

Q-Pix: Kiloton-scale pixelated liquid noble TPCs

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(on behalf of the Q-Pix consortium)

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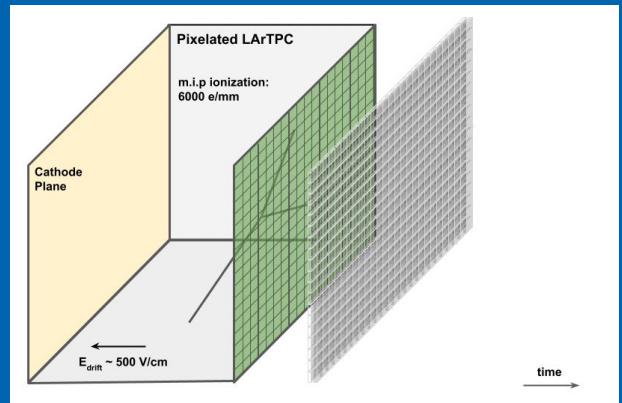
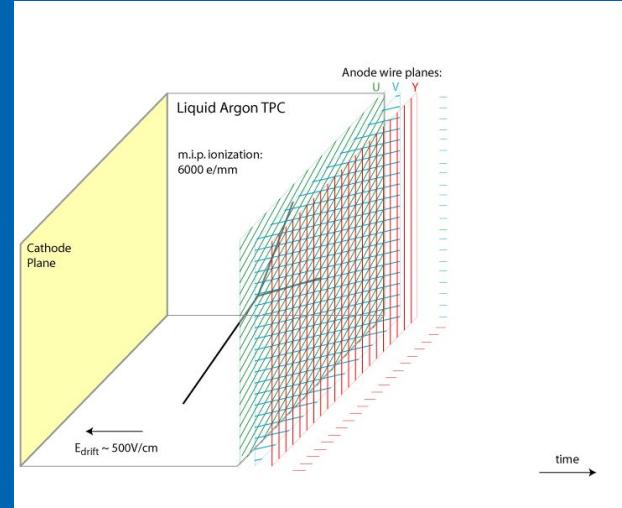


Q-Pix consortium would like to thank the DOE for its support via DE-SC0020065 award, DE-SC 0000253485 award, and FNAL-LDRD-2020-027

Work based on original paper by Dave Nygren (UTA) and Yuan Mei (LBNL): arXiv:1809.10213

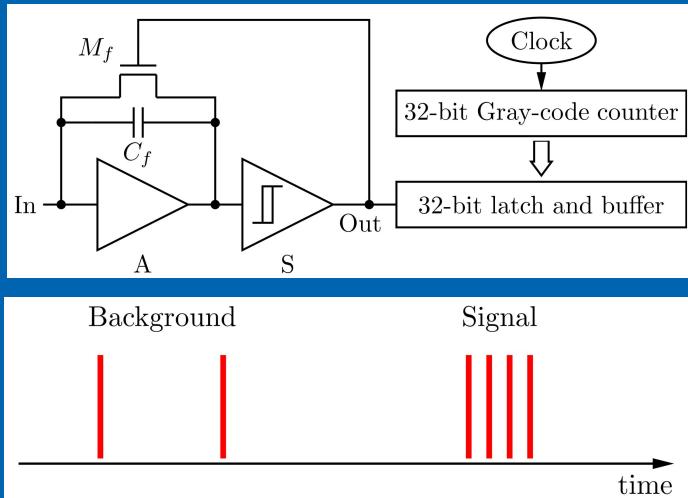
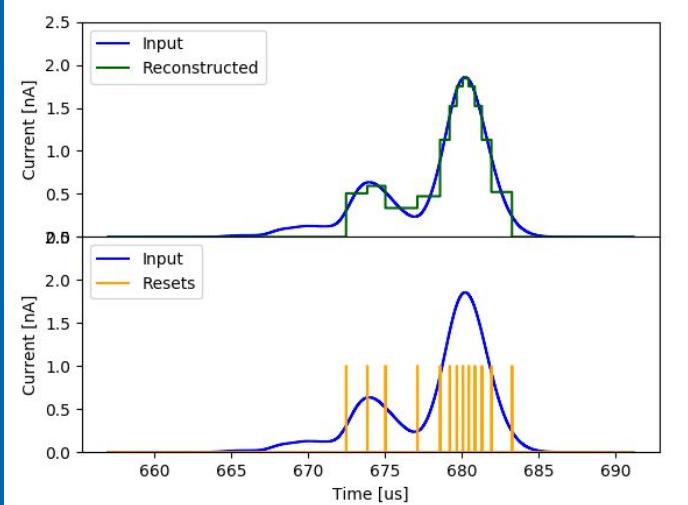
What is Q-Pix?

- Q-Pix is a novel readout solution that is attempting to solve the problem of how do you readout large (kiloton scale) LArTPC's using 3D pixel based readout
 - (Example: 2 meter x 2 meter readout)
 - 3mm wire pitch w/ three planes = 2450 channels
 - 3mm pixel pitch = 422,000 channels
 - LArPix ([JINST 13 P10007](#)) readout has pioneered this frontier showing a low power pixel based readout can be done
- Q-Pix is targeting its design around an environment where most of the time there is nothing of interest happening (e.g. large scale, underground detector), but where you want to be ready instantly to capture signals at the very threshold of detection

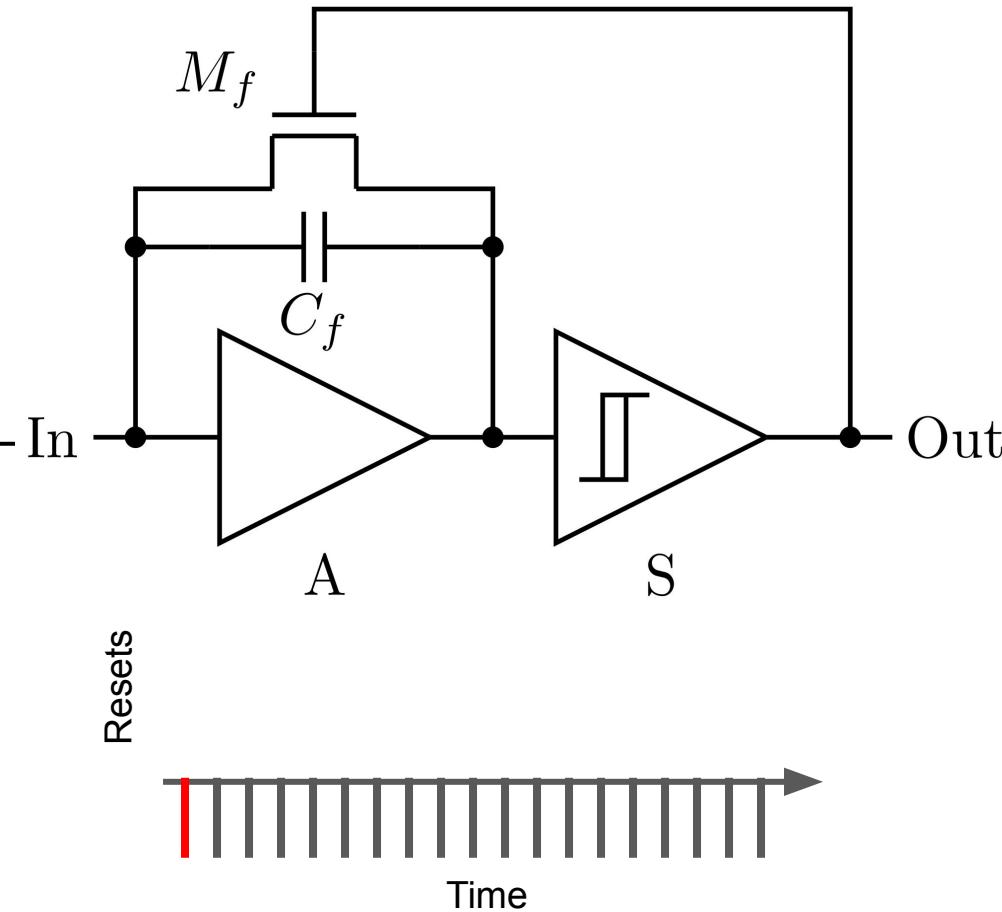
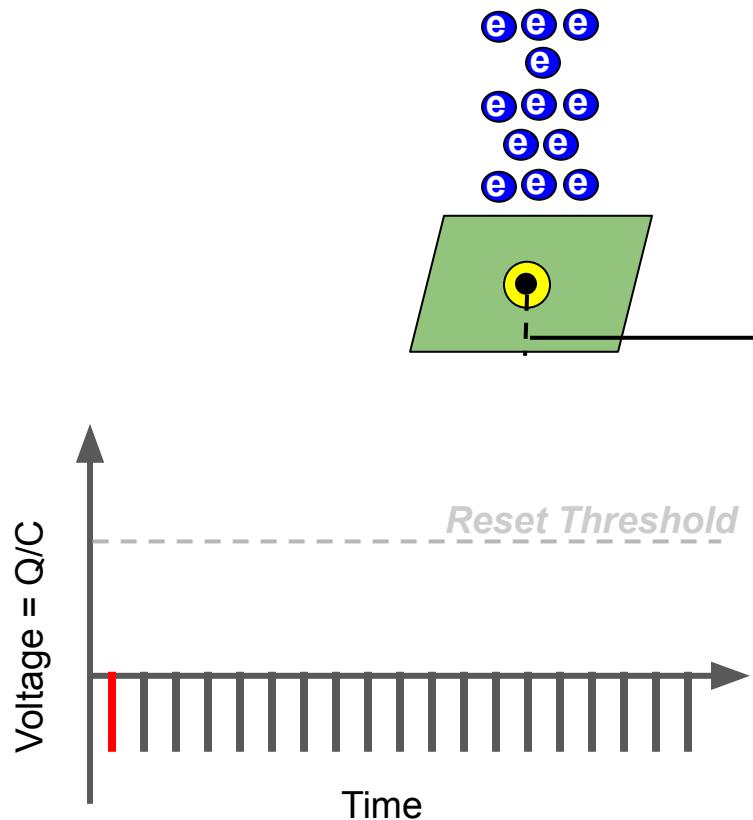


Q-Pix: An “unorthodox” solution

- The Q-Pix pixel readout follows the **“electronic principle of least action”**
 - **Don’t do anything unless there is something to do**
 - Offers a solution to the immense data rates
 - Allows for the pixelization of massive detectors
- Q-Pix offers an innovation in signal capture with a new approach and measures **time-to-charge:(ΔQ)**
 - Keeps the detailed waveforms of the LArTPC
 - Opens the door to other innovative technical solutions (e.g. novel VUV photon detection)

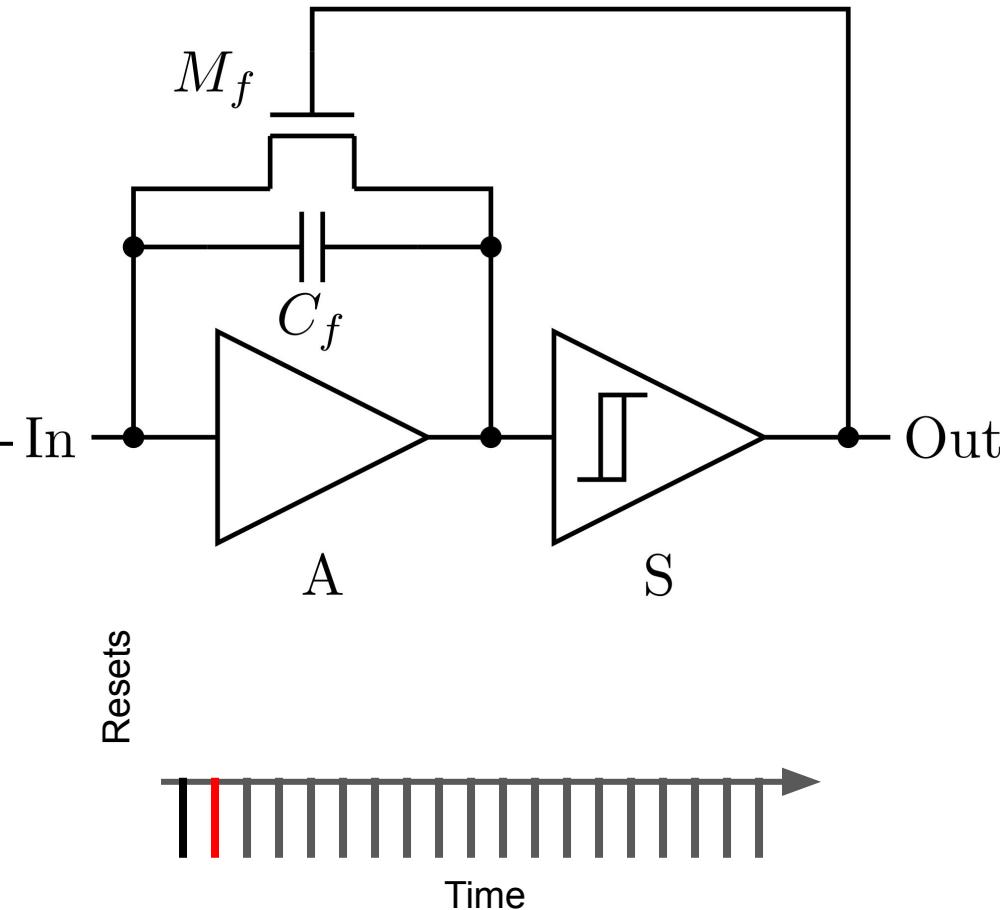
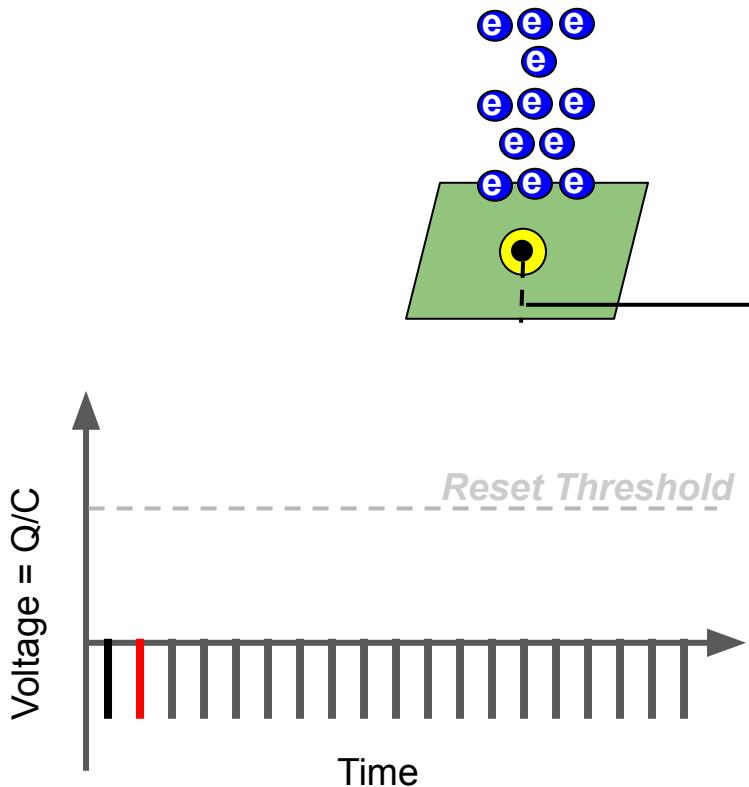


Toy Example



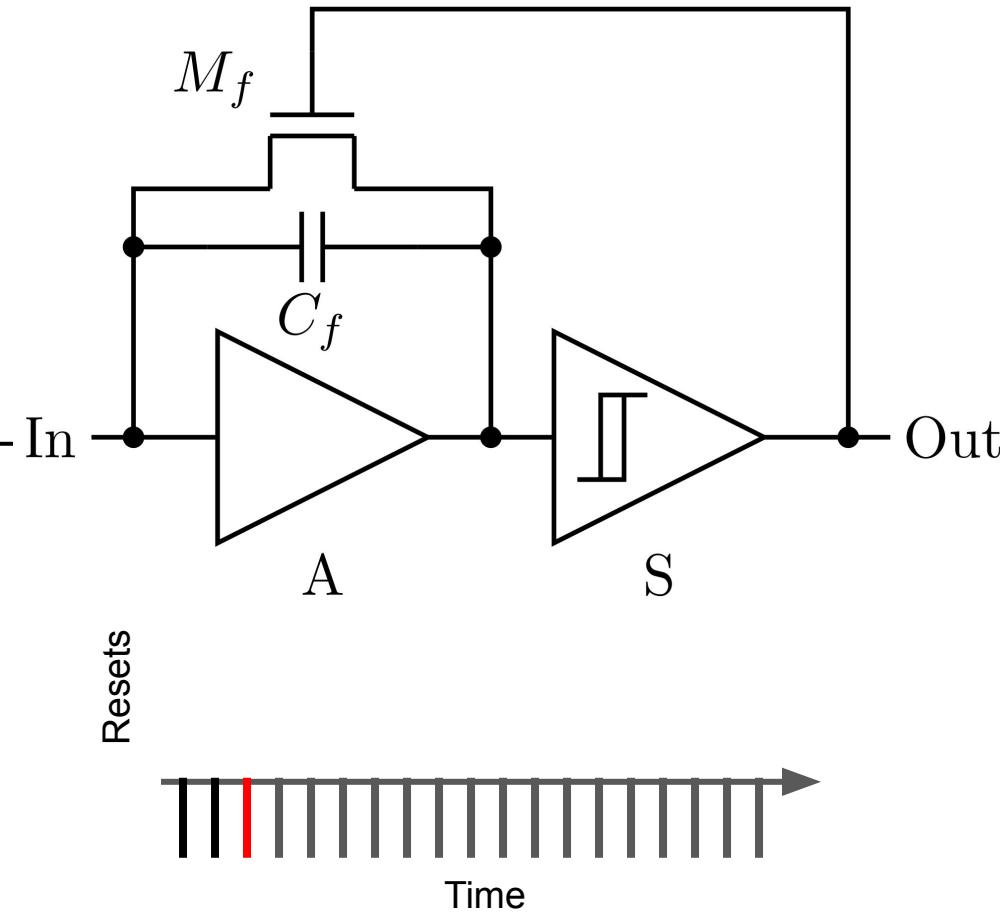
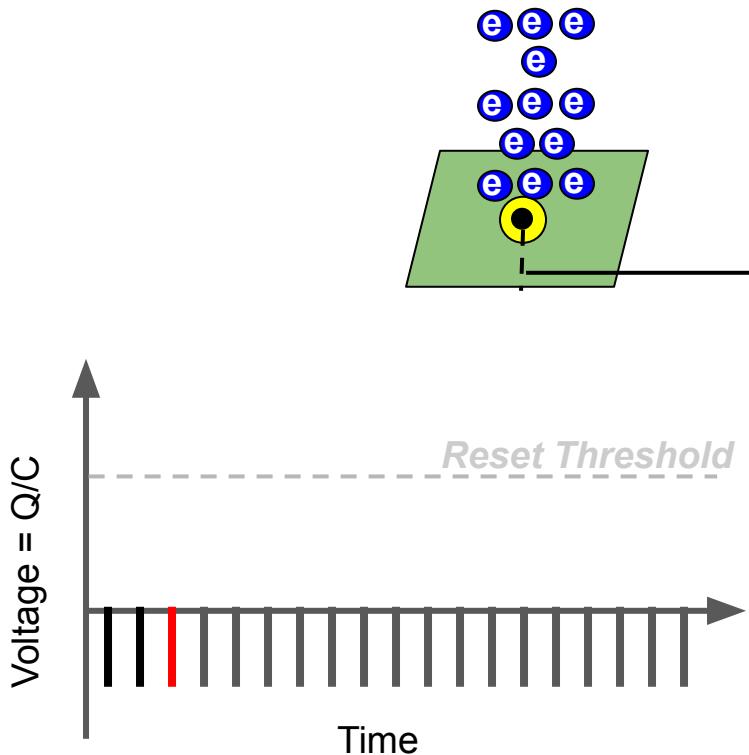
Note: We'll assume the RTD happens for 5 electrons, the reset happens faster than the drift of the next bunch, and this occurs without charge loss

Toy Example



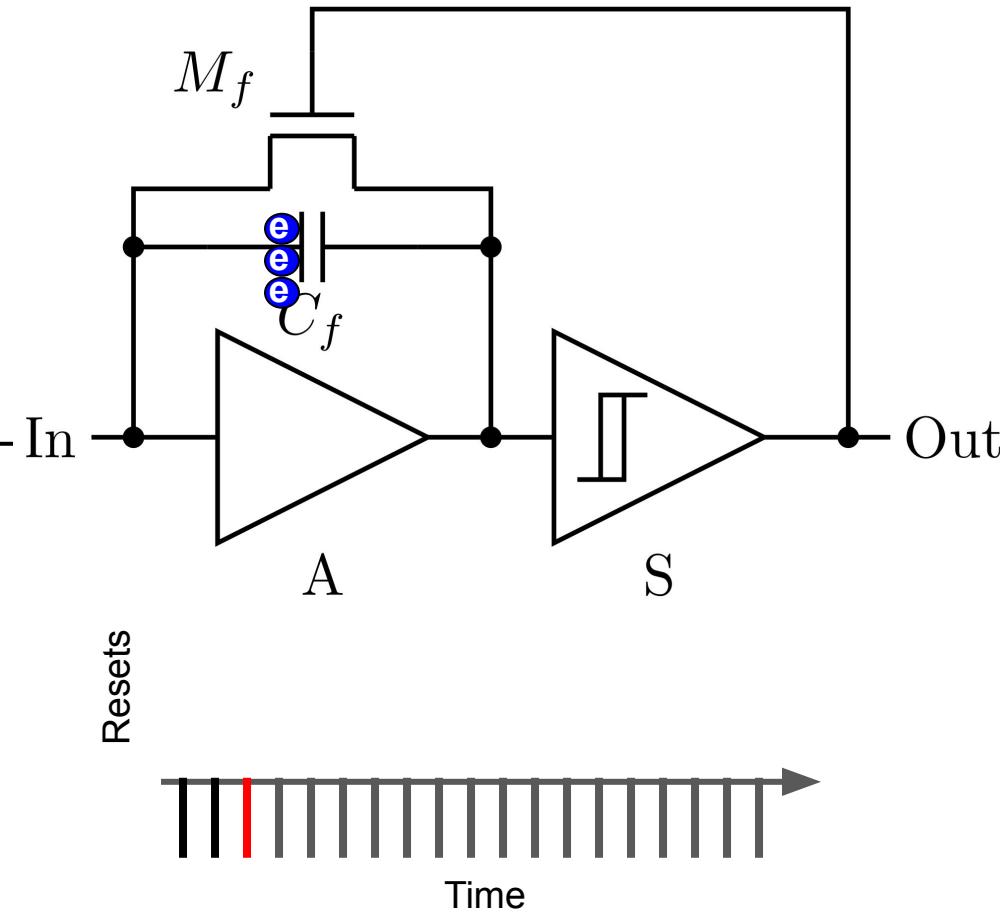
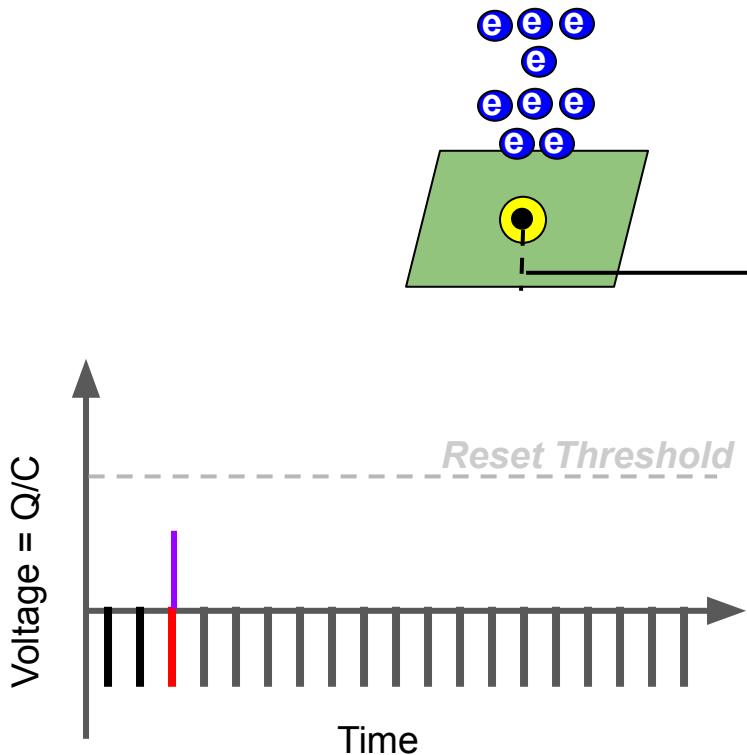
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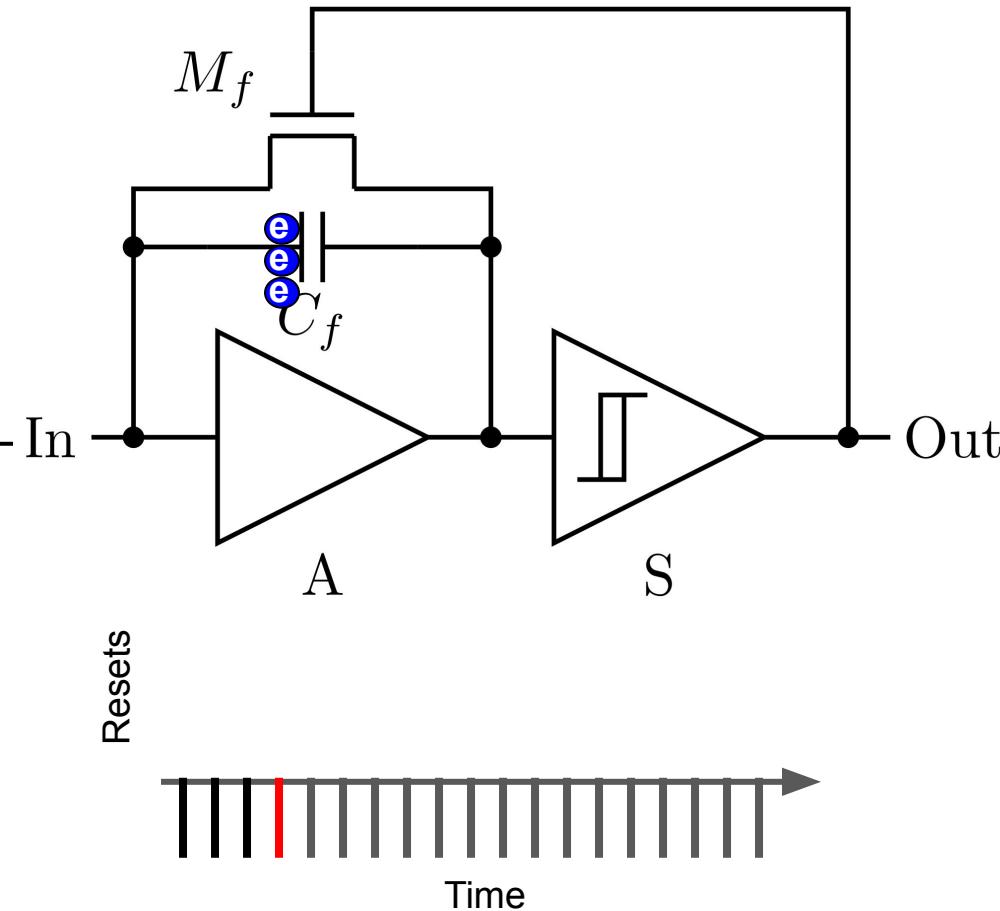
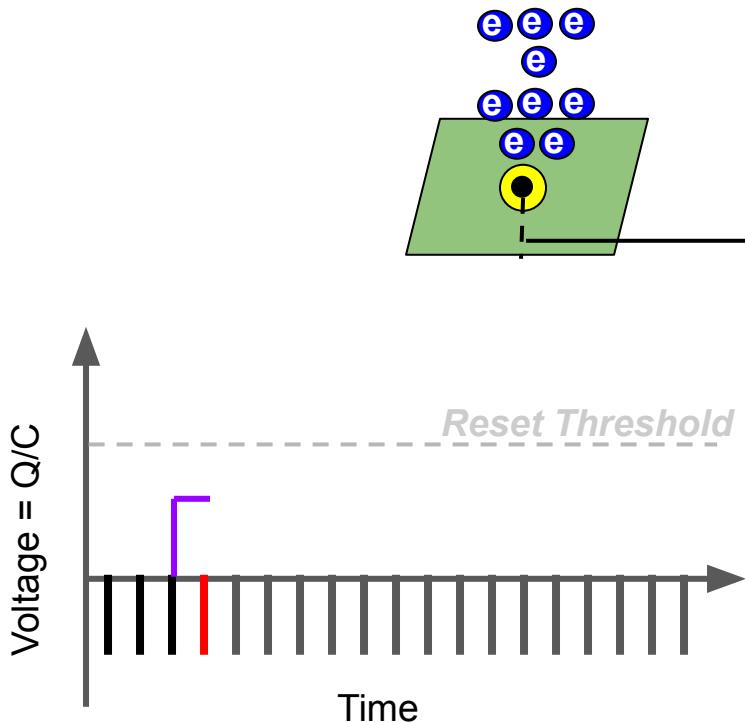
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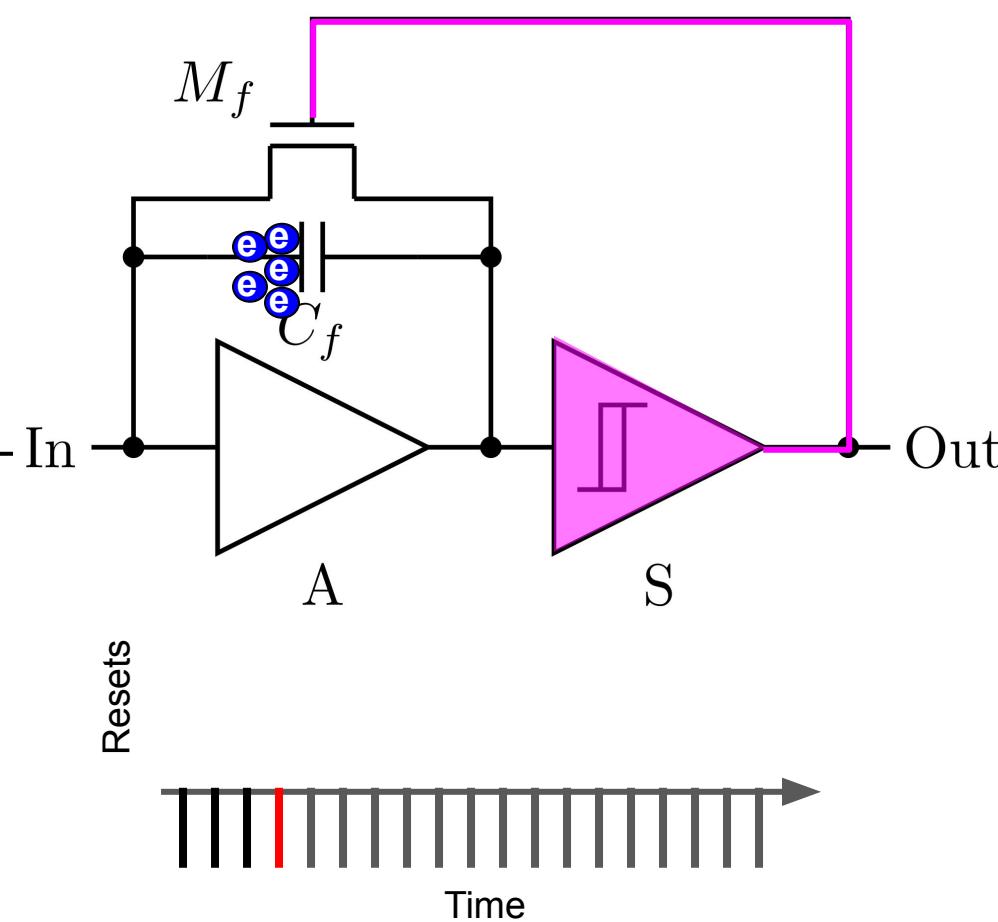
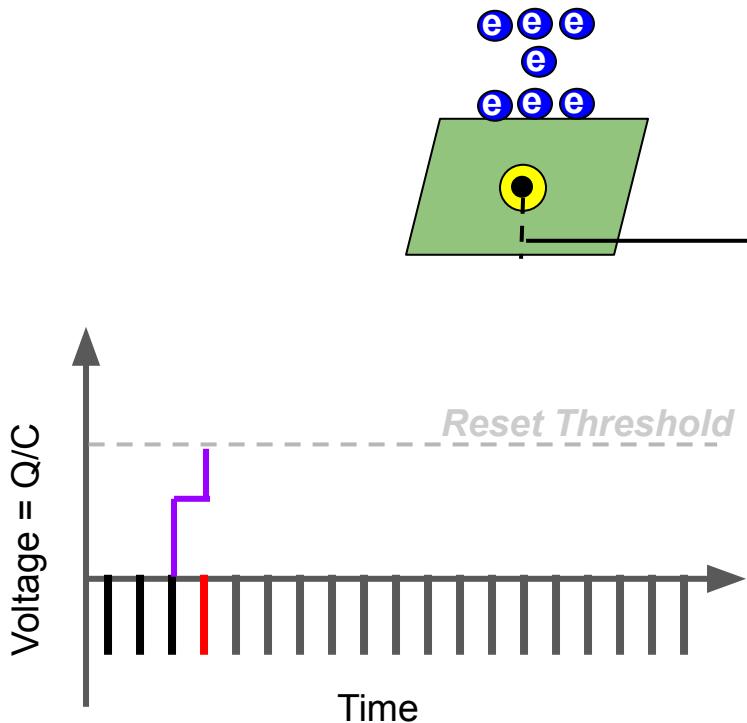
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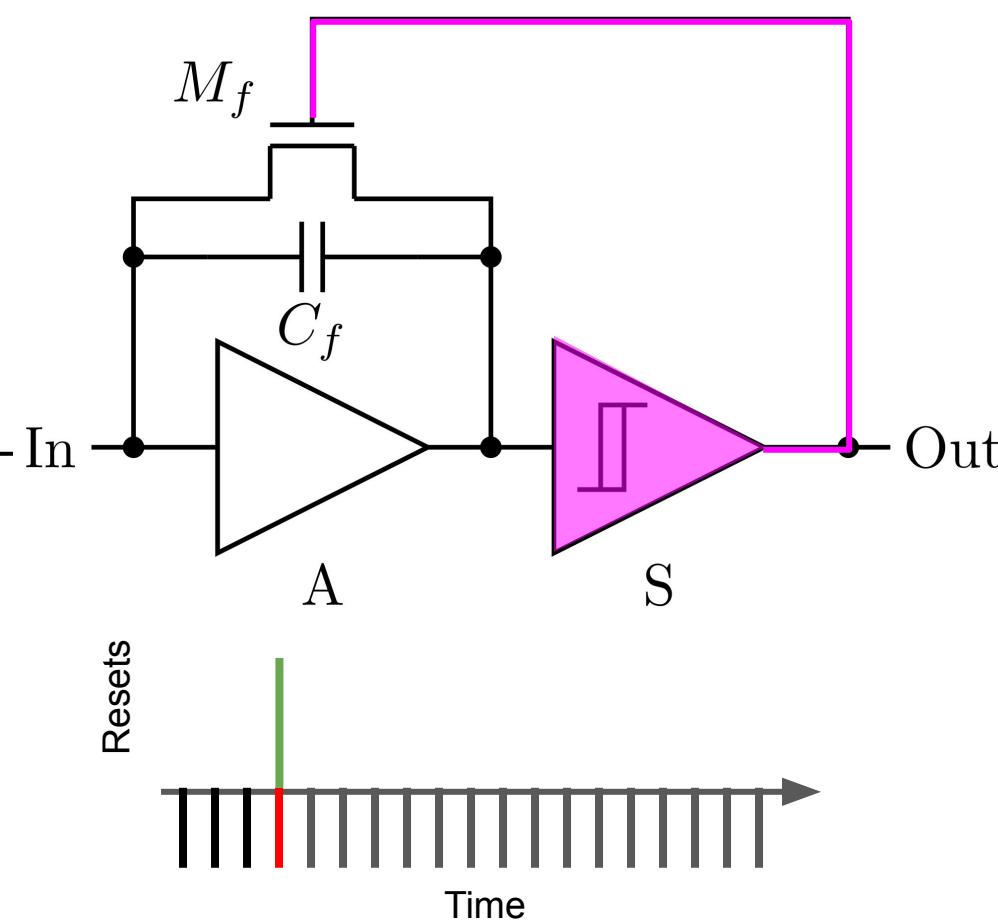
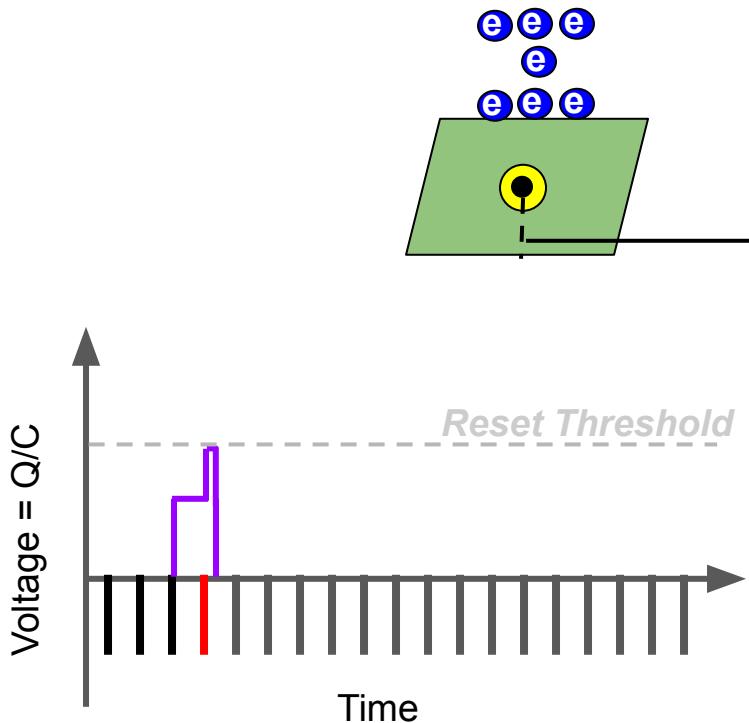
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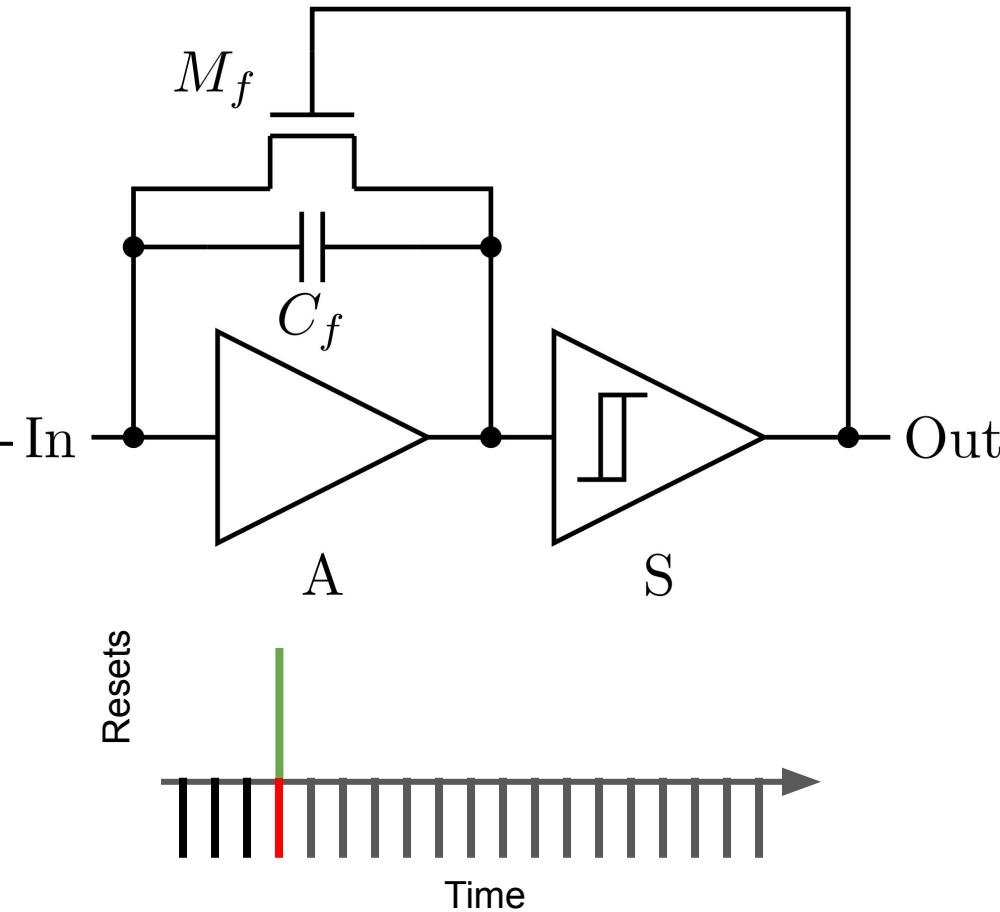
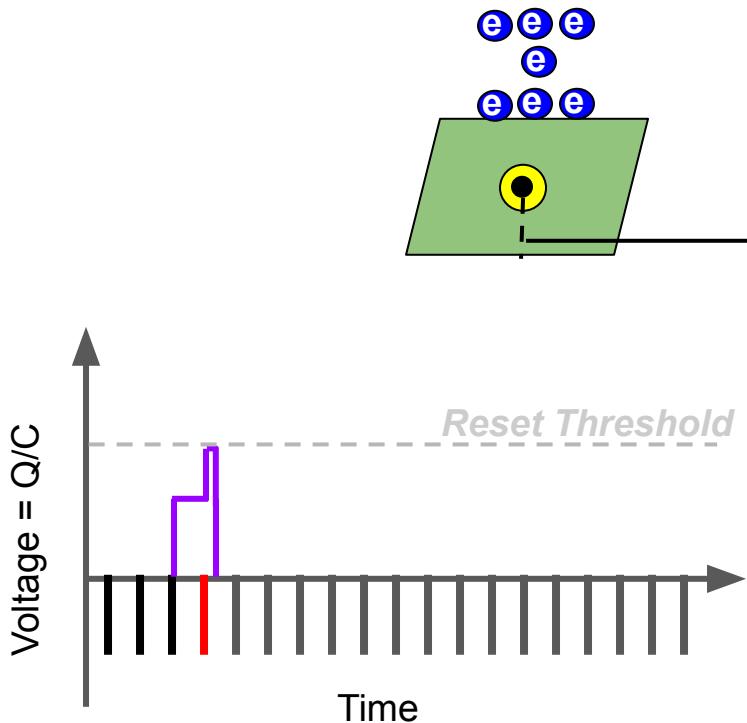
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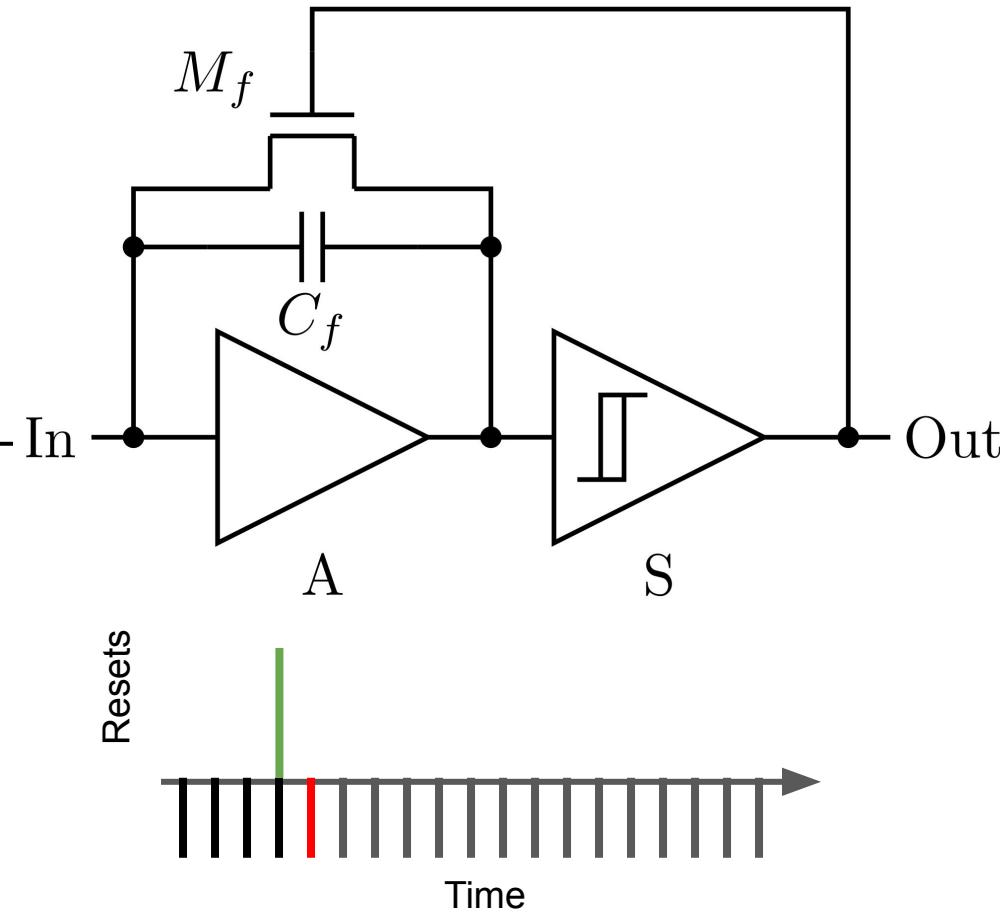
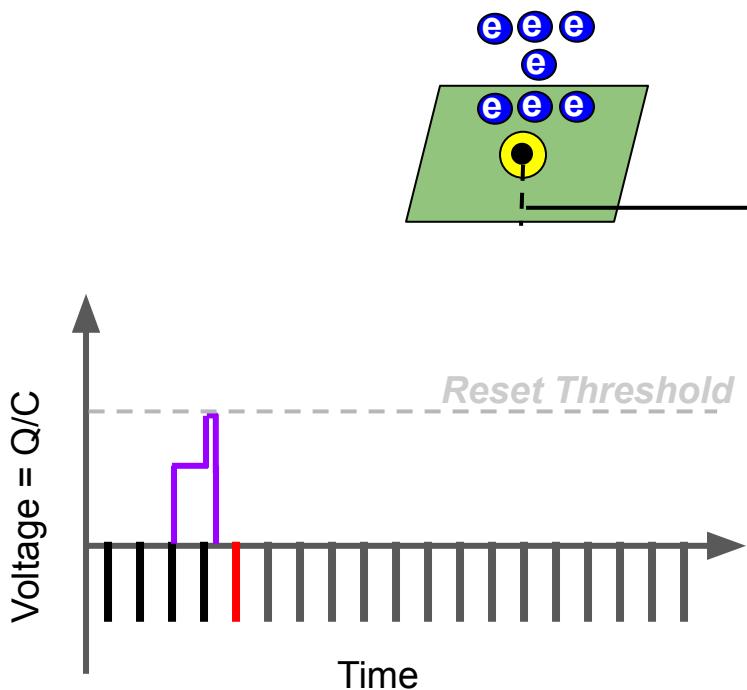
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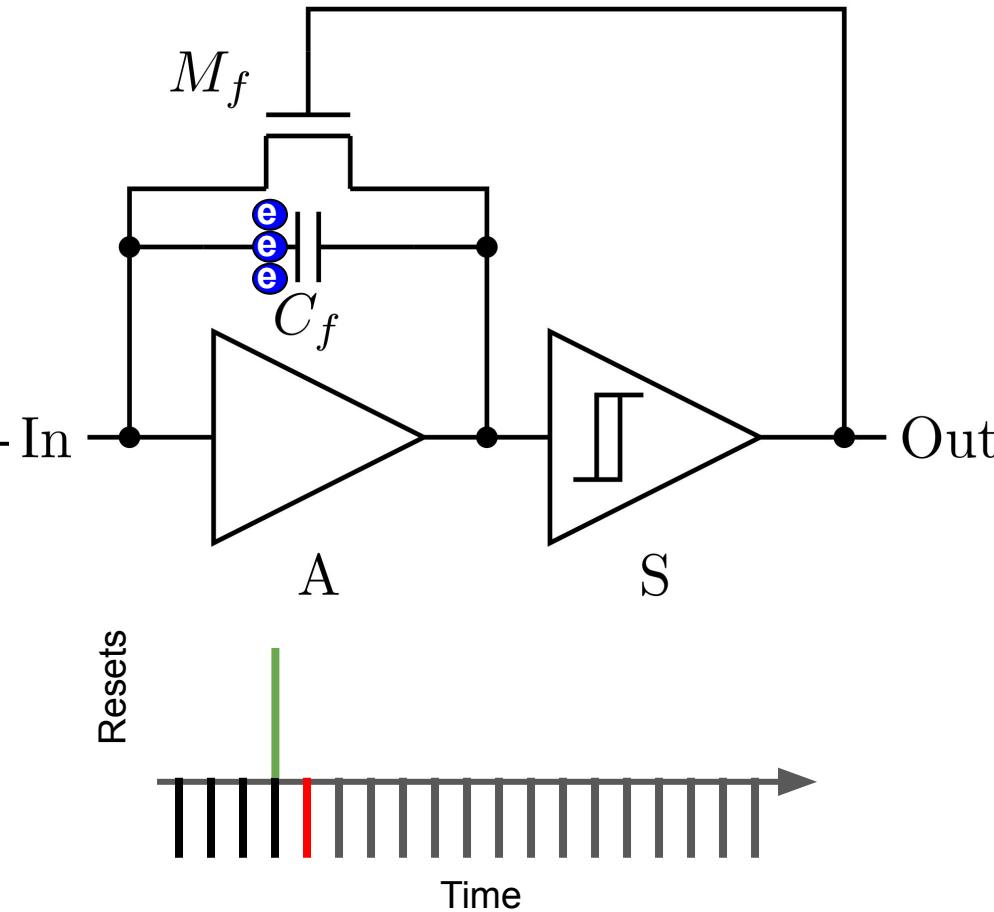
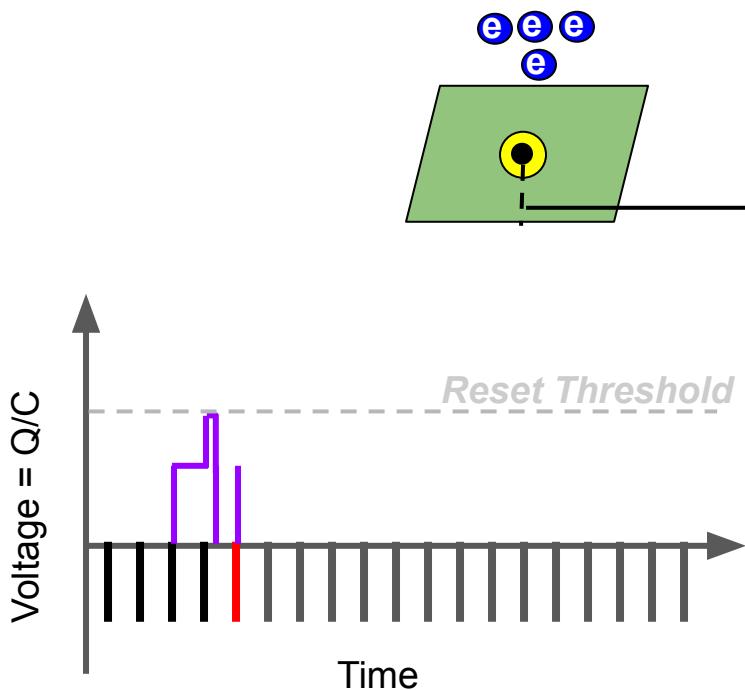
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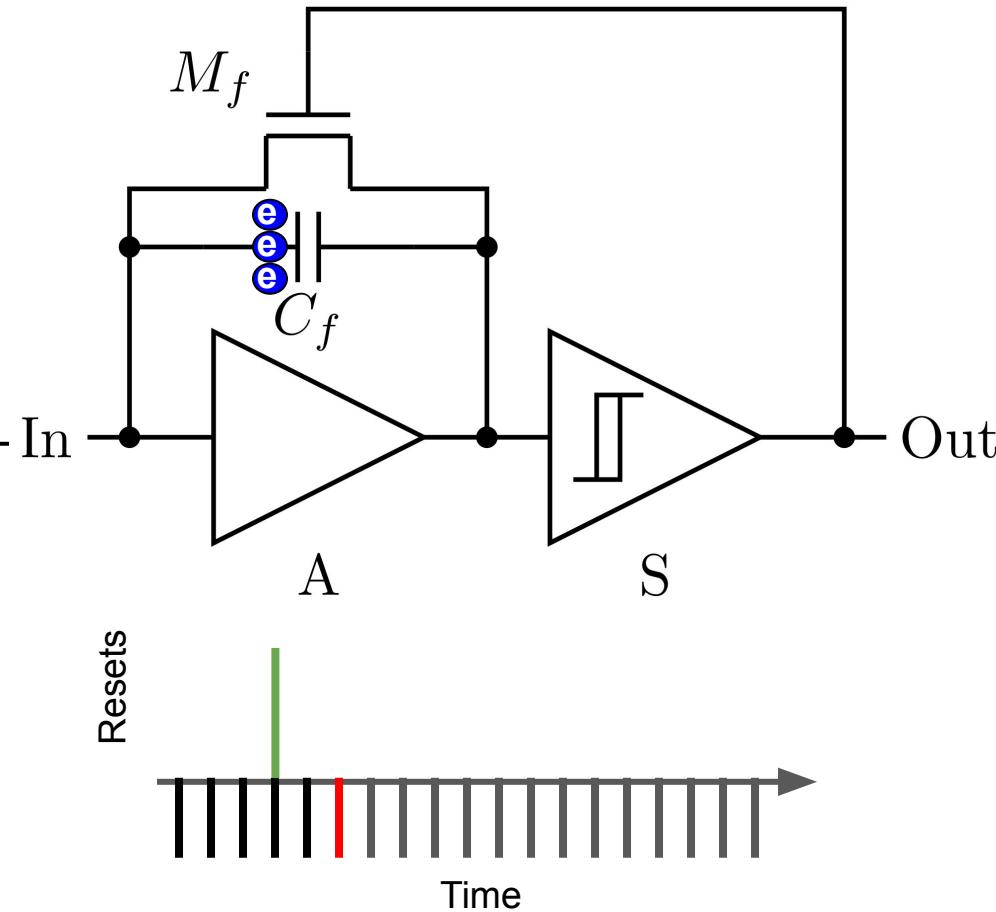
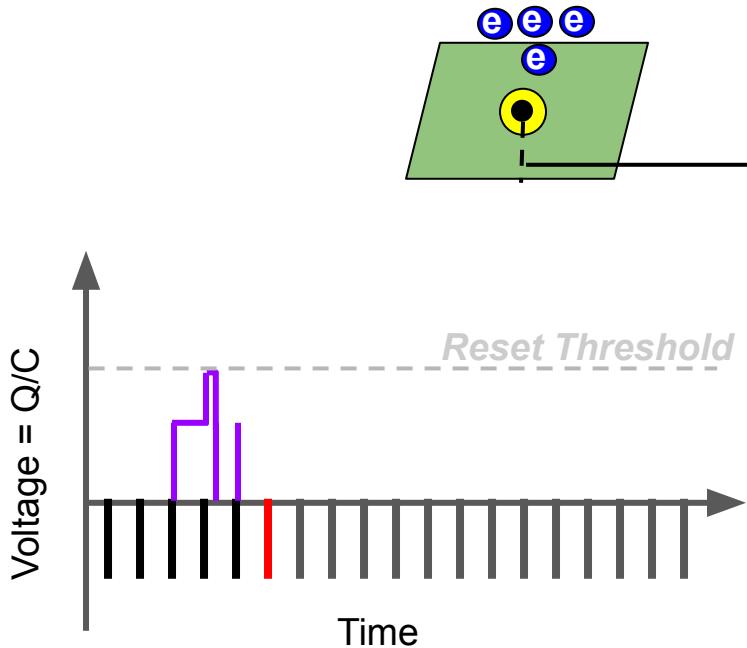
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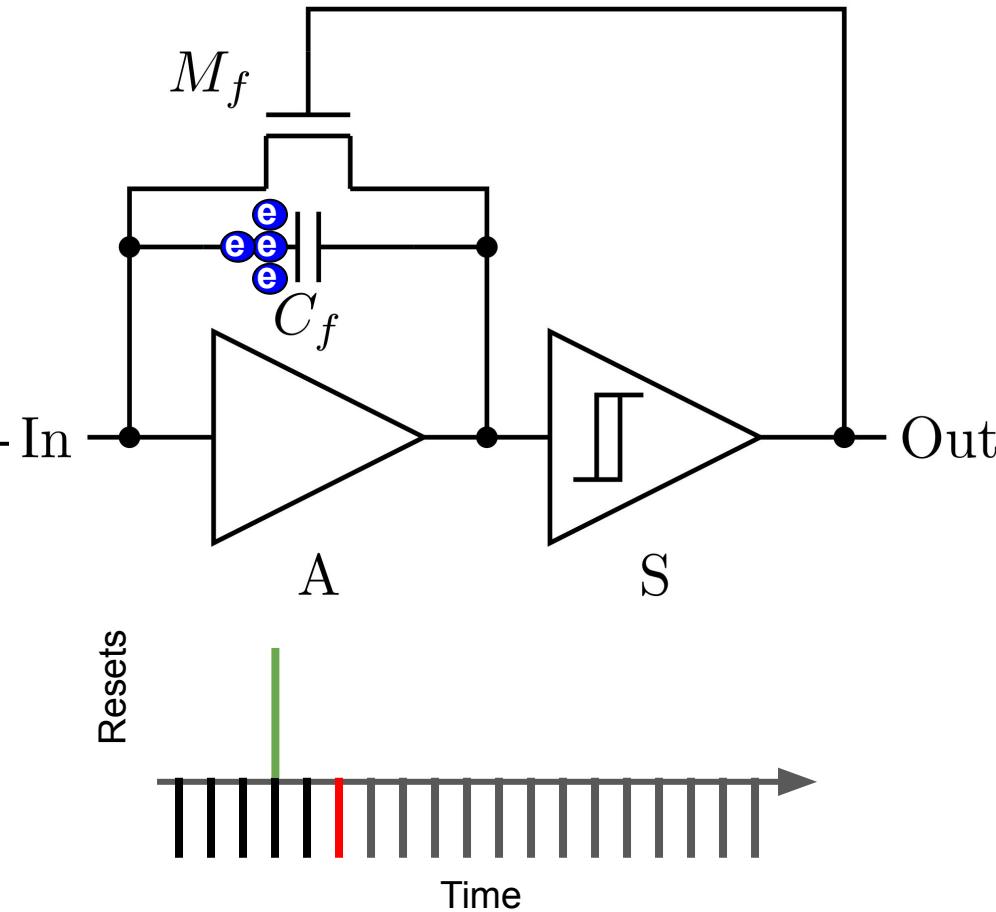
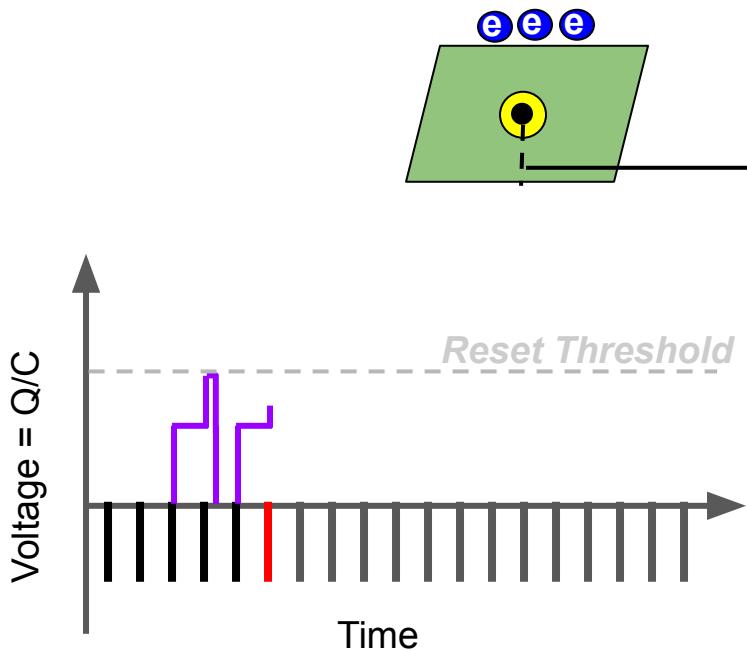
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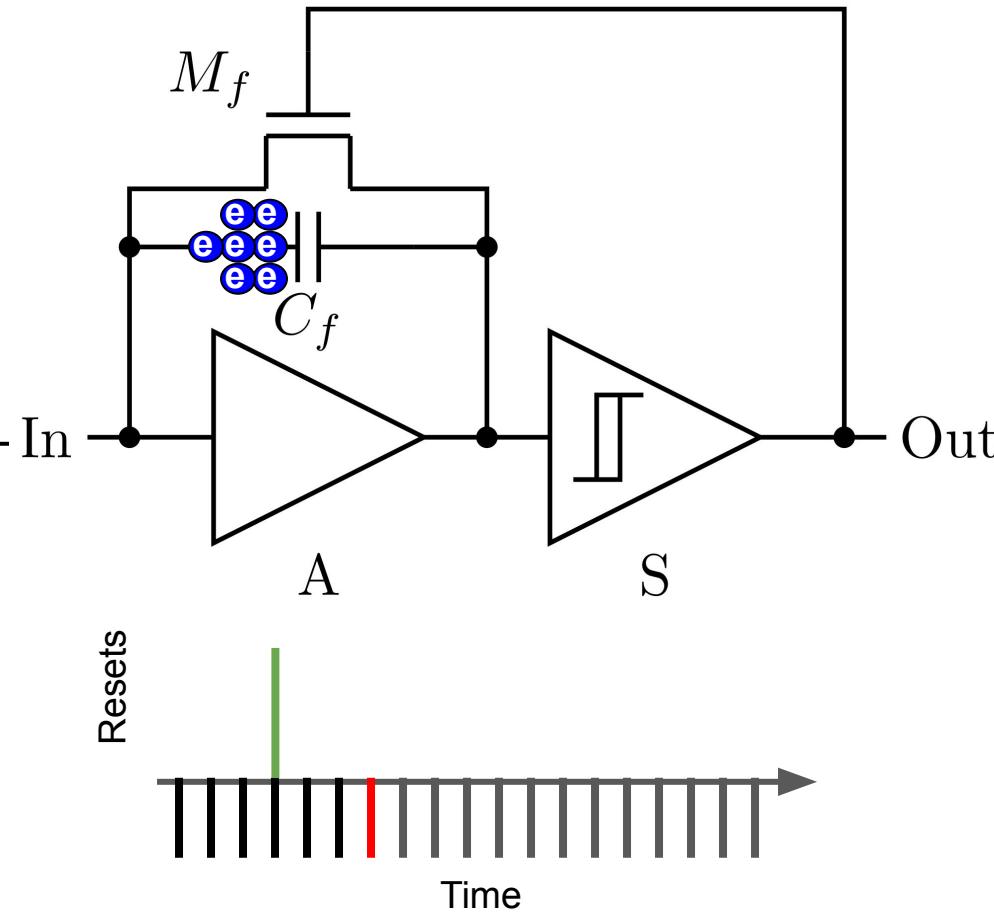
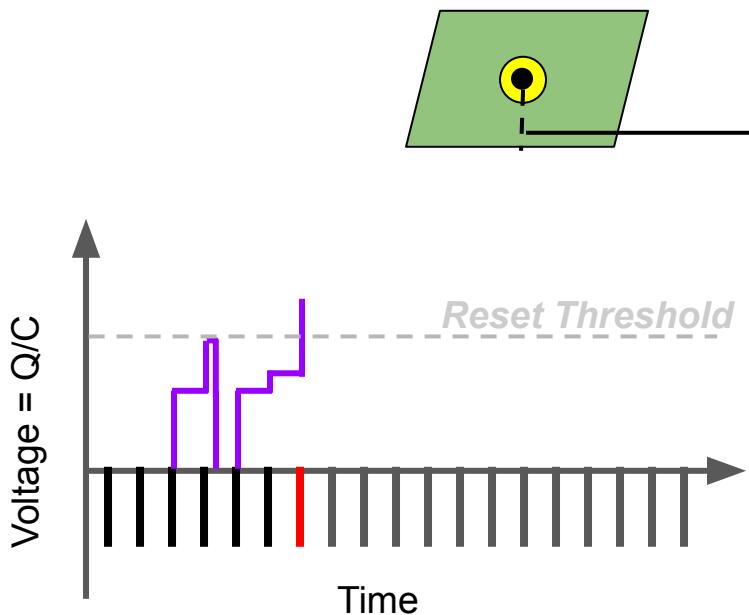
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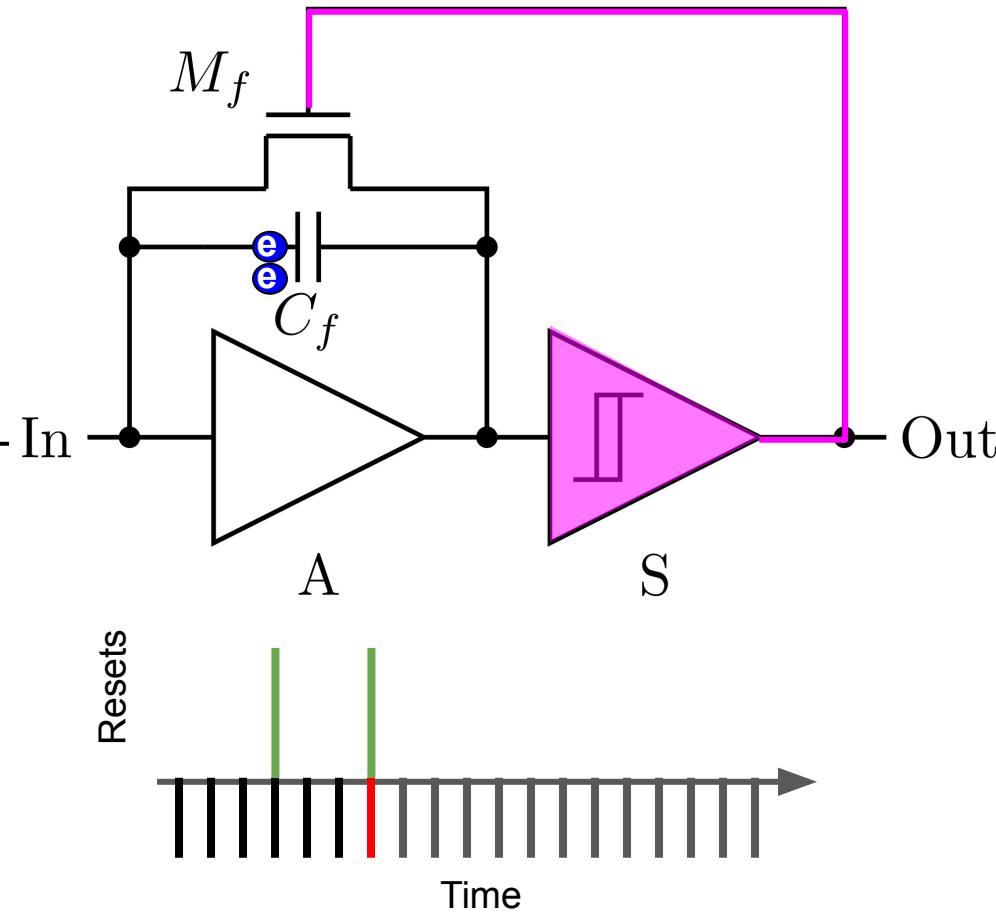
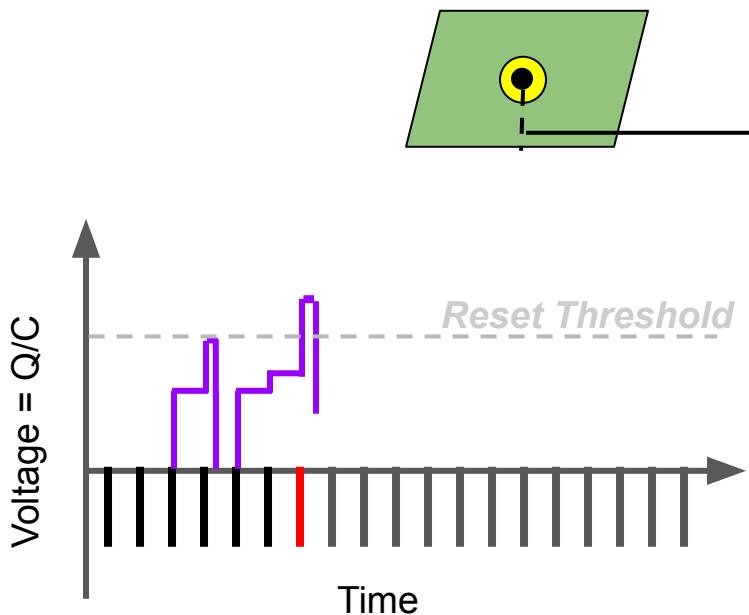
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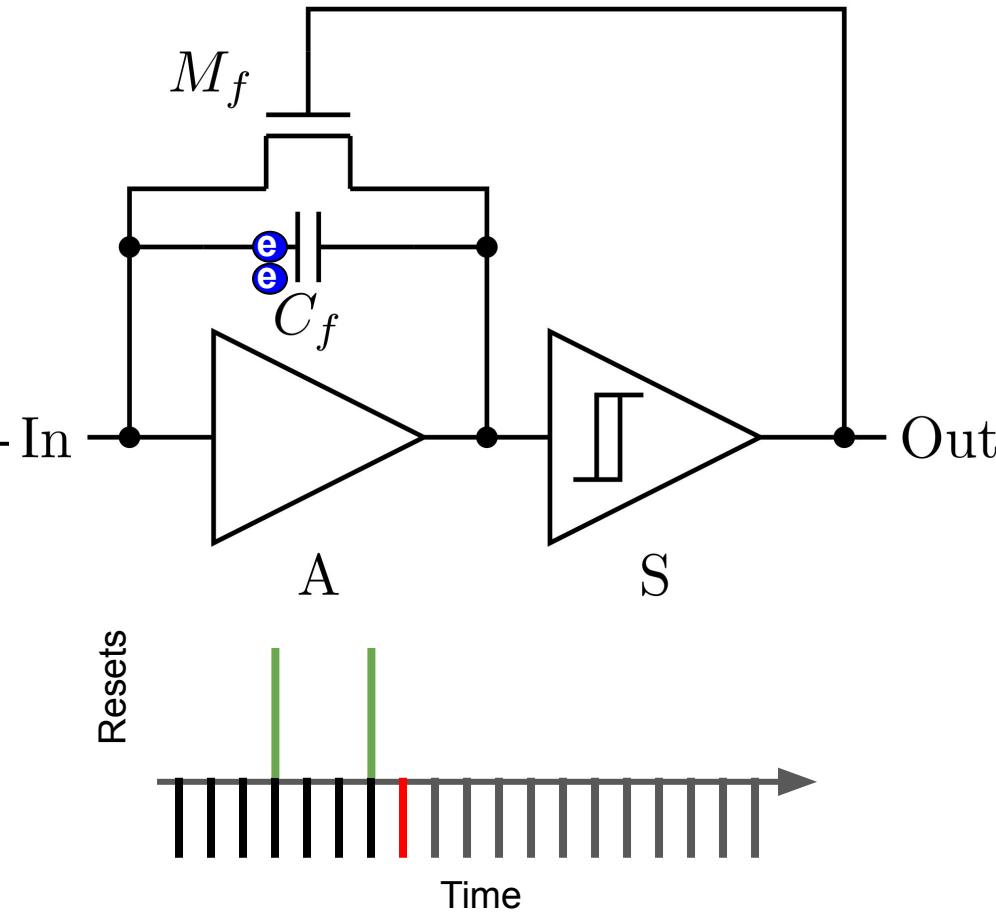
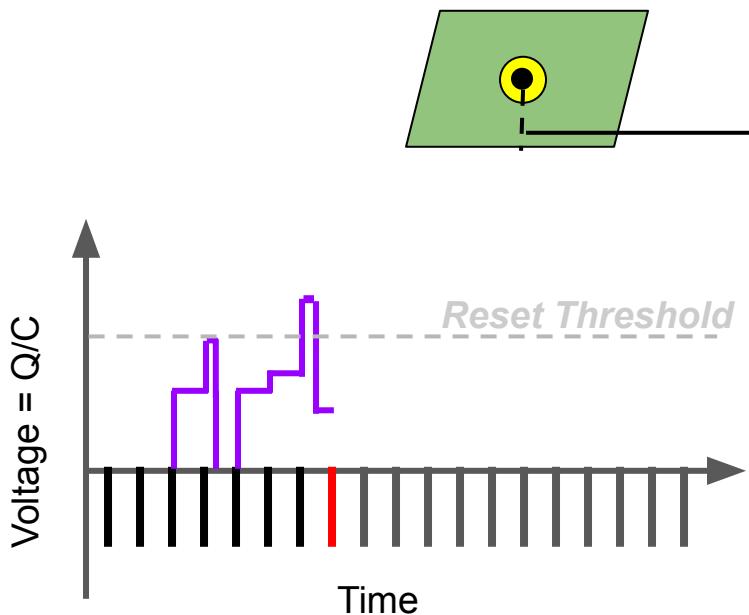
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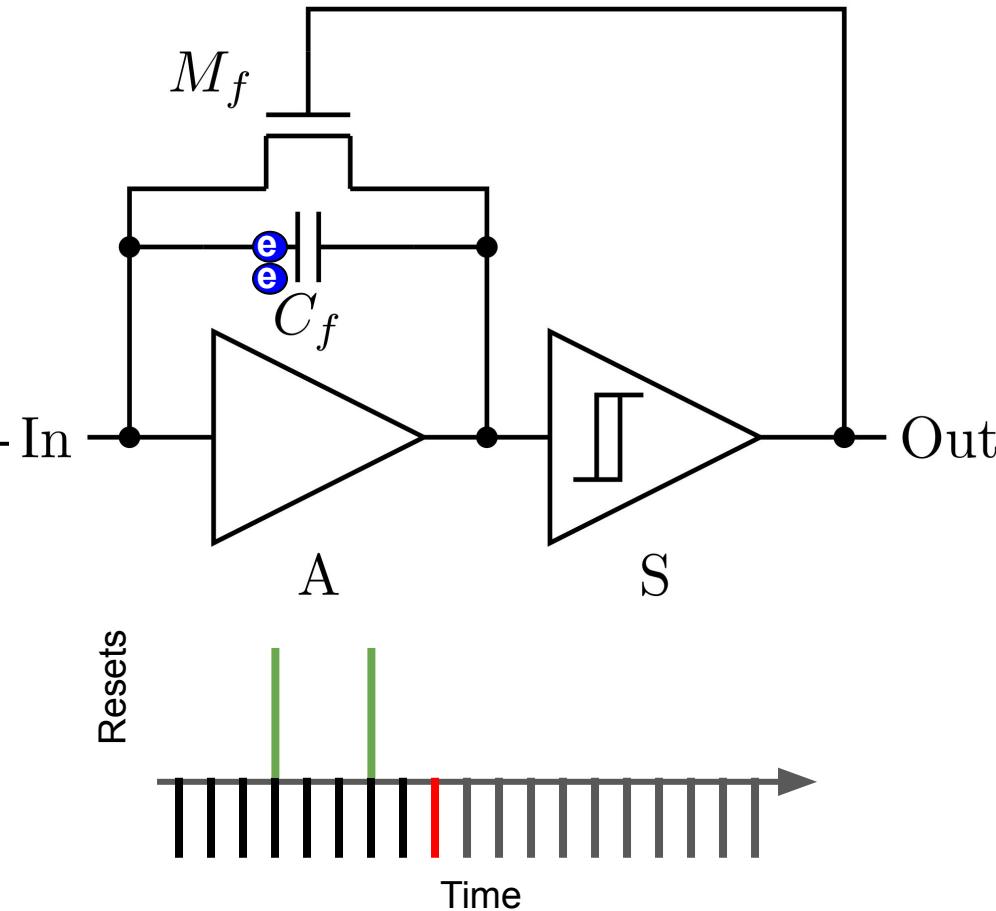
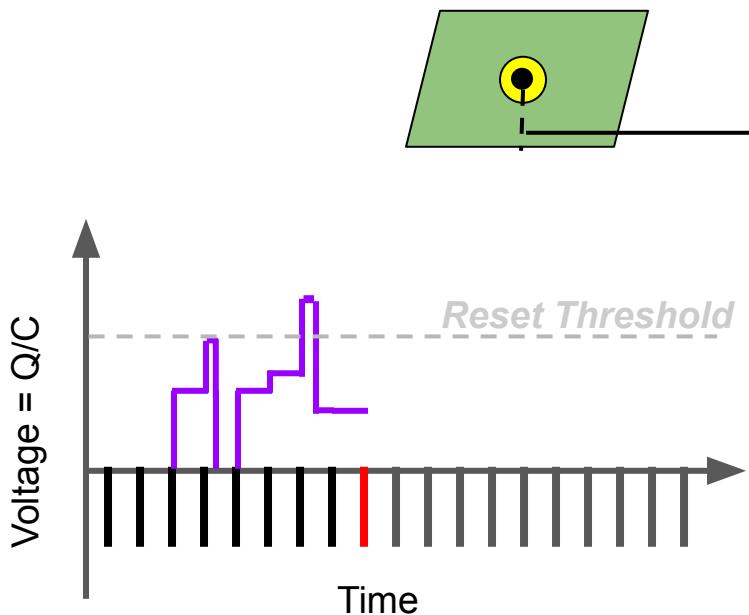
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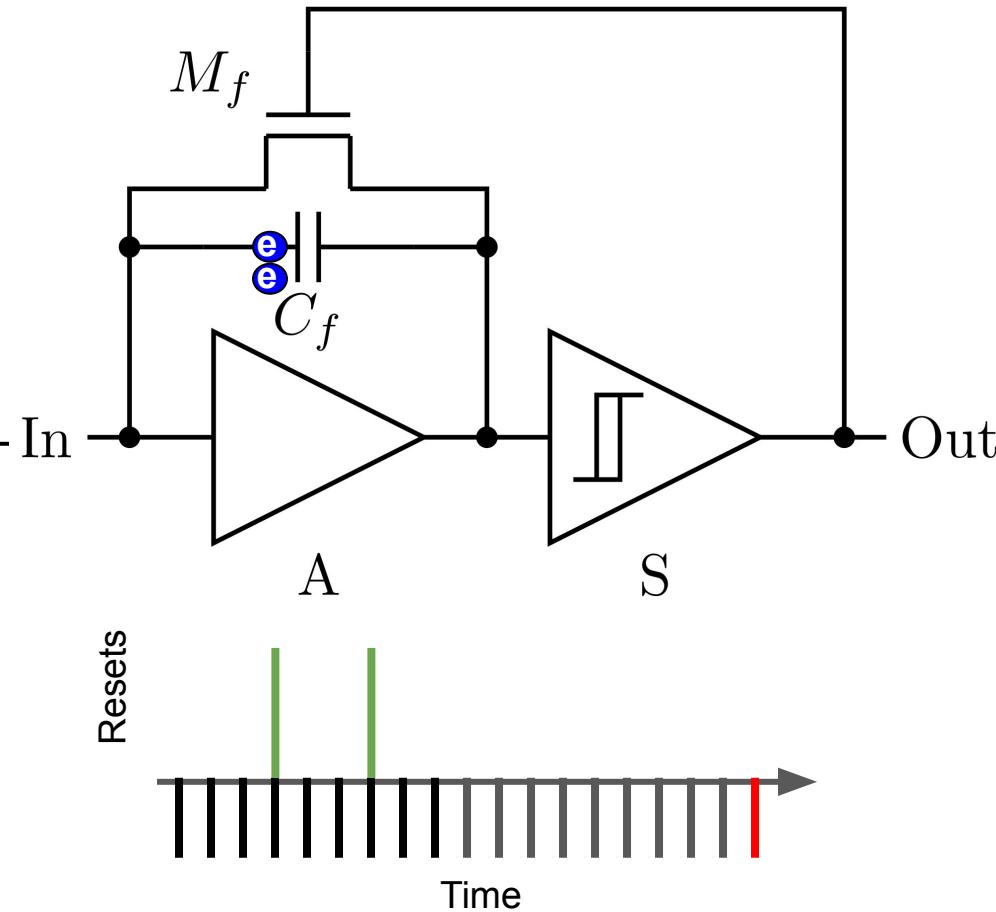
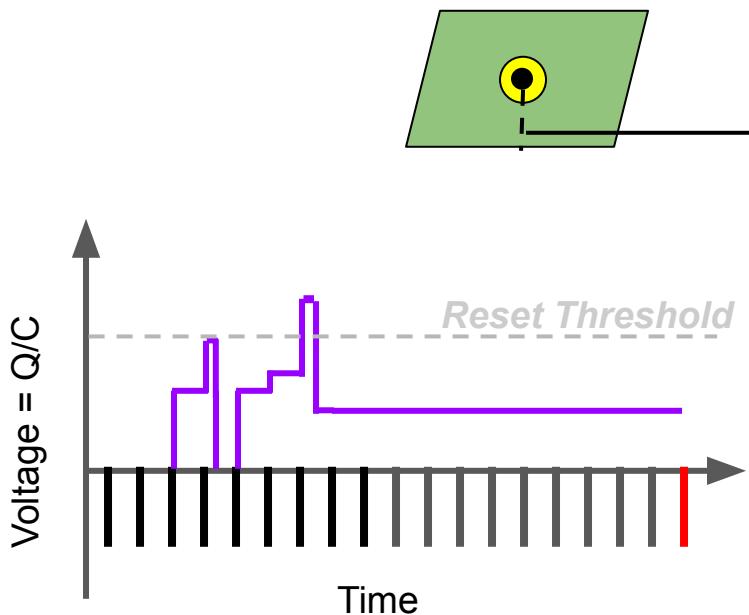
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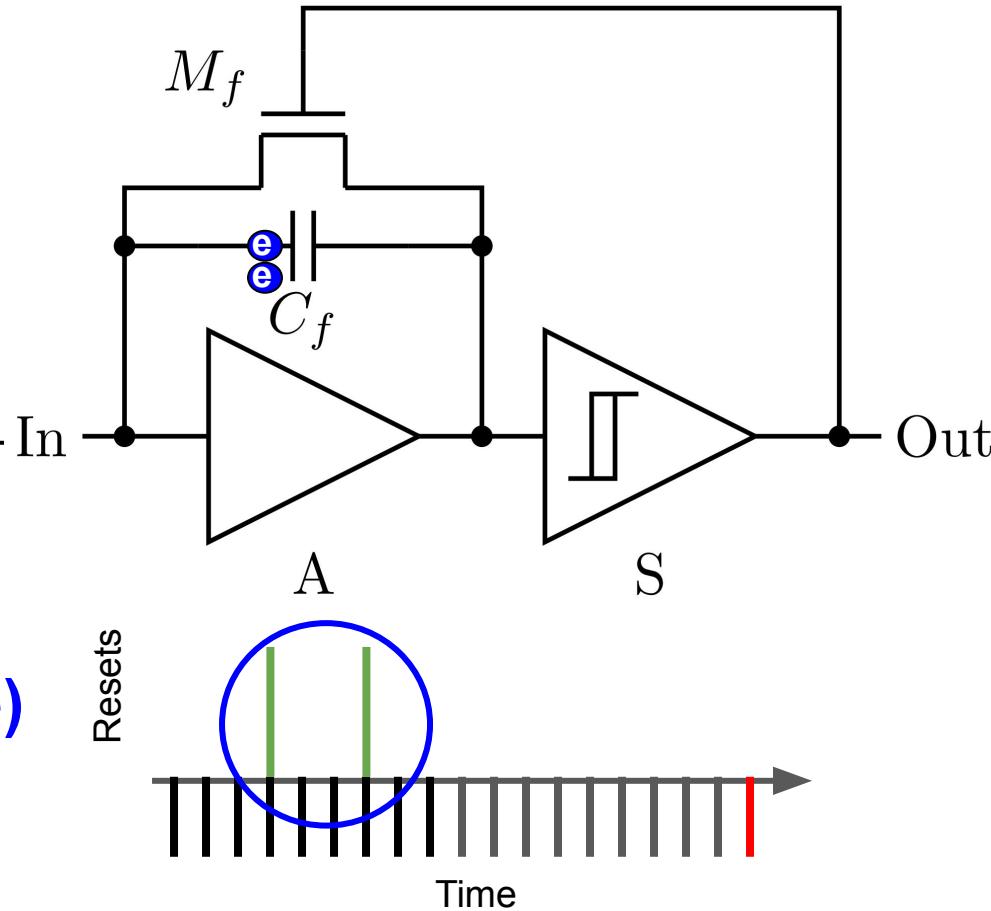
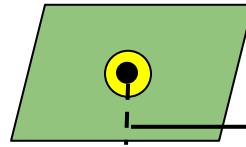
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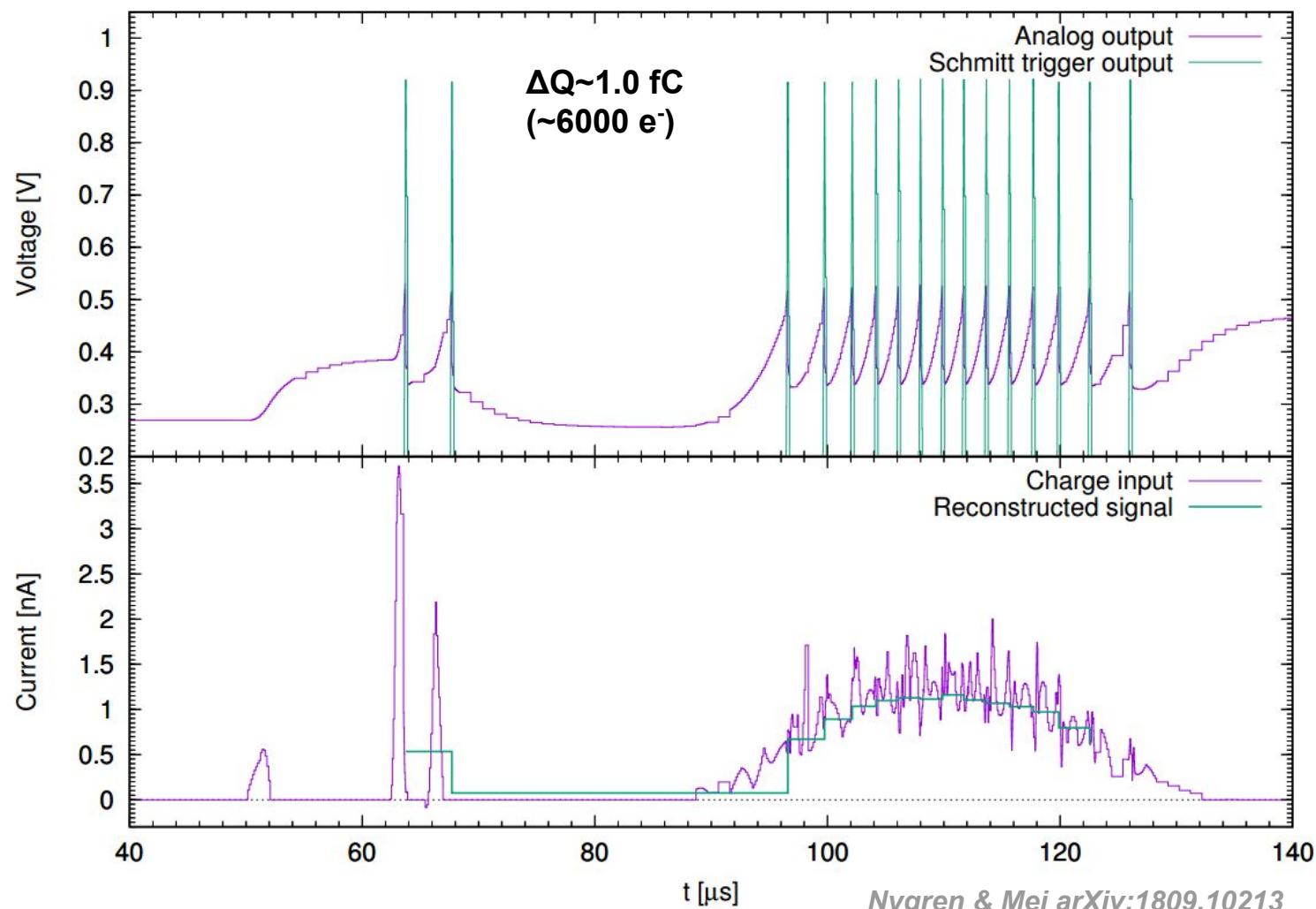


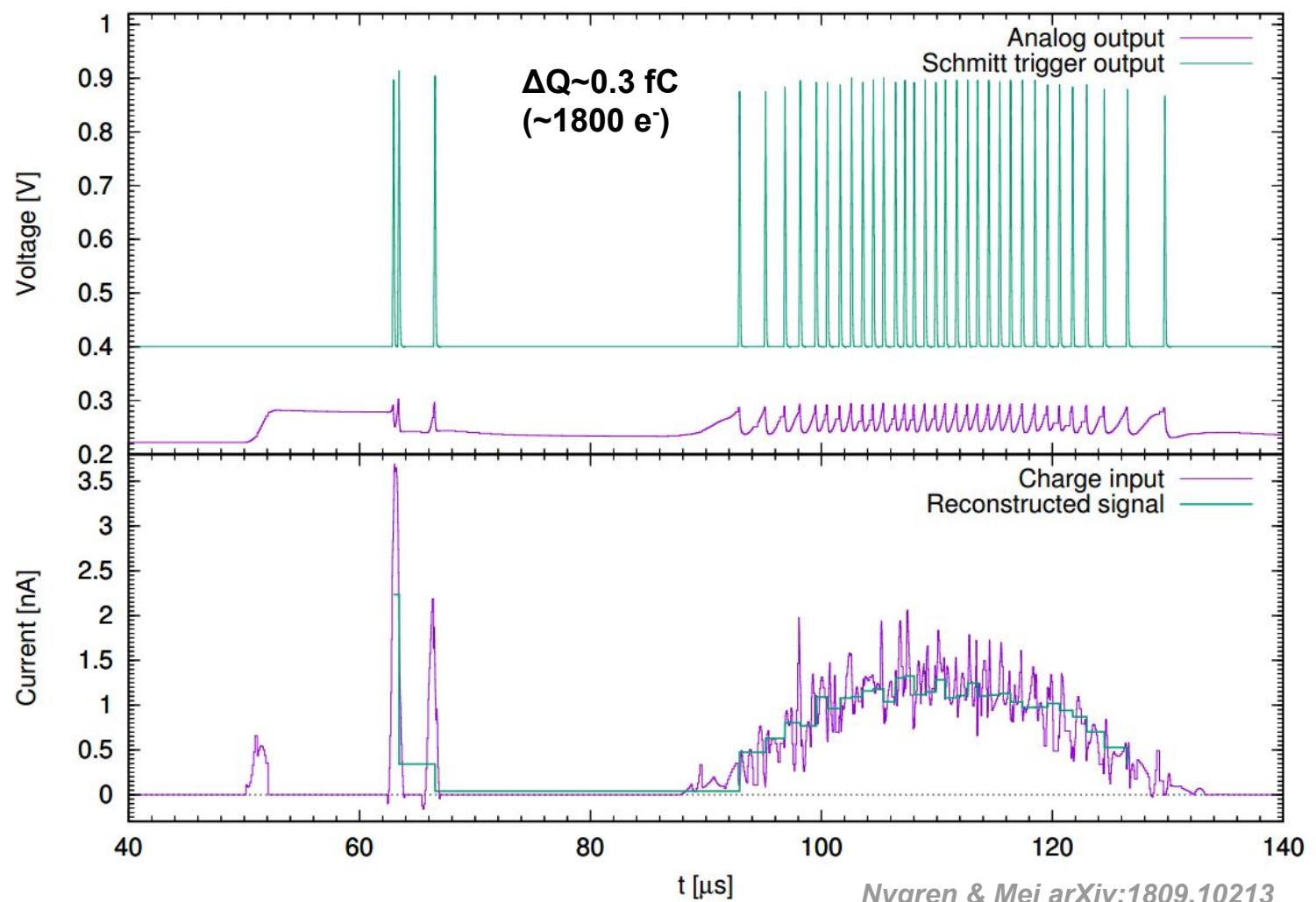
What I have here is a fixed amount of charge ΔQ (10 electrons in our toy example) during a time Δt

This gives me a current seen by the pixel during this time!

What is new here?

- Take the difference between sequential resets
 - Reset Time Difference = RTD
- Total charge for any RTD = ΔQ
- RTD's measure the **instantaneous current** and captures the waveform
 - Small average current (background) = Large RTD
 - Background from ^{39}Ar $\sim 100 \text{ aA}$
 - Large average current (signal) = Small RTD
 - Typical minimum ionizing track $\sim 1.5 \text{ nA}$
- One free running clock per ASIC ($\sim 50 \text{ MHz}$)
 - Required precision @ $1.6\text{mm}/\mu\text{s}$ drift speed $\delta f/f \sim 10^{-6}$ per second
- Time stamping routine has the ASIC asked ~ 1 per second “what time is it?”
 - ASIC captures local time and sends it
 - Simple linear transformation to master clock synced to GMT
 - RTD's calculated “off chip”

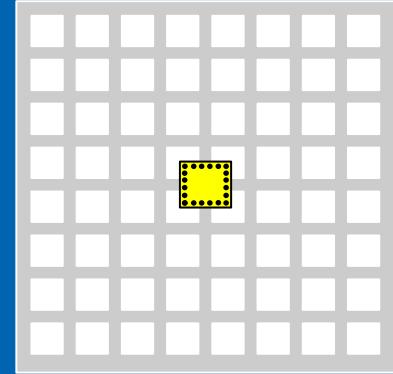
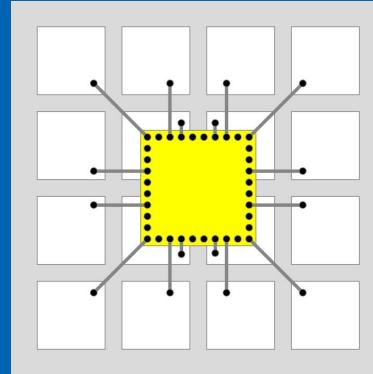




Q-Pix ASIC Concept

- **16-64 pixels / ASIC**

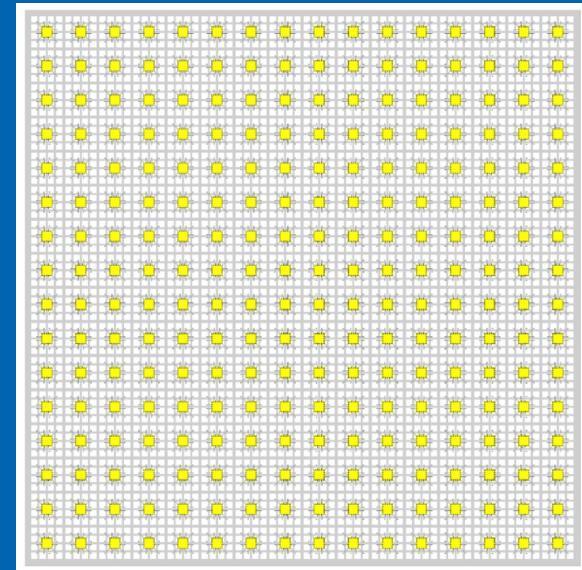
- 1 Free-running clock/ASIC
- 1 capture register for clock value, ASIC, pixel subset
- Necessary buffer depth for beam/burst events
- State machine to manage dynamic network, token passing, clock domain crossing, data transfer to network (many details to be worked out)



- **Basic unit would be a “tile” of ASICs**

(4092 4mm x 4mm pixels)

- Tile size 25.6 cm x 25.6 cm

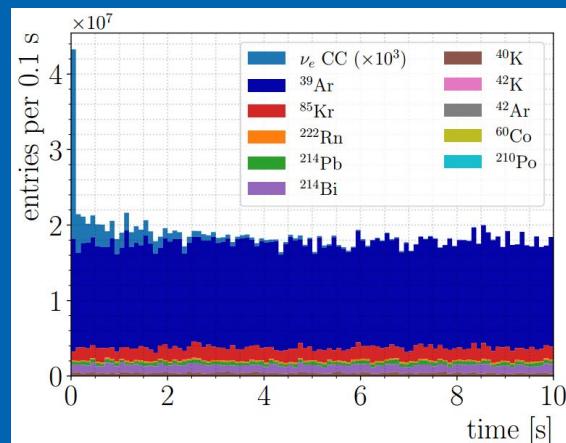
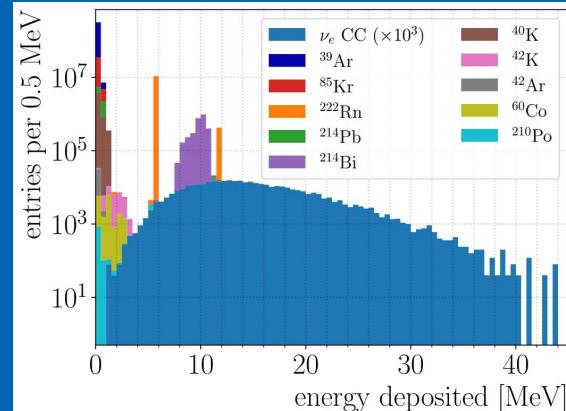


Q-Pix Consortium

- A consortium of universities and labs has formed to realize and test the Q-Pix concept
 - Being done in collaboration with LArPix (JINST 13 P10007) readout for the DUNE near detector (See D. Dwyer's talk coming shortly)
 - There has been substantial progress on many aspects of the design (too many to highlight in one talk)
 - Two mature analog designs in preparation for submission later this year (Penn)
 - Development of the digital readout and clock (Hawaii)
 - Substantial development on physics impacts and simulation studies (Harvard/UTA/A&M)
 - Plus much more....
- 

Highlight: Q-Pix Supernova Physics Paper

- We just completed a study to show how Q-Pix enhances the low energy physics capabilities of a kTon scale LArTPC.
- We decided to focus on Supernova Neutrinos as the benchmark and were able to make some key comparisons to published DUNE work
- The study developed here actually goes one step further than the DUNE work by including radiological backgrounds in the simulation
 - Even with this added complication, the Q-Pix architecture offers significant enhancement in the physics that is enabled (especially at low energy!)

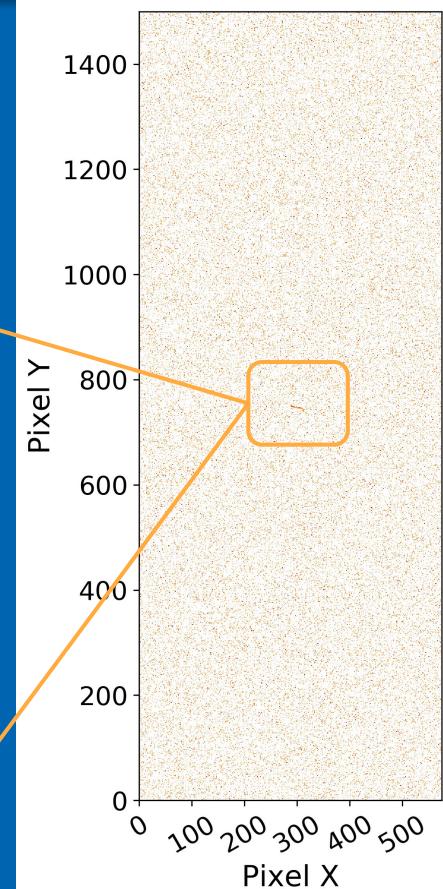
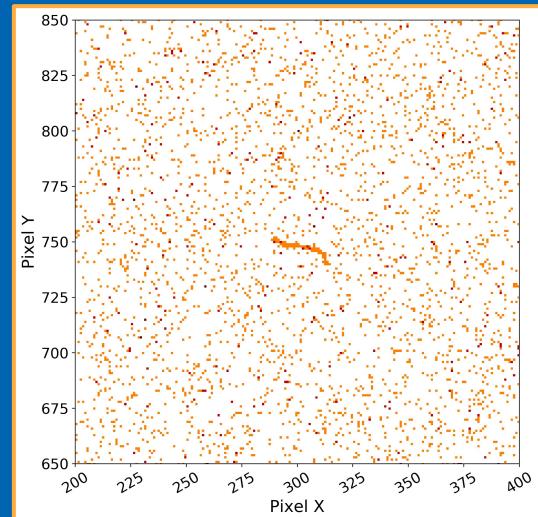


Q-Pix work in the context of DUNE (Supernova)

Compressing a **full 10s of background** in an APA with a single **supernova neutrino** (no cuts) on to the pixel plane the neutrino track is clearly visible.

This readout doesn't require a trigger (the data is readout from the pixel plane automatically)

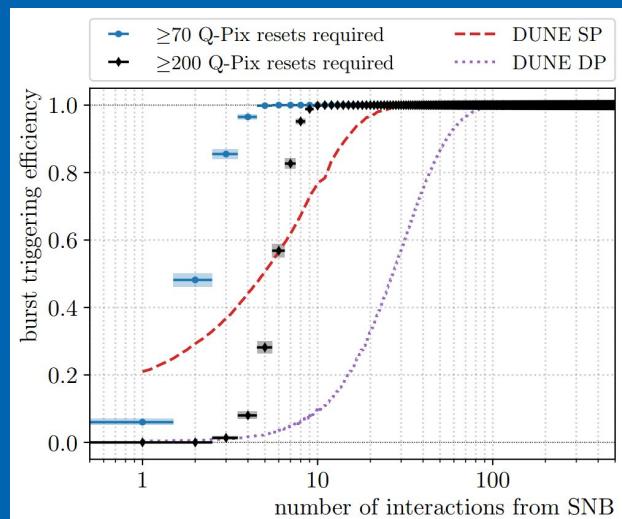
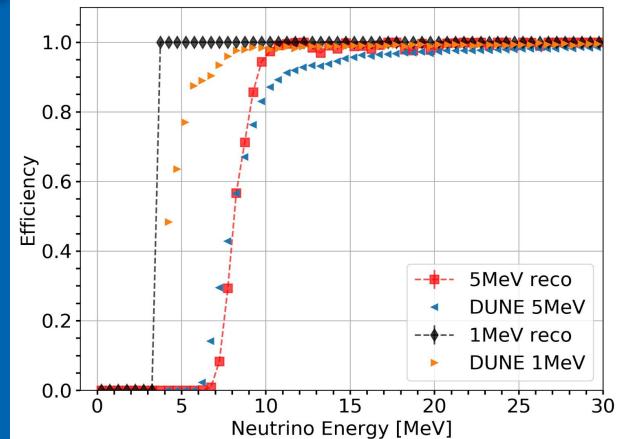
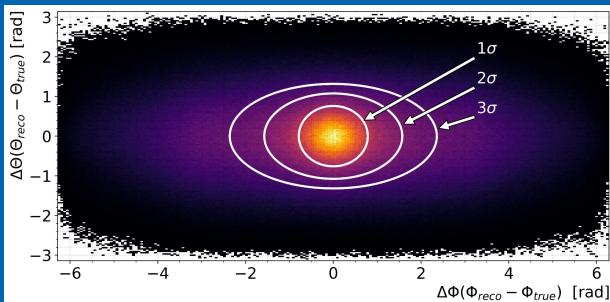
- Represents ~ 2MB of readout
 - Currently in DUNE this would represent ~100 GB
- Can (potentially) use diffusion to place the event in the volume
- Any light detection system will aid in finding the t_0 (R&D ongoing)



Highlight: Q-Pix Supernova Physics Paper

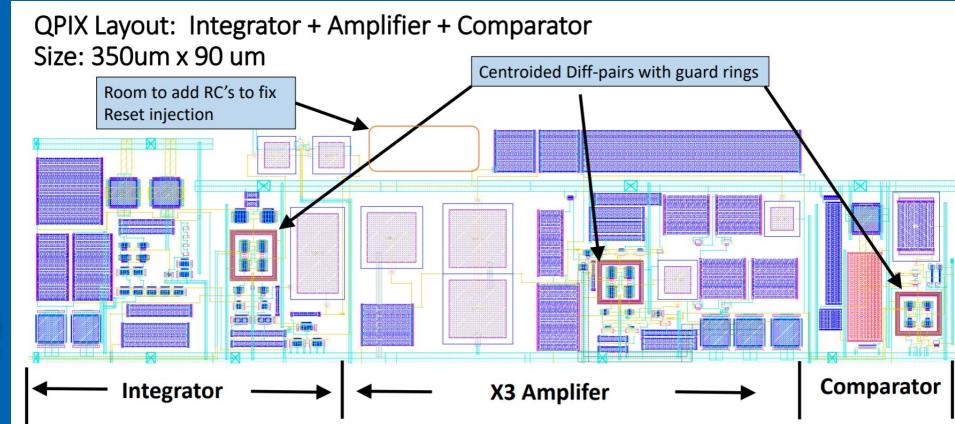
Key Takeaways

- Q-Pix significantly enhances the efficiency of reconstructing **low energy supernova neutrino events**
- Even in the presence of radiological backgrounds, the Q-Pix architecture allows for a **high purity and high efficiency identification of supernova neutrino candidates**
- The **data rate is orders of magnitude ($\sim 10^6$) less for the same energy threshold** and manageable at lower energy thresholds (5.7 MB/s for 10kTon at 147 keV threshold)
- 3D pixelization allows for **supernova burst pointing accuracy to < 20 degrees** from a single 10kTon module



Q-Pix Prototyping

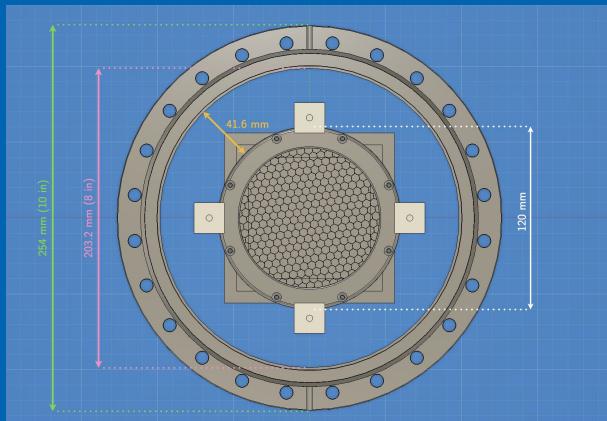
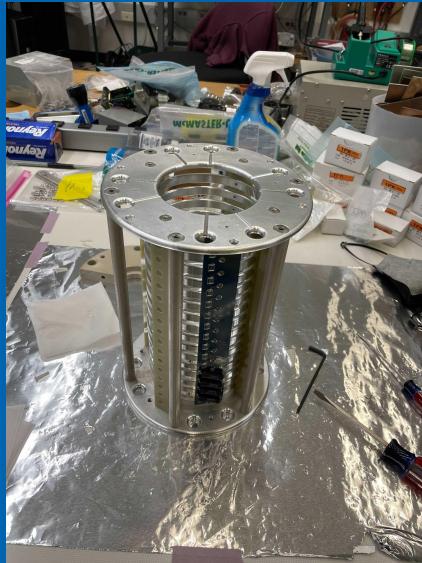
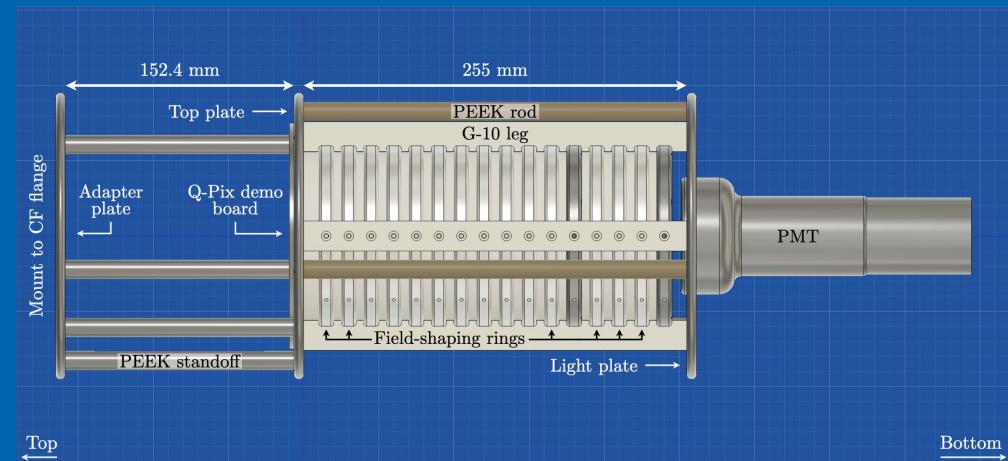
- **Q-Pix has a mature design in TSMC 180nm which is preparing for production imminently**
 - Expect prototype chips in 2022
- **Working with FNAL, we've also managed to make progress in a more modern process (65nm) and hope to have a series of test structures produced in late 2022**
- **We've also found an open source package (Skywater 130nm PDK) where Google will pay for prototypes and the tools can be shared with anyone**
 - This is an exciting development in general for ASIC developers and I'm happy to talk more about this with interested people



Q-Pix Prototyping

In collaboration with Roxanne (at that time at Harvard) we built and initially commissioned a test TPC (UTA/H) to be used for initial Q-Pix boards

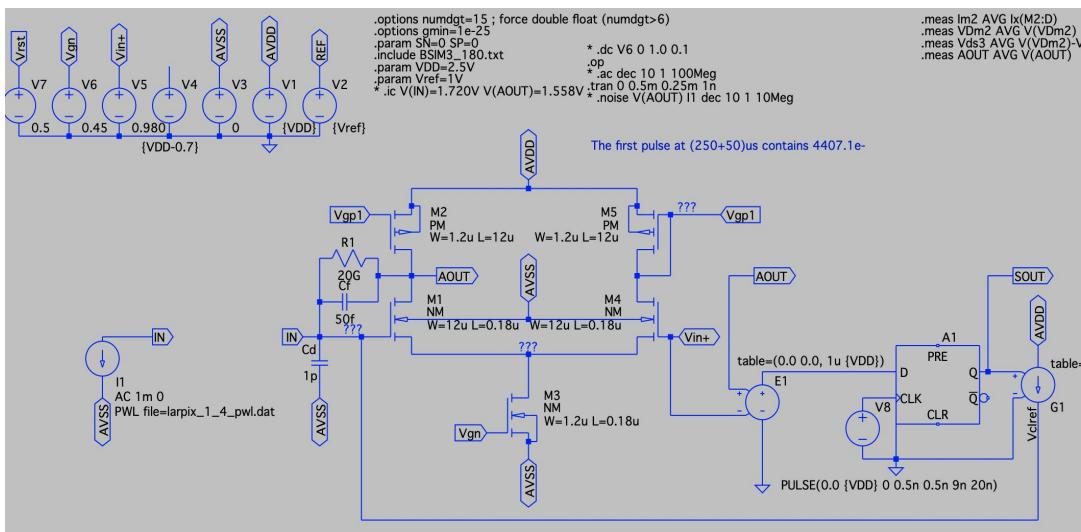
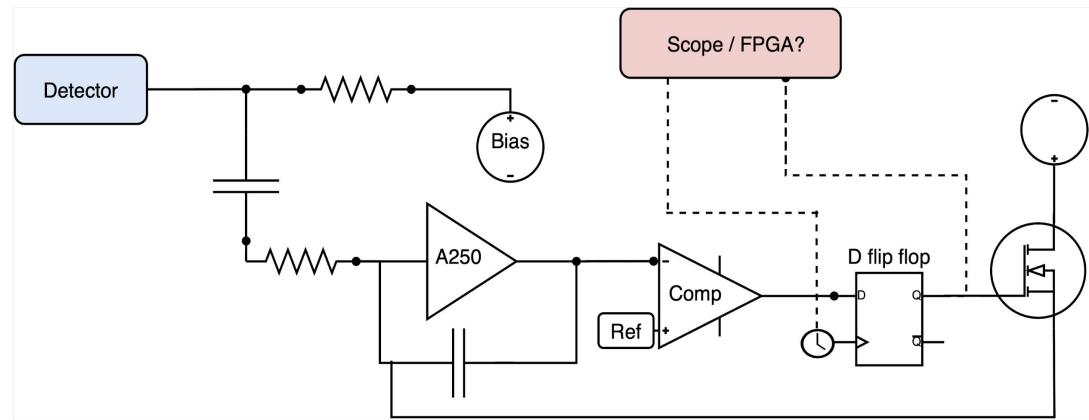
- 9.2 cm active diameter
- 18 cm drift
- Can do Q+L studies



Commercial Off The Shelf Q-Pix Demonstrator

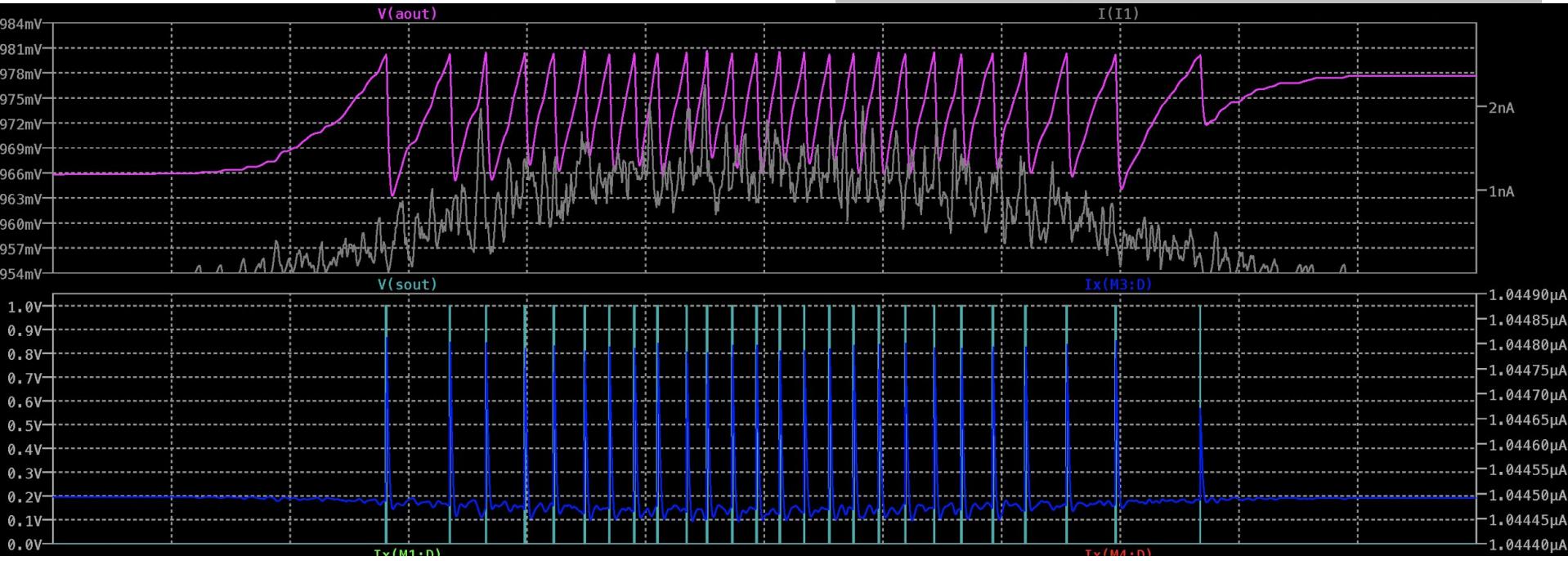
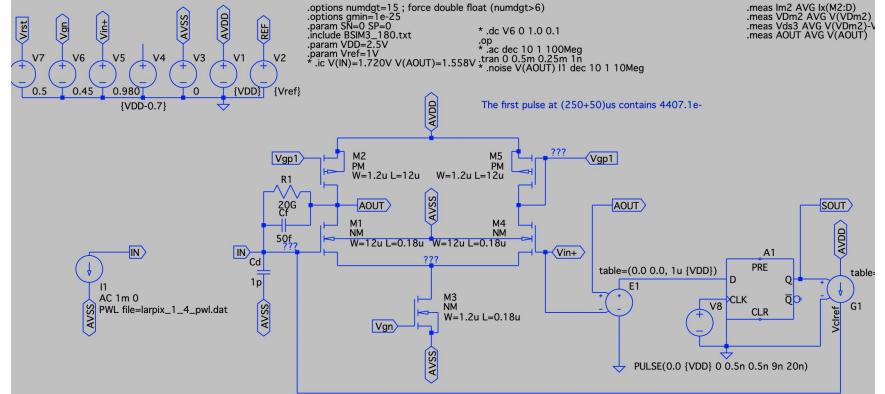
Yuan Mei (LBNL) came up with a LTSpice simulation on the idea of how you might build an COTS version of the Reset circuit

We have since worked on expanding this idea to demonstrate the Q-Pix concept while the first prototype is being produced

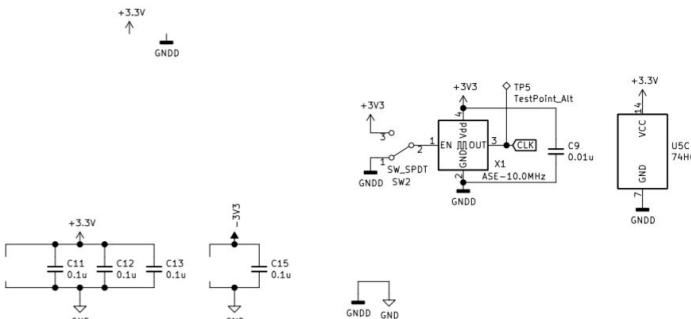
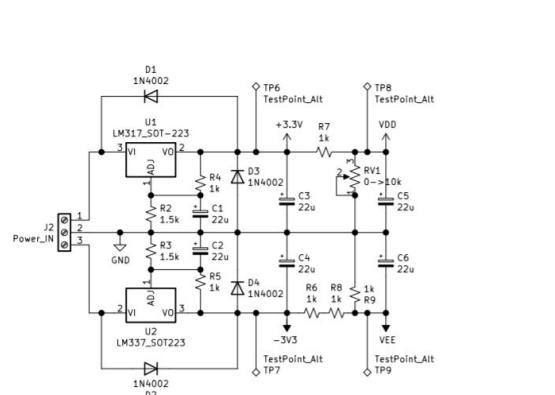
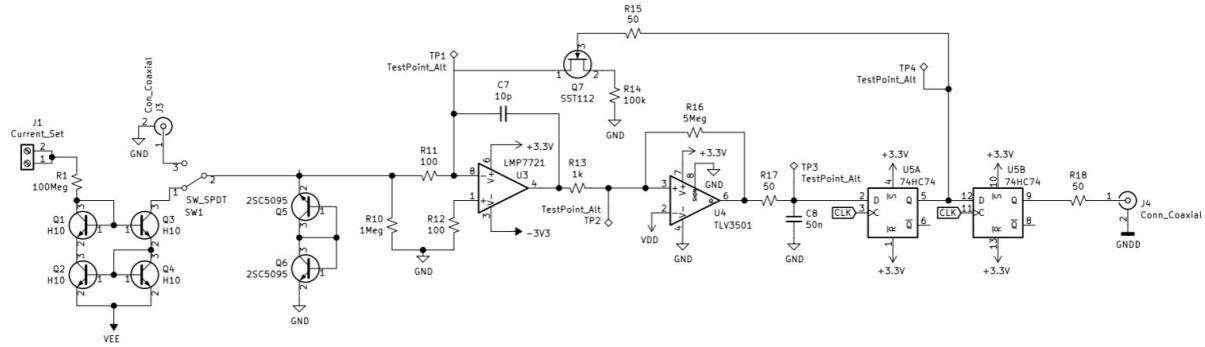


COTS Q-Pix

Spice simulation shows a nice response with output signals on the order of 1 Volt for a simulated input physics current



COTS Q-Pix



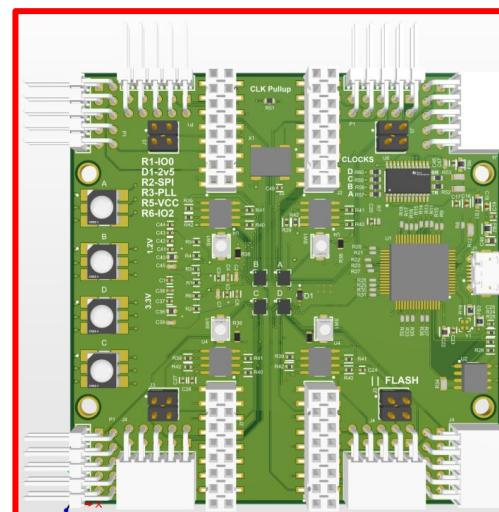
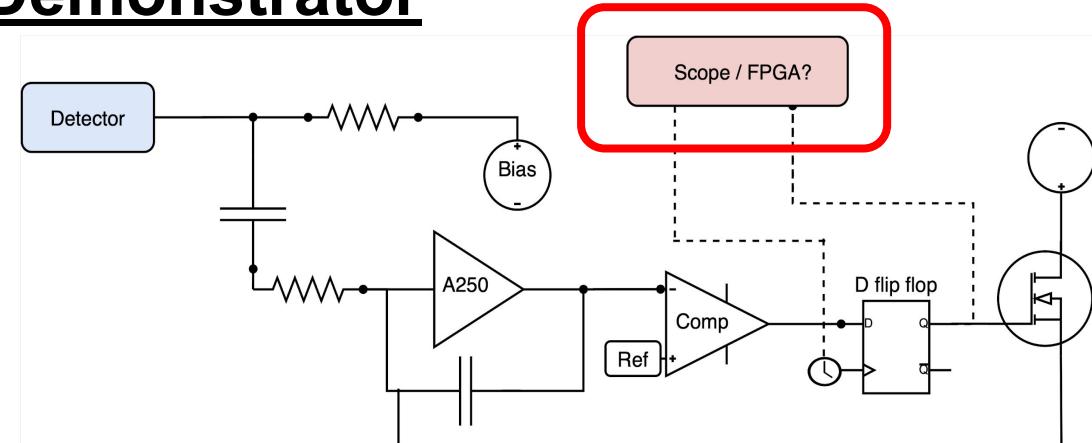
- We are constructing and testing single channel test boards now at UTA looking at multiple COTS components
 - Hope to have a set of chosen components on the 3-4 week time scale and begin scaling to a demonstrator
 - Work done with Manchester, Wesley, Hawaii, and UTA

Simplified Analog Q-Pix Demonstrator

University of Hawaii also worked on an FPGA board which will emulate the digital side of the Q-Pix readout

This prototype board will provide an clock for the D flip-flop, and can take in multiple analog input signals

This prototype board has just been assembled at UTA and is currently being tested

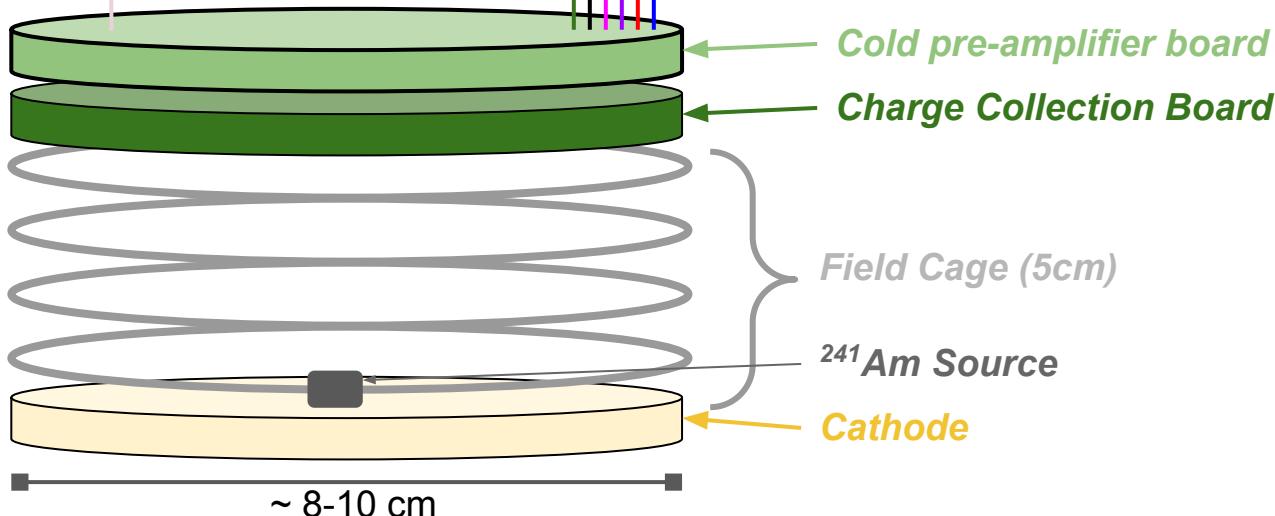


Goals of the COTS Q-Pix Demonstrator

- Construct a COTS IC version of the Q-Pix reset circuit (with a threshold that is inline with achievable noise levels using macroscopic IC components)
 - $O(10's\ fC)$
 - The COTS Q-Pix will be in the warm (but could be cooled to help performance)
- Measure its performance compared to a conventional charge integration circuit using a physics based source for ionization and a charge calibration source
 - Radioactive source seems to me to be the easiest way to go for the physics based ionization source (^{241}Am / ^{60}Co / other ideas)
 - Discharge capacitor circuit is probably sufficient for the charge injection calibration source
- **Bonus Goal:** Use the setup to measure the amount of transverse diffusion in a small Gas Argon (GAr) and Liquid Argon (LAr) Time Projection Chamber
 - Undoubtedly this is going to be a bit harder to do....but I think is very achievable and would be a nice demonstration that the Q-Pix readout method can perform physics quality measurements

Charge Fidelity

Charge Injection Source



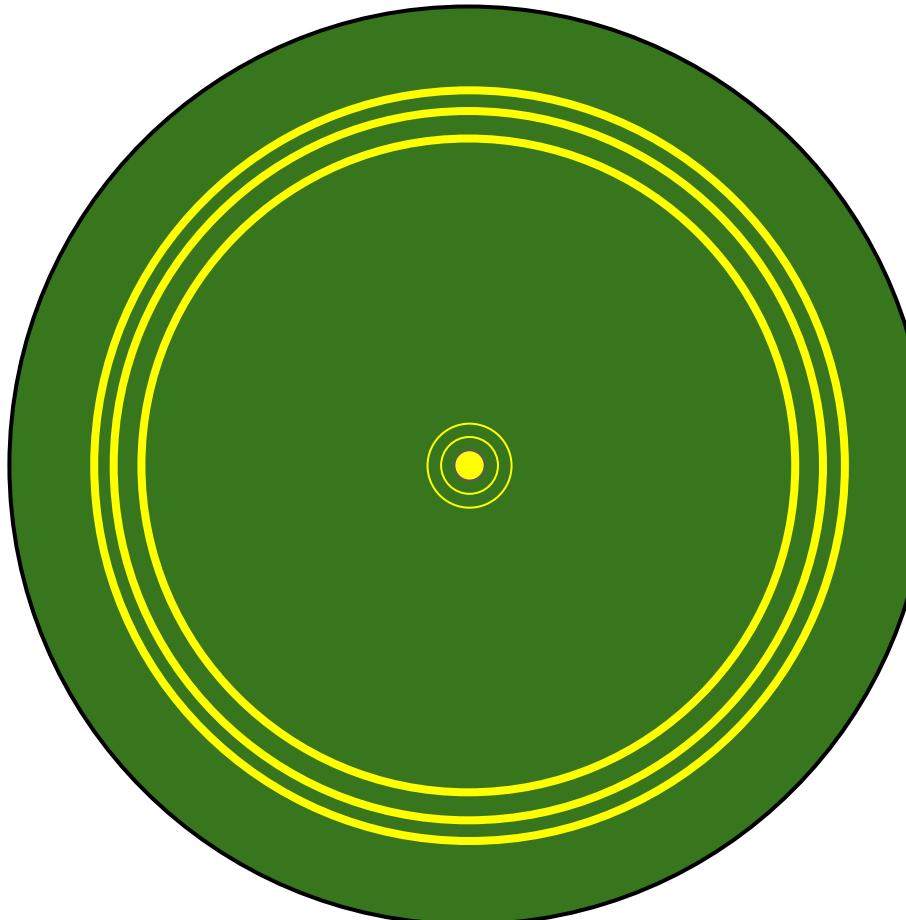
I think you will have 10's of channels which can be readout

10's of channels simplified analog Q-Pix

Hawaii FPGA Q-Pix Board

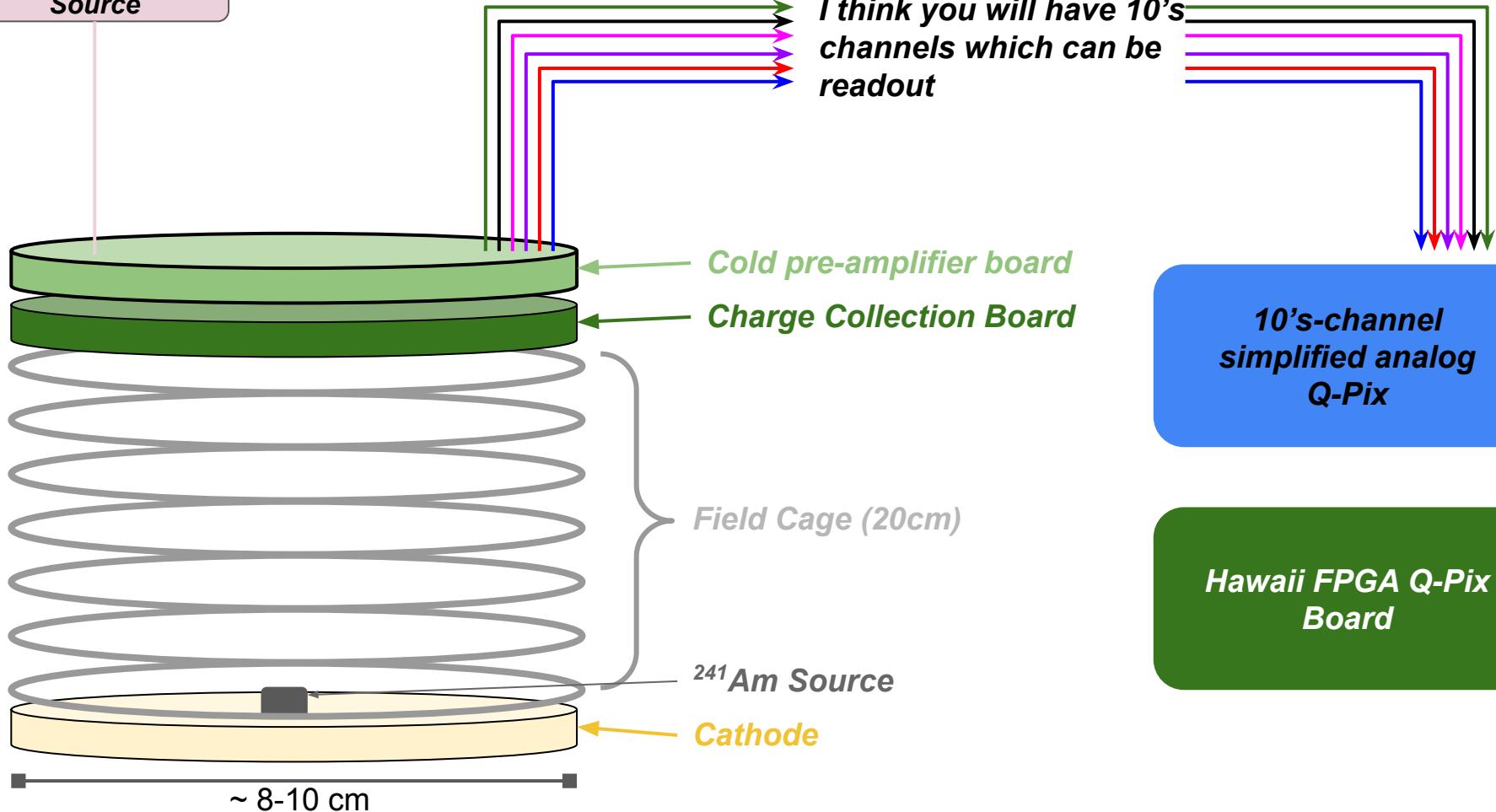
Charge Collection Board

The inner ring will be as closely spaced as we can get the PCB manufacturer to place them to allow for a diffusion measurement in liquid argon



The outer rings are placed around the expected diffusion distance for GAr with some tolerance between them so we can see the diffused charge

**Charge Injection
Source**



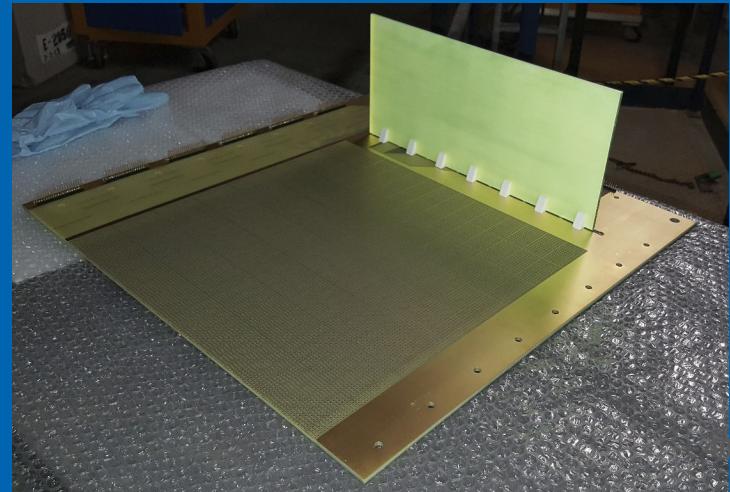
**Hawaii FPGA Q-Pix
Board**

**10's-channel
simplified analog
Q-Pix**

*I think you will have 10's
channels which can be
readout*

Light Detection

- Conventional LArTPC's use the semi-transparent wires to their advantage and place their photon detectors behind the wire planes
 - Requires WLS 😠
- Pixel detectors have an opaque charge collection surface making use of this solution impossible
 - Alternative mounting schemes have been / are being explored
- **How do you turn a vice into a virtue?**

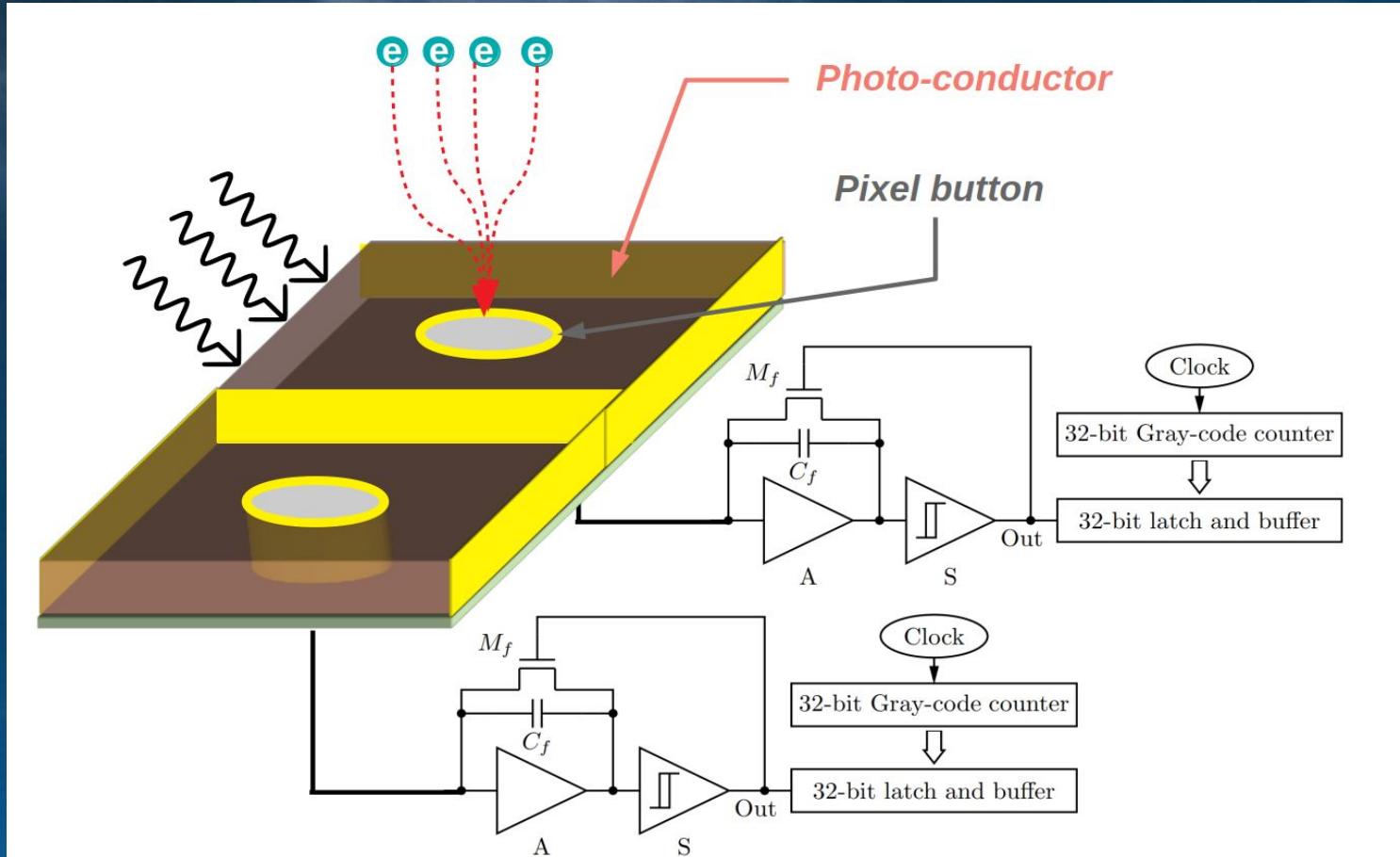


Pixels which also are photo-sensitive?

- What if the whole APA could collect light?
- A pixel plane sensitive to UV photons and ionization charge SIMULTANEOUSLY would be a major breakthrough
 - Your effective instrumented area becomes enormous!
 - Even if the device has low efficiency you have a huge gain
 - Q-Pix could be an “enabling technology” to realize this for LArTPC’s



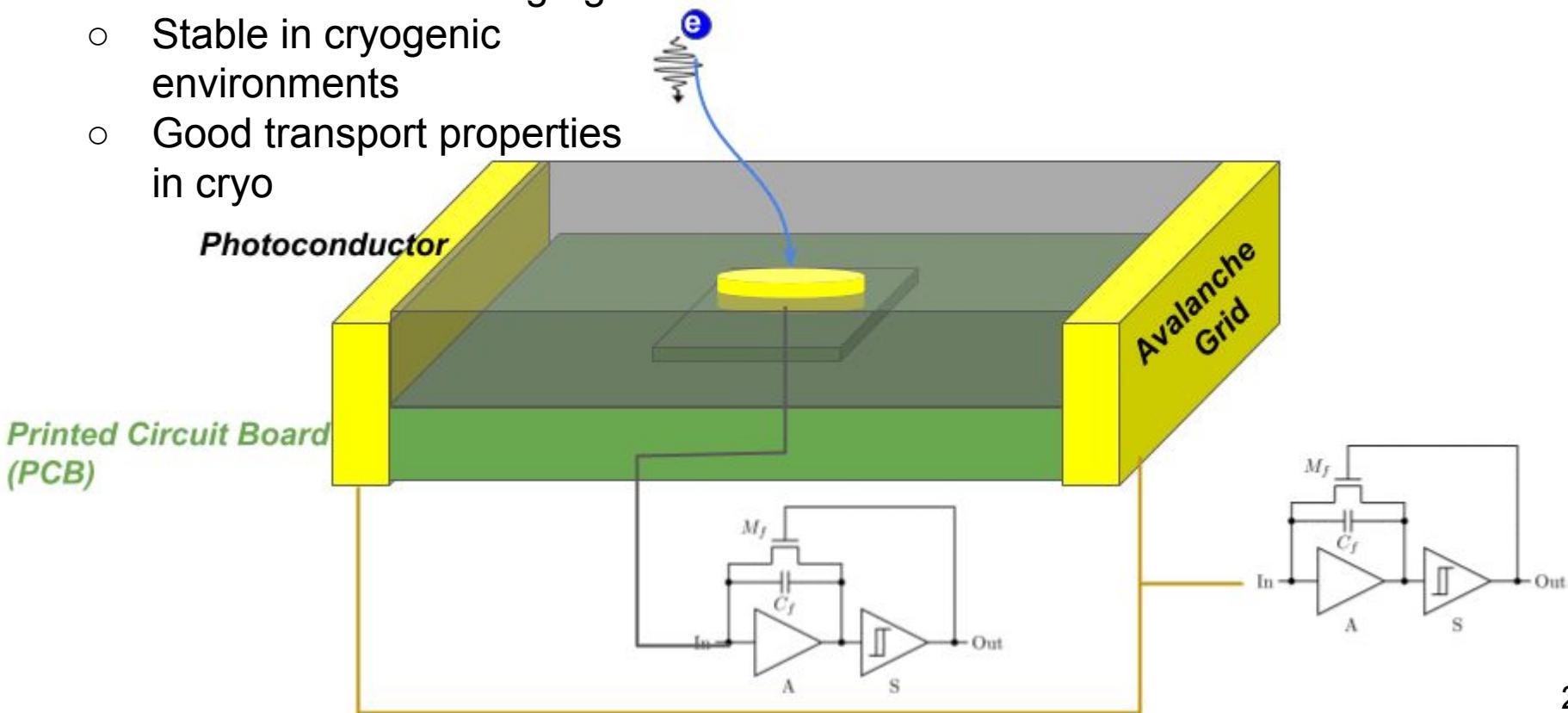
Multi-modal Pixel (conceptual sketch)



- **Searching for a material with:**
 - Good optical absorption for VUV photons (<200 nm)
 - Able to achieve charge gain
 - Stable in cryogenic environments
 - Good transport properties in cryo

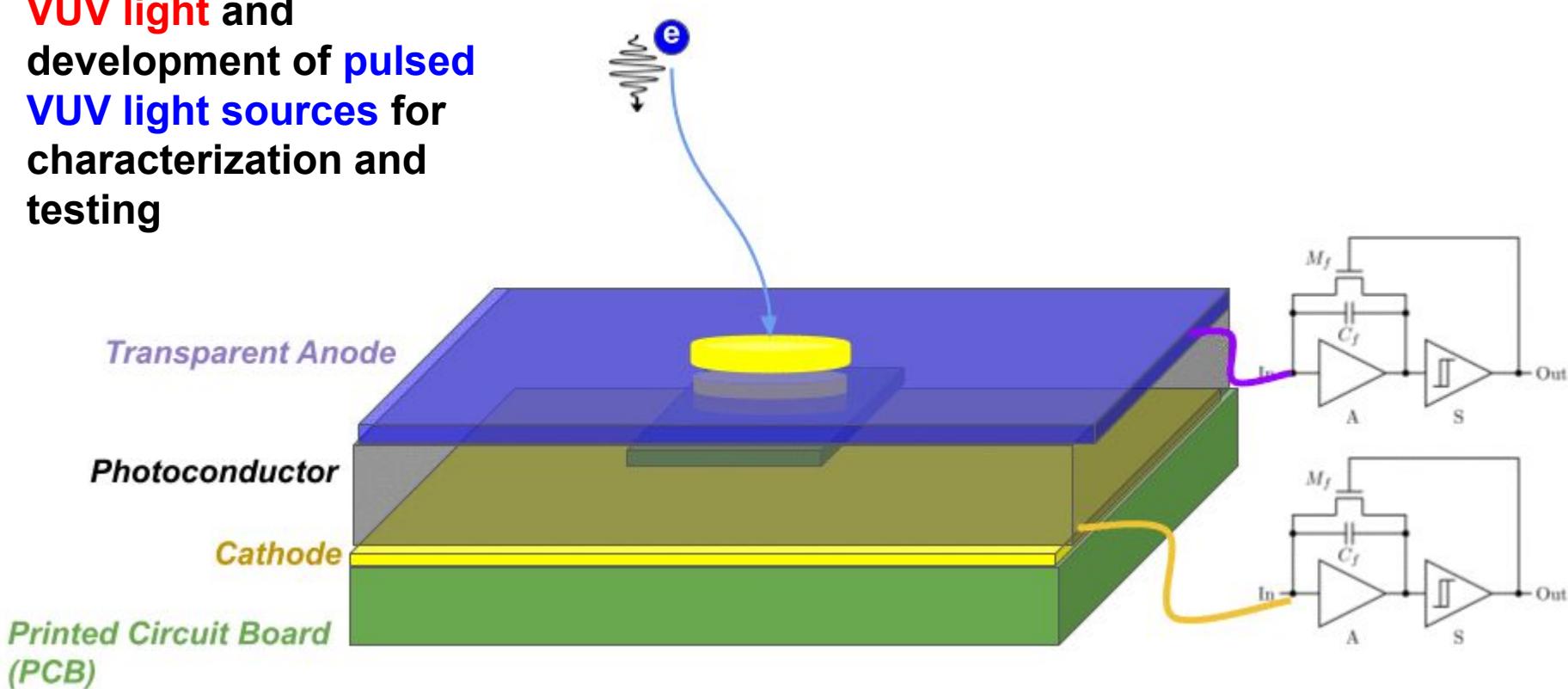
*Speed of light: 11.23 cm/ns (**112,300 mm/μs**)*

*Speed of charge (at 500 V/cm): 0.00016 cm/ns (**1.6 mm/μs**)*



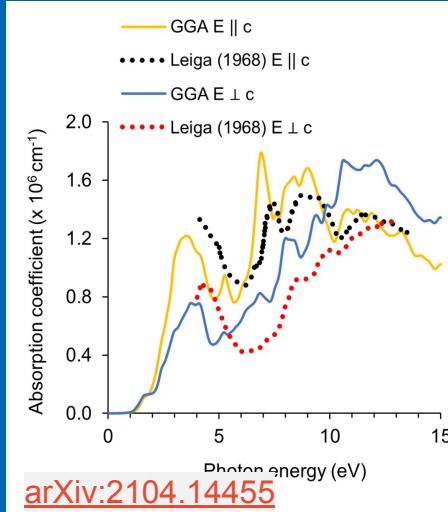
- This has also opened research into **electrodes which are transparent to VUV light** and development of **pulsed VUV light sources** for characterization and testing

Speed of light: 11.23 cm/ns (**112,300 mm/ μ s**)
 Speed of charge (at 500 V/cm): 0.00016 cm/ns (**1.6 mm/ μ s**)

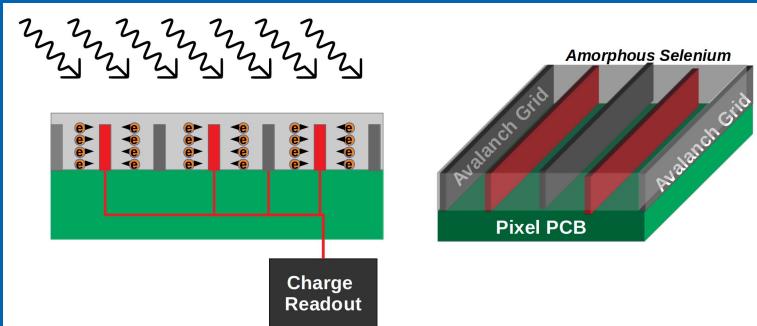


Exploring Amorphous Selenium

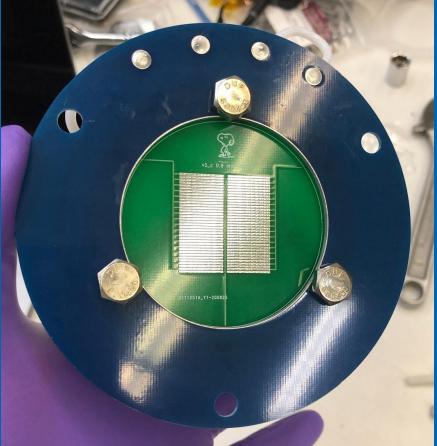
- There are a large number of potential photoconductors to be explored which could satisfy what we would like to do
 - Perovskites, Nanoplatelets, Organic Photodiodes, Selenium, etc....
 - Good opportunity to collaborate broadly with material science experts, national labs, and university groups
- We began with an investigation into amorphous selenium
 - Broadly used in medical imaging devices
 - Relatively cheap and has an easy manufacturing process (thermal evaporation)
 - Largely unexplored (but very promising) properties in VUV wavelengths
 - Example of a DFT calculation done with condensed matter theorist to understand selenium properties ([arXiv:2104.14455](https://arxiv.org/abs/2104.14455))



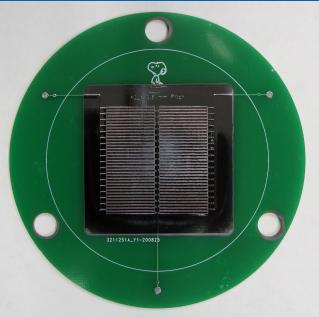
[arXiv:2104.14455](https://arxiv.org/abs/2104.14455)



Evolution of prototyping thus far



Work at UTA / ORNL



Commercial PCB with 127 μm trace spacing
Max field (5 V/ μm)



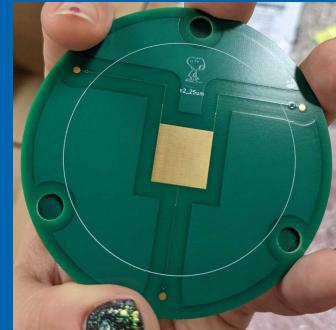
Work at UTA / ORNL



Commercial PCB with 127 μm trace spacing (cold electronics)
Max field (5 V/ μm)

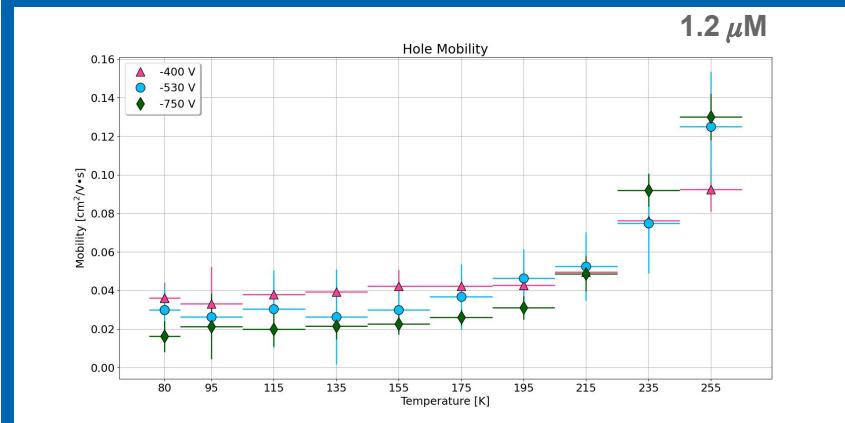
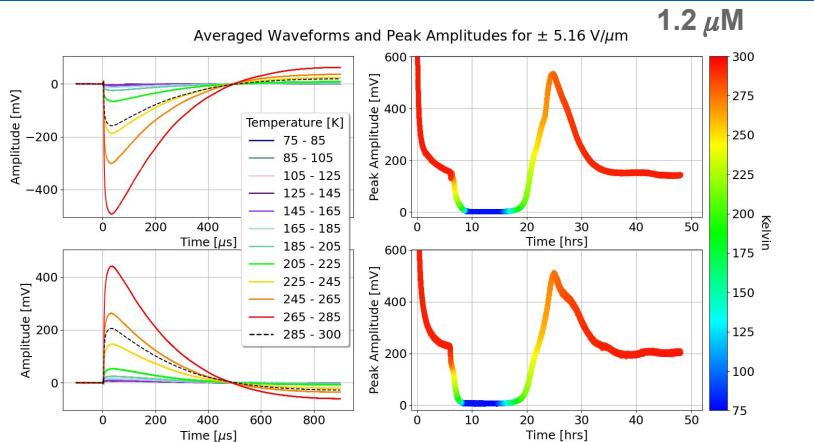
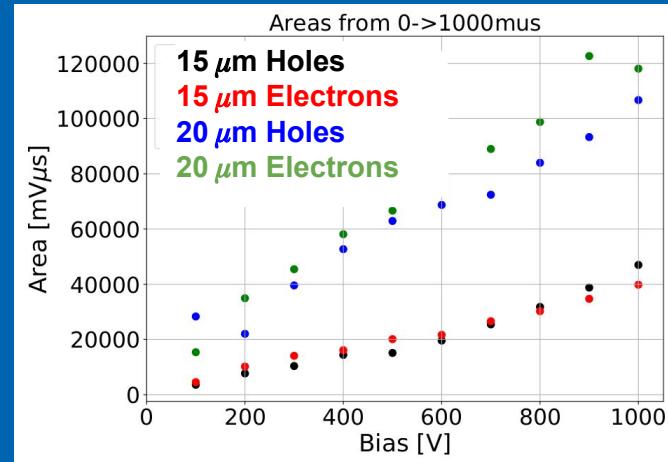
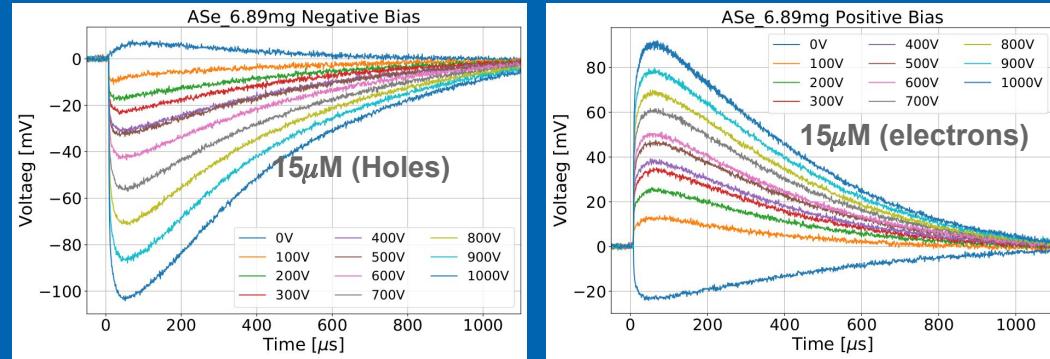


Work at UCSC / UTA / FNAL



Custom PCB with 25 μm trace spacing
Target field (40 V/ μm)

First test results (low field)

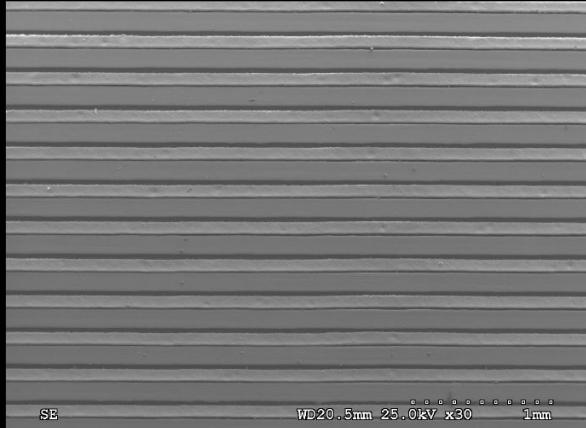


Selenium Stability in Cryo

30 X

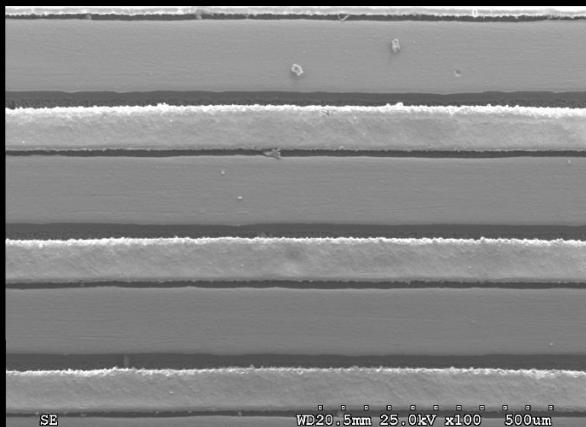
PRE LIQUID NITROGEN

POST LIQUID NITROGEN



SE WD 20.5mm 25.0kV x30 1mm

100 X



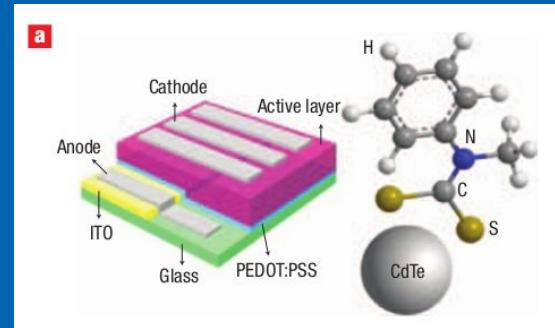
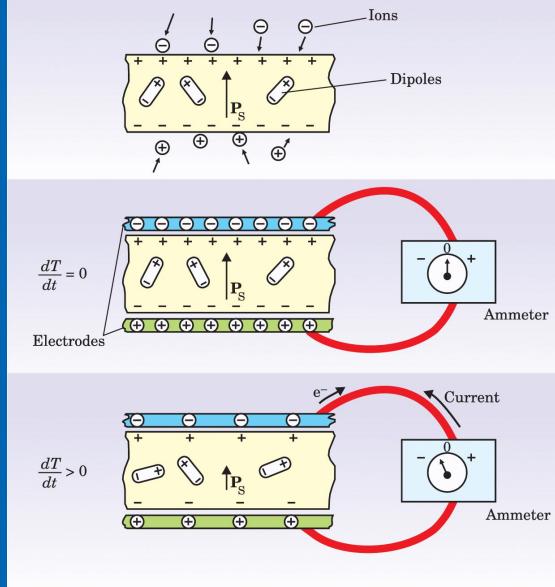
SE WD 20.5mm 25.0kV x100 500um

SE WD 28.7mm 25.0kV x100 500um

Thermally evaporated aSe is shown to be cryogenically stable under rapid cryocycling (< 5 mins warm to cold to warm)

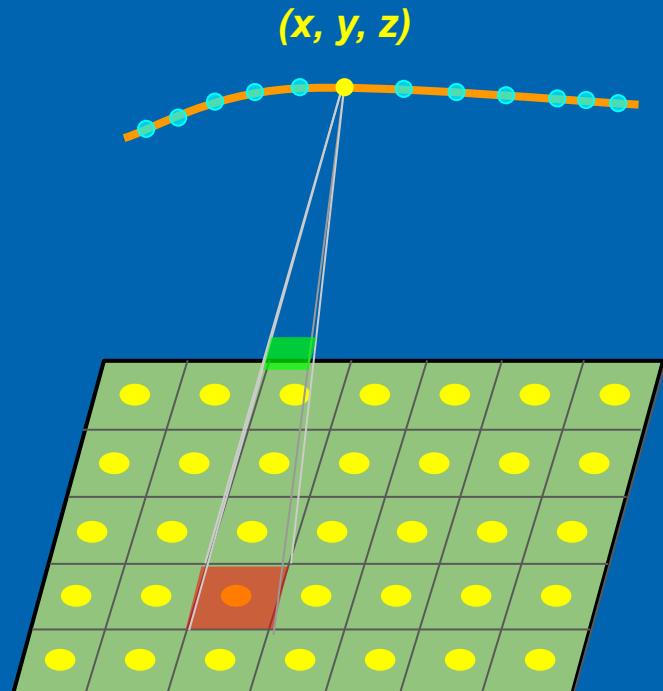
Opportunities for Q-Pix

- There are a number of other photoconductor candidates to be explored and working in the context of SoLAr would allow further engagement with their photon detection / material science expertise
 - a-Se: Direct light to charge
 - ZnO: Pyro-photonic devices
 - CdTe: Nano-particle photoconductors
 - Cryogenic organic semiconductor devices
 -(many more being thought about)
- If found to be viable, demonstration with low energy neutrinos could be a critical step to their overall adoption

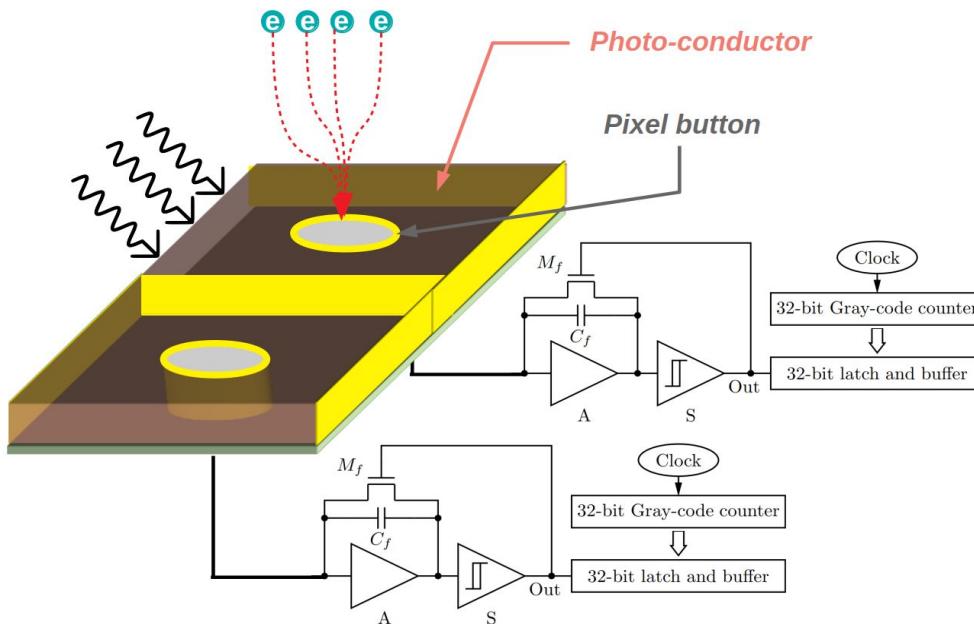


What would you do with such a photon detection?

- UTA has started a set of simulation studies to quantify what you can do with this type of simulation
- We are leveraging the work done in the context of the Semi-Analytic Photon Simulation Method
 - Eur.Phys.J.C 81 (2021) 4, 349
- The simulation allows us to calculate the number and timing information for the photons arriving at a pixel
- For purposes of speed I'm also assuming that each Photon Detecting Pad is 10 pixels by 10 pixels (4.0 cm^2)



What is the idea of a Charge (Q) and Light (L) Sensor?



The idea comes with three assumptions:

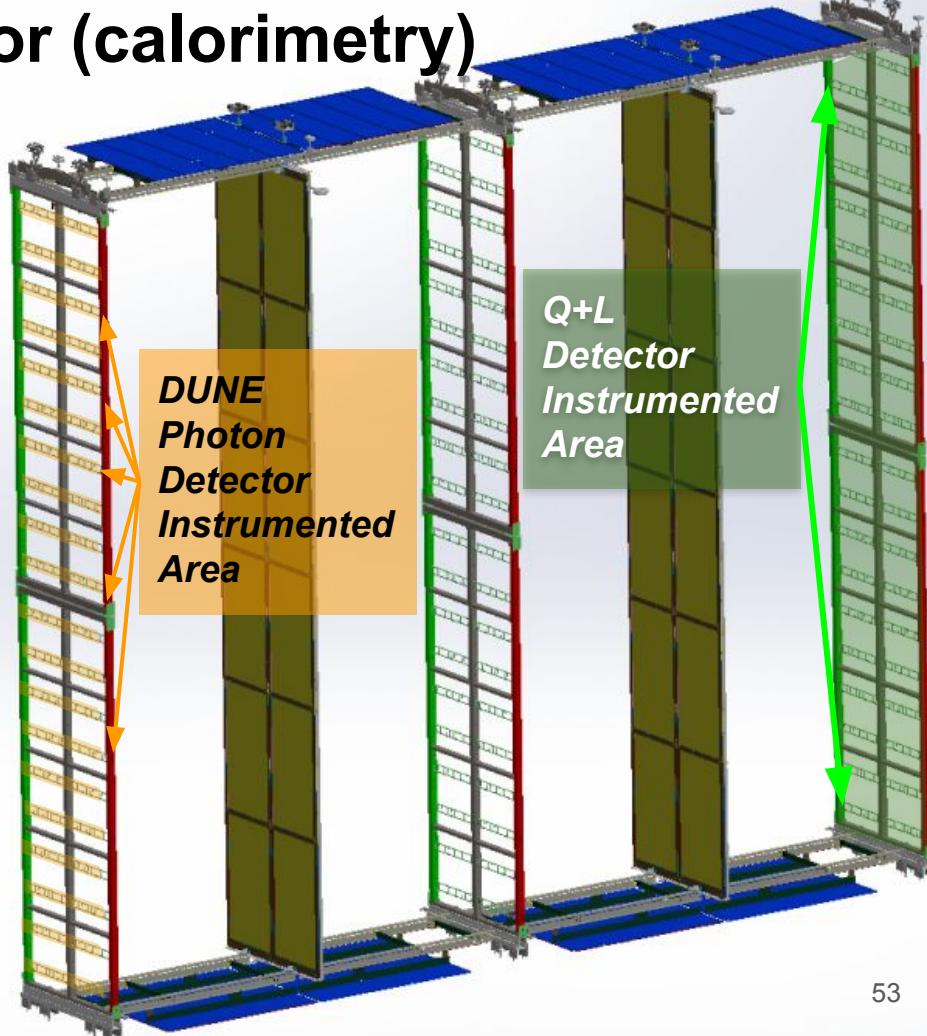
- 1) Pixelated readout for the ionization charge (Q-Pix)
- 2) A material coating the pixel plane which converts VUV light to charge
- 3) The same (or very similar) electronics used to readout the signal from the photoconverted charge

Thoughts on Charge (Q) and Light (L) Sensor

- For the events I'll show in the coming slides they are placed 'randomly' in a argon volume (on average 1.5 meters away from the pixel plane)
 - Majority of the light arrives in the first 100 ns, the rest over 2000ns
- The charge will arrive on average 937 μ s (937,000 ns) later
(400x later than the late light, 9000x later than the prompt light)
 - Speed of light: 11.23 cm/ns (**112,300 mm/ μ s**)
 - Speed of charge (at 500 V/cm): 0.00016 cm/ns (**1.6 mm/ μ s**)
- An event 1 cm away from the pixel plane has the light signal arrive in 0.9 ns and the charge arrives 6250 ns
 - I conclude that anything that is in a reasonable fiducial region (> 1cm) will be distinguishable using just the time of the signal
- Light events will also have a signal from the traces buried below the selenium while charge events do not!

Things to do with a Q+L Sensor (calorimetry)

- Currently DUNE 10kT photon detector coverage is **130 m²/10kT**
 - Window area for each XArapuca supercell (435.24 cm^2) x 10 supercells/APA x 152 APA's per 10kT x 2 (Double sided)
- If a Q+L Pixel Sensor can be realized, then your photon detector coverage is **200,000 m²/ 10kT**
 - APA Surface area ($135,700 \text{ cm}^2$) * 152 APAs/10kT



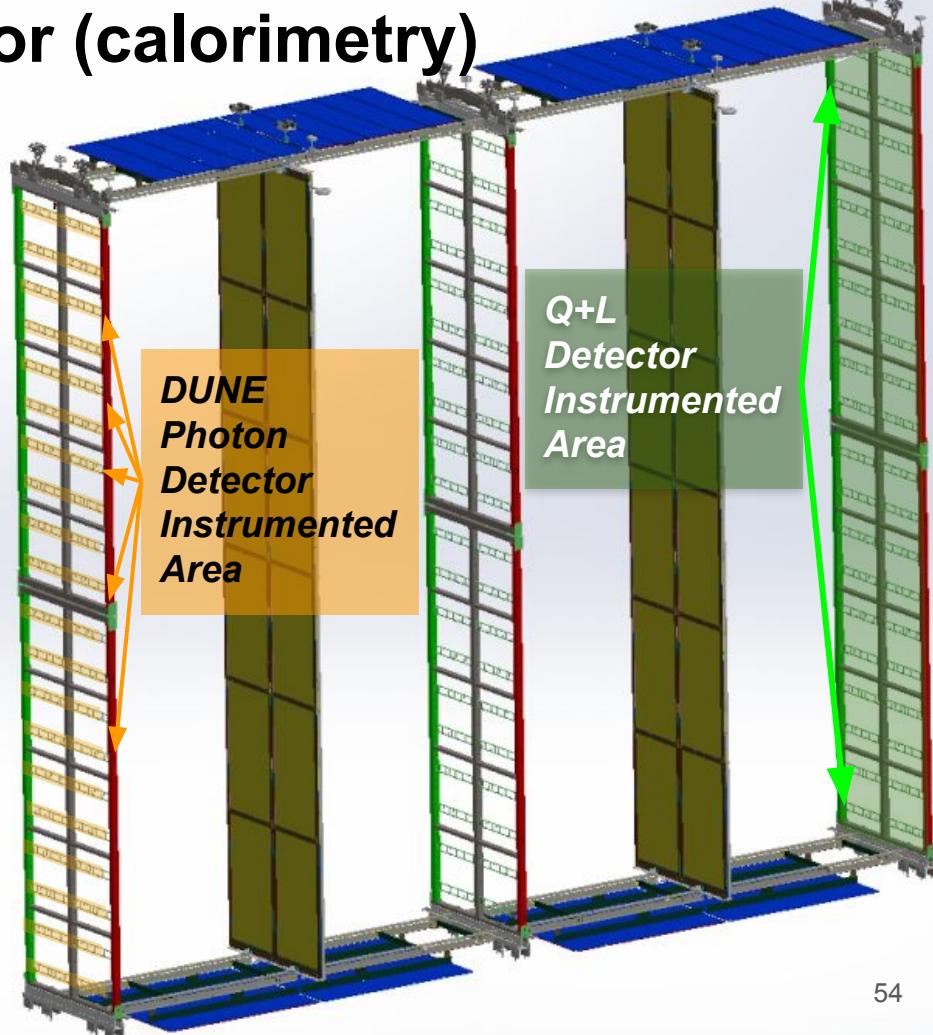
Things to do with a Q+L Sensor (calorimetry)

- The gain in effective surface area is a factor of ~1000!

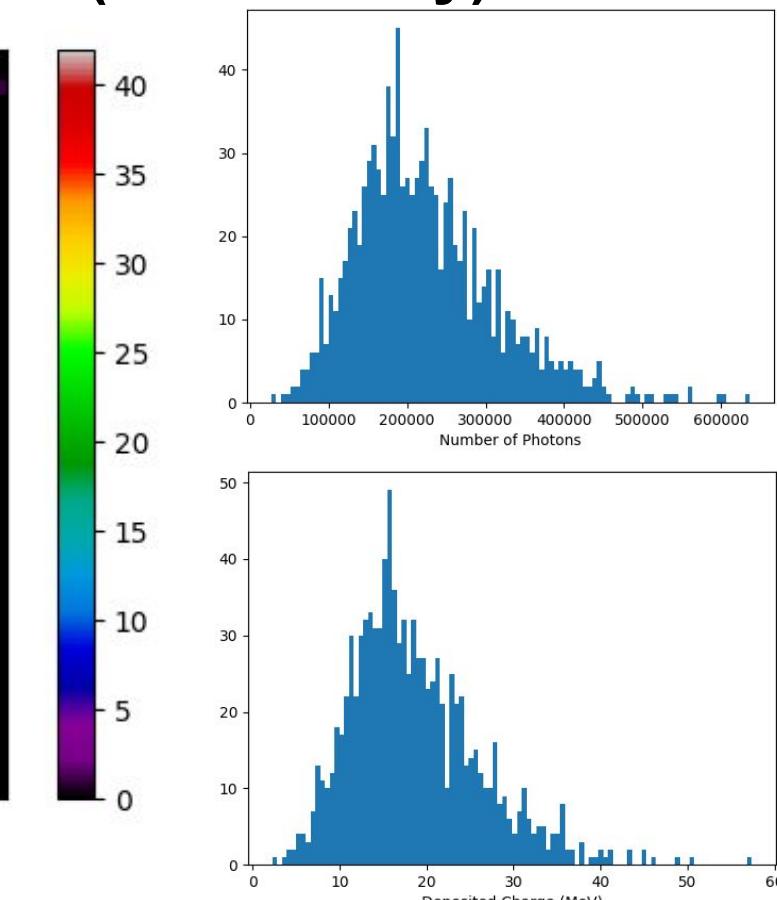
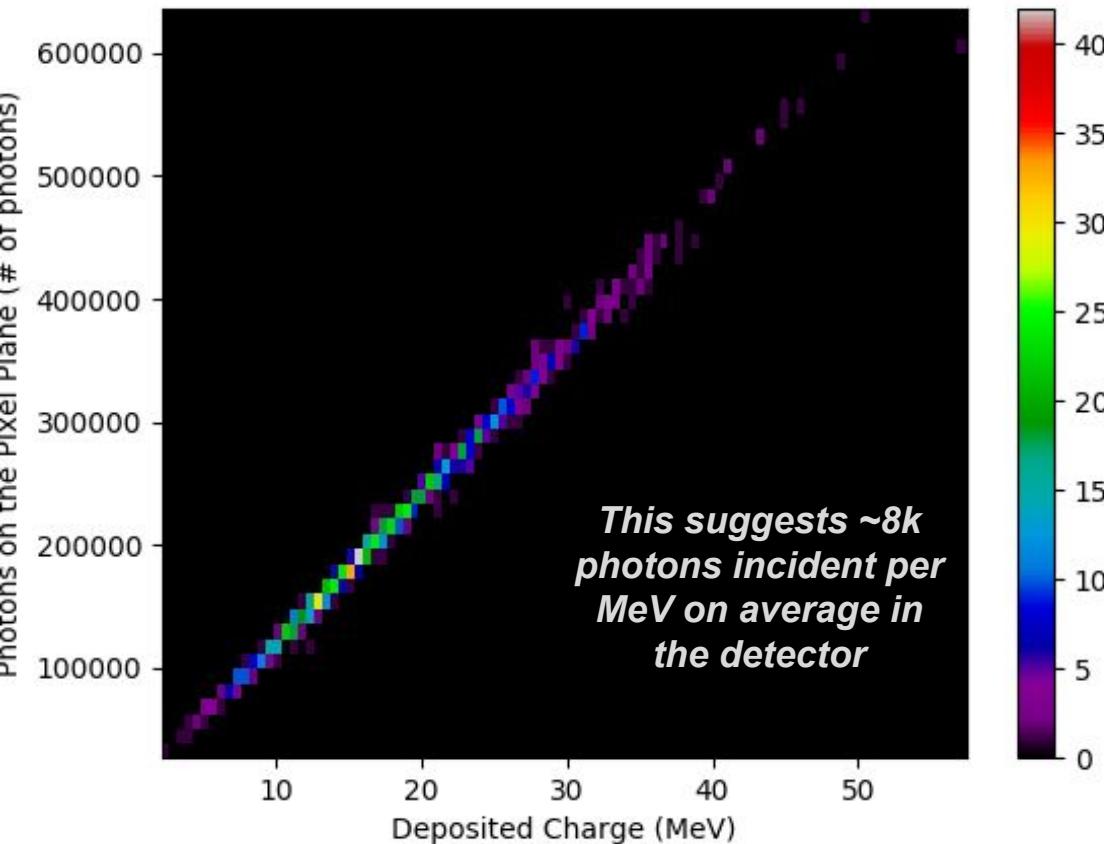
Note: The current efficiency assumed to achieve the physics outlined above is 1.3% efficiency for a photon to turn into a detected photoelectron (X-Arapuca has shown > 3% efficiency)

This is equivalent to a surface area of 23 cm² at 100% efficiency

- This huge gain in surface area suggests for even modest efficiency, a Q+L sensor would vastly enhance the physics!



Things to do with a Q+L Sensor (calorimetry)

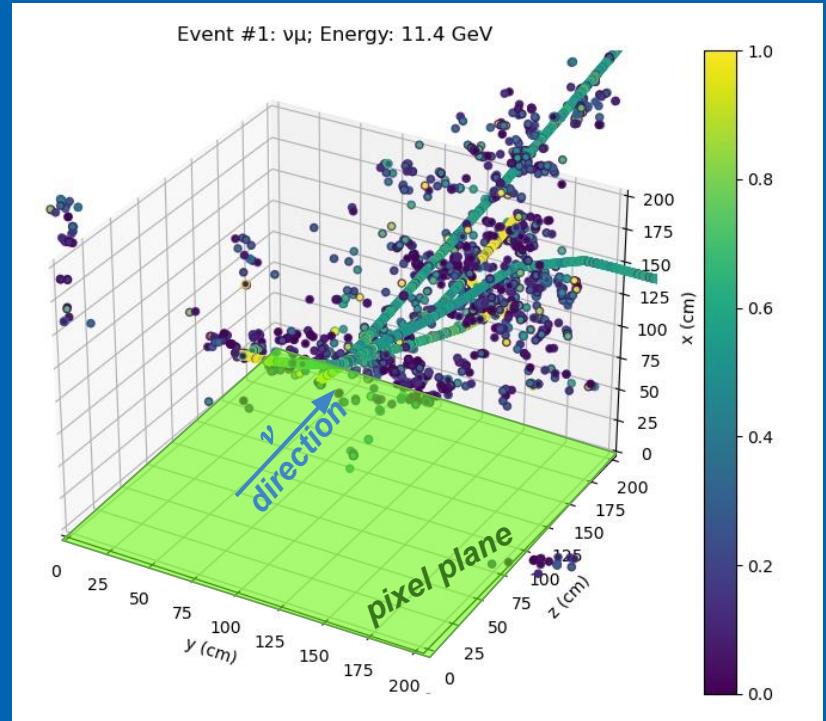
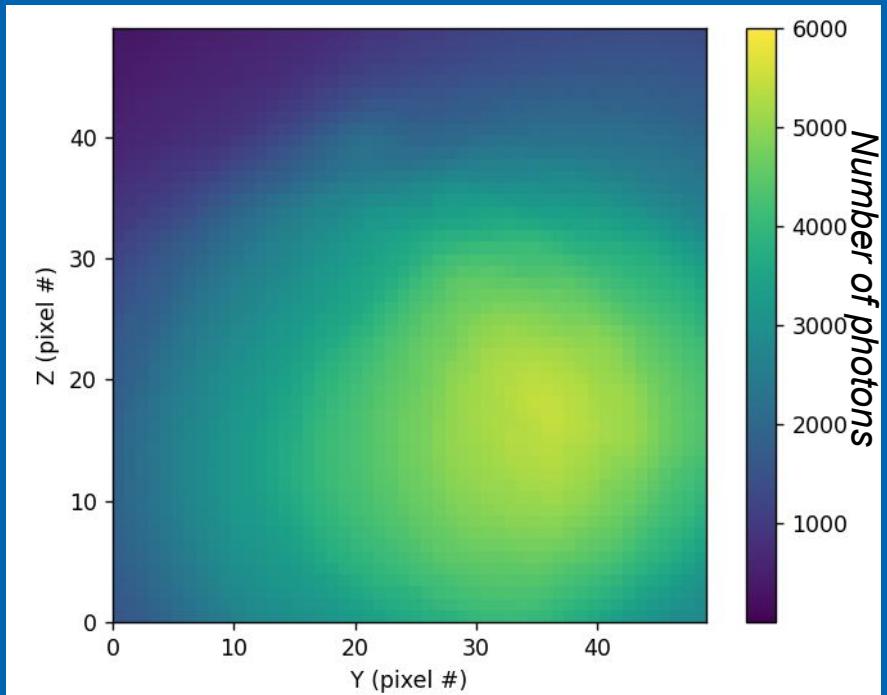
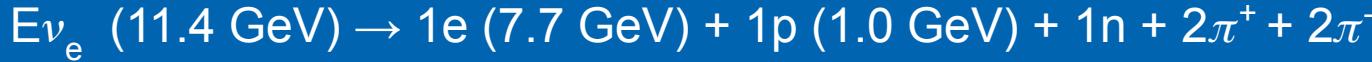


- 1000 Marley (Supernova neutrino) events

Example Outputs (Event # 1, ArCube_0000.root)

(3m (drift) x 2m (y) x 2m (z) detector,
neutrino vertex at x = 100cm, y = 100 cm, z = 100cm)

neutrino Energy: 11.378541					
FSP 0	PDG:	13	Energy:	7.726225272569373	
FSP 1	PDG:	2212	Energy:	1.0261371891164894	
FSP 2	PDG:	211	Energy:	0.08893548219256471	
FSP 3	PDG:	-211	Energy:	0.1618356069146468	
FSP 4	PDG:	2112	Energy:	0.12308557336131537	
FSP 5	PDG:	211	Energy:	1.0154998508301367	
FSP 6	PDG:	-211	Energy:	0.5974021138847361	

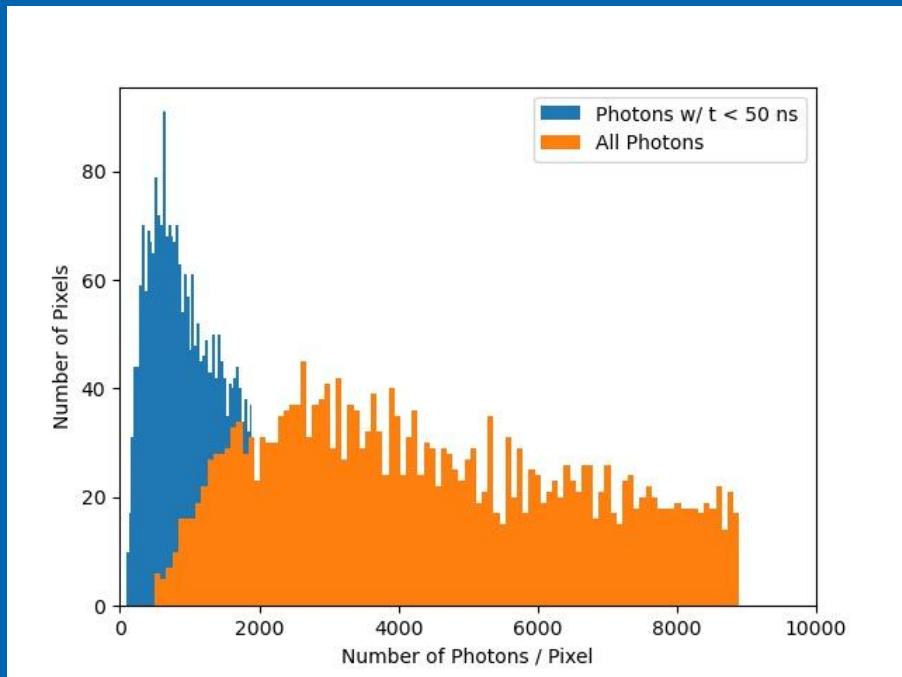
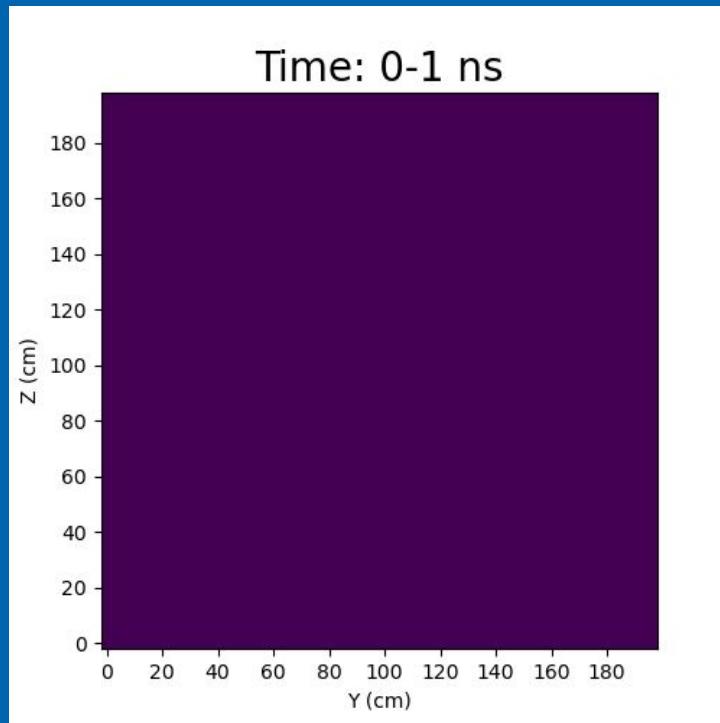


Example Outputs

(Event # 1, ArCube_0000.root)

(3m (drift) x 2m (y) x 2m (z) detector,
neutrino vertex at x = 100cm, y = 100 cm, z = 100cm)

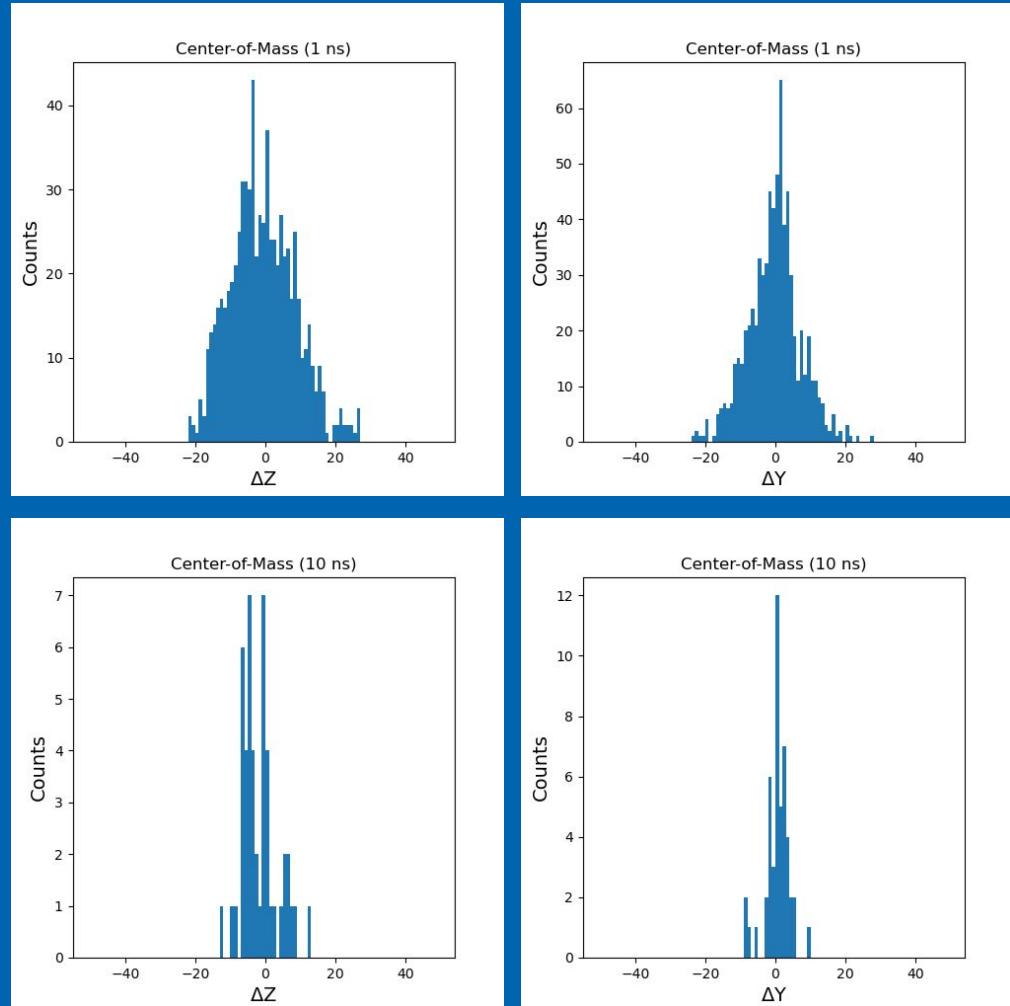
```
neutrino Energy: 11.378541
FSP 0 PDG: 13 Energy: 7.726225272569373
FSP 1 PDG: 2212 Energy: 1.0261371891164894
FSP 2 PDG: 211 Energy: 0.08893548219256471
FSP 3 PDG: -211 Energy: 0.1618356069146468
FSP 4 PDG: 2112 Energy: 0.12308557336131537
FSP 5 PDG: 211 Energy: 1.0154998508301367
FSP 6 PDG: -211 Energy: 0.5974021138847361
```



Example Outputs

By comparing the “center of mass” of the light profile to where the “center of mass” of the charge is we can start to examine how well we can associate the various light signals to specific depositions of charge

We are in the exploration stage of figuring out what you do with this level of information



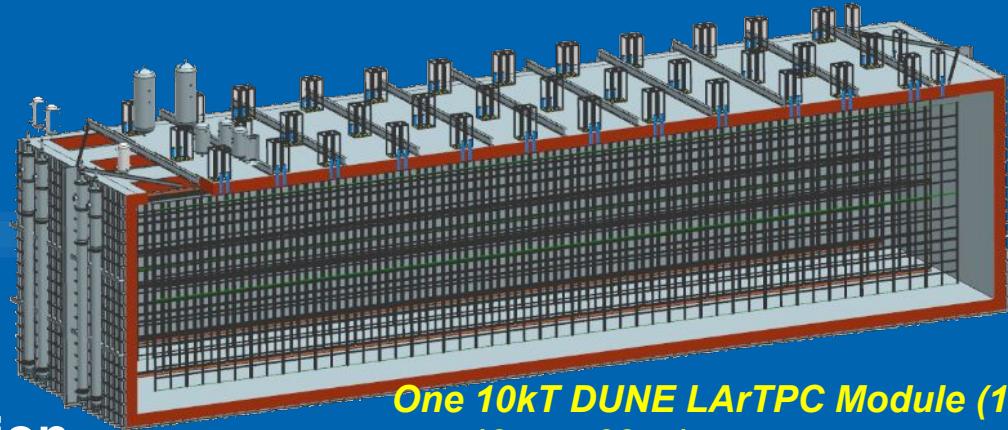
Conclusions

- **Q-Pix offers an exciting R&D opportunity for large scale pixel based readout at the limit of detection threshold**
 - Lots of ongoing work, with the first prototype chips expected this year
 - Parallel efforts to explore various submission / design concepts
- **An intensive prototyping program is underway to show the conferred benefits of the Q-Pix concept**
 - Small scale TPC (UTA/H) to be used for testing
 - Exploration of COTS options to demonstrate the functionality underway
 - Lots of opportunities to collaborate
- **Q-Pix may enable novel Q+L solutions**
 - Many potential photoconductors are being explored
 - Simulation efforts underway to quantify the conferred benefit
 - Very open to more collaboration, input, and thoughts

Backup Slides

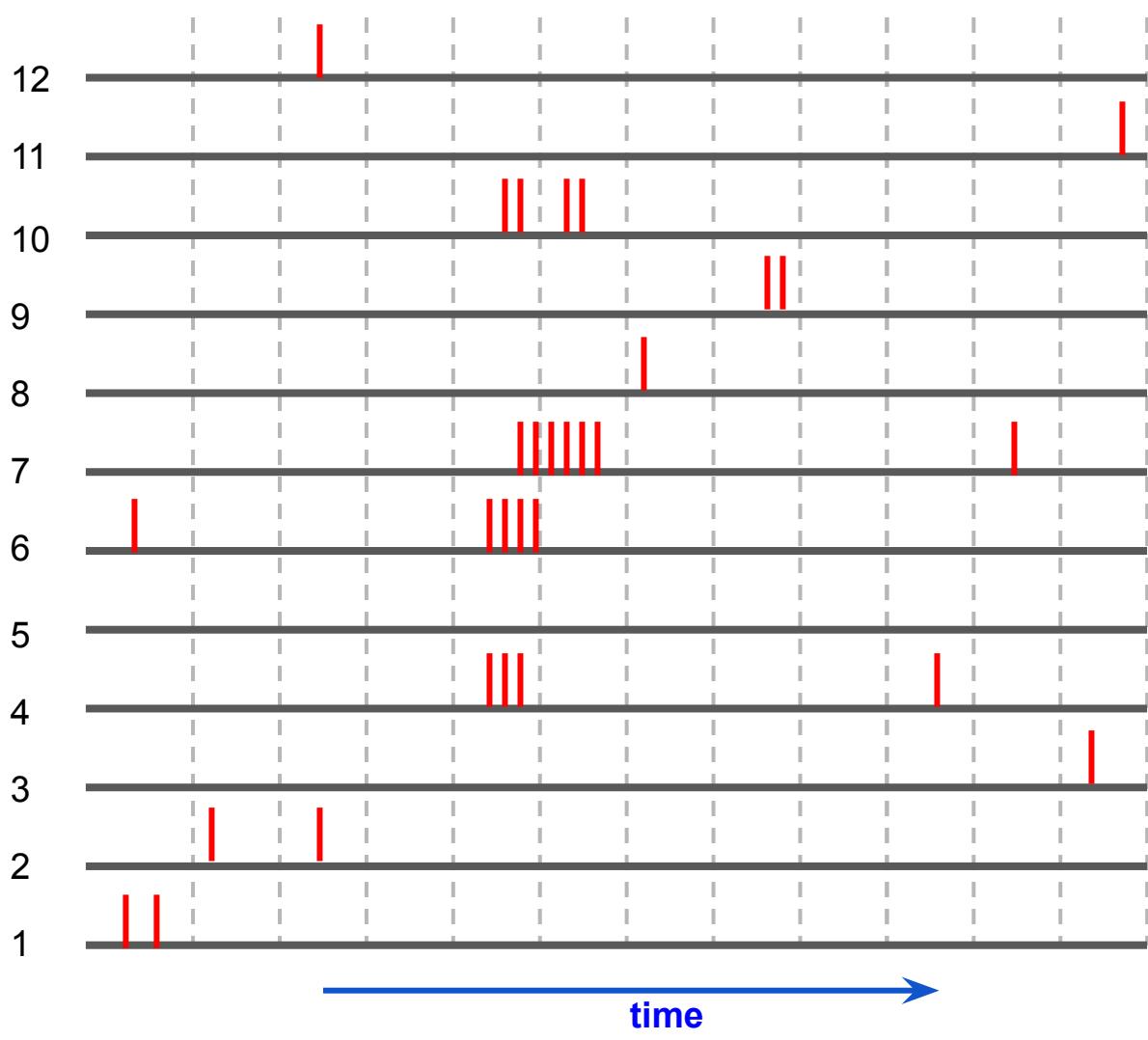
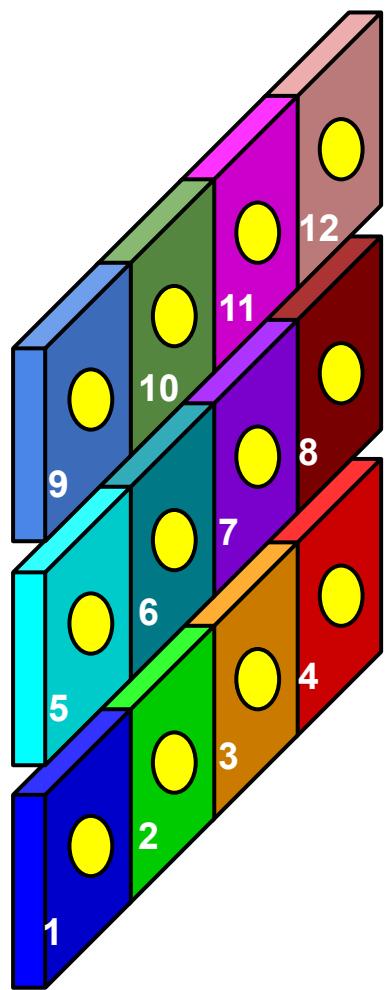
Data Rates for 10 kTon

- We imagine each tile is 16x16 ASICs and one readout plane (APA) has 11,136 tiles per APA
- We perform the clock calibration 1/second (perhaps less often)
 - This gives 16,384 bits / tile
- The total data rate is thus set by the number of readout planes
 - 3.5 meter drift = 4 APA's = 16,384 bits/tile x 44,552 tiles ~ 90 Mbytes/s
 - Full burst of supernova events w/ radiological backgrounds in simulation only adds ~24 Mbytes/s of data

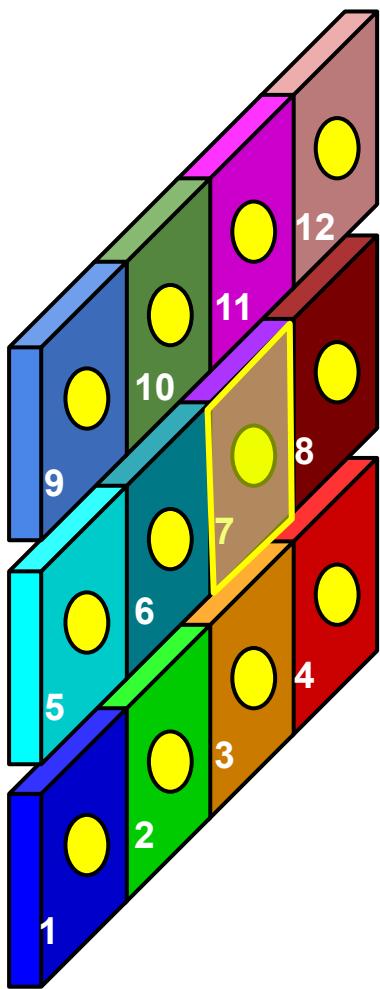


*One 10kT DUNE LArTPC Module (18 m x 19 m x 66 m)
¼ the total size of DUNE*

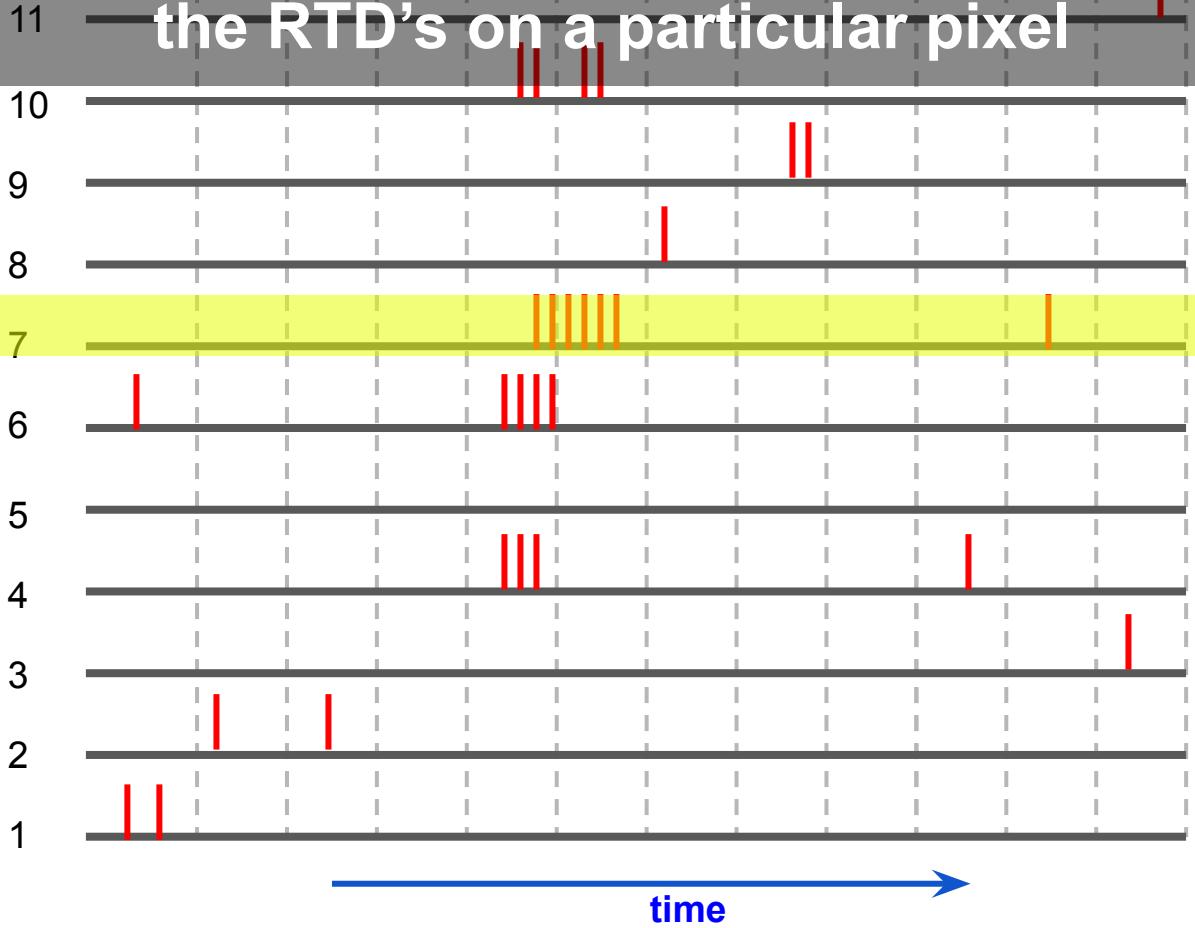
| = 1 RTD



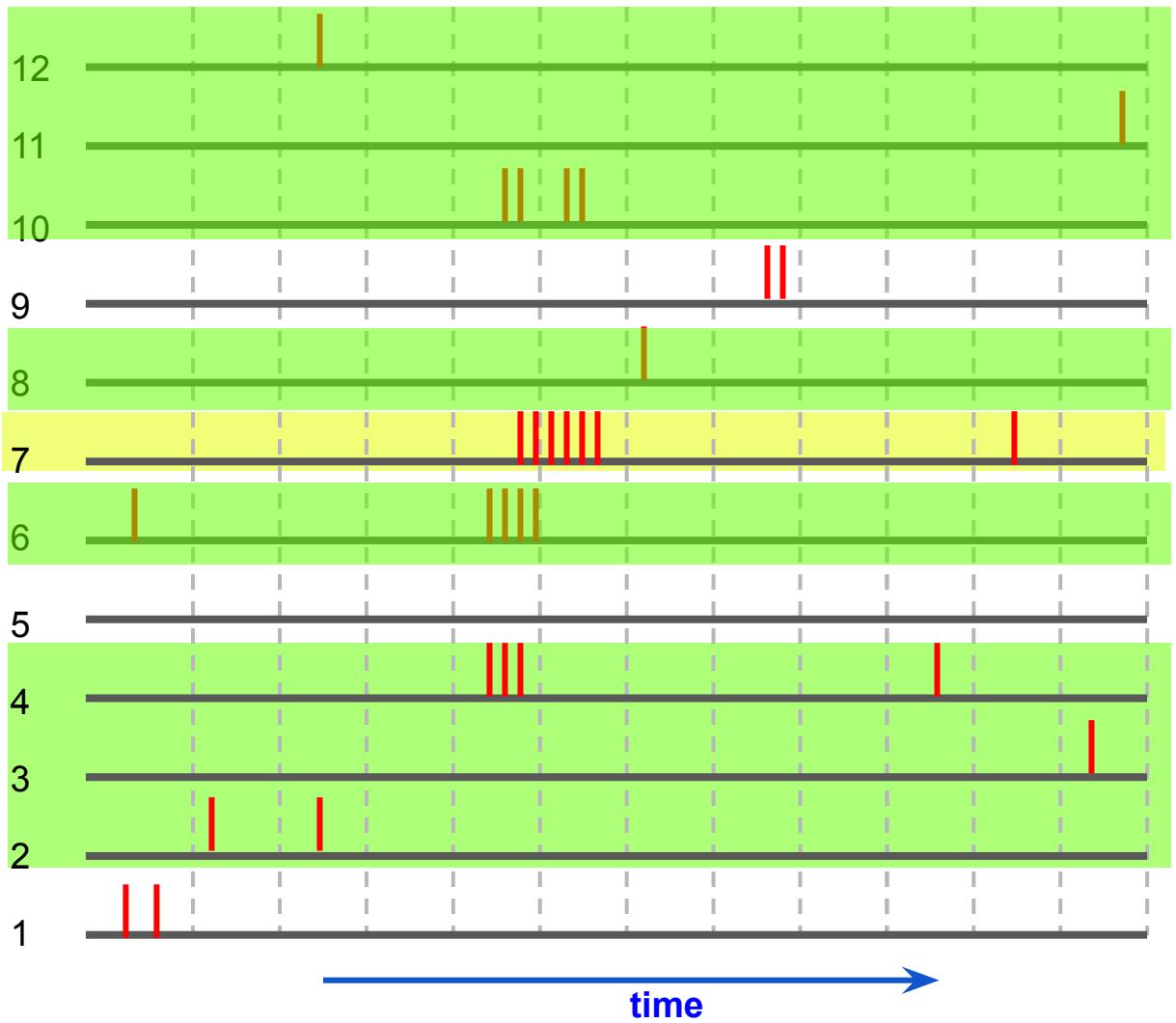
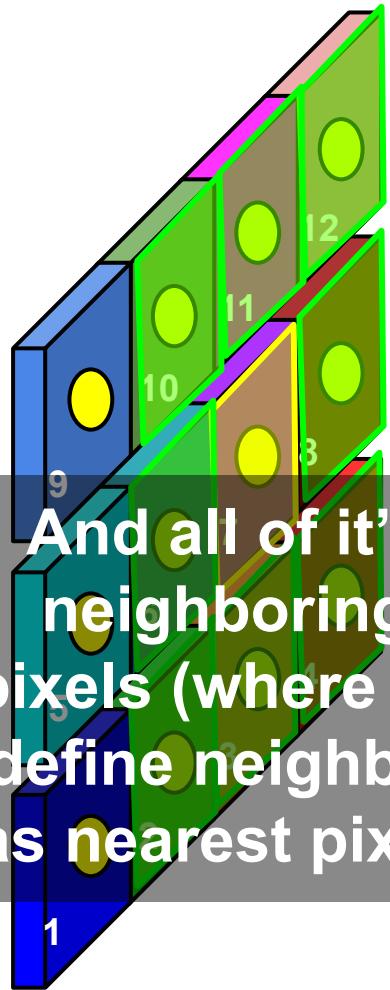
| = 1 RTD



For this example, we start by analyzing the RTD's on a particular pixel

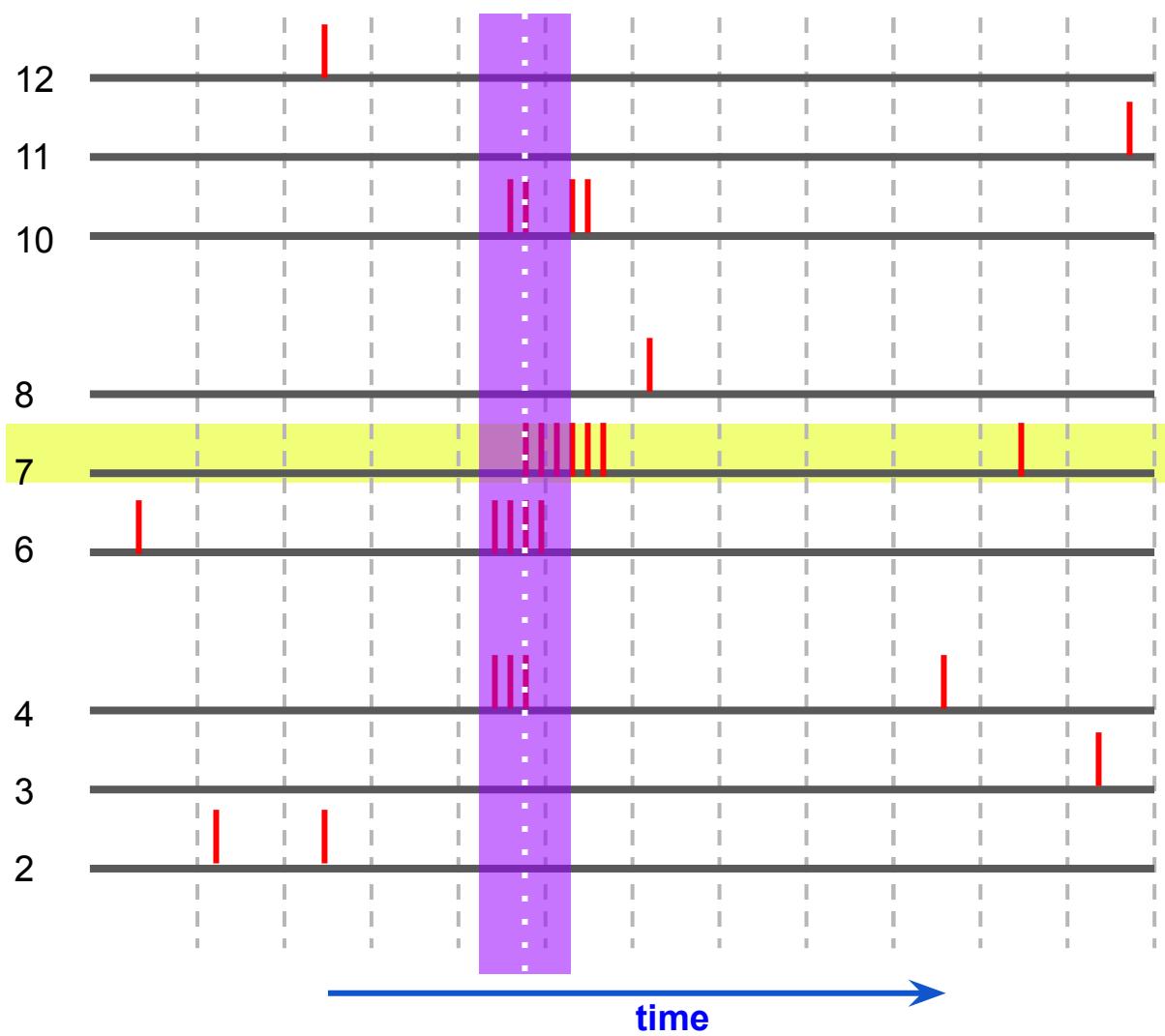


| = 1 RTD

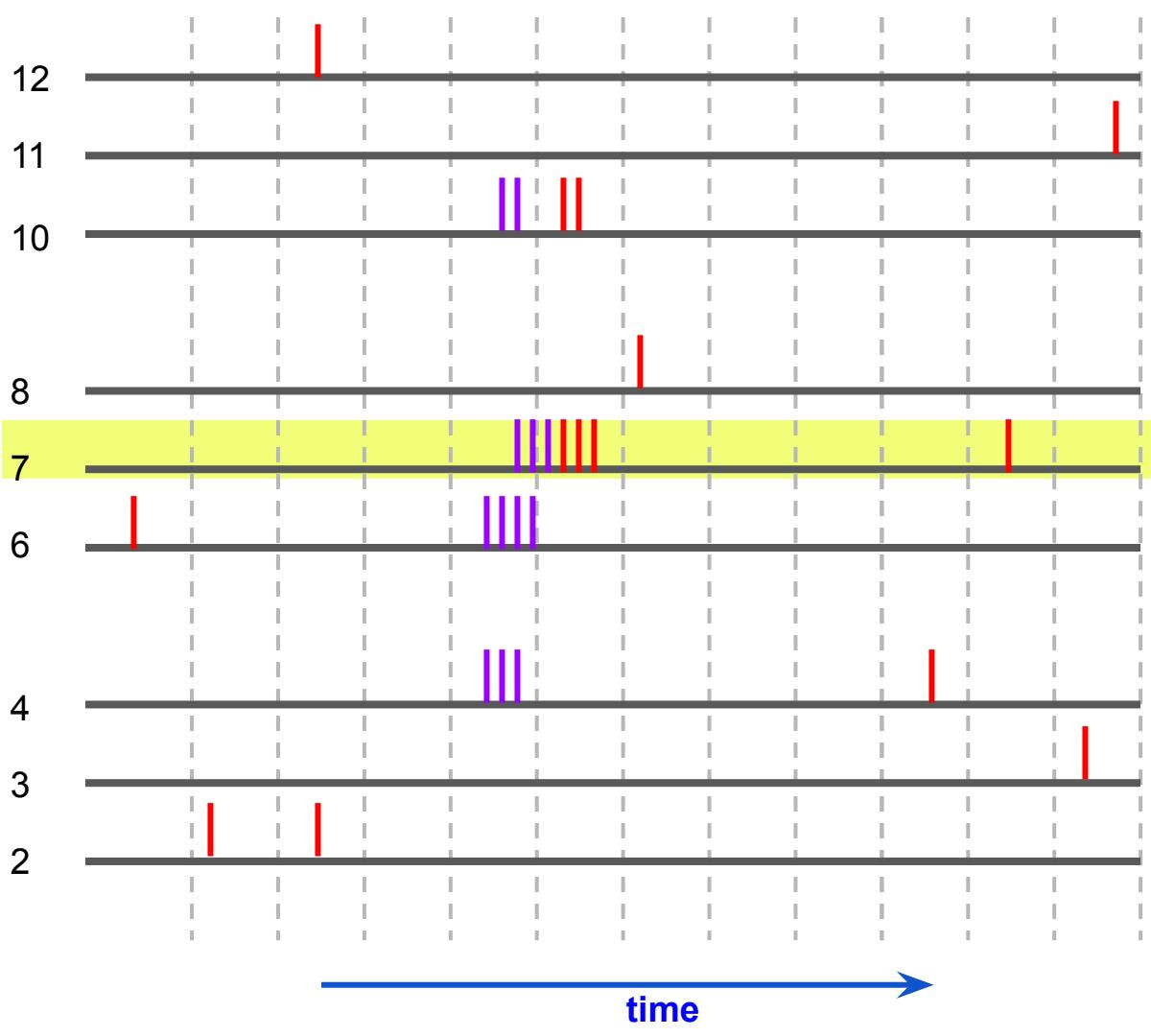
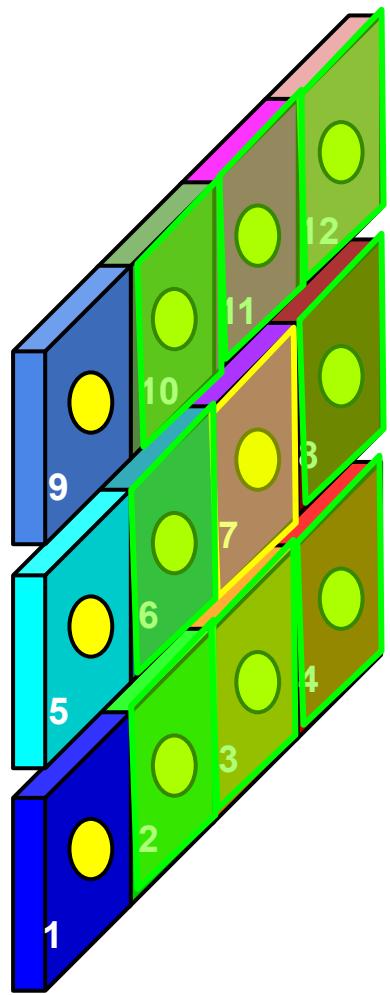


| = 1 RTD

We now define an interval in time around which we will “cluster” together RTD’s and begin from the first RTD

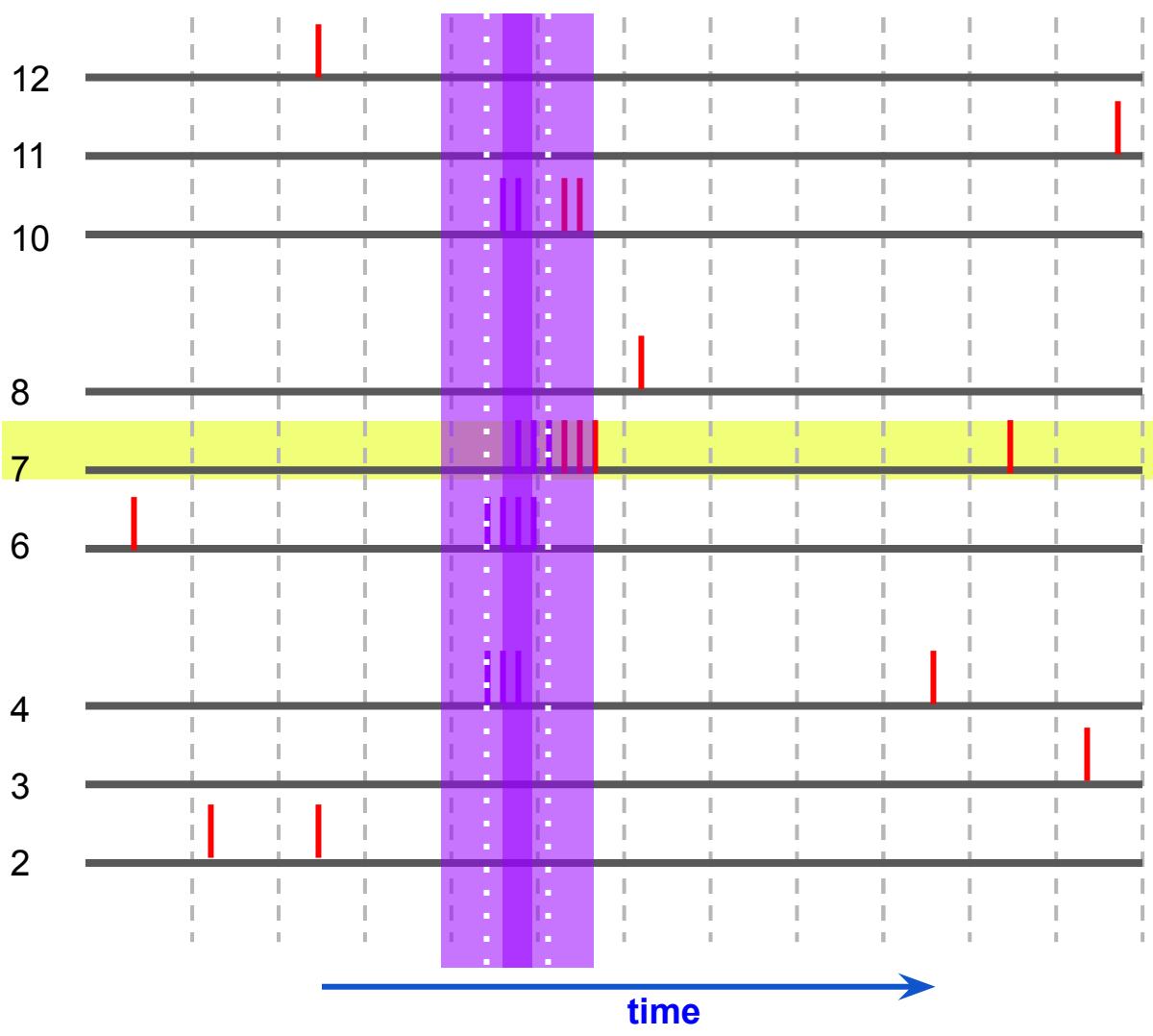


| = 1 RTD



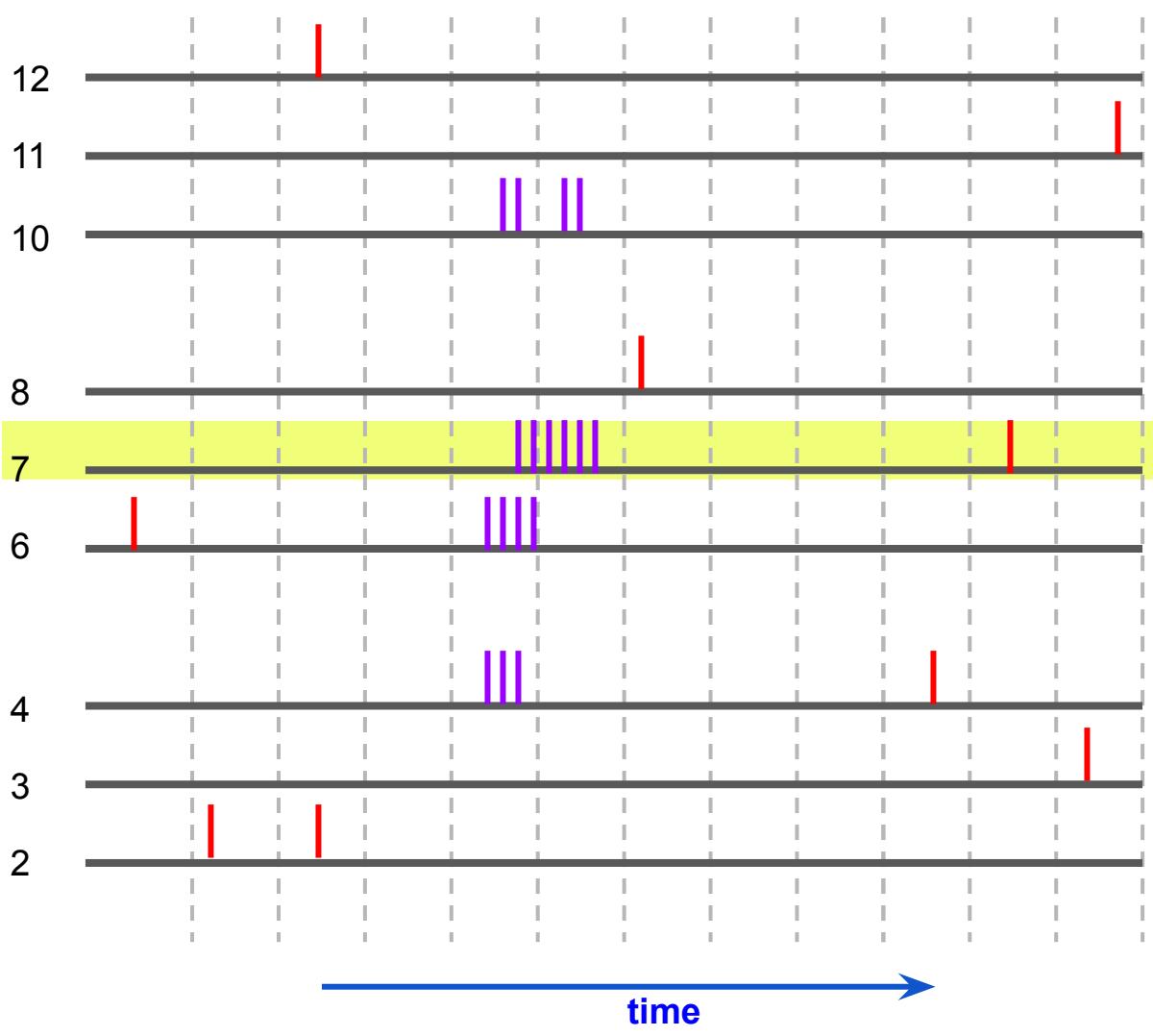
| = 1 RTD

The process now repeats growing outward in time till there are no more RTD's to cluster



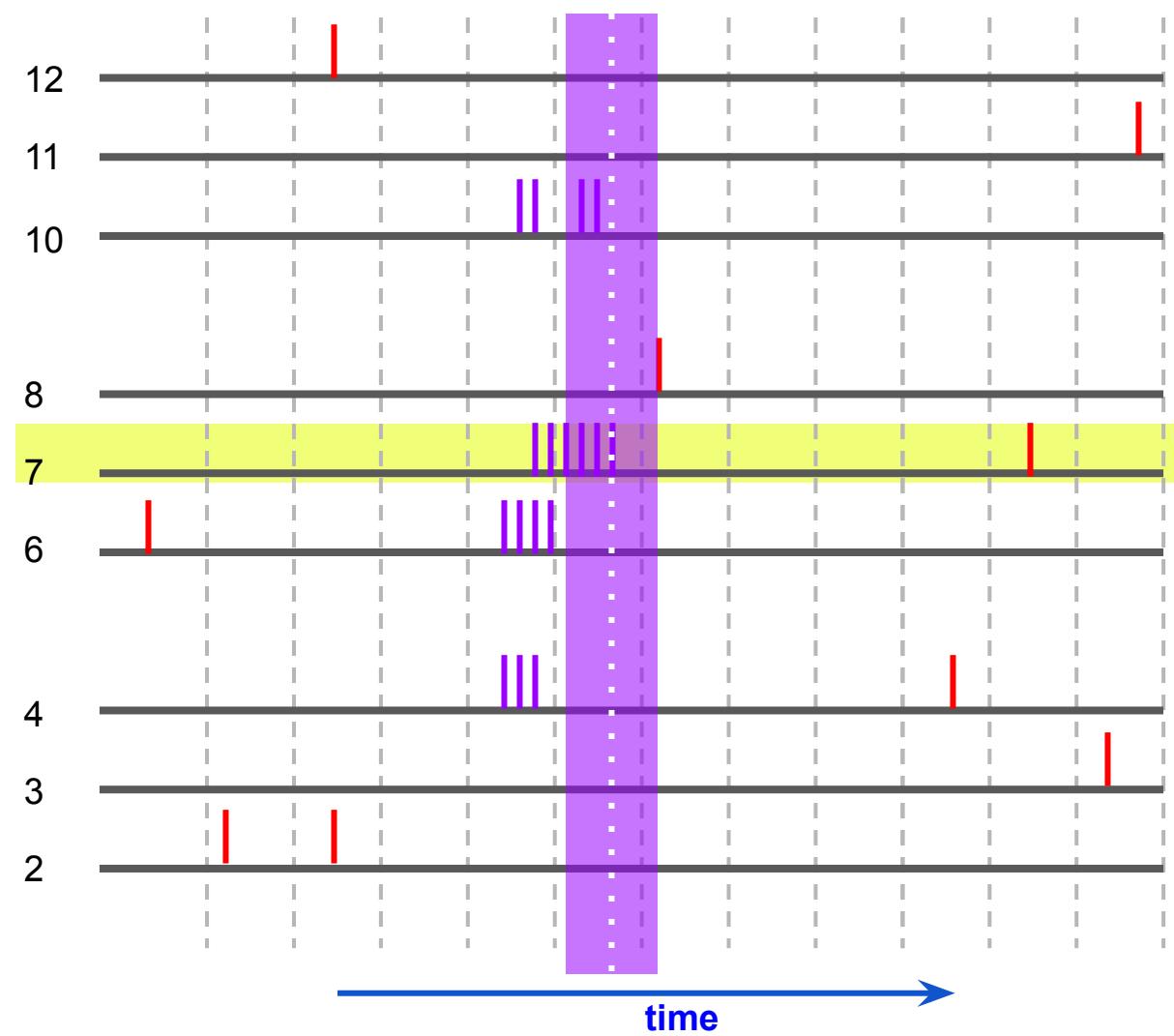
| = 1 RTD

The process now repeats growing outward in time till there are no more RTD's to cluster

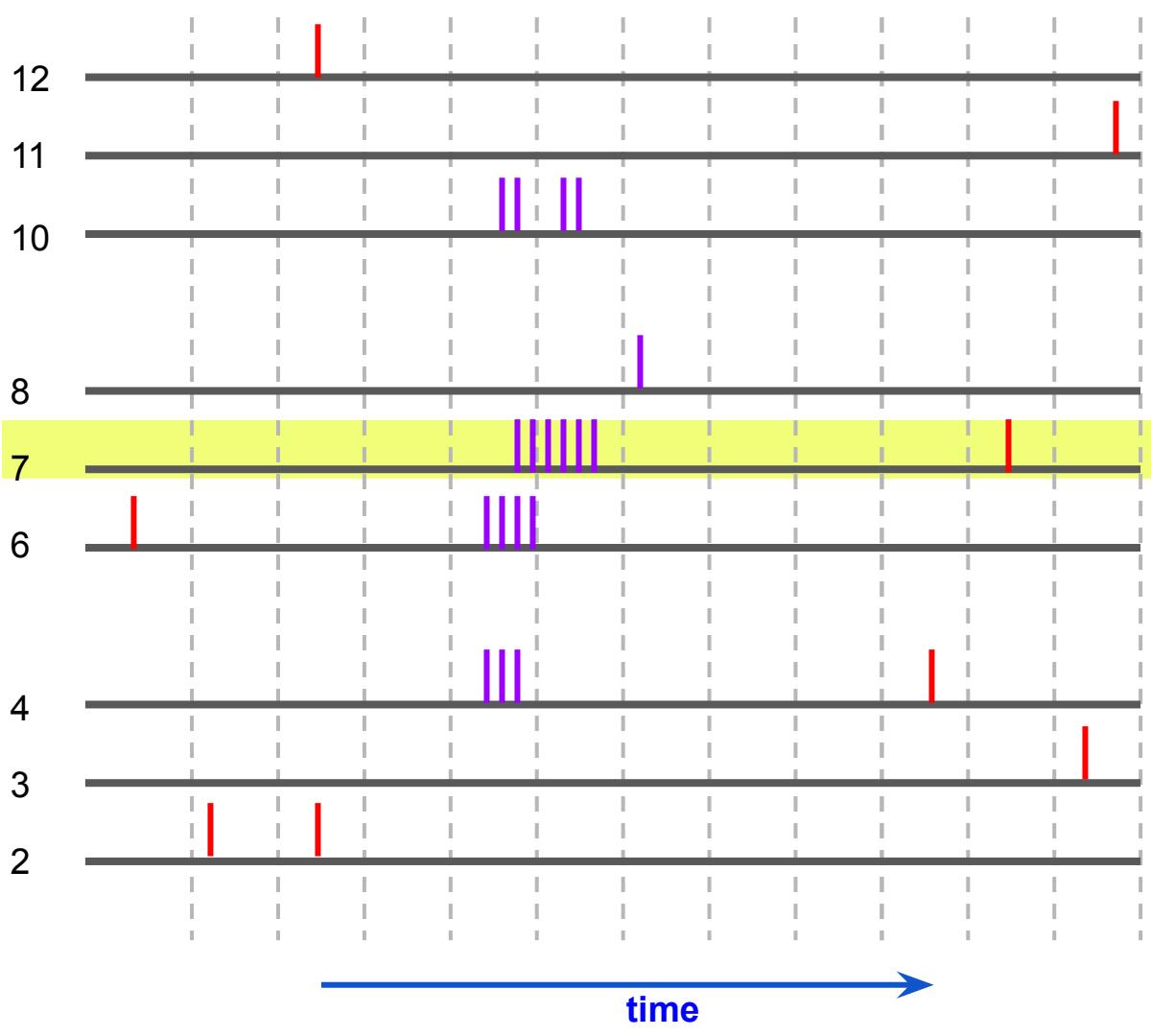
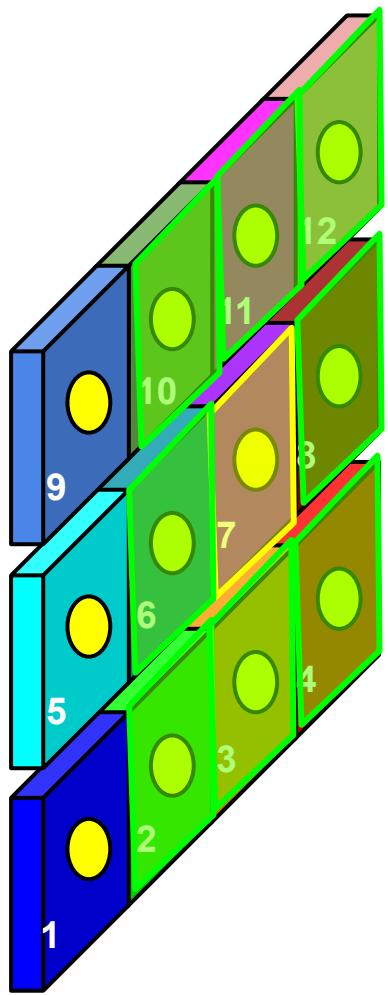


| = 1 RTD

The process now repeats growing outward in time till there are no more RTD's to cluster

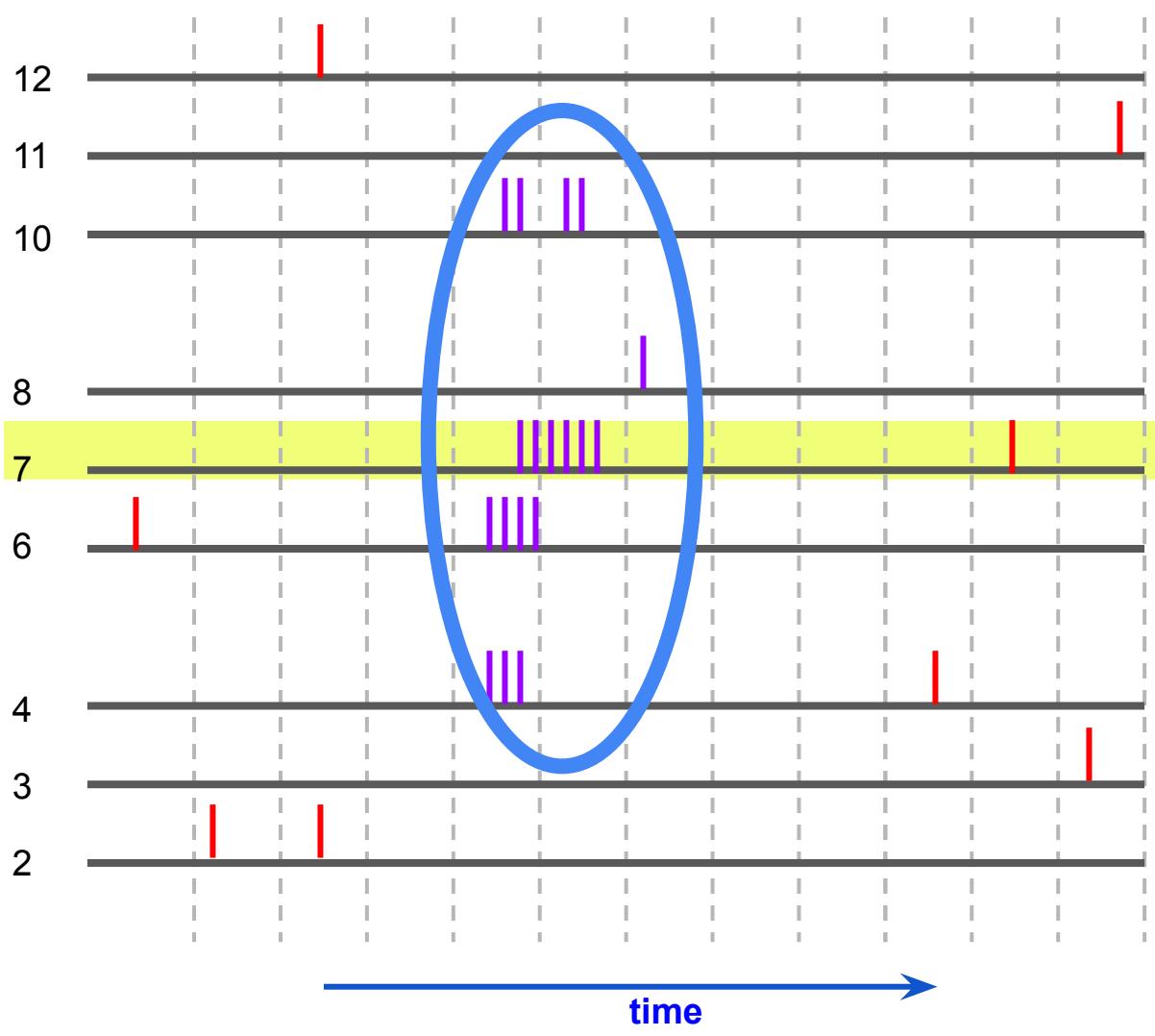
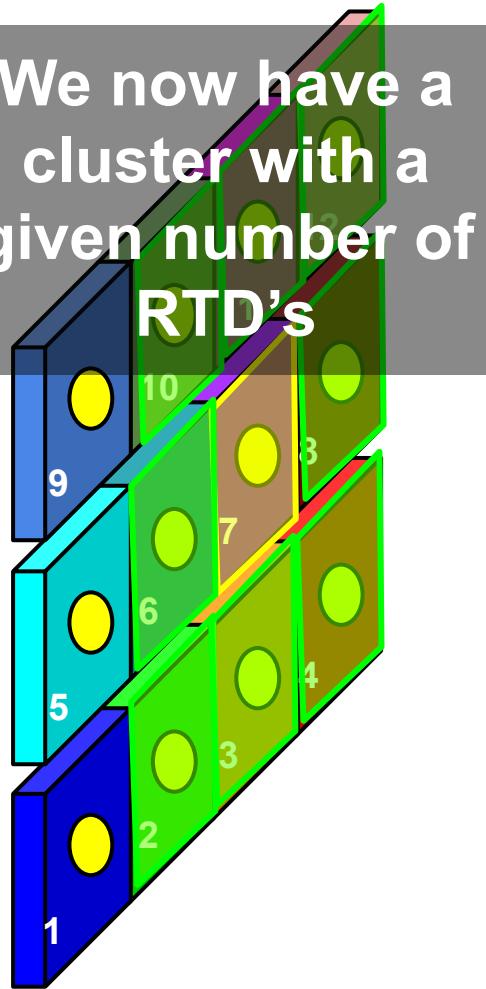


| = 1 RTD



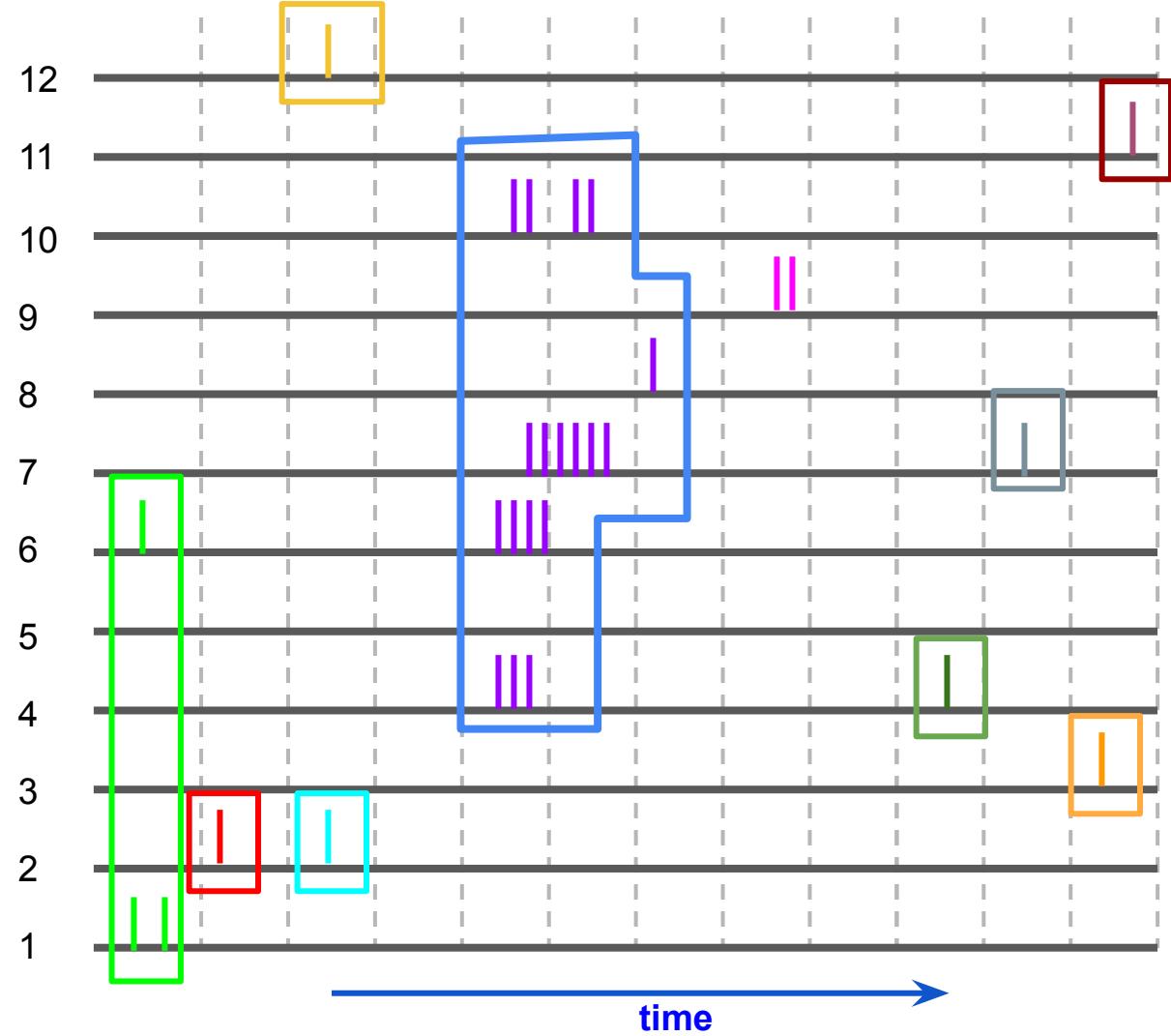
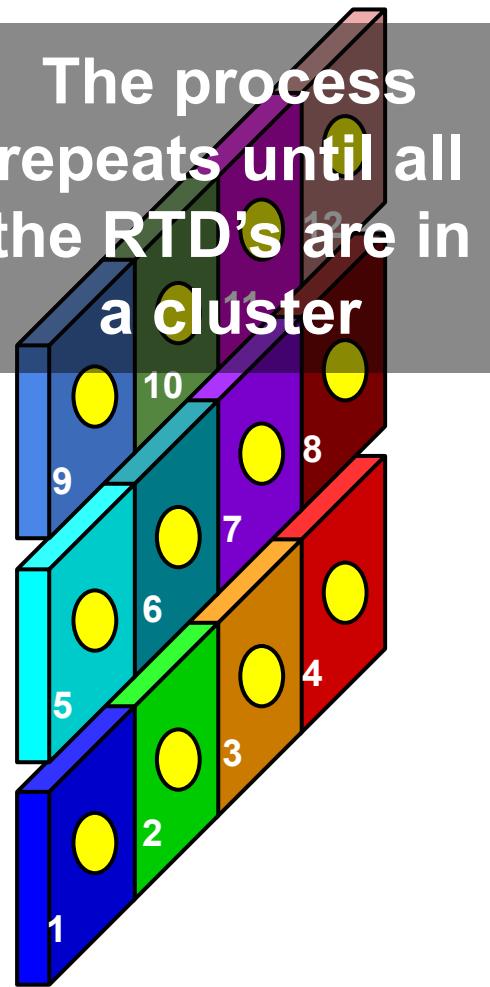
| = 1 RTD

We now have a cluster with a given number of RTD's



| = 1 RTD

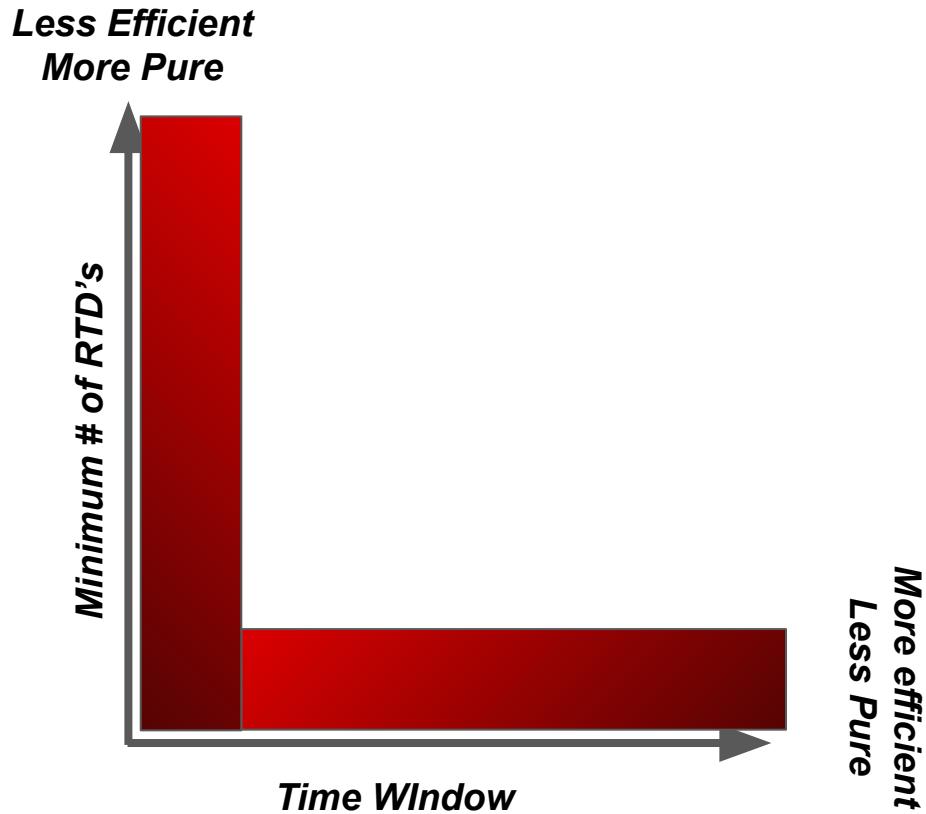
The process repeats until all the RTD's are in a cluster



We thus have two dimensions to optimize this clustering algorithm against

- 1) Length of the time window to cluster things
- 2) Minimum number of RTD's to classify as a cluster

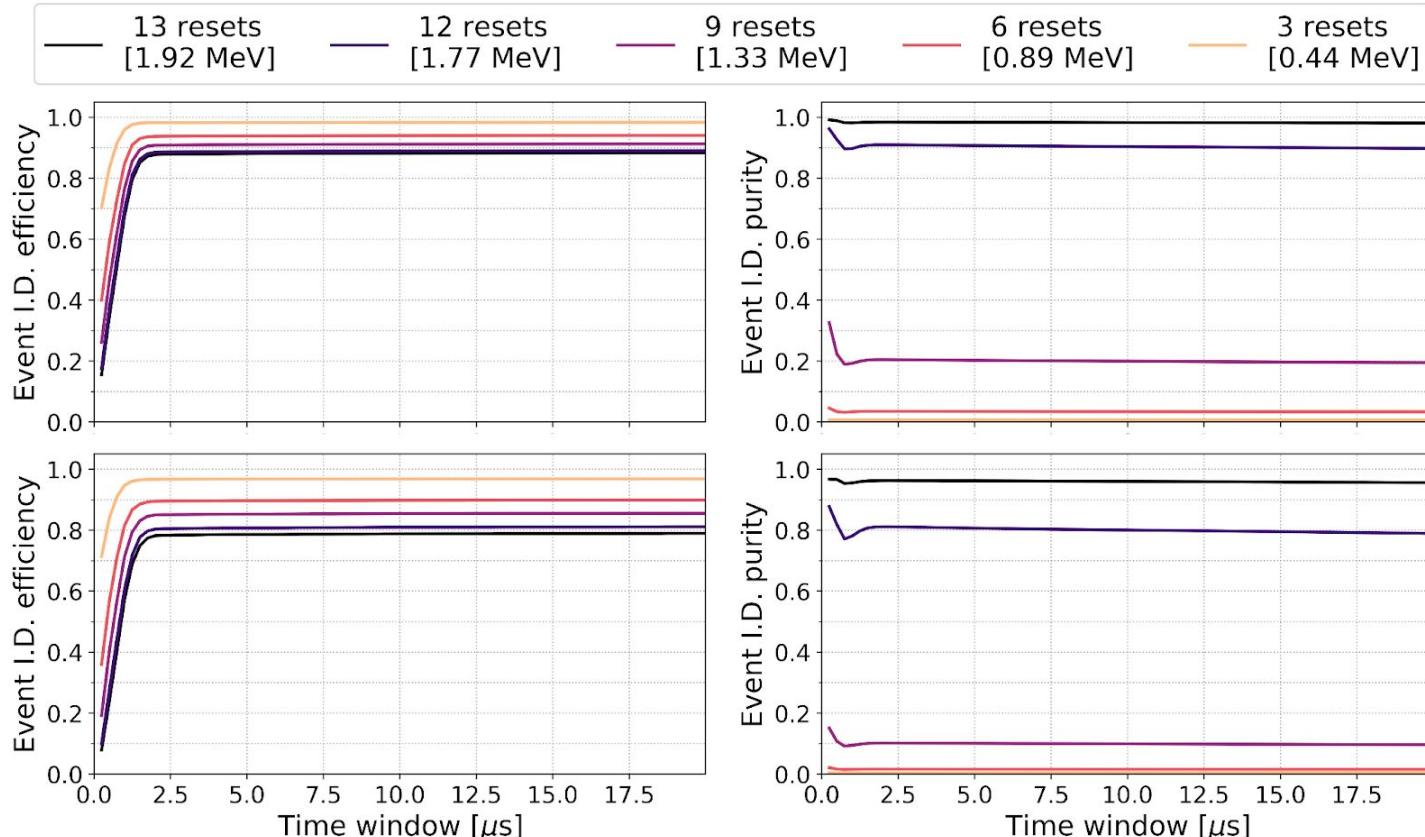
We could try to optimize on the number of “nearest neighbors”...but for low energy events on pixel seems like a reasonable dimension to leave fixed



Picking a time window

Anything above $2.5 \mu\text{s}$ appears to give flat efficiencies and purities regardless of the number of resets in the cluster

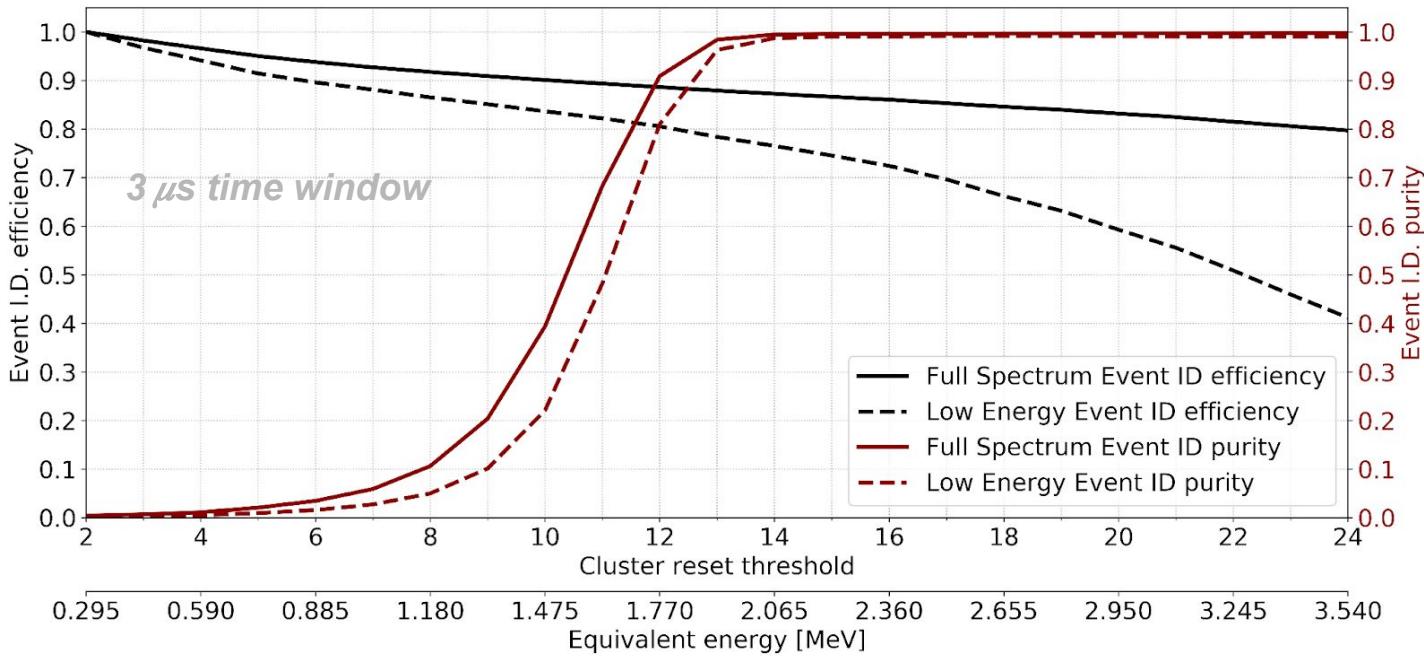
We choose
 $3\mu\text{s}$



Efficiency = #sig in window / total #sig

Purity = #sig in window / #sig and background in window

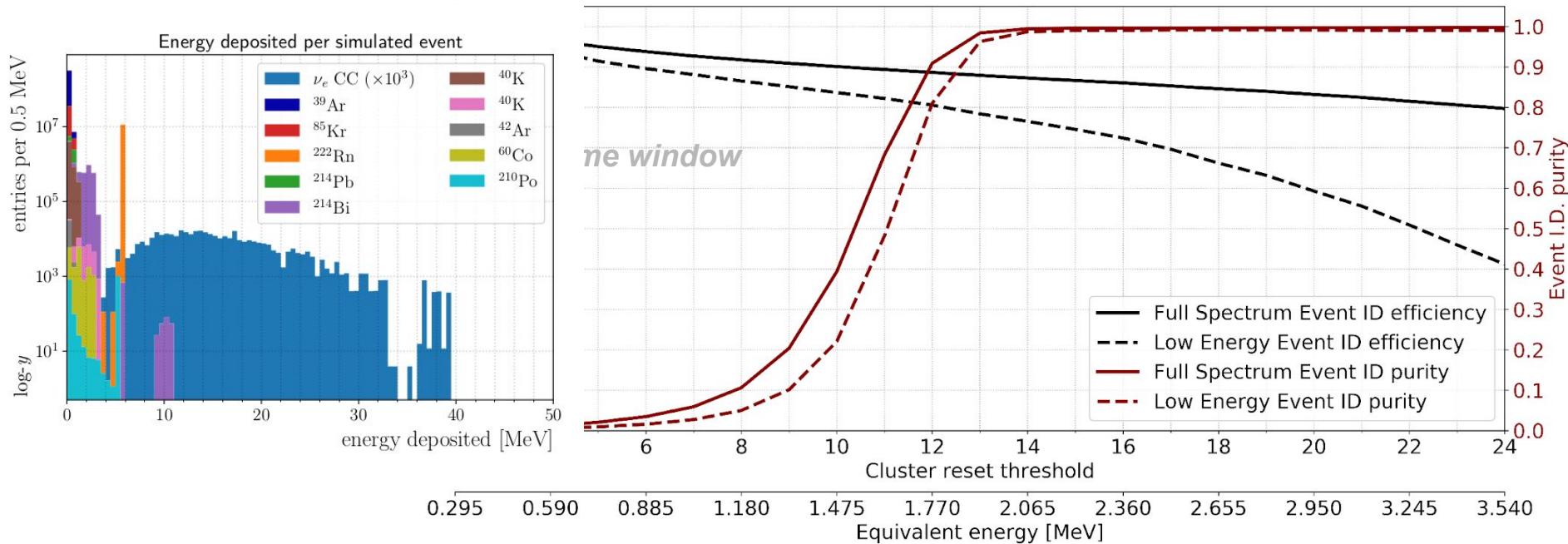
Picking a minimum number of RTD's in a cluster



Efficiency = #sig in window / total #sig

Purity = #sig in window / #sig and background in window

Picking a minimum number of RTD's in a cluster

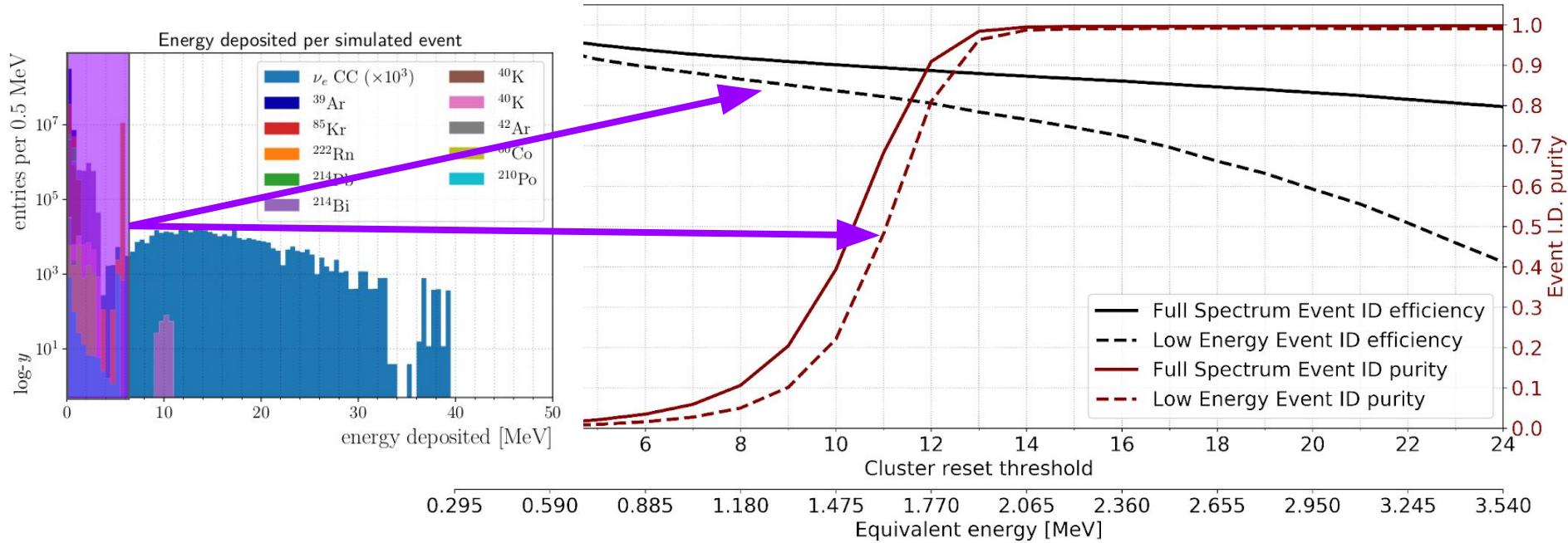


This is the spectrum of deposited energy we are looking at

$$\text{Efficiency} = \# \text{sig in window} / \text{total } \# \text{sig}$$

$$\text{Purity} = \# \text{sig in window} / (\# \text{sig and background in window})$$

Picking a minimum number of RTD's in a cluster

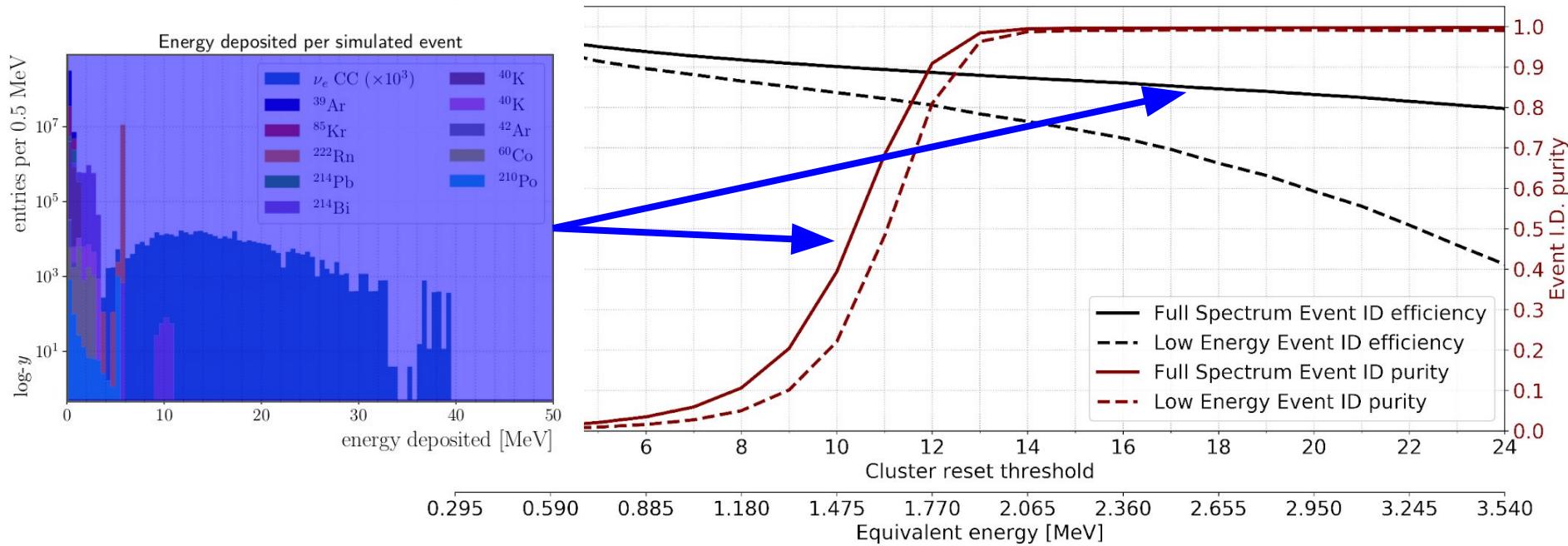


Dashed lines are for events with < 5 MeV deposited energy in the event

Efficiency = #sig in window / total #sig

Purity = #sig in window / #sig and background in window

Picking a minimum number of RTD's in a cluster

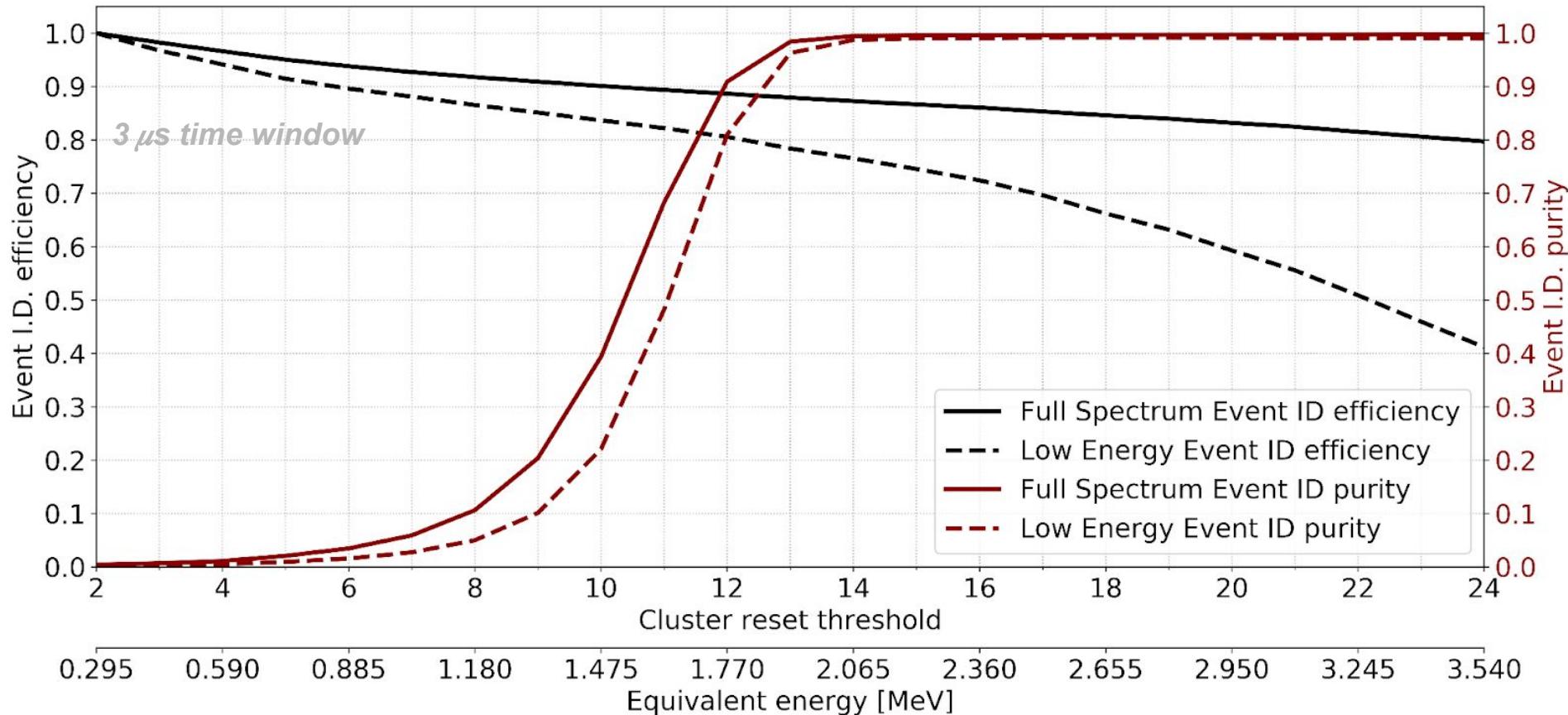


Solid lines are analyzing events from the full spectrum

Efficiency = #sig in window / total #sig

Purity = #sig in window / #sig and background in window

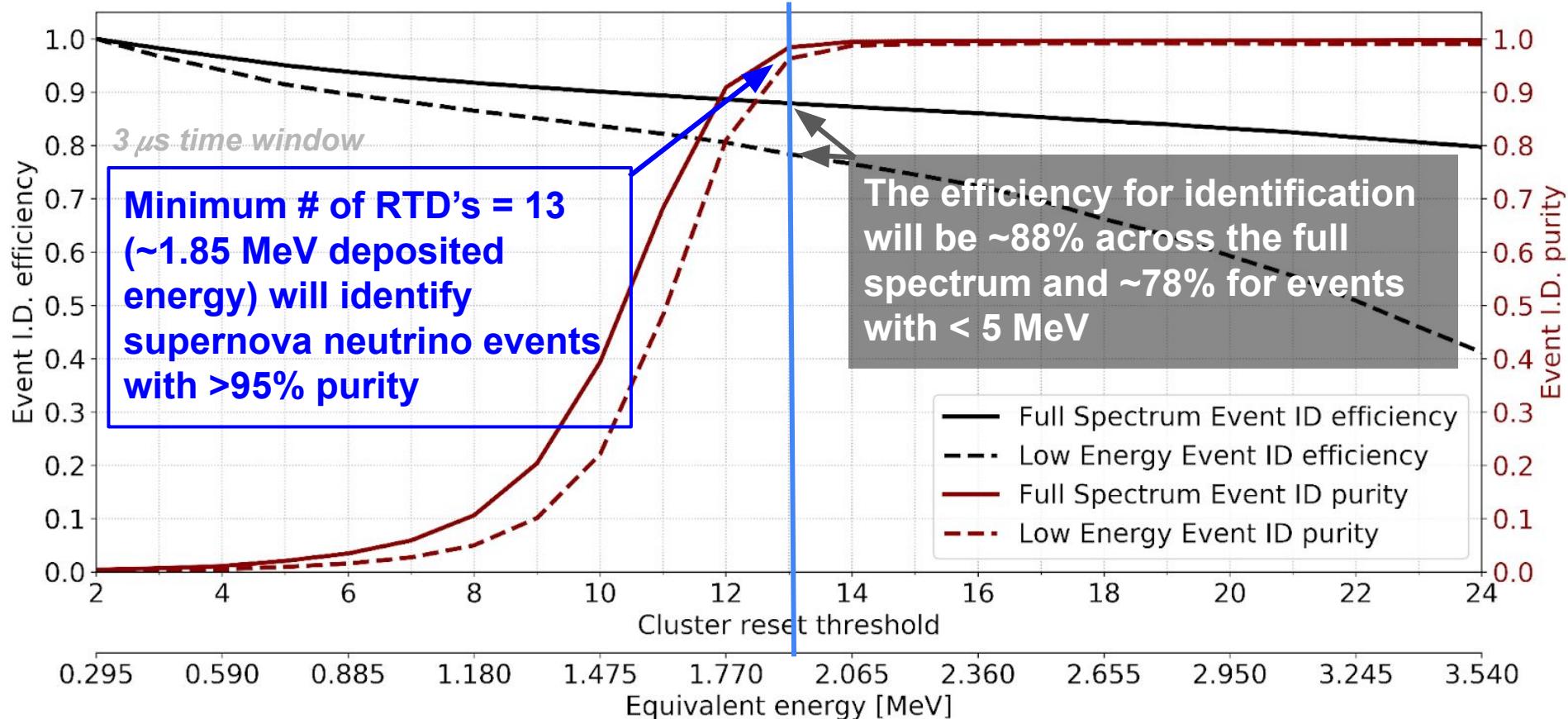
Picking a minimum number of RTD's in a cluster



Efficiency = #sig in window / total #sig

Purity = #sig in window / #sig and background in window

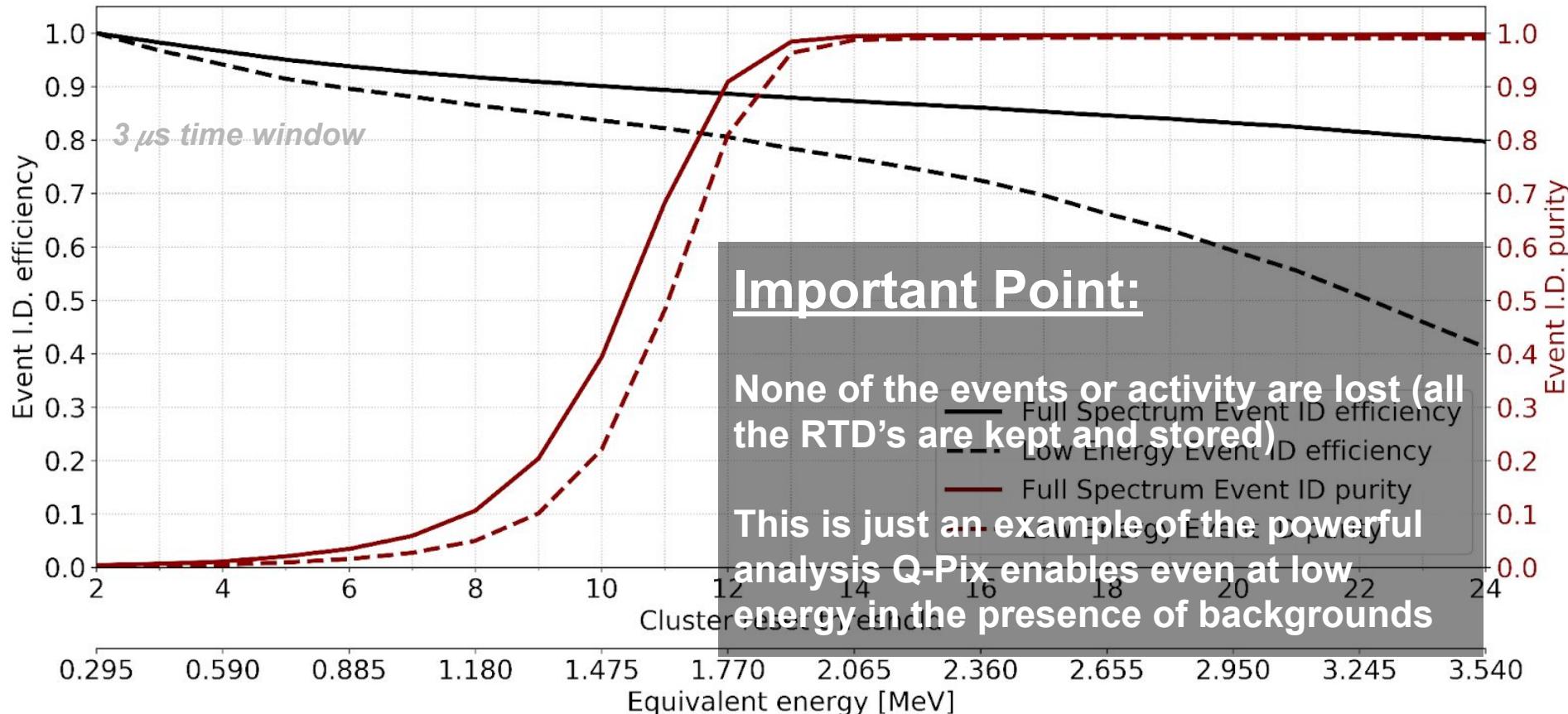
Picking a minimum number of RTD's in a cluster



Efficiency = #sig in window / total #sig

Purity = #sig in window / #sig and background in window

Picking a minimum number of RTD's in a cluster



Efficiency = #sig in window / total #sig

Purity = #sig in window / #sig and background in window