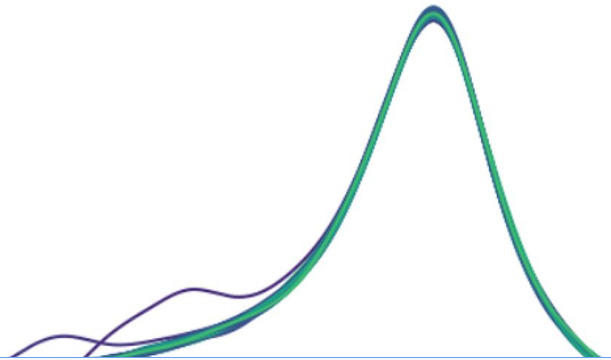
LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

UCL

Detector and background modelling for $0\nu\beta\beta$ searches in LEGEND -200

Toby Dixon (UCL)



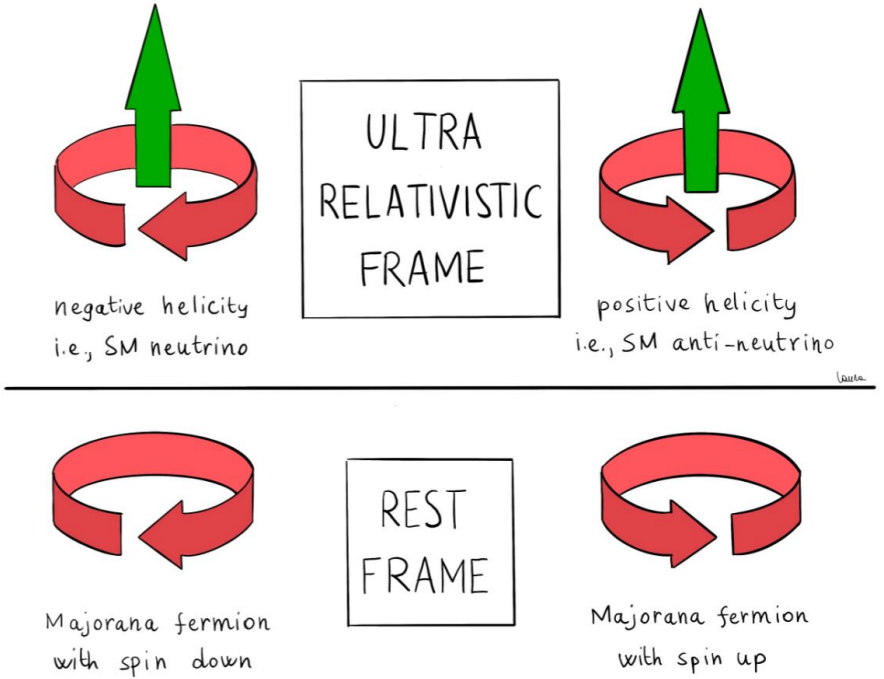
Motivation

*"What distinguishes **matter** from **antimatter?**'*

- Clear for charged particles but what abou neutral ones? eg. neutrinos

Intrinsic property or just the **helicity**?

- Especially interesting now we know **neutrinos have mass**
- So they have a **rest frame**



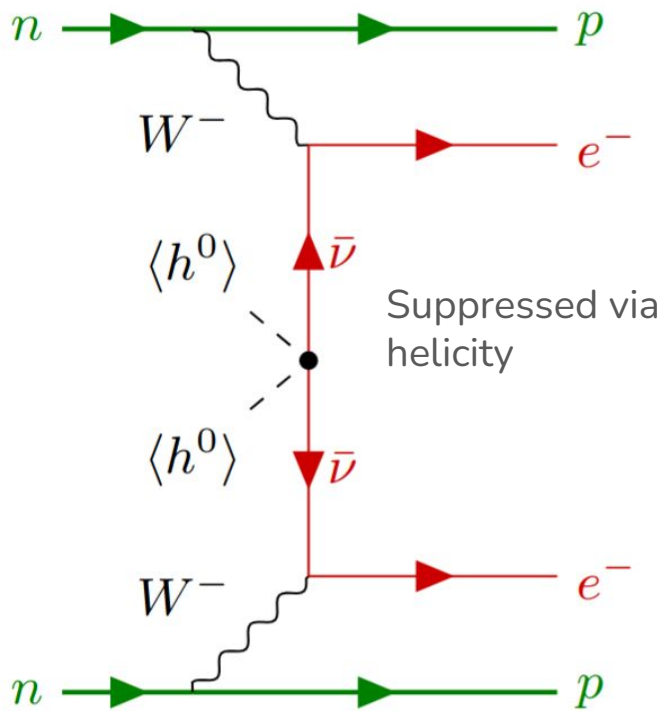
Taken from arxiv:2202.01787

Neutrinoless double beta decay ($0\nu\beta\beta$)

- Neutrinoless double beta decay (**0νββ**) probes matter-antimatter asymmetry with neutrinos

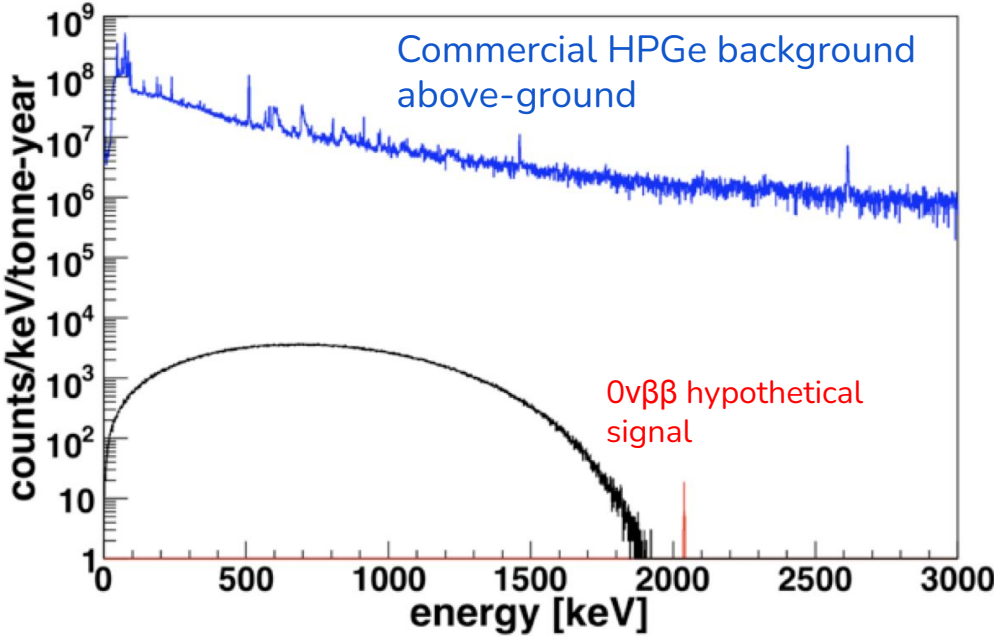
$$2n \rightarrow 2p + 2\,e^-$$

- Would **violate Lepton number** conservation "convert antimatter into matter"
- **Bonus**: Would enable a different mechanism to generate the neutrino masses



Searching for $0\nu\beta\beta$ in ^{76}Ge

- Signal is expected to be vanishingly small!



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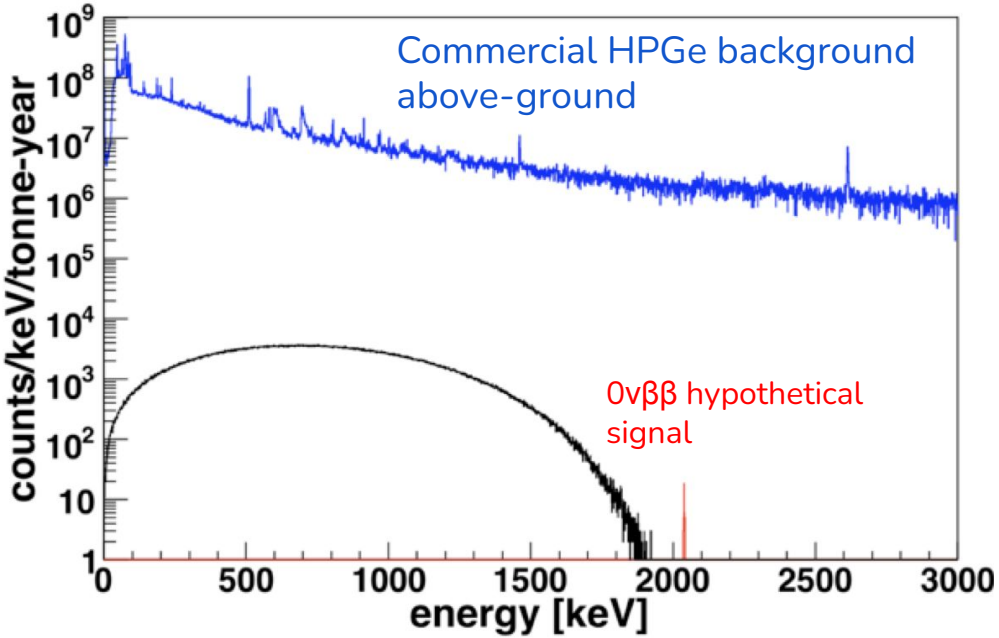
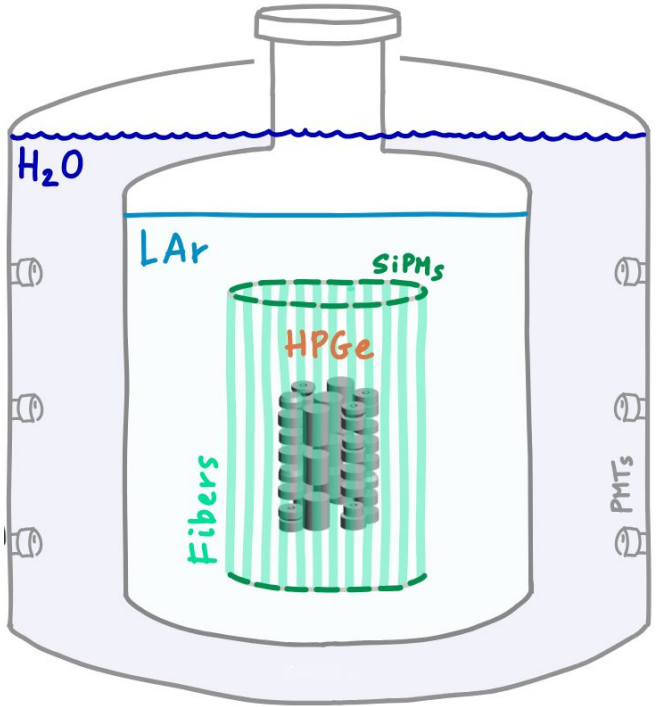
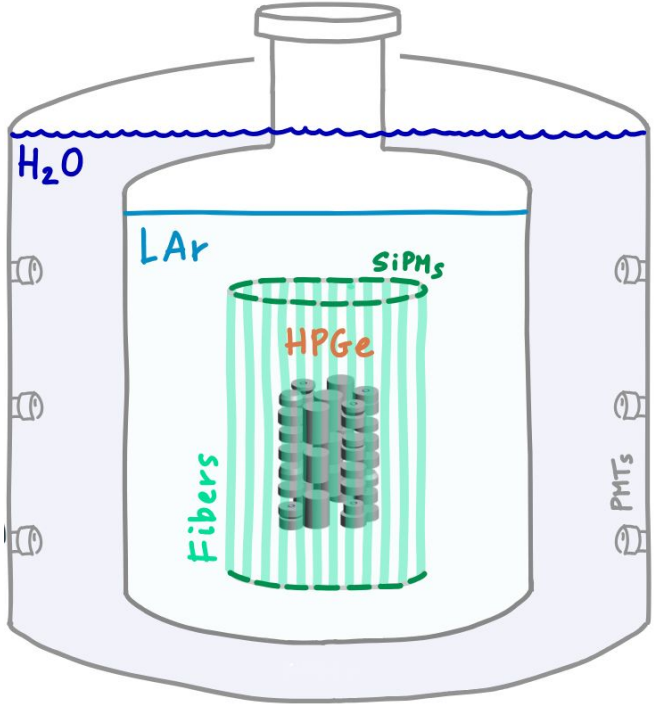




Searching for $0\nu\beta\beta$ in ^{76}Ge

- Operated **underground**
  - Shielding from cosmic rays
- **Active shielding** with pure water and liquid argon
- **Radiopure materials**
- High-purity Germanium (HPGe) detectors
  - Enriched in ^{76}Ge → **high efficiency!**
  - **Exquisite energy resolution** and topological **background rejection capacity**
  -



The LEGEND experimental program

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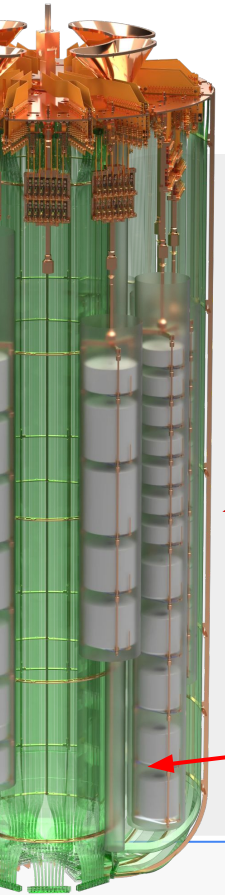
*"develop a **phased**, ^{76}Ge-based double-beta decay experimental program with **discovery potential** at a half-life beyond 10^{28} yr"*

The LEGEND experimental program



*"develop a **phased**, ^{76}Ge-based double-beta decay experimental program with **discovery potential** at a half-life beyond 10^{28} yr"*

LEGEND-200

Begin to explore inverted neutrino masses

- Currently running at LNGS
- ~*140* kg[1] of Ge detectors immersed in liquid argon

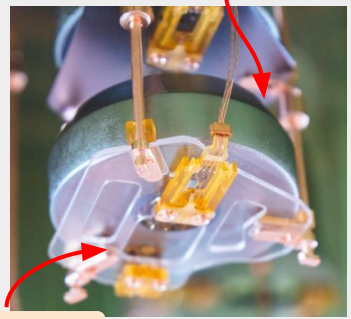
Germanium

Nylon foils

Surrounded by LAr

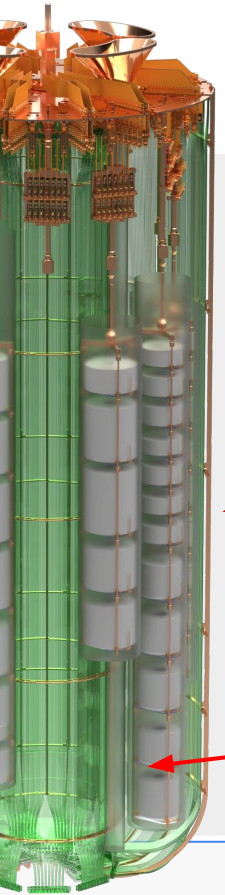
Optical fibers

Holders



Electronics

The LEGEND experimental program



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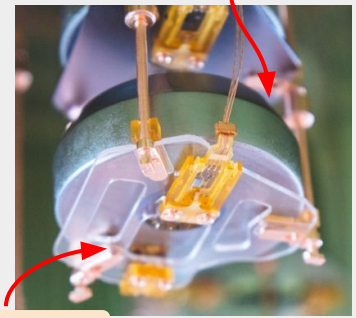


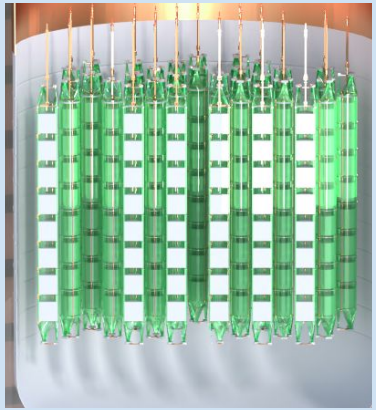
Electronics

Design depends on the lessons learnt in L-200

LEGEND-1000

Fully explore inverted neutrino masses

- Planned with 1000 kg of Ge



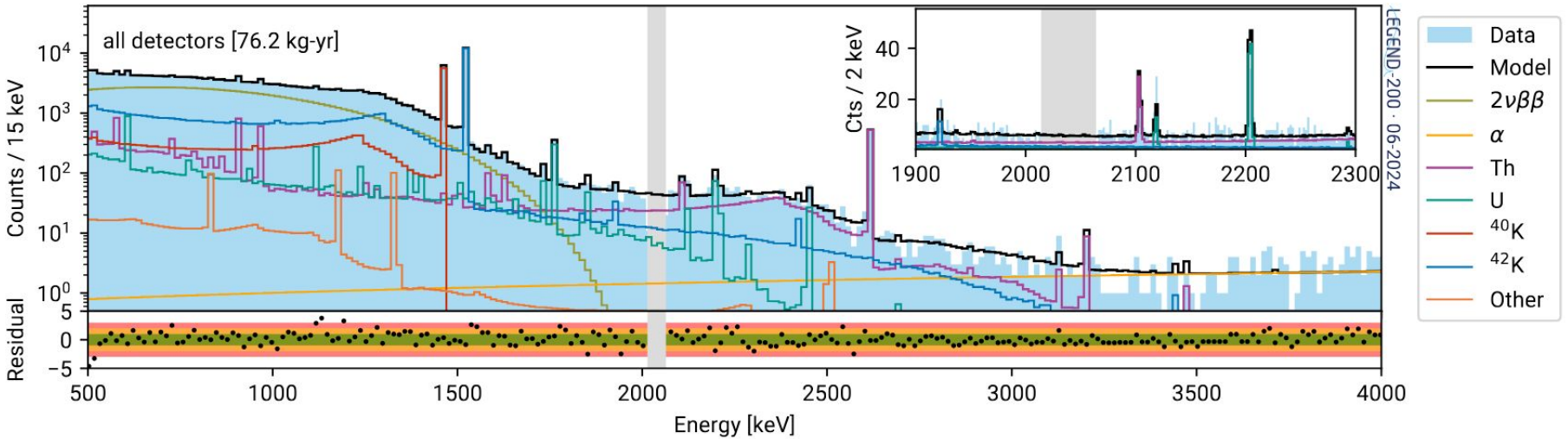
Background modelling LEGEND -200

Dedicated modelling of the experimental data

- Where does the background come from (mitigation)?

Spectral fit based on simulated **Monte-Carlo templates**

Only before LAr veto and pulse shape cuts

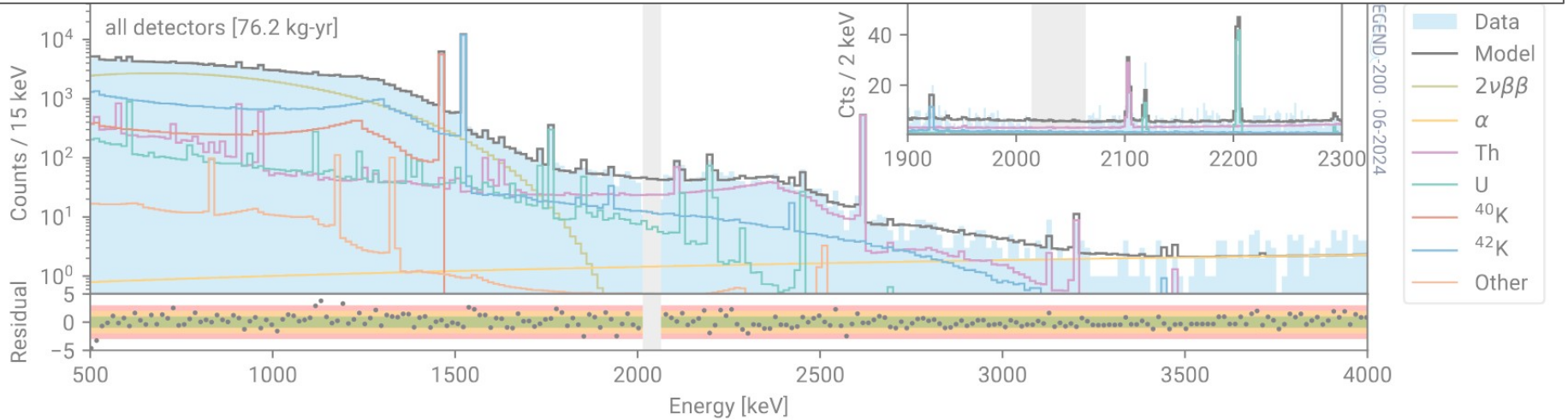


Background modelling LEGEND -200

Good **agreement with the data**!

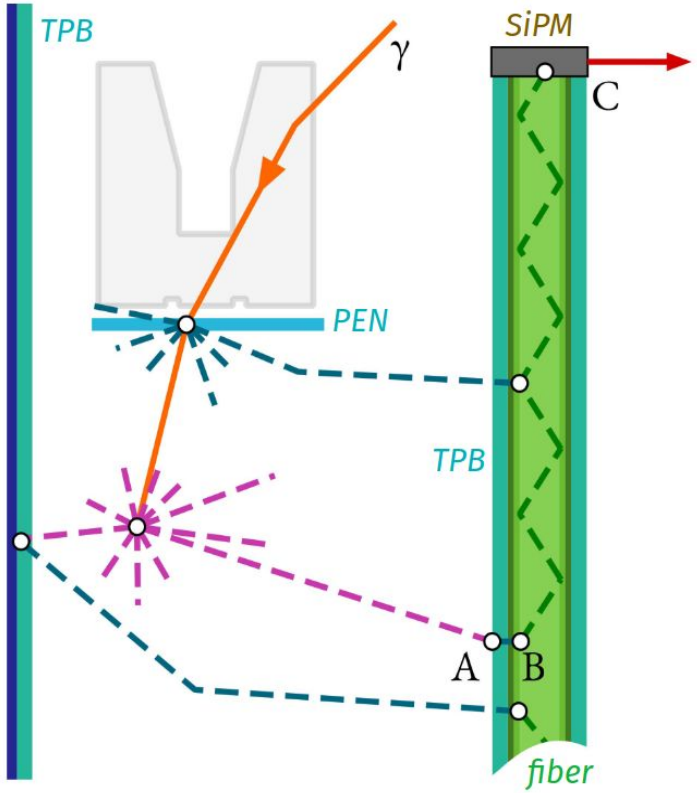
Predicts a **flat, featureless spectrum** at the expected $0\nu\beta\beta$ signal region

Potential of this work is limited by the modelling being only performed **before active suppression cuts**



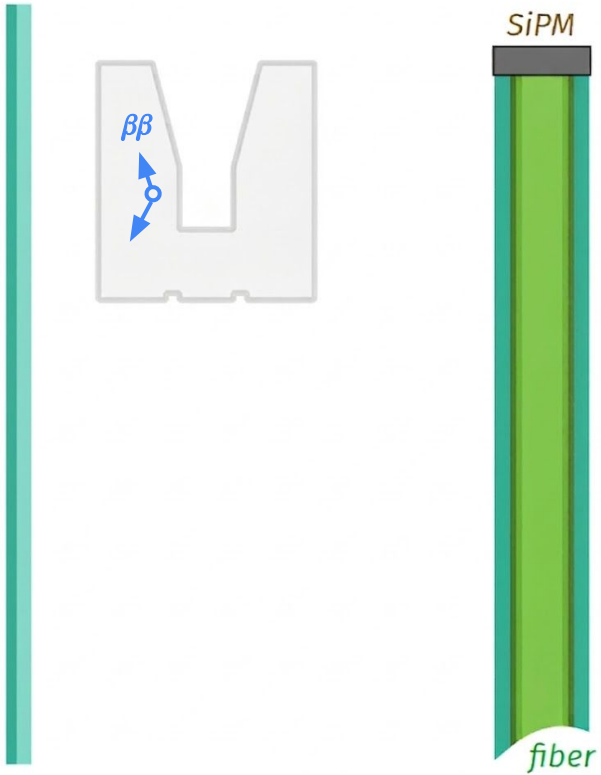
Background reduction strategies

- **Backgrounds**
  - Many γ's scatter in LAr
  - Scintillation light signal that can veto evens
  - Multiple scatter events in the HPGe can also be removed due to distinct pulse shape



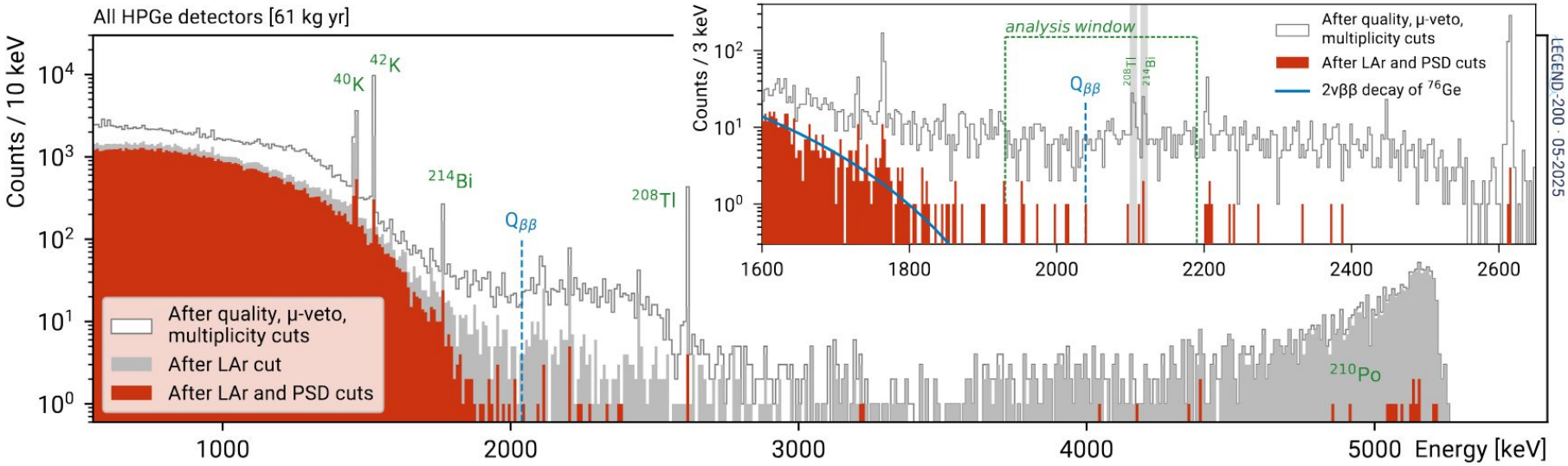
Background reduction strategies

- **Backgrounds**
  - Many γ's scatter in LAr
  - Scintillation light signal that can veto evens
  - Multiple scatter events in the HPGe can also be removed due to distinct pulse shape
- **Signal events**
  - Only single interaction in a HPGe detector



Towards background model after analysis cuts

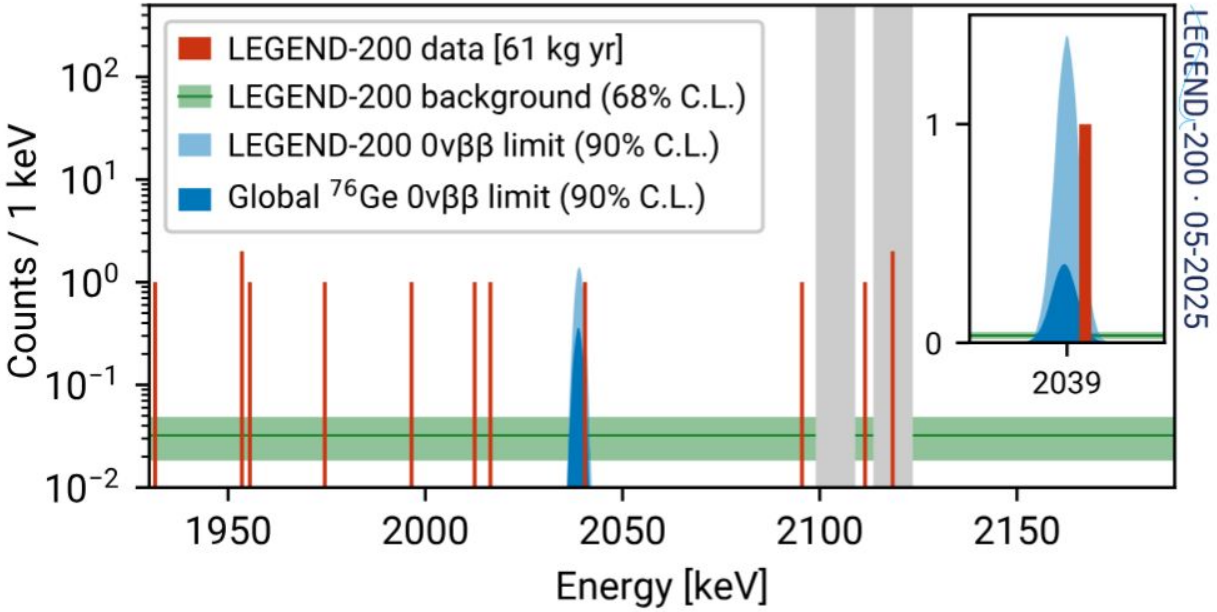
- These selection cuts **remove most of the events**
- What is the fraction remaining?



First $0\nu\beta\beta$ search results from LEGEND 200

Now published in PRL!

- Based on this data we can **search for $0\nu\beta\beta$**
- Based on first year of LEGEND-200 data
- No **evidence found!**



First $0\nu\beta\beta$ search results from LEGEND 200

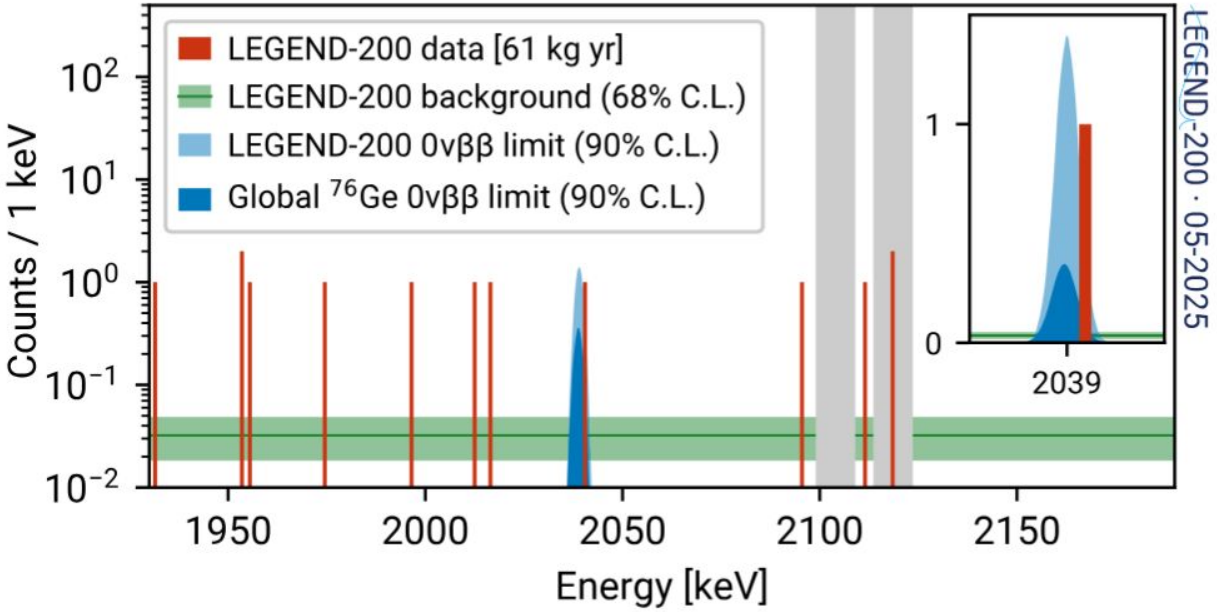
Now published in PRL!

- Simple peak search
- No sophisticated background model or multivariate analysis

After **combination** with past ^{76}Ge experiments

$T_{1/2} > 1.9 \times 10^{26}$ yrs

Fully **open-source** package to perform the statistical analysis [link]



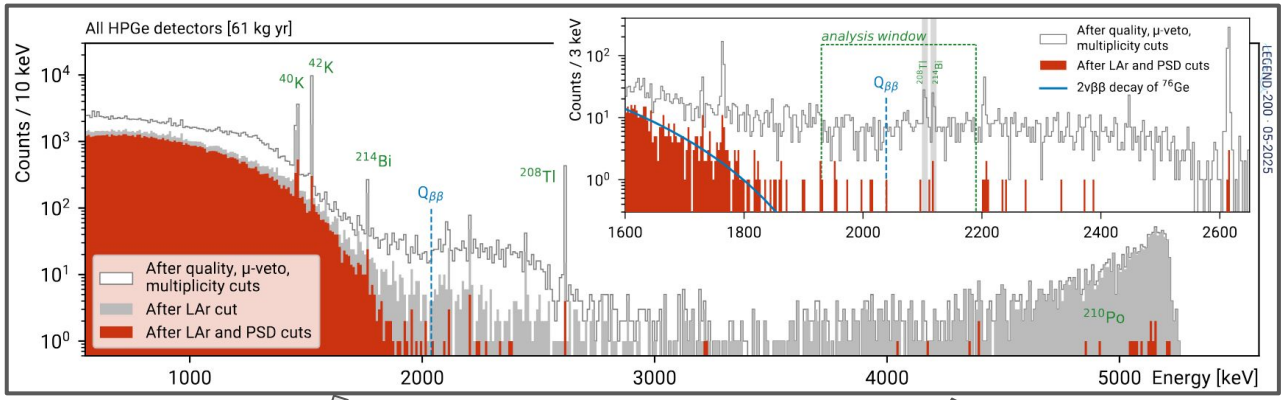
Towards background model after analysis cuts

But we aim to also **model the data** after these cuts

Modelling the data

after all cuts

would enable:



Design optimisation and background mitigation

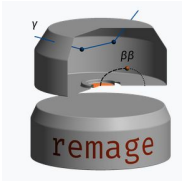
More advanced analysis strategy for $0\nu\beta\beta$

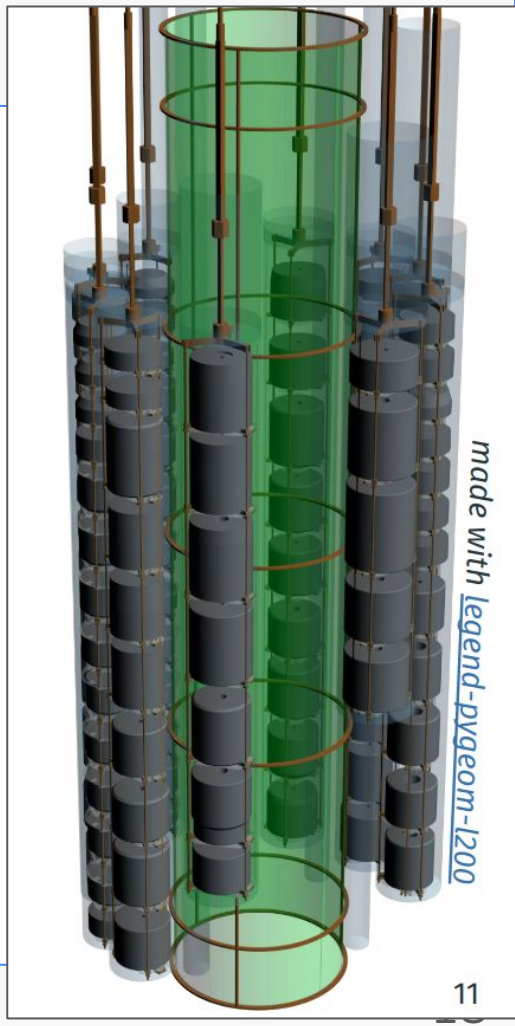
Unlock further physics studies!

In the long run, this is also a critical step towards any discovery being "convincing"...

Simulations in LEGEND -200

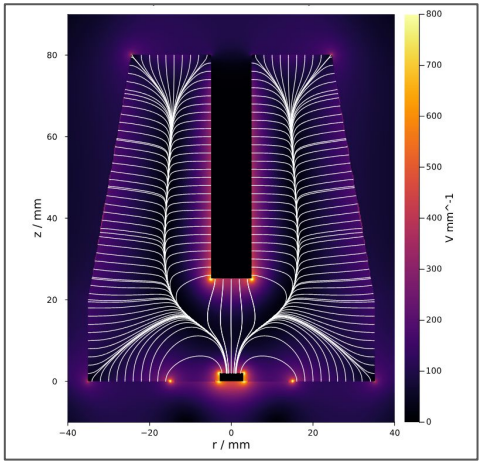
- Based on `remage` : Geant4 framework for low background experiments: **fully open software source!**
- Geometry **fully implemented** in *python*
  - Automatic extraction of the HPGe geometries, and detector layout from existing metadata
- Open source software [link]
- Full integration of optical parameters, for LAr scintillation read out



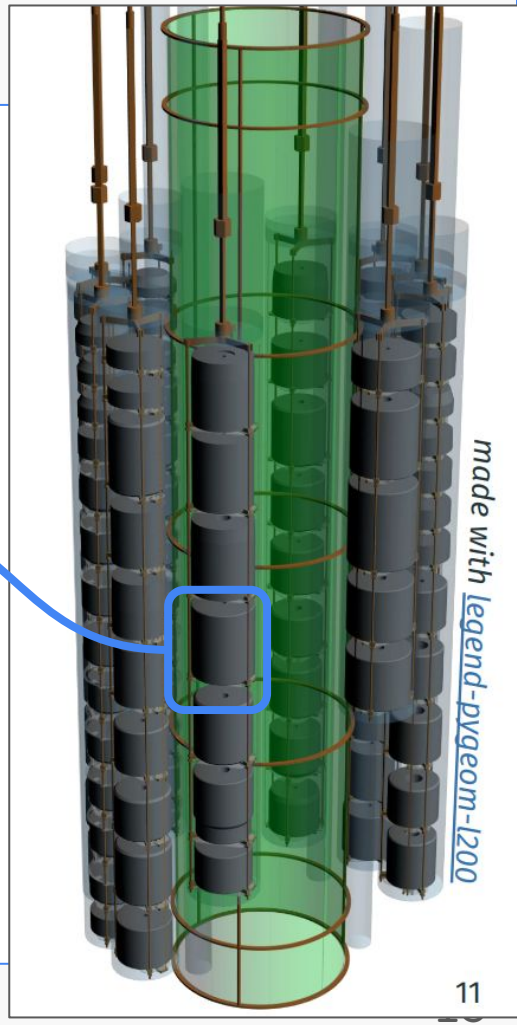


Pulse shape discrimination simulations

- HPGe detectors are **not just calorimeters!**
- **Signal pulse shape** can discriminate signal from background
  - Difficult to simulate!
    - Computationally intensive
    - Many input parameters
    - Many detectors
  - Developed **partially-data driven methods** able to simulate for all detectors

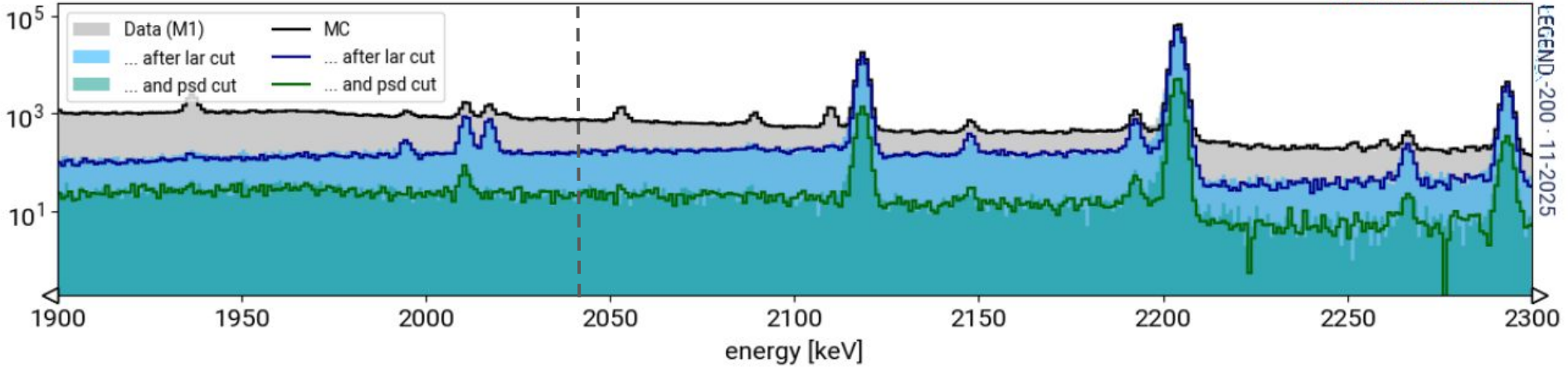


Fast enough to simulate every simulated MC event!

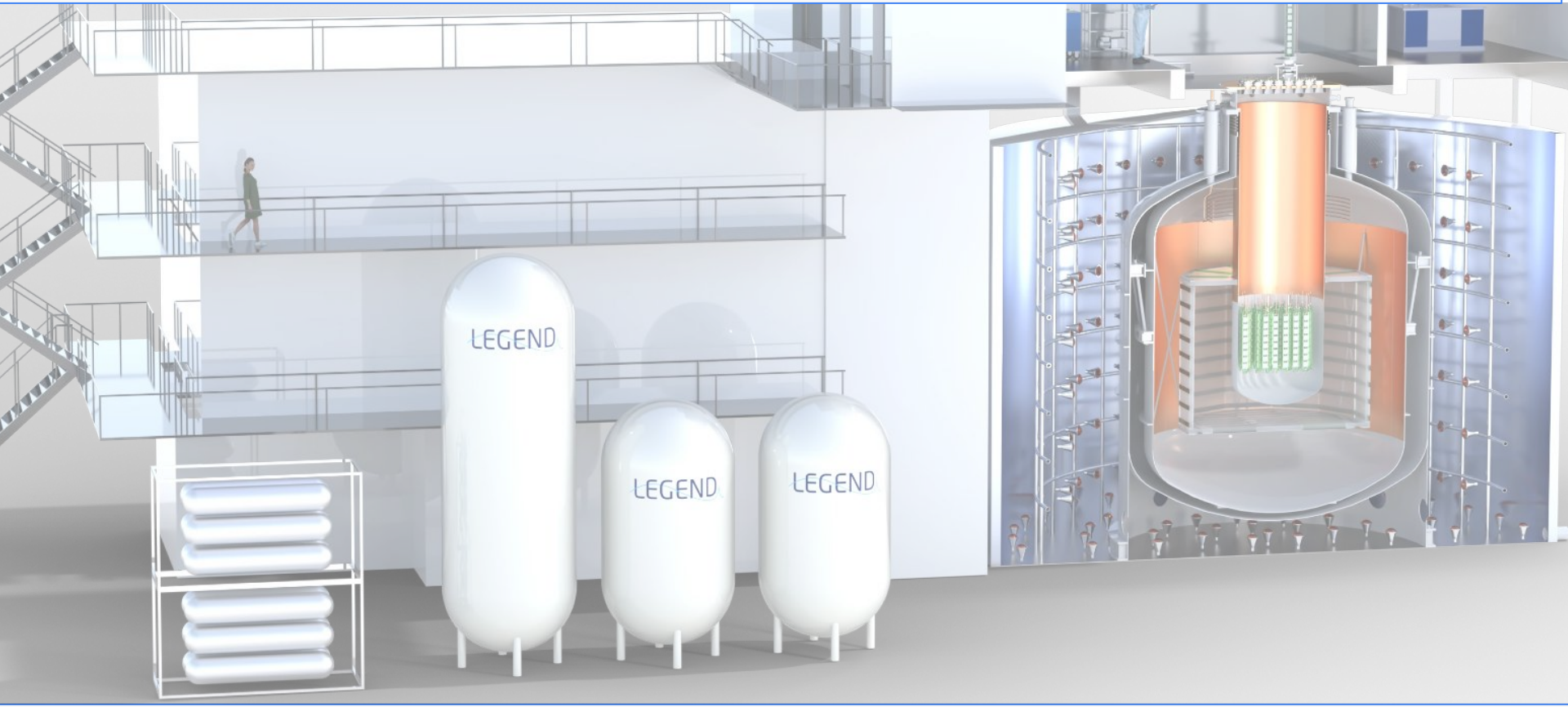


[WIP] validation with in-situ characterisation data

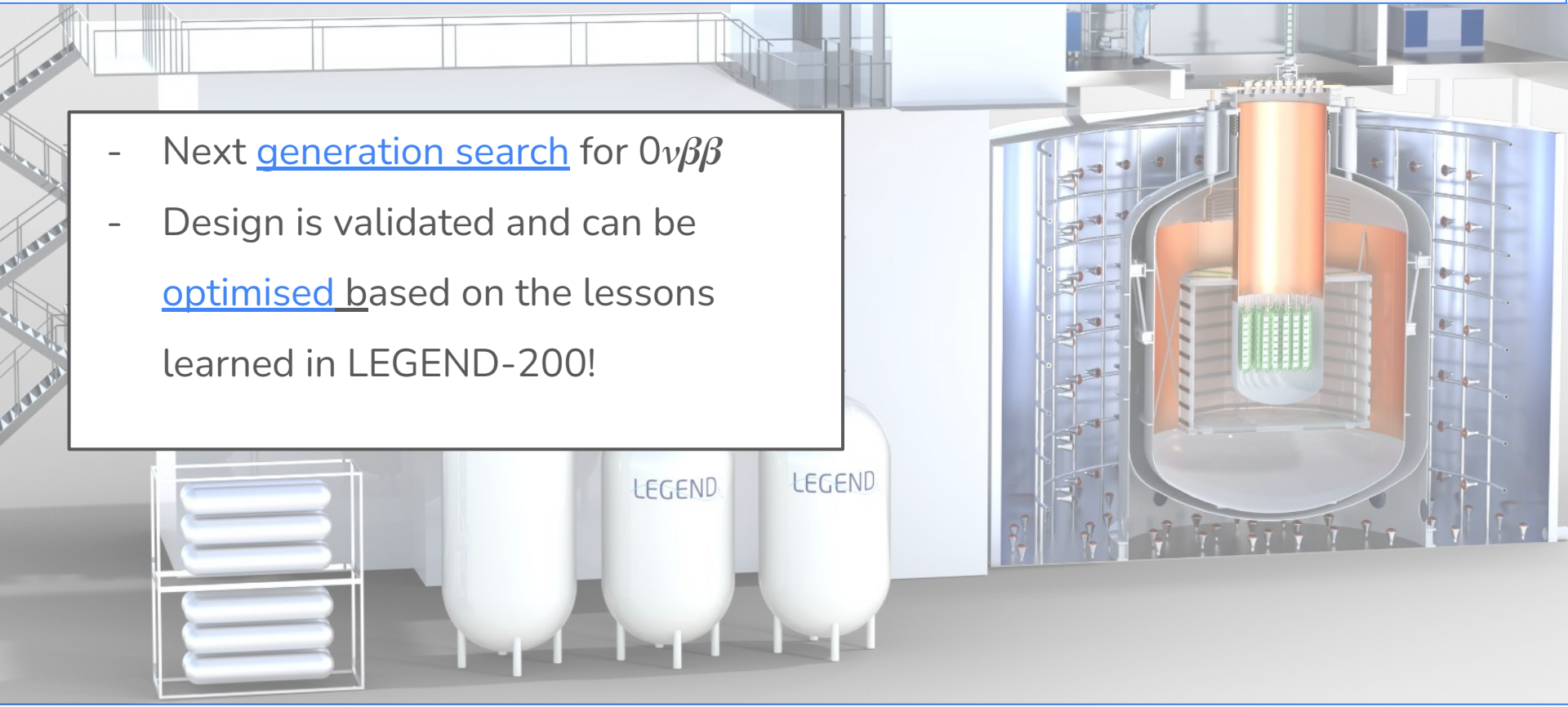
- Critical to **validate** these simulations on **experimental data**
- Controlled calibration (^{228}Th and ^{226}Ra) data taken in-situ in LEGEND-200
- **Good agreement** between data and simulations! Also after LAr veto cut



LEGEND -1000



LEGEND -1000



- Next generation search for $0\nu\beta\beta$
- Design is validated and can be optimised based on the lessons learned in LEGEND-200!

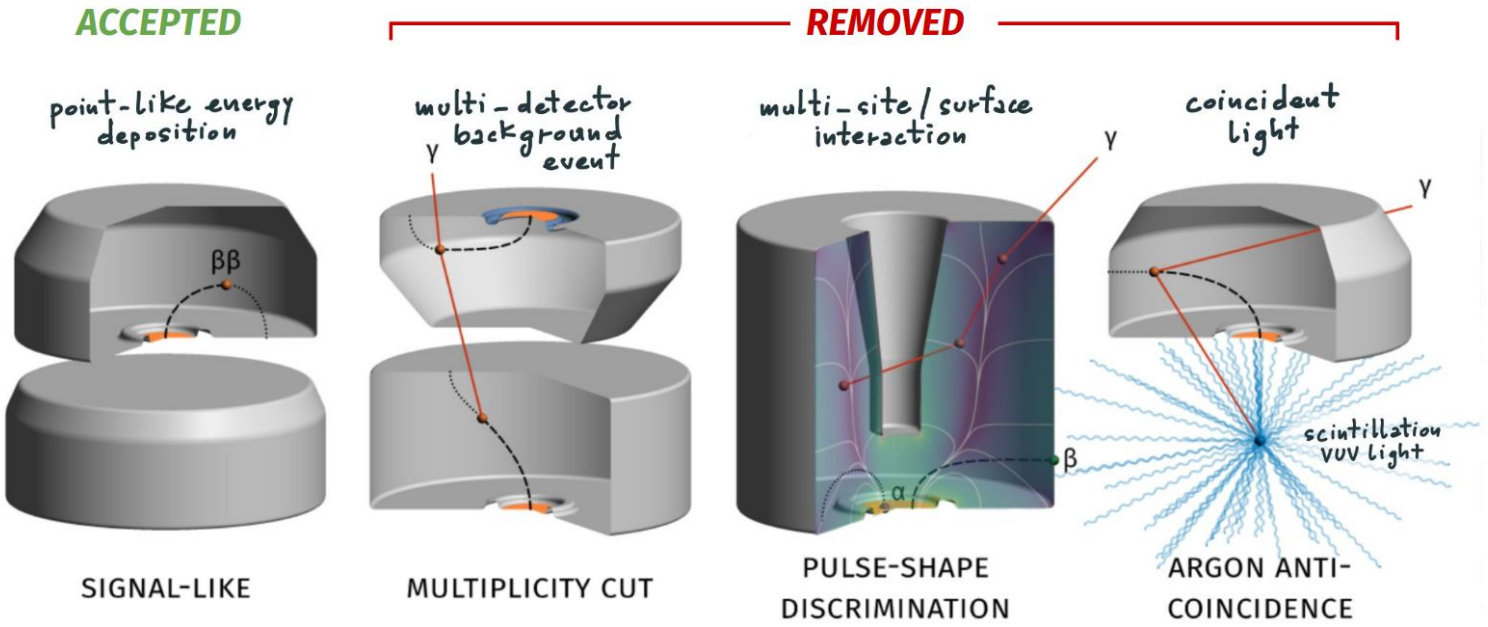
Summary

- LEGEND-200 has begun searching for neutrinoless double beta decay
- Over the next years LEGEND-200 will reach unprecedented sensitivity to $0\nu\beta\beta$
- But to push the limits even further we need a predictive model of the data
- Difficult task but we are making progress
  - New Monte-Carlo software framework
  - Novel methods for pulse shape discrimination simulations
  - Dedicated in-situ data from LEGEND-200

Thanks for the attention!

Background reduction strategy

HPGe in LAr technology allows to dramatically reduce the rate of backgrounds!



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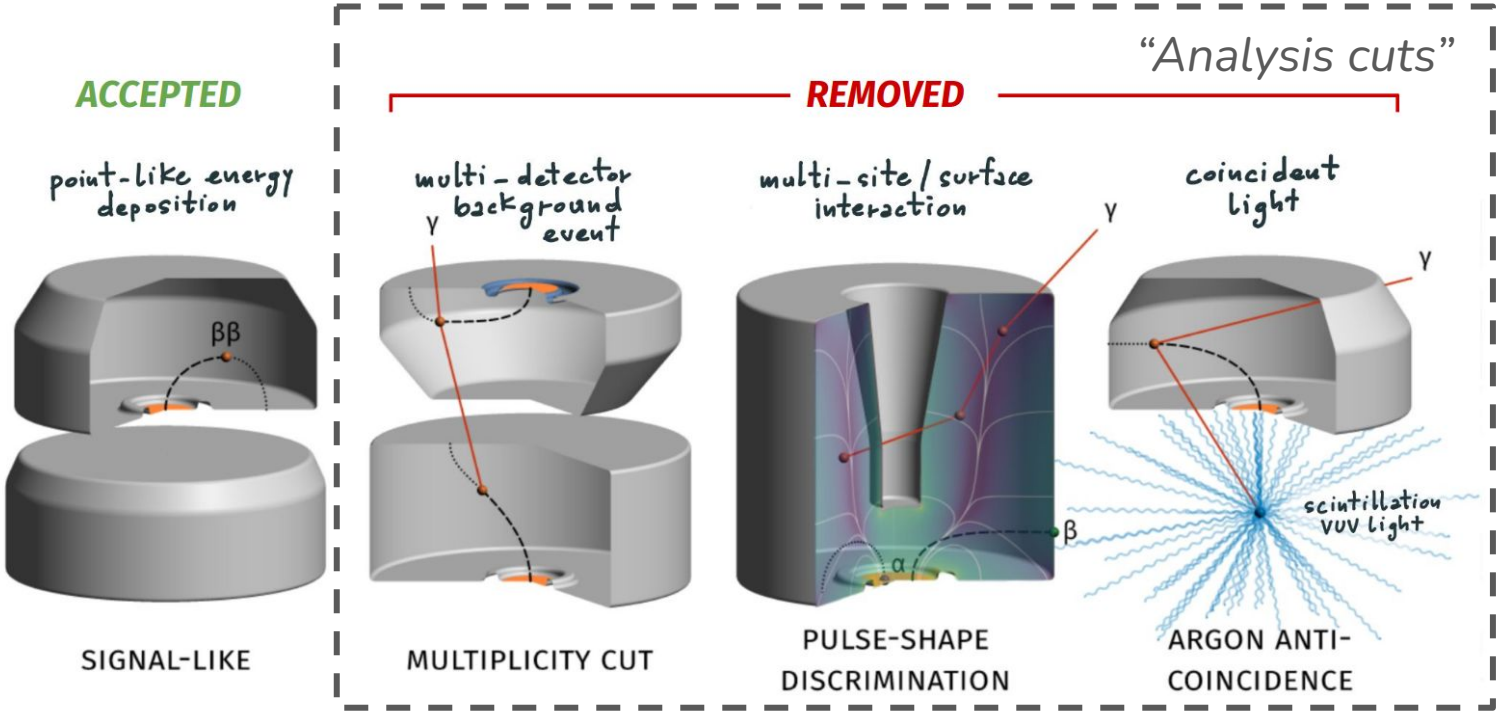
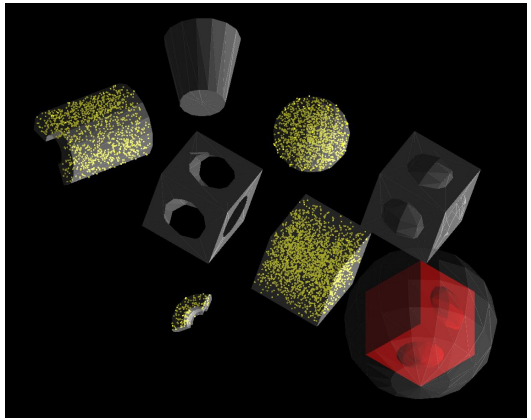


Backup

remage: a modern geant4 framework for low background experiments

- Very **challenging** goal!
- This requires more **advanced simulation tools**
- **Framework separating geometry from** tracking (Geant4)
- Fully open source software



Features

- Focus on validation, tests run continuous via github continuous integration [link]
- Full documentation [link]

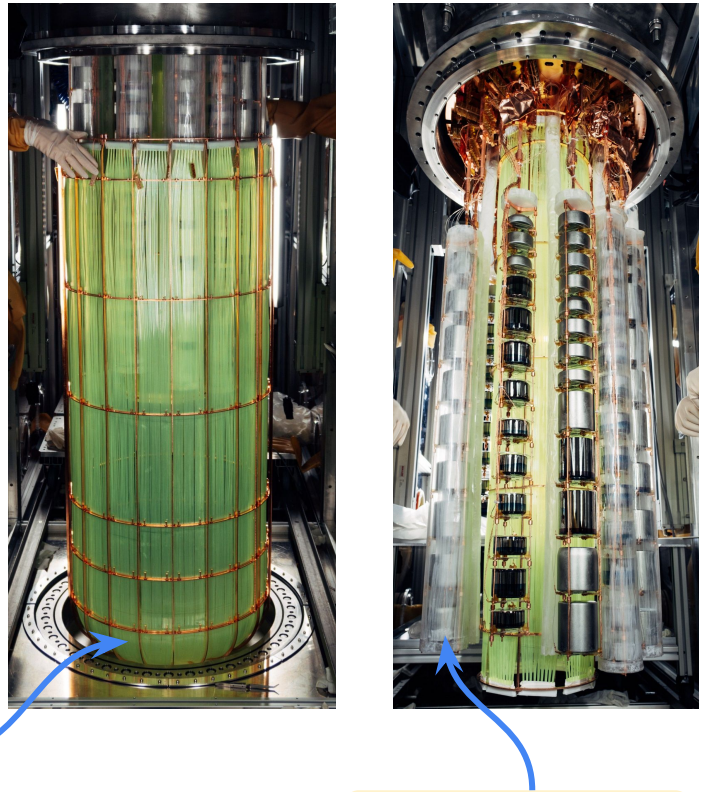
Special background runs - *"in-situ screening"*

- Utilize LEGEND-200 as a **screening station** itself
- Took two ***special background runs*** where components of the experiment were removed

This data provides a model independent constraint on their contribution to the background

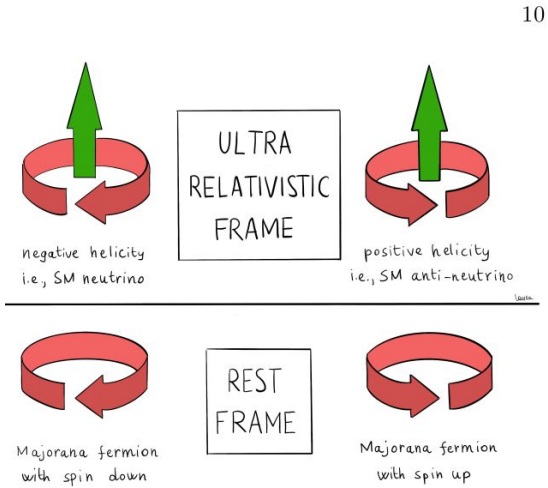
- Identified **contribution of ^{226}Ra on optical fibers + supports**
- Data included in the background model fit

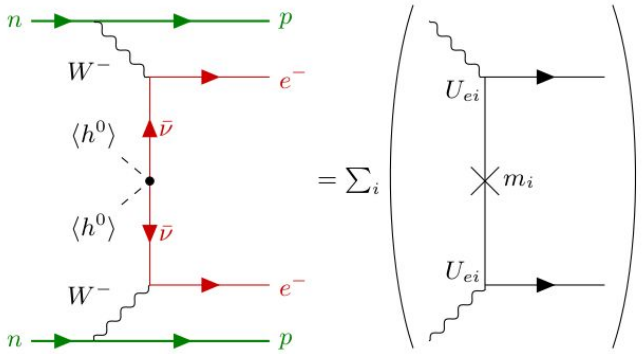
More details in backup slides



Light Majorana neutrino exchange

- Add a **dimension 5** term in EFT (Weinberg operator)
- Leads to a **Majorana mass term** for the neutrinos
- Introduction of a heavy right handed neutrino leads to the small neutrino mass via the see-saw mechanism
- **Exchange of Majorana neutrinos** leads to the 0vbb decay





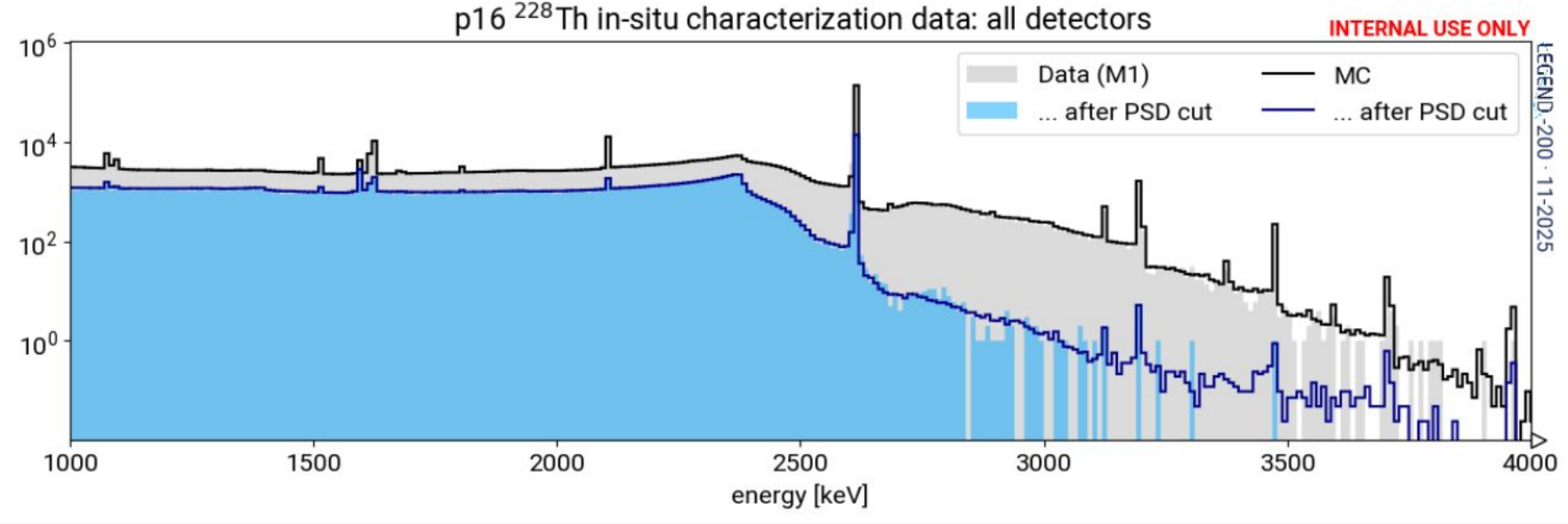
$$= \sum_i \left(U_{ei} \times m_i \, U_{ei} \right)$$

$$\frac{1}{T^{0\nu}_{1/2}} = G_{01}\, g_A^4 \left(M^{0\nu}_{\text{light}} \right)^2 \frac{m^2_{\beta\beta}}{m_e^2},$$

Simulation of p16 high statistics special calibration data

Currently **only analysed a single run** (~10% of total statistics)

- *Confirms the excellent agreement and uniformity*
- *This data will enable **precision studies** of the detector response!*



PSD simulations

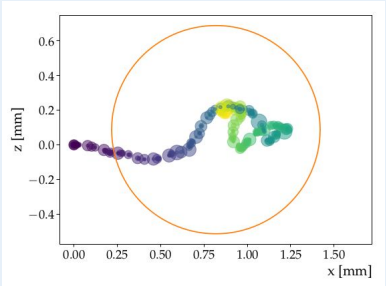
How can we predict if a **simulated event** would **pass a PSD cut**?

Heuristic methods

For example “r90”

Drift time heuristic (L1k CDR) attempts to improve on this

- But **PSD pars. of interest** are not modelled!



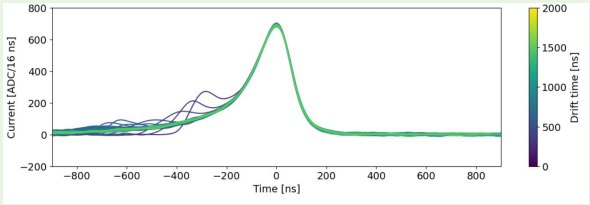
“Semi-heuristic” / emulator

Approximate the full pulse shape simulation

- Exploit the very uniform response of IC detectors

Data driven:

- Current response measured and **calibrated** with data



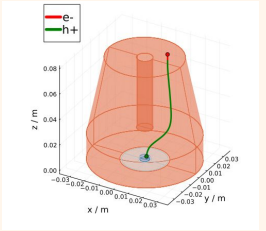
Full pulse shape simulations

Full **charge drift simulation** for every event

- Can include additional effects important for a **precision study**

Currently **extremely computationally intensive**

-



*Increasing **CPU time** and increasing **complexity** (difficulty to tune)*

Template based A/E "emulator"

A/E estimate

- Factorises current estimation into:
  - **Data driven** template
  - **Time offsets** from SSD
- Helps disentangle the systematics!

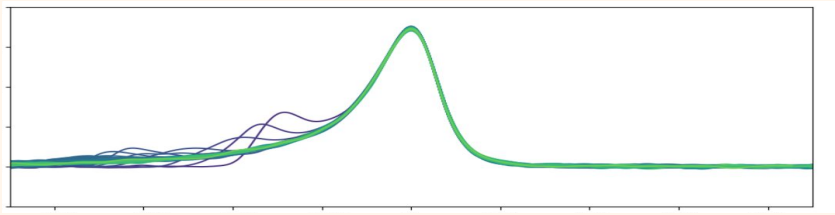
Waveform template: fitted to data!

Drift time map (SSD)

$$A(t) = \sum_{\text{edep}} E_i \times T(t, \mu = t_i, \vec{\nu})$$

Geant4 steps or clusters

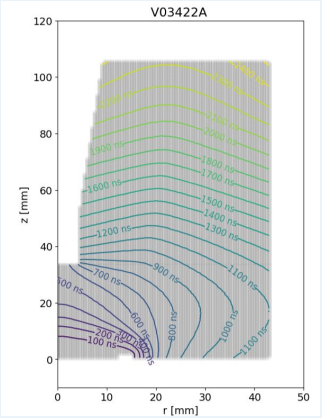
Data driven impulse response template



- Calibrated on data
- Main systematic is **uniformity of the response**
  - Waveform comparisons with known drift time

Time offsets from SSD

- Systematics from impurities, mobility models etc.
- Validation by **comparing drift time to data**



Bayesian $0\nu\beta\beta$ fit

- Developed a flexible open source [software] to perform this analysis
- Few counts
  - **unbinned likelihood** exploits the full information in the data
- Handle the **changing of parameters** for different detectors

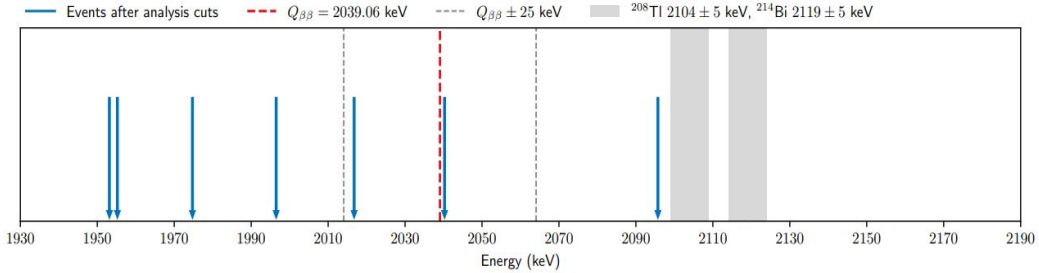
Num. terms >> total counts

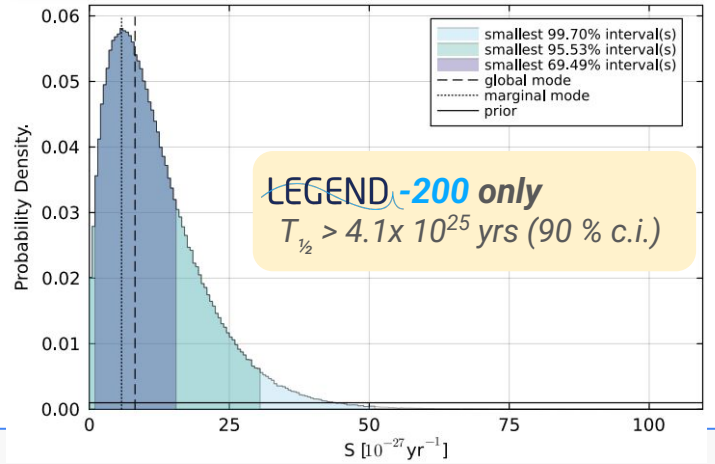
Detectors runs

$$\log(\mathcal{L}) = \sum_{d=0}^{N_d} \sum_{r=0}^{N_r} \left(\text{Pois}(n_{d,r}; B_{d,r} + S_{d,r}) \times \sum_{i=0}^{n_{d,r}} (B_{d,r} \times f_b(E_i) + S_{d,r} \times f_s(E_i)) \right)$$

Background rate per detector

Signal parameters vary by detector





~~LEGEND~~ ***-200 only***

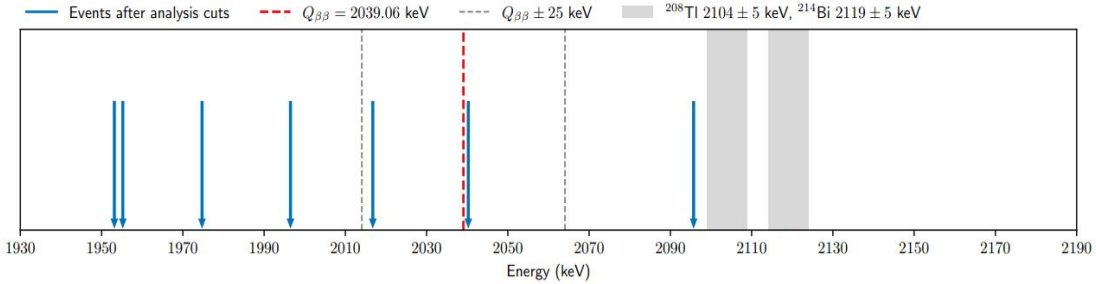
$T_{½} > 4.1 \times 10^{25}$ *yrs (90 % c.i.)*

- Performed statistical tests to check the **uniformity of the background** across the detector
- Alternative approach with **Bayesian Hierarchical model** and correlated bkg. also used

Detail in backup slides

$0\nu\beta\beta$ analysis

- No evidence of $0\nu\beta\beta$ found
- Limit set based on the posterior distribution after marginalising over background rates / all nuisance parameters



L-200 only

$T_{½} > 4.1 \times 10^{25}$ yrs (90 % c.i.) :

- few % differences changing background model / using correlated bkgs

L-200 + GERDA + MJD

$T_{½} > 1.8 \times 10^{26}$ yrs (90 % c.i.)

- Most stringent constraint for 76Ge