QPix: Achieving kiloton scale pixelated readout for Liquid Argon Time Projection Chambers

Jonathan Asaadi
University of Texas at Arlington

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

Neutrino Physics

- **Neutrinos are among a handful of known fundamental particles**
  - They are one of the least well understood particles
- **Currently we have measurements of the three mixing angles** (θ_{12}~34°, θ_{13}~9°, θ_{23}~45°), **two mass splittings** (Δm_{21}~7.4x10^{-5} eV, Δm_{31}~2.5x10^{-3} eV)
- **However, there is much left unknown for neutrino oscillations**
  - CP-Violation ?
  - Mass Ordering ?
  - Octant of θ_{23} ?

- **And many questions precision neutrino oscillation measurements can tell us**
  - Supernova Dynamics
  - Origin of matter/anti-matter asymmetry

Neutrino Detectors

In order to answer these questions, next generation neutrino experiments will require that detectors are:

1. **Big/Scalable**
   Put a large number of nuclei in the path of the neutrino
2. **Sensitive Charge and Light**
   We want to collect information about the charged particles produced
3. **High Resolution**
   We want to collect as much information about what took place during the neutrino interaction to understand the physics

Noble liquid detectors are a good candidate for use in neutrino detectors because they have many of these attractive properties

Liquid Argon Time Projection Chamber

	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	

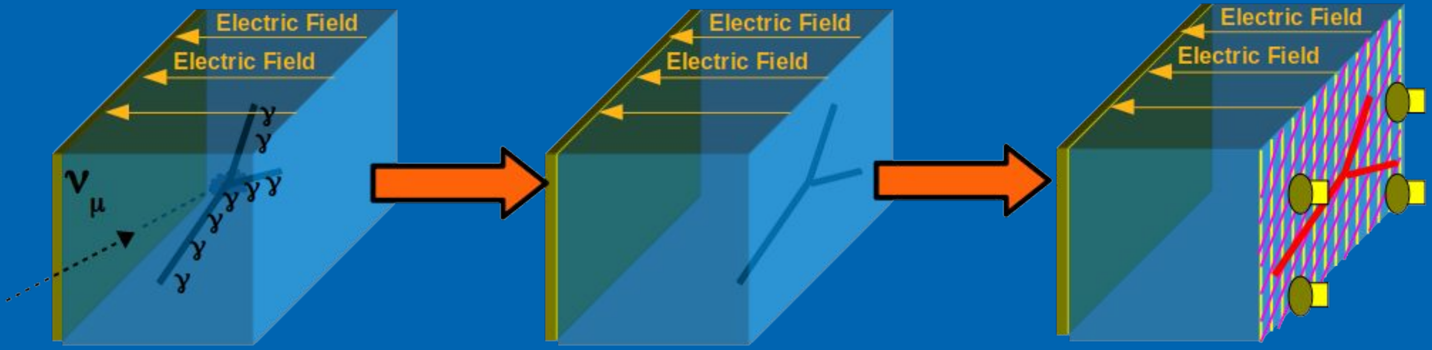
→ **Dense**
40% more dense than water

→ **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



Neutrino interaction in LAr produces ionization and scintillation light

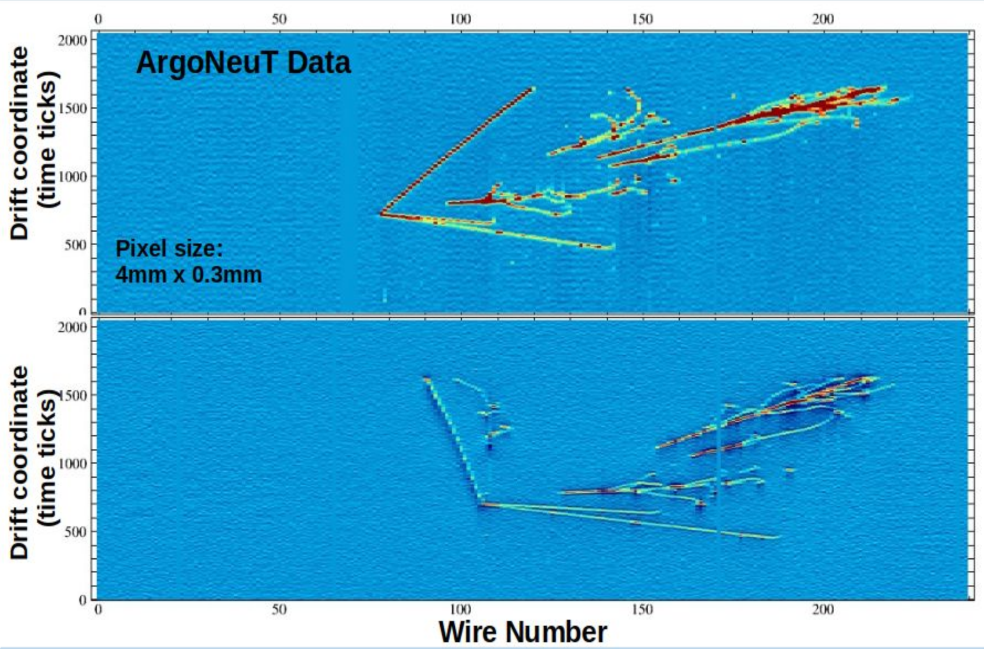
Drift the ionization charge in a uniform electric field

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

Liquid Argon Time Projection Chamber

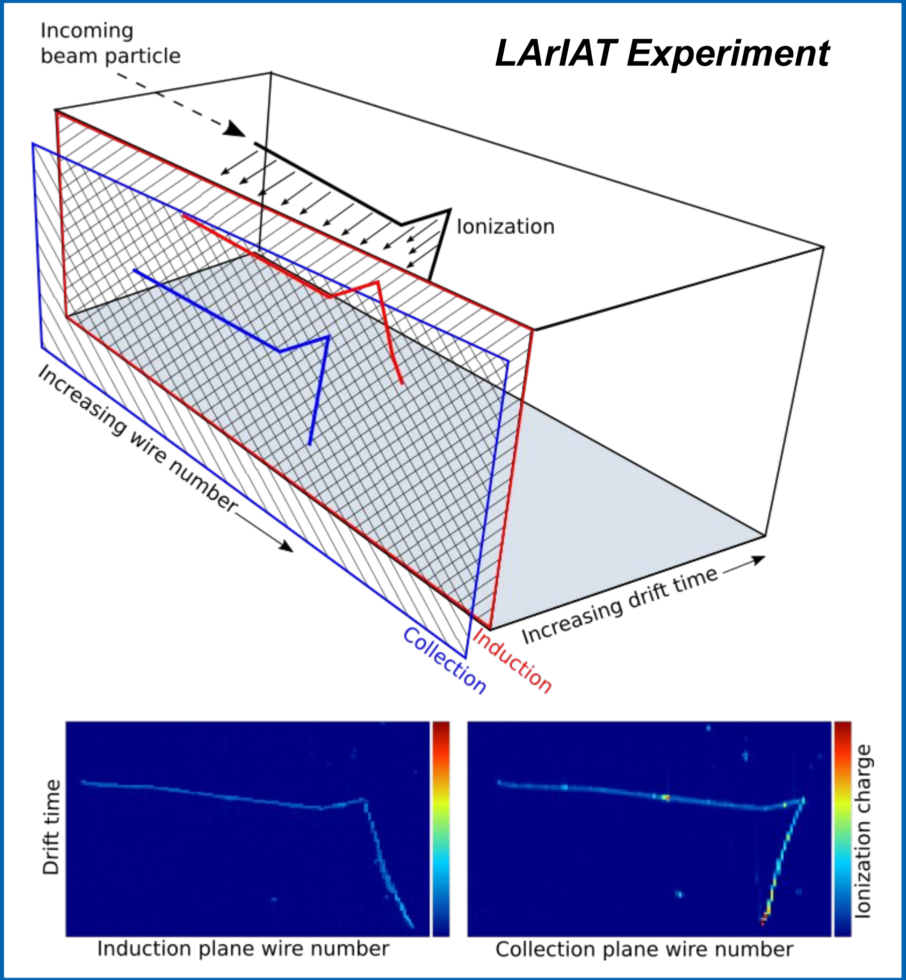
- Liquid Argon Time Projection Chambers (LArTPC's) offer access to very high quality and detailed information
- Leveraging this information allows unprecedented access to detailed neutrino interaction specifics from MeV - GeV scales
- Capturing this data w/o compromise and maintaining the intrinsic 3-D quality is an essential component of all LArTPC readouts!

2D-Projective Readout



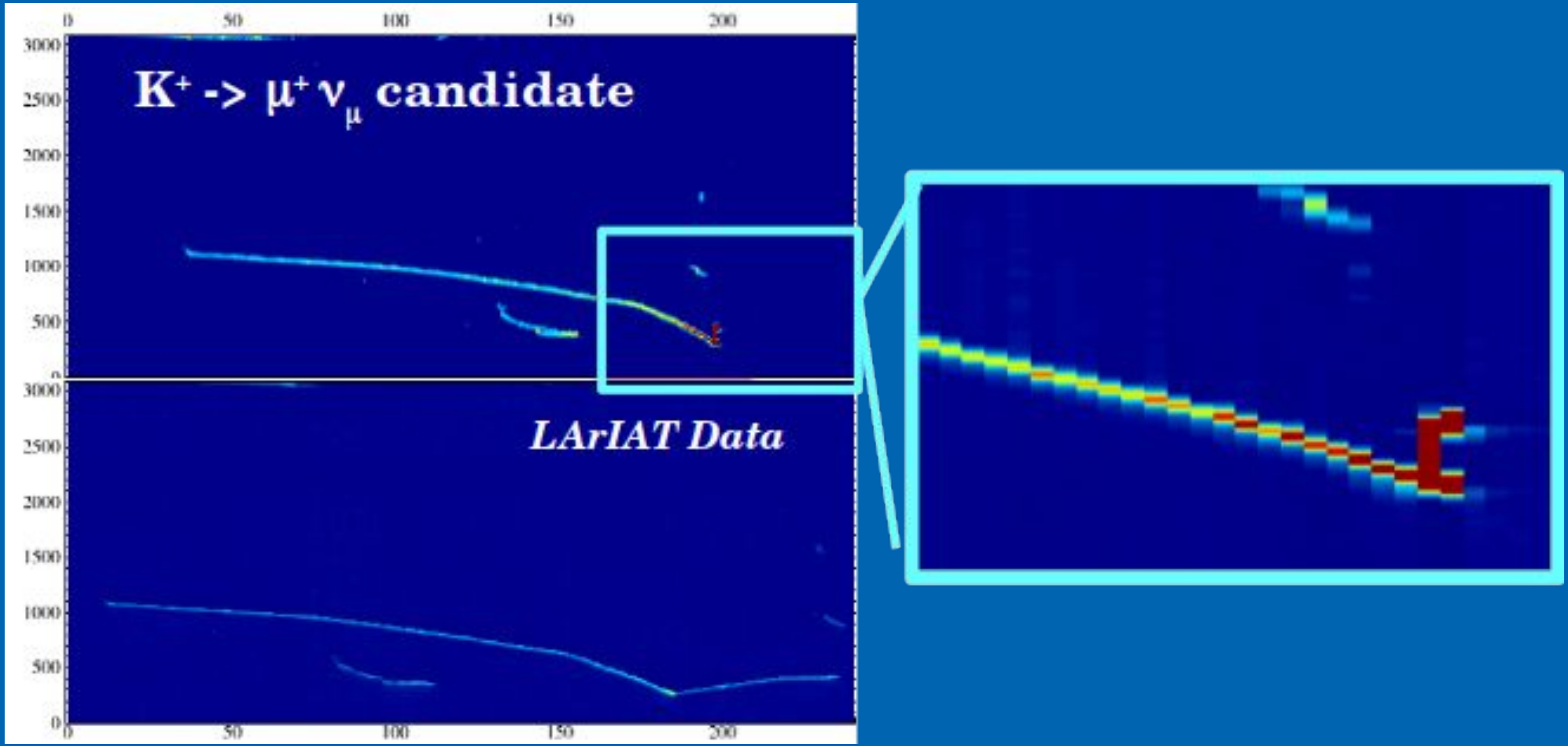
Liquid Argon Time Projection Chamber

- **Conventional LArTPC's use sets of wire planes at different orientations to reconstruct the 3D image**
  - Challenge in reconstruction of complex topologies
  - Sometimes can even be a challenge for simple topologies



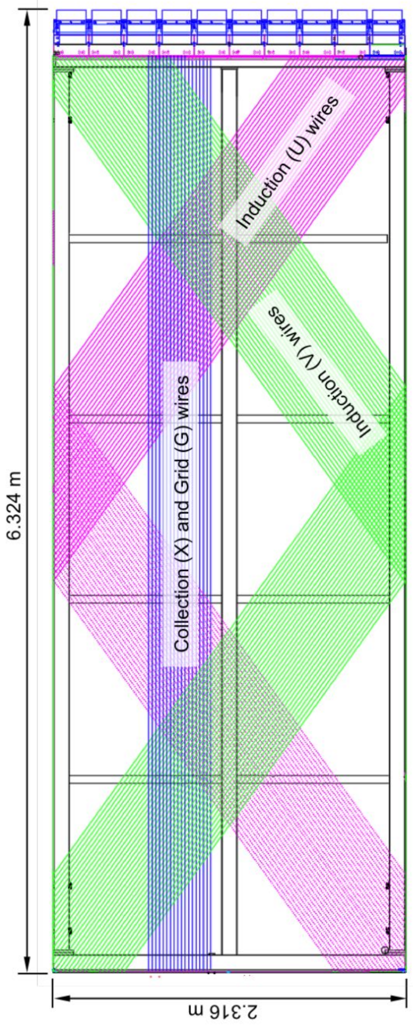
Liquid Argon Time Projection Chamber

Intrinsic reconstruction pathologies associated with charge deposited along the direction of the wires



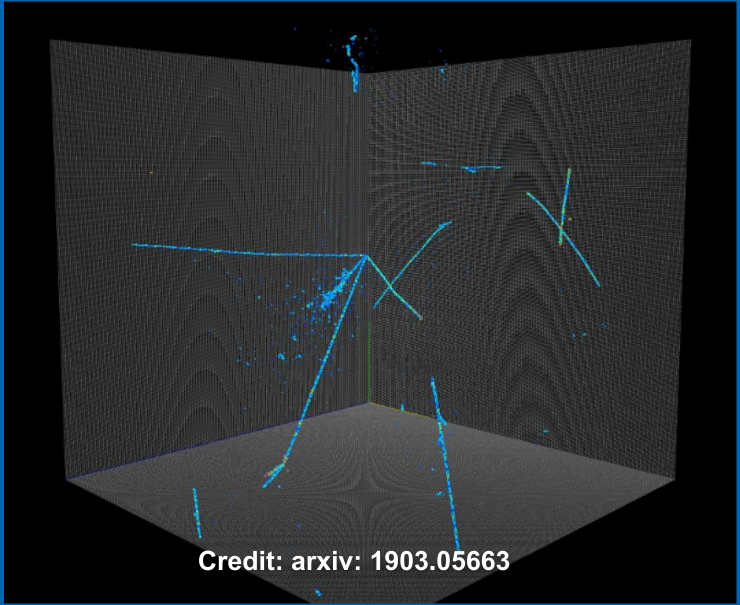
Introduction

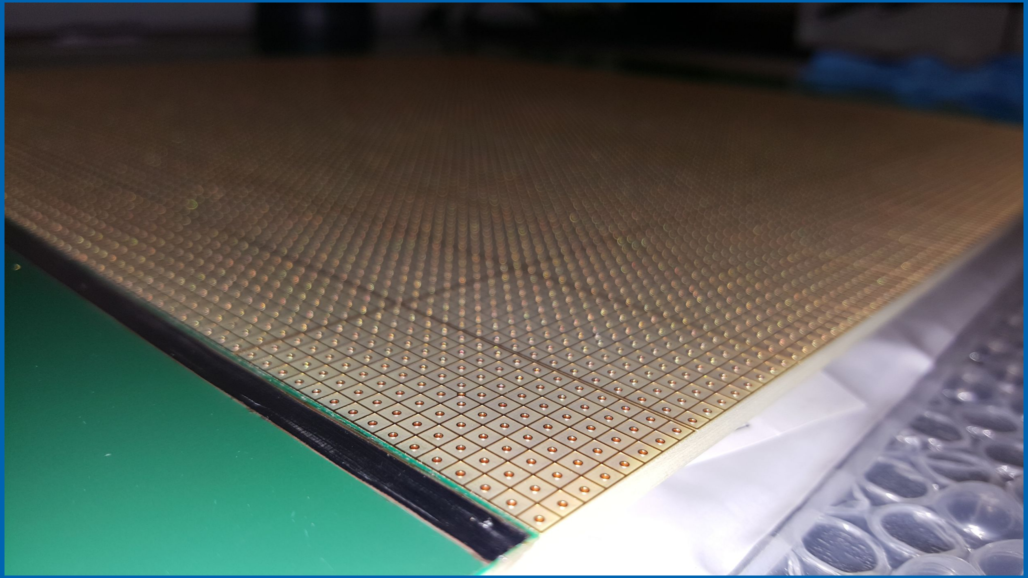
- **kiloTon scale LArTPC's use "wrapped wire" geometries to reduce the number of readout channels**
  - Challenging to engineer such massive structures
  - Possible ambiguities associated with the readout increase with the wrapped geometry
  - Wire failure poses risk to loss of readout of an entire APA
    - Requires extensive (expensive) QA/QC
- **The number of events in future large scale experiments are few and precious**
  - Don't want to lose any to readout/reconstruction



Introduction

- **Readout of a LArTPC using pixels instead of wires can solve the shortcomings of projective wire readout**

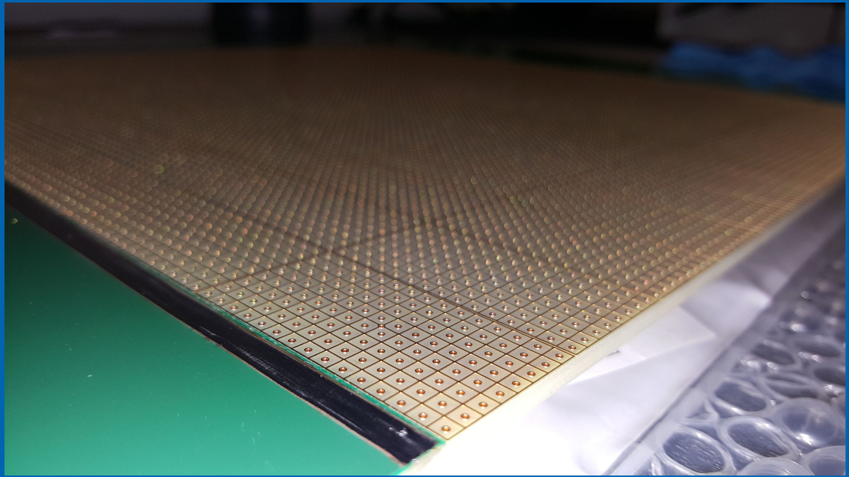




3D-Pixel Readout

Introduction

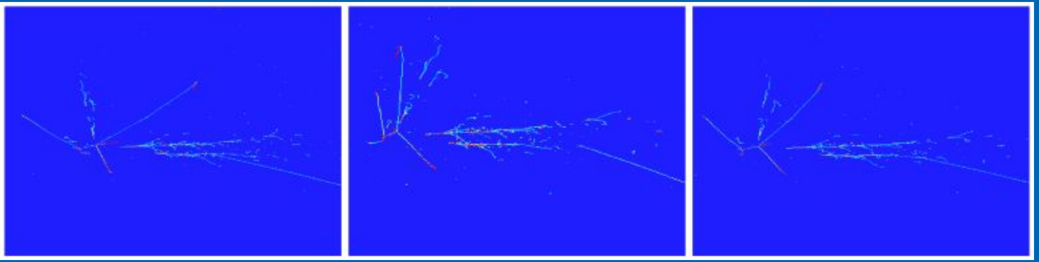
- **Readout of a LArTPC using pixels instead of wires can solve the shortcomings of projective wire readout**
  - Comes at a "cost" of many more channels!
    - Example: 2 meter x 2 meter readout
      - **3mm wire pitch w/ three planes = 2450 channels**
      - **3mm pixel pitch = 422,000 channels**
- **Requires innovation in readout electronics to meet the heatload restrictions for the increase in readout channels!**
  - **Requires an "unorthodox" solution**



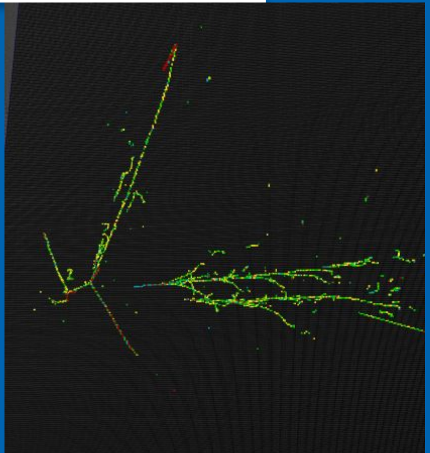
How much better is pixel vs wire readout?

- Attempt quantify how much “better” a 3D pixel based LArTPC performs compared to a 2D projective wire readout LArTPC
  - Classify event identification
  - In a perfect world we would compare the complete readout and reconstruction of two detectors side by side to do this
    - *Such a readout and reconstruction chain doesn’t exist!*
- Using modern machine learning techniques, we trained two parallel networks on identical simulated neutrino interactions
  - Network 1: 3D pixel based readout
  - Network 2: 2D projective wire readout
    - For both of these networks, we assumed ideal detectors with perfect response and no reconstruction pathologies

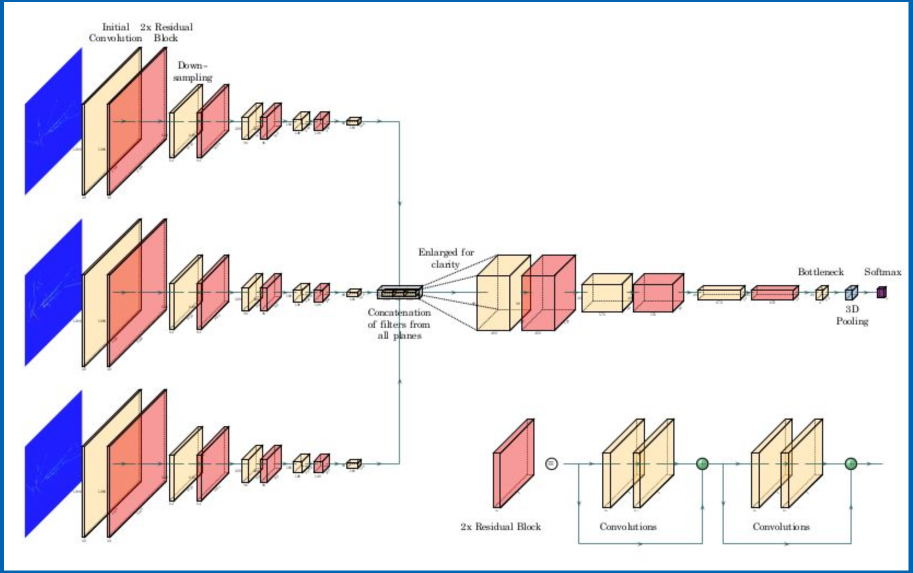
How much better is pixel vs wire readout?

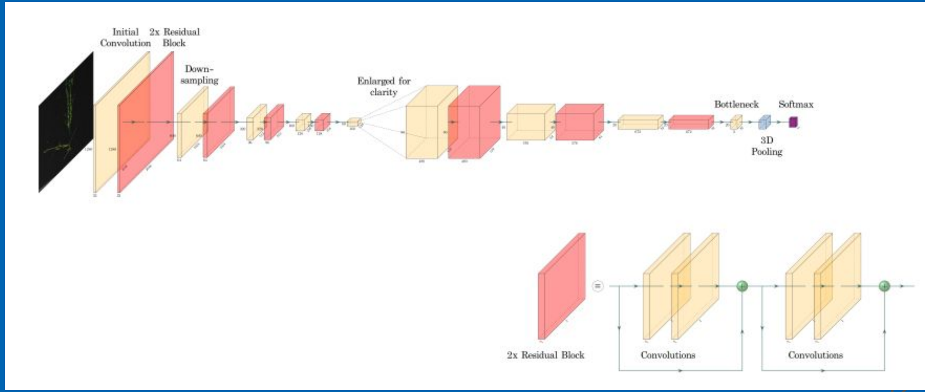


4mm x 4mm 2d wires



4mm x 4mm 3d voxels





3D vs 2D Readout

- **Simulation studies comparing the readout of 2D projective LArTPC's to 3D pixel LArTPC's shows that 3D based readout offers significant improvement in all physics categories!**
  - **ν_e-CC inclusive:** 17% gain in efficiency and 12 % gain in purity
  - **ν_μ-CC inclusive:** 10% gain in efficiency for 99% purity
  - **NCπ^0:** 13% gain in efficiency and 6% gain in purity
  - Also offers gains in Neutrino-ID classification and final state topology ID

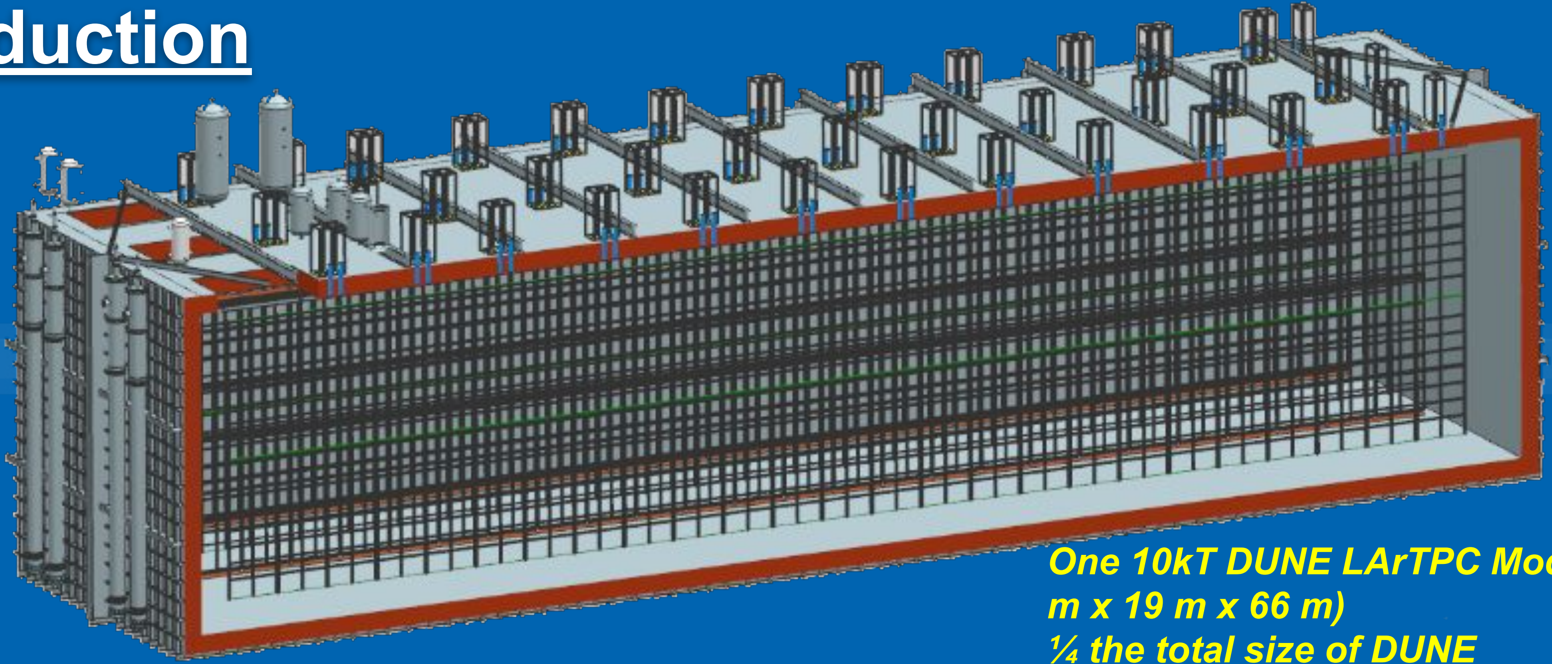
****** Improvements like these can lead to significantly shorter experimental running time required to meet desired physics goals!***

Table 2: Confusion matrix for neutrino interaction.

		3D Truth Label			2D Truth Label		
		ν_e CC	ν_μ CC	NC	ν_e CC	ν_μ CC	NC
Predicted Label	ν_e CC	**0.96**	0.01	0.02	0.93	0.02	0.03
	ν_μ CC	0.02	**0.95**	0.07	0.02	0.91	0.07
	NC	0.02	0.04	**0.91**	0.05	0.07	0.90

JINST **15** P04009 *(arXiv:1912.10133)*

Introduction

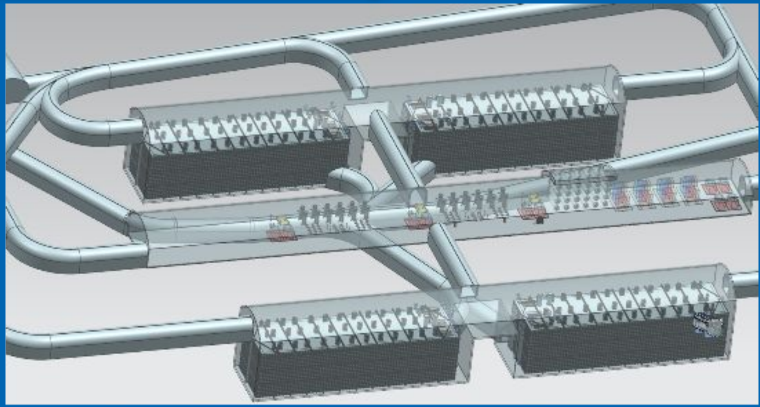


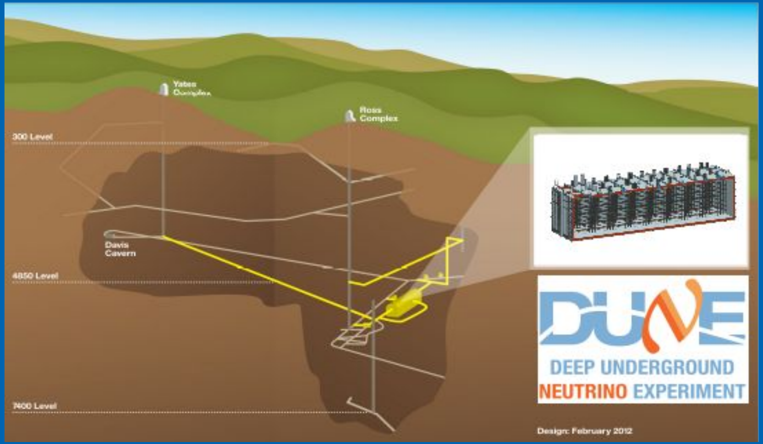
One 10kT DUNE LArTPC Module (18 m x 19 m x 66 m)
¼ the total size of DUNE

- **To readout such massive detectors with pixels requires an enormous number of channels**
  - **$\mathcal{O}$(130 million) per 10 kTon at 4mm pitch**
  - **Requires an “unorthodox” solution**

Big detectors = Big Data (but not all useful)

- **Kiloton scale LArTPC's (such as DUNE) afford a huge "big data" challenge to extract all the details offered by LArTPC**
  - **1 second of DUNE full stream data ~4.6 TB (for 1.5 million channels)**
    - **1 year of full stream data ~ 145 EB (exabytes)**
- **However, most of the time there is "nothing of interest" going on in the detector**
  - **But you must be ready "instantly" when something happens**
  - **Requires an "unorthodox" solution**

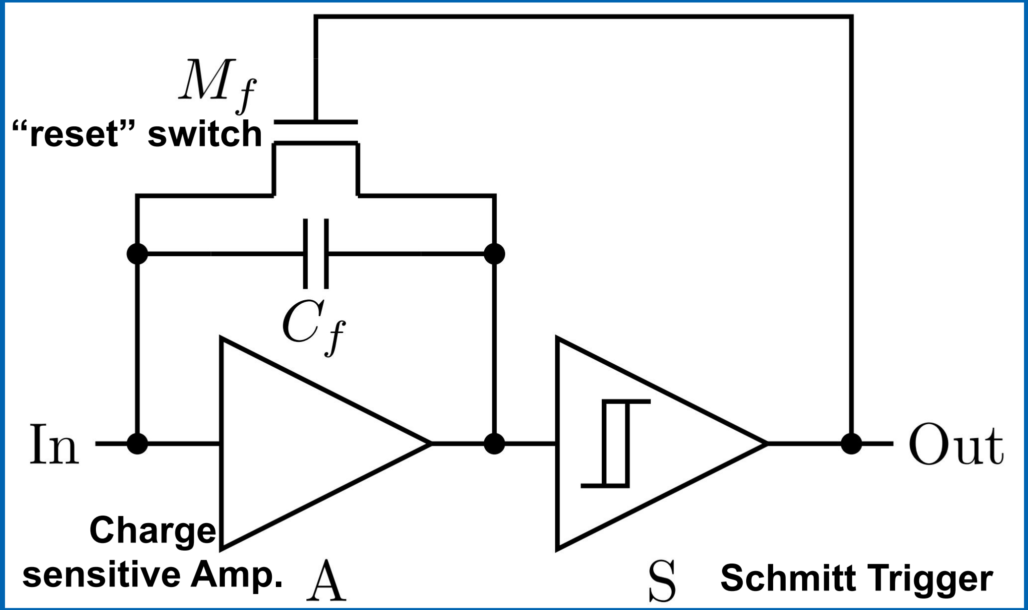




An “unorthodox” solution

- **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
            - Quiescent data rate $\mathcal{O}$(50 Mb/s)
        - 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**
    - **Attempts to exploit ^{39}Ar to provide an automatic charge calibration**
- **“Novelty does not automatically confer benefit”**
    - **Much remains to be explored**

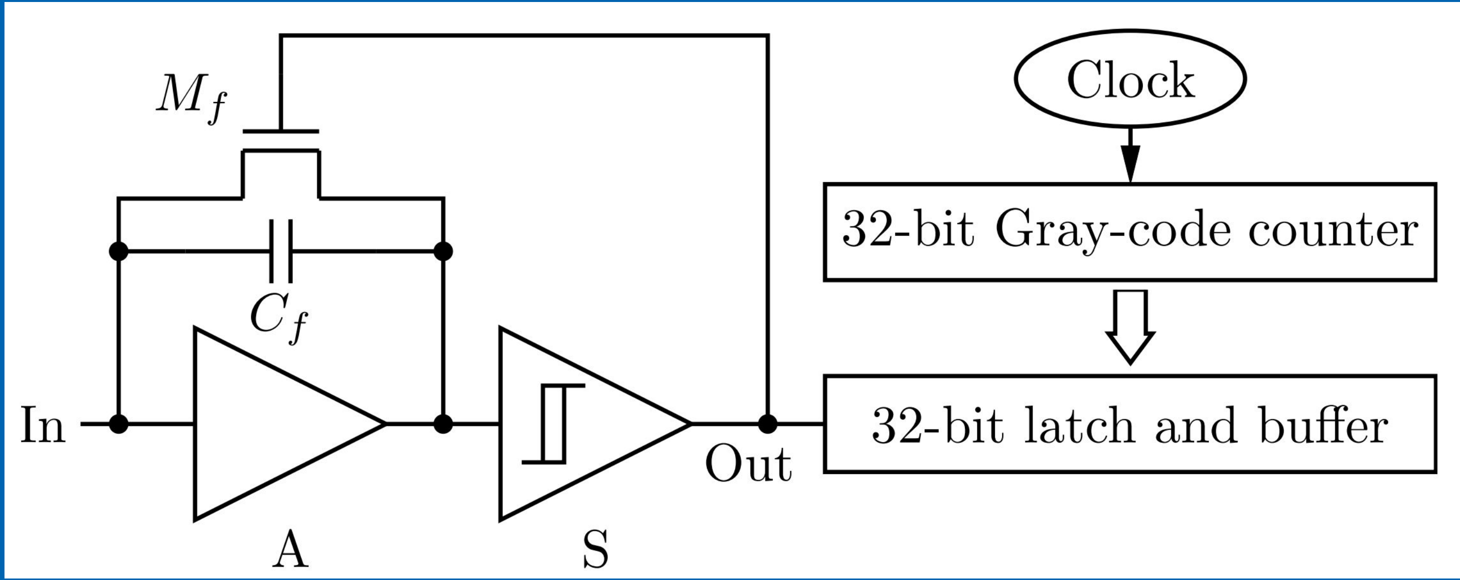
Q-Pix: The Charge Integrate-Reset (CIR) Block



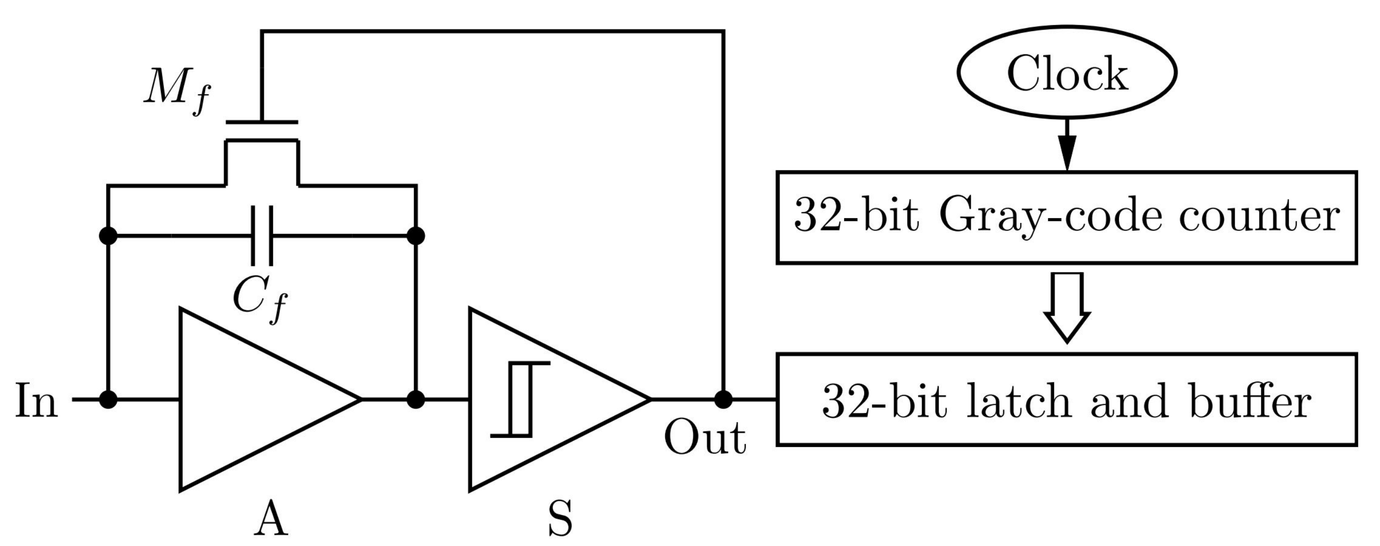
- Charge from a pixel (In) integrates on a charge sensitive amplifier (A) until a threshold (V_{th}~$\Delta Q/C_f$) is met which fires the Schmitt Trigger which causes a reset (M_f) and the loop repeats

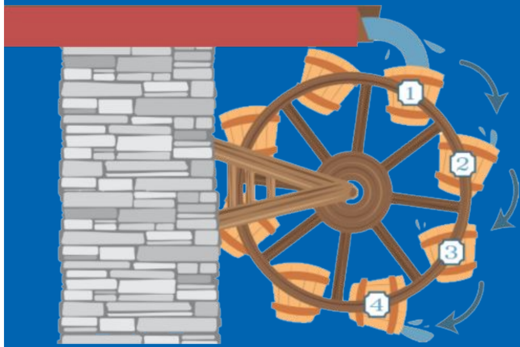
Q-Pix: The Charge Integrate-Reset (CIR) Block

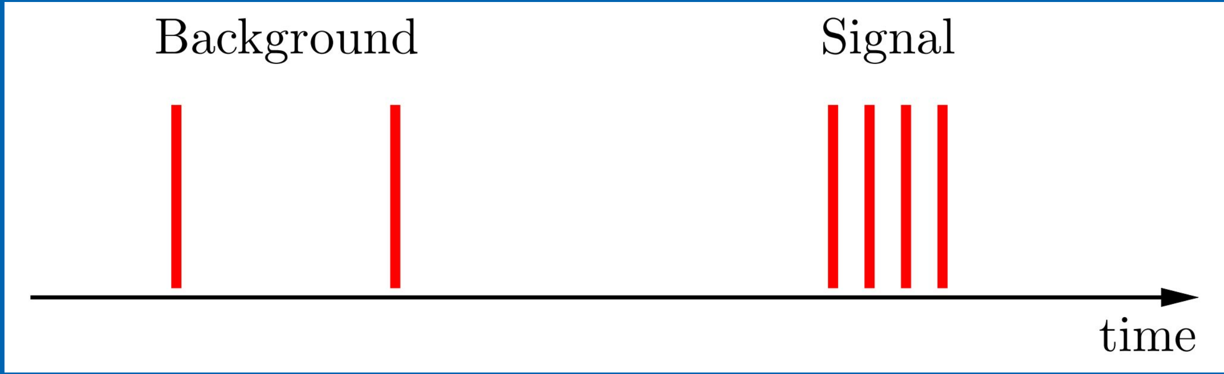
- **Measure the time of the "reset" using a local clock (within the ASIC)**
- **Basic datum is 64 bits**
  - 32 bit time + pixel address + ASIC ID + Configuration + ...



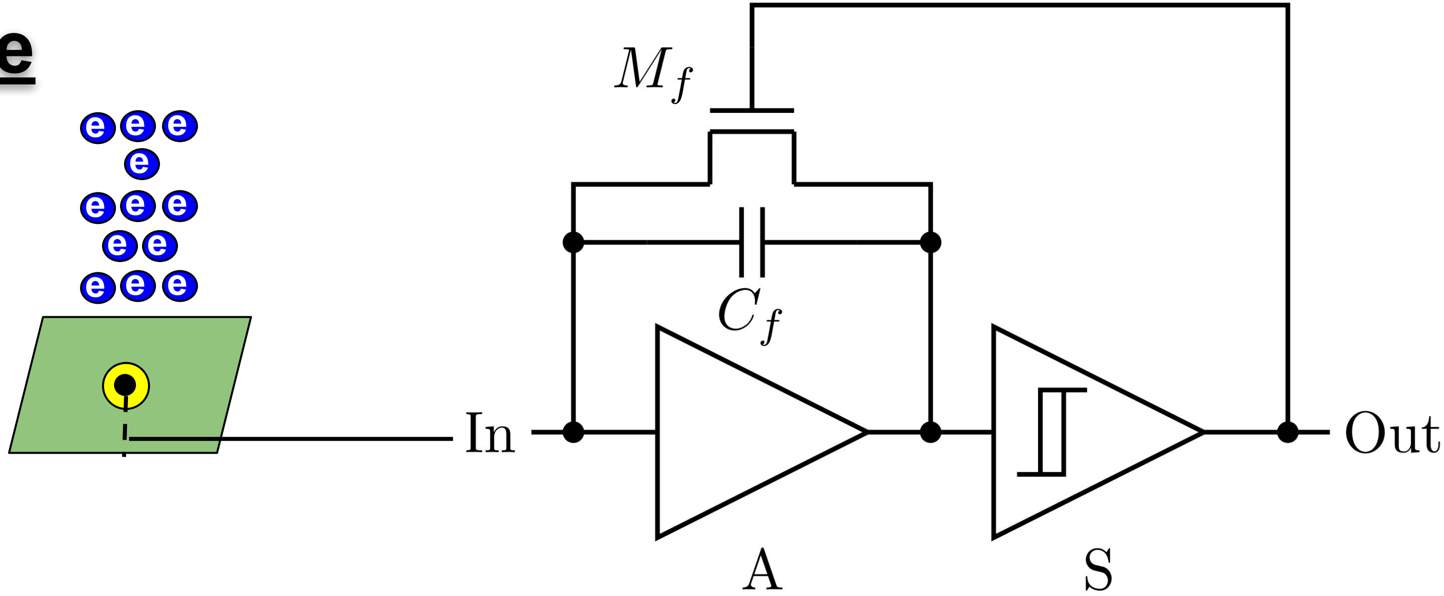
Reset Time Difference

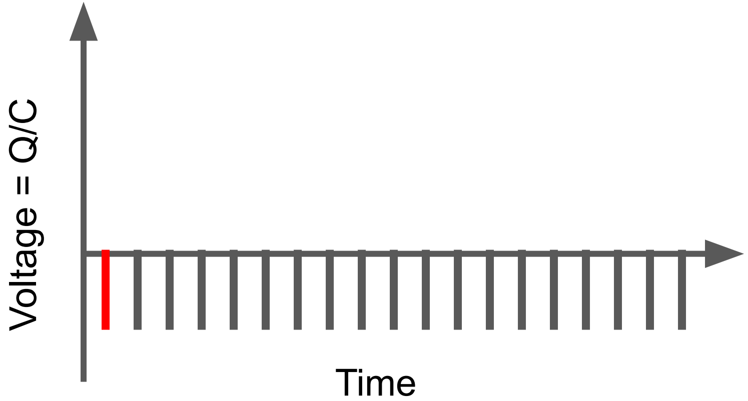


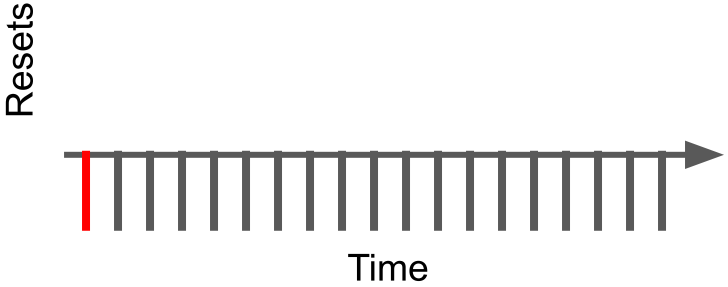




Toy Example







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

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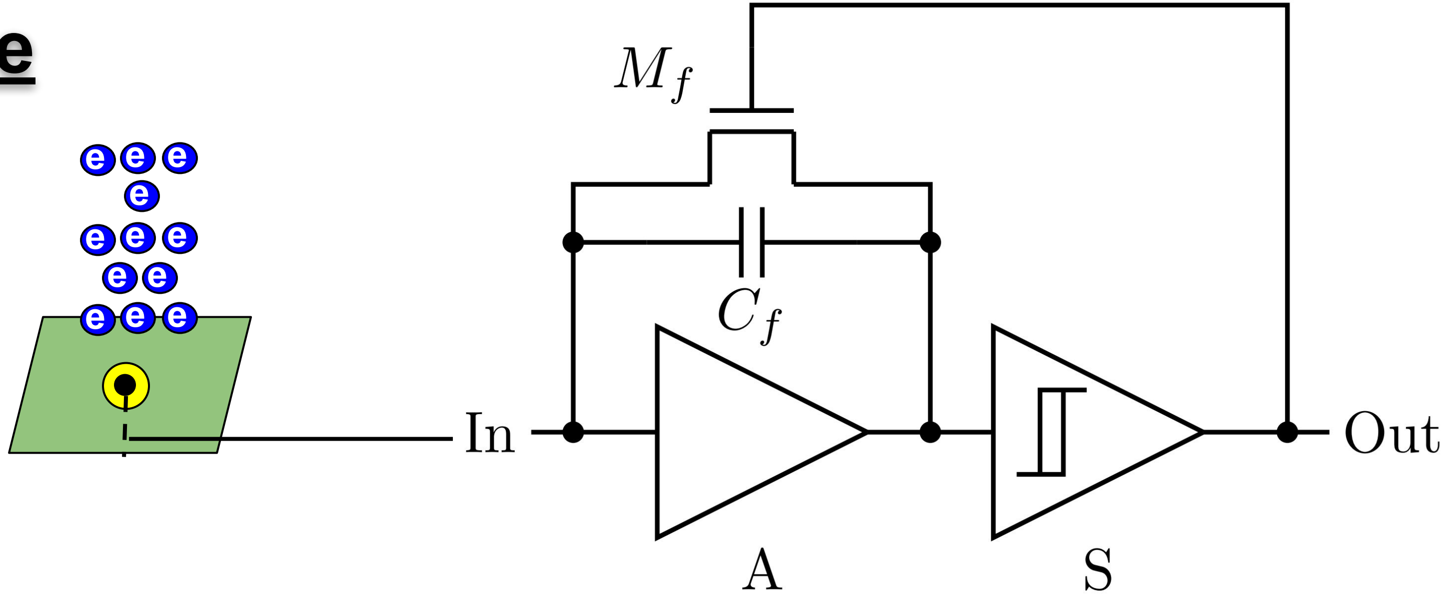

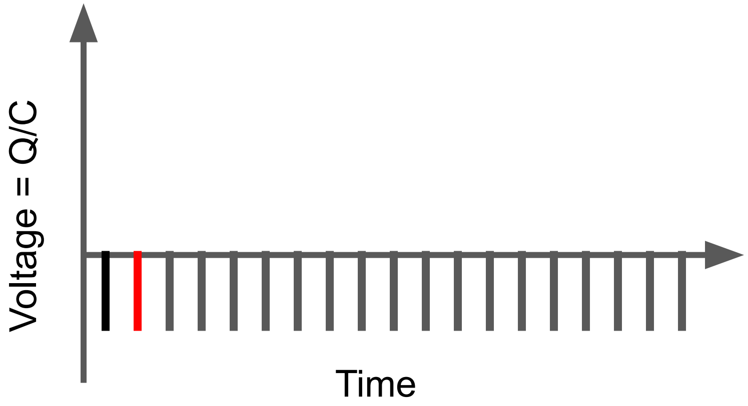

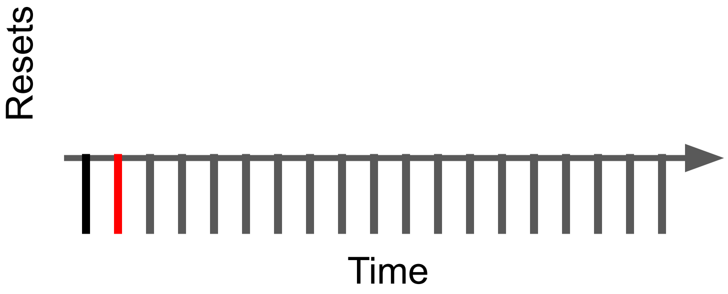

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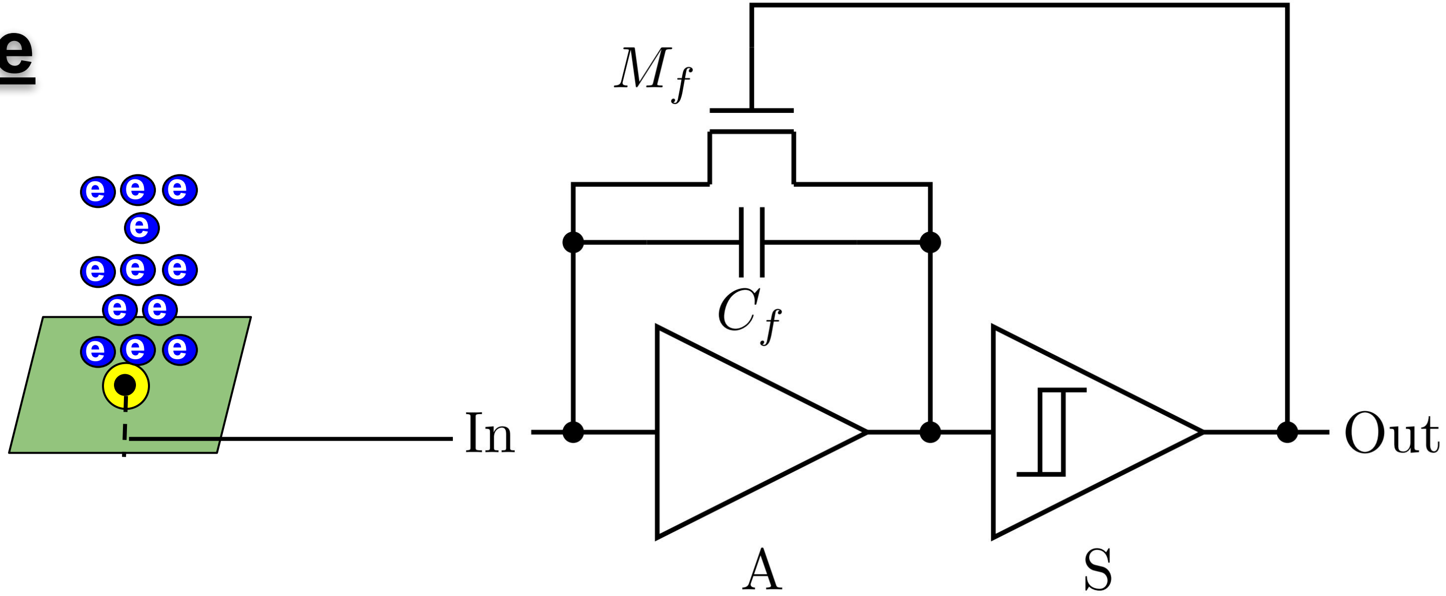

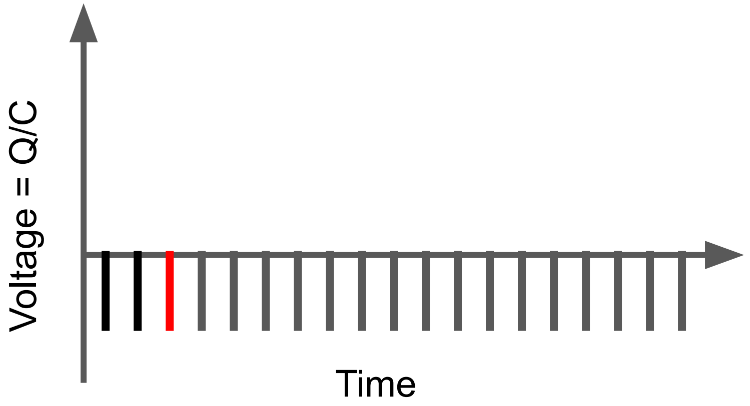

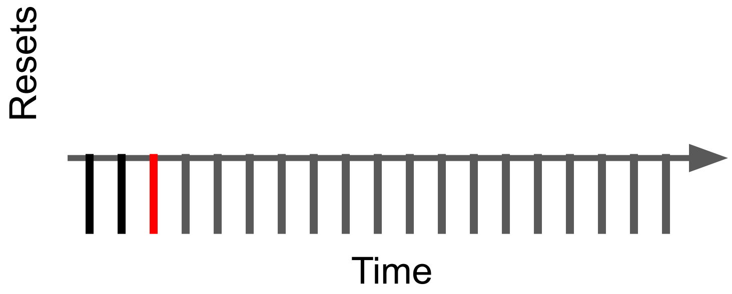

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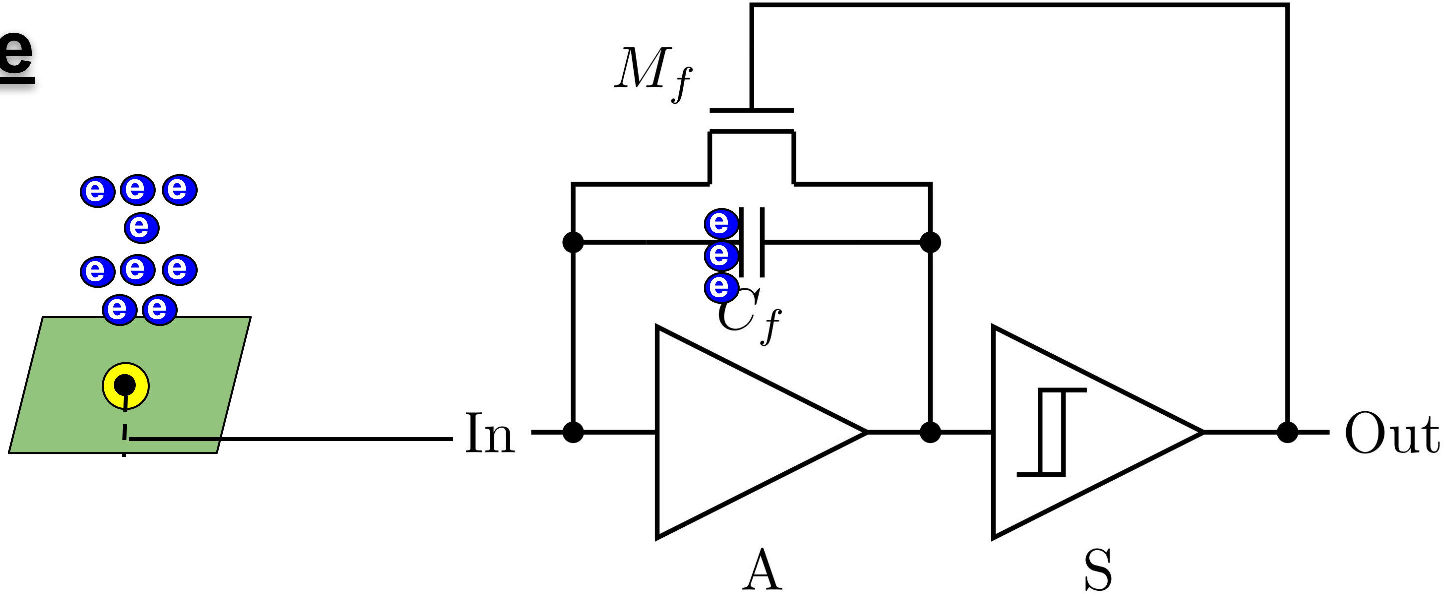

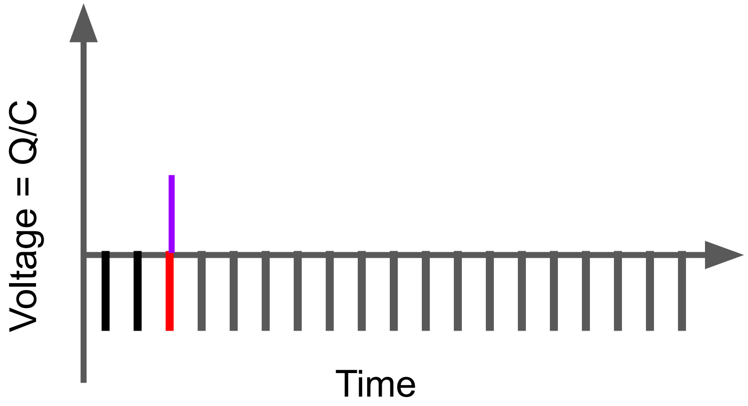

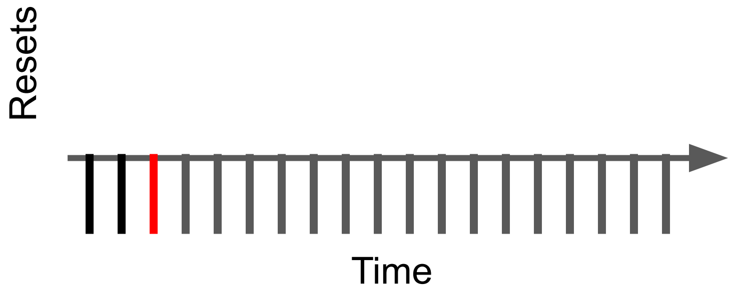

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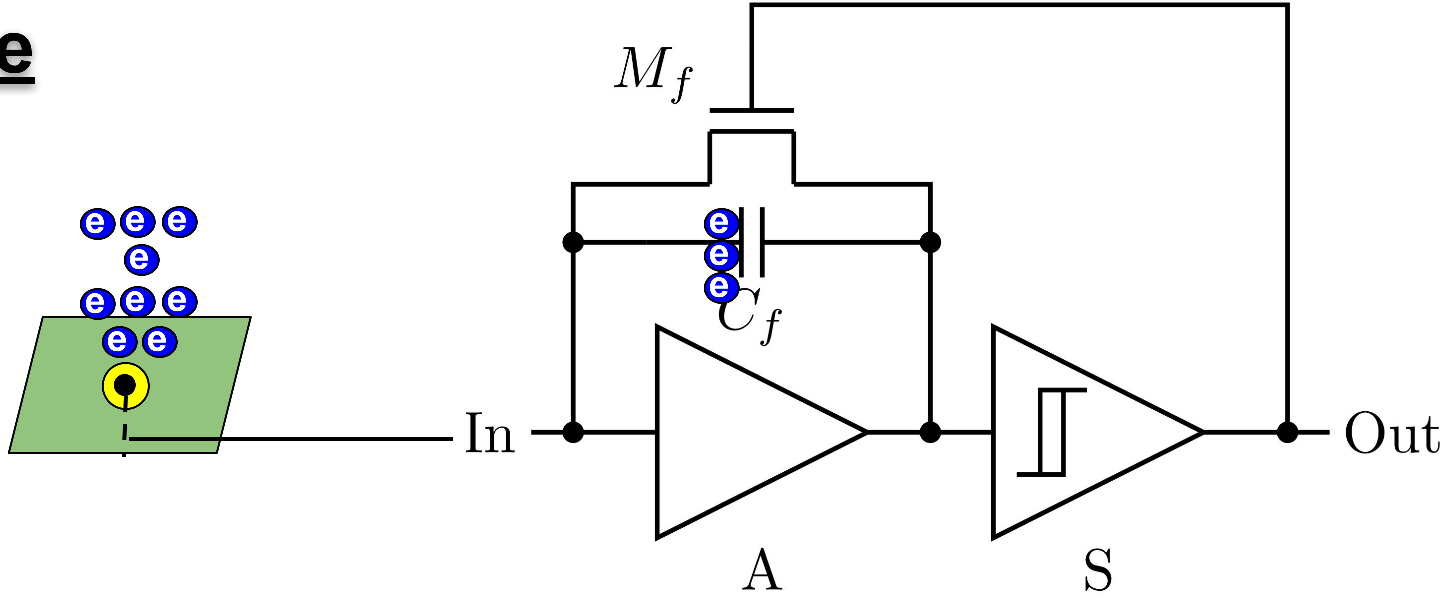

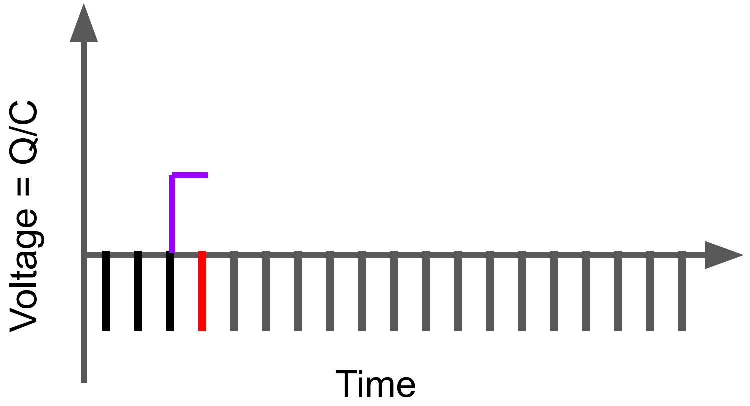

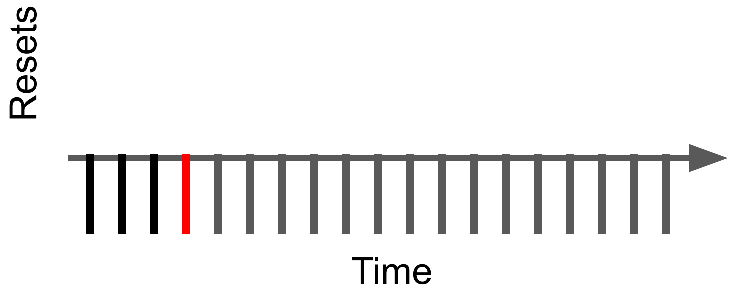

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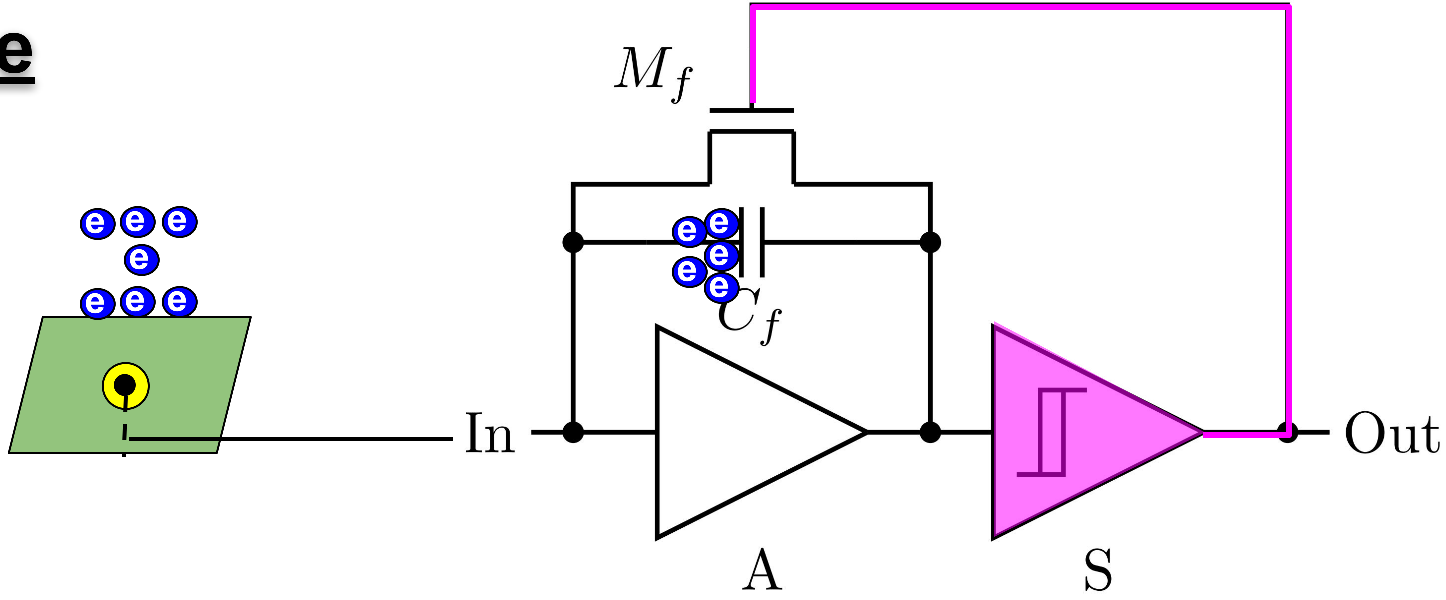

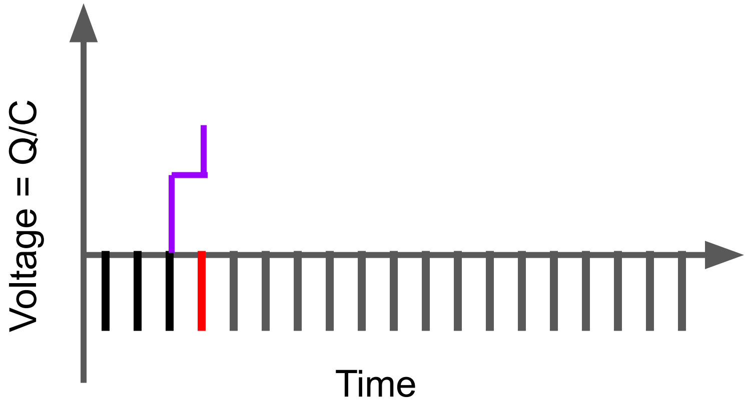

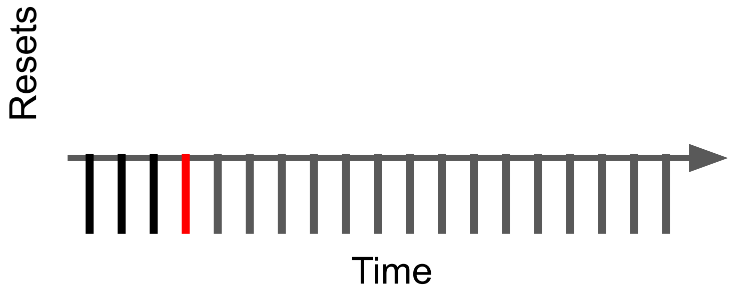

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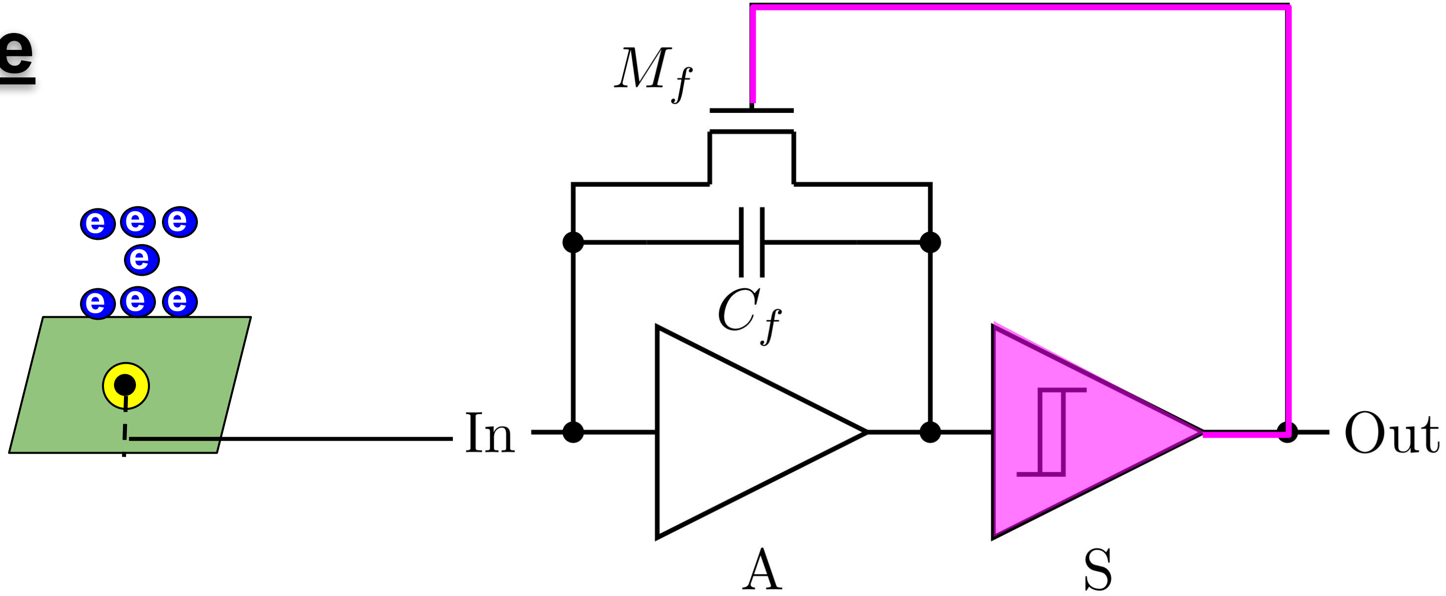

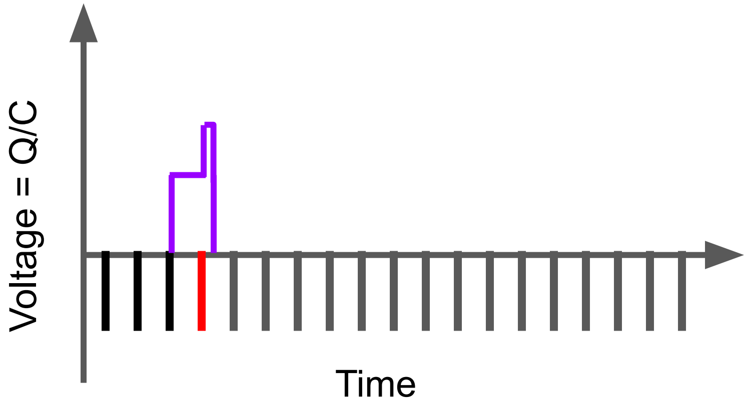

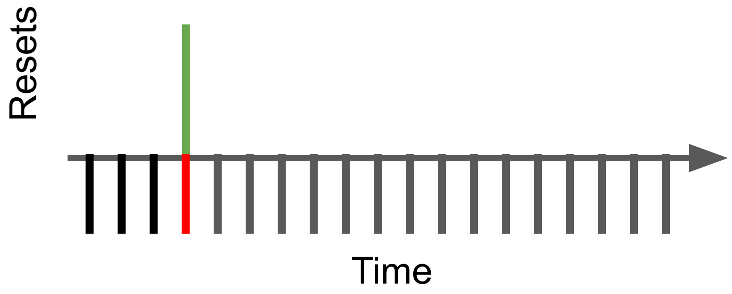

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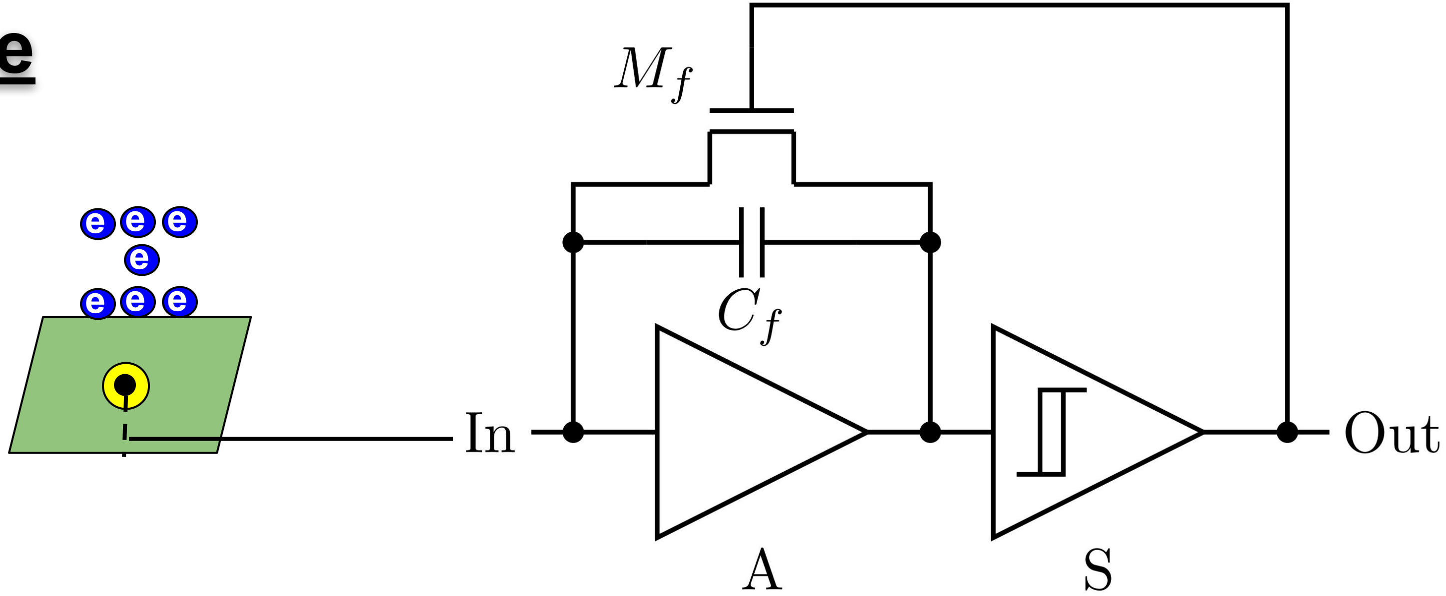

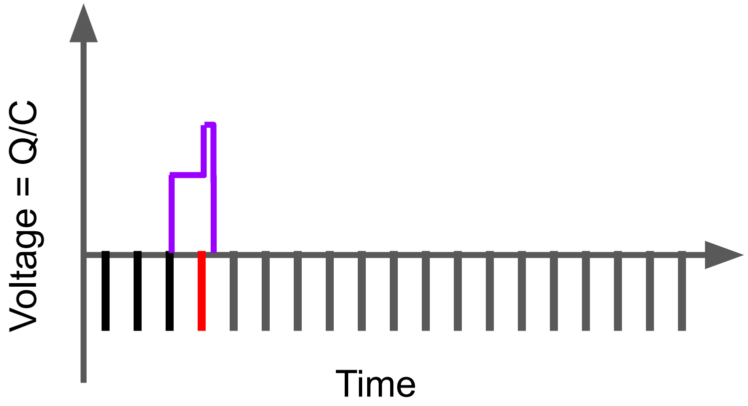

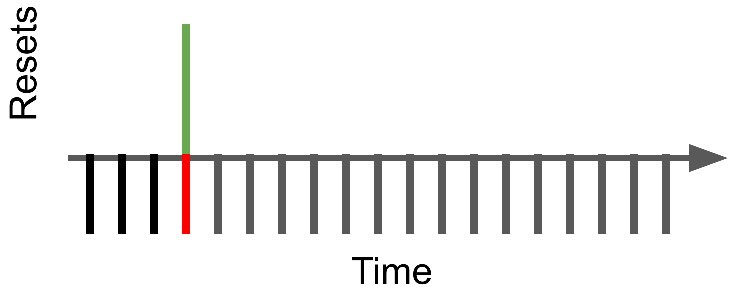

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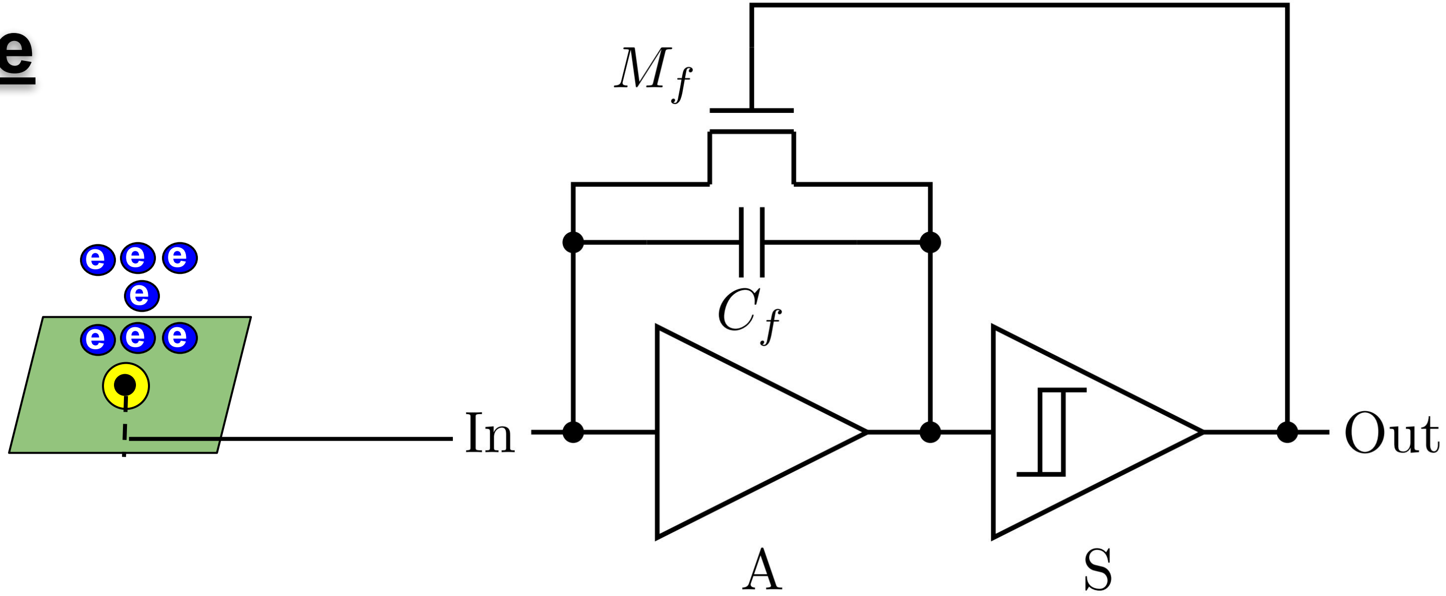

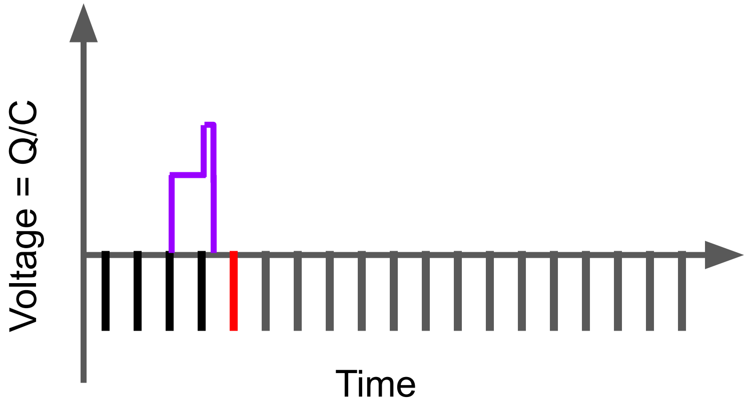

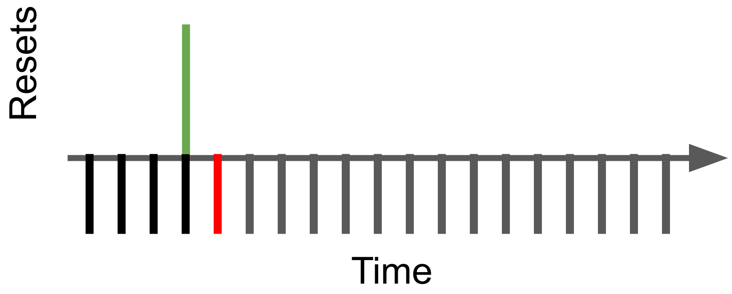

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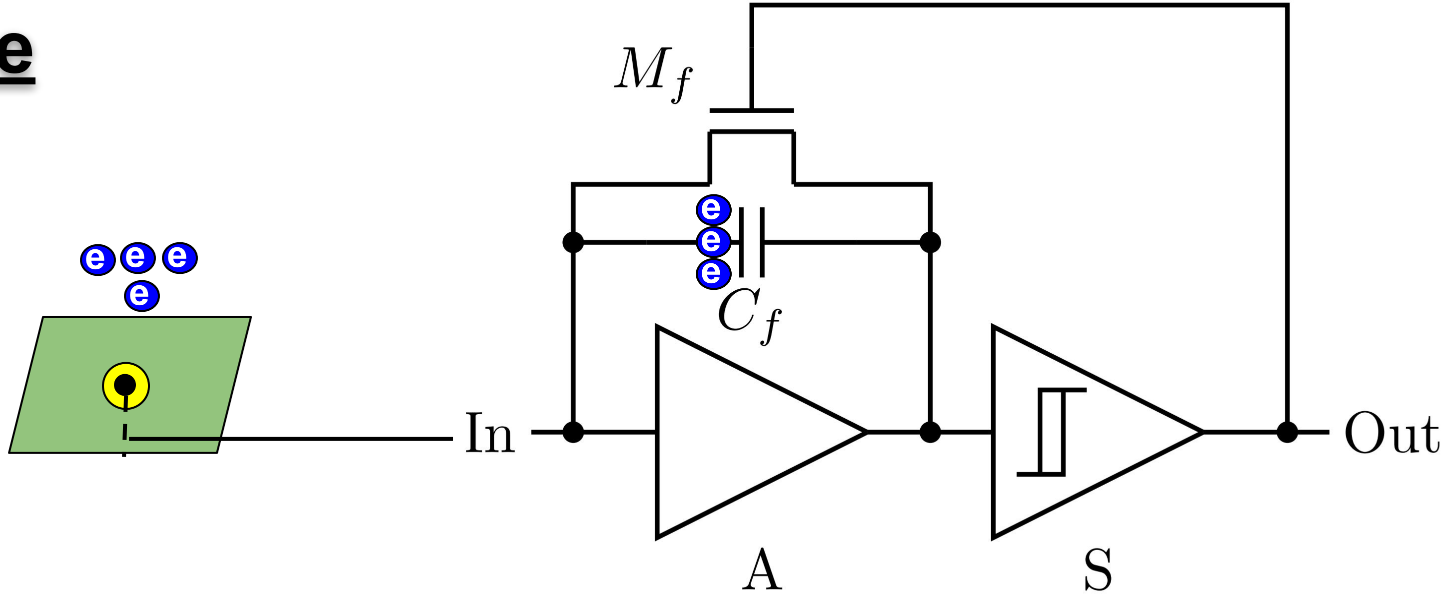

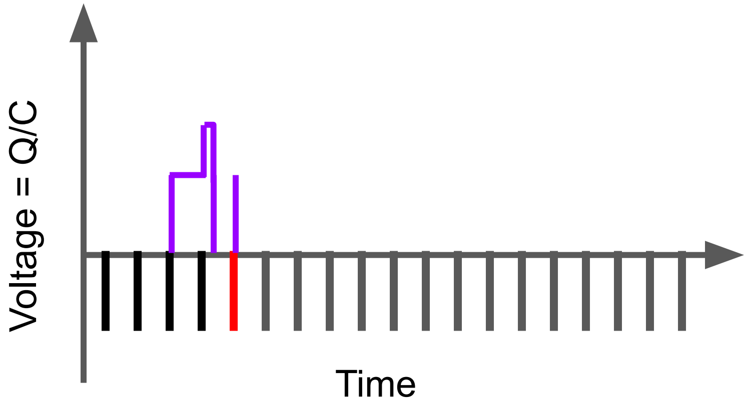

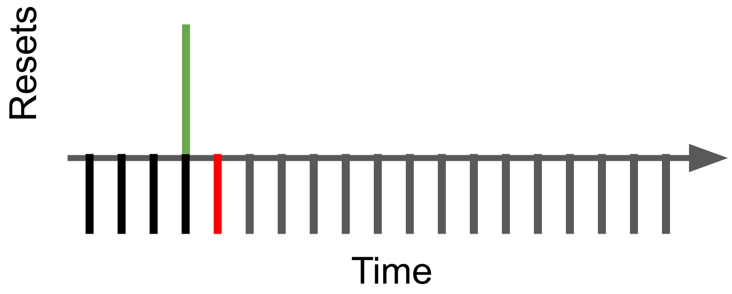

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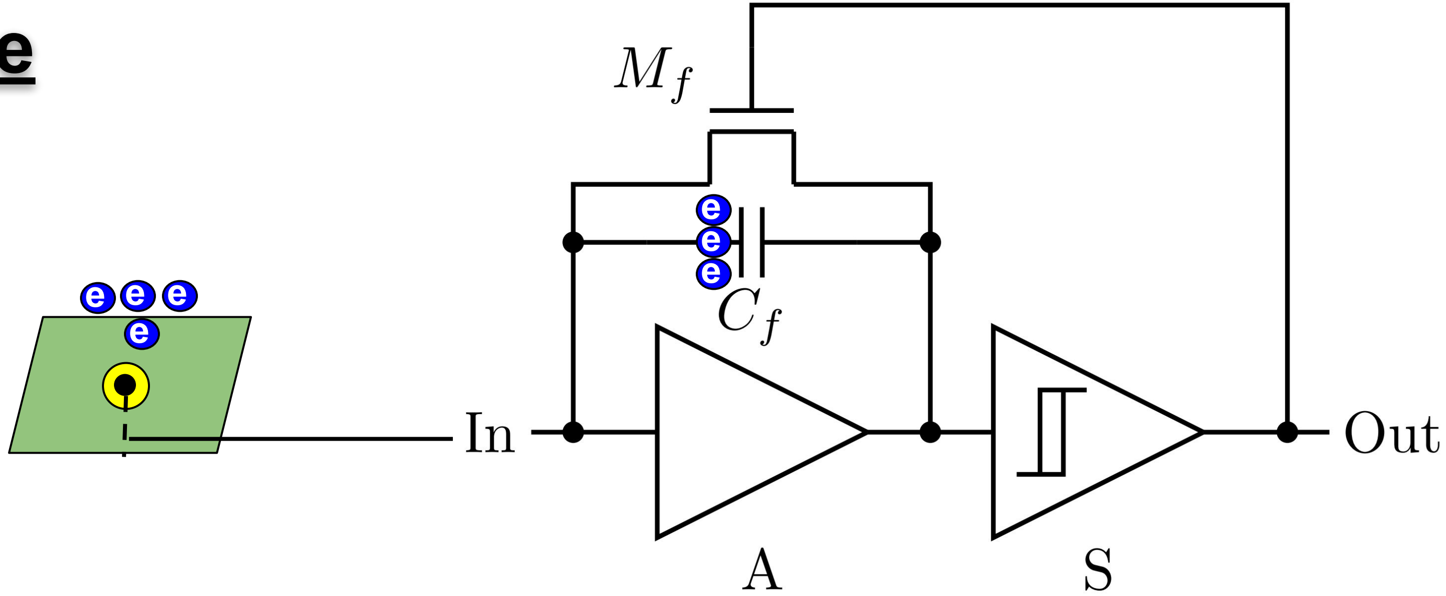

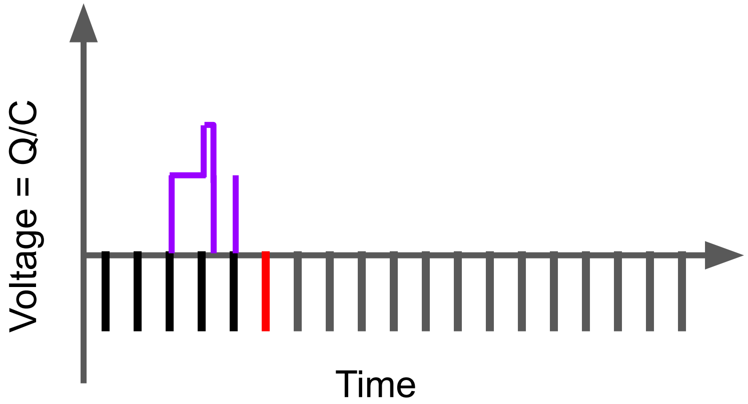

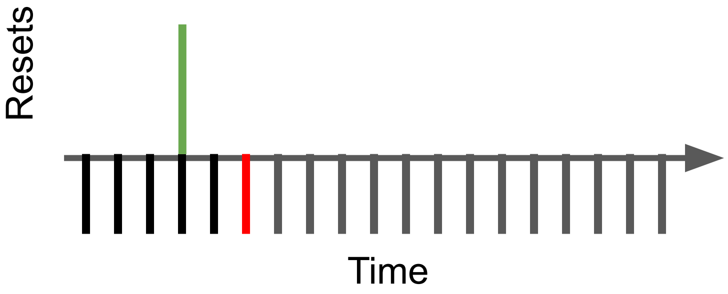

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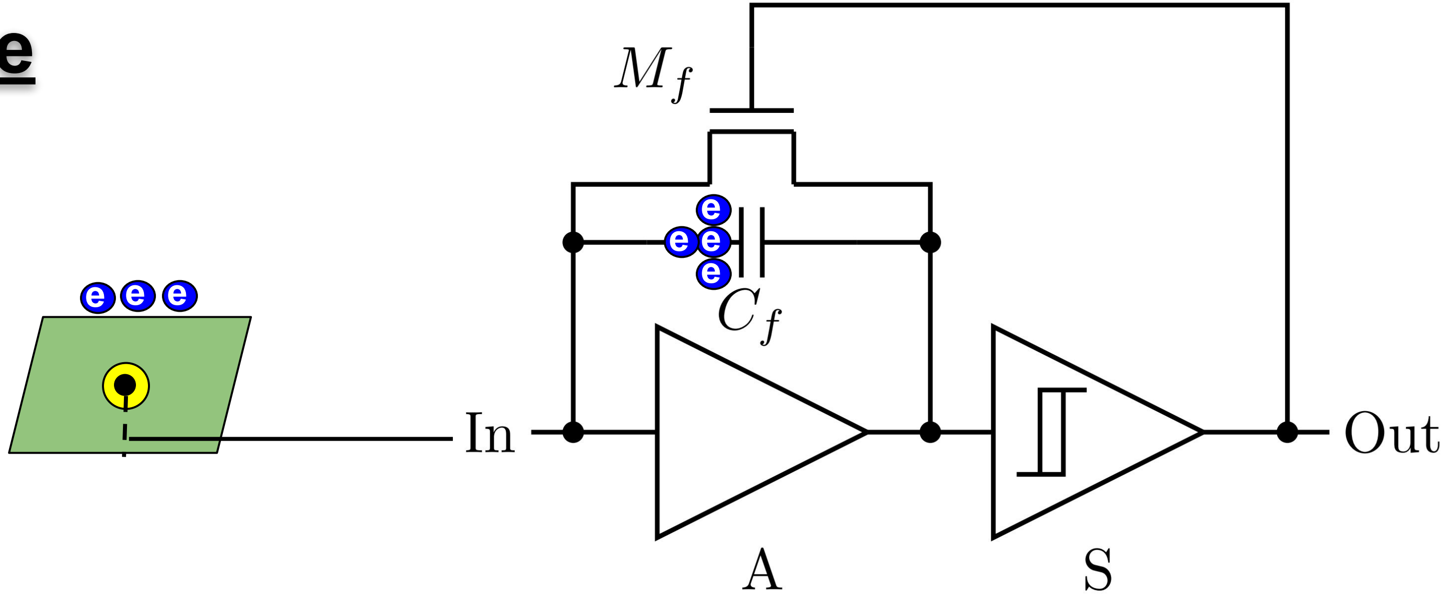
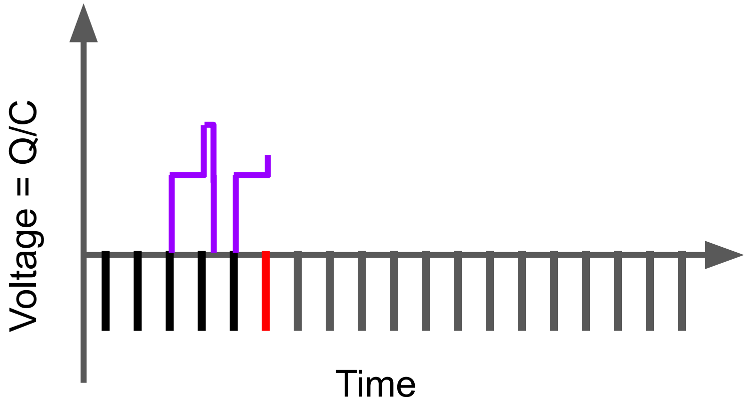
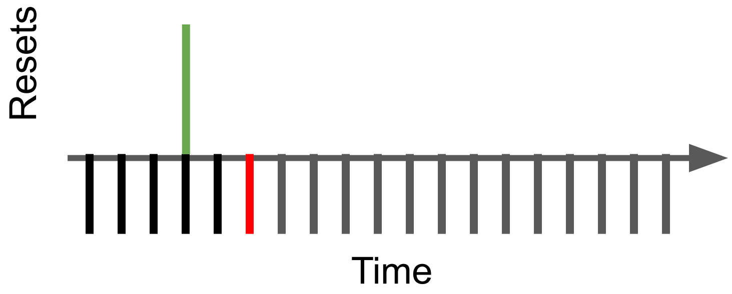
Toy Example







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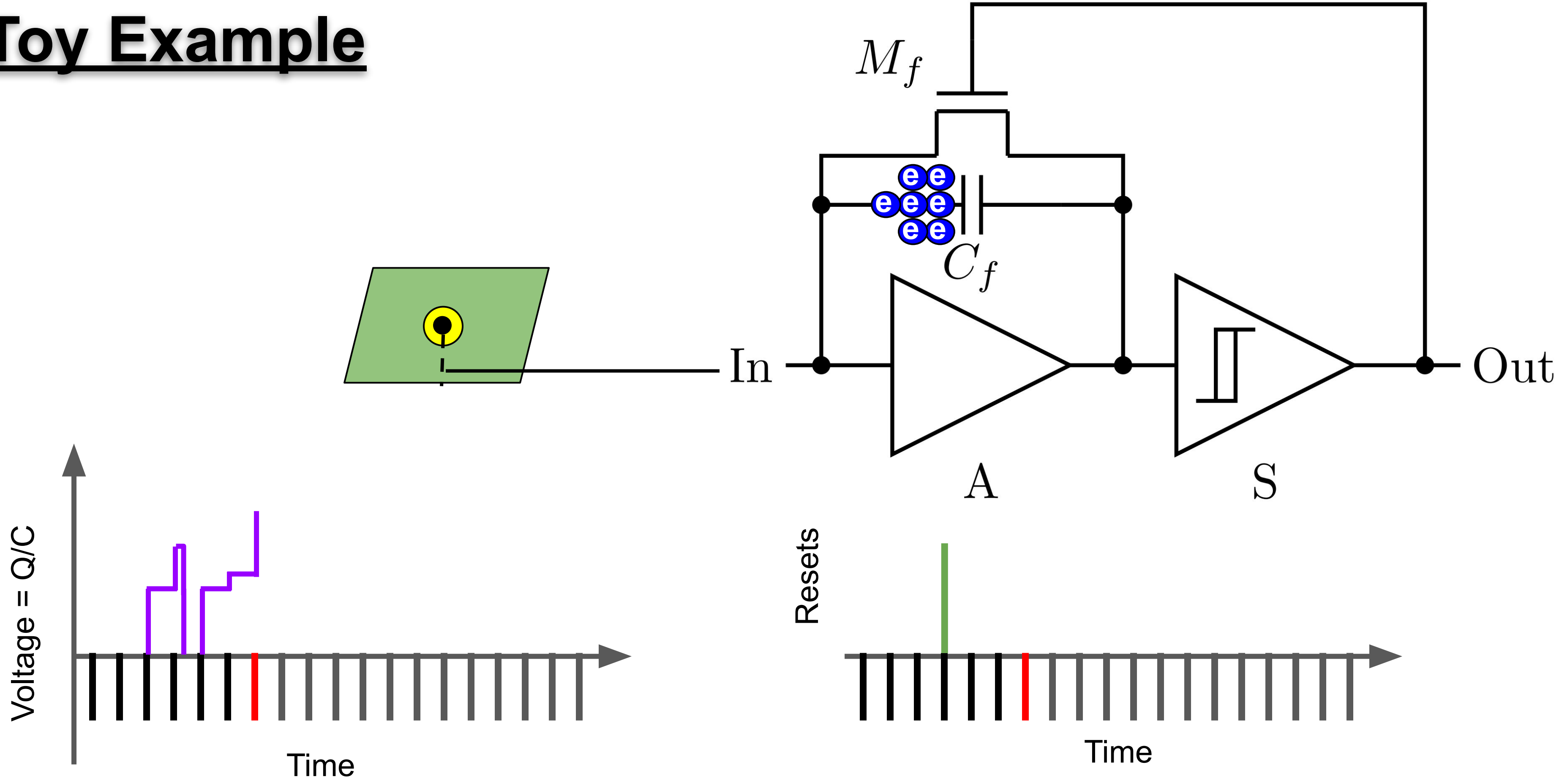

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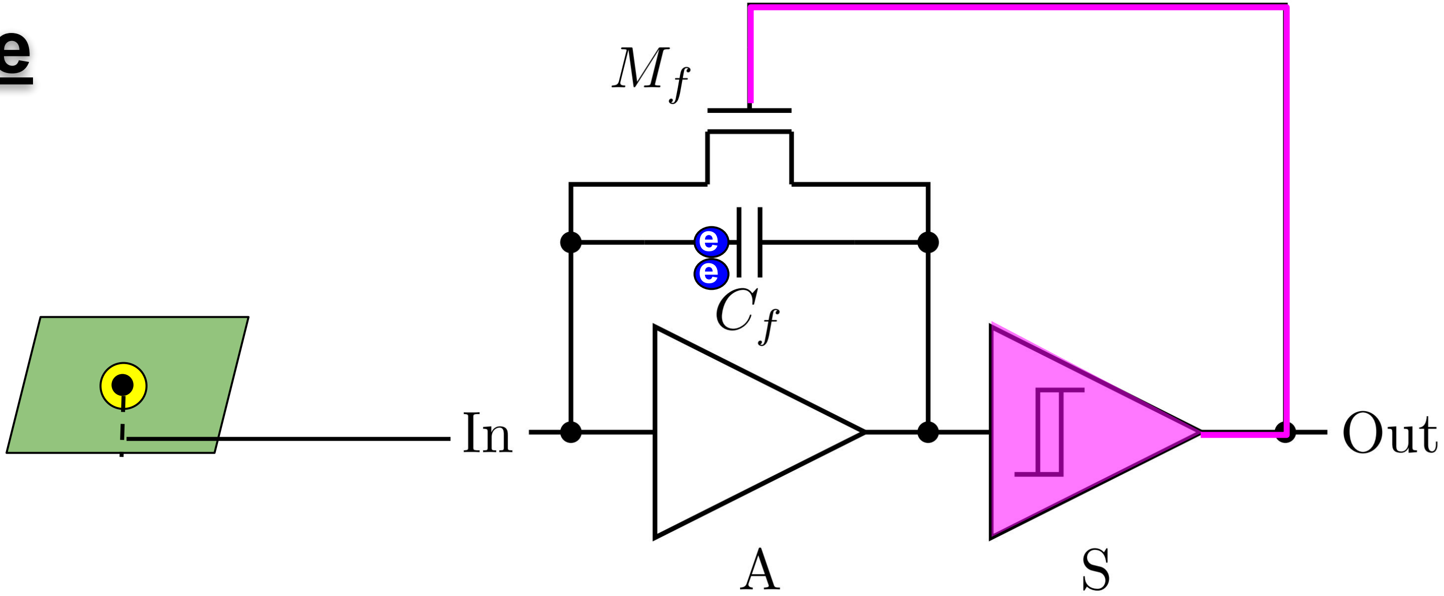

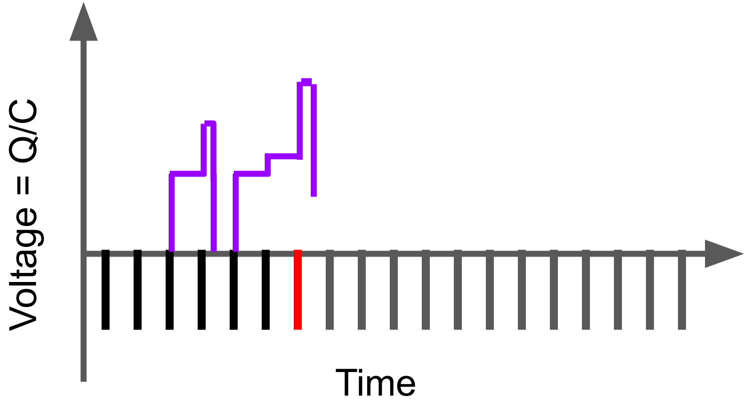

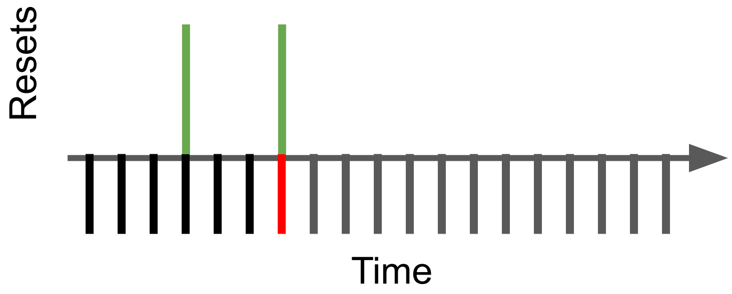

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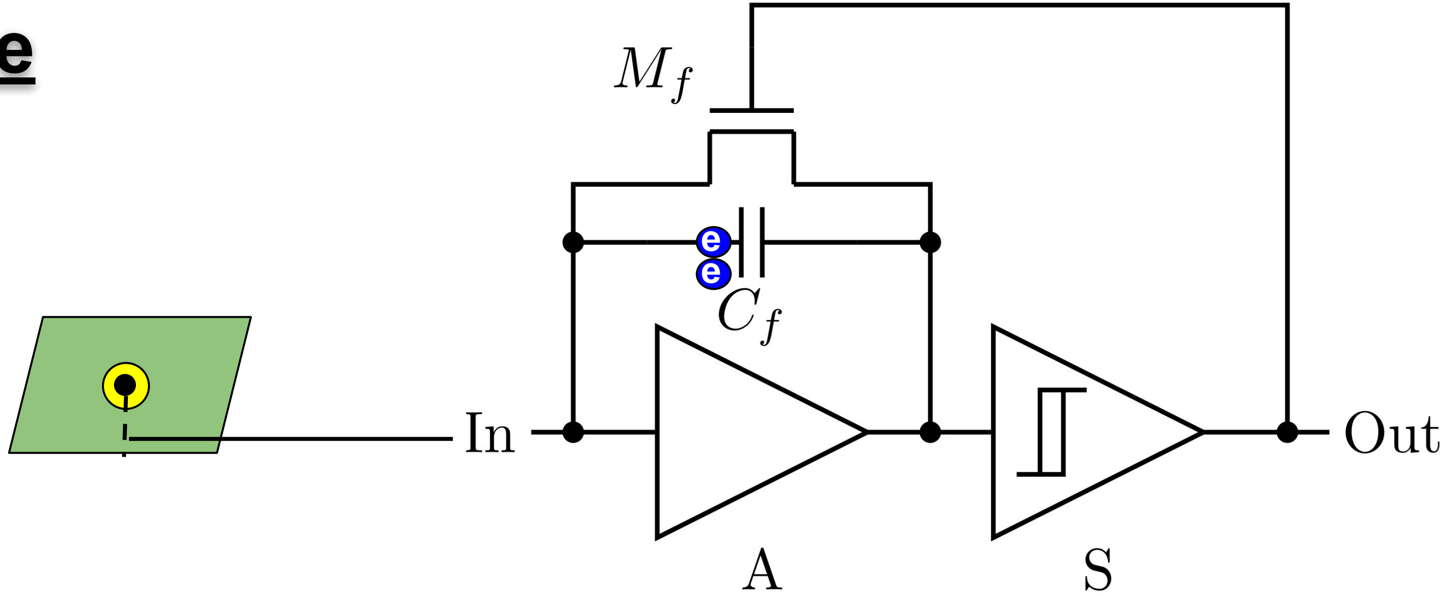

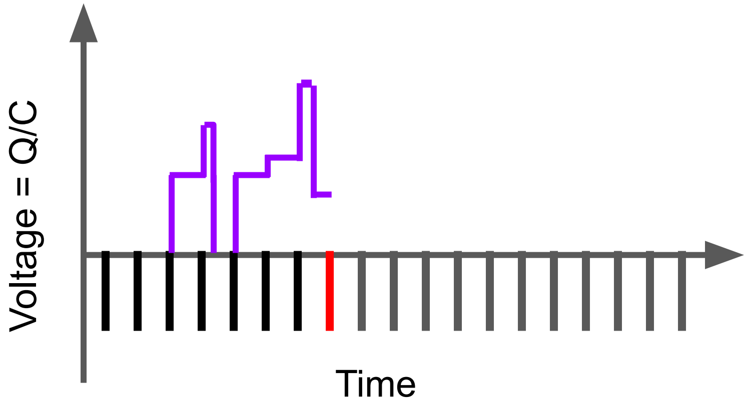

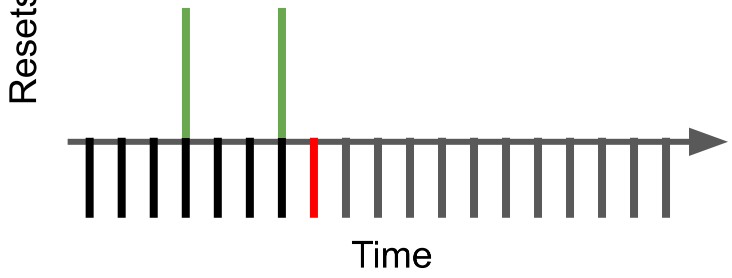

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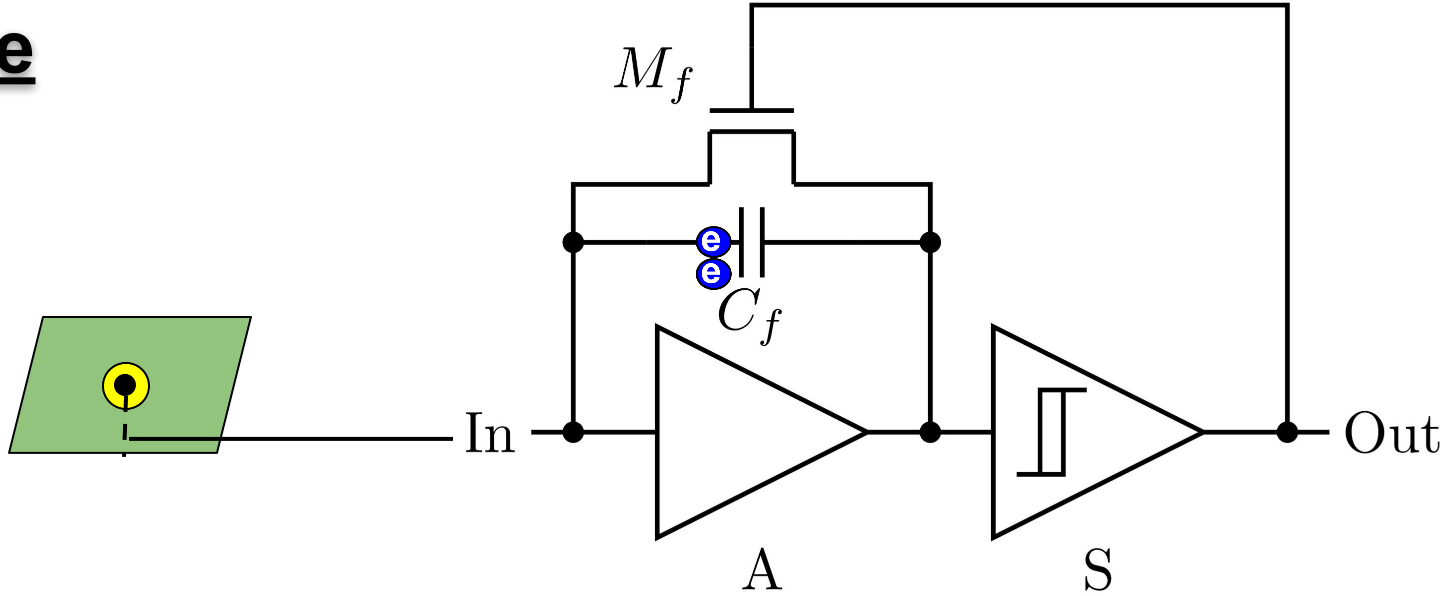

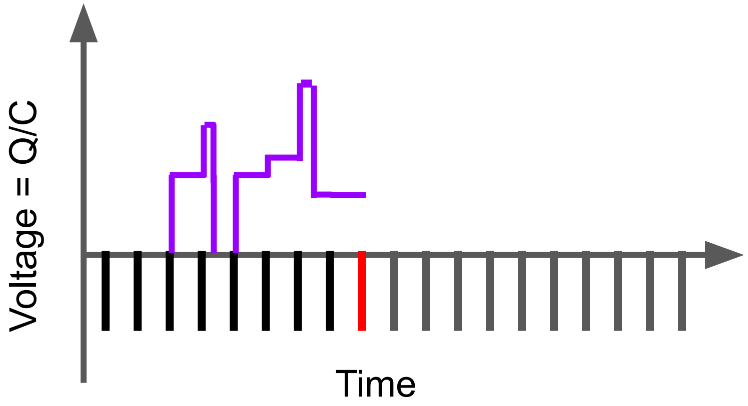

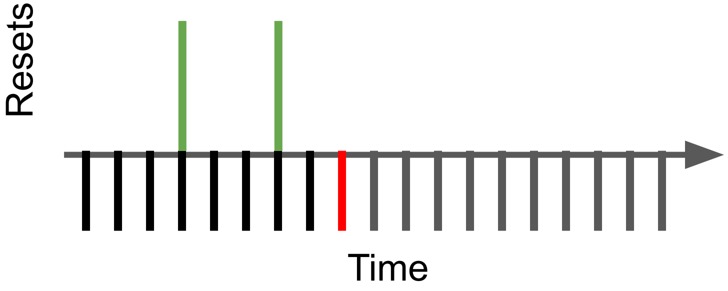

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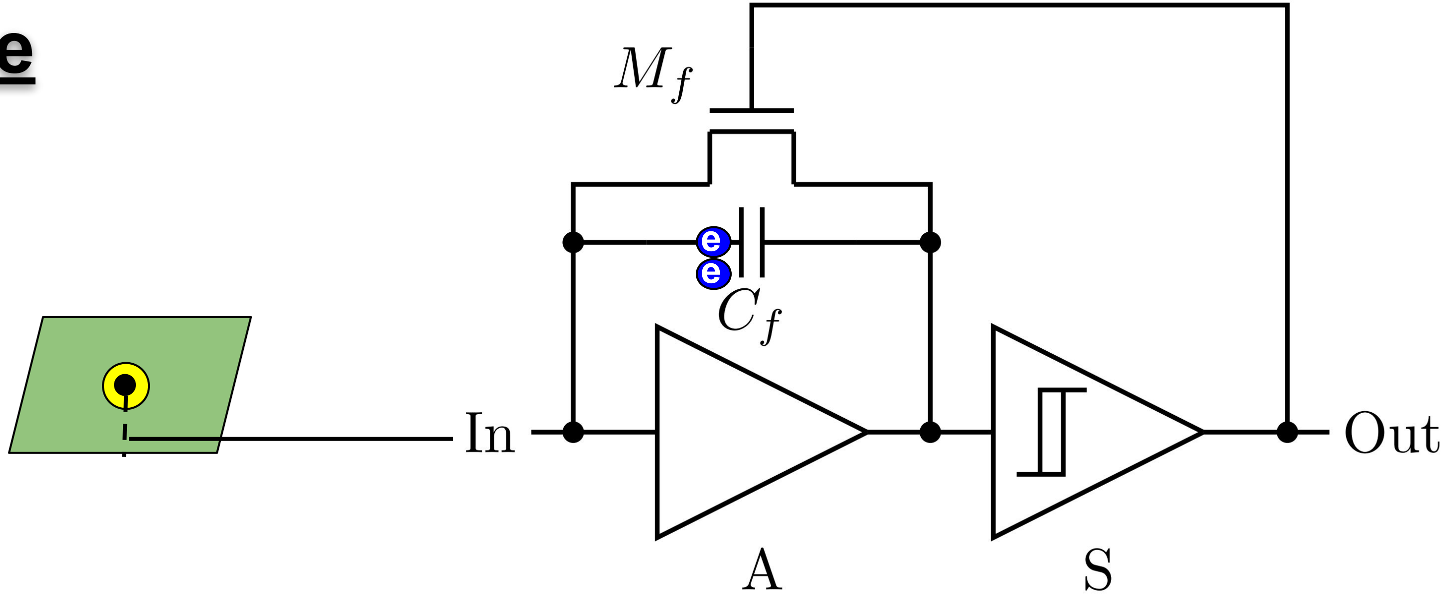

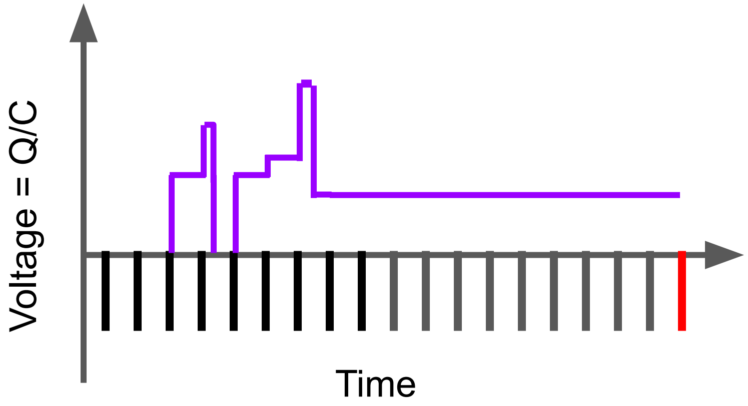

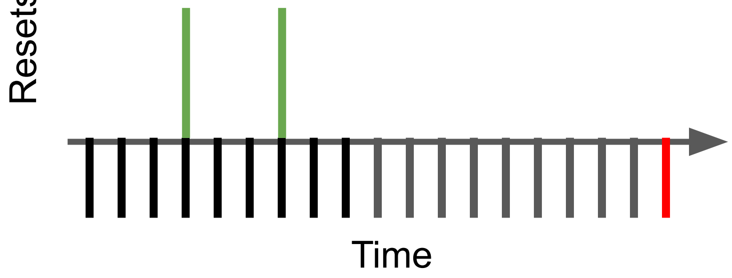

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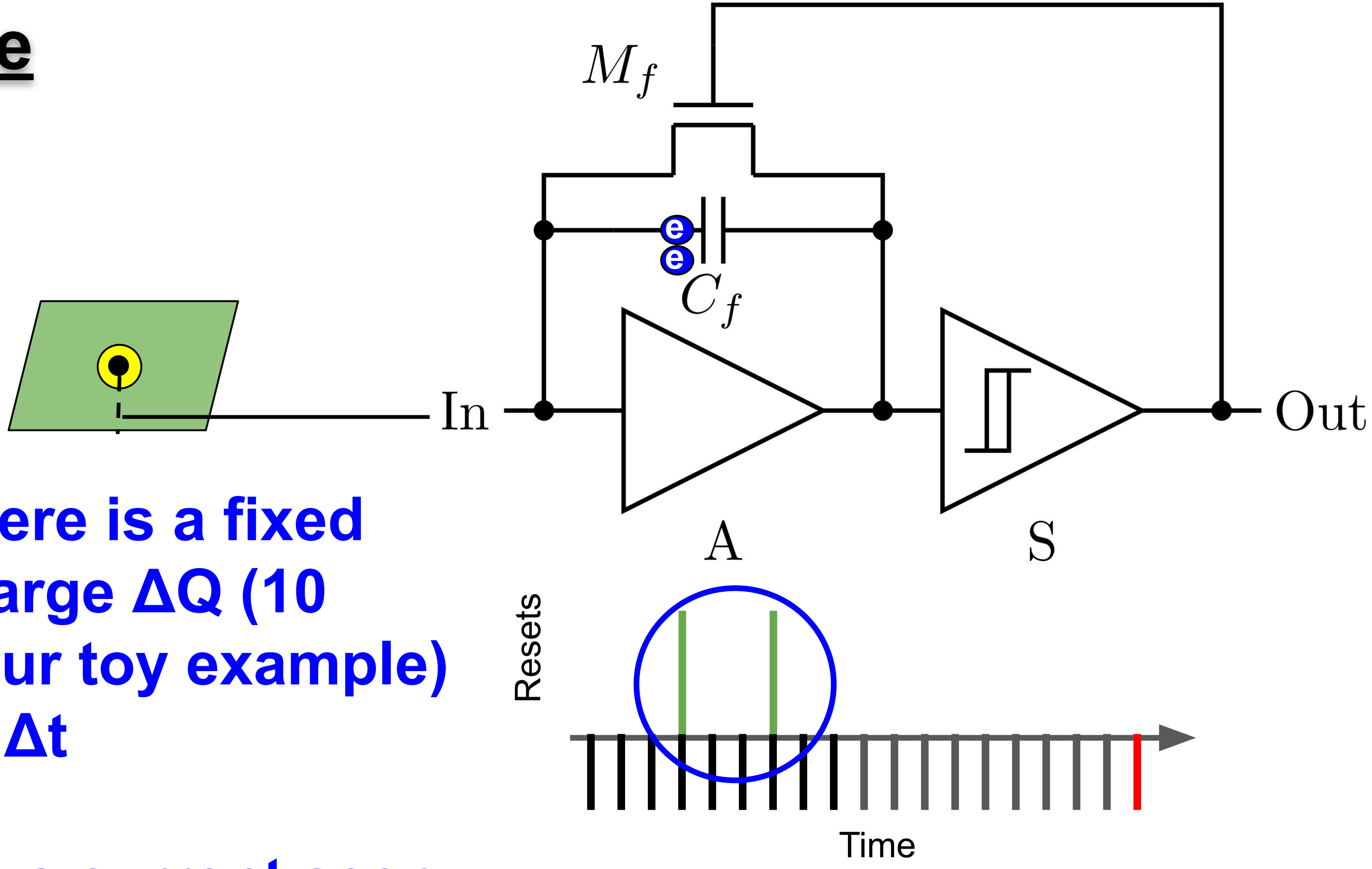
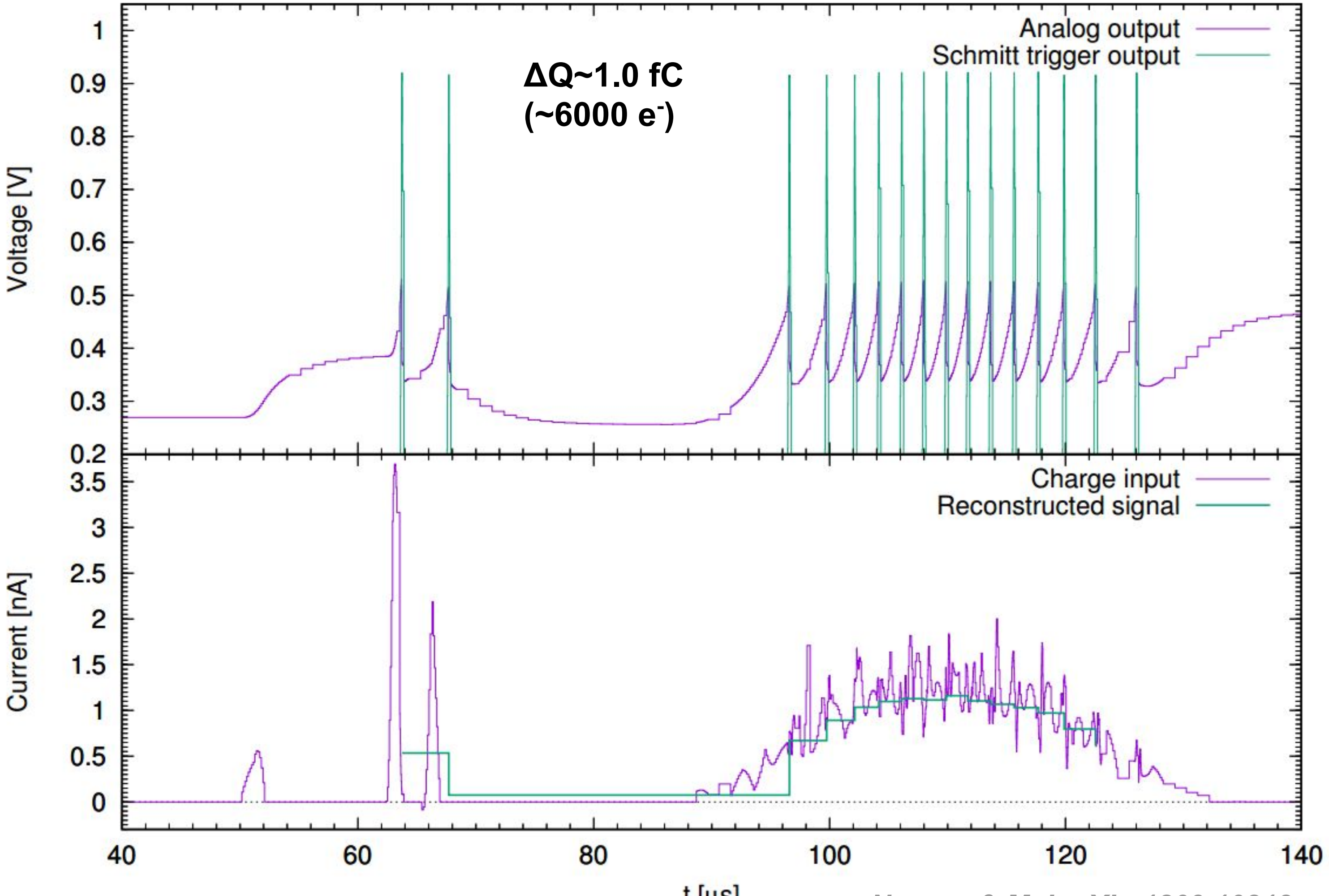


What I have here is a fixed amount of charge ΔQ (10 electrons in our toy example) during a time Δt

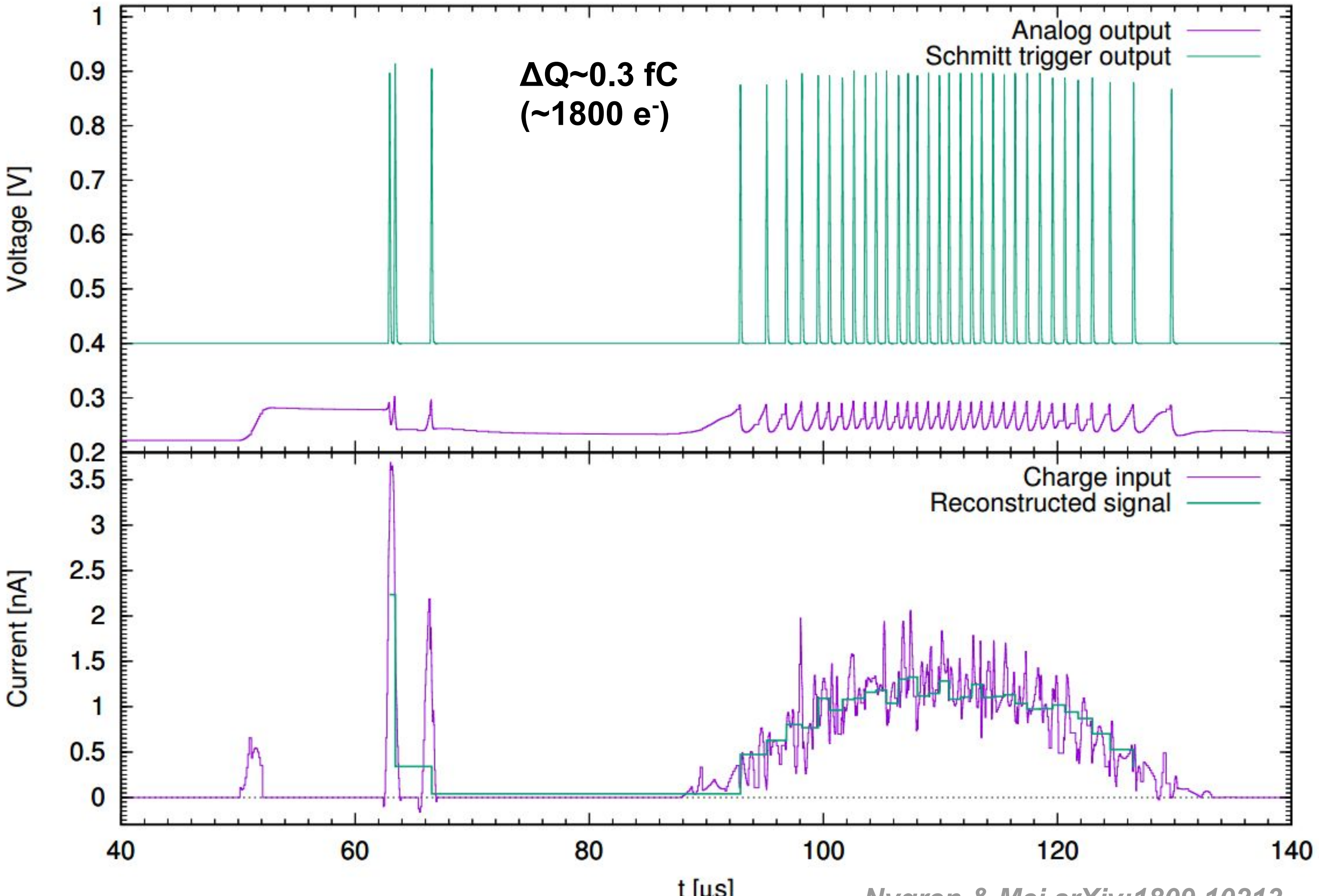
This gives me a current seen by the pixel during this time!

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 ~ 100 aA
  - Large average current (signal) = Small RTD
    - Typical minimum ionizing track ~ 1.5 nA
- Signal / Background ~ 10^7
  - Background and Signal should be easy to distinguish
  - No signal differentiation (unlike induction wires)



Nygren & Mei arXiv:1809.10213



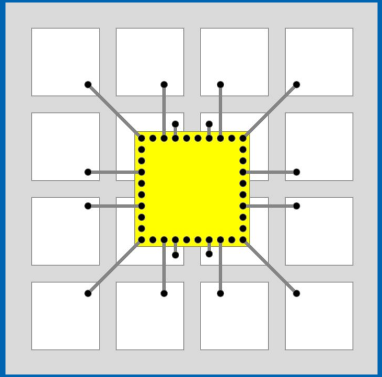
Nygren & Mei arXiv:1809.10213

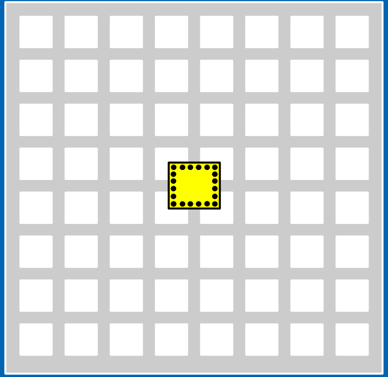
How the time stamping works

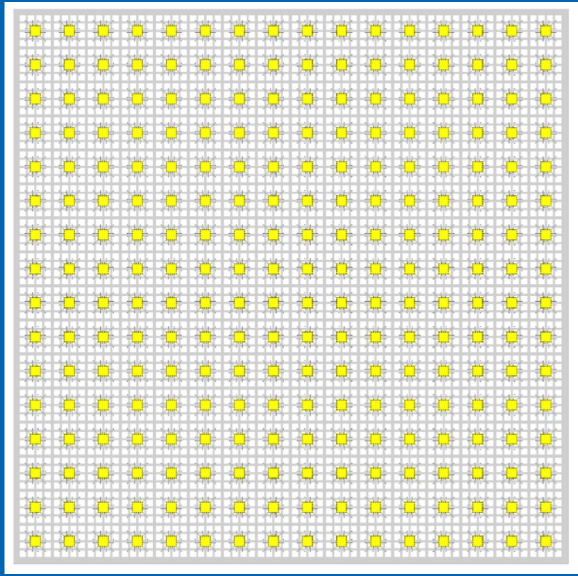
- One free running clock per ASIC (50-100 MHz)
  - Required precision for DUNE $\delta f/f \sim 10^{-6}$ per second
    - Expect this to be easily achieved in liquid argon
- Time stamping routine has the ASIC asked once per second “what time is it?”
  - ASIC captures local time and sends it
  - Simple linear transformation to master clock synced to GMT
  - RTD’s calculated “off chip”
- Has this idea been realized before?
  - YES! In ICECUBE (by Nygren)
    - Oscillator precision achieved > 10^{-10} /s (hard to measure)

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

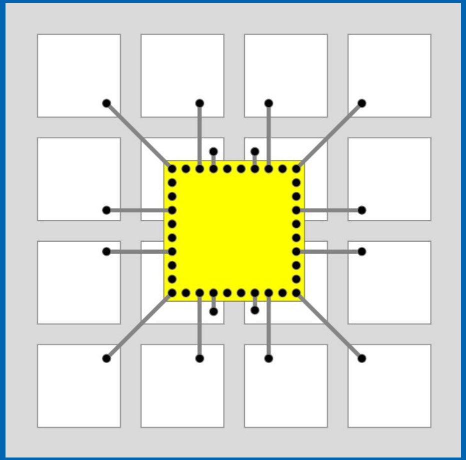


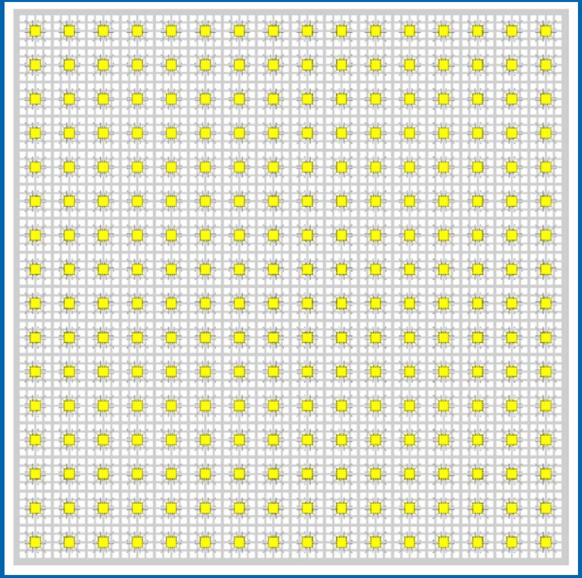




Q-Pix ASIC Concept

- **ASICs will be in one of six states**
  - Data Acquisition (DAQ)
  - Local Time Capture (LTC)
  - Wave Propagation (WP)
  - Data Transfer (DT)
  - Initiate Data Acquisition (IDAQ)
  - Control State (CS)
- **A major feature of Q-Pix is dynamic network generation within a tile.**



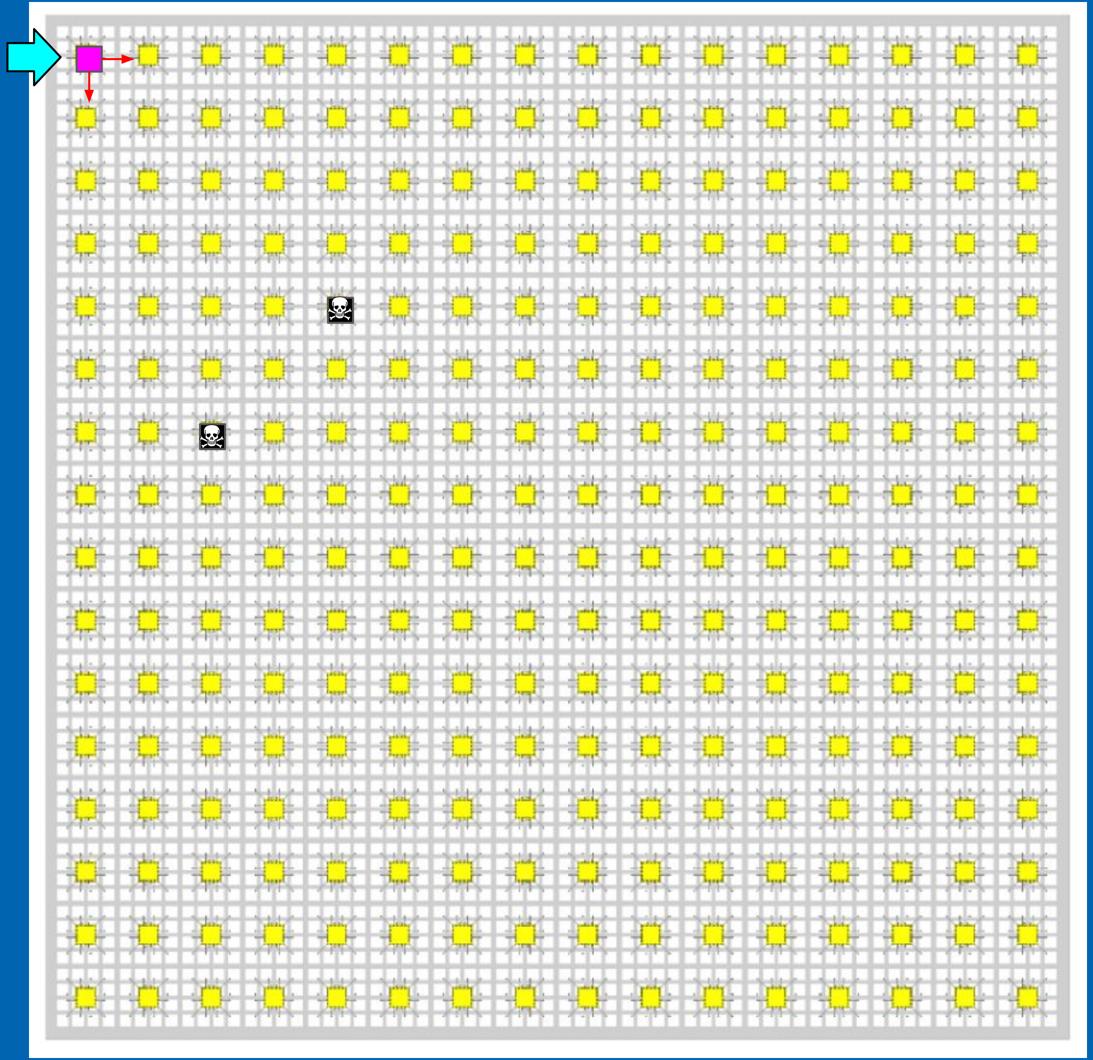


Local Time Capture

A transition to this state begins with the introduction of an **accurately timed 'time stamp token'** at a chosen place on the periphery of the tile.

More than one available entry point is foreseen to reduce SPF risk.

This first ASIC to receive the token then asserts the token in a defined sequence to all of its other x-y neighbors; in principle, up to three neighbors could accept.



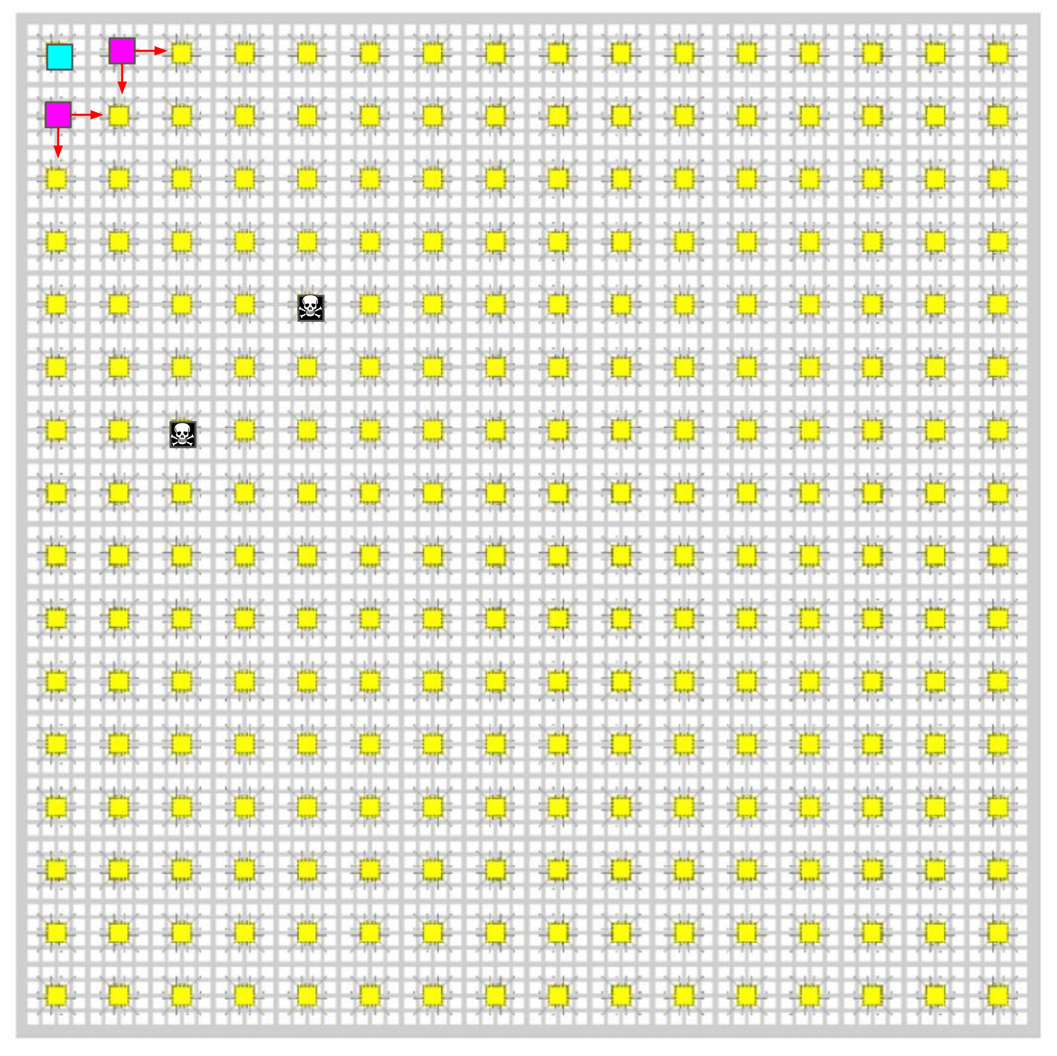
Wave Propagation(WP)

Neighboring ASICs now receive the token.

Assertion to one ASIC by two neighbors is resolved by the accepting ASIC choosing just one, following a pre-programmed sequence.

Each ASIC in this chain remembers from whom it has accepted the token.

An intra-tile network is thus dynamically established and maintained.

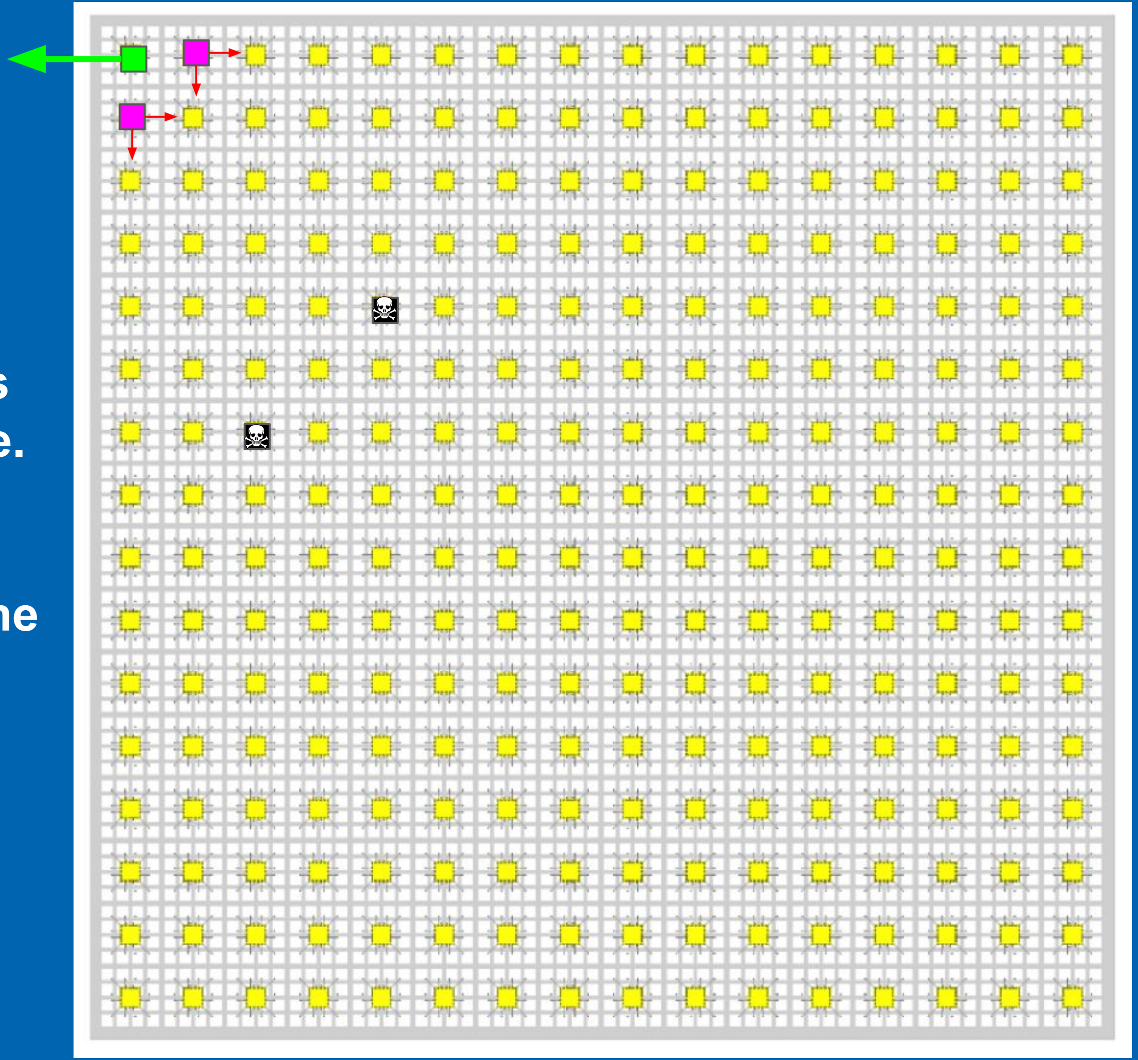


Data Transfer (DT)

As soon as the first ASIC learns that the token has been either accepted or rejected by all of its neighbors, readout of all of its data captured since the previous time-stamp token will commence.

Data will include at least the one forced time capture caused by the time-stamp token.

Each ASIC attempts to push backward its data to the ASIC from whence it accepted the time-stamp token.

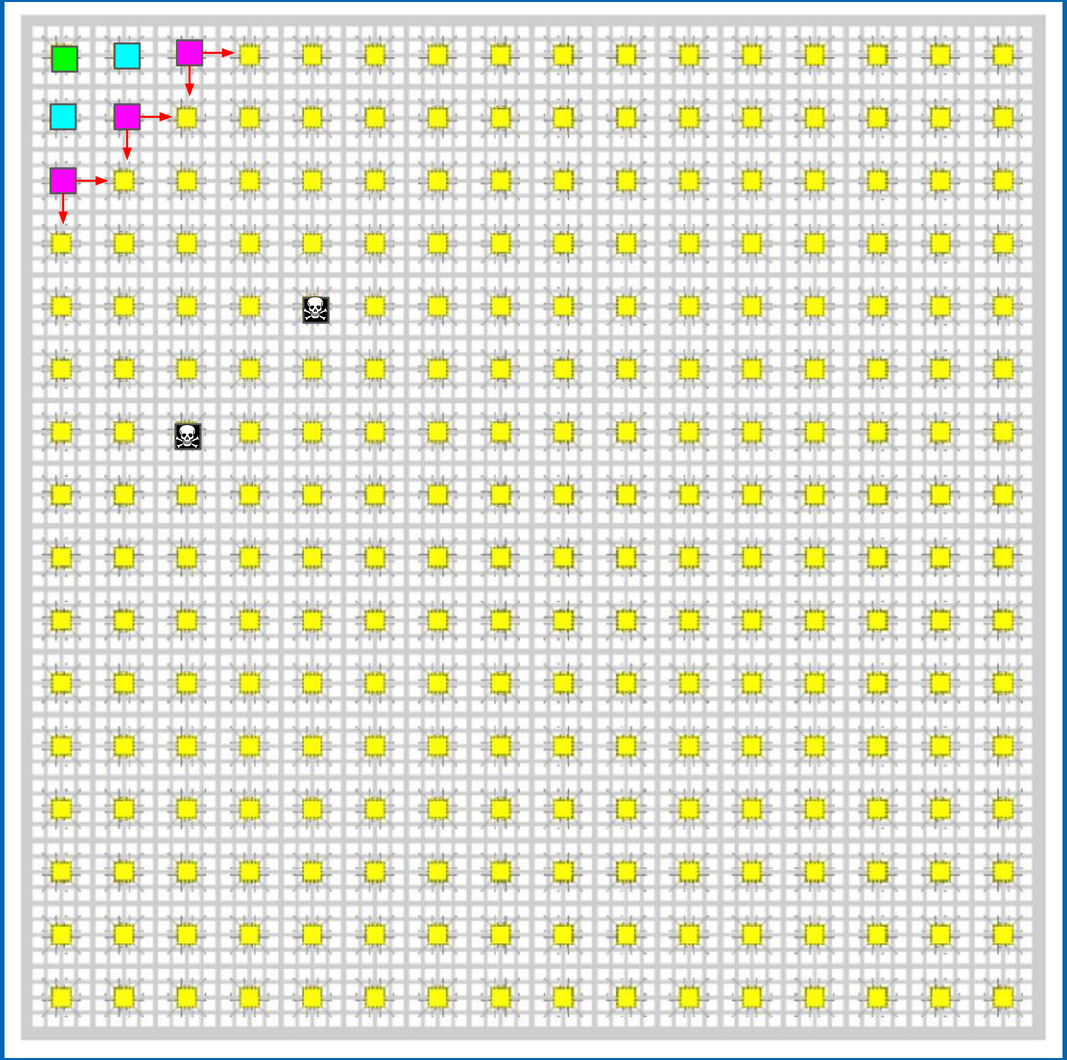


WP and DT continues

When an ASIC is empty after data transfer it must accept a data transfer token impressed from any neighbor.

All data is pushed through the dynamically established network to complete the DT. The DT phase reproduces the LTC wave in reverse but much more slowly.

Off-plane data acquisition external to the cryostat determines when all ASICs have reported data, permitting transition back to DAQ

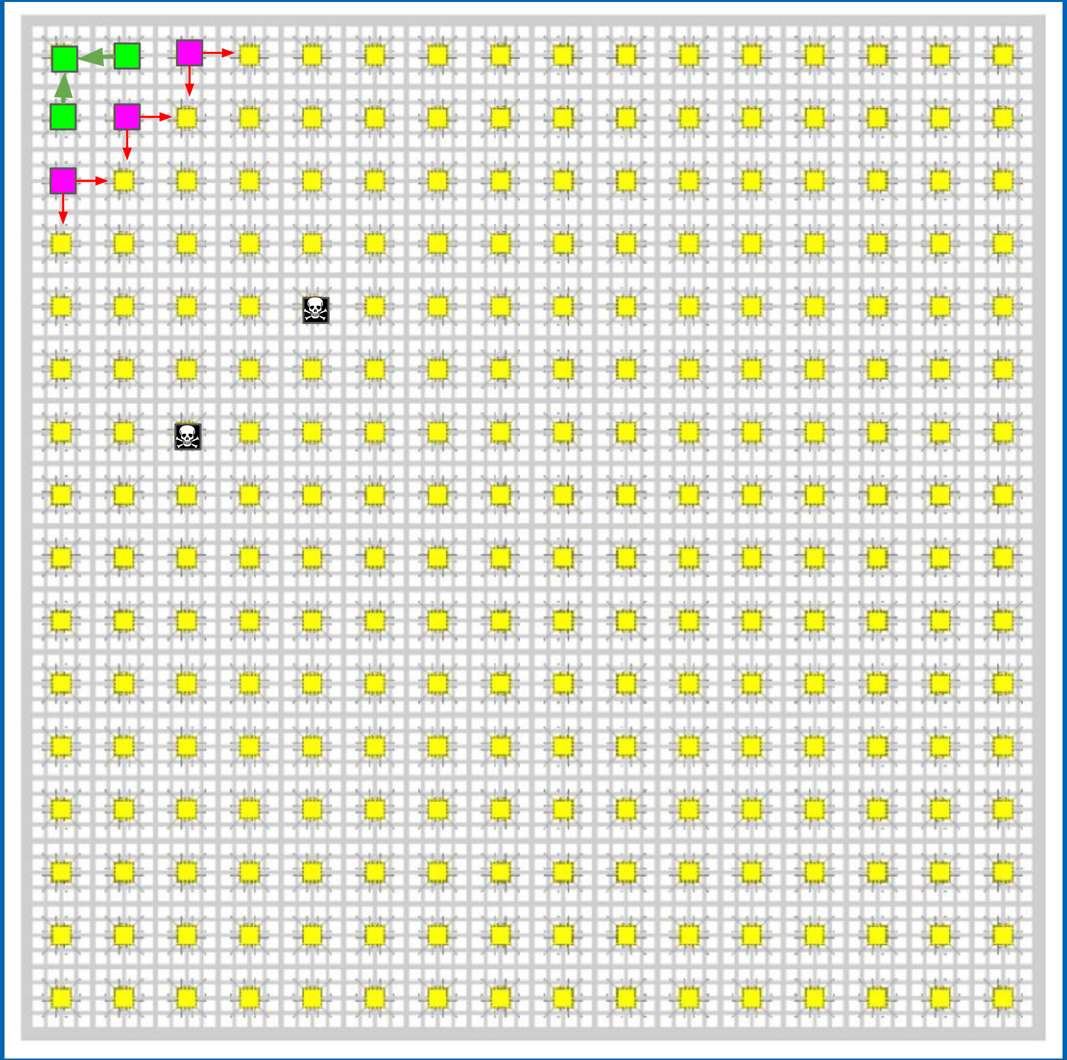


WP and DT continues

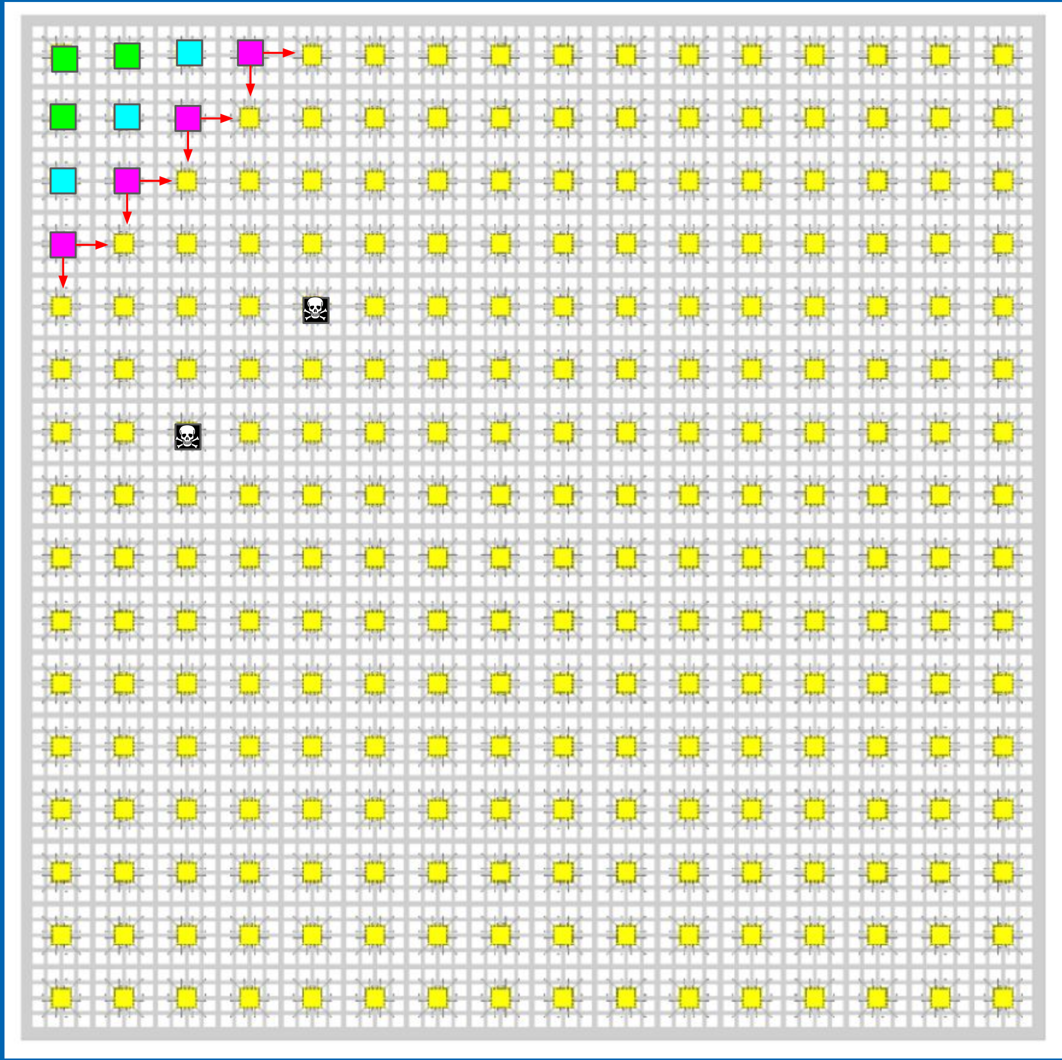
Data are likely to be pushed through an average of perhaps 16 ASICs but it seems unlikely to be pushed through more than 32 ASICs.

While an inefficiency is present here, the data load is very small and infrequent.

Very substantial resilience and mechanical simplicity is obtained.



And the beat goes on….



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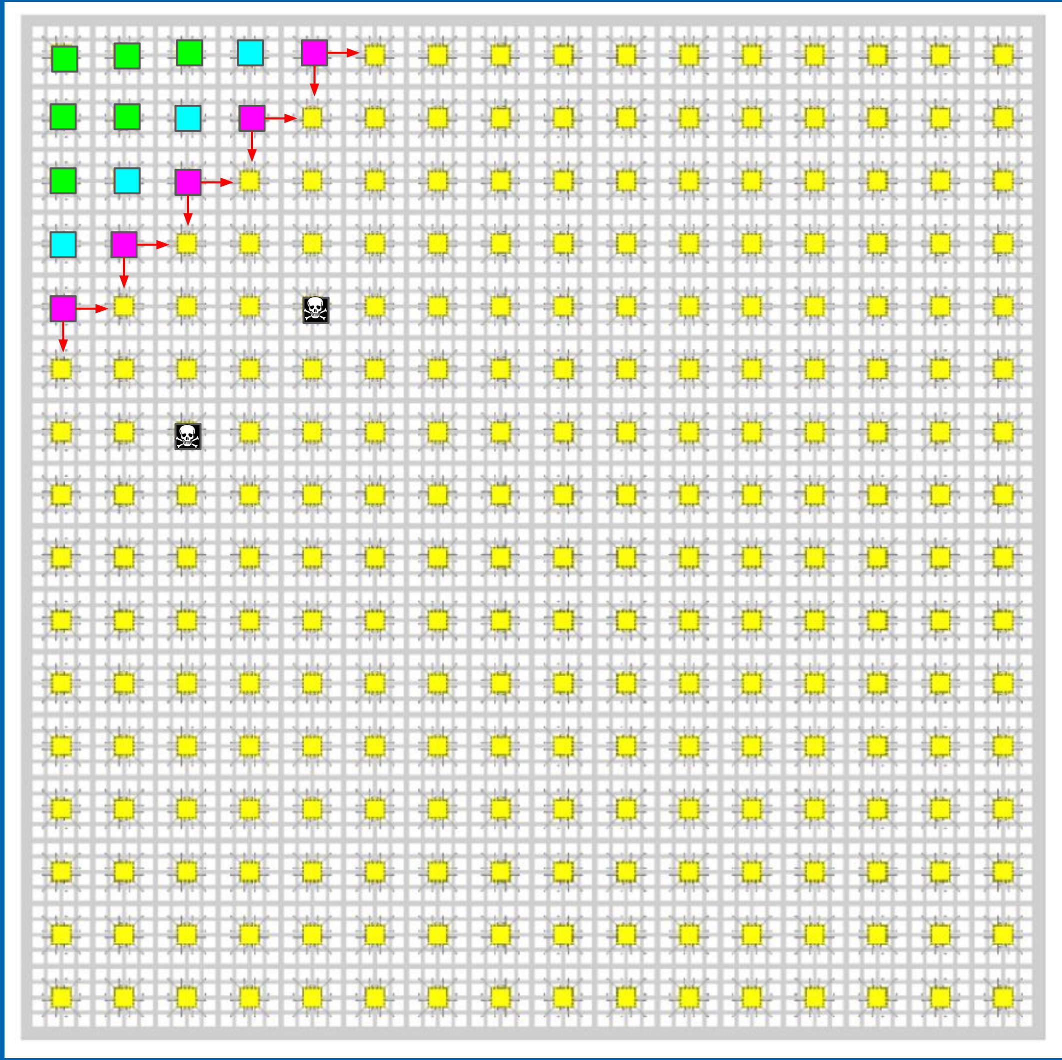

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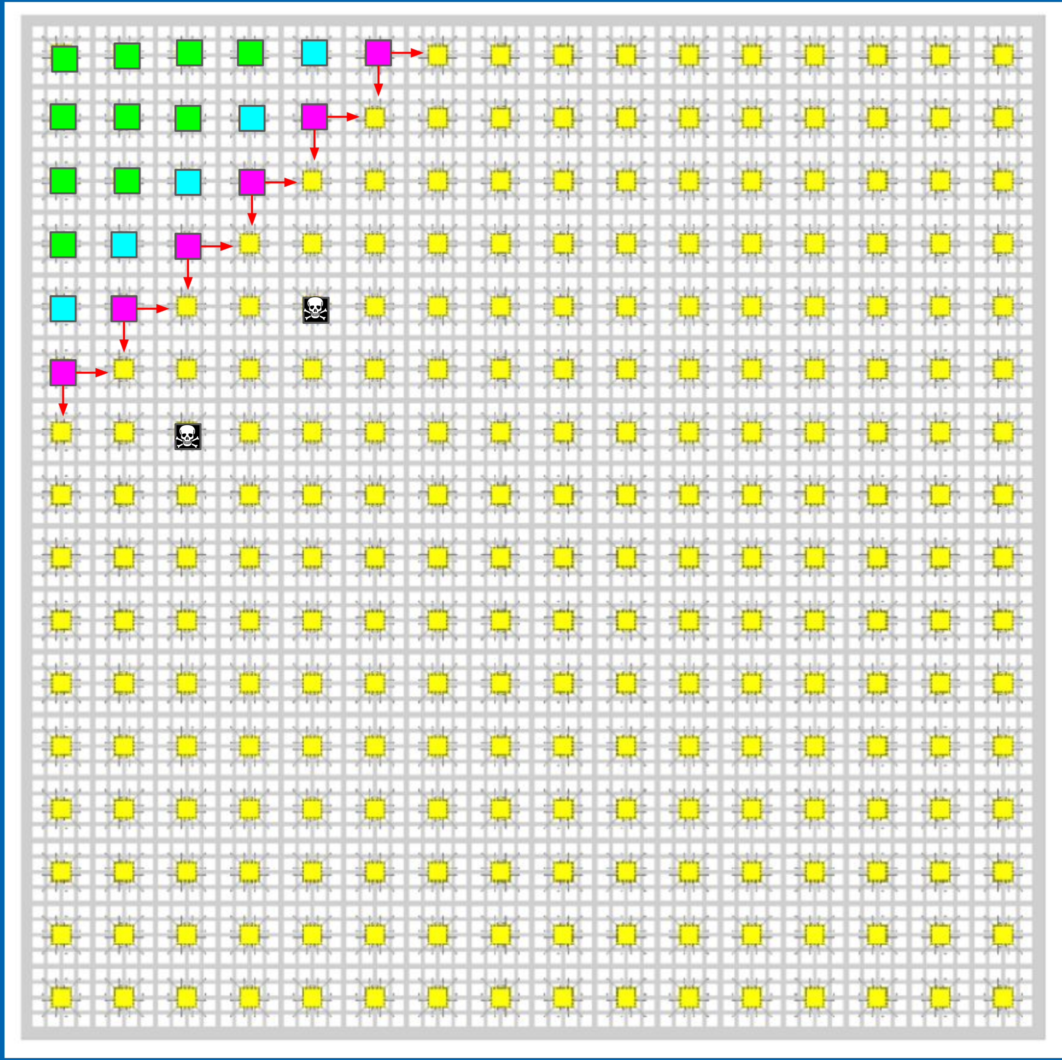

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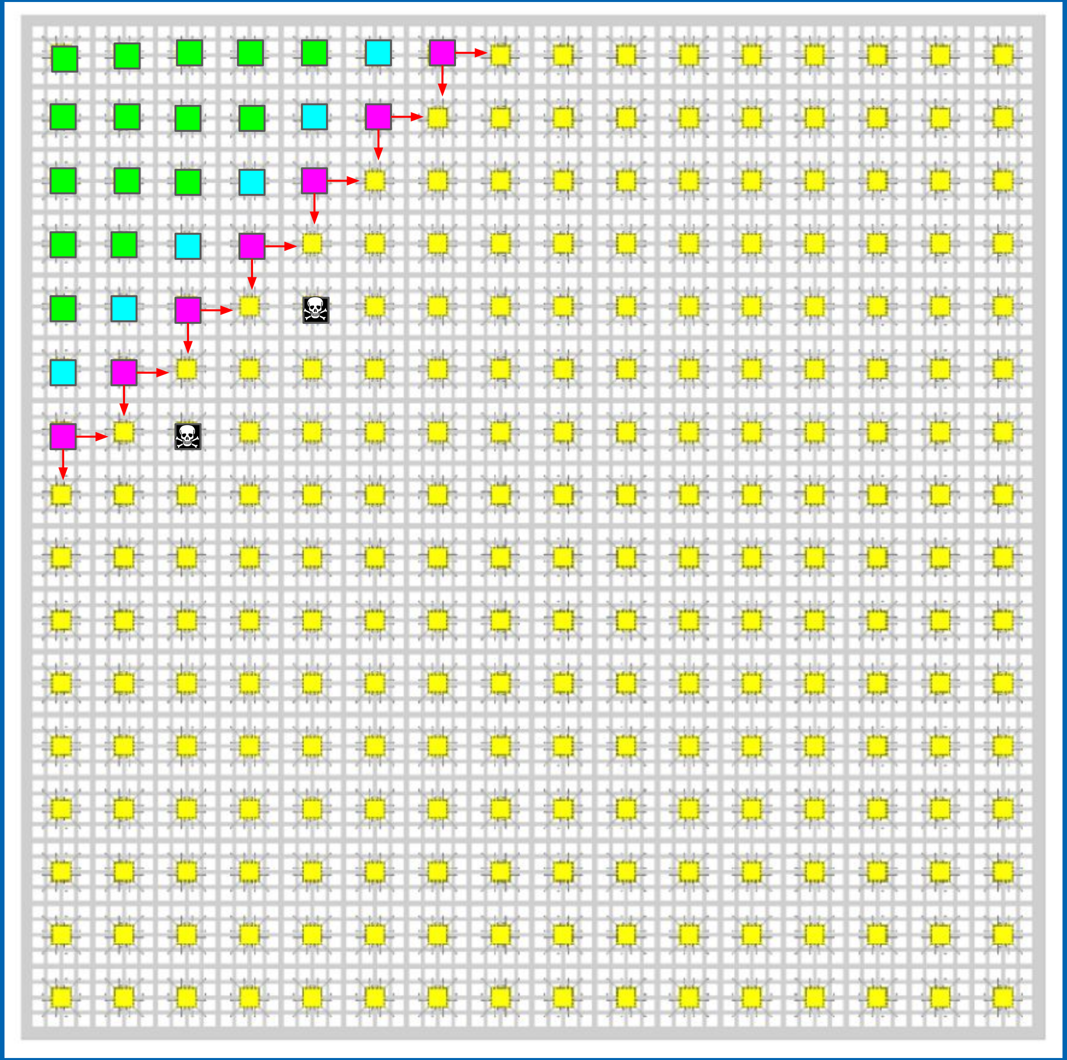
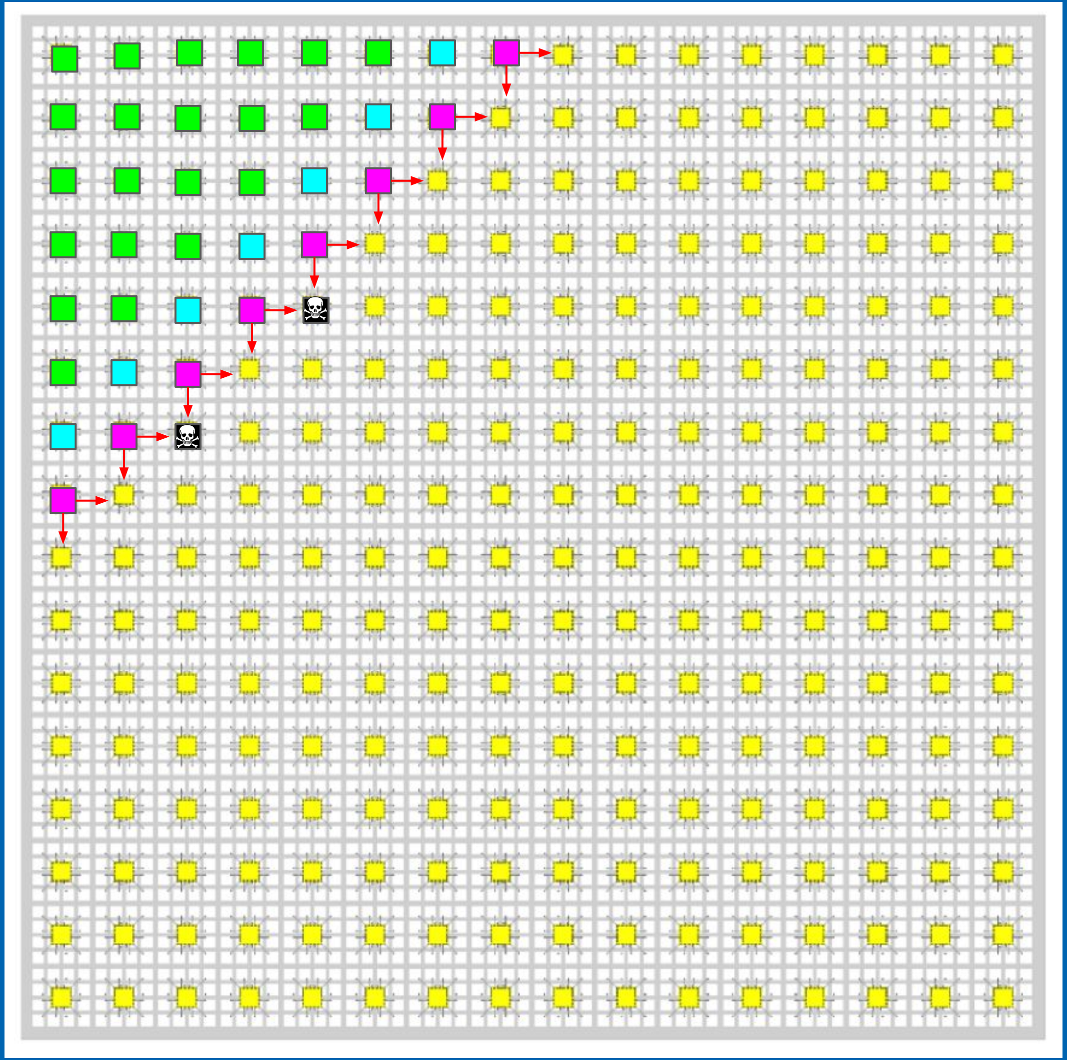


Reslience to Single Point Failure

Unresponsive chip(s) will be bypassed by the encircling wave.

 **= dead/unresponsive chip**



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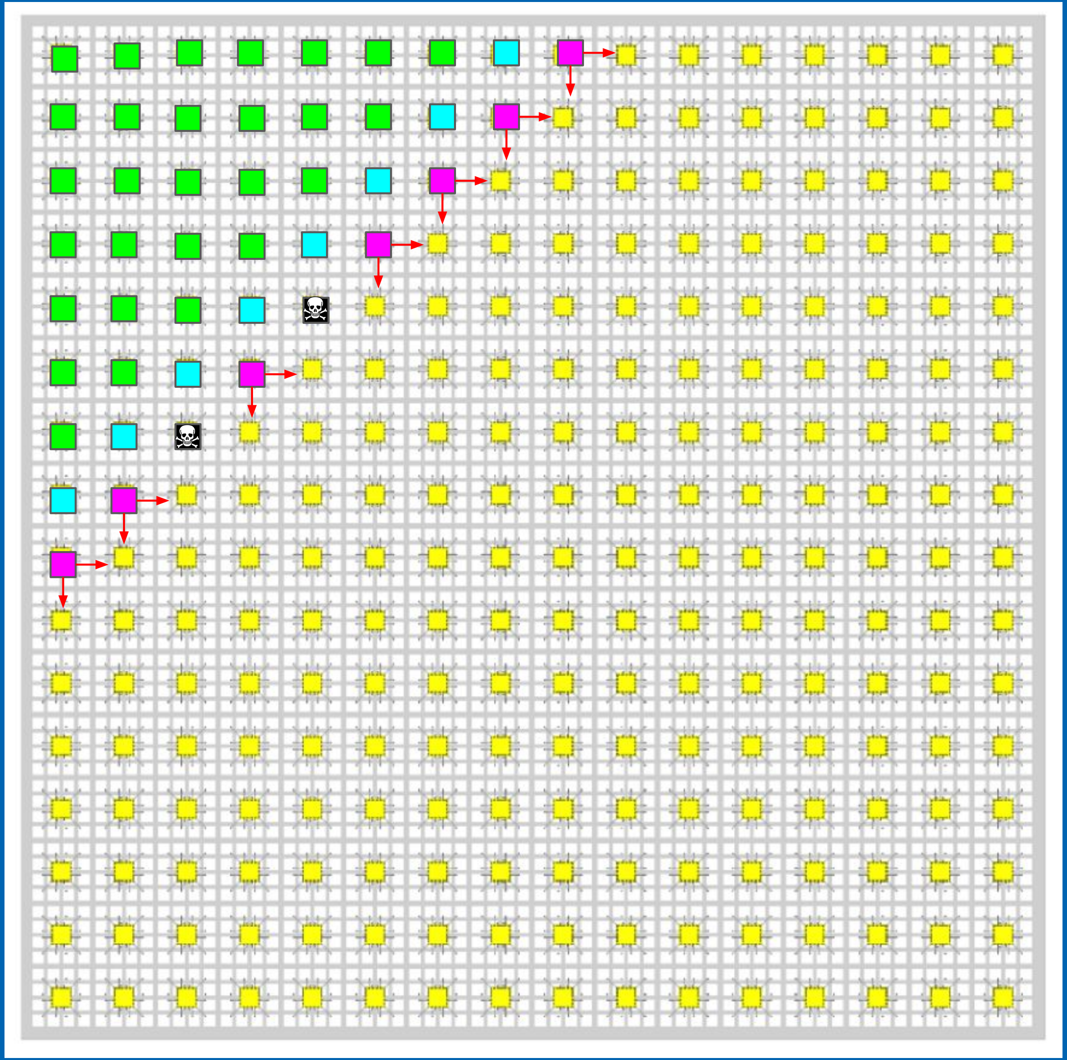
Should an ASIC fail at any time a new dynamic network must, and will, automatically establish itself.

Although the network pattern itself is irrelevant, it can be recovered from the sequence of received data.



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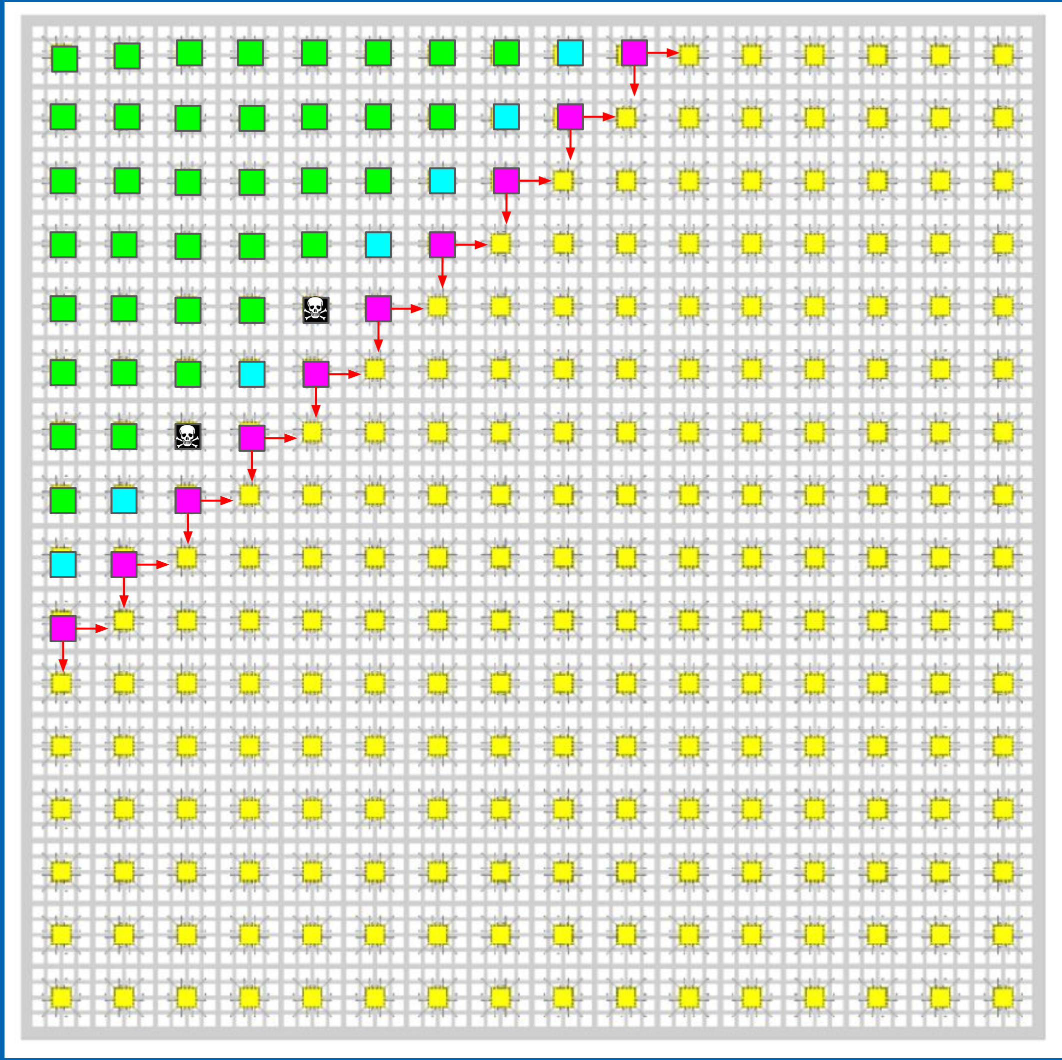
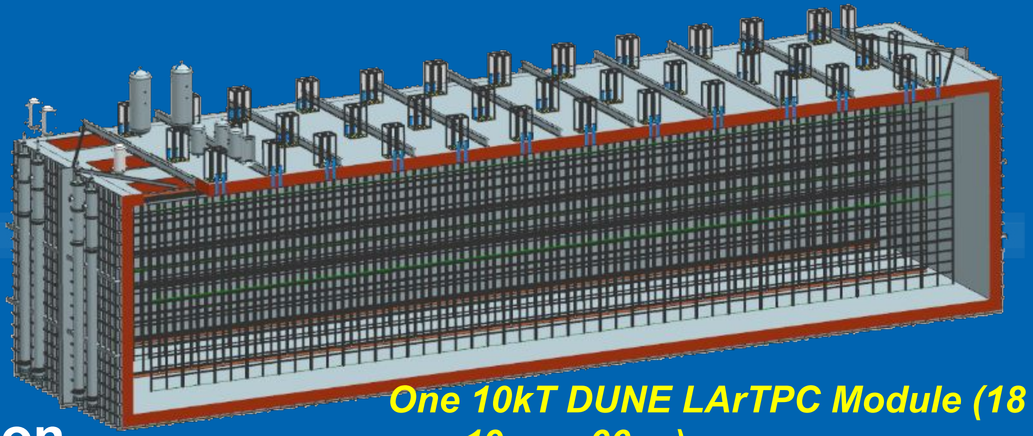


Data Rates for 10 kTon

- **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



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

- **The total data rate is thus set by the number of readout planes**
  - 7 meter drift = 2 APA’s = 16,384 bits/tile x 22,276 tiles ~ 40.5 Mbytes/s
  - 3.5 meter drift ~ 90.5 Mbytes/s
    - The detector can be made more modular!
    - Reduce the demands on the HV, purity, diffusion, etc...

Q-Pix Consortium

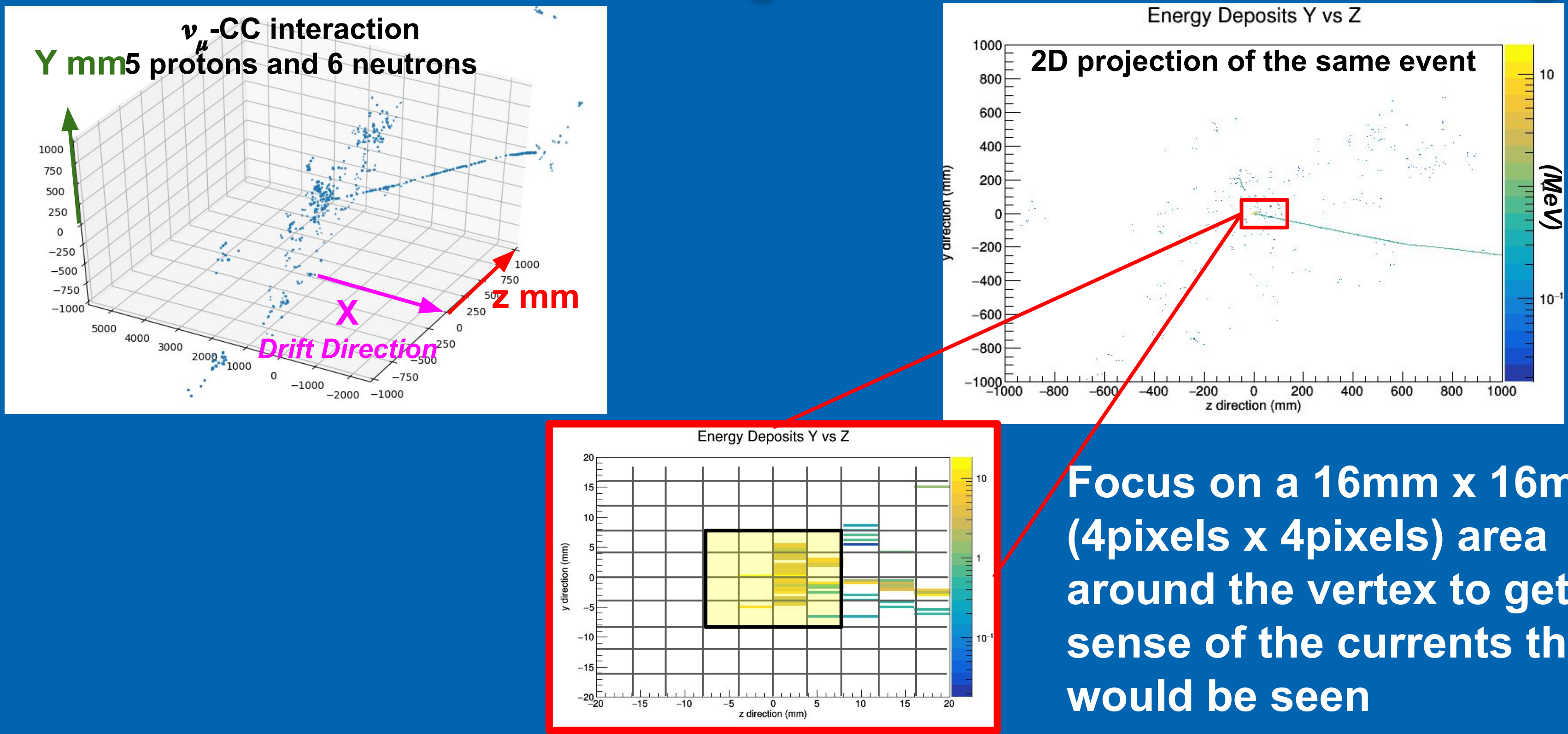
- **A consortium of universities and labs has formed to realize and test the Q-Pix concept**
    - Being done in close collaboration with LArPix (JINST 13 P10007) readout for the DUNE near detector

Q-Pix Consortium

- Five central ideas being worked on
  - Circuit Design: A prototype of the front-end + oscillator is expected to be completed in the next 6 months
  - Physics Simulations: Quantify the conferred benefit of pixel vs. wire readout and the requirements of the ASIC design
  - CIR Input: all extraneous leakage current at the input node needs to be small (aA)
  - Clock: $\delta f/f \sim 10^{-6}$ per second
  - Light Detection: Exploring new ideas using photoconductors on the surface of the pixels

Physics Simulation

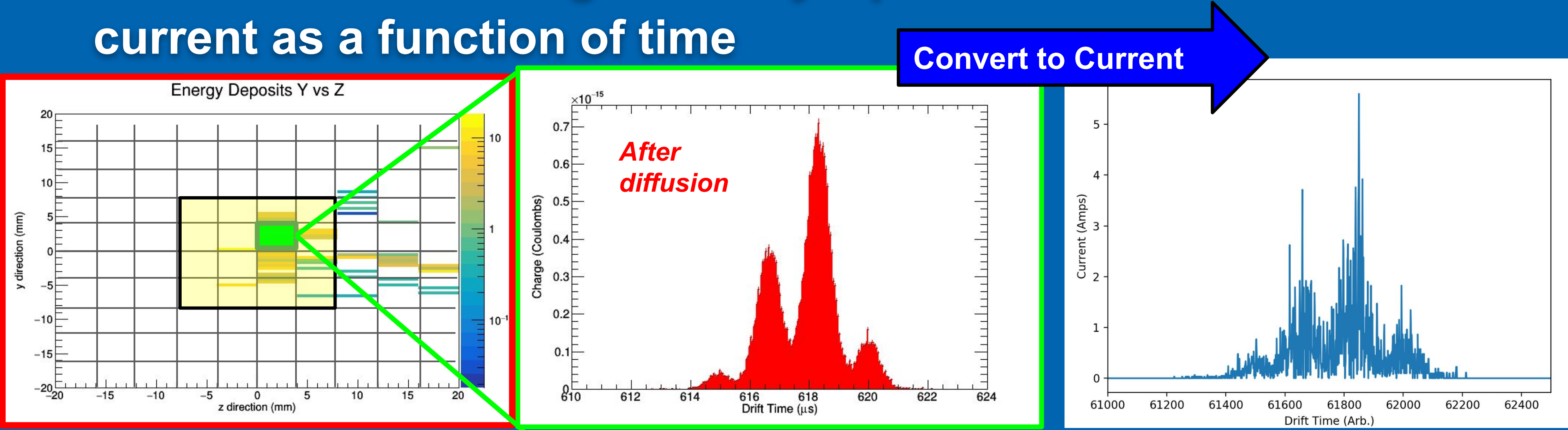
- To help quantify the range of currents the Q-Pix ASIC will need to reconstruct we are using of neutrino interactions in argon



Focus on a 16mm x 16mm (4pixels x 4pixels) area around the vertex to get a sense of the currents that would be seen

Physics Simulation

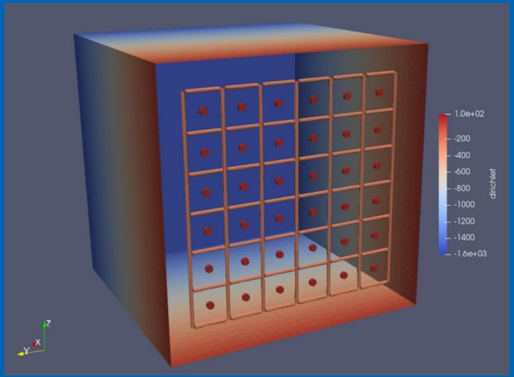
- **We can take the charge seen by a pixel and translate this into current as a function of time**

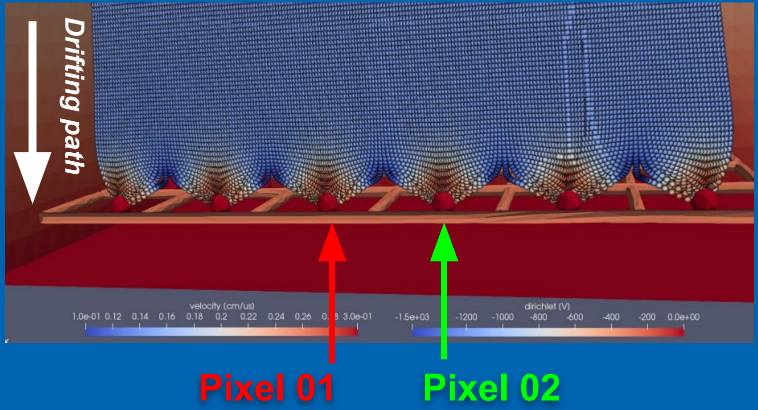


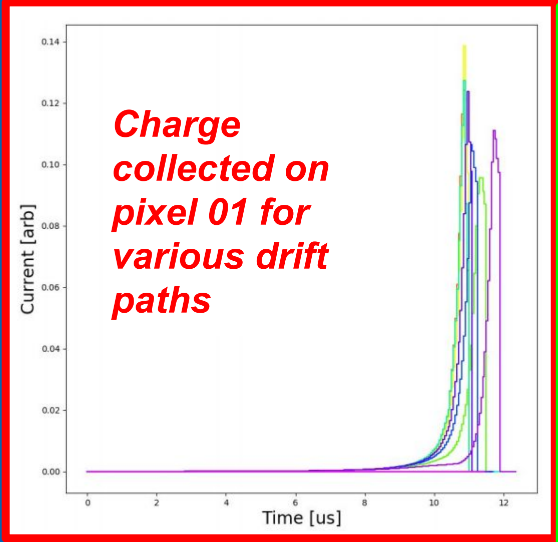
- **We can then use this simulation to set the physics requirements on the Q-Pix ASIC**
  - Allowed reset time, minimum ΔQ, etc…
  - Ongoing studies exploring non-beam (supernova, proton decay, etc…) and beam related parameters

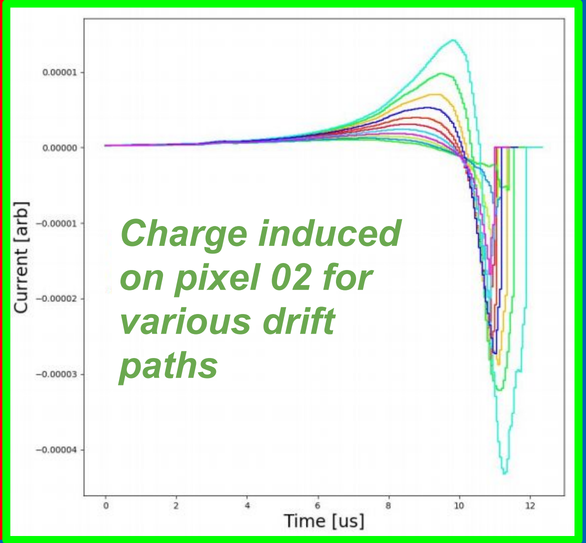
Physics Simulation

- **We are also developing the full charge response using Boundary Element Method (BEM++)**
  - Estimate the response and any induced charge seen on adjacent pixels
    - Preliminary results suggest this is $\mathcal{O}(1\%)$









Physics Simulation

Calculation from: https://arxiv.org/pdf/1508.07059.pdf

- **Measurement of Longitudinal Diffusion**
  - Using a small sample muons a novel technique in Q-Pix can be seen

The electron current measured on a plane perpendicular to the drift direction at a distance d from a point source is given by

$$j(t) = \frac{n_0}{\sqrt{4\pi D_L t}} \exp\left(-\frac{(d - vt)^2}{4D_L t} - \lambda vt\right) \quad (2)$$

where n_0 is the initial electron density, v is the drift speed, t is the arrival time of the electrons on the plane, and λ is equal to the inverse of the mean free path of the electron.

This function approaches a true Gaussian when $d \cdot v$ is large and D_L is small. For the case being considered $v = 0.1648cm/\mu s$ and $d > 10cm$ so, $d \cdot v \geq 1.6 \times 10^5 cm^2/s$. This is large when compared to $D_L = 6.82cm^2/s$.

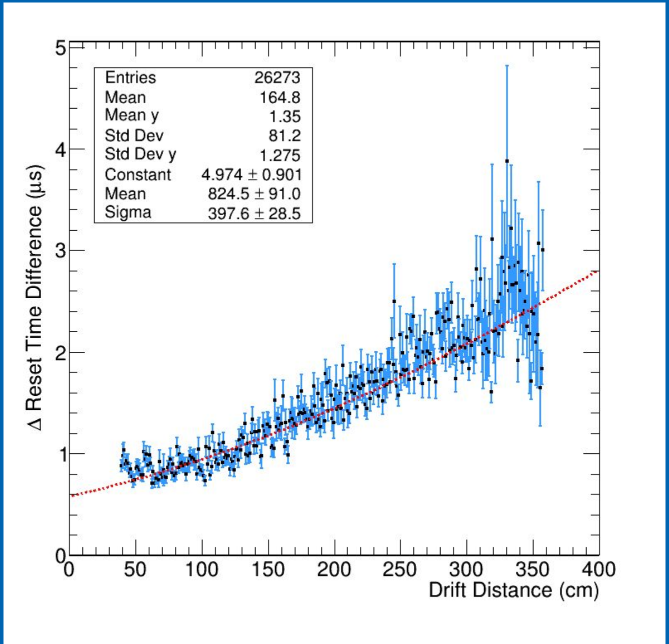
The Reset Time Difference (RTD) literally stands for

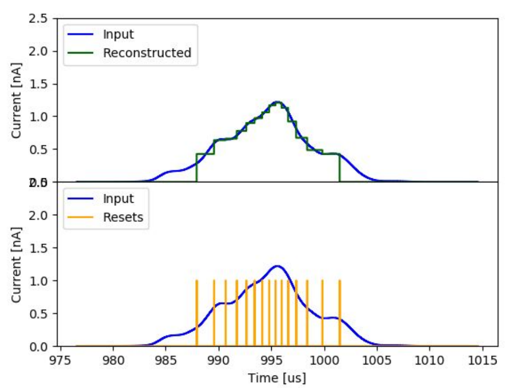
$$RTD = \frac{\Delta Q}{\Delta t} = j(t) \quad (6)$$

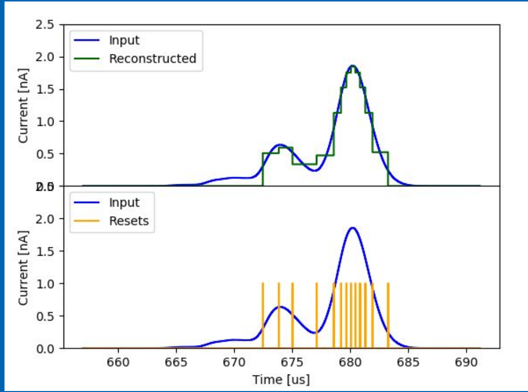
Thus if we plot the average RTD seen over a sample as a function of the drift distance, we should see the Gaussian relationship

Physics Simulation

- **Measurement of Longitudinal Diffusion**
  - The average RTD versus the drift length yields a distribution which carries the diffusion information along with it
  - Allows for a fundamental measurement with few statistics
- **$D_L^{Measured} = 6.47 \pm 0.97\ cm^2/s$**
  - $D_L^{Simulation} = 6.82\ cm^2/s$

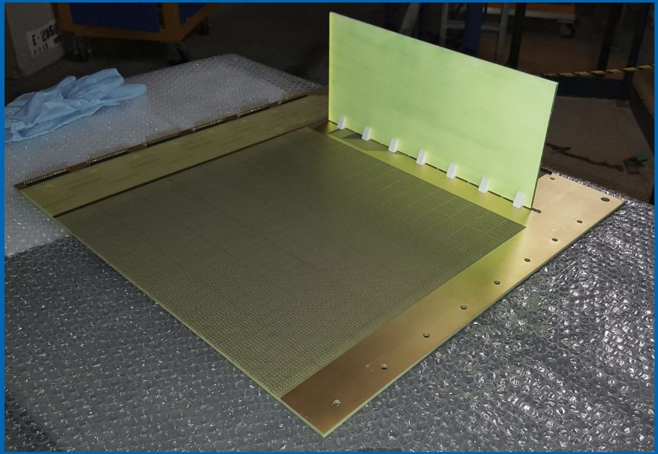






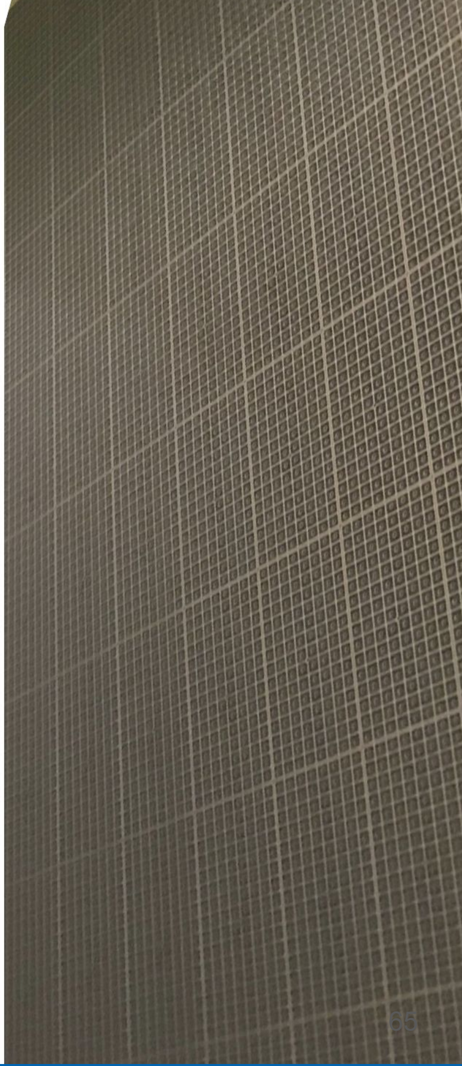
Light Detection

- **Conventional LArTPC's use the semi-transparent wires to their advantage and place their photon detectors behind the wire planes**
- **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?**



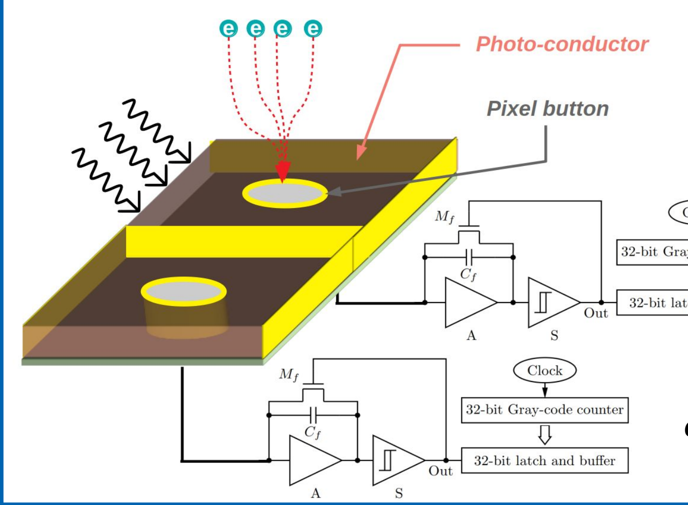
Pixels which also are photo-sensitive?

- **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



Light Detection

- **One very "blue sky" idea currently being considered is to see if the same pixels which collect ionization charge can be used to detect UV photons**



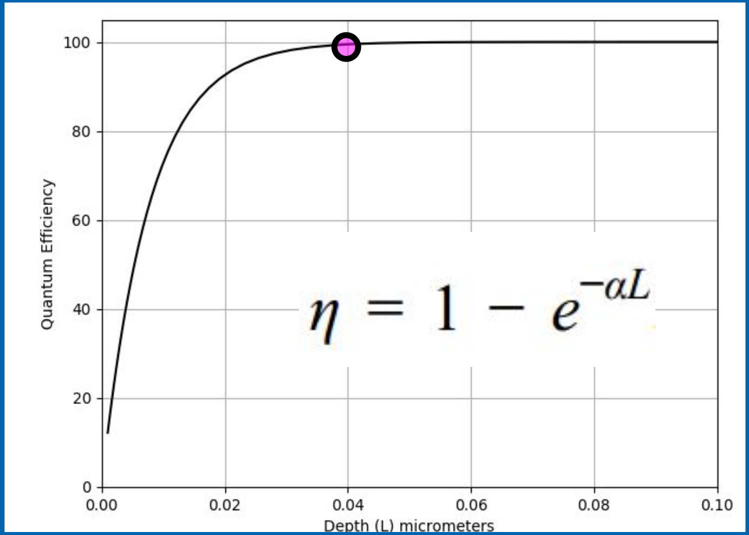
Conceptual sketch of device

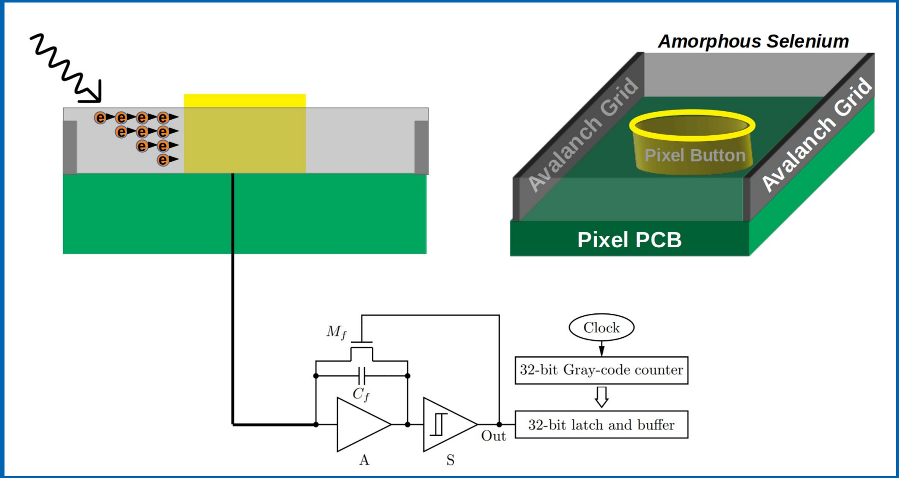
  - **Currently exploring different thin-film photo-conductors which may offer an opportunity**
    - Exploring amorphous Selenium's properties
      - Commonly used in X-Ray digital radiography devices
    - Recently became very interested in Pyroelectric Photodetectors
      - "Pyro-Phototronic" devices seem very promising and have been operated in cryogenic environments very recently

- **If realized, offers a transformative opportunity in LArTPC's**

Amorphous Selenium

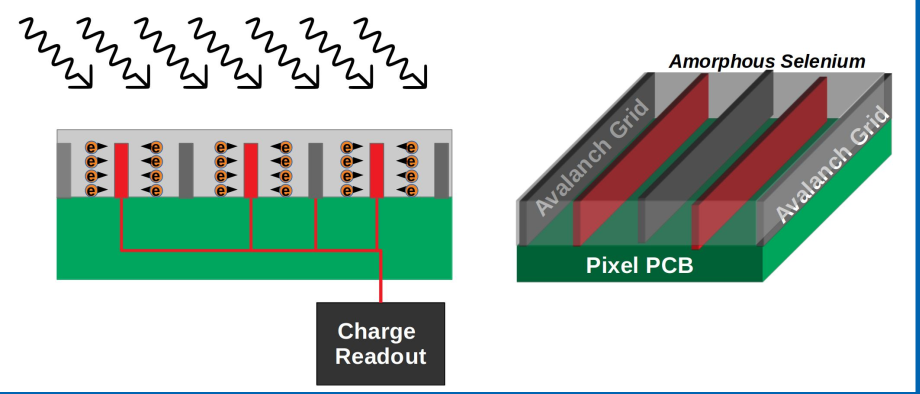
- **Literature search suggests the absorption coefficient for a-Se at 128nm is 130 μm^{-1}**
- **This would suggest a 1μm thick thin film would already be >99% QE for converting light to charge!**
- **Moreover, gain in the a-Se is possible with the application of moderate E-field**
  - Early calculations suggest $\mathcal{O}$(100) - $\mathcal{O}$(1000) electrons per pixel pad for $\mathcal{O}$(MeV) levels of activity



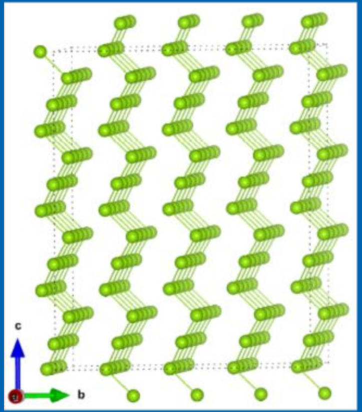


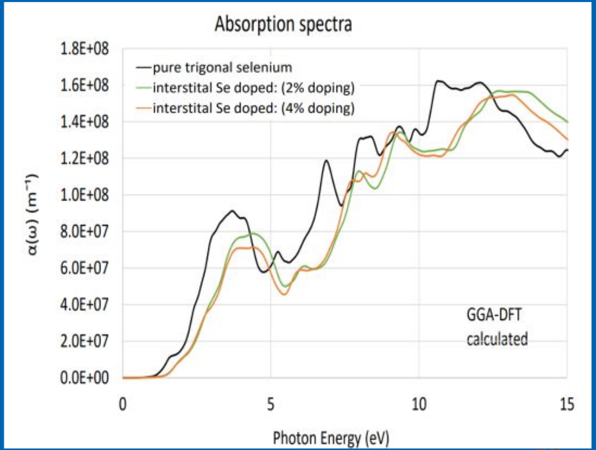
Amorphous Selenium

- **Prototype board's are being prepared at UTA to test the viability of this idea in liquid argon and with VUV light**
  - Partnered with E. Gramellini (FNAL) with an LDRD



- **Ongoing simulation work from UTA condensed matter theorist will help us understand alternative doping methods and opto-electronic properties to optimize for**



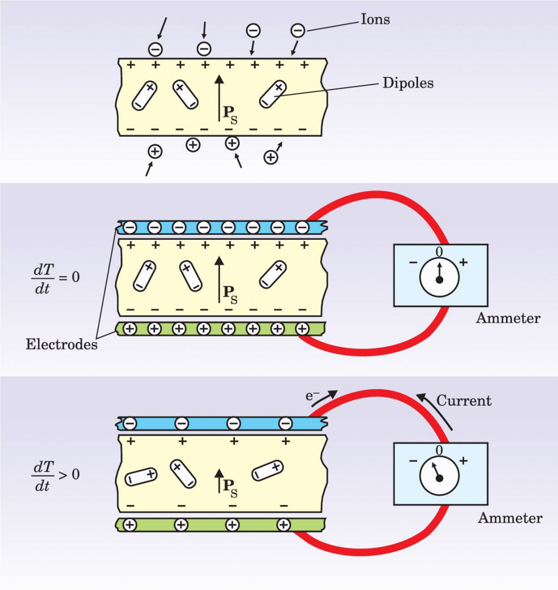


Pyroelectric Photodetectors

Effect originates from the spontaneous polarization of the material (e.g. PZT, CdS, and ZnO) that, in the absence of an electric field, lead to surface charges within the material

External surface will capture free charges from the environment in order to become electrically neutral

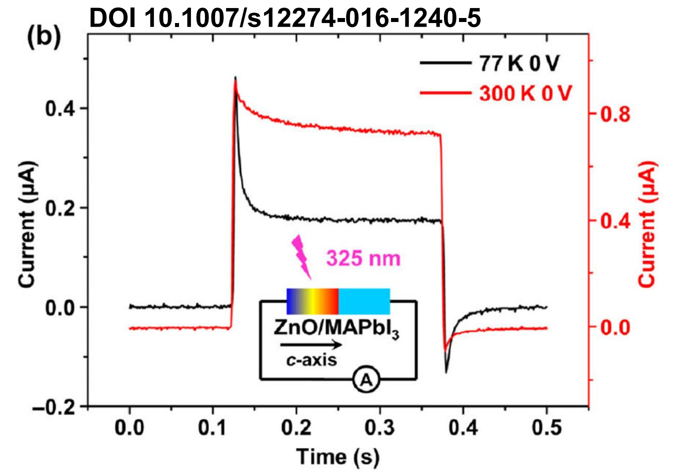
When the temperature of the material increases ``rapidily'' the spontaneous polarization decreases simultaneously. However, the charge captured on the surface typically has a low mobility which one can exploit to create a `pyroelectric current'

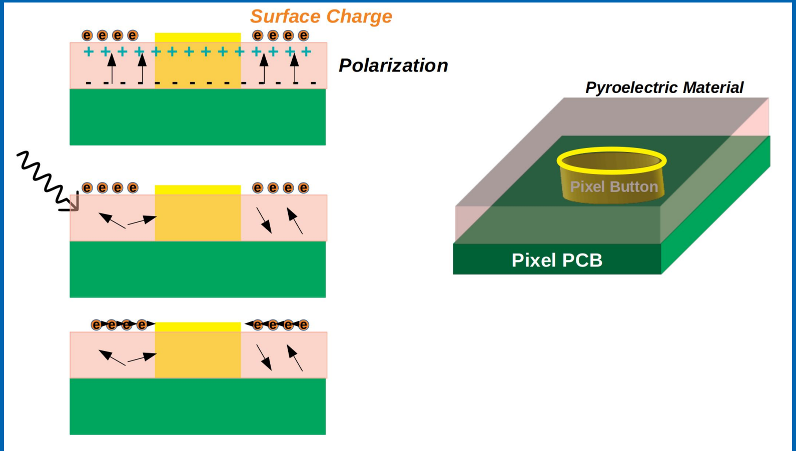


Pyroelectric Photodetectors

- These materials have seen a lot of advancement in recent years towards becoming photodetectors
  - Thanks to Alex (ANL) for bringing these devices to our attention
- Many recent advancements include:
  - Tests in cryogenic environments exposed to UV light (325nm)
  - Improved response times to the 10-100 of ns timescales
  - Integration into CMOS device
- Offers another interesting opportunity!

DOI 10.1007/s12274-016-1240-5





Conclusions

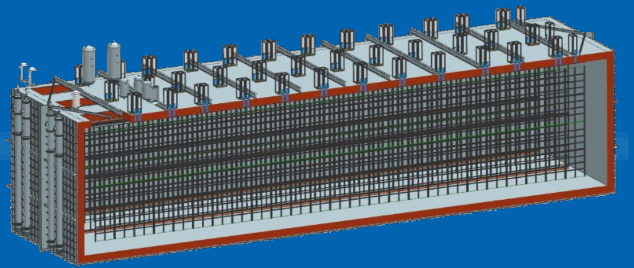
- Readout requirements for kiloton scale LArTPC's offer many challenges to fully exploit the rich data they have to offer
  - We must optimize for discovery!!!
- Low threshold pixel based readout can optimize for discovery the impact of these detectors
  - Requires an unorthodox solution
- The Q-Pix concept may afford a way to pixelize a kiloton scale LArTPC and retain all the details of data
  - The devil lives in the details, but an effort is underway with promising preliminary results
  - Stay tuned for more updates!

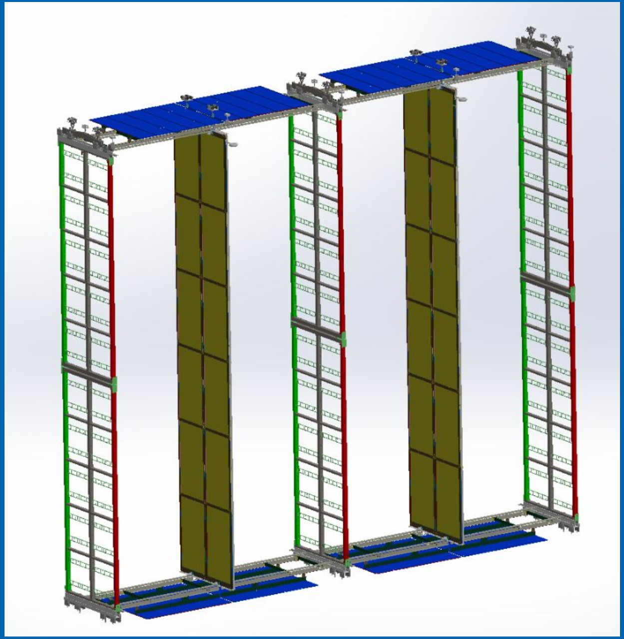
Q-Pix consortium would like the thank the DOE for its support via DE-SC0020065 award

Backup Slides

Current light collection designs

- **Limited real estate for Light Collection System in the wire planes**
- **How much of the available APA has photon detection capability?**
  - X-Arapuca Design: 130 m^2/10kT
    - **Window area for each supercell (435.24 cm^2) x 10 supercells/APA x 152 APA's per 10kT x 2 (Double sided)**
  - APA Active Area: ~200,000 m^2/ 10kT
    - (135,700 cm2) * 152 APAs/10kT
- **Surface area instrumented is ~ 0.06%**
  - Actually less when you take efficiency of the device into account





****** *Not meant to disparage the current technology in any way...instead meant to give context to the problem***

Electron - Hole Pair creation

The minimum amount of energy absorbed by the incident radiation that is needed to create a single EHP is termed EHP creation energy $W_{0\pm}$ and determines the intrinsic sensitivity of the material used as a radiation detection medium. $W_{0\pm}$ is also called the ionization energy of the medium. The photogeneration efficiency η can be redefined as the fraction of EHPs which do not recombine relative to all EHPs created by an incident photon. The latter definition is better suited for a photogeneration process initiated by an x-ray or a gamma-ray (thousands of EHP created by a single photon).

The average energy $W_{\pm}$ per freed EHP (EHP that escapes recombination and can be potentially successfully collected) is given by

$$W_{\pm} = \frac{W_{0\pm}}{\eta}. \qquad (2.9)$$

Taken from thesis: ELECTRICAL PROPERTIES OF AMORPHOUS SELENIUM BASED PHOTOCONDUCTIVE DEVICES FOR APPLICATION IN X-RAY IMAGE DETECTORS GUEORGUI STOEV BELEV 2007

The amount of energy ΔE absorbed by the material from the radiation and the electric charge ΔQ that can be are related by the quantity $W_{\pm}$ through

$$\Delta Q = q\frac{\Delta E}{W_{\pm}}, \tag{2.10}$$

where q is the charge of the electron.

Typically $W_{0\pm}$ increases with the bandgap E_g of the photoconductor and for crystalline semiconductors it follows the Klein rule [81]

$$W_{0\pm} \approx 2.8\,E_g + \varepsilon_{\text{phonons}}, \tag{2.11}$$

where $\varepsilon_{\text{phonons}}$ is a phonon energy term that involves multiple phonons. For amorphous semiconductors as suggested by Que and Rowlands [82], the relaxation of conservation of momentum rule leads to

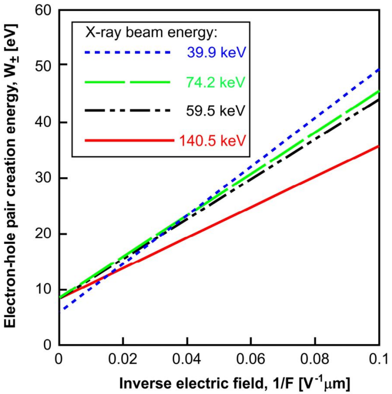
$$W_{0\pm} \approx 2.2\,E_g + \varepsilon_{\text{phonons}}. \tag{2.12}$$

Taken from thesis: ELECTRICAL PROPERTIES OF AMORPHOUS SELENIUM BASED PHOTOCONDUCTIVE DEVICES FOR APPLICATION IN X-RAY IMAGE DETECTORS GUEORGUI STOEV BELEV 2007

However, $W_{\pm}$ in a-Se, as in a number of other low-mobility solids, depends both on the applied field F and energy E of the incident photons because the photogeneration efficiency η supposedly depends on both of these quantities. There have been numerous experiments, with a wide range of conflicting results devoted to measuring $W_{\pm}$ in a-Se as a function of applied electric field and the energy of the incident photons. One of the most recent and most detailed experimental works is due to Blevis et al. [83]. In the latter work the authors have used various monoenergetic photon sources and have clearly shown that $W_{\pm}$ depends on both energy of the incident photons and on the applied electric field across the a-Se layer. However, even that set of experimental data is not complete because the dependence of $W_{\pm}$ on temperature has not been investigated.

[83] I. Blevis, D. Hunt, J. Rowlands, "Measurement of x-ray photogeneration in amorphous
selenium", Journal of Applied Physics, 85, pp. 7958-7963, 1999
Need this reference!

The usual way to find $W_{0\pm}$ from $W_\pm$ versus electric field F data is to extrapolate to infinite electric field plotting $W_\pm$ vs $1/F$. Part of the data of Blevis et al. [83] replotted in that way is presented in Figure 2.11. Although the lines corresponding to different x-ray photon energies have different slopes they all converge to $W_{0\pm}$ in the range 6-8 eV and that value is relatively independent from the energy of the incident photons. Previous measurements by Kasap and coworkers have resulted in $W_{0\pm} \approx 6\,\text{eV}$ for x-ray beams with average energies in the range of 32-53 keV [84]. Application of Klein rule with $E_g = 2.22$ eV and $0.5\,\text{eV} \le \varepsilon_{\text{phonons}} \le 1.0\,\text{eV}$ (the latter taken from [81]) gives $6.71\,\text{eV} \le W_{0\pm} \le 7.16\,\text{eV}$ whereas Que and Rowlands rule gives $5.38\,\text{eV} \le W_{0\pm} \le 5.89\,\text{eV}$. The scatter in the existing experimental data makes very difficult



$$\Delta Q = q\frac{\Delta E}{W_\pm}, \qquad W_\pm = \frac{W_{0\pm}}{\eta}.$$

So we'll assume W_{0+-} is 7 eV and the quantum efficiency is 99% giving W_{+-} = 7.07 eV

Amorphous Selenium as a UV-Photon Detector

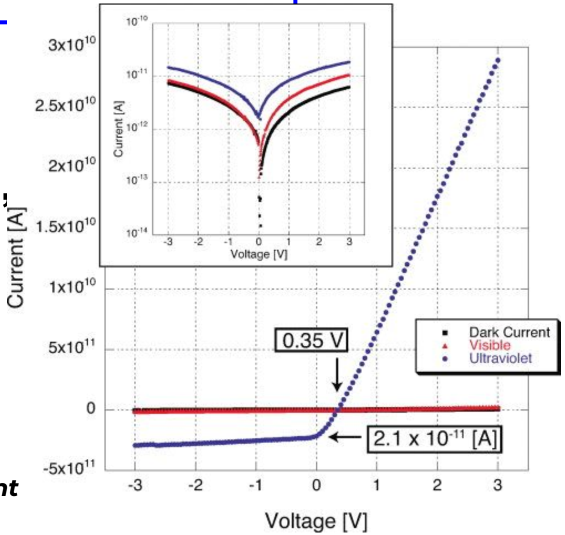
- **In the last 6'ish years there has even been some considerable development in using a-Se for direct photon detection in the UV range**

A transparent ultraviolet triggered amorphous selenium p-n junction

Appl. Phys. Lett. **98**, 152102 (2011); https://doi.org/10.1063/1.3579262

Ichitaro Saito[1, a)], Wataru Miyazaki[2], Masanori Onishi[2], Yuki Kudo[3], Tomoaki Masuzawa[2], Takatoshi Yamada[4], Angel Koh[5], Daniel Chua[5], Kenichi Soga[1], Mauro Overend[1], Masami Aono[6], Gehan A. J. Amaratunga[1], *and* Ken Okano[2]

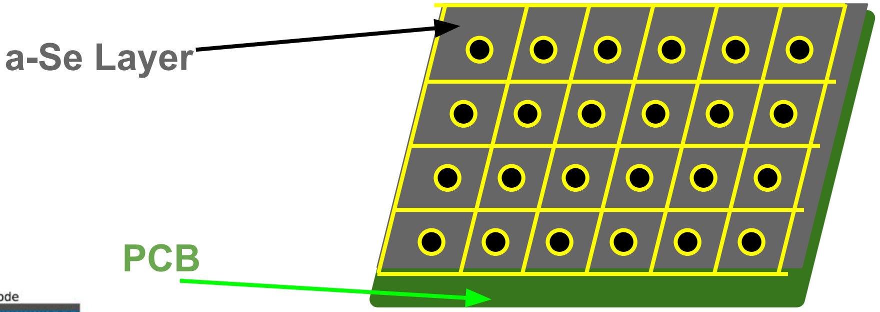
- **This paper even reports "**an amorphous selenium (a-Se) film p-n junction fabricated through an inexpensive and simple process of thermal evaporation and electrolysis**"**
  - Looking at light using a D2 lamp (100 - 400 nm) with an irradiance of ~3 mW/m^2 at 254 nm

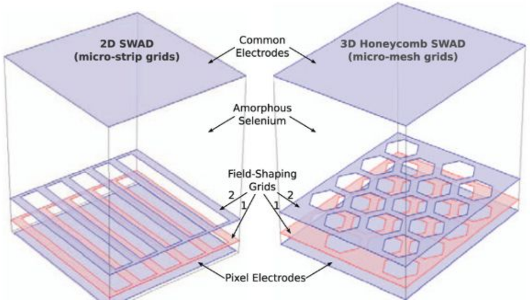


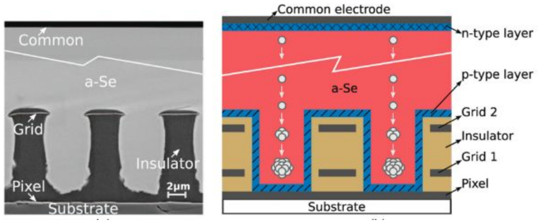
I-V characteristics of the dark current, photocurrent in the visible range, and the photocurrent of in the UV range. The inset is the semilog plot of the I-V characteristics before electrolysis.

Amorphous Selenium for Q-Pix

- **Some open thoughts I have:**
  - This looks promising if you could use a cheap method of fabrication and adherence of a thin film of doped a-Se to a PCB board that would allow for electron to be liberated and guided to a pixel button.
  - Could use field shaping electrodes and grounded (biased?) pixel buttons
    - Question about the necessary field for good detection that I am still trying to work out (some of the reading seems to suggest ~V/μm...which seems hard)
  - There is also literature suggesting with a little engineering you can achieve avalanche in these detectors (see paper here) around 80 V/μm increasing the viability of this as a photon detector





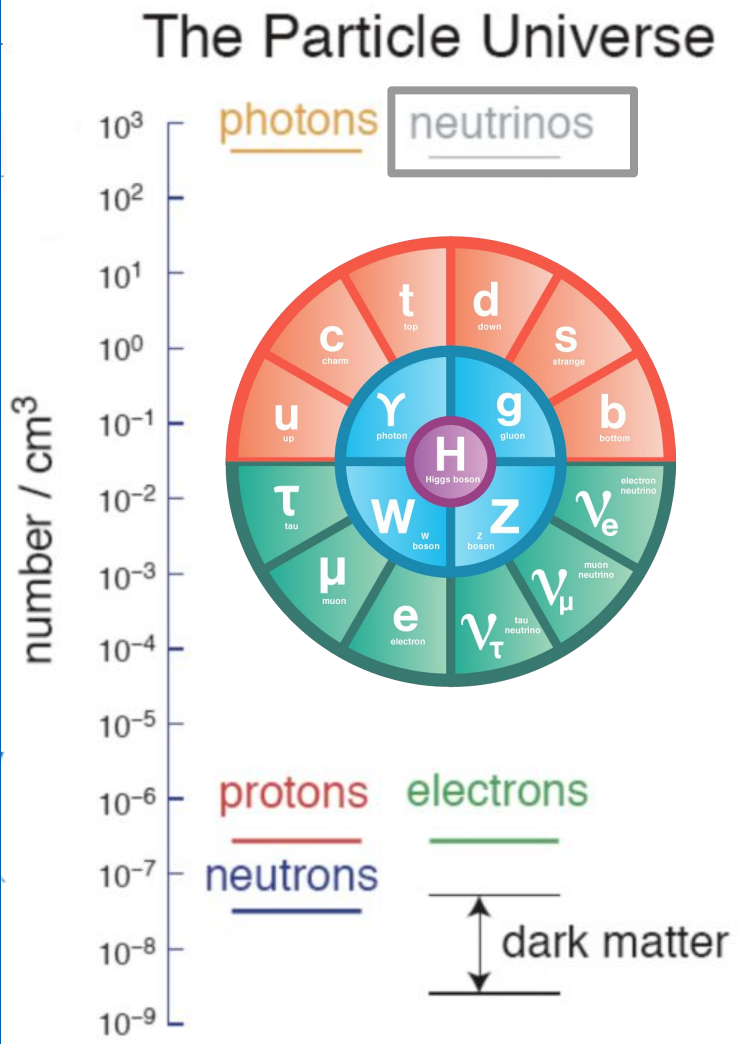


Amorphous Selenium for Q-Pix

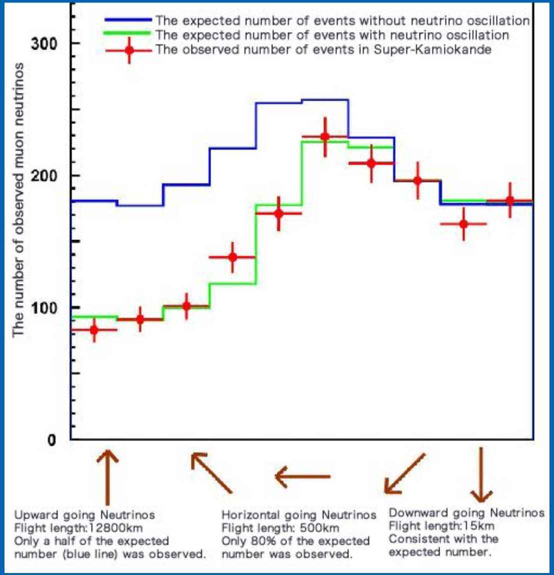
- Things look interesting enough (to me) that myself and a student are going to spend some amount of brain/simulation time trying to come up with a realistic model of what we would expect to see from scintillation light in liquid argon
- I've identified a few commercial companies to talk to about manufacturing, samples, doping, adhesion, etc
    - e.g. Hologic Inc., Varex, Canon, etc...
- Any input into what we should be thinking about, trying to calculate, and model is greatly appreciated! (any additional collaboration is also welcome!)
- Some relevant papers
    - Useful thesis with solid state theory for a-Se
    - 2013 historical review of a-Se photon detectors
    - UV (200 - 400 nm) a-Se detector
    - VUV (100 - 400 nm) a-Se detector
    - Field shaping multi-well avalanche a-Se detectors
    - MC method for photon counting in a-Se detectors

Introduction

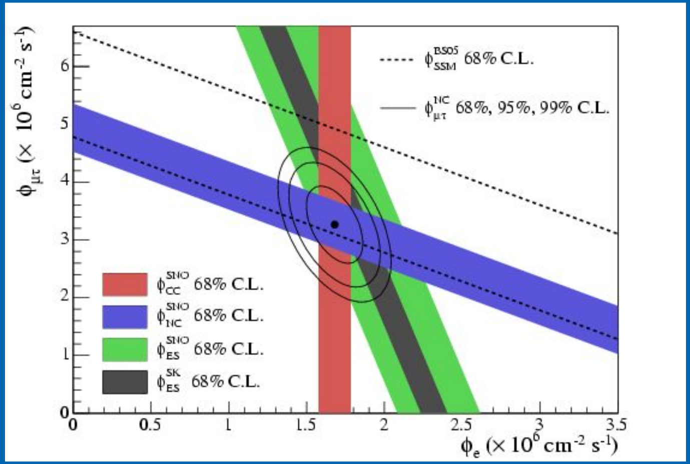
- **Neutrinos are among a handful of known fundamental particles**
  - The most abundant massive particle in the universe (They are everywhere!)
- **Despite their abundance, they are very difficult to detect**
  - Only interact via the weak nuclear force (which turns out to be very weak)
- **Neutrinos also change their flavor while propagating**
  - The simplest explanation is that neutrinos have distinct mass and mix



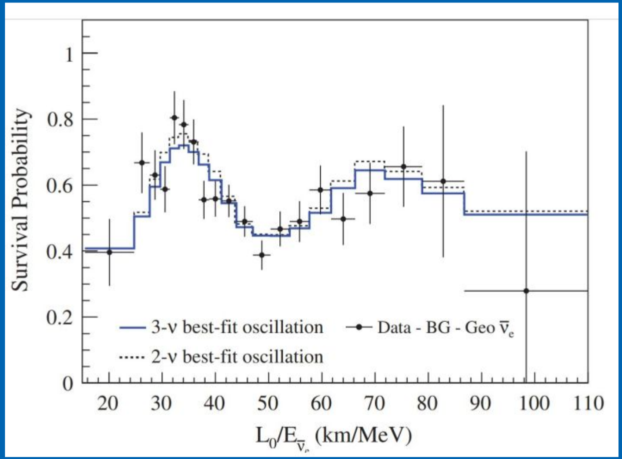
Neutrino Oscillation Physics



Atmospheric Neutrinos



Solar Neutrinos



Reactor Neutrinos

- **The phenomenon of neutrino oscillations is now decidedly established across multiple experimental probes**

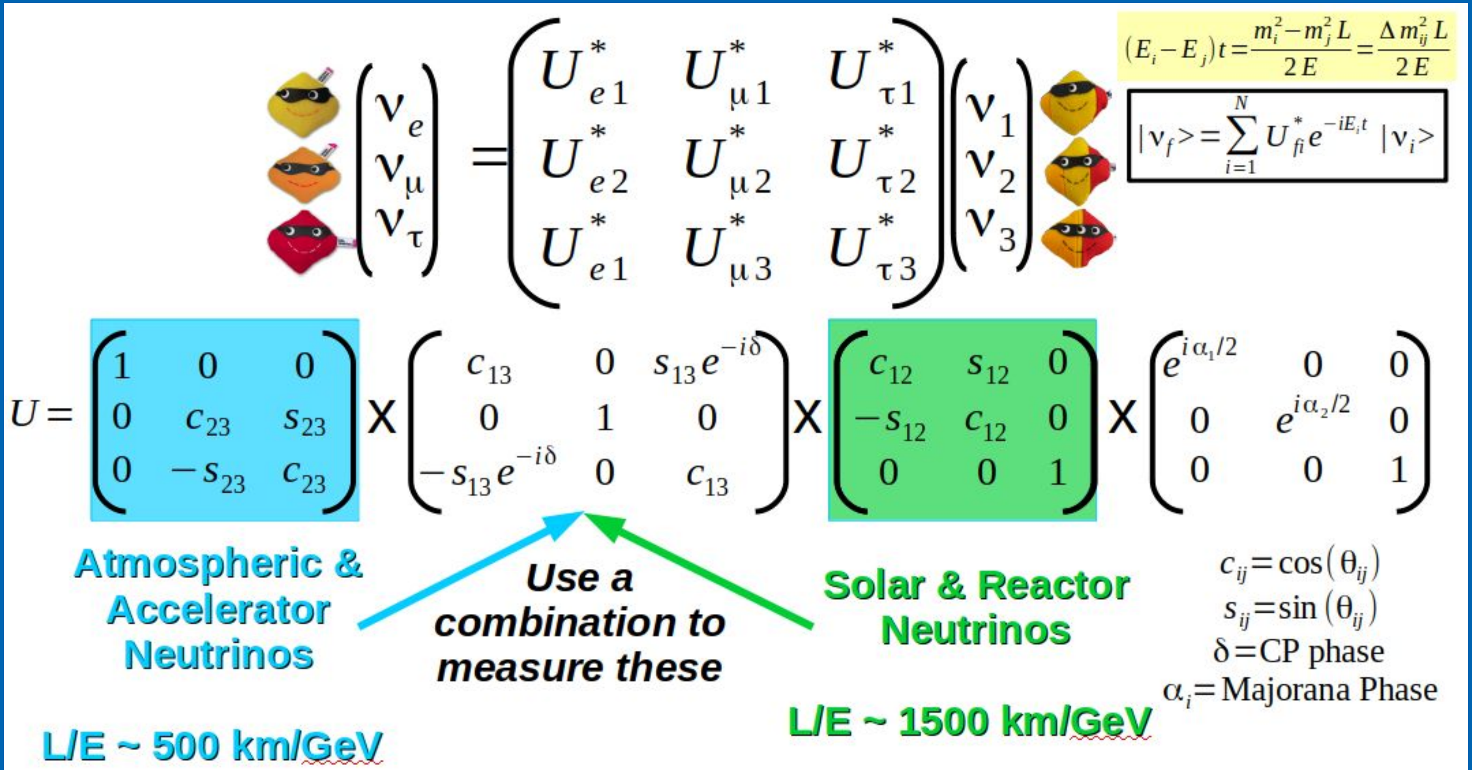
Neutrino Oscillation Physics

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{\mu 1} & U^*_{\tau 1} \\ U^*_{e2} & U^*_{\mu 2} & U^*_{\tau 2} \\ U^*_{e1} & U^*_{\mu 3} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$|\nu_f> = \sum_{i=1}^{N} U^*_{fi} e^{-iE_i t} |\nu_i>$$

$$(E_i - E_j)t = \frac{m_i^2 - m_j^2 L}{2E} = \frac{\Delta m_{ij}^2 L}{2E}$$

- Neutrino oscillations can be understood by relating the flavor states to the mass states via a unitary mixing matrix
- The time evolution of the states can be characterized in terms of mass difference, distance of propagation, and energy

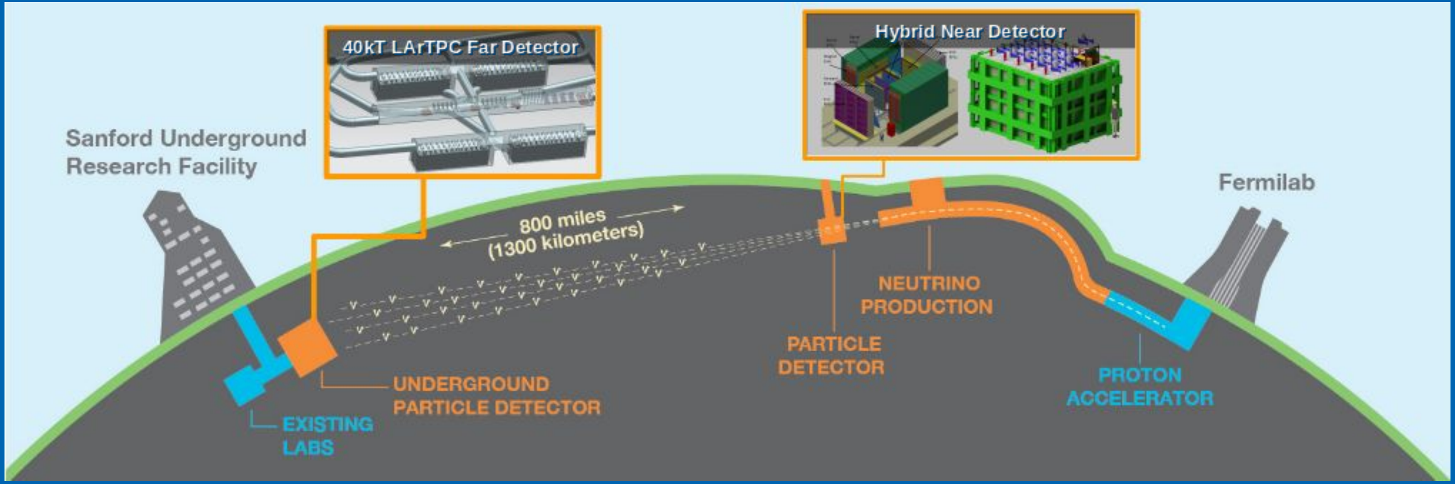


The mixing is described by three masses (m_1, m_2, m_3), three mixing angles (θ_{23}, θ_{12}, θ_{13}), a CP-phase (δ), and two Majorana phases (α_1, α_2)

Deep Underground Neutrino Experiment (DUNE)

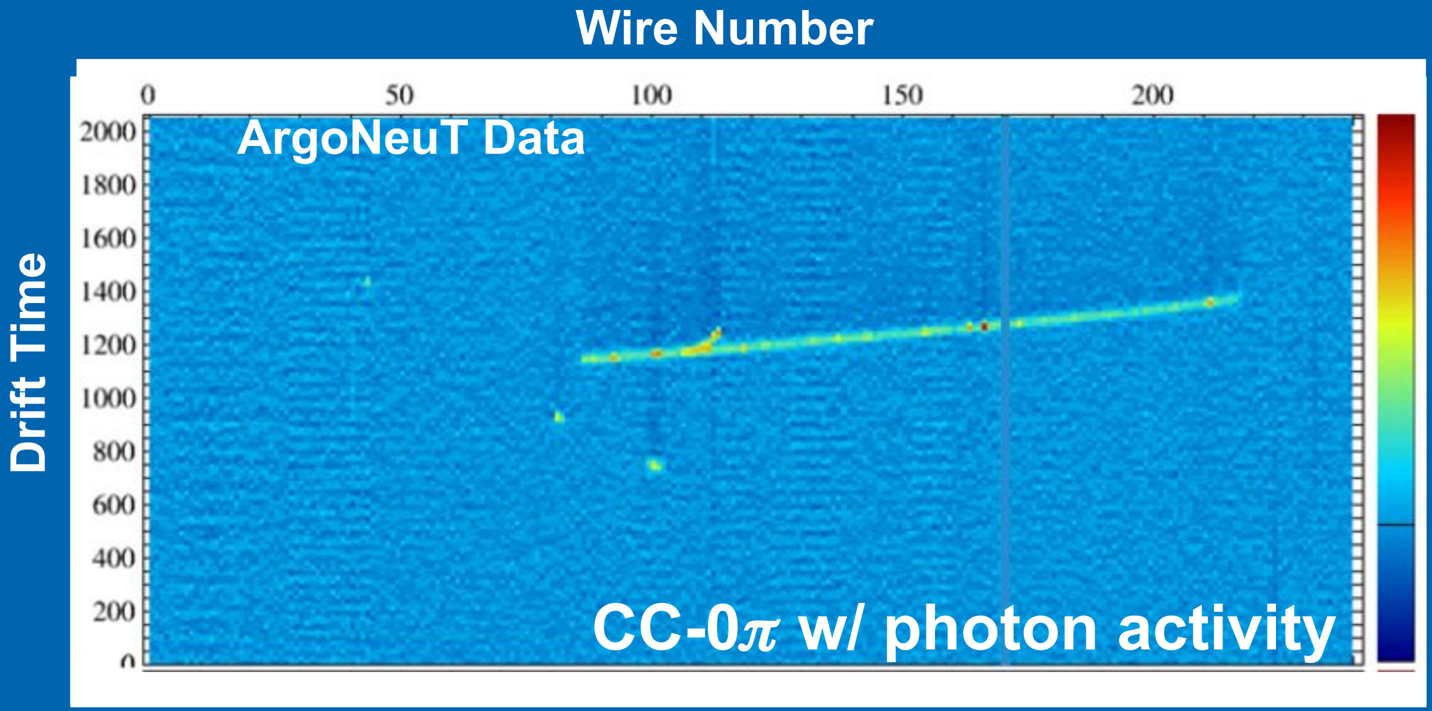
DUNE will be the premier long baseline neutrino experiment

- Multi-megawatt, high intensity, wide band neutrino beam produced at Fermilab directed towards the Sandford Underground Research Facility
- 40 kT (fiducial mass) LArTPC far detector
  - Four 10kT modules modules located at the 4850 level
- Highly capable neutrino near detector
  - Capable of fully characterize the spectrum and flavor composition of the beam



Introduction

- **Liquid Argon Time Projection Chambers (LArTPC's) offer access to very high quality and detailed information**



Introduction

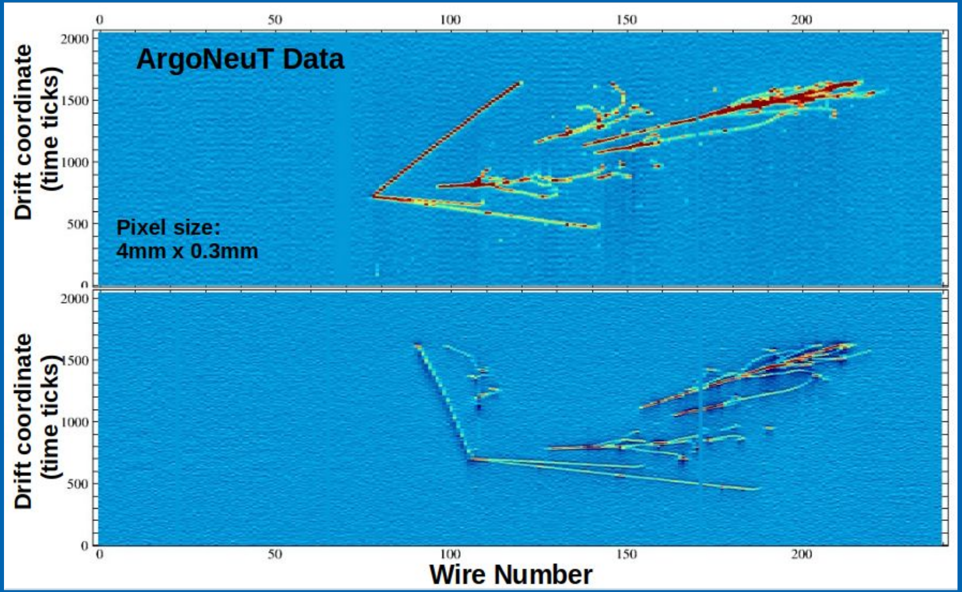
- **Leveraging this information allows unprecedented access to neutrino interaction specifics from MeV - GeV scales**

Drift Time

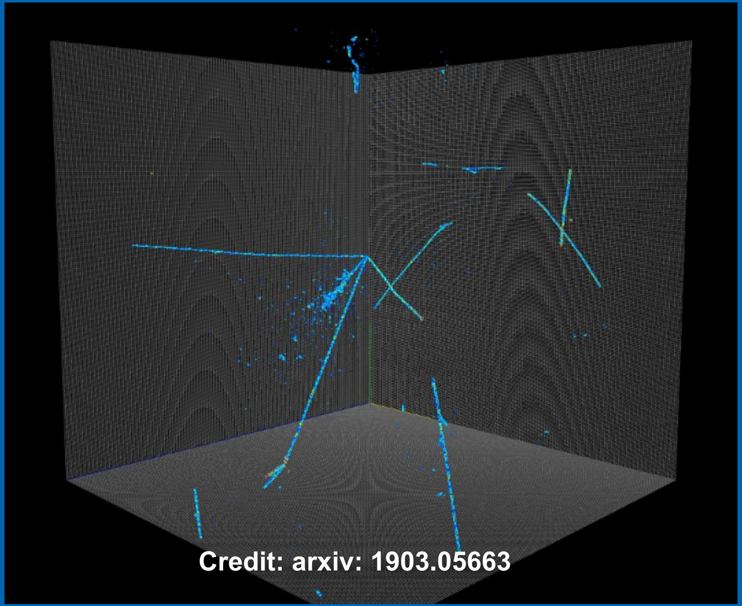
Wire Number

Introduction

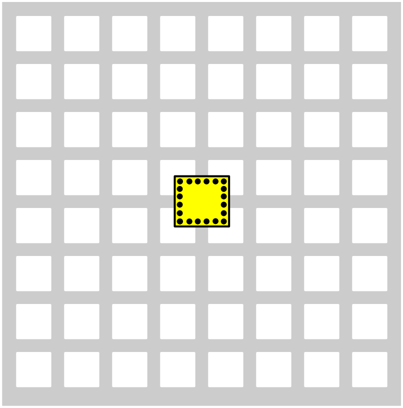
- **Capturing this data w/o compromise and maintaining the intrinsic 3-D quality is an essential component of all LArTPC readouts!**

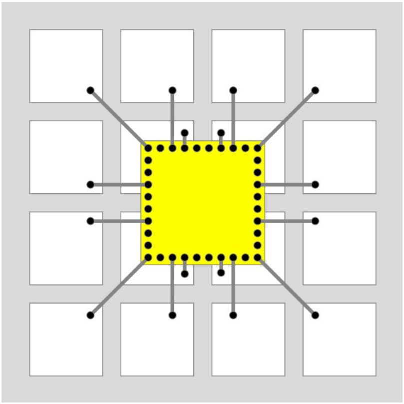


2D-Projective Readout



3D-Pixel Readout

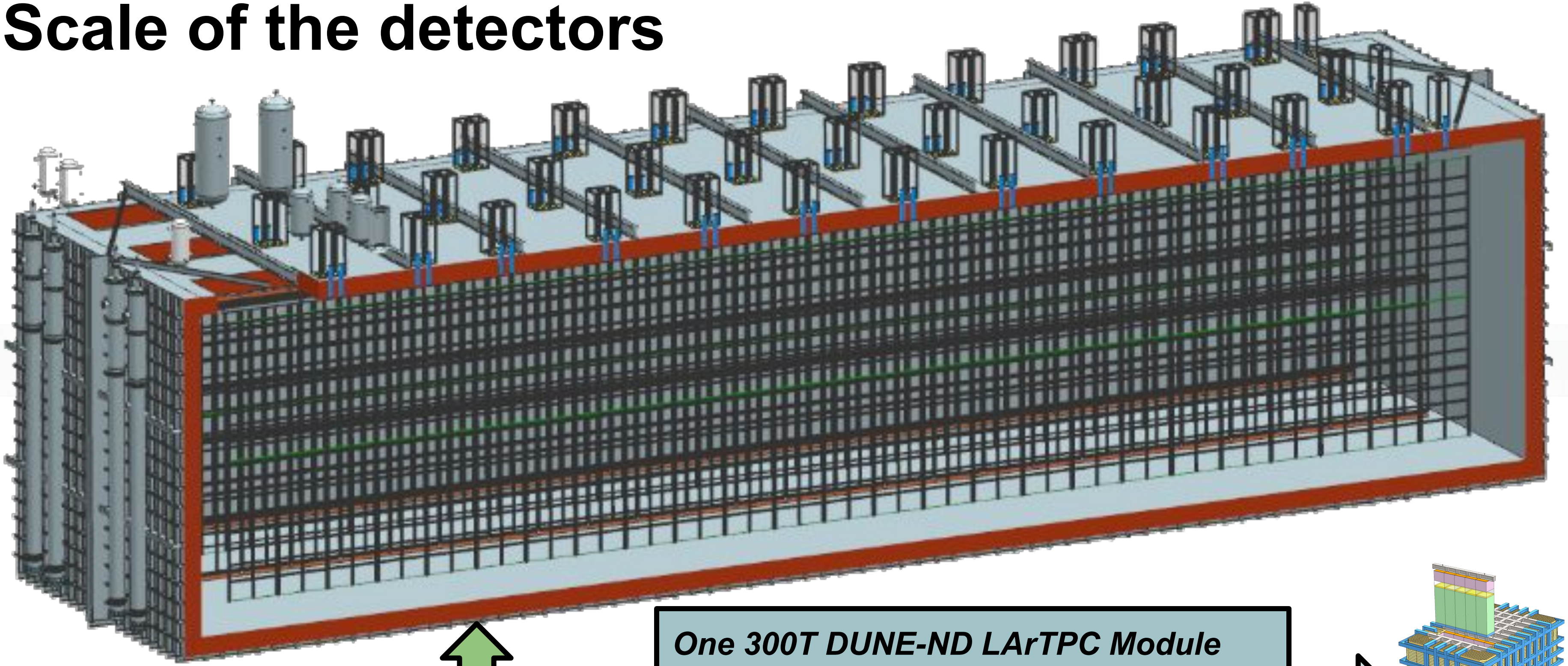




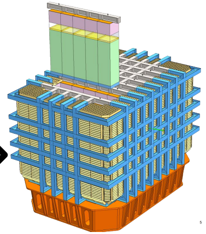
Point of the plot

- **Trying to show the number of events recorded by detector for assuming one year of fiducial mass**
  - Detector 1: DUNE Liquid Argon Near Detector (147 Tons of Argon)
  - Detector 2: DUNE Far Detector (10 kT of Argon)
- **DUNE has to be sensitive to a wide range of energies to do the physics it wants to do!**
  - The near detector is driven by the beam physics
  - The far detector has a really broad range of energies and more low energy things it wants to be sensitive to
- **Emphasize that the rates of the events in one year of data taking is very different between the near and far detector**
  - Every event in the far detector is precious!
  - Can come from a wide range of energies, topologies, and sources!

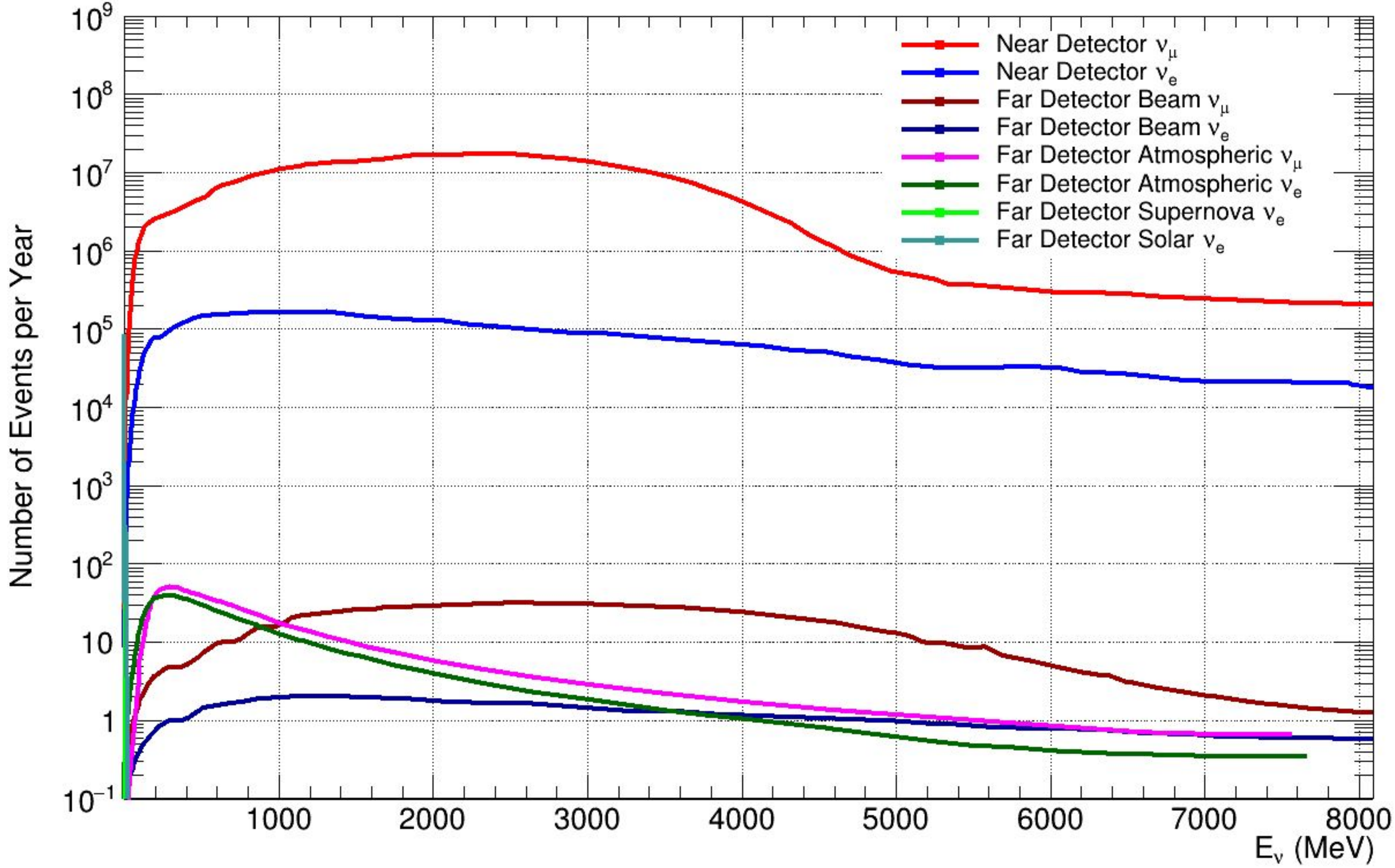
Scale of the detectors



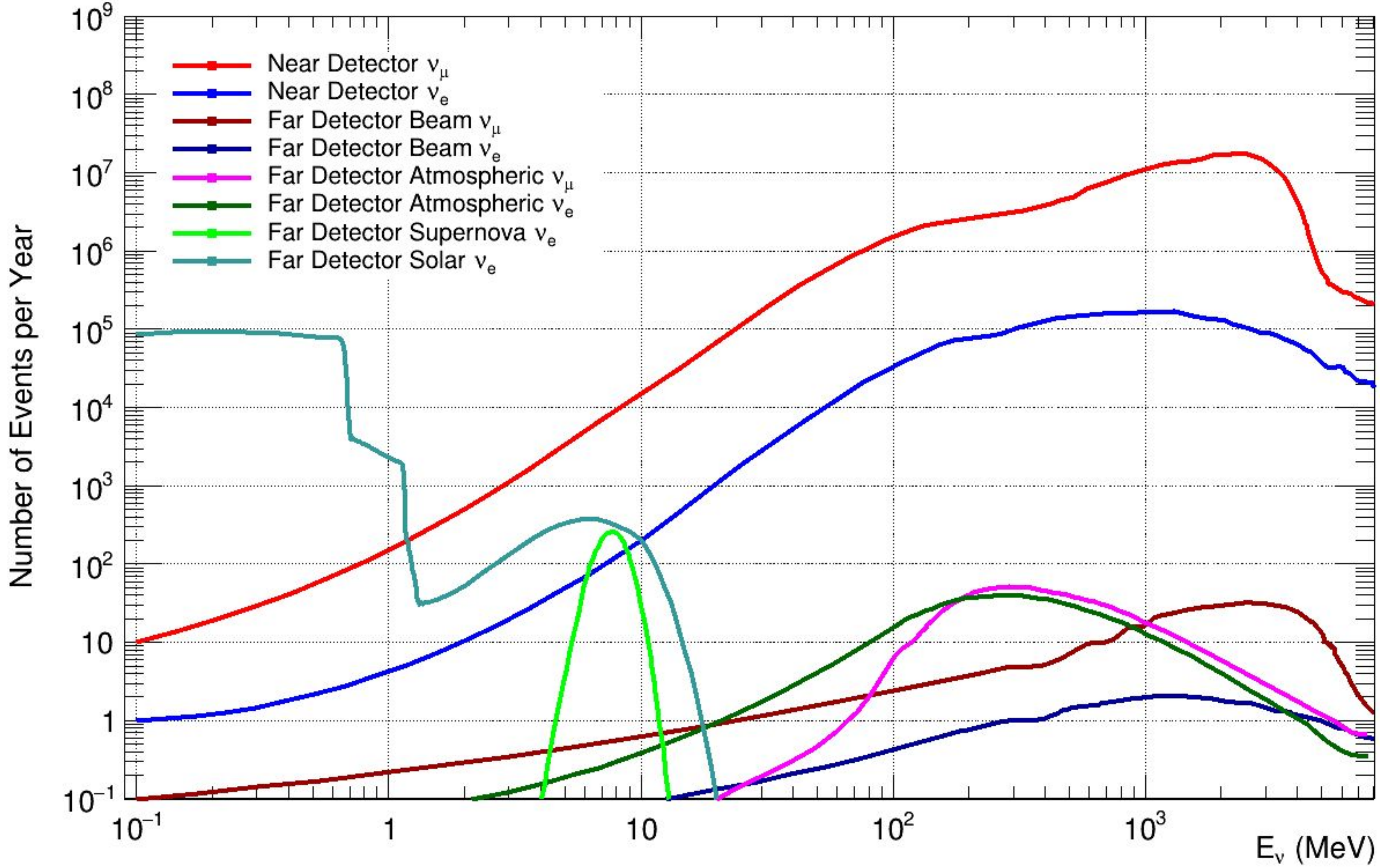
One 300T DUNE-ND LArTPC Module (11m x 8 m x 7 m)
⅓ of the DUNE Near Detector



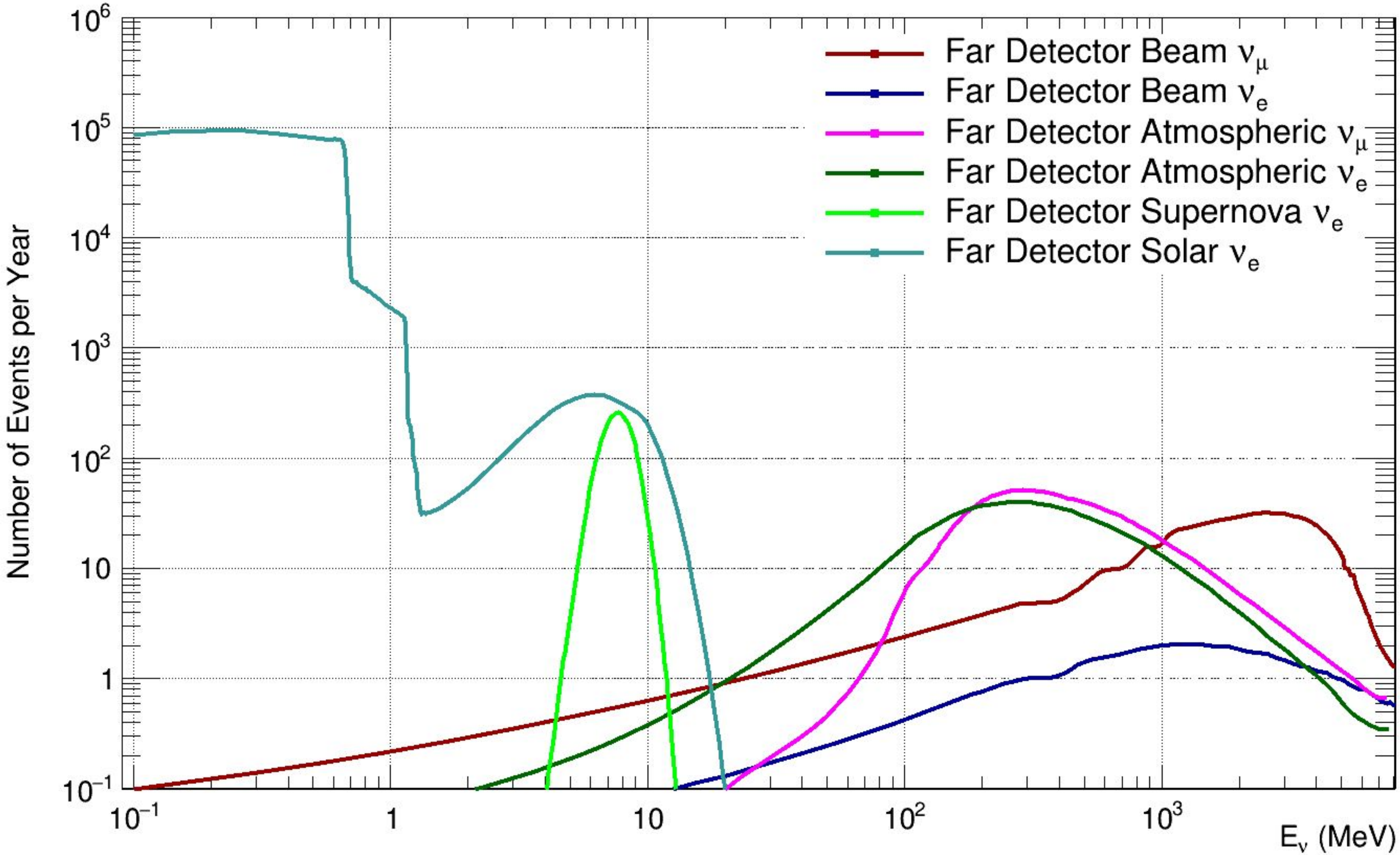
One 10kT DUNE LArTPC Module (18 m x 19 m x 66 m)
¼ the total size of DUNE



Everything h
in a linear x-a



Everything h... in a log x-axis



Just the detector

Amorphous Selenium for Q-Pix

- **Some open thoughts I have:**
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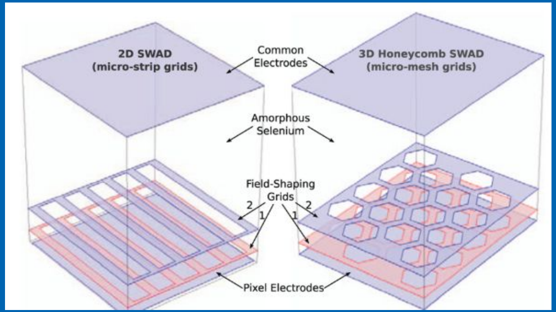
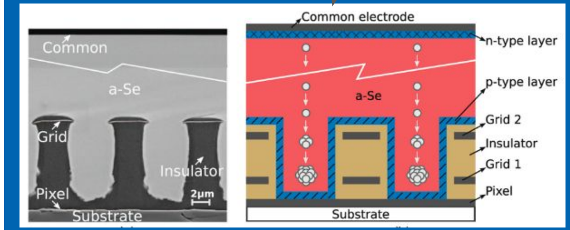
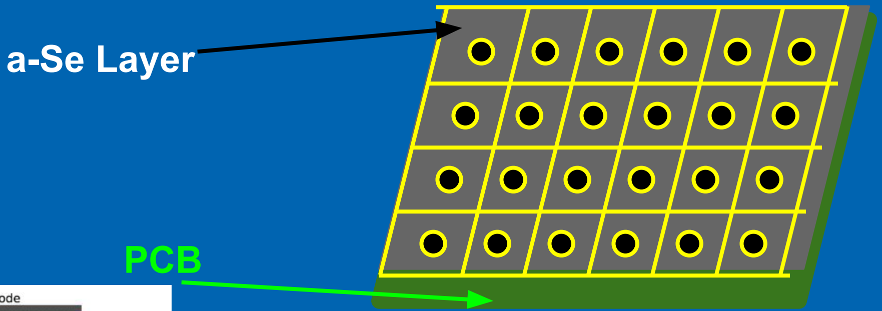
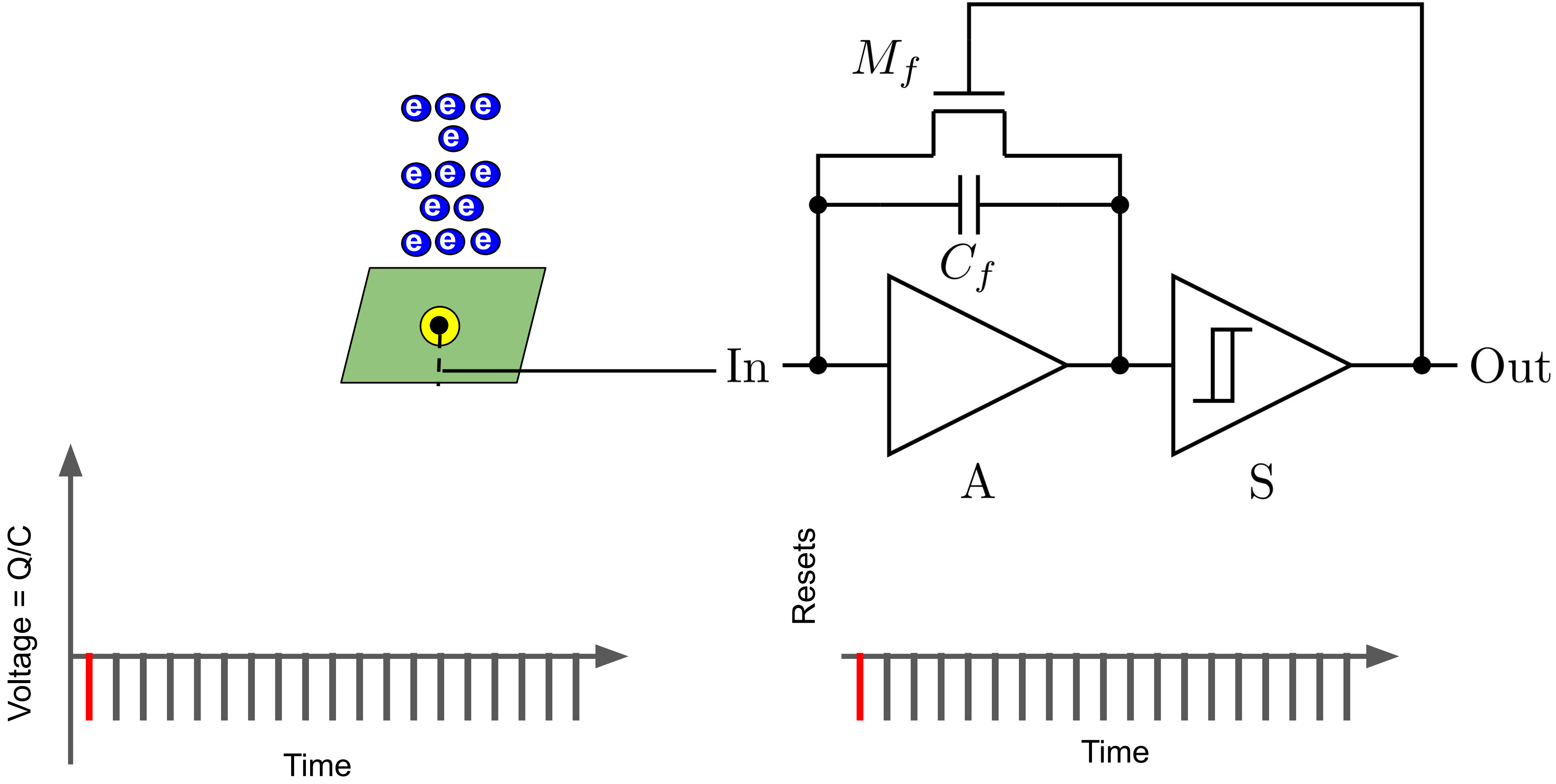
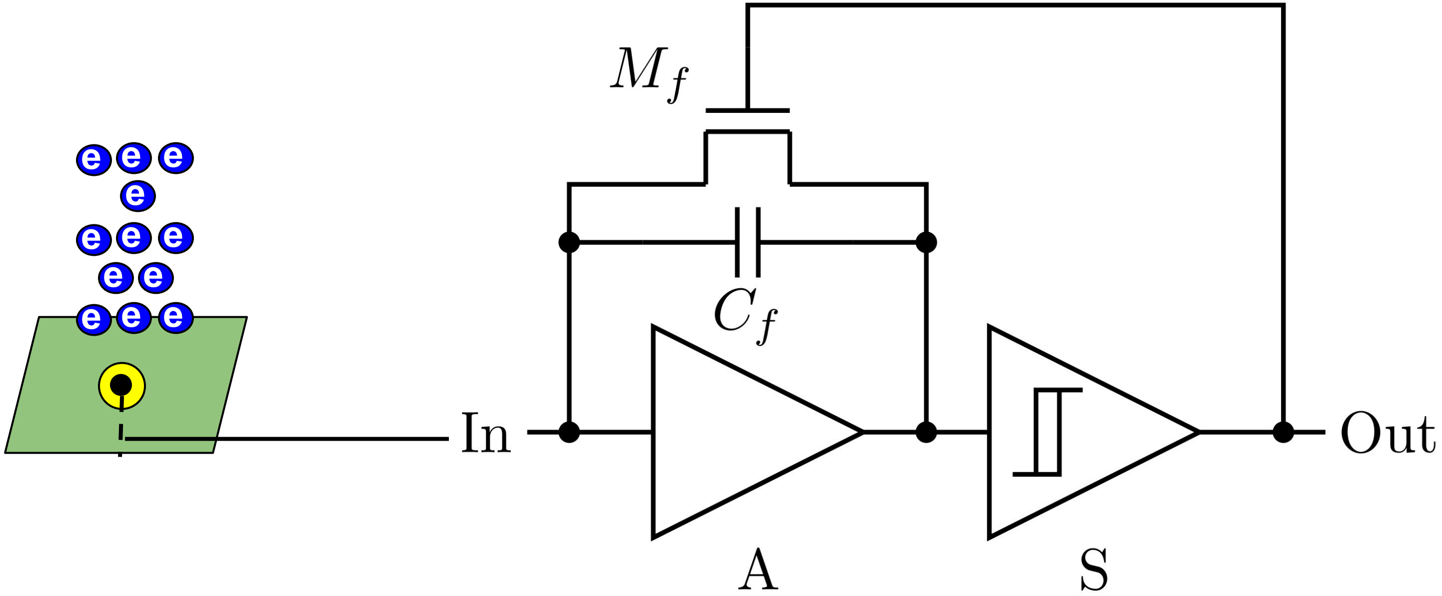


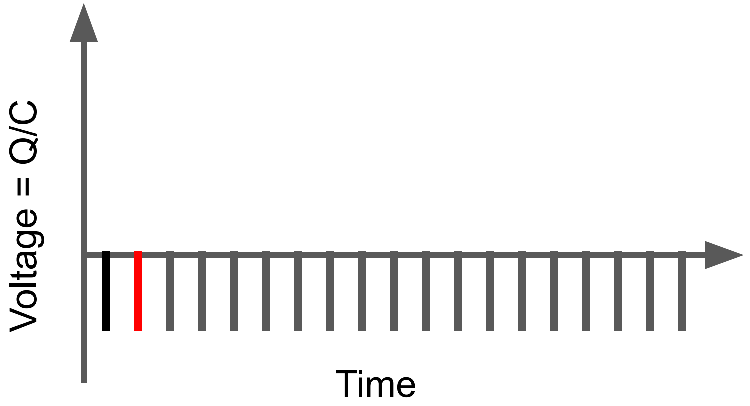


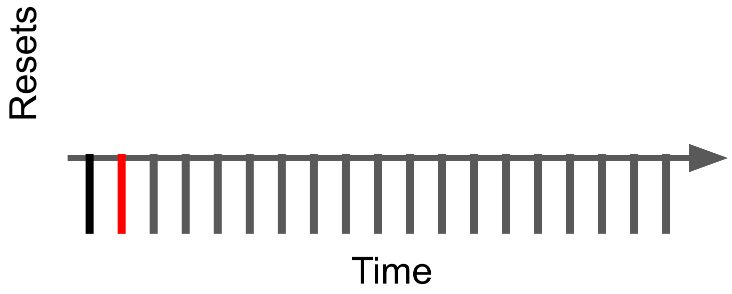




Note: We'll assume the RTD happens for 5 electrons, the reset happens faster than the drift of the next bunch, and this occurs without charge loss







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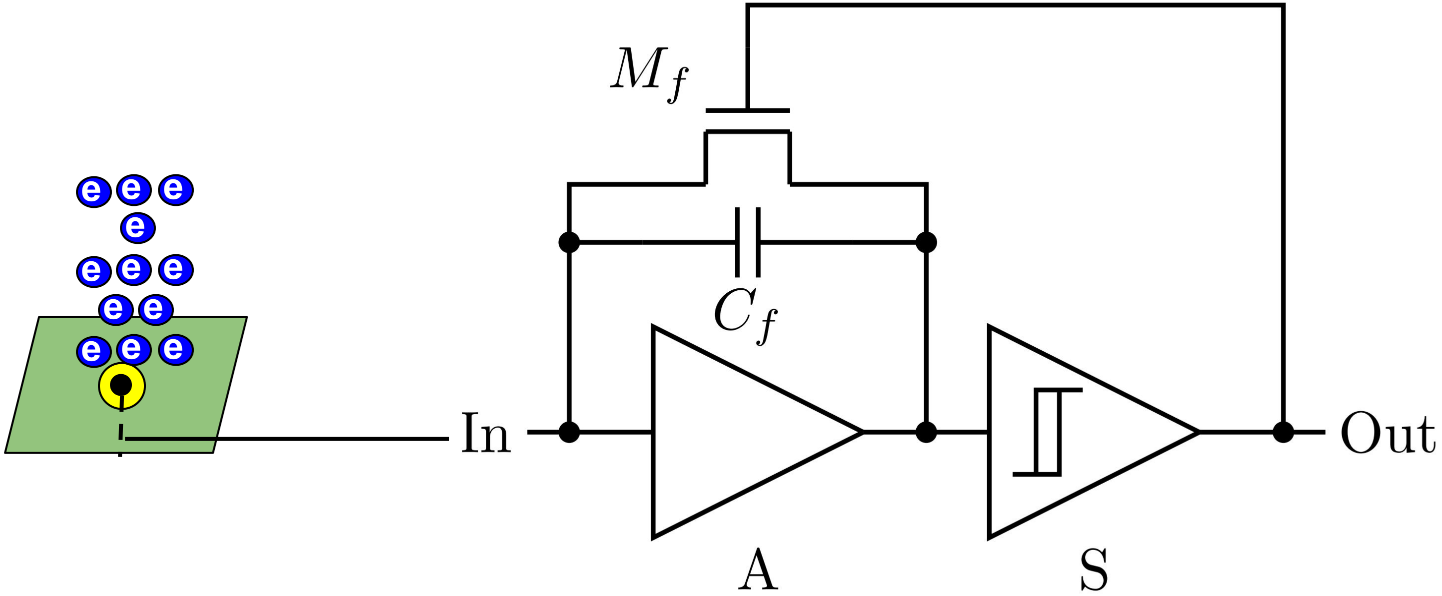
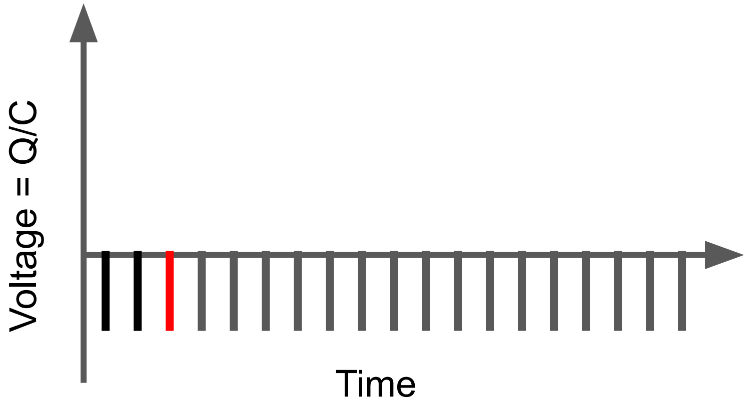
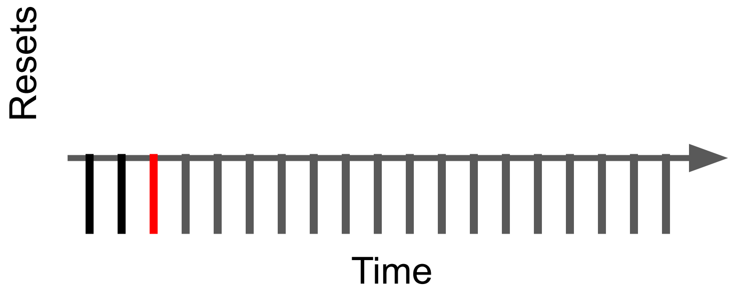
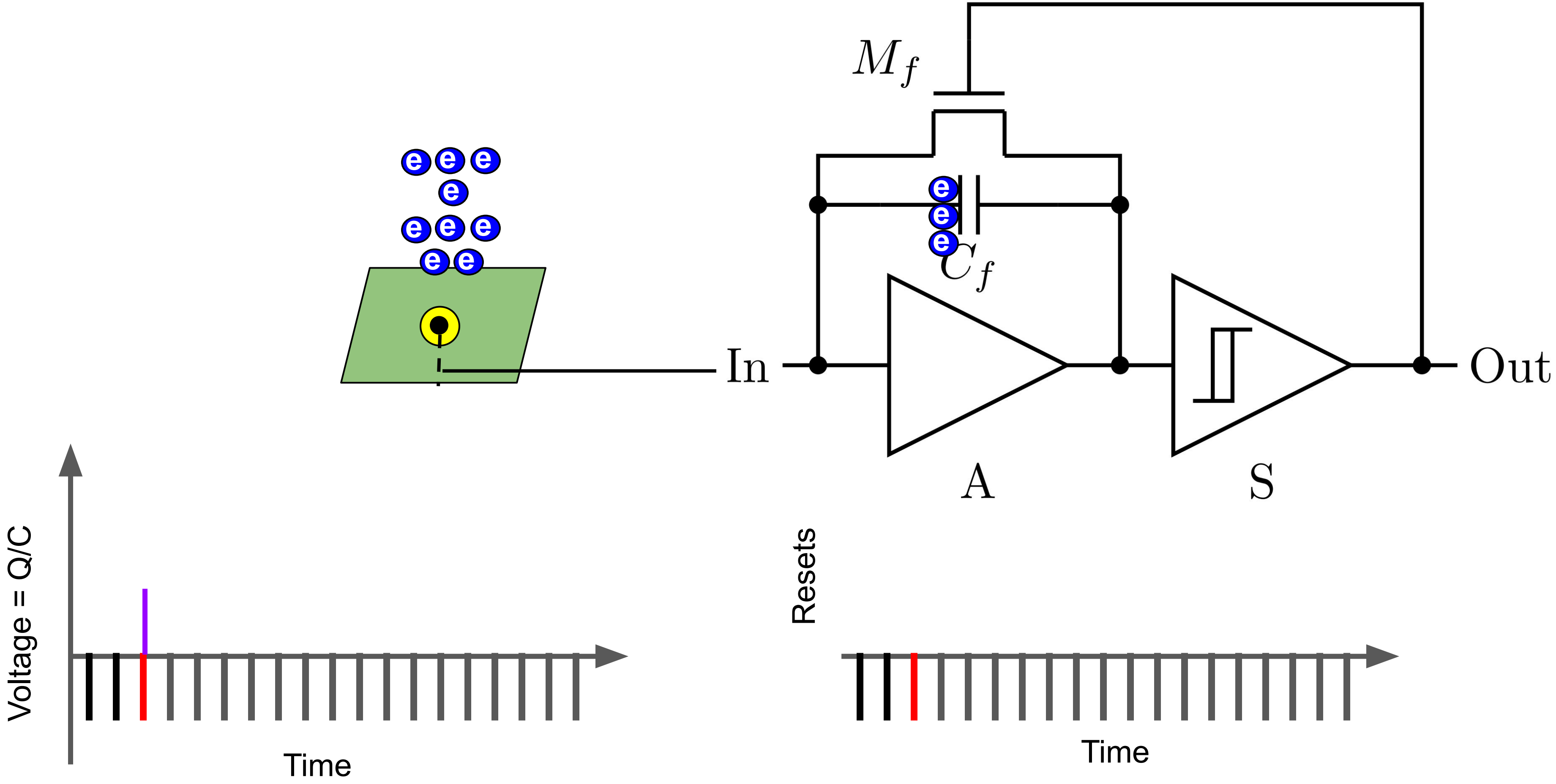






Note: We'll assume the RTD happens for 5 electrons, the reset happens faster than the drift of the next bunch, and this occurs without charge loss



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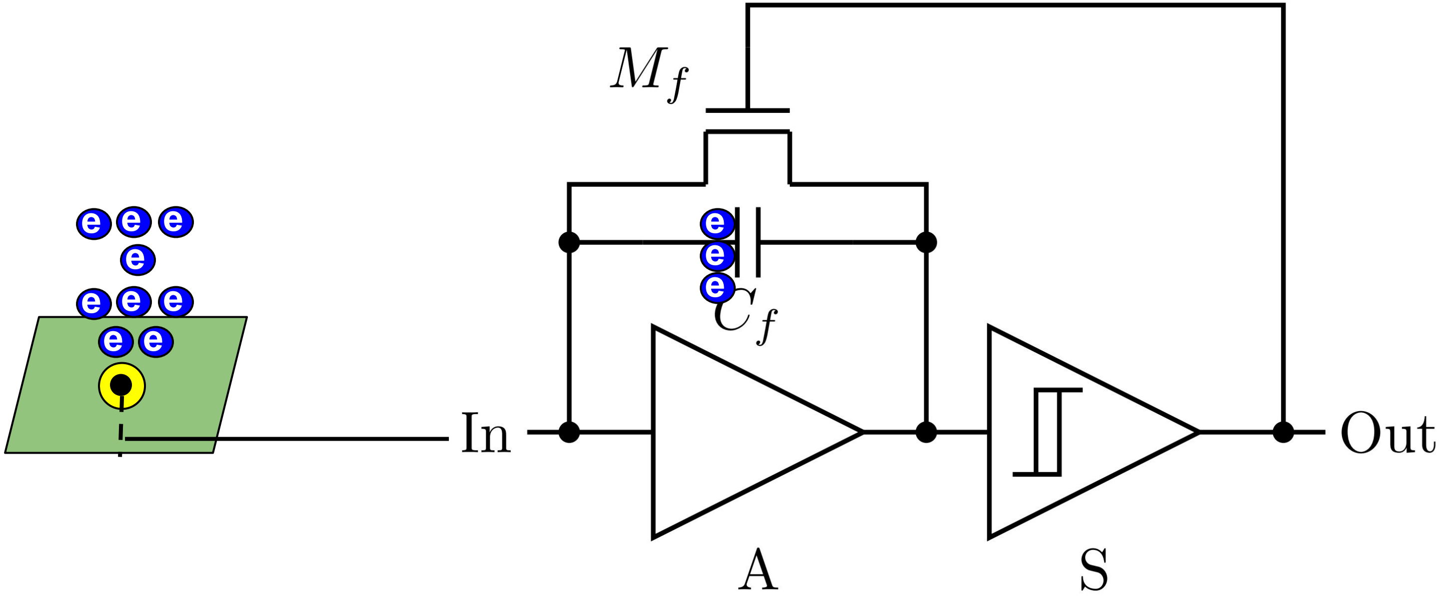

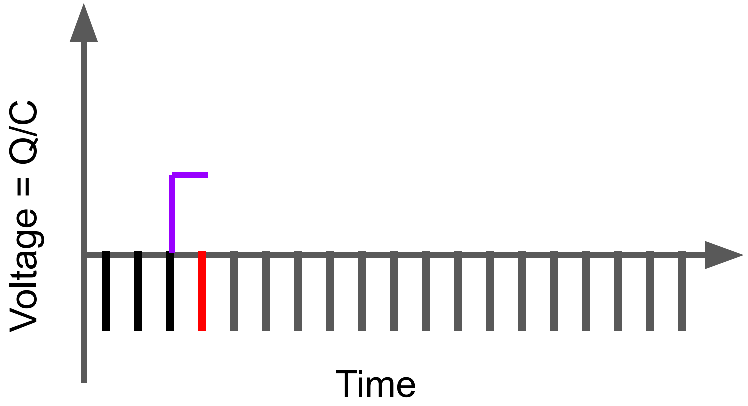

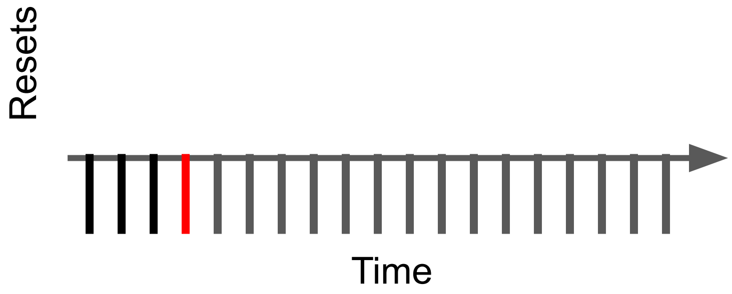

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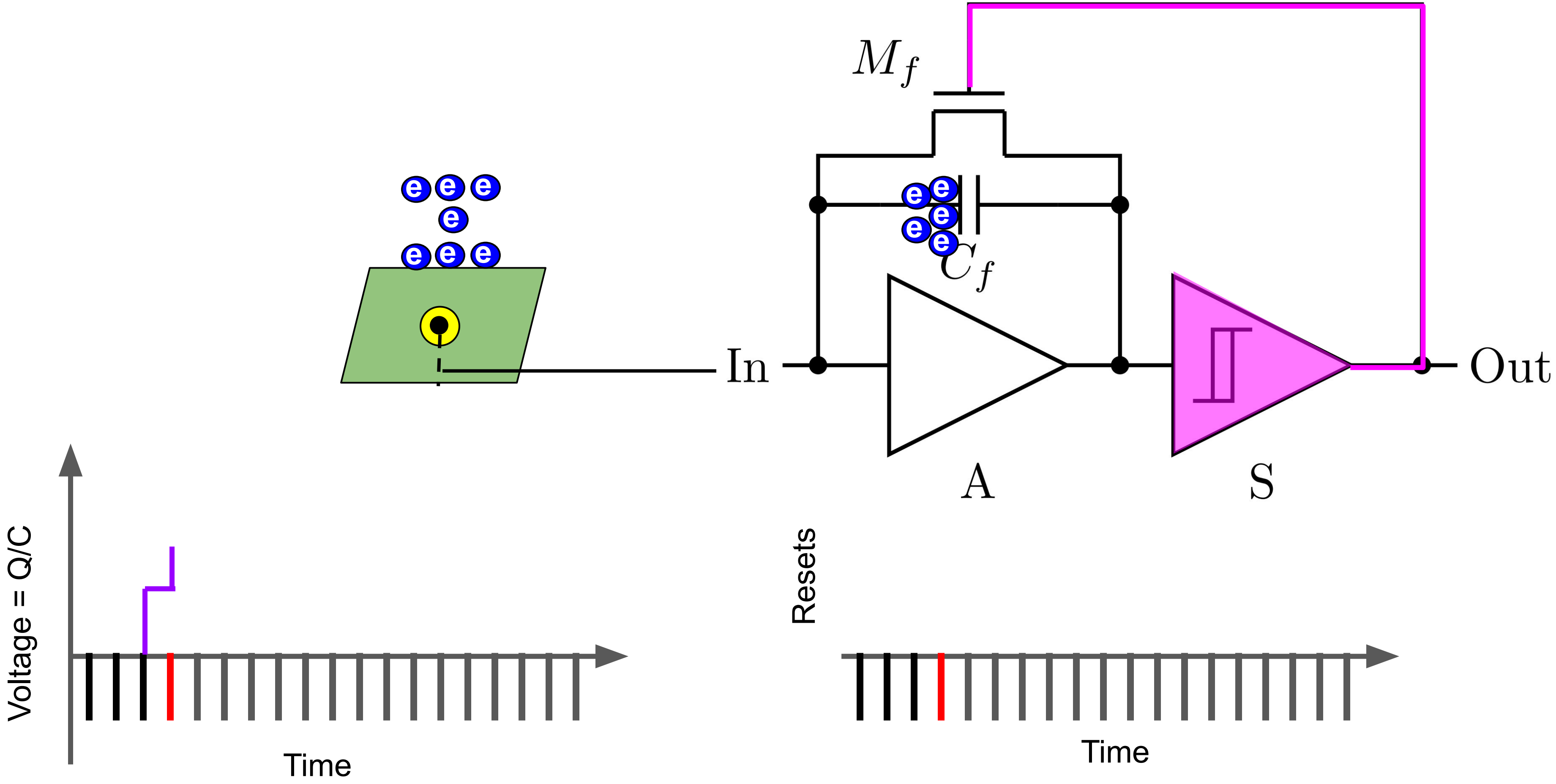

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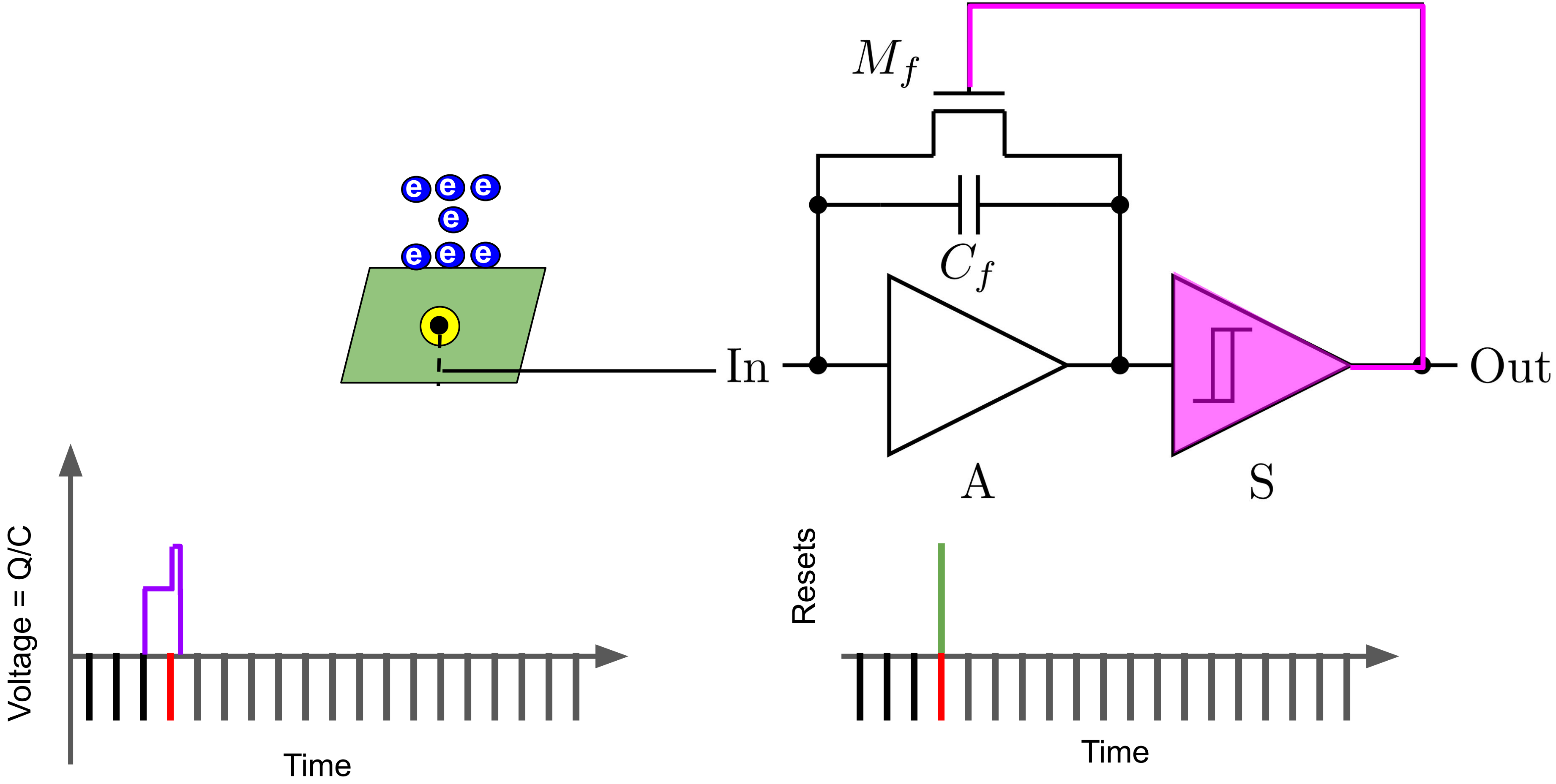

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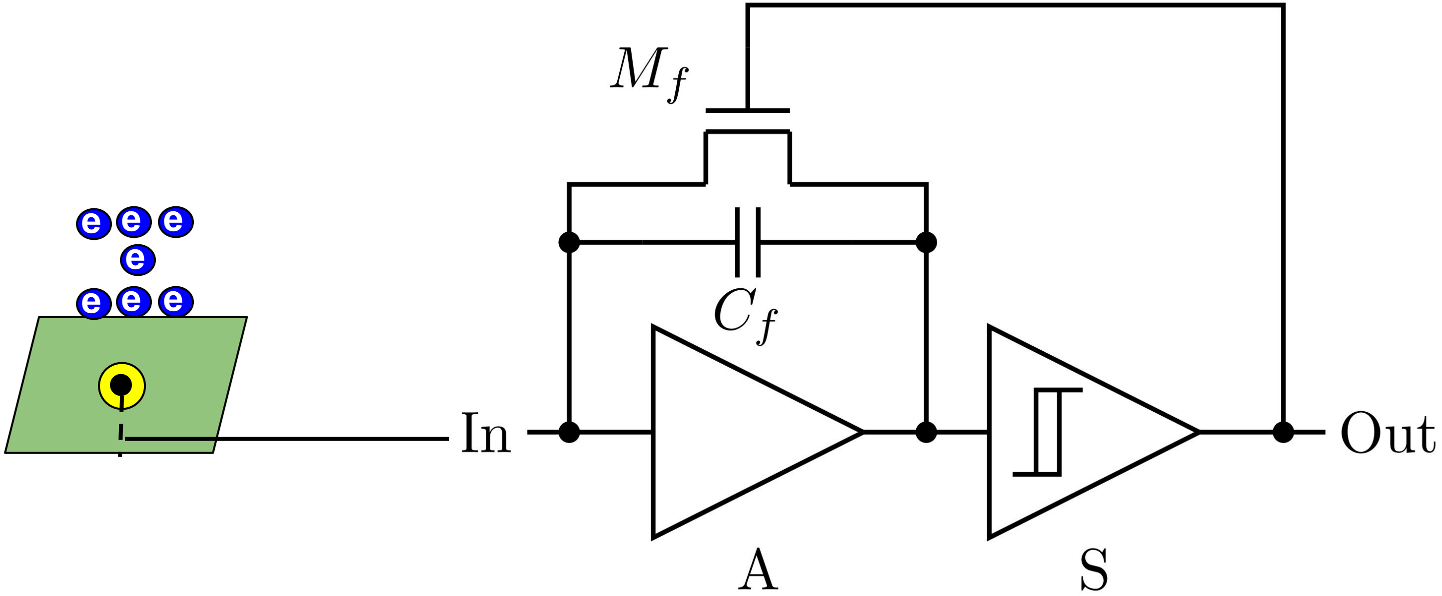

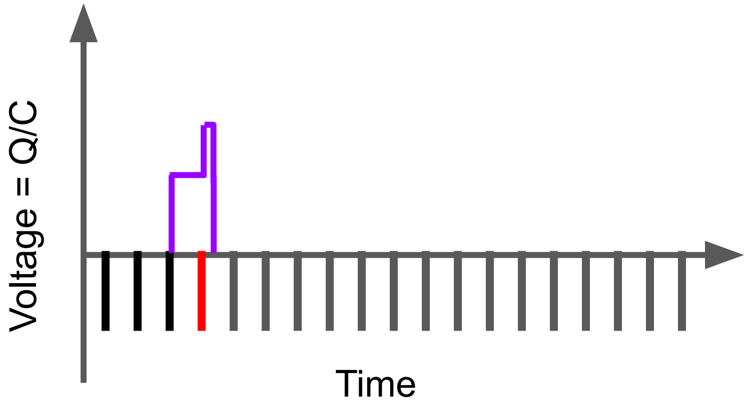

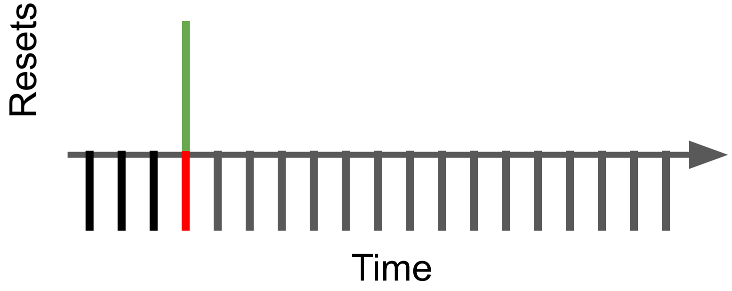

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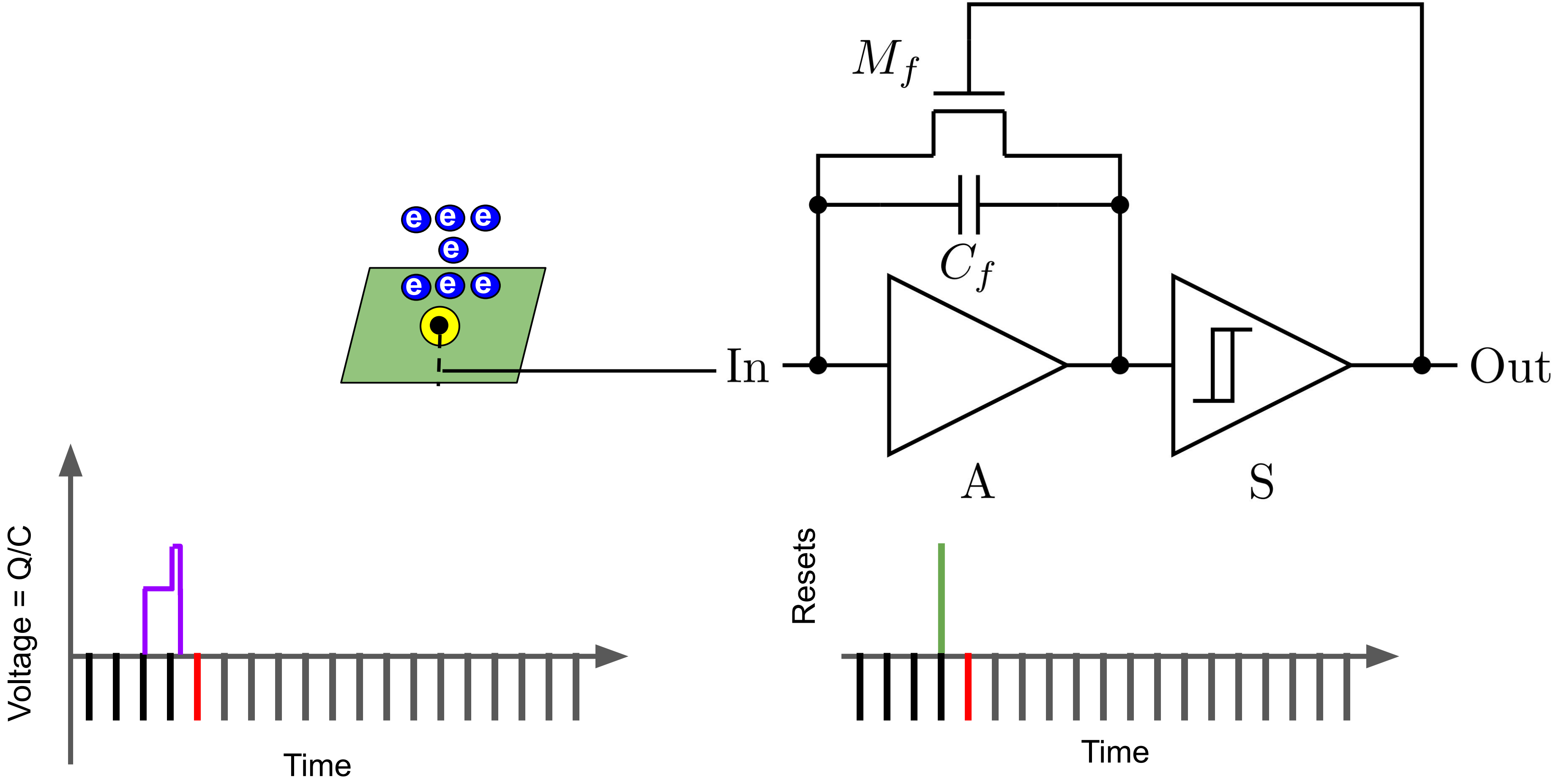

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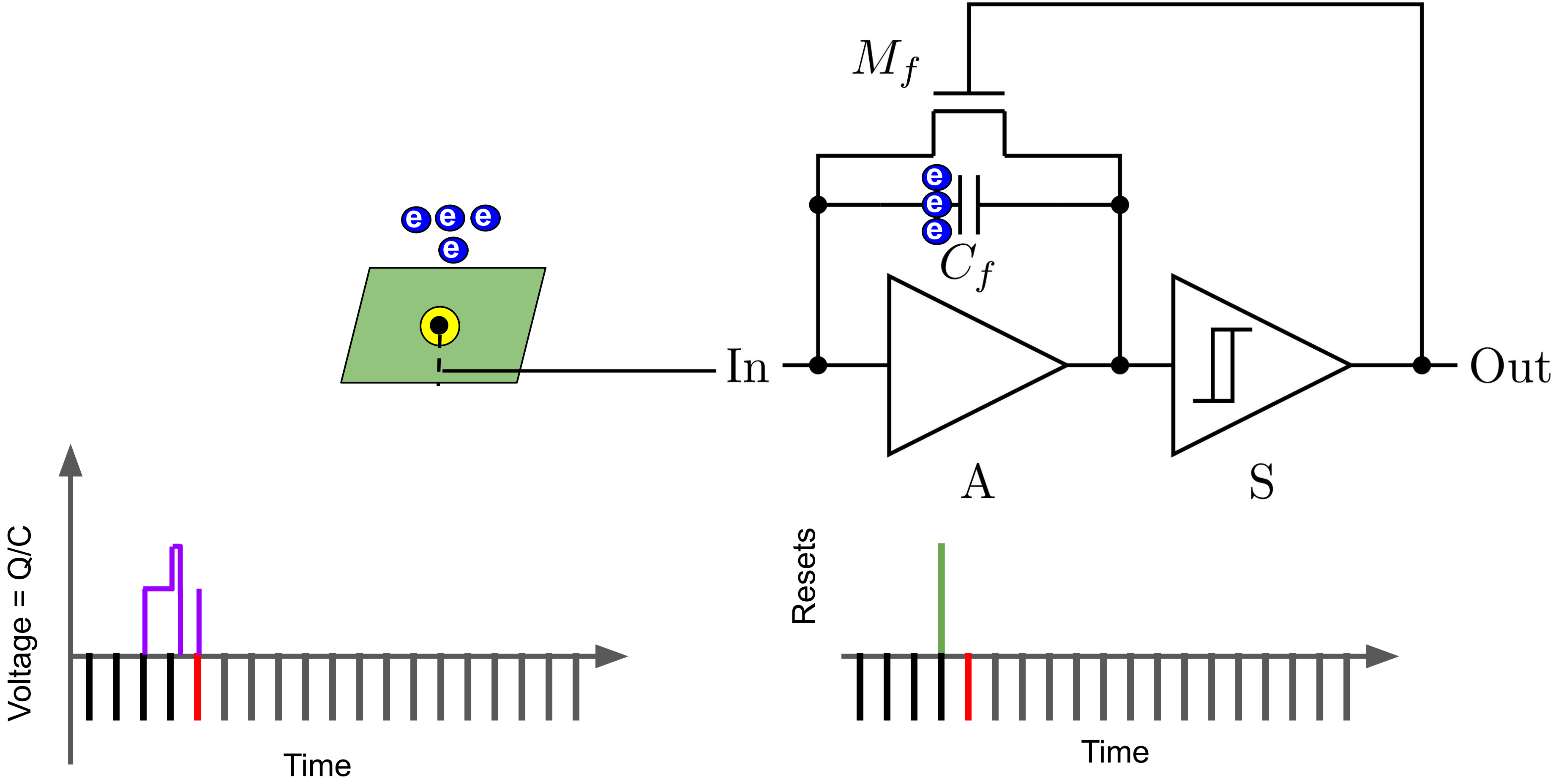

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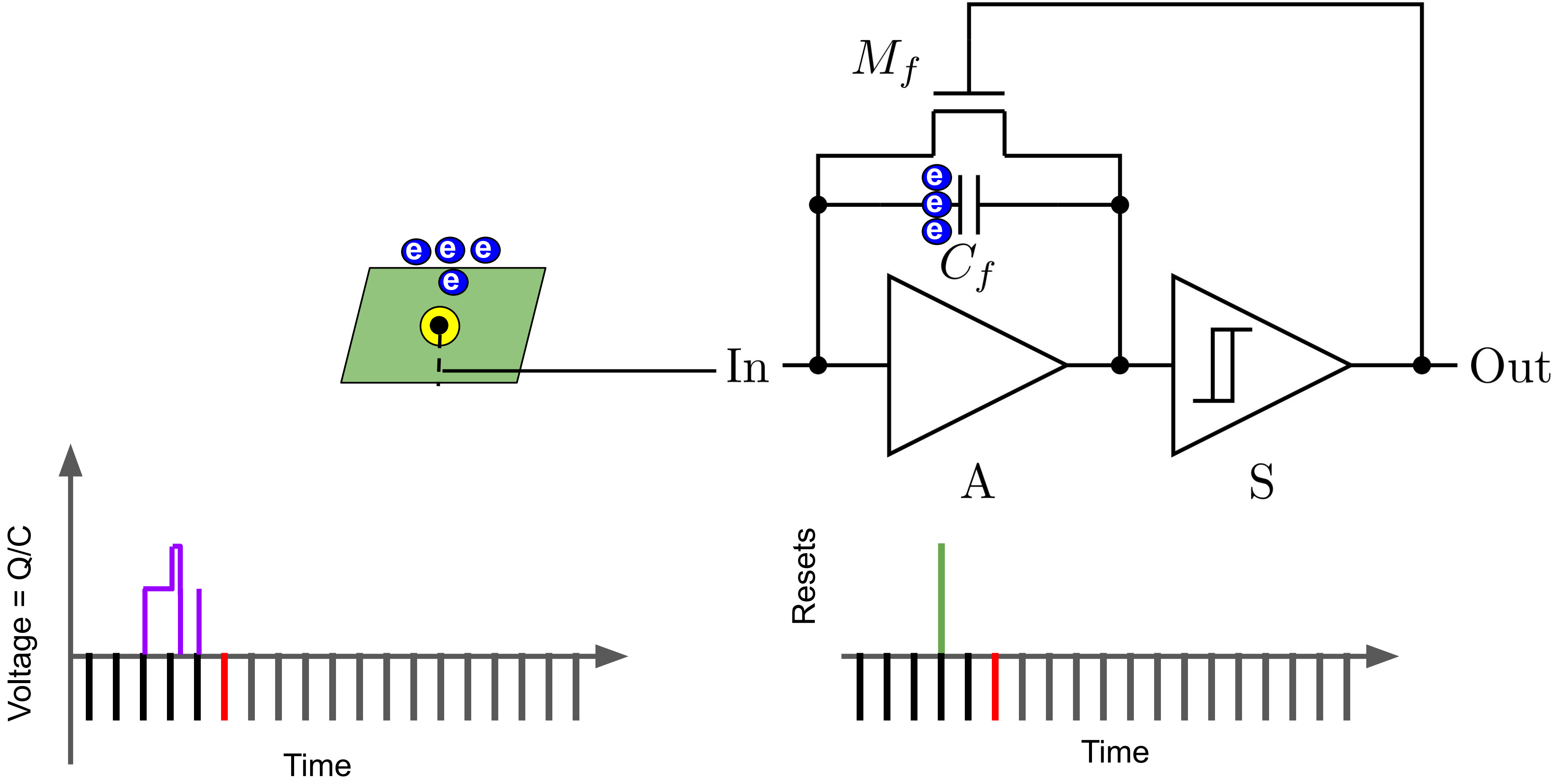

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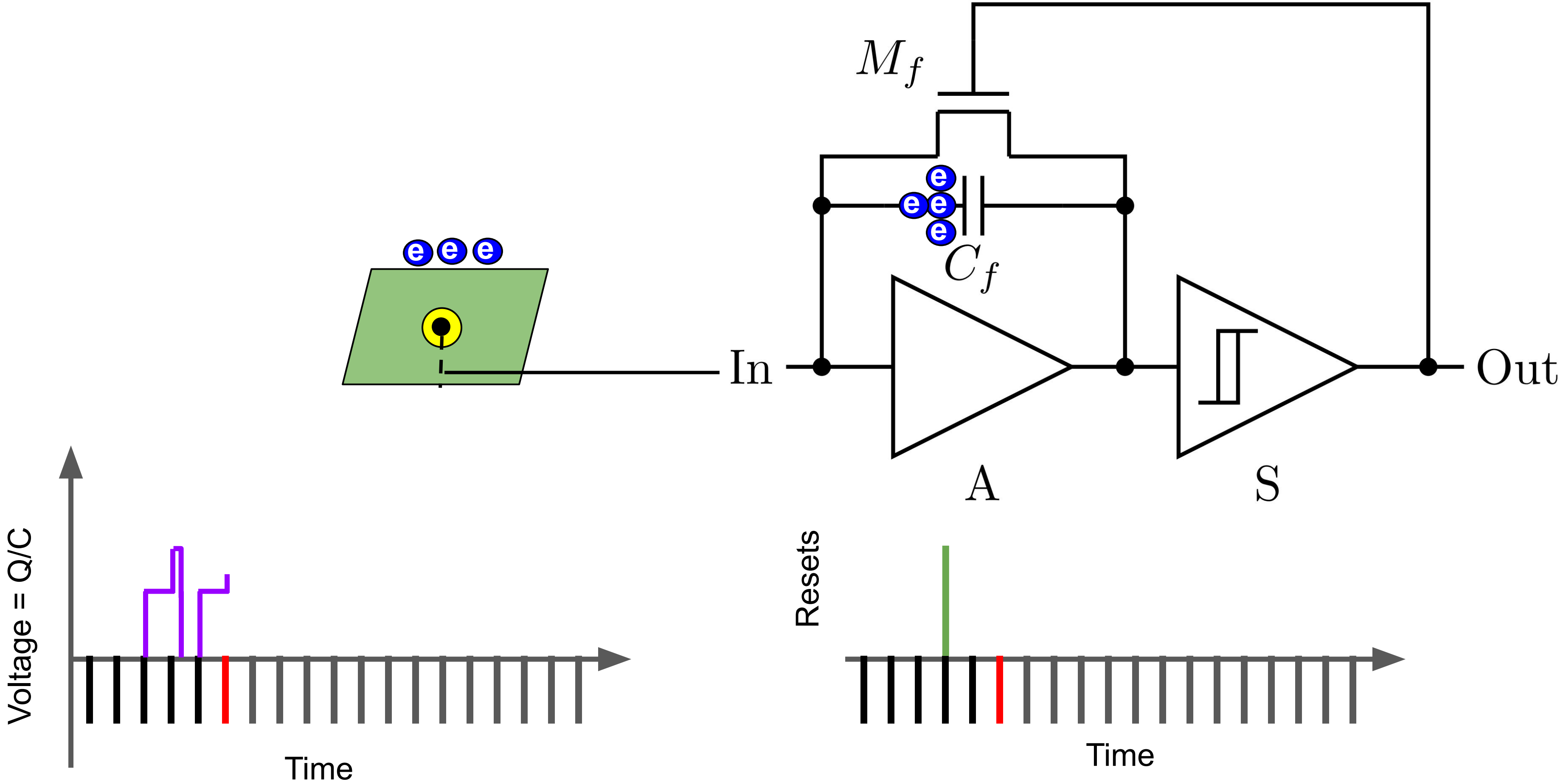

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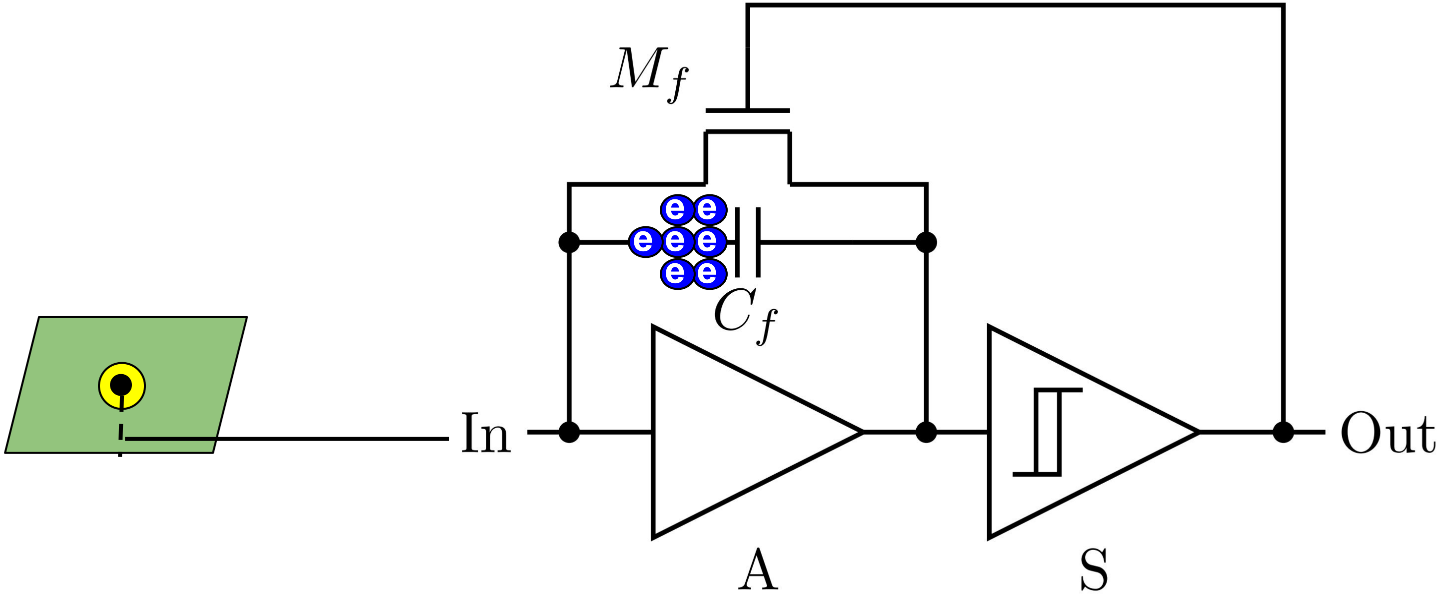

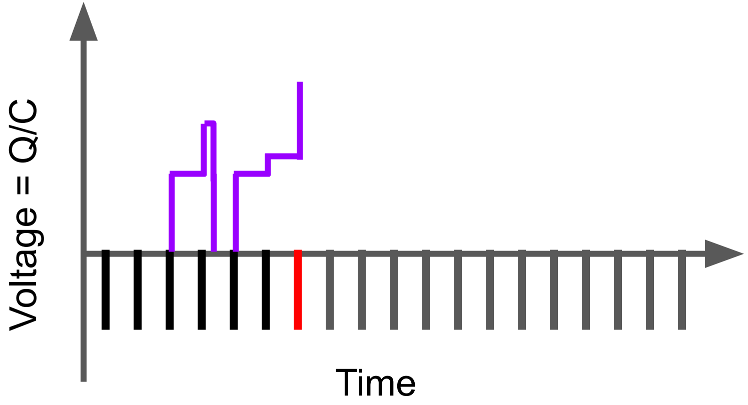

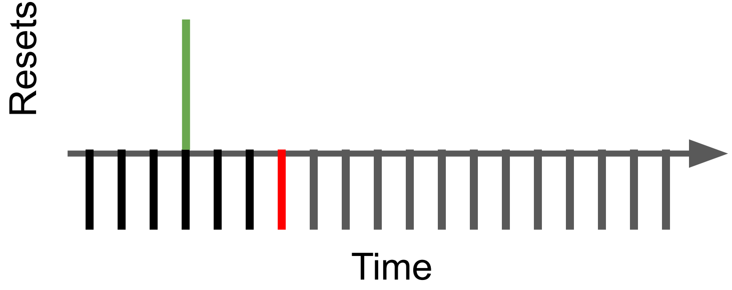

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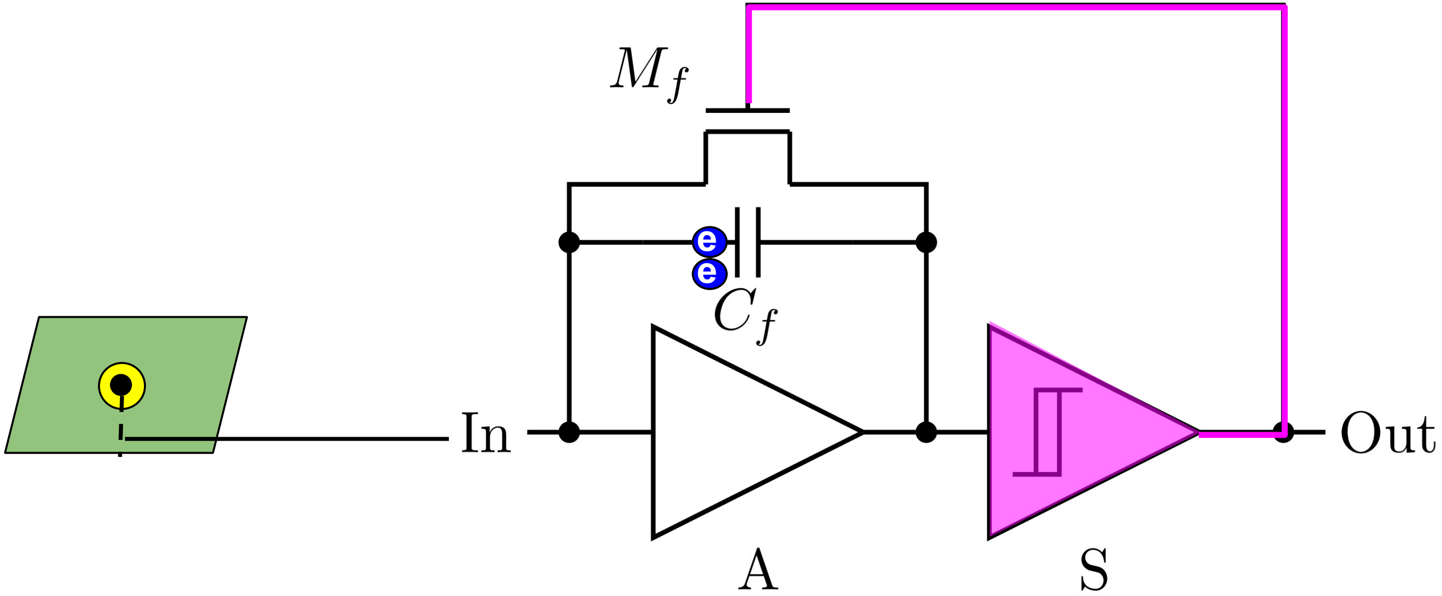

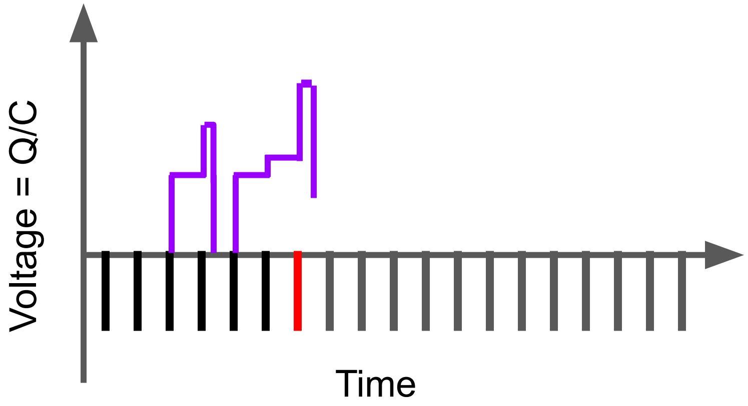

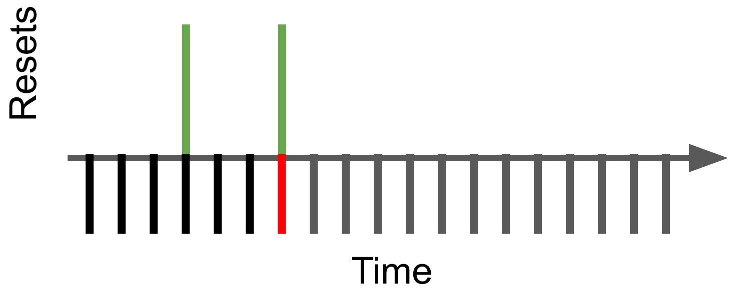

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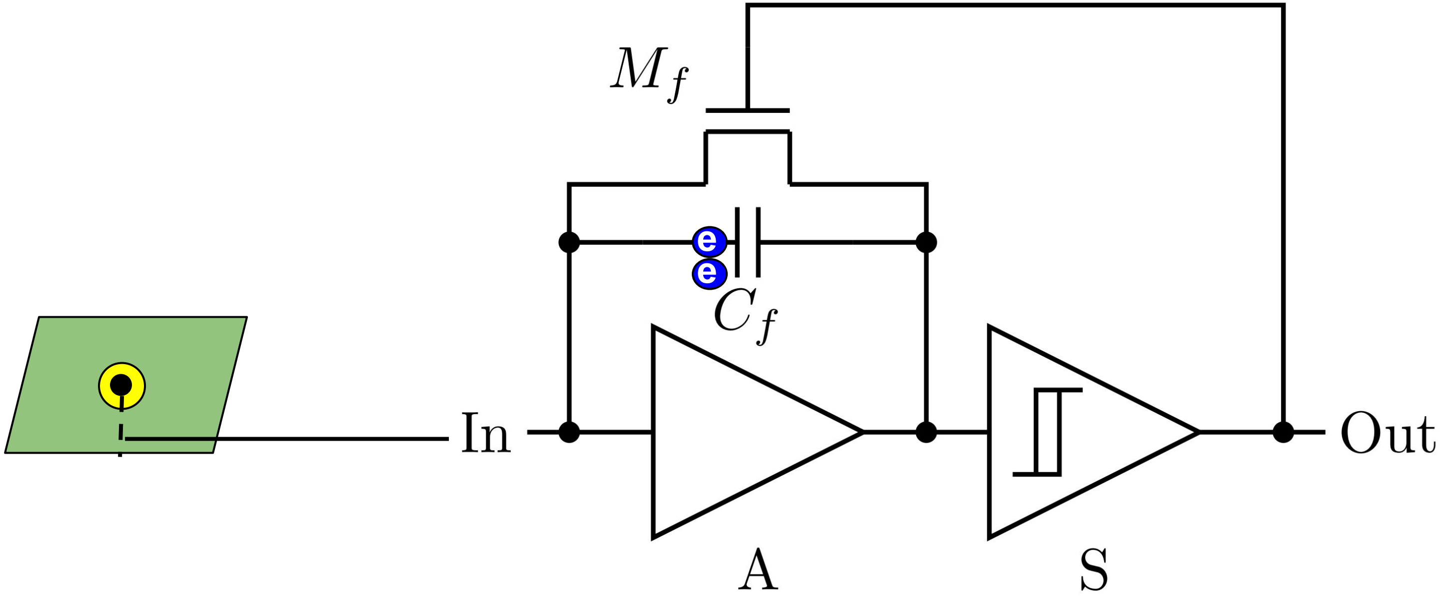

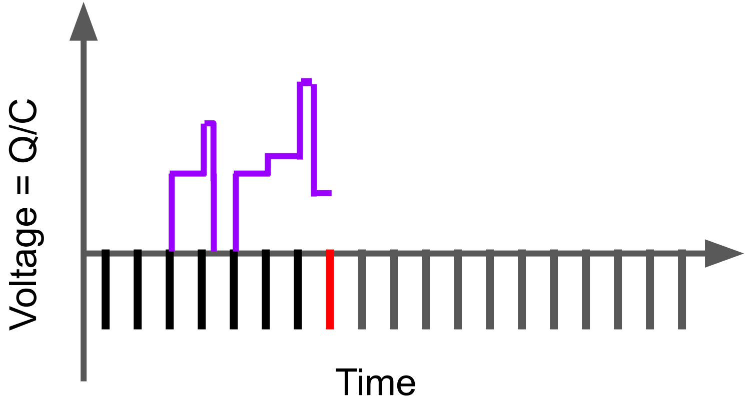

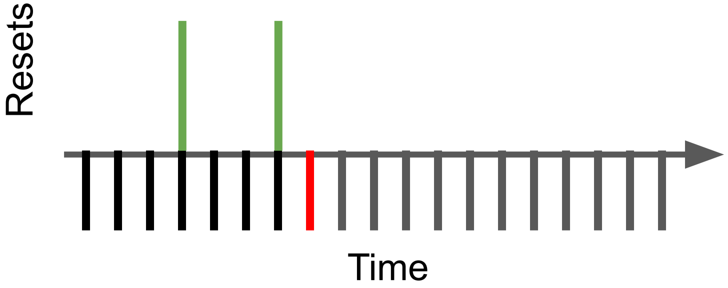

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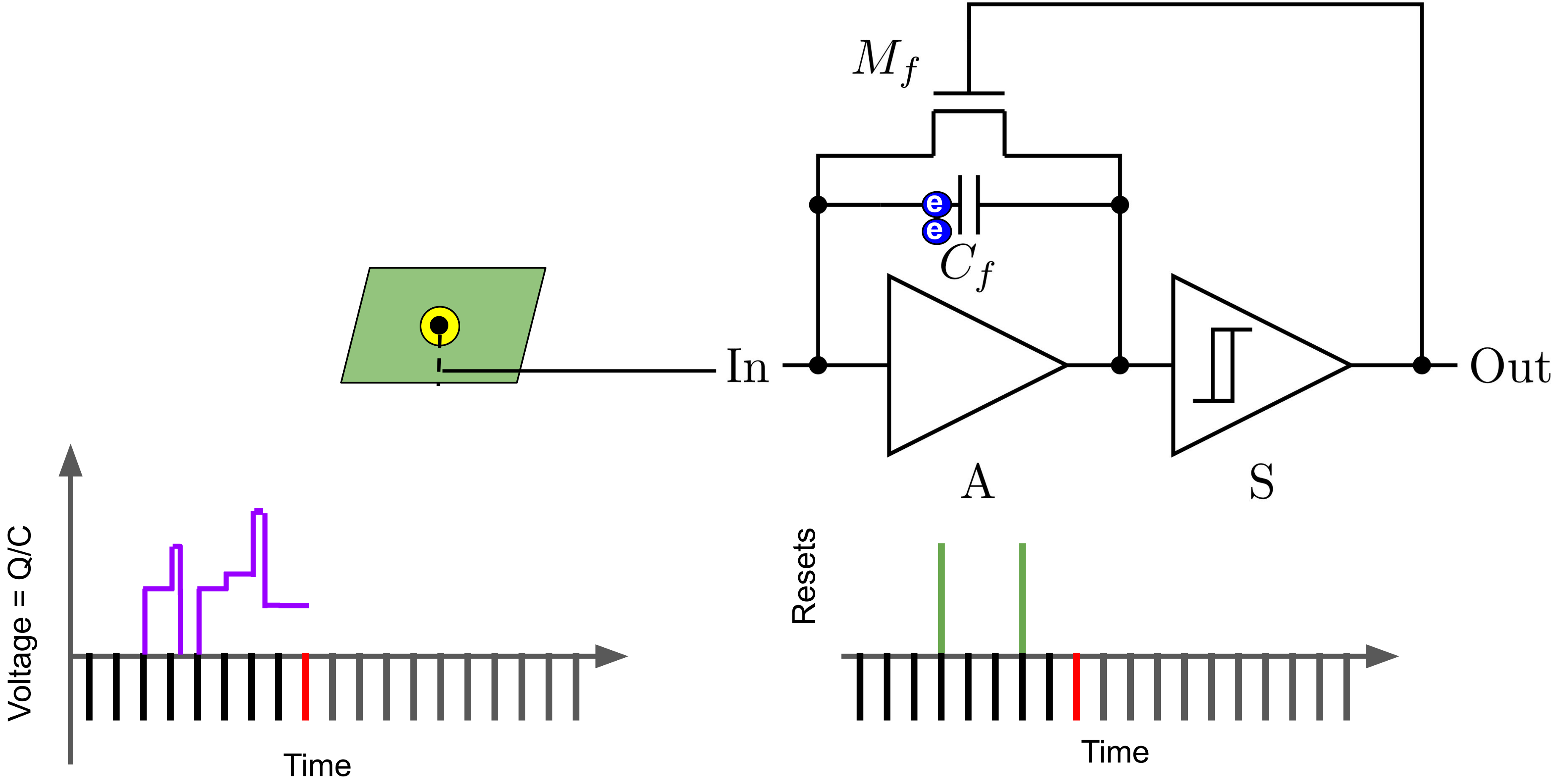

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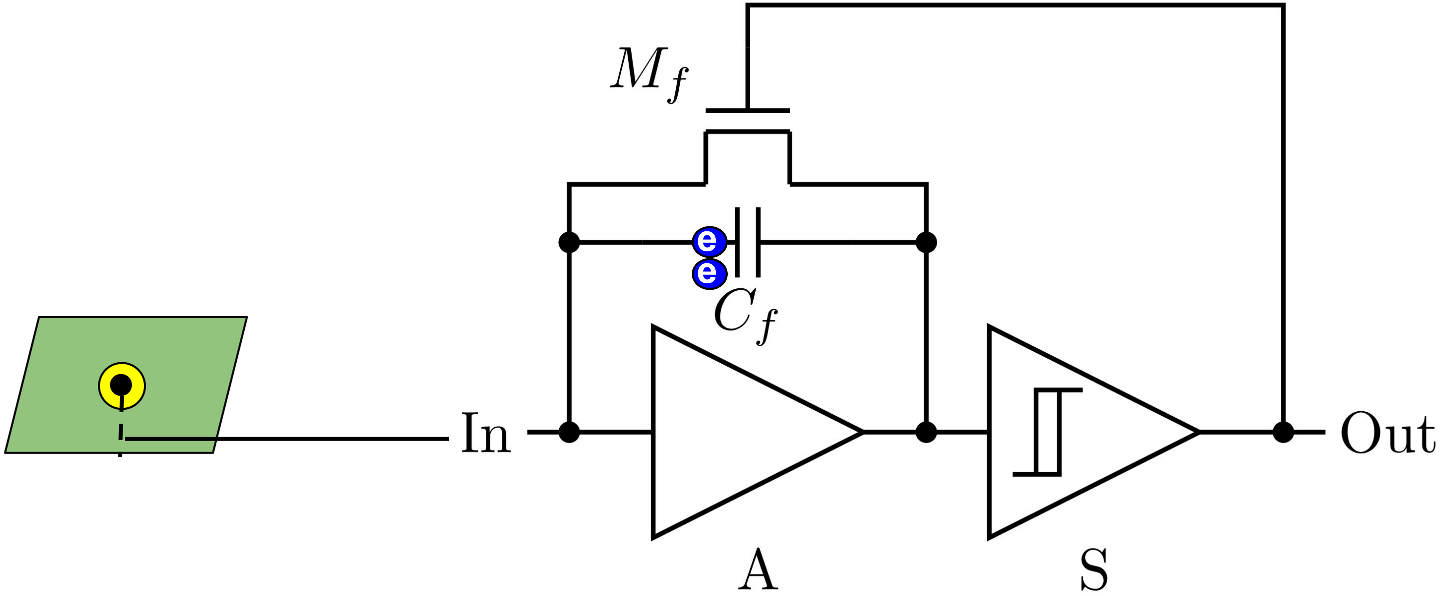

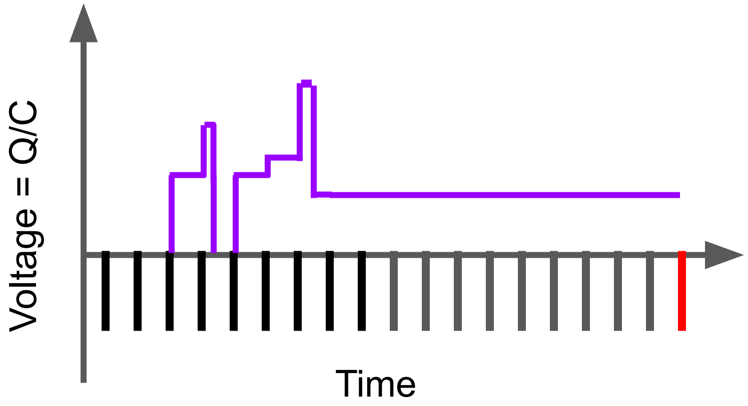

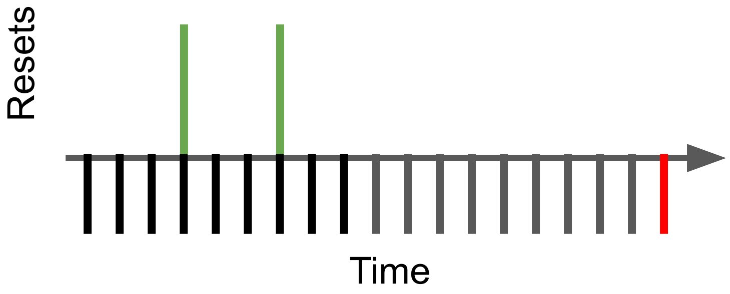

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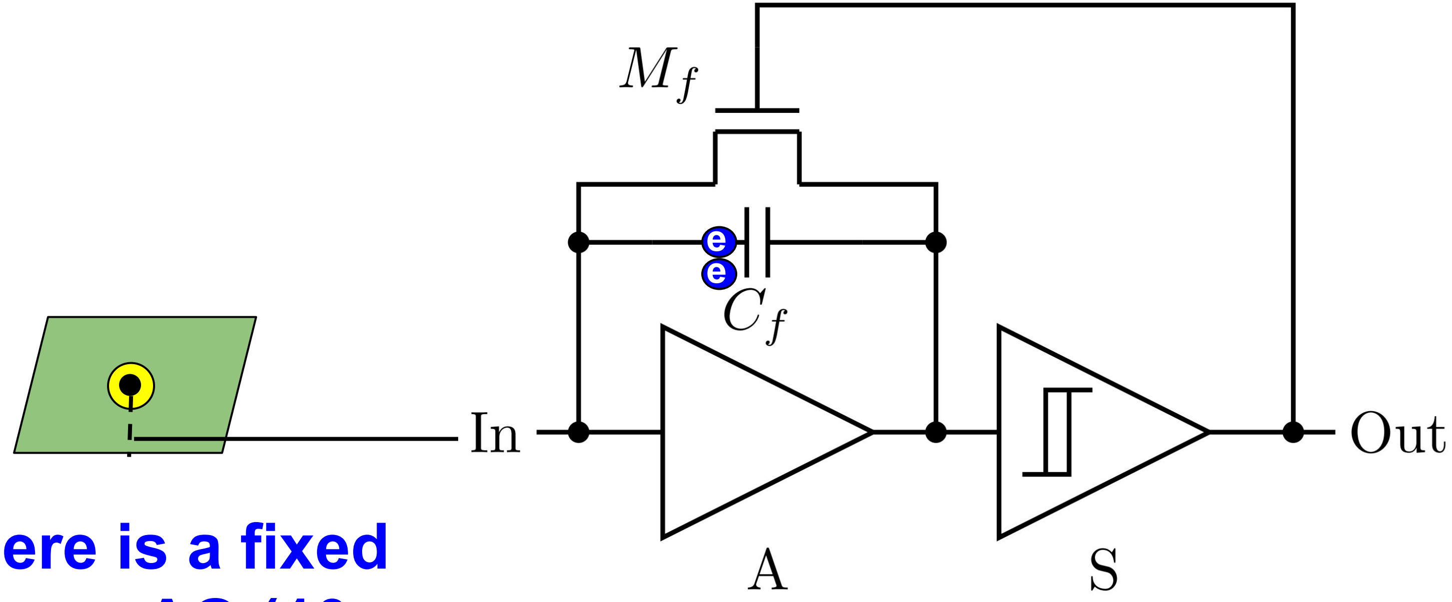
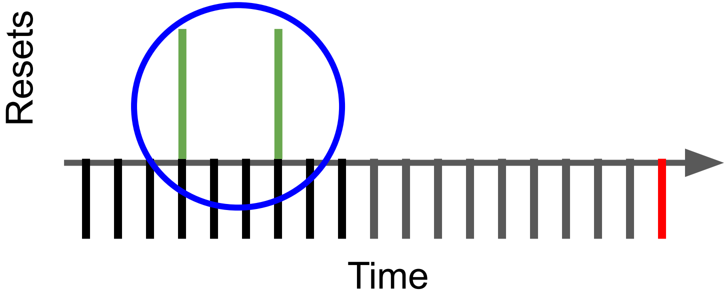


What I have here is a fixed amount of charge ΔQ (10 electrons in our toy example) during a time Δt



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