Data Quality and Cosmogenic Background Studies for the LEGEND experiment

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Supervisor: prof. Natalia Di Marco

AstroParticle Physics – XXXVI Cycle

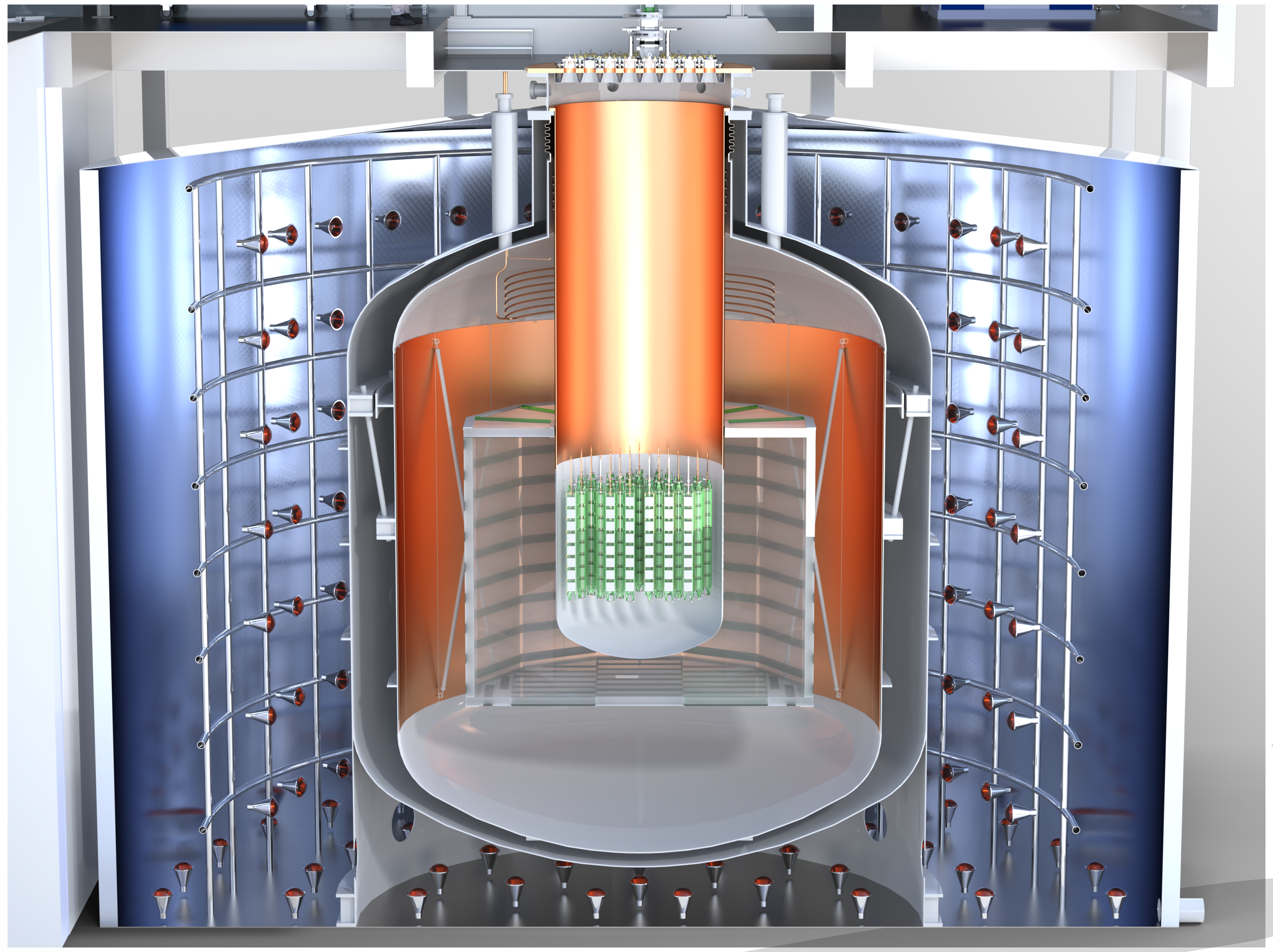
GSSI

INFN LNGS

3rd Year PhD Research Activities Report – 24/10/2023

LEGEND Phases

LEGEND Mission: “The collaboration aims to 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.”



MAJORANA Demonstrator

completed in ~2020

GERDA

LEGEND-200

200 kg using GERDA infrastructure at LNGS

Background Index* Goal: $< 2.5 \times 10^{-4}$ counts/(keV kg yr)

$T^{0\nu}_{1/2} > 10^{27}$ yr after **5 years of data**

LEGEND-1000

1000 kg in a new infrastructure (SNOLAB or LNGS)

Background Index* Goal: $< 1 \times 10^{-5}$ counts/(keV kg yr)

$T^{0\nu}_{1/2} > 10^{28}$ yr after **10 years of data**

↓

LEGEND-1000 will span the inverted ordering and part of the normal ordering space

***Background Index**: number of counts around $Q_{\beta\beta}$ divided by M, t and energy window

Research Activities – Overview

My research activities are divided between background analysis for LEGEND-200 and μ related simulations for LEGEND-1000

LEGEND-200:

- selection and validation of physics dataset (used for TAUP analysis)
- analysis of gamma lines rate in High Purity Ge (HPGe) detectors

this talk

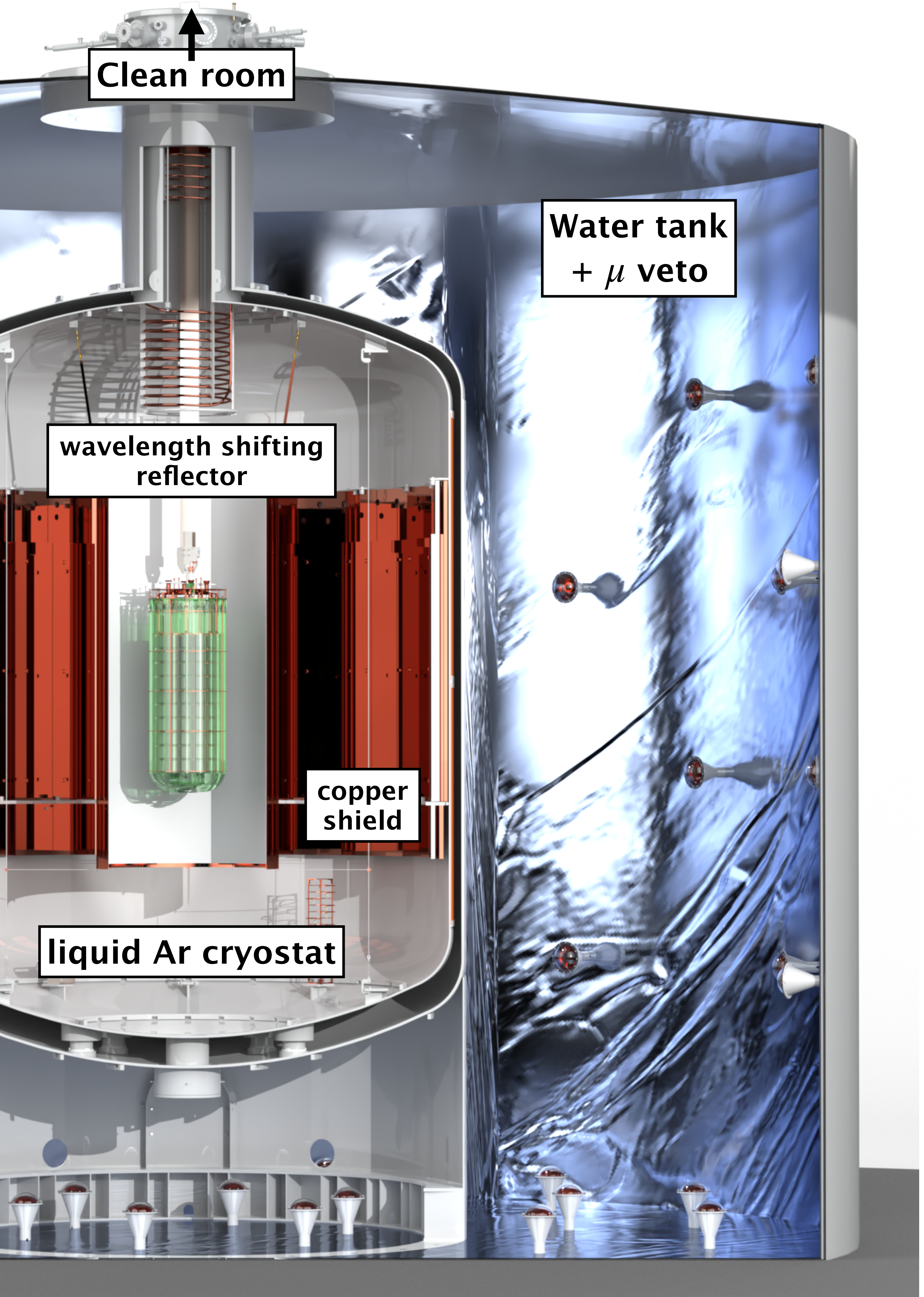
LEGEND-1000 @LNGS:

backup

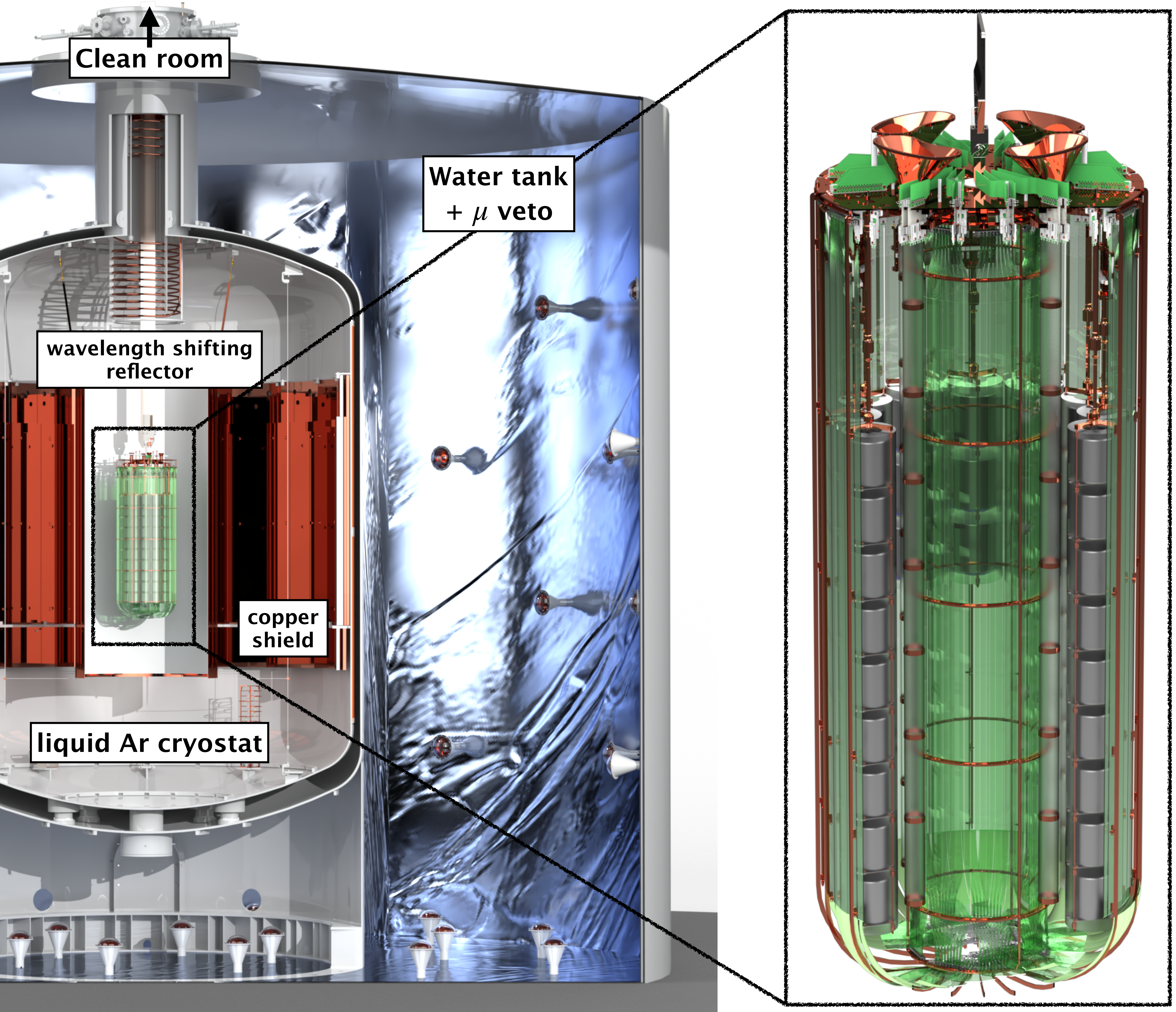
- study and design of instrumentation for Atmospheric Ar volume
- study of cosmogenically produced neutrons and their interactions
- study of radiogenic background and possibility of vetoing it

LEGEND-200: Event rates from γ lines

LEGEND-200: Design



LEGEND-200: Design



LEGEND-200: Design

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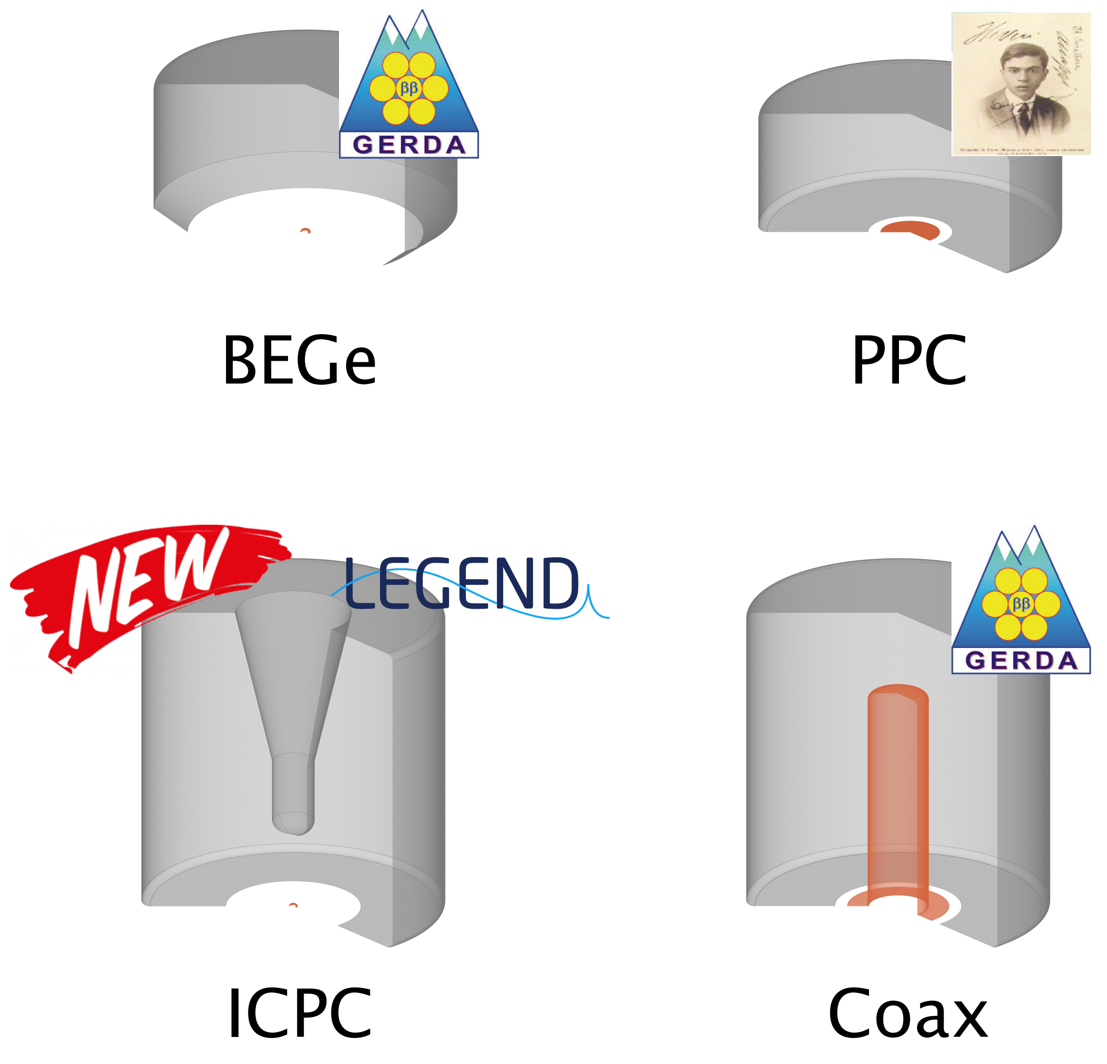
LEGEND-200: Status of the experiment

- October 2022: 142 kg of HPGe detectors installed (101 detectors)
- 130 kg usable for analysis
  (12 detectors off due to hardwares failures)

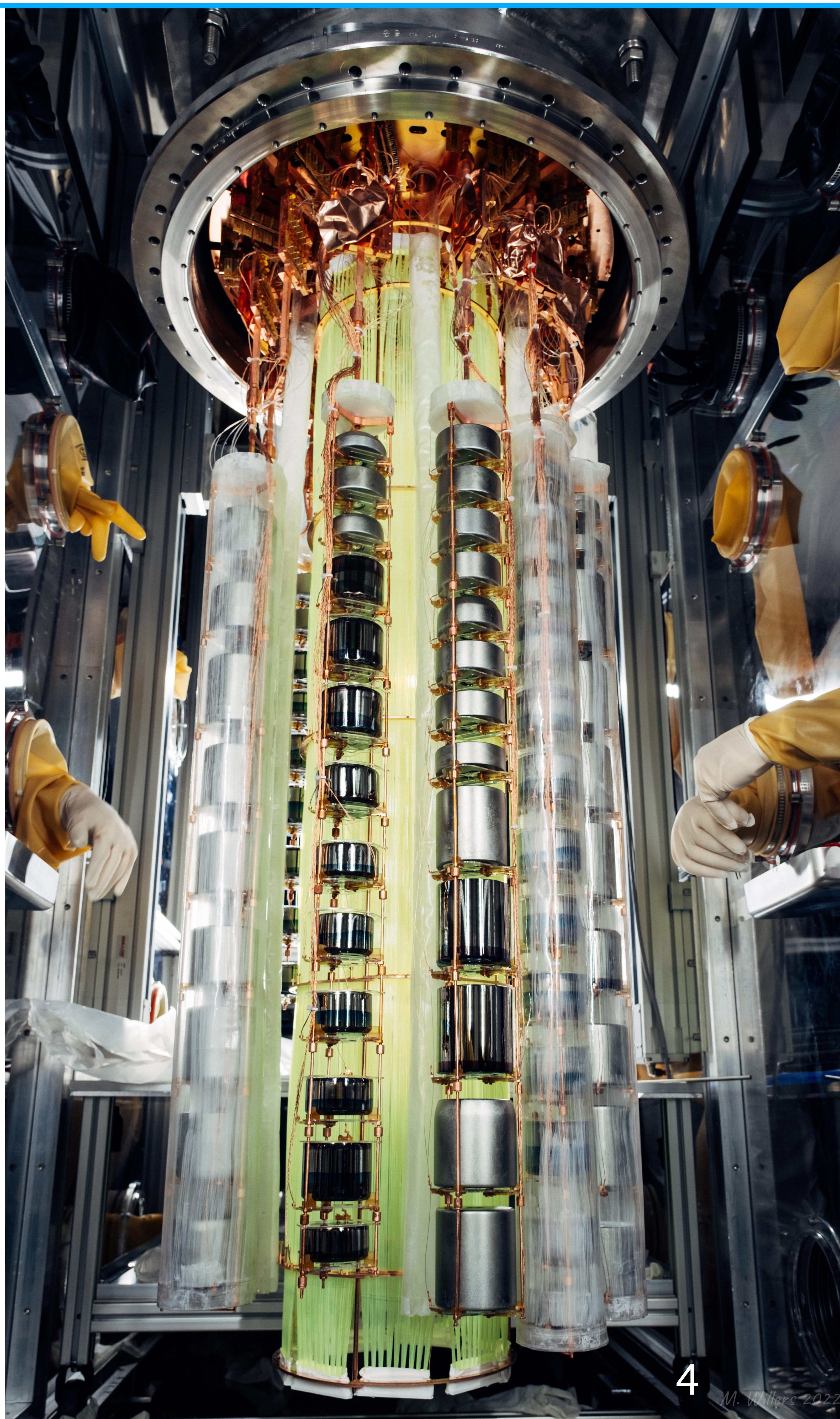


Dataset selected:

- data from March to May 2023
- first LEGEND background results presented @ the TAUP conference in Vienna
- next data release 90 kg·yr @Neutrino24

May/June 2024: hardware upgrade and installation of new HPGe detectors

Exposure (kg yr)	ICPC	BEGe	COAX	PPC
14.8	9.4	2.1	1.9	1.4



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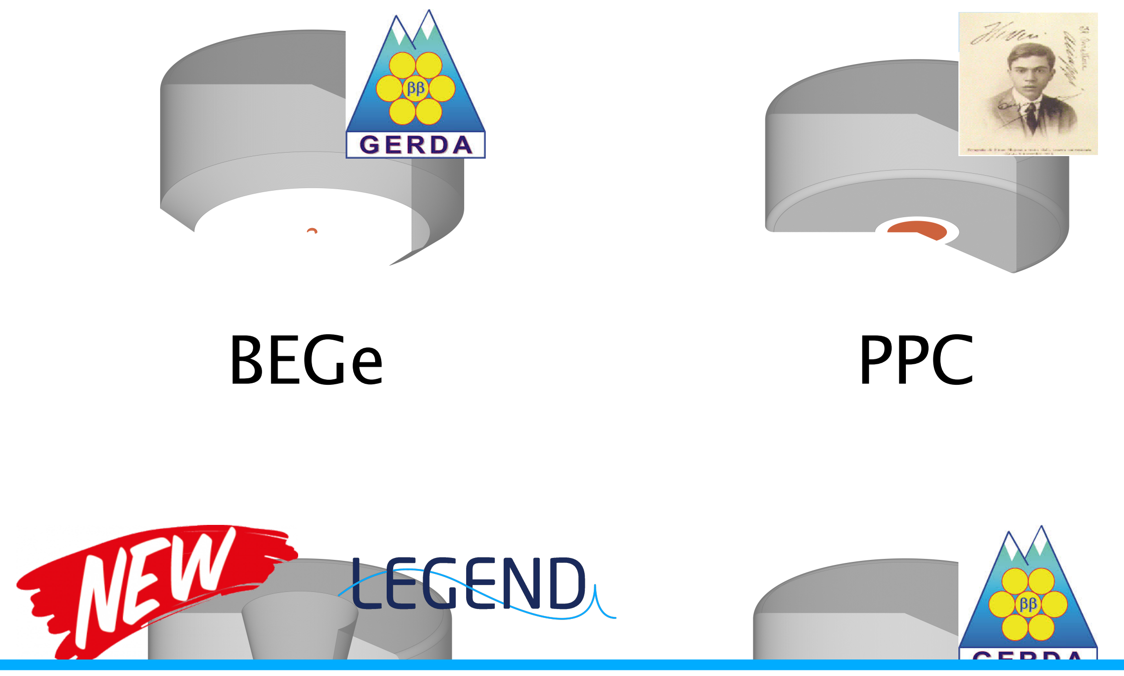

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My contribution: selection and validation of the dataset for physics analysis (+ python package for HPGe stability monitoring)

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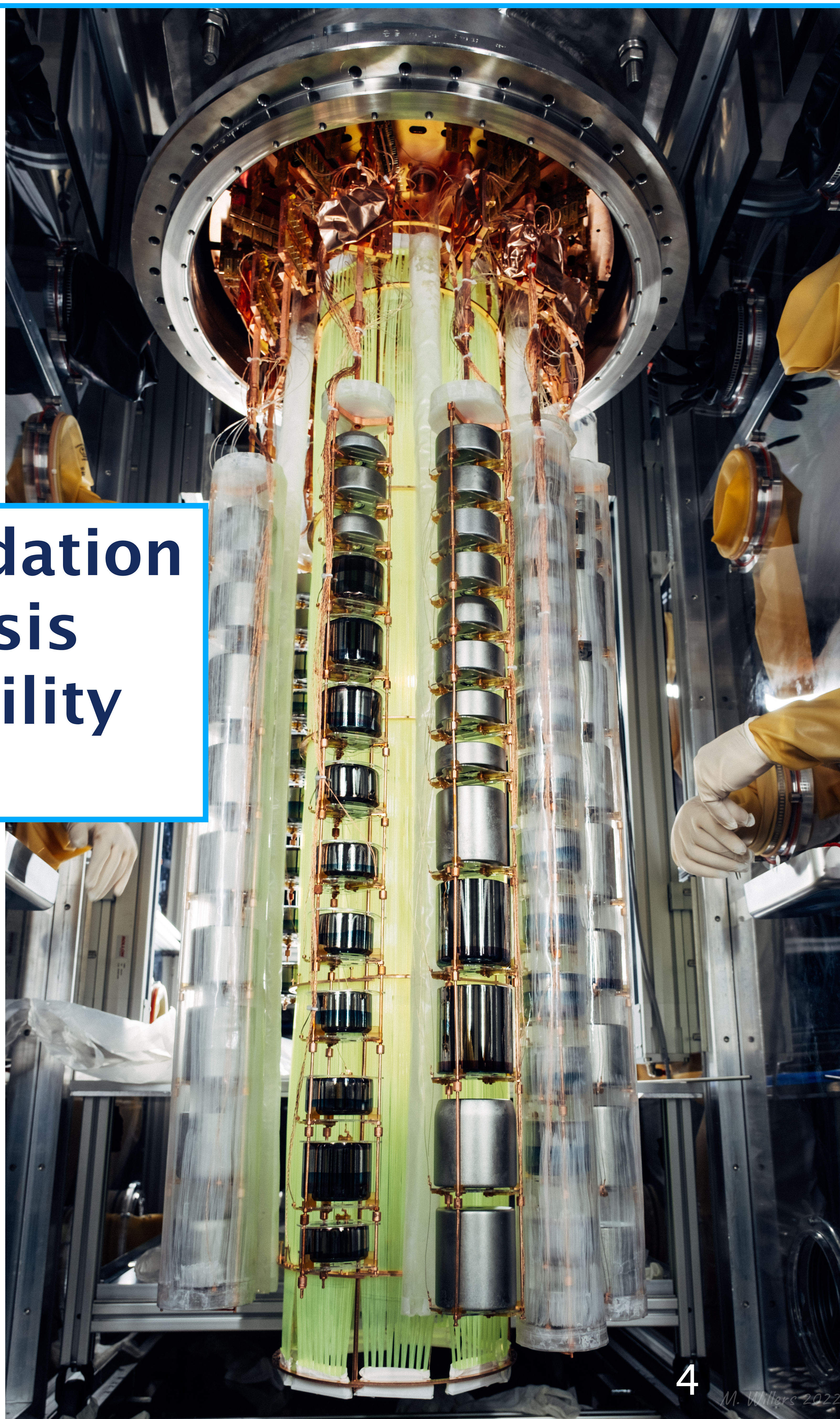
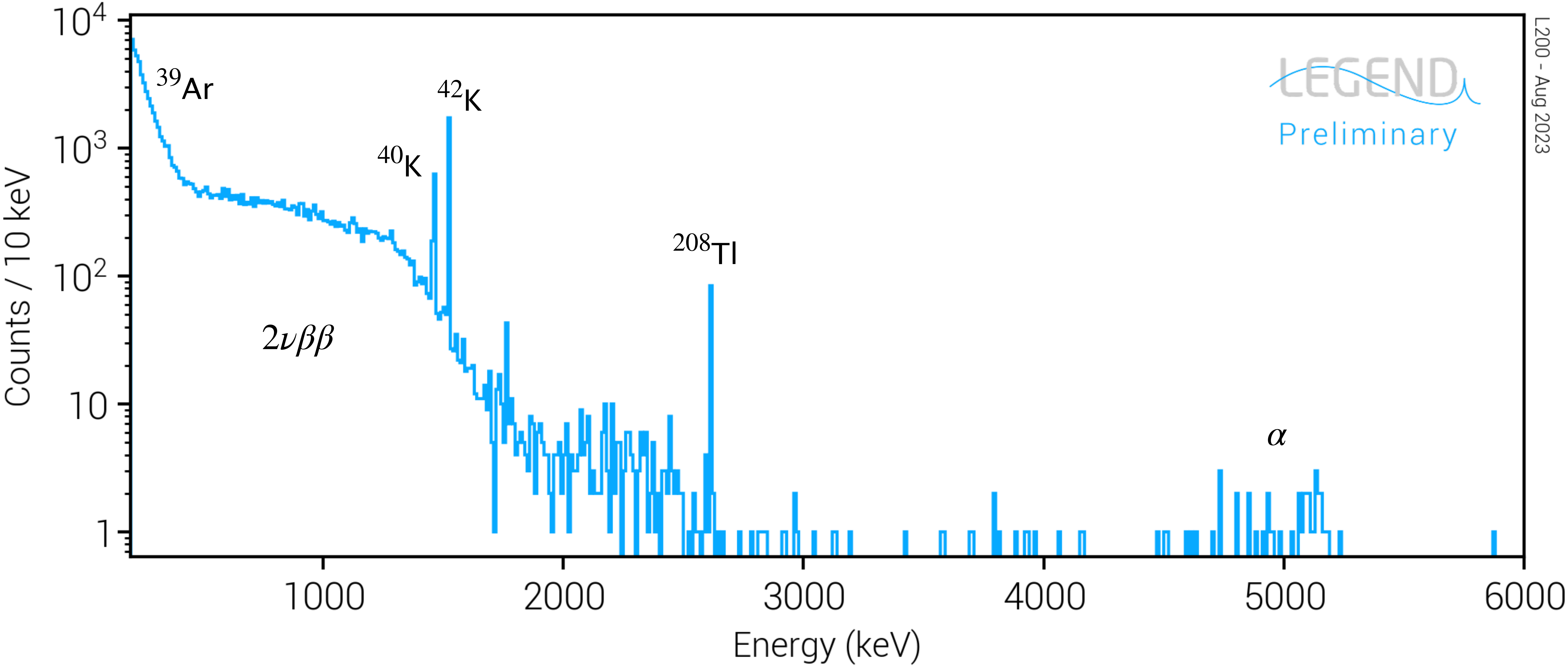


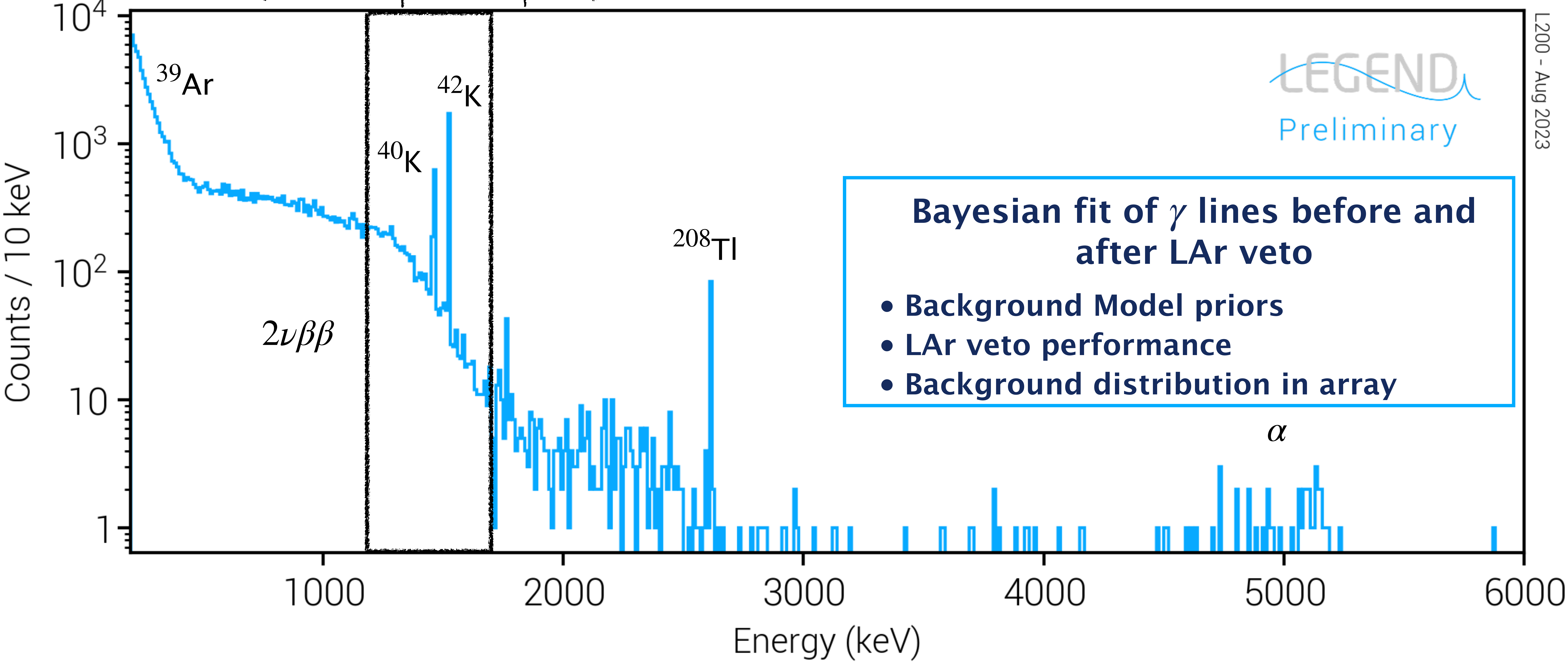
Energy spectrum & features



Energy spectrum & features

focus on ^{40}K and ^{42}K
because of high statistics
(and low exposure acquired)

Question: "What about ^{208}Tl and ^{214}Bi?
Have you tried comparing with GERDA"
Answers in the BACKUP!!



Bayesian fit of γ lines before and after LAr veto

- **Background Model priors**
- **LAr veto performance**
- **Background distribution in array**

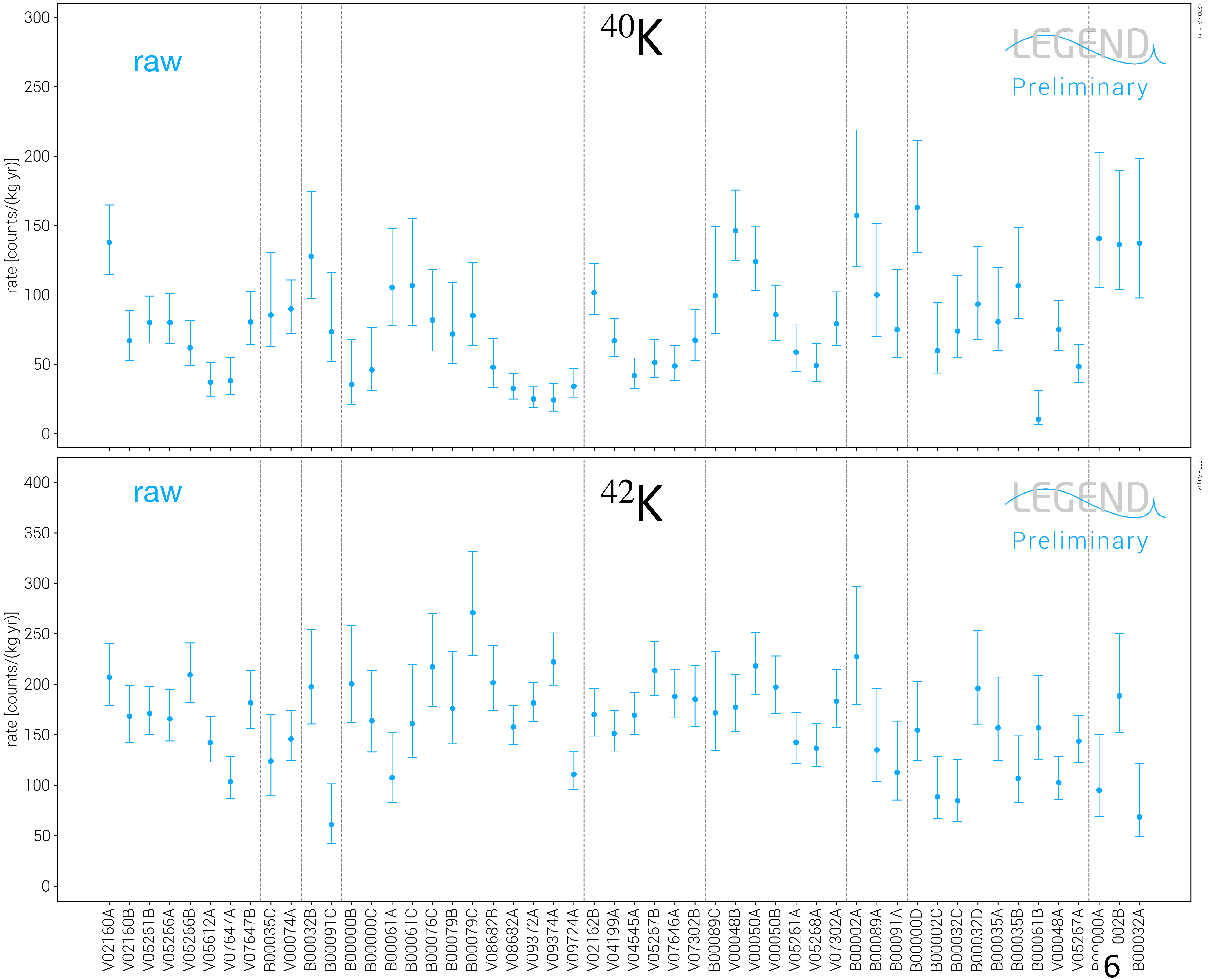
Event rate by channel

^{40}K

- traces everywhere (cables, fibers, …)
- decays by EC: γ line, no β
- **NO** E dep. in Ar is expected

^{42}K

- produced by ^{42}Ar in Ar volume
- drifts in high voltage electric field
- β^- decay: γ line + β (Q = 3.5 MeV)
- E dep. in Ar is expected



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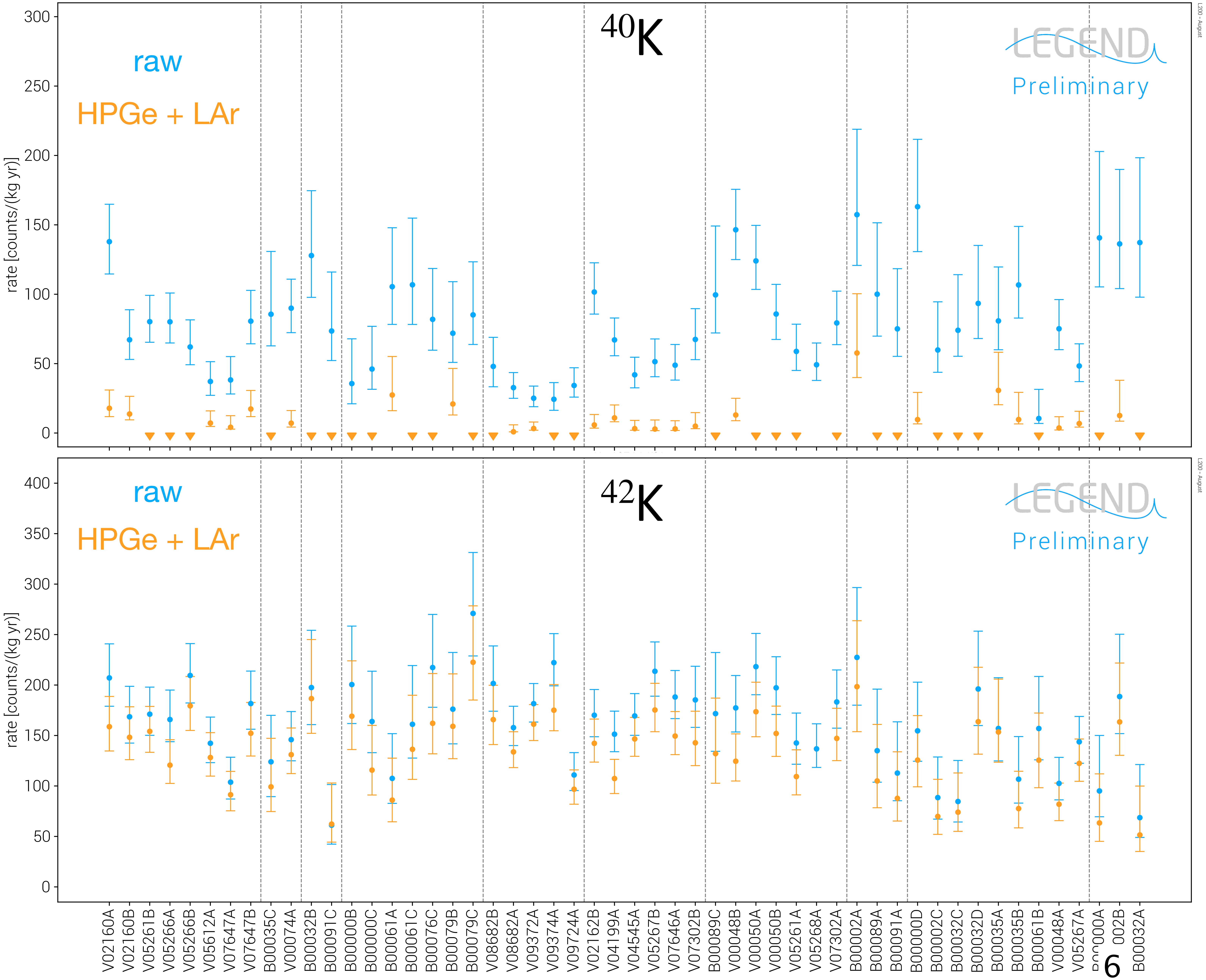

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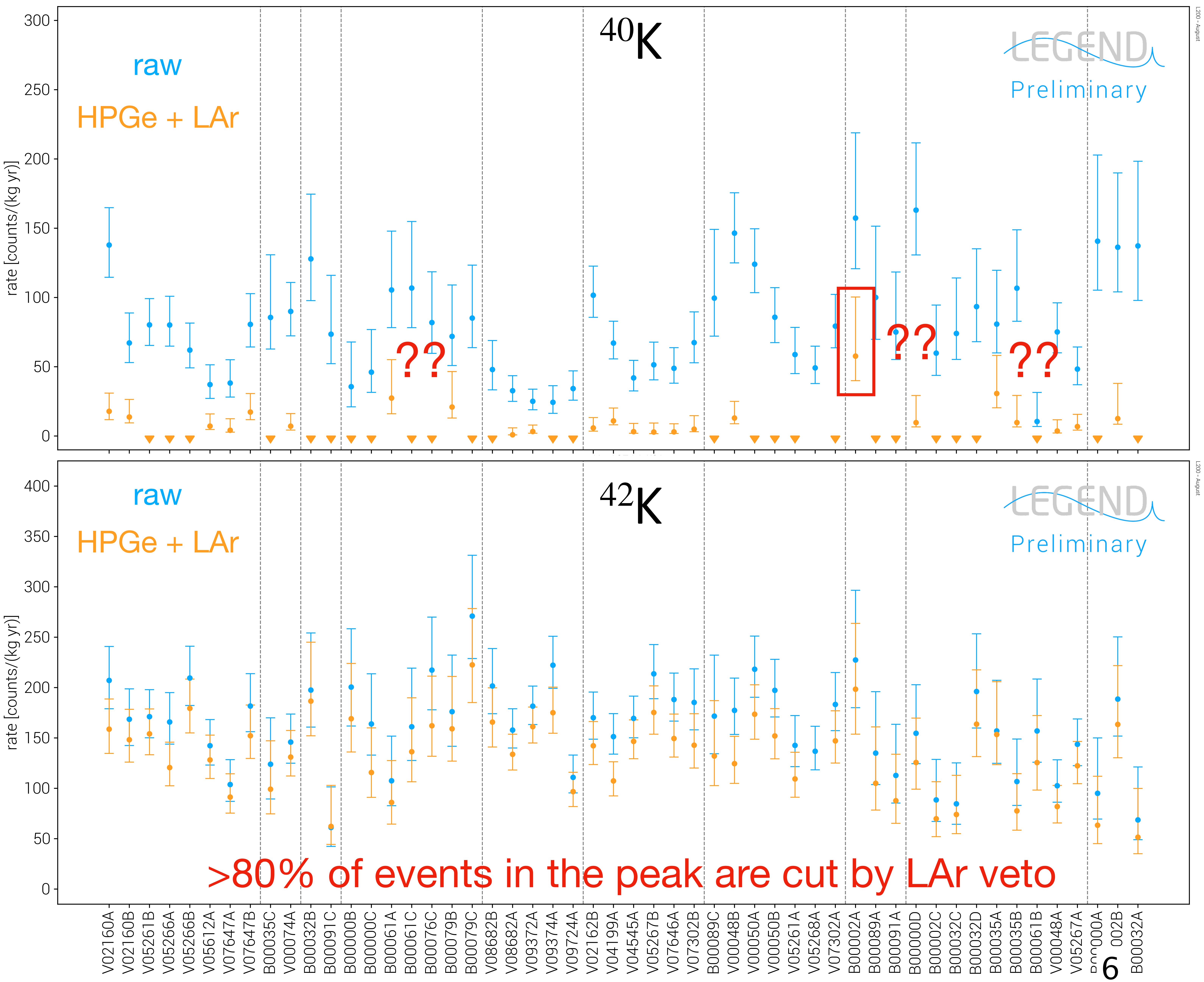
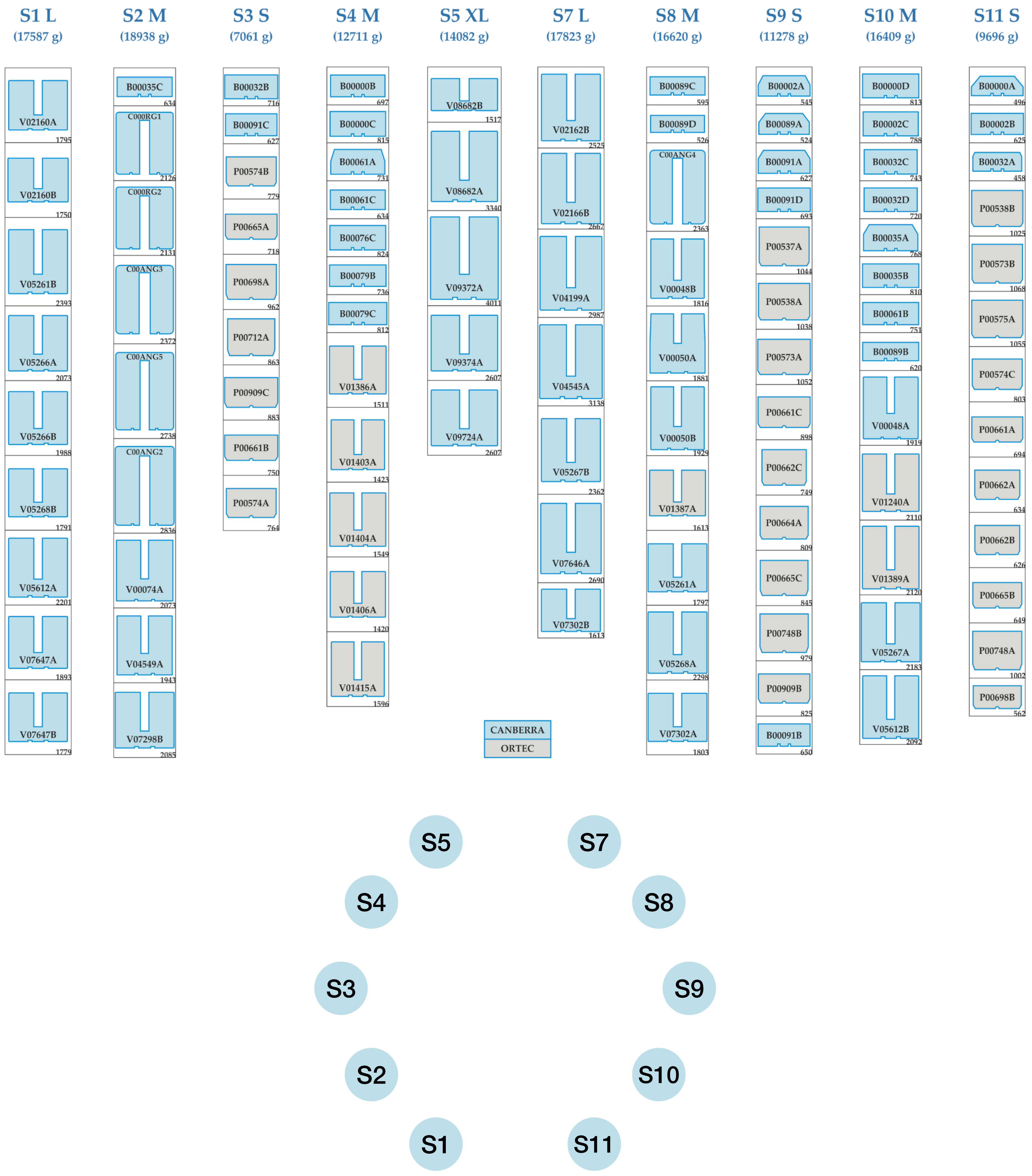
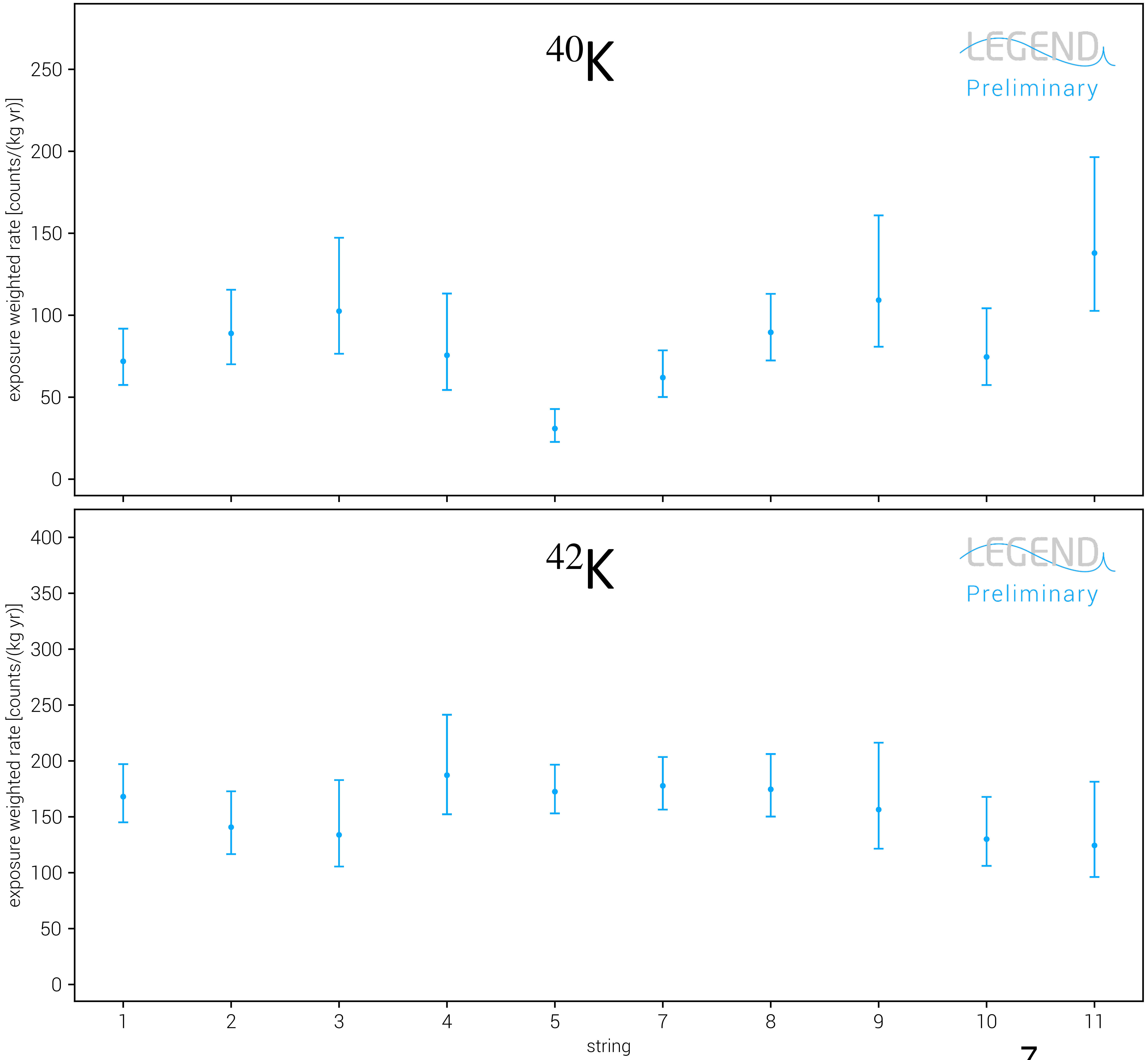


Event rate by string





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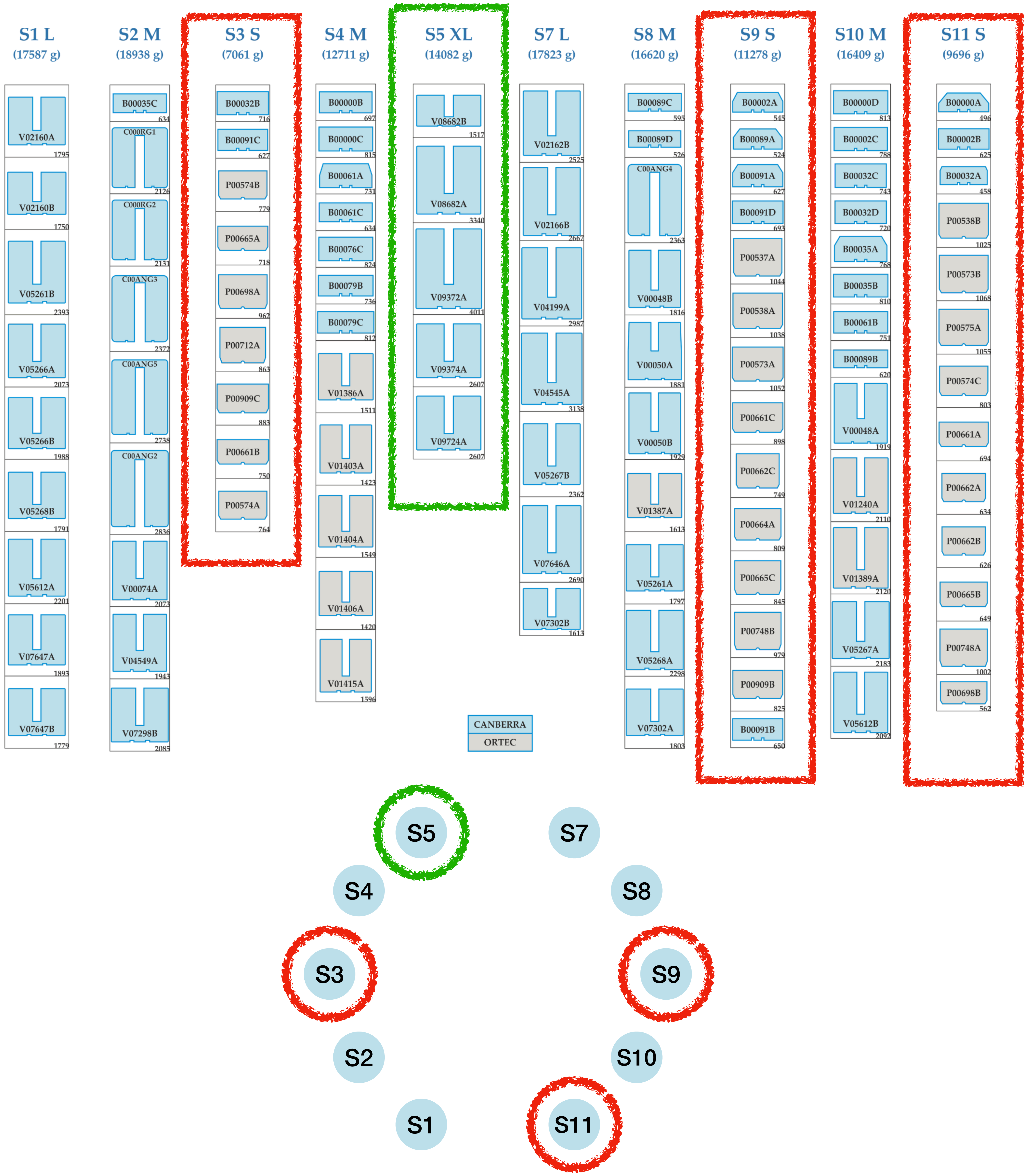
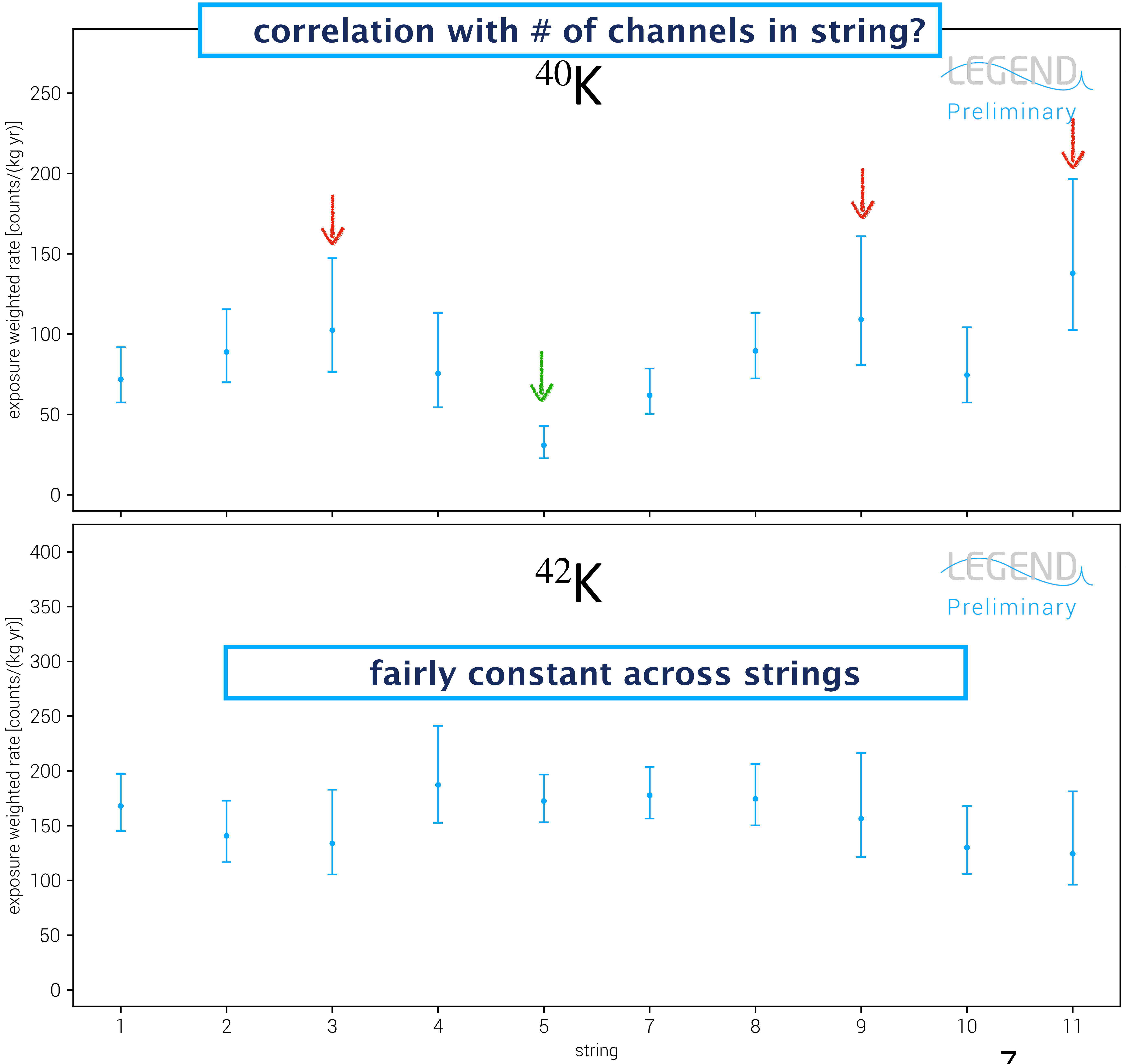
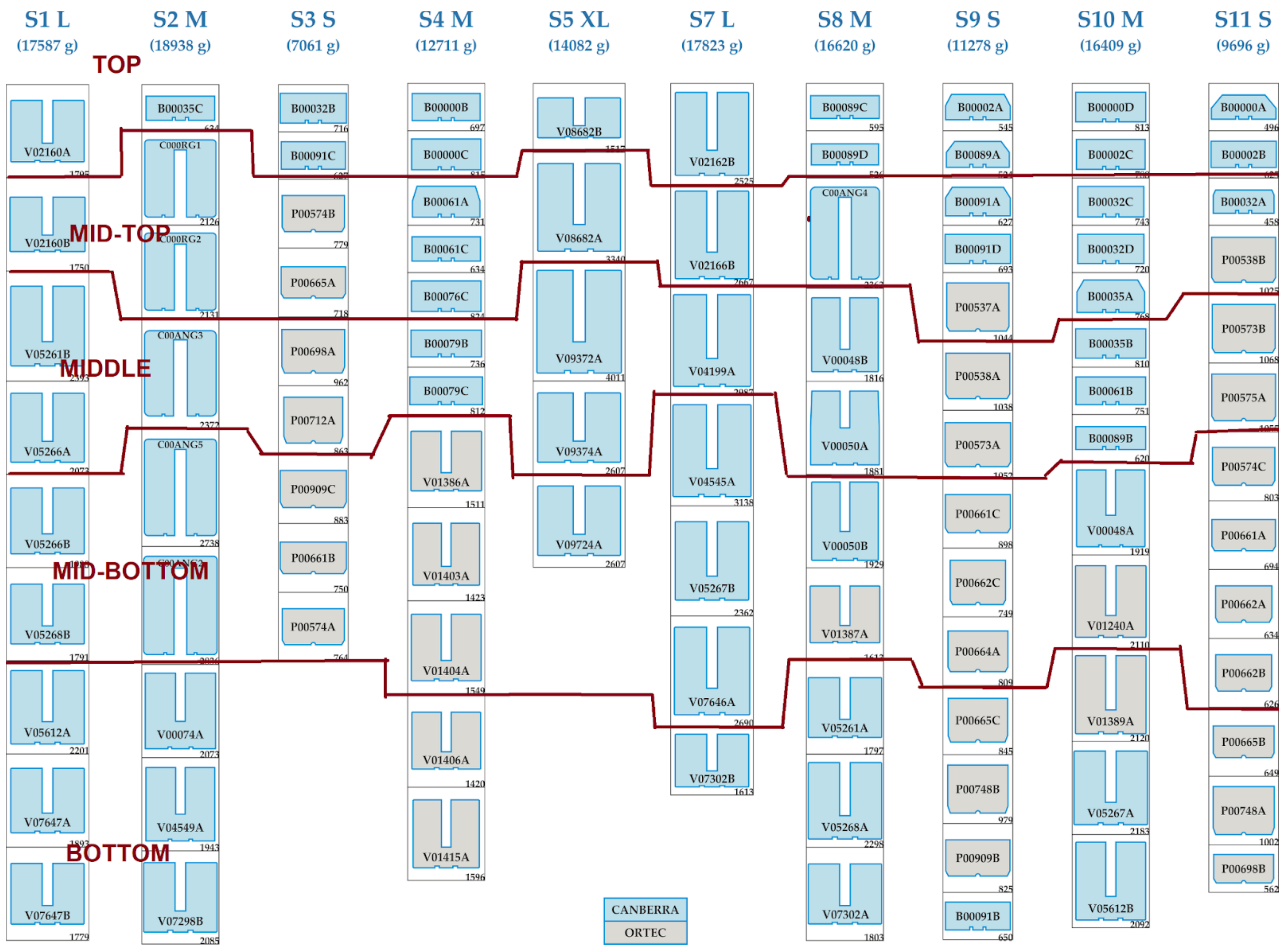
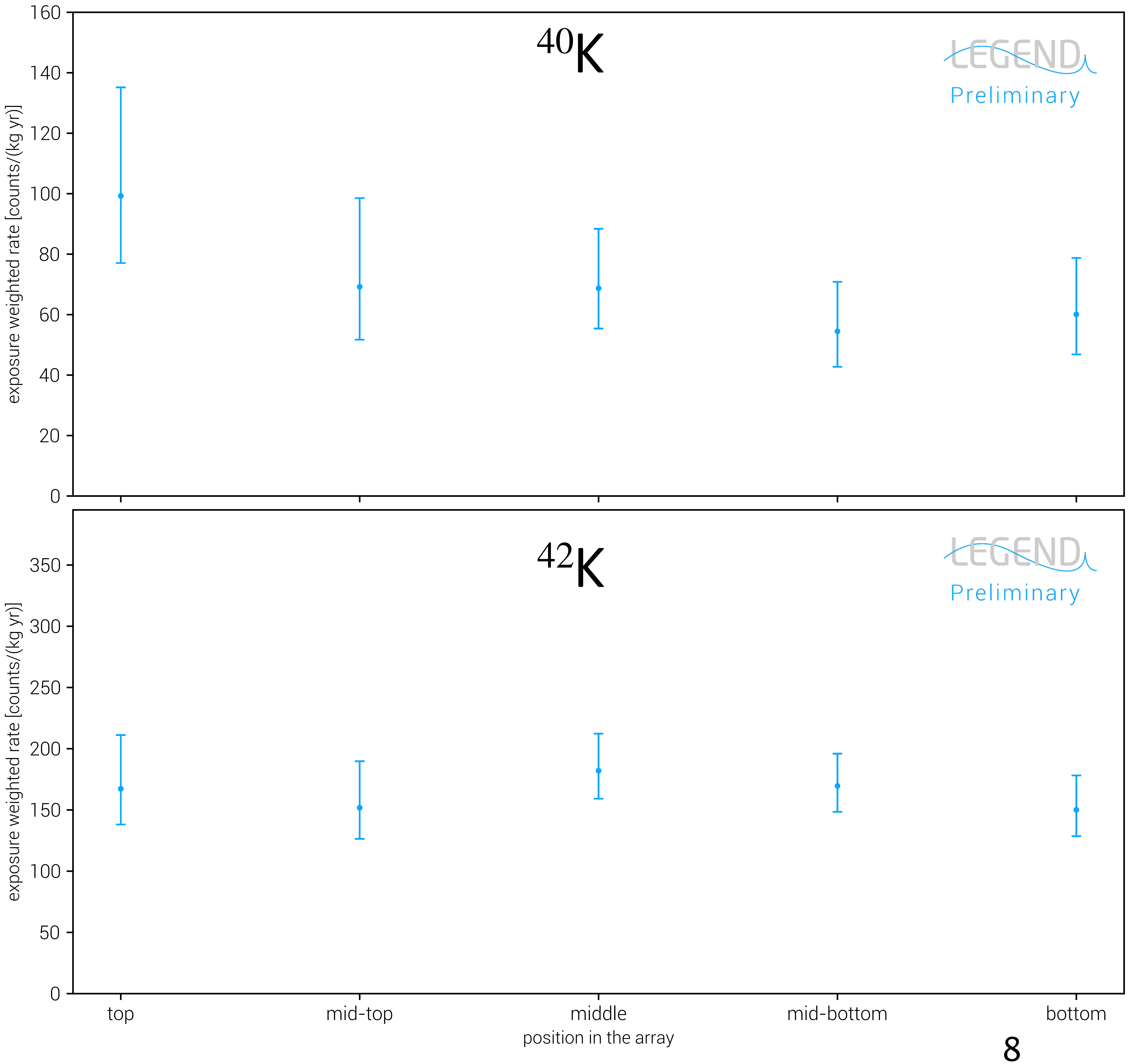




Event rate by position in string





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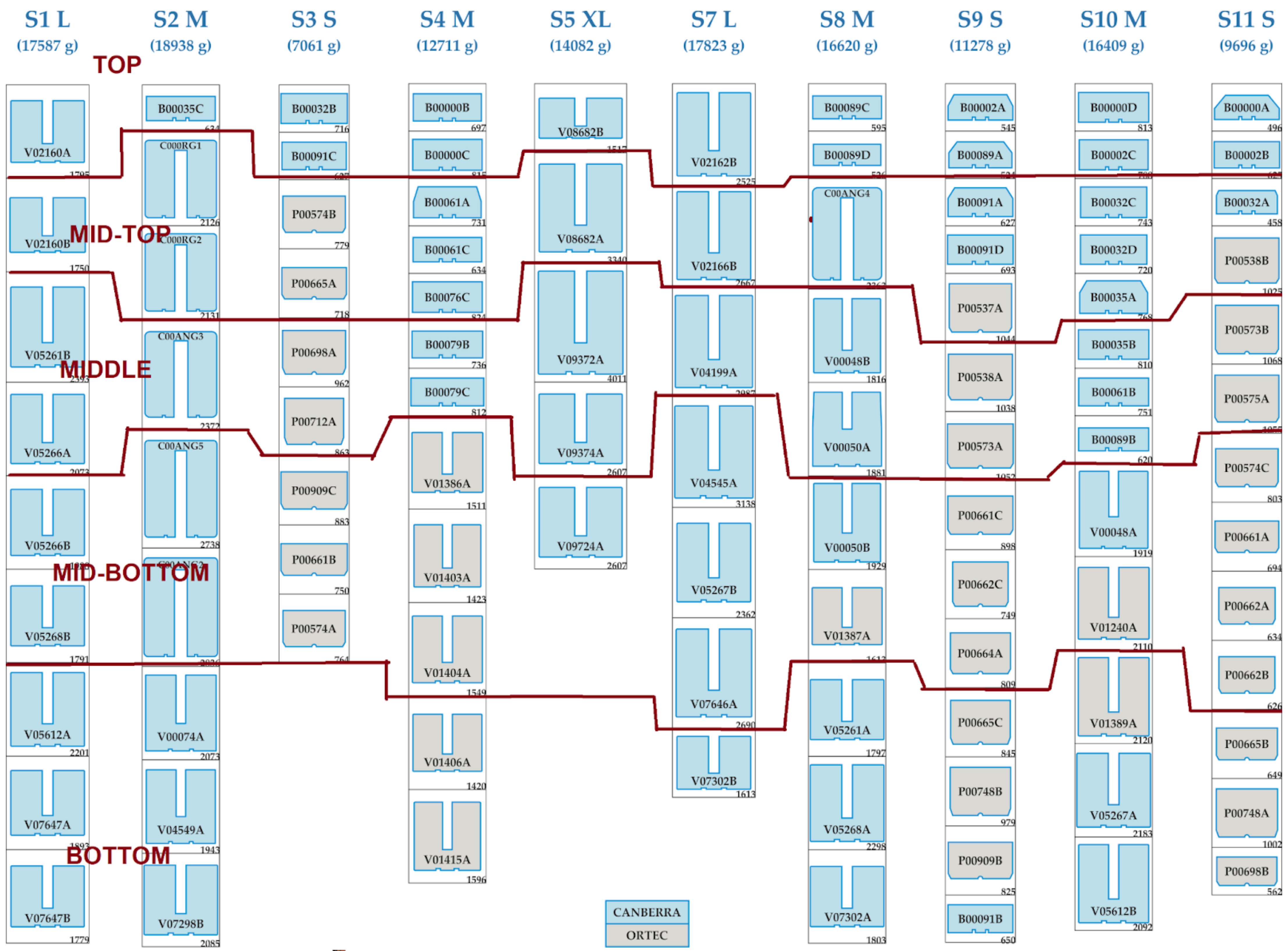
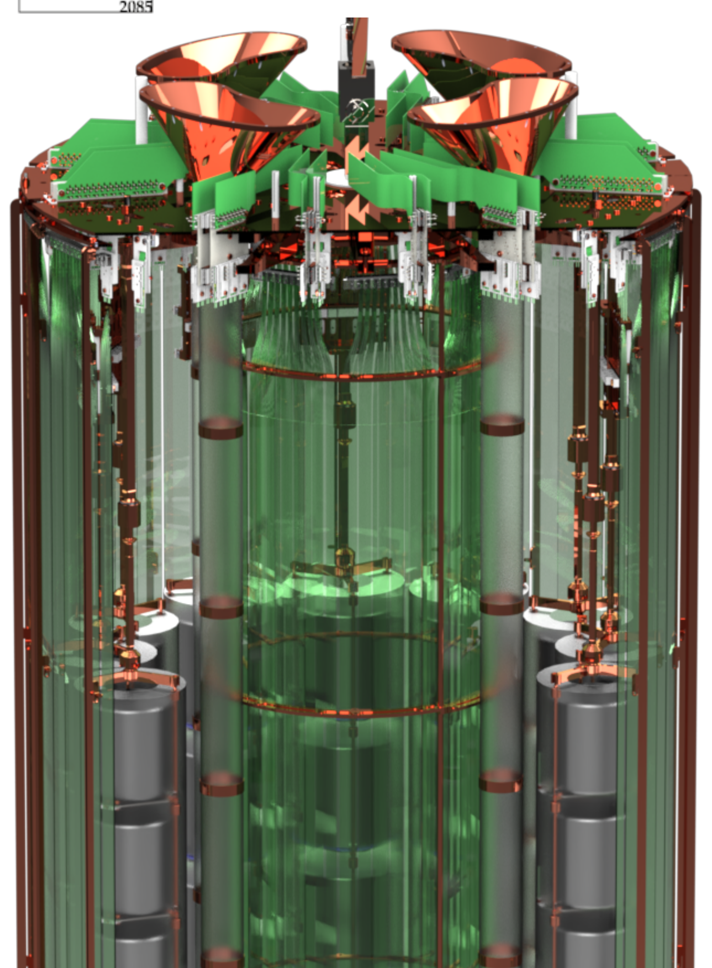
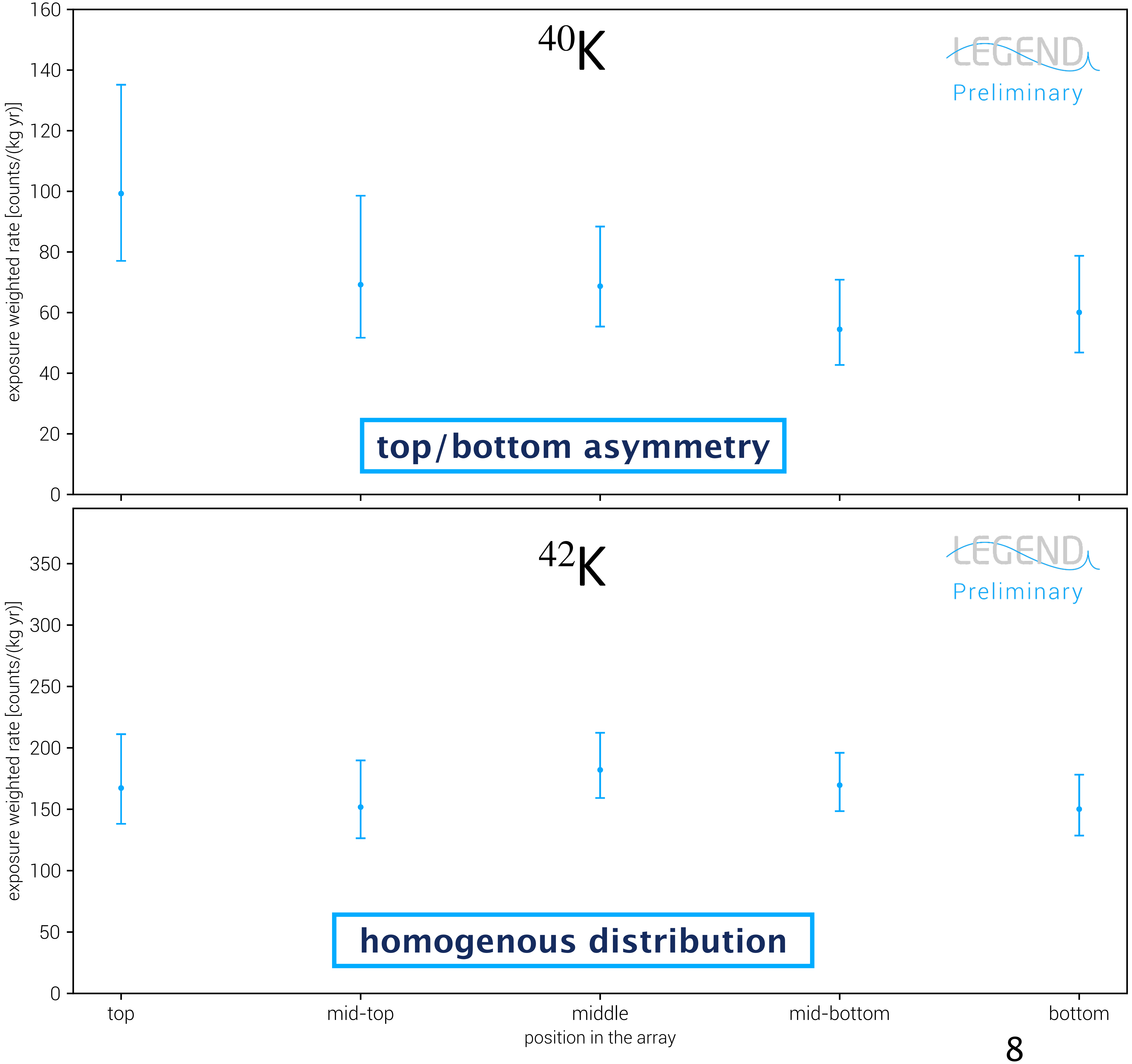




more material
at the top
of the array
than the bottom part
(electronics, string holders,...)

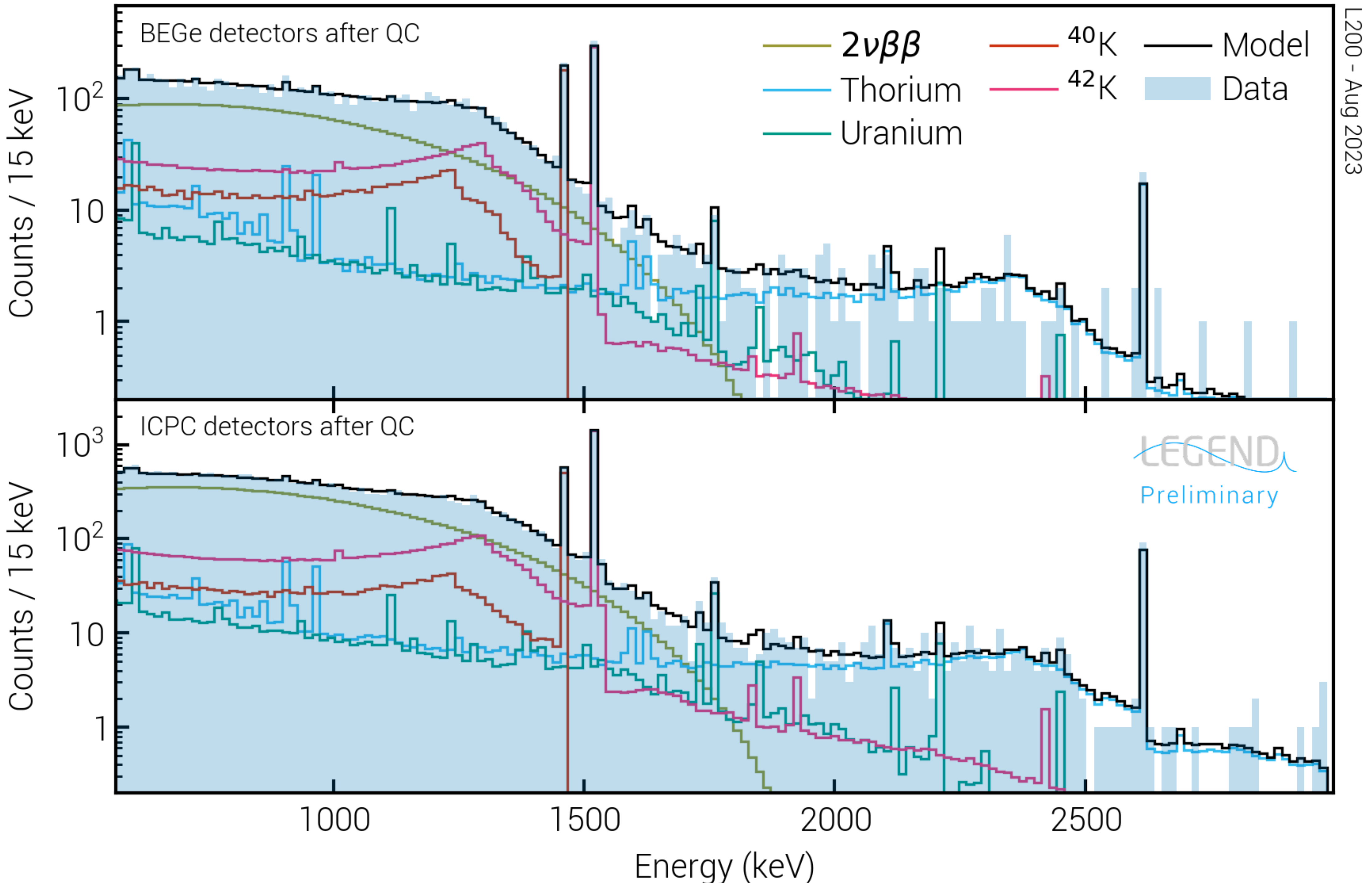


Plans for next (and last) year

LEGEND-200:

- K results compatible with expectations
- no new γ lines wrt GERDA
- not enough statistics for clear conclusions on other gamma lines (yet)
  - rerun same analysis with ~90 kg·yr (as GERDA Phase II)
  - compare with GERDA (very preliminary in the backup)

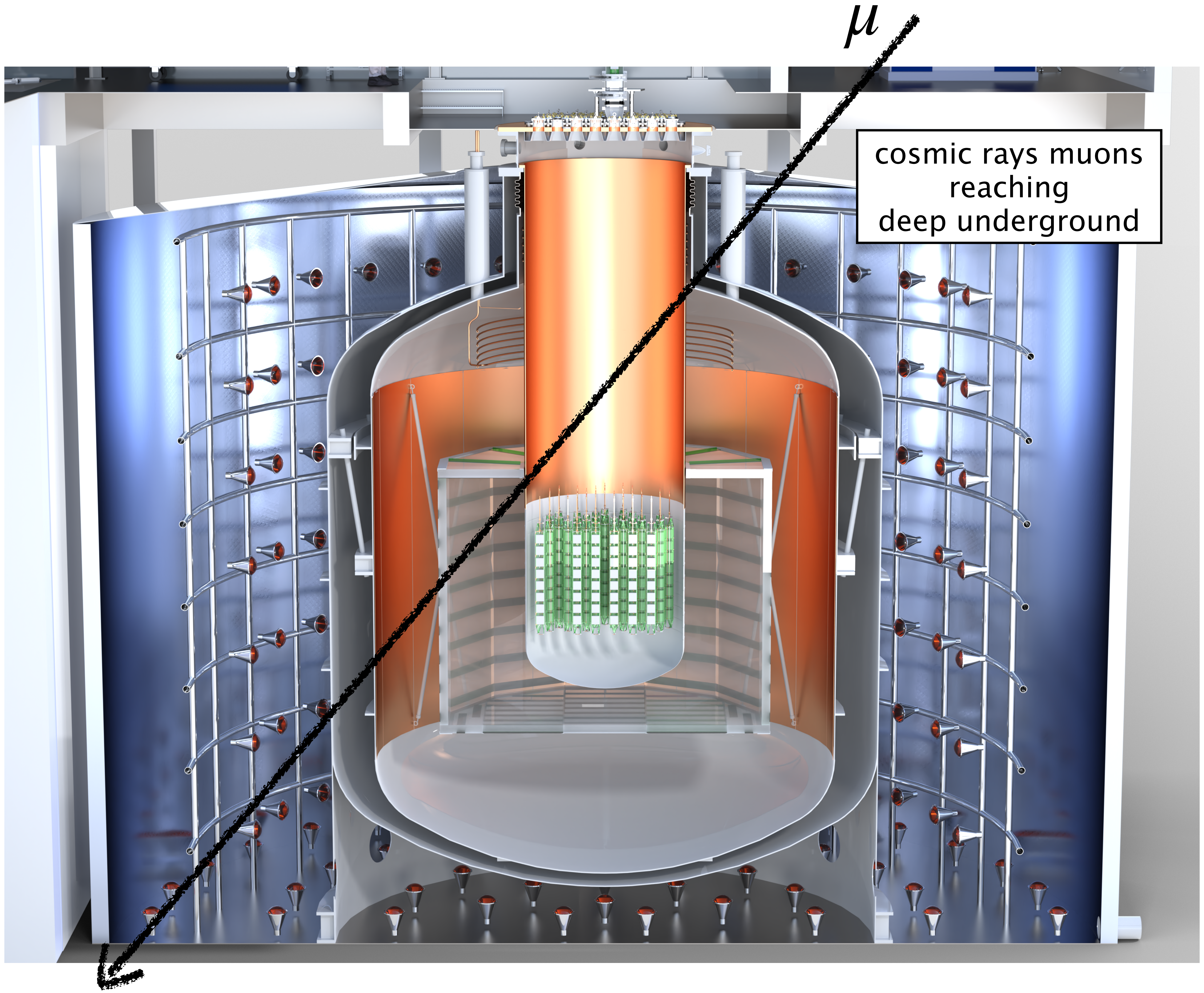
$\Rightarrow$ use LEGEND-200 as prototype to study μ–induced bkg for LEGEND-1000 @LNGS



LEGEND-1000*: Atmospheric Ar Instrumentation

*discussion valid for the LNGS design

LEGEND-1000: μ–induced background



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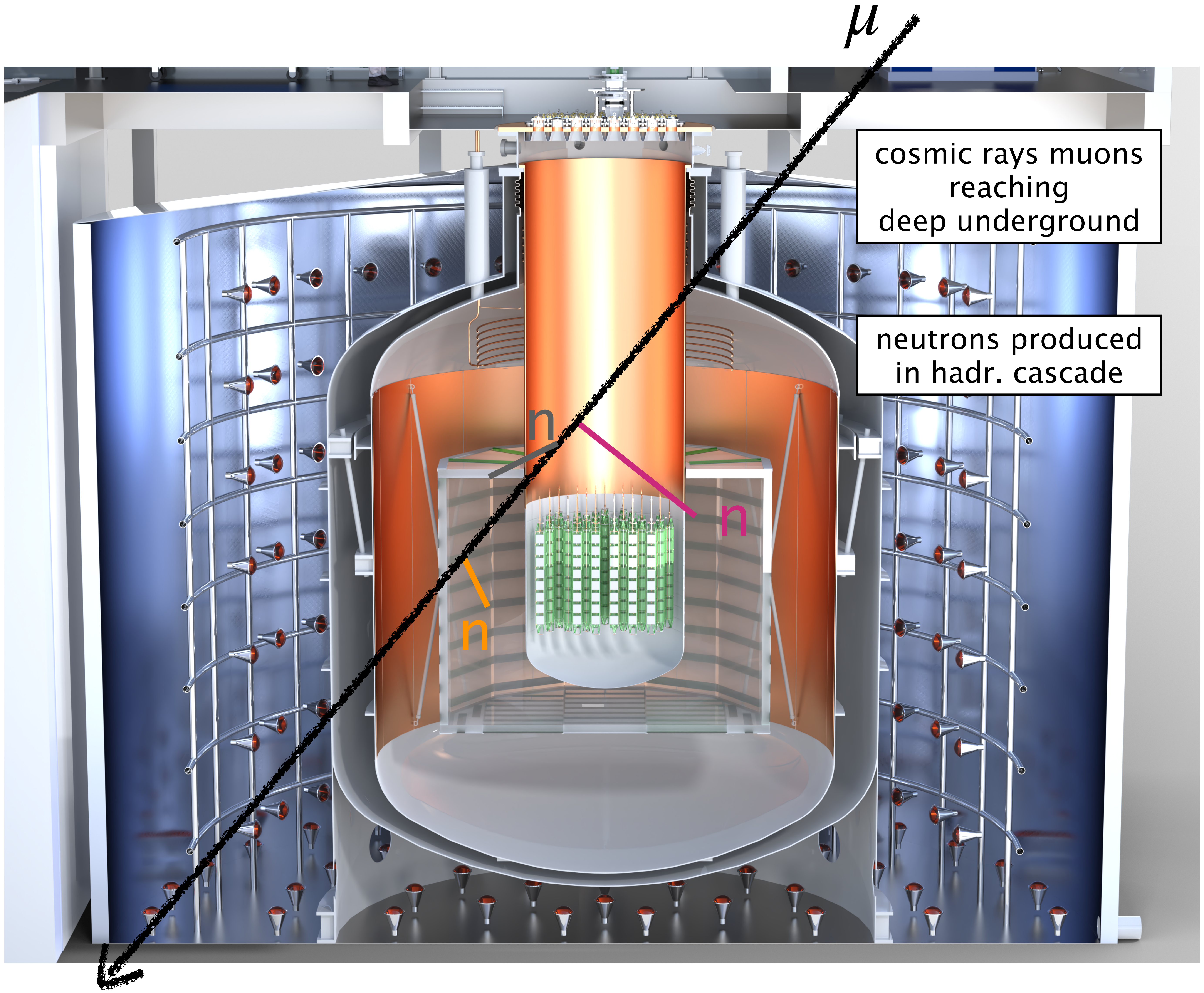

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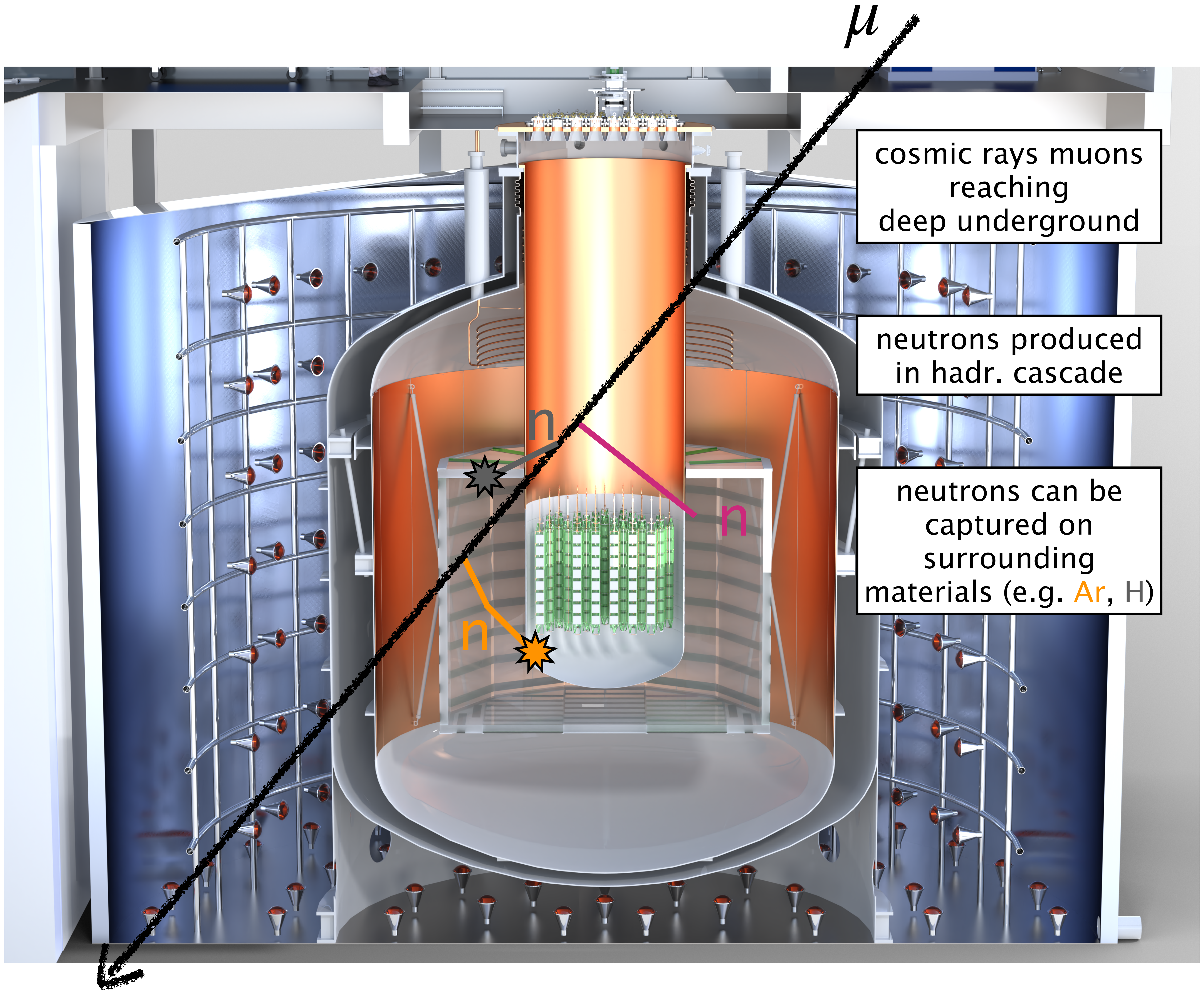

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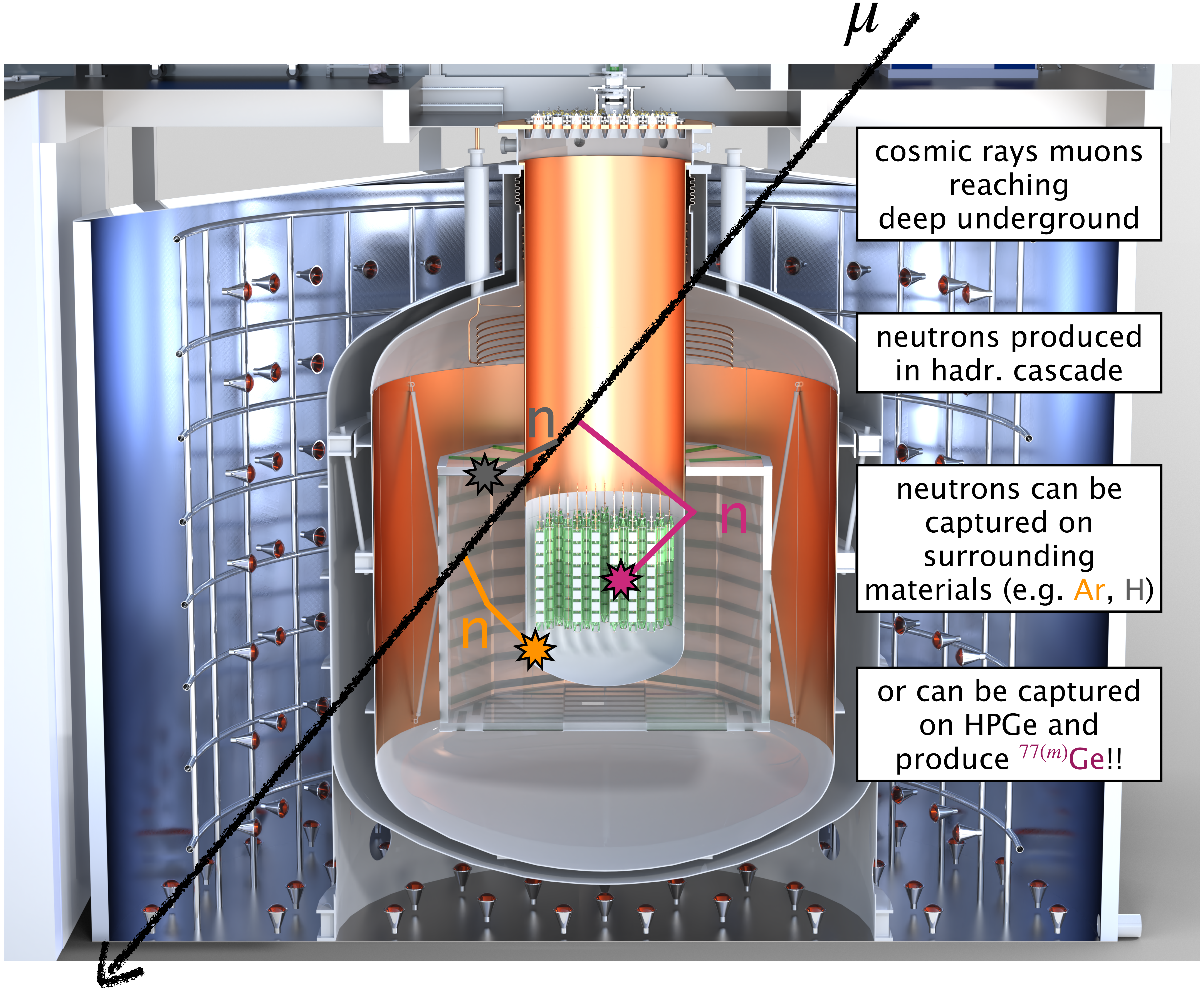
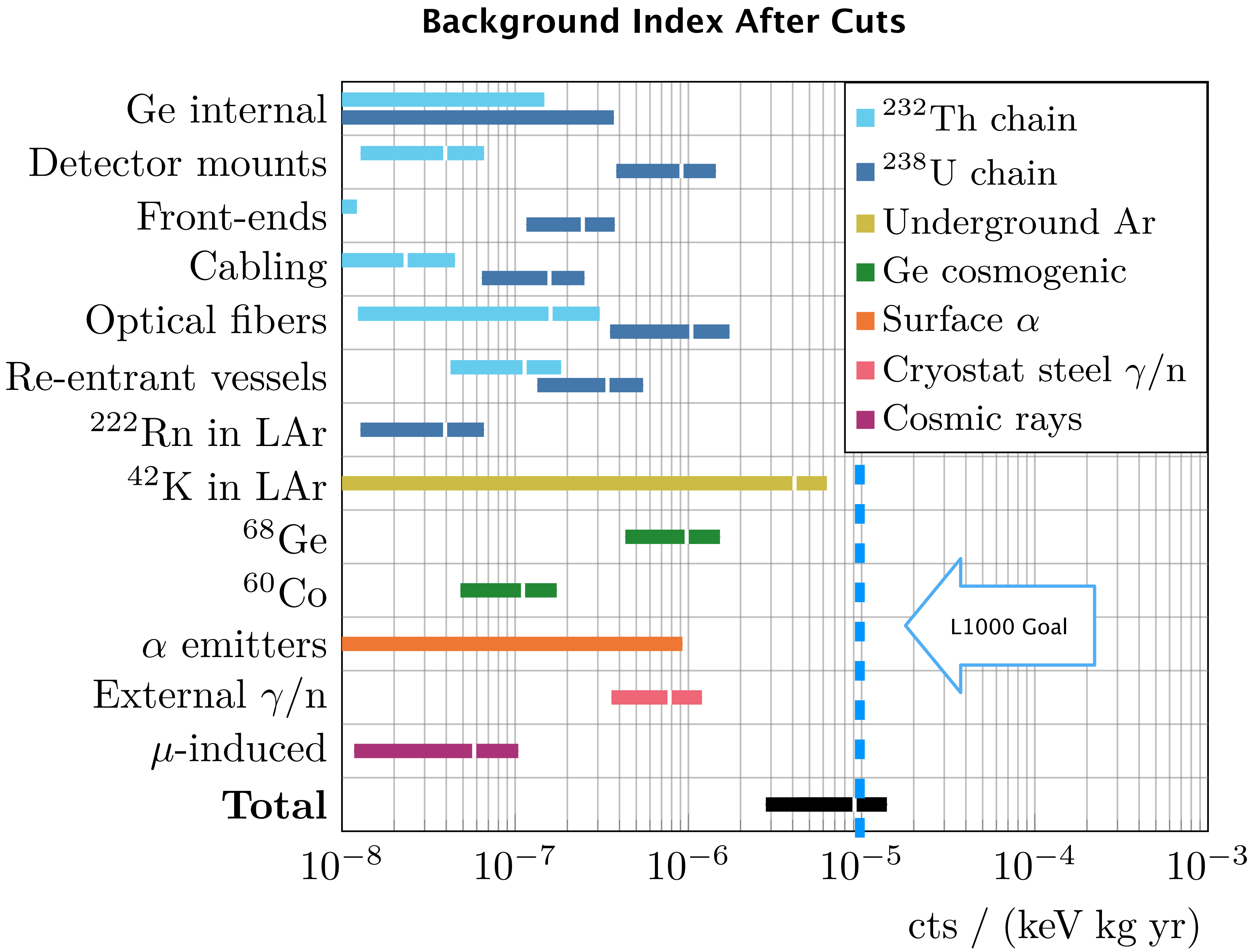


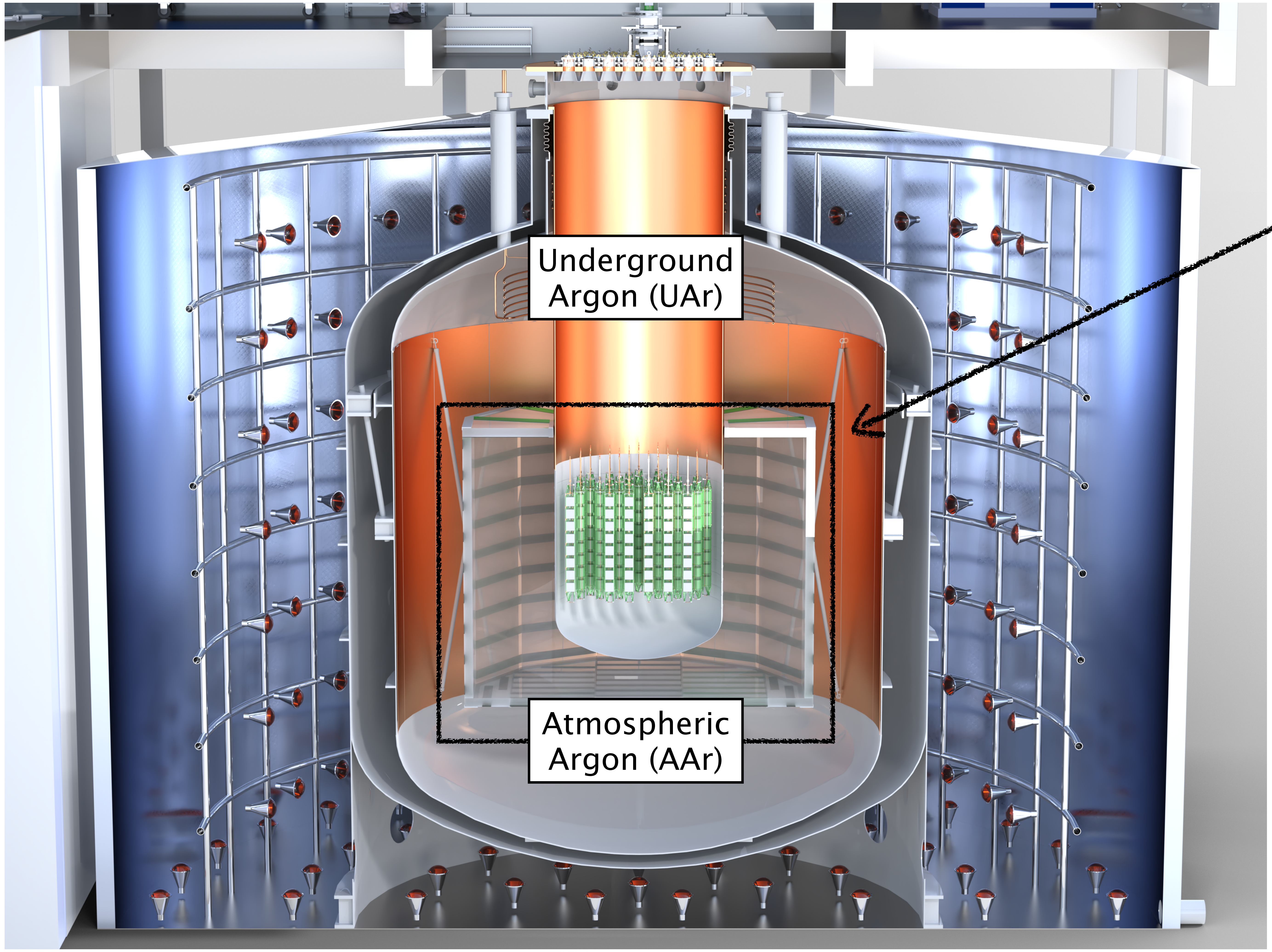


LEGEND–1000 Background Goal: $< 10^{-5}$ counts/(keV·kg·yr)

μ–induced background @SNOLAB: ($\sim$ 6000 m.w.e.) $< 10^{-7}$ counts/(keV·kg·yr)

μ–induced background @LNGS: ($\sim$ 3400 m.w.e.) $> 10^{-5}$ counts/(keV·kg·yr)

LEGEND-1000: LNGS Design



How to *virtually* increase LNGS depth and reduce cosmogenic background?

Passive shielding

- PMMA shield to slow down neutrons and capture them in Ar before arriving to Ge

- x2 reduction of $^{77(m)}$Ge
- Th/U background within 10% of total L1000 bkg after cuts
- neutrons' induced bkg negligible

results shown during
last passage of the year

Tag production of $^{77(m)}$Ge

- ^{77}Ge and ^{77m}Ge produced by n capture in muon events with high neutron multiplicity

- identify conditions to tag whether a detector is likely to have a neutron capture occurring inside

$$4.0^{+3.0}_{-2.9} \times 10^{-7}$$

counts/(keV·kg·yr)

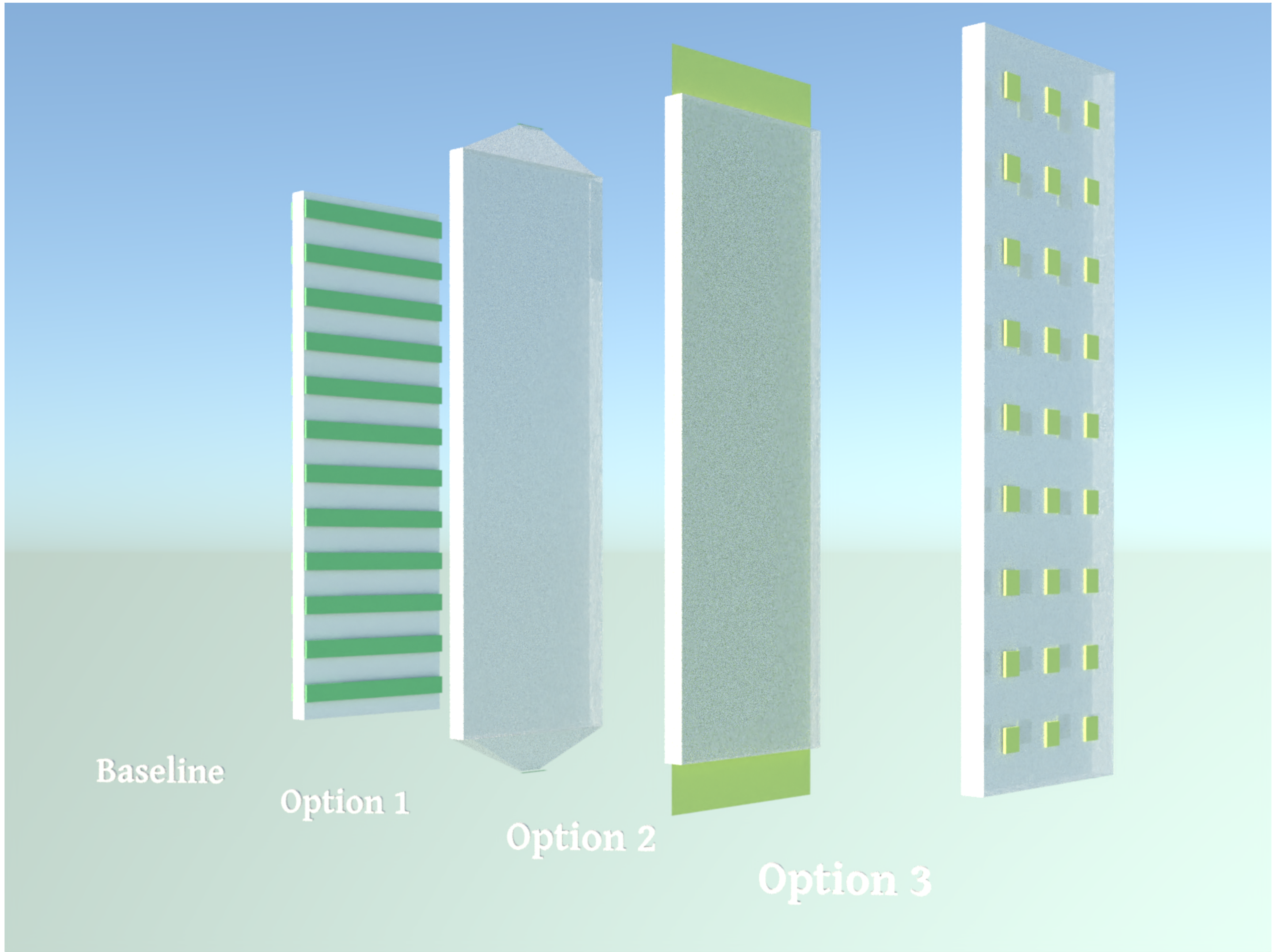
LEGEND-1000: Atmospheric Argon Instrumentation

Install (cost-effective) instrumentation on neutron moderator to further improve tagging of μ-induced background

Options considered:

Baseline. Light guides on moderator panel & SiPM readout on left/right sides

1. Entire PMMA panel as single light guide
2. Optical fibers inside PMMA panel to improve light collection
3. SiPM tiles on the PMMA panel surface



Neutron Veto Instrumentation for LEGEND-1000 at LNGS

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

TAUP VIENNA 2023

Michele Morella on behalf of the LEGEND collaboration
Gran Sasso Science Institute, INFN LNGS

See also my poster @TAUP23

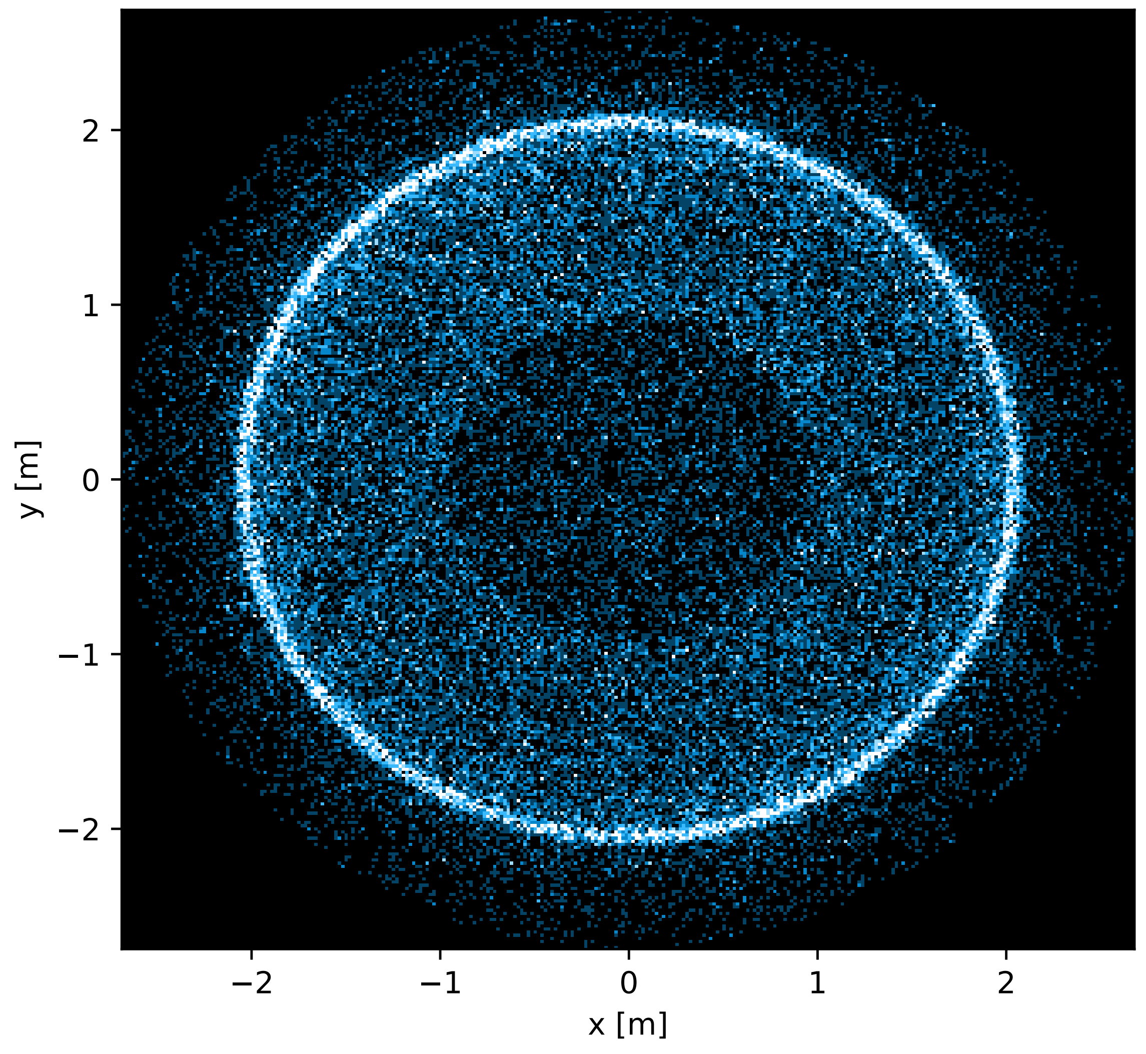
Question: "Why inst. on the moderator? Why not also around the Reentrant Tube, for example?" Answer in the BACKUP!!

Instrumentation Simulation

Knowing the physics process releasing energy in argon,
how many scintillation photons are actually detected
by the different instrumentation designs?

Physics

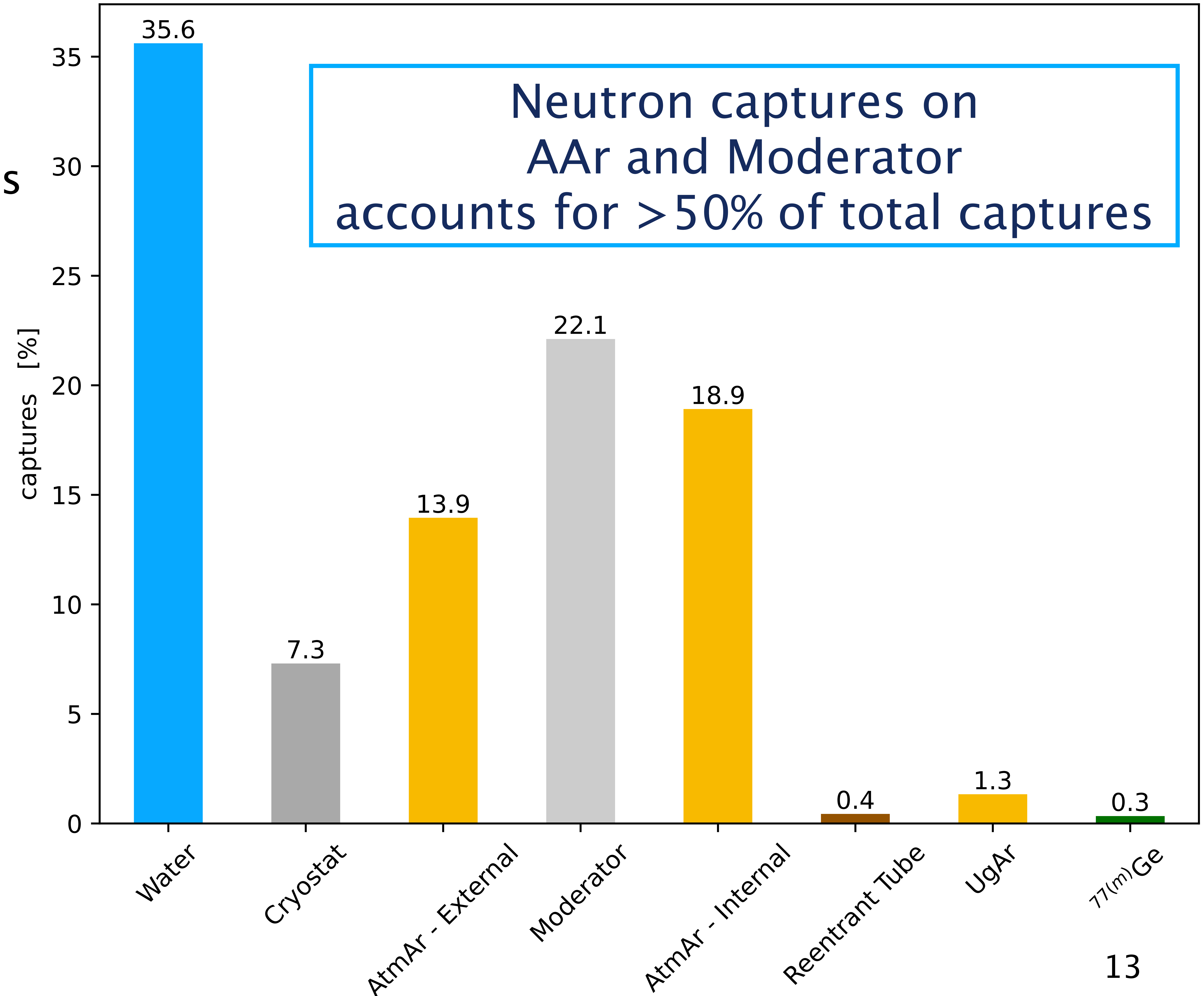
which physics process to detect?
how much energy and where is
releasing energy in argon?



Instrumentation Simulation: Physics

What? ⇒ neutron capture on Ar

Why? ⇒ $^{77(m)}$Ge produced in high neutron multiplicity events

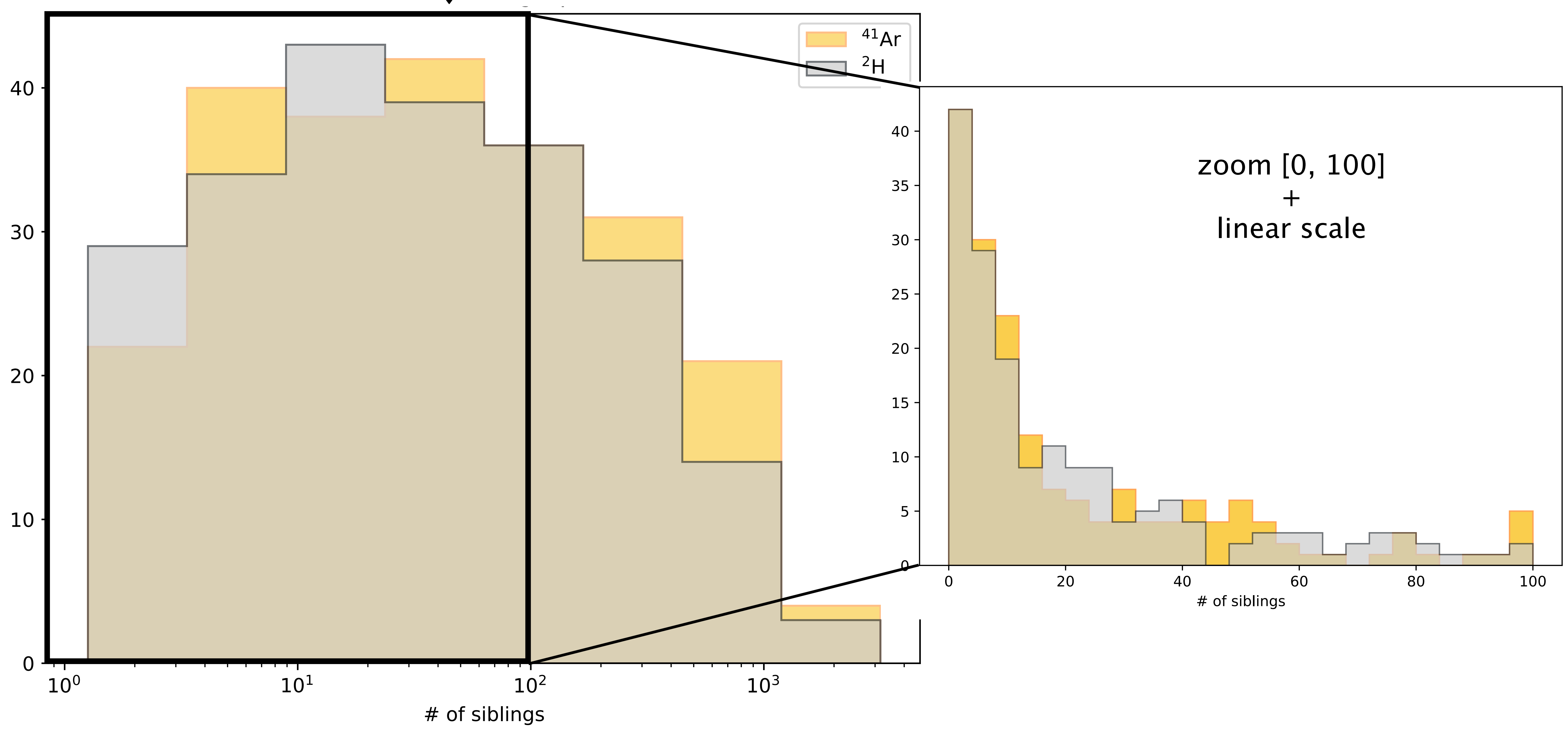


Instrumentation Simulation: Physics

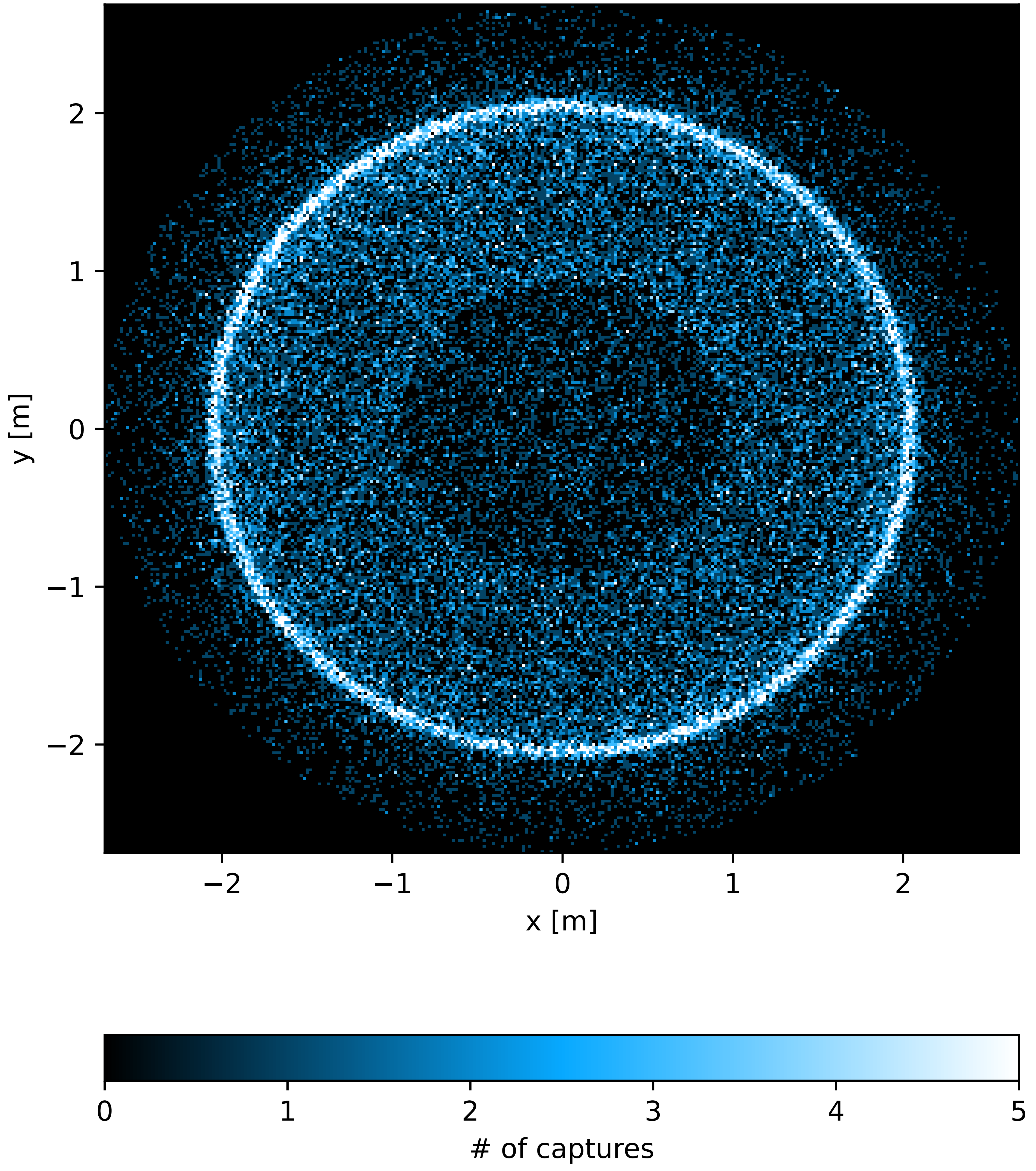
What? ⇒ neutron capture on Ar

Why? ⇒ $^{77(m)}$Ge produced in high neutron multiplicity events

How many neutron captures per $^{77(m)}$Ge? ⇓



Where? ⇓



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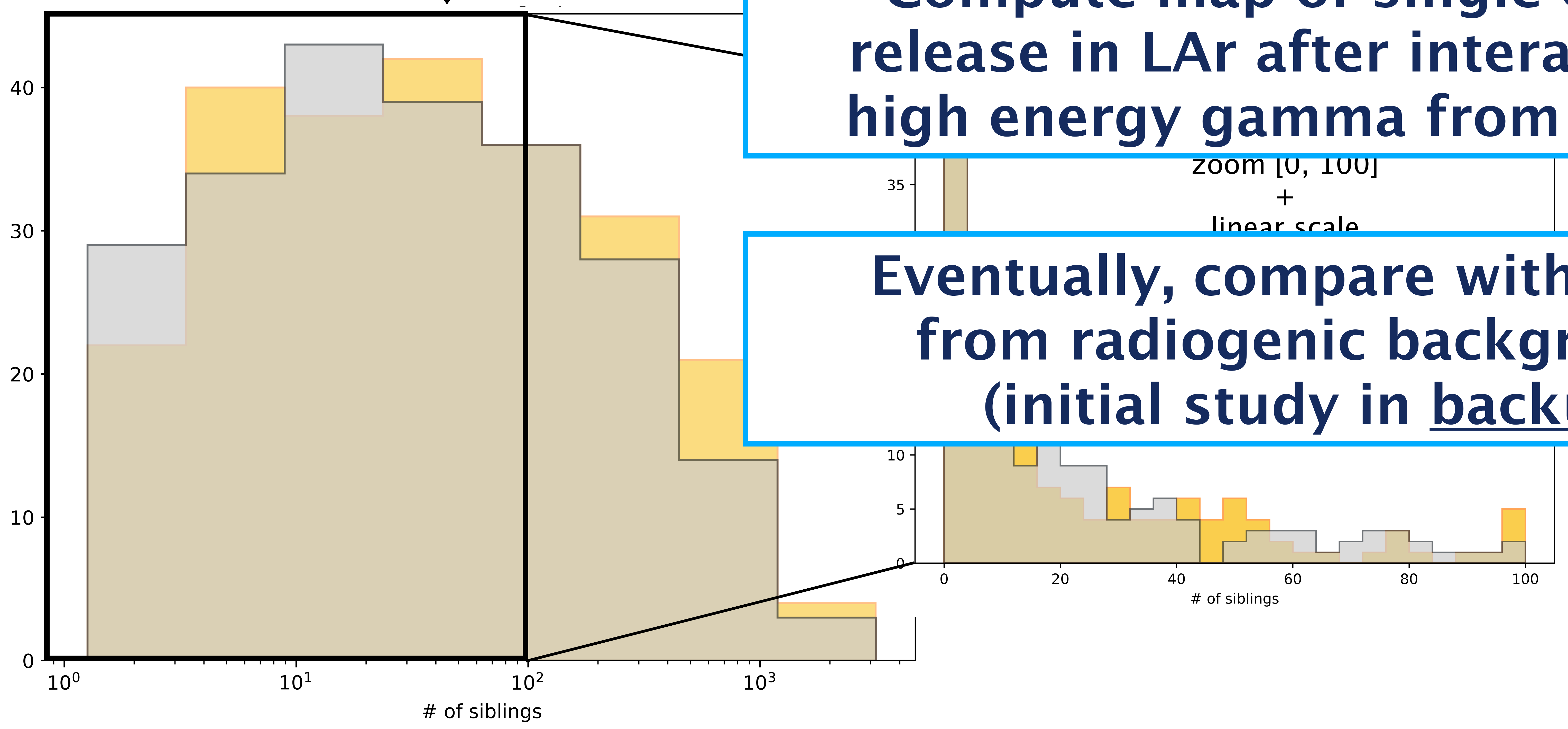

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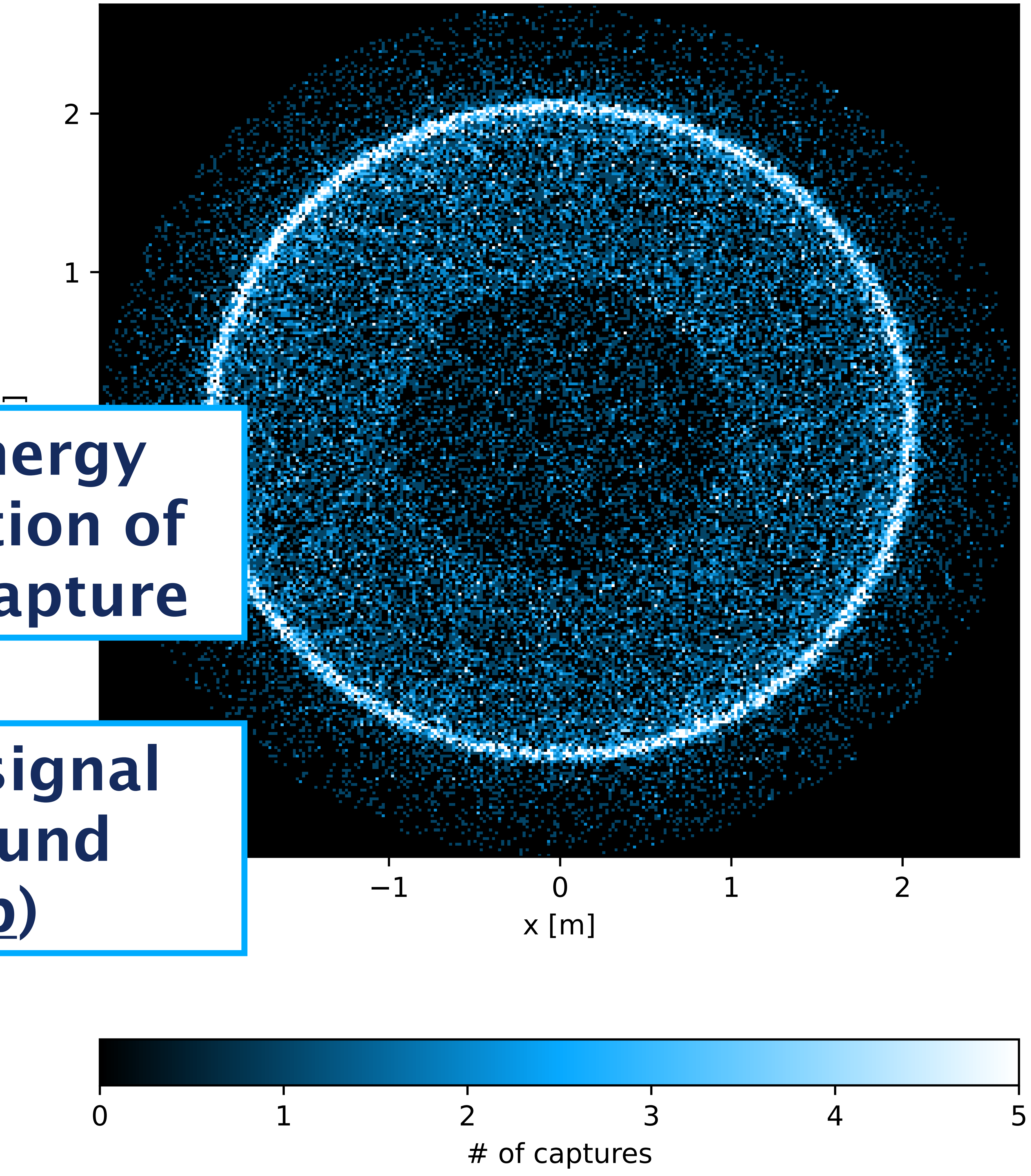


Compute map of single energy release in LAr after interaction of high energy gamma from capture

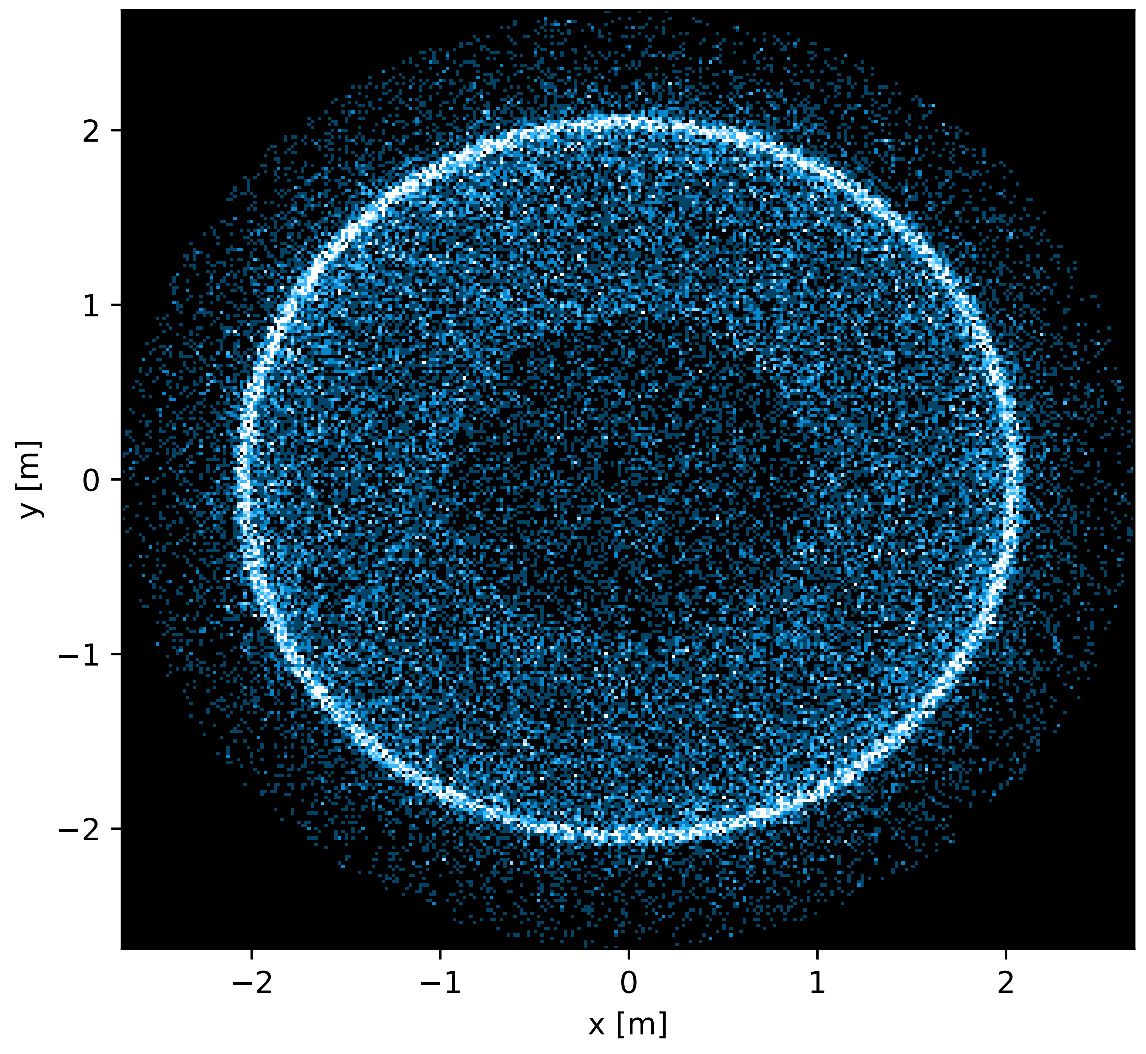
Eventually, compare with signal from radiogenic background (initial study in backup)

Instrumentation Simulation

Knowing the physics process releasing energy in argon, how many scintillation photons are actually detected by the different instrumentation designs?

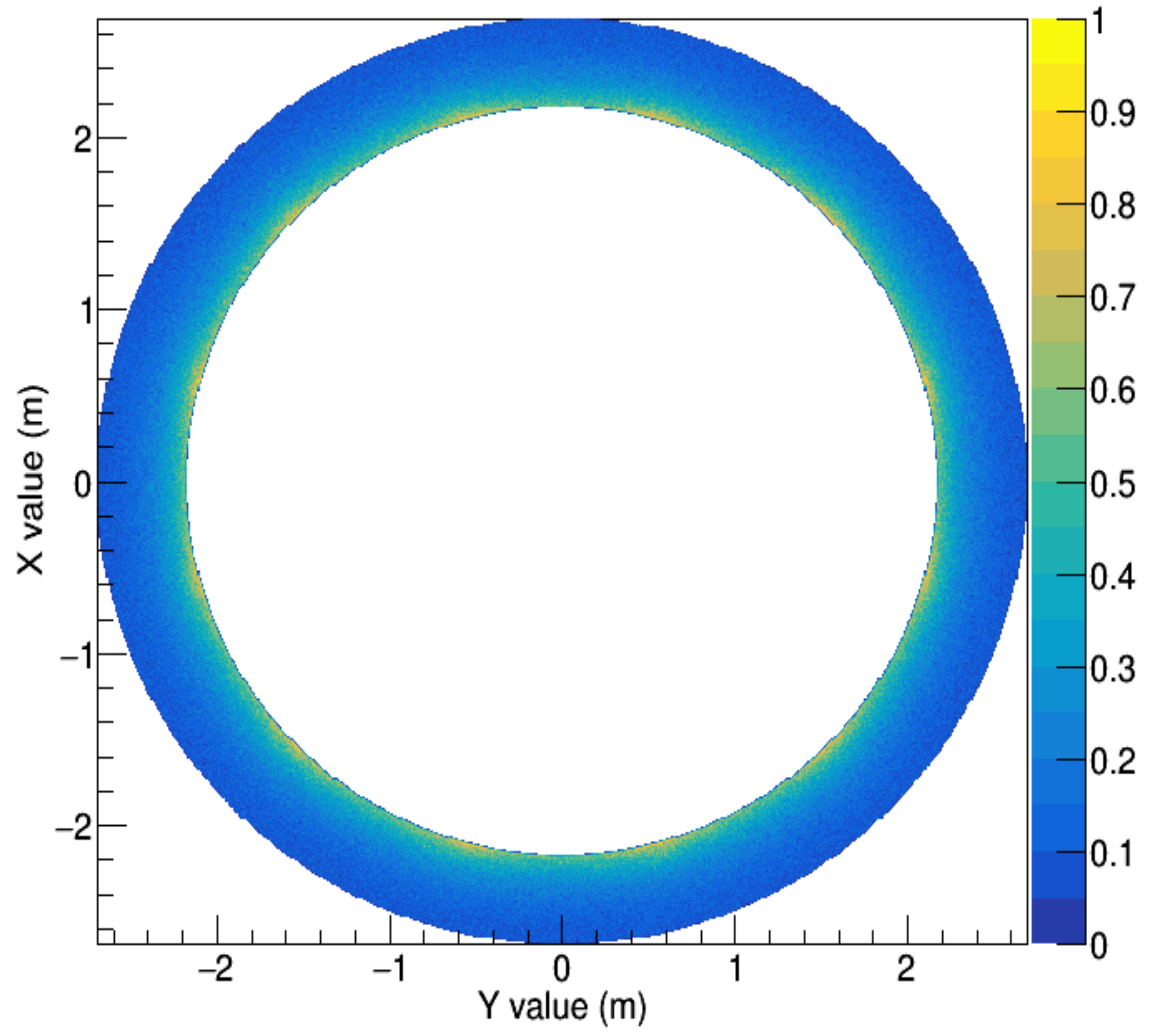
Physics

which physics process to detect?
how much energy and where is releasing energy in argon?

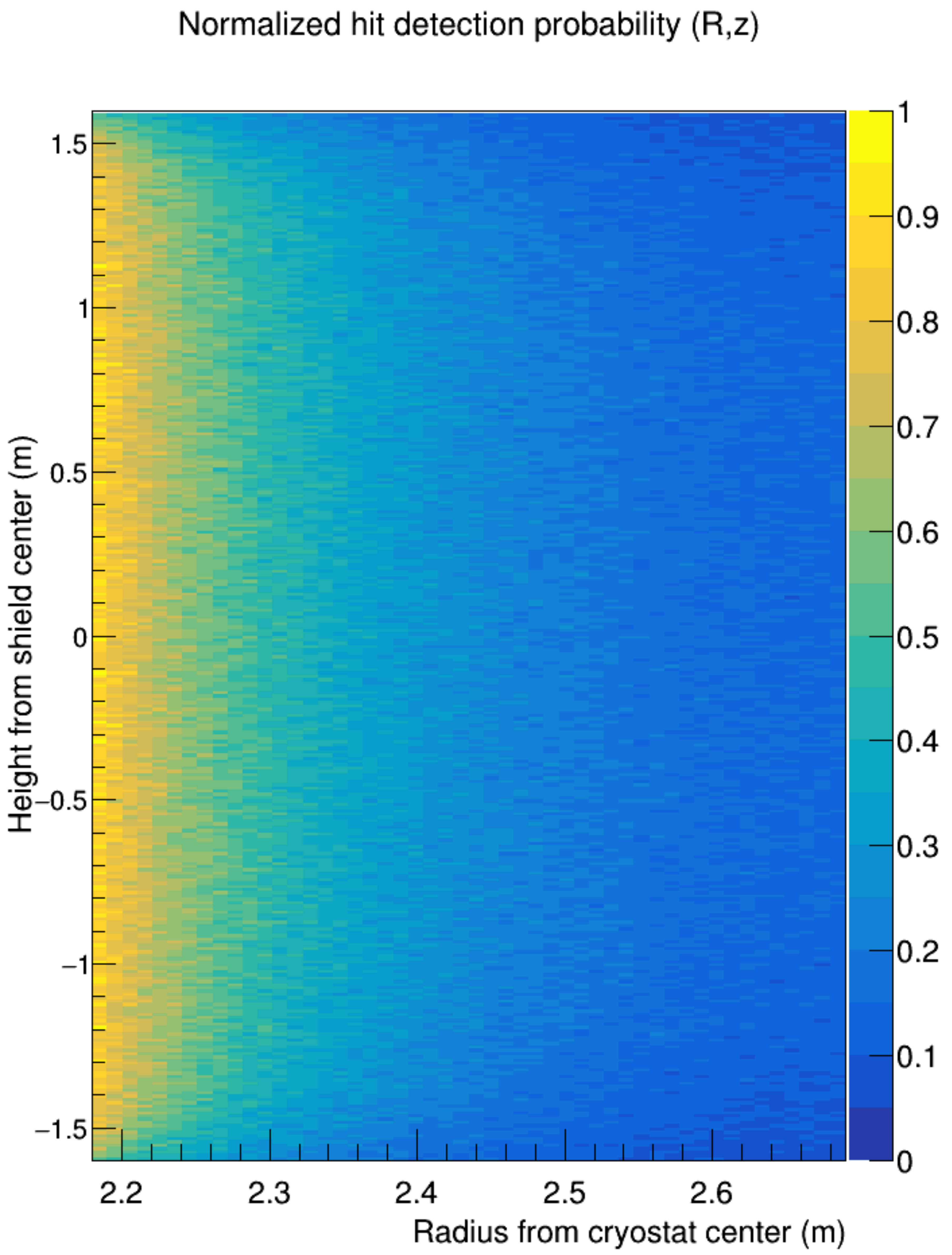


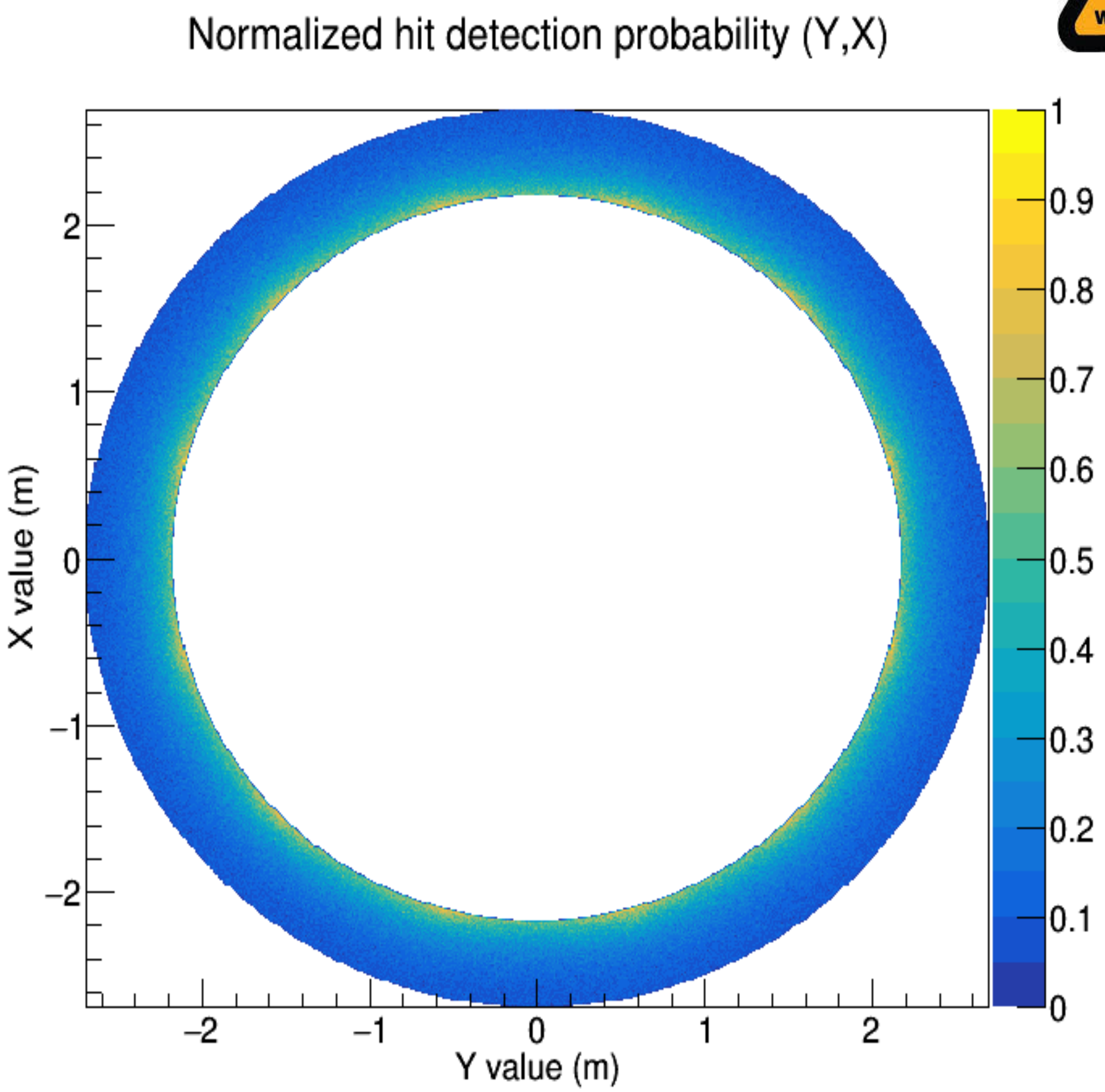
Photons' Transport

probability of optical photons produced at (x,y,z) in Ar arriving at point (x', y', z') at instrumentation location



Instrumentation Simulation: Photons Transport





WORK IN PROGRESS

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probability of optical photons
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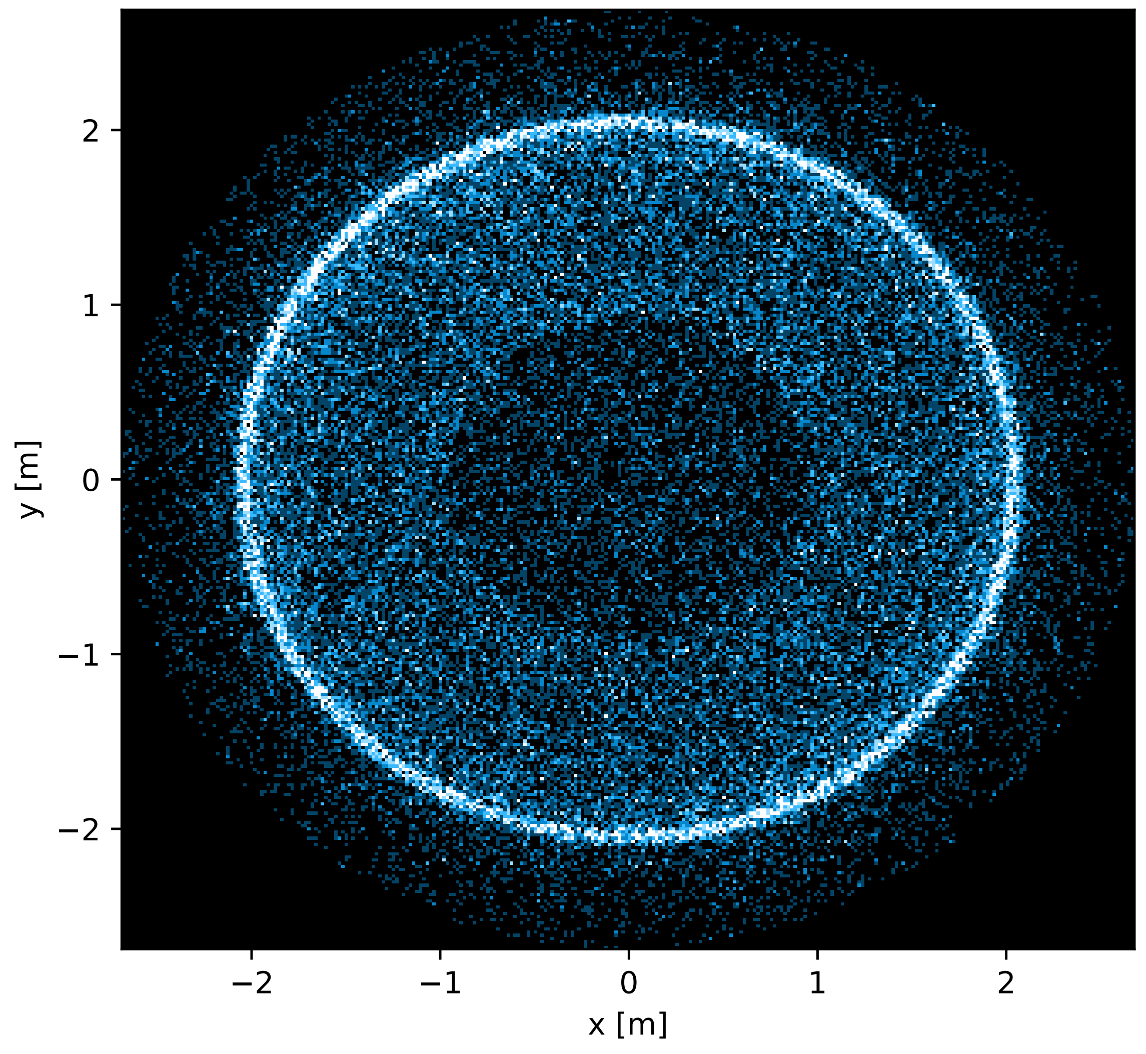
Instrumentation

probability to generate a Photoelectron
(once an optical γ reaches inst. location)



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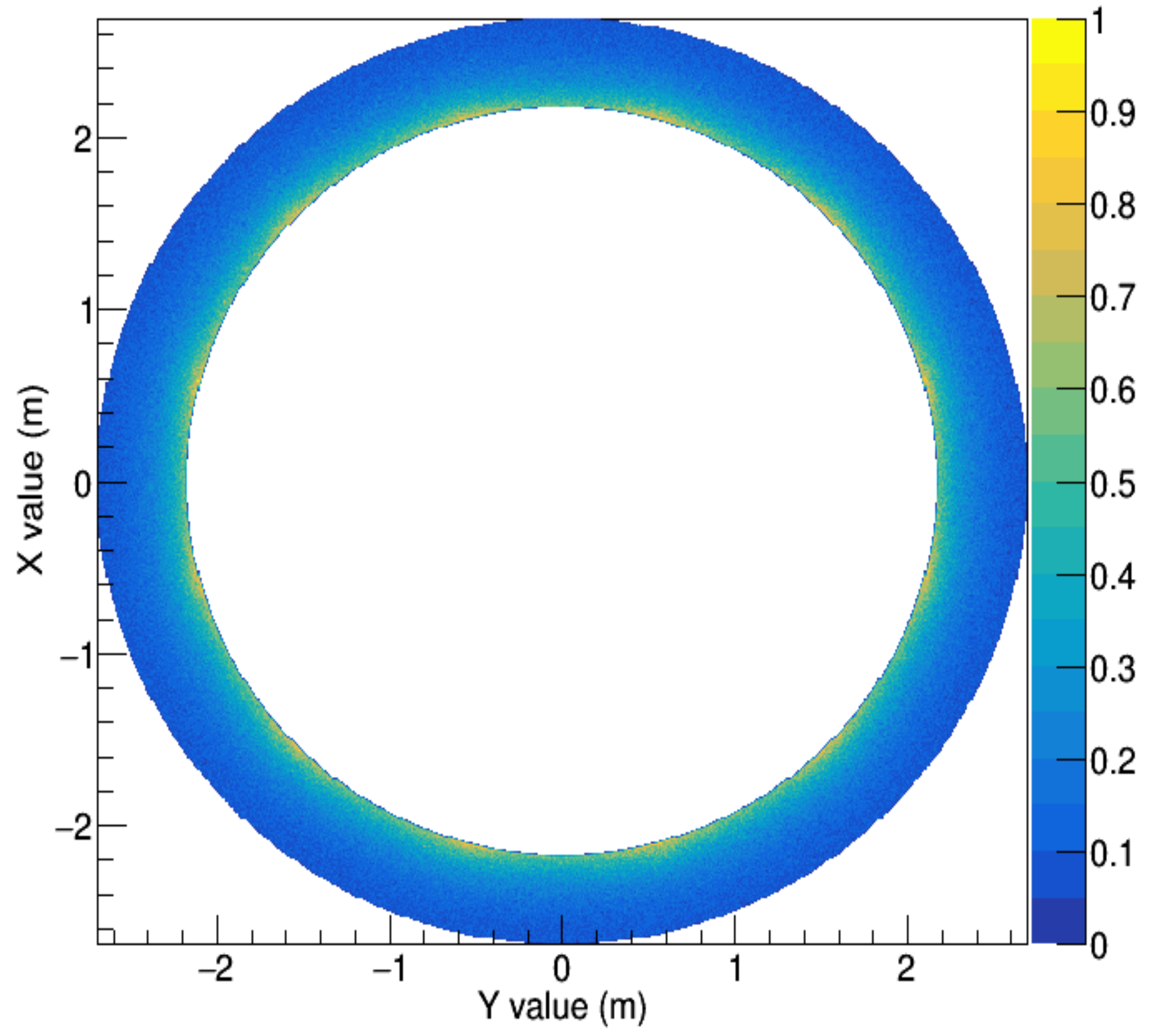

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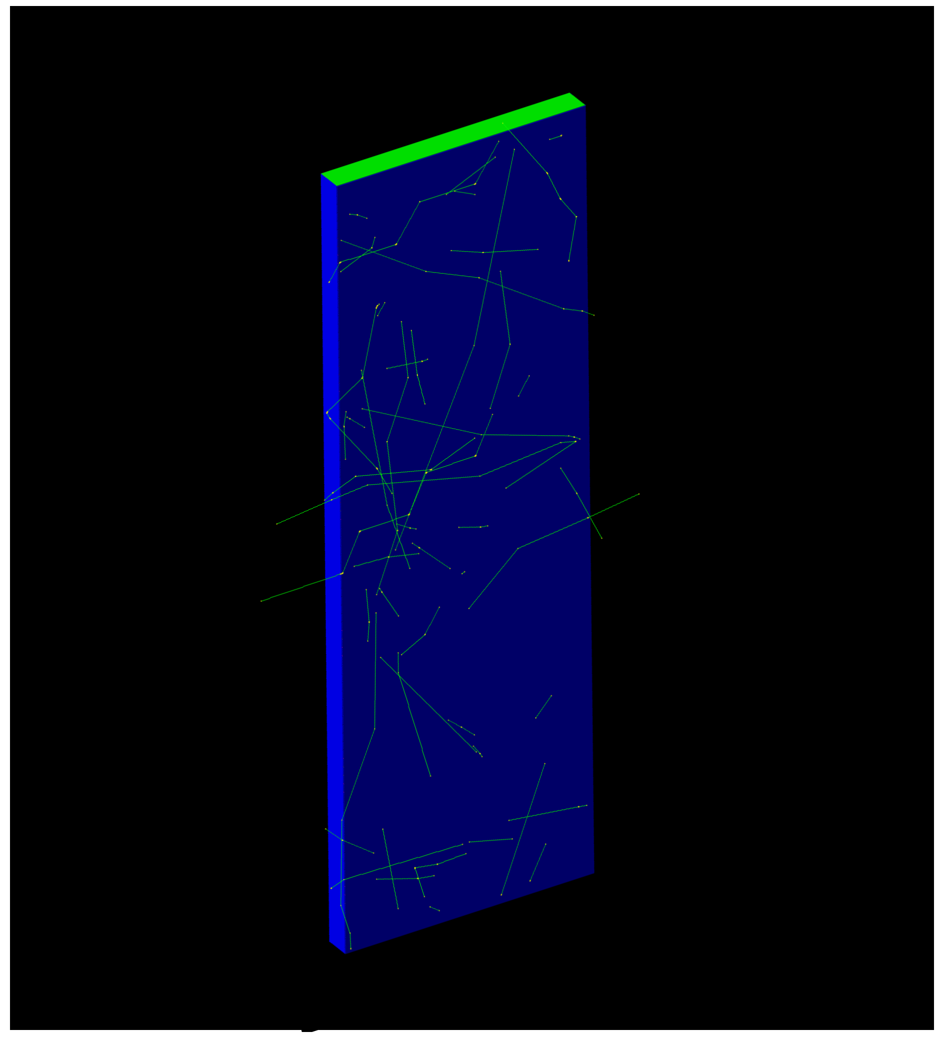


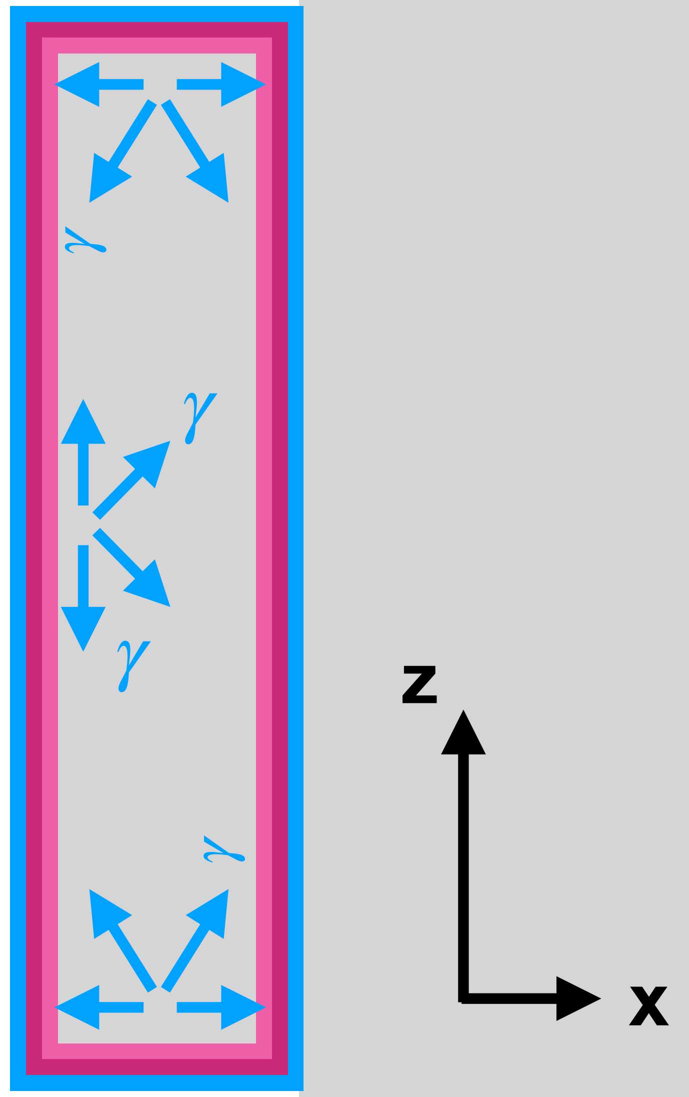
Instrumentation Simulation: Instrumentation

simulate propagation of optical photons in light guide to estimate trapping efficiency & estimate the others from literature

$$\varepsilon_{active\ surface} \times \varepsilon_{WLS} \times \varepsilon_{trapping} \times \varepsilon_{coupling} \times \varepsilon_{quantum}$$

	baseline	panel as light guide	panel with fibers	SiPM tiles
N SiPM	1778	1778	936	O(30k)
$\varepsilon_{active\ surface}$	0.4	1	1	0.08
ε_{WLS}	1	1	1	1
$\varepsilon_{trapping}$	0.05	0.05	1E-4	1
$\varepsilon_{coupling}$	0.4	0.05	1	1
$\varepsilon_{quantum}$	0.3	0.3	0.3	0.3
ε_{TOT}	2.4E-3	7.5E-4	3E-5	2E-2

Baseline design



Panel side view

Instrumentation Simulation

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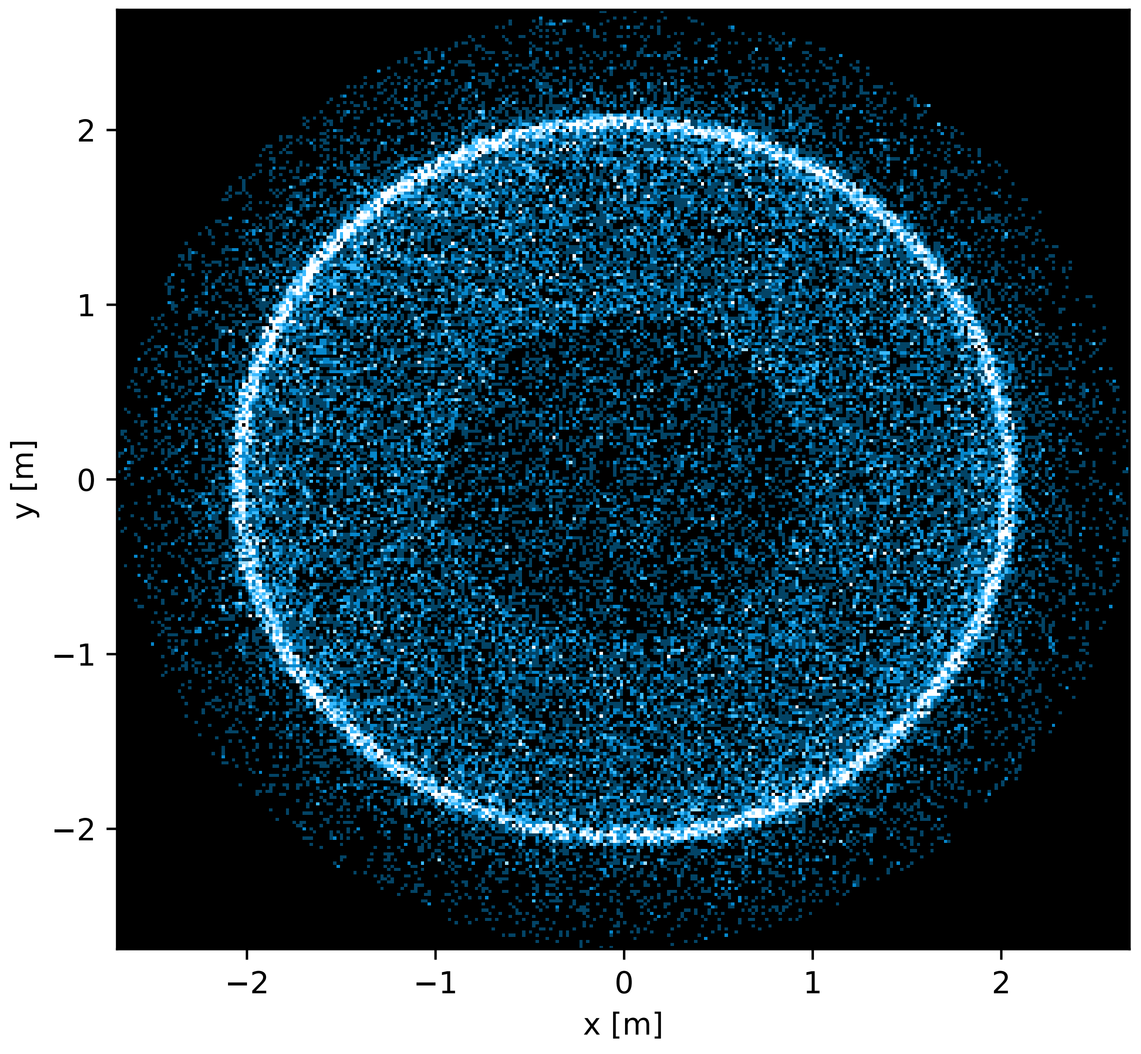

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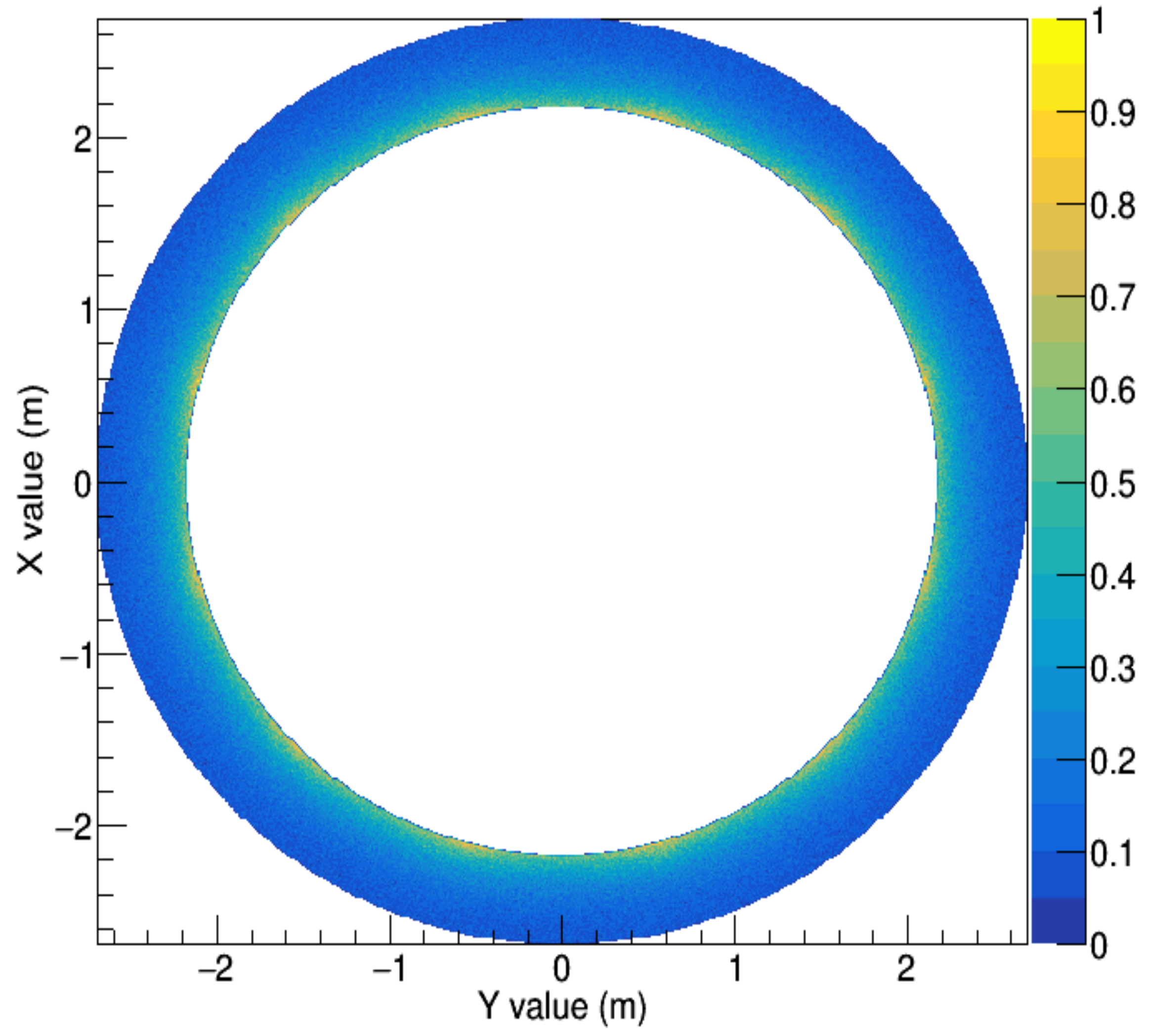

Instrumentation

probability to generate a Photoelectron
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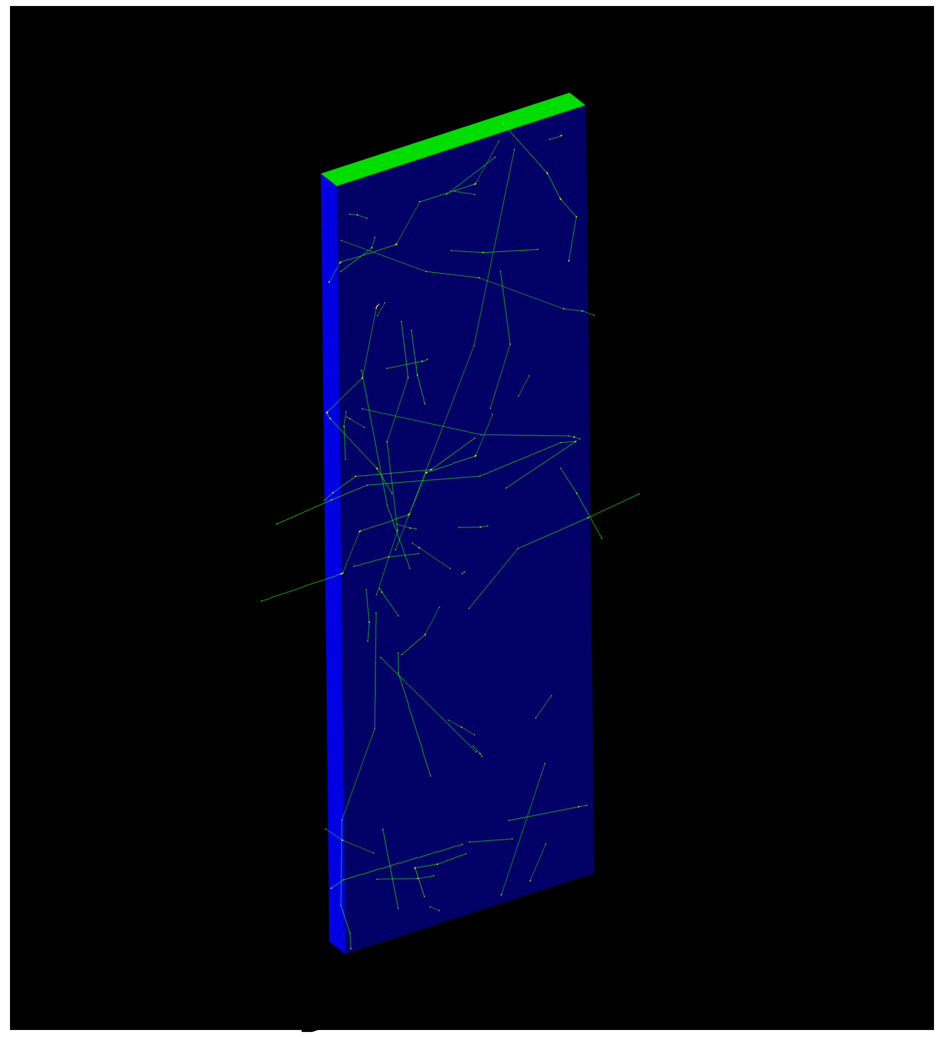


Multiply all factors and use # of PE as figure of merit

Plans for next (and last) year

LEGEND-200:

- K results compatible with expectations
- no new γ lines wrt GERDA
- not enough statistics for clear conclusions on other gamma lines (yet)
    - rerun same analysis with ~90 kg·yr (as GERDA Phase II)
    - compare with GERDA (very preliminary in the backup)

⇒ use LEGEND-200 as prototype to study μ–induced bkg for LEGEND-1000 @LNGS

LEGEND-1000 @LNGS:

Atmospheric Argon instrumentation

physics

- get more accurate model for gamma cascade after neutron capture
- extend to also radiogenic background (see backup)

photons transport

- implement probability map

instrumentation

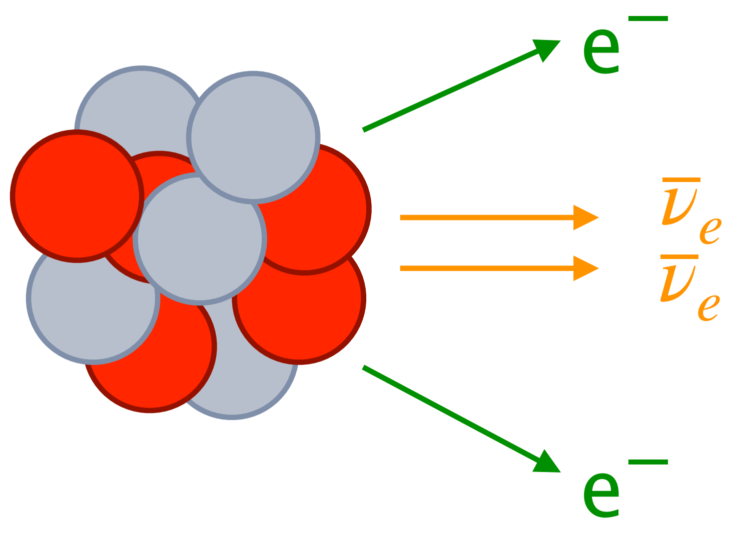
Preliminary instrumentation choice will be shown at the next collaboration meeting in Vancouver (December 2023)

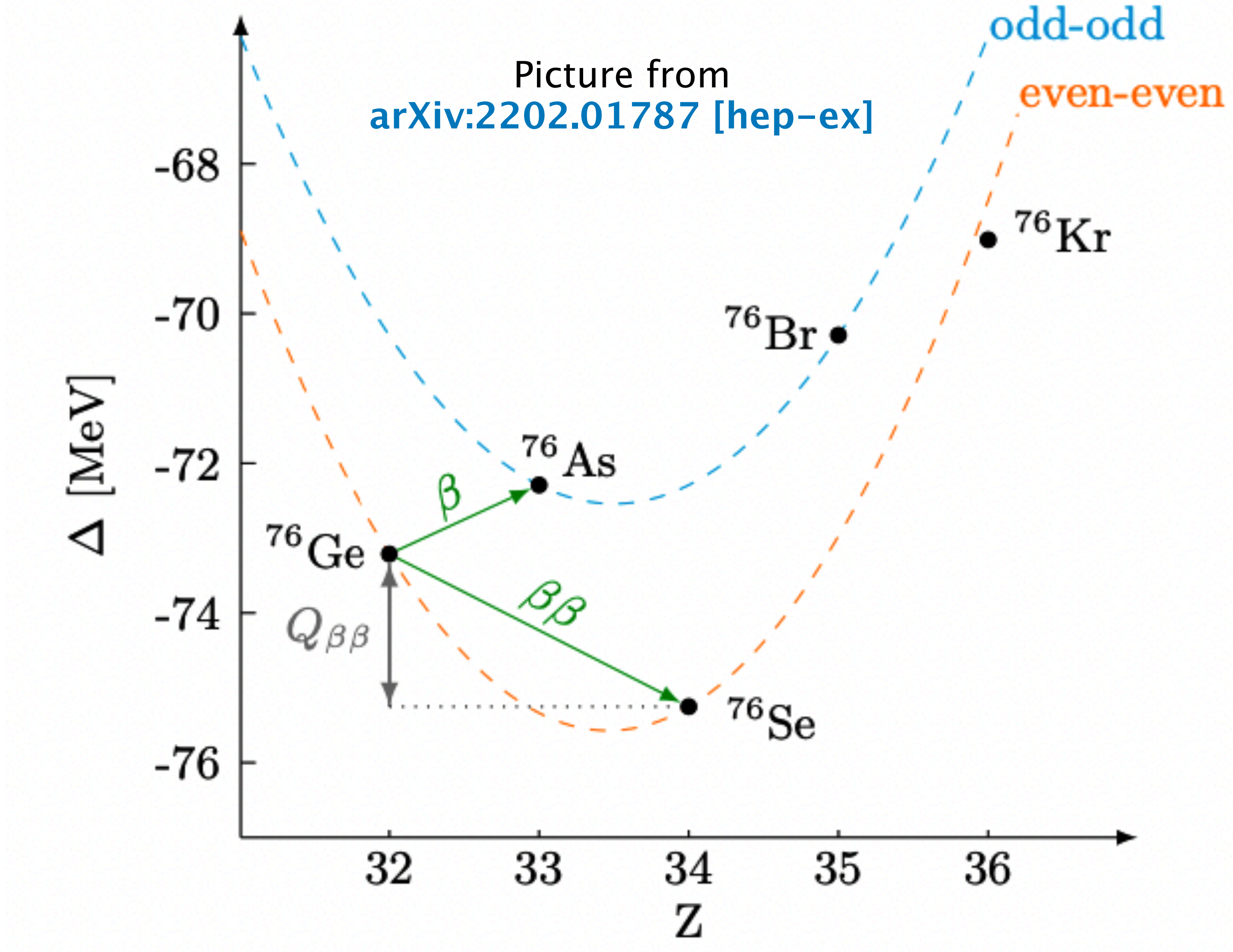
⇒ Next year final design choice and hardware testing

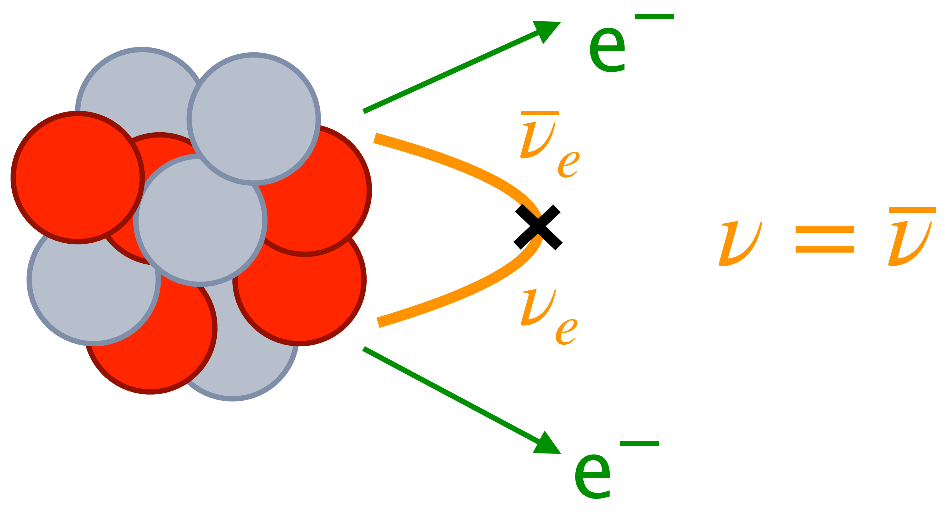
BACKUP

Double Beta Decay

When a single β-decay is energetically not allowed…



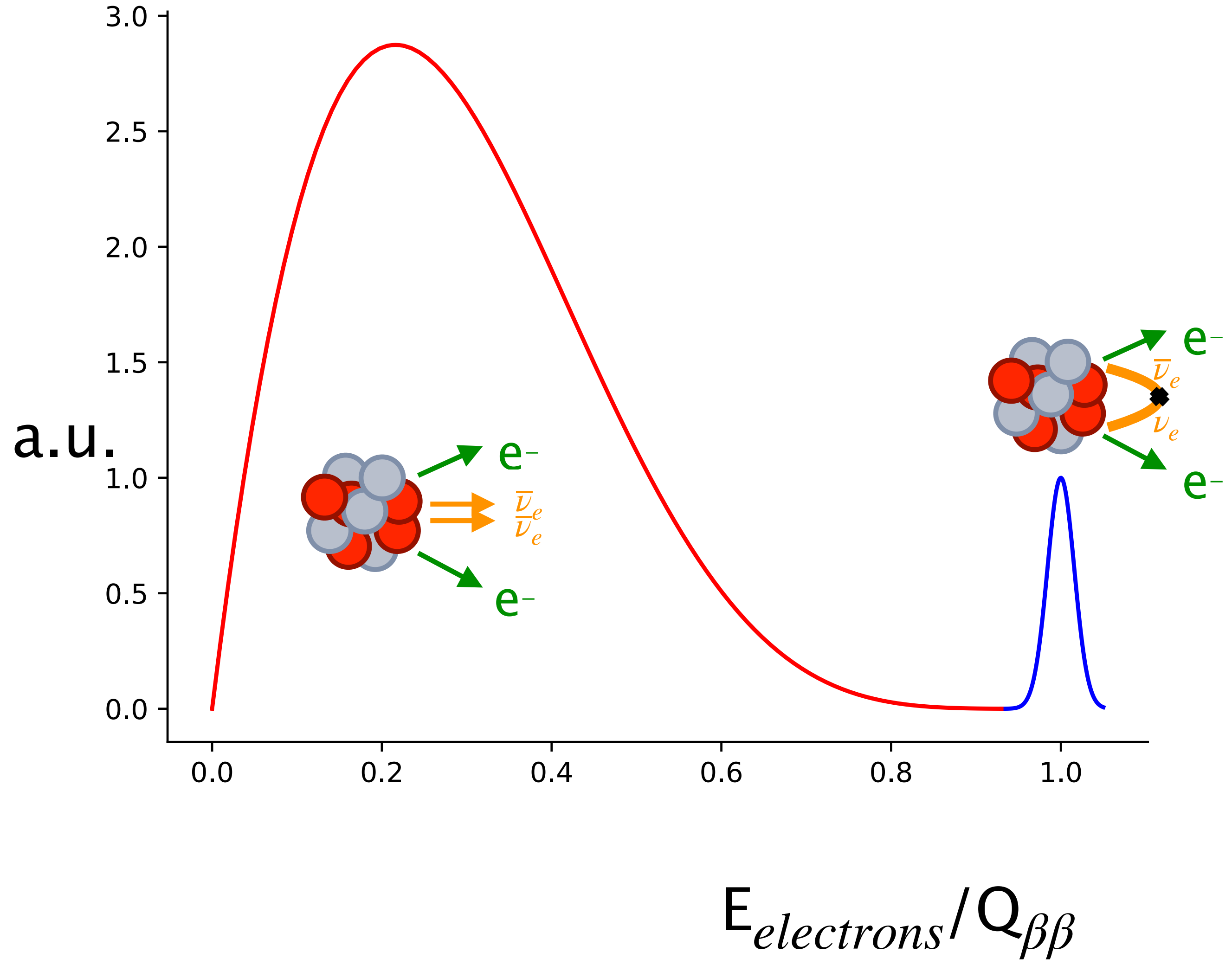




$2\nu\beta\beta$: N(A,Z) → N(A,Z+2) + 2e$^-$ + 2$\overline{\nu}_e$

Already observed in about 10 isotopes:

- Allowed in the Standard Model (SM)
- if single β-decay final state is energetically not accessible
- $T_{1/2} \sim 10^{18} \div 10^{22}$ yr



$0\nu\beta\beta$: N(A,Z) → N(A,Z+2) + 2e$^-$ ~~+ 2$\overline{\nu}_e$~~

Never observed so far, not allowed in SM:

- L and B-L violation: ΔL = 2
- $\nu = \overline{\nu}$ (Majorana particle)
- hint on matter/antimatter asymmetry
- information about ν mass scale and ordering

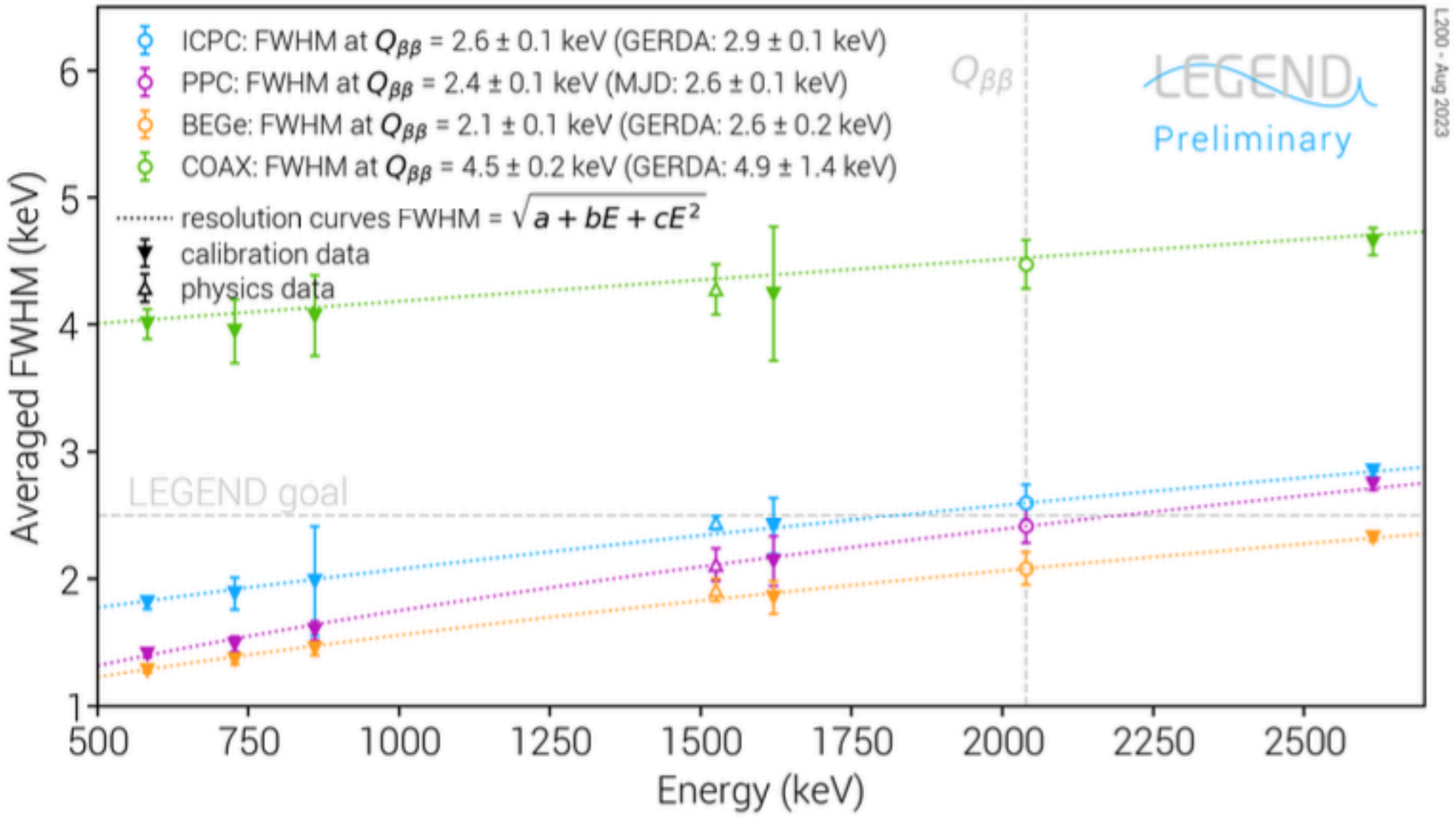
LEGEND

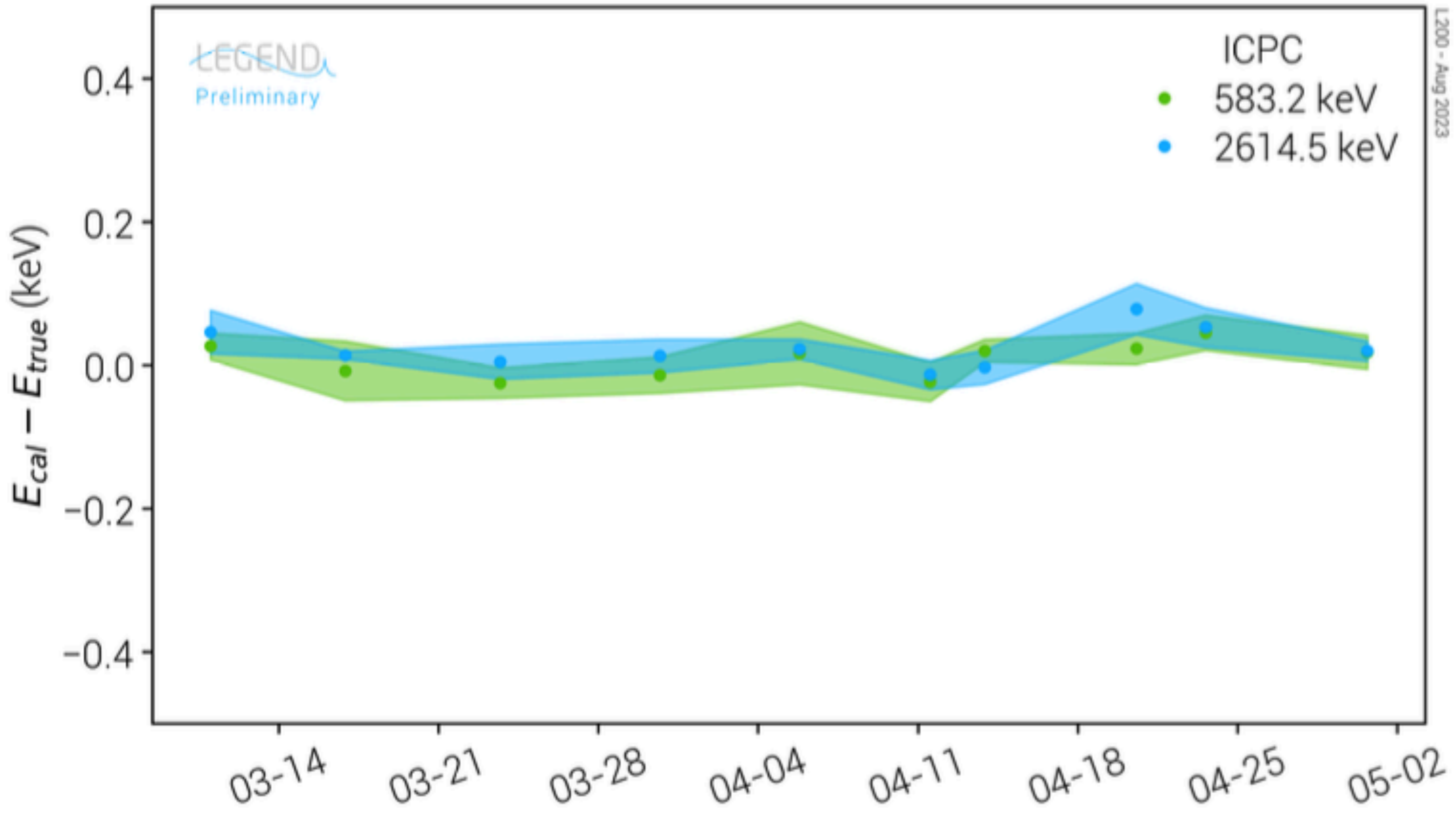
Energy Resolution & Stability

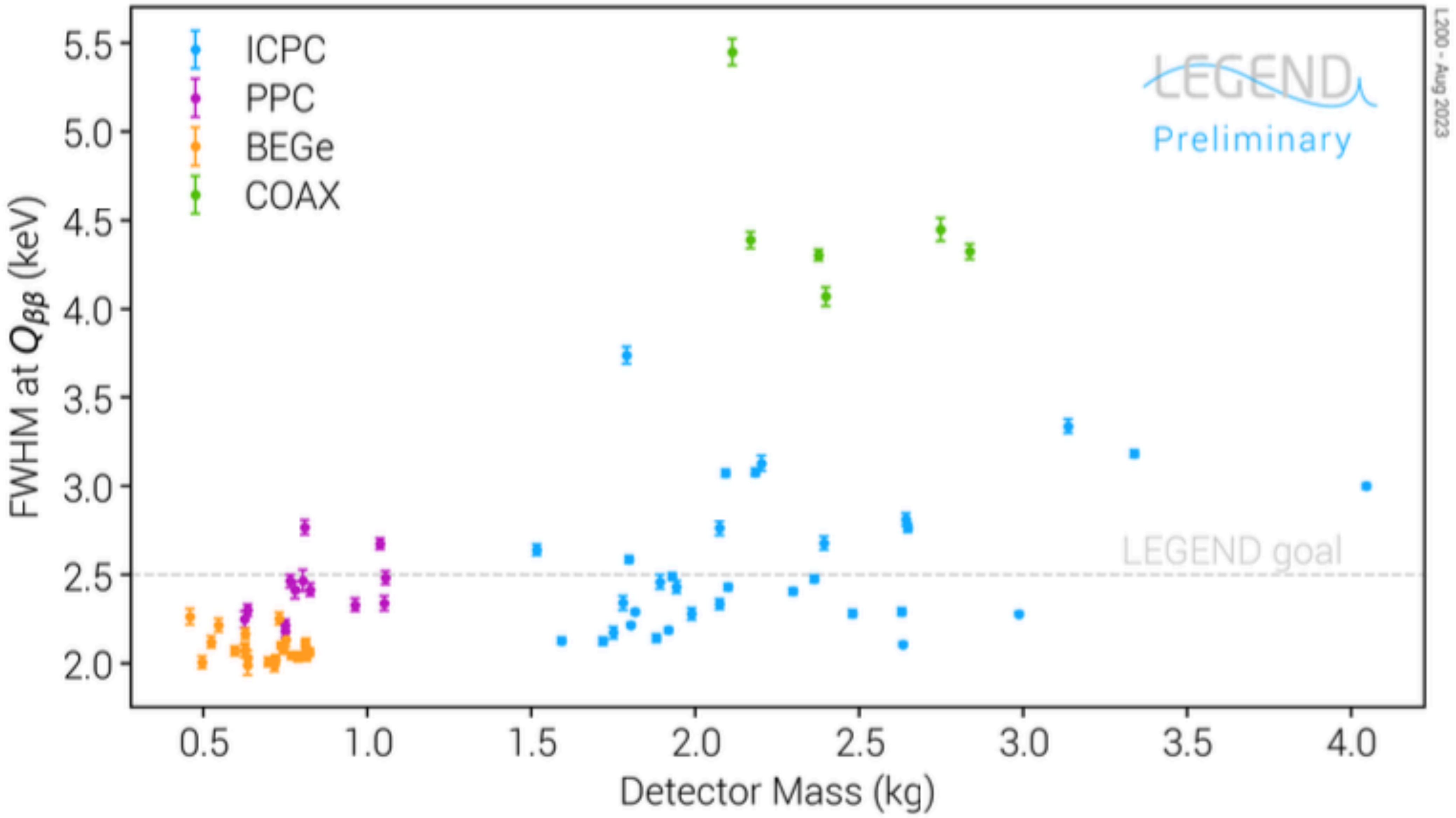
from M. Willers @TAUP2023

Weekly energy calibration between physics runs using ^{228}Th sources

- Overall improvement in energy resolution @ $Q_{\beta\beta}$
- Energy scale very stable between calibrations







M. Willers | L-200 from construction to physics data taking | 29. Aug. 2023

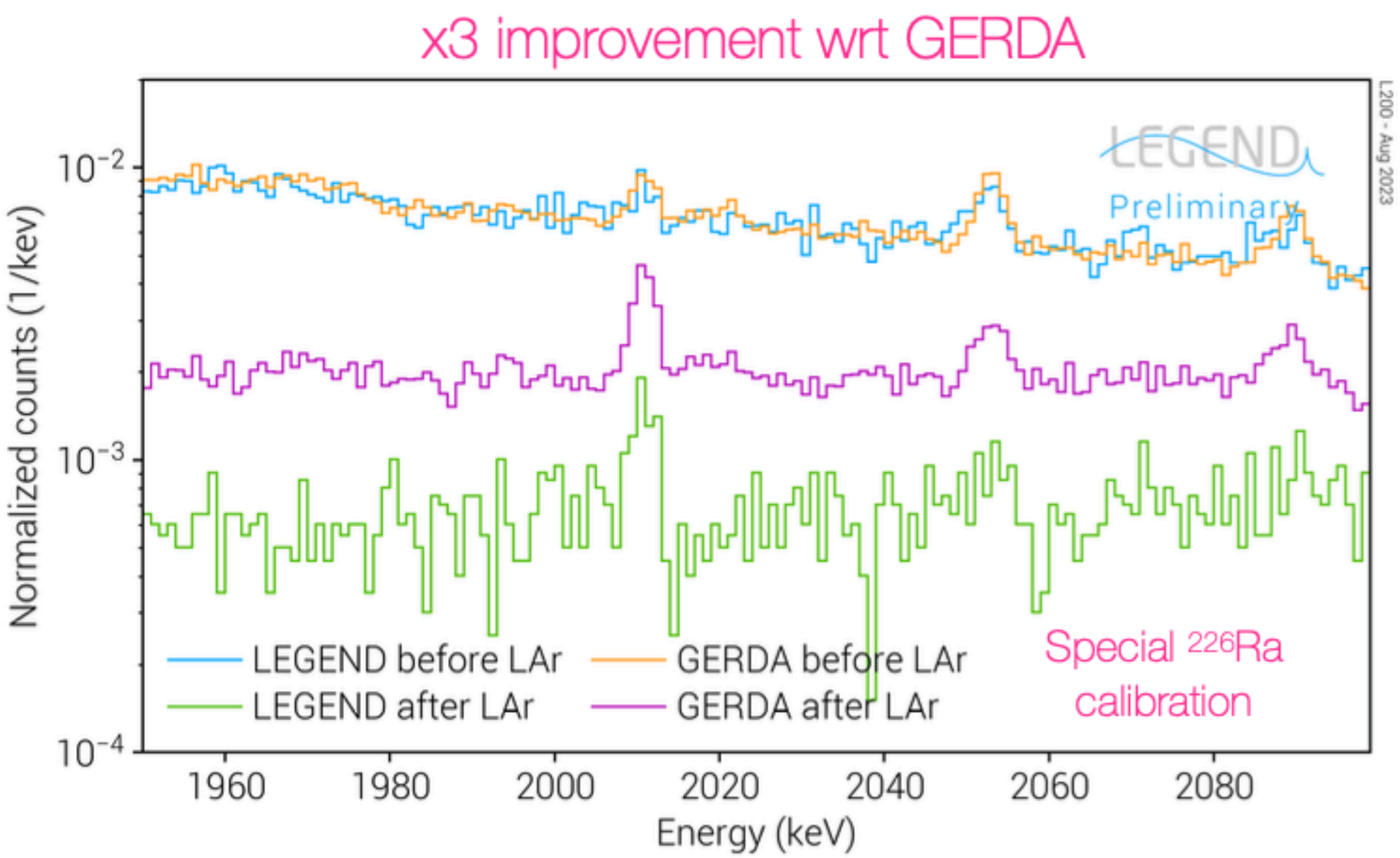
LAr Instrumentation

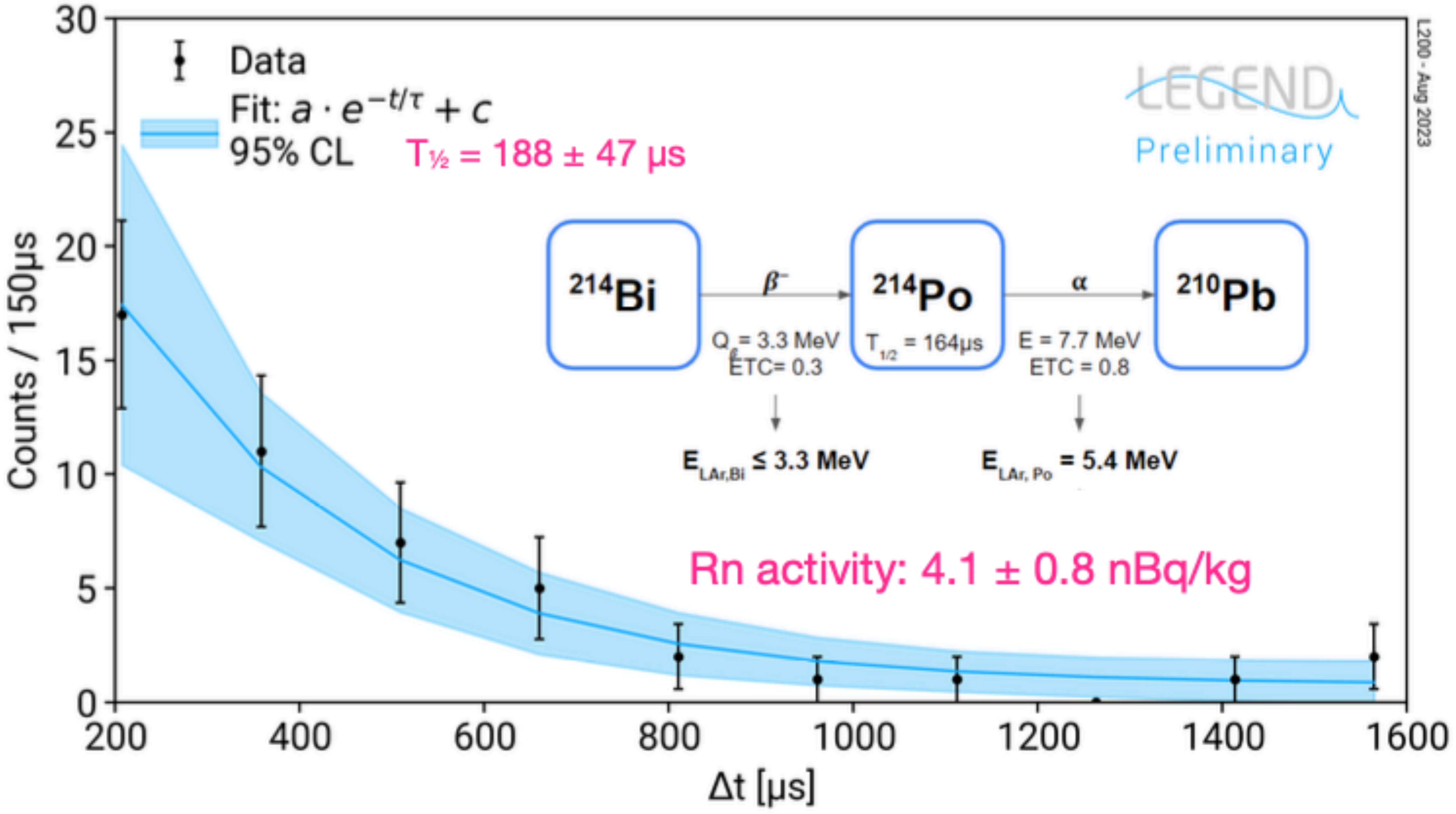
from M. Willers @TAUP2023

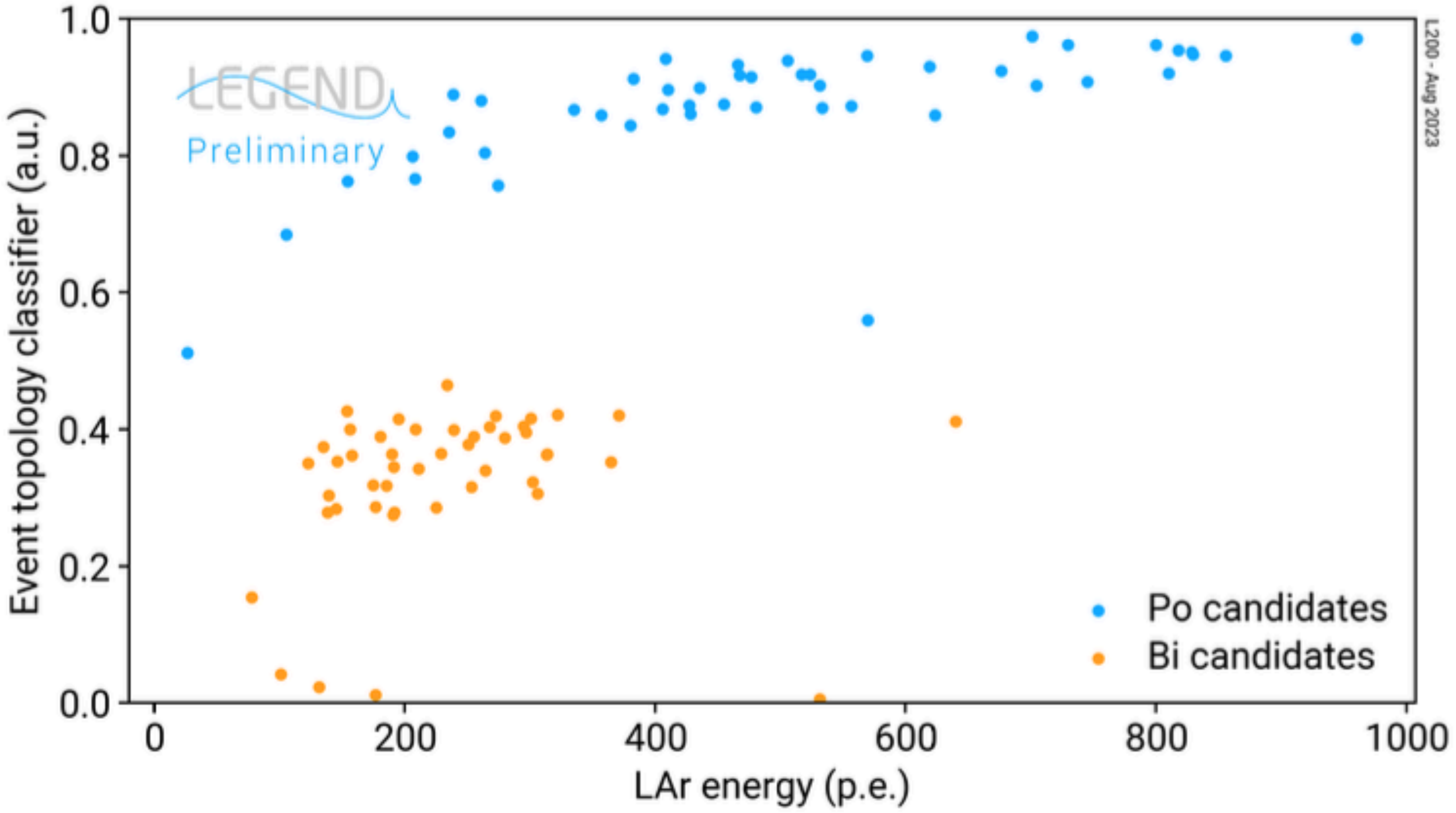
- With improved p.e. yield comes improved background suppression
- We can use time information from LAr signal for particle identification:

→ application e.g. BiPo tagging

LAr instrumentation now acts as a full-fledged detector







Background Index

from K. von Sturm @TAUP2023

- First 10.1 kg yr of LEGEND-200 data
- ICPC & BEGe
- LAr accepted
- PSD accepted

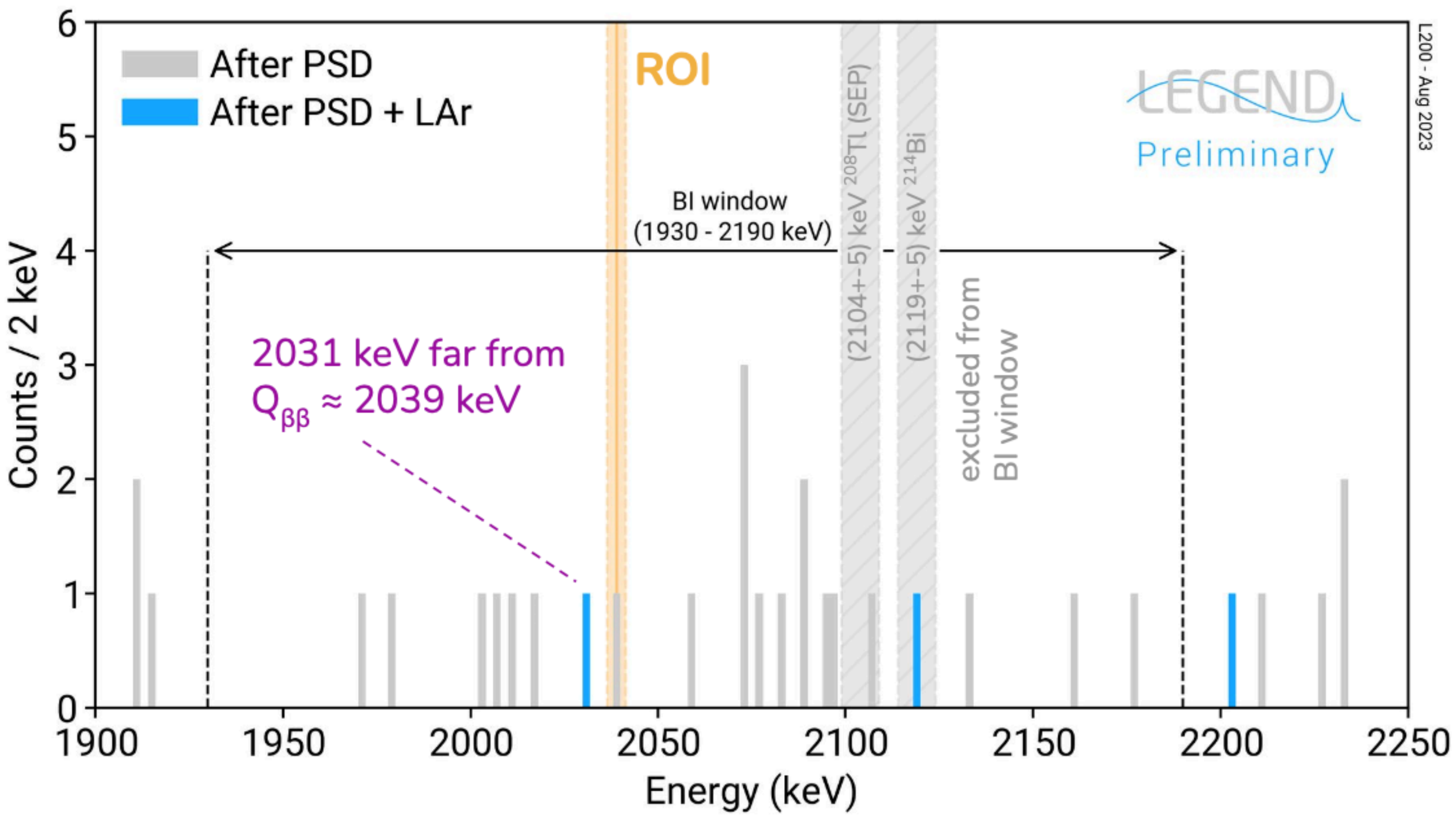
- BI is compatible with LEGEND-200 goal

  2 x 10^{-4} cts/(keV kg yr)

- Expect 0.48 cts
- Probability to observe

  #cts > 0 ~ 38%

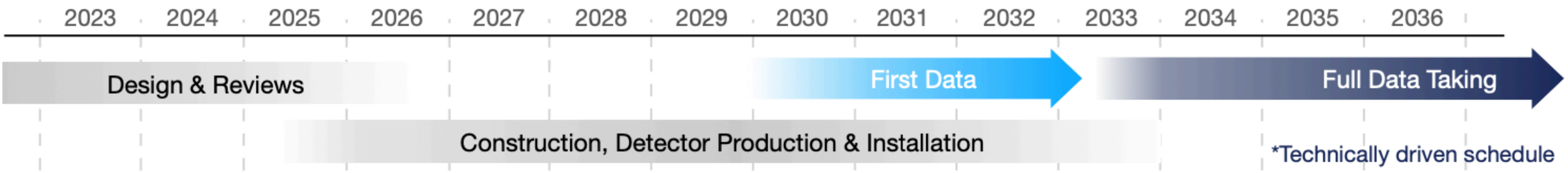
window 240 keV & exposure 10.1 kg yr



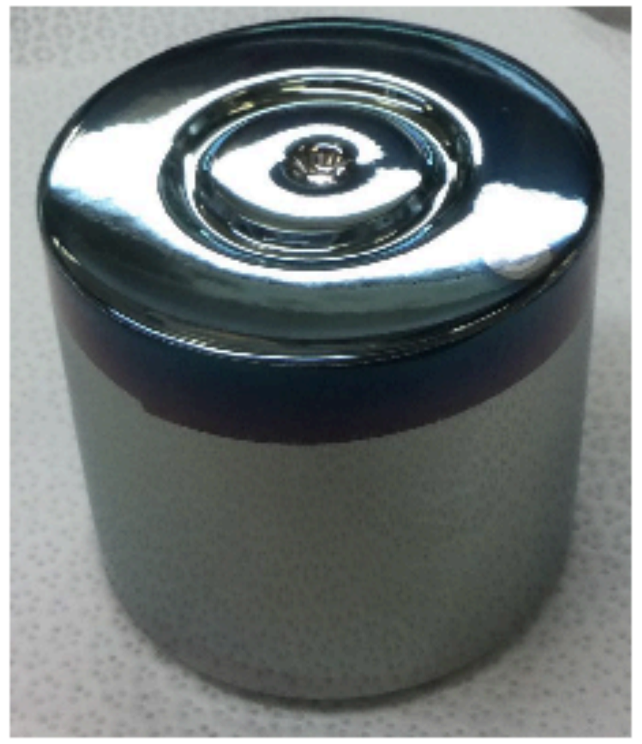
	LEGEND-200 BI 68% CL (cts/keV/kg/yr)	GERDA Phase II unblinded BI 68% CL (cts/keV/kg/yr)
After LAr & PSD	4.1 [1.5,11.4] x 10^{-4}	5.2 [3.9,6.8] x 10^{-4}

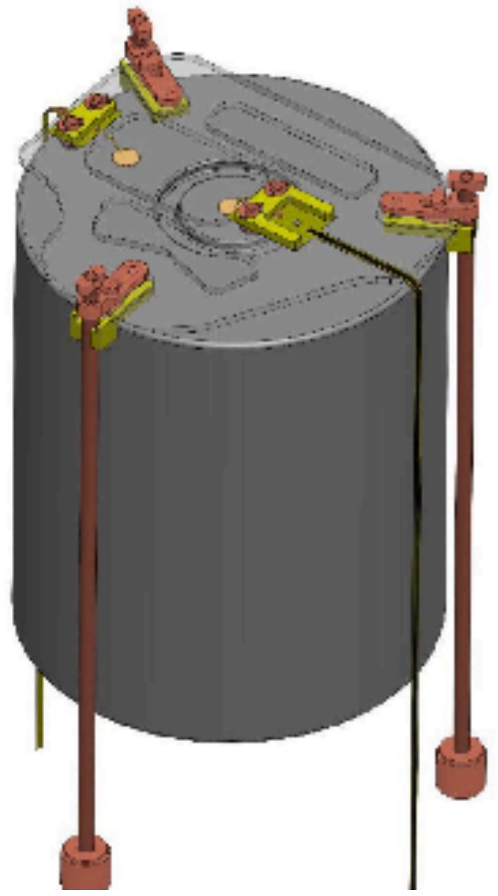
LEGEND-1000 Timeline & Outlook

from V. Guiseppe @TAUP2023

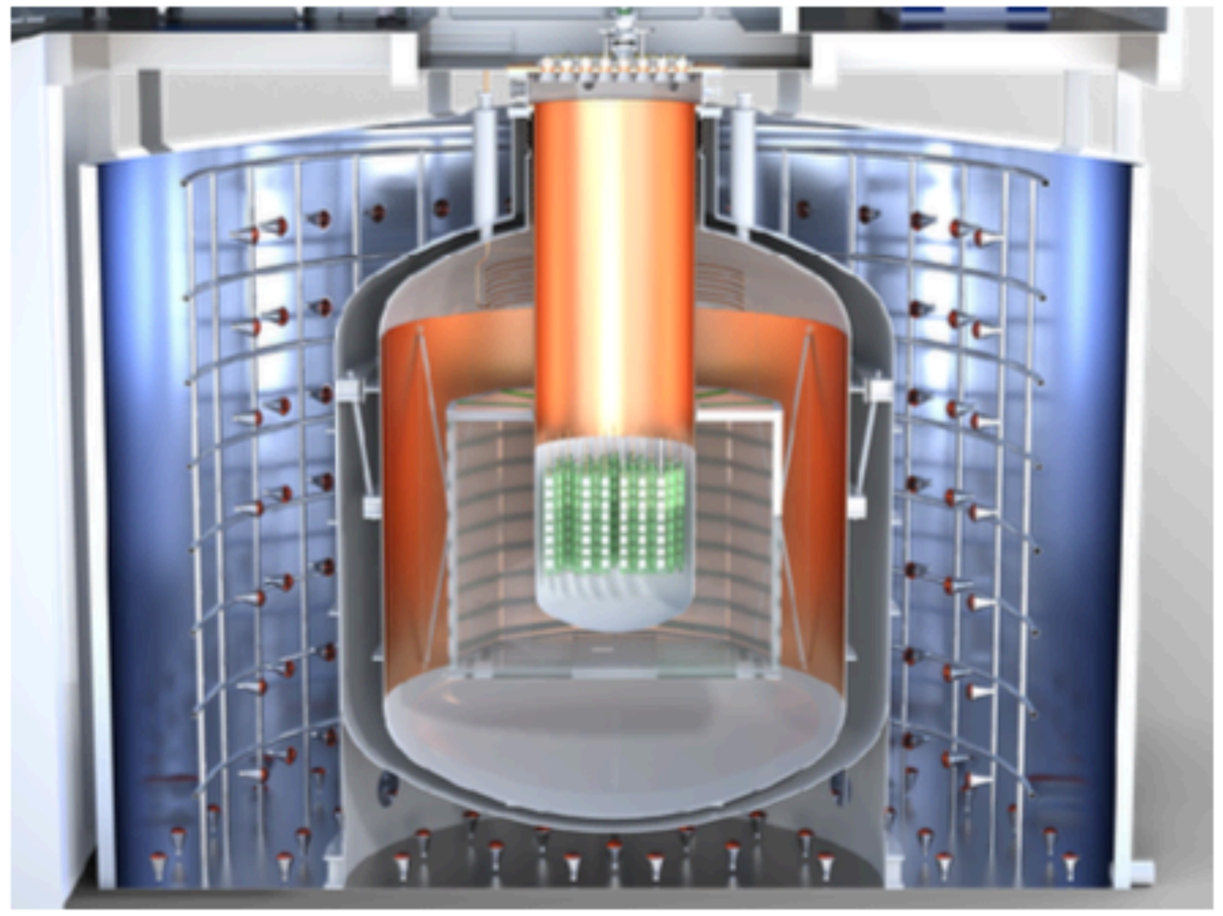


- LEGEND-1000 is optimized for a quasi-background-free 0νββ search
  - It builds on breakthrough developments by GERDA, MAJORANA, and LEGEND-200
  - LEGEND has a low-risk path to meeting its background goal of 10^{-5} counts/(keV kg yr)
  - Low backgrounds, excellent resolution, and event topology discrimination allow for an unambiguous discovery of 0νββ decay at $T_{1/2} = 10^{28}$ years
- The reference design accommodates siting in SNOLAB Cryopit or LNGS Hall C





LEGEND Website
https://legend-exp.org/



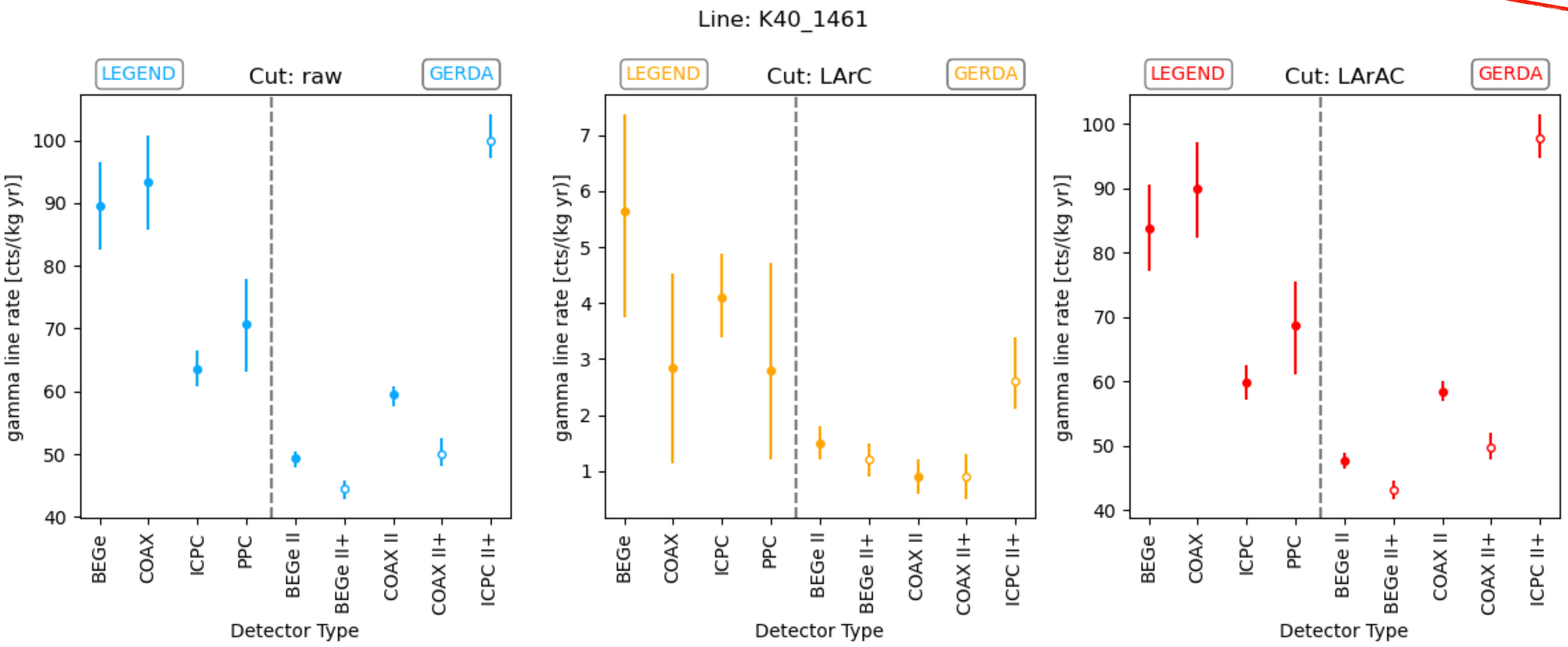
Gamma lines analysis

Fit Procedure

- Fit the intensity of known gamma lines with BAT v1.0.0:
  - binned spectra - bin size of 0.25 keV
  - window of ±20 keV around the peak
  - gaussian signal + background [quadratic(<500 keV), linear(500-2000 keV), flat(>2000 keV), step(for K40)]
  - strong (0.2 or 0.5 keV) priors on peak position and FWHM
  - fit is performed in steps
    - 1) fit only the background range with the background model
    - 2) fit the full model with fixed position/resolution - these ROOT fits are used to define the parameter ranges for the BAT fit
    - 3) only then the bayesian BAT fit is performed
- results quoted as global mode + smallest 68.3% interval (or 90% upper C.I. limit)

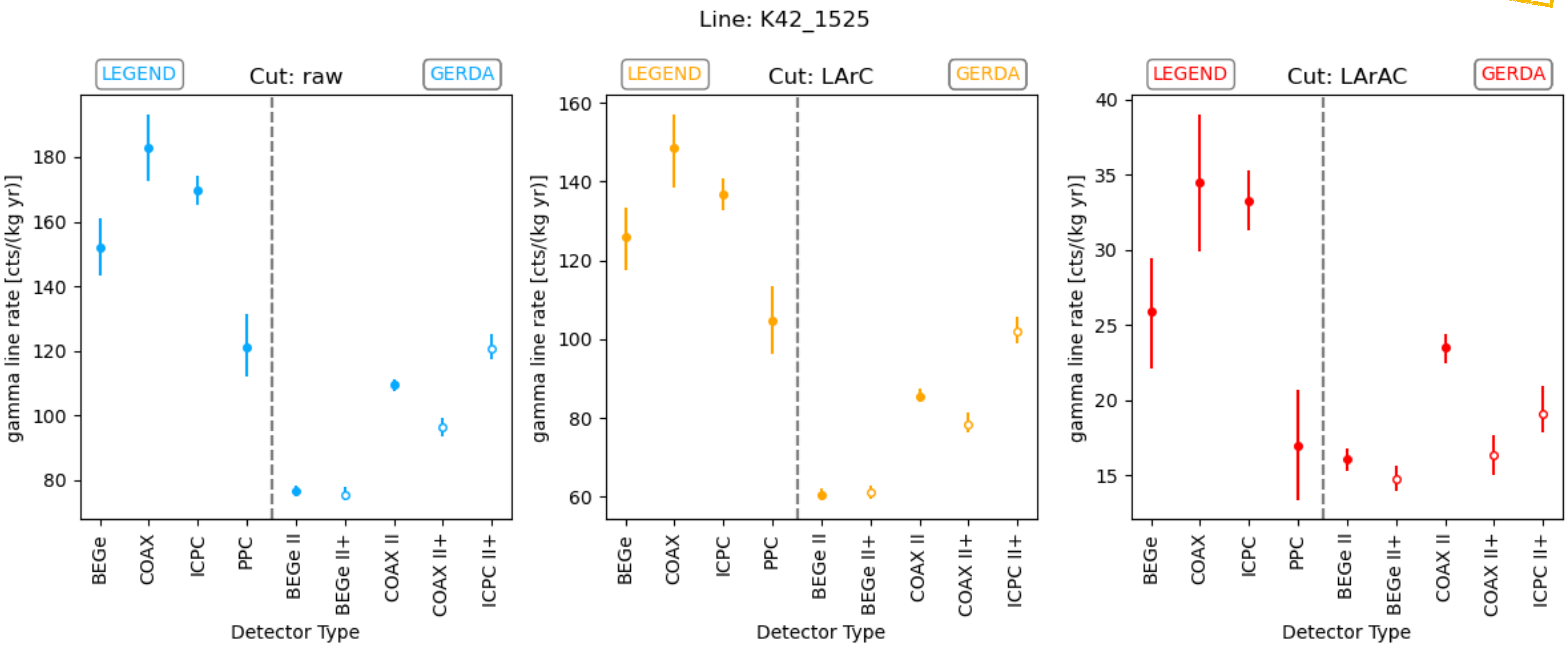
K40 – electron capture

No Energy release in Ar expected



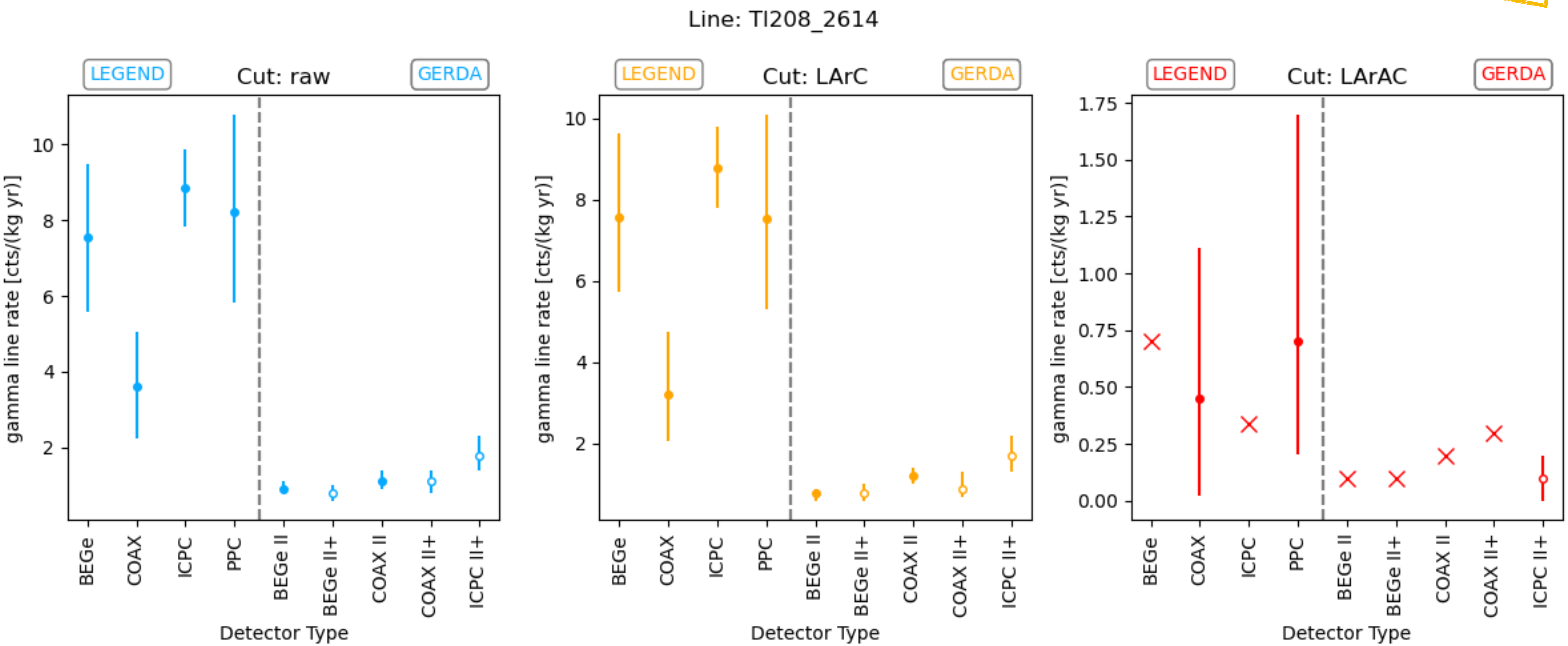
K42 – β decay, Q=3.5 MeV

Energy release in Ar expected



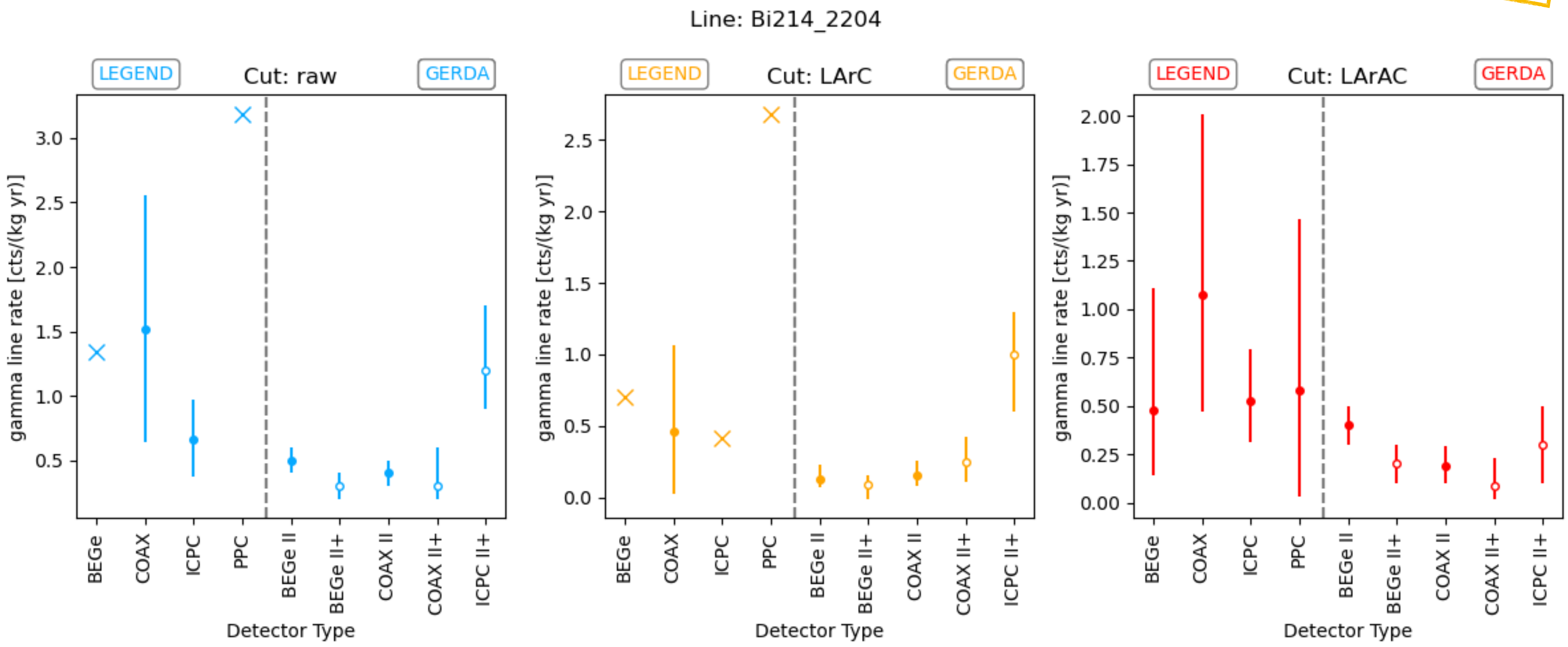
Tl208 – β decay, Q=5 MeV, many γ

Energy release in Ar expected



Bi214 – β decay, Q=3.2 MeV

Energy release in Ar expected



Other gamma lines + GERDA comparison results

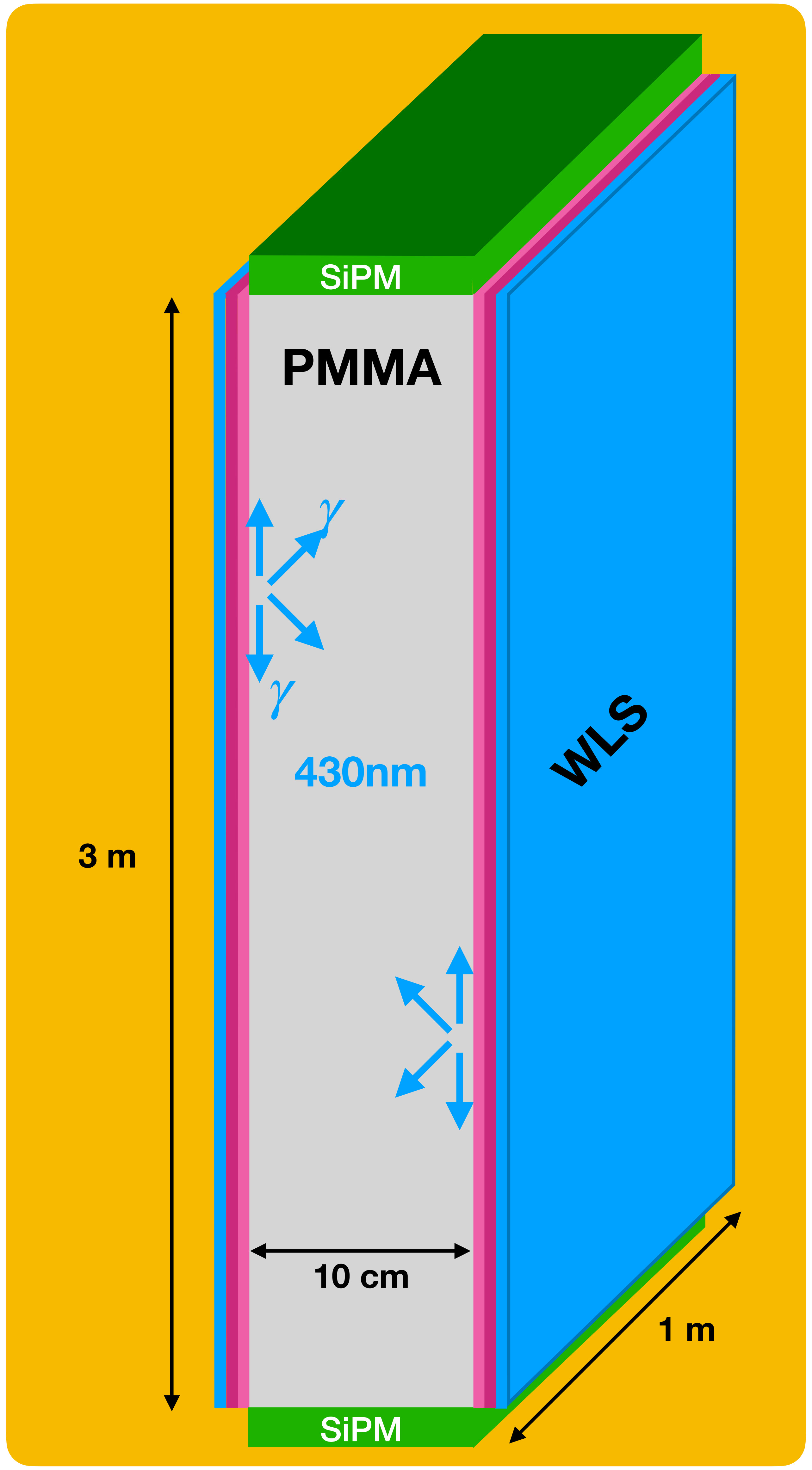
Take away message:

- background before cuts higher than GERDA
  - expected, more material and more channels
  - detector with bigger volumes

- need more exposure to evaluate also LAr veto
  - big statistical uncertainty propagating on Survival Fraction calculation

Instrumentation

Design comparison – Trapping efficiency estimate



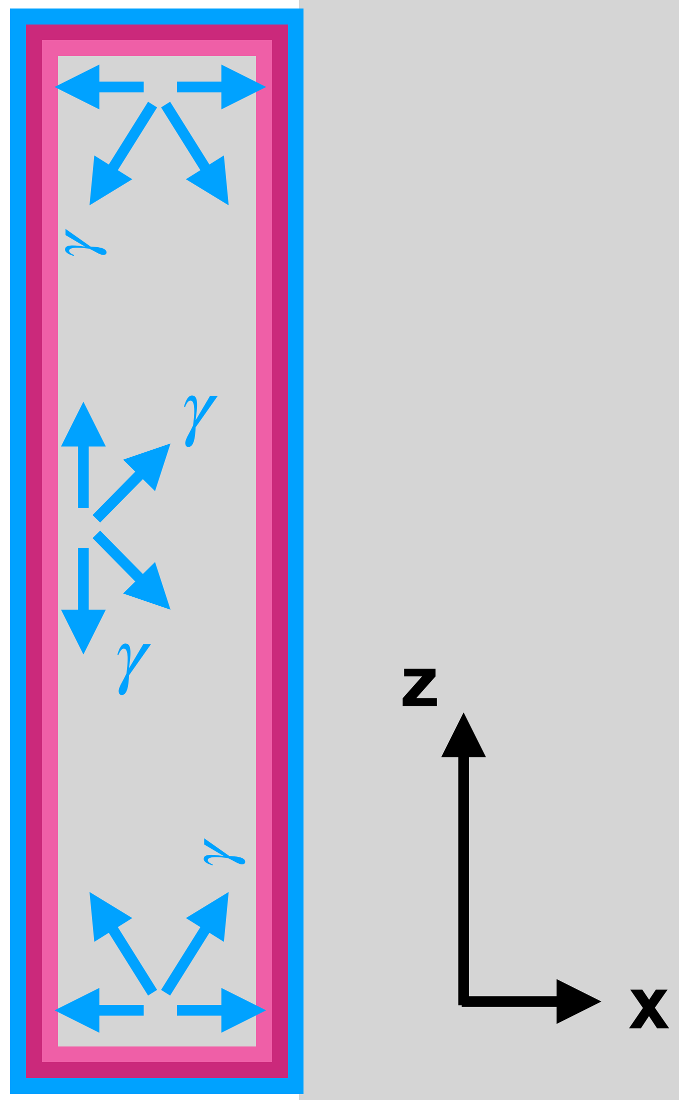
- Counting how many photons arrive at **SiPM** if they are already inside light guide

- simulating PEN 430nm photons already inside light guide (light guide bar, moderator panel, etc.)

- both panel and light guide made of PMMA (PMMA attenuation Length **[1, 5]m @430nm**)

- Considered also 2 layers of cladding material between WLS and PMMA

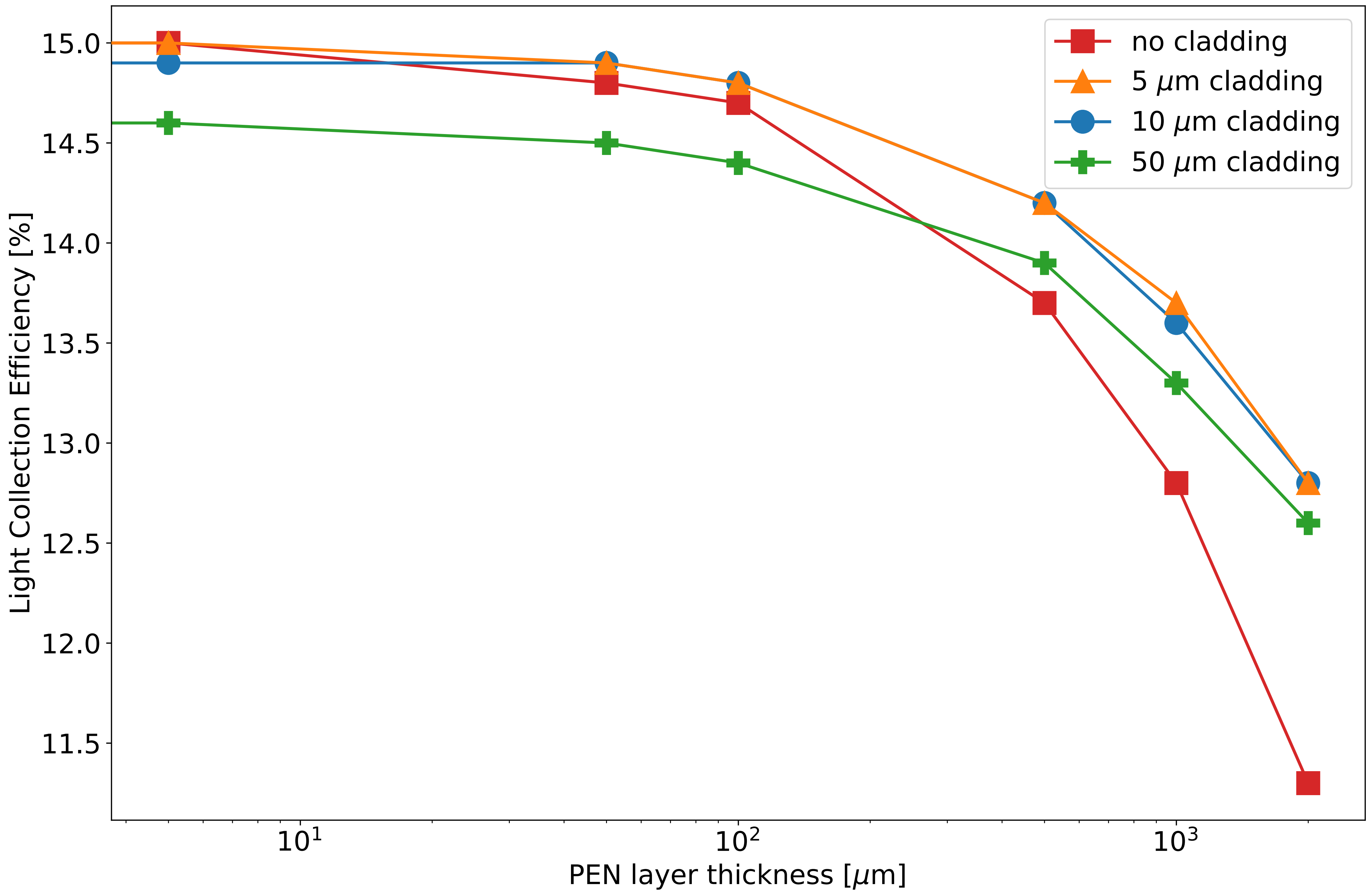
Baseline design



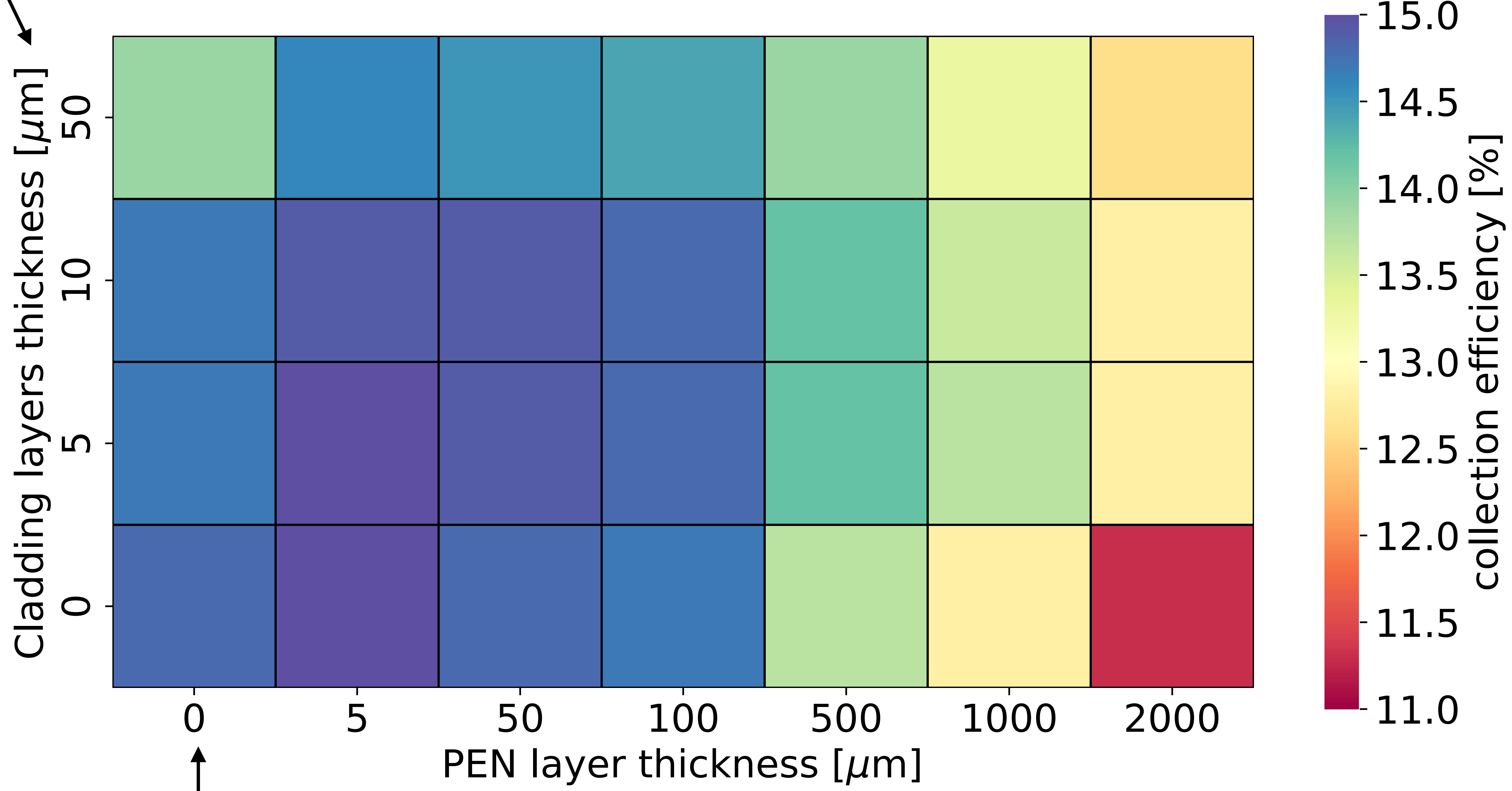
Moderator side view

Design comparison – Cladding layers effect

thickness of single cladding layer
total cladding thickness is 2x as reported



no clad



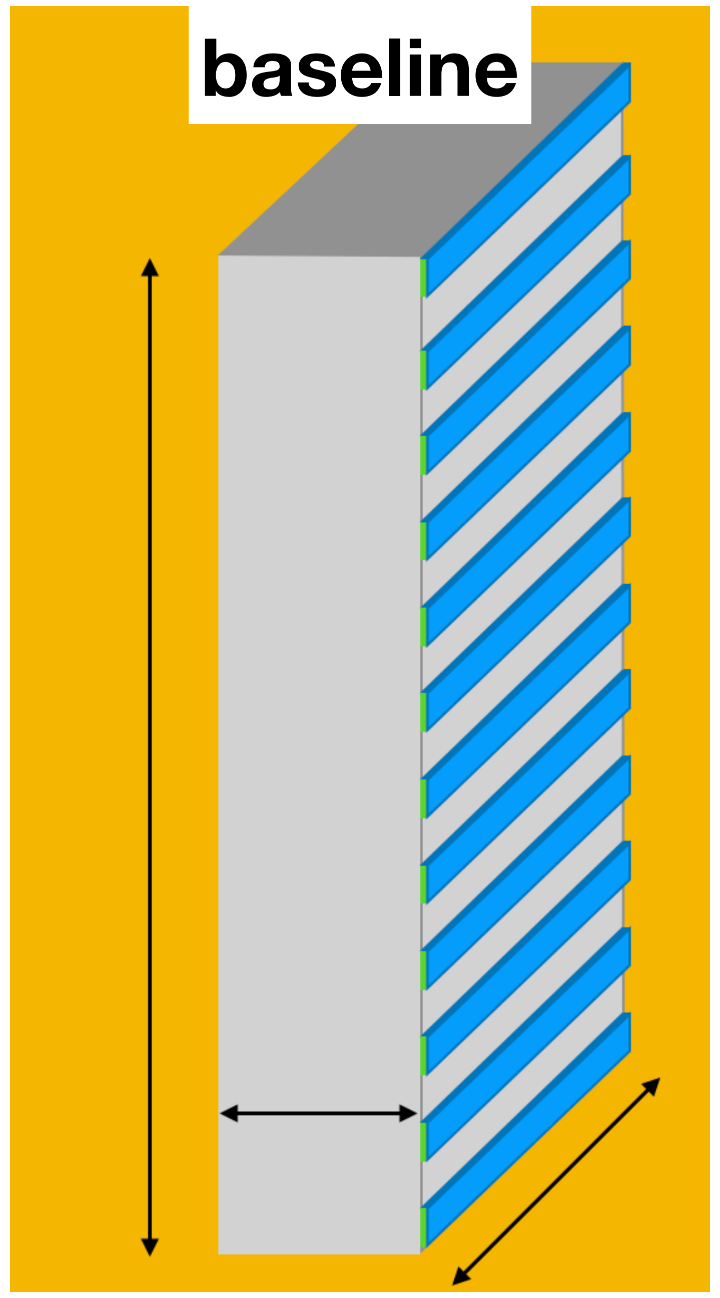
no PEN

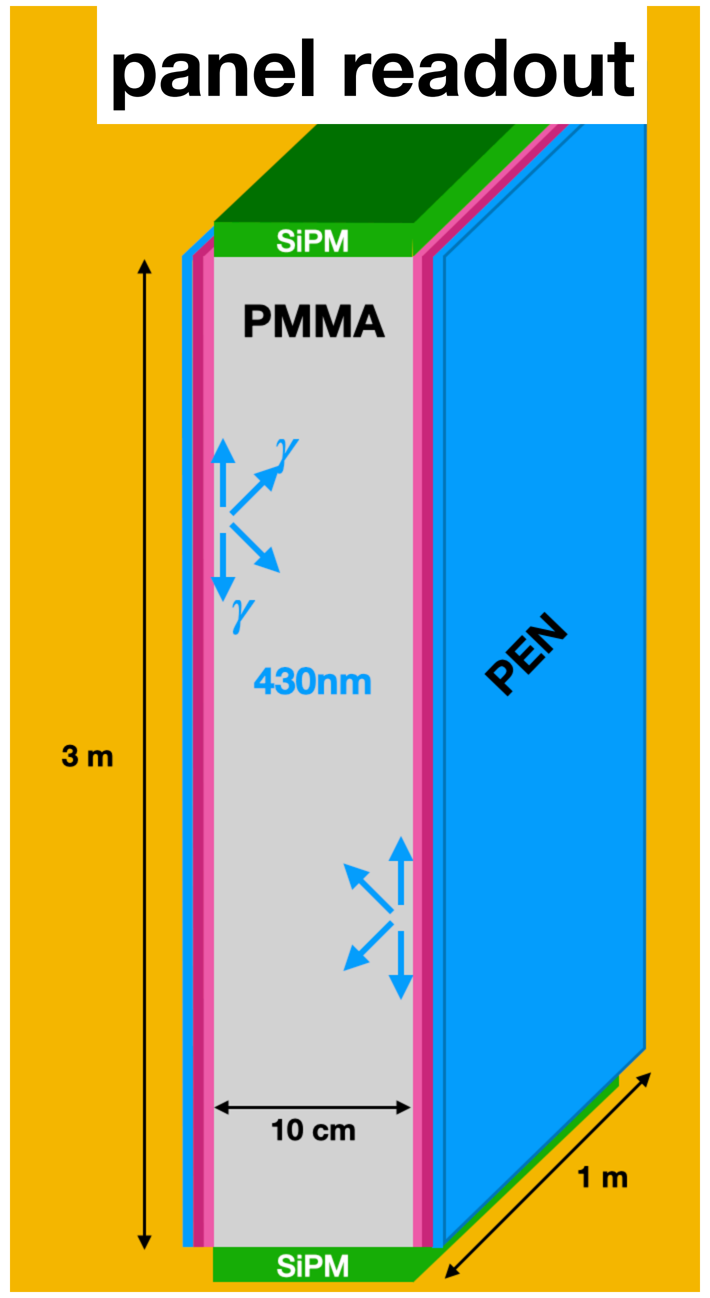
trapping efficiency constant up to 100 μm

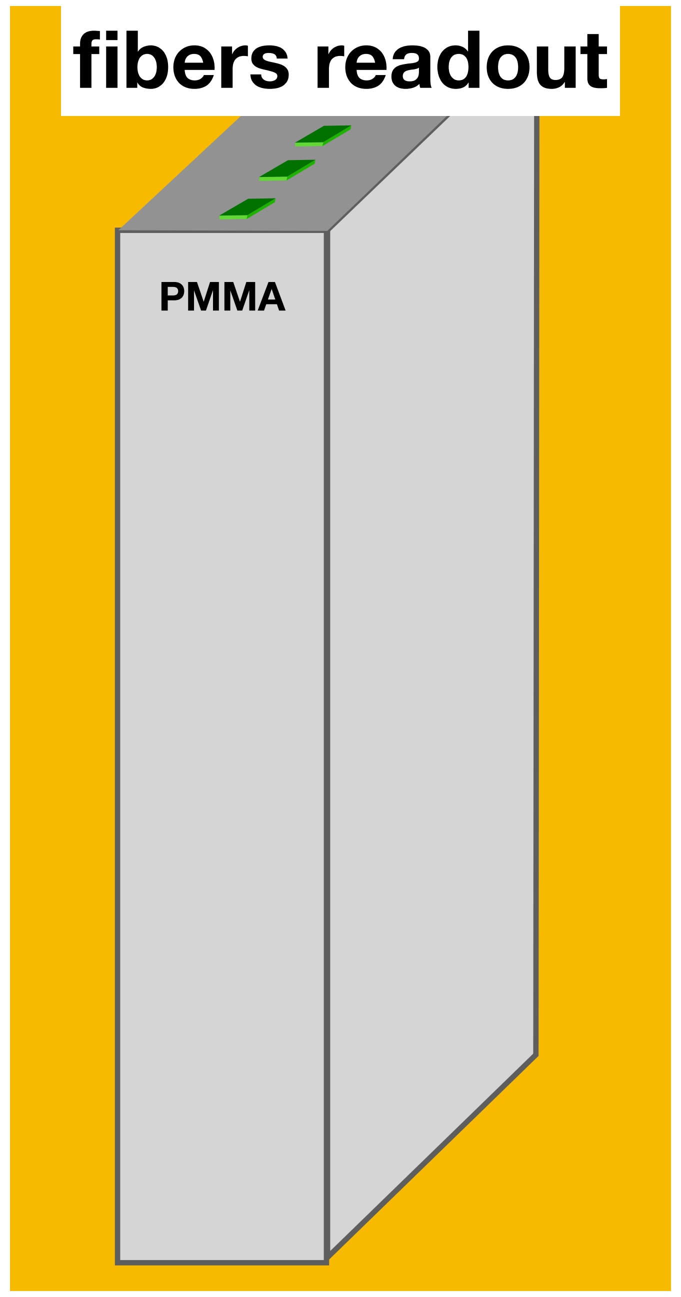
increasing cladding thickness also worsen CE

cladding layers improve trapping efficiency by a few %

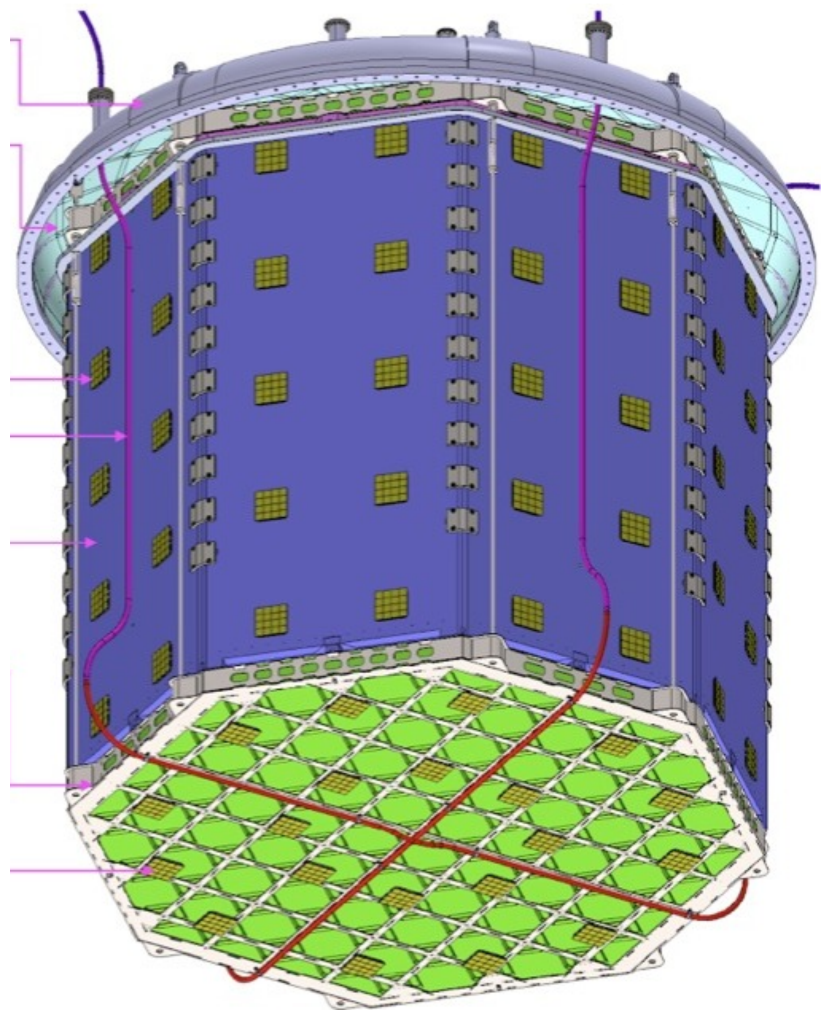
Design comparison – Instrumentation





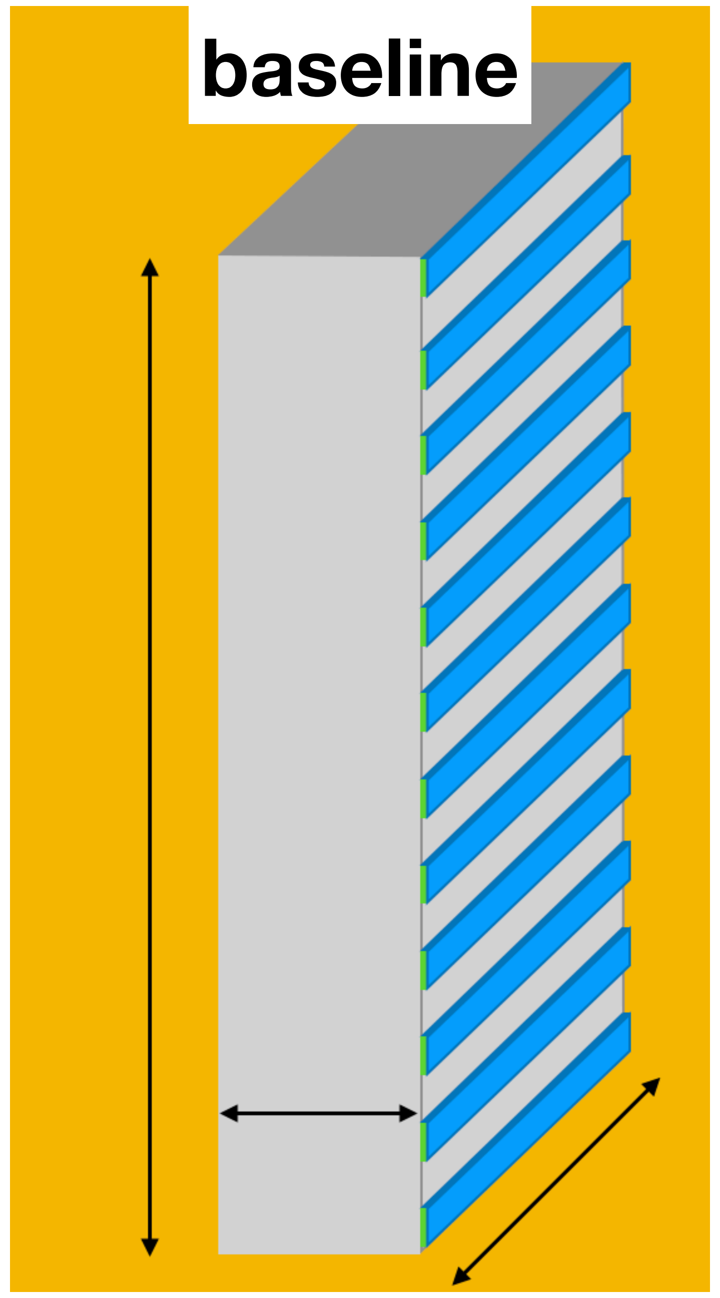


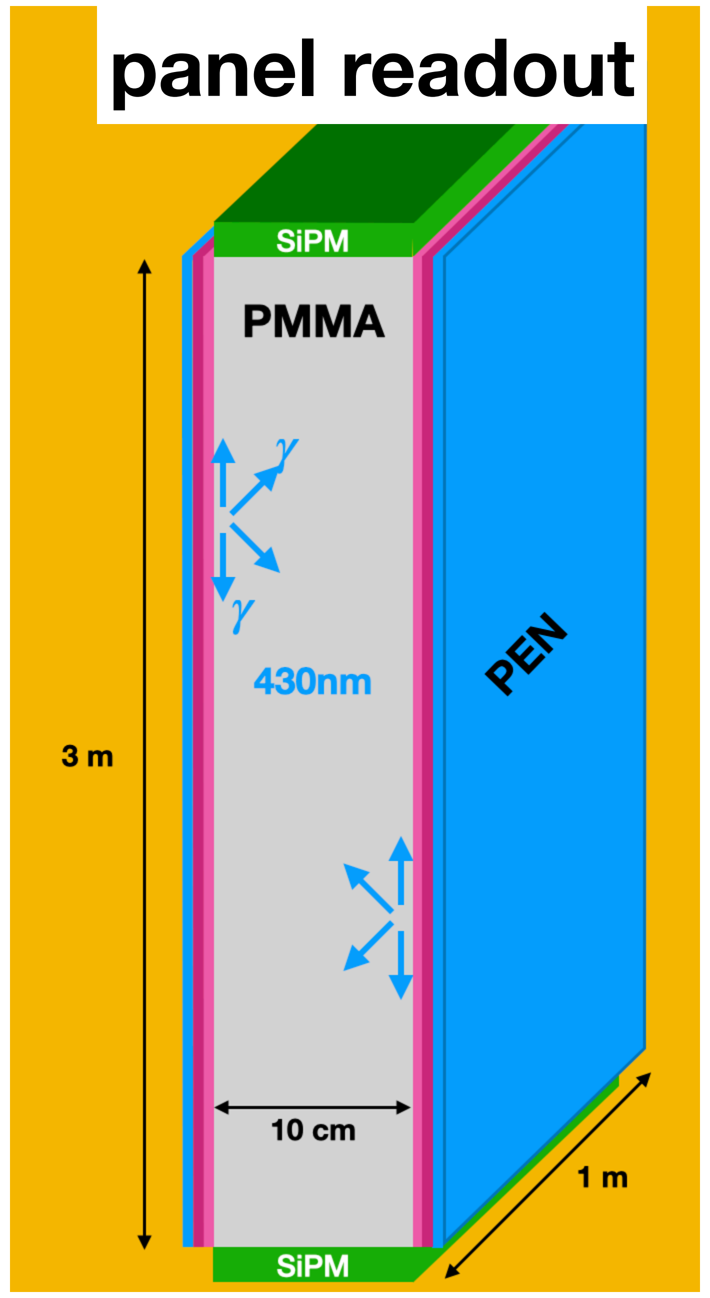
single SiPM readout

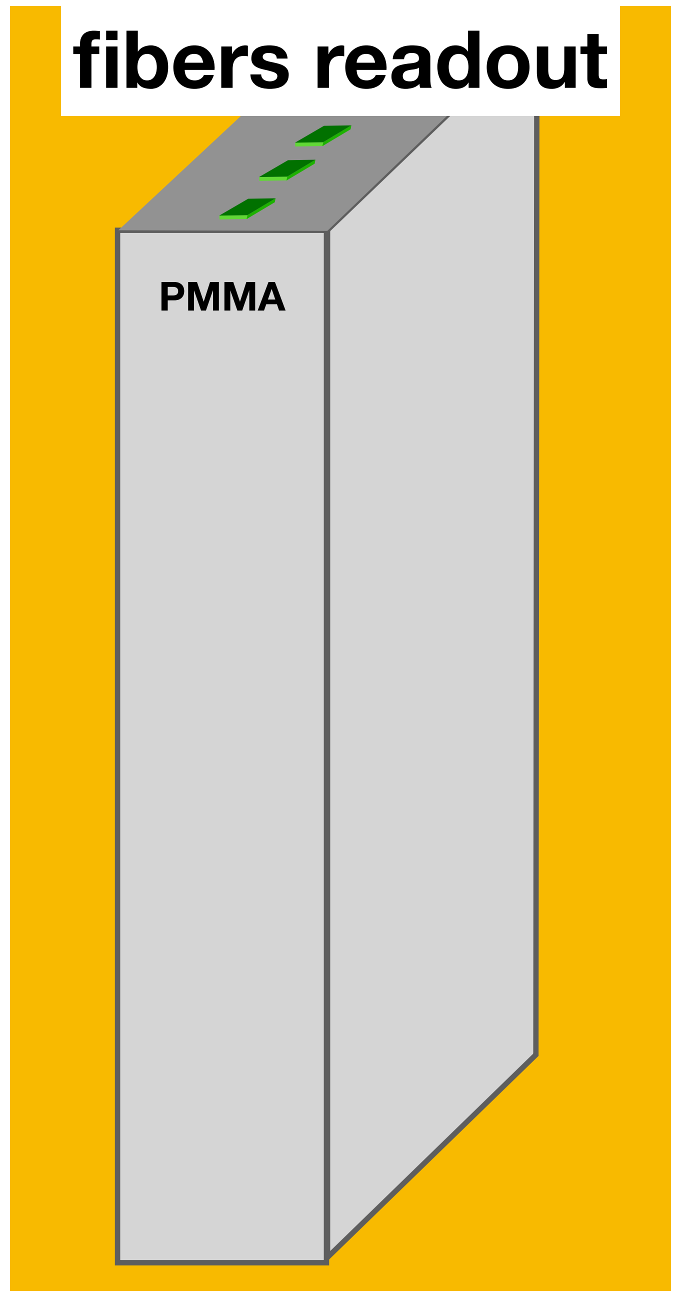


	baseline	panel readout	fibers readout	single SiPM readout
$\varepsilon_{trapping}$	0.05	0.05	1E-4	1

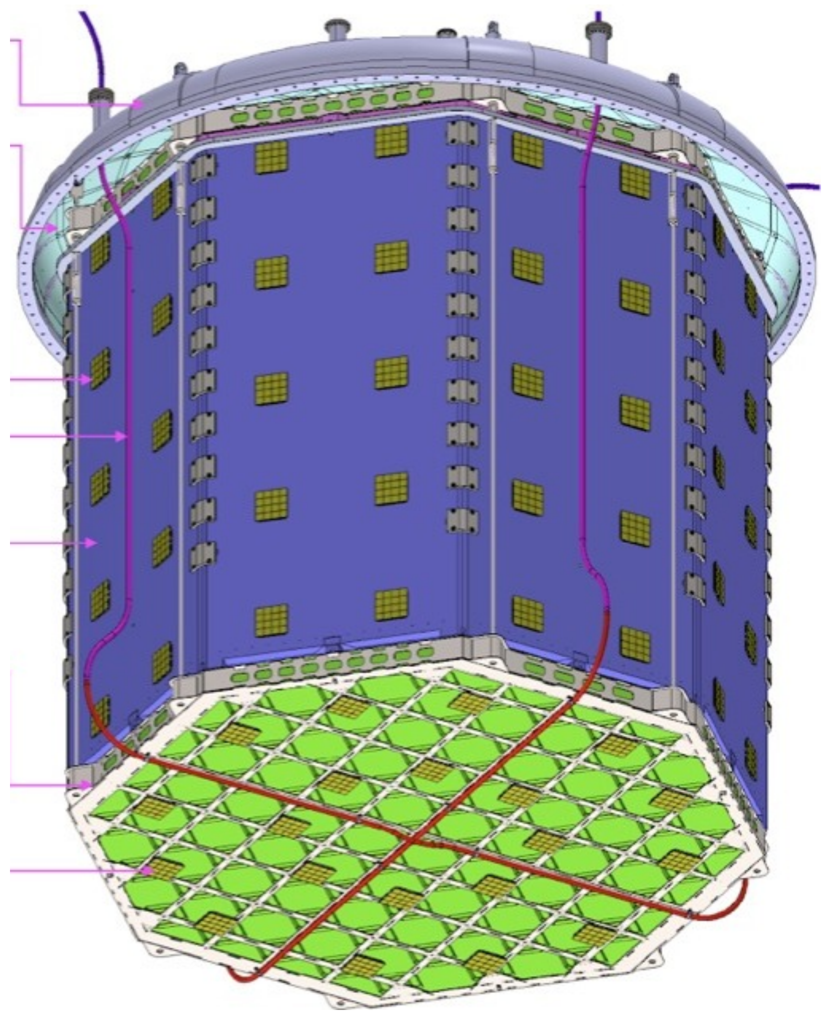
Design comparison – Instrumentation







single SiPM readout

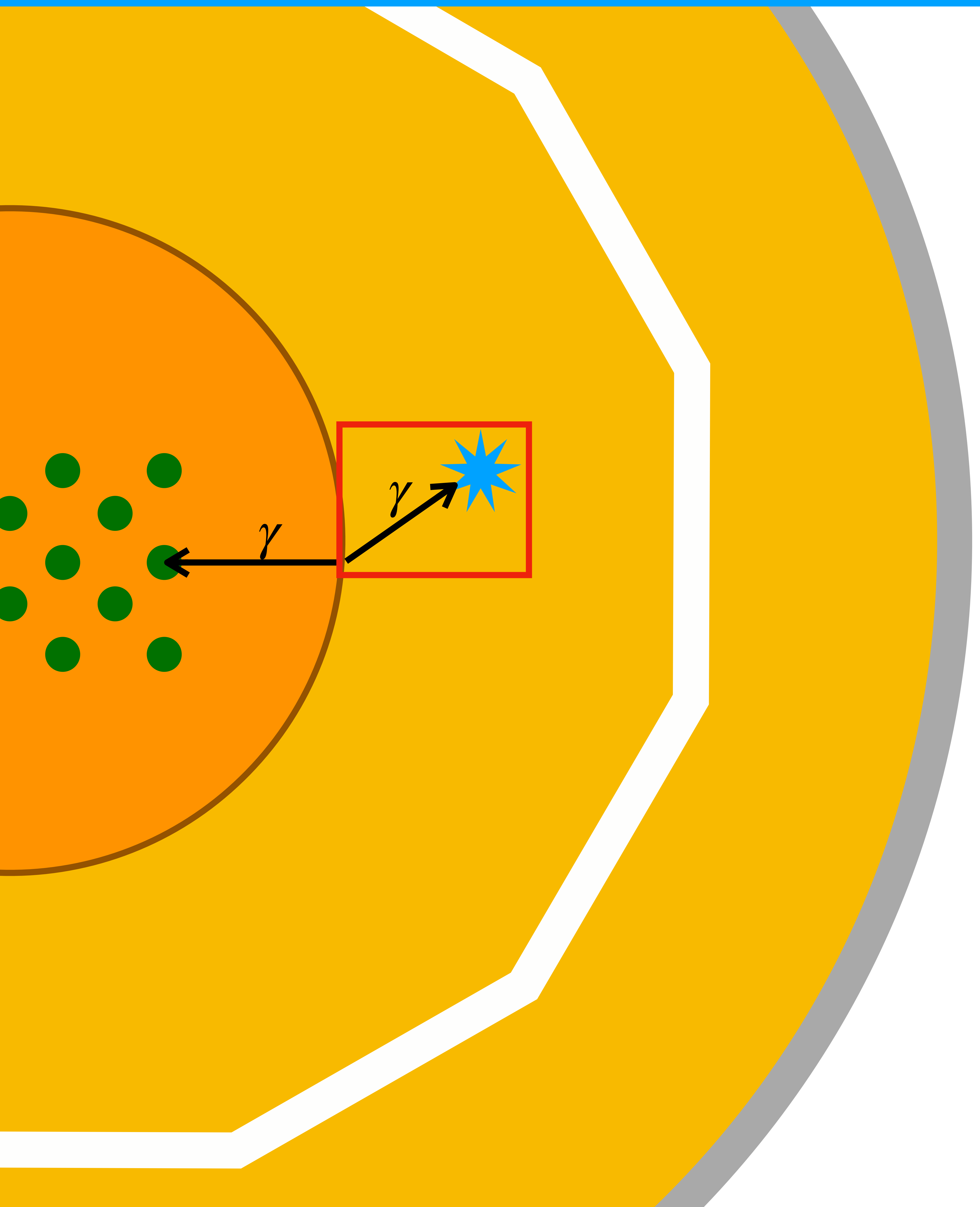


	baseline	panel readout	fibers readout	single SiPM readout
N SiPM	1778	1778	936	O(30k)
$\varepsilon_{active\ surface}$	0.4	1	1	0.08
ε_{WLS}	1	1	1	1
$\varepsilon_{trapping}$	0.05	0.05	1E-4	1
$\varepsilon_{coupling}$	0.4	0.05	1	1
$\varepsilon_{quantum}$	0.3	0.3	0.3	0.3
ε_{TOT}	2.4E-3	7.5E-4	3E-5	2E-2

Radiogenic from copper Reentrant Tube

Goal of these simulations

Preliminary



Problem: Th/U photons from Reentrant Tube (RT) releasing energy in HPGe without any release in UAr

Solution: tag photons emitted in coincidence interacting inside AAr volume

Next slides:

- simulate Th/U in RT volume
- compute total energy released in HPGe, UAr, AAr
- select events with energy in **HPGe but NO UAr**
- **compute BI around $Q_{\beta\beta}$ and correlate with energy in AAr**
- **compute distance of energy releases from RT**

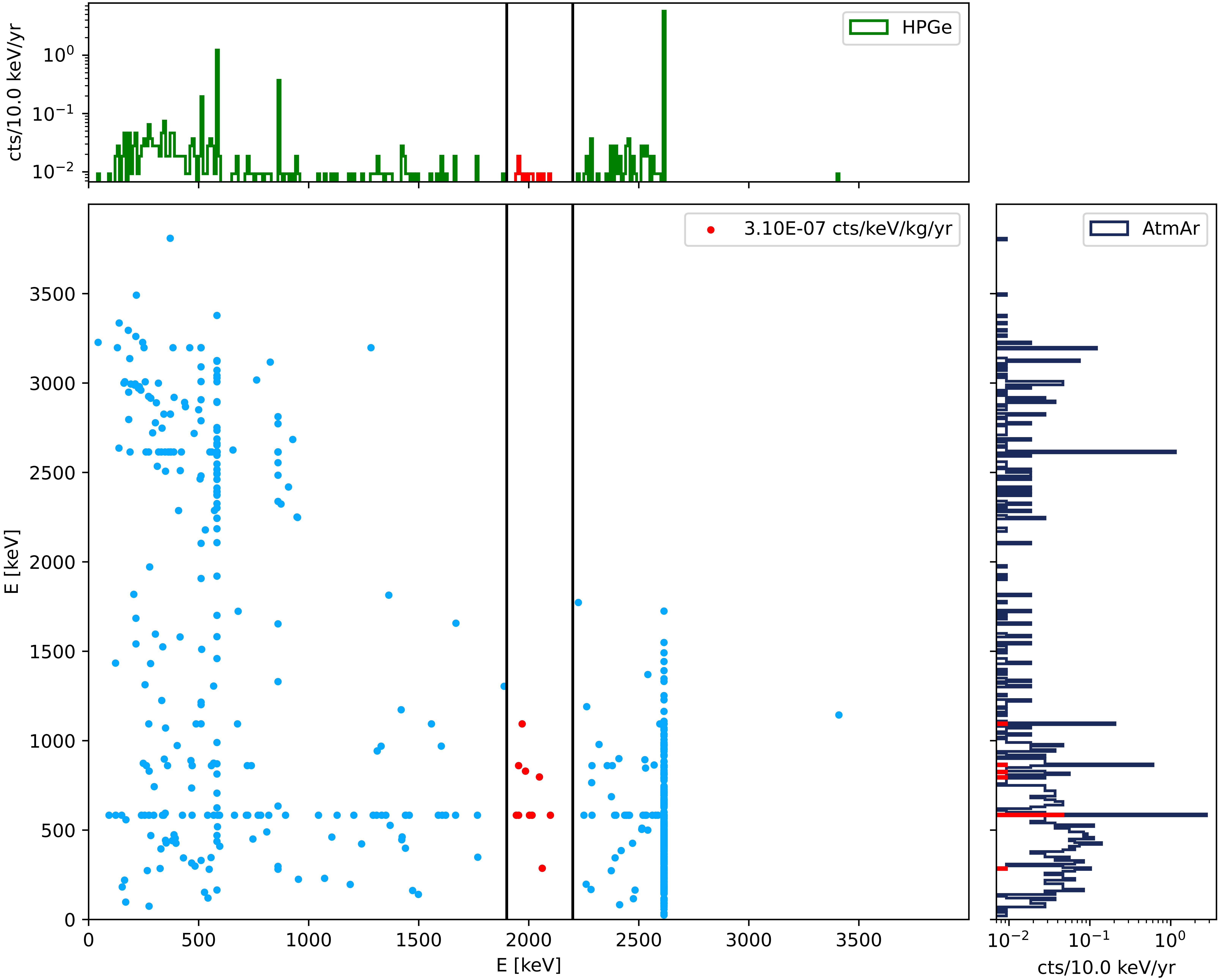
Simulations: Details

Preliminary

- simulations done using warwick-legend
- ^{208}Tl and ^{214}Bi decays simulated homogeneously inside RT volume
- RT thickness: 3 mm
- RT radius: 0.95 m
- RT radius: 4 m inside cryostat
- copper activity assumed: 0.3 μBq (from pCDR)

Tl208 – HPGe vs AtmAr

Preliminary



Events selection:

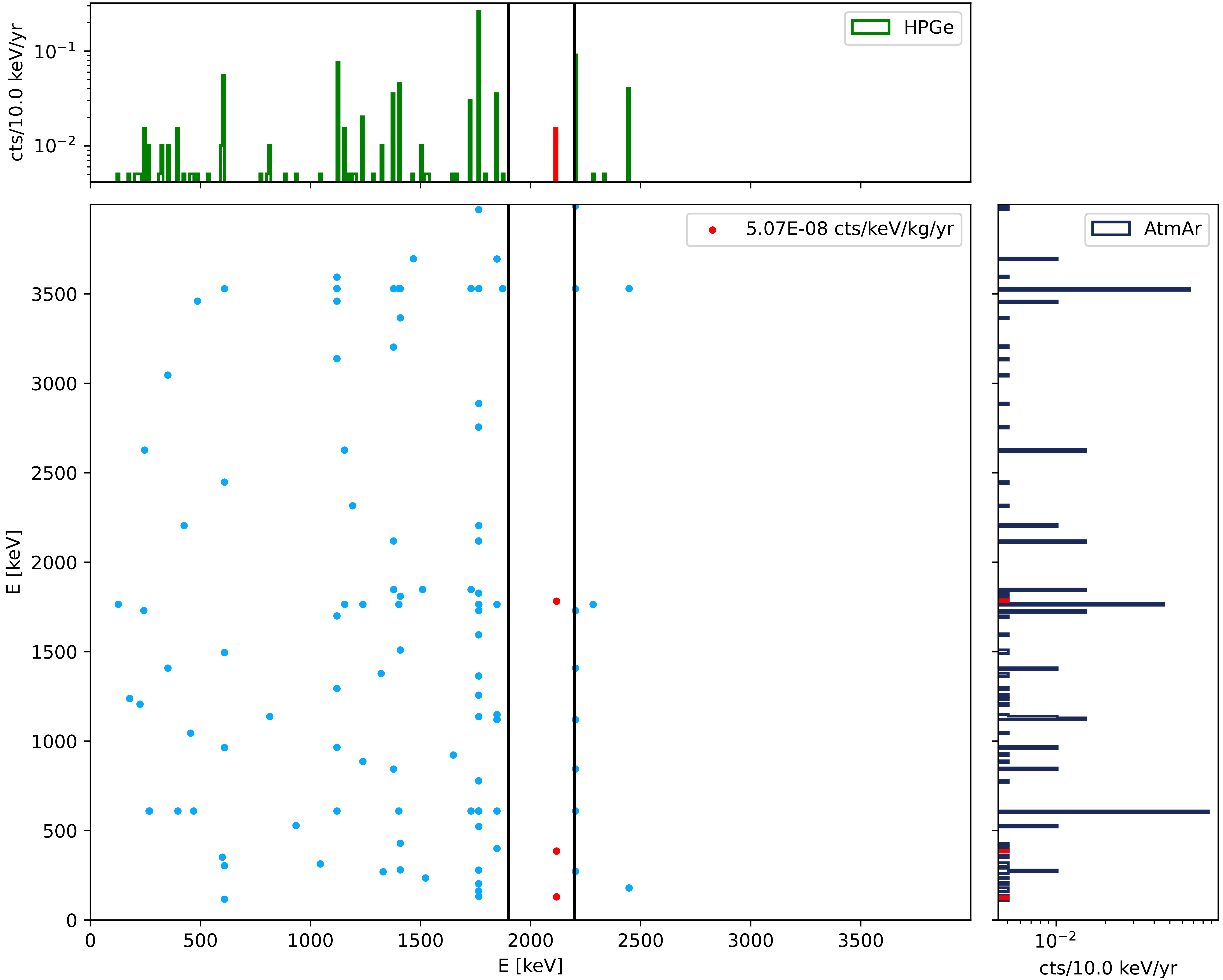
- energy release in single HPGe
- energy release in AtmAr
- **NO** energy release in UgAr
- **NO** PSD or LAr veto applied

Events in ROI [1900, 2200] keV:

- 10 events surviving
- AtmAr energy <1200 keV
- BI 3.10×10^{-7} cts/keV/kg/yr

Bi214 – HPGe vs AtmAr

Preliminary



Events selection:

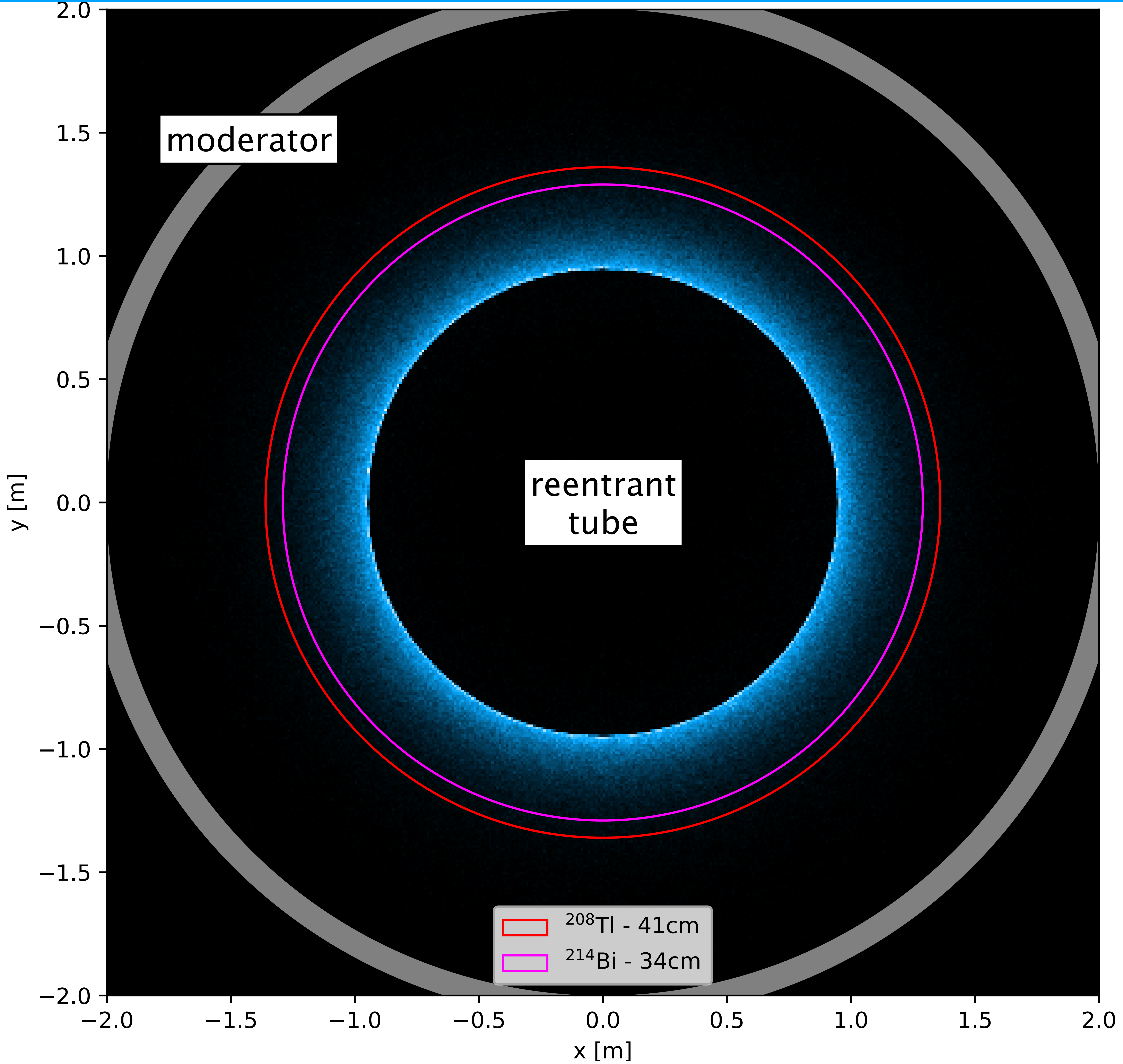
- energy release in single HPGe
- energy release in AtmAr
- **NO** energy release in UgAr
- **NO** PSD or LAr veto applied

Events in ROI [1900, 2200] keV:

- 3 events surviving
  (more statistics needed…)
- BI 5.07×10^{-8} cts/keV/kg/yr

Energy release – Position

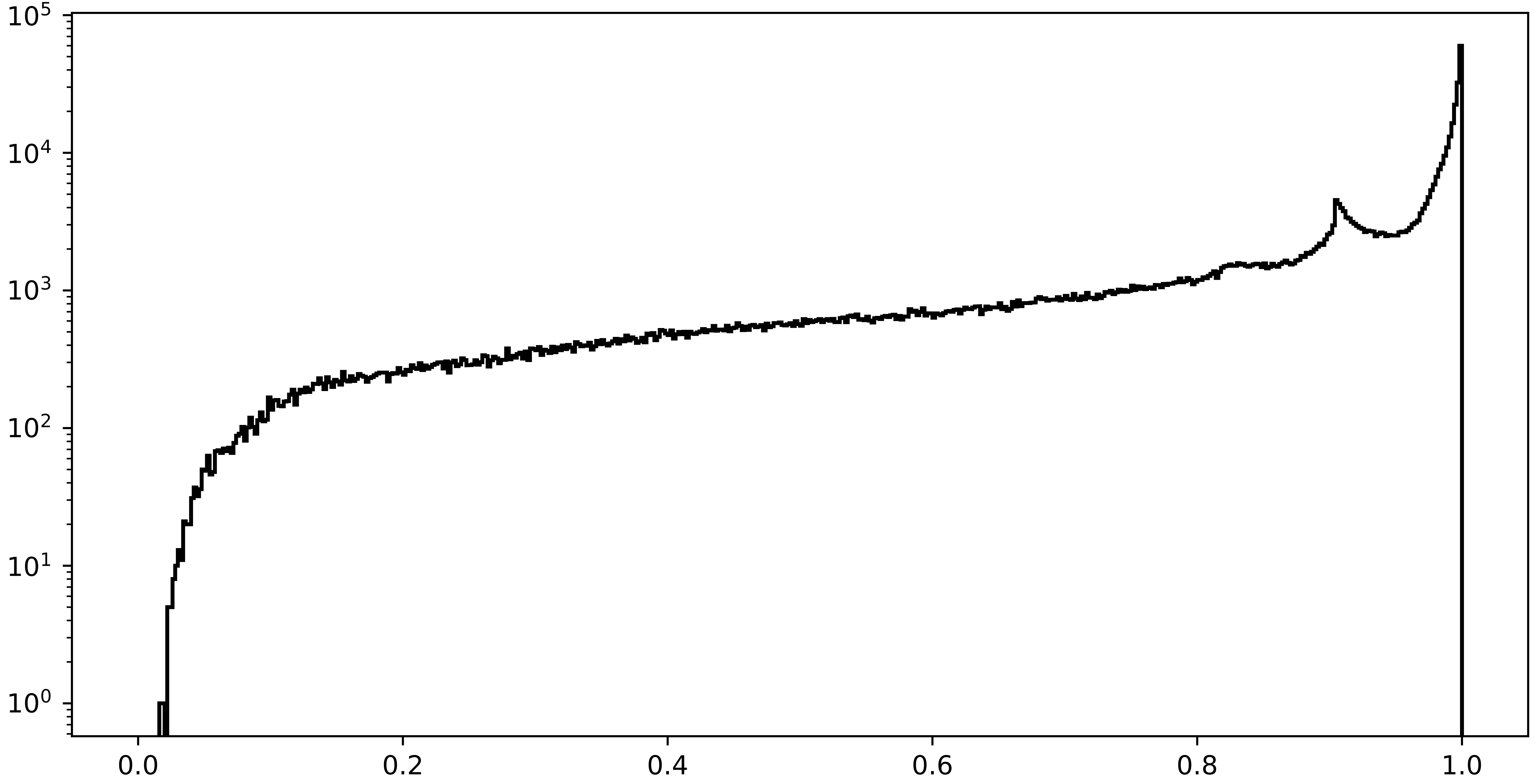
Preliminary



- radius from RT in which 90% of energy is released
- 34cm for ^{214}Bi
- 41cm for ^{208}Tl

Neutron interactions with moderator inside LEGEND

Final Energy / Initial Energy (Argon)



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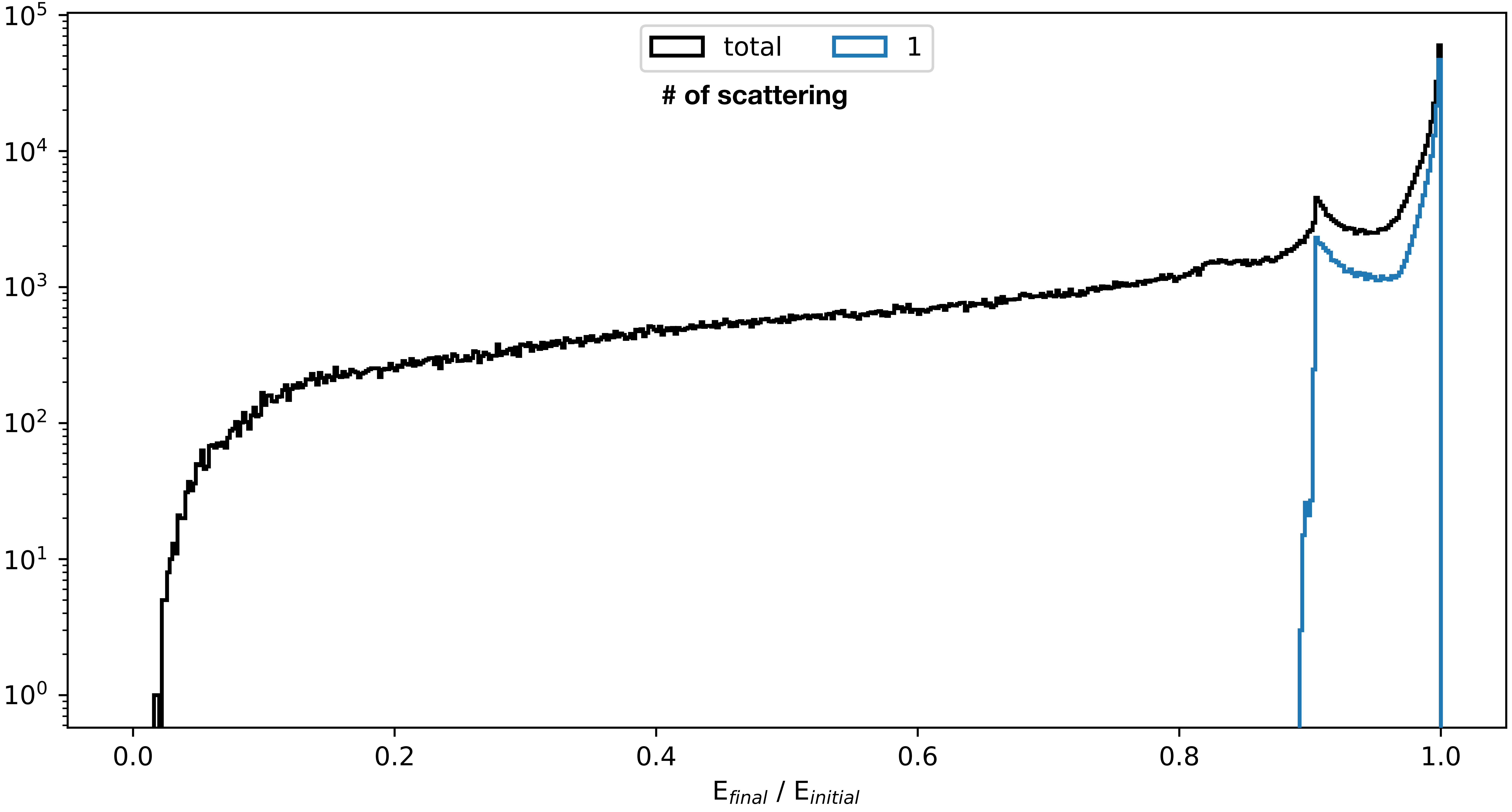

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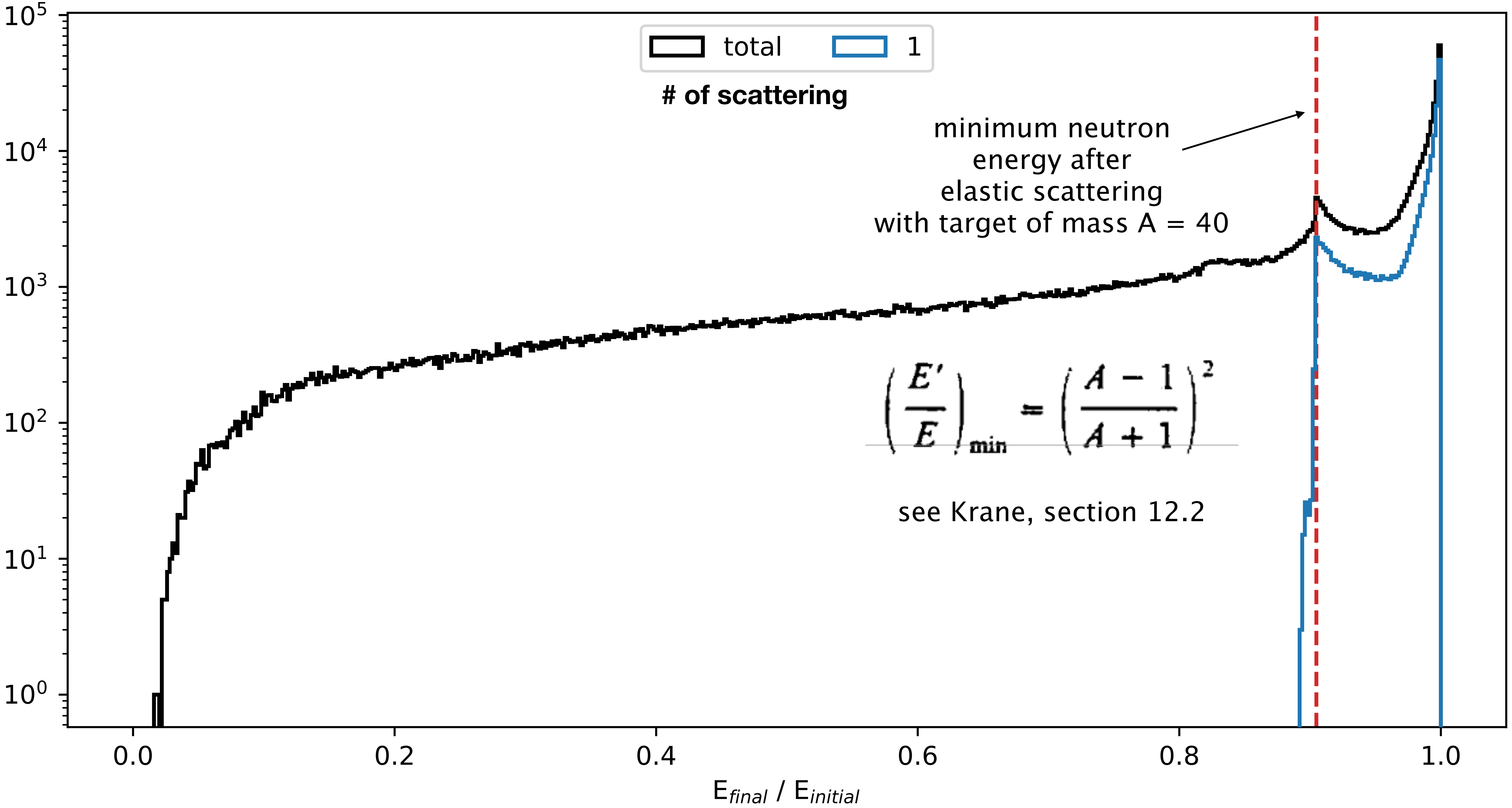

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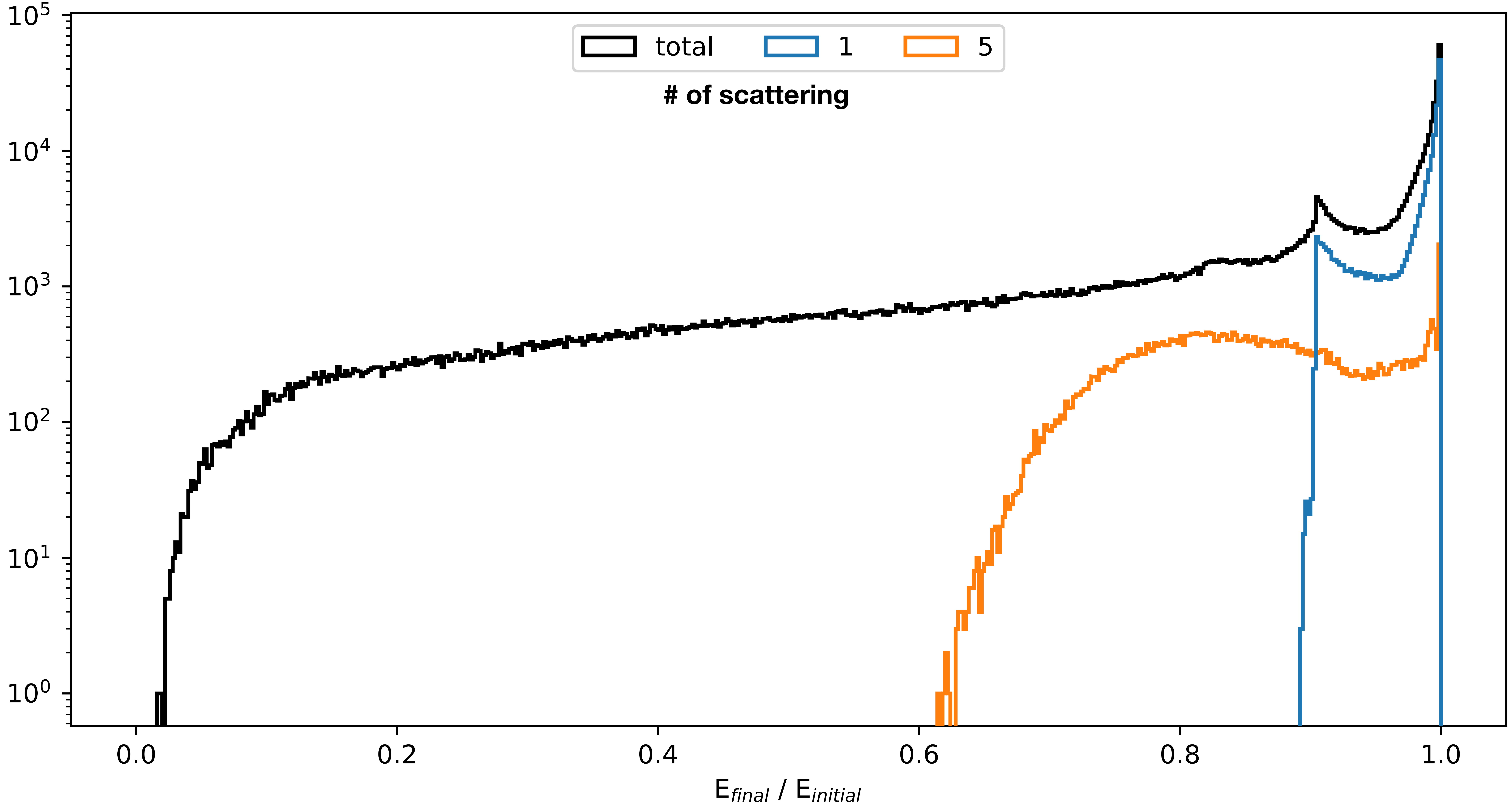

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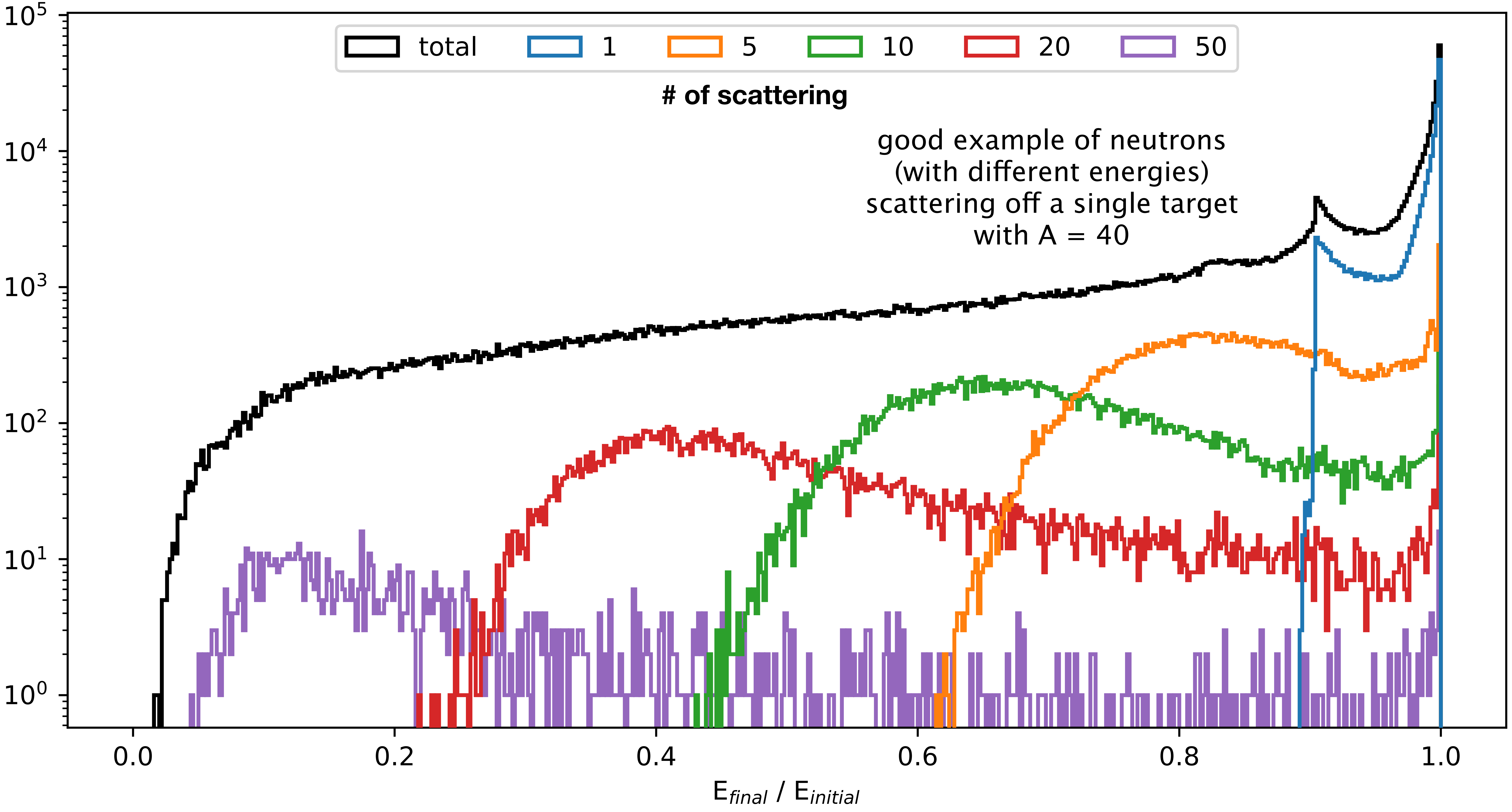
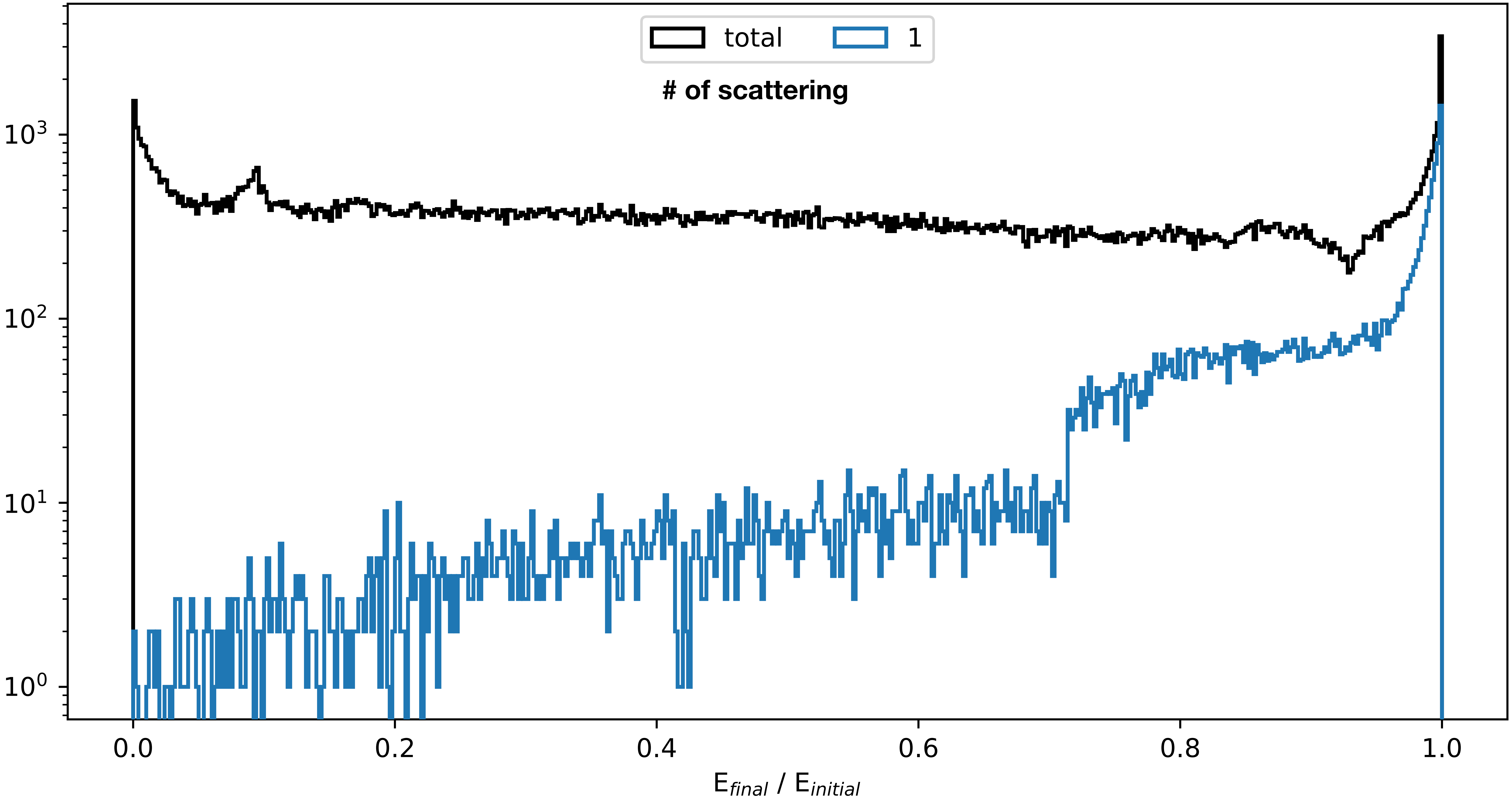
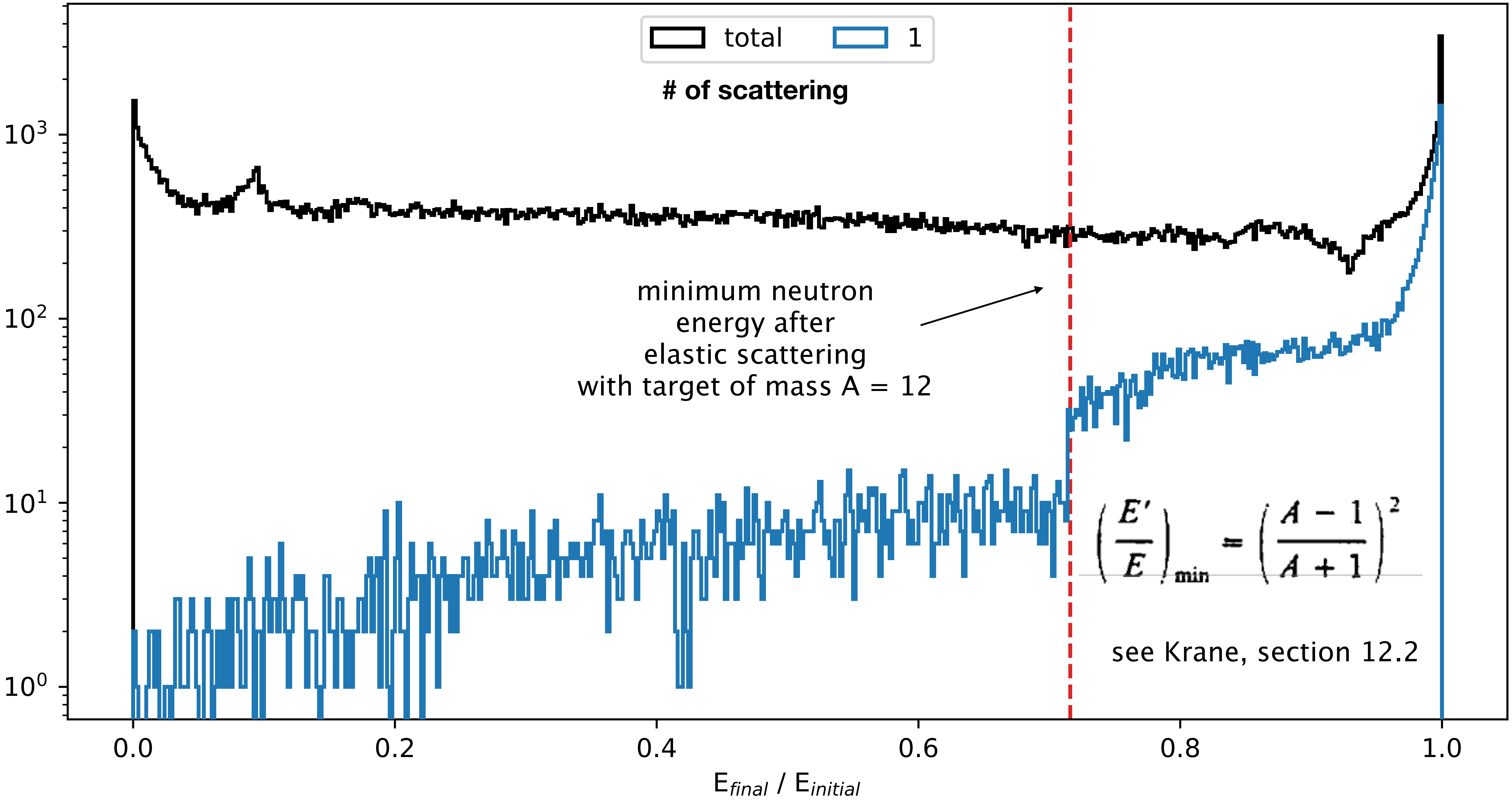


Final Energy / Initial Energy (moderator)



Final Energy / Initial Energy (moderator)



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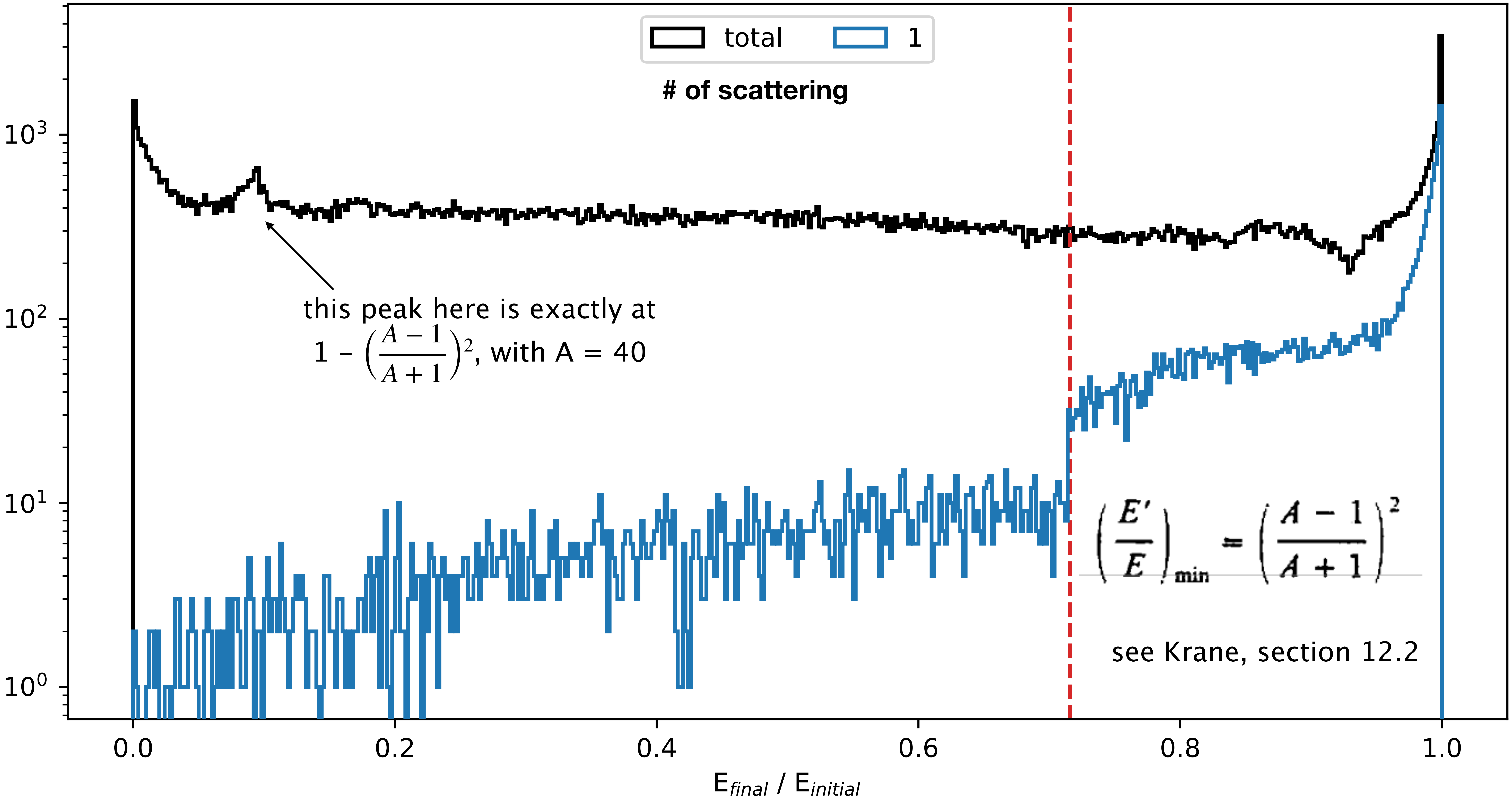

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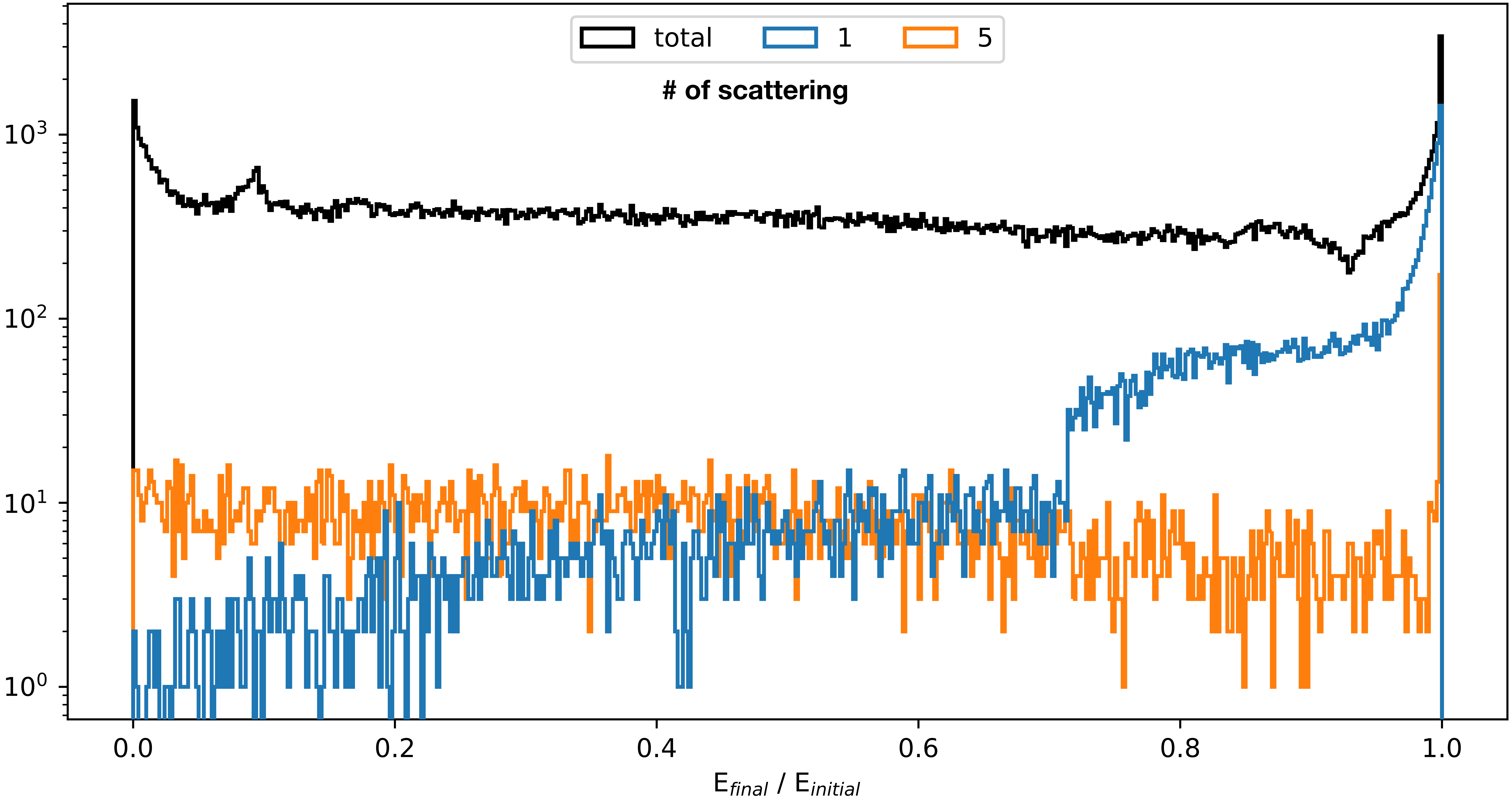

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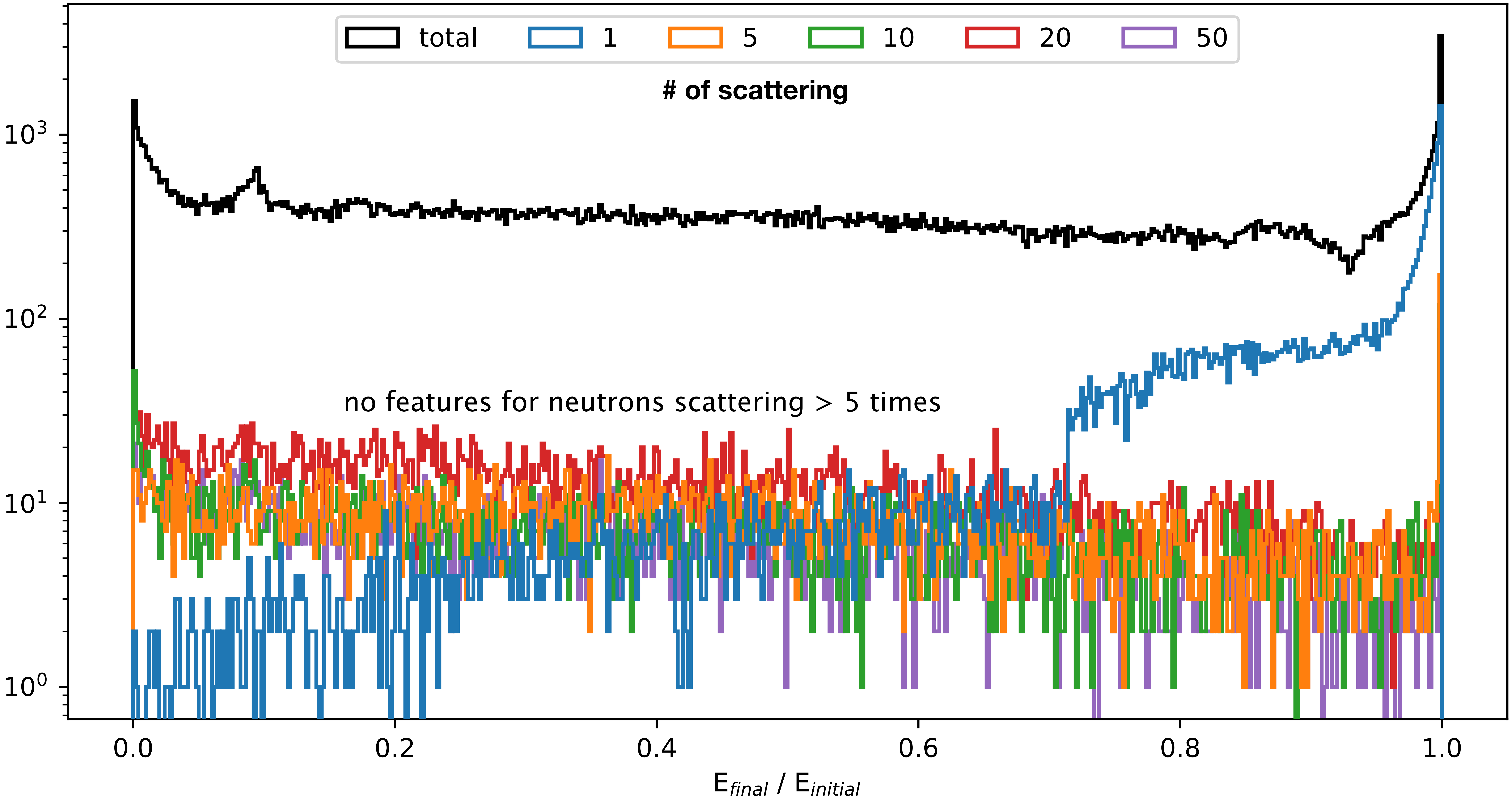
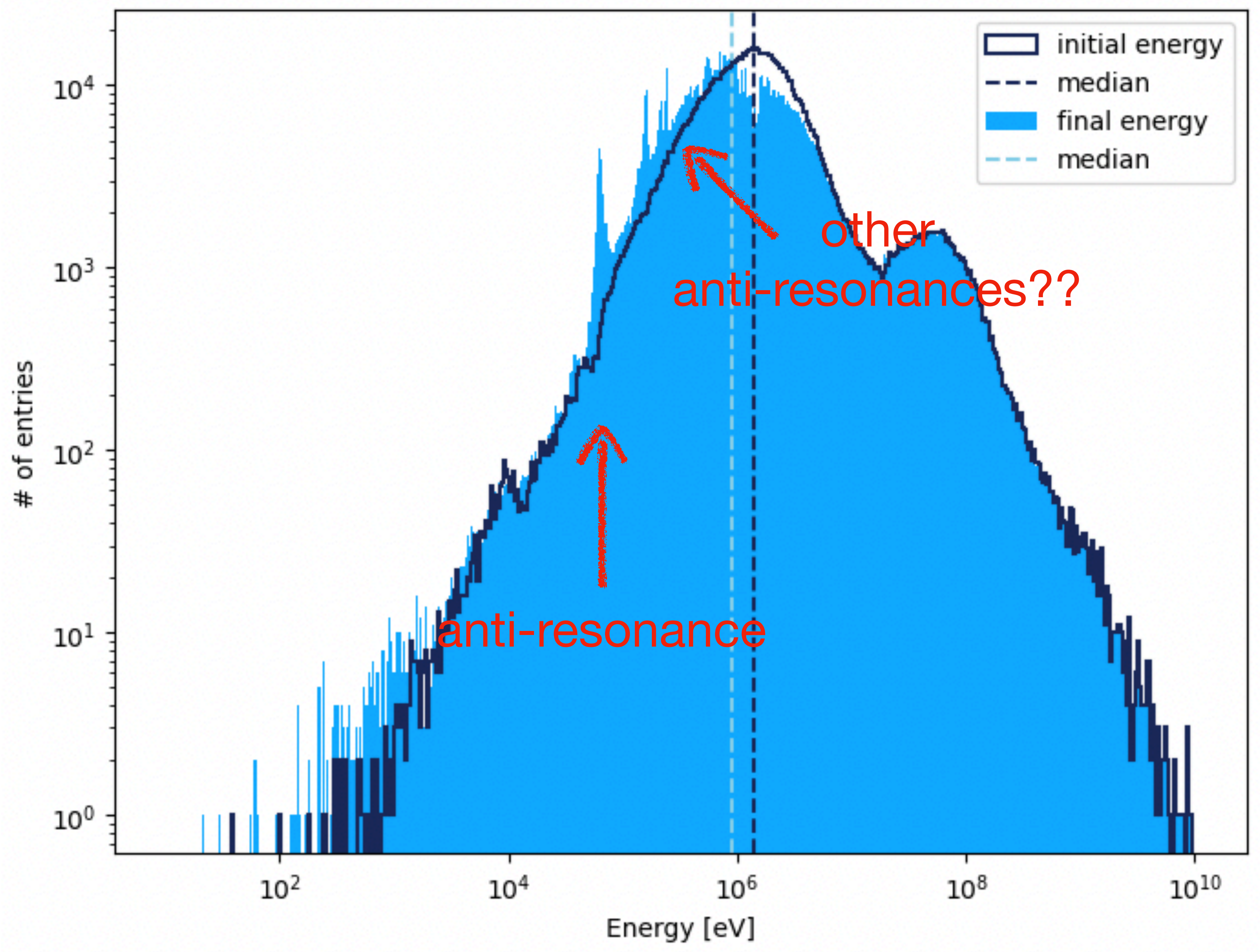
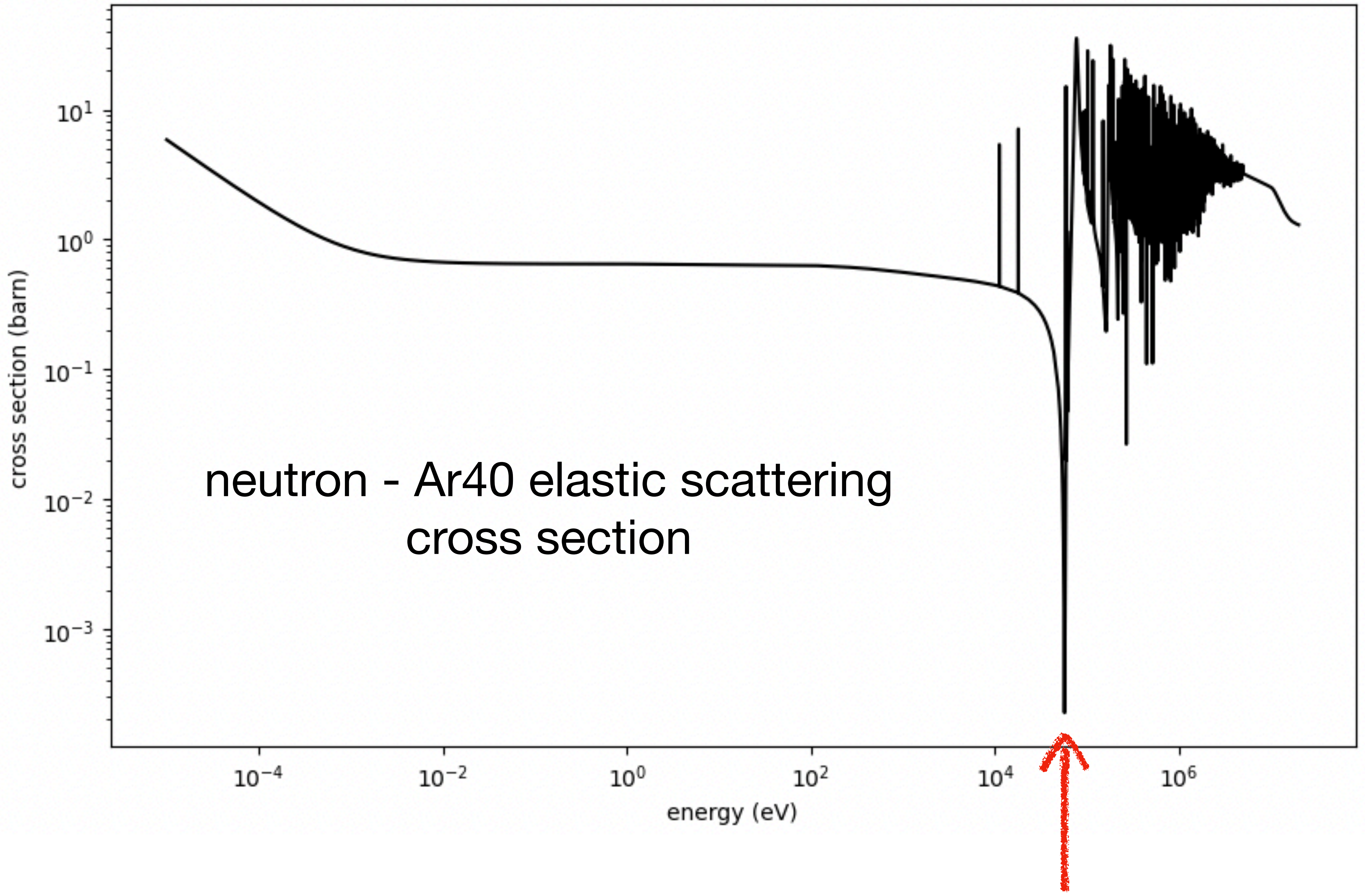


Conclusions

Neutrons having anti-resonance energy
(nearly) stop scattering off Ar40

i.e., higher population
of neutrons at those energies

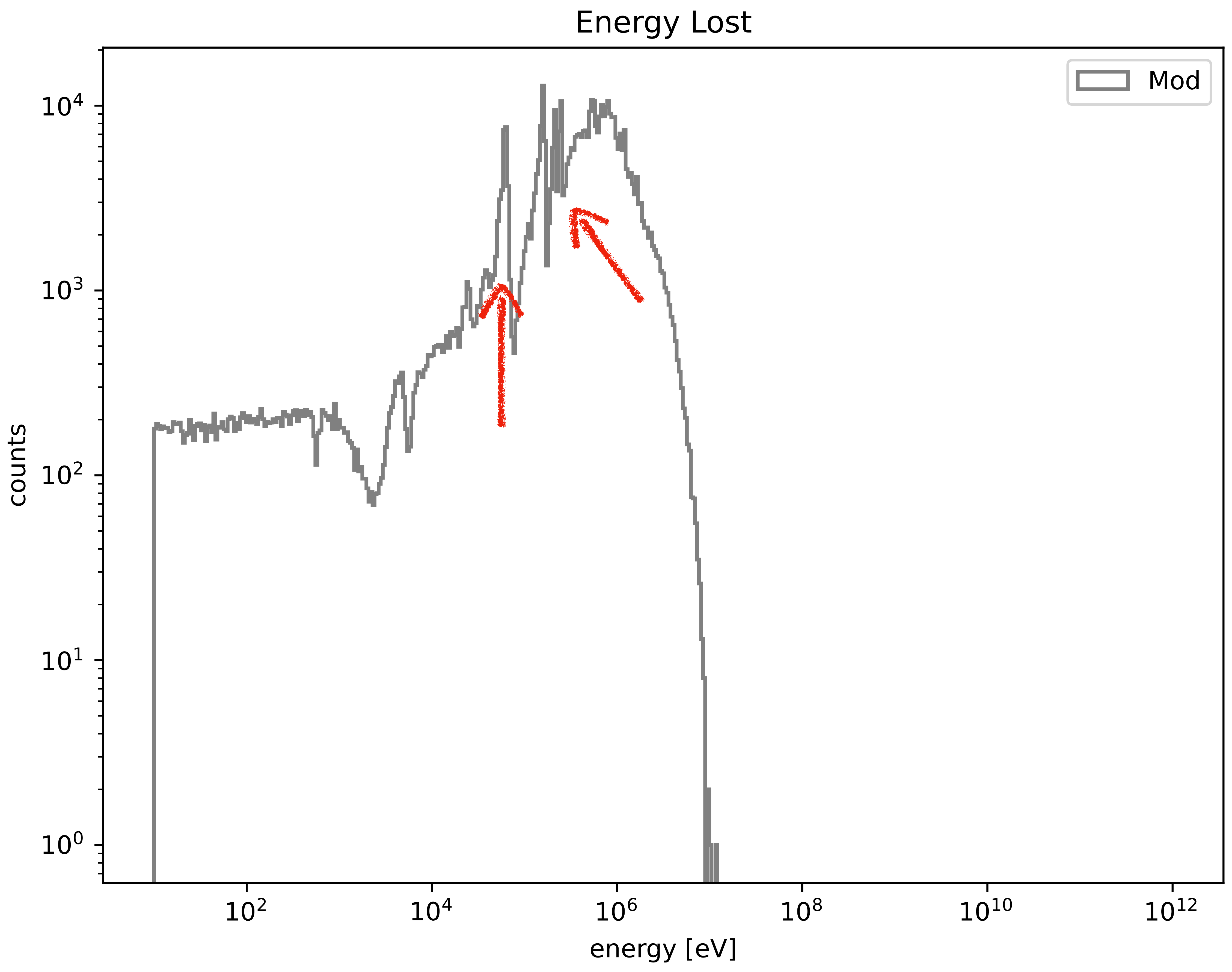


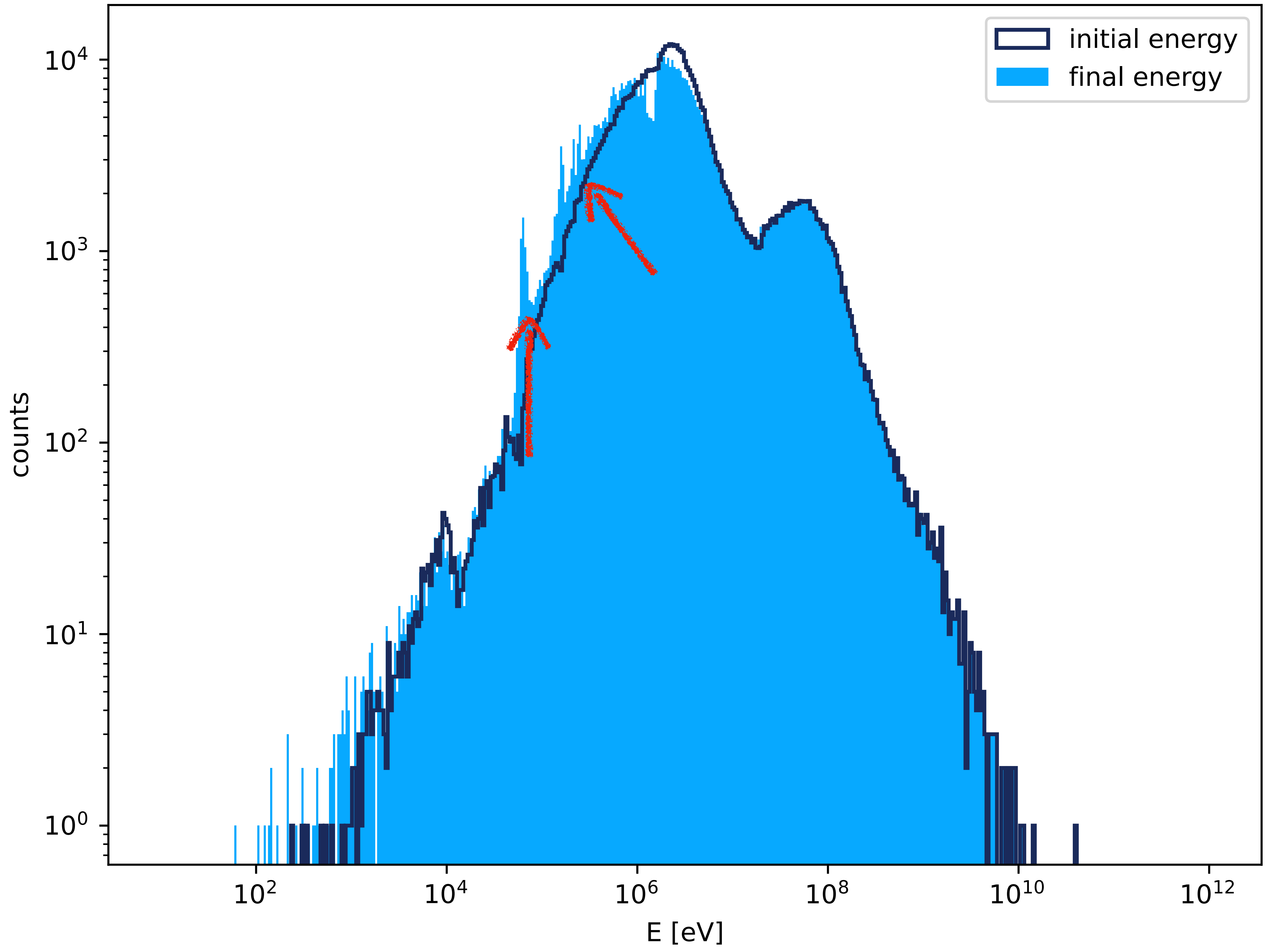


what happens when these neutrons
enter the moderator?

Conclusions

looking at the energy lost inside the moderator,
the same “spiky” feature at the same energy
of neutrons scattering off Ar40 is visible!!





Conclusions

looking at the energy lost inside the moderator,
the same “spiky” feature at the same energy
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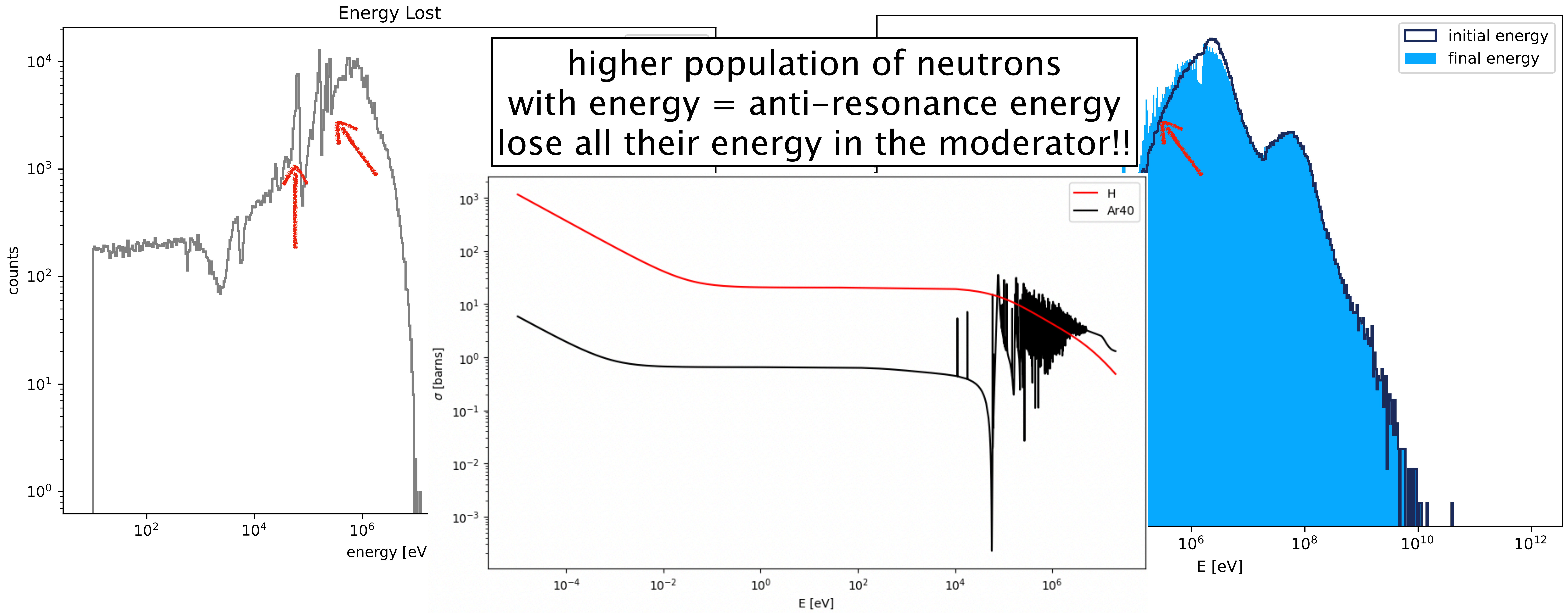

higher population of neutrons
with energy = anti-resonance energy
lose all their energy in the moderator!!