# Update on SoLAr and pixel R&D

***Task 9.2***

*Anyssa Navrer-Agasson, on behalf of the SoLAr Collaboration*

**2nd AIDA Innova Annual Meeting - 24-27 April 2023**

# Low energy neutrino physics in LArTPCs

✳ Large Liquid Argon Time Projection Chambers (**LArTPCs**) have **significant potential** for low energy neutrino physics

- 10 kt module with 5 MeV threshold

✳ **Solar neutrinos**

✳ **Supernova neutrino** bursts

✳ **Diffuse supernova neutrino background**

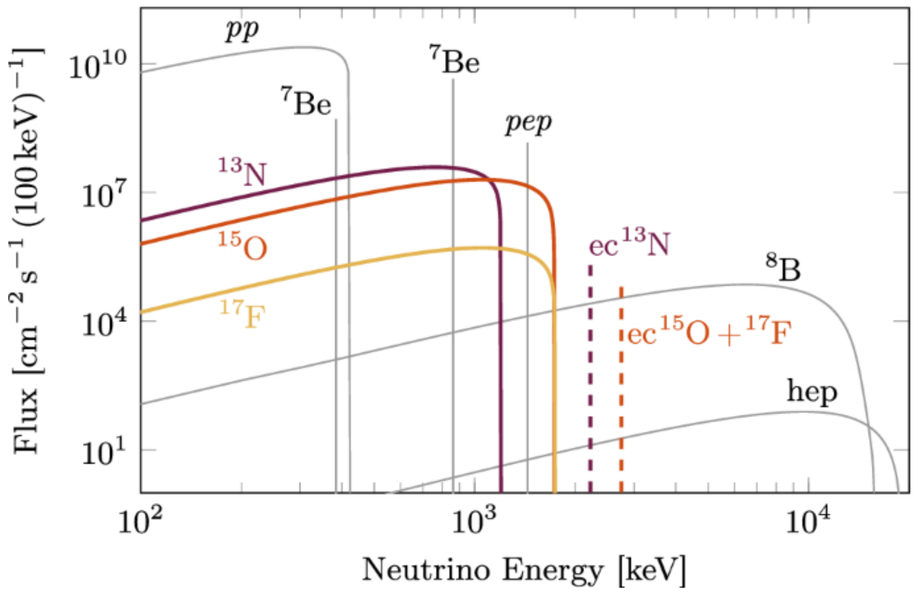
## Challenges

- **Materials** not optimised for searches requiring low backgrounds
- Limited low energy **resolution**
- Difficult **reconstruction** of low energy events

Charged Current (**CC**) interaction: $\nu_e$ + **$^{40}$Ar** → **e$^-$ + $^{40}$K***

Elastic scattering (**ES**): $\nu_x$ + **e$^-$** → $\nu_x$ + **e$^-$**

**Agostini et al, Eur. Phys. J. C 80, 1091 (2020)**



# The SoLAr concept

## Integrated charge & light readout tile for low energy neutrino physics in LAr

**Integrate developing technologies**

- ✴Next generation VUV SiPMs
- ✴Novel pixel readouts

**Combine light and charge**

- ✴ Improve triggering and energy resolution
- ✴ 7% energy resolution target

**Improve background rejection**

- ✴Pulse Shape Discrimination
- ✴Directionality

arXiv:2203.07501 [hep-ex]
August 25, 2022

SoLAr: Solar Neutrinos in Liquid Argon

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Justin Evans, Roxanne Guenette, David Marsden, Nicola McConkey, Anyssa Navrer-Agasson, Guilherme Ruiz, Stefan Söldner-Rembold [1], *University of Manchester, United Kingdom*

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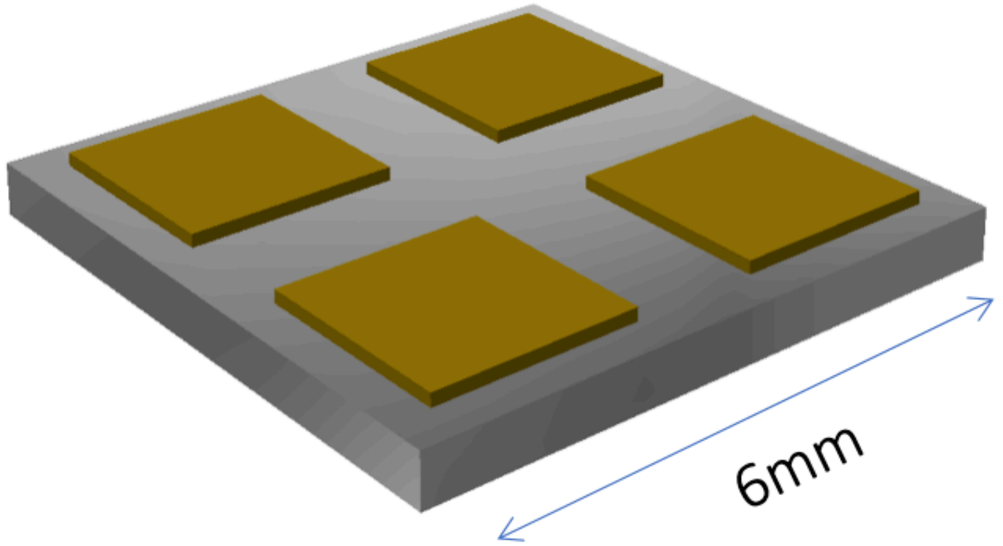
Francesco Di Capua, Giuliana Fiorillo, *University of Naples "Federico II" and INFN Napoli*

John F. Beacom, *Ohio State University, Columbus, OHio, USA*

Francesco Capozzi, *Instituto de Fisica Corpuscular, Universidad de Valencia & CSIC, Spain*

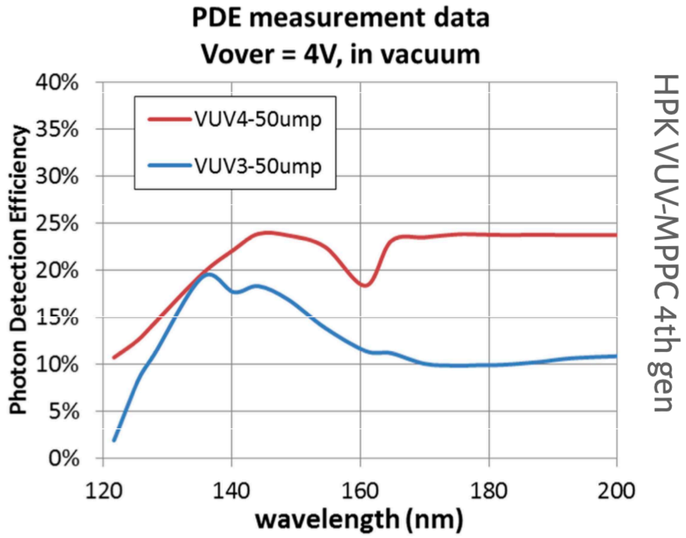
# SoLAr Readout Unit

- One MPPC readout channel
  - All silicon pad
- 4 charge readout channels
  - 4 metallised zones deposited over the silicon substrate as charge pads
  - Electrically connected by means of through via
- 50% light readout coverage for the SRU

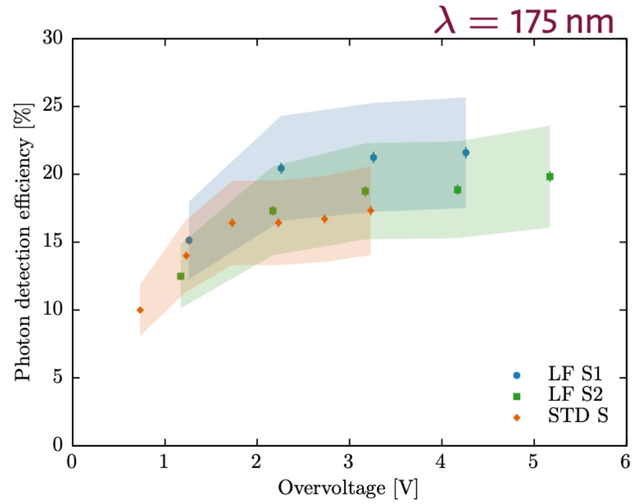


# SoLAr design: photon detection system

- **New generation SiPMs**:
  - **High photon detection efficiency** at LAr scintillation wavelength
  - Hamamatsu 4th generation MPPC
  - FBK VUV-HD technology




HPK VUV-MPPC 4th gen




Jamil et al. (nEXO Coll) IEEE Trans.Nucl.Sci. 65 (2018) 11

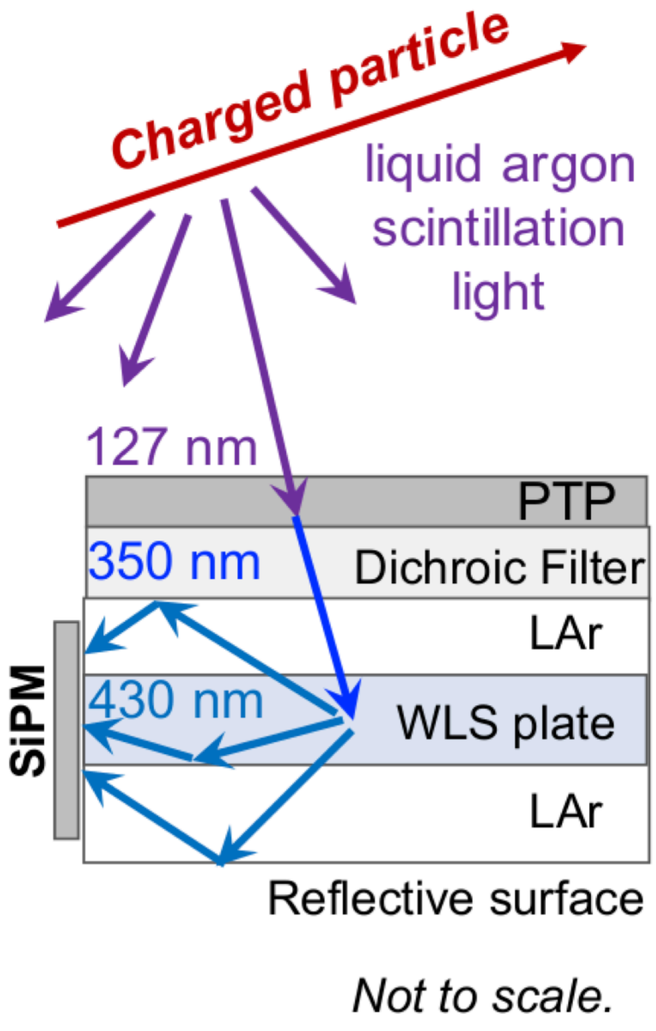
# SoLAr design: photon detection system

✳ **New generation SiPMs**:

- **High photon detection efficiency** at LAr scintillation wavelength
- Hamamatsu 4th generation MPPC
- FBK VUV-HD technology

✳ Can be combined with **light traps**

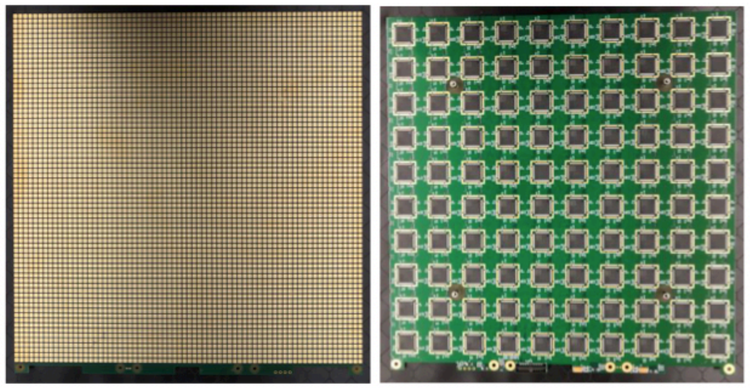
- Improve photodetector **coverage**
- Consider DUNE X-ARAPUCA design



# SoLAr design: charge readout

## LArPix

- Low power
- Self triggered digitisation and readout
- Technology **demonstrated in ArgonCube**
- **Available now**
  - **Used for first prototypes**



*32 cm by 32 cm anode PCB tile*

## Q-Pix

- Developed to **solve the data rate issue** of pixellated readouts
- **Electronic principle of least action**
- Saves time stamps instead of full waveforms

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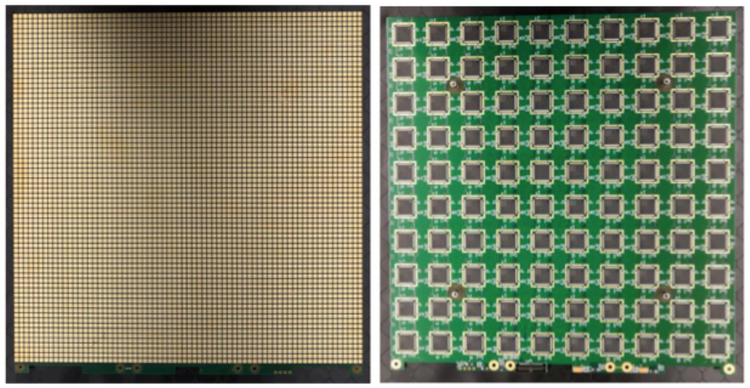

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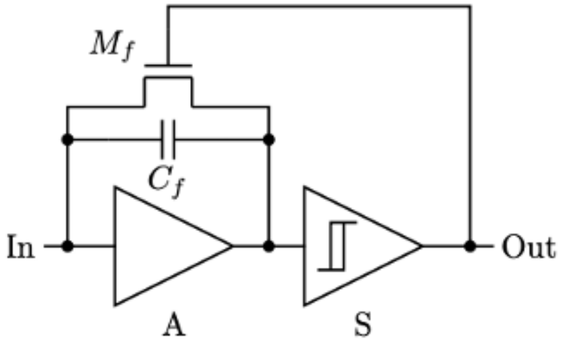


- Each channel integrates Charge Integrate Reset circuit
- Resets when charge > $\Delta Q/C_f$
- Measure reset times with embedded clock

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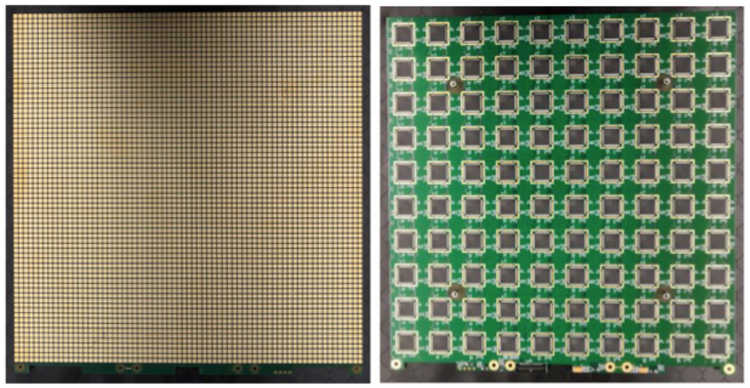

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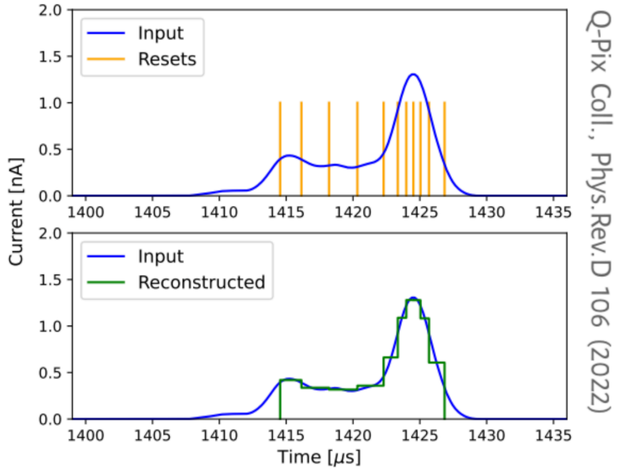


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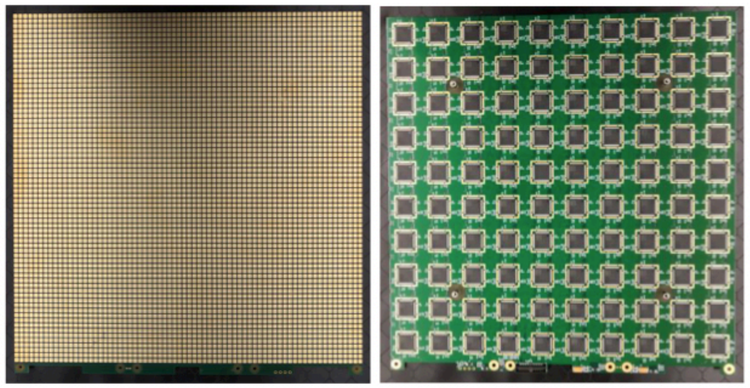

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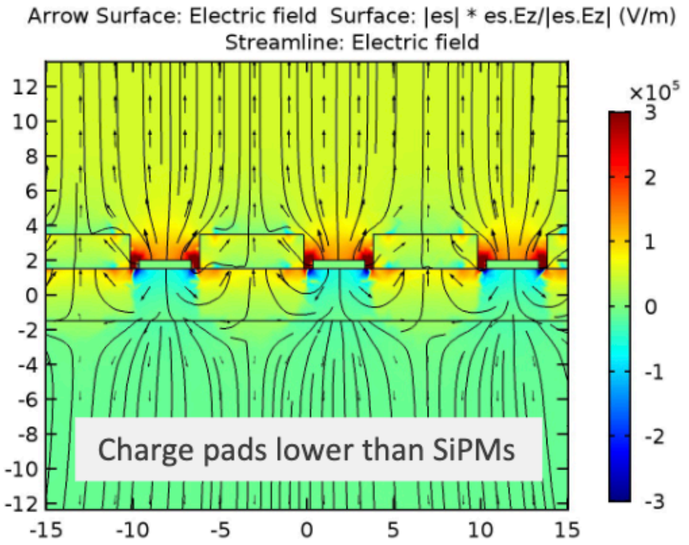
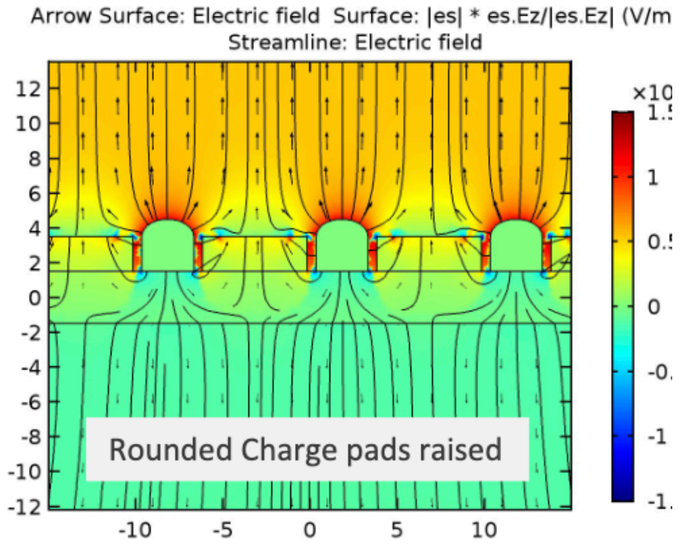
- Background rejection by looking at Reset Time Difference (**RTD**)
  - Long RTD → small average current → background
  - Short RTD → high average current → signal

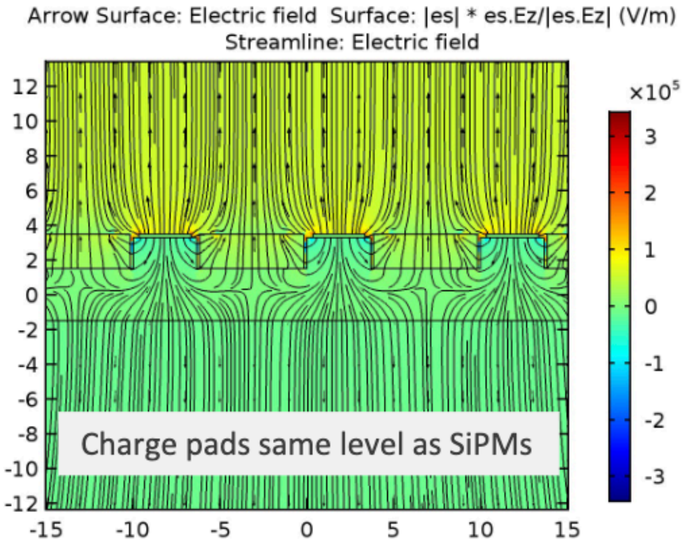
# Simulation

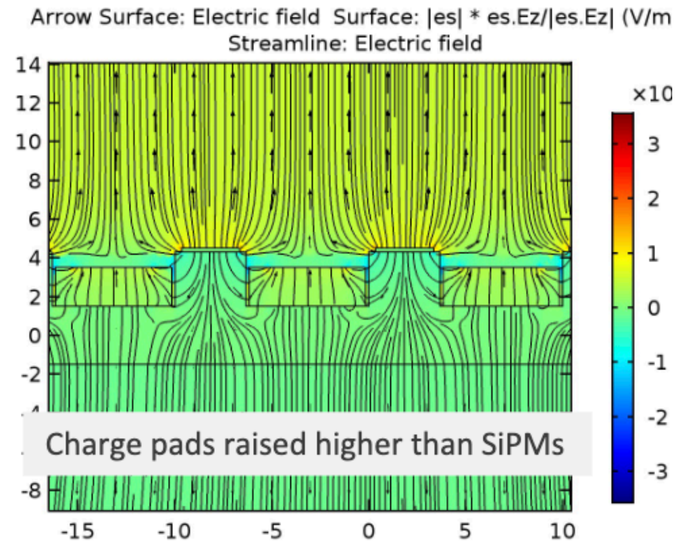
# Electric field simulations

- How do the E-field lines bend near the SiPMs?
- What is the charge collection efficiency?
- How does the shape of the pixels affect the E-field?
- Can we float the SiPMs to some negative voltage in order to deflect electrons towards the charge pads?
- Field simulation with COMSOL
- Near perfect electron collection efficiency in some conditions



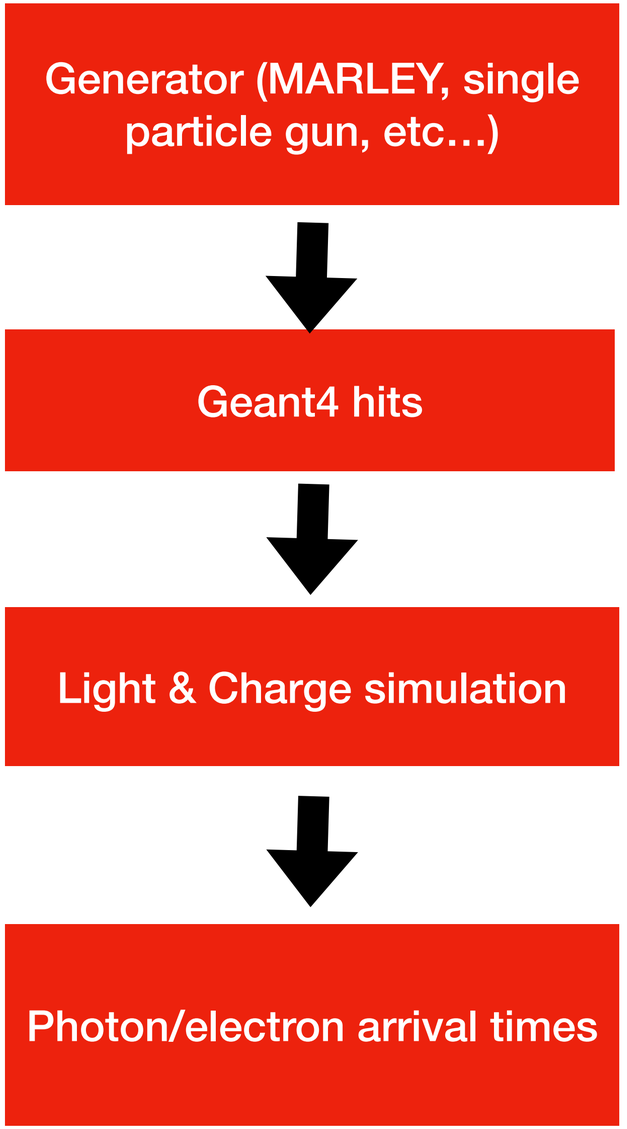



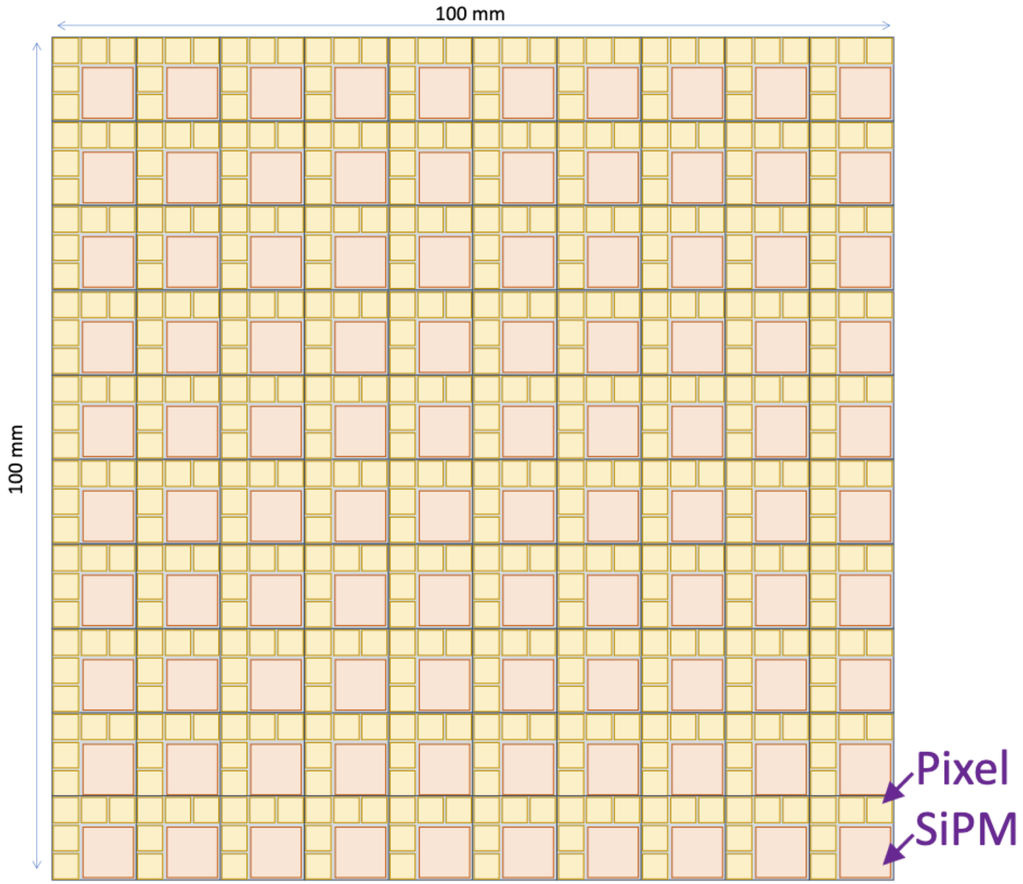



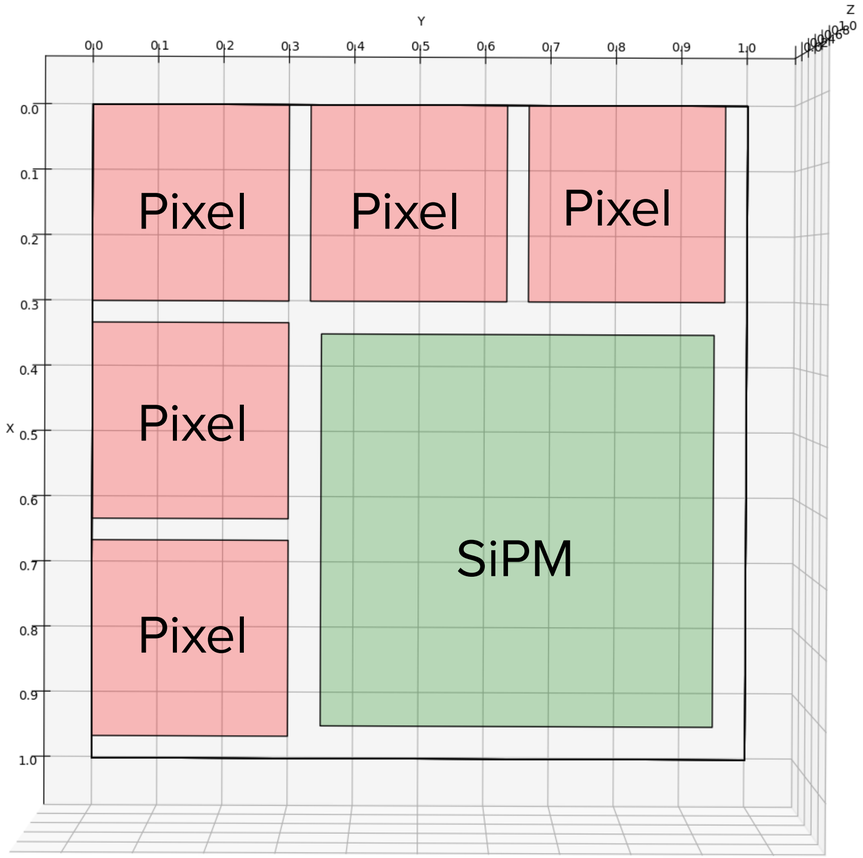
# Charge & Light simulation workflow

- Use MARLEY or particle gun to simulate primary interaction
- GEANT4  propagates particles through the detector
- Energy deposits passed to light and charge simulation
  - Both inherit from the Q-Pix simulation
- Scintillation (ionisation) calculated using LArQL implementation
- Photon (electron) arrival times generated according to LAr properties



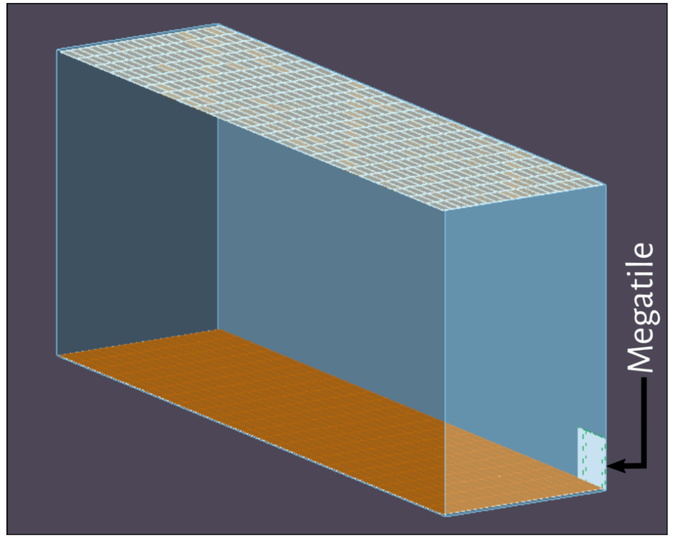
# Tile design

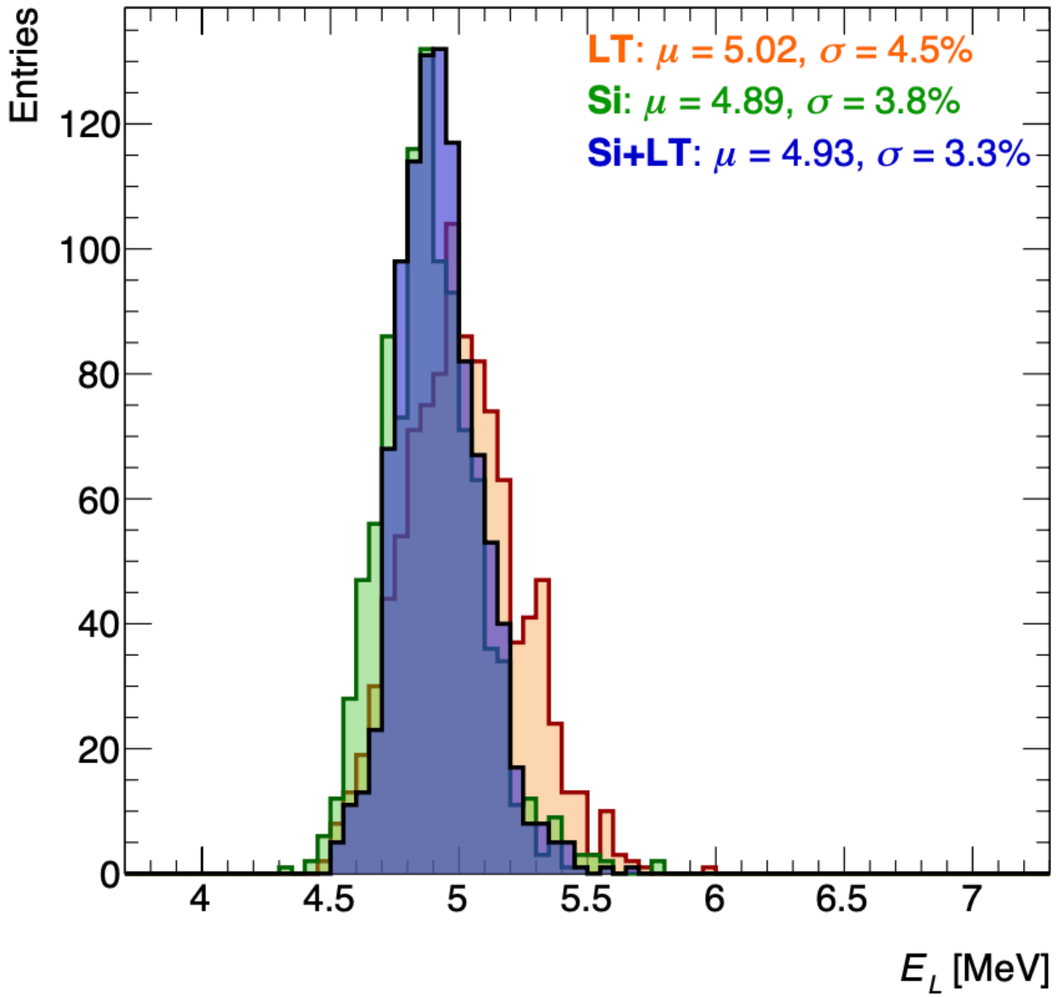

100 mm
100 mm
Pixel
SiPM


Y
Z
X
Pixel
Pixel
Pixel
Pixel
Pixel
SiPM

# Energy resolution

- 10 kt module
- 15% PDE for anode VUV SiPMs
- Light traps on top and bottom of the detector
  - 3% PDE



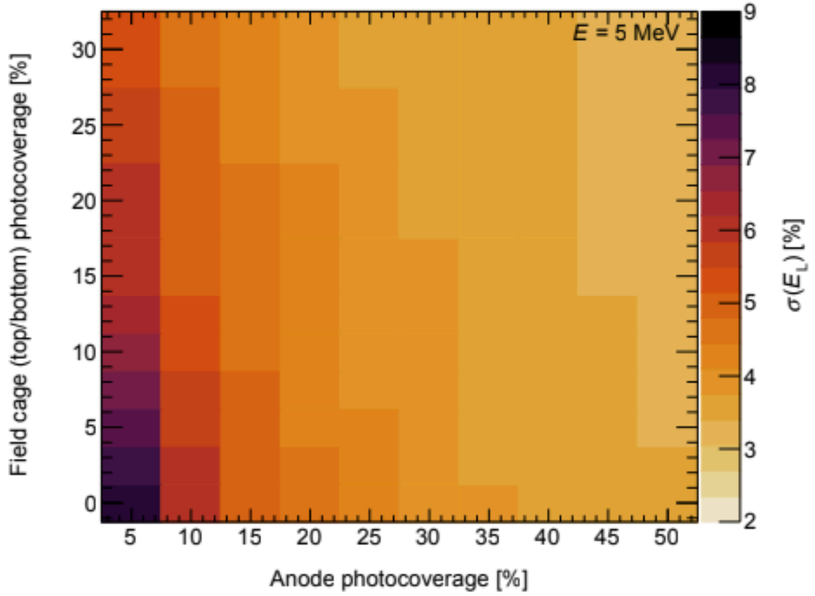



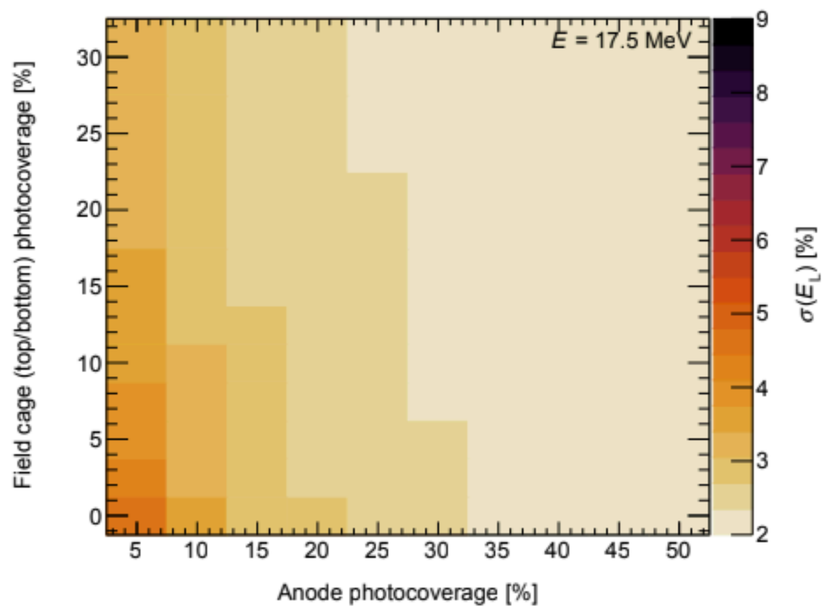

$$E = \frac{N_{\text{hits}}^{\text{Si}} + N_{\text{hits}}^{\text{LT}}}{\langle \text{LY} \rangle \cdot \left( \Omega^{\text{Si}}(\boldsymbol{x})\, \epsilon\, \text{PDE}^{\text{Si}} + \Omega^{\text{LT}}(\boldsymbol{x})\, \text{PDE}^{\text{LT}} \right)}$$

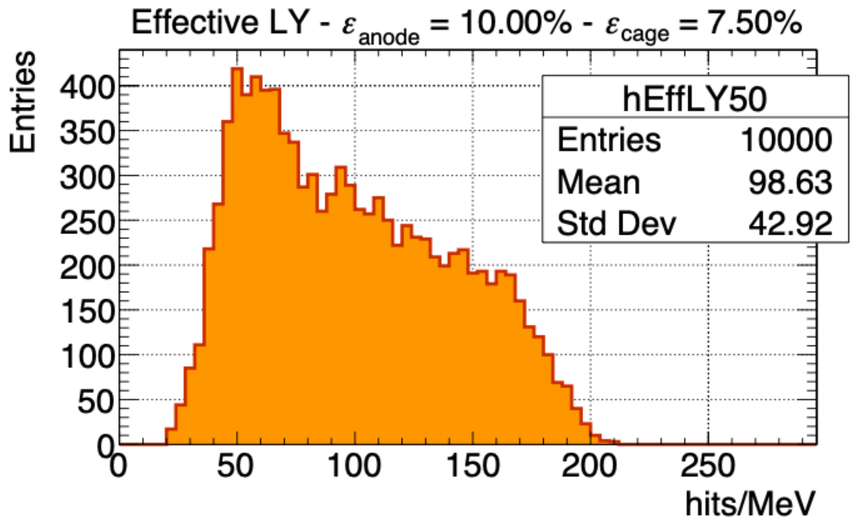
| | |
|---|---|
| $\langle \text{LY} \rangle$ | Avg LY |
| $\Omega(\boldsymbol{x})$ | Visibility |
| $\epsilon$ | tile photocoverage (30.6%) |

# Resolution as a function of coverage

- Light-only energy resolution of 7% with 10% anode photo-coverage and 5-10% field cage coverage
- In this configuration, we get ≈ 100 hits/MeV



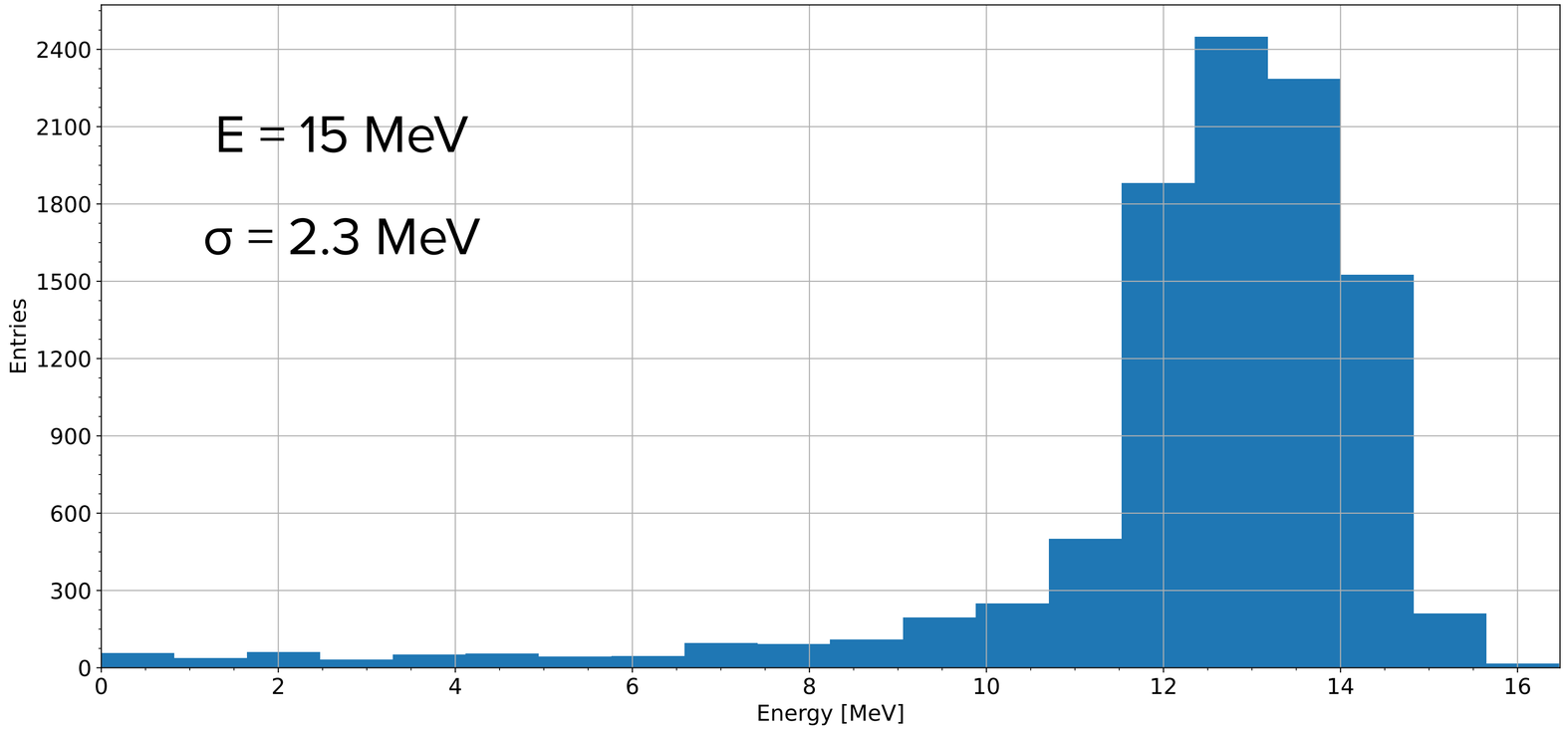



# First look at charge readout: Q-Pix

- Q-Pix resets channels when a certain integrated charge is reached
- > 90% electron detection efficiency

$$E = \frac{N_{electrons}}{CY} = \frac{N_{resets} \times 6250}{CY}$$

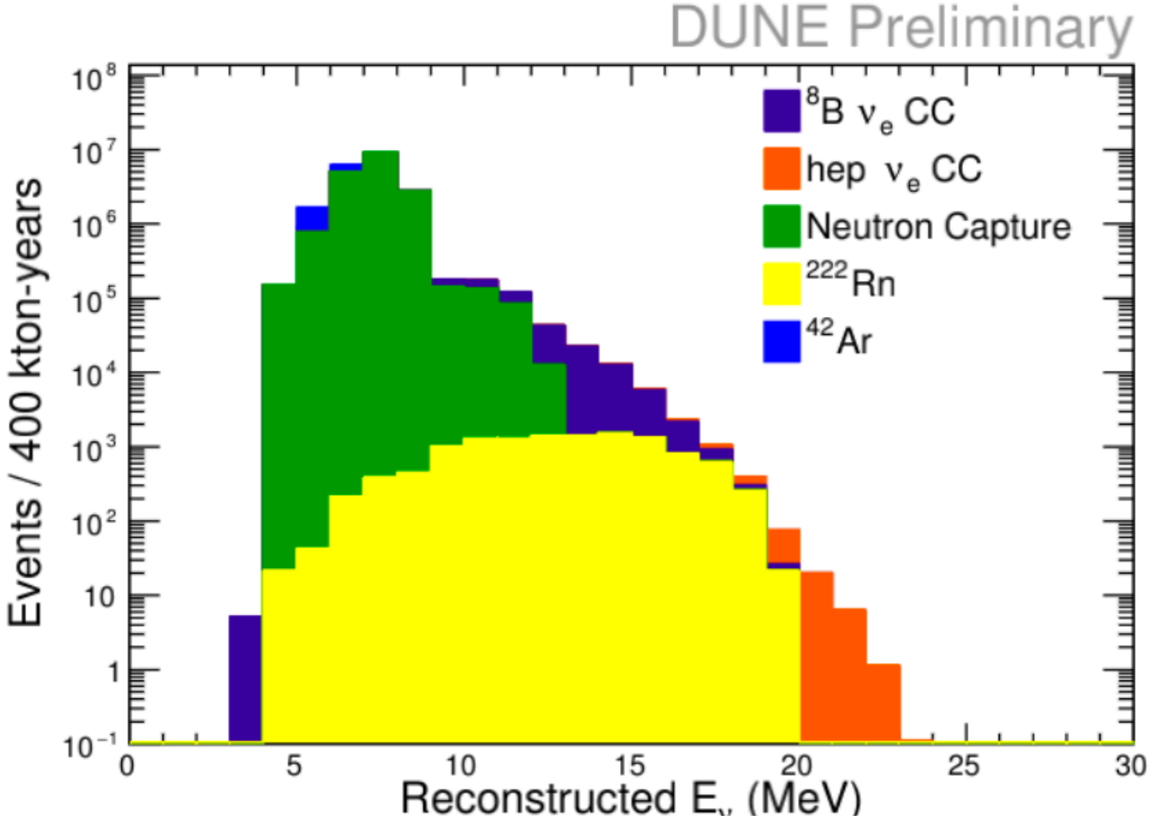


# Low energy backgrounds in LArTPCs

- **Argon isotopes** ($^{39}$Ar, $^{42}$Ar)

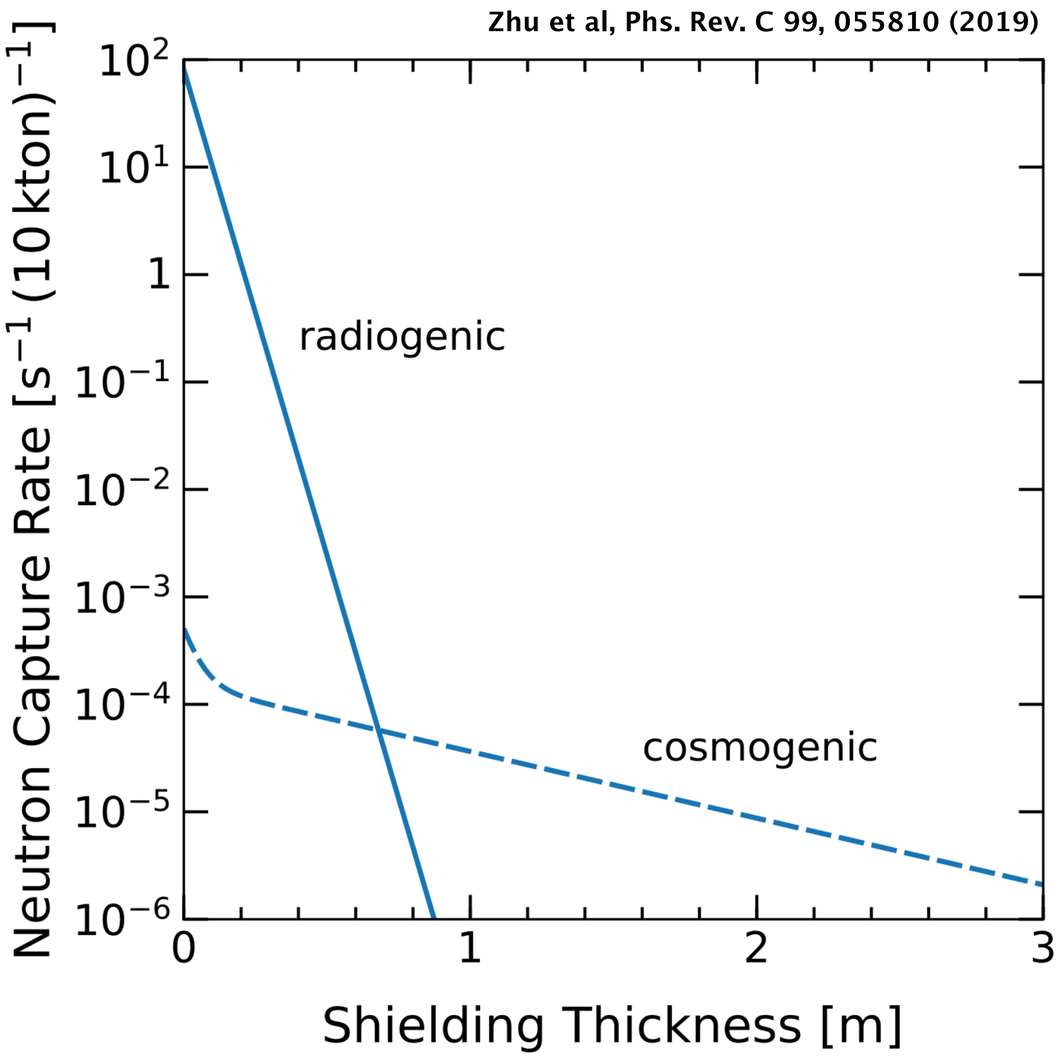
- **$^{222}$Rn chain**
  - **$^{40}$(α, γ)** events particularly dangerous
  - Alpha travels before being captured
  - **15 MeV gamma** resulting from alpha capture

- **External backgrounds**
  - Environmental neutrons
  - Cosmogenic background



# Background mitigation

- **Materials**
  - Select **radiopure materials**
    - All silicon readout
  - **Neutron shielding**



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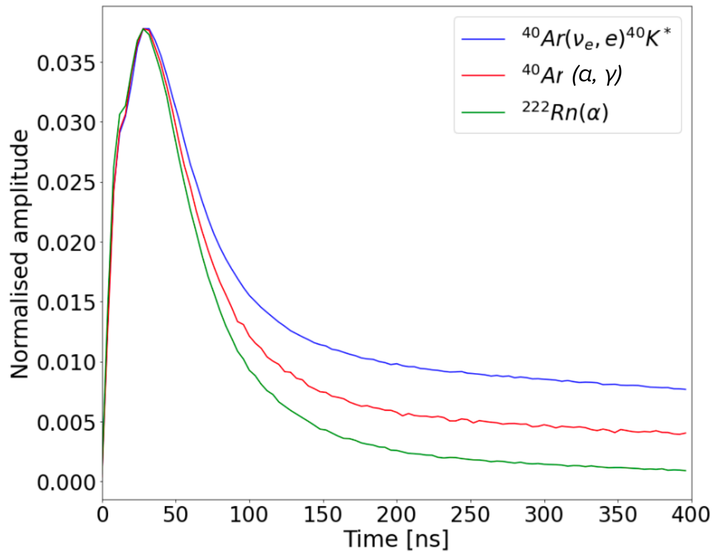
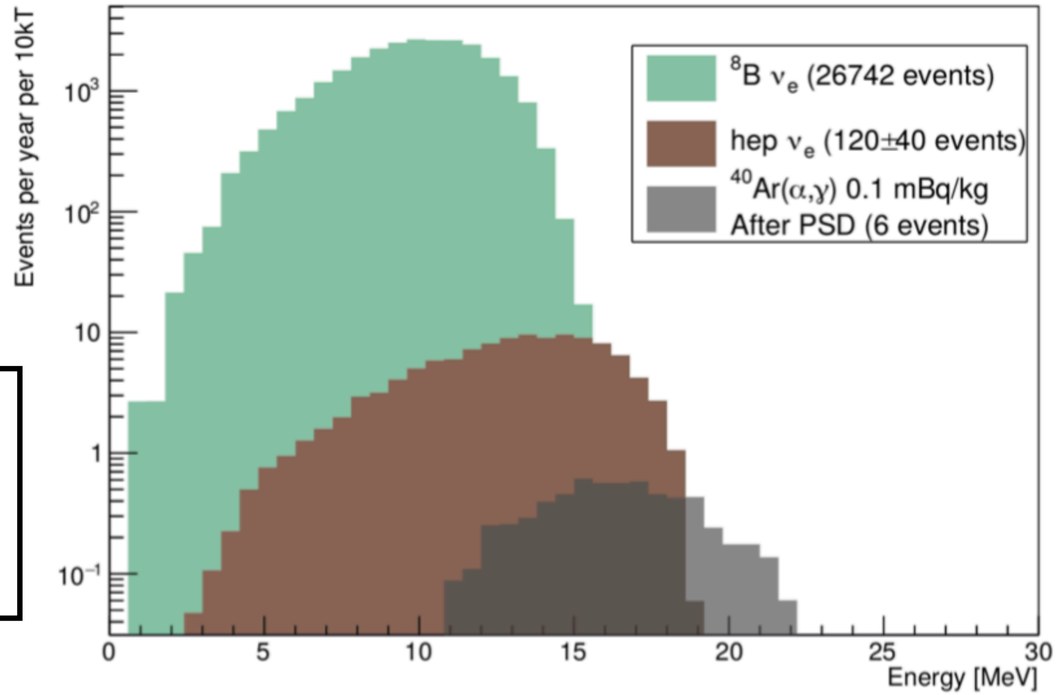



✴ **Materials**

✴ **Pulse Shape Discrimination**

- Light collection in SoLAr allows to make use of pulse shape discrimination
- Particularly useful against **$^{40}$(α, γ)** events

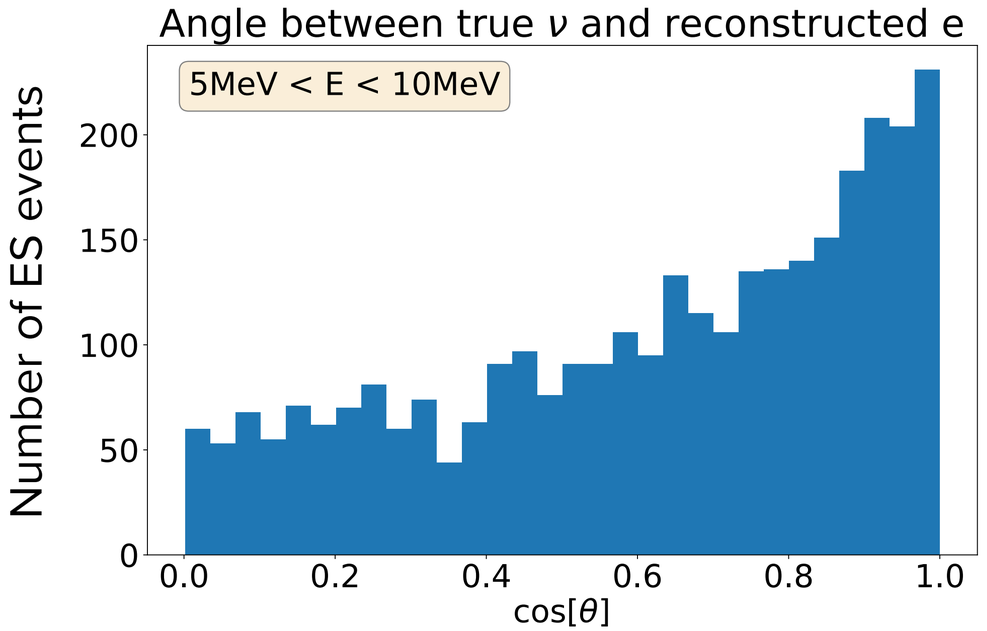



Study made with X-ARAPUCA detectors in a DUNE-sized module

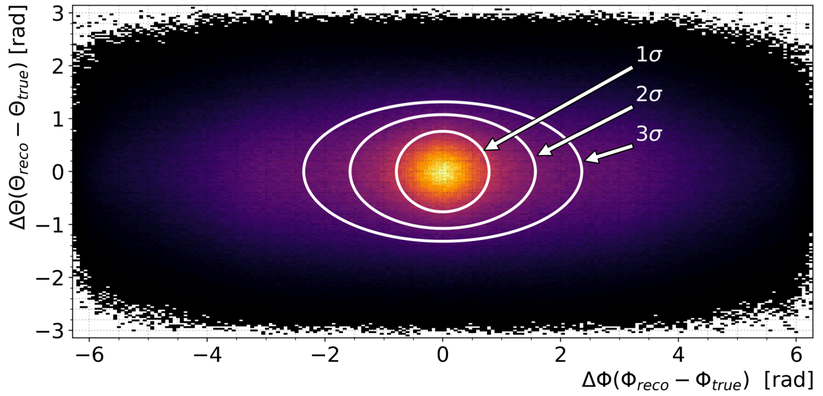
- Should perform even better with SoLAr design!

# Background mitigation

- **Materials**
- **Pulse Shape Discrimination**
- **Directionality**
  - Q-Pix demonstrated the ability to reconstruct supernova neutrinos direction
    - Powerful background rejection tool for solar neutrinos
  - We are now replicating this study for solar neutrinos



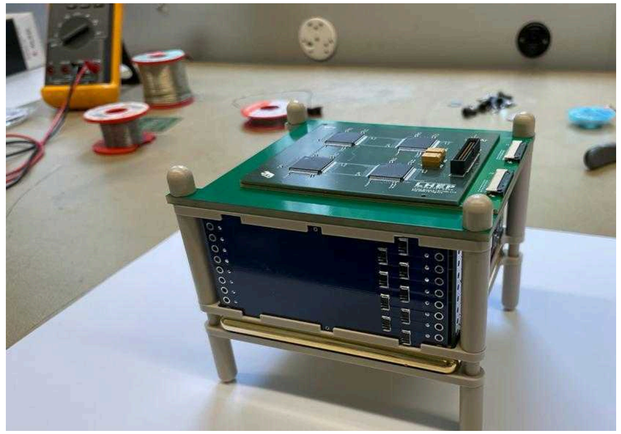

Kubota et al, Phys. Rev. D 106, 032011 (2022)



# Prototypes

# SoLAr program

## Small scale tests at LHEP Bern



2022-2024

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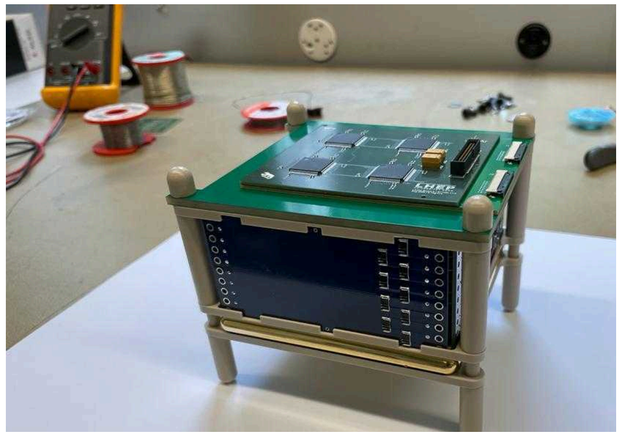
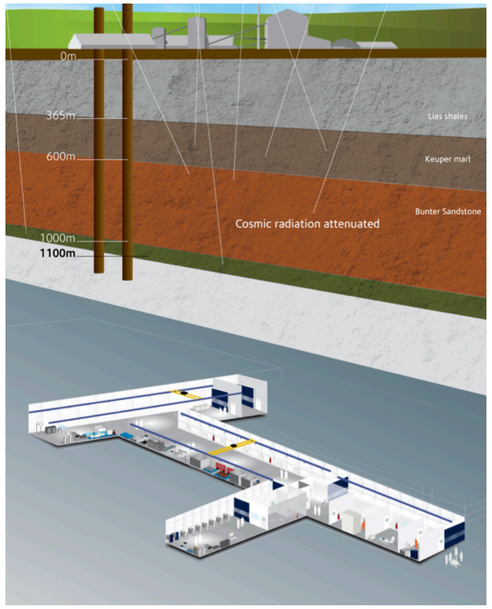


2022-2024

## Medium scale demonstrator




~2025-2030

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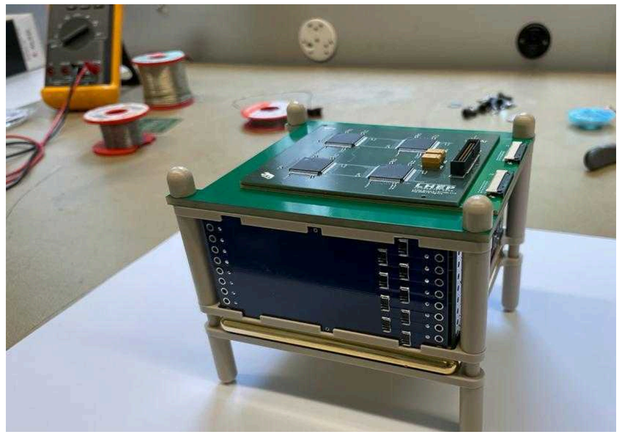

2022-2024

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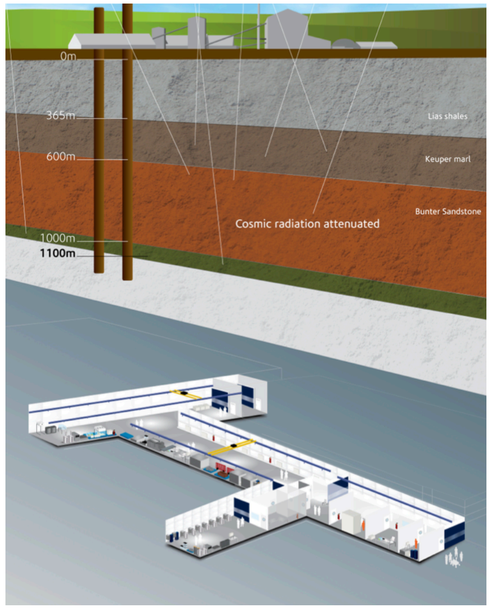
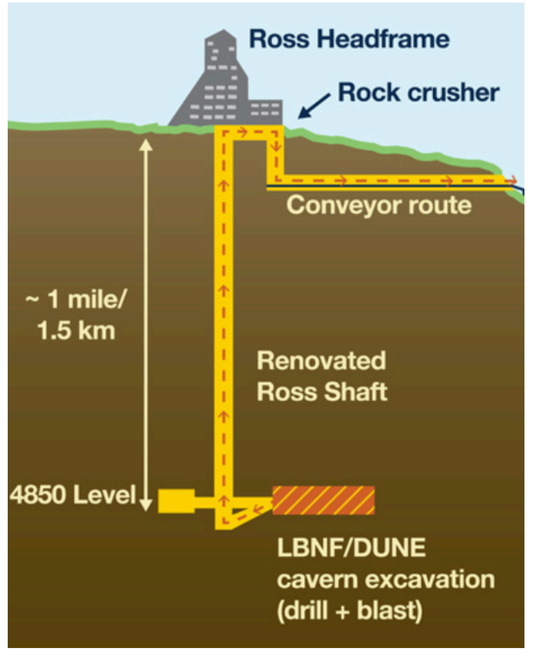



~2025-2030

2030 -

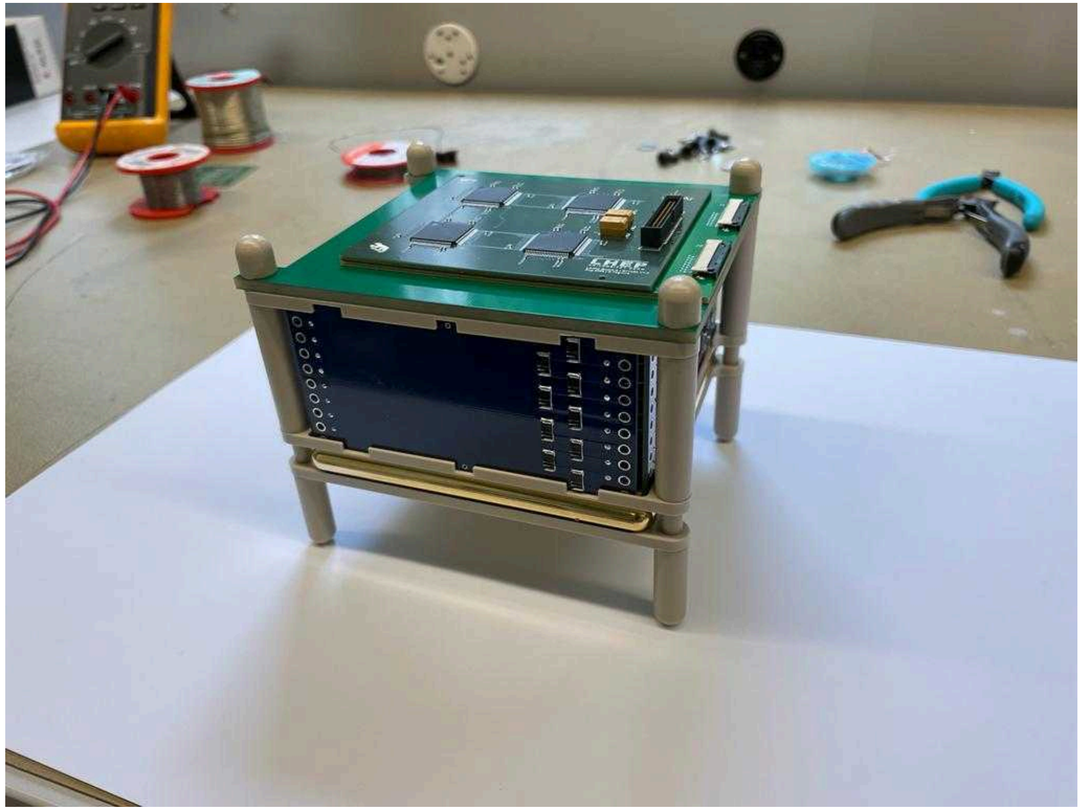



## DUNE Module of Opportunity?

# Bern SoLAr prototypes

**Goals**

- Operate an **integrated charge & light readout tile** for the first time
- Investigate **detector effects**:
  - Cross-talk, charge accumulation on SiPMs
- Observe cosmic muons tracks

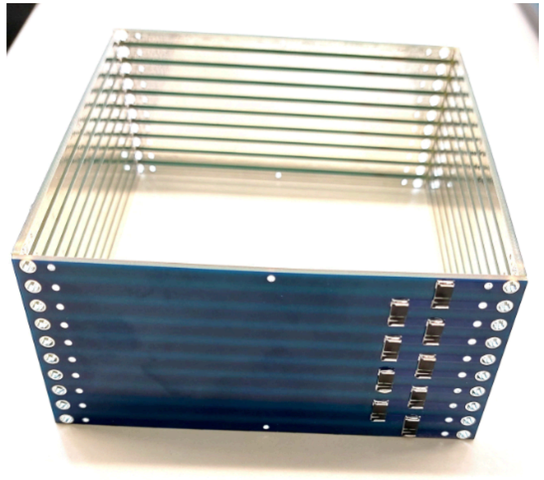


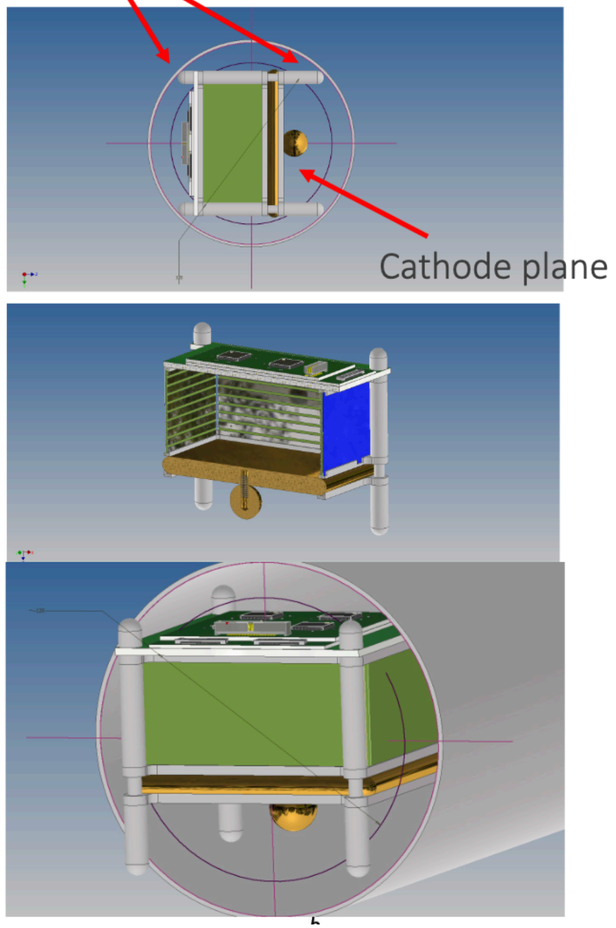
**V1 prototype** (October 2022)

# SoLAr Prototype V1

## TPC design

- Inner diameter of TPC: 14 cm
- Dimensions of the TPC:
  12 x 10 x 5 $cm^3$
- Drift distance ~5 cm





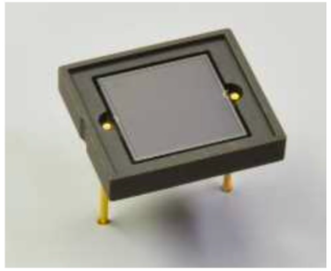

**Goals**

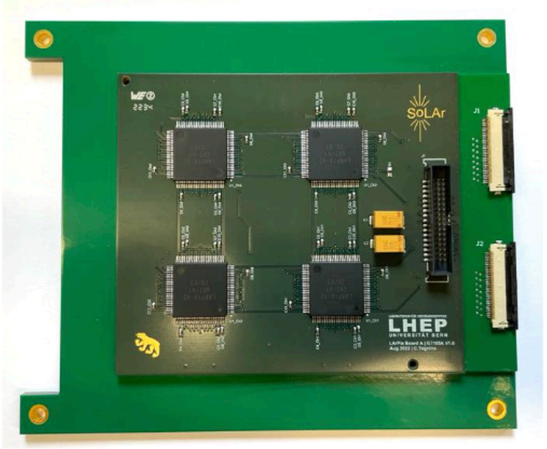
- Build and operate an **integrated charge & light readout tile** for the first time

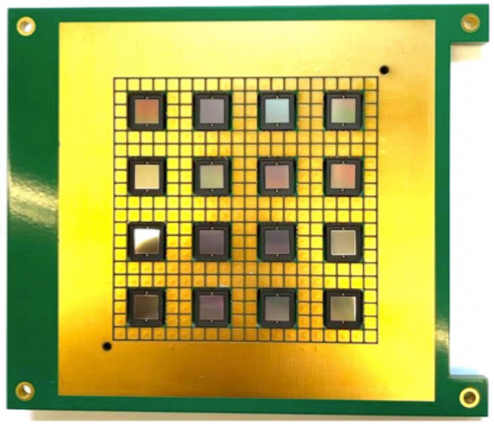
# SoLAr Prototype V1

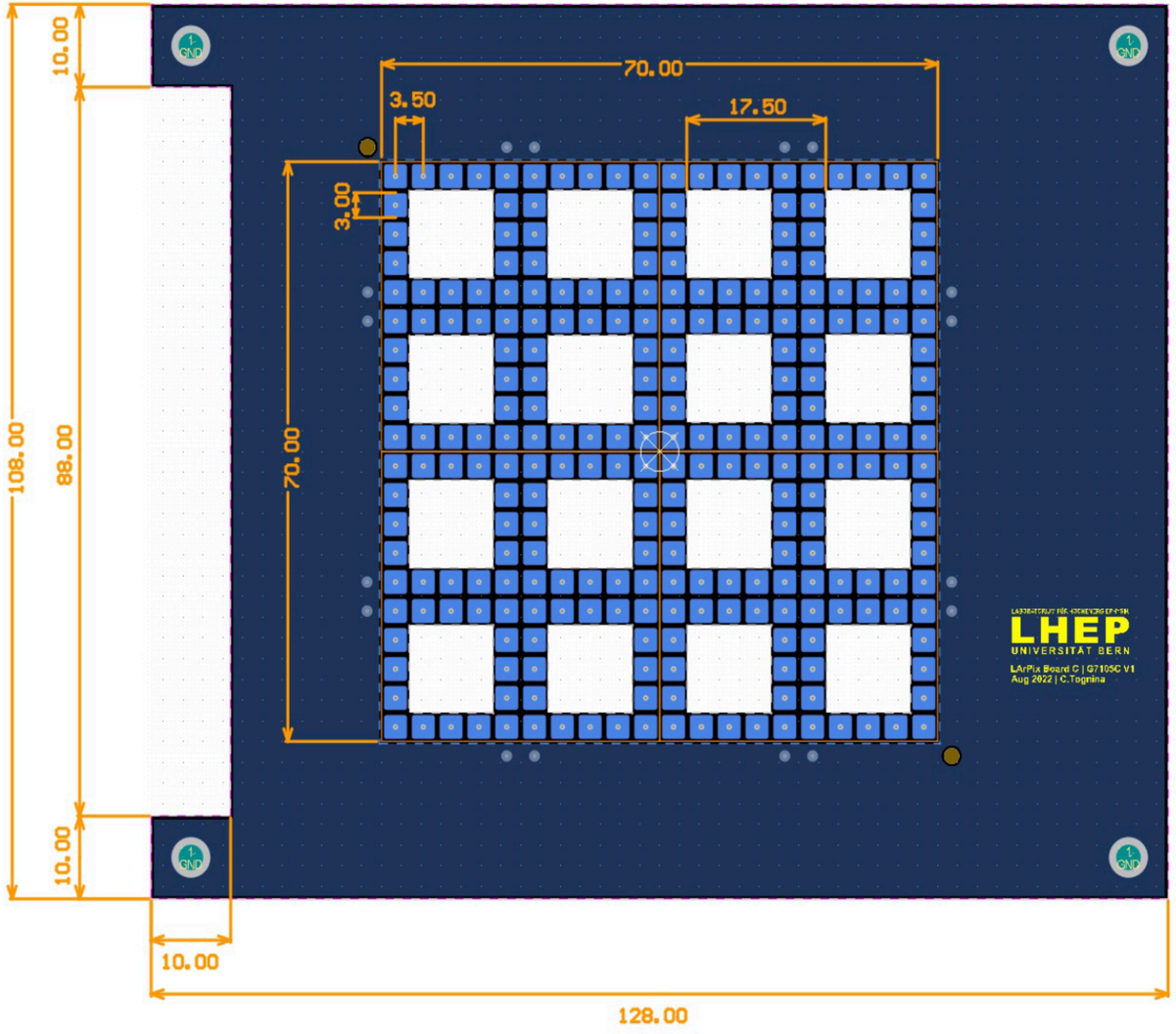
## Anode plane design

- 16 VUV SiPMs
- 4 LArPix chips
- Charge pixel pads: 3mm
- SiPM sensitive area: 6 x 6 mm$^2$
- Readout area: 7 x 7 cm$^2$





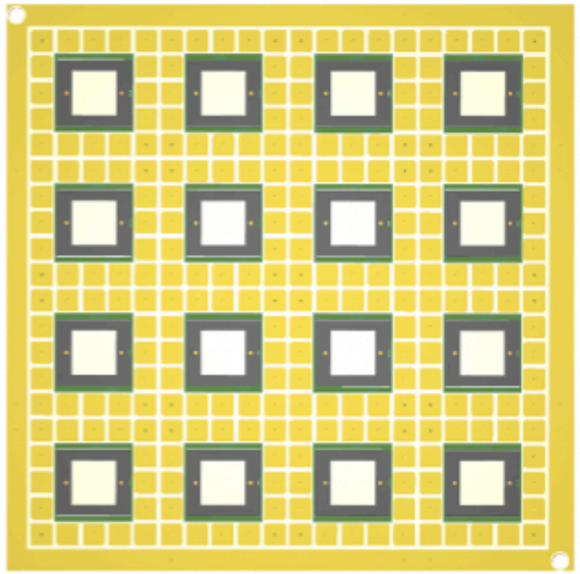


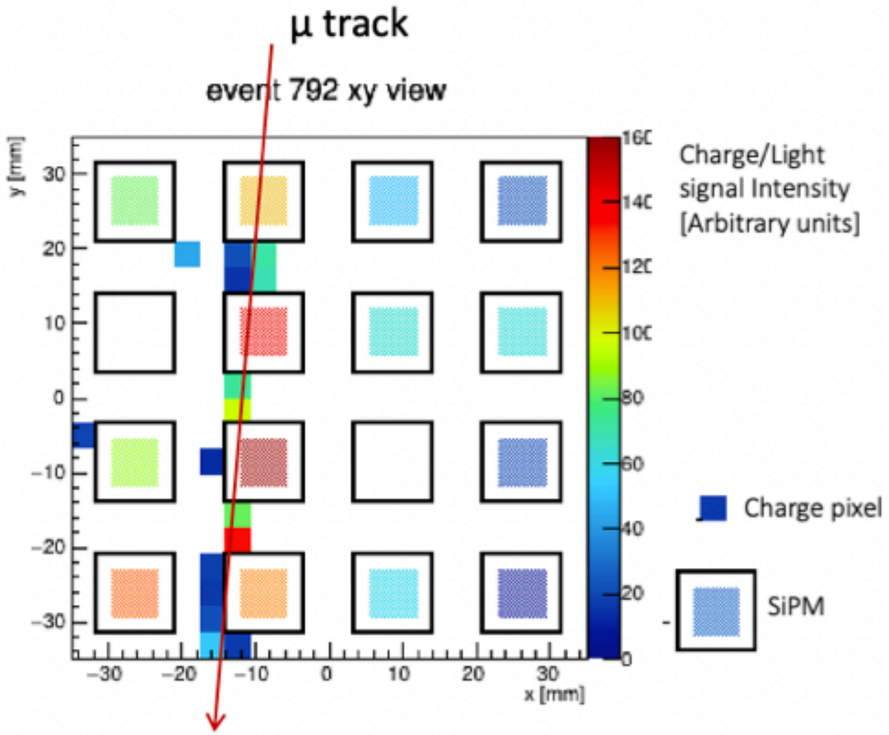
# SoLAr Prototype V1

**First tracks with integrated charge + light readout!**

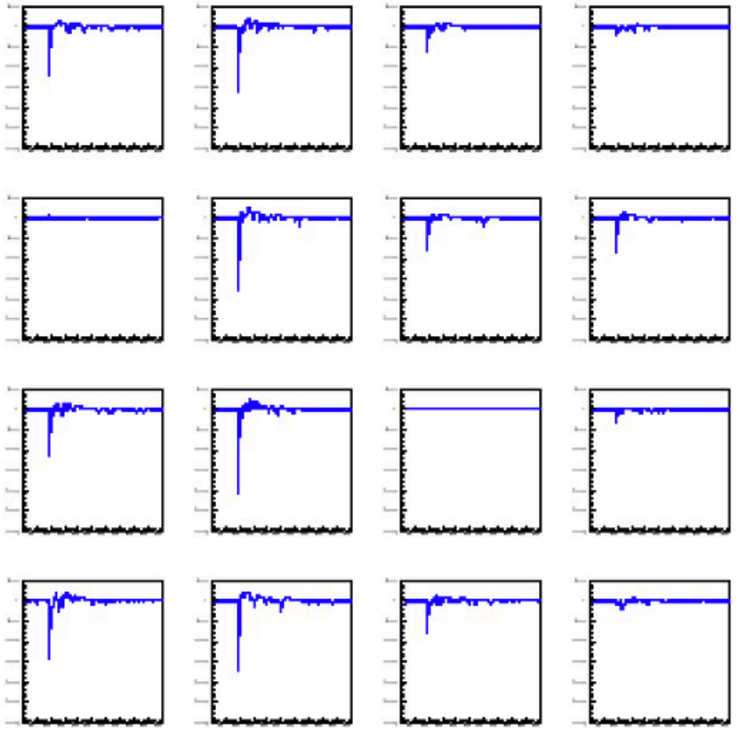
Collected ~100k cosmic events over 3 days

Anode plane visual guide






SiPM waveforms



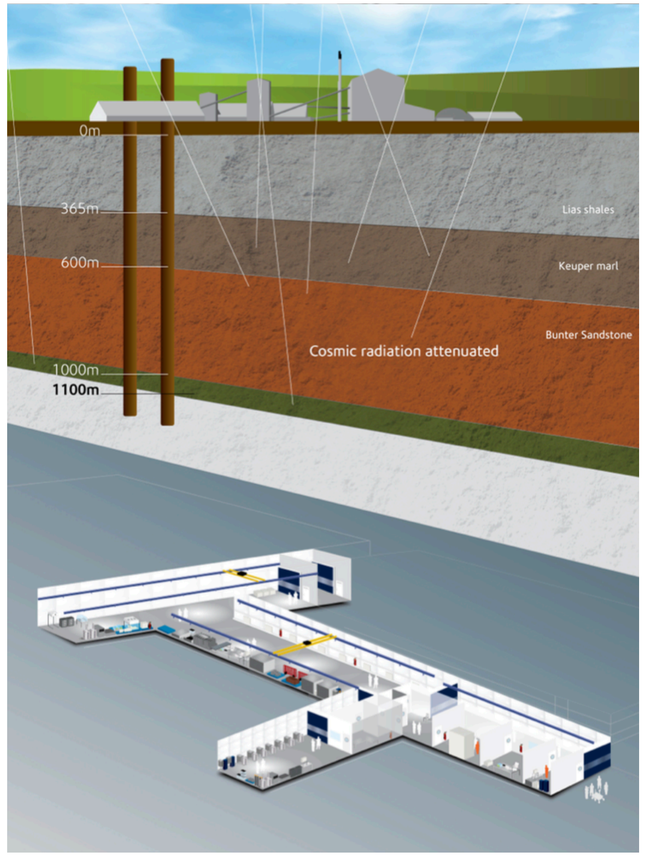
# SoLAr Prototype V2

- Planned for **Spring 2023**
- SiPM coverage 1/16
- 30 x 30 $cm^2$ readout tile
  - Similar size to mid-scale demonstrator base unit
- 64 LArPix chips
- 64 Hamamatsu VUV SiPMs

**Goals**

- Compare photon detection performance with simple pixel tile
  - ArcLight: PDE = 0.2%
  - SoLAr tile: PDE = 1/16 x 15% = 0.9%

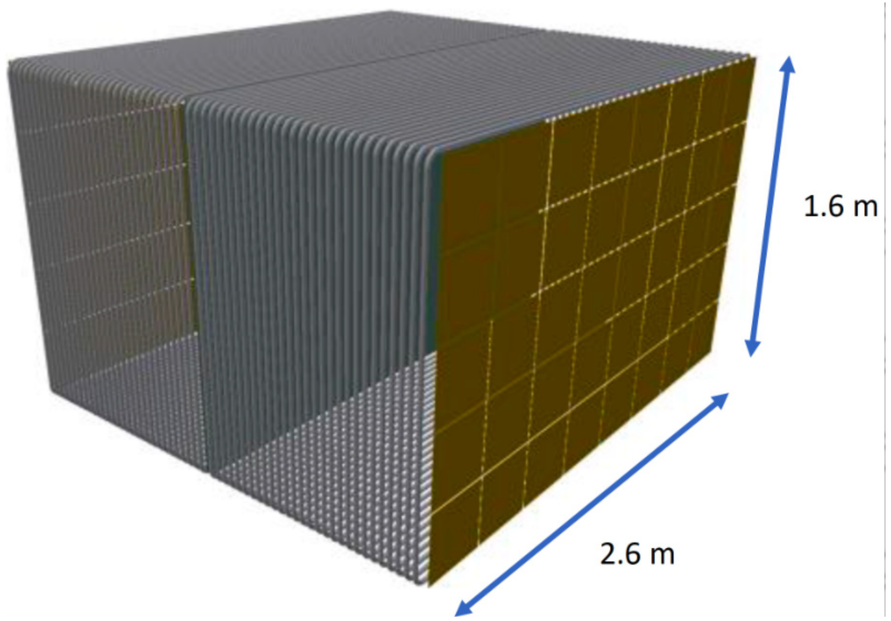
# Medium-scale demonstrator




- Planned in **Boulby Underground Laboratory (UK)**
  - 1 100 m rock overburden

**Science goals**

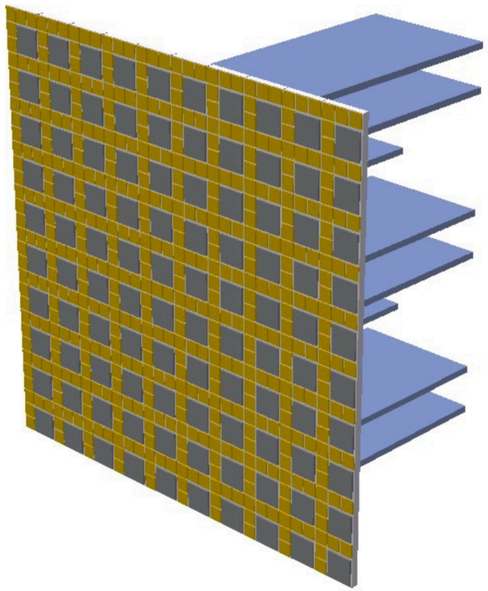
- **Validate** SoLAr performance
- **Observe** $^{8}B$ flux with > 5 σ significance
- **Estimate** sensitivity to solar neutrinos for Module of Opportunity



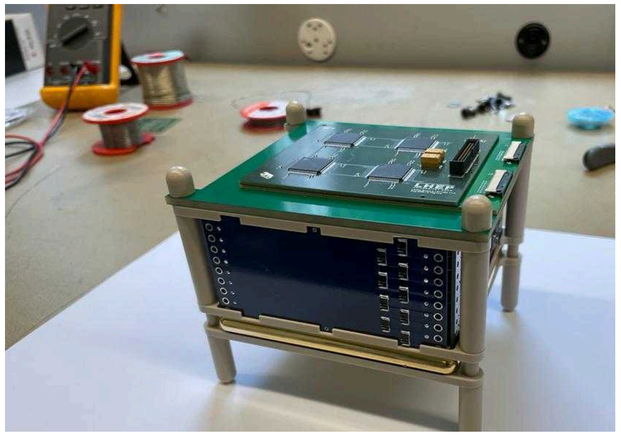

- 1.6 x 2.6 x 2 $m^3$ (1 m drift length)
- 31 x 31 $cm^2$ tiles
- Light traps on 4 sides of the TPC

# Summary

- SoLAr aims to extend the physics LArTPCs in the **MeV-scale range**
  - New anode tile with **integrated charge & light readout**

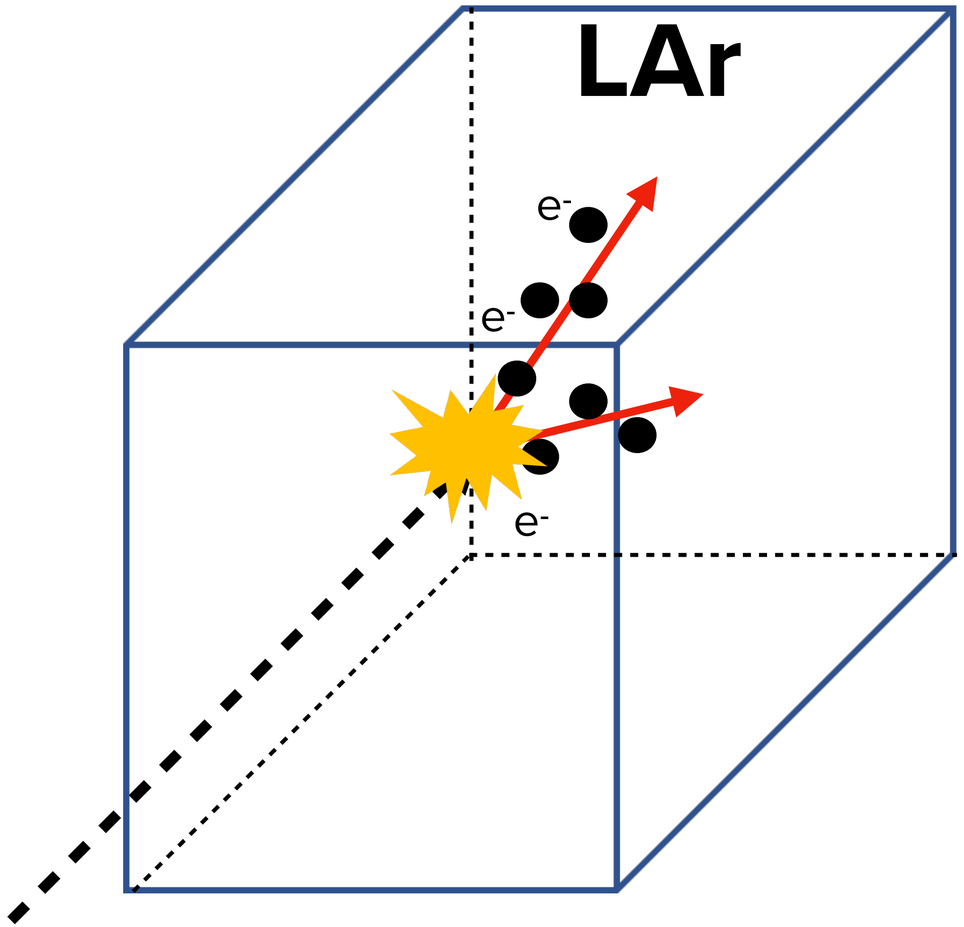


- **Staged R&D approach:**
  - **First operation** of charge & light readout sensors **on the same plane**
    - Data analysis ongoing
    - Second run with bigger tile in the next few months
  - Design of a **medium scale 10 ton demonstrator**
  - Performance studies for a **10 kton module**



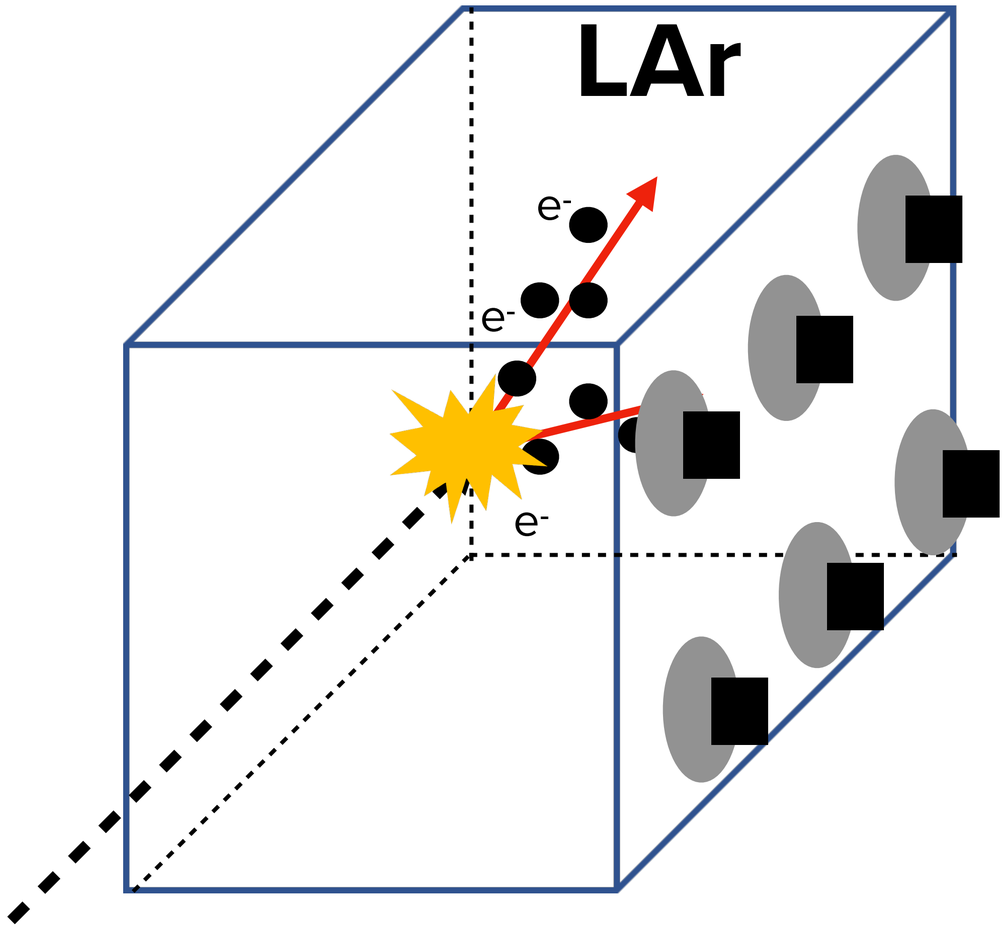
# Backup

# LArTPC essentials



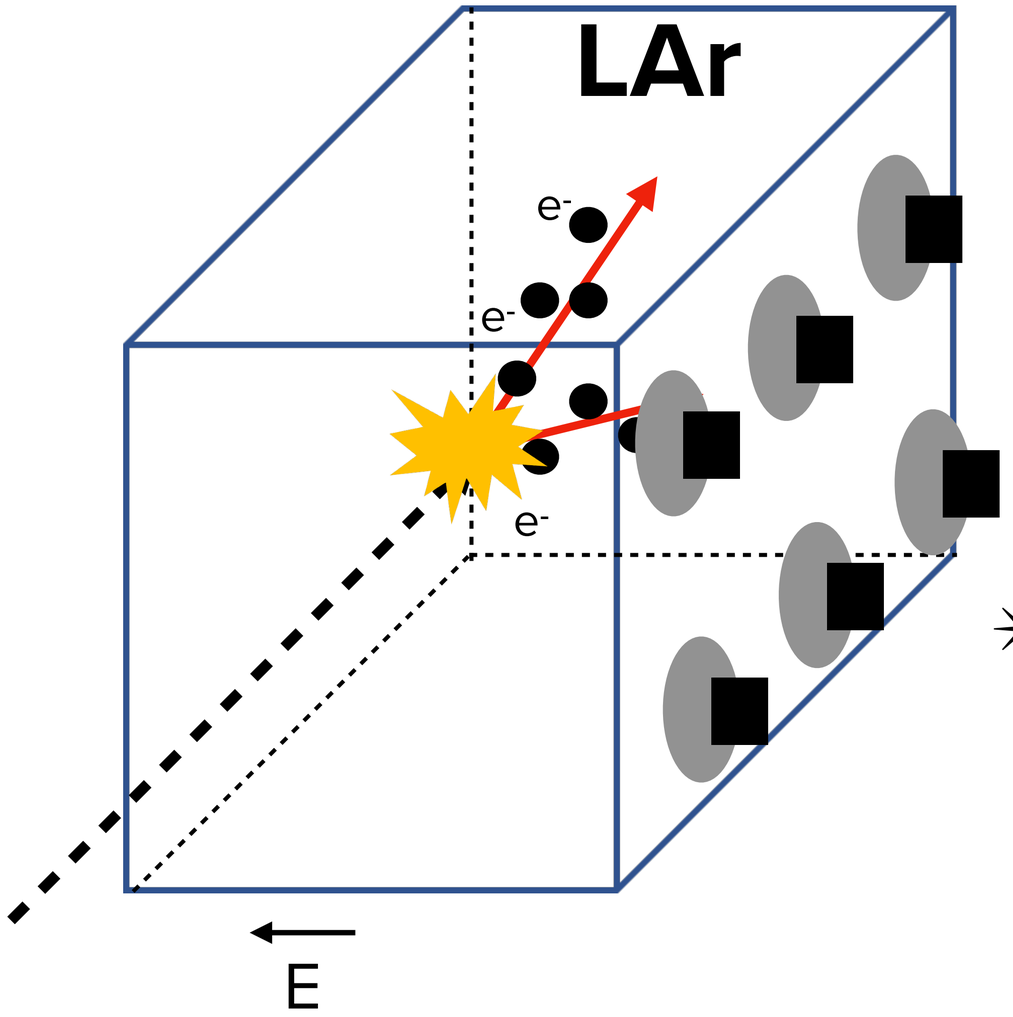

- (Large) volume of liquid argon (**LAr**)
  - Particle crosses the LAr volume
  - Creates ionisation and scintillation

# LArTPC essentials



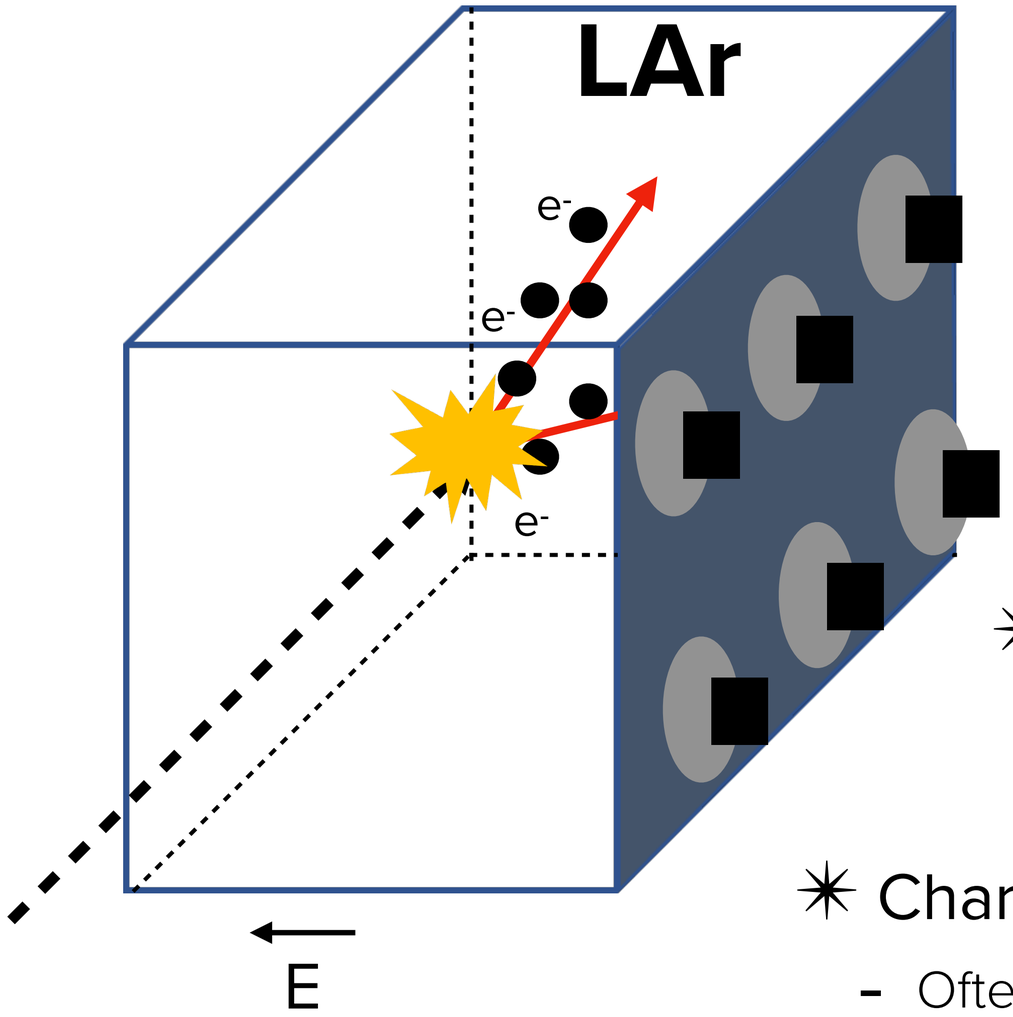

- (Large) volume of liquid argon (**LAr**)
  - Particle crosses the LAr volume
  - Creates ionisation and scintillation
- Light readout
  - Provide interaction timing

# LArTPC essentials



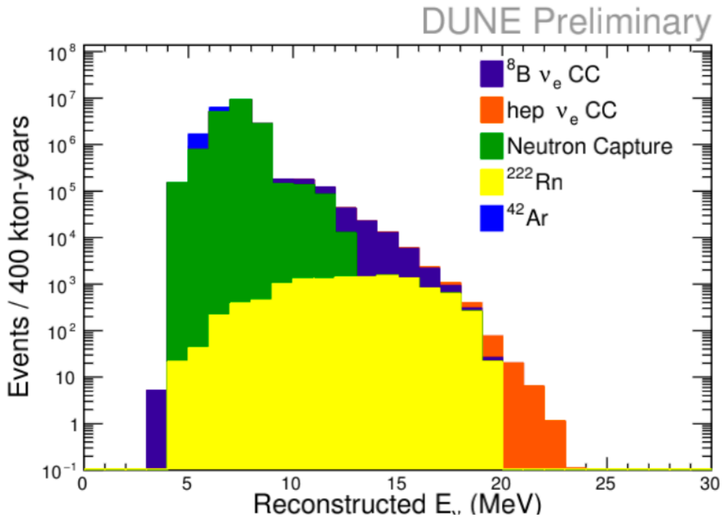

- (Large) volume of liquid argon (**LAr**)
  - Particle crosses the LAr volume
  - Creates ionisation and scintillation
- Light readout
  - Provide interaction timing
- Electric field
  - Electrons drift to the anode

# LArTPC essentials



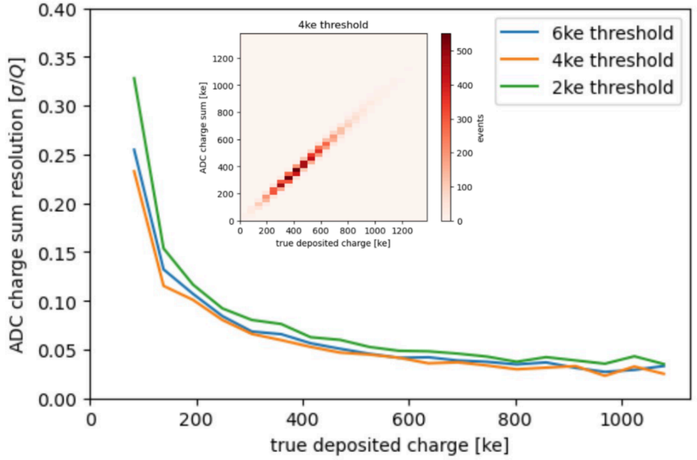

- (Large) volume of liquid argon (**LAr**)
  - Particle crosses the LAr volume
  - Creates ionisation and scintillation
- Light readout
  - Provide interaction timing
- Electric field
  - Electrons drift to the anode
- Charge readout at the anode
  - Often wire planes

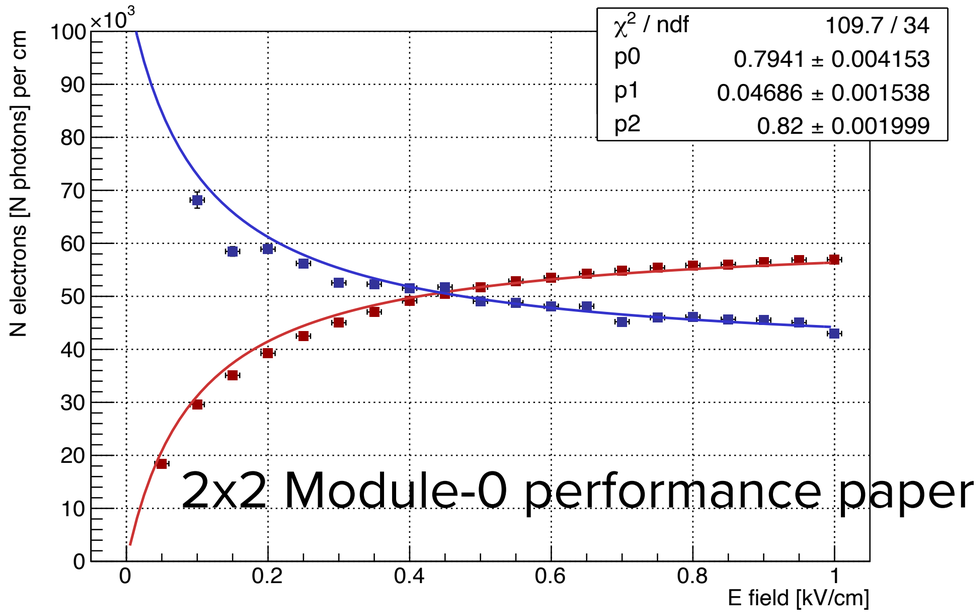
# Energy reconstruction improvements




- Need few % resolution at 20 MeV to resolve the hep flux
  - Pixellated charge readout resolution $\frac{\sigma_q}{Q} \approx 5\%$
  - Gets better with combination with light
  - All in place to achieve the required resolution!

**LArPix charge sum resolution**



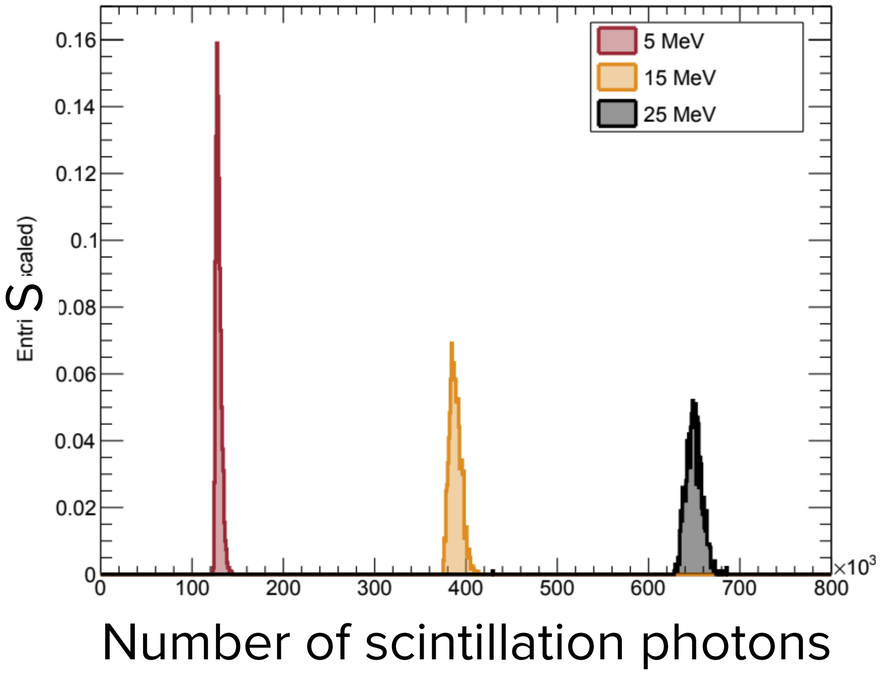



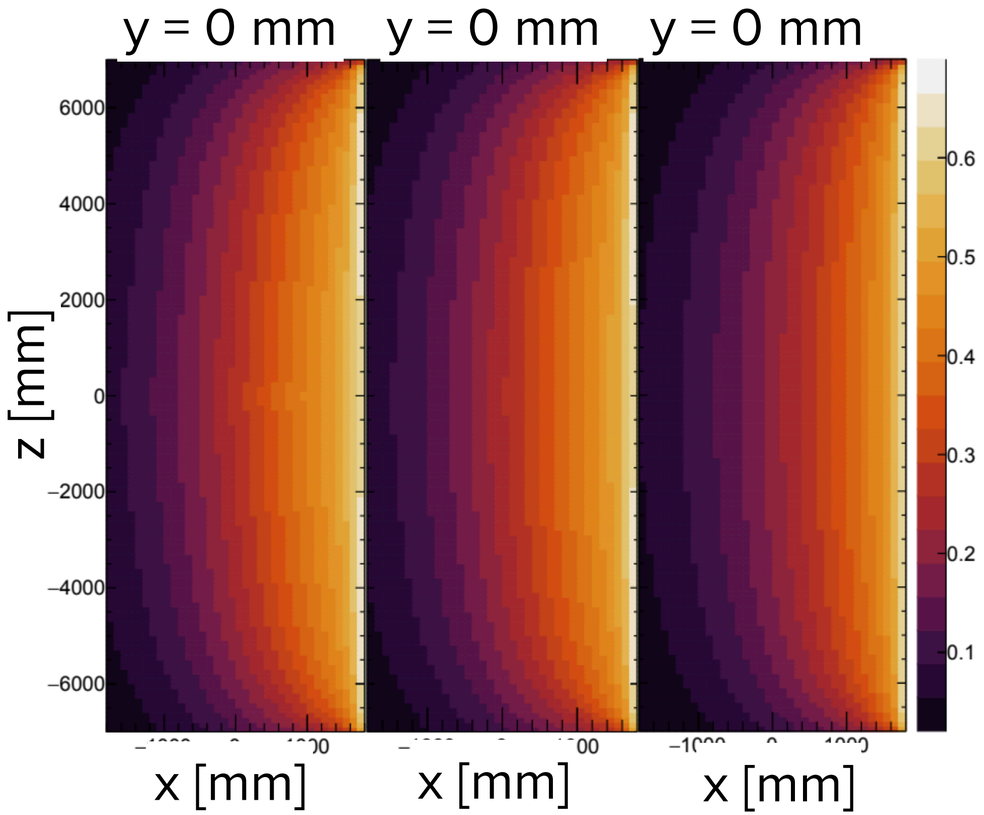

2x2 Module-0 performance paper

# Energy reconstruction: light

$$E_L = \frac{N_{photons}^{detected}}{< LY > \times vis \times PDE}$$

15%



# SoLAr prototype V1

## Light waveform

- Example of a SiPM signal waveform from a muon crossing the LAr volume
- Negative signals typically have an overshoot, disturbing the silence level
- Delayed individual photons from the slow component of the LAr scintillation light can be clearly identified.

- The waveforms are integrated over an integration window and calibrated to obtain number of photons