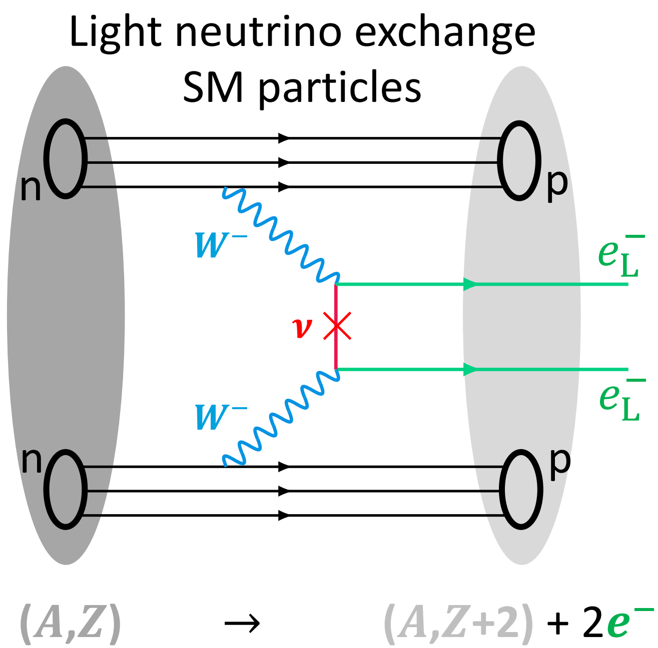

$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}$

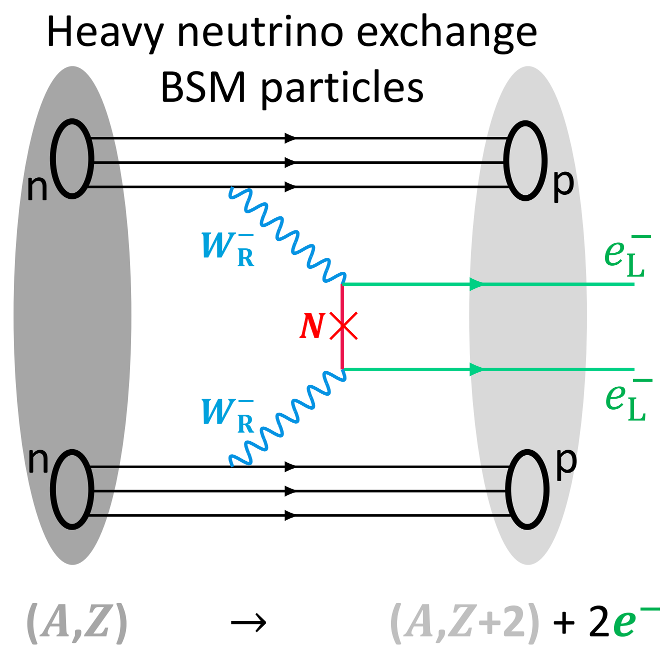



Such process:

- ✓ energetically favored in some isotopes ($^{76}$Ge, $^{82}$Se, $^{100}$Mo, $^{130}$Te, $^{136}$Xe, …)
- ✓ is predicted by the SM [Goppert-Mayer – 1935]
- ✓ is measured experimentally

# Neutrinoless double beta decay - $0\nu\beta\beta$



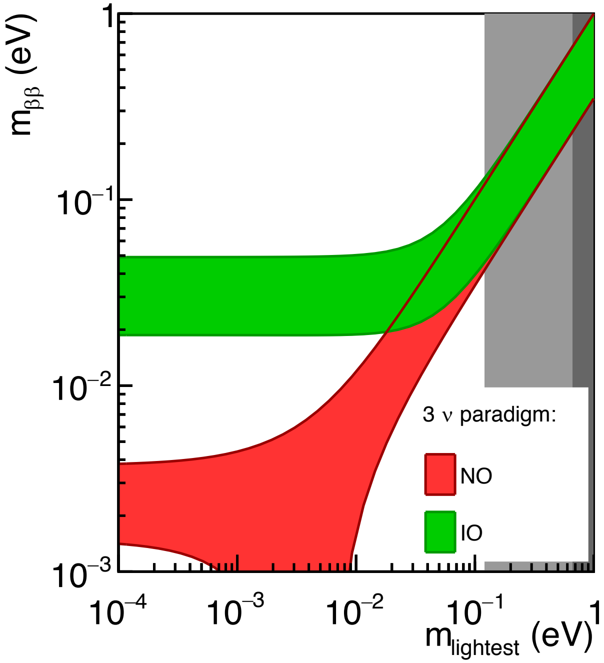




Such process:

- ✓ **violates the Lepton Number** by 2 units = New Physics!
- ✓ determines the nature of neutrinos: **Majorana particle** $\boldsymbol{\nu = \bar{\nu}}$ [Valle – 1982]
- ✓ gives information on the $\nu$ mass via $m_{\beta\beta}$ (light neutrino exchange scenario)
- ∞ has never been observed so far

➢ High sensitivity due to the Avogadro number: $\sim 10^{25}$ Ge nuclei / kg

# « Light neutrino exchange »




$$ {T^{0\nu}_{1/2}}^{-1} = g_A^4 \, G^{0\nu} \, \left|M^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} $$

| | |
|---|---|
| $T^{0\nu}_{1/2}$ | experimentally probed half-life |
| $g_A$ | axial vector coupling cnst = 1.25(?) |
| $M^{0\nu}$ | nuclear matrix element (NME) |
| $G^{0\nu}$ | phase space factor |
| $m_e$ | electron mass |

Challenges

Mass hierarchy not yet probed conclusively by T2K NOvA

- Attractive: Minimal model without requiring new particles (mediator = active $\nu$)

$$ m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right| $$

$U$ = PMNS matrix [NuFit 19']

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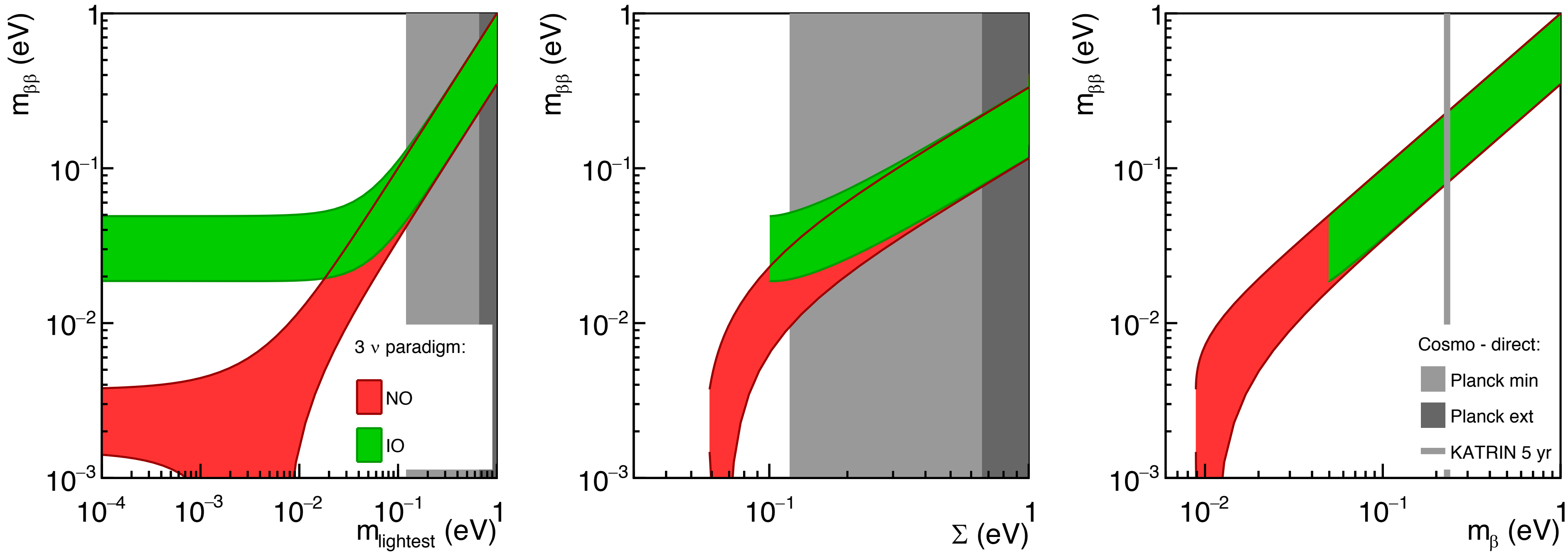


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$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right| \qquad \Sigma = \sum_{i=1}^{3} m_i \qquad m_\beta = \sqrt{\left| \sum_{i=1}^{3} U_{ei}^2 m_i^2 \right|}$$

$U$ = PMNS matrix [NuFit 19']

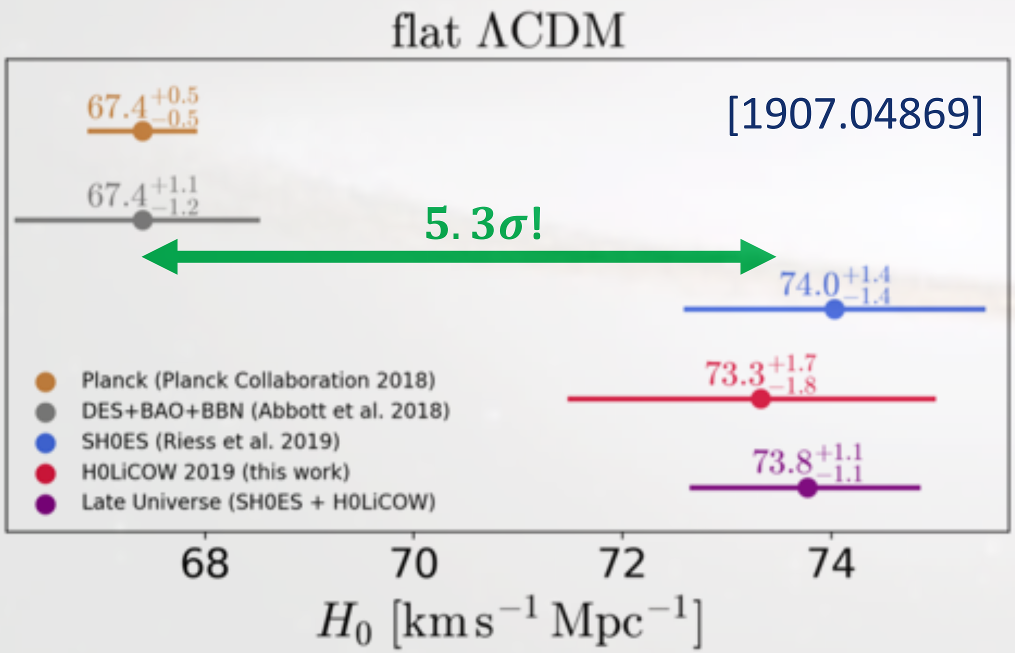
- Direct relationship with the cosmological neutrino mass sum and direct mass measurement
- Rich complementarity in case of non-zero measurement in one of the channels

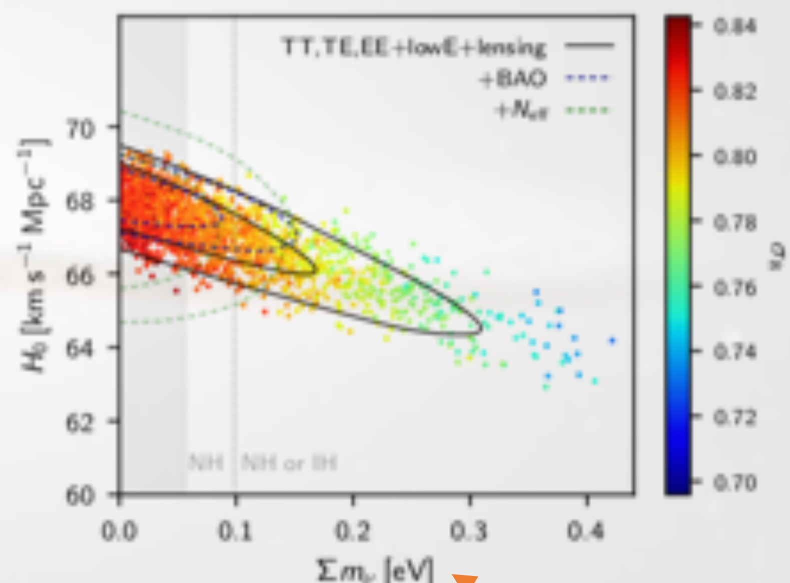
NB: Hubble constant "problem" shows some limitations

# Cosmological detour : H0 « problem »

- H0 = Hubble constant in [km/s/Mpc], measuring how fast the Universe is expanding
- Special workshop organized in July 2019 to review all the H0 measurements:
  “ **Tensions between the Early and the Late Universe”**
  all the slides at http://online.kitp.ucsb.edu/online/enervac-c19/

[Planck, 1807.06209]

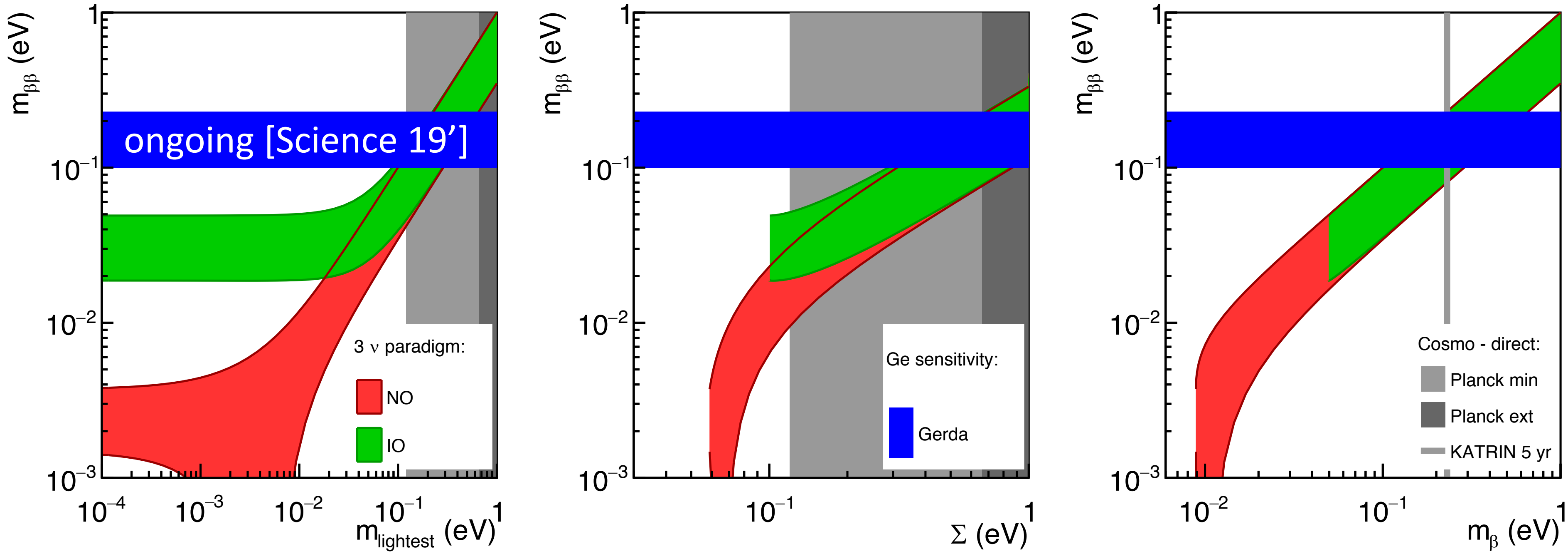



the evidence. Most attendees voted for a Hubble constant “problem” with tails in favor of both “tension” and “crisis” and with no support for something less. Therefore it appears that the issue is serious, not only taking the uncertainties at face value, but also in the eyes of the community as represented by the KITP workshop participants.

- directly connected to the previous plots
- phenomenology not 100% under control
- models dependence

# « Light neutrino exchange »

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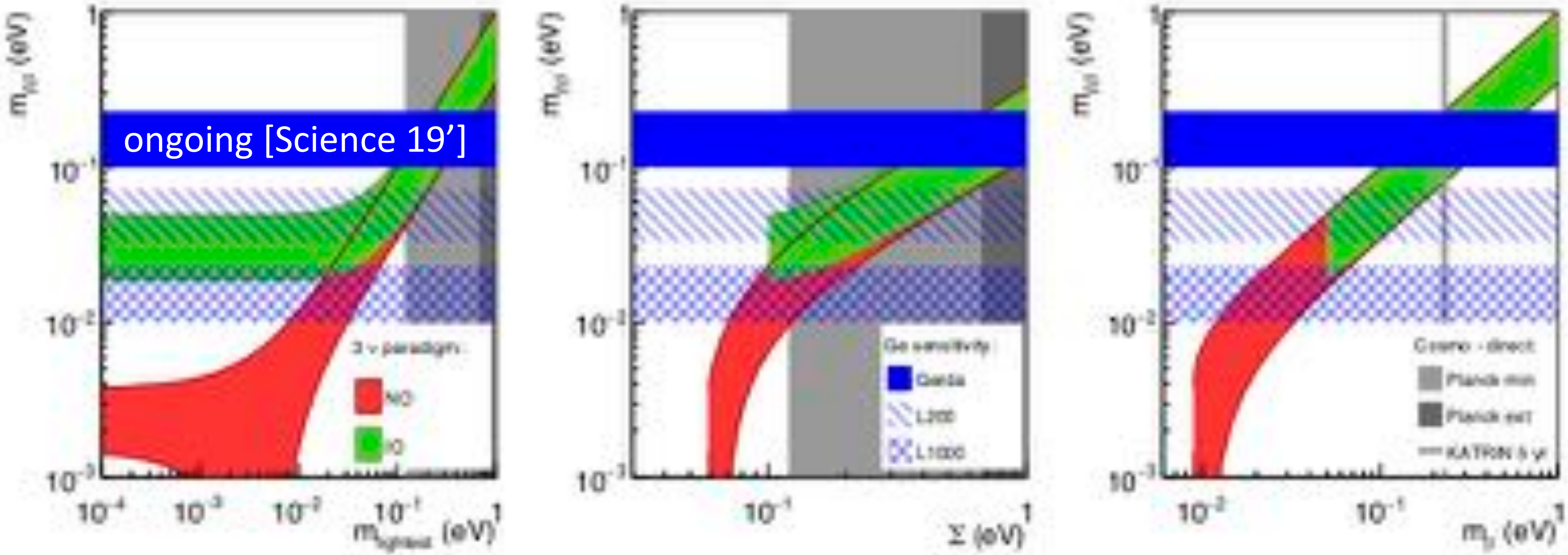


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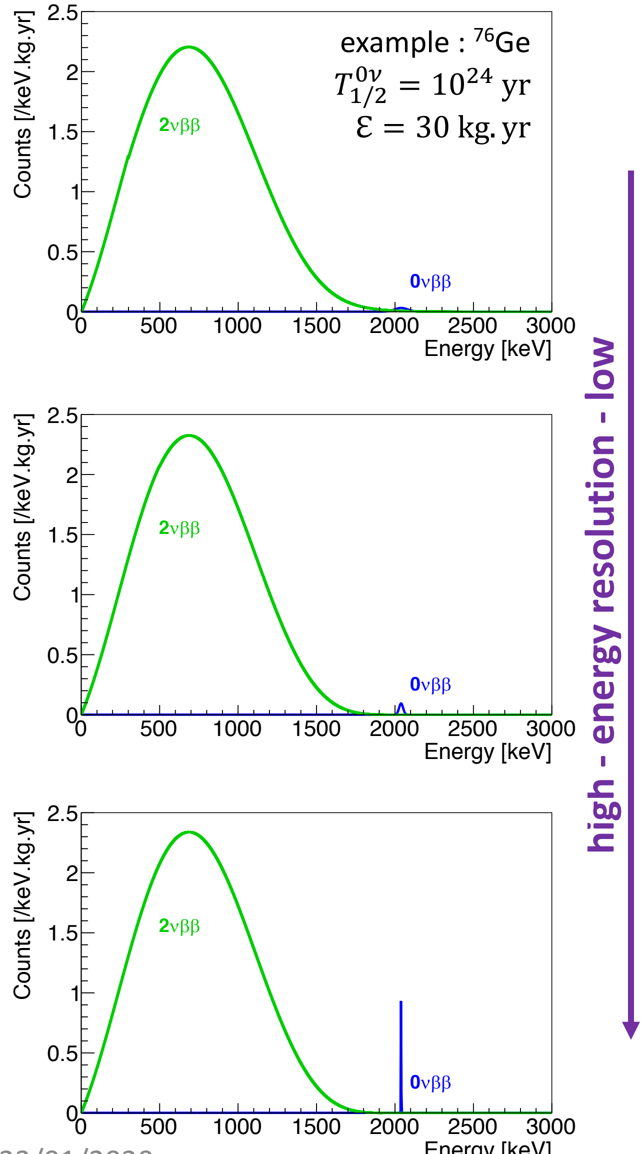
# $0\nu\beta\beta$ decay experimental signature



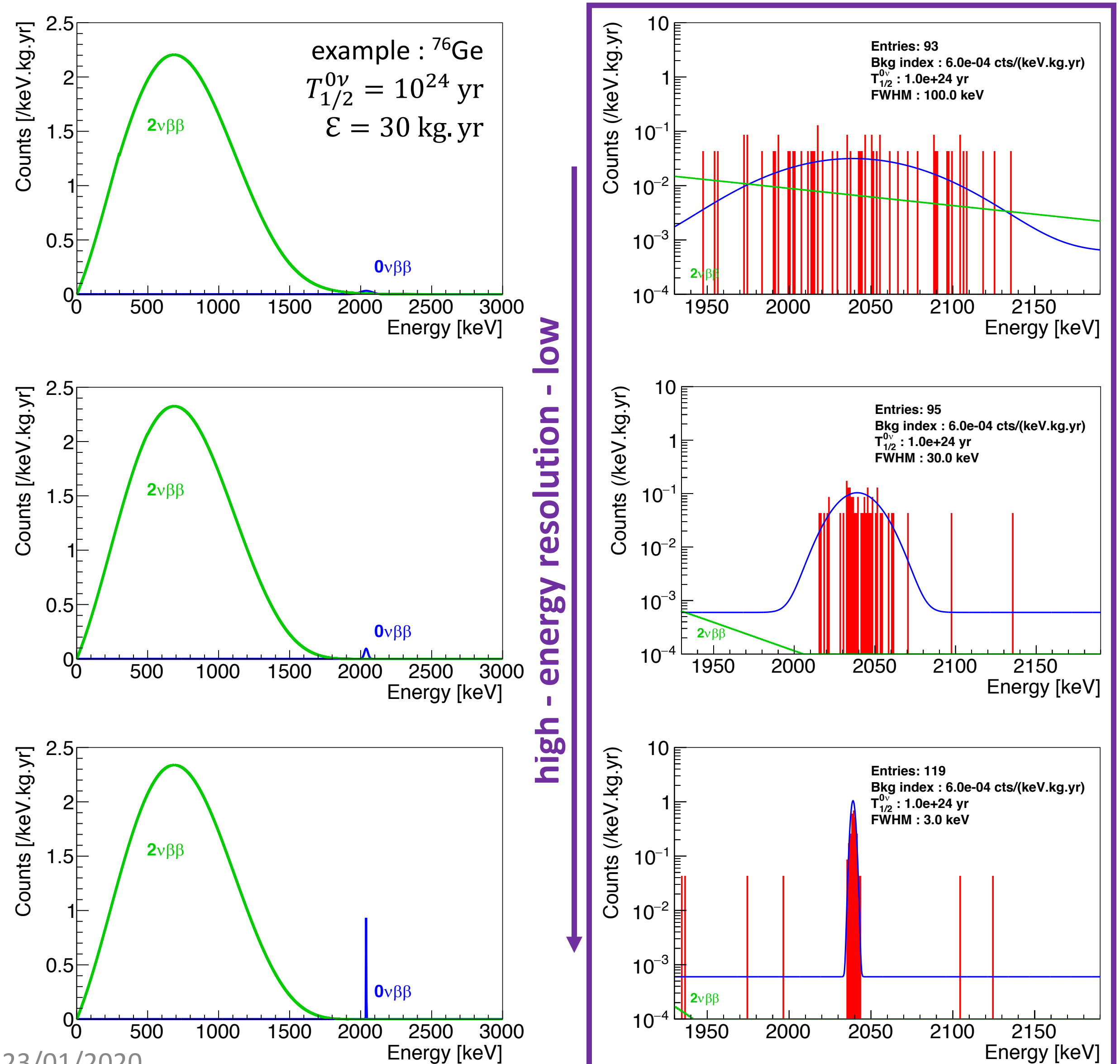

- $2\nu\beta\beta$ continuum + peak at $Q_{\beta\beta}$

- $T^{0\nu}_{1/2} = \ln 2 \,.\, \frac{N_A}{m_A} \,.\, \epsilon \,.\, \mathcal{E} \,.\, \frac{1}{N^S}$

- **Key points:**
  - Avogadro number: $N_A$
  - Efficiency [%] x exposure [kg.yr]: $\epsilon \,.\, \mathcal{E}$
  - Energy resolution [keV]
  - $\mathrm{BI} = \frac{N^B}{\mathcal{E} \,.\, \Delta E}$ [cts/(keV.kg.yr)]

- **Topology :**
  - Signal = *Single-Site Event (SSE)*
  - Background $\gamma$ = *Multi-Site Event (MSE)*
    $\alpha/\beta$ = *Surface Event*

# $0\nu\beta\beta$ decay experimental signature



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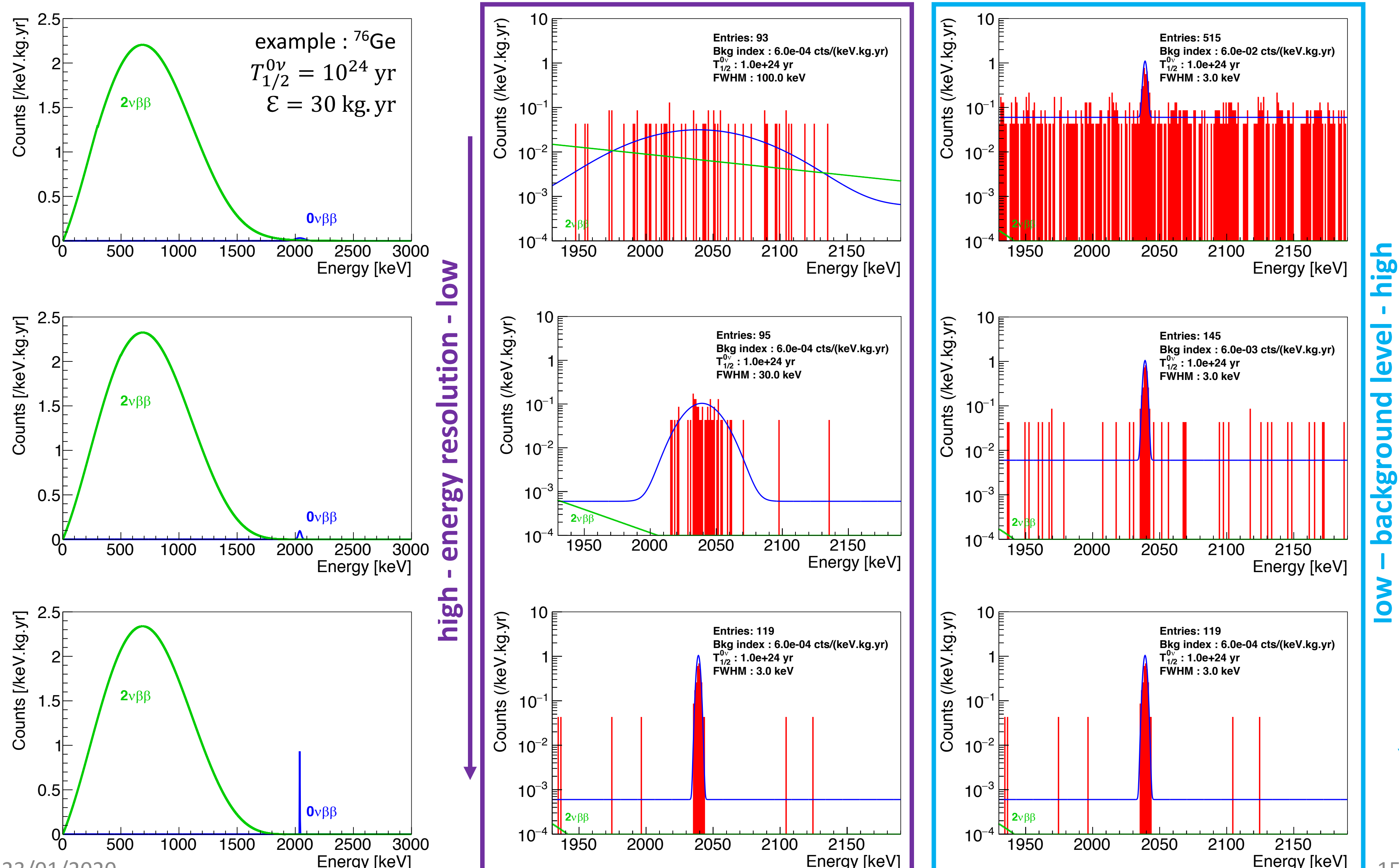

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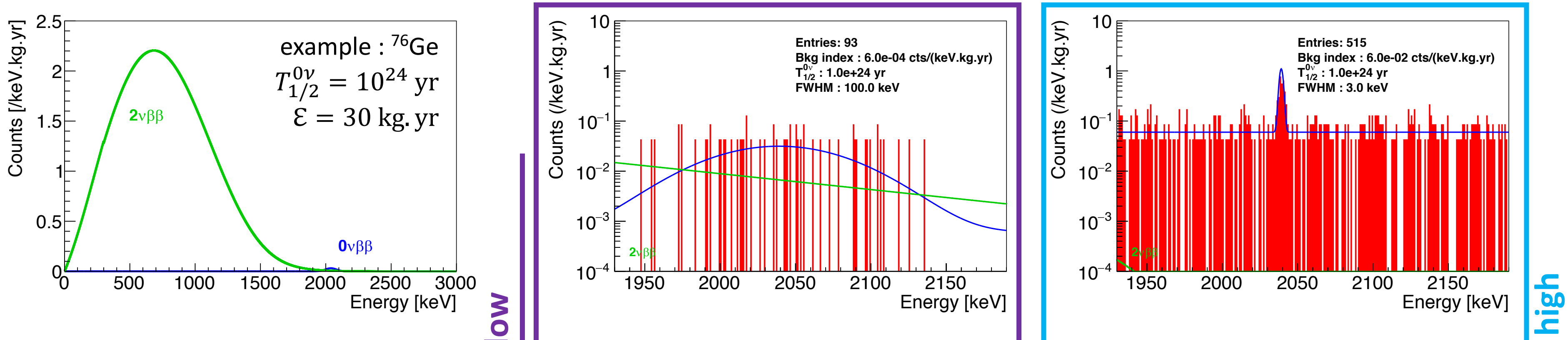
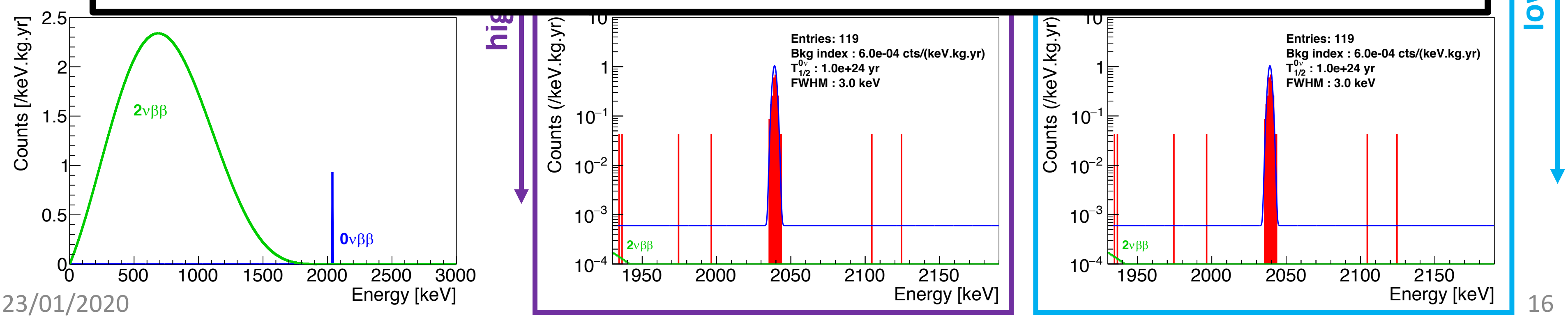



**Two statistical notions scrutinized:**

*see detailed discussion in: [1705.02996]*

- sensitivity for limit setting (90% C.L.)
  « *limit on the signal strength assuming no signal* »

- $3\sigma$ discovery potential sensitivity
  « *minimal signal strength for which a discovery is expected with 3σ C.L.* »

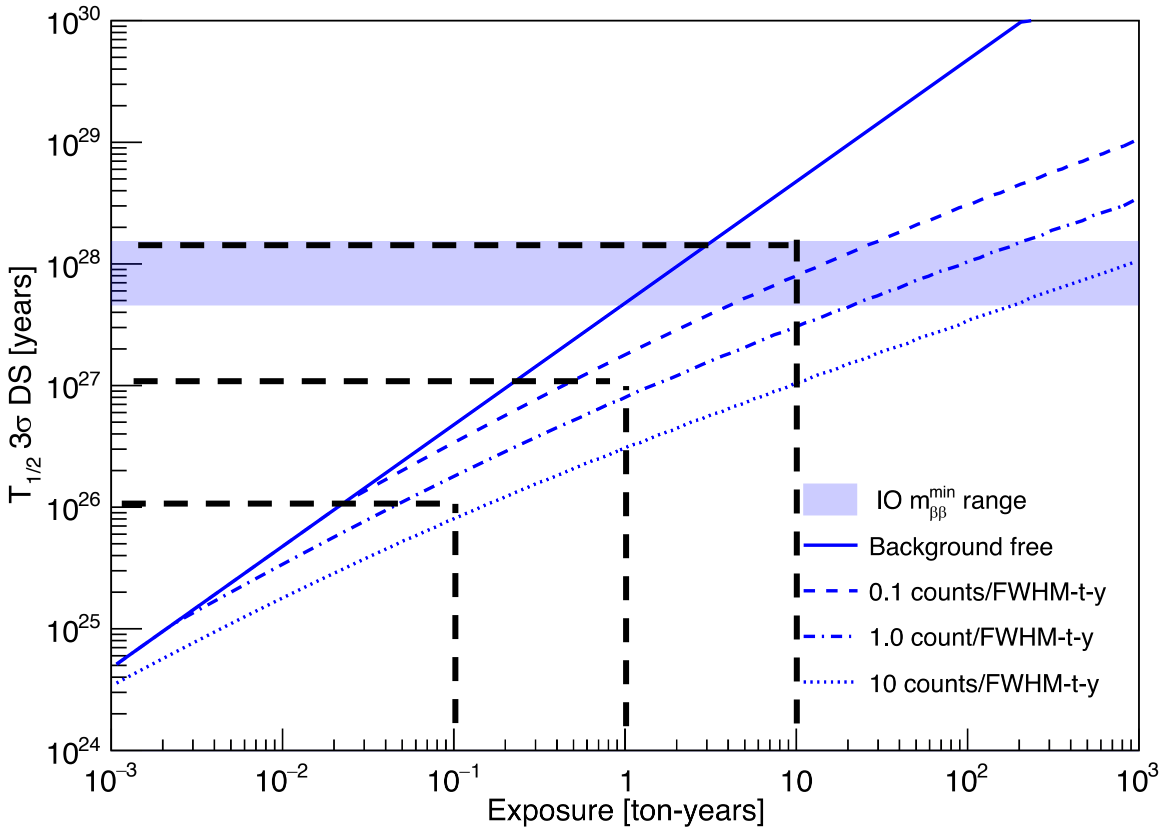


# Figure of merit – discovery potential

*« minimal signal strength for which a discovery is expected with 3σ C.L. »*

*see detailed discussion in: [1705.02996]*

example : $^{76}$Ge (88% enr.)




Defines the experimental design in terms of

- exposure (mass et duration)
- background goal (passive/active veto, detector design, analysis techniques)

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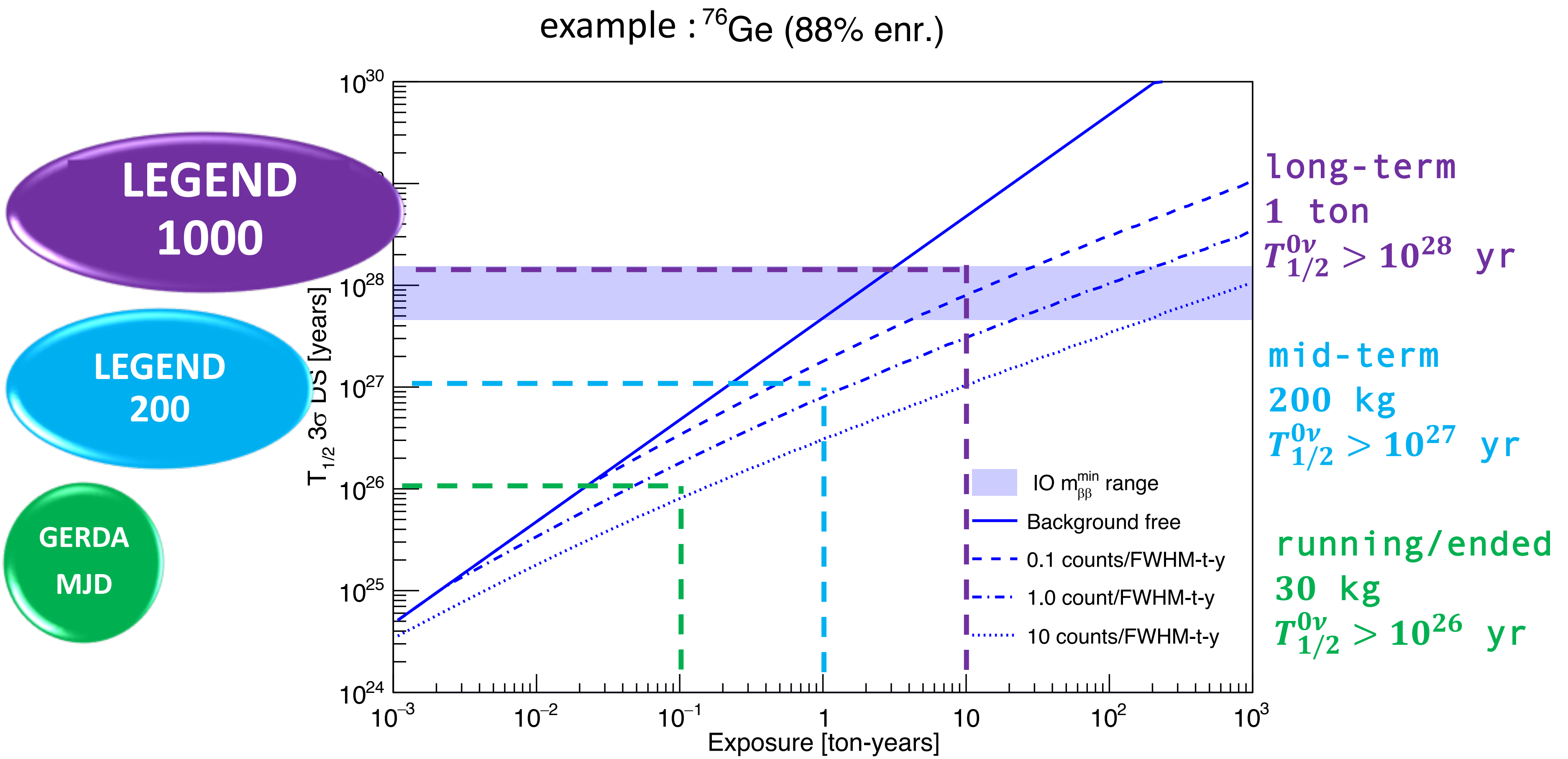


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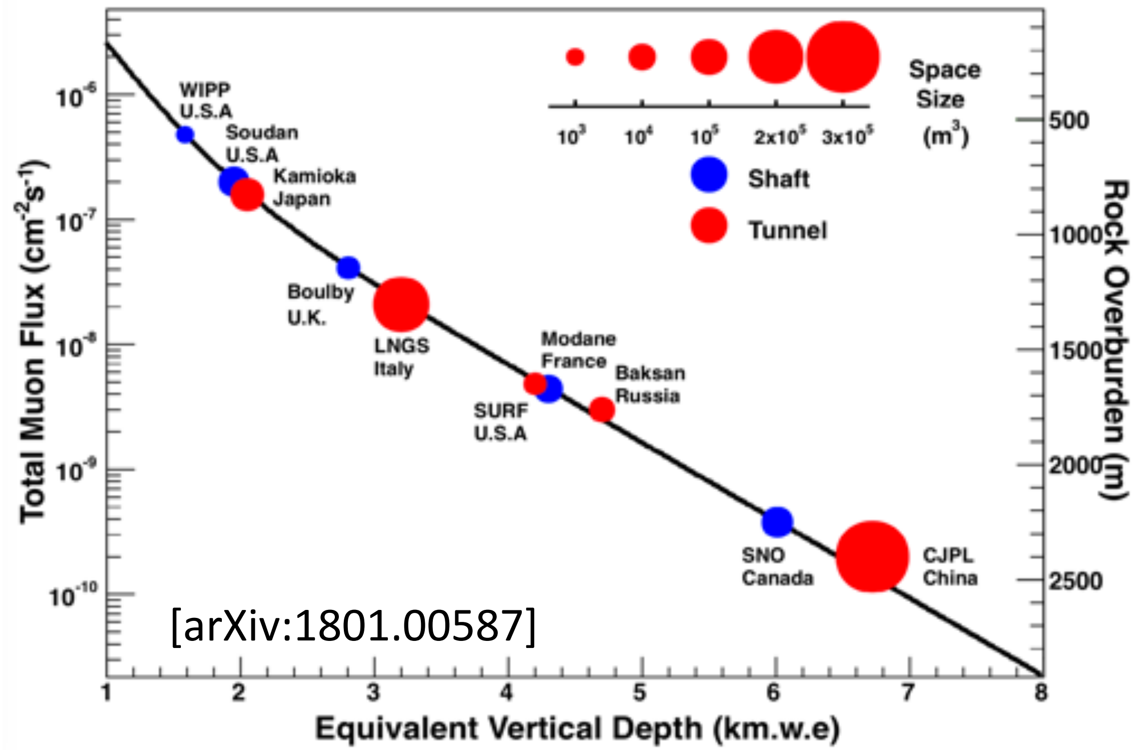
# Underground laboratories worldwide




- Underground = passive background suppression for « free »
- Isotopic activation suppression (neutron capture– e.g. $^{76}\mathrm{Ge} + n \rightarrow {}^{77\mathrm{m}}\mathrm{Ge} \rightarrow {}^{77}\mathrm{As}$ + **2.7 MeV**)
- Large experimental infrastructure required (shielding, cryostat, instrumentation)
- Size/depth/access compromise taken into account by the collaborations

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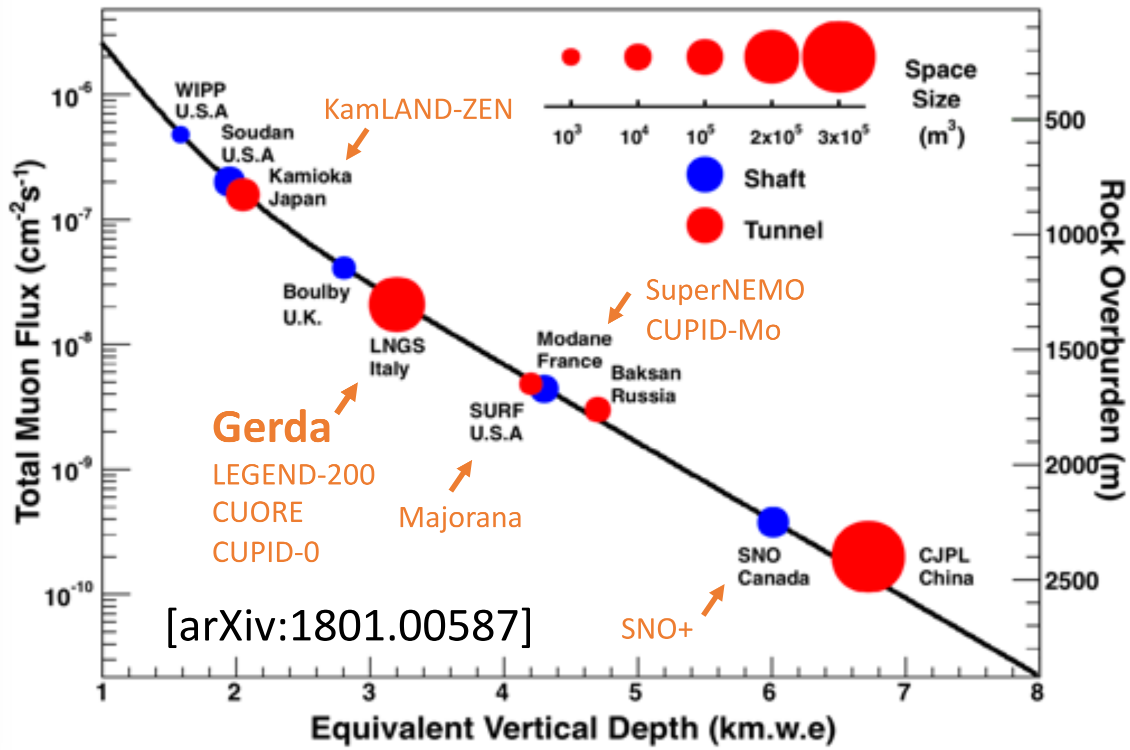


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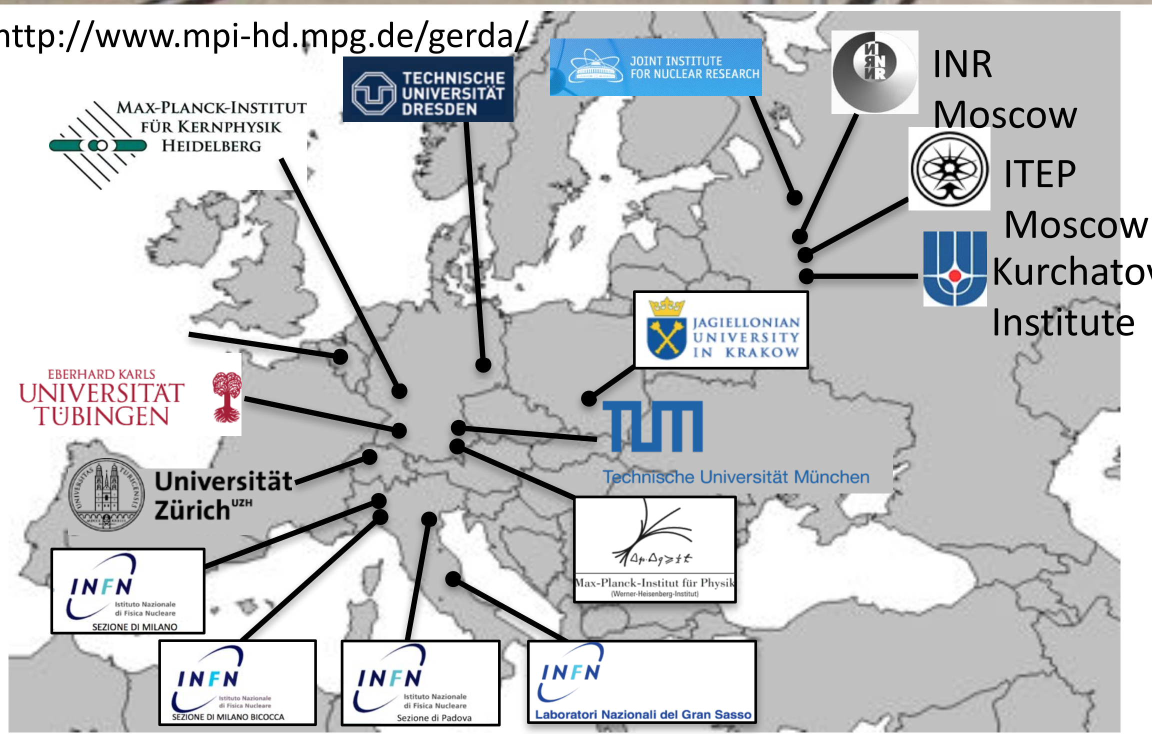
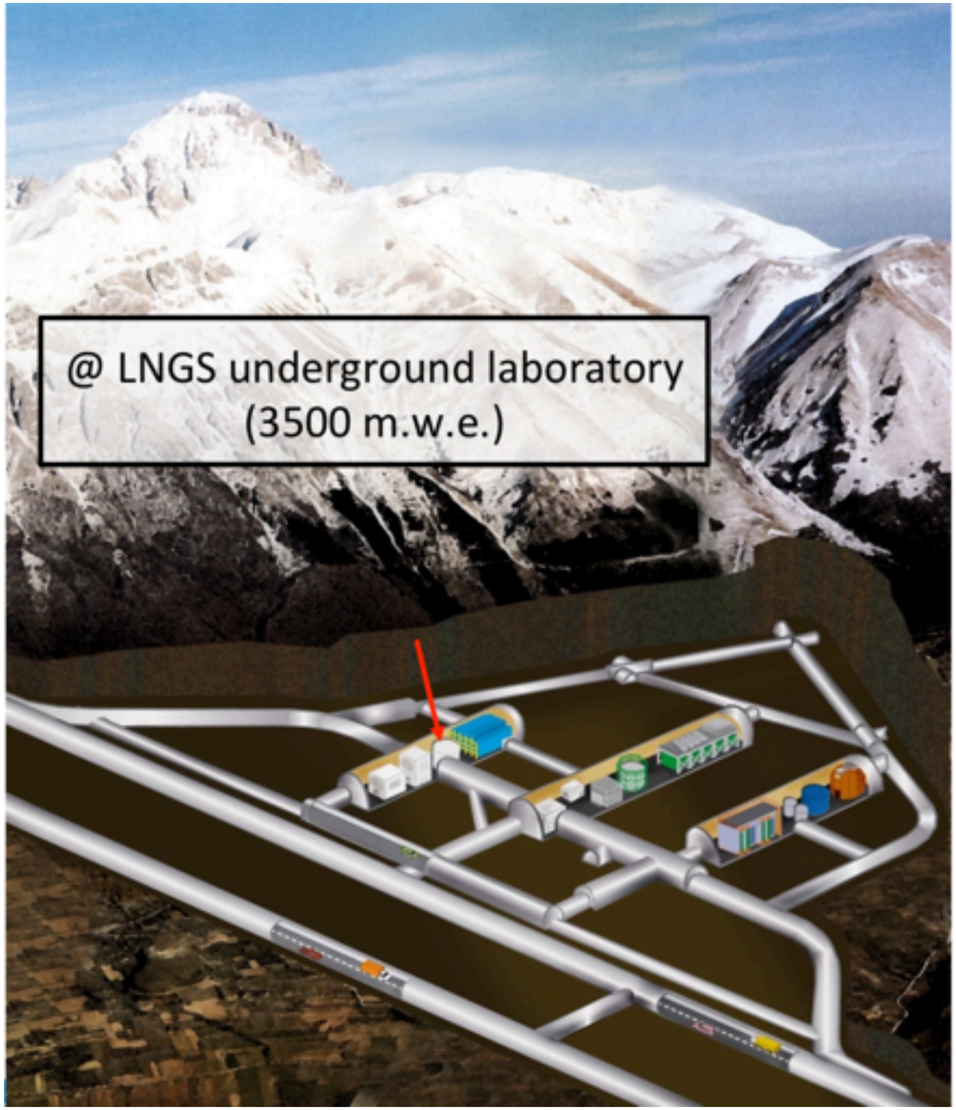
http://www.mpi-hd.mpg.de/gerda/

About 100 scientists from Europe



# GERDA location @ LNGS

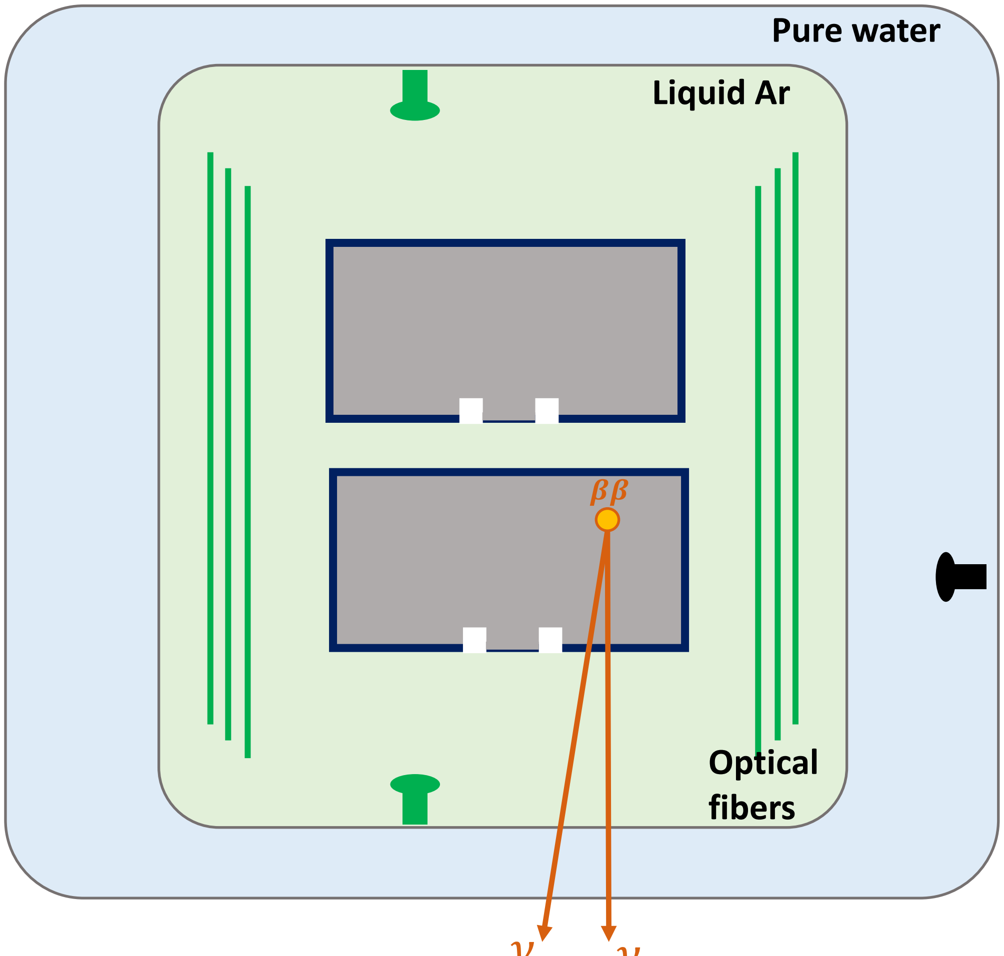



Large space available at LNGS
+ convenient access via highway

# Toward the background-free regime

- signal signature

$\beta\beta$ decay signal: single energy deposition in a 1 mm$^3$ volume



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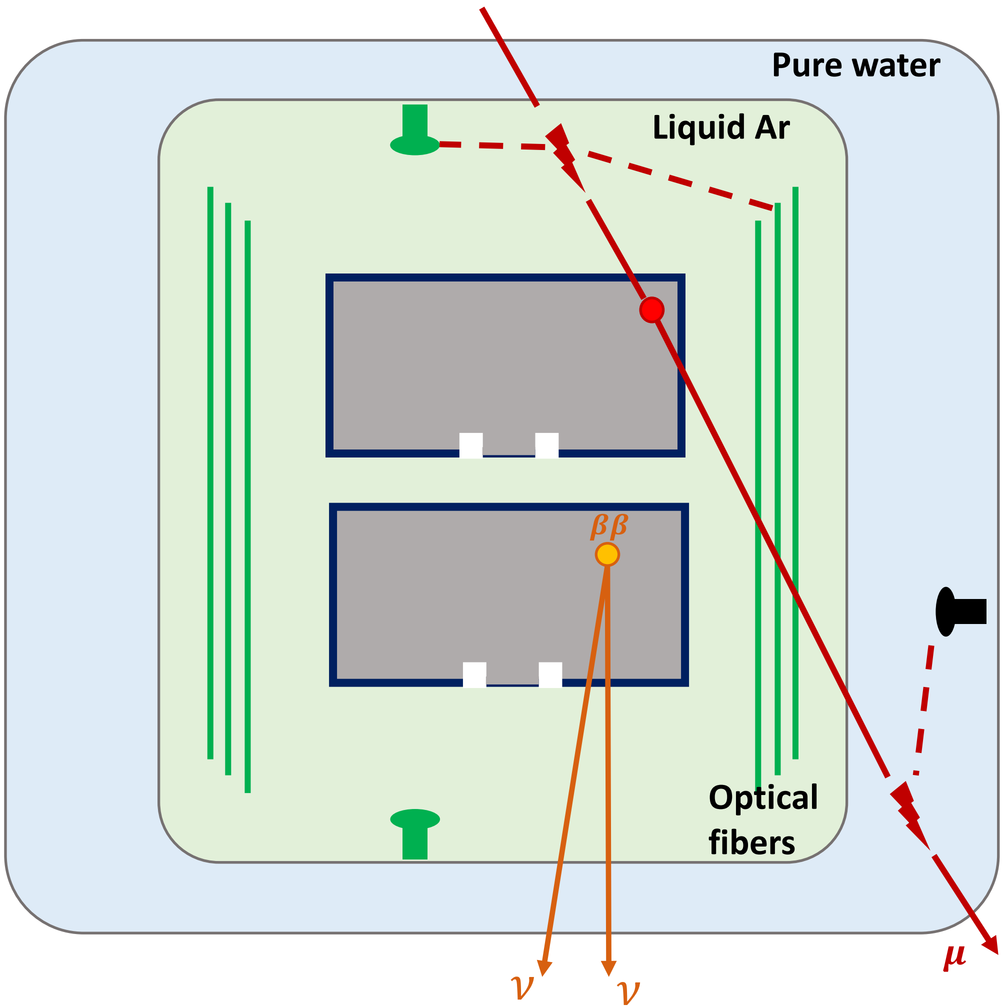


Muon veto based on Cherenkov light and plastic scintillator

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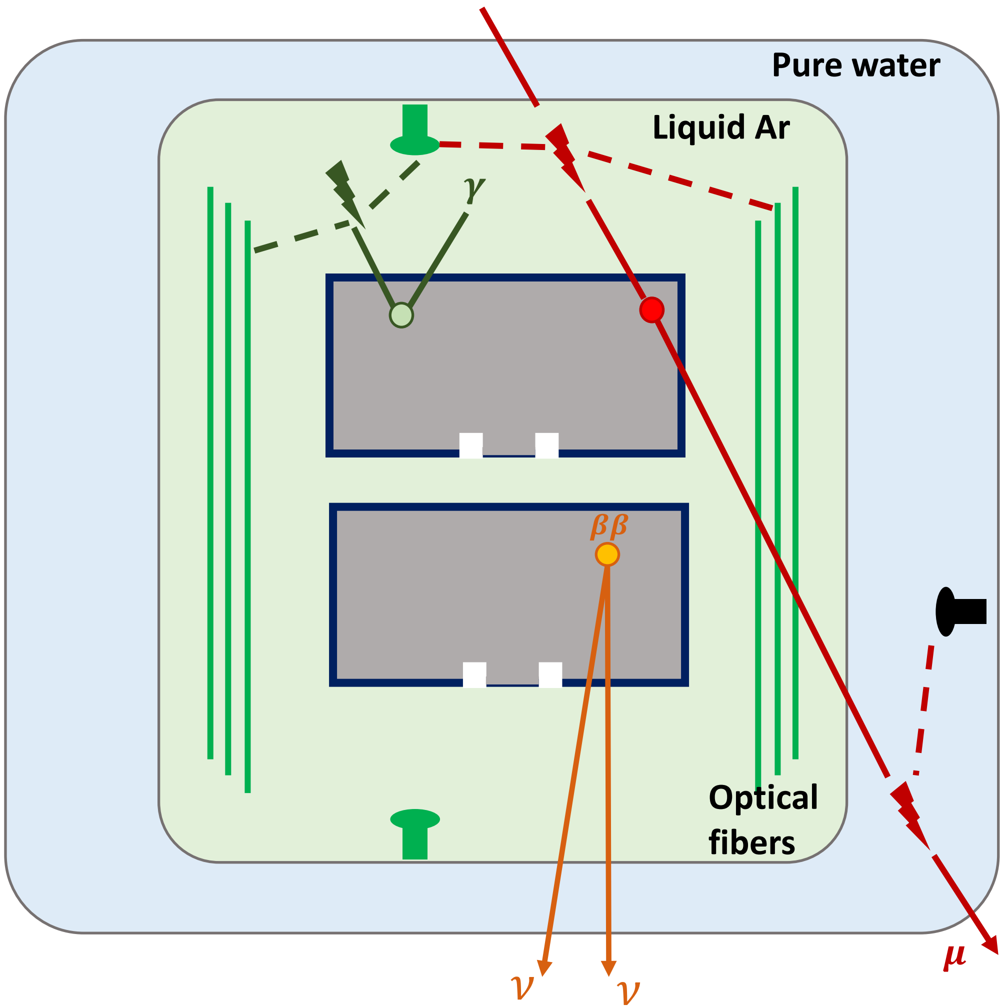


LAr veto based on Ar scintillation light read by fibers and PMT

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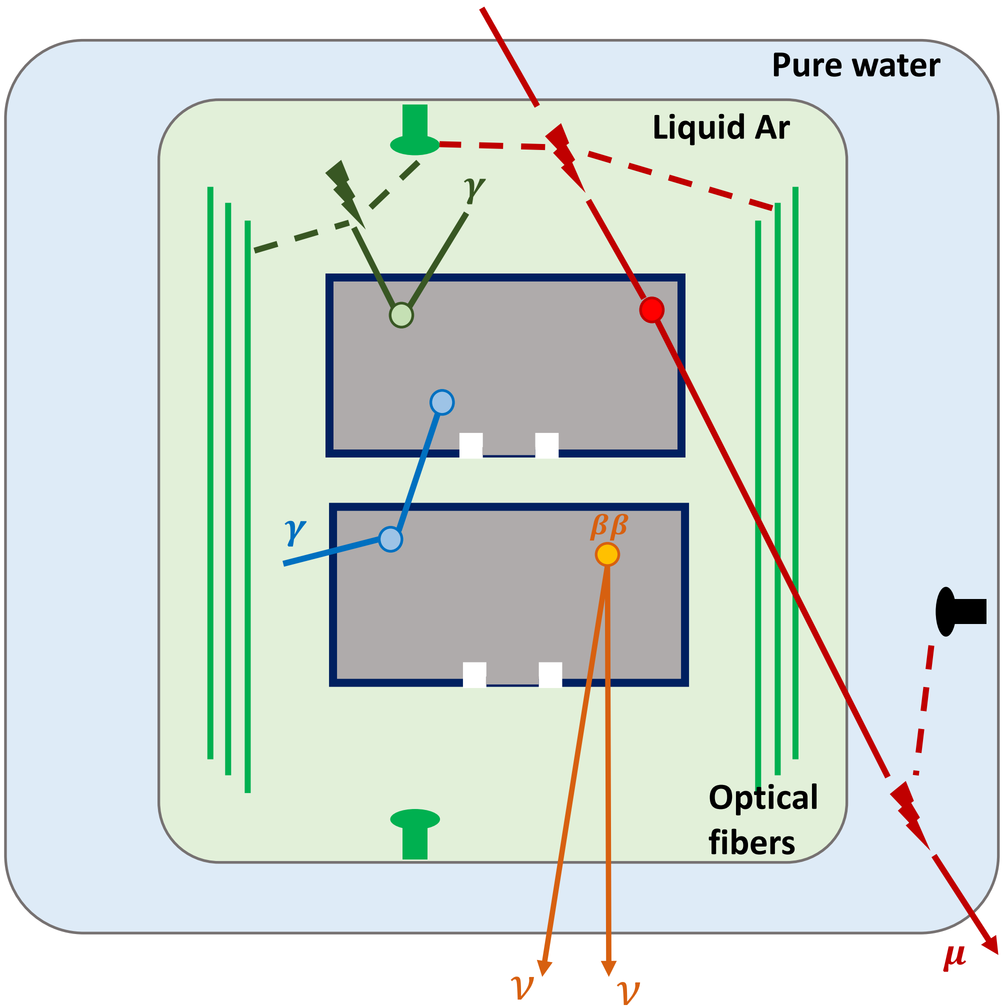


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Ge detector anti-coincidence

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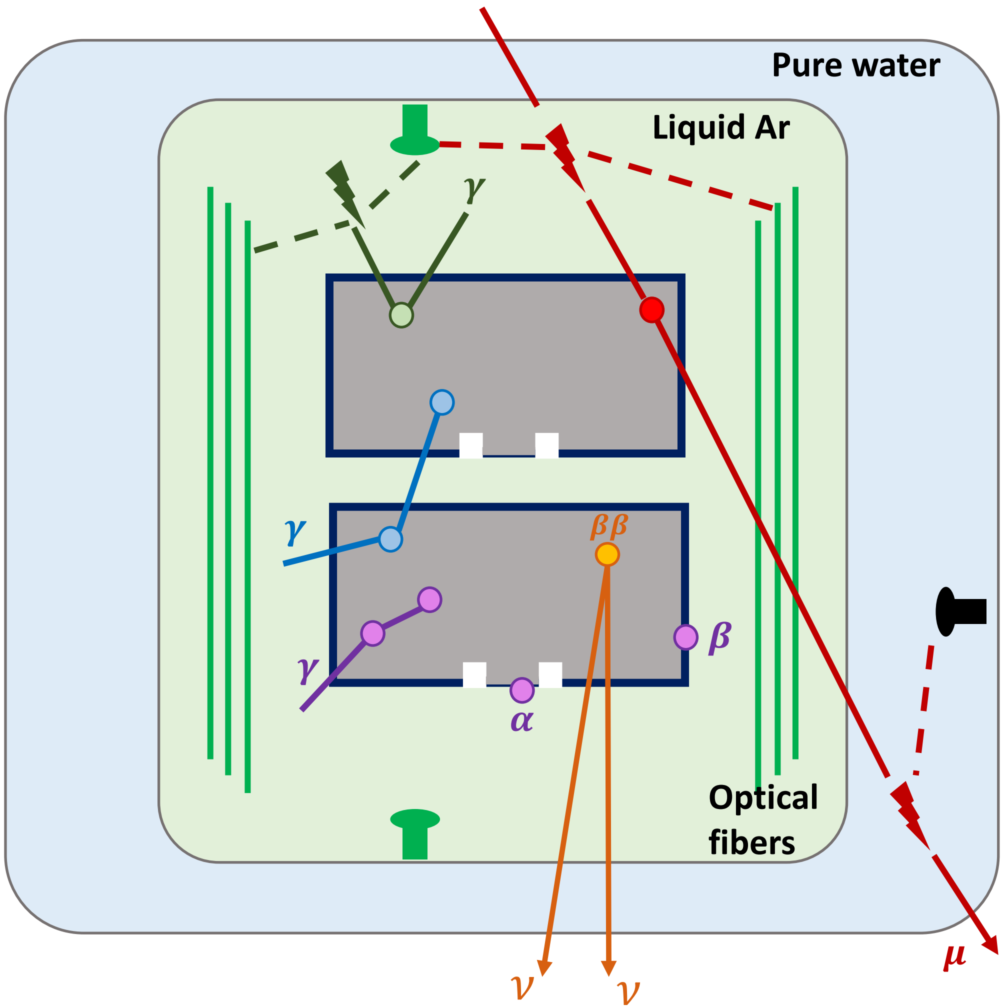


$\beta\beta$ decay signal: single energy deposition in a 1 mm$^3$ volume

Pulse shape discrimination (PSD) for multi-site and surface $\alpha$, $\beta$ events

Ge detector anti-coincidence

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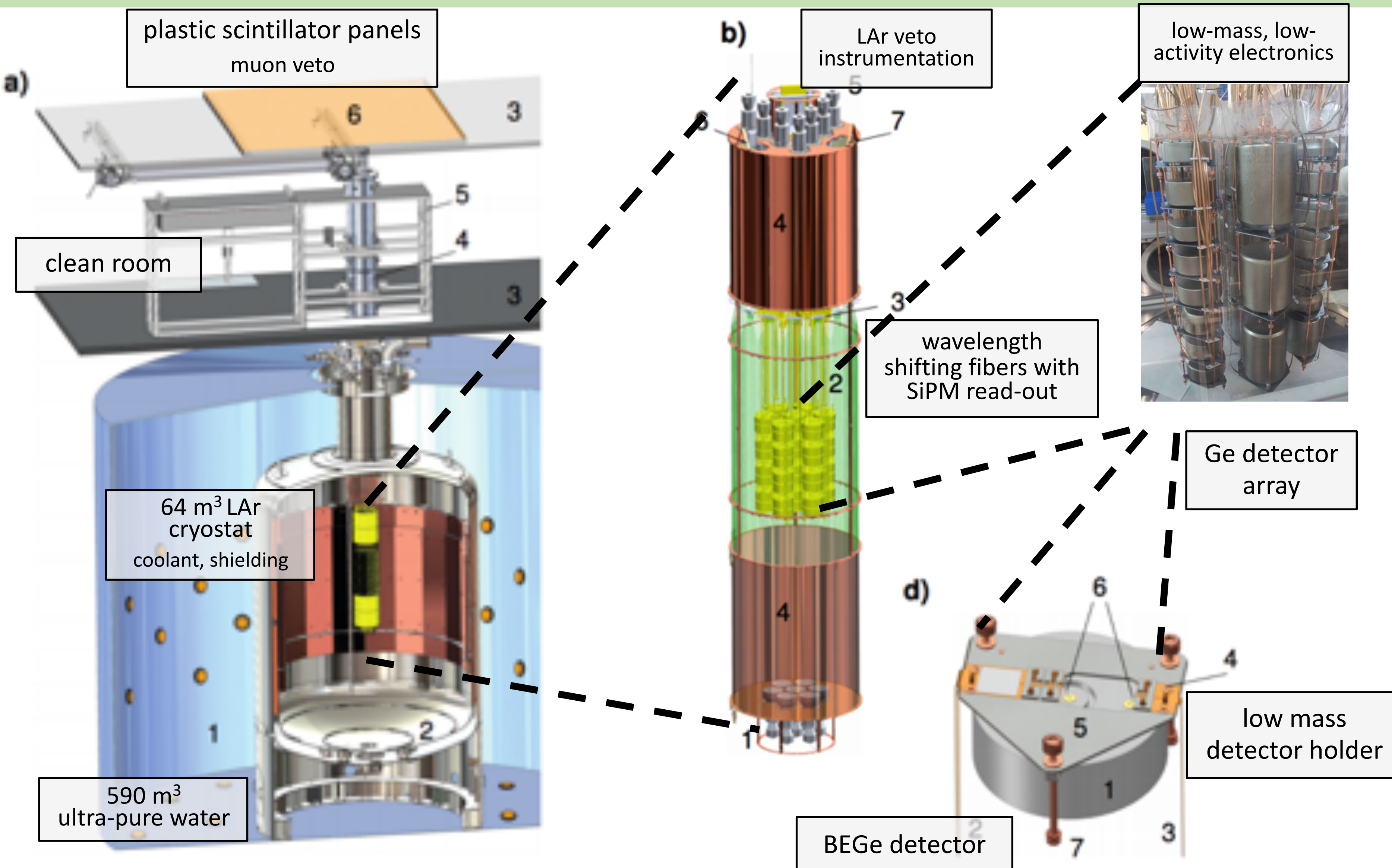
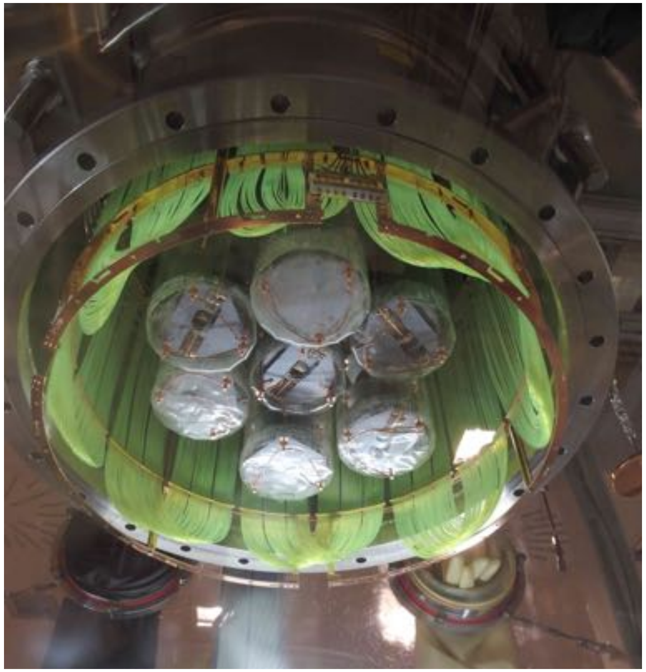
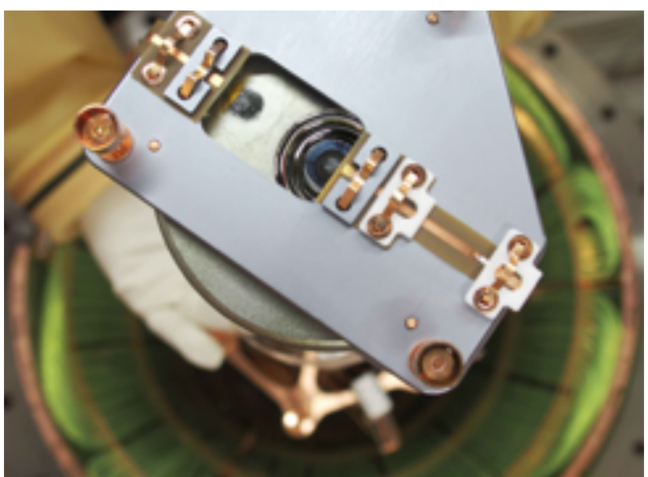
# GERDA Phase II: From concept to design

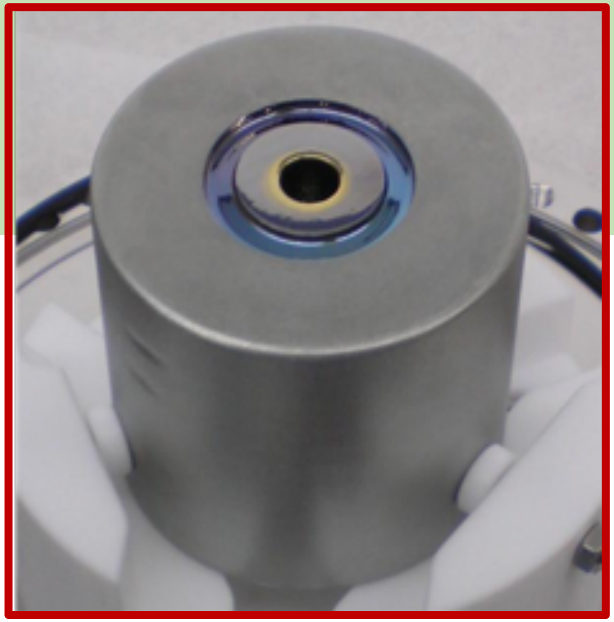


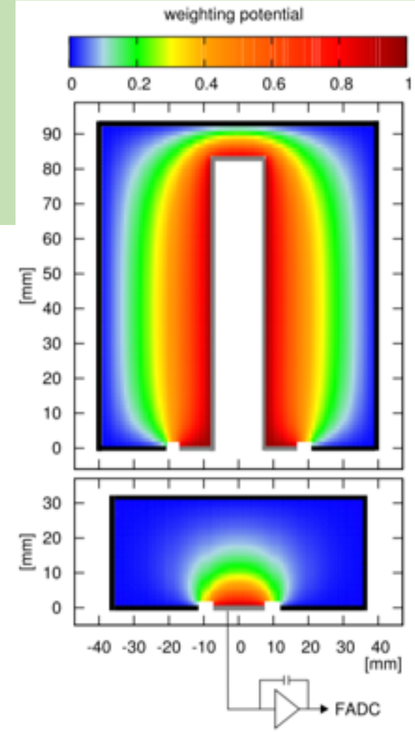

Slide: L. Pandola – TAUP 2017

# Ge detectors phase II







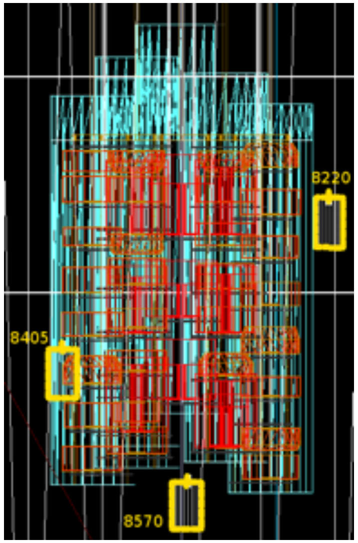


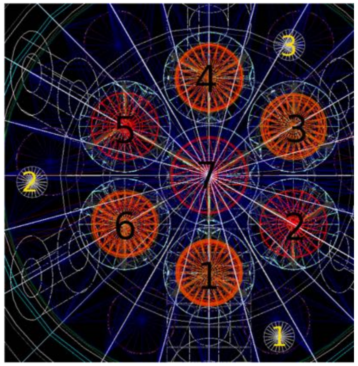

**7 strings with 40 detectors:**

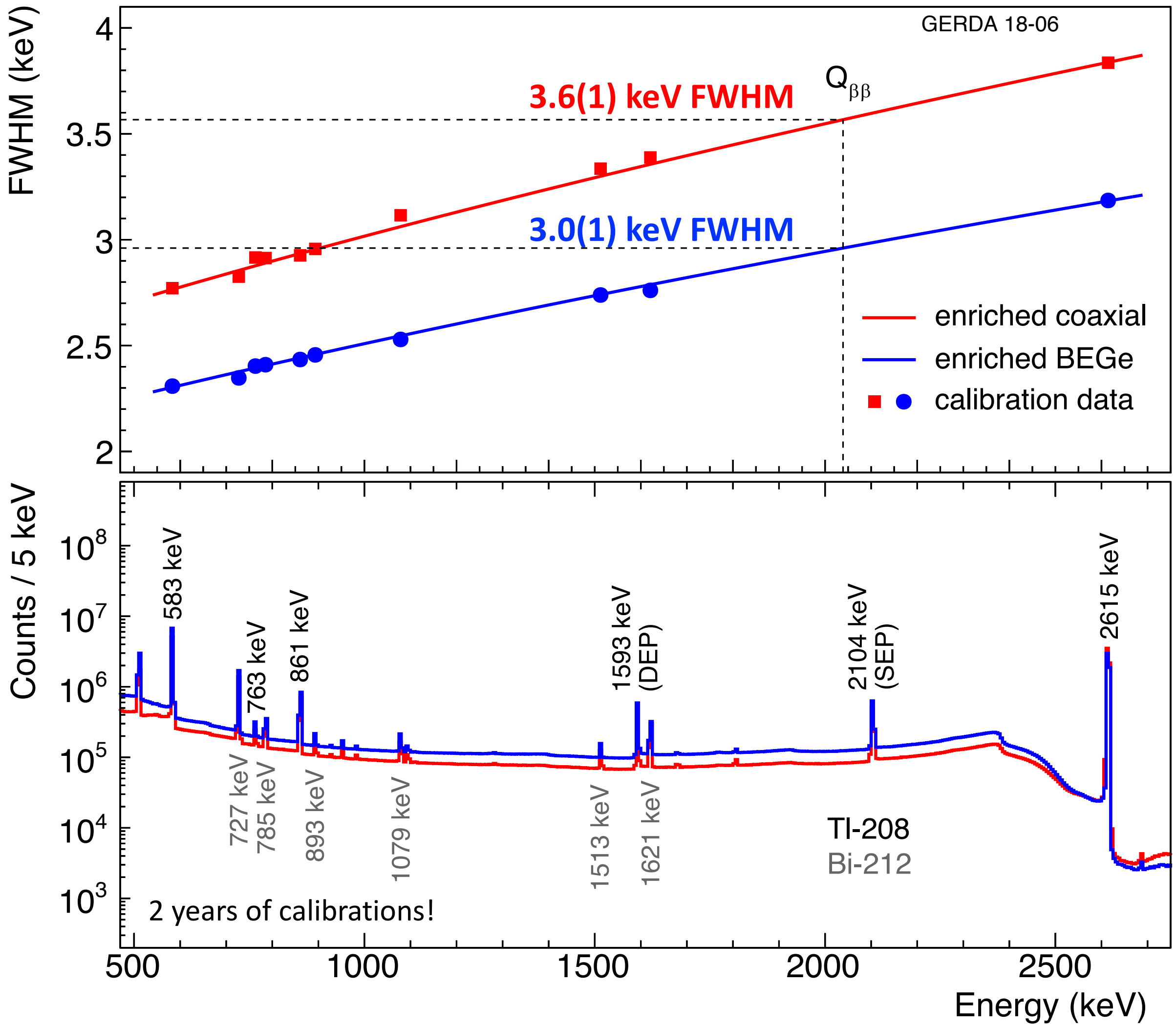
- *3 natural semi-coaxial (7.6 kg)*
- **7 enriched semi-coaxial (15.6 kg)**
- **30 enriched BEGe (20.0 kg)**

# Energy calibration

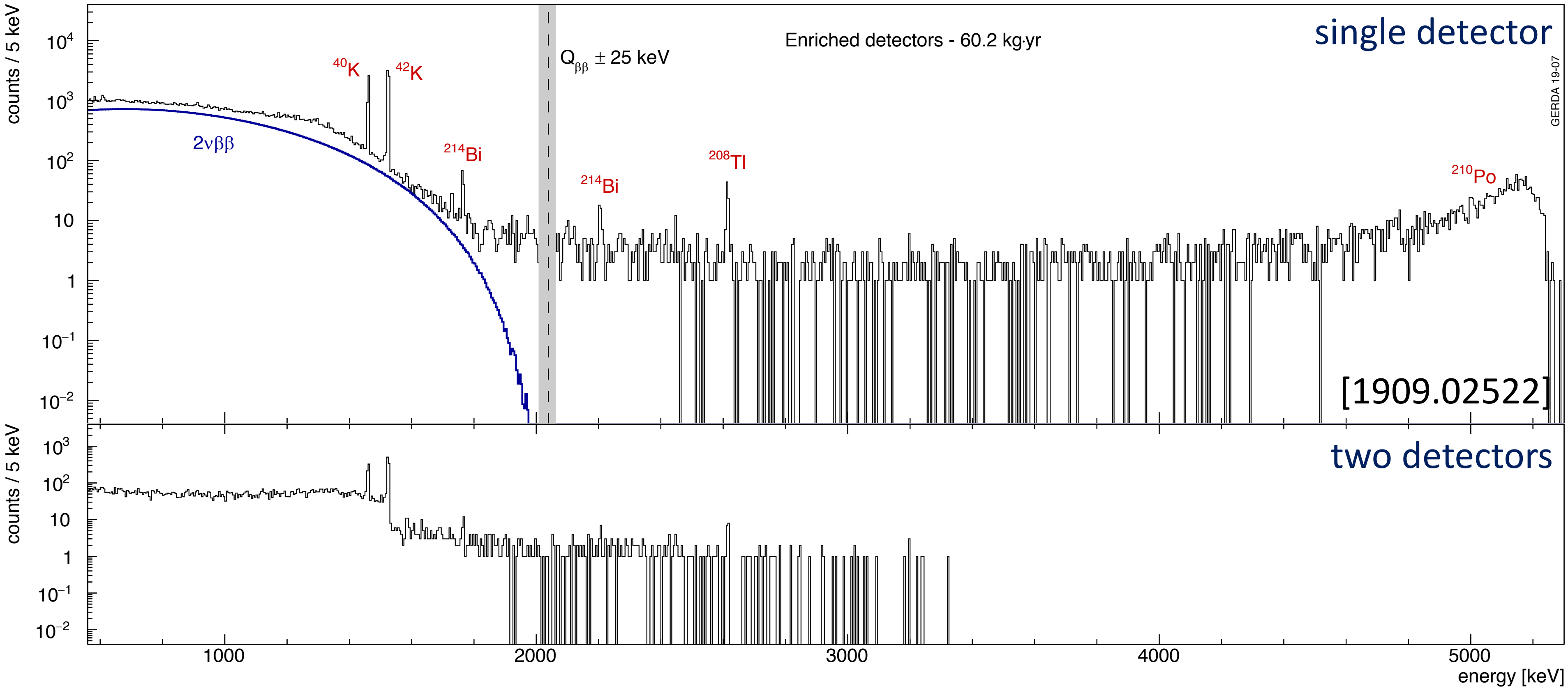
3 weak $^{228}$Th sources
lowered every ~ week



# Phase II physics data before cuts



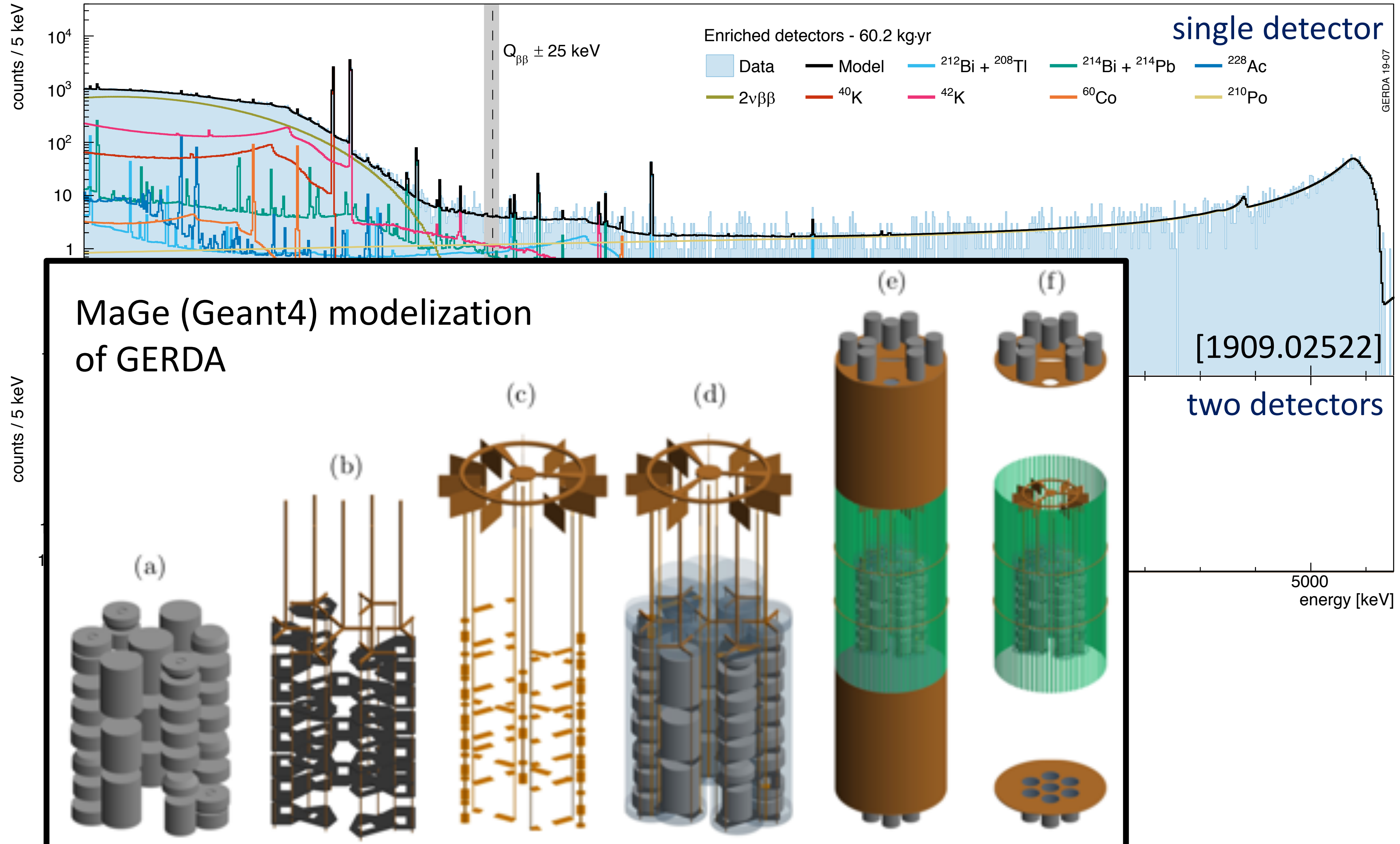

**Published data collection:** from Dec. 2015 to April 2018

**Blinding strategy:** Hide events falling in $Q_{\beta\beta} \pm 25$ keV into non-public files

**Data quality** + **muon veto** applied

Energy range above $^{39}$Ar spectrum ($Q_{\beta} = 565$ keV)

# Phase II physics data modeling before cuts



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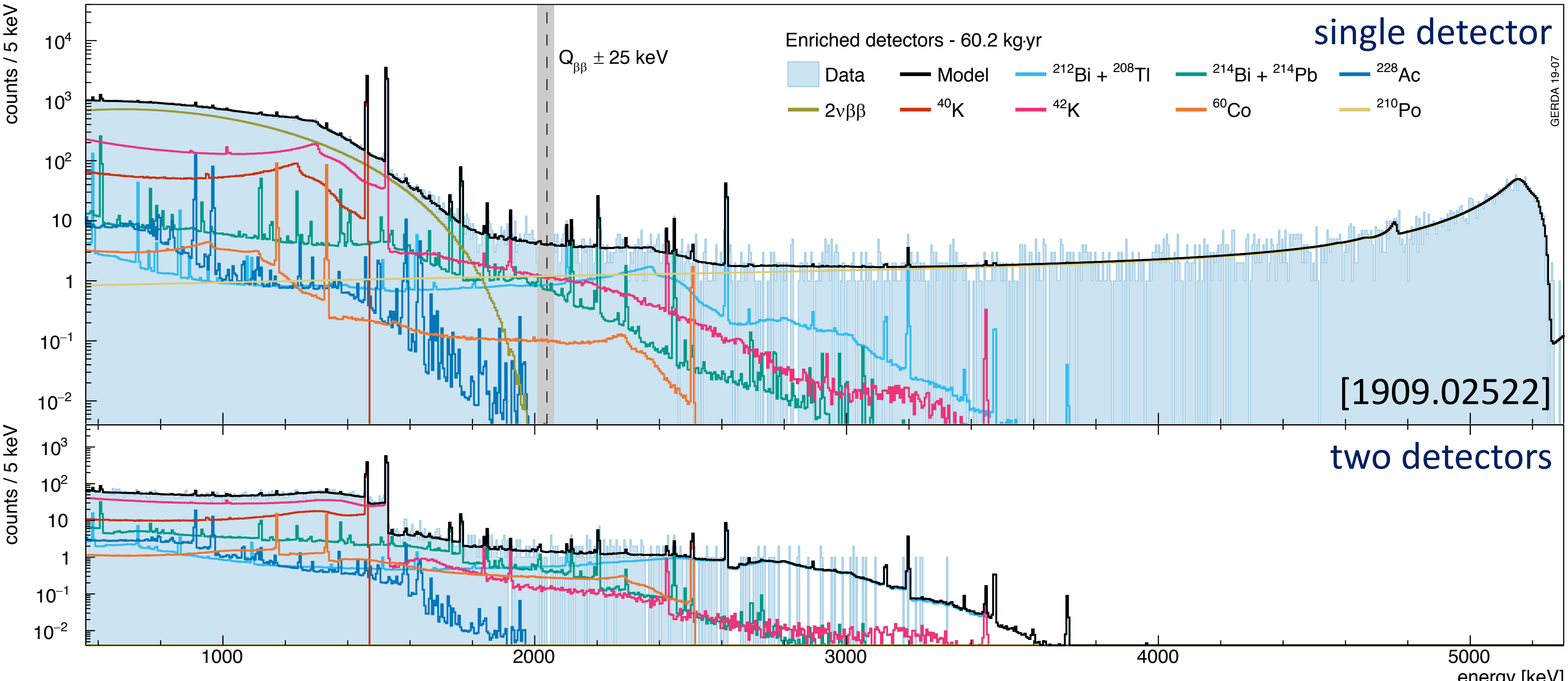
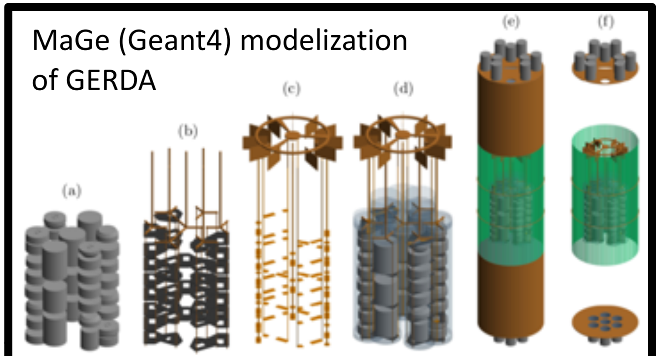



MaGe (Geant4) modelization of GERDA



**Fine modelling** of all individual parts
**Priors**: Constrains from screening measurements
**Weakness**: Fairly high degeneracy of some components

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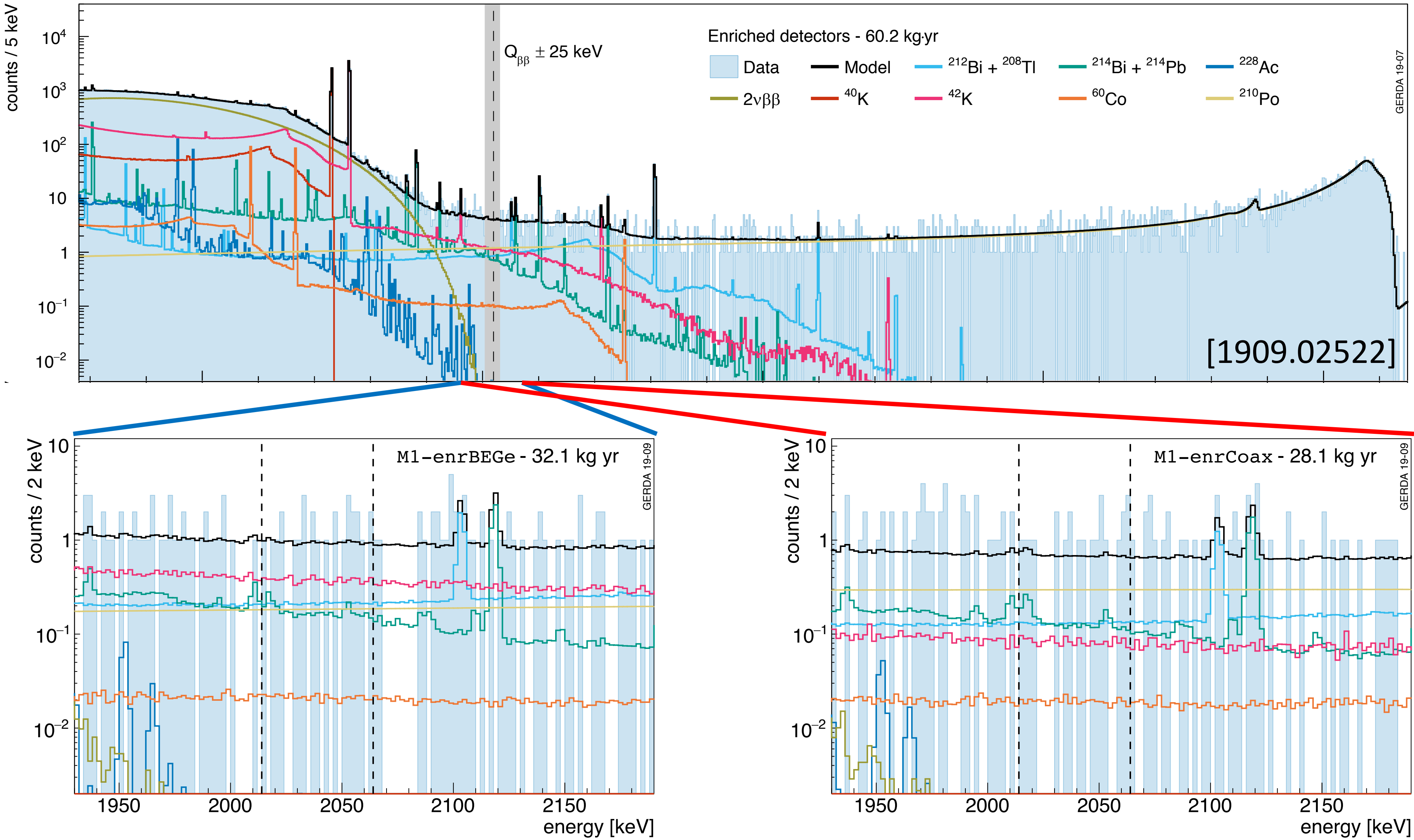
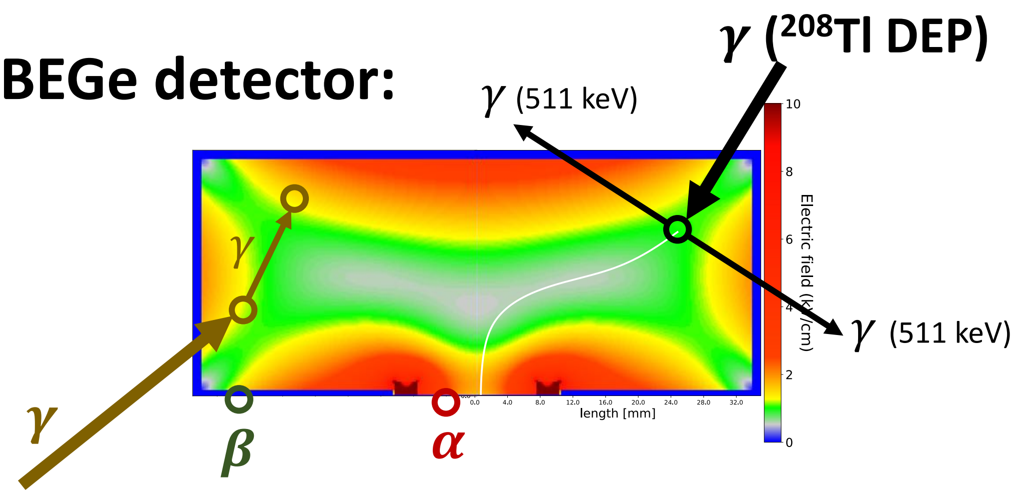



**Main outcome:** Flat background hypothesis in the region of interest is valid

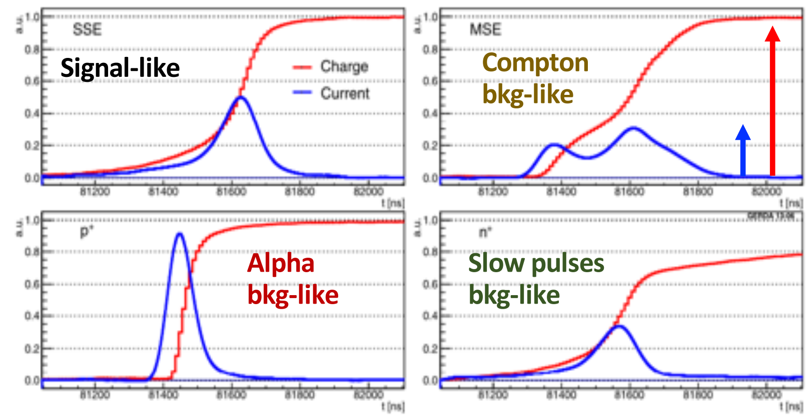
# Pulse shape discrimination

- **$^{208}$Tl DEP** (1592 keV) used as a proxy for **Single-Site Events** (SSE)
- **Multi-Site Events** (MSE) cut set such that 90% of $^{208}$Tl DEP events survive
- **Alphas** and **Betas** cut thanks to specific signal time profile

**BEGe detector:**

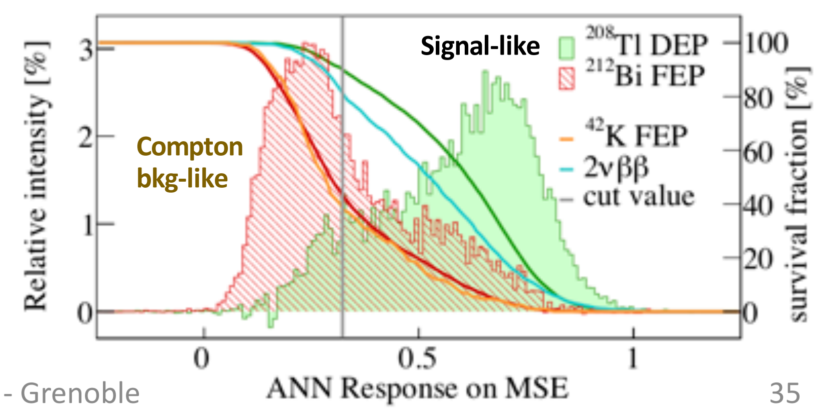



- **BEGe** cut parameter: **A/E**



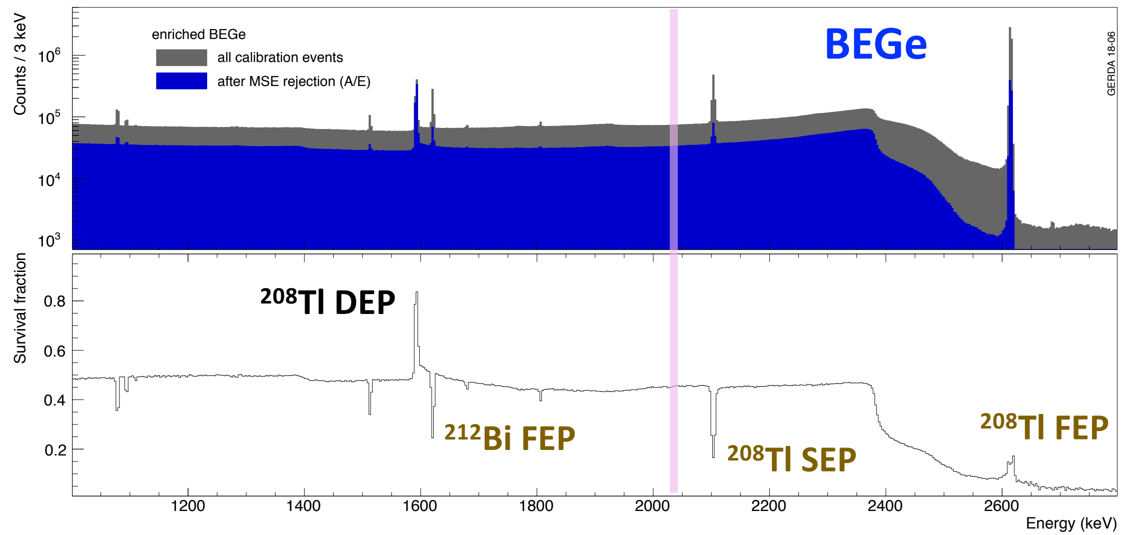

NB: 100 MHz / 10 $\mu$s long trace

- **Semi-coaxial** cut parameter: Artificial Neural network + rise time

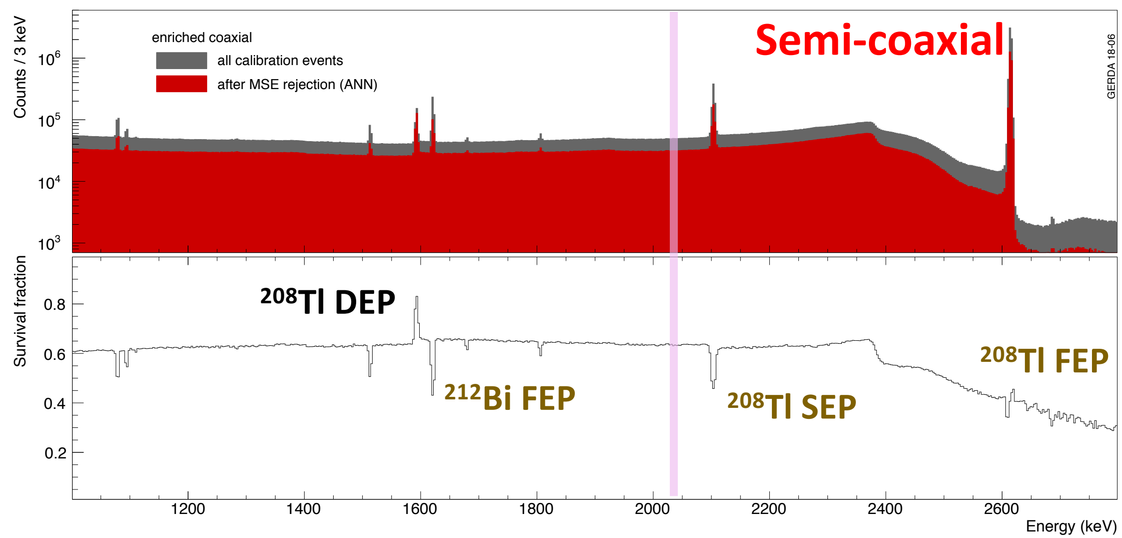


# PSD on calibration data

- **$^{208}$Tl DEP** (1592 keV) used as a proxy for **Single-Site Events** (SSE)
- **Multi-Site Events** (MSE) cut set such that 90% of $^{208}$Tl DEP events survive
- **Alphas** and **Betas** cut thanks to specific signal time profile

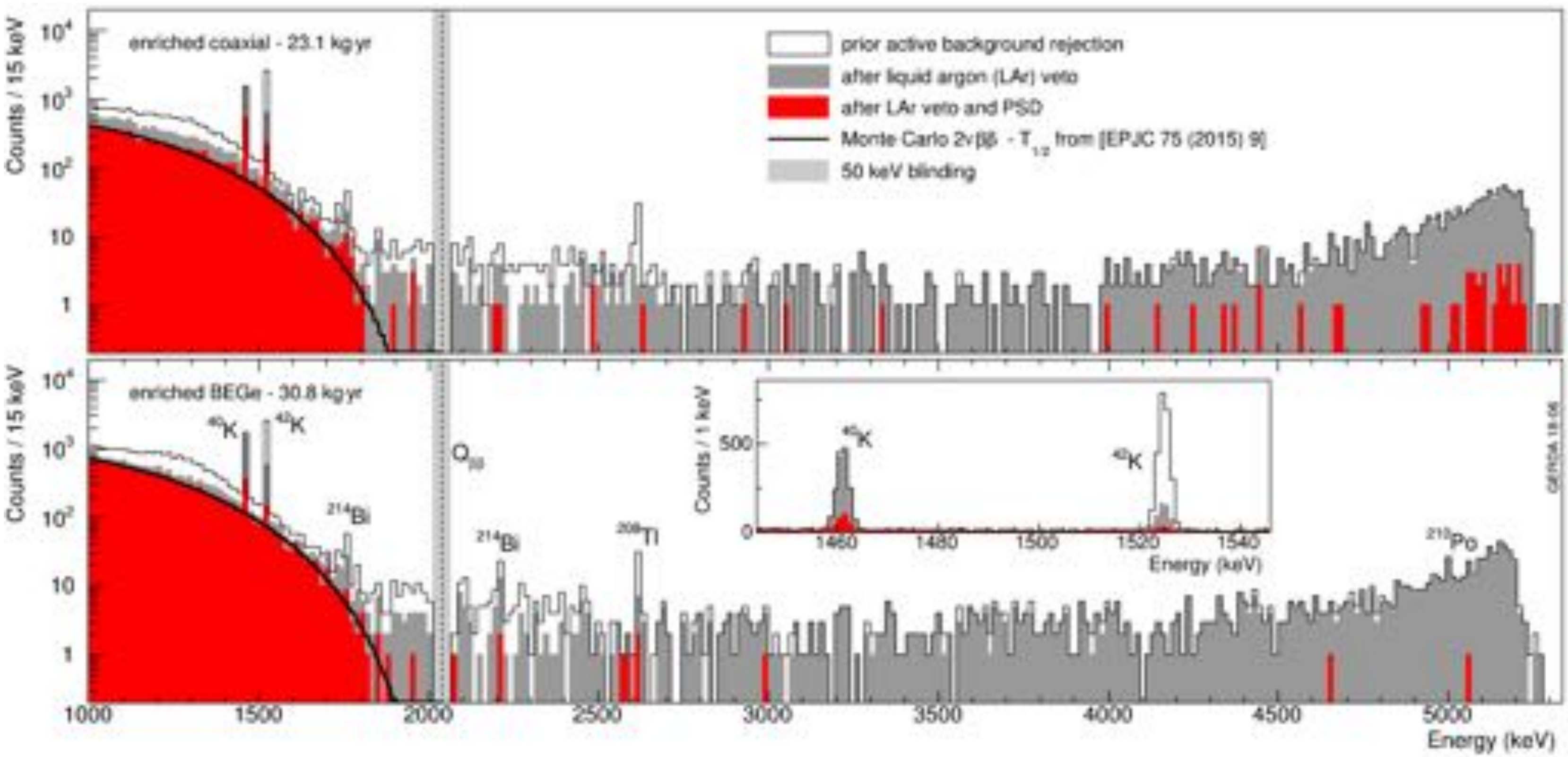



- Much better performance with **point contact** BEGe detectors w.r.t. semi-coaxial detectors
- **A/E** much simpler analysis better control of the systematics



# Phase II physics data release at Nu18

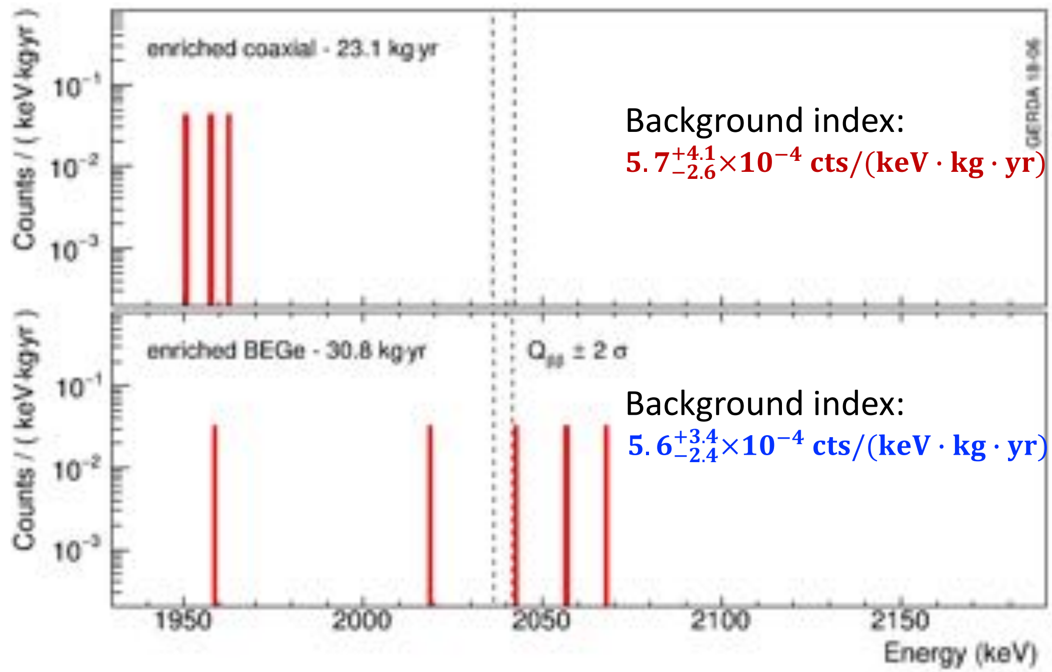
Data taking from Dec. 2015 to April 2018 – Science (2019)

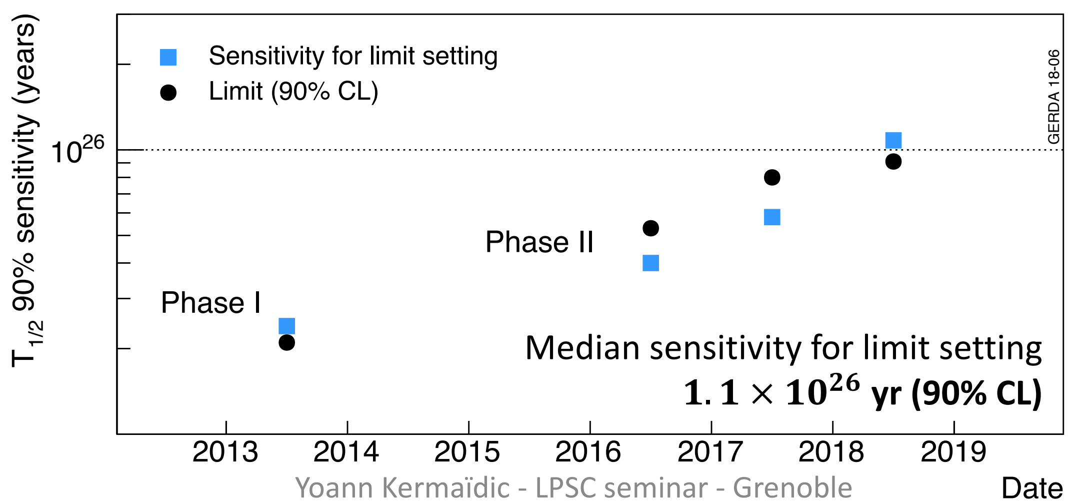



- [600-1300] keV - $2\nu\beta\beta$ decays produce single-site events -> No suppression
- [1450-1530] keV - Strong suppression of $^{40}K$ and $^{42}K$ gamma lines (MSE)
- [> 3000] keV - Suppression of almost all $\alpha$ events (p+ contact)

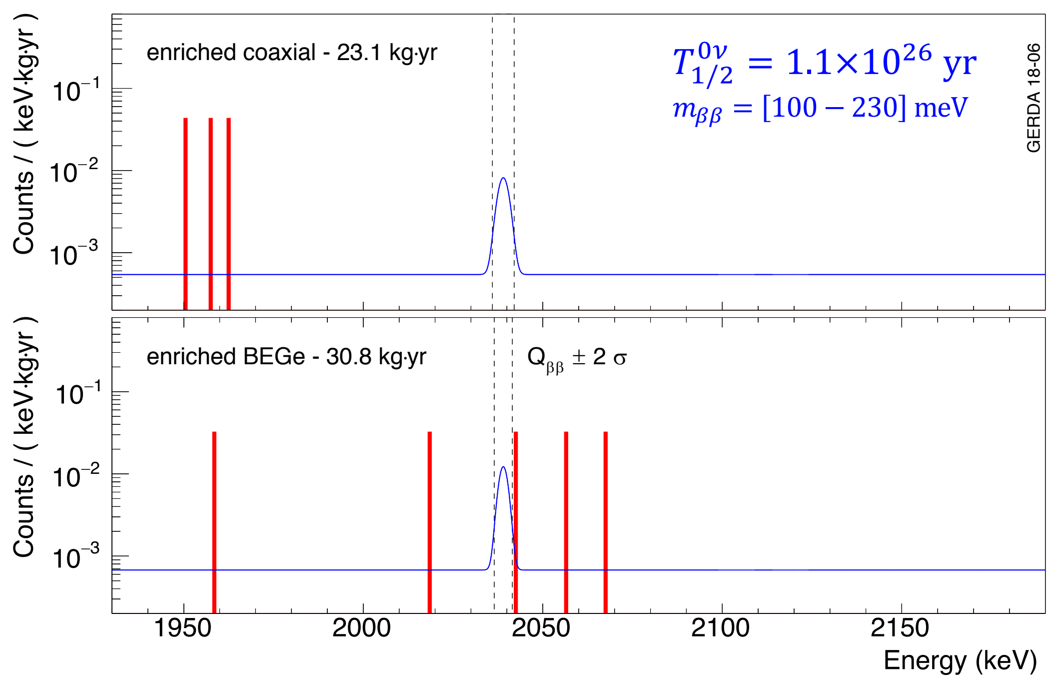
# Energy spectrum after unblinding!

Science (2019)

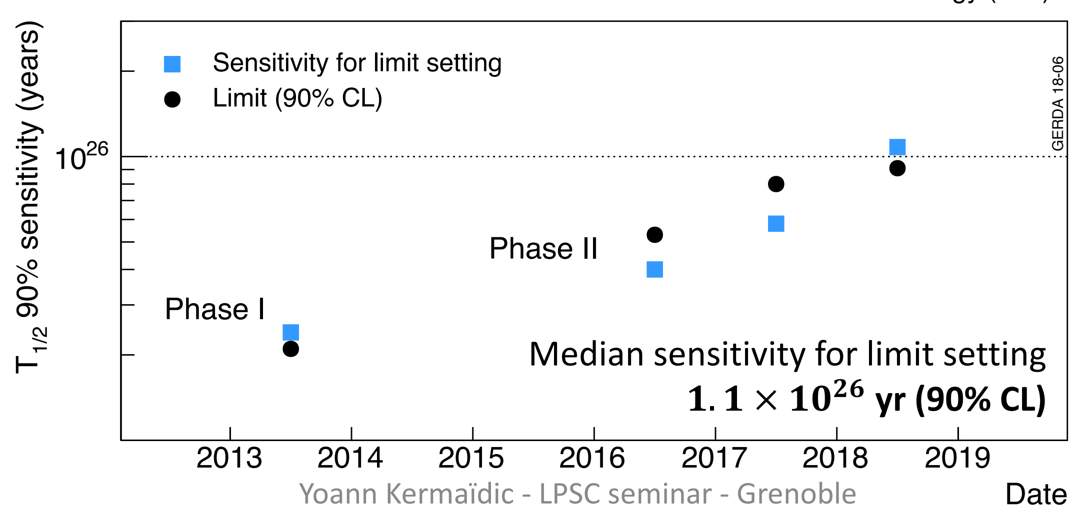


# Energy spectrum after unblinding!




Science (2019)




Median sensitivity for limit setting

**$1.1\times10^{26}$ yr (90% CL)**

# Since last unblinding

**Upgrade of the detector array + LAr veto** (May 2018)

- Increase the LAr veto fibers coverage
- Installed cleaner cables
- Added five ICPC $^{76}$Ge detectors [Y.K. et al] (2018) ~ +9 kg

  NB: 3 continuous weeks underground with a team of 10 people



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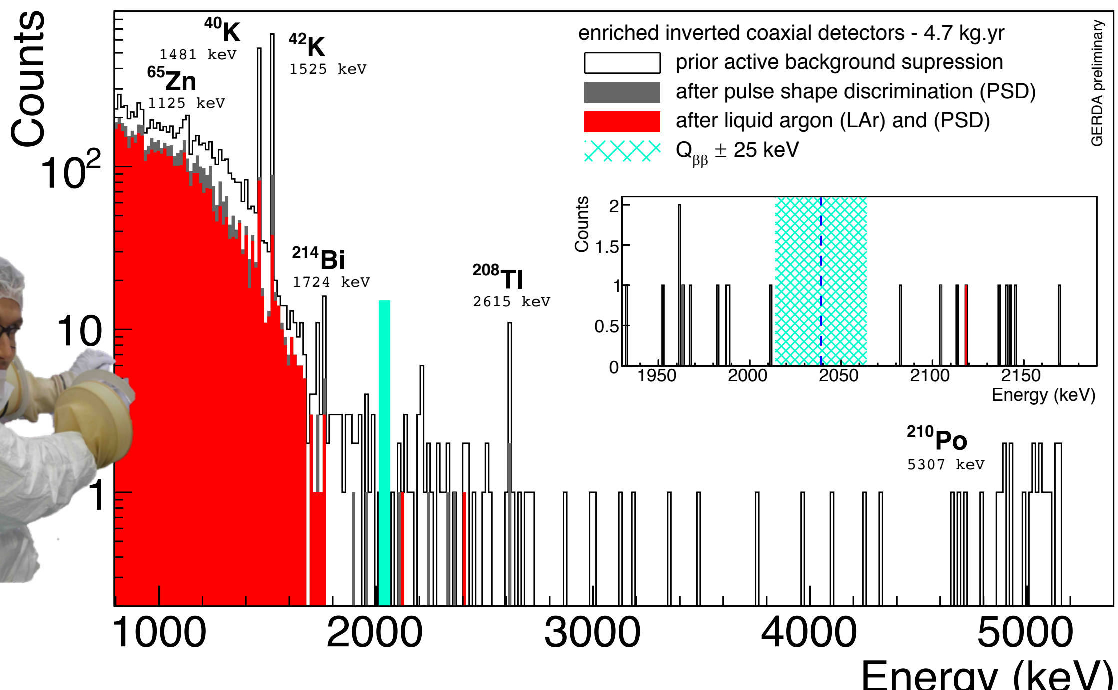




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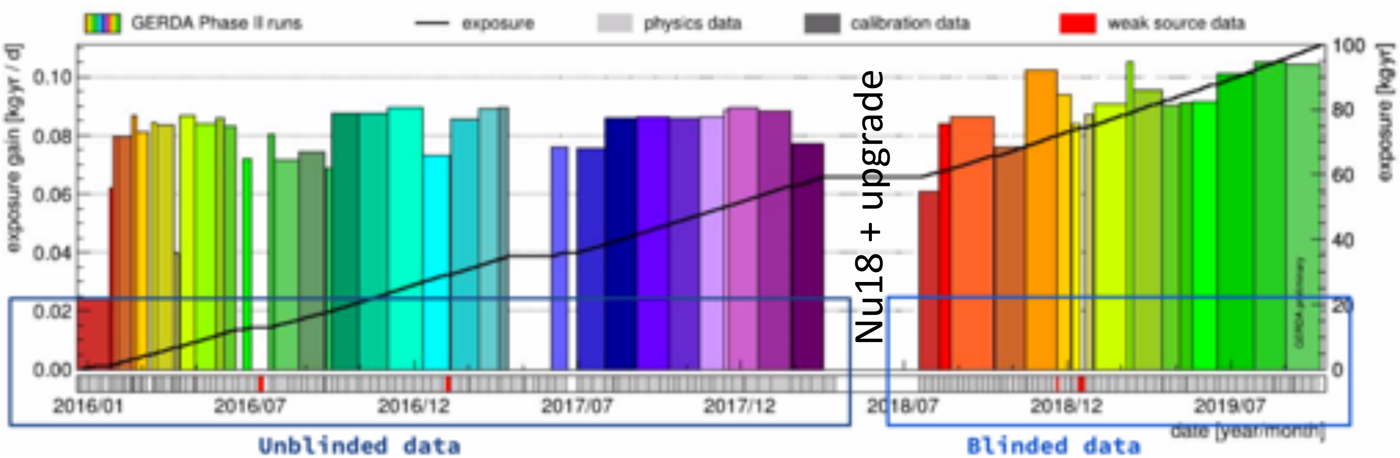
- Added five ICPC $^{76}$Ge detectors [Y.K. et al] (2018) ~ +9 kg

**Data taking ended in Dec. 2019**

- Goal in exposure 100 kg.yr reached




- Next (final) unblinding session planned in March 2020!

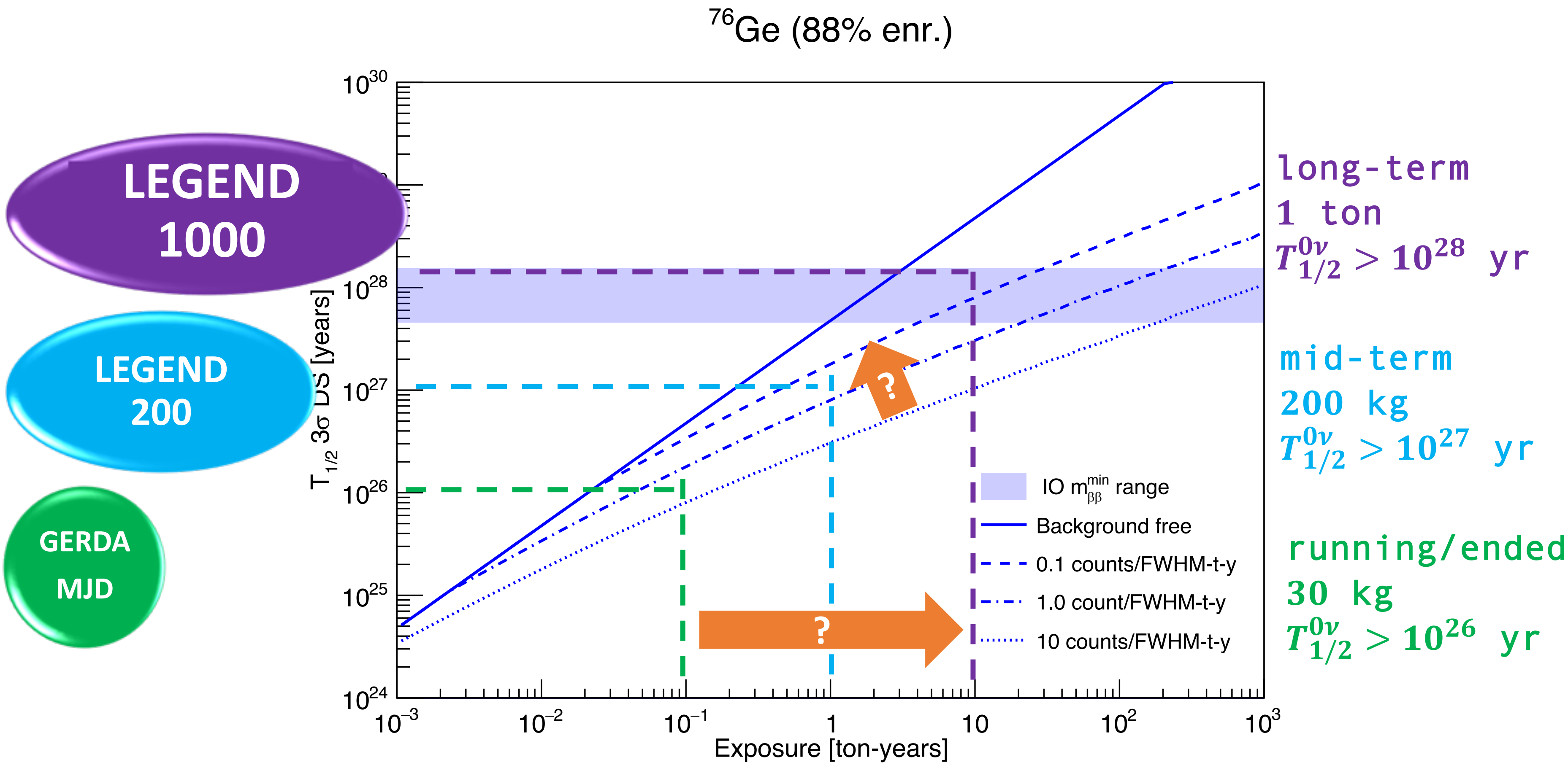


# Landscape after TAUP 2019

| experiment | isotope | $T_{1/2}^{0\nu}$ [$\times 10^{26}$ years] | $m_{\beta\beta}$ [meV] | Ref. |
|---|---|---|---|---|
| GERDA | $^{76}$Ge | 1.1 | [100-230] | Science aav8613 (2019) |
| Kamland-Zen | $^{136}$Xe | 0.8 | [61-165] | PRL 117, 082503 (2016) + TAUP 2019 |
| Majorana | $^{76}$Ge | 0.5 | [200-433] | PRC 100, 025501 (2019) |
| EXO-200 | $^{136}$Xe | 0.5 | [78-239] | PRL 123, 161802 (2019) |
| CUORE | $^{130}$Te | 0.2 | [75-350] | arXiv :1912.10966 |

- $T_{1/2}^{0\nu}$ sensitivity reported (not the lower limit)
- $m_{\beta\beta}$ is mainly estimated from the lower $T_{1/2}^{0\nu}$ limit except for Gerda
- Nuclear Matrix Elements result in clear different goals for $T_{1/2}^{0\nu}$ depending on the isotope
- Inverted hierarchy $m_{\beta\beta}$ lower value is 20 meV

# Scaling-up / getting cleaner!




Defines the experimental design in terms of

- exposure (mass et duration)
- background goal (passive/active veto, detector design, analysis techniques)

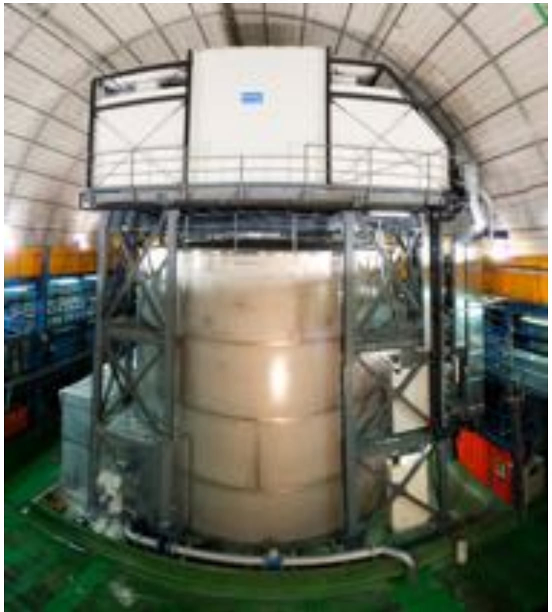
# After GERDA and MAJORANA:

**Legend collaboration:**
- 47 institutions, ~240 scientists
- GERDA / MAJORANA / external contributors

**Staged approach to reach $\mathbf{10^{28}}$ yr sensitivity:**
- LEGEND-200 $\rightarrow \mathbf{10^{27}}$ **yr** after 5 years
- LEGEND-1000 $> \mathbf{10^{28}}$ **yr** (hosting lab under investigation)


**LEGEND-200 phase:**
- Up to 200 kg of $^{76}$Ge
- Modification of existing GERDA infrastructure at LNGS
- Improved background index
- Data start in 2021
- Most of funding secured
- **NEWS:**

**First six enriched ICPC L200 detectors produced + first Majorana det. ready**



# LEGEND-200 Background Reduction

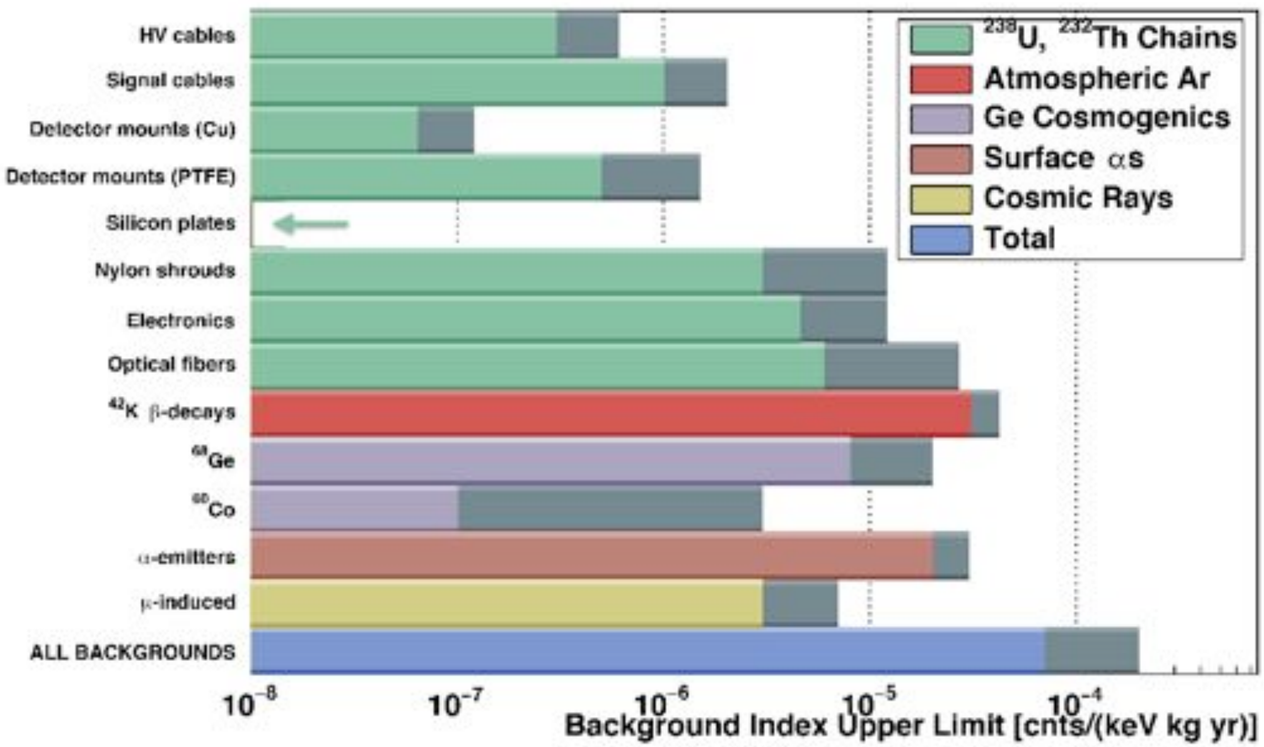
LEGEND-200: reduction of backgrounds from **$^{42}$K, $^{214}$Bi, $^{208}$Tl** by x5 relative to GERDA/MAJORANA.

Feasibility of these required reduction factors have already been shown in GERDA, MAJORANA and in dedicated test stands (e.g. LArGe).

- Improved radiopurity levels (cables (x7), electro-formed Cu, PTFE, ...)
- Increased detector mass (≥x2) leads to proportional reduction from near-by parts
- Higher purity LAr: increased scintillation light yield and attenuation length
- Improved scintillation light readout (x2 shown in test stand)
- Reduction of electronic noise leads to improved PSD
- Increase n+ ‘dead’ layer thickness from 0.8 to 1.3 mm (x3 for $^{42}$K)
- Optimized PSD analysis for n+ and p+ surface events
- Larger detectors have better surface/volume ratio reducing surface backgrounds

From these developments, we expect a background reduction of at least x5 compared to GERDA/MAJORANA. The background goal will be met.

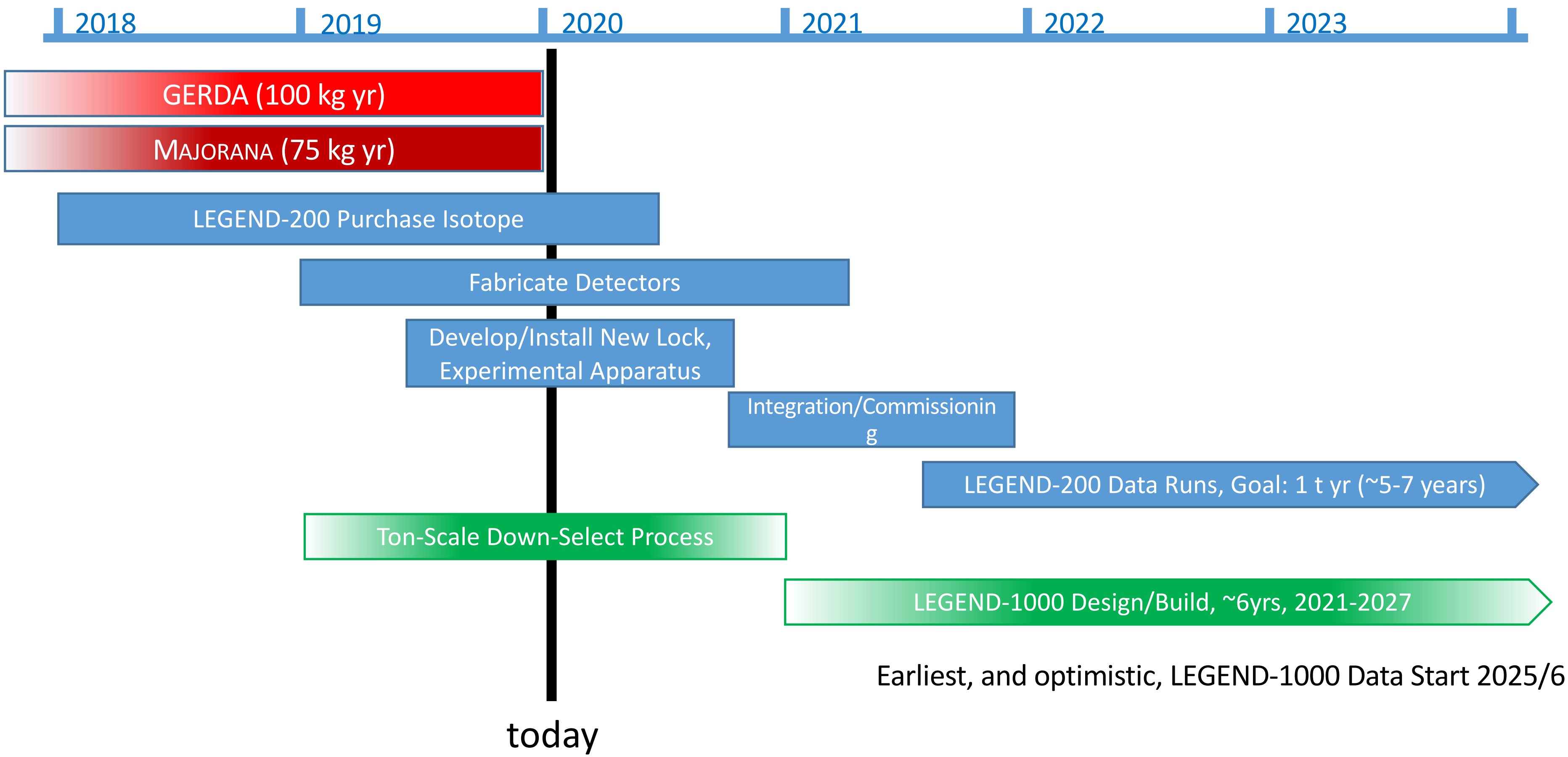
# LEGEND-200 Background Projections




- Monte Carlo simulations based on experimental data and material assays.
- Background rate after anti-coin., PSD, LAr veto cuts.
- Assay limits correspond to the 90% CL upper limit. Grey bands indicate uncertainties in overall background rejection efficiency

$Q_{\beta\beta}$ background index upper limit: **[0.7–2.0] x10−4 cts/(keV.kg.yr)** or **[0.2–0.5] cts/(FWHM.ton.yr)**

# Schedules


2018
2019
2020
2021
2022
2023
GERDA (100 kg yr)
MAJORANA (75 kg yr)
LEGEND-200 Purchase Isotope
Fabricate Detectors
Develop/Install New Lock, Experimental Apparatus
Integration/Commissionin g
LEGEND-200 Data Runs, Goal: 1 t yr (~5-7 years)
Ton-Scale Down-Select Process
LEGEND-1000 Design/Build, ~6yrs, 2021-2027
Earliest, and optimistic, LEGEND-1000 Data Start 2025/6
today

# $^{76}Ge$ procurement

First $GeO_2$ from URENCO (Nl) - 09/18

First metal conversion of URENCO material from PPM (Ge).

24.7 kg from ECP (Ru) – 02/19

20.3 kg from URENCO

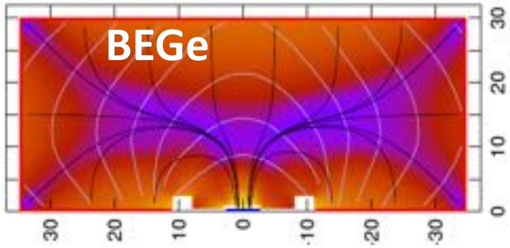
# Ge detectors for LEGEND-200

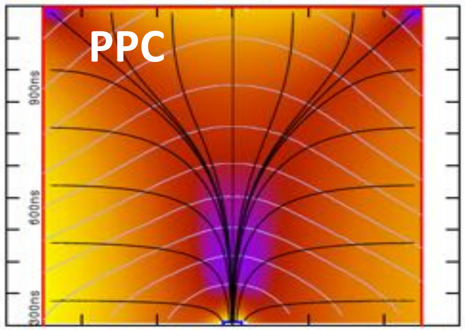
**GERDA BEGes and MAJORANA PPCs**

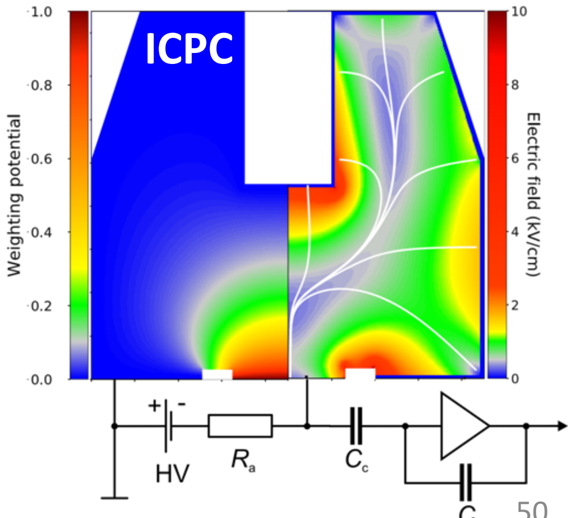
- ✓ Excellent energy resolution
- ✓ Superb pulse-shape sensitivity to reject multi-site and surface background events
- • But relatively small: <m> = 0.66 and 0.85 kg, respectively

**New Inverted-Coaxial Point Contact detectors**

- ✓ First design proposed in 2011 [R. Cooper et al, 11']
- ✓ Large active mass up to 3 kg
- ✓ Excellent pulse shape discrimination performance [YK et al. 18']
- ✓ Lower surface to volume ratio
- ✓ Reduced background due to lower number of channels per mass of $^{76}$Ge
- ✓ Production has started early 2019. About 60 detectors expected by fall 2021

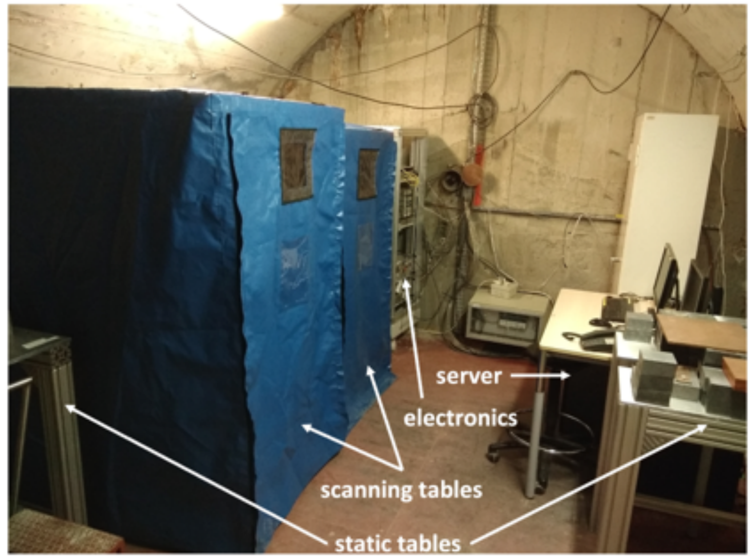


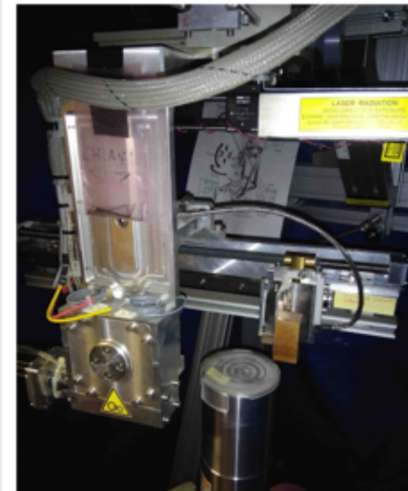



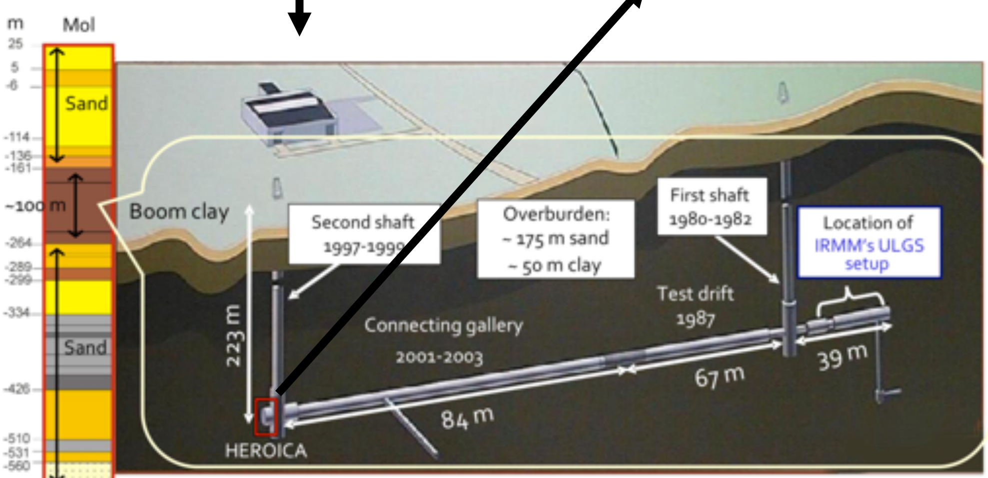



# Underground Ge detector characterization

HADES lab in Mol



$^{241}$Am movable source

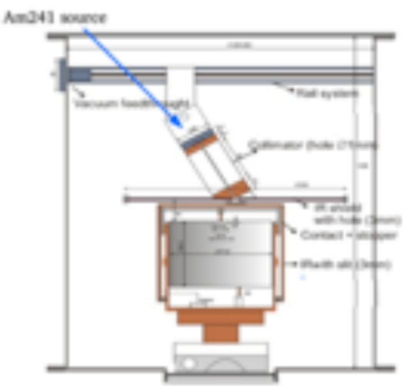



- ✓ Muon-induded activation and background mitigation
- ✓ **6 enriched detectors scanned in October 2019**
- ✓ Performances validated (Energy res., op. voltage, …)
- ✓ Much more to come in 2020


$^{228}$Th static source

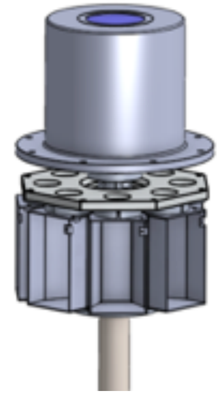
# Detector R&D with natural detectors

**TUBE @TUM**
*running*

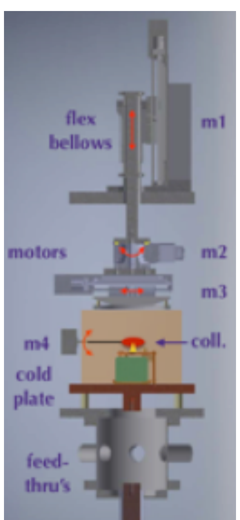



**GALATEA @MPP**
*running*

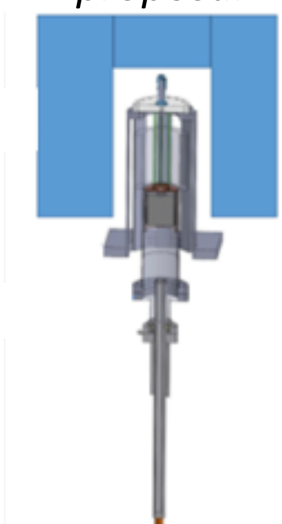

**scanner @LBL**
*proposal*



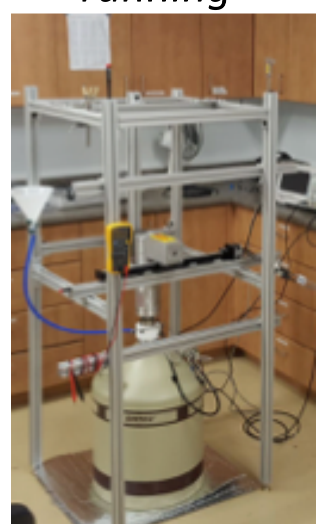
**CAGE @UW**
*commissioning*




**scanner @UNC**
*proposal*



**scanner @Queen's**
*running*



- Large amount of scanners in Europe and in the US
- Allow for position dependence response
- **Crucial for understanding the Pulse Shape Discr.**
- **Surface scans of $\alpha$, $\beta$ and low energy $\gamma$**

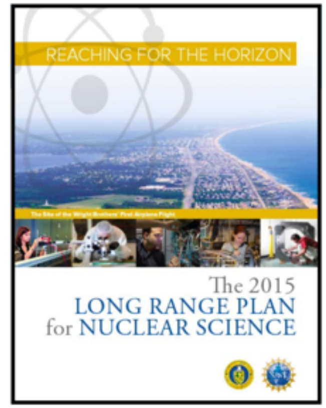
# LAr veto and string assembly

- **LAr veto**
  - ➢ Take advantage of GERDA experience
  - ➢ Design studies + fibers production ongoing
  - ➢ Optimization of light collection

- **14 $^{76}$Ge detector strings positioning**
  - ➢ Extensive Monte-Carlo simulations
  - ➢ Compromise between background and cuts efficiency
  - ➢ Statistics for weekly calibration

# LEGEND-1000 considerations

- **Down-selection process in the US**
  in competition with nEXO – CUPID – (?)



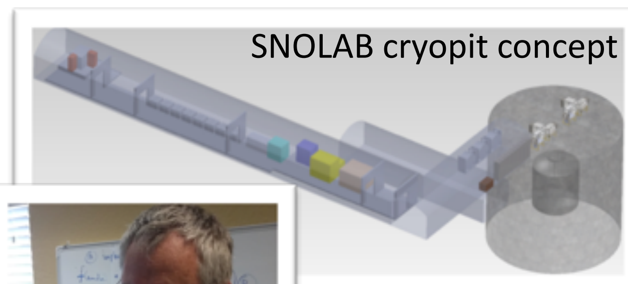

"We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment."

[arXiv:1910.04688]

- **Recommandation from the APPEC**
  Astroparticle Physics European Consortium

| |
|---|
| *Recommendation 3. A multi-isotope program at the highest level of sensitivity should be supported in Europe in order to mitigate the risks and to extend the physics reach of a possible discovery.* |

- **Initial concept includes:**
  - x6 background suppression w.r.t. LEGEND-200
  - Deeper hosting lab (LNGS under investigation)
  - LAr veto depleted in $^{42}$K
  - R&D for even larger Ge detectors
  - Cleaner fabrication process


SNOLAB cryopit concept

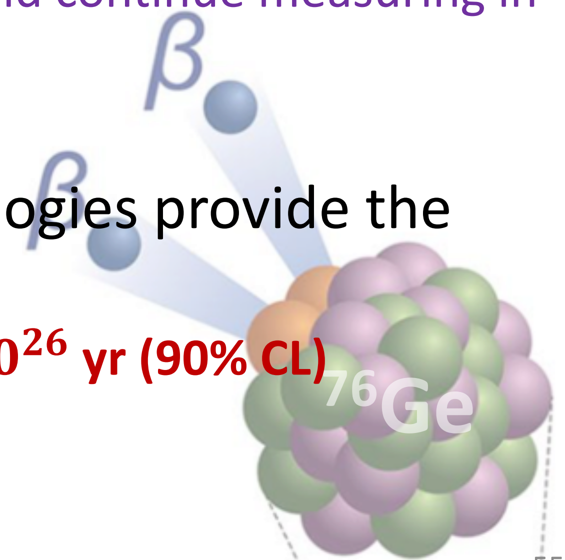

6 kg Ge ICPC "mock-up" about a factor of two larger than any previous single-crystal detector!

# Summary

- $0\nu\beta\beta$ decay, if discovered, has far reaching consequences in particle physics! $\boldsymbol{\nu = \overline{\nu}}$ / **LNV** / **interplay with cosmology** (many isotopes needed!)

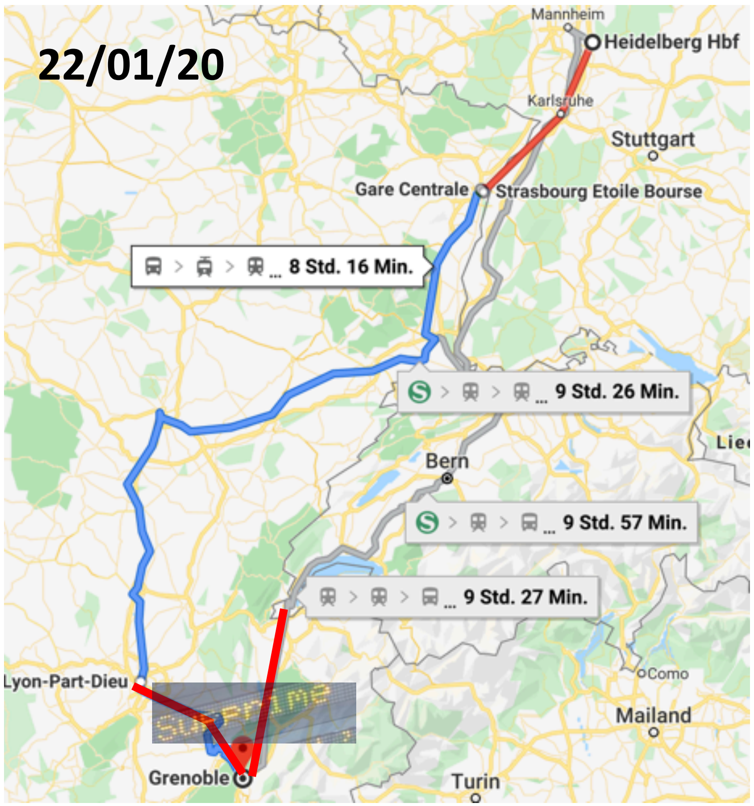
- $^{76}$Ge isotope offers excellent properties especially for signal discovery:
  - ➢ Energy resolution, background-free regime, high detection efficiency
  - ➢ Possibility to reach $T_{1/2}^{0\nu} = 10^{28}$ yr sensitivity
  - ➢ "the new physics is at **any** corner!" therefore we should continue measuring in all directions, regardless of physics models

- GERDA and Majorana Demonstrator best technologies provide the path to next generation experiment
  - ➢ First time **to surpass the $\mathbf{10^{26}}$ yr sensitivity**: $\mathbf{1.1 \times 10^{26}}$ **yr (90% CL)**
  - ➢ First LEGEND-200 detectors produced
    Ongoing efforts to start in 2021!



# Like trains …

… the most difficult part is to reach the final step …



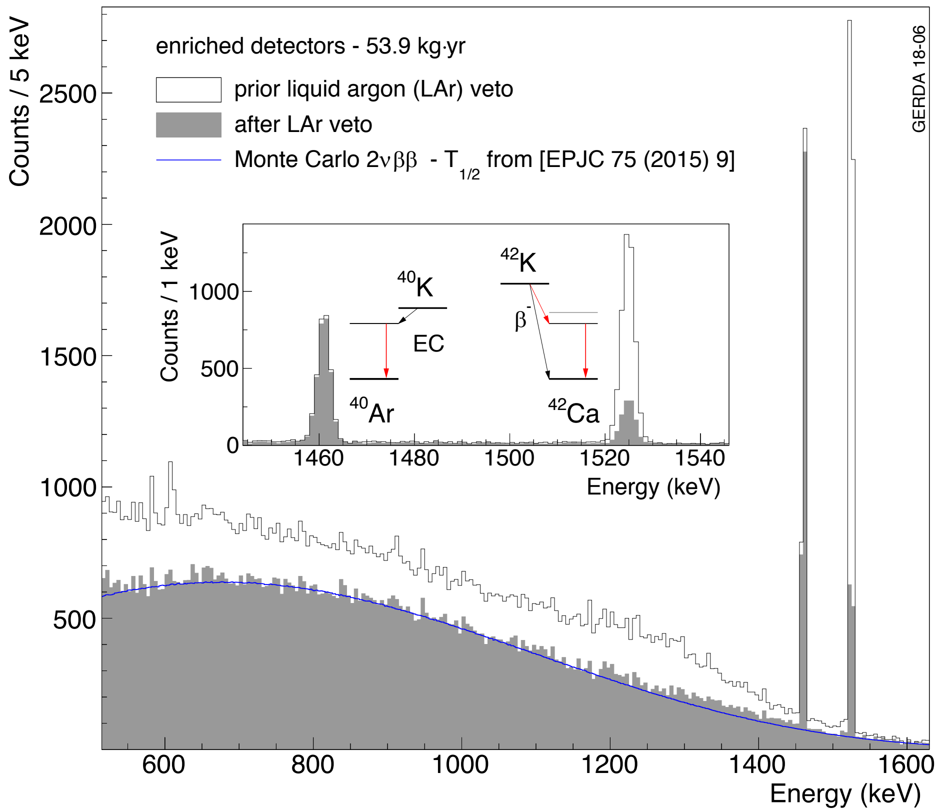

| Type de circulation | |
|---|---|
| N° de circulation | 96648 |
| | |
| ! GENÈVE CFF | 18:42 |
| BELLEGARDE-SUR-VALSERINE GARE | 19:11 |
| CULOZ | 19:46 |
| ANNECY | - |
| RUMILLY | - |
| AIX LES BAINS - LE REVARD | 20:07 |
| CHAMBERY-CHALLES-LES-EAUX | 20:21 |
| MONTMÉLIAN | |
| PONTCHARRA SUR BRÉDA ALLEVARD | |
| GRENOBLE UNIVERSITÉS GIÈRES | |
| GRENOBLE Gare Routière | |
| GRENOBLE | |

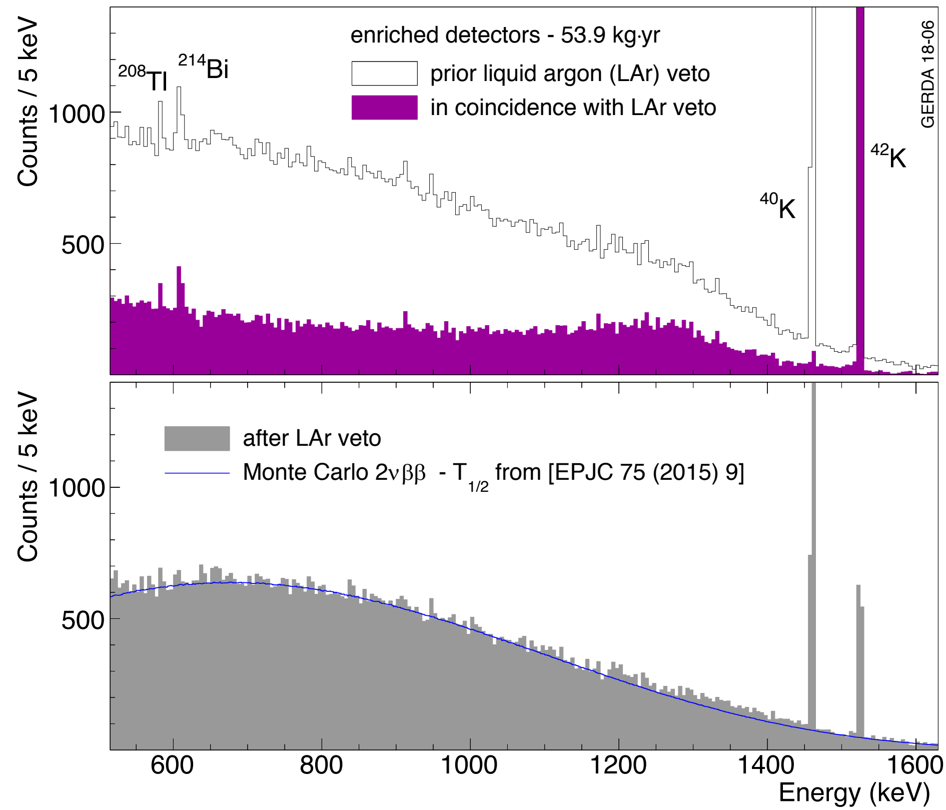
… but we finally make it to the final destination!

**So let's remain optimist!**

# LAr veto efficiency

No suppression of $^{40}$K – all energy contained in Ge detector
High suppression of $^{42}$K - $\gamma$ accompanied with a beta making light in LAr



# A/E pulse shape discimination

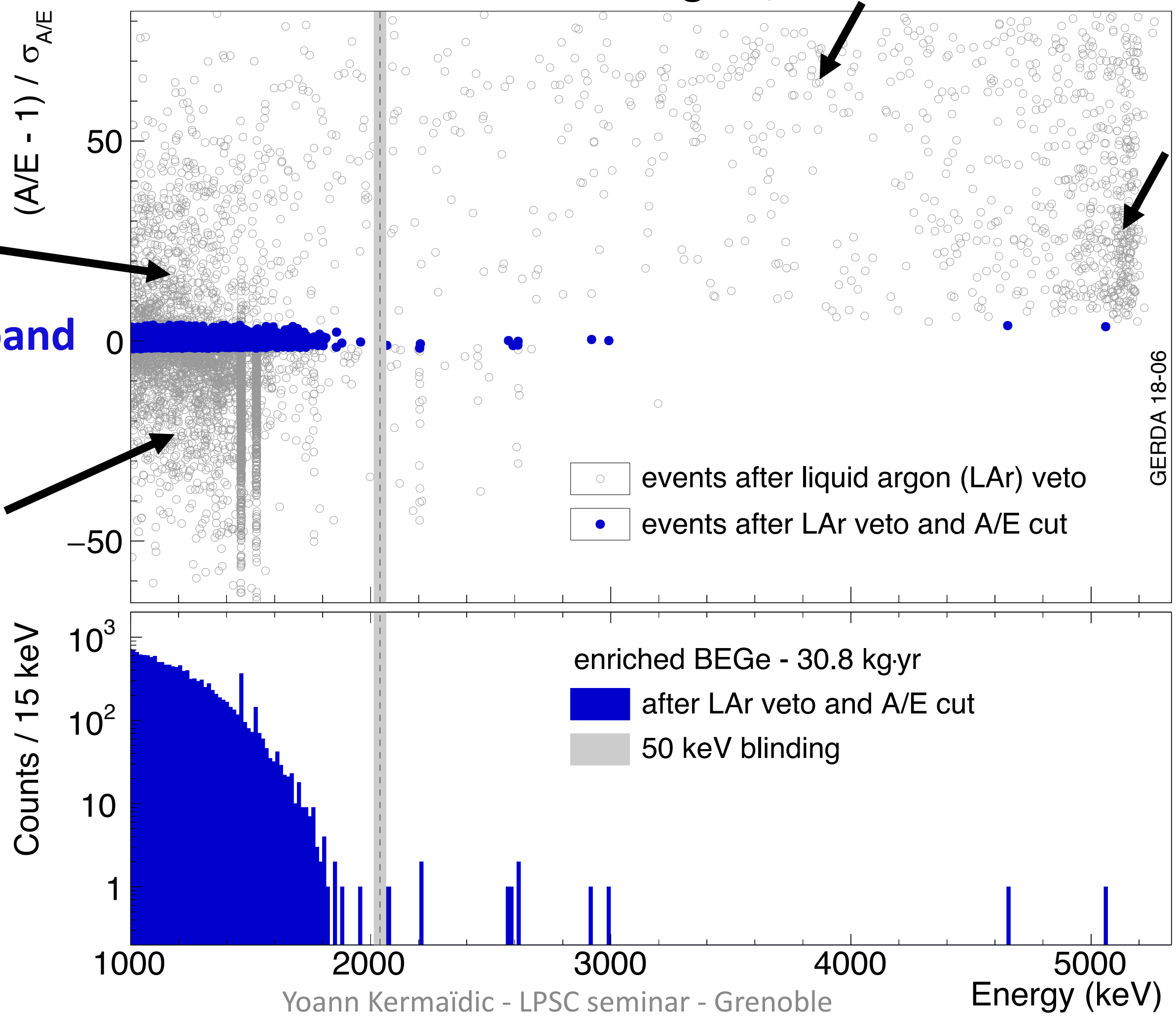
degraded Alpha events
on the p-contact
high A/E

near p-contact
Single-Site events
high A/E

Alpha events on
the p-contact
high A/E

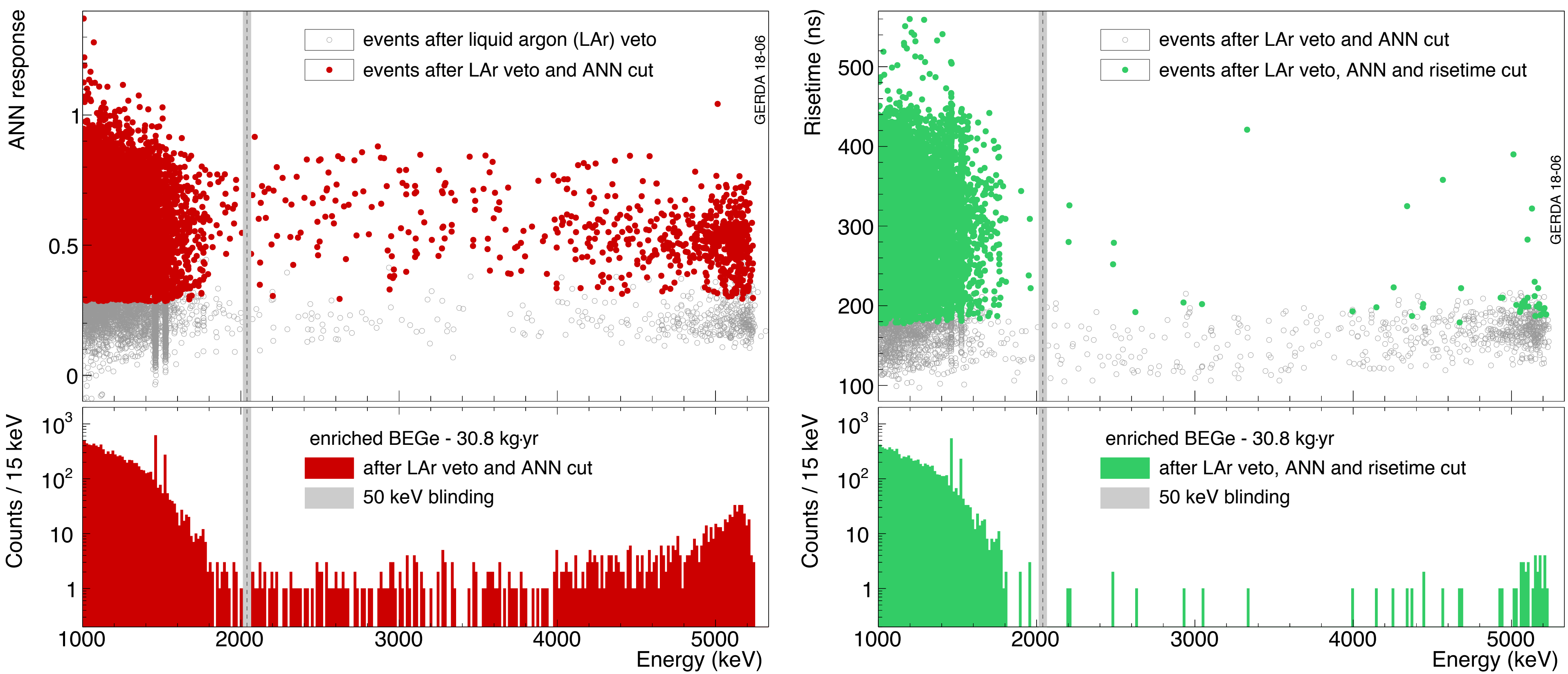
**Single-Site events band**

Multi-Site events
+ Surface
low A/E

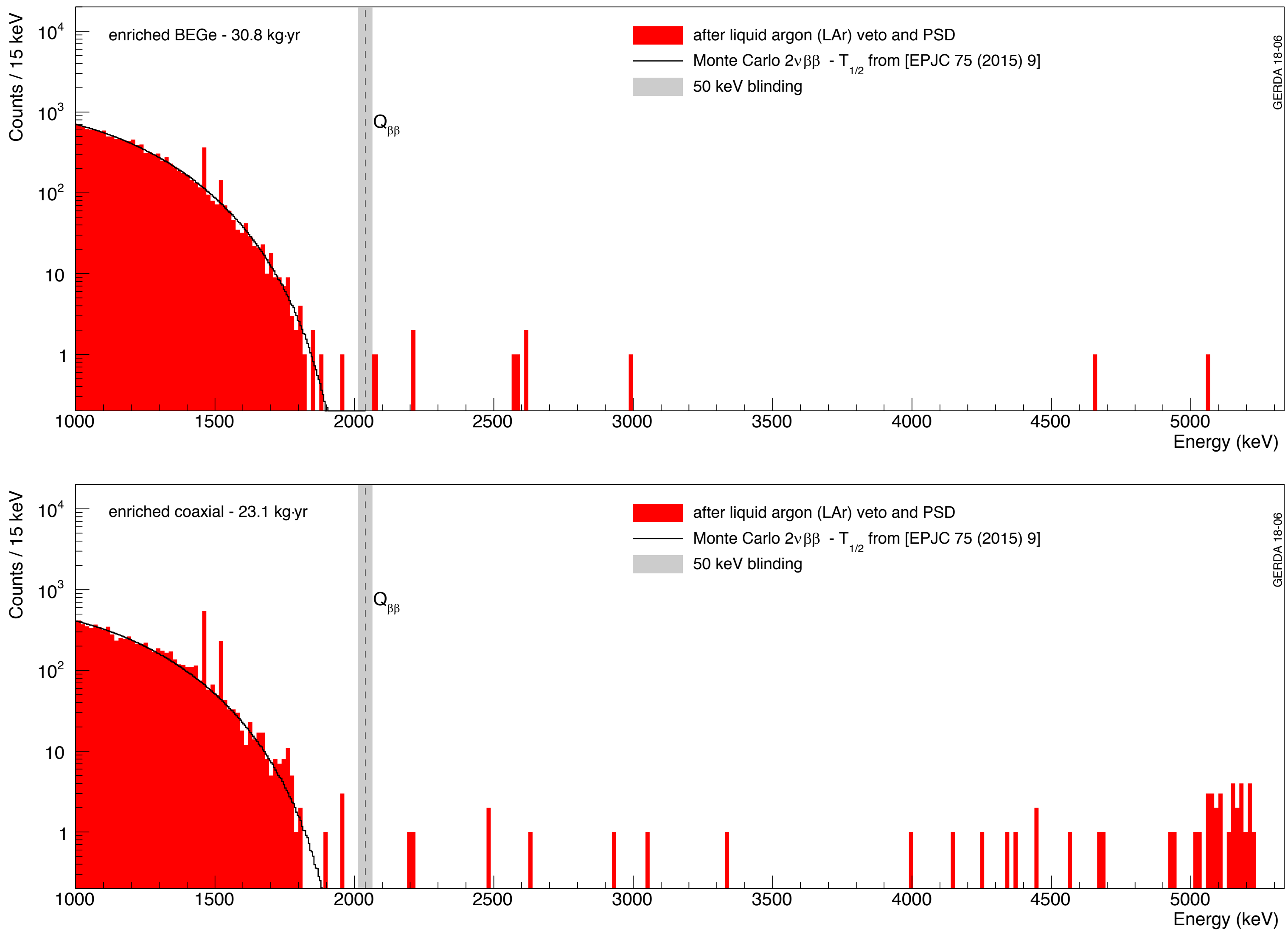


# Semi-coax detector PSD

**Aritificial Neural Network** trained on SSE / MSE discrimination – High alpha rate surviving
**Risetime** cut set to remove fast « p-contact » events – high proportion of alphas

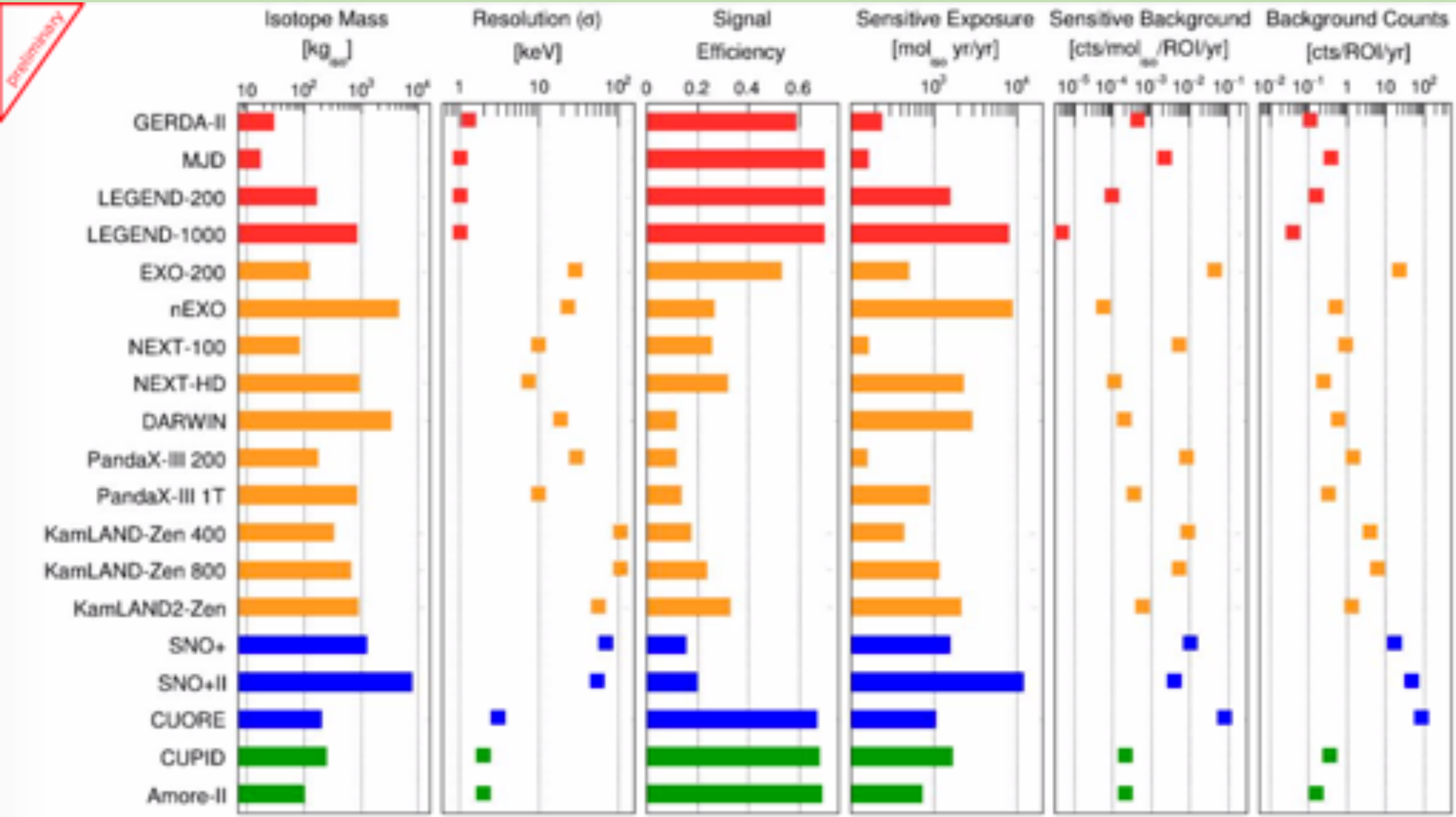


# GERDA energy spectrum after all cuts



# Exhaustive review

slide from M. Agostini (TAUP 2019)




$^{76}$Ge – $^{136}$Xe – $^{130}$Te – $^{100}$Mo