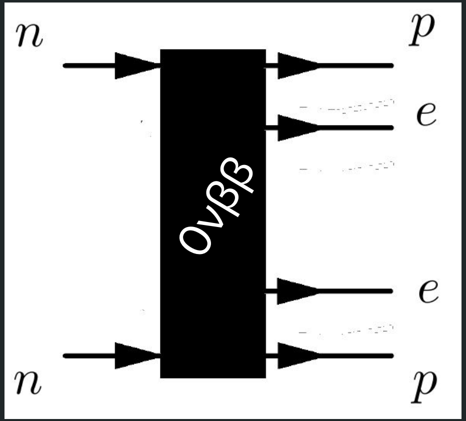
New Results from GERDA

Matteo Agostini for the GERDA Collaboration

Technical University of Munich (TUM)

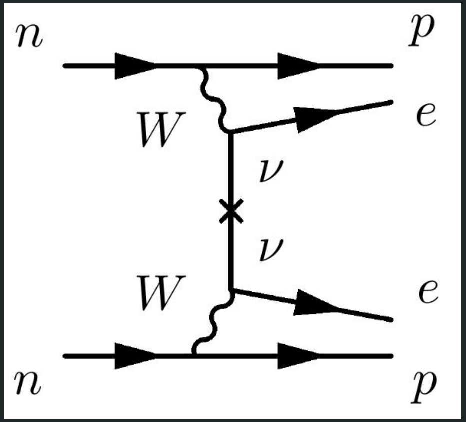
Astroparticle Physics in Germany, Set 17-19 2018, Mainz

Neutrinoless Double-β Decay



Hypothetical nuclear transition:

- ➢ foreseen by many extensions of the SM
- ➢ 2 leptons created from pure energy → matter creation
- ➢ possible only if neutrinos are Majorana particles



Minimal SM extension → 3 **massive Majorana** neutrinos:

- ➢ probability proportional to $\boldsymbol{m_{\beta\beta}}(\theta_{12}, \theta_{13}, m_1, m_2, m_3, \alpha_1, \alpha_2)$
- ➢ interplay with oscillation experiments → $m_{\beta\beta} > 17$ meV for IO
- ➢ interplay with neutrino direct mass searches and cosmology

Neutrinoless Double-β Decay

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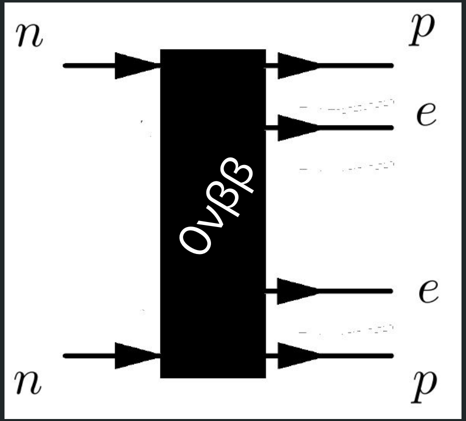
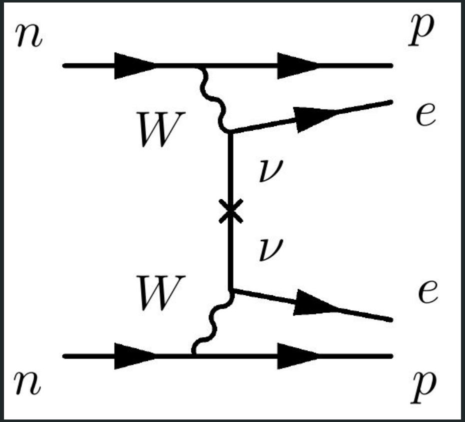




Minimal SM extension → 3 **massive Majorana** neutri...

- probability proportional...
- in... meV for IO
- ...et mass searches and cosmology

$T_{1/2}$ limits in the range 10^{21} - 10^{26} yr

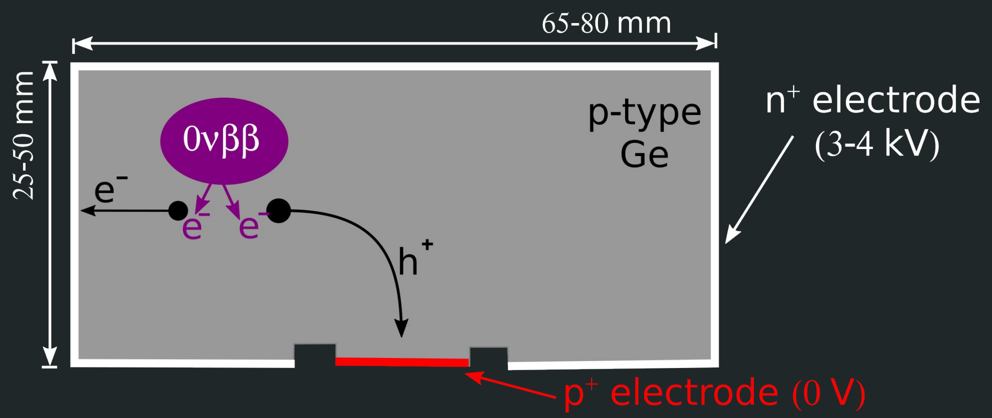
< 50% chance for an atom to decay in 100 trillion times the age of the Universe

GERDA Detection Strategy

Search for 0νββ decay of $^{76}Ge \rightarrow {}^{76}Se + 2e^-$

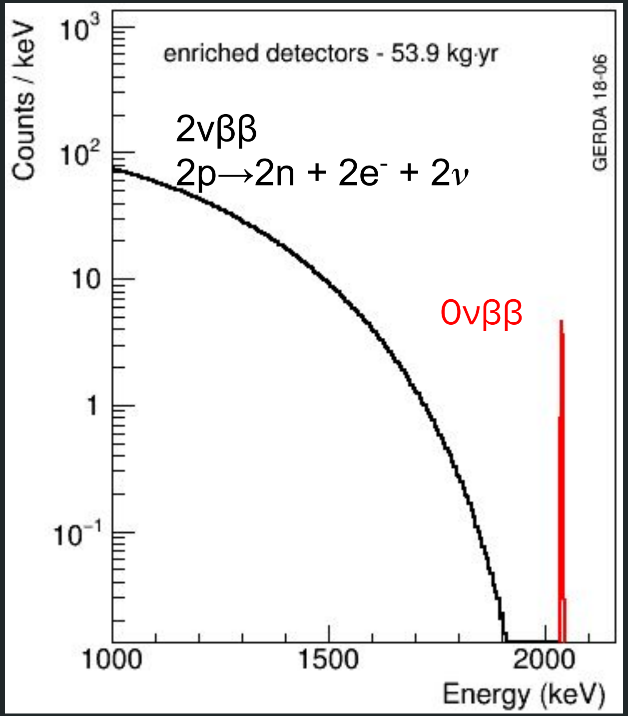
Semiconductor Ge detectors (87% ^{76}Ge):

- source = detector → high efficiency
- radio-pure → no intrinsic background
- high density → e^- absorbed in ~1 mm
- semiconductor → $\Delta E < 0.1\%$ at $Q_{\beta\beta}$



0νββ signature:

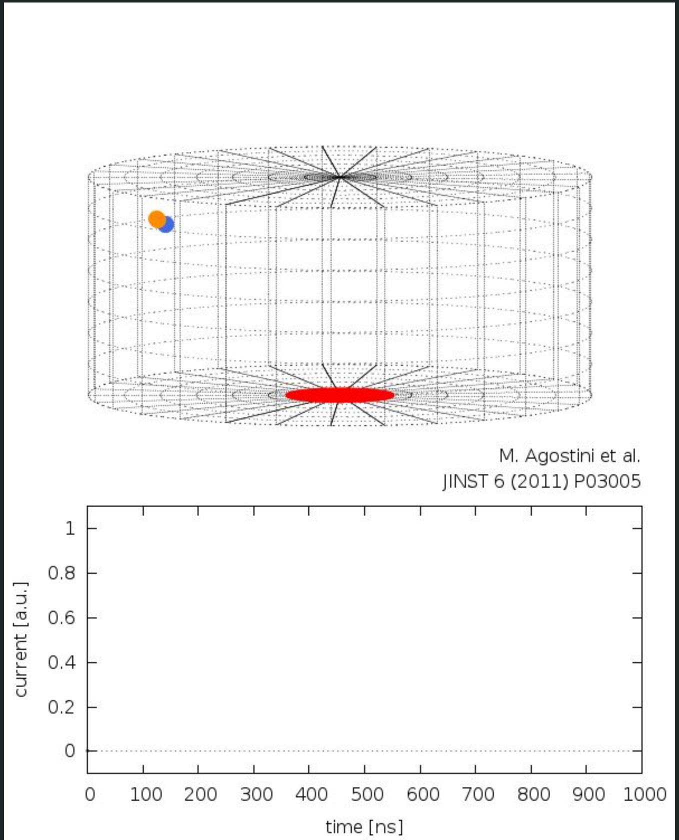
- point-like event in bulk volume
- sharp energy peak at 2039 keV (FWHM = 3-4 keV)



Signal/Background Discrimination

Ge detector as time-projection chambers:

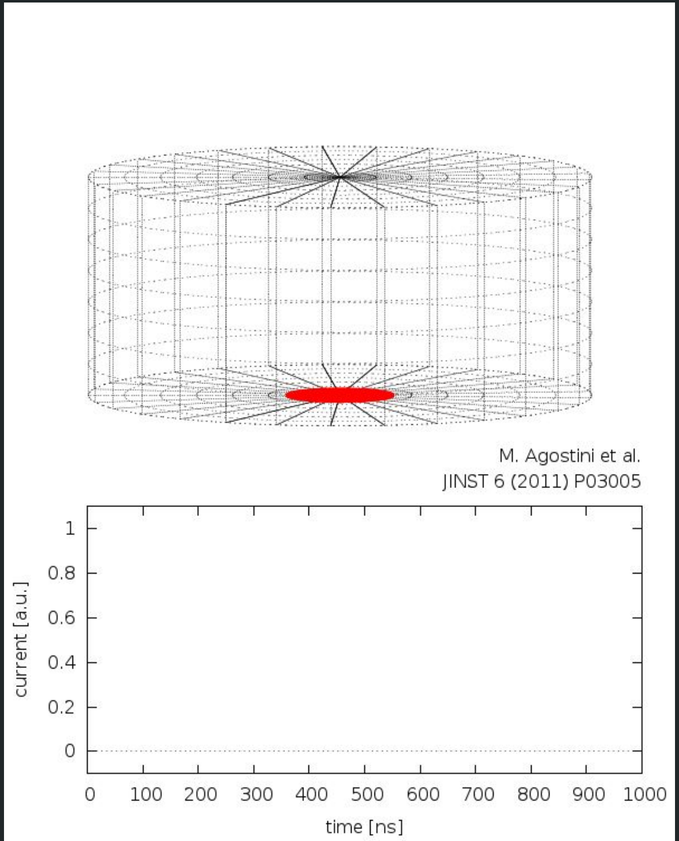
➢ 0νββ events ➔ single site interactions in bulk volume



Signal/Background Discrimination

HPGe detector as time-projection chambers:

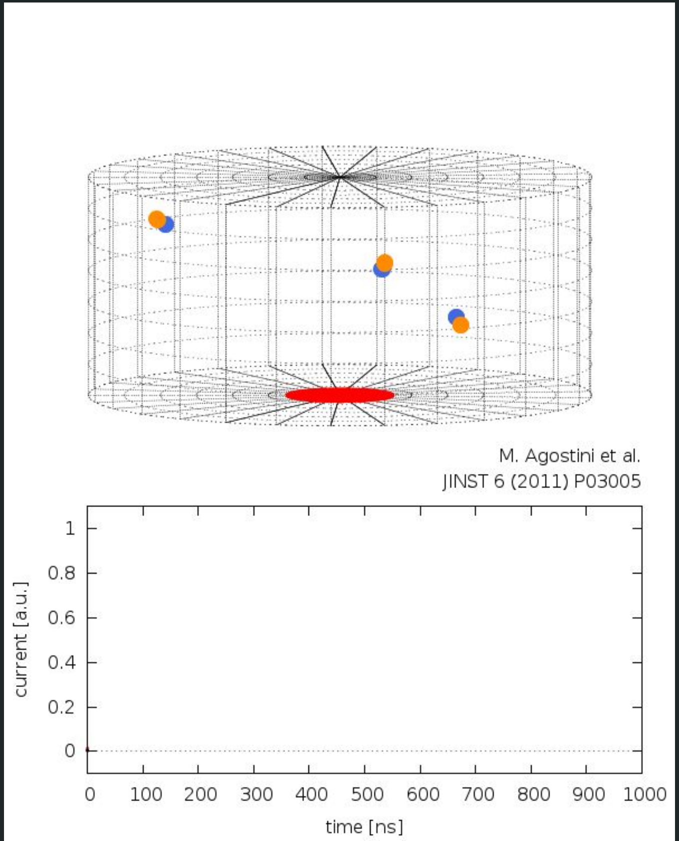
➢ $0\nu\beta\beta$ events → single site interactions in bulk volume



Signal/Background Discrimination

HPGe detector as time-projection chambers:

- ➢ 0νββ events ➔ single site interactions in bulk volume
- ➢ γ-rays ➔ multiple Compton scattering



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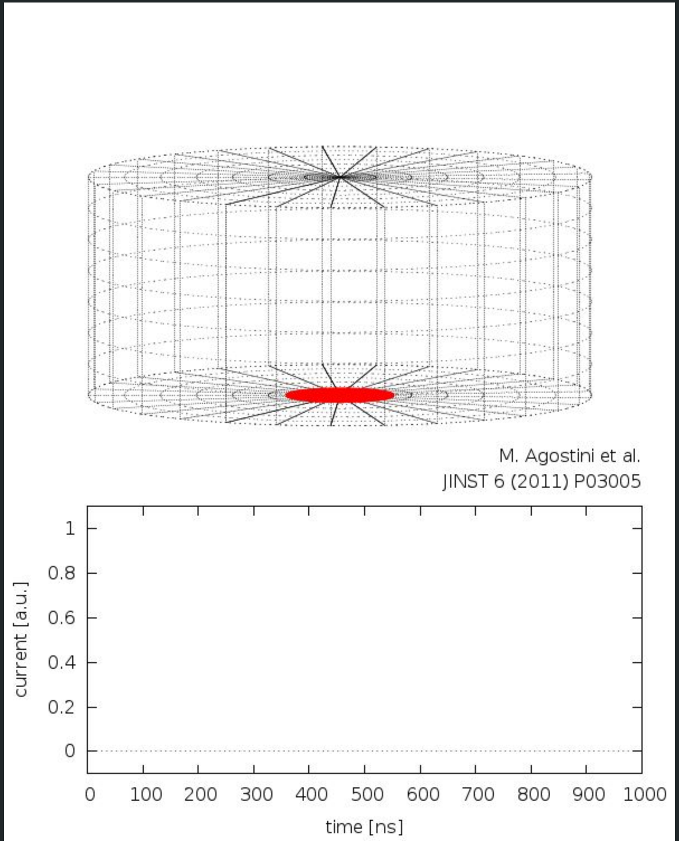

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- ➢ 0νββ events ➔ single site interactions in bulk volume
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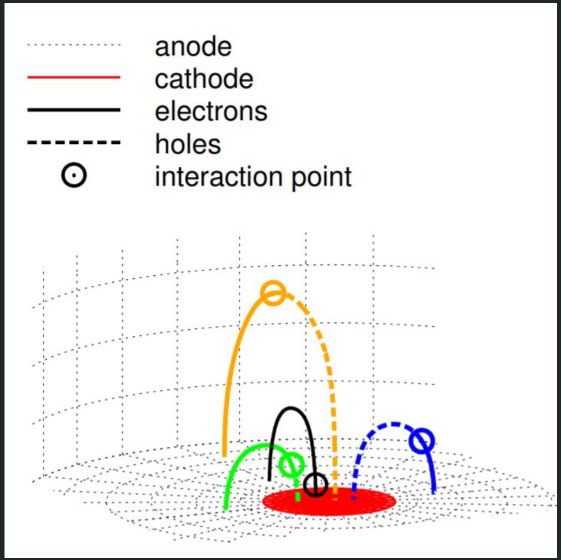
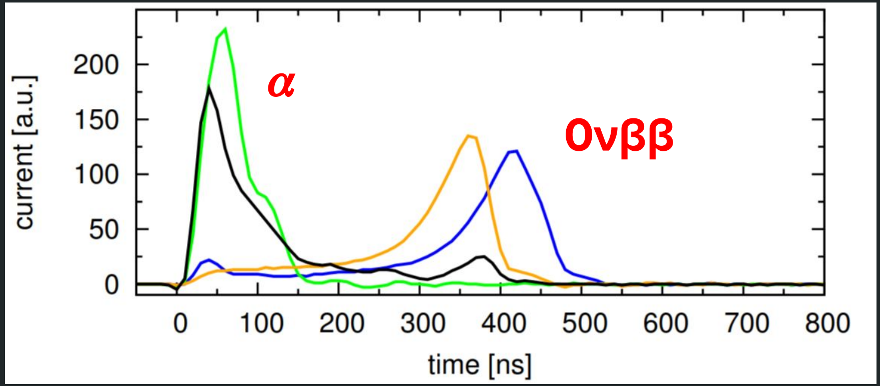
- ➢ <u>α/β-rays</u> <u>➔ surface events</u>





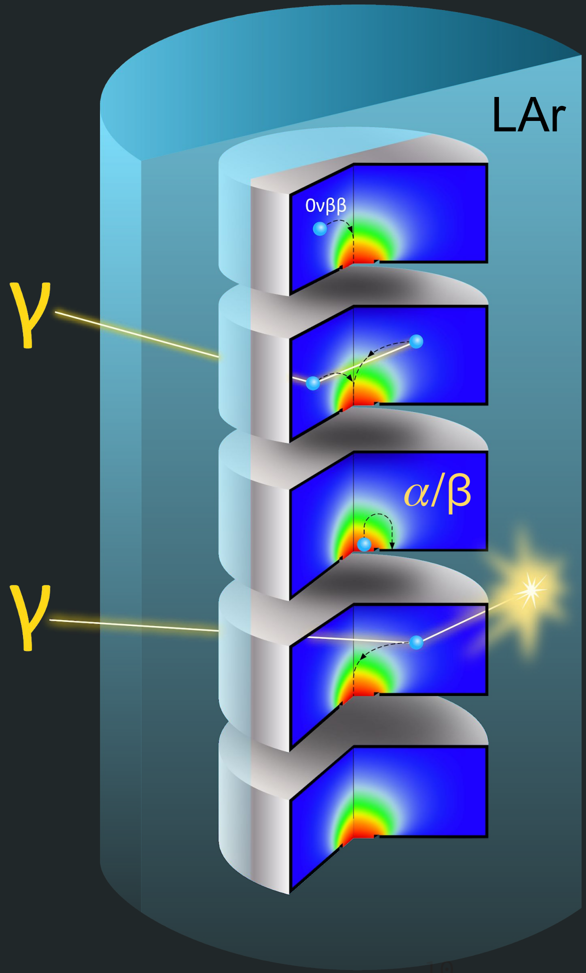
Signal/Background Discrimination

HPGe detector as time-projection chambers:

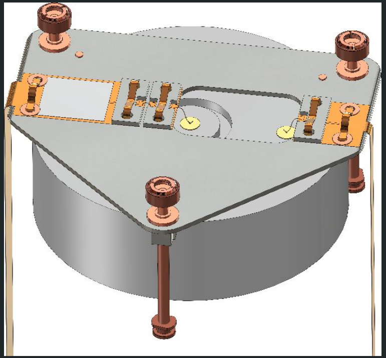
- ➢ 0νββ events → single site interactions in bulk volume
- ➢ γ-rays → multiple Compton scattering
- ➢ α/β-rays → surface events

Liquid Argon (LAr):

- ➢ keep detectors at operational temperature
- ➢ ultrapure shield against radioactivity
- ➢ active veto against backgrounds releasing energy in LAr



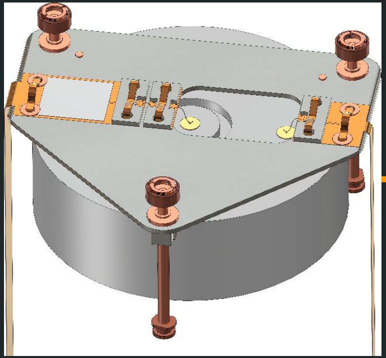
The Setup



Detectors mounting:

- ➢ low mass holders
- ➢ contacting with wire bonding

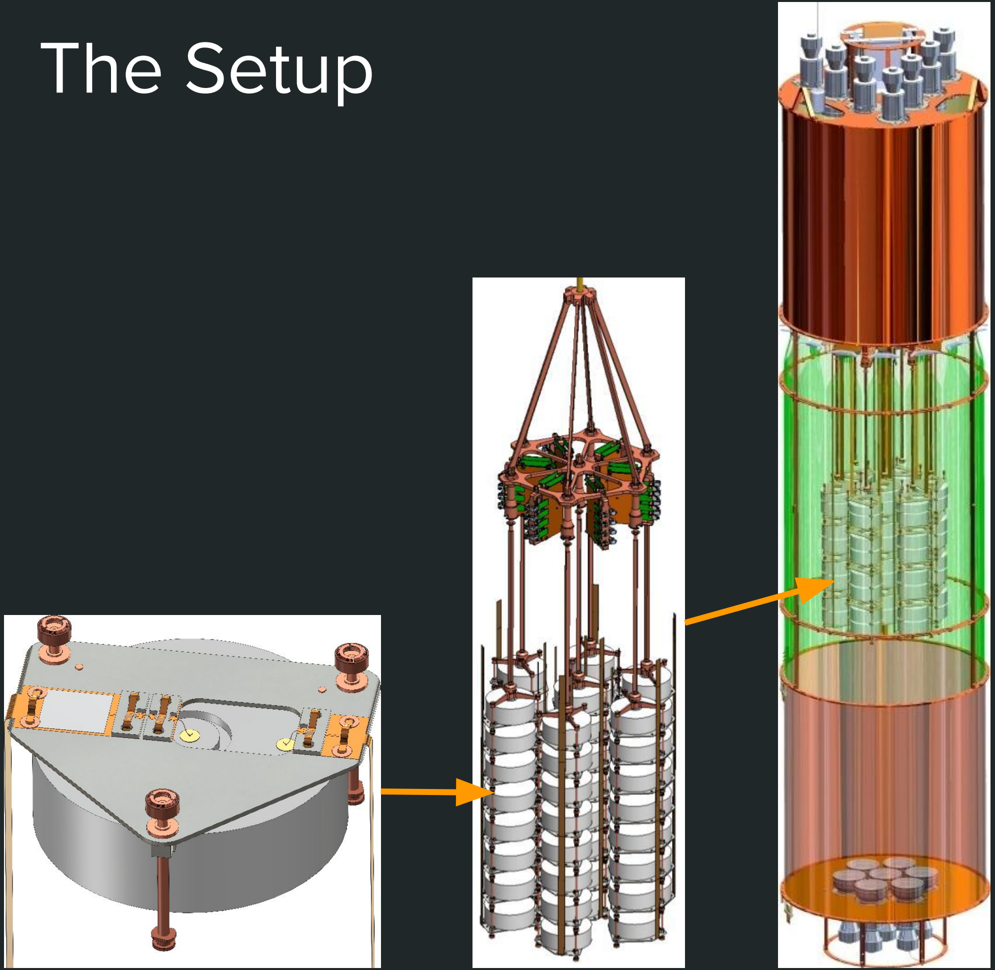
The Setup



Array deployed in Dec 2015:

- ➢ 7 strings / 40 detectors
- ➢ 30 enriched BEGe (20 kg)
- ➢ 7 enriched Coax (15.6 kg)
- ➢ 3 natural Coax (7.6 kg)

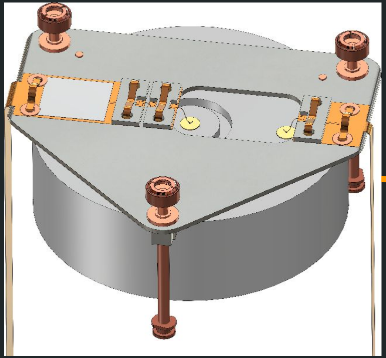
The Setup

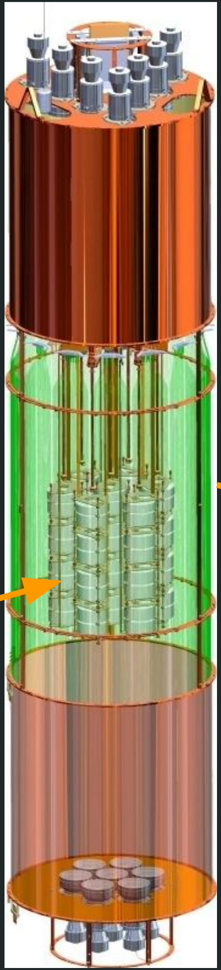


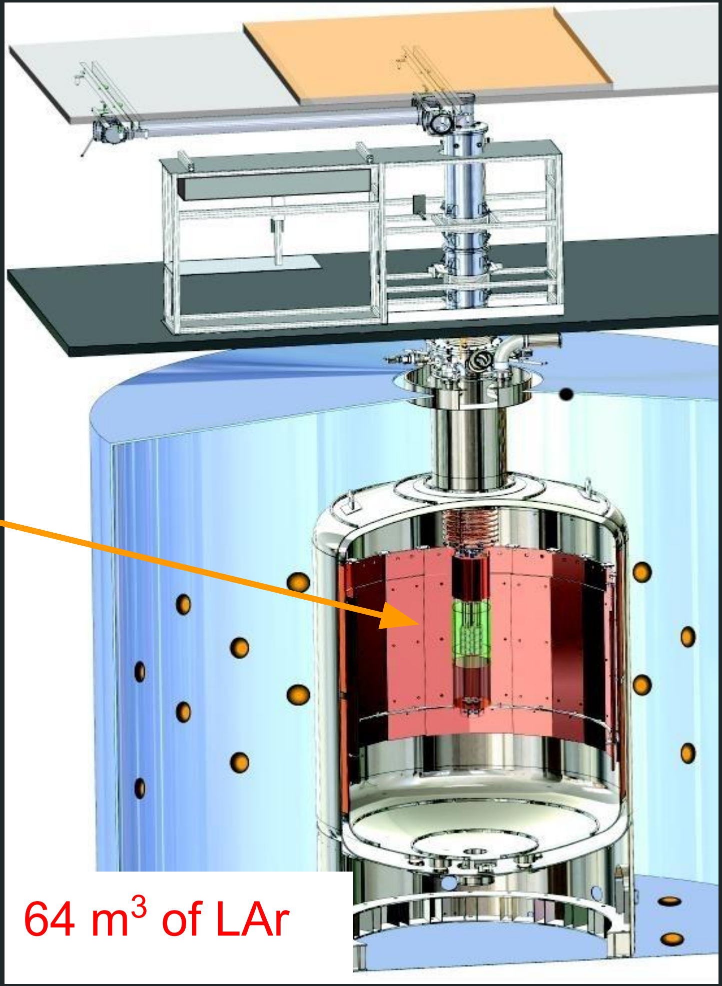
LAr scintillation detection:

- 16 PMTs (9 top / 7 btm)
- ~1 km fibers with WLS + 90 SiPMs
- nylon mini-shroud around each string coated with WLS

The Setup







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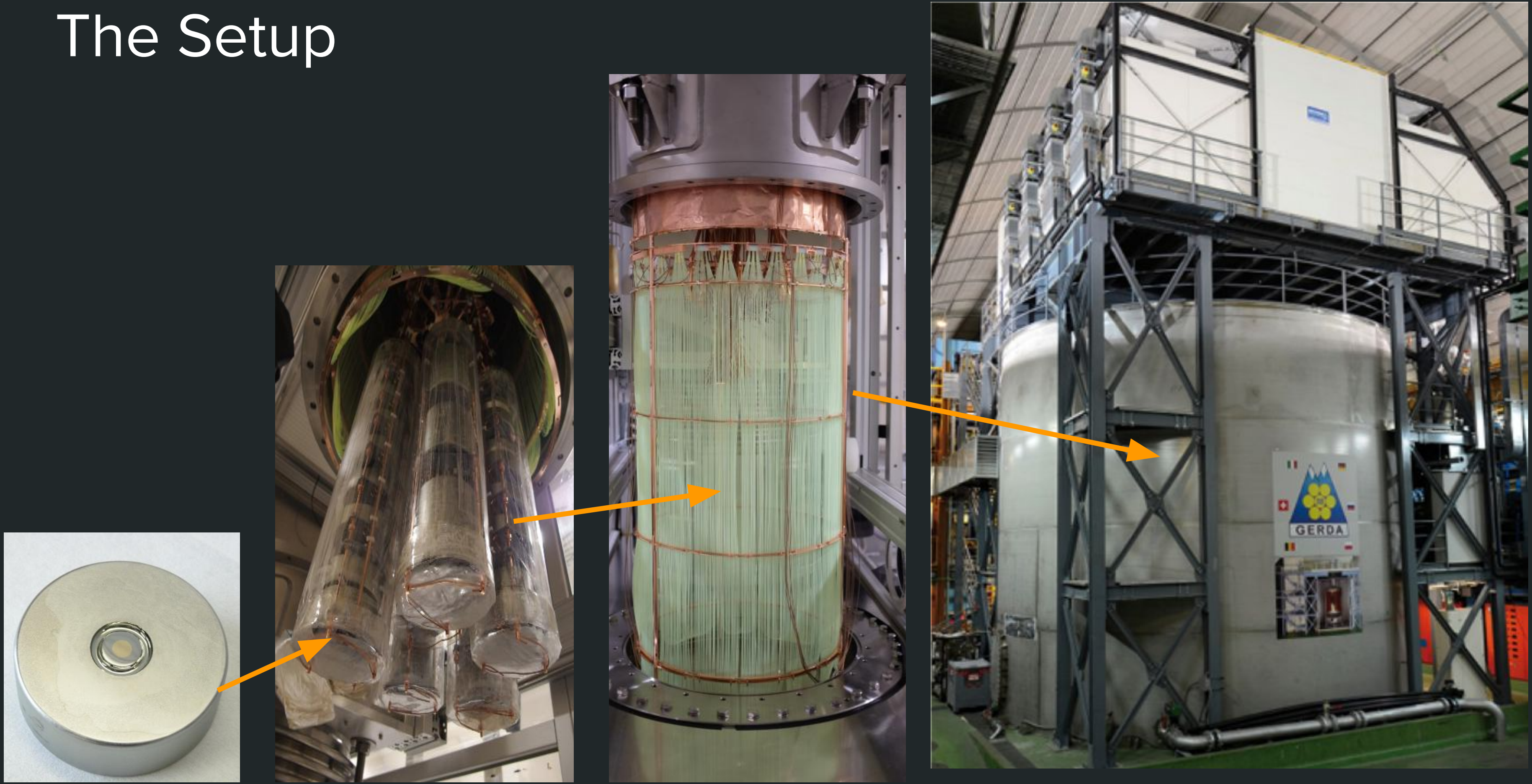
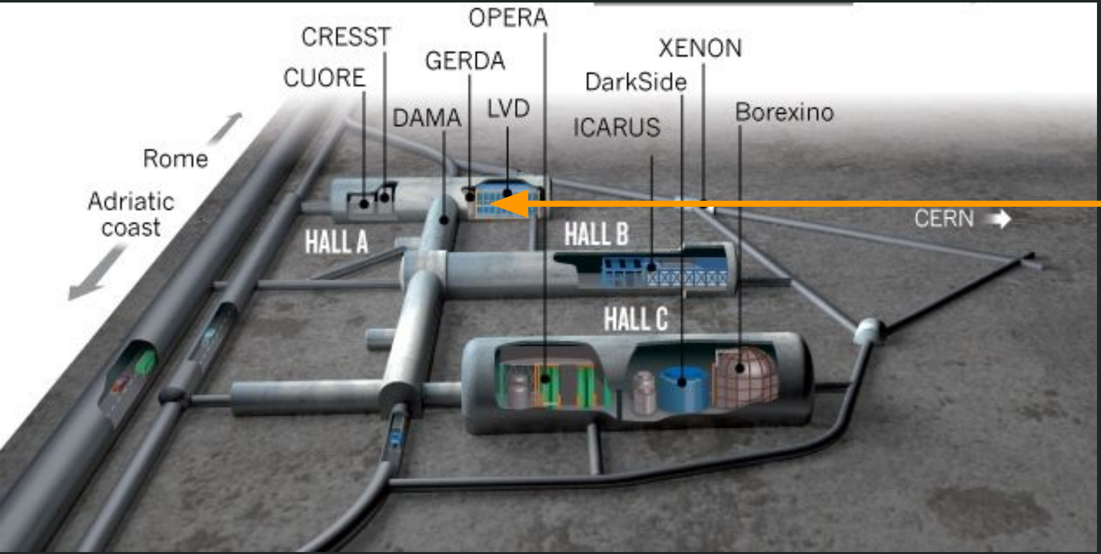
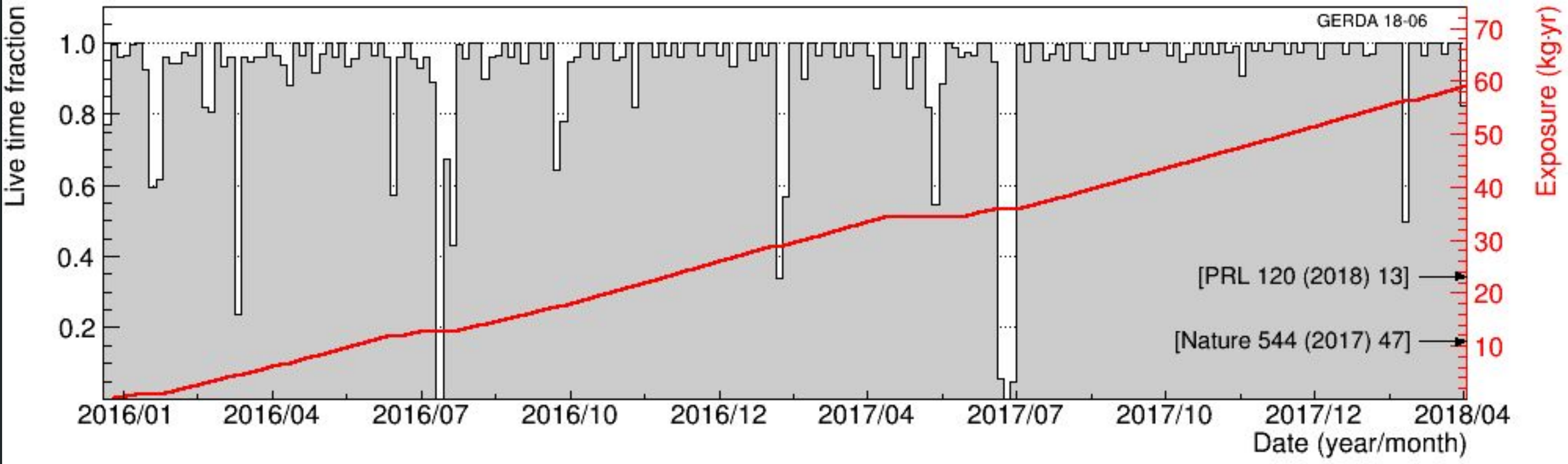


The Setup

LNGS (INFN)
3500 m.w.e.

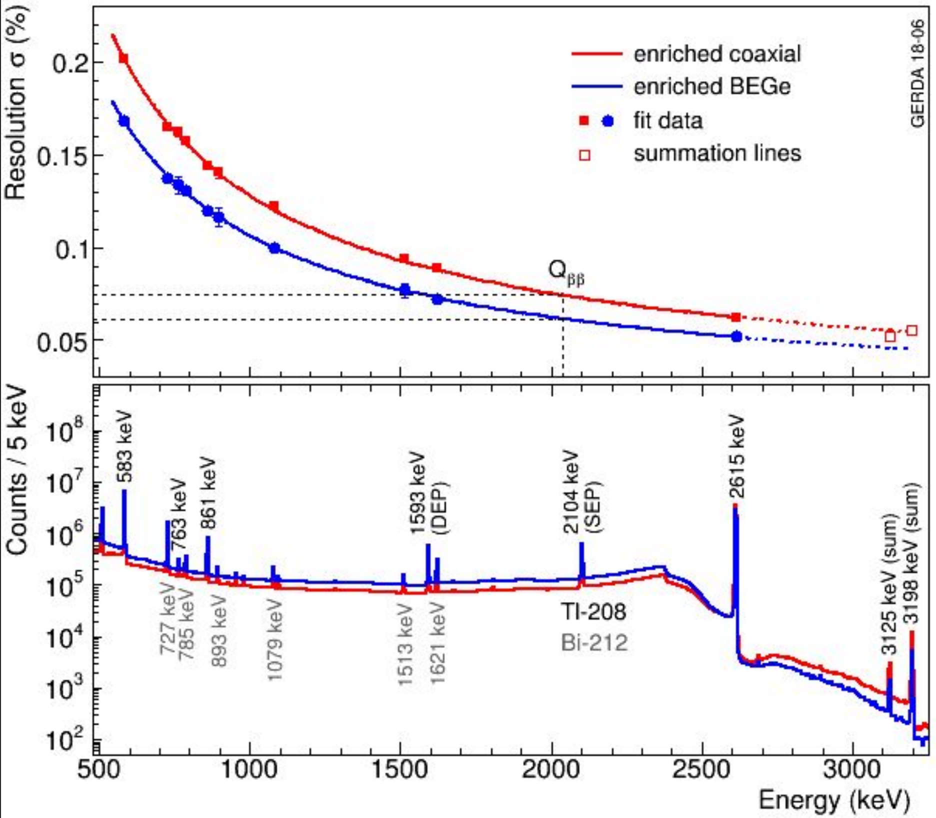


Phase II Data Taking

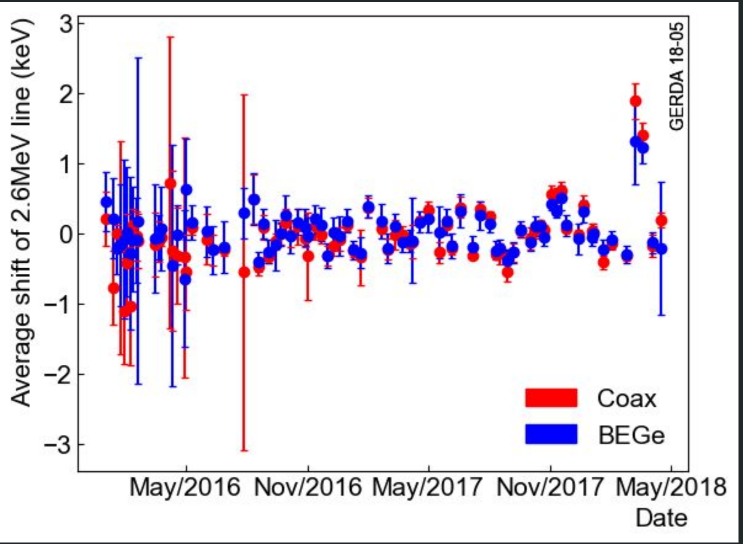


- Dec 2015 → Apr 2018: 835 d live time
- 93% duty cycle
- Phase II Exposure: 59 kg yr
- Phase I + Phase II: 82 kg yr

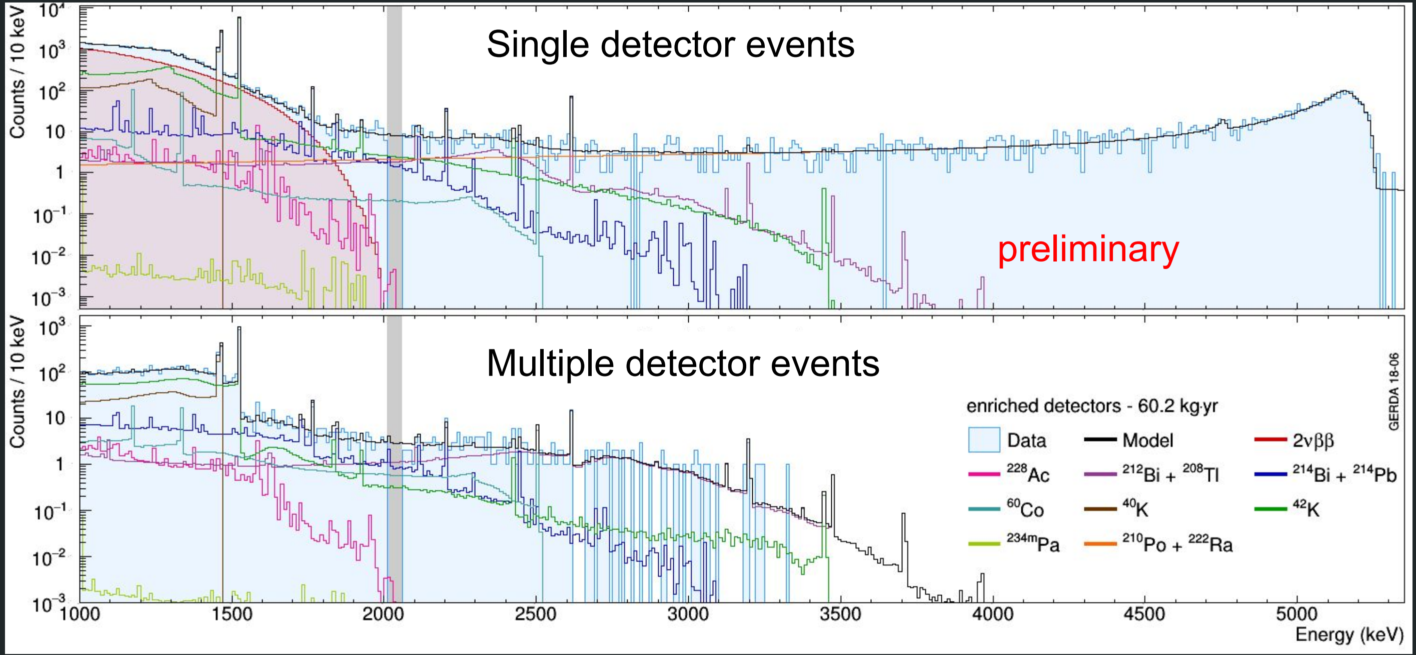
Energy Scale



- ➢ Weekly calibration with Th-228 sources
- ➢ Fluctuations between calibrations <1 keV
- ➢ Resolution at $Q_{\beta\beta}$ better than 0.1% (3-4 keV FWHM)

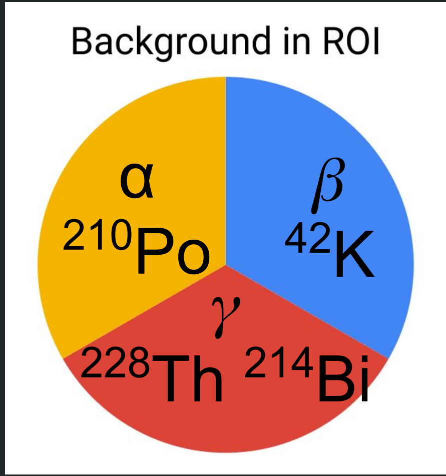


The Background Before Analysis Cuts



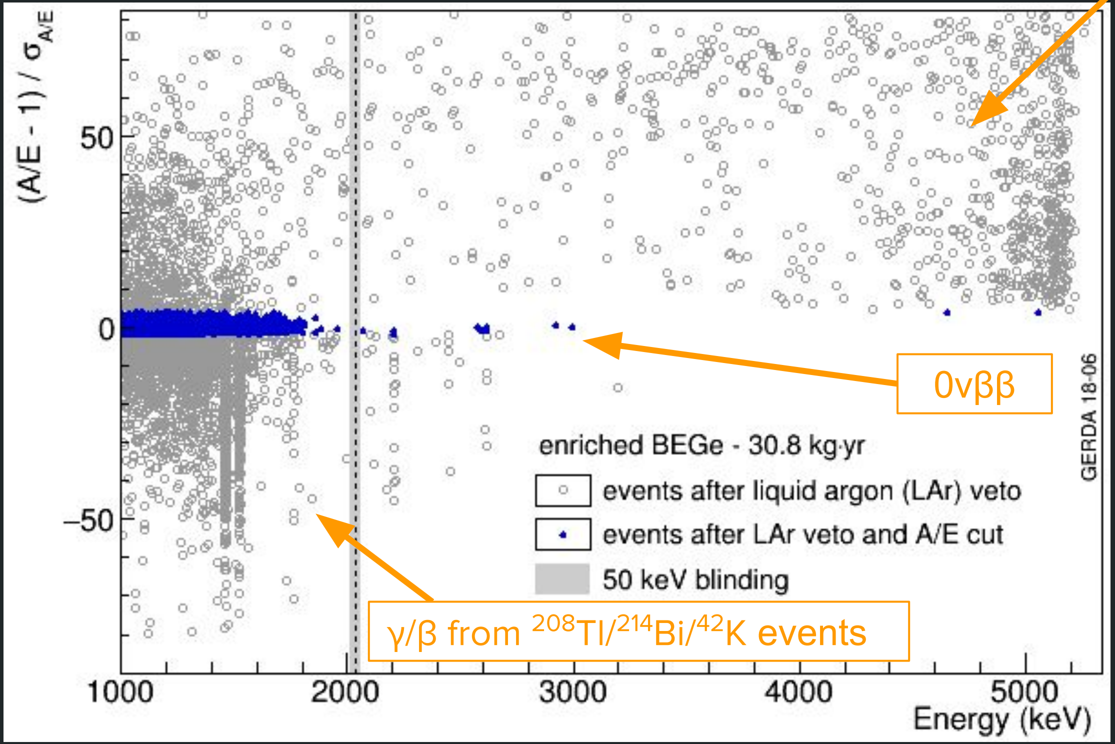
Multivariate fit:

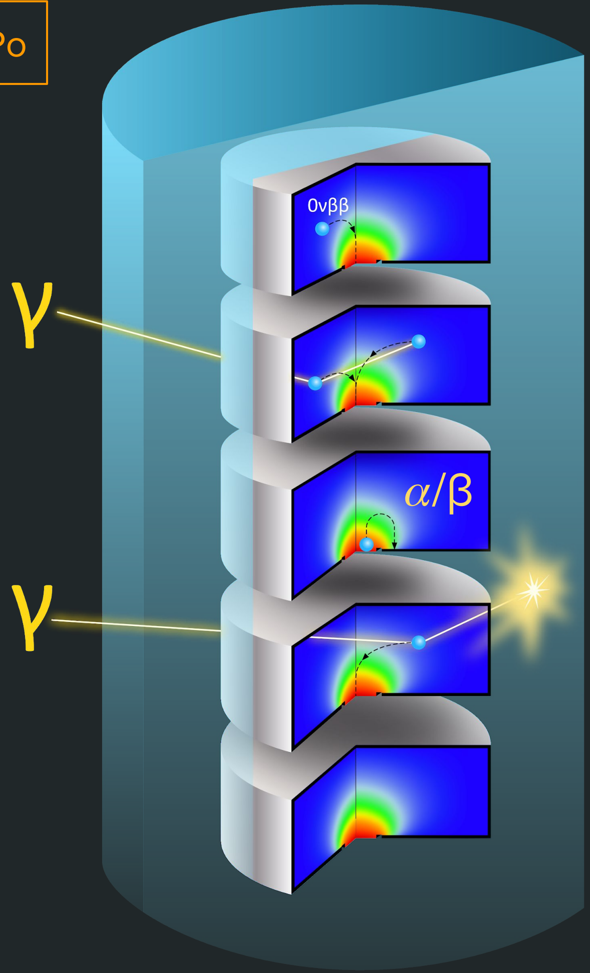
- ➢ multiplicity 1 & 2 events
- ➢ detectors type and position
- ➢ screening as priors



- ➢ α-decays from ^{210}Po and ^{222}Rn (surface events on p+ electrode)
- ➢ β-decays from ^{42}K in the LAr (surface events on n+ electrode)
- ➢ γ-decays from ^{228}Th & ^{214}Bi in cables & holders & electronics

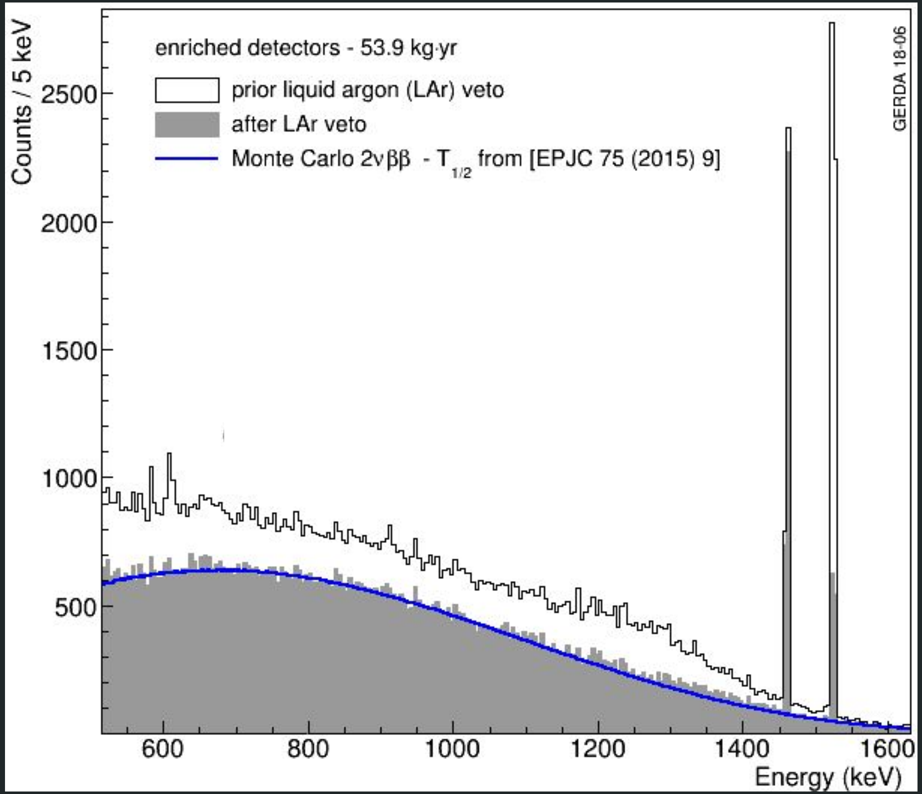
Pulse Shape Discrimination



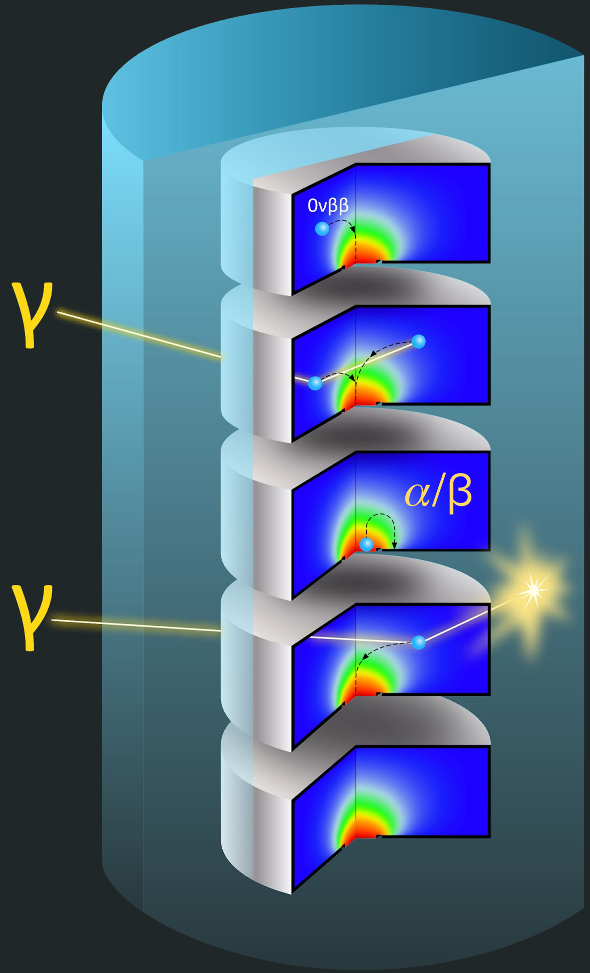


0νββ efficiency ➜ ε_{BEGe}= (87.6+2.5)% ε_{coax}= (71.2+4.3)%

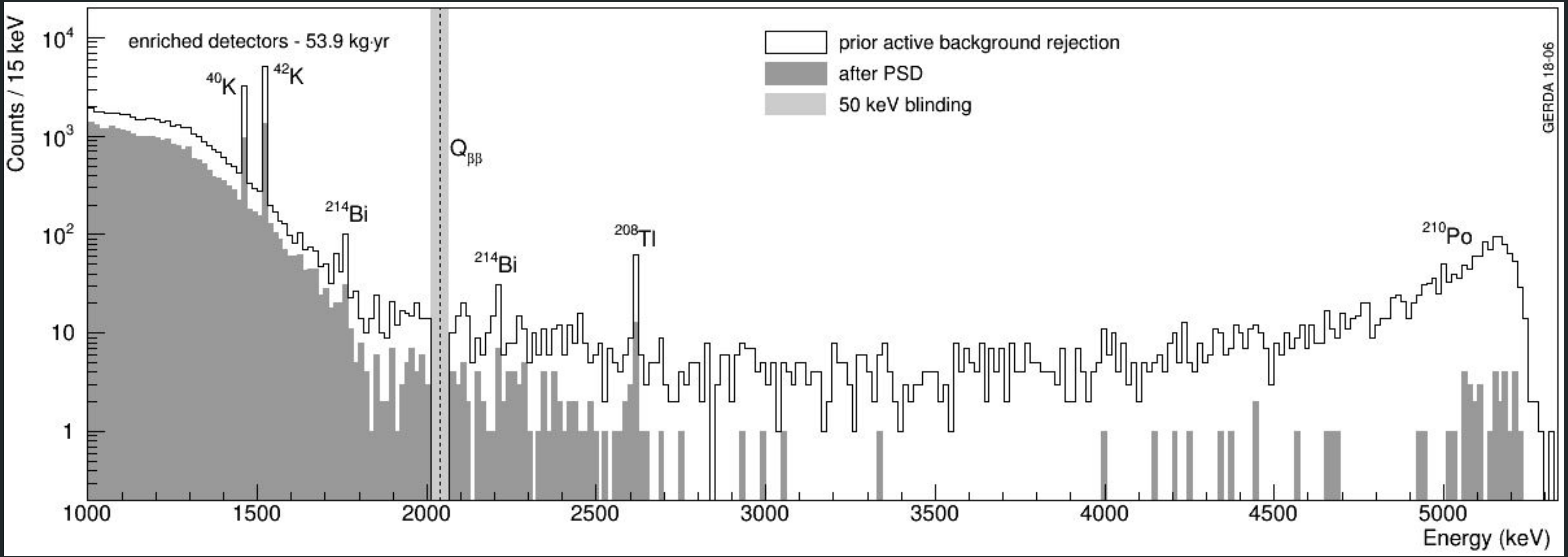
LAr Scintillation Anti-Coincidence



Dead time
~2%

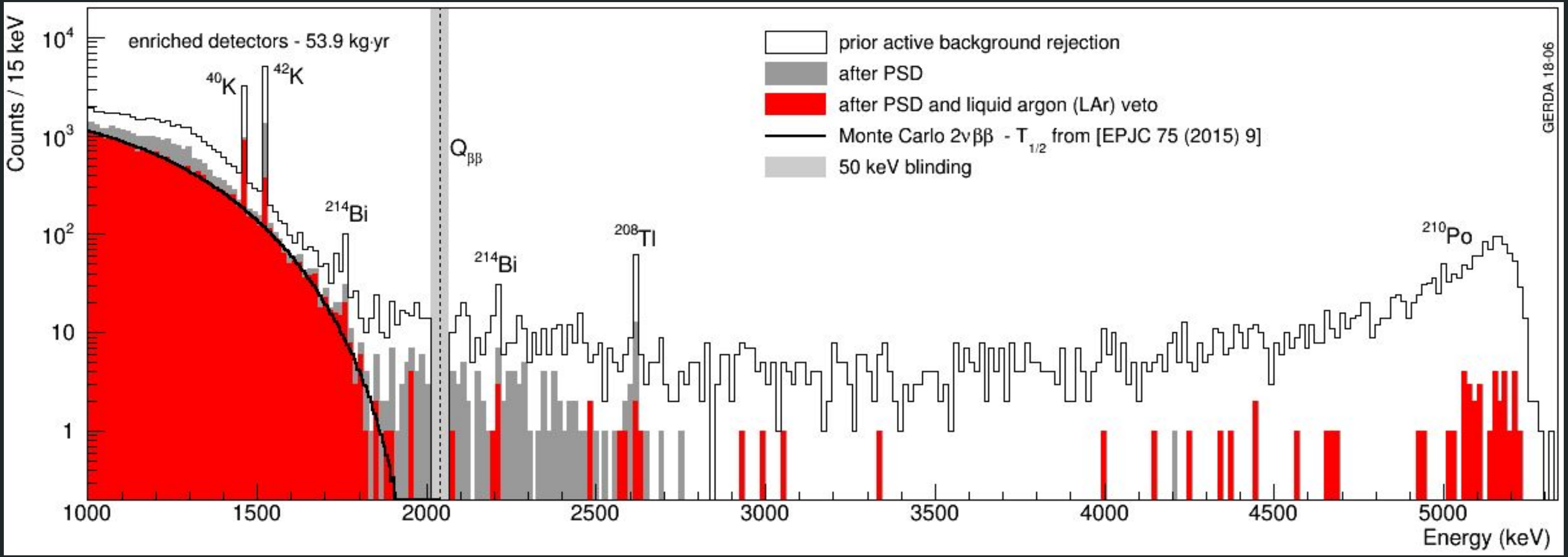


Active Background Suppression



PSD: α/β background suppressed by a factor 100   PSD+LAr: γ background suppression by a factor 6-200

Active Background Suppression



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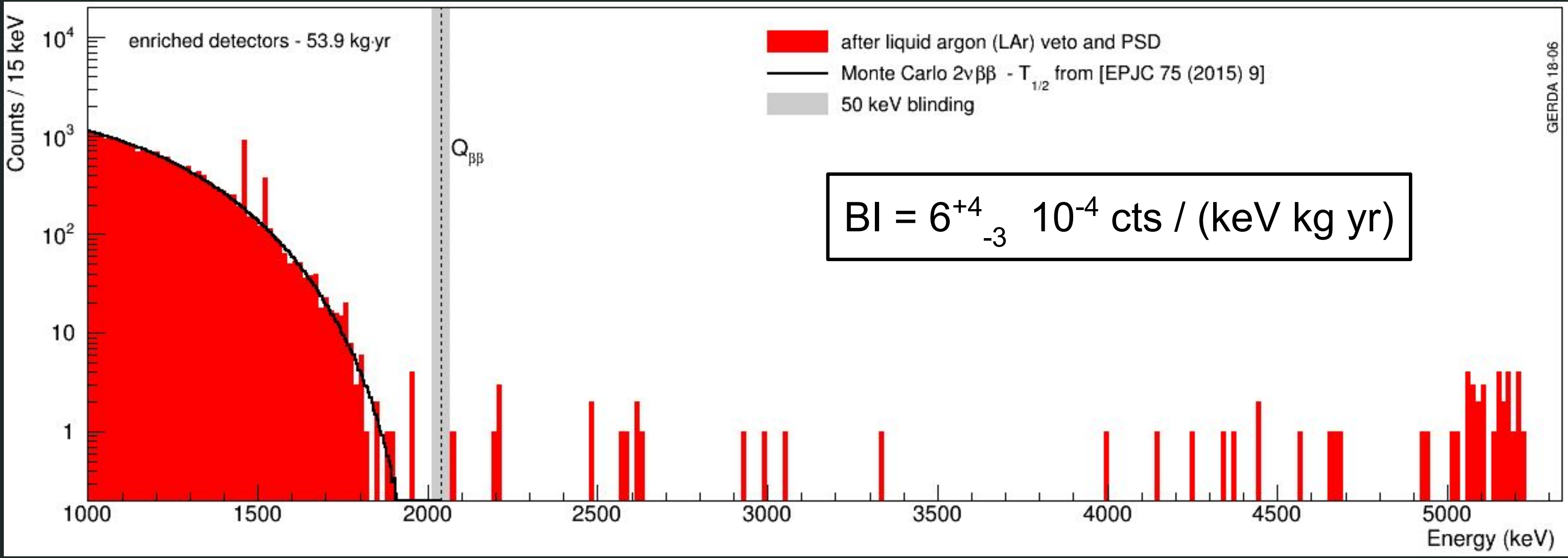


$BI = 6^{+4}_{-3}\ 10^{-4}$ cts / (keV kg yr)

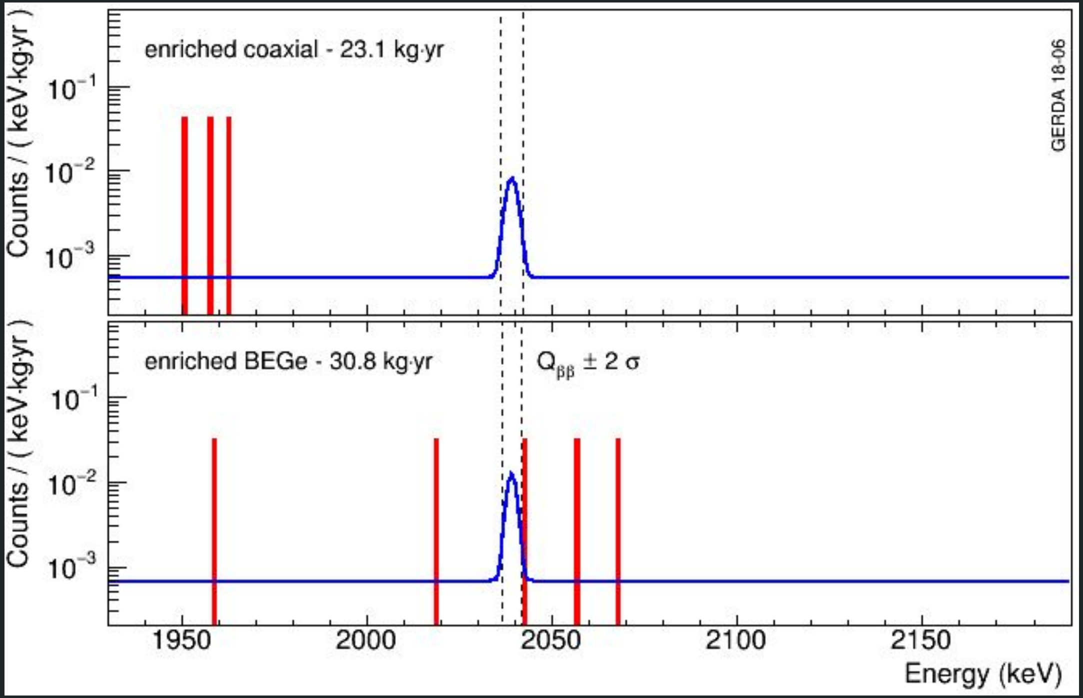
0νββ experiment with the lowest background in the ROI!

Statistical Analysis

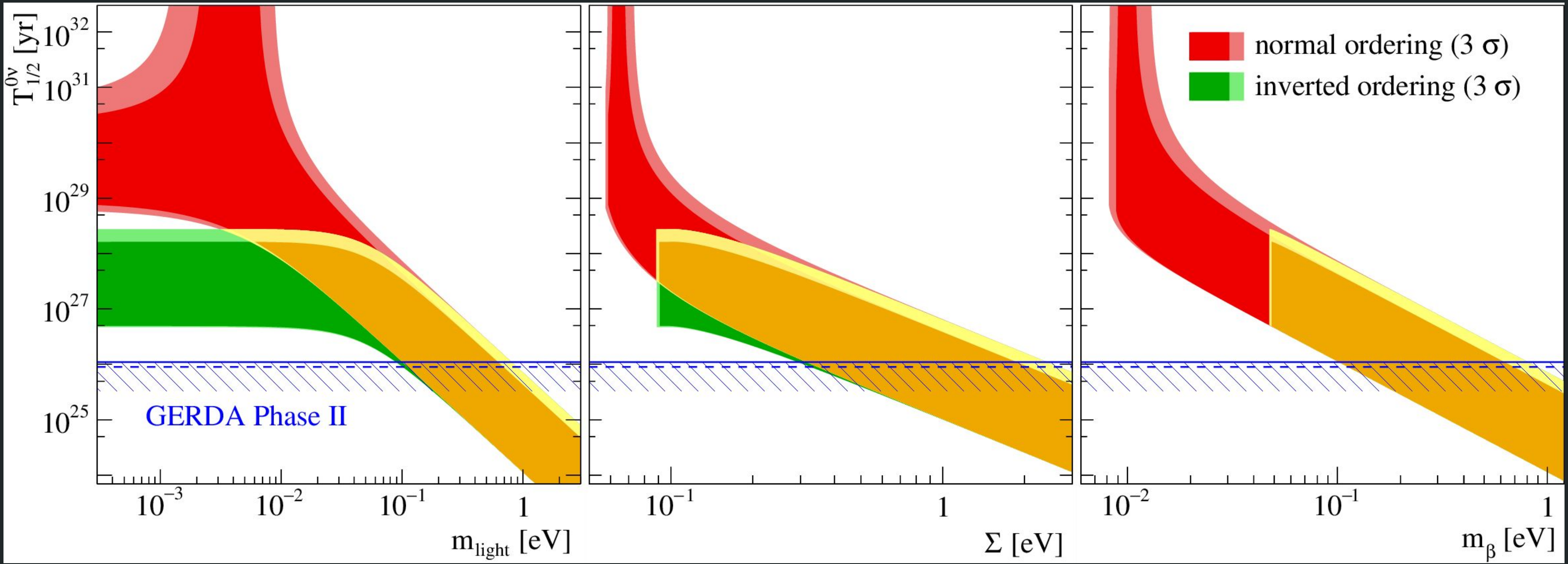
High Resolution & Background Free
1 count at $Q_{\beta\beta}$ ➔ ~2 sigma signal

Phase I & II combined fit:

- ➢ frequentist unbinned likelihood
- ➢ simultaneous fit of 7 data sets
- ➢ best fit for **no 0νββ signal**
- ➢ $\mathbf{T_{1/2} > 0.9\ 10^{26}}$ **yr** (90% C.L.)
- ➢ sensitivity $\mathbf{T_{1/2} > 1.1\ 10^{26}}$ **yr**
- ➢ $m_{\beta\beta} < (0.11 - 0.25)$ eV

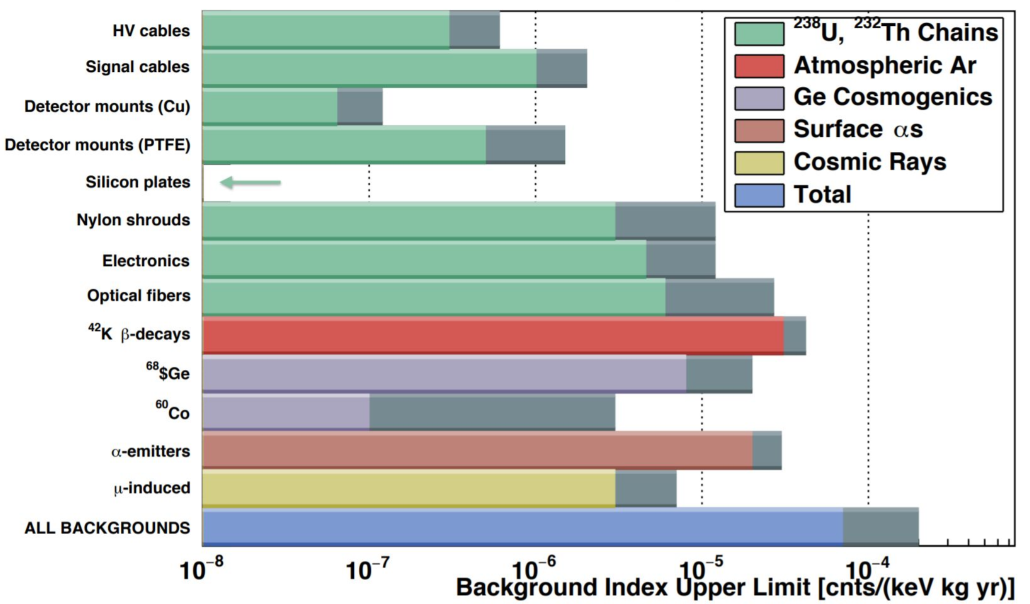


Implications for Neutrino Physics



- Degenerate Majorana masses probed!
- Next target inverted ordering band
- 0νββ searches, cosmological surveys and direct mass measurements give complementary information!

LEGEND
Large Enriched Germanium Experiment for Neutrinoless ββ Decay



New project built on GERDA and MAJORANA:

- ➢ GERDA → LAr veto system
- ➢ MAJORANA → low background material
  → front-end electronics

Staged approach:

- ➢ L200 → 200 kg mass in GERDA infrastructure
  → anticipated background < 2 10^{-4} cts/keV/kg/yr
  → discovery power up to $T_{1/2}$ ~ 10^{27}
- ➢ L1000 → 1000 kg mass in new setup (TBD)
  → discovery power up to $T_{1/2}$ ~ 10^{28}

Funding for L200 largely secured!

Construction in 2020

Commissiong in 2021

Outlook

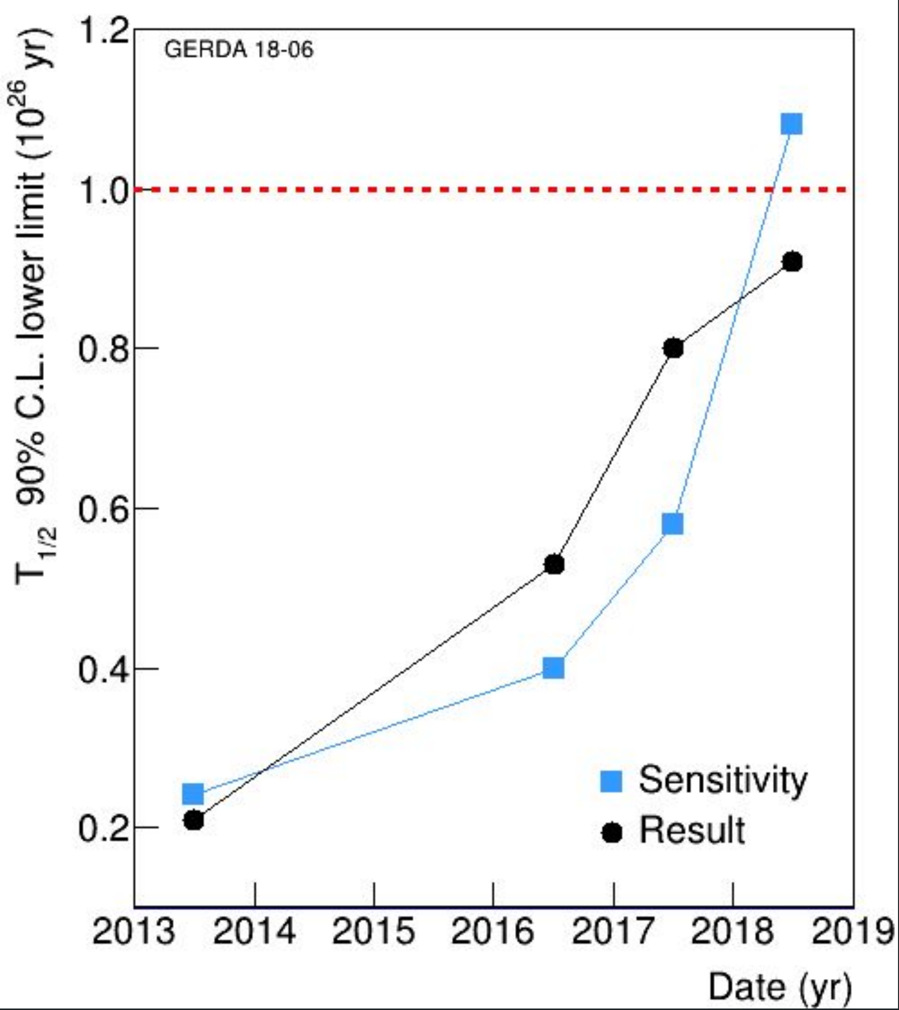
GERDA: high-resolution & background-free search for $0\nu\beta\beta$ in ^{76}Ge:

BI = 6 10^{-4} cts / (keV kg yr)

$\Delta E < 0.1\%$ at $Q_{\beta\beta}$

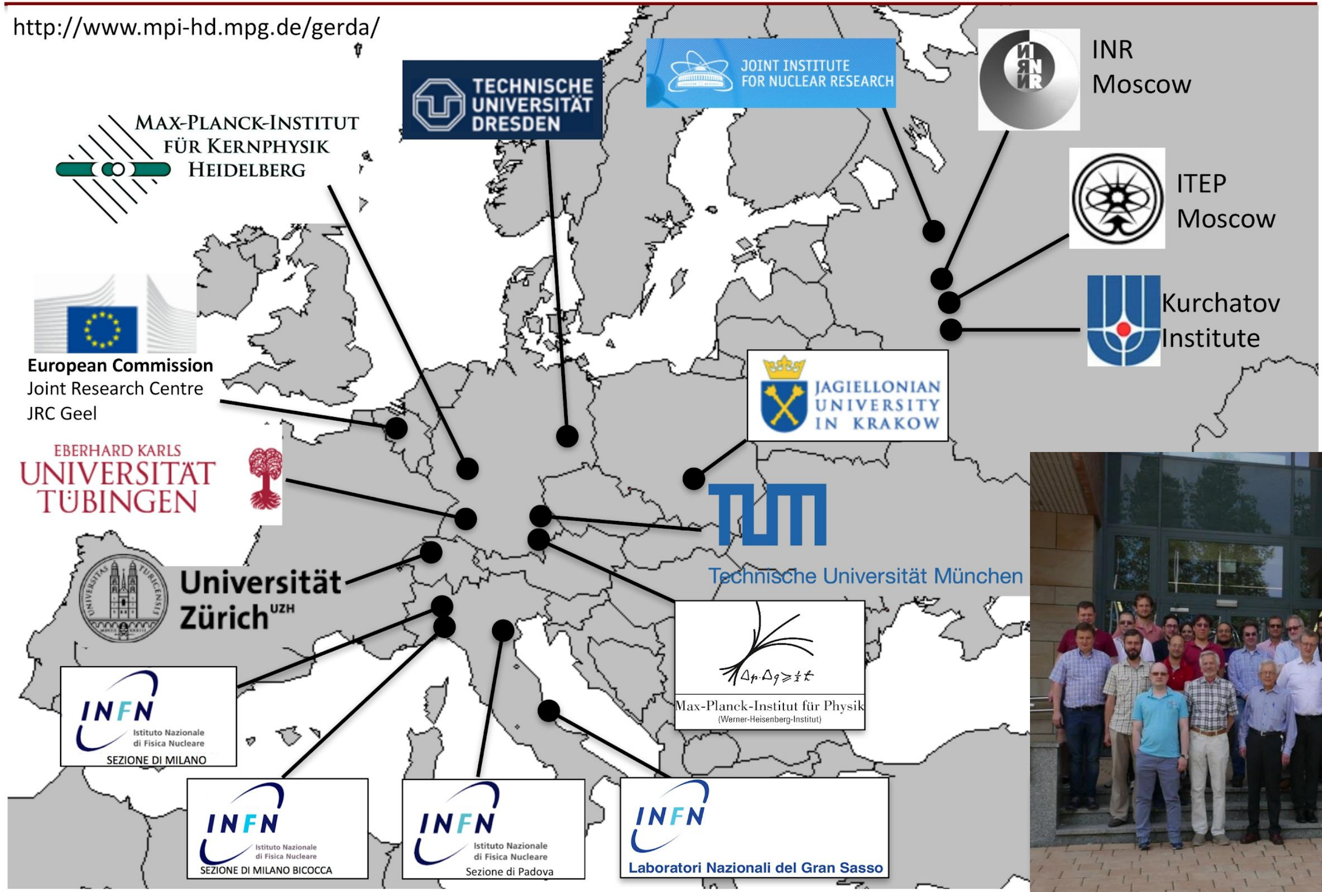
GERDA probed $T_{1/2}$ values at the 10^{25} yr scale.
Pioneering exploration of the 10^{26} yr scale!

GERDA keeps taking data. LEGEND-200 is in preparation to reach $T_{1/2}$ ~ 10^{27} yr and beyond



The GERDA Collaboration

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



GERDA

Backup slides

A portal to Physics beyond the Standard Model

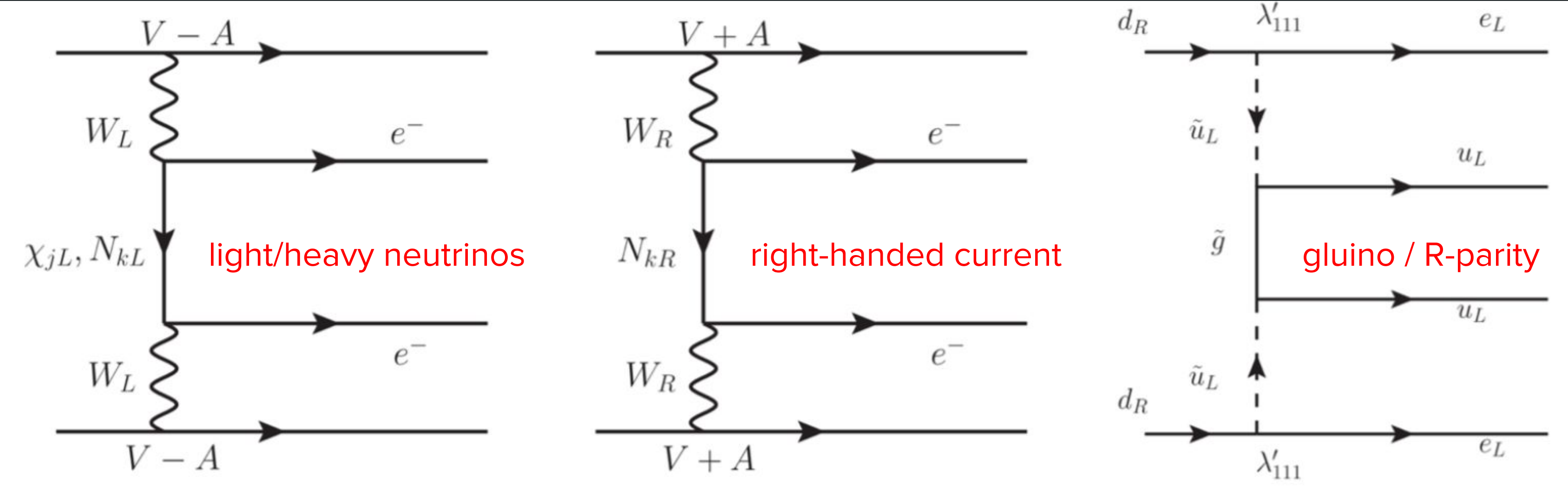
The rate of the process ($1/T_{1/2}$) is proportional to the coherent sum of all mechanisms involved:

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}(Q,Z) \cdot \left| \sum_{\text{mech. } i} \mathcal{M}_i \cdot \eta_i \right|^2$$

Phase Space Factor

Nuclear Matrix Element

Mechanism



[Faessler et al, PRD, 83, 11 (2011), 113003]

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Phase Space Factor

Nuclear Matrix Element

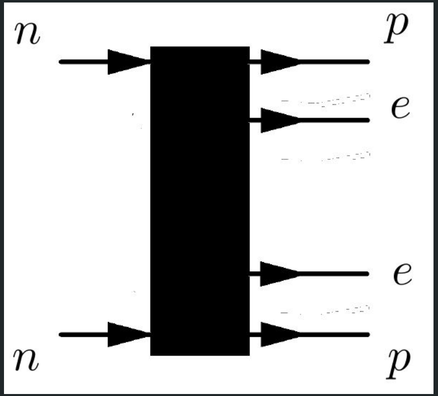
Mechanism

Sensitivity to new Physics is proportional to the sensitivity to $T_{1/2}$:

- $T_{1/2}$ is for $0\nu\beta\beta$ decay what $\sqrt{s}$ is for LHC
- It would be interesting to factorize NME into two contributions:
  - NME_{state}: initial/final nuclear state
  - NME_{prop}: propagator and diagram
- F.O.M. to compare experiments: $\sqrt{(T_{1/2}\ G^{0\nu}\ NME^2_{state})}$

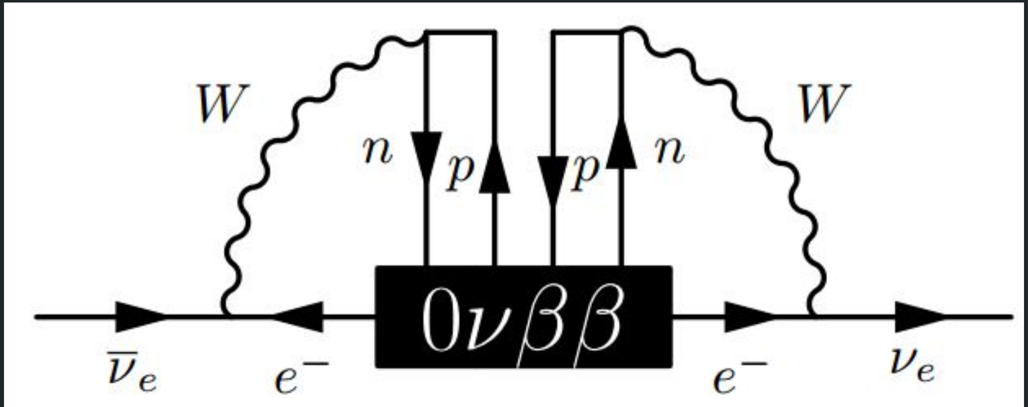
$0\nu\beta\beta$ and the Origin of Neutrino Masses

Independently from underlying physics: if $0\nu\beta\beta$ decay exists, neutrinos are Majorana particle!



Black Box theorem:
$0\nu\beta\beta$ operator can be rearranged to produce a neutrino/antineutrino oscillation (i.e. a Majorana mass term)

[Schechter, Valle, PRD 25 (1982) 2951]



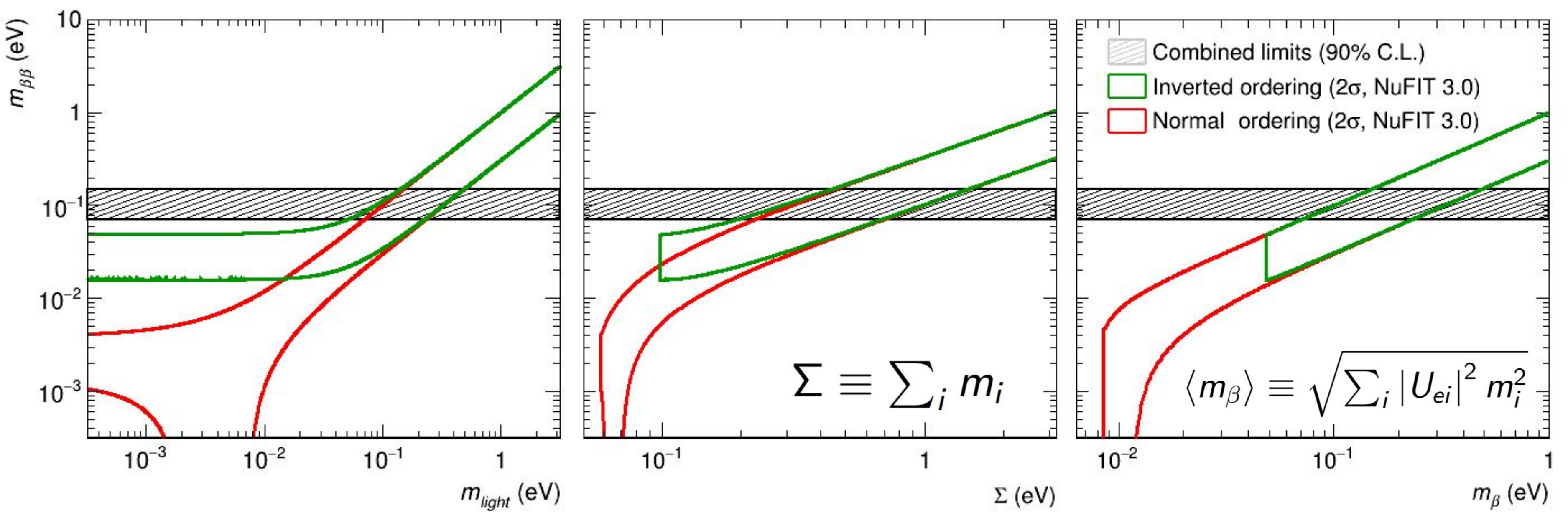
Note: bulk of neutrino mass not given by $0\nu\beta\beta$ operator

[Duerr et al., JHEP 1106 091,2011]

Neutrino Mass Observables

Cosmology (Planck, Euclid)
sum of neutrinos masses

Beta-decay kinematic (KATRIN)
electron neutrino mass

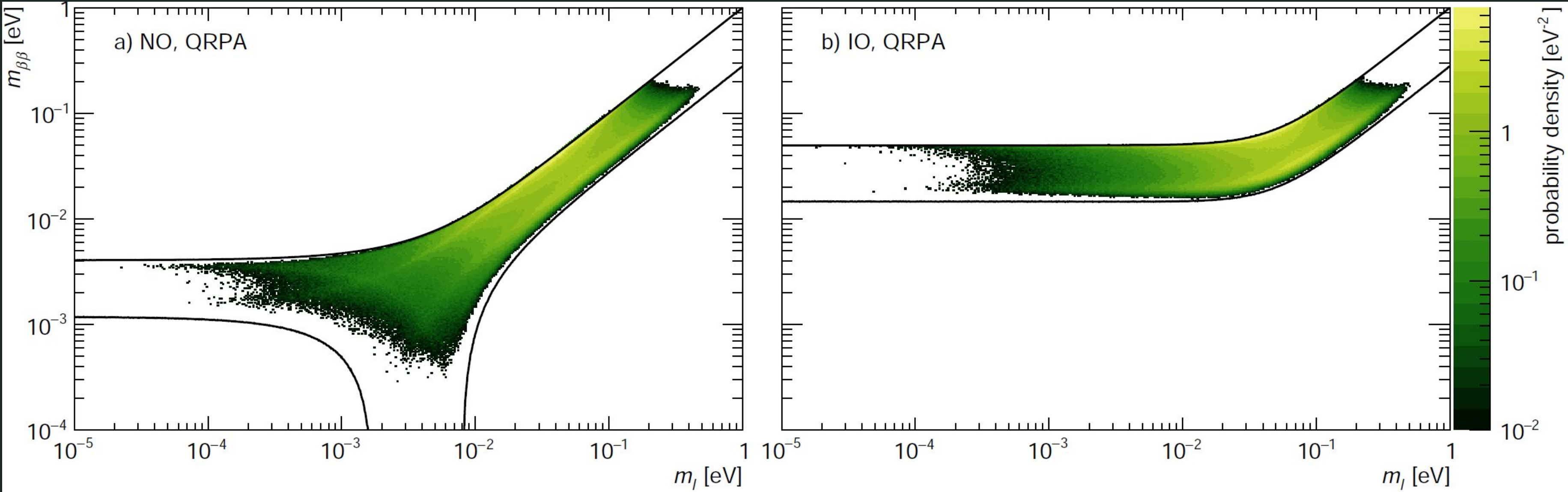


- ➢ Degenerate Majorana masses probed!
- ➢ Next target inverted ordering band

- ➢ $0\nu\beta\beta$ searches, cosmological surveys and direct mass measurements give complementary information!

Probability Density from Global Fits

In absence of neutrino mass mechanisms or flavour symmetries that fix the value of the Majorana phases or drive $m_{lightest}$ to zero, the probability distribution for $m_{\beta\beta}$ is pushed to large values:

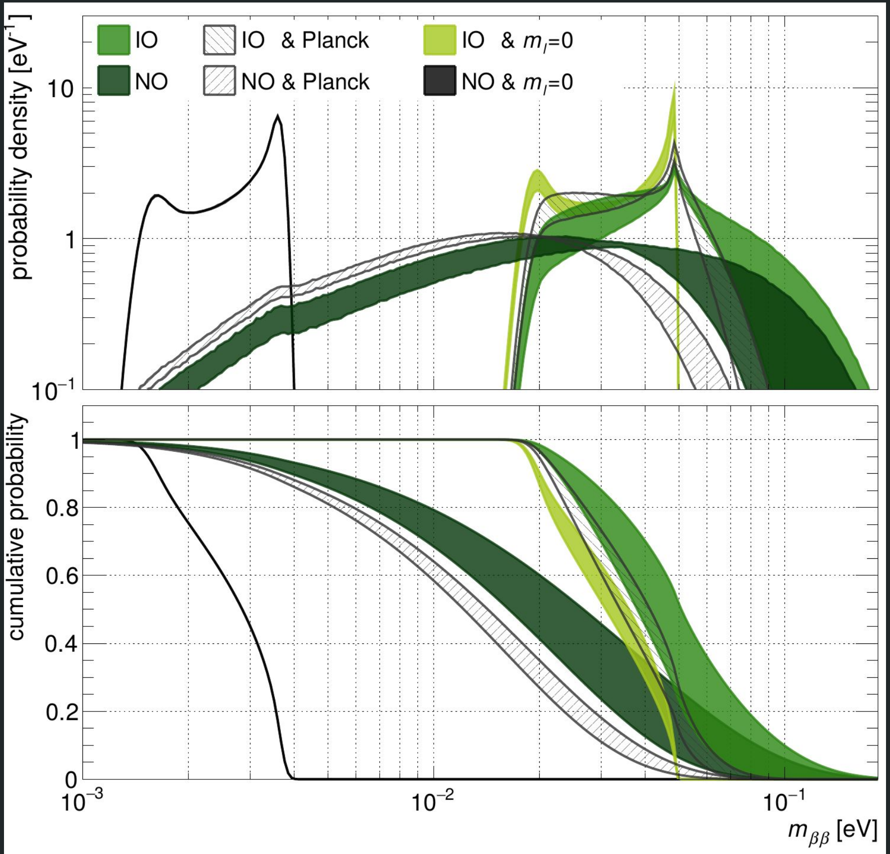


[**M.A.**, G Benato and J A Detwiler, PRD 96, 053001 (2017)]

Flat prior for the Majorana phases ➜ small $m_{\beta\beta}$ values require a fine tuning of the parameters

Probability density from global fits

- data in the analysis: oscillations + $0\nu\beta\beta$ + (cosmology)
- bands shows deformation due to NME uncertainty
- $0\nu\beta\beta$ constraints on $m_{lightest}$ competitive with cosmology



Bulk of probability at reach with next generation experiments

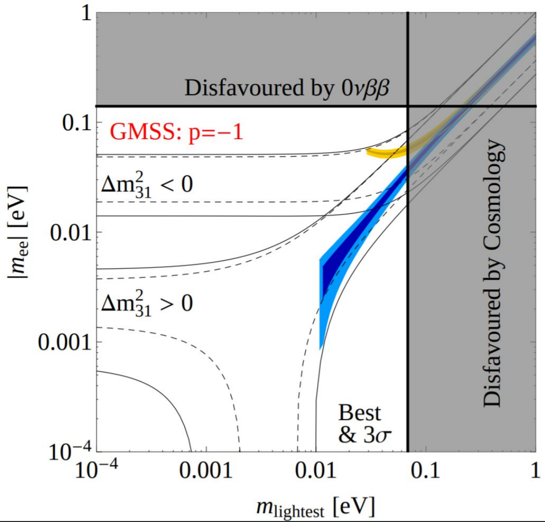
[**M.A.**, G Benato and J A Detwiler, Phys. Rev. D 96, 053001 (2017)]
see also [A Caldwell et al, Phys.Rev. D96 (2017) no.7, 073001]

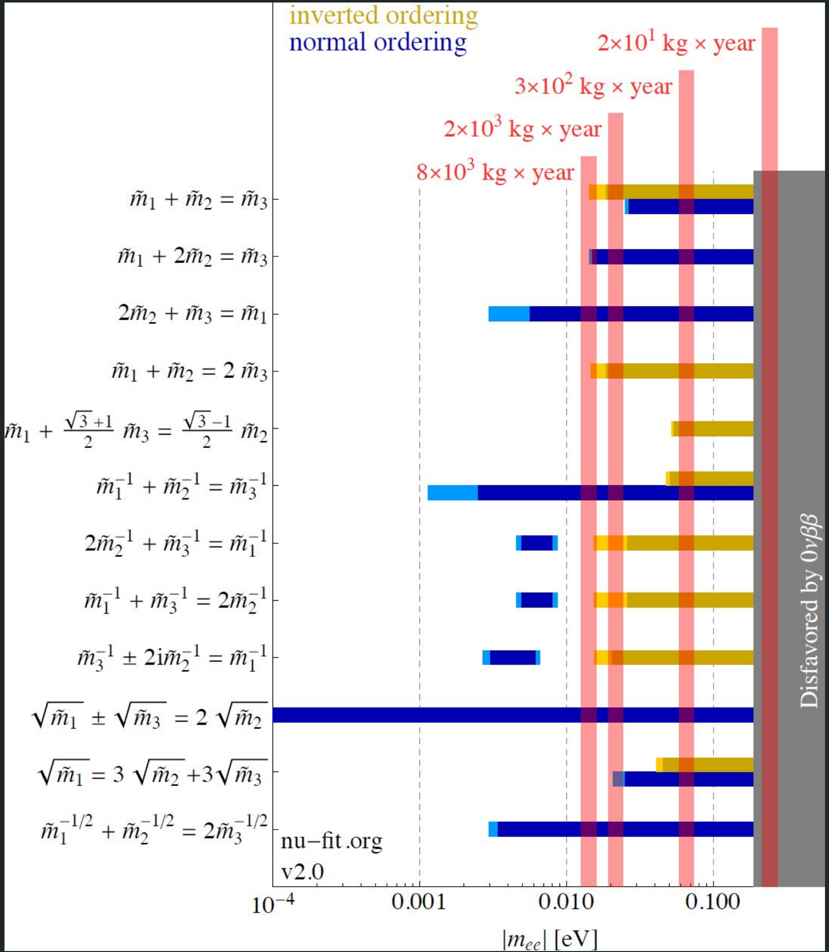
[King, Merle, Stuart, JHEP 1312, 005 (2013)]
[**M.A.**, Merle, Zuber EPJ C76 (2016) no.4, 176]

Flavour Models

3-neutrino framework extended with additional finite symmetry groups to explain the values of mixing angles and mass eigenstates:

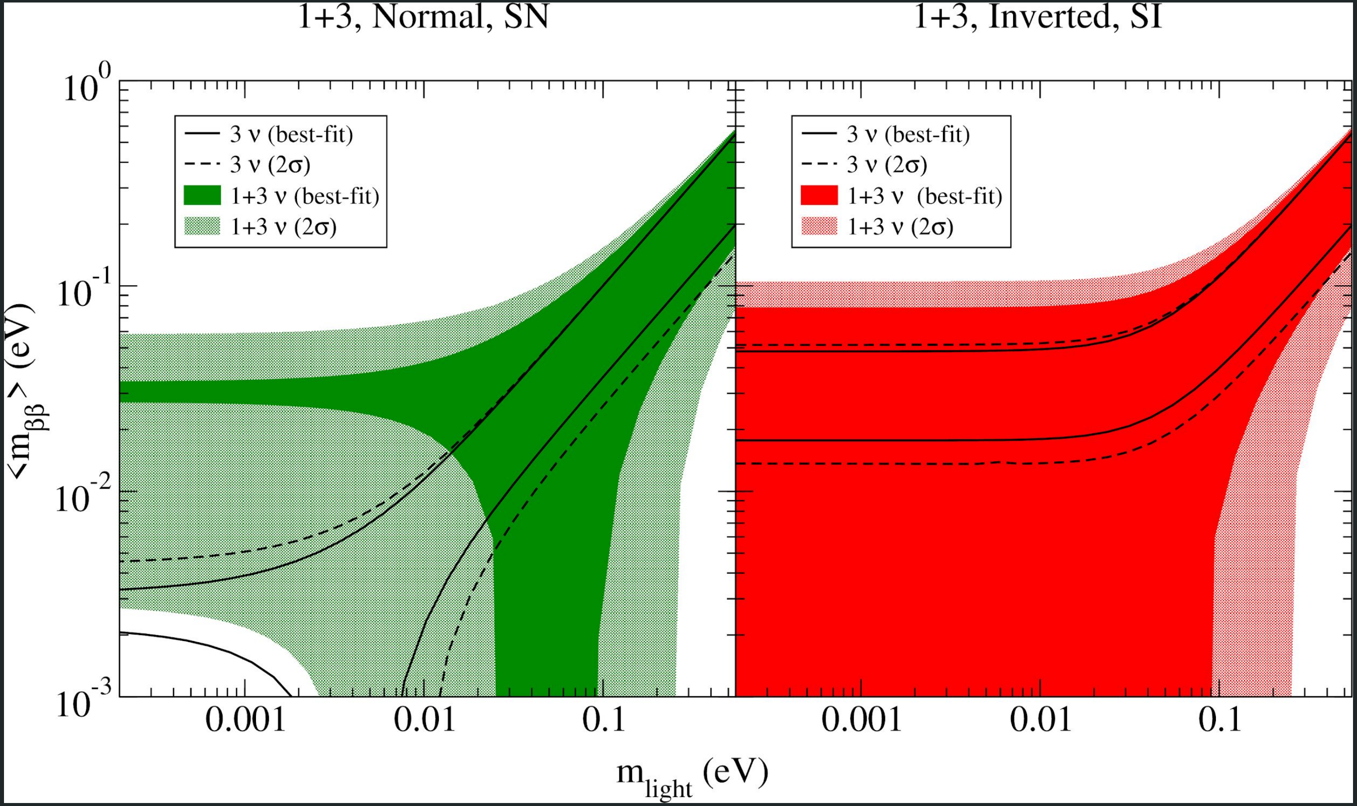
- ➢ new correlations between observables (sum rules) schrink range allowed for $m_{\beta\beta}$
- ➢ some models will be probed with early stages of the next-generation experiments





3+1 Models

Adding a sterile neutrino changes dramatically the parameter space of interest. Current experiments are testing the IO horizontal band!



[W Rodejohann, Int.J.Mod.Phys. E20(2011)]

Signal and Background rates

[**M.A.**, G Benato and J A Detwiler, PRD 96, 053001 (2017)]

$$N_{0\nu\beta\beta} = \ln 2 \cdot \varepsilon \cdot N_{atoms} \cdot \frac{t}{T^{0\nu}_{1/2}}$$

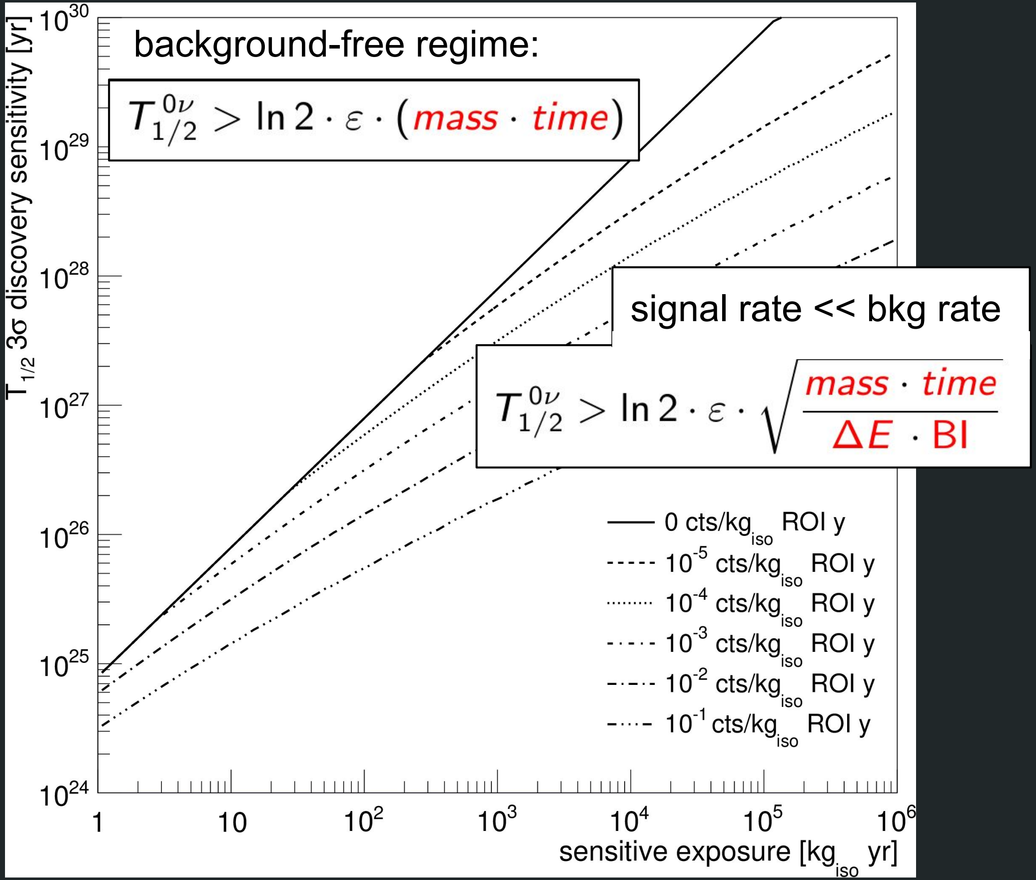
$T_{1/2} = 10^{25}$ yr -> $O(1)$ event / (10 kg yr)

$T_{1/2} = 10^{26}$ yr -> $O(1)$ event / (100 kg yr)

$T_{1/2} = 10^{27}$ yr -> $O(1)$ event / (1 t yr)

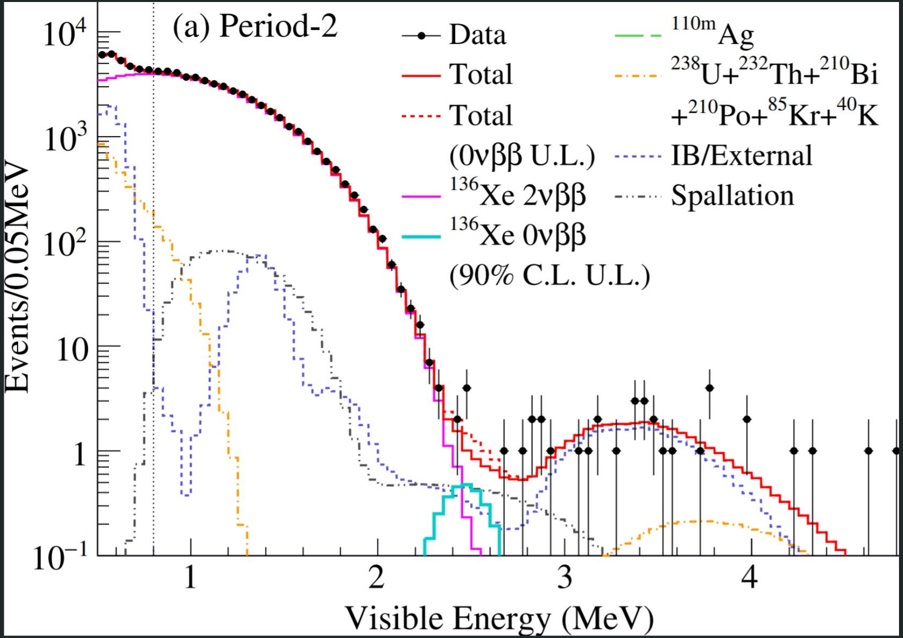
$T_{1/2} = 10^{28}$ yr -> $O(1)$ event / (10 t yr)

For a discovery, background rate in ROI ($Q_{\beta\beta} \pm$ 1-2 σ) must be similar to signal rate



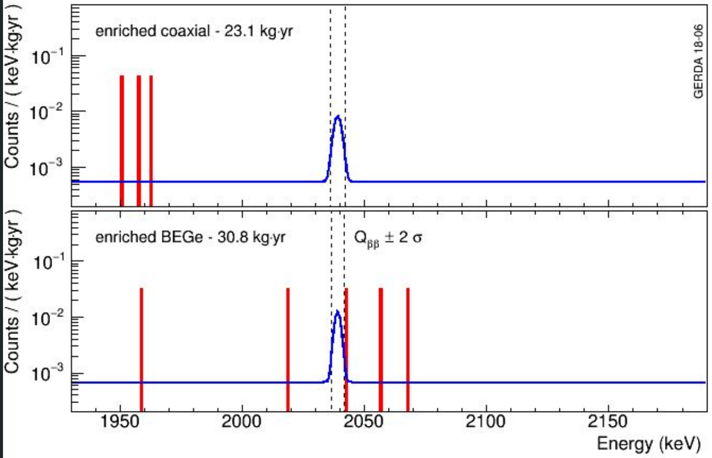
Signal Extraction and background shape uncertainty

KamLAND-Zen: *O*(10) cts/ROI + complex shape

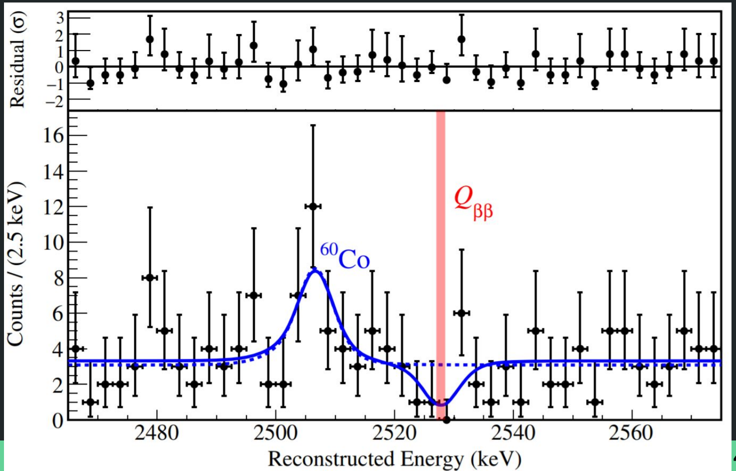


[PRL. 117 (2016) no.10, 109903]

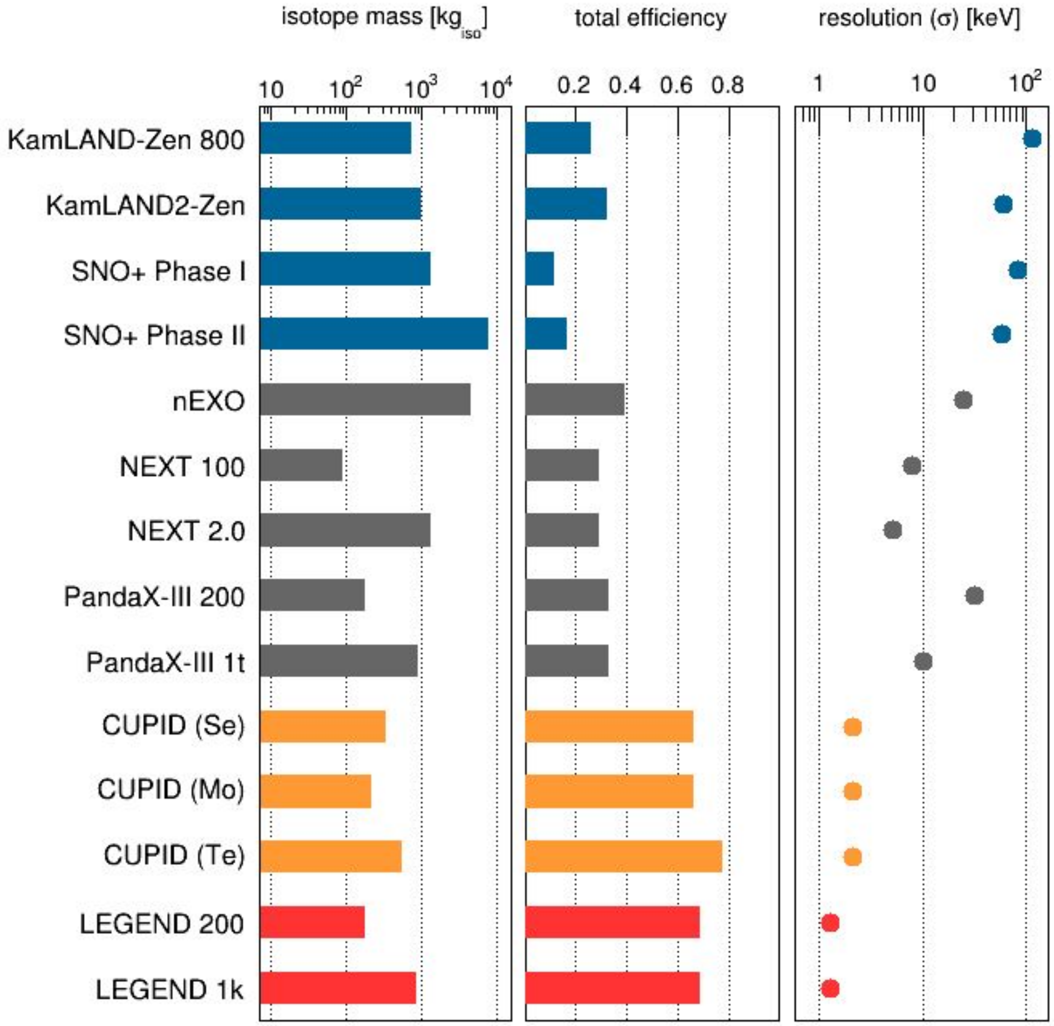
GERDA: *O*(0.1) cts/ROI + simple shape



CUORE: *O*(10) cts/ROI + simple shape



[PRL 117 (2016) no.10, 109903]

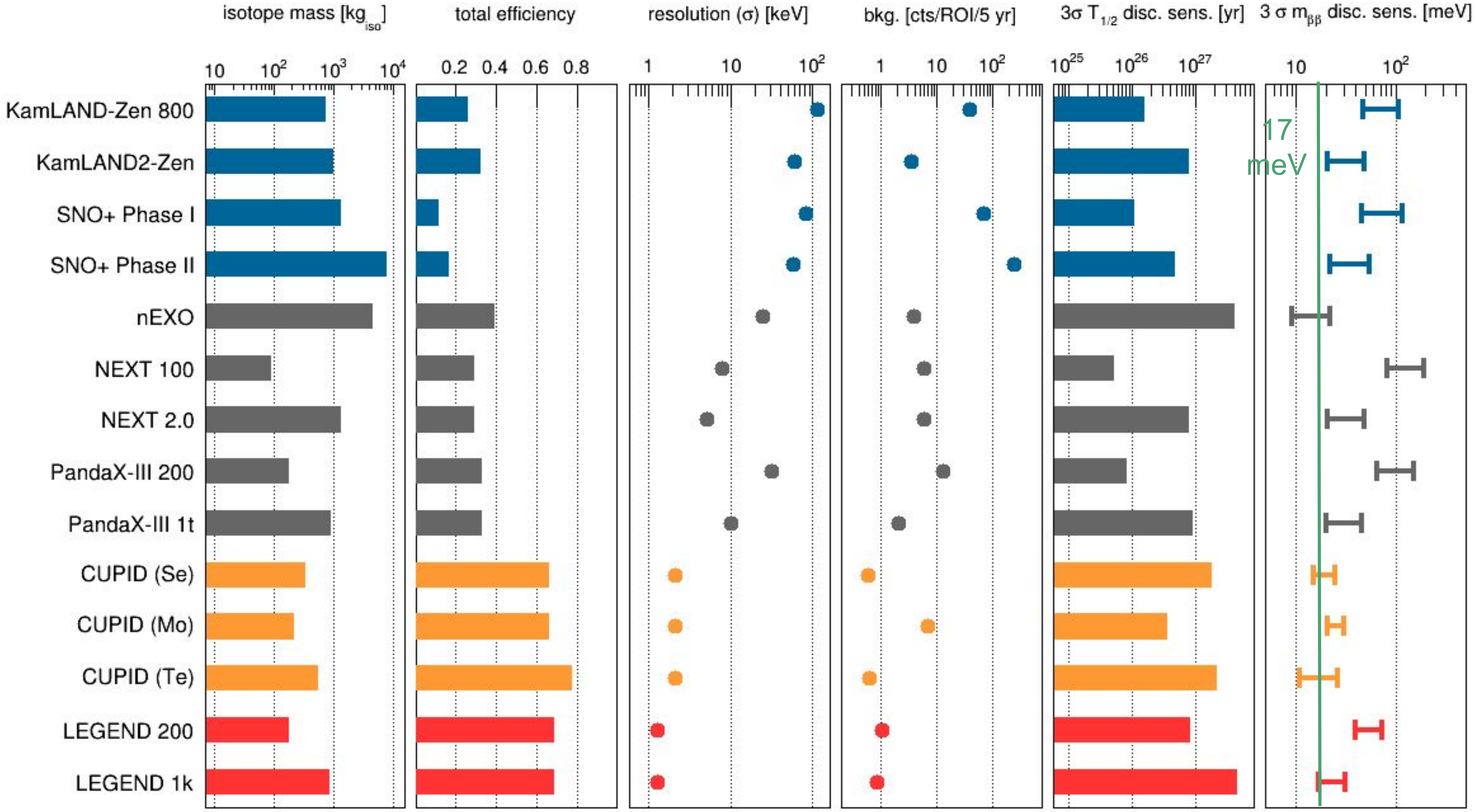


Exp Parameters

Efficiency includes:

- ➢ sensitive Volume
- ➢ sensitive ROI
  - ➢ bgk-free: $Q_{\beta\beta} \pm 2\,\sigma$
  - ➢ gauss bkg: $Q_{\beta\beta} \pm 1.2\,\sigma$
  - ➢ poor-resolution: $[Q_{\beta\beta}, Q_{\beta\beta} \pm 1.2\,\sigma]$
- ➢ containment
- ➢ analysis cut (e.g. pulse shape)

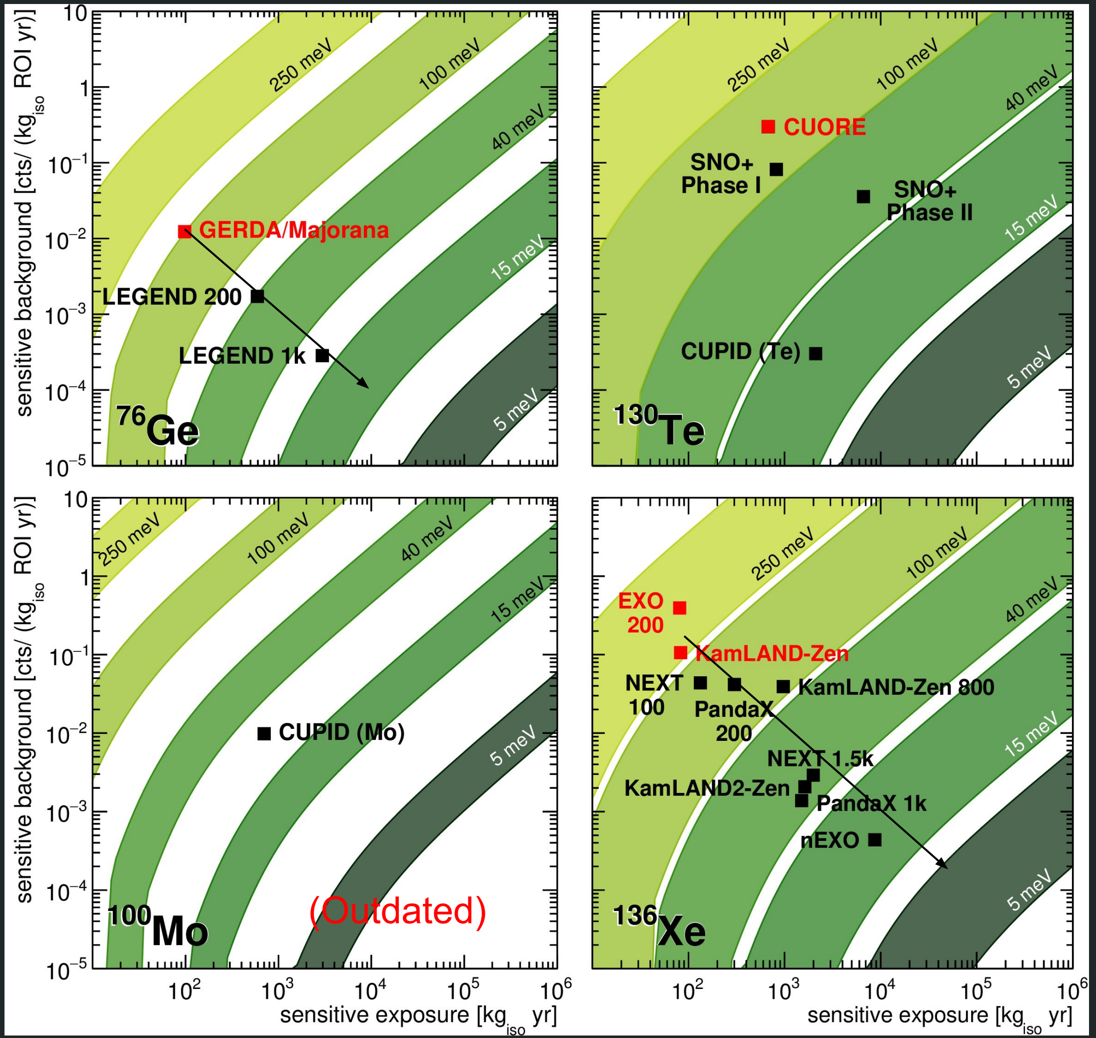
Adapted from [**M.A.** et al., PRD 96, 053001 (2017)]
[Courtesy of Christoph Wiesinger]


isotope mass [kg_iso]
total efficiency
resolution (σ) [keV]
bkg. [cts/ROI/5 yr]
3σ T1/2 disc. sens. [yr]
3 σ mββ disc. sens. [meV]
17 meV
KamLAND-Zen 800
KamLAND2-Zen
SNO+ Phase I
SNO+ Phase II
nEXO
NEXT 100
NEXT 2.0
PandaX-III 200
PandaX-III 1t
CUPID (Se)
CUPID (Mo)
CUPID (Te)
LEGEND 200
LEGEND 1k

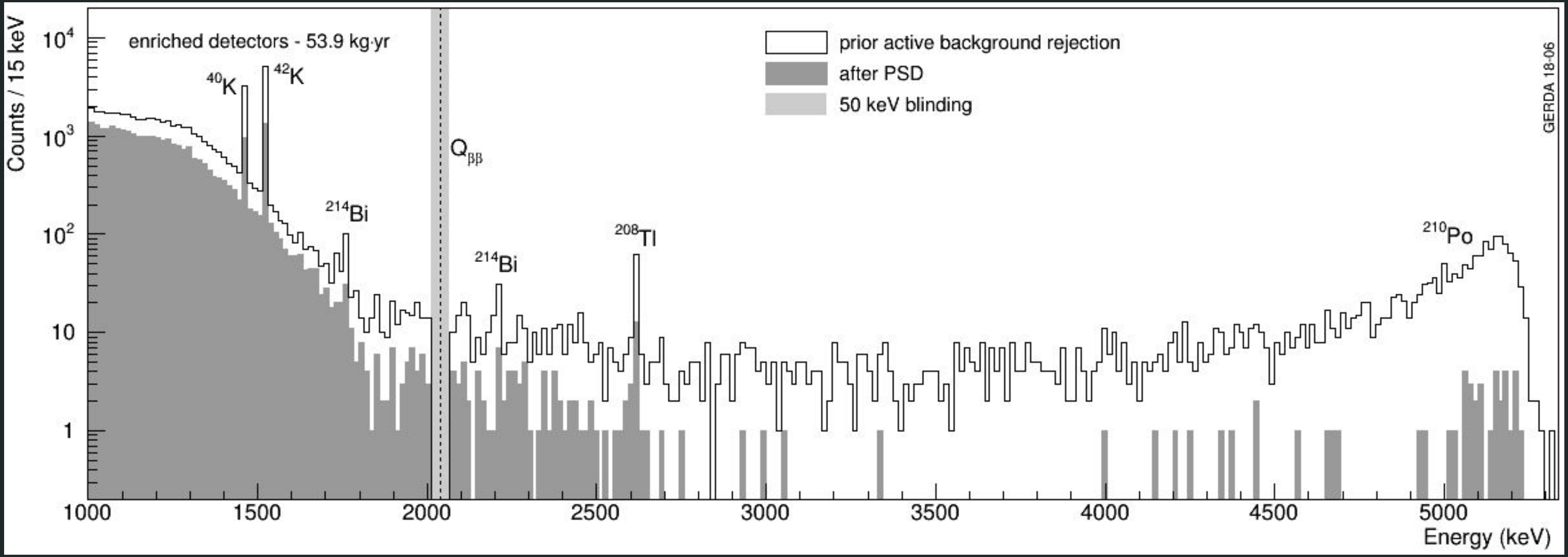
Sensitivity

- ➢ Ge experiments pursue a staged approach. Each stage as background level and exposure goals such to be background free
- ➢ Xe experiments reduce the background by self-shielding. Development along a clear direction with the attempt to get background free (helps for discovery)
- ➢ Sensitivity does not take into account the uncertainty/reliability of the signal extraction

[**M.A.**, G Benato and J A Detwiler, PRD 96, 053001 (2017)]



Active Background Suppression - PSD



Expected suppression factors at $Q_{\beta\beta}$:

~ 100 for α from ^{210}Po

~ 2 for γ from $^{208}Tl/^{214}Bi$

~ 100 for β from ^{42}K