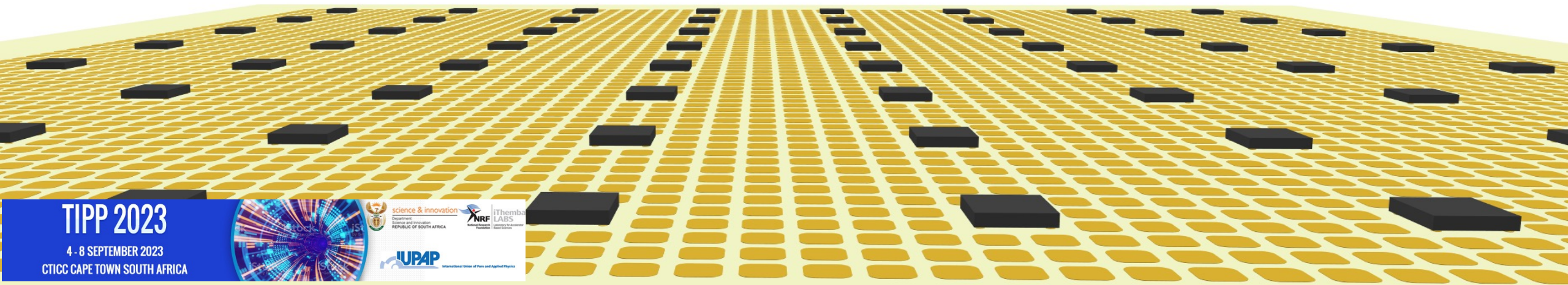
SoLAr Prototype Detector

Saba Parsa, University of Bern on behalf of the SoLAr collaboration

TIPP Conference, Cape Town, 4-8 September 2023



Solar neutrinos in Liquid Argon

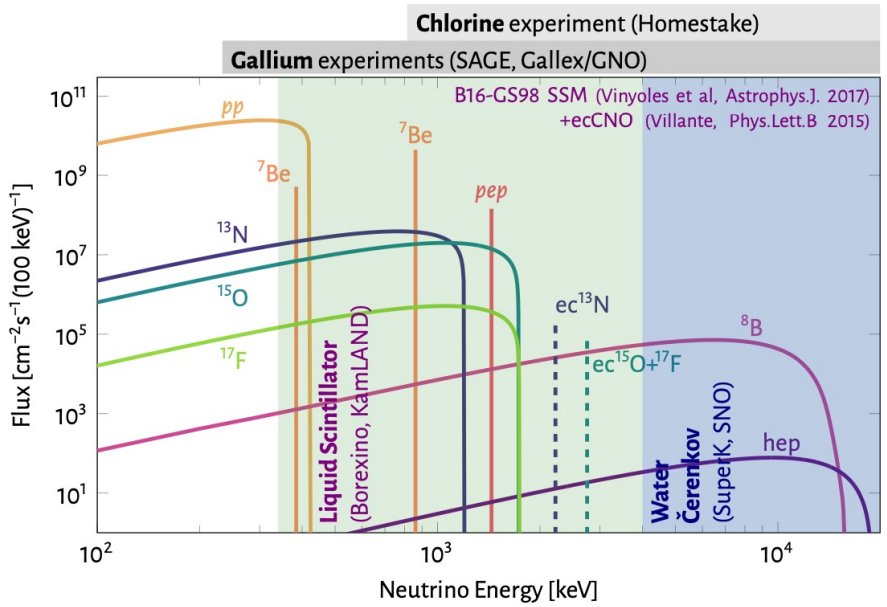
Novel detector concept

Ability to identify ”MeV-scale” events in space and time online (not possible in current LArTPCs)

- Large Volume LAr-TPC
- True 3D reconstruction from pixelated charge
- 3D reconstruction also from light with arrays of VUV SiPMs on the same anode readout plane
- Online localized trigger logic to cope with high data rates
- **GOAL:** develop and demonstrate a new readout technology

Physics motivation

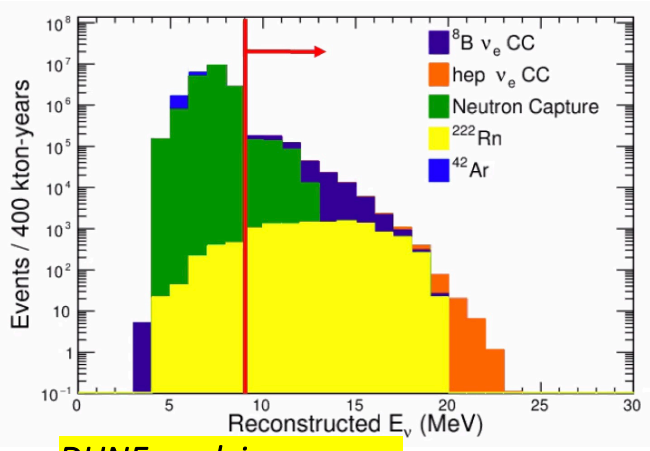
Aim is to reach to the required sensitivity for Solar hep neutrinos and other low energy physics at MeV energy scale. Supernova neutrino burst detection.



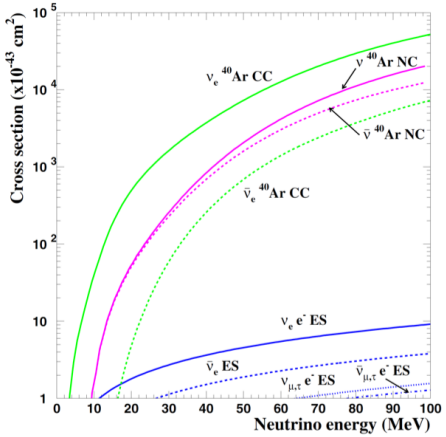
Main challenges

At MeV energy scale physics

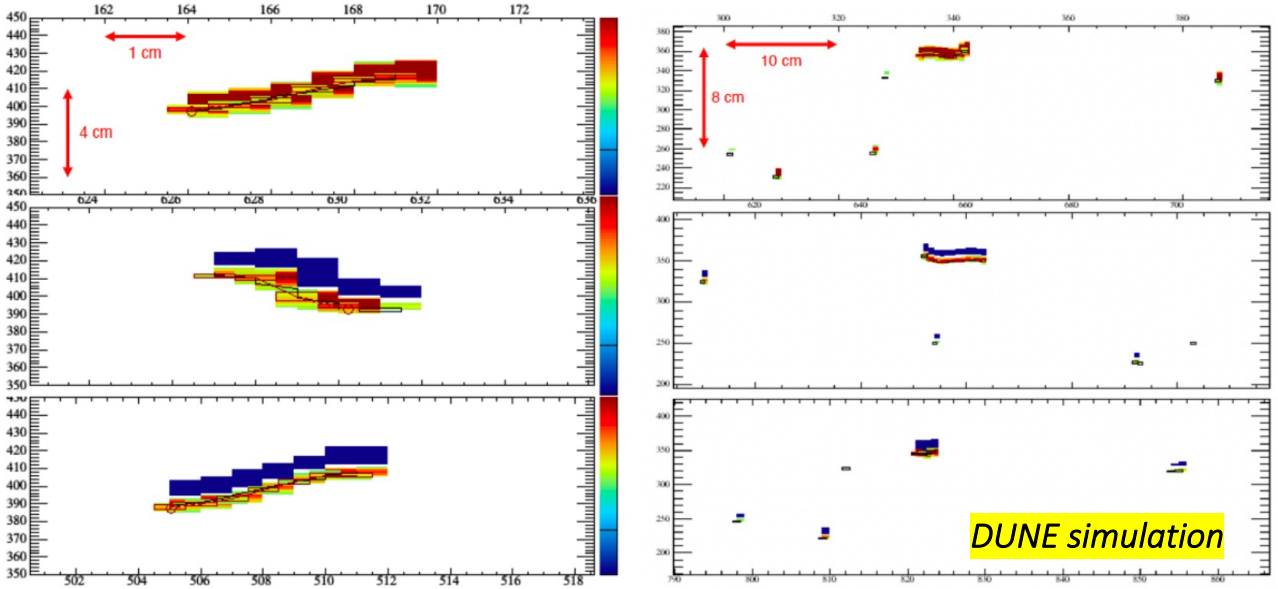
- Develop an efficient event reconstruction (including de-excitation gammas)
- Identify neutrino direction (angular resolution)
- Tag different neutrino flavors
- Achieve an excellent energy resolution
- Develop low-energy background reduction strategy
- Good calibration at MeV energies across the detector volume



DUNE work in progress



MeV scale neutrino events in LAr



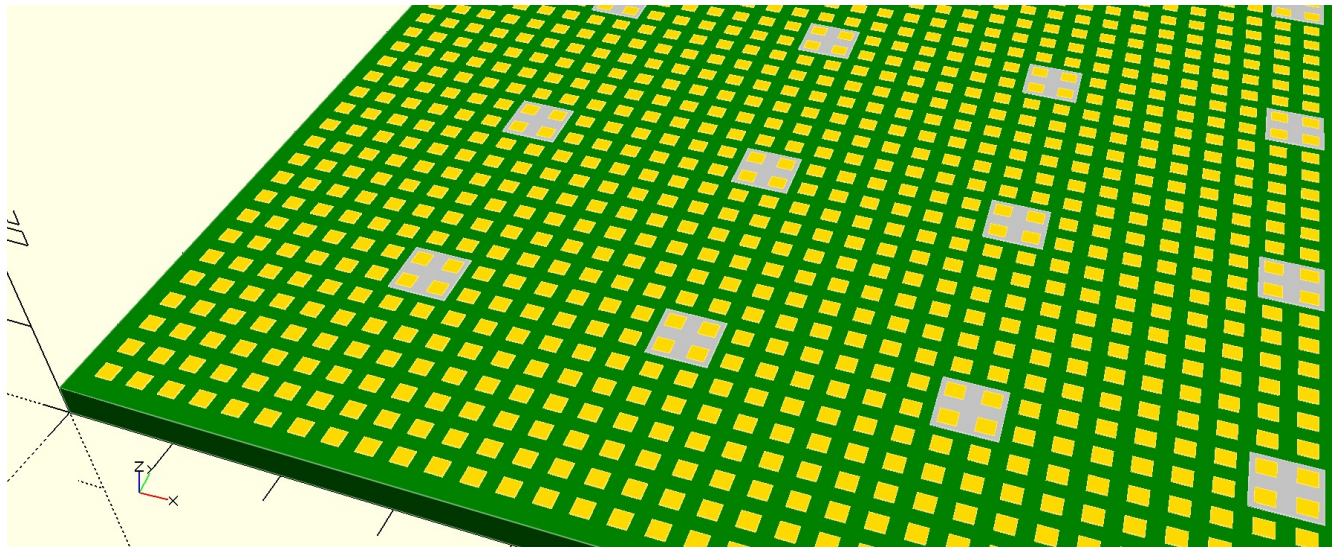
Elastic scattering
Can we reconstruct direction?

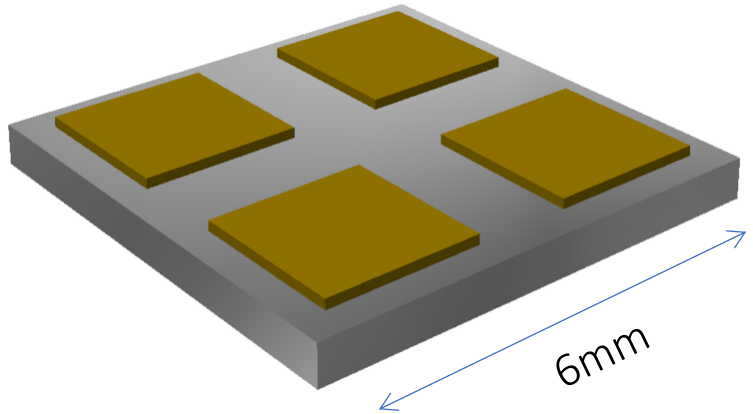
Charged Current

SoLAr Cell

A Modified VUV SiPM with 4 charge pads

- All-silicon pad, CMOS layer divided into many p-n junctions and operates as a VUV SiPM
- Four metalized zones deposited over the silicon substrate as charge pads
- The pads electrically connected by means of through silicon vias.
- Charge pads are uniformly distributed along the anode plane with any choice of SoLAr cell unit coverage.



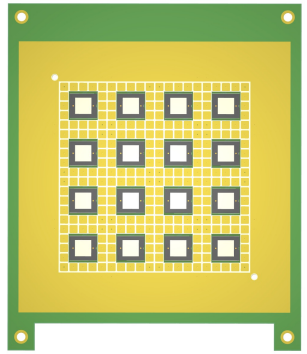


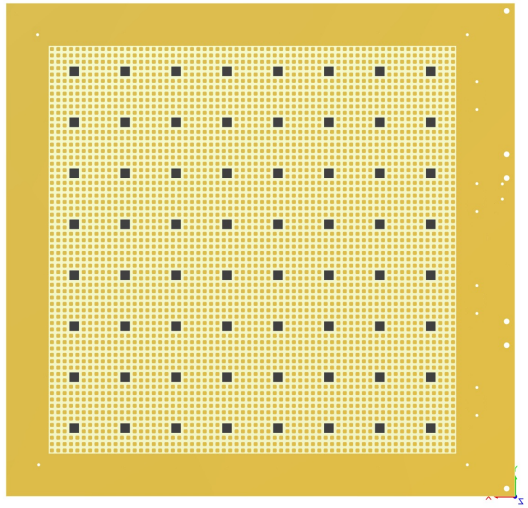
Technology demonstration

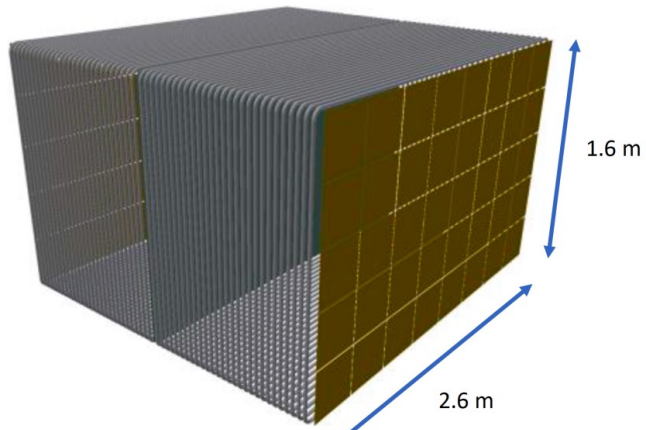
- First test aimed at understanding effects of having charge pixel pads and VUV SiPMs on the same plane ✓
- New generation of edgeless SMD packaged VUV SiPMs is a critical step forward, it has through silicon via for biasing the SiPM ✓
- R&D and Collaboration with Hamamatsu and/or FBK for development of the special VUV SiPMs with charge pads on the surface connected by through silicon via
- Optimization of the tile layout based on the simulations input
- ASIC based readout electronics in cold for the light as well as charge (LArPix, LightPix, Q-Pix)

Prototyping Road Map

- Small scale SoLAr prototype v1 @Bern (successful test in October 2022)
  - 7cm x 7cm Anode plane (3 stacked PCB)
  - 16 VUV SiPMs with ceramic package and pins
  - 4 LarPix-v2a chips
- Small scale SoLAr prototype v2 @Bern (successful test in July 2023)
  - 30cm x 30cm (1 PCB)
  - 64 SMD packaged VUV SiPMs
  - 64 LArPix-v2b chips
- Small scale prototype with improved SiPMs (charge pads on top)
  - Test of alternative readout chips LightPix and Q-Pix when available
- Mid scale, SoLAr Demonstrator @Boulby (2025-2028?)
  - Few-ton scale detector underground (Boulby, UK, 1100 m overburden)
  - 30 × 30 cm^2 readout anode tiles (≈ 6400 pixels/tile)
  - First measurement of flavor tagged solar neutrinos in LAr



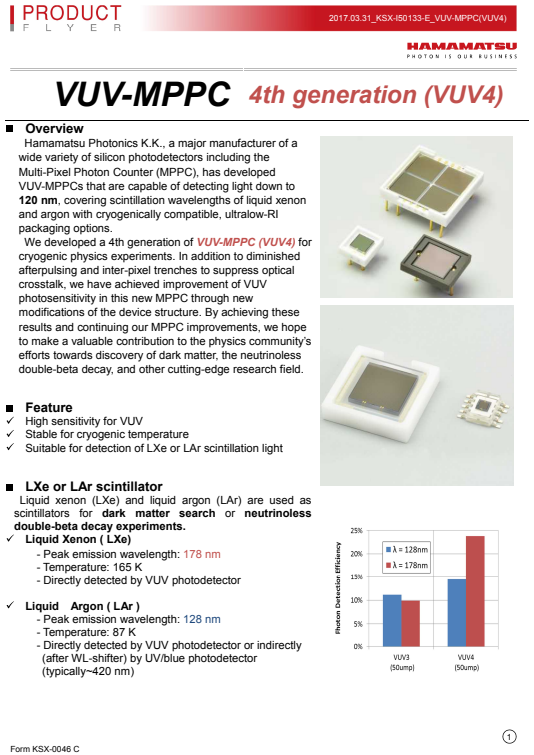




SoLAr Prototype-v1

Objectives and limitations

- SiPM type: Hamamatsu S13370-6050CN
- Ceramic packaged with pins
- 15 % PDE for 128 nm, VUV


PRODUCT FLYER
2017.03.31_KSX-I50133-E_VUV-MPPC(VUV4)
HAMAMATSU
PHOTON IS OUR BUSINESS

VUV-MPPC *4th generation (VUV4)*

Overview

Hamamatsu Photonics K.K., a major manufacturer of a wide variety of silicon photodetectors including the Multi-Pixel Photon Counter (MPPC), has developed VUV-MPPCs that are capable of detecting light down to **120 nm**, covering scintillation wavelengths of liquid xenon and argon with cryogenically compatible, ultralow-RI packaging options.

We developed a 4th generation of *VUV-MPPC (VUV4)* for cryogenic physics experiments. In addition to diminished afterpulsing and inter-pixel trenches to suppress optical crosstalk, we have achieved improvement of VUV photosensitivity in this new MPPC through new modifications of the device structure. By achieving these results and continuing our MPPC improvements, we hope to make a valuable contribution to the physics community's efforts towards discovery of dark matter, the neutrinoless double-beta decay, and other cutting-edge research field.

Feature

✓ High sensitivity for VUV
✓ Stable for cryogenic temperature
✓ Suitable for detection of LXe or LAr scintillation light

LXe or LAr scintillator

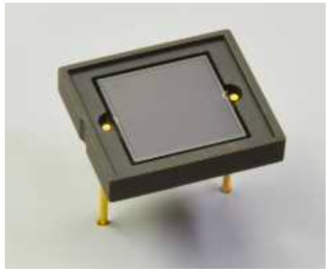
Liquid xenon (LXe) and liquid argon (LAr) are used as scintillators for **dark matter search** or **neutrinoless double-beta decay experiments.**

✓ **Liquid Xenon (LXe)**
- Peak emission wavelength: 178 nm
- Temperature: 165 K
- Directly detected by VUV photodetector

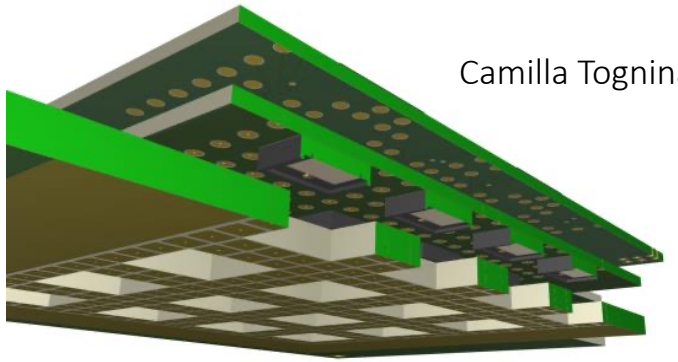
✓ **Liquid Argon (LAr)**
- Peak emission wavelength: 128 nm
- Temperature: 87 K
- Directly detected by VUV photodetector or indirectly (after WL-shifter) by UV/blue photodetector (typically~420 nm)

Form KSX-0046 C

- Operate the charge and light integrated anode readout plane in a small-scale LAr-TPC ✓
- Investigate crosstalk between the readouts ✓
- Investigate charge accumulation on SiPMs if any
- Observe cosmic muon tracks ✓



- Ceramic packaged Hamamatsu VUV SiPMs with pins
- Not possible to have one single PCB with µ-via stackup, since the SiPM pins would interfere with the LArPix ground pads
- Solution: a stackup that's built with 3 different PCBs soldered together.

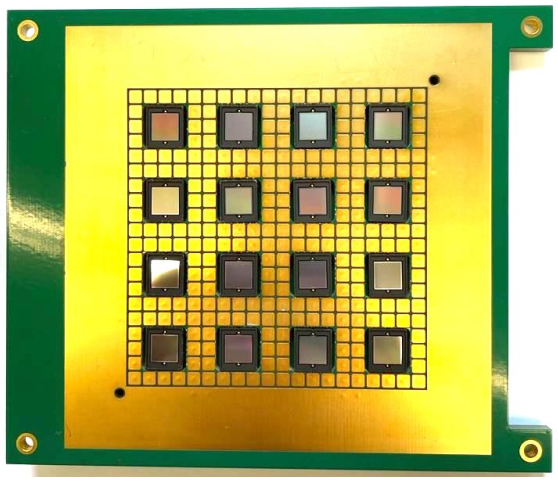


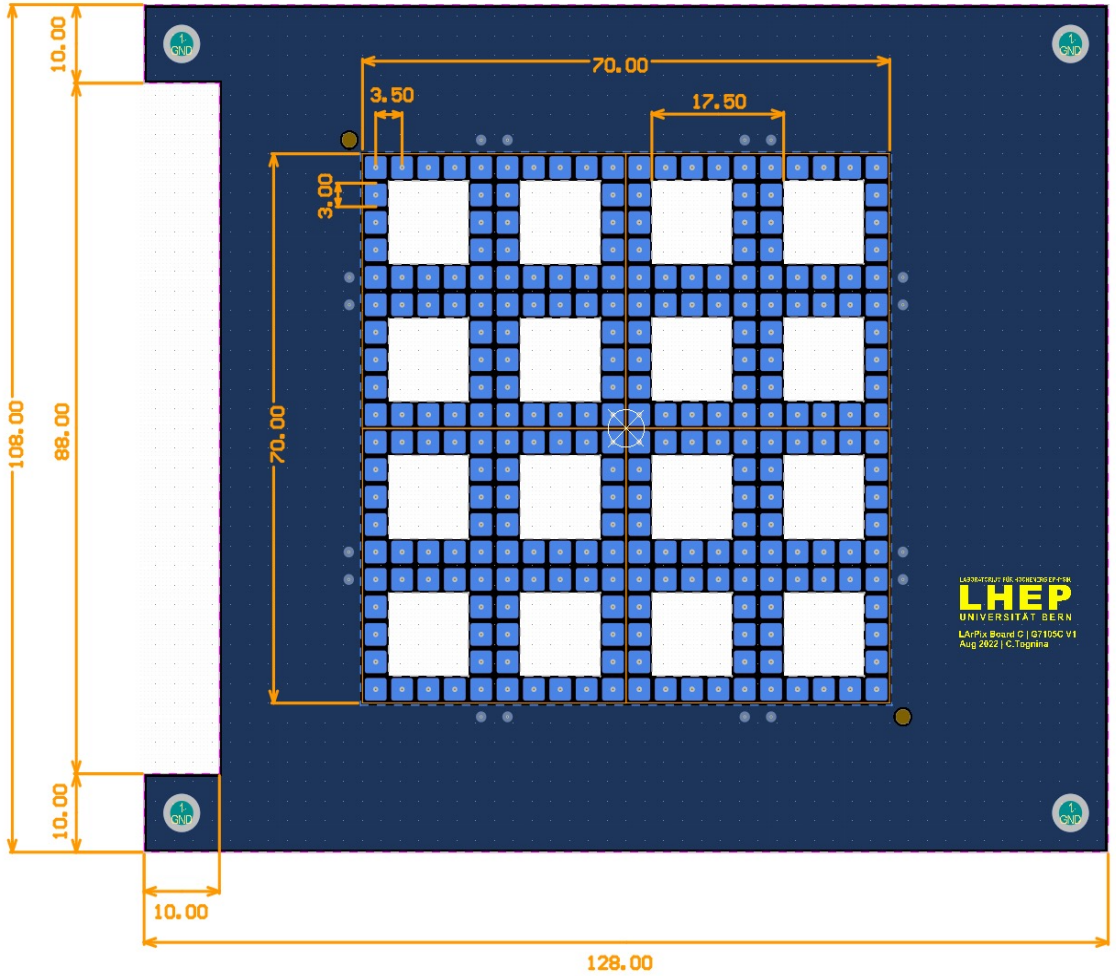
Camilla Tognina

SoLAr Prototype-v1

Anode plane design

- Charge pixel pads: 3mm
- Pixel pitch: 3.5mm
- SiPM sensitive area 6mm x 6mm
- SiPM pitch: 17.5mm
- Readout area: 70mm x 70mm



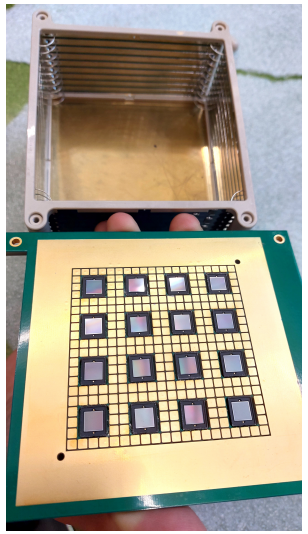


SoLAr Prototype-v1

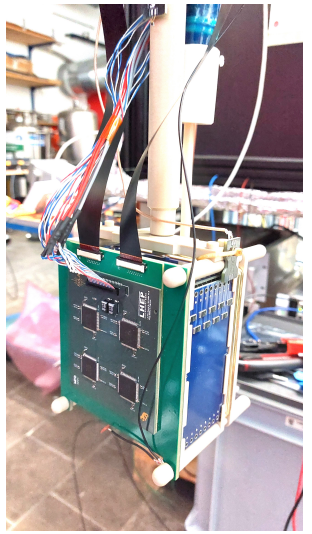
Cosmic run

25-26 October 2022 (~24h operation)

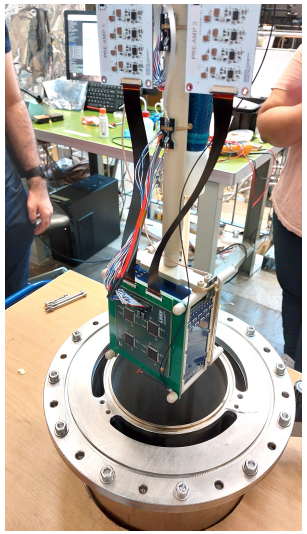
- Continuous collection of 10 min data files, data is stored in separate files for charge and light
- Light trigger signal is recorded in the charge data stream as an external marker
- Average light trigger rate 5Hz



Inside the TPC

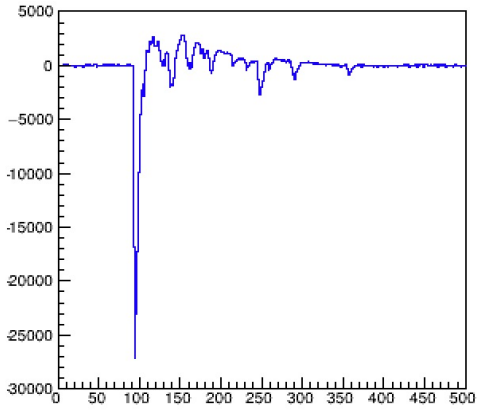


SoLAr-v1 TPC

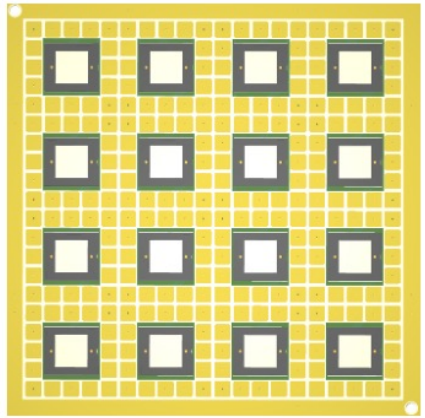


Insertion into cryostat

A single light waveform

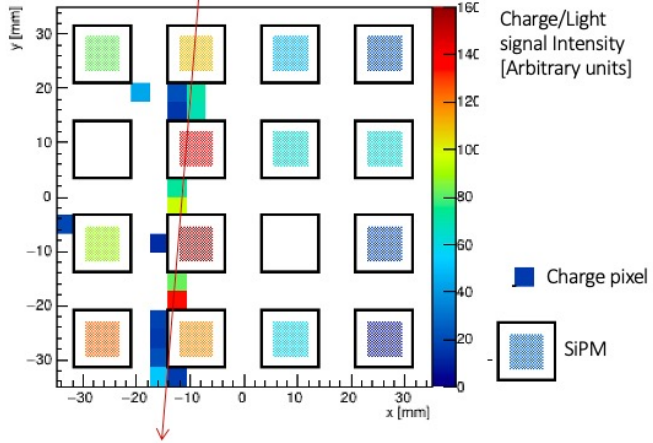


Anode plane visual guide

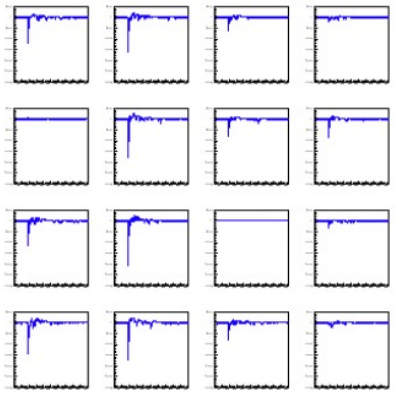


μ track

event 792 xy view



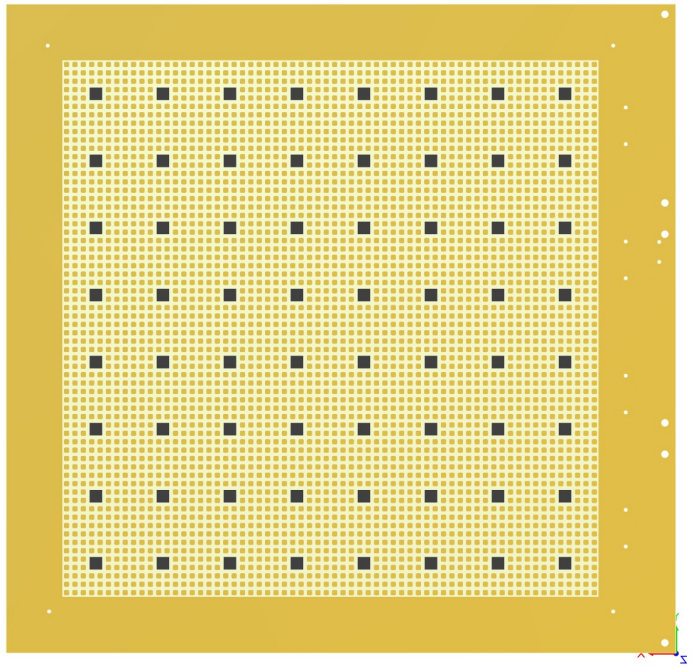
SiPM waveforms

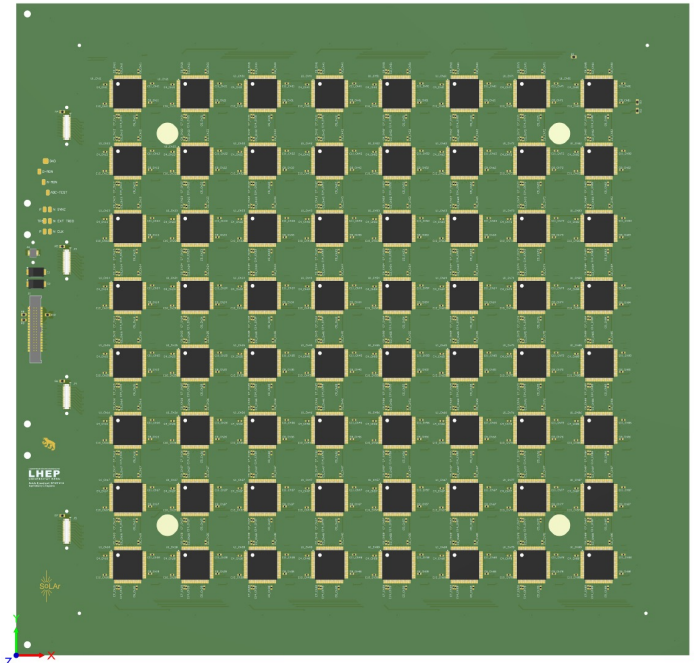


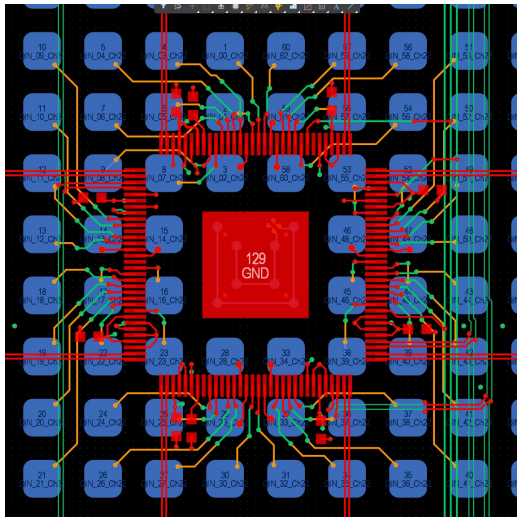
SoLAr prototype-v2

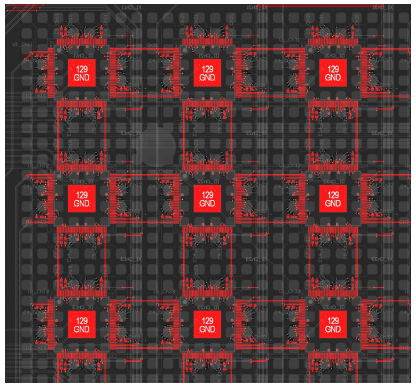
Anode tile layout

- Tile Dimensions 31cm x 32 cm
- Divided into 8x8 regions
  - 1 region = 60 pixels + 1 SiPM
  - Pixel pitch: 4mm
- 64 LArPix (60 routed channels)
- 64 Hamamatsu VUV SiPMs
  - SMD type, 6mmx 6mm
  - SiPM pitch: 32 mm

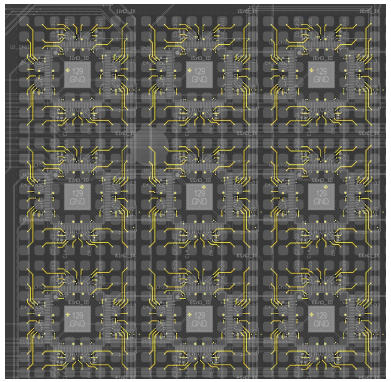




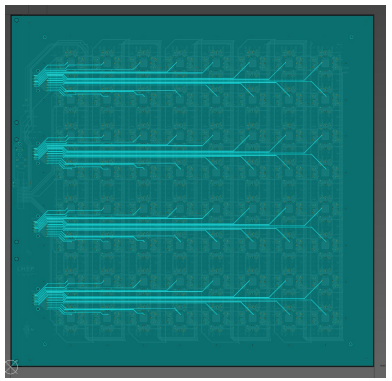




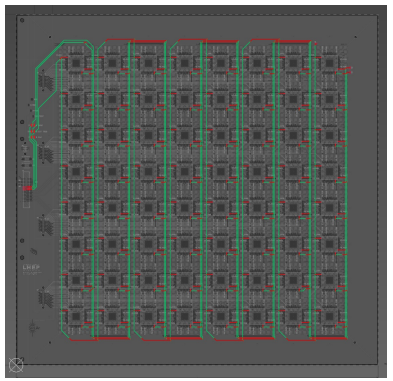
Hydra network



Pixel traces



SiPM traces

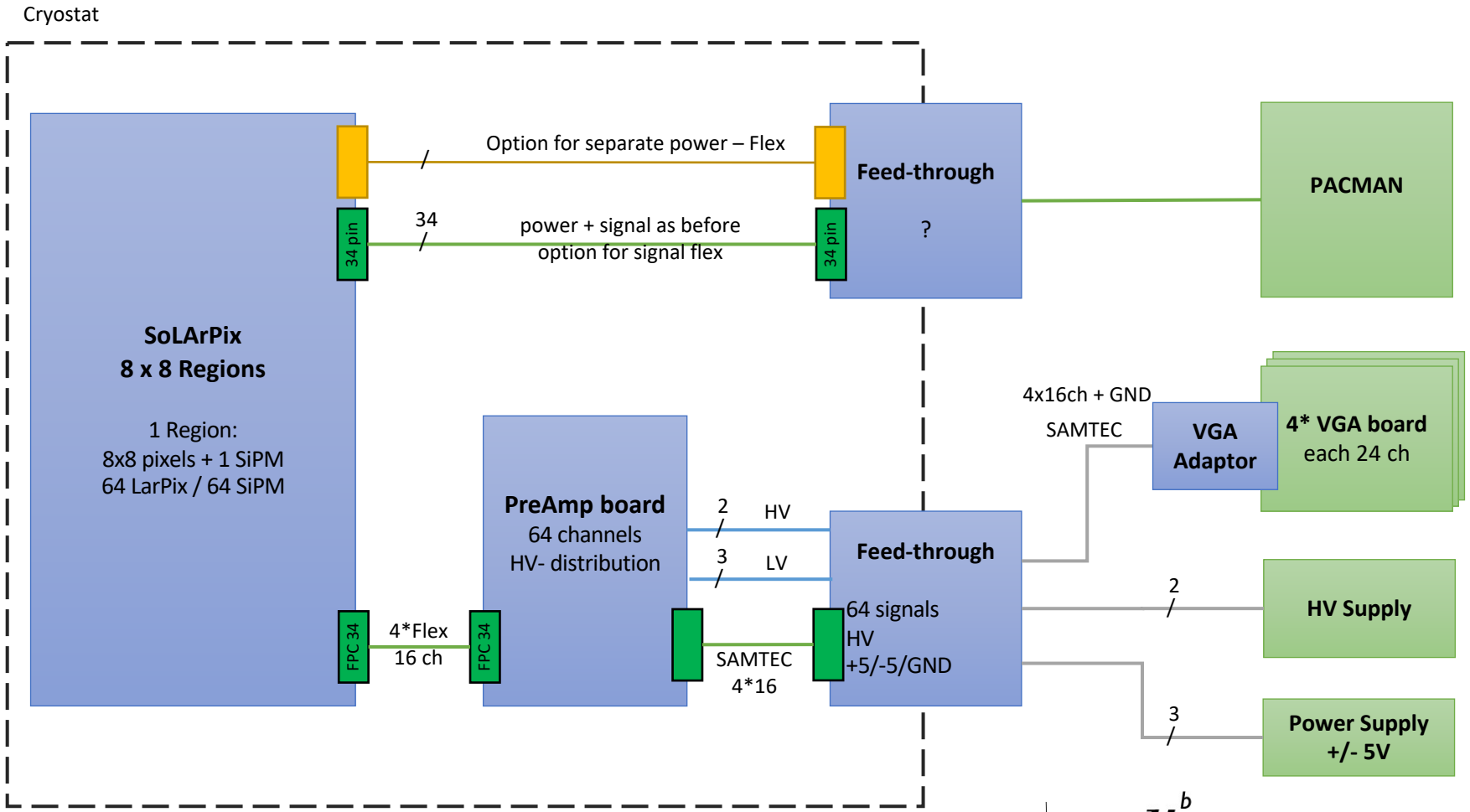


Digital traces

SoLAr prototype-v2

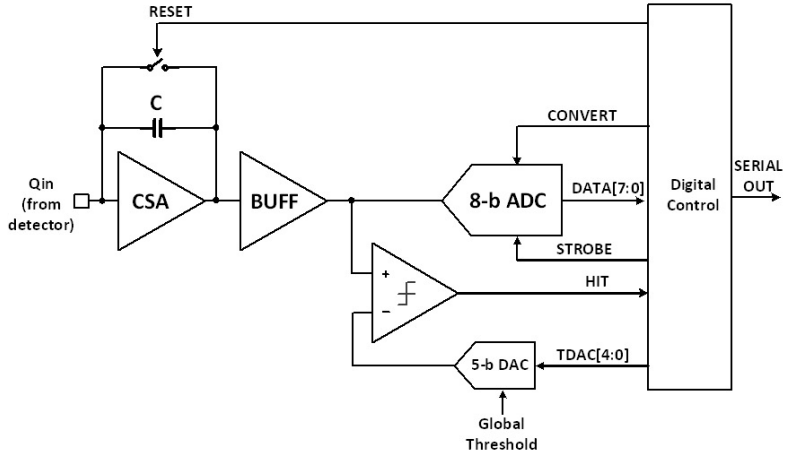
Readout diagram

- Charge readout: LArPix-v2b chips + PACMAN
  - Continuous Self-triggering ~ 100% live
  - Low power, low noise
  - Channel threshold ~ 100 keV
- Light readout: VUV SiPM+ Preamp + VGA + ADC
  - 62.5 MHz sampling frequency
  - 10 µs digitized window
  - Trigger on the Sum of up to 6 SiPMs



LarPix ASIC

performance in ND-LAr prototype modules



Developed by LBL for the DUNE near detector ND-LAr

Low-power, integrating amplifier with self-triggered digitization and readout

Pixel dormant until signal exceeds tunable threshold

- Integrates charge for ~3μs (4 mm drift), then digitizes - Ready for next signal

Pixels are continuously active

- Modest data volumes: ~1 MB/s per square meter of anode in surface cosmic-ray flux

End-to-end system architecture – *large-format pixel anode tiles, cables, feedthroughs, controller, etc*.

- Scalable to O(M) channel systems
- Mechanically and cryogenically robust
- O($0.10) per channel system cost, incl. cables/controllers/assembly/etc

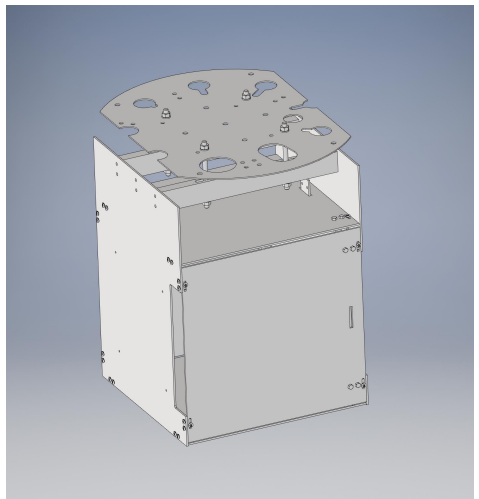
Specification	Value
Gain	4.5 µV/e^-
Power	< 200 µW/channel
Dynamic range	1.3 V
ADC resolution	8 bits
Pixel multiplexing	6.4 k channels / cable
Noise	~850 e^-
Charge resolution	< 1200 e^-
Spatial resolution	1.1 mm
Saturation level	~ 200 ke^-
Channel threshold	~ 100 keV

SoLAr Prototype-v2

Single Cube TPC Setup for Cosmic run

3-10 July 2023

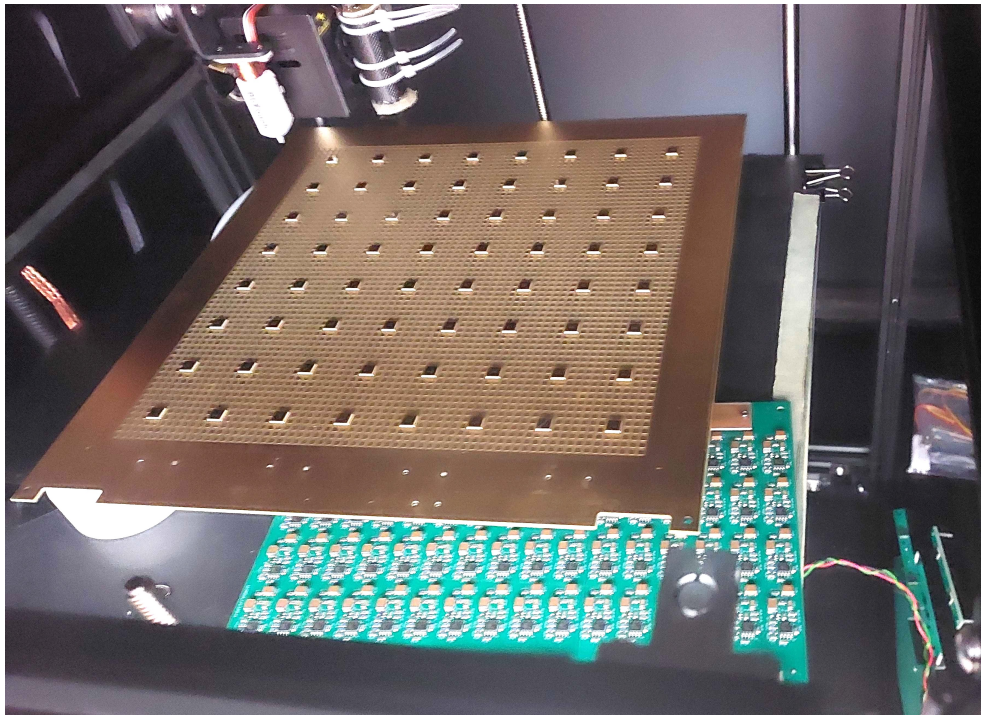
- SoLAr prototype-v2 tile was assembled in the Single Cube setup
- Test was performed in the single module cryostat at Bern



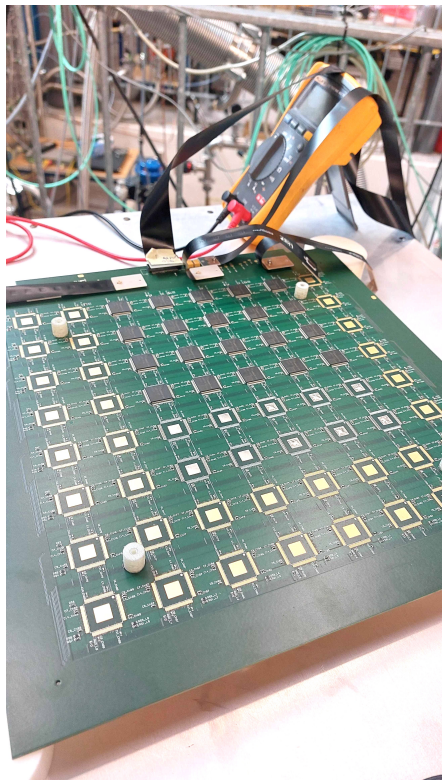
SoLAr Prototype-v2

Anode tile warm test and assembly

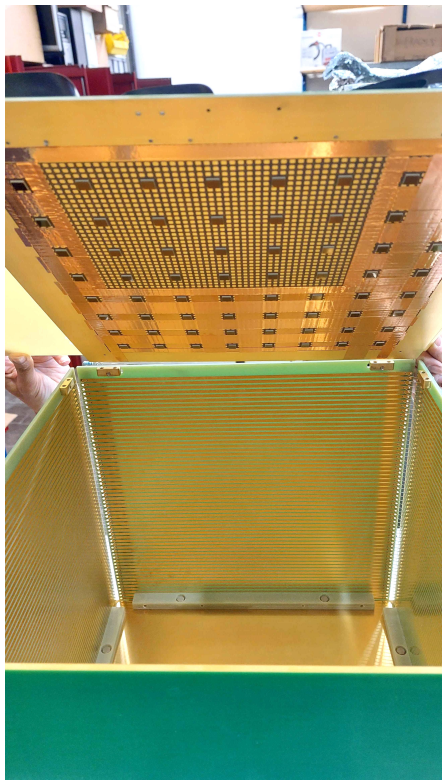
- Anode tile was populated with 64 SiPMs and 20 LArPix
- Un routed pixels were grounded with copper tape



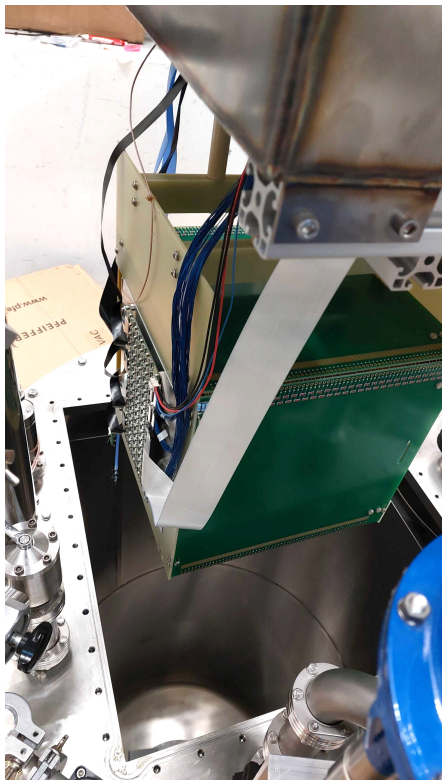
Warm SiPM test in a blackbox



Warm LArPix test



Inner view of the TPC



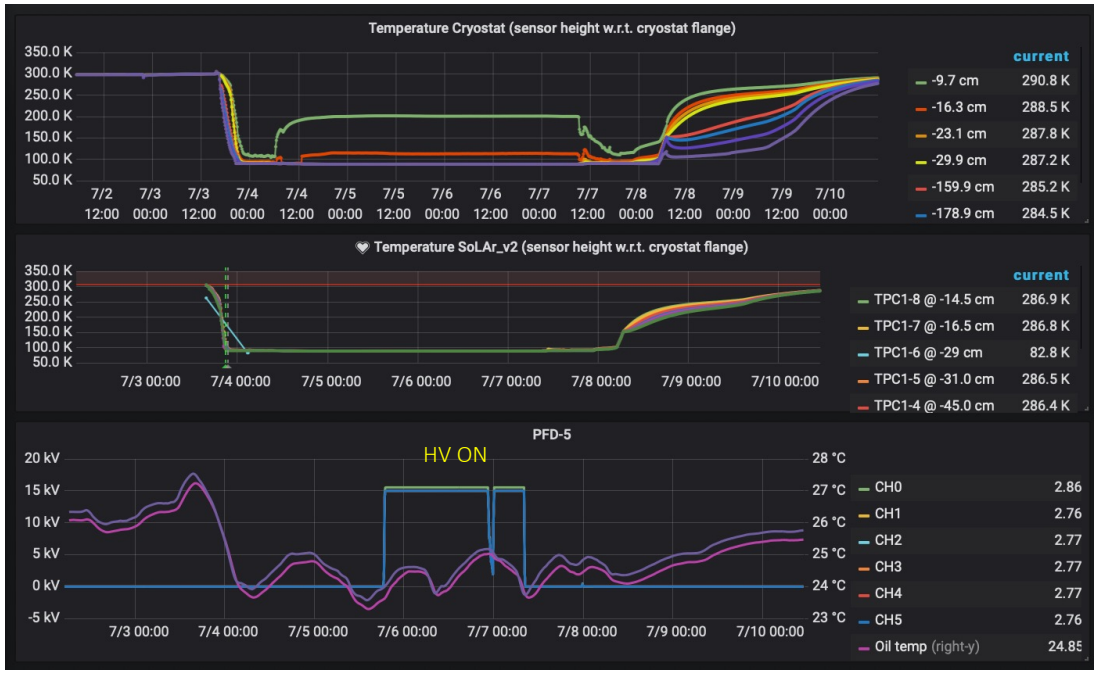
Insertion into cryostat

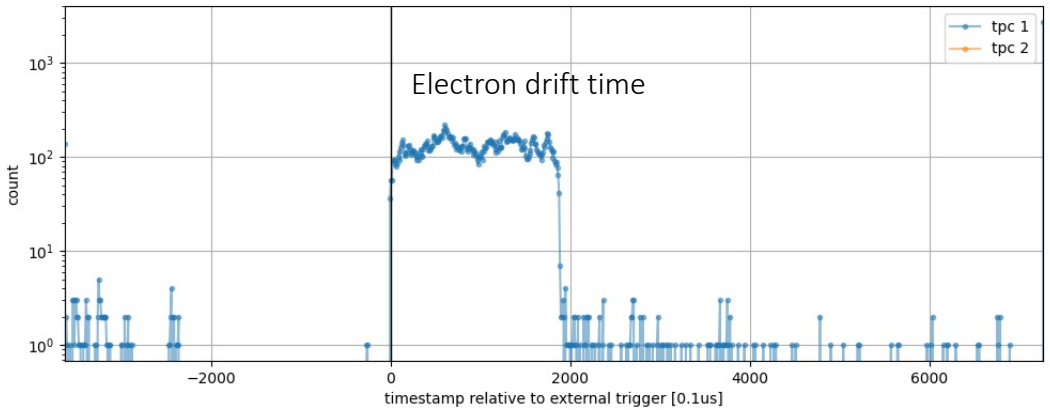
SoLAr prototype-v2

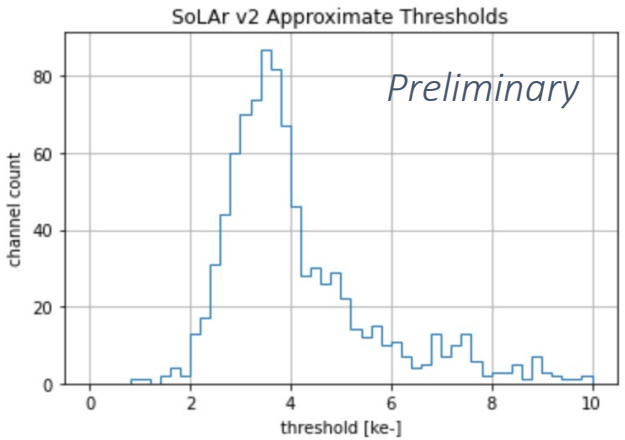
Run overview

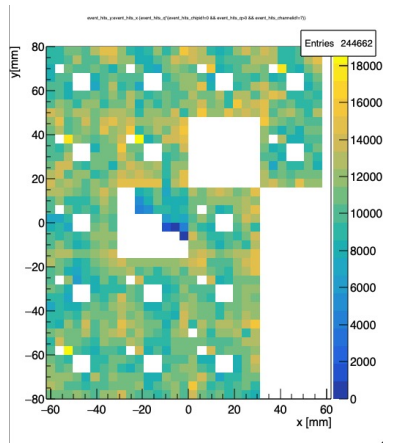
3-4 July -> Cooldown and Filling
4-5 July -> System bring up
5-7 July -> HV ON, tunning and cosmic data taking
7-10 July -> drain and warm up

- Two days of cosmic run with nominal HV 15 kV
- Achieved good LAr purity
- Achieved very low charge hit threshold ~ 3.8 ke$^-$ → 100 keV
- Special Cobalt-60 source run
- Special runs with varied SiPM bias over voltage
- Special runs with HV = 7.5 kV and HV =3.75 kV







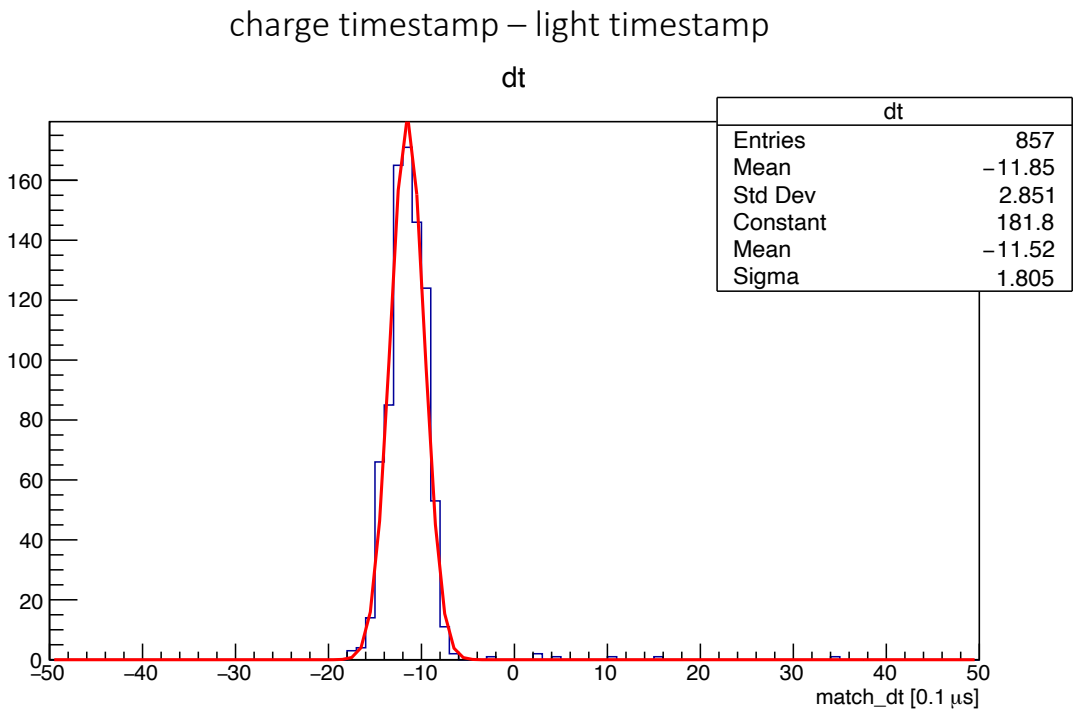


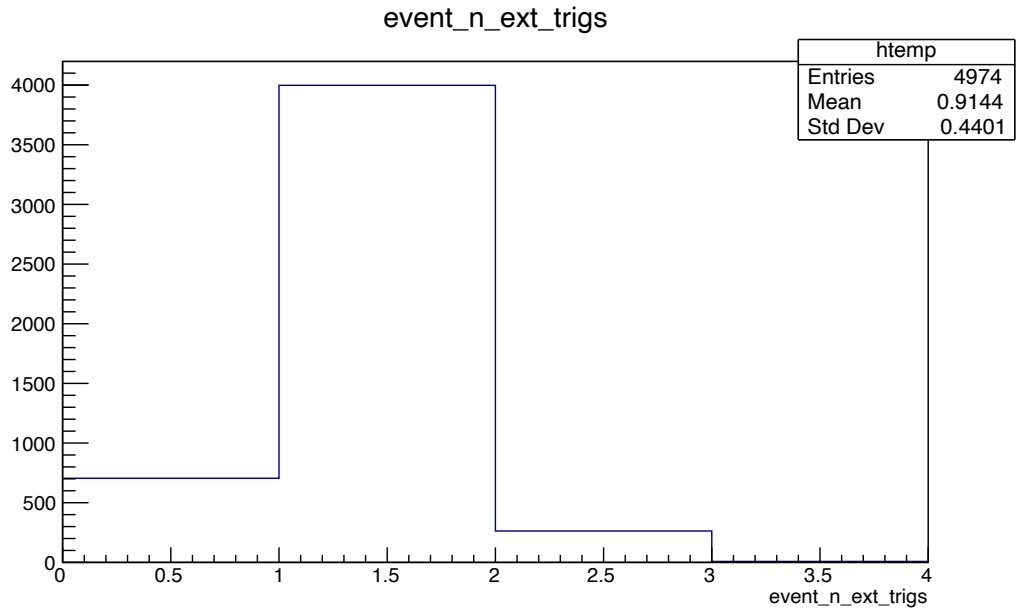
Hit map -> Location of disabled charge pixels

SoLAr prototype-v2

Light and charge matching efficiency

Match efficiency 85.7% of the charge events found a corresponding light event match with a search window of 10 µs

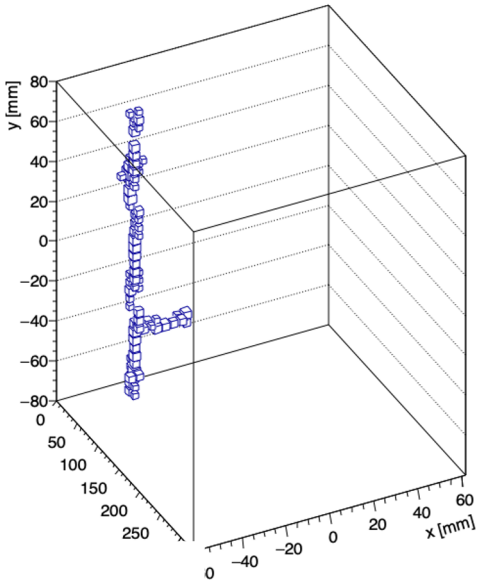




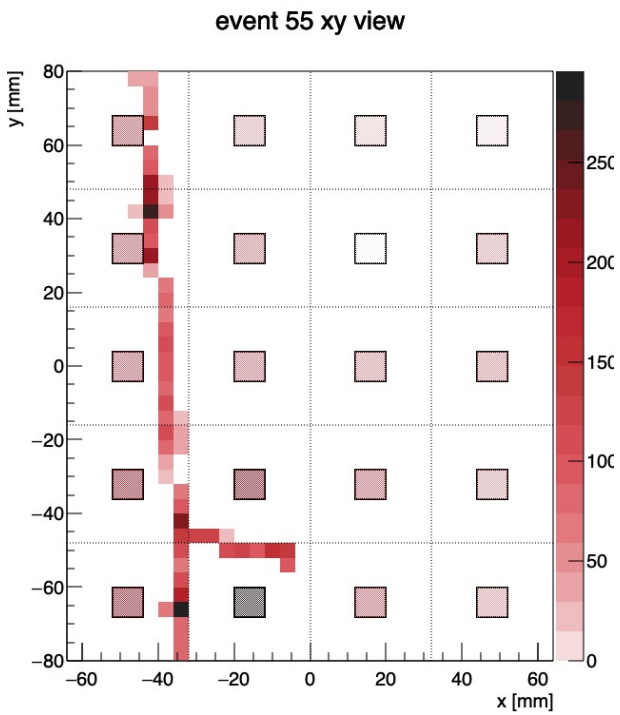
The Light trigger signal is recorded as a marker in the charge readout data stream

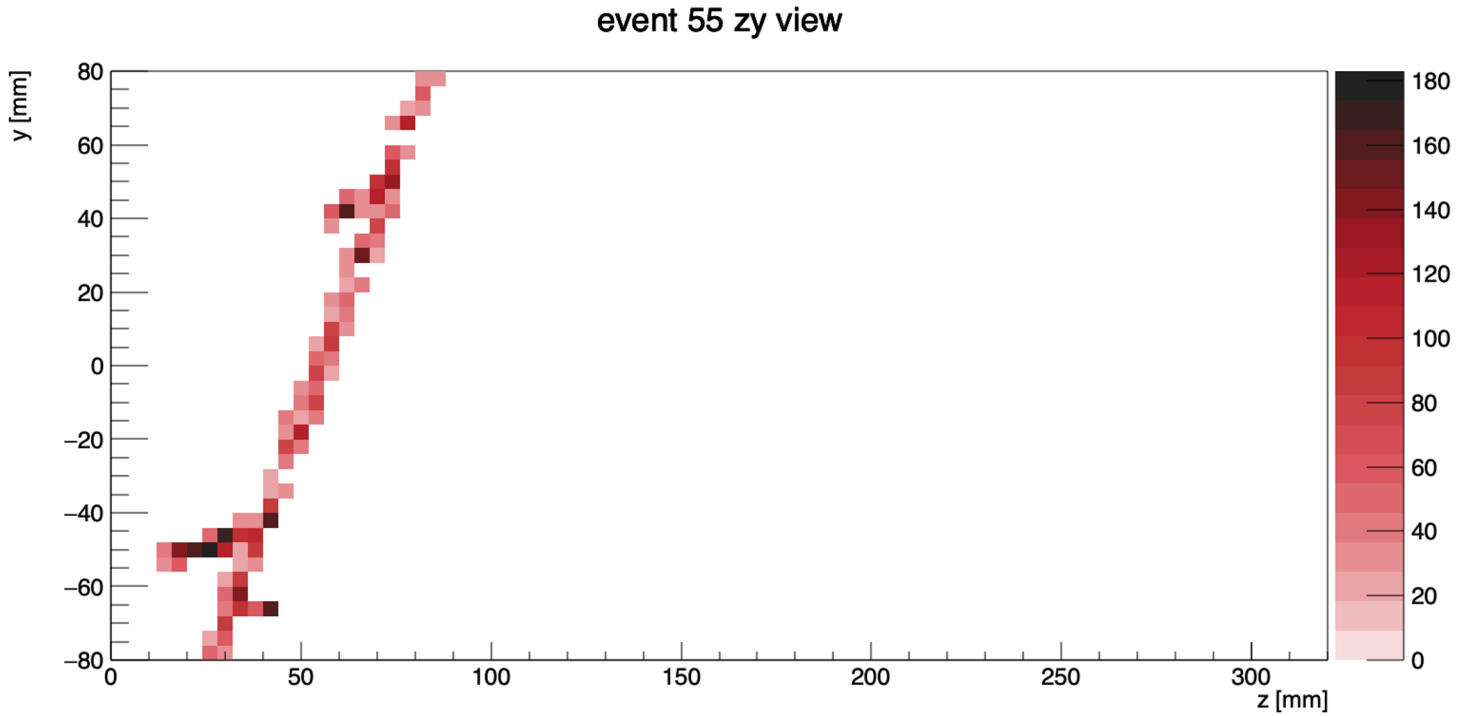
SoLAr prototype-v2

Light and charge combined 3D display of a Cosmic muon track



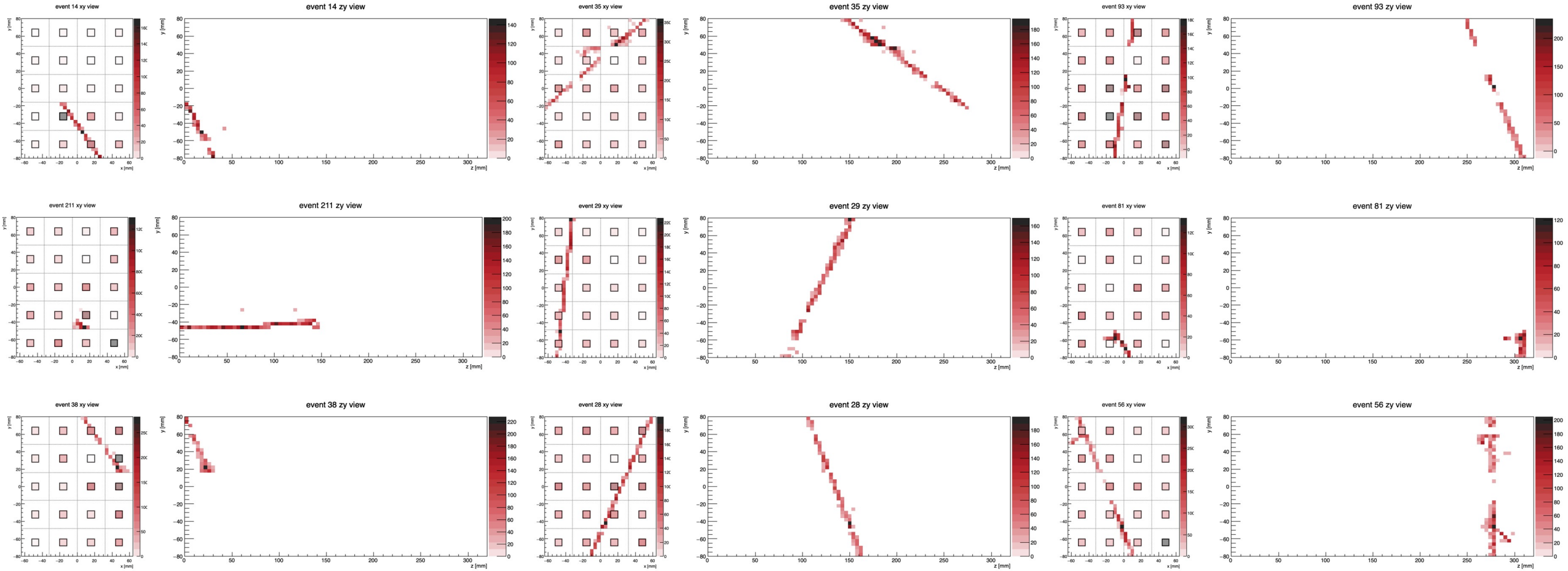
- Anode plane is located at z=0
- SiPMs are visualized as square boxes in the xy view
- SiPMs relative light intensity is presented as fill color (arbitrary units)





SoLAr prototype-v2

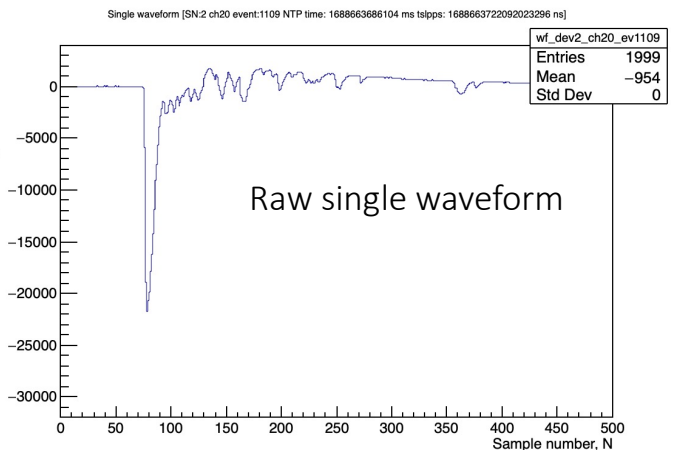
Cosmic track gallery

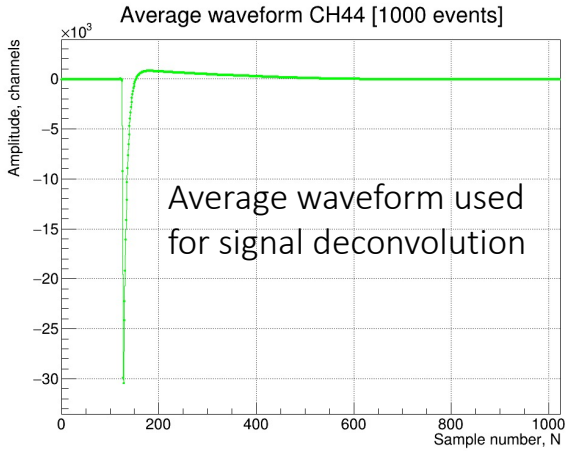


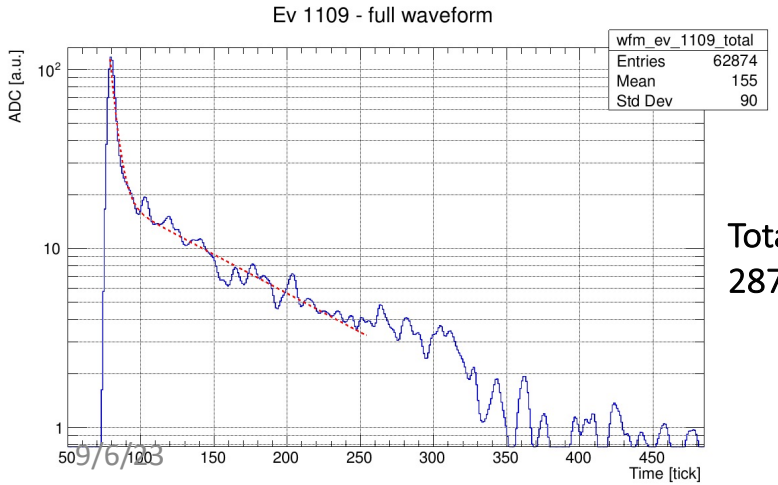
SoLAr prototype-v2

Light waveforms

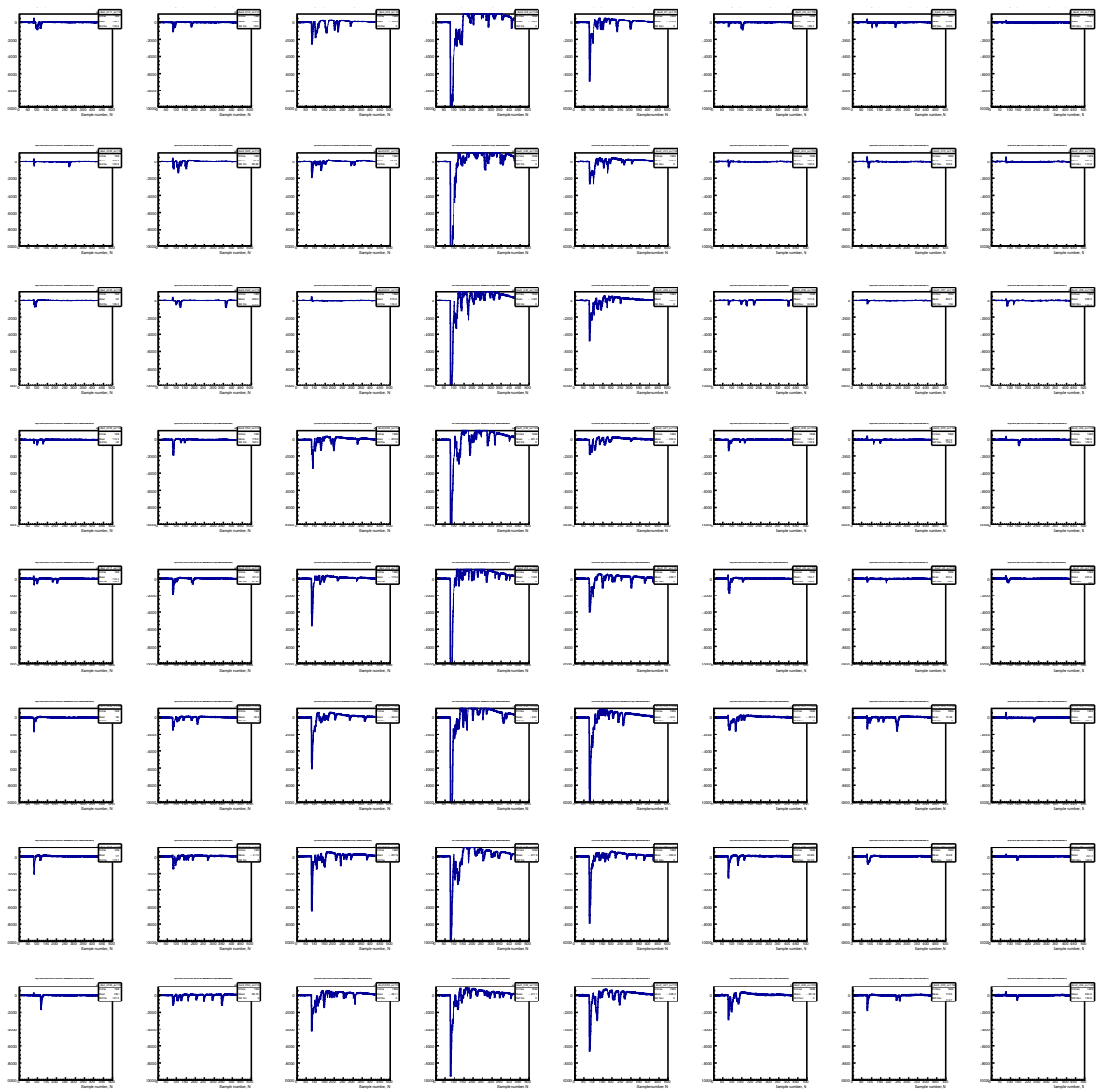
- Array of 64 SiPMs
- Position reconstruction form light is viable







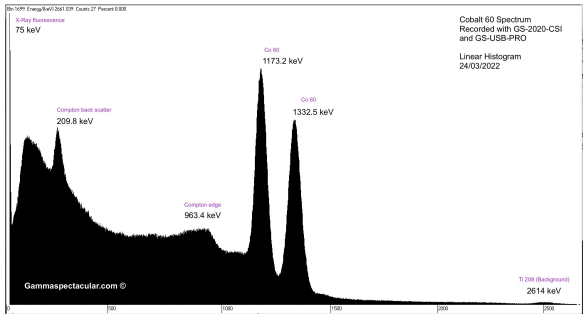
Total event light yield
2876.47 [p.e]

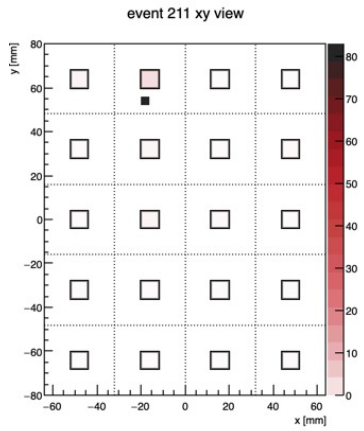


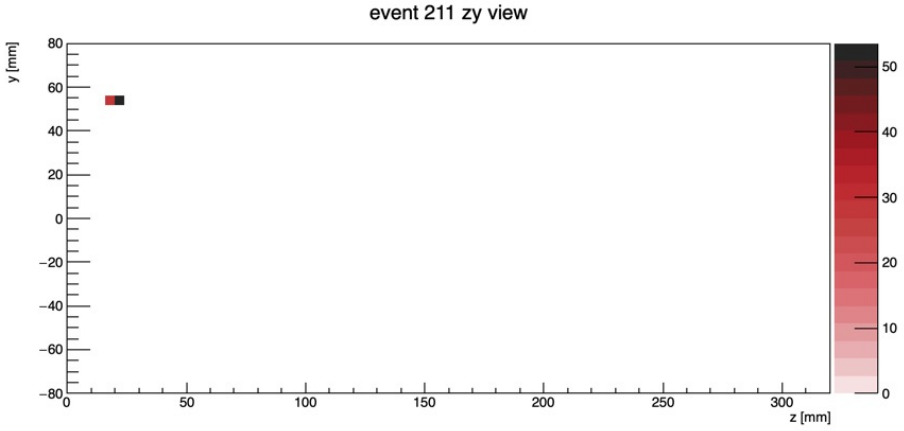
SoLAr prototype-v2

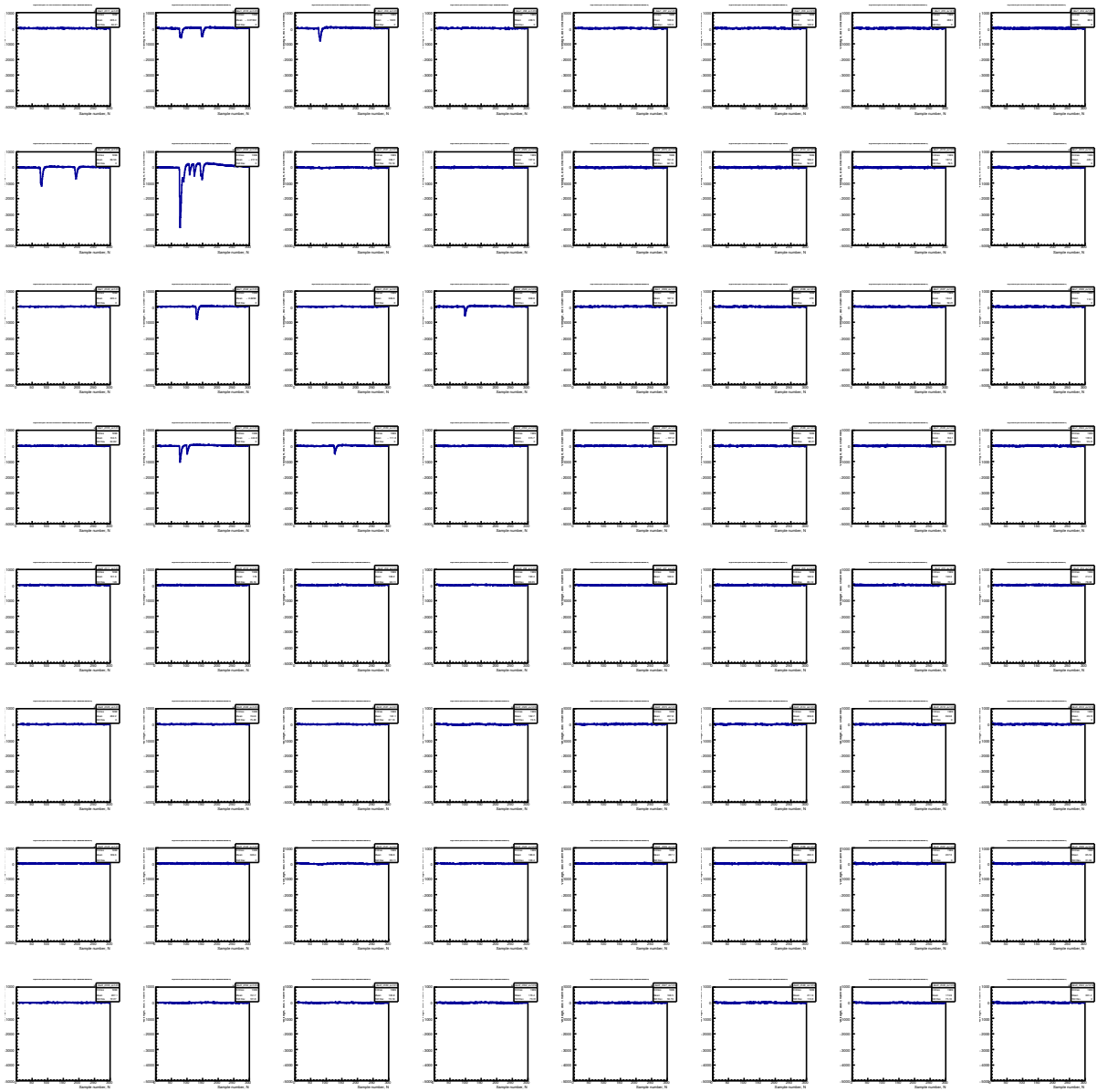
Cobalt-60 event

- Co-60 spectrum peaks @ 1.17 and 1.33 MeV
- Isolated point like events with matched light
- Interesting sample to study energy resolution and position resolution





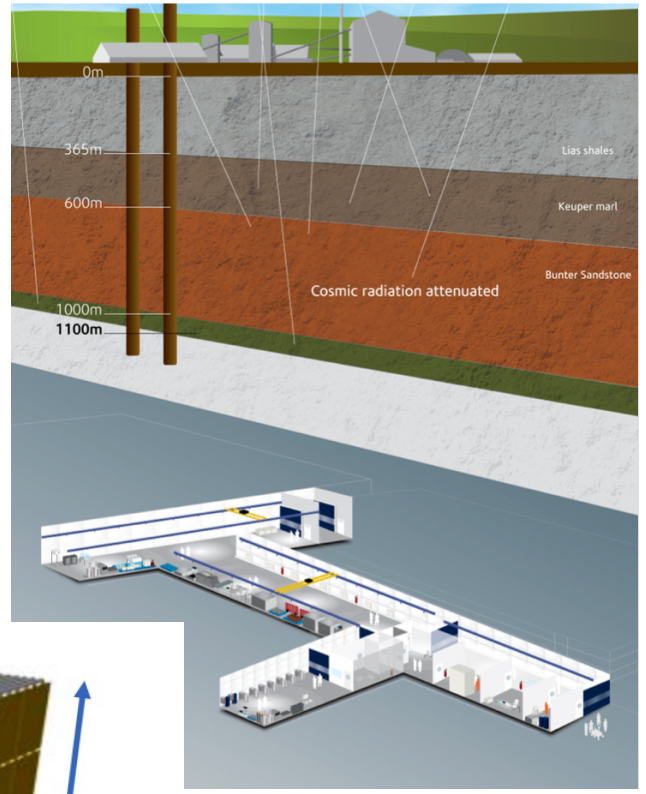




Next? Medium scale program

Candidate location -> Boulby Underground Laboratory (UK)

- 1100 m rock overburden

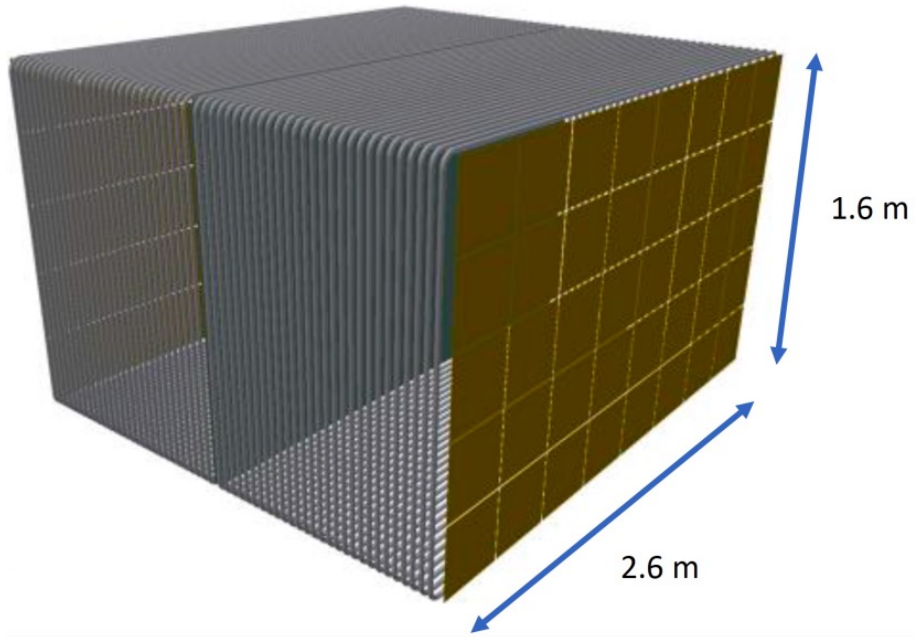


Science goals

- **Validate** SoLAr concept performance
- **Observe** neutrinos from 8B flux
- **Estimate** sensitivity to solar neutrinos for Module of Opportunity

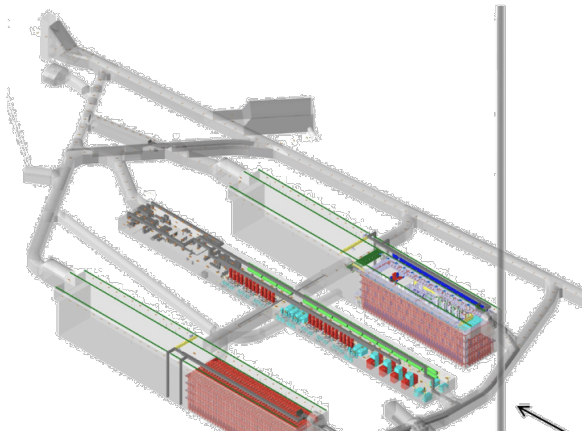
Detector Concept

- 1.6 x 2.6 x 2 m^3 (1 m drift length)
- 30 x 30 cm^2 tiles
- Light traps on 4 sides of the TPC



Summary and Outlook

- First successful demonstration of a SoLAr prototype with charge and light on the same anode plane
- Second SoLAr prototype took cosmic data last month and data analysis is ongoing
- Future R&D and prototyping program aims to benchmark new technology and delivers a SoLAr cell unit with charge pads implemented on the surface of a VUV SiPM device, and testing of LightPix and Q-Pix chips as they become available
- Simulation efforts in progress (understanding background sources, developing mitigation strategies, quantifying the sensitivity to solar neutrinos > 5 MeV
- A medium scale demonstrator @Boulby would aim to satisfy the requirement of tracking and calorimetric resolutions for low neutrino energy physics
- Integrate the SoLAr design concept in the DUNE Module of Opportunity



Backup

ND-LAr Modular design

- Modular TPC
- Optical segmentation
- Short range drift
- Low profile field cage
- High photo-coverage light readout
- Pixelated charge readout