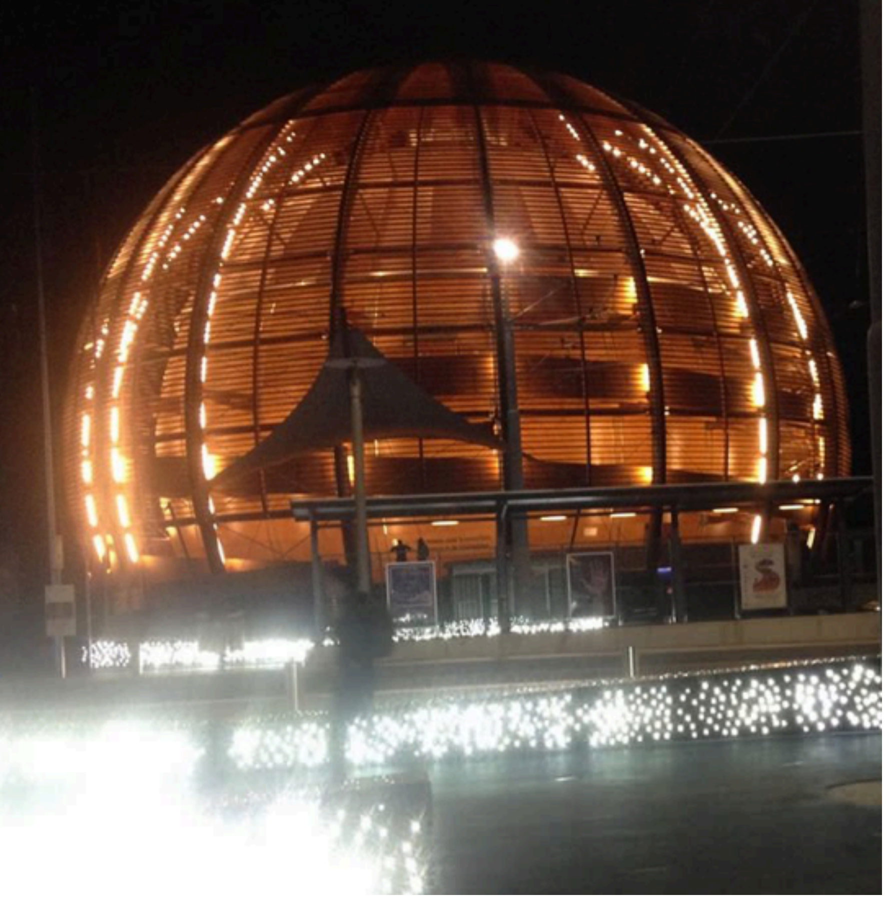


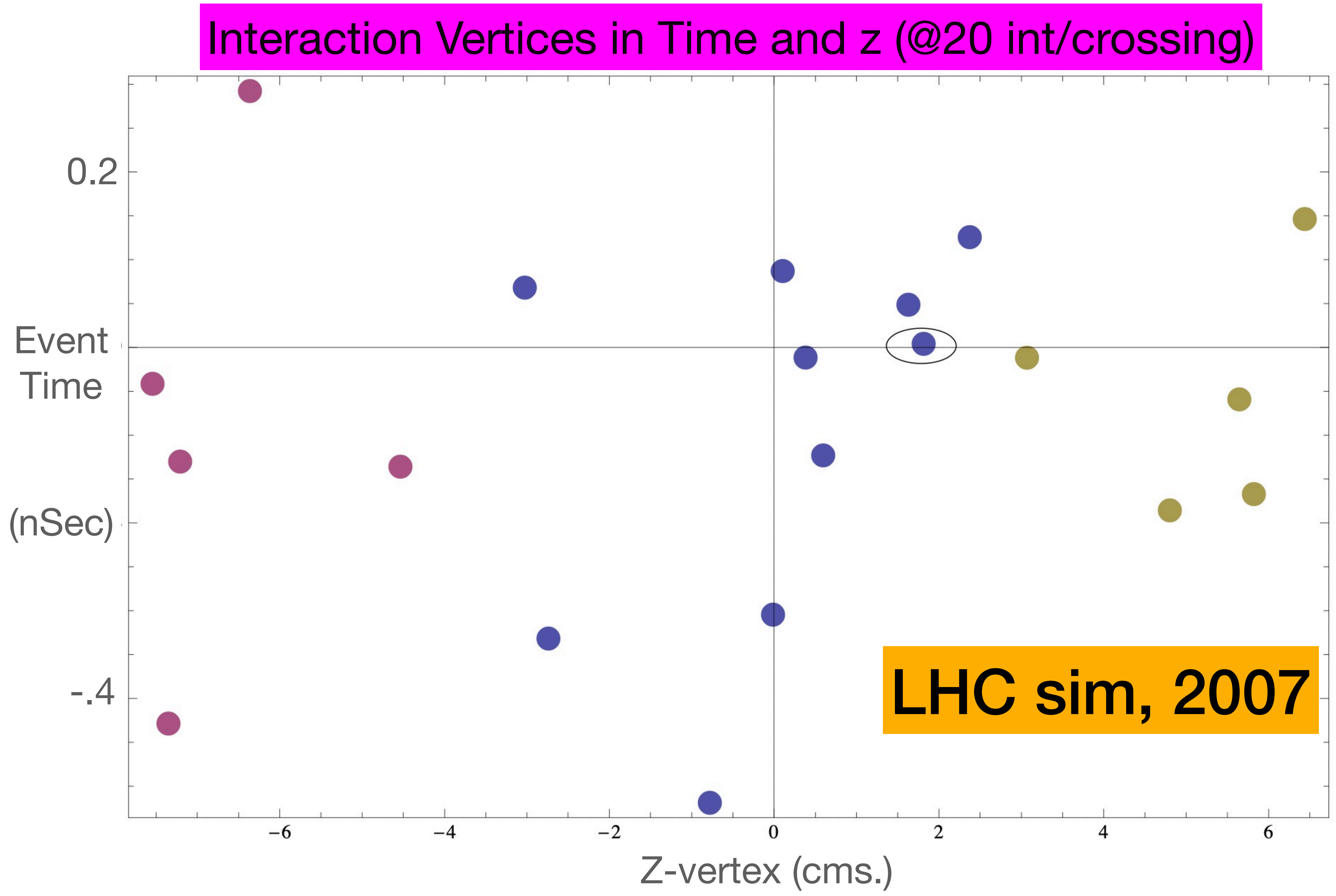
Signal Processing for SiPM timing applications in the presence of High Dark Count Rate

- SiPMs now a popular, fast, low-noise photodetector
- In HEP applications noise (aka Dark Count) Rate goes
    - From 10^{-2} Hz/mm^2 (see Savarese, DarkSide talk today)
    - to >10^9 Hz/mm^2 (see C. Perez, CMS BTL talk today *)
- CMS now intense program to meet SiPM timing goals *
- In This talk I demonstrate Signal Processing technique
    - ->potentially beneficial in CMS & elsewhere

Sebastian White Nov. 29 , 2022

CPAD WG1, Stony Brook

Original Motivation for MIP timing in ATLAS and CMS HL-LHC upgrades



LHC simulation: SNW, 2007 - https://arxiv.org/pdf/0707.1500.pdf

Model LHC Bunch crossing:

- Bunch length (emittances)
- Crossing angles and Beta*

Gaussian Densities-> Time invariant Z-vertex shape of events

Time tagging could resolve Z overlaps.

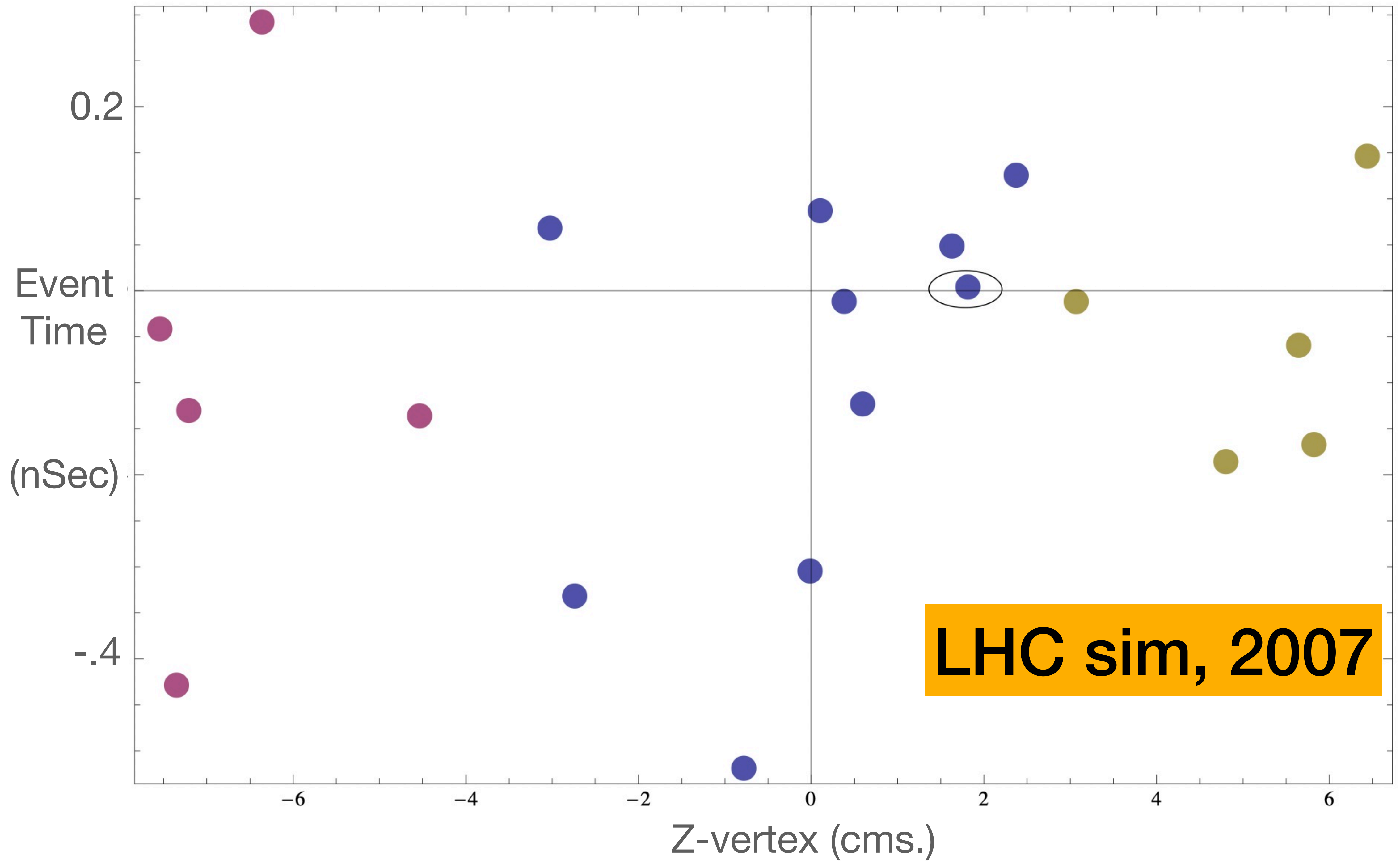
Mitigating Physics Backgrounds due to Pileup:

- Previous collider (Tevatron) reached mu~6 int./crossing—> z-vertex an adequate discriminant
- Z-vertex time to <100 picoseconds —> extends viability to higher pileup

- Since TDR, CMS exploring additional physics enabled by MTD (pid in Heavy Ions, LLPs, etc.)

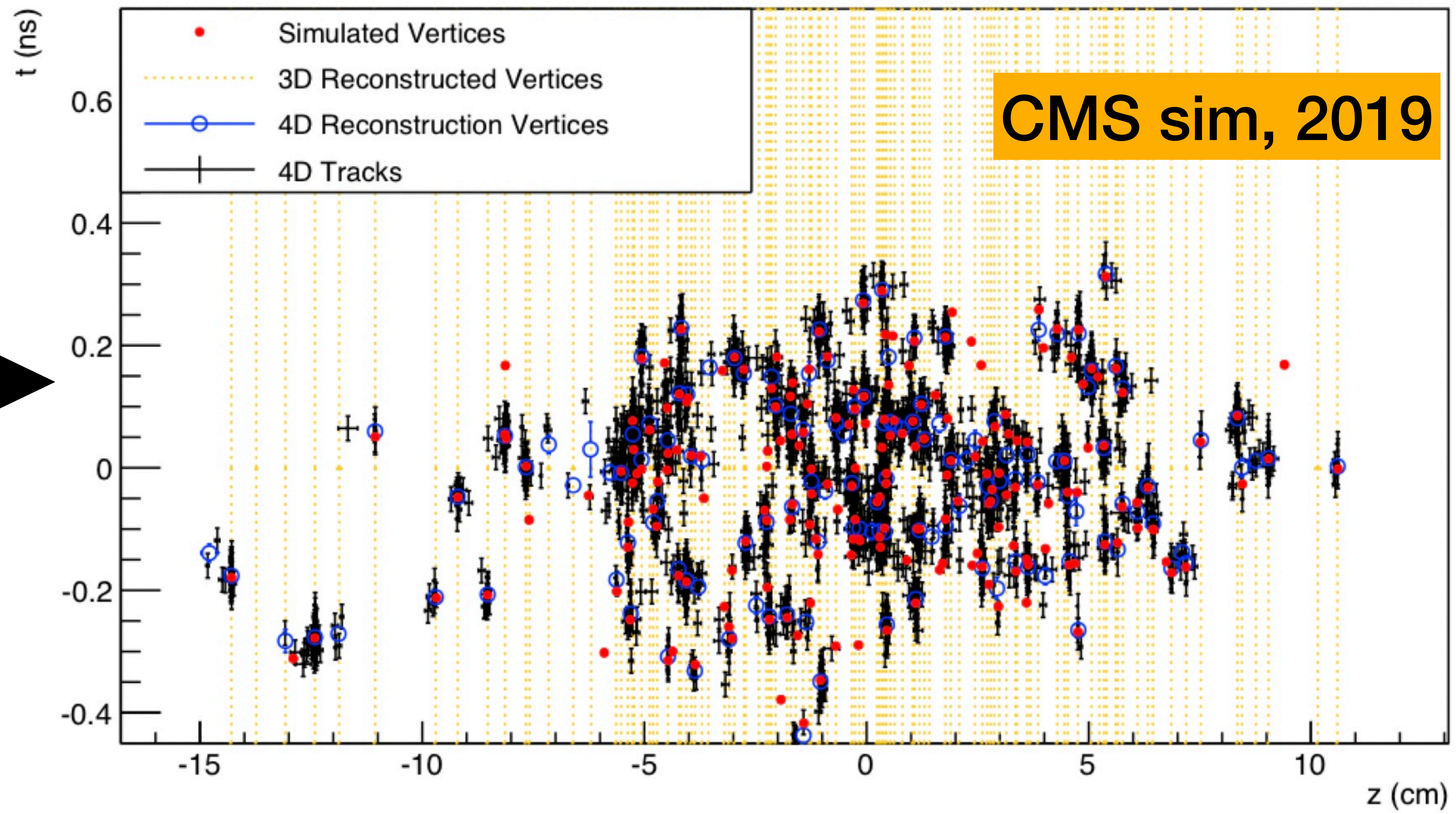
Original Motivation for MIP timing in ATLAS and CMS HL-LHC upgrades

Interaction Vertices in Time and z (@20 int/crossing)



LHC simulation: SNW, 2007 - https://arxiv.org/pdf/0707.1500.pdf

CMS Simulation (@140 int/crossing)



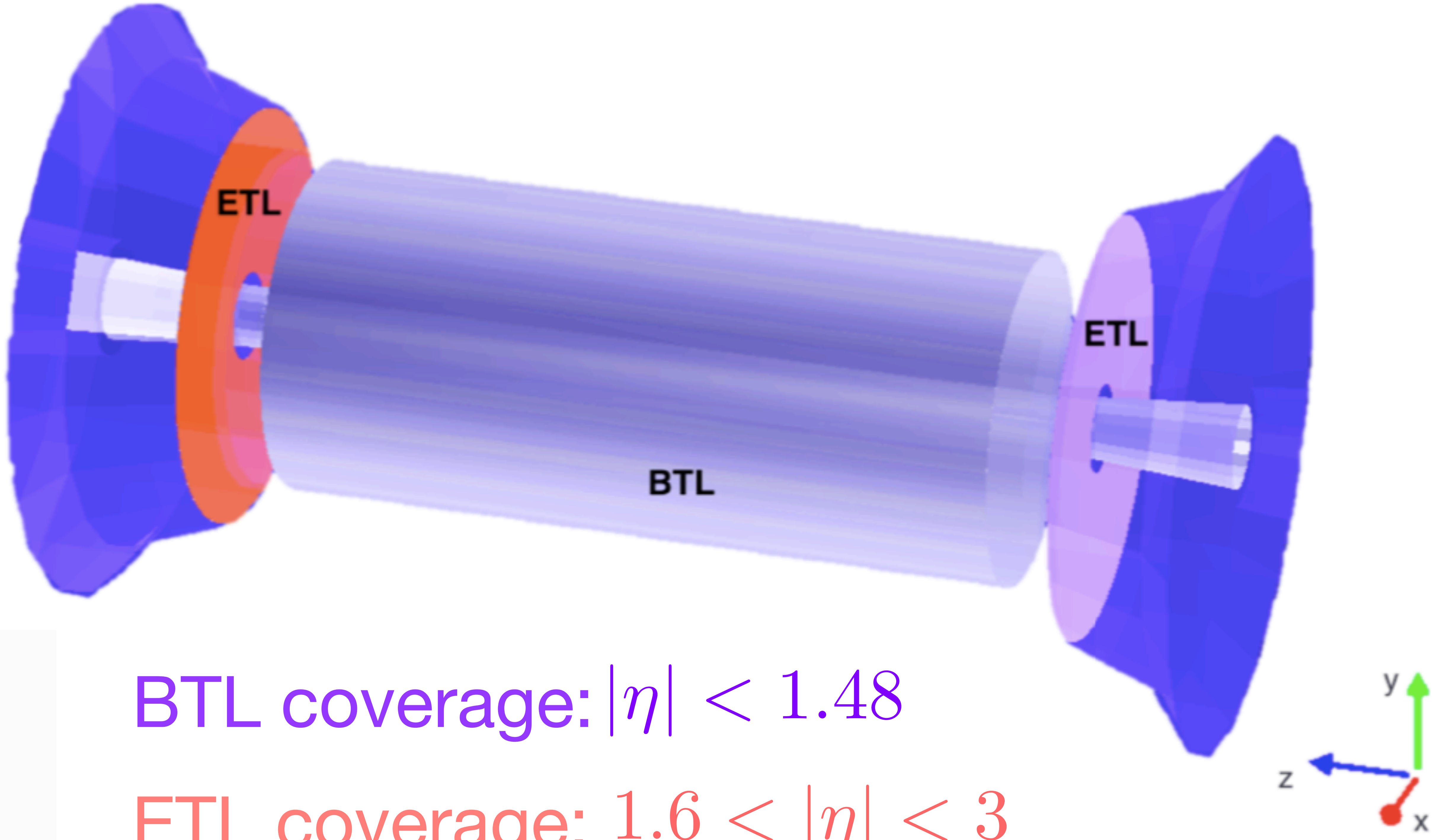
CMS performance simulation, 2019- CERN-LHCC-2019-003

Mitigating Physics Backgrounds due to Pileup:

- Previous collider (Tevatron) reached mu~6 int./crossing—> z-vertex an adequate discriminant
- Z-vertex time to <100 picoseconds —> extends viability to higher pileup

- Since TDR, CMS exploring additional physics enabled by MTD (pid in Heavy Ions, LLPs, etc.)

CMS approach: “Hermetic Timing”



BTL coverage: $|\eta| < 1.48$

ETL coverage: $1.6 < |\eta| < 3$

Consequences:

- Radiation dose @HL-LHC to 3000 fb^{-1}
  -> Large dose variation over timing detector
  ->Reaches ~2 e^{14} neq/cm^2 max in BTL
- Also particle density-> pixel size-> small pixel in ETL

For ETL, producers of “Low Gain Avalanche Diodes” -> matched to ETL requirements

What Technology for <u>Barrel</u> Timing?

- Occupancy-> ~ 1cm^2 pixel size
- Radiation tolerance to ~2 e^{14} n_{eq}/cm^2
- Time resolution 30-> 70 picoseconds BOL->EOL at HL-LHC

Candidates for Barrel Timing:

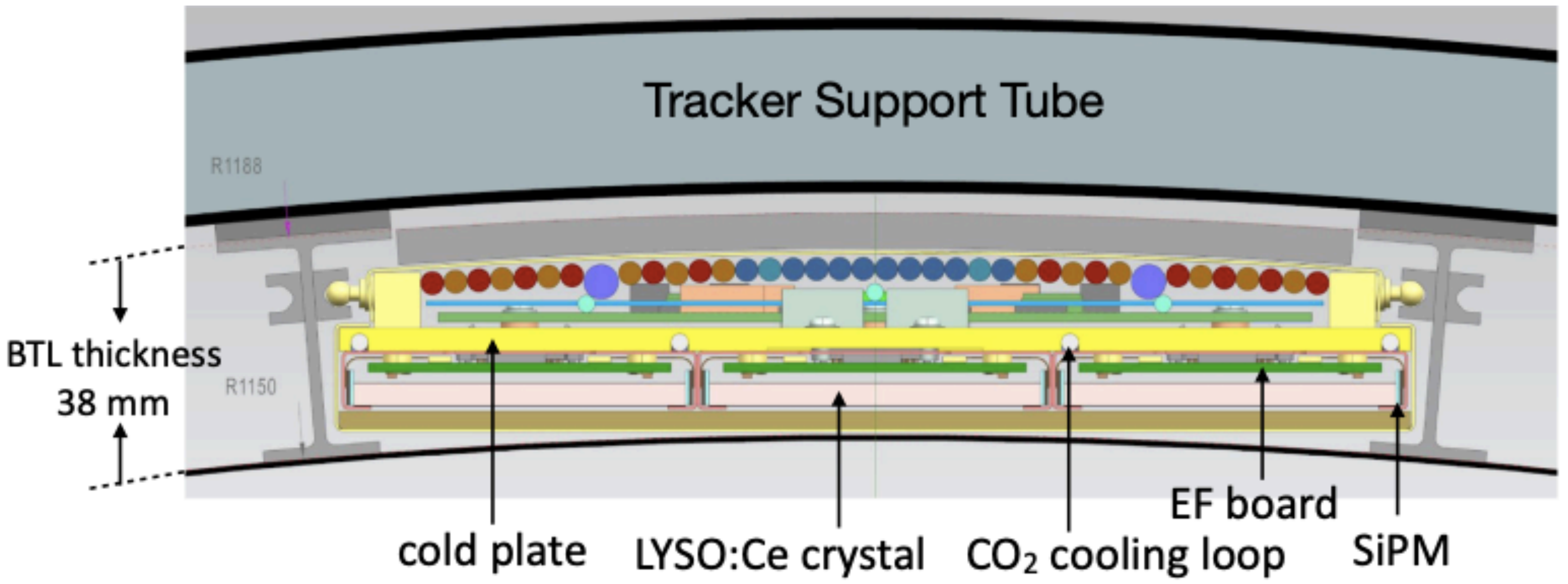
- Several Approaches discussed in ALICE 3 LOI
  CERN-LHCC-2022-009
- See also J. Va’vra: HL-eIC timing talk
  https://indico.bnl.gov/event/14504/timetable/#20220623.detailed
- Also RD51 and RD50 R&D “common projects”

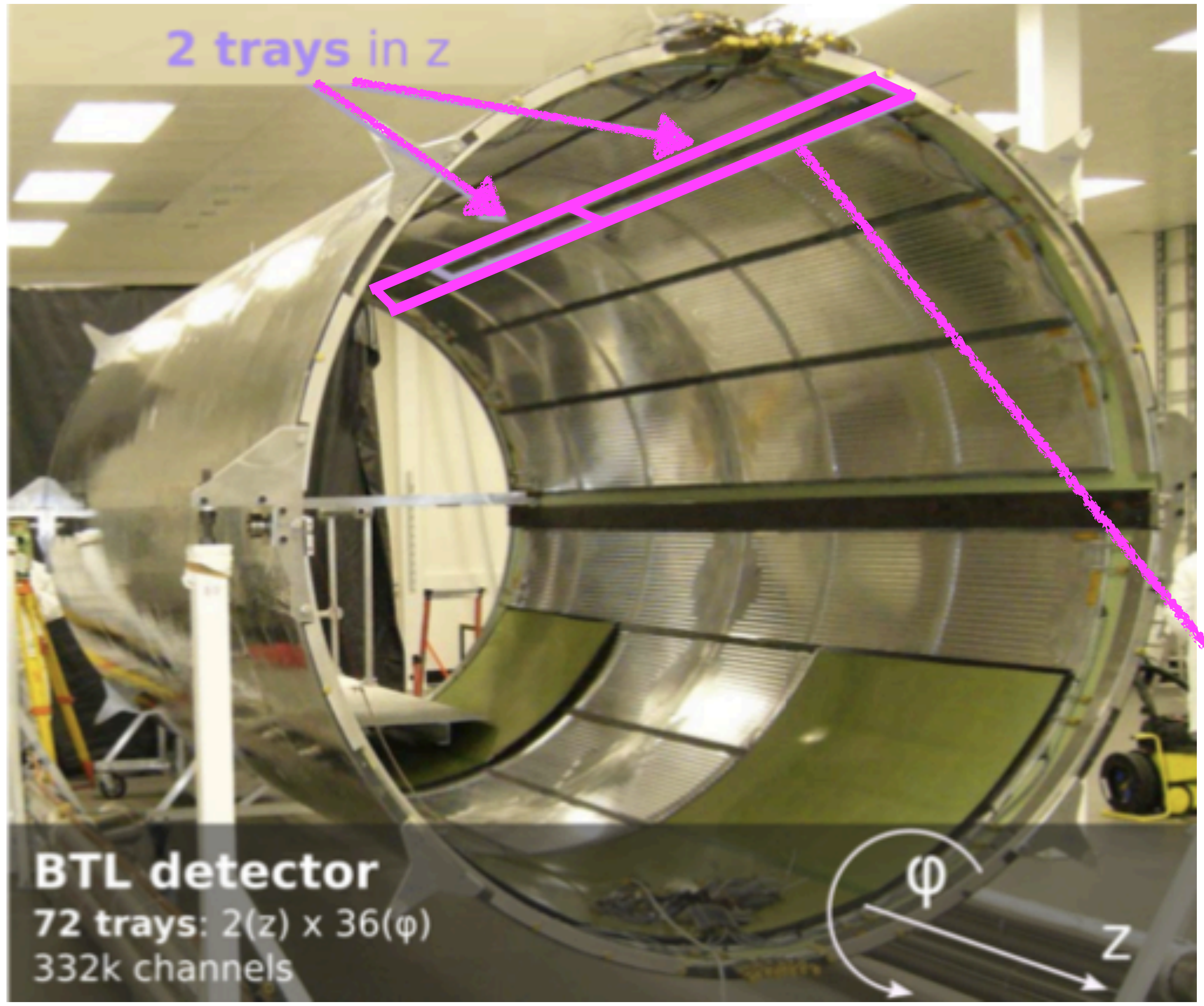
  https://doi.org/10.1016/j.nima.2021.165076
  (1 cm^2 pixels, <25 picosecond jitter)$^{\text{PICOSEC}}$

  Silicon:High Gain Avalanche Diodes:
  https://doi.org/10.1016/j.nima.2019.162930
  (64 mm^2, ~27 psec)

CMS Barrel Timing Layer (BTL)

T= -35°C with CO_2 cooling





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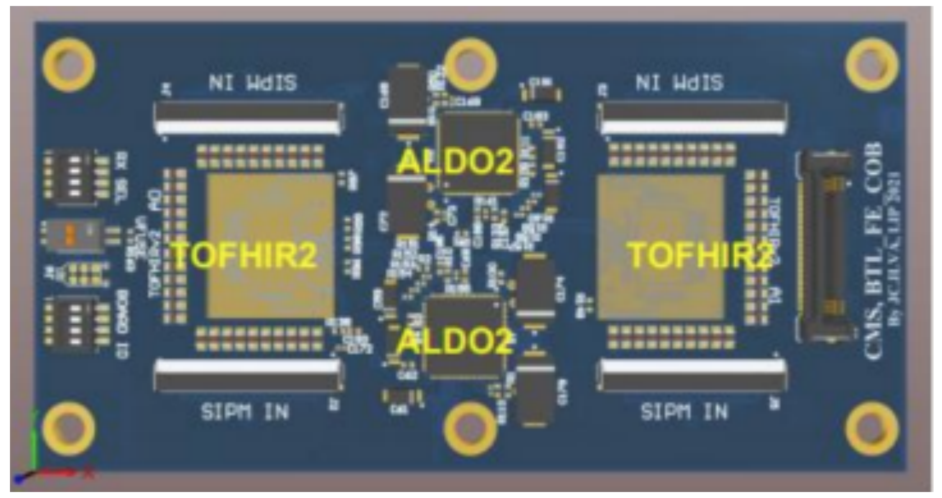
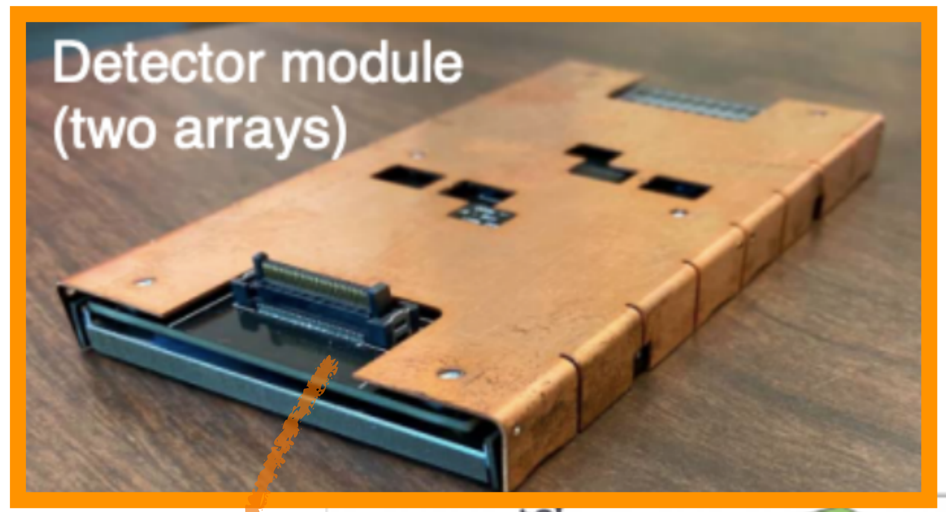
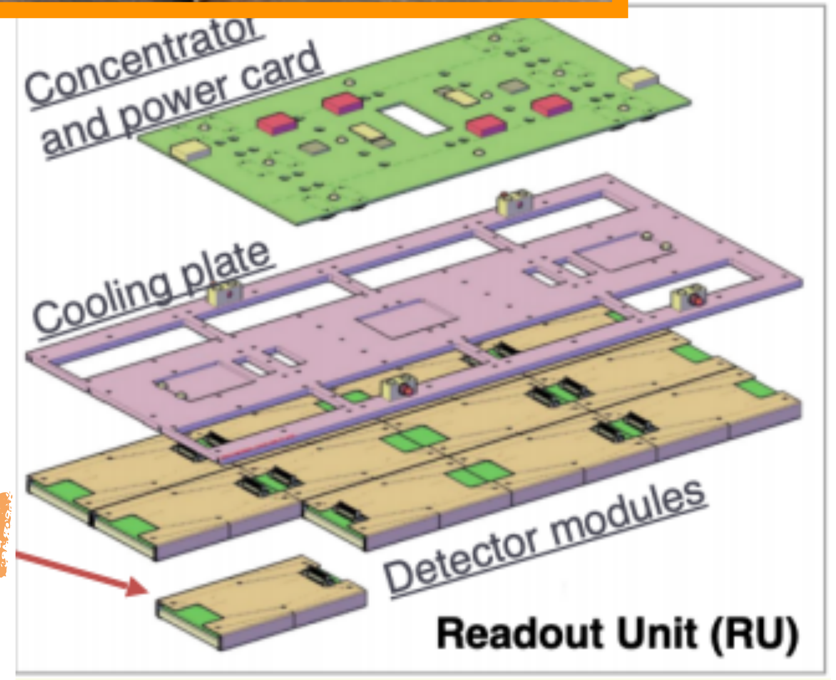
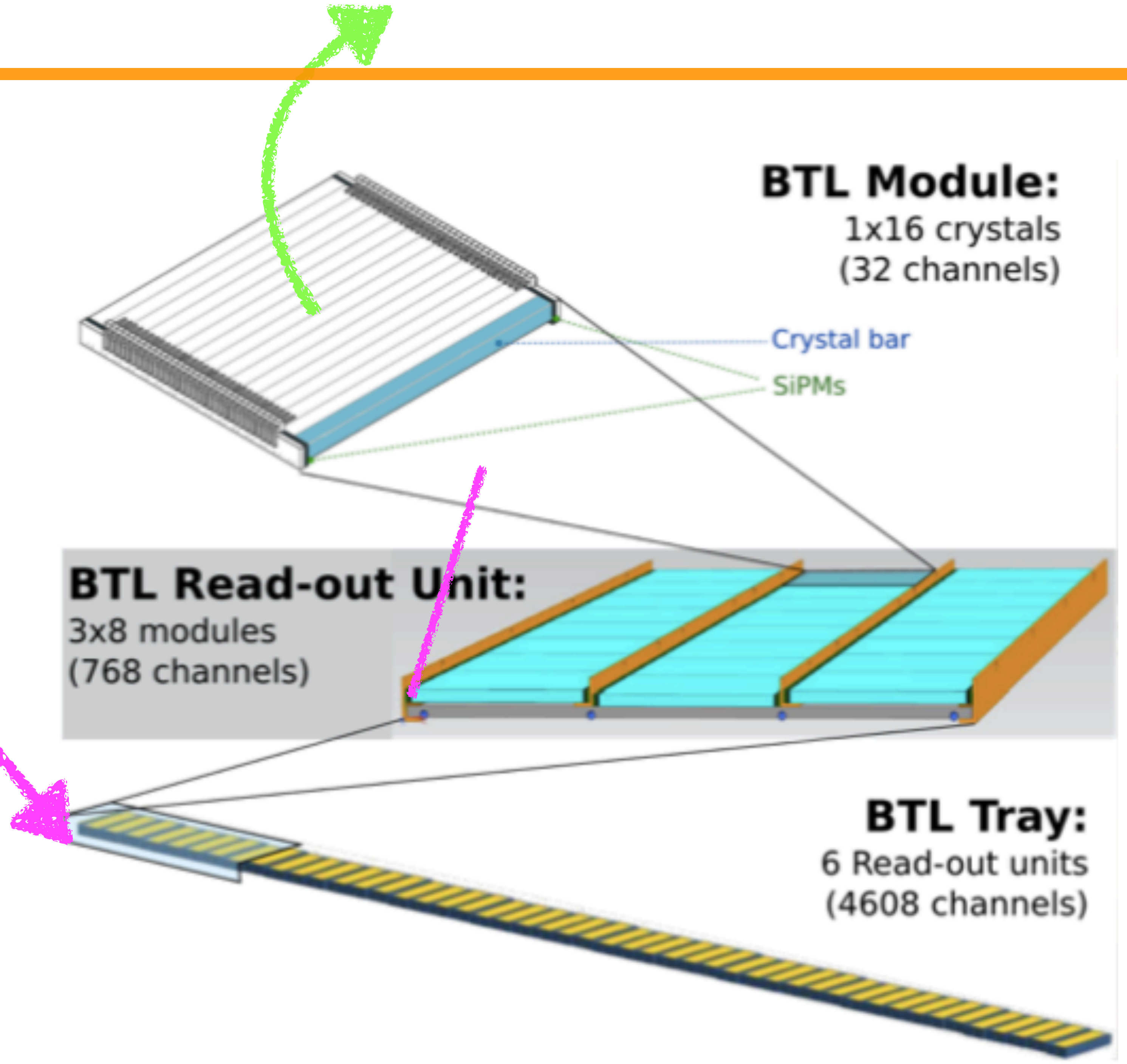


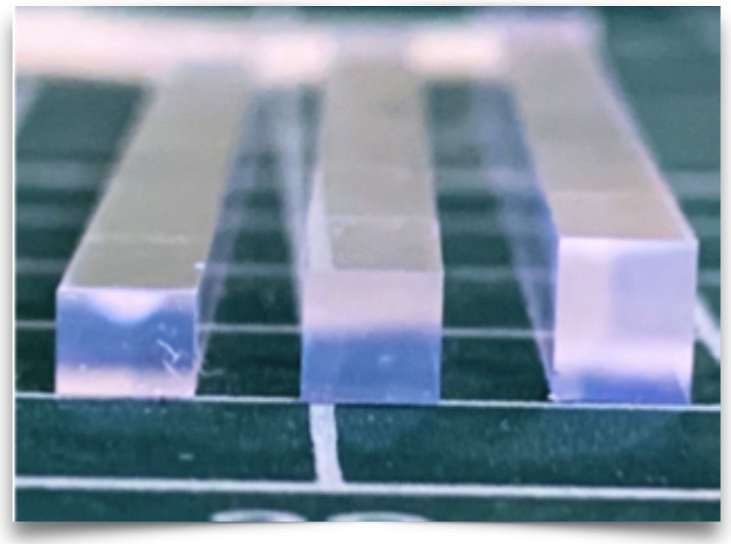
TOFHIR ASIC

=







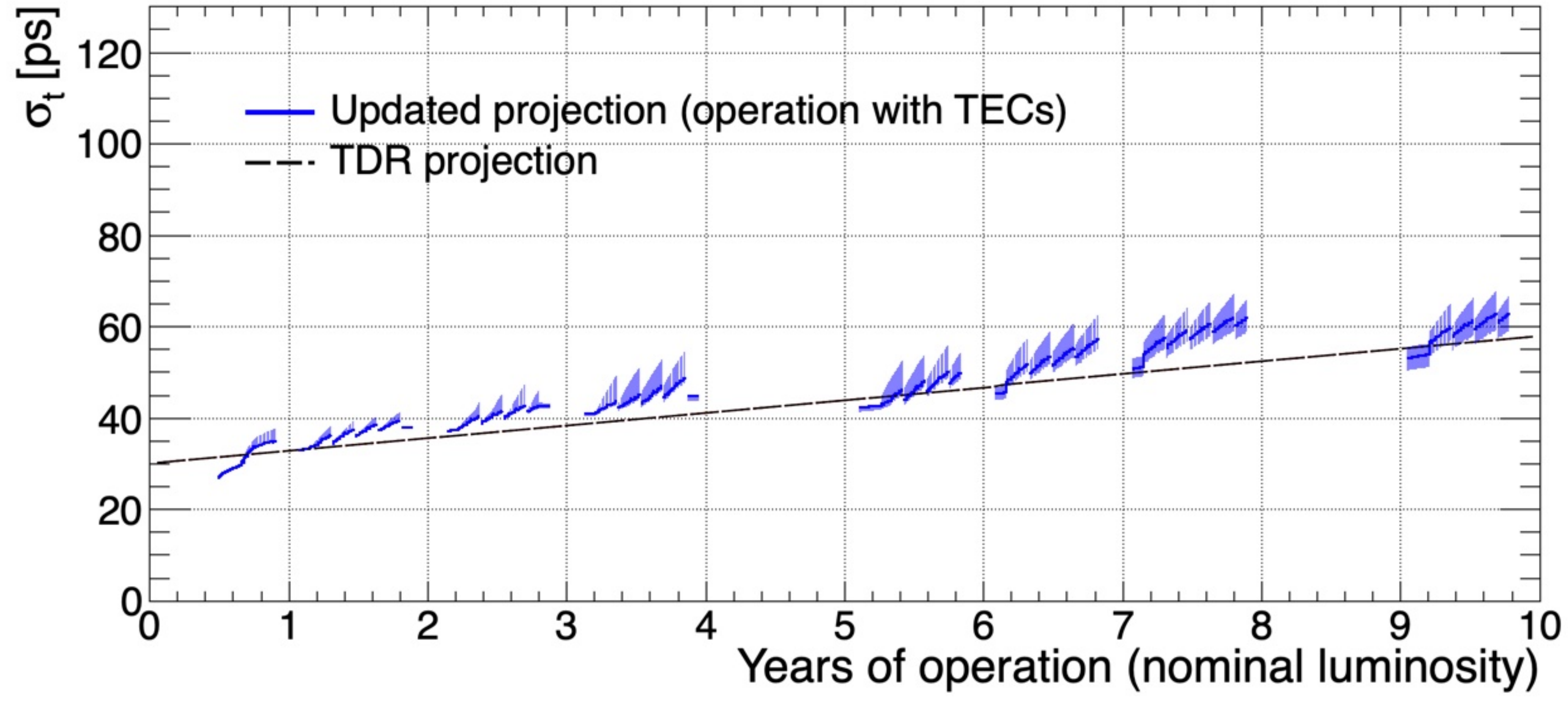


Type	t (mm)	|Eta|
1	3.75	0-0.7
2	3	0.7 - 1.1
3	2.4	1.1 - 1.5

L=56.2 mm, w=3.12 mm

CMS Technology Selection: LYSO Bars/SiPM readout

Current CMS Projection of BTL Performance over HL-LHC



- LYSO/SiPM timing was an “existing, proven” technology.

  Inverse of HEP spinoff->Medical Imaging

But performance under high radiation (-> high DCR) not a given.

New culture: Detector R&D-> “think about EOL performance”

<u>In CMS BTL intense activity to achieve above projection:</u>

- Agressive Cooling and annealing (when beam off).-> TEC
- Enhanced signal -> modify SPAD size and C_{grid}, etc of SiPM
- Some aspects still to be tested.

Can we do still better using improved Signal Processing?

(Rest of this talk)

Outline for rest of talk

- *Evidence for a tool to specifically reduce DCR time jitter with new signal processing from beam data*
  (not discussed here)
- Systematic scan of Dark Count Rate in lab data
  -> properties of DCR noise
- Common Aspects of 1/f noise in music, neuroscience, etc
- Demonstration of a “DCR noise mitigation tool” based on

  ∂t and $\partial \frac{dV}{dt}$ correlation
- Summary

Complement CMS Test Beam data with
Systematic scan of Dark Count Rates (DCR) in lab (laser) data.

2019 laser data taken in Joram Lab (former LHCb fiber QC).

Used Hamamatsu 3x3 SiPM package S12572-015C-172 , custom TIA (T. Anderson, U. Va)-> LRS scope @ 20 GSa/s , DCR varied via LED or irradiated SiPMs.

- Discussed in:"*Digitized Waveform Signal Processing for Fast Timing: An Application to SiPM Timing in the Presence of Dark Count Noise*", SNW & A. Heering (mostly Discuss benefit of SDL shaping)

https://arxiv.org/pdf/2003.02765.pdf

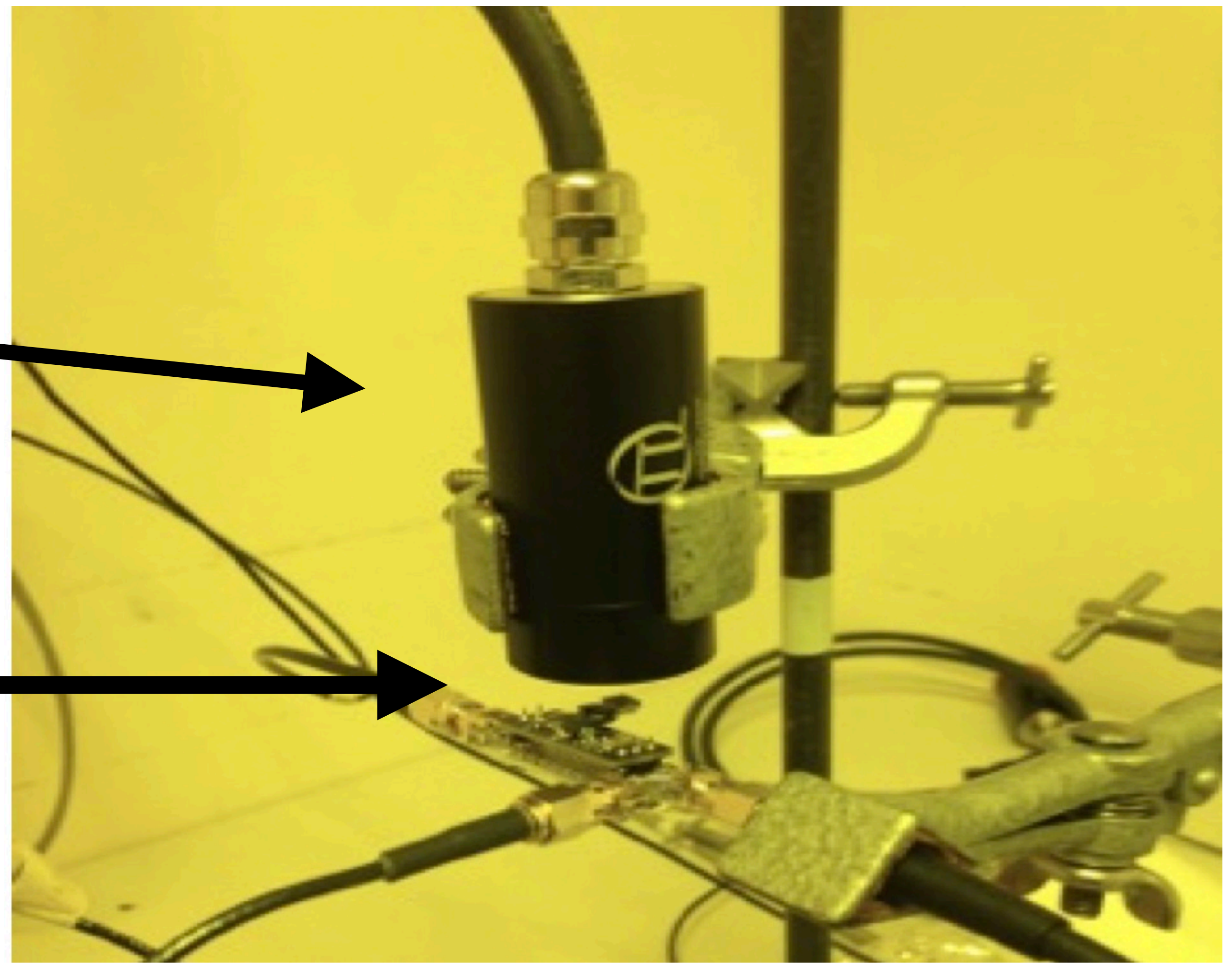
Nominal DCR= 0., 1. ,2. ,5. ,9. ,20. GHz

SiPM Over voltage 2.0 V

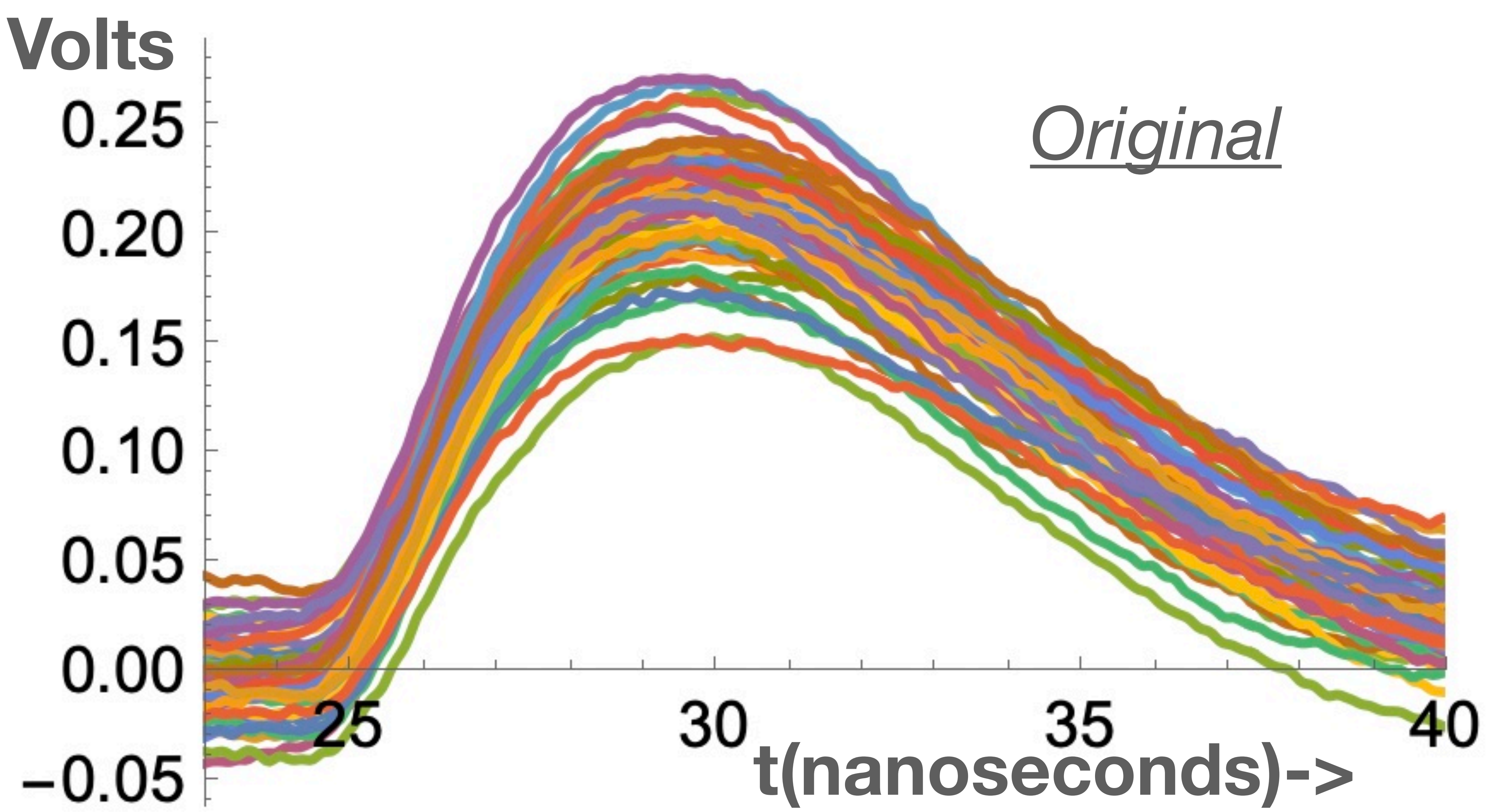
<Npe> ~150, 390 p.e.

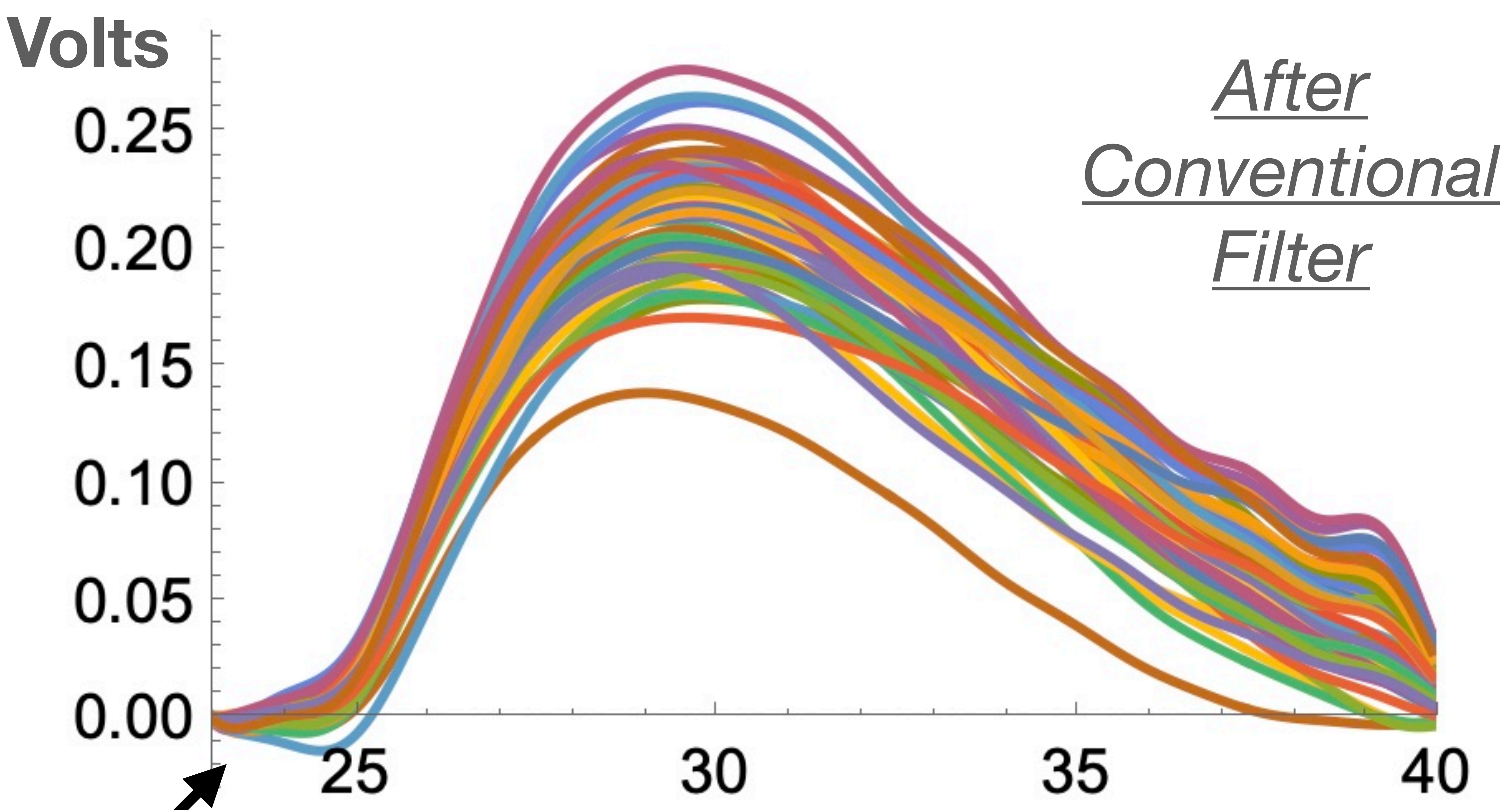
PicoQuant Laser Head
(0.35 nsec rms, 497 nm.)
SiPM and TIA board

(Not shown: SiPM cooling)



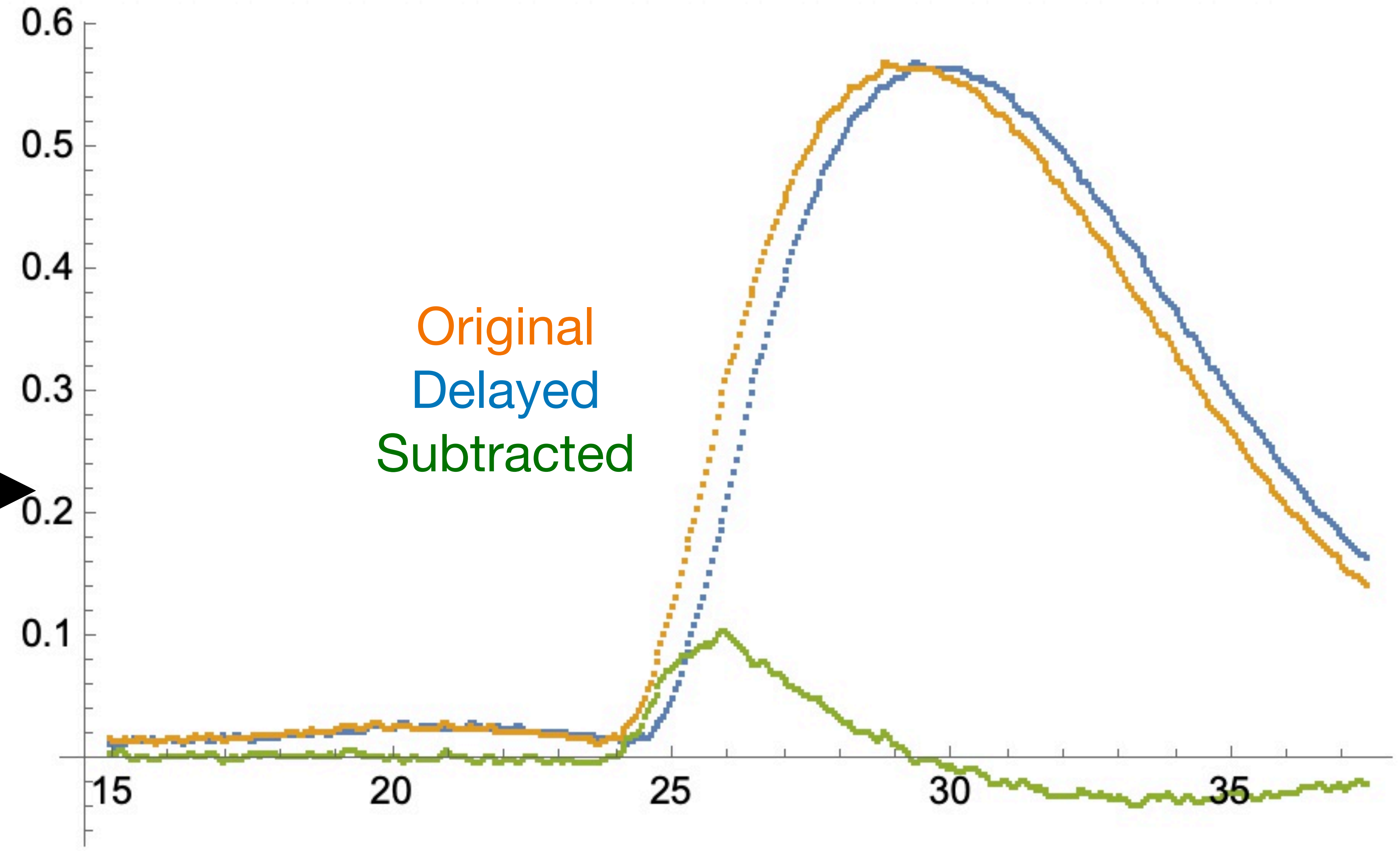
Typical waveforms(several laser intensities) Laser data, 20 GHz DCR, OV=2 volts



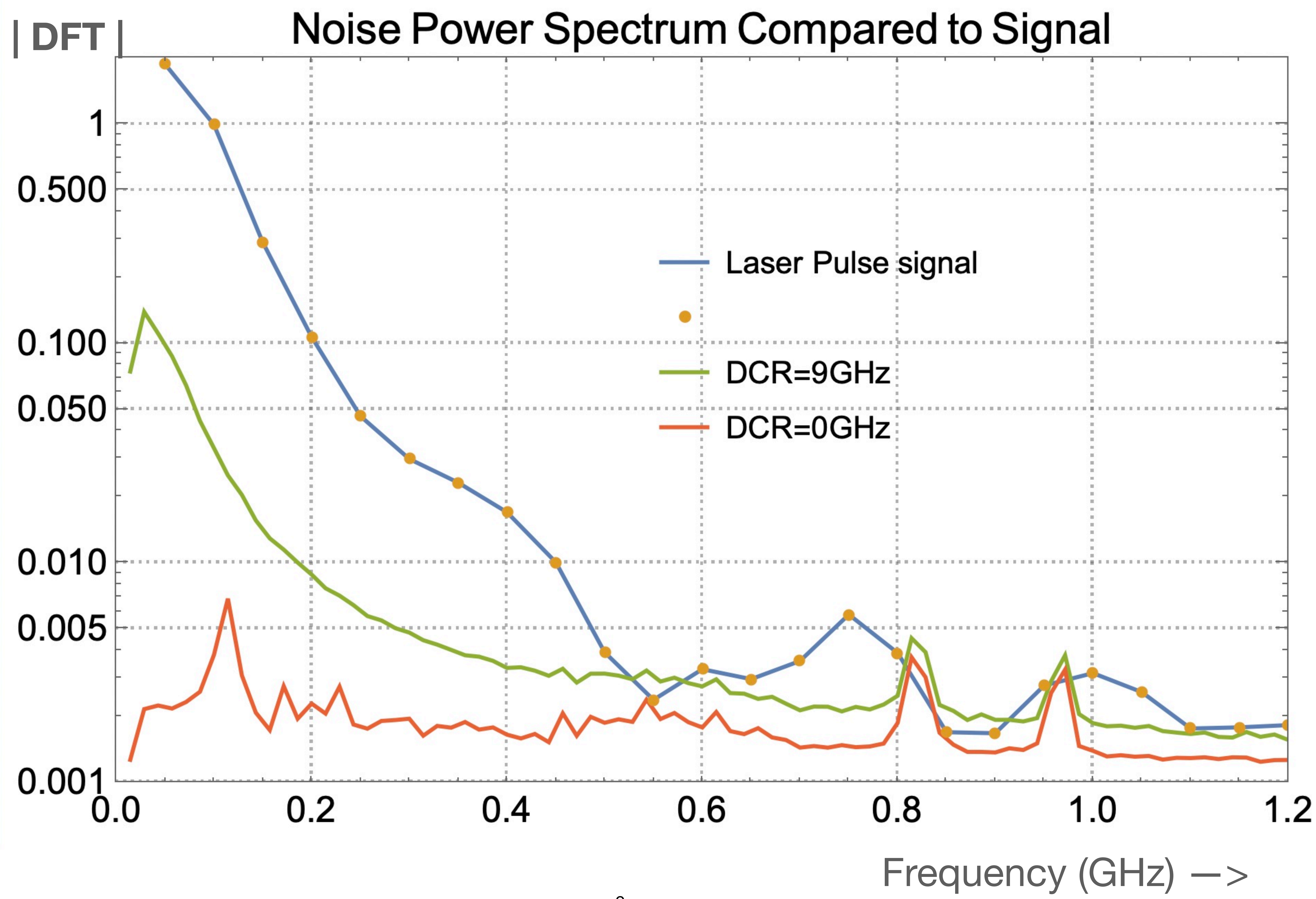


Familiar techniques used to mitigate jitter:

- **High Frequency: 500 MHz low pass filter (cp right vs. Left)**
- **Low Frequency:**
  - **Active baseline Restoration**
  - **(or Single Delay Line Shaping a la TOFHIR)**



In Frequency Domain Signal and DCR noise similar.

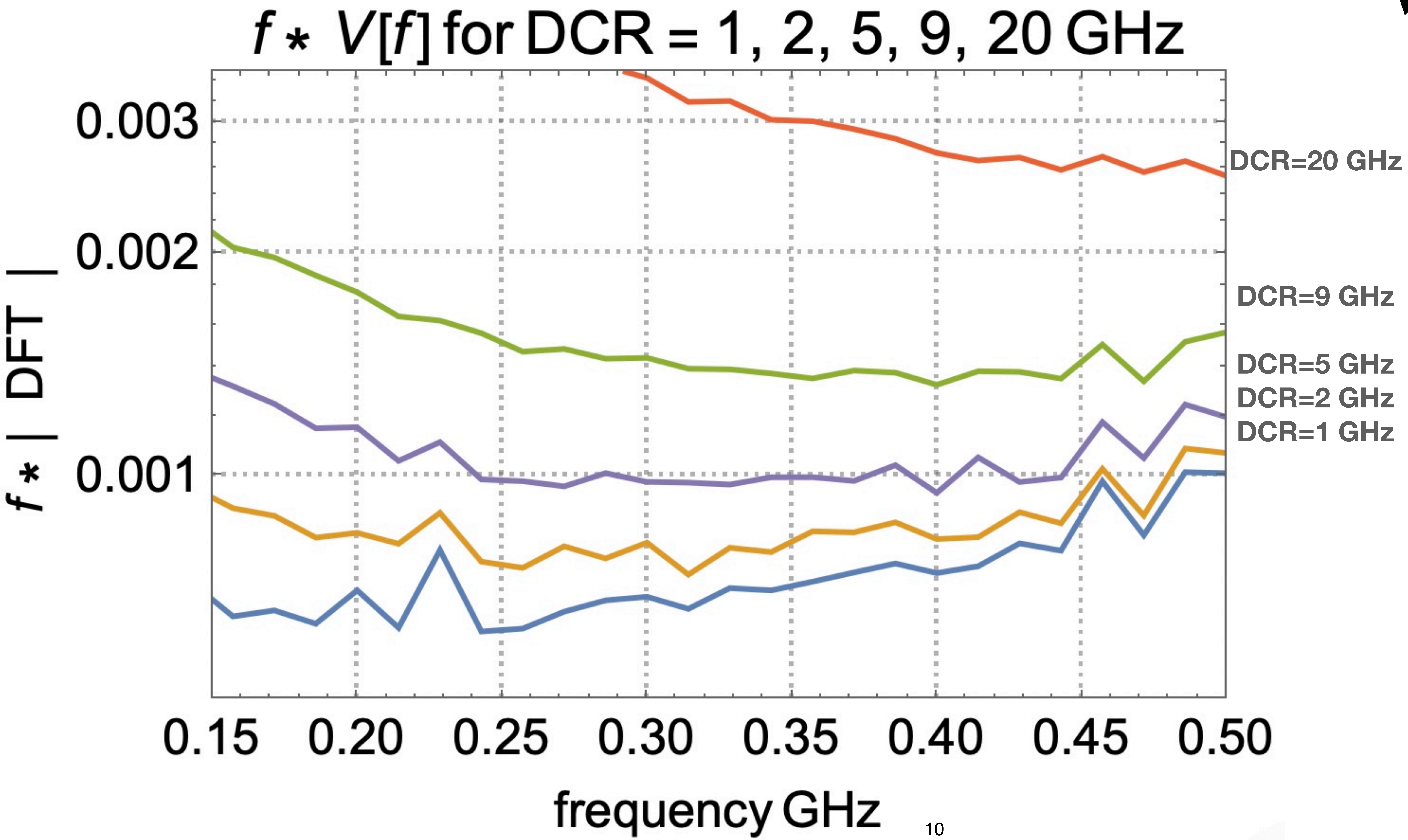


Frequency Spectrum of Dark Count Noise Seems reasonable

(Square Root of) Power Spectrum

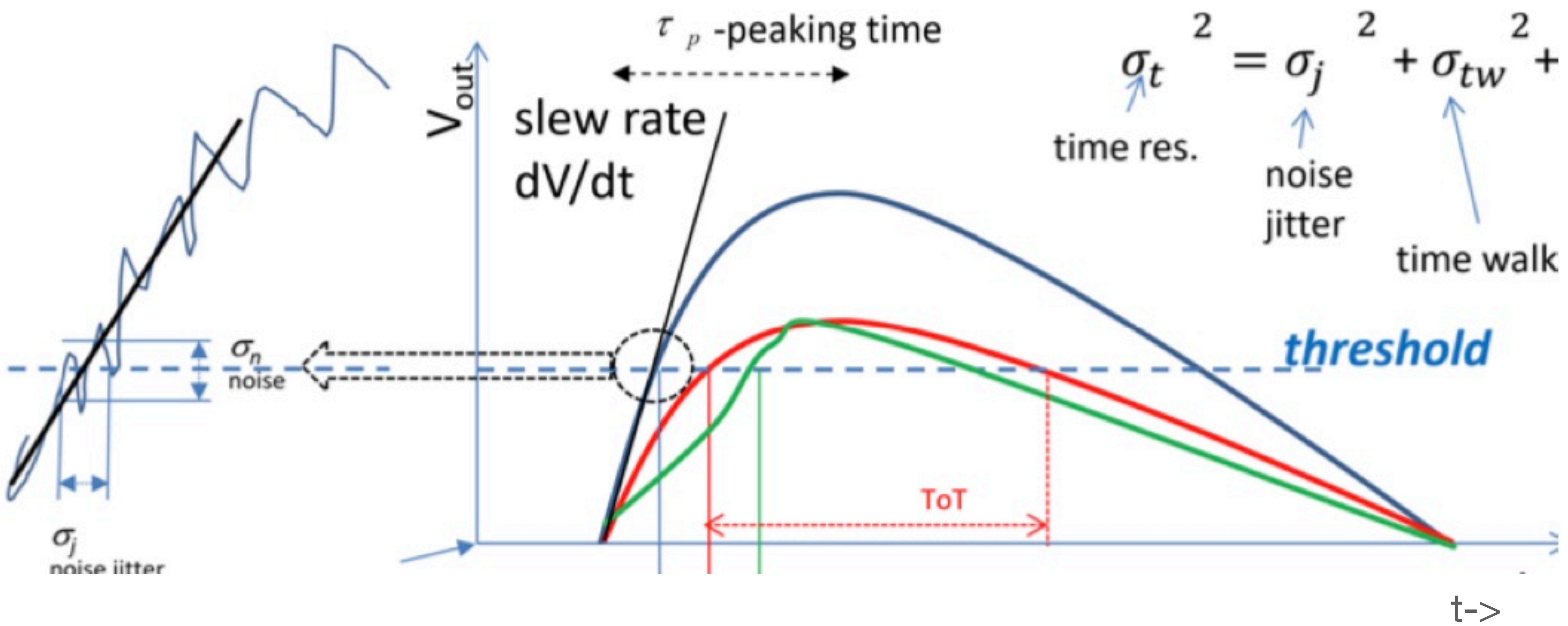
- ie | DFT| of DCR noise

“**D**iscrete **F**ourier **Transform**”

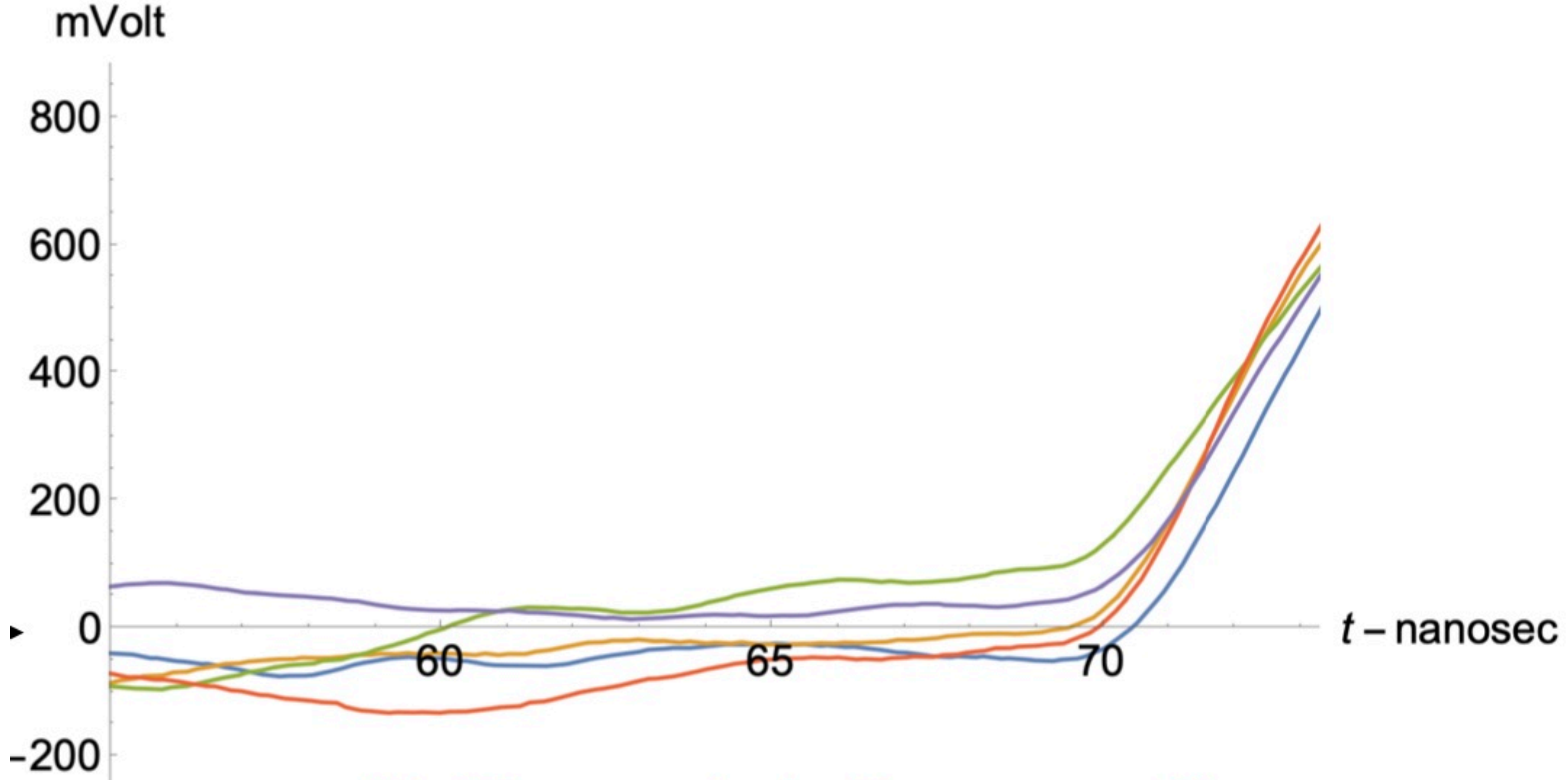


Workflow for DCR jitter Mitigation

1) Day-1
This part is familiar.
HF noise-> filter, 2 thresh..
Correctible Amplitude walk
(W. Digitized WFs -> CF technique)



Irradiated SiPM waveforms before baseline resoration



2) Day-2
DCR-> unstable baseline
=> Restore Actively or
w. Single Delay Line Shaping (a la TOFHIR)
We Don't account for baseline slope.
This is key to the following.

Nb: Traces selected have same Q

Some Definitions:

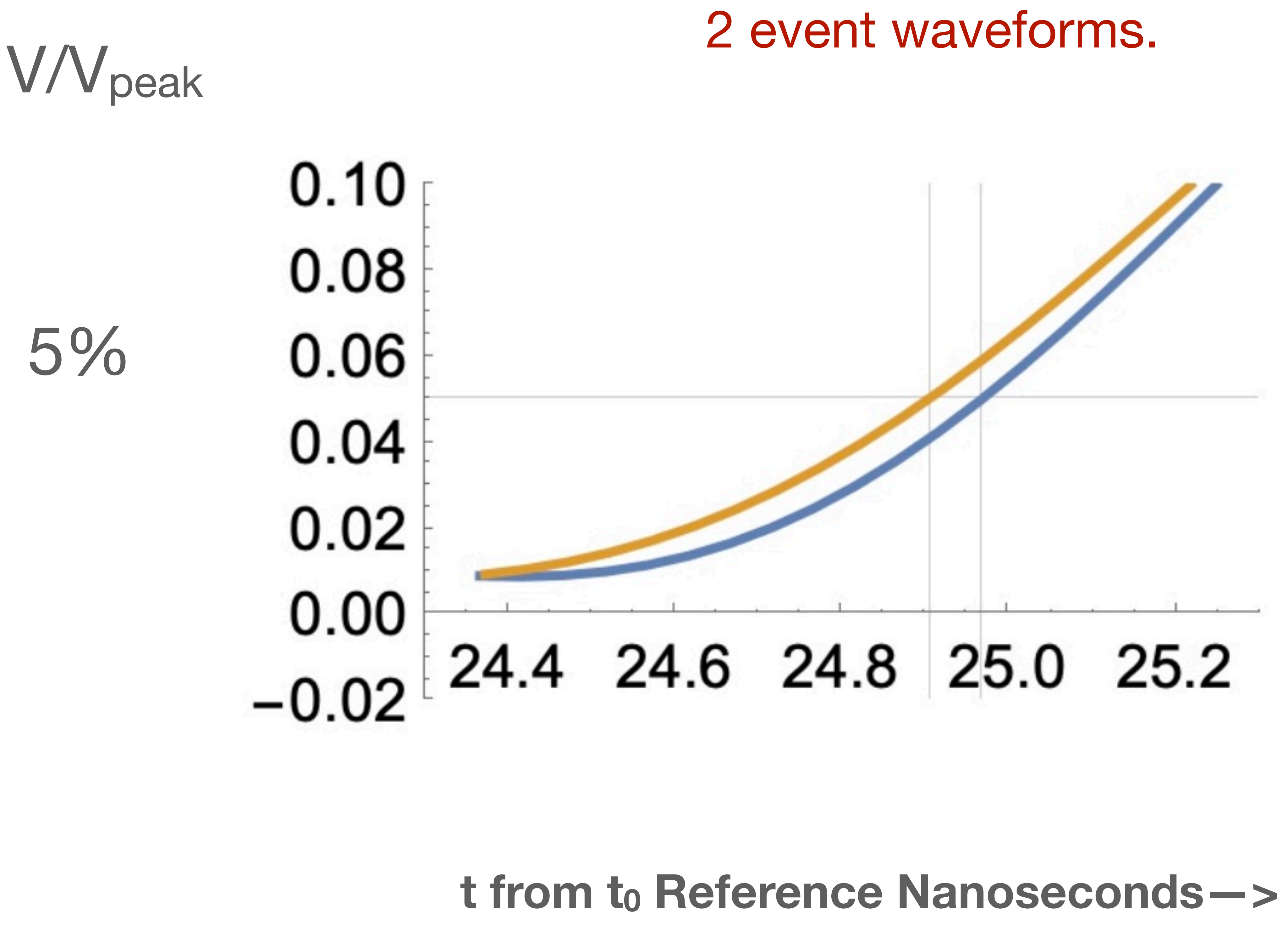
The Data sets

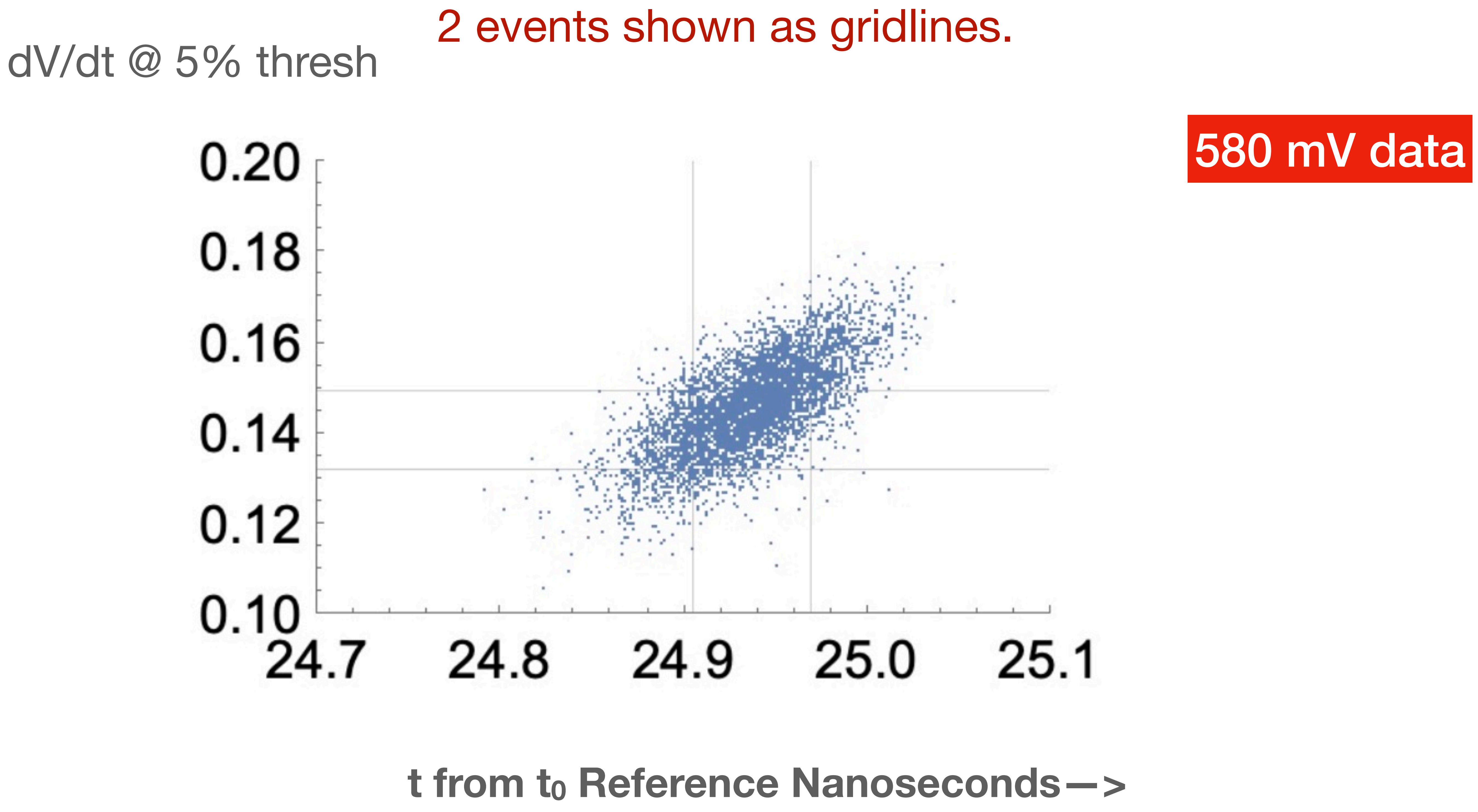
1) Joram Lab. SNW& A. Heering: (ibid) used for rest of this talk

2) April,May ’21 FNAL TB: see Dec. 17,2021 TB analysis mtg.

https://indico.cern.ch/event/1106612/contributions/4655573/attachments/2367458/4042828/signal_processing_DCR_SNW.pdf

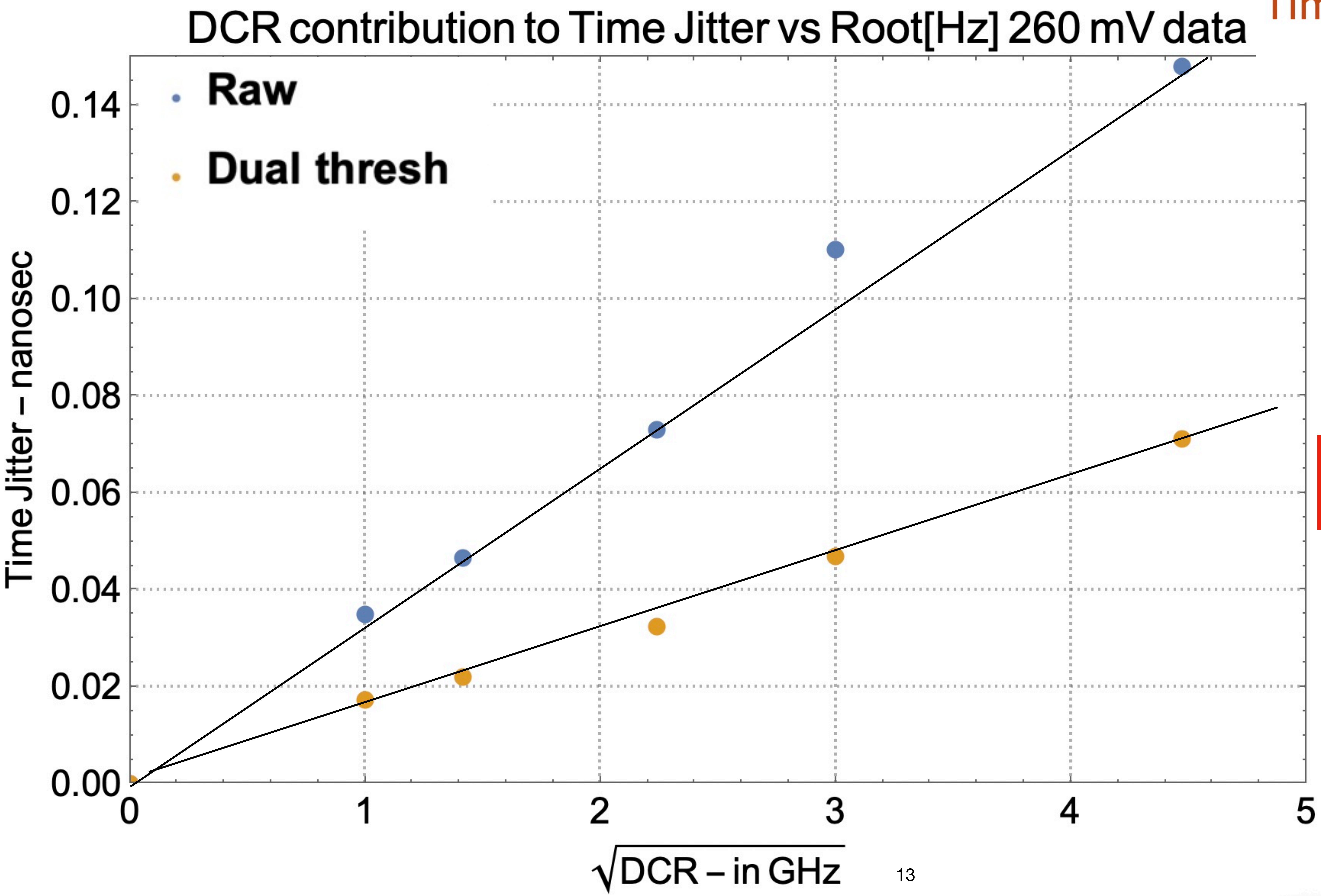
Correlated Jitter in Hi DCR (up to ~20 GHz) Joram lab data:





Example of Effectiveness: 260 mV laser data at 5%CF threshold timing

Shows here that Correction from $\partial \frac{dV}{dt}$ predicts ∂t very effectively.

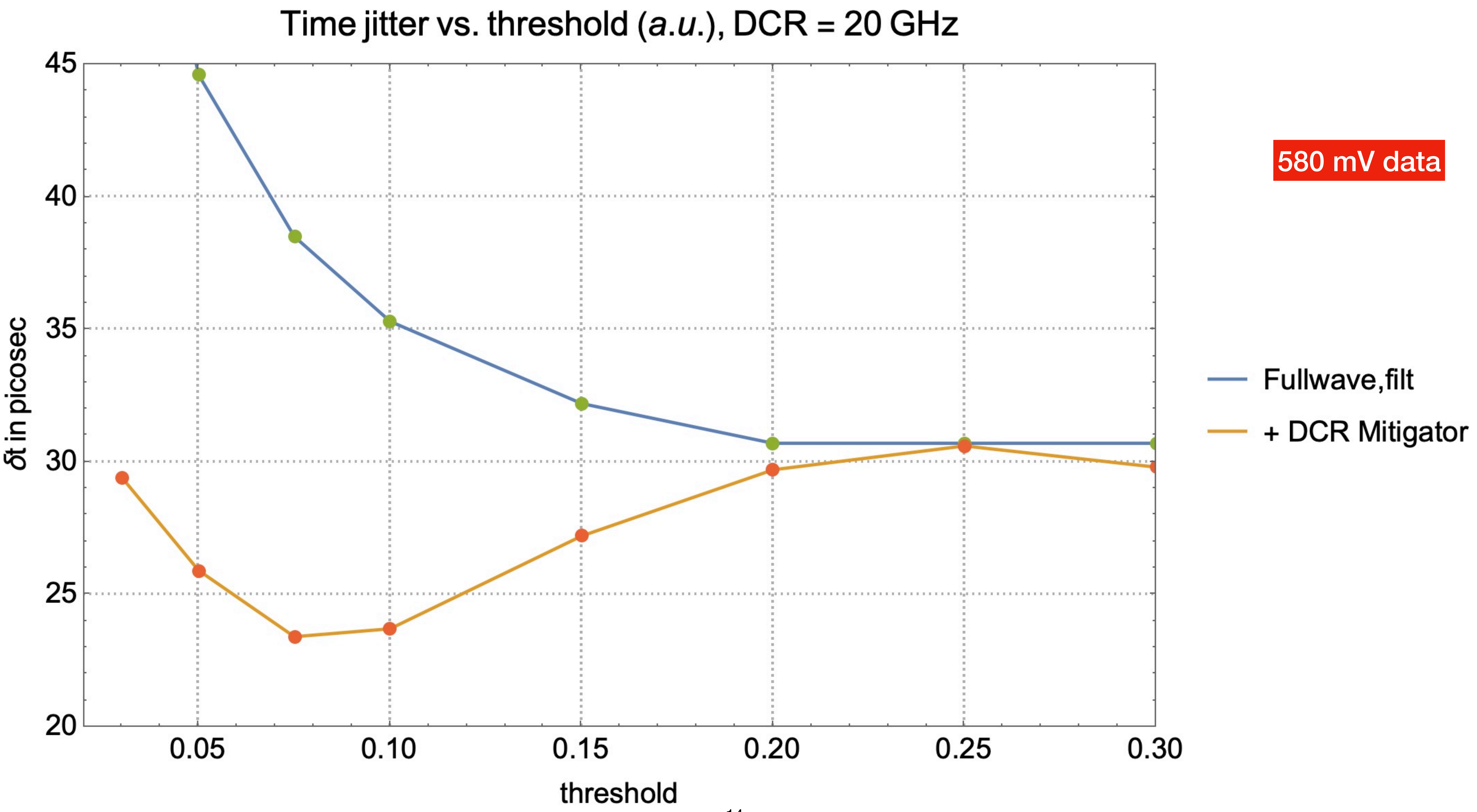


Time resolution Contributions

$$(\partial t_{overall})^2 = (\partial t_{DCR=0})^2 + (\partial t_{DCR})^2$$

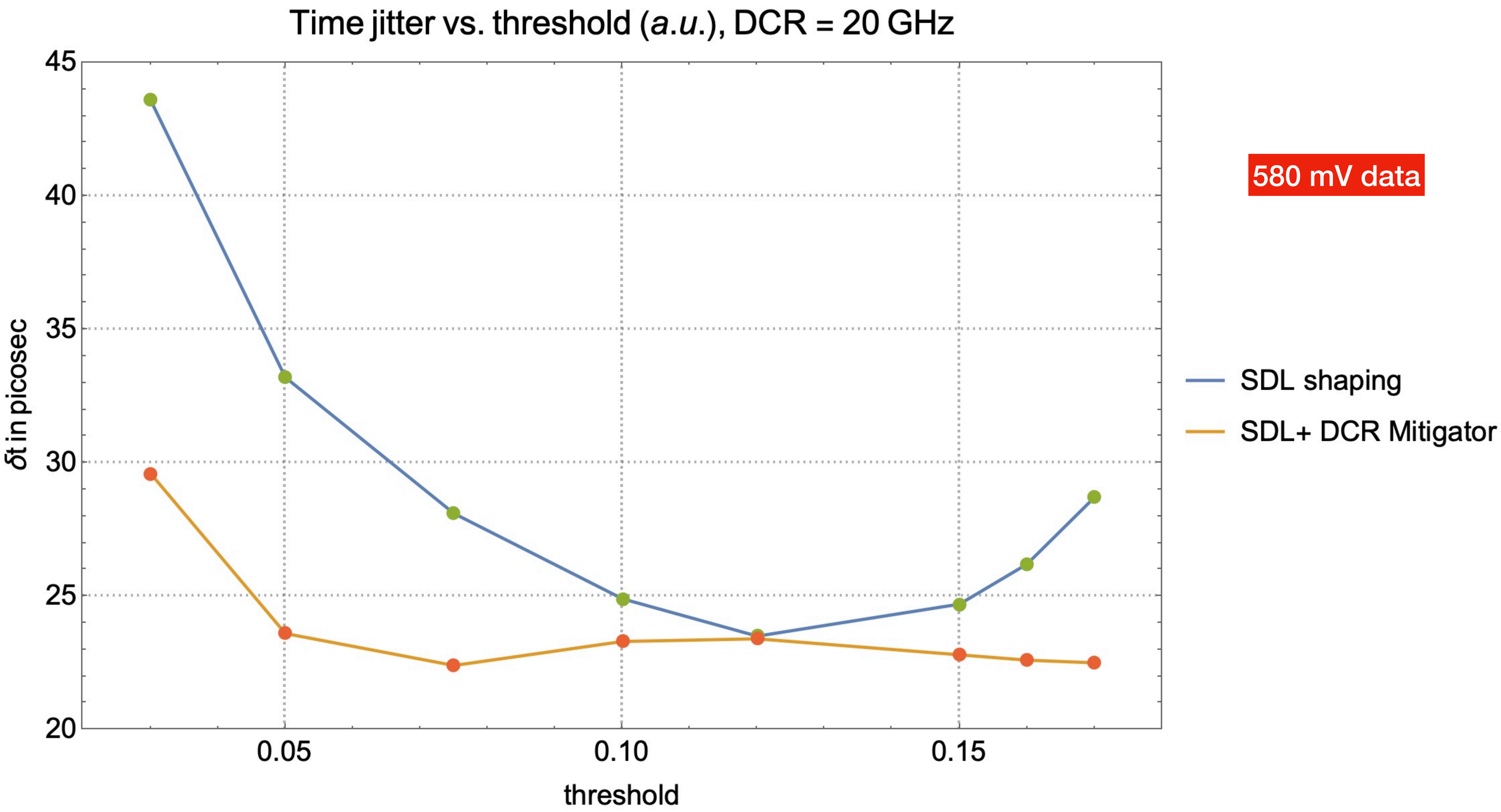
Why Sqrt[DCR] ?
Notion that jitter~ fluctuations

Next 2 slides show recent analysis of DCR=20 GHz w & w/o SDL shaping



580 mV data

Using 0.6 nanosecond Single Delay Line Shaping



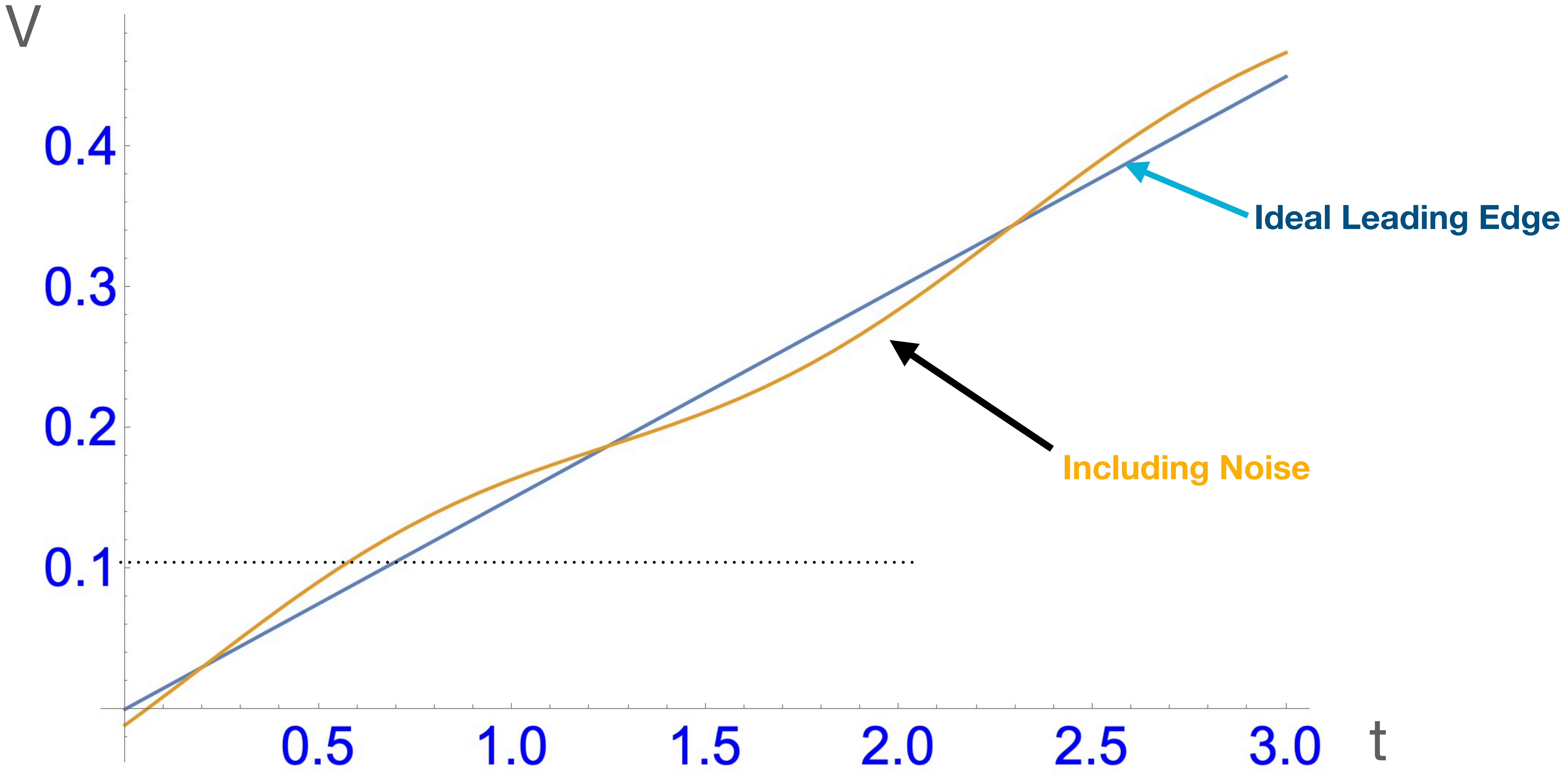
Observations:

- SDL Shaping (ie CMS ASIC) doesn’t eliminate usefulness of tool
- Recent attempts to apply tool to ASIC* data inconclusive
- Hard to build prescription for use in ASIC* w/o clear picture of origin
- Nb: Previous slides used CF technique but ASIC* has fixed Thresh.
- In following slides we show by simulation that:

  Combining 1/f noise w baseline restoration leads to correlation tool

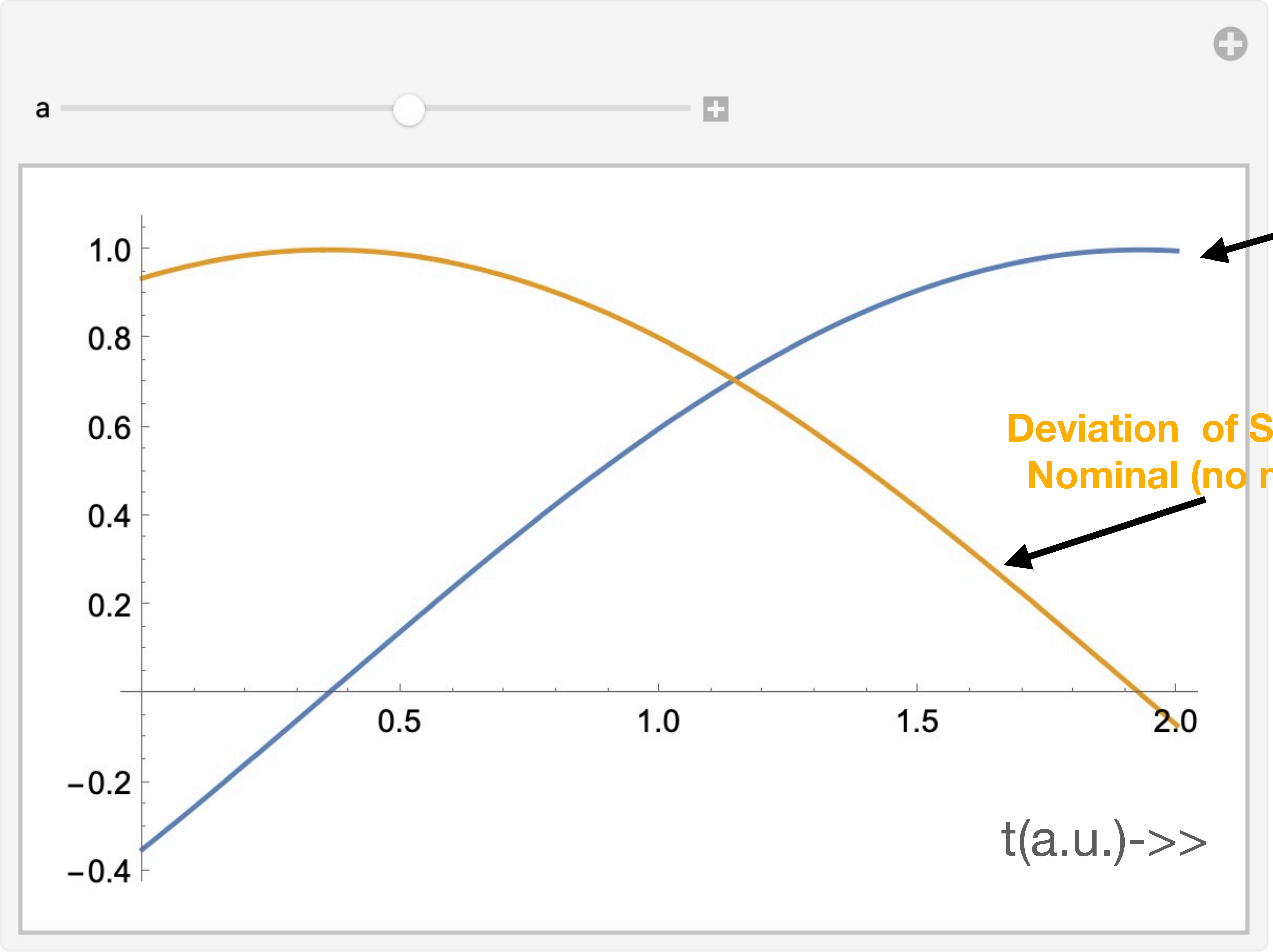
* ASIC== “TOFHIR” ASIC by PETSYS/LIP

Assume Event waveform has a simple noise term as Sin[f*t+c]



Is there a correlation in beginning of wave between
(1) $(\partial V \to \partial t)$ and
2) $\partial \frac{dV}{dt}$ ie derivative of noise term) ?

```
Manipulate[Plot[{(Sin[1 * (x - a)]), (Cos[a - x])}, {x, 0, 2}
```



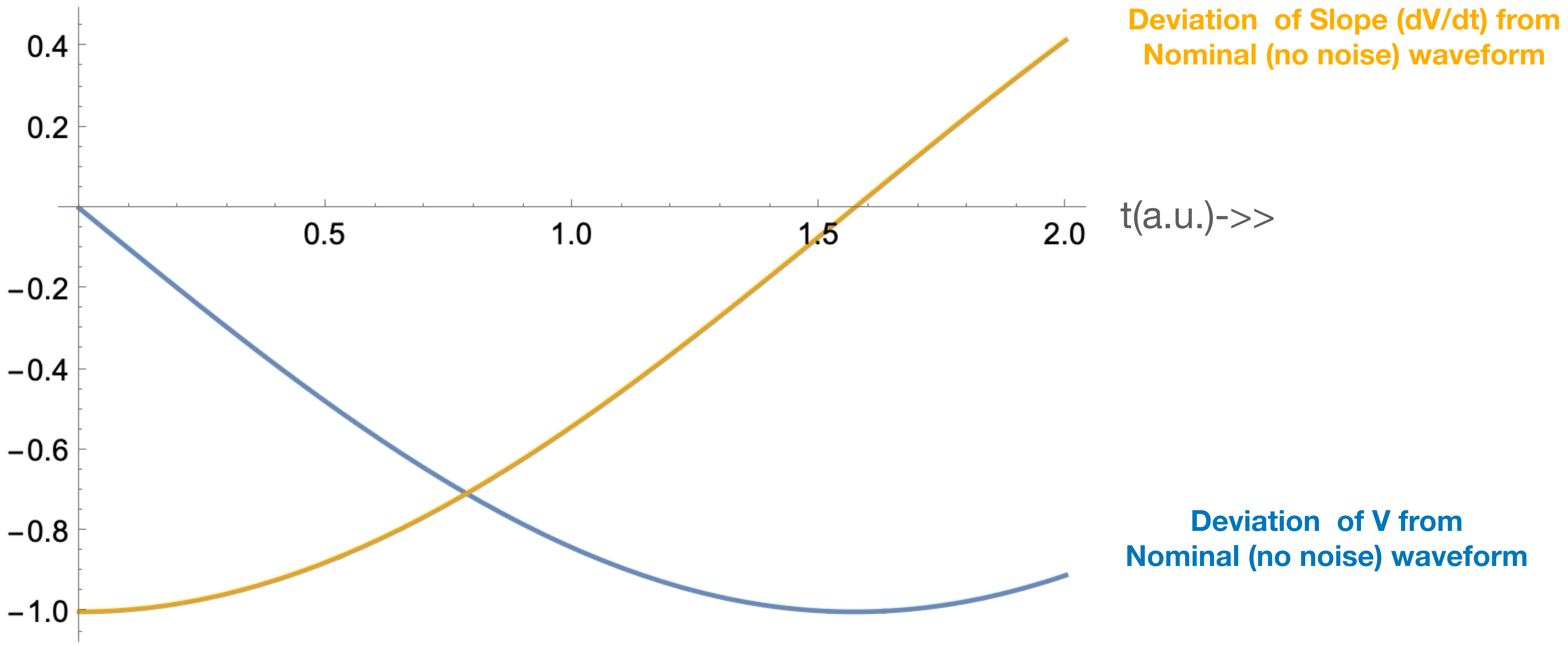
Deviation of V from Nominal (no noise) waveform

Deviation of Slope (dV/dt) from Nominal (no noise) waveform

Answer: "no"

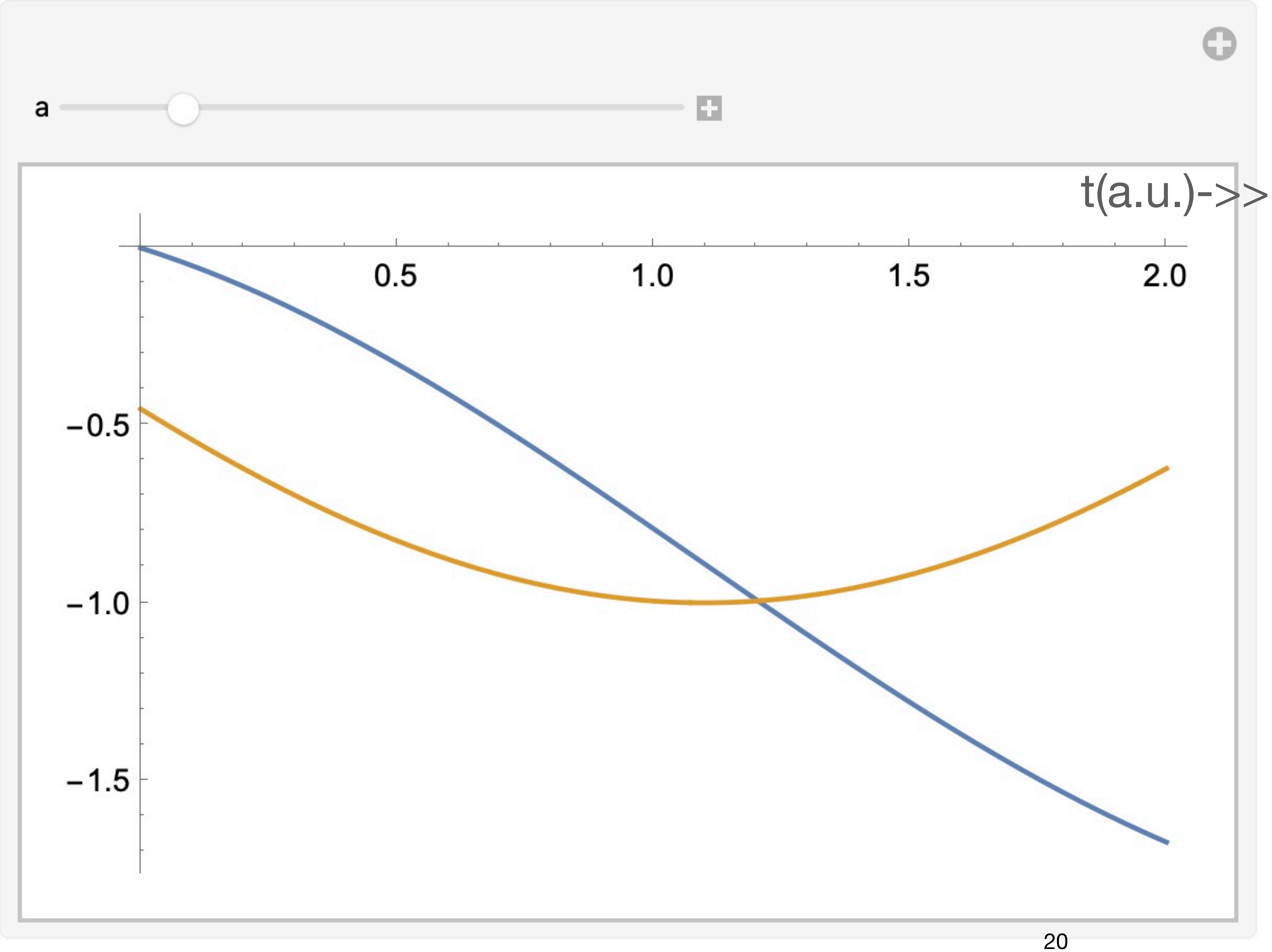
Flips sign depending on phase

Animation Showing Phase Dependence
(Click on slide to run animation)



What happens if we introduce Baseline Restoration?

```
Manipulate[Plot[{(Sin[1*(x - a)] - Sin[-a]), (Cos[a - x])},
```



Answer: "yes"

Now $(\partial V \rightarrow \partial t)$ and $\partial \frac{dV}{dt}$

Move together

If ∂V +'ve-> ∂t -'ve

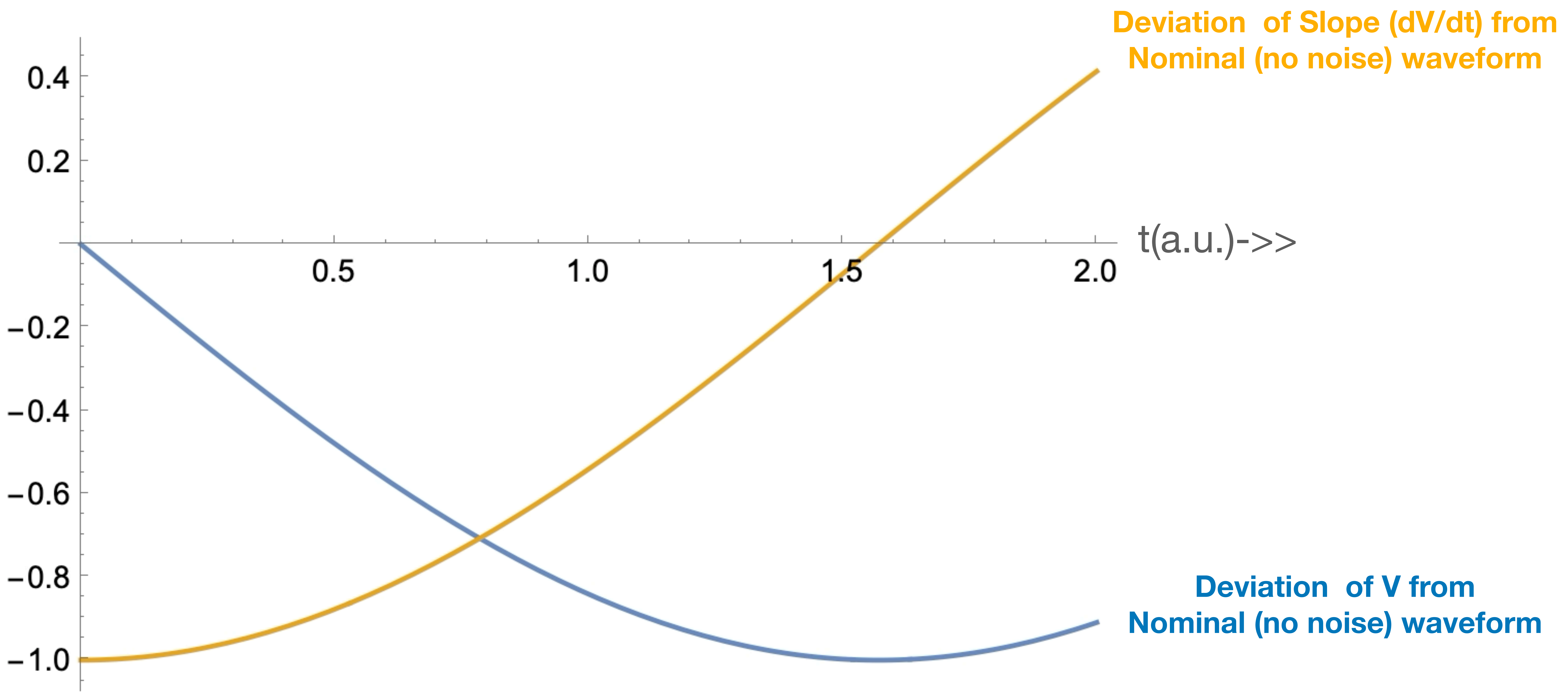
And $\partial \frac{dV}{dt}$ +'ve

We can use a measure of $\partial \frac{dV}{dt}$

to Correct timing for Noise effect !!

Analogous to Amplitude Walk Correction

Animation Showing Phase Dependence
(Click on slide to run animation)



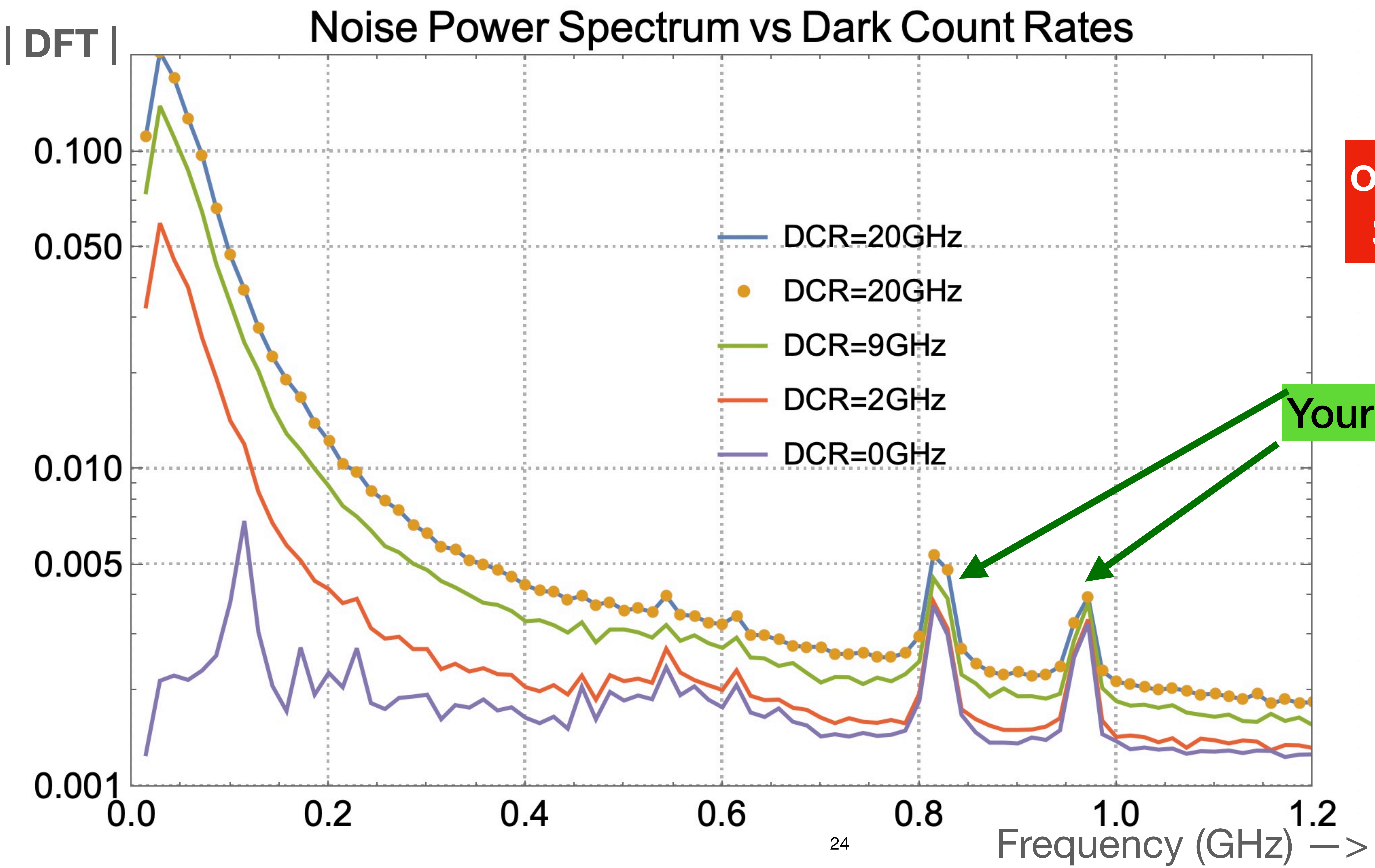
Summary

- Have demonstrated a tool to reduce time jitter due to DCR
- **Likely to be useful in SiPM timing applications w high DCR noise**
- Usefulness in CMS BTL project to be demonstrated with ASIC
- Also suggests new ASIC architectures:
    - Output signal slope @threshold?
    - Process waveforms w. Amplitude correction

Backup

3)Properties of DCR Noise:

HF noise (ie GSM @ 0.8 & 1 GHz) Easy to remove.
But DCR similar to Signal



only noise Sources

Your cell phone?

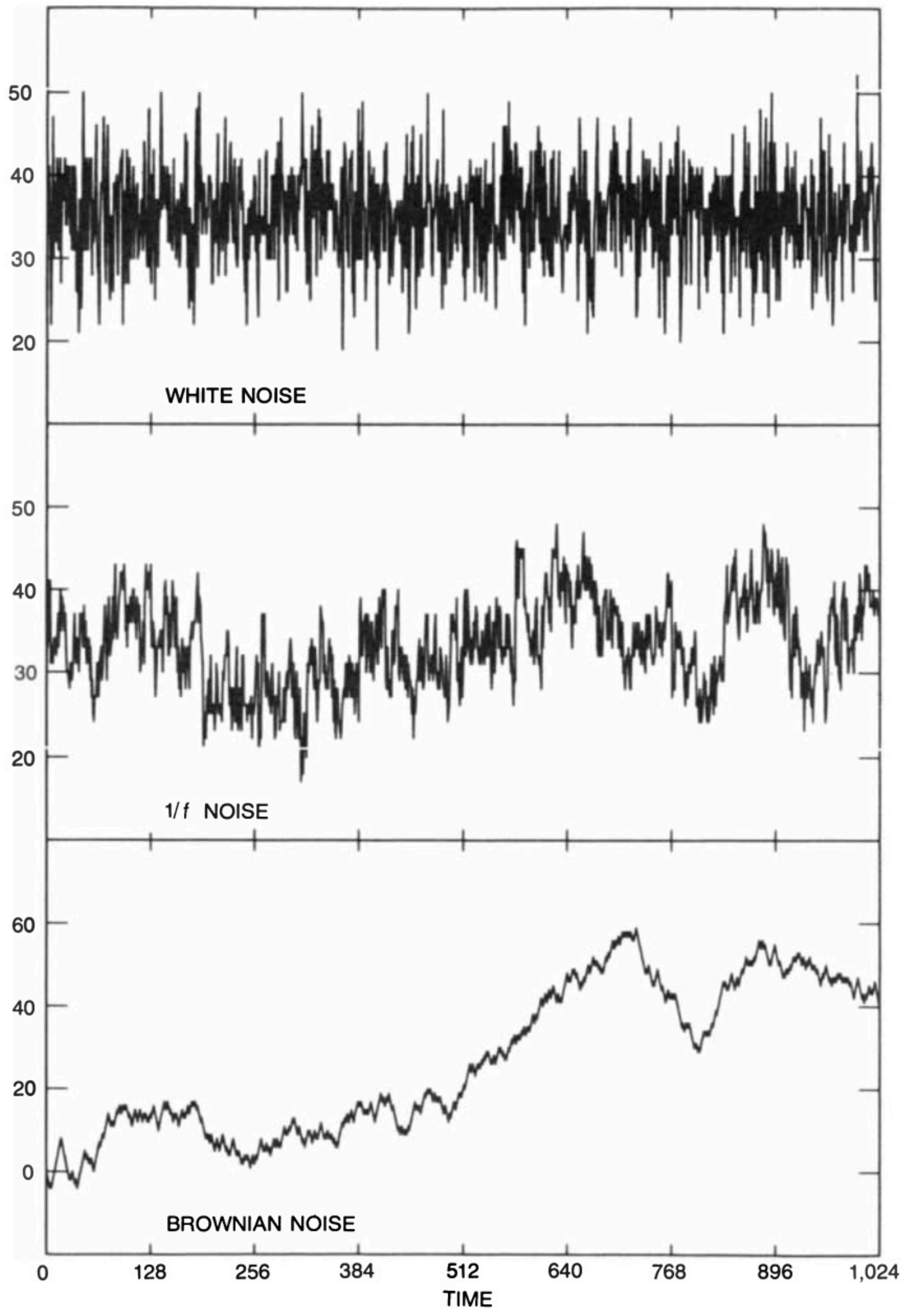
Common Aspects of $1/f^n$ Noise

- Unexpected "flicker noise" seen by Johnson (1925)
- Then Schottky derivation from train of pulses:

$$N(t,t_k) = N_0 e^{-\lambda(t-t_k)} \text{ for } t \geq t_k$$

$$\Rightarrow \quad S(\omega) = \lim_{T\to\infty}\frac{1}{T}\left\langle |F(\omega)|^2\right\rangle = \frac{N_0^2}{\lambda^2+\omega^2}\lim_{T\to\infty}\frac{1}{T}\left\langle\left|\sum_k e^{i\omega t_k}\right|^2\right\rangle = \frac{N_0^2 n}{\lambda^2+\omega^2}$$

- Since 1925 observed in many systems:
  frog nerve membrane (Vervain & Derksen 1968),
  Music (Ross & Clarke 1975), Astronomy (Press 1978)…
  See Backup Slide examples
- Signal Processing for 1/f noise (eg Radeka 1969)
  - **But Not AFAIK for timing**



Typical patterns of white, 1/f and Brownian noise