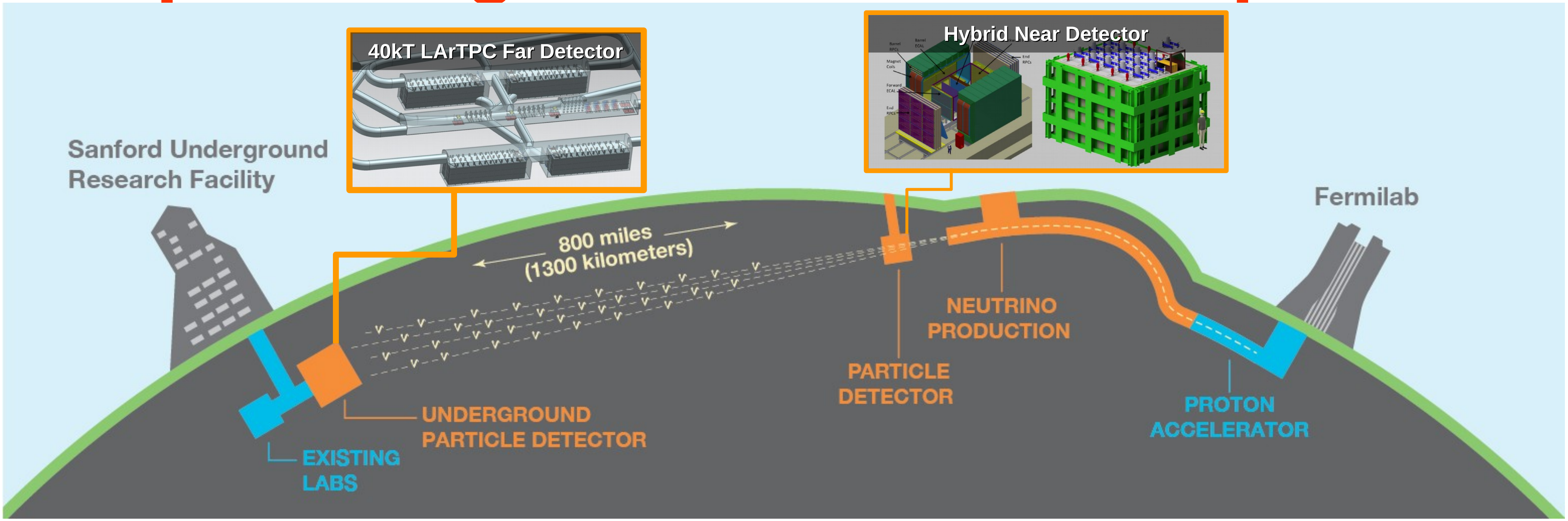
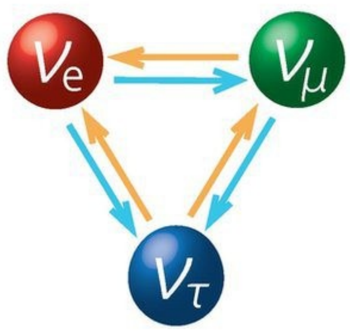
Deep Underground Neutrino Experiment

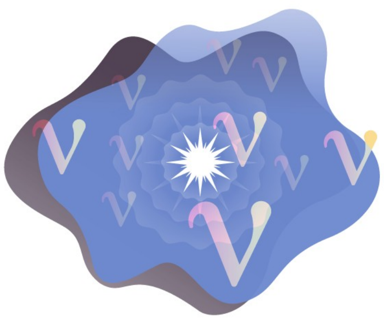


- **DUNE will be the premier long baseline neutrino experiment**
  - Multi-megawatt, high intensity, wide band neutrino beam
    - Produced at Fermilab directed towards the Sanford Underground Research Facility
  - 40 kT (fiducial mass) Liquid Argon Time Projection Chamber (LArTPC) far detector
    - Four 10kT modules modules located at the 4850 level
  - Highly capable neutrino near detector
    - High statistics neutrino cross-section measurements and capability to fully characterize the spectrum and flavor composition of the beam

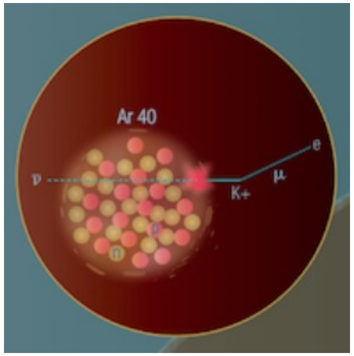
Physics of DUNE



- **Oscillation Physics**
  - Search for CP violation in the ν sector
  - Measure the mass hierarchy
  - Precision measurement of oscillation mixing parameters



- **Supernova Physics**
  - 99% of the energy of a supernova is carried away by neutrinos
  - Observation of the time and flavor profile provides insight into the collapse and evolution of supernova
  - DUNE will have unique sensitivity to ν_e flavor



- **Nucleon Decay/Oscillation Searches**
  - Unique sensitivity for proton decay offered by LArTPC technology ($p \rightarrow \bar{\nu}K^+$)
  - $n\bar{n}$ oscillation and proton decay predicted by beyond SM theories

Liquid Argon Time Projection Chamber

Liquid Argon is an excellent choice for neutrino detectors:

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm³]	0.125	1.2	1.4	2.4	3.0	1
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation [γ /MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	

Note: This table was first produced by Mitch Soderberg and if he had patented it he would have 10's of dollars because it shows up in every LAr talk I've ever seen!

→ **Dense**

40% more dense than water

→ **Abundant**

1% of the atmosphere

→ **Ionizes easily**

55,000 electrons / cm

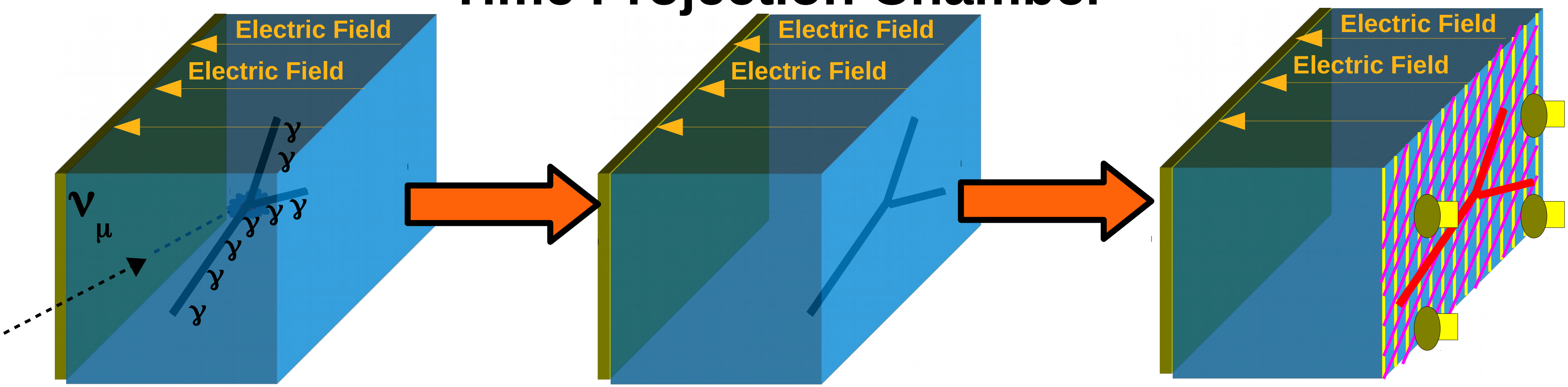
→ **High electron lifetime**

Greek name means "inactive"

→ **Produces copious scintillation light**

Transparent to light produced

Time Projection Chamber

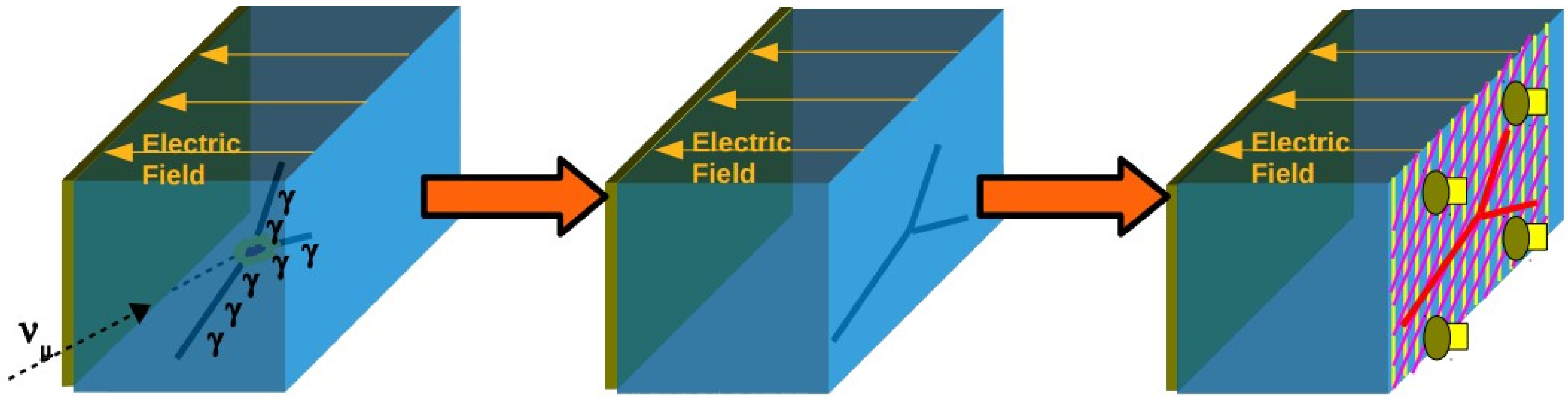


Neutrino interaction in LAr produces ionization and scintillation light

Drift the ionization charge in a uniform electric field

Read out charge and light produced using precision wires and PMT's

LArTPC Wire Readout



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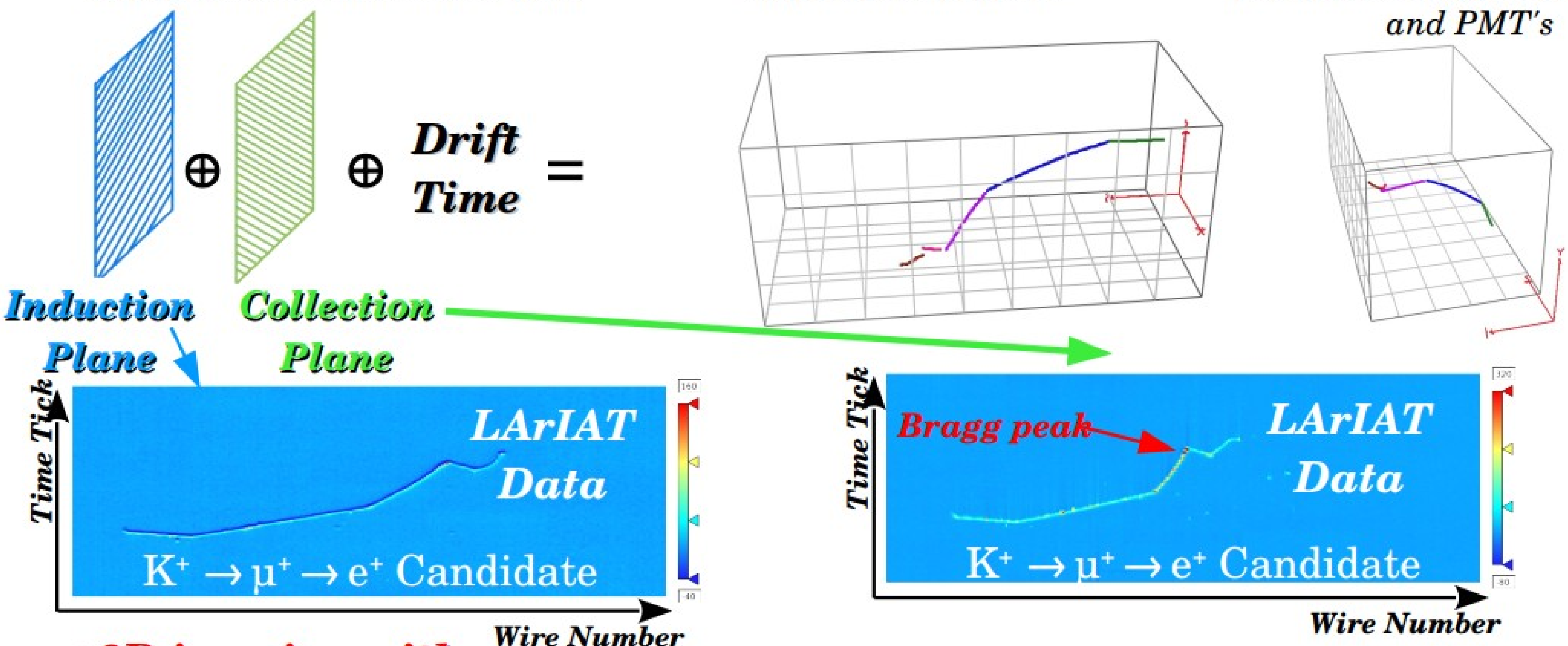
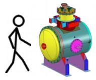


✓ ***3D imaging with mm space resolution***

✓ ***Calorimetry information***

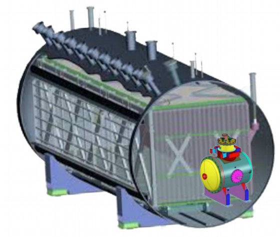
✓ ***PID capabilities***

The Scale of Things....



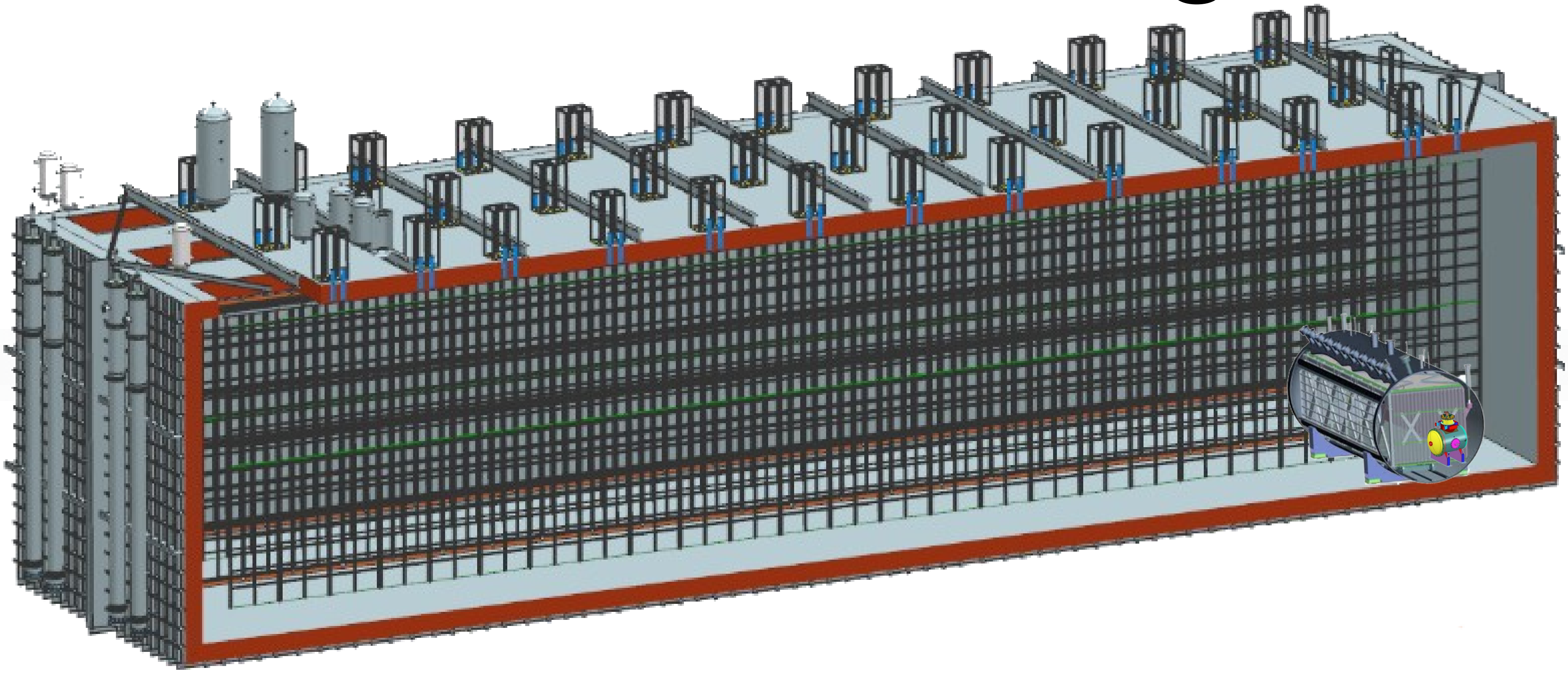
- **One LArIAT TPC (0.25 tons) (0.4 m x 0.47 m x 0.9 m)**
  - Small detector with a big heart!

The Scale of Things....



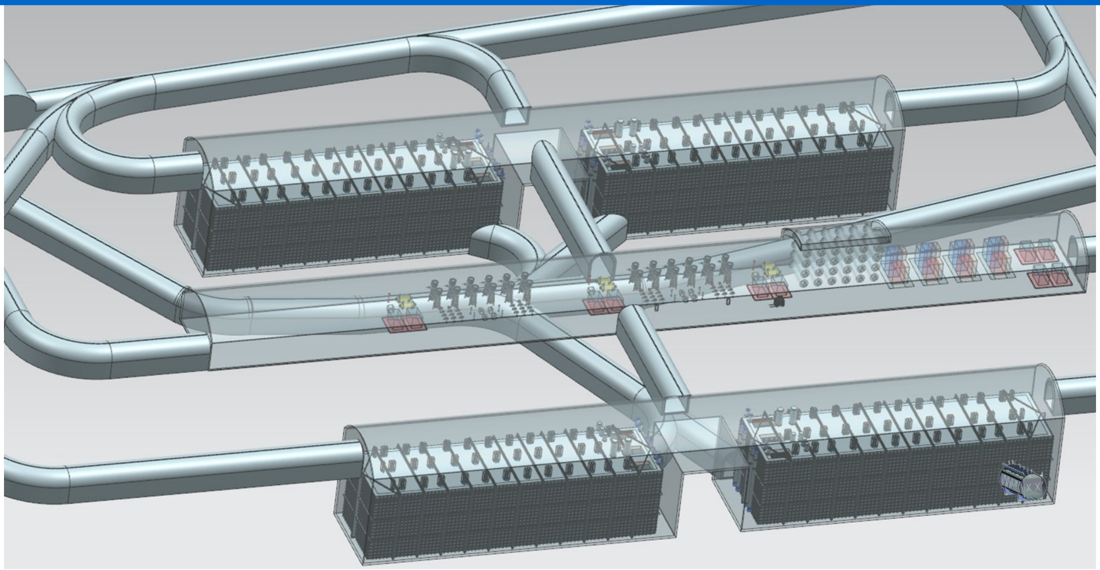
- **One MicroBooNE TPC (80 tons) (2.2 m x 2.5 m x 10 m)**
  - Largest operating LArTPC in the US

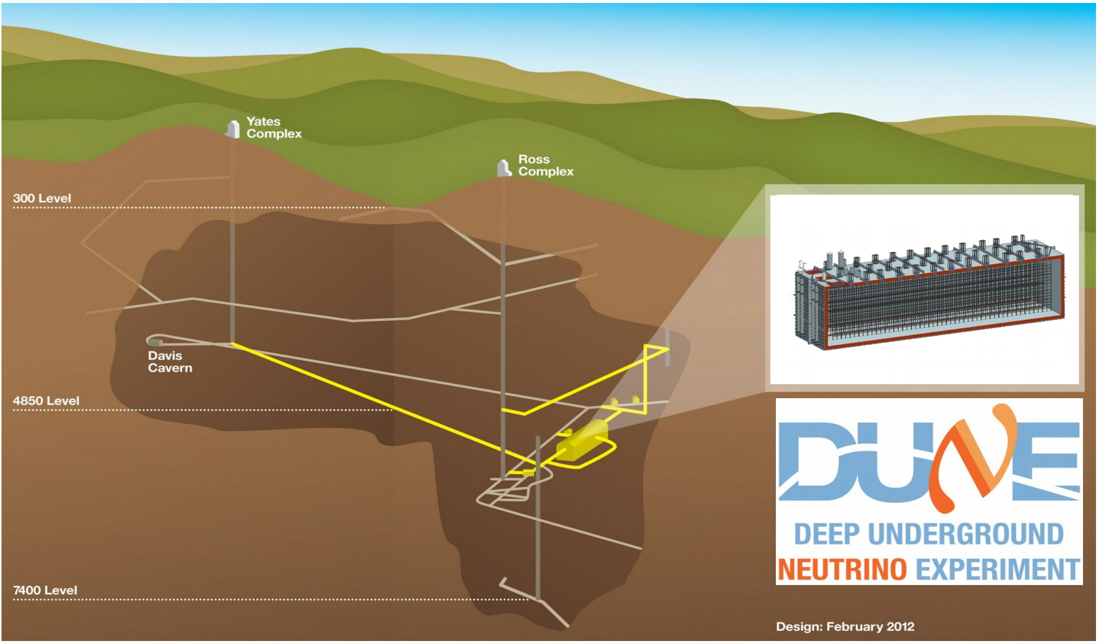
The Scale of Things....



- **One 10kT DUNE LArTPC Module (18 m x 19 m x 66 m)**
  - ¼ the total size of DUNE

The Scale of Things….





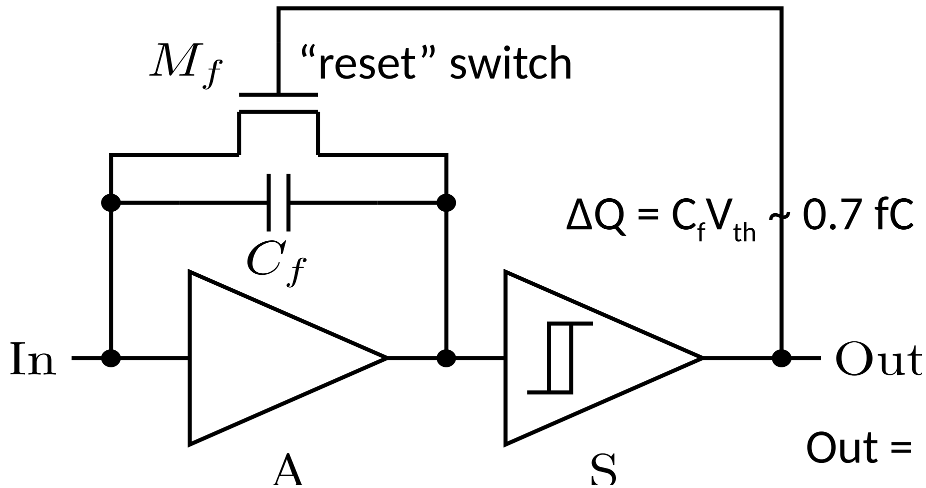
- **Four of these modules will be positioned about 1 mile underground**
  - 1,500,000 channels reading out continuously with GPS time precision
- **Huge "big data" challenge**
  - 1 second of full stream data = 4.6 TB
  - 1 year of full stream data = 145 EB (that's exabytes!!!)
    - We will need smarter ways to readout these detectors and to understand them robustly
- **Need to maximize the detectors for DISCOVERY!!!!**

Q-Pix

- **Original idea put forward by D. Nygren (UTA) and Y. Mei (LBNL)**
  - **Goal**: Optimized discovery potential !
  - LArTPC: information quality is very high, thus the technical pathway must:
    - capture information without compromise !
    - maintain intrinsic 3-D quality !
  - Aspiration: complete pixelization of DUNE FD
    - Immense FD scale → unorthodox solution
    - Electronic principle of “Least Action”
    - New approach: measure time-to-charge: ΔQ
- **A genuine innovation for signal capture:**
  - Detailed waveforms provide: track profiles, track continuity, dE/dx, …
  - Exploit ^{39}Ar decays to provide:
  - automatic absolute charge-energy calibration
  - High intrinsic *single-point-failure* resilience
- **Novelty does not automatically confer benefit!**
  - Much remains to be explored…

Q-Pix

The Charge Integrate-Reset (CIR) Block



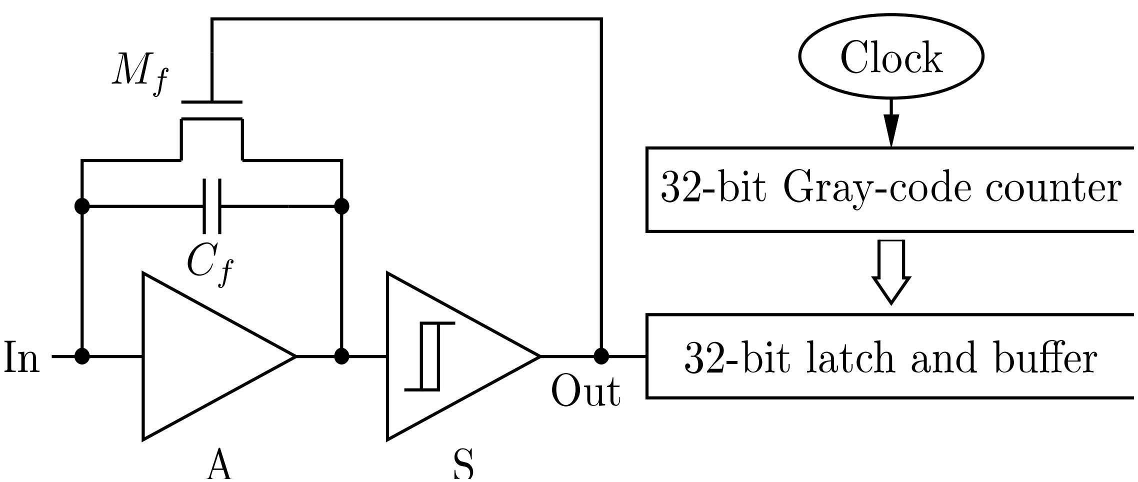
$\Delta Q = C_f V_{th} \sim 0.7$ fC ($4.4ke^-$)

Out = "reset"

A = Charge sensitive amplifier

S = Schmitt trigger

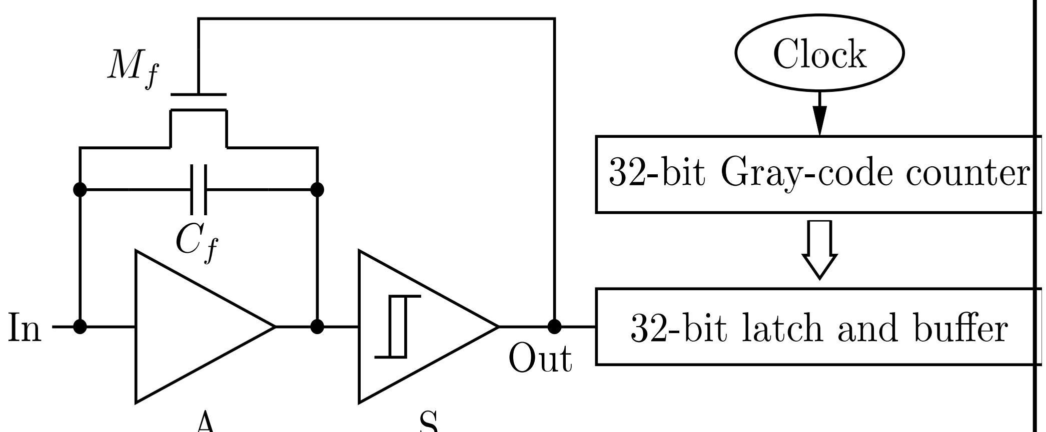
V_{th} = threshold



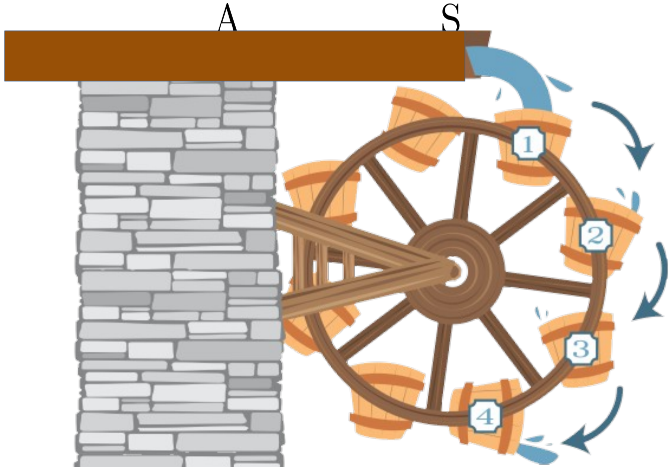
- **Measure the time of "reset"**
  - Clock is local (within the ASIC)
    - Free-running oscillator @ 50-100MHz
  - Basic Datum is 64 bits: 32 bit time + pixel addresses + ASIC ID + configuration + ...

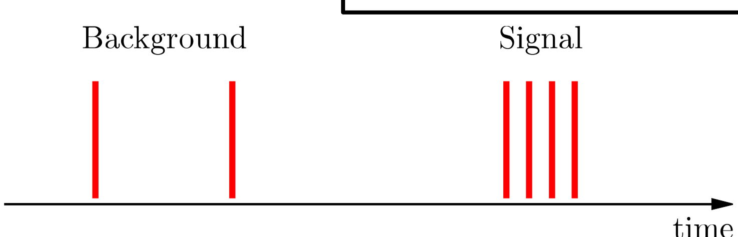
What is new here?

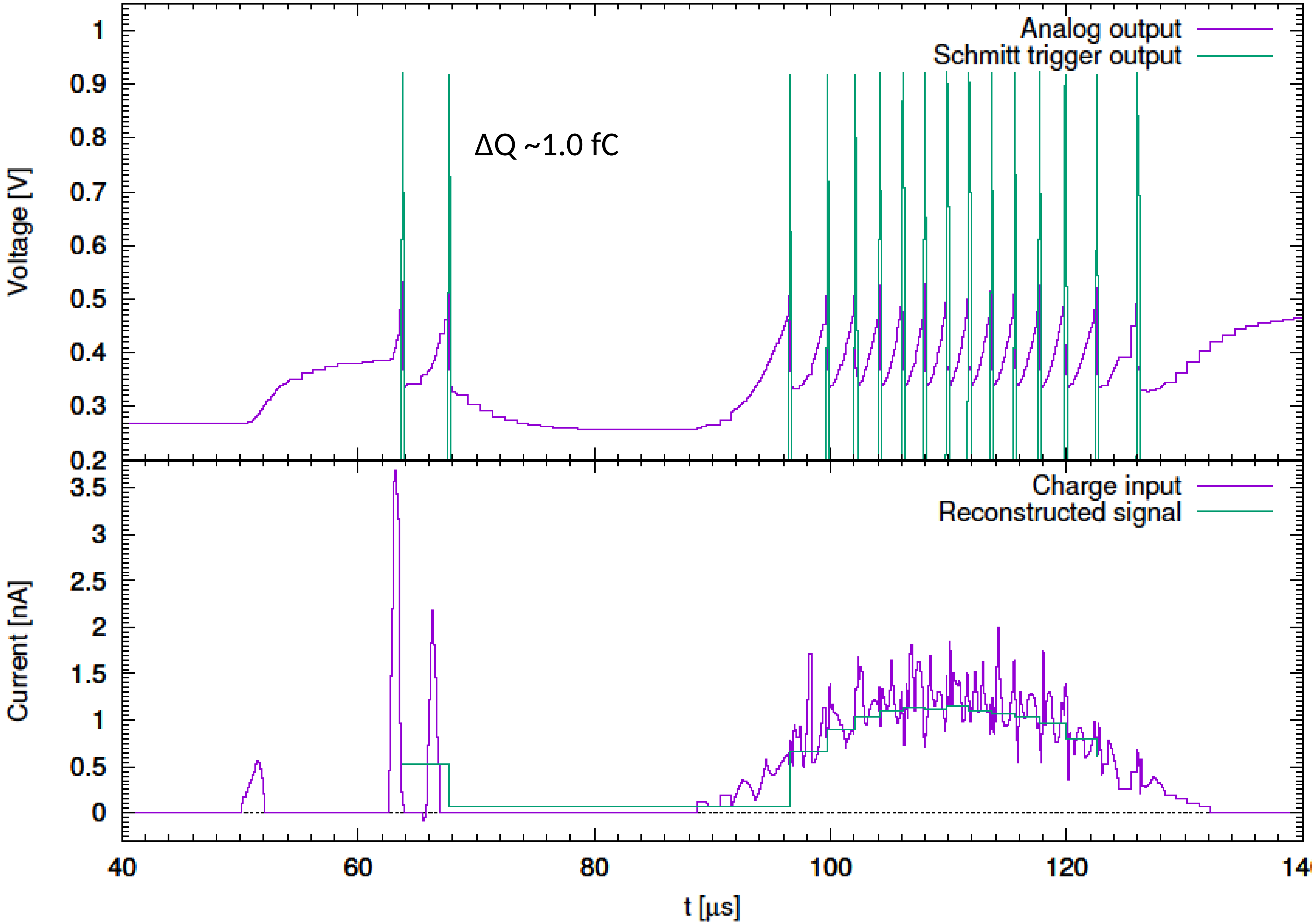
- **Take the <u>difference</u> between <u>sequential</u> resets**
  - This is the **Reset Time Difference = RTD**
  - Total charge for any **RTD = ΔQ**
- **RTDs are not generated at ASIC level;**
  - **RTDs** are computed off-detector



- **RTDs capture the waveform**
  - **RTD** measures instantaneous current
  - Small average current (background): <u>Large</u> RTD
    - "Background" current from ^{39}Ar is ~100 aA
  - Large average current (signal): <u>Small</u> RTD
    - Typical track current from min-I is ~1.5 nA
  - **S/B ~ 10^7**
  - **Background and signal are easy to distinguish**

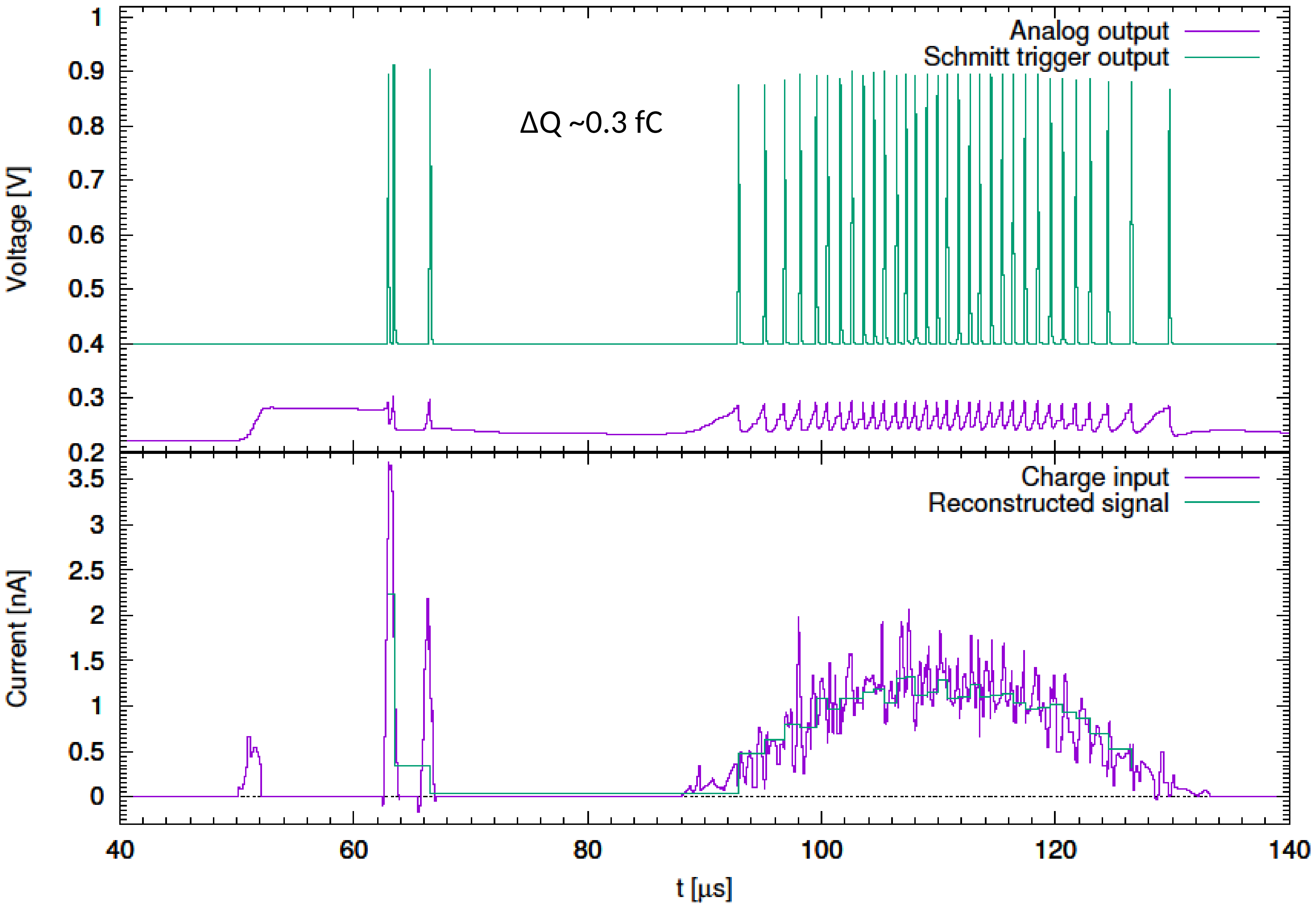






Signal: a contiguous sequence of small RTDs

A conventional current waveform of arbitrary length and complexity can be reconstructed from the RTD sequence.



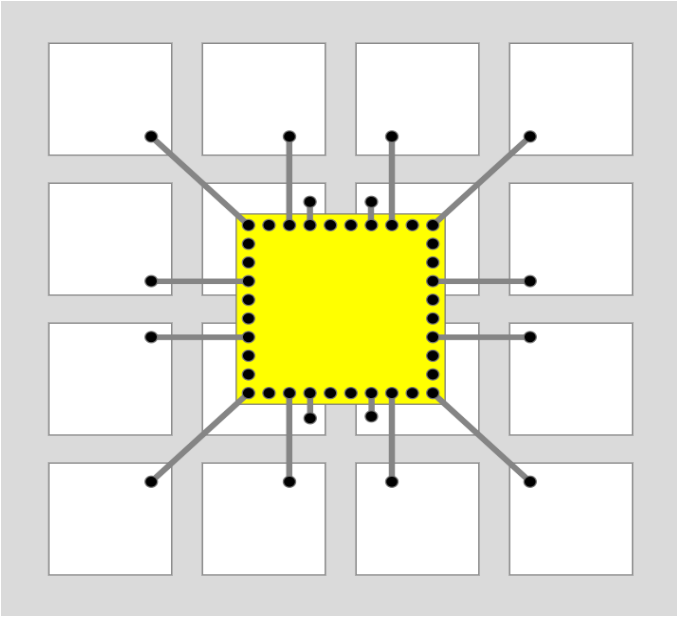
Analog output
Schmitt trigger output
ΔQ ~0.3 fC
Voltage [V]
Charge input
Reconstructed signal
Current [nA]
t [μs]

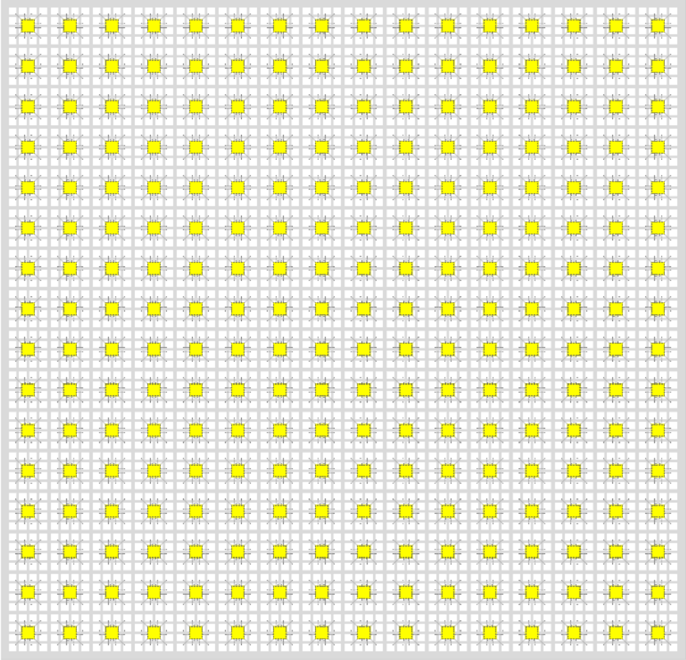
How the time stamping works

- **One clock per ASIC runs freely (50-100 MHz)**
  - Require that the local clock is stable
    - δf/f < 1 x 10-6 per second
- **The time stamping routine has the ASIC asked once per second “what time is it?”**
  - ASIC captures local time and sends it at ~1 Hz
  - Simple linear transformation to the master clock sync to GMT
- **Has this idea been realized before?**
  - YES!!! In ICECUBE (by Nygren)
    - +/- 2ns RMS in 1km of ice
    - Oscillator precision in IceCube is ~1x10-10 /s (difficult to measure)
- **DUNE will require +/- 1 microsecond precision**
  - δf/f < 1 x 10-6 per second
    - Probably easy to achieve in LAr

Q-Pix ASIC Concept

- **16-32 pixels/ASIC**
  - 1 Free-running clock/ASIC
  - 1 capture register for clock value, ASIC, pixel subset
  - Necessary buffer depth for beam/burst events
  - State machine to manage: dynamic network, token passing, clock domain crossing, data transfer to network, exception states (many details still to be worked out)
- **Envisioned building "tiles" of 16x16 ASICs (4092 4mmx4mm pixels)**
  - Tile size of 25.6 cm x 25.6 cm





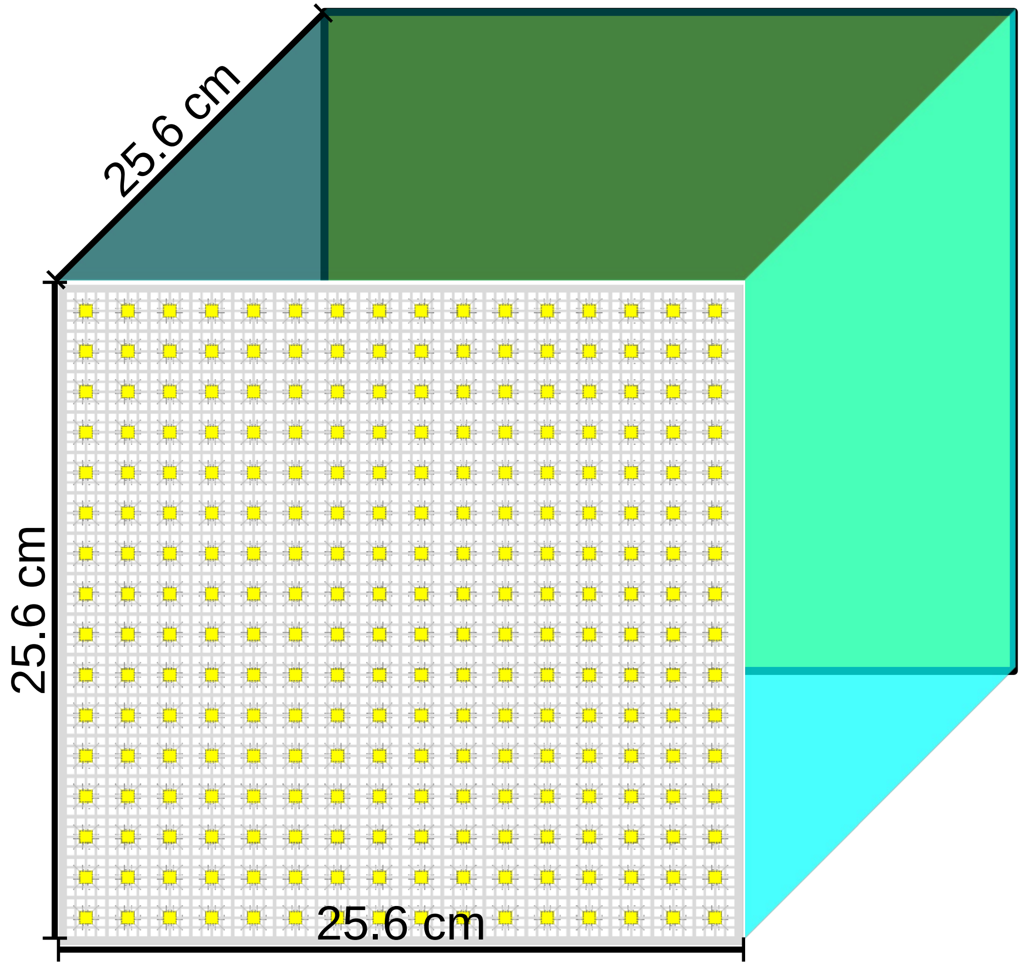
Many ideas still being ironed out

Four central ideas still being worked on

- **CIR Input:**
  - all extraneous leakage currents at the CIR input node are small compared to ^{39}Ar current
  - This must be tested in a realistic setup…
- **Clock:**
  - Must be stable: $\delta f/f < 1 \times 10^{-6}$ per second
  - I think this will be easy…
- **Surface Charge Creep:**
  - Must be negligible relative to ^{39}Ar current
  - This may require surface physics expertise…
- **Light Detection with pixel boards:**
  - Existing solutions for pixel readout light detection exist (are they sufficient for DUNE-FD?)
  - New ideas using a-Se coating being pursued (crazy idea?)
  - Looking into manufacturing transparent PCB's (cost?)
- **Small consortium of universities and labs are pursuing this effort**
  - UTA, U. Penn, U. Hawaii, Harvard, Argonne, LBNL
  - More collaboration always welcome!

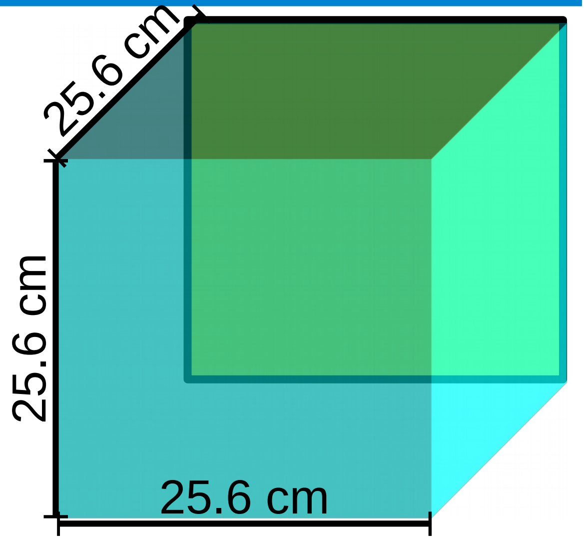
Proposed Ideas for TAMU Project

- Goal
  - Produce a small scale simulation of the signal output of a Q-Pix pixel LArTPC detector seeing charged particles from neutrino interactions
  - Use this simulation to inform questions on circuit design, performance requirements, and

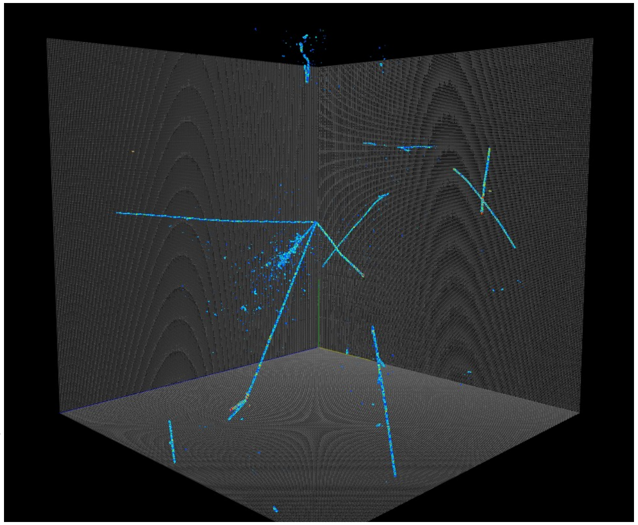


First steps

- **Using standalone GEANT4 simulation, construct a simple liquid argon detector**
  - Cube of liquid argon floating in space

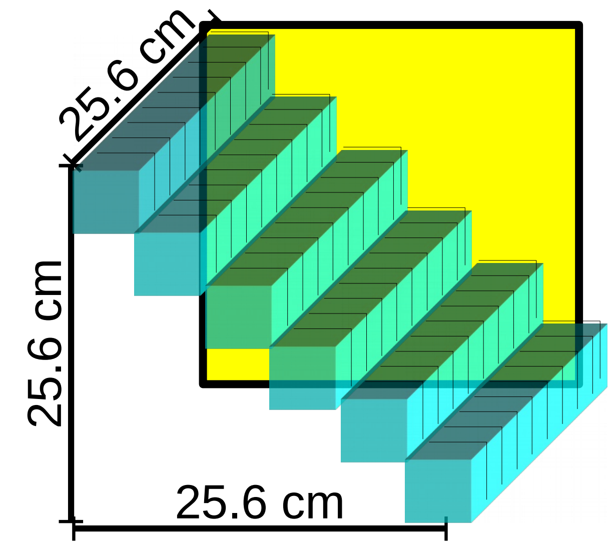


- **Simulate single charged particle interacting in the volume producing ionization**
  - Launch muons, pions, electrons, etc….
  - Momentum range 100 MeV – 2 GeV
    - Might just start with all the same momentum (500 MeV) for the particle types

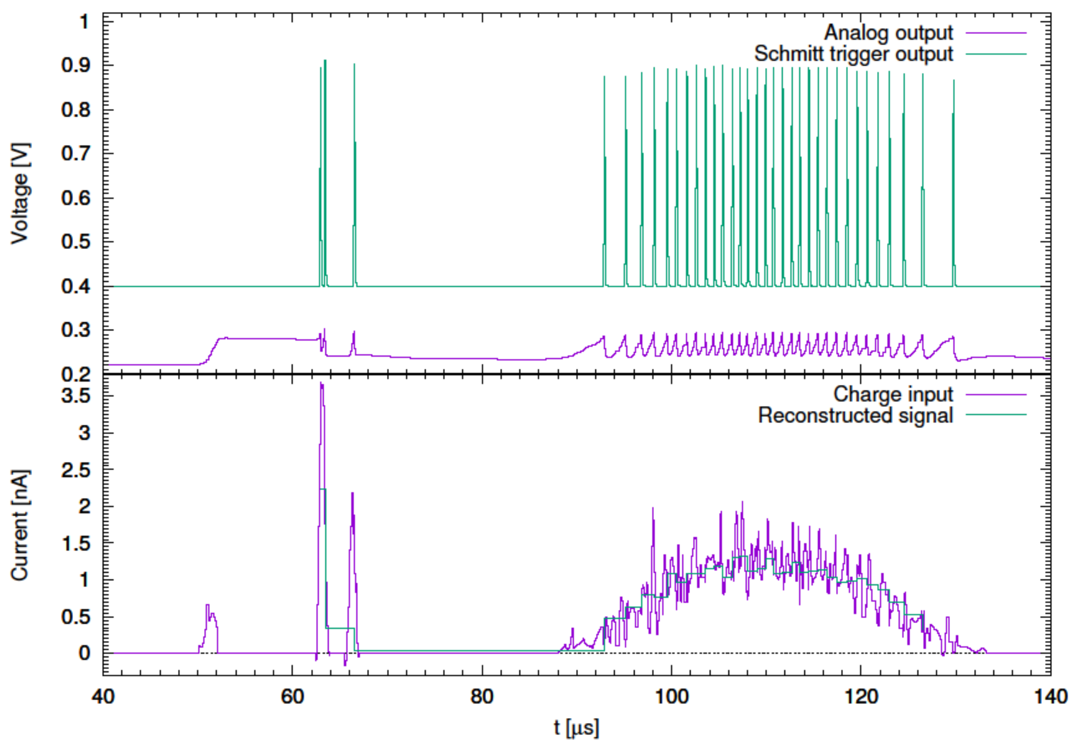


First steps

- **“Voxelize” the detector (4mm height, x 4mm length x 0.2 mm in drift direction)**
  - This allows a very crude translation from number of ionization electrons produced in a voxel to a current which will be seen by a Q-Pix detector

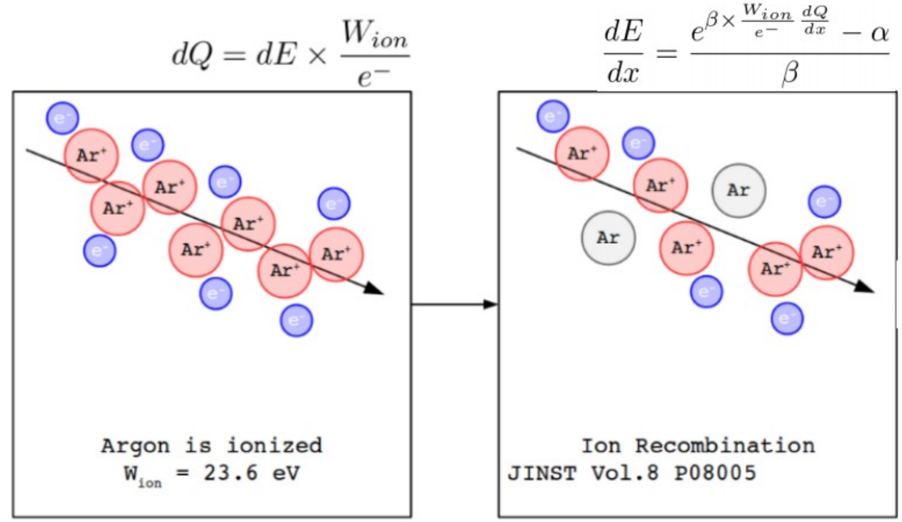


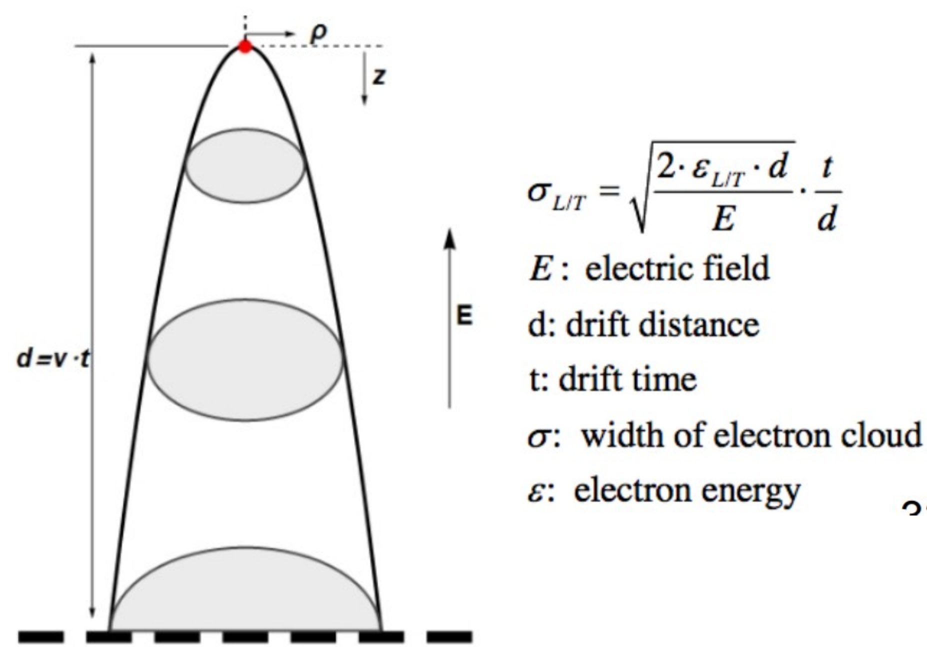
- **Translate this current into a similar input as what was first used in the initial Q-Pix study**
  - Focused on producing the purple lines in the figure on the right



Next steps

- **This model would assume 100% electron transport with no recombination, no impurities, and no diffusion**
  - Could add each of these pieces as a small add-on package to make the current simulation more and more realistic
  - Computational versions of implementing all of these exist in the literature and in some example code (don't have to reinvent the wheel)
    - https://arxiv.org/pdf/1503.00377.pdf
    - https://pubs.acs.org/doi/full/10.1021/jp201149w
    - https://arxiv.org/pdf/1306.1712.pdf





Next steps

- Once the steps for single particle simulation look like they are understood, could move to doing full neutrino interactions, looking at supernova neutrinos, thinking about exotic signatures….skies the limit
- **Simple set of starting tools**
  - Python based package for working with Geant4 has been developed by some of our collaborators at LBNL
    - https://github.com/dadwyer/argon_box
  - Some details on using GEANT4 standalone
    - http://ftp.jaist.ac.jp/pub/Linux/Gentoo/distfiles/BookForAppliDev-4.10.1.pdf
  - Two students of mine developed (about two years ago) a nice user interface for C++ based interations with GEANT
    - https://github.com/Davenport-Physics/DarkGeant4