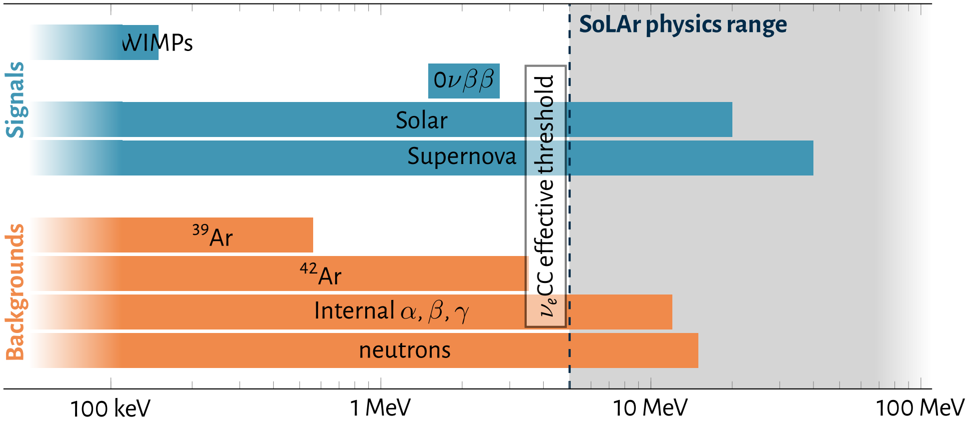
Daniele Guffanti
University & INFN Milano-Bicocca
for the **SoLAr Collaboration**

The SoLAr proposal: Project status and synergies with APEX

DUNE Far Detector 3 Mini-Workshop, Stony Brook - June 28, 2023

Low-Energy Liquid Argon Environment



Adapted from T. Bezerra et al (SLoMo), J.Phys.G 50 (2023) 6 e-Print: 2301.11878 [hep-ex]

The SoLAr project: widening the low-energy window

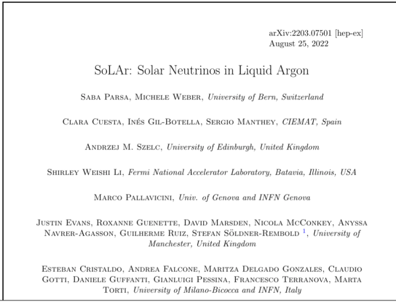
Opportunities for low-energy solar neutrinos in liquid argon

Leverage **state of the art LArTPC** technology to
design a detector **optimized for low-energy** studies
while retaining good performance for high energy events

GOAL: develop and demonstrate a new technology to expand DUNE physics reach in the MeV scale.

- Lower threshold to solar neutrino measurement
- Supernova neutrino burst
- DSNB(?)

Integrate the SoLAr design in the DUNE **Module of Opportunity**
one full DUNE volume



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

SoLAr: Solar Neutrinos in Liquid Argon

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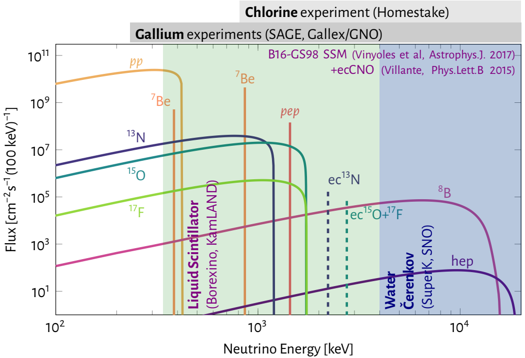
(Moderate) Low-energy neutrino physics with in LAr

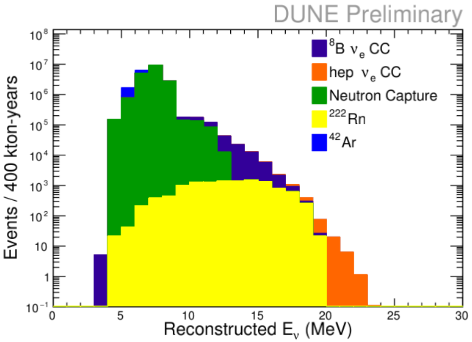
DUNE has a huge potential for **low-energy** neutrino physics

- **Solar neutrinos**
  - High precision oscillation physic with ^{8}B
  - Discovery and first measurement of **hep** neutrinos



Challenges @ DUNE

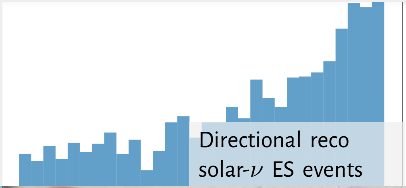
- Significant **backgrounds**
- Limited **energy resolution** @ low-energy
- Difficult **reconstruction** @ low-energy



Key concepts for the MeV-scale challenge

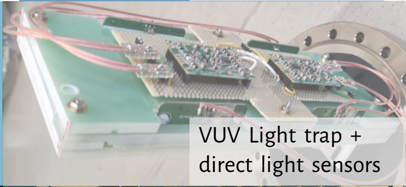
Improved background suppression

More accurate material selection, passive shielding, **pulse-shape** discrimination, **direction** reconstruction



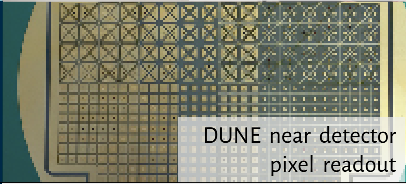
Improved light sensors:

Arapuca-style modules + **VUV SiPMs integrated on the anode**
Exploit the light signal in LAr to perform **combined Q + *L* calorimetry**: Target $\Delta E/E \approx 7\%$



Pixelated readout:

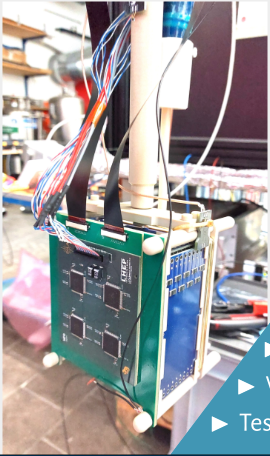
Pixel readout plane will enhance event reconstruction, while replacing TPC wires is expected to simplify construction and installation



Roadmap

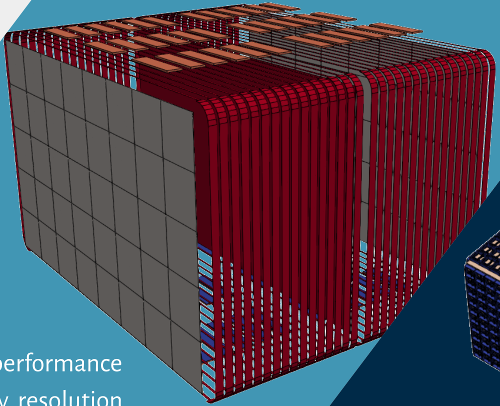
Phase I: Prototyping

Development of integrated charge+light readout

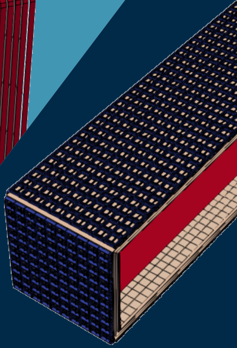


Phase II: Medium Scale Experiment

First detection of solar neutrinos in LAr



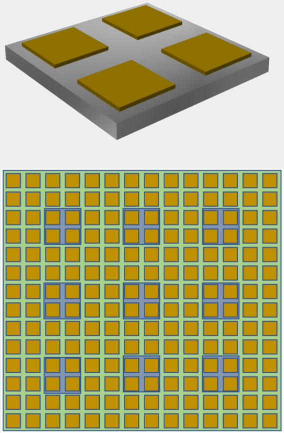
- Prove low-energy performance
- Validate target energy resolution
- Test background suppression methods



Phase III: DUNE MoO

SoLAr tile R&D Status

The SoLAr Readout Unit

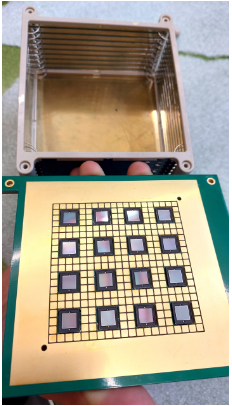


- One MPPC readout channel
- 4 charge readout channels
- 50% light readout coverage for SRU

Pixel readout options

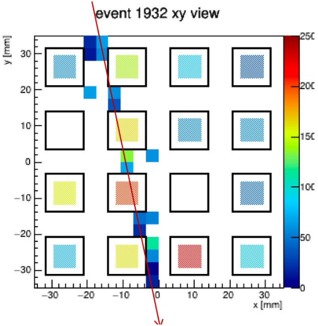
- **LArPix**
  Tested in ArgonCube
  Acceptable data-rate
- **QPix**
  Very low data-rate

2022: First Integration of a **light+charge module**



S. Parsa, MoO workshop, Valencia 2022

SoLAr tile V1 - LHEP Bern
Tested in a $12 \times 10 \times 5\,\mathrm{cm}^3$ TPC
(area $7 \times 7\,\mathrm{cm}^2$, 5 cm drift)

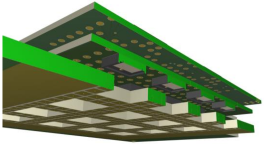


SoLAr tile V2

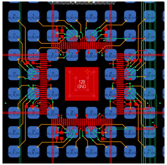
New SoLAr tile prototype (**V2**) ready for testing

- Tile dimension: $32 \times 32\ \mathrm{cm}^2$
- Divided into 8×8 regions (64 — 4 pixel, 1 SiPM)
- 64 LArPix (60 ch. used)
- 64 Hamamatsu VUV MPPC with independent readout
- Complete re-design of the PCB

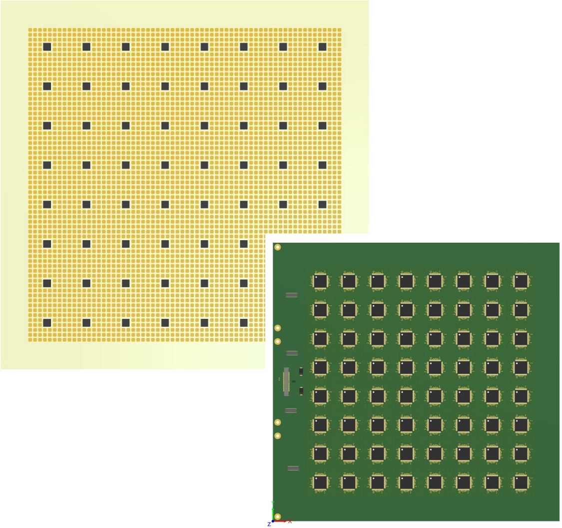
SoLAr tile V1 → SoLAr tile V2



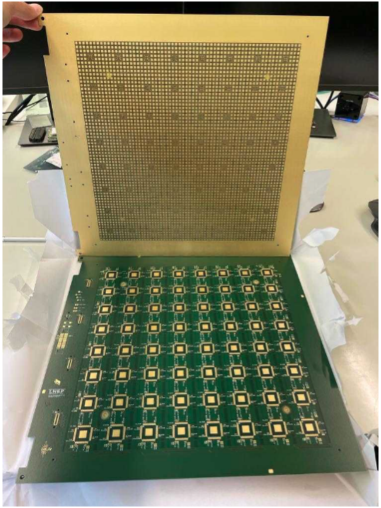
Three PCB stacked

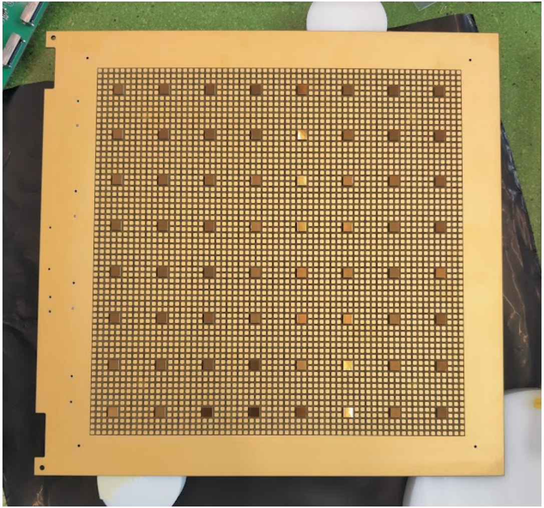


Single multilayer PCB



Live updates from Bern

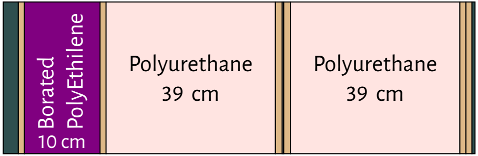


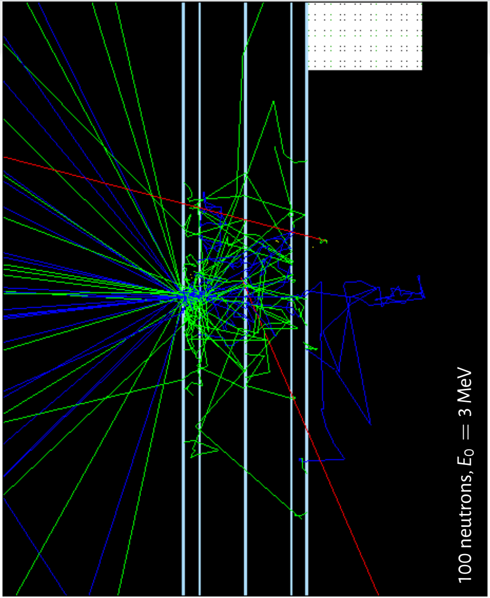


Background suppression

Neutrons are the most troublesome background in DUNE

- **Cryostat** produced in (α, n) reactions in steel
  Should be under control
- **Internal** produced in (α, n) reactions in LAr
  Need to reduce ^{222}Rn level
- **Cavern** produced in the surrounding rock





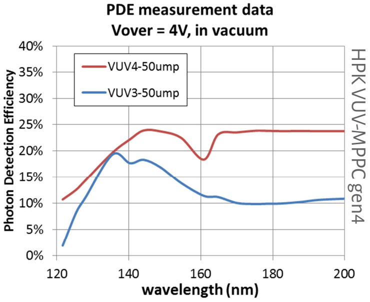
Light detection in SoLAr

Light detection crucial to improve the low-energy performance

- Energy resolution
- Pulse shape discrimination
- Event reconstruction

SRU silicon light sensors (anode)

VUV SiPMs major progress over the past decade (FBK, HPK)



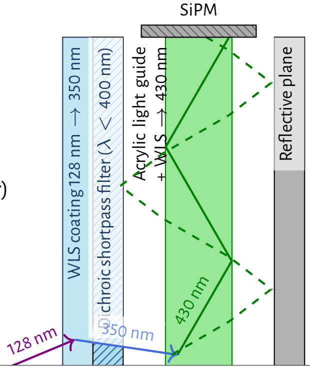
X-ARAPUCA light traps (membrane/cathode)

Well-established technology in the DUNE framework

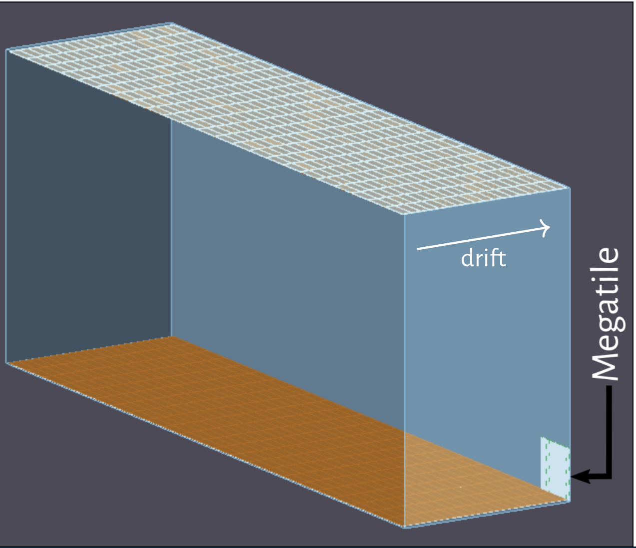
Enable large photo-coverage

Flexible placement (signal- and power-over-fiber)

PDE: 2–3%



Light calorimetry preliminary studies



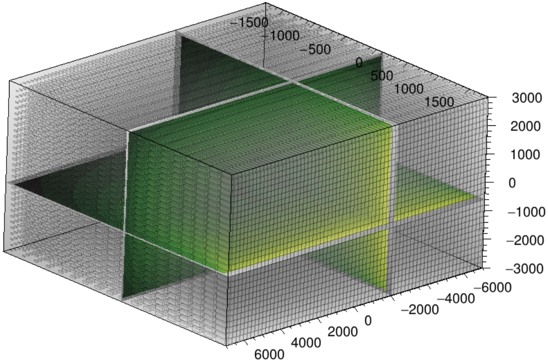
Geant4-based simulation of DUNE HD-like module (based on 1x2x6 geometry)

- Integrates LArQL model for scintillation/ionization production
- Geant4-based photon propagation + Semi-analytical model (no WLS process included)
- Full coverage of floor/ceiling of cryostat with X-ARAPUCA-like modules
- No field cage included

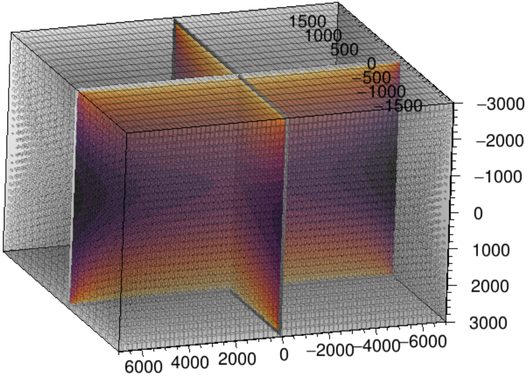
Visibility maps

Photosentive anode makes more uniform light yield

visibility = $\mathbb{E}[N_{\text{ph}} \text{ detected}] / N_{\text{ph}}$ produced



SoLAr tiles
(full photo-coverage)



X-ARAPUCAs
(full photo-coverage)

Preliminary coverage studies

Ideal case: $N_{\text{hits}} = E \cdot \langle \text{LY} \rangle \cdot \Omega(\boldsymbol{x}) \cdot \varepsilon \cdot \text{PDE}$

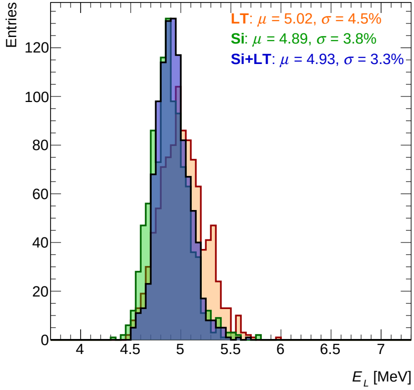
$\langle \text{LY} \rangle$	Average Light Yield
$\Omega(\boldsymbol{x})$	Visibility
ε	Photo-coverage fraction

Including multiple readout systems (anode + membrane)

$$E_L = \frac{N_{\text{hits}}^{\text{SRU}} + N_{\text{hits}}^{\text{X-A}}}{\langle \text{LY} \rangle \cdot \left[\Omega^{\text{SRU}}(\boldsymbol{x})\, \varepsilon^{\text{SRU}}\, \text{PDE}^{\text{SRU}} + \Omega^{\text{X-A}}(\boldsymbol{x})\, \varepsilon^{\text{X-A}}\, \text{PDE}^{\text{X-A}}\right]}$$

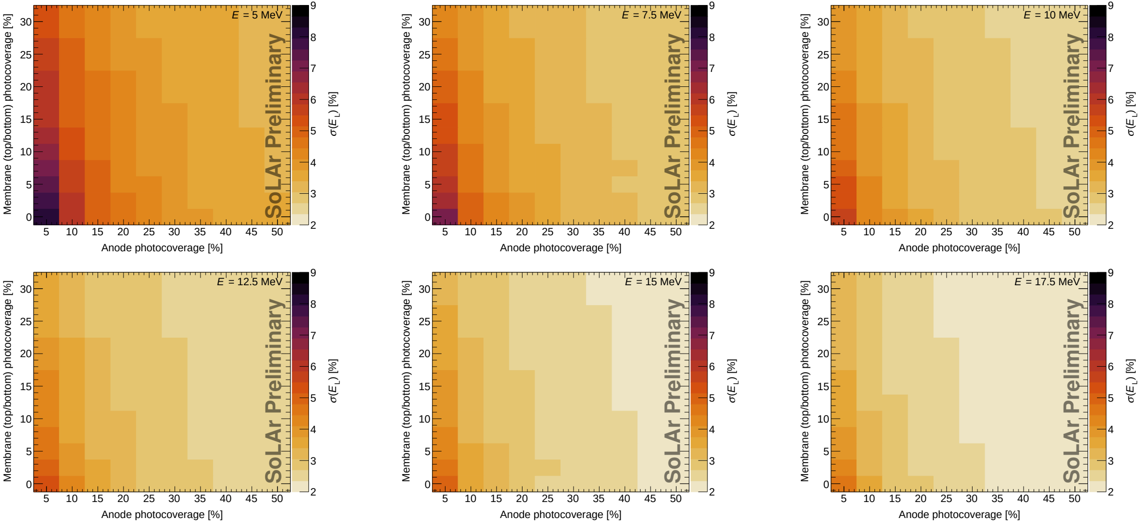
Simple but reliable energy reconstruction method

- Energy resolution estimated from reconstructed energy spread
- Events uniformly generated with min distance from membrane ≈ 65 cm



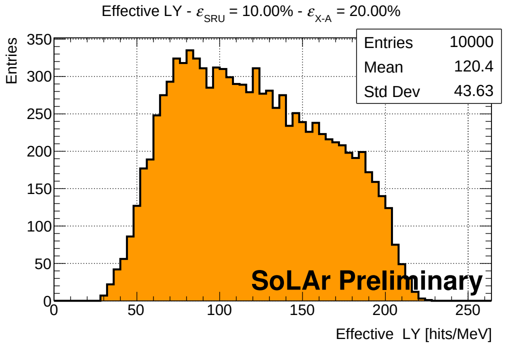
Detector center, G4 phot propagation
semi-analytical reconstruction

Preliminary results



Preliminary conclusions

Anode photo-coverage of 10% +
Membrane photo-coverage of 20%
enough to reach the target 7% energy resolution



$\langle LY \rangle \approx 120$ hits/MeV = $6\times$ FD-HD baseline

Caveats

- Study performed using HD configuration to be repeated in FD-VD mode
- No noise/crosstalk taken into account
- Perfect position reconstruction assumed
- No WLS re-emission in the TPC considered
- Perfect modeling of light propagation and detection assumed

Synergies with APEX

APEX instrumented field cage offers a very competitive alternative to the FD-VD option considered so far in combination with the SRU-based anode

- **Active buffer**
  A LAr buffer between the field cage and the membrane will suppress neutron and γ background.
  - Can a membrane PDS help in tagging background events interacting in the buffer before entering the active volume?
  - More active mass for SNB events
  - How much light will leak from field cage to the membrane and vice-versa?

- **High effective light yield**
  APEX can provide a very large optical coverage $\rightarrow$ many photons $\rightarrow$ good energy resolution
  - How accurately can we model the light propagation?
  - How the WLS light will look on the SRU anode?

Conclusions

New test campaign to start

Ready to run a new test campaign with the **SoLAr V2** tile for new charge + light combined measurement

More pixels, more SiPMs and more advanced than **SoLAr V1**

Progress in sensitivity studies

Simulation and analysis studies to asses the potential and requirements of SoLAr are progressing.

We will **incorporate APEX** concept in our studies

SoLAr Snowmass paper: `arXiv:2203.07501 [hep-ex]`