Oak Ridge National Laboratory

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# Need for Speed
# Fast Timing for HEP Experiments


Oskar Hartbrich

Oak Ridge National Laboratory



U.S. DEPARTMENT OF ENERGY

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# Materials and Acknowledgements

A lot of the material and and diagrams in this presentation were prepared by others:

P. Orel, G. S. Varner: “Femtosecond Resolution Timing in Multi-GS/s Waveform Digitizing ASICs”
IEEE Transactions on Nuclear Science ( Volume: 64, Issue: 7, July 2017)

N Cartiglia: “Signal formation and timing with LGAD sensors” (various presentations)

N. Cartiglia: “Why shot noise in LGAD does not degrade time resolution?” (AIDA 2020 meeting 2019)

W. Riegler, G. Aglieri Rinella: “Time resolution of silicon pixel sensors”
JINST 12 P11017 (arxiv: https://arxiv.org/abs/1706.04883 )

N. Cartiglia et al: “4D tracking: present status and perspectives”
NIM A Volume 1040, 1 October 2022, 167228 (arxiv: https://arxiv.org/abs/2204.06536)

N. Cartiglia et al: “An Introduction to Ultra-Fast Silicon Detectors”
CRC Press

Presentations from Zhenyu Ye, Alexander Kiselev, Jennifer Ott and others at CPAD 2024 here at UTK!

# Timing in HEP – Current and Future

Every large HEP experiment is currently working on a super fast timing upgrades.

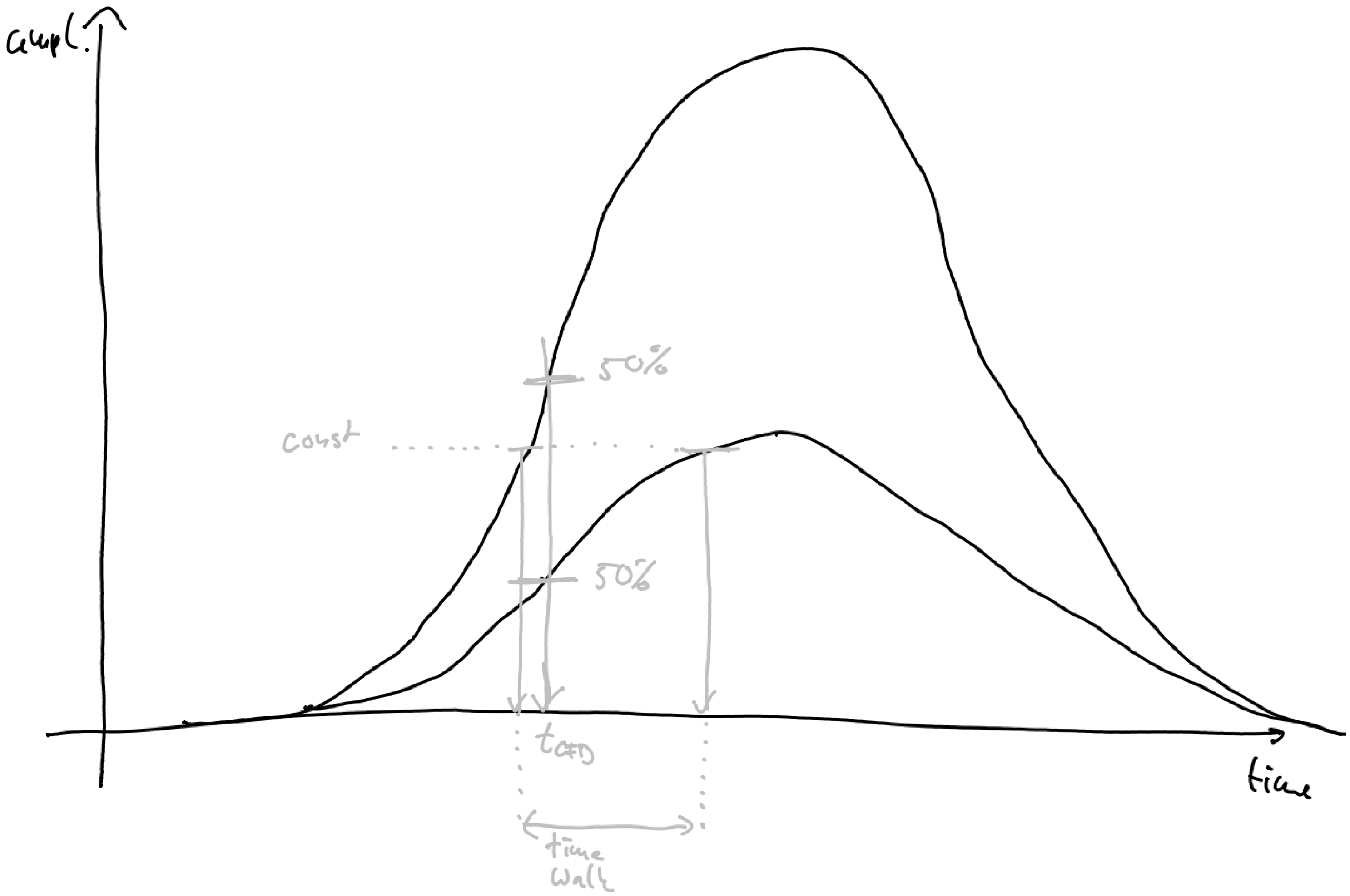
Every planned future HEP (and adjacent) experiment is planning for super fast timing capabilities.

Timing is everything.

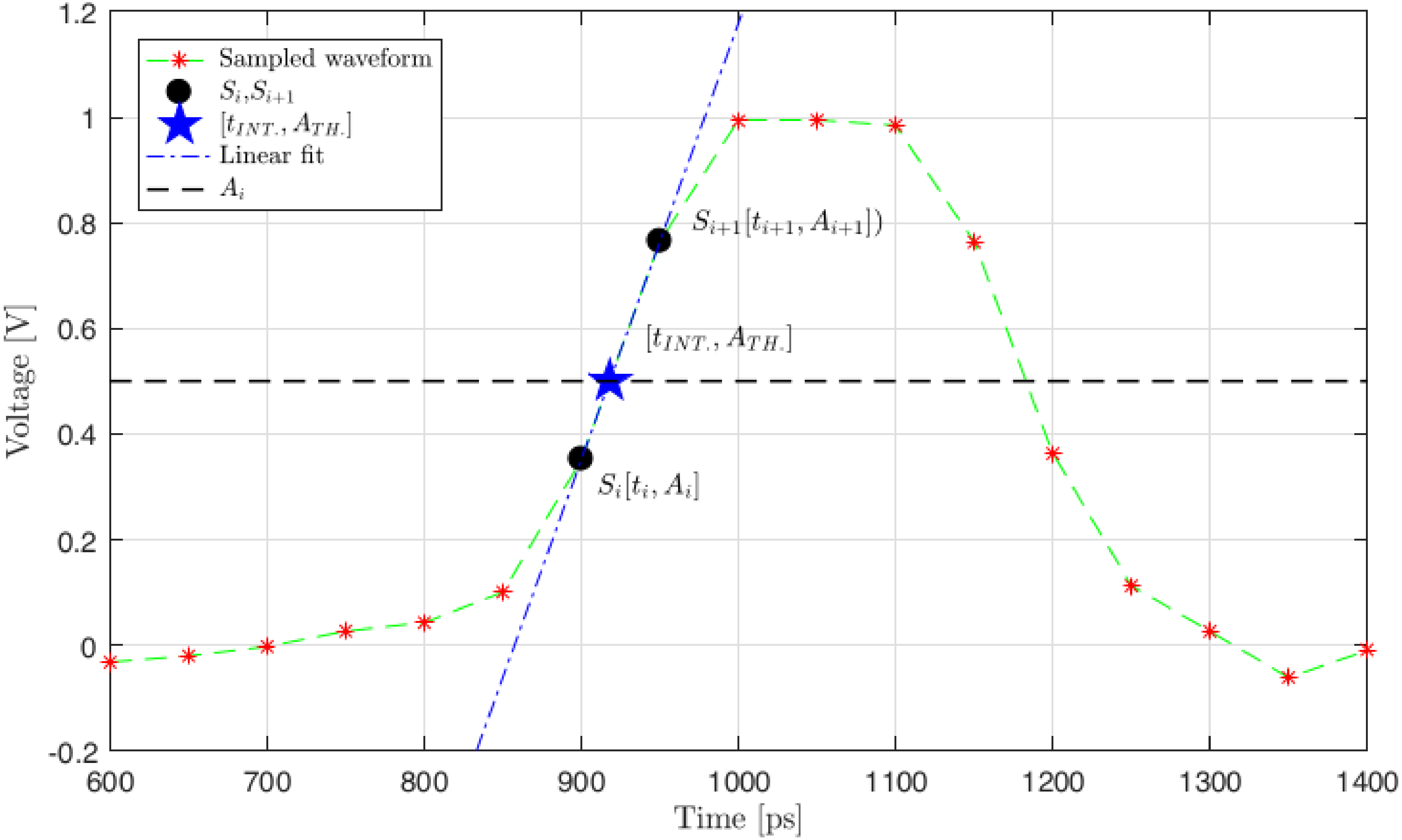
# Timing

Given some signal, at which time did it occur?

# Timing



# Timing



Sampled waveform
$S_i$,$S_{i+1}$
$[t_{INT.}, A_{TH.}]$
Linear fit
$A_i$
$S_{i+1}[t_{i+1}, A_{i+1}])$
$[t_{INT.}, A_{TH.}]$
$S_i[t_i, A_i]$
Voltage [V]
Time [ps]
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
600
700
800
900
1000
1100
1200
1300
1400

# Timing

Given some signal: at which time did it occur?

**Constant threshold**

Needs timewalk correction from amplitude measurement

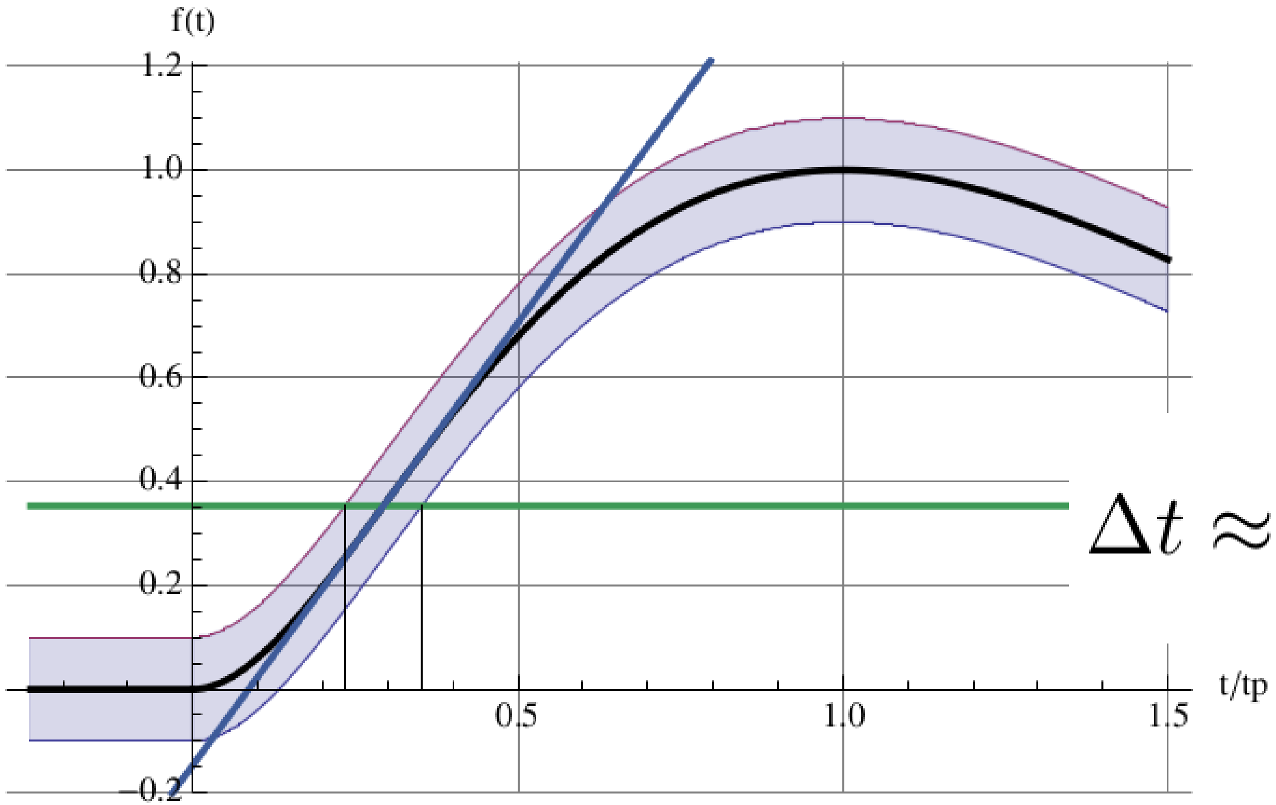
**Constant fraction**

Can be done in analog circuitry (how?)

Can be done “digitally” from waveform sampling

# Timing Uncertainty

Amplitude noise yields timing uncertainty

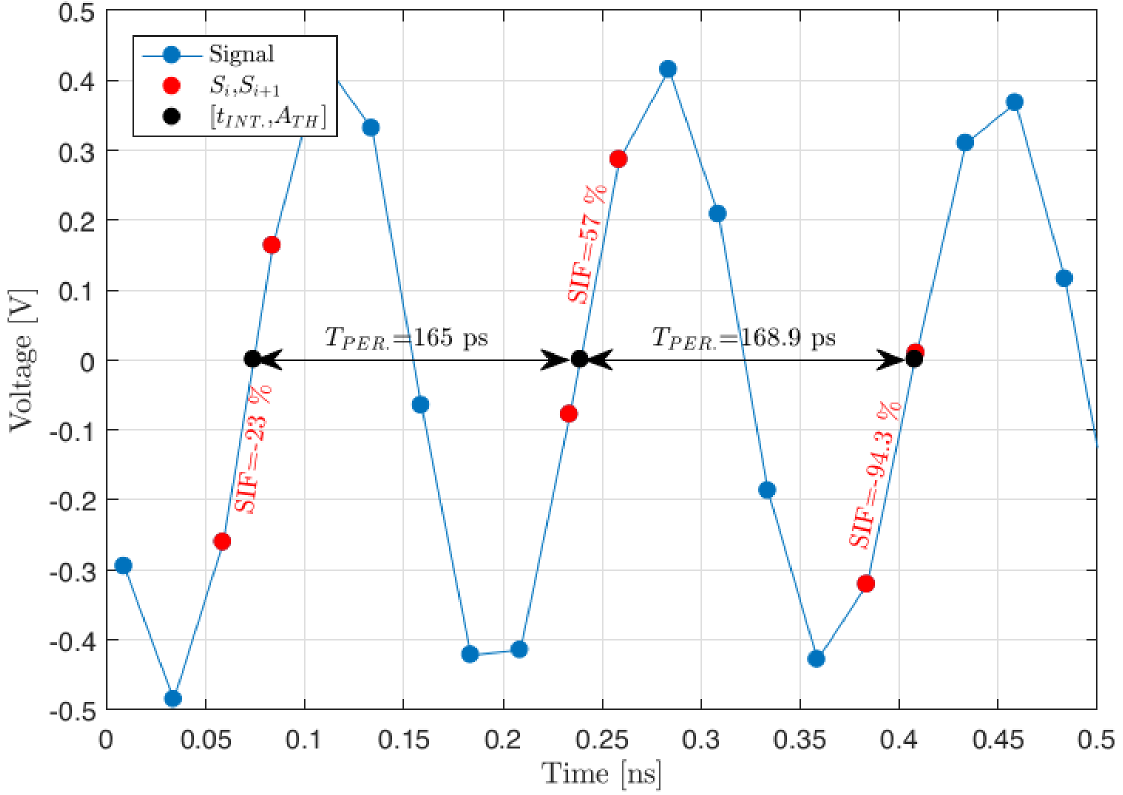



$$\Delta t \approx \frac{\Delta u}{U} \frac{1}{\sqrt{3 f_{SAMP.} BW}}$$

# Just sample faster?

Just increasing sampling speed will not help much if using two points:

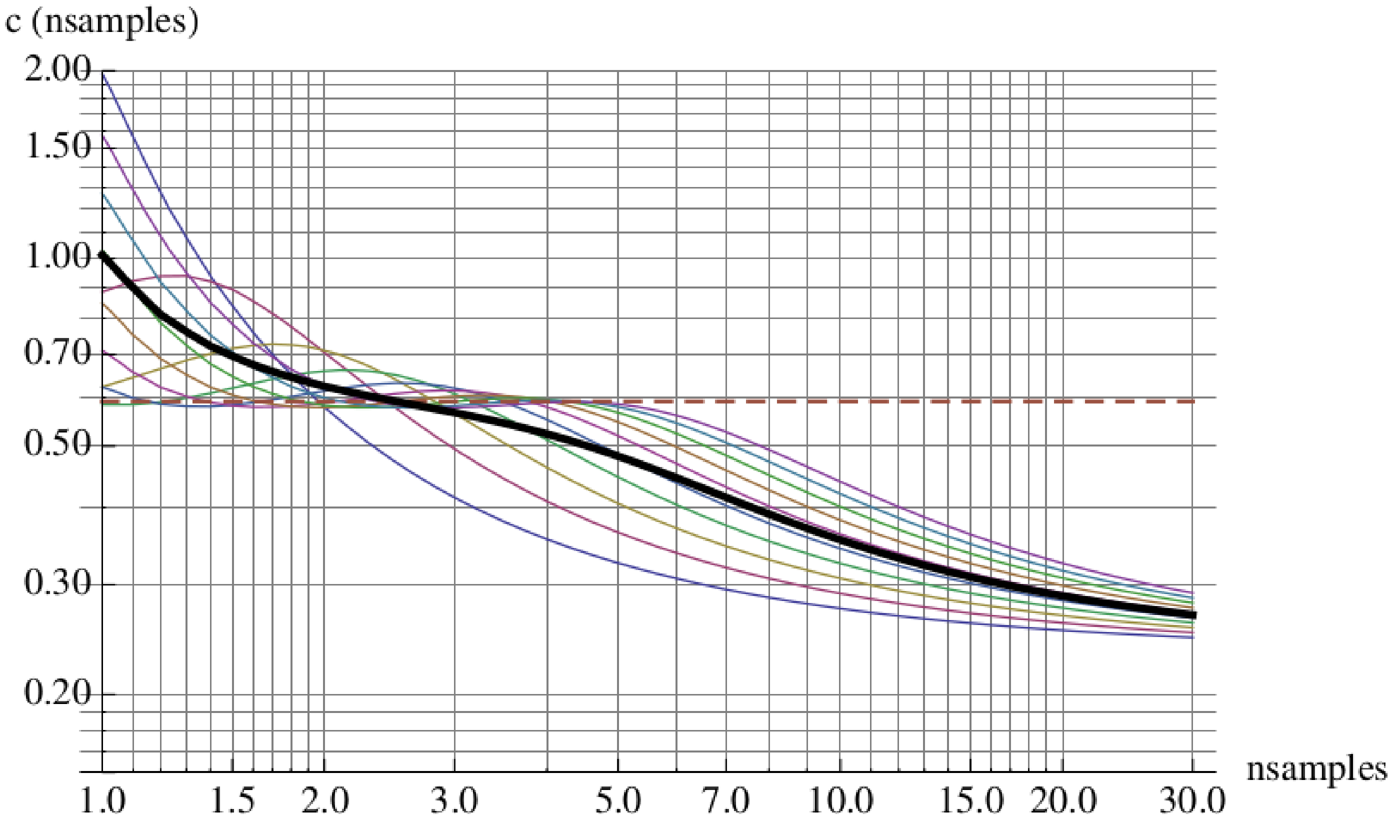
Noise of two points will always contribute
Sometimes even dominated by full noise of single sample



# Just sample faster?

Template transient fit over several points will help

Needs very fast sampling and excellent understanding of signal shapes
Somewhat mediocre returns….



# Instead: Improve Signal-to-Noise Ratio (SNR)

Timing uncertainty scales with peaking time t_p:

$$\sigma_t \begin{aligned} &= \frac{\sigma_{\text{noise}}}{A} \, t_p \times (0.59, 0.57, 0.54, 0.51) \quad \text{for} \quad n = 2, 3, 4, 5 \\ &= \frac{\sigma_{\text{noise}}}{A} \frac{1}{f_{\text{bw}}} \times (0.10, 0.12, 0.13, 0.14) \quad \text{for} \quad n = 2, 3, 4, 5 \end{aligned}$$

Series noise of any amplifier scales with 1/sqrt(t_p):

$$\sigma_{\text{noise}}^2 = \frac{1}{2} e_n^2 C^2 \int_{-\infty}^{\infty} f'(t)^2 dt = \frac{1}{2} e_n^2 C^2 \frac{n^2 (2n-2)!}{t_p} \left(\frac{e}{2n}\right)^{2n}$$

Go for very short peaking time, increase dV/dt

use the best amplifier you can afford (in power budget)

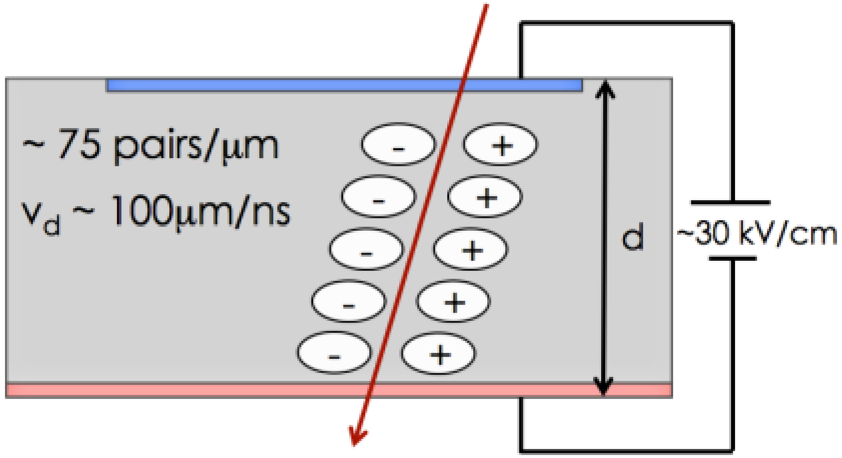
# Timing in Silicon Sensors

# Signal Formation in Silicon

We need a large, fast signal.

What is controlling the slew rate?

$$\frac{dV}{dt} \propto ?$$

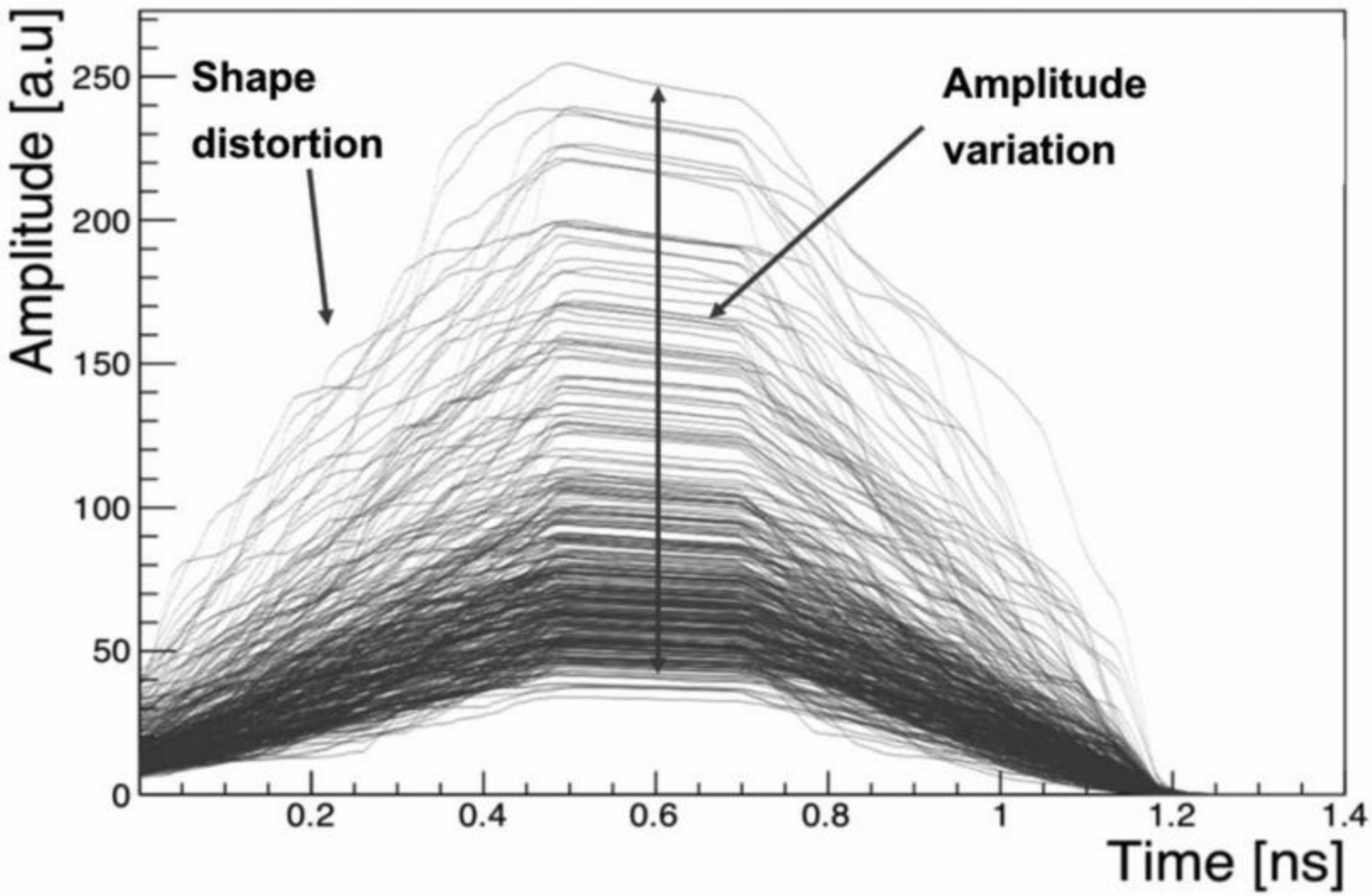



Separated charges start moving inside silicon bulk under influence of electric field

**Motion** of charges induces a current on electrodes (**not** charges reaching electrodes!)

Signal ends when charges reach the electrode

# Signal Shape Distortions



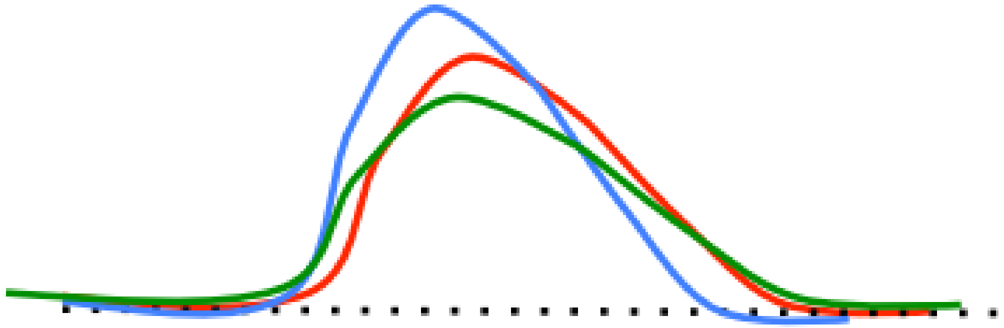
# How to get a nice signal? – a little bit of Shockley-Ramo

Signal uniformity is key!

$$i \propto q v E_w$$

Drift velocity

Weighting field



# Drift Velocity

$$i \propto q v E_w$$

→ Highest possible E field to saturate velocity
→ Highest possible resistivity for velocity uniformity

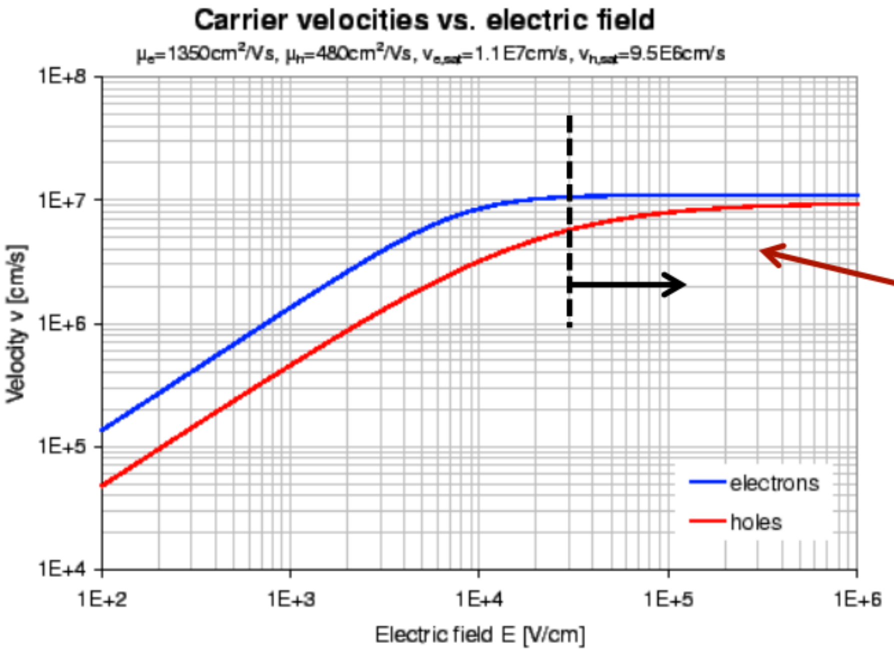



**Figure:** Electron and hole velocities vs. the electric field strength in silicon.

**We want to operate in this regime**

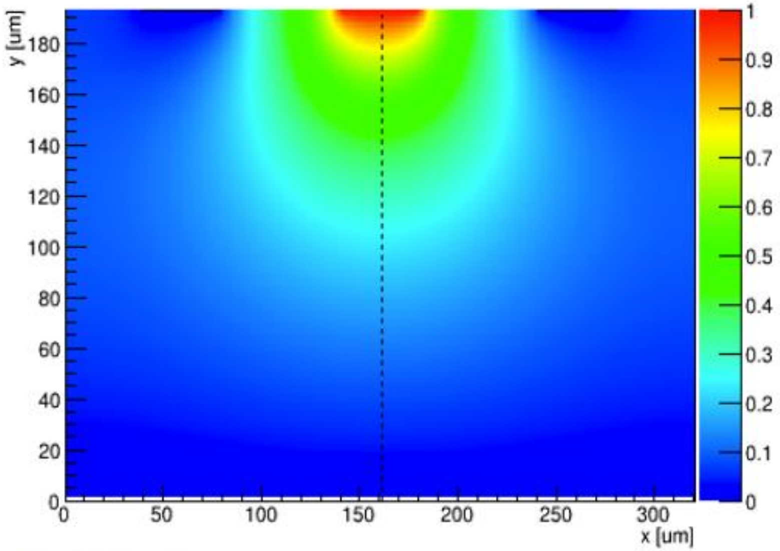
# Weighting Field

Need uniform weighting field

Entirely depends on diode geometry

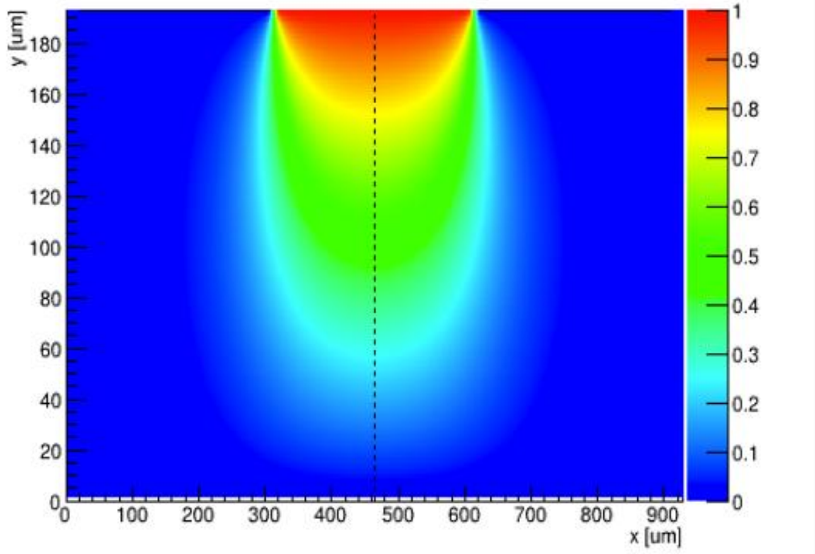
$$i \propto qvE_w$$

Strip: 100 μm pitch, 40 μm width




**Bad:** almost no coupling away from the electrode

Pixel: 300 μm pitch, 290 μm width




**Good:** strong coupling almost all the way to the backplane

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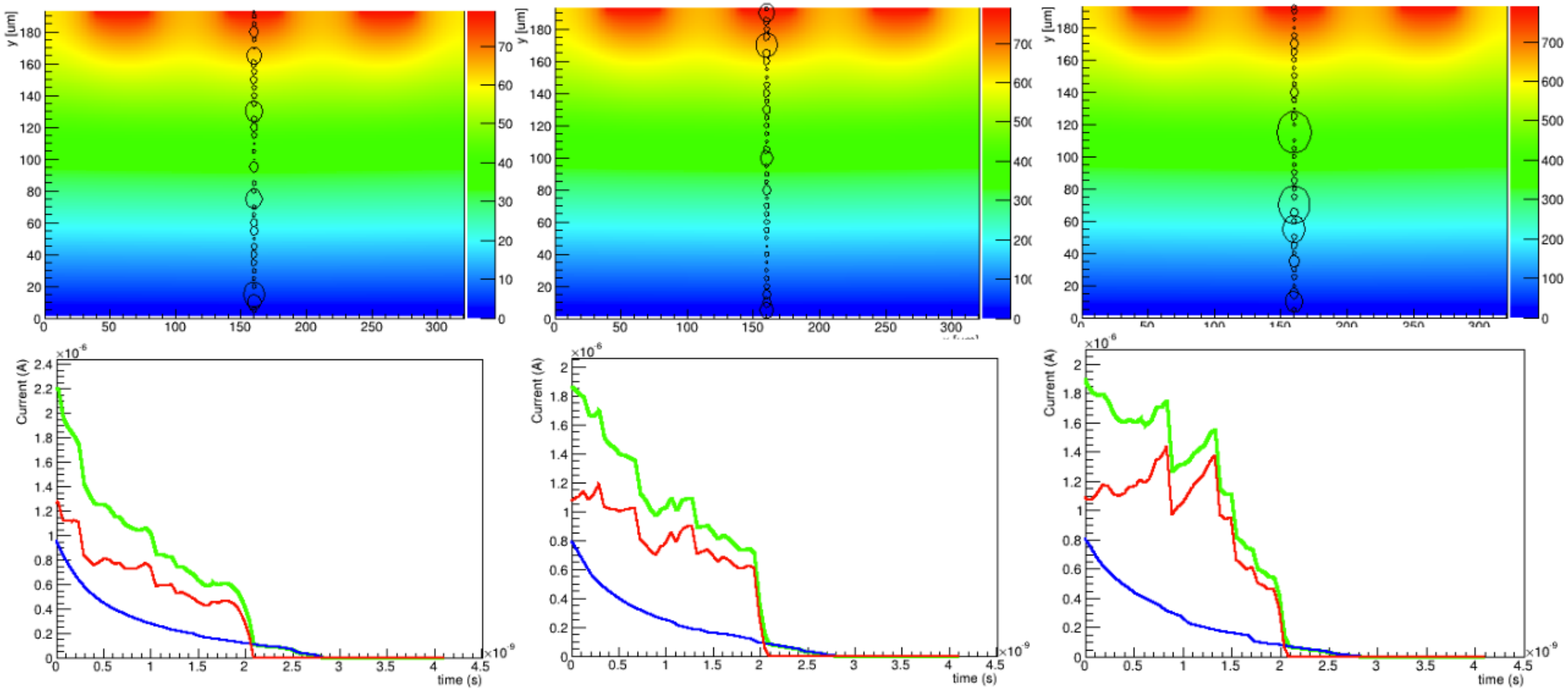
# Non-uniform depositions

**Landau fluctuations**

cause amplitude variation – corrected by timewalk/CFD

cause non-uniform charge deposition:

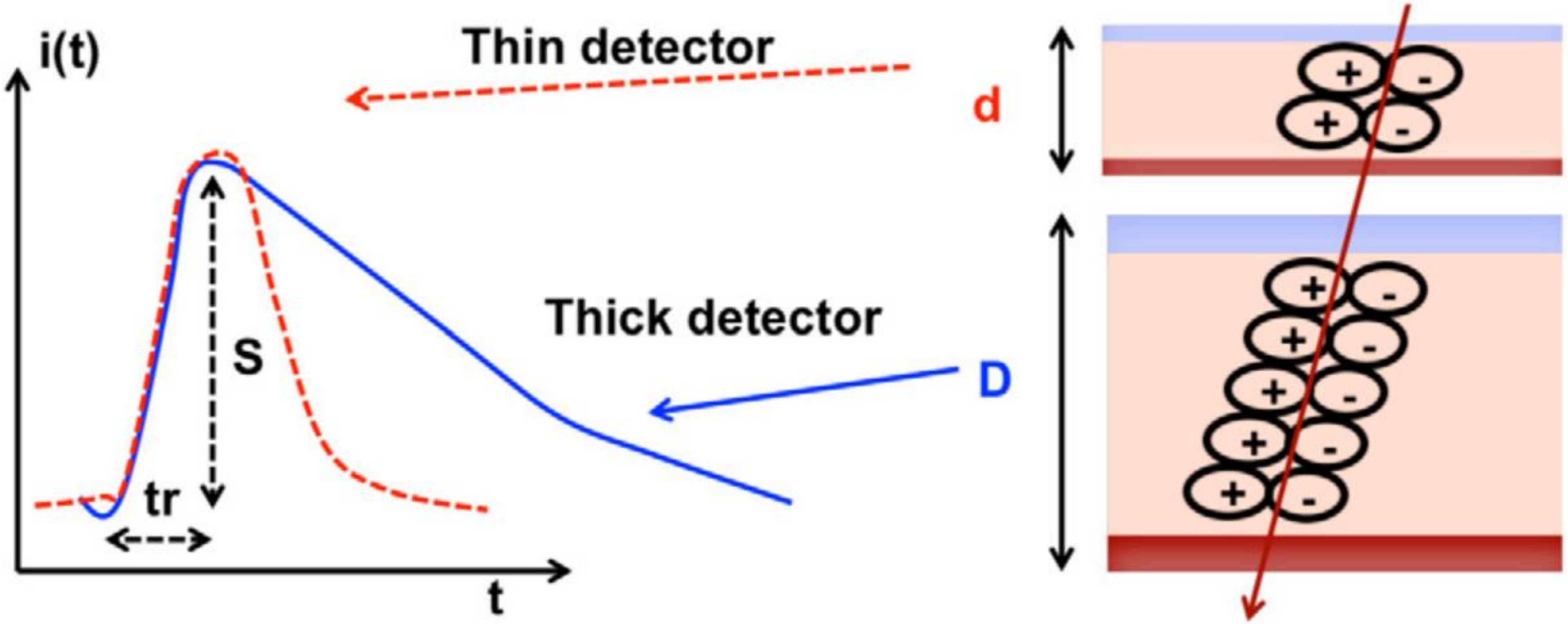


# Sensor Thickness

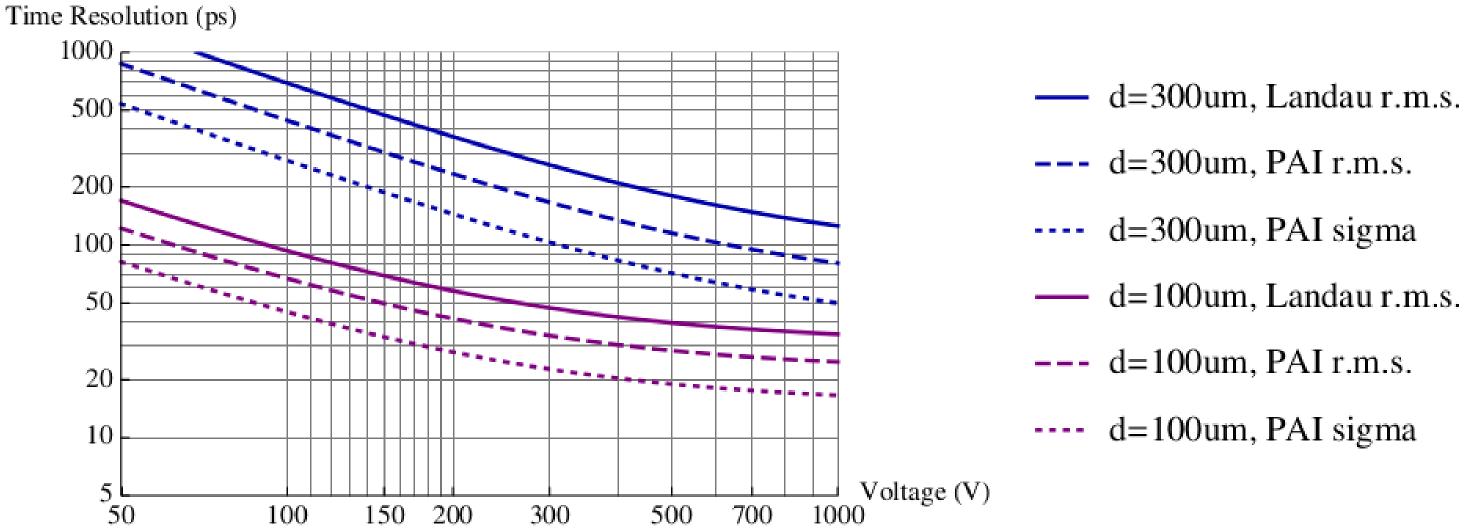
Thicker sensors produce more signal…

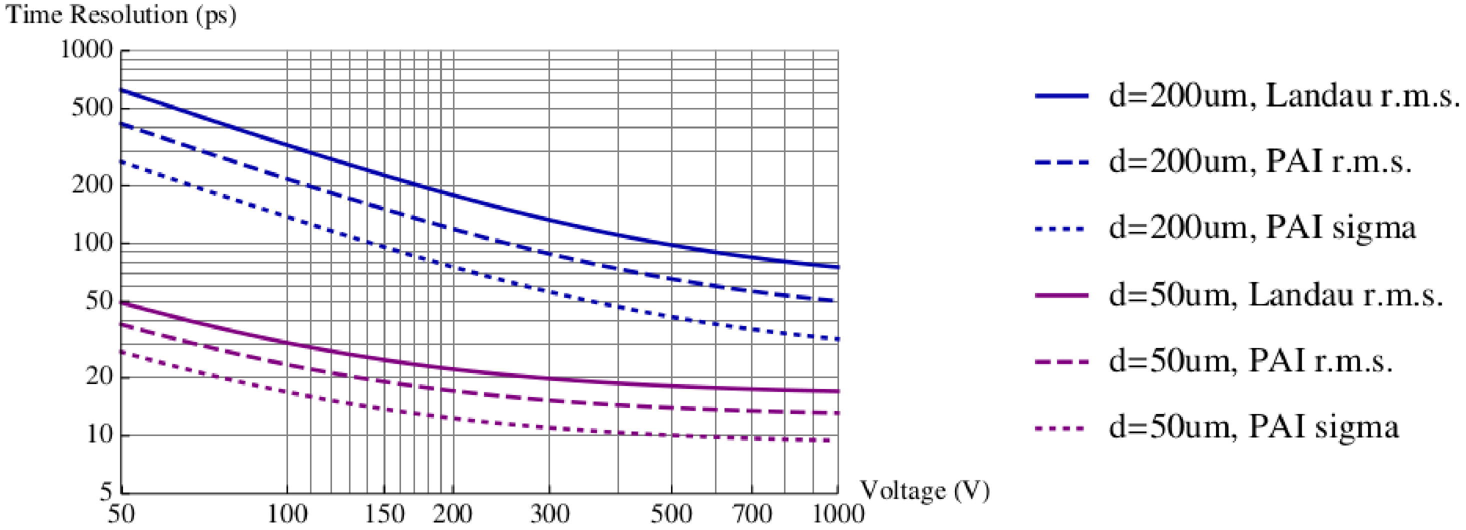
…but the initial signal slew rate does not depend on the sensor thickness!

I_max in a silicon diode is always ~1.5uA



# Timing in Silicon Sensors – no internal amplification



# So What?

Overall silicon sensor time resolution:

$$\sigma_t^2 = \sigma_{\text{Jitter}}^2 + \sigma_{\text{Ionization}}^2 + \sigma_{\text{Distortion}}^2 + \sigma_{\text{TDC}}^2.$$

Bringing us back to the perfect preamplifier…

$$\sigma_{\text{Jitter}}^2 = \frac{1}{2} e_n^2 C^2 \int_{-\infty}^{\infty} f'(t)^2 dt = \frac{1}{2} e_n^2 C^2 \frac{n^2 (2n-2)!}{t_p} \left(\frac{e}{2n}\right)^{2n}$$

How about amplifying the signal directly in the sensor?

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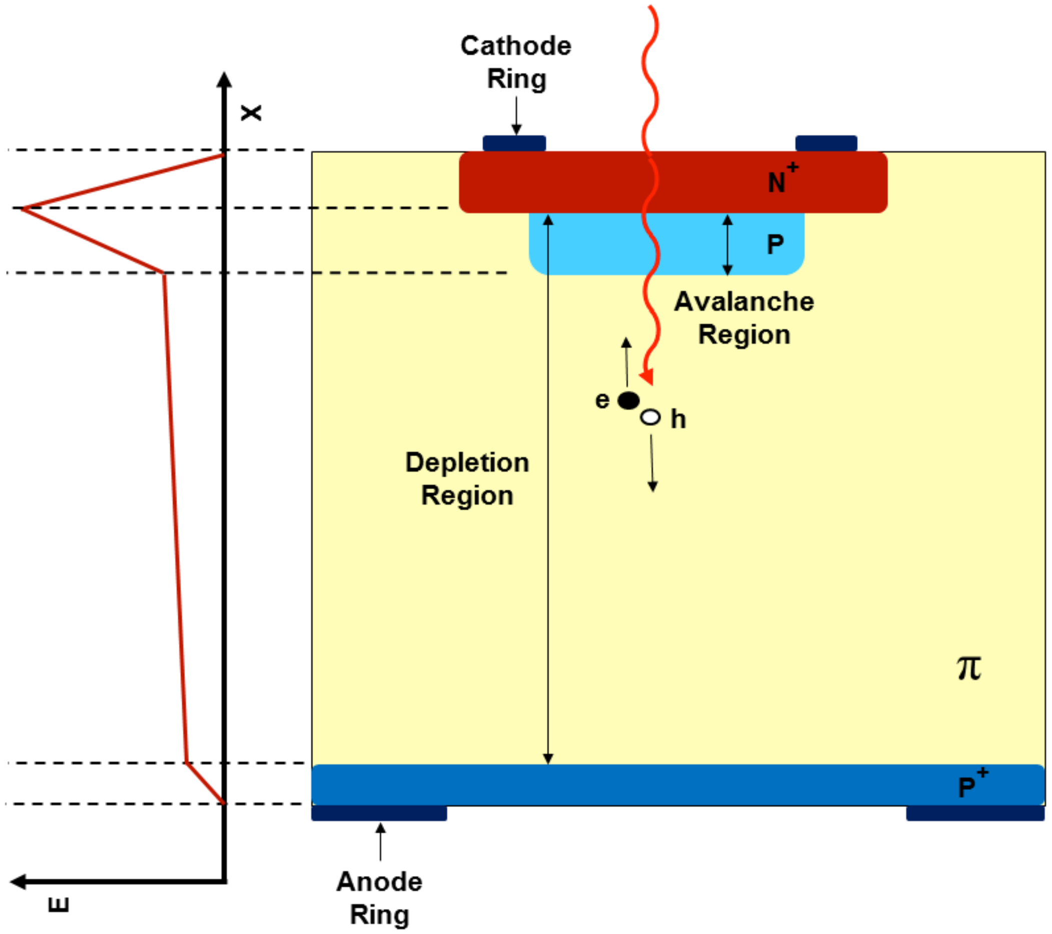
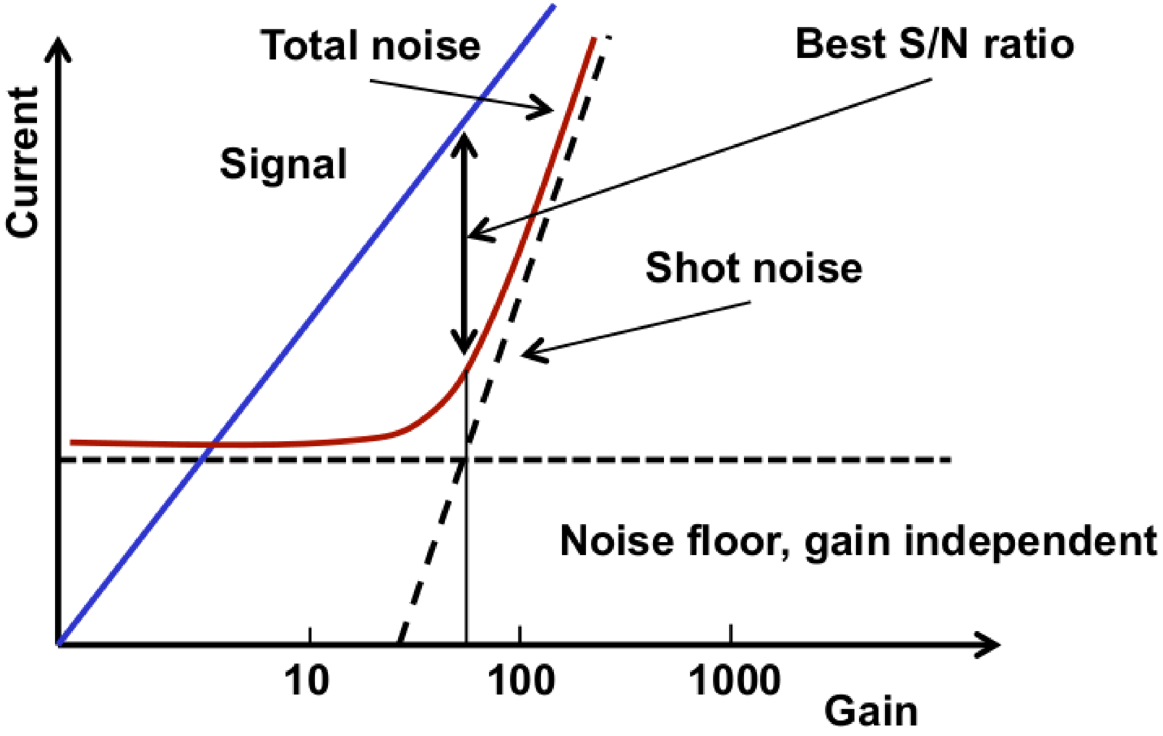
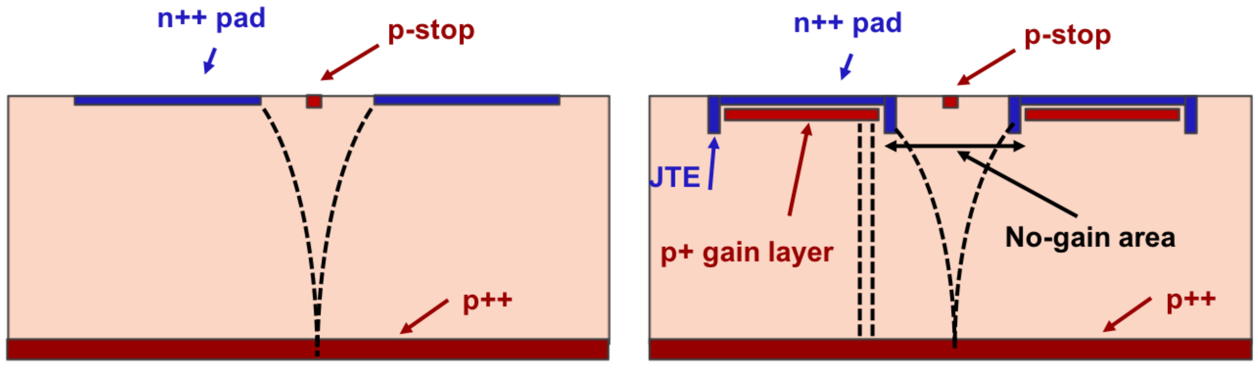
# Amplification in Silicon



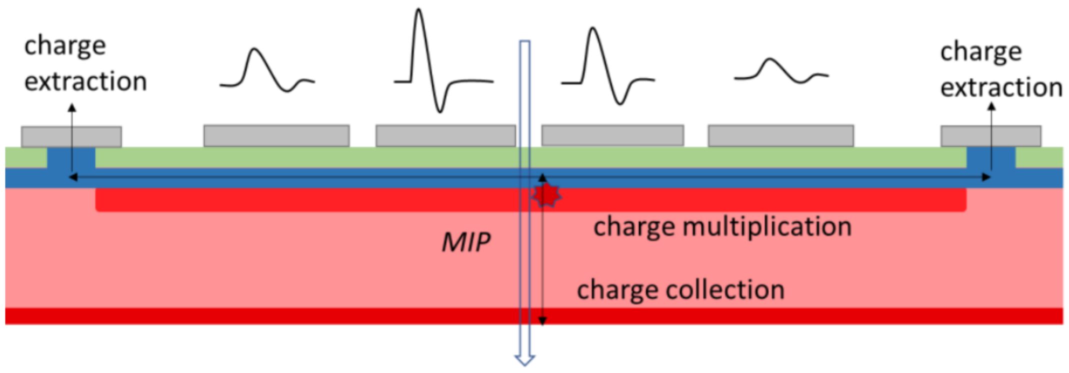



# LGADs and AC-LGADs




a) Traditional Silicon detector

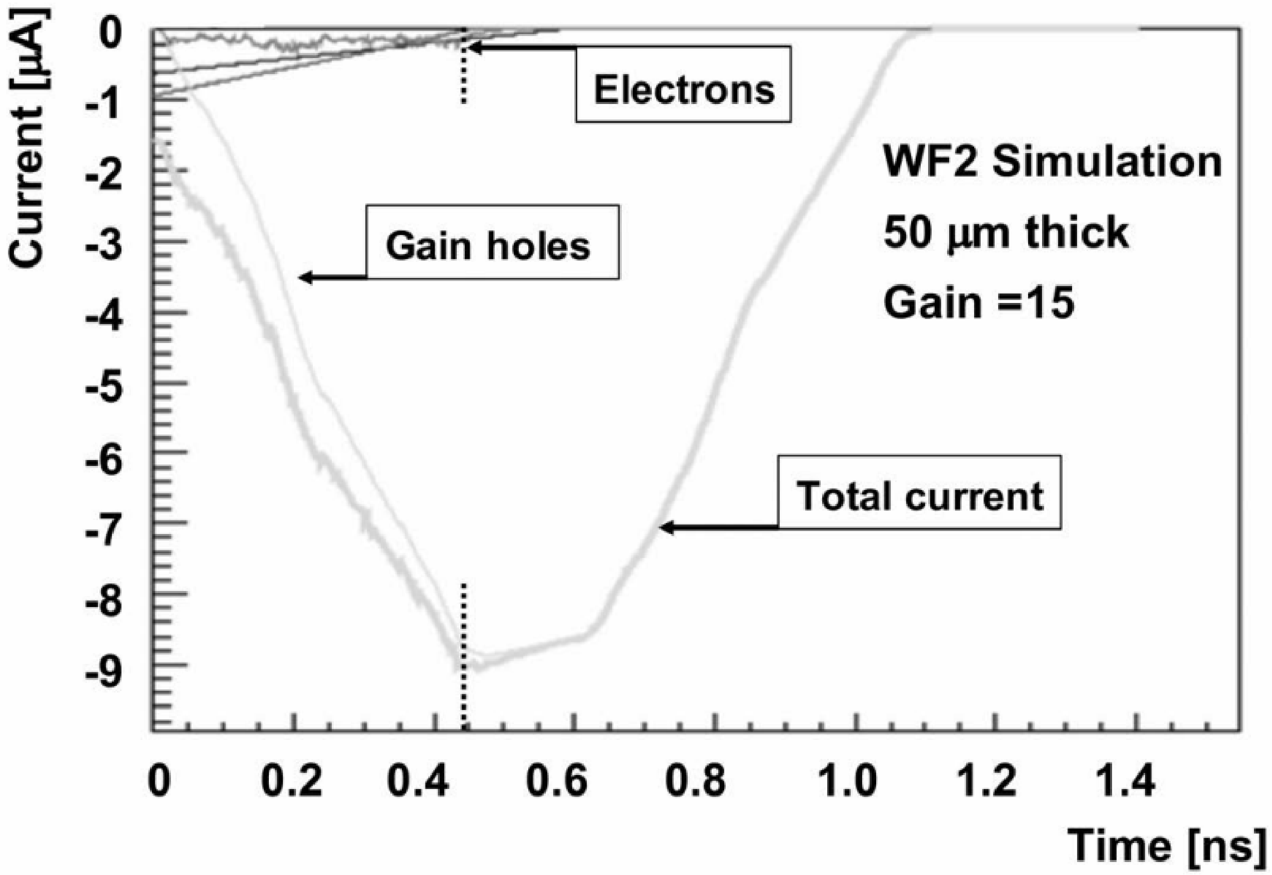
b) UFSD



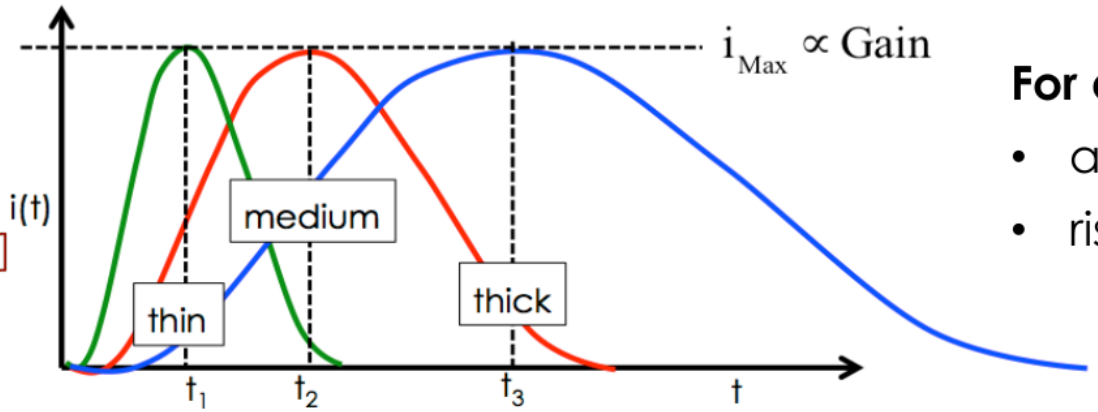
# Signals of LGADs

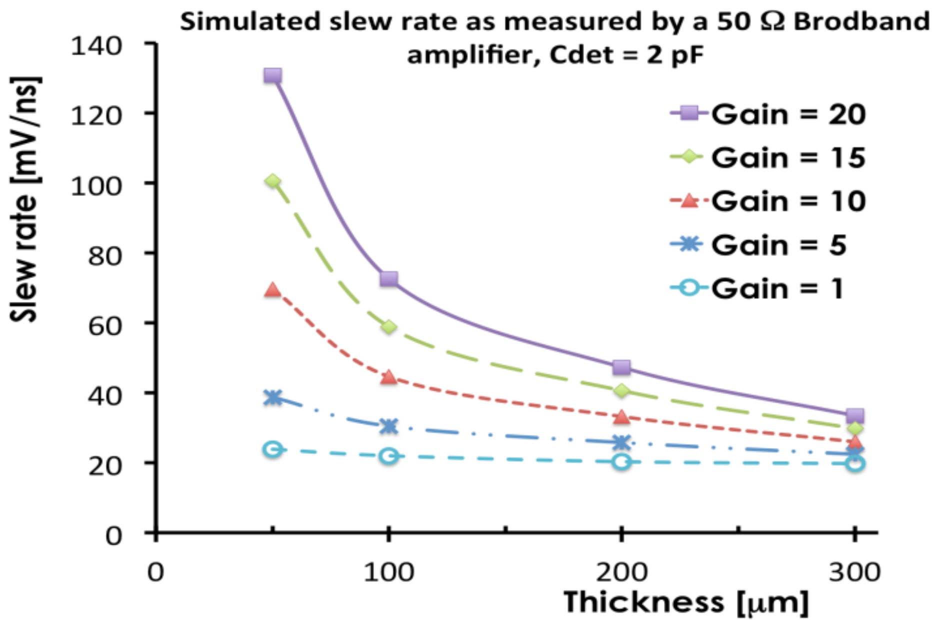
Gain holes always travel full width of silicon

Slew rate now depends on thickness.



# Signals of LGADs




**For a fixed gain:**

- amplitude = constant
- rise time ~ 1/thickness

**The slew rate:**

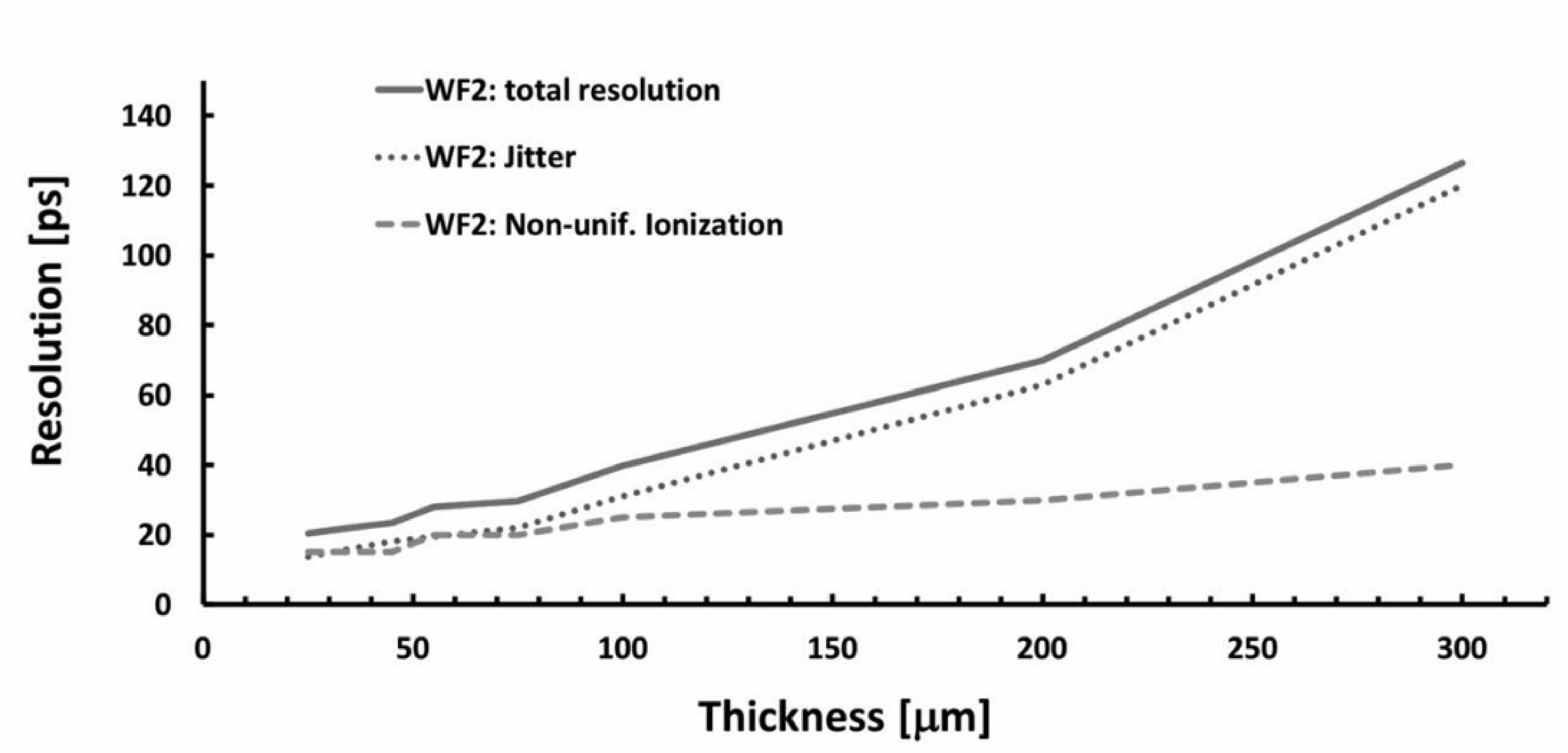
- Increases with gain
- Increases ~ 1/thickness

$$\frac{dV}{dt} \propto \frac{G}{d}$$

➔ **Go thin!!**

**Significant improvements in time resolution require thin detectors**

# Hitting the Landau Limit



# Some Current Applications

Chosen entirely by my personal preference and involvement.

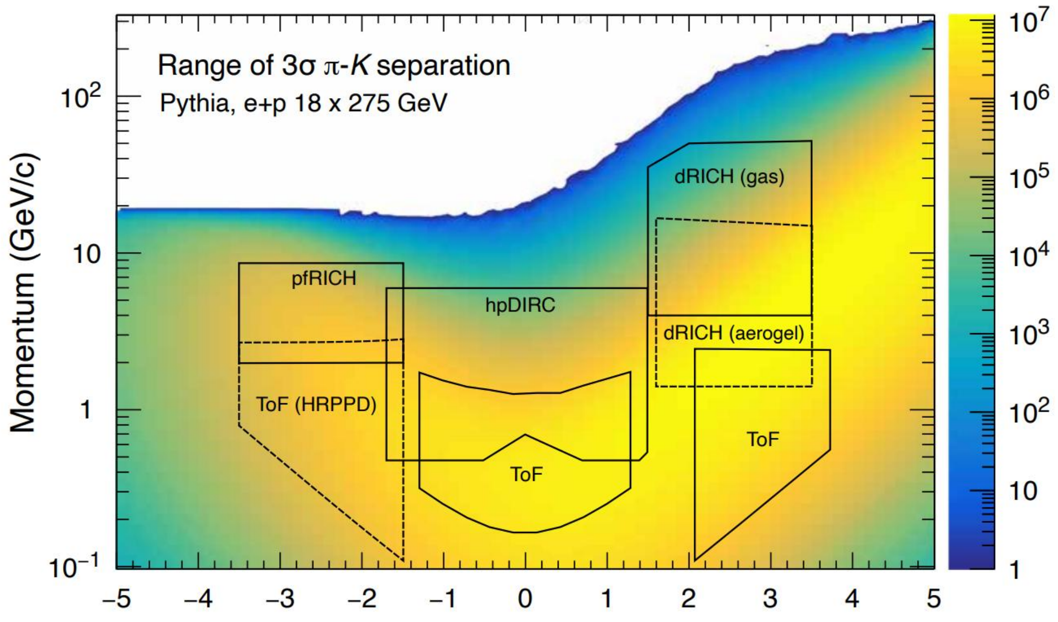
There were dozens of talks on exciting developments and projects for fast timing sensors and detector concepts at CPAD 2024 here at UTK last year, I could not possibly give justice to the field.

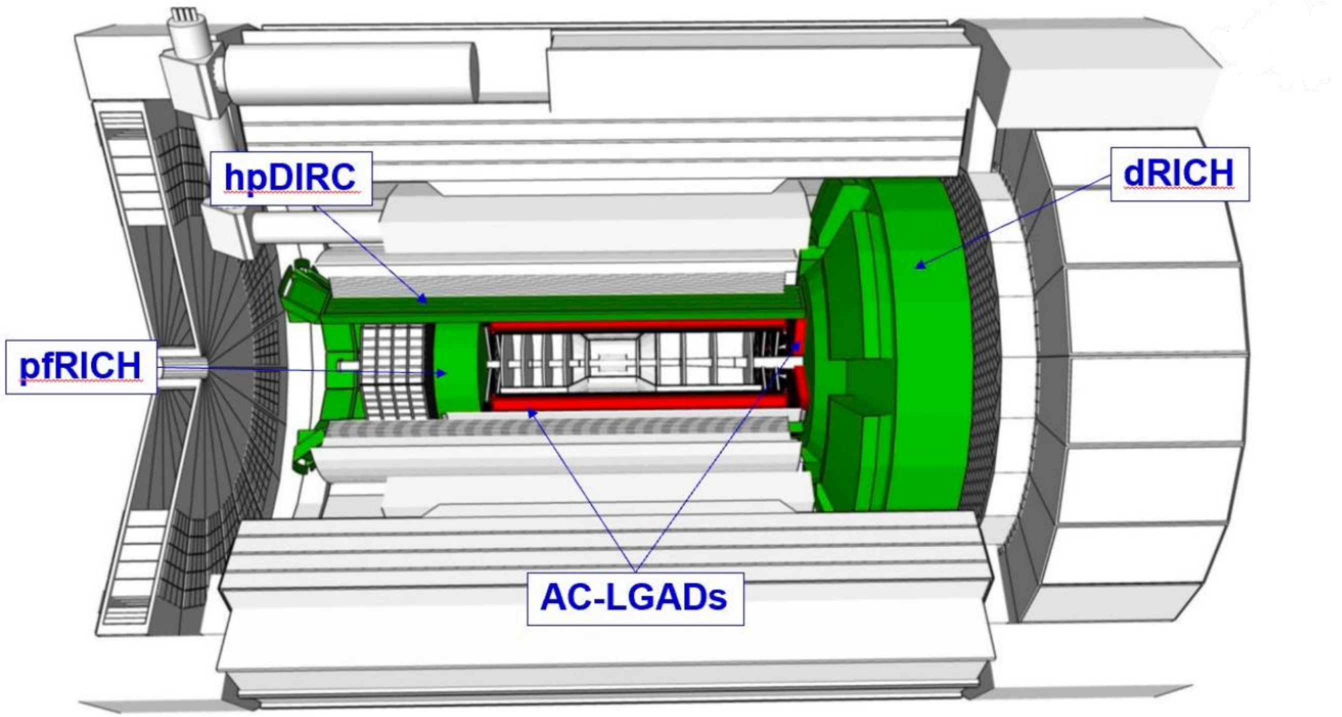
# ePIC TOF – AC-LGADs Galore

ePIC is the first detector at the upcoming Electron-Ion Collider at BNL

ePIC will unravel the structure of nuclear matter and the QGP

Full PID coverage in full momentum range required

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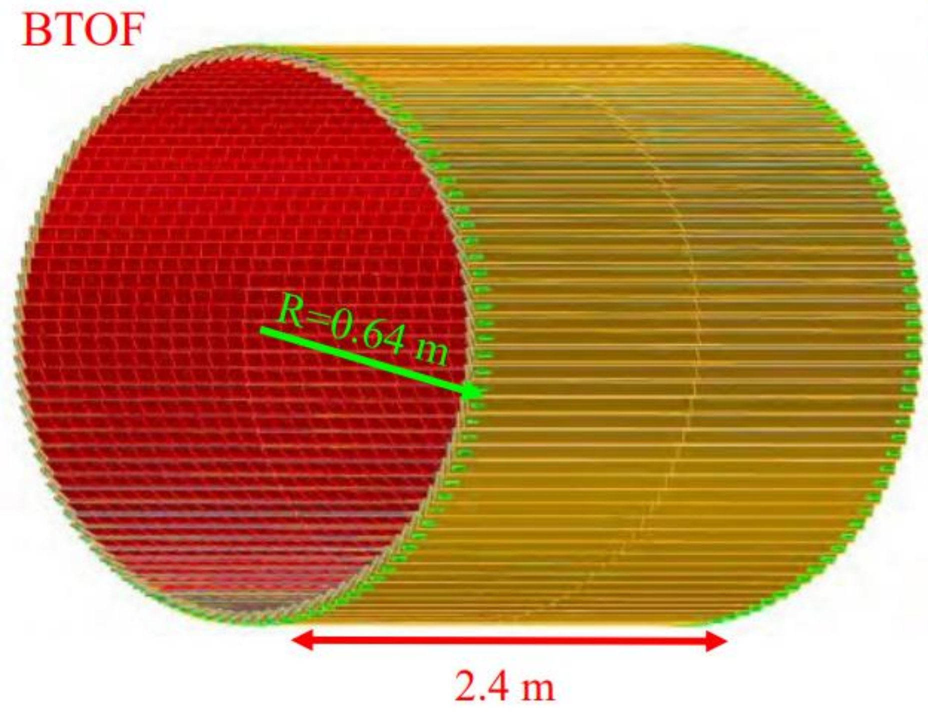
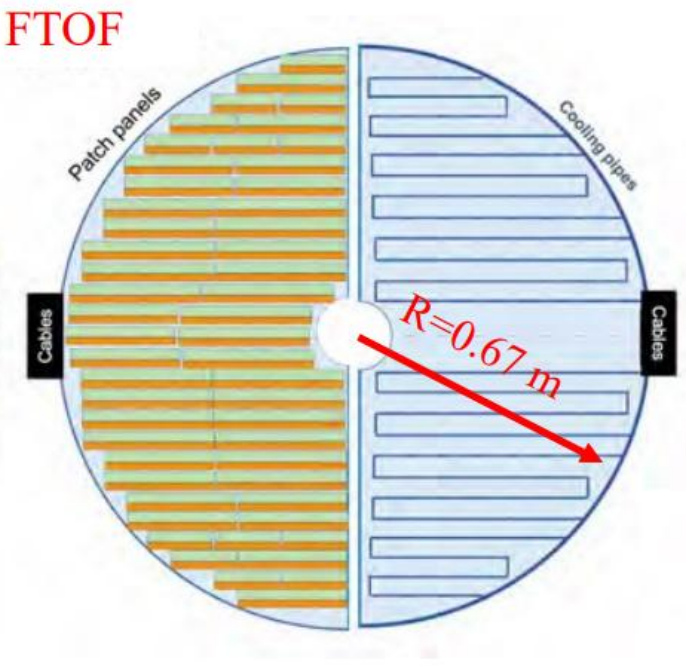
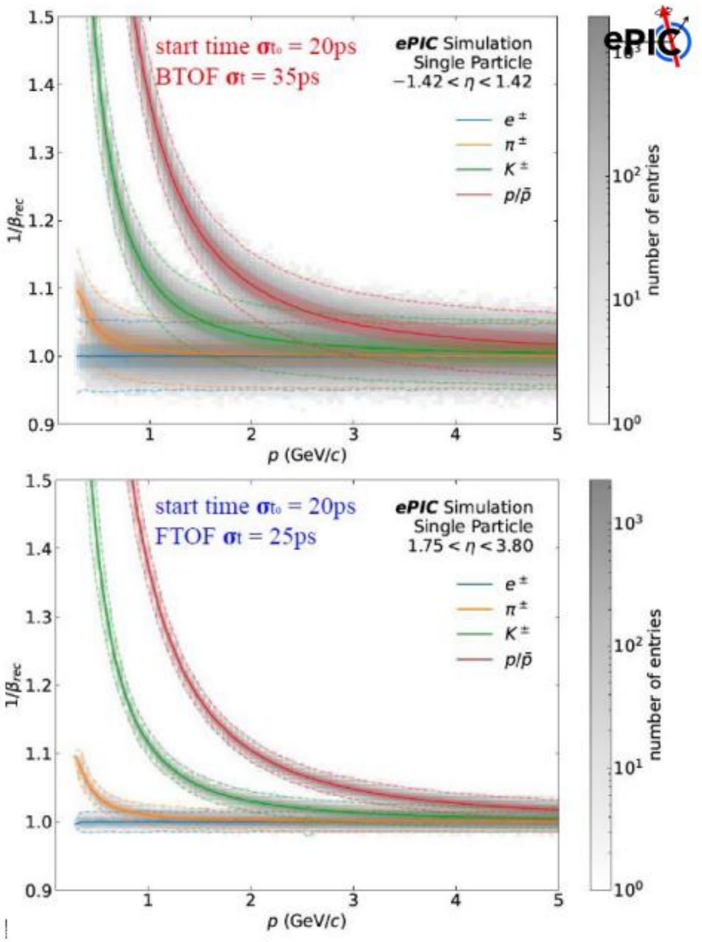
# AC-LGAD Detectors for ePIC



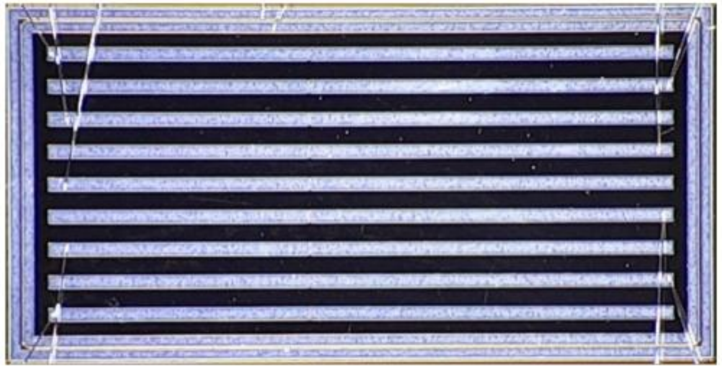

| | Area ($m^2$) | Channel size ($mm^2$) | # of Channels | Timing Resolution | Spatial resolution | Material budget |
|---|---|---|---|---|---|---|
| **Barrel TOF** | 10 | 0.5*10 | 2.4M | 35 ps | 30 $\mu m$ in $r \cdot \varphi$ | 0.01 $X_0$ |
| **Forward TOF** | 1.4 | 0.5*0.5 | 5.6M | 25 ps | 30 $\mu m$ in x and y | 0.05 $X_0$ |
| **B0 tracker** | 0.07 | 0.5*0.5 | 0.28M | 30 ps | 20 $\mu m$ in x and y | 0.05 $X_0$ |
| **RPs/OMD** | 0.14/0.08 | 0.5*0.5 | 0.56M/0.32M | 30 ps | 140 $\mu m$ in x and y | no strict req. |

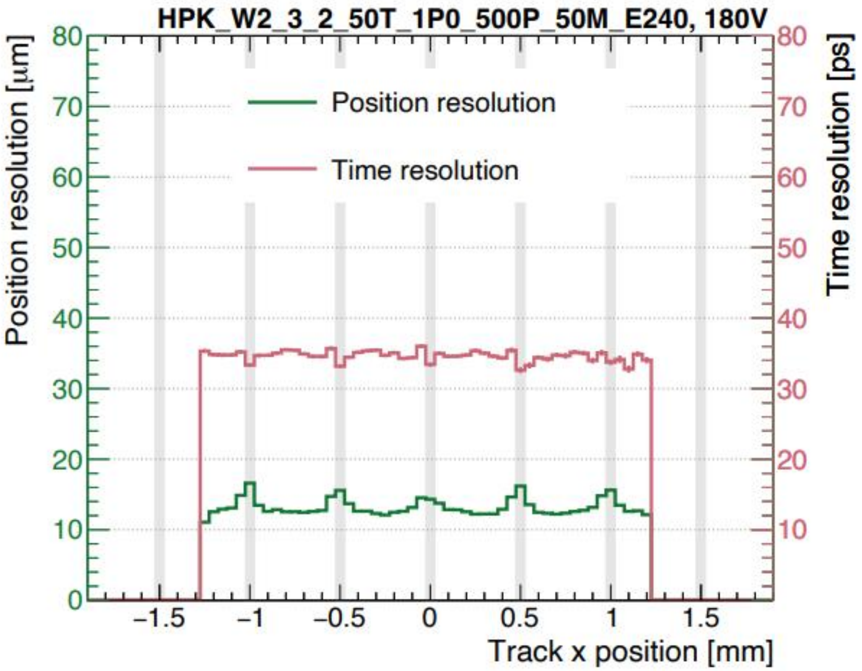
# ePIC TOF Sensor Tests

Chosen entirely b

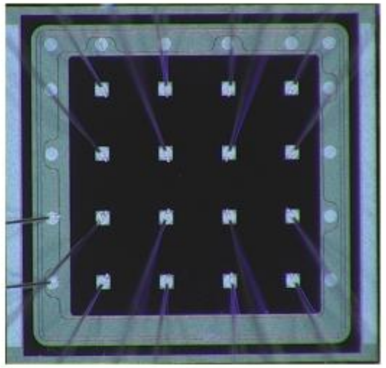
There were dozei
concepts atCPAI

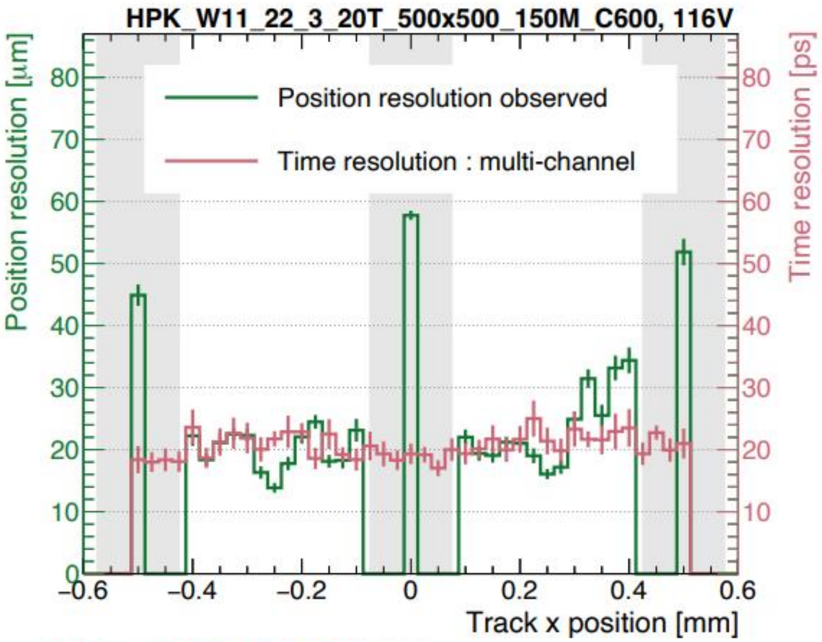
HPK Strip Sensor (4.5x10 mm²)






HPK Pixel Sensor (2x2 mm²)






Zhenyu Ye @ LBNL

arXiv:2407.09928

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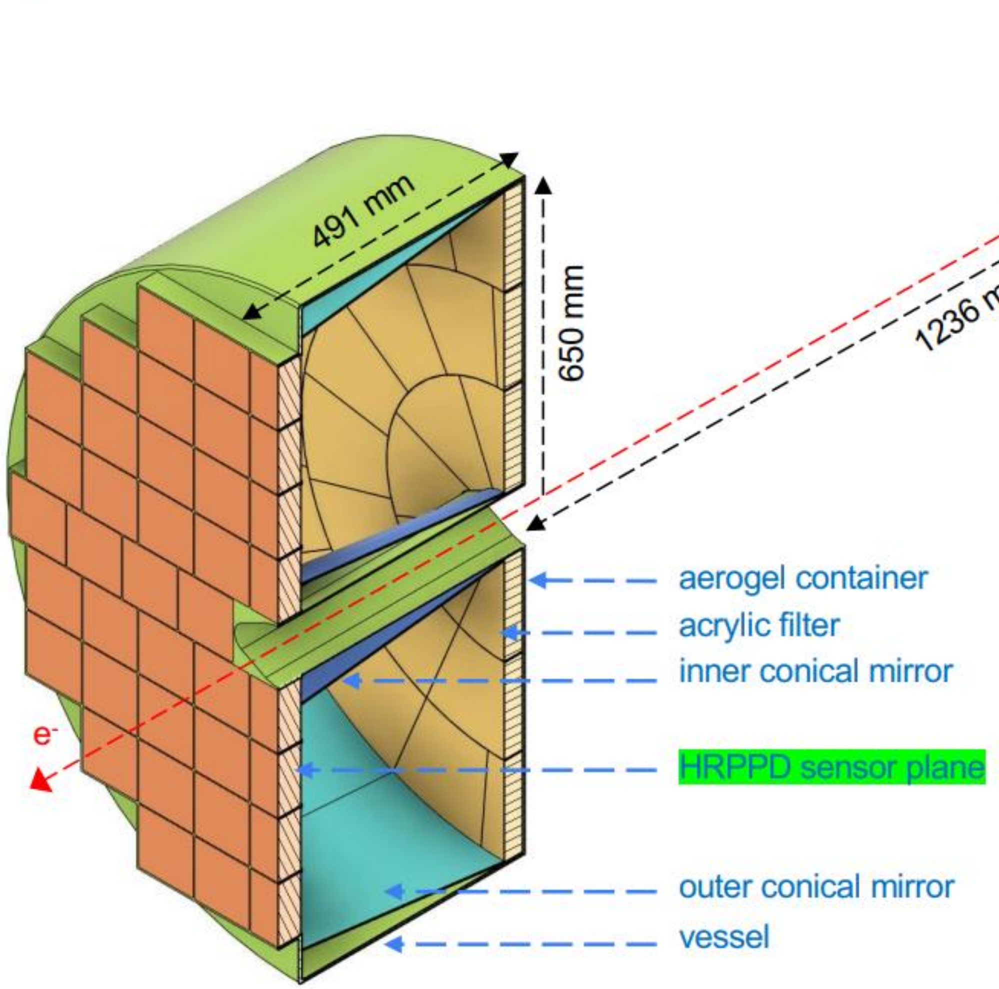
# Bonus: what about the ePIC backward TOF?

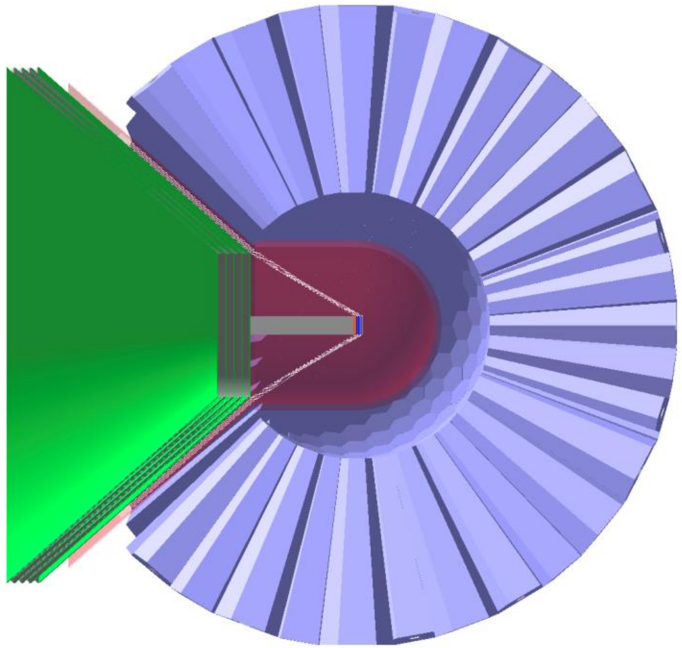
## pfRICH for ePIC detector electron-going endcap




- A classical proximity focusing RICH
  - with a high-resolution timing capability
- Pseudorapidity coverage: $-3.5 < \eta < -1.5$
- Uniform performance in this $\{\eta,\phi\}$ range
- <20ps $t_0$ reference for the ToF subsystems
- >3$\sigma$ $\pi$/K separation up to ~ 7.0 GeV/c
- ~100% geometric efficiency

Alexander Kiselev, BNL

# PIONEER – The first full 5D AC-LGAD tracker?



PIONEER

A next generation rare pion decay experiment

# Physics Case I: Precision Test of Lepton Flavor Universality

Lepton universality:

- Gauge coupling the same for all flavors
- PIONEER will test this fundamental principle to 0.01%

Pion decay ratio $R_{e/\mu} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}$

- provides unique opportunity

$R_{e/\mu}(Exp) = 1.23270(230) \times 10^{-4}$ (0.18%)

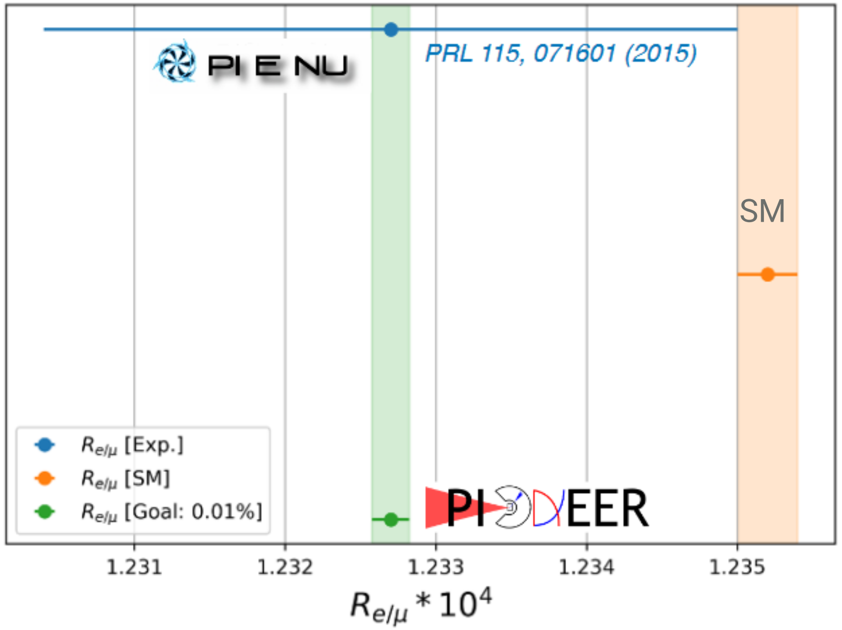
$R_{e/\mu}(SM) = 1.23524(015) \times 10^{-4}$ (0.01%)

PIENU at TRIUMF
Cirigliano & Rosell

$$\frac{g_\mu}{g_e} = 1.0010 \pm 0.0009$$

- Note:
  - Very high precision SM prediction*), theory 15x more precise than experiment
  - Strong helicity suppression
  - *) 0.01 % uncertainty in NNLO EFT calculation of EW corrections

- PIONEER goal (Phase I)



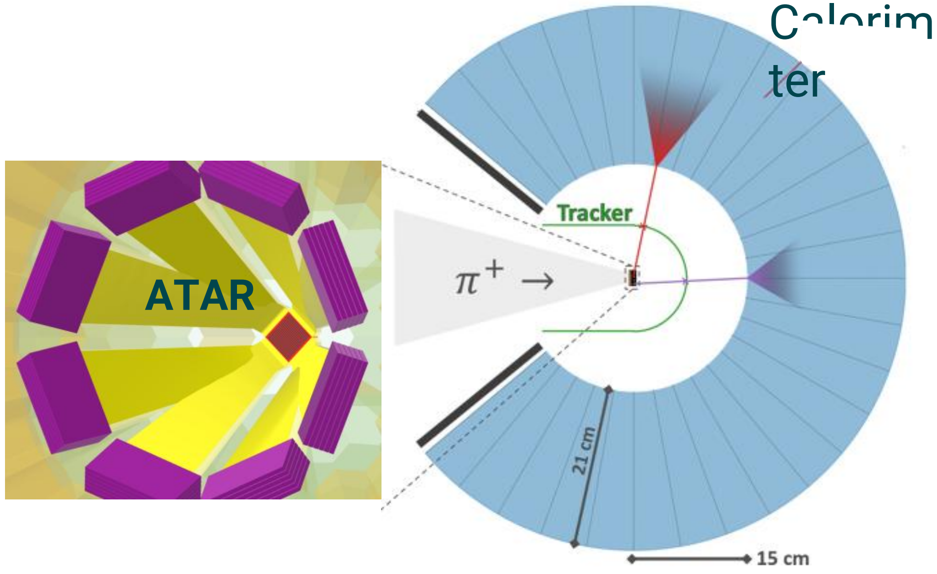

- PIONEER physics reach
  - unprecedented LFU sensitivity **0.01%** territory
  - many BSM scenarios exist
    - $Wl\nu$ coupling, 4-fermion operators
  - sensitive to high (PeV) mass scales
    - pseudoscalar, scalar

# Basics of $R_{e/\mu} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}$ measurement

Pion stops in the target

- $\pi^+ \to \mu^+ \nu(\gamma)$ **99.99%**
  $\mu^+ \to e^+ \nu\bar{\nu}(\gamma)$ **100 %**
- $E_e$ = 0.5-52.8 MeV
- $\pi^+ \to e^+ \nu(\gamma)$ $\mathbf{1.23 \times 10^{-4}}$
- $E_e$ = 69.8 MeV

LYSO Calorimeter



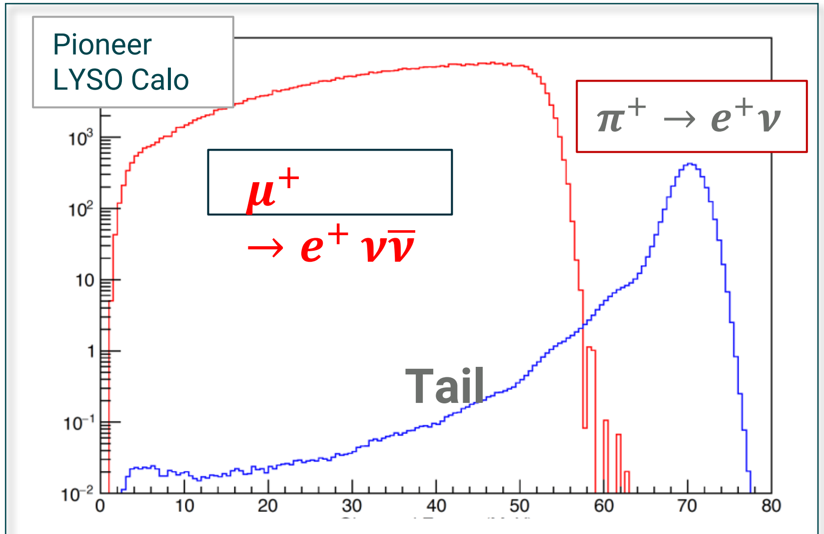

| | m(MeV) | $\tau$(ns) |
|---|---|---|
| $\pi$ | 139.6 | 26.03 |
| $\mu$ | 105.7 | 2197 |

Even with state-of-the-art CALO

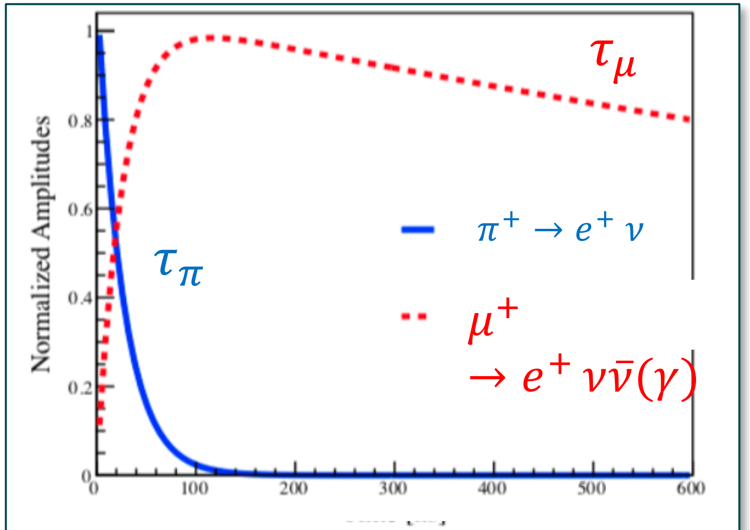
significant rad. tail for $\pi^+ \to e^+ \nu$

time spectra remain powerful for separation of event types

information beyond CALO critical to suppress background @ $10^{-4}$ precision




e+ energy deposition in CALO




Time spectrum

Peter

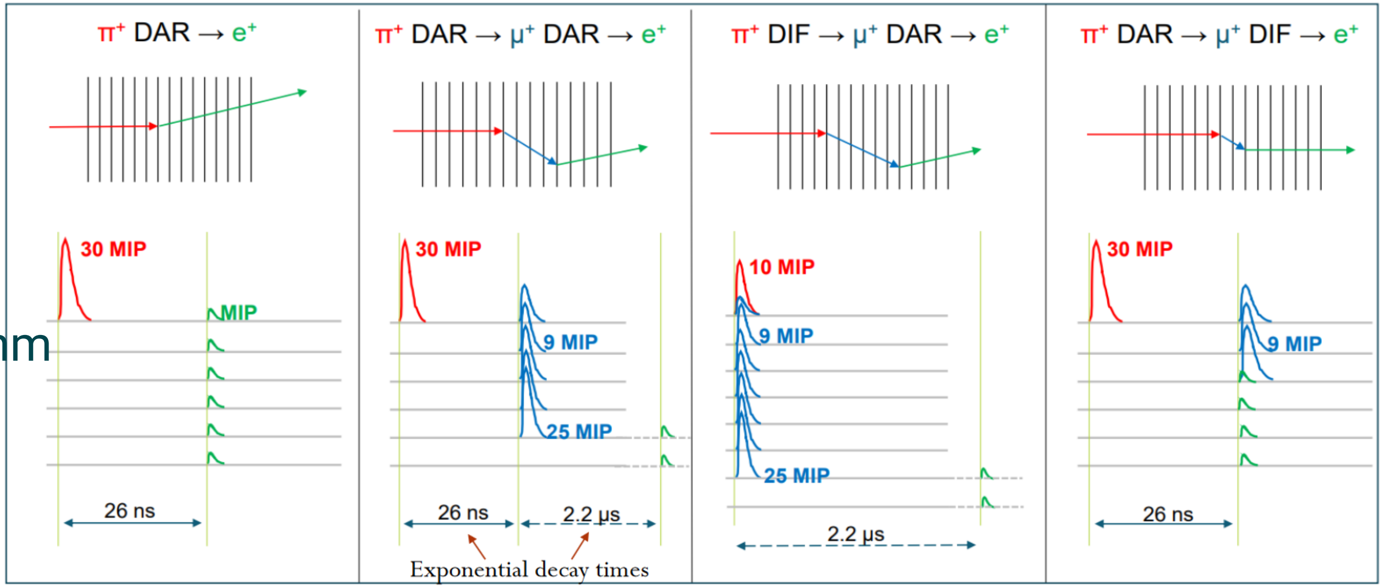
Spectra simplified, signals only, no background

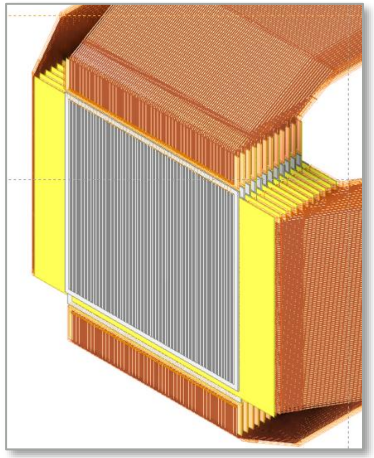
# Active Target ATAR 5-D tracker is key to separate events

Notation

- DAR decay at rest
- DIF decay in flight

$R_\pi \sim 4$ mm, $R_\mu \sim 0.8$ mm



Early PIONEER design of Si detector stack

- Specs
  - dimensions
    20 x 20 x 5.76 mm
    48 sensor layers with
    120 μm thickness, 200 μm strips
  - t: Δt ~ 200 ps, pulse pair 2 ns
  - E: few 100 dyamic range, $\sigma_E < 10$ %
  - stack: fully active, "no: dead material

5-D tracker can provide
rich information **(x, y, z, t, E)**

Baseline Technology
Low Gain Avalanche Diodes LGADs

# An Attempt of a Summary

Picosecond timing is at the front and center of all future HEP experiments and upgrades

- “plain” silicon sensors can reach 20ps timing resolution if the right (power hungry) preamplifier is used
- Internal avalanche amplification improves the SNR considerably, improving achievable time resolution
    - AC-LGADs are the best current candidate for true 4D tracking detectors for future experiments

- Future experiments of all sizes are already planning for AC-LGAD based detectors

- The future is here.