Detection Technologies for LArTPC that enables supernova neutrino detection

All
Polarization
And
Frequencies
Are
Welcome here

Shion Kubota

Harvard University, PhD candidate

Hello!

Born and raised in Japan until 18yo (1997-2015) 🇯🇵

Moved to MA, USA for undergrad and PhD (2015-2022) 🇺🇸

Moved to Manchester, UK (2022-) 🇬🇧

Moving to Berkeley, USA for Chamberlain Fellowship at LBNL (2025-) 🇺🇸

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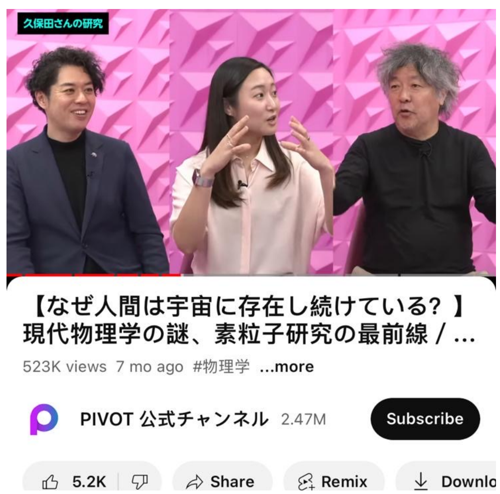

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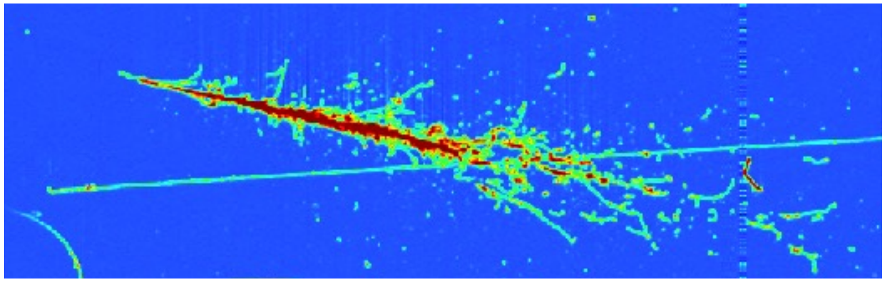
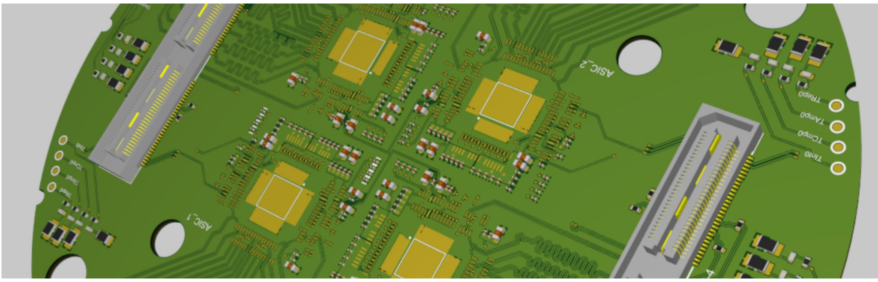
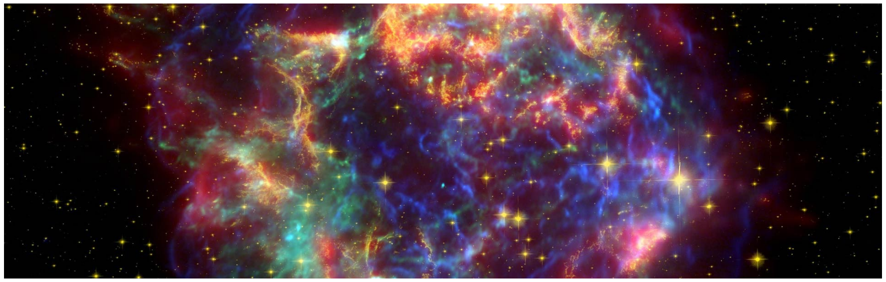
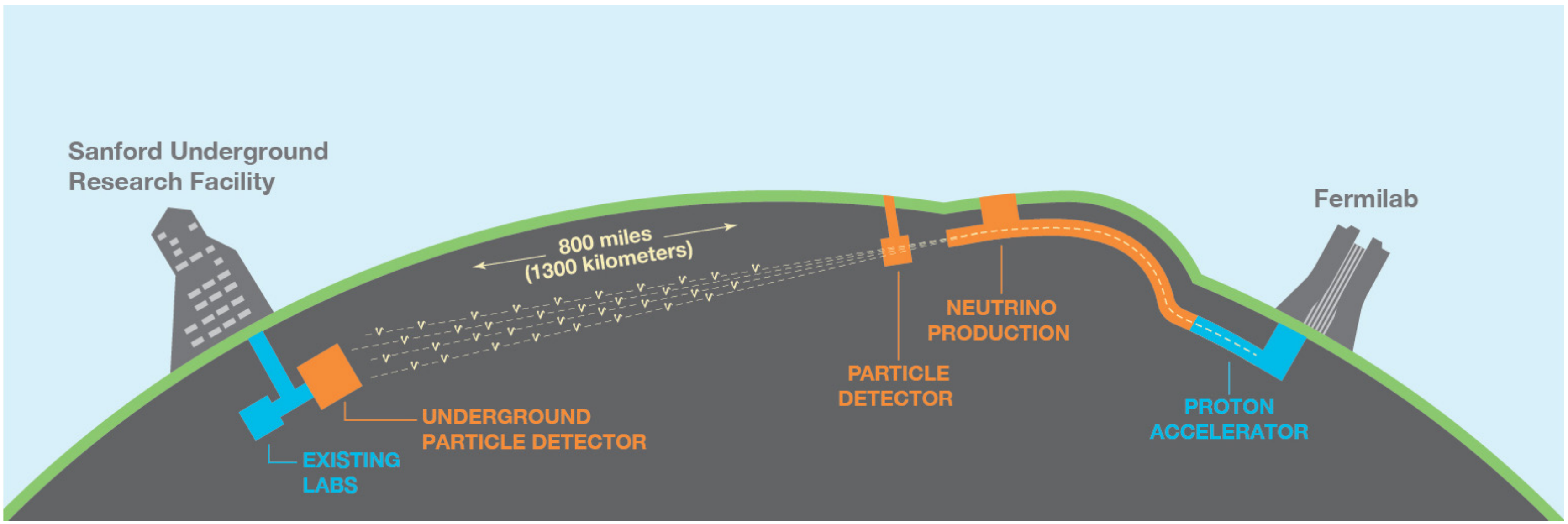






DUNE : Deep Underground Neutrino Experiment



DUNE : Deep Underground Neutrino Experiment

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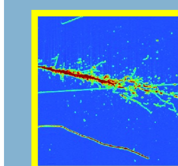
Hyper-Kamiokande

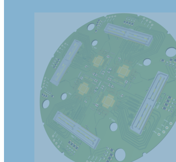
- Located in Kamioka, Japan
- Beam from JPARC
- Distance : 295km
- Medium : Water
- Total Volume : 260kt

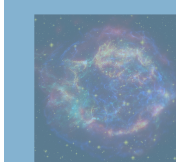
DUNE — DEEP UNDERGROUND NEUTRINO EXPERIMENT

- Located in South Dakota, USA
- Beam from Fermilab
- Distance : 1300km
- Medium : Liquid Argon
- Total Volume : 70kt

MANCHESTER 1824
The University of Manchester







DUNE : Deep Underground Neutrino Experiment

Hyper-Kamiokande   DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

- Located in Kamioka, Japan
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- Distance : 295km
- Medium : Water
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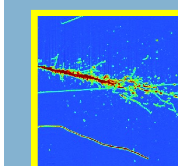
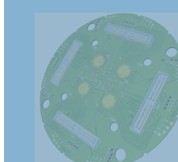
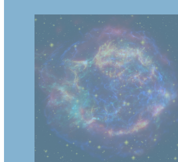
But share similar physics goals
→ Could be complement of each other!



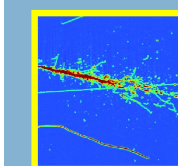


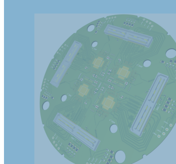


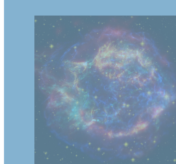
DUNE : Deep Underground Neutrino Experiment

Under construction, aiming to address the following physics questions:

- Which neutrino is heavier/lighter than which?
- How much does neutrino violate CP symmetry?
- Can we observe proton decay?
- How does supernovae explosion happen?
- How does ‘sun’ work?







DUNE : Deep Underground Neutrino Experiment

Under construction, aiming to address the following physics questions:

- Which neutrino is heavier/lighter than which?
- How much does neutrino violate CP symmetry?

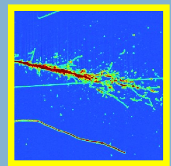
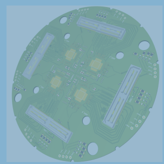
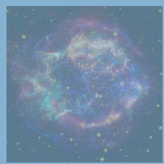
Main physics goals of
Long baseline experiments

- Can we observe proton decay?
- How does supernovae explosion happen?

Additional physics studies
DUNE is trying to perform

- How does 'sun' work?

⇦ ...and maybe DUNE can also investigate this too

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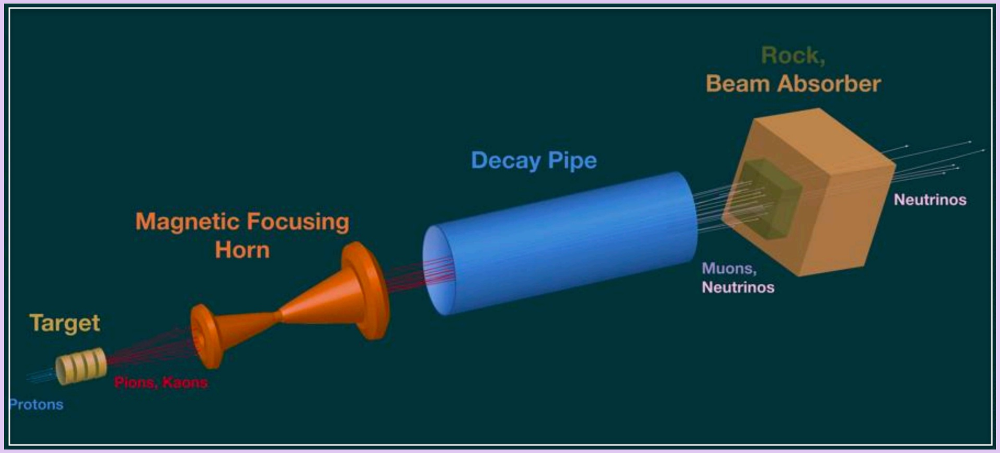
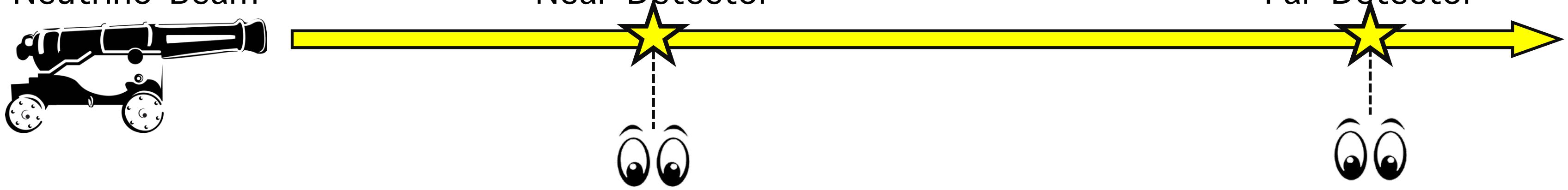
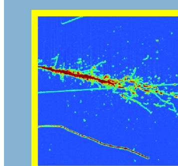


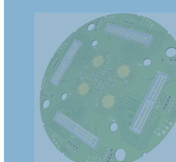
By switching the magnetic horn, you can either select π^+ or π^-.

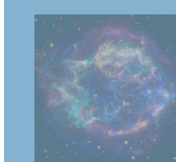
π^+ produces neutrinos and antimuons.
π^- produces antineutrinos and muons.

Neutrino Beam Near Detector Far Detector





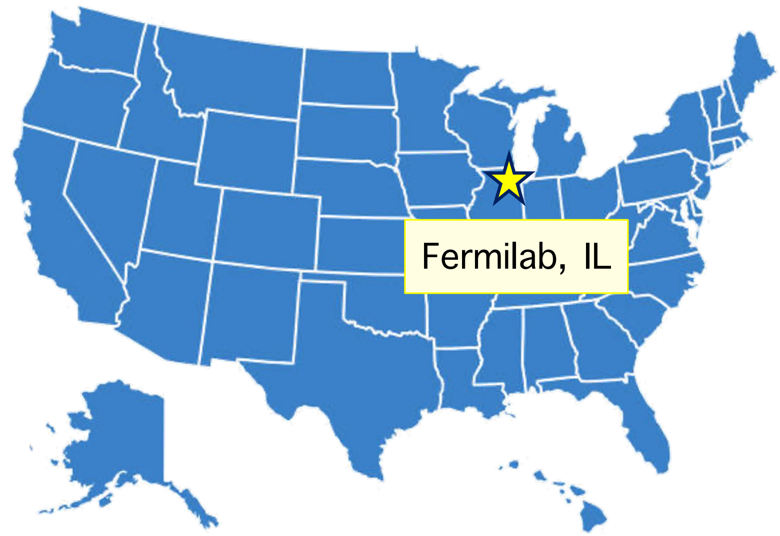


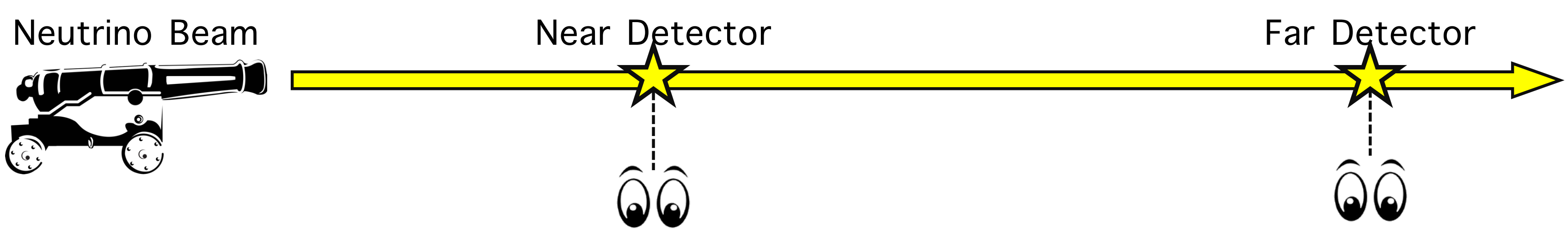


DUNE : Deep Underground Neutrino Experiment

Built closer to (near) the neutrino beam

- Monitors beam status
- Measures un-oscillated spectrum
- Constrains systematic uncertainties





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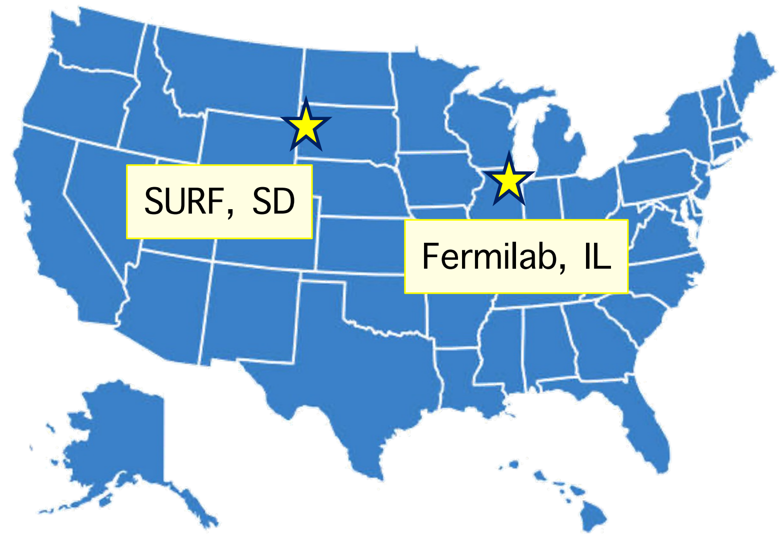
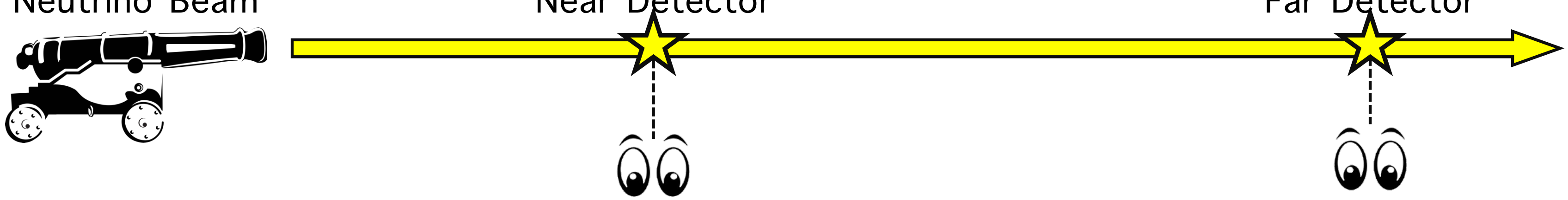
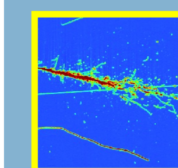
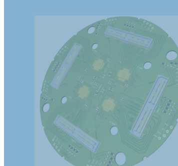
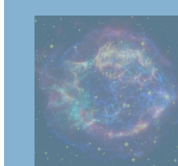










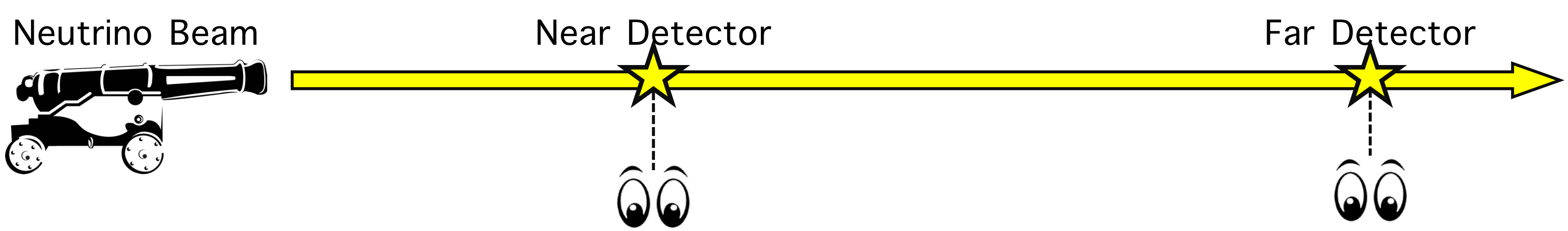
DUNE : Deep Underground Neutrino Experiment

Built closer to (near) the neutrino beam

- Monitors beam status
- Measures un-oscillated spectrum
- Constrains systematic uncertainties

Built farther away from neutrino beam

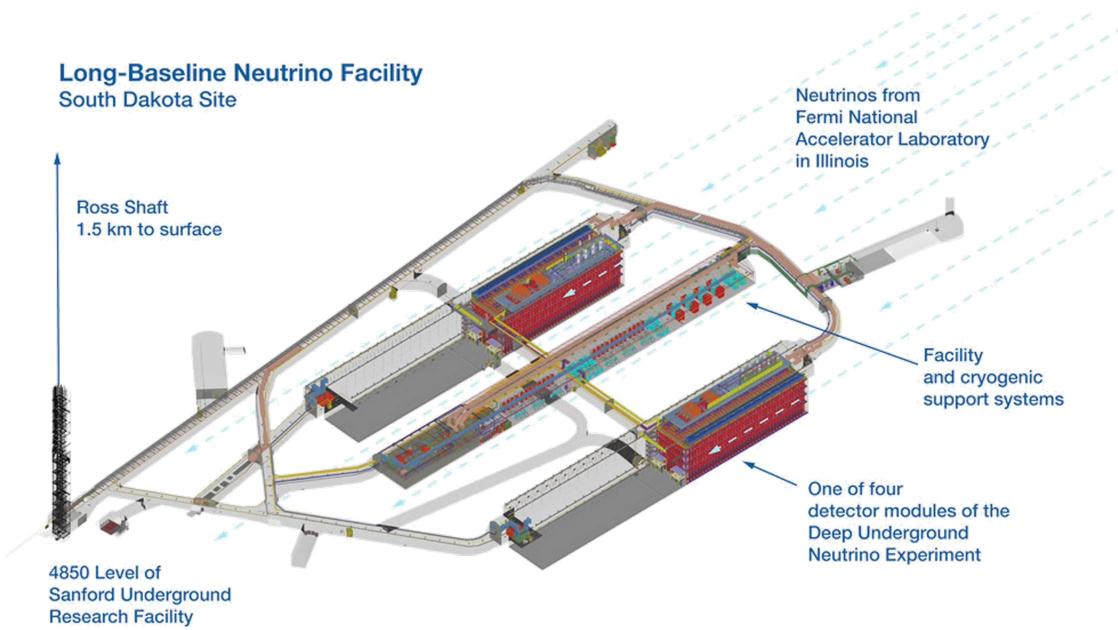
- Much bigger than Near Detector
- Take data of oscillation studies
- Looks for rare events



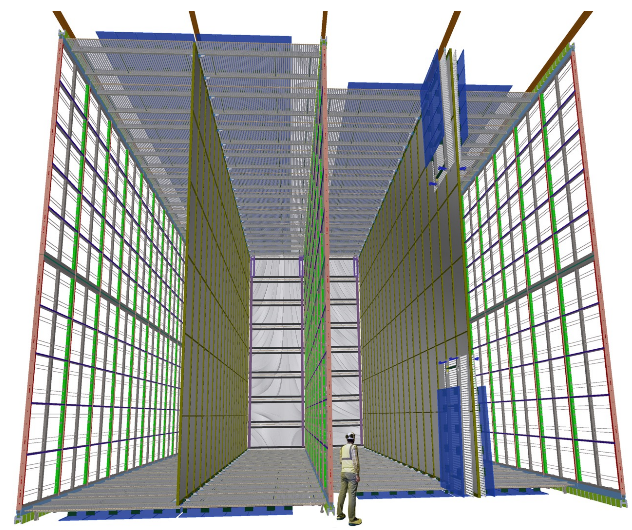
DUNE : Deep Underground Neutrino Experiment

Planned to have 4 modules (First 2 with decided technology, others TBD)

⇨ First two with Liquid Argon Time Projection Chamber (LArTPC)



Dimension : 15.1m x 14.0m x 62.0m



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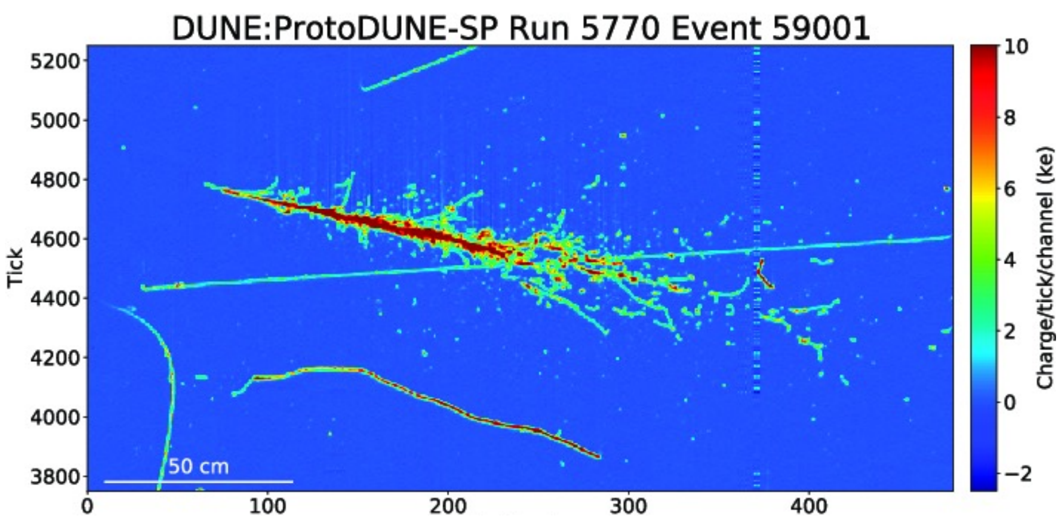

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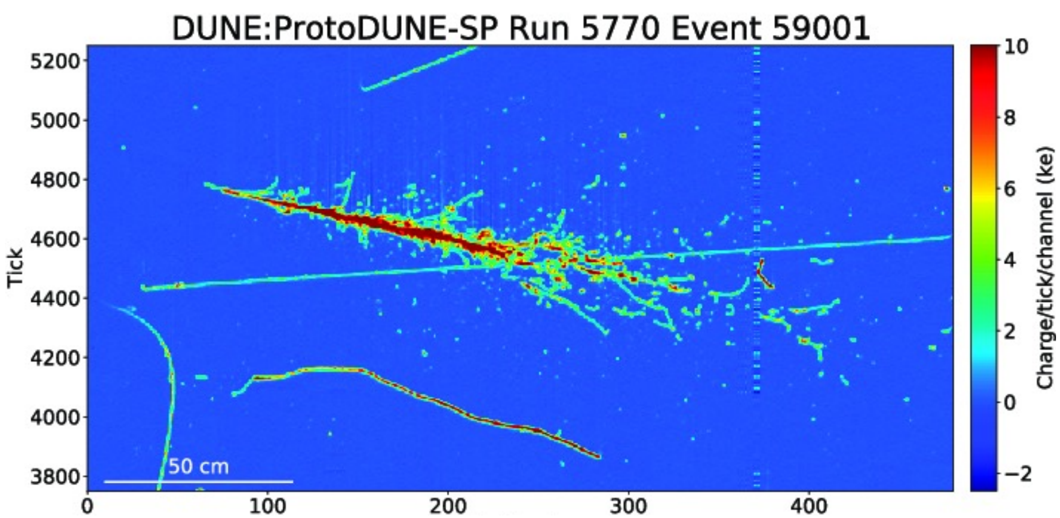
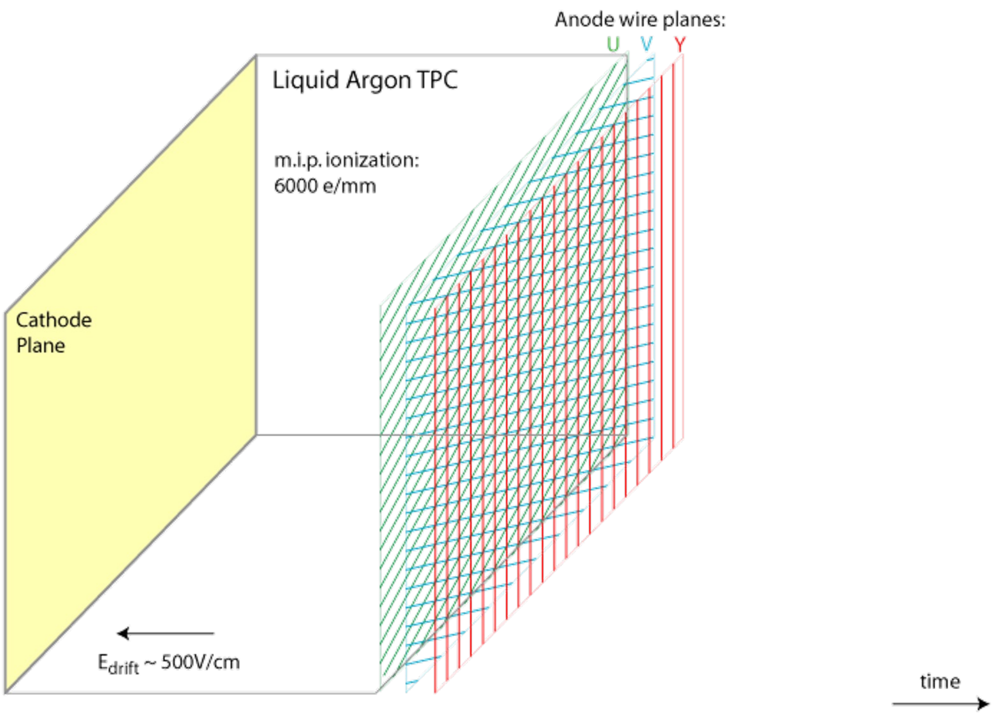


- Higher density
- Transparency to its own scintillation
- High dielectric strength
- Long charge drift distance

Liquid Argon Time Projection Chamber (LArTPC)



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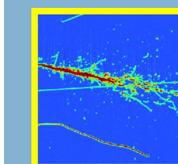

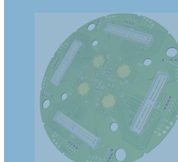

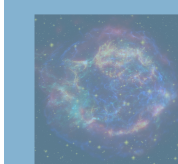

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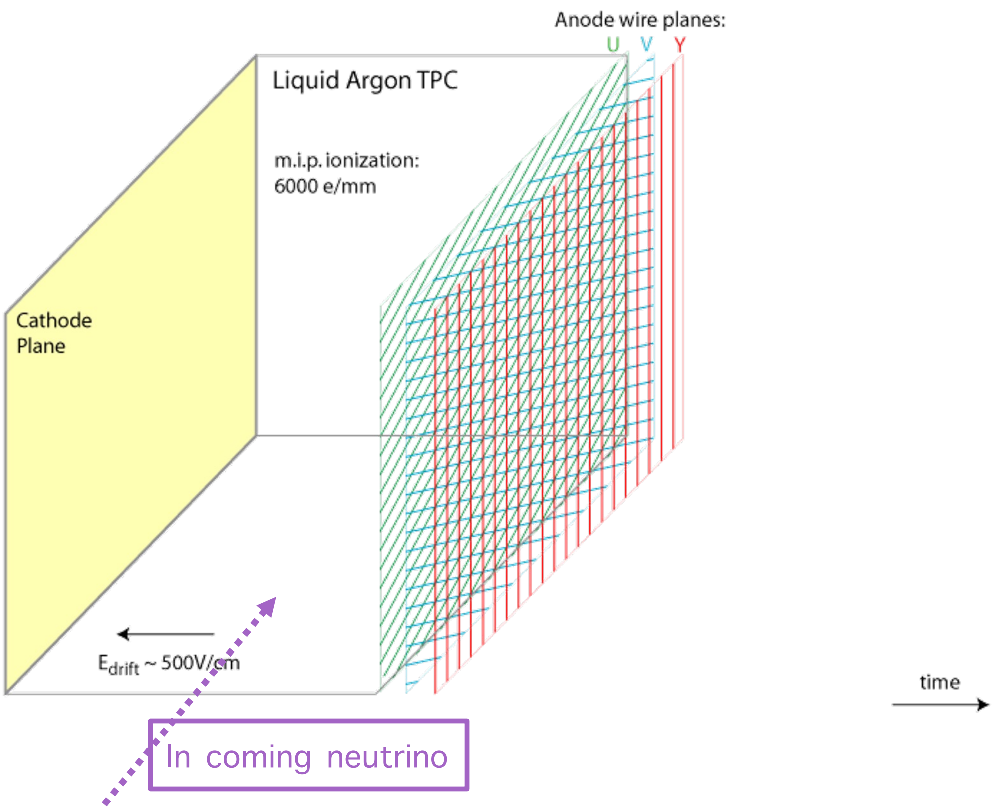

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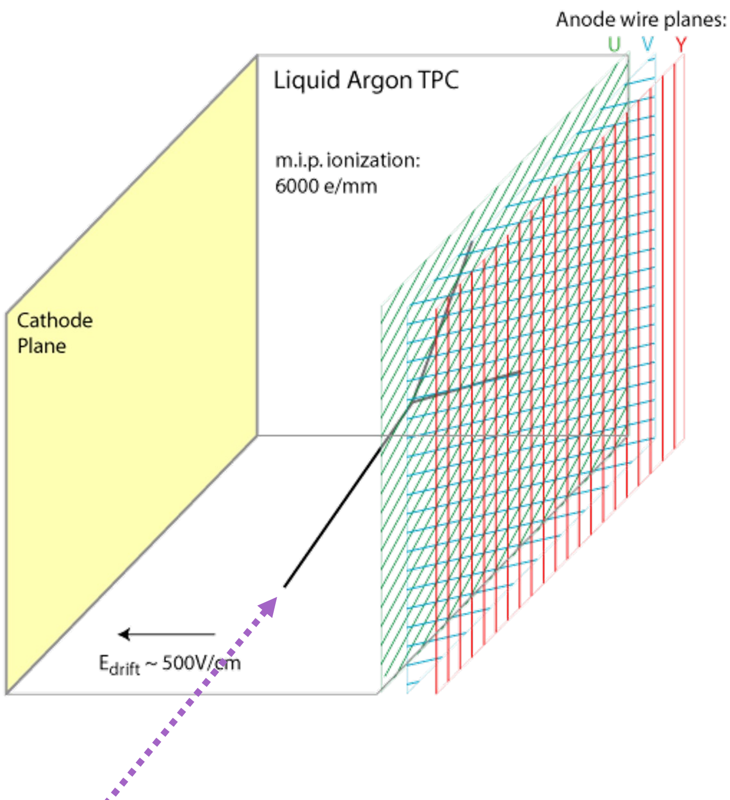

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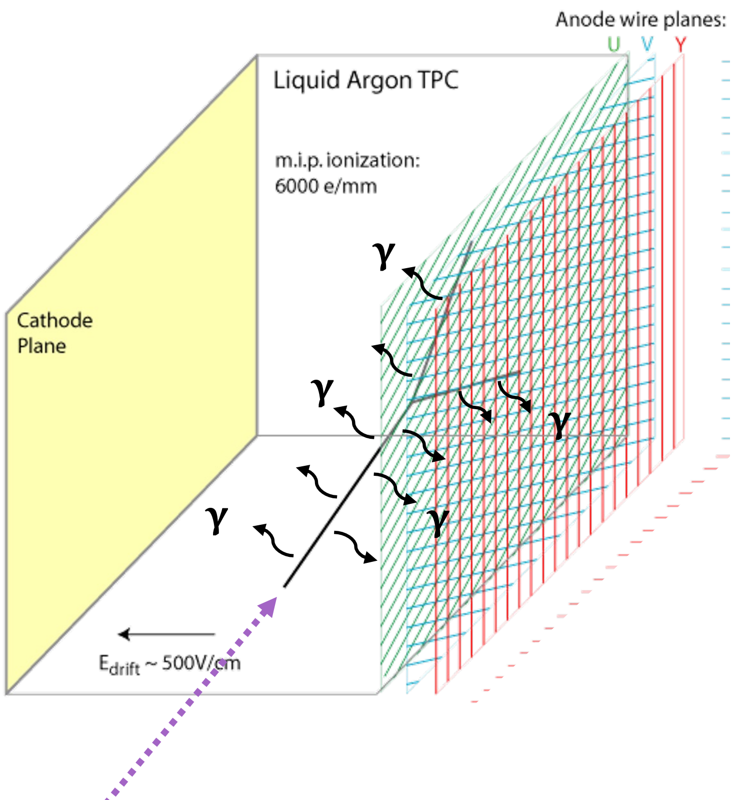

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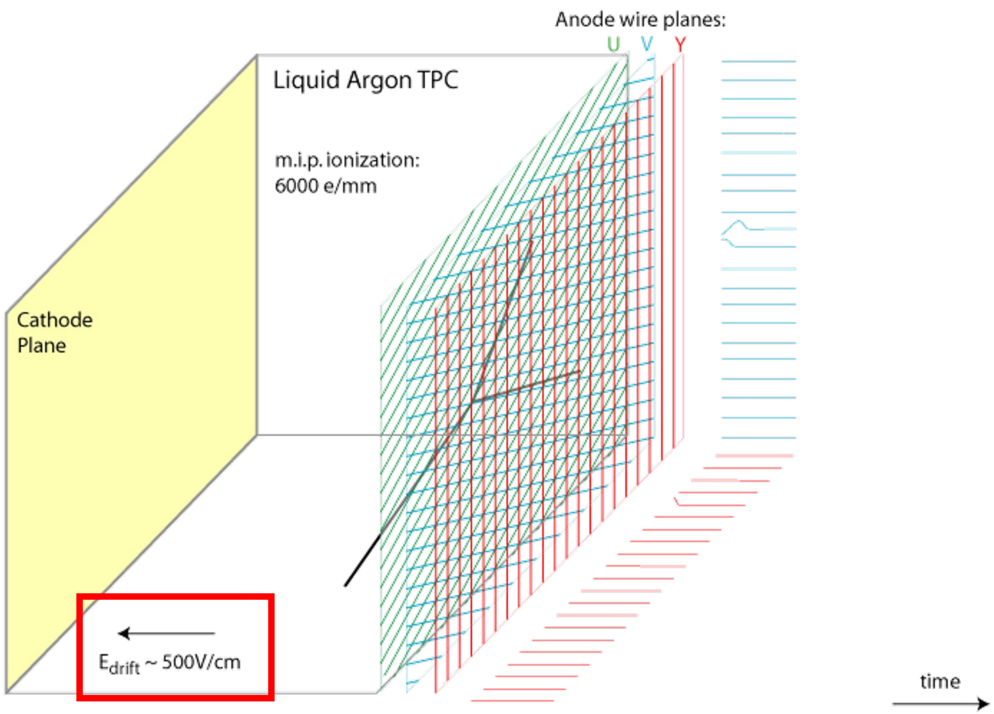

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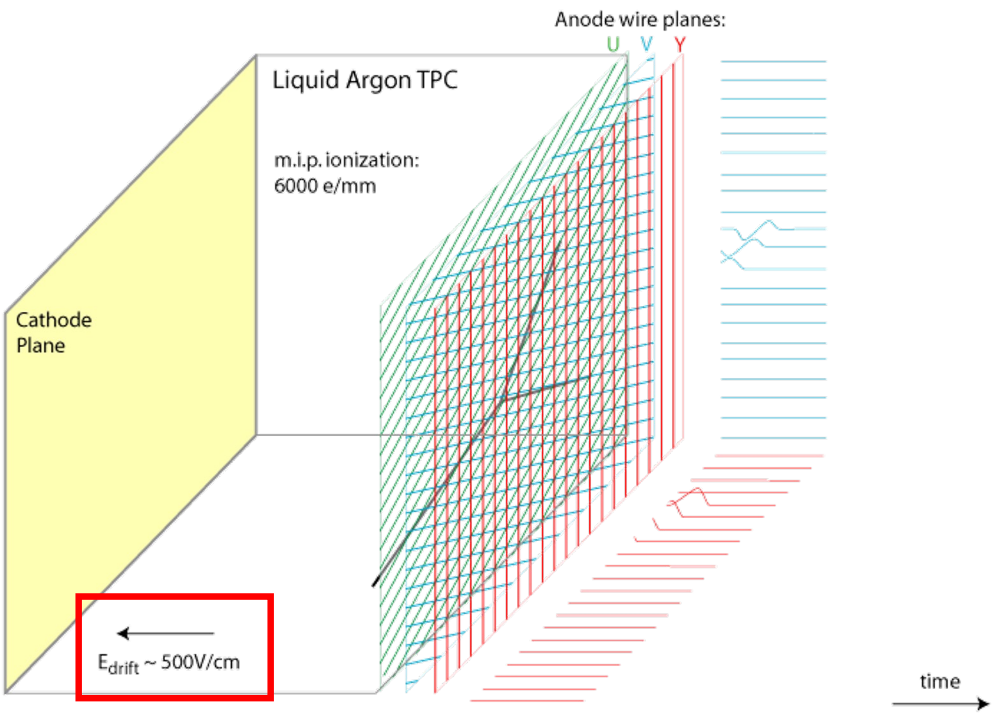

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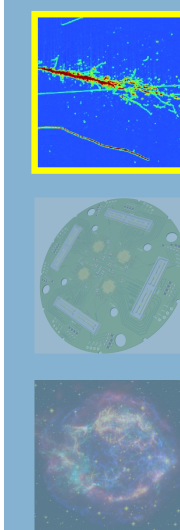

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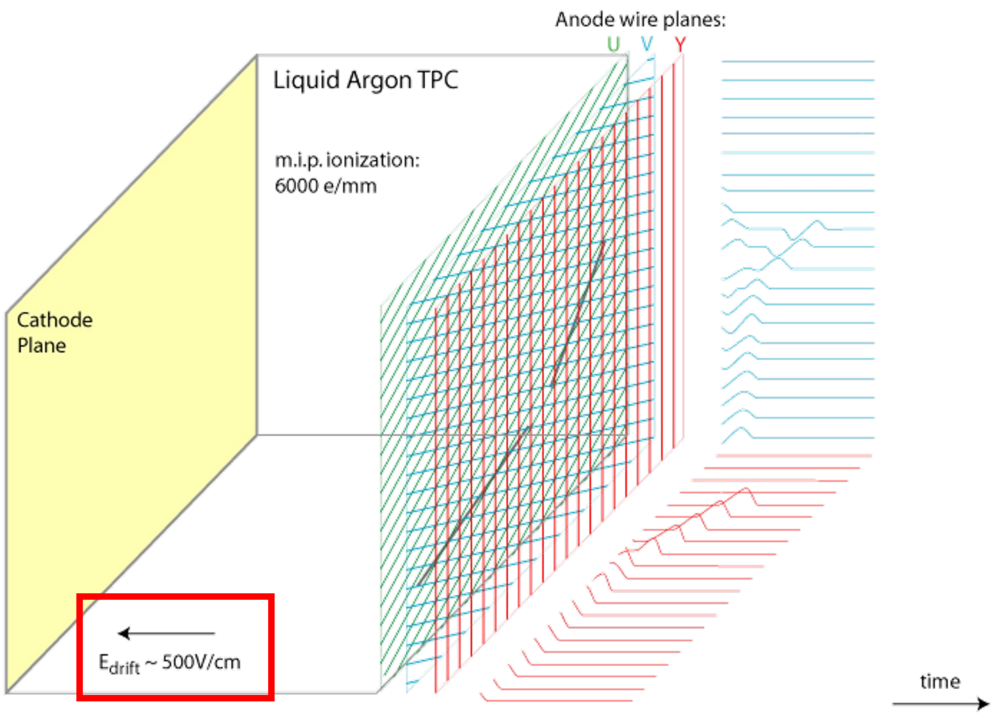

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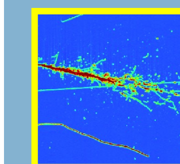
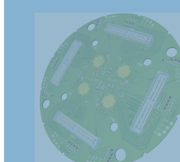
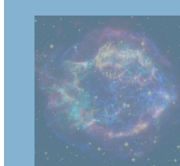
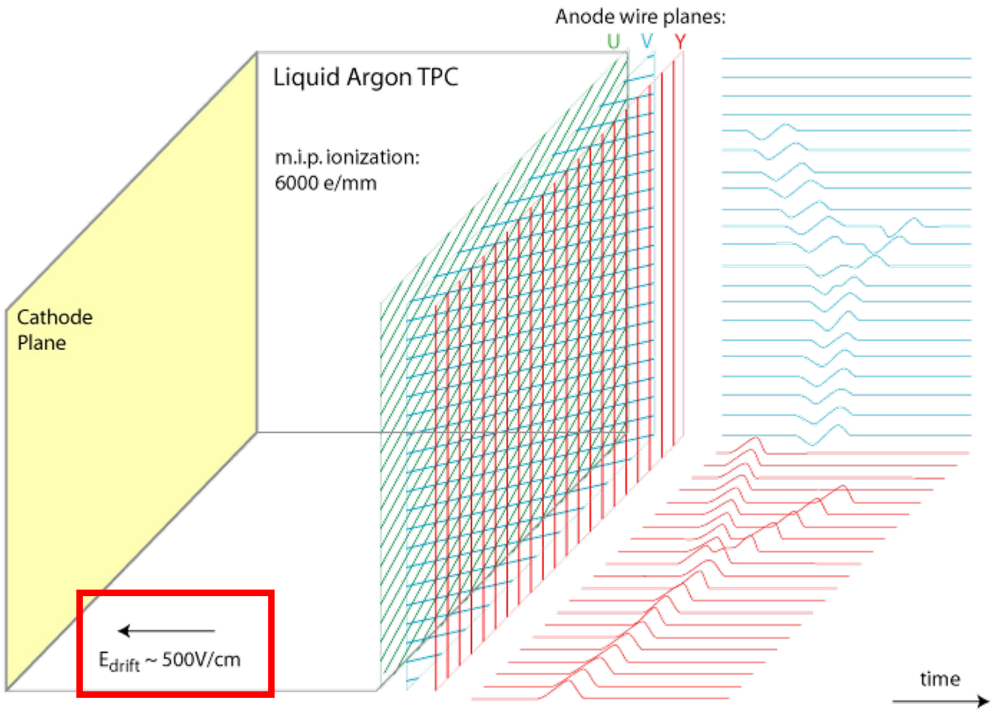






Liquid Argon Time Projection Chamber (LArTPC)



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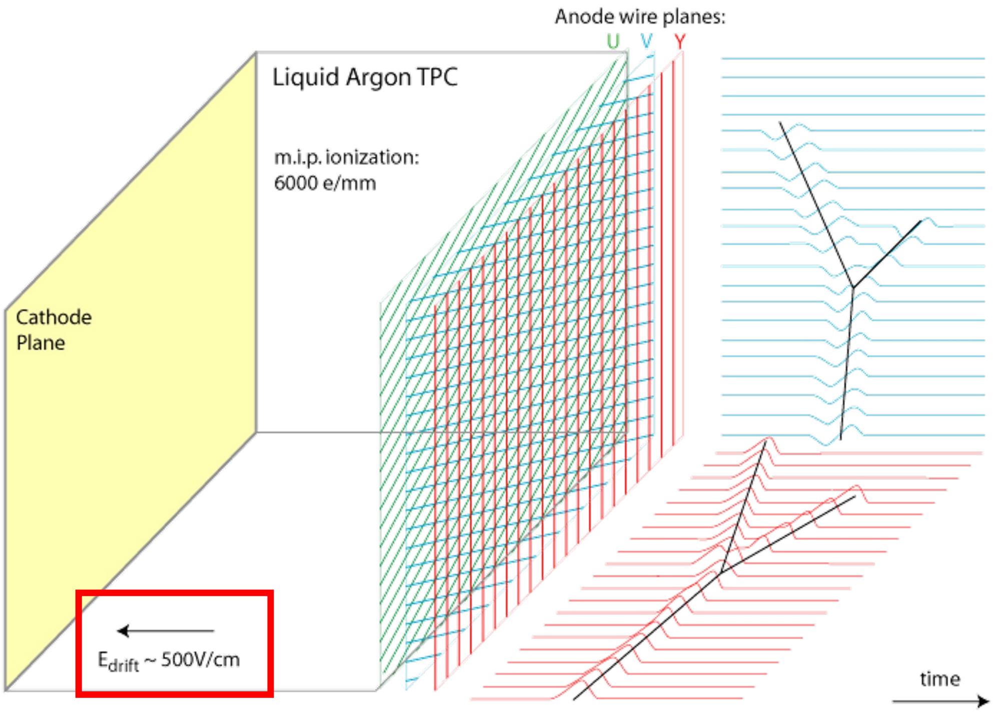

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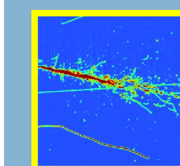

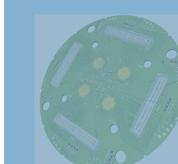

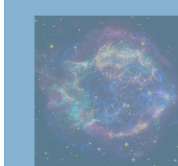

APA (Anode Plane Assembly)

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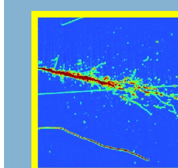
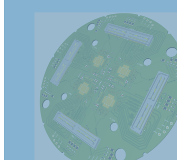
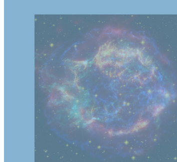
Each module has over 10,000 wires!

150 APA modules will be installed in DUNE!







How can we improve?

<u>?????</u>

New R&Ds that can maximize the potential of DUNE

<u>Wire-based LArTPC</u>

Well established technology

How can we improve?

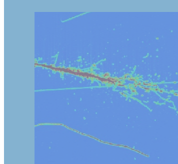
E.g. Q-Pix, LArPix

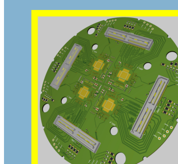
Pixel-based LArTPC

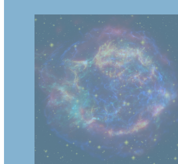
New R&Ds that can maximize the potential of DUNE

Wire-based LArTPC

Well established technology



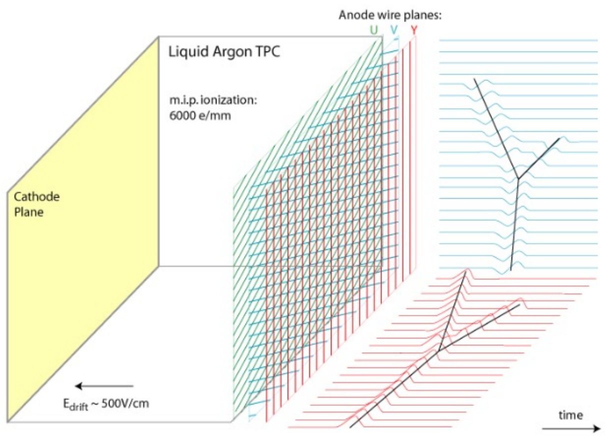


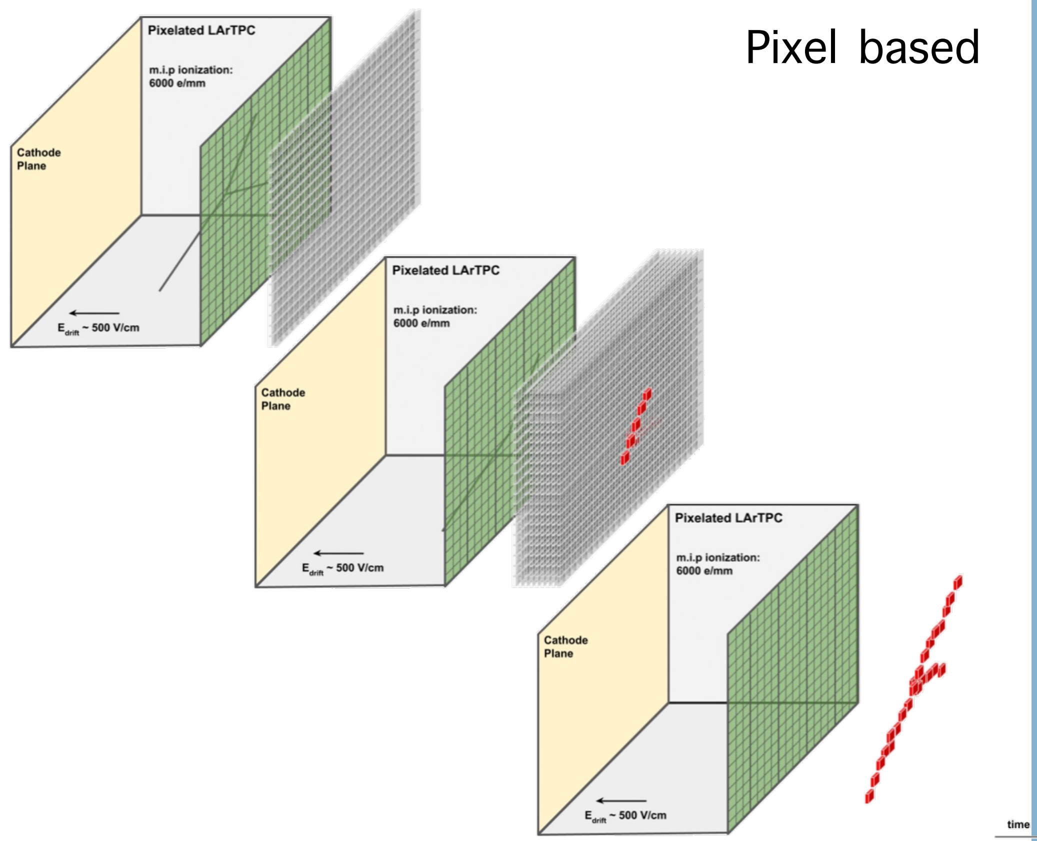


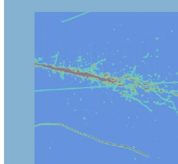
Pixelated LArTPC is the way!

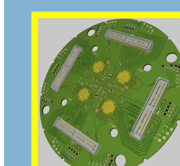
Wire based

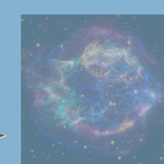
Pixel based











Pixelated LArTPC is the way!

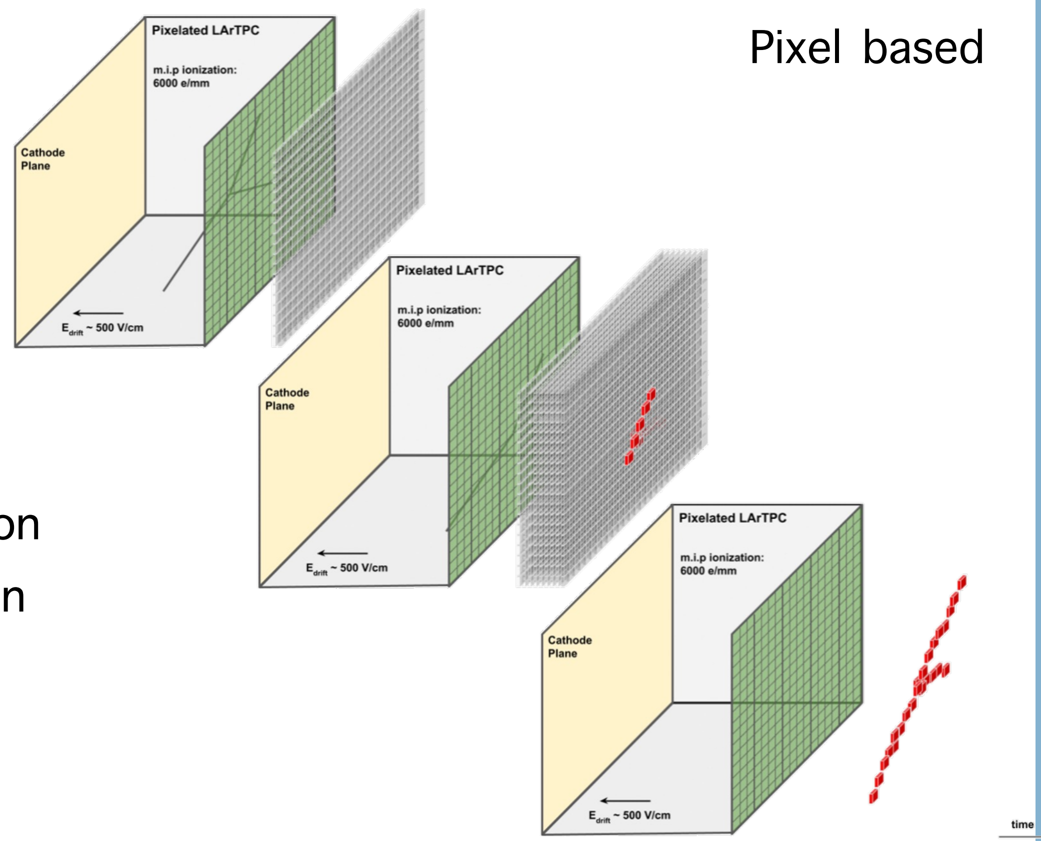
Pixel based

Challenge:

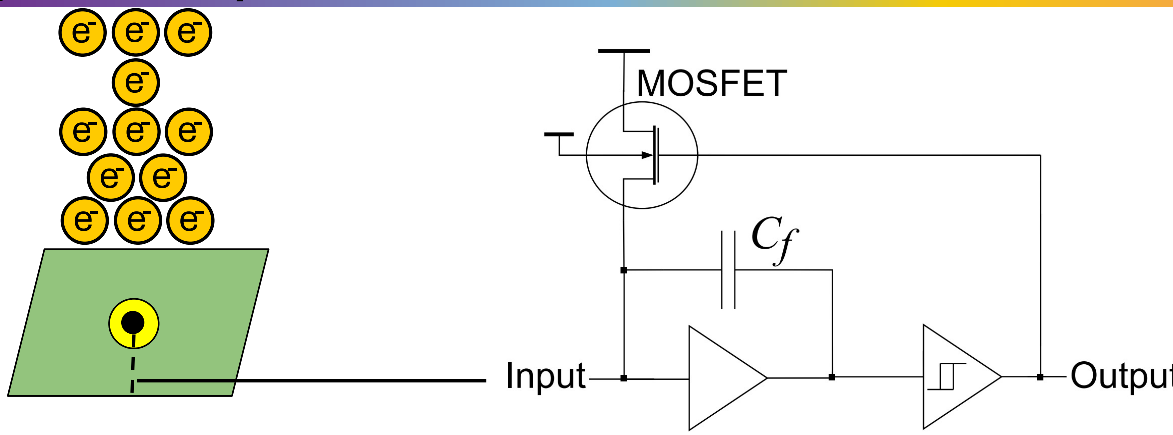
increase in the number of channels

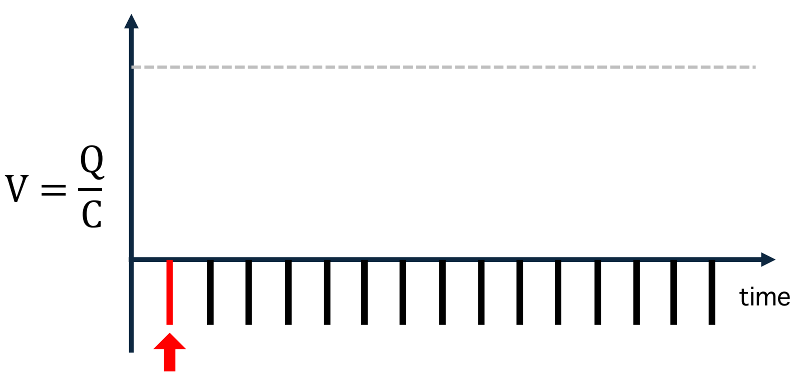
Solutions by Q-Pix:

1) Electronic principle of least action
2) New way to quantize information

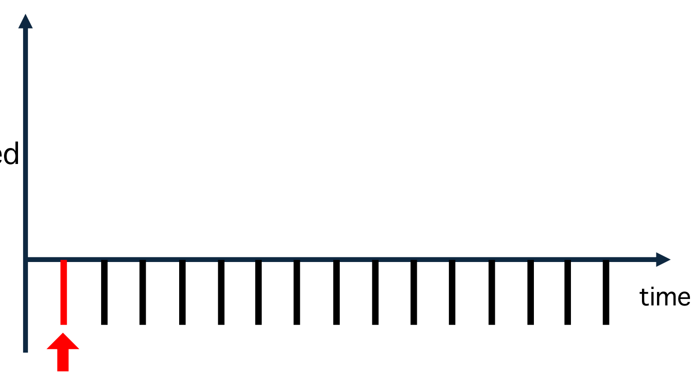


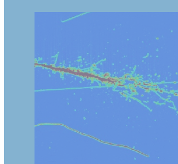
Q-Pix Toy Example

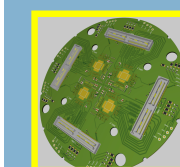


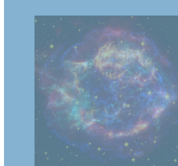


Signal recorded
By Q-Pix

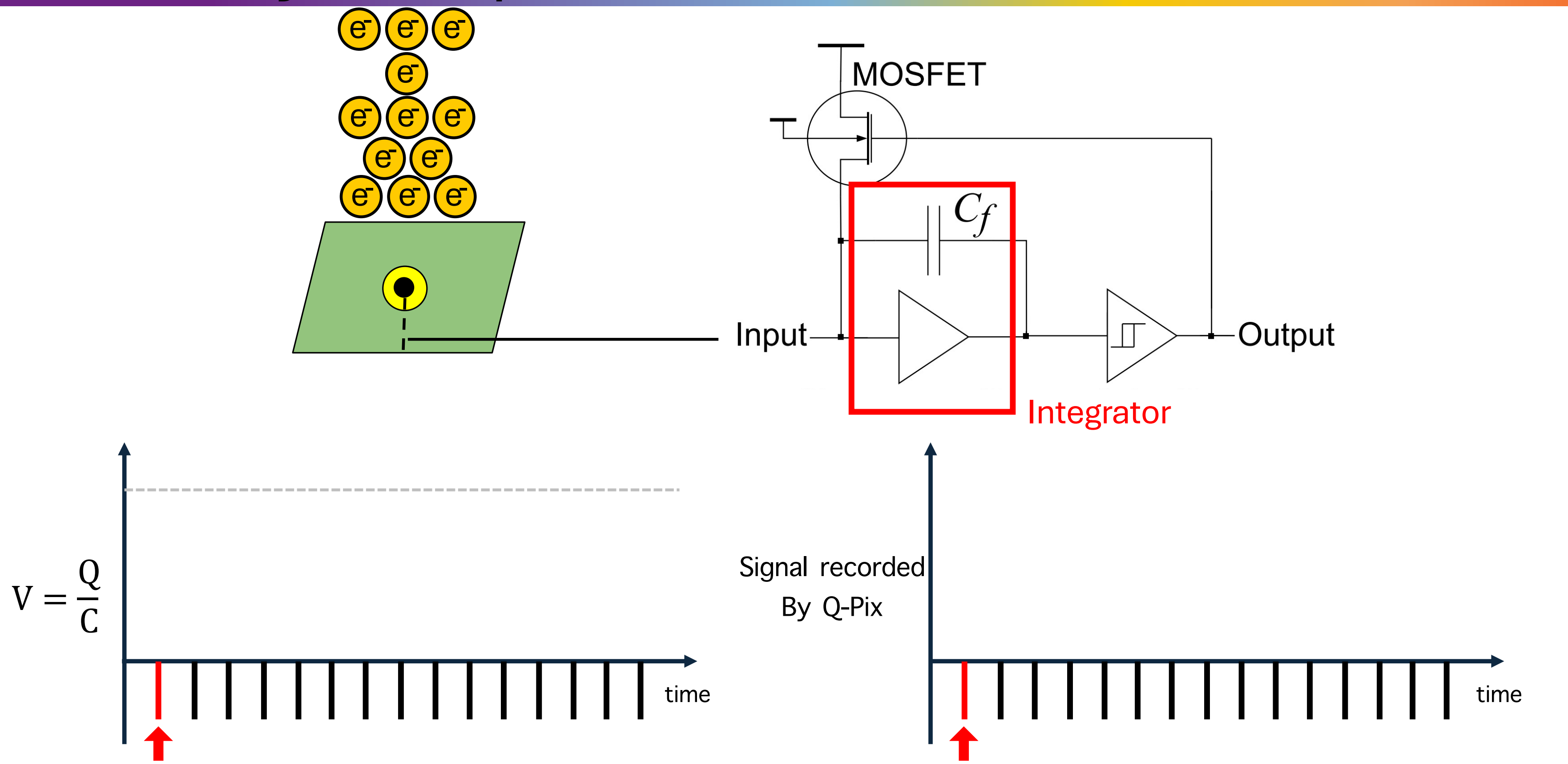




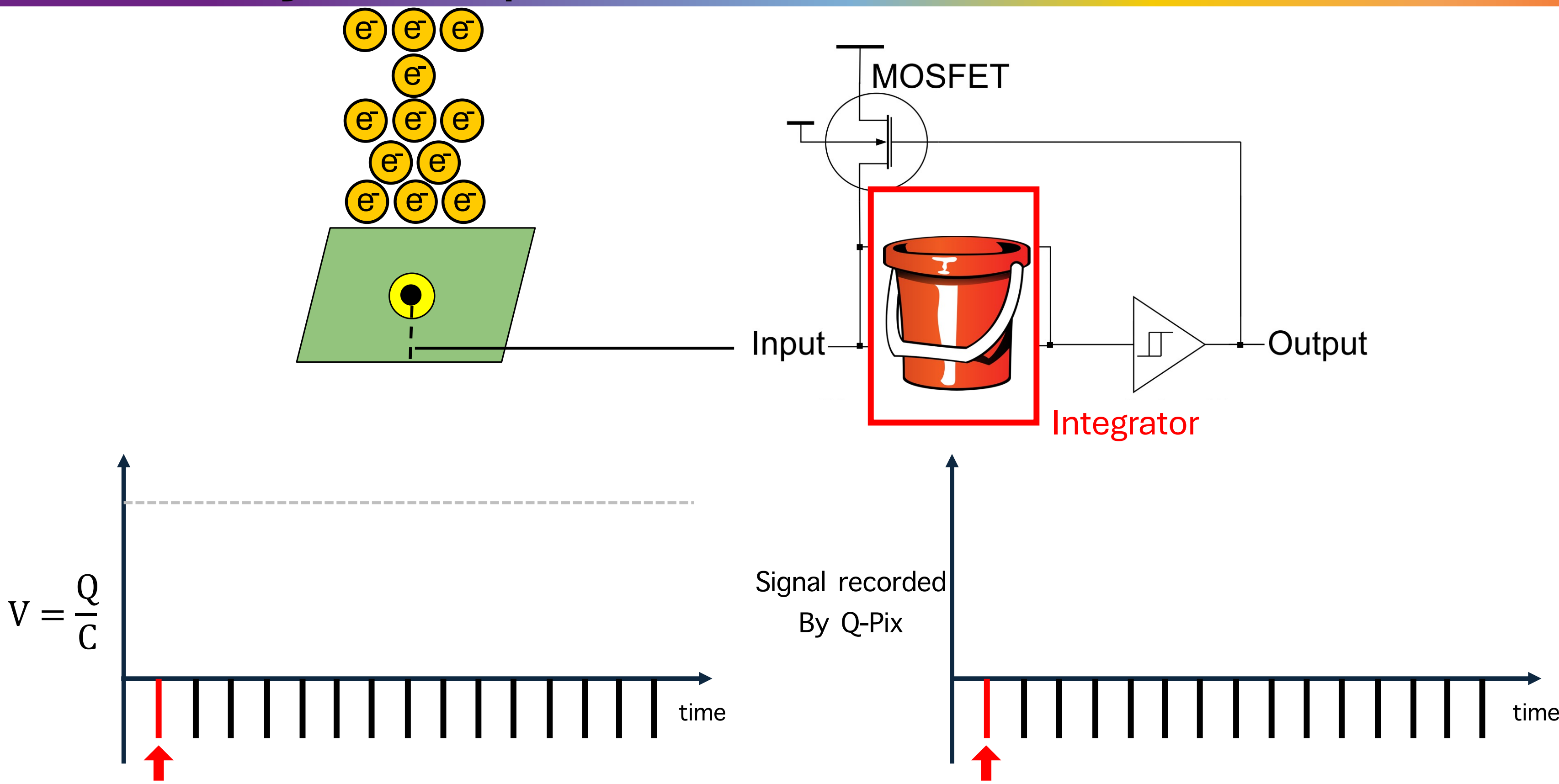


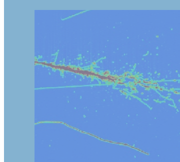


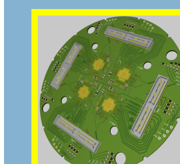
Q-Pix Toy Example

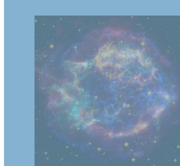


Q-Pix Toy Example

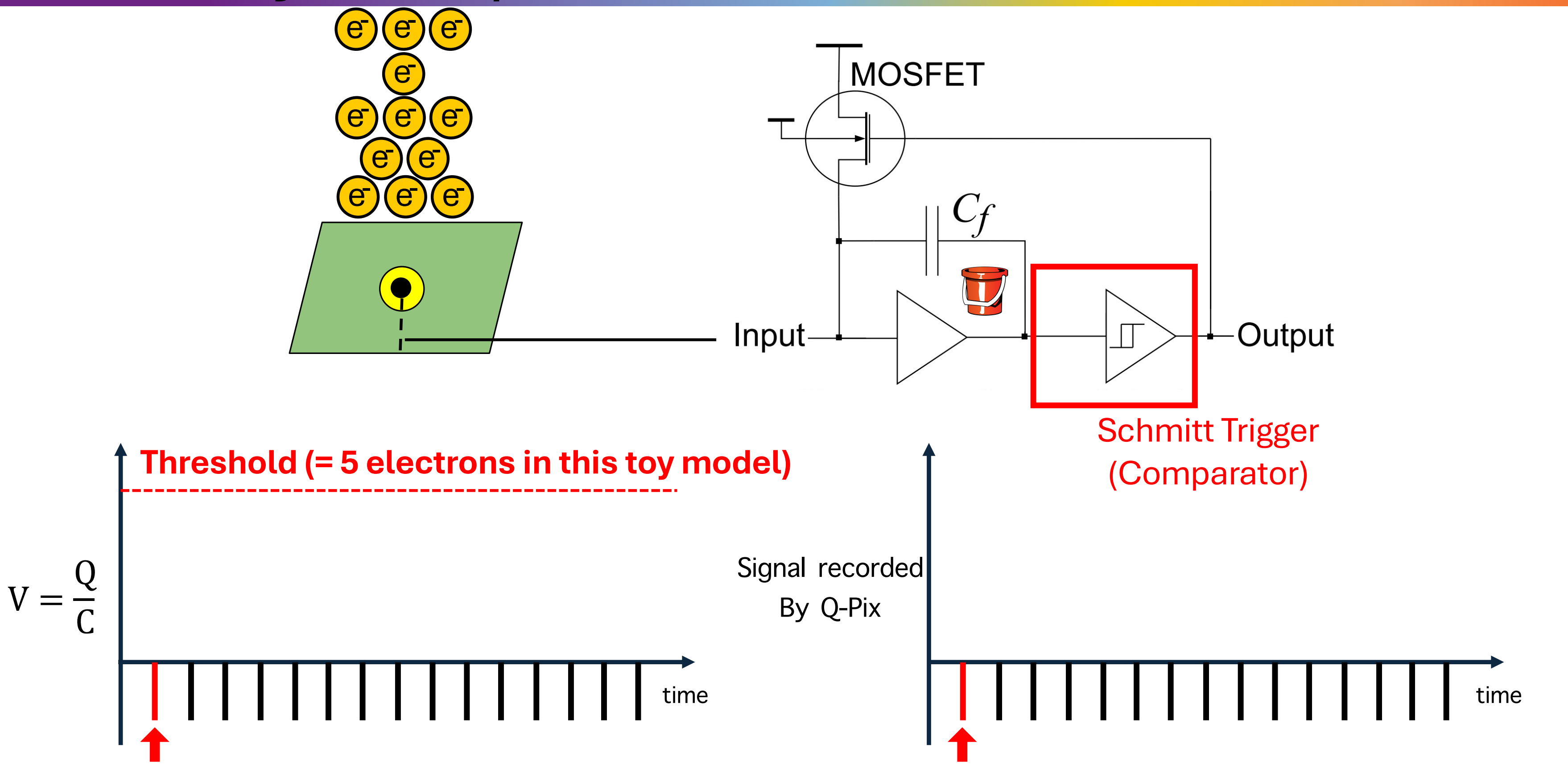




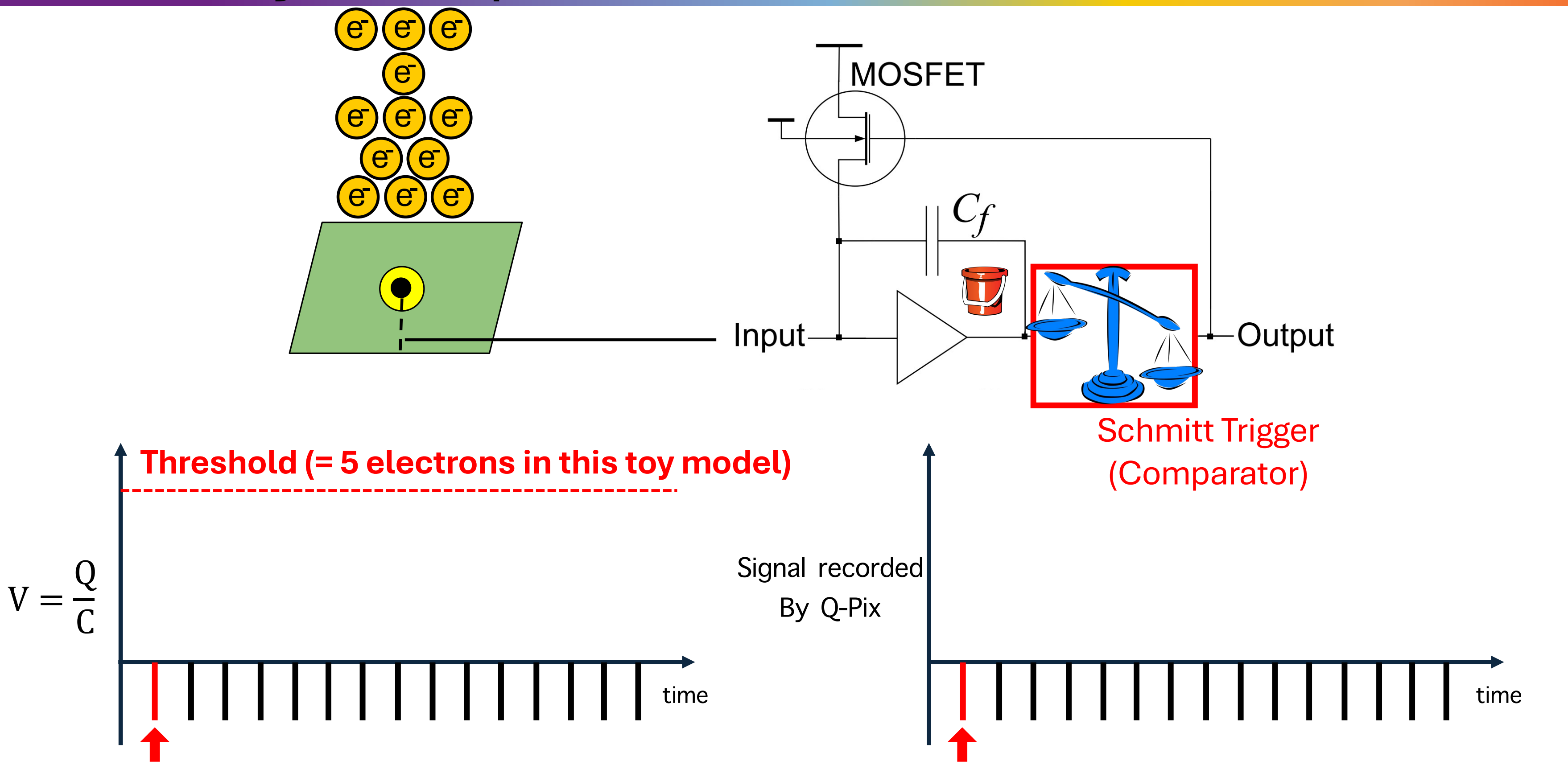


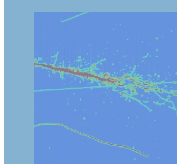


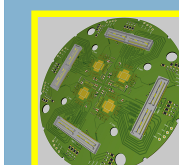
Q-Pix Toy Example

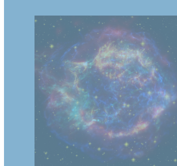


Q-Pix Toy Example

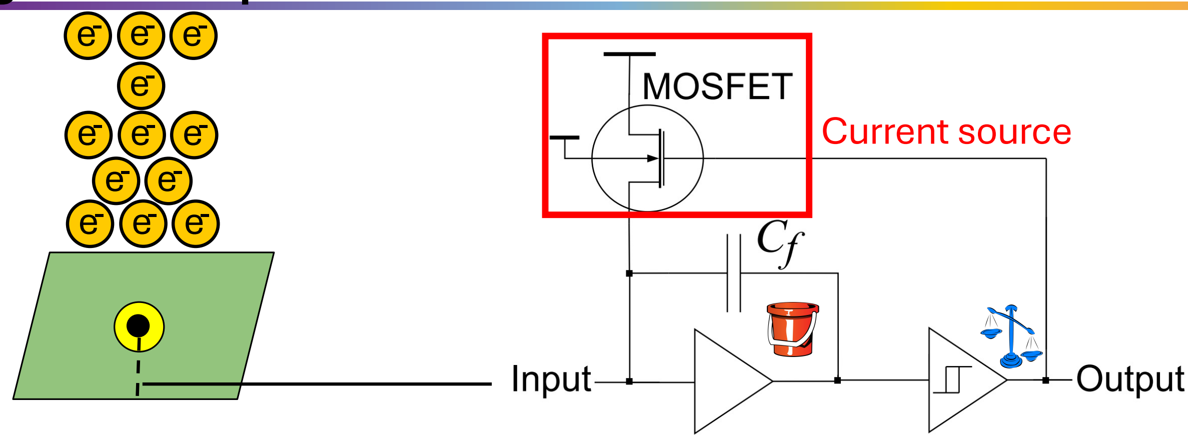


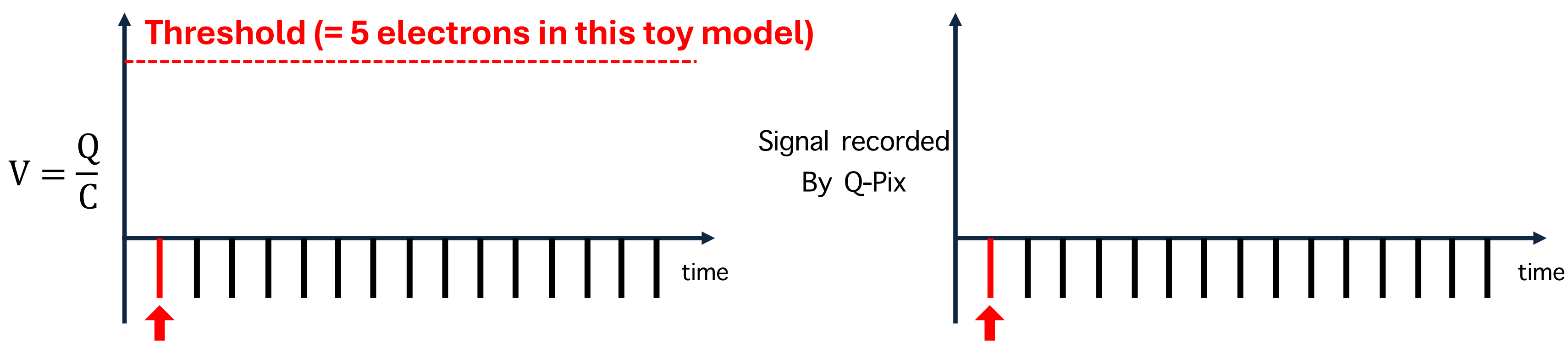






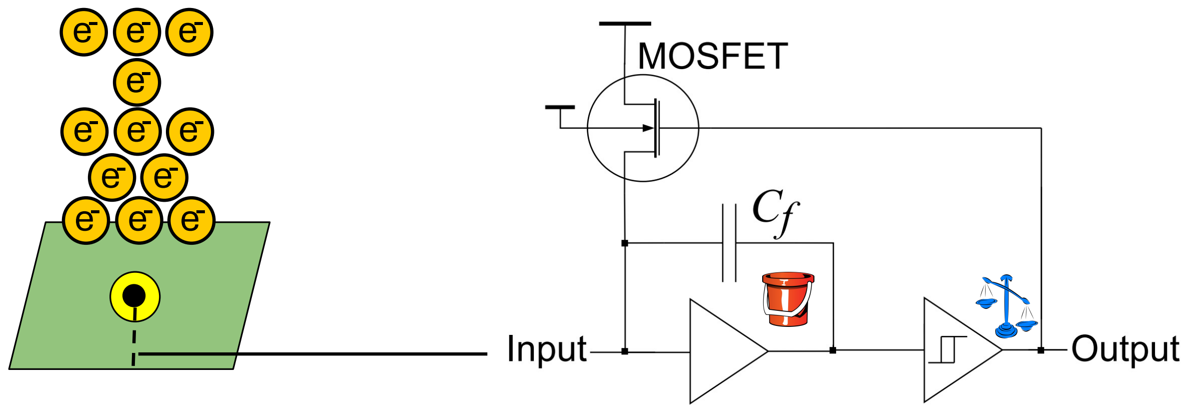
Q-Pix Toy Example

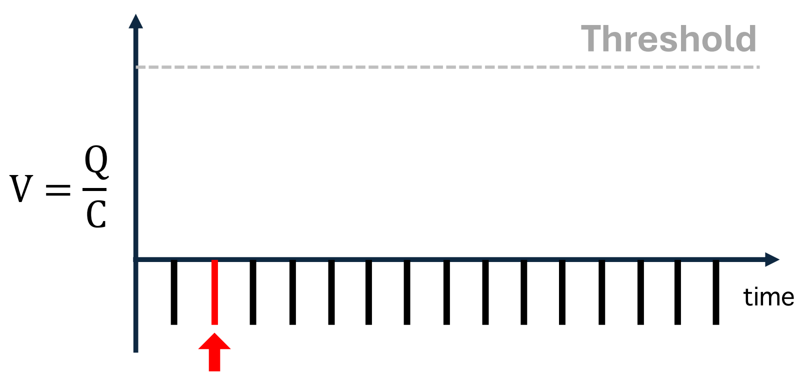


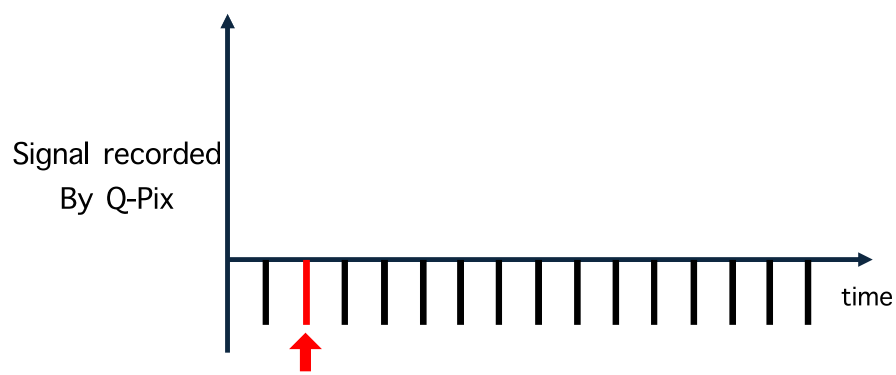


※ the signal happens for 5 electrons

Q-Pix Toy Example







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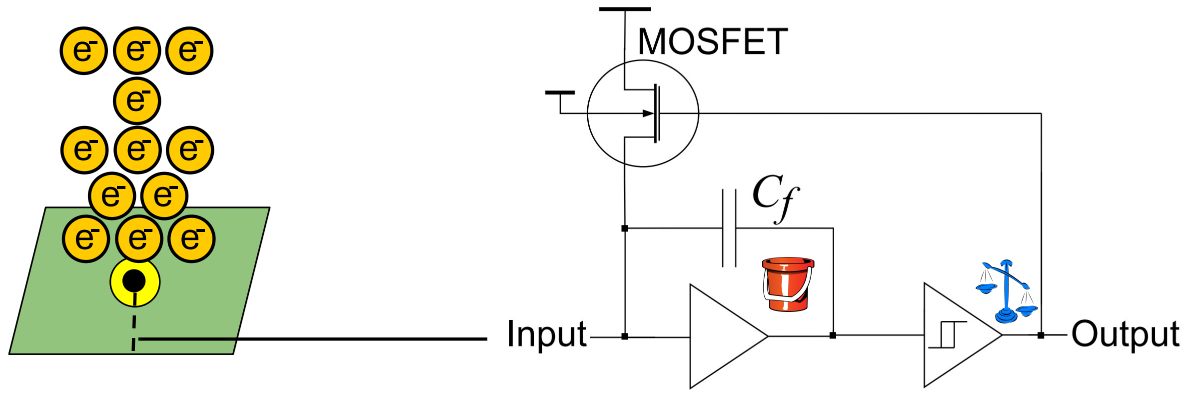
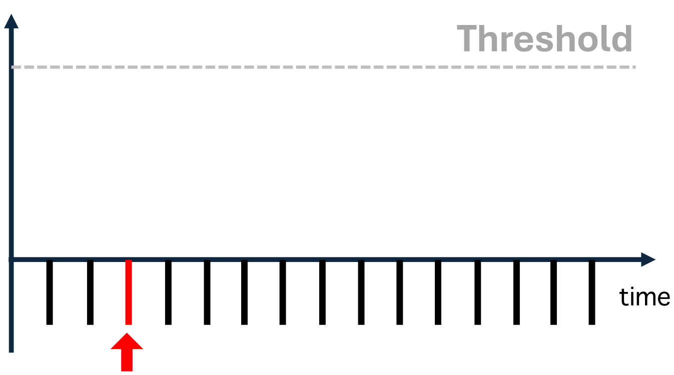
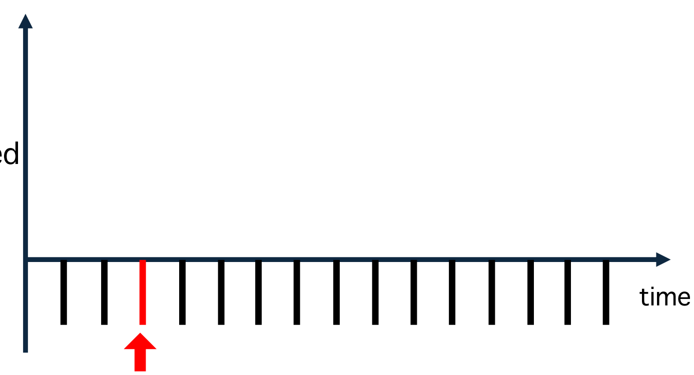
Q-Pix Toy Example





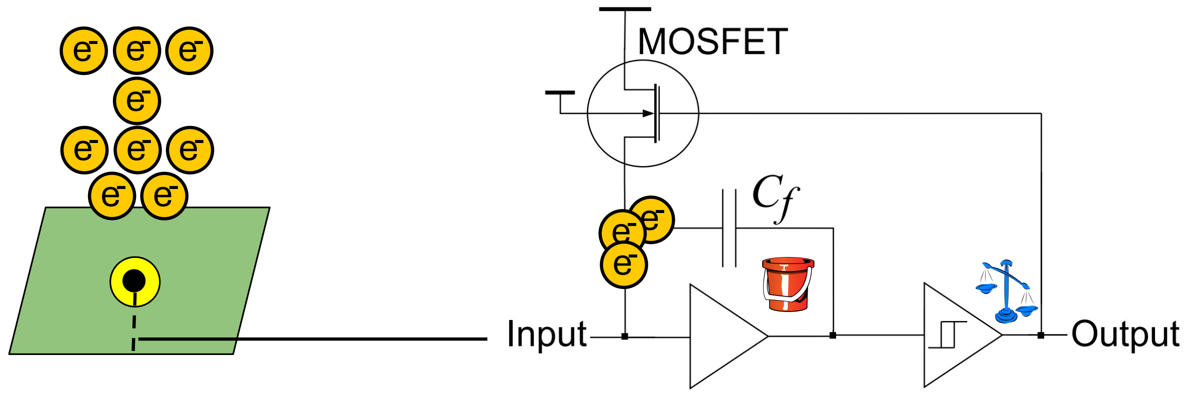
$$V = \frac{Q}{C}$$

Signal recorded
By Q-Pix

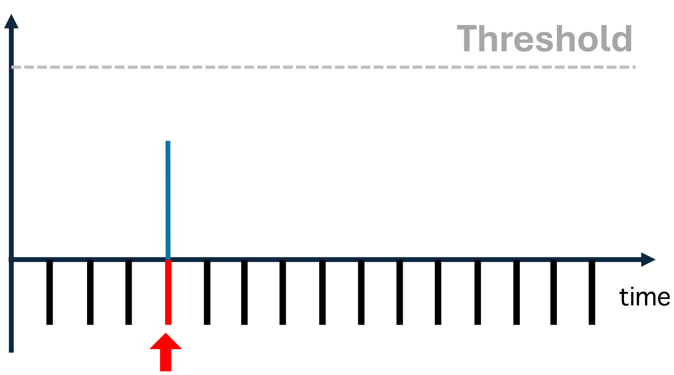


※ the signal happens for 5 electrons

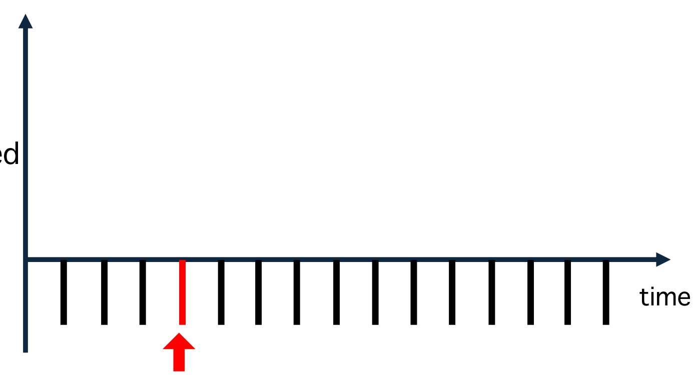
Q-Pix Toy Example



$$V = \frac{Q}{C}$$

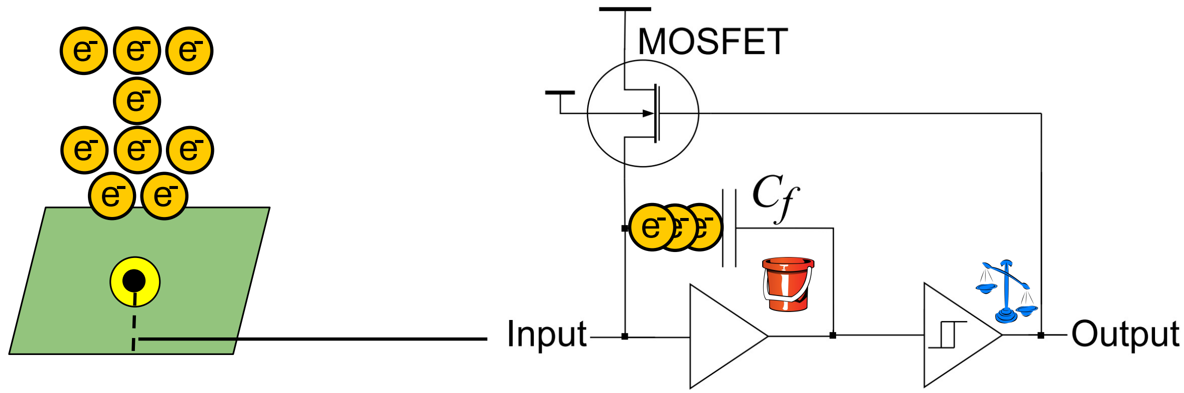


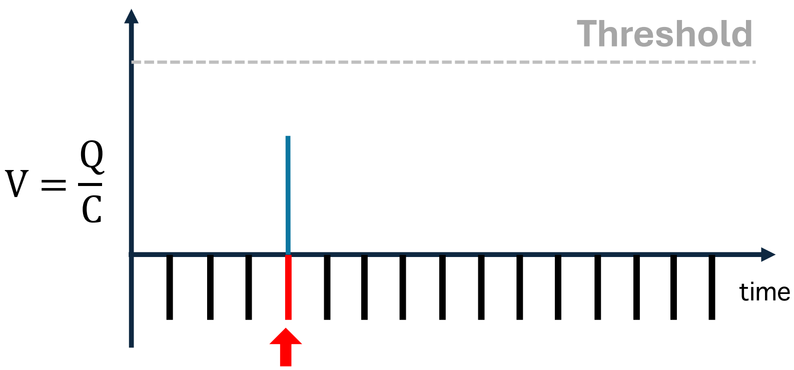
Signal recorded
By Q-Pix



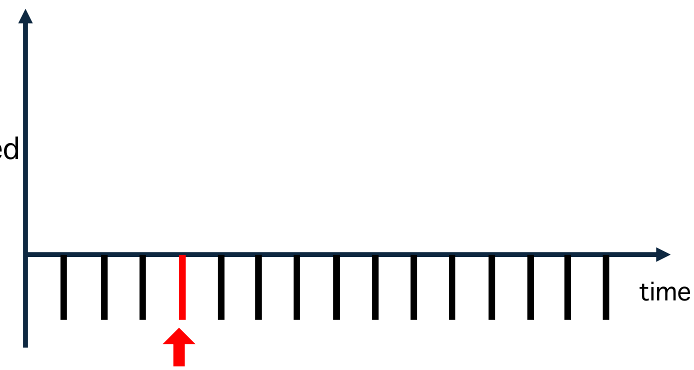
※ the signal happens for 5 electrons

Q-Pix Toy Example

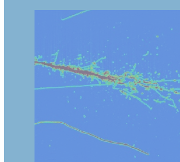


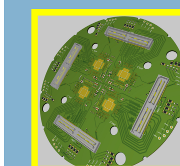


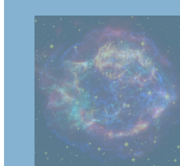
Signal recorded
By Q-Pix



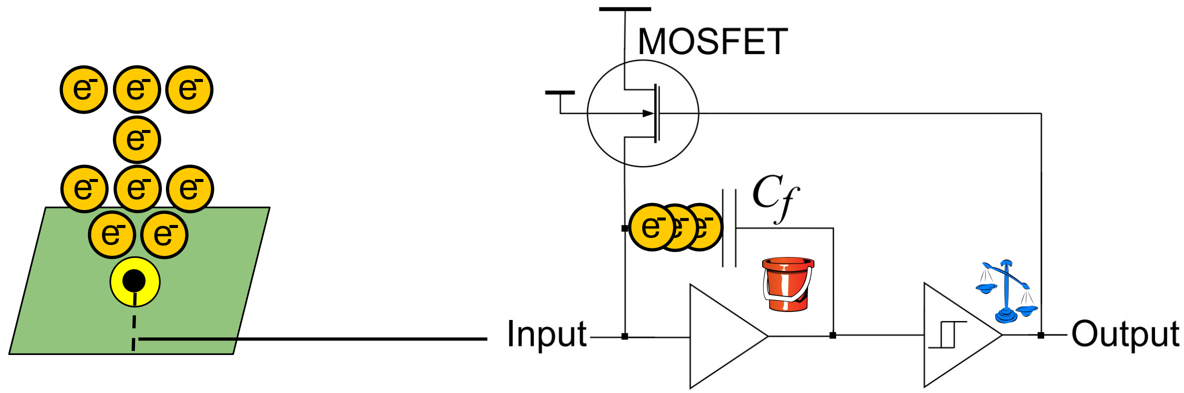
※ the signal happens for 5 electrons

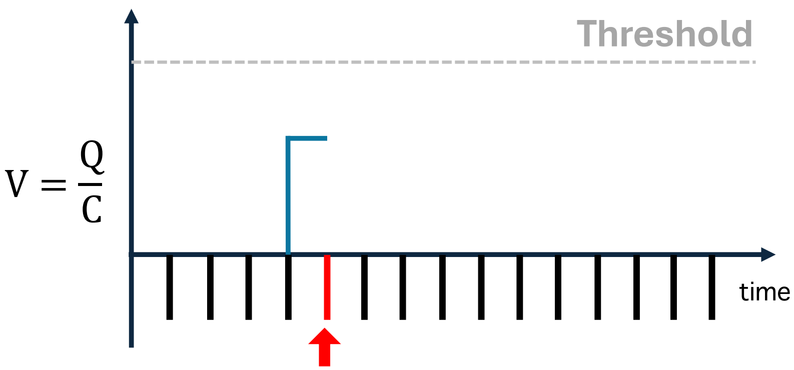


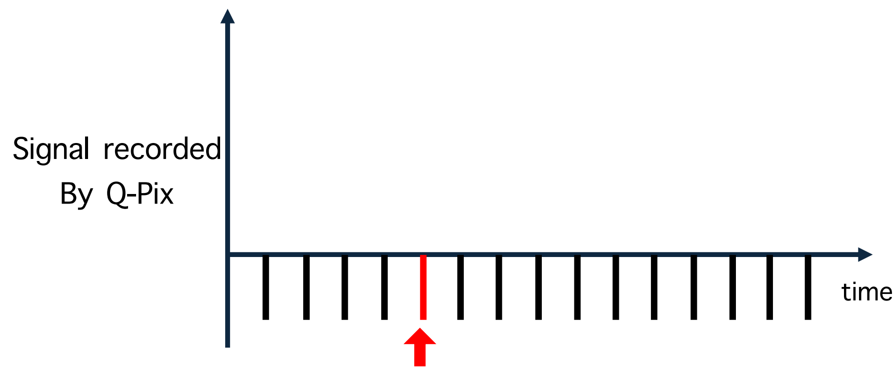




Q-Pix Toy Example







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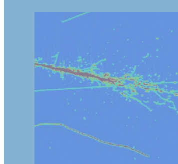
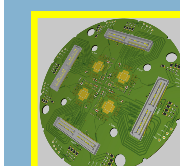
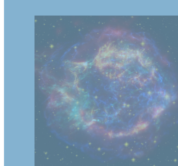
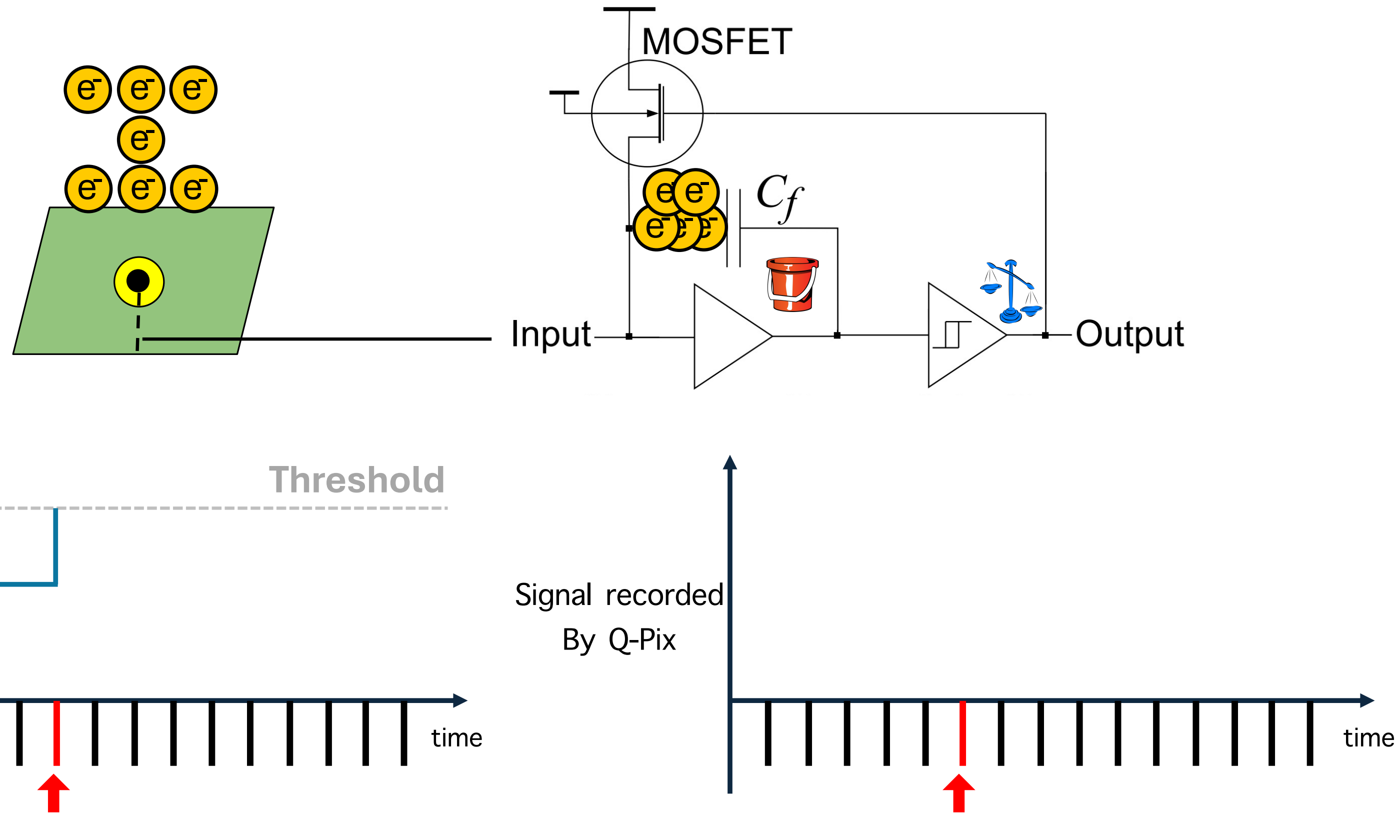




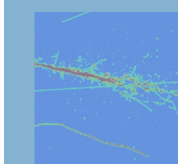


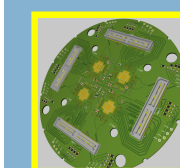
Q-Pix Toy Example

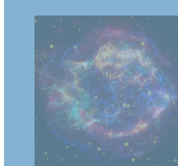


$$V = \frac{Q}{C}$$

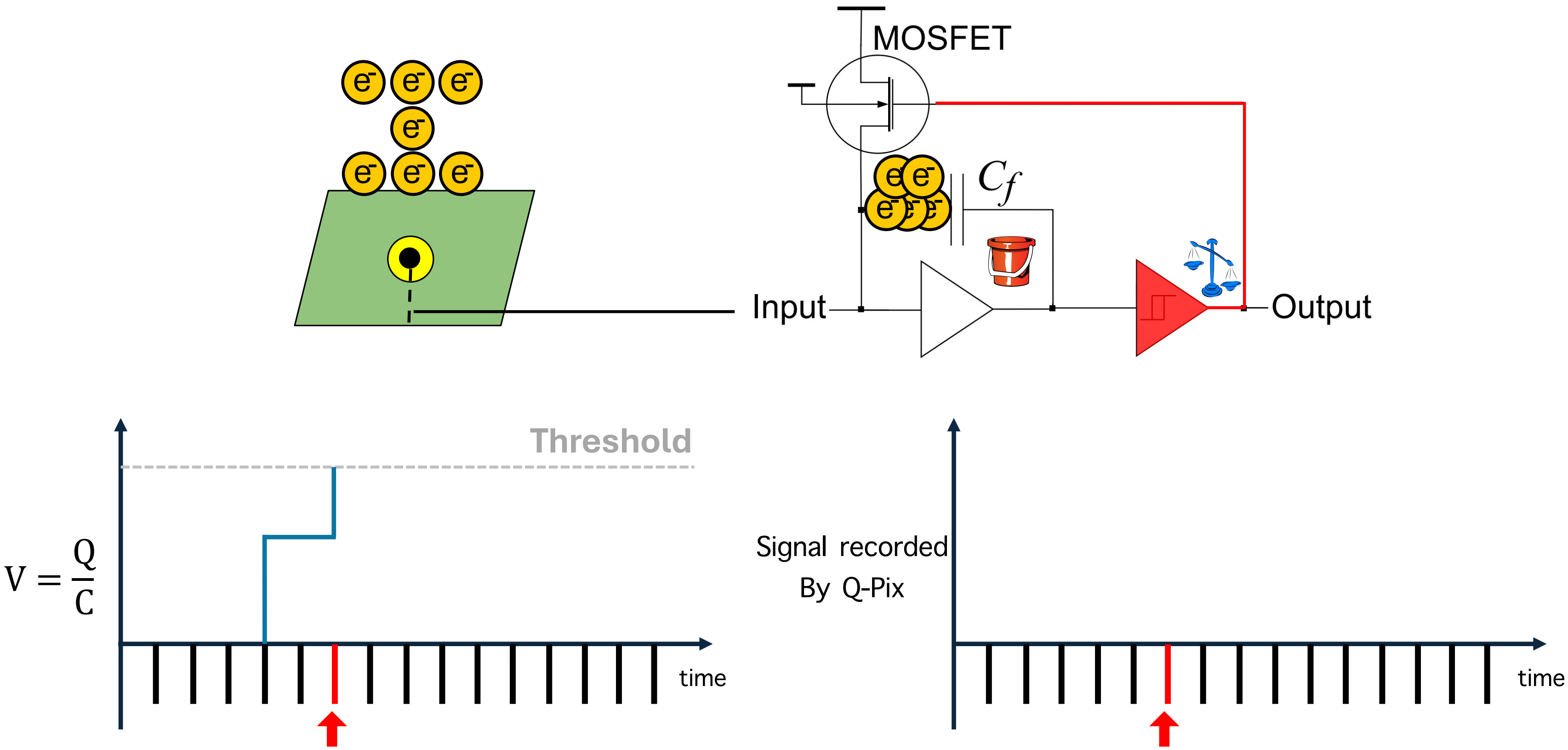
※ the signal happens for 5 electrons







Q-Pix Toy Example



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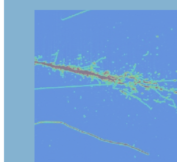
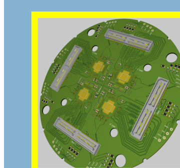
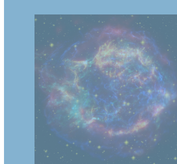
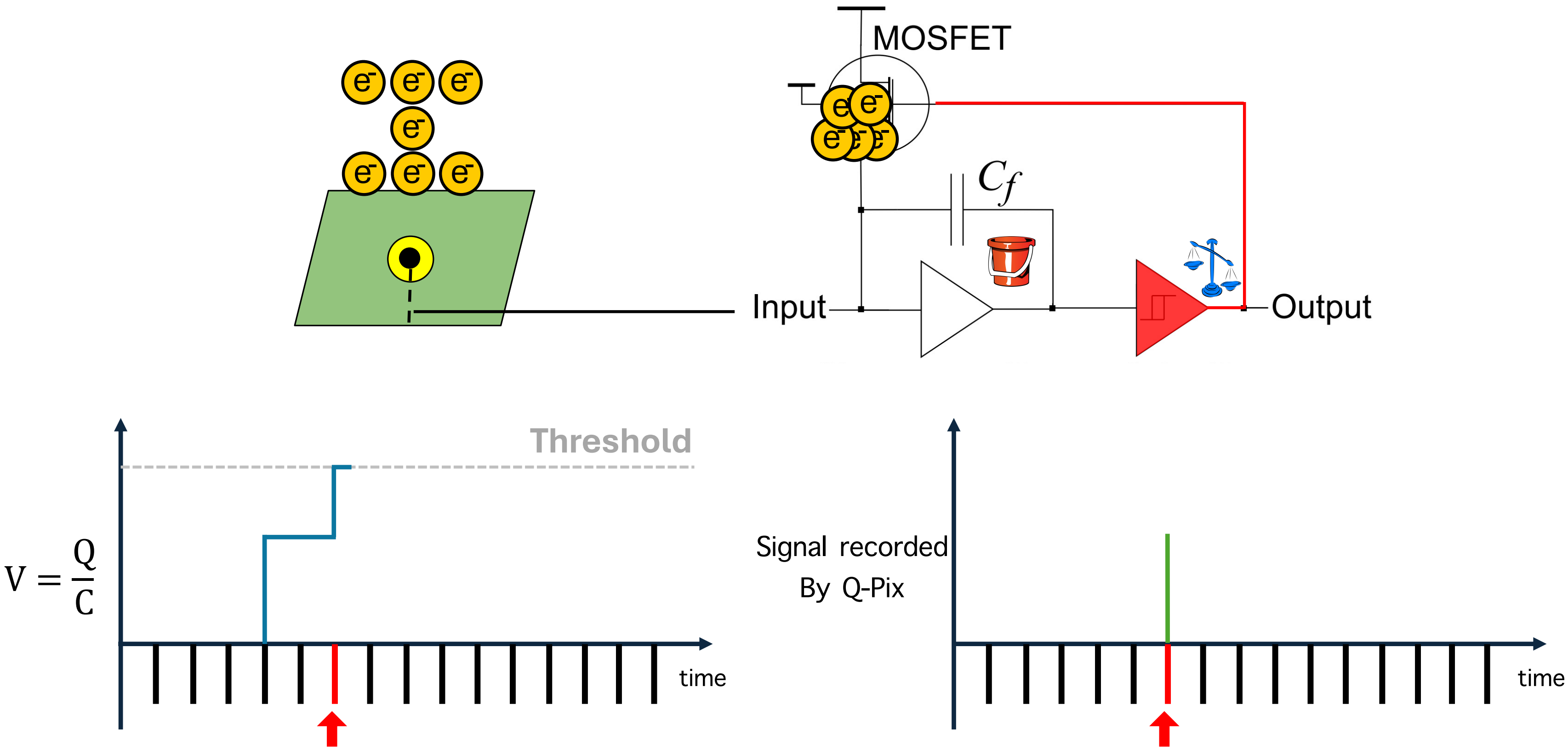


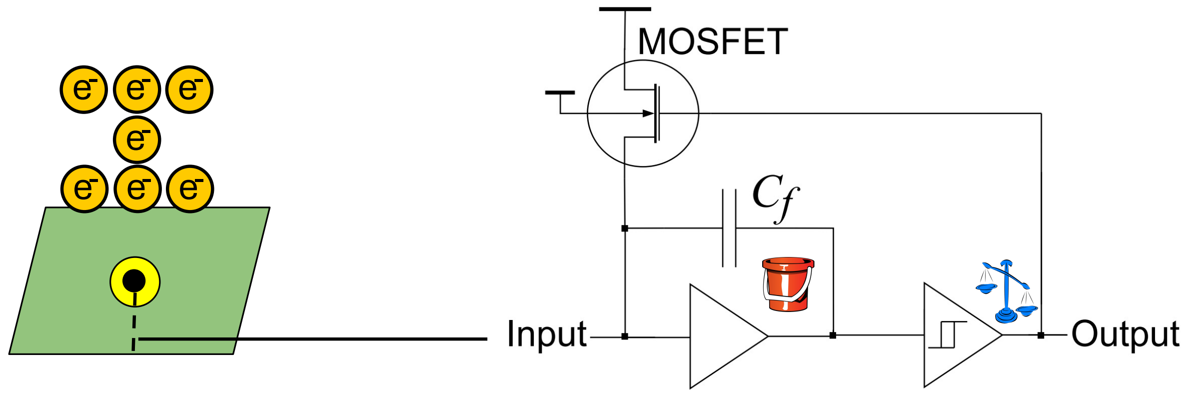


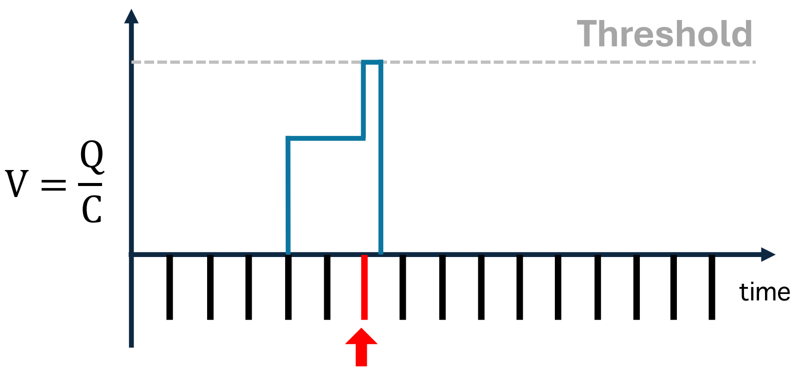


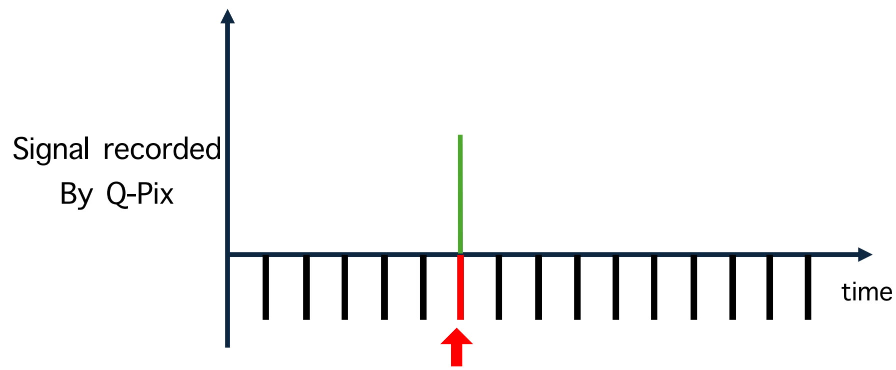
Q-Pix Toy Example



Q-Pix Toy Example

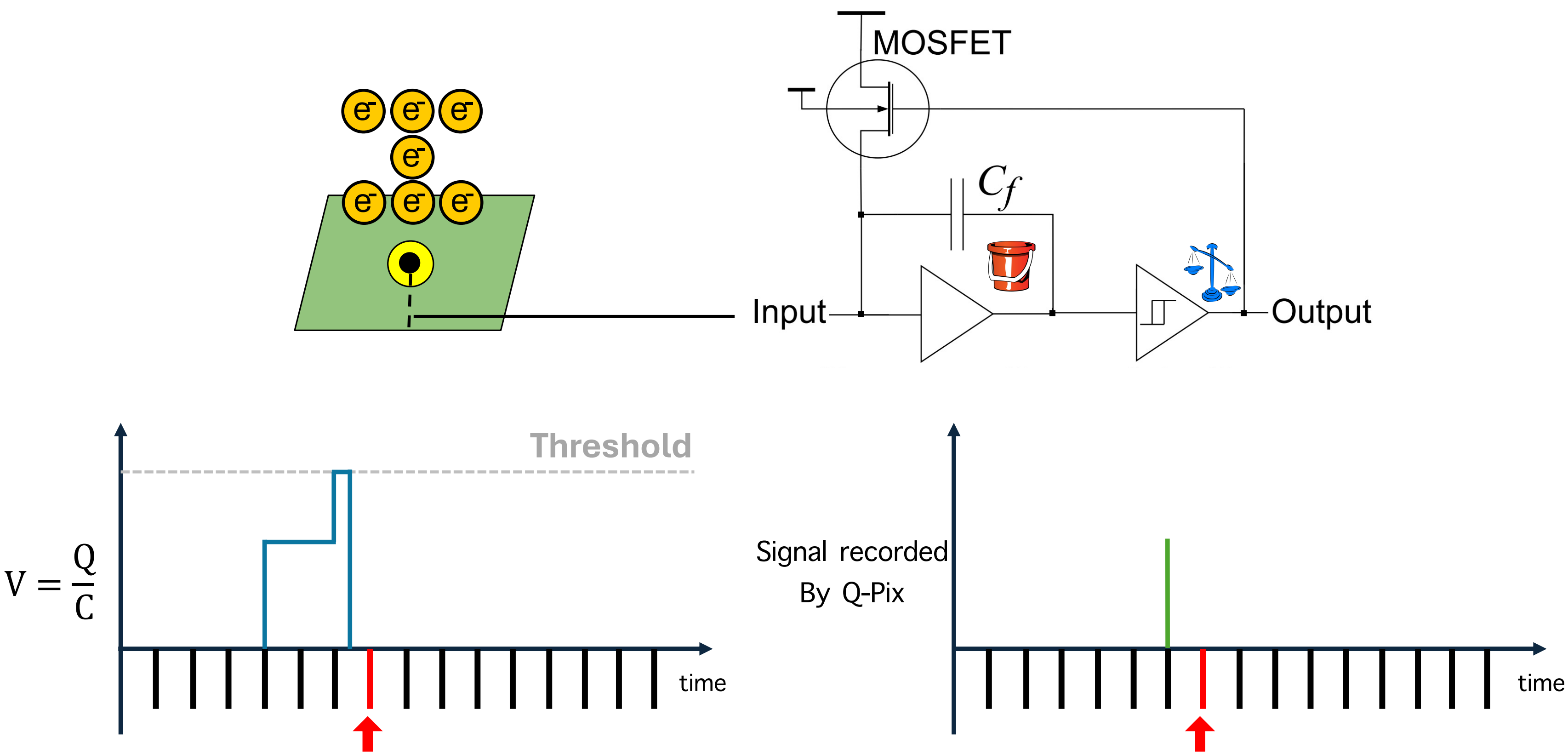






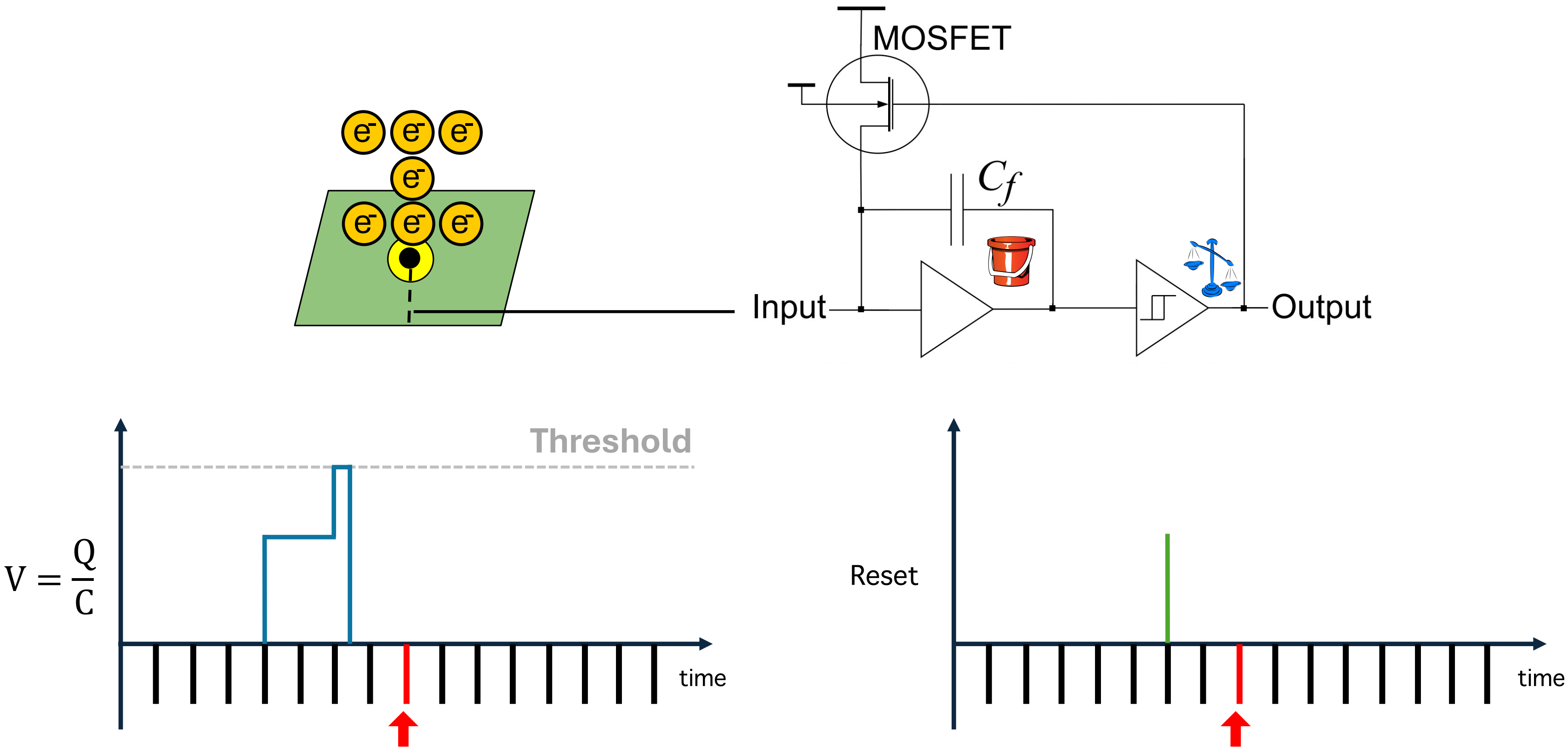
※ the signal happens for 5 electrons

Q-Pix Toy Example



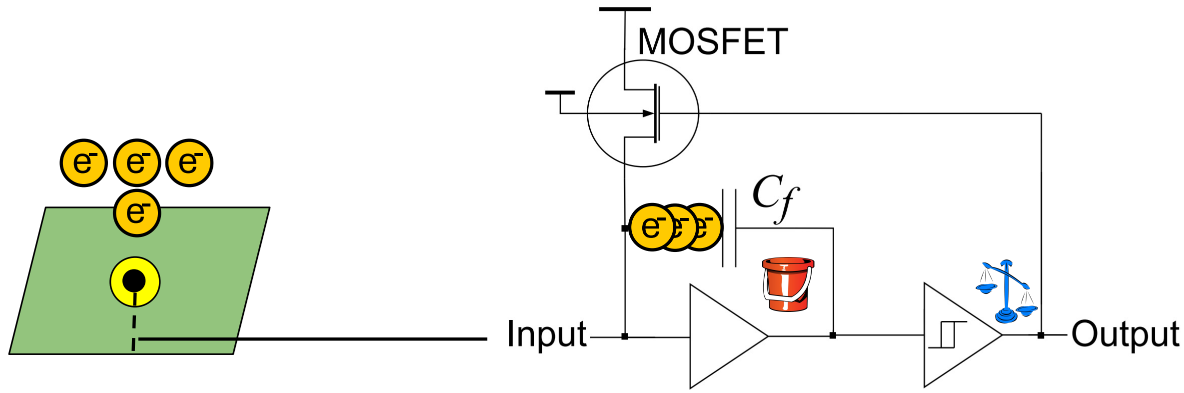
※ the reset happens for 5 electrons

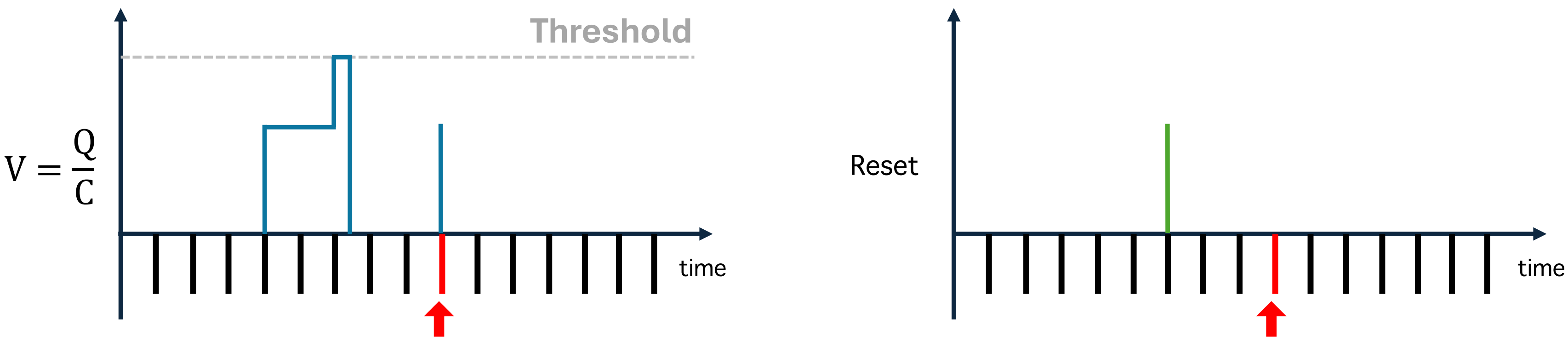
Q-Pix Toy Example



※ the reset happens for 5 electrons

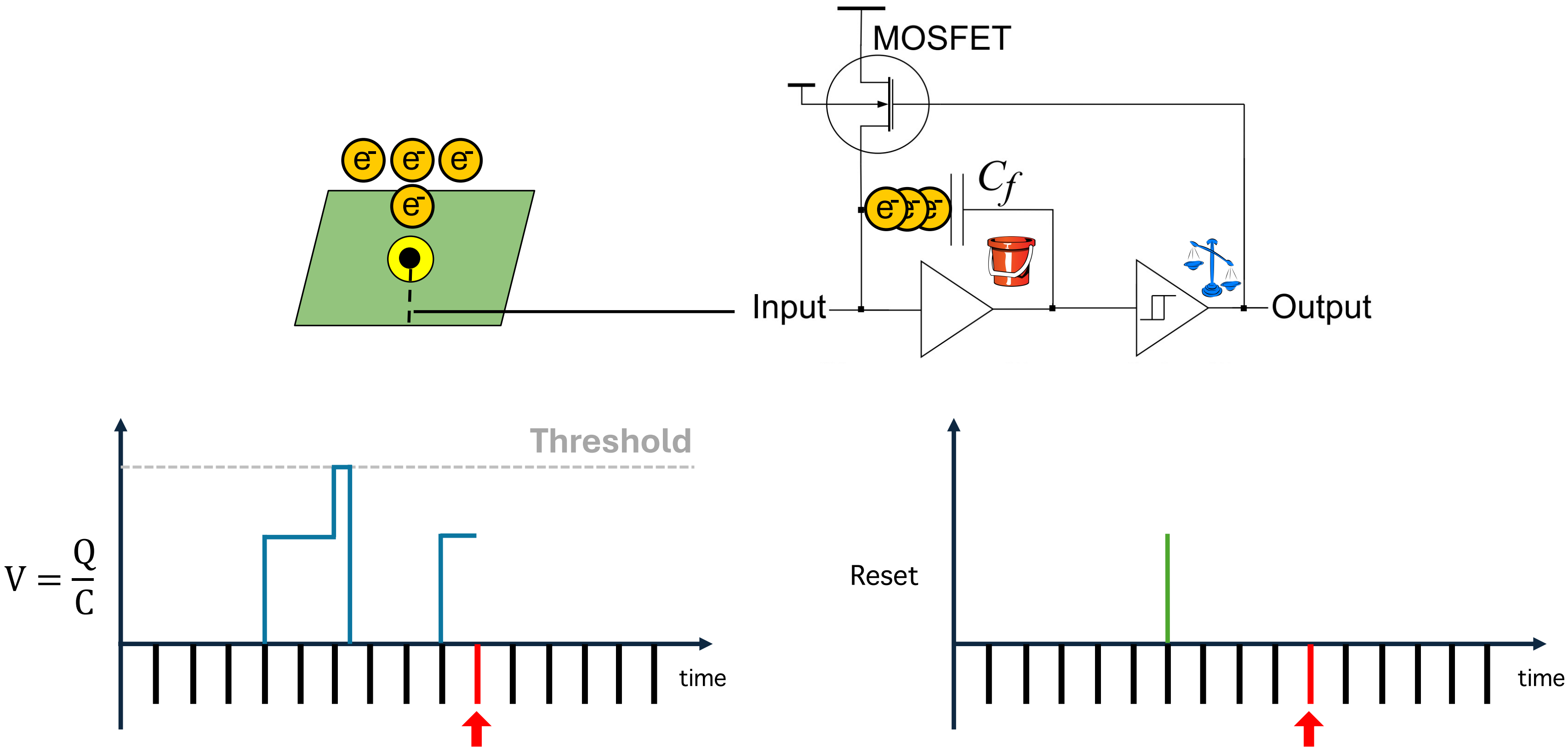
Q-Pix Toy Example





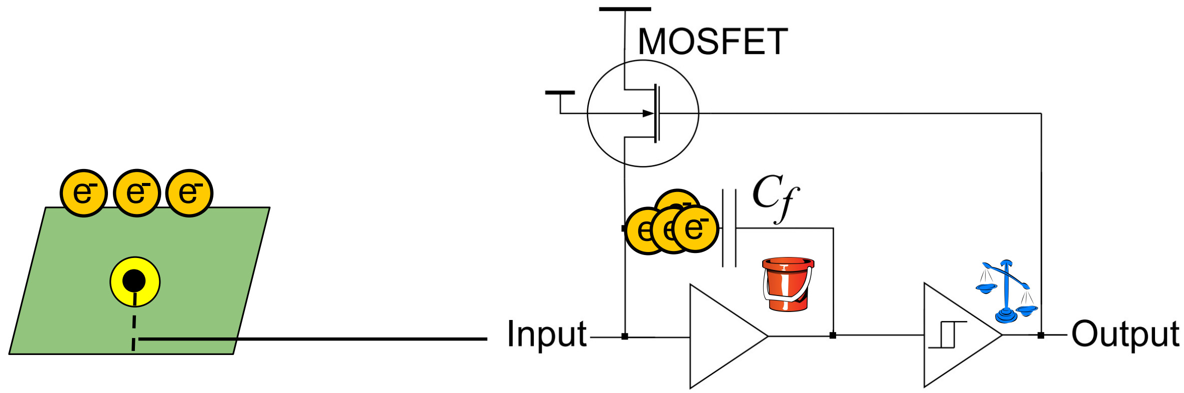
※ the reset happens for 5 electrons

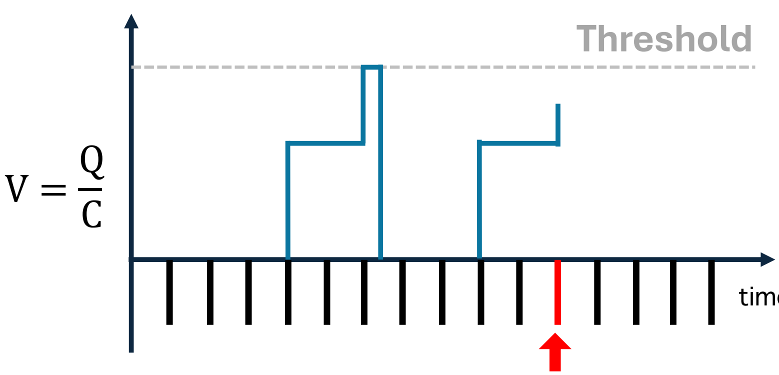
Q-Pix Toy Example

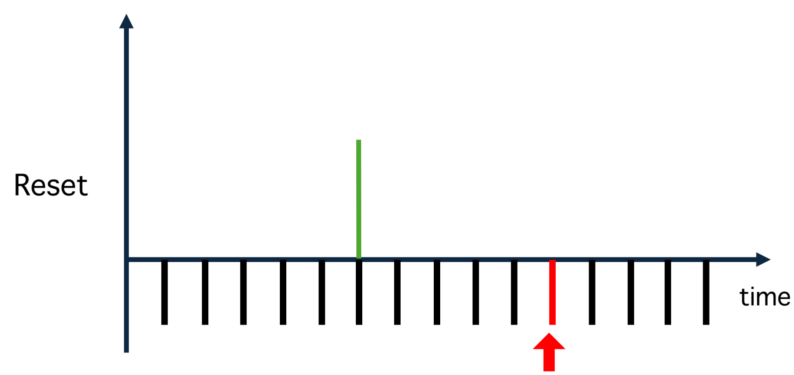


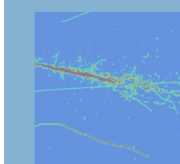
※ the reset happens for 5 electrons

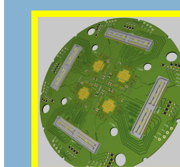
Q-Pix Toy Example

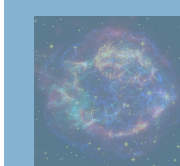




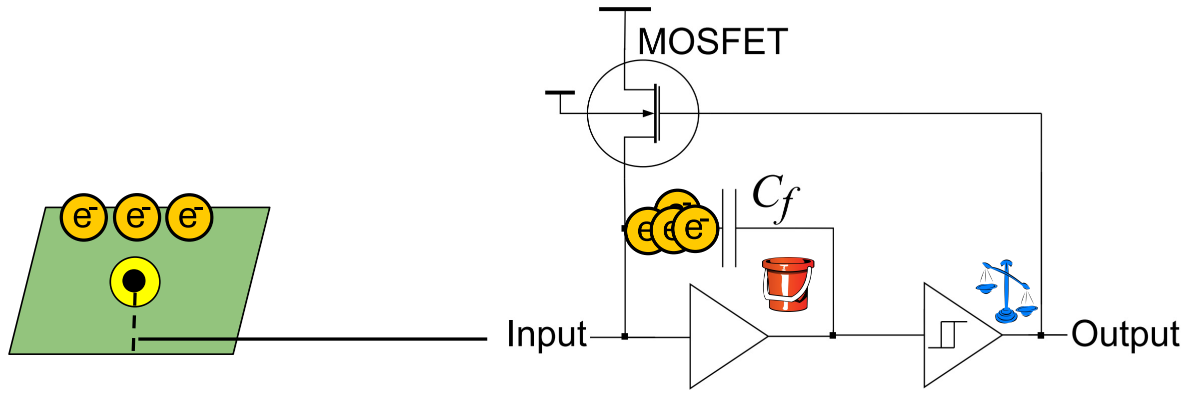


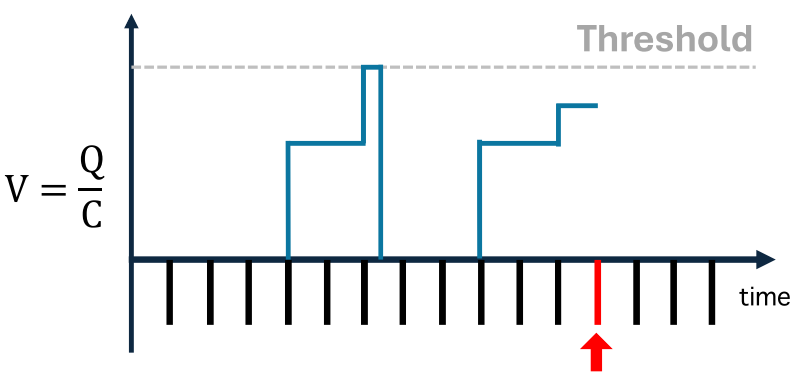


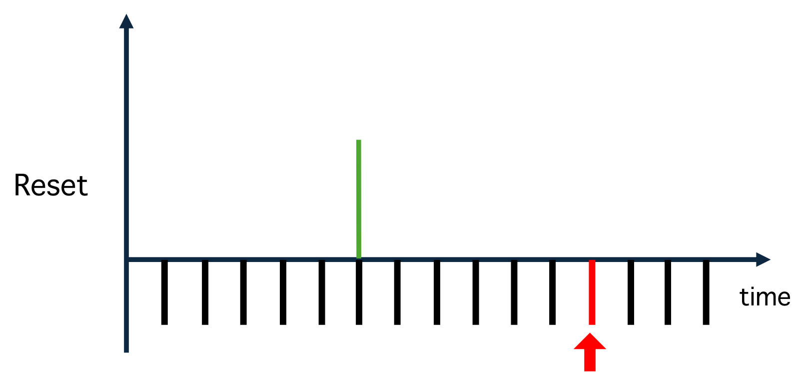




Q-Pix Toy Example

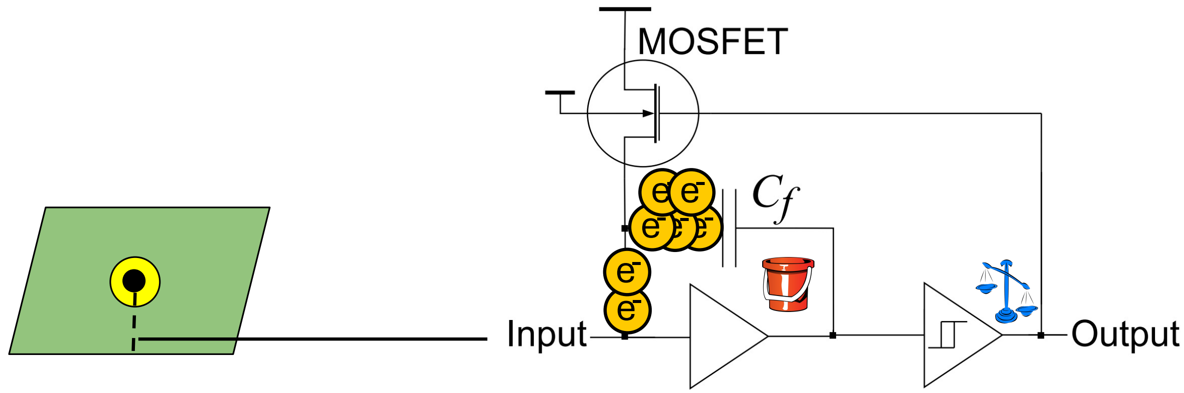


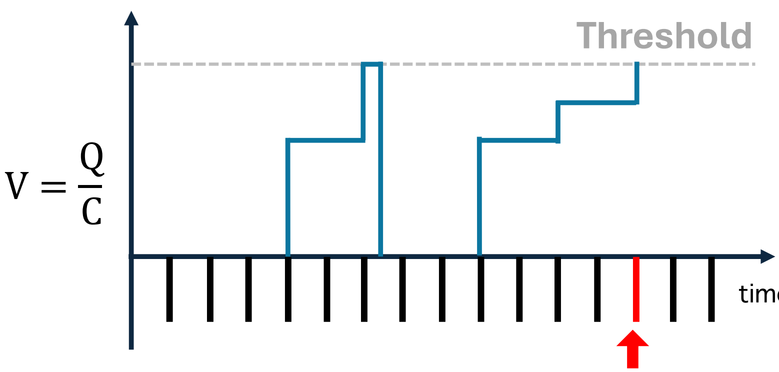


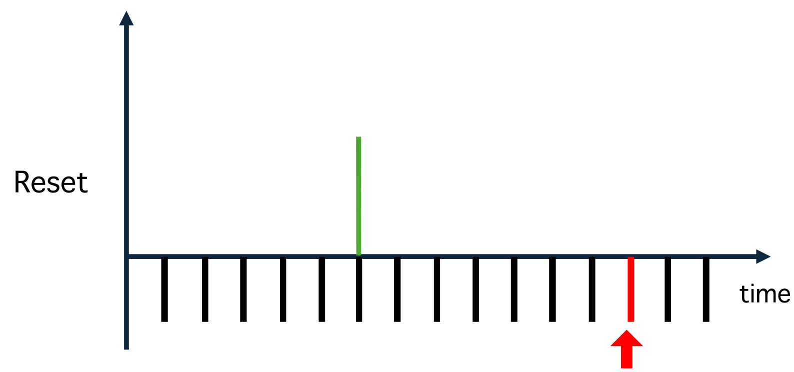


※ the reset happens for 5 electrons

Q-Pix Toy Example

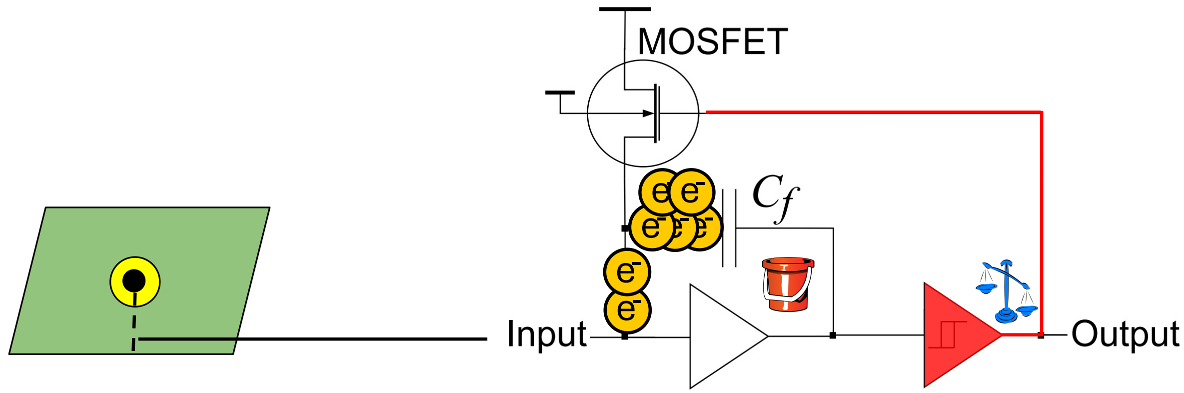


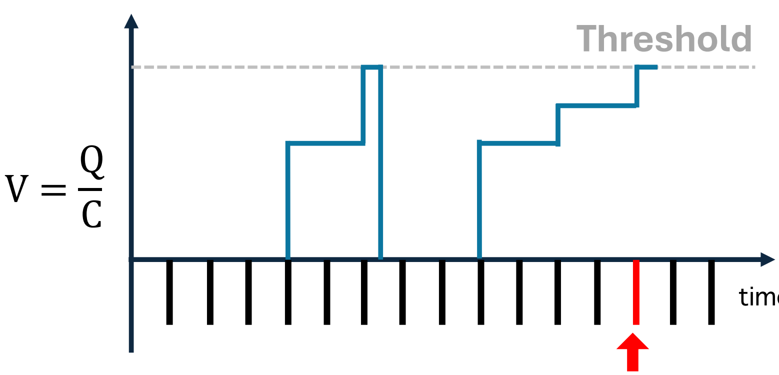


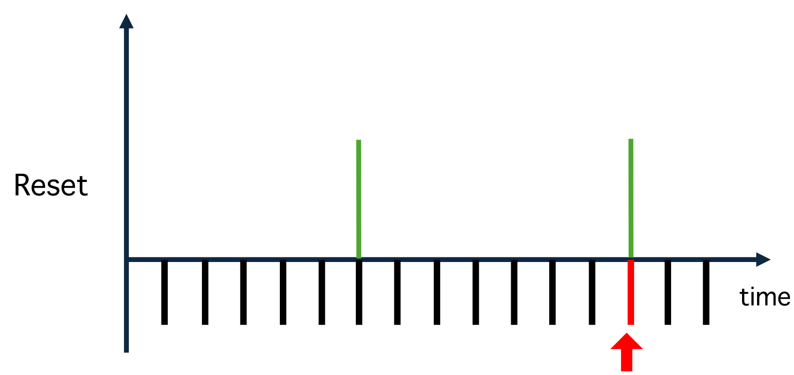


※ the reset happens for 5 electrons

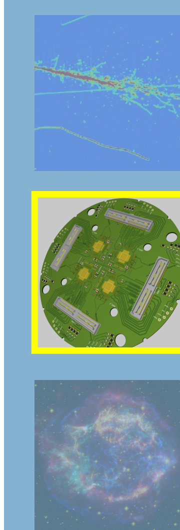
Q-Pix Toy Example



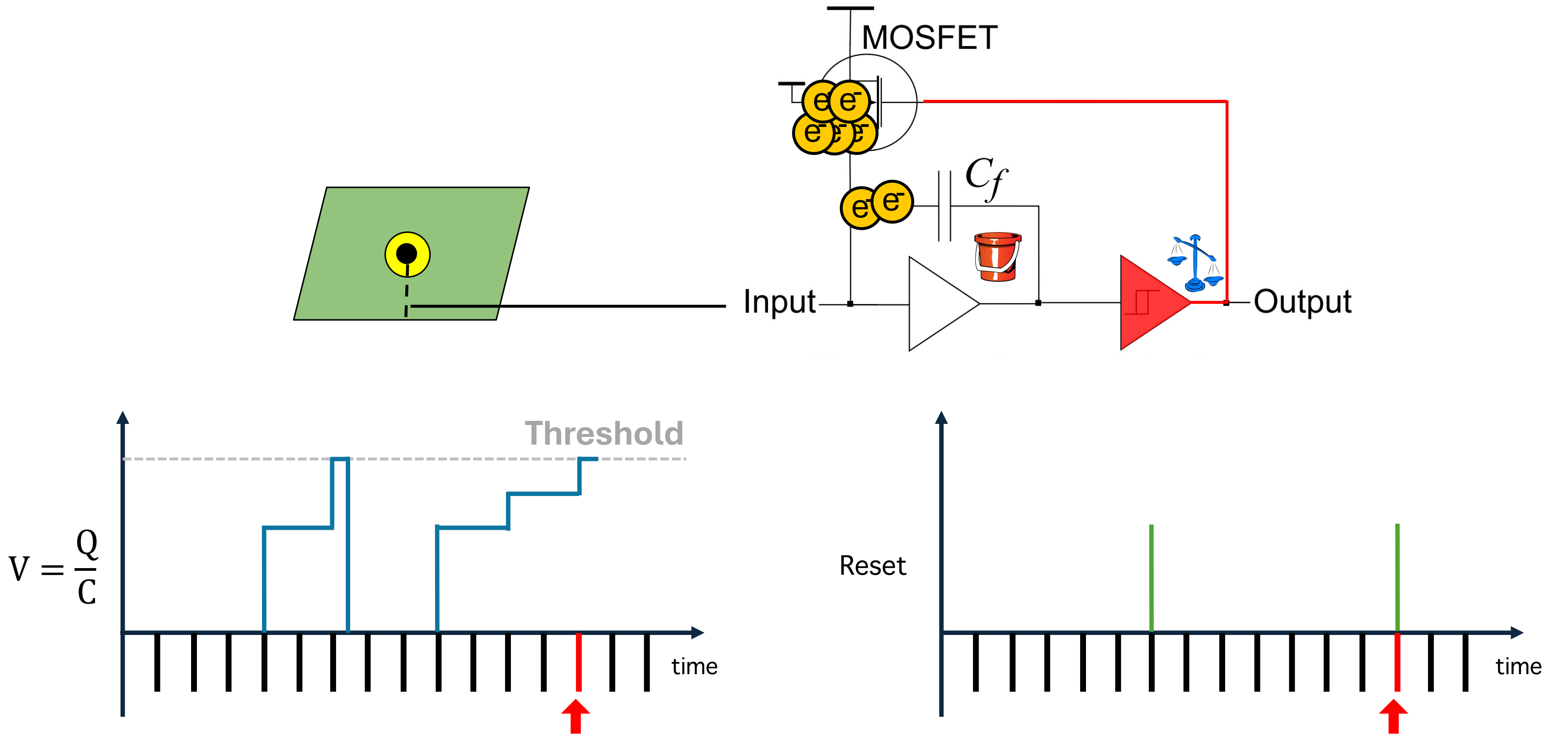




※ the reset happens for 5 electrons

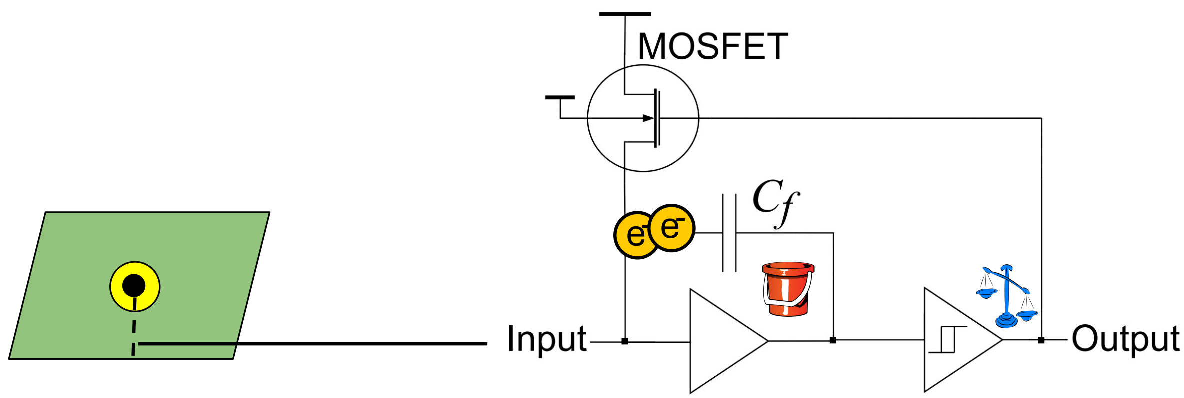


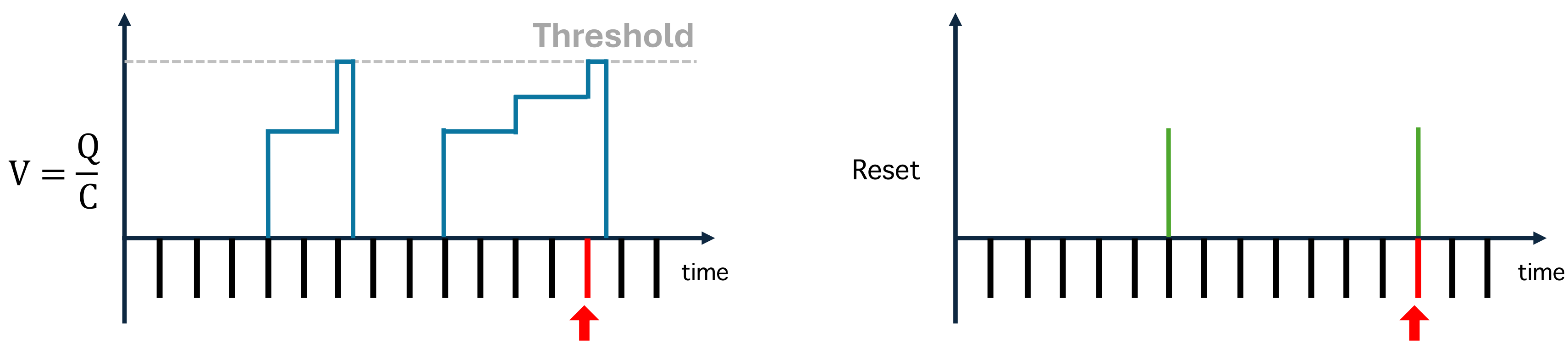
Q-Pix Toy Example



※ the reset happens for 5 electrons

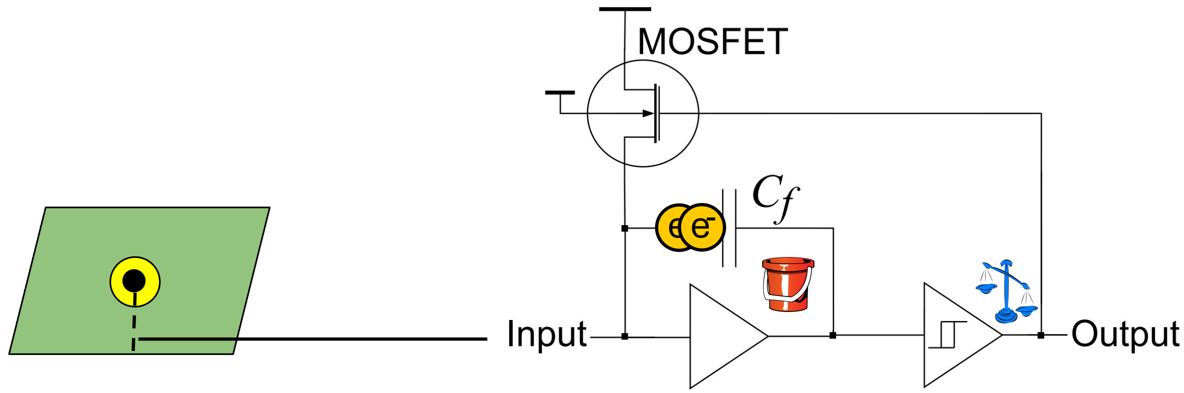
Q-Pix Toy Example

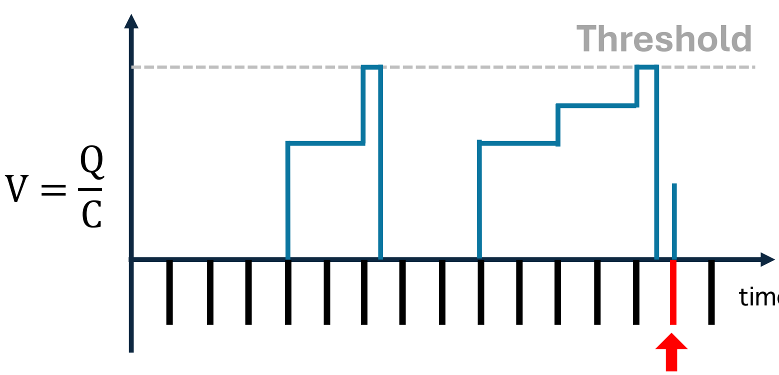


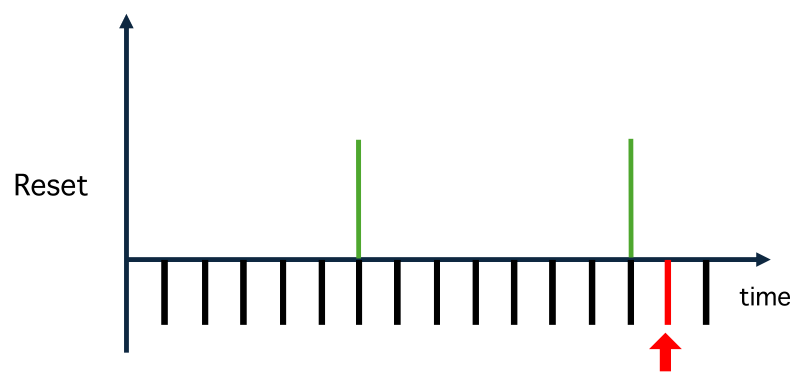


※ the reset happens for 5 electrons

Q-Pix Toy Example







※ the reset happens for 5 electrons

Q-Pix Toy Example

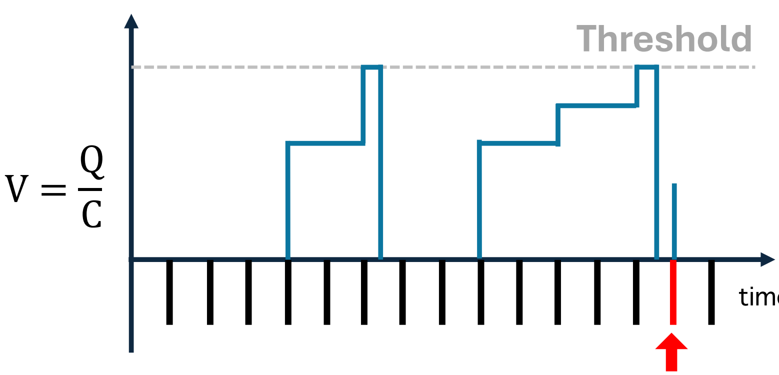
※ the reset happens for 5 electrons

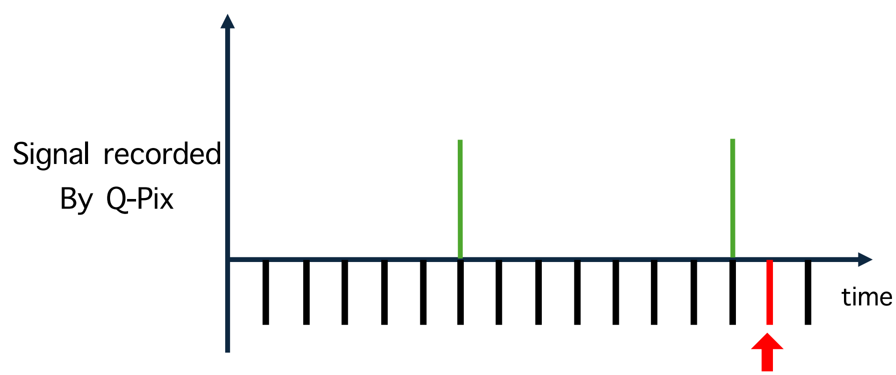
We are measuring

how long it took (Δt) to accumulate fixed amount of Q

Instead of recording the entire waveform,

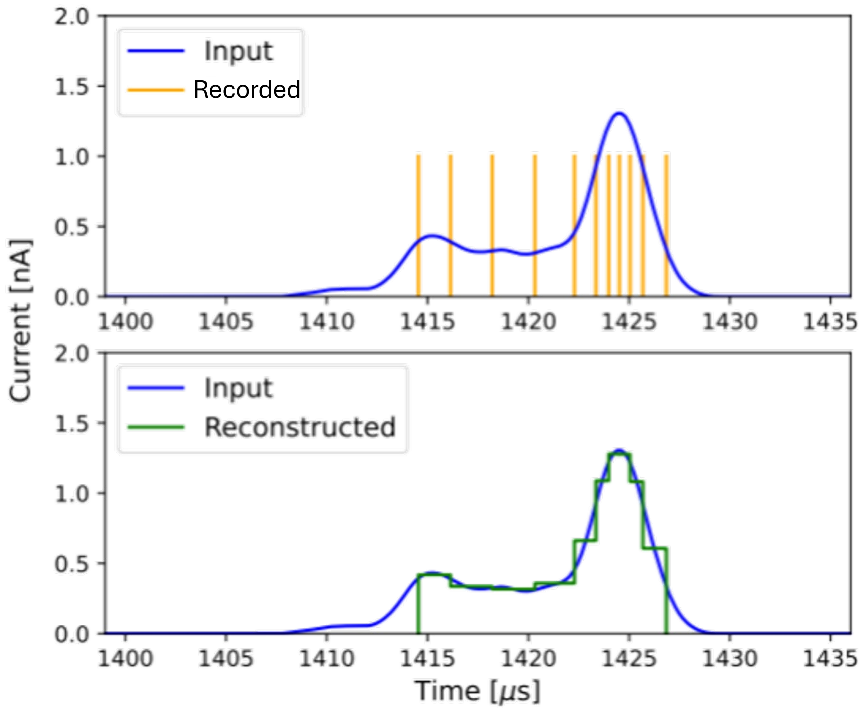
we only need to record time stamps!

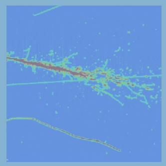


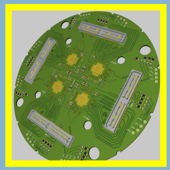


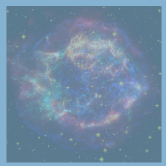
※ the signal happens for 5 electrons

Q-Pix's Solution

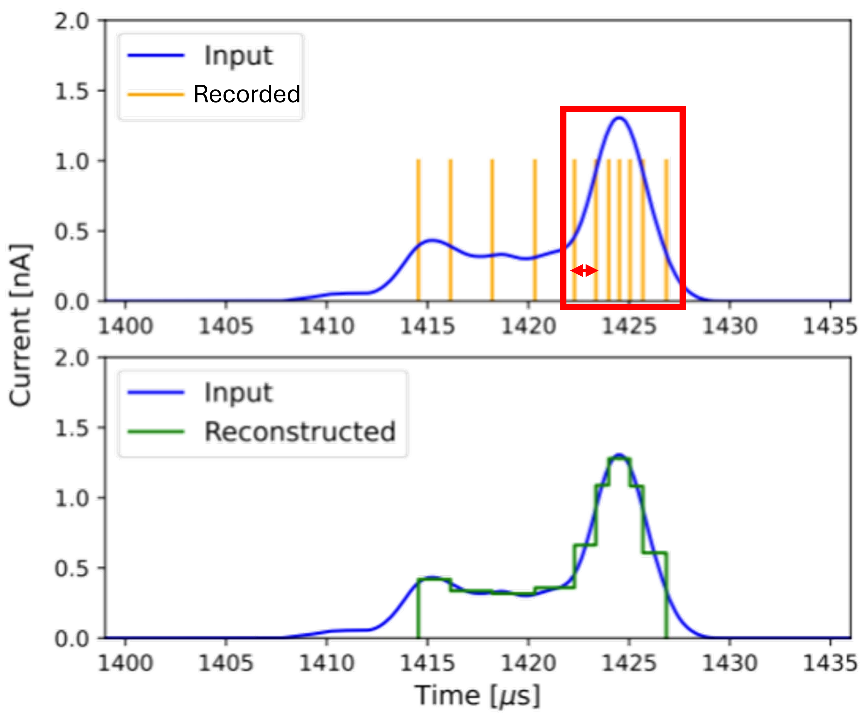








Q-Pix's Solution



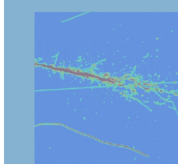
Denser area

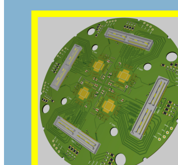
⇩

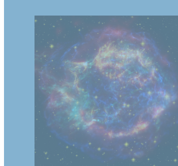
took pixel **less** time to get unit amount of charge

⇩

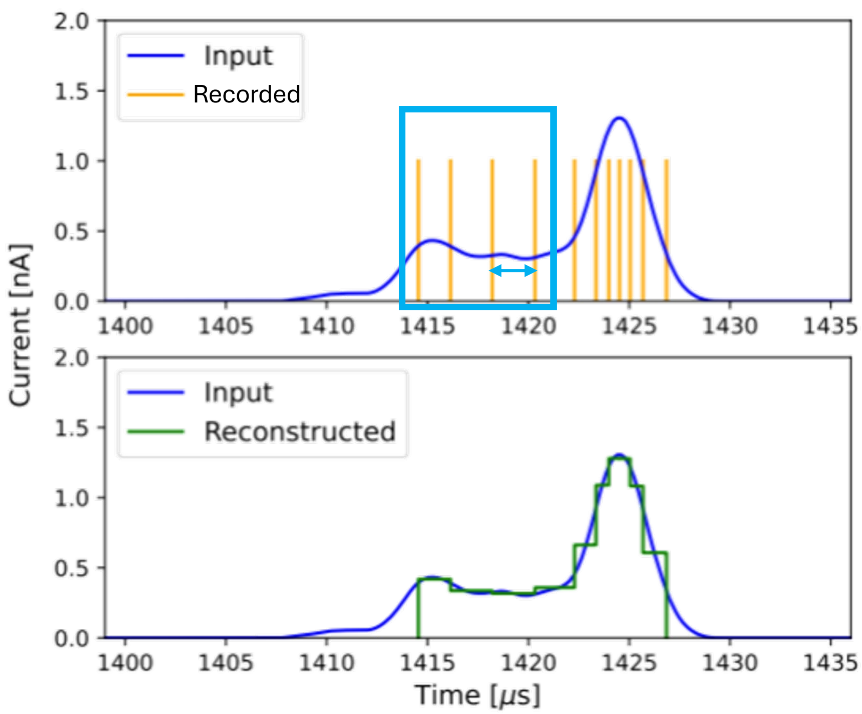
More current







Q-Pix's Solution



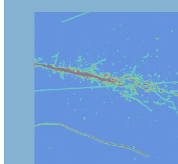
Sparse area

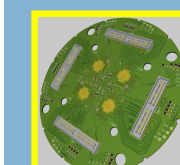
⇩

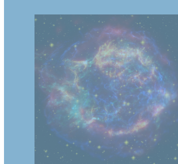
took pixel **more** time to get unit amount of charge

⇩

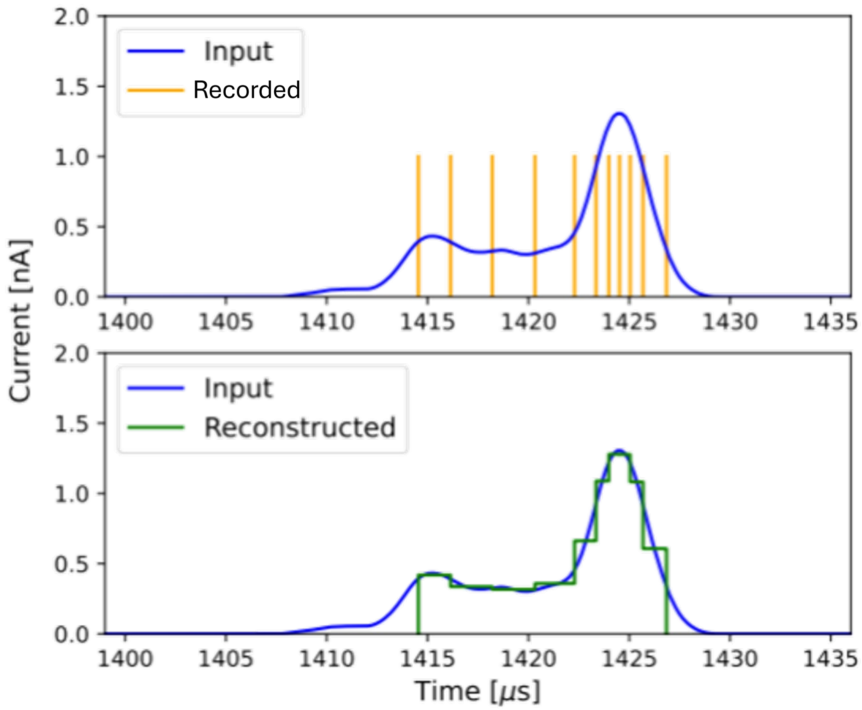
Less current







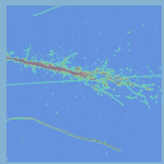
Q-Pix's Solution

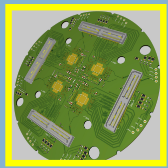


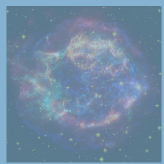
With this method,
the data rate is **10^6 times less**
than the traditional wire readout!

⇩

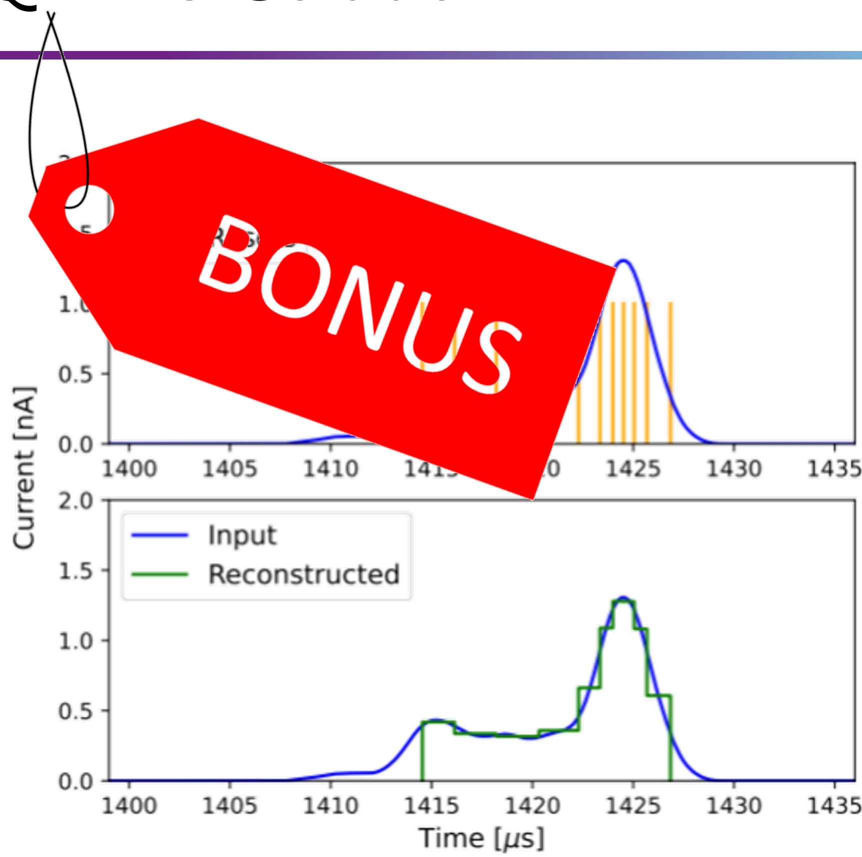
Q-Pix can offer a direct solution
to the data-rate problem that
pixelized kton-scale LArTPC has

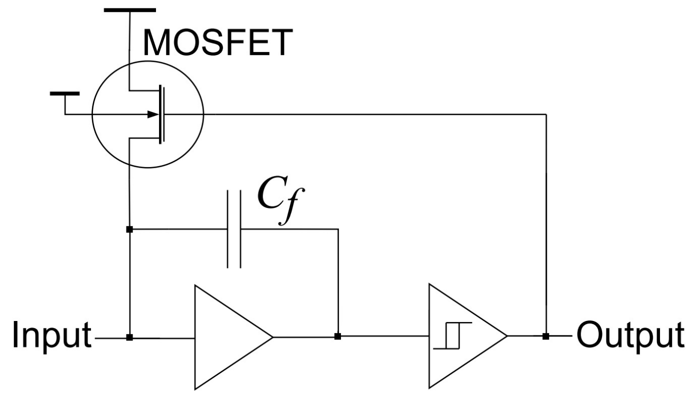






Q-Pix's Solution

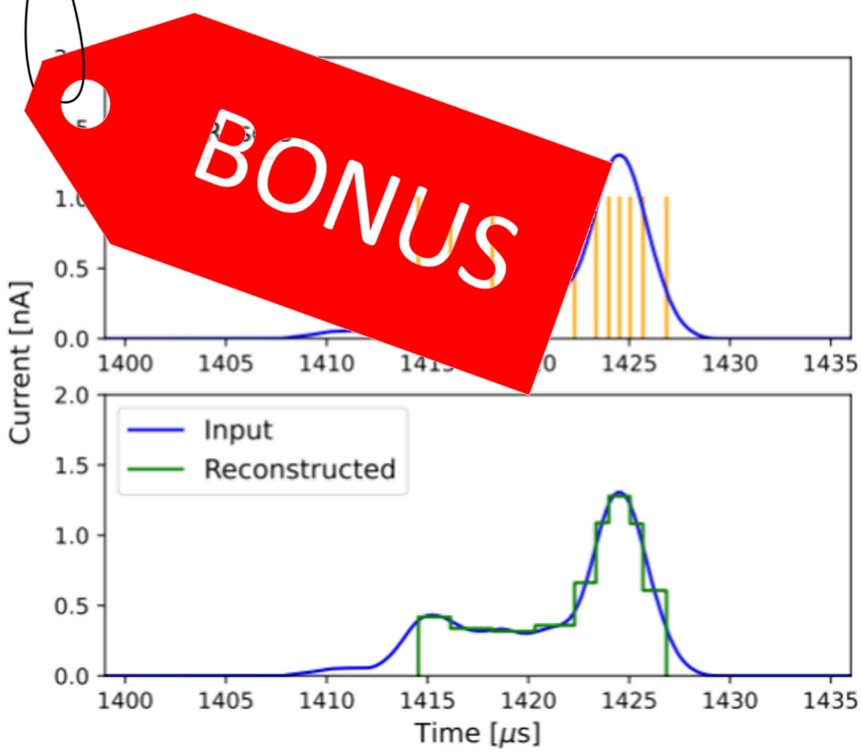


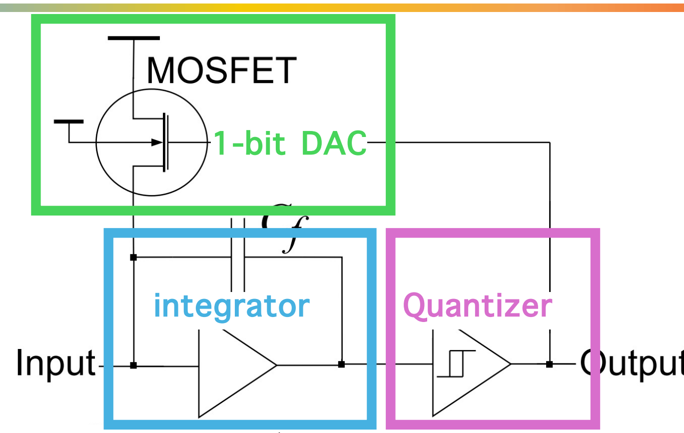


Moreover, this can be seen as

<u>one-bit Sigma-Delta modulator</u>

Q-Pix's Solution

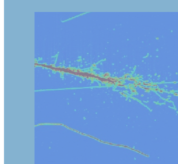


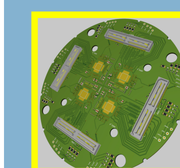


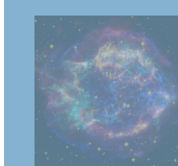
Moreover, this can be seen as

<u>one-bit Sigma-Delta modulator</u>

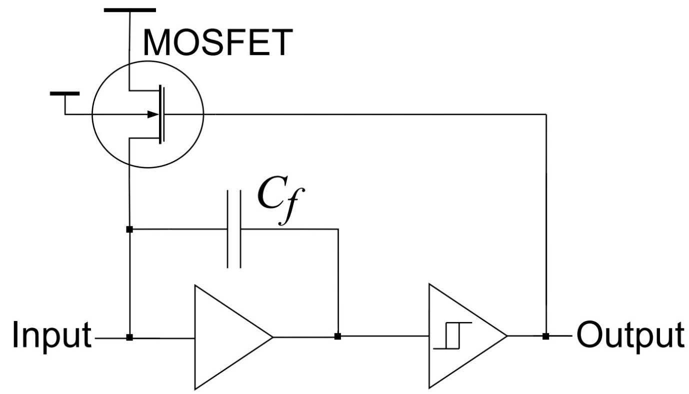
- Greater flexibility in data type
- More efficient data analysis
- More applications

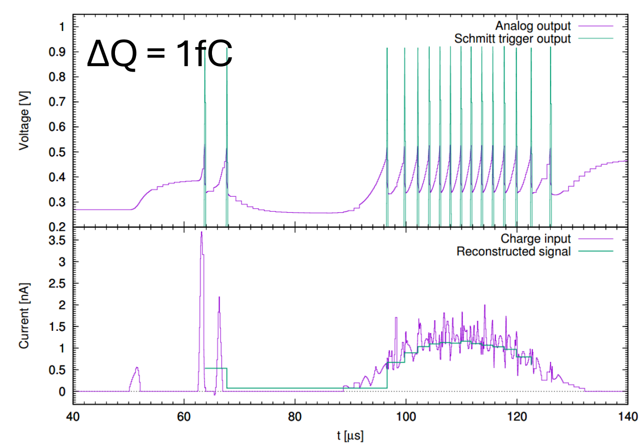




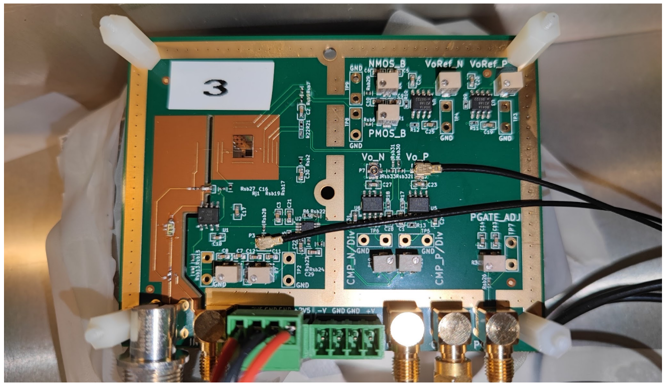


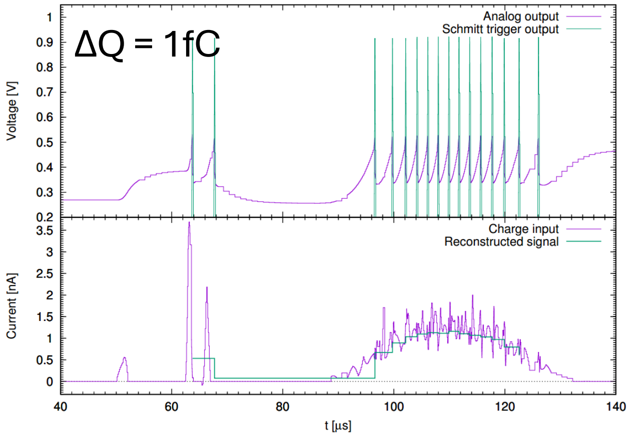
Demonstrating Q-Pix with commercial components

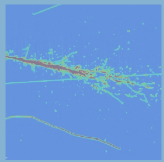


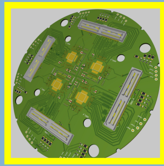


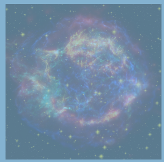
Demonstrating Q-Pix with commercial components



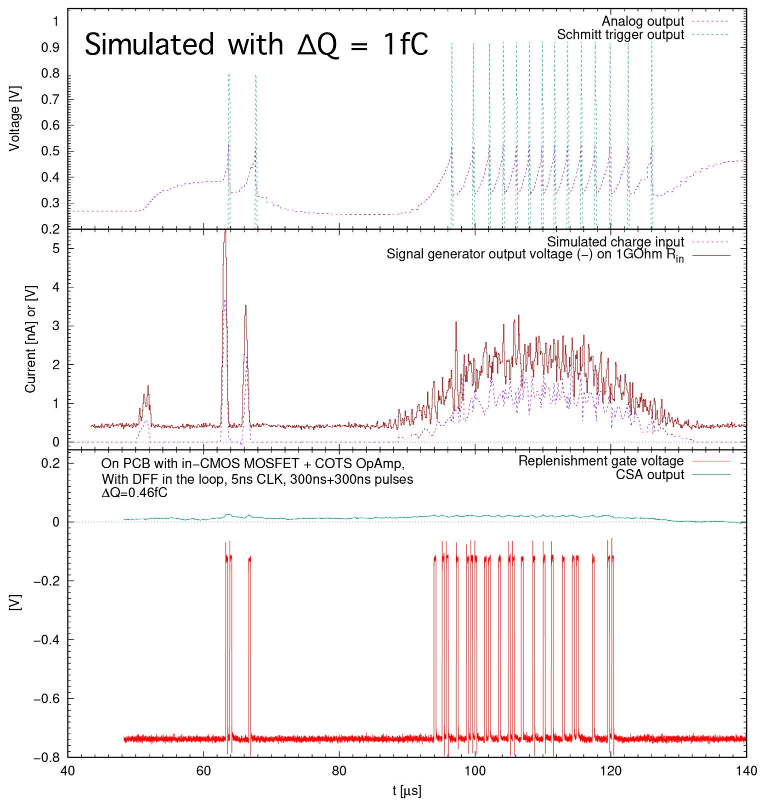


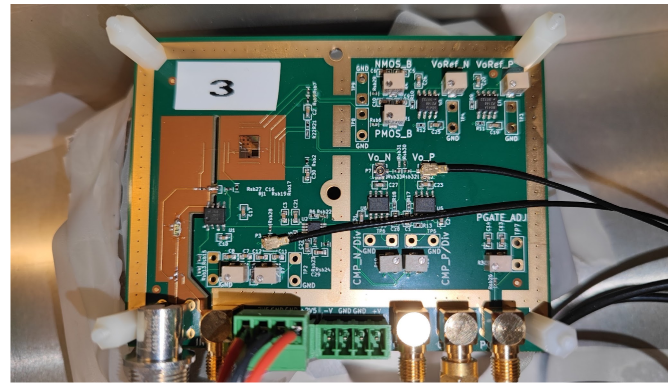




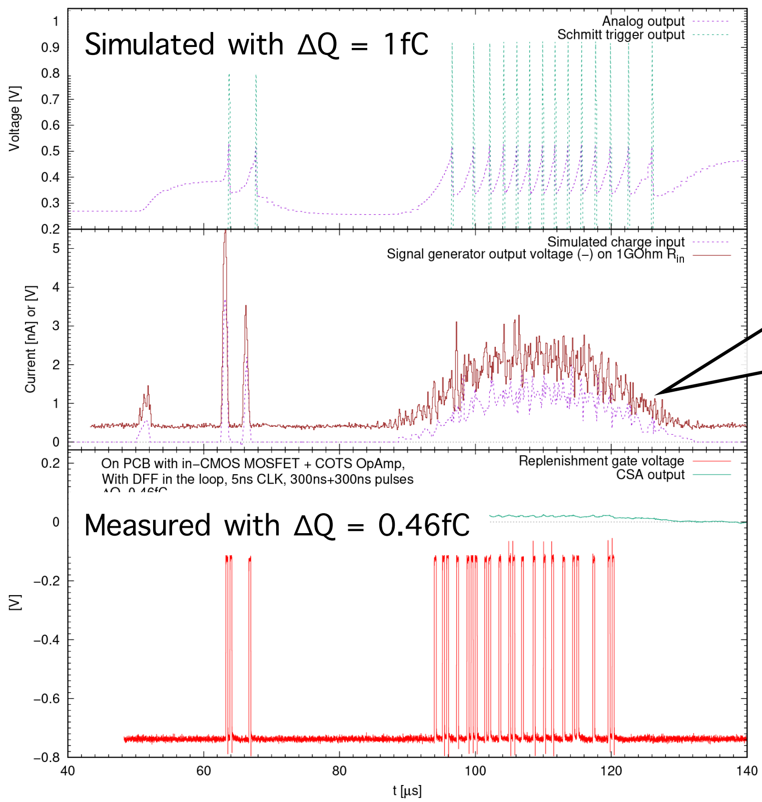


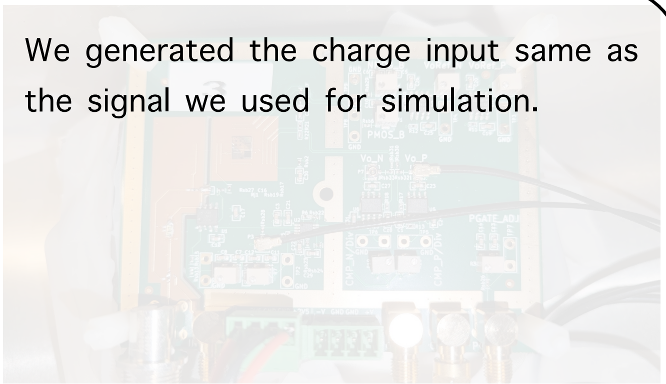
Demonstrating Q-Pix with commercial components



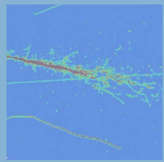


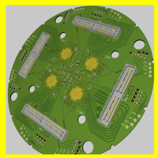
Demonstrating Q-Pix with commercial components

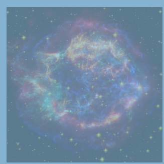




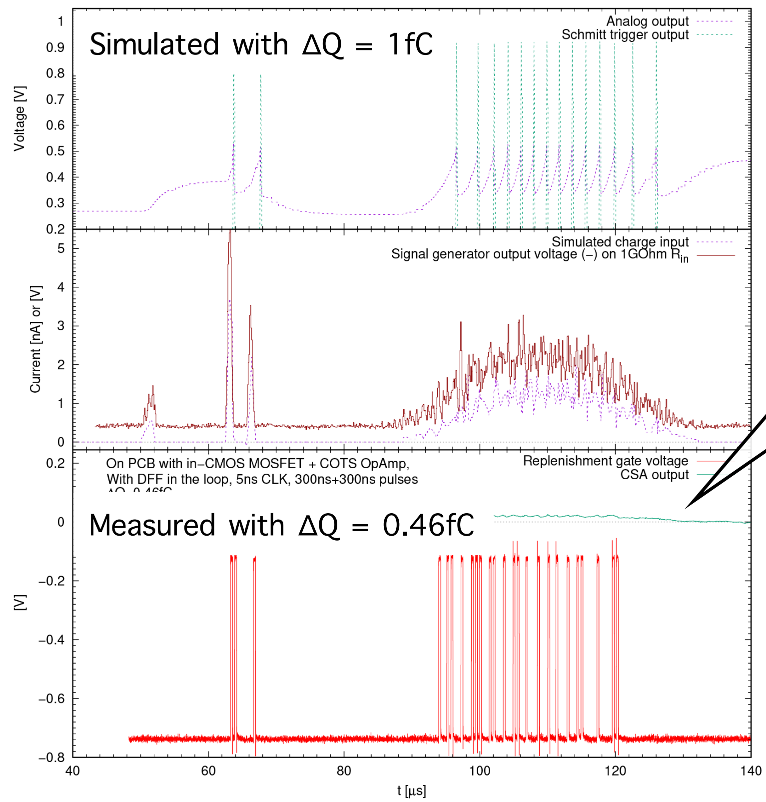
1. We generated the charge input same as the signal we used for simulation.







Demonstrating Q-Pix with commercial components

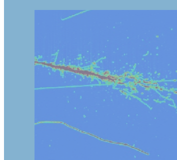


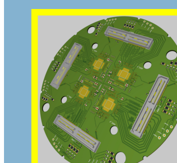
1. We generated the charge input same as the signal we used for simulation.
2. Fed it to the Q-Pix front-end made with commercial components
3. We could get better results than simulation!

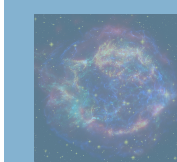
<u>0.46 fC enables **~50 KeV signal detection!**</u>

Demonstrating the Q-Pix front-end using discrete OpAmp and CMOS transistors

Peng Miao[a], Jonathan Asaadi[b], James B. R. Battat[d], Mikyung Han[a], Kevin Keefe[e,b], S. Kohani[e], Austin D. McDonald[b,c], David Nygren[b], Olivia Seidel[b], Yuan Mei[a,b,*]

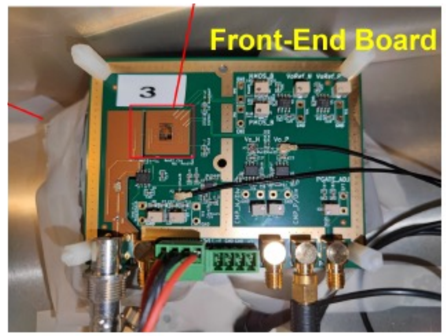






Journey of Hardware Development

- Demonstrating the Q-Pix front-end using discrete OpAmp and CMOS transistors (arXiv: 2311.09568)

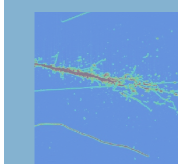


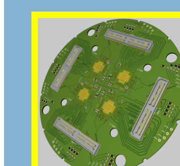
- First operation of a multi-channel Q-Pix prototype: measuring transverse electron diffusion in a gas time projection chamber (arXiv:2402.05734V3)

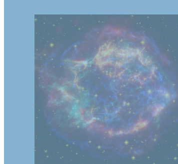
Q-Pix reconstruction mechanism demonstrated with mostly COTS

Q-Pix's capability in physics studies demonstrated with COTS

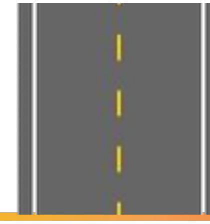
First Q-Pix ASICS' functionality demonstrated

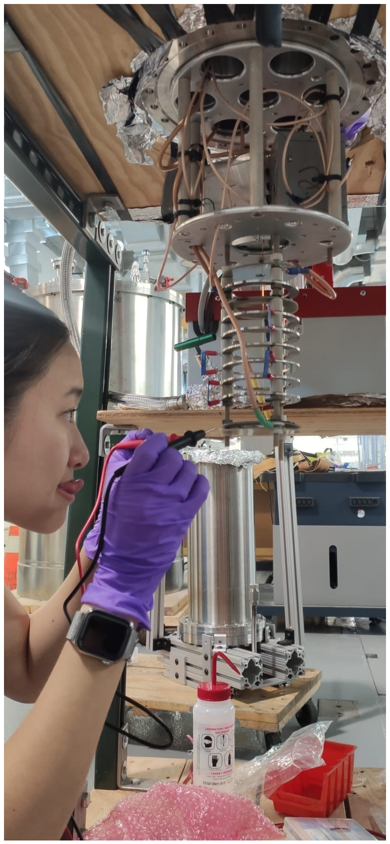


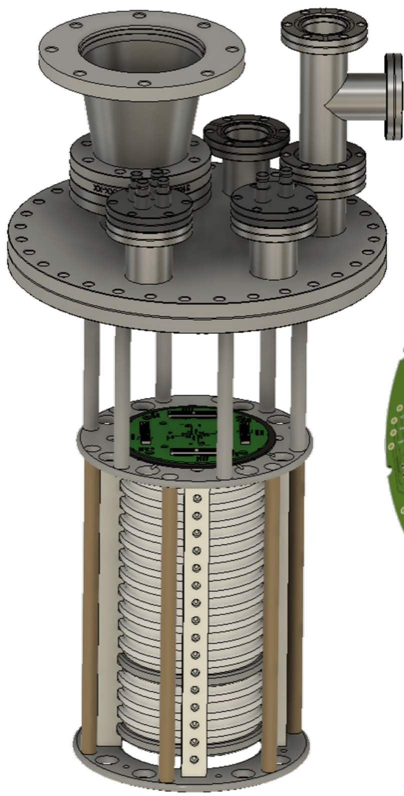


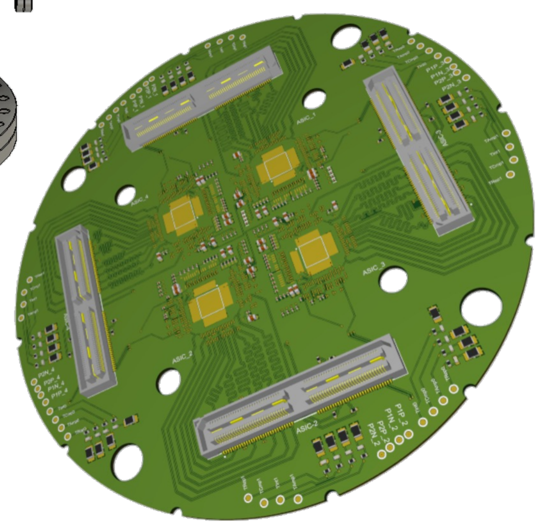


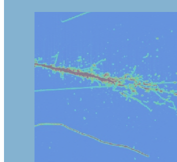
And finally the first test in LAr!

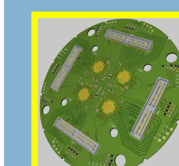


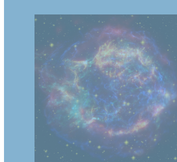






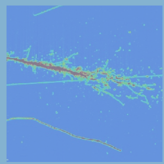


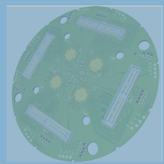




Physics with Q-Pix

<u>'maximize the discovery potential of a kiloton scale LArTPC'</u>





Physics with Q-Pix

<u>'maximize the discovery potential of a kiloton scale LArTPC'</u>

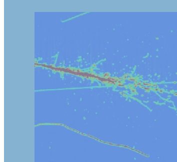
- Which neutrino is heavier/lighter than which?
- How much does neutrino violate CP symmetry?

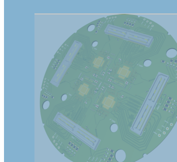
} Main physics goals of Long baseline experiments

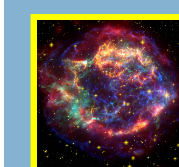
- Does proton decay?
- How does supernovae explosion happen?

} Additional physics goals DUNE is trying to achieve

- How does 'sun' work? ⇦ …and maybe DUNE can also investigate this too







Physics with Q-Pix

<u>'maximize the discovery potential of a kiloton scale LArTPC'</u>

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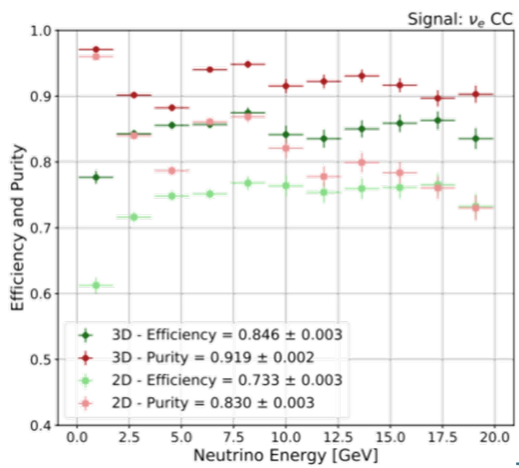
Main physics goals of Long baseline experiments



	Accuracy [%]	
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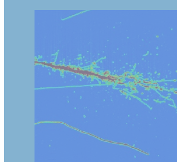
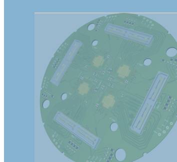
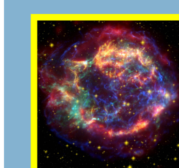
Neutrino Interaction	**94**	91
Proton Multiplicity	**91**	87
Charge Pion Presence	**94**	91
Neutral Pion Presence	**95**	94

<u>Enhancing Neutrino Event Reconstruction with Pixel-Based 3D Readout for Liquid Argon Time Projection Chambers</u>
C. Adams, M. Del Tutto, J. Asaadi, M. Bernstein, E. Church, R. Guenette, et al., JINST 15 (04), P04009







Physics with Q-Pix

‘maximize the discovery potential of a kiloton scale LArTPC’

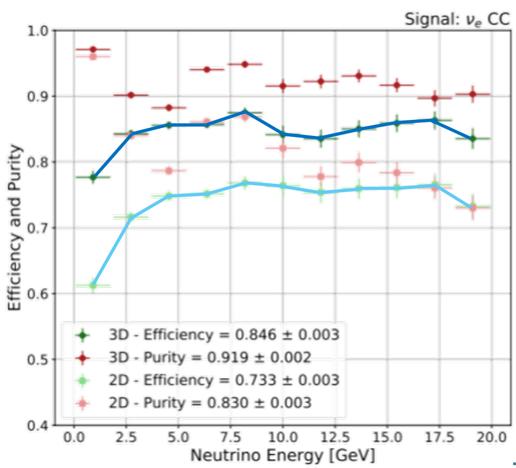
- Which neutrino is heavier/lighter than which?
- How much does neutrino violate CP symmetry?

Main physics goals of Long baseline experiments

Efficiency =

$$\frac{\text{\# of signal events identified}}{\text{\# of signal events simulated}}$$

3D efficiency
2D efficiency



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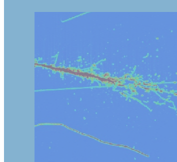

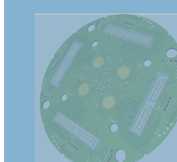

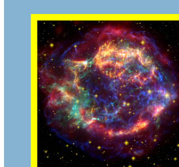

Physics with Q-Pix

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- Which neutrino is heavier/lighter than which?
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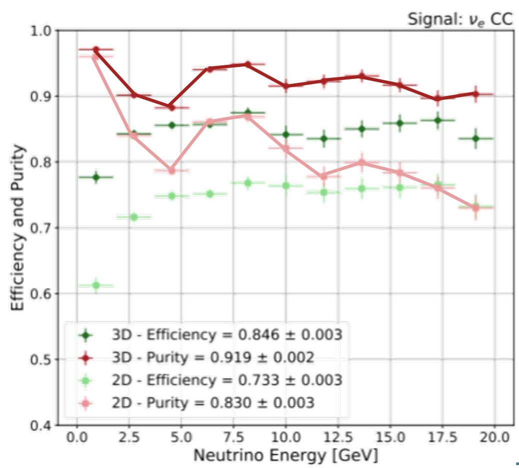
Main physics goals of Long baseline experiments

Purity = $\frac{\text{\# of signal events}}{\text{\# of events identified as signal}}$

3D purity
2D purity



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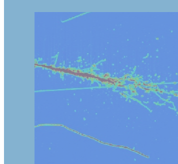

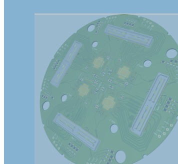

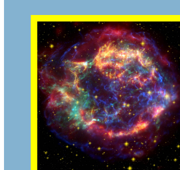

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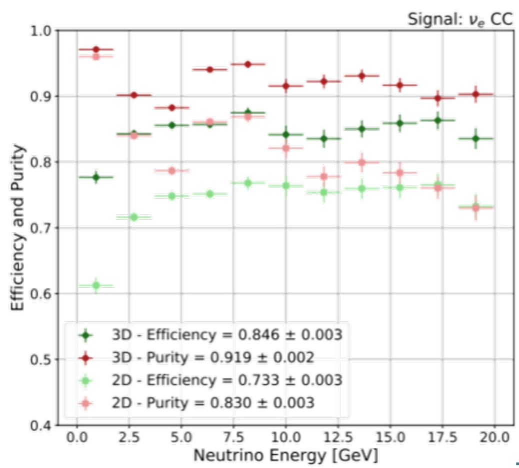

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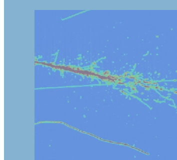

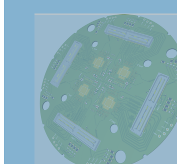

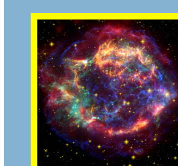

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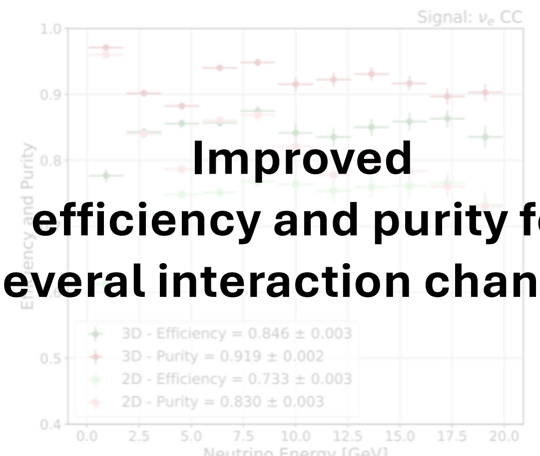

Improved efficiency and purity for several interaction channels

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Enhanced event reconstruction accuracy

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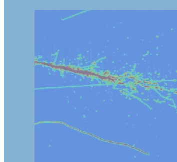

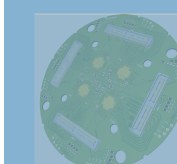

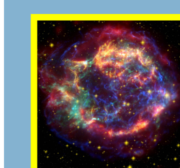

Physics with Q-Pix

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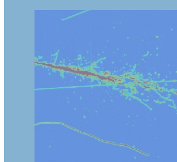
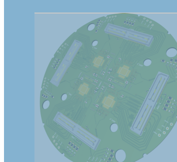
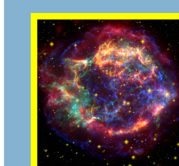
- Which neutrino is heavier/lighter than which?
- How much does neutrino violate CP symmetry?

Has been shown that pixel detectors can improve!

- Can we observe proton decay?
- How does supernovae explosion happen?
- How does 'sun' work?







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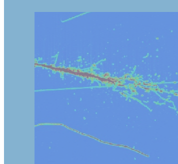
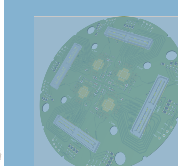
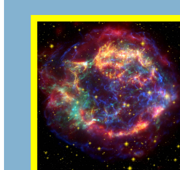
This is what I focused on during my Ph.D.!

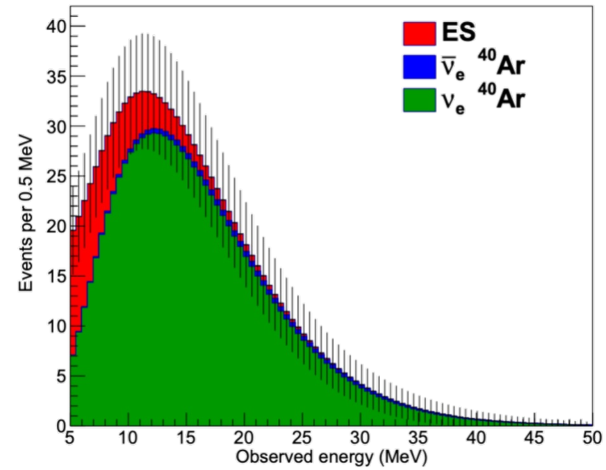






Supernova neutrino studies with Q-Pix

- Supernova neutrinos are suitable for assessing Q-Pix's capability in lower energy region
- This could be the benchmark as we could make some key direct comparisons to published work from DUNE.



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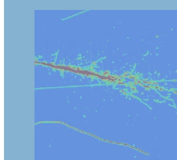
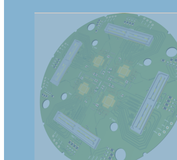
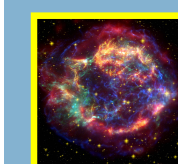
Phys.Rev.D 106 (2022) 3, 032011







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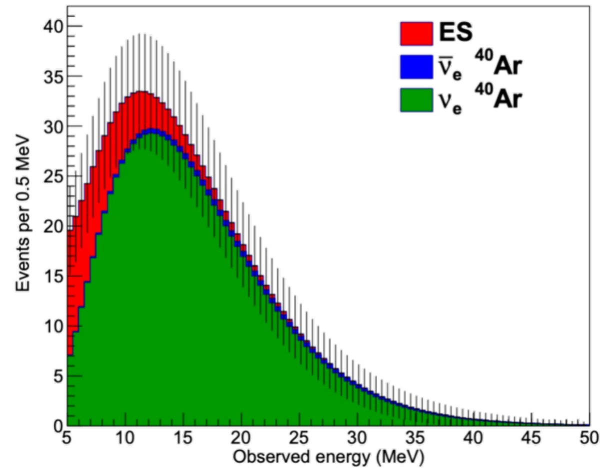

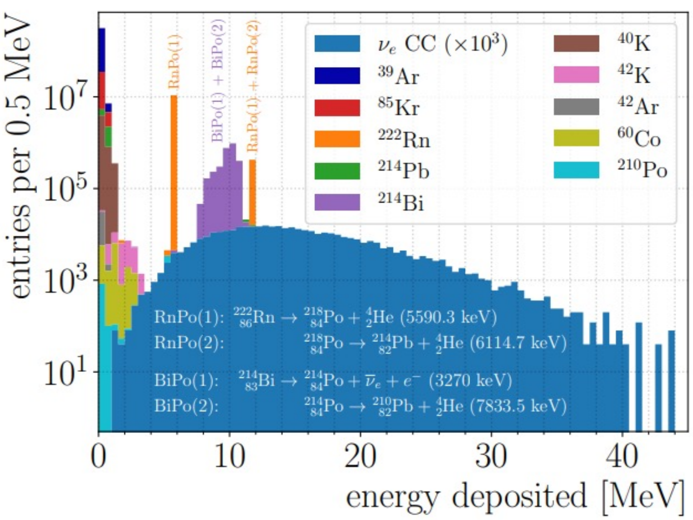

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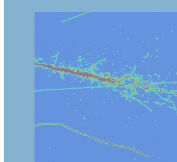

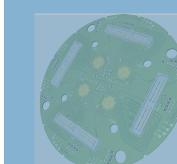

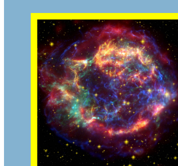

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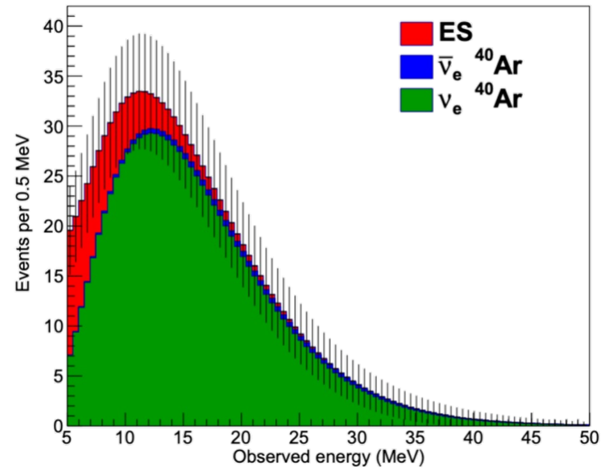

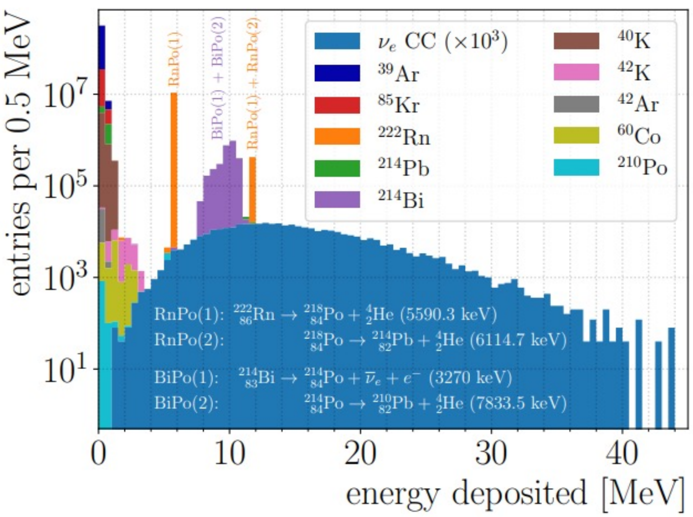

Even with the inclusion of radiogenic backgrounds,
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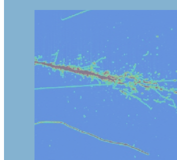
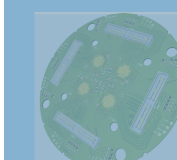
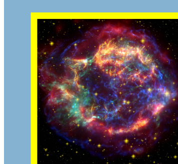


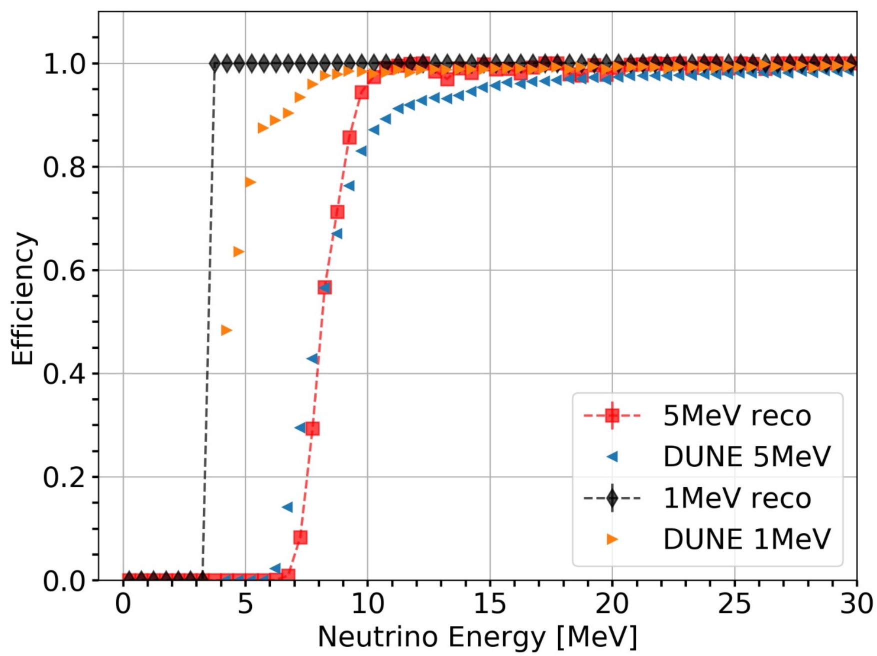


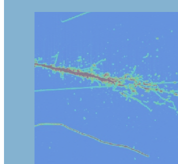


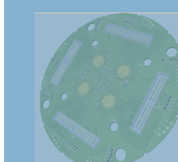
Supernova neutrino studies with Q-Pix

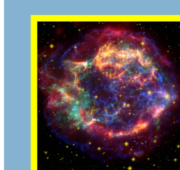
- Q-Pix significantly enhances the event reconstruction efficiency of low energy supernova neutrino.

- The efficiency rises to nearly 100% very rapidly and maintains this high efficiency down to lower neutrino energy.









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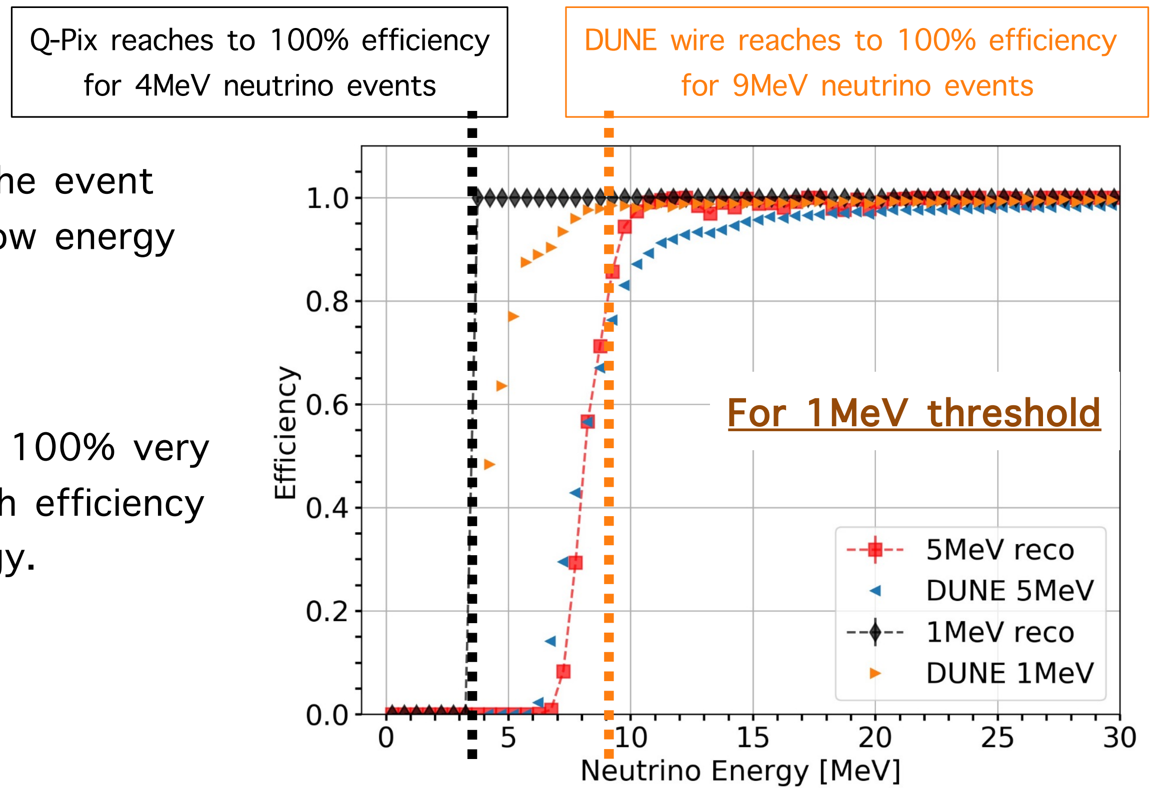

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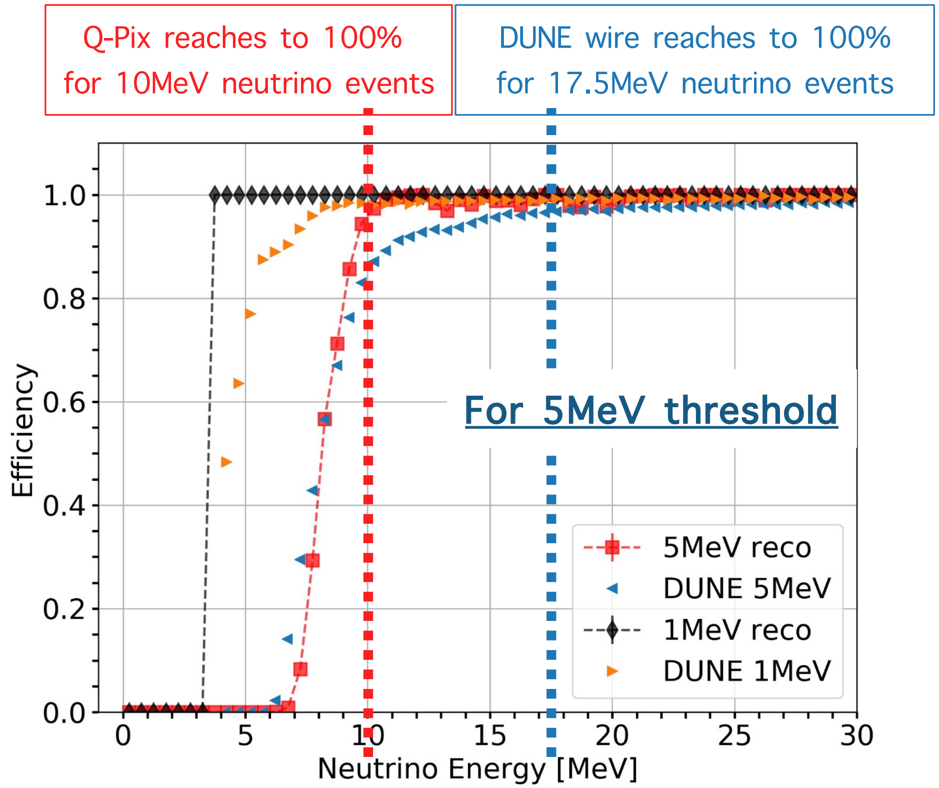
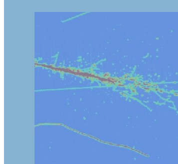
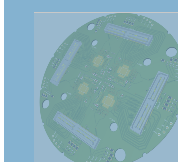
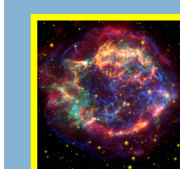


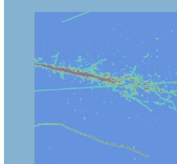


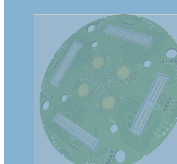


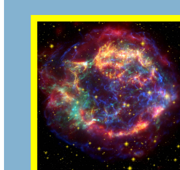


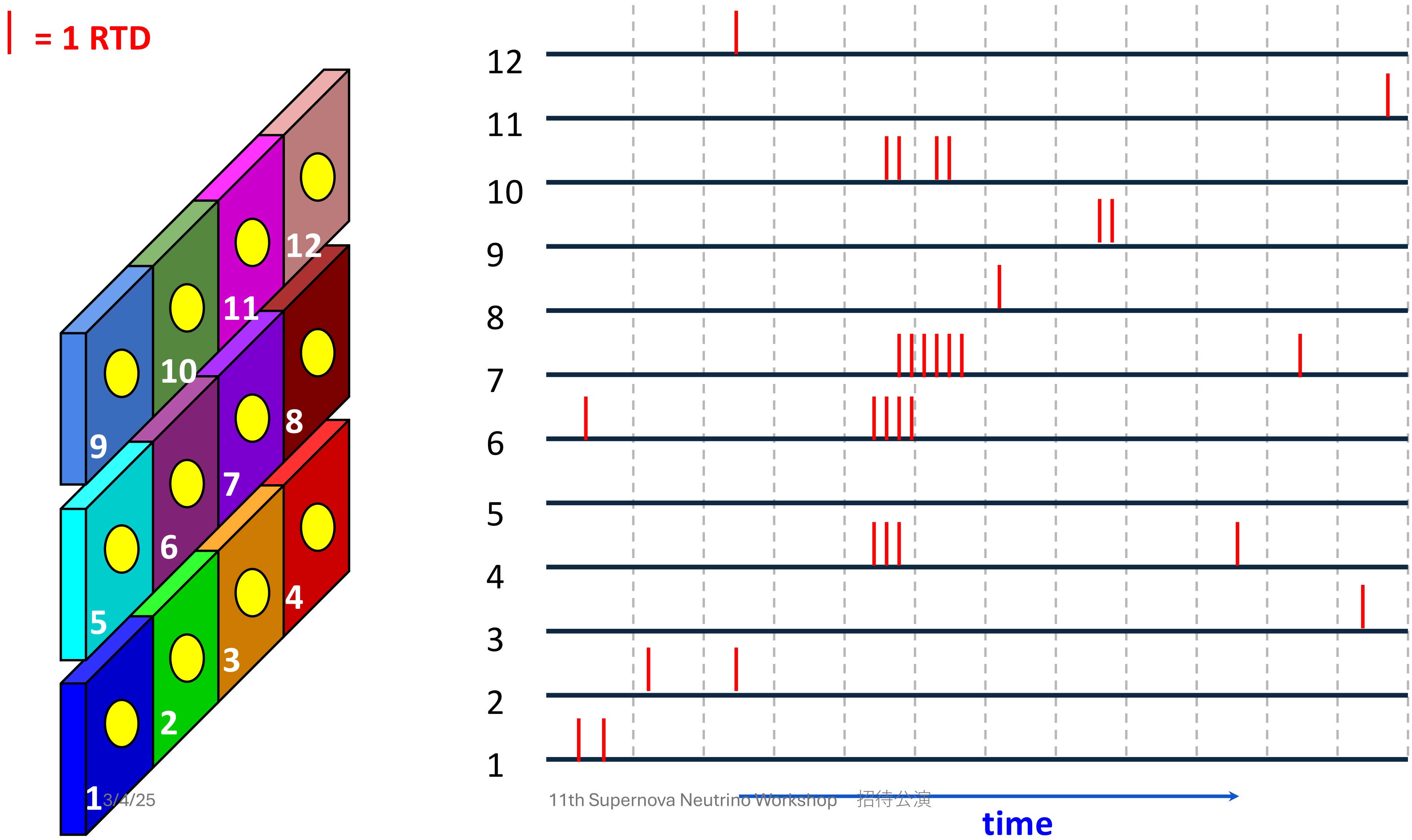
Supernova Event Identification

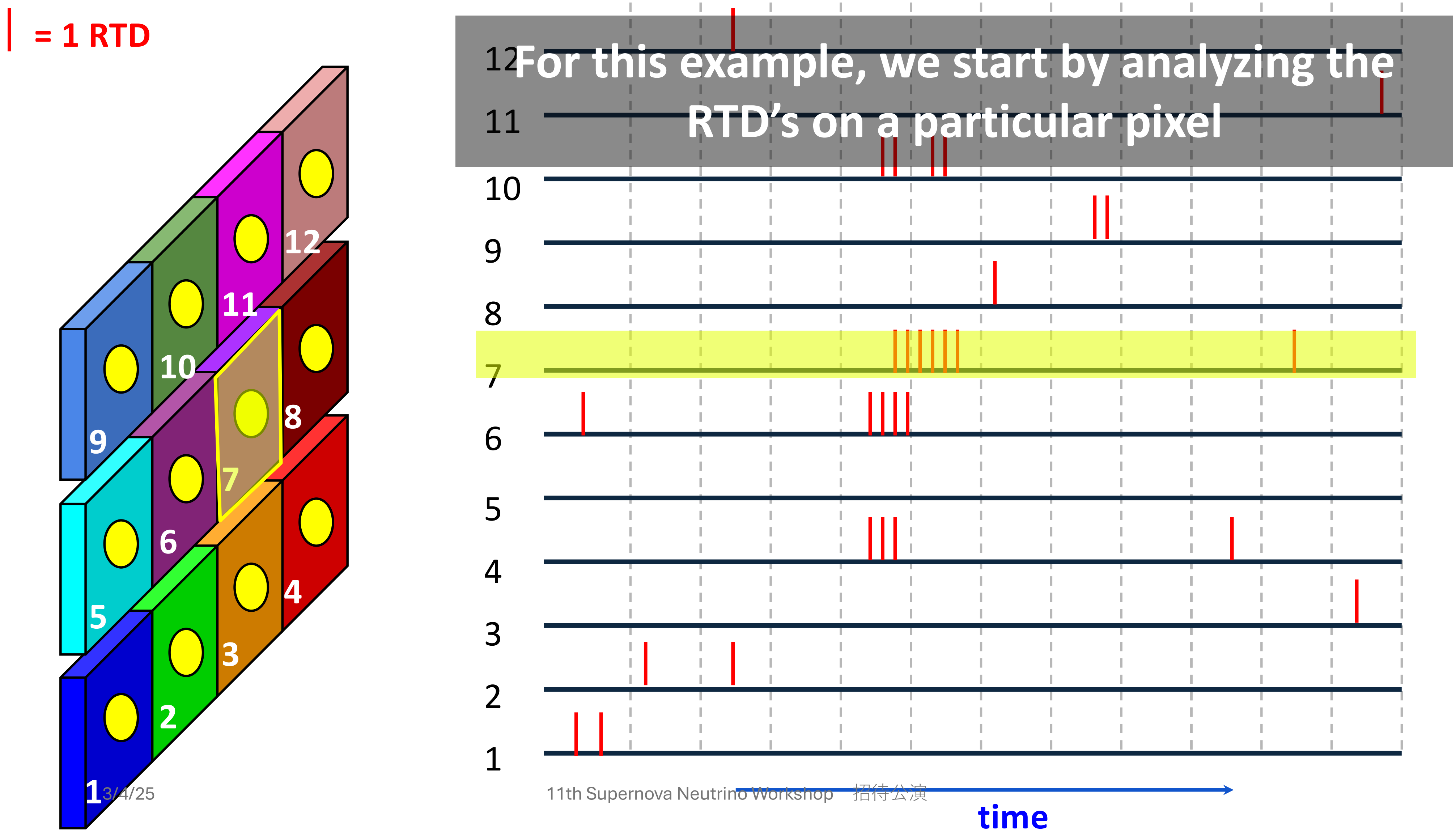
- Employs “Clustering Algorithm”



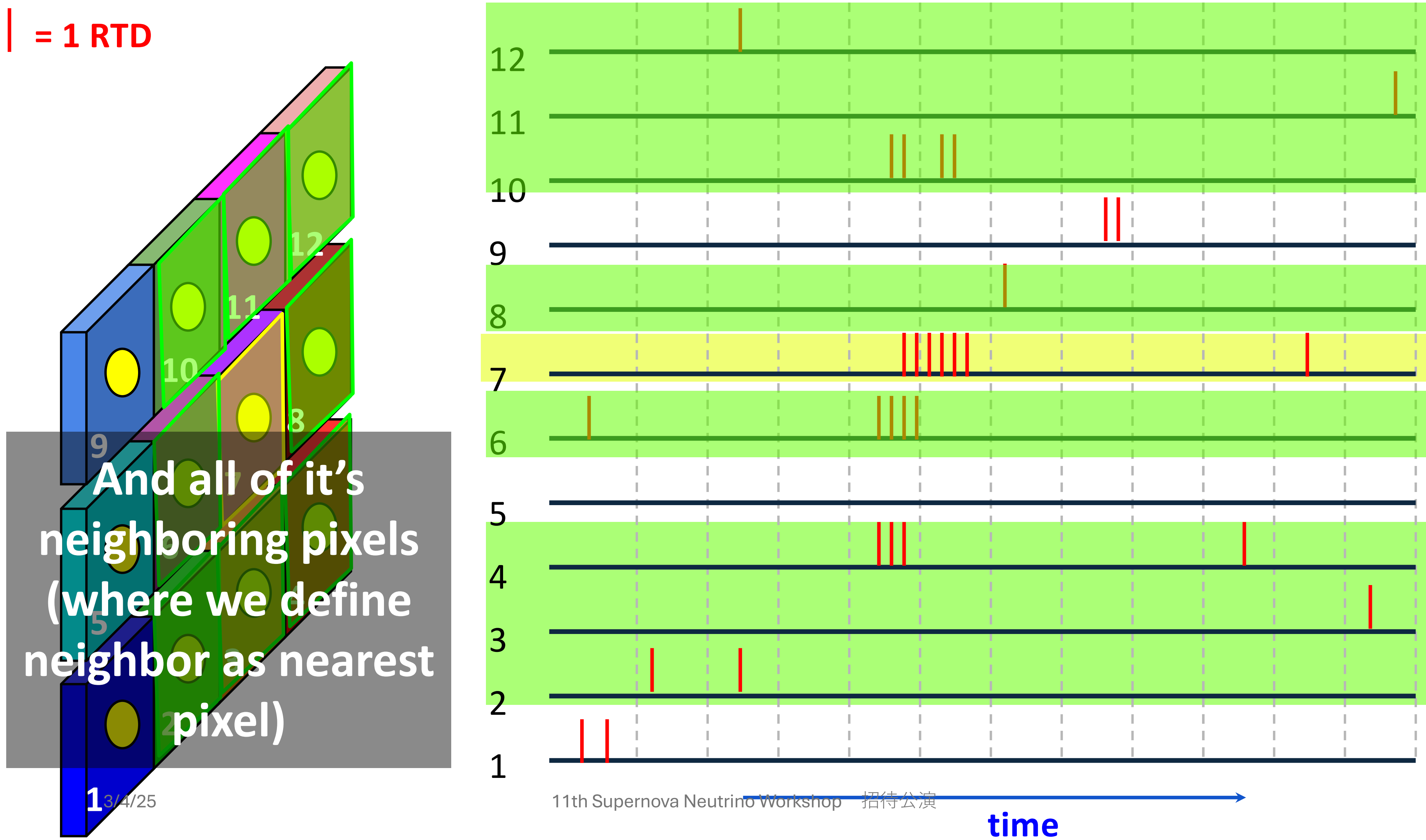





= 1 RTD
12
11
10
9
8
7
6
5
4
3
2
1
12
11
10
9
8
7
6
5
4
3
2
1
time



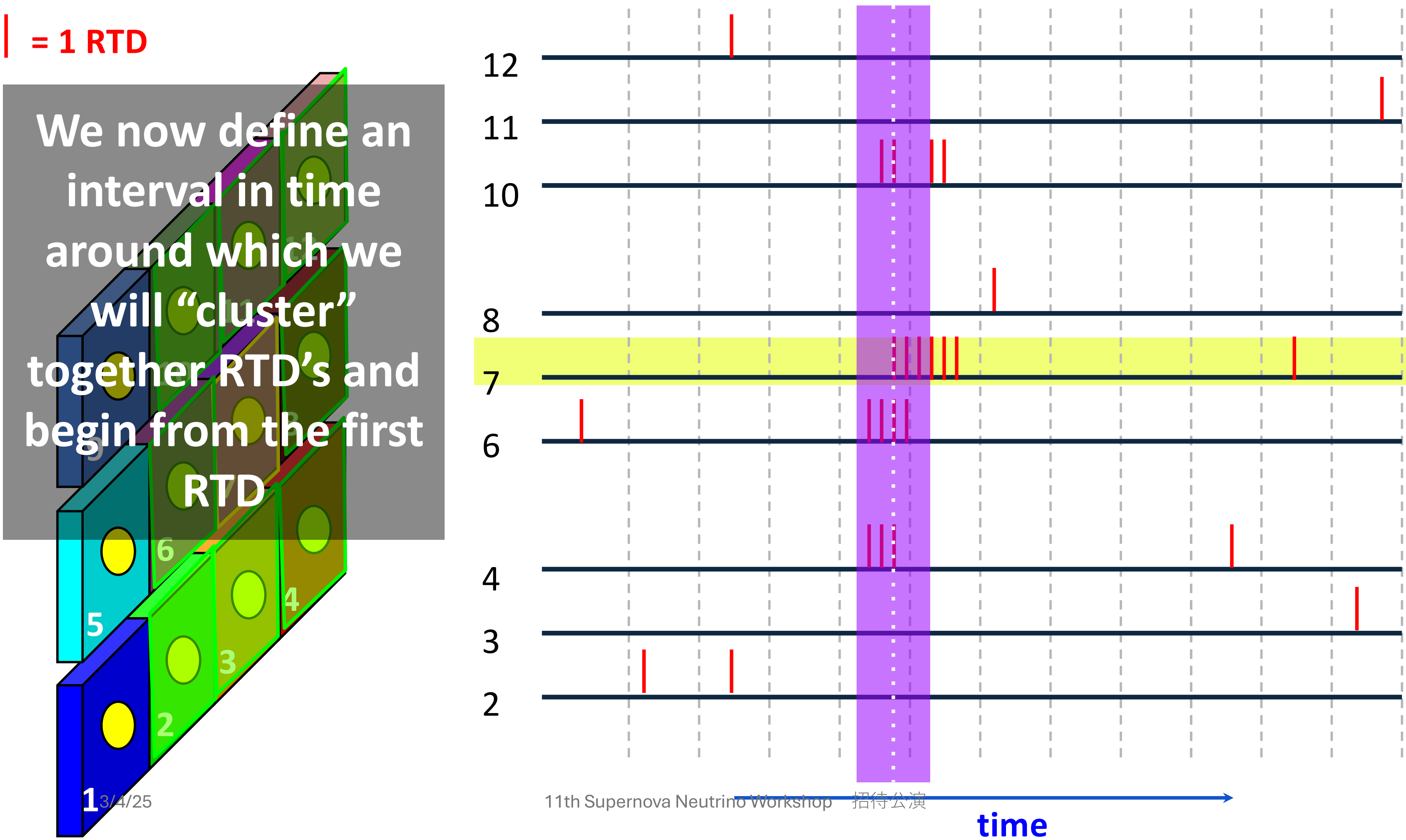
For this example, we start by analyzing the RTD's on a particular pixel

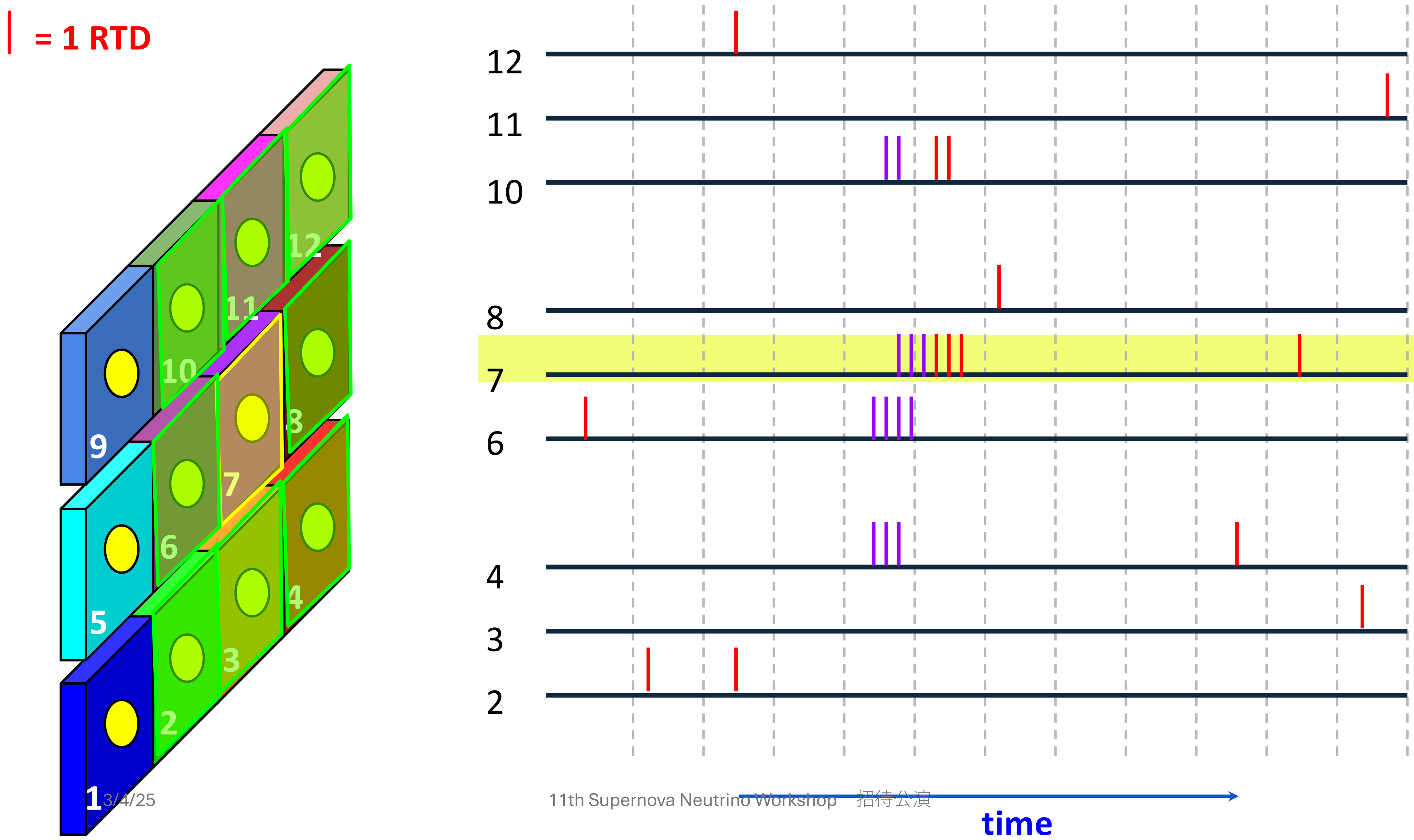


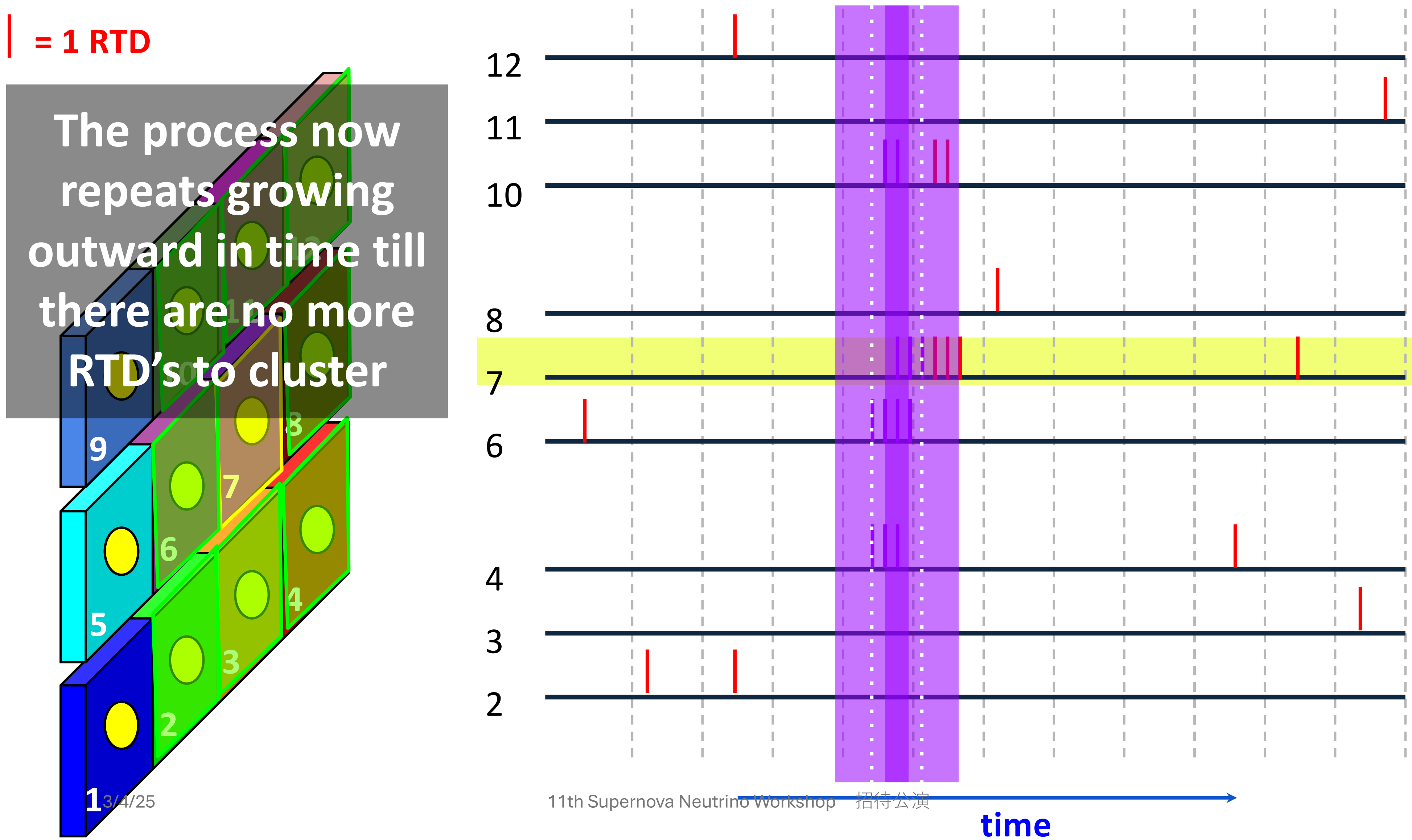
And all of it's neighboring pixels (where we define neighbor as nearest pixel)

| = 1 RTD

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



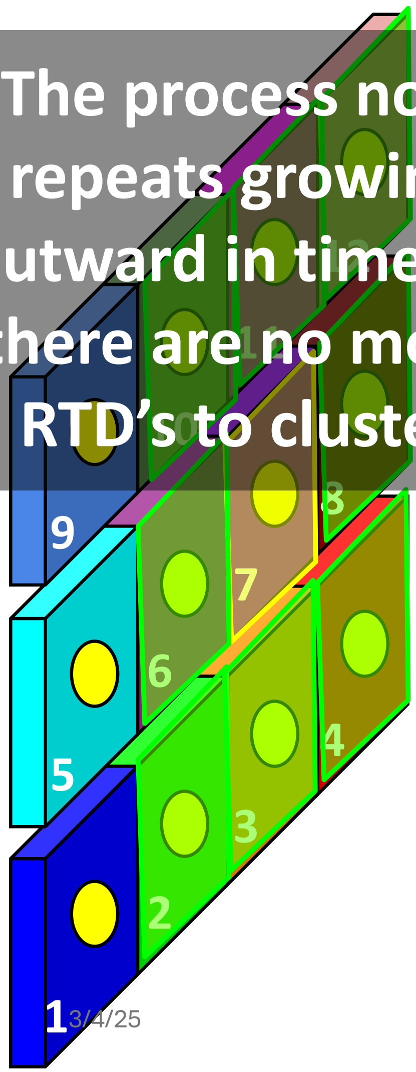

= 1 RTD
12
11
10
8
7
6
4
3
2
9
10
11
12
8
7
6
5
4
3
2
1
time

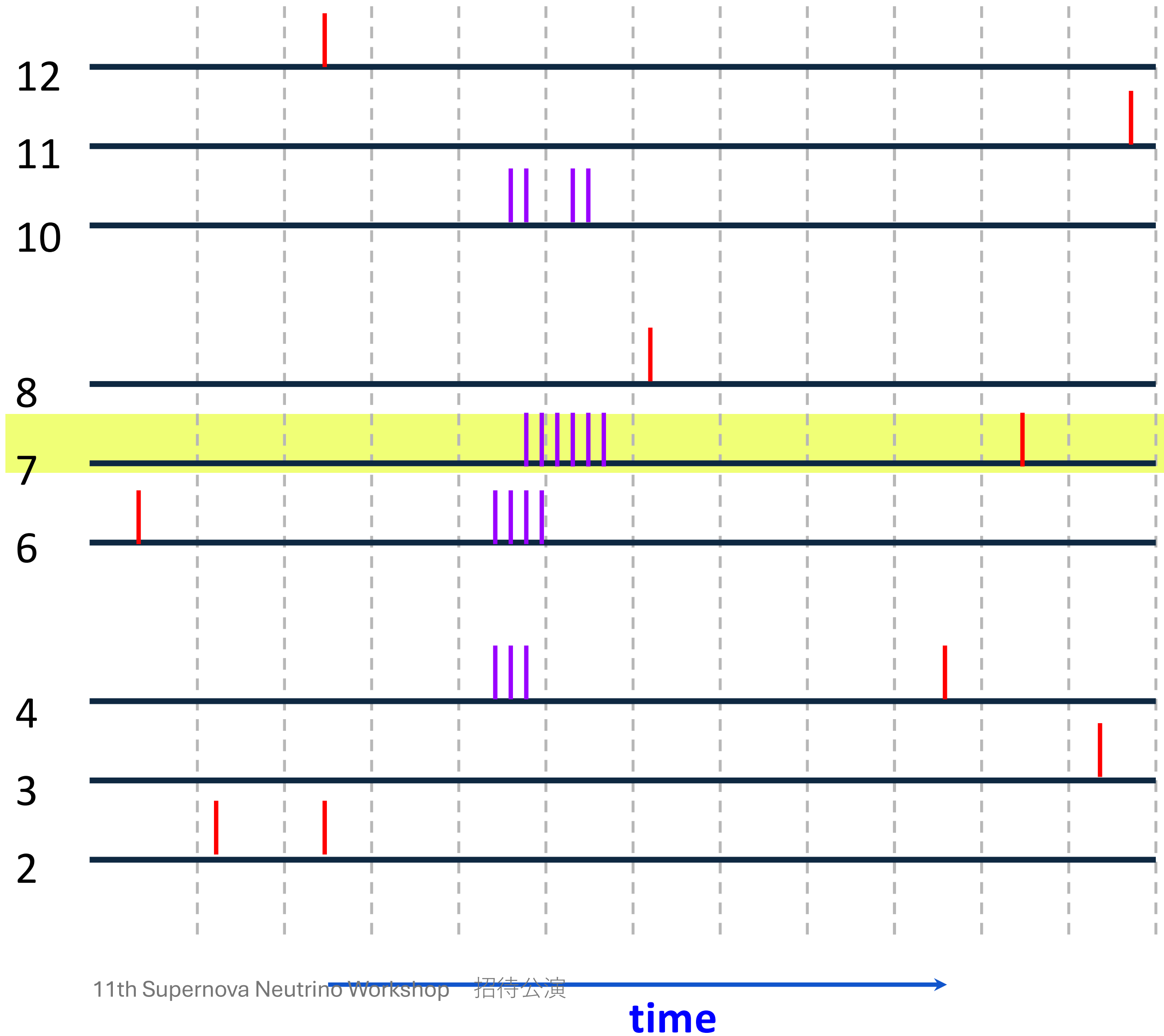


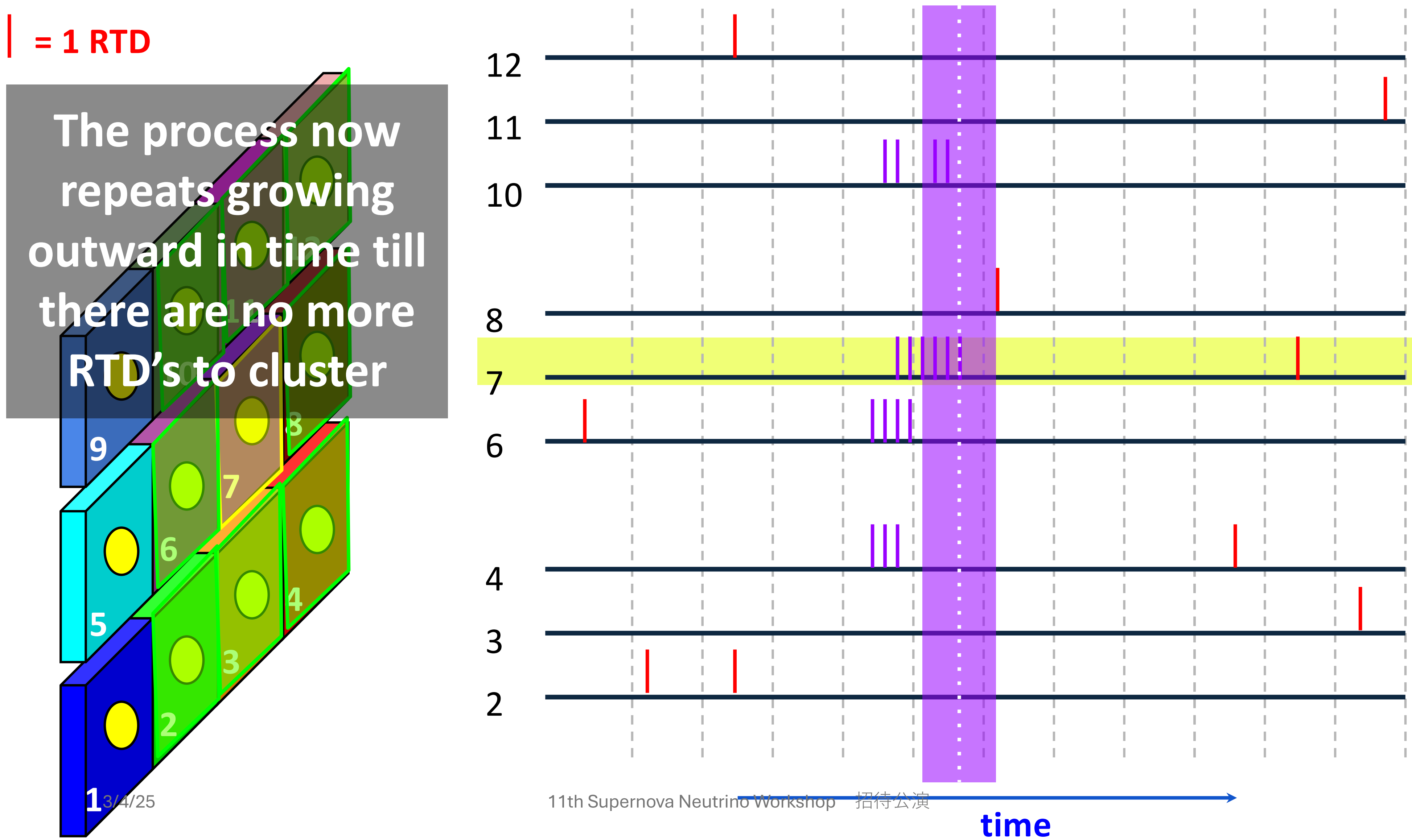
= 1 RTD
The process now repeats growing outward in time till there are no more RTD's to cluster
12
11
10
8
7
6
4
3
2
9
5
1
7
6
2
3
4
8
time

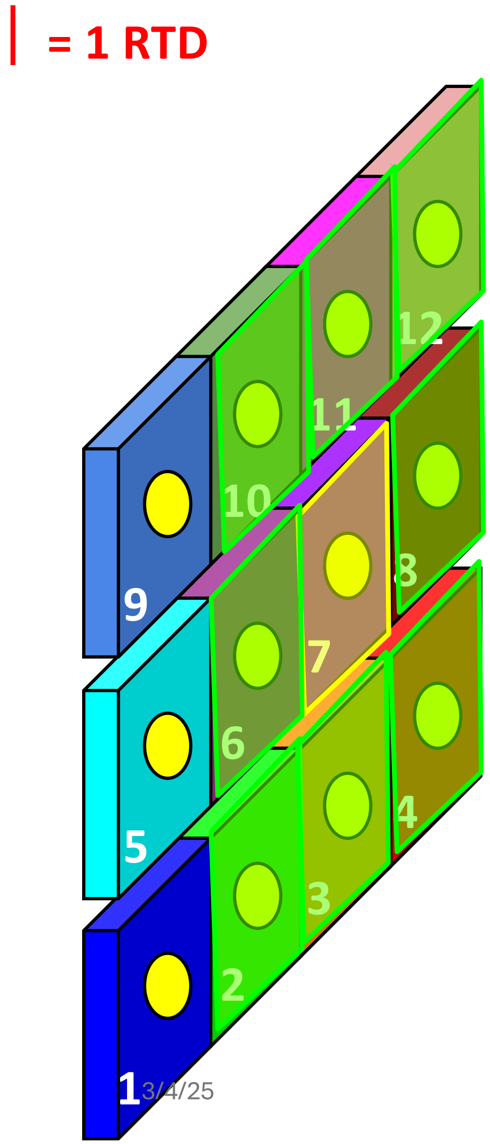
= 1 RTD

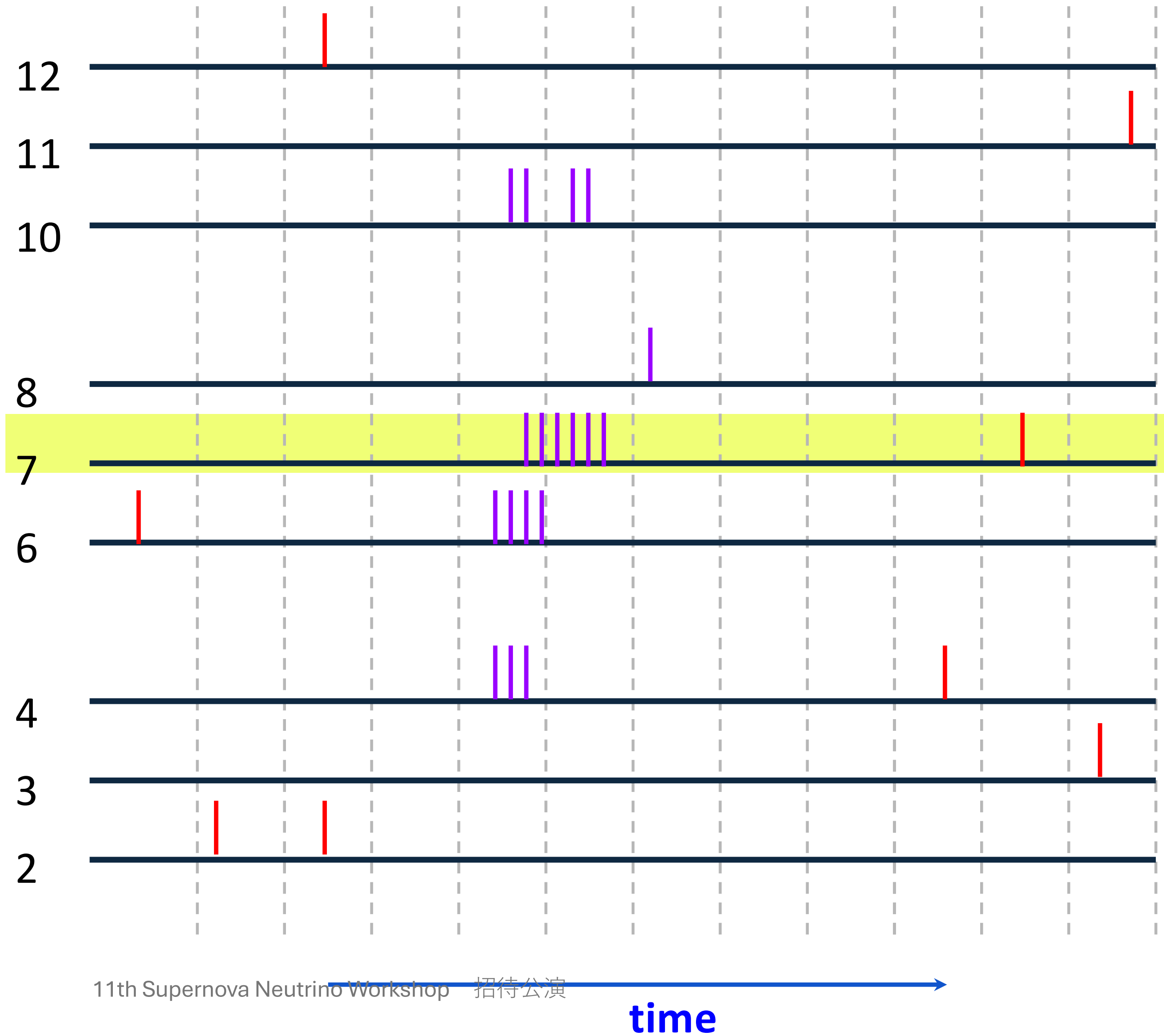
The process now repeats growing outward in time till there are no more RTD’s to cluster

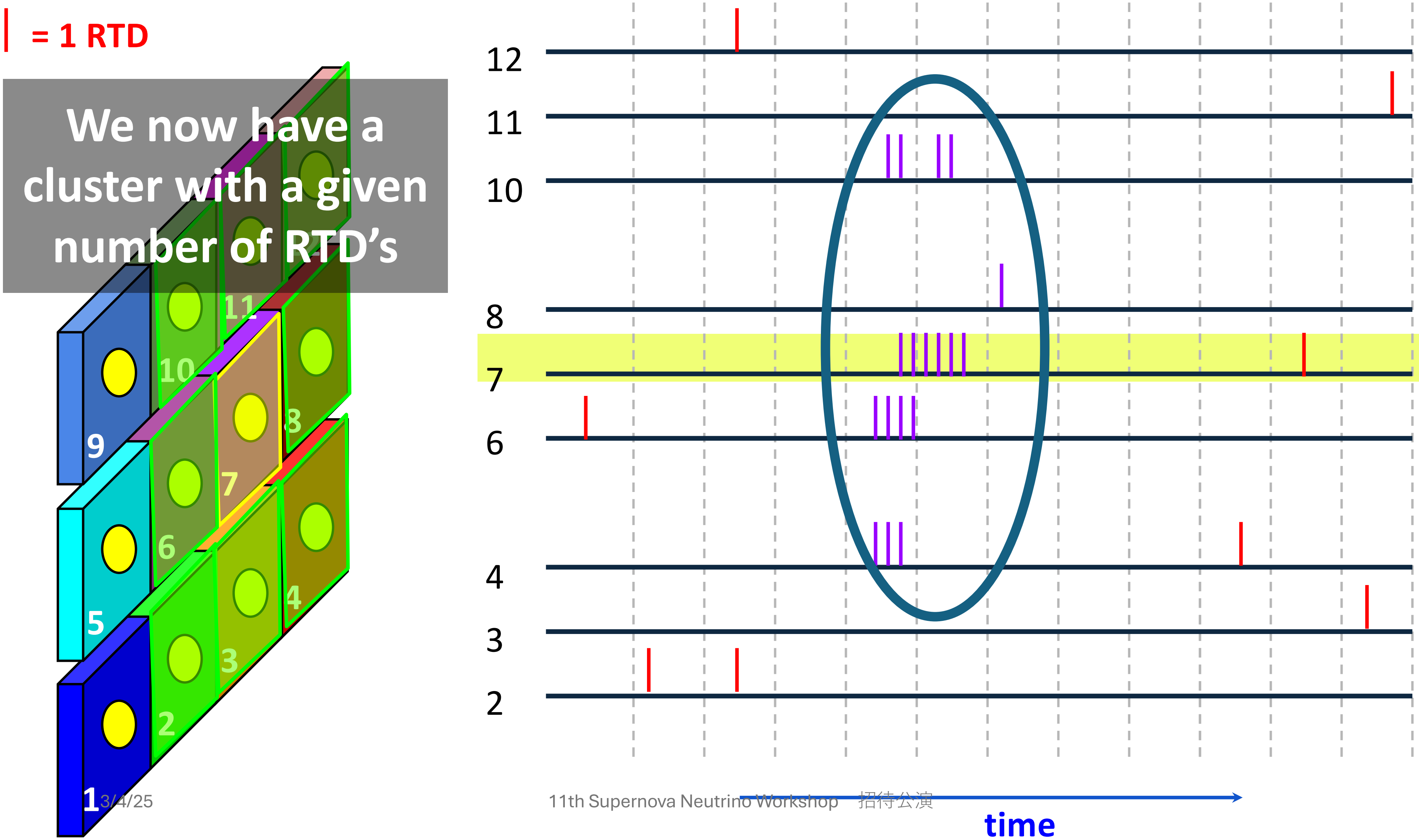





| = 1 RTD
The process now repeats growing outward in time till there are no more RTD's to cluster
9
5
1
6
7
8
4
3
2
12
11
10
8
7
6
4
3
2
time

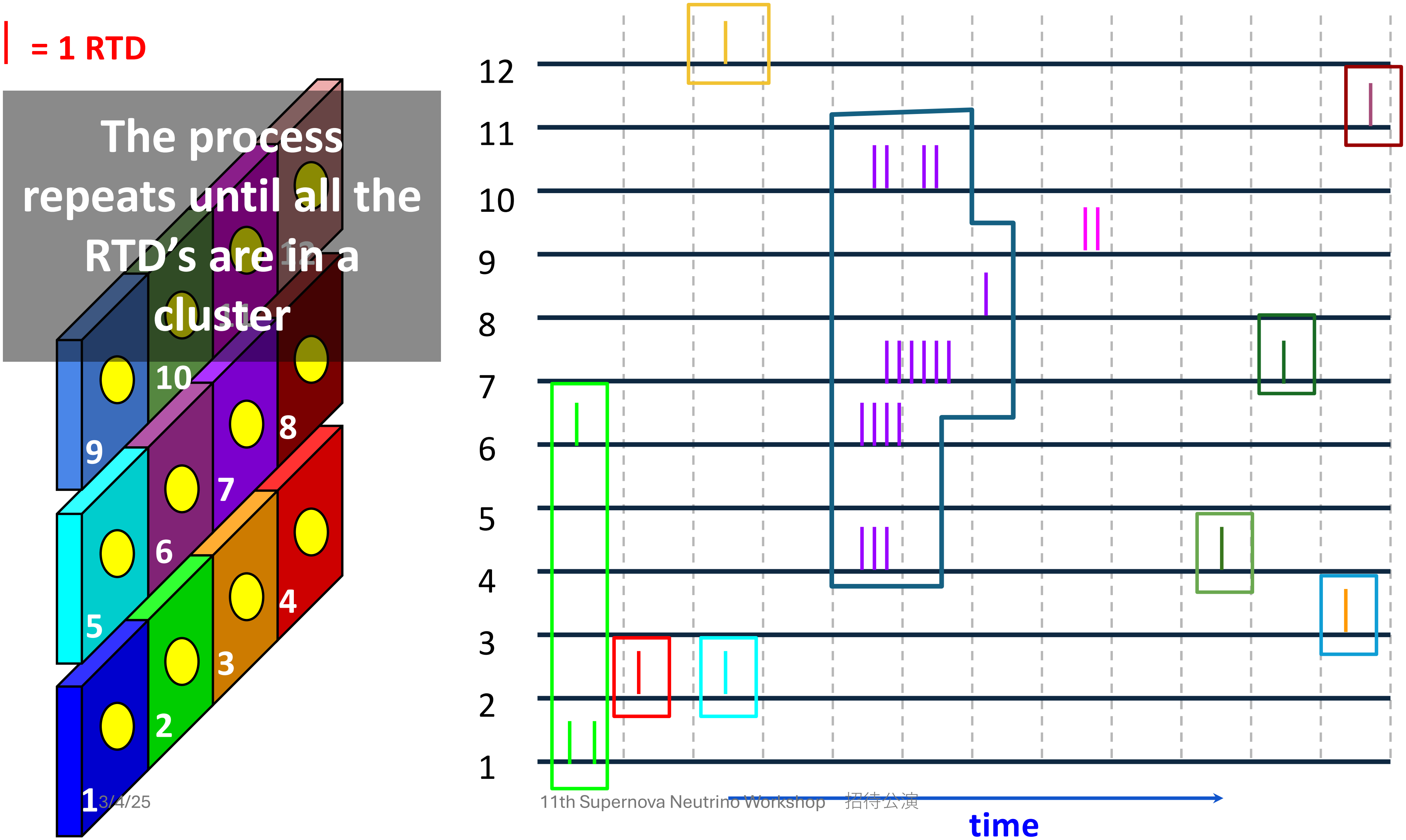

= 1 RTD
9
10
11
12
8
7
6
5
4
3
2
1


12
11
10
8
7
6
4
3
2
time



= 1 RTD
We now have a cluster with a given number of RTD's
12
11
10
8
7
6
4
3
2
1
2
3
4
5
6
7
8
9
10
11
time

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

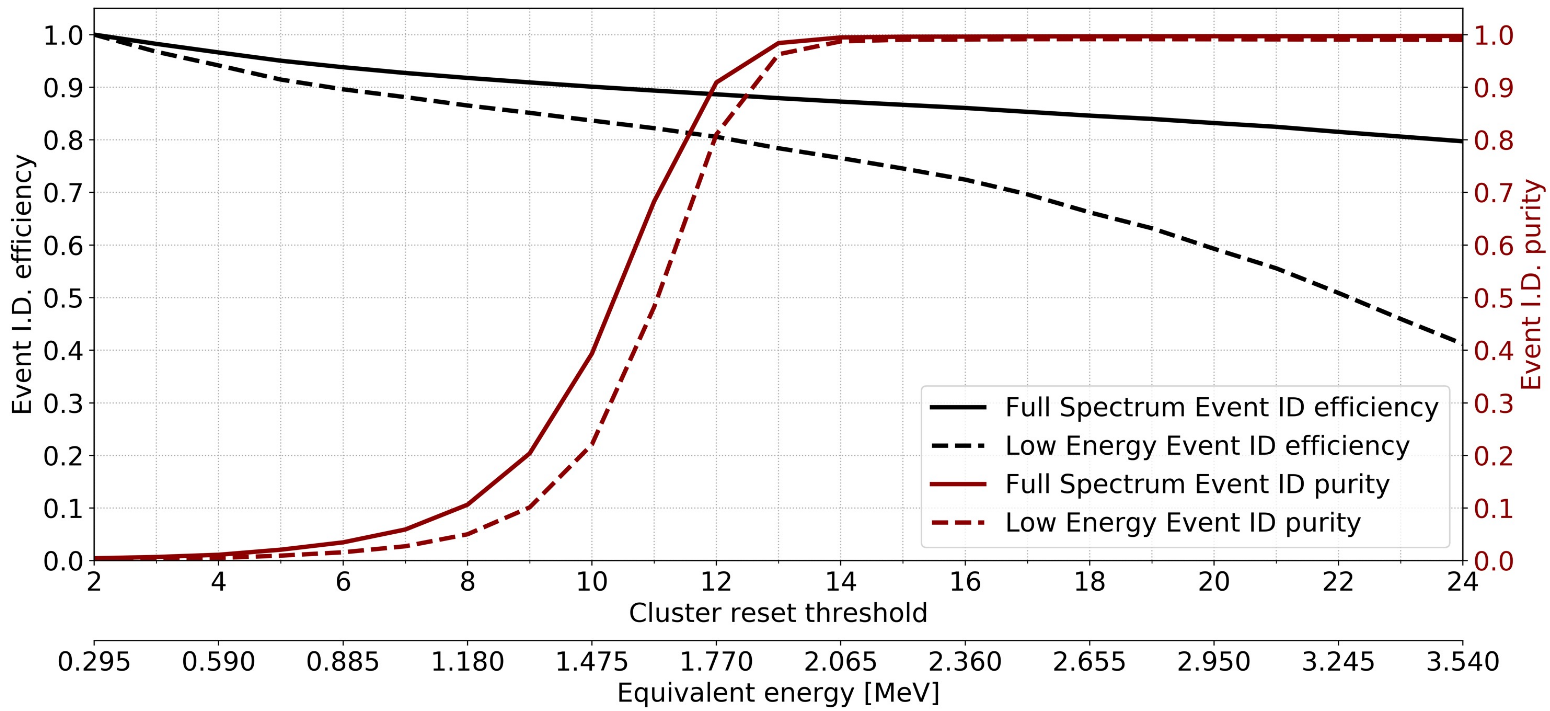


Supernova Event Identification

- Employs “Clustering Algorithm”

$$\text{Efficiency} = \frac{\text{\# of signal events identified}}{\text{\# of signal events simulated}}$$

$$\text{Purity} = \frac{\text{\# of signal events}}{\text{\# of events identified}}$$



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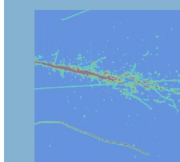
- Employs "Clustering Algorithm"

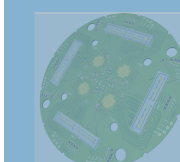
So far, it's been shown that

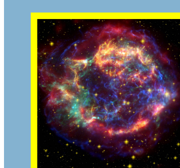
Q-Pix can detect each neutrino event with enhanced capabilities!

Now, we will explore

how well we can identify SNs using those detected neutrinos

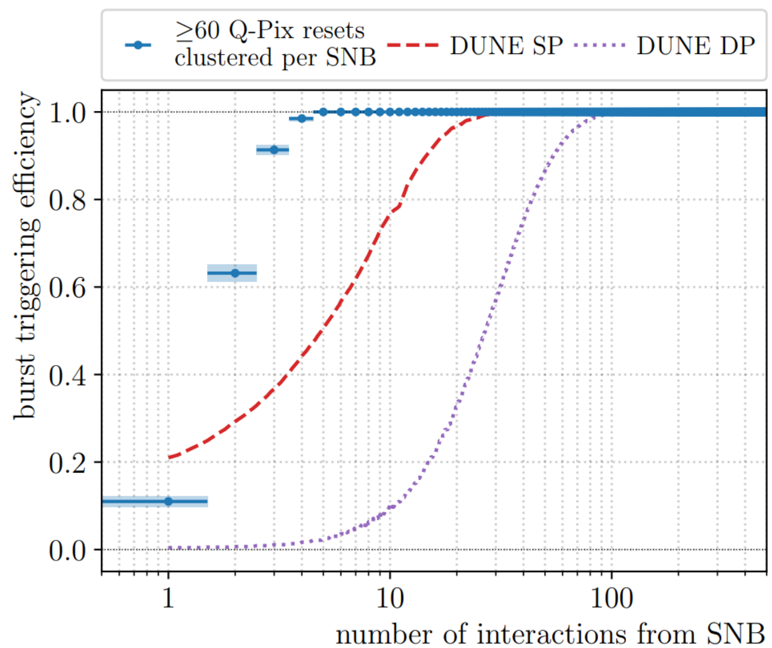


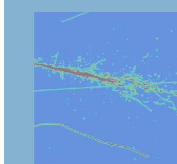


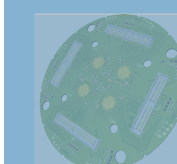


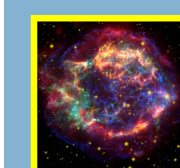
Supernova neutrino studies with Q-Pix

- A Q-Pix 10 kTon module is 100% efficient for SNB out to 80kpc
    - By comparison, conventional DUNE is 100% efficient for SBN only out to 30kpc
- Q-Pix improves the reach of DUNE to SNB by >2.5 times









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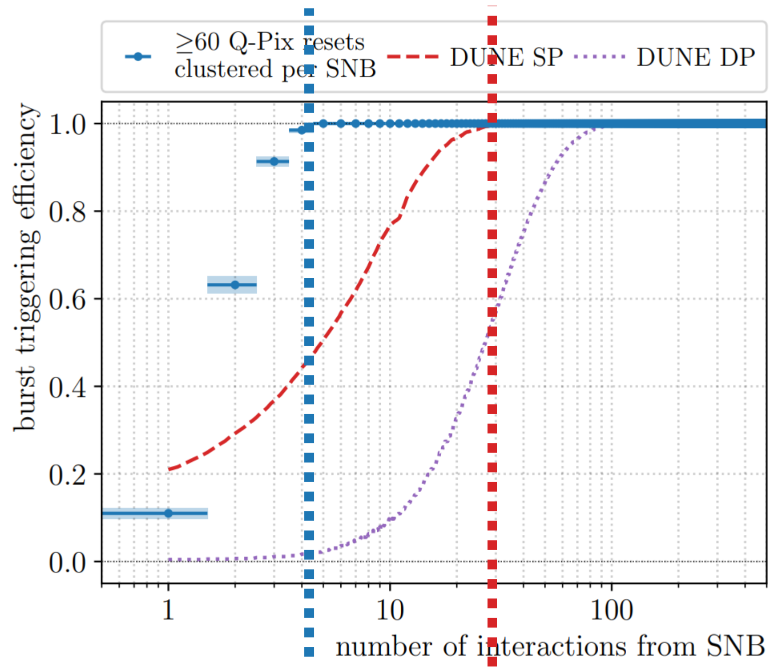
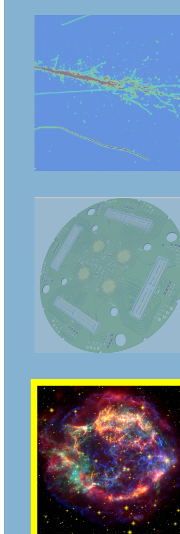


4 neutrino events → 80kpc

30 neutrino events → 30kpc

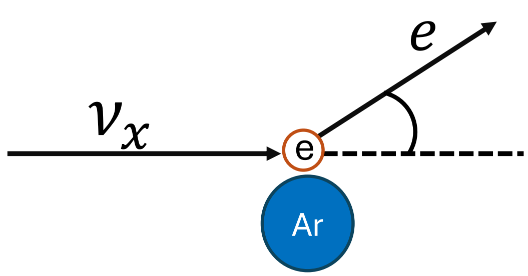


Supernovae pointing studies

How does neutrino interact with atom?

Elastic Scattering (ES) Events

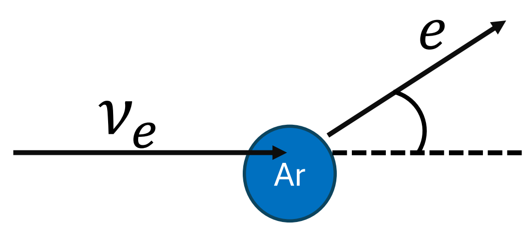
$$\nu_X + e^- \rightarrow \nu_X + e^-$$



Outgoing electron's direction
$\approx$
Incoming neutrino's direction

Charged Current (CC) Events

$$\nu_e +^{40}\mathrm{Ar} \rightarrow e^- +^{40}\mathrm{K}^*$$



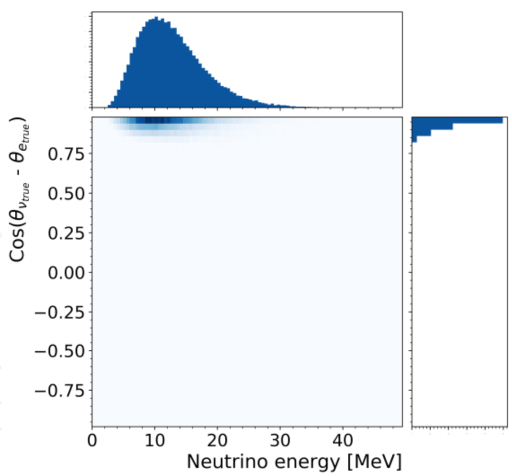
Outgoing electron's direction
$\neq$
Incoming neutrino's direction

This study's result has been published from PRD in 2020

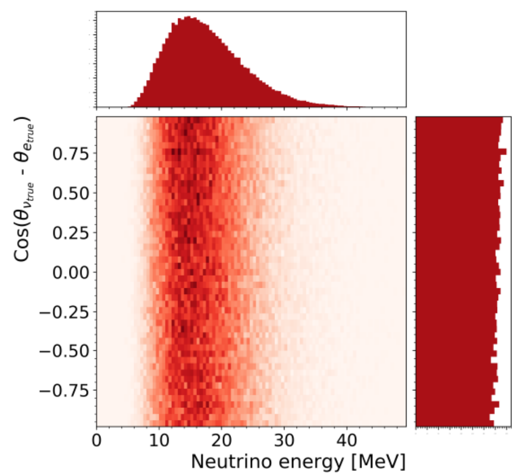
Supernovae pointing studies

How does neutrino interact with atom?

Elastic Scattering (ES) Events



Charged Current (CC) Events



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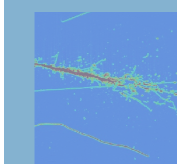
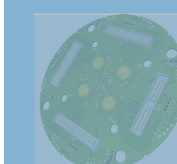
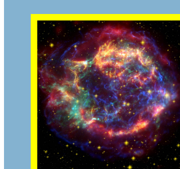


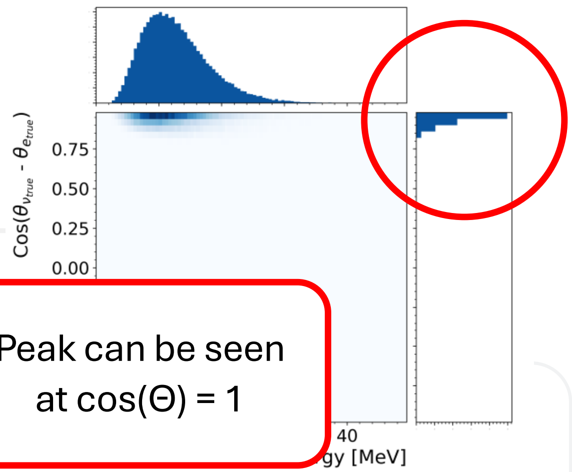




Supernovae pointing studies

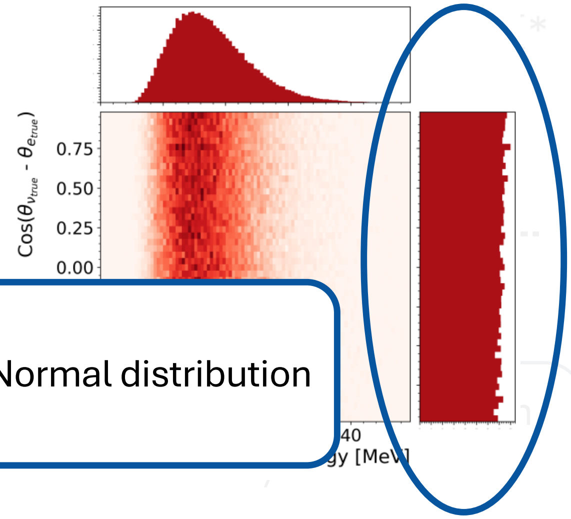
How does neutrino interact with atom?

Elastic Scattering (ES) Events



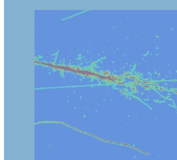
Peak can be seen at cos(Θ) = 1

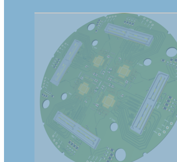
Charged Current (CC) Events

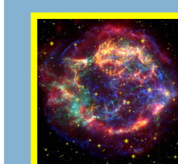


Normal distribution

This study's result has been published from PRD in 2020



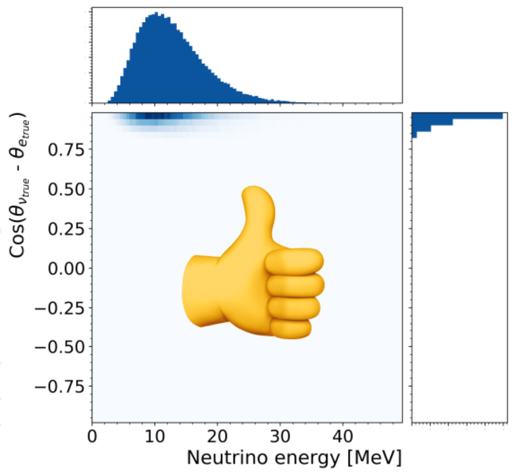




Supernovae pointing studies

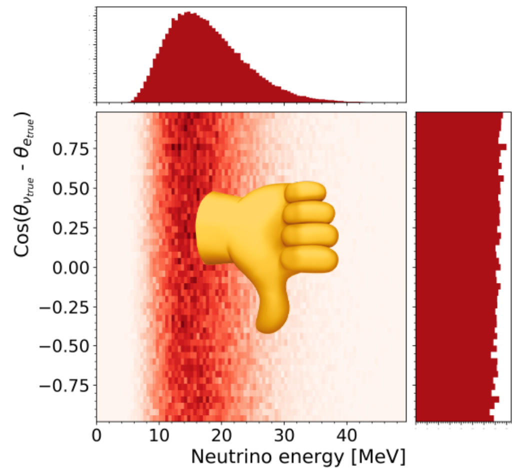
How does neutrino interact with atom?

Elastic Scattering (ES) Events



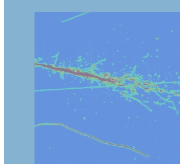
Can be used for directionality analysis

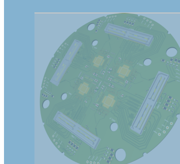
Charged Current (CC) Events

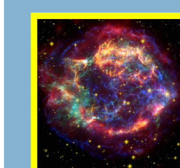


Cannot be used for directionality analysis

This study's result has been published from PRD in 2020



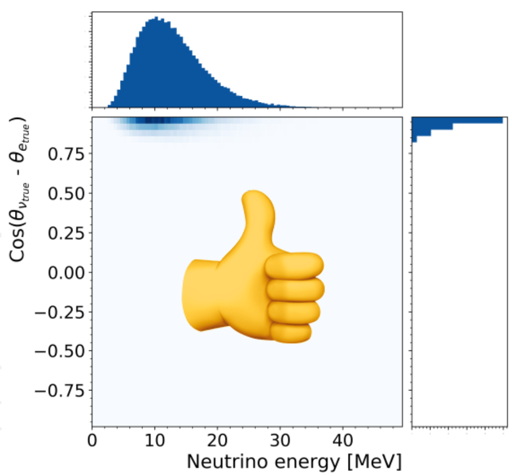




Supernovae pointing studies

How does neutrino interact with atom?

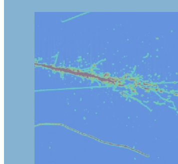
Elastic Scattering (ES) Events

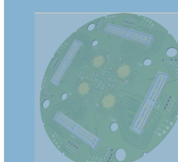


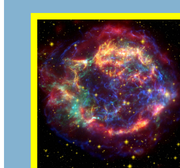
Can be used for directionality analysis

Since $\vec{\nu} \approx \overrightarrow{e_1}$
we can infer SN neutrino's direction
by reconstructing the direction
of primary electron of ES events

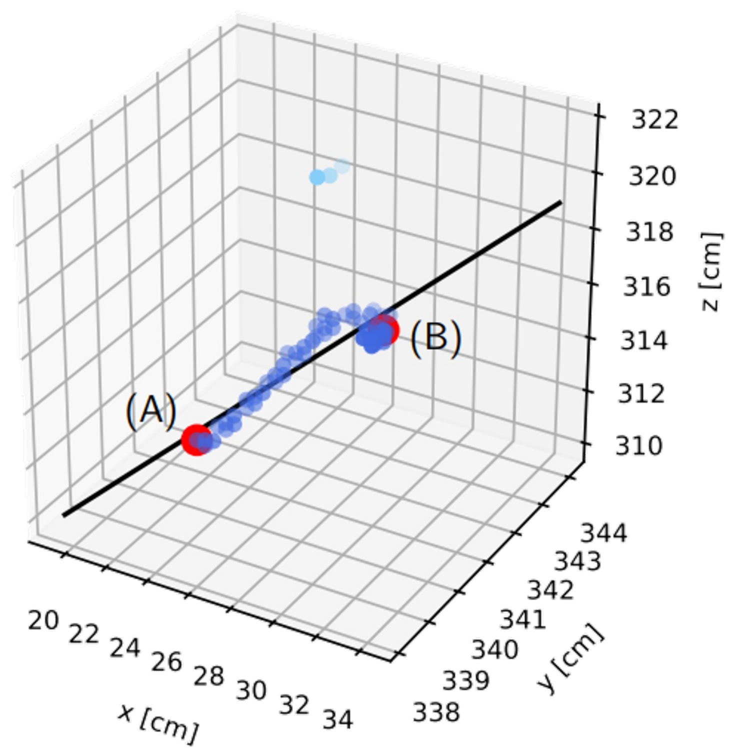
This study's result has been published from PRD in 2020







Supernovae pointing studies

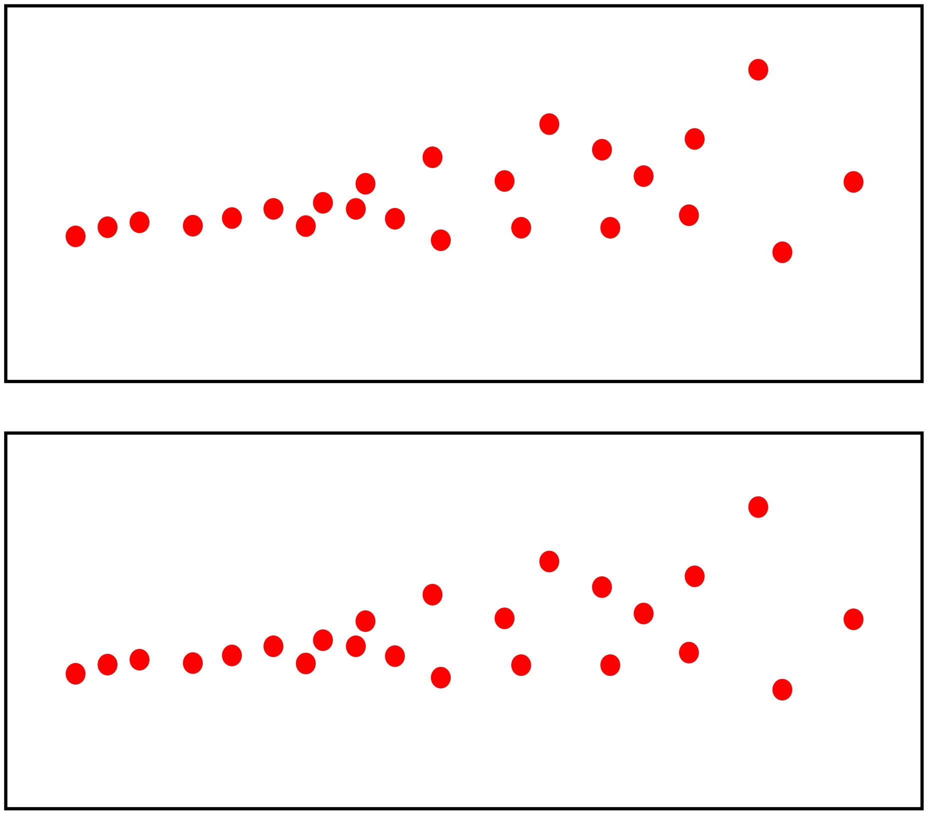


The axis of the neutrino's track
can be easily determined with linear fit

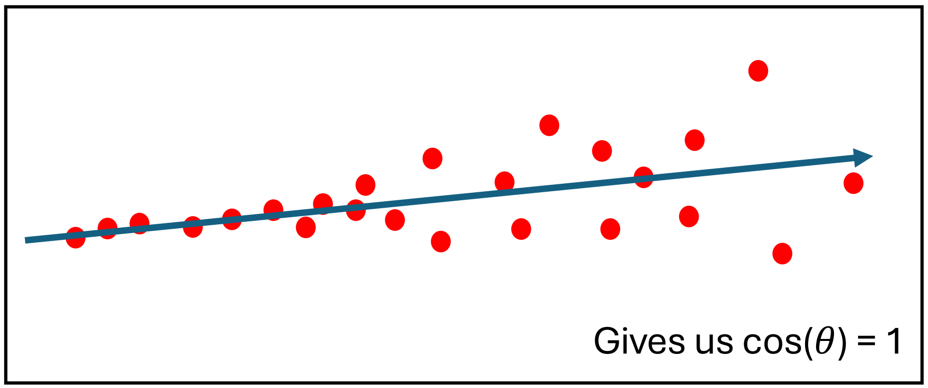
↓

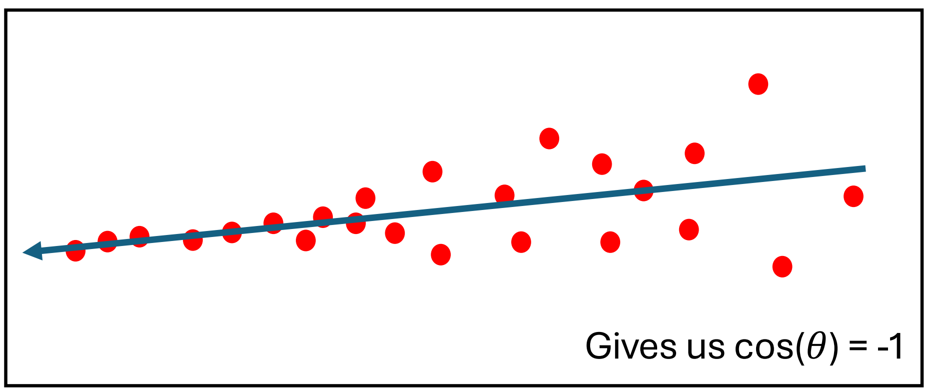
But what about directionality?

Directionality Flipping

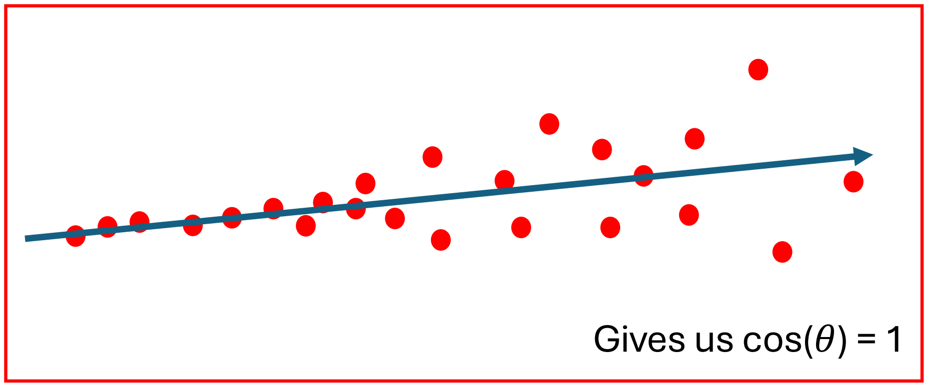


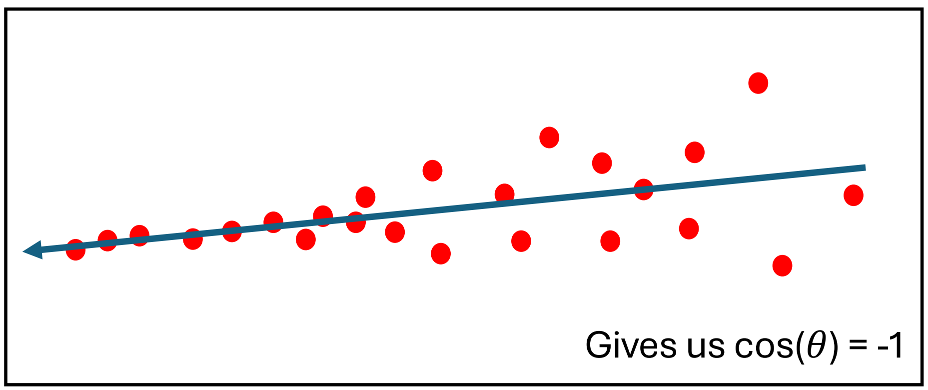
Directionality Flipping





Directionality Flipping

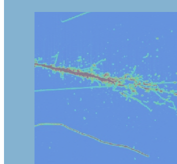


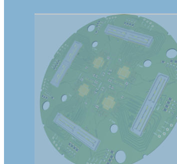


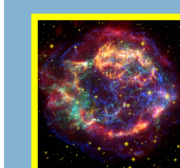
Electron scatters more often as it loses energy.

More scattered = less energy = end of the track

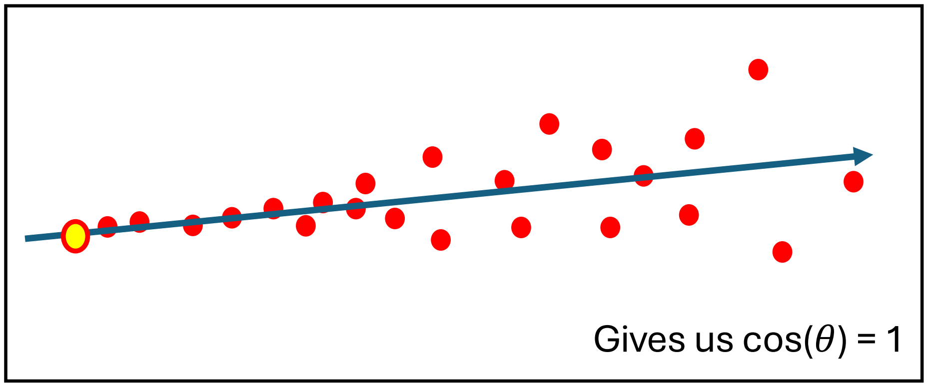
Less scattered = more energy = beginning of the track

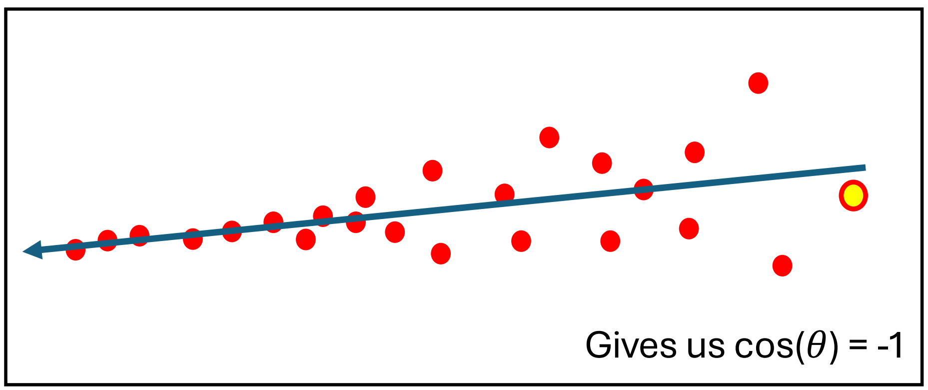






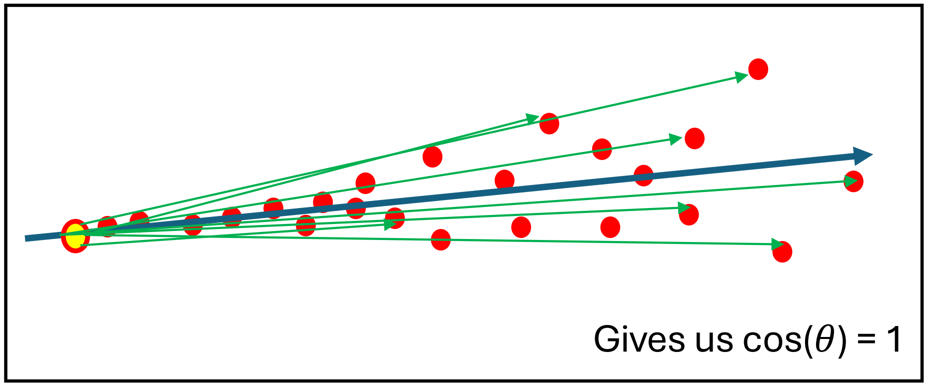
Directionality Flipping

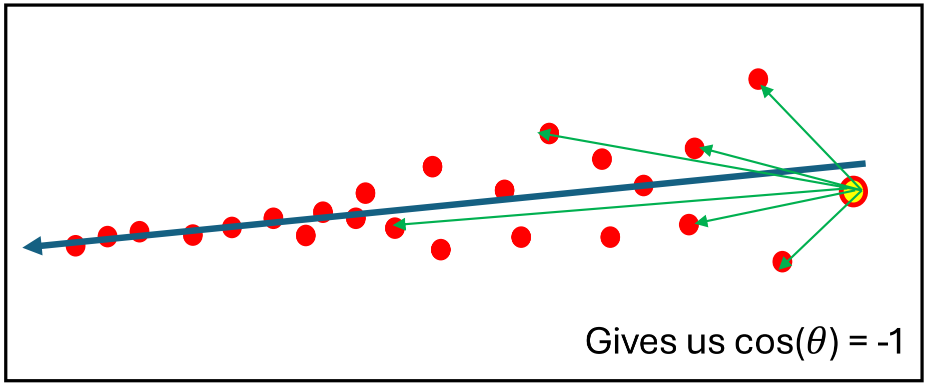




Pick data points at both ends

Directionality Flipping

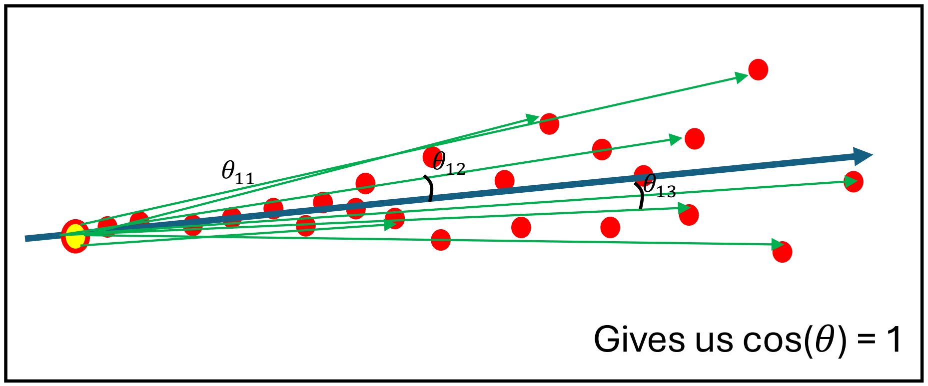


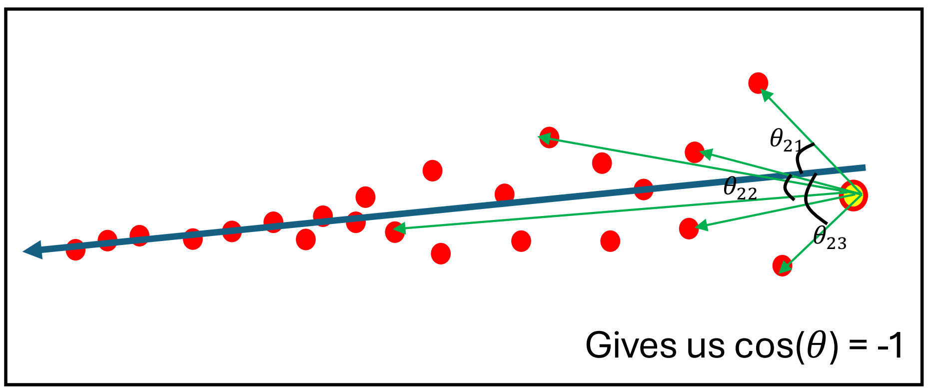


Pick data points at both ends

Draw line from two ends to every single data point

Directionality Flipping



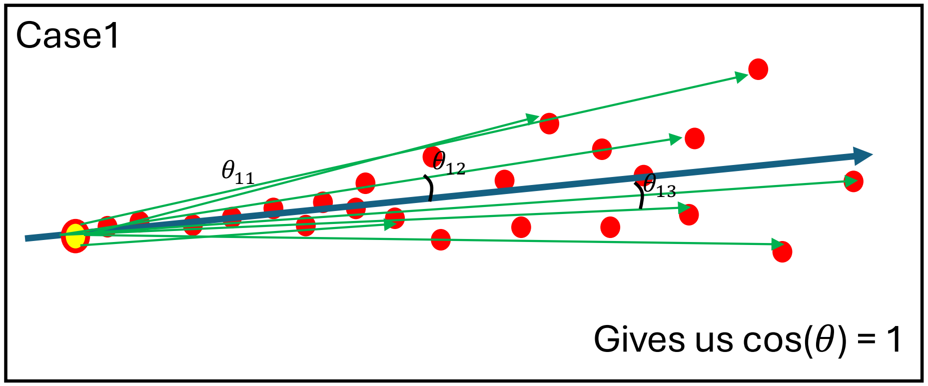


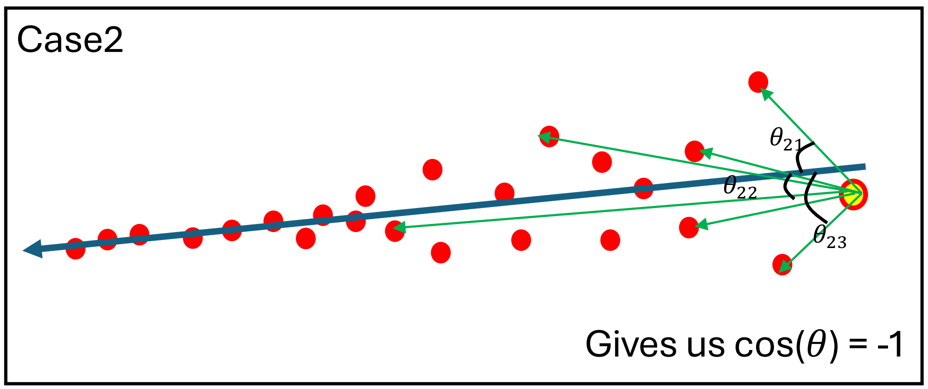
Pick data points at both ends

Draw line from two ends to every single data point

Calculate the cosine of angle between the lines and computed axis, and sum them

Directionality Flipping





Pick data points at both ends

Draw line from two ends to every single data point

Calculate the cosine of angle between the lines and computed axis, and sum them

θ values are smaller → cos(θ) values are bigger

sum_cos_case1 = $\cos(\theta_{11}) + \cos(\theta_{12}) + \cos(\theta_{13}) \cdots$

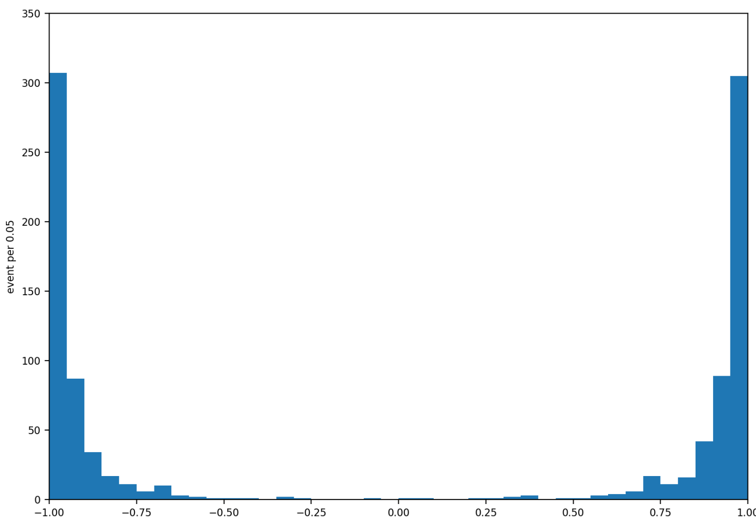
θ values are bigger → cos(θ) values are smaller

sum_cos_case2 = $\cos(\theta_{21}) + \cos(\theta_{22}) + \cos(\theta_{23}) \cdots$

sum_cos_case1 > sum_cos_case2

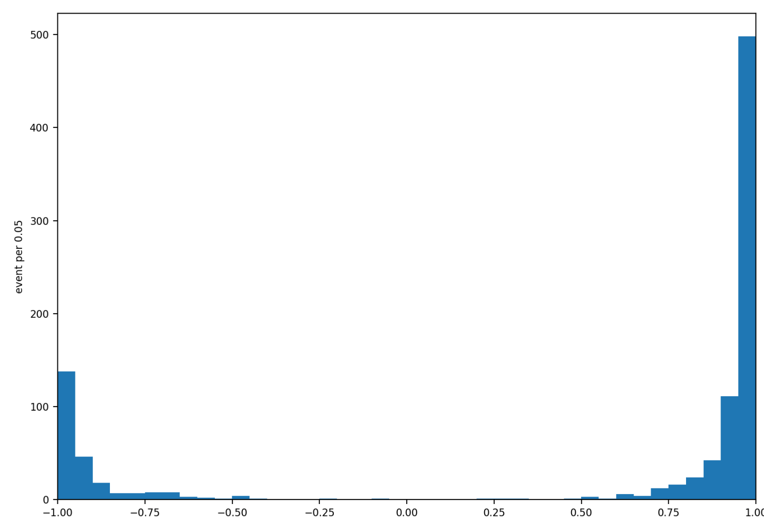
Directionality Flipping

Direction reconstruction **before** flipping

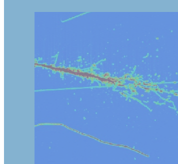


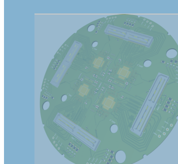
$\cos(\theta_\nu - \theta_e)$

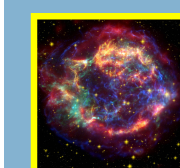
Direction reconstruction **after** flipping



$\cos(\theta_\nu - \theta_e)$

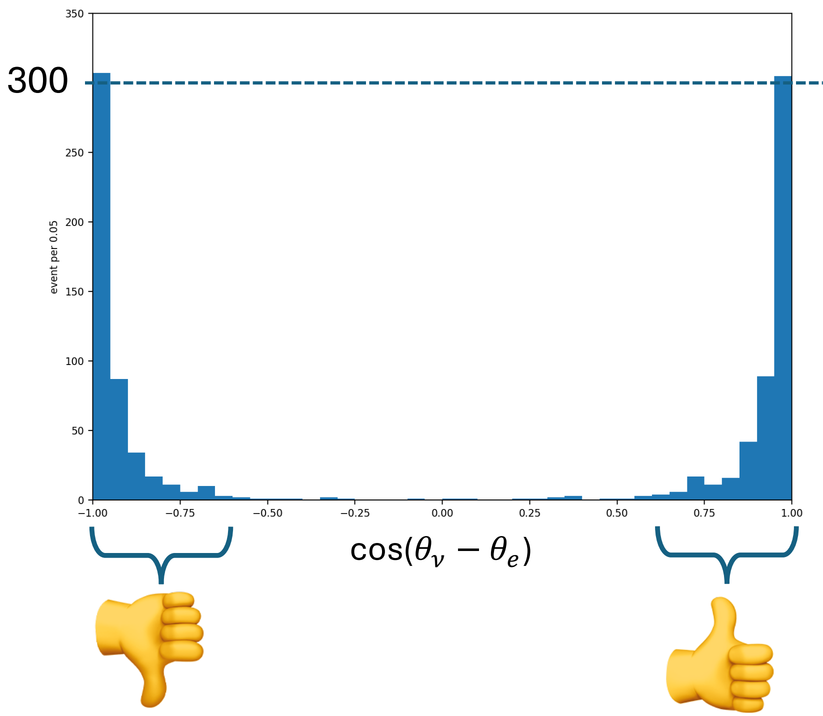




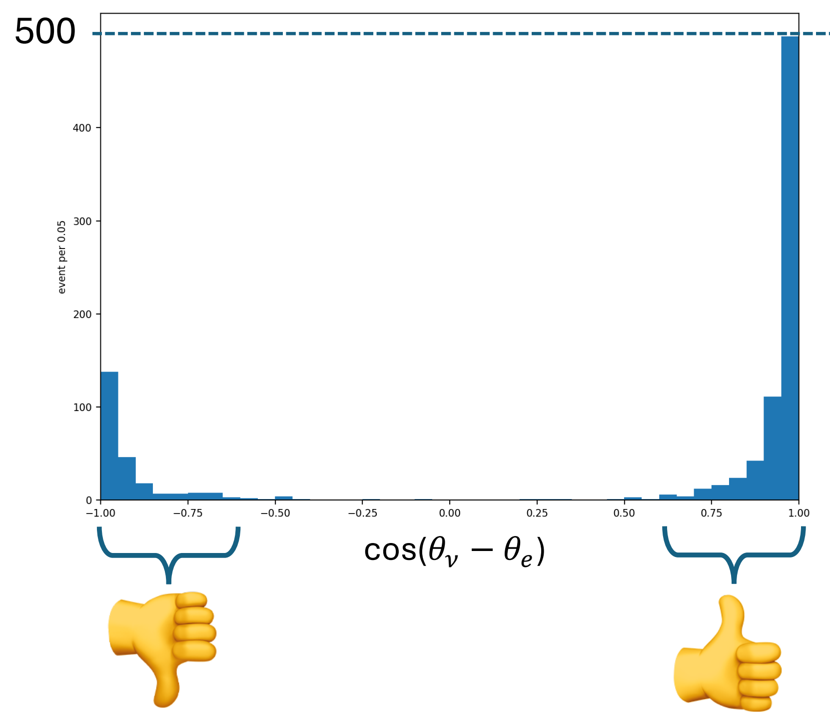


Directionality Flipping

Direction reconstruction **before** flipping

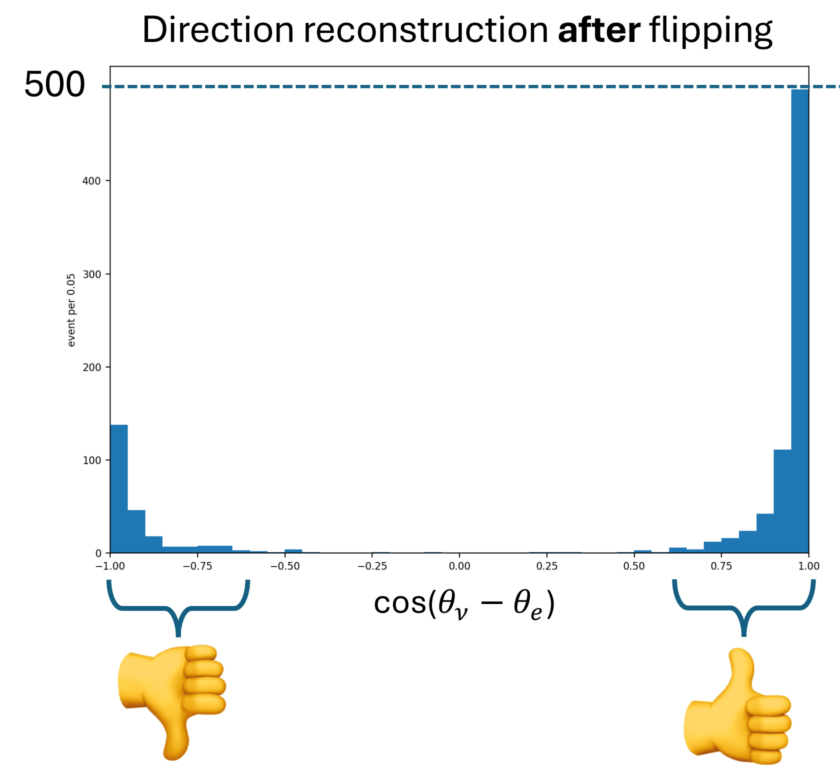


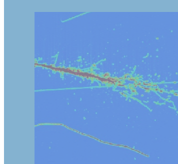
Direction reconstruction **after** flipping

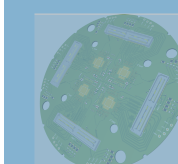


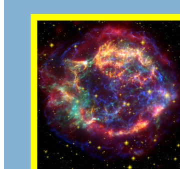
Directionality Flipping

The flipping method can enhance the accuracy of directionality reconstruction of neutrinos





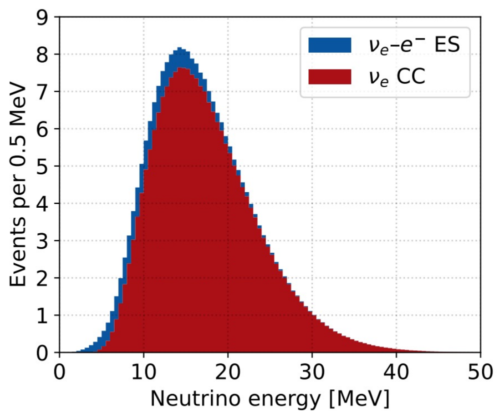




Supernovae pointing studies

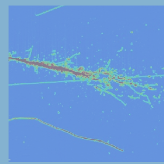
In this studies, we don't perform event classification between ES and CC.

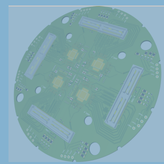
However, we could pick the ES's peak from the ensemble of two kinds.



Channel	Liver-more	GKVM	Garching
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	2648	3295	882
$\overline{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	224	155	23
$\nu_X + e^- \rightarrow \nu_X + e^-$	341	206	142
Total	3213	3656	1047

This study's result has been published from PRD in 2020





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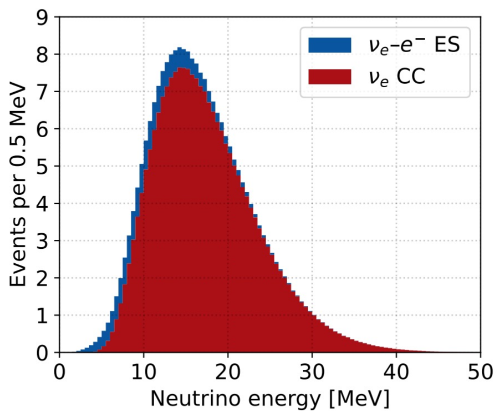

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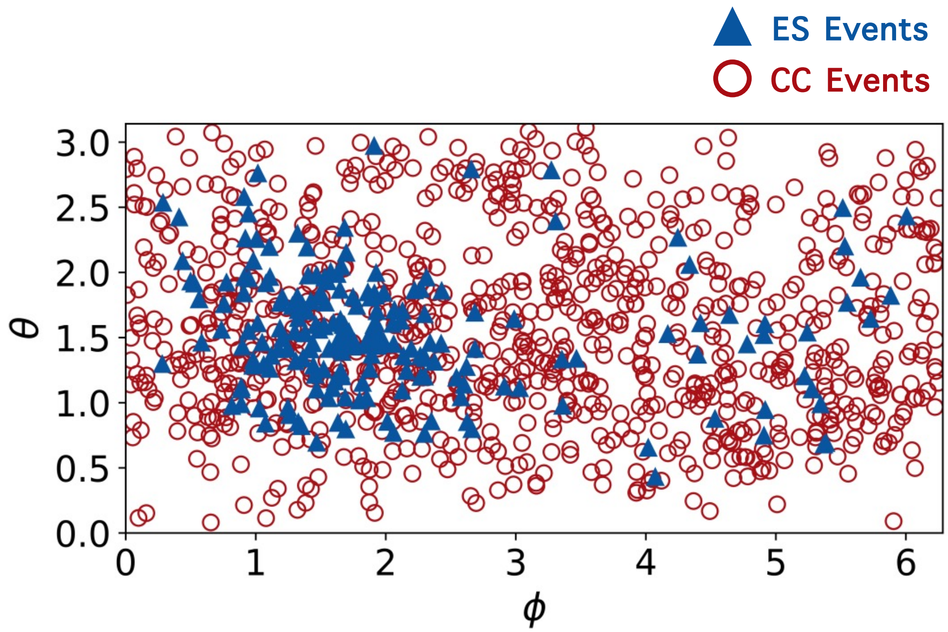

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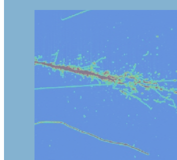
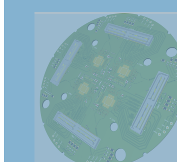
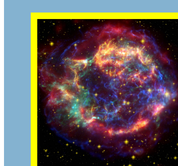
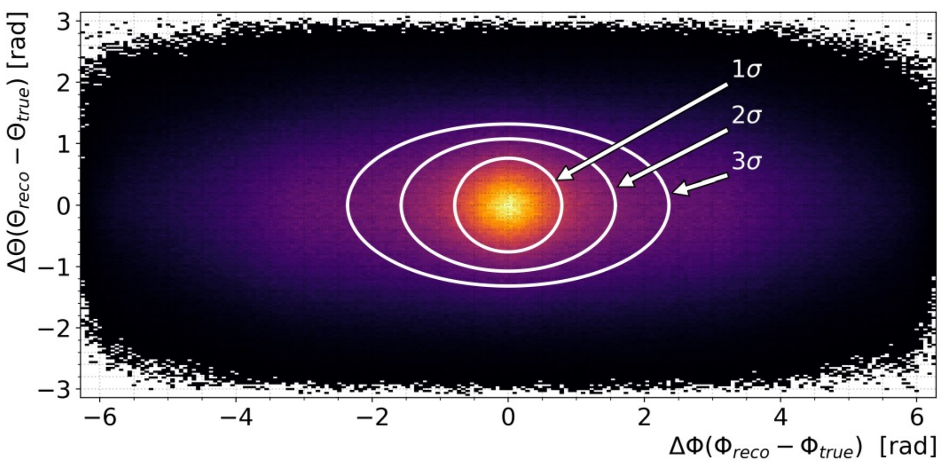






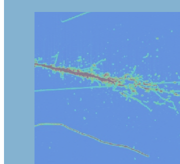
Supernovae pointing studies

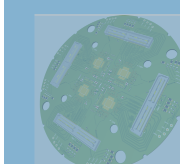
10000 unique supernova explosions were isotopically simulated.

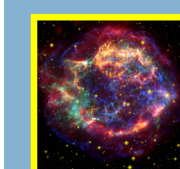


10 kpc supernova reconstructed within
$\theta = 33^\circ$ and $\phi = 45^\circ$ at 1σ, and
$\theta = 99^\circ$ and $\phi = 135^\circ$ at 3σ

This study's result has been published from PRD in 2022







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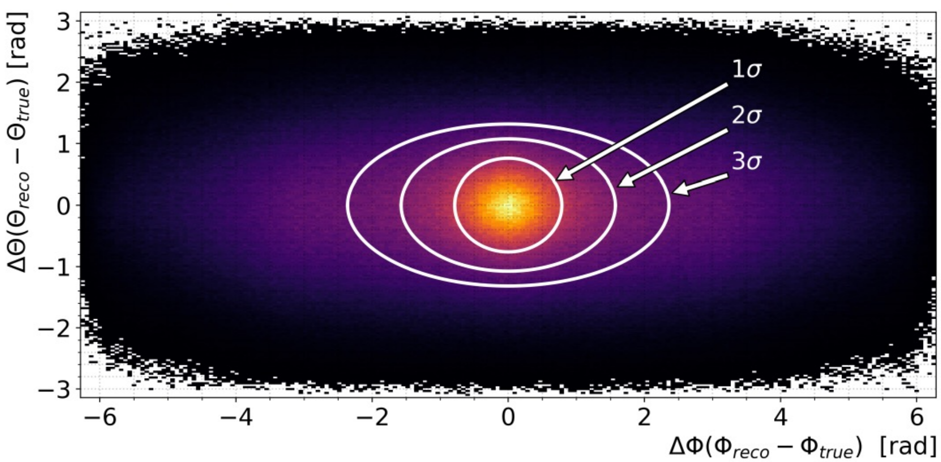
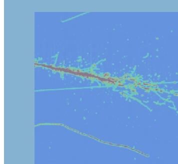


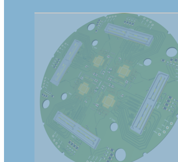
10 kpc supernova reconstructed within
θ = 33° and ϕ = 45° at 1σ, and
θ = 99° and ϕ = 135° at 3σ

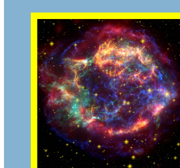
In recent DUNE results (July 2024), it was claimed that pointing resolution * of 102 degrees.

This is very exciting, because our studies with Q-Pix have already shown similar capabilities;
we can expect enhanced supernova studies with Q-pix!

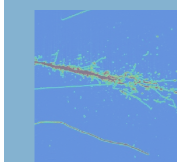
This study's result has been published from PRD in 2022

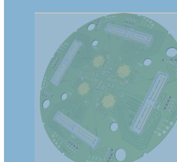


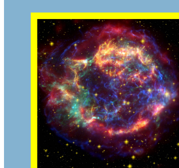


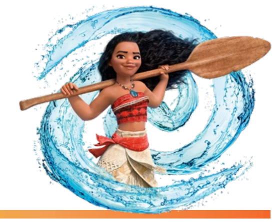


How far can we go?









How far can we go?

'maximize the discovery potential of a kiloton scale LArTPC'

Paper published from JINST in 2020

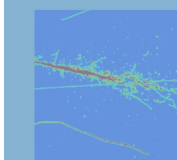
Enhancing beam event studies

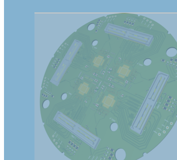
Paper published from PRD in 2022

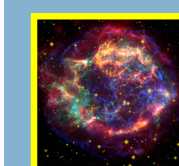
Enhancing supernovae studies

~10GeV range : high energy neutrinos

< 40MeV range : low energy neutrinos







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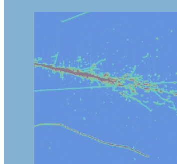

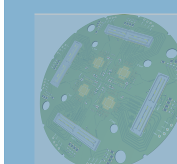

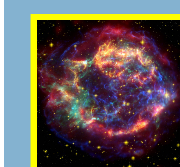

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Paper published from JINST in 2020

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Paper published from PRD in 2022

Enhancing supernovae studies

Paper In preparation

Enabling solar studies

～10GeV range : high energy neutrinos

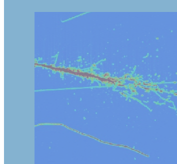
< 40MeV range : low energy neutrinos

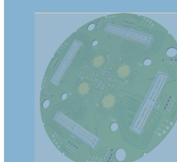
< 15MeV range : very low energy neutrinos

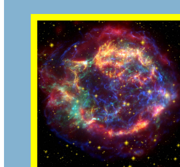
How far can we go?

- Good tracking
- Good energy resolution
- Low energy threshold
- Data handling
- Background handling

Enabling solar studies







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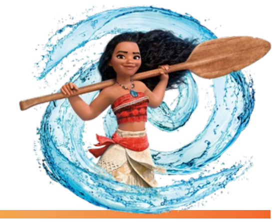

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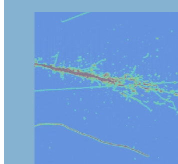
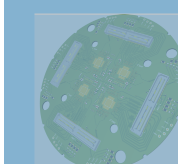
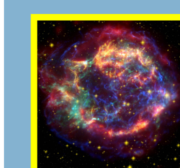
Enabling solar studies

These can be inheritably given by pixel technologies, as shown in the beam studies paper ✅







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Good tracking

Good energy resolution

Low energy threshold

Data handling

Background handling

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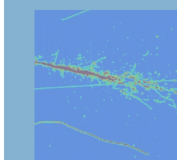
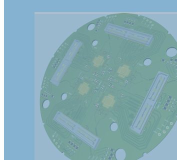
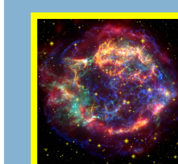
Q-Pix excels in this!

Can reduce the data amount by factor of 10^6! ✅







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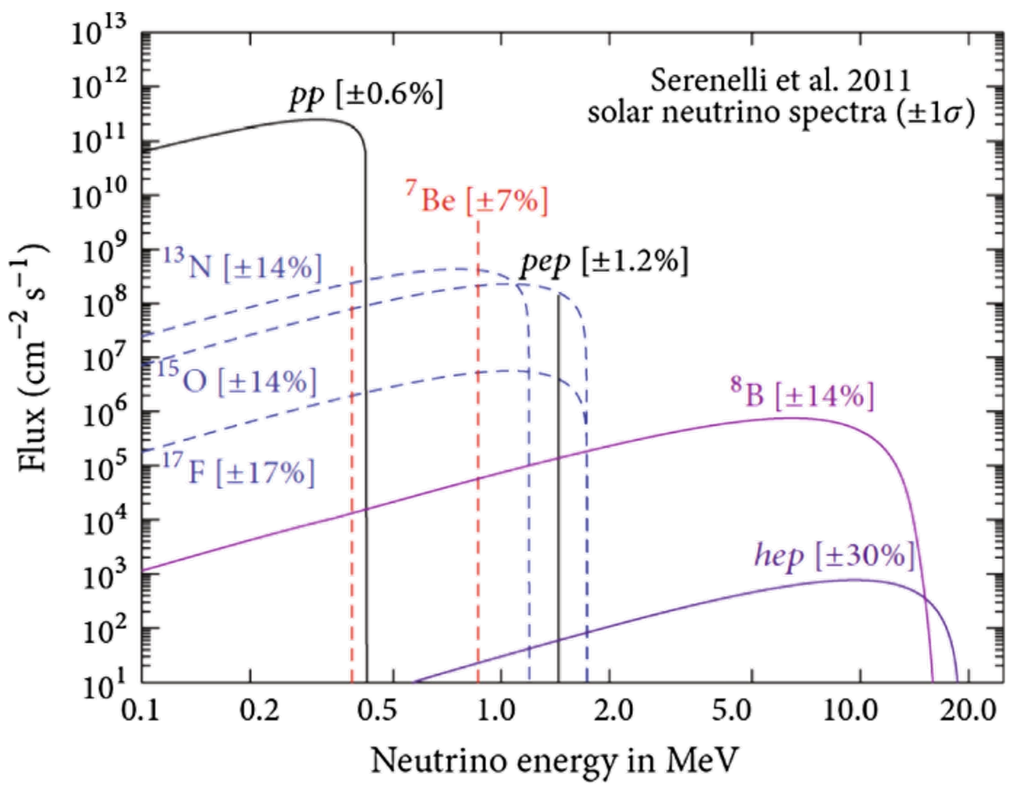
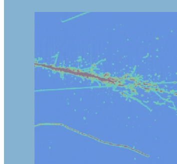
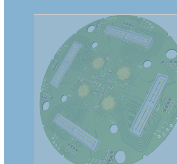
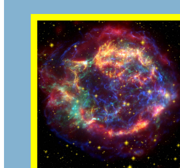


Suzuki, Y. The Super-Kamiokande experiment. *Eur. Phys. J. C* **79**, 298 (2019)

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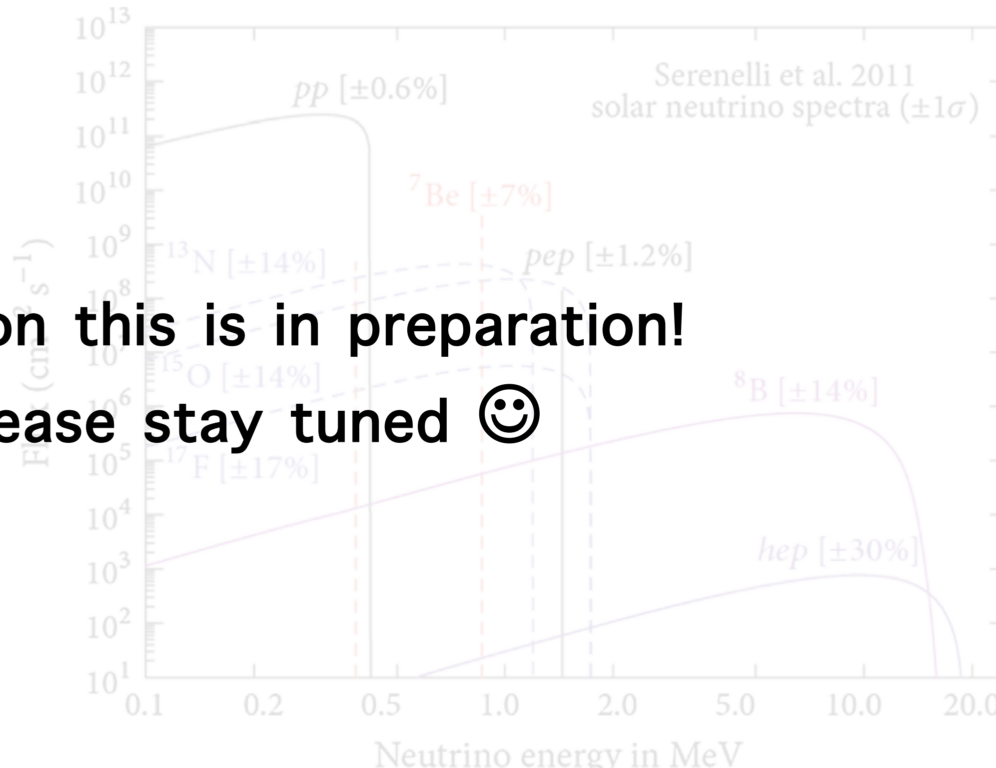
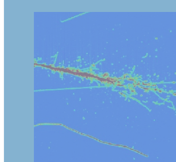
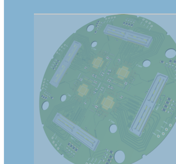


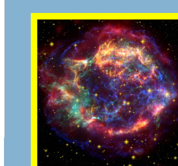
Paper on this is in preparation!

Please stay tuned ☺

Suzuki, Y. The Super-Kamiokande experiment. *Eur. Phys. J. C* **79**, 298 (2019)



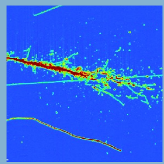


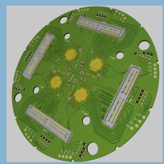


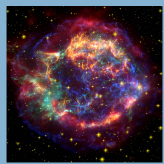
Summary

- DUNE is under construction, first 2 modules will be with chosen technology, the last 2 to be decided.
- DUNE's capability can be further enhanced with pixelated readout.
- Physics studies have shown that pixels would improve DUNE's physics reach in beam, supernova neutrino, and solar neutrino (paper in preparation) studies.
- Q-Pix prototype is being tested now, and more R&D activities will continue for the upcoming years.

  ⇨ Further investigation and analysis with pixel-based readout technologies!

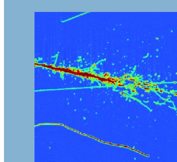


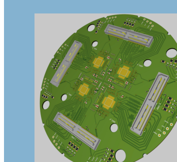


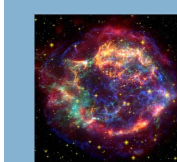


Thank you!

I would like to thank all the collaborators on DWA and Q-Pix work!

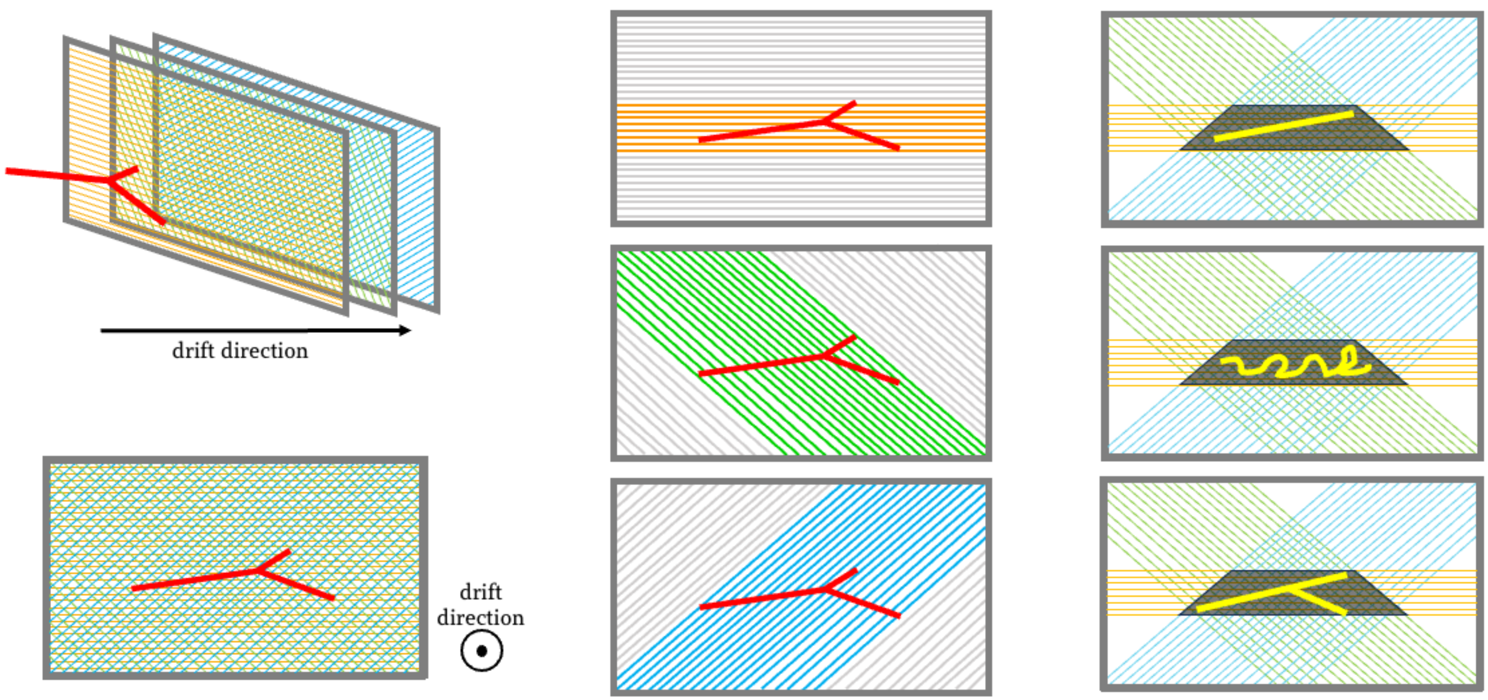


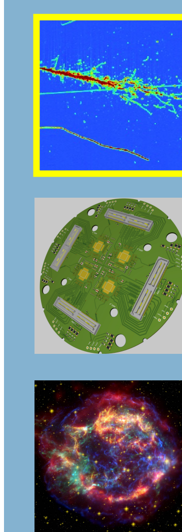




BACKUP

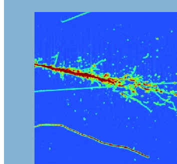
Wire Ambiguity

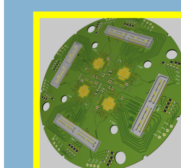


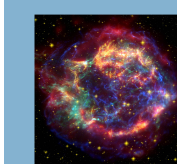


Q-Pix and LArPix

Specification	Q-Pix	LArPix	DUNE Cold Electronics
Threshold	**Target:** 0.3–0.5 fC (1800–3100 electrons)	**Self Trigger Threshold:** 0.9 fC [1] (5800 electrons)	0.7 fC [3] (4300 electrons)
Noise	**Target:** $\leq$ 500 electrons	850 electrons [2]	500–700 electrons [4]
Data Rate	1.0×10^{-4} kB/s/m^2 at 1 MeV deposited energy threshold [6]	1 MB/s/m^2 when operating on the surface with cosmics rays [1]	0.4 MB /s/m^2 at 10 MeV deposited energy threshold [5]
Saturation	10^9 electrons CIR can reliably handle 25 nA	2×10^6 electrons; Dynamic Range on 8-bit ADC with 1 bit at noise limit	5×10^6 electrons; Dynamic Range on 12-bit ADC with 1 bit at noise limit
Power	20–25 μW/channel	60–100 μW/channel	50 mW/channel







Sigma Delta Modulator

Integrator

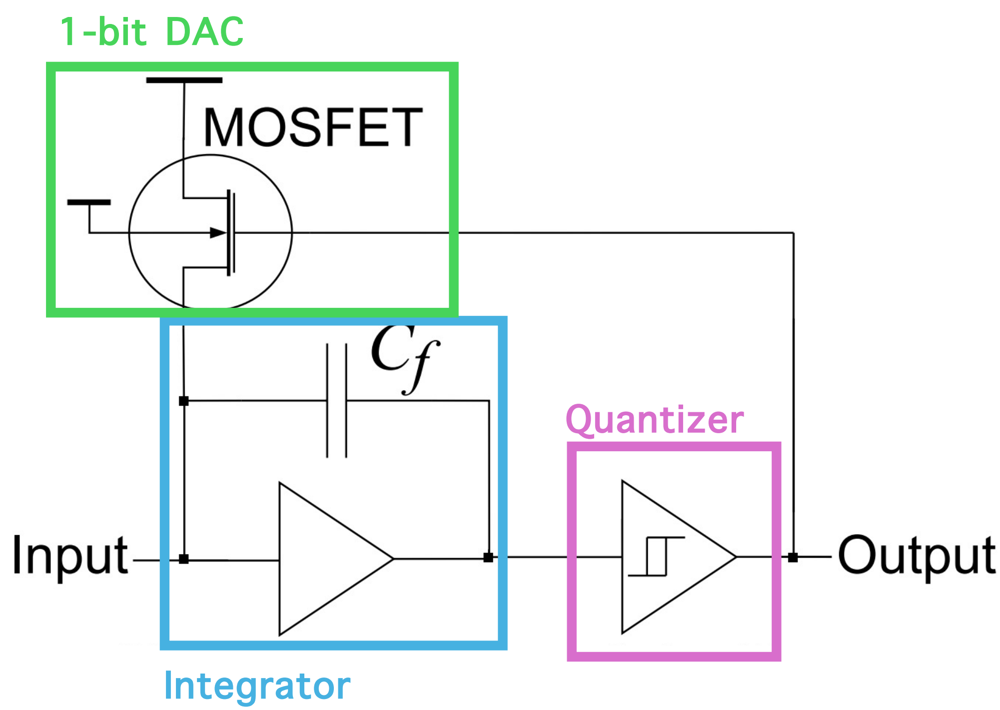
Sums the input signal over time, effectively smoothing it and making the system more tolerant to noise.

Quantizer

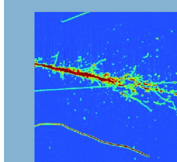
Converts the analog signal from the integrator into a digital signal. It is a single-bit quantizer with output of either 0 or 1.

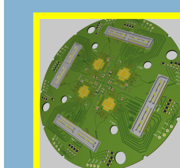
DAC

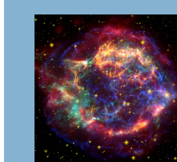
Receives the output from the quantizer and converts the digital output back into an analog signal. It limits the amount of charge on Cf.



[Paper published on this]

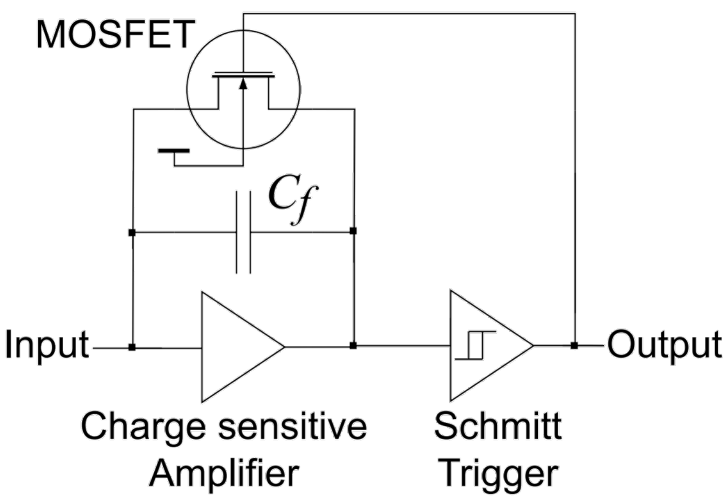




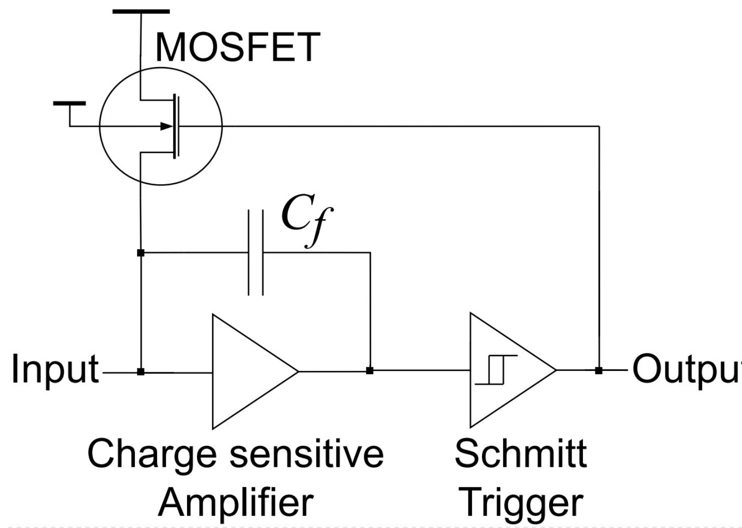


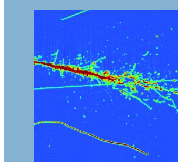
Reset vs Replenishment scheme

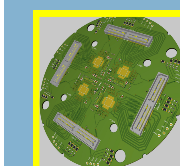
Reset

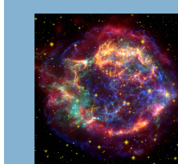


Replenishment









Profile used for SN studeis

Isotope	Rate [Bq/kg]	Region	Region mass [kg]	Rate [Bq]	Number of decays (per 10 s window)
^{210}Po	0.2	PD [Bq/m^2]	2.46856	0.493712	5
^{60}Co	0.0455	CPA	90	4.095	41
^{40}K	0.49	APA	258	1,264.2	12,642
^{39}Ar	1.010	bulk LAr	$\sim$70,000	70,700	707,000
^{42}Ar	0.000092	bulk LAr	$\sim$70,000	6.44	64
^{42}K	0.000092	bulk LAr	$\sim$70,000	6.44	64
^{222}Rn	0.04	bulk LAr	$\sim$70,000	2,800	28,000
^{214}Pb	0.01	bulk LAr	$\sim$70,000	700	7,000
^{214}Bi	0.01	bulk LAr	$\sim$70,000	700	7,000
^{85}Kr	0.115	bulk LAr	$\sim$70,000	8,050	80,500

TABLE I. Summary of the radiogenic backgrounds, adapted from Ref. [64], outlining the particular radioactive isotope, the region the isotope originates from, the estimated decay rate for the isotope, and the expected number of decays in a 10-second simulation window.