Review of single photon imaging techniques with fast timing for applications in space and particle physics, and the life sciences

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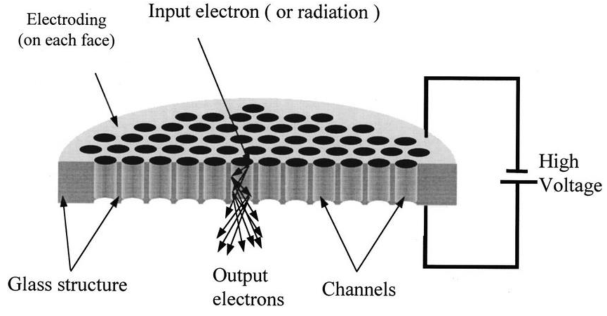
Scope

- Vacuum tube devices
  - Imaging and timing with MCP detectors
  - MCP-based Imaging photomultipliers
  - Hybrid MCP-based devices
- Solid state devices
  - Silicon photomultiplier arrays – CTA SST camera
  - Digital SiPMs
  - Large format SPAD Arrays
- NOT A COMPREHENSIVE LIST

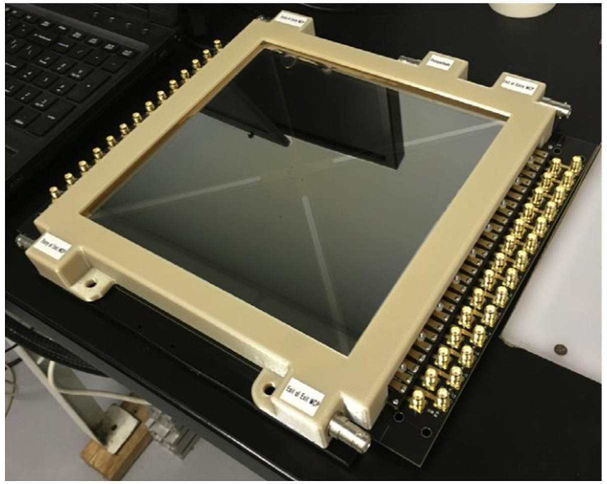
Imaging and Timing with MCPs

- Monolithic array of miniature electron multipliers
- Intrinsic imaging capability – with suitable readout
- Large formats available
- Miniaturization → improved timing cf. conventional PMTs
  - SPTR ~30 ps rms
- But:
  - Broad pulse height distribution
  - Limited lifetime/charge extraction
  - Vacuum tube requirement
  - Photocathode limitations
  - High voltage

MCP schematic

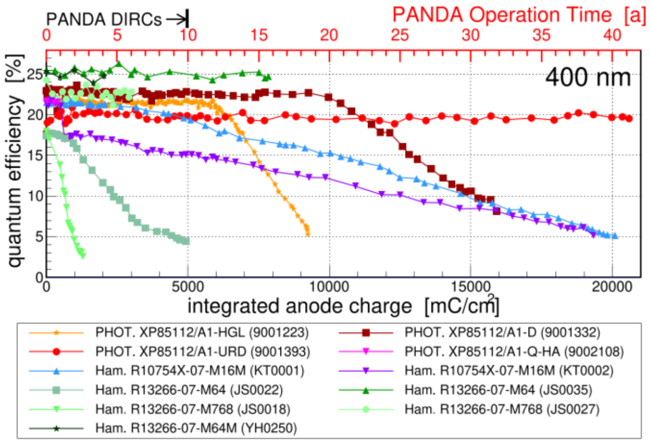


LAPPD 195 mm × 195 mm

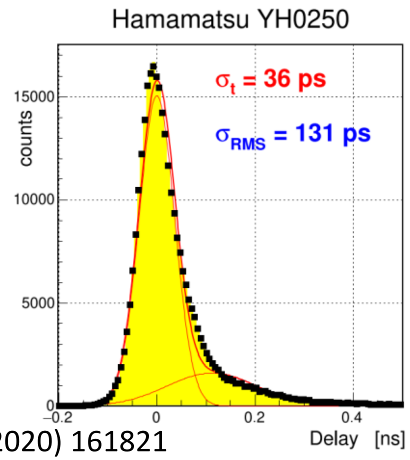


Minot, NIMA 936 (2019) 527–531

Photocathode lifetime



Time resolution



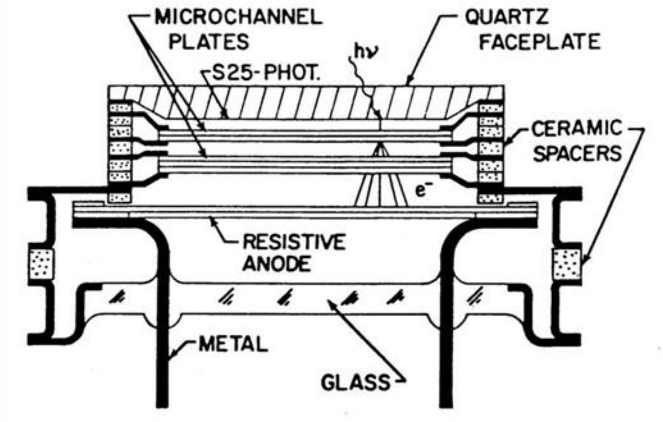
Lehmann, NIMA 952 (2020) 161821

MCP-based Imaging photomultipliers

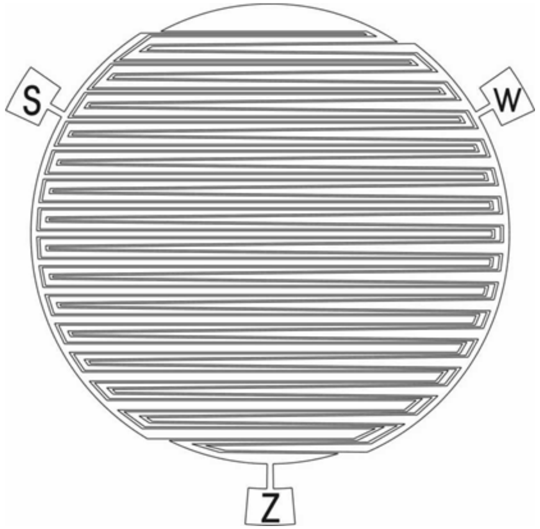
Direct electronic readouts

- Global charge division
  - Resistive anode,
  - Wedge and strip, Vernier anode
  - Delay line
- Features:
  - Low electronics channel count – originally great advantage
  - Flexible format, custom manufacture
  - But serial event processing – limits count rate (especially as electronics improve)

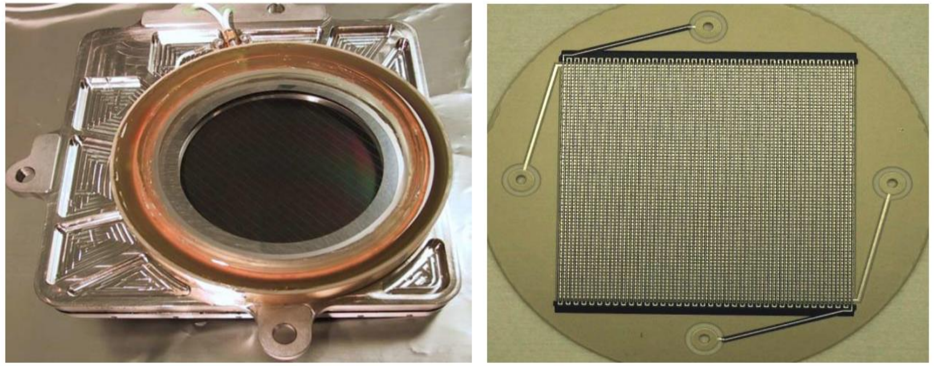
Ranicon detector – resistive anode



Wedge & strip anode



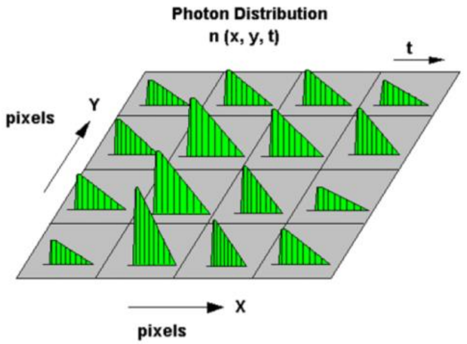
GALEX double delay line DDL detector

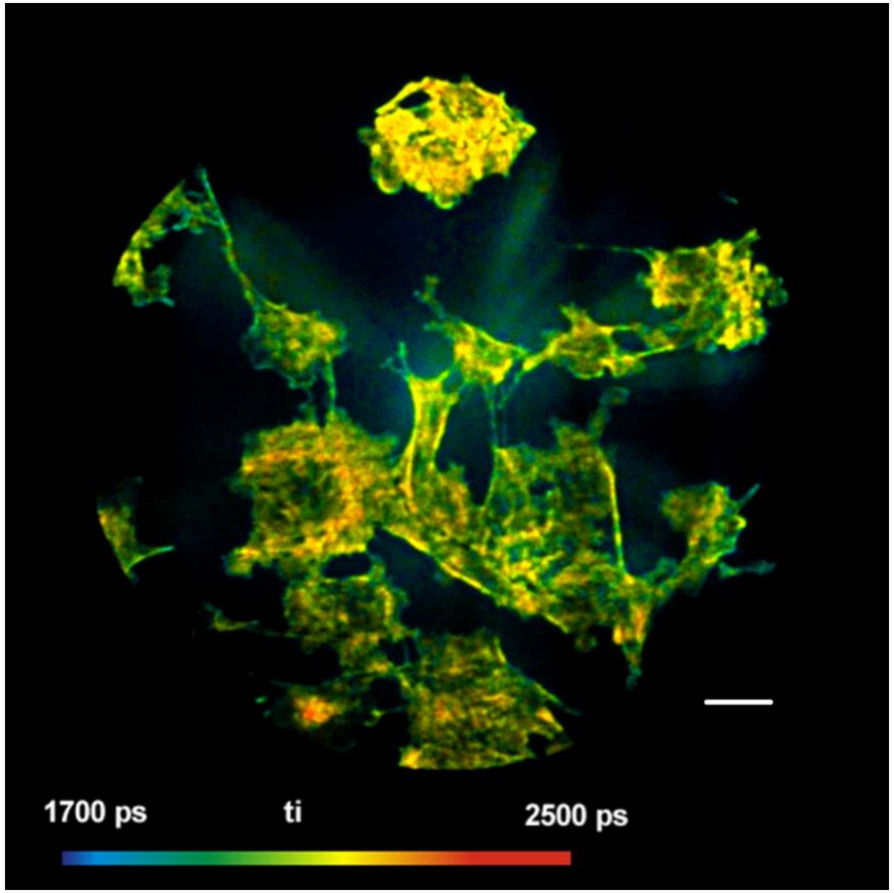


MCP-based Imaging photomultipliers

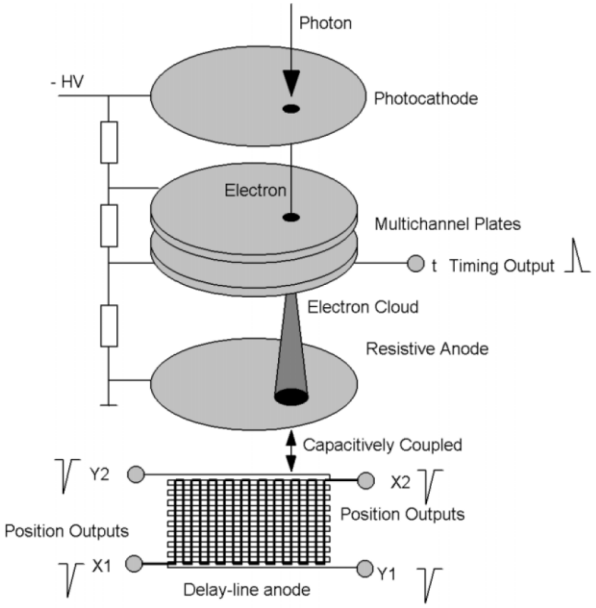
Direct electronic readouts

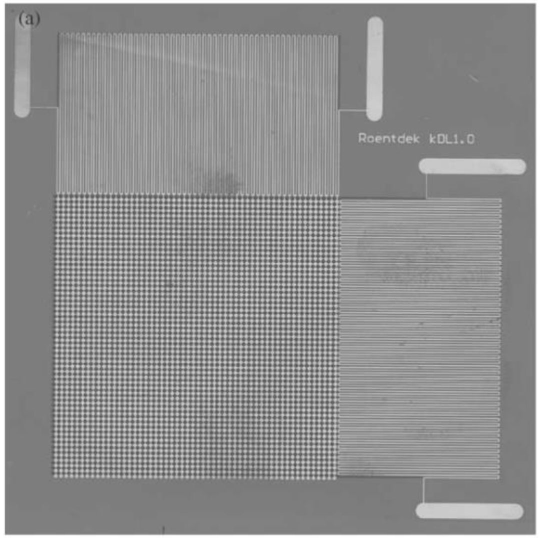
- Crossed Delay Line
  - Wide-field TCSPC FLIM
  - Single photon x,y,t → fluorescence decay time





Hirvonen, RSI 87, 093710 (2016)

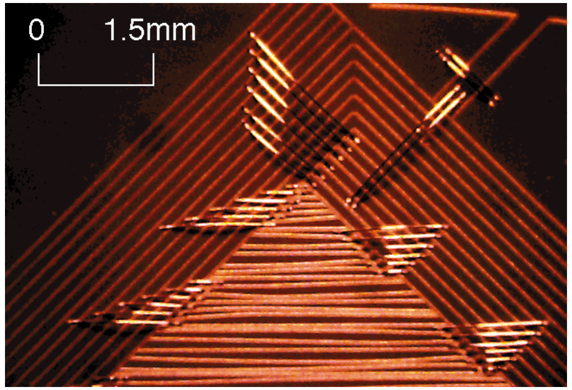




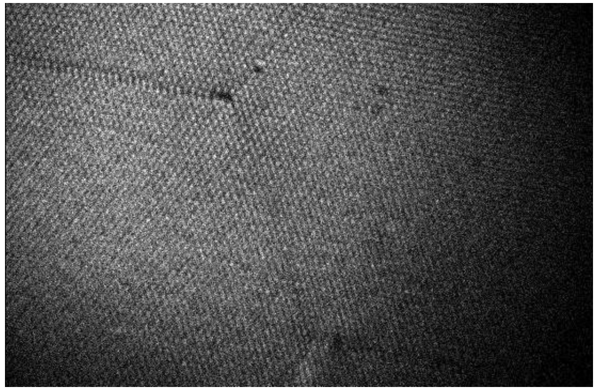
MCP-based Imaging photomultipliers

Direct electronic readouts

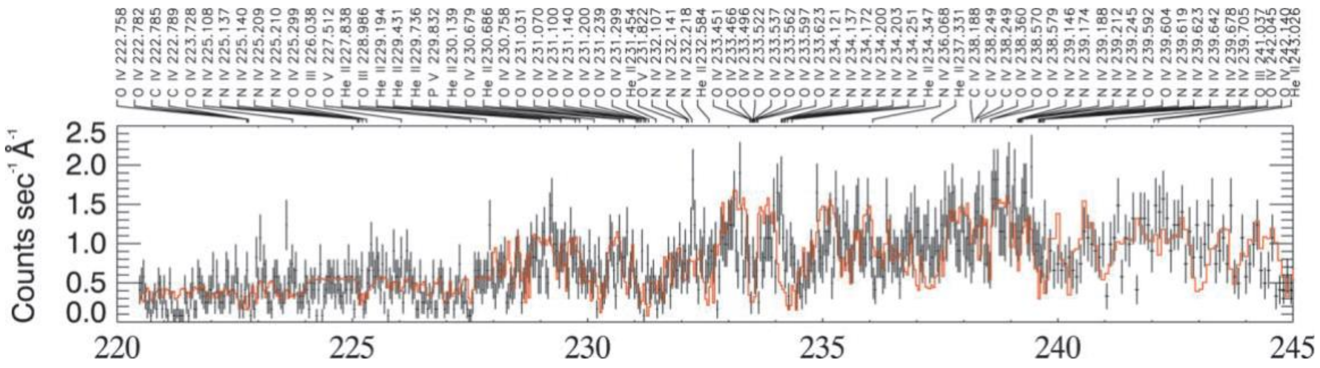
- Vernier Anode
  - UV Astronomy - Spectroscopy
  - Cyclically varying electrodes
  - Utilise a Vernier position encoding technique
  - Spatial resolution greater than charge measurement accuracy
  - Flight heritage
    - Leicester/MSSL J-PEX sounding rocket EUV spectrometer



Close-up of the nine-electrode pattern



MCP pore limited image resolution



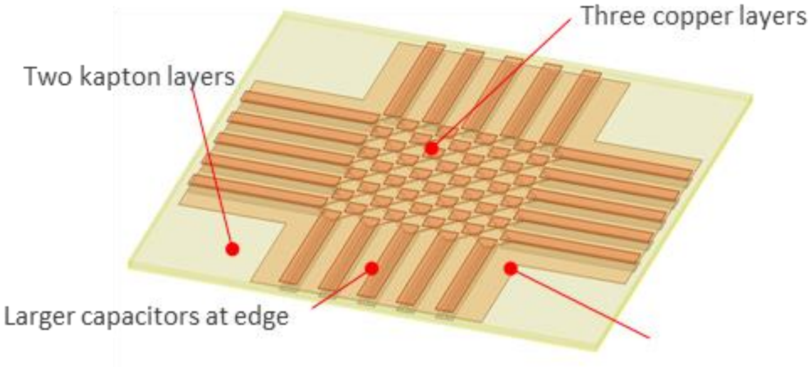
MNRAS 362(4), pp. 1273-1278

Conneely, Proc. SPIE (2013), 8859, 88590W

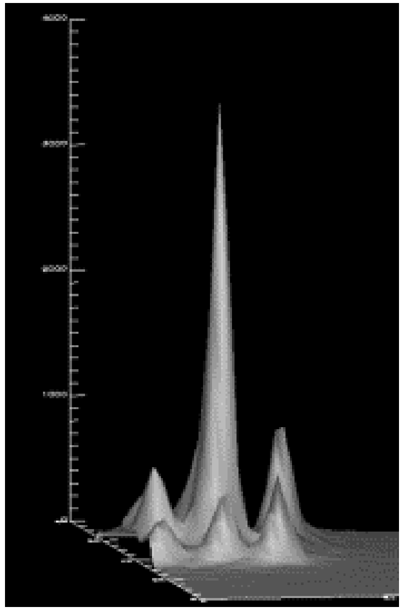
MCP-based Imaging photomultipliers

Direct electronic readouts

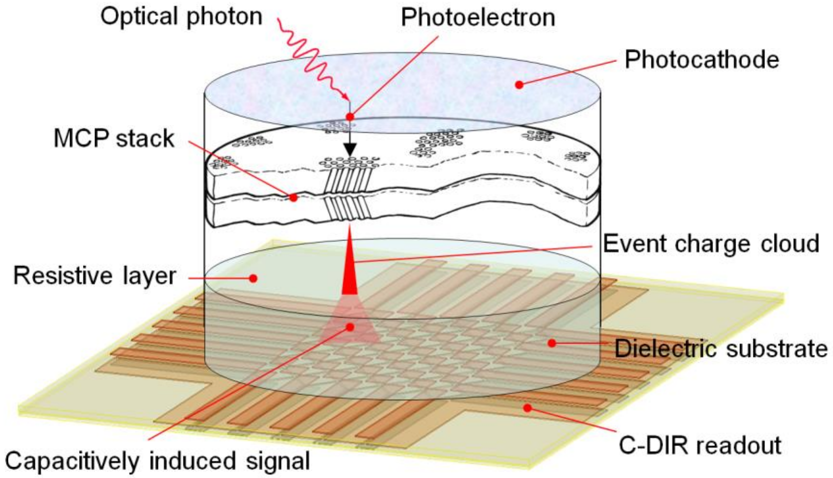
- Capacitive division readout (C-DiR)
  - Capacitively coupled electrode array
  - Signal collected at 4 corner nodes
  - Low capacitance array – high speed
  - Can exploit full MCP timing potential
  - Spatial resolution greater than charge measurement accuracy
  - Flight heritage
    - Leicester/MSSL J-PEX sounding rocket EUV spectrometer



Schematic of the C-DiR readout



3 x 3 1 mm pitch pinhole mask imaged using ToT with NINO + HPTDC electronics

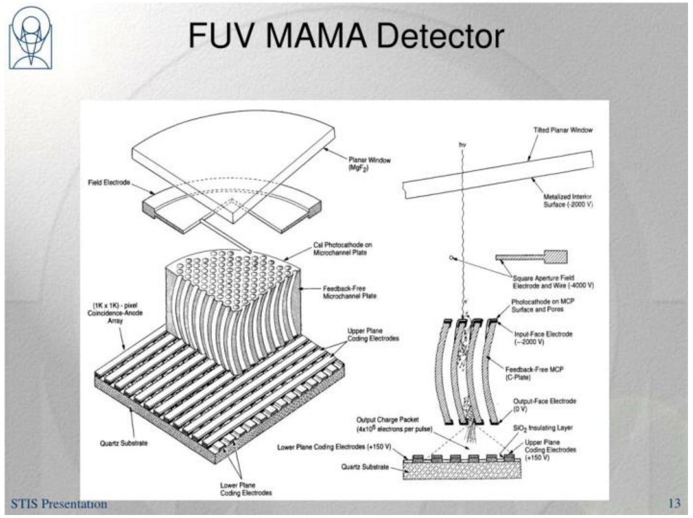


Schematic of a C-DiR-based MCP intensifier

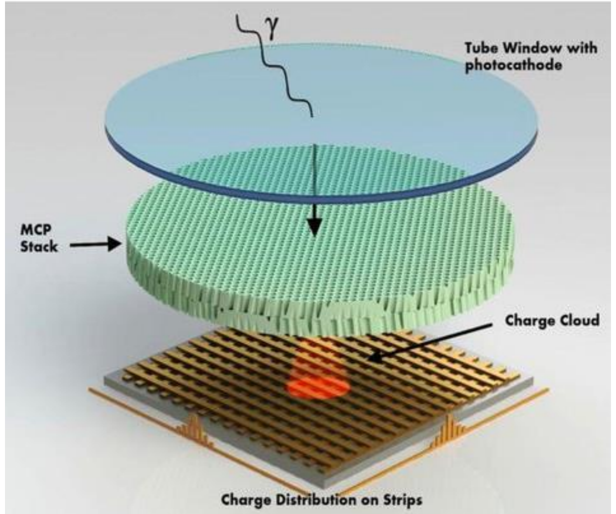
MCP-based Imaging photomultipliers

Direct electronic readouts

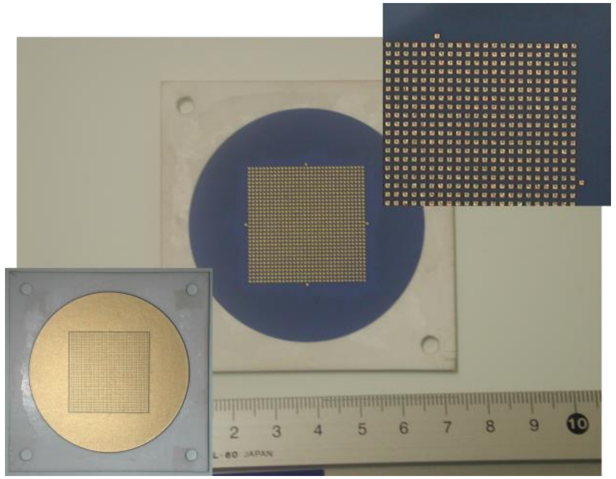
- Localised charge division
    - Pixelated electronic readout
    - Strip readout –cross-strip, (began with MAMA on HST)
- Features
    - Requires much higher channel count
    - Finer structure – manufacture can be more challenging
    - Allows parallel event readout → higher throughput
    - Smaller geometry → lower noise, lower gain, higher resolution, faster electronics, higher count rate
    - Timing – electronics dependent
    - Centroiding → sub-pitch resolution
        - Centroiding results using PetSYS TOFPET TDC system
        - Time-over-threshold → signal amplitude



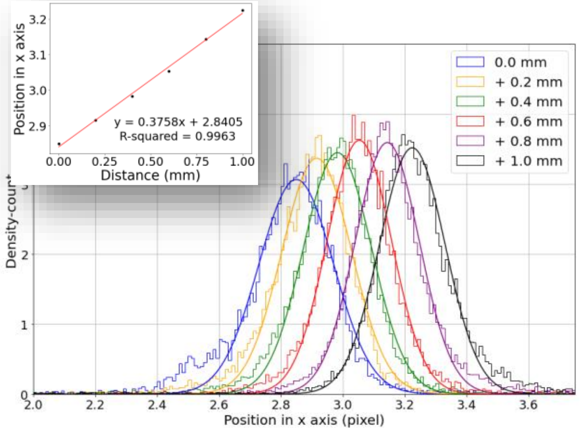
HST MAMA detector - Timothy



Crossed strip detector - Siegmund



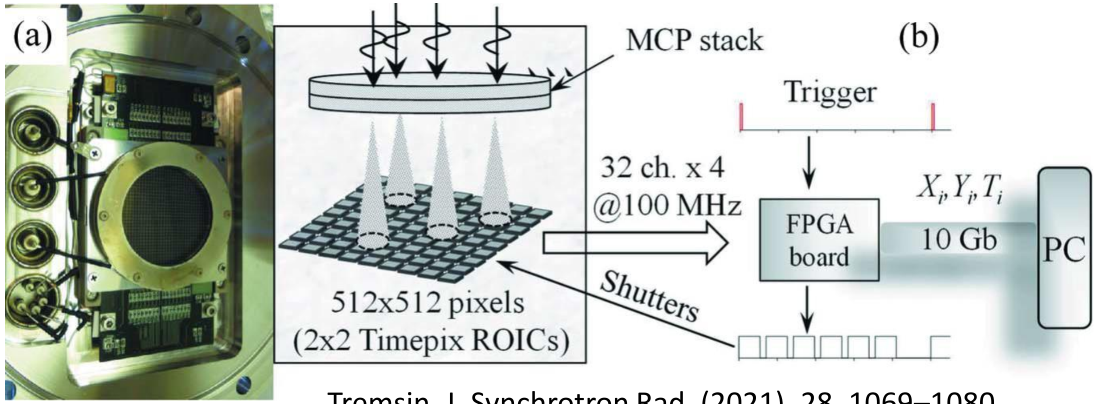
IRPICS pixellated detector - Lapington



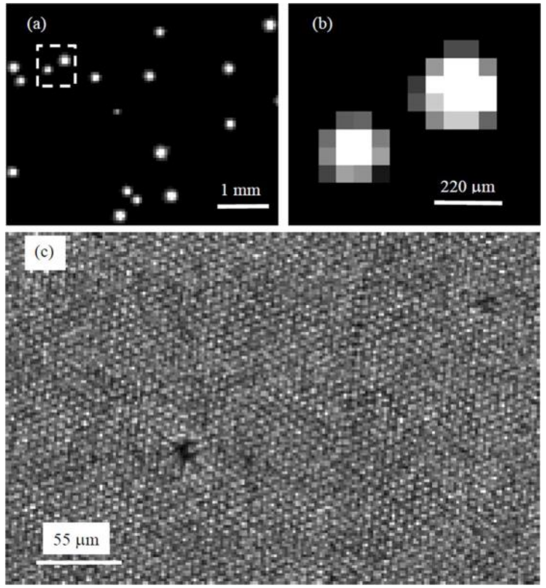
Centroiding using TOFPET – Sudjai, PSD12 poster

Vacuum tube hybrid solutions

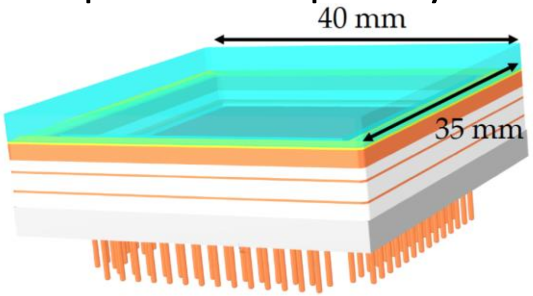
- ICCD, ICMOS – no picosecond timing
  - 1MHz CMOS at 182x32 yesterday
- Medipix/Timepix as a direct MCP event collector
  - no Si detection element
- High pixel count and readout speed → very high throughout
- Can't achieve MCP-limited time resolution, but:
  - First gen Timepix frame-based – 10 µs
  - Timepix3 event-driven mode →1.6 ns
  - Timepix4 → 200 ps
- Spatial resolution
  - 6 µm with event centroiding – pore limited resolution
  - ToT charge measurement at MCP gain ~10^4 e^-
  - Good for high rate and long lifetime
  - Potential issues:
    - Vacuum tube processing and lifetime
    - Mechanical integration and feedthroughs



Tremsin, J. Synchrotron Rad. (2021). 28, 1069–1080



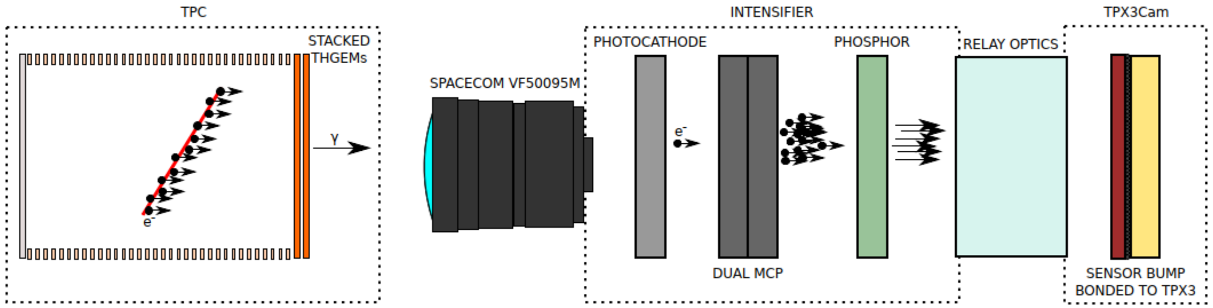
Proposed Timepix4 hybrid



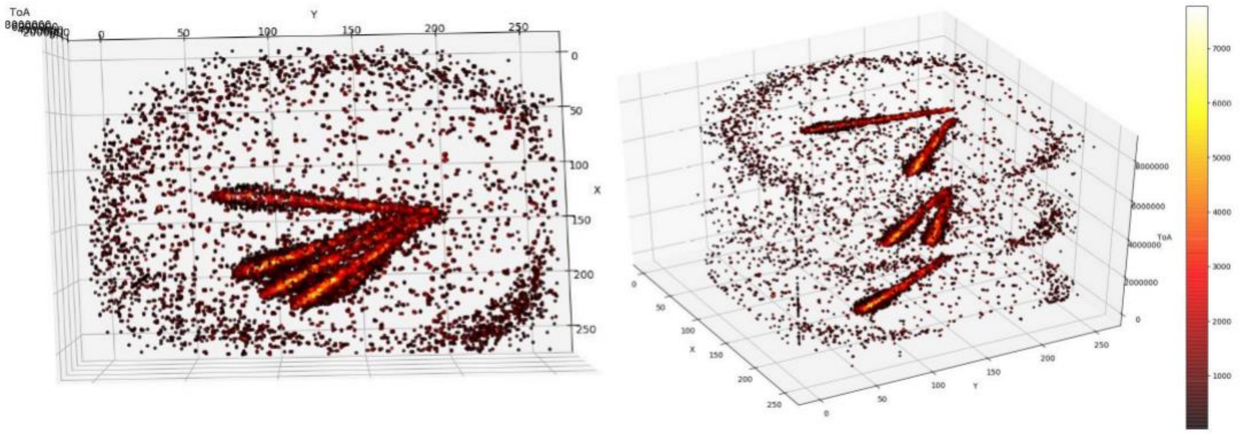
Fiorini et al 2018 JINST 13 C12005

Other hybrid solutions

- Intensified optical Timepix
  - 3D TPC readout
  - MCP intensifier + Timepix 3 camera
  - light sensitive silicon sensor bump bonded onto a TPX3 chip
  - 256 x 256 pixel^2 format, 0.7 mm/pixel
  - ToA → 1.6 ns time resolution →Z resolution < 1mm



2D versus 3D visualization of TPC readout using Timepix3 camera

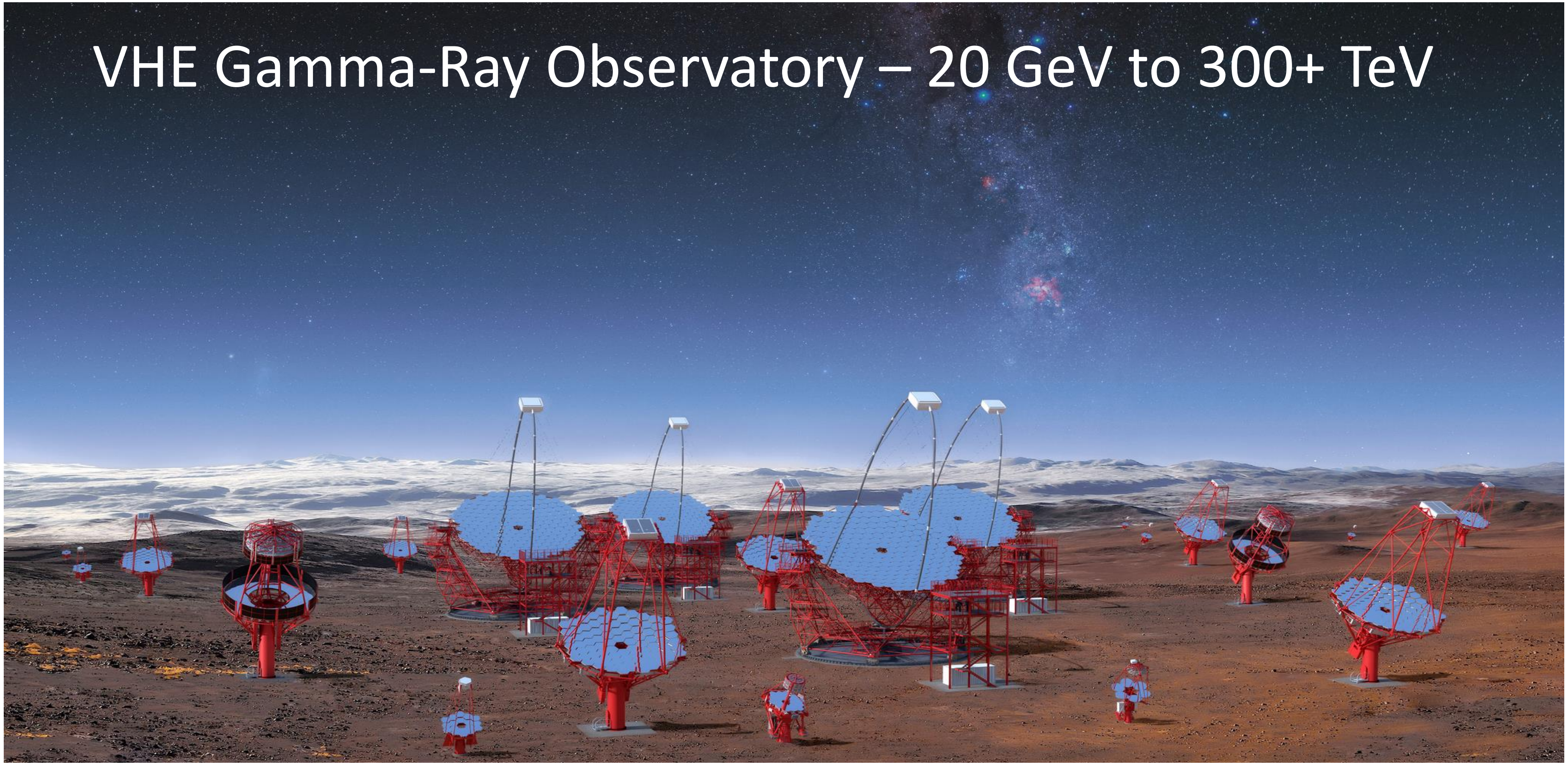


Roberts et al 2019 JINST 14 P06001

Solid State devices

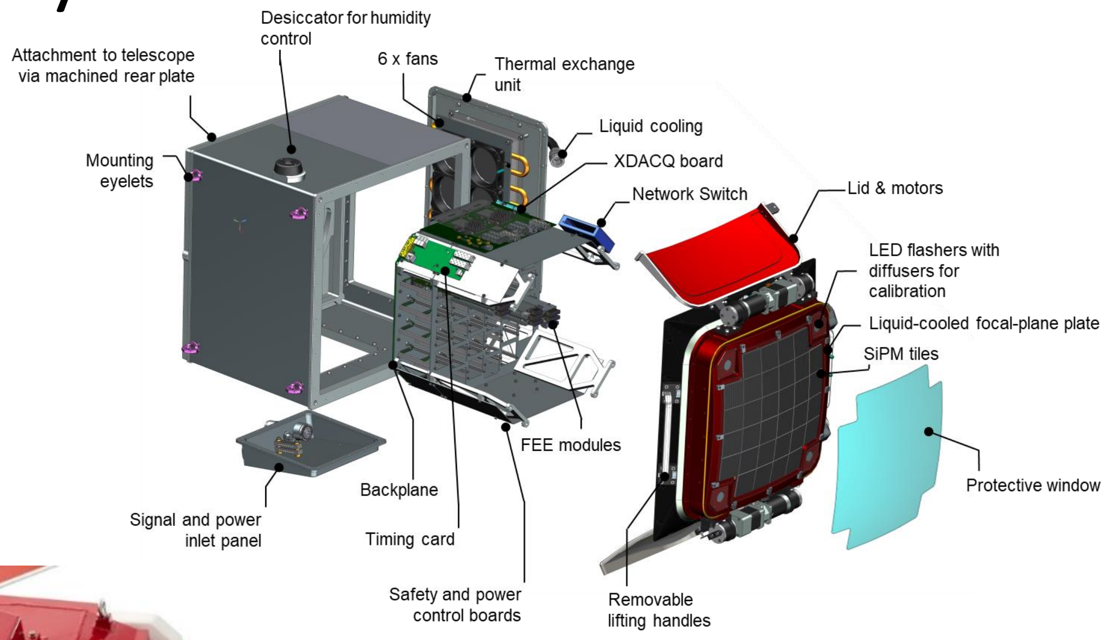
- Silicon photomultiplier arrays – CTA SST camera
- Linearly-graded SiPMs
- Digital SiPM
- Large format SPAD Arrays

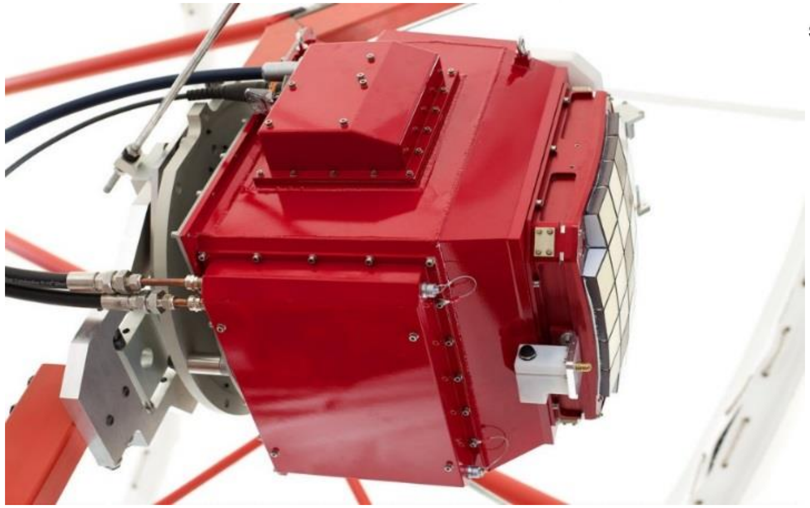
Cherenkov Telescope Array – SiPM array



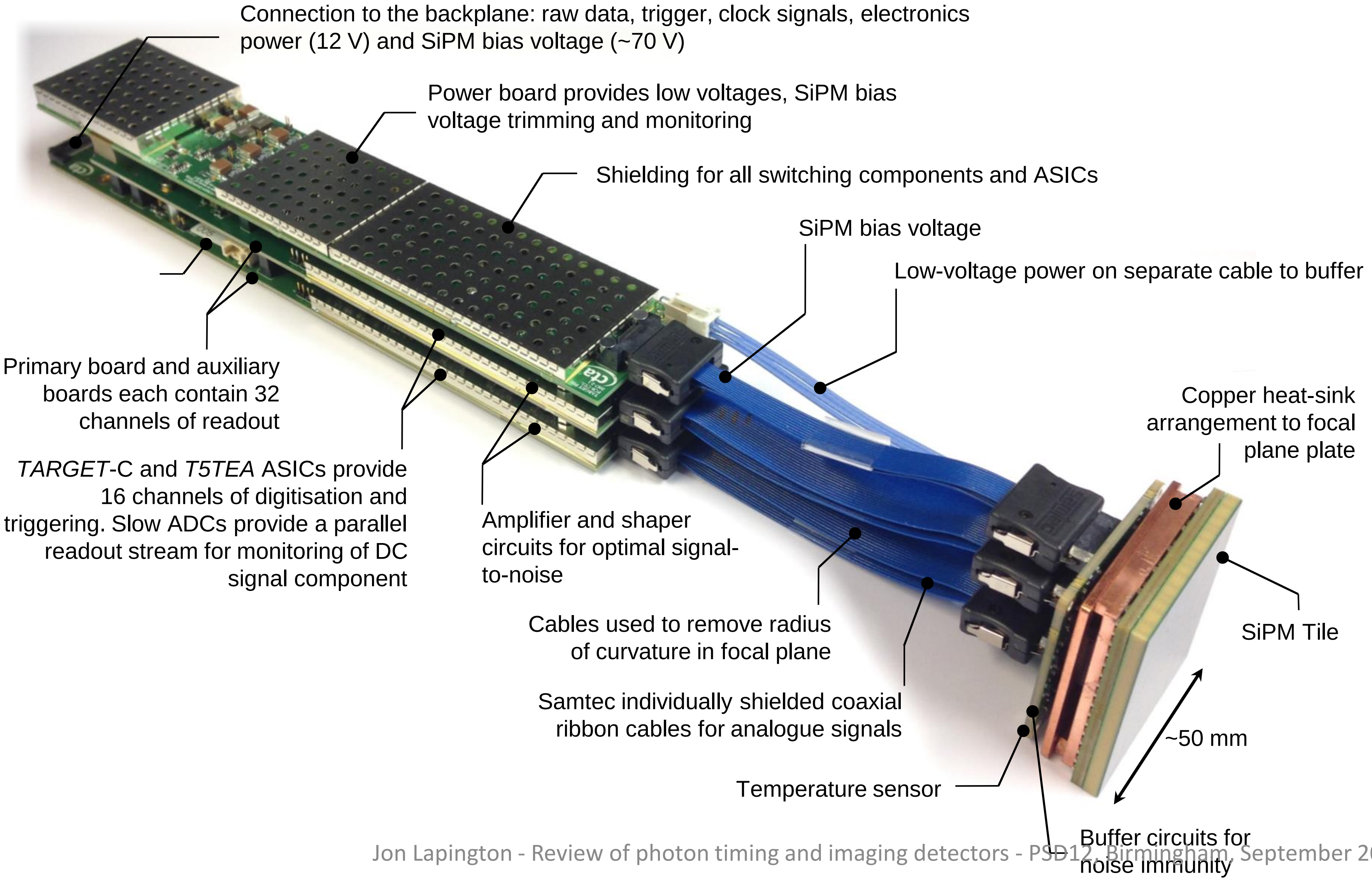
Silicon photomultiplier arrays

- Small-sized Telescope for CTA
  - SiPM-based camera
  - 2048 6x6 mm2 SiPM pixels
  - Organised as separate 32 modules
  - 1 GSa/s waveform capture per pixel using TARGET ASIC
  - Time resolution: <150 ps

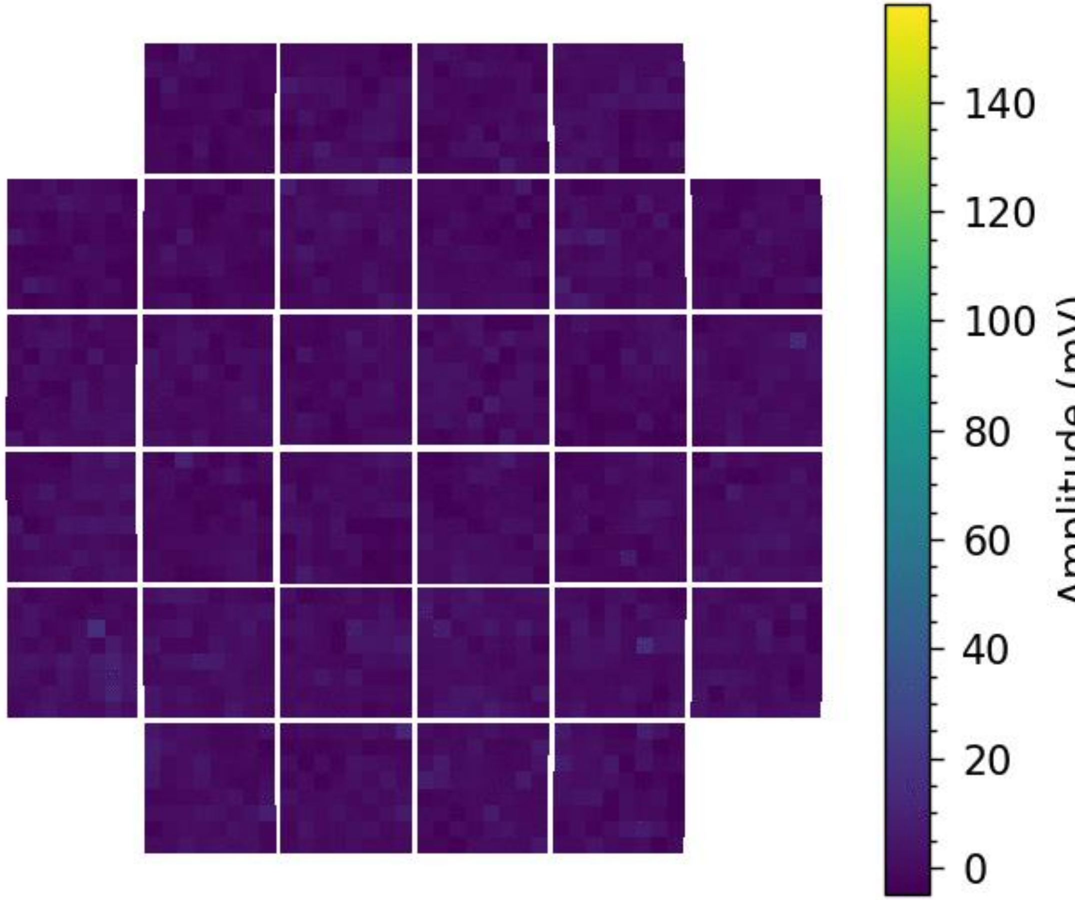




SST Prototype Camera Module

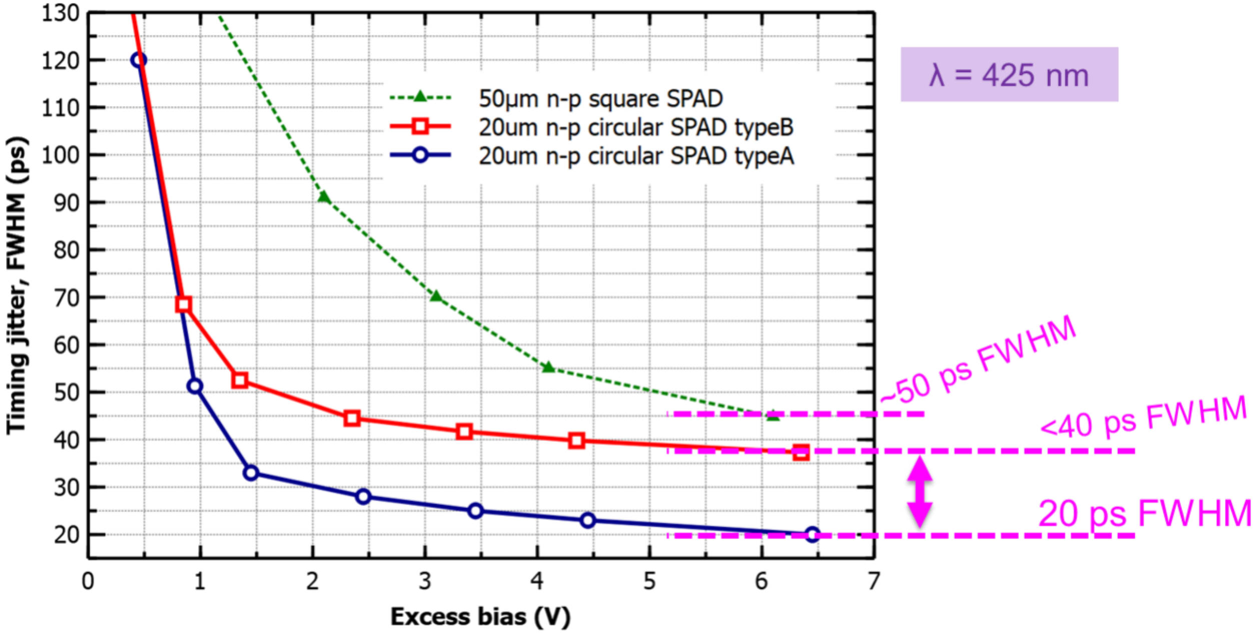


On-sky camera tests with Italian ASTRI telescope – Serra La Nave Observatory, Mt. Etna

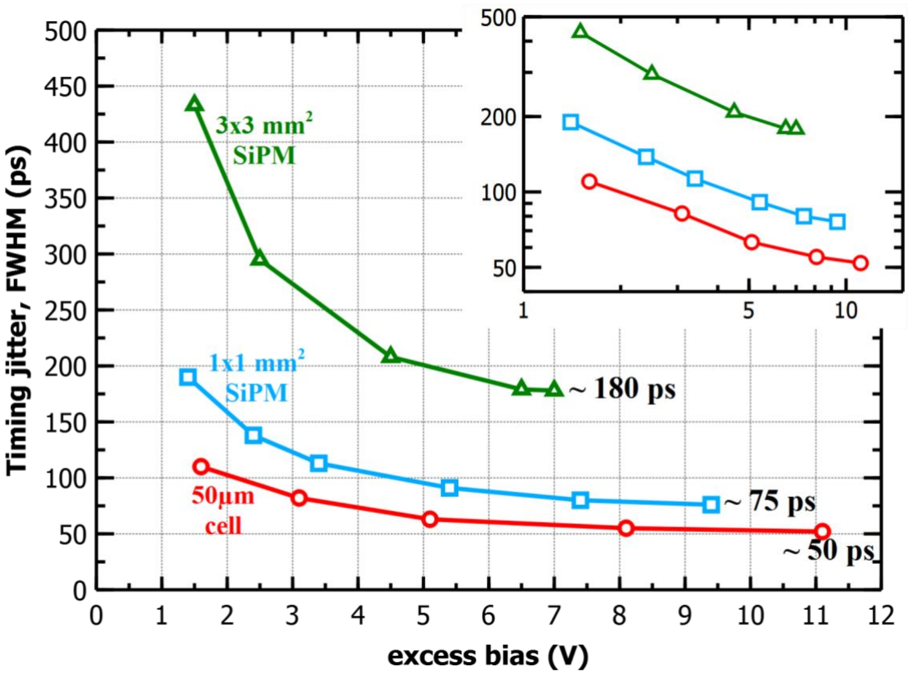


SPAD and SiPM time resolution

SPTR of Single SPADs



SPTR of SiPMs

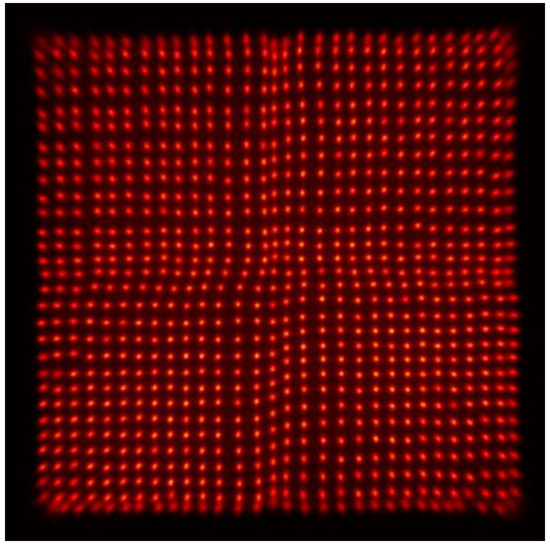


Mazzi - FBK SiPM technology

Linearly Graded SiPMs

- Each microcell has 2 quench resistors and resistive divider
- Event measurement at 4 readout nodes → x,y cell identification

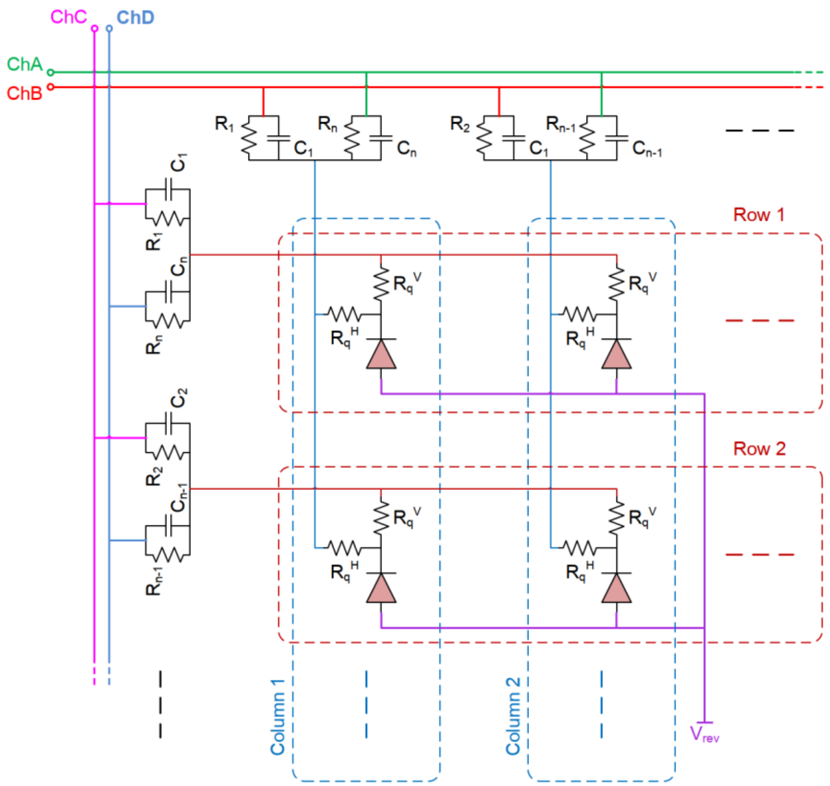
2 x 2 LG-SiPMs with scintillators for small animal PET



Mazzi - FBK SiPM technology

$$Q = Q_A + Q_B + Q_C + Q_D;$$

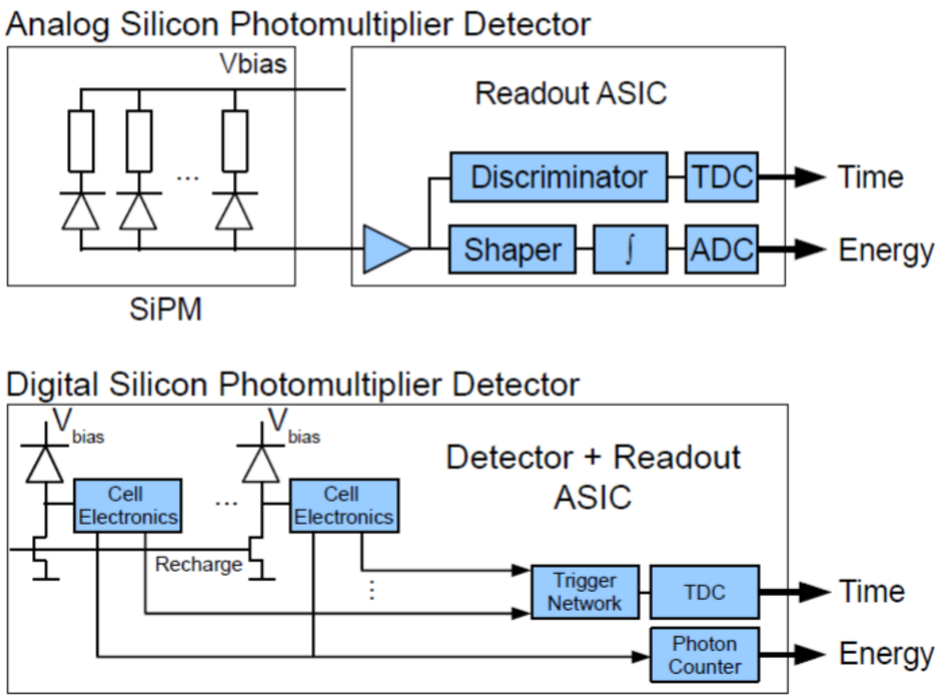
$$X = \frac{Q_A - Q_B}{Q_A + Q_B}; \quad Y = \frac{Q_C - Q_D}{Q_C + Q_D};$$



Gola et al 2020 JINST 15 P12017

Digital Silicon photomultipliers

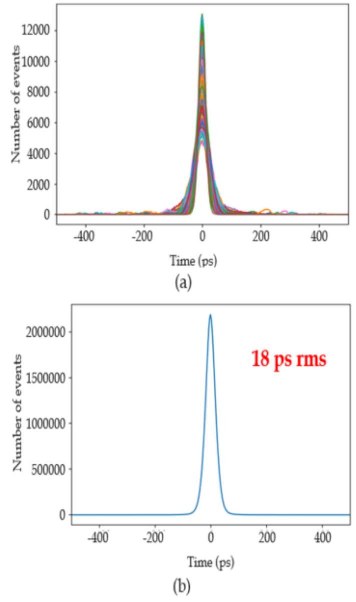
Original Philips Digital SiPM concept

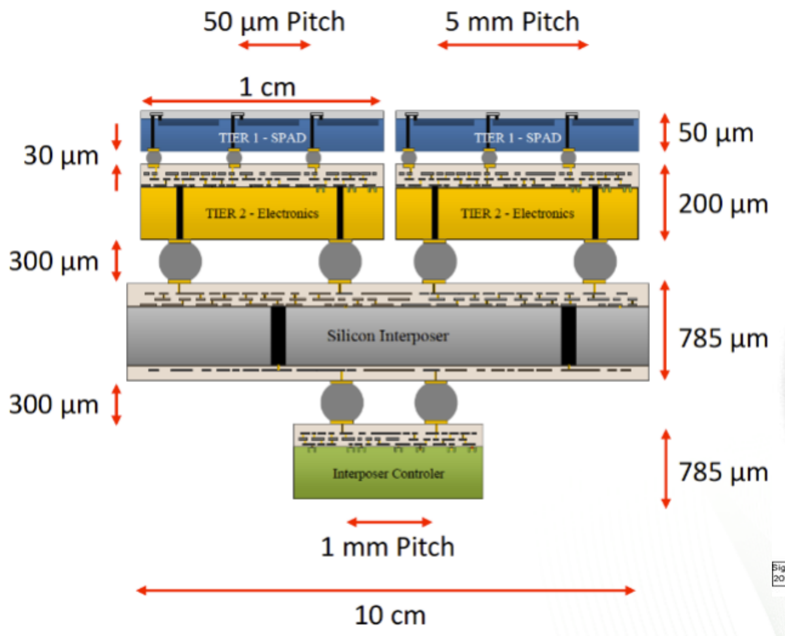


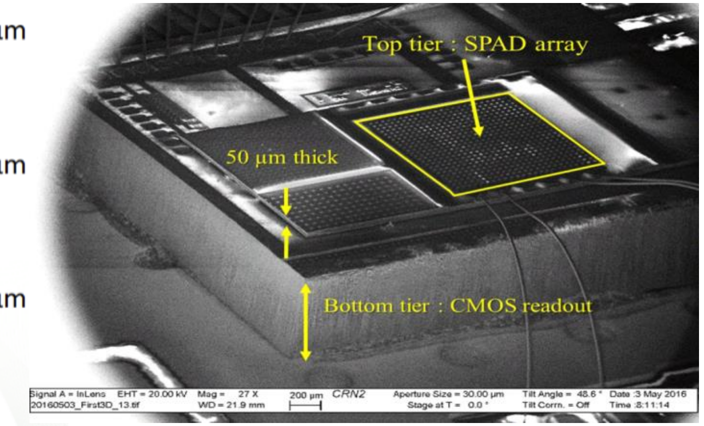
IEEE Nuclear Science Symposium / Medical Imaging Conference, Orlando, FL October 28, 2009

TRIUMF-Sherbrooke 3D digital SiPM

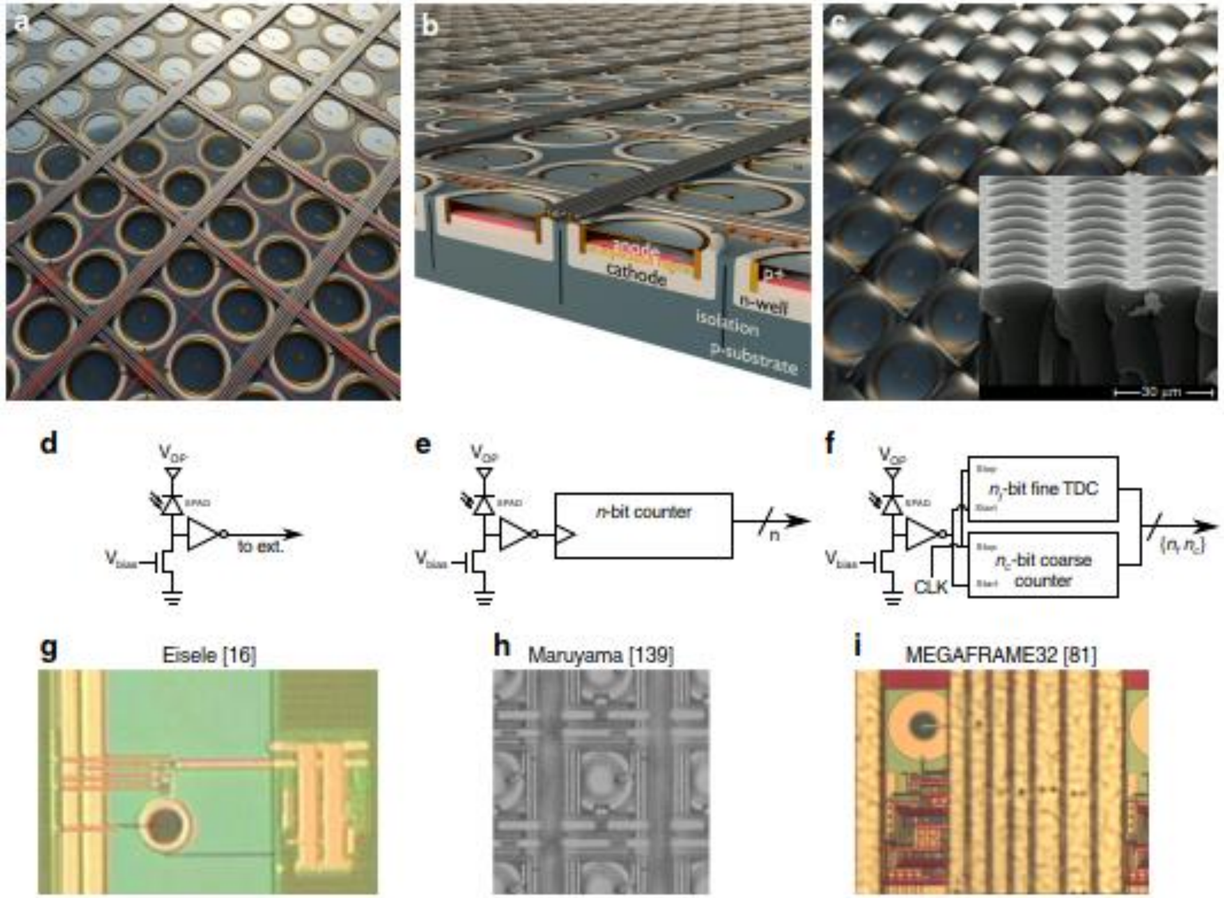
- Primarily developed for PET, not imaging
- TSMC CMOS 65 nm technology - 256 pixels
- Optimizes array SPTR for PET
- Skew correction per SPAD → 18 ps rms jitter
- Identity of fired pixel → possibility for imaging







Spad Array Architectures

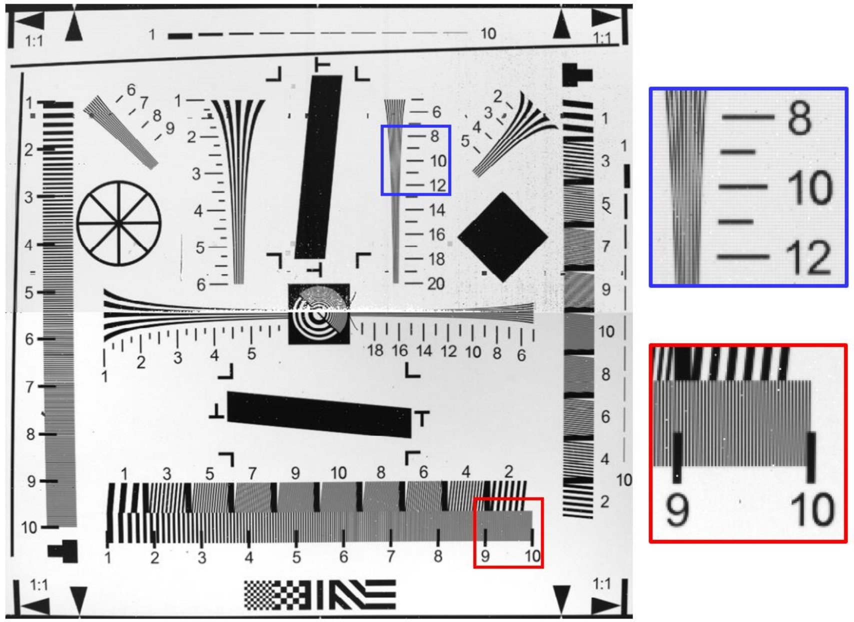


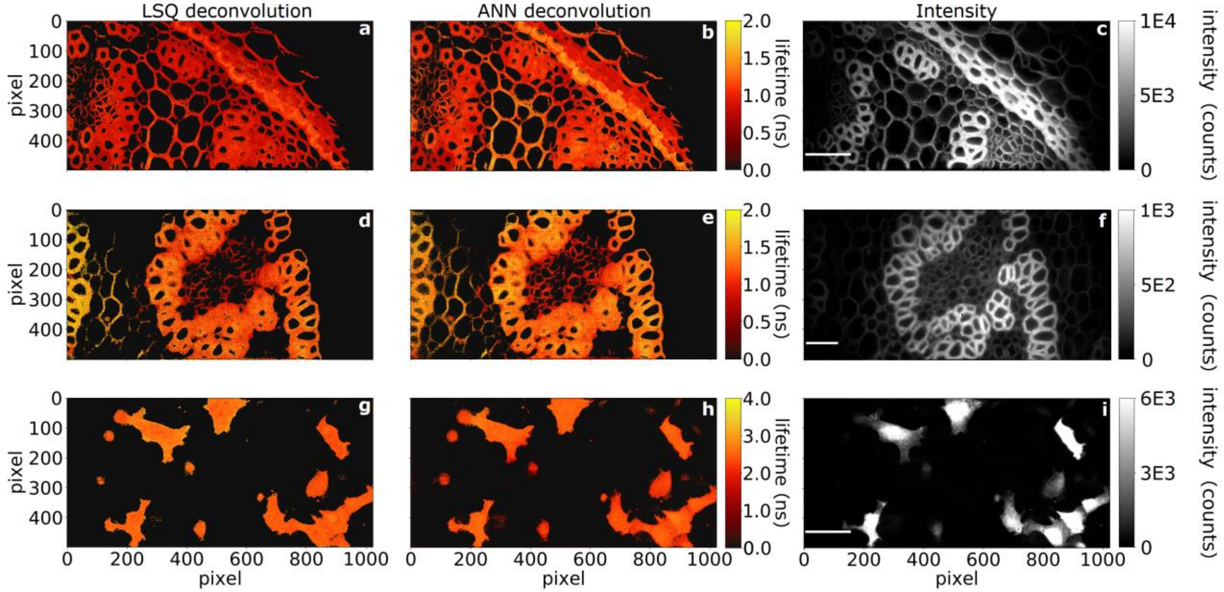
a) Top view
b) Cross-section
c) SEm inset view
d) Photon to pulse electronics
e) Photon counting electronics
f) Photon timing electronics
g) to i) Example pixel micrographs

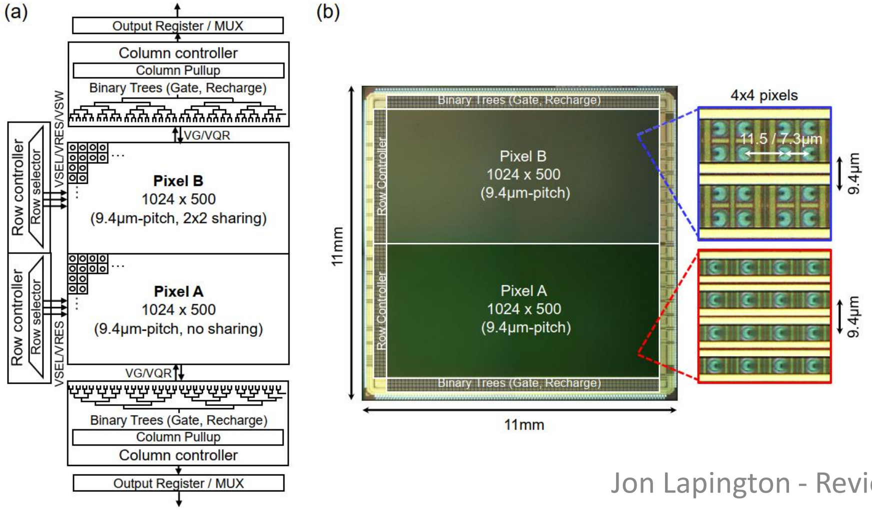
From: Bruschini et al. Light: Science & Applications (2019)8:87

Large SPAD arrays

- First 1M pixel SPAD camera
- Time-gated:
  - Minimum gate length 3.8 ns
  - Gate variation 120 ps FWHM
  - Frame rate 24 kfps
- Used for FLIM in gated mode
- ANN for data analysis
- Many devices for biophotonics – see Bruschini et al. Light: Science & Applications (2019) 8:87



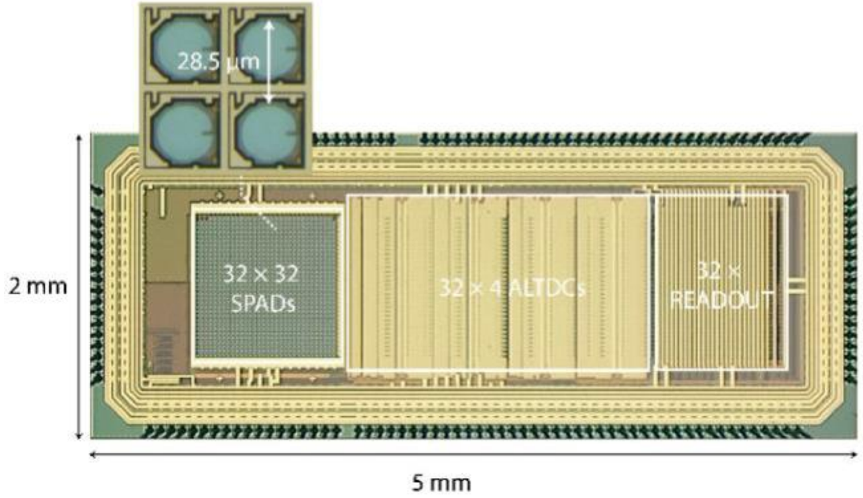




Large SPAD arrays

- SPAD arrays also available for TCSPC
- With TDCs and high rate capabilities
- LinoSPAD:
  - 256 x 1 array
  - 64 FPGA- based 25 ps TDCs
- Piccolo:
  - 32 x 32 array
  - 128 column 49 ps TDCs
  - 224 Mevents/s
- Erdogan
  - 1024 x 16 array
  - 512 per-pixel 50 ps TDC
  - 16.5 Gevents/s

Piccolo, 32 × 32 CMOS SPAD for LIDAR



Zhang, Sensors 18, 4016 (2018)

Conclusions

- These are a small fraction of the techniques being proposed for high resolution photon timing and imaging.
- As Heinz Graafsma stated yesterday, “You cannot develop the ultimate detector for every application” but there’s so much more choice of devices now
- Largely because of the availability of custom miniaturized electronics: this has been disruptive for fast photon-counting timing and imaging techniques
- Another point (also repeated at PSD12): higher spatial and temporal resolution → much bigger datasets. How do we deal with these?
- Value of machine learning not only for calibration (ToT linearization per channel), event centroiding, and data reduction, but for data selection/analysis
- For space applications, this is especially important e.g. where distant planetary missions have heavily restricted telemetry bandwidth