ICCUB

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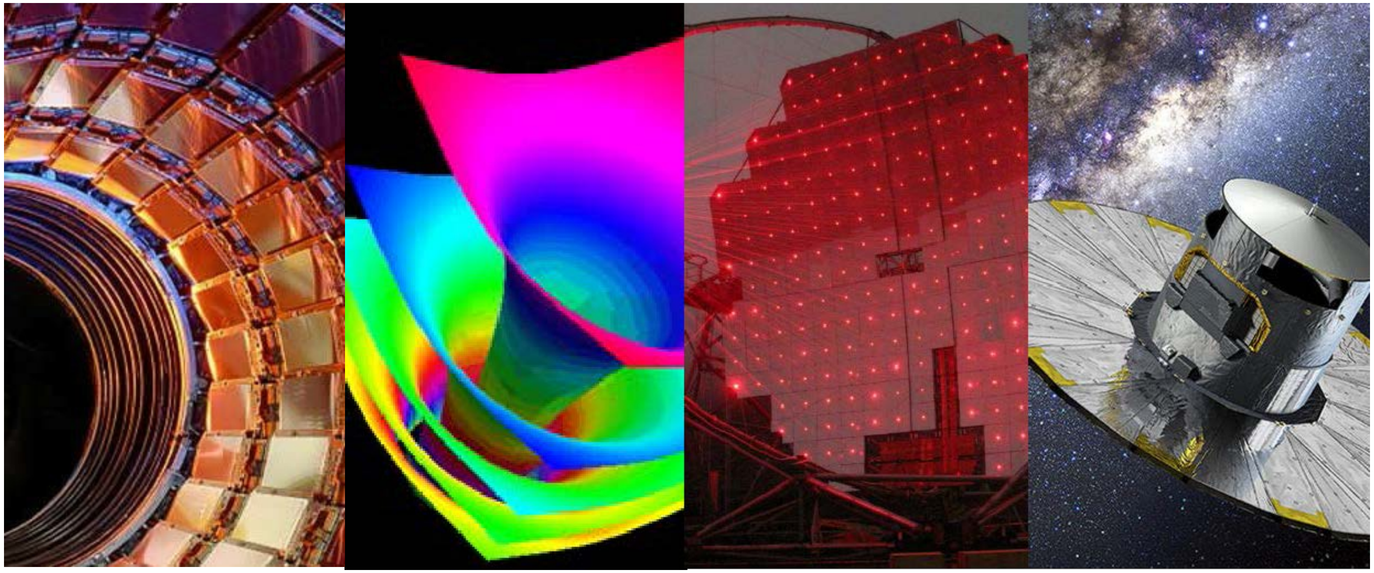
Institute of Cosmos Sciences



Time Resolution of Large Area Low Light Level Sensors

R. Ballabriga, J.M Fernández, L. Garrido, D. Gascon, E. Grauges, **S. Gomez**, G. Guixé, J. Mauricio, R. Manera, E. Picatoste, D. Sanchez, A. Sanmukh, A. Sanuy

ICCUB – Universitat de Barcelona

SiPM workshop

Bari

04/10/2019

UNIVERSITAT DE BARCELONA

Outlook

I. **Introduction**
II. Multi-Channel Readout (HRFlexToT)
III. Active Summation (MUSIC)
IV. Towards a Hybrid Single Photon Sensor (FastIC & FastICPix)
V. Discussion

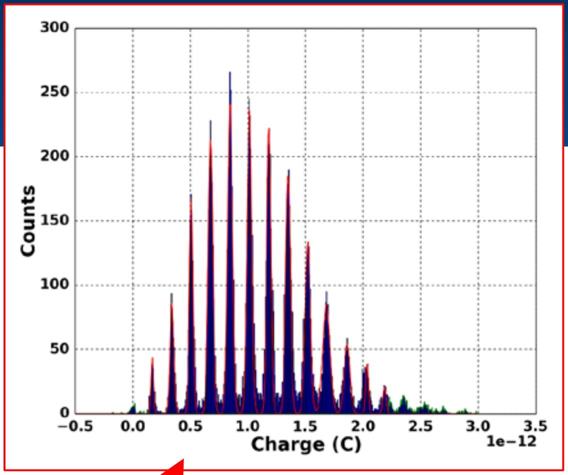
I. Introduction

- Institute of Cosmos Science of the Univ. of Barcelona (ICCUB)
  - Particle and Nuclear Physics, Astrophysics and Cosmology
  - Theory, Observation, Space Missions and Experiment
    - LHCb, BaBar, CTA, Gaia, Solar Orbiter, Ariel, HERD
- Long track record on development of detectors based on photosensors and associated readout electronics
  - Calorimeters, Scintillating Fiber Trackers, RICH
  - Cherenkov Telescopes
  - Medical Imaging
- Strong interest in picosecond timing
  - LHCb phase-II upgrade
  - ToF PET

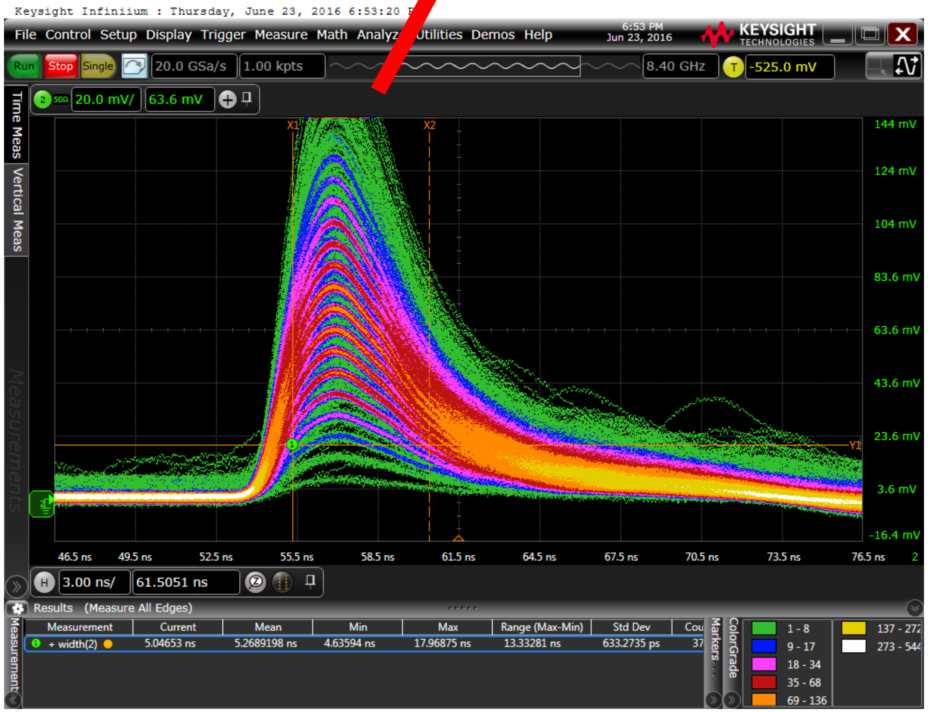
I. Introduction

- SiPMs are replacing PMTs in many applications:
  - Higher PDE
  - Accurate photopeak resolution
  - Better time resolution
  - More compact and robust
  - Lower bias voltage
  - Insensitive to magnetic field

- Astrophysics
- Particle Physics
- Medical Imaging
- Homeland security
- LIDAR (autonomous driving)



Charge spectrum by integration



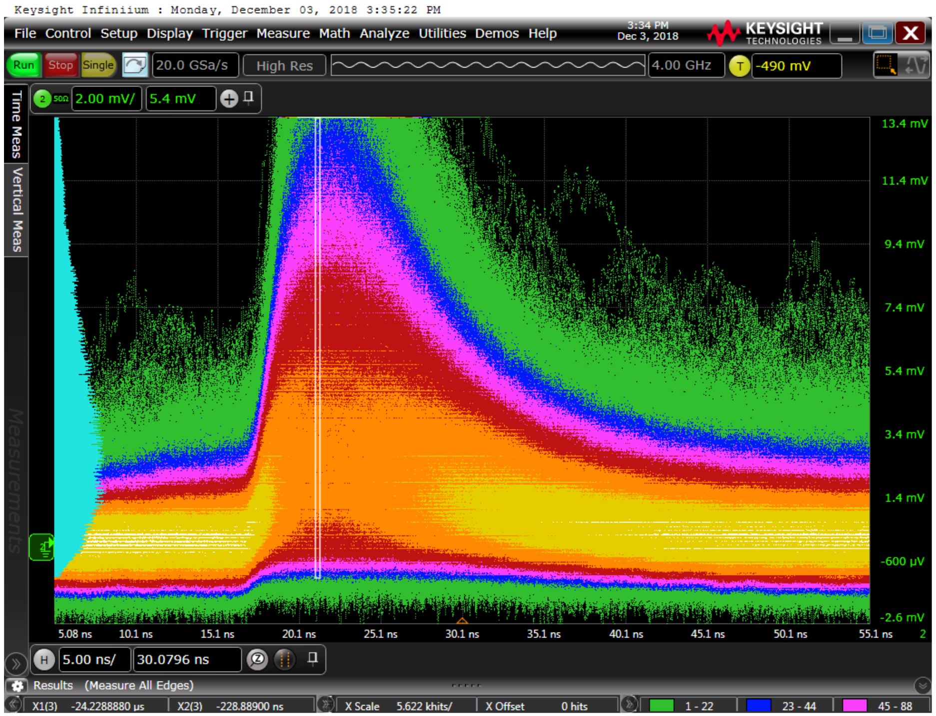
Results (Measure All Edges)

Measurement	Current	Mean	Min	Max	Range (Max-Min)	Std Dev	Cou
+ width(2)	5.04653 ns	5.2689198 ns	4.63594 ns	17.96875 ns	13.33281 ns	633.2735 ps	37

I. Introduction

- SiPMs are replacing PMTs in many applications:
  - Higher PDE
  - ~~Accurate photopeak resolution~~
  - ~~Better time resolution (faster rise time)~~
  - More compact and robust
  - Lower bias voltage
  - Insensitive to magnetic field

NOT TRUE FOR LARGE AREA (> 1 cm^2) DEVICES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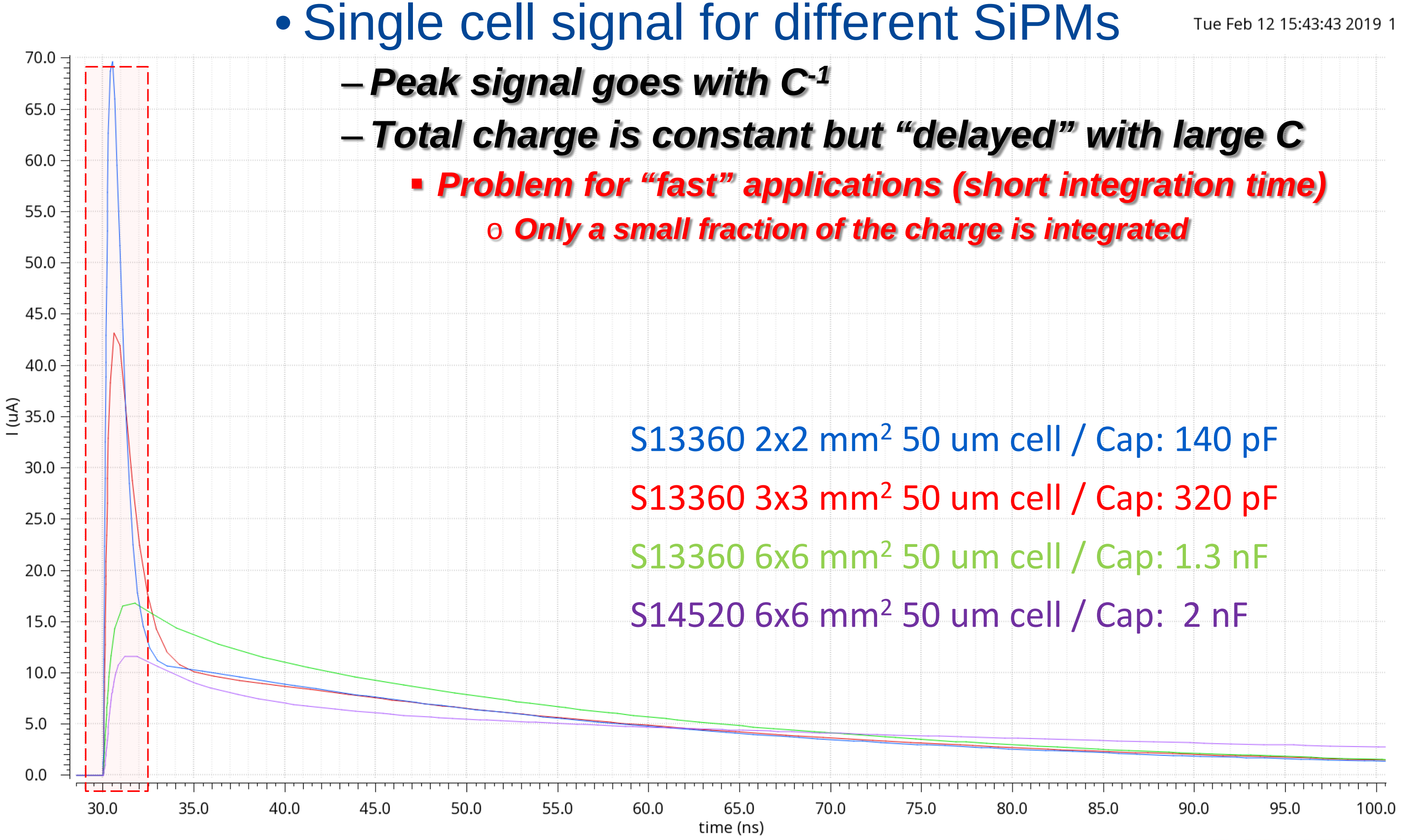
I. Introduction
Pulse Shape vs Sensor Area

- Single cell signal for different SiPMs
  - ***Peak signal goes with C^{-1}***
  - ***Total charge is constant but "delayed" with large C***
    - ***Problem for "fast" applications (short integration time)***
      - ***Only a small fraction of the charge is integrated***



S13360 2x2 mm^2 50 um cell / Cap: 140 pF

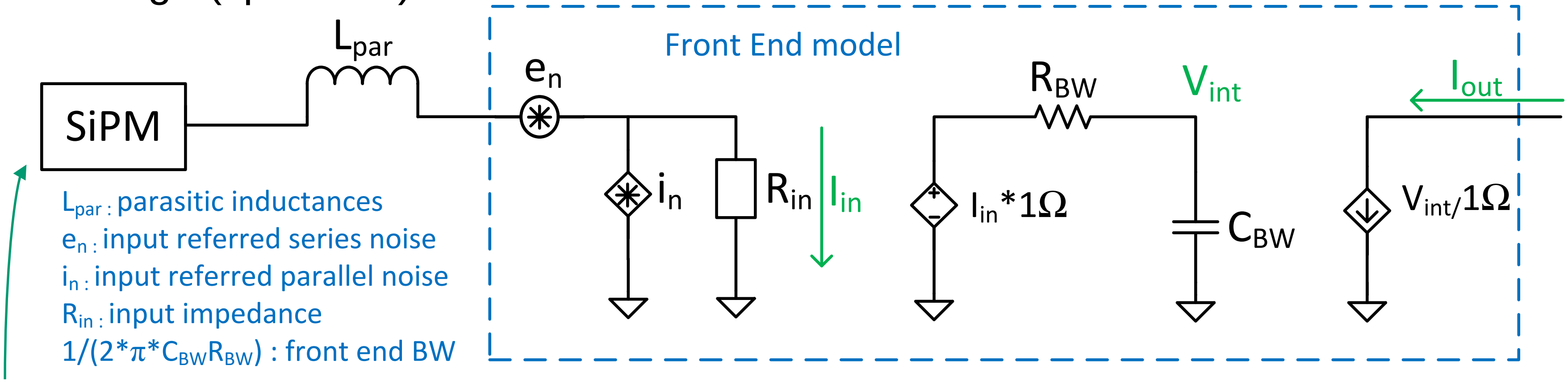
S13360 3x3 mm^2 50 um cell / Cap: 320 pF

S13360 6x6 mm^2 50 um cell / Cap: 1.3 nF

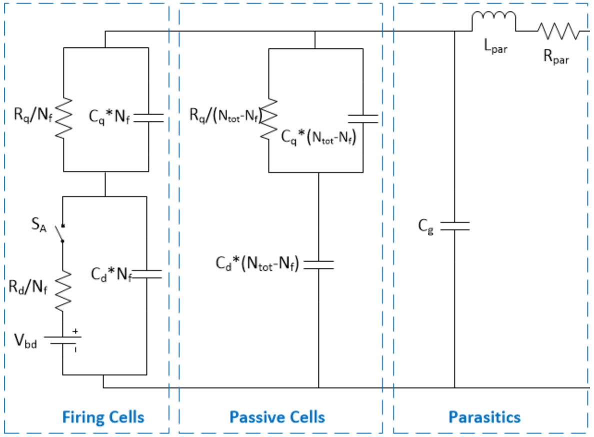
S14520 6x6 mm^2 50 um cell / Cap: 2 nF

I. Introduction
Front end model

- A more detailed model of the front end
  - Not just an impedance
- Need to include also noise and FE BW to evaluate resolution
  - Charge (spectrum) and time



L_{par} : parasitic inductances
e_n : input referred series noise
i_n : input referred parallel noise
R_{in} : input impedance
$1/(2*\pi*C_{BW}R_{BW})$: front end BW

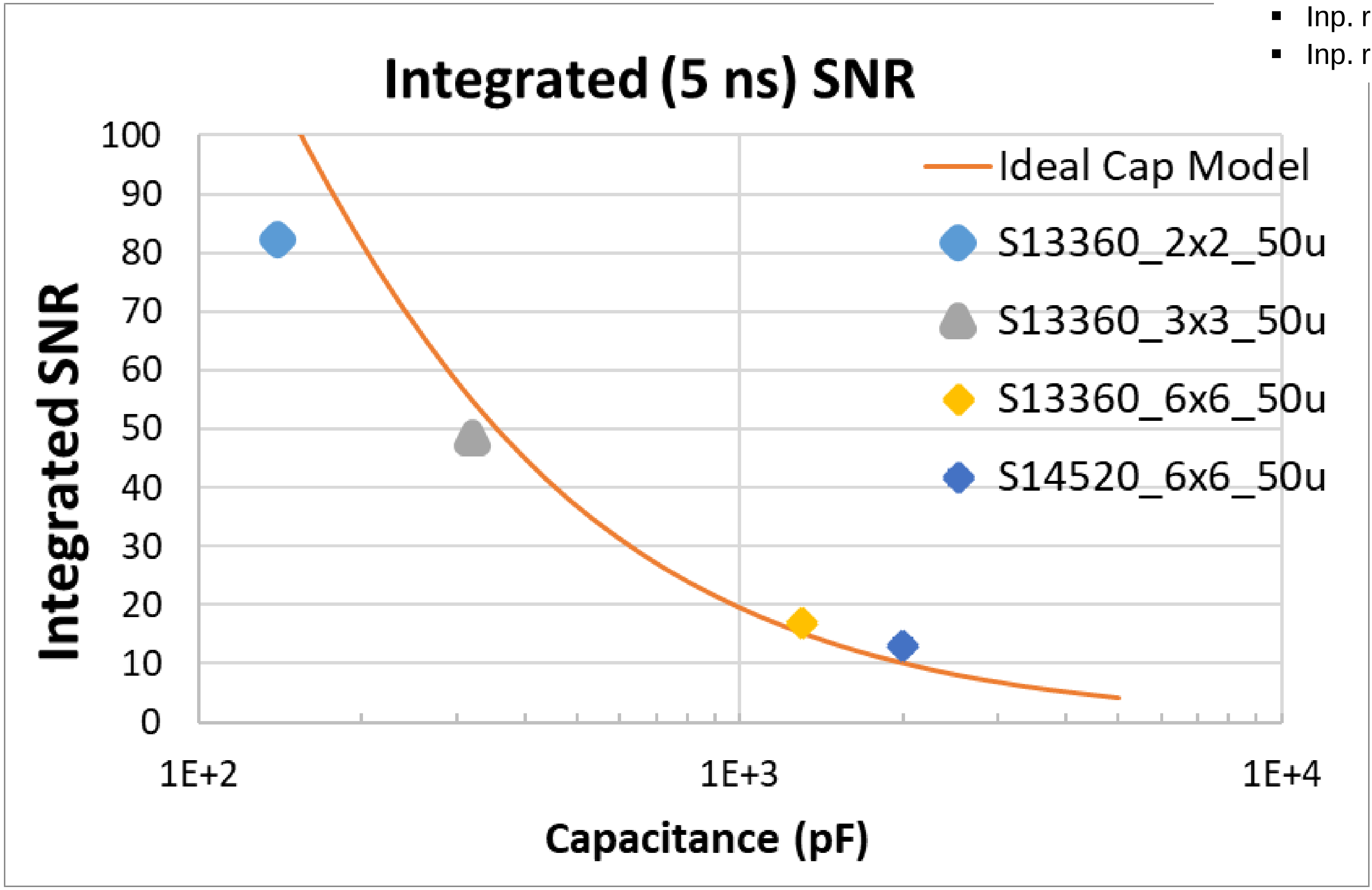


SiPM model (F.Corsi et al) or single Capacitance (ideal)

I. Introduction
Large area SiPMs

- Energy/light is typically measured by integration
- This is reflected in charge spectrum (finger plot)

- SiPM overvoltage: 4.5 V
- Amplifier parameters
  - Rin = 15 Ω
  - BW = 500 MHz
  - Inp. ref. ser. noise: 2 nV/sqrt(/Hz)
  - Inp. ref. par. noise: 10 pA/sqrt(/Hz)



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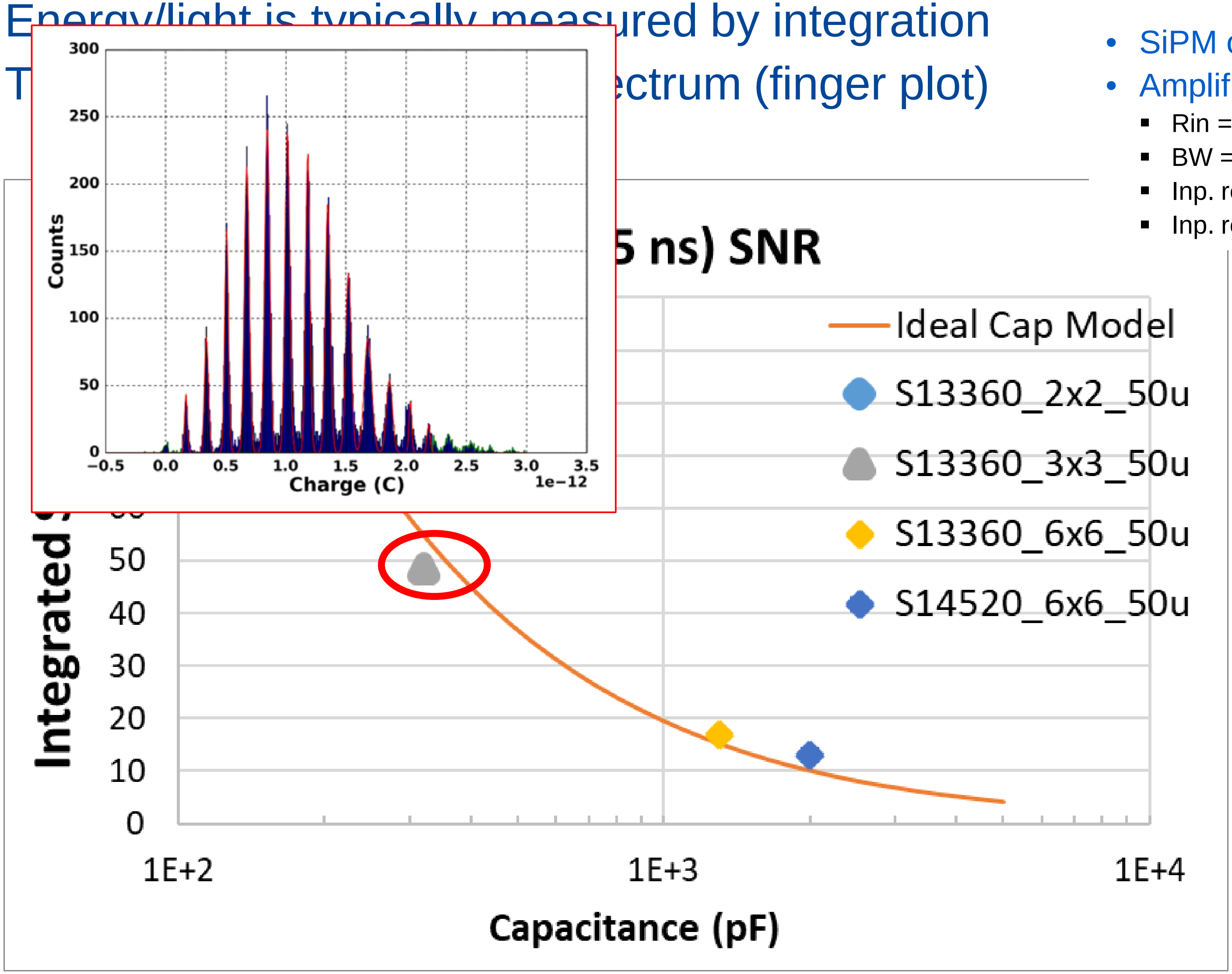

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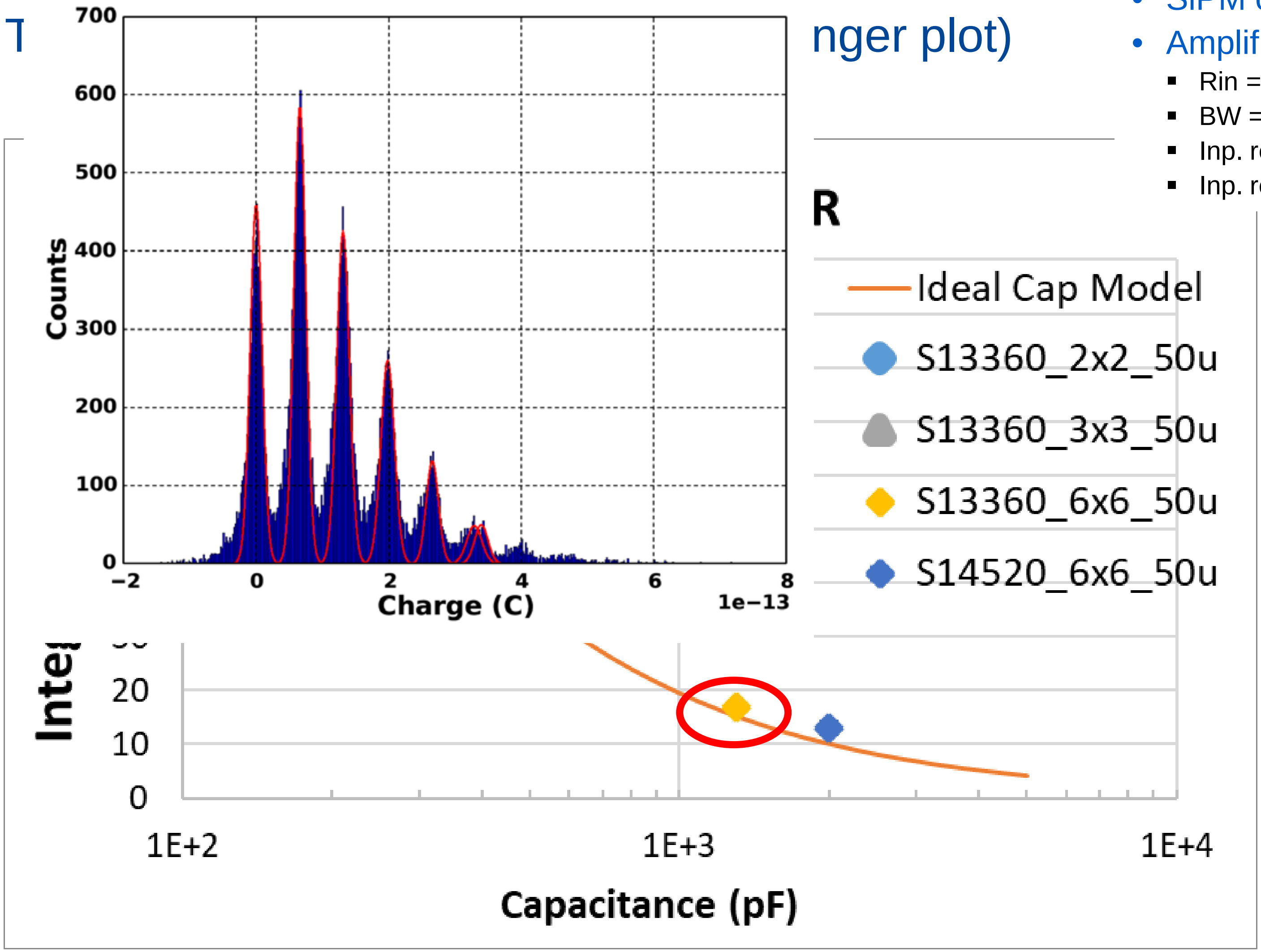

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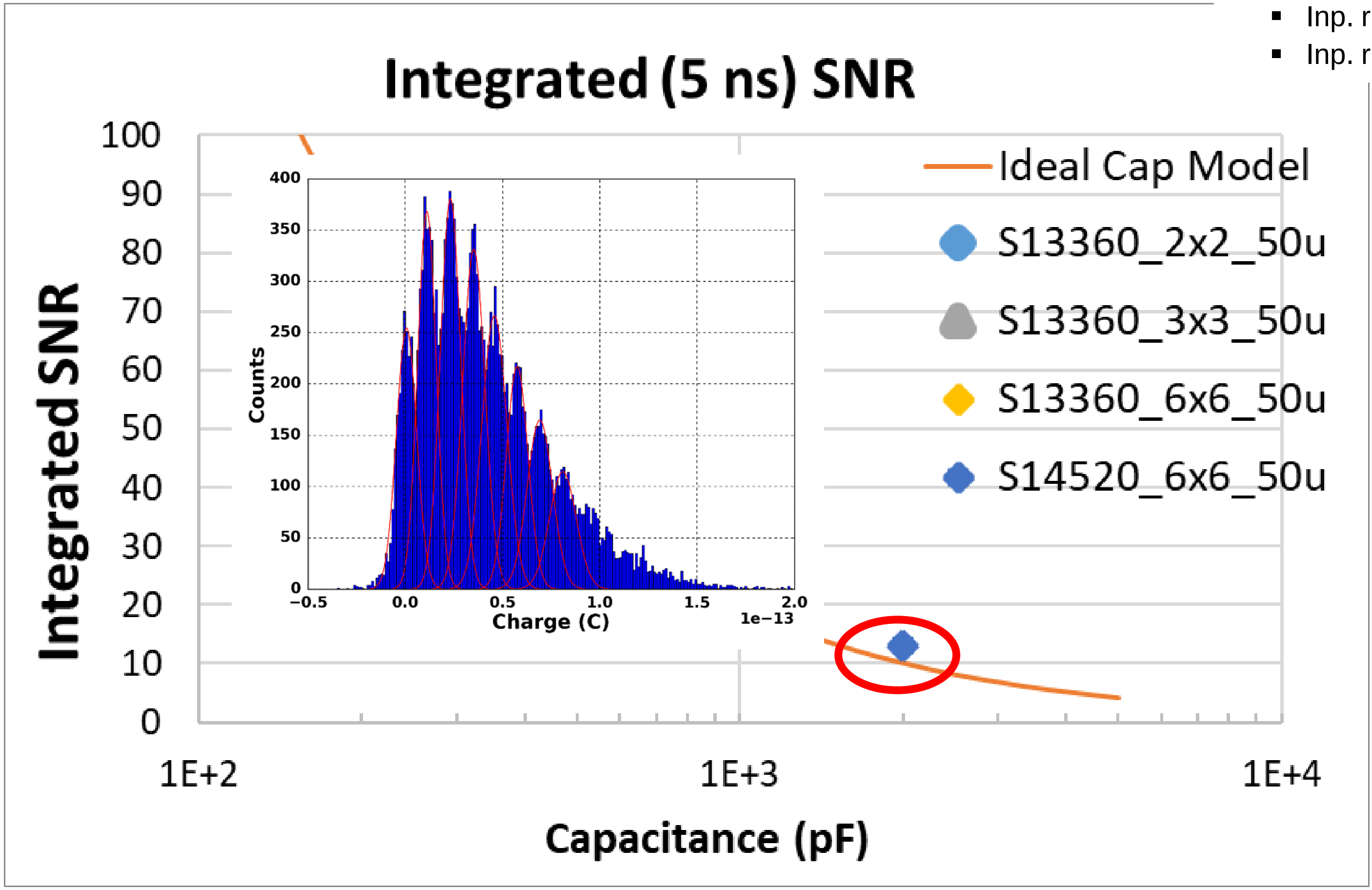


I. Introduction
Large area SiPMs: jitter

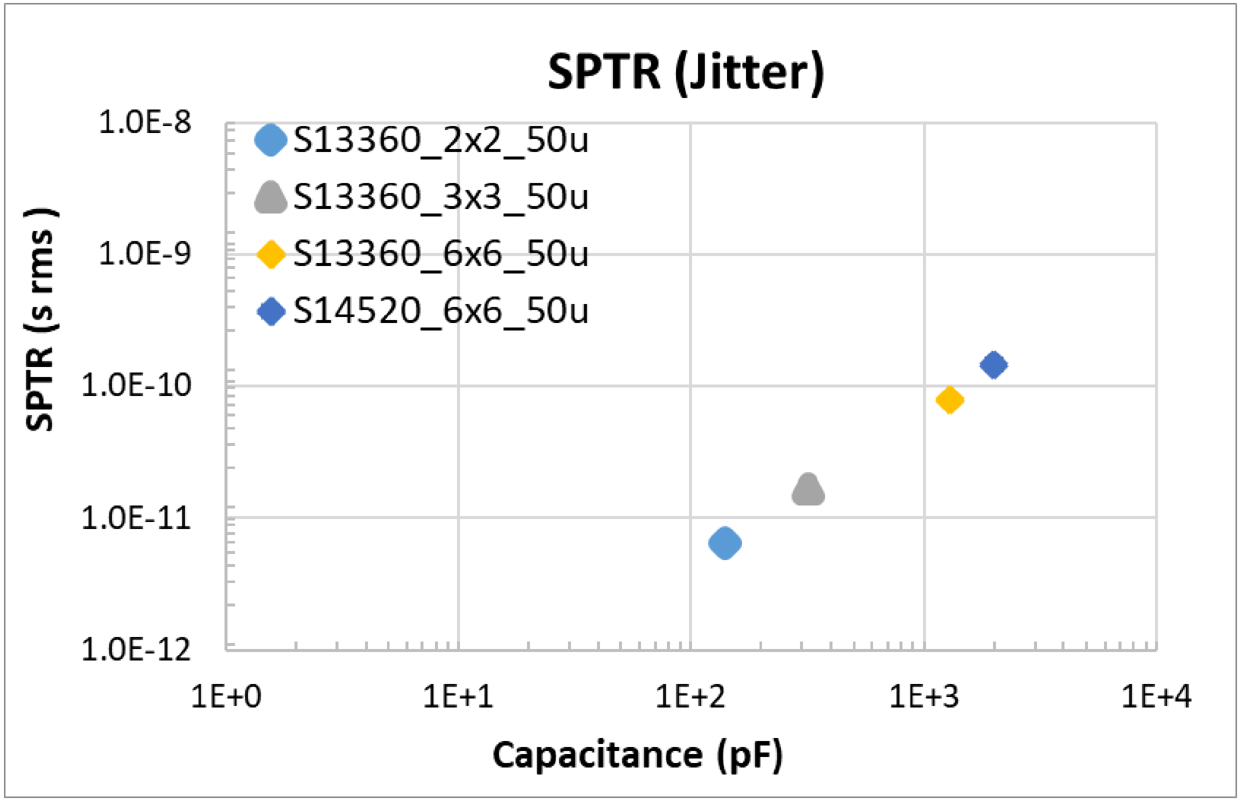
- Jitter (Single Photon Time Resolution, SPTR):

$$\mathrm{SPTR} = \frac{I_{no}}{\partial I_{o1p}/\partial t}$$

I_{no} → Integrated output noise

$\partial I_{o1p}/\partial t$ → 1 cell signal gradient

  - Only electronics contribution (no SPAD jitter or skews)



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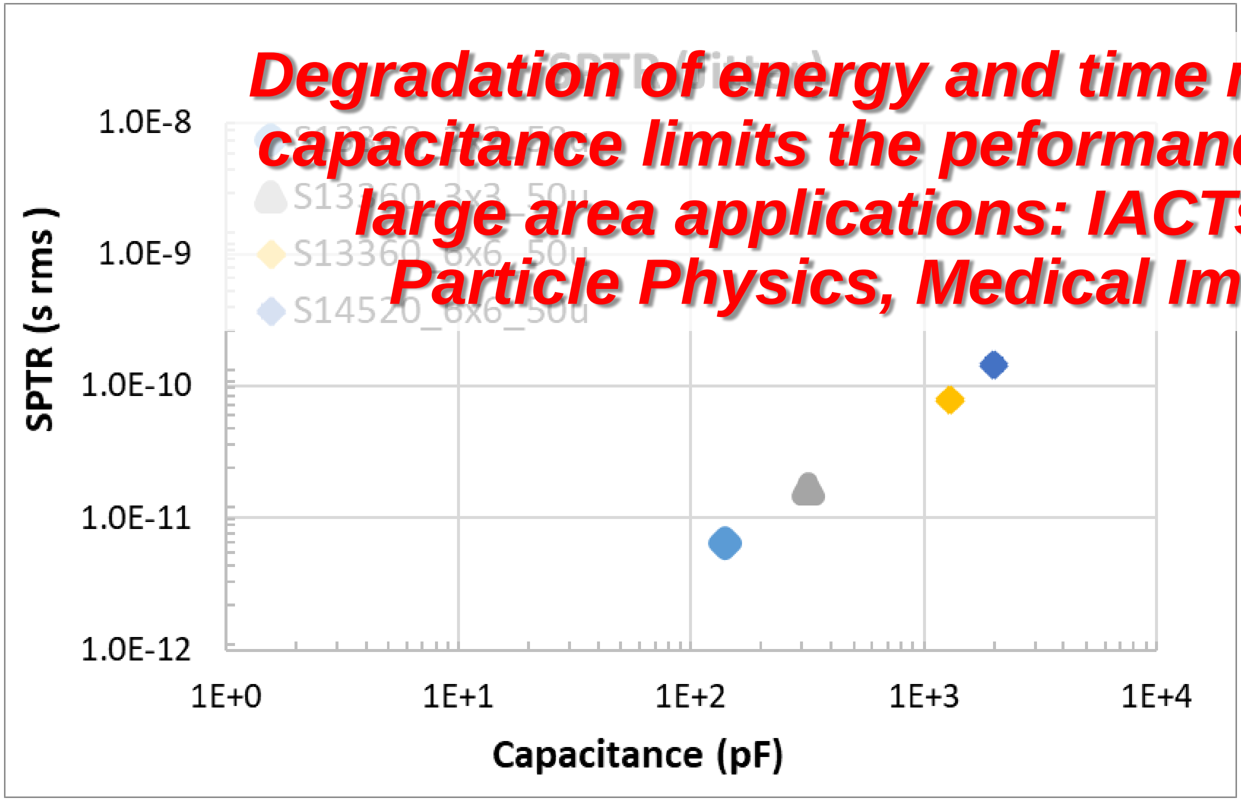

Degradation of energy and time resolution with capacitance limits the peformance of SiPMS in large area applications: IACTs Cameras, Particle Physics, Medical Imaging, etc

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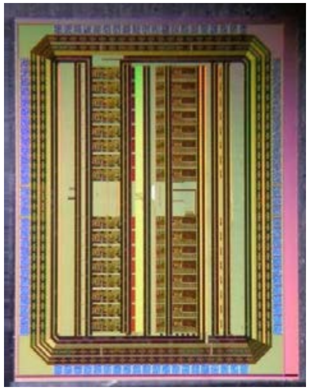
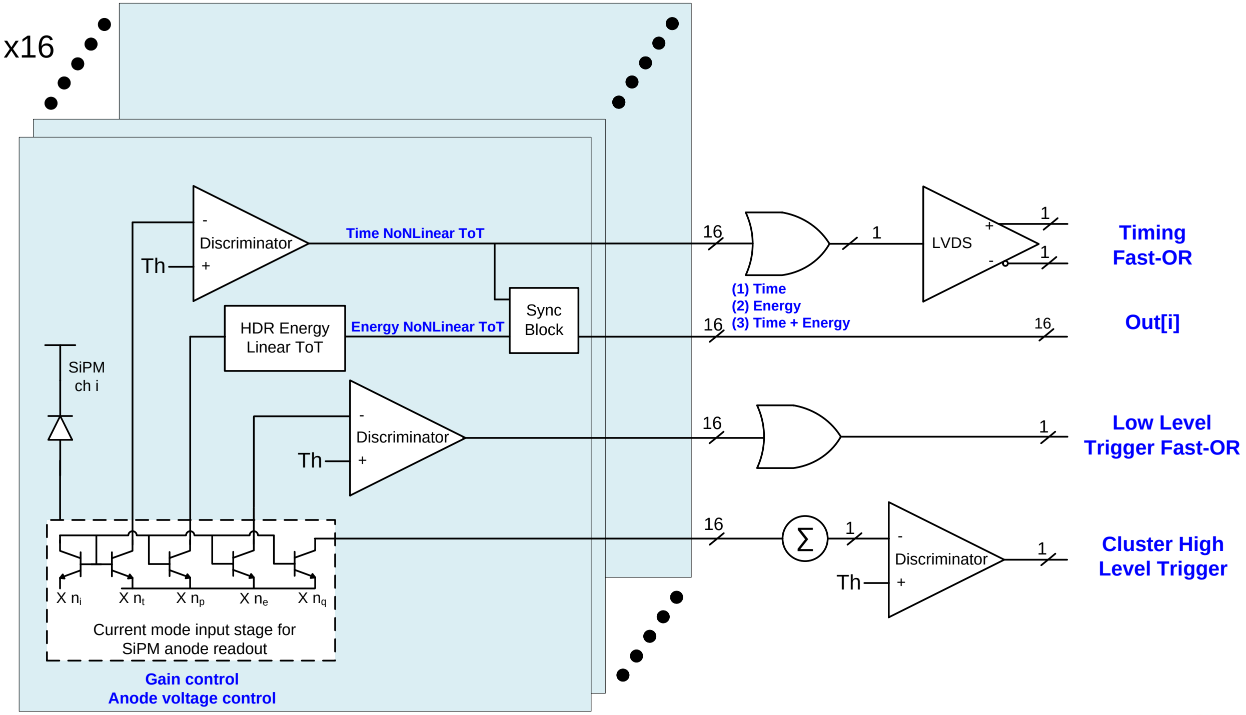
II. MultiCh readout: HRFlexToT

- **HRFlexToT current mode ASIC.**
  - Linear Time over Threshold with high dynamic range (>9 bits)
  - Lower power consumption (about 3.5 mW/ch)
  - Different trigger levels and cluster trigger for monolithic crystals.
  - Different scintillator time constants.

HRFlexToT

180 nm CMOS





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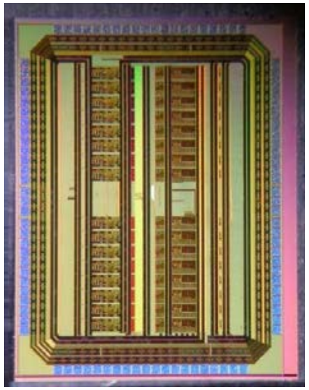
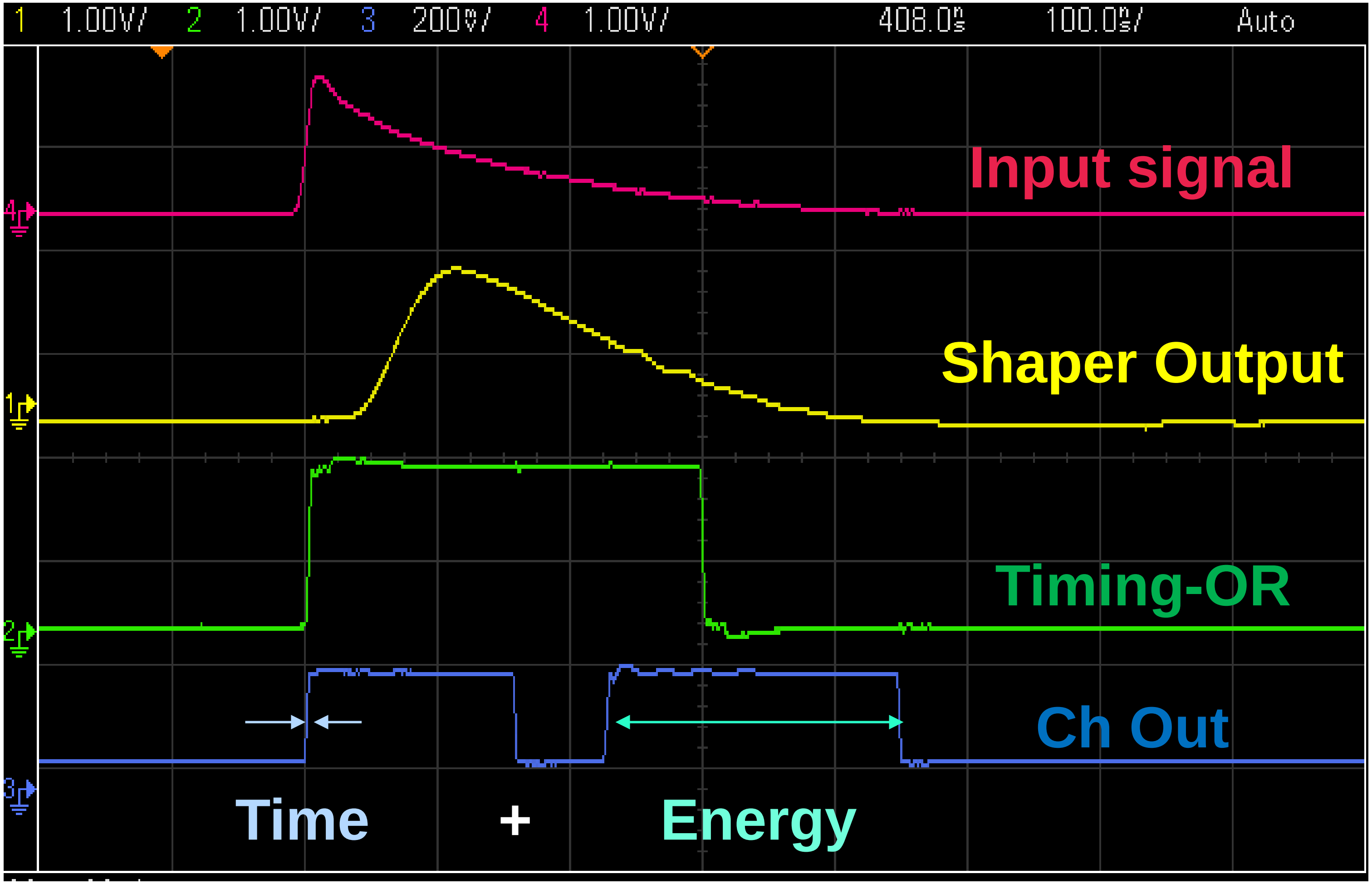
II. MultiCh readout: HRFlexToT

HRFlexToT

180 nm CMOS





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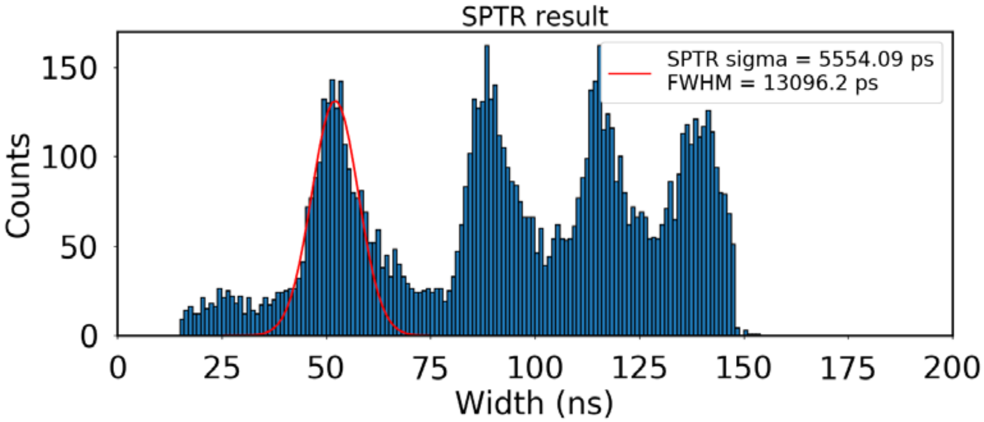
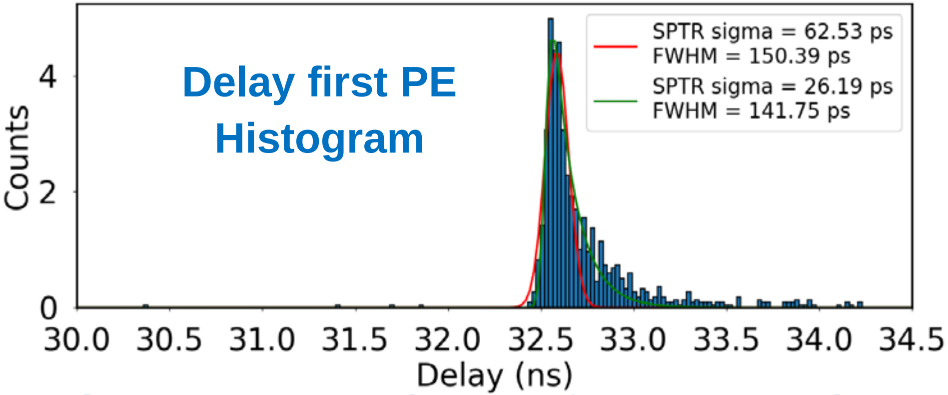
II. MultiCh readout: HRFlexToT

Time width Histogram



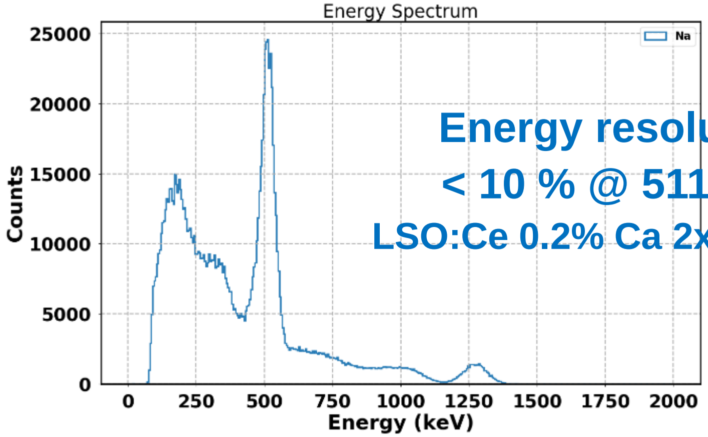
Delay first PE Histogram



Bias voltage 38V (11.5V of Overvoltage)

Sensor	NINO*	HRFlexToT*
HPK S13360 (3x3mm^2, 50μm pixel pitch)	160 ps (10V of VoV)	167 ps (10V of VoV)
FBK NUV-HD (4x4mm^2, 40μm pixel pitch)	135 ps (12V of VoV)	142 ps (11.5V of VoV)

***SPTR in terms of FWHM**



Energy resolution < 10 % @ 511 keV

LSO:Ce 0.2% Ca 2x2x5 mm^3

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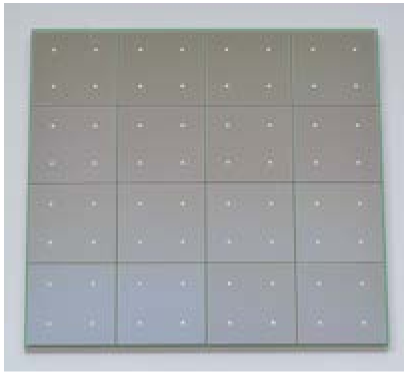
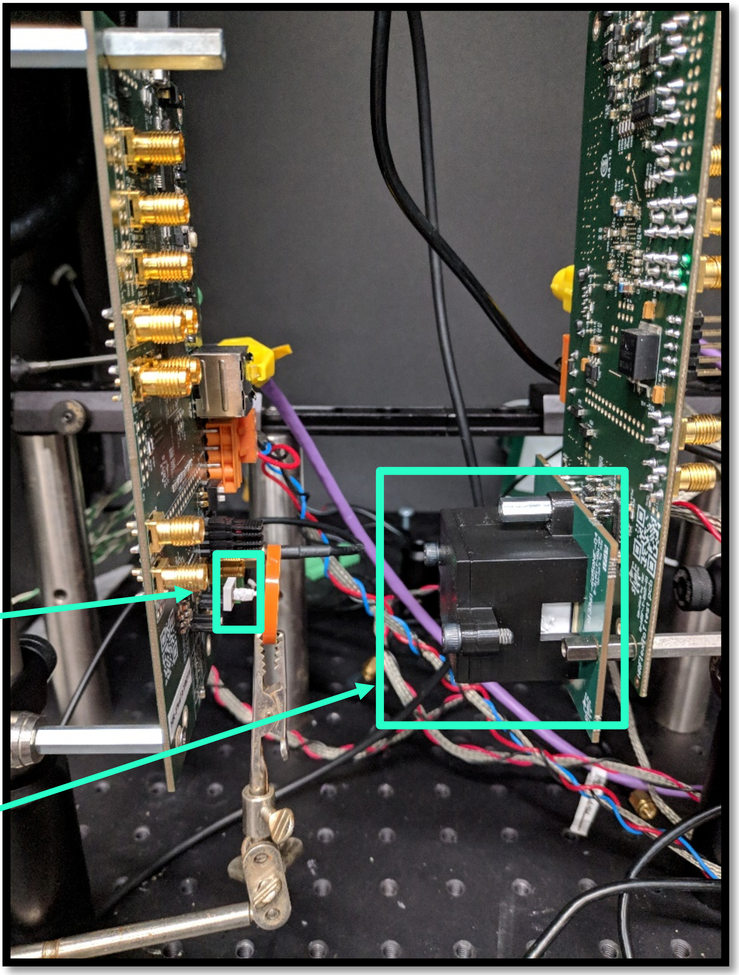
L. Freixas, J. Marin, J.M. Perez. P. Rato et alt.

II. MultiCh readout: HRFlexToT: monolithic crystals

- Coincidence Time Resolution (CTR)
- Sensors and crystals involved:
  - Reference detector:
    - LSO:Ce 0.2% Ca 2x2x5 mm^3
    - S13360-3050CS (1 channel, 3x3 mm^2)
    - Jitter $= 90ps\ FWHM$
  - Monolithic crystal:
    - LFS 20x25x25 mm^3 (with Teflon)
    - S13361-6050PE-04 (16 channel, 6x6 mm^2)



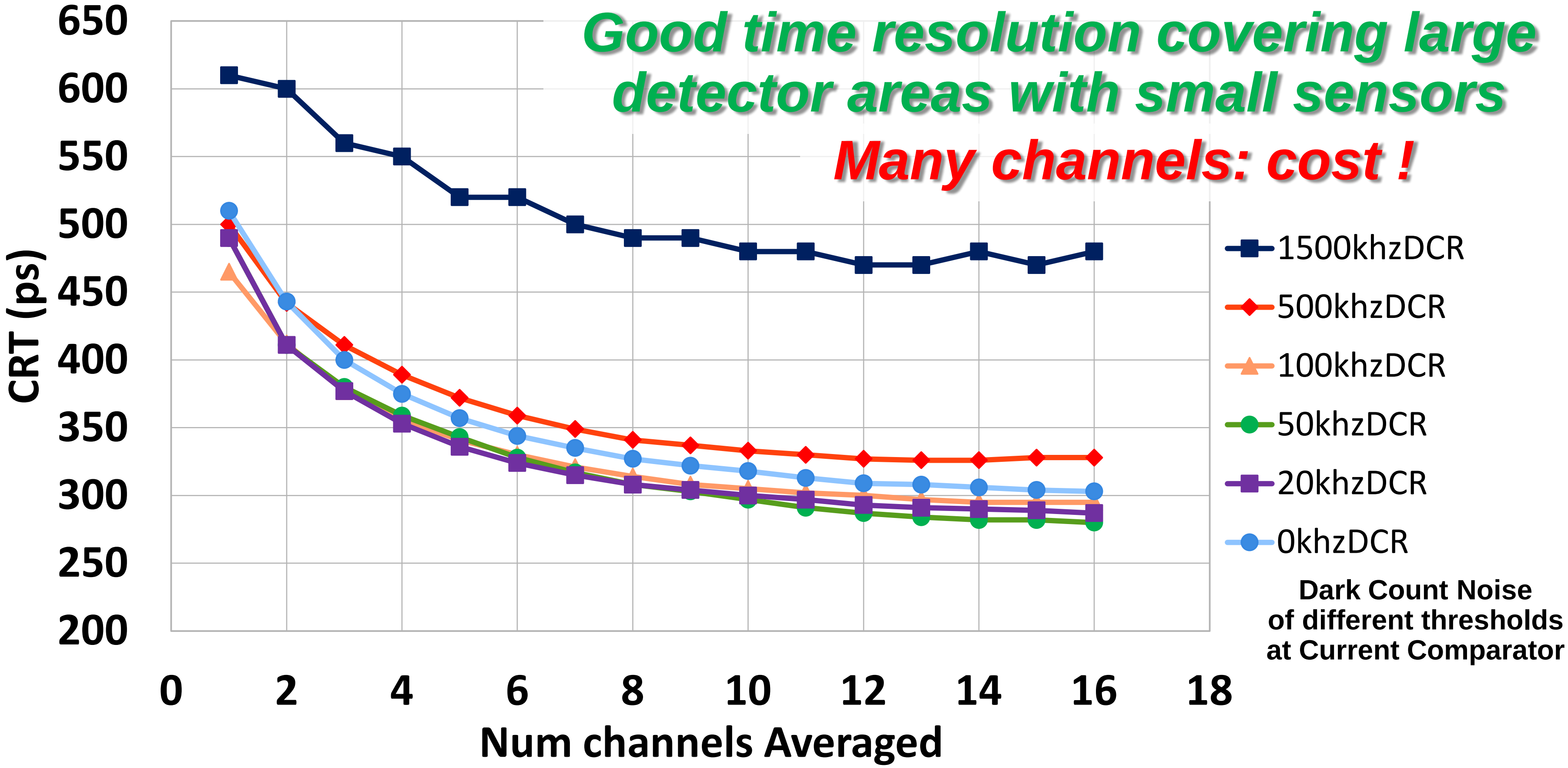


Reference detector

Monolithic detector

II. MultiCh readout: HRFlexToT: monolithic crystals

- Time-walk correction + averaging of the N fastest channels.



Good time resolution covering large detector areas with small sensors

Many channels: cost !

Dark Count Noise of different thresholds at Current Comparator

CTR = 280 ps FWHM → Measured

CTR = 236 ps FWHM → After subtracting TDC and Reference jitter

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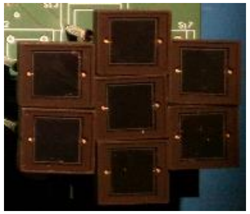
III. Combining small sensors: active summation: MUSIC

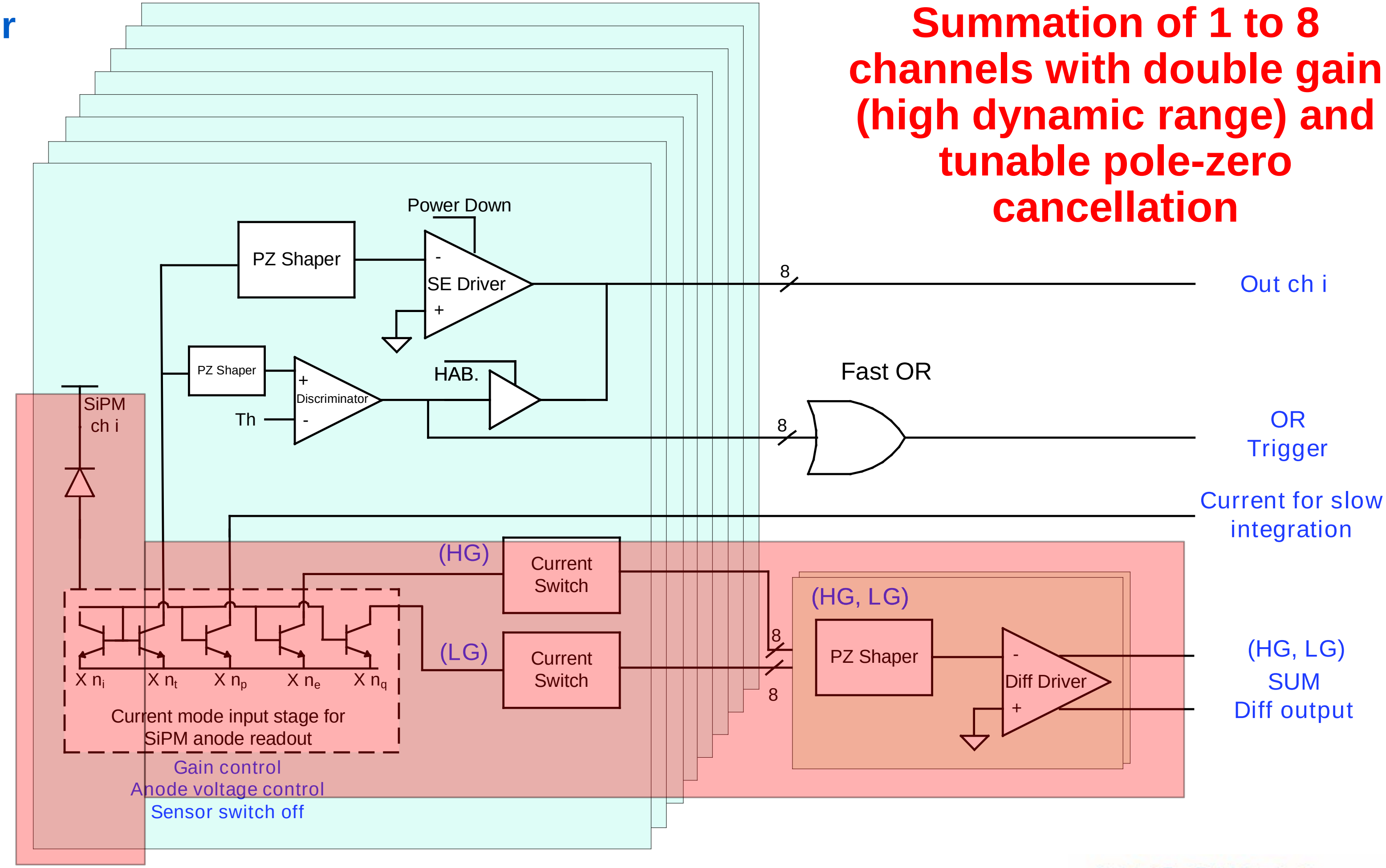
- MUSIC 8 ch ASIC performs single ch or summation

1 x PMT (CTA)
18 mm diameter

≈



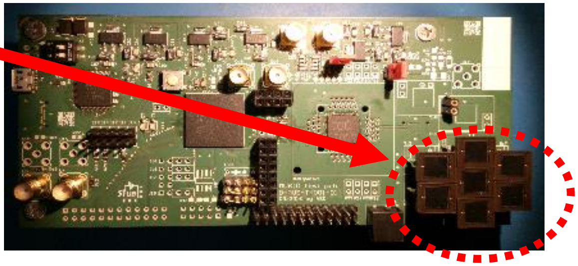
7 x SIPM
6x6 mm^2 each

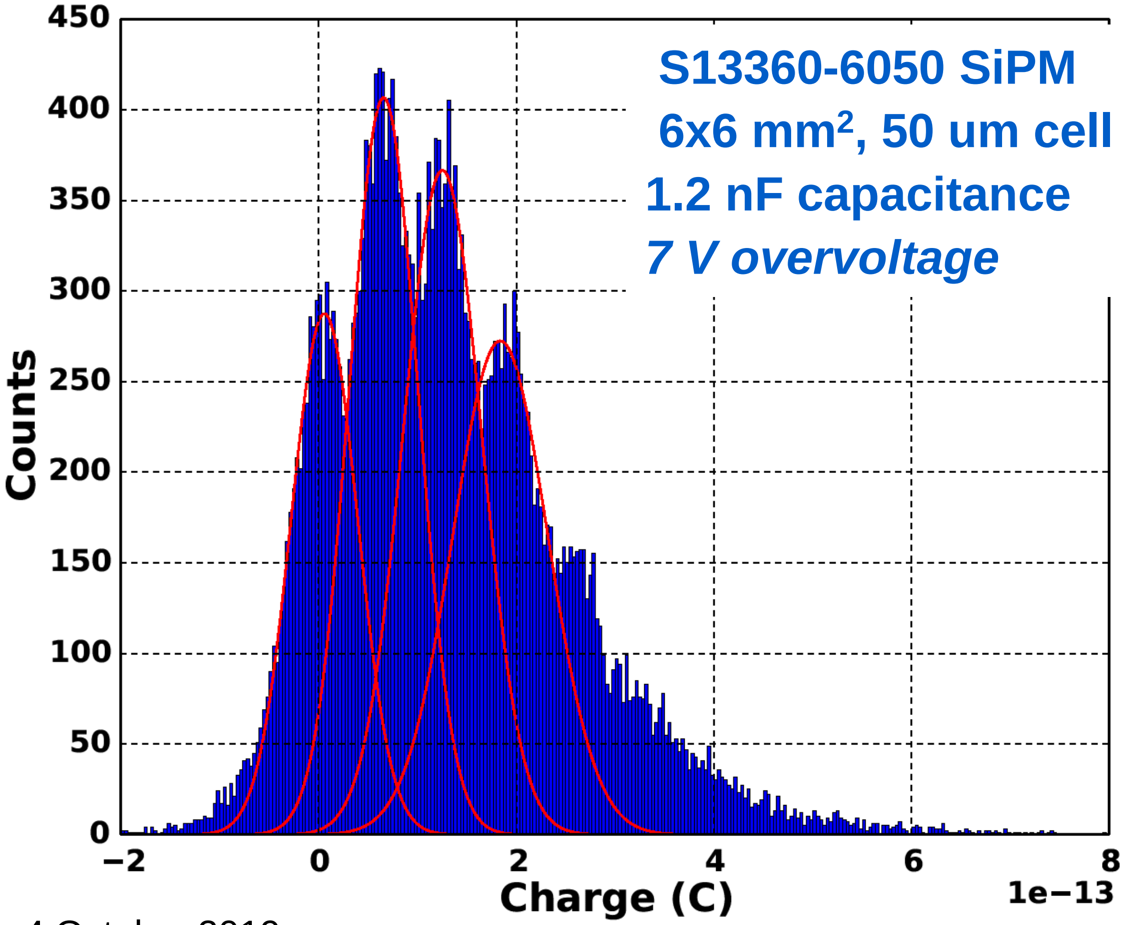


Summation of 1 to 8 channels with double gain (high dynamic range) and tunable pole-zero cancellation

III. Combining small sensors: active summation : MUSIC

- MUSIC configuration: the adder takes 7 channels
  - – Noise is much higher (sqrtr(7))
  - – But pe (cell) peaks can still be identified
  - – Channels have been equalized by MUSIC anode ctrl voltage





S13360-6050 SiPM

6x6 mm^2, 50 um cell

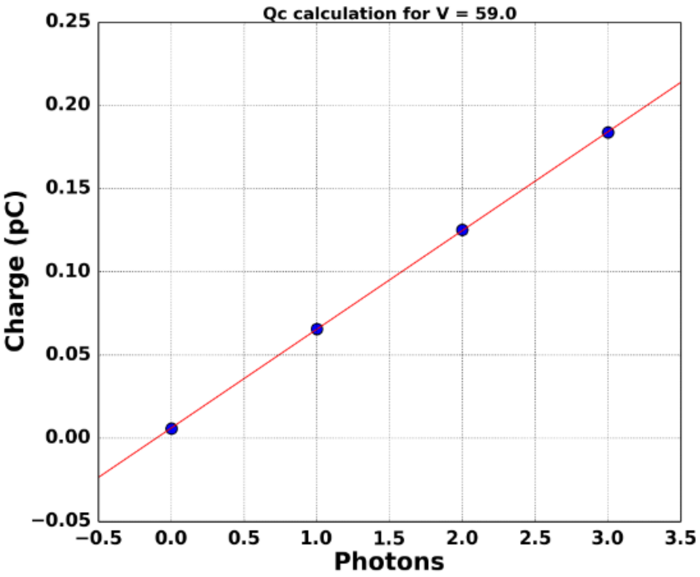
1.2 nF capacitance

7 V overvoltage

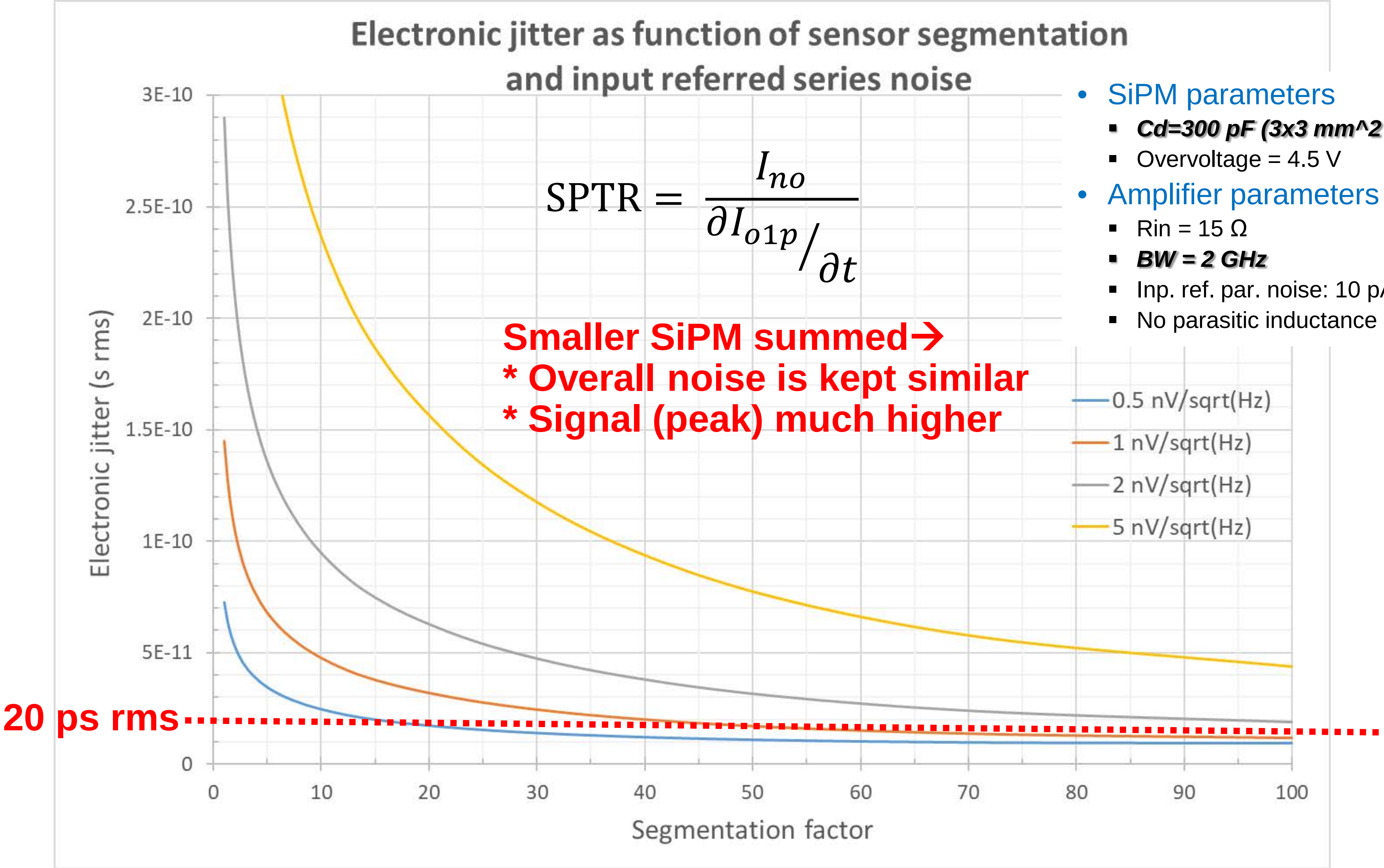
1 x PMT
18 mm diameter

≈

7 x SIPM
6x6 mm^2
each



III. Combining small sensors: active summation



$$\mathrm{SPTR} = \frac{I_{no}}{\partial I_{o1p} / \partial t}$$

Smaller SiPM summed→
*** Overall noise is kept similar**
*** Signal (peak) much higher**

- SiPM parameters
  - ***Cd=300 pF (3x3 mm^2 device)***
  - Overvoltage = 4.5 V
- Amplifier parameters
  - Rin = 15 Ω
  - ***BW = 2 GHz***
  - Inp. ref. par. noise: 10 pA/sqrt(/Hz)
  - No parasitic inductance

More details in NSS-2019

'Optimal design of single-photon sensor front-end electronics for fast-timing applications, J.M. Fernandez-Tenllado, D. Gascon, R. Ballabriga, S. Gomez, J. Mauricio, M. Campbell'

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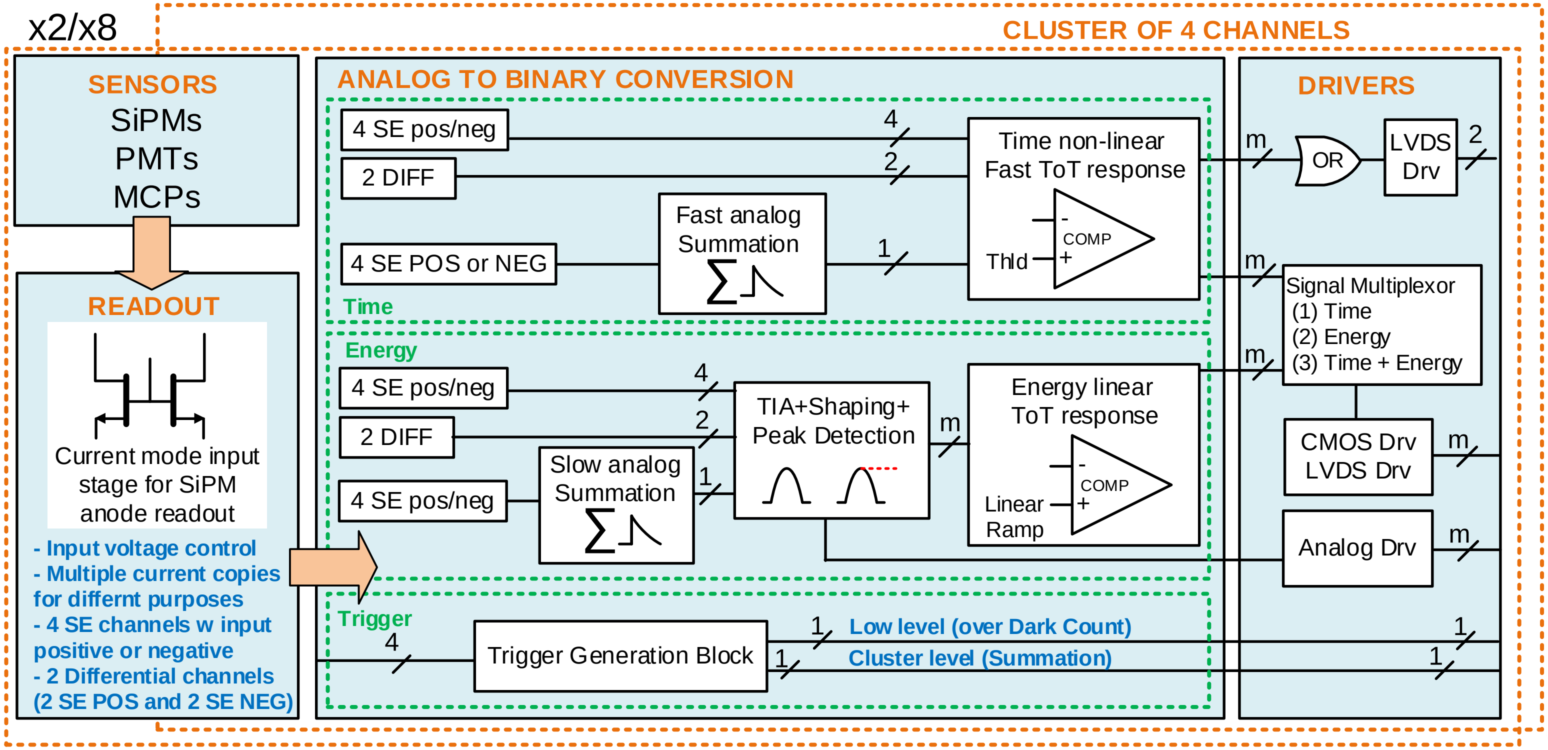
IV. Towards a picosecond hybrid single photon sensor
First step: 65 nm FE: FastIC

- FASTIC current mode ASIC.
  - **8 Inputs:** 8 Single Ended (positive or negative) or 4 differential.
  - **4/8 Outputs:** CMOS, LVDS and Analog.
  - Summation in clusters of 4 channels.
  - Energy: Linear Time over Threshold with high dynamic range.
  - Different trigger levels and cluster trigger for monolithic crystals.

- First submission scheduled for end 2019: 8 ch
- Final chip: 32 channel (< 10 mW/ch)



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IV. Towards a picosecond hybrid single photon sensor
First step: 65 nm FE: FastIC Performance

- Preliminary simulation benchmarking of FASTIC:

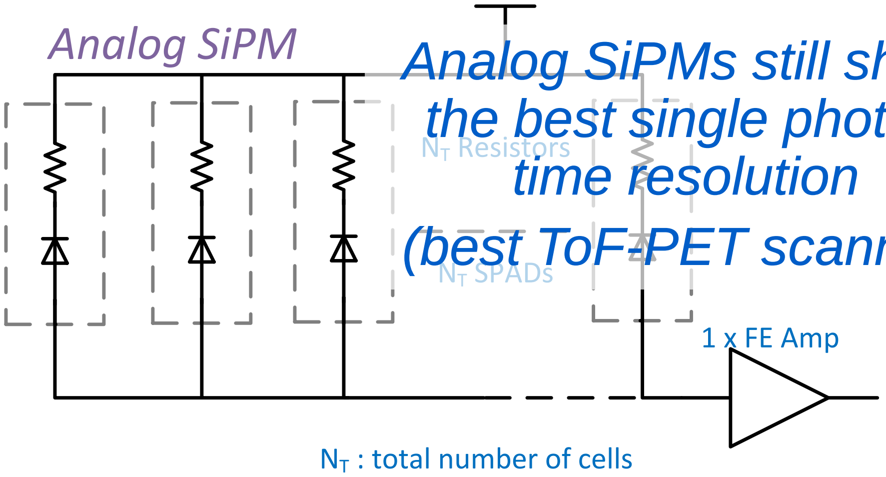
	Jitter (ps), sigma, 1 firing cell							
Sensor	**Over-voltage**	**NINO**	**HRFlexToT**	**S.E. (+)**	**S.E. (-)**	**DIFF**	**SUM4 (+)**	**SUM4 (-)**
		Extrapolation	**Simulation**					
LCT4, 50 um, 3600 cells	4,5	31,12	39	25	38,6	22	-	-
LCT5 S13360, 50 um, 3600 cells	4,5	29,86	37,42	31	29	23,6	20,8	18,9
	7	17,96	22,5	18,5	18	15	13,3	12,8
	10	11,81	14,8	13,5	13	11	9	8

- FASTIC in DIFF and SUM modes should outperform NINO:

	Jitter (ps), sigma, 1 firing cell							
Sensor	**Over-voltage**	**NINO**	**HRFlexToT**	**S.E. (+)**	**S.E. (-)**	**DIFF**	**SUM4 (+)**	**SUM4 (-)**
		Extrapolation	**Simulation**					
LCT4, 50 um, 3600 cells	4,5	0	20,20	-24,49	19,37	-41,47	-	-
LCT5 S13360, 50 um, 3600 cells	4,5	0	20,20	3,67	-2,97	-26,53	-43,57	-58,00
	7	0	20,20	2,94	0,25	-19,70	-35,00	-40,28
	10	0	20,20	12,51	9,15	-7,37	-31,23	-47,64

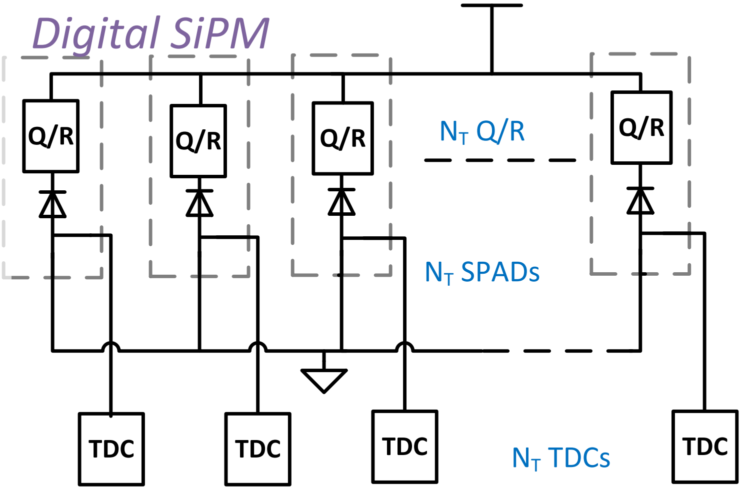
IV. Towards a picosecond hybrid single photon sensor
Analog versus Digital SiPMs

- Digital SiPMs might overcome C limitation, however:
  - Limited fill factor due to in pixel electronics
    - Solved by 3D integration ?
  - Power and resource hungry:
    - 1 TDC per pixel or complex TDC sharing
  - Digital FE and trigger network jitter



Analog SiPMs still show the best single photon time resolution

(best ToF-PET scanner)



Q/R: Quenching and recharge circuit

Pros
- Simplicity
- High Fill Factor (PDE)

Cons
- Large capacitance degrades timing
- Xtalk deagrades timing

Pros
- Individual photon timing available

Cons
- Complexity (cost and power)
- Fill factor degradation
- Xtalk degrades timing

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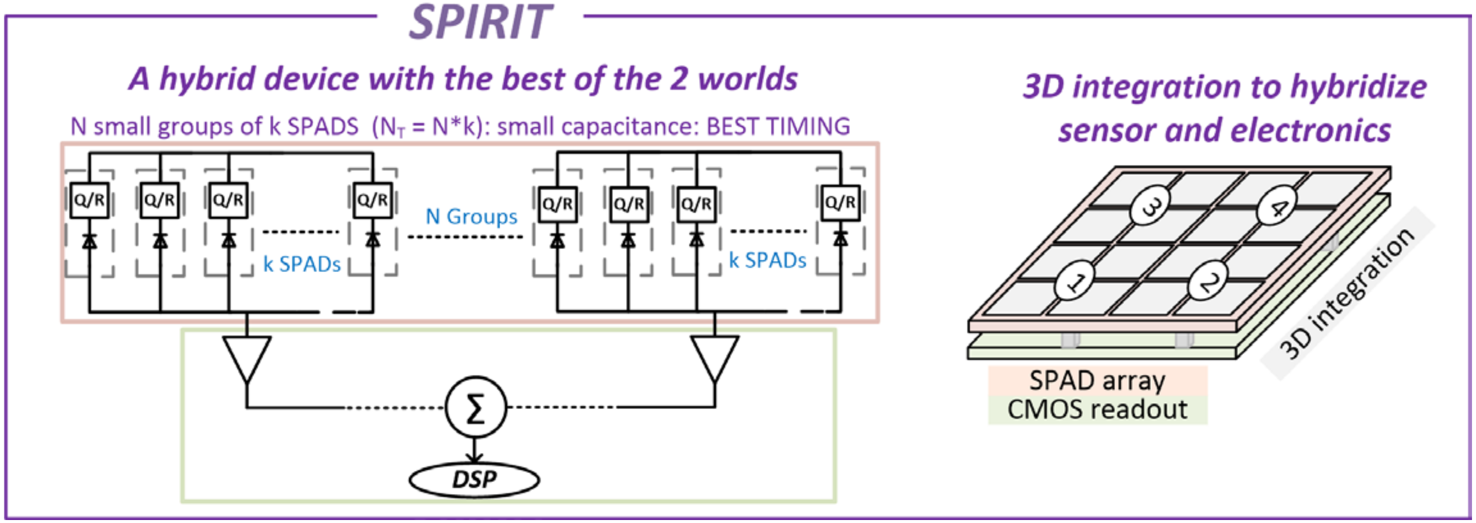
IV. Towards a picosecond hybrid single photon sensor
Hybrid sensor and FastICPix ASIC

- **New hybrid sensor**
  - Idea is to ***combine actively the signal of small micropixel sub-arrays***
  - *Based* on the ***best*** single photon ***sensor technologies***
  - With ***ultrafast readout*** electronics (≤ 65 nm) using ***3D integration***



- First step ongoing: approved **ATTRACT H2020 project**
  - Phase-I: FastICPix: validate our approach in a full system simulation
- **Unprecedented time resolution** for large sensitive areas
  - Active summation and combination of small groups of SPADs which show a capacitance **two orders of magnitude lower than aSiPMs**

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V. Discussion

- The performance of SiPM as large area detector is still hampered by huge detector capacitance
  - Particularly for fast shaping times or to achieve the ultimate timing
- Improving FE electronics may help
  - Lower noise and input impedance, higher bandwidth, etc
  - But the margin of improvement is limited:
    - Noise: power increase, thermal noise of passives, common-mode
    - Bandwidth: interconnection parasitics (RLC) imposes a limit in the effective BW or Slew rate one can achieve with large sensors
- Sensor segmentation and active summation can help
  - Encouraging results with **MUSIC chip** and good prospects with **FastIC**
- A hybrid single photon sensor may approach the limit SPTR
  - Large segmentation: capacitance “reduced” by 2 orders of magnitude
  - Parasitics won’t limit the bandwidth anymore
  - Compatible with alternative technologies: pixelated MCPs, tynodes, etc

Thanks a lot for your attention !!!

Questions ?

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UNIVERSITAT DE BARCELONA

ICCUB Institute of Cosmos Sciences EXCELENCIA MARÍA DE MAEZTU

Back up Sergio

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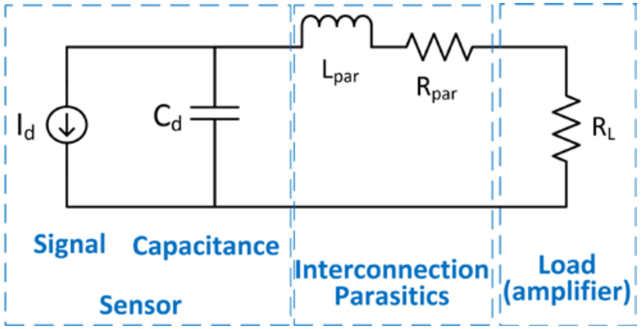
I. Introduction

• Single Photon Sensors

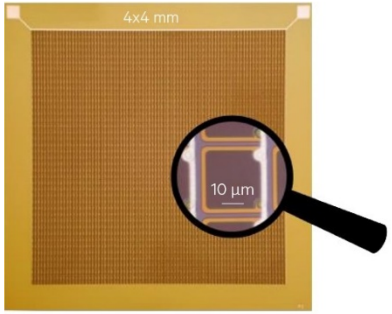
Vacuum Photomultipliers

- G = 10^5 – 10^7
- Cd ~ 10 pF
- L ~ 10 nH
- SPTR * < 50 ps FWHM
  - MCP-PMTs

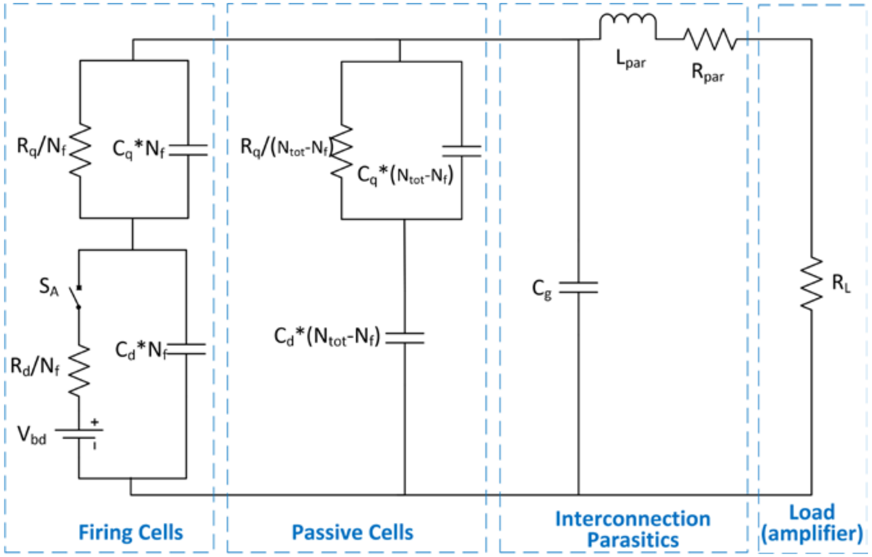


Silicion Photomultipliers

- G* = 10^5 – 10^7
- Cd from 10 pF to 1 nF
- L ~ 10 nH
- SPTR < 100 ps FWHM
  - Small SiPMs



www.azosensors.com/article.aspx?ArticleID=865

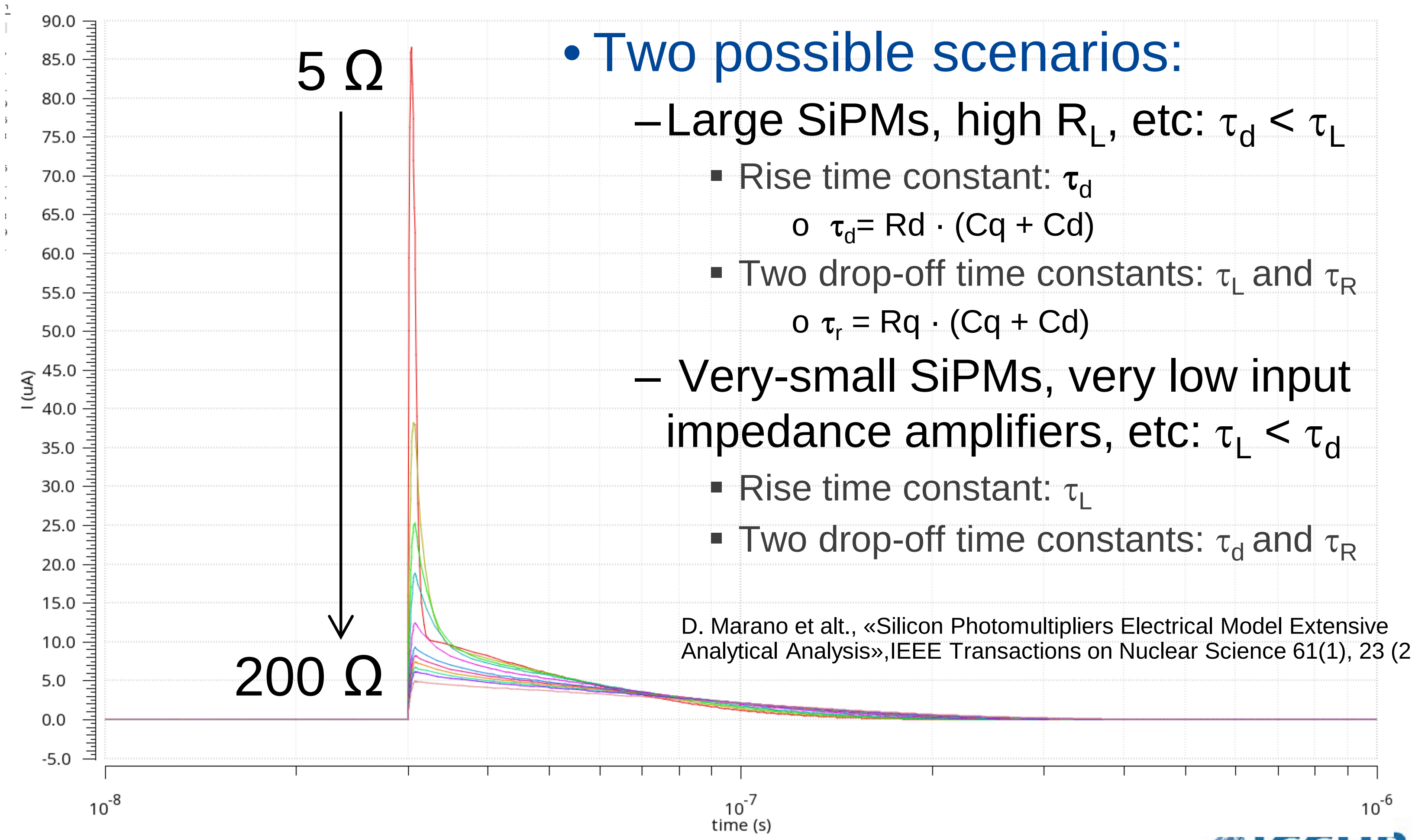


* SPTR: Single Photon Time Resolution

* Effective SiPM gain is not obvious: strong dependence on shaping times

I. Introduction
Load impedance (current)

- The signal (load current) shape and amplitude depends on R_L
  - Peak current signal is inversely proportional to R_L

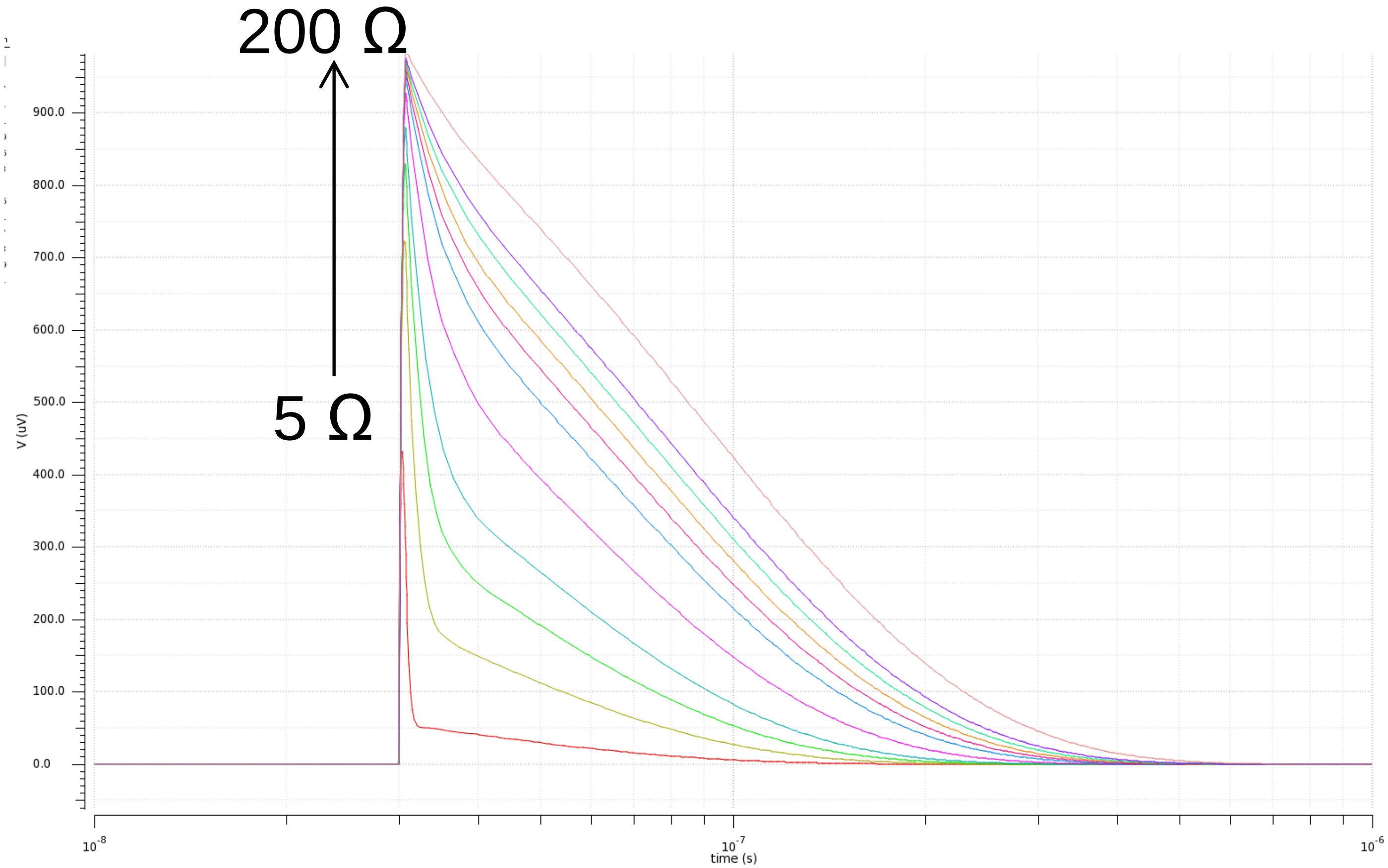


- Two possible scenarios:
  - Large SiPMs, high R_L, etc: $\tau_d < \tau_L$
    - Rise time constant: τ_d
      - o $\tau_d = Rd \cdot (Cq + Cd)$
    - Two drop-off time constants: τ_L and τ_R
      - o $\tau_r = Rq \cdot (Cq + Cd)$
  - Very-small SiPMs, very low input impedance amplifiers, etc: $\tau_L < \tau_d$
    - Rise time constant: τ_L
    - Two drop-off time constants: τ_d and τ_R

D. Marano et alt., «Silicon Photomultipliers Electrical Model Extensive Analytical Analysis»,IEEE Transactions on Nuclear Science 61(1), 23 (2014).

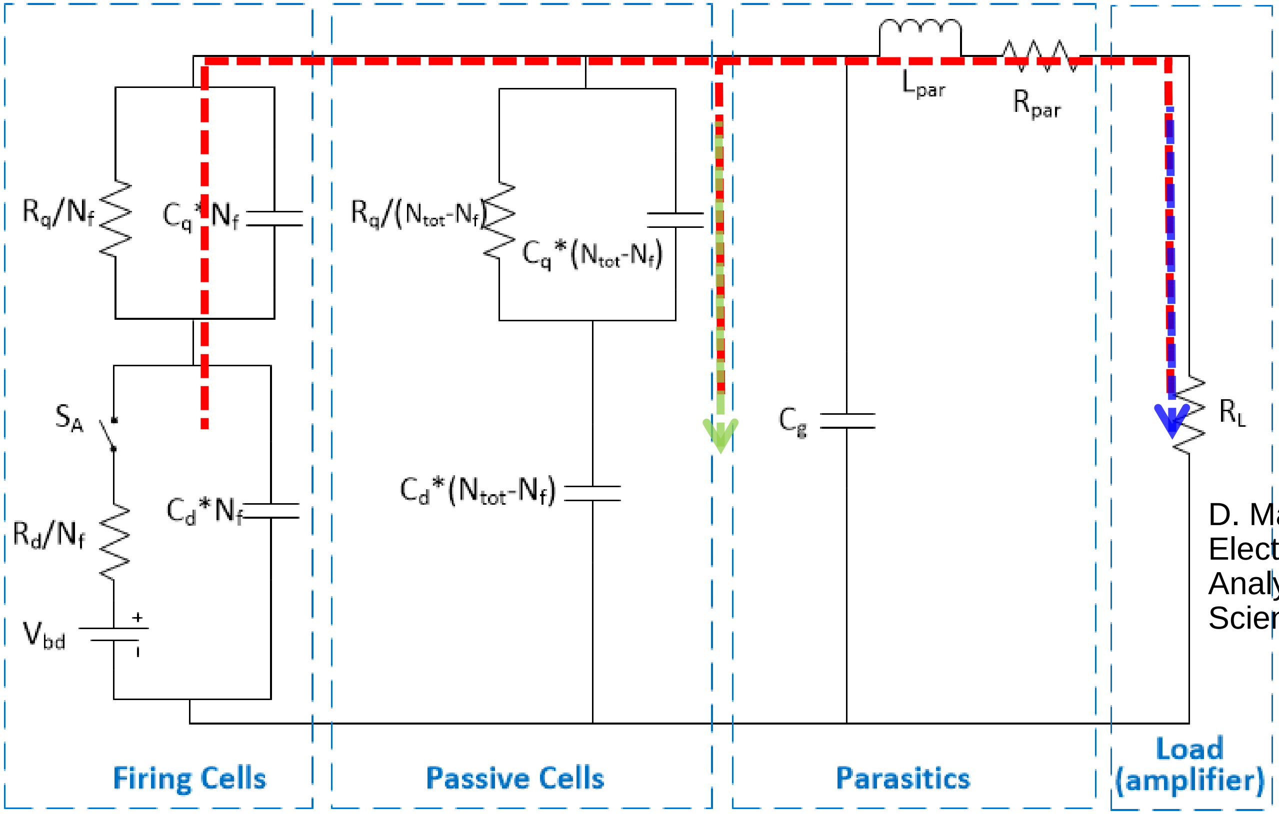
I. Introduction
Load impedance (voltage)

- If we sense the load voltage the situation is a little bit different:
  - Shape also depends on R_L (long drop-off times for large R_L)
  - But now the signal increases with R_L (particularly for low τ_L)



I. Introduction
Parasitic Capacitance effect

- Passive cells and load impedance form a low pass filter !
  - We are sensing the current or the voltage on R_L
  - Passive cells and parasitic capacitances create a current divider with R_L
  - Peak signal goes with $Cpar^{-1}$



Low pass filter time constant:

$$\tau_L \approx R_L \cdot N_{tot} \cdot (Cq \,//\, Cd)$$

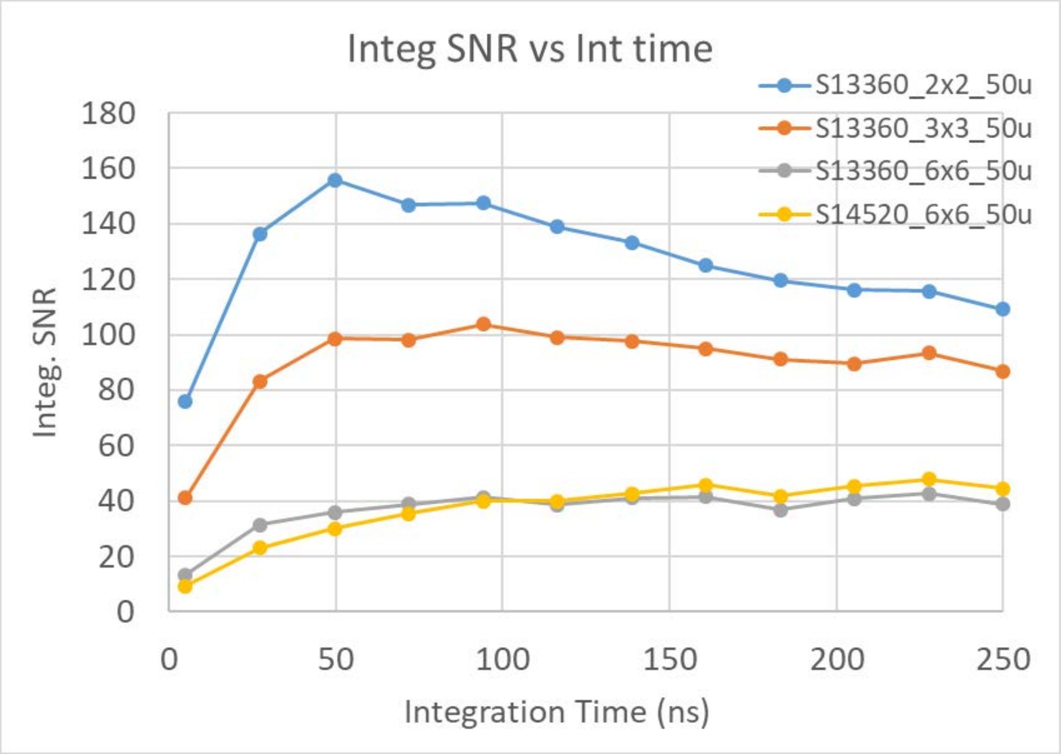
***** *Approximate: we should include also Cg here*

D. Marano et alt., «Silicon Photomultipliers Electrical Model Extensive Analytical Analysis»,IEEE Transactions on Nuclear Science 61(1), 23 (2014).

I. Introduction
Integration (shaping) time

- Longer shaping times help to dramatically improve SNR of the charge spectrum
  - Application dependent !
- Longer shaping times:
  - Increase signal collection (important for large devices)
  - Mitigates the effect of series noise
    - Warning: but increases the effect of parallel noise (important for small devices)!

- SiPM overvoltage: 4.5 V
- Amplifier parameters
  - Rin = 15 Ω
  - BW = 500 MHz
  - Inp. ref. ser. noise: 2 nV/sqrt(/Hz)
  - Inp. ref. par. noise: 10 pA/sqrt(/Hz)



Disclaimer: increasing integration time may not work because of DCR, correlated noise, pile-up…

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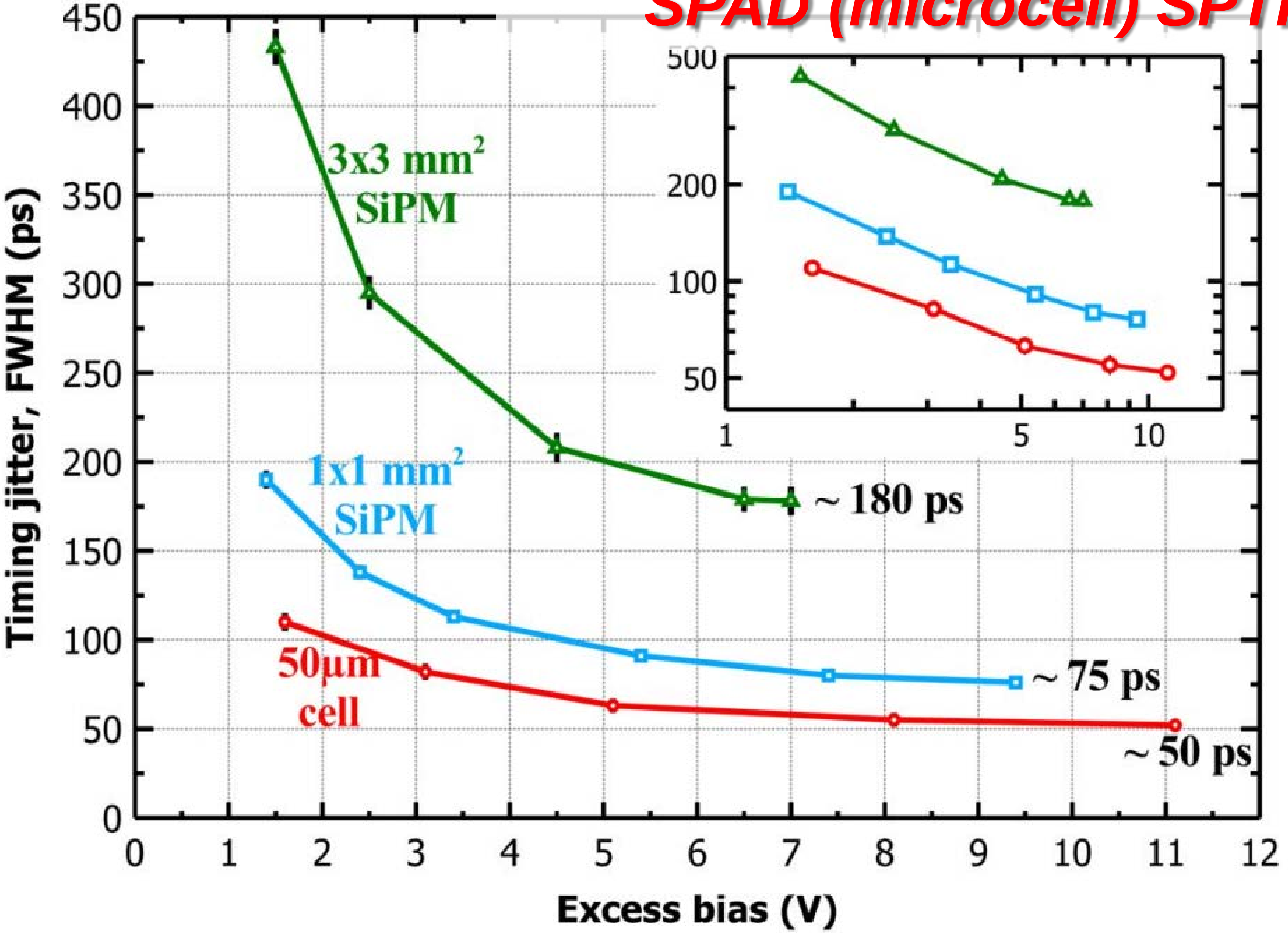
I. Introduction

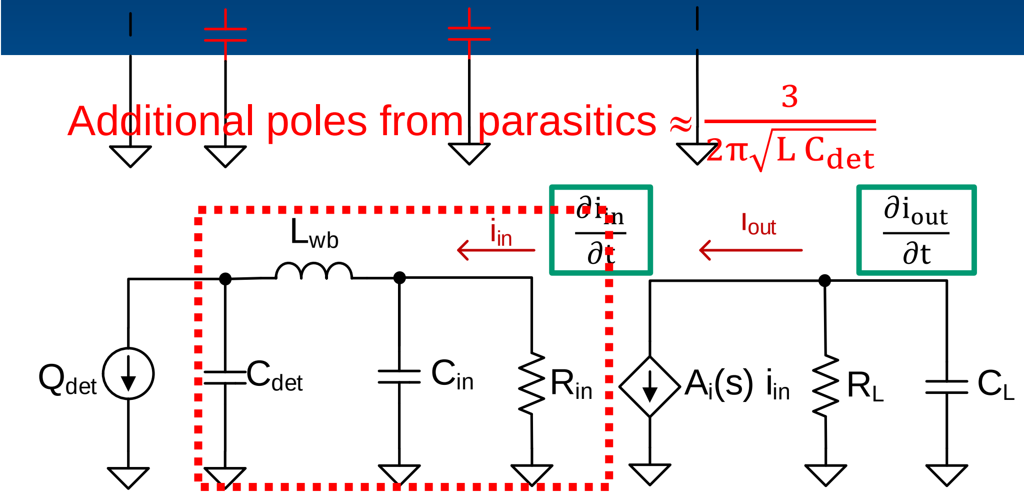
Large area SiPMs: jitter

SiPM technology is still far from the SPAD (microcell) SPTR limit



F. Acerbi *et al.*, "Characterization of Single-Photon Time Resolution: From Single SPAD to Silicon Photomultiplier," in *IEEE Transactions on Nuclear Science*, vol. 61, no. 5, pp. 2678-2686, Oct. 2014.

I. Introduction: Effect of interconnects (inductance)

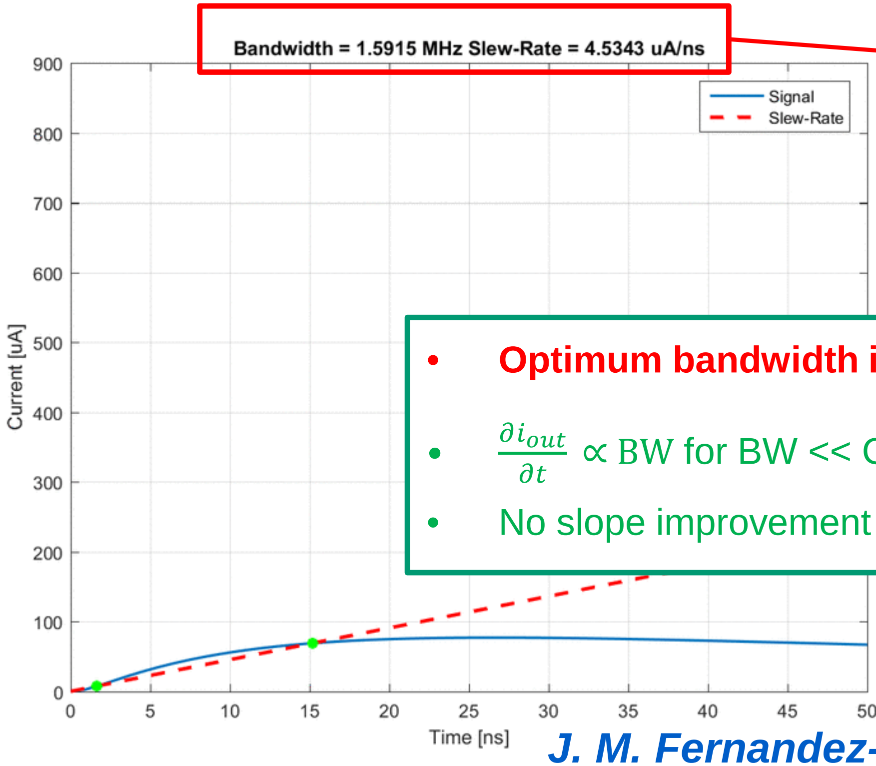


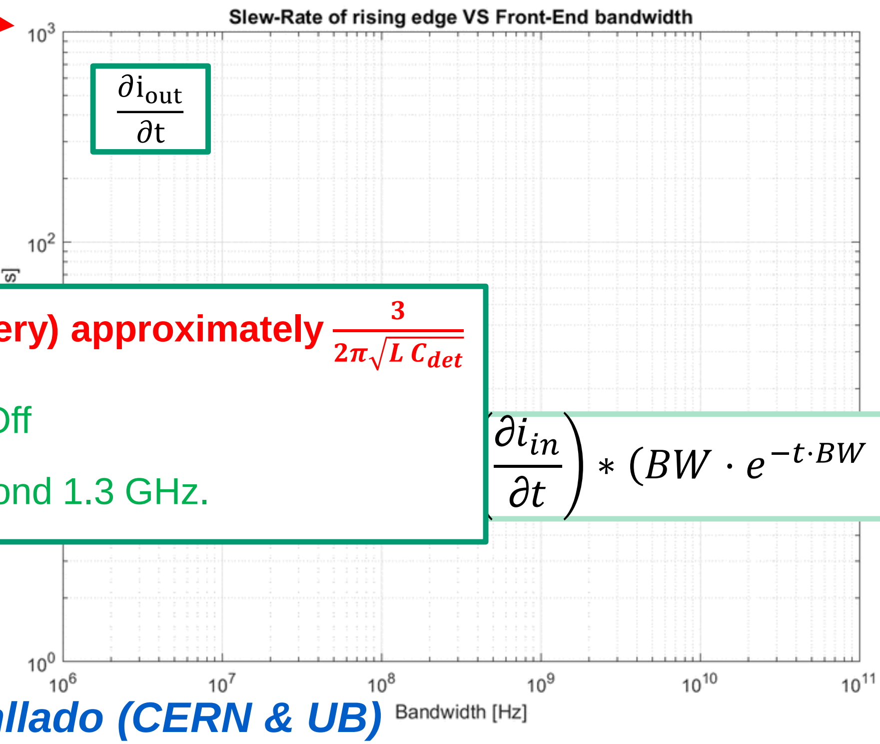
Additional poles from parasitics $\approx \frac{3}{2\pi\sqrt{L\,C_{det}}}$

Optimum bandwidth for connecting inductances 5 nH – 25 nH and Cdet = 10 pF – 1 nF

Lwb / Cdet

5 nH / 10 pF	5 nH / 1 nF	25 nH / 10 pF	25 nH / 1 nF
1.3 GHz	270 MHz	560 MHz	81 MHz


Bandwidth = 1.5915 MHz Slew-Rate = 4.5343 uA/ns


Slew-Rate of rising edge VS Front-End bandwidth

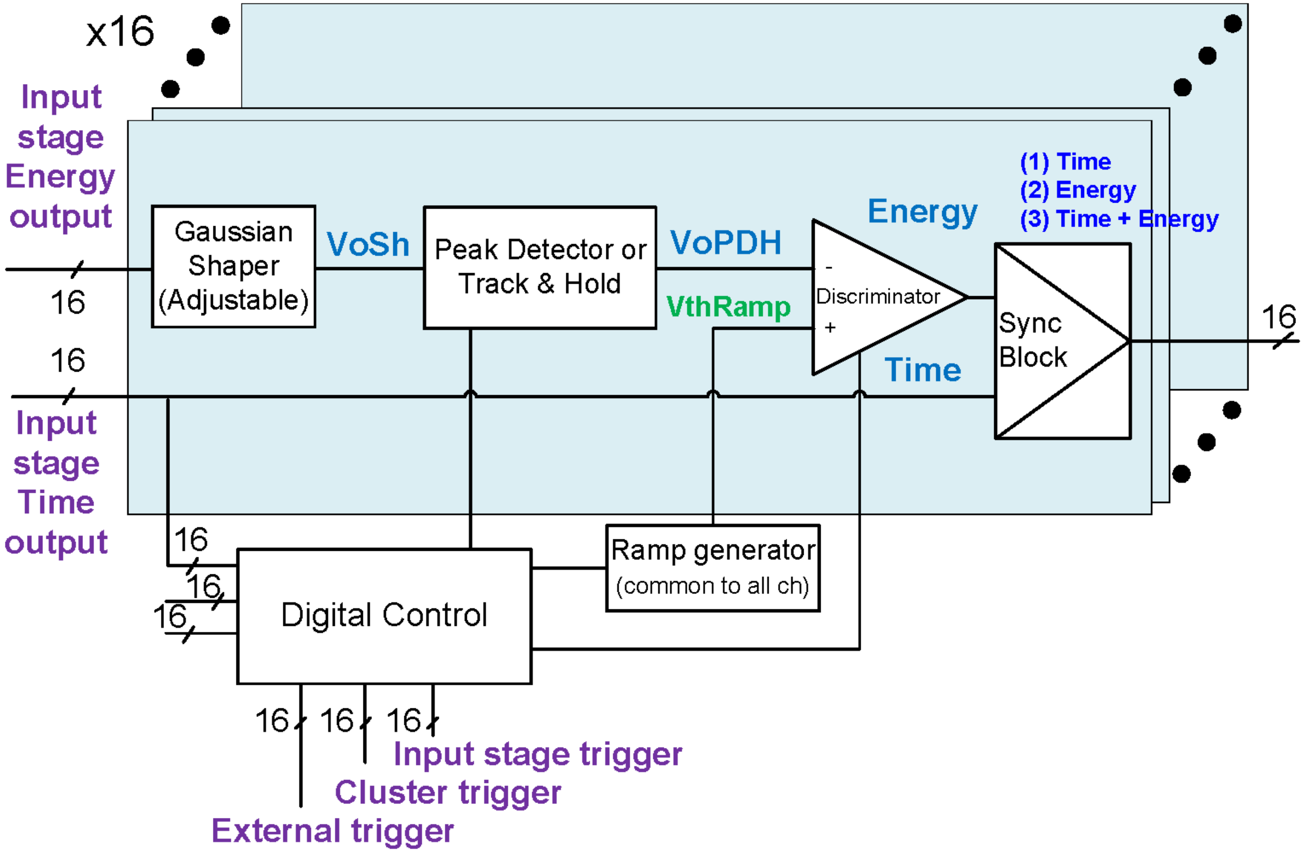
- **Optimum bandwidth is (very) approximately $\frac{3}{2\pi\sqrt{L\,C_{det}}}$**
- $\frac{\partial i_{out}}{\partial t} \propto$ BW for BW << Cut-Off
- No slope improvement beyond 1.3 GHz.

$$\left(\frac{\partial i_{in}}{\partial t}\right) * \left(BW \cdot e^{-t \cdot BW}\right)$$

J. M. Fernandez-Tenllado (CERN & UB)

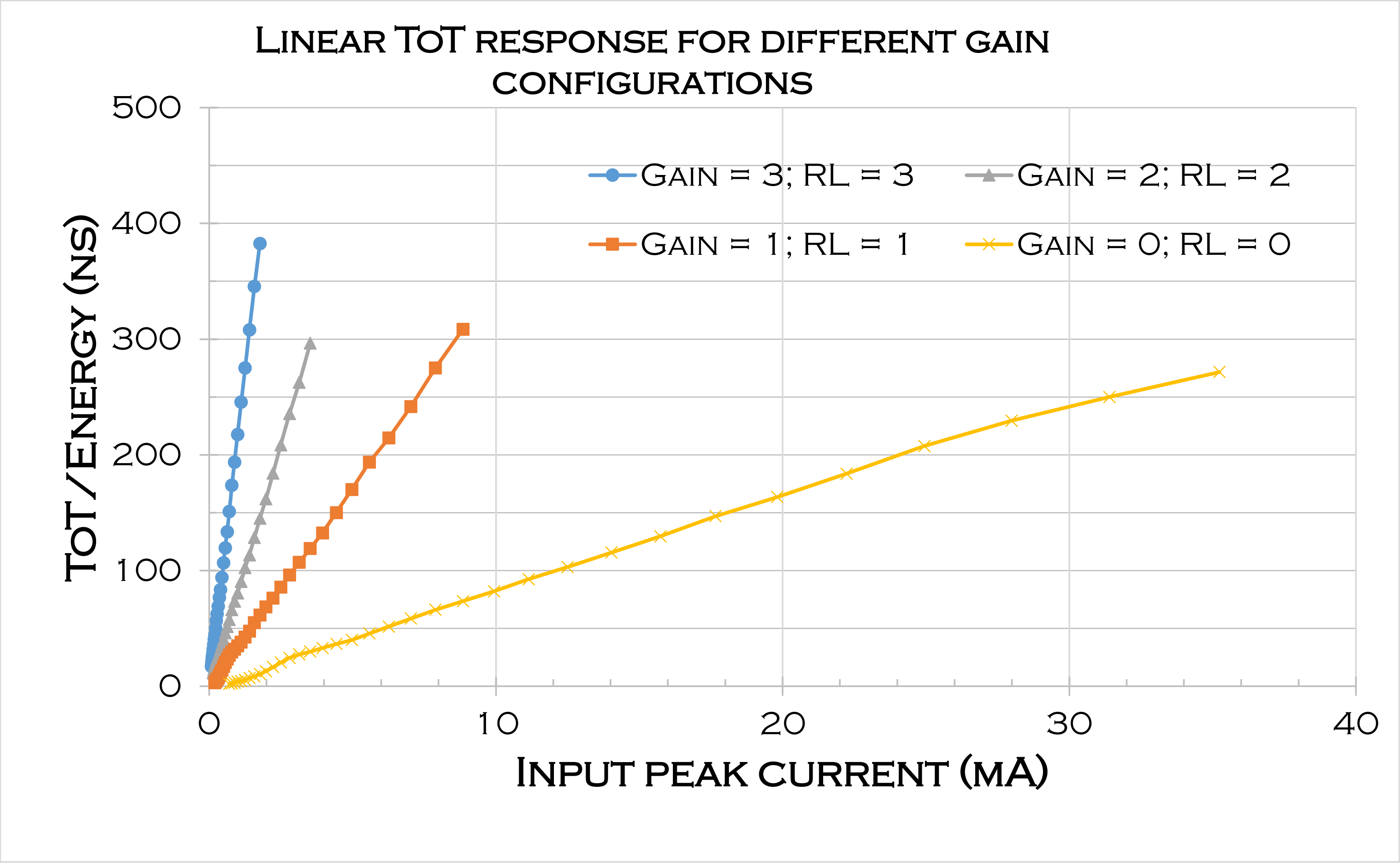
II. MultiCh readout: HRFlexToT

- **Linear energy readout**



S. Gomez, D. Sanchez, D. Gascon, J. Mauricio et alt,
L. Freixas, J. Marin, J.M. Perez. P. Rato et alt.

II. MultiCh readout: HRFlexToT



S. Gomez, D. Sanchez, D. Gascon, J. Mauricio et alt,
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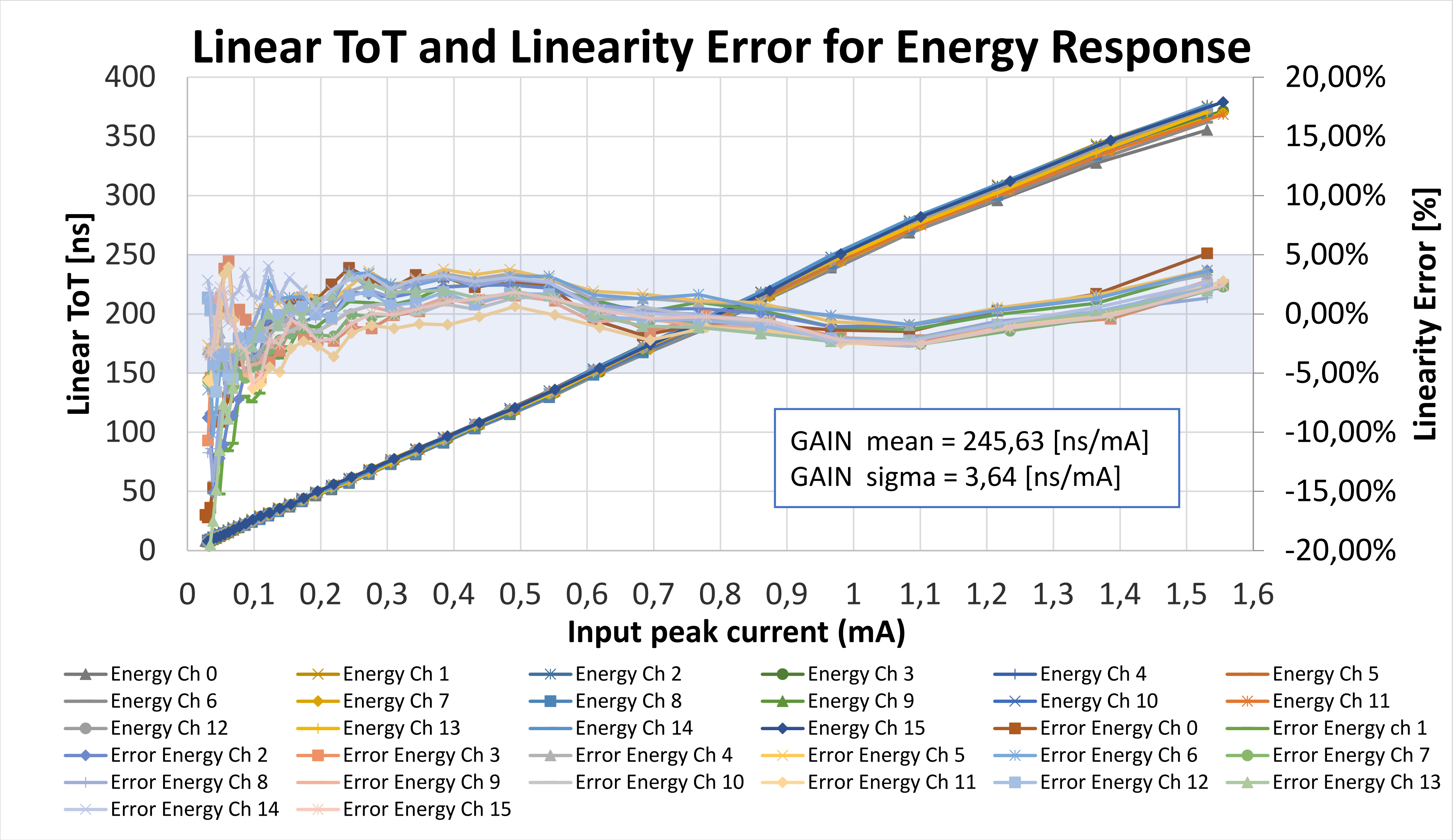


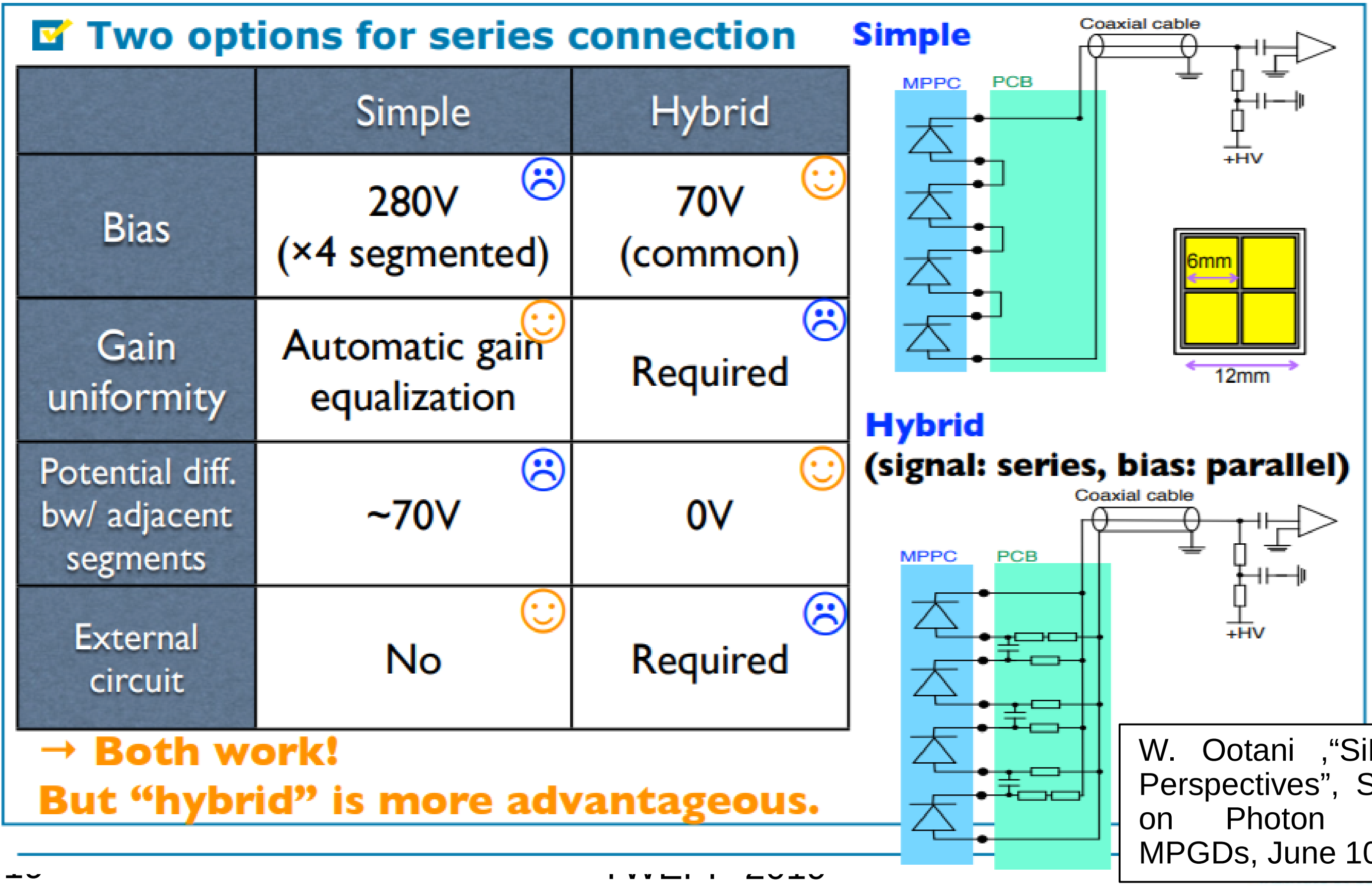
GAIN mean = 245,63 [ns/mA]
GAIN sigma = 3,64 [ns/mA]

4 October 2019

S. Gomez, D. Sanchez, D. Gascon, J. Mauricio et alt,
L. Freixas, J. Marin, J.M. Perez. P. Rato et alt.

III. Combining small sensors (passive)

- Alternative to obtain large area sensors:
  - Parallel connection: large capacitance !
  - Series (simple or hybrid) connection: lower capacitance (but lower signal):
    - Useful for reducing sensor recovery time not so clear for SNR (depends on amplifier Zin)



☑ **Two options for series connection**

	Simple	Hybrid
Bias	280V (×4 segmented) ☹	70V (common) ☺
Gain uniformity	Automatic gain equalization ☺	Required ☹
Potential diff. bw/ adjacent segments	~70V ☹	0V ☺
External circuit	No ☺	Required ☹

→ Both work!
But "hybrid" is more advantageous.

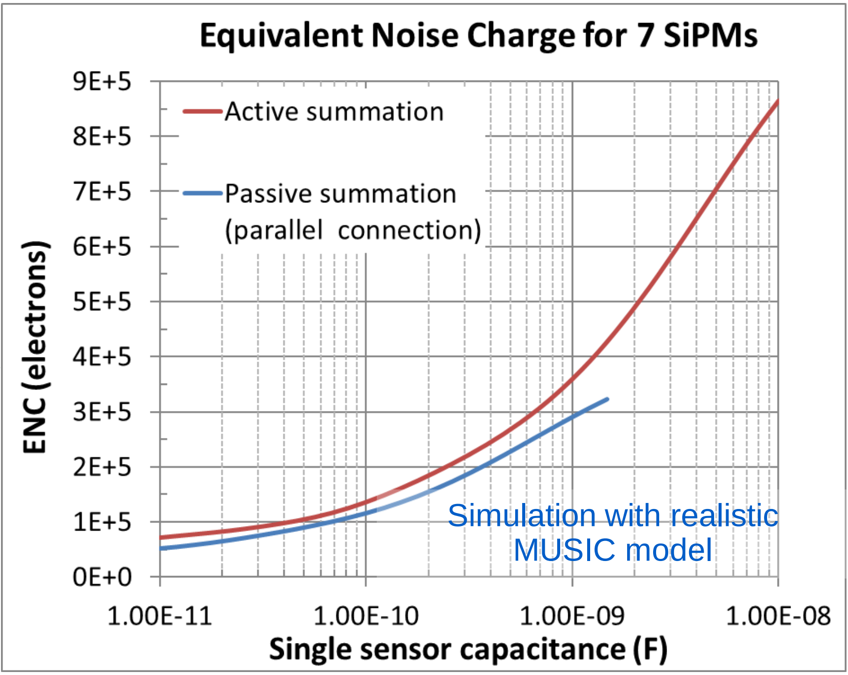
Simple

Hybrid
(signal: series, bias: parallel)

W. Ootani ,"SiPM, Status and Perspectives", Special Workshop on Photon Detection with MPGDs, June 10-11, 2015 CERN

III. Combining small sensors: active summation

- Why active summation?
  - Assume a large sensor is divided in *m* smaller subunits
    - $C_{largeDet} = m \cdot C_{smallDet}$
  - Total noise for active and passive summation can be similar
    - If series noise dominates
      - $\sigma_{n,largeDet} \sim \sqrt{m} \cdot \sigma_{n,smallDet}$
    - If we sum m small detectors
      - $\sigma_{n,m \cdot smallDet} \sim \sqrt{m} \cdot \sigma_{n,smallDet}$
    - Thus
      - $\sigma_{n,m \cdot smallDet} \sim \sigma_{n,largeDet}$ ⟹
  - But signal (peak) much higher!
    - Peak signal goes with C^{-1}
      - $S_{pk,m \cdot smallDet} \sim m \cdot S_{pk,largeDet}$
  - Summation circuit requirements:
    - Low noise and high BW



Simulation with realistic MUSIC model

III. Combining small sensors: active summation : MUSIC

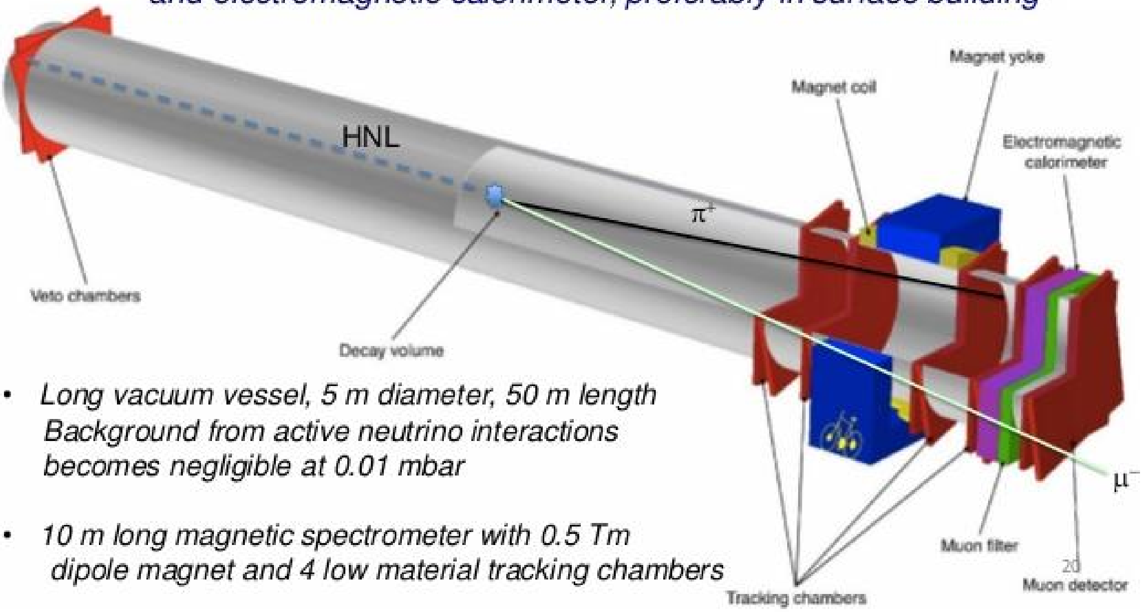
- SHIP experiment is a new general-purpose beam dump facility at the SPS (CERN) to search for hidden particles
  - Predicted by a very large number of recently elaborated models of Hidden
  - Dark matter, neutrino oscillations, and the origin of the full baryon asymmetry

SHiP

Search for Hidden Particles

- *Reconstruction of the HNL decays in the final states: $\mu^-\pi^+$, $\mu^-\rho^+$ & $e^-\pi^+$*

→ *Requires long decay volume, magnetic spectrometer, muon detector and electromagnetic calorimeter, preferably in surface building*



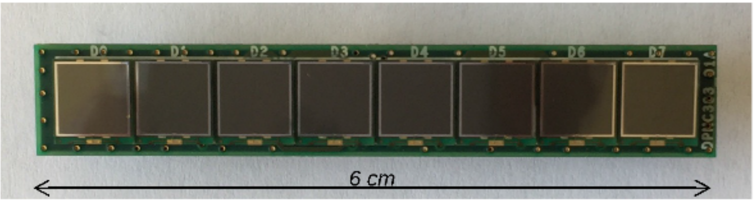
- *Long vacuum vessel, 5 m diameter, 50 m length Background from active neutrino interactions becomes negligible at 0.01 mbar*
- *10 m long magnetic spectrometer with 0.5 Tm dipole magnet and 4 low material tracking chambers*

III. Combining small sensors: active summation : MUSIC

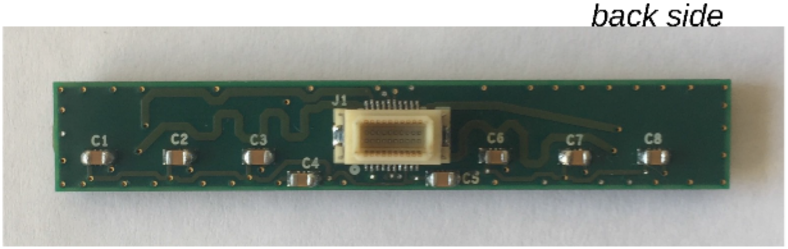
Bar and sensors for ToF/ND280

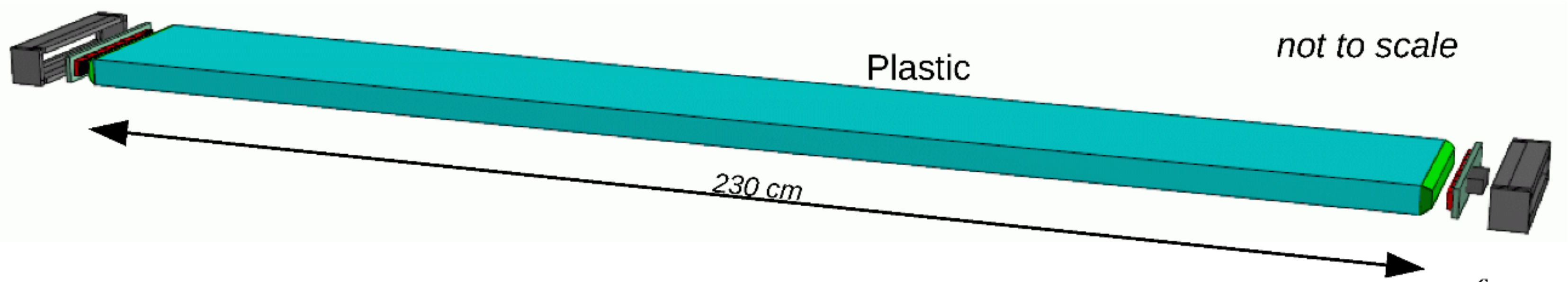
- Bar: 230 cm x 6 cm x 1 cm
- Plastic material:
  - EJ200 (BC408) or EJ208(BC412)
  - Attenuation length ~4 m
  - 1.42 kg/bar
- Readout from both ends
  - 8 sensors of 6 mm x 6 mm
  - Example: S13360-6050PE

front side



back side

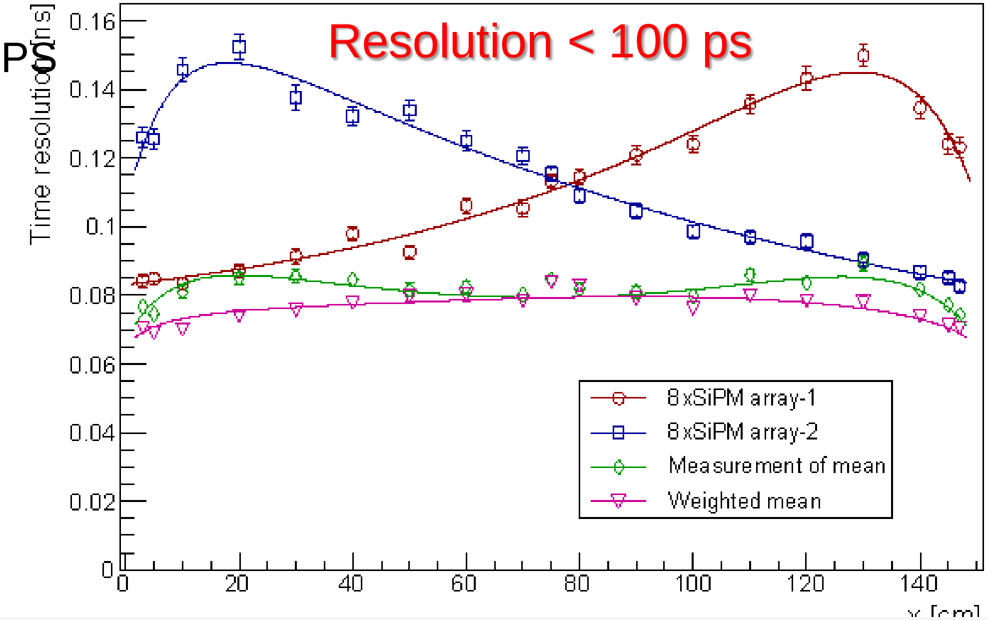




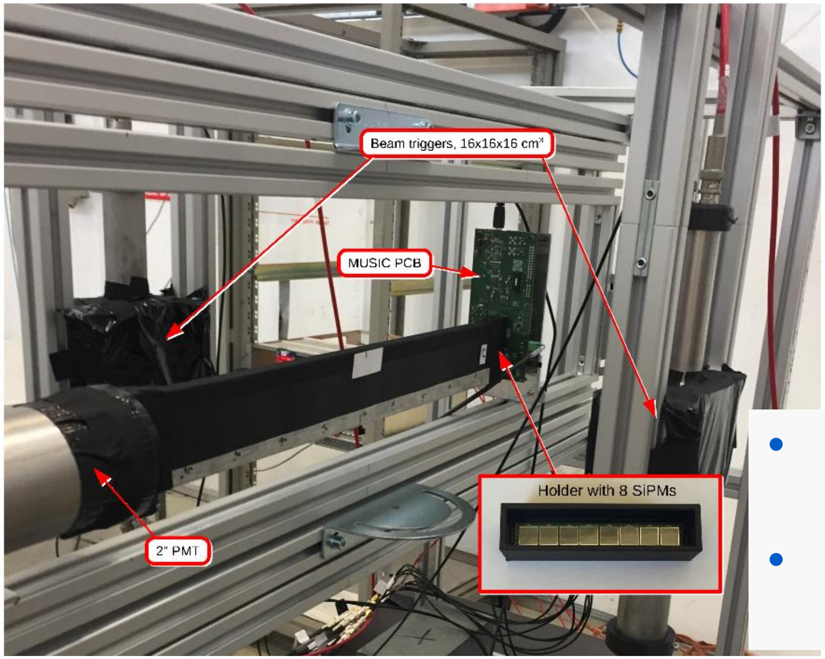
III. Combining small sensors: active summation: MUSIC

- Timing sub-detector test beam with MUSIC chip
  - By Univ. Geneva & Univ. Zurich
  - MUSIC in summation mode (8 6x6 mm^2 SiPMs)
    - Bar read-out at both ends
  - 2.5 GeV/c muon beam at the CERN PS
  - Readout with Wavecatcher
    - Fast analog memory (LAL & IRFU/CEA)

NIM, 924, 2019



Resolution < 100 ps



- Measurements with the 150 cm x 6 cm x 1 cm bar.
- Time resolution as measured by the SiPM arrays at both ends of the bar as a function of the interaction point along the bar.

© A. Kornezev (Univ. Geneva)

IV. Towards a picosecond hybrid single photon sensor
First step: 65 nm FE: FastIC

- Technical and financial collaboration between CERN (**KT funded**) and University of Barcelona (ICCUB) (**Grant FPA2016-80917-R**)

Photomultiplier

SiPM, PMT, MCP

Analog Front-End

Amplifier/Discriminator

Digital Back-End

Time-to-Digital Conv.

- Technological advancement in detector and FE technology
  - Enormous progress in SiPMs and MCPs
  - New TDC development @ CERN: picoTDC (~3 ps bin).
- **FastIC: new Front-End chip in 65 nm**
  - Multipurpose chip: SiPMs, MCPs, etc
    - Single ended (pos/neg), differential and active summation
    - Binary (linear / non-linear ToT) and Analog output
  - First submission scheduled for end 2019: 8 ch
  - Final chip: 32 channel (< 10 mW/ch)

M. Campbell, R. Ballabriga, N. Egidos, J.M. Fernandez, X. Llopart
D. Gascon, S. Gomez, R. Manera, J. Mauricio, A. Sanmukh

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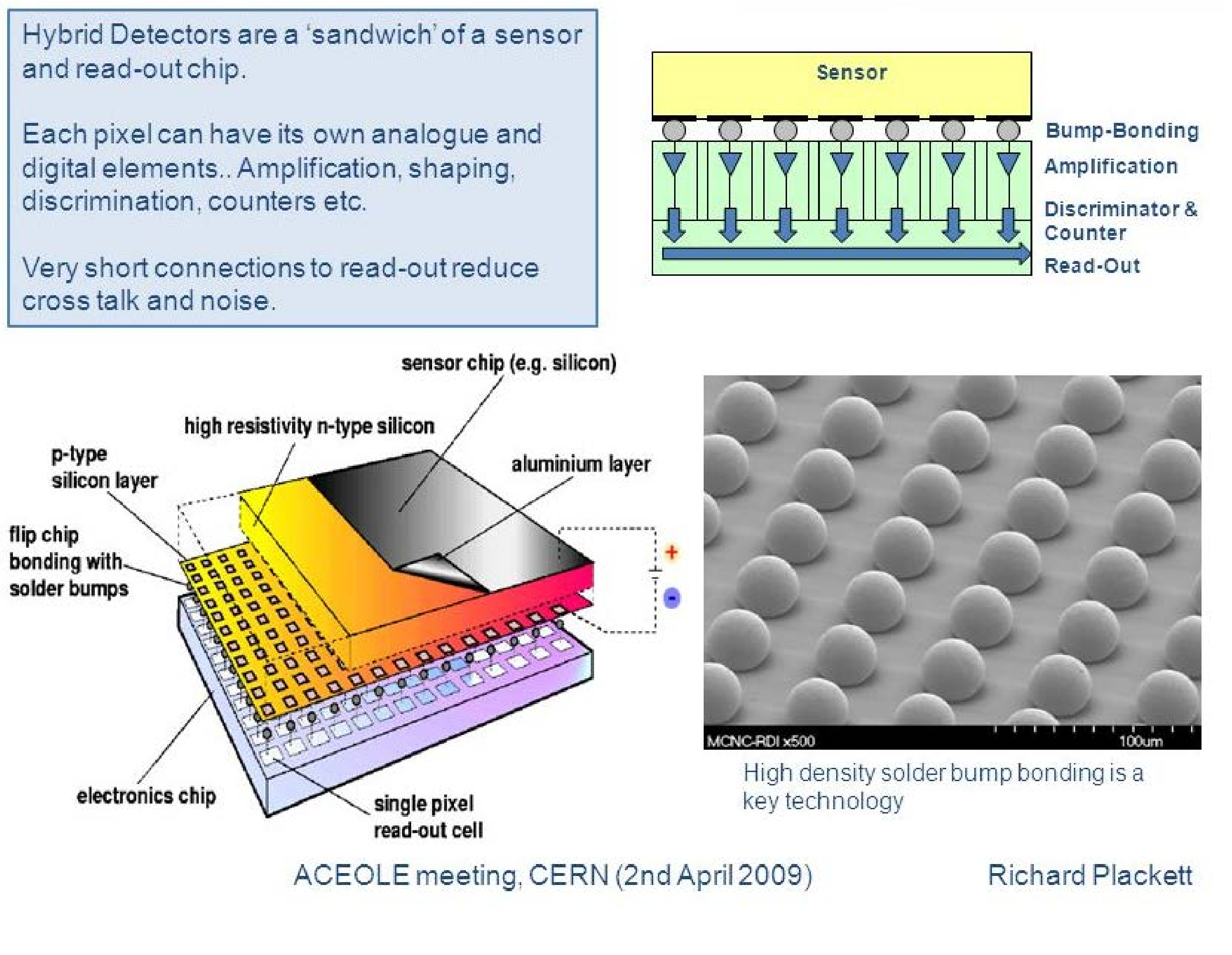
From channels to pixels →

M. Campbell, R. Ballabriga, N. Egidos, J.M. Fernandez, X. Llopart
D. Gascon, S. Gomez, R. Manera, J. Mauricio, A. Sanmukh

IV. Towards a picosecond hybrid single photon sensor
Hybrid implementation

- **New hybrid single photon sensor**
  - Using hybrid technology
  - Well-known for pixel detectors (& CMOS imagers)



Hybrid Detectors are a 'sandwich' of a sensor and read-out chip.

Each pixel can have its own analogue and digital elements.. Amplification, shaping, discrimination, counters etc.

Very short connections to read-out reduce cross talk and noise.

High density solder bump bonding is a key technology

ACEOLE meeting, CERN (2nd April 2009)

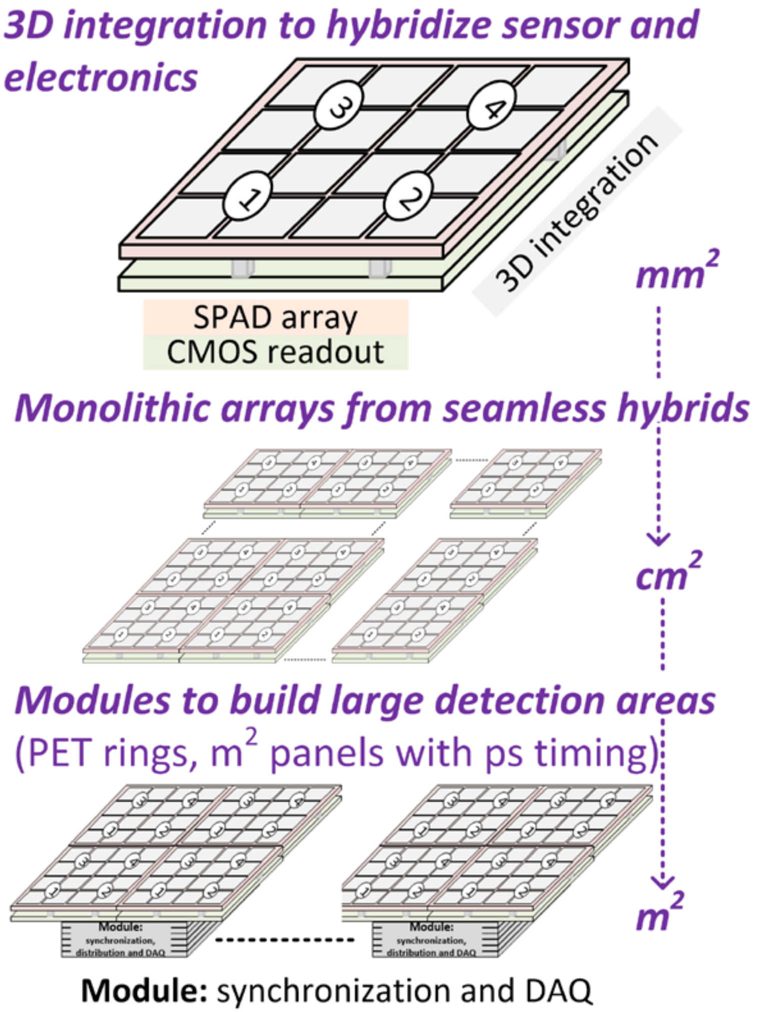
Richard Plackett

Collaboration with CERN Medipix team

M. Campbell, R. Ballabriga, N. Egidos, J.M. Fernandez, X. Llopart

IV. Towards a picosecond hybrid single photon sensor
Adaptability and Scalability

- **Adaptability and reconfigurability**:
  - Sensor layer easily exchanged to target different applications
  - The resolution can be dynamically adjusted
- **Scalability**: the architecture and the 3D integration approach allow to build arbitrarily large arrays
- **Low cost** for mass production
  - Will be based on mass production CMOS processes
  - 3D integration requirements are quite relaxed compared to 3D SPAD imagers
    - TSV pitch > 300 µm



3D integration to hybridize sensor and electronics

Monolithic arrays from seamless hybrids

Modules to build large detection areas
(PET rings, m^2 panels with ps timing)

Module: synchronization and DAQ

M. Campbell, R. Ballabriga, N. Egidos, J.M. Fernandez, X. Llopart
D. Gascon, S. Gomez, R. Manera, J. Mauricio, A. Sanmukh

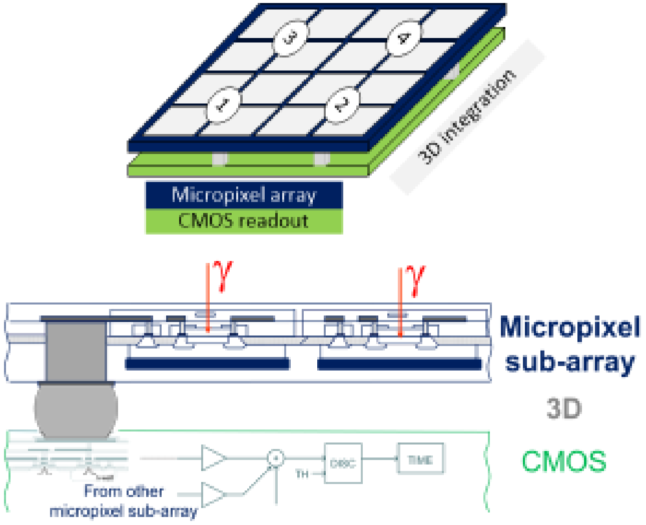
IV. Towards a picosecond hybrid single photon sensor ATTRACT

- First step ongoing**: approved ATTRACT H2020 project**
  - **Phase-I: FastICPix:** validate our approach in a full system simulation

DEVELOPING BREAKTHROUGH TECHNOLOGIES FOR SCIENCE AND SOCIETY

FastICPix: Integrated Signal Processing for a New Generation of Active Hybrid Single Photon Sensors with Picosecond Time Resolution

The Idea is to combine actively the signal of small micropixel sub-arrays based on the fastest single photon sensor technologies with ultrafast readout electronics using 3D integration.



It could have applications in medical imaging by enabling real time PET (Positron Emission Tomography), LIDAR, fluorescence lifetime imaging, homeland security and IOT / vision systems.

Our project is coordinated by the University of Barcelona **in partnership with** CERN.

It is part of wider collaborative effort involving sensor and ASIC design, 3D integration, module and applications with additional collaborators: CEA, EPFL, FBK, IFAE, LAL and University of Geneva.

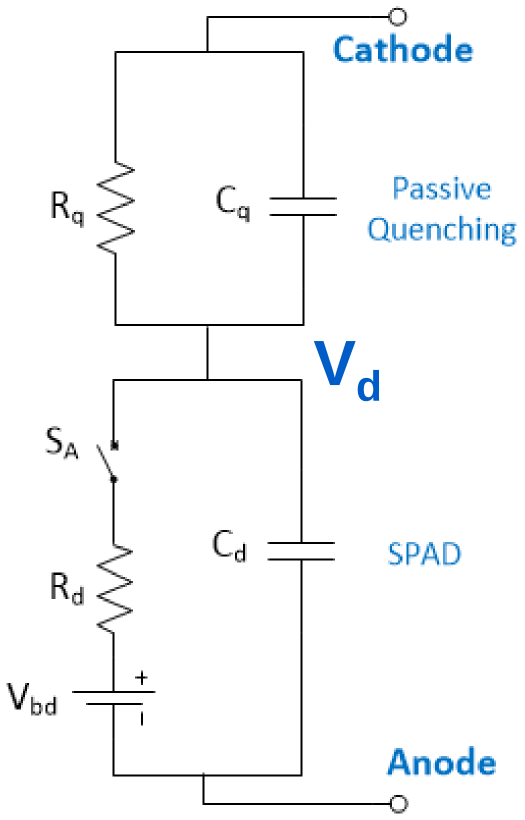
Contact email dgascon@fqa.ub.edu

Attract Kick-Off Meeting, Geneva, May 2019

M. Campbell, R. Ballabriga, N. Egidos, J.M. Fernandez, X. Llopart
D. Gascon, S. Gomez, R. Manera, J. Mauricio, A. Sanmukh

Back up David

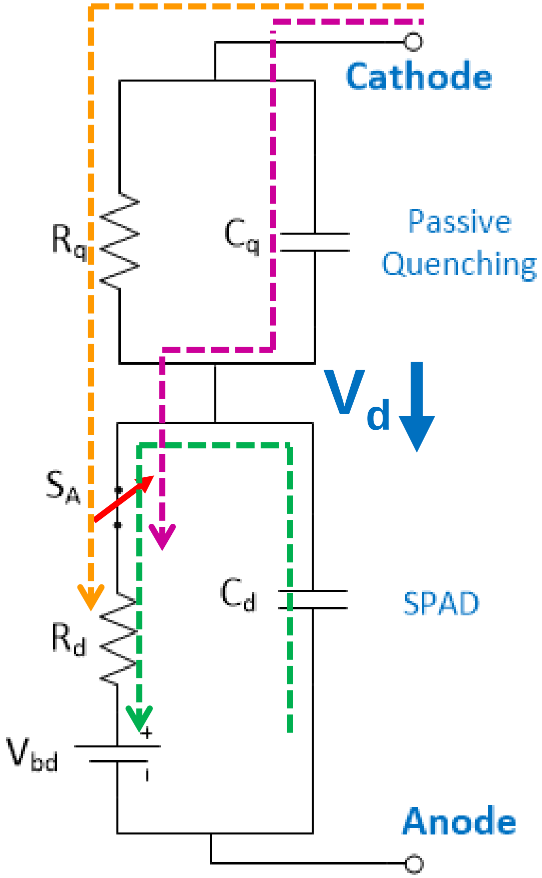
I. The signal: model of a micro-cell



- Model of a passively quenching micro-cell
  - –Junction (Single-Photon Avalanche Diode, SPAD)
    - Cd: diode capacitance (Vd is the voltage across the diode)
    - Rd: junction resitance limiting avalanche current
      - o Determined by the electric field in the junction and the mobility of the charge carriers
    - Vbd: breakdown voltage
    - S_A: switch modeling the avalanche (closes). Quenches (opens) when:
      - o Electric field in the avalanche not large enough
        - ➢ Active quenching: lowering voltage
      - o Insufficient amount of free charge carriers inside the junction at any given time
        - ➢ Passive quenching: limiting current I_{Smin} (uA)
  - –Quenching resistor
    - Rq: quenching resistance
    - Cq: parasitic capacitance of the quenching resistor

N. Otte et alt., “Silicon Photomultiplier Handbook," *Under Preparation*

I. The signal: model of a micro-cell: avalanche



1) When avalanche starts S_A closes

2) Cd discharges through Rd

- Current limited by Rd

3) Vd decreases

- $I_{Rd}(t)$ decreases

4) Cq is charged

- Potential cathode to anode is fixed (V_{bias})
- During avalanche micro-cell signal (current flowing into cell) is due to Cq charging
- Time constant is $\tau_d = Rd \cdot (Cq + Cd)$

4) Current also flowing through Rq

- $I_{Rq}(t)=(V_{bias}-Vd(t))/Rq$

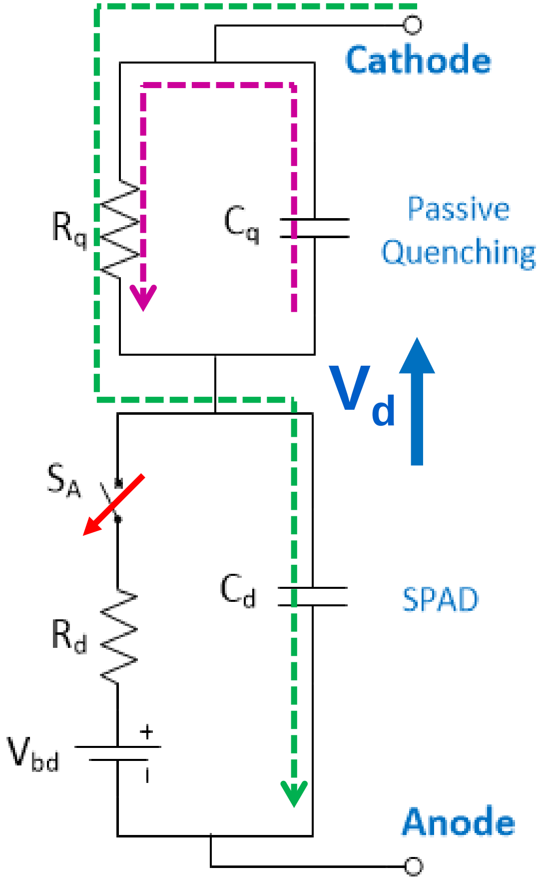
5) Avalanche stops at t_q when $I_{Rd}(t)< I_{Smin}$

- At that moment $Vd(t_q)$
- If Rq is not high enough: no quenching !!!

Min Rq ?

$Rq+ Rd>(Vbias-Vbd)/(I_{Smin})$

I. The signal: model of a micro-cell: recharge



1) When avalanche is quenched S_A opens

2) Cd is recharged through Rq
   - Time constant is $\tau_r = Rq \cdot (Cq + Cd)$

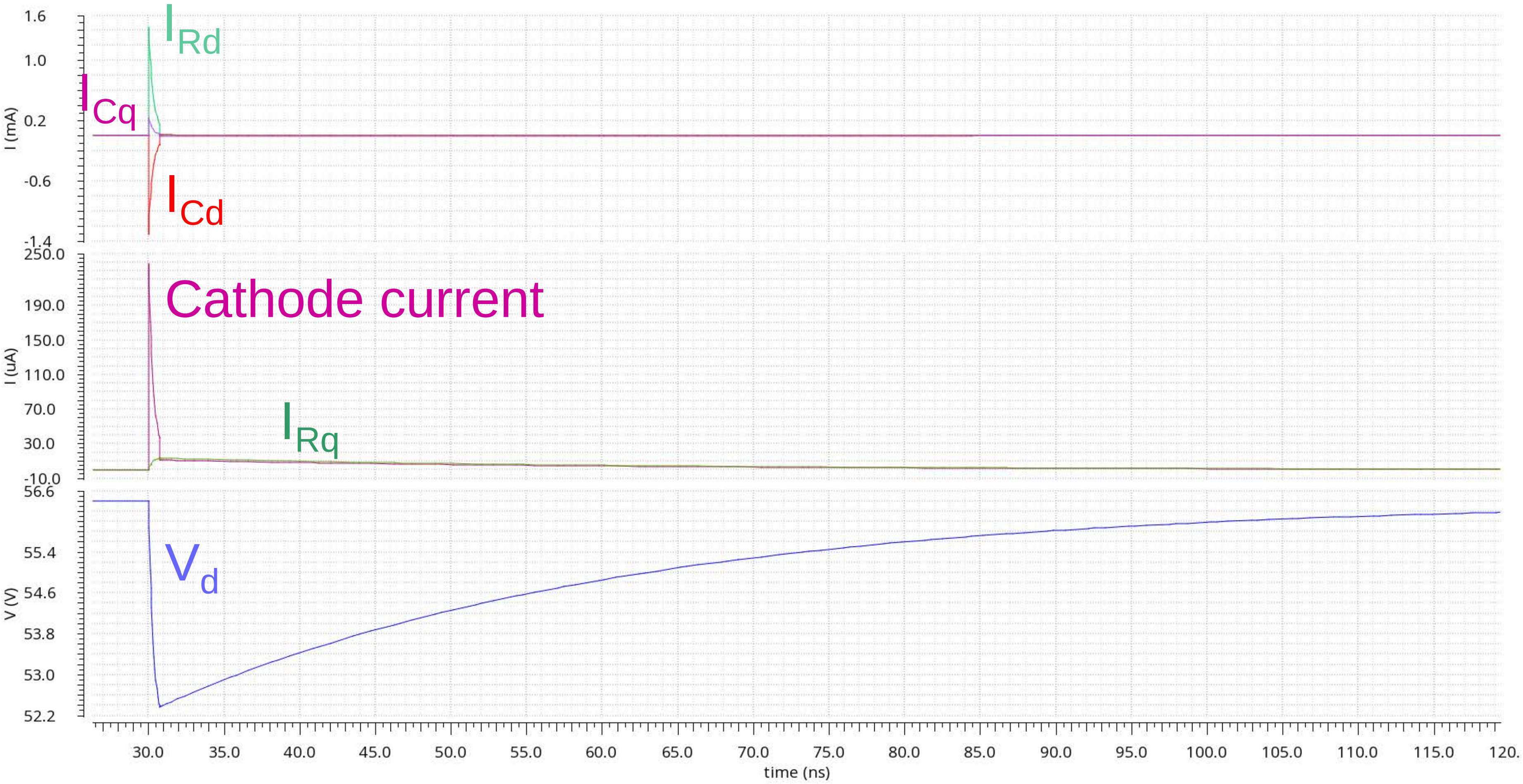
3) Vd increases
   - $I_{Rq}(t)$ decreases

4) Cq is discharged through Rq

5) Recharge ends when $Vd(t)=V_{bias}$
   - At this point all currents are null

N. Otte et alt., "Silicon Photomultiplier Handbook," *Under Preparation*

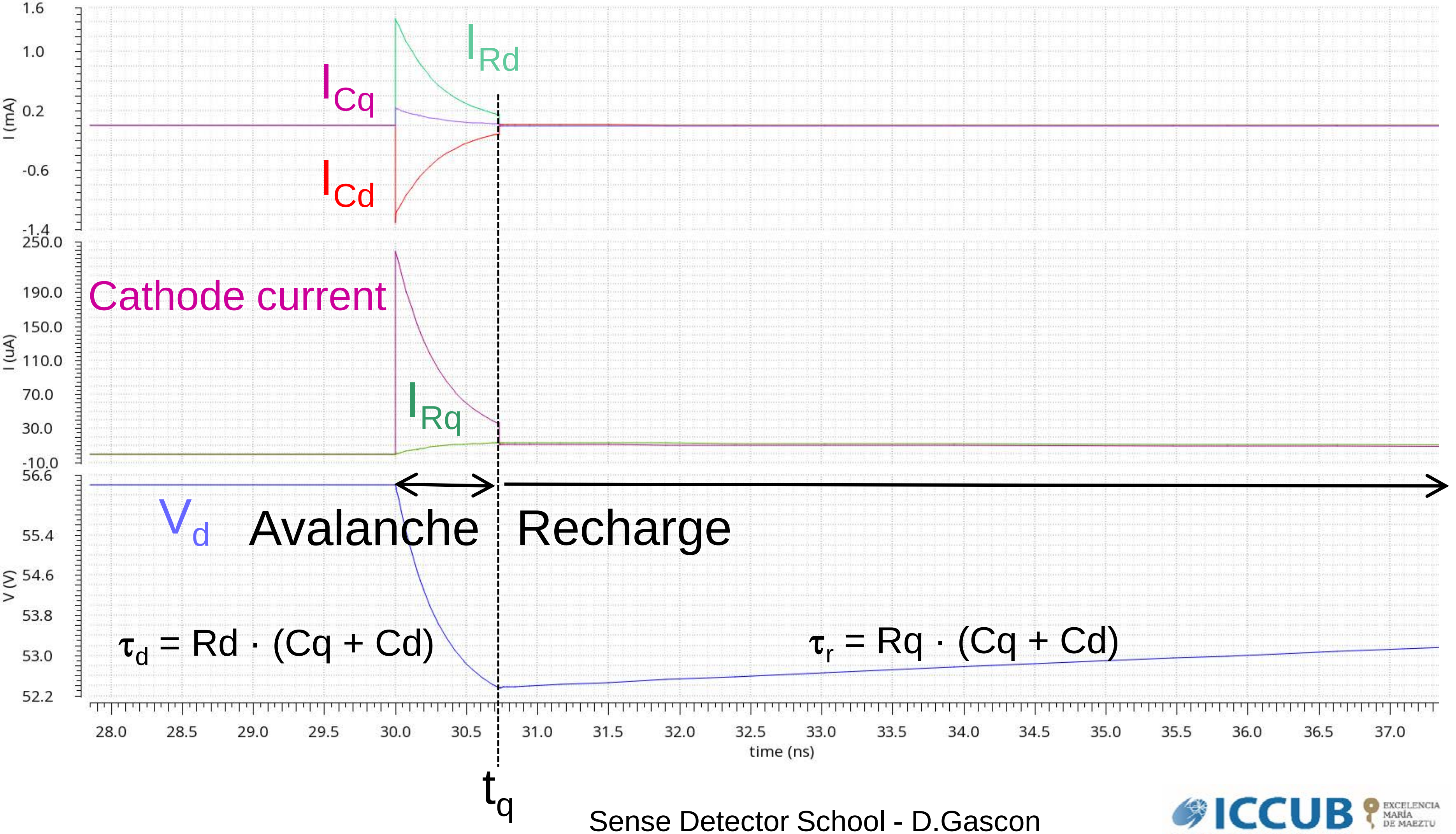
I. The signal: model of a micro-cell: simulation



- **Simulation parameters:** Cd=84.5 fF, Cq=16.8 fF, Rq=300.8 KΩ, Rd= 3 KΩ, Vbd=51.9 V, Vbias=Vbd+4.5V, S_A quenching current: 40 uA

I. The signal: model of a micro-cell: simulation

- Let’s zoom around quenching time t_q:

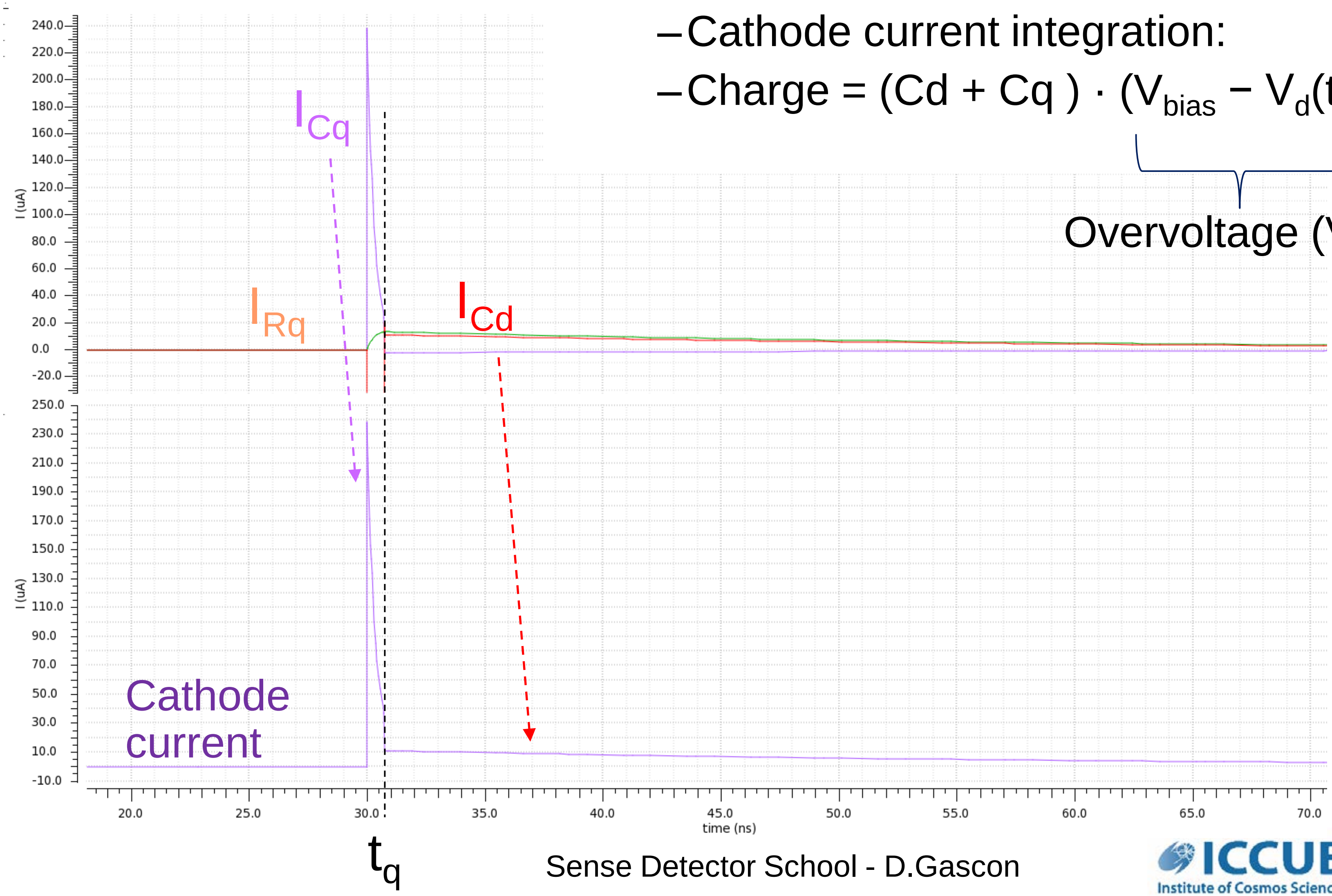


$\tau_d = Rd \cdot (Cq + Cd)$

$\tau_r = Rq \cdot (Cq + Cd)$

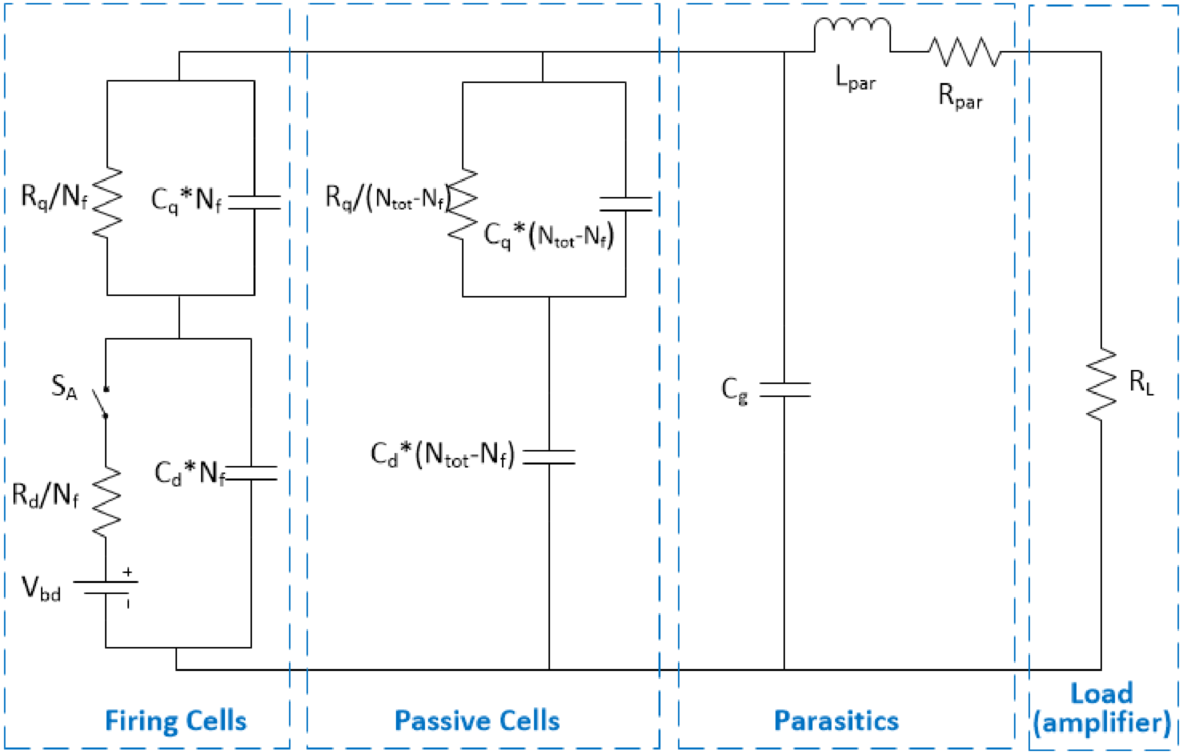
I. The signal: model of a micro-cell: simulation

- Signal-charge (gain):
  - Cathode current integration:
  - $\text{Charge} = (Cd + Cq) \cdot \underbrace{(V_{bias} - V_d(t_q))}_{\text{Overvoltage (Vov)}}$



I. The signal: model of a complete SiPM

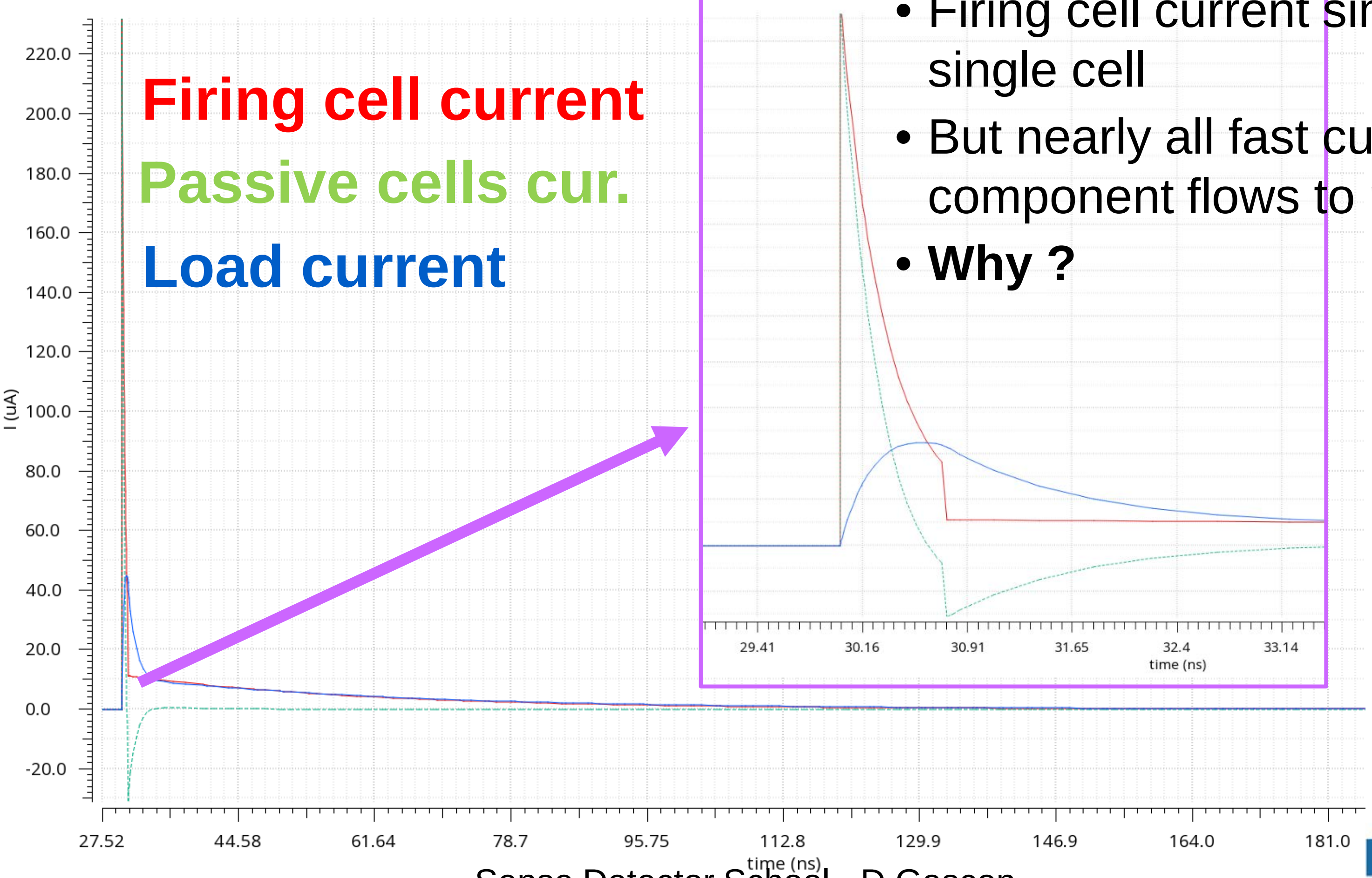
- Complete model of SiPM with N_{tot} cells:
  - Active (firing) cells (N_f)
  - Passive (not firing) cells ($N_{tot} – N_f$)
  - Parasitic components
  - Load impedance



- Parasitic elements:
  - *Cg*: interconnection parasitic capacitance
  - *Rpar*: interconnection parasitic resistance
  - *Lpar*: interconnection parasitic inductance
- Load:
  - Usually the input impedance of the front end amplifier
  - Or just a resistor
    - For instance a 50 Ω scope

I. The signal: model of a complete SiPM

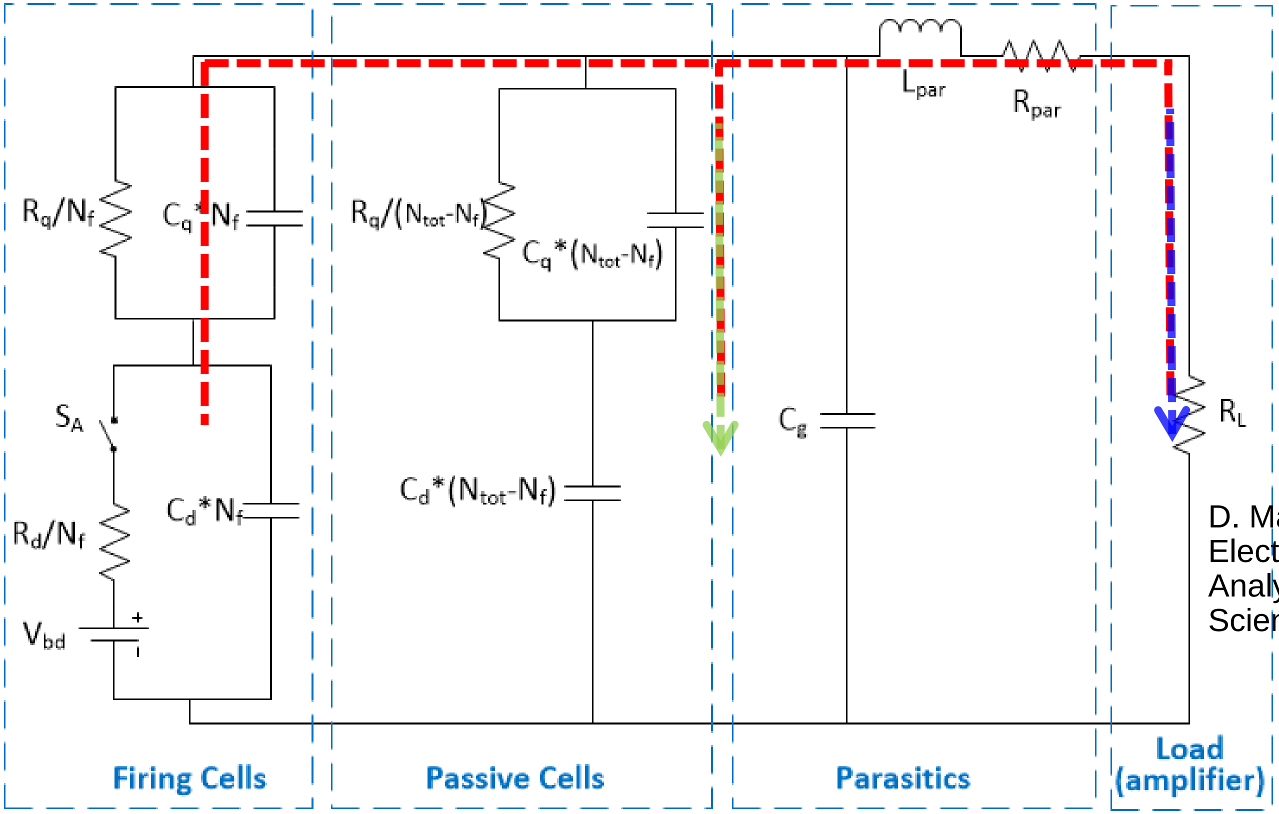
- Simulation for a typical 3x3 mm^2 SiPM with 3600 cells:
  - 1 firing cell. Size: 50 µm similar parameters as previous simulations
  - Cg: 18 pF and Rload: 15 Ω



- Firing cell current similar as for single cell
- But nearly all fast current component flows to passive cells
- **Why ?**

I. The signal: model of a complete SiPM

- Passive cells and load impedance form a low pass filter !
  - We are sensing the current or the voltage on R_L
  - Passive cells and parasitic capacitances create a current divider with R_L
  - Peak signal goes with $Cpar^{-1}$



Low pass filter time constant:

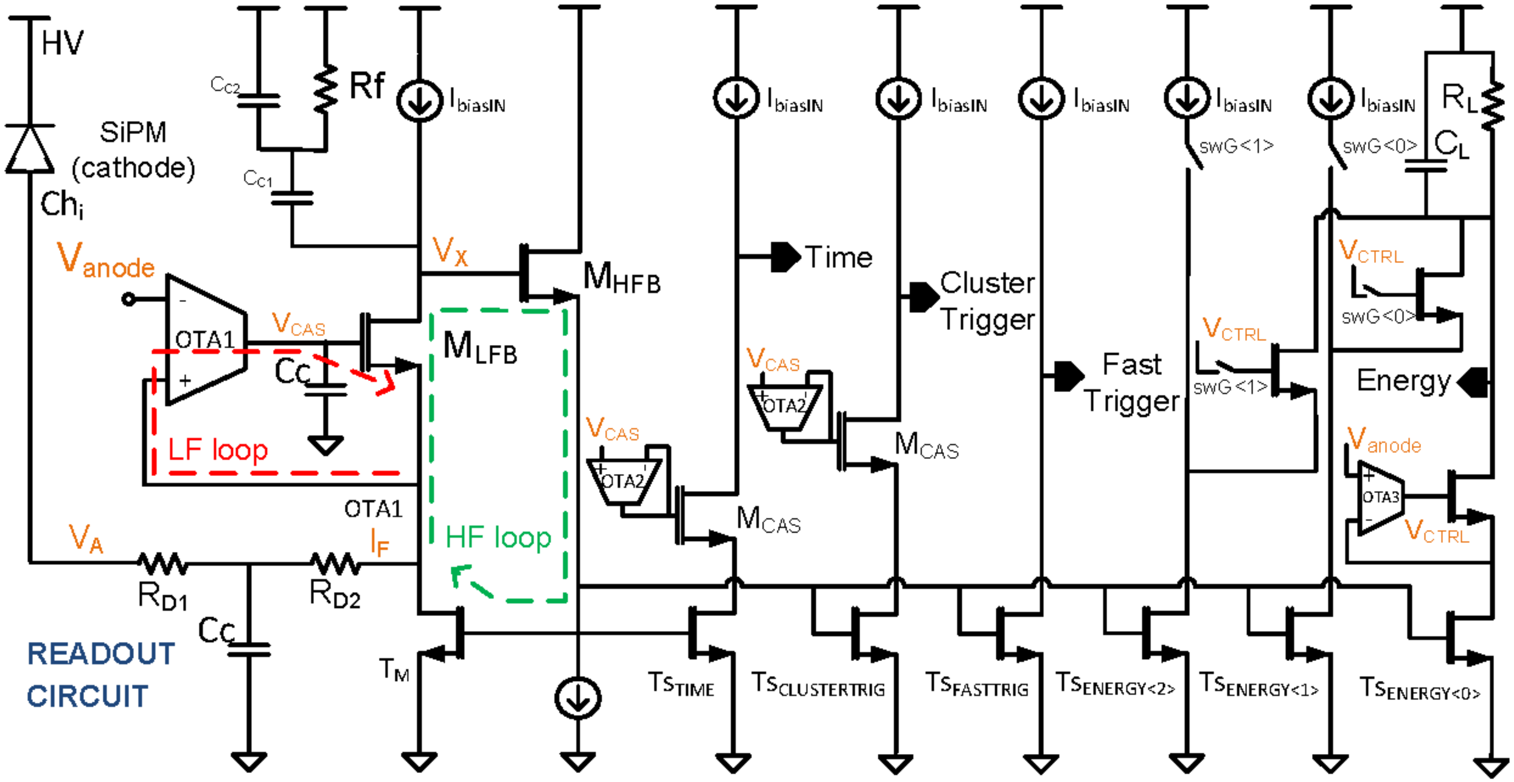
$$\tau_L \approx R_L \cdot N_{tot} \cdot (Cq // Cd)$$

** Approximate: we should include also Cg here*

D. Marano et alt., «Silicon Photomultipliers Electrical Model Extensive Analytical Analysis»,IEEE Transactions on Nuclear Science 61(1), 23 (2014).

II. MultiCh readout: HRFlexToT: **current based**

- **Input stage design**



S. Gomez, D. Sanchez, D. Gascon, J. Mauricio et alt,
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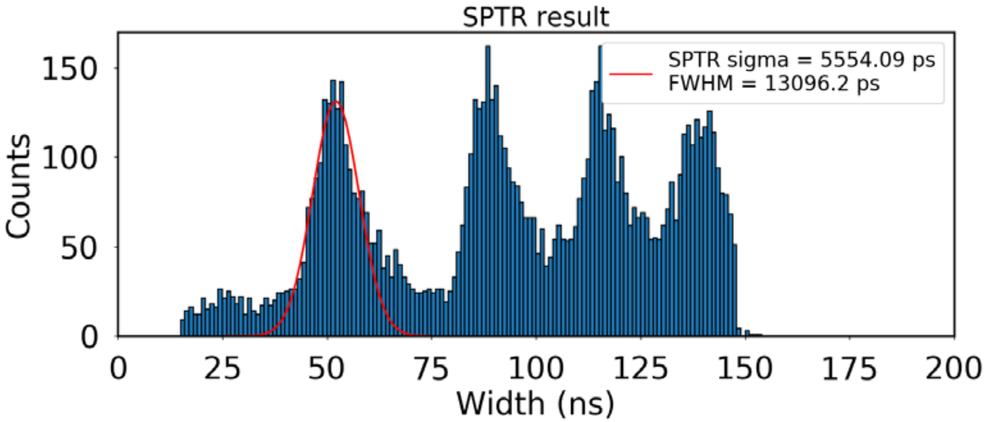
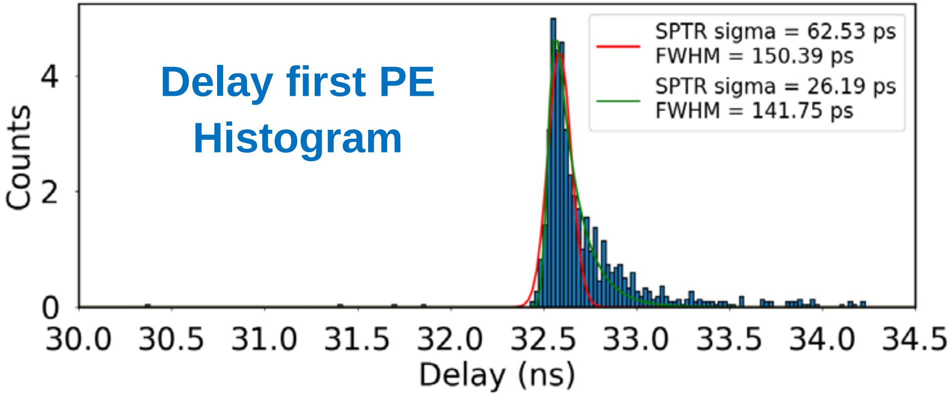
II. MultiCh readout: HRFlexToT

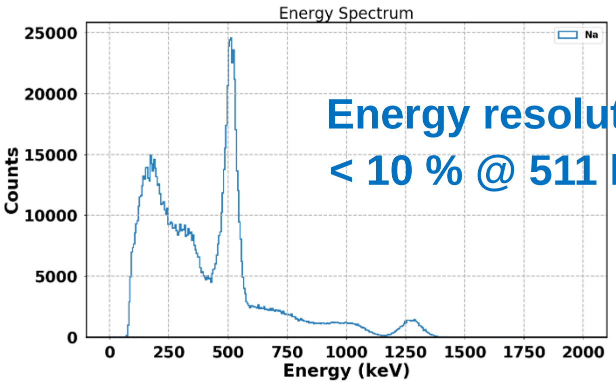
Time width Histogram




Delay first PE Histogram

- **Bias voltage 38V (11.5V of Overvoltage)**

Sensor	NINO	HRFlexToT
HPK S13360 (3x3mm^2, 50μm pixel pitch)	160 (10V of Ov)	167 (10V of Ov)
FBK NUV-HD (4x4mm^2, 40μm pixel pitch)	135 (12V of Ov)	142 (11.5V of Ov)



Energy resolution < 10 % @ 511 keV

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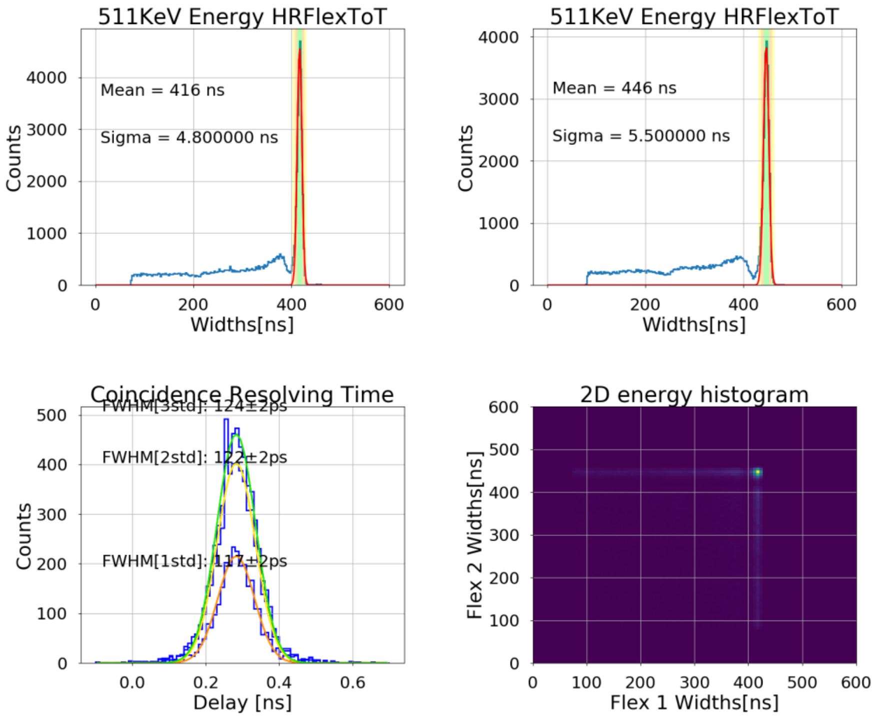
II. MultiCh readout: HRFlexToT::**CTR results using HPKK sensor**

- **Sensor: HPK S13360-3050PE 3x3mm^2, 50μm pixel pitch.**
- **Crystal: LSO:Ce Ca 0.2% of 2x2x5mm^3**

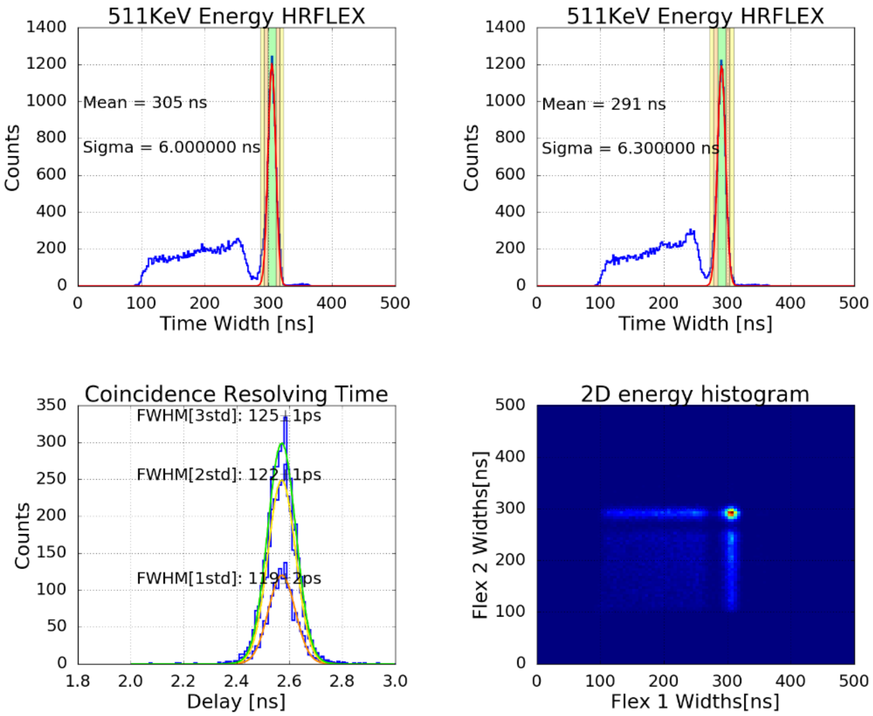


FWHM = 117ps

HRFlexToT Bias voltage 61V (8V of Overvoltage)

II. MultiCh readout: HRFlexToT:: **CTR results using FBK sensor**

- **Sensor: NUVHD 4x$4mm^2$, 30μm pixel pitch.**
- **Crystal: LSO:Ce Ca 0.2% of 2x2x5mm³**

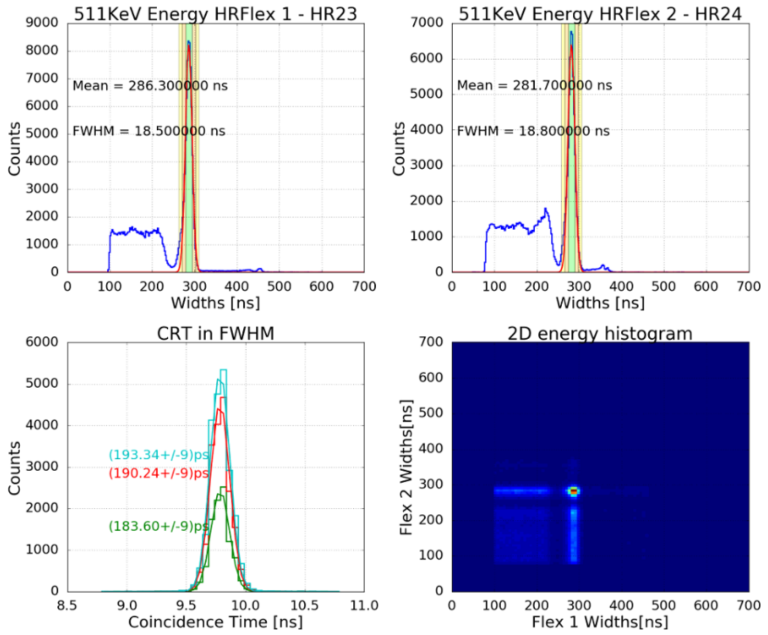


FWHM = 119ps

HRFlexToT Bias voltage 39V (12V of Overvoltage)

II. MultiCh readout: HRFlexToT:: **CTR results using FBK sensor**

- **Sensor ref: HPK S13360-3050PE 3x3mm^2, 50μm pixel pitch. Crystal: LSO:Ce Ca 0.2% of 2x2x5mm³**
- **Sensor measuring: HPK S13360-6050CS 6x6mm^2, 50μm pixel pitch. Crystal: LFS of 3x3x20mm³**

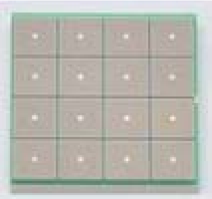


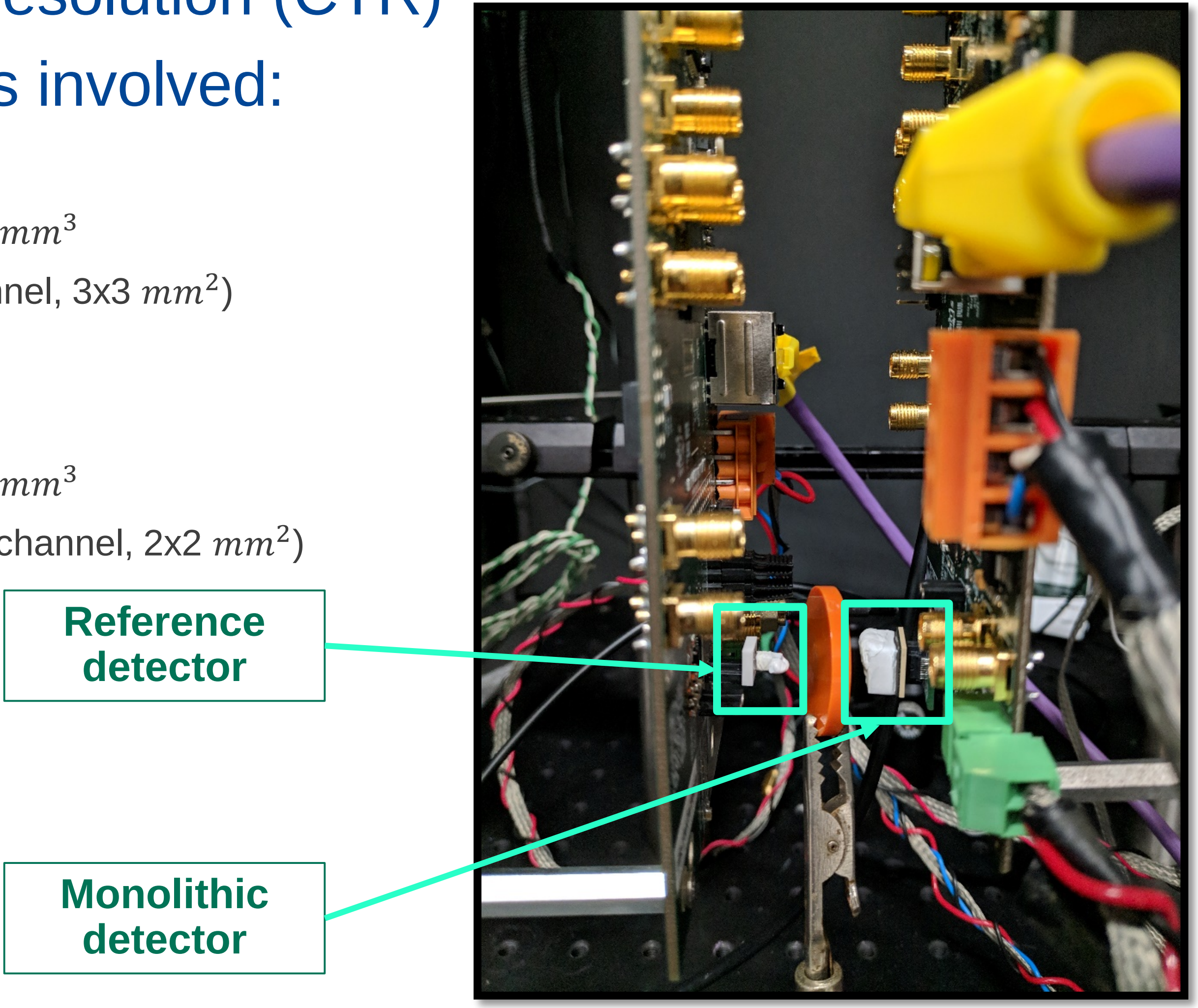
FWHM = 190ps

HRFlexToT Bias voltage 58V (6V of Overvoltage)

II. MultiCh readout: HRFlexToT: monolithic crystals

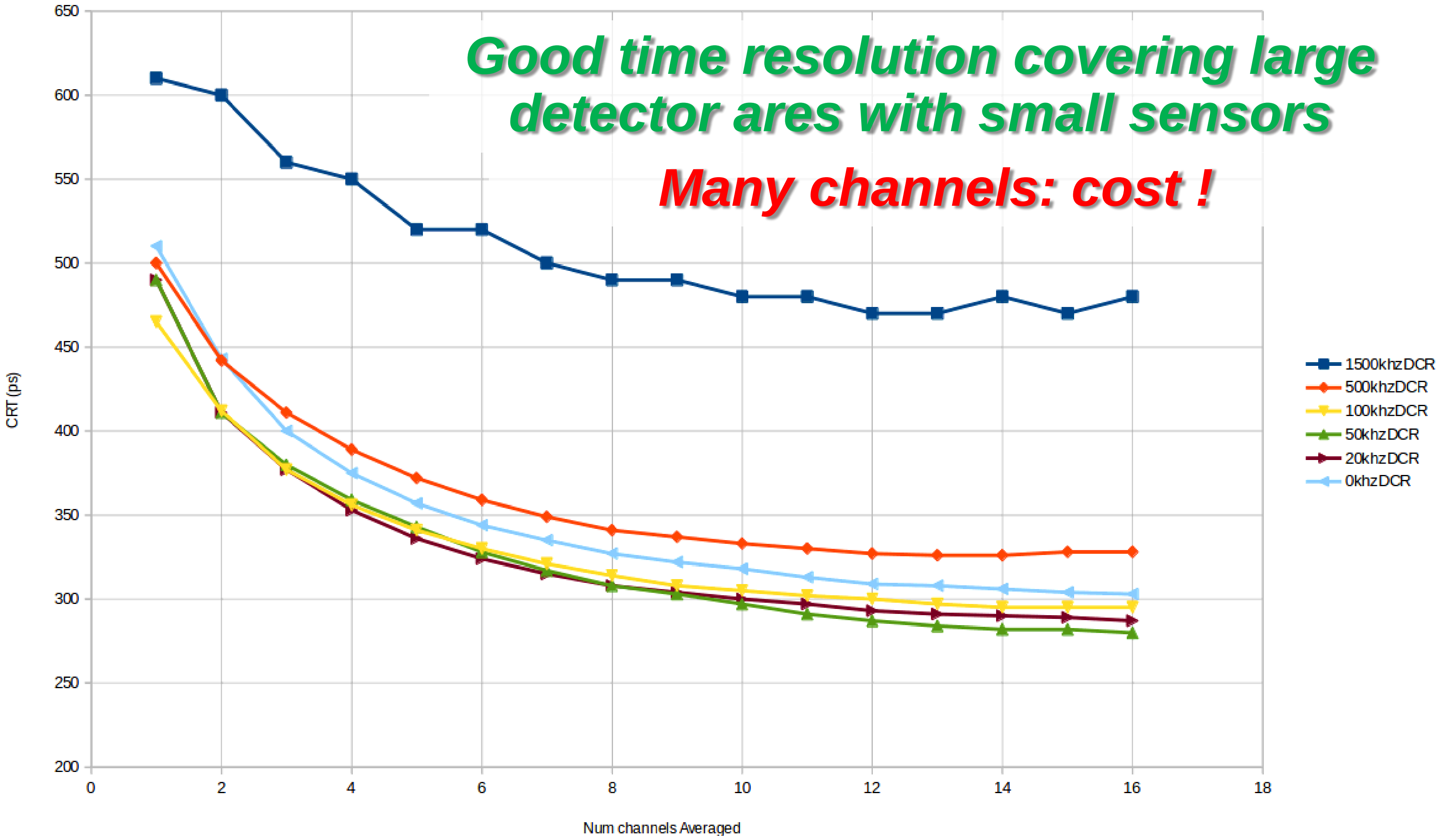
- Coincidence Time Resolution (CTR)
- Sensors and crystals involved:
  - Reference detector:
    - LSO:Ce 0.2% Ca 2x2x5 mm^3
    - S13360-3050CS (1 channel, 3x3 mm^2)
    - Jitter $= 90ps\ FWHM$
  - Monolithic module:
    - LSO:Ce 0.2% Ca 8x8x5 mm^3
    - S13361-2050PE-04 (16 channel, 2x2 mm^2)





II. HRFlexToT: Time-walk correction + averaging timestamps (MONOLITHIC WITH TEFLON)

- Time-walk correction + averaging of the N fastest channels.



Good time resolution covering large detector ares with small sensors

Many channels: cost !

4 October 2019

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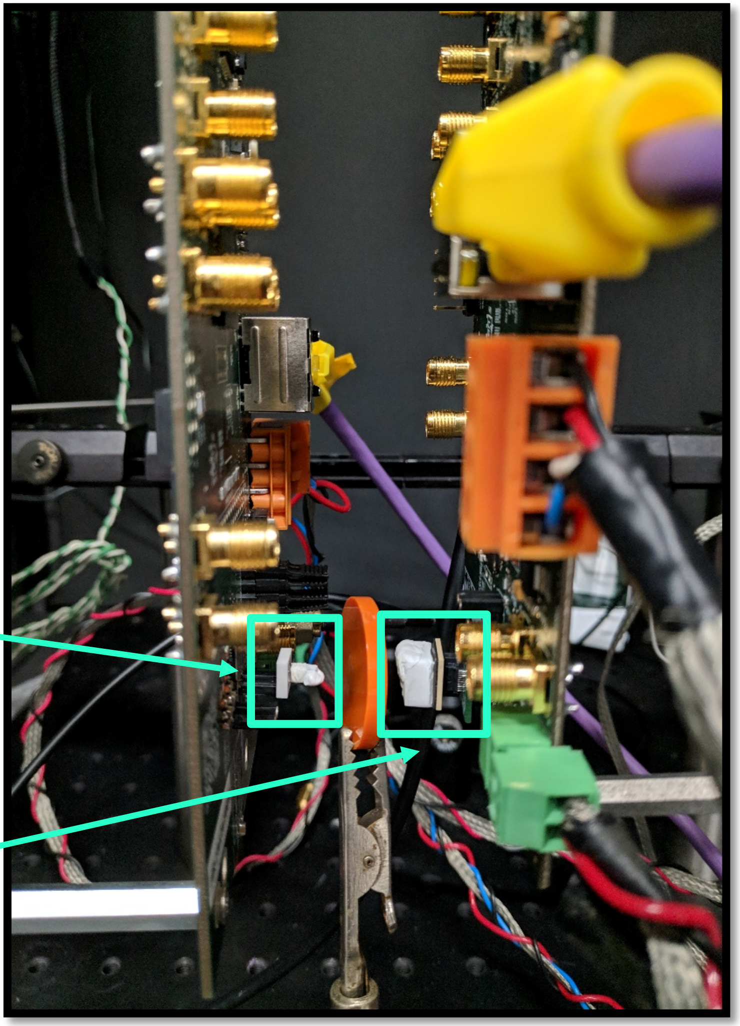
II. MultiCh readout: HRFlexToT:: **monolithic crystals**

- Sensors and crystals involved:
  - Reference detector:
  - S13360-3050CS (1 channel, 3x3 mm^2) + LSO:Ce 0.2% Ca 2x2x5 mm^3.
    - Jitter $= 90ps\ FWHM$
  - Monolithic module:
  - S13361-2050PE-04 (16 channel, 2x2 mm^2) + LSO:Ce 0.2% Ca 8x8x5 mm^3

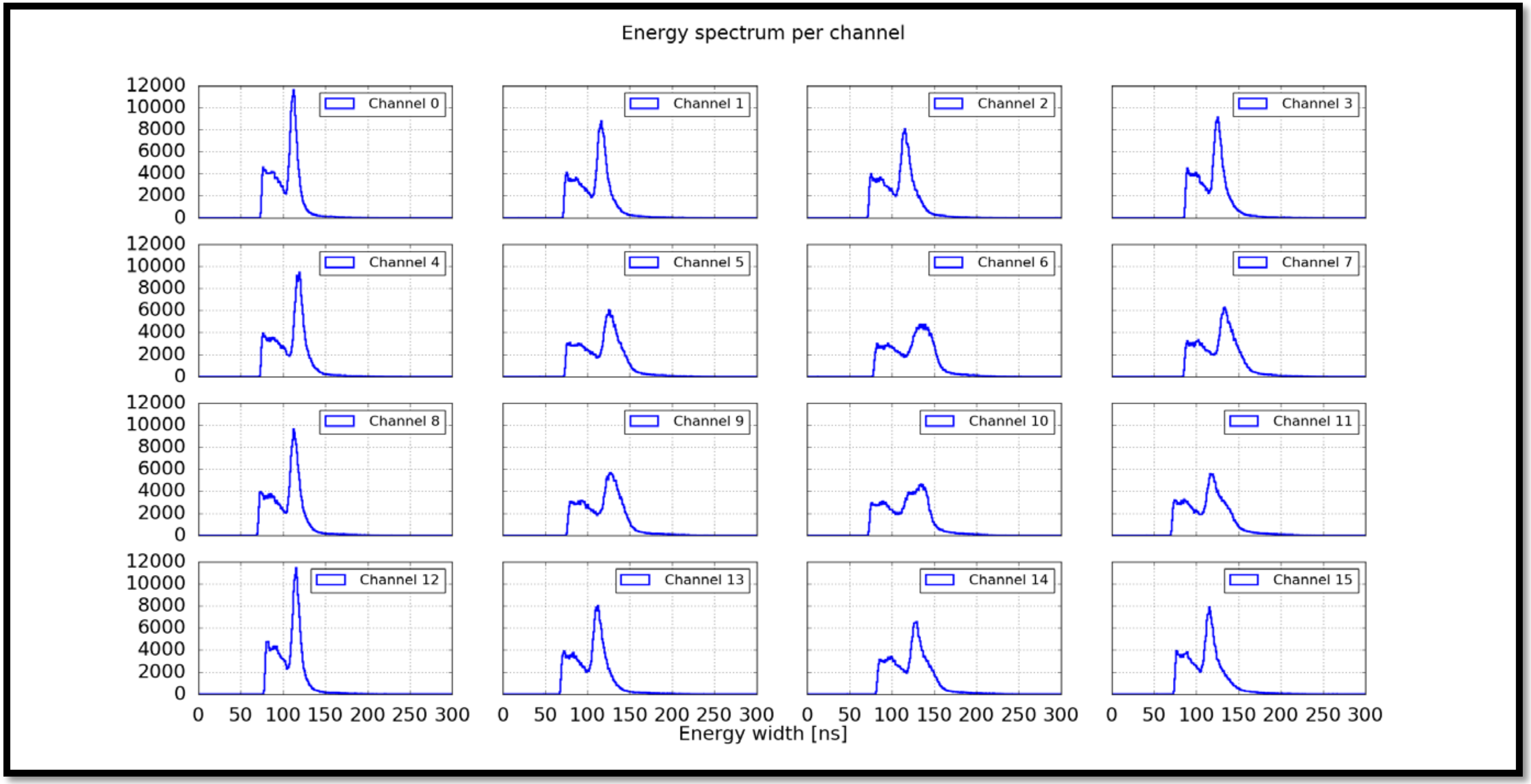


Reference detector

Monolithic detector

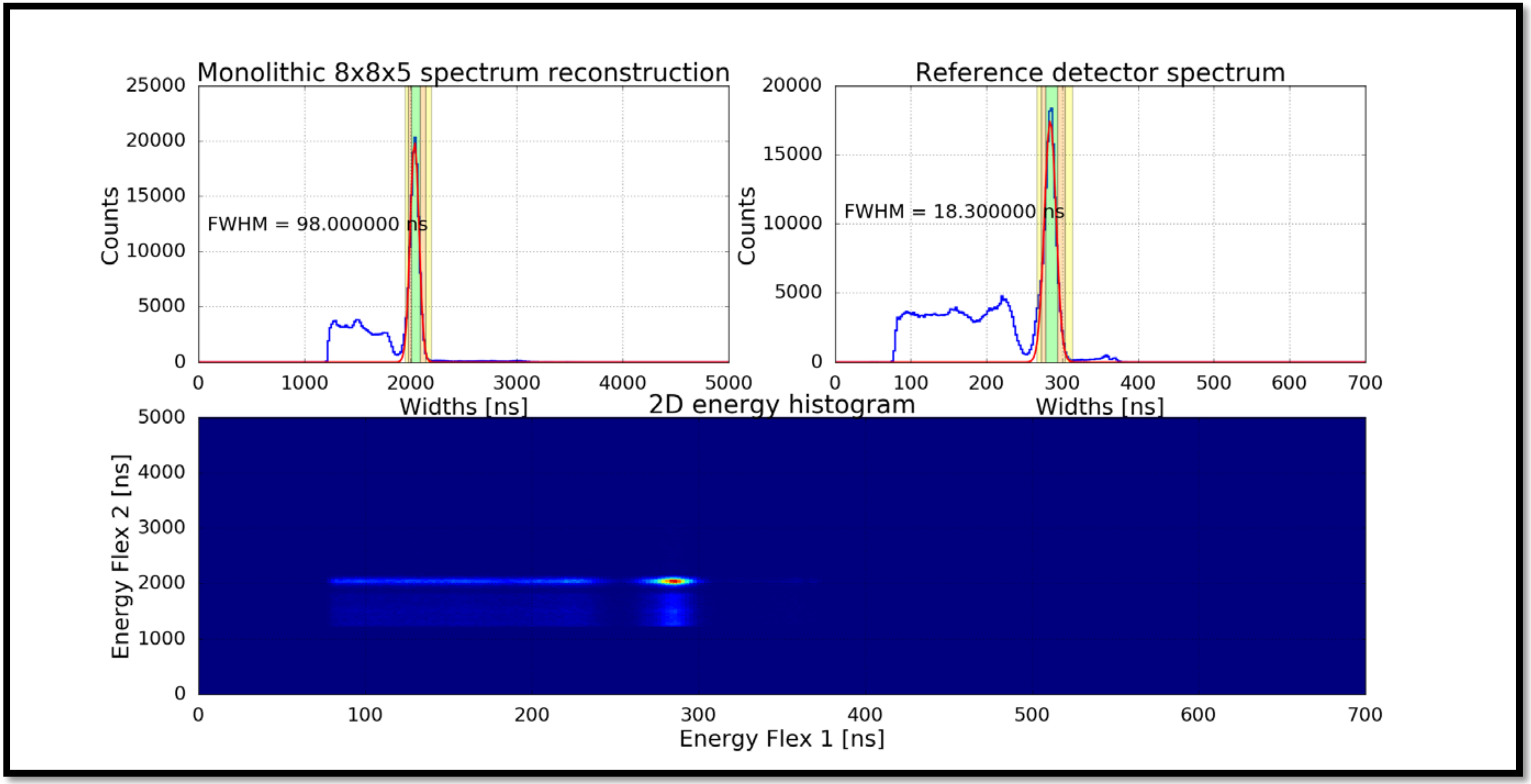
II. MultiCh readout: HRFlexToT:: **monolithic crystals**

- Histogram showing the energy deposited in each of the 16 channels (FPGA based readout including TDC):



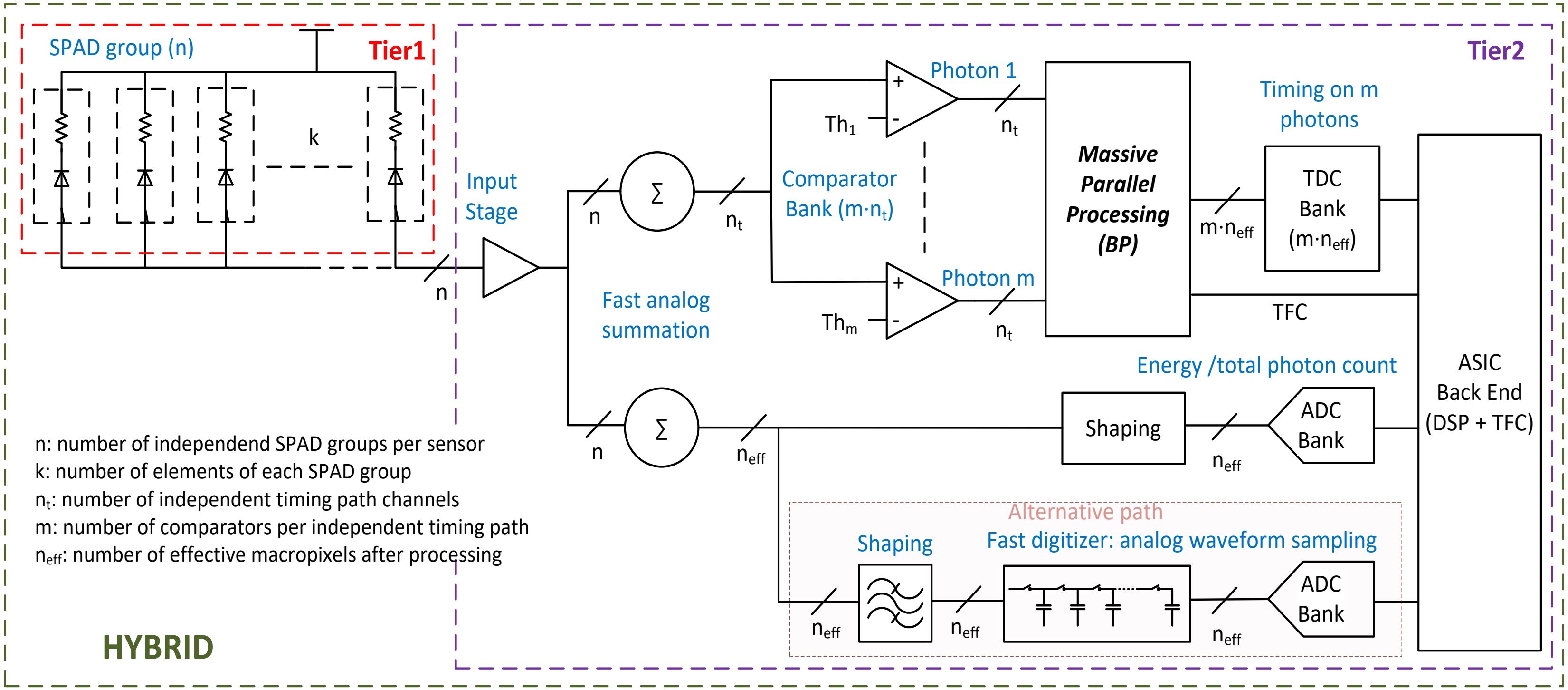
II. MultiCh readout: HRFlexToT:: **monolithic crystals**

- Energy reconstruction on the monolithic and energy deposited on the reference detector:



IV. Towards a hybrid photosensor Architecture

- **Intelligence**:
  - Bank of comparators and TDCs
  - The time of arrival of multiple photons is computed by an embedded (via 3D integration) massive parallel signal processing network
  - An alternative signal processing by on-chip fast analog waveform sampling also integrated



n: number of independend SPAD groups per sensor
k: number of elements of each SPAD group
n_t: number of independent timing path channels
m: number of comparators per independent timing path
n_{eff}: number of effective macropixels after processing