Performance Evaluation of the Timing Resolution of an AC-LGADs Bonded to a Si-Ge BJT ASICs

Issei Horikoshi[A], Yua Murayama[A], Koji Nakamura[B], Koji Sato[A], Lorenzo Paolozzi[C], Carlo Fenoglio[C], Mateus Vicente Barreto Pinto[C]

University of Tsukuba[A], KEK[B], University of Geneva[C]

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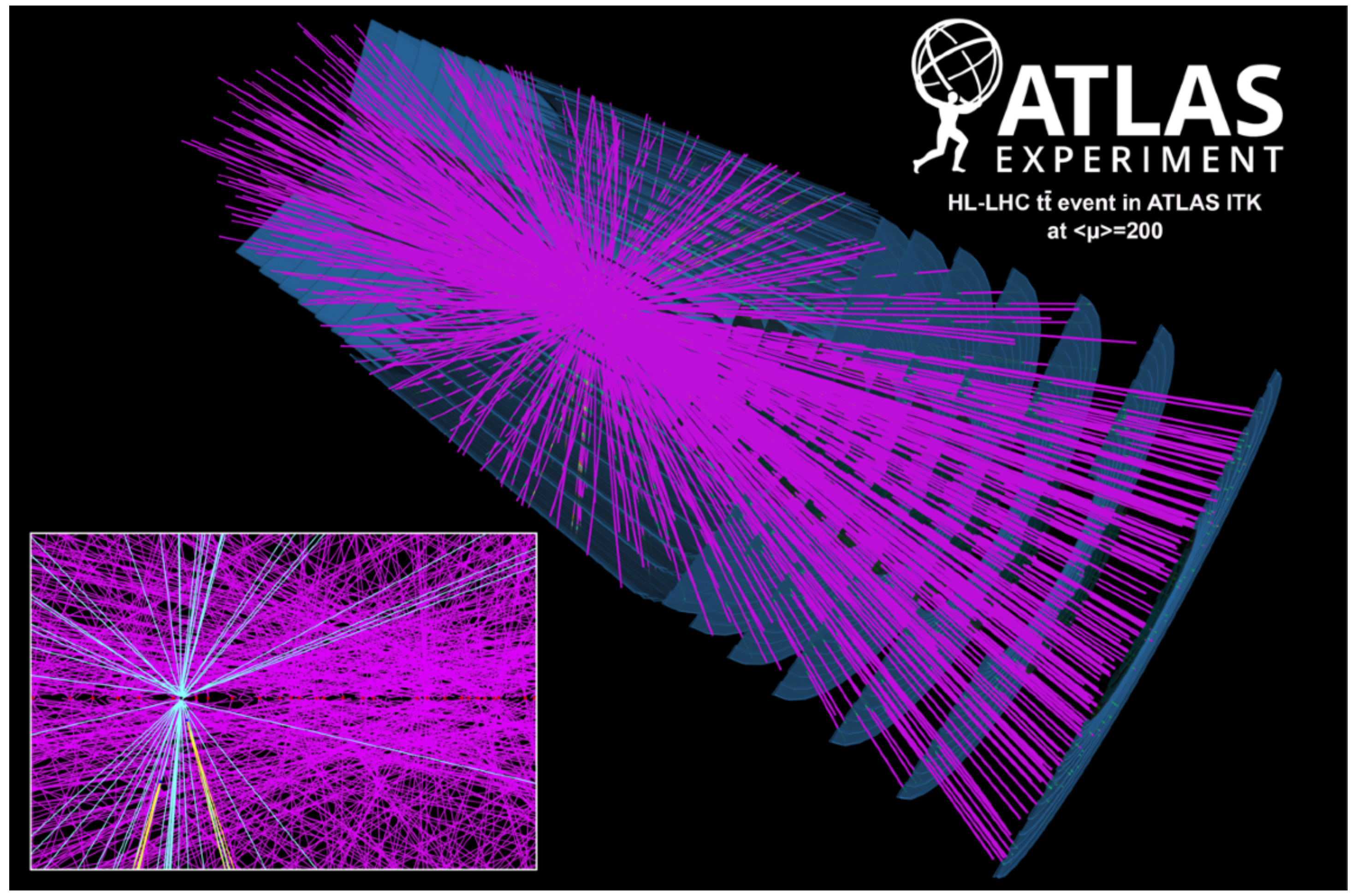
Motivation

Future Collider Experiment

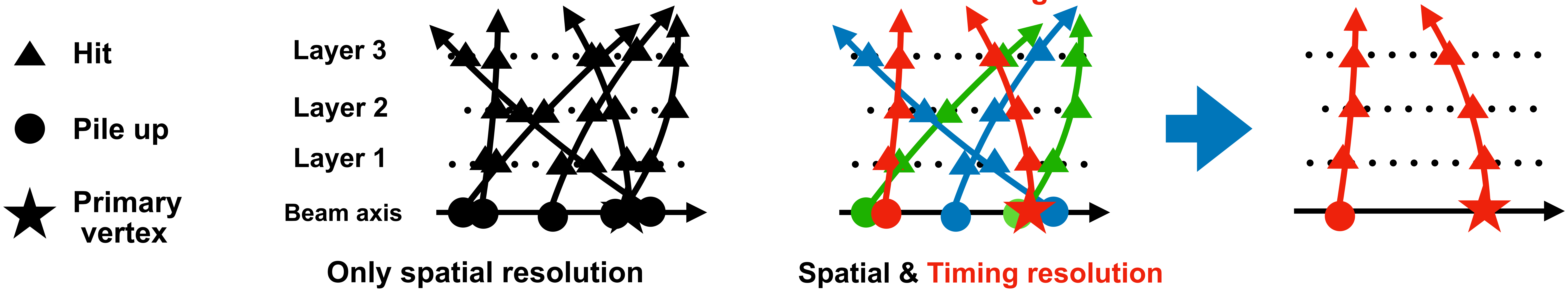
- The number of particles impacting per bunch crossing will increase due to the high luminosity collider experiment.
- **4D tracking** by detectors with both spatial and timing resolution will provide reliable track reconstruction.



↑ HL-LHC pile up simulation
[1] Exploring the scientific potential of the ATLAS experiment at the High-Luminosity LHC

Requirement for timing tracker at HL-LHC

- **~30 ps** timing resolution & **O(10 μm)** spatial resolution.

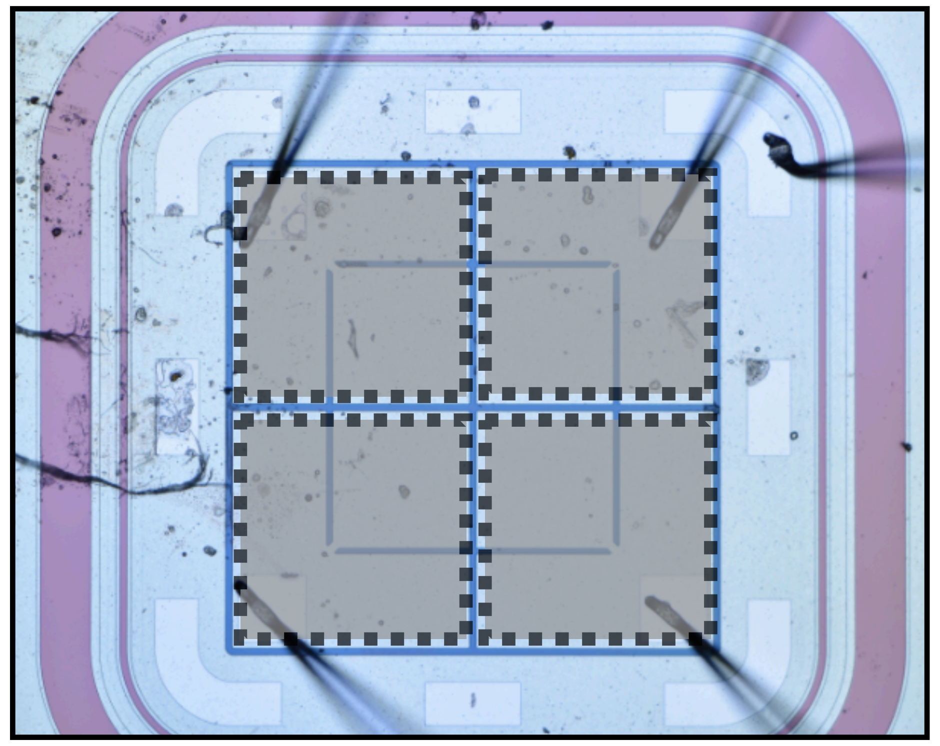


LGAD(Low-Gain Avalanche Diode)

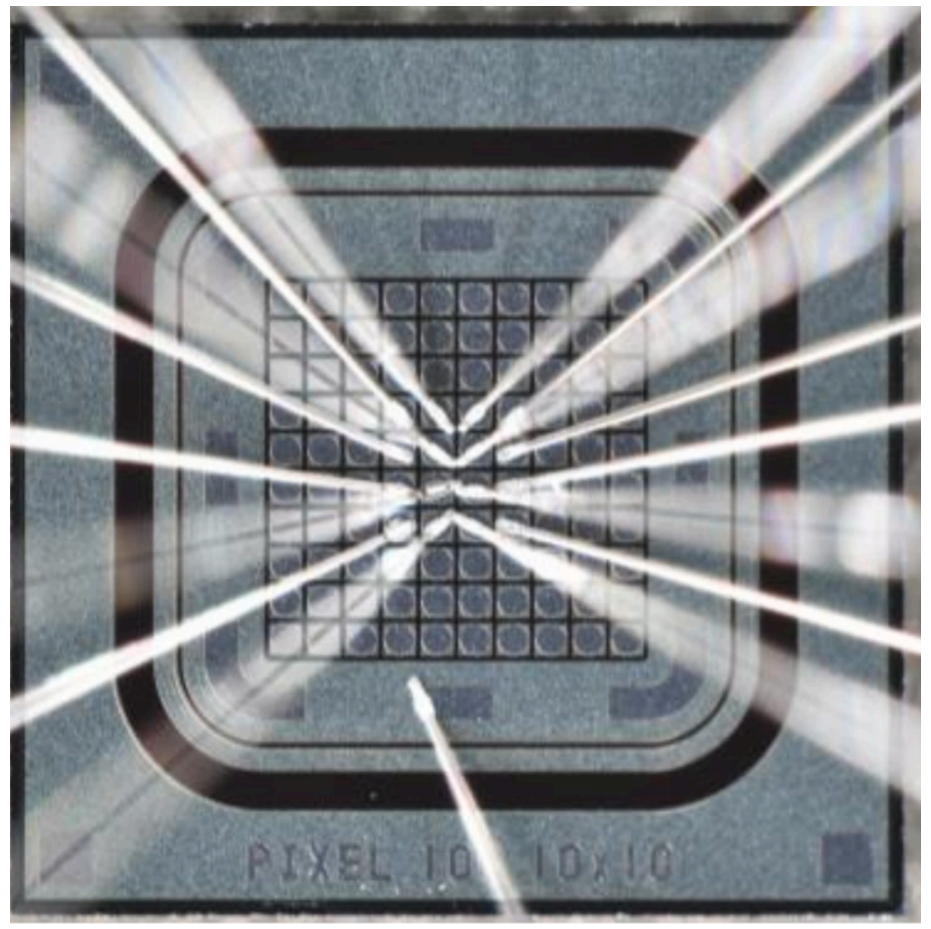
- High electric field are created by implanting the p⁺ layer (gain layer) and can cause avalanche multiplication.

AC-LGADpix

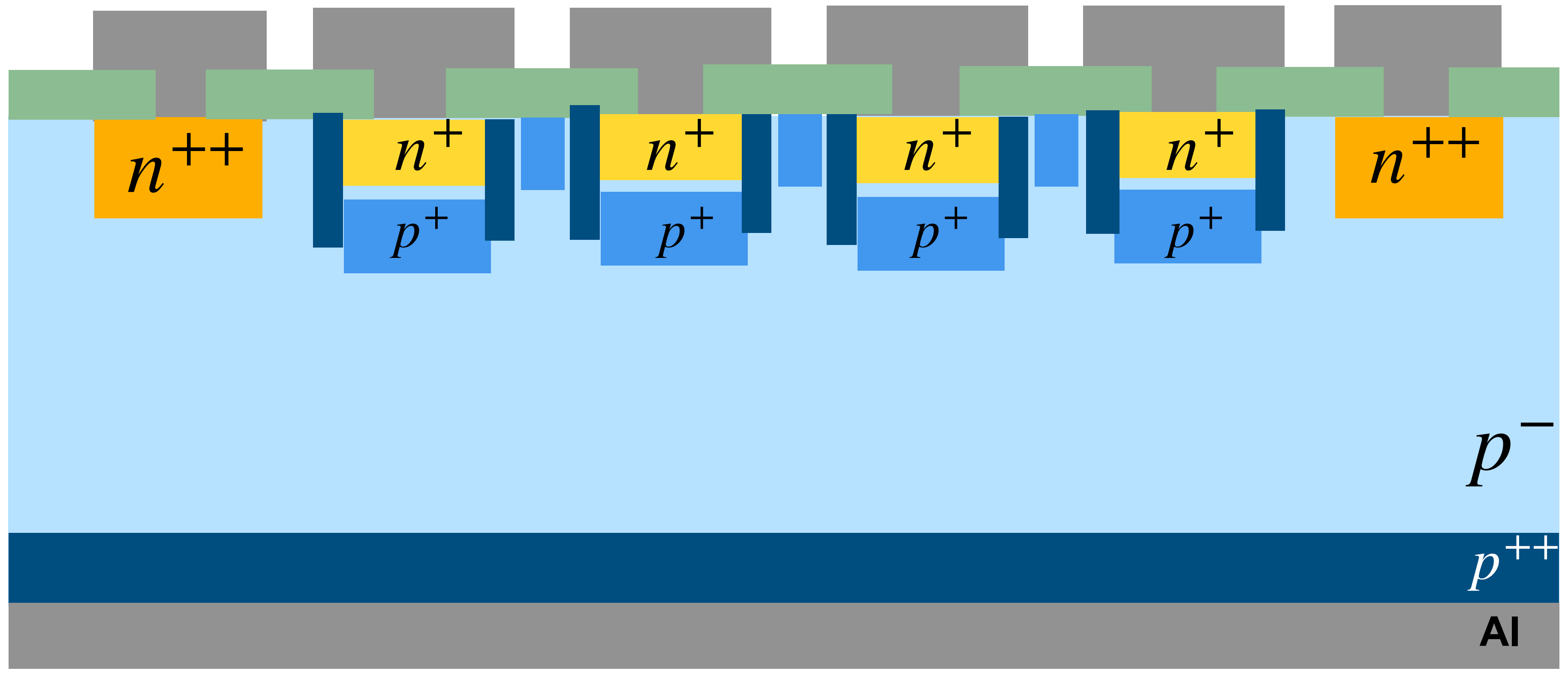
- AC-LGAD is AC coupled LGAD by an oxide layer.
- **AC-LGADpix** developed with (HPK) Hamamatsu Photonics K.K. have a excellent timing resolution as well as a **100µm×100µm pitch** pixelated electrodes.
- AC-LGADpix have **no dead region** by uniformly installing the gain layer.



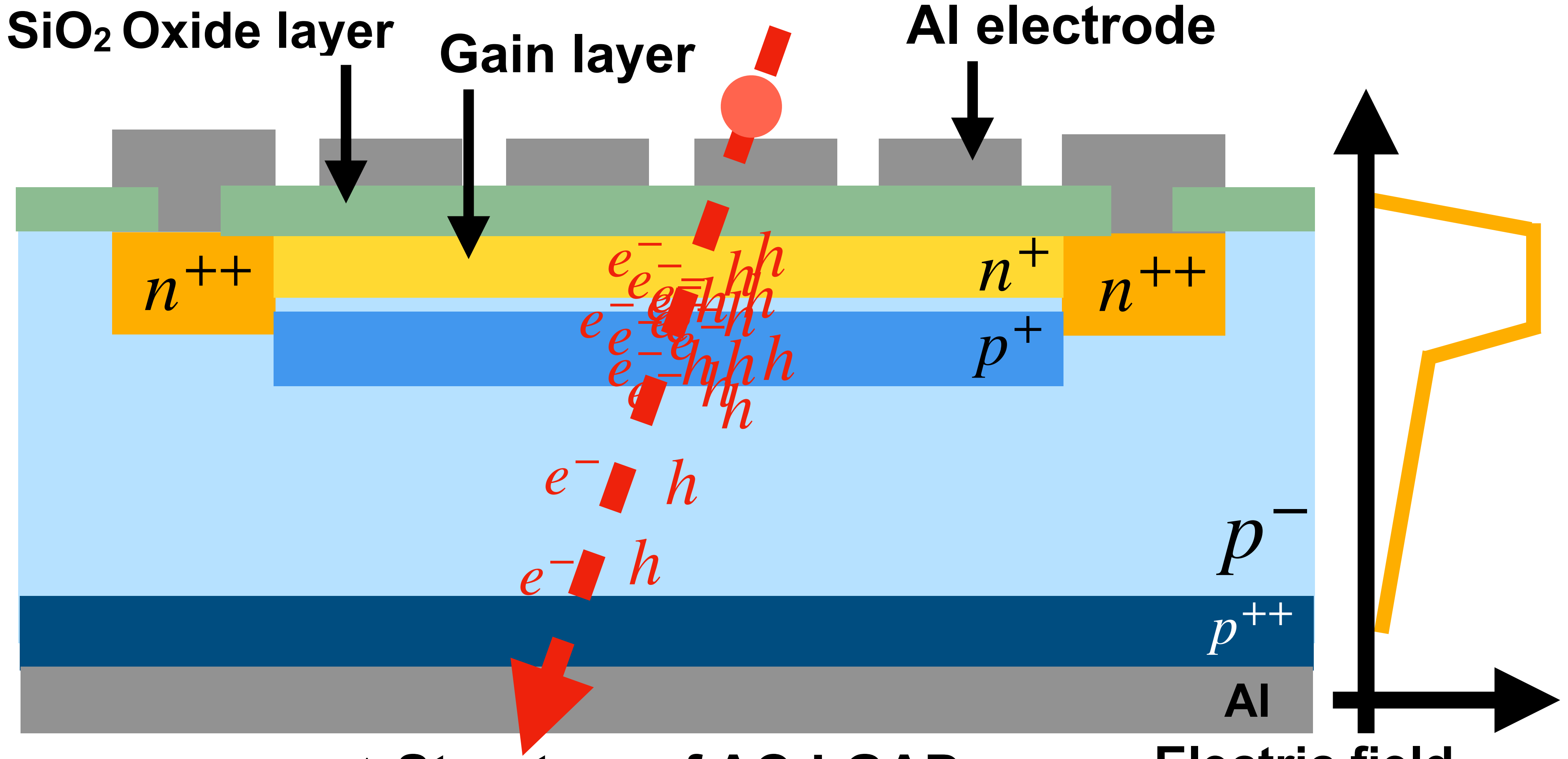
↑ 500µm pitch AC-LGAD



↑ pixel 100µm pitch AC-LGADpix



↑ Structure of Normal-LGAD



↑ Structure of AC-LGAD

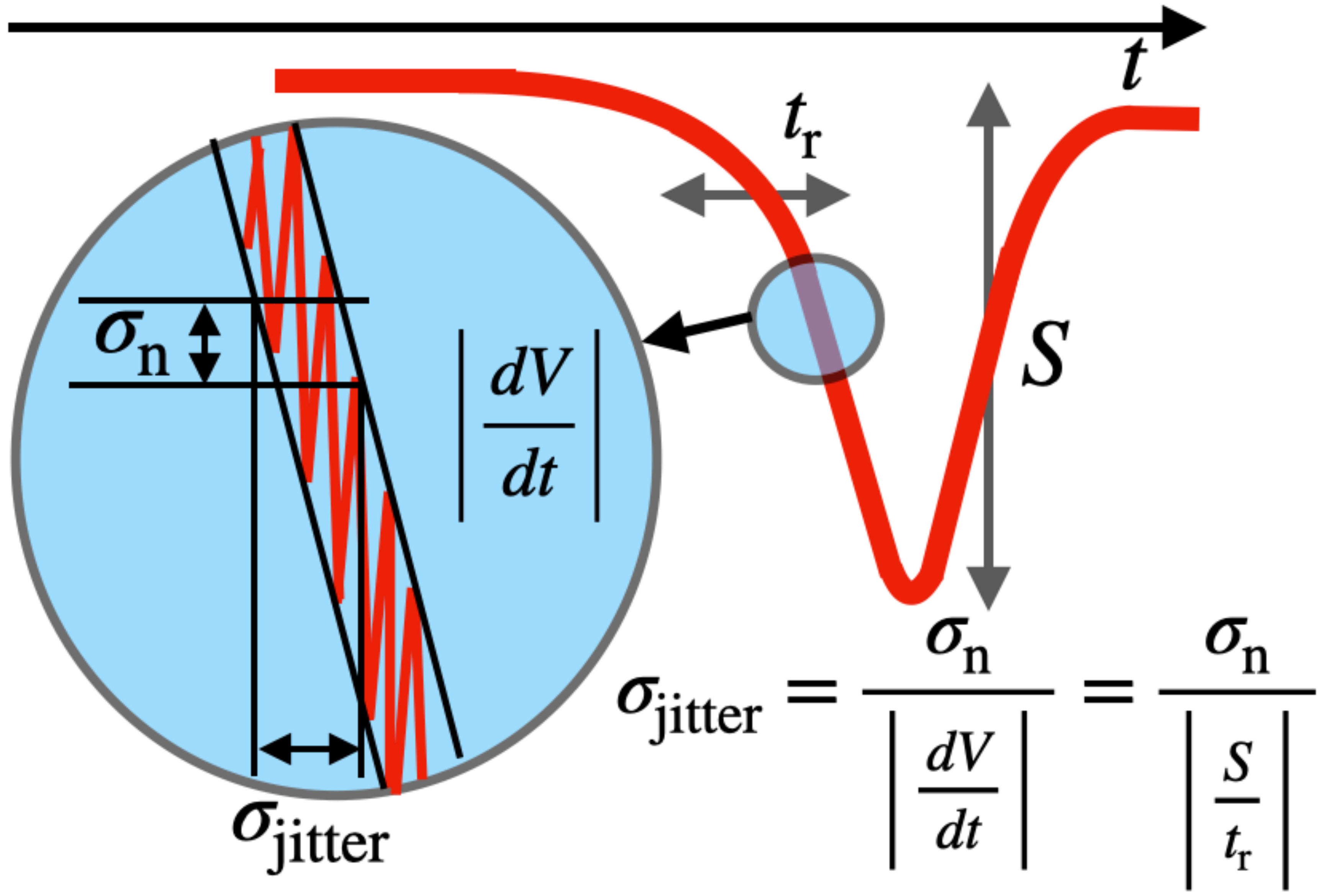
Timing resolution of AC-LGAD

Timing resolution of AC-LGADs is affected by 3 factors: jitter, time walk and charge collection noise.

$$\sigma_t^2 = \sigma_j^2 + \sigma_{tw}^2 + \sigma_{CCN}^2$$

Jitter σ_{jitter}

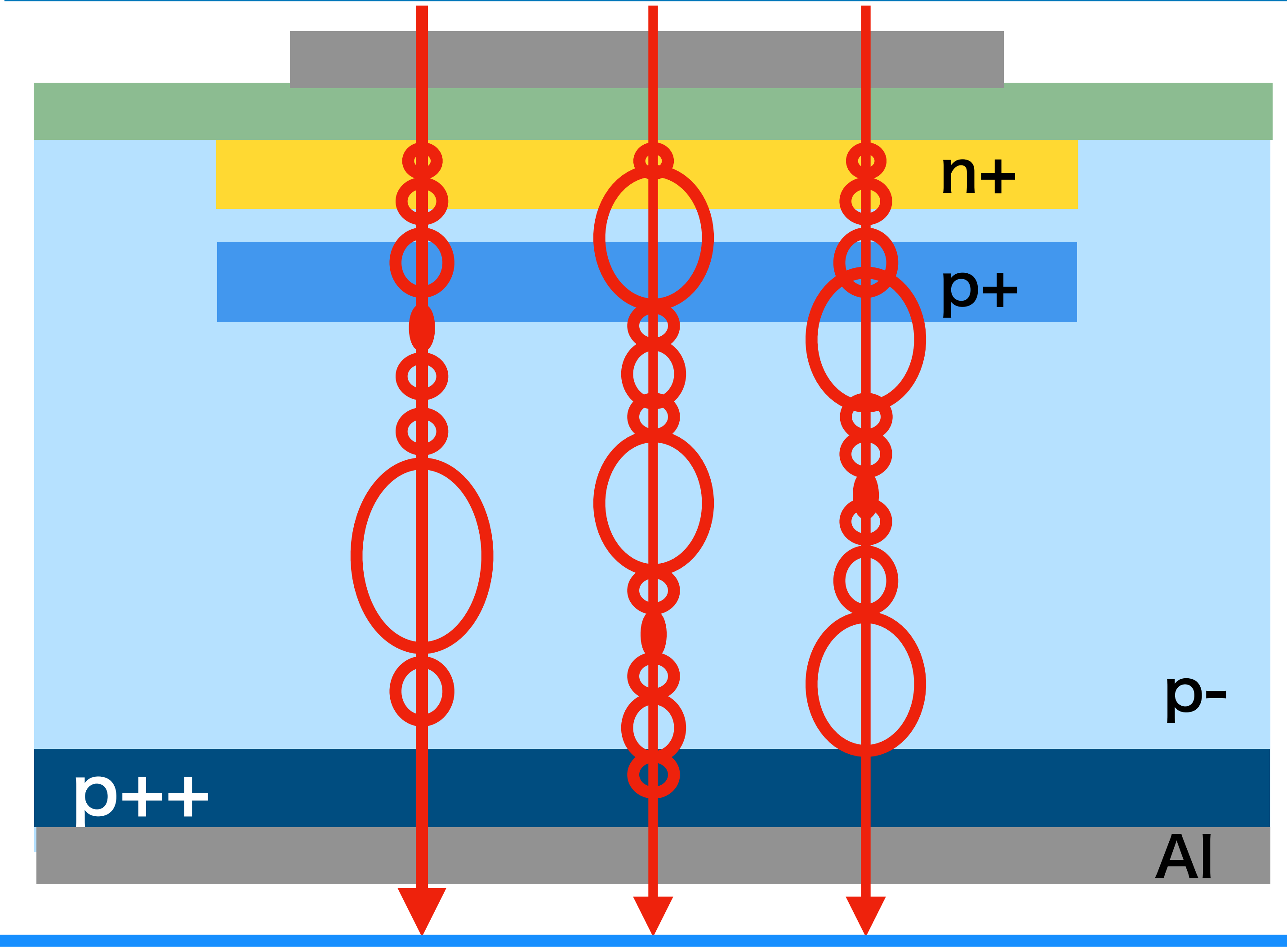
Jitter refers to time fluctuations caused by electronic noise.



Charge Collection Noise

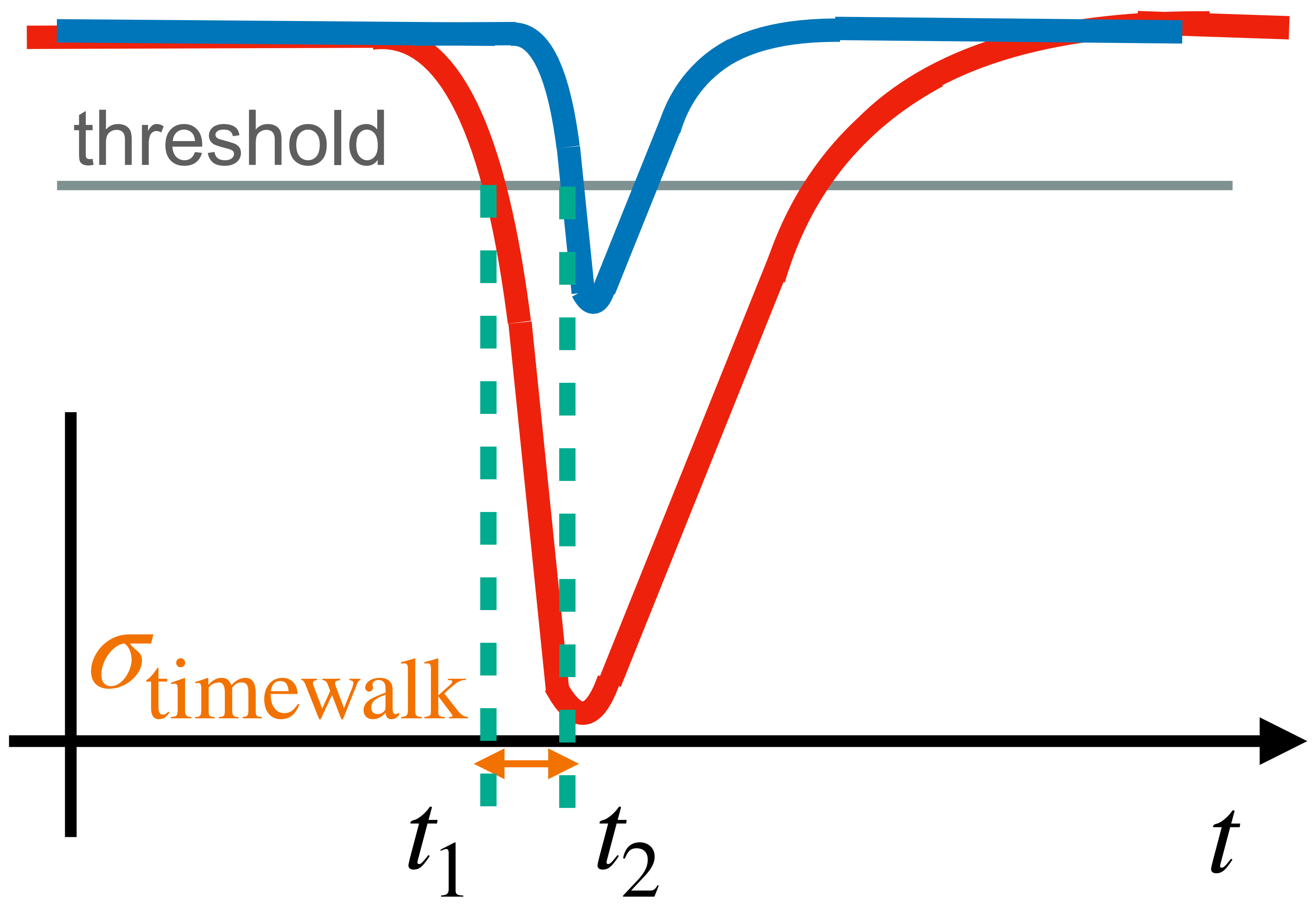
$\sigma_{\mathrm{charge-collection}}$

CCN refers to time fluctuations caused by Non-uniformity energy deposit.



Timewalk $\sigma_{\mathrm{timewalk}}$

Timewalk refers to time fluctuations caused by difference of pulse height.



Timing resolution of AC-LGAD

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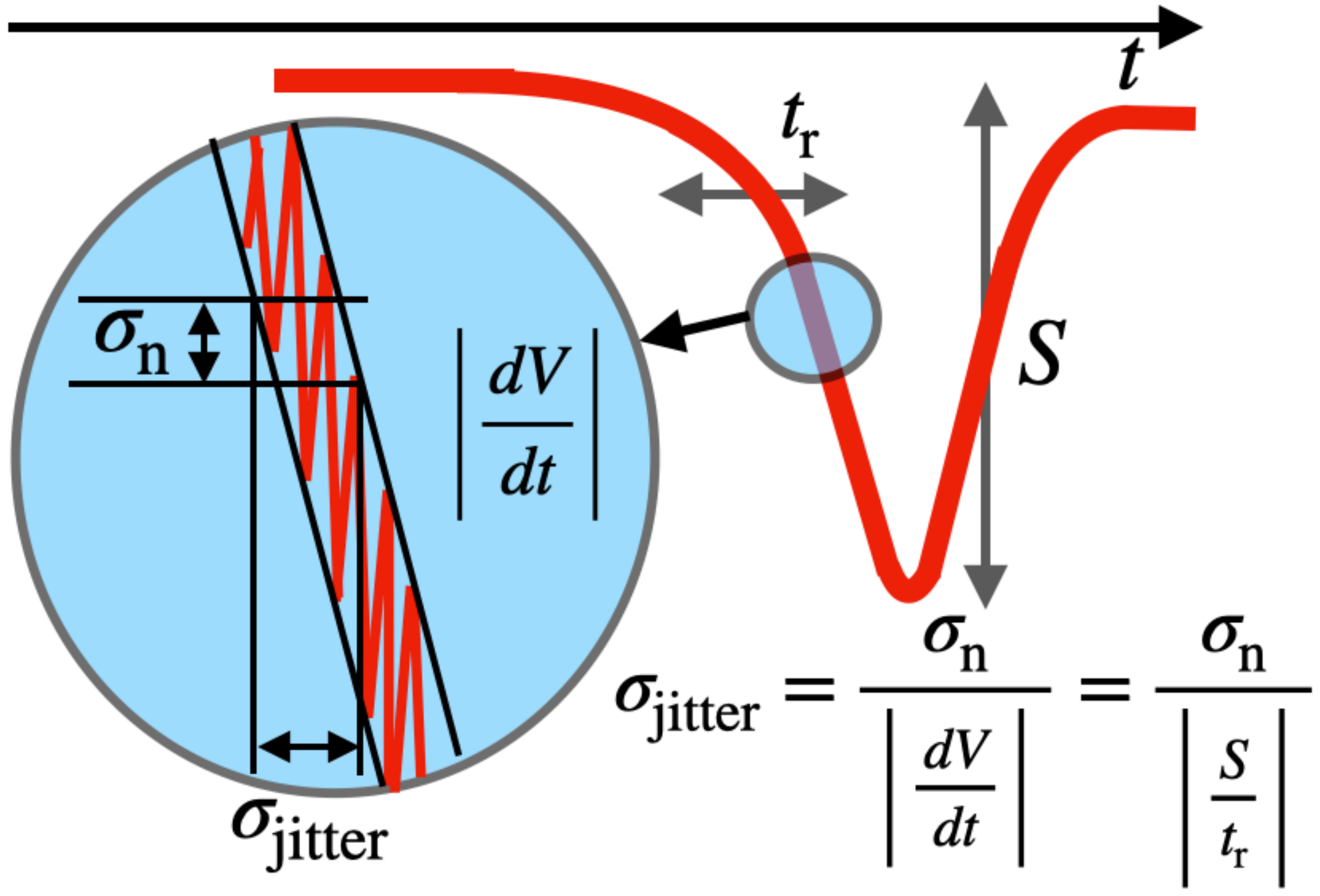

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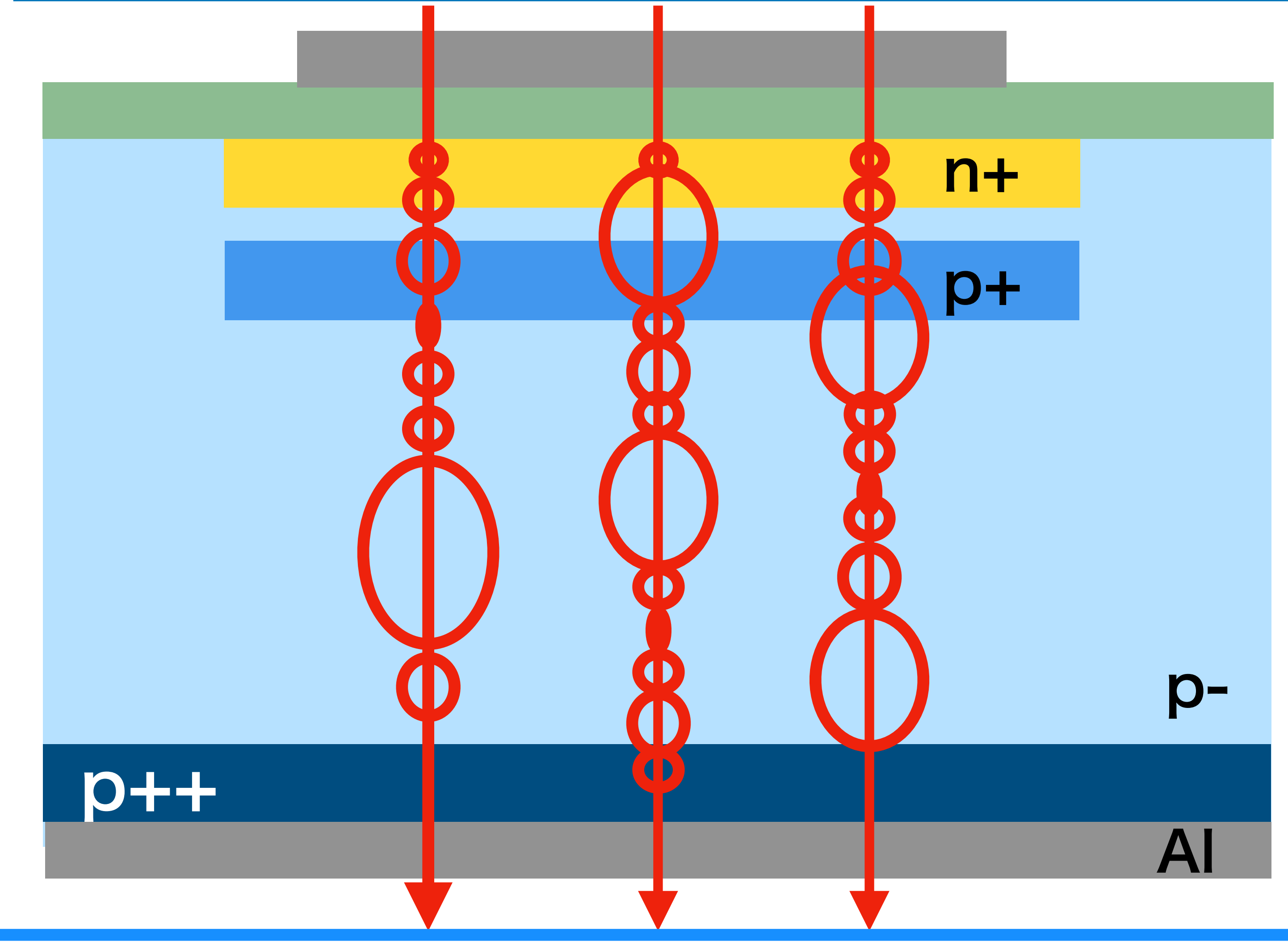

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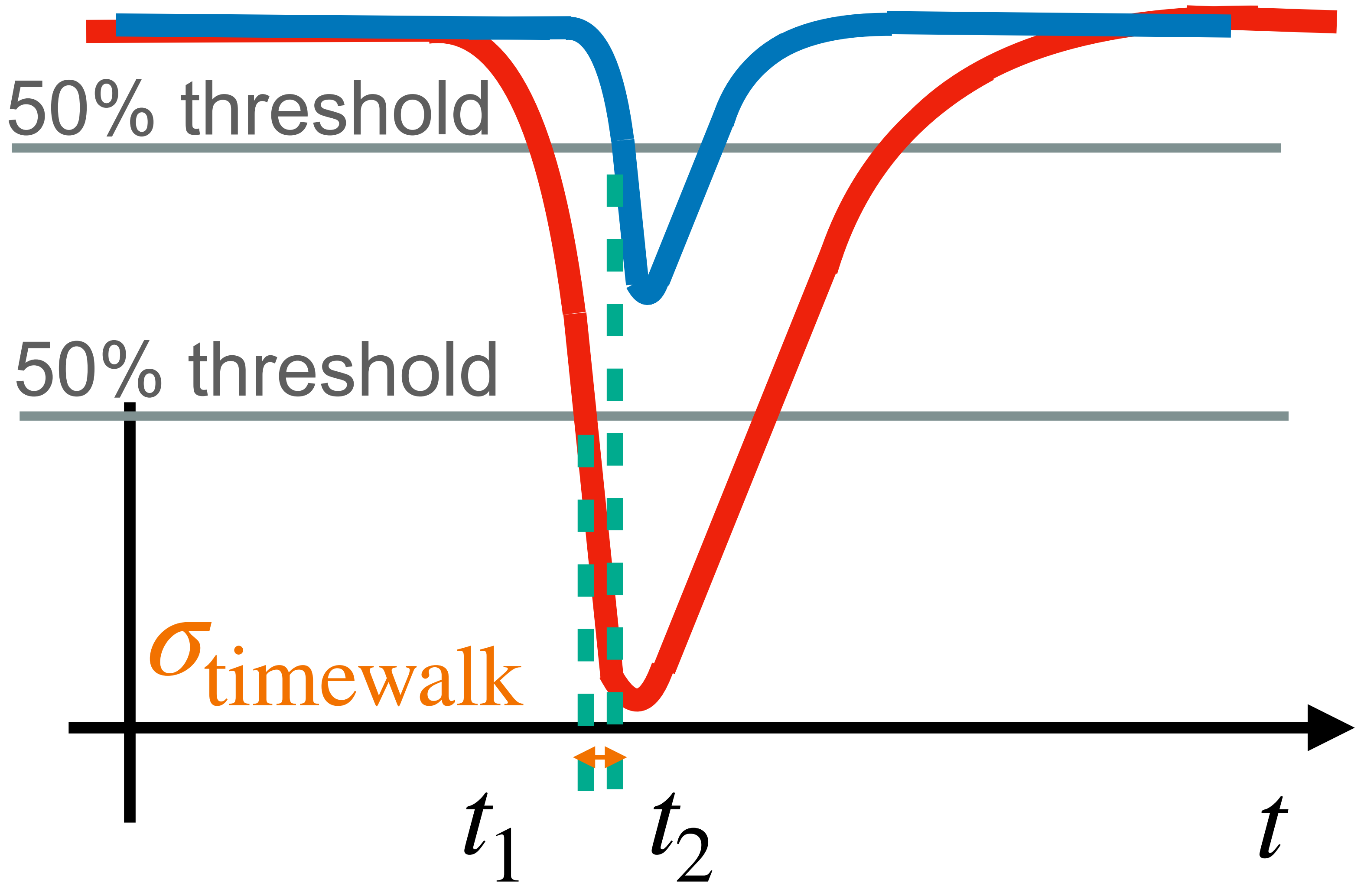
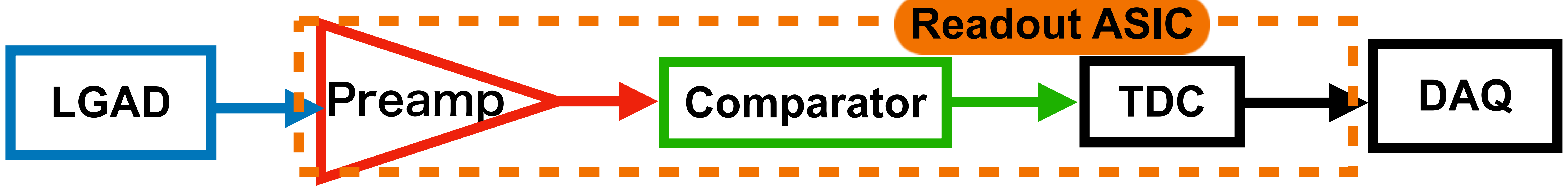
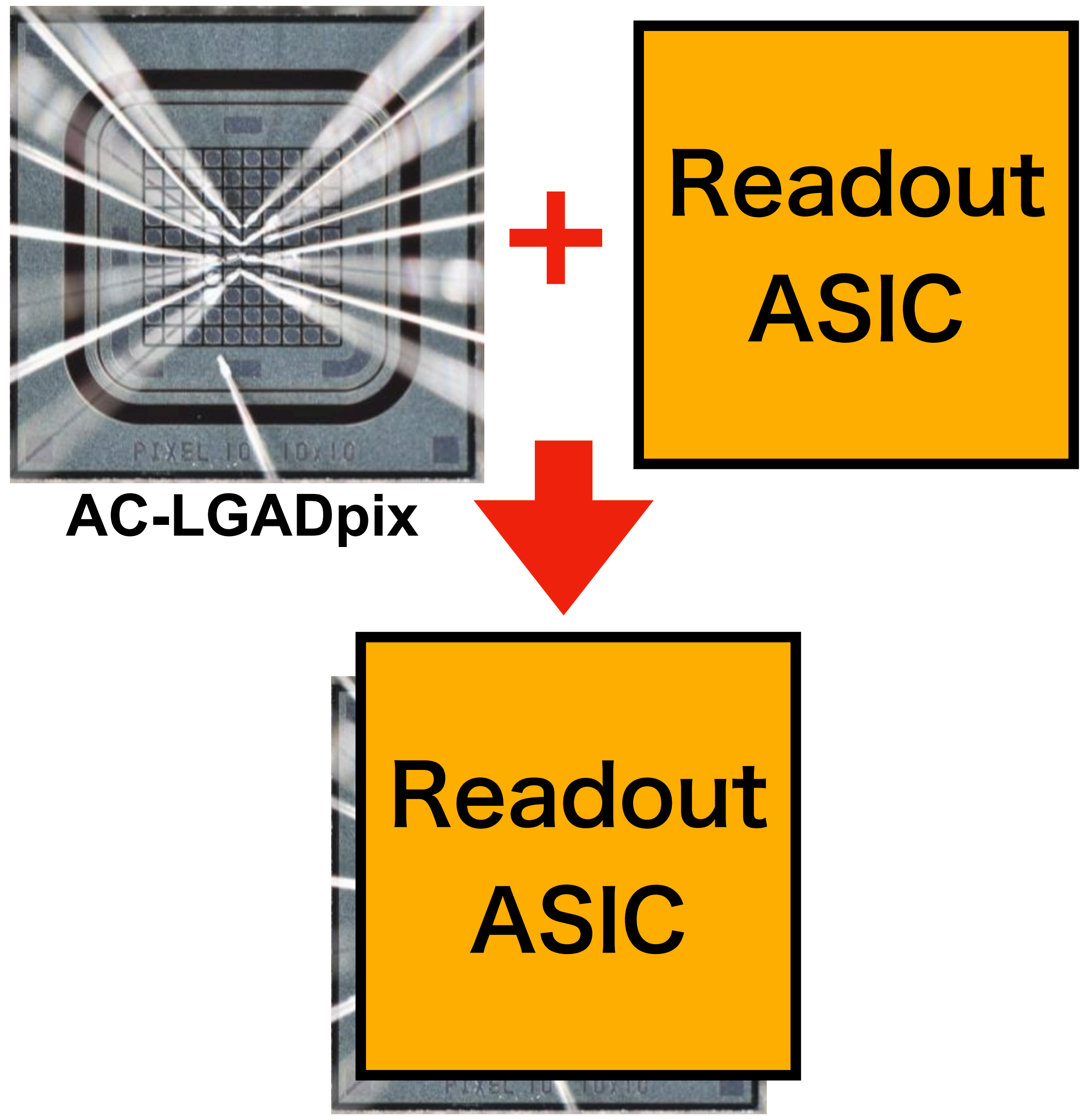


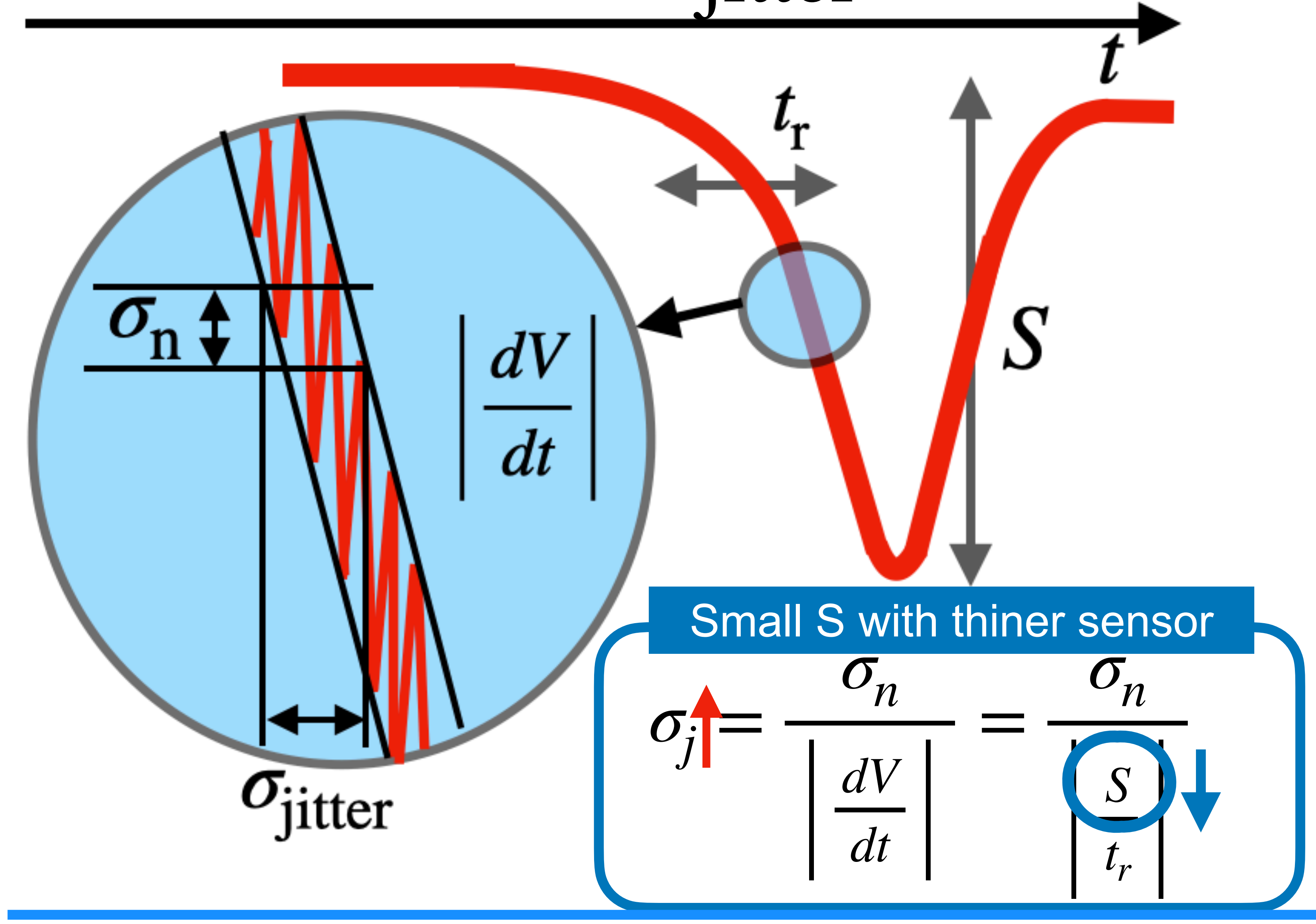
Motivation of ASIC



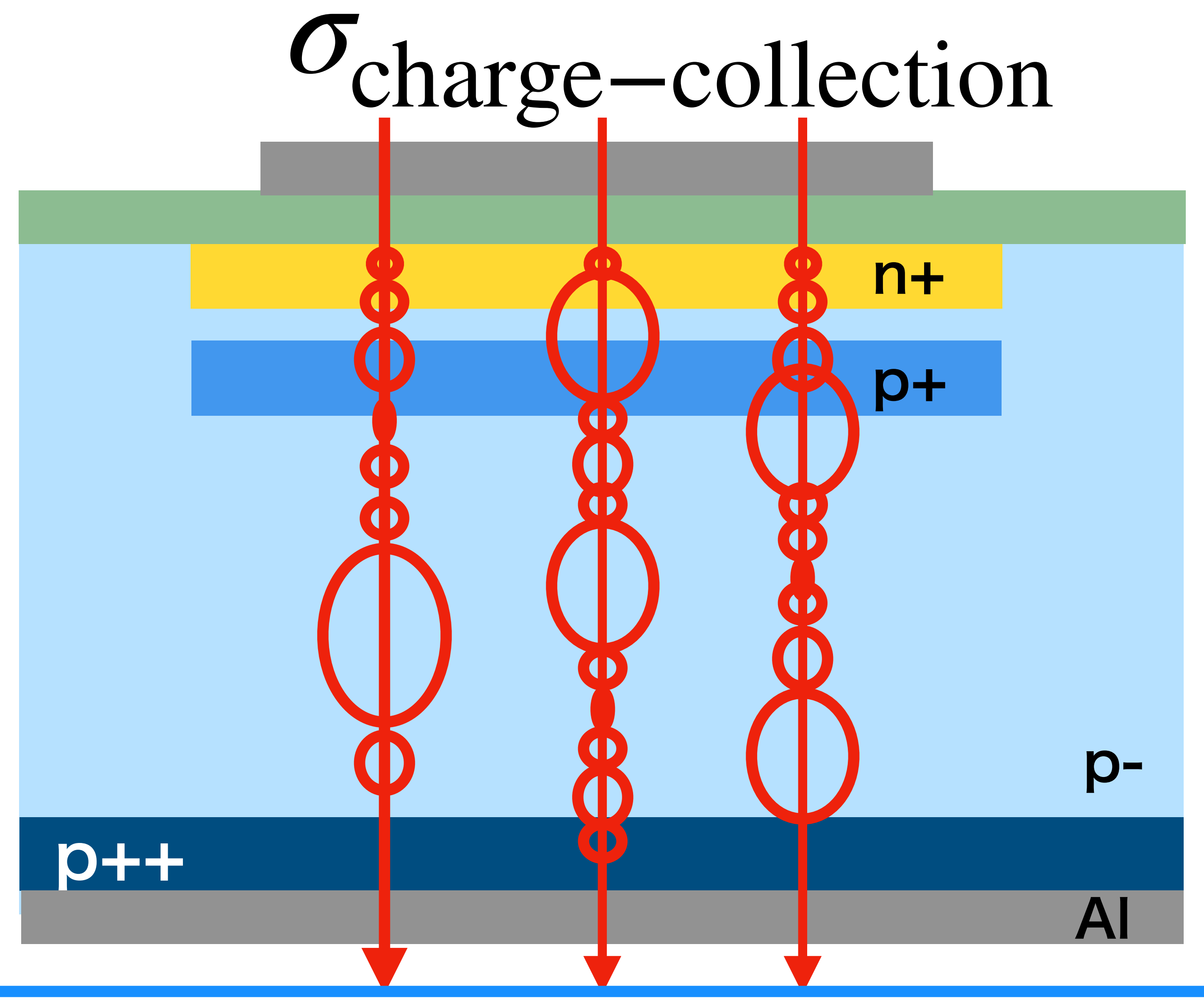
- Jitter and Charge Collection Noise have a trade-off relationship.
- Increased electrode density demands more readout channels.
- Need to develop ASICs :
  → **low electronic noise** (= high signal noise ratio)
  → **low power consumption** (Heat generation must not exceed the cooling system)

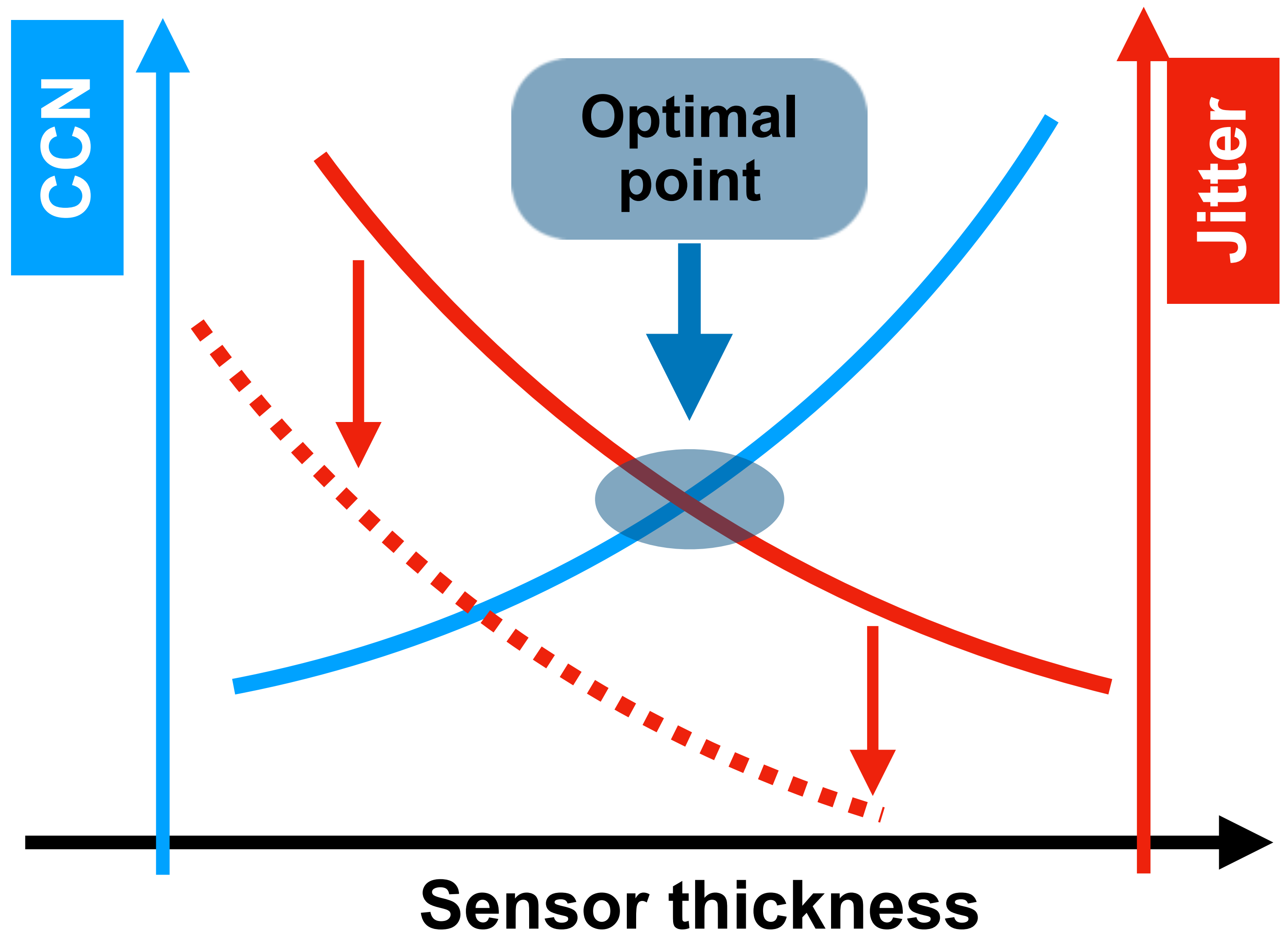


Jitter σ_{jitter}



Charge Collection Noise





Si-Ge BJT ASIC

Features of Si-Ge ASIC

- Si-Ge (Silicon-Germanium) BJT ASIC.
  →Process : IHP 130nm BJT process.
- The preamp is made of HBT : Heterojunction Bipolar Transistor
- The Input electrode is a 10×10 matrix (100×100 μm^2).
  →To readout detector signals, we connected by wire-bonding.
- We evaluated timing resolution by reading out AC-LGAD signal through the three analog outputs.

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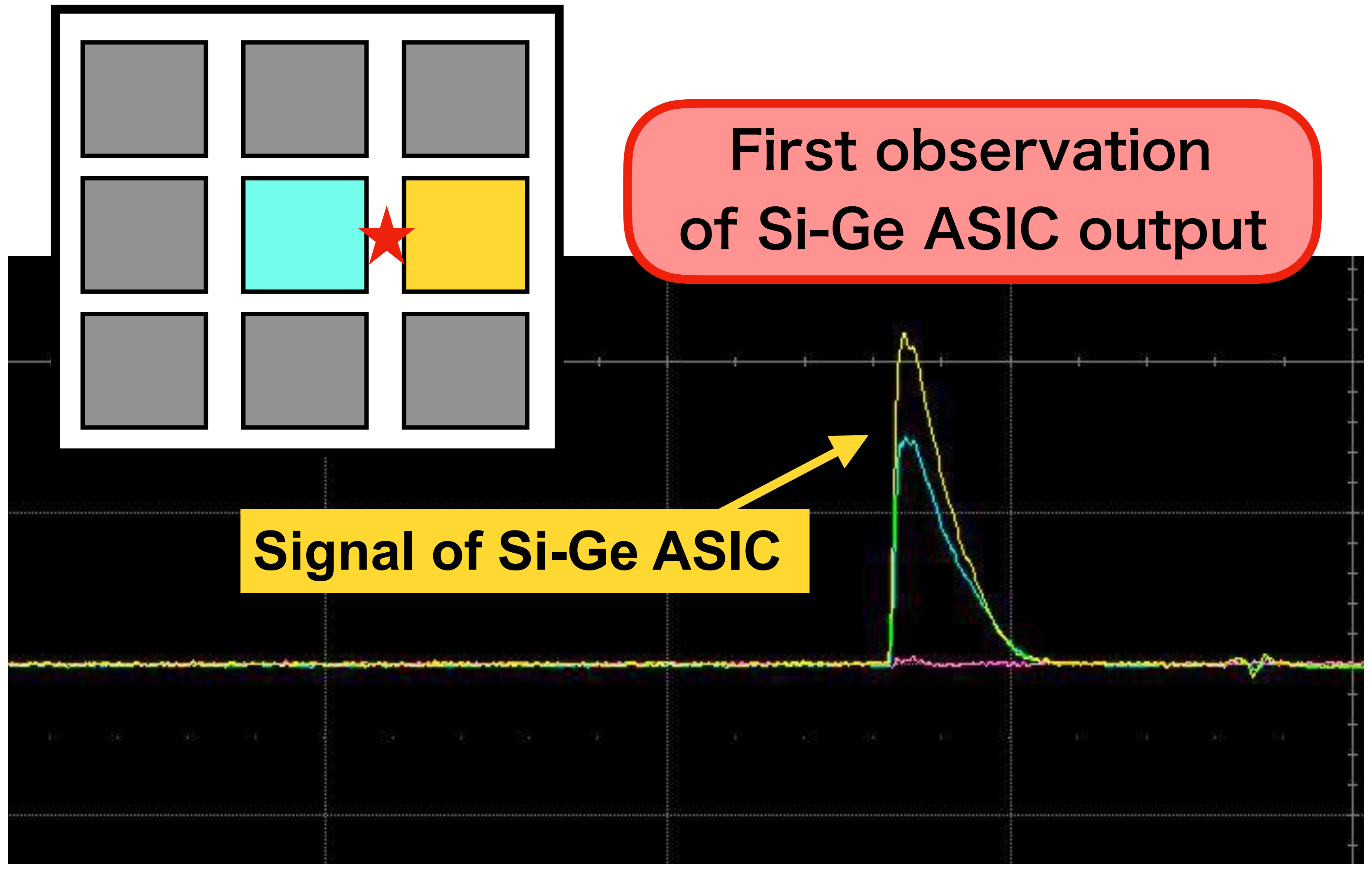
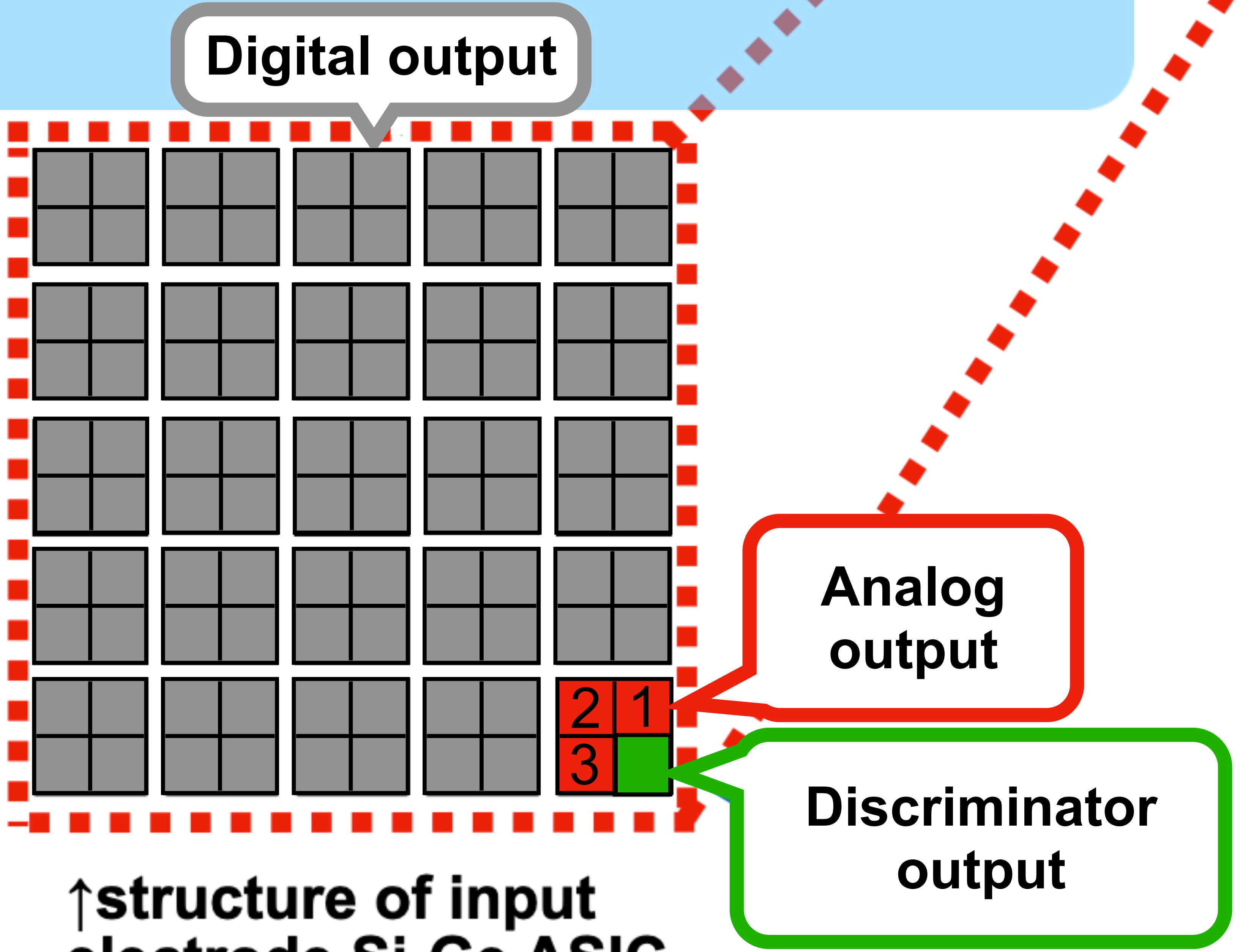
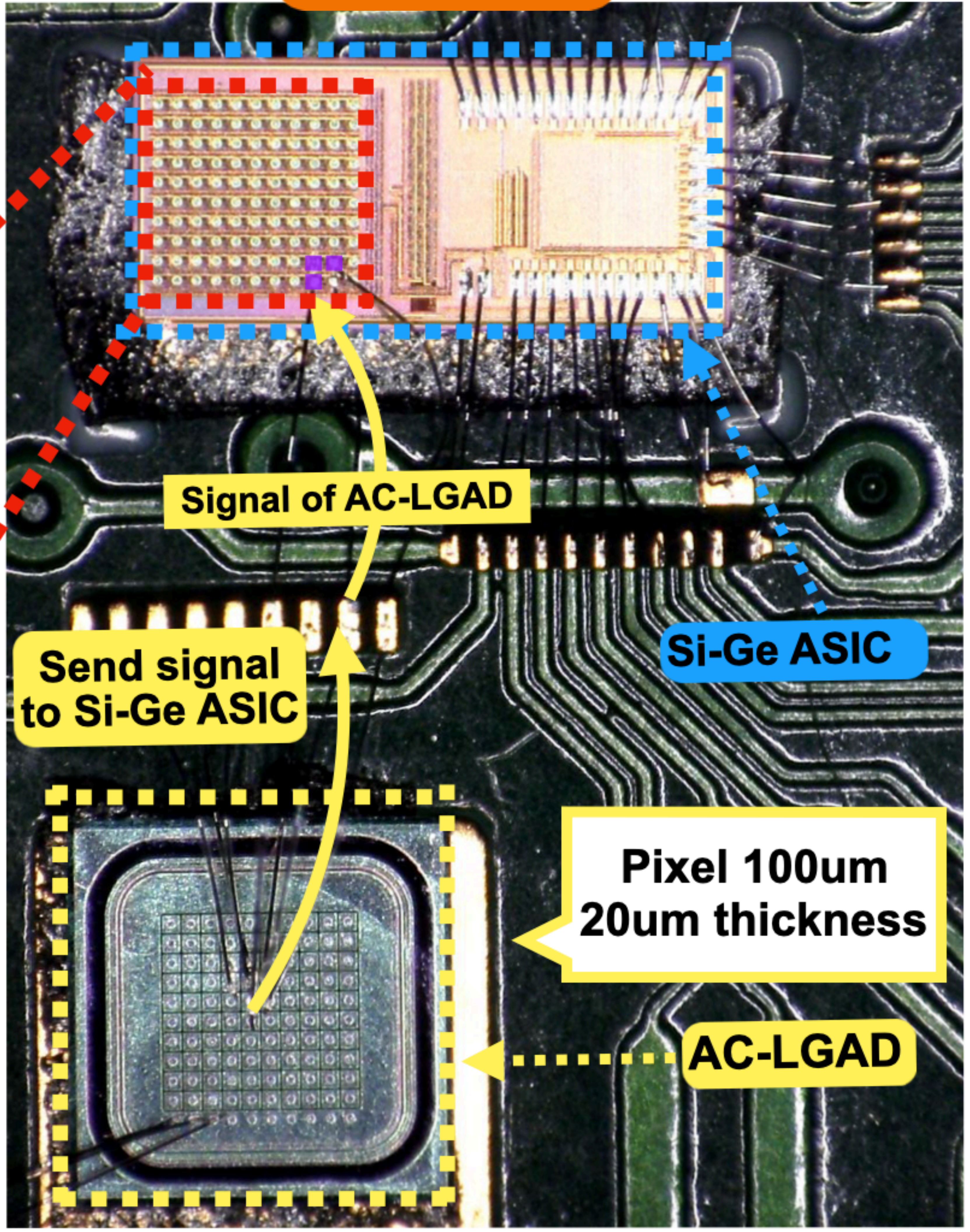


↑The signal of Si-Ge ASIC



↑structure of input electrode Si-Ge ASIC



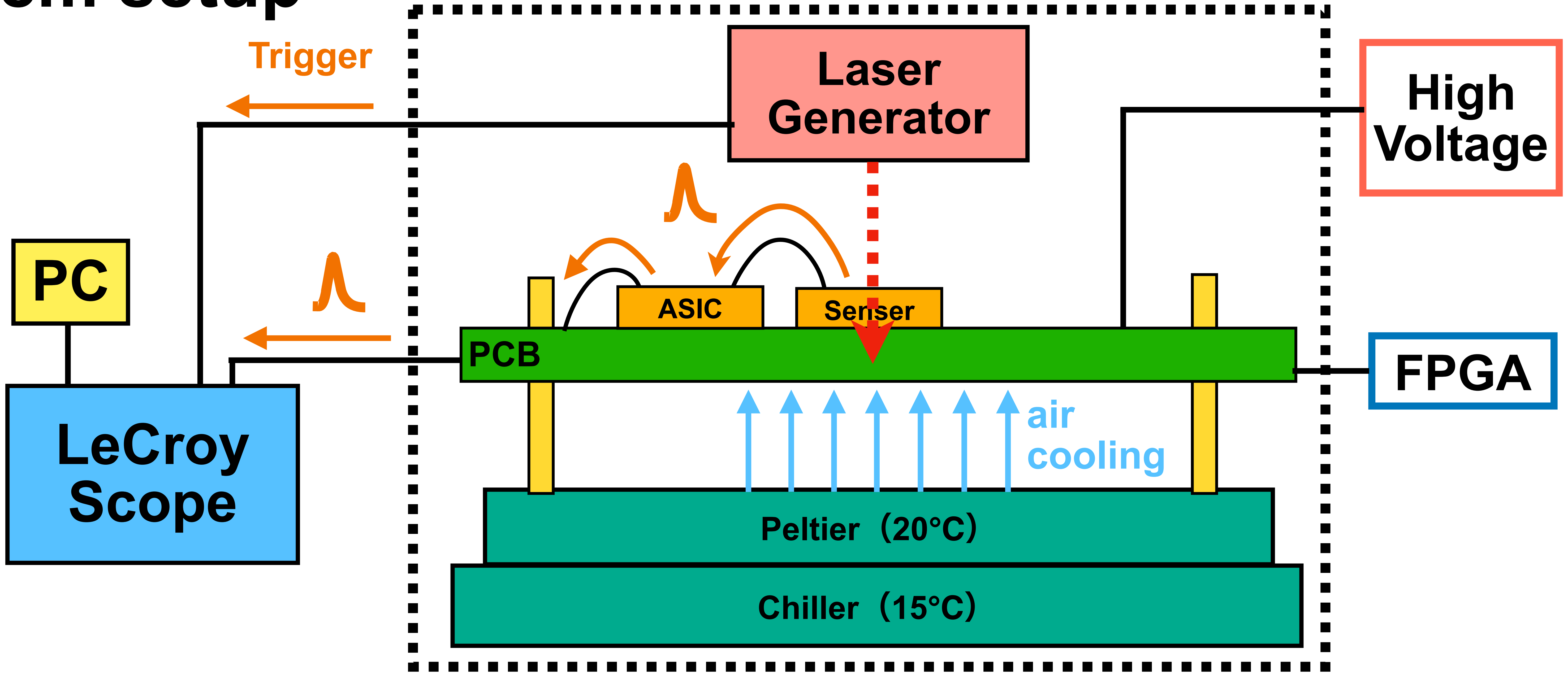
↑Connection of Si-Ge ASIC to AC-LGAD

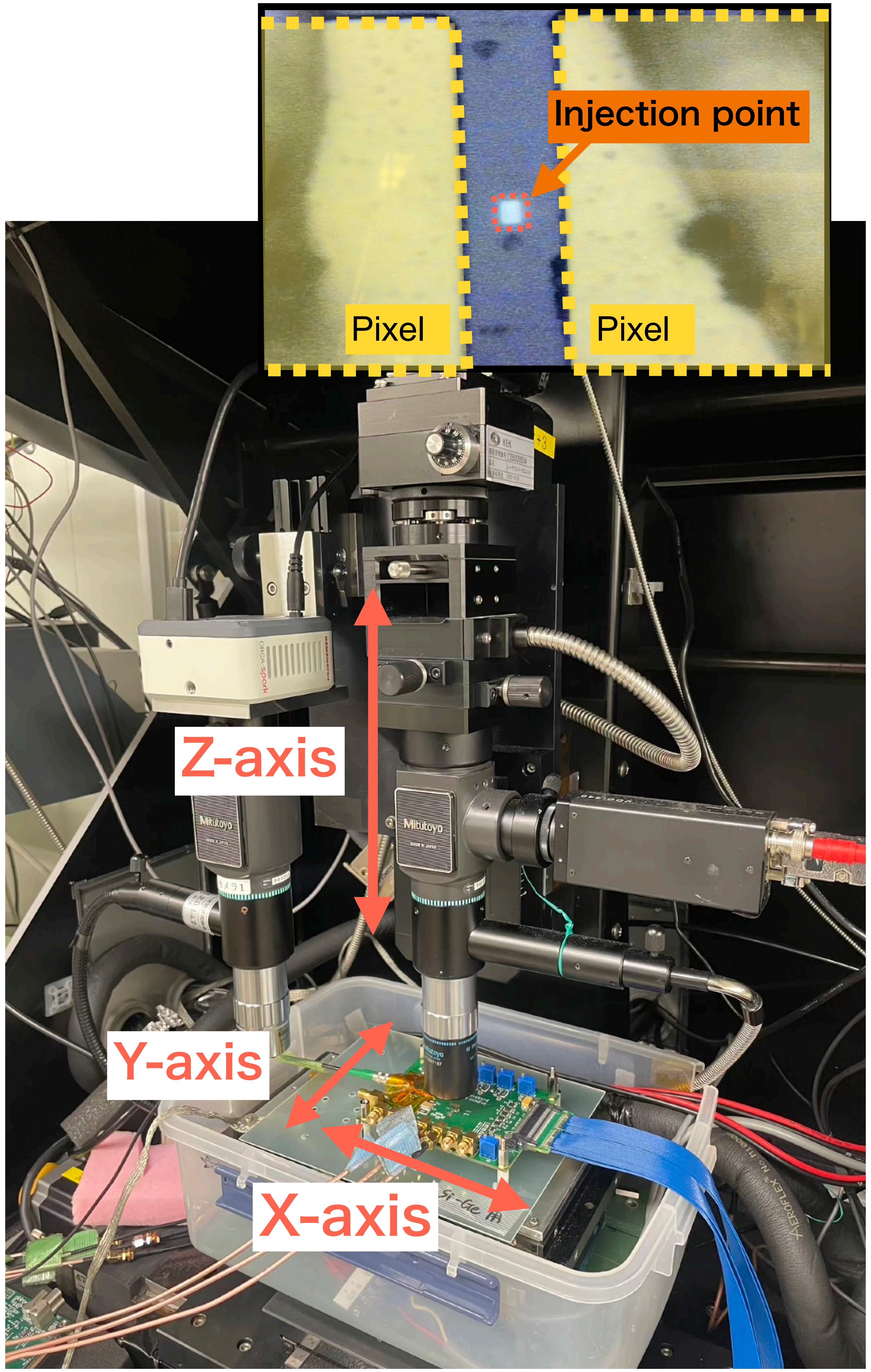
Setup for the laser measurement

Measurement by infrared laser

- Infrared pulse laser ：Wavelength is 1064 nm.
- Laser size can be narrowed **2μm** by this setup.
  →We can inject laser between pixels.
- In this setup, We can evaluate jitter, isolated from charge collection noise.

System setup

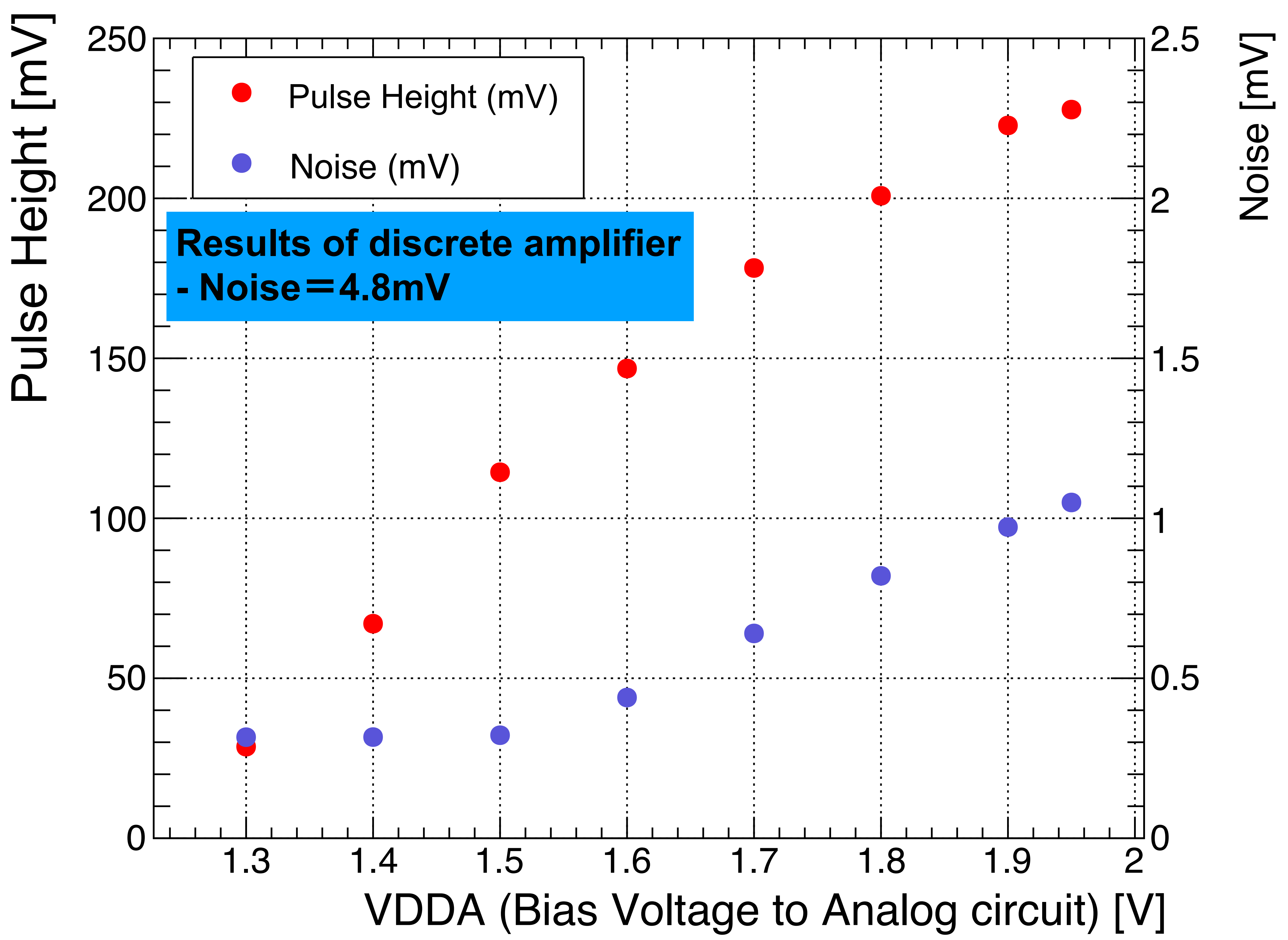


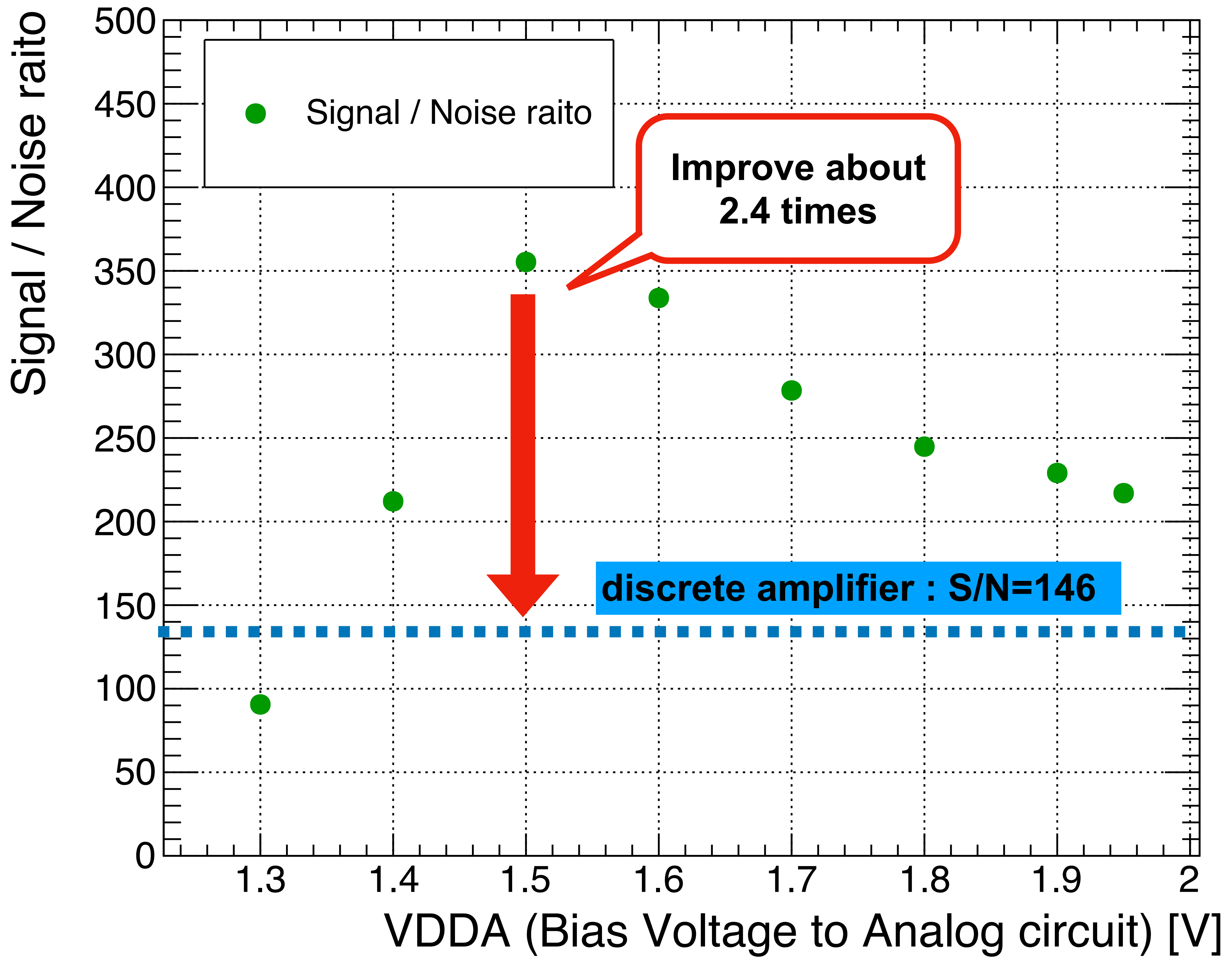


↑ the infrared pulse laser

Result of Laser Measurement

The best V_{DDA} (Bias Voltage to Analog circuit)

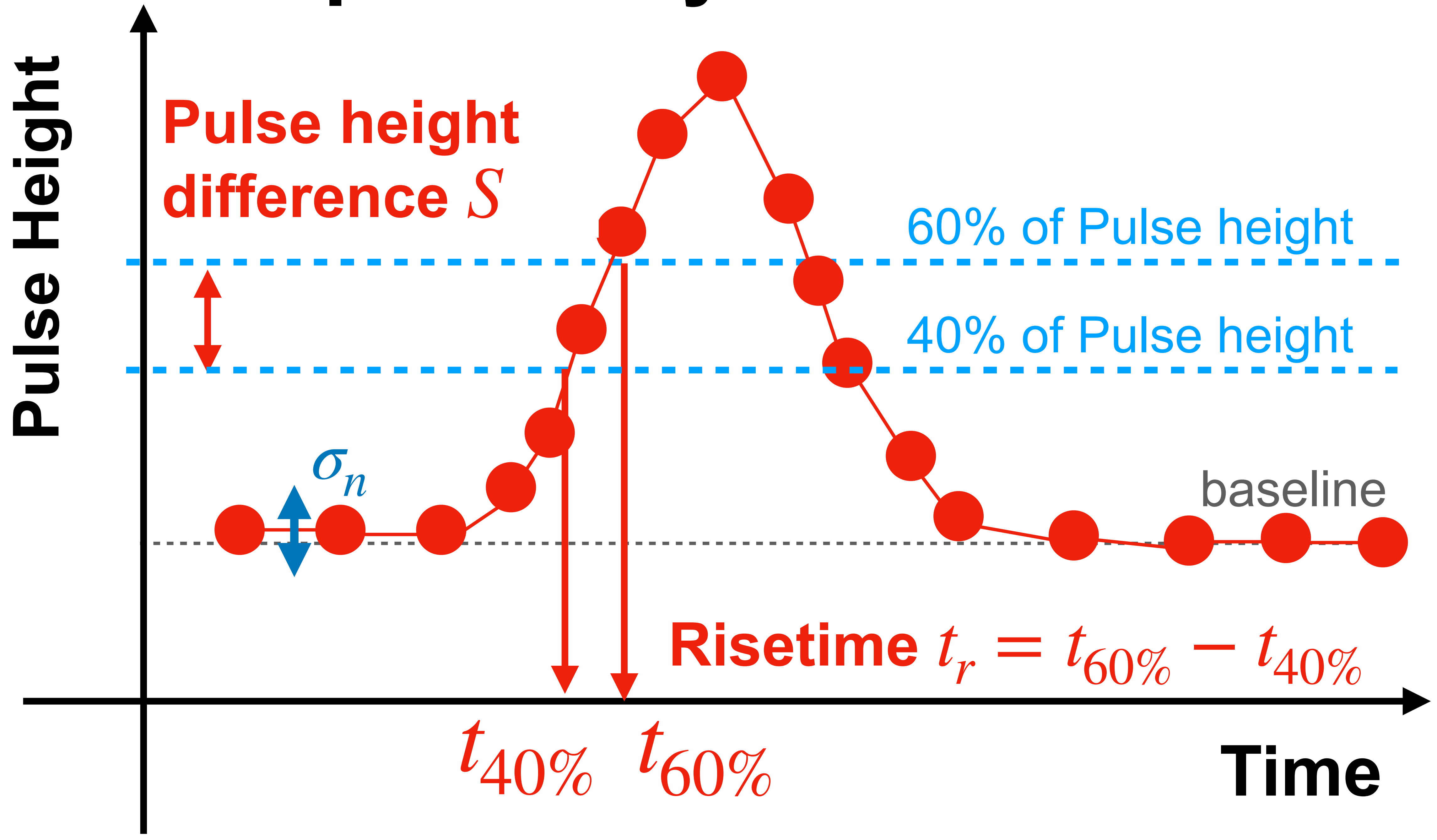


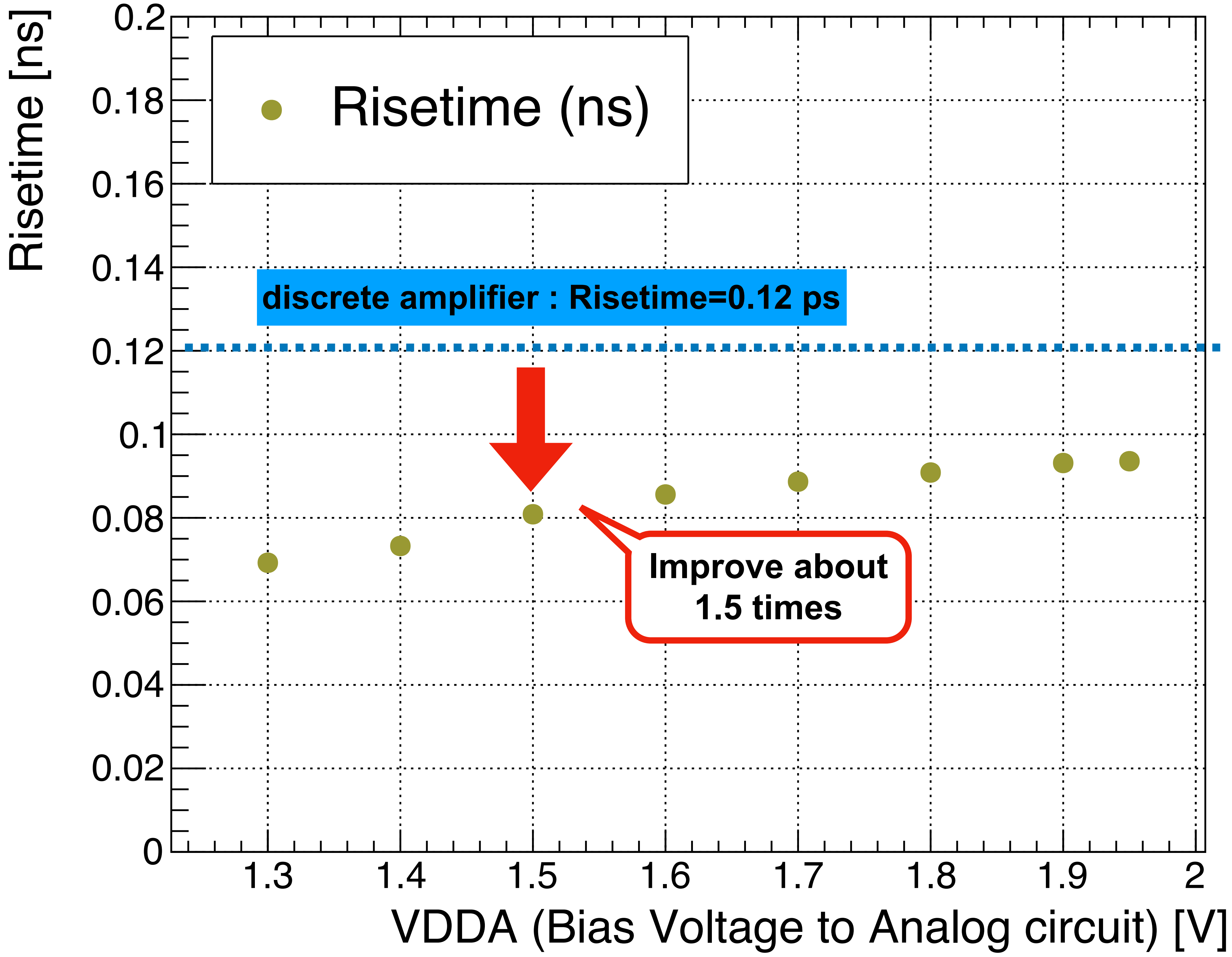


- As V_{DDA} was increased, both signal and noise was increased.
→noise level **~ 0.3 mV** with Si-Ge ASIC a factor 16 improvement over discrete amplifier.
- The best analog voltage is **1.5 V**
→ The SN of Si-Ge ASIC is **2.4 times** better than discrete amplifier.

Result of Laser Measurement

V_{DDA} dependency of risetime



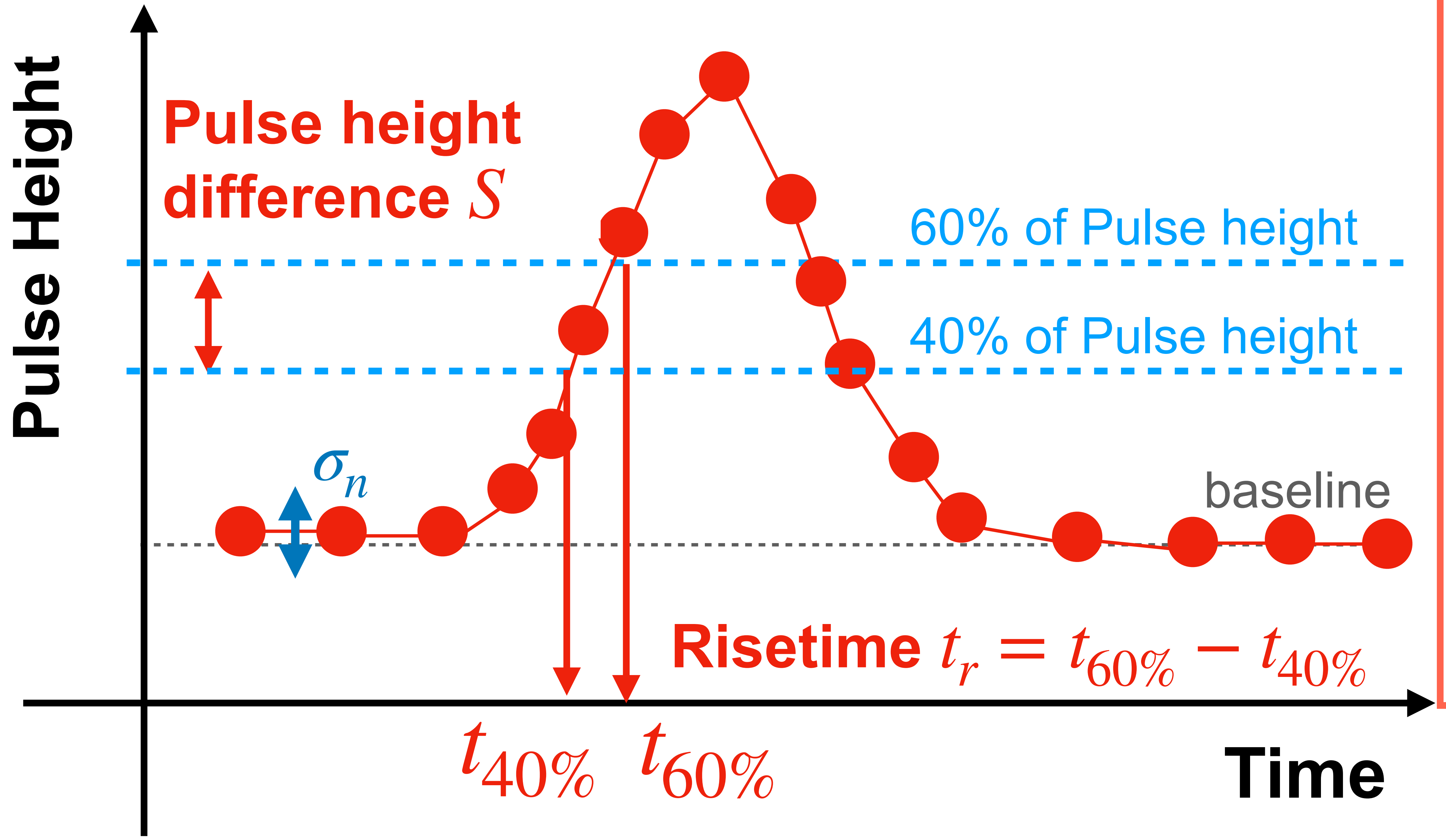


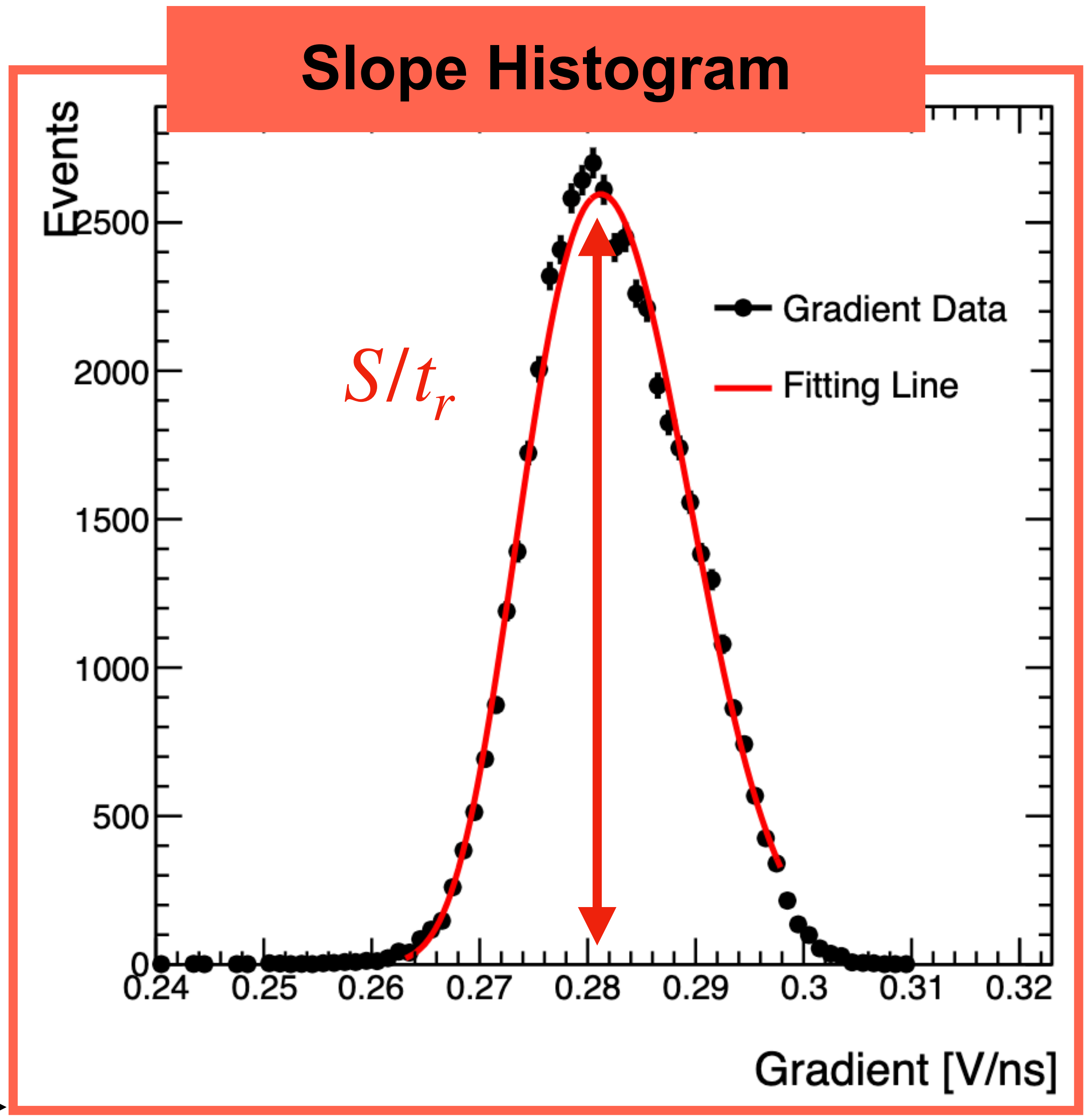
- We define risetime as the time for signal to rise from 40% to 60% of pulse height.
- The risetime of Si-Ge ASIC is **1.5 times** better than discrete amplifier.
- Si-Ge ASIC is excellent performance at the signal noise ratio and risetime.

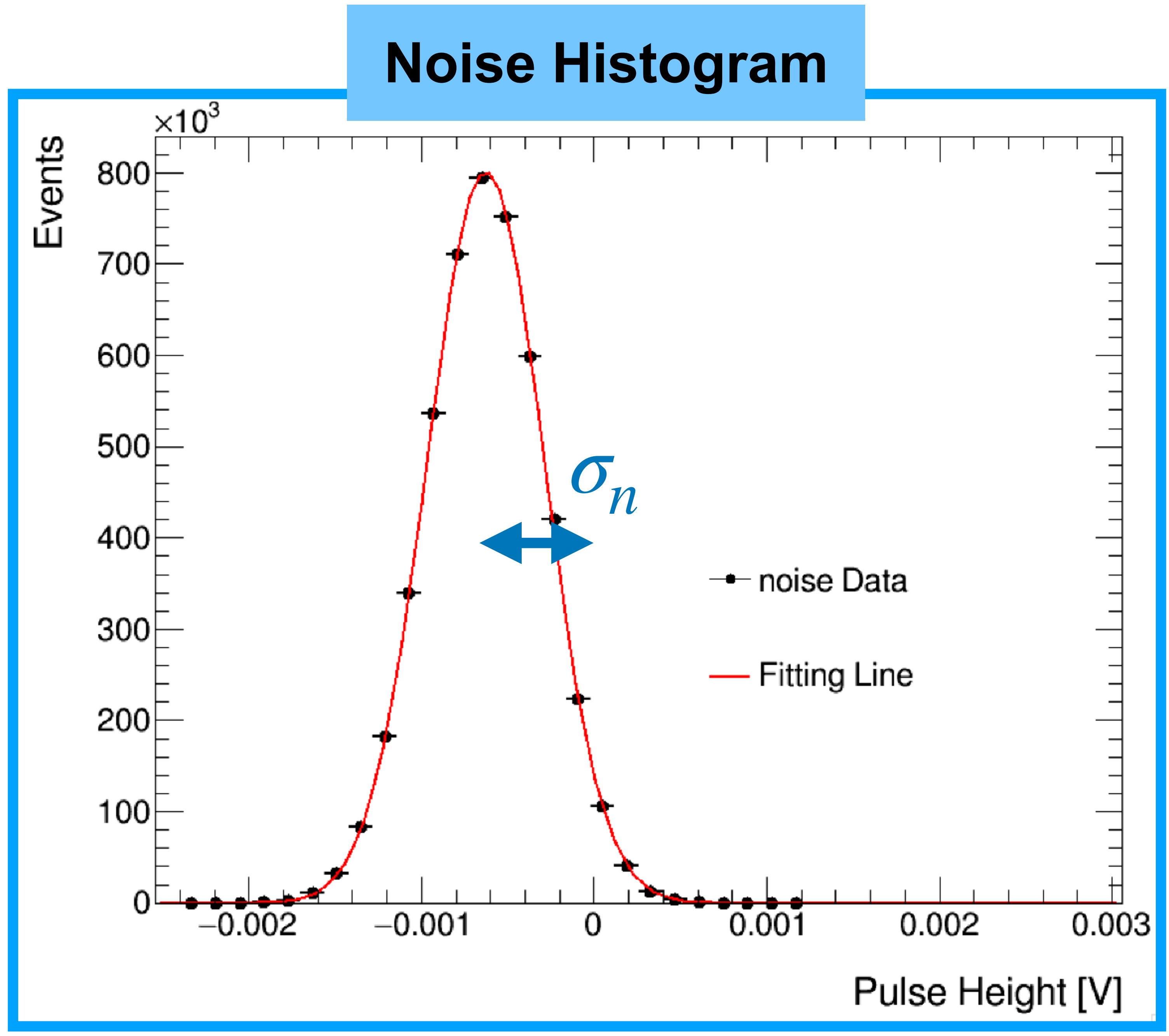
$$\sigma_j = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|} = \frac{\sigma_n}{\left|\frac{S}{t_r}\right|}$$

Analysis

Analysis of Jitter







- I need a noise and signal slope to calculate a jitter.
- **The noise** is a sigma of pulse height histogram in region without signals.
- **The slope** is a mode of slope histogram which is difference from 40% to 60% pulse height and risetime.

Calculate the Jitter

$$\sigma_{\text{jitter}} = \frac{\sigma_{\text{n}}}{\left|\frac{dV}{dt}\right|} = \frac{\sigma_{\text{n}}}{\left|\frac{S}{t_{\text{r}}}\right|}$$

Result of Laser Measurement

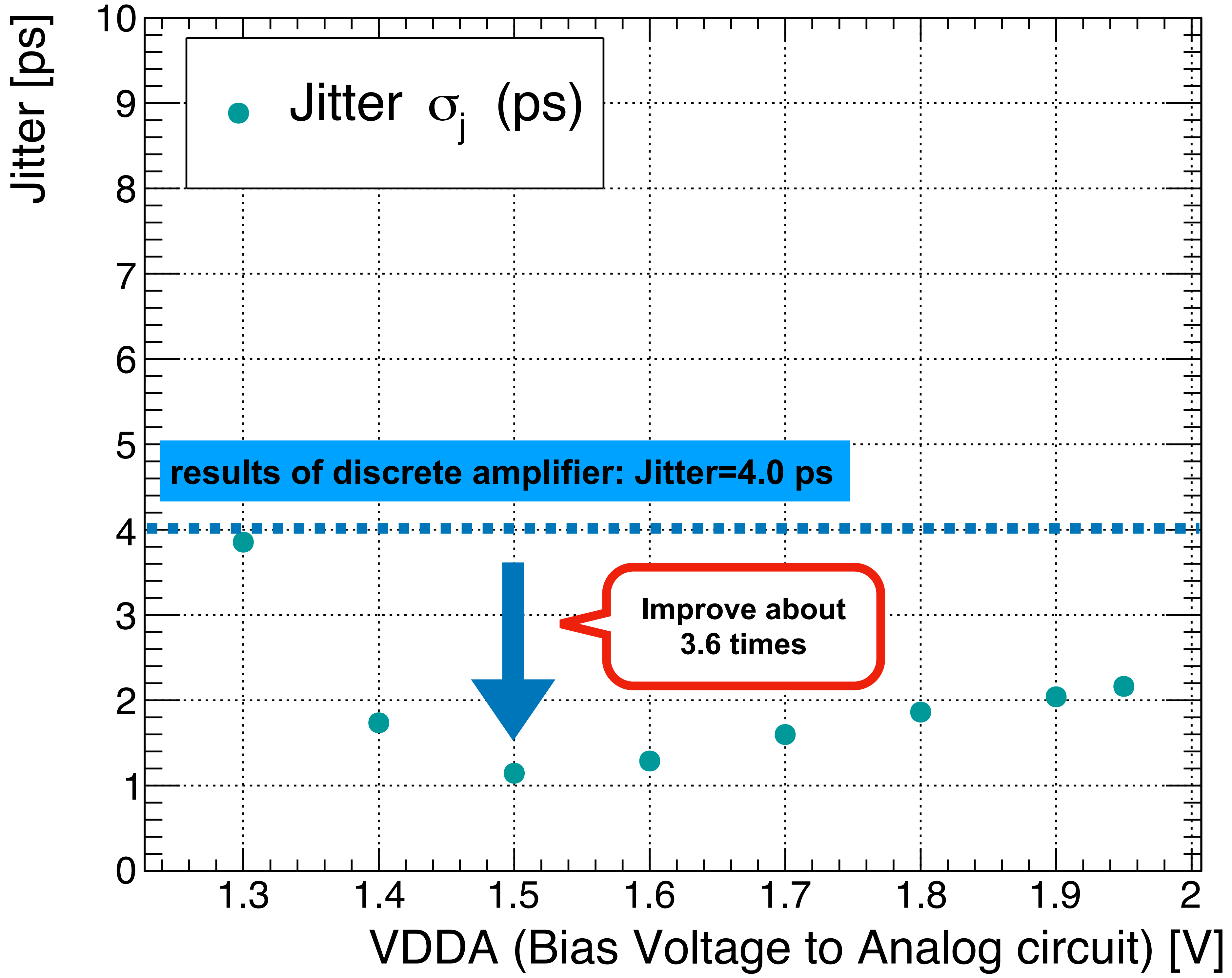
$$\sigma_{\text{jitter}} = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|} = \frac{\sigma_n}{\left|\frac{S}{t_r}\right|}$$

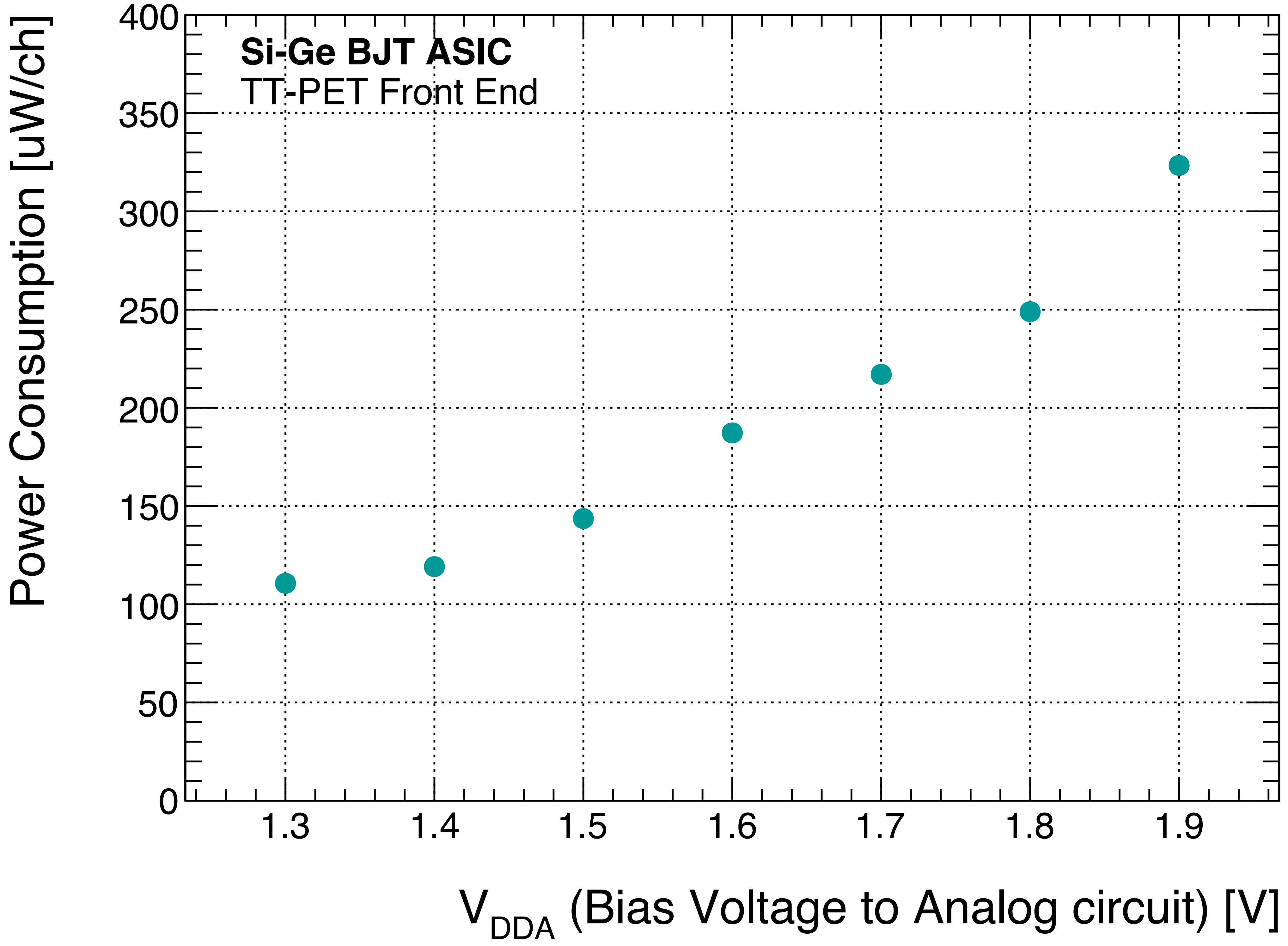
V_{DDA} dependency of jitter & power consumption

- The best analog voltage is **1.5 V**
  → The Jitter of Si-Ge ASIC is **3.6 times** better than discrete amplifier.

- Power consumption of Si-Ge ASIC preamp is **144 μW/channel** at V_{DDA} 1.5 V.

- Si-Ge ASICs are better jitter and power consumption than discrete amplifiers.

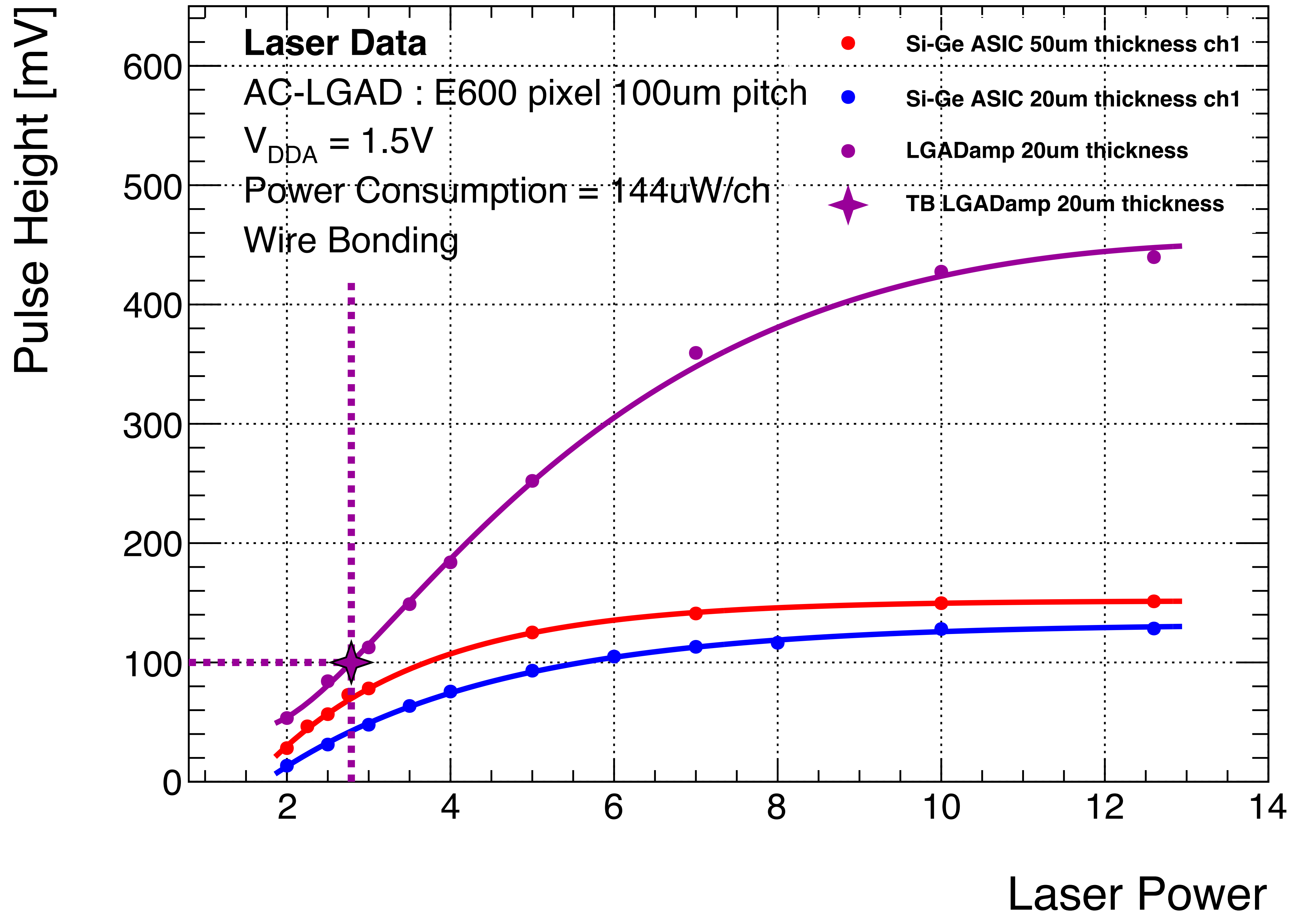


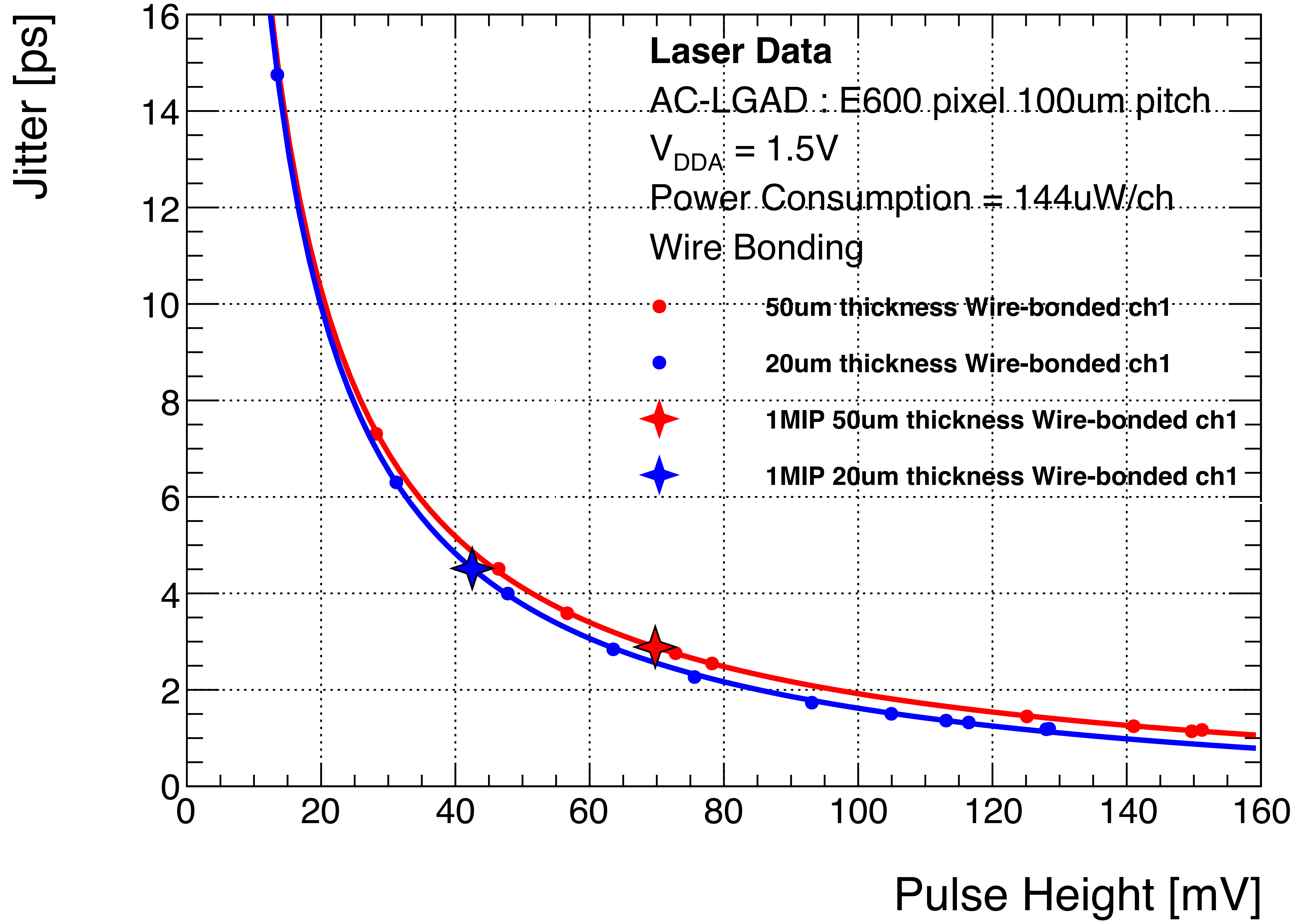


Result of Laser Measurement

$$\sigma_{\mathrm{jitter}} = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|} = \frac{\sigma_n}{\left|\frac{S}{t_r}\right|}$$

Input signal dependency of Jitter





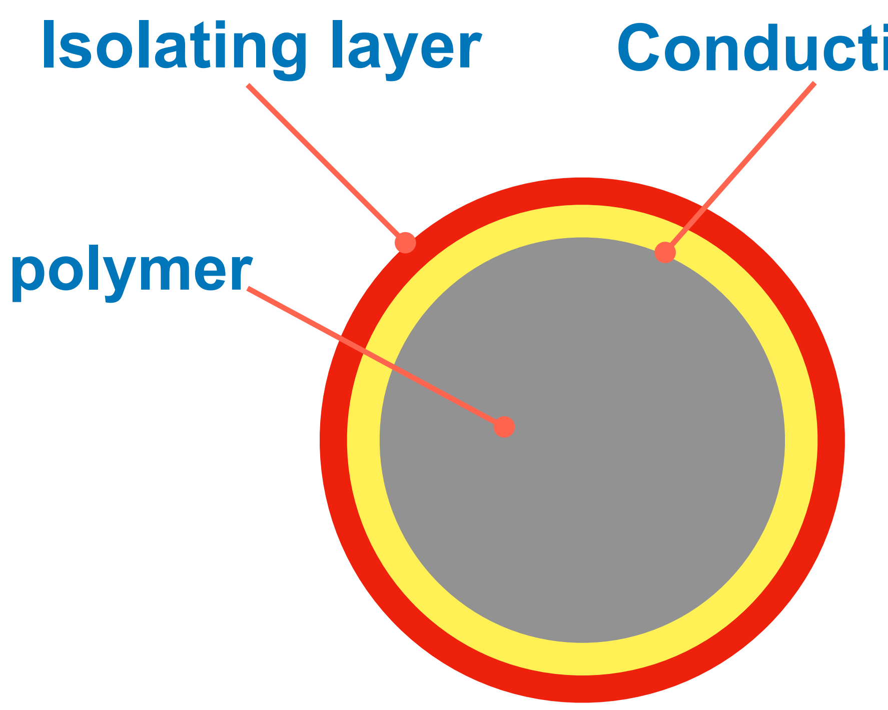
- Pulse height of 20um thickness AC-LGAD is ~100mV at test beam.
  →Laser power of 1MIP (Minimum Ionizing Particle) is 2.8
- The Jitter of Si-Ge ASICs with 1MIP
  → **4.5 ps** with AC-LGAD 20um thickness.
  → **2.9 ps** with AC-LGAD 50um thickness.

	50um thickness	20um thickness
Pulse Height	70 mV	43 mV
Jitter	2.9 ps	4.5 ps

Flip-Chip Bonding

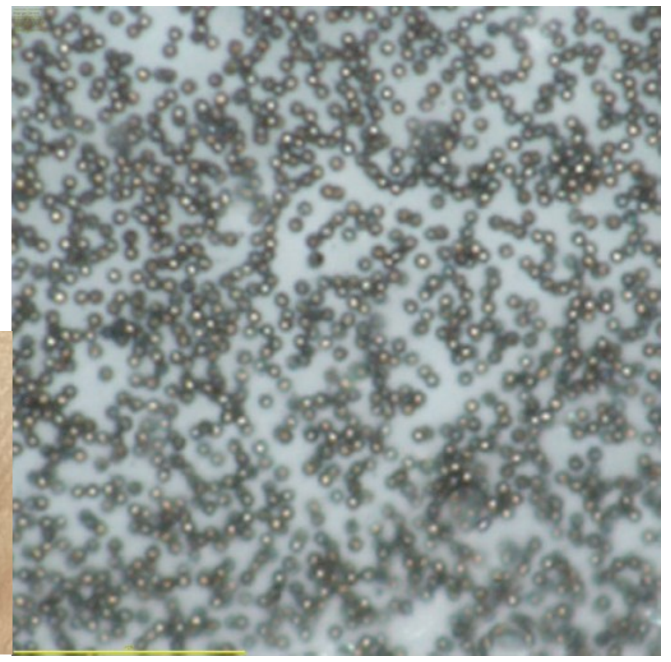
ACF Flip-chip Si-Ge ASIC

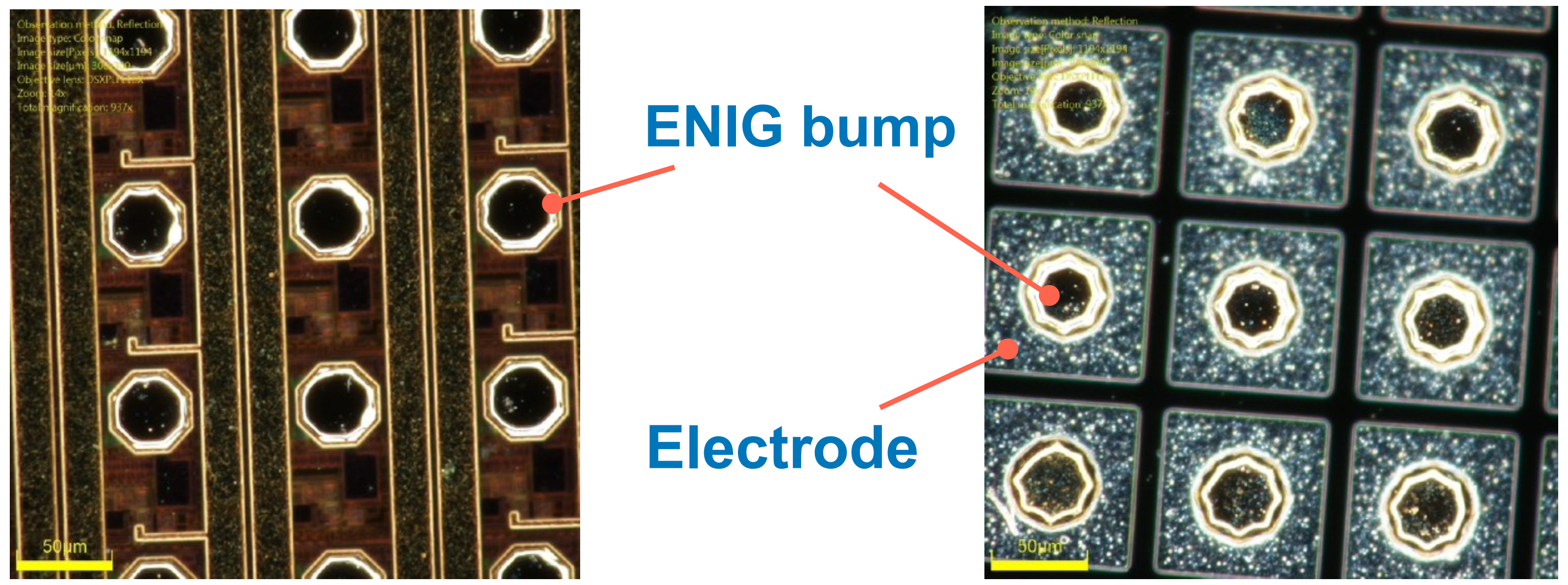
- AC-LGADs and Si-Ge ASICs are flip-chipped by crushing the **ACF** (Anisotropic Conductive Film).
- The structure of ACF is that the polymer is coated with a conductive and an insulating layers.
- ENIG (Electroless Nickel Immersion Gold) bump are formed on the electrode of both Si-Ge ASICs and AC-LGADs at CERN.
- They can be connected by crashing conductive particles with ENIG bumps at University of Geneva.



↑conductive particle cross-section view


↑ACF

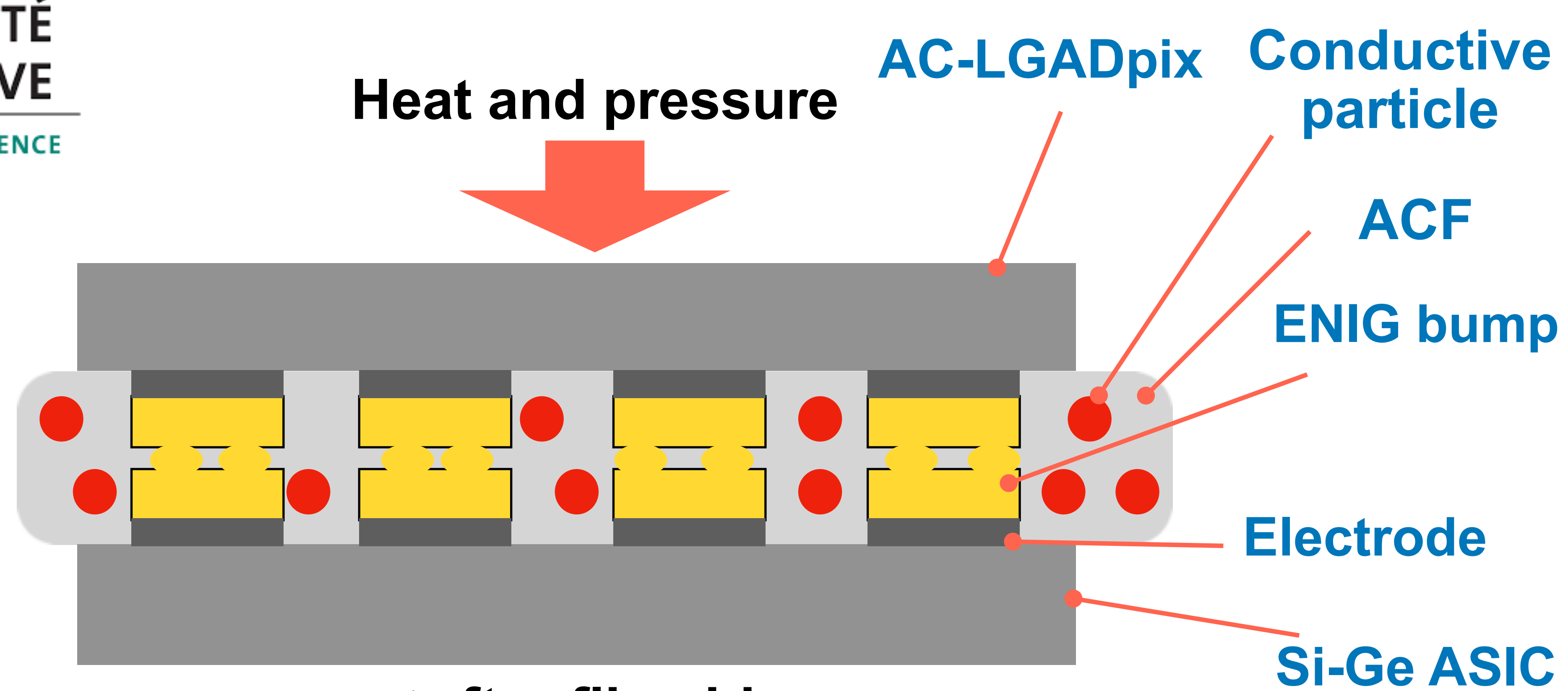

↑zoom picture of ACF



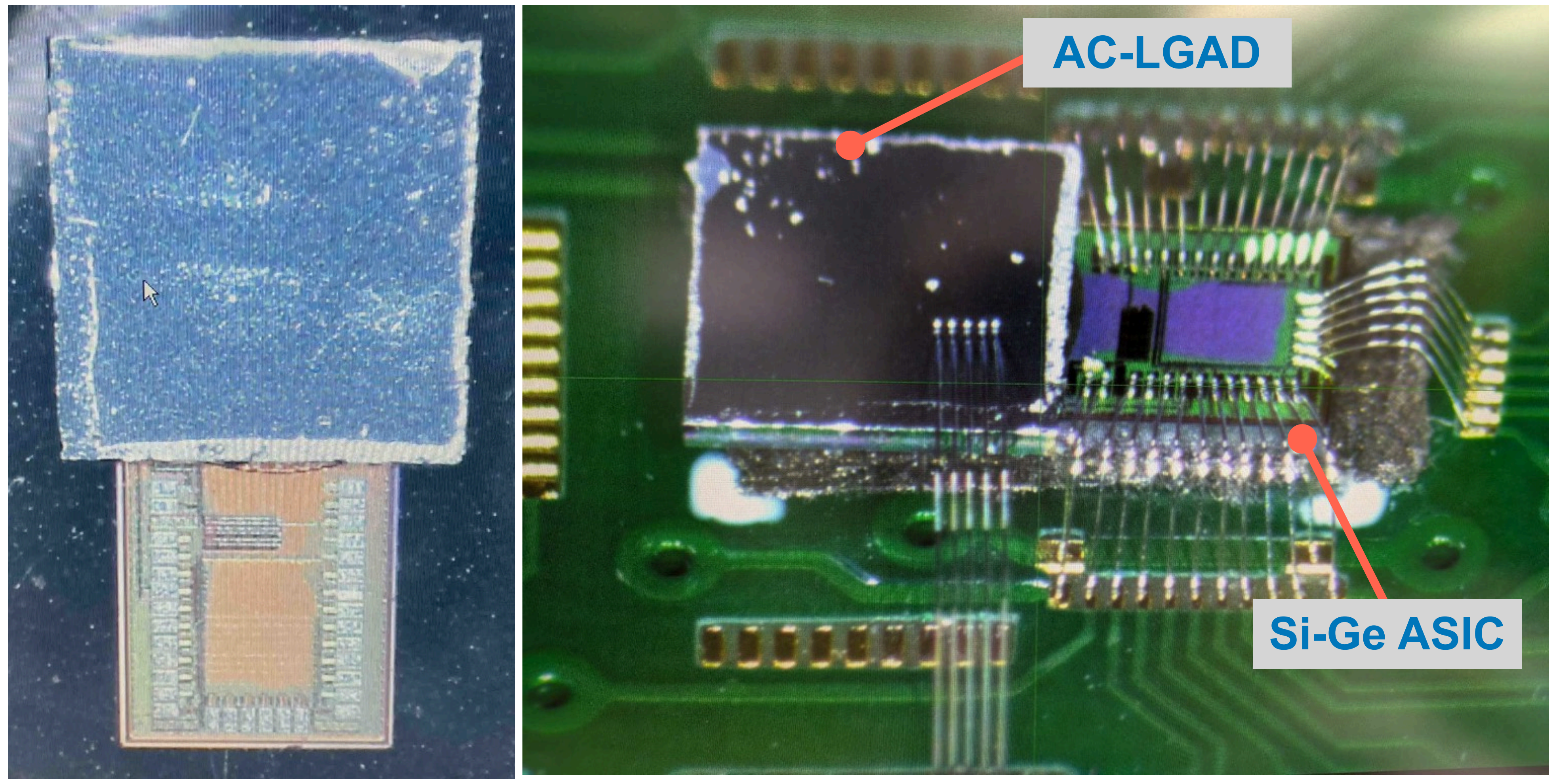
↑ENIG bump on the Si-Ge ASIC and AC-LGAD

[2] 2nd DRD3 week : Development of in-house plating and hybridization technologies for pixel detectors

↑ Flip-Chip-Bonder (ACCμRA 100)



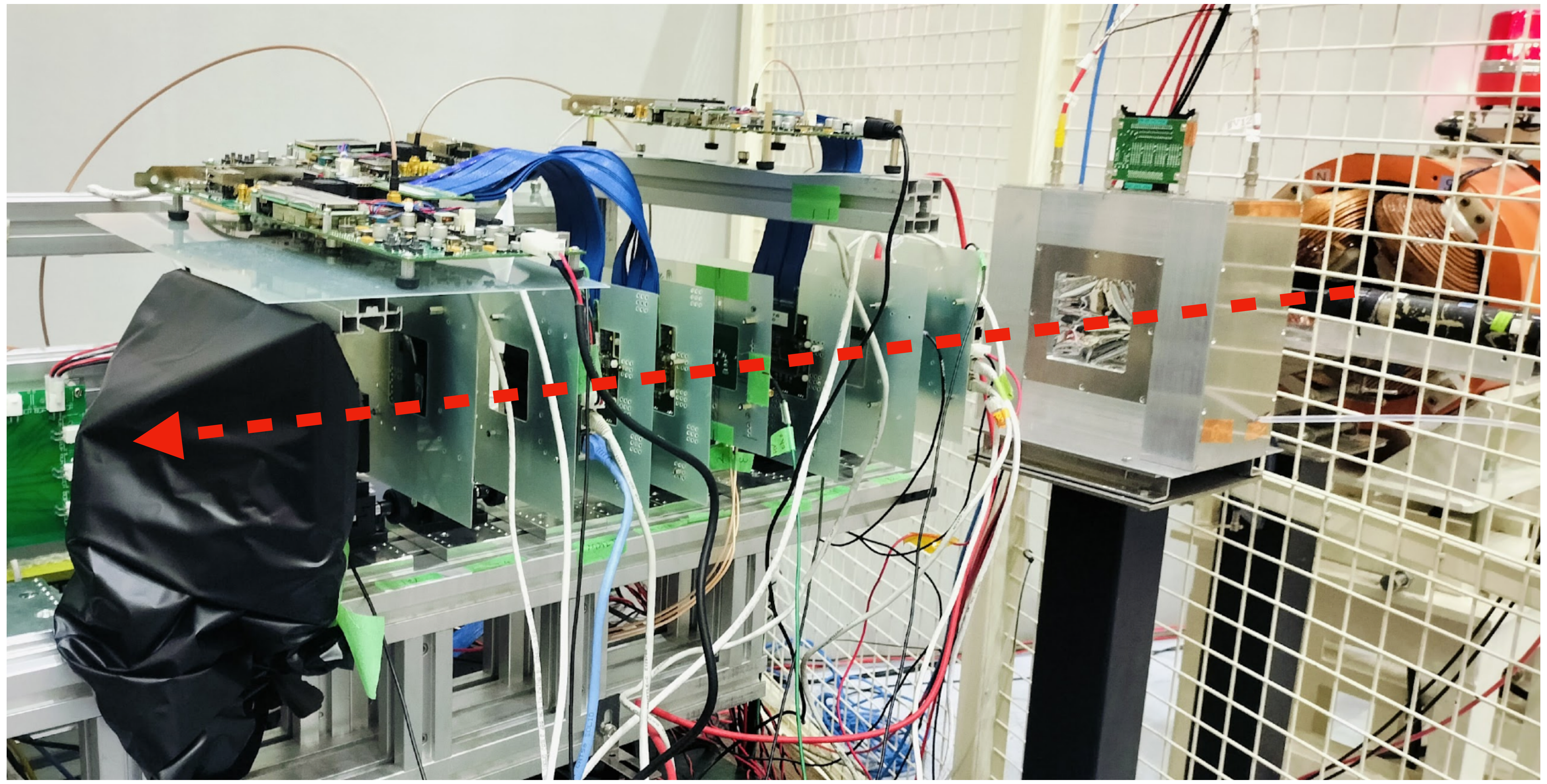
↑after flip chip



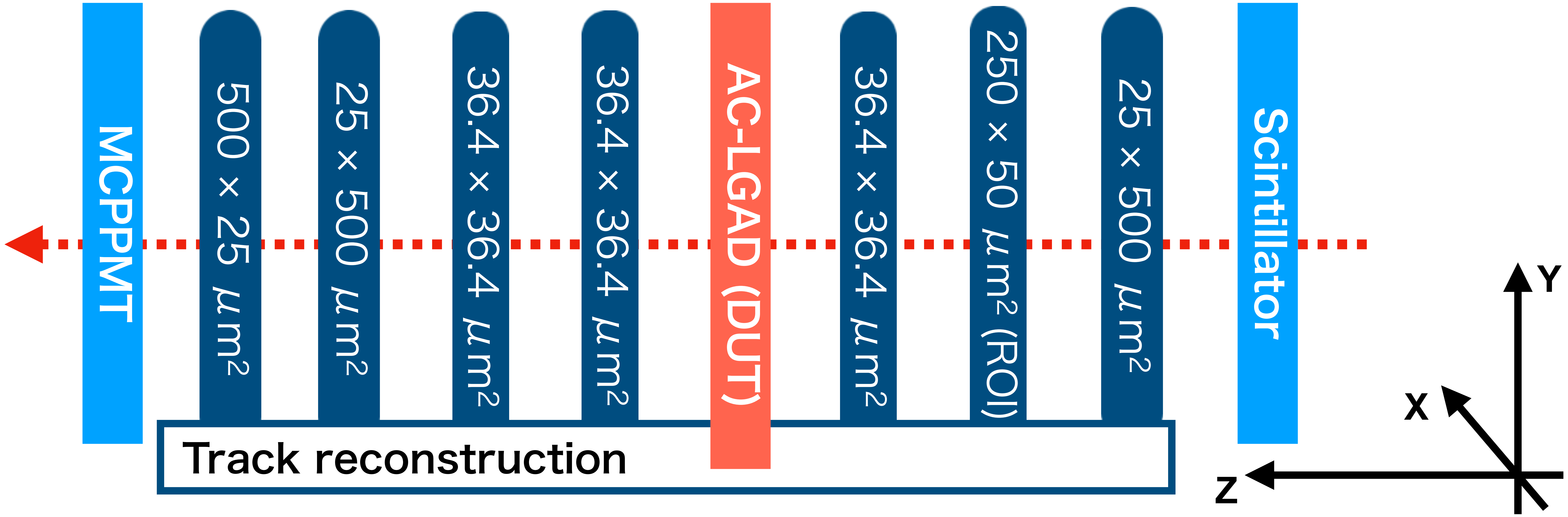
Test Beam Measurement at KEK AR-TBL

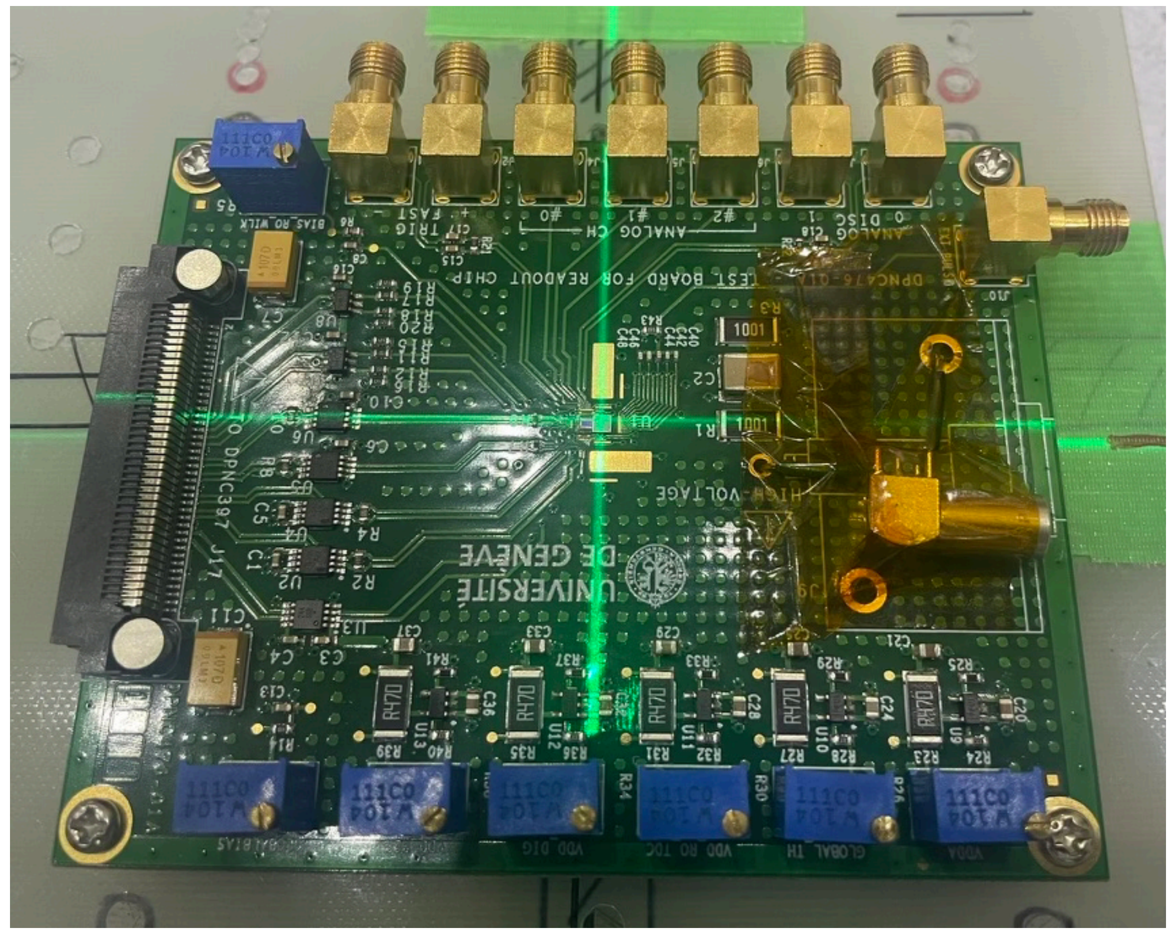
Status & Setup

- The beam is 3 GeV electron beam.
- We used 7 layers for tracking reconstruction.
  →FEI4 (25×500 μm²) Dual chip : 3 layers
  →FEI4 (50×250 μm²) Quad chip : 1 layer
  for Region of Interest (ROI)
  →MALTA2 (36.4×36.4 μm²) : 3 layers
- DUT : AC-LGAD ACF bonded Si-Ge ASIC



↑ Test beam setup at KEK ARTBL



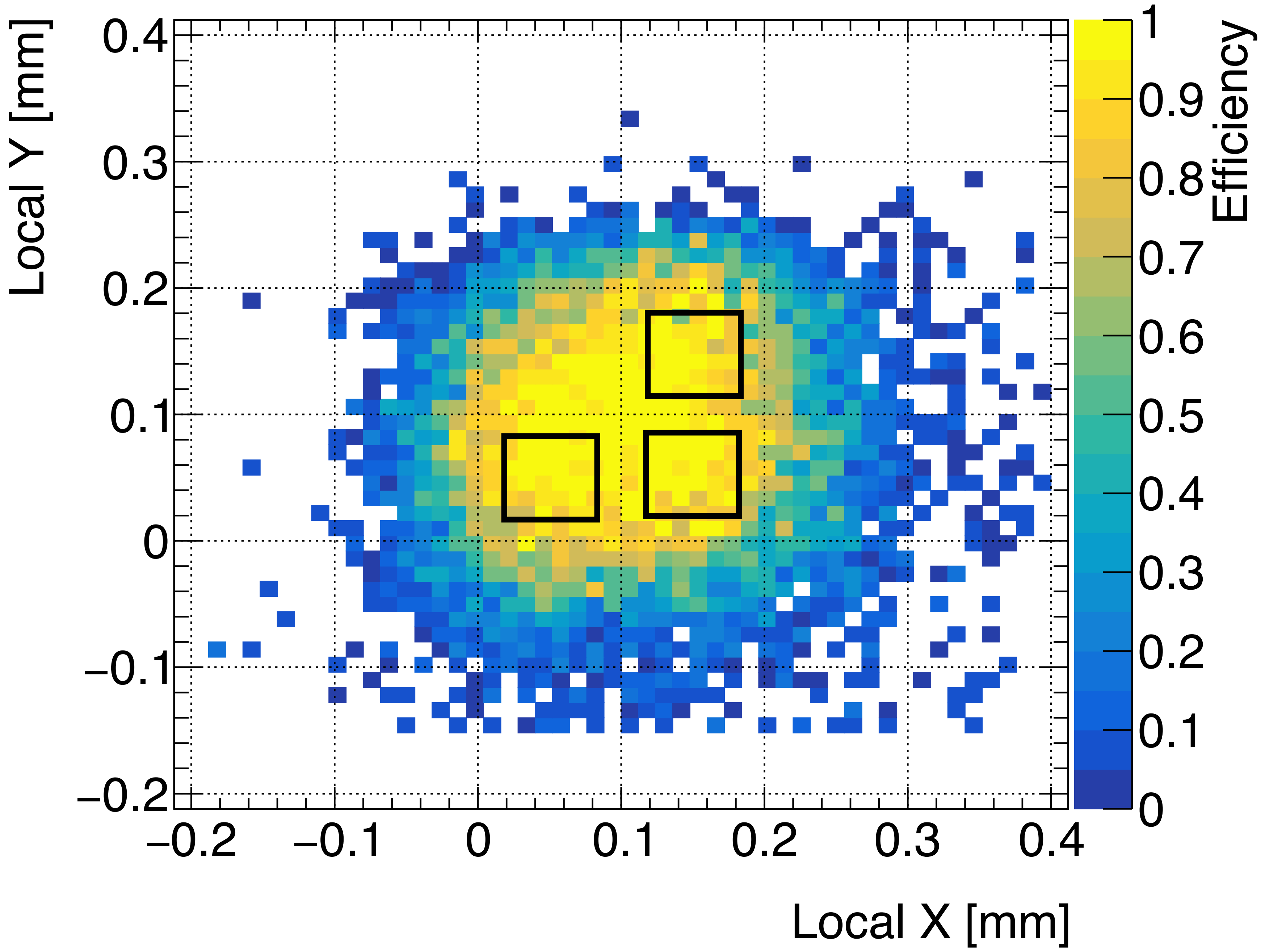


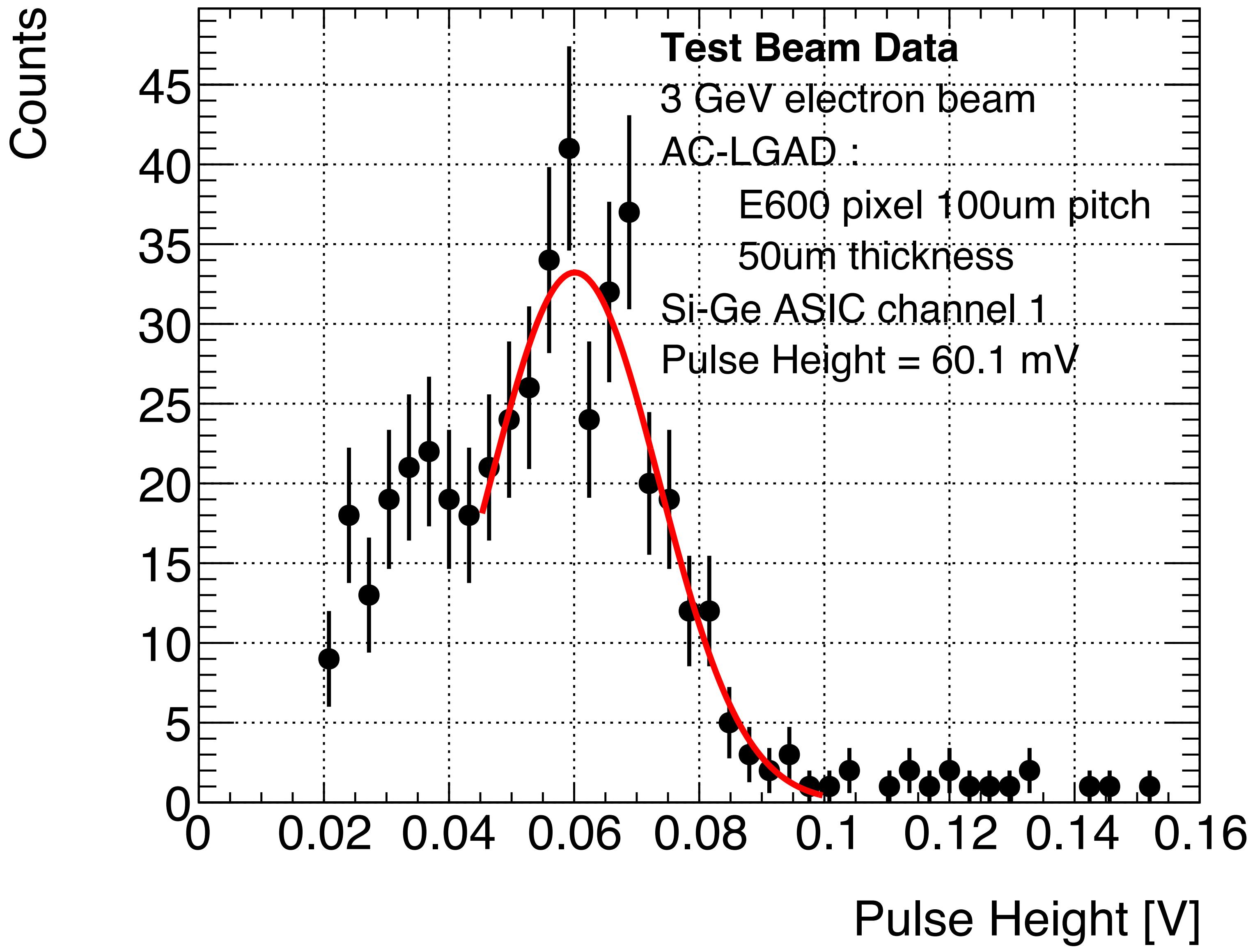
↑ AC-LGADpix+Si-Ge

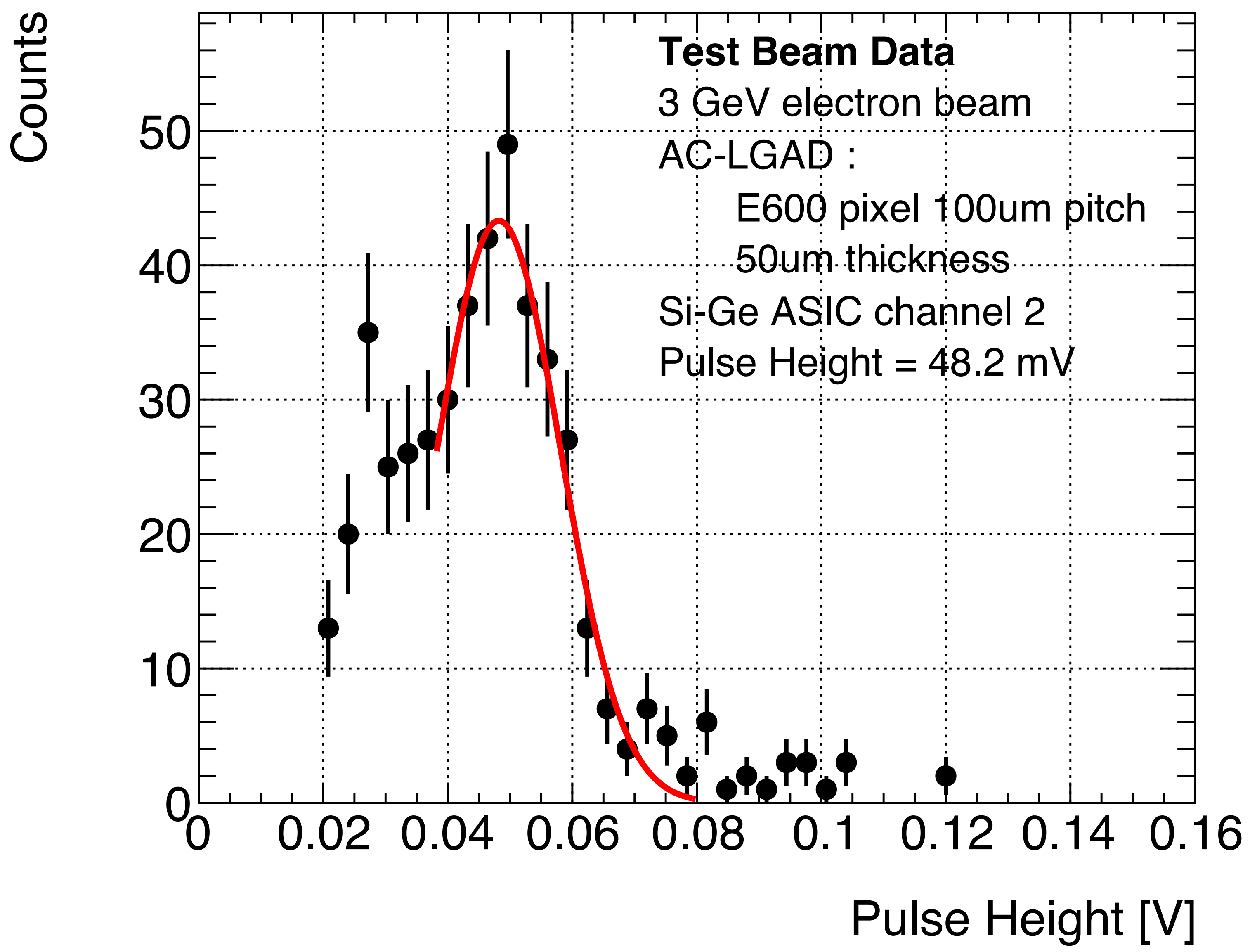
Results of Test Beam Measurement

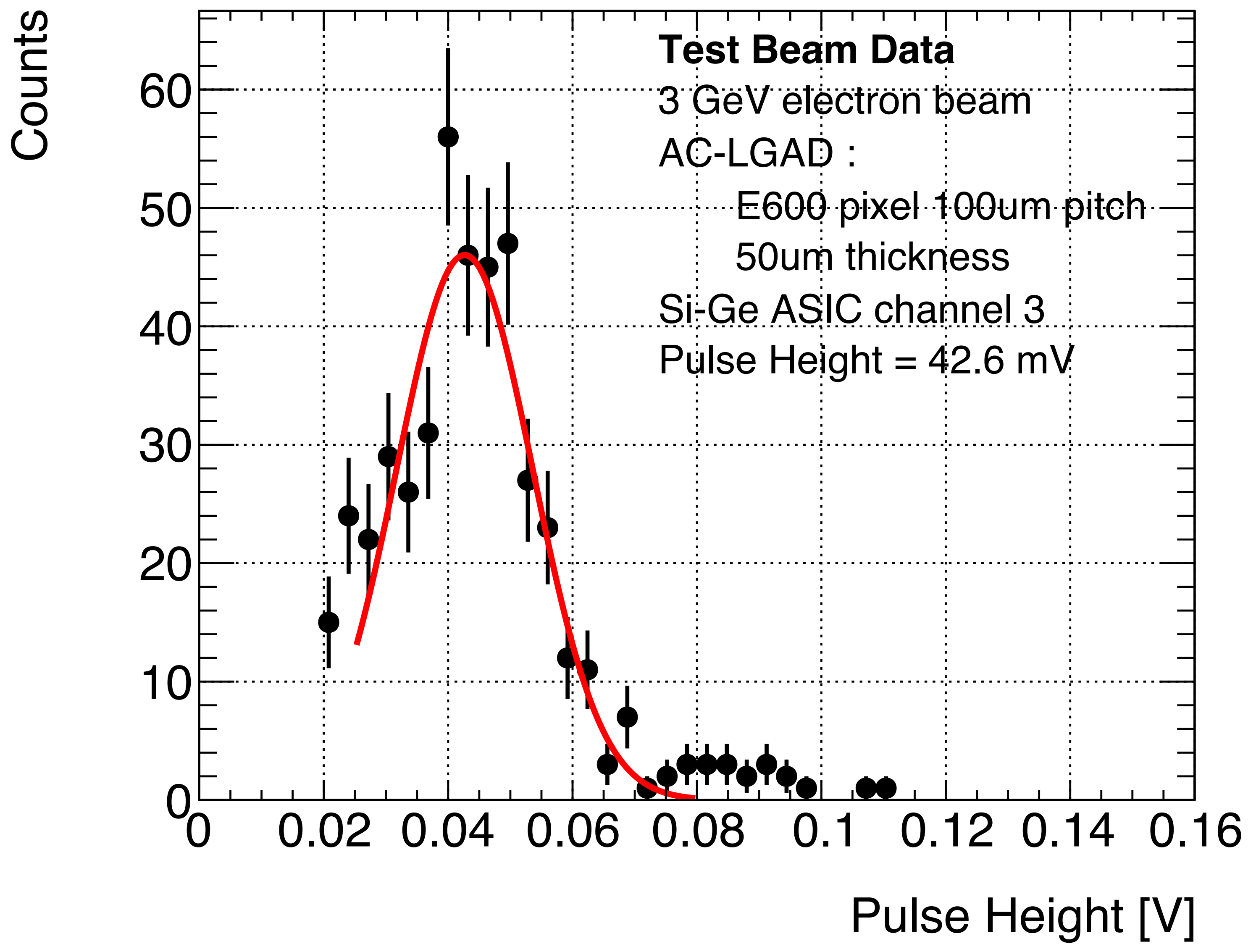
Pulse Height for each pixel

- Create a pulse height distribution within a 60μm x 60μm range centered on the pixel to eliminate crosstalk event.
- Channel 1 had the largest signal at **60 mV**, while the signals from channel 2 and 3 were smaller than channel 1.
  →Due to differences in Si-Ge ASIC amplification.
- Pulse height of ACF sample is 60mV and WB sample is 70mV.





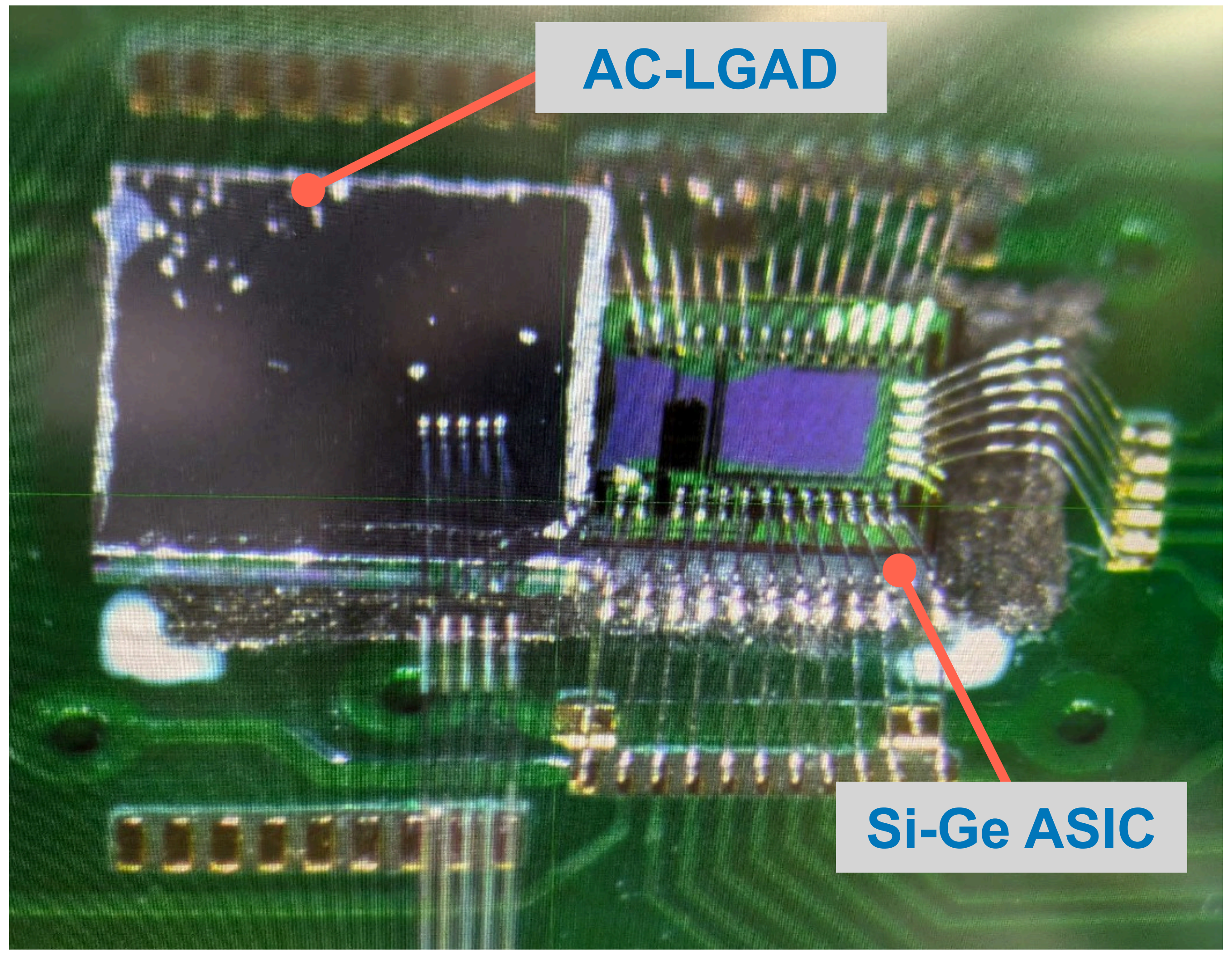




Summary

AC-LGADpix & ASIC development

- AC-LGADs have **no dead region** by uniformly installing the gain layer.
- Need to develop ASICs with **low electronics noise** and **low power consumption**.



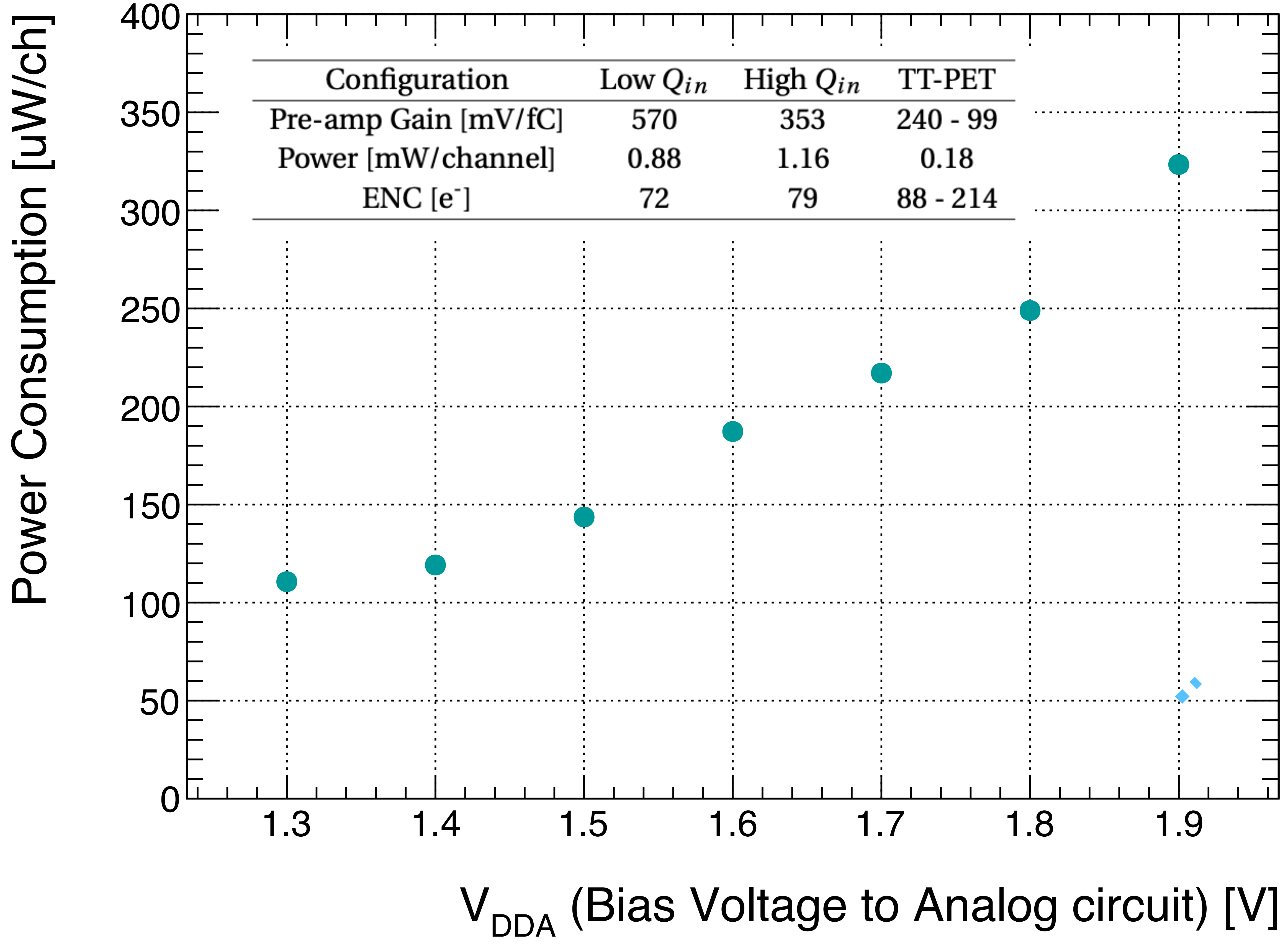
Si-Ge BJT ASIC

- Si-Ge ASIC : IHP 130nm BJT process
  →Preamp power consumption is **144uW/channel**.
- The Jitter of Si-Ge ASICs
  → **4.5 ps** with AC-LGAD 20μm thickness.
  → **2.9 ps** with AC-LGAD 50μm thickness.
- Measured AC-LGAD ACF bonded Si-Ge ASIC using 3 GeV electron beam at KEK in Japan
- Pulse height of Si-Ge ASIC using the test beam
  →**60 mV** with ACF bonded AC-LGAD 50μm thickness
  →**70 mV** with wire bonded AC-LGAD 50μm thickness

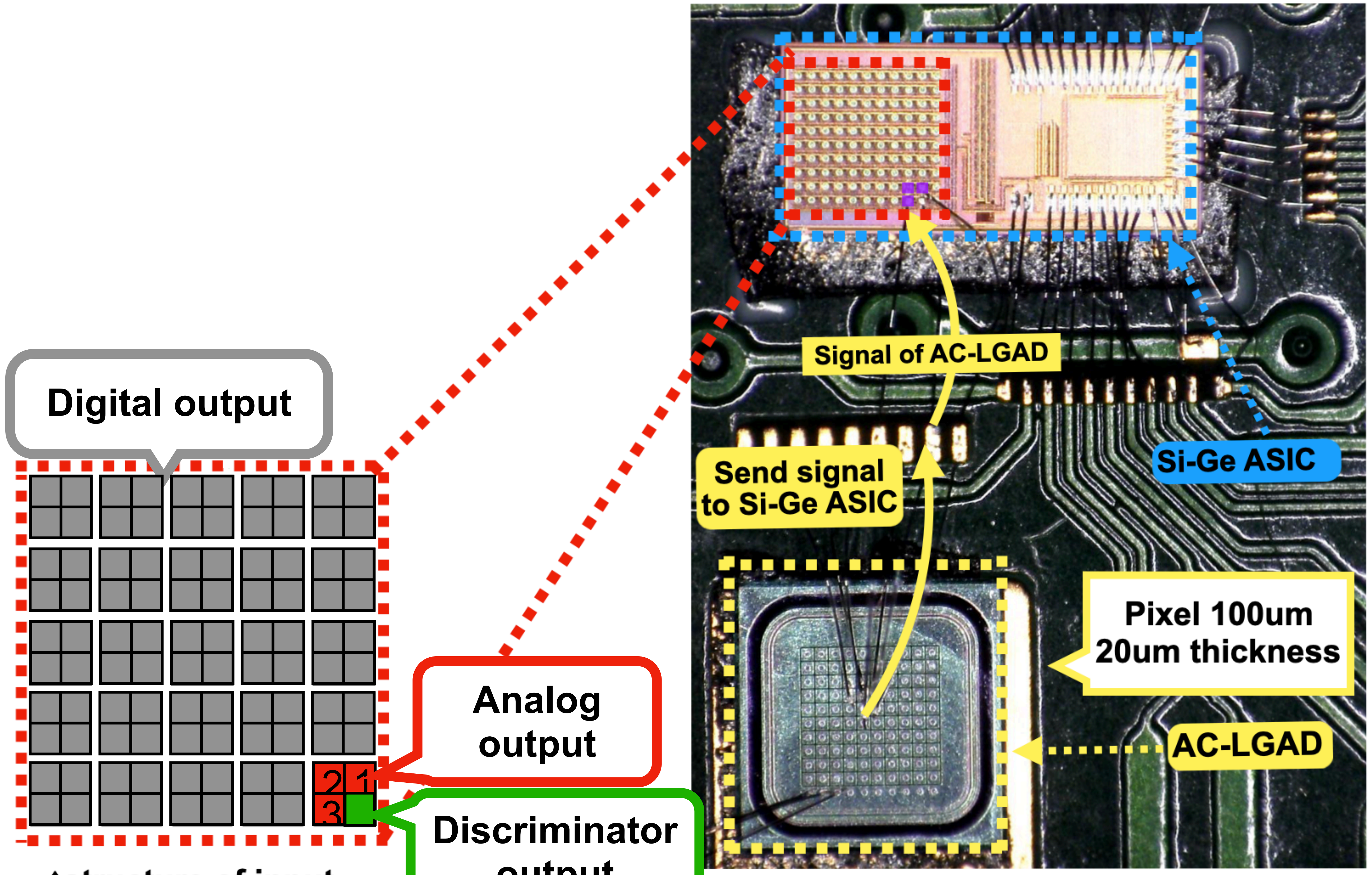
	50um thickness ACF bonding	50um thickness Wire bonding	20um thickness Wire bonding
Pulse Height	60 mV	70 mV	43 mV
Jitter	-	2.9 ps	4.5 ps

Backup

Power consumption



Configuration	Low Q_{in}	High Q_{in}	TT-PET
Pre-amp Gain [mV/fC]	570	353	240 - 99
Power [mW/channel]	0.88	1.16	0.18
ENC [e$^-$]	72	79	88 - 214



↑structure of input electrode Si-Ge ASIC

↑Connection of Si-Ge ASIC to AC-LGAD

HBT

- Si-Ge (Silicon-Germanium) BJT ASIC.
  →Process : IHP 130nm BJT process.
- The preamp is made of HBT : Heterojunction Bipolar Transistor
- The Input electrode is a 10×10 matrix (100×100 μm²).
  →To readout detector signals, we connected wire-bonding.
- We evaluated timing resolution by reading out AC-LGAD signal through the three analog outputs.
- Doping of Germanium is ingredient → can get electric field

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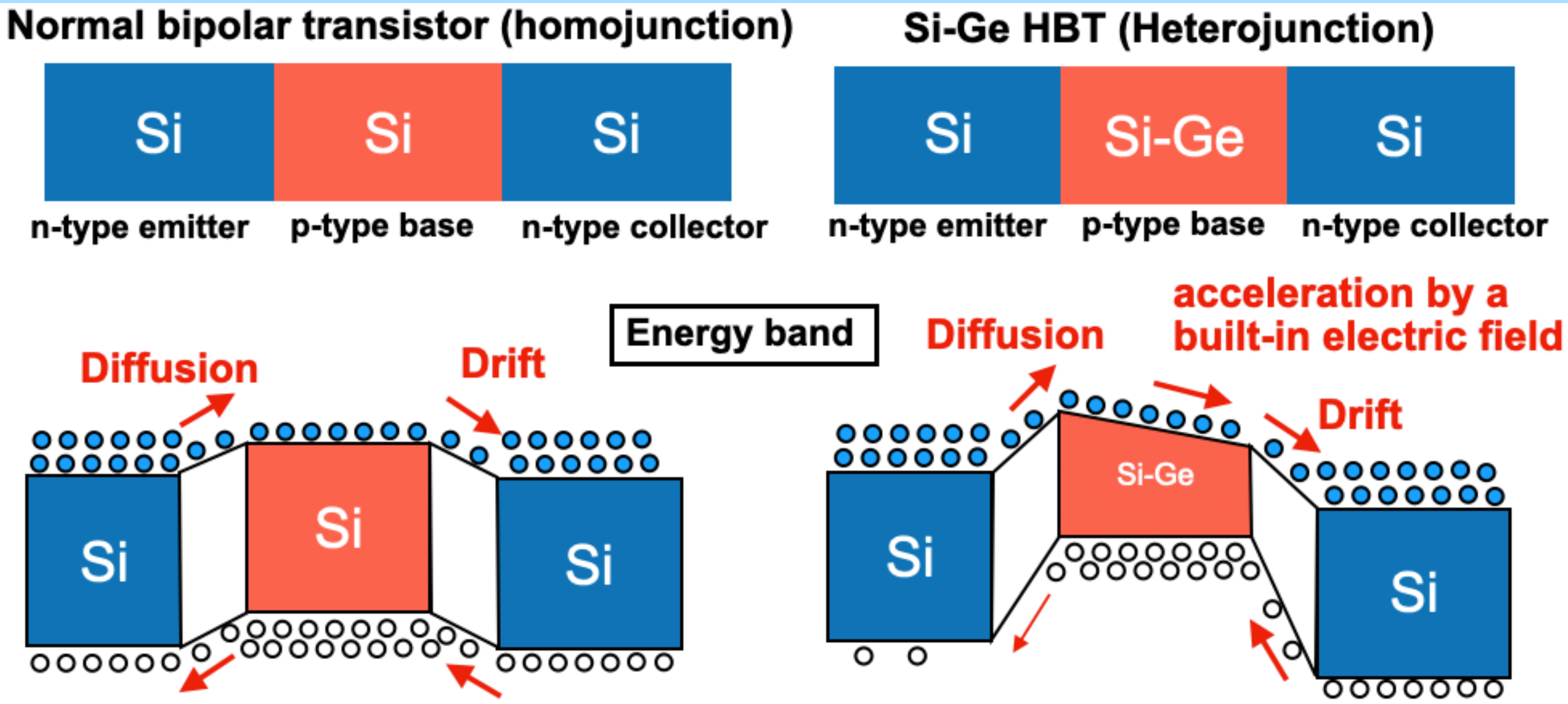
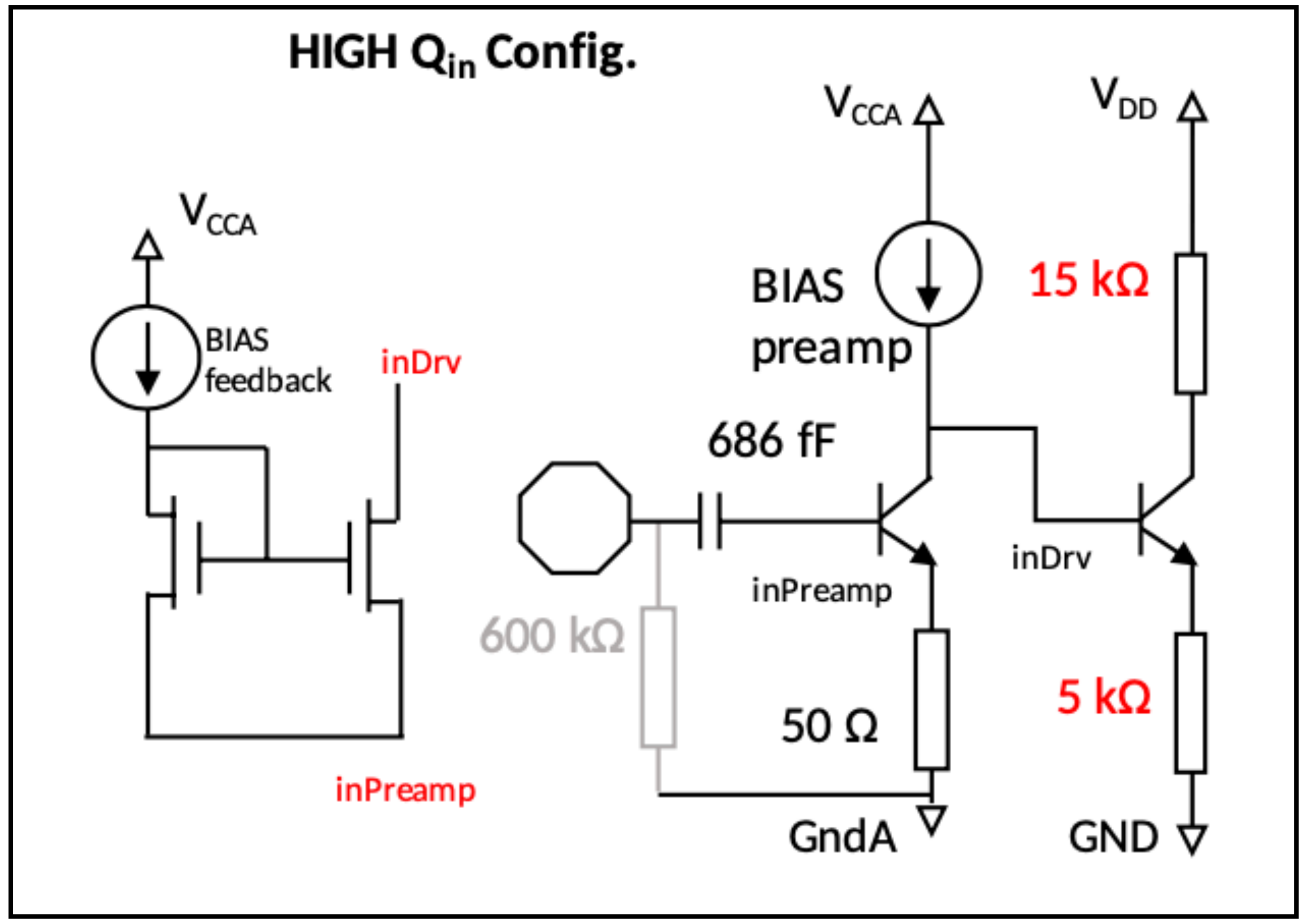
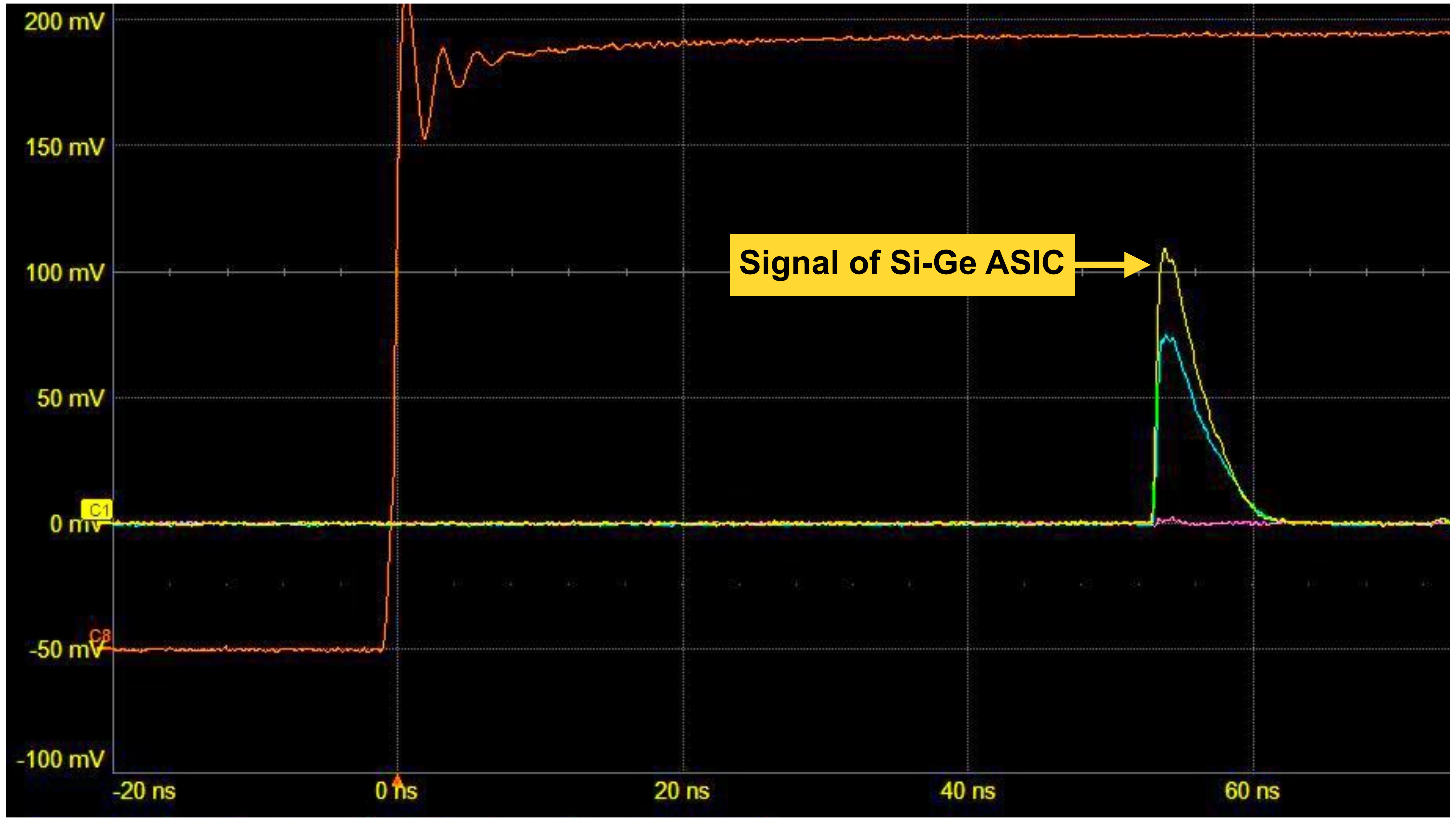


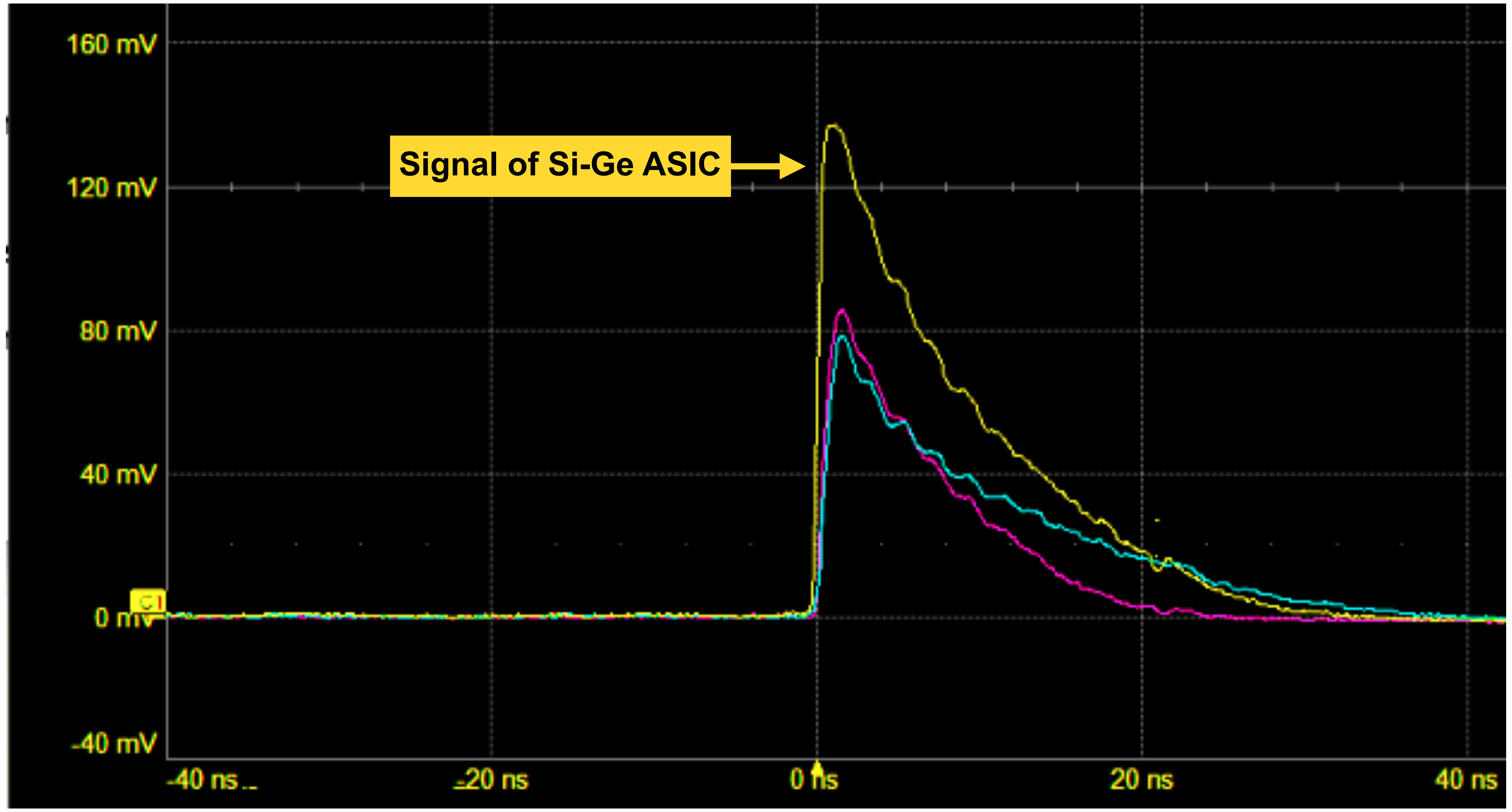


Si-Ge ASIC

wire-bonded 20um thick AC-LGAD
using infrared laser



ACF-bonded 50um thick AC-LGAD
using radioactive source

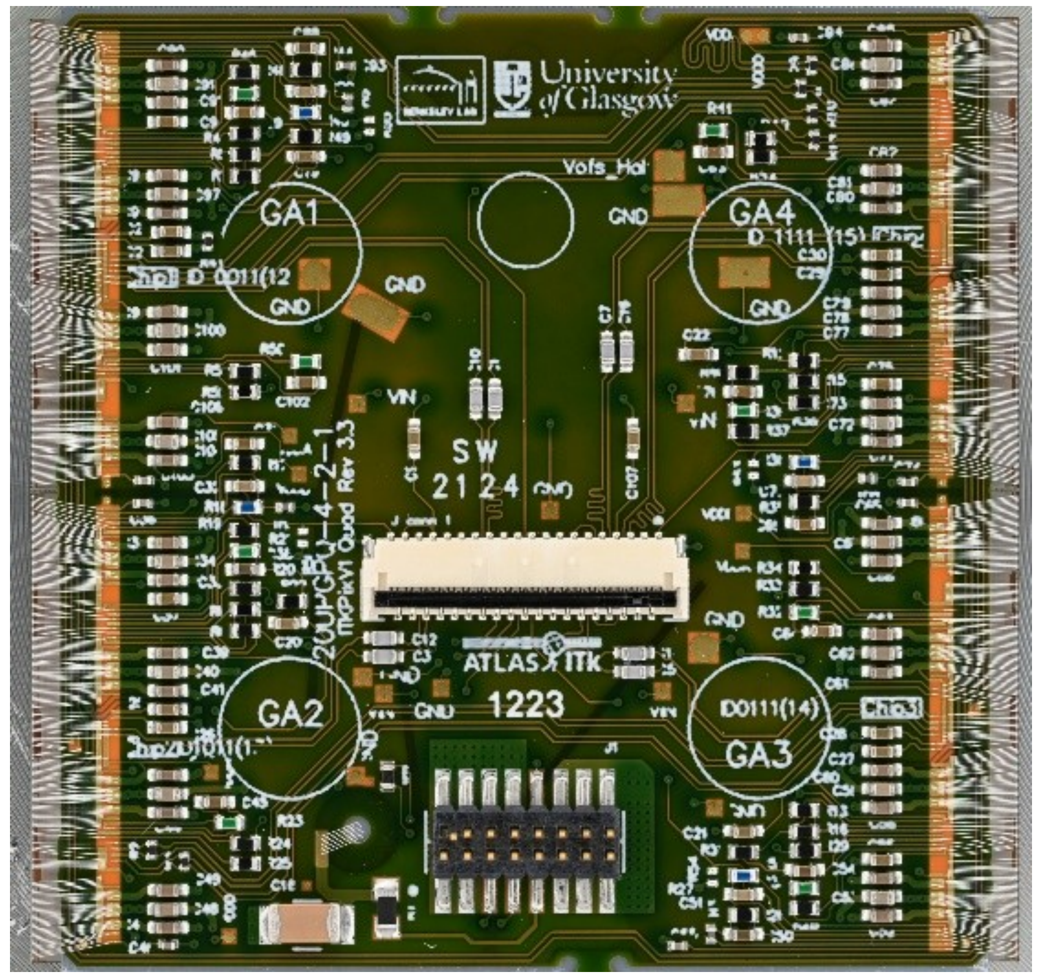


Power consumption

Other detector power consumption

ITk (Inner Traker)

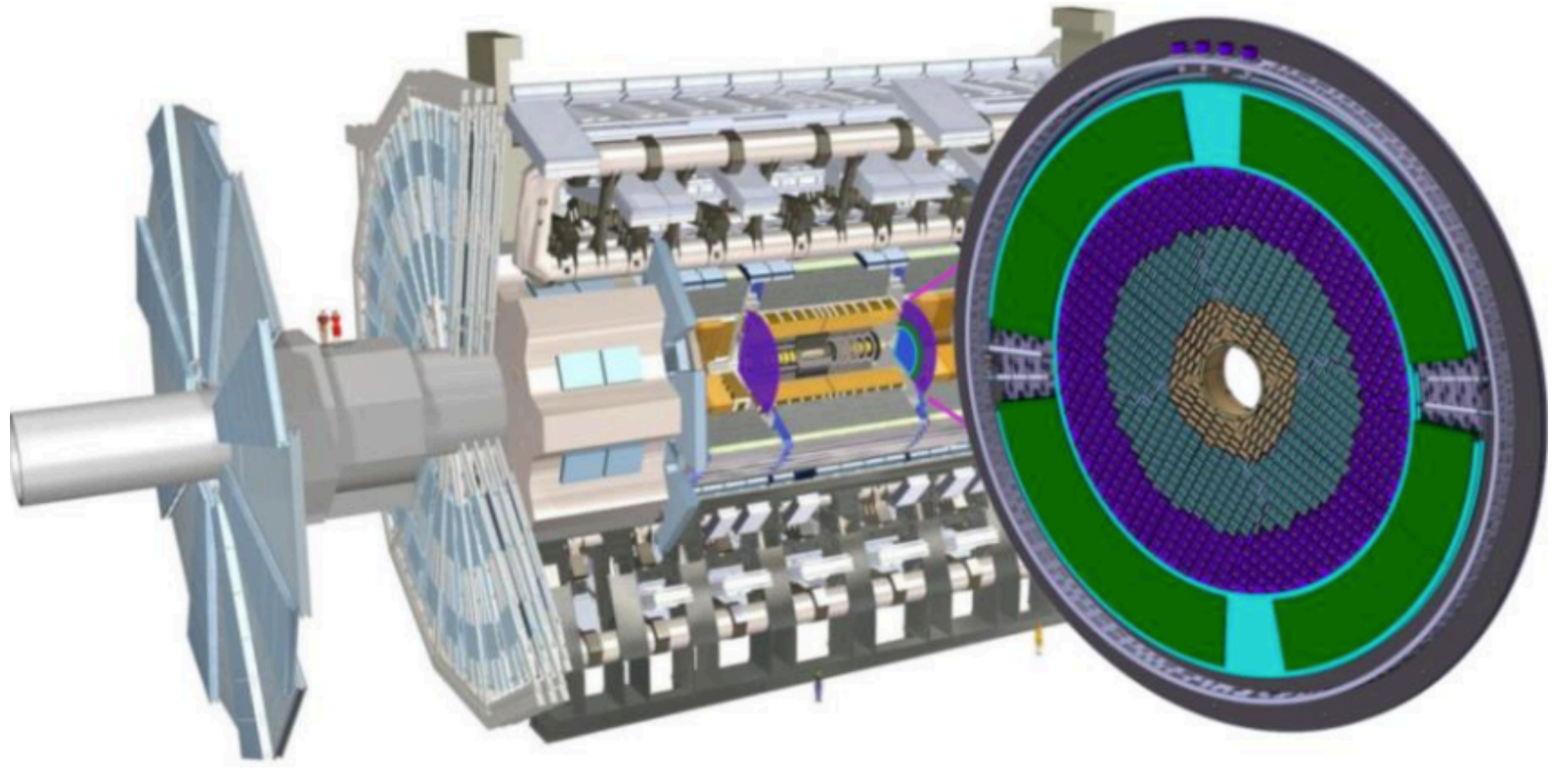
- ITk ASIC： RD53b
- 1channel size：50um×50um
- Power consumption：0.8W/cm^2 = 40uW/channel
  →Si-Ge ASIC is 144uW/channel, 1.4W/cm^2 (only preamp)



↑ITk

HGTD <u>(High Granularity Timing Detector)</u>

- HGTD ASIC：ALTIROC2
- 1channel size : 1.3mm×1.3mm
- Power consumption：0.6W/cm^2 = 10mW/channel

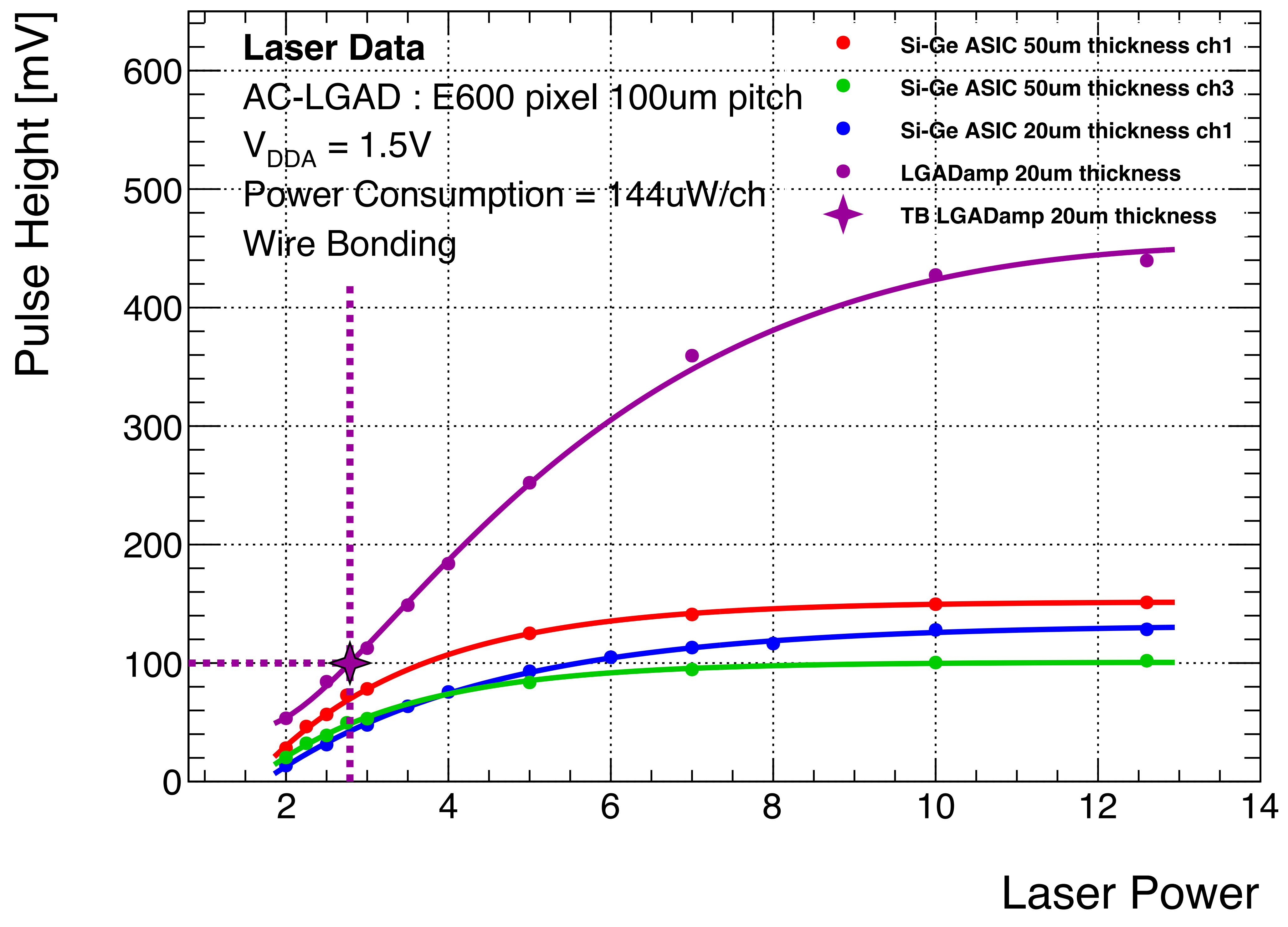


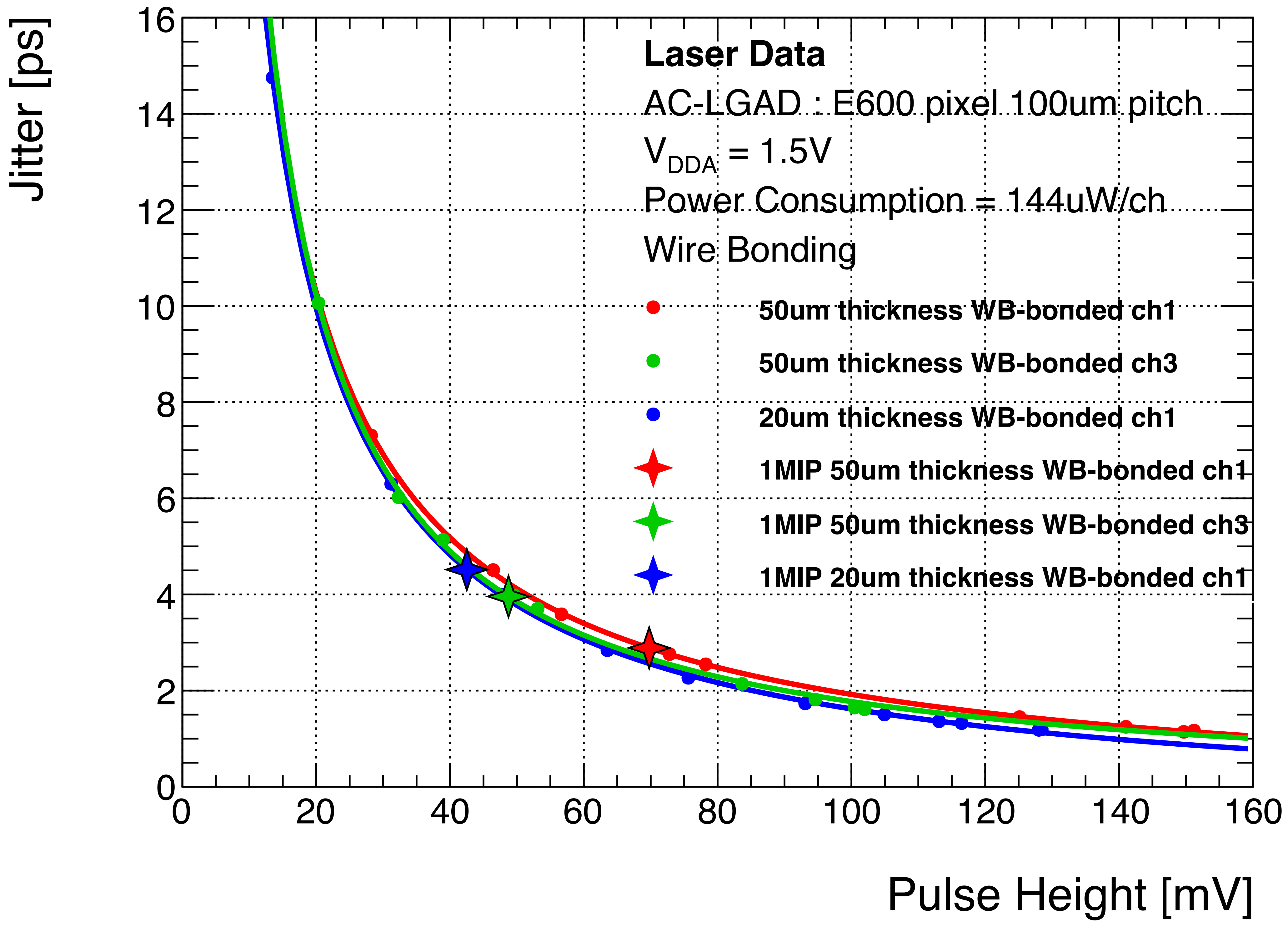
↑HGTD

Result of Laser Measurement

Input signal dependency of Jitter

$$\sigma_{\text{jitter}} = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|} = \frac{\sigma_n}{\left|\frac{S}{t_r}\right|}$$





- Laser power of 1MIP (Minimum Ionizing Particle) is 2.8
  →Pulse height of 20um thickness AC-LGAD is ~100mV at test beam.

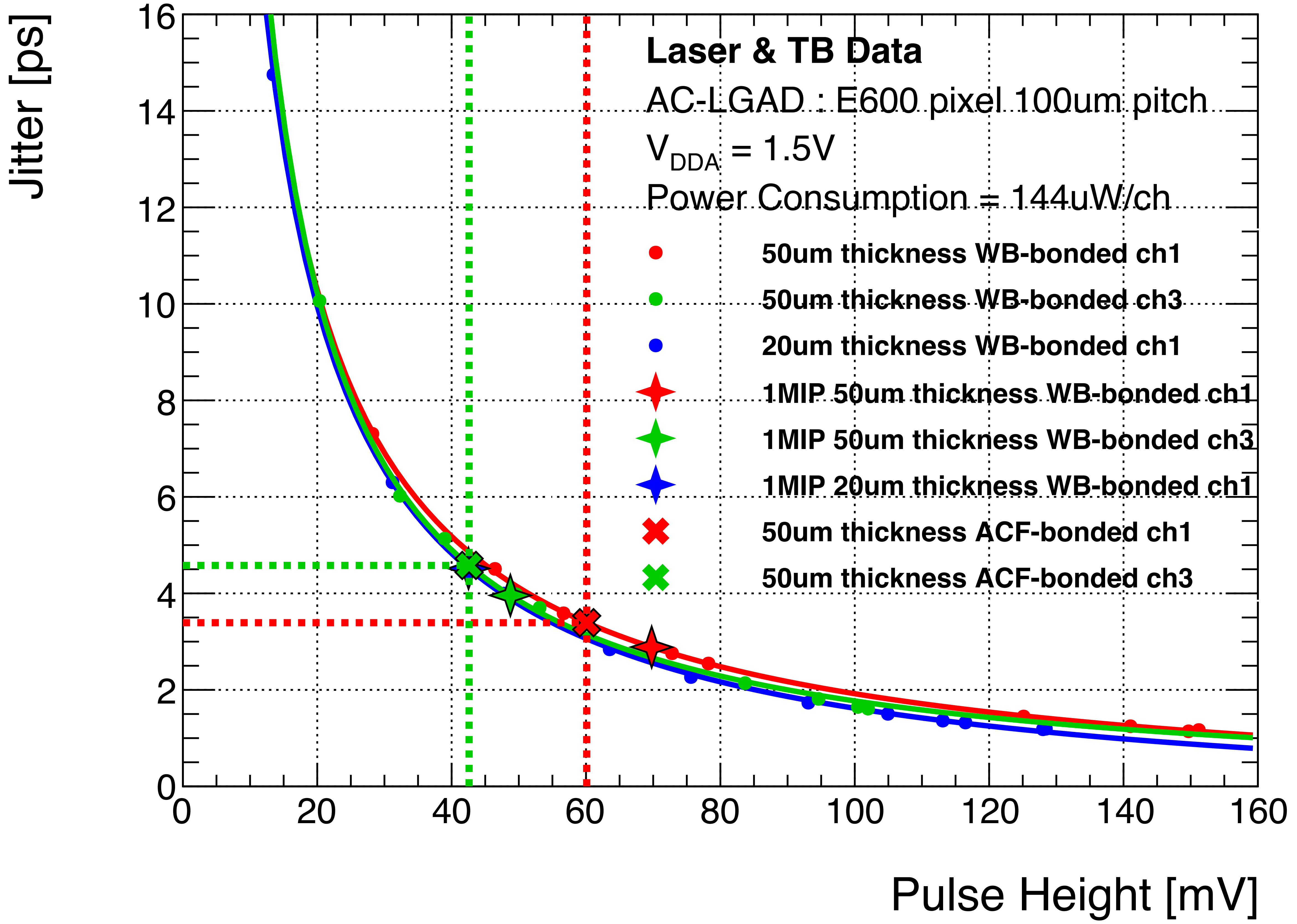
- The Jitter of Si-Ge ASICs with 1MIP
  → **4.5 ps** with AC-LGAD 20um thickness ch1.
  → **2.9 ps** with AC-LGAD 50um thickness ch1.

	50um ch1	50um ch3	20um ch1
Pulse Height	70 mV	49 mV	43 mV
Jitter	2.9 ps	4.0 ps	4.5 ps

Results of Test Beam Measurement

Jitter at Laser and TB

- measured jitter in the test beam using laser data (Pulse height vs Jitter).
- Sensor type:
  AC-LGAD 50um thickness WB or ACF
- Jitter of Si-Ge ASIC using the test beam
  →**3.4 ps** with ACF bonded
- Jitter of Si-Ge ASIC using the laser
  →**2.9 ps** with wire bonded
- Compared to wire bonding, ACF bonding produces smaller signals.
  →Contact resistance is caused by ACF bonding.



	Test Beam ACF ch1	Test Beam ACF ch3	Laser WB ch1	Laser WB ch3
Pulse Height	60 mV	43 mV	70 mV	49 mV
Jitter	3.4 ps	4.6 ps	2.9 ps	4.0 ps