LEGEND UK

Open Workshop @ UCL on March 31

R&Ds in LEGEND

HPGe semiconductor detectors

- **New detector concepts.** Explore new detector geometries, contact solutions, or electrode segmentation to maximise the sensitivity of LEGEND-1000 and beyond
- **Larger-volume long-collection-time detectors.** R&D on detector manufacturing processes (e.g. crystal pulling, annealing, electrode production) focusing on their connection with the final crystal properties and impact on charge trapping, charge cloud dynamics, surface currents, slow pulses, etc.
- **Mass production facilities.** Prepare test-stands and procedures to accept and characterise hundreds of detectors, assessing their spectroscopic and pulse-shape discrimination performance, active volume, uniformity of the surface response, depletion voltage, etc.
- **Advanced characterisation.** Design, build and exploit advanced detector characterisation test-stands to map the detector response, both in the bulk of the detector and on its surface. Examples are Compton coincidence scanning stations or vacuum cryostat containing both the detector and movable collimated alpha/beta/gamma sources.
- **High-precision measurements of charge carrier mobilities in Ge.** Set up an R&D program to measure the relation between electric field and charge carrier velocities in the Ge material used to produce the LEGEND detectors, including its dependence on crystallographic axis, impurity concentration, crystal annealing cycles and growing history.

Electronics and DAQ

- **DAQ.** Design, assemble, test and install the DAQ system, including the FADCs, triggering logic, firmware, and online data reduction.
- **HPGe detector read-out electronics.** Design and deliver ultra-low background front-end electronics and subsequent amplification stage usable at cryogenic temperature, fulfilling challenging background/bandwidth/cross-talk/noise specs
- **LAr light sensor read-out electronics.** Design and deliver fast low-background cryogenic read-out solutions for the LAr light sensors
- **Slow control.** Develop slow control system, network and protocols, integrate sensors used to monitor the experimental infrastructure, alarm system, automatic emergency operations.

Electronics and DAQ

DAQ:

Requirements:

- Spectroscopic response and ~keV energy resolution needs high signal fidelity
- Signal “trace” recorded for offline pulse shape analysis

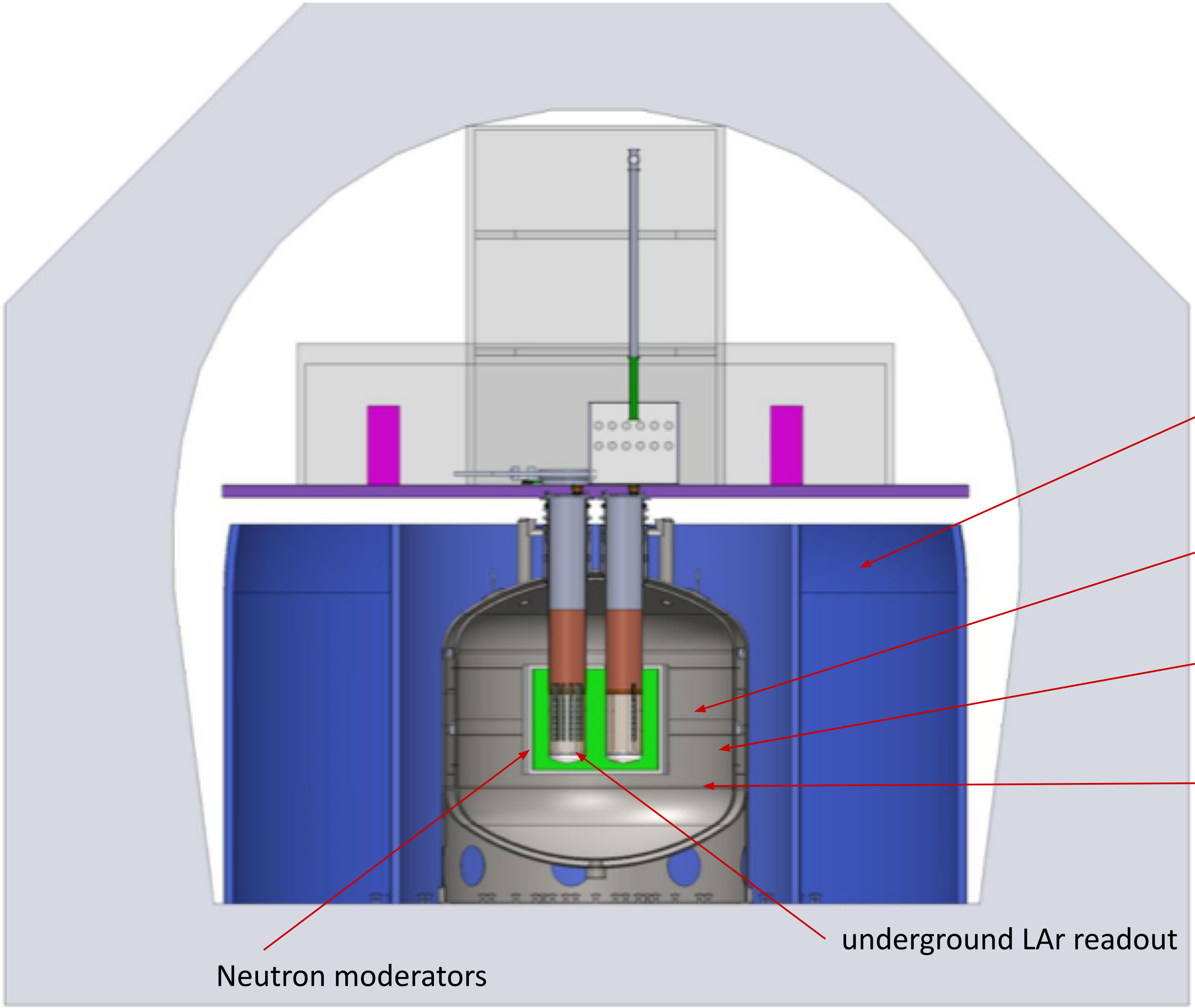
Performance:

- Typical minimum spec FADCs 100Mhz / 14bit over a 2.25V dynamic range
- MWD (or equivalent) algorithm required to recover energy resolution

Liquid argon detector

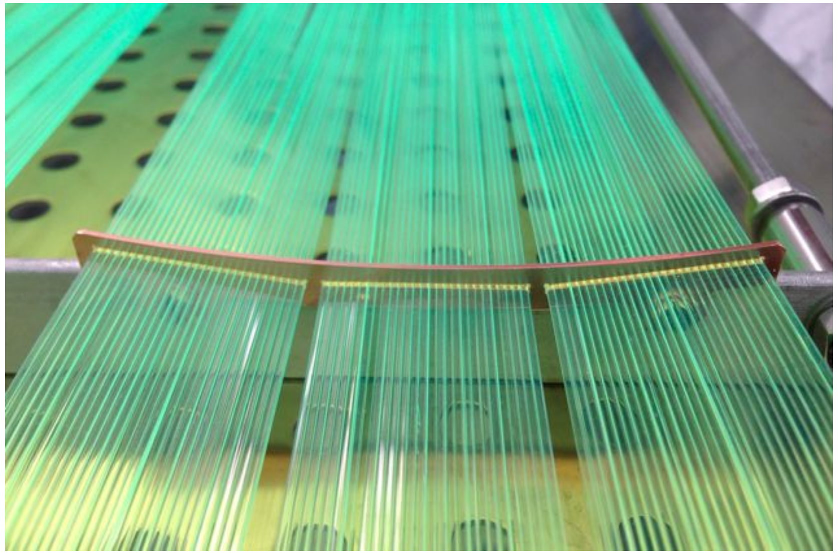
- **Light sensors.** Explore new light sensor technologies, including R&D with SiPM, and prepare characterization/testing capabilities for mass production.
- **LAr optical properties.** Measure liquid Ar optical properties (i.e. light yield, attenuation length, triplet lifetime) as a function of Ar purity and specific contaminants. Design/build monitoring systems for the standard and underground Ar of LEGEND-1000.
- **Light read-out.** Explore and optimise the LAr scintillation light read-out strategy, including fibres scheme and potential scintillating materials, with the optical and MC simulations.

Liquid argon detectors

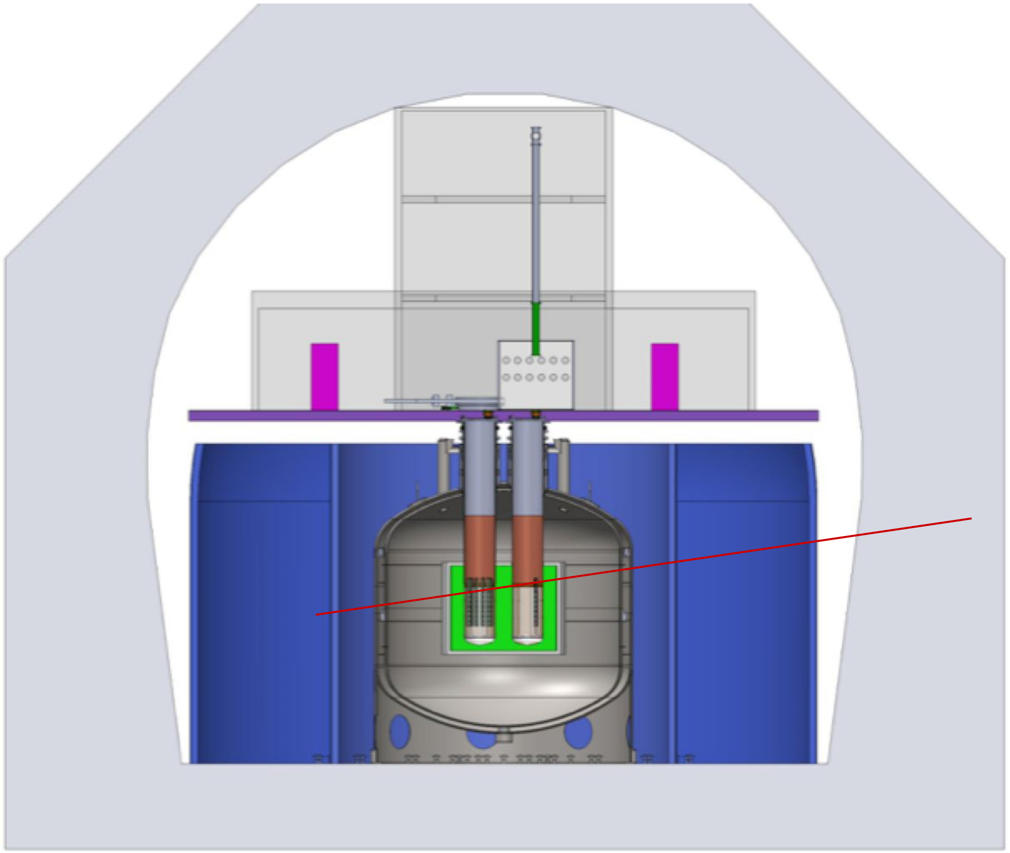


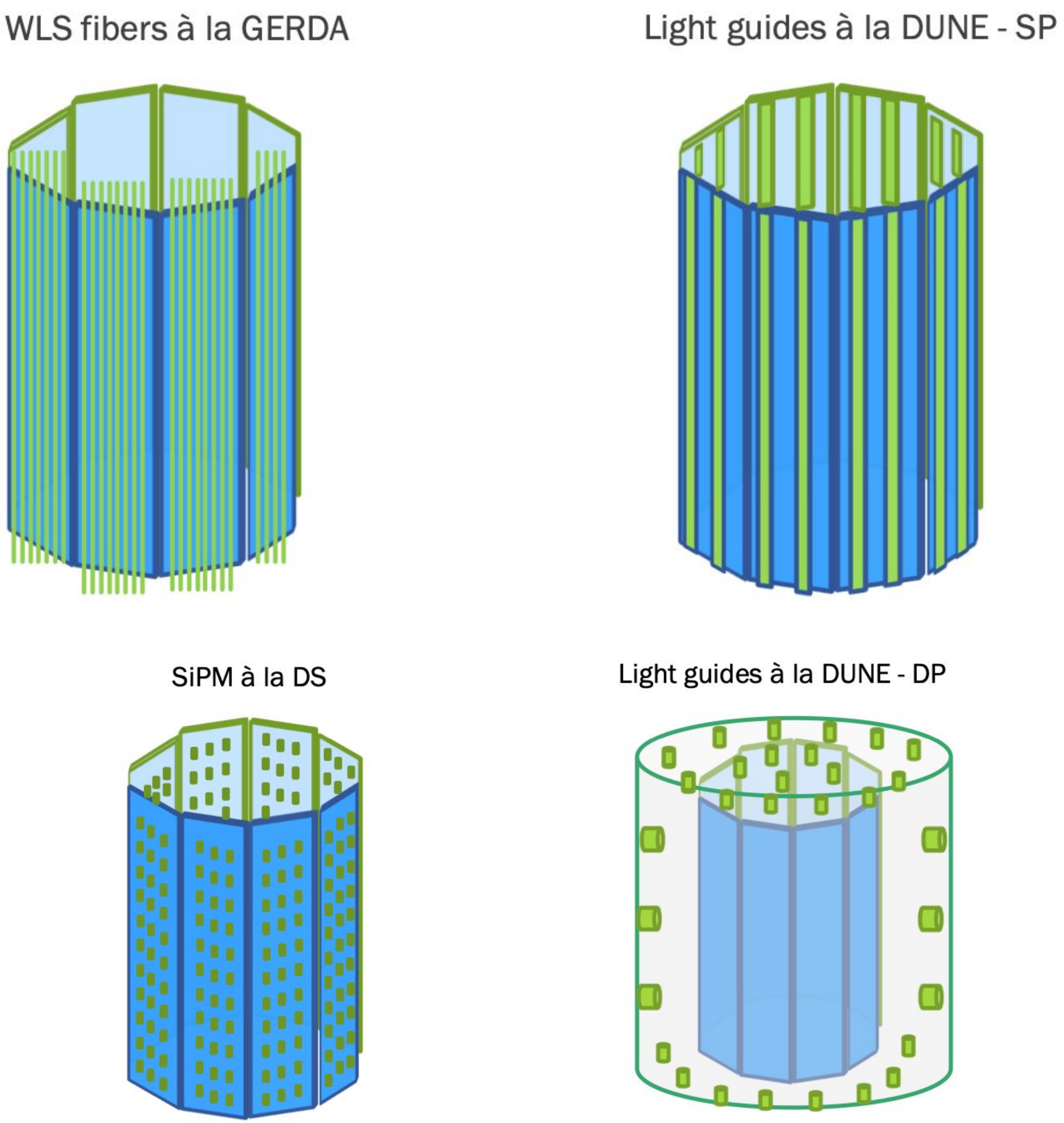
Liquid argon detectors

- (modest) Improvement of fiber radio purity ongoing R&D
- Scale-up of TPB evaporation system
- State-of-the-art SiPMs instead of SiPMs from Ketek (FBC, Hamatsu, …)
- Consider also SiPMs >3x3mm
- New SiPMs require new packaging technique (back contacts)
- Scale-up for machining of high-purity substrates and SiPM packaging, bonding and characterization



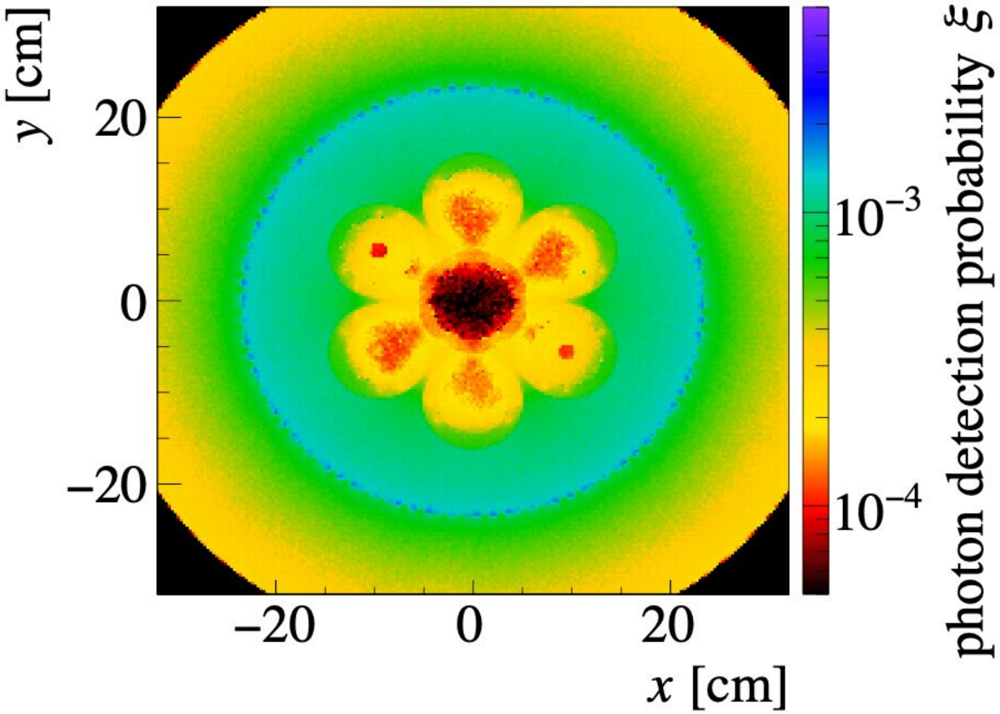
Liquid argon detectors



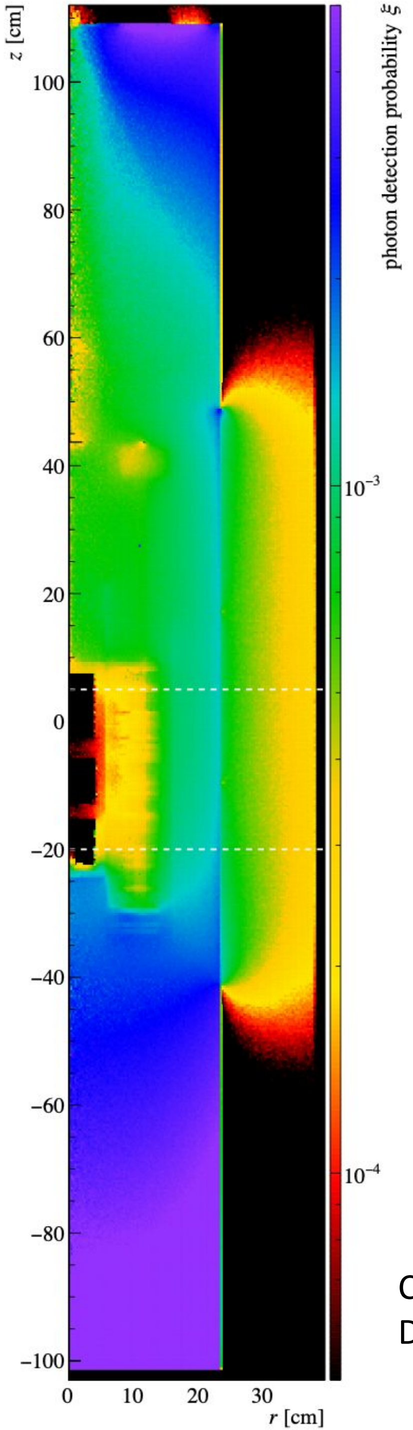


courtesy N. Di Marco, G. Salamanna, R. Brugnera

Liquid argon detectors simulations



Photon detection probability map. The detection probabilities reach from almost percent-level close to the photo detectors, to <10−4 within the densely packed array. The slice shown in the bottom projection is indicated in the top panel.

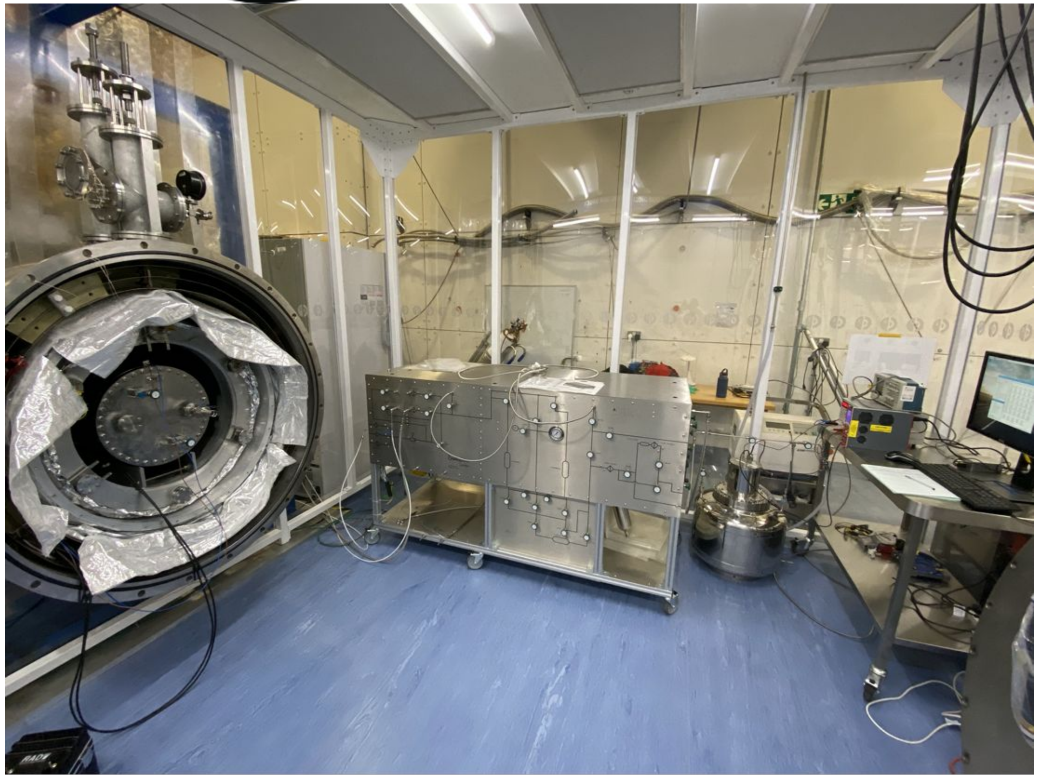


C.Wiesinger (TUM), Dissertation 2020

Assay & Screening

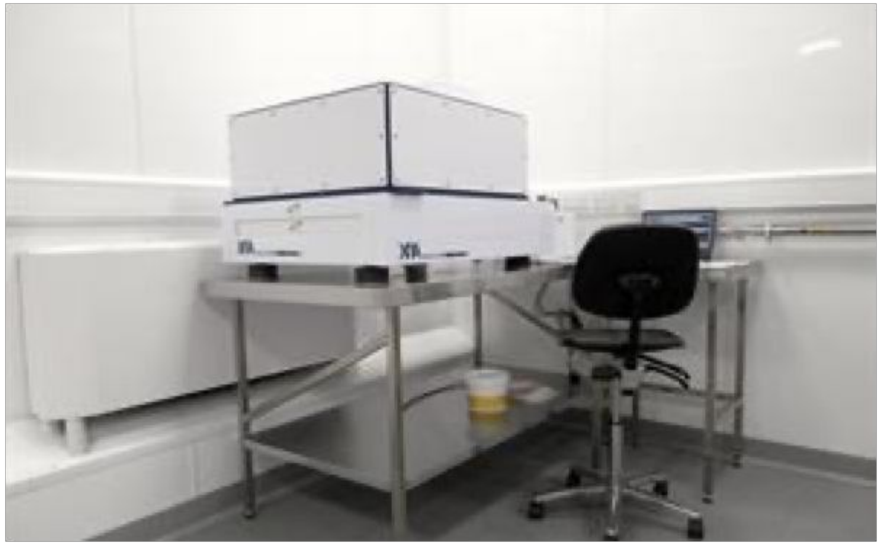
- **Material screening and assay.**
  - Existing facilities include ICPMS at UCL, HPGe array at Boulby (BUGS), Surface Detectors (XIA) at Boulby
  - Collaboration with DM community on cold Rn emanation (CREF@RAL)
- **R&D/Challenges to address**
  - Upgrade BUGS to reach ~10 uBq/kg levels (e.g. multi-array HPGe in coincidence)
  - Improve ICPMS sensitivity to deep sub-ppt/ppq levels (pre-concentration, …)
  - Rn Emanation into LAr
  - Improve surface (alpha) radioassay sensitivities
- **Material selection and procurement.**
  - Identify the most radiopure materials, producers and supply chain.

Assay & Screening



Cold Rn Emanation

BUGS (HPGe assay)



XIA surface alpha screening

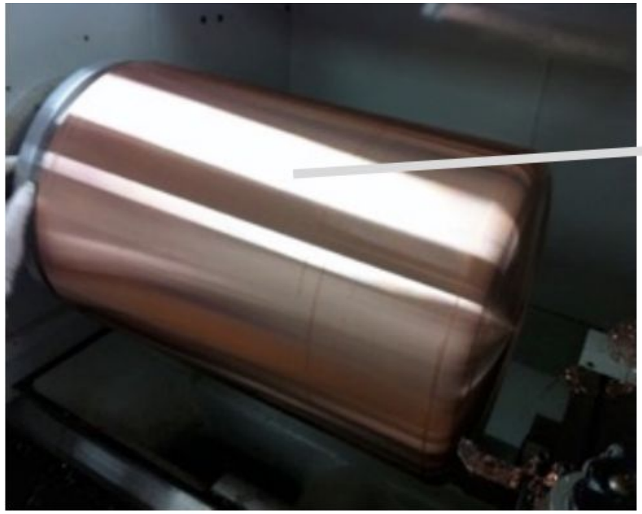
Novel materials

- **Novel materials.** Explore new materials (e.g. transparent plastics to construct the detector holders maximising the read-out efficiency of the liquid argon scintillation light) or material production systems (e.g. electroformed copper), exploiting synergies with ongoing efforts in the UK dark-matter community.
- **Techniques and materials for encapsulating HPGe detectors.** Explore solutions to surround each HPGe detector with a layer of material separating the Ge surface from LAr and reducing background due to Ar-42 beta-decays.

Novel materials

Why novel materials?

A background-free experiment requires utmost radiopurity of all materials used - still optimising and searching.



Examples:

- (OFHC) copper is generally fairly radiopure, but this could be improved by using electroformed copper processed underground (i.e. being protected from cosmic rays)
- “Passive” construction parts could be replaced by “active self-vetoing” components.
  - emit scintillation light when a decay occurs within
  - acts as wavelength shifter for LAr scintillation rather than simply absorbing it

How to improve even further on radiopurity?

- radiopure electronic components?
- Your ideas are welcome!

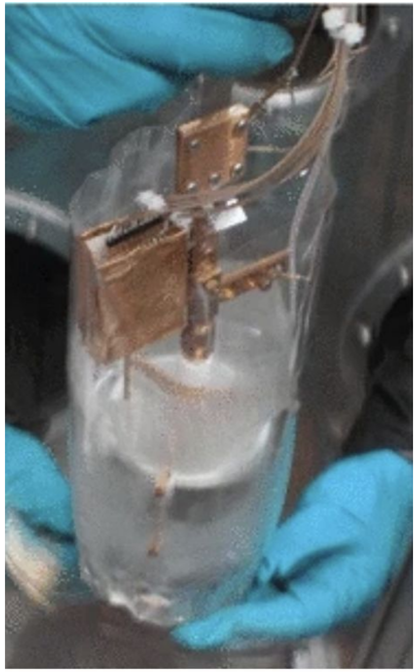
Novel materials

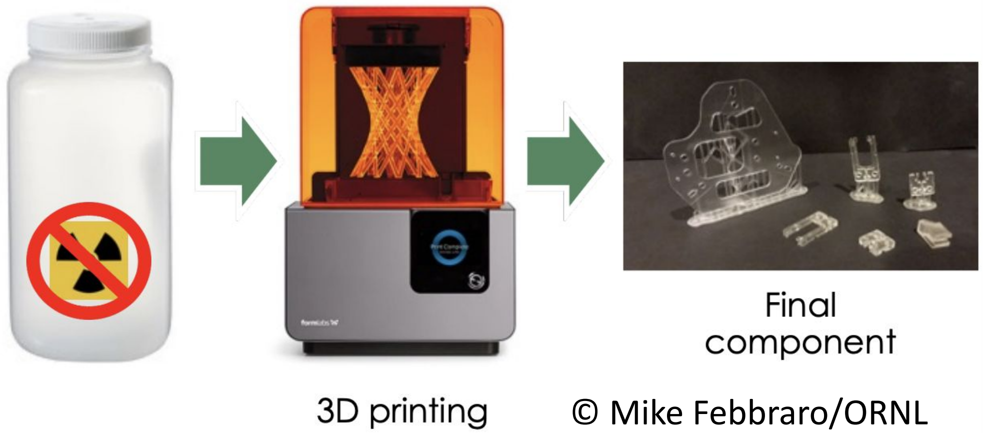
Encapsulating HPGe detectors?

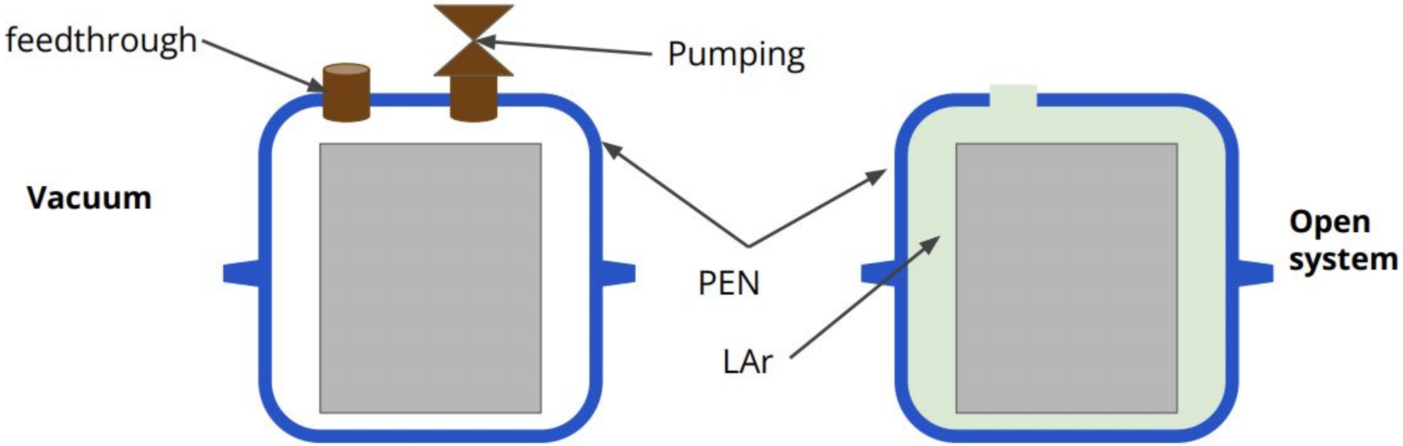
LAr contains residual ^{42}Ar, need to prevent this from reaching the HPGe-detectors

- Up to now: Nylon shrouds
- Idea for L1T: capsules from PEN…
- … including feedthroughs and vaccum?
- …or from other self-vetoing construction materials?
- … or even 3D-printed?

Your ideas?







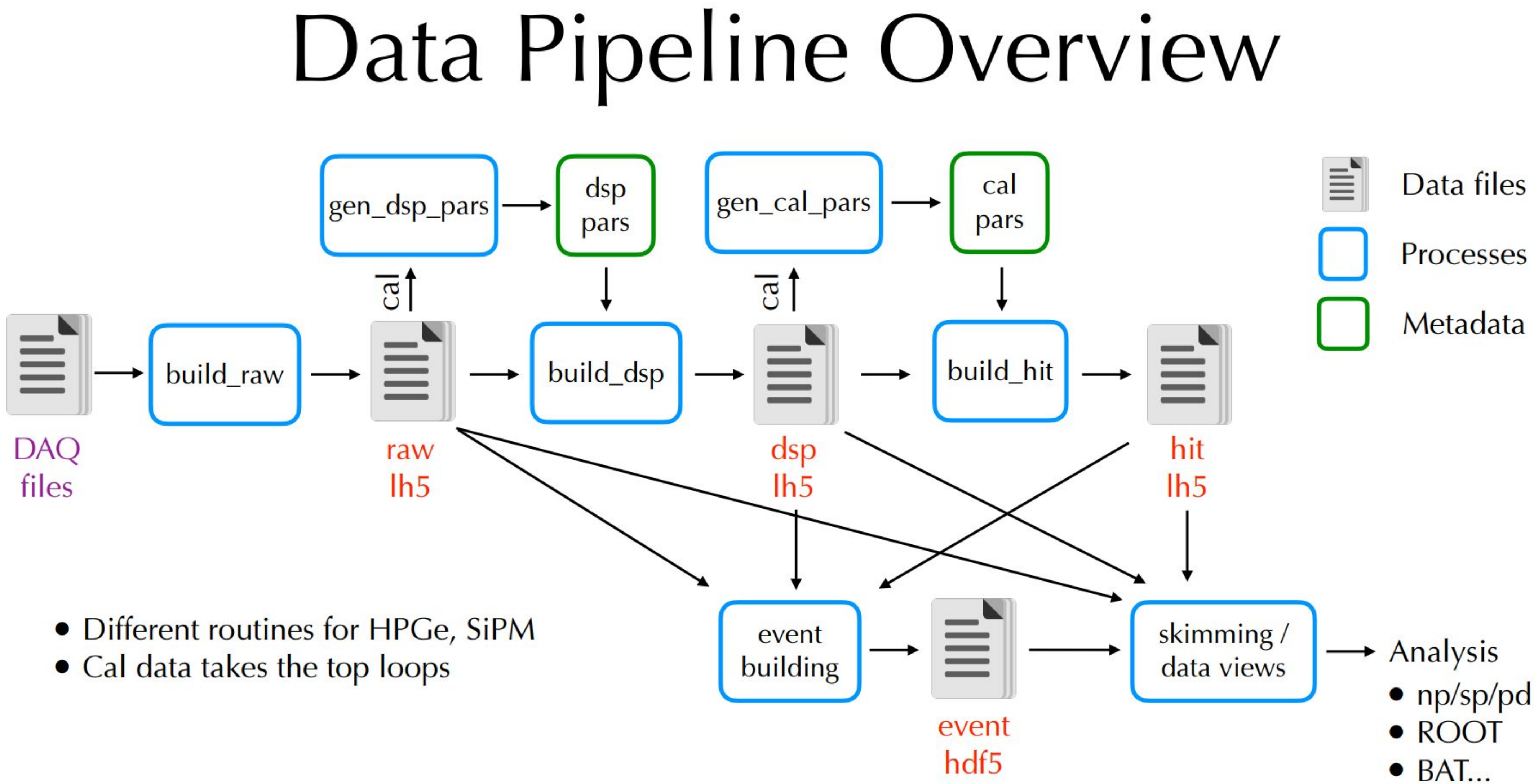
Infrastructure, Cryostat, Assembly, and Installation

- **Cryogenic and LAr infrastructure.** Design and construct challenging infrastructure, including pumping systems, LAr circulation and purification facilities, solutions to handle underground Ar including the re-entrant vessels in the cryostat, emergency systems and monitoring tools.
- **Lock-system and clean room.** Design, build and install the hardware infrastructure needed to mount and lower the detector array into the cryostat, including vacuum feedthroughs.
- **Detector Array.** Integrate and assemble the components of the detector arrays, including LAr/HPGe detectors, holding systems, contacting, cabling, and read-out electronic chain

Analysis, Simulations, and Computing

- **Software and hardware infrastructure.** Design and install computer infrastructure, including the above and underground networks, servers, and storage. Develop computing control interfaces, databases, web tools and automatic data flow managers. Design software solutions for distributed high-performance computing resources (e.g., NERSC) and GPUs. Design and implement analysis and simulation software frameworks.
- **Machine learning and advanced analysis techniques.** Develop techniques for event tagging and reconstruction (e.g. convolutional networks for data quality or MLP for pulse shape discrimination) and advanced digital signal processing (e.g. denoising and optimal filters in time and frequency domains).
- **Simulation models.** Develop and tune models for HPGe detectors (including their surface response and charge cloud deformations), LAr scintillation and light sensor (including optical simulations), and cosmic rays.
- **Background Analysis Tools and Methods.** Build multivariate fitting frameworks and procedures. Apply them to investigate background contributions in LEGEND-200, evaluate the impact on LEGEND-1000’s background budget, and guide the experimental design.
- **Statistical tools and physics analysis.** Build frequentist and Bayesian methods to extract a single which can potentially be composed of just a few events over the entire duration of the experiment, tracking the operational performance of each of the hundreds of HPGe detectors deployed in LEGEND.

Analysis, Simulations, and Computing



- Different routines for HPGe, SiPM
- Cal data takes the top loops

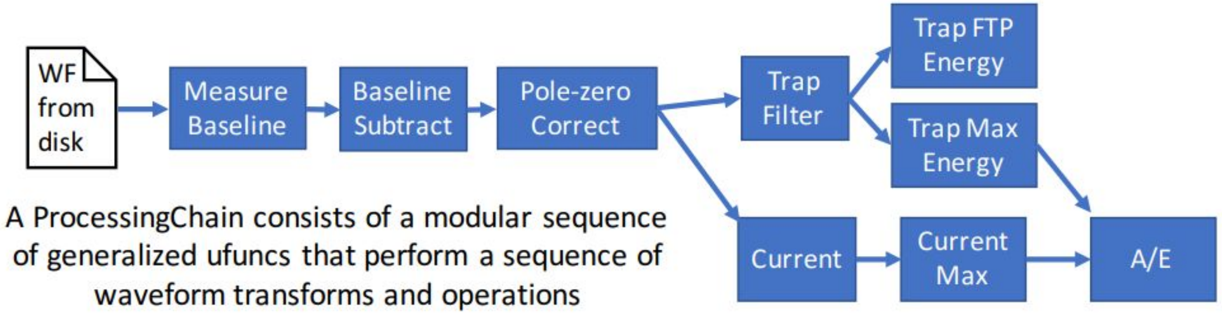
Analysis
- np/sp/pd
- ROOT
- BAT...

Analysis Framework Choices

- Data Format: HDF5
  - advanced features
  - formal spec
  - well-supported
  - portable
- Processes: python (pygama)
  - extensive standard library
  - wrapped or auto-generated C code where needed (e.g. DSP)
  - fast learning curve
  - skill building
- Metadata: json in GitHub
  - human-readable
  - version control
- Workflow: snakemake
  - make-like target:dependencies logic
  - python integration
- Secondary Stack: Julia
  - performance
  - validation and experimentation

pygama Digital Signal Processing

- ProcessingChain DSP framework uses generalized ufuncs
- Modular: can write processors using pure numpy, numba, or C/C++; "python is the glue"
- Fast: ufuncs are meant to be vectorized
- Simple: a processor is bare-bones and simple to write; external utilities exist for testing/visualizing



A ProcessingChain consists of a modular sequence of generalized ufuncs that perform a sequence of waveform transforms and operations

```python
from numba import guvectorize


@guvectorize(["void(float32[:], int32, int32, float32[:])",
              "void(float64[:], int32, int32, float64[:])",
              "void(int32[:], int32, int32, int32[:])",
              "void(int64[:], int32, int32, int64[:])"],
             "(n),(),()->(n)", nopython=True, cache=True)
def trap_filter(wf_in, rise, flat, wf_out):
    """
    Symmetric trapezoidal filter
    """
    wf_out[0] = wf_in[0]
    for i in range(1, rise):
        wf_out[i] = wf_out[i-1] + wf_in[i]
    for i in range(rise, rise+flat):
        wf_out[i] = wf_out[i-1] + wf_in[i] - wf_in[i-rise]
    for i in range(rise+flat, 2*rise+flat):
        wf_out[i] = wf_out[i-1] + wf_in[i] - wf_in[i-rise]
                  - wf_in[i-rise-flat]
    for i in range(2*rise+flat, len(wf_in)):
        wf_out[i] = wf_out[i-1] + wf_in[i] - wf_in[i-rise]
                  - wf_in[i-rise-flat] + wf_in[i-2*rise-flat]
```

Example: trap filter gufunc written using numba