CADMO:
Dark Matter searches around DUNE

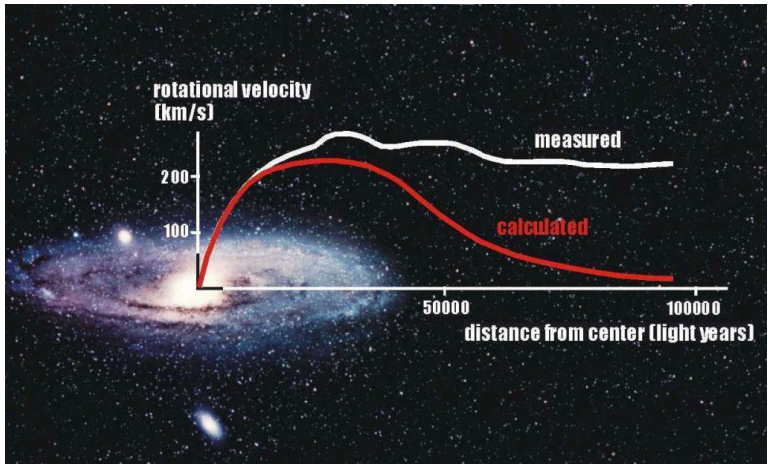
A. Branca

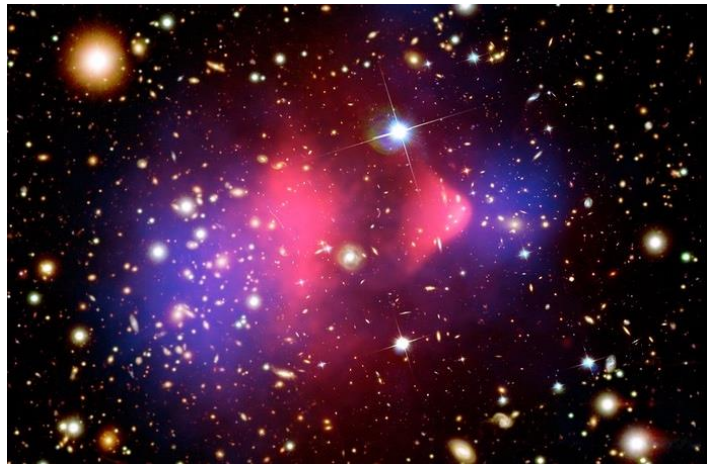
University & INFN of Milano-Bicocca

On behalf of the CADMO Milano-Bicocca group

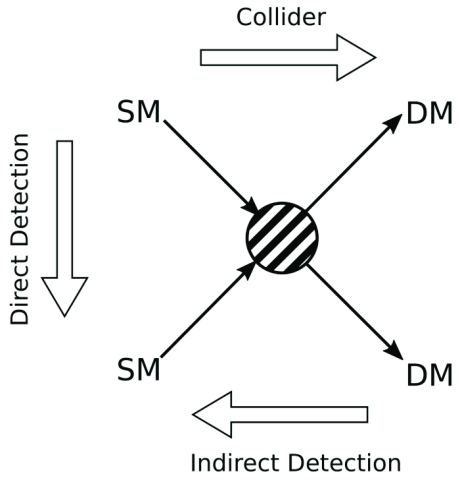
A universe full of Dark Matter

Overwhelming gravitational evidence for Dark Matter

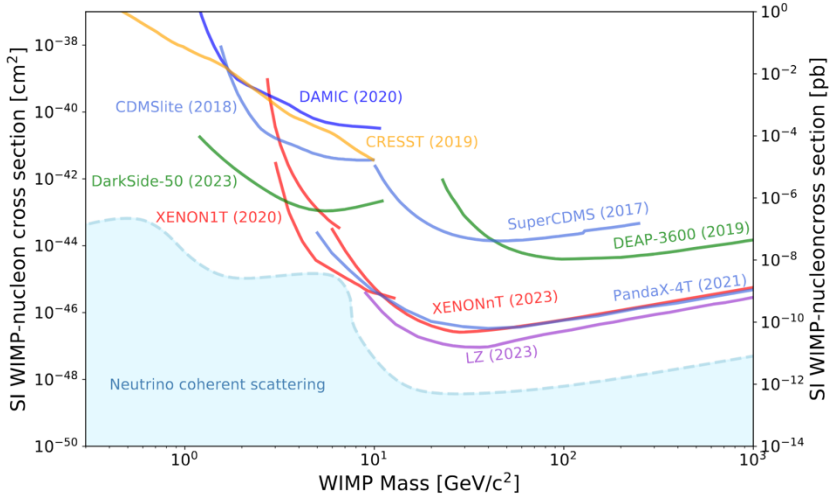




Nonetheless, no convincing non-gravitational signal so far!



S. Navas et al. (Particle Data Group), Phys. Rev. D 110, 030001 (2024)



A large effort in direct detection search focused on Weak Interacting Massive Particles (WIMP), driven by the "WIMP miracle"

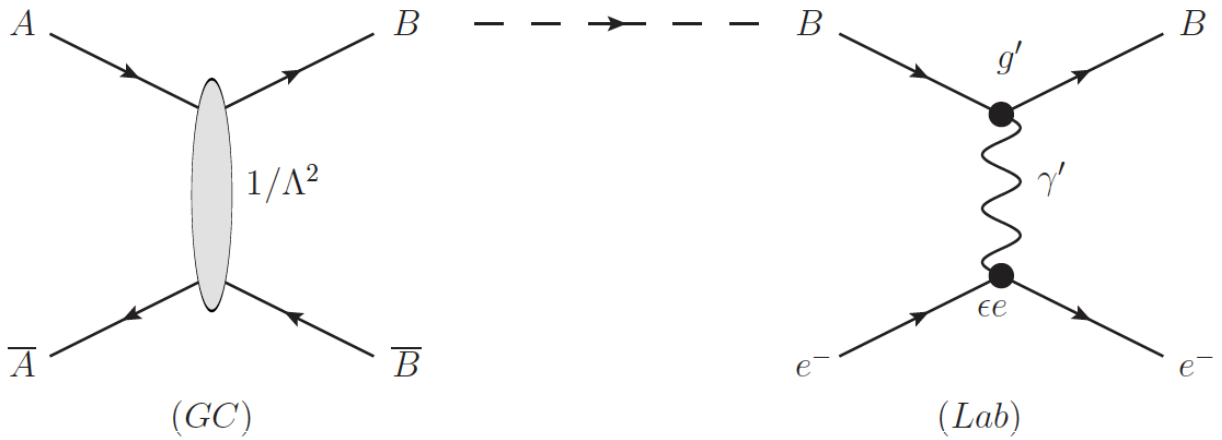
Beyond simple paradigms: Boosted Dark Matter

Expanding the DM searches to encompass different signal types is an experimental opportunity to overcome a possible simplified WIMP paradigm.

New classes of DM models, called Boosted Dark Matter (BDM), have been proposed:

- WIMP paradigm is expanded to a multicomponent dark sector, including a component with large Lorentz boost produced by the decay or annihilation of another dark particle in a location dense of DM

K. Agashe et al JCAP10(2014)062



The objective of CADMO is to develop a new detector technology to gain sensitivity to BDM in LAr based detectors

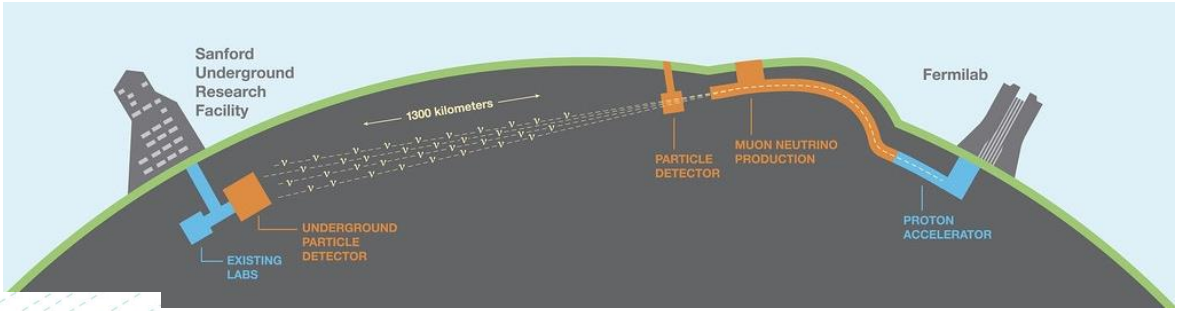
The Deep Underground Neutrino Experiment

A single experiment that will be able to explore the three-flavour neutrino model with unprecedented precision (measure of oscillation parameters, CP violation in lepton sector, mass pattern,…) exploiting a wideband neutrino beam.

But also pursue a broad programme in astroparticle physics and rare event searches (supernova neutrinos, solar neutrinos, proton decay, dark matter…).

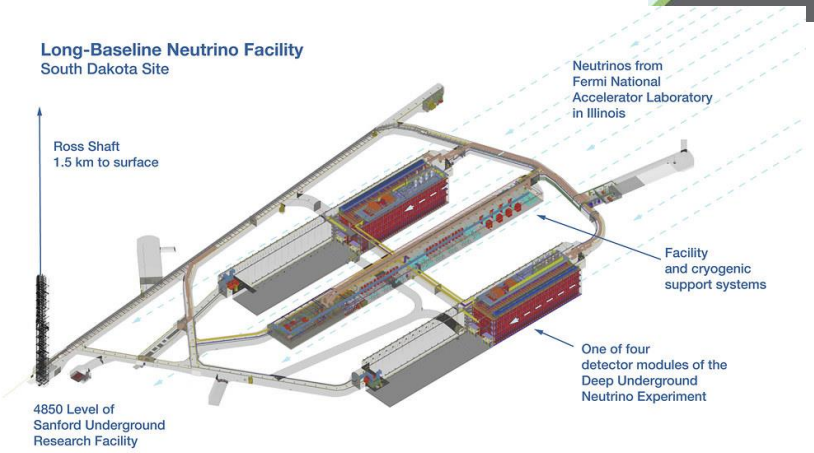
SURF @ South Dakota:

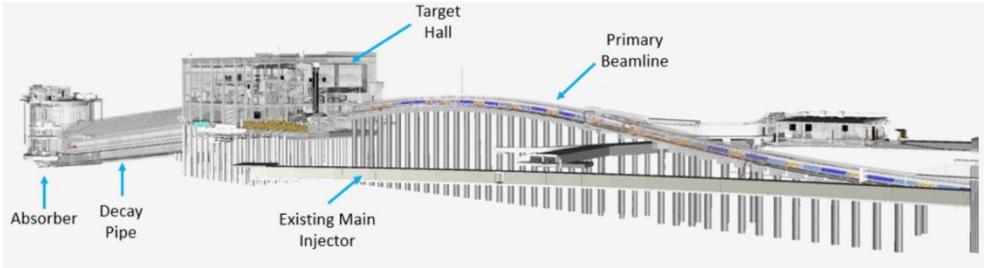
- LArTPCs detectors;
- 1.5 km rock overburden;



LBNF @ Fermilab:

- 120 GeV protons on target;
- 1.2 MW beam power;
- 2.5 GeV mean neutrino energy

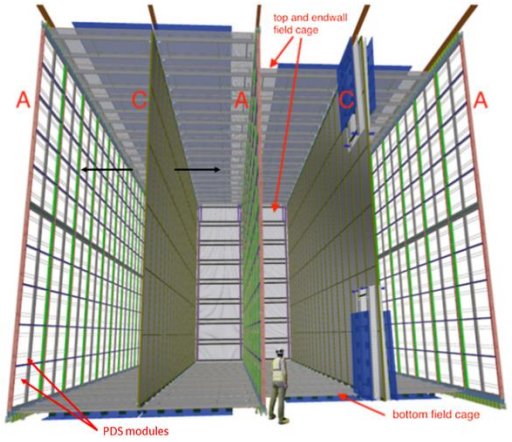




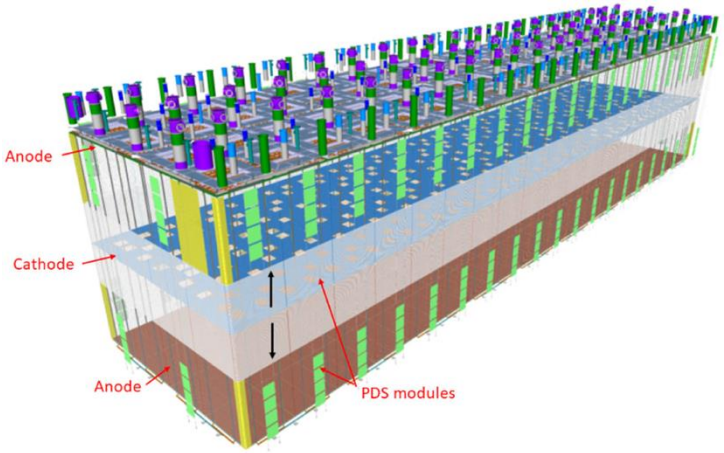
DUNE Far Detectors

DUNE Phase I: will run 2 LArTPCs with a total fiducial mass of 20 kton (data taking with natural neutrinos in 2029 and beam in 2030)

FD1



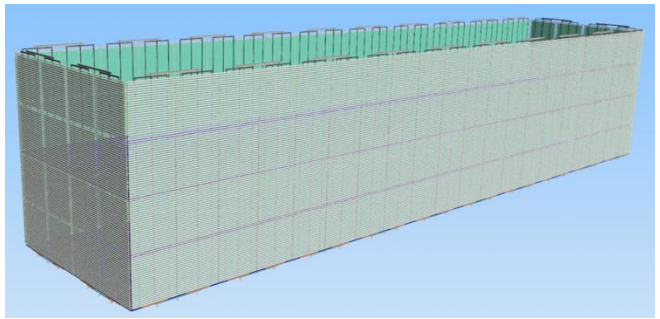
FD2



- Horizontal drift (left): wire readout anode planes, volume divided in four drift regions;
- Vertical drift (right): top and bottom strips anode planes, volume divided in two drift regions;
- The far detectors are complemented by a near detector complex enabling precision physics by flux constrain;

DUNE Phase II: 2 additional LArTPCs for a total fiducial mass of 40 kton and beamline upgrade to >2 MW

FD3



FD4

The Module of Opportunity

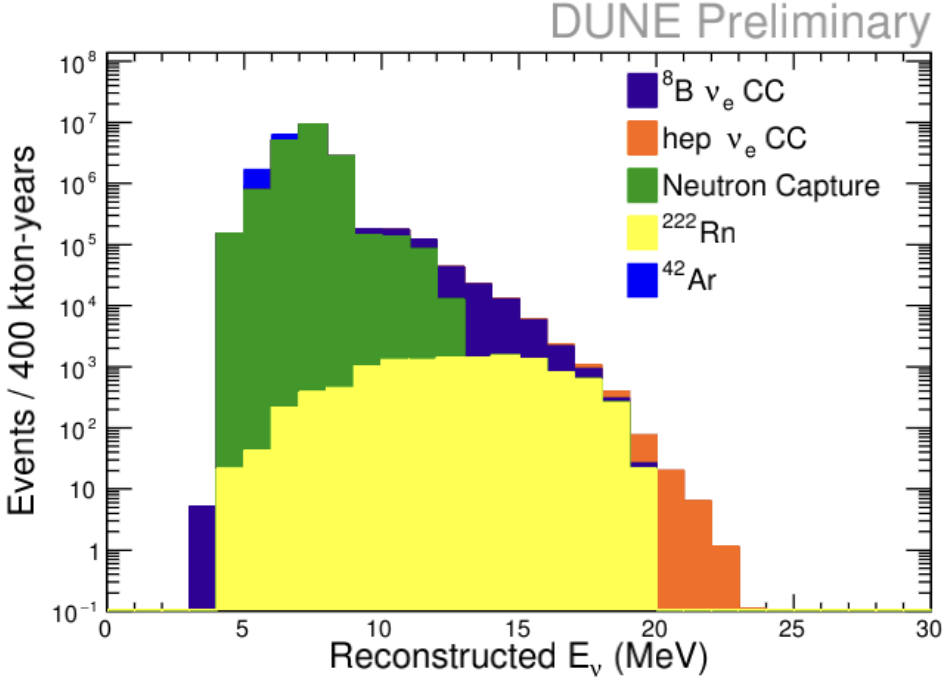
- Design based on vertical drift modules;
- Minimal improvements to light collection system for FD3, light detectors integrated in field cage;
- FD4 is the "Module of Opportunity", where more advanced technology is employed to expand the primary science program and address new physics questions;

DUNE & low energy neutrino physics

DUNE design is mainly optimized for beam neutrinos @ 2.5 GeV, but also huge potential for low energy range

Opportunities

- **Solar neutrinos**: in argon, ν_e CC interactions w/ ^{40}Ar and ES w/ electrons (directionality)
  - High precision oscillation physics with ^{8}B
  - Discovery and first measurement of hep neutrinos
- **Supernova neutrino bursts**: large amount of ν_e interactions from galactic supernova explosion
- **Boosted Dark Matter**: multi-MeV interactions of neutrino like particle pointing toward galactic center



Challenges

- Material not optimized for low-background mitigation
- Limited low energy resolution
- Difficult to reconstruct events at low energies

The SoLAr & CADMO projects

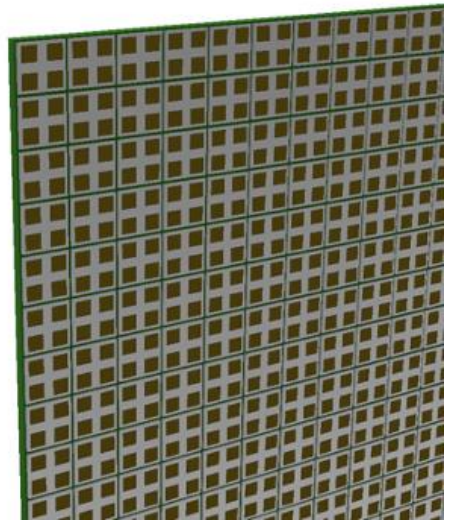
The goal of the SoLar project is to develop and demonstrate a new technology to enable and exploit DUNE capabilities at the MeV scale

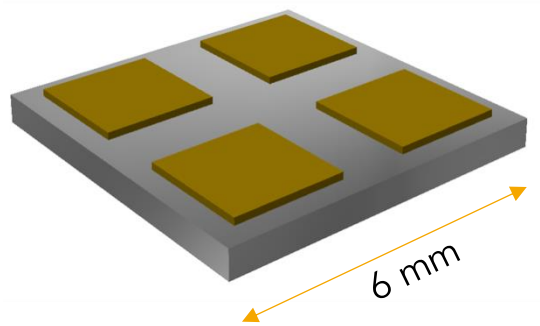
- Concept: anode integrating charge & light readout for LAr TPCs detectors to perform low energy neutrino physics
- A possible technology choice for the DUNE "Module of Opportunity"

arXiv:2203.07501 [hep-ex] 24 Aug 2022

arXiv:2408.12725 [physics.ins-det] 22 Aug 2024

- **Combination of light & charge**: Improvement energy resolution (target $\Delta E/E \approx 7\%$) and trigger
- **Better background rejection**: exploit pulse shape discrimination and directionality
- **Integration of developing technology**: VUV SiPMs and charge readout pixels



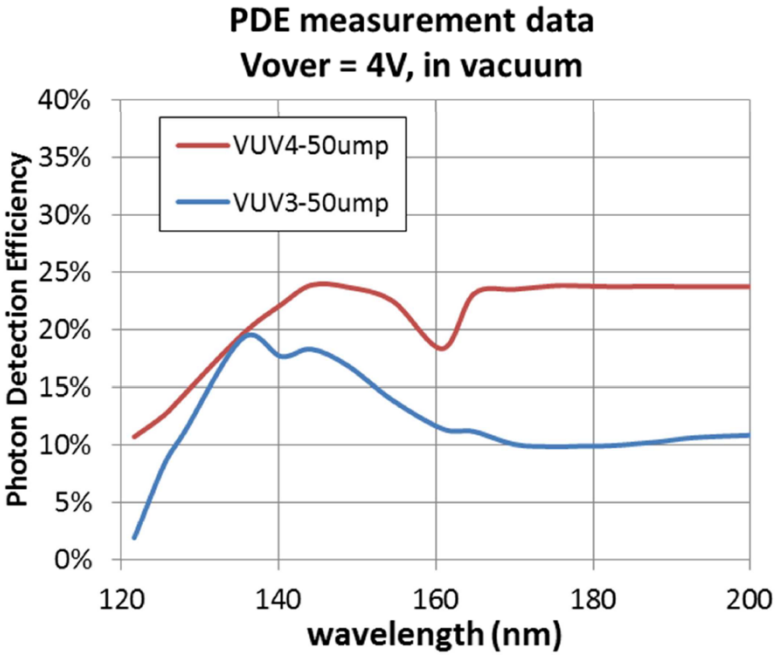


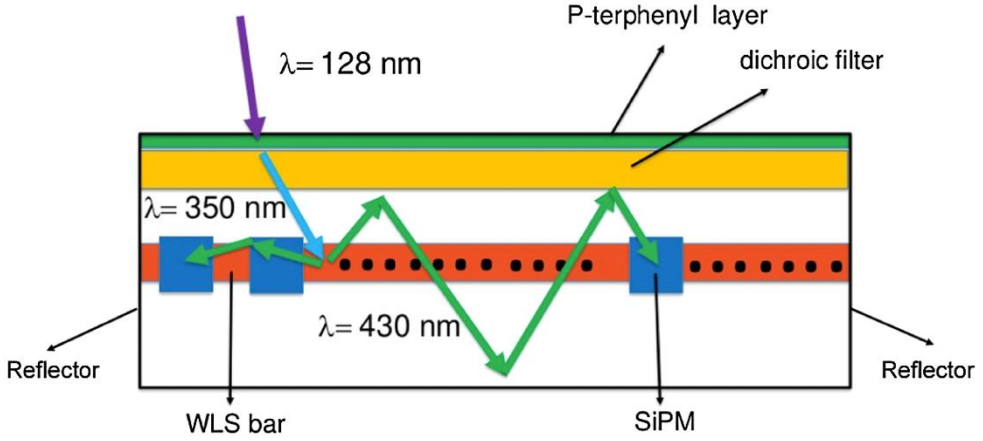
SoLAr developments in Milano-Bicocca are framed within CADMO: the development of the charge & light readout is an essential feature to enable the search for Boosted Dark Matter in DUNE

LAr scintillation light detection

Conventional SiPMs architecture use anti-reflective coating (SiO_2 or Si_3N_4) w/ high absorption for VUV photons. Moreover, these photons are absorbed within few nanometers from surface:

- Standard ways to detect LAr scintillation light are to shift the photons to wavelength corresponding to high PDE for SiPMs





X-ARAPUCA

Hamamtsu developed SiPMs sensitive to VUV photons (VUV 4th generation), w/ a PDE of 15% @ 128 nm, which are the one used for the SoLAr prototypes

The first anode prototype

First results published in November 2024:

final results of the anode prototype (SoLAr Prototype-v1) tested at the University of Bern in 2022

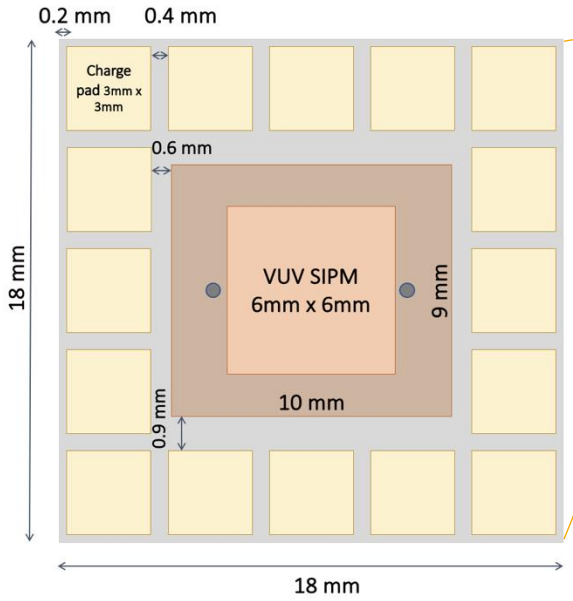
- 7 × 7 cm^2 anode on Printed Circuit Board (PCB)
- Pixelated charge readout system using 4 LArPix chips
- Neighboring Hamamatsu VUV SiPMs (15% PDE @ 128 nm)

JINST 19 (2024) P11010

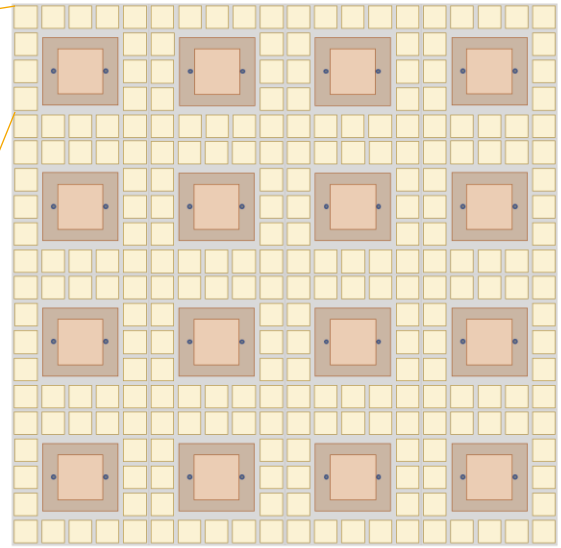
Objective of protoype test

- Operation of the charge & light integrated anode in a small scale LArTPC
- Measurement of cosmic muon tracks
- Investigation of cross-talk between readouts

Schematic of single cell



Schematic of full anode

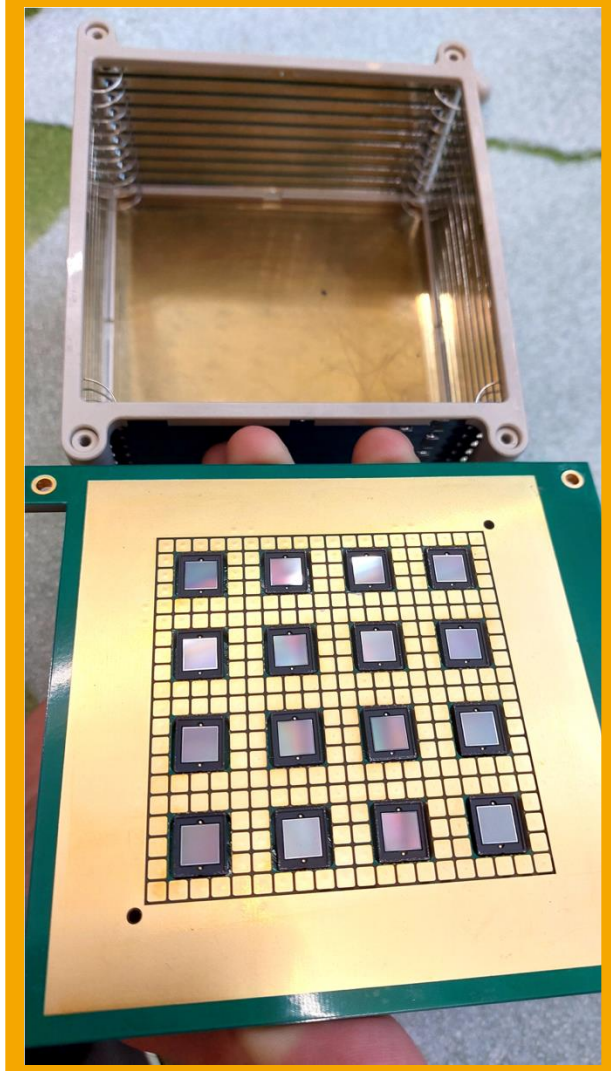


Results of the first anode prototype

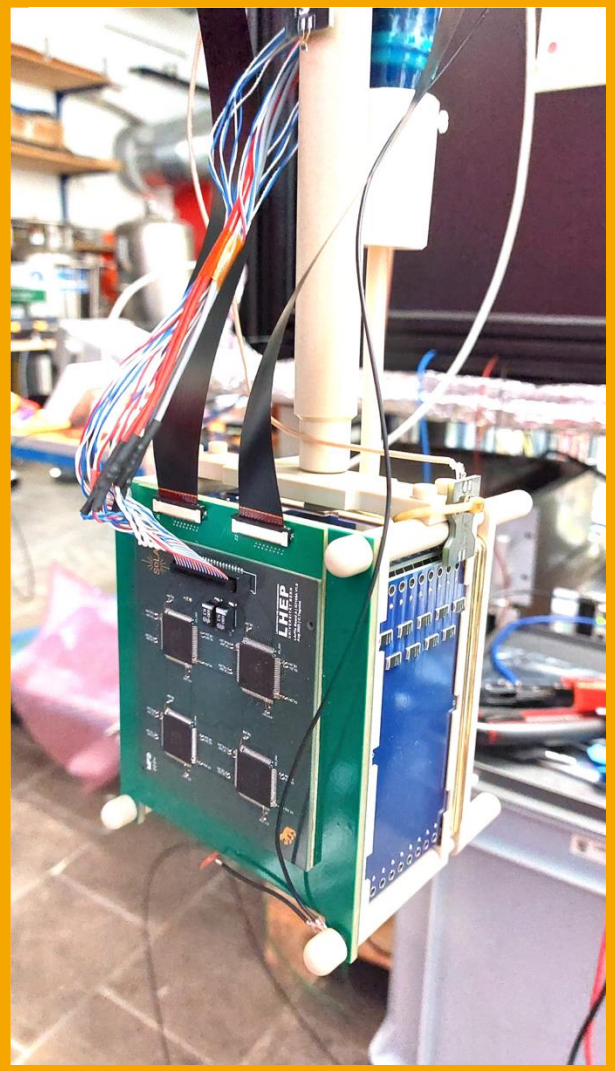
Experimental setup:

- TPC dimensions in the anode plane 11.8×10.8 cm^2, w/ sensitive area of 7×7 cm^2
- Drift length of 5 cm
- Dimensions constraints from the inner cryostat volume (diameter of 14 cm)
- Drift electric field of 500 V/cm

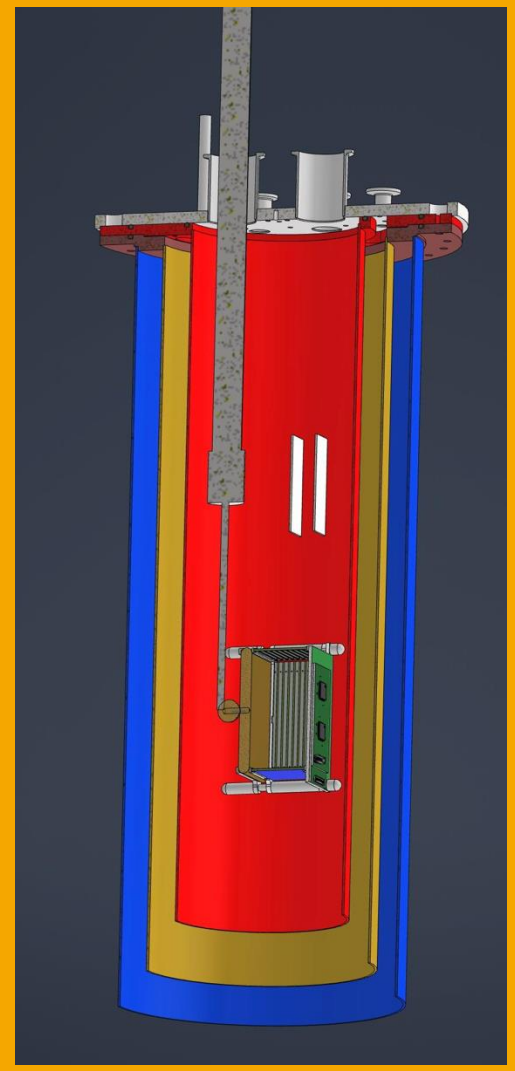
TPC anode/cathode/side-panels



TPC Prototype-v1



Cryostat section view



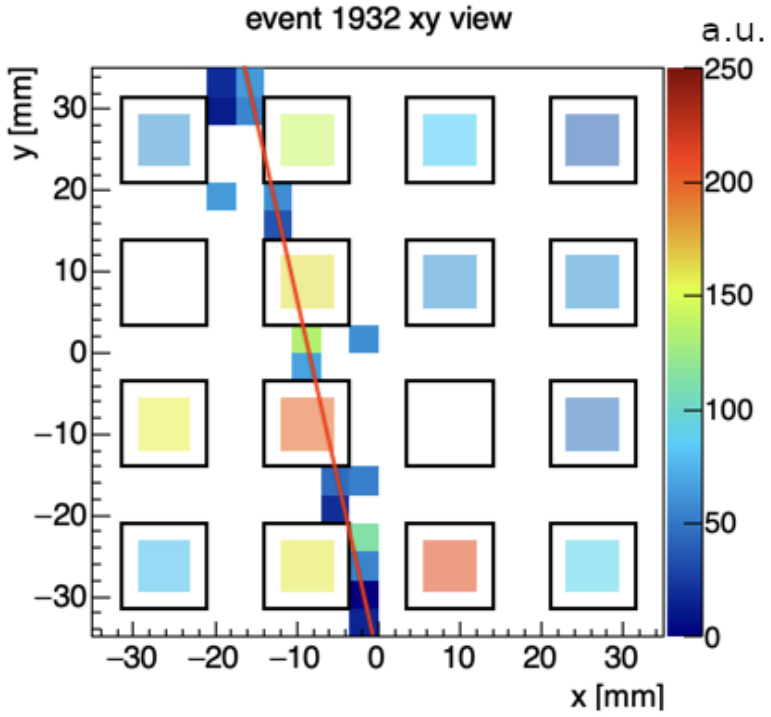
Results of the first anode prototype

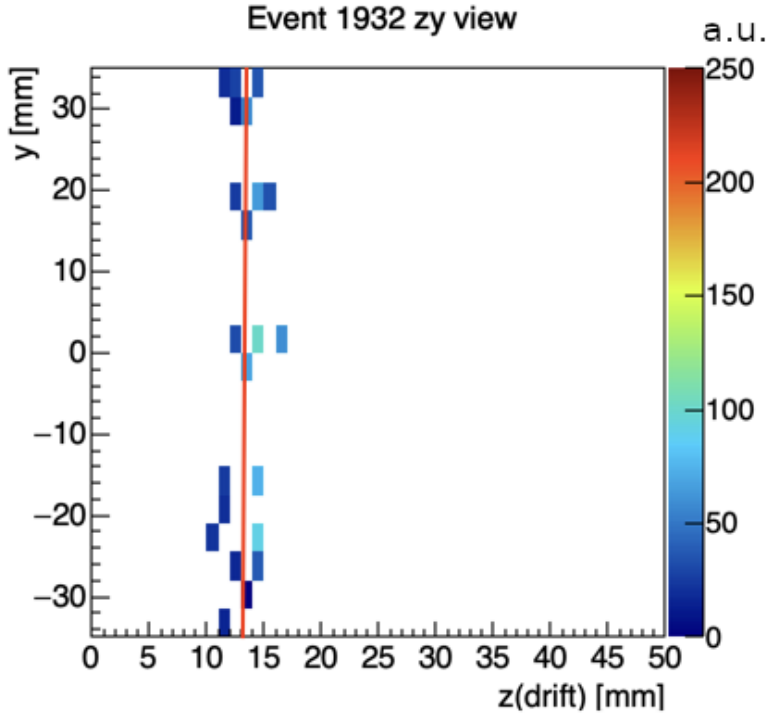
About 70.000 events collected during the operation of the prototype

- Clear indication of muon tracks from the patterns of charge & light signals
- Drift distance of electrons obtained using t_0 trigger time given by light signals
- Unambiguous 3D hits of muon tracks

Major milestone

- First combined detection of light & charge on a dual-pixel anode plan in a LArTPC
- Demonstration of SoLAr concept, exploiting light & charge for reconstruction and trigger

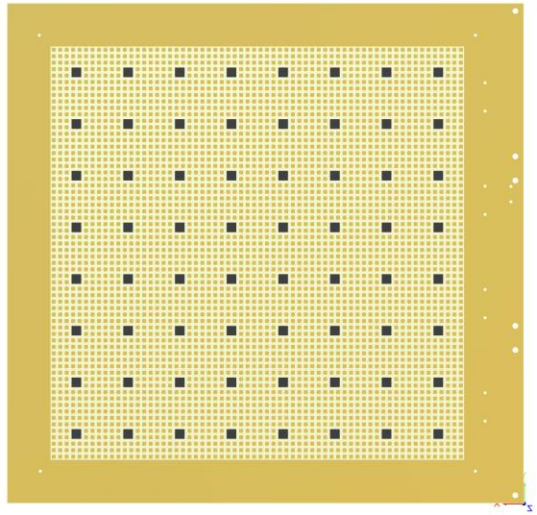




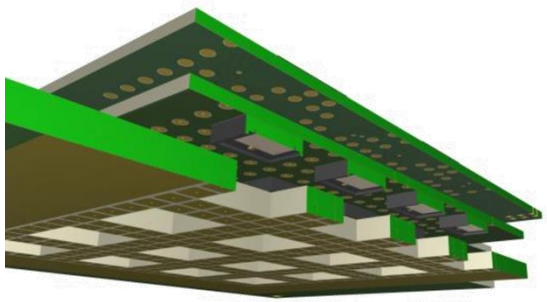
The second anode prototype

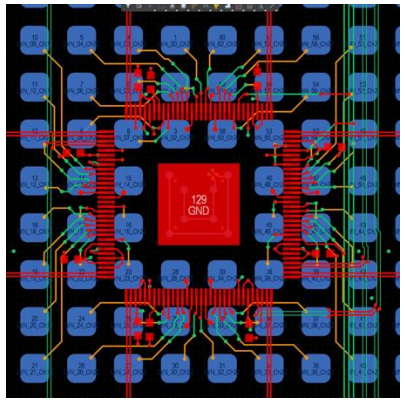
A larger area anode prototype (SoLAr Prototype-v2) tested at the University of Bern in 2023

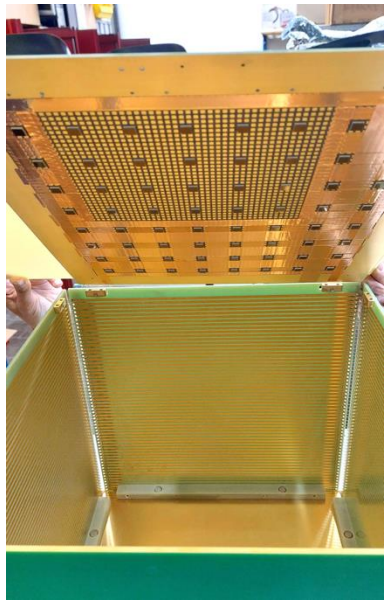
- 30×30 cm^2 anode on Printed Circuit Board (PCB)
- Divided in 8×8 regions (1 region = 60 pixels + 1 SiPM)
- Pixelated charge readout system using 64 LArPix chips
- 64 Hamamatsu VUV SiPMs (15% PDE @ 128 nm)
- Test of a larger TPC volume

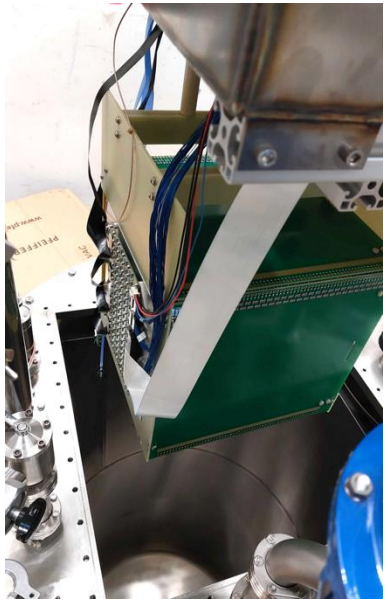


New PCB design: from 3 stacked layers to single multilayer PCB









Second anode prototype: preliminary results

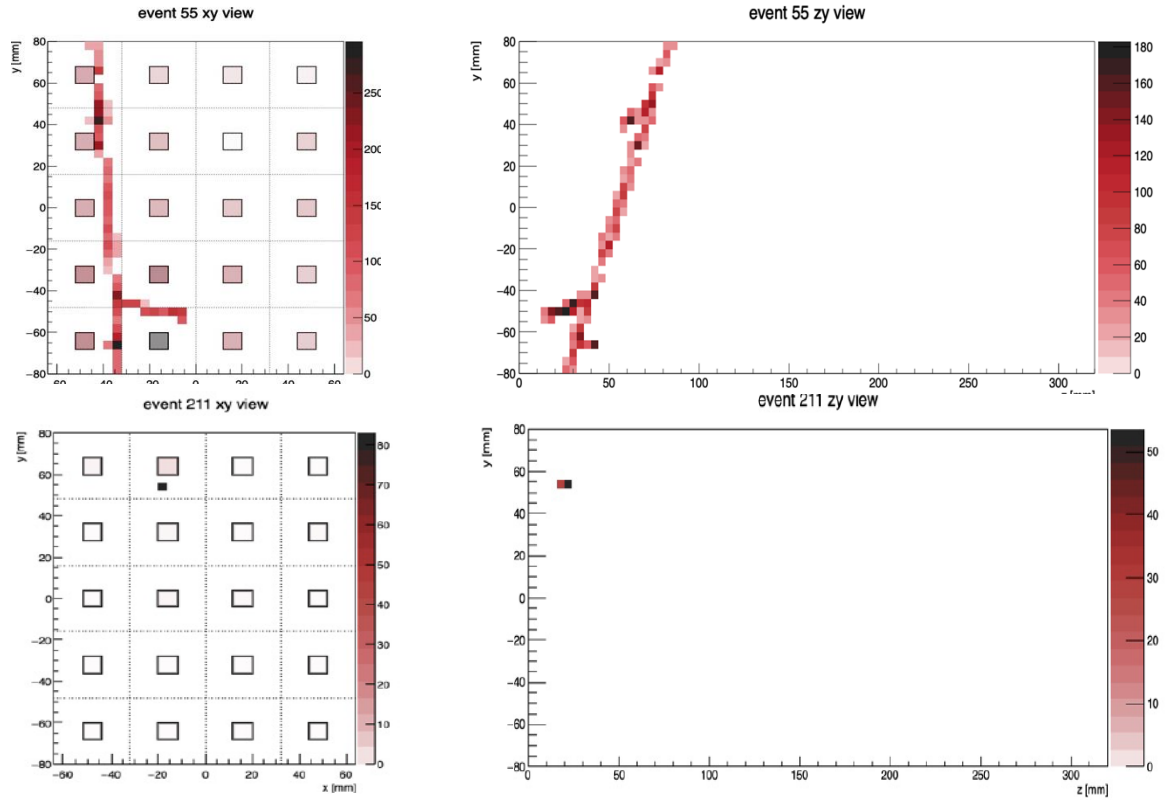
Light and charge combined reconstruction of cosmic muon tracks

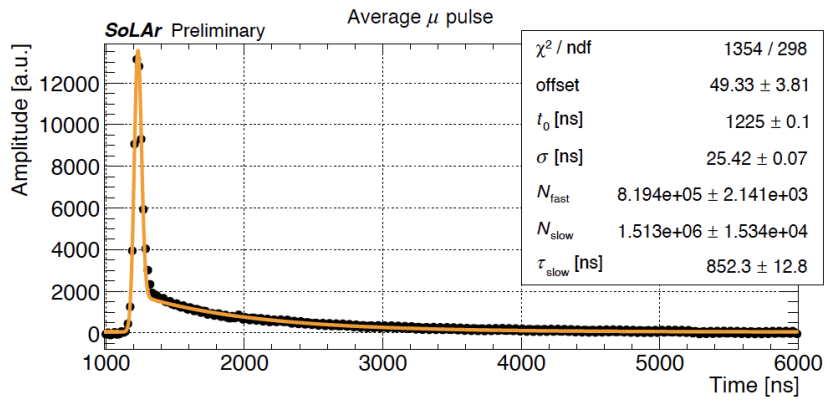
- About 86% of the charge events have a corresponding light event match

Special ^{60}Co source run: interesting to study isolated point-like events w/ matched light

- Studies of energy and position resolution ongoing

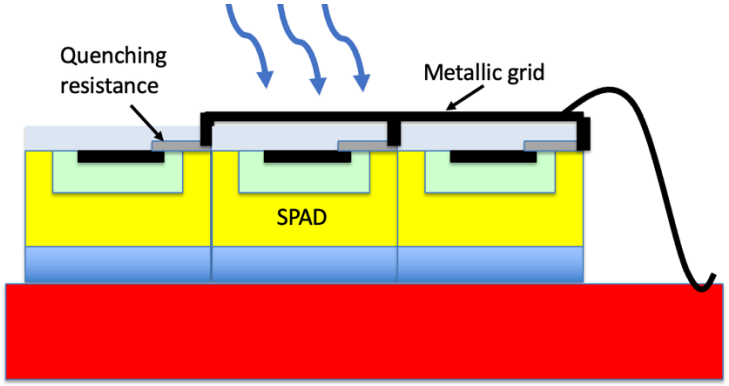
Measurement of time profile of the scintillation light (from cosmic run lasted about 80 mins)



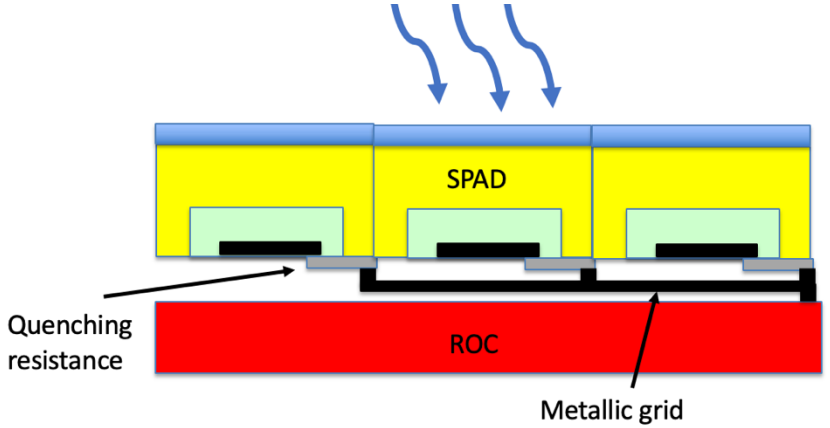


Next steps: back-illuminated SiPMs & new readout

Back-illuminated VS standard SiPMs architecture:



Standard architecture



Back-illuminated

- Electrical connections and high-field region in one side ("frontal-side")
- Other side ("back-side") is free of structures

Back-illuminated architecture allow higher fill factors (almost 100%) and furthermore to increase considerably the PDE for VUV photons by specific surface treatments.

Collaboration w/ Fondazione Bruno Kessler (FBK) to develop a new technology to enhance the PDE @ 128 nm (>20%) exploiting surface treatments in back-illuminated SiPMs

✓ FBK and UniMiB are establishing a research agreement (2025-2026) funded by BiCoQ and FBK

SiPM readout will be integrated into new cryogenic ASIC:

- possibly based on the INFN ALCOR v2 design enhanced by a charge integration stage and operated with large capacitance SiPMs
- Development of the charge integration stage in the next year

Summary

- CADMO goal: development of new devices for the detection of photons in the extreme ultraviolet to search for dark matter candidates beyond the WIMP paradigm
- Focus of the activity: development of integrated light & charge readout for LAr TPCs, undertaken by Milano-Bicocca as part of the SoLAr Collaboration
- First milestone in November 2024: published final results of first anode prototype using VUV SiPMs tested at the University of Bern in 2022 (JINST 19 (2024) P11010)
- Second prototype with larger area tested in 2023, ongoing data analysis
- FBK & UniMiB establishing research agreement for 2025-2026, funded by BiCoQ and FBK, for the development of back-illuminated SiPMs with enhanced PDE @ 128 nm
- SiPMs readout will be integrated in new cryogenic ASIC, development in 2025