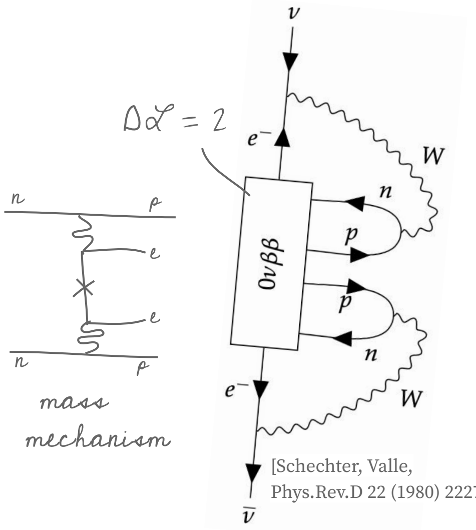
No neutrinos not yet *found*

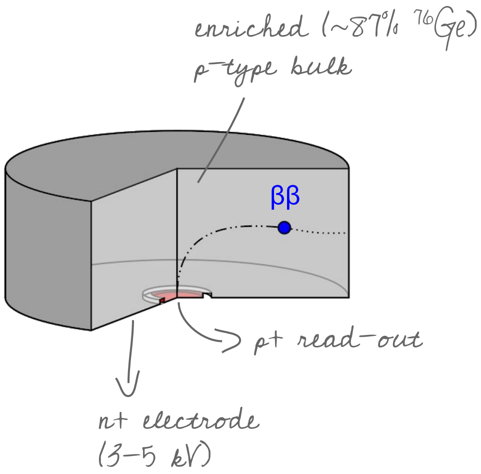
Final result of GERDA and the physics potential of LEGEND

Christoph Wiesinger TUM, Neutrino GdR, 24th November 2020

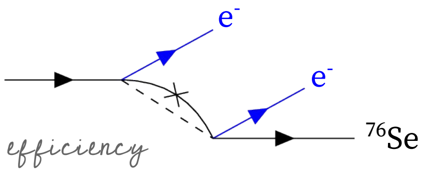


[Schechter, Valle, Phys.Rev.D 22 (1980) 2227]

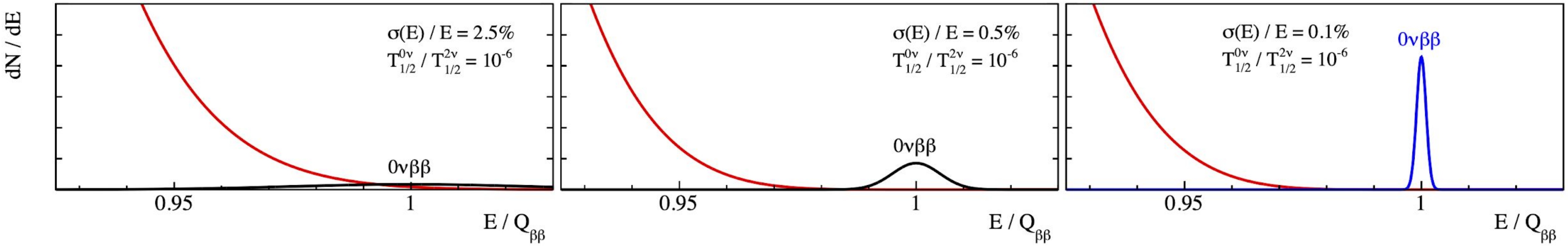
Experimental approach



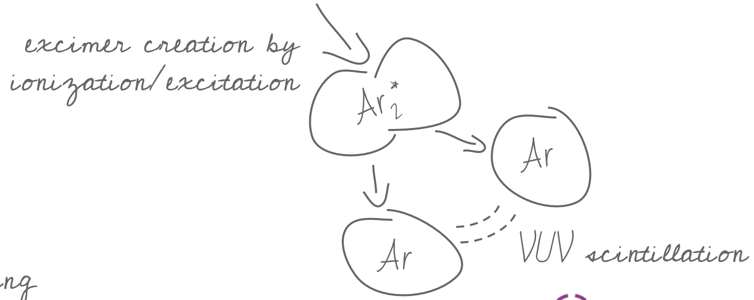
HPGe detectors enriched in ^{76}Ge

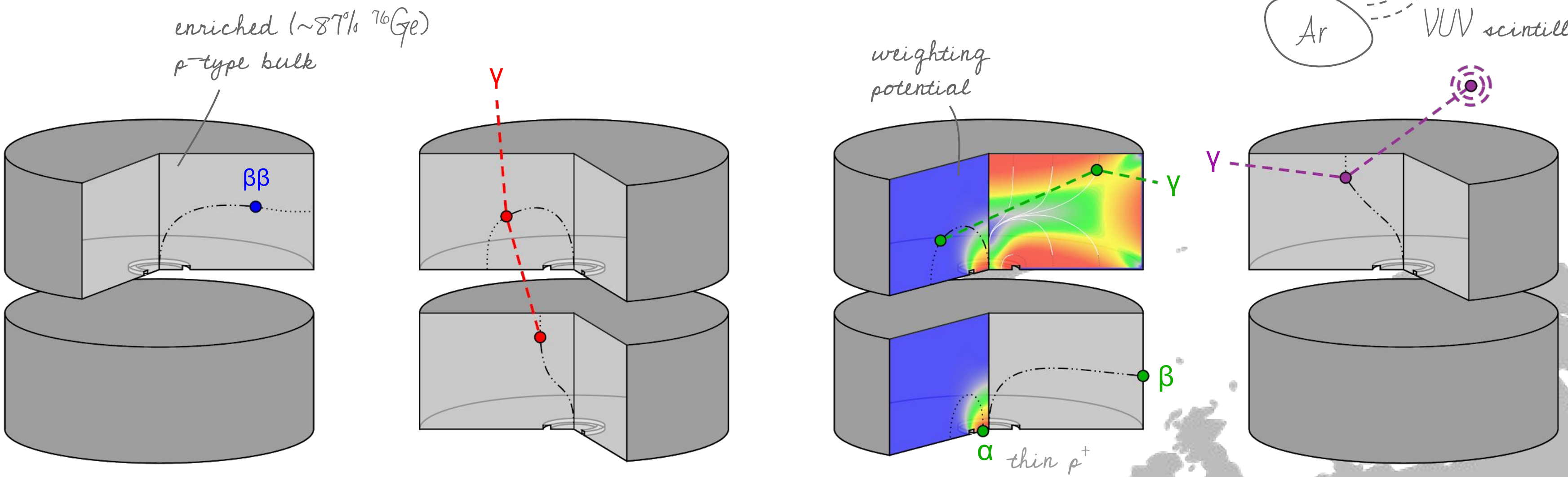


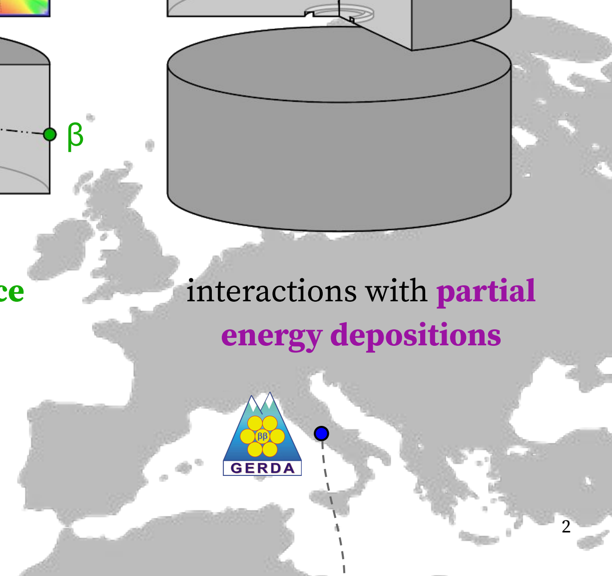
- source = detector *-> high efficiency*
- **high-purity** material *-> no intrinsic background*
  [Astropart.Phys. 91 (2017) 15-21]
- energy resolution $\boldsymbol{\sigma(E) / E < 0.1\%}$ at $\mathbf{Q_{\beta\beta} = 2039\ keV}$
- high stopping power *-> topology information*



Topology discrimination







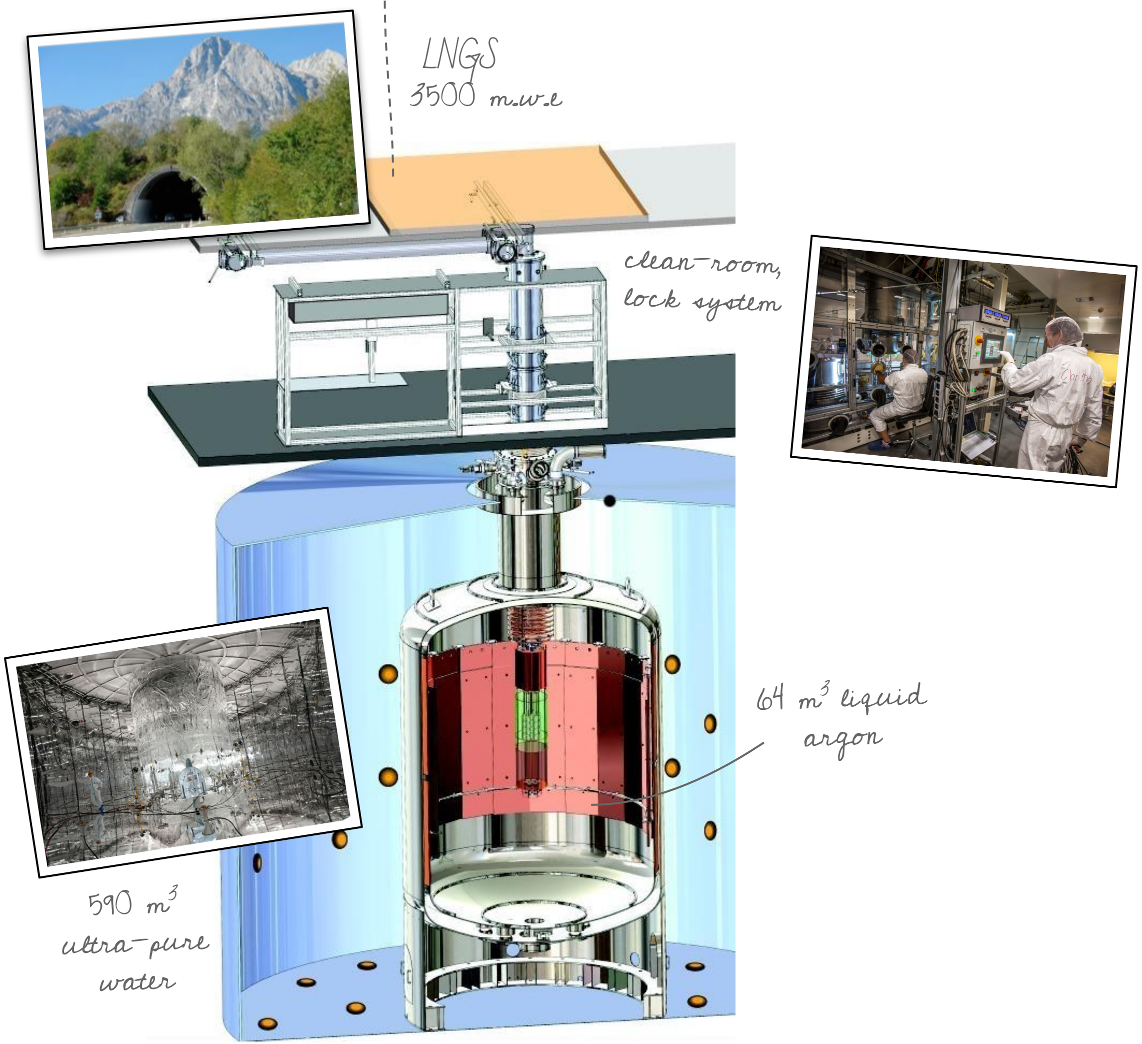
differentiate **point-like** $\beta\beta$ topology from:

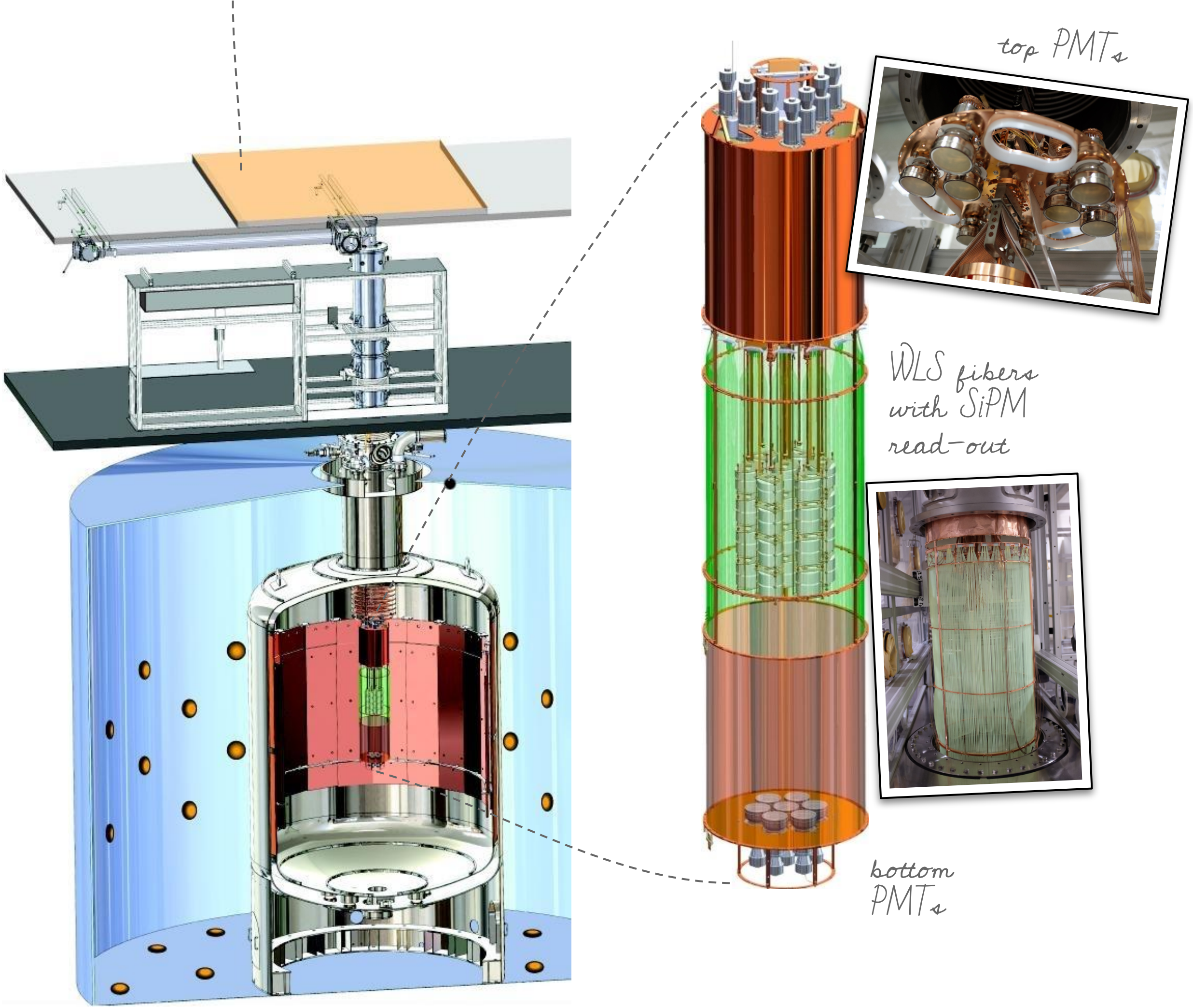
multi-detector interactions

multi-site/surface interactions

interactions with **partial energy depositions**

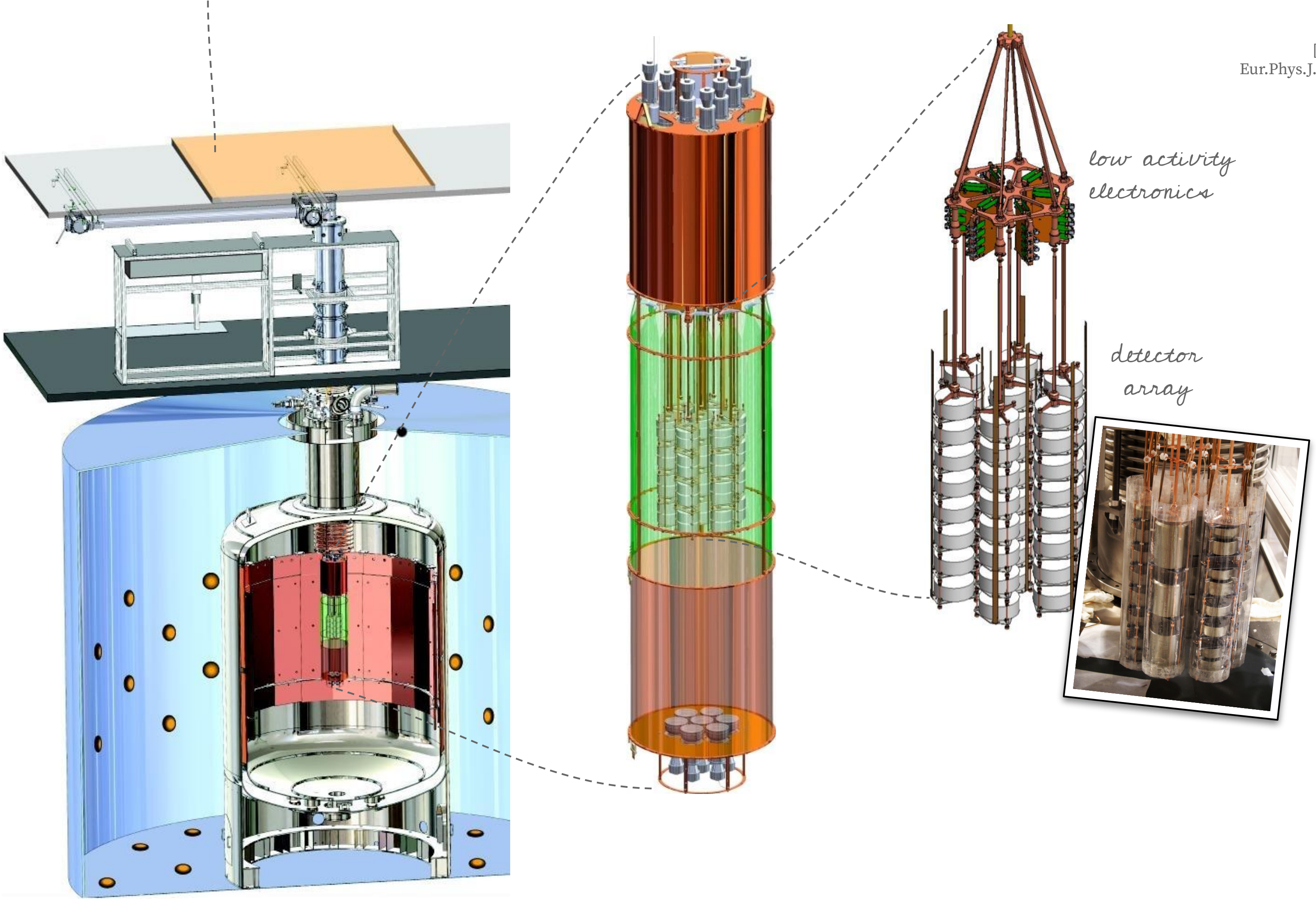
[Nature 544 (2017) 47,
Eur.Phys.J. C78 (2018) no.5, 388]



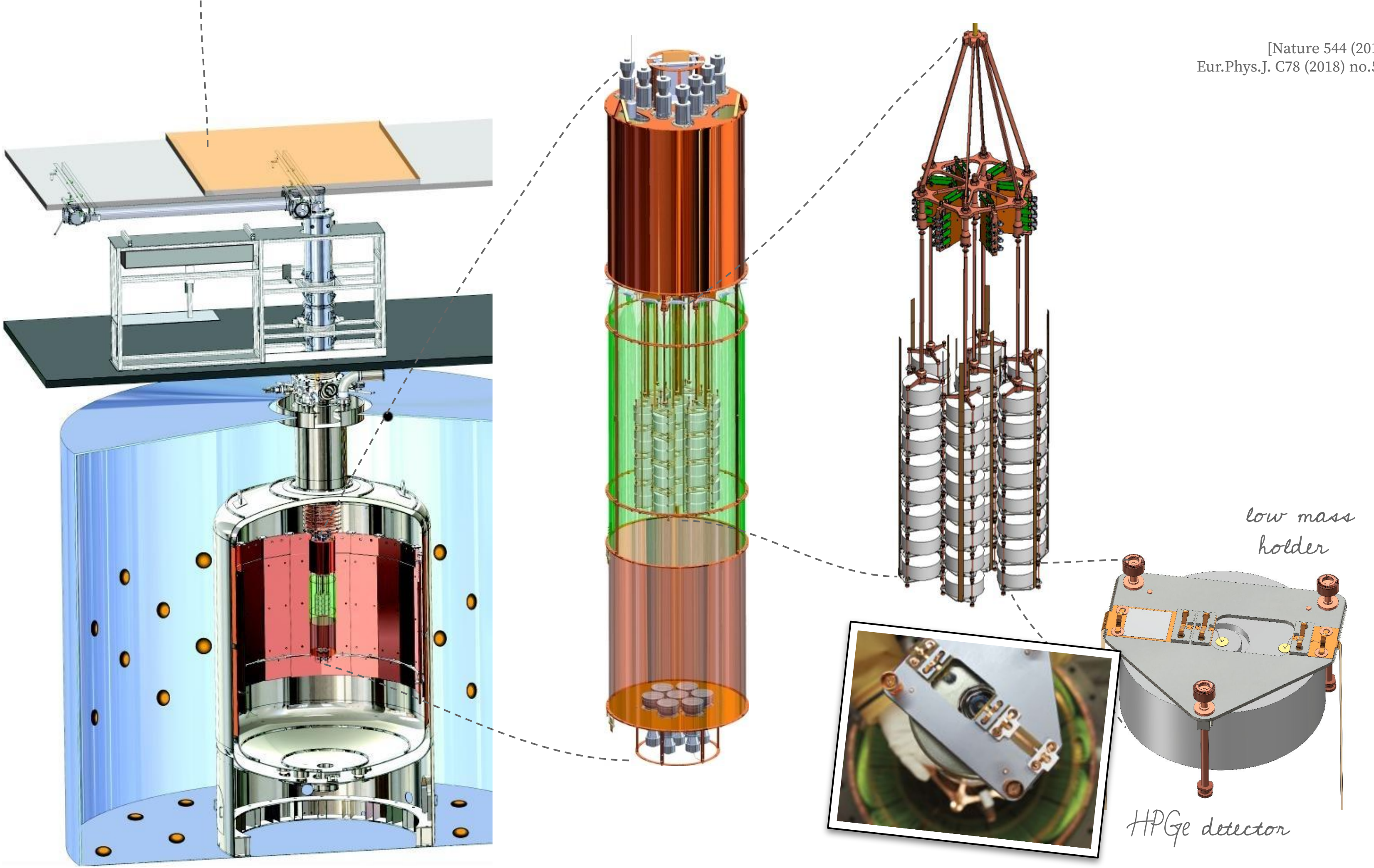


[Nature 544 (2017) 47,
Eur.Phys.J. C78 (2018) no.5, 388]

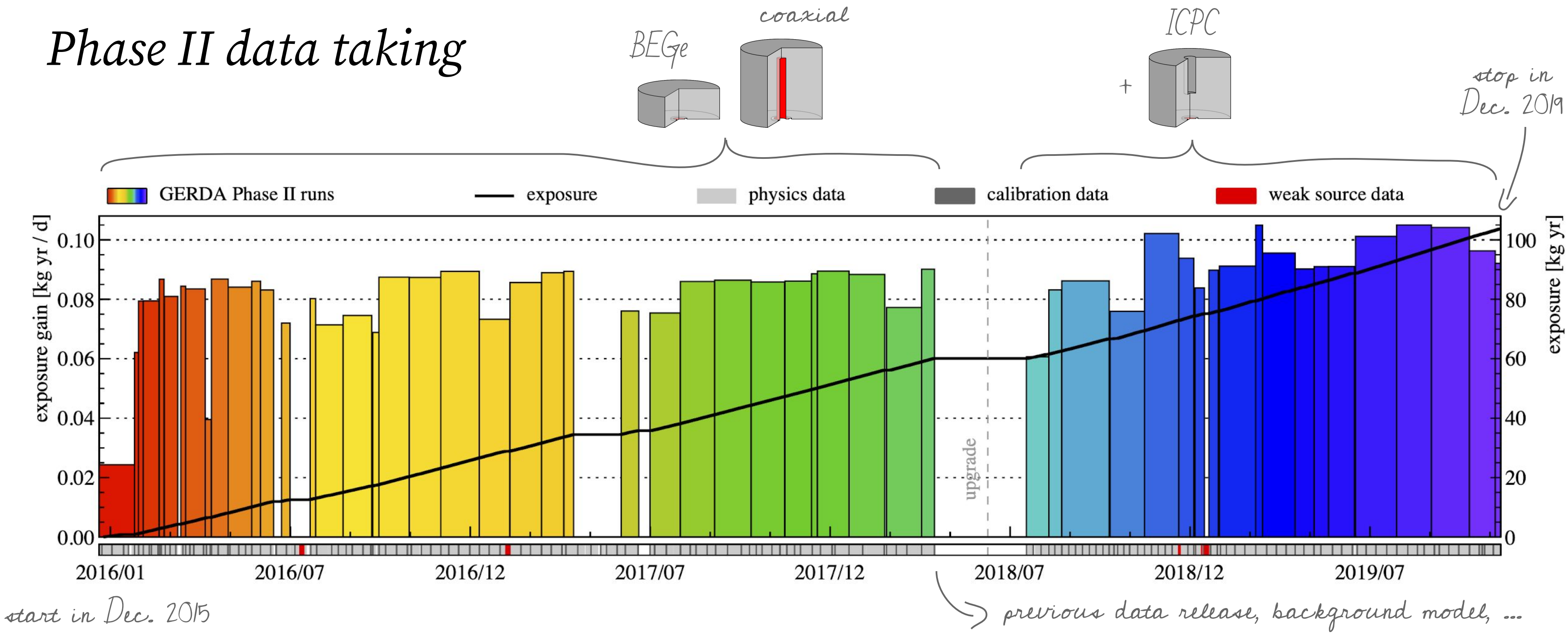
[Nature 544 (2017) 47,
Eur.Phys.J. C78 (2018) no.5, 388]



[Nature 544 (2017) 47,
Eur.Phys.J. C78 (2018) no.5, 388]

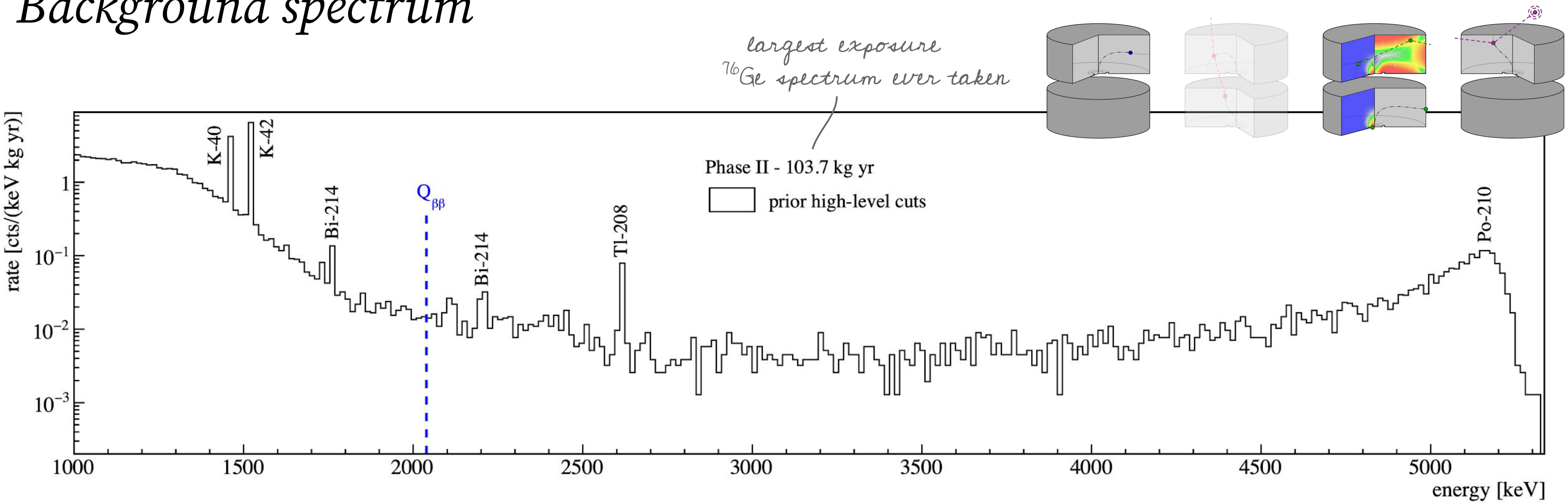


Phase II data taking

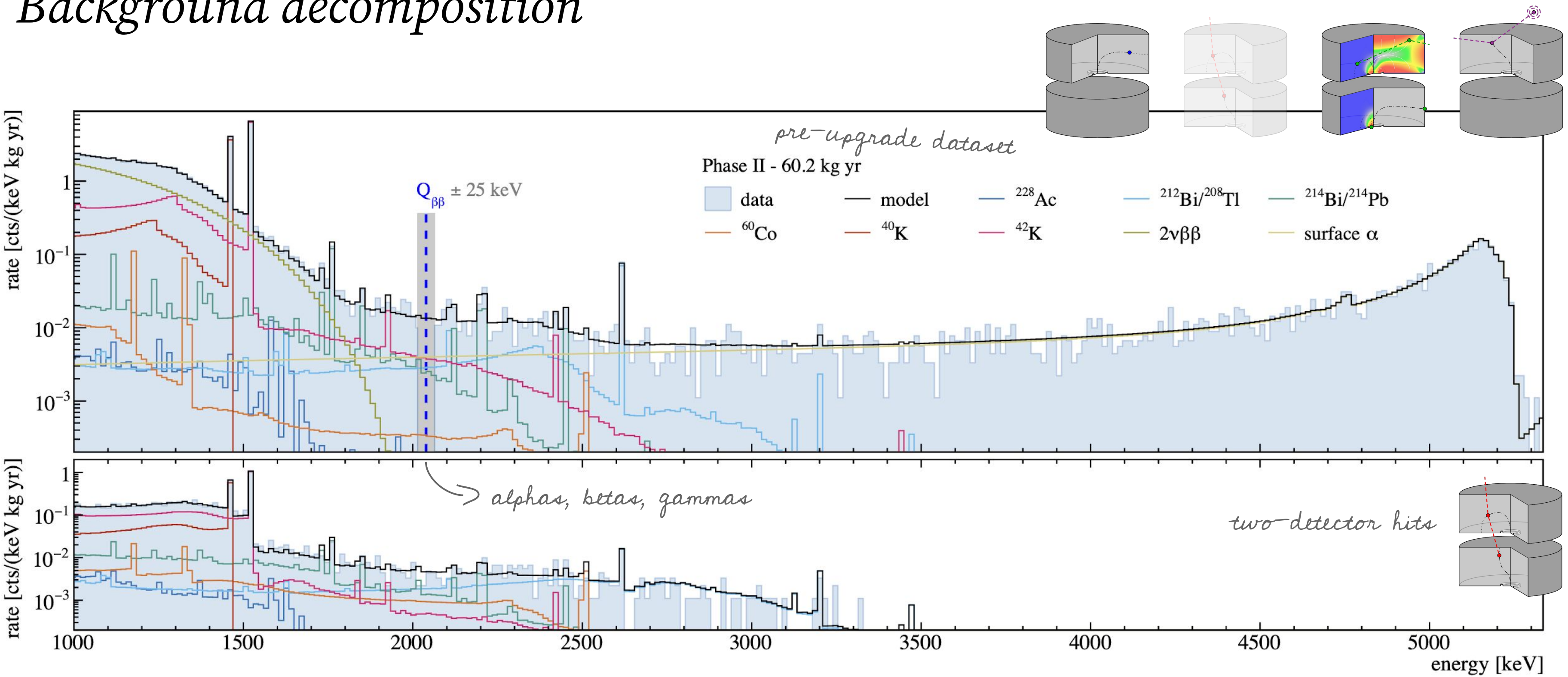


- pre-/post-upgrade data taking with **35.6 / 44.2 kg** of enriched HPGe detectors
- **4 yr** operation, with about **90%** duty cycle (incl. upgrade works), **103.7 kg yr** of data selected for

Background spectrum



Background decomposition

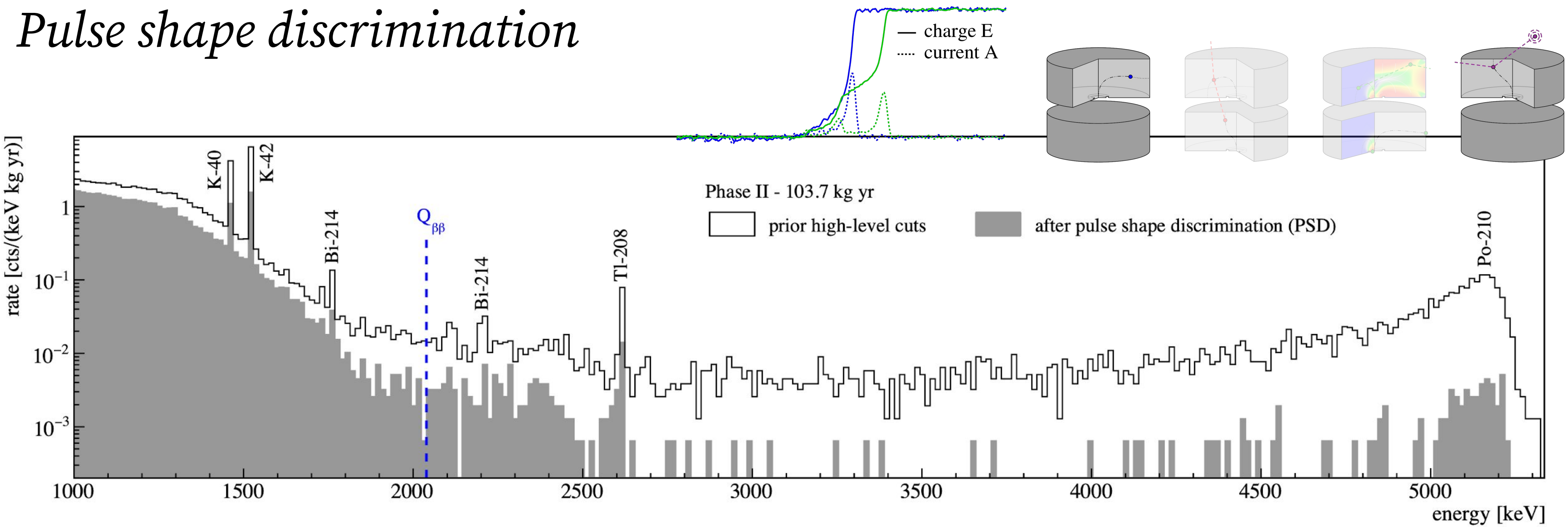


- combined Bayesian fit to multiple datasets with Monte Carlo *pdf*s for **nearby components**

[JHEP 03 (2020) 139]

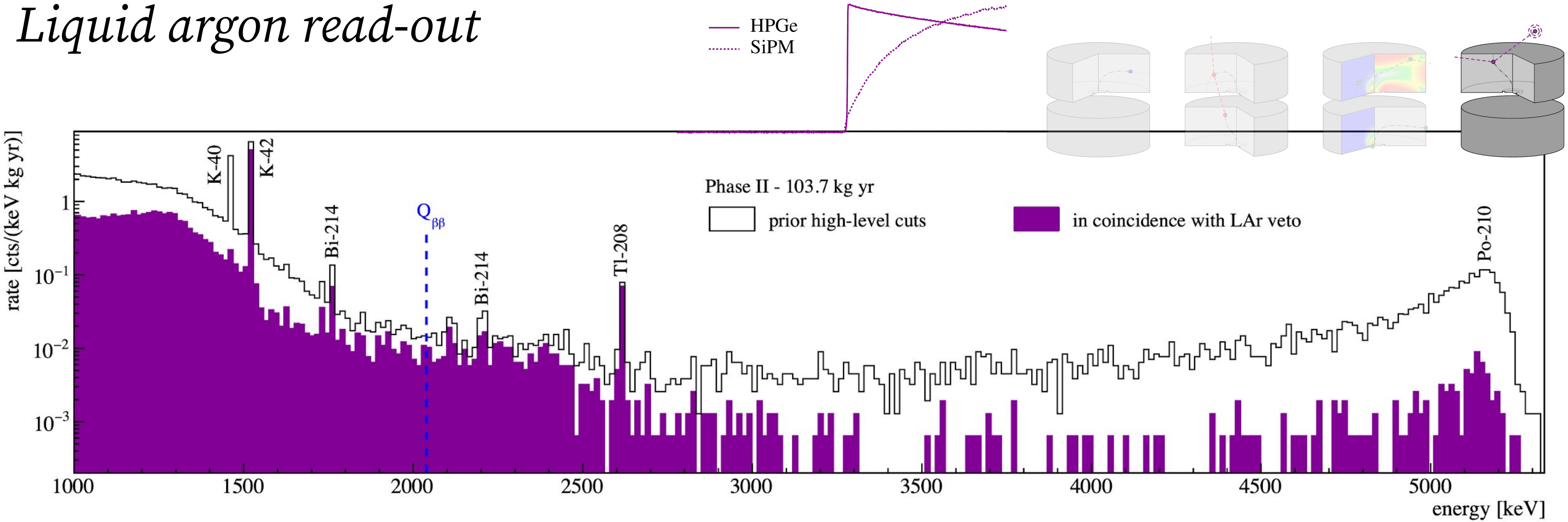
screening measurements as priors

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 as signal proxy
- $0\nu\beta\beta$ signal efficiency **~90%** (~70% for coaxials)

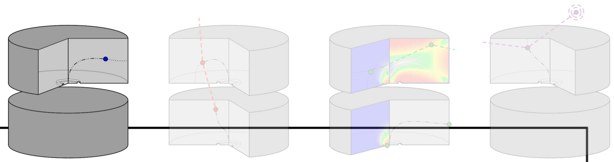
Liquid argon read-out

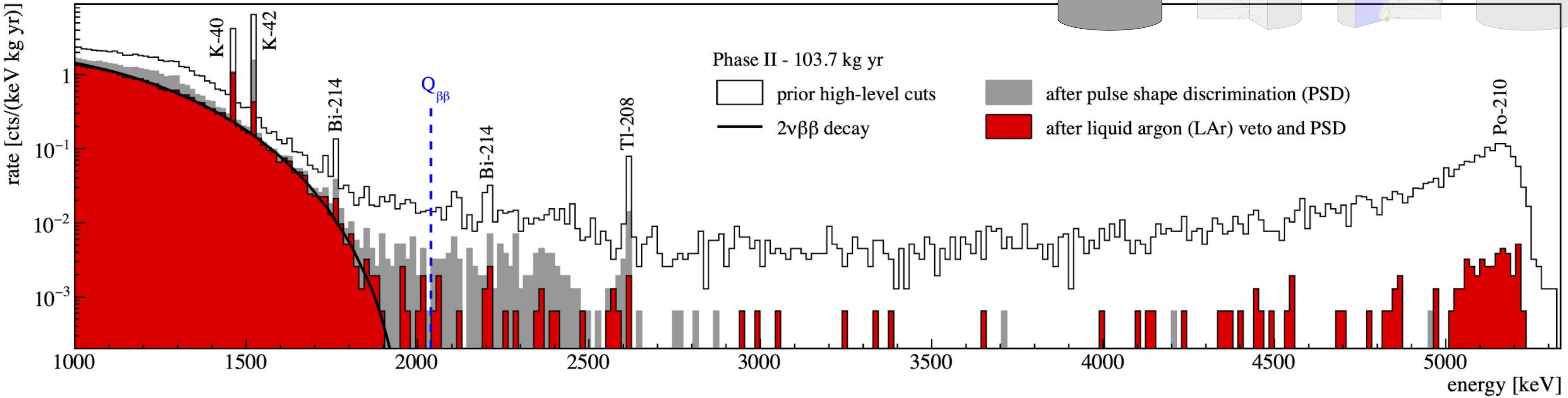


- channel-wise **(anti-)coincidence condition** (PMTs/SiPMs)
- **sub-PE threshold**, contains characteristic scintillation **timing** (triplet emission)   *lifetime ~1 μs*
- 0νββ signal efficiency (1 - random coincidence rate) **> 97%**

^{39}Ar, dark rate

Final Phase II spectrum



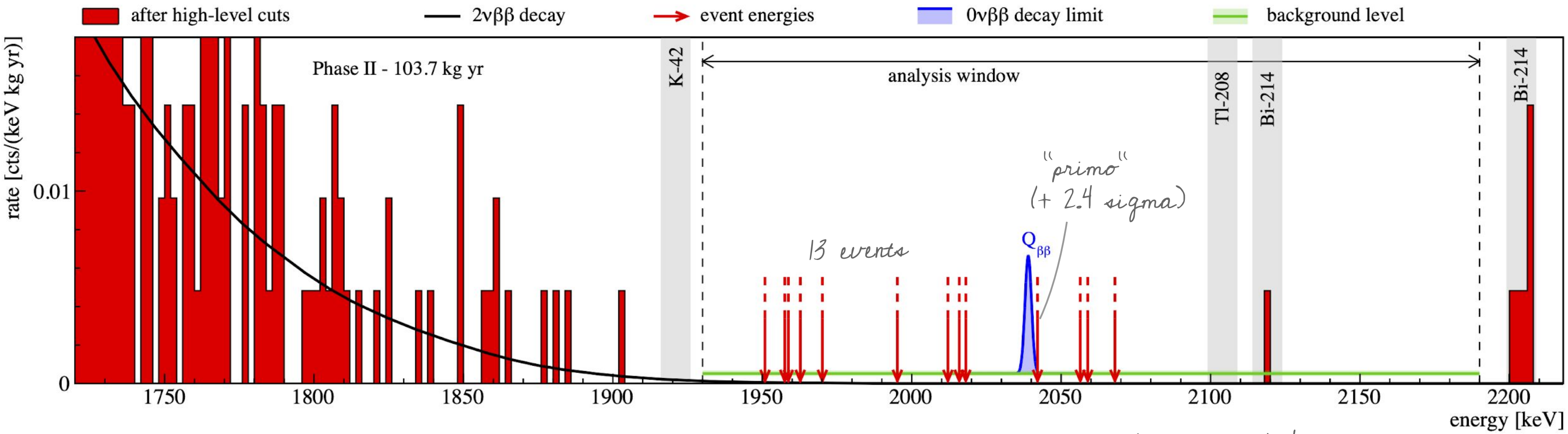


- “clean” **2νββ continuum** *shape analysis in preparation*
- sparse **single counts at > $Q_{\beta\beta}$**

no alphas in BEGe / ICPC

Final GERDA result

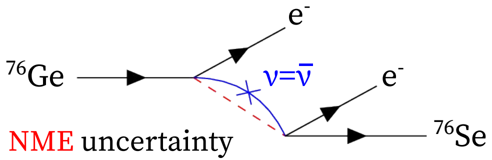
< 1 cts in 100 kg yr and 5 keV



resolution tracked

- background index **5.2$^{+1.6}_{-1.3}$ · 10^{-4} cts/(keV ky yr)**, energy resolution **~3 keV** (FWHM) per detector/period
- 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 · 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_{bb}

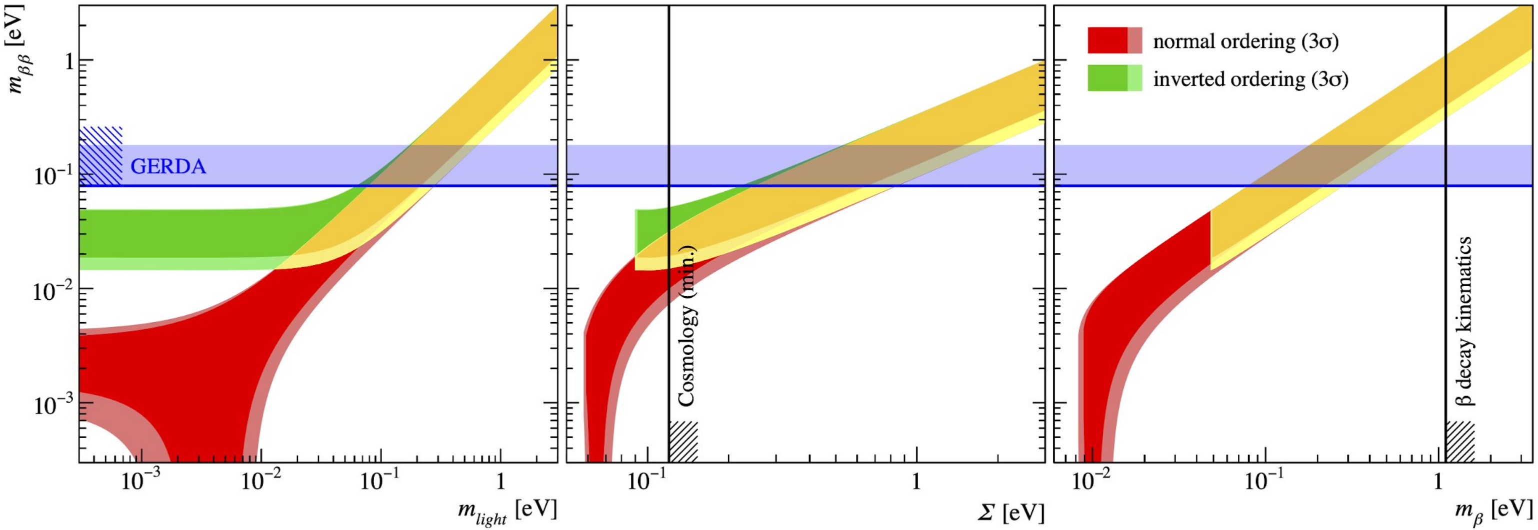
Mass observables



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**

others:

KamLAND-Zen: < [0.05,0.23] eV

CUORE: < [0.07,0.34] eV

-> Planck+BAO: **Σ < 0.12 eV**

[Aghanim et al., arXiv:1807.06209]

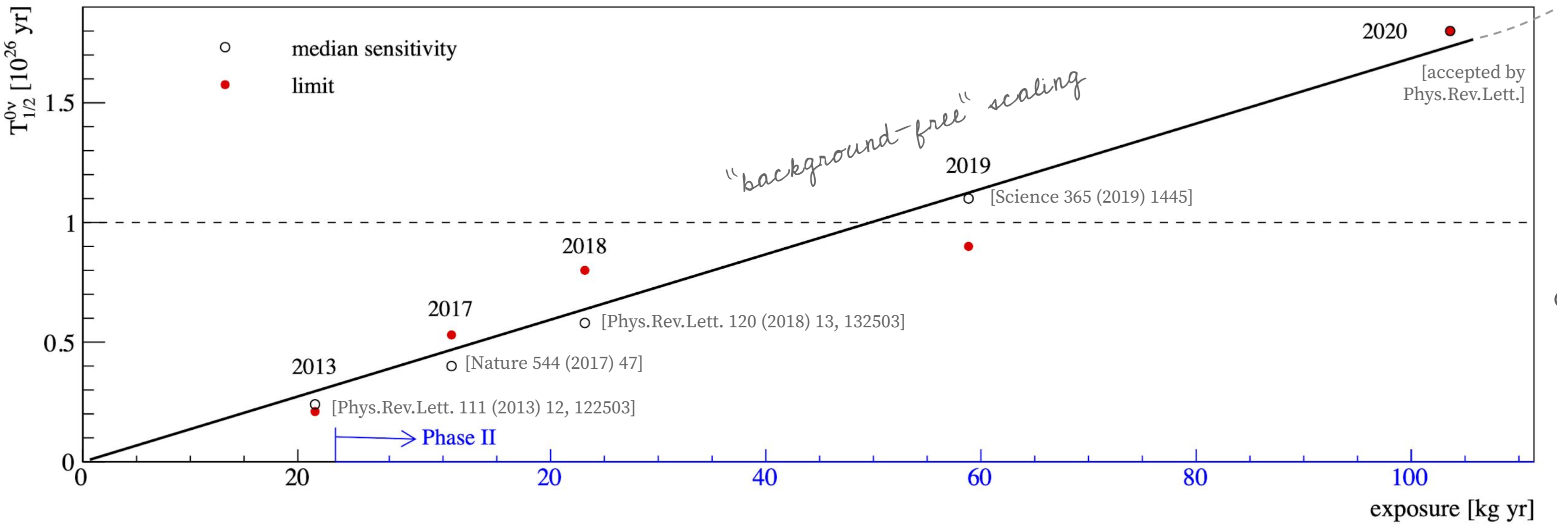
-> KATRIN: **m_β < 1.1 eV**

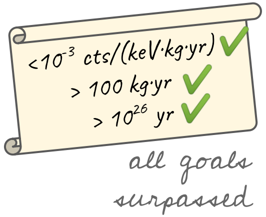
[Aker et al., Phys.Rev.Lett. 123 (2019) no.22, 221802]

- 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_b < [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, BSM physics) to come

Combine the best from two worlds

Majorana Demonstrator

29.7 kg of enriched p+ point contact (PPC) detectors with **low noise electronics** in compact shield from **underground electroformed copper**

background:	$(4.7\pm0.8)\cdot10^{-3}$ cts/(keV kg yr)
$T_{1/2}$ sensitivity:	$>4.8\cdot10^{25}$ yr (90% C.L.) [Alvis et al., Phys.Rev. C100 (2019) no.2, 025501]
where:	SURF (SD)
when:	ongoing

GERDA Phase II

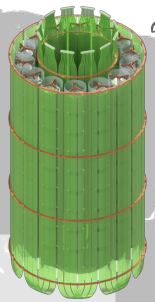
44.2 kg of enriched BEGe/coaxial/ICPC detectors operated in low A **active LAr shield**

background:	$5.2^{+1.6}_{-1.3}\cdot10^{-4}$ cts/(keV kg yr)
$T_{1/2}$ sensitivity:	$>1.8\cdot10^{26}$ yr (90% C.L.) [accepted by Phys.Rev.Lett.]
where:	LNGS (IT)
when:	**completed**

Combine the best from two worlds

LEGEND

*"… 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."*



? SNOLAB

? SURF

? LNGS

? CJPL

LEGEND-1000

1000 kg, staged via individual payloads

background:	10^{-5} cts/(keV·kg·yr)
$T_{1/2}$ sensitivity:	$>10^{28}$ yr
where:	**to be selected**
when:	contingent on funding decisions

LEGEND-200

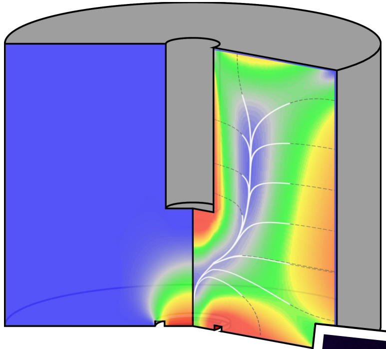
up to **200 kg** of enriched ICPC(/BEGe/PPC) detectors in GERDA infrastructure

background:	$< 2\cdot10^{-4}$ cts/(keV·kg·yr)
$T_{1/2}$ sensitivity:	$>10^{27}$ yr
where:	LNGS (IT)
when:	**2021**

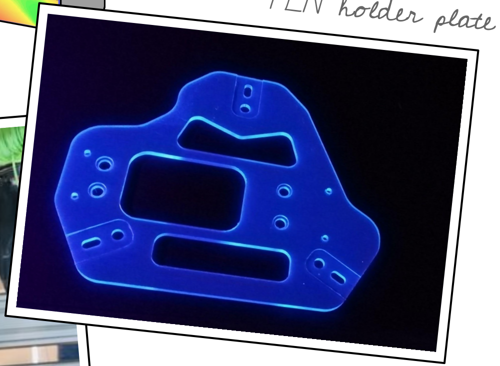
1/3 of GERDA

Key technologies

- large mass HPGe detectors, inverted coaxial point contact (**ICPC**) detectors
  [Cooper et al., Nucl.Instrum.Meth. A665, 25 (2011) 25-32]
    - active mass up to **3 kg**
    - excellent PSD performance
      [Domula et al., Nucl.Instrum.Meth. A891 (2018) 106-110]
- improved LAr scintillation light read-out
- elaborate material selection
    - **radiopurity** (electroformed copper, underground Ar for L1000)
    - optically active materials (PEN structures)
      [Efremenko et al., JINST 14 (2019) 07, P07006]
- enhanced **active background rejection**, e.g. delayed-coincidence cuts for muon-induced ^{77m}Ge
  [Eur.Phys.J.C 78 (2018) 7, 597]



inverted coaxial detector

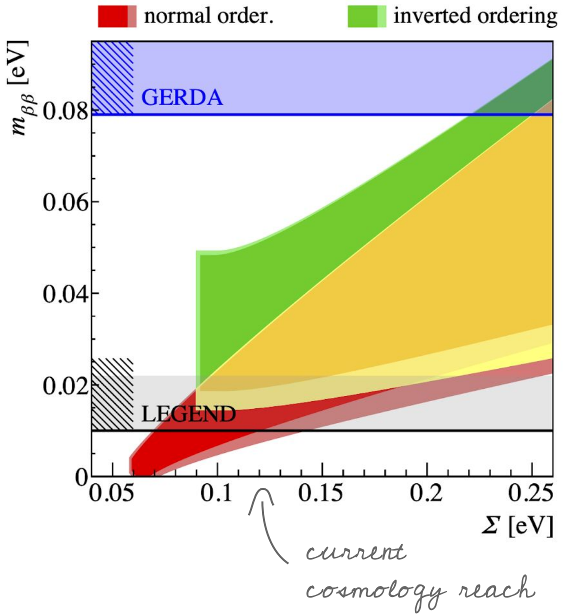


PEN holder plate

first detector strings during post-GERDA tests

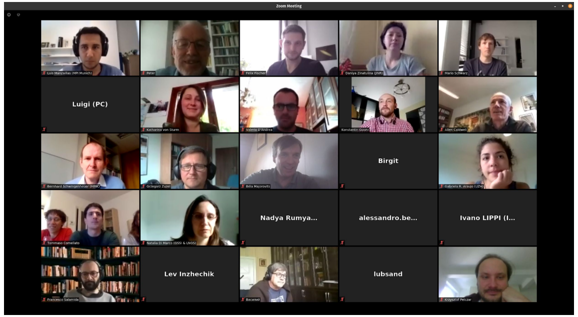
Conclusions cont'd

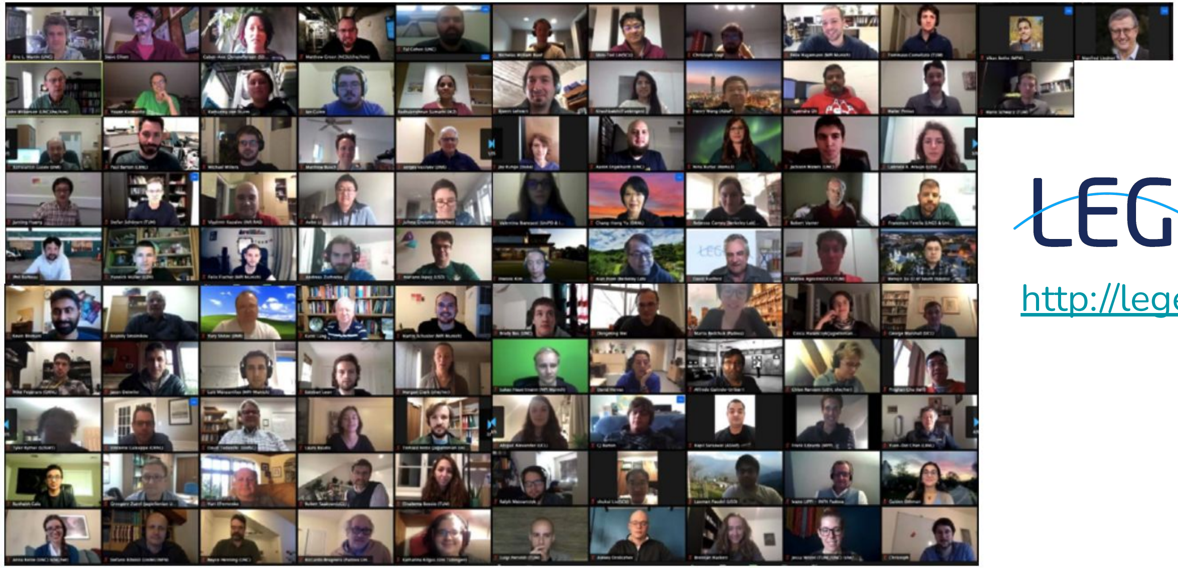
- construction of **LEGEND-200** in GERDA infrastructure at LNGS is ongoing, **first data** is expected in **2021**
- **LEGEND-1000** R&D is proceeding, cryostat design will adapt to **site selection**
- LEGEND will probe half-lives **beyond 10^{28}**, and have a unique **discovery power** provided by the combination of excellent energy resolution and ultra-low background expectation



GERDA

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





LEGEND

http://legend-exp.org/

*Back*up

Nuclear physics aspects

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

- **$0\nu\beta\beta$ decay** rate defined by interplay of **BSM physics** and **nuclear structure** details

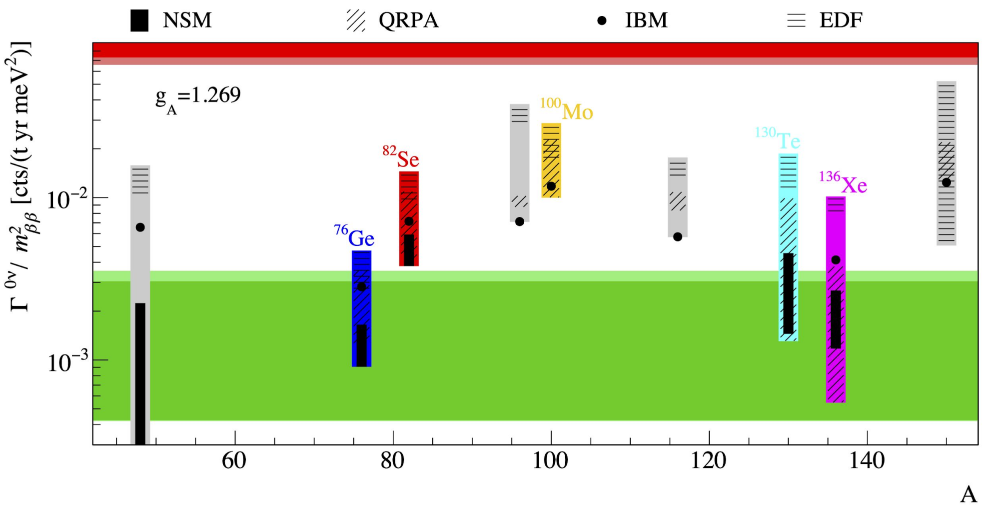
$$\Gamma^{0\nu} = \frac{N_A}{M(^A\mathrm{X})} \cdot ln(2) \cdot G^{0\nu} \cdot |g_A^2\, \mathcal{M}^{0\nu}|^2 \cdot \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

$\sim 10^{28}\ t^{-1}$

$\sim 10^{-14}\ yr^{-1}$

~ 10

$\sim 10^{-14}$ (for $m_{bb} < 100$ meV)



normal ordering

inverted ordering

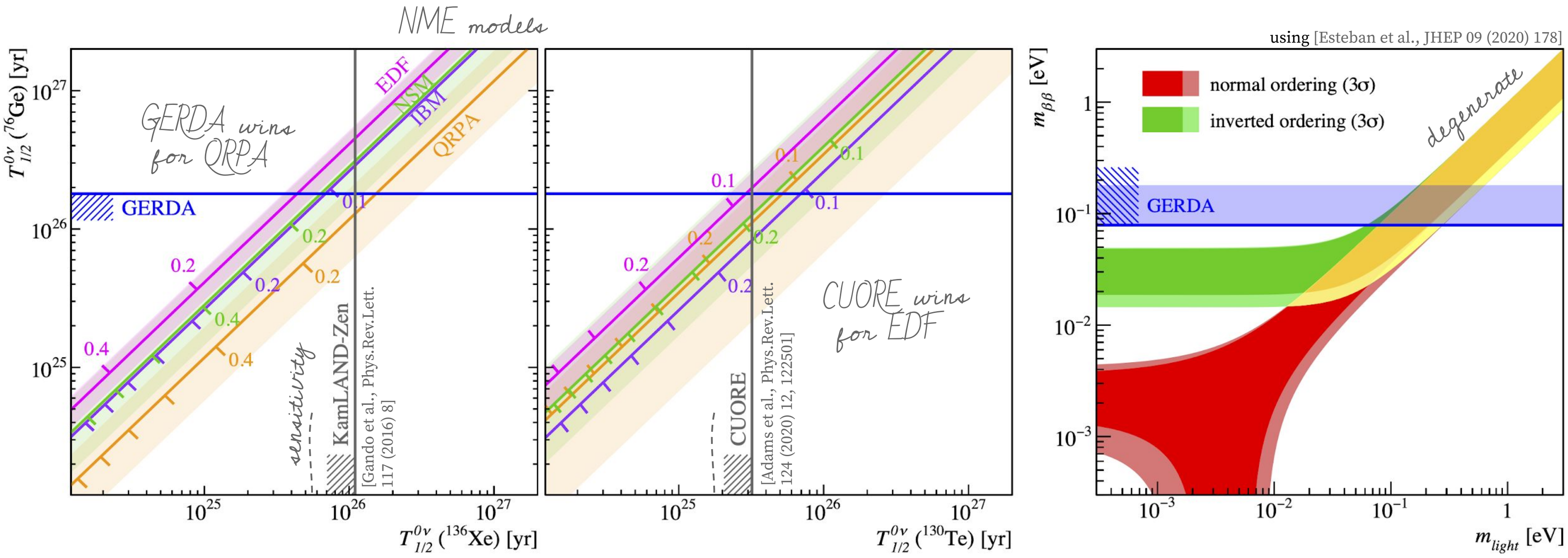
1 cts/(t · yr)

- 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



Background projections