CADMO
direct detection of dark matter

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Candidate dark matter beyond the WIMP paradigm

In the 1990s, the direct search of dark matter was mostly focused on the search of weak interacting massive particles (WIMP) because of a strong theory bias called “the WIMP miracle”

WIMP (Weak Interacting Massive Particle): it is a new elementary particle which interacts via gravity and any other force, which is as weak as (or weaker) than the weak nuclear force, but non-vanishing in its strength. If WIMP exist, candidates are expected to have been produced thermally in the early Universe, similarly to the particles of the Standard Model according to Big Bang cosmology, and usually will constitute **cold dark matter**.

To explain the observed Dark Matter property, the WIMP annihilation cross section must be

$$\langle \sigma v \rangle \simeq 3 \times 10^{-26} \, \mathrm{cm}^3 \, \mathrm{s}^{-1}$$

which is about the cross section of a 100 GeV particles interacting by electroweak force

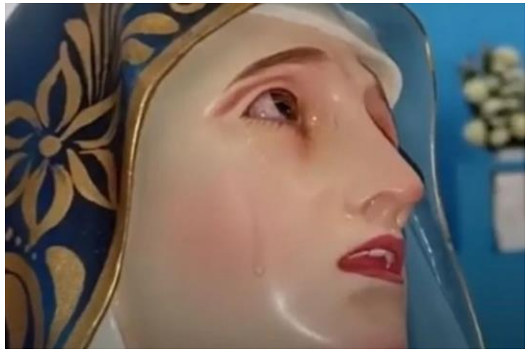
The WIMP miracle is the observation that most supersymmetric extension of the Standard Model predict exactly this class of particles!

A fake miracle?

The WIMP miracle requires particle that interact with ordinary matter producing low energy scattering at E<1 MeV and that can be produced on-shell in high-energy colliders. Most of the models predicted observations of these particles at the LHC, which never occurred. Three options:

Dark Matter has a sole gravitational origin and there is no connection between this problem and the Standard Model of particle physics.

This is equivalent to saying that the WIMP miracle is just a coincidence we should ignore



The idea is good, but the implementation is wrong.

We should look at the most general class of particles that fulfil the requirement of a dark matter candidate and weakly interact with ordinary matter.

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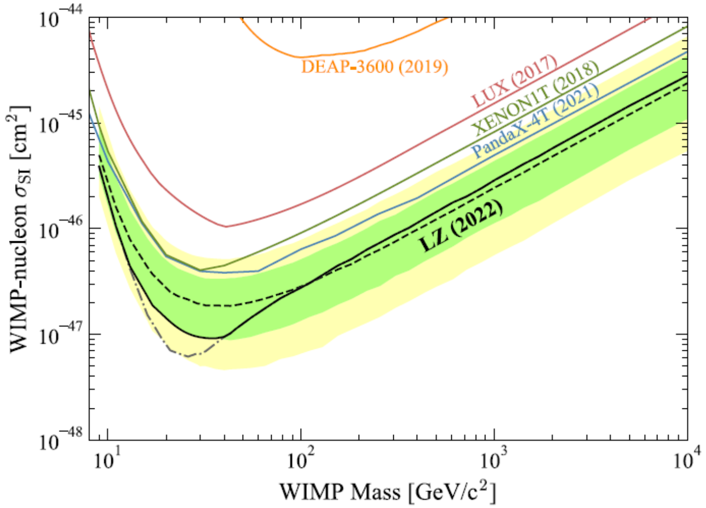
The WIMP miracle exists but we are too pessimistic: there is still a fraction of the parameter phase to be explored because supersymmetric theories have many free parameters and realizations.



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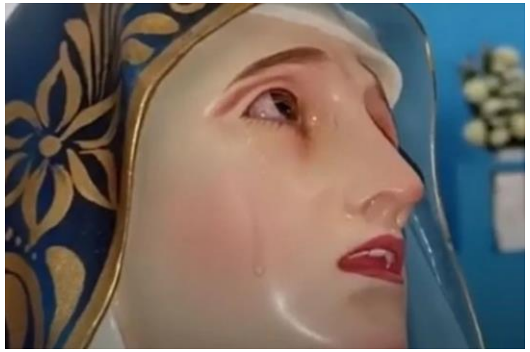

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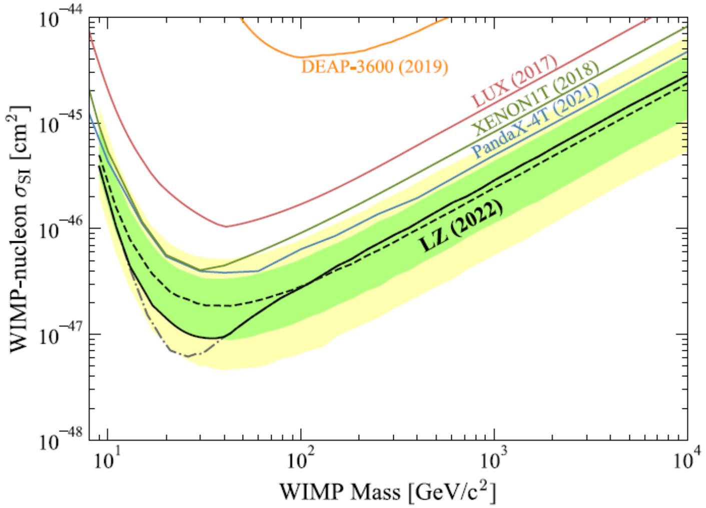
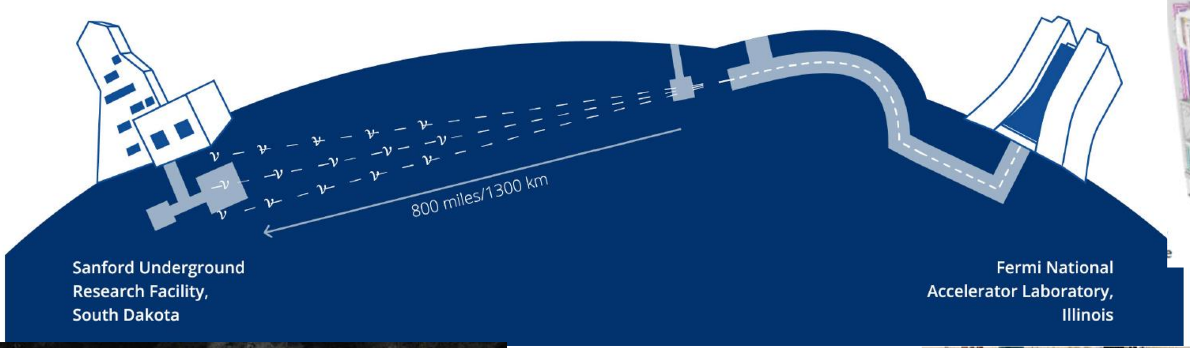
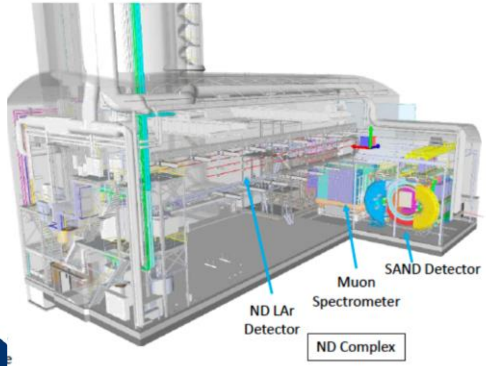
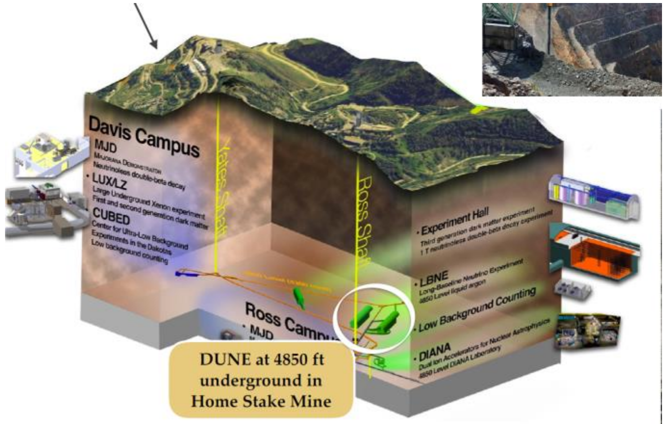


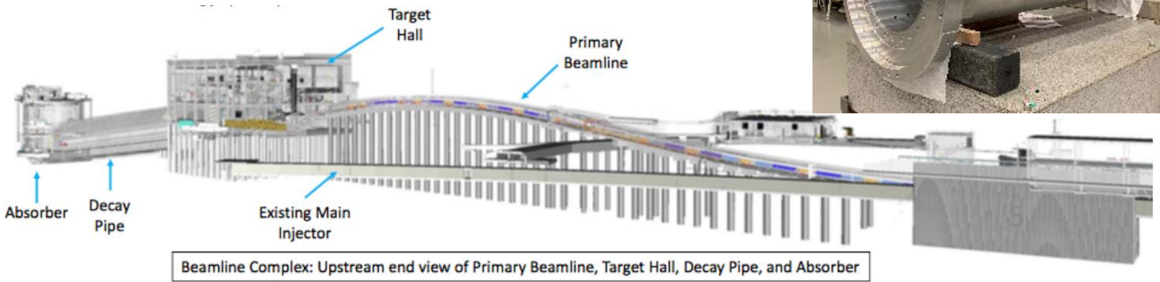
The Long Baseline Neutrino Facility and SURF

The implementation of the DUNE science require two major facilities: a broad-band neutrino beam with 1.2 MW power upgradable to 2.4 MW power and the SURF laboratories in South Dakota. **These long-lasting facilities are going to play in neutrino physics a role similar to the Simon observatory or the LHC**. They are aimed at feeding a broad, top-class programme in neutrino physics, astroparticle and multi-messenger astronomy, rare event search and physics beyond the standard model for several decades.





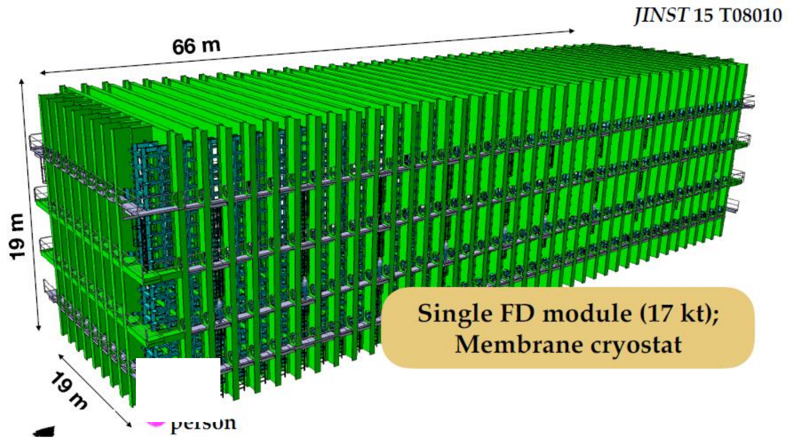




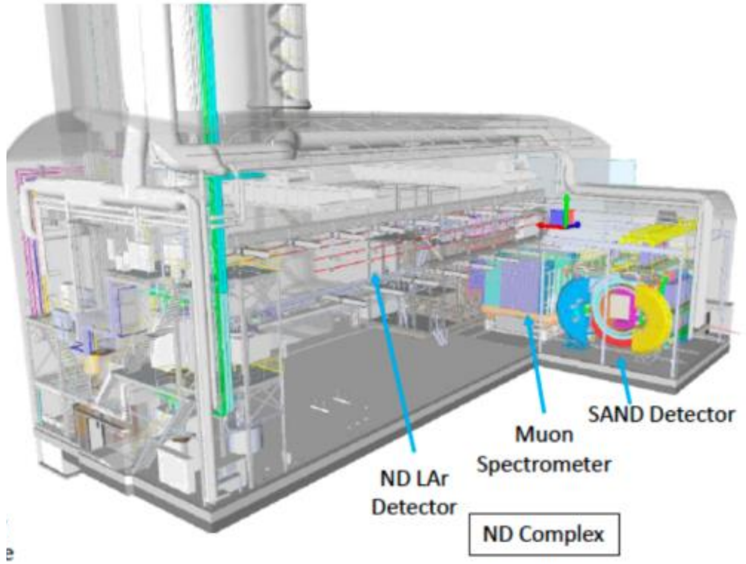
DUNE in a nutshell

Mass: the DUNE far detector comprises 4 modules of liquid argon for a **total fiducial mass of 40 kton** (full mass **70 kton**).

Resolution: DUNE is based on the technique with **the best particle imaging capability** available at kton scale: the Liquid Argon TPC (C. Rubbia, 1977)



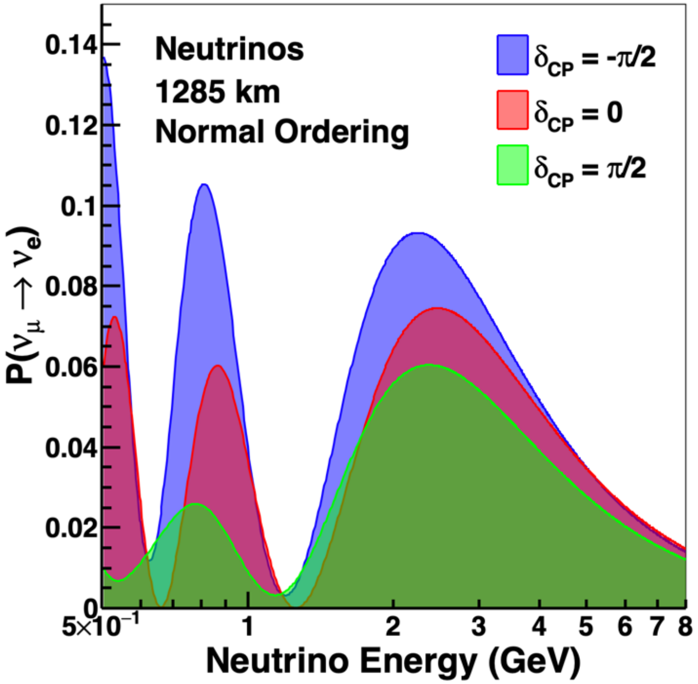
Precision: DUNE employs a **near detector complex** for beam characterization based on a movable (NDLAr, TMS/NDGar) + on-axis (SAND) detector.



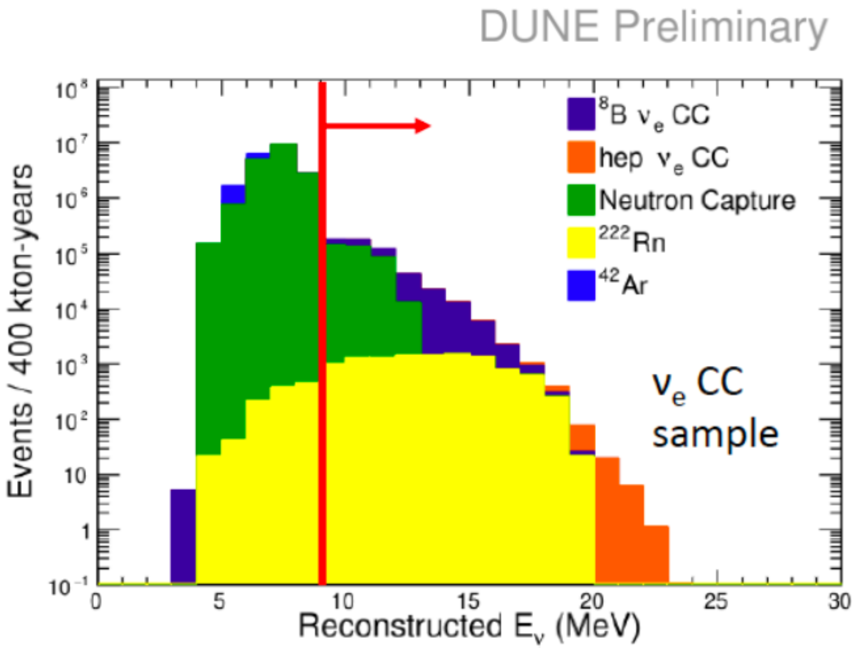
Beam observables: $\nu_\mu \rightarrow \nu_e$ oscillations and its CP conjugate $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$; ν_μ survival probability at the far detector. **Natural sources**: atmospheric and solar neutrinos. Transient sources like supernove neutrinos. Forbidden decays like $p \rightarrow K\nu$ proton decay

Reaping the DUNE opportunity

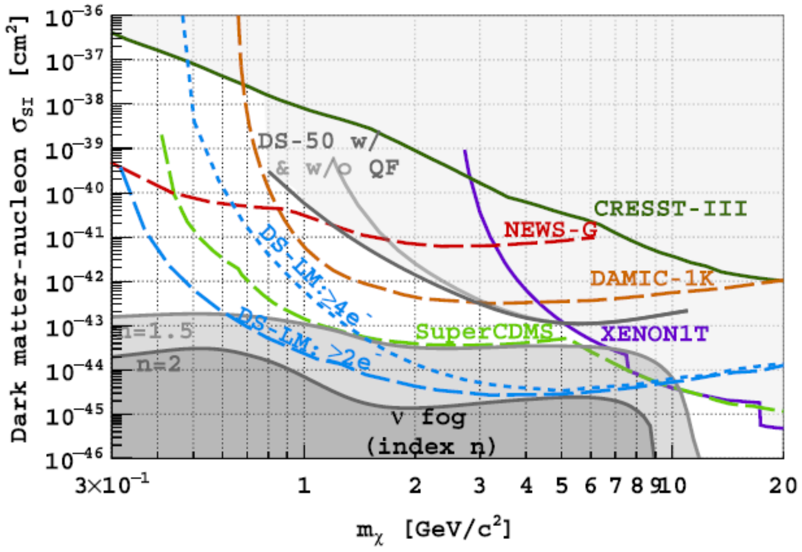
DUNE is schedule to start data taking with natural neutrinos in 2029 and with beam in 2030 using two detectors, 10 kton each and will be upgraded with two additional detectors later on ("Phase II"). It will thus be the most precise underground observatory in the 2030s looking for weakly interacting particles of cosmic origin. Still, its design is mostly optimized for the artificial neutrinos produced at Fermilab (2.5 GeV energy). Since argon is reach of ^{39}Ar, it is unlikely we will ever be able to go below a few MeV using natural argon but... **there is a wealth of physics at the MeV scale waiting to be enabled by DUNE**



Current design: multi-GeV events. No cosmic WIMP events expected here



The 1-100 MeV is a region still to be explored!



Search for the WIMP miracle with depleted Argon (Darkside, Argo)

Mind the gap

The energy region between 1 and 100 MeV is where DUNE gives its best in the global context of astroparticle physics because most of the events at this scale are below threshold for large mass water Cherenkov detectors like SuperKamiokande or HyperKamiokande. What we find here:

- **Solar neutrinos:** neutrinos produced by the sun reach DUNE with an energy between 2 and 20 MeV. DUNE is particularly sensitive to these neutrinos because they are electron neutrinos that are absorbed by argon through $\nu_e + {}^{40}Ar \rightarrow 40K^* + e^-$, which has a large cross section and a clear signature. DUNE also observe $\nu_e + e^- \rightarrow \nu_e + e^-$ scatterings and the electron direction point toward the sun.

- **Supernova neutrinos:** in the occurrence of a galactic supernova explosion, DUNE will observe thousands of ν_e interactions and shed light on the supernova explosion mechanism, including neutronization

- **Boosted dark matter:** BDM expands the weakly interacting massive particle (WIMP) paradigm to a multicomponent dark sector that includes a component with a large Lorentz boost obtained today due to decay or annihilation of another dark particle at a location dense with DM. In this class of models, the boosted component can scatter off standard model particles similarly to neutrinos, and can thus be detected at neutrino experiments. **The classical signature of boosted dark matter are monochromatic multi-MeV interactions of an invisible (neutrino-like) particle pointing toward the galaxy center.**

Due to its unprecedented mass, DUNE is the only game in town for boosted dark matter interacting with nucleons and is competitive with HyperKamiokande if BMS interacts with electrons

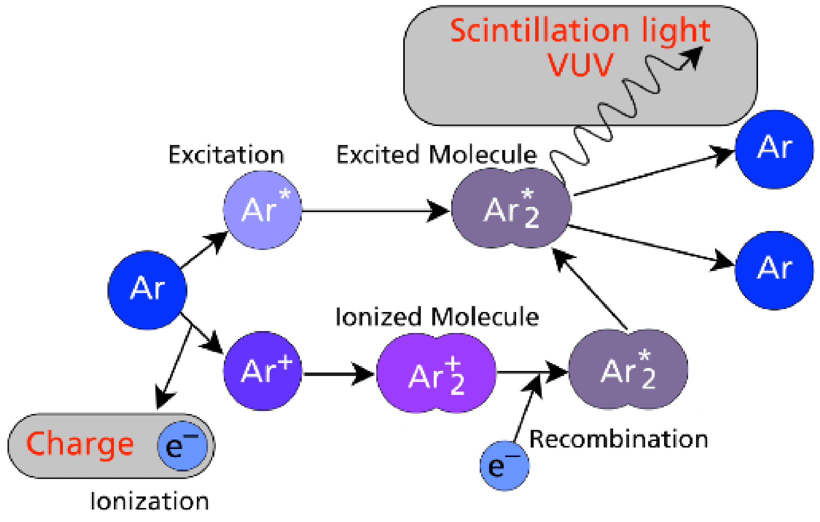
Filling the gap

The Department of Physics of Milano Bicocca steers the effort to “fill the MeV gap” in DUNE since 2021. Such leadership dates back to the foundation of the SoLAr Collaboration, which is aimed at devising a novel technology to record and identify low energy events in DUNE and implement this technology in the third and fourth DUNE module. In particular,

- The reason why a liquid argon TPC like DUNE has a limited performance at the MeV scale is due to the fact that charge diffusion limits the space precision at about 1 mm and MeV events show few-mm tracks

- The DUNE performance at the MeV scale can be enhanced by recording the **scintillation light of argon**

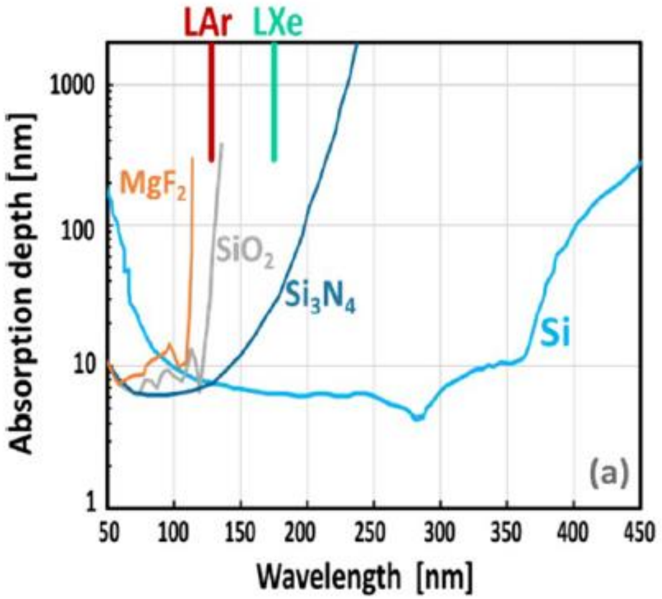
- The most advanced identification method of low energy events in DUNE is based on the simultaneous observation of charge and light in the same detector component (the TPC anode)

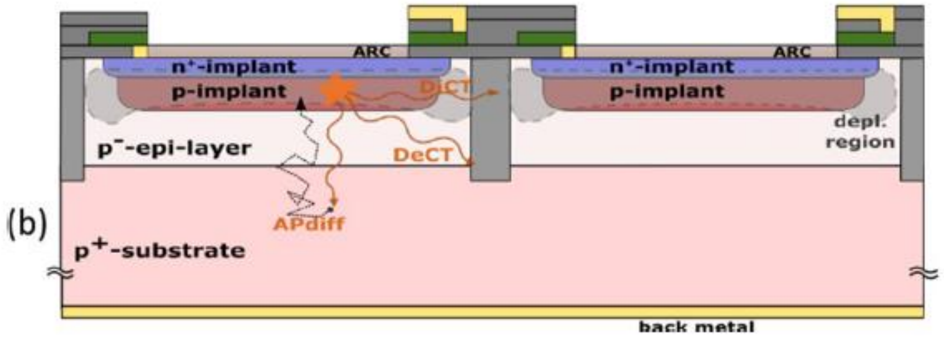


There are several ways to observe the 128 nm scintillation light of argon but all of them rely on shifting these photons to more amenable frequencies. CADMO exploits and further develop a technology breakthrough occurred a few years ago: **all-silicon devices directly sensitive to VUV light – the VUV-Silicon Photomultipliers**

The first 10nm

NUV SiPMs exploit Anti-reflective coatings to increase the trasmitted light. But most coatings absorb VUV light! The standard Si_3N_4 choice is very unfortunate.





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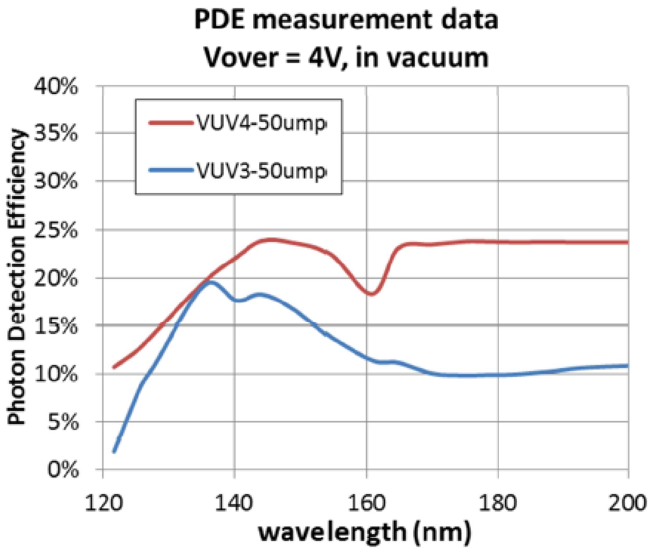
There are two ways to achieve sensitivity to VUV photons:

- **The Hamamatsu way:** development of conventional SiPMs that are not based on SiO_2 coatings and trenches. Optical insulation is achieved by metal-in-trench while the active area is protected by a proprietary microlayer that is partially transparent to VUV light
- **The FBK way:** use of backside illuminated SiPMs where the primary electron-hole pair is transported by an electric field in the back of the device and undergo avalanche multiplication. The front-face is thus free of dead areas and the coating that usually protect the dice is completely removed.

The CADMO light detection device

CADMO is setting up R&D framework agreement to provide compact VUV SiPMs that can be incorporated in a monolithic anode that reads both charge and light

- **The basic CADMO anode** exploits a new class of Hamamatsu VUV SiPMs developed by Hamamatsu in 2022-23 in collaboration with Univ. of Milano Bicocca and Univ. of Bern. They are VUV-4th generation device where dead areas are minimized by Through Silicon Vias and can be arranged in tiles



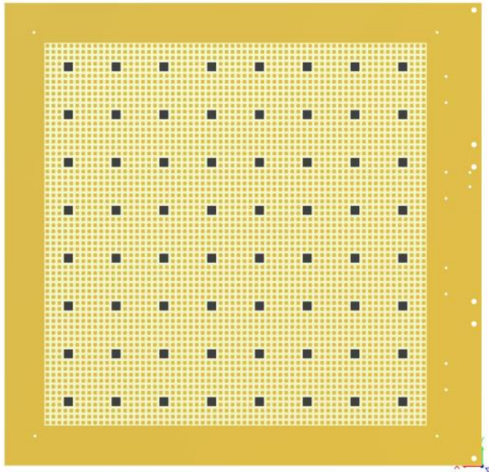
- **The advanced CADMO anode** will exploit the FBK backilluminated SiPM developed by FBK and INFN (IBIS project) interspersed with charge readout electrodes (pixels) read by a custom ASIC for integrated light-charge detection

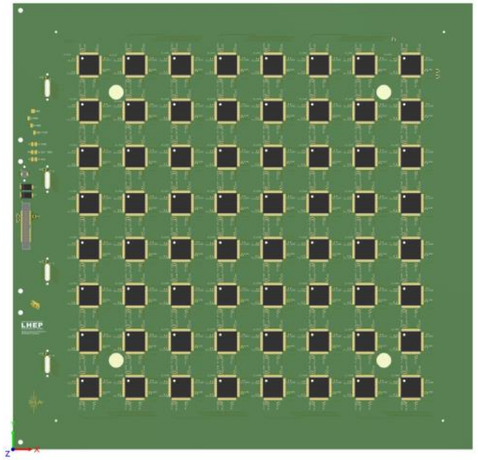
Toward an integrated light charge device

CADMO is aimed at a fully integrated anode that records charge and light and initial prototyping made in the framework of the SoLAr R&D was extremely successful

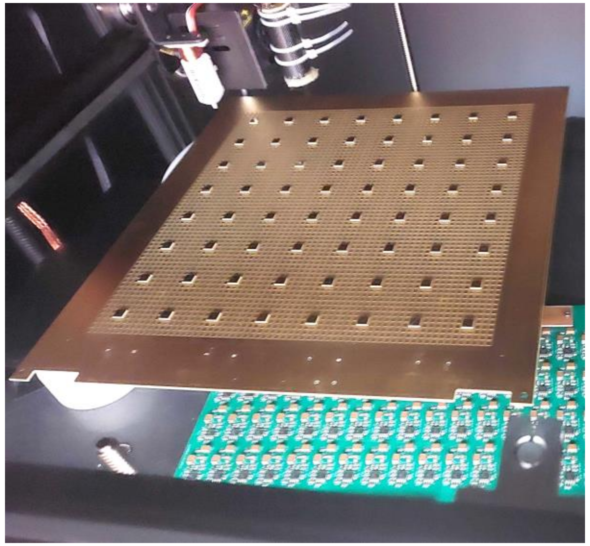
Tile Dimensions 31cm x 32 cm

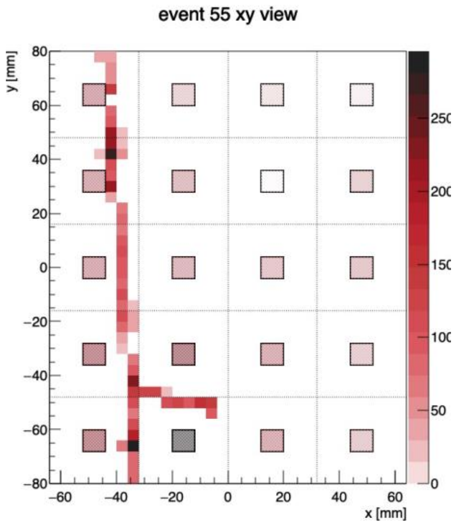
- Divided into 8x8 regions
- 1 region = 60 pixels + 1 SiPM
- Pixel pitch: 4mm
- 64 LArPix (60 routed channels)
- 64 Hamamatsu VUV SiPMs
- SMD type, 6mmx 6mm
- SiPM pitch: 32 mm

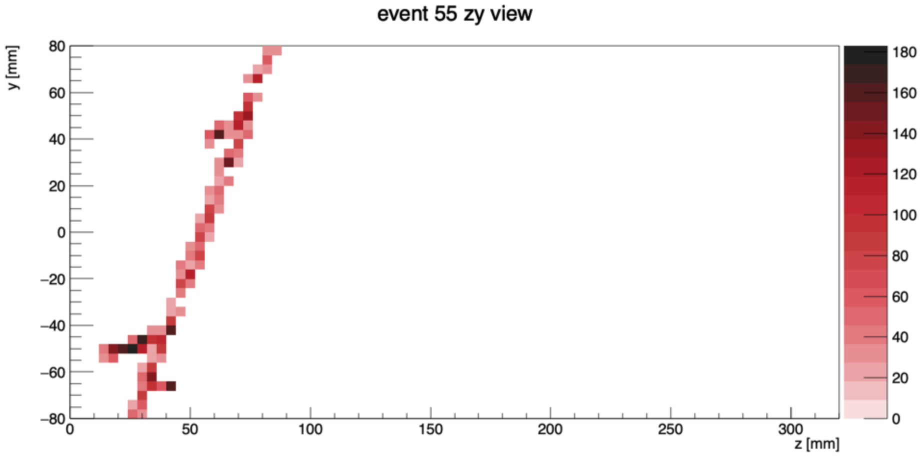




Charge readout fully integrated using a custom ASIC (LArPix) but SiPM readout not integrated yet (daughterboard with warm amplifiers)



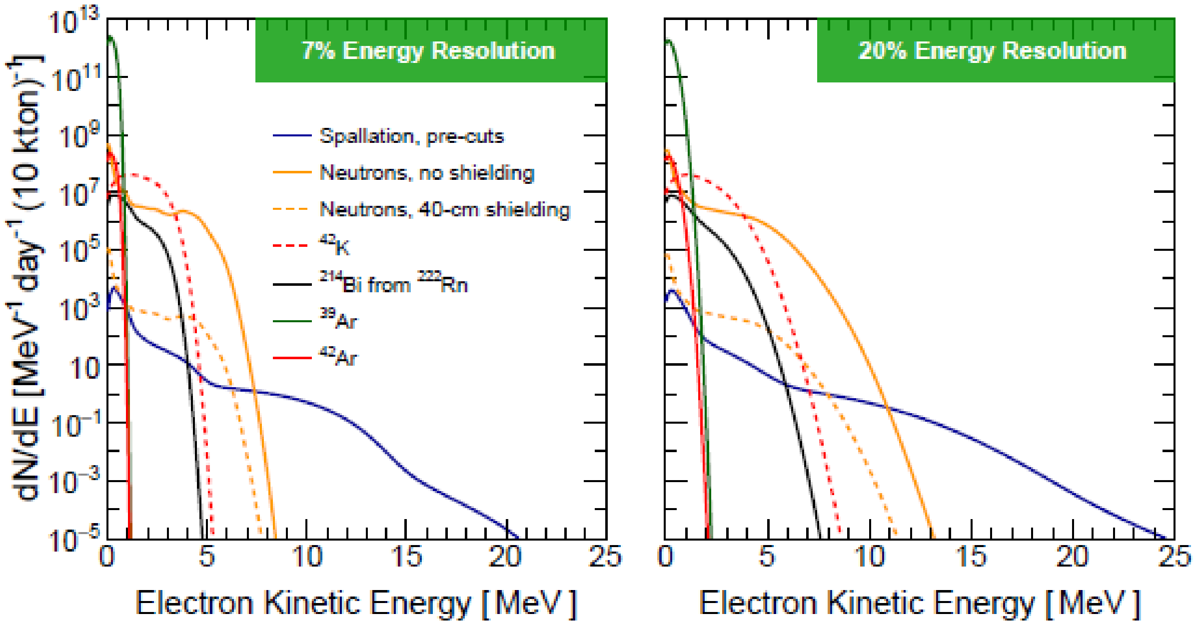




The impact of an integrated charge-light readout

An integrated charge-light anode offers two potential advances to the technology of DUNE:

- It improves significantly **energy resolution** at the MeV scale and offers a venue to identify faint signals originating from **boosted dark matter**. Even if the signal is non-monochromatic (solar neutrinos) it enable a powerful background suppression in the whole energy range above the ^{39}Ar "intrinsic" background.



- It enables "**voxelization**": the possibility to identify the volume where the interaction occurred and trigger only the most interesting part of the detector for event reconstruction. This feature is key to keep the data throughput of gigantic TPC as DUNE to a sustainable rate.

The impact on dark matter search

An integrated charge-light anode offers two potential advances to the science of DUNE:

- It improves directionality, i.e. the capability of pointing the origin of the MeV event candidate
- It improves the identification of the region-of-interest of potential excesses, which is a unique feature of any dark matter candidate beyond the WIMP scenario.

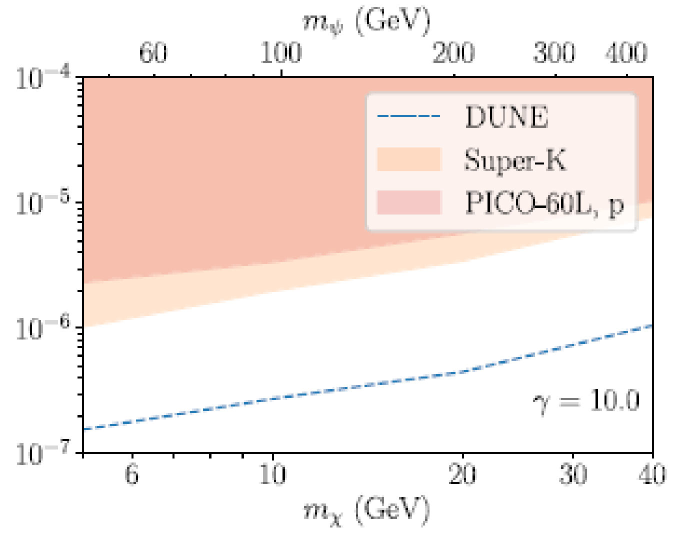
TABLE I. Summary of the volume, threshold (kinetic) energy, and angular resolution of considered experiments from Refs. [47–49] for SK, HK, and DUNE, respectively. p_e^{th} at SK and HK could be lowered below 0.1 GeV with worse angular resolution. Angular resolution gets better with higher p_T.

Experiment	Volume (Mt)	p_e^{th} (GeV)	p_p^{th} (GeV)	θ_e^{res}	θ_p^{res}
SK	0.0224	0.1	1.07	3°	3°
HK	0.56	0.1	1.07	3°	3°
DUNE	0.04	0.03	0.05	1°	5°

Doojin Kim et al, PRL 119 (2017) 161181

TABLE II. Required fluxes with which our reference points become sensitive in various experiments.

Experiment	Run time (yr)	e-ref. 1 (10^{-7} cm^{-2} s^{-1})	e-ref. 2 (10^{-7} cm^{-2} s^{-1})	p-ref. 1 (10^{-7} cm^{-2} s^{-1})	p-ref. 2 (10^{-7} cm^{-2} s^{-1})
SK	13.6	170	7.1	3500	5200
HK	1	88	3.7	1900	2800
HK	13.6	6.7	0.28	140	210
DUNE	1	190	9.0	150	1600
DUNE	13.6	14	0.69	11	120



J. Berger et al, PRD 103 (2021) 095021

- We expect a further lowering of the threshold down to 10 MeV, whose impact will further be assessed in the framework of CADMO.

Conclusions

- Since 2018 our Department is strongly involved in the design and construction of DUNE and, in particular, of the Photon Detection System

- This choice was particularly fortunate because light detection is now the core of the R&D for DUNE Phase II and is grounded on technology advances that occurred just a few years ago, where Unimib leverages **strong industrial partnerships**:
  - VUV SiPMs (this talk)
  - Novel photosensitive materials (Glass-to-Power), optical devices (Zaot) and photosensors (Hamamatsu Italy, Fondazione Bruno Kessler)

- CADMO addresses a key item for establishing the Phase II of DUNE: the capability to perform high precision measurements of scattering at the MeV scale using a novel device that reap the partnership and expertise gained in the last five years

- The integrated anode we are developing records both scintillation light and ionization charge, enhancing the energy resolution of DUNE down to 7% and offering particle tracking down to a few MeV threshold.

- This feature is key to identify the low energy scattering of boosted dark matter in a broad class of models where particles are originated from the galaxy center because the signal as a unique signature, which is particularly well suited for DUNE: **an excess of monochromatic multi-MeV interactions of an invisible (neutrino-like) particle pointing toward the galaxy center.**