Fiber-coupled digital SiPMs for Large Time Projection Chambers

6th International Workshop on New Photon-Detectors (PD24)

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Nov 20th, 2024

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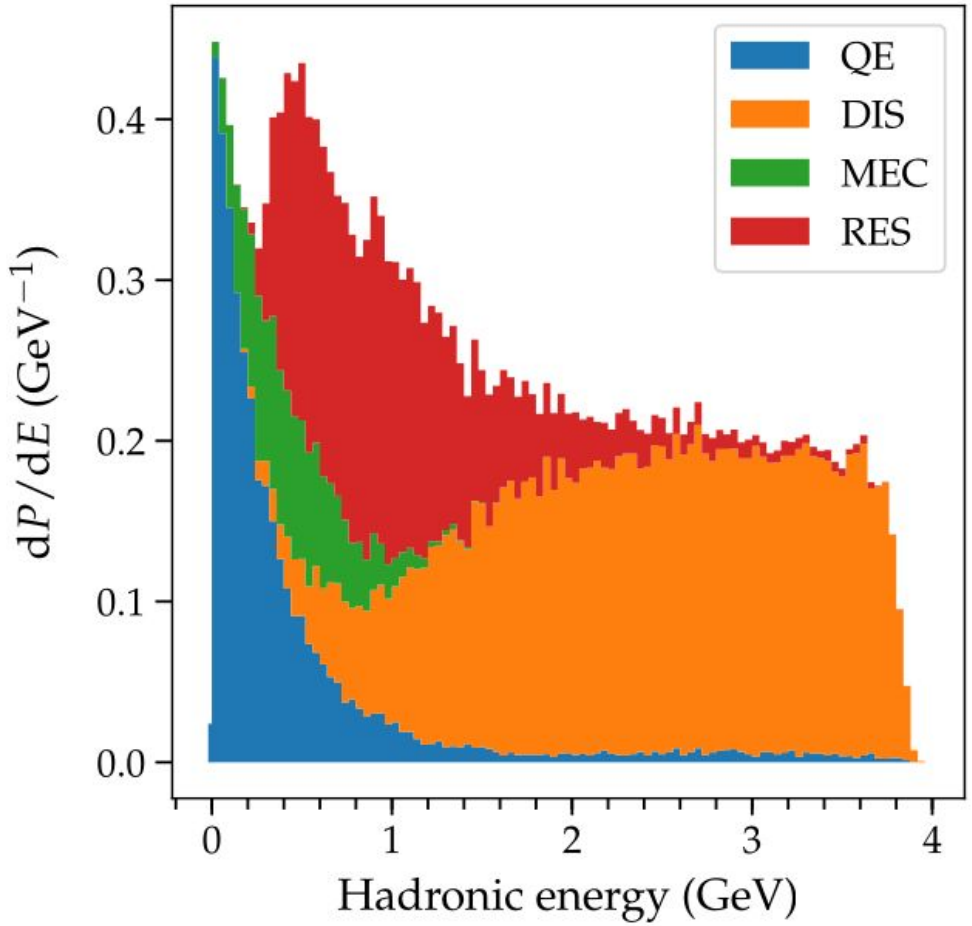
Issues facing beam-neutrino reconstruction

The following is based on discussion with reconstruction experts (thanks Francois Drielsma & Kazu Terao):

GeV neutrinos will cause deep inelastic scattering, producing multiple hadrons and re-interactions in the final state.

This complicates reconstruction through vertex identification and missing energy via neutrons.

The plot spans energies relevant to DUNE.

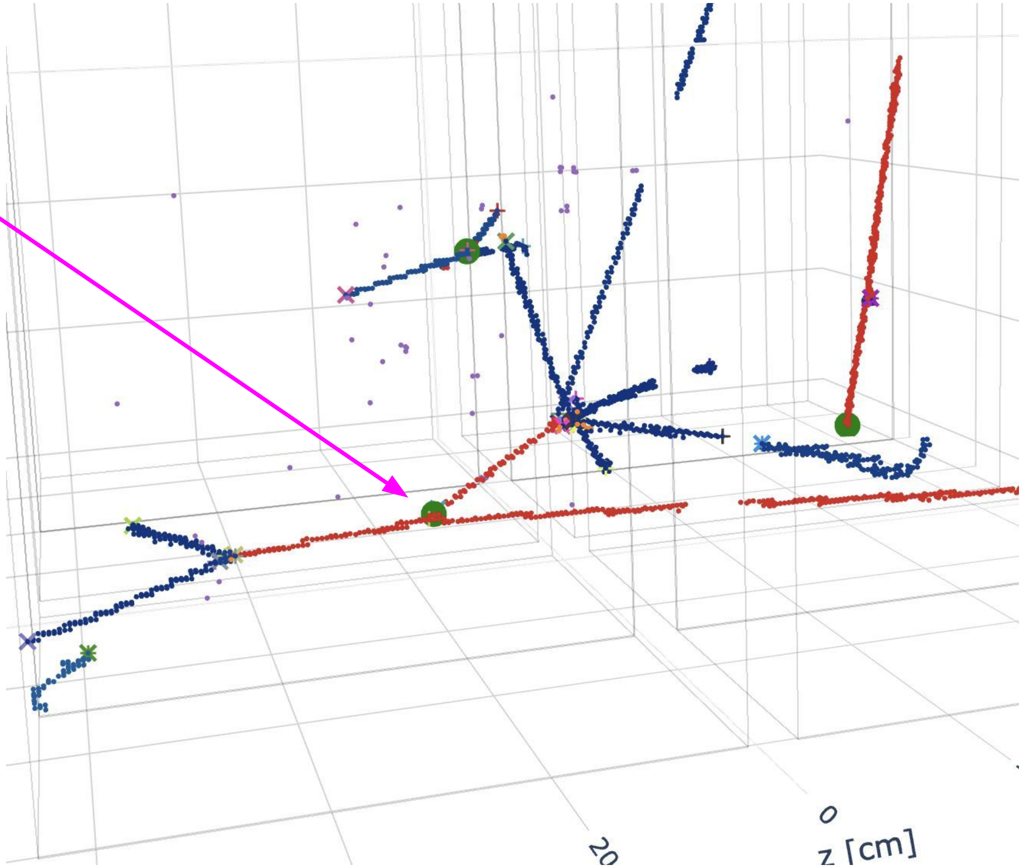


arXiv:1811.06159v3

Deep inelastic scattering

Non-obvious primary vertex

Beam direction



Simulation of the NuMI beam on argon

Neutrons in Argon

Neutrons can carry away a significant amount of energy from the vertex or shower fluctuations.

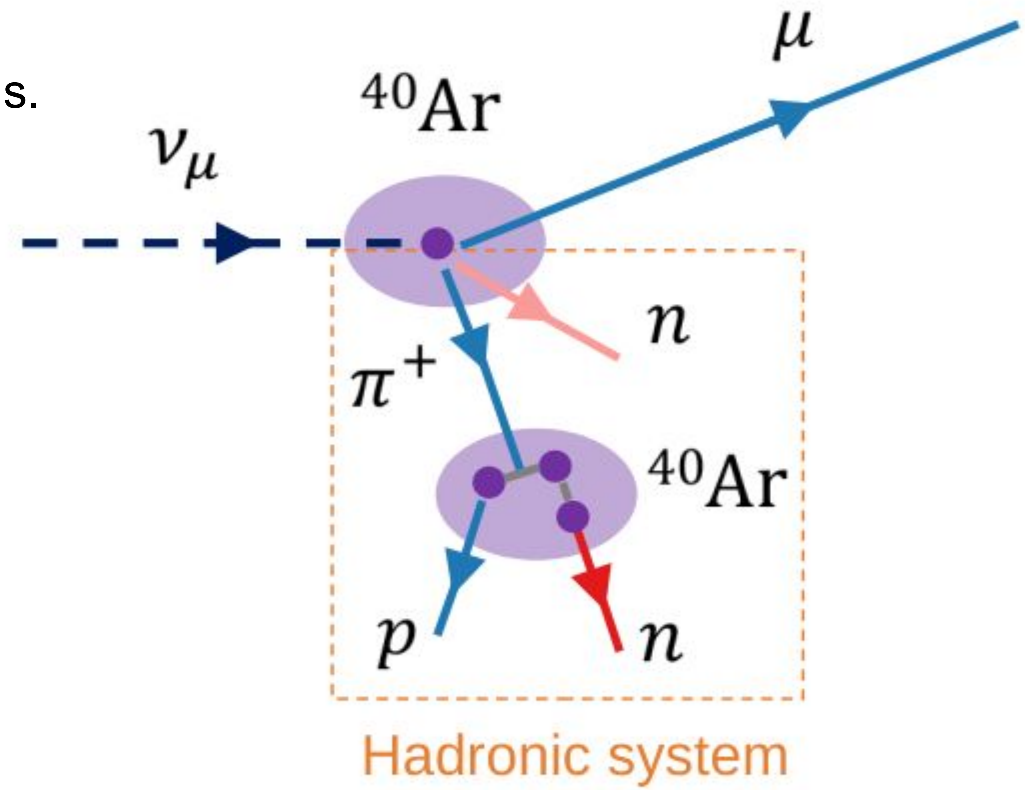
Fast neutrons typically cause a p/Ar recoil within a few ns.

With prompt light, reconstruction through time of flight may be possible:

10 MeV = 4 cm/ns

100 MeV = 12 cm/ns

1 GeV = 26 cm/ns



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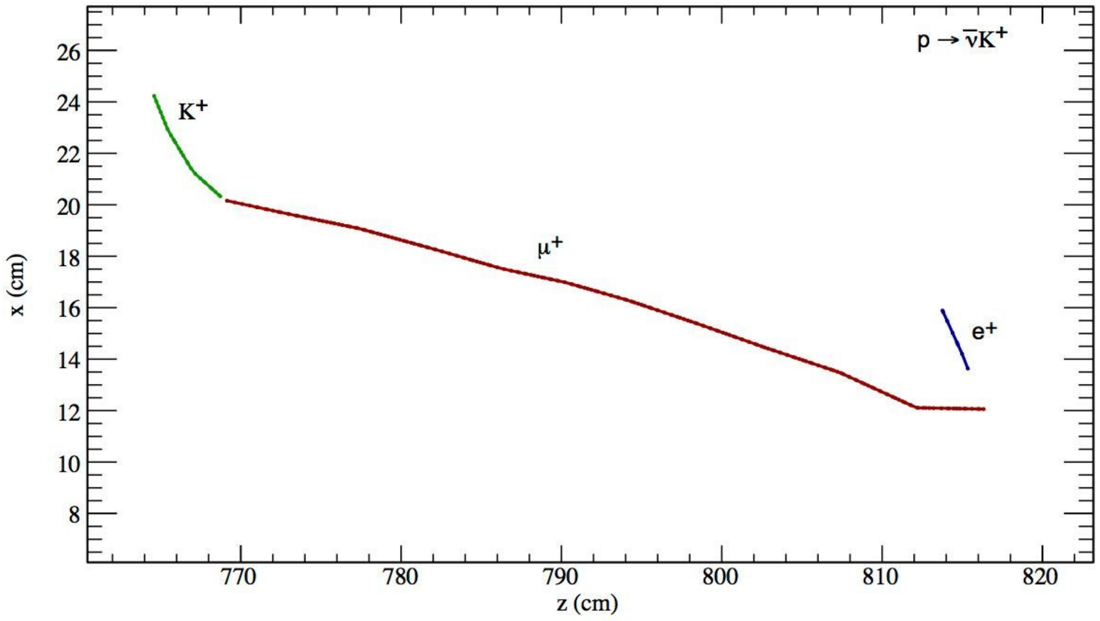
Prompt light for proton decay

In Argon, without measuring the 12.4 ns k^+ lifetime, it is extremely difficult to distinguish $K^+ \rightarrow \mu^+$ from atmospheric neutrinos.



Particle identification through timing is a extremely powerful tool currently missing from large TPCs.

It would also help with $\pi \rightarrow \mu$, K^0 long $\rightarrow X$, etc. as long as the lifetime is over a few ns.

Using prompt light in Argon

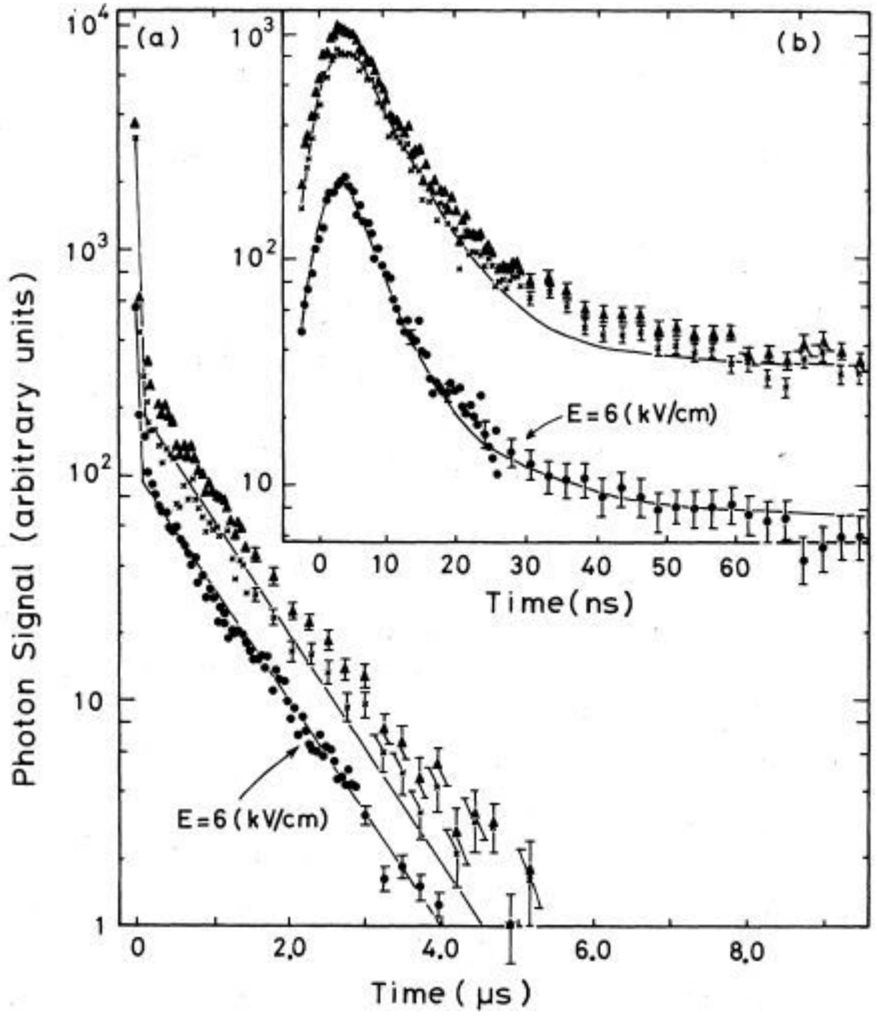
A MIP produces ~5k photons/cm at 128 nm from different excited states:

-Singlet states have a decay lifetime of O (1) ns.

-Triplet states have a lifetime of O (1) μs.

Rayleigh scattering smears out photon arrival times by O (10) ns for propagation distances of O (1) m.

To have access to prompt light, optical paths must be less than the Rayleigh scattering length, and the sensor response must be O(1) ns or better.



Event reconstruction with prompt light

By instrumenting the bulk TPC volume with an IceCube-esque light readout in combination with charge readout, prompt light can be exploited to enhance event reconstruction

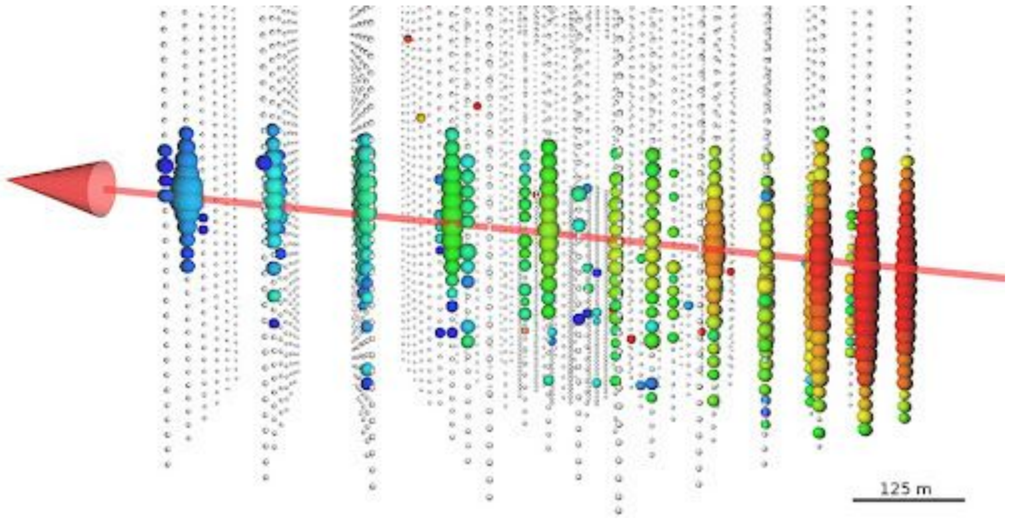
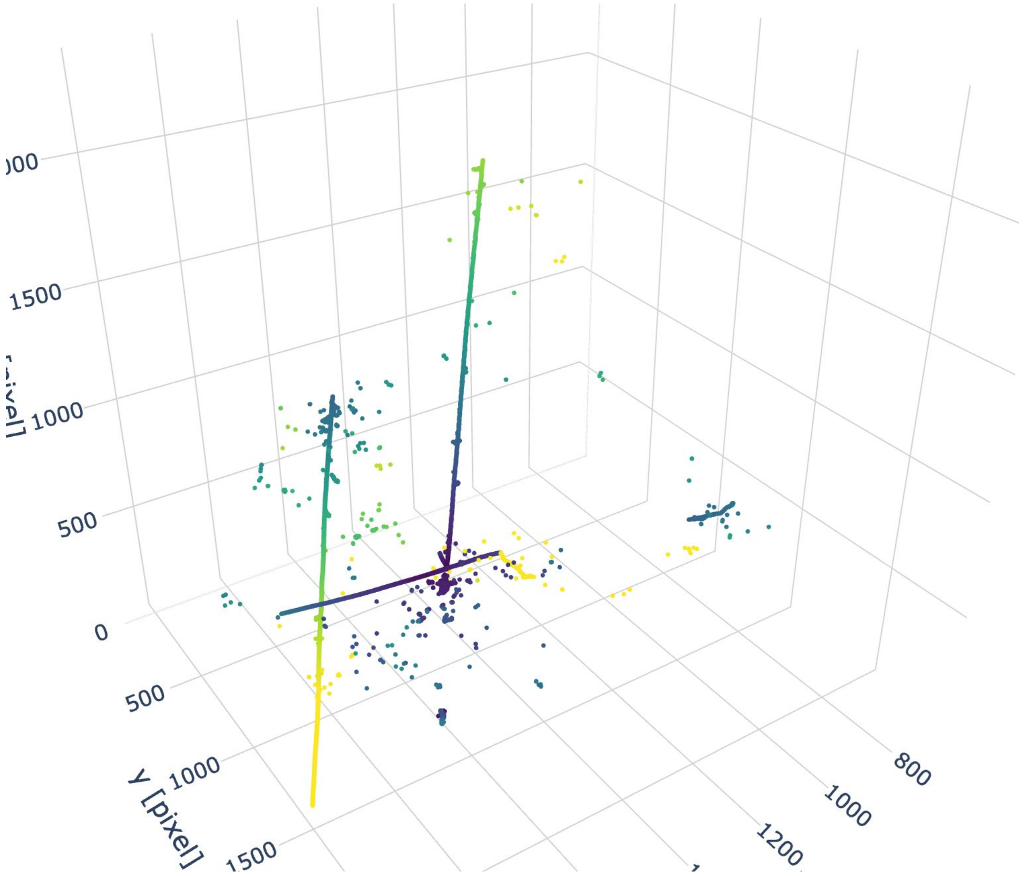


Image credit: IceCube



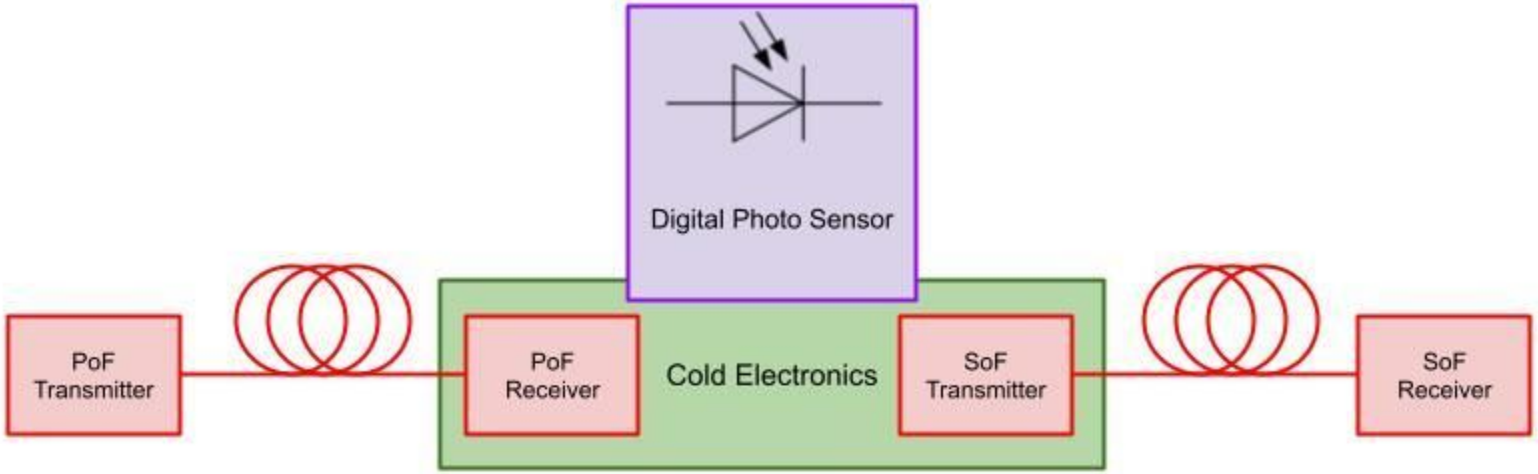
Green = early, Yellow = late.

The late Michele electron confirms muon decay

The goal

Recent advancement in power over fiber (PoF) and signal over fiber (SoF) have enable light readout at the TPC cathode (JINST/19/P10019), thanks to Bill Pellico of FNAL.

Considering the need to access prompt light, PoF and SoF become enabling technologies to deploy digital light sensors within the drift volume of TPCs.



Why digital sensors?

Channel densities…

Power limitations (efficiency and heat input) make it problematic to amplify and digitize multiple SiPM waveforms.

Digital signal multiplexing simplifies data transmission without channel density constraints.

Given a sufficient sensor density, waveform analysis is not needed, only the time at which a threshold is cross.

Digital SiPMs are ideal for this application.

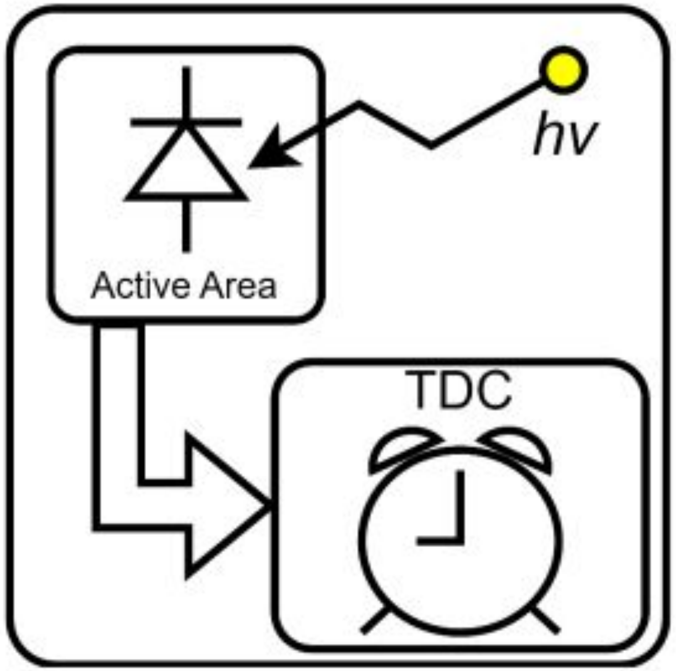
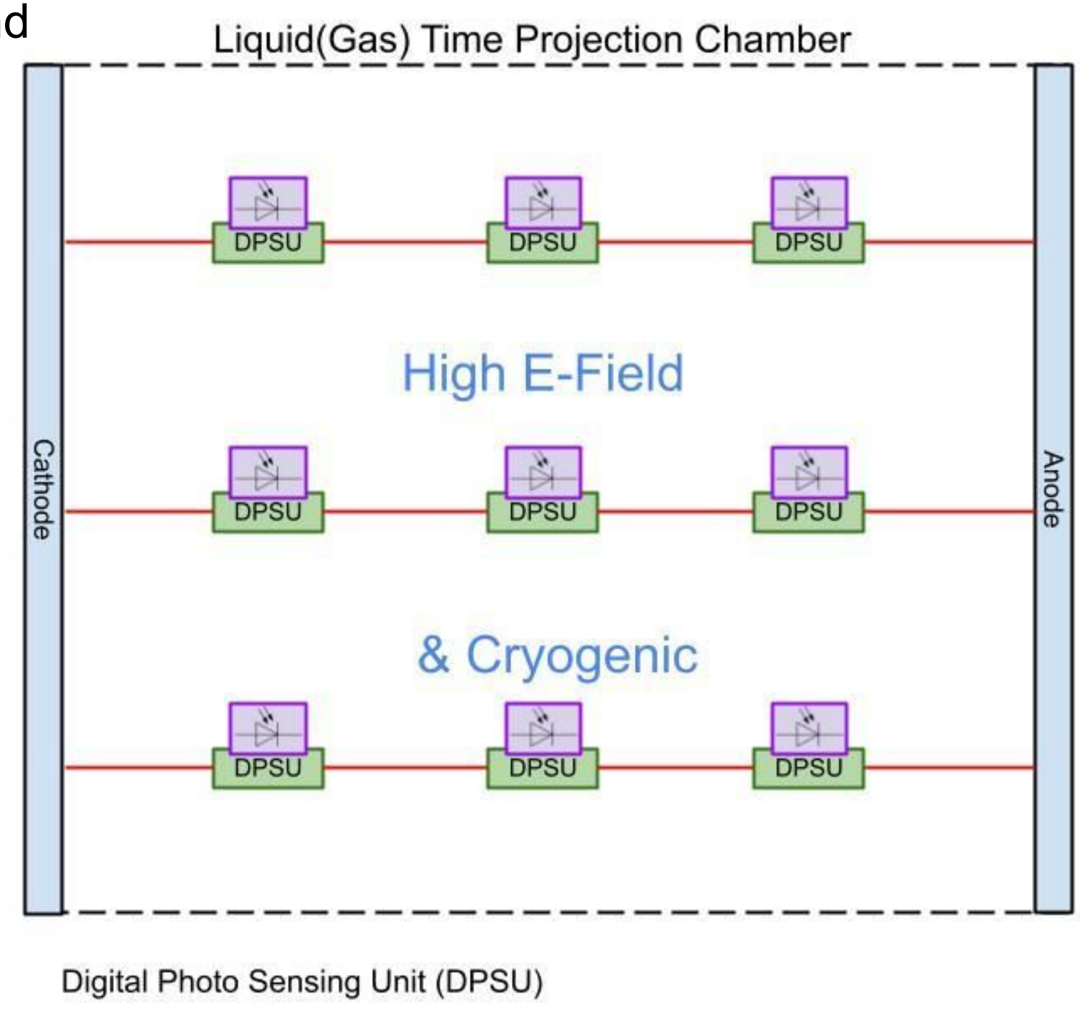


Image credit: FBK

Detector concept

Fiber-coupled digital SiPMs could be strung between anode and cathode in an array.

- Providing localized triggers.
- Simplify the DAQ by reducing data rates.
- Enables particle identification through timing.
- Tagging/reconstruction non-obviously-spatially-correlated activity (neutrons, lambda decays, K^0 short/long decays, etc.) to improve energy reconstruction.
- Provide robustness against N2 contamination.



How would this look in a detector

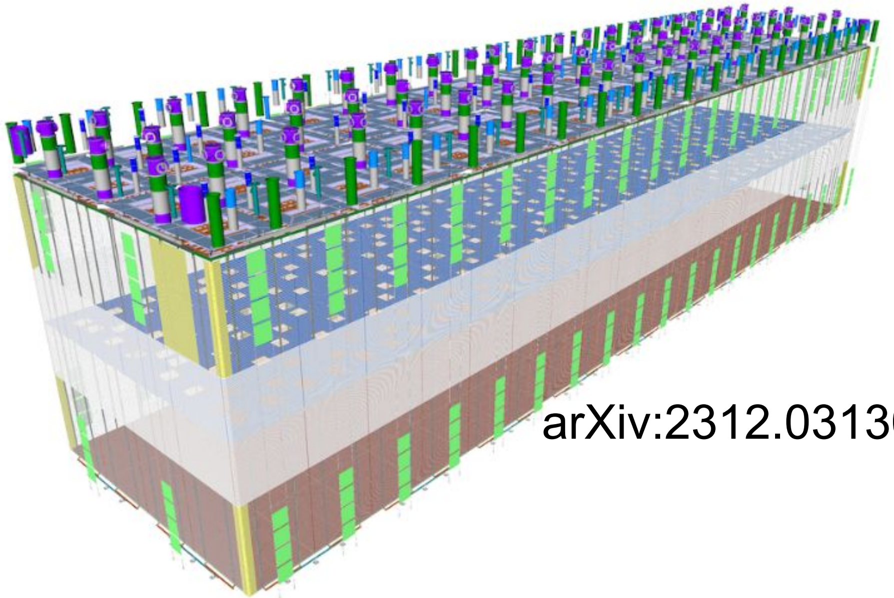
Take DUNE vertical-drift as an example
60 m long x 13 m wide x 13.5 m tall

To ensure optical path is never more than a scattering length, strings of sensors are displaced at 1.5x the Rayleigh scattering length (1.5m).

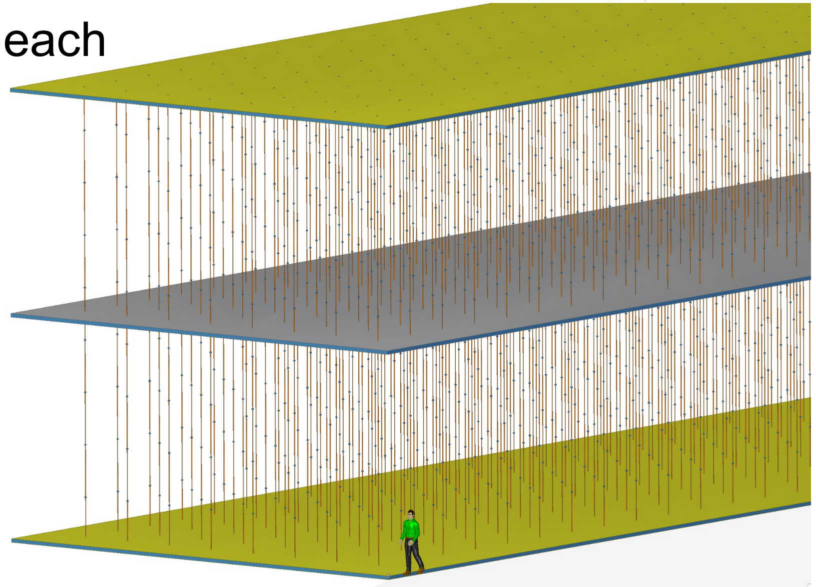
The same separation is applied along the each string.

Yielding and 8 x 39 grid of stings with 8 sensors on each string. Total of only 2.5k sensors units.

Allowing ample coverage for charge collection.



arXiv:2312.03130



What pieces are needed?

Power over fiber
The FNAL/DUNE method has been demonstrated, but at ~50% efficieny it represents a large heat load. Methods to increase efficiency are required.

Signal over fiber
Cryogenic fiber-coupled diodes have been demonstrated, but are power hungry. External lasers with data transmission via modulation such as Sherbrooke's silicon photonics DAQ (techrxiv.172565555.56657721), or FNAL's SParkDream, are promising.

Digital SiPMs
There are multiple advancements in dSiPMs but typically sensitivities, sans WLS, peak above 400 nm.

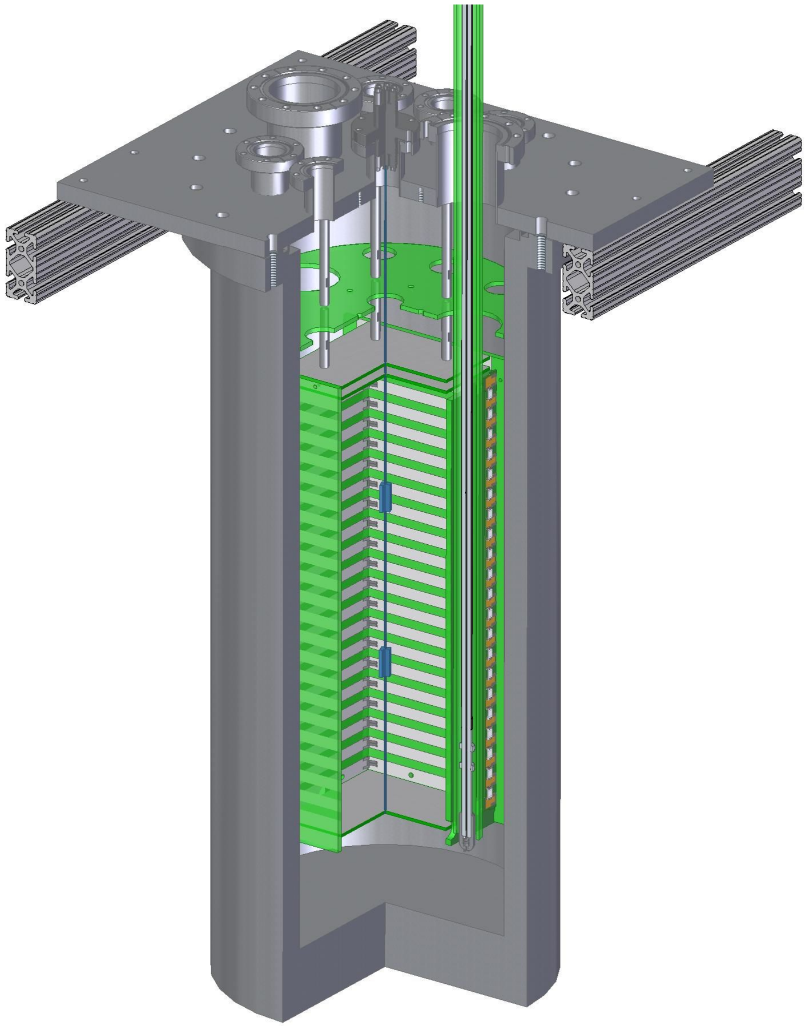
VUV SPADs
Standard CMOS structures do not transmit at 128 nm. Integral WLS needs to be investigated, or custom SPADs. Custom SPADs will require bespoke ASIC.

Efforts at SLAC - PoF

Power over Fiber
For LAr/LXeTPCs using pulsed sources to mitigate heat input through reduced duty cycle.

Working towards cryogenic demonstration with FBK's SuperEllen sensor. Thanks to N. Massari, M. Gandola, L. Gasparini, & J. Dalmasson.

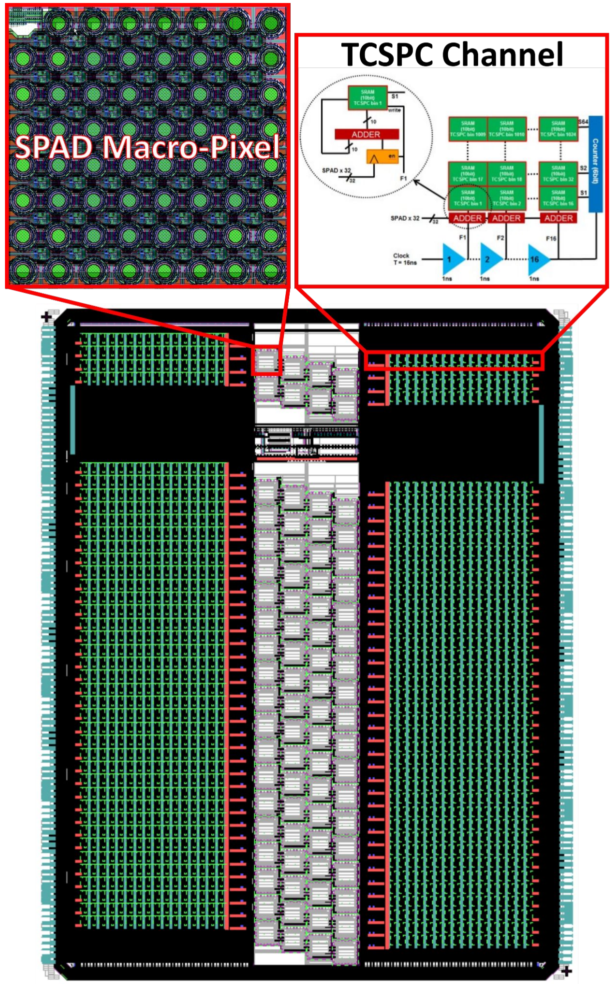
Goal of applying SLAC's experience with cryogenic electronics to optimizing sensor control architecture.



PoF 50 cm drift LArTPC currently under construction

Efforts at SLAC - VUV sensitivity

Time-Correlated Single Photon Counting (TCSPC) chip for LiDAR, 80 macro-pixels with 32 SPADs each



VUV SPADs
SLAC (Bojan Markovic) has been developing SPADs for LIDAR. We are now building on this effort to develop VUV-sensitive SPADs.

We will investigate etching CMOS SPADs to silicon and then microwave annealing.

We are also working on the development of custom SPADs.

Summary

Power and signal over fiber have enabled a TPC design that exploits the features of digital SiPMs

Prompt scintillation light can be utilized by deploying digital SiPMs inside the bulk volume of TPCs.

Granular light detection will simplify even reconstruction and improve energy resolution.

This meets the HEP Basic Research Needs (PRD26 Thrust 2) of addressing challenges in scaling technologies.

The technologies needed to produce such detector are sufficiently mature to begin a serious design effort.

Collaboration is welcome.