LArTPC's for MeV Physics

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"Mini-Workshop for MeV Gamma-ray Missions"

GRAMS Collaboration Meeting
Day 1 - June 20, 2022

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

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In this talk:

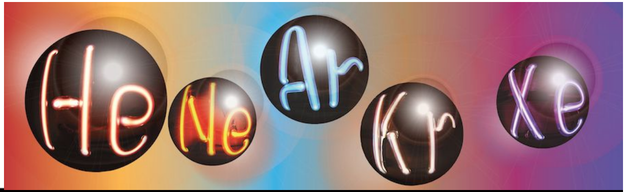
- (Single-phase) LArTPC technology
- Current applications
- Low-energy physics with LArTPCs

Liquid Argon Time Projection Chamber

Time Projection Chamber (TPC): chamber with E, B field, for particle tracking
Originally invented in late 1970's: David R. Nygren

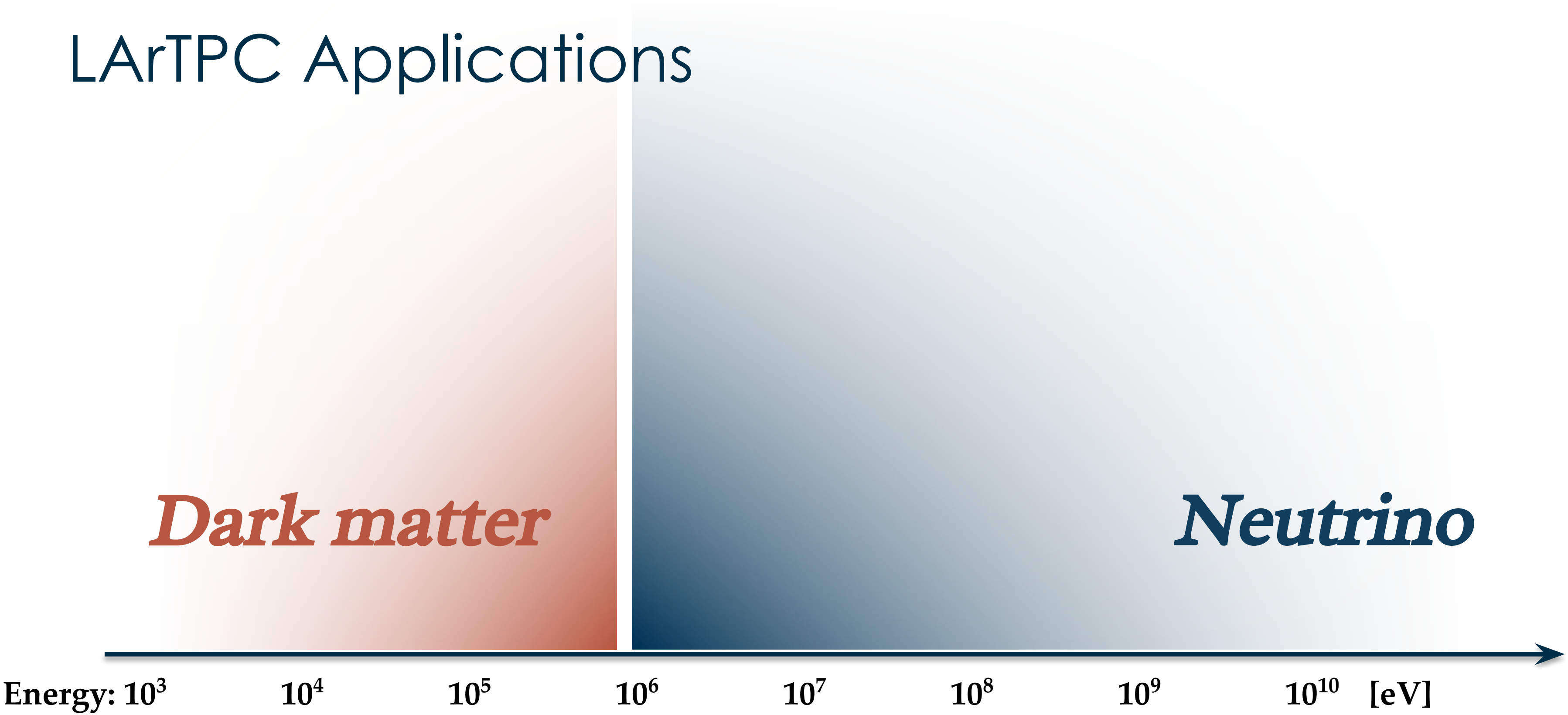
Liquid Argon TPC (LArTPC): cryogenic liquid argon as interaction and tracking medium
(xenon, krypton, and other noble liquids also possible)
LArTPC originally devised in 1977: Carlo Rubbia

Today, LArTPCs are in use extensively for
neutrino and direct
dark matter detection
experiments…



Boiling Point [K] @ 1atm	4.2	27.1	87.3	120	165
Density [g/cm³]	0.125	1.2	1.4	2.4	3
Radiation Length [cm]	755.2	24	14	4.9	2.8
dE/dx [MeV/cm]	0.24	1.4	2.1	3	3.8
Scintillation [γ/MeV]	19,000	30,000	40,000	25,000	42,000
Scintillation λ [nm]	80	78	128	150	175
Approx. Cost [$/kg]	52	330	5	330	1200

LArTPC Applications



LArTPC Applications

Dual-phase LArTPCs

Single-phase LArTPCs

Dark matter

Neutrino

Energy: 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} [eV]

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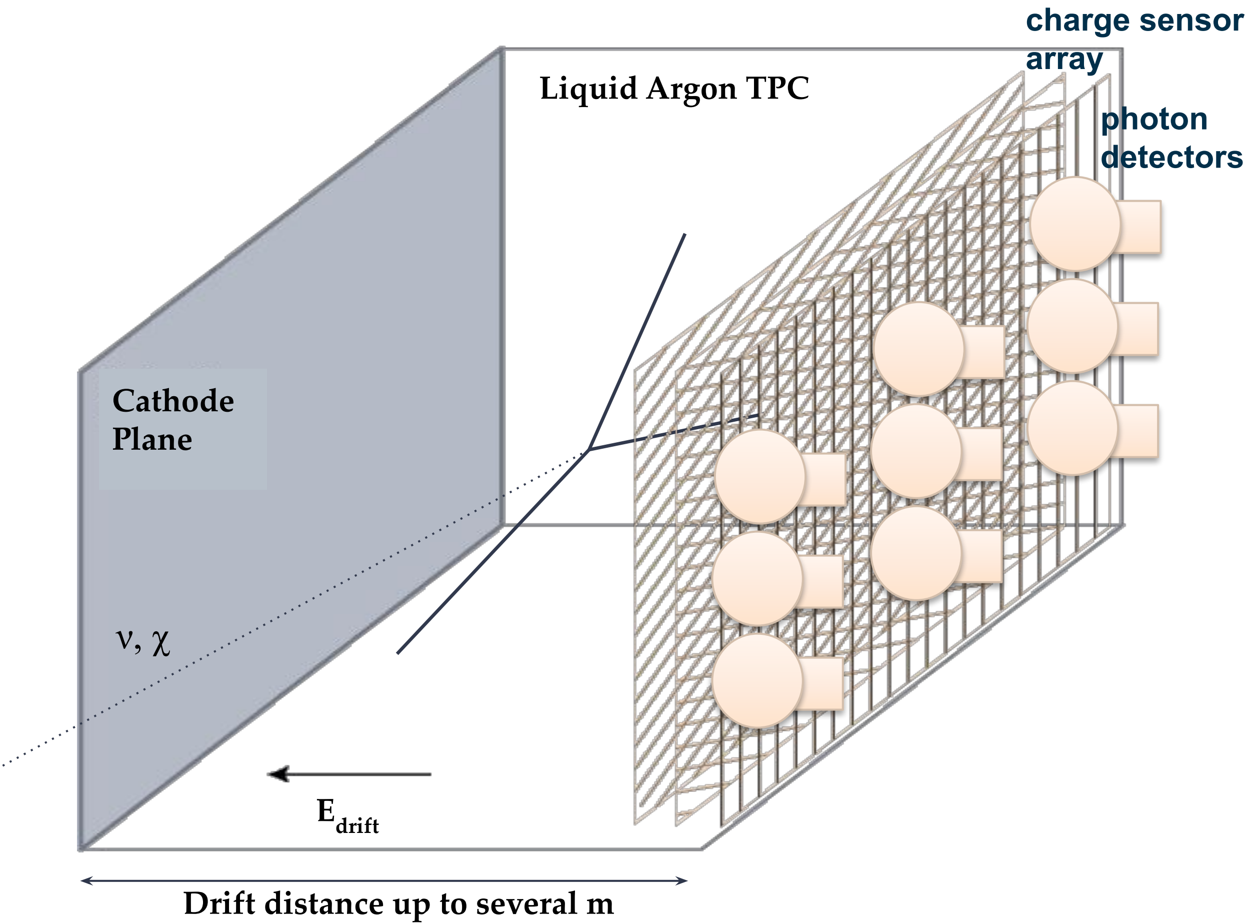
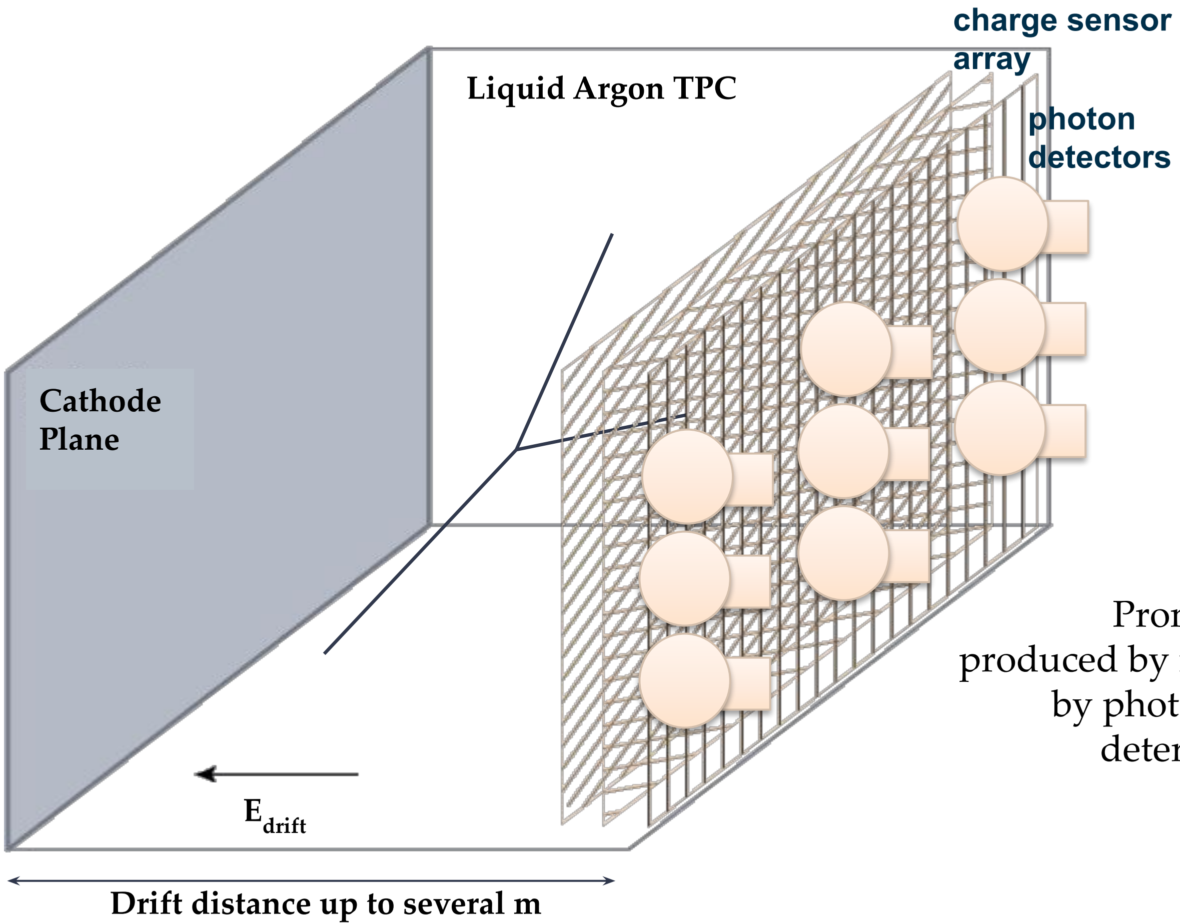
Single-phase LArTPC operating principle

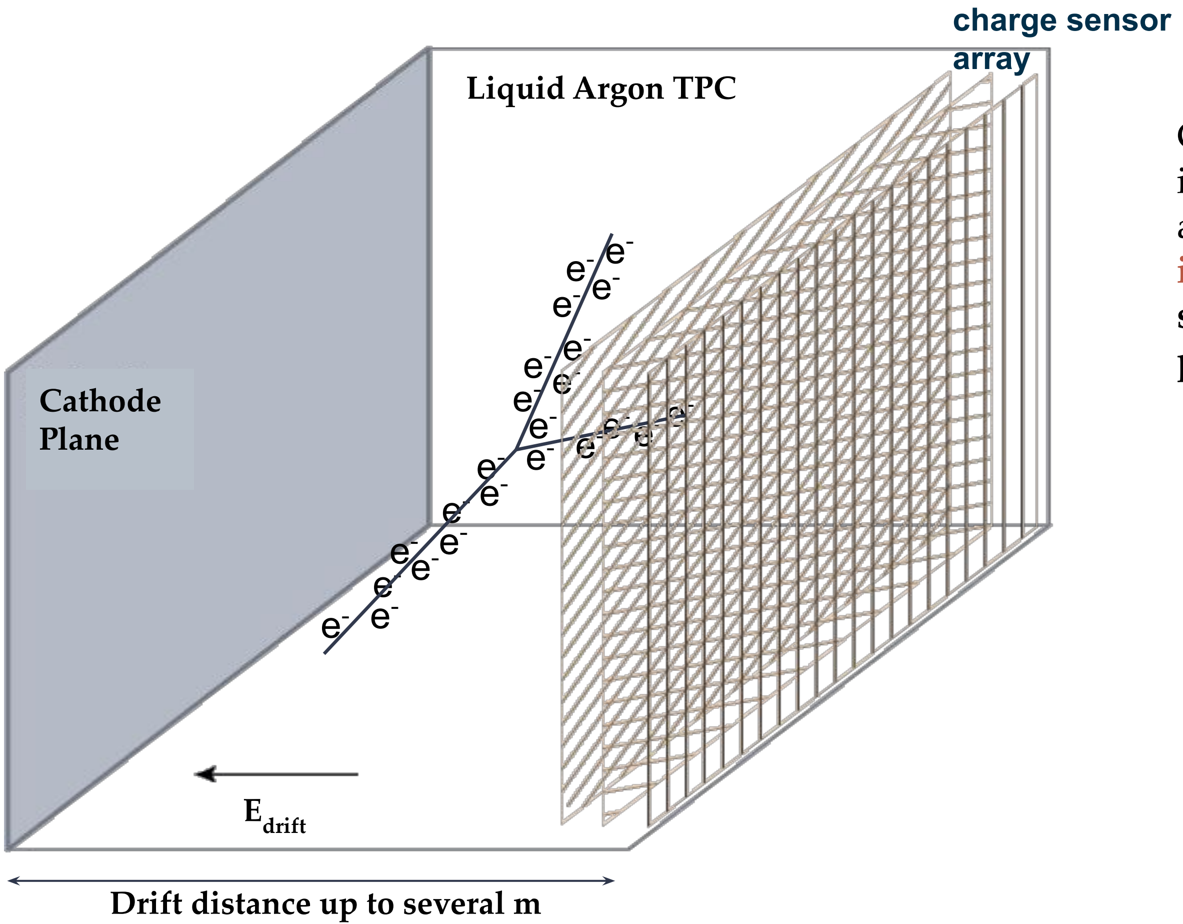


Single-phase LArTPC operating principle



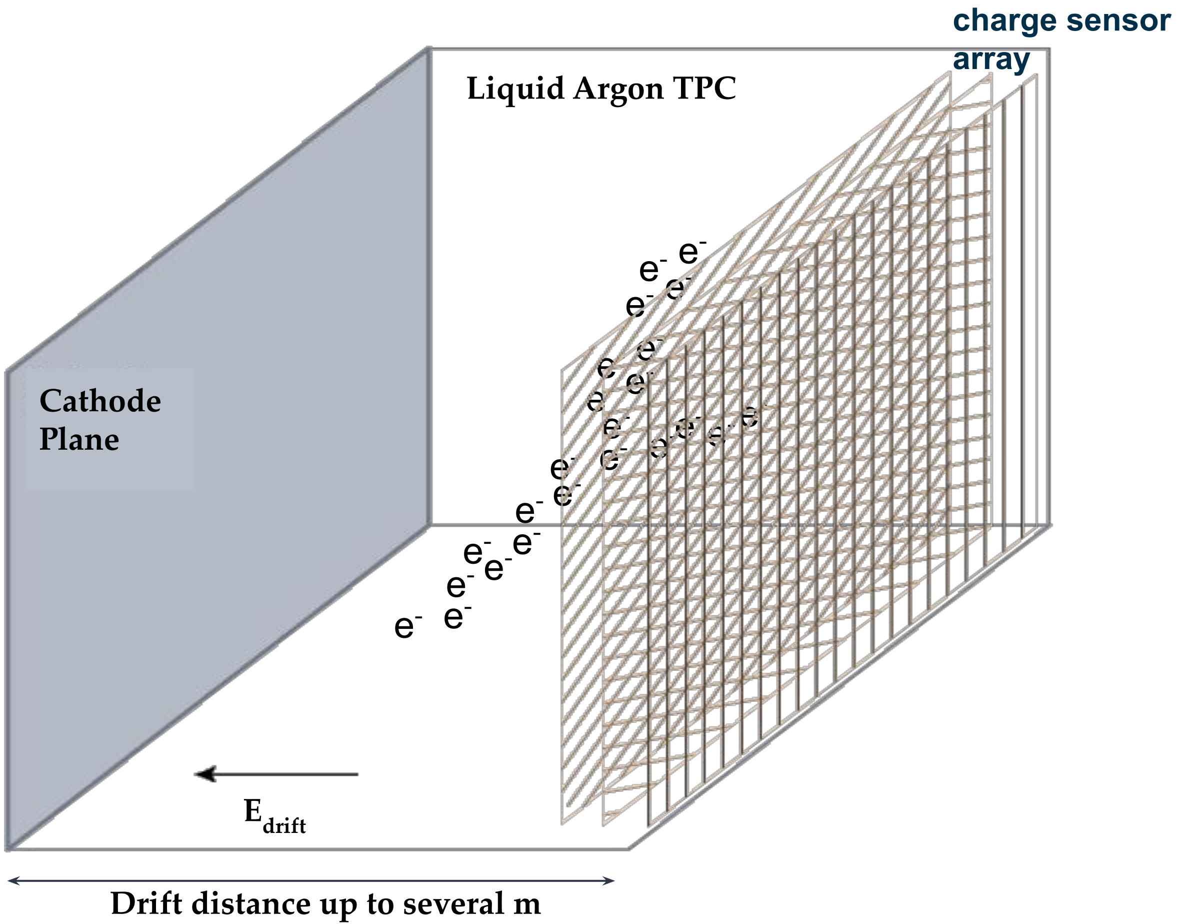
Prompt **scintillation light (~few ns)** produced by interaction products is detected by photo-sensitive detectors for **event t_0** determination (allows for triggering)

Single-phase LArTPC operating principle



Charged particle tracks produced in neutrino interaction ionize argon atoms; ionization charge drifts to **finely segmented charge collection planes** over up to ~few ms.

Single-phase LArTPC operating principle



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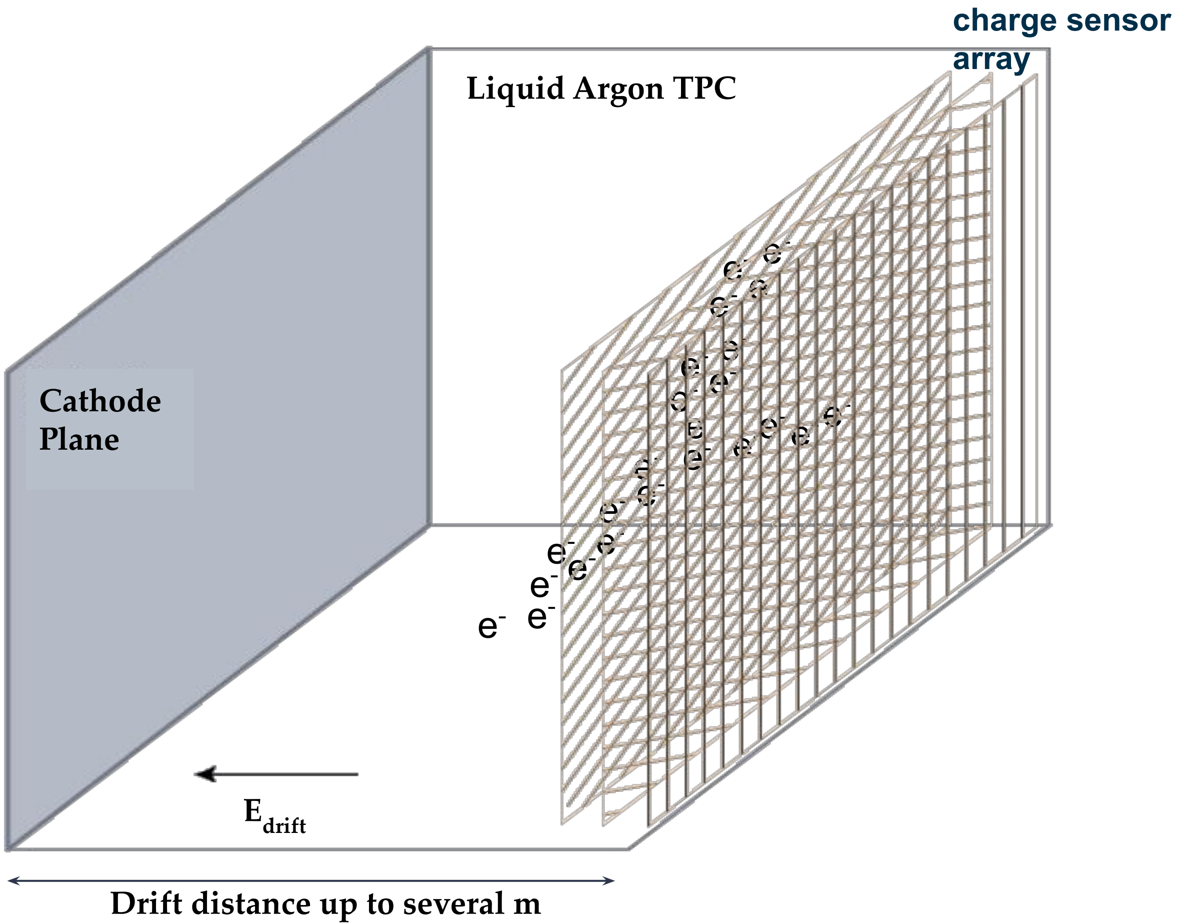

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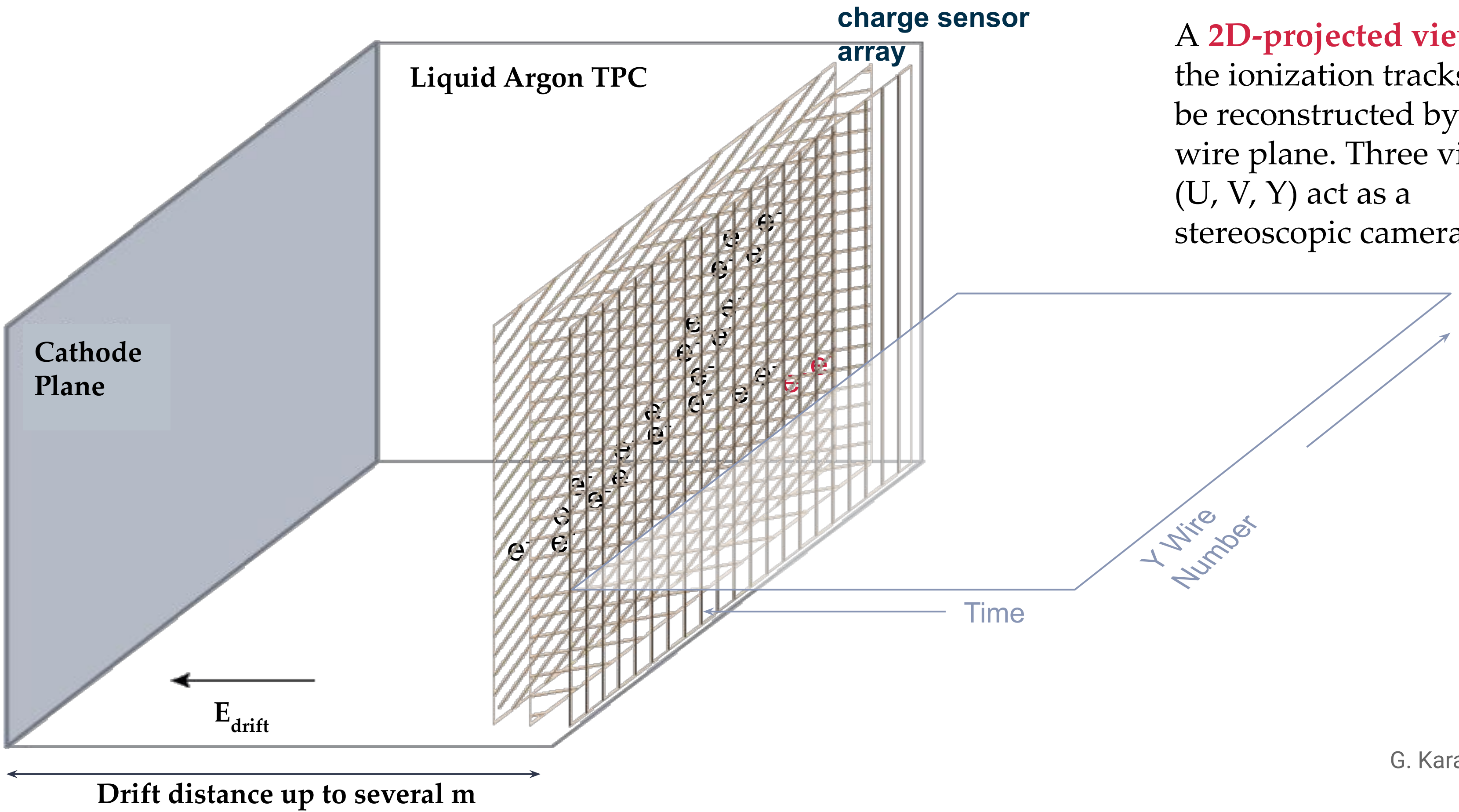
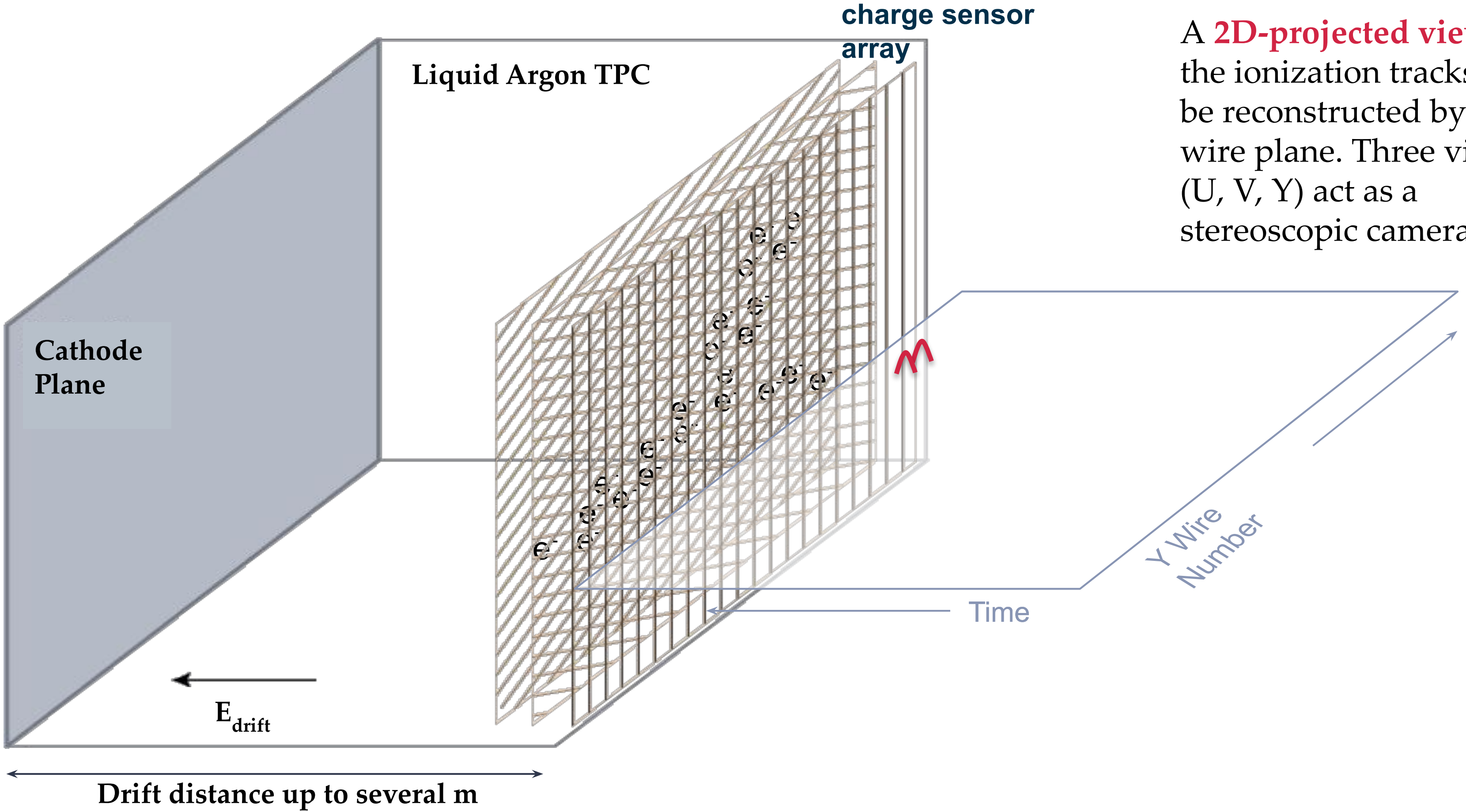


A **2D-projected view** of the ionization tracks can be reconstructed by each wire plane. Three views (U, V, Y) act as a stereoscopic camera.

Single-phase LArTPC operating principle



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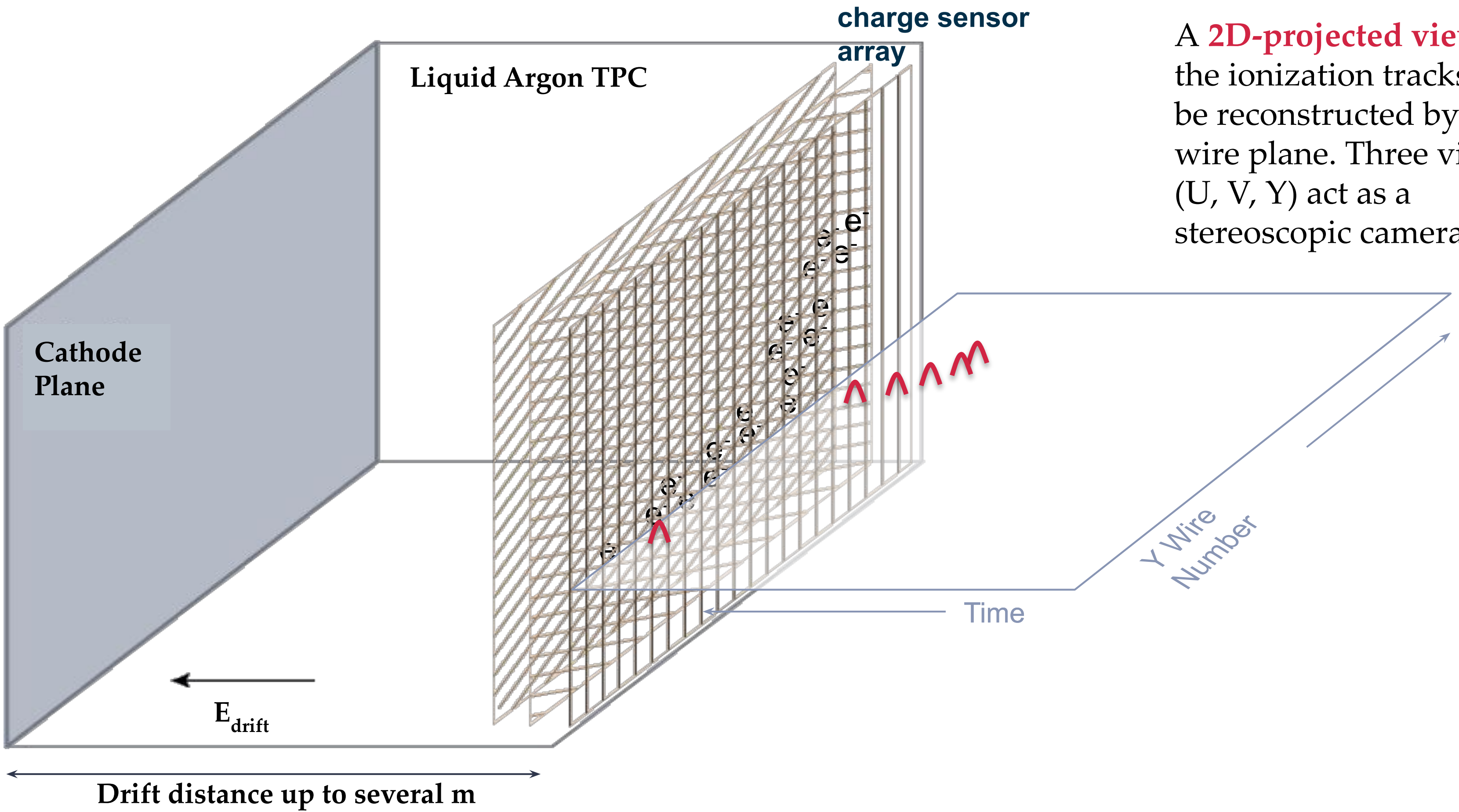

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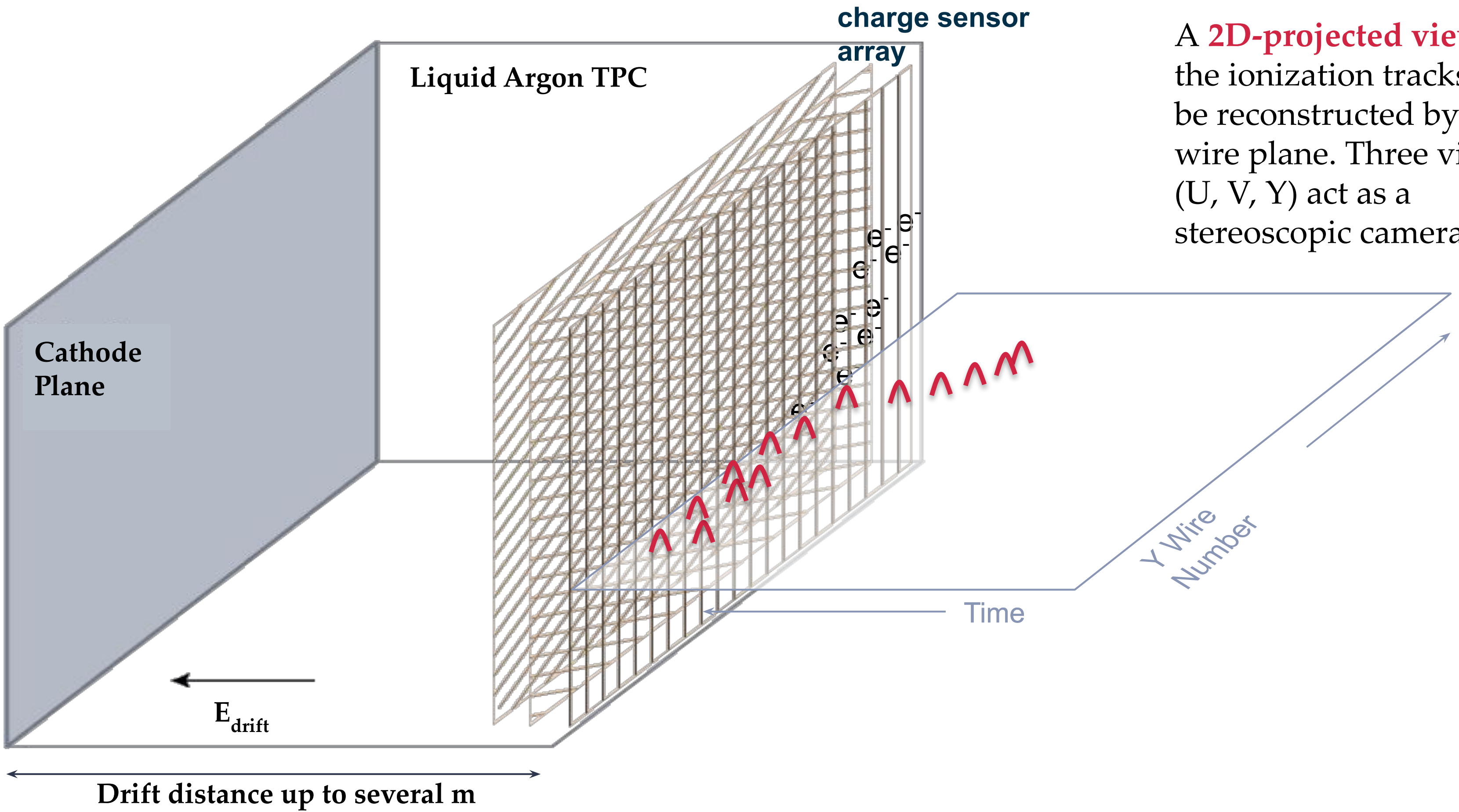

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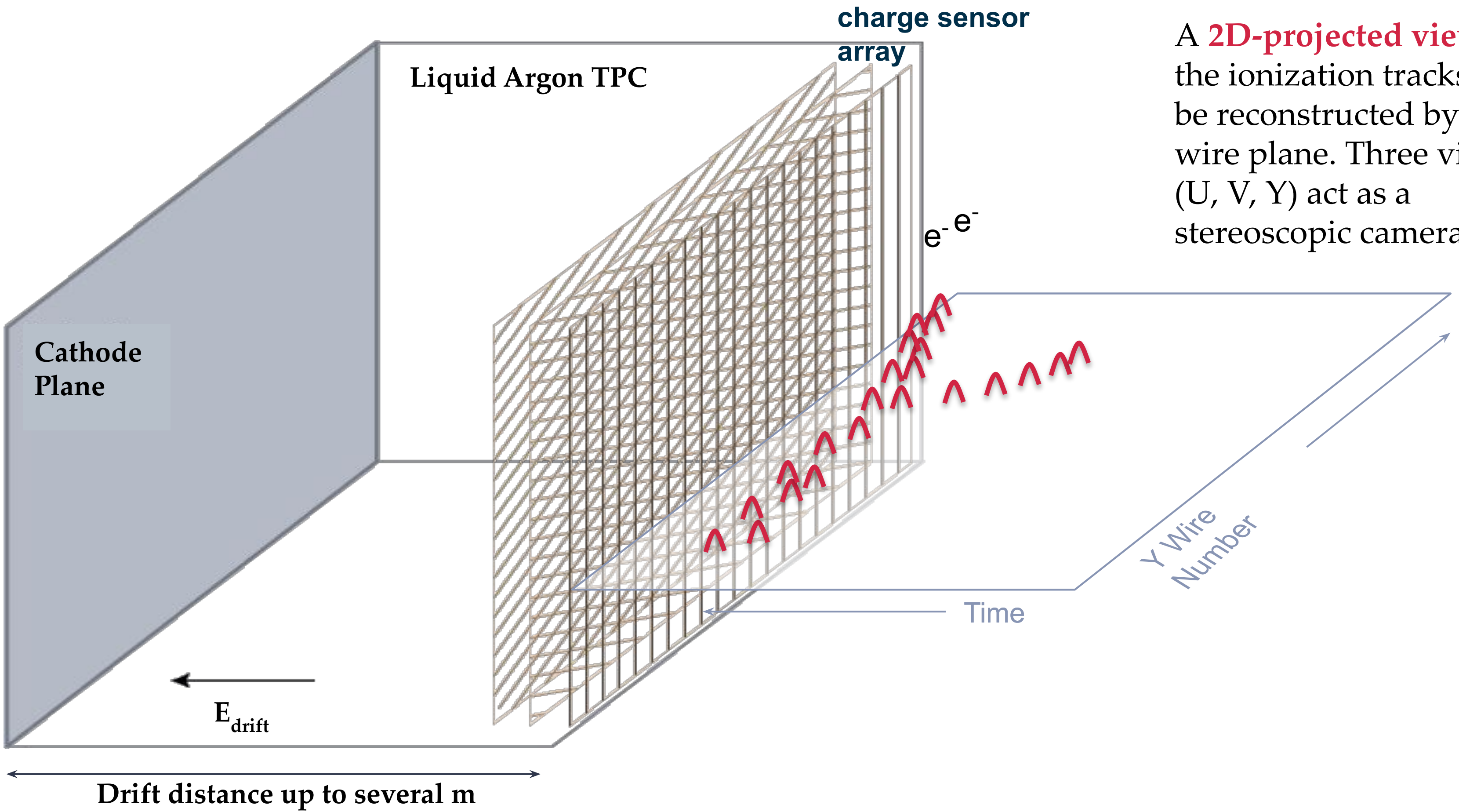
Single-phase LArTPC operating principle



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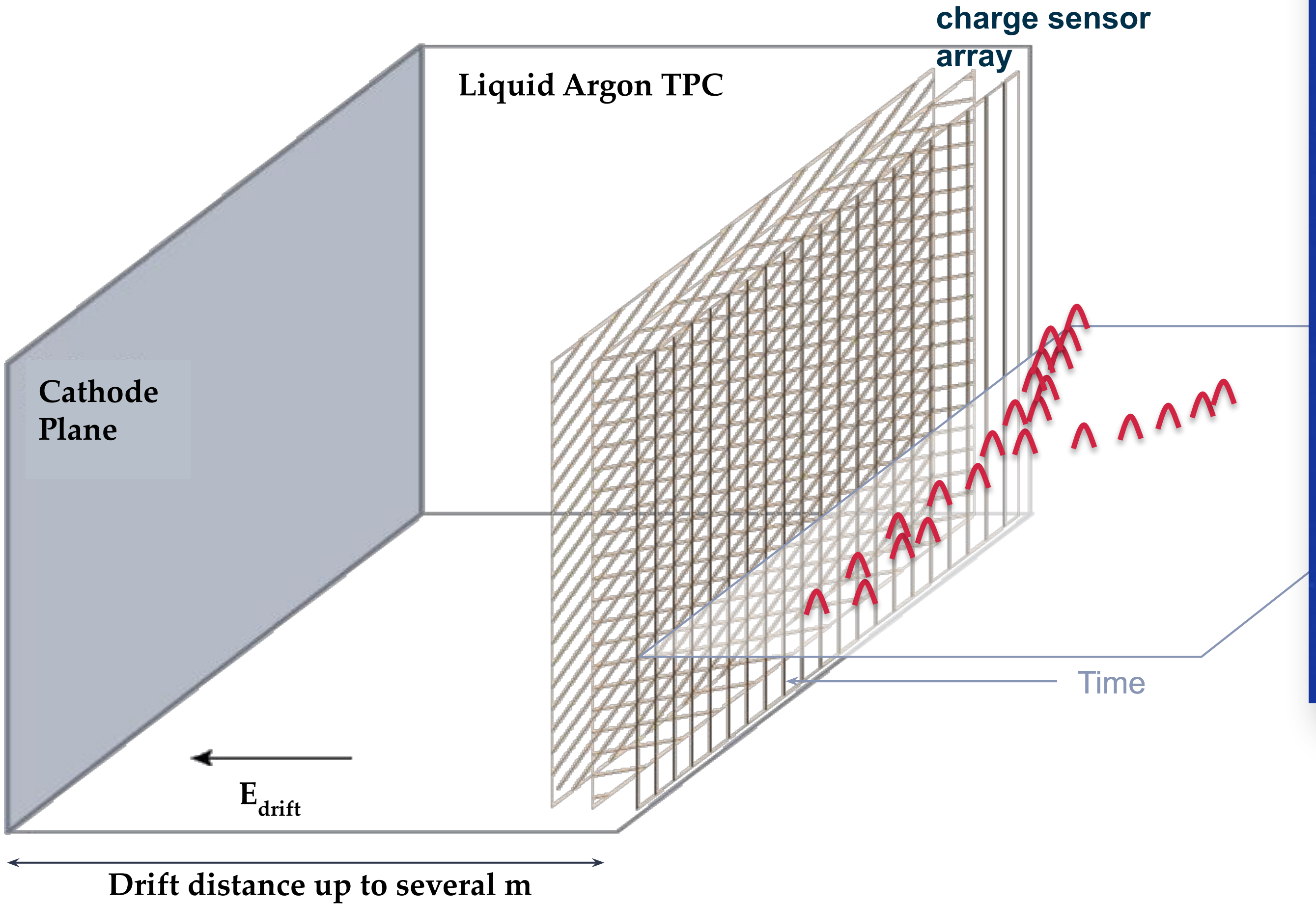

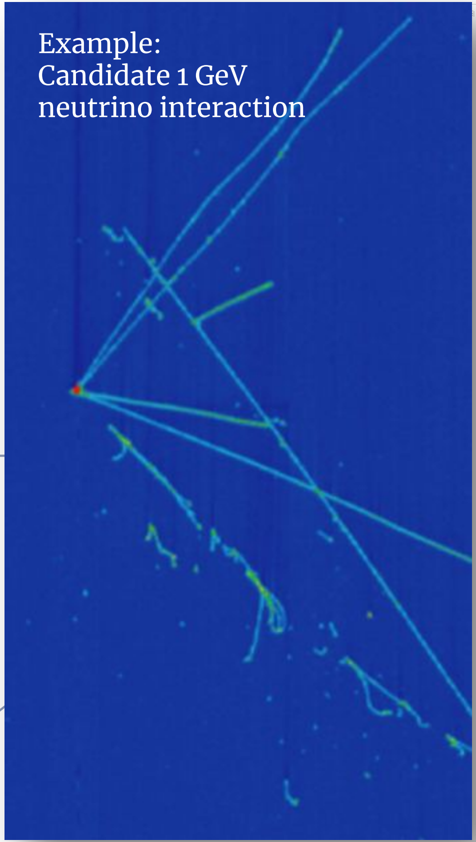

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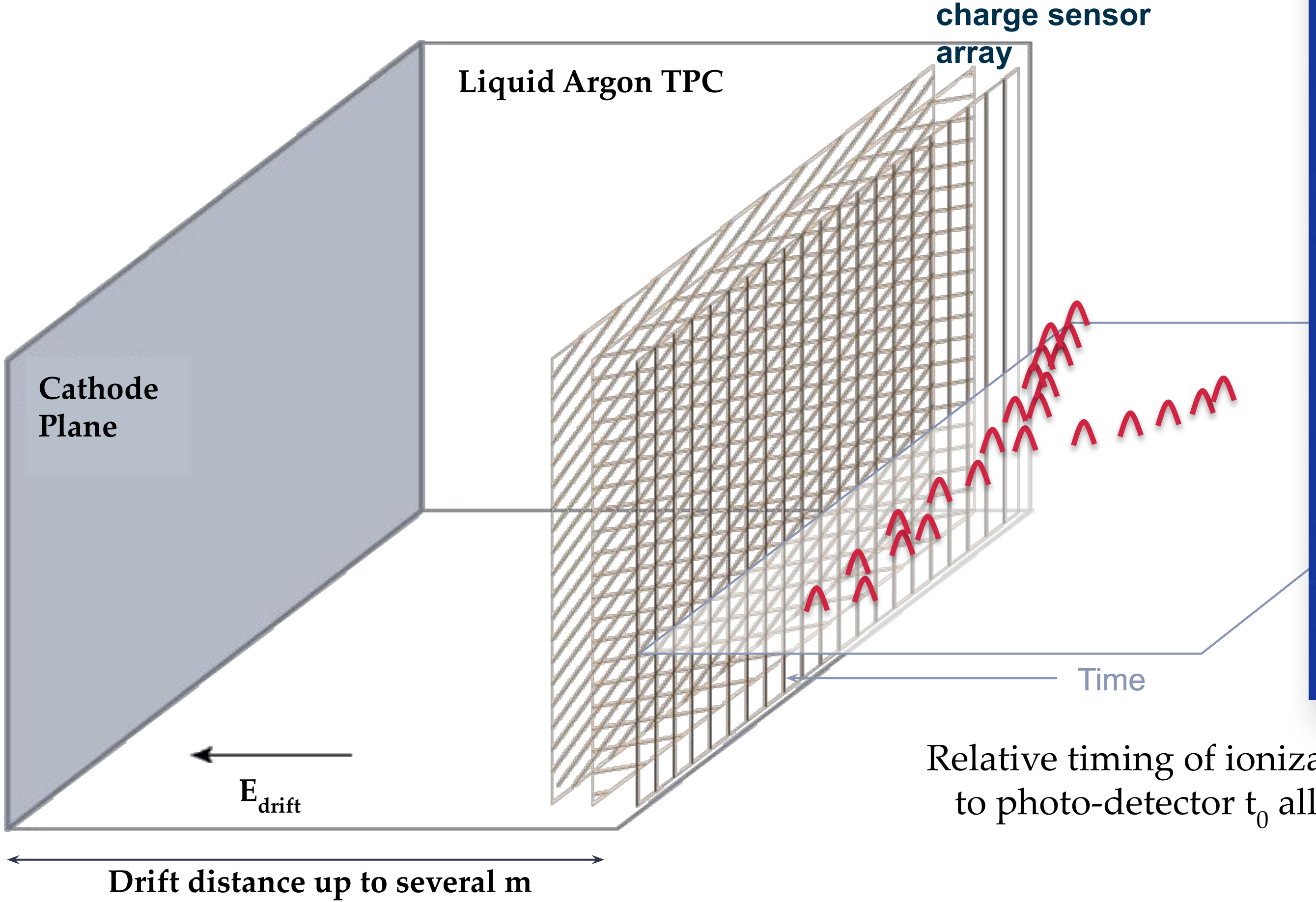
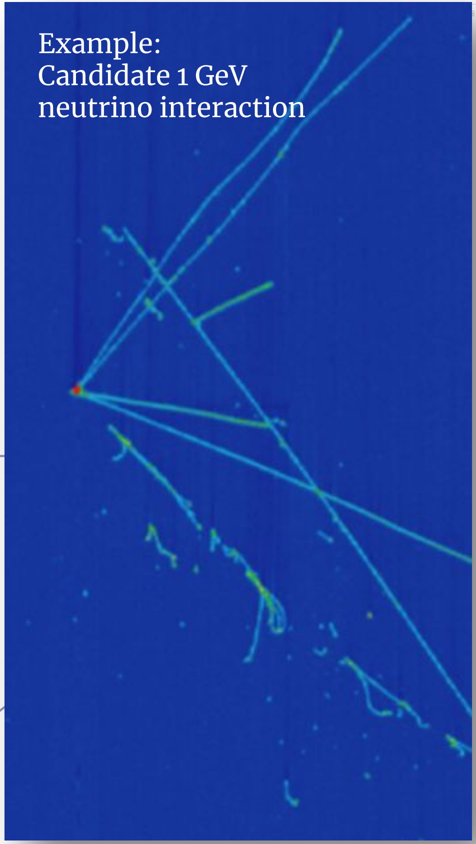
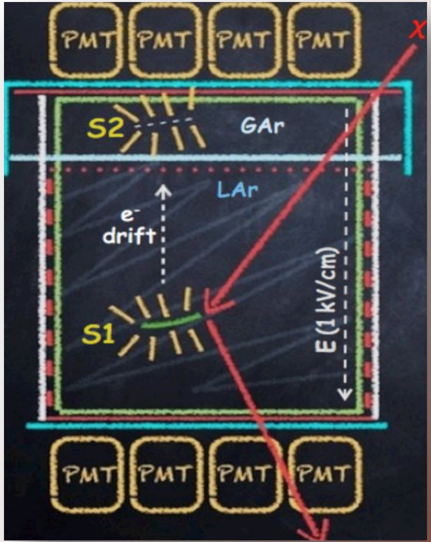




Relative timing of ionization signal with respect to photo-detector t_0 allows for drift coordinate determination.

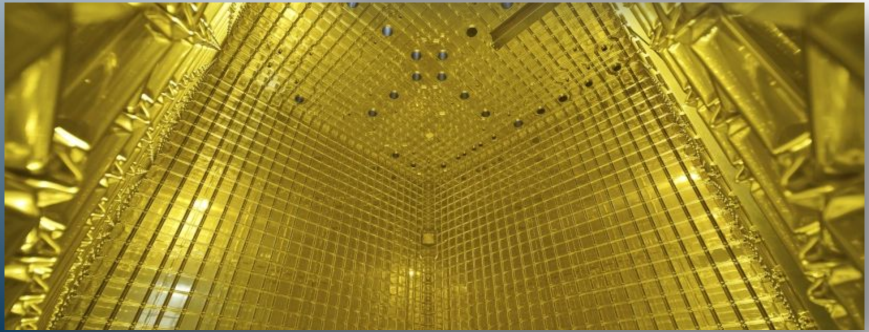
LArTPC Applications*

DarkSide



MicroBooNE

DUNE

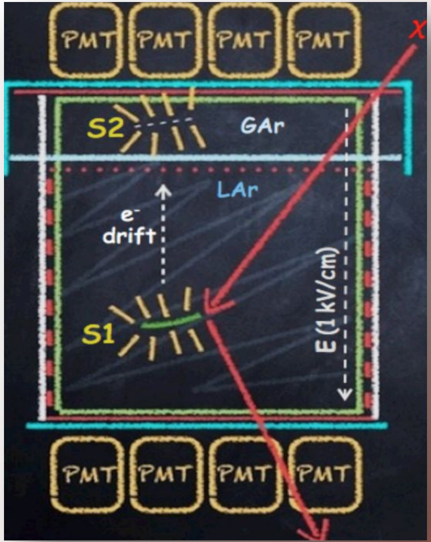


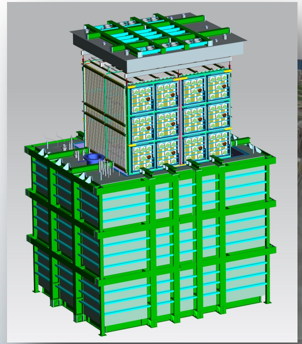
Energy: 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} [eV]

**selected examples*

LArTPC Applications*

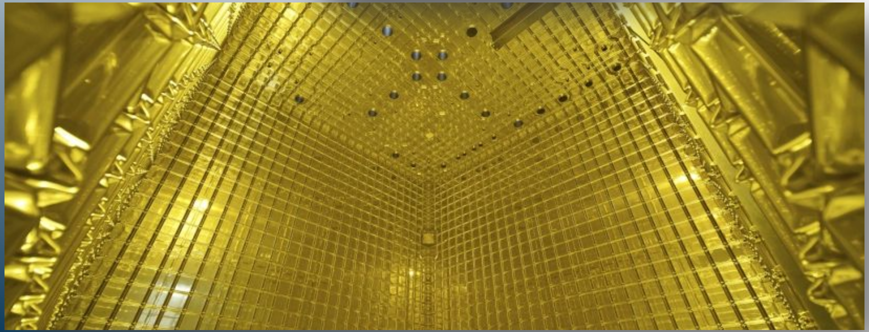
DarkSide





MicroBooNE,
SBND

DUNE



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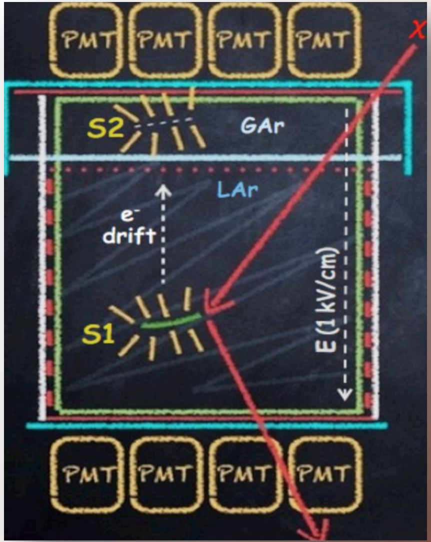
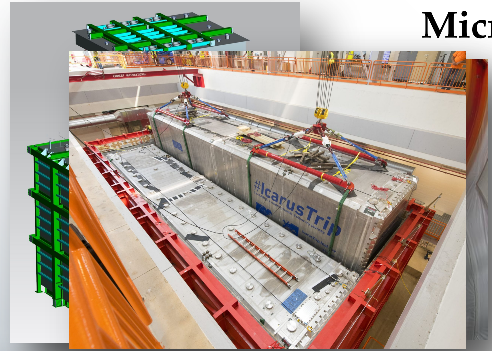
LArTPC Applications*

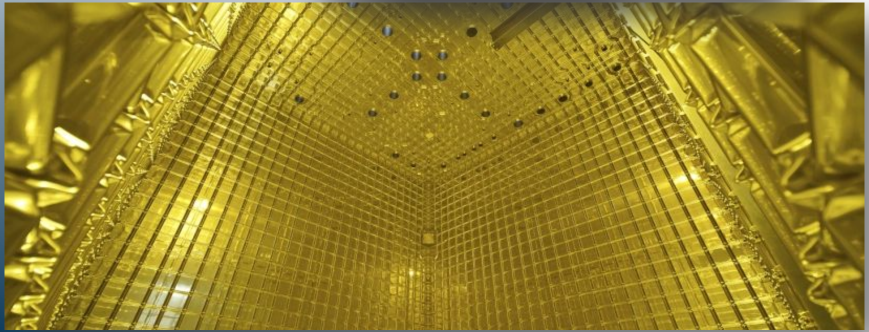
DarkSide



MicroBooNE,
SBND, ICARUS



DUNE



Energy: 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} [eV]

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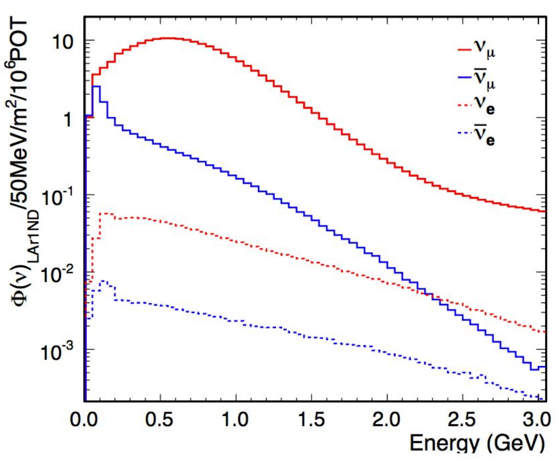
LArTPCs are widely used in neutrino physics:

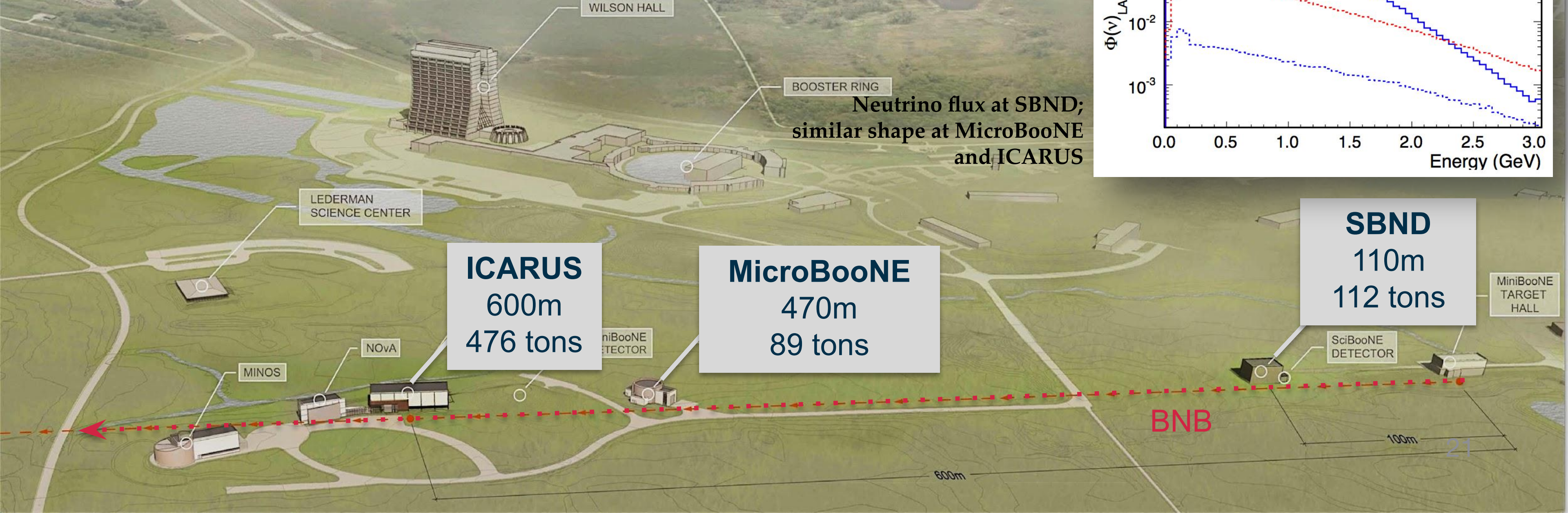
Short Baseline Neutrino (SBN) program at Fermilab, US

Three LArTPC detectors, accelerator-based neutrino beam: 0.1-3 GeV

- Short-baseline neutrino oscillations: $\nu_\mu \rightarrow \nu_e$
- High-statistics neutrino cross-section measurements



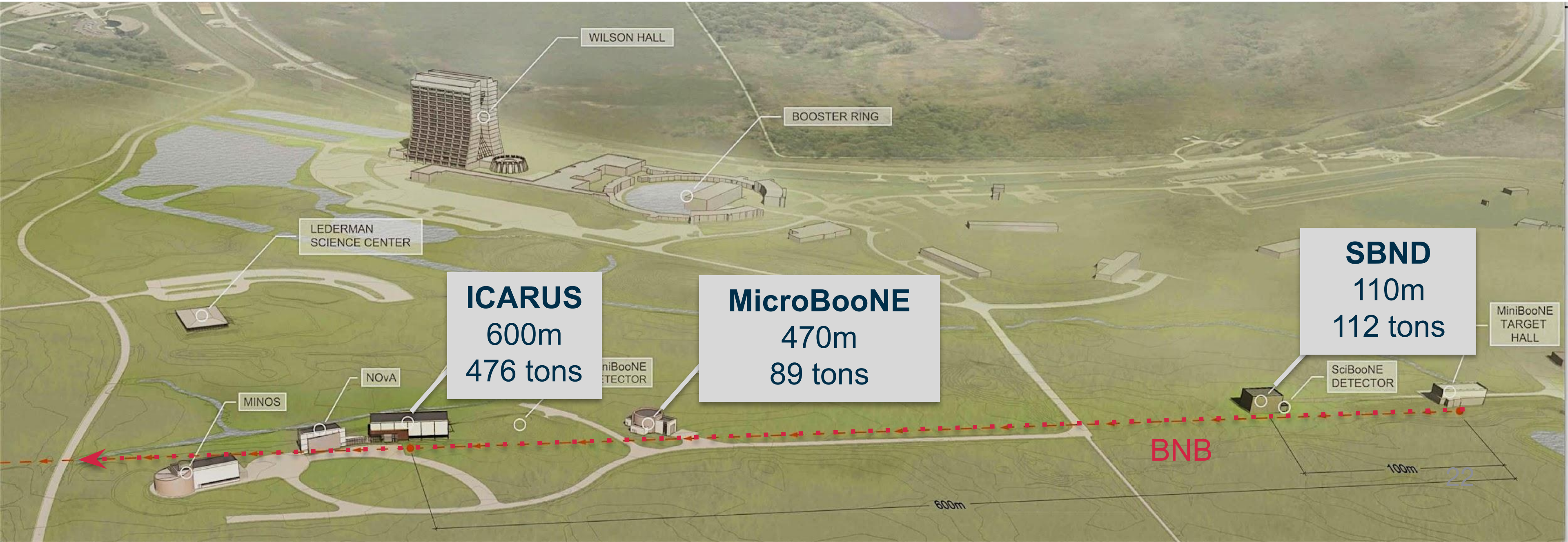
Neutrino flux at SBND; similar shape at MicroBooNE and ICARUS



LArTPCs are widely used in neutrino physics:

Short Baseline Neutrino (SBN) program at Fermilab, US

- MicroBooNE ran during 2015-2020
- ICARUS began operations in 2021
- SBND will begin operations in 2023



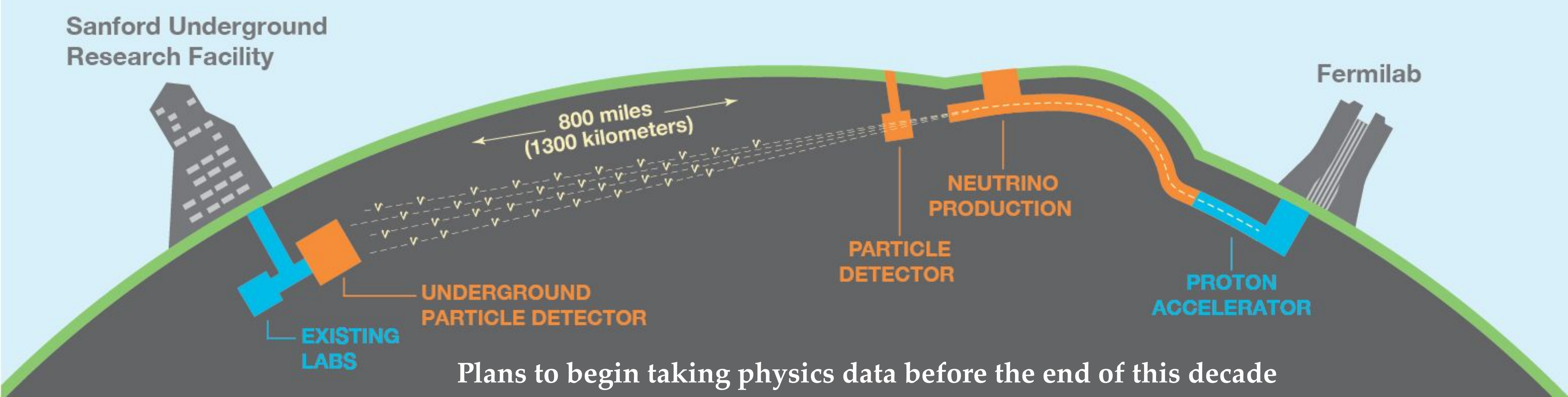
LArTPCs are widely used in neutrino physics:

Deep Underground Neutrino Experiment (DUNE), US

- High-intensity muon neutrino and antineutrino beams (E~1 GeV)
- Near detector at Fermilab: with liquid argon component, establishes event rate without oscillations
- Far detector at SURF: large 40kton LArTPC, 1.5km underground, measures event rate after oscillations

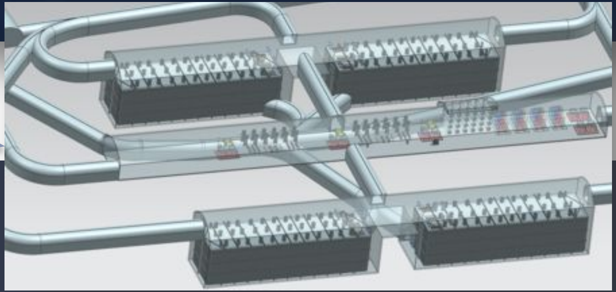
Primary physics goals:

- Three-neutrino oscillations: $\nu_\mu/\bar{\nu}_\mu \to \nu_\mu/\bar{\nu}_\mu$, and $\nu_\mu/\bar{\nu}_\mu \to \nu_e/\bar{\nu}_e$
- Ordering of neutrino masses, δ_{CP}



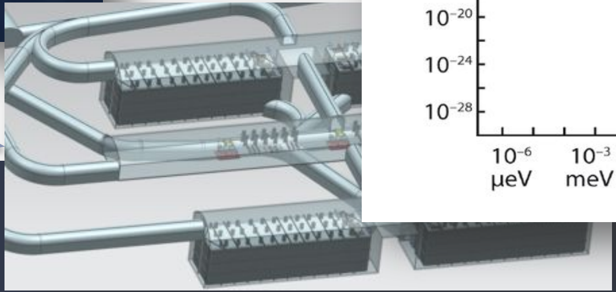
Plans to begin taking physics data before the end of this decade

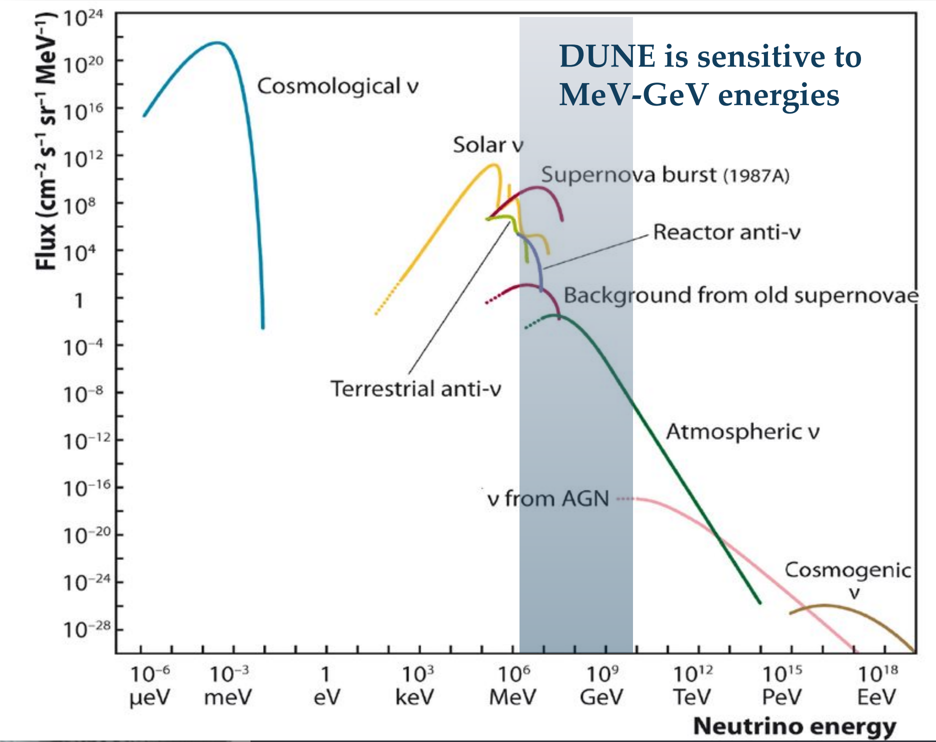
DUNE as a cosmic observatory



4x 10kton LArTPC modules
1 mile underground

Cosmic neutrino flux spectrum and DUNE





4x 10kton LArTPC modules
1 mile underground

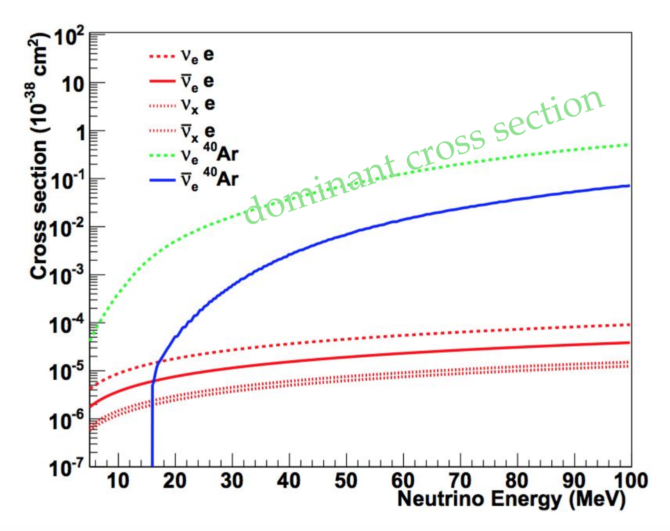
Solar/Supernova ν's in DUNE

Low energy signature: E_ν ~ few to tens of MeV, visible in the detector primarily through

$$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$$

short electron track

nearby de-excitation gammas, Compton scattering



In case of a **galactic supernova**, DUNE expects to observe up to thousands of neutrino interactions over the duration of the burst

Channel	Events "Livermore" model	Events "GKVM" model
$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$	2720	3350
$\bar{\nu}_e + {}^{40}\text{Ar} \rightarrow e^+ + {}^{40}\text{Cl}^*$	230	160
$\nu_x + e^- \rightarrow \nu_x + e^-$	350	260
Total	3300	3770

[DUNE TDR, assumes 10kpc]

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Solar/Supernova ν's in DUNE

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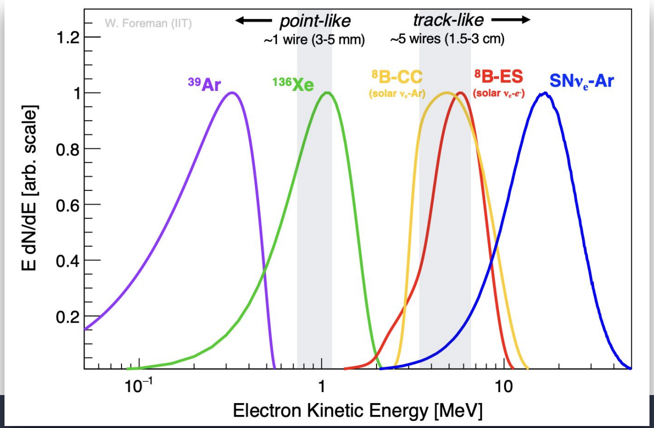

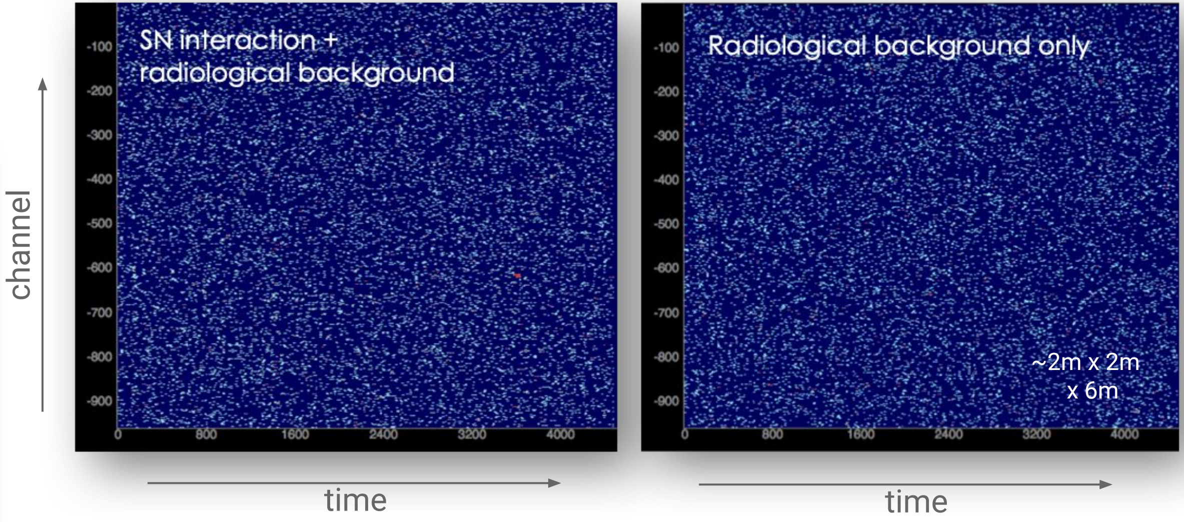

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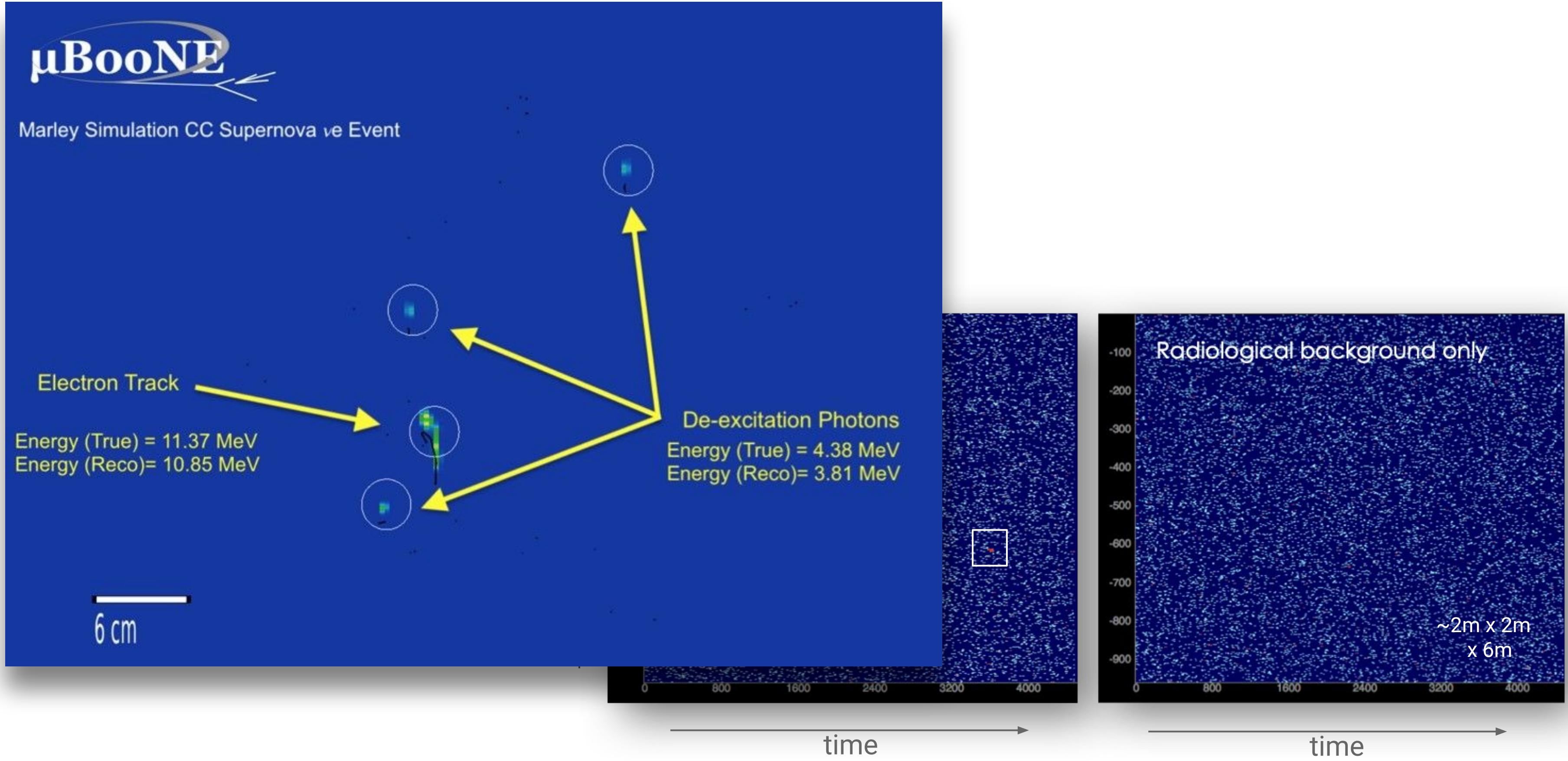
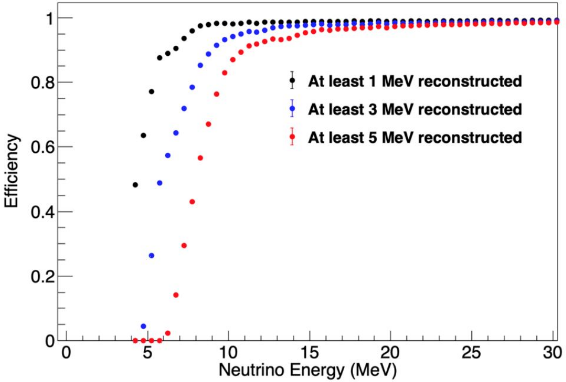
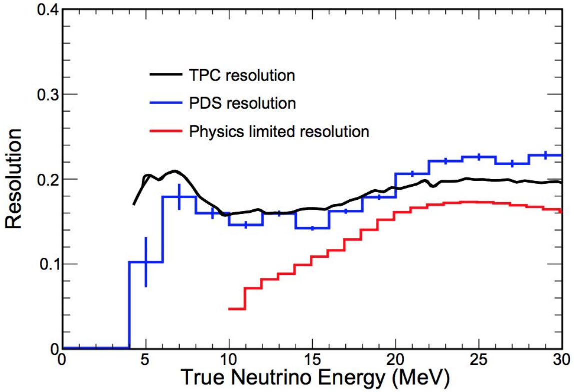
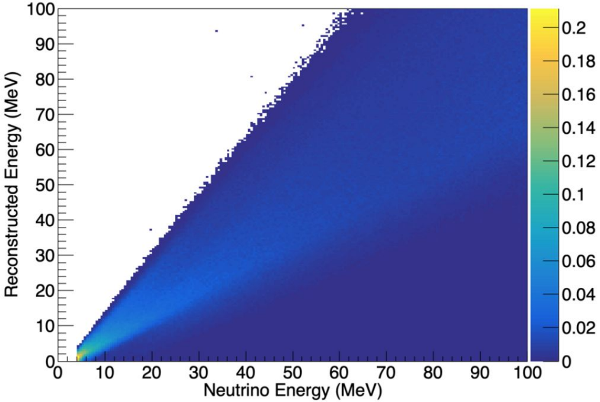

μBooNE
Marley Simulation CC Supernova νe Event
Electron Track
Energy (True) = 11.37 MeV
Energy (Reco)= 10.85 MeV
De-excitation Photons
Energy (True) = 4.38 MeV
Energy (Reco)= 3.81 MeV
6 cm
Radiological background only
~2m x 2m
x 6m
-100
-200
-300
-400
-500
-600
-700
-800
-900
0
800
1600
2400
3200
4000
time
time

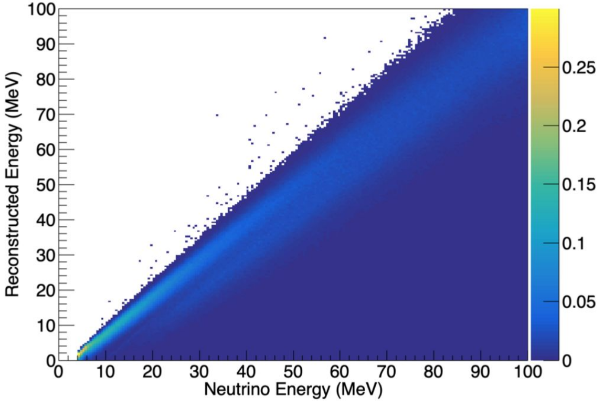
Solar/Supernova ν's in DUNE





Efficient reconstruction at energies below a few MeV becomes increasingly more challenging;
~15-20% energy resolution



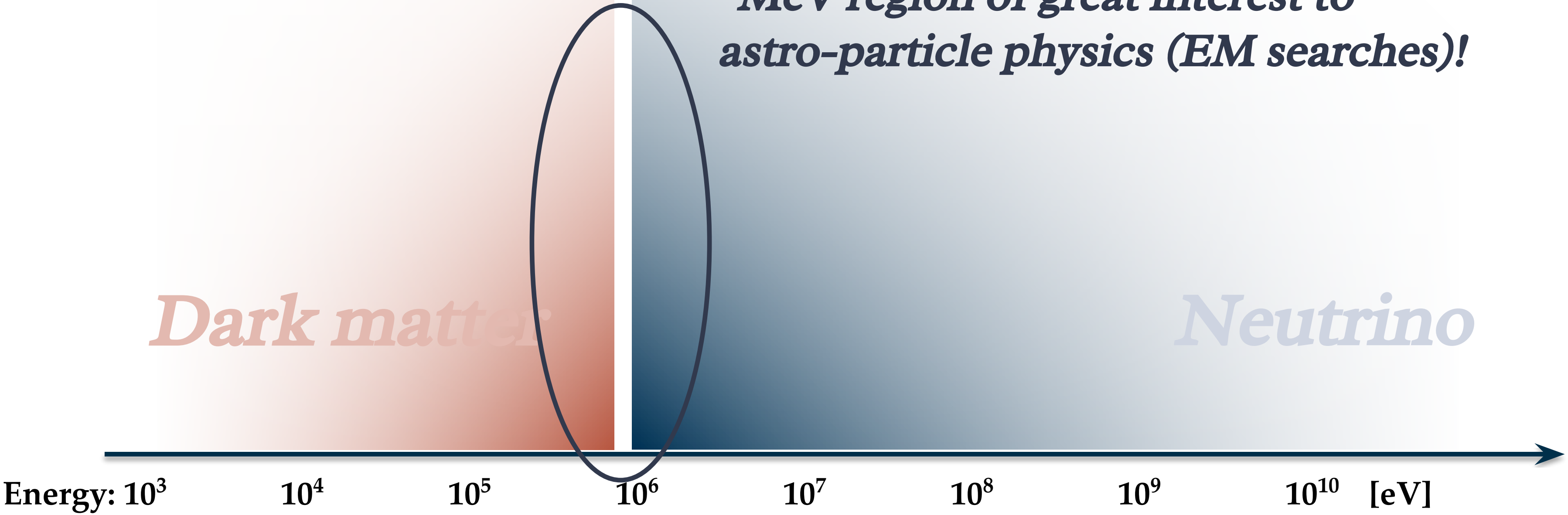


Improvements in energy resolution with inclusion of light-based drift correction

[DUNE TDR]

LArTPC Applications: MeV range?

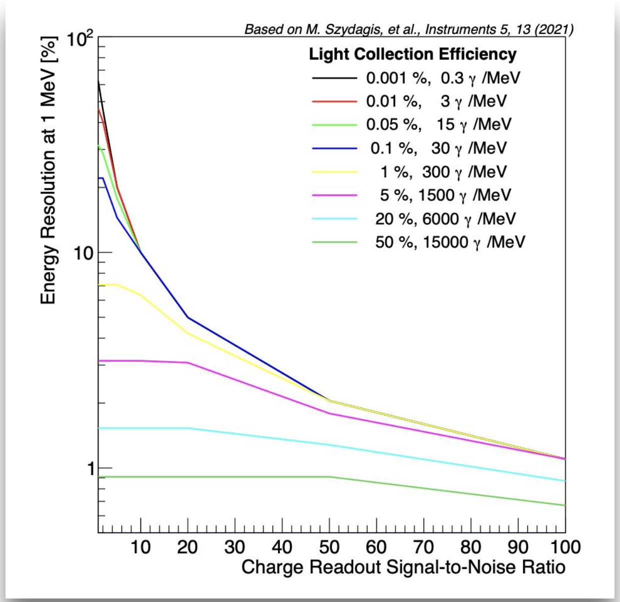
~MeV region of great interest to astro-particle physics (EM searches)!



Significant interest in community to extend low-energy reach of single-phase LArTPCs!

Novel ideas for future LArTPC technology that enhance low-energy capabilities are being explored, including:

- novel charge enhancement and readout systems
- enhanced photon detection
- xenon doping
- low-radioactivity argon (important for large detectors)



Low-Energy Physics in Neutrino LArTPCs

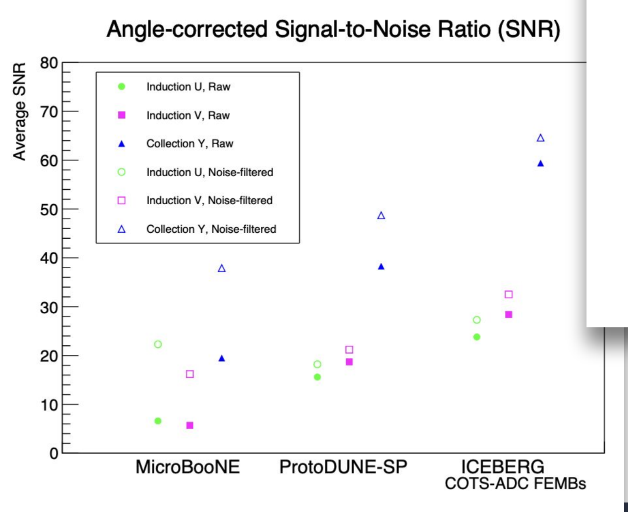
arXiv:2203.00740

Contributed Paper to Snowmass 2021

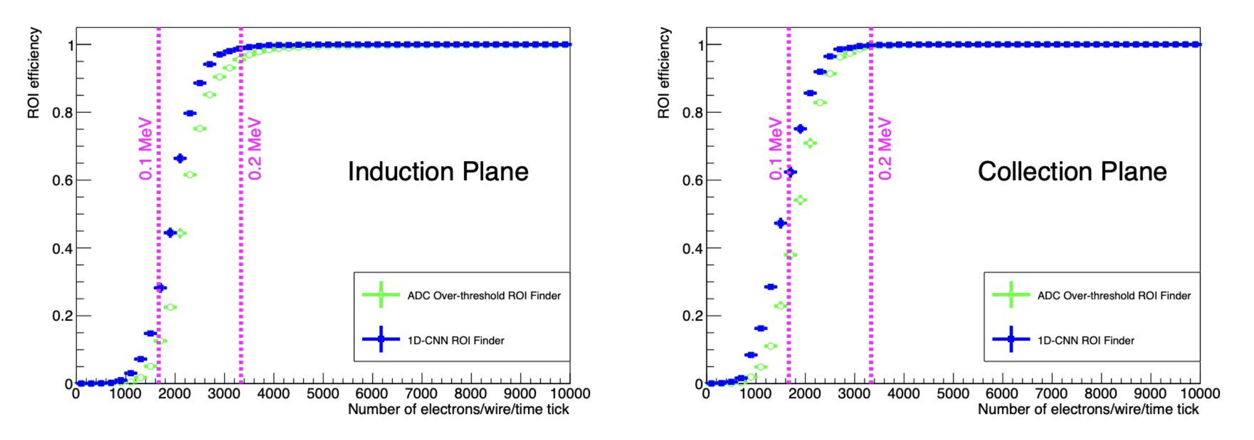
D. Caratelli,[17,*] W. Foreman,[44,*] A. Friedland,[99,*] S. Gardiner,[33,*] I. Gil-Botella,[21,*] G. Karagiorgi,[26,*] M. Kirby,[33,*] G. Lehmann Miotto,[20,*] B. R. Littlejohn,[44,*] M. Mooney,[27,*] J. Reichenbacher,[100,*] A. Sousa,[23,*] K. Scholberg,[29,*] J. Yu,[108,*] T. Yang,[33,*]

Advancements in signal processing and reconstruction

SNR for digitization in warm vs. cold



Improved hit finding using machine learning

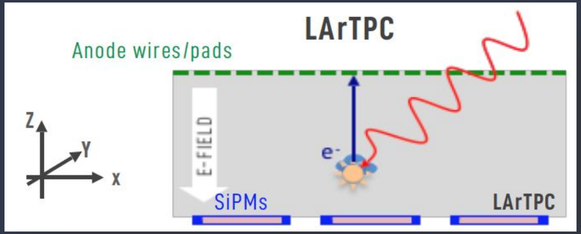


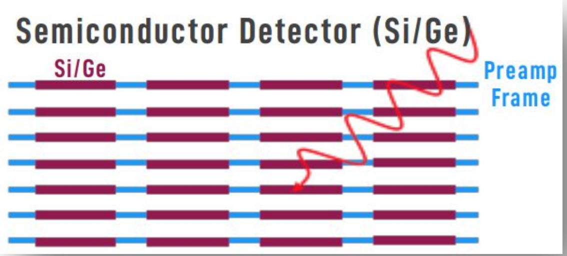
(a) Induction Plane.

(b) Collection Plane.

Technology parameters

LArTPC		Silicon detector
1.4	ρ (g/cm3)	2.3/5.3
~80K	$T_{operation}$	~240K/~80K
$	cost	$$$
scintillation light + ionization electrons	Signal	electrons, holes
wires/pixels on anode plane	X, Y positions	(X-Y) double-sided strips
from drift time	Z position	from layer #
1 layer	# of layers	# of Layers 1 layer multi-layers
#	# of electronics ch.	###
almost no dead volume	dead volume	detector frame, preamps
identified with pulse shape	neutron bkgd	no rejection capability





Summary

The single-phase LArTPC is a mature detector technology, extensively used in accelerator-based neutrino experiments.

The community recognizes the **opportunity for applications to astro-particle physics**, which can be extended to target the “MeV gap” region.

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Thank you!
Q&A.

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