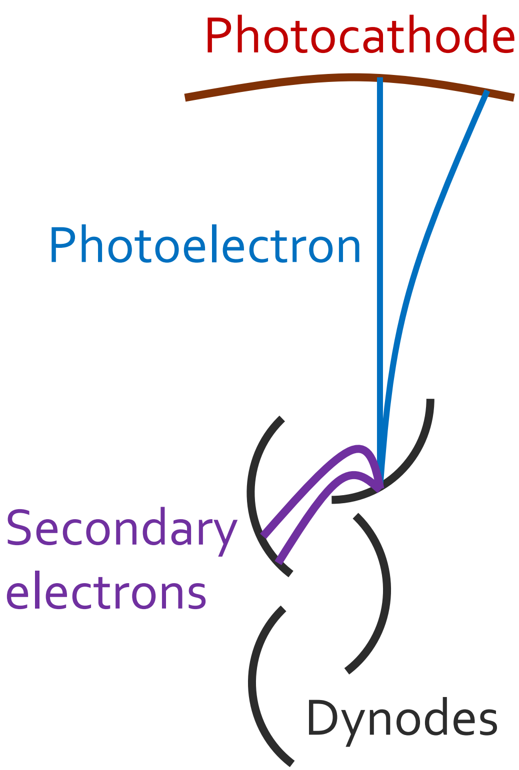
Photodetection with precision timing

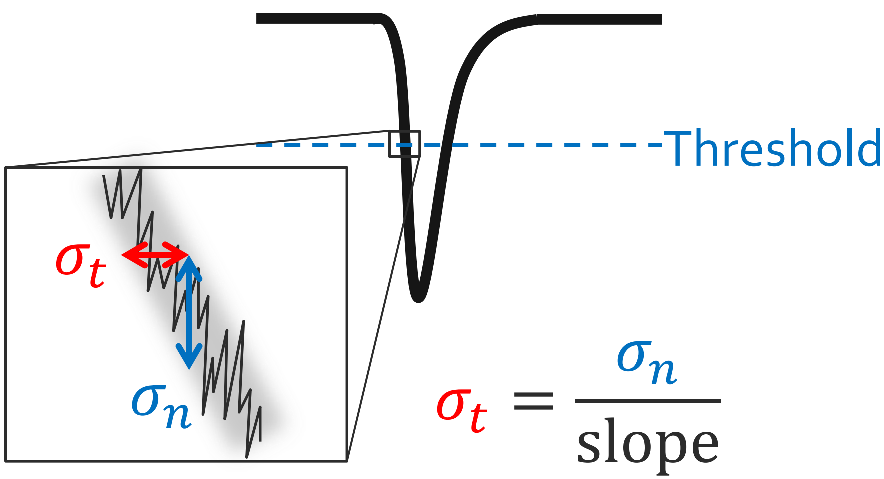
Kodai Matsuoka (KEK, Nagoya)

Factors which dictate time resolution

Transit time spread (TTS) of the electrons

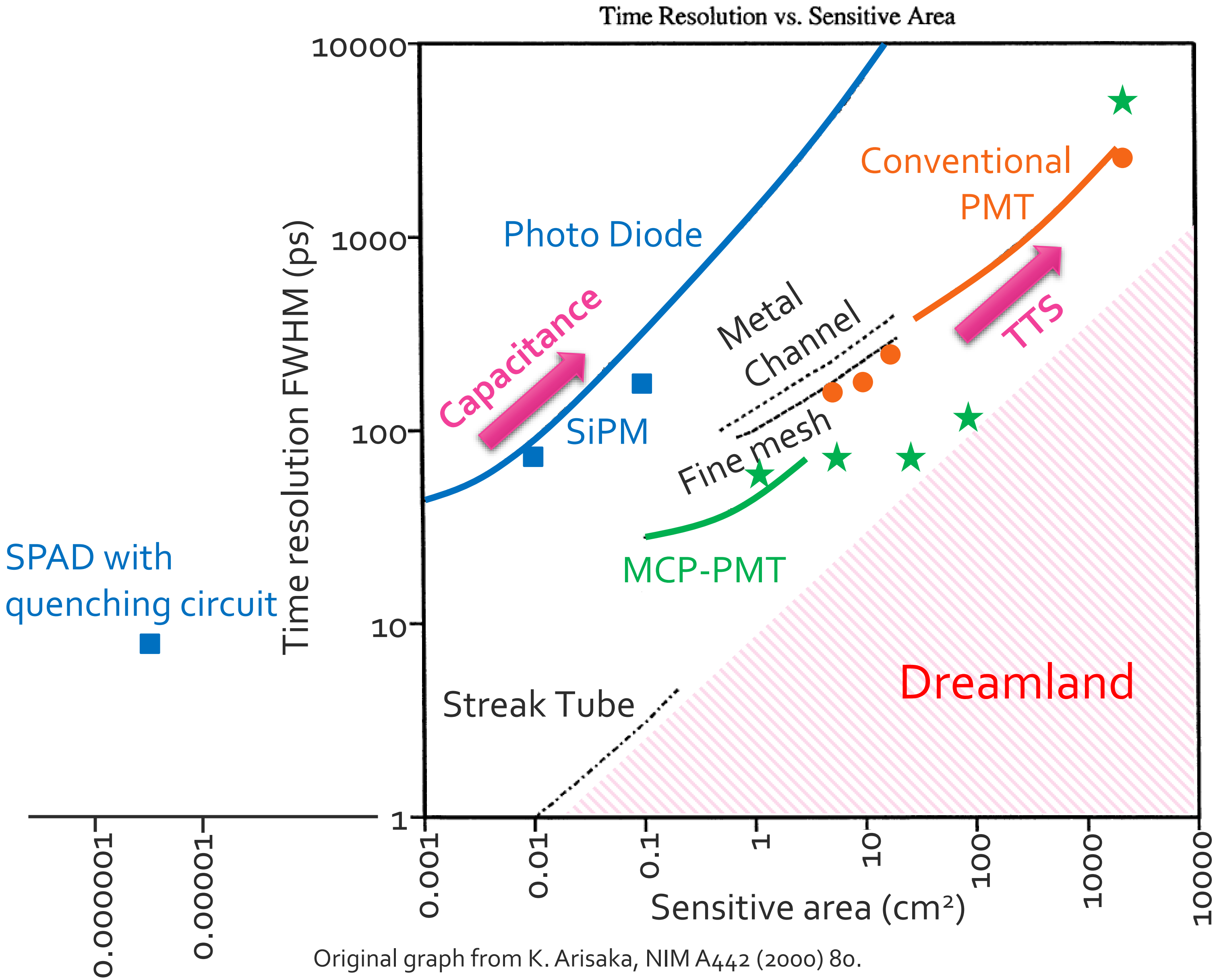


Noise
(fluctuation of the baseline)



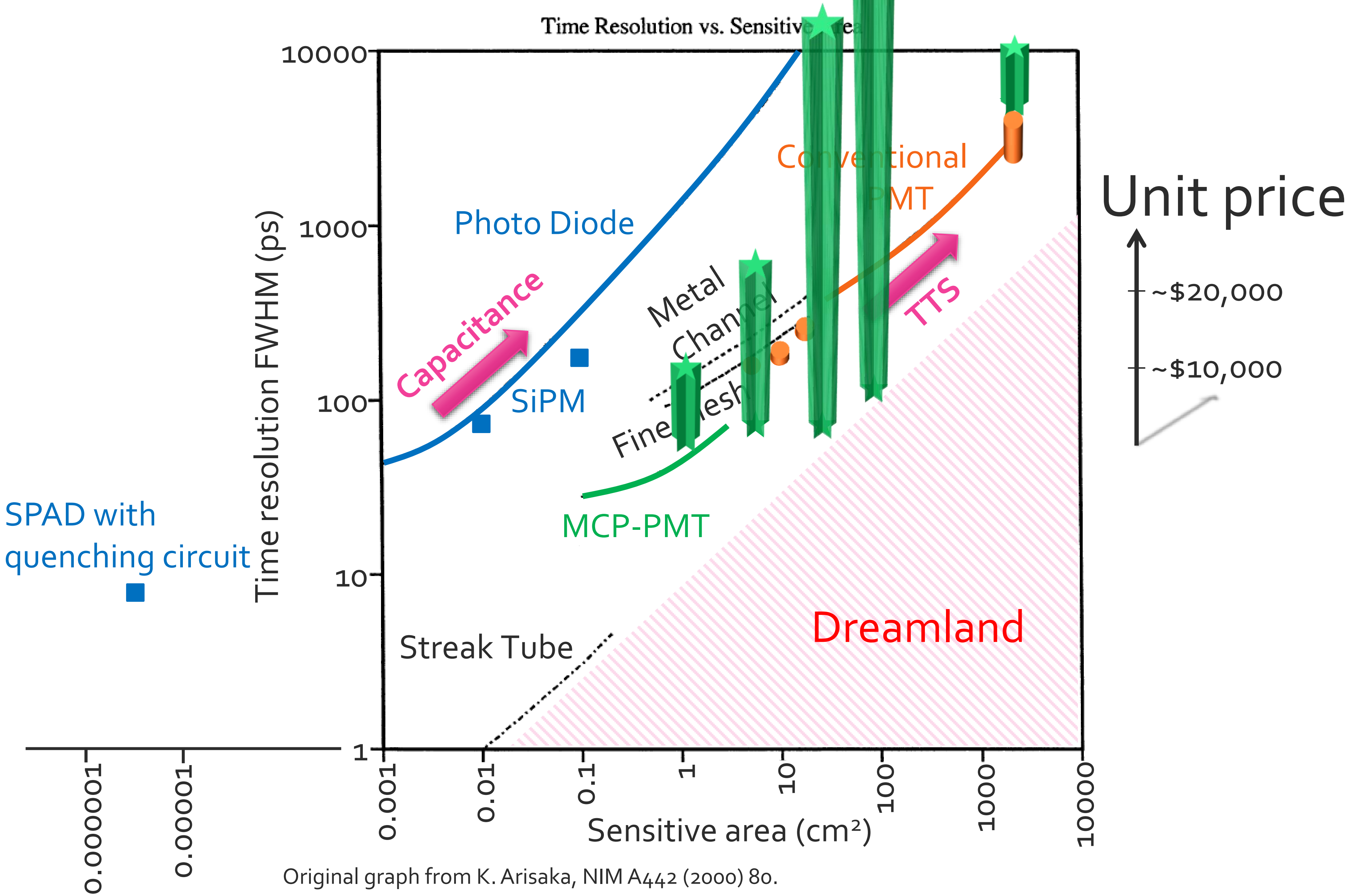
$$\sigma_t = \frac{\sigma_n}{\text{slope}}$$

Single photon time resolution



Original graph from K. Arisaka, NIM A442 (2000) 80.

Single photon time resolution

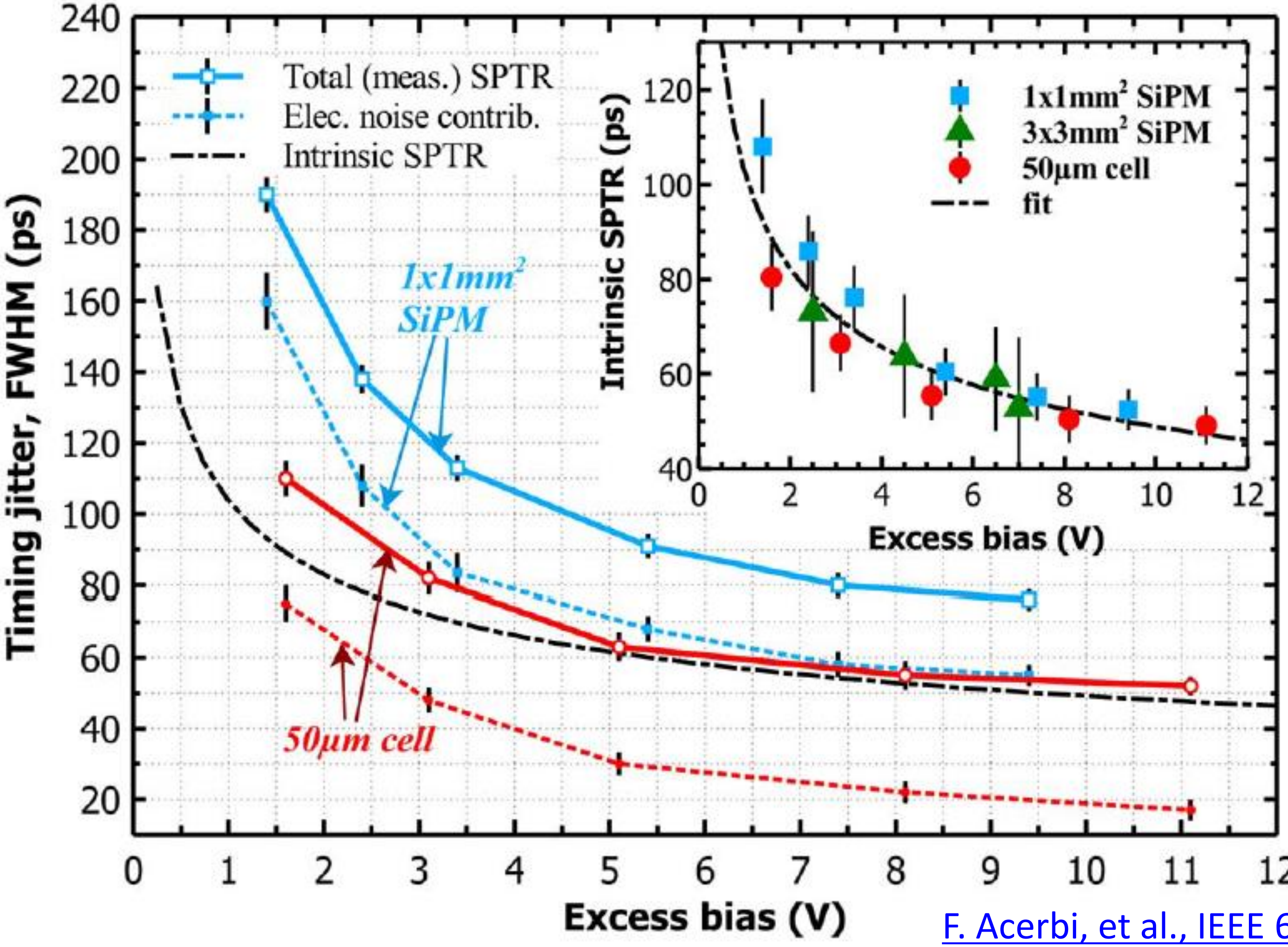


Original graph from K. Arisaka, NIM A442 (2000) 80.

SiPM time resolution

Electronic noise is the dominant limiting factor.

- Larger cell → higher capacitance → slower signal

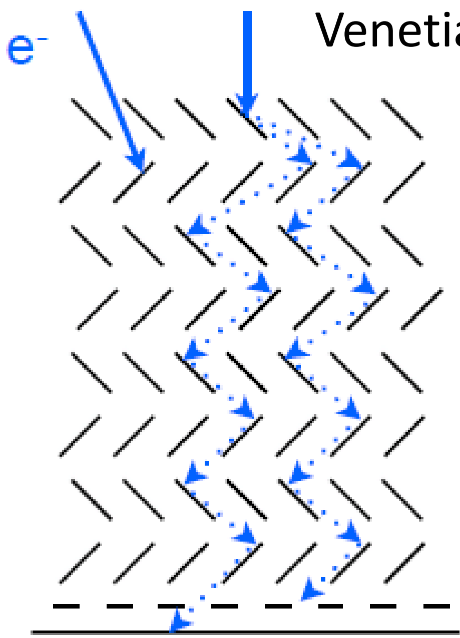


F. Acerbi, et al., IEEE 61 (2014) 2678

Conventional PMT time resolution

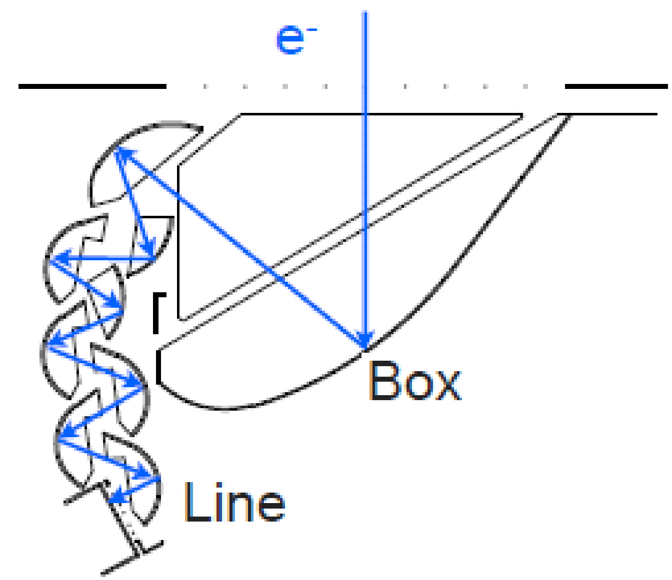
20” PMT（R3600-05）

20” PMT（R12860）



Venetian-Blind

Box-Line dynode



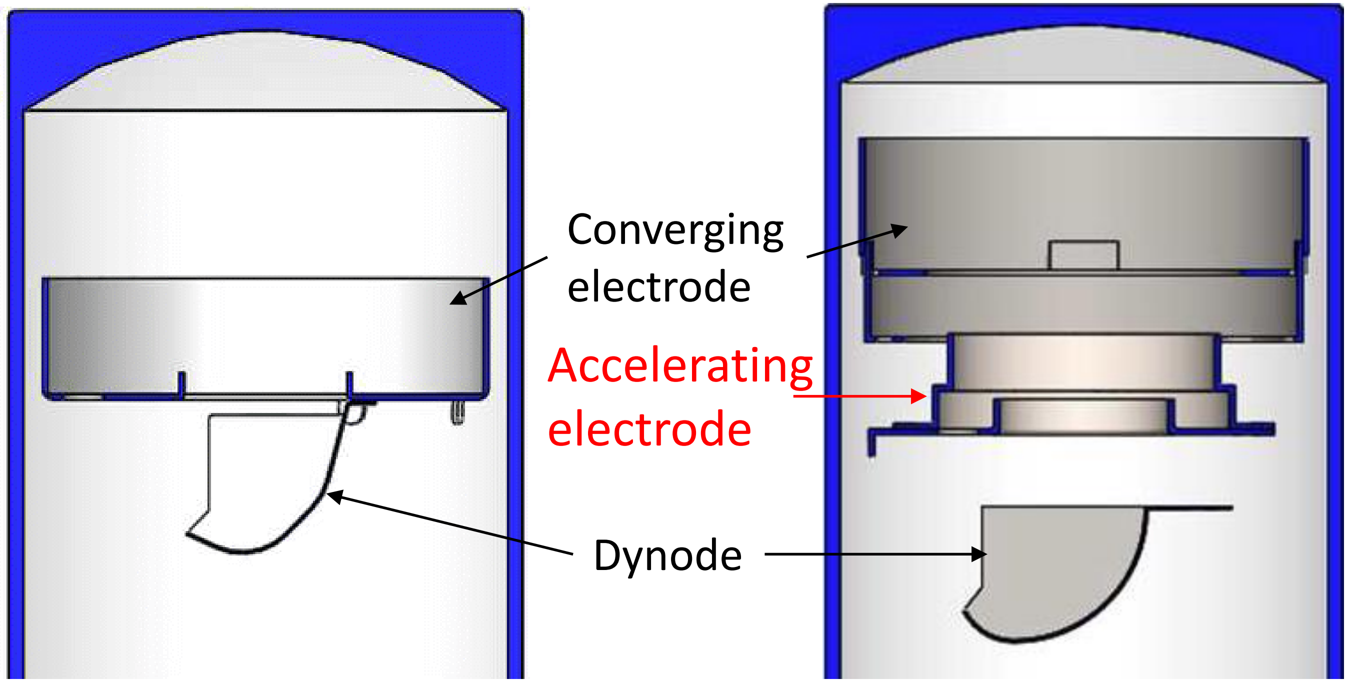
TTS(FWHM):
5.5 ns → 2.7 ns

Conventional PMT time resolution

1-1/8” PMT
（R12845）

Conventional product

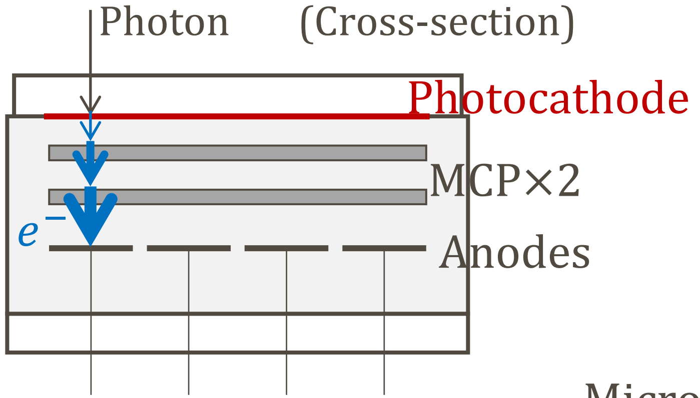
R12845

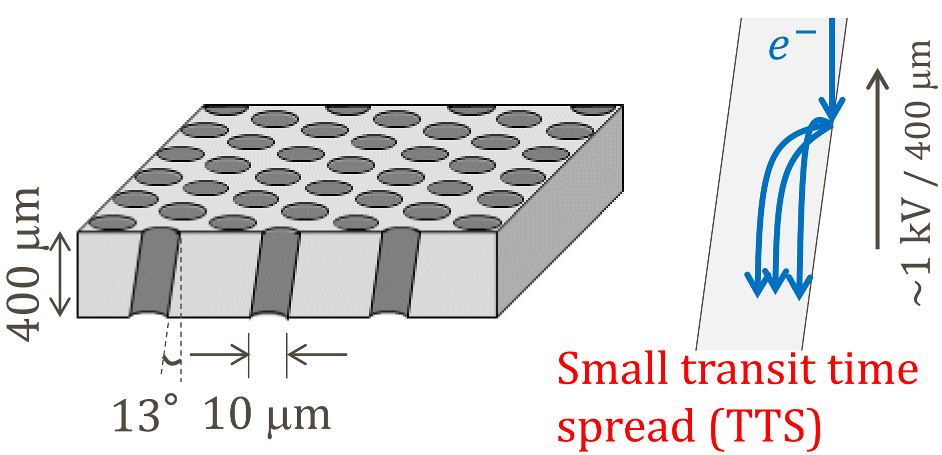


Taken from Kamitani-san’s (HPK) slides

TTS(FWHM): 270 ps → 170 ps

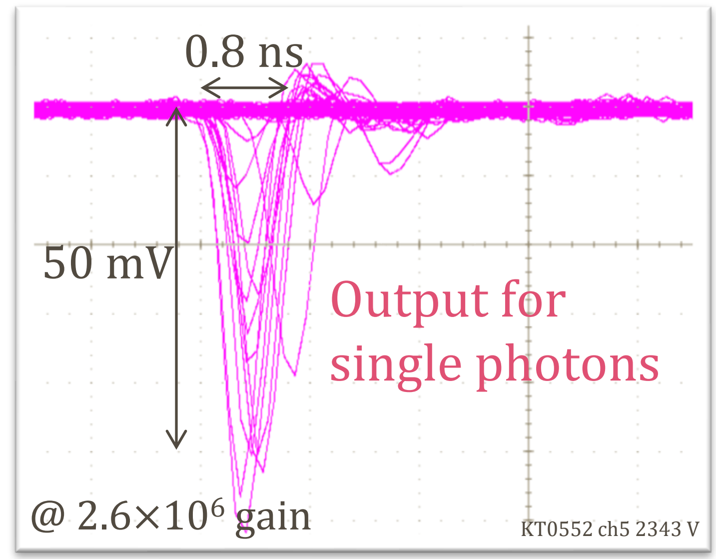
Micro-Channel-Plate (MCP) PMT





(MCP for Belle II TOP)

Oscilloscope (2.5 GHz bandwidth)



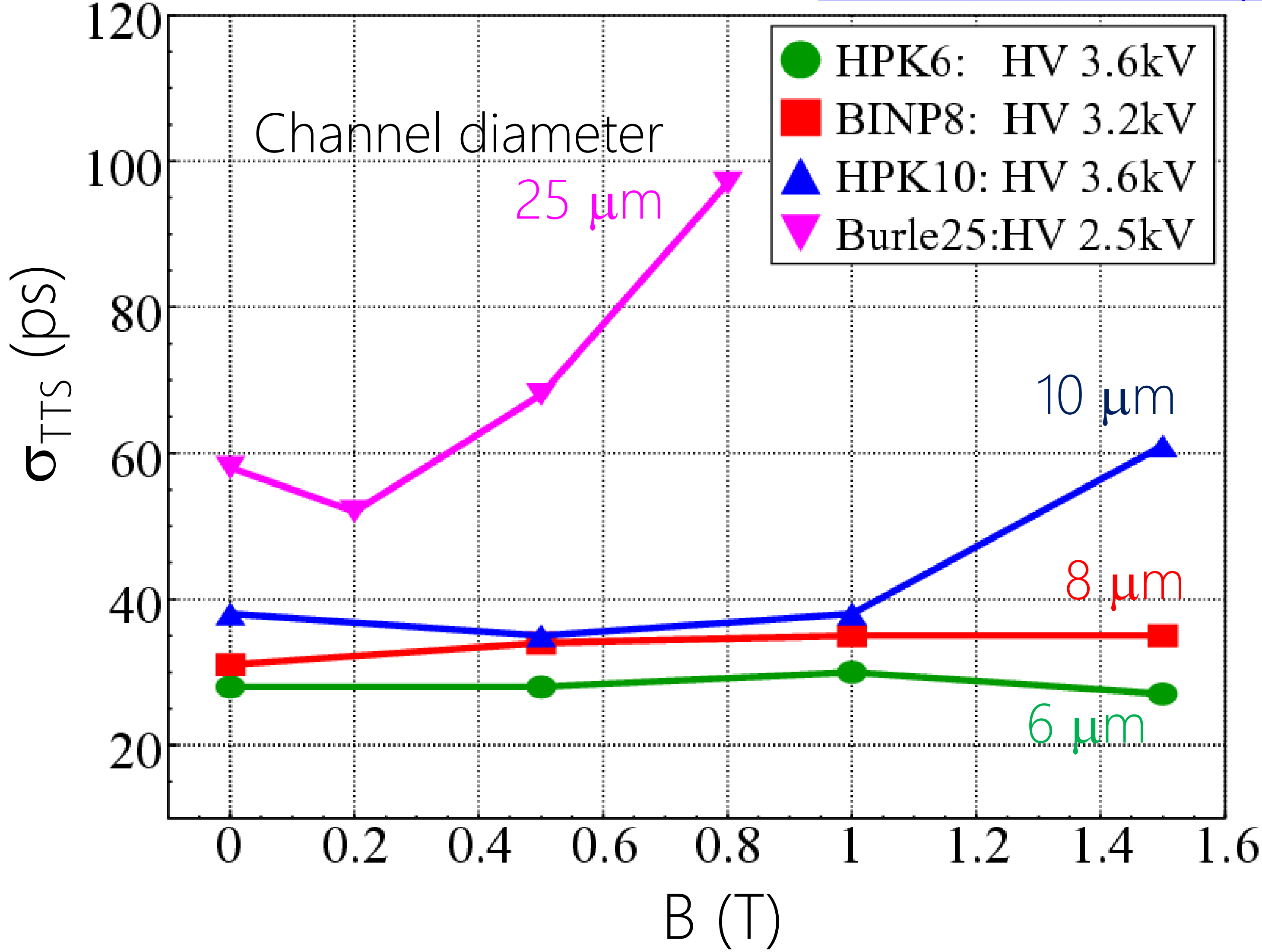
Excellent time resolution ($\sigma\sim30$ ps)

Major drawback:

- Short lifetime of the photocathode
- Cost

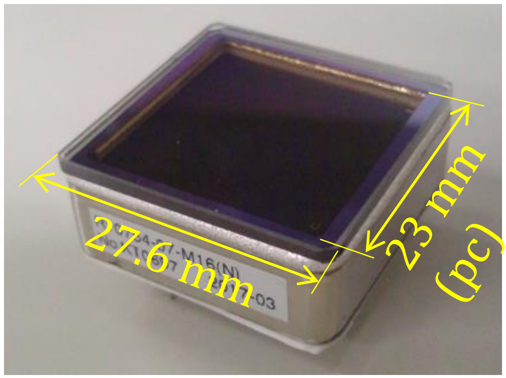
MCP-PMT time resolution

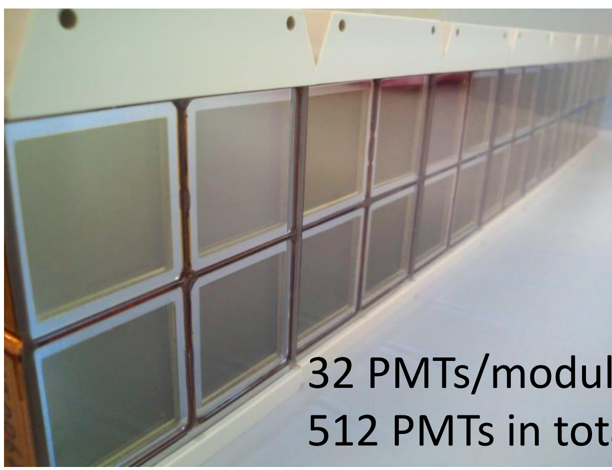
M. Akatsu, et al., NIM A528 (2004) 763



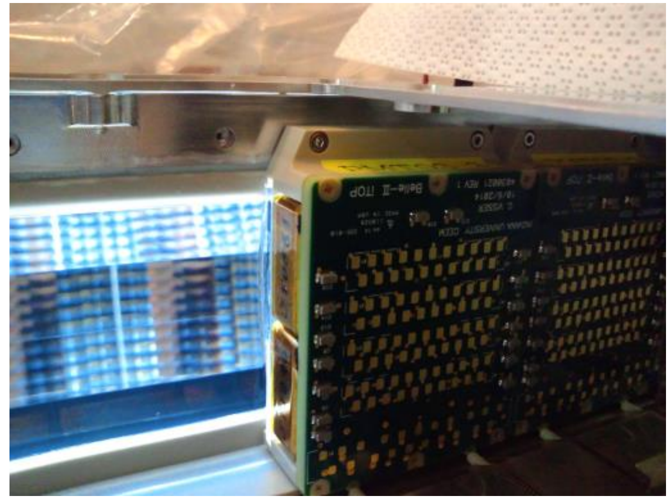
MCP-PMTs for Belle II TOP detector

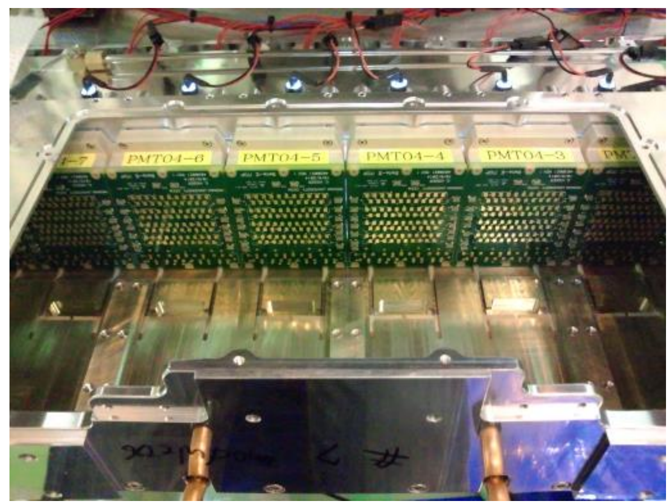
Developed at Nagoya Univ.
in collaboration with Hamamatsu





32 PMTs/module
512 PMTs in total

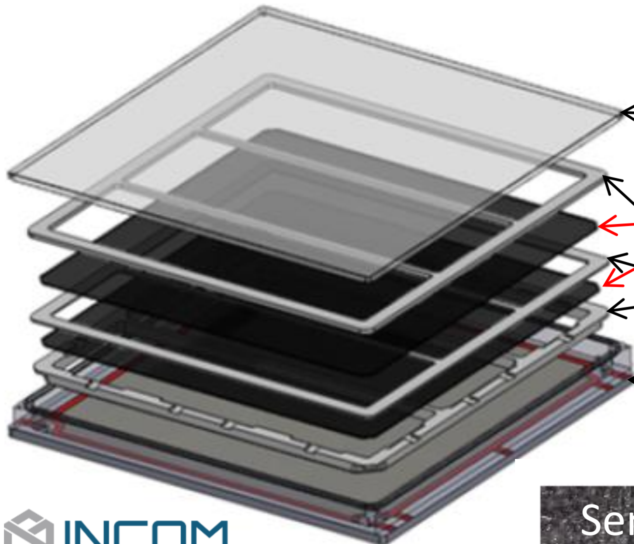




Worked well for TOP since 2016.

Probably MCP-PMTs are the current best choice when
one needs a large photocoverage with time resolution < 50 ps.

LAPPD™ (Large Area Picosecond Photo-Detector)

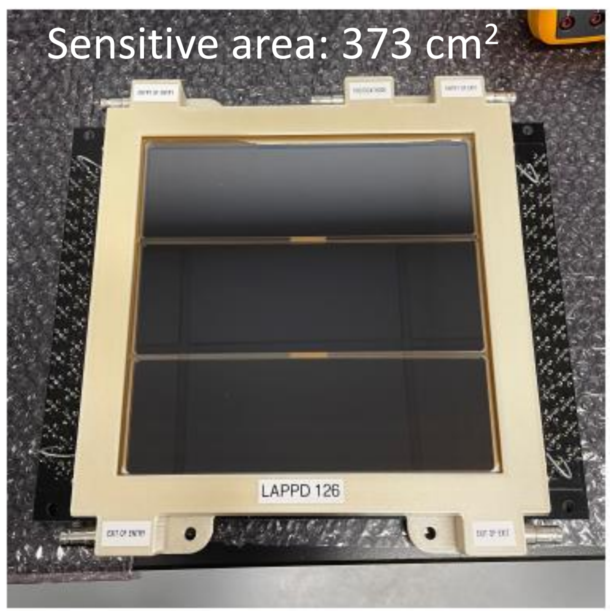


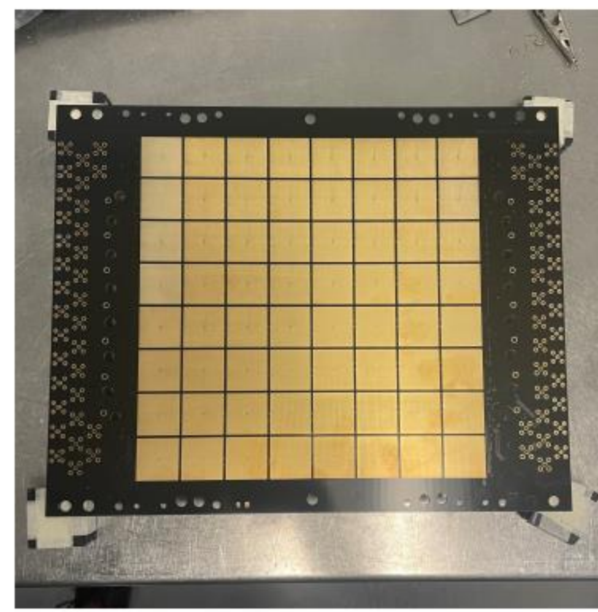
Window + photocathode

203 x 203 mm^2 lead-free ALD glass capillary array MCPs

Glass spacers

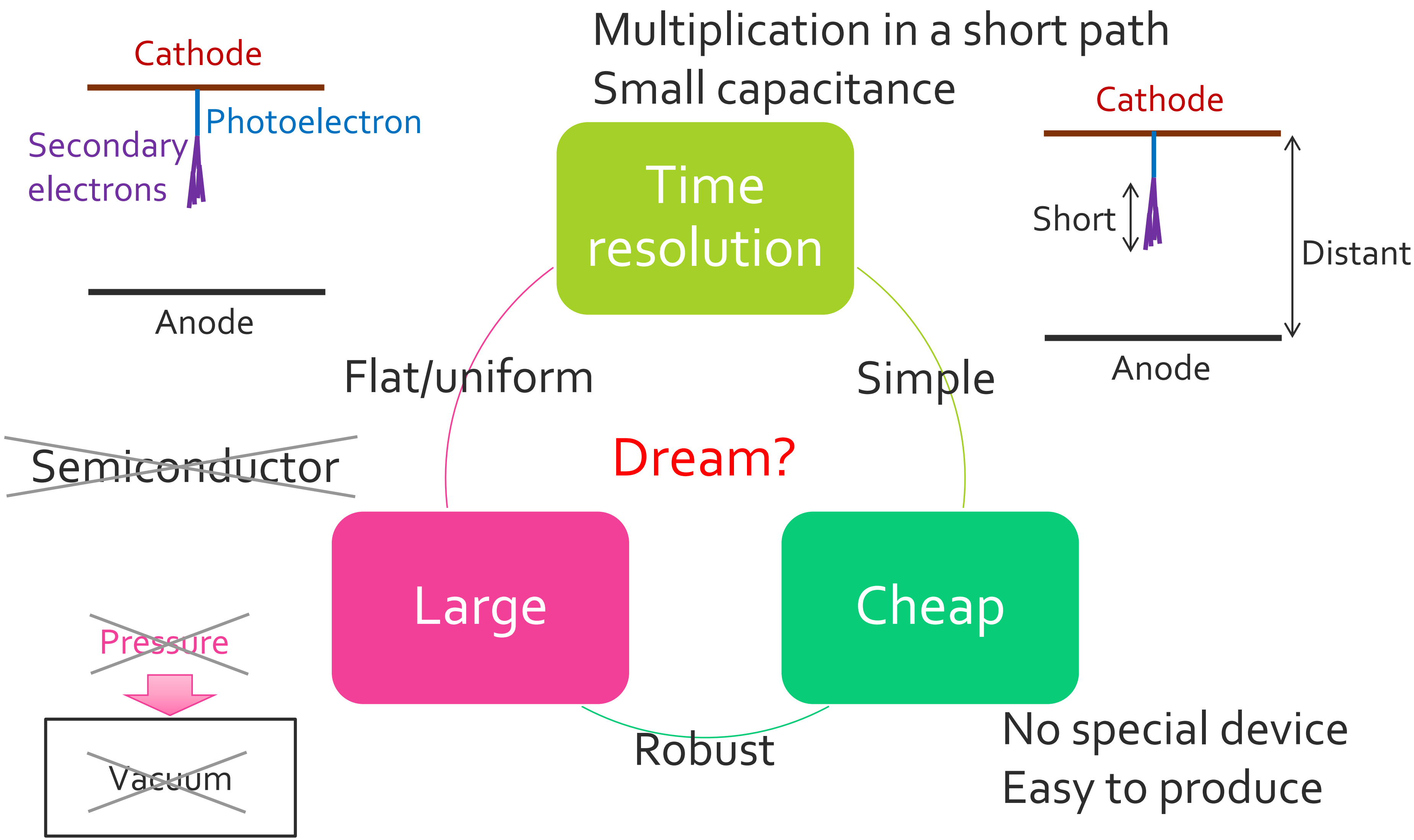
Resistive anode with coupled patterned anode (Gen-II)



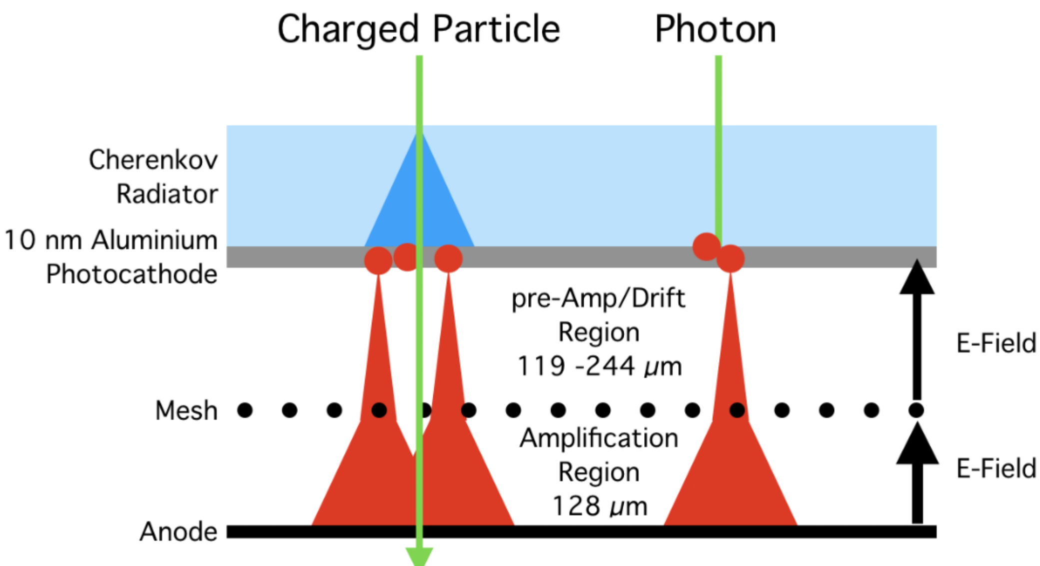


Expect much lower cost per unit area than the other MCP-PMTs.

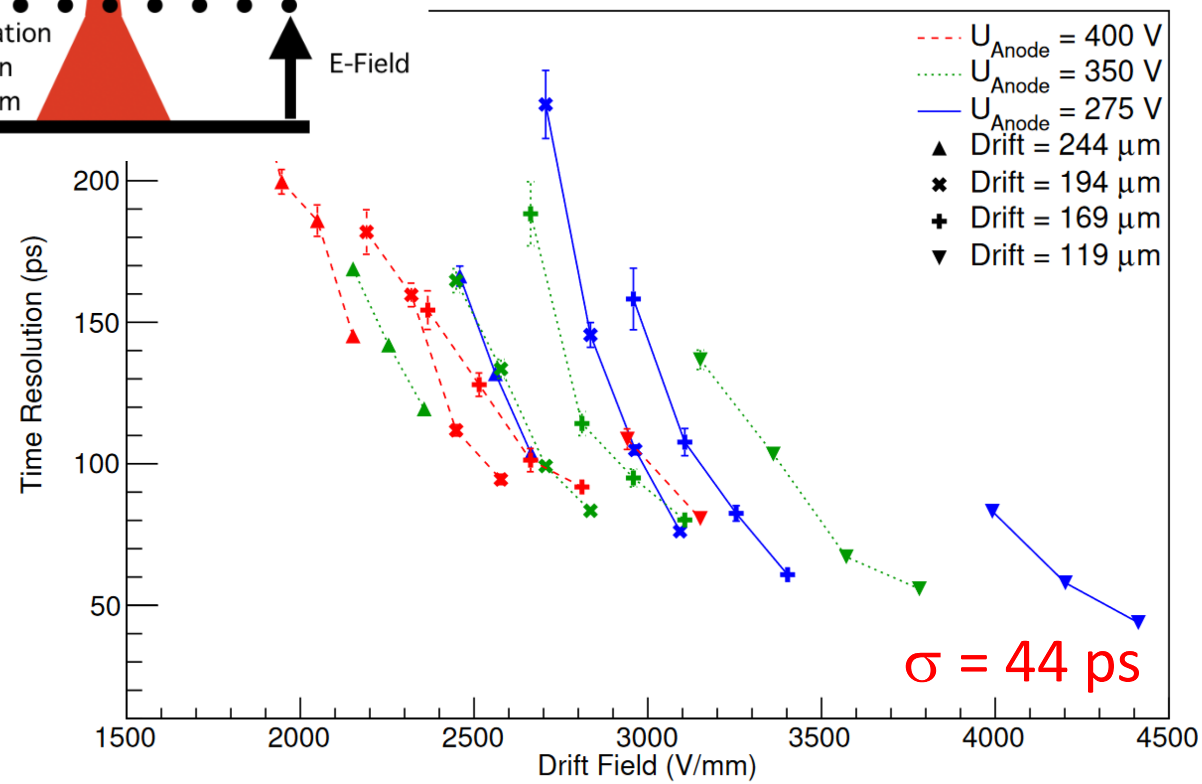
Detector of the trinity?



PICOSEC-Micromegas detector



JINST 15 (2020) C04053

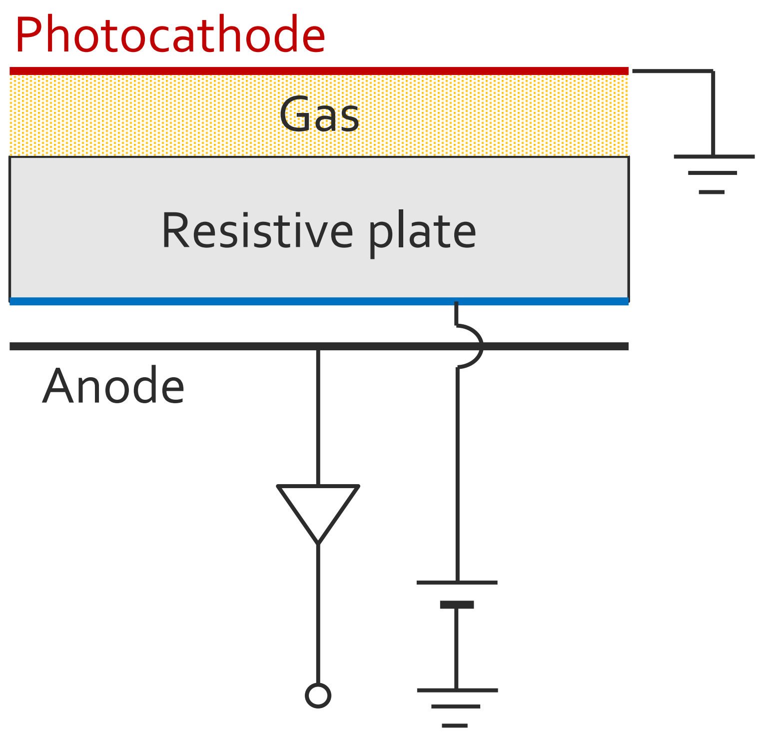


Gaseous Photomultiplier (GasPM)

- **Excellent time resolution, large photocoverage, low cost**

➢ Fast avalanche multiplication process in the gas

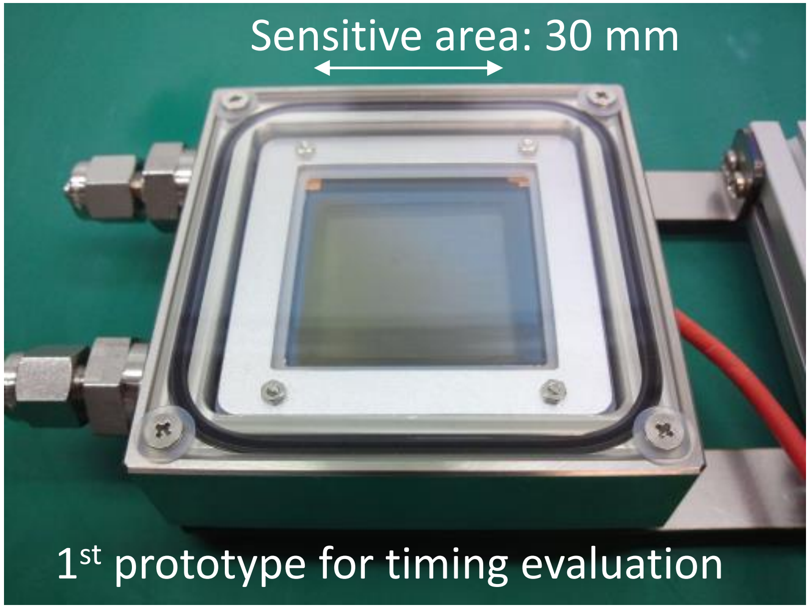
➢ High electric field in the narrow gap without electric breakdown thanks to the resistive plate



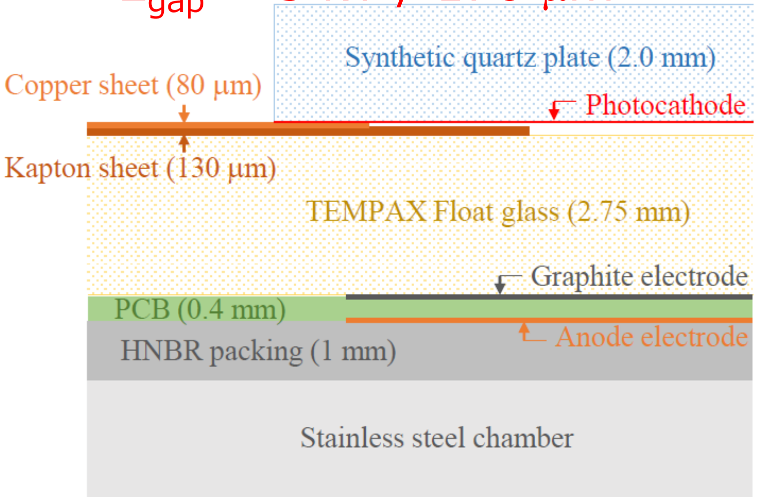
Self-produced GasPM prototype

To have fast iteration, to reduce cost

- LaB_6 photocathode
  - Work function:
    2.3-3.3 eV (clean surface)
    ＋ <1.4 eV (oxidized)
    … Less deteriorated
  - Extremely low QE
- TEMPAX for resistive plate
  - Volume resistivity: 10^{15} Ωcm
    … Hard to breakdown but
    no high-rate capability
- Commercially available cheap components only
- Assembled on a table

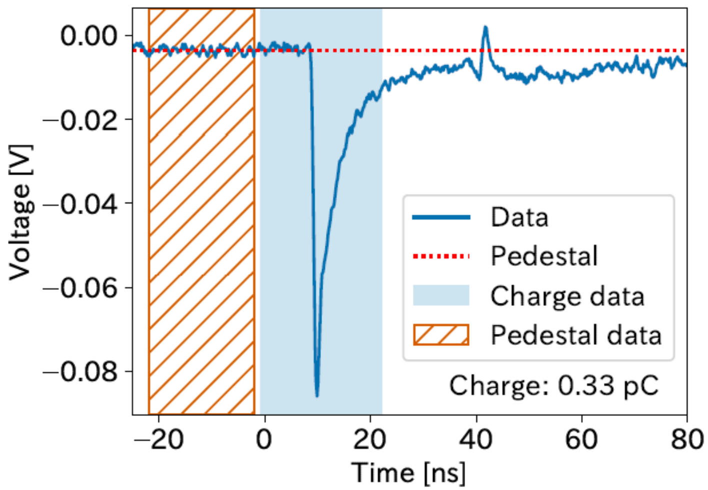


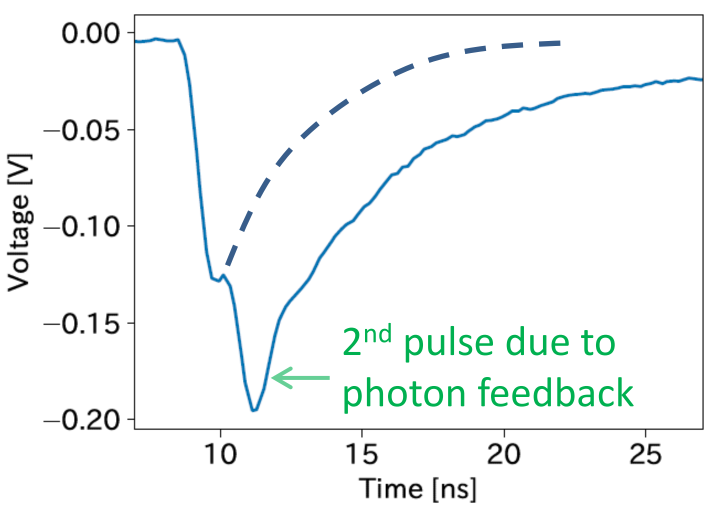
90% R134a + 10% SF_6
E_{gap} = 3 kV / 170 μm

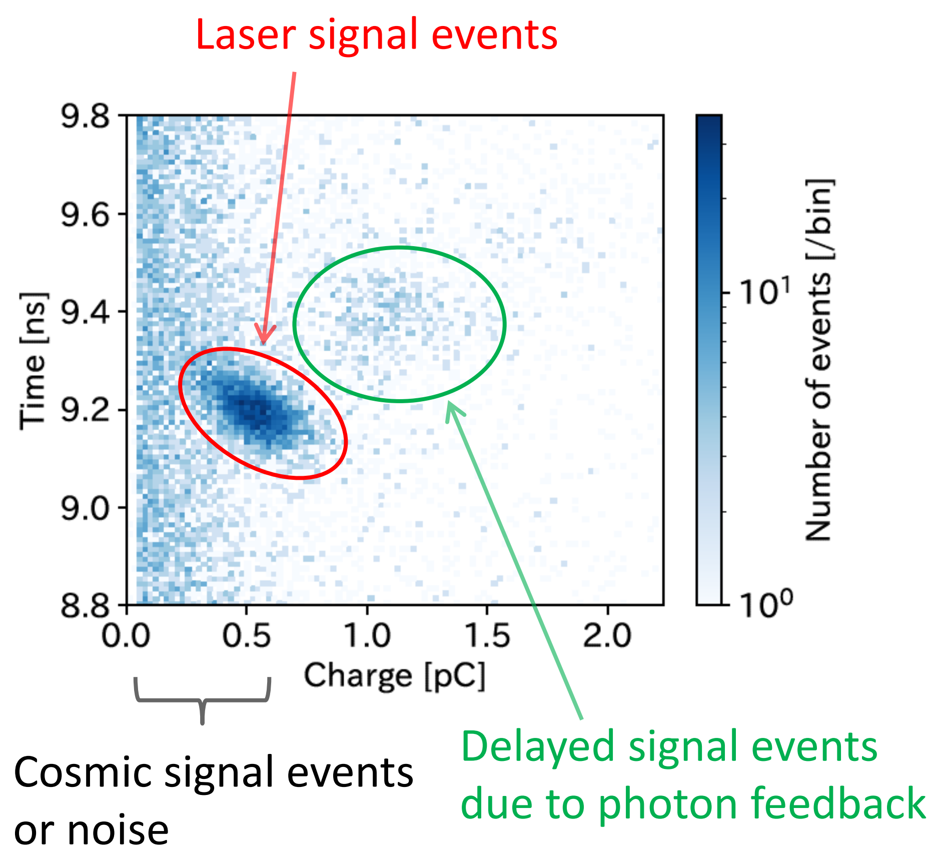


Evaluation with pico-second pulse laser

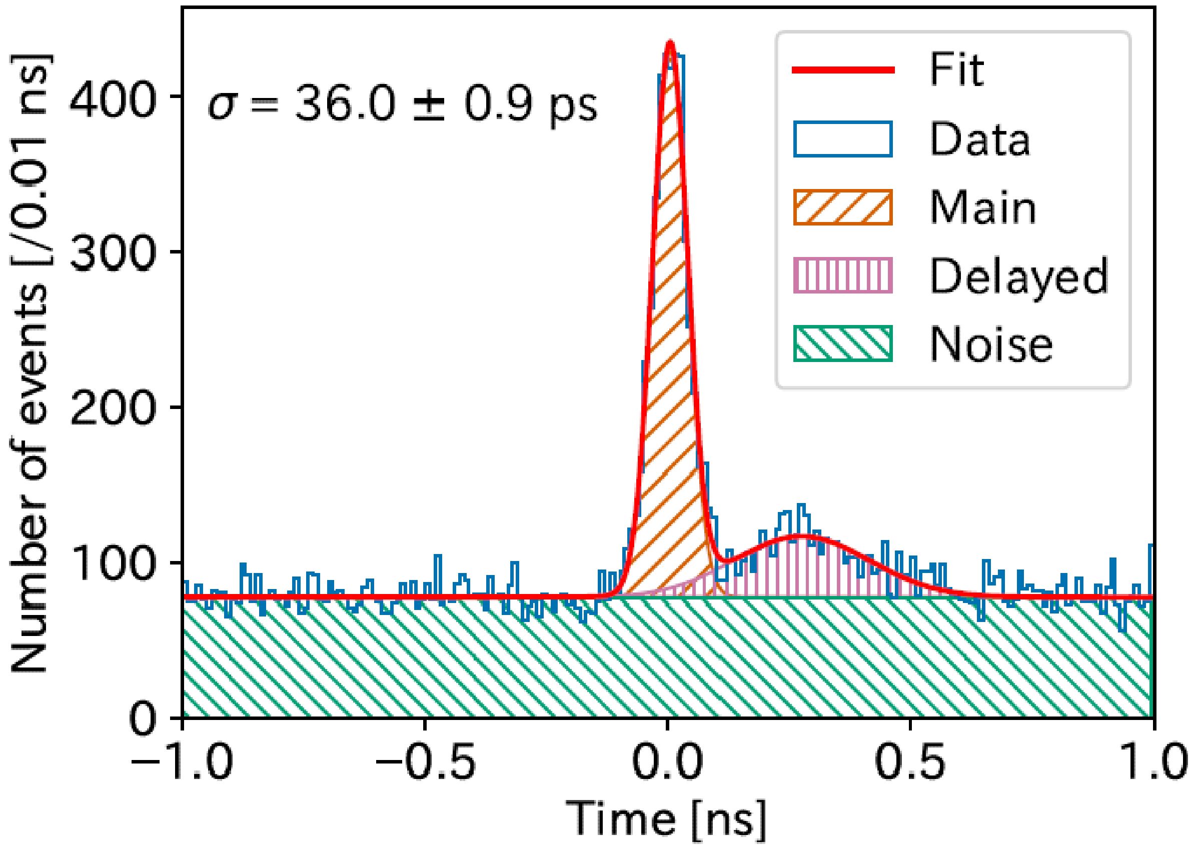
- Laser (λ = 375 nm) at 100 MHz repetition → 0.02 Hz signal
- Read out by a digitizer (DRS4 evaluation board; 5 GSPS, 14-bit ADC)







GasPM time resolution



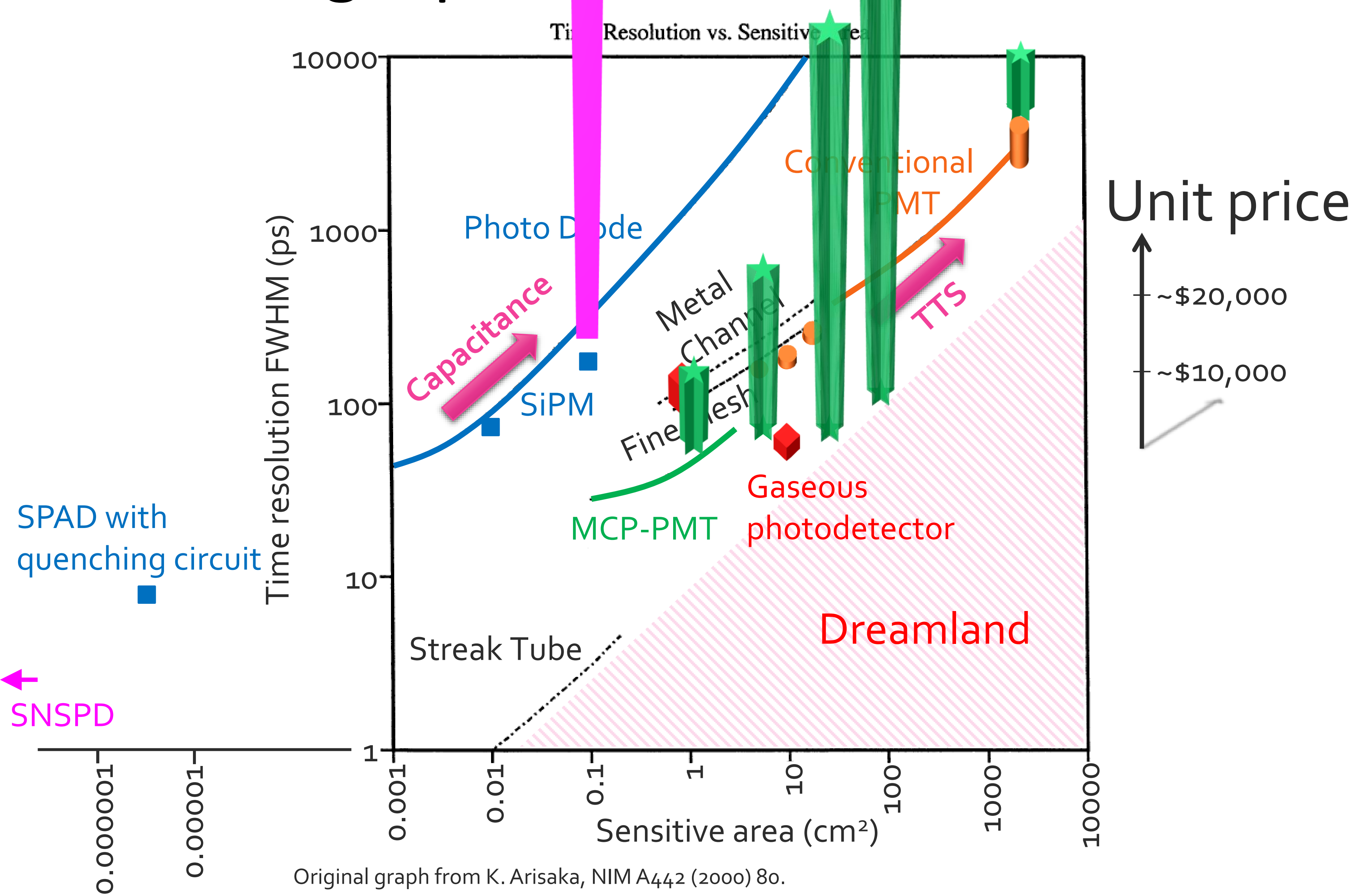
Intrinsic time resolution of GasPM: 25.0 ± 0.9 ps

(better than expensive MCP-PMTs)

- Laser pulse width: 21.8 ± 0.5 ps
- Time resolution of the readout system: 14.0 ± 0.3 ps

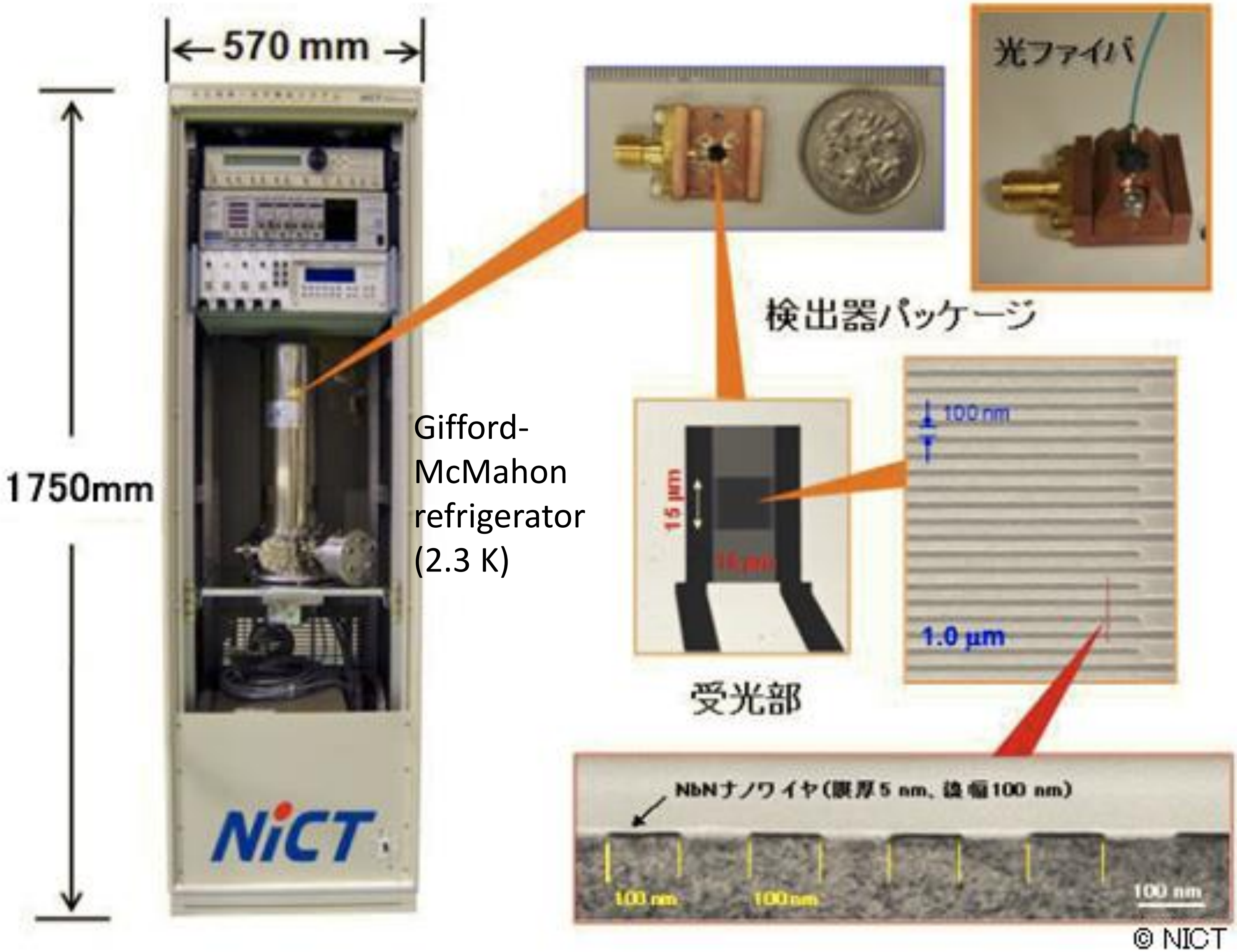
arXiv:2302.12694

Single photon time resolution



Original graph from K. Arisaka, NIM A442 (2000) 80.

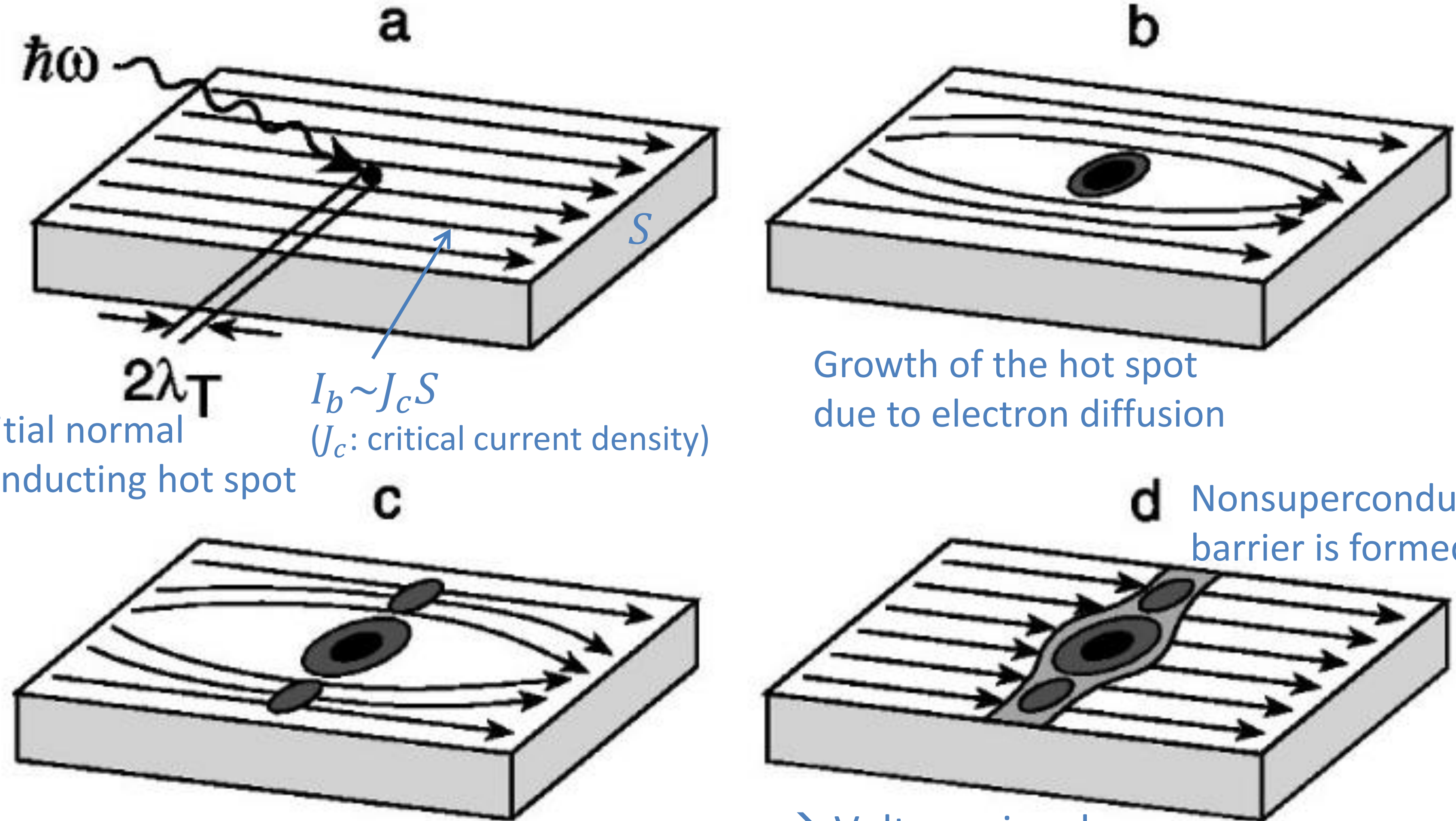
Superconducting nanowire single-photon detector (SNSPD)



SNSPD working principle

Appl. Phys. Lett. 79 (2001) 705

$\hbar\omega \gg 2\Delta$ (superconducting energy gap = 10^{-2}- 10^{-3} of semiconductors)



Initial normal conducting hot spot

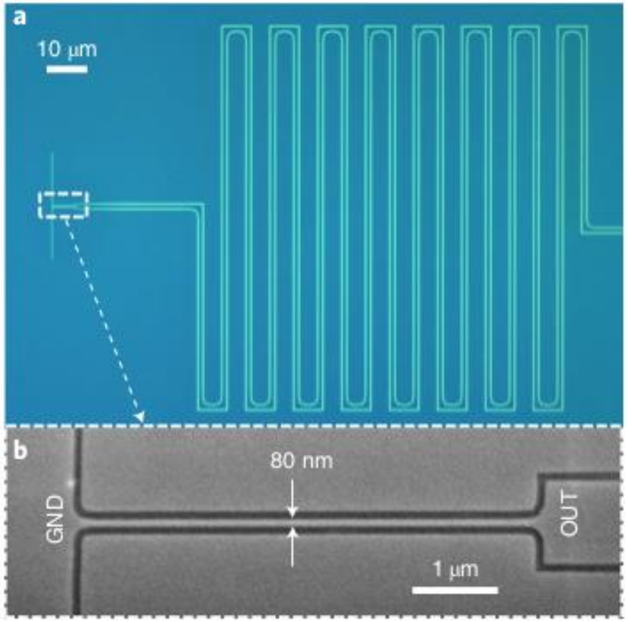
$I_b \sim J_c S$
(J_c: critical current density)

Growth of the hot spot due to electron diffusion

Nonsuperconducting barrier is formed

→ Voltage signal

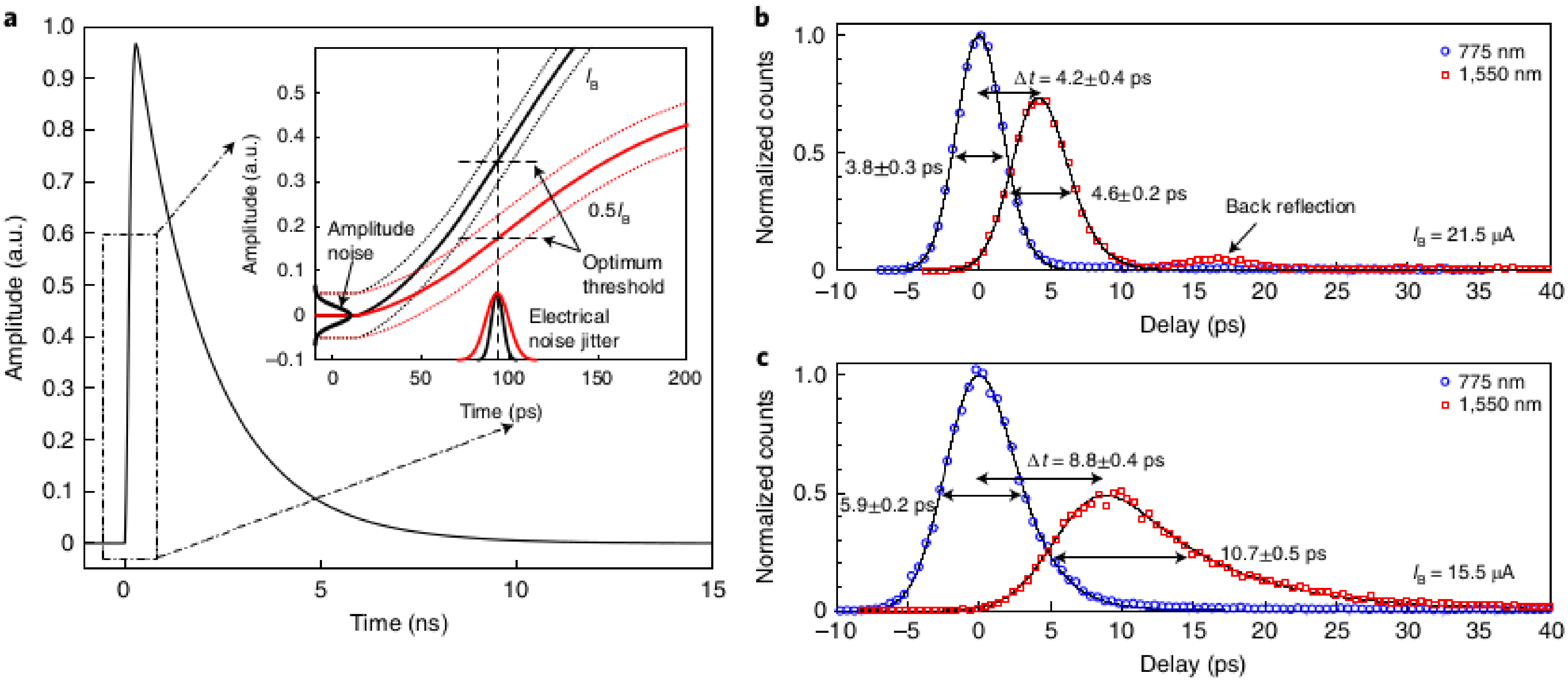
e Hot spot heals itself due to energy loss of electrons by electron-phonon scattering



SNSPD time resolution

Free-running single-photon detector with the best time resolution: 2.6 ps (FWHM) at 532 nm

[Nature Photonics, 14 (2020) 250]



Summary (personal comments)

- If you only need picosecond time resolution, you have several choices of photodetectors. Each detector has different pros and cons (time resolution, sensitive area x efficiency, cost). There are no perfect photodetectors best in all aspects.
- Gaseous photodetectors could potentially outperform the other "conventional" photodetectors.
  → Our R&D of GasPM
  - 25 ps single photon time resolution was demonstrated.
  - More R&D needed for application in HEP experiments.
- SNSPD could potentially become perfect in far future.
- To achieve sub-picosecond time resolution, "novel" working principle of photodetection like SNSPD will be required.