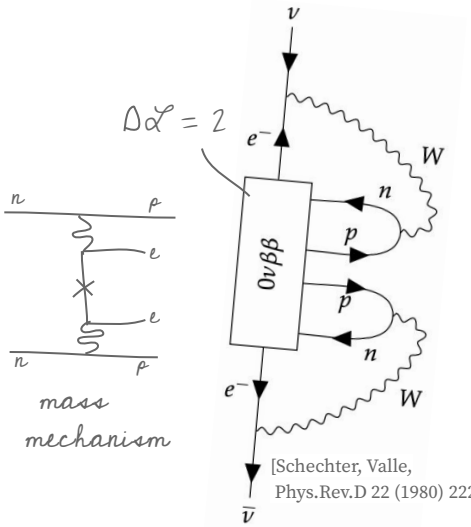
No neutrinos not yet found

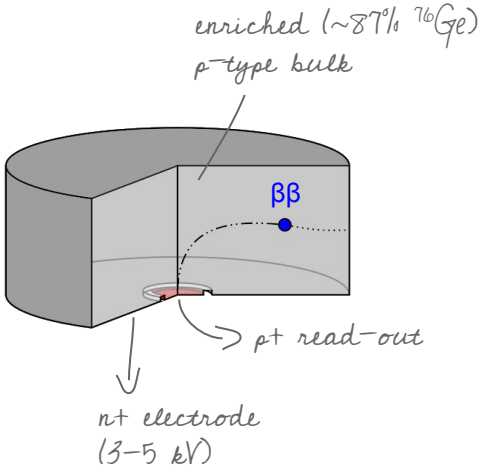
The final result of GERDA and the physics potential of LEGEND



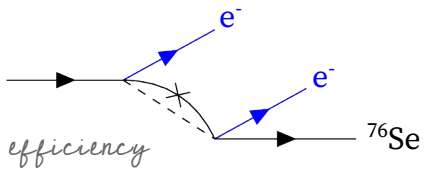
[Schechter, Valle, Phys.Rev.D 22 (1980) 2227]

Christoph Wiesinger (TUM) for the GERDA and LEGEND collaborations, 8th June 2021

Experimental approach

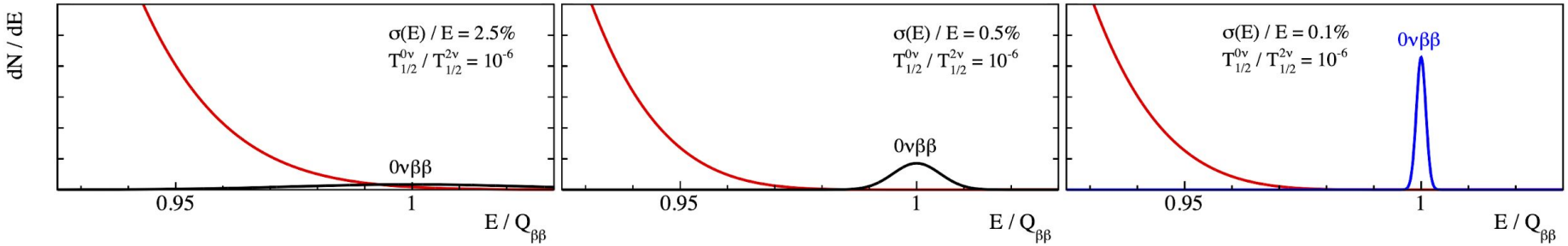


HPGe detectors enriched in ^{76}Ge

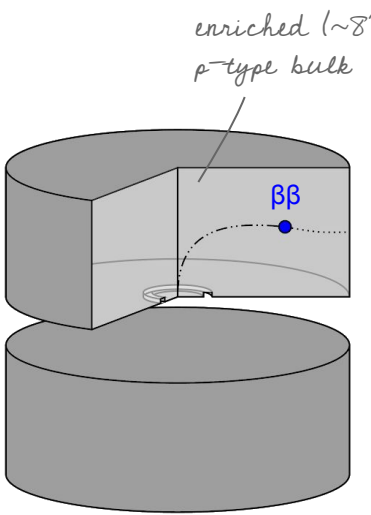


- source = detector → *high efficiency*
- energy resolution $\sigma(E) / E < 0.1\%$ at $Q_{\beta\beta} = 2039$ keV
- **high-purity** material → *no intrinsic background*
  [Astropart.Phys. 91 (2017) 15-21]
- high stopping power → *topology information*

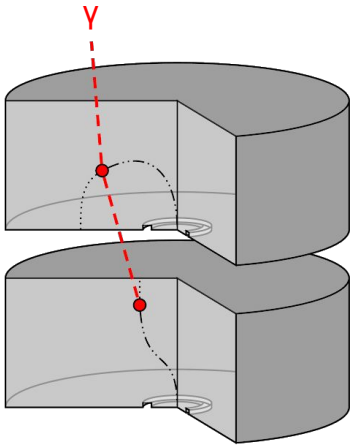
HPGe detectors



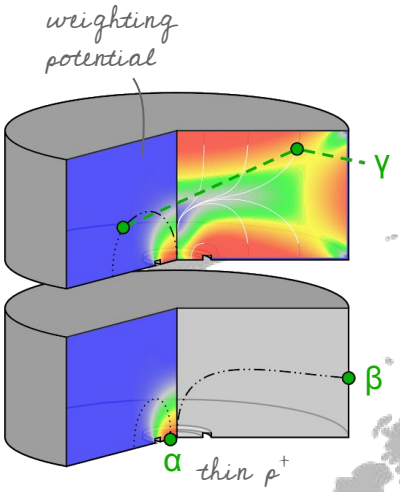
Topology discrimination



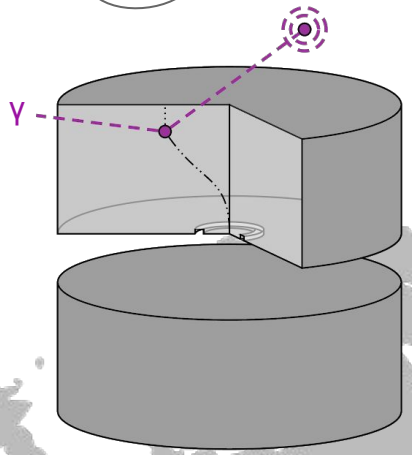
differentiate **point-like** $\beta\beta$ topology from:



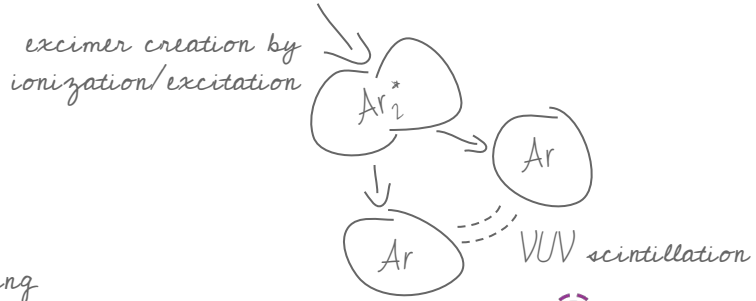
multi-detector interactions

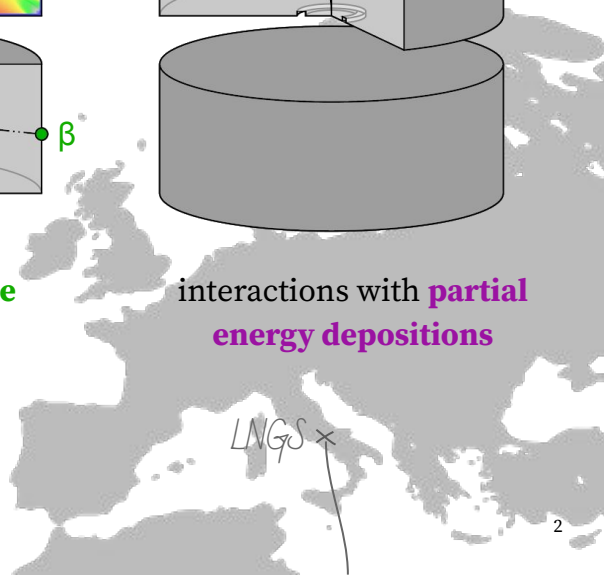


multi-site/surface interactions

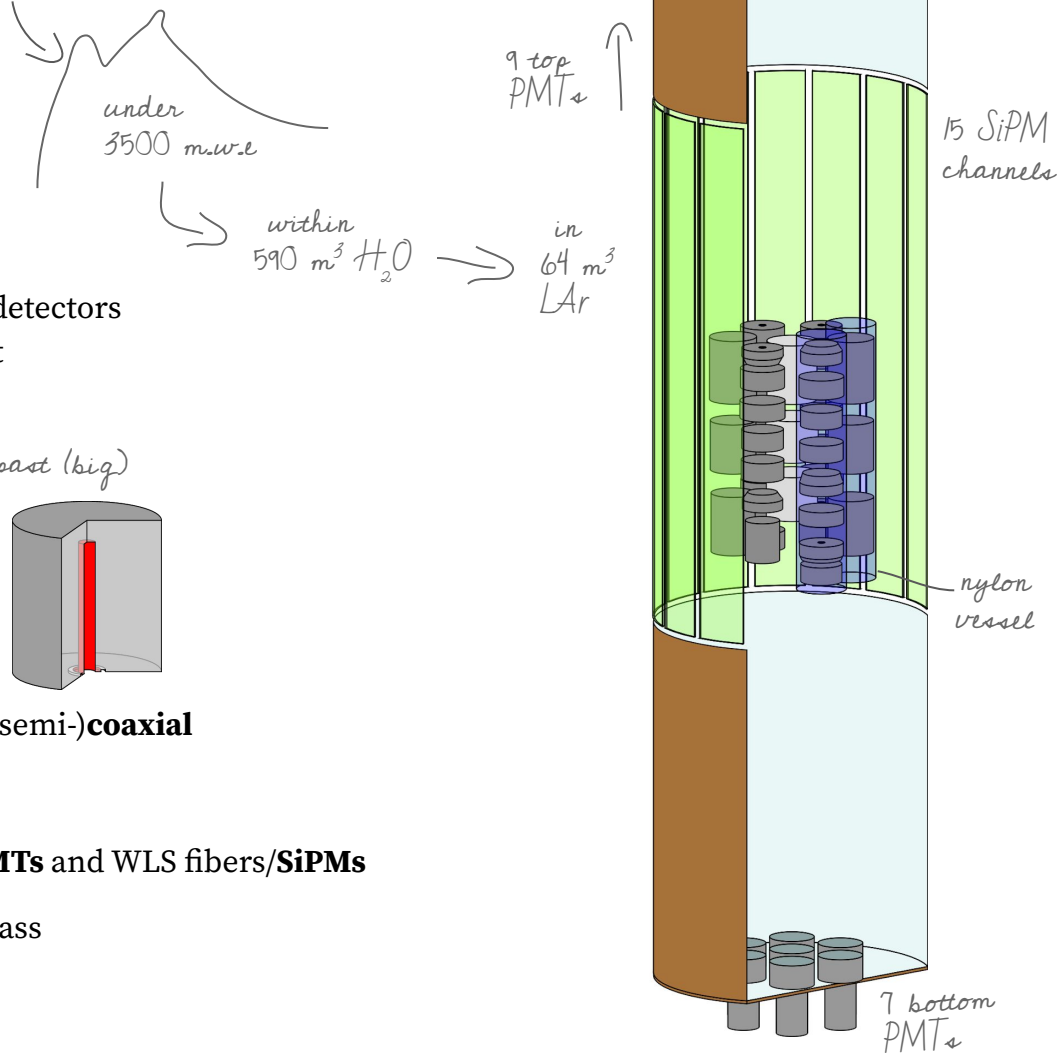


interactions with **partial energy depositions**

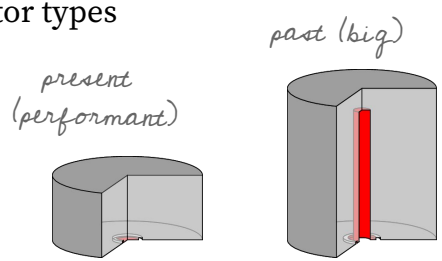




GERDA Phase II



- **35.6 kg** (later **44.2 kg**) of **enriched HPGe** detectors in ultra-low background **LAr** environment
  [Eur.Phys.J. C78 (2018) no.5, 388]
- two (later three) detector types

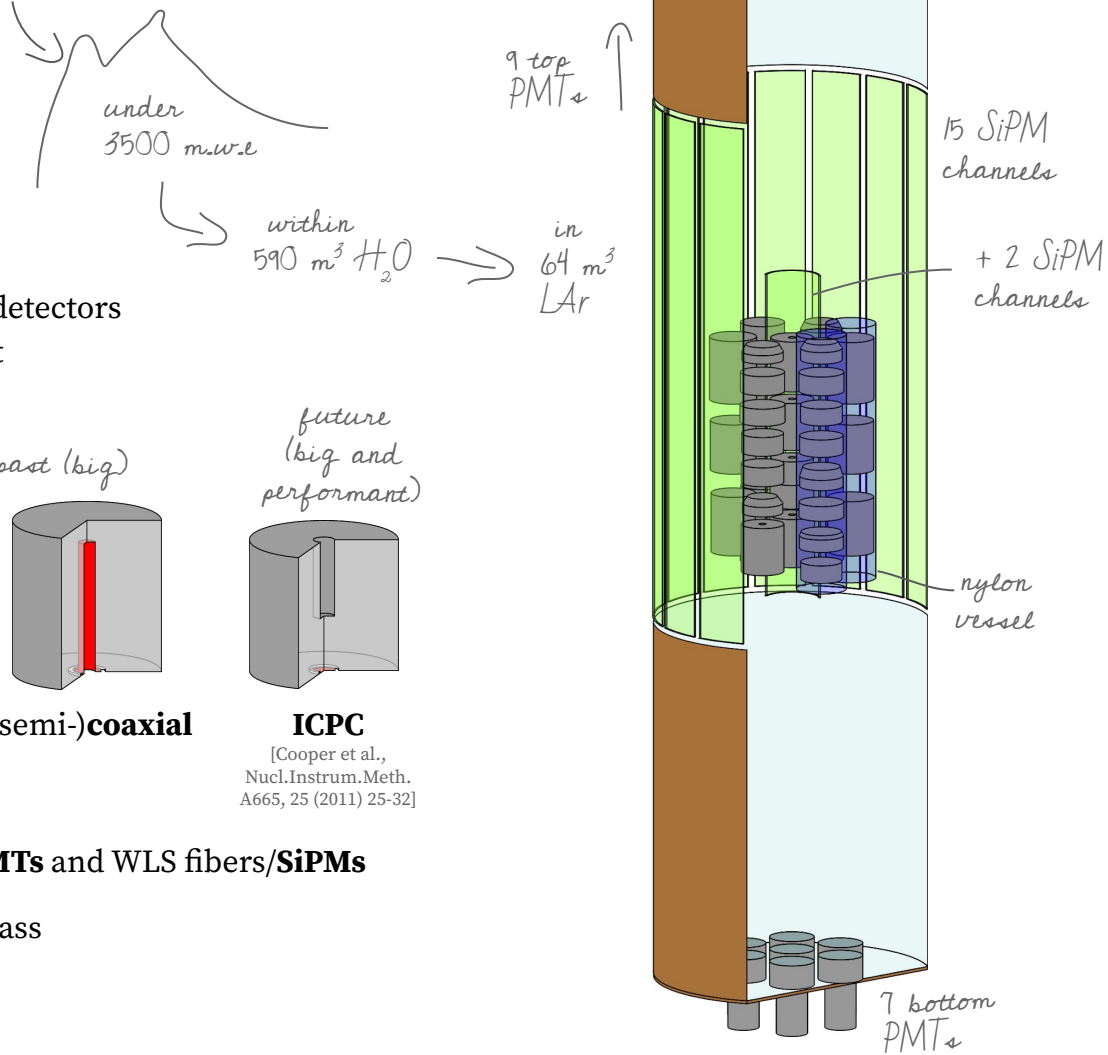


BEGe
[Budjas et al., JINST 4 (2009) P10007]

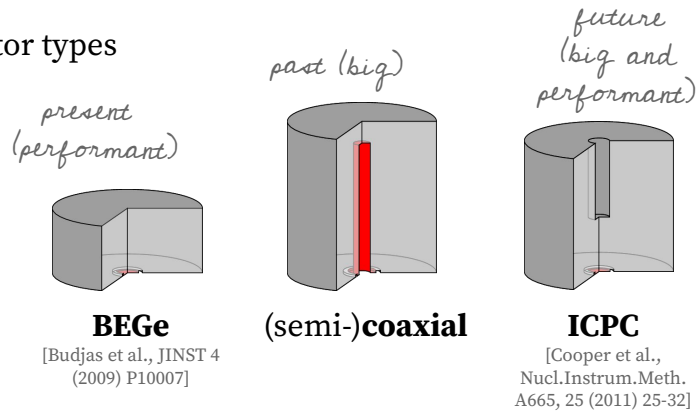
(semi-)**coaxial**

- hybrid **scintillation** light read-out with **PMTs** and WLS fibers/**SiPMs**
- **low activity** materials and little passive mass

GERDA Phase II

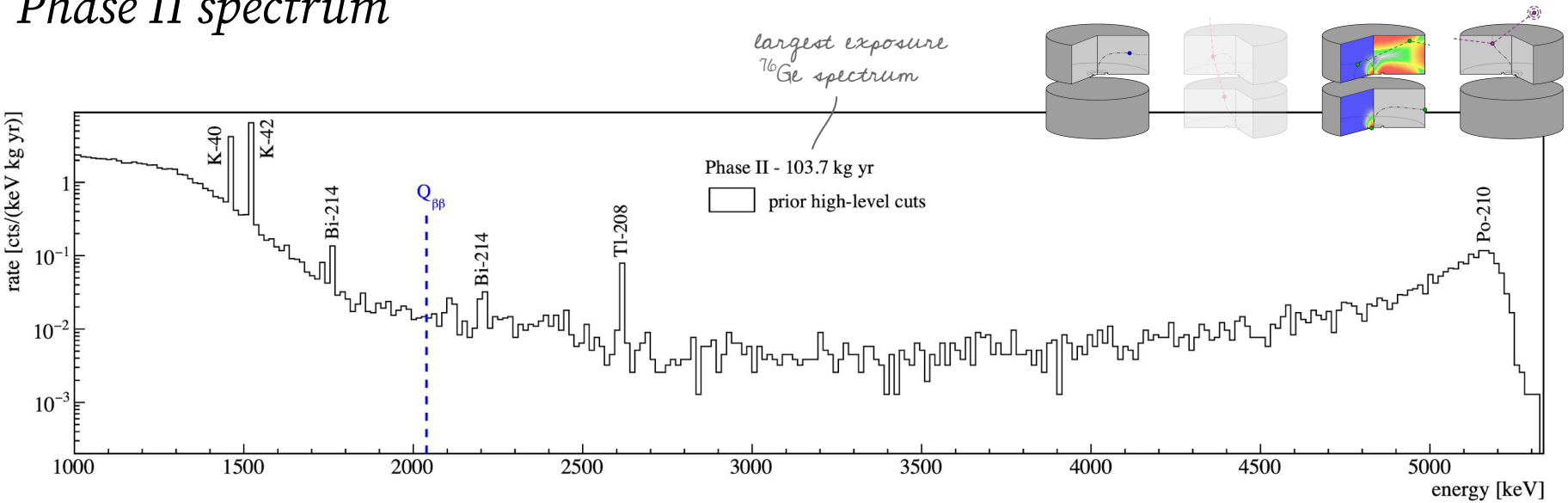


- **35.6 kg** (later **44.2 kg**) of **enriched HPGe** detectors in ultra-low background **LAr** environment
  [Eur.Phys.J. C78 (2018) no.5, 388]
- two (later three) detector types



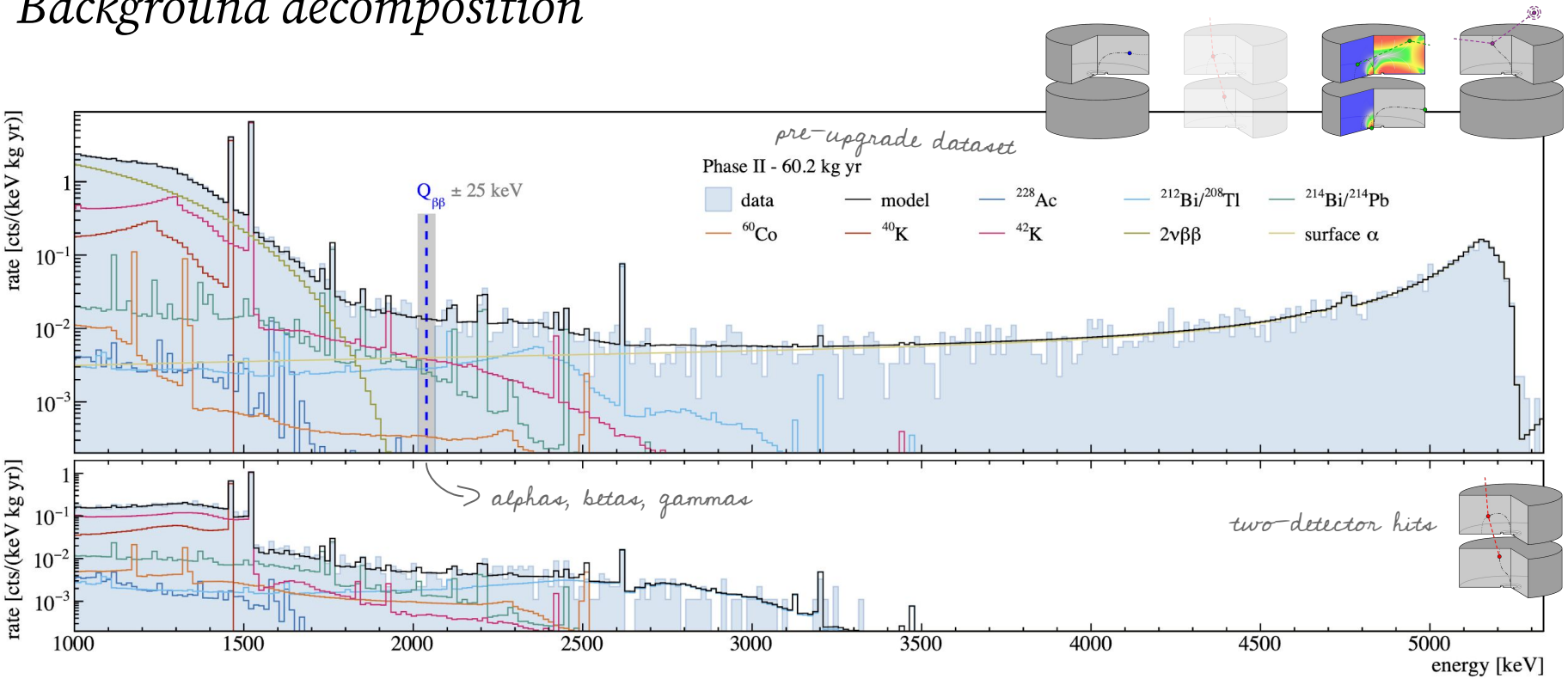
- hybrid **scintillation** light read-out with **PMTs** and WLS fibers/**SiPMs**
- **low activity** materials and little passive mass

Phase II spectrum



- taken from **2015** to **2019**, with close to **90%** duty cycle (incl. upgrade works)
- **103.7 kg yr** selected for analysis

Background decomposition

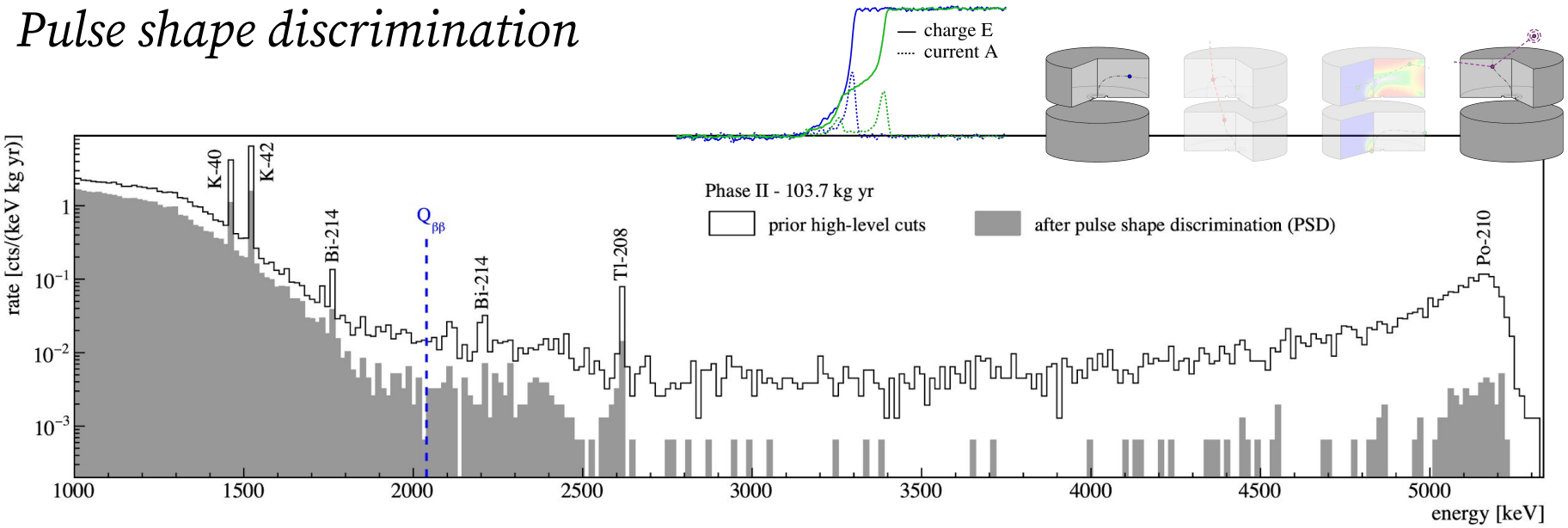


- combined Bayesian fit to multiple datasets with Monte Carlo *pdf*s for **nearby components**

[JHEP 03 (2020) 139]

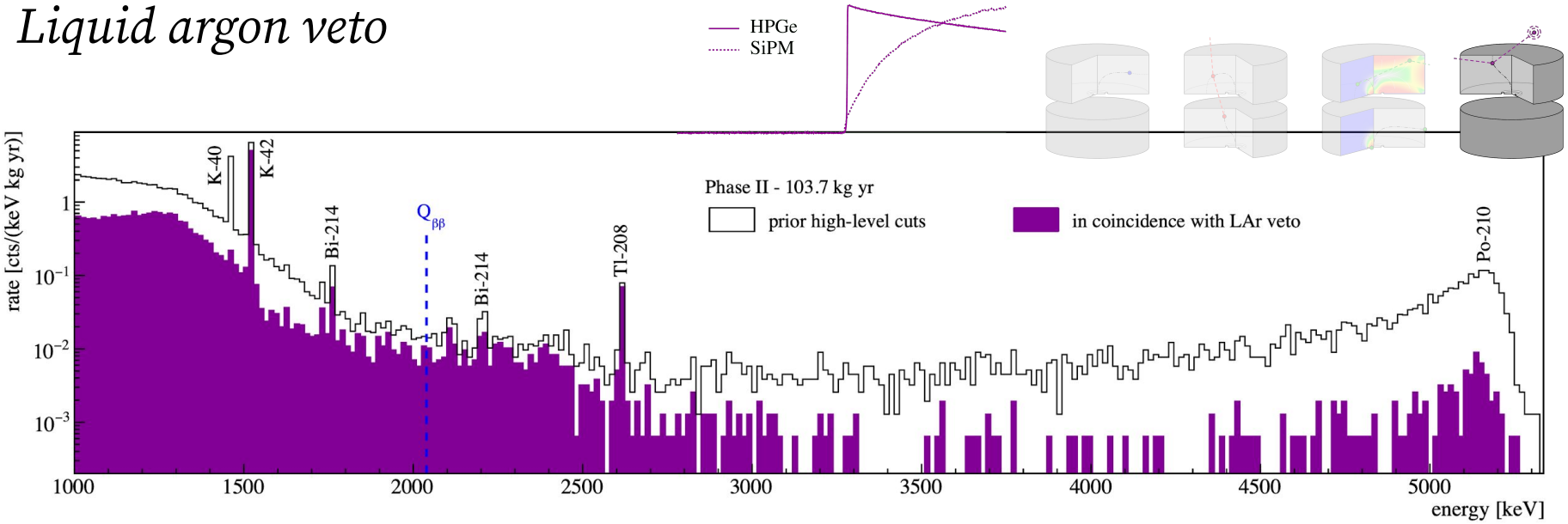
screening measurements as priors

Pulse shape discrimination



- two-sided **mono-parametric** A/E cut for **BEGe / ICPC** detectors
  [Budjas et al., JINST 4 (2009) P10007]
- artificial neural network analysis plus consecutive risetime cut for coaxial detectors
  [Eur. Phys. J. C73 (2013) 2583]
- cut definition / training with ^{228}Th **calibration data** -> ^{208}Tl DEP is signal proxy
- 0νββ signal efficiency **~90%** (~70% for coaxials)

Liquid argon veto



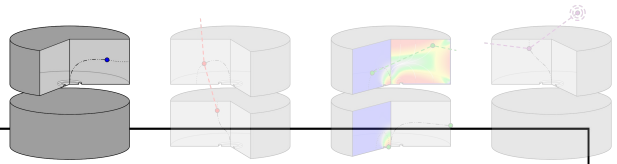
- channel-wise **(anti-)coincidence condition** (PMTs/SiPMs)

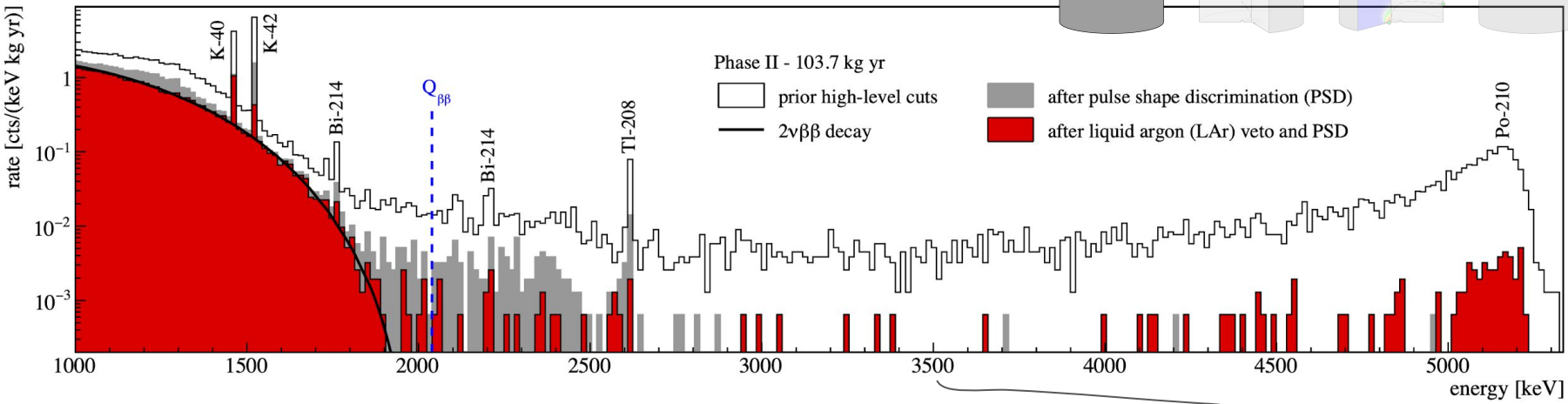
triplet lifetime ~1 μs

- **sub-PE threshold** over characteristic scintillation **emission time**
- 0νββ signal efficiency (1 - random coincidence rate) **> 97%**

^{39}Ar, dark rate

Final Phase II spectrum



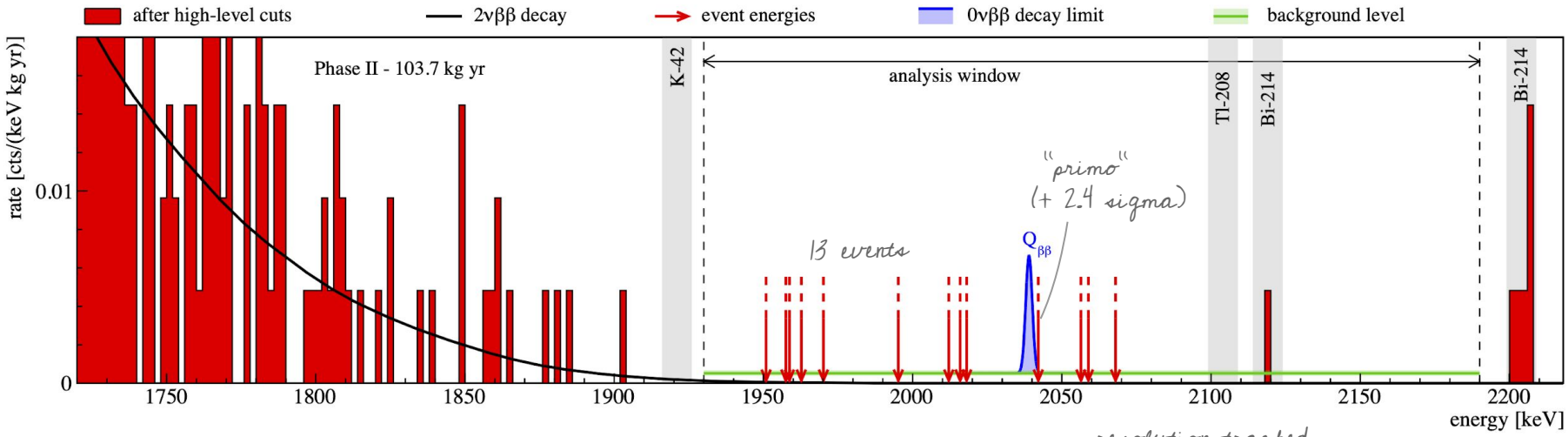


no surviving alphas in BEGe / ICPC

- "pure" **2νββ continuum** → 2nbb precision studies, see E. Bossio's poster
- sparse **single counts** at > $Q_{\beta\beta}$

Final GERDA result

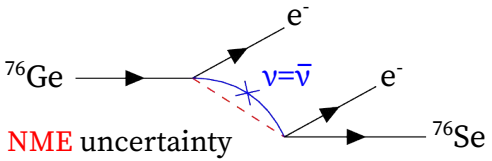
< 1 cts in 100 kg yr and 5 keV



resolution tracked per detector/period

- background index $\mathbf{5.2^{+1.6}_{-1.3} \cdot 10^{-4}}$ **cts/(keV kg yr)**, energy resolution **~3 keV** (FWHM)
- combined (data partitions, Phase I) **unbinned maximum likelihood fit** Gaussian signal on flat background
  [Nature 544 (2017) 47]
- **Frequentist**: $N^{0\nu} = 0$ best fit, $\boldsymbol{T_{1/2} > 1.8 \cdot 10^{26}}$ **yr** (median sensitivity -"-) at 90% C.L.,
  Bayesian: flat prior on rate, $T_{1/2} > 1.4 \cdot 10^{26}$ yr at 90% C.I. $> 2.3 \cdot 10^{26}$ yr for flat prior on $m_{\beta\beta}$

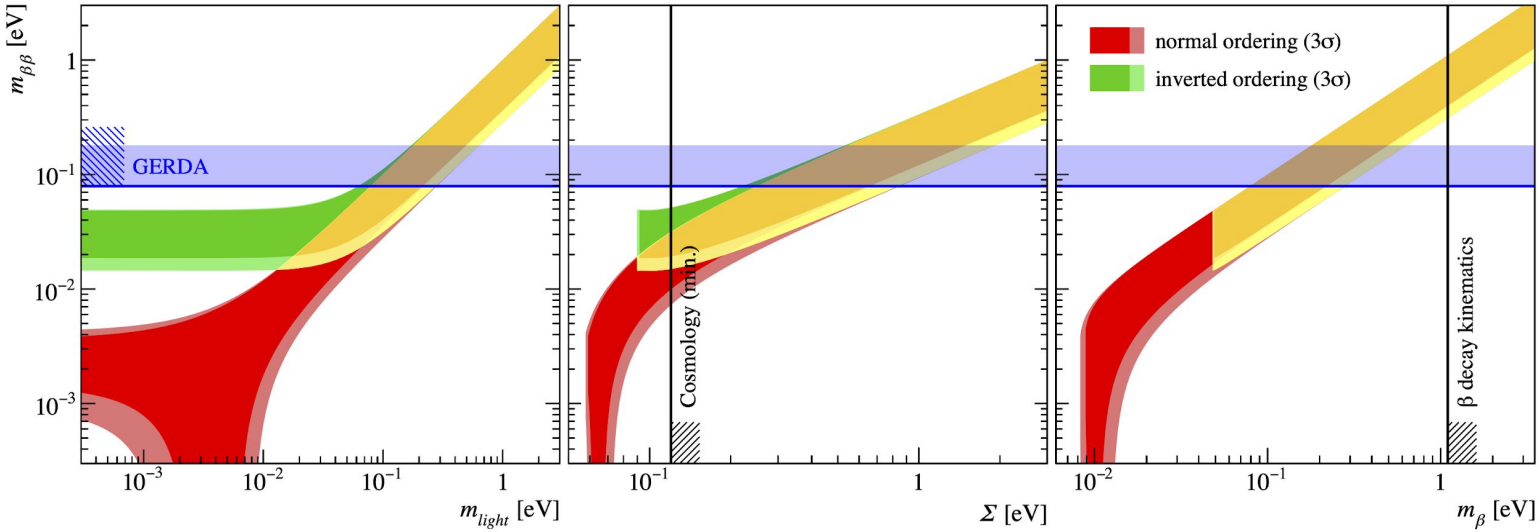
Mass constraints



NME uncertainty

[Engel, Menéndez, Rept.Prog.Phys. 80 (2017) no.4, 046301]

three flavour oscillation parameters from [Esteban et al., JHEP 09 (2020) 178]



$m_{\beta\beta}$ < [0.08,0.18] eV

-> Planck+BAO: Σ < 0.12 eV

[Aghanim et al., arXiv:1807.06209]

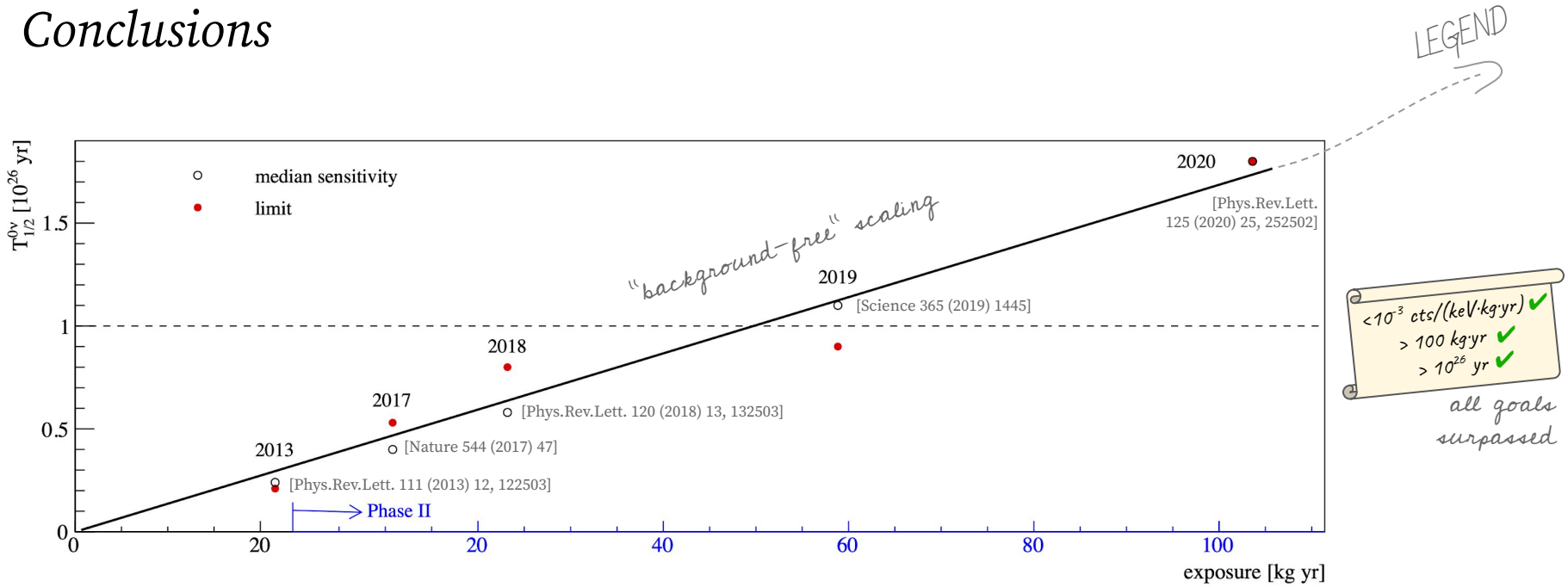
-> KATRIN: m_β < 1.1 eV

[Aker et al., Phys.Rev.Lett. 123 (2019) no.22, 221802]

- given "standard" assumptions 0νββ decay searches constrain **neutrino mass**
- **interplay** with cosmology / direct mass measurements -> m_{light} < [0.1,0.5] eV, sum < [0.2,1.5] eV, m_β < [0.1,0.5] eV

[Science 365 (2019) 1445]

Conclusions



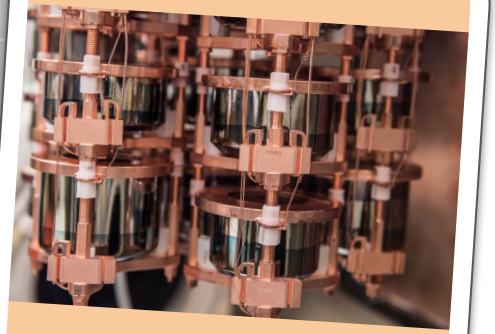
- GERDA has finished successfully *first experiment with sensitivity beyond 10^{26} yr*
- **no signal found** *–> no neutrinos not found*
- further results (2νββ decay, exotics) to come

Take the best

SURF

LNGS

^{76}Ge MAJORANA Dem.

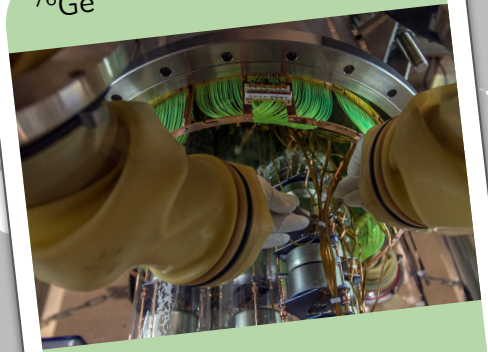


mass	29.7 kg
background	$(4.7\pm0.8)\cdot10^{-3}$ cts/(keV kg yr)
resolution	**(2.53±0.08) keV (FWHM)**
sensitivity	$>4.8\cdot10^{25}$ yr (90% C.L.)
location	SURF (SD)
status	completed

best resolution

[Alvis et al., Phys.Rev. C100 (2019) no.2, 025501]

^{76}Ge GERDA



mass	44.2 kg
background	**$5.2^{+1.6}_{-1.3}\cdot10^{-4}$ cts/(keV kg yr)**
resolution	(2.6±0.2) keV (FWHM)
sensitivity	**$>1.8\cdot10^{26}$ yr (90% C.L.)**
location	LNGS (IT)
status	completed

lowest background

[Phys.Rev.Lett. 125 (2020) 25, 252502]

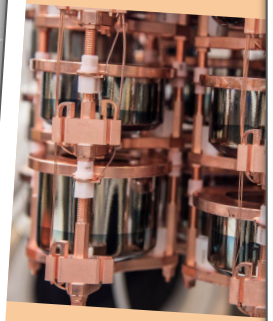
.. and combine them

*"... develop a **phased**, **^{76}Ge** based double-beta decay experimental program with **discovery potential** at a half-life **beyond 10^{28} years**, using **existing resources** as appropriate to expedite physics results."*

SURF

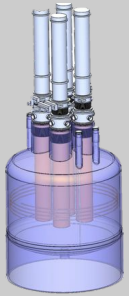
LNGS

^{76}Ge **MAJOR**



mass	29.7 kg
background	(4.7±0.8)·10^{-3} cts/(k
resolution	**(2.53±0.08) keV (FV**
sensitivity	>4.8·10^{25} yr (90% C.L.)
location	SURF (SD)
status	completed

^{76}Ge **LEGEND-1000**



mass	1000 kg (indiv. payloads)
background	**10^{-5} cts/(keV kg yr)**
resolution	2.5 keV (FWHM)
sensitivity	**> 10^{28} yr**
location	**to be selected**
status	contingent on funding

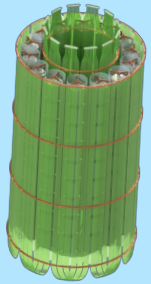
best resolution

[Alvis et al., Phys.Rev. C100 (2019) no.2, 025501]

^{76}Ge **GER**

mass	44.2 kg
background	**$5.2^{+1.6}_{-1.3}$·10^{-4} cts/(ke**
resolution	(2.6±0.2) keV (FWHM
sensitivity	**>1.8·10^{26} yr (90% C.L**
location	LNGS (IT)
status	completed

^{76}Ge **LEGEND-200**



mass	up to 200 kg
background	2·10^{-4} cts/(keV kg yr)
resolution	2.5 keV (FWHM)
sensitivity	**> 10^{27} yr**
location	LNGS (IT)
status	under constr., **start 2021**

[Phys.Rev.Lett. 125 (2020) 25, 252502]

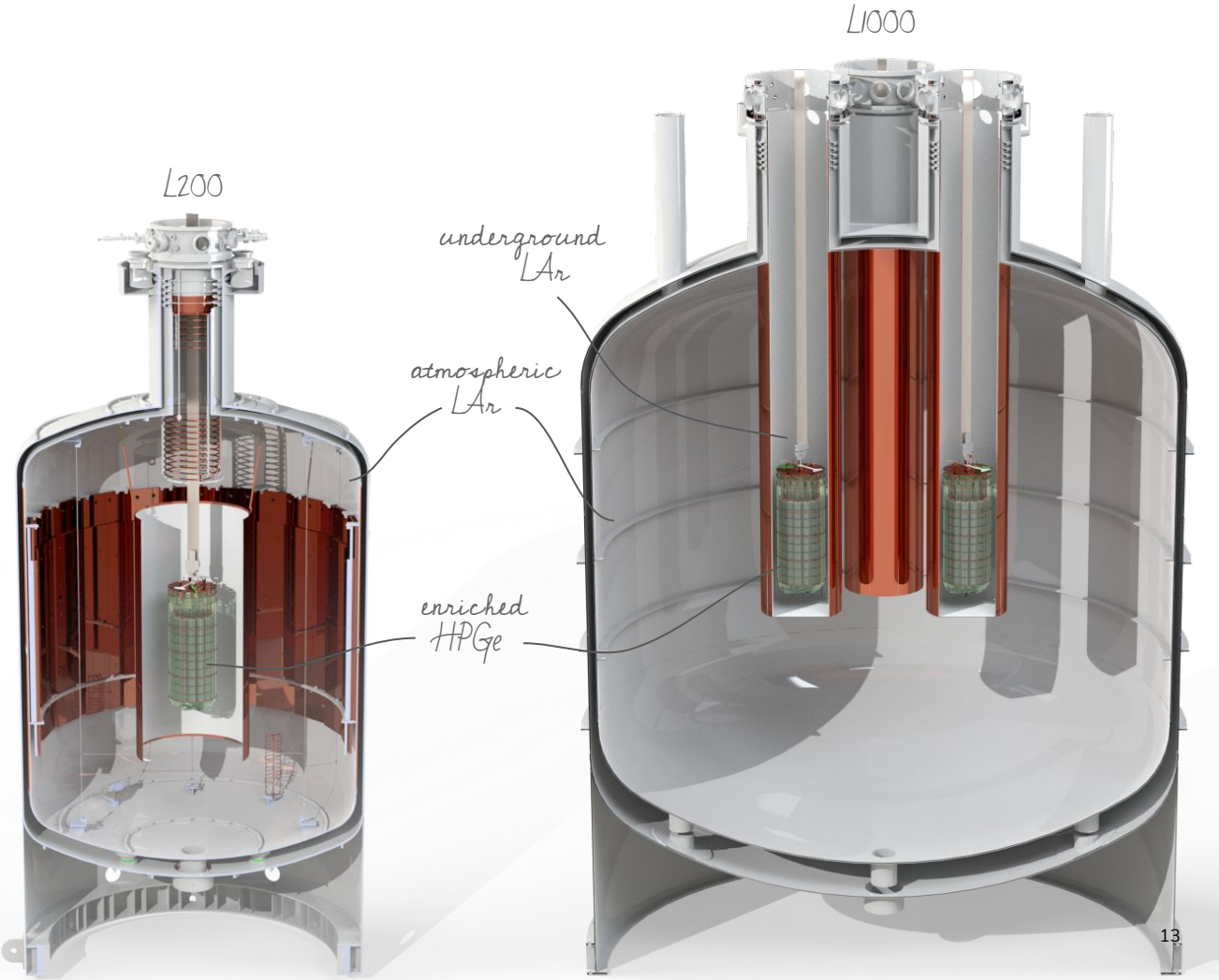
Staged approach

LEGEND-200:

- **200 kg** in existing infrastructure at **LNGS**
- **14 string array**, improved light collection and electronics
- first data in **2021**

LEGEND-1000:

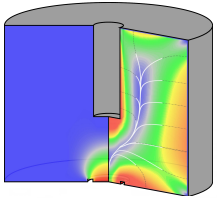
- **4 payloads** with up to 300 kg in **underground LAr** containment
- early data with first payload



LEGEND-200

- existing GERDA and MAJORANA HPGe detectors plus new **ICPC detectors** in **14 string** circular configuration

less auxiliaries, surface-to-volume, peak-to-Compton



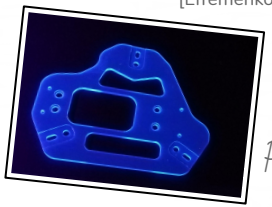
- increased LAr quality, **light yield** and **photo collection**

better background rejection

- improved **electronics** and noise condition

better topology information

- elaborate material selection
  - **electroformed copper**
    [N. Abgrall et al., Nucl.Instrum.Meth. A828 (2016) 22-36]
  - **PEN** structural components
    [Efremenko et al., JINST 14 (2019) 07, P07006]

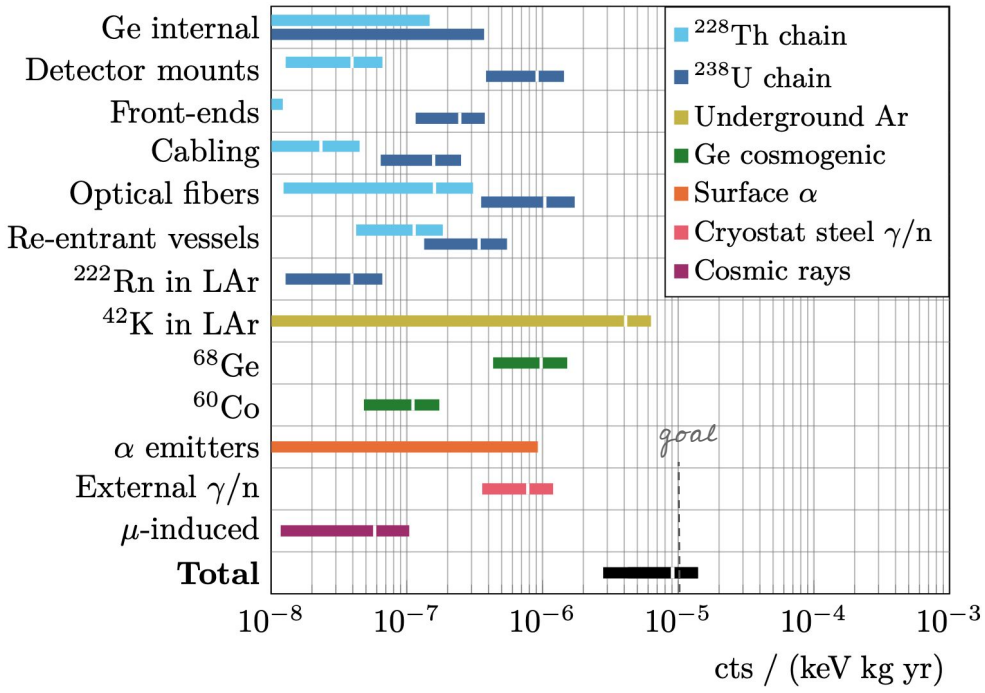


PEN holder plate

- projected background **10^{-4} cts/keV/kg/yr**

below requirement

LEGEND-1000 background projections



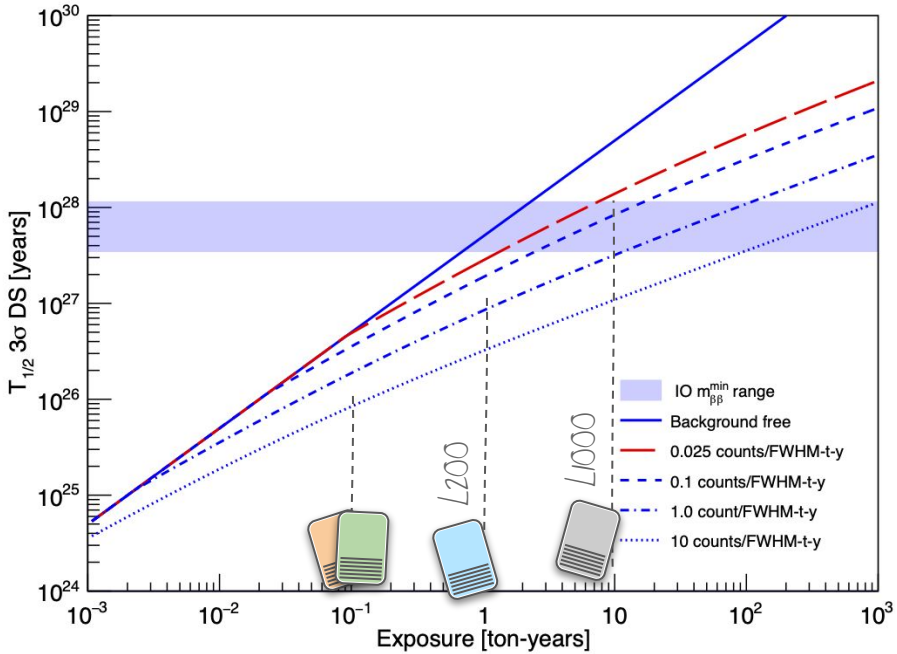
- background contributions **at $Q_{\beta\beta}$ after cuts**
- **Monte Carlo** prediction using assay measurements and data-driven cut performances

  only x1/10 from L200
- reaches **10^{-5} cts/keV/kg/yr** goal
- improvements due to
  - detector sizes 2.6 kg ICPCs
  - **underground argon**
  - new electronics solutions ASICs, cables
  - reduced non-active auxiliaries

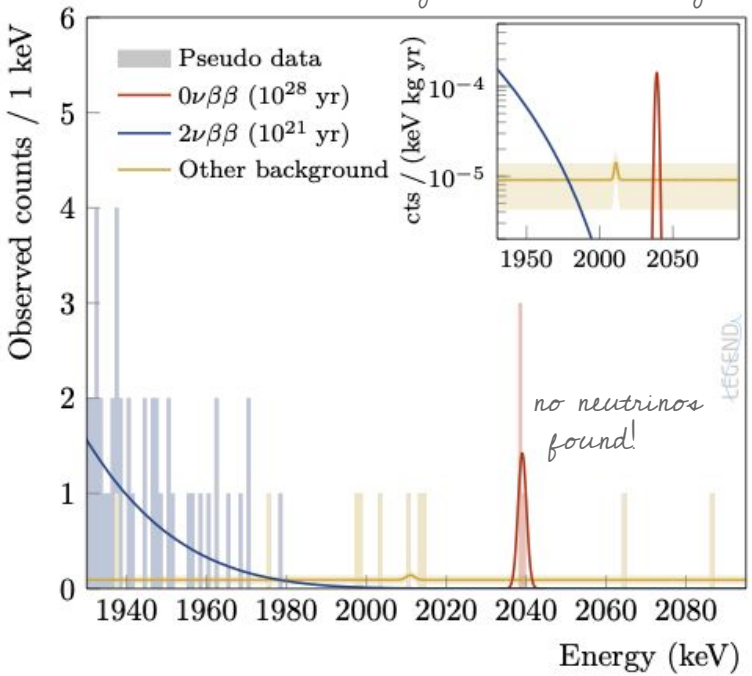
    self-vetoing PEN

Discovery sensitivity

50% chance



toy dataset with 10 t yr

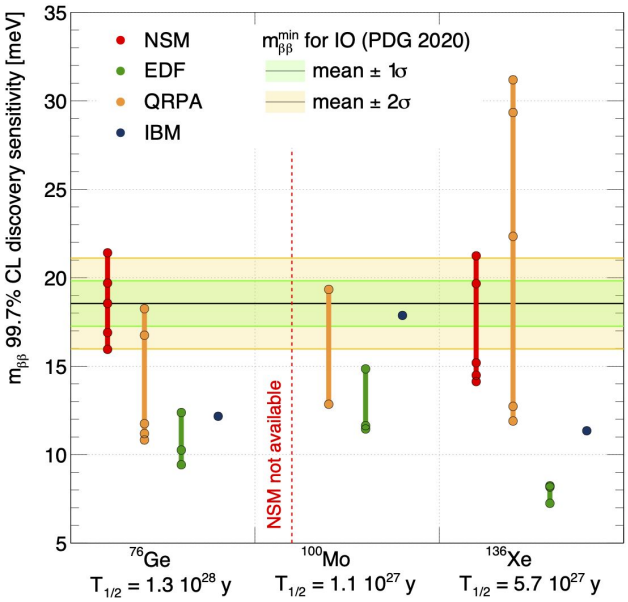


- LEGEND-200 will have discovery sensitivity up to $\mathbf{T_{1/2} > 10^{27}}$ **yr**, LEGEND-1000 will expand until $\mathbf{T_{1/2} > 10^{28}}$ **yr**, probe the **inverted ordering** scenario, and significant fraction in case of normal ordering

Conclusions cont'd

first detector strings during post-GERDA tests

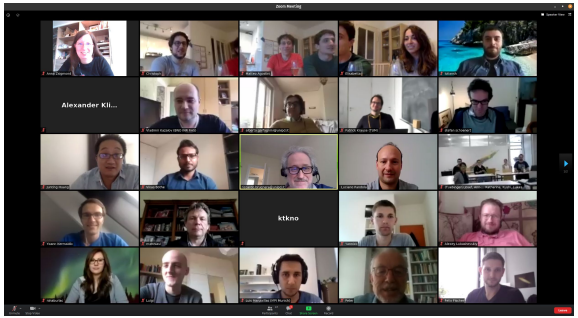
- construction of **LEGEND-200** in GERDA infrastructure at LNGS is ongoing, **first data** is expected in **2021**
- both LEGEND-200 and **LEGEND-1000** are projected to fulfill their background goals
- LEGEND will probe half-lives **beyond 10^{28} yr**, and have a unique **discovery power** provided by the combination of excellent energy resolution and ultra-low background expectation

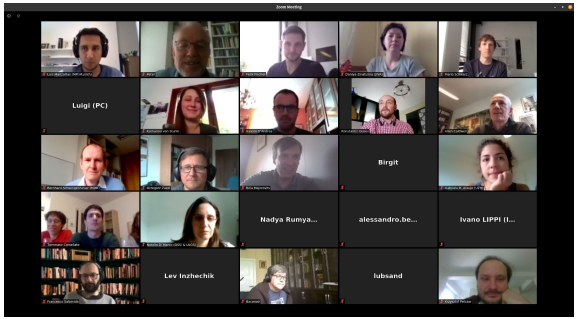


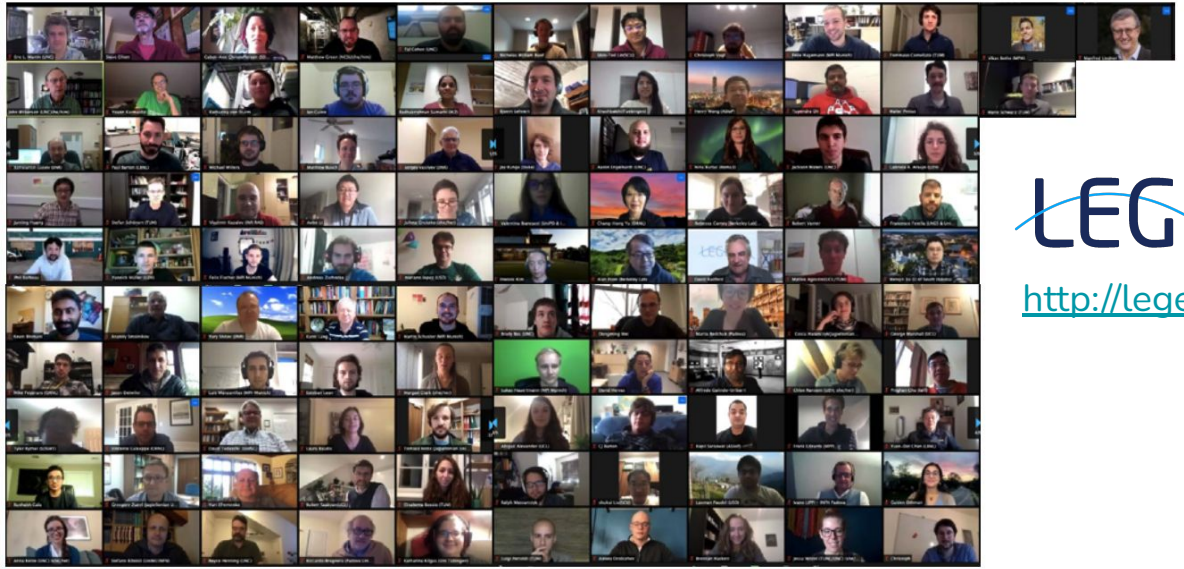
LEGEND

GERDA

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







LEGEND

http://legend-exp.org/

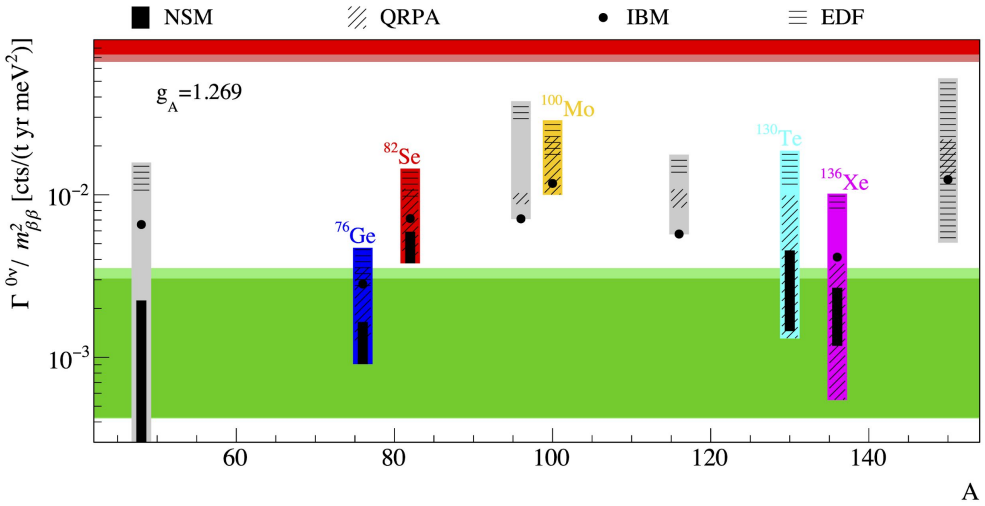
Backup

Nuclear physics aspects

- SM-allowed **2νββ decay** observed in **11** out of 35 naturally abundant **even-even nuclei**
  [Tretyak, Zdesenko, Atom.Data Nucl.Data Tabl. 80 (2002) 83-116]

- **0νββ decay** rate defined by interplay of **BSM physics** and **nuclear structure** details

$$\Gamma^{0\nu} = \underbrace{\frac{N_A}{M(^A\mathrm{X})}}_{\sim 10^{28}\ t^{-1}} \cdot \underbrace{ln(2)}_{\sim 10^{-14}\ yr^{-1}} \cdot G^{0\nu} \cdot \underbrace{\left|g_A^2\,\mathcal{M}^{0\nu}\right|^2}_{\sim 10} \cdot \underbrace{\left(\frac{m_{\beta\beta}}{m_e}\right)^2}_{\sim 10^{-14}\ (\text{for } m_{\beta\beta} < 100\ \text{meV})}$$

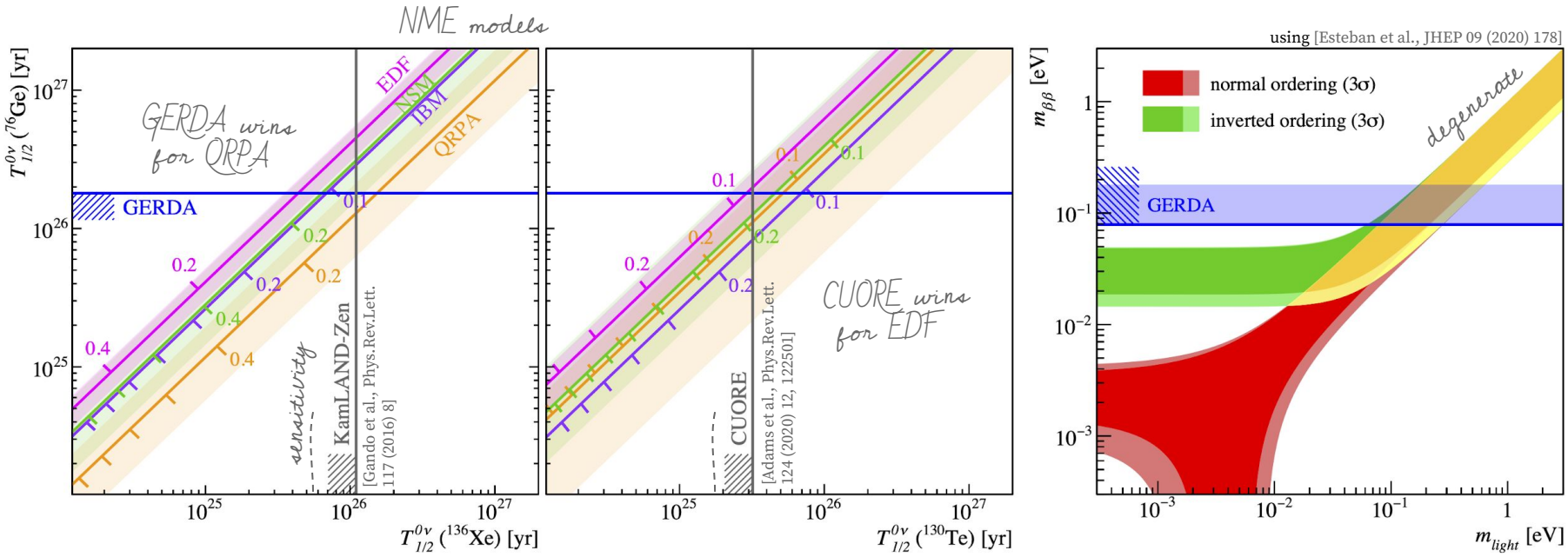


- nuclear model dependence, **matrix element** uncertainty
  [Engel, Menéndez, Rept.Prog.Phys. 80 (2017) 4, 046301]

- ***ab initio*** calculations may solve quenching issue
  [Yao et al. Phys.Rev.Lett. 124 (2020) 23, 232501]

- there is no **super-isotope**
  like [Robertson, Mod.Phys.Lett.A 28 (2013) 1350021]

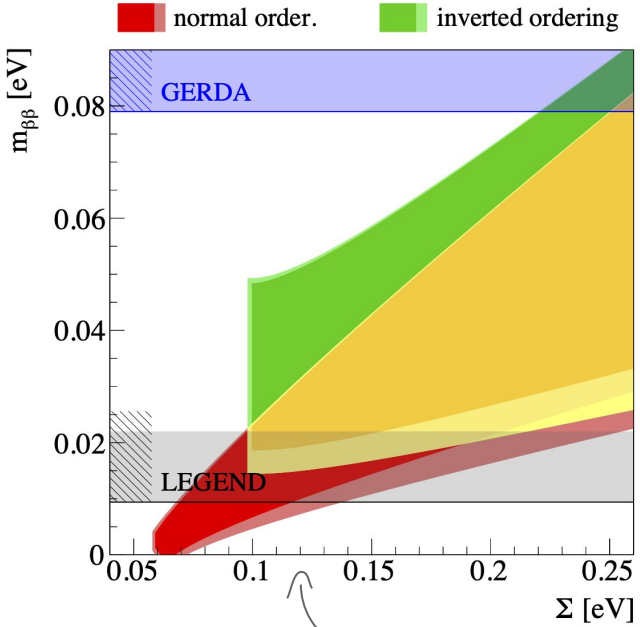
GERDA result comparison



Conclusions cont'd

first detector strings during post-GERDA tests

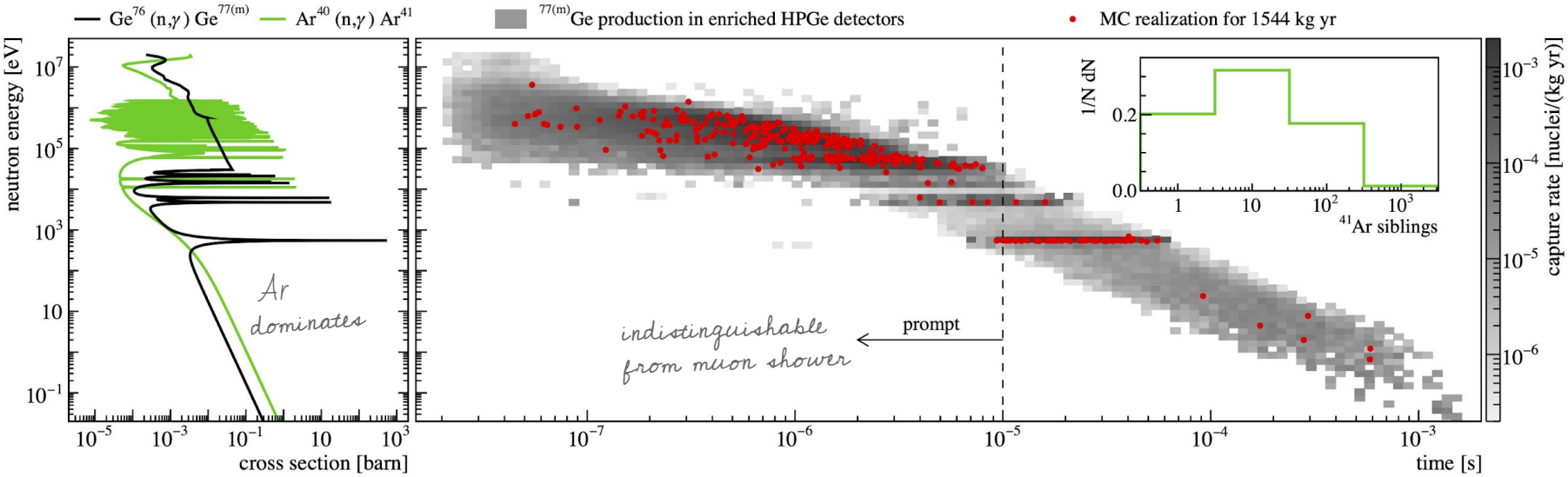
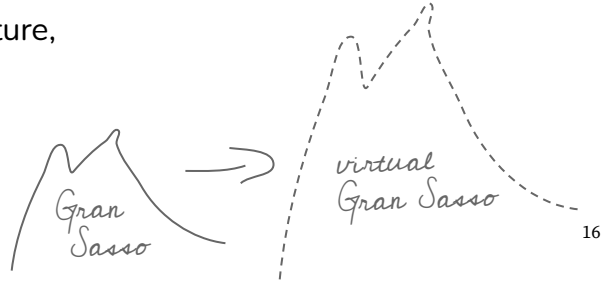
- construction of **LEGEND-200** in GERDA infrastructure at LNGS is ongoing, **first data** is expected in **2021**
- both LEGEND-200 and **LEGEND-1000** are projected to fulfill their background goals
- LEGEND will probe half-lives **beyond 10^{28}**, and have a unique **discovery power** provided by the combination of excellent energy resolution and ultra-low background expectation



complementary to cosmological probes

Virtual depth by active background rejection

[Eur.Phys.J.C 78 (2018) 7, 597]



- **depth-dependent** in-situ production of **$^{77(m)}$Ge** by muon-induced neutron capture, **(0.21+-0.01) nuclei/(kg yr)** in GERDA at LNGS
- single-beta **^{77m}Ge** background can be reduced by **delayed tagging cuts**, active reduction cuts place LNGS at **~5000 m.w.e virtual overburden**