# The 2x2 Demonstrator

## Demonstration of a modular liquid argon detector for the DUNE Near Detector

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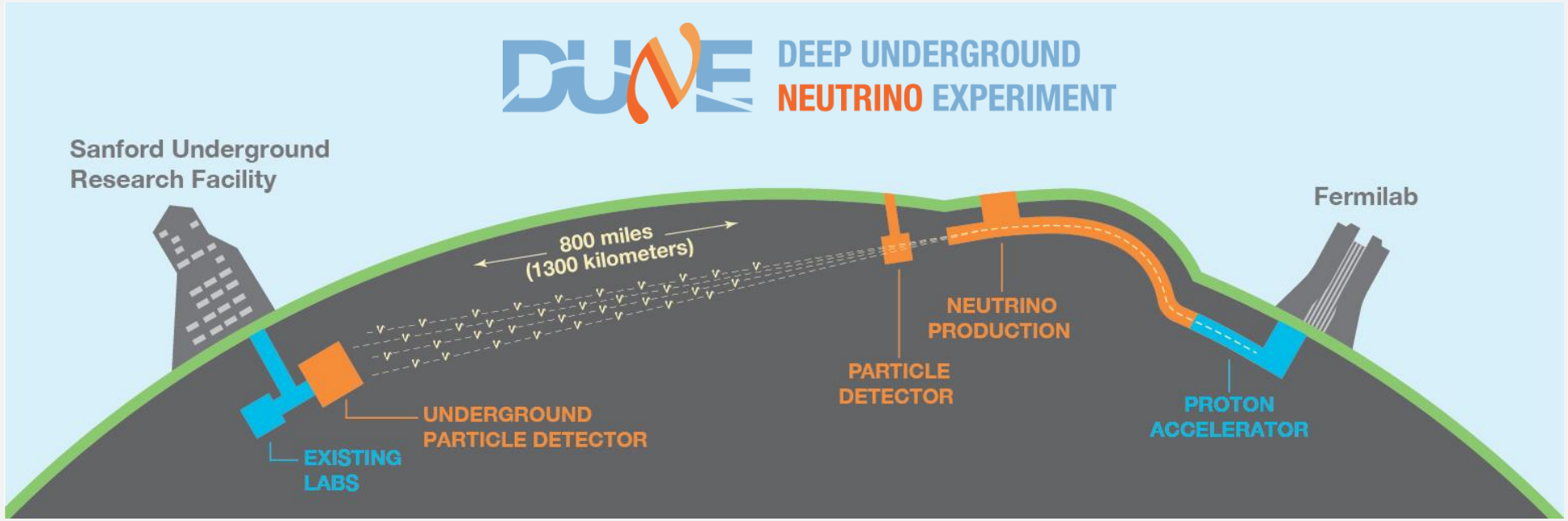
University of Bern

on behalf of the DUNE collaboration

IPRD 2023, 27.09.2023

# Deep Underground Neutrino Experiment (DUNE)




**Long baseline oscillation experiment (1285 km)**

- Measure unoscillated $\nu$ beam at near detector (ND)
- Measure oscillated $\nu$ beam at far detector (FD)

**Main goals**

- Explore CP violation in the leptonic sector
- Resolve the hierarchy of $\nu$ mass eigenstates
- Non-beam physics (e.g. supernova $\nu$)

**How to improve uncertainties?**

- Unprecedented intensity $\nu_\mu$ ($\bar{\nu}_\mu$) beam: 2.4 MW
- High detector mass: 4x10kt FD, 67t ND
- Reduce systematic errors with advanced near detector

# Near Detector Complex

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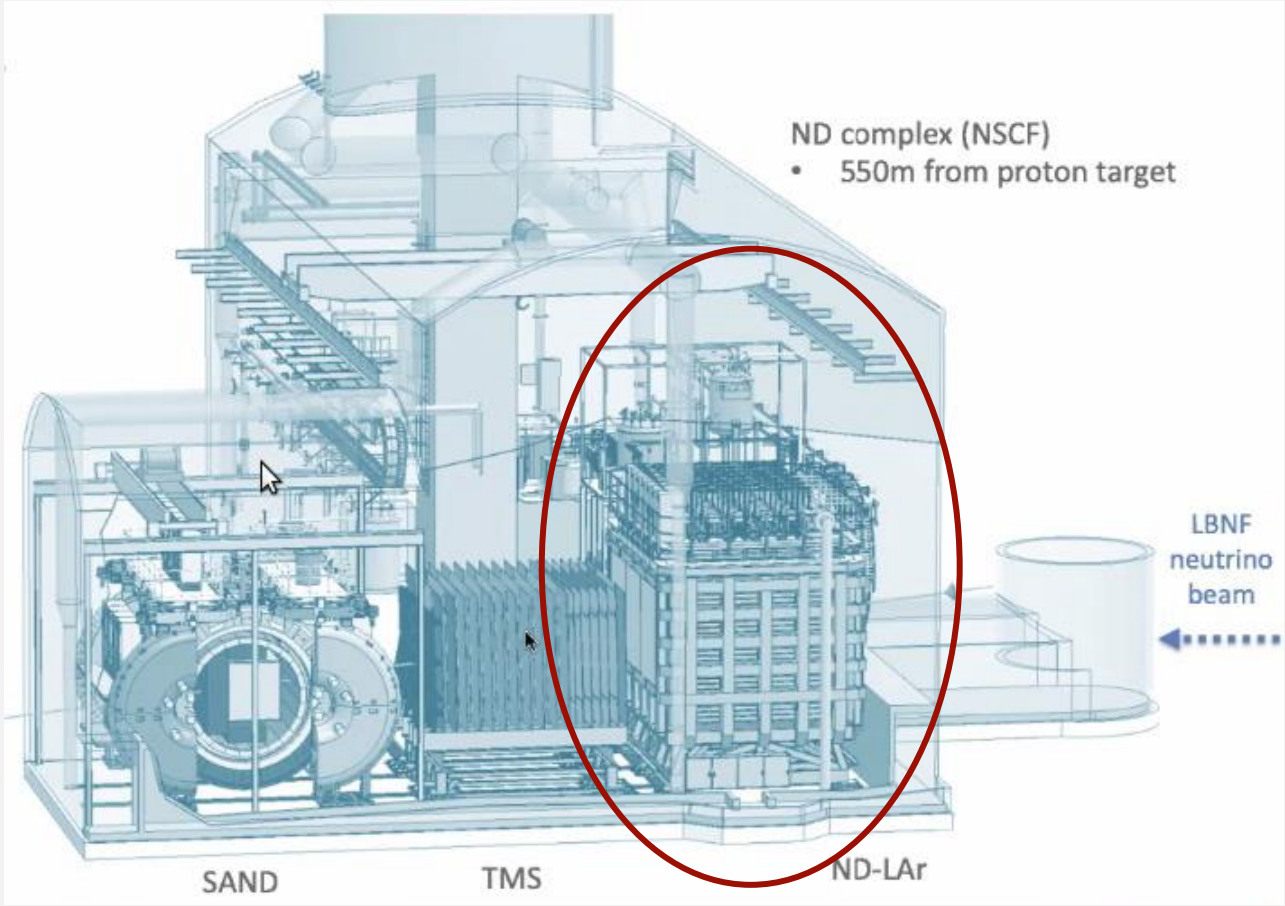
- Precise measurements of neutrino flux and cross-section are essential for oscillation analysis.
- ND complex:
  - Liquid Argon Time Projection Chamber (ND-LAr)
  - Muon spectrometer (TMS / ND-GAr)
  - Flux monitoring system (SAND)
- ND-LAr:
  - Reducing uncertainties via consistent target choice with the far detector
  - Rich stand-alone physics program



# Liquid Argon Near Detector (ND-LAr)

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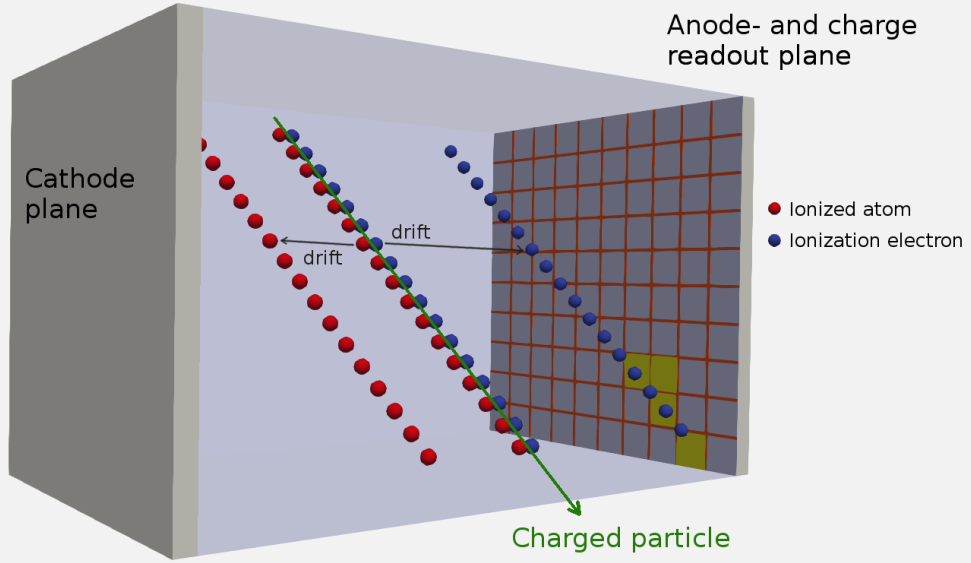
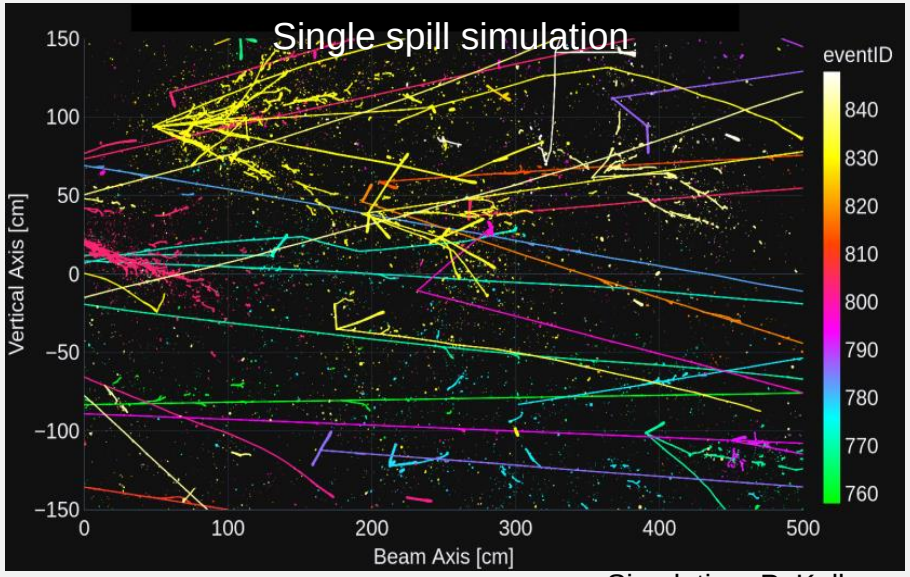
- Detector size optimised for contained hadronic activity: 7 x 5 x 3 $m^3$
- Operation in high-rate environment: ~50 $\nu$ beam related interactions per Spill (1.2 MW beam)
- For Monolithic Design:
  - Drift time at 0.5 kV/cm: >4 ms for 7m
  - Spill duration O(us)
  - Prompt light signals at O(ns) needed for track/vertex matching
  - Resolution of light signals limited by Rayleigh scattering and slow scintillation light

⇒ **Optical Segmentation with modularised design!**




Simulation: P. Koller

# ND-LAr: ArgonCube Concept

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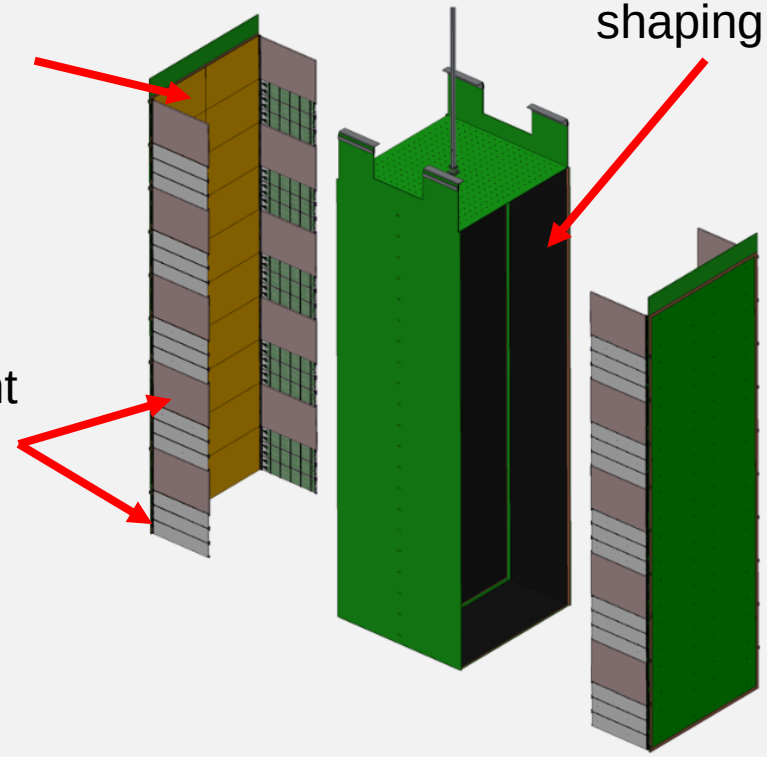
- ND-Lar: 5 x 7 modules (1m x 1m x 3m)
- One module : Two TPCs (70 TPCs!)
- **TPCs optically isolated**

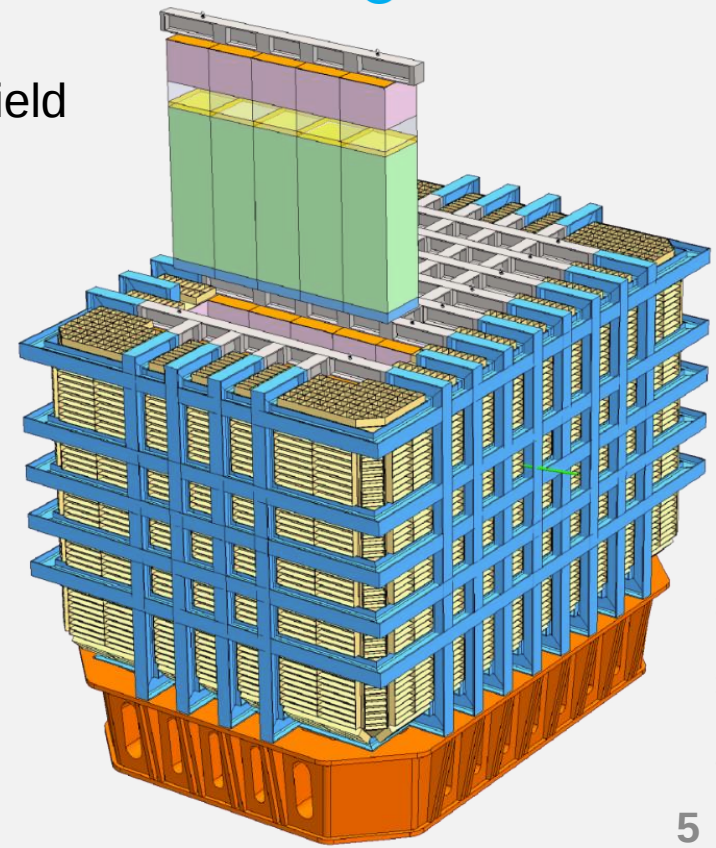
ArgonCube

**Pixelated** charge readout with cold amplification and digitisation – LArPix

**Large area - dielectric** VUV light detection with SiPM readout – ArCLight + LCM

**Resistive shell**
homogeneous E-field shaping





# ND-LAr Prototyping Campaign

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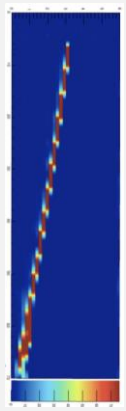
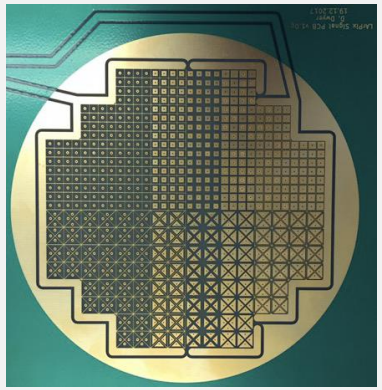
## Isolated tests of novel technologies

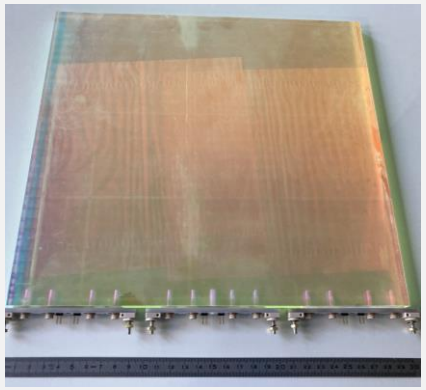
Resistive Shell



Pixelated r/o



ArCLight / LCM

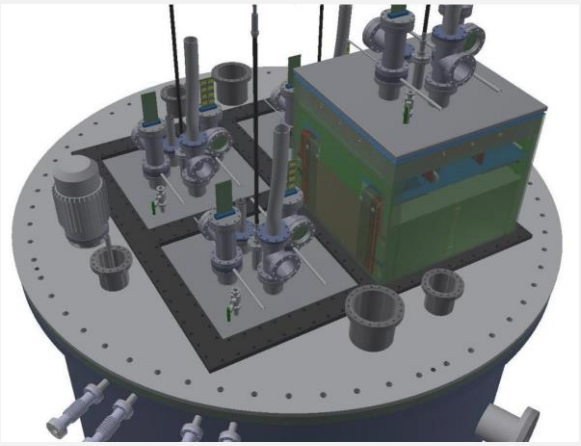


## Single Module for 2x2

First test of integration of all subsystems

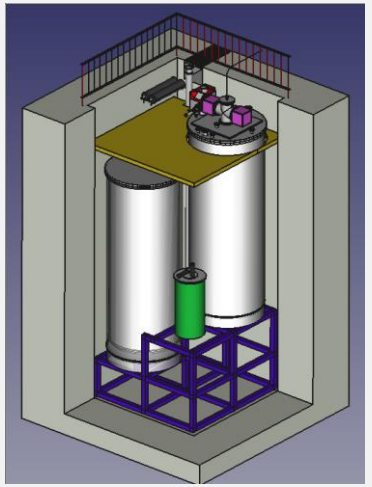
## 2x2 Demonstrator @ NuMI (see next slides)

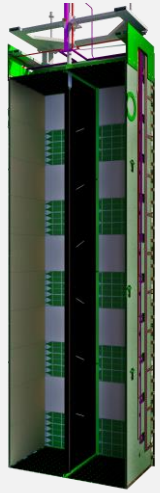
First combined test of multiple modules in a neutrino beam



## Full Size Demonstrator

First test of a ND sized single module





# 2x2 Demonstrator @ NuMI

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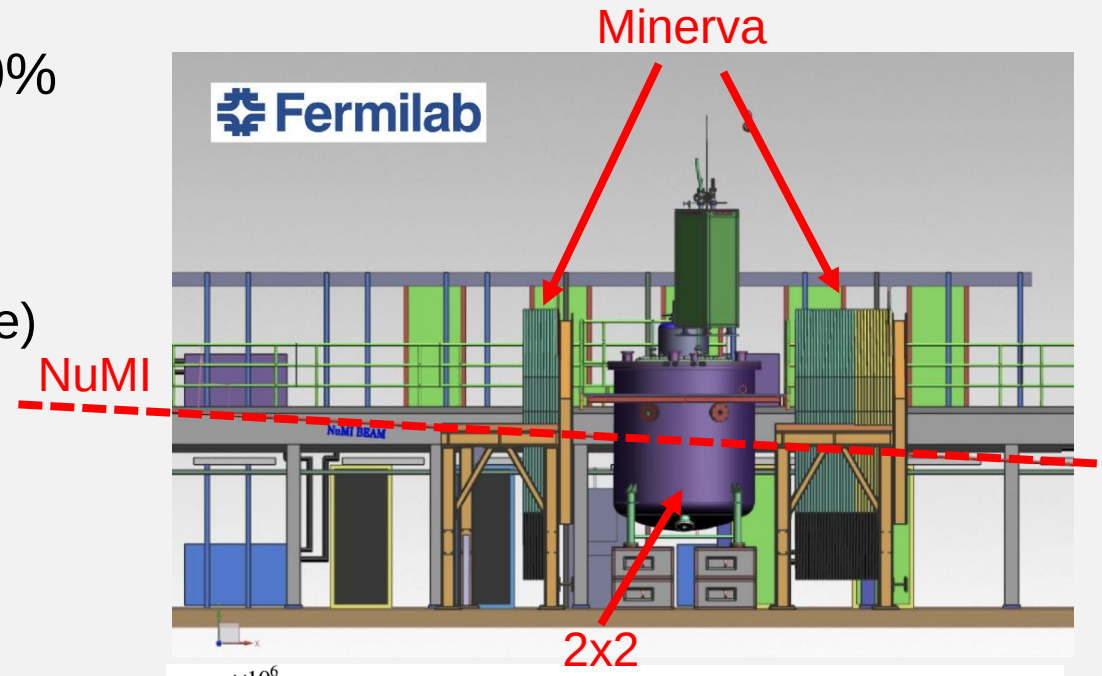
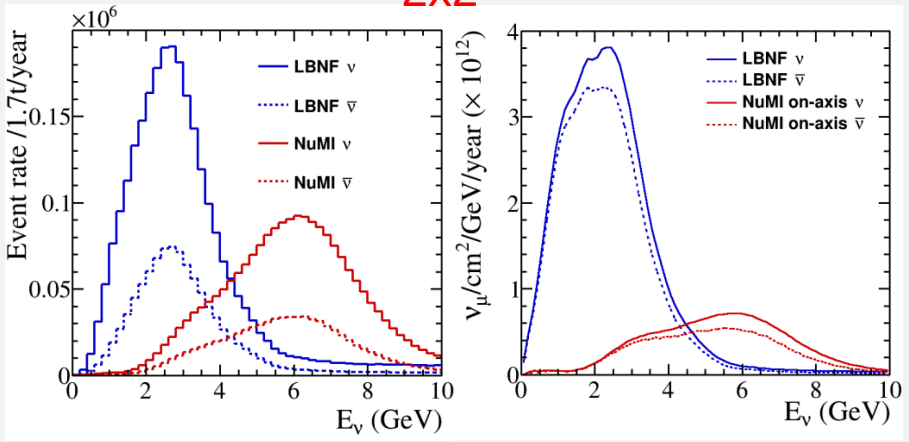
- 2x2 arrangement of 4 prototype modules (~60% of full size)
  - 2.4t active LAr mass
  - 8 optically isolated TPCs
  - 384 light readout channels (25% optical coverage)
  - 337k charge readout pixels with 4mm pitch
- Operation at NuMi beam at Fermilab
  - 107 m rock overburden (300 m.w.e.)
  - Up- and downstream Muon trackers (Minerva)
- Demonstration of multi-module operation and reconstruction
  - Development of end-to-end analysis chain
  - Exercise particle reconstruction over multiple TPCs
  - Neutrino cross-section measurements



# Light readout

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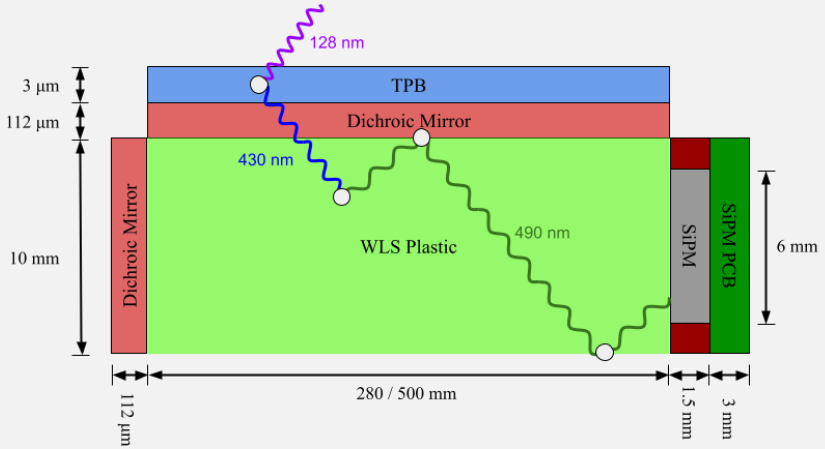
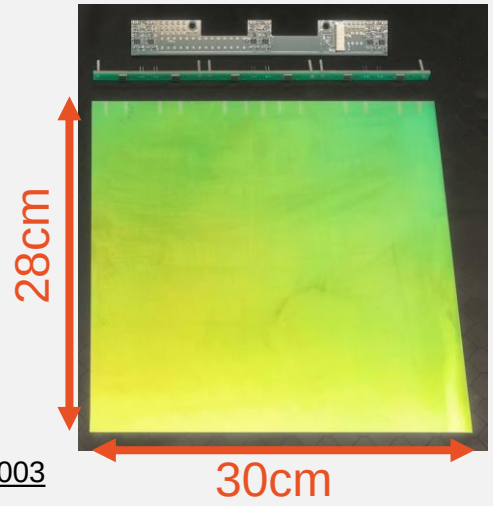
## Two complementary detector systems:

### ArCLight (ArgonCube Light detector)

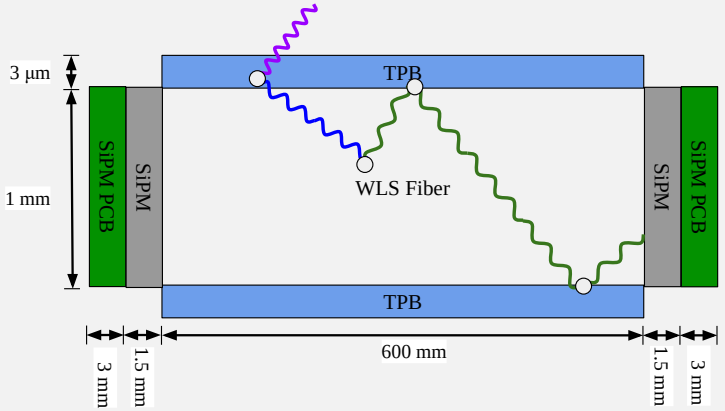



- \+ Large sensitive area (~100%)
- \+ Wide dynamic range
- \+ High spatial resolution (~5cm)
- \+ Efficiency (~0.2%)

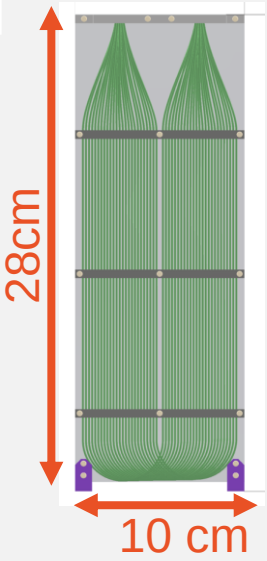



https://doi.org/10.3390/instruments2010003

### Light collection module (LCM)



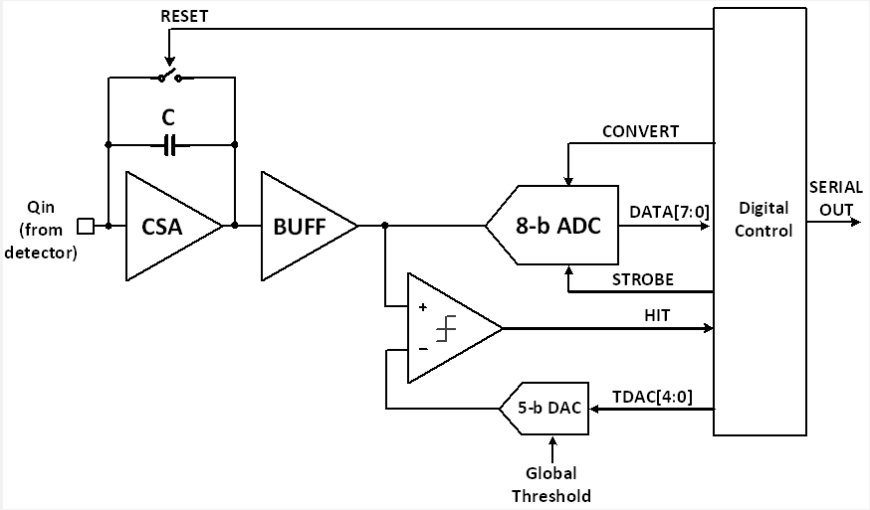

- \+ Easy scalable to large size
- \+ Simple and rigid design
- \+ Spatial resolution ≃ Tile width (only vertical axis)
- \+ Efficiency (~0.6%)

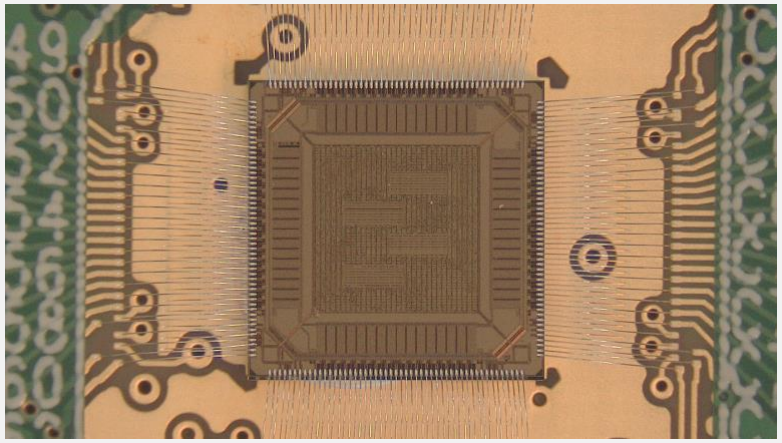



https://doi.org/10.1088/1748-0221/15/07/C07022

# Charge readout: LArPix

- Readout ASIC for pixelated charge readout
  - Designed for cold operation
  - Low-power, integrating amplifier (<200 $\mu$W/channel)
  - 64 channels per ASIC
  - Self-triggered digitization and readout
- Continuous readout mode
  - Tuneable threshold to “wake up” ASIC from dormant mode
  - <200keV energy threshold per channel
  - Low I/O data rate (~5 Mb/s per I/O channel)
- Scalable System
  - Dynamic chip-to-chip I/O routing to cope with single-chip failures
  - Scalable to $\mathcal{O}$(1 million) channel systems
  - $\mathcal{O}$($0.10) per channel system cost, incl. cables/controllers/assembly/etc.

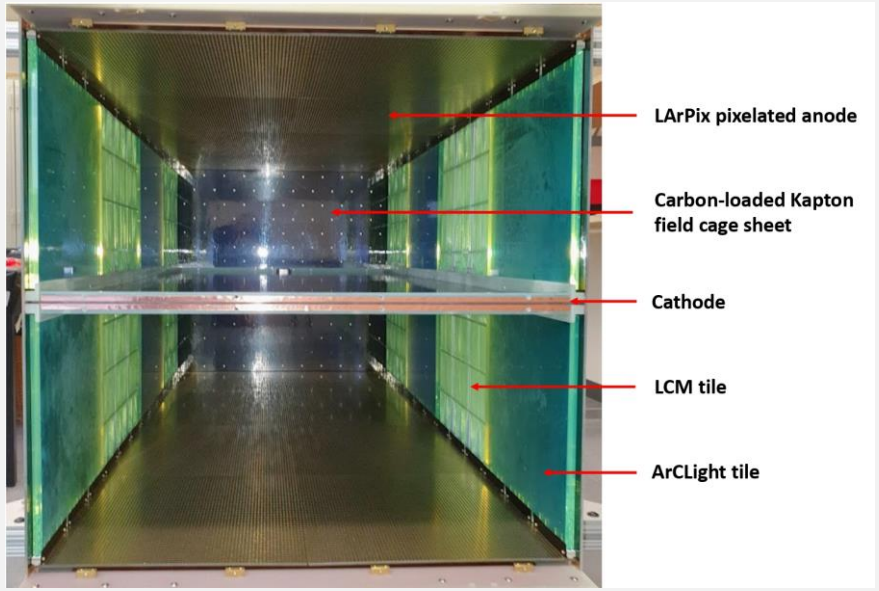


https://doi.org/10.1088/1748-0221/13/10/P10007

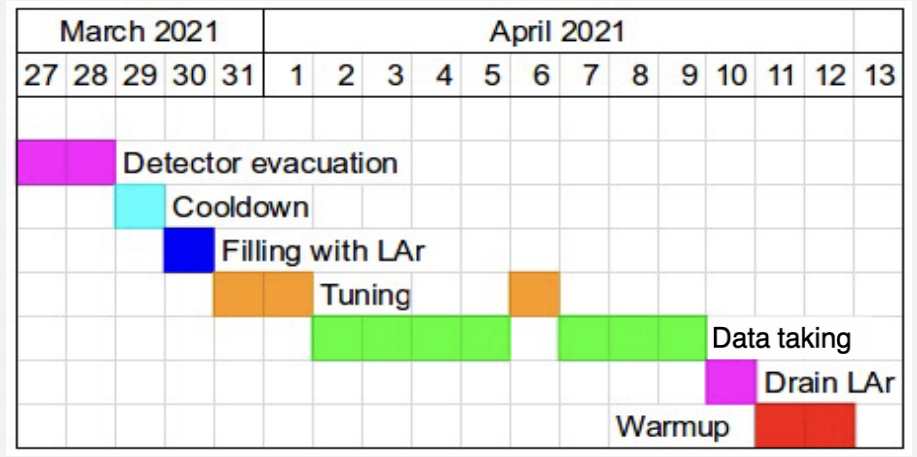
# SingleModule @ Bern

- 2021-2023: Successfully tested four single modules
- First test of full integration of all detector subsystems
- Module size: 0.6m x 0.6m x 1.5m
- $\mathcal{O}$(100 million) cosmic ray events recorded




LAr test facility at Bern

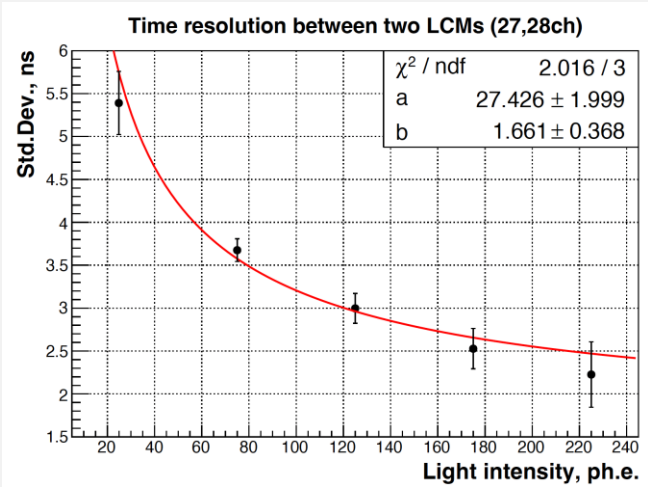

Module 0 run overview



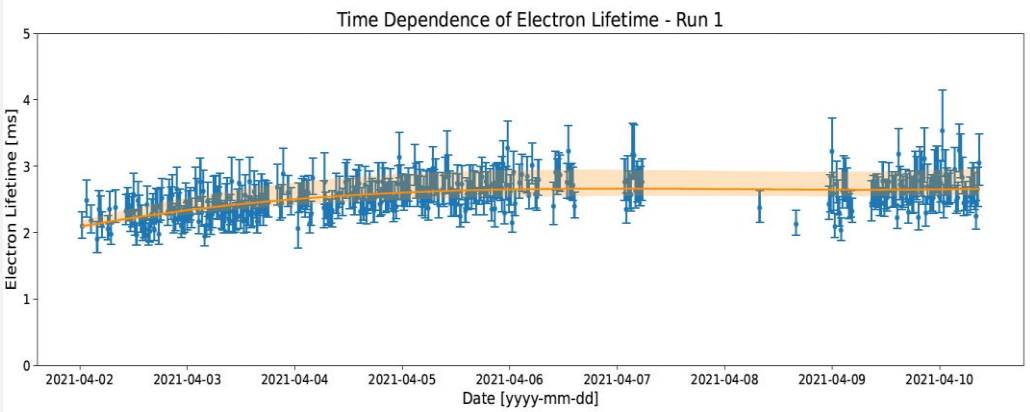
# Single Module results

- Low-level detector performance
  - LAr purity, drift field uniformity, mechanic rigidity, ...
  - Light readout: efficiency, spatial and time resolution, ...
  - Charge readout: Threshold optimisation, pixel response, ...
- Cosmic ray physics event analysis
  - Charge-Light matching, electron recombination studies, ...
  - Event studies: Michel electron, EM shower, ...

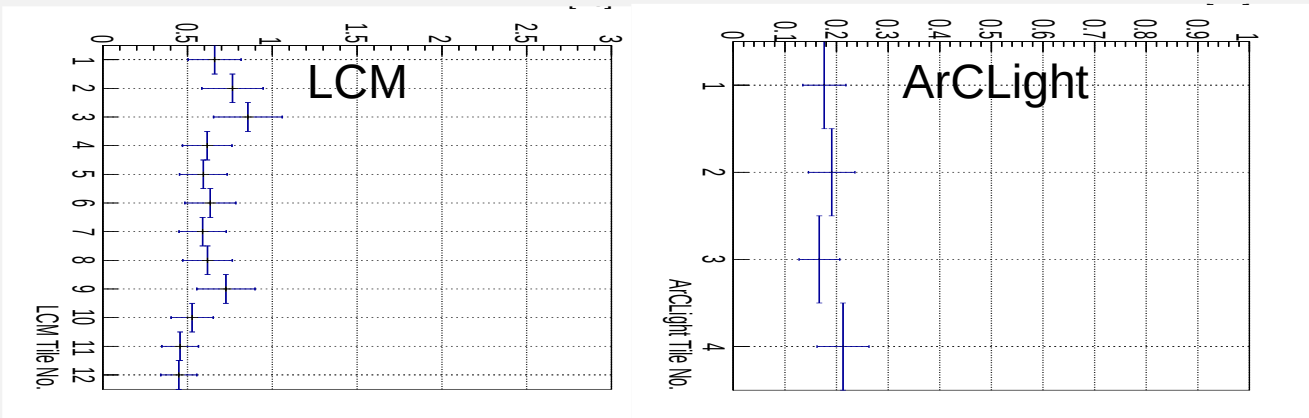
Light time resolution




LAr purity




Photon detection efficiency

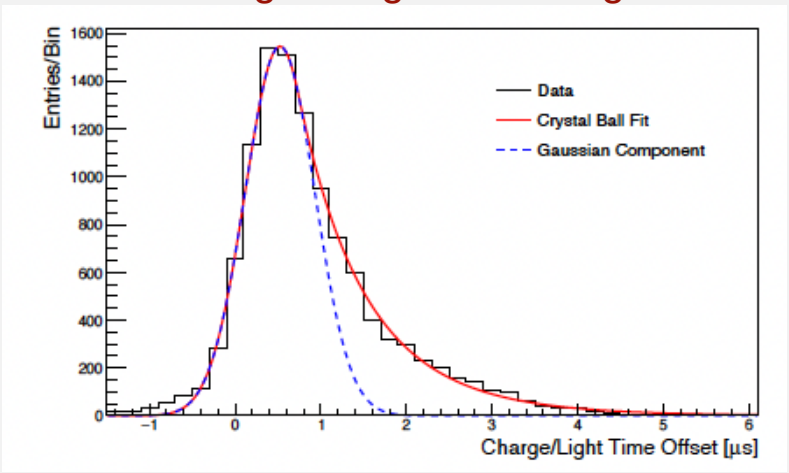



All detector requirments fullfilled!

# Single Module results

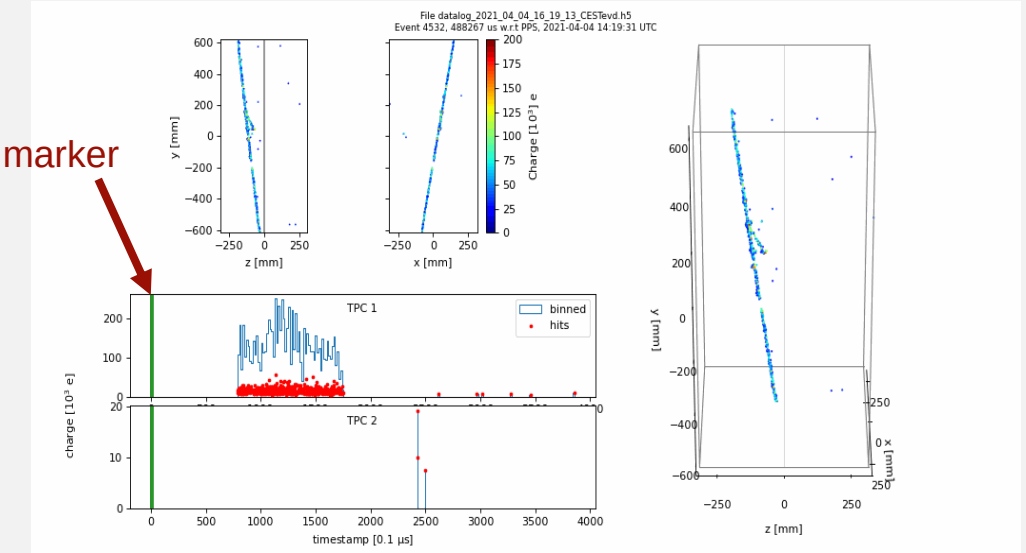
- Low-level detector performance
  - LAr purity, drift field uniformity, mechanic rigidity, ...
  - Light readout: efficiency, spatial and time resolution, ...
  - Charge readout: Threshold optimisation, pixel response, ...
- Cosmic ray physics event analysis
  - Charge-Light matching, electron recombination studies, ...
  - Event studies: Michel electron, EM shower, ...

## Charge – Light matching

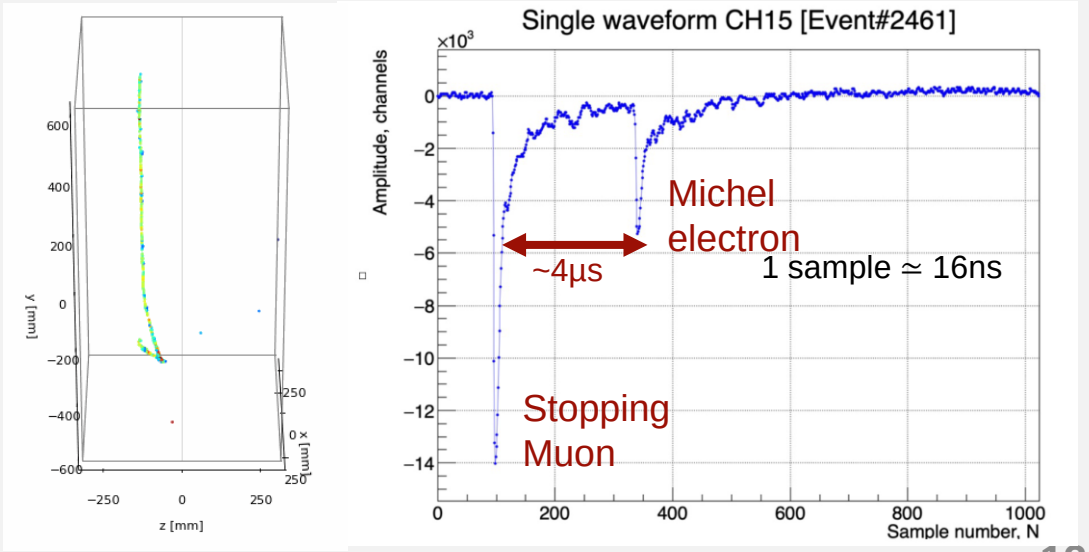



## Muon event

Light T0 marker

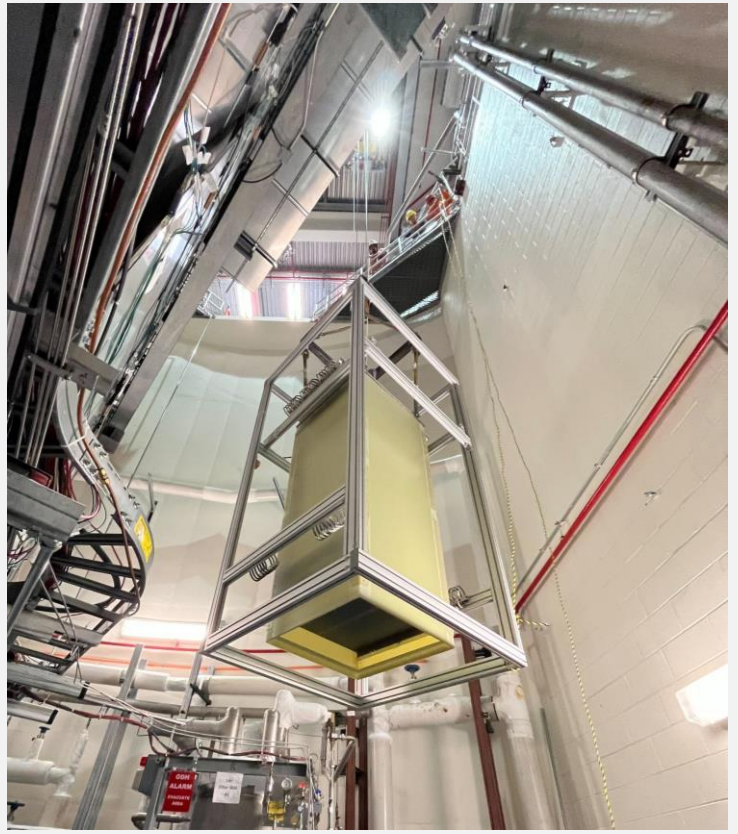



## Michel electron



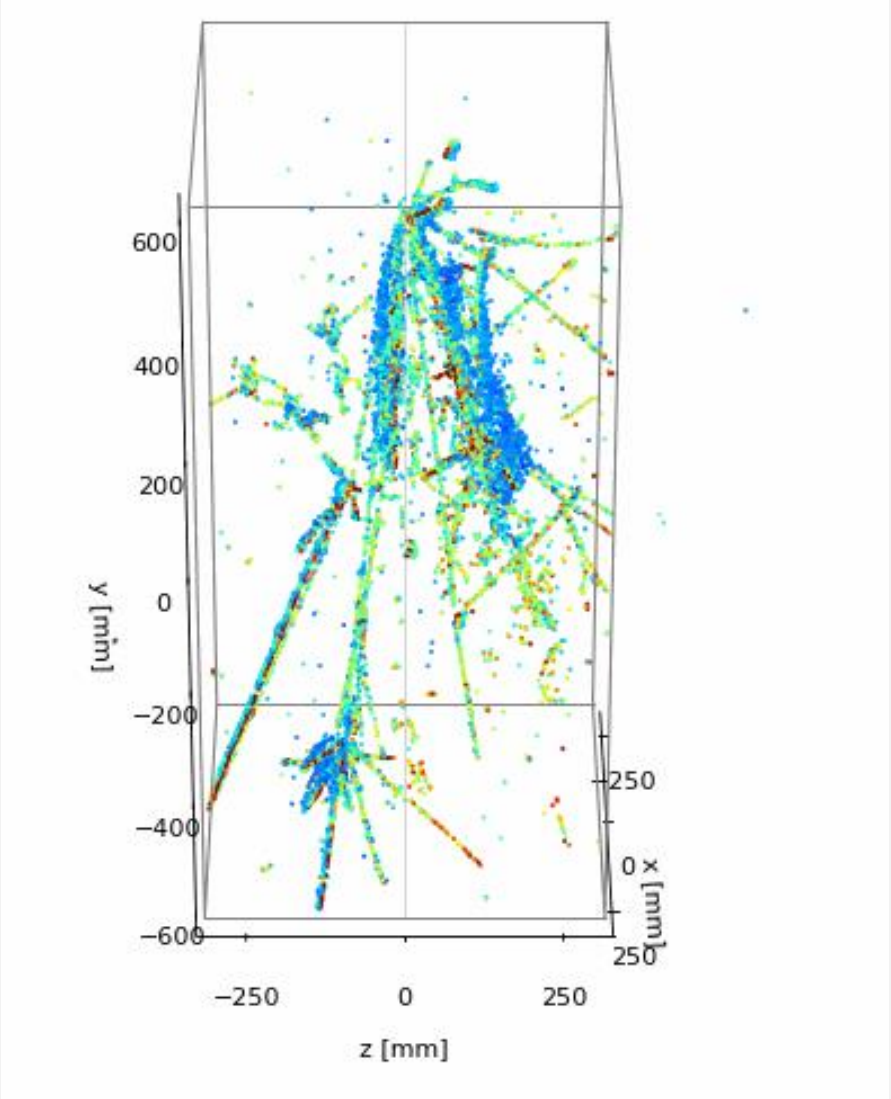
# Status of 2x2

- Final commissioning phase starting now
- Muon tracker planes fully assembled and tested
- All modules at Fermilab, cryostat insertion in the next weeks
- **Start taking beam data in the beginning of 2024!**




# Summary

- Modular LAr-TPC Design for DUNE Near Detector's High Multiplicity Environment.
- The 2x2 demonstrator validates the feasibility of multi-module operation and reconstruction.
- During single-module runs, we have demonstrated the effective operation of all detector subsystems, which include:
  - A charge readout system with over 75k pixelated channels.
  - A large-scale dielectric light readout system with an optical coverage of 25% and 96 SiPMs.
- 2x2 data will enable the first physics outcome from the DUNE project focusing on $\nu$-Ar interaction studies



# Backup

# TPB coating

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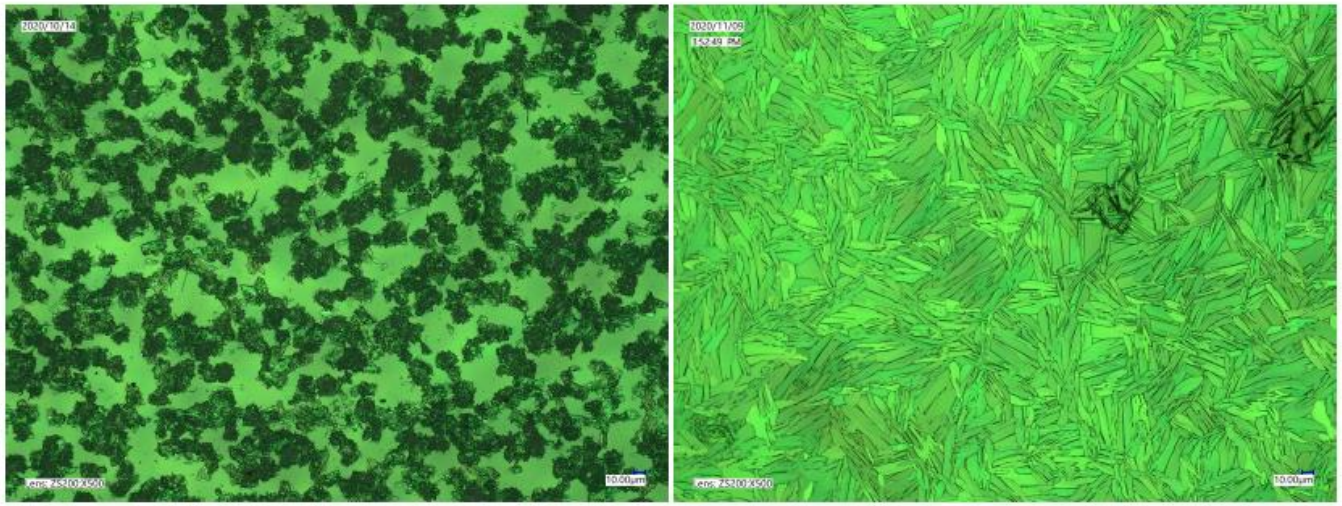
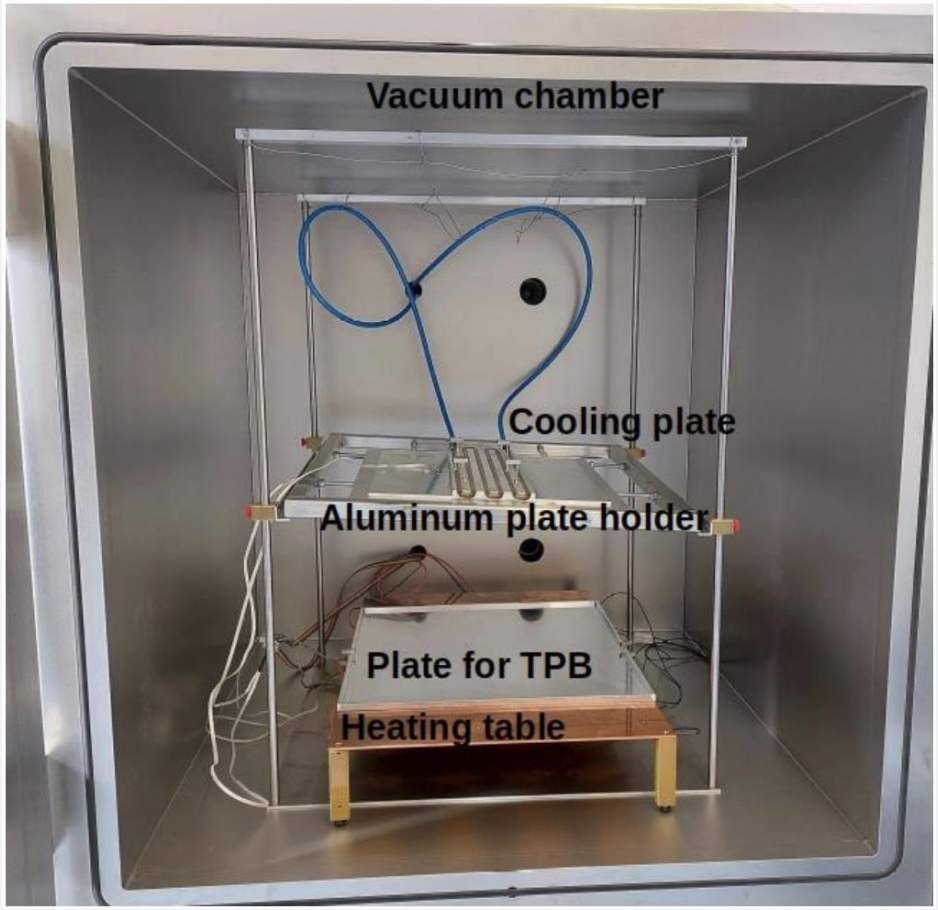
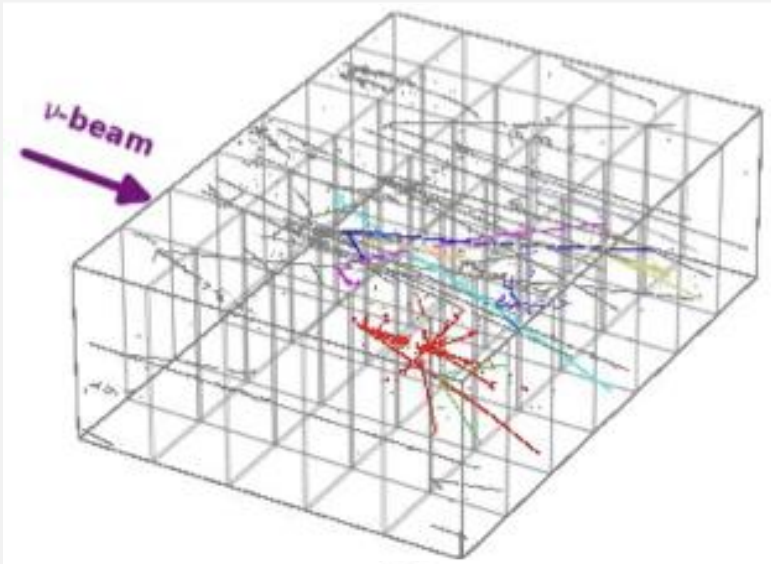
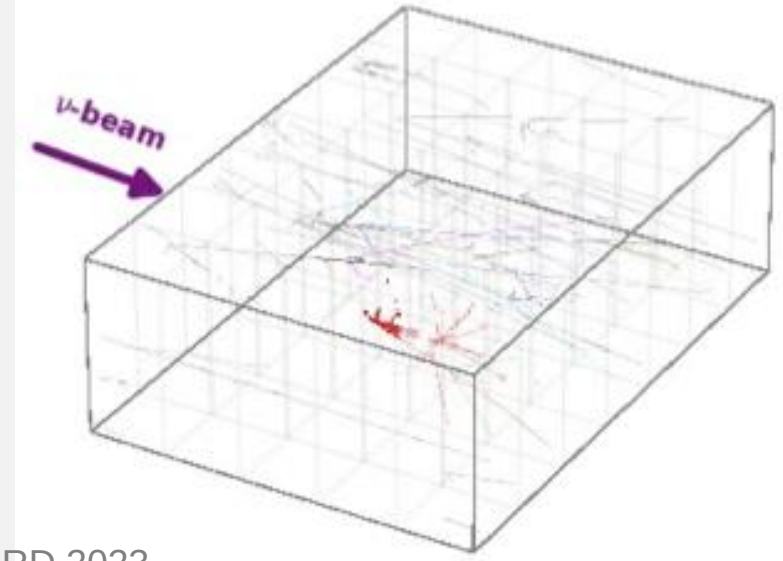
- First prototypes: Air brush coating
  - Non-uniform and small surface coverage
- Solution: Vacuum evaporation deposition
  - Reaching coverage >90% and high uniformity
  - Reproducable

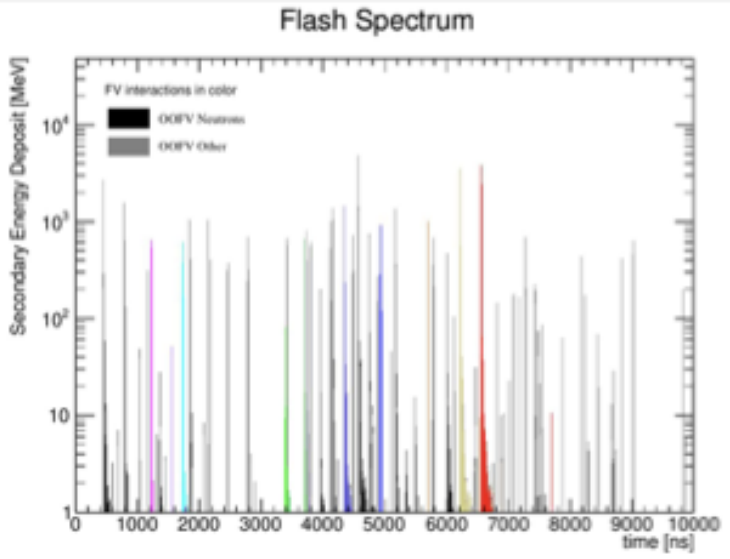


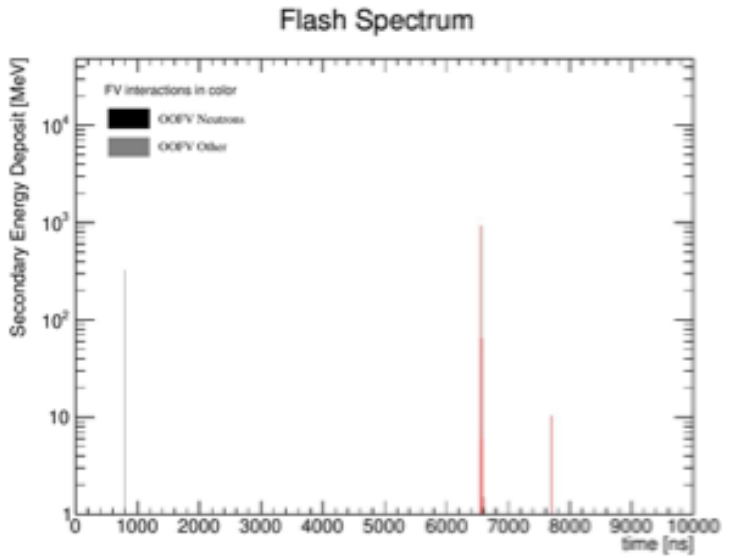
(a) Air brush (b) Evaporation deposition




μ-beam


μ-beam

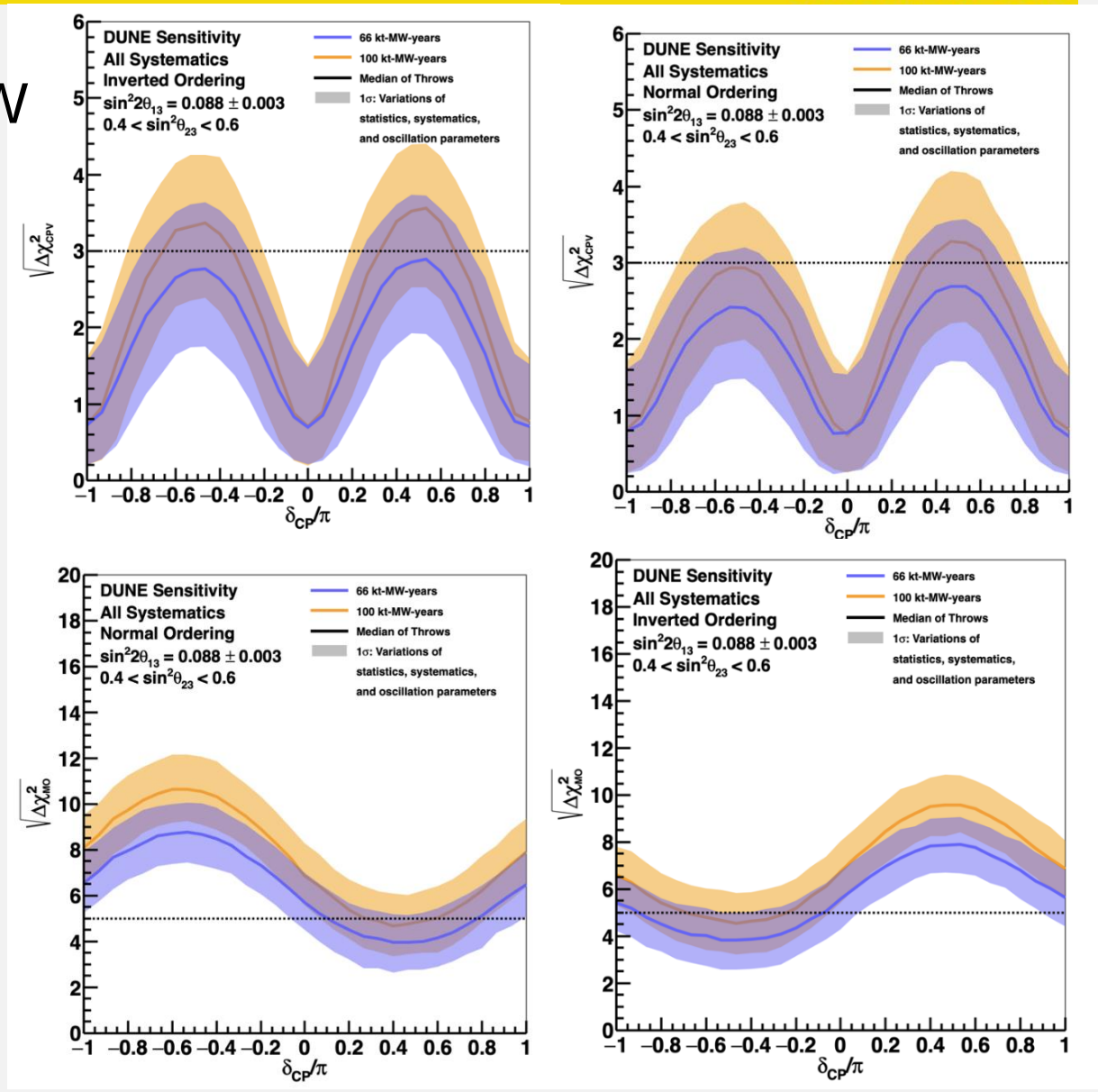

Flash Spectrum
FV interactions in color
OOFV Neutrons
OOFV Other
Secondary Energy Deposit [MeV]
time [ns]


Flash Spectrum
FV interactions in color
OOFV Neutrons
OOFV Other
Secondary Energy Deposit [MeV]
time [ns]

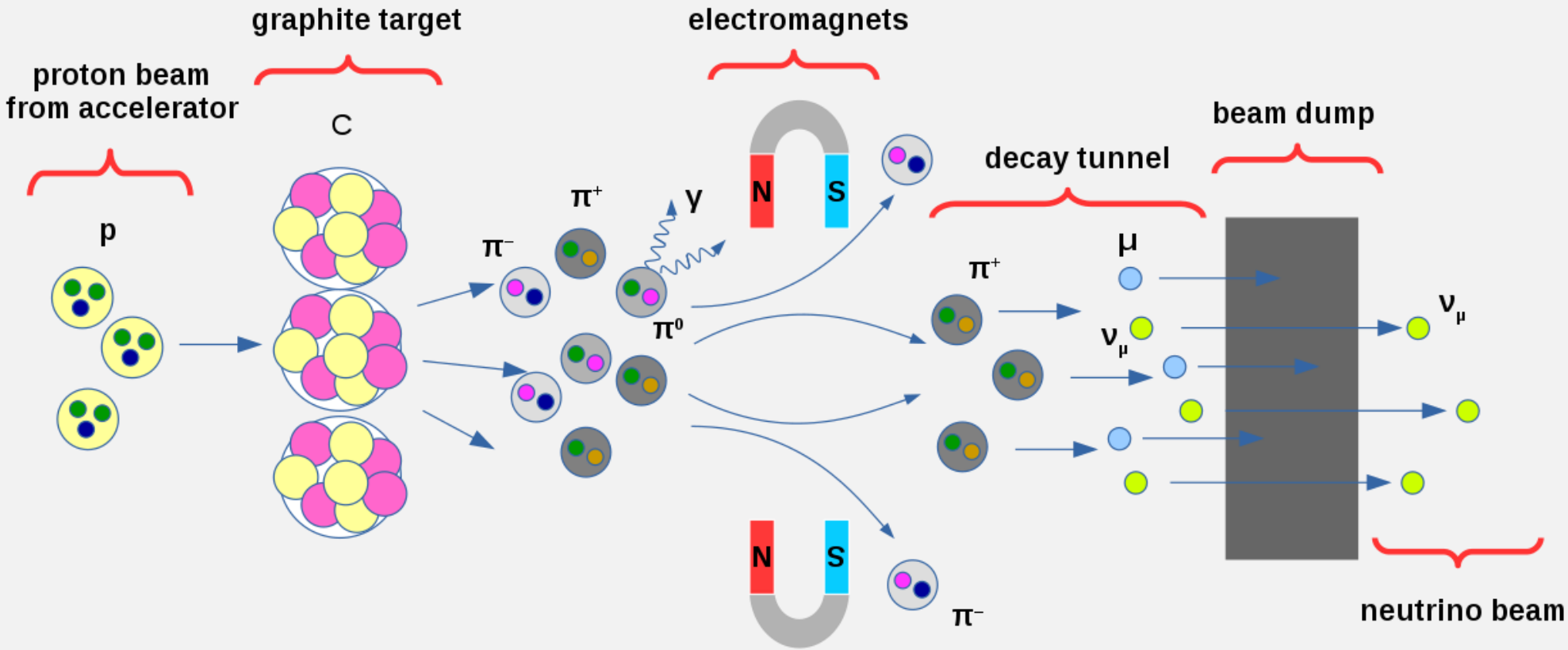
# Sensitivity

- Nomial beam power: 1.2 (2.4) MW
- 10kT per FD module
- With full configuration:

  48kT-MW-year



# Beam production

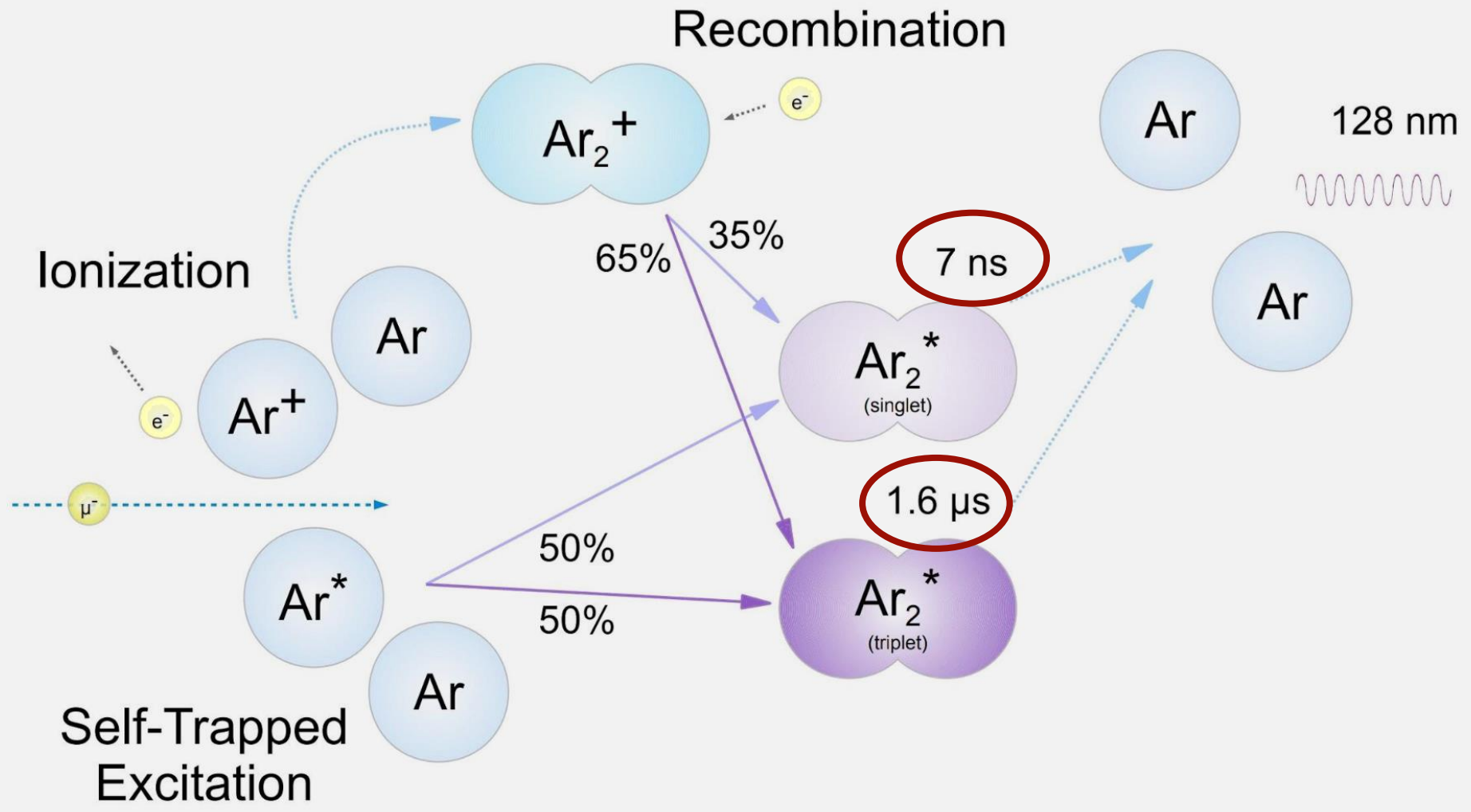


# Interaction rate

$$R(\vec{\mathbf{x}}) = \overbrace{\Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}})}^{\text{Near}} \times \underbrace{P(\nu_A \to \nu_B)}_{\text{Far}}$$

- **Event rate; Neutrino flux; Cross section; Detector smearing; Oscillation probability.**

# Scitillation Light



# ArCLight: Spatial resolution