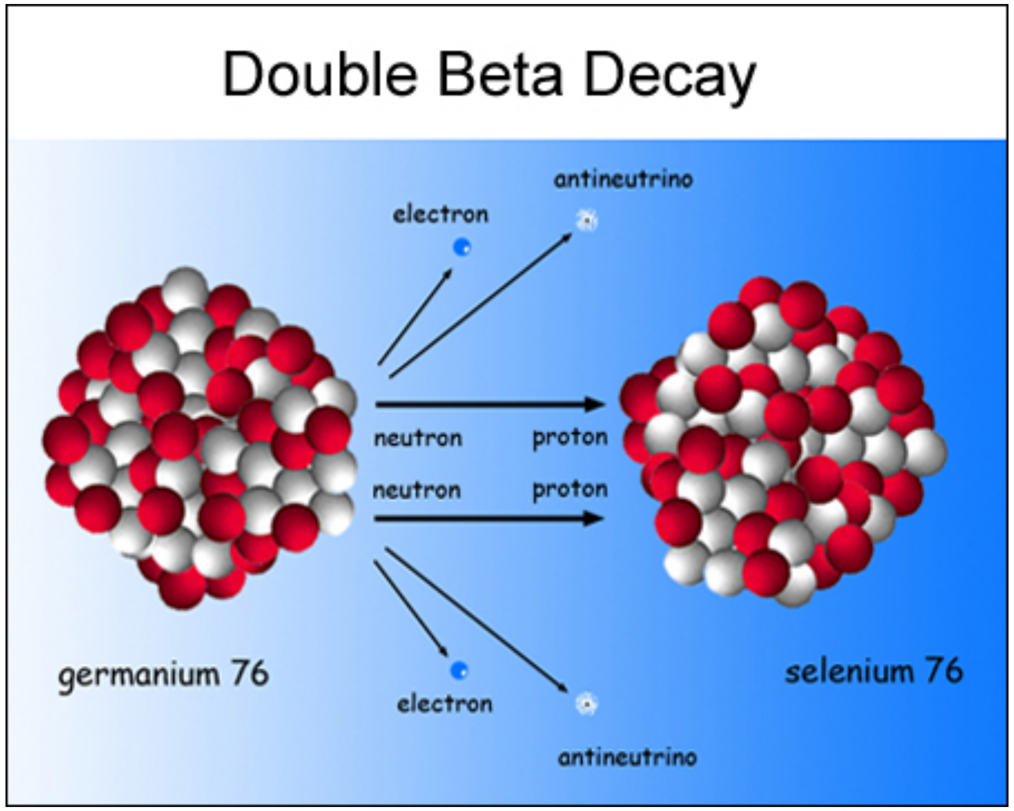
Lecture 6: Searches for 0ν2β decays

PhD cycle XXXIV

0ν2β decays

ΔL=0



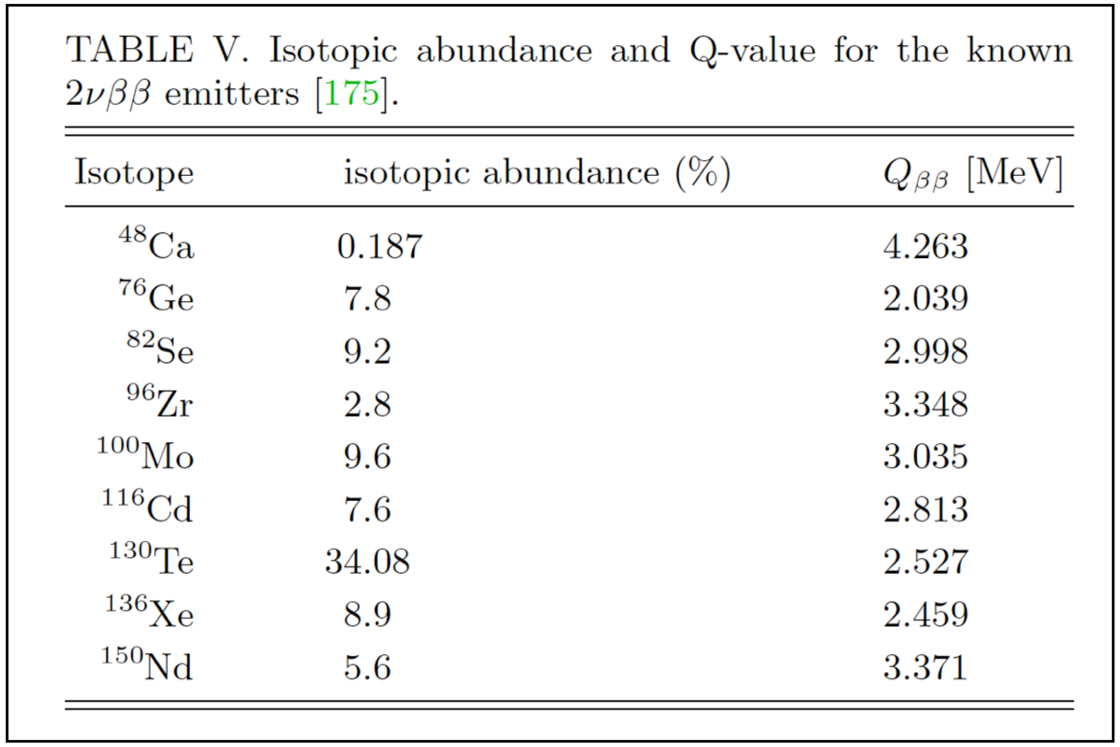


TABLE V. Isotopic abundance and Q-value for the known $2\nu\beta\beta$ emitters [175].

Isotope	isotopic abundance (%)	$Q_{\beta\beta}$ [MeV]
^{48}Ca	0.187	4.263
^{76}Ge	7.8	2.039
^{82}Se	9.2	2.998
^{96}Zr	2.8	3.348
^{100}Mo	9.6	3.035
^{116}Cd	7.6	2.813
^{130}Te	34.08	2.527
^{136}Xe	8.9	2.459
^{150}Nd	5.6	3.371

$$Q_{\beta\beta} = M(Z+2) - M(Z) - 2m_e$$

- Two beta decays at the same time
- Only a few isotopes able to undergo 2β
  - those with peculiar energy level arrangements such that the emission is more convenient than the unstable isotope

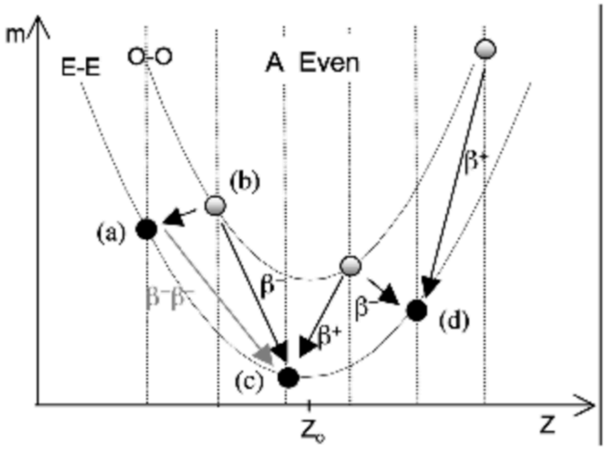


Figure 2: Ground state mass parabola for isobaric nuclei, showing the necessary configuration for double beta decay. Only the one (a) on the even-even (E-E) shell, whose β-decay is blocked (b) but which could decay via two subsequent steps (c) is allowed to do double beta decay. The shift of the parabola of the odd-odd (O-O) nuclei is due to the nuclear pairing energy [2].

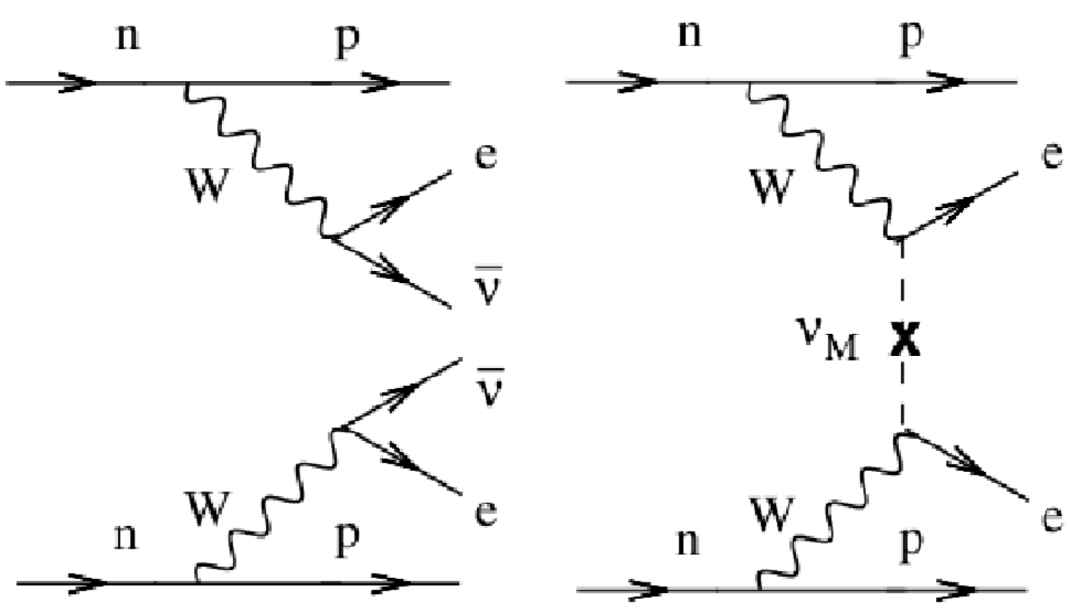
$$2\nu\beta\beta : (A, Z) \rightarrow (A, Z+2) + 2e^- + 2\nu_e$$

2nd order process, observed, $T_{1/2} \sim 10^{19}$-10^{24} yrs

^{76}Ge: $T_{1/2} \sim 10^{21}$ yrs

0ν2β decays

ΔL=2



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  - those with peculiar energy level arrangements such that the emission is more convenient than the unstable isotope

$0\nu\beta\beta : (A, Z) \rightarrow (A, Z{+}2) + 2e^-$

new physics, $T_{1/2} > 10^{25}$ yrs

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

2nd order process, observed, $T_{1/2} \sim 10^{19}$-10^{24} yrs

^{76}Ge: $T_{1/2} \sim 10^{21}$ yrs

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\ \left|M^{0\nu}\right|^2 \left(\frac{\langle m_{ee}\rangle}{m_e}\right)^2$$

nuclear matrix element

phase space factor

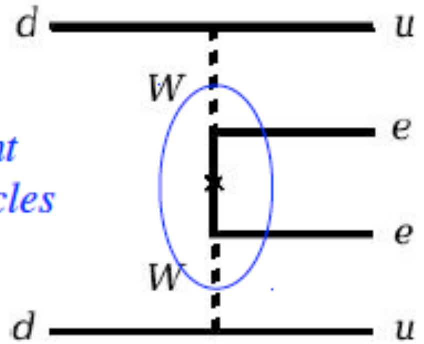
$$\langle m_{ee}\rangle = \left|\sum_i U_{ei}^2 m_i\right|$$

effective Majorana neutrino mass

Why look for it...

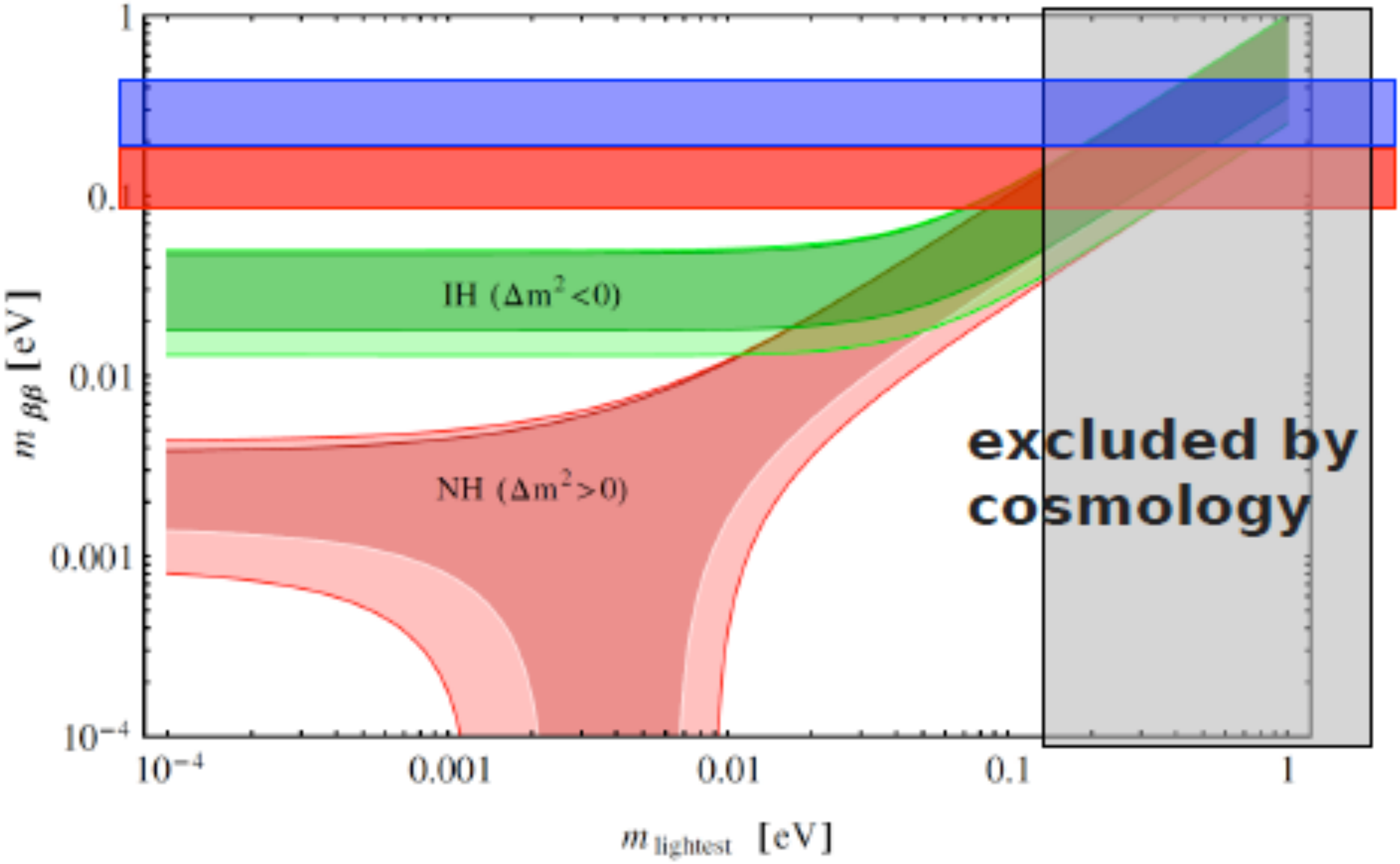
◆ Only way to determine if neutrino is its own antiparticle:

$\nu = \bar{\nu}$ ⇒ ***Majorana particle***



exchange of light Majorana particles

S. Dell'Oro, S. Marcocci, F. Vissani, PRD 90 (2014)



$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\ \left|M^{0\nu}\right|^2 \left(\frac{\langle m_{ee}\rangle}{m_e}\right)^2 \qquad \langle m_{ee}\rangle = \left|\sum_i U_{ei}^2 m_i\right|$$

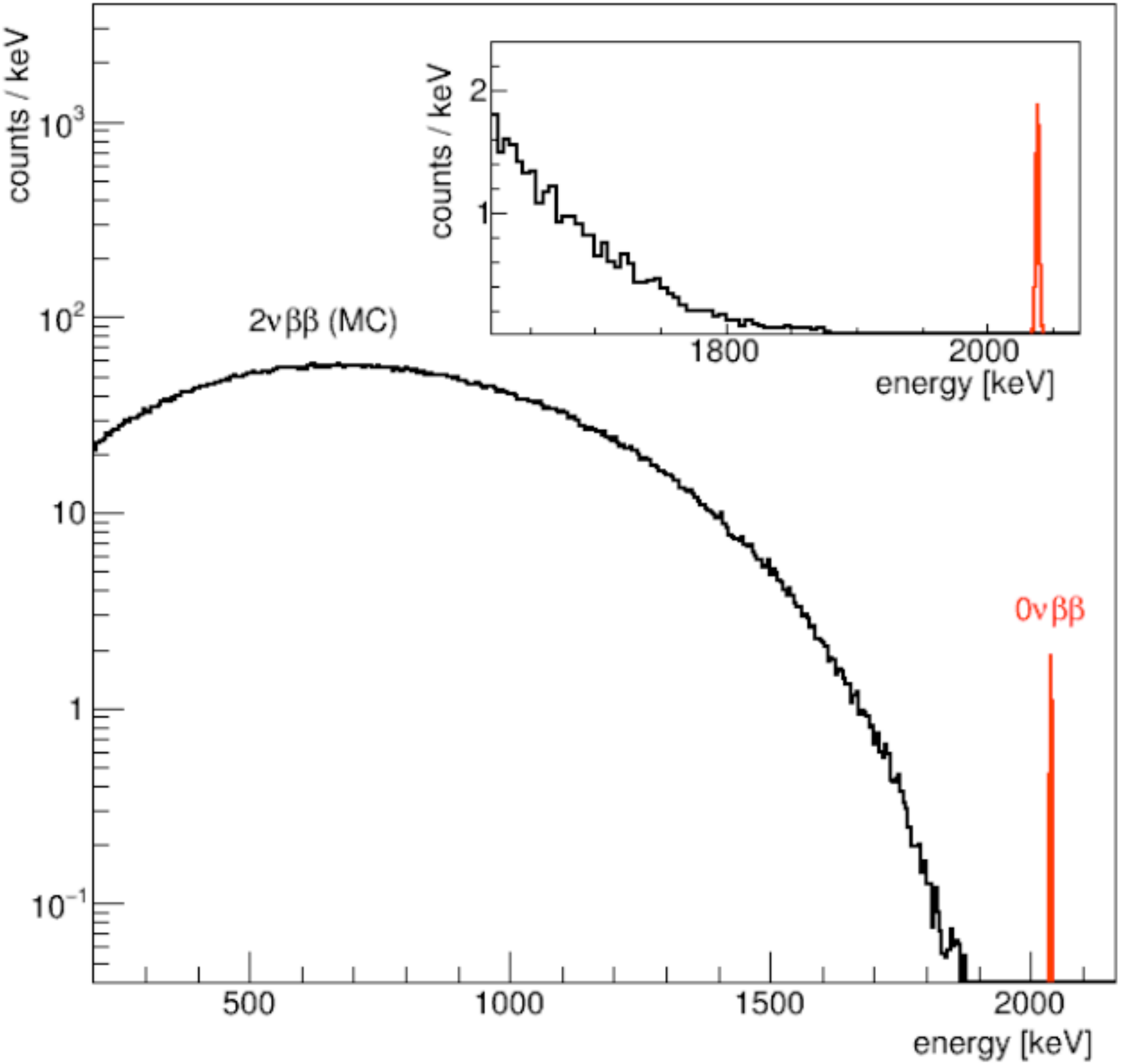
phase space factor

nuclear matrix element

effective Majorana neutrino mass

- A weighted average of neutrino masses enters the decay rate (decay half life)
- **NB: experiments measure $T^{0nu}_{1/2}$**
- Limits on m_{ee} from above, can also exclude IH
  - because one is still looking only at electron flavour, therefore a mix of mass eigenstates, with their MH arrangement in $<m_{ee}>$
  - <u>nuclear matrix element uncertainties are the biggest spoiler in the conversion</u>

What to look for...



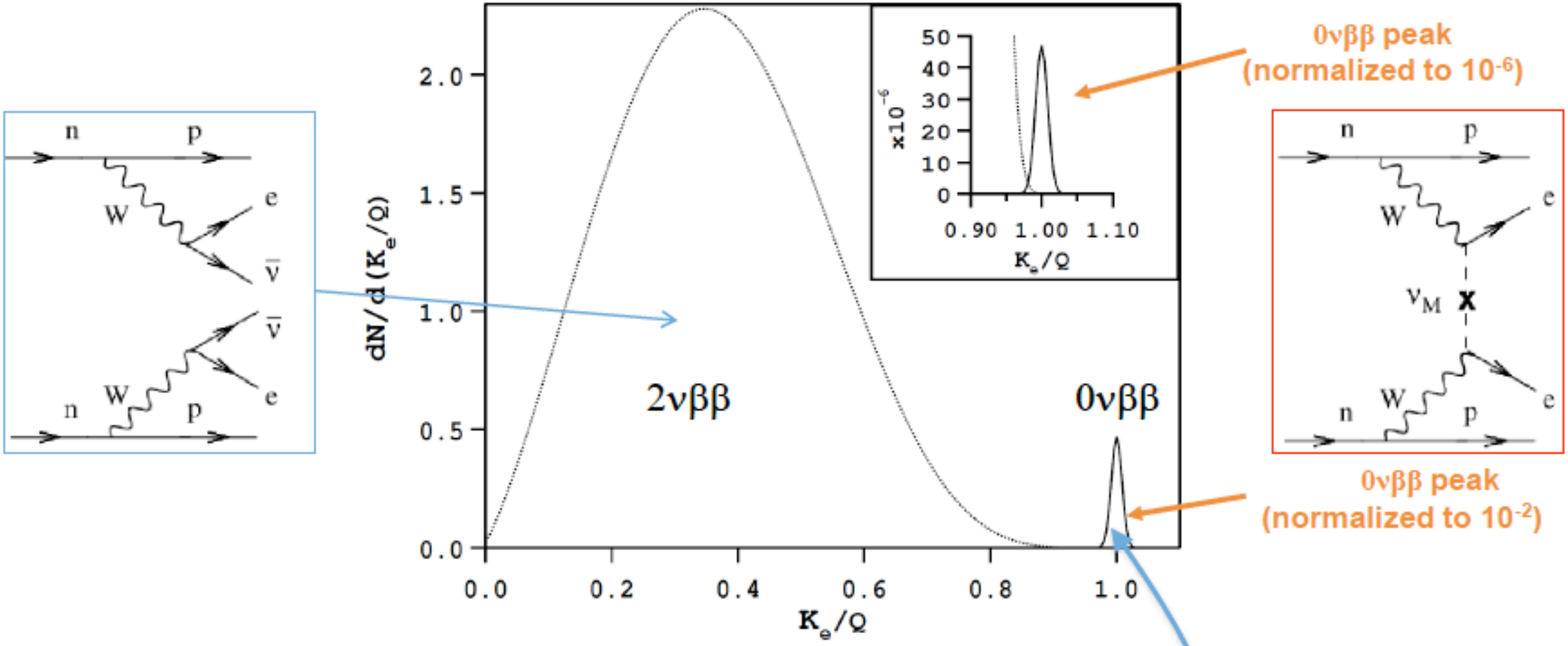
$2\nu\beta\beta : (A, Z) \rightarrow (A, Z+2) + 2e^- + 2\nu_e$

$0\nu\beta\beta : (A, Z) \rightarrow (A, Z+2) + \boxed{2e^-}$

Measure overall energy of "2e" considered as "one body" in a 2-body decay → with no neutrinos it's a line at $E = Q_{\beta\beta}$

Neutrinoless double beta decay

[arXiv:hep-ph/0611243]



$0\nu\beta\beta$ peak (normalized to 10^{-6})

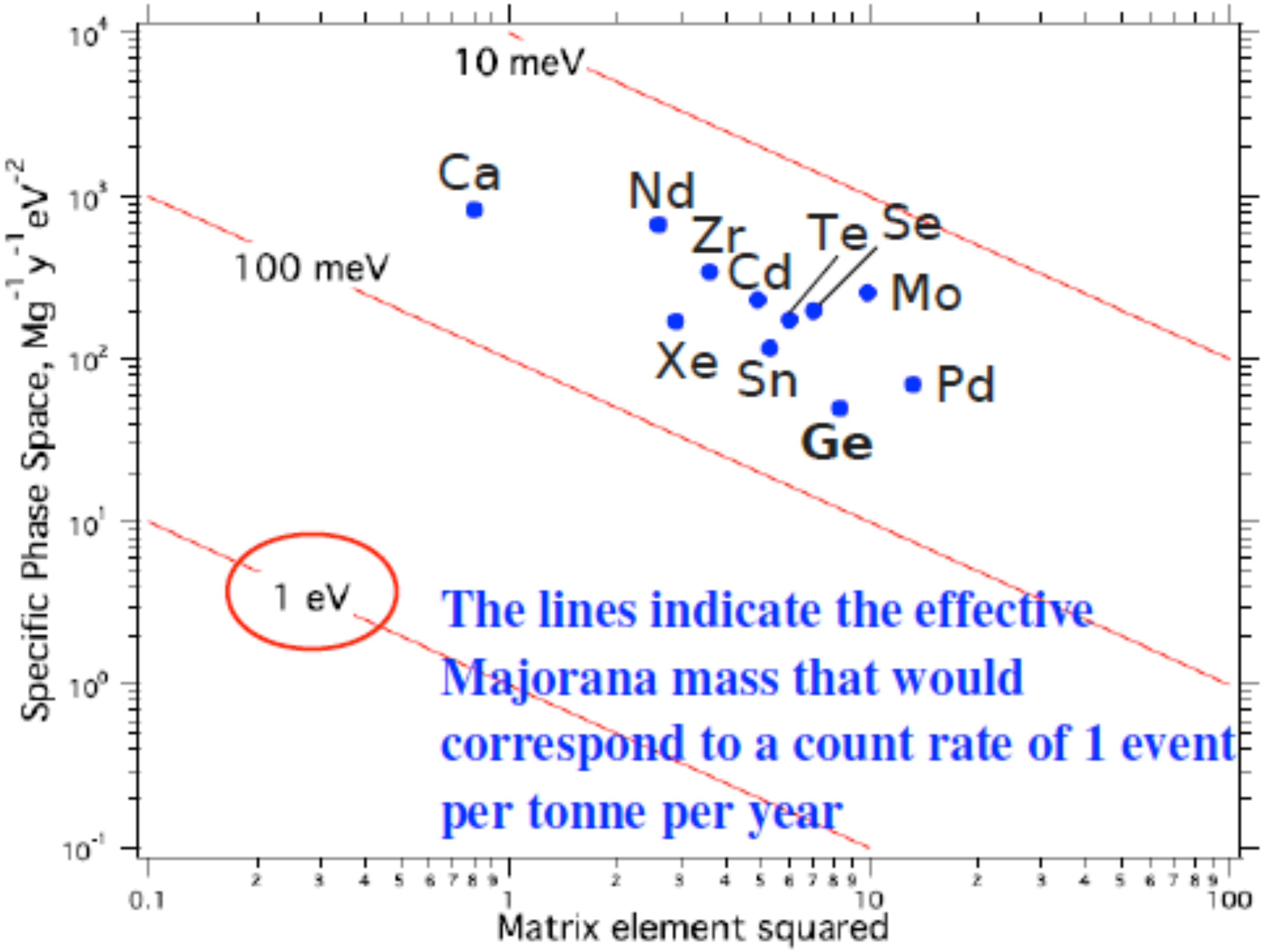
$0\nu\beta\beta$ peak (normalized to 10^{-2})

kinetic energy K_e of the two electrons in units of kinematic endpoint (Q)

Smeared by the energy resolution of the hypothetical detector

Comparing different isotopes

R.G.H. Robertson arXiv:1301.1323



The lines indicate the effective Majorana mass that would correspond to a count rate of 1 event per tonne per year

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\ \left|M^{0\nu}\right|^{2} \left(\frac{\langle m_{ee}\rangle}{m_e}\right)^{2} \qquad \langle m_{ee}\rangle = \left|\sum_i U^2_{ei} m_i\right|$$

nuclear matrix element

phase space factor

effective Majorana neutrino mass

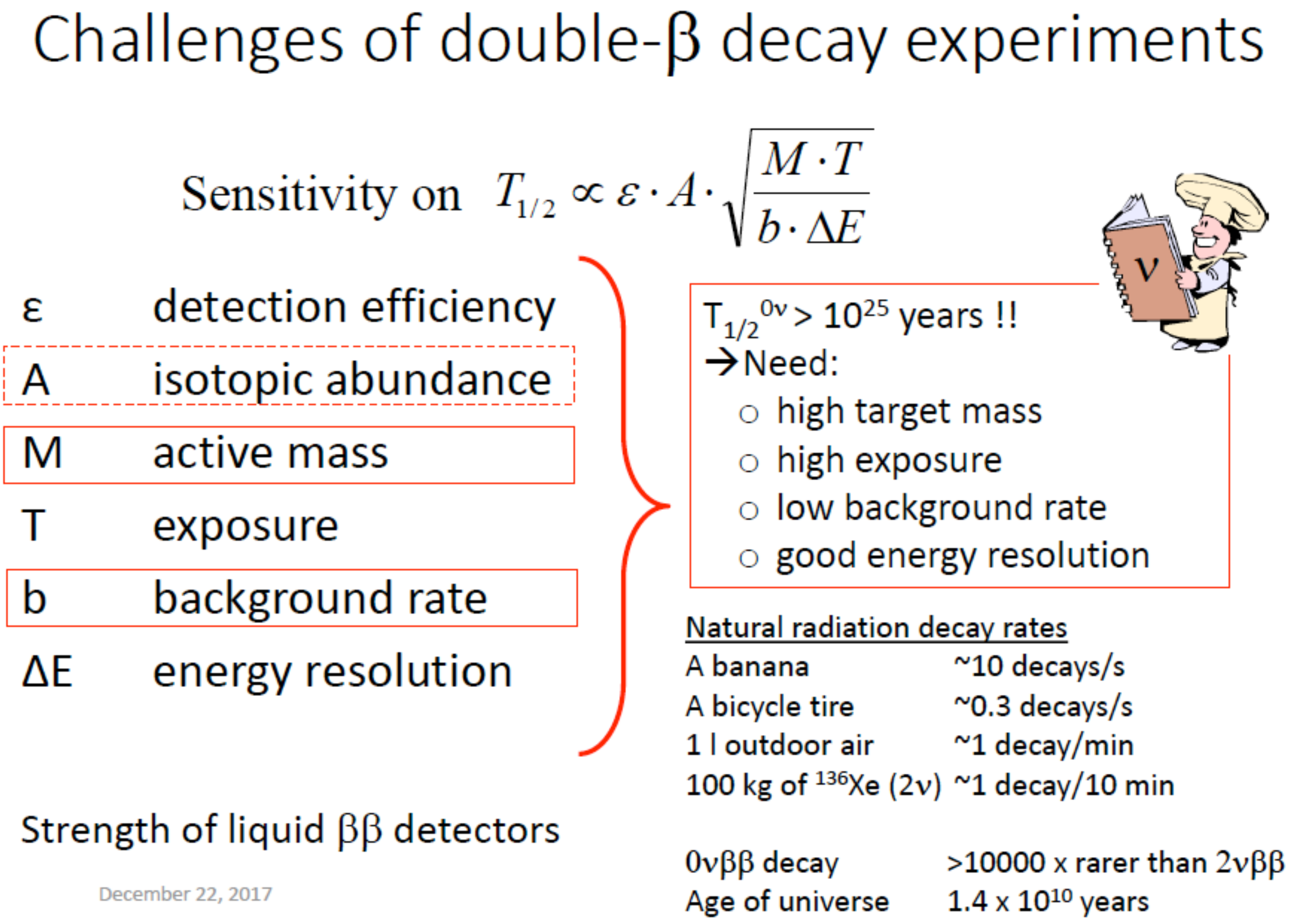
No theoretical preference

- Phase Space and NME inversely correlated. Tend to compensate.
- Theoretical uncertainties very large

Experimental/practical criteria

- Enrichment cost
- Energy resolution
  - Narrow peak for discovery
- Background index
  - Ultraclean components
  - Avoid surfaces
    - Especially in a vacuum
- Scalability
  - Liquids, gases, large crystals

How to look for it...



Challenges of double-β decay experiments

Sensitivity on $T_{1/2} \propto \varepsilon \cdot A \cdot \sqrt{\frac{M \cdot T}{b \cdot \Delta E}}$

ε	detection efficiency
A	isotopic abundance
M	active mass
T	exposure
b	background rate
ΔE	energy resolution

$T_{1/2}^{0\nu} > 10^{25}$ years !!

→Need:

- ○ high target mass
- ○ high exposure
- ○ low background rate
- ○ good energy resolution

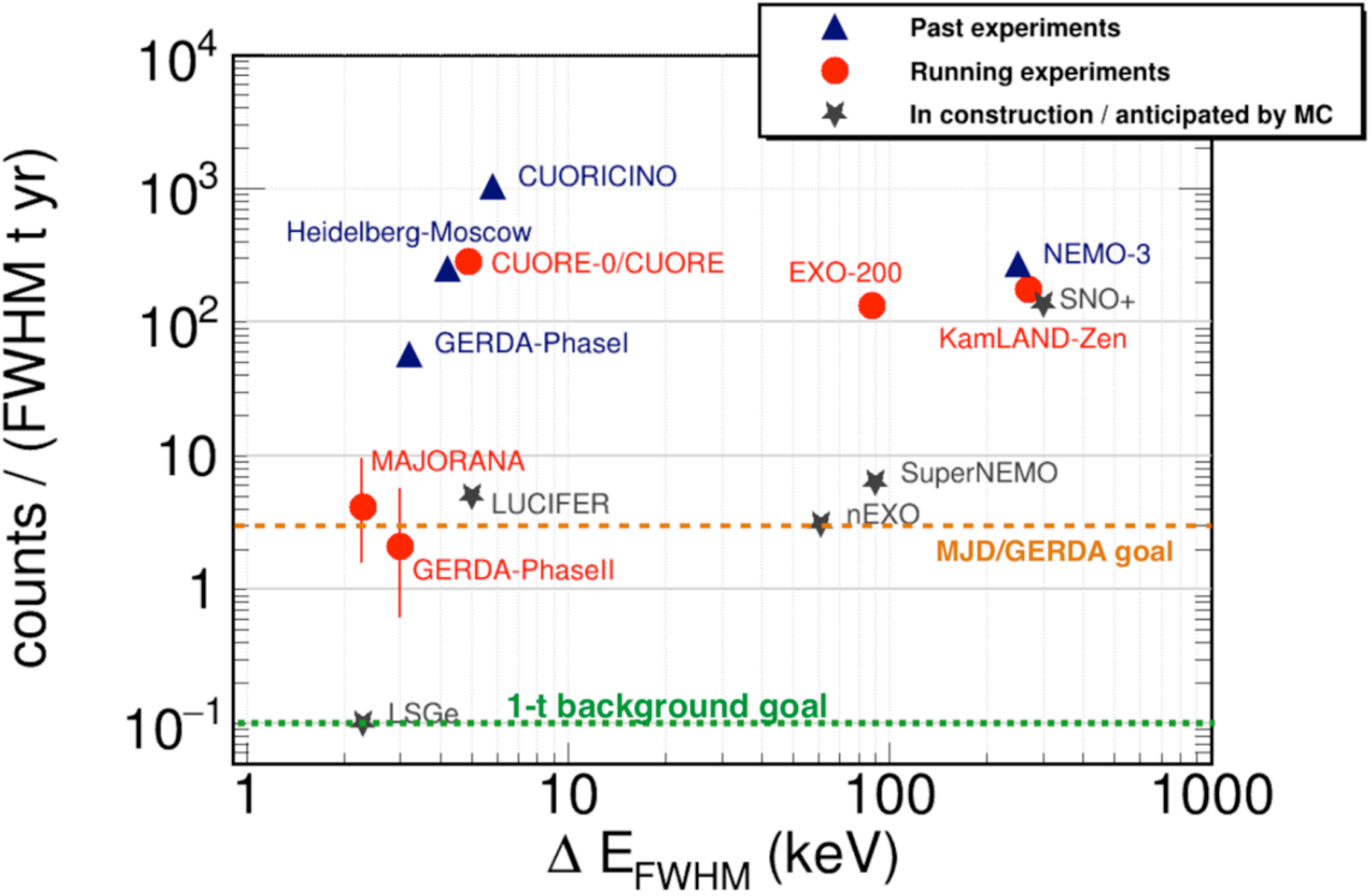
Natural radiation decay rates

A banana	~10 decays/s
A bicycle tire	~0.3 decays/s
1 l outdoor air	~1 decay/min
100 kg of ^{136}Xe (2ν)	~1 decay/10 min

0νββ decay	>10000 x rarer than 2νββ
Age of universe	1.4 x 10^{10} years

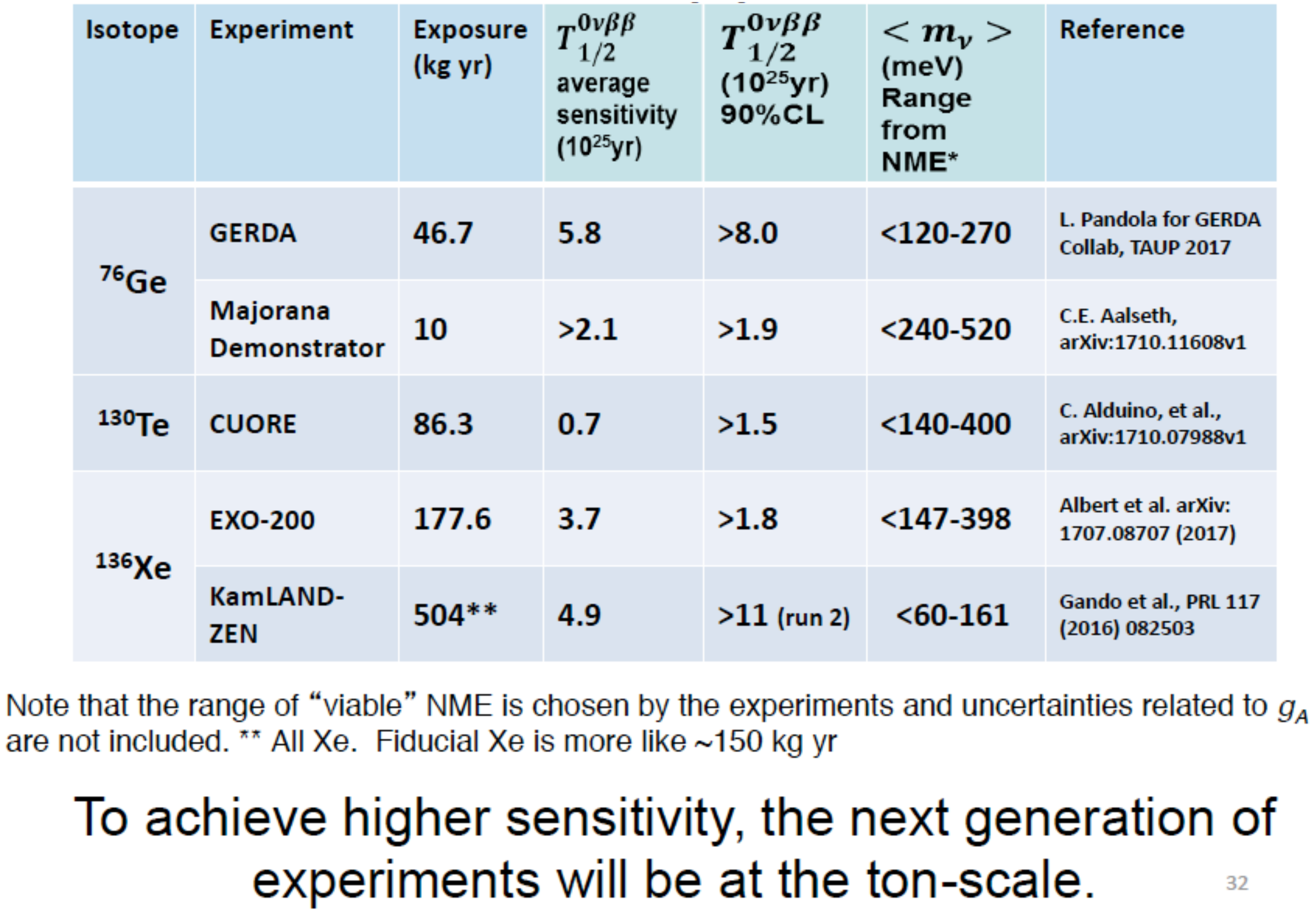
Strength of liquid ββ detectors

December 22, 2017



▲ Past experiments
● Running experiments
★ In construction / anticipated by MC
CUORICINO
Heidelberg-Moscow
CUORE-0/CUORE
EXO-200
NEMO-3
SNO+
KamLAND-Zen
GERDA-PhaseI
MAJORANA
LUCIFER
SuperNEMO
nEXO
MJD/GERDA goal
GERDA-PhaseII
LSGe
1-t background goal
counts / (FWHM t yr)
10^{4}
10^{3}
10^{2}
10
1
10^{-1}
1
10
100
1000
ΔE_{FWHM} (keV)

Synoptic comparison *(not most up to date)*



Isotope	Experiment	Exposure (kg yr)	$T^{0\nu\beta\beta}_{1/2}$ average sensitivity (10^{25}yr)	$T^{0\nu\beta\beta}_{1/2}$ (10^{25}yr) 90%CL	$< m_\nu >$ (meV) Range from NME*	Reference
^{76}Ge	GERDA	46.7	5.8	>8.0	<120-270	L. Pandola for GERDA Collab, TAUP 2017
	Majorana Demonstrator	10	>2.1	>1.9	<240-520	C.E. Aalseth, arXiv:1710.11608v1
^{130}Te	CUORE	86.3	0.7	>1.5	<140-400	C. Alduino, et al., arXiv:1710.07988v1
^{136}Xe	EXO-200	177.6	3.7	>1.8	<147-398	Albert et al. arXiv: 1707.08707 (2017)
	KamLAND-ZEN	504**	4.9	>11 (run 2)	<60-161	Gando et al., PRL 117 (2016) 082503

Note that the range of "viable" NME is chosen by the experiments and uncertainties related to g_A are not included. ** All Xe. Fiducial Xe is more like ~150 kg yr

To achieve higher sensitivity, the next generation of experiments will be at the ton-scale.

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https://indico.ph.qmul.ac.uk/indico/getFile.py/access?contribId=36&resId=1&materialId=slides&confId=170

https://zenodo.org/record/1287604#.XH2VfNF7kcg

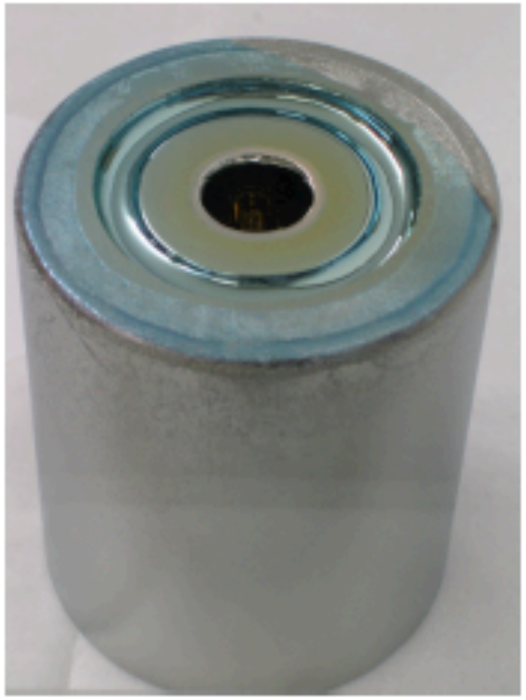
Isotope: Germanium
Example: Gerda

Searching in ^{76}Ge

$$S \sim \epsilon \cdot f \cdot \sqrt{\frac{M \cdot t_{run}}{BI \cdot \Delta E}}$$

non-zero background

BI = counts/(keV·kg·yr)



Germanium detector

S: sensitivity
ε: efficiency
f: abundance of 0νββ isotope
M: detector mass

t_{run}: measurement time
BI: background index
ΔE: energy resolution at $Q_{\beta\beta}$

Advantages of Germanium:

- **High ε**: Source = Detector
- **Small instrinsic BI**: High purity Ge
- **Excellent ΔE**: FWHM ~ (0.1-0.2)%
- Well-established technology

Disadvantages of Germanium:

- at $Q_{\beta\beta}$ = 2039 keV more challenging to reach **low enough background**
- **Small f of ^{76}Ge:** 7.8% → Enrichment needed! → **~ 86% in GERDA**
- Limited sources of crystal & detector manufacturers
- Small $G^{0\nu}(Q_{\beta\beta},Z)$

Gerda @ LNGS: Background reduction

- **GERDA situated in LNGS underground laboratories**
- 3800 m.w.e.

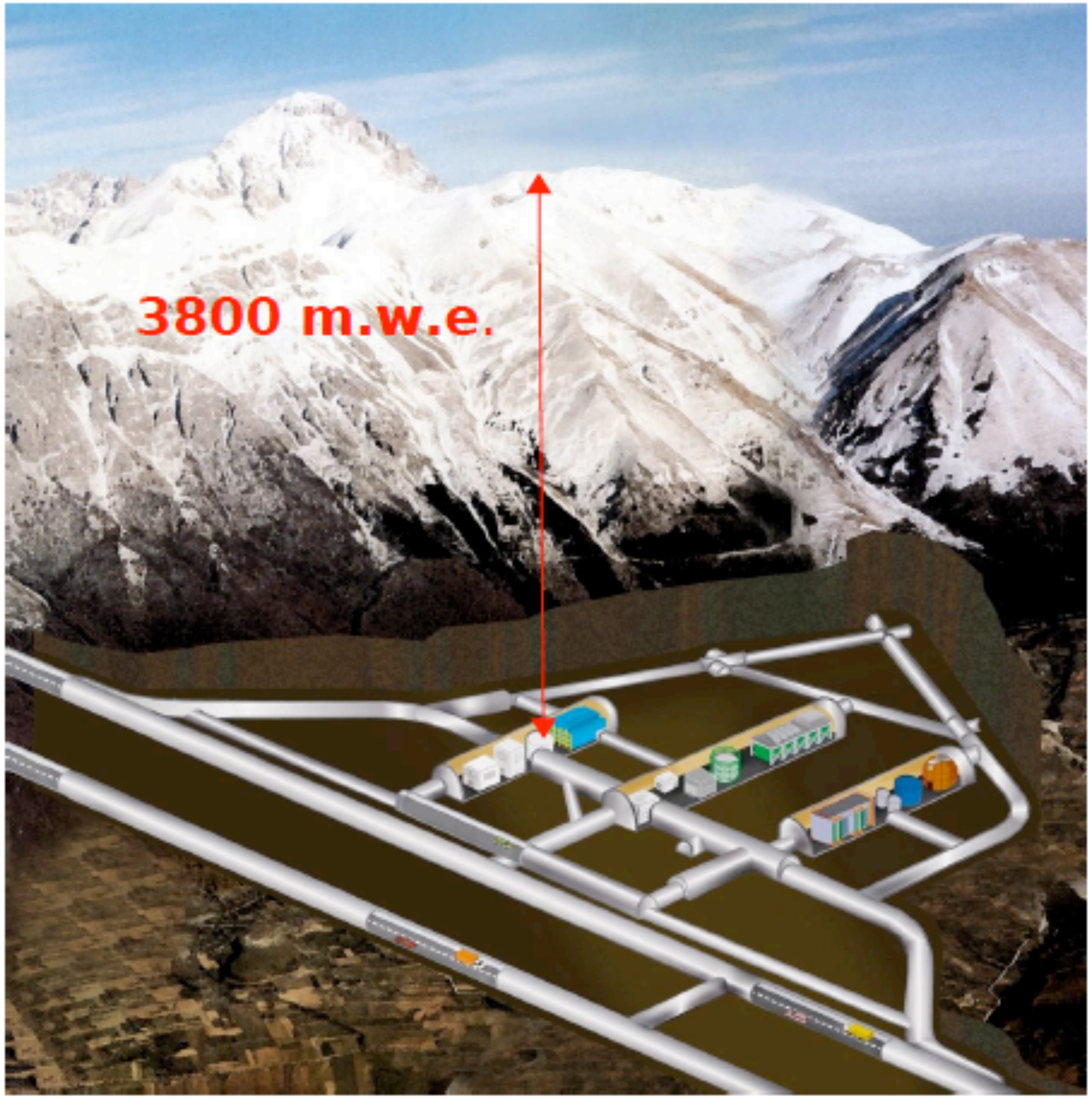
Possible **backgrounds** from:

External:

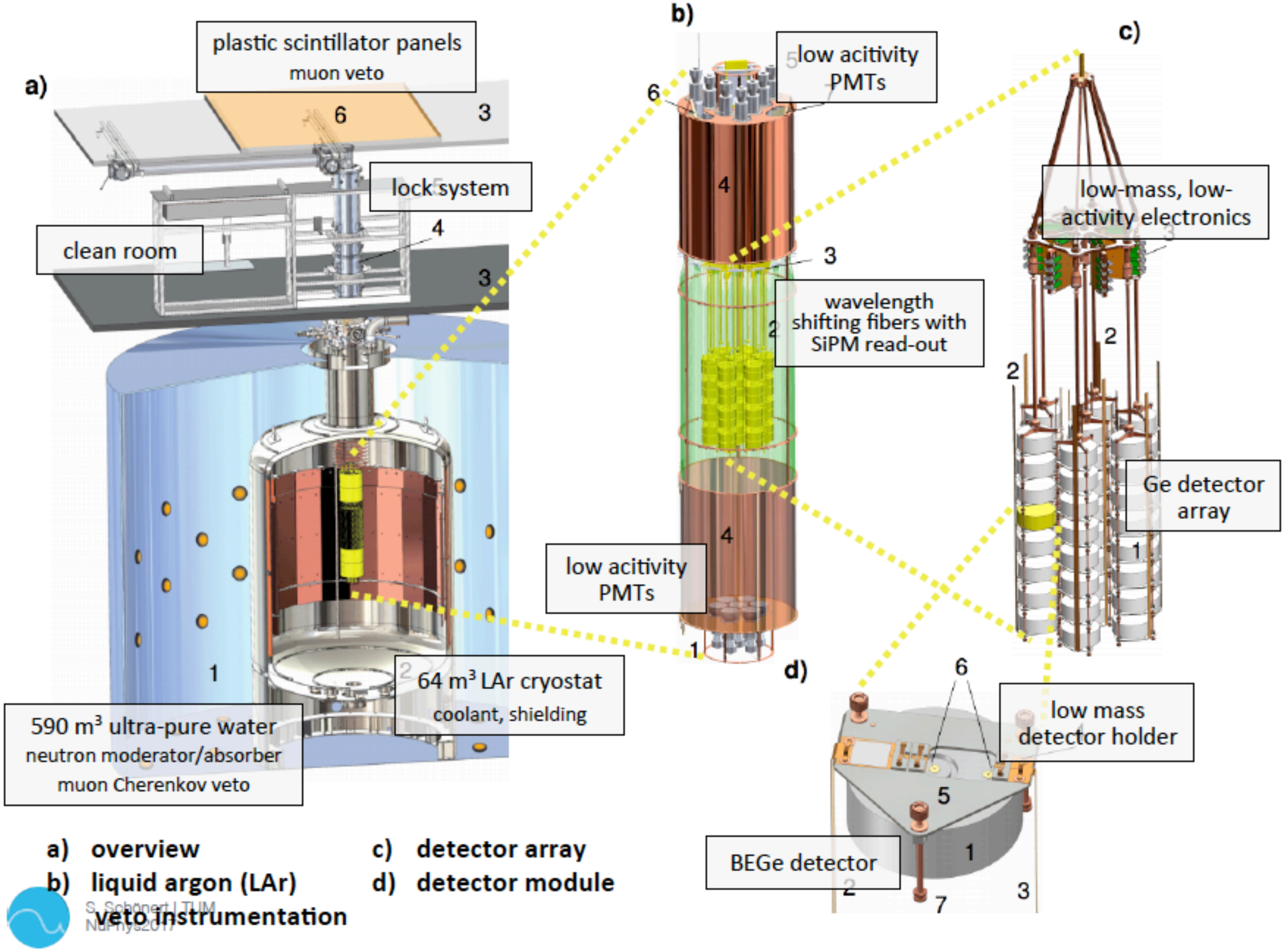
- γ from Th and U chain
- neutrons
- μ from cosmic rays (prompt and delayed)

Internal:

- cosmogenic ^{60}Co ($T_{1/2}$=5.3 yr)
- cosmogenic ^{68}Ge ($T_{1/2}$=271 d)
- Radioactive surface contaminations



Gerda



a) overview
b) liquid argon (LAr) veto instrumentation
c) detector array
d) detector module

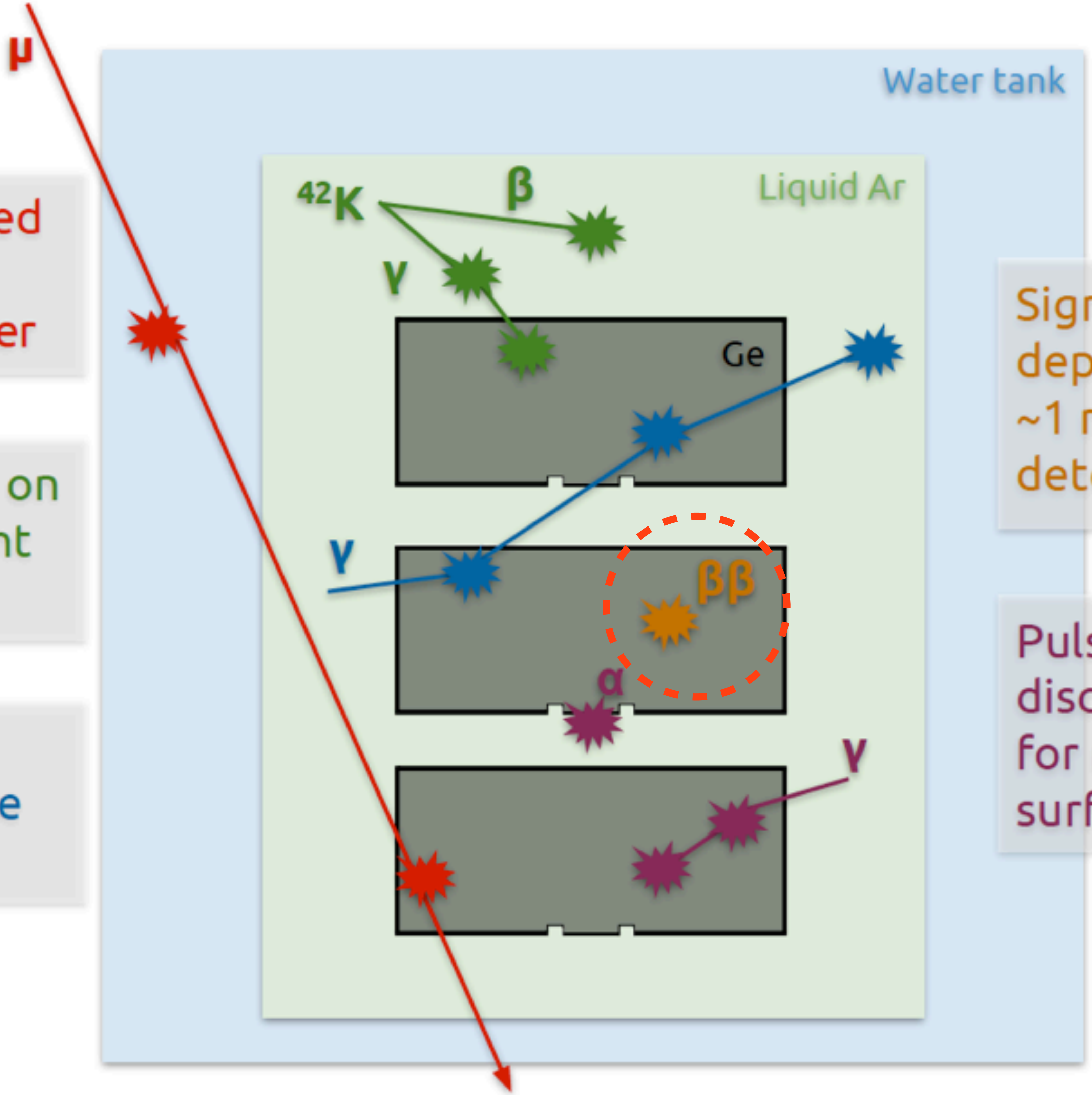
- high-purity germanium (HPGe) detectors enriched in ^{76}Ge to (86–88)%: source + detector
- detectors mounted in low-mass holders (to minimize radioactive bkg)
- embedded in liquid argon (LAr): cryogenic coolant and absorber against external radiation
- ultrapure water tank: buffer around cryostat as additional absorber + Cherenkov muon veto

BACKGROUND REDUCTION CONCEPT

Muon veto based on Cherenkov photons in water

LAr veto based on scintillation light from γs and βs

Detector anti-coincidence of the array

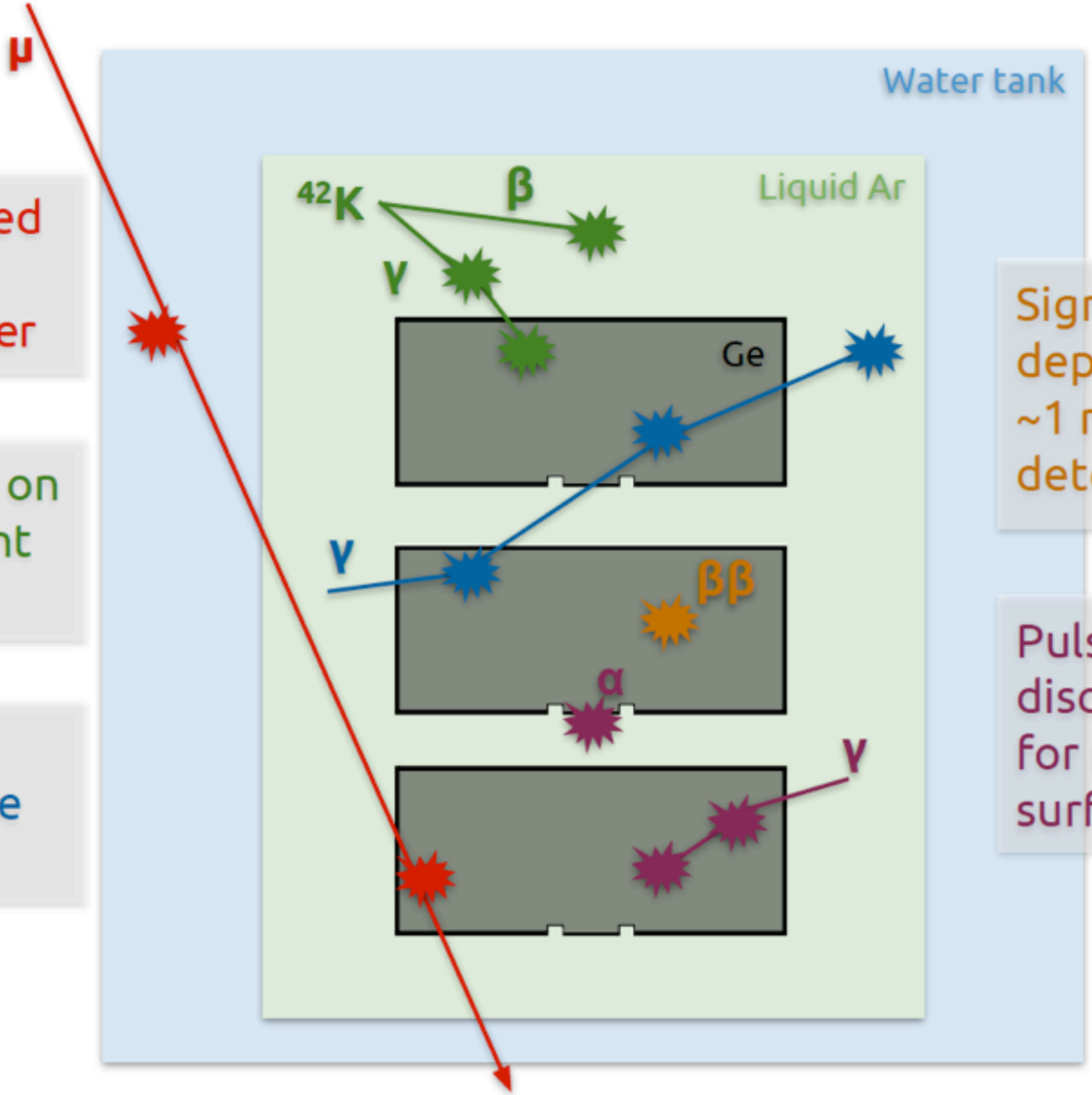


Signal: single energy deposition within ~1 mm^3 of the detector volume

Pulse shape discrimination (PSD) for multi-site and surface events

BACKGROUND REDUCTION CONCEPT

Gerda



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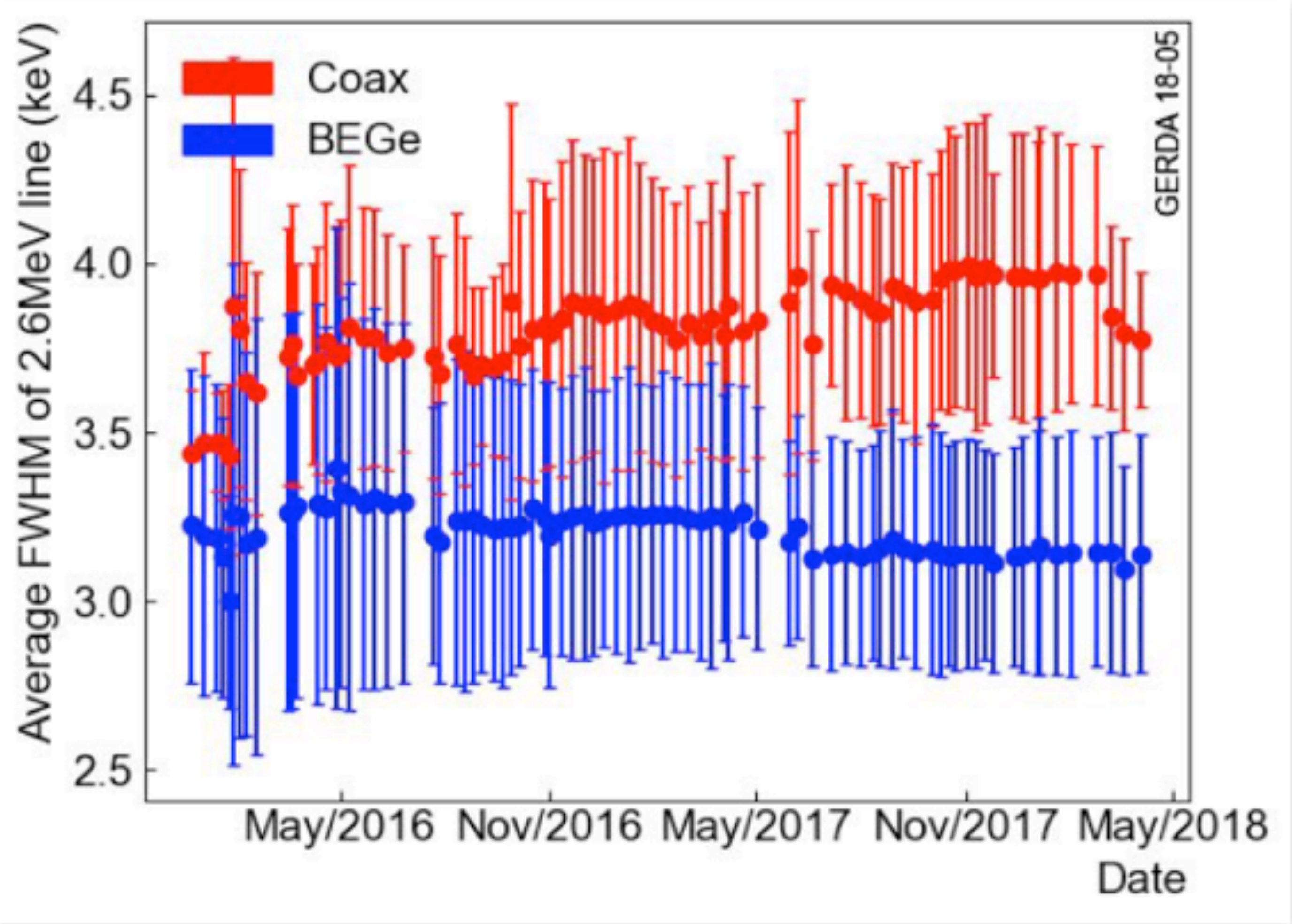
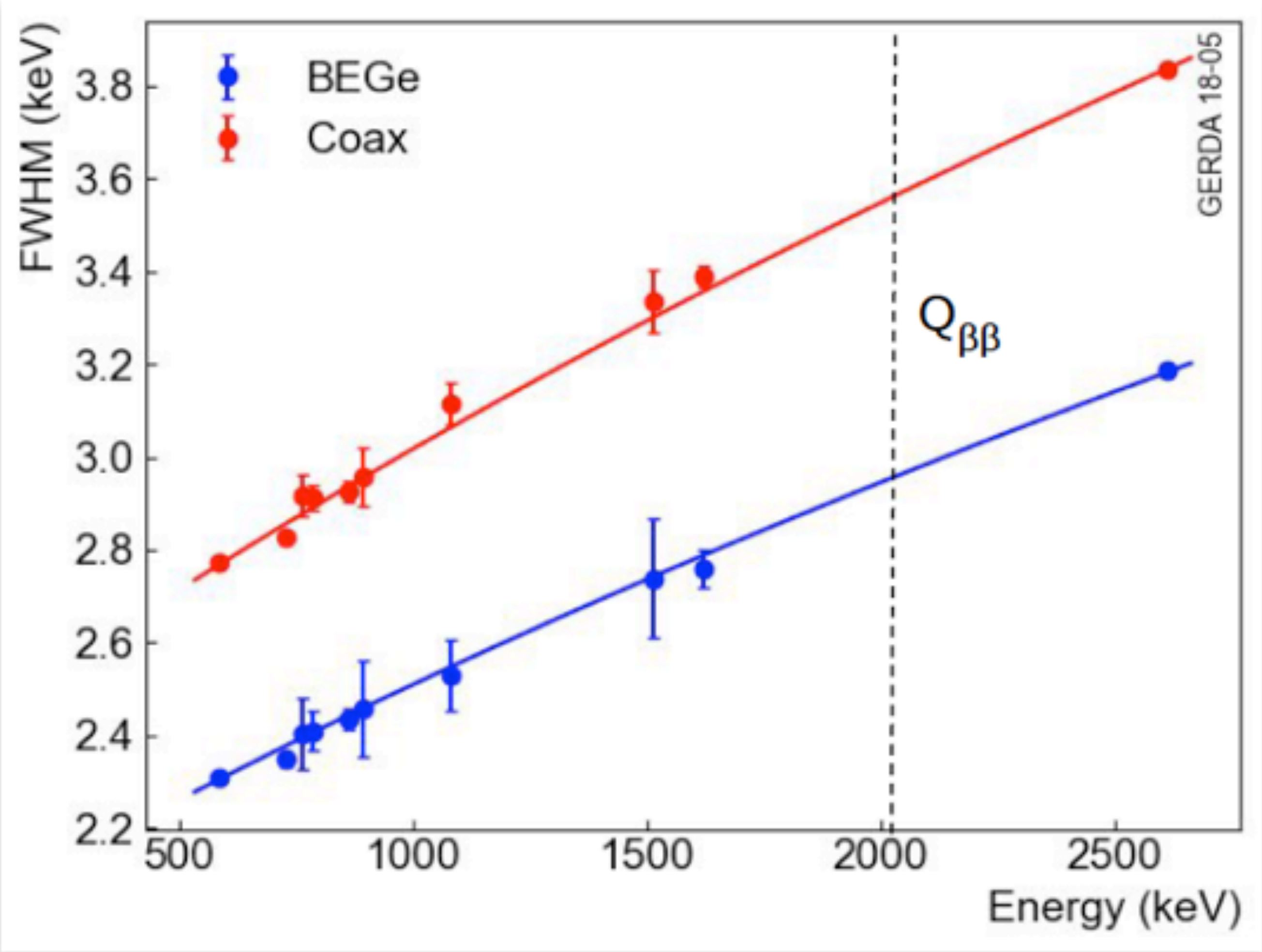
Energy resolution





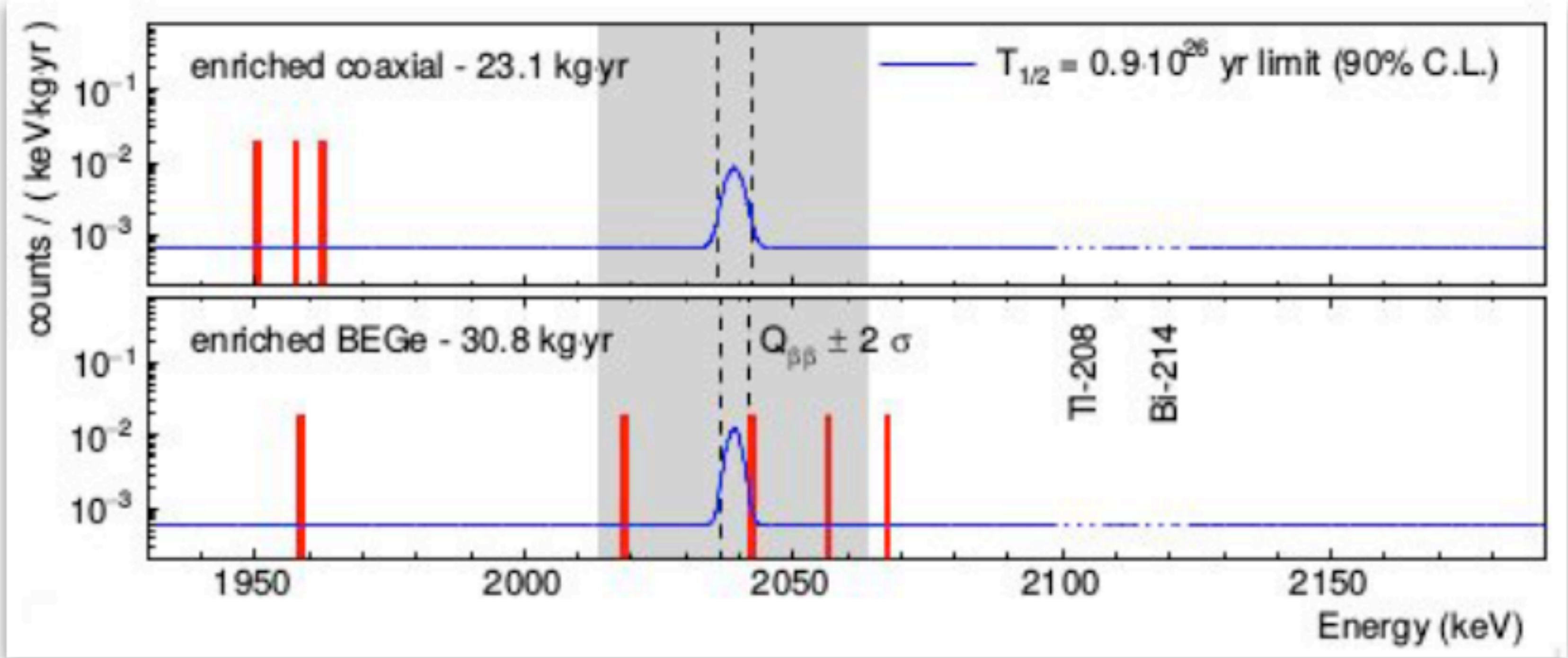
- Weekly calibrations with ^{228}Th sources
- Energy resolution stable over more than two years

- Energy resolution at $Q_{\beta\beta}$

  Coax → 3.6(1) keV

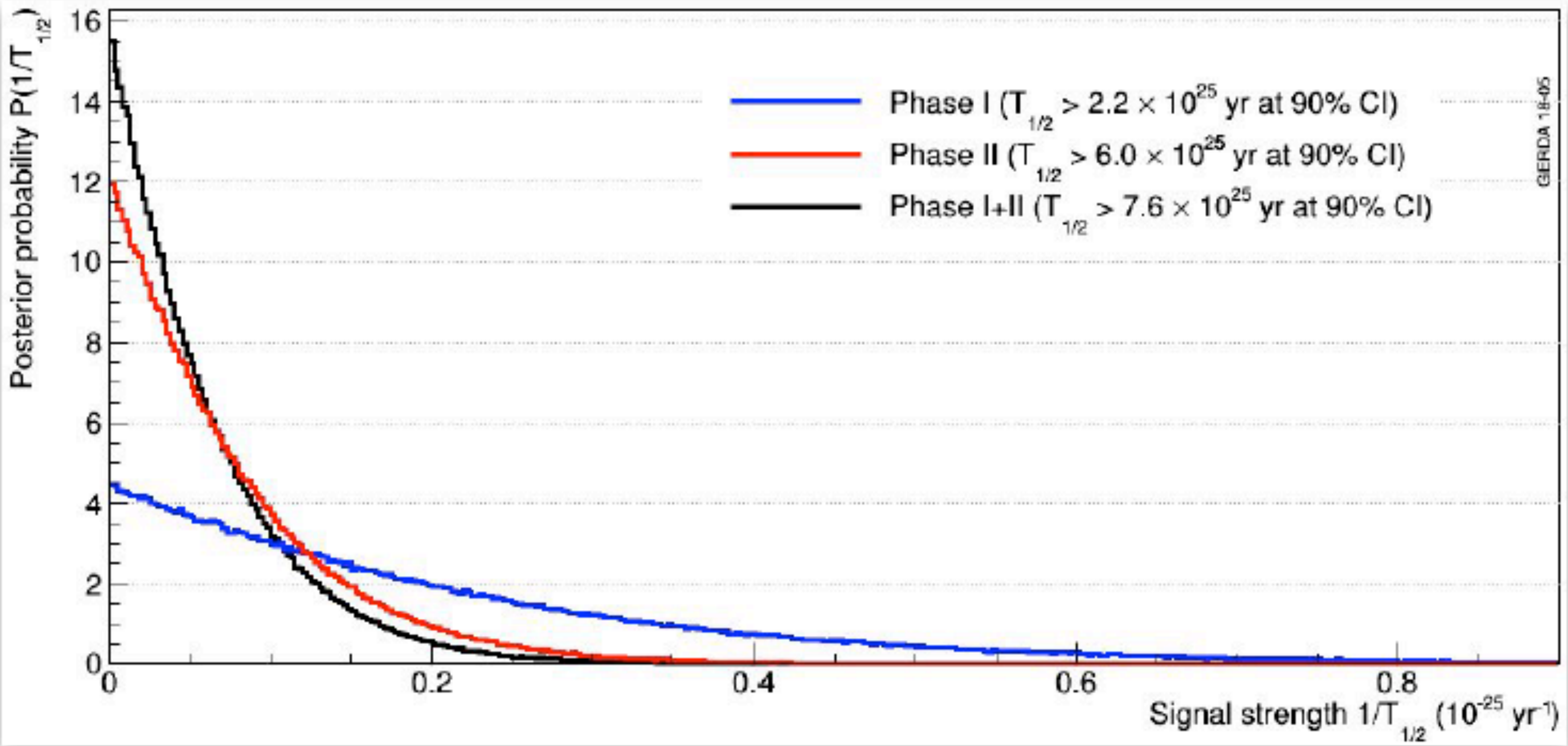
  BEGe → 3.0(1) keV

Most recent result, run II-b



Bayesian analysis

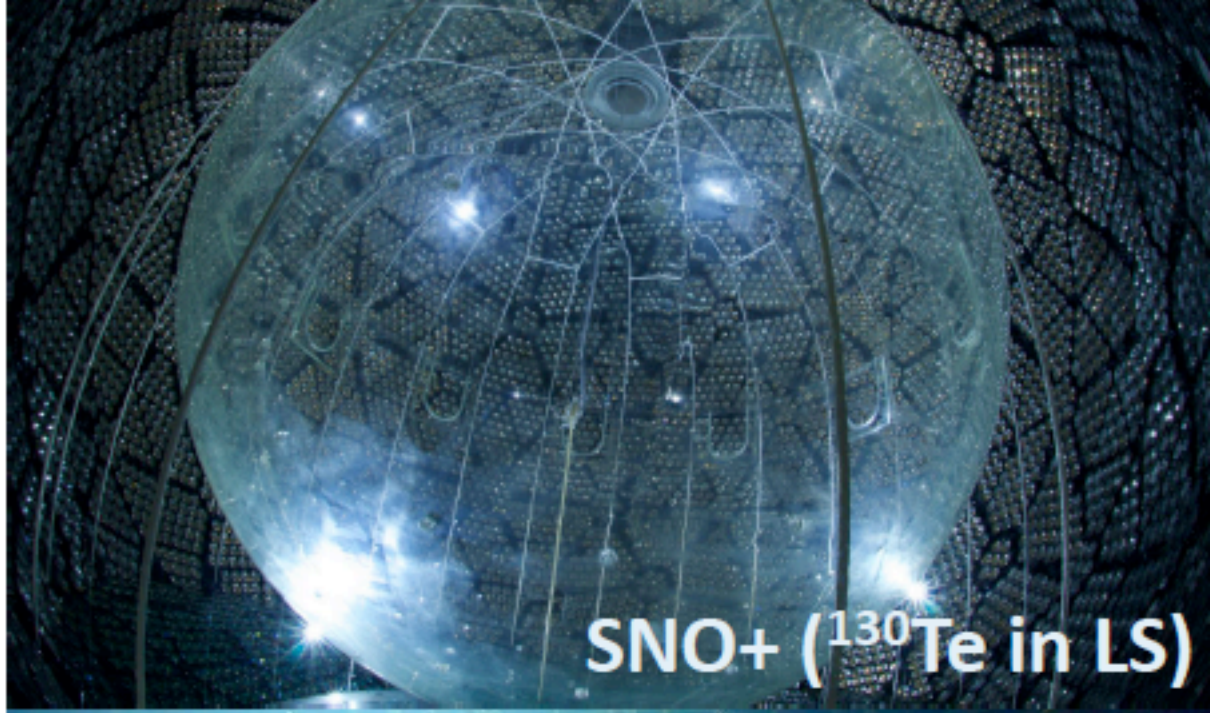
- Median sensitivity $0.8 \cdot 10^{26}$ yr (90% CI)
- Best fit → background only $\frac{P(\text{signal+background})}{P(\text{background})} = 0.054$
- $T_{1/2} > 0.8 \cdot 10^{26}$ yr (90% CI)
- Probability of stronger limit 59%



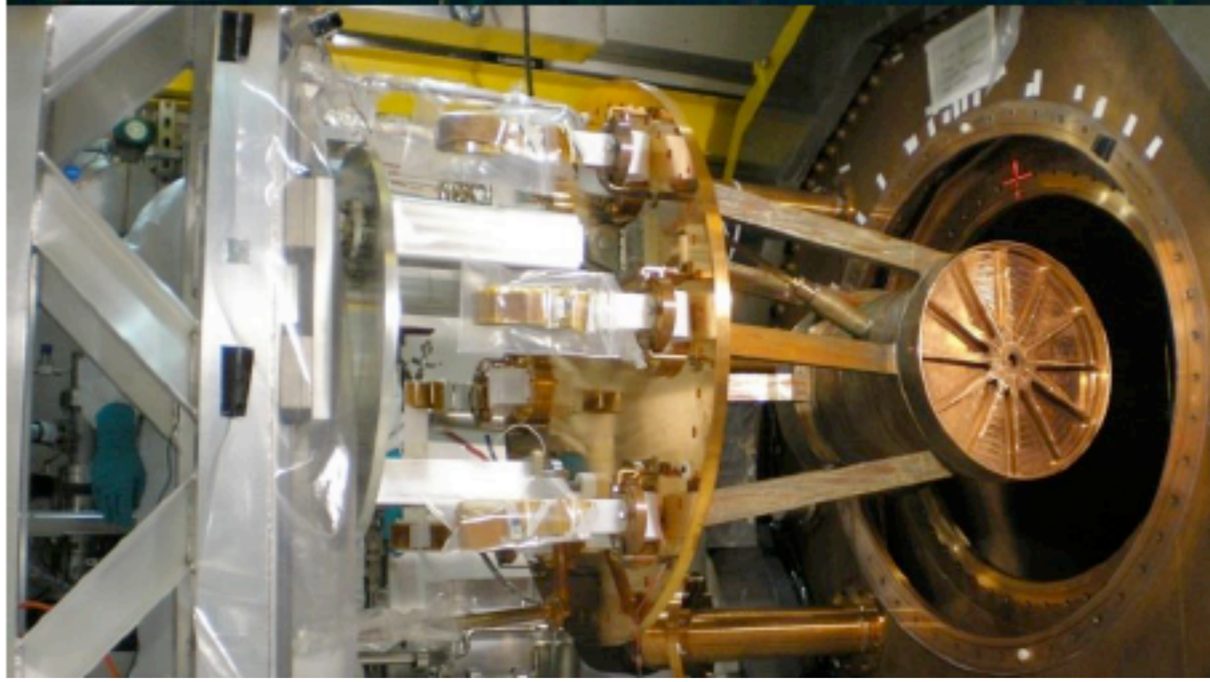
Phys. Rev. Lett. 120, 132503 + summer 2018 updates

Isotope: Te, Xe
Examples: LS

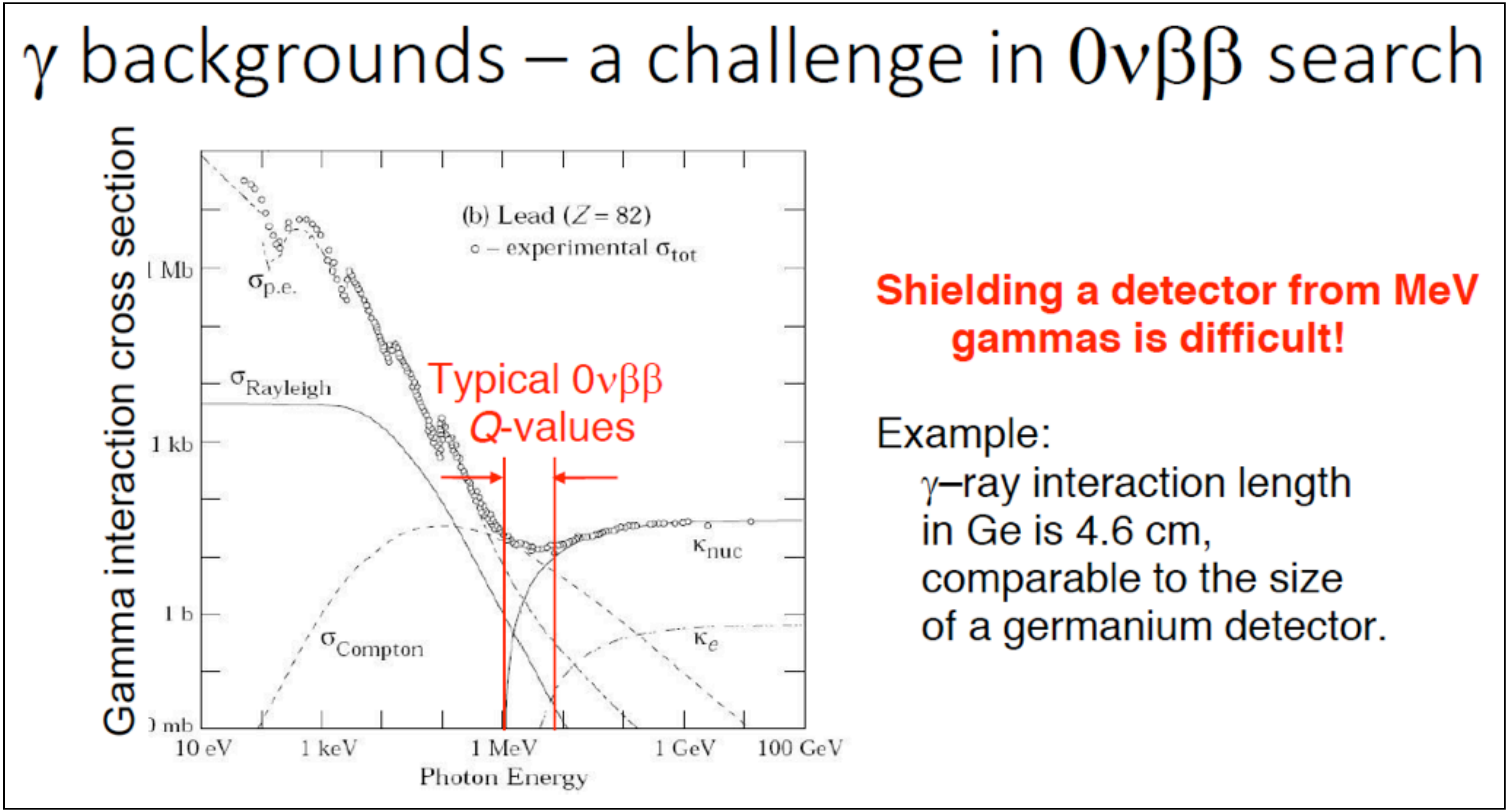
(SNO+, KLZ, EXO)


SNO+ (^{130}Te in LS)


KamLAND-ZEN (^{136}Xe in LS)



Why LS?



γ backgrounds – a challenge in 0νββ search

Shielding a detector from MeV gammas is difficult!

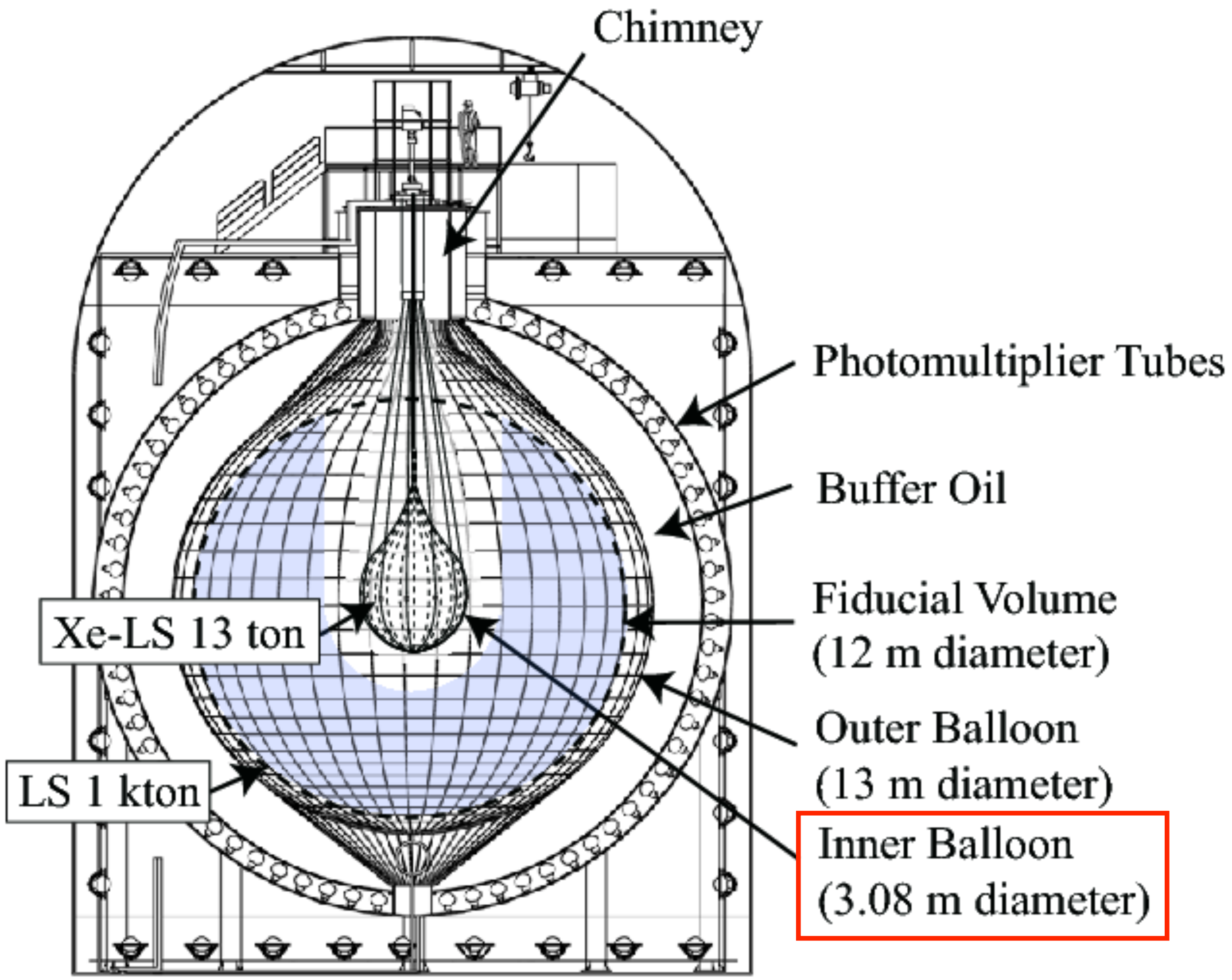
Example:

γ–ray interaction length in Ge is 4.6 cm, comparable to the size of a germanium detector.

1 km underground in Kamioka

Current world best limit from

KamLAND-Zen



90% enriched ^{136}Xe

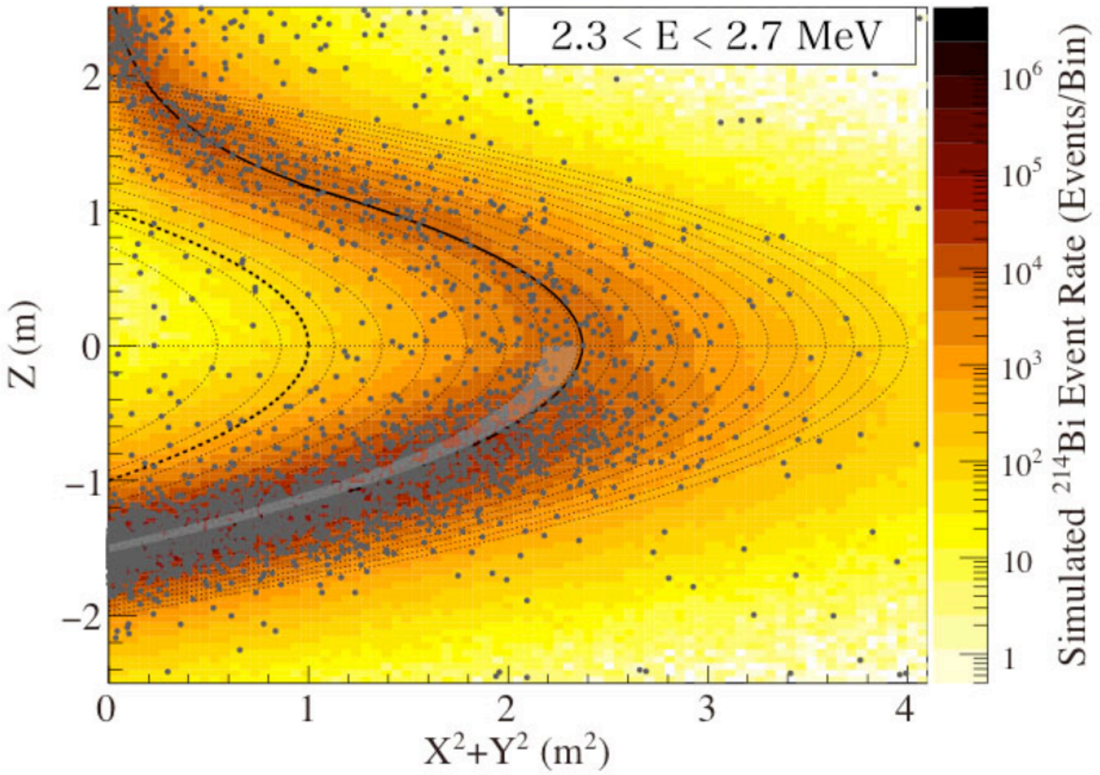
- 320kg for phase-1
- 380kg for phase-II
- 750kg for Zen 800 (to start in months)

largest amount so far

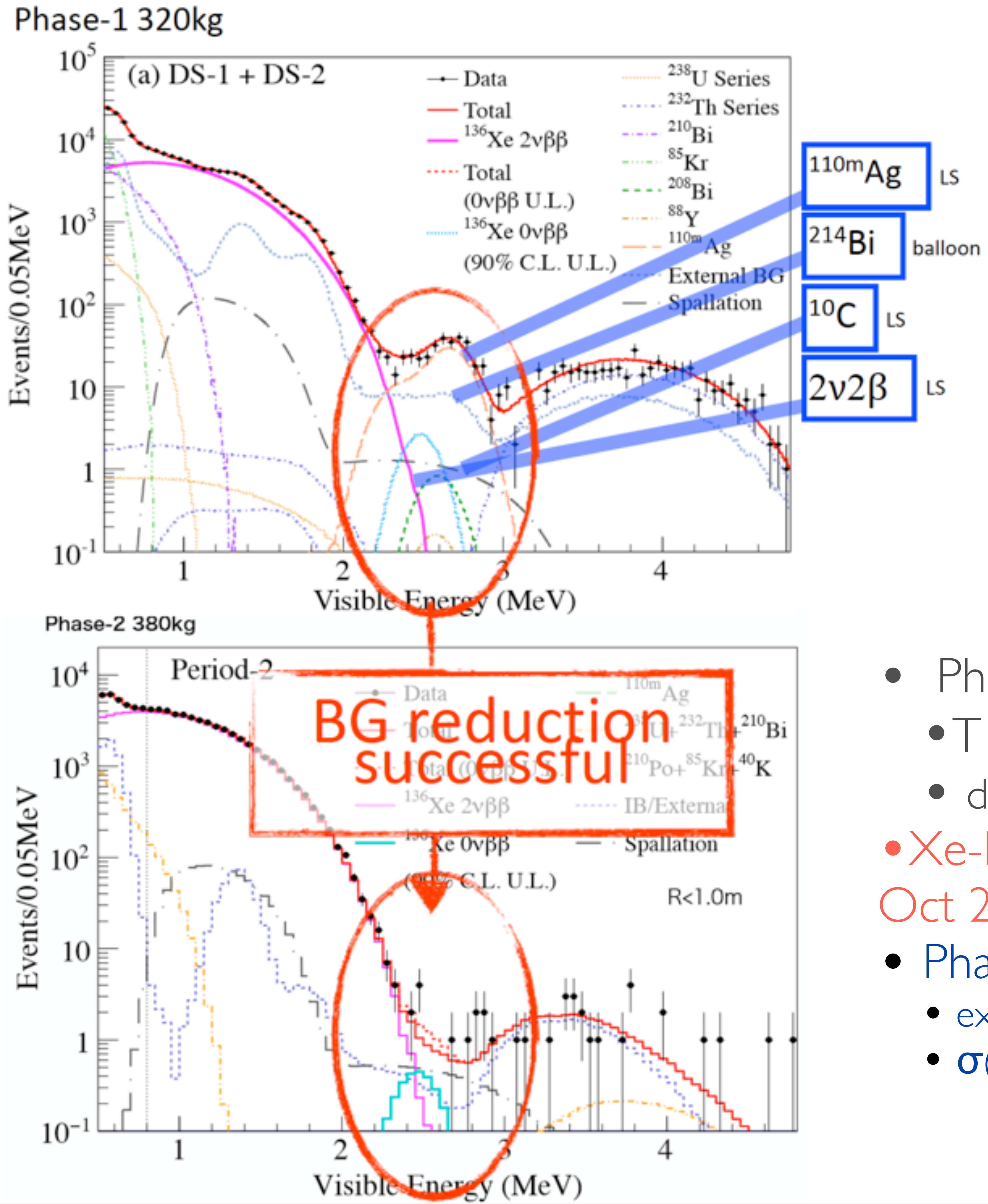
https://arxiv.org/pdf/1605.02889.pdf

- Xe+LS allows to have source and detector at once, minimizing other materials
- enriched LS (decane, PC): 90. 77% ^{136}Xe
  - ^{136}Xe → ^{136}Ba + $2e^-$
  - Q = 2458 keV, higher than most γ rays from common radioactive nuclides
- scintillation only
- getting to several tons of Xe feasible keeping bkg low ("easy" to purify)

- exploits existing detection infrastructure and radio-purity of KamLAND
  - 1200 m^3, U: 3.5 10^{-18}g/g, Th: 5.2 10^{-17}g/g
  - reactor neutrino detector (KamLAND) acts as photon screen for KLZ



E.g.: http://iopscience.iop.org/article/10.1088/1742-6596/888/1/012031



Phase-1,2 combined results

$$T^{0\nu}_{1/2} > 1.07 \times 10^{26}\ \mathrm{yr}$$

$$\langle m_{\beta\beta} \rangle < (61 - 165)\ \mathrm{meV}$$

- Phase-I: Oct 2011 to Jun 2012
  - $T_{1/2}^{0\nu} > 1.9\ 10^{25}$ yr
  - dominant ^{110}Ag from Fukushima!
- Xe-LS purification campaign until Oct 2013
- Phase-II: Nov 2013 to Oct 2015
  - exposure of 504 kg yr of ^{136}Xe
  - $\sigma(E)/E = 7.3\%/\sqrt{E(\mathrm{MeV})}$

NOT most up to date

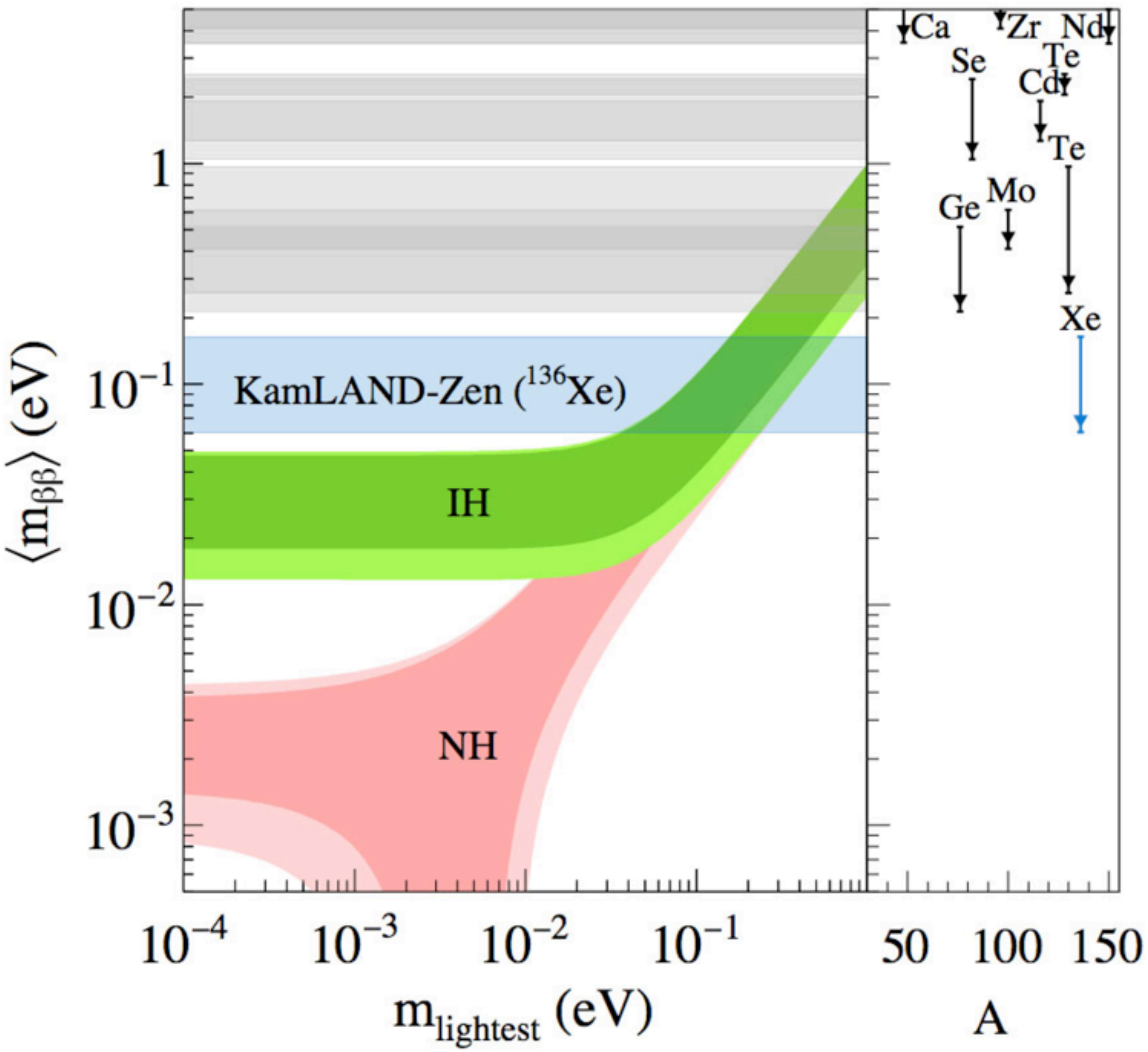


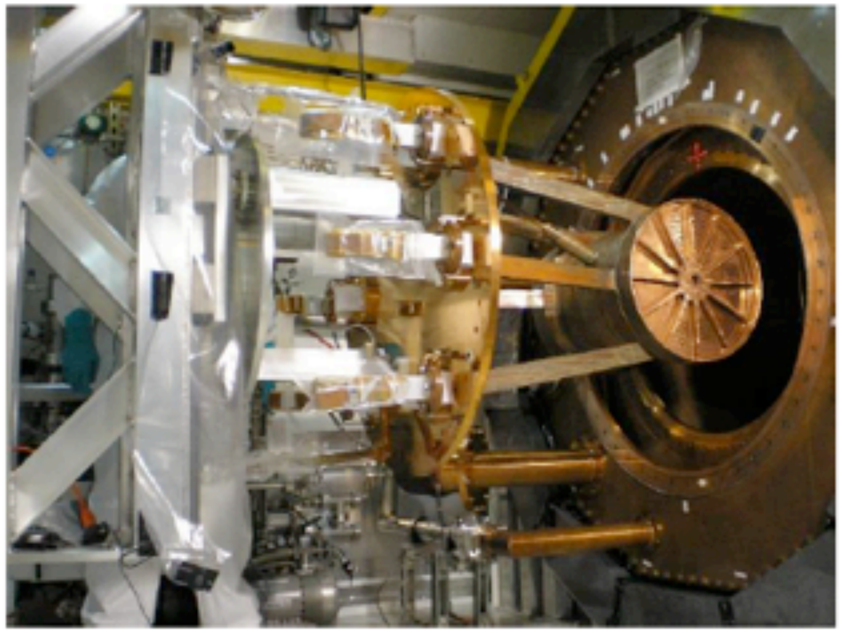
Figure 5. Effective Majorana neutrino mass $\langle m_{\beta\beta} \rangle$ as a function of the lightest neutrino mass, m_{lightest}. The dark shaded regions are from the best-fit neutrino oscillation parameters for the NH and IH mass hierarchies. Light shaded regions are the 3σ ranges of the oscillation parameter uncertainties. Horizontal bands indicate 90% C.L. upper limits on the $\langle m_{\beta\beta} \rangle$ from KmaLAND-Zen and other experiments.

Remember: assumes one calculation on **NME**, but large variations (up to factor 3!) from different nuclear models (see Giunti-Kim p.504)

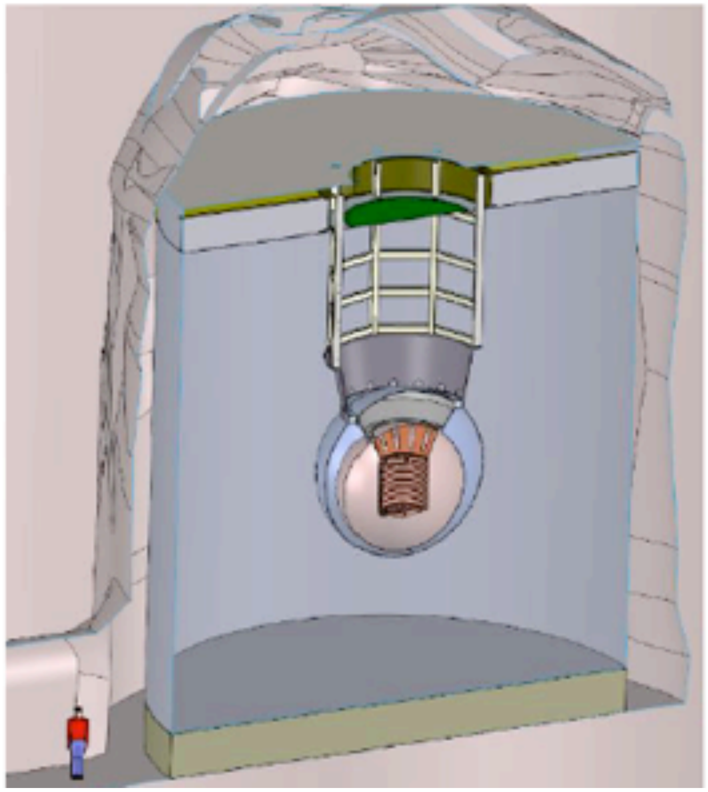
Searching for $0\nu\beta\beta$ in ^{136}Xe

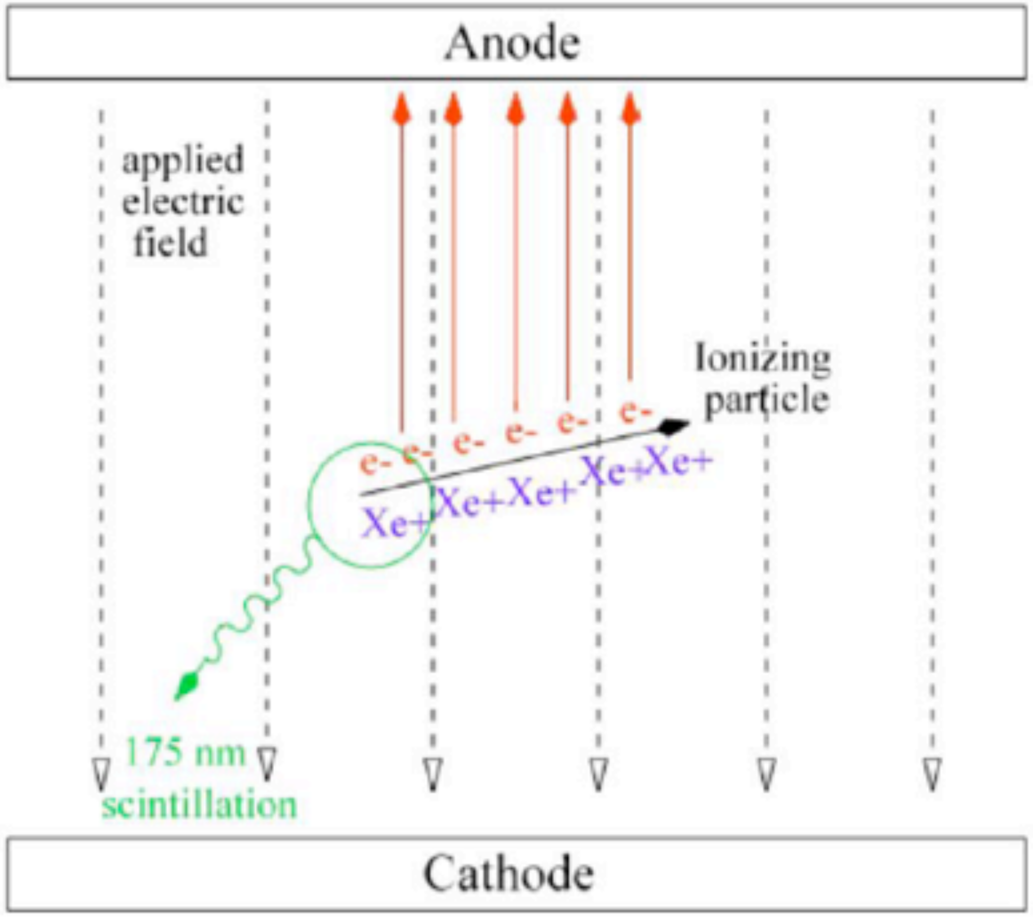
Phased approach:

1. EXO-200: 200kg liquid-Xe TPC



2. nEXO: future 5-ton liquid Xe (SNO lab cryopit)

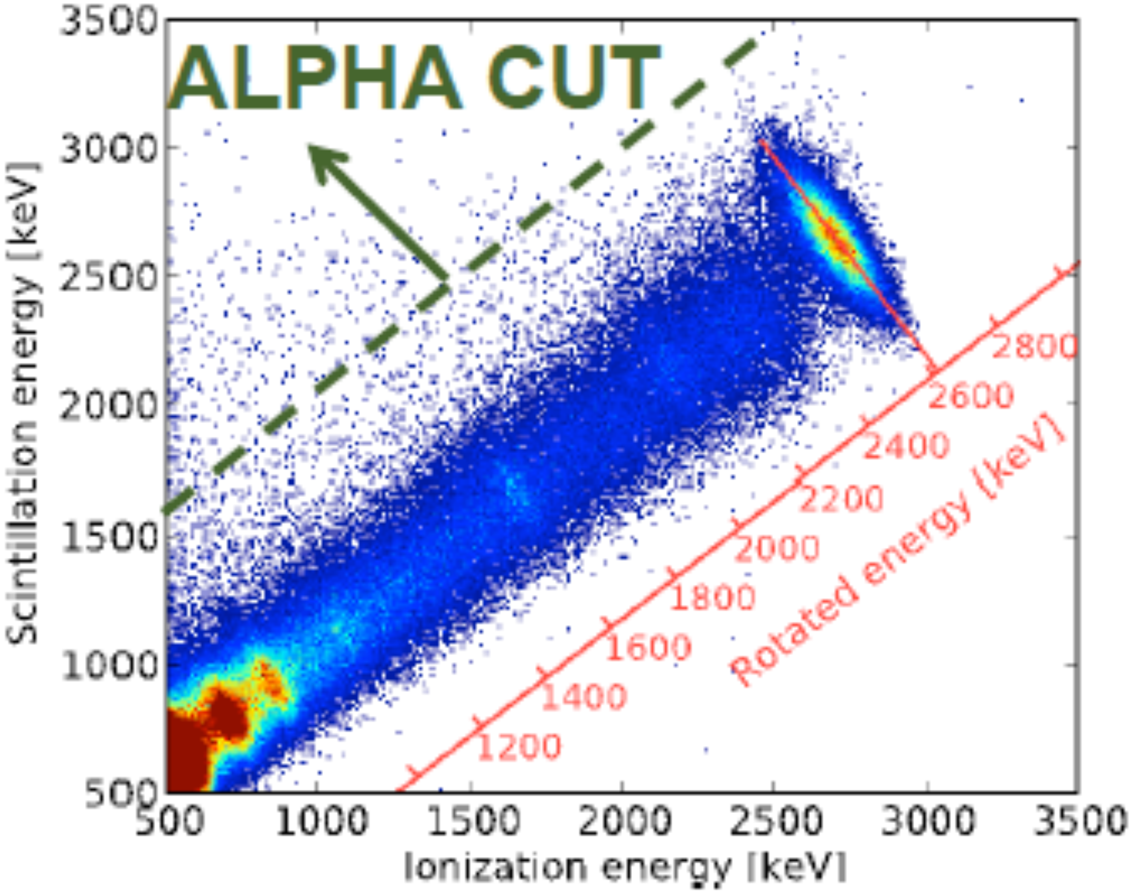




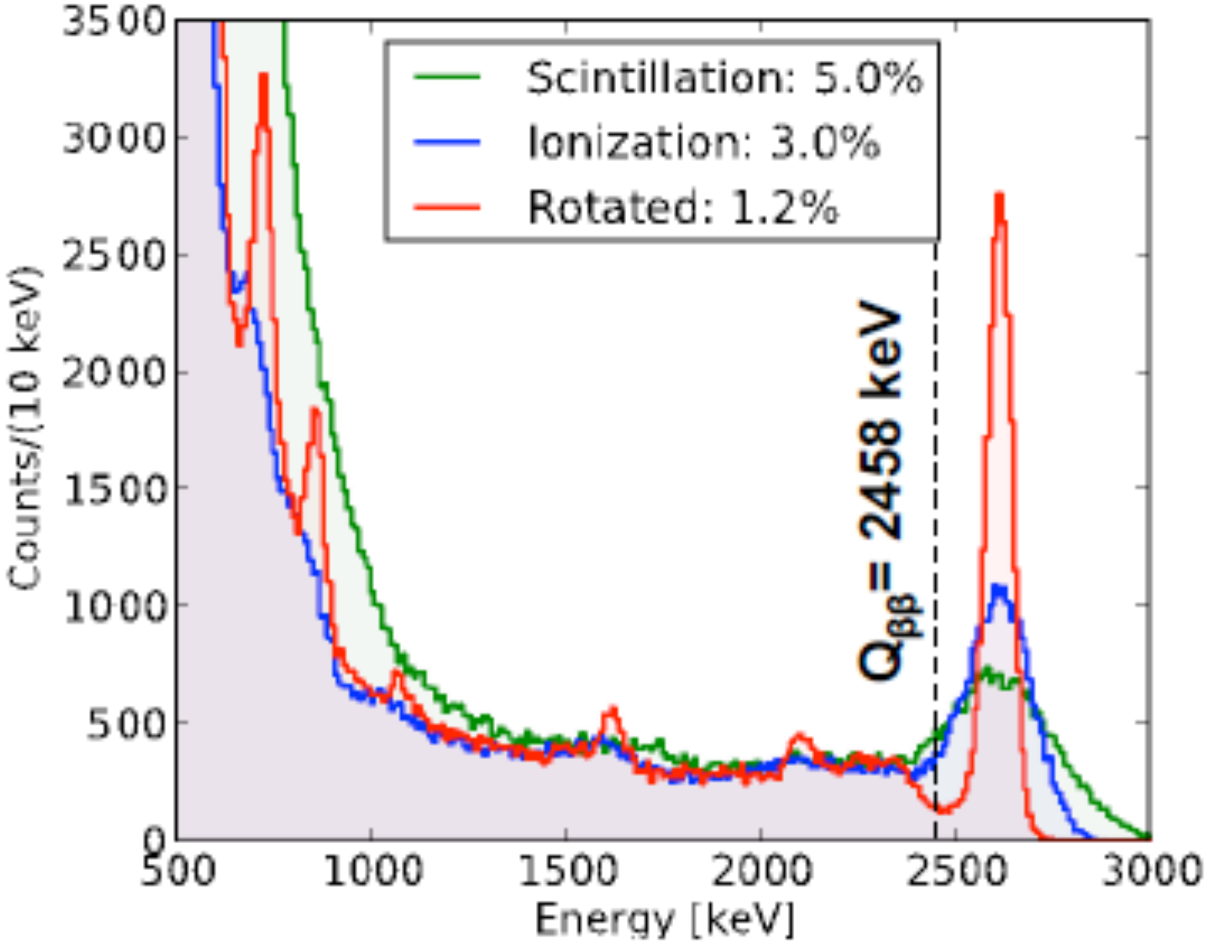
Liquid-Xe Time Projection Chamber

- Liquid Xe at 168K
- Detection of scintillation light and secondary charges
- 2D read out of secondary charges at segmented anode
- Full 3D event reconstruction:
  1. Energy reconstruction
  2. Position reconstruction
  3. Event Multiplicity

Scintillation vs. ionization, ^{228}Th calibration:

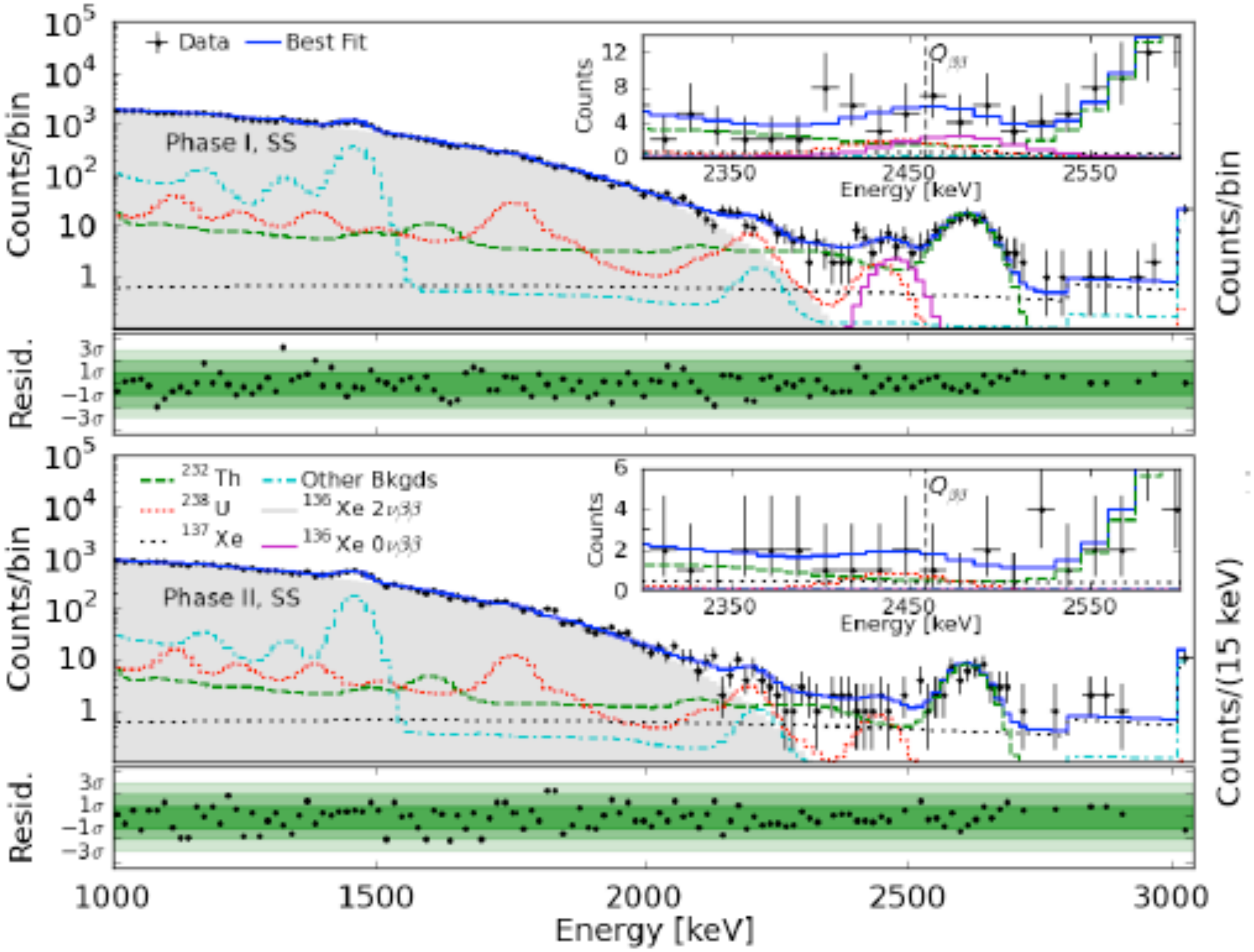


Reconstructed energy, ^{228}Th calibration:



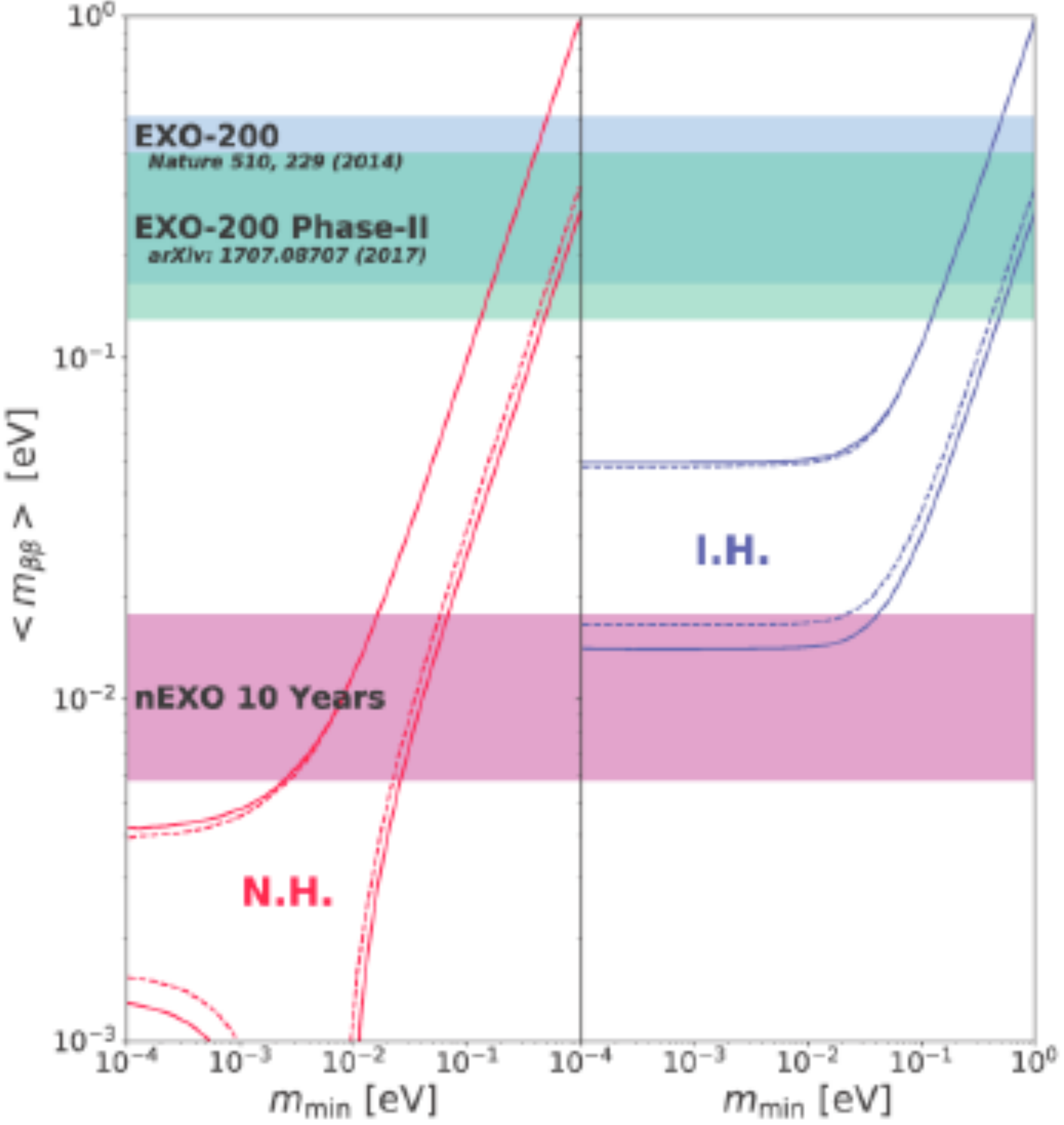
- E resolution better for ionization (3.5%) than scintillation (7%)
- combined gets down to ~1.2% at Q value
- correlated measurements
  - rotation angle provides best resolution (from calibration with ^{228}Th)

- Combine Phase I + Phase II profiles



- BI ~ (1.5 ± 0.2) 10^{-3}
- Bkg rejection exploits event topology like Gerda

https://arxiv.org/abs/1707.08707



Sensitivity of 3.7 x 10^{25} yr (90% CL)

$T_{1/2}^{0\nu\beta\beta} > 1.8 \times 10^{25}$ yr

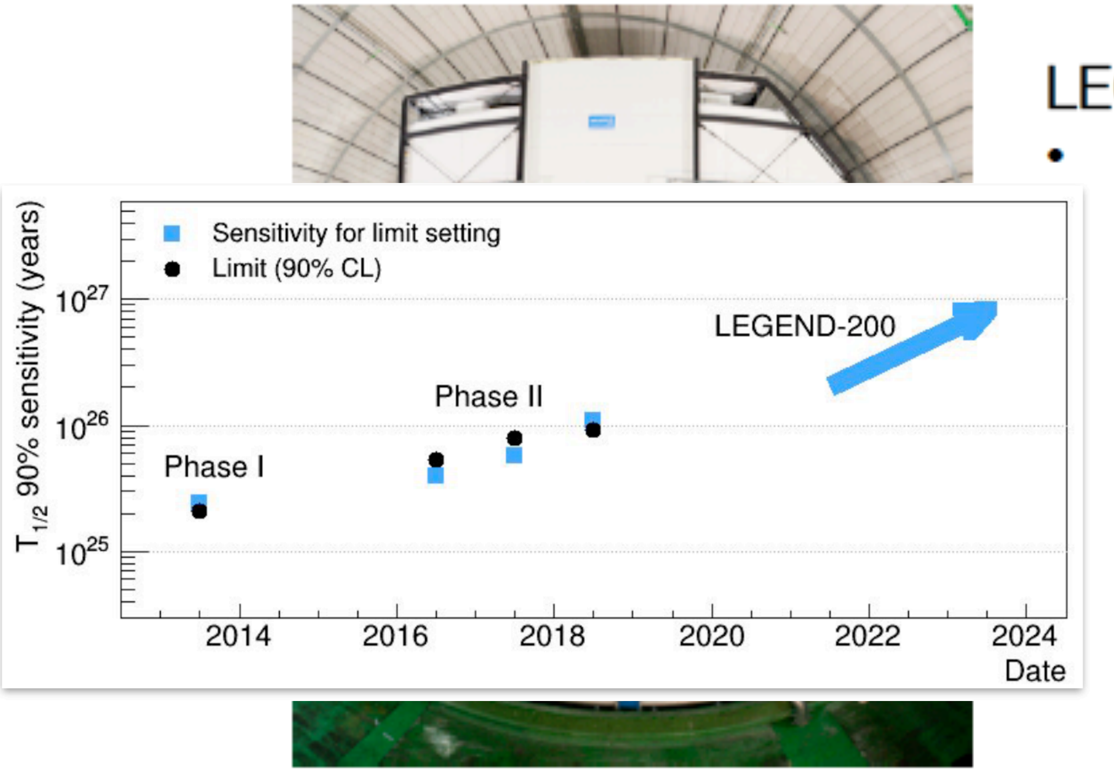
$\langle m_{\beta\beta} \rangle < 147 - 398$ meV

(90% C.L.)

Exo200-II

Future of Ge

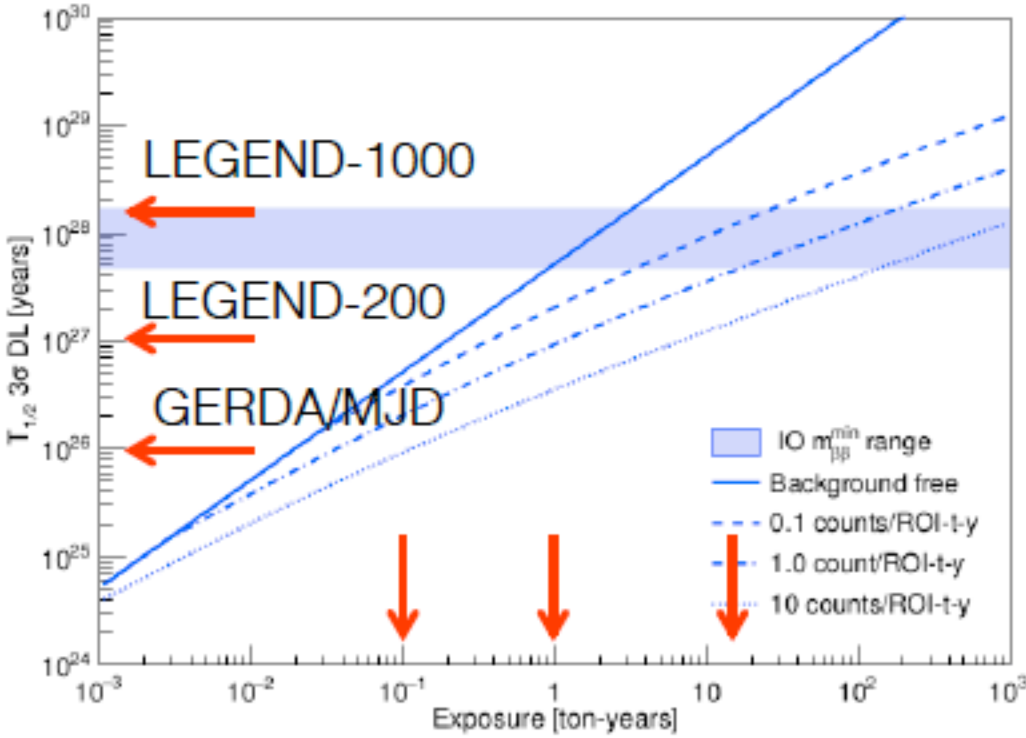
LEGEND program



LEGEND-200 (first phase):

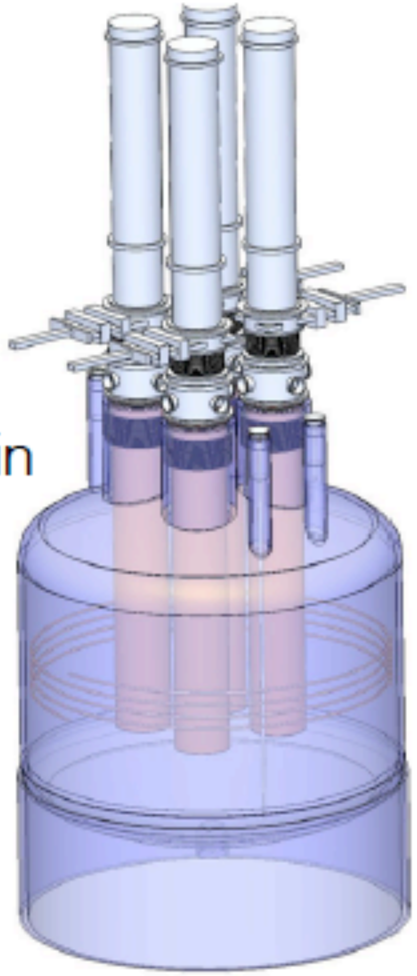
- up to 200 kg of detectors
- BI ~0.6 cts/(FWHM·t·yr)
- use existing GERDA infrastructure at LNGS
- design exposure: 1 t·yr
- Sensitivity 10^{27} yr

Sensitivity for 3σ signal discovery



LEGEND-1000 (second phase):

- 1000 kg of detectors (deployed in stages)
- BI <0.1 cts/(FWHM·t·yr)
- Location tbd
- Design exposure 12 t·yr
- $1.2\cdot10^{28}$ yr



17 meV discovery sensitivity for “worst case” NME of 3.5

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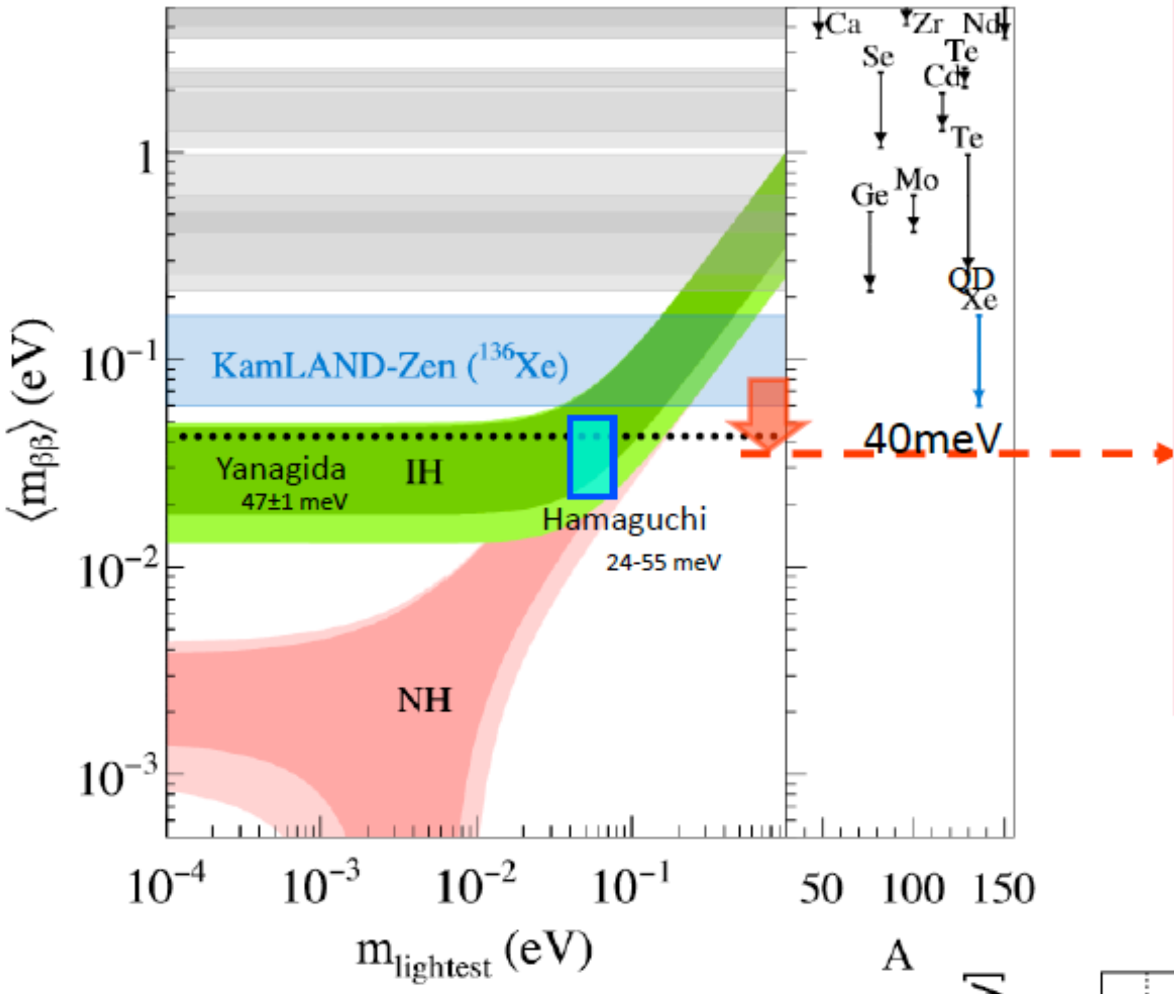
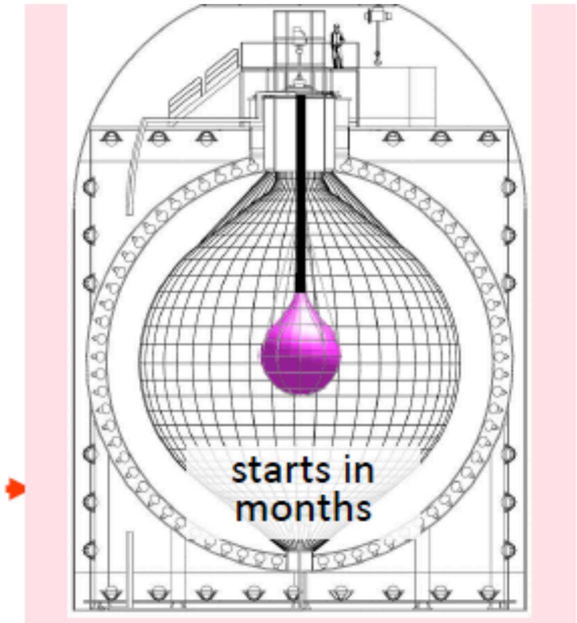
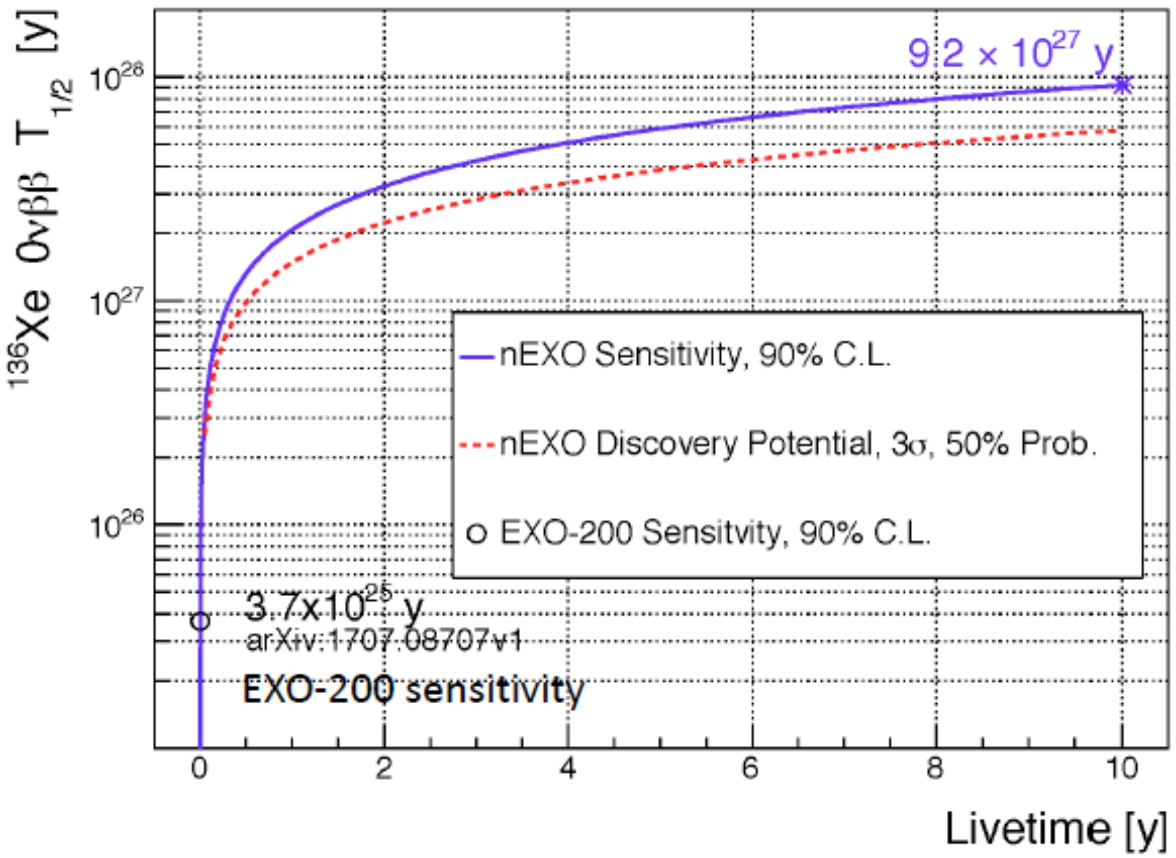
Future of Xe





low BG film, 750 kg xenon
KamLAND-Zen 800

$5x10^{26}$y (5y)



Methodology:

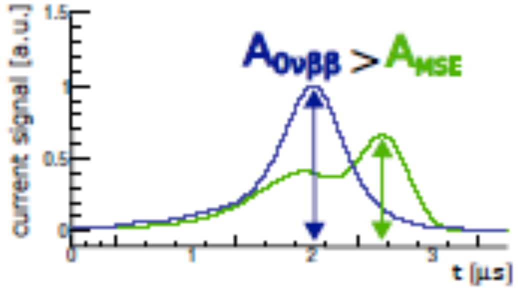
- 3860 kg fiducial Xe
- 90% enrichment
- 1% σE/E resolution
- Realistic background projections based on measurements
- EXO200-like analysis

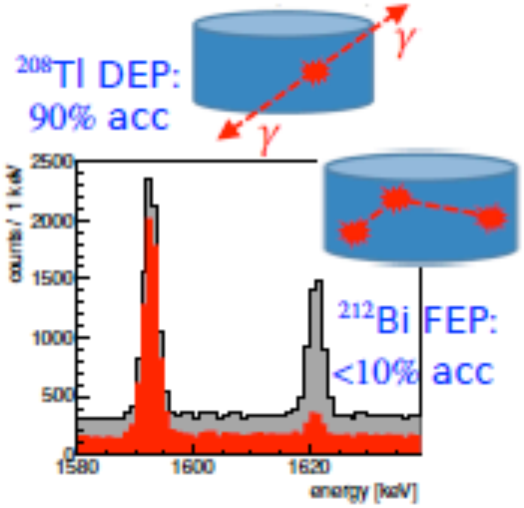
Back-up

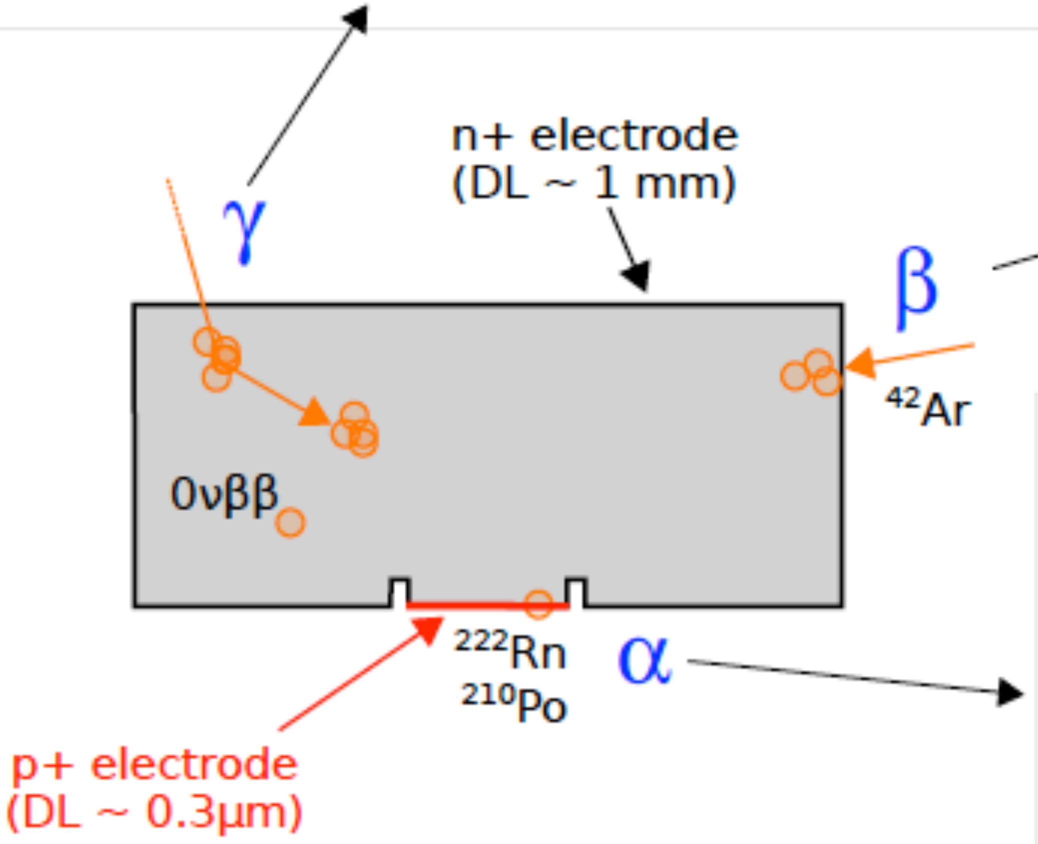
Phase II upgrade: BEGe detectors

Broad Energy Germanium

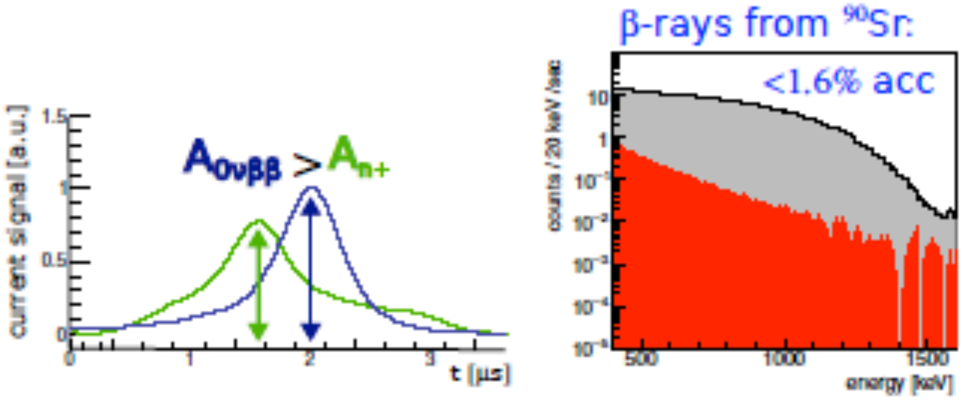
γ interactions:
- multiple Compton scattering (MSE)
- sequence of peaks in current signal
- Double escpape peak (DEP): proxy for $0\nu\beta\beta$ events



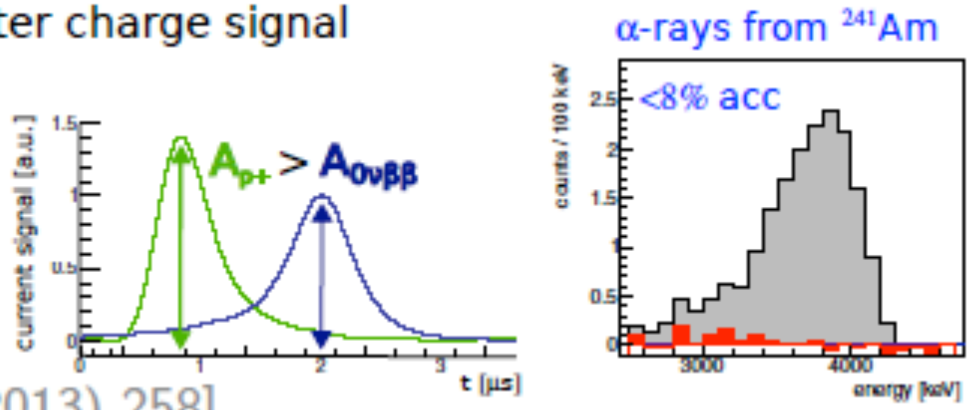




events on n+ surface:
- semiconductor junction -> weak E field
- slow current signal



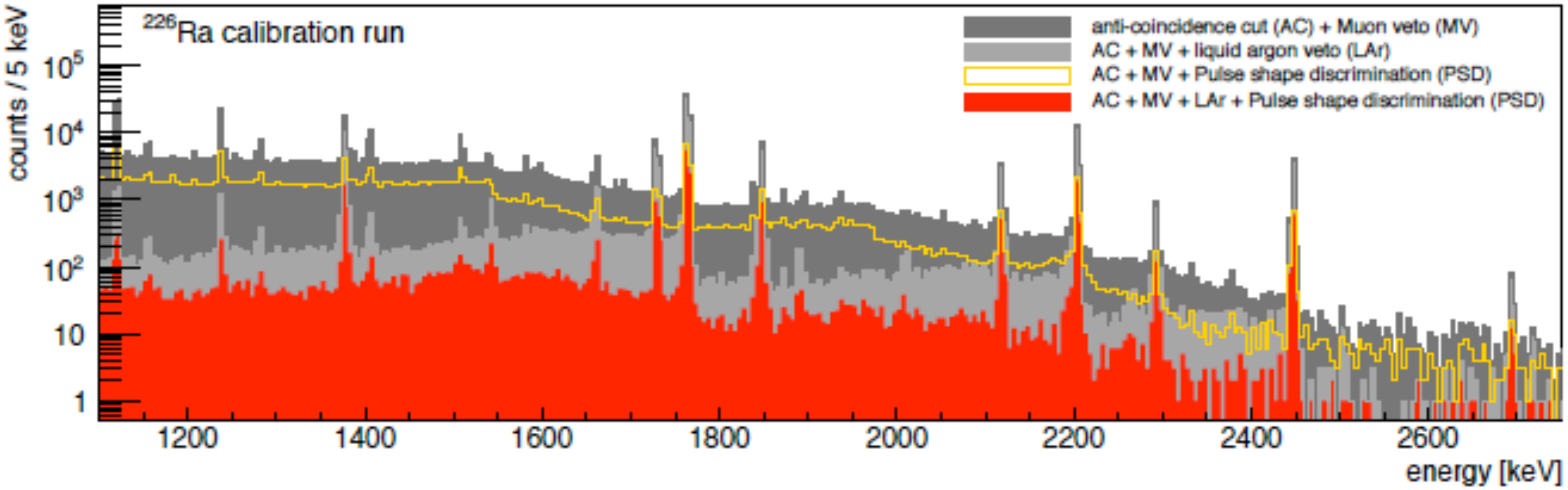
events on p+ electrode:
- electron drift faster then holes
- faster charge signal

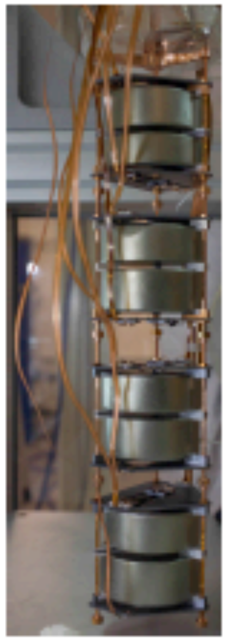


[JINST 6 2011 P03005, JINST 4 2009 P10007, EPJC 73 (2013) 258]

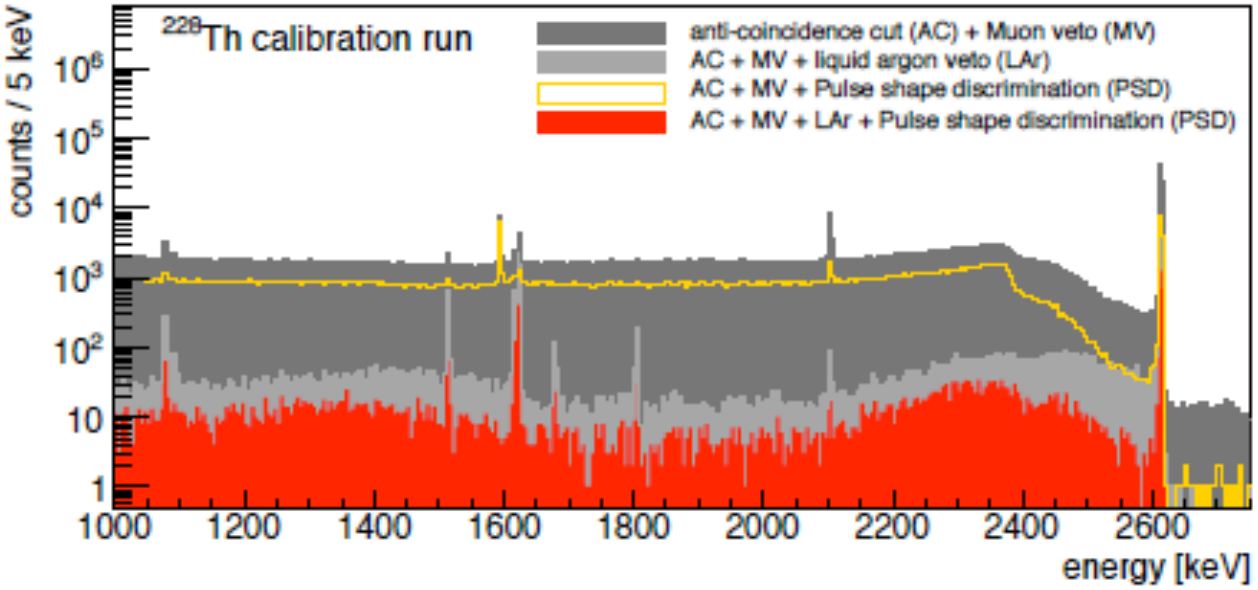
PSD and LAr veto during Phase II commissioning

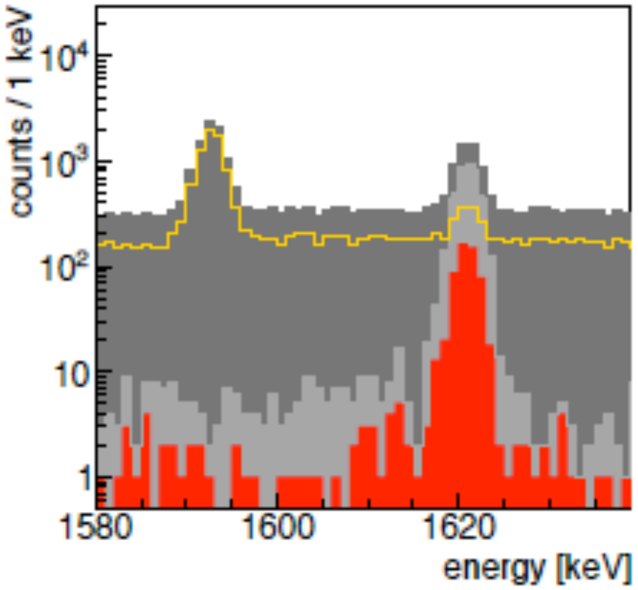
^{226}Ra calibration run (single BEGe string in GERDA):

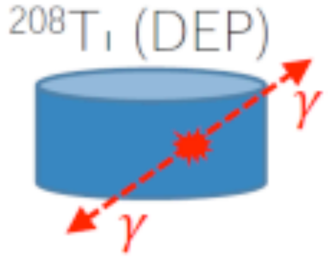


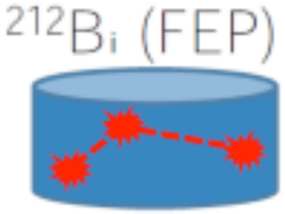


^{228}Th calibration run:







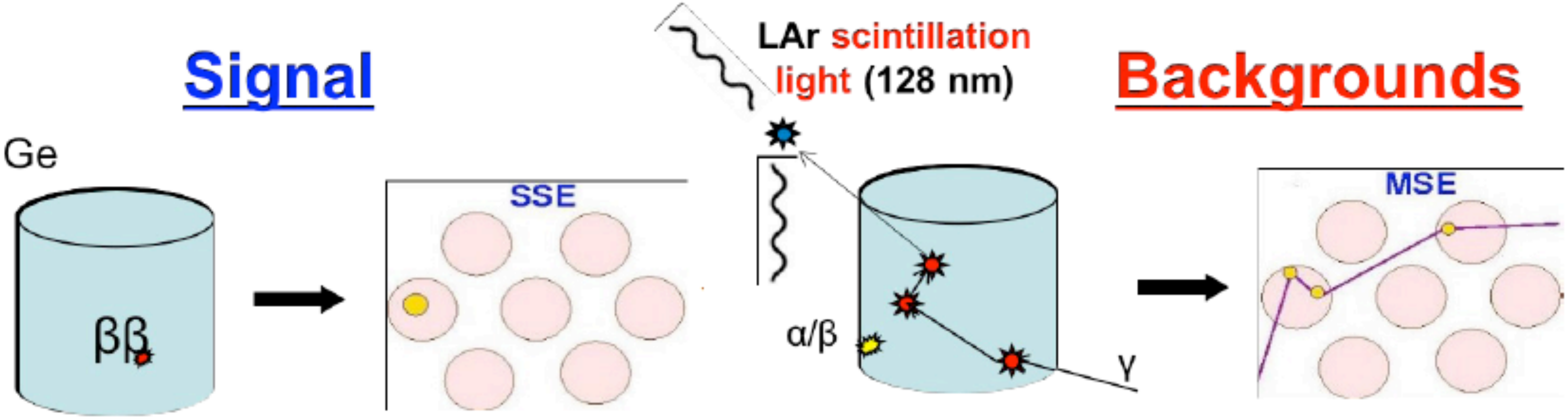


Combined suppression factors: 27±2 (for ^{226}Ra) and 300±28 (for ^{228}Th)

Suppression depends on isotope, location and detector configuration

main components before LAr veto/PSD:
- α from ^{210}Po,^{226}Ra
- β from ^{42}K
- γ from ^{214}Bi,^{208}Tl

Active background reduction tools



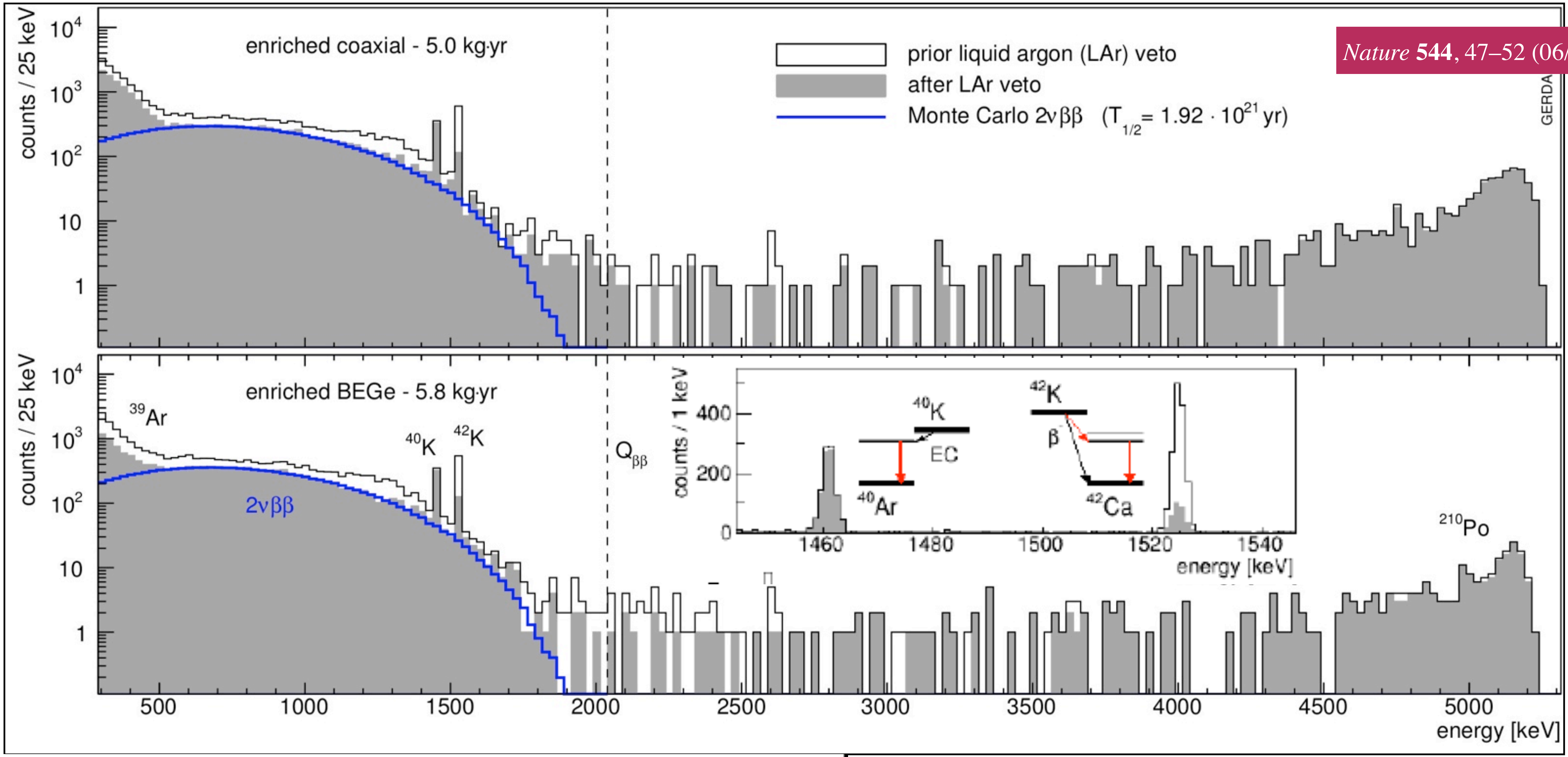
Signal

Point-like (single-site) energy deposition inside one HP-Ge diode

Backgrounds

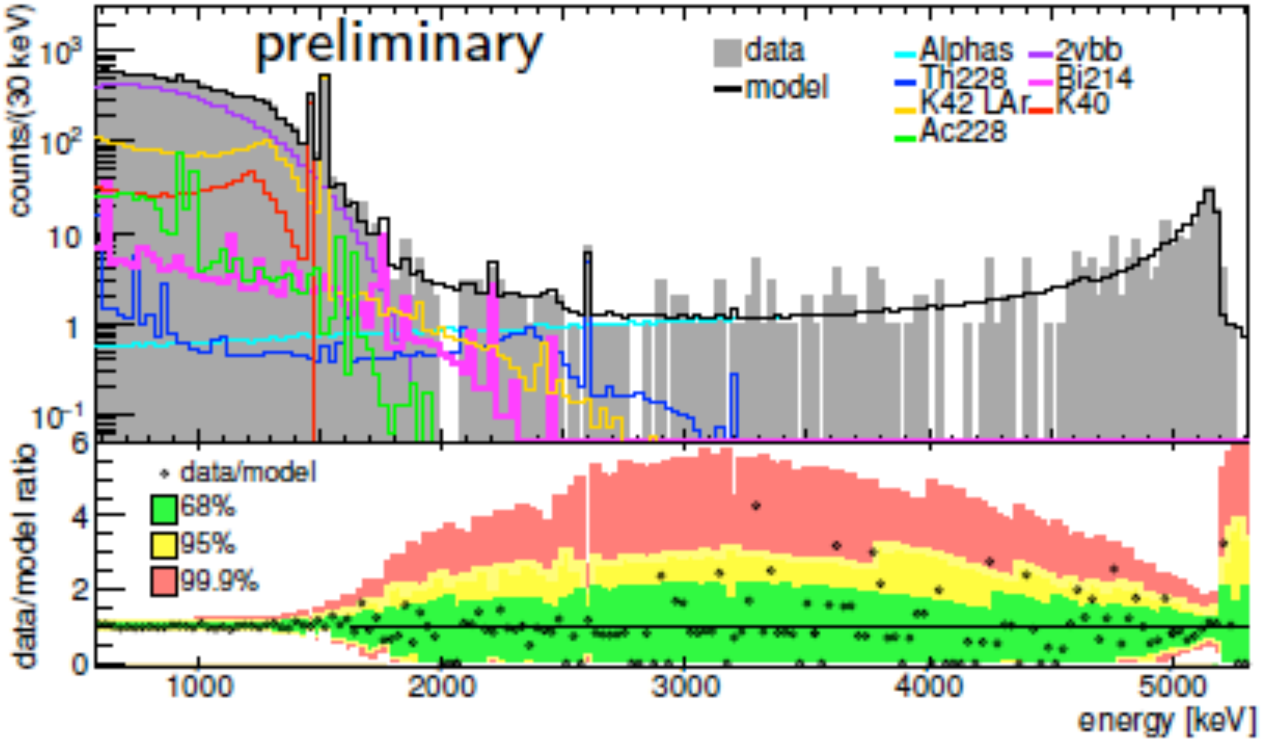
Multi-site energy deposition inside HP-Ge diode (Compton scattering), or **surface** events

- **Anti-coincidence** with the **muon veto** (MV)
- Anti-coincidence **between detectors** (cuts multi-site) (AC)
- **Active veto** using LAr scintillation (LAr Veto)
- **Pulse shape** discrimination (PSD)



Nature **544**, 47–52 (06/04/2017)

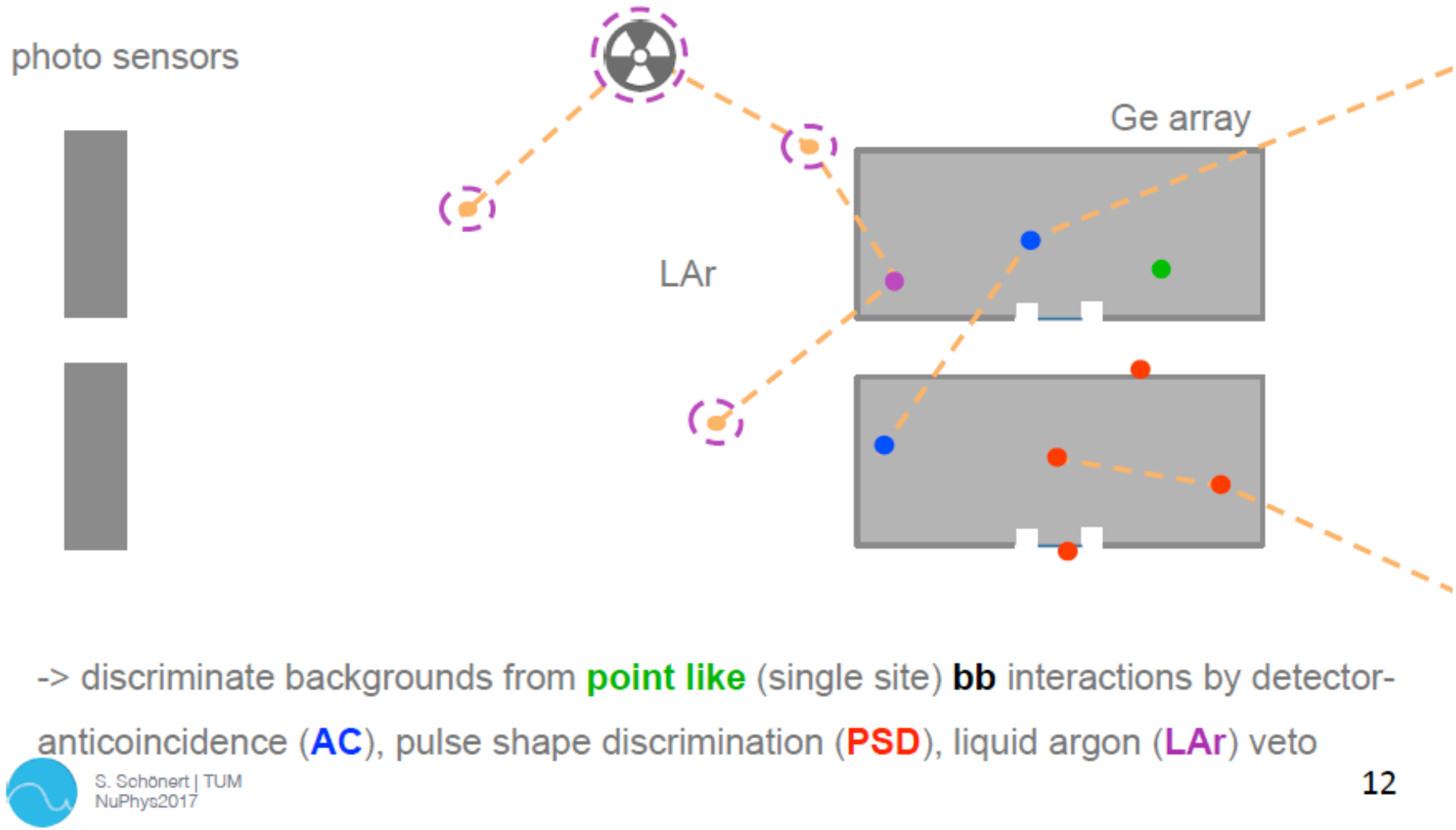
BEGe: global fit p-value=0.3



- same isotopes as in Phase I
- Th/Ra contributions consistent with screening results
- main components before LAr veto/PSD:
  - α from ^{210}Po, ^{226}Ra
  - β from ^{42}K
  - γ from ^{214}Bi, ^{208}Tl
- flat background in the ROI

Gerda

Active background suppression



-> discriminate backgrounds from **point like** (single site) **bb** interactions by detector-anticoincidence (**AC**), pulse shape discrimination (**PSD**), liquid argon (**LAr**) veto

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"PSD" now enhanced (new BEGe) and "LAr" now possible (LAr bath)

see e.g. Majorovits, Phys.Proc. 61 (2015) 254-259 https://arxiv.org/pdf/1205.5608.pdf

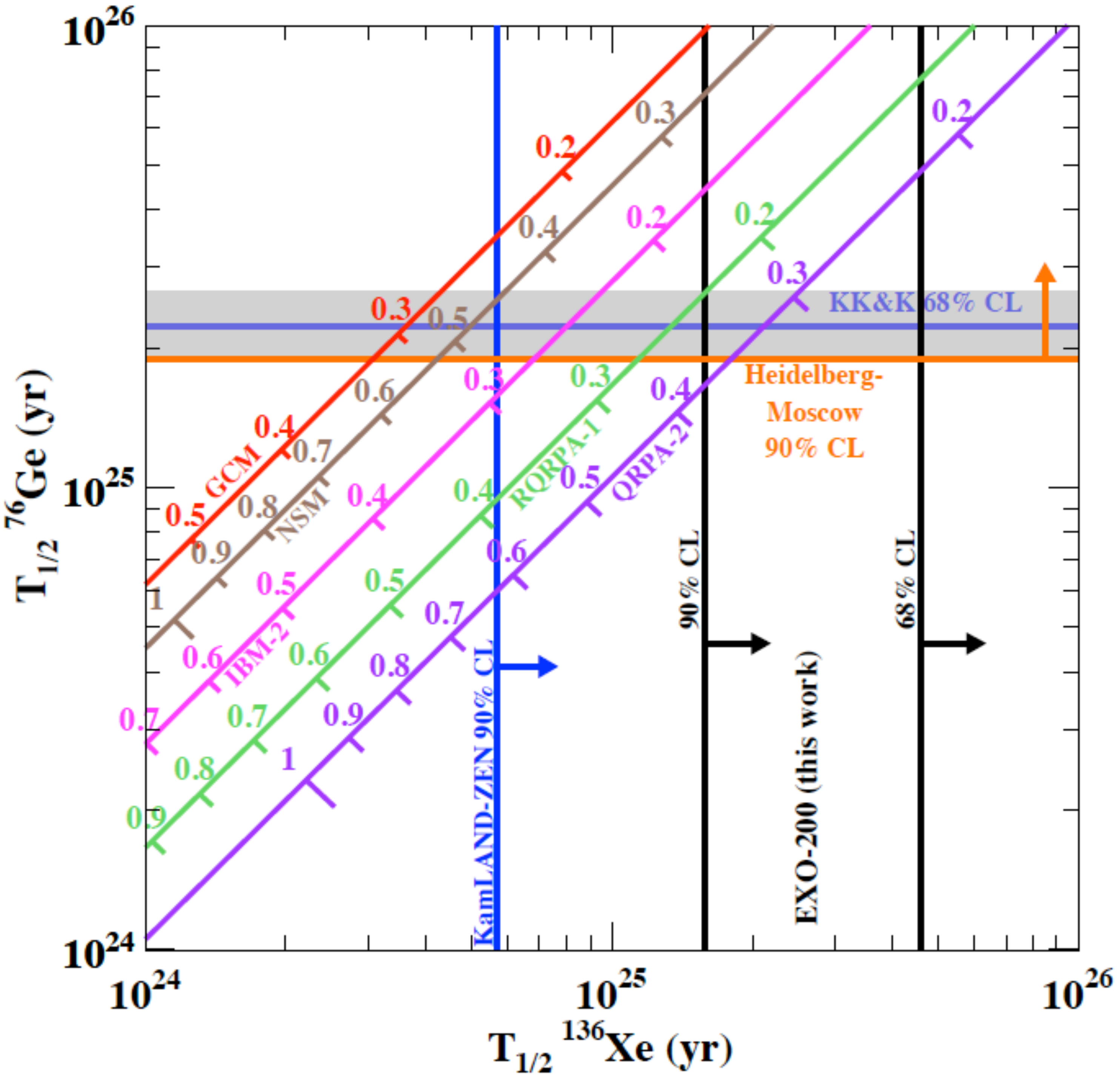

FIG. 6: Relation between the $T_{1/2}^{0\nu\beta\beta}$ in ^{76}Ge and ^{136}Xe for different matrix element calculations (GCM [20], NSM [21], IBM-2 [22], RQRPA-1 [23] and QRPA-2 [5]). For each matrix element $\langle m\rangle_{\beta\beta}$ is also shown (eV). The claim [4] is represented by the grey band, along with the best limit for ^{76}Ge [19]. The result reported here is shown along with that from [7].

Phase II final array configuration

- Deployed in Dec 2015
- 30 enriched BEGe (20 kg)
- 7 enriched Coax (15.8 kg)
- 3 natural Coax (7.6 kg)

⇒ 35.8 kg of enr detectors