Detecting Signals into the Noise: Franco Manfredi in memoriam

5 December 2016

Aula Volta, University of Pavia , Pavia, Italy

Toward the Ultimate Low-Noise Front-End Electronics for X-γ Ray Detectors

The Heritage of *Franco Manfredi* to Current Research

Giuseppe Bertuccio

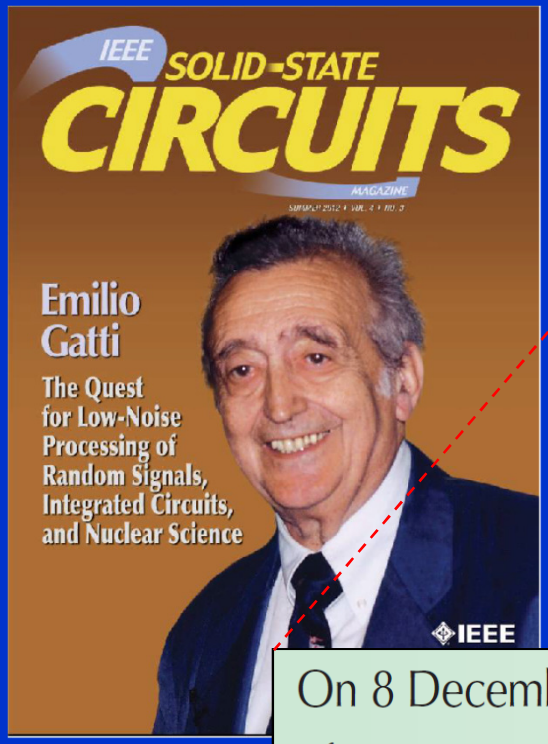
Politecnico di Milano - Italy

Department of Electronics, Information and Bioengineering

and

National Institute of Nuclear Physics - Milano

2012 : Franco Manfredi Last Letter



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his university career at the Polytechnic of Milan where, in 1998, he became a professor of nuclear electronics. He was professor in two more Italian universities, Milan and Pavia, until 1997, when he joined the Lawrence Berkeley National Laboratory in Berkeley, California, as a senior staff scientist. His primary research interests include low noise circuits and systems and front-end circuits based on low-noise monolithic technologies. Part of his activity was done in collaboration with Brookhaven National Laboratory of Upton, New York, and Max Planck Institute of Munich, Germany. He has published more than 100 papers in international journals.

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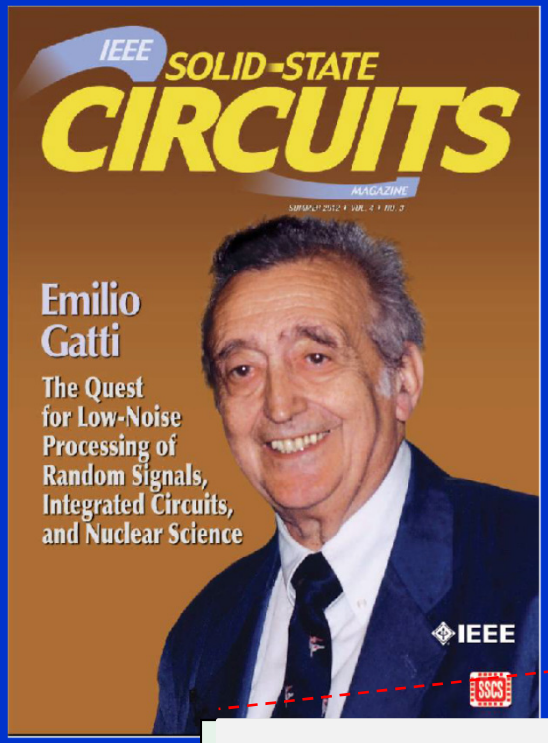

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—Pier F. (Franco) Manfredi

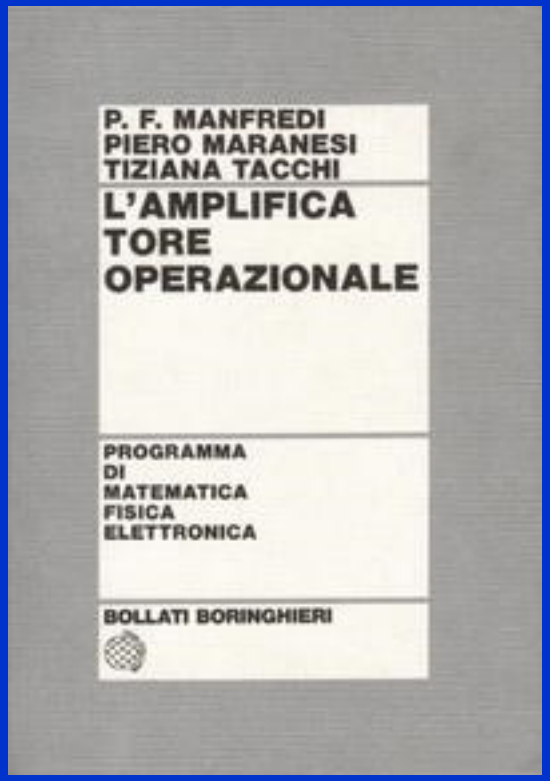
Emilio Gatti Research Group in ’90

at Politecnico di Milano

at a Conference…

1983: My first knowledge of Prof. Franco Manfredi

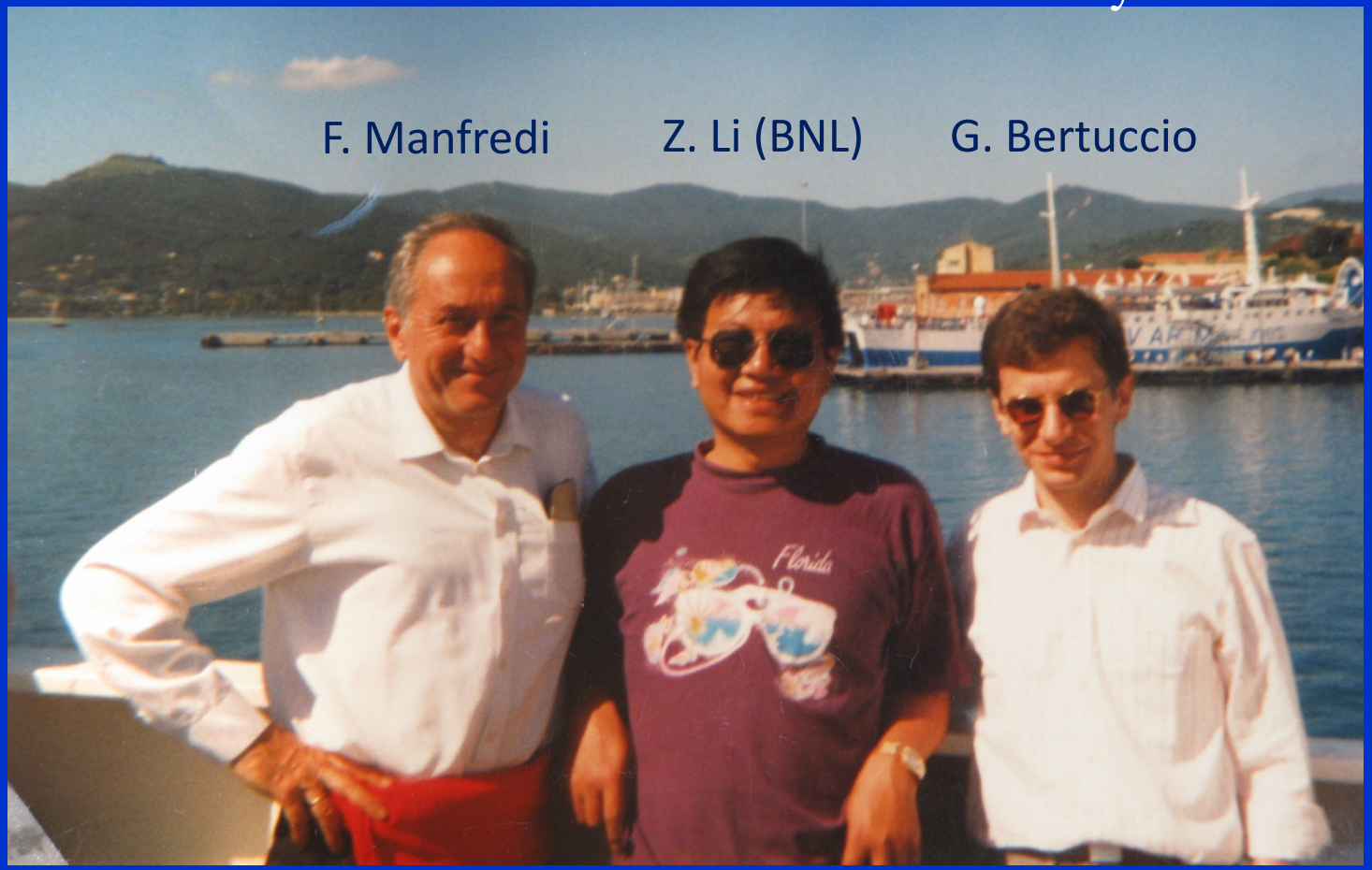
as student of nuclear engineering at Politecnico di Milano



June 1994

coming back from Isola d'Elba

Conference "Frontier Detectors for Frontier Physics"



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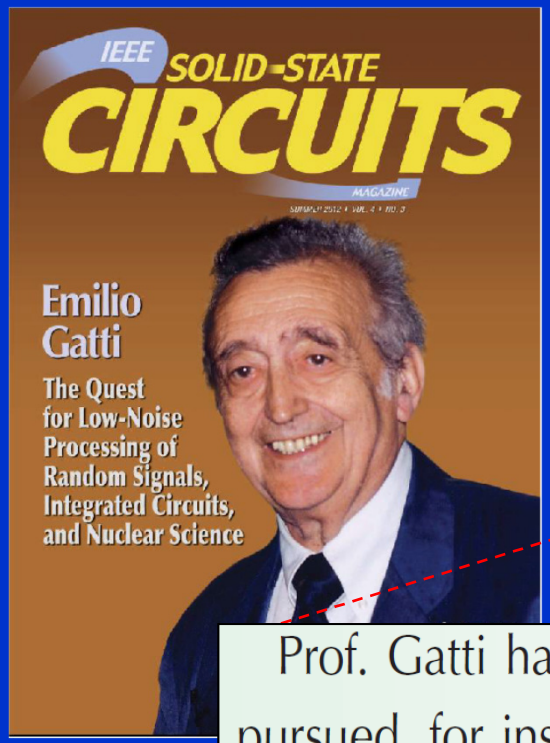

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the Heritage of *Franco Manfredi*
to Current Research

Franco Manfredi and the electronics for X-y ray spectroscopy

1978: Preamplifier for X-Ray

NUCLEAR INSTRUMENTS AND METHODS 156 (1978) 553-557 ; © NORTH-HOLLAND PUBLISHING CO.

X-RAY PREAMPLIFIER EMPLOYING PULSED DRAIN FEEDBACK

C. BUSSOLATI, P. F. MANFREDI, D. MARIOLI

Politecnico di Milano, Sez. di Brescia, I.N.F.N., Sez. di Milano, Italy

and

R. KRASOWSKI

Academy of Mining and Metallurgy, Cracow, Poland

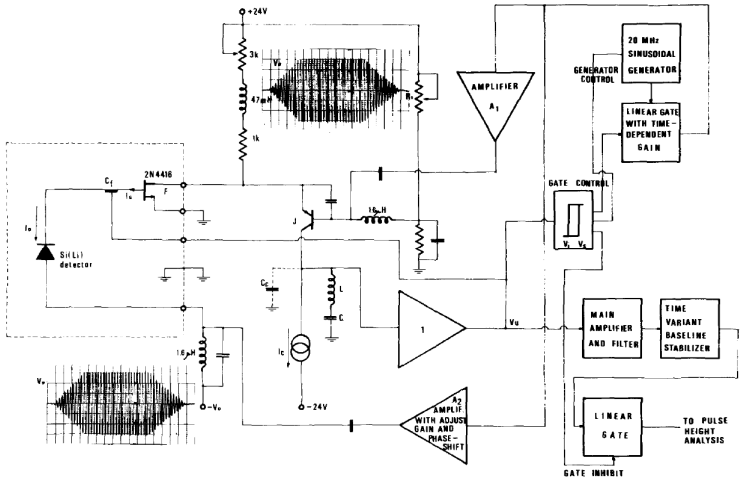


Fig. 3. Circuit diagram of a charge-sensitive preamplifier employing pulsed drain-feedback.

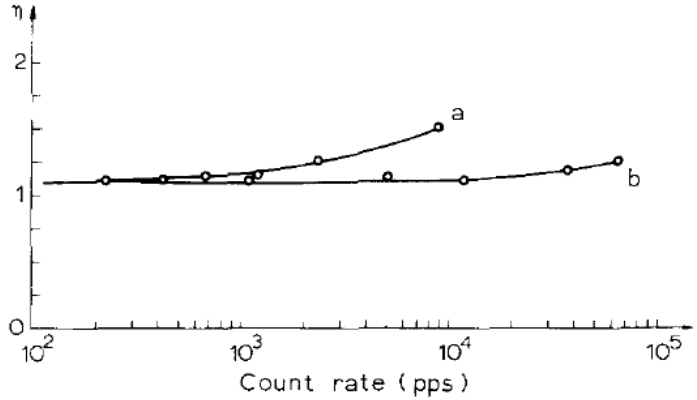
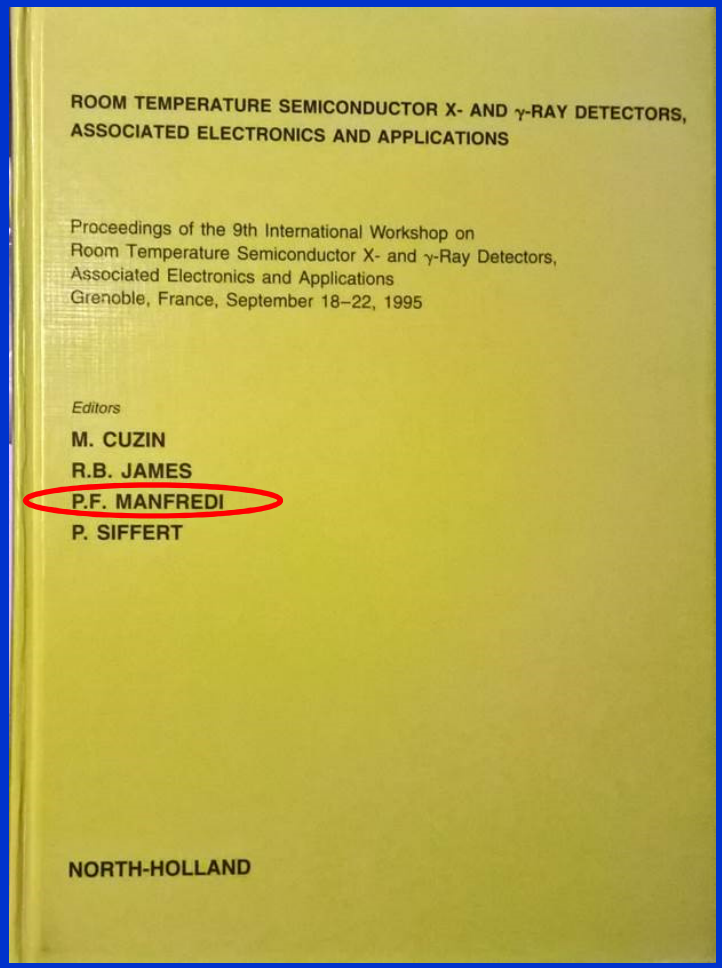


Fig. 4. Resolution versus counting rate characteristics for the drain-feedback preamplifier. a) continuous mode; b) pulsed feedback. The vertical axis represents the ratio

1995: RTSD Conference Scientific Committee

Room Temperature Semiconductor X- and γ-Ray Detectors, Associated Electronics and Applications



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Nuclear Instruments and Methods in Physics Research A 380 (1996) 308–311
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

JFET-based monolithic preamplifiers for spectrometry applications[1]

P.F. Manfredi*, V. Re, V. Speziali
Dipartimento di Elettronica, Università di Pavia, via Ferrata 1, 27100, Pavia, Italy[2]

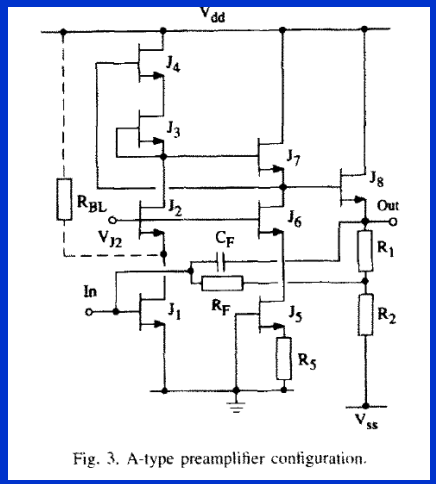
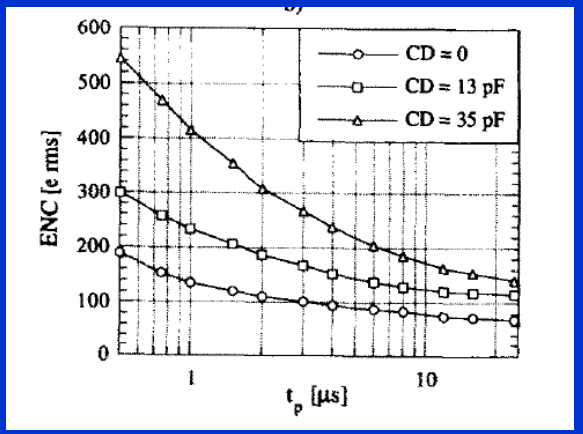


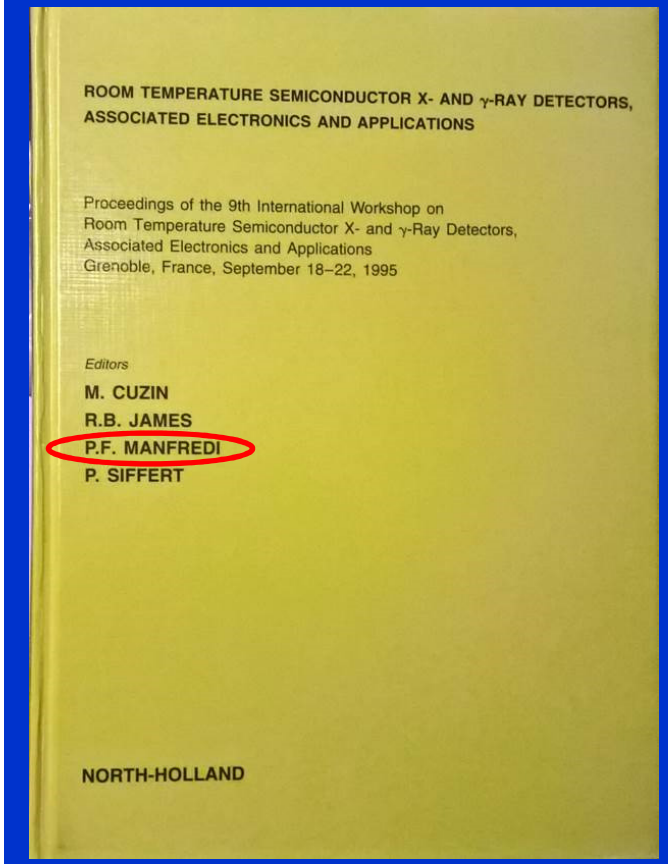
Fig. 3. A-type preamplifier configuration.



ENC ≈ 100 electrons r.m.s. for C_D≈10pF

1995: RTSD Conference

Invited talk asked by Franco Manfredi



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Nuclear Instruments and Methods in Physics Research A 380 (1996) 301–307

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Criteria of choice of the front-end transistor for low-noise preamplification of detector signals at sub-microsecond shaping times for X- and γ-ray spectroscopy

G. Bertuccio, A. Pullia, G. De Geronimo

Dipartimento di Elettronica e Informazione, Politecnico di Milano P.zza Leonardo da Vinci 32, 20133, Milano, Italy

Comparative Study of Noise Performace of JFET, MOSFET, MESFET, HEMT and BJT

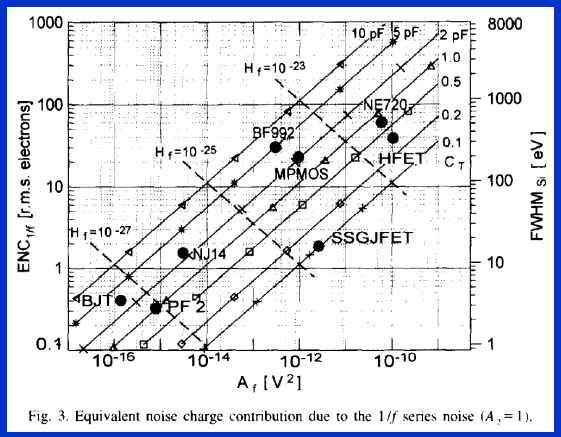
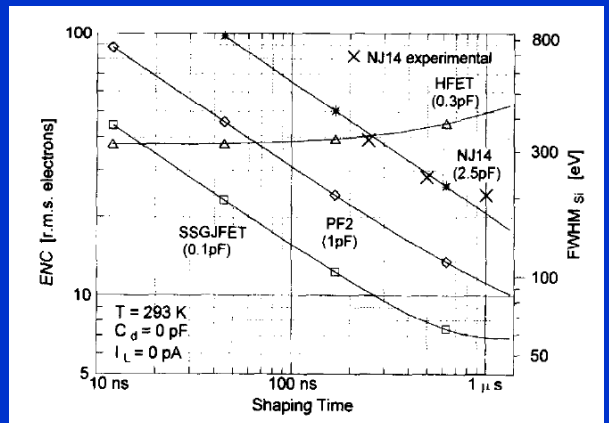


Fig. 3. Equivalent noise charge contribution due to the 1/*f* series noise ($A_f = 1$).



AToM CMOS ASIC applied to X-Ray Detectors

Presented at 1999 RTSD Conference in Vienna

ELSEVIER

Nuclear Instruments and Methods in Physics Research A 458 (2001) 382–391

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

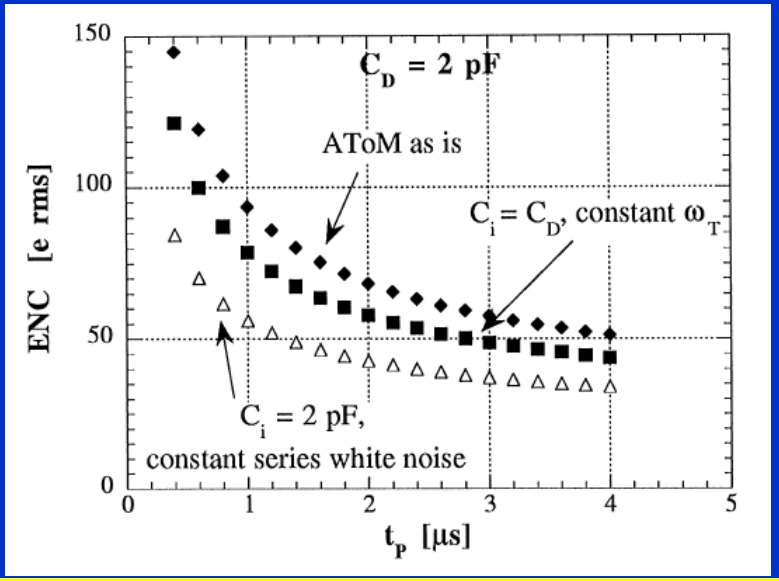
www.elsevier.nl/locate/nima

Noise limits of AToM, a128 channel CMOS readout chip in applications with room temperature high granularity detectors

P.F. Manfredi[a,b], L. Ratti[c,d], V. Re[d,b,*], N.A. Roe[a], V. Speziali[c,b]

- CMOS 0.8µm
- 128 channels
- analog processing and A/D conversion
- Designed for Si microstrip in HEP application

Study of a design suitable for X-γ ray spectroscopy detectors

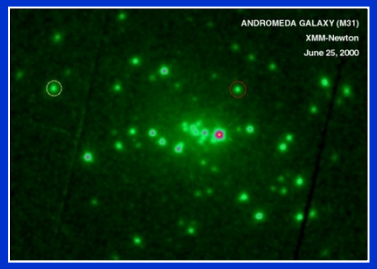


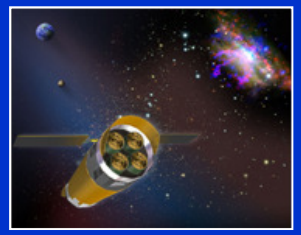
ENC ≈ 50 electrons r.m.s. for C_D≈2pF

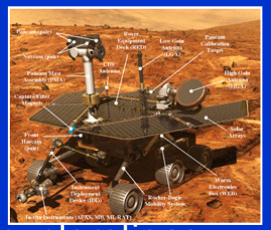
Why X-Ray Detectors are interesting for a Front-End Electronics Designer?

Applications of X-Ray Detectors

Astrophysics

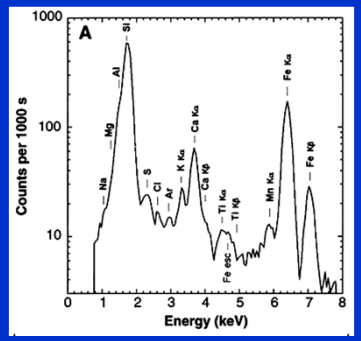






X-γ ray telescopes
Universe and planetary explorations

Material study



X-Ray fluorescence analysis

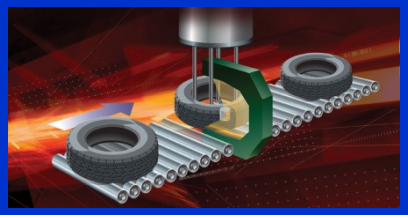
Works of arts analysis

Medical

Security

Quality assurance

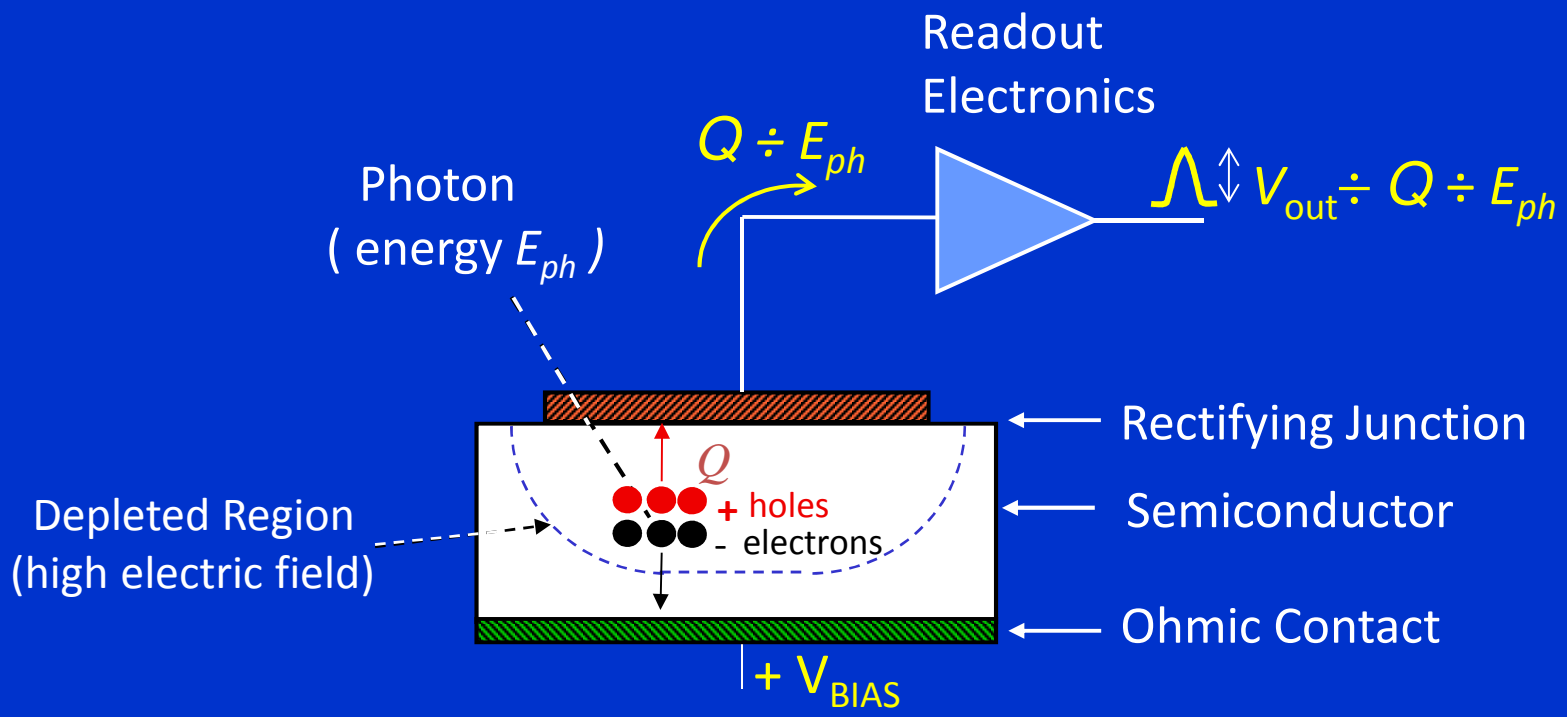
(Food, Electronics, Pharma, Tire…)



Waste recycling

Electronics for X-Ray Detectors

Where is the challenge?



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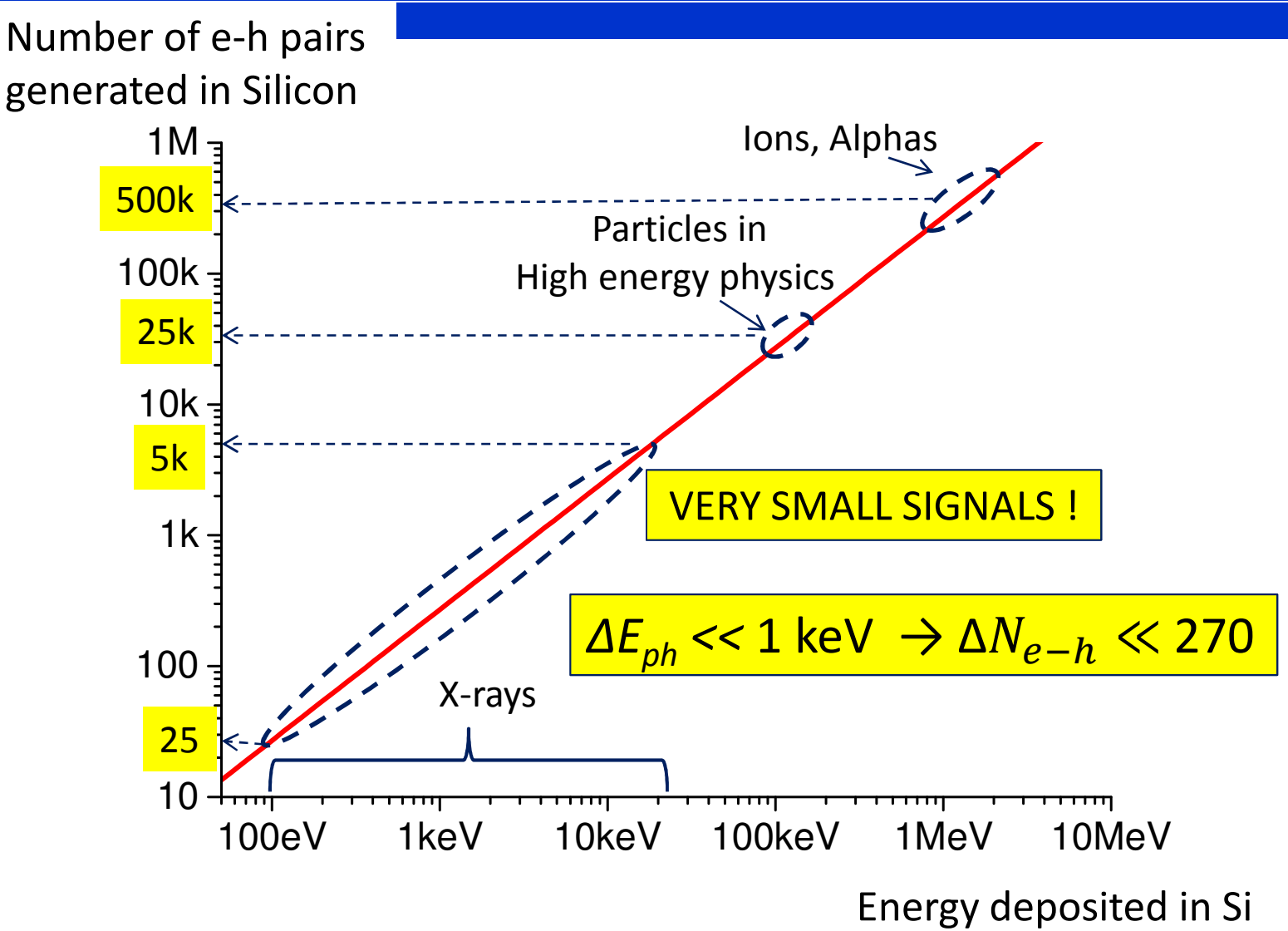

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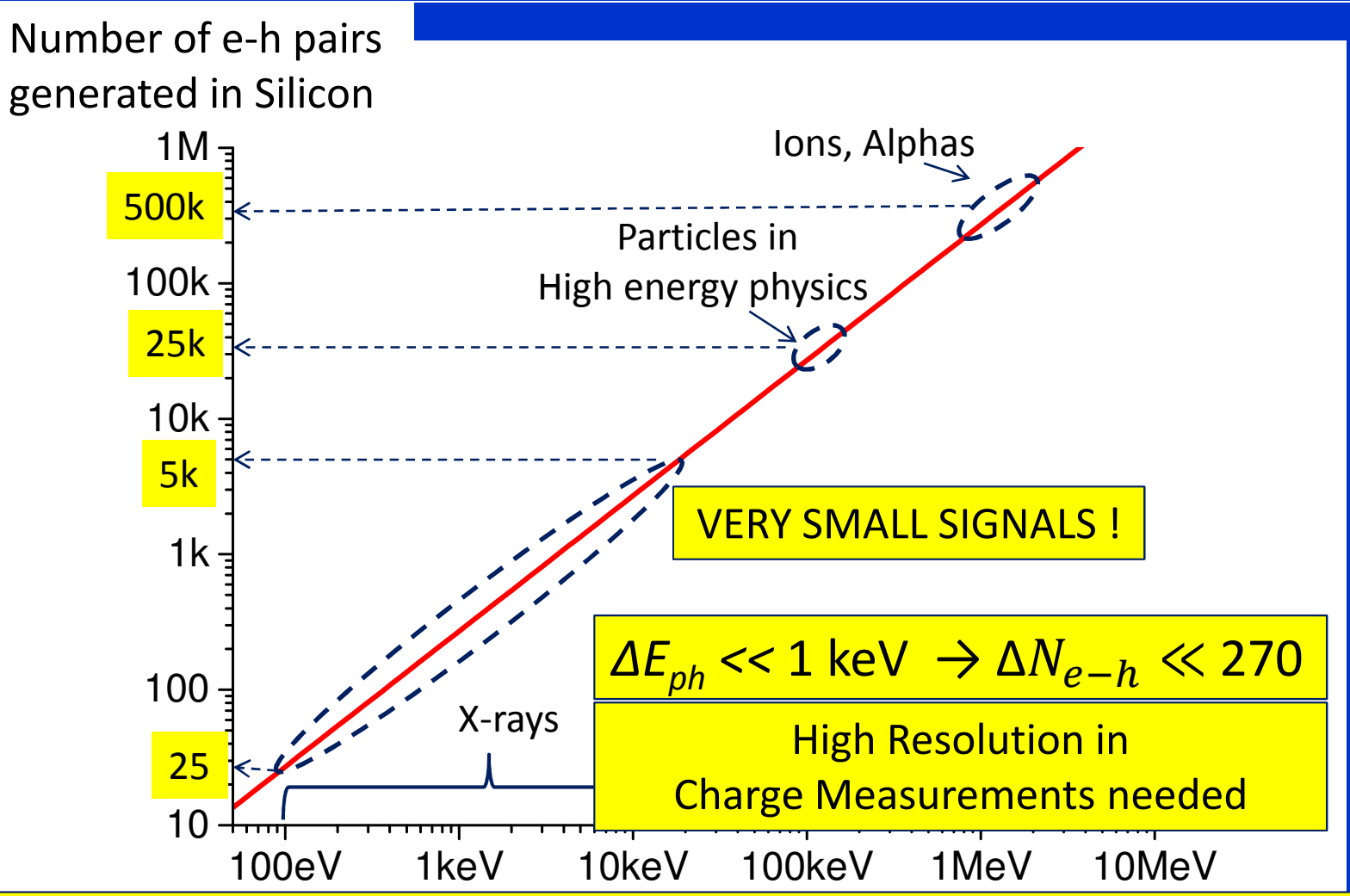
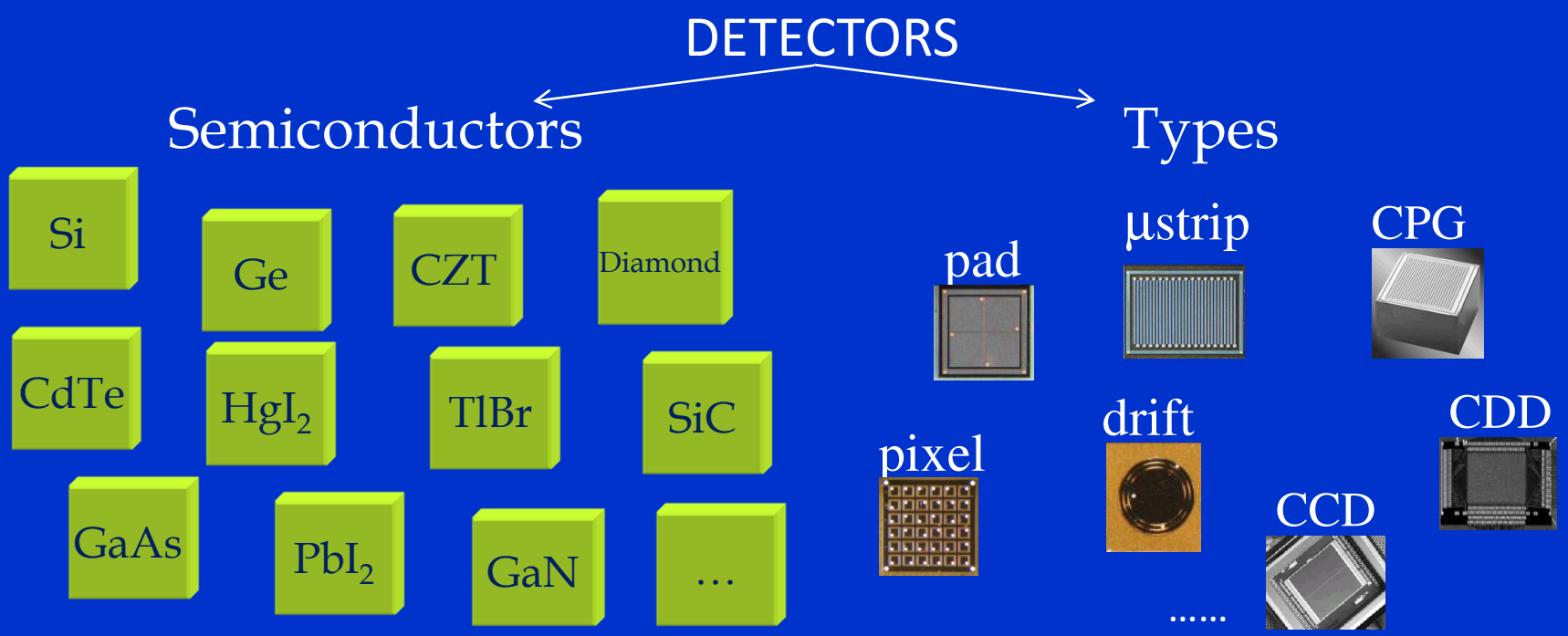


Readout Electronics is required to have
Equivalent Noise Charge of few tens or even few electrons r.m.s.

Electronics for X-Ray Detectors



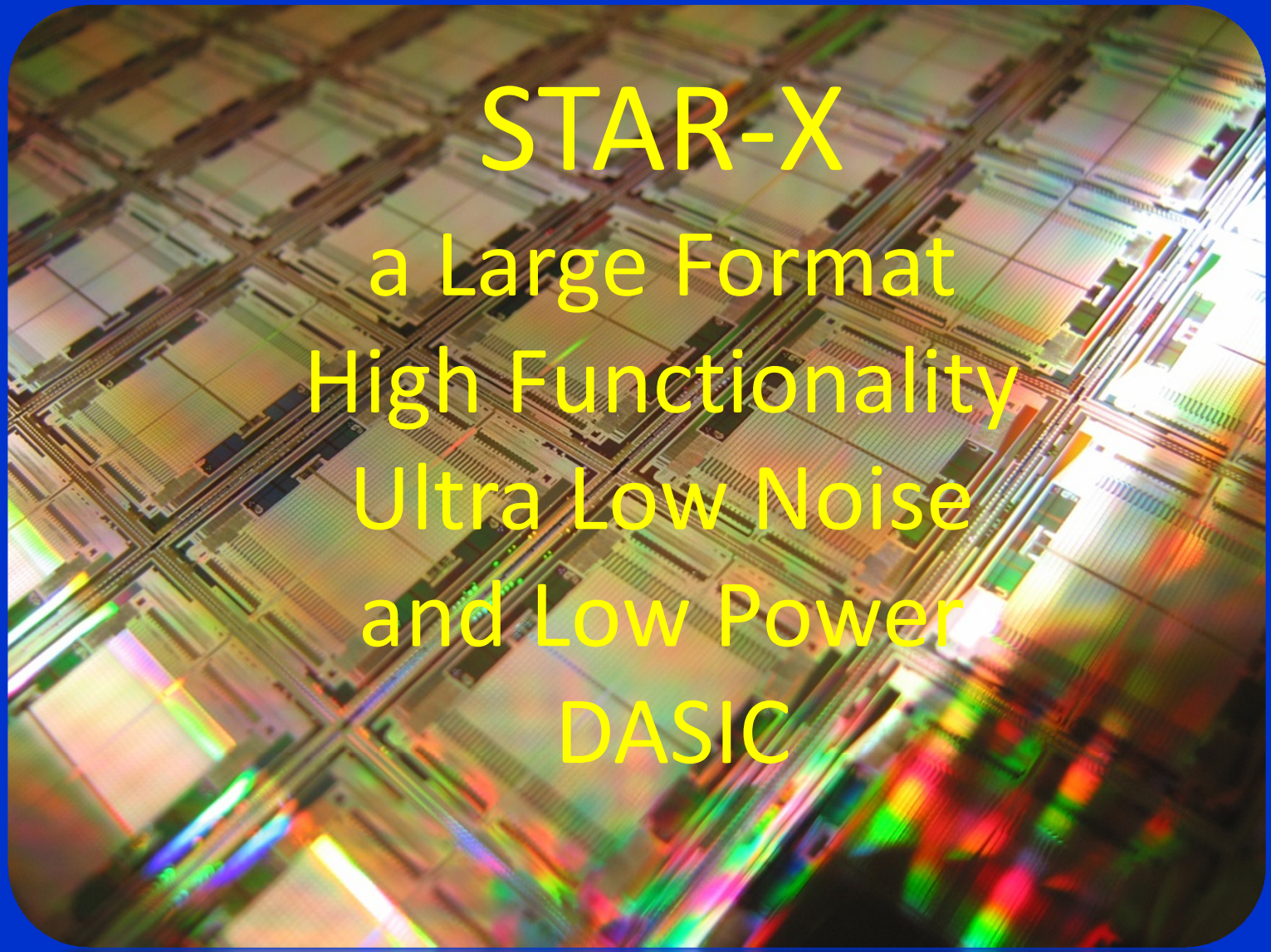
DASIC more than *ASIC*

Detector and Application Specific IC

Toward The Ultimate Low-Noise Front-End Electronics

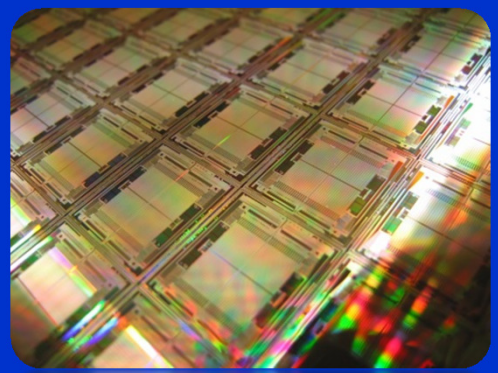
two examples:

- A Complex, High Functionality, Ultra Low-Noise DASIC
- An Ultimate-Low Noise Fully Integrated CMOS Charge Sensitive Preamplifier


STAR-X
a Large Format
High Functionality
Ultra Low Noise
and Low Power
DASIC

STAR-X

A Large Format X-Ray Detector Readout DASIC



esa — Supervision

ThalesAlenia Space — Project Management & Readout System Design

DASIC Designer Groups

POLITECNICO DI MILANO — Front-End Electronics Design

Giuseppe Bertuccio

UNIVERSITÁ DEGLI STUDI DI PAVIA — Back-end Electronics Design

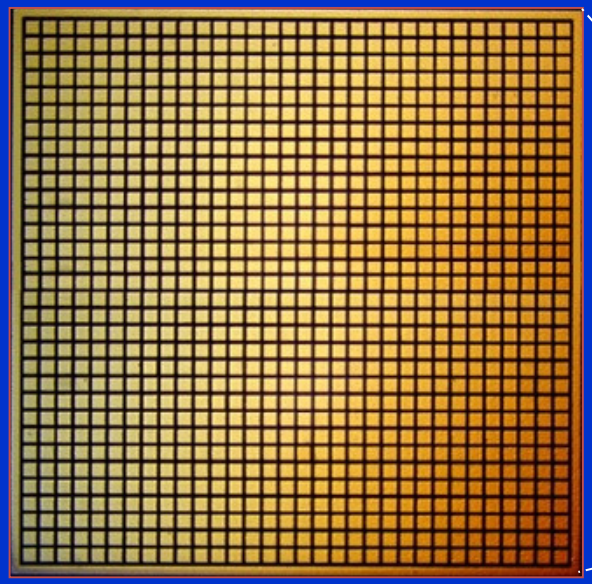
Piero Malcovati

STAR-X DASIC

for GaAs pixel detector for X-ray Imaging with Space Telescopes

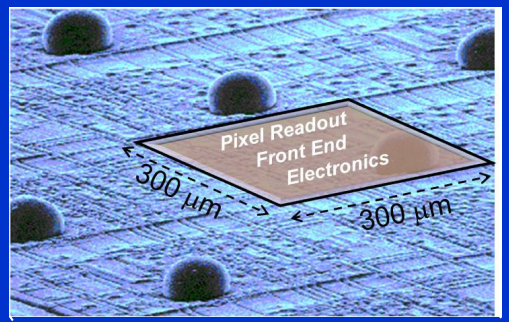
GaAs detector 32 x 32 pixels

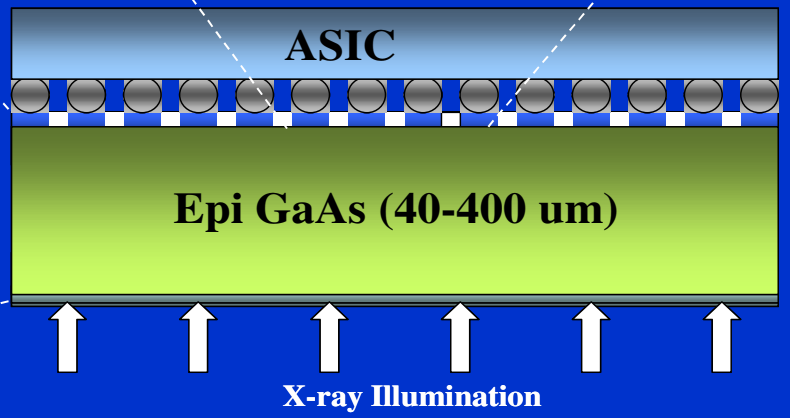
Pixel size: 250 µm X 250 µm



1 cm

1 cm

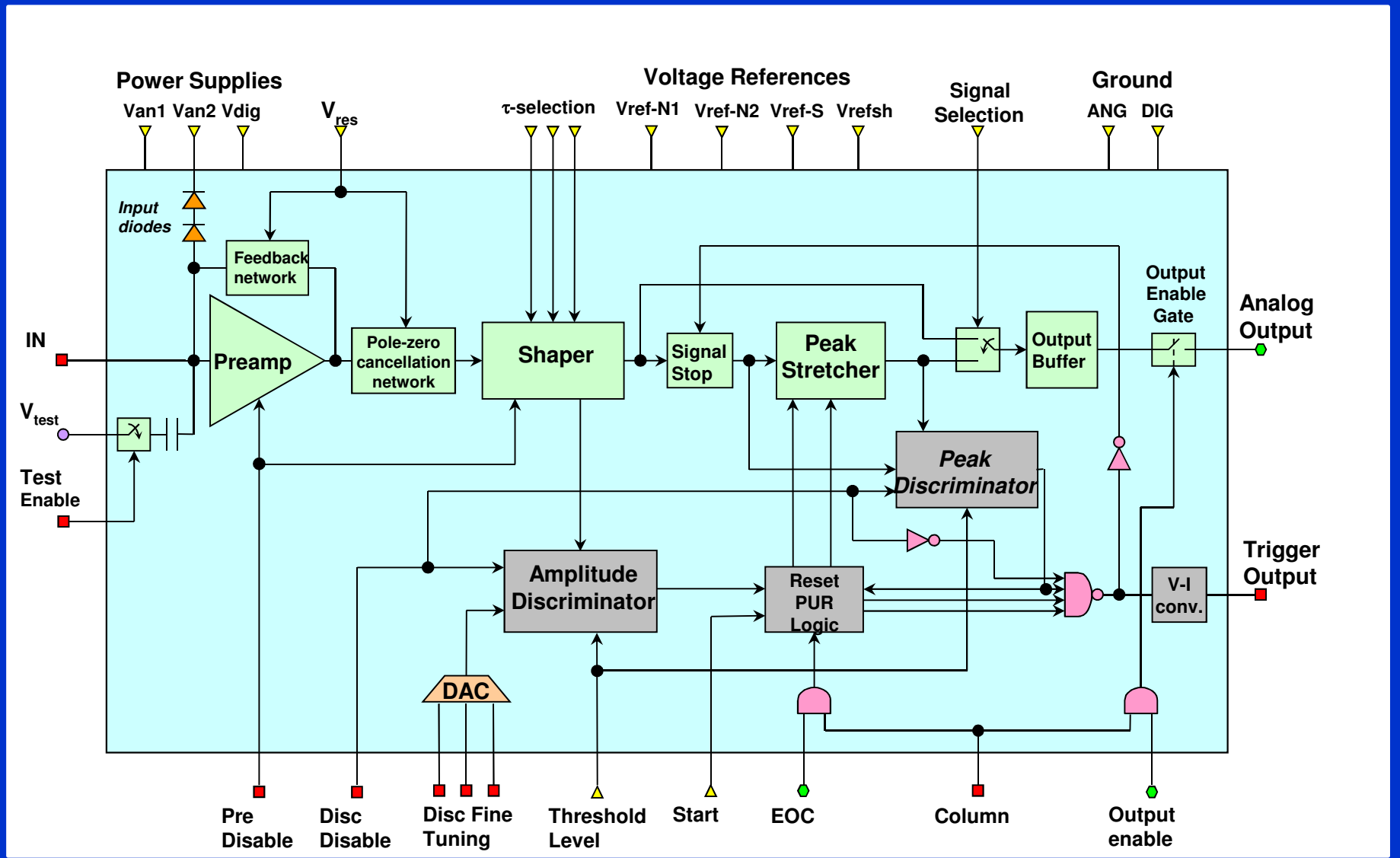




X-Ray Energy Range

500 eV – 50 keV (120 to 12k electrons)

Front-End: The Readout Pixel Cell (RPC)



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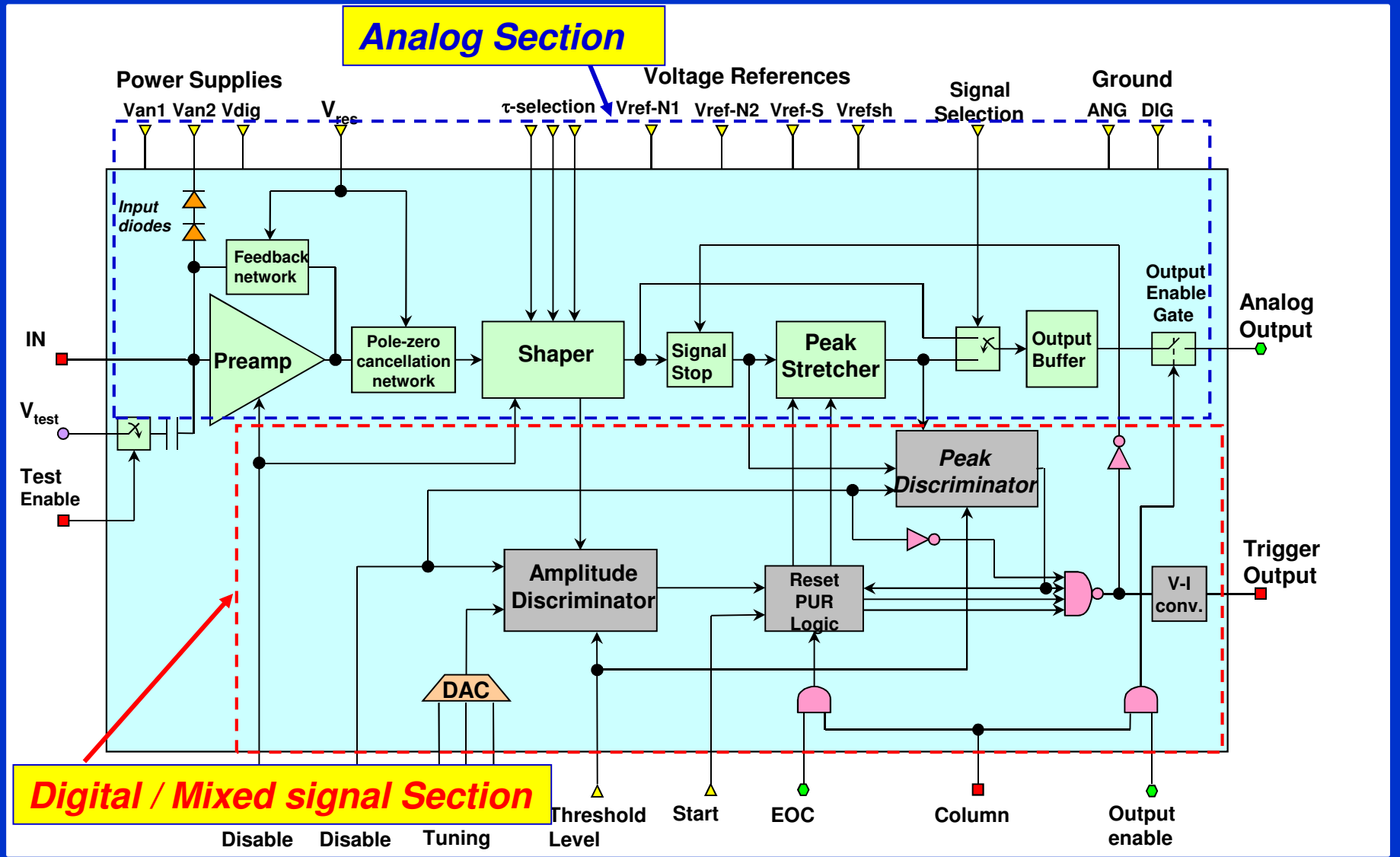
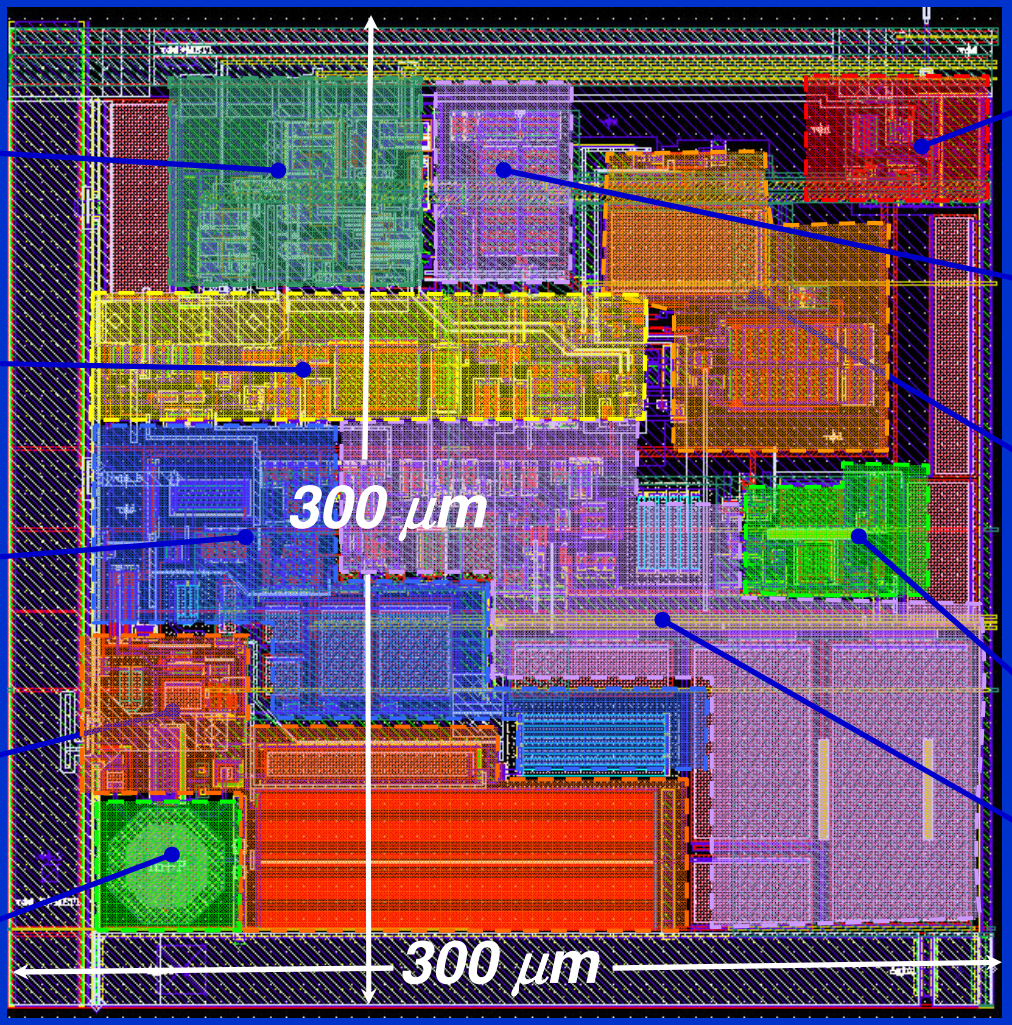


Readout Pixel Cell Layout



Reset/PUR Logic +Trigger Trasm. << 1 µW

Amplitude Discriminator 37 µW

Shaper 1st 98 µW

Charge Preamplifier 115 µW

Input Pad Ø=35 µm

Output Buffer 49 µW

Peak Discriminator 21 µW

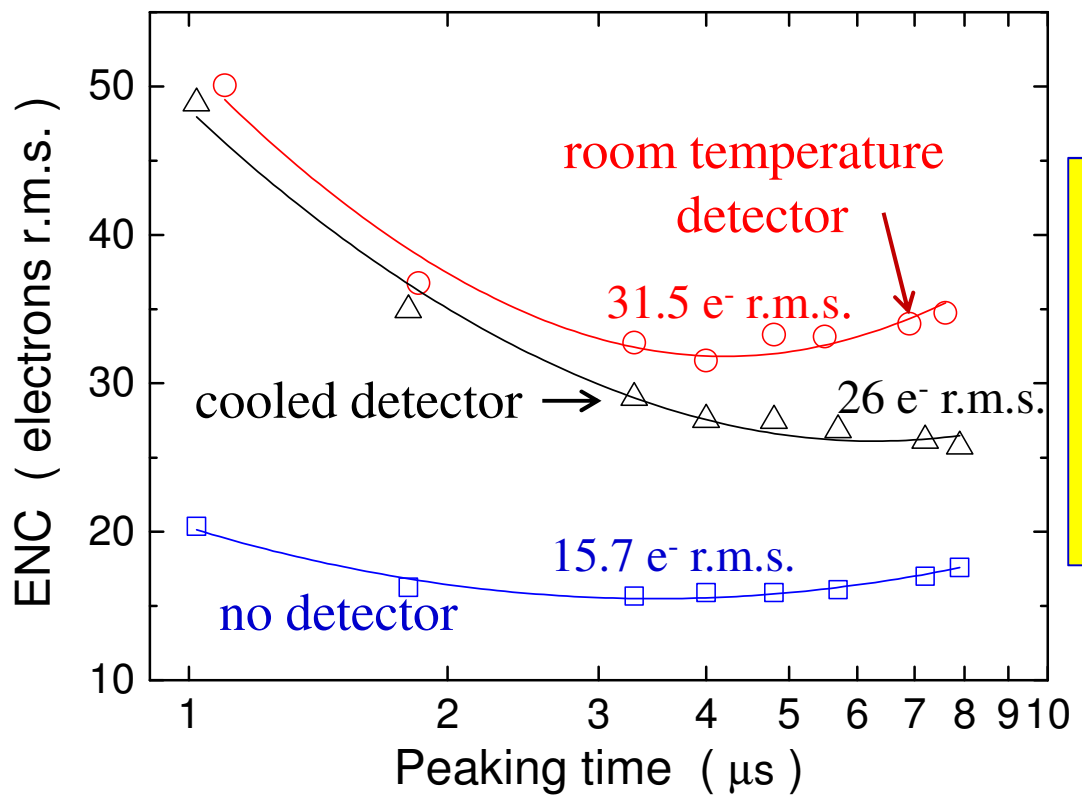
Peak Stretcher 35 µW

DC stabilizer

Shaper 2nd 71 µW

Total Power Consumption: 483 µW

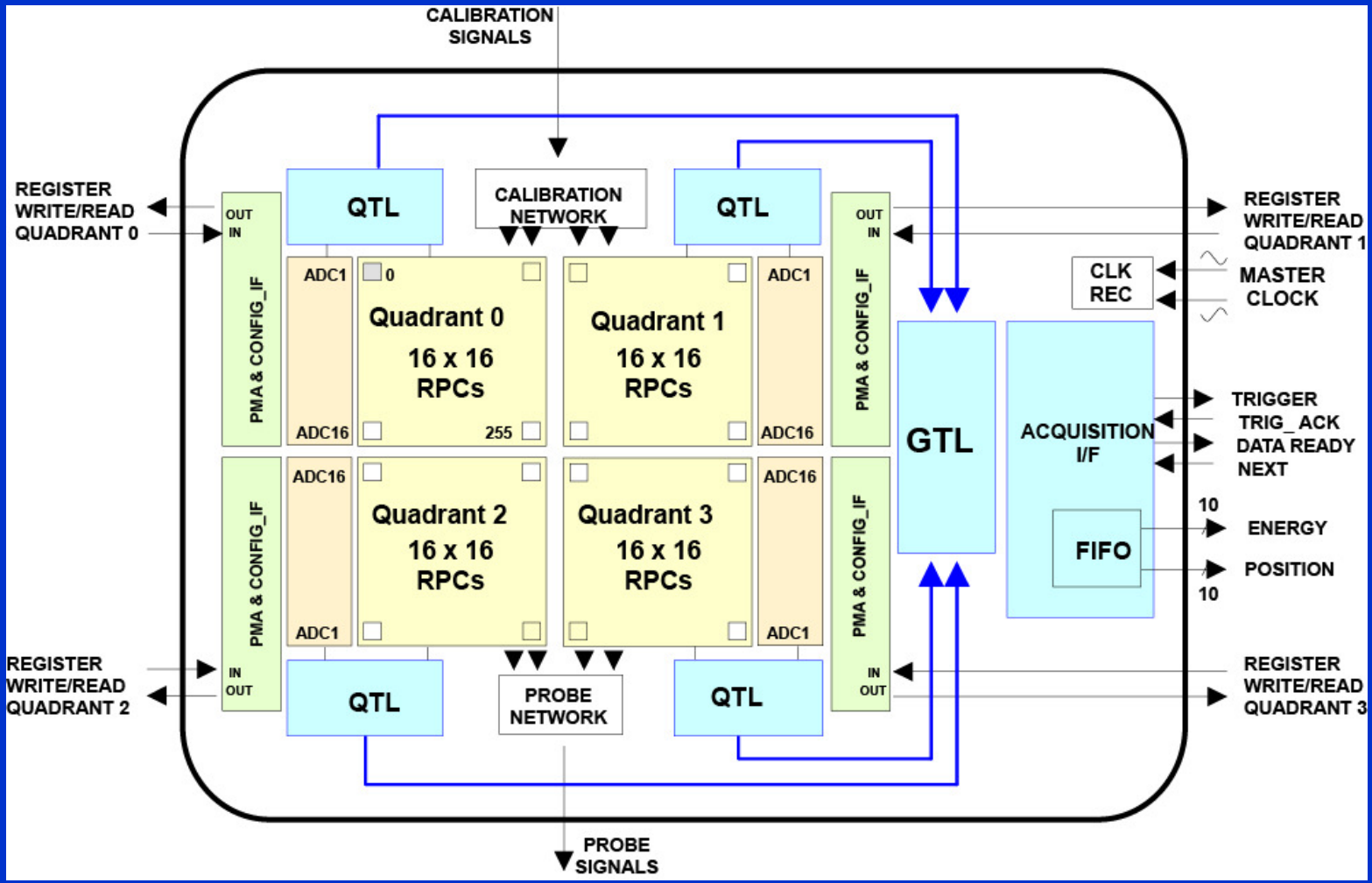
RPC Equivalent Noise Charge



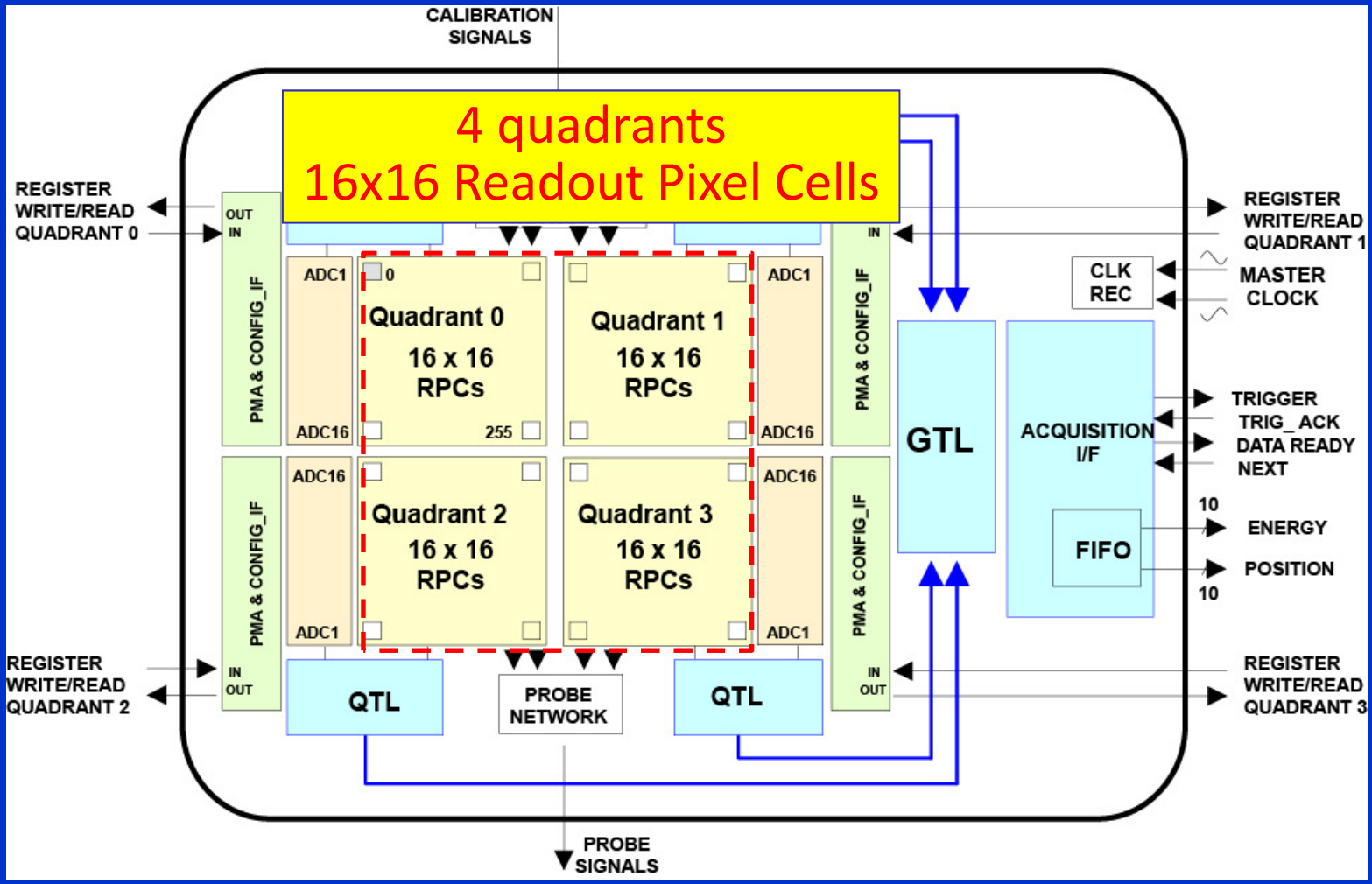
Measurement made on a test chip with a single isolated Readout Pixel Cell

Front-End Electronics Noise
15.7 electrons r.m.s @ 3 us peaking time

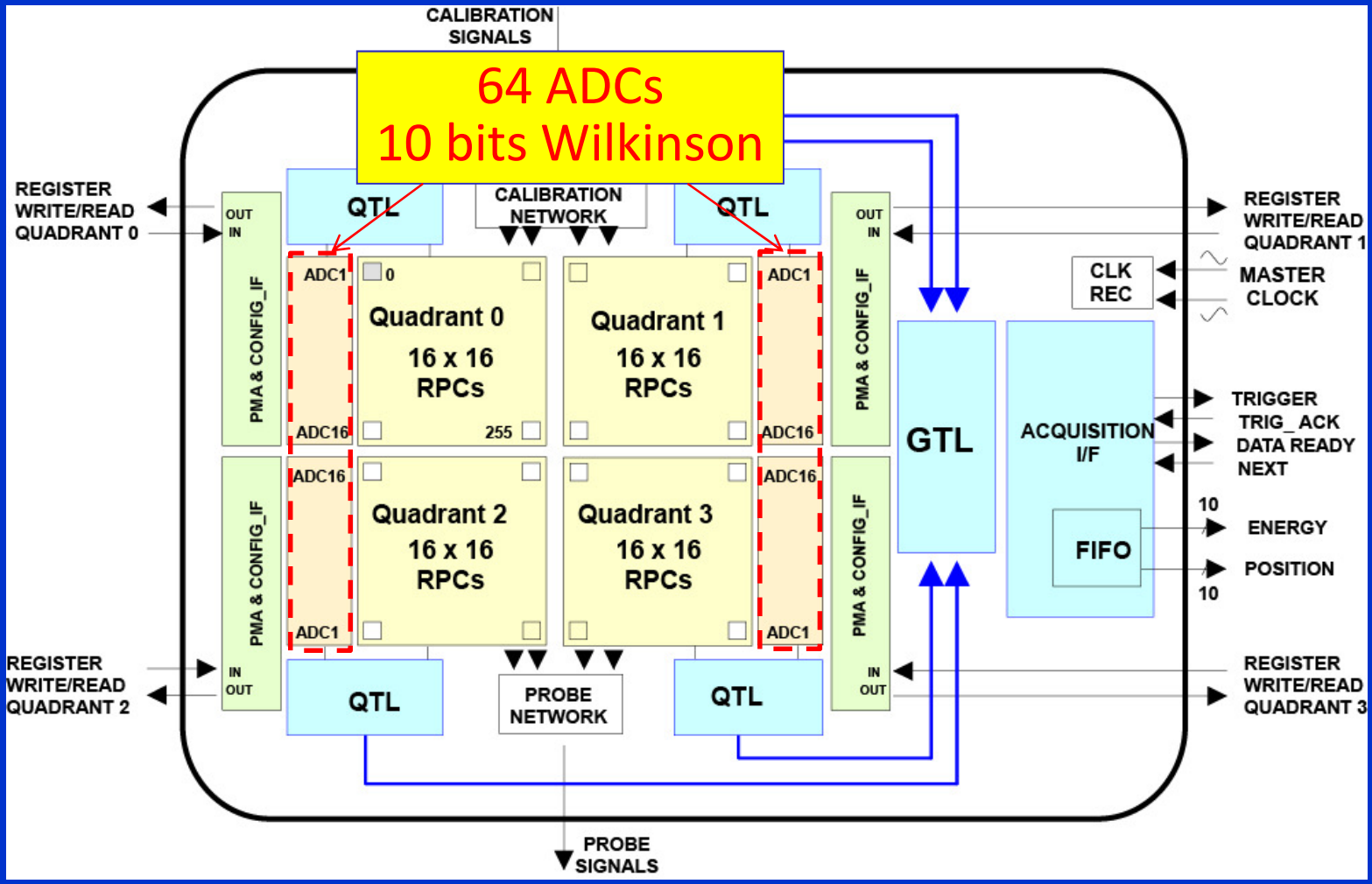
STAR-X Architecture



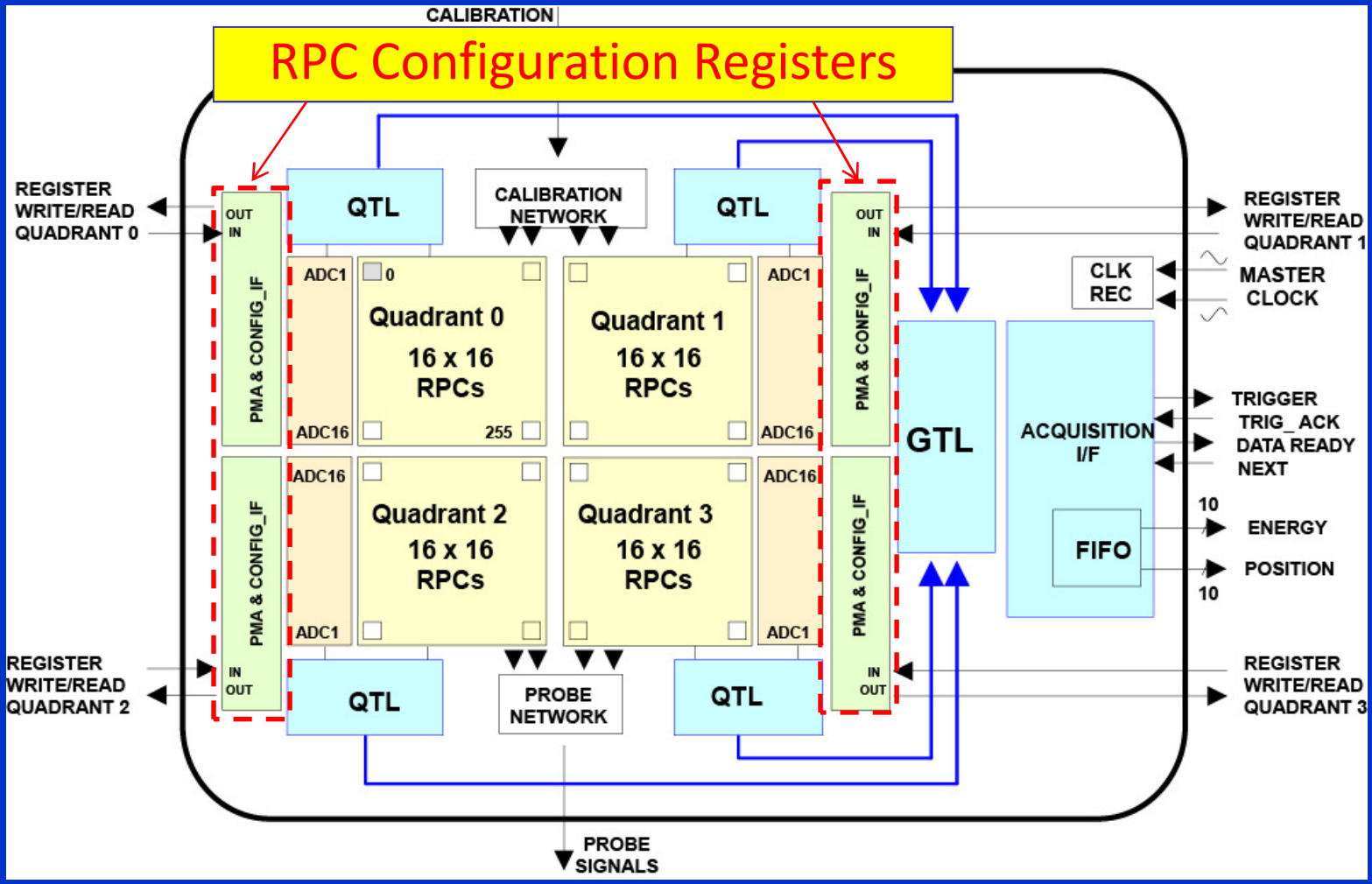
STAR-X Architecture



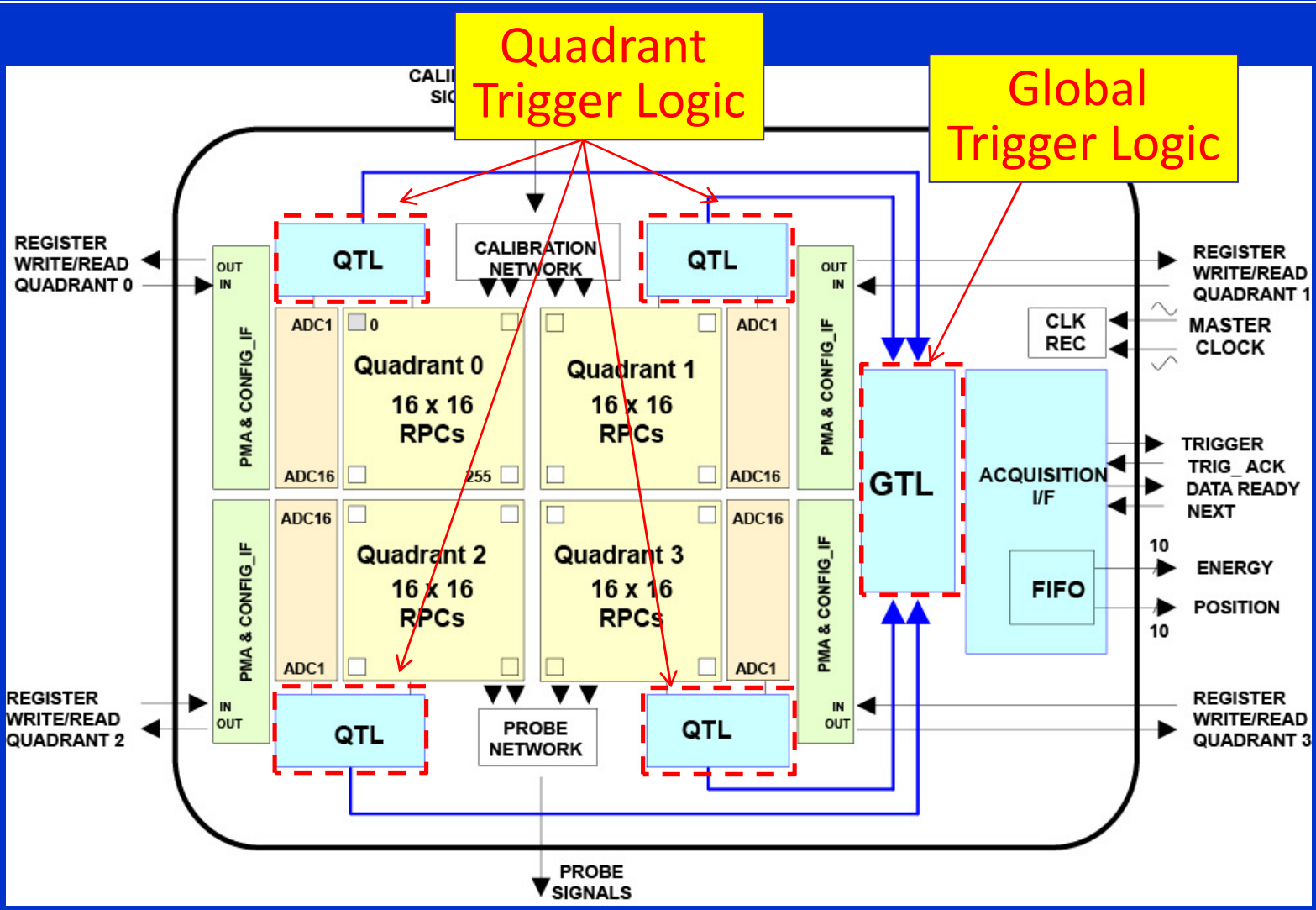
STAR-X Architecture



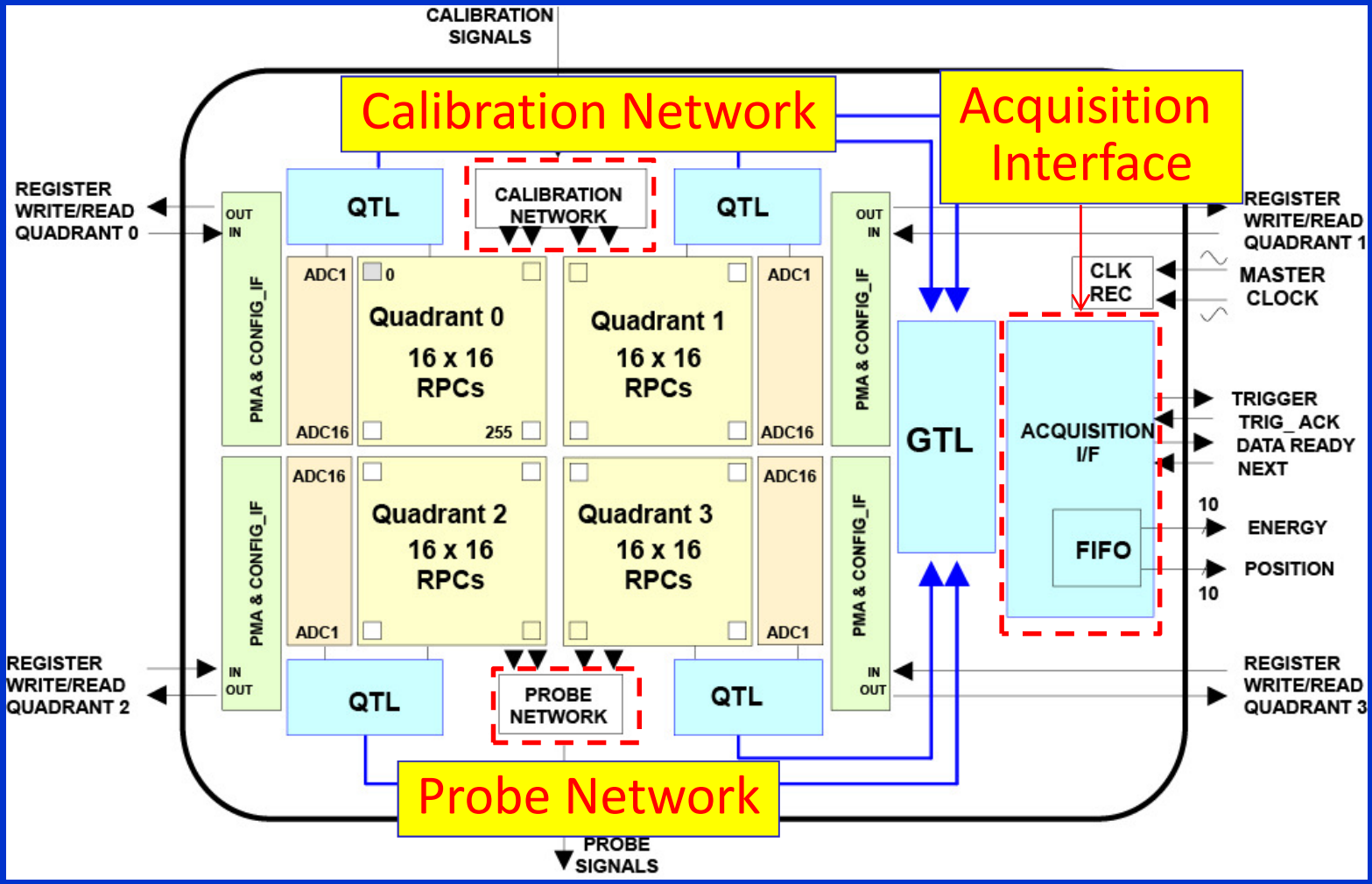
STAR-X Architecture



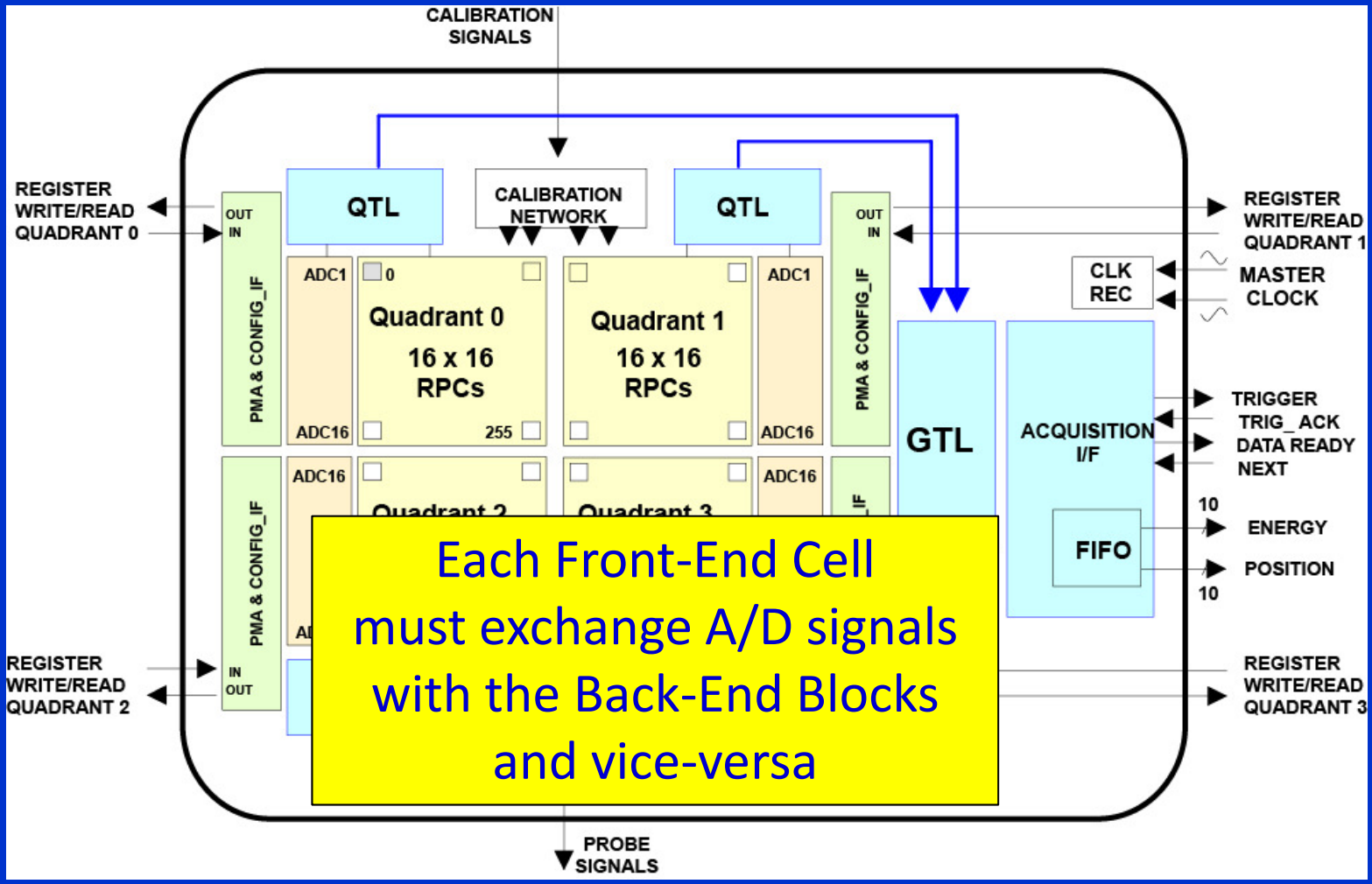
STAR-X Architecture



STAR-X Architecture

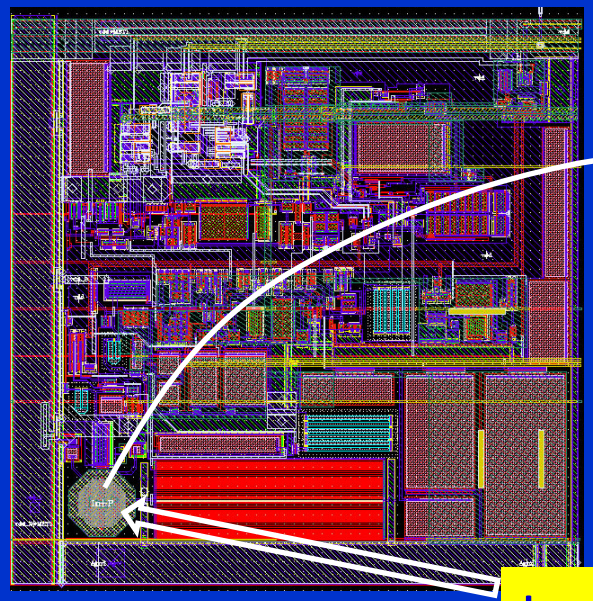


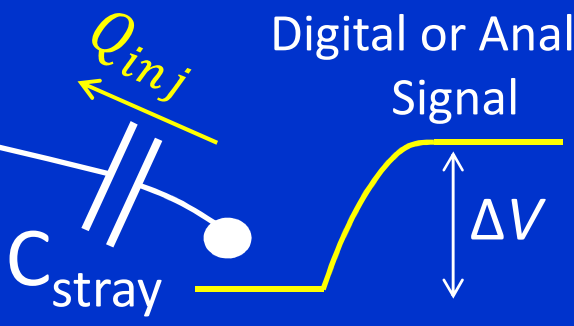
STAR-X Architecture



Each Front-End Cell must exchange A/D signals with the Back-End Blocks and vice-versa

Low Noise Front-End…not sufficient!





$$Q_{inj} = C_{stray}\Delta V$$

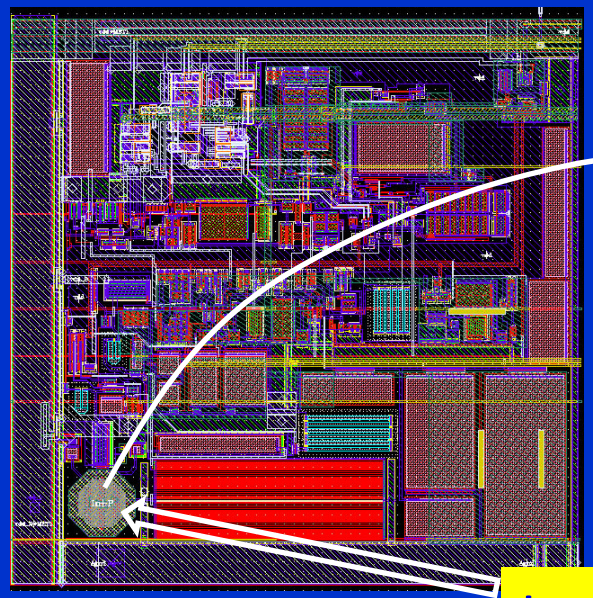
Input: Charge Sensitive Virtual Ground Node

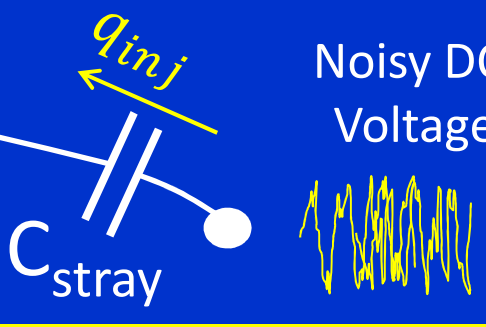
$$Q_{inj} < \min(Q_{signal}) = 120 \text{ electrons}$$ (500 eV X-ray in GaAs)

⇩ $\Delta V \approx 1$ Volt

$C_{stray} < 0.02$ fF !

Low Noise Front-End…not sufficient!





$$q_{inj(noise)} = C_{stray} v_n$$

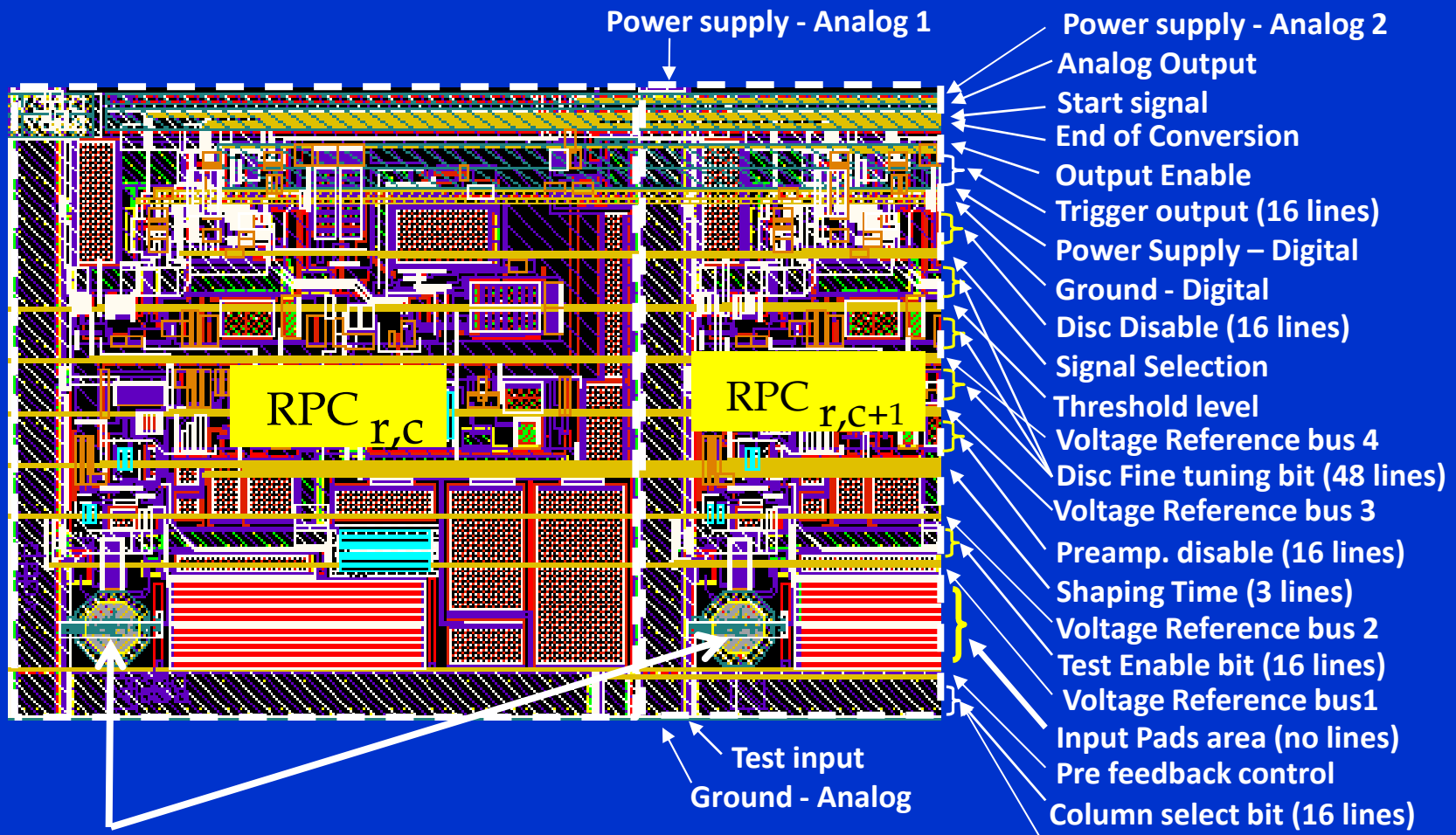
Input: Charge Sensitive Virtual Ground Node

$q_{inj(noise)} \ll ENC$ = 16 electrons r.m.s.

⇩

Stringent constraints on C_{stray} and v_n

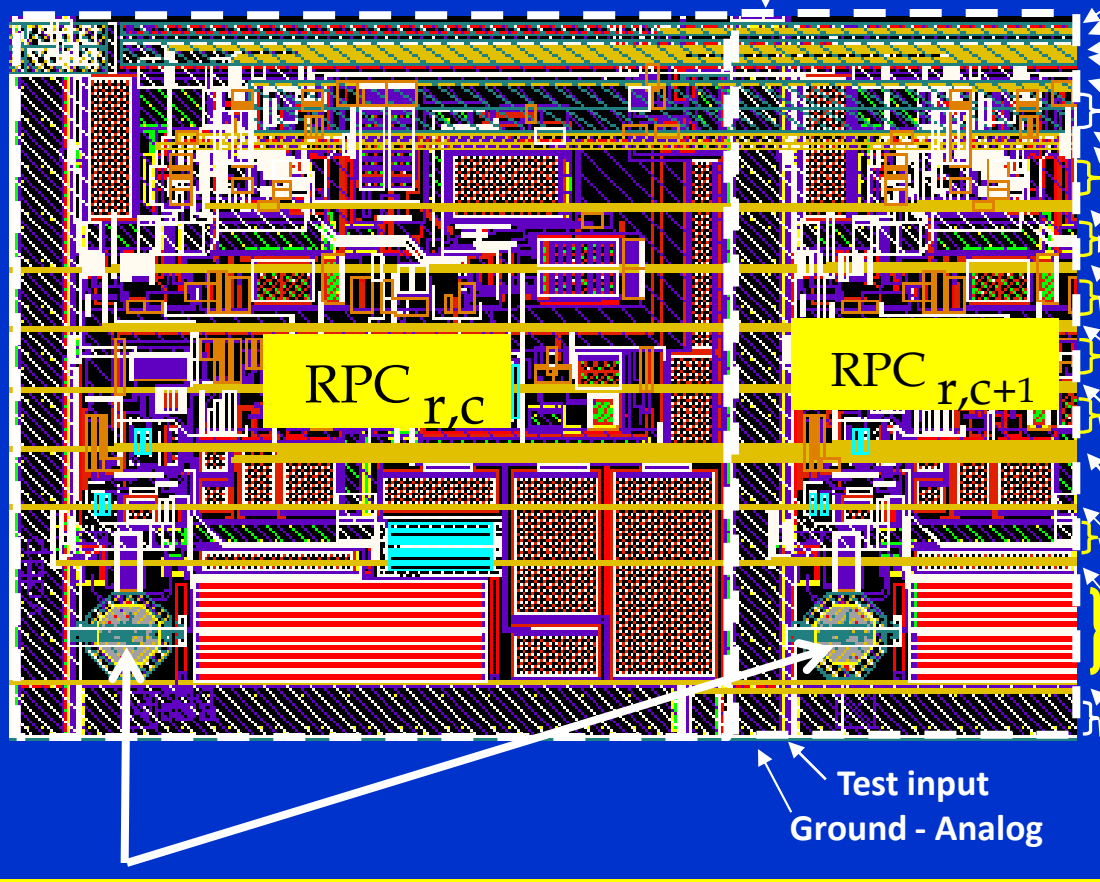
Power and I/O Lines



Inputs: Charge Sensitive Virtual Ground Node

Power and I/O Lines

Lines with switching activity during acquisition (up to 10^6 input signals per second on the full pixel matrix)

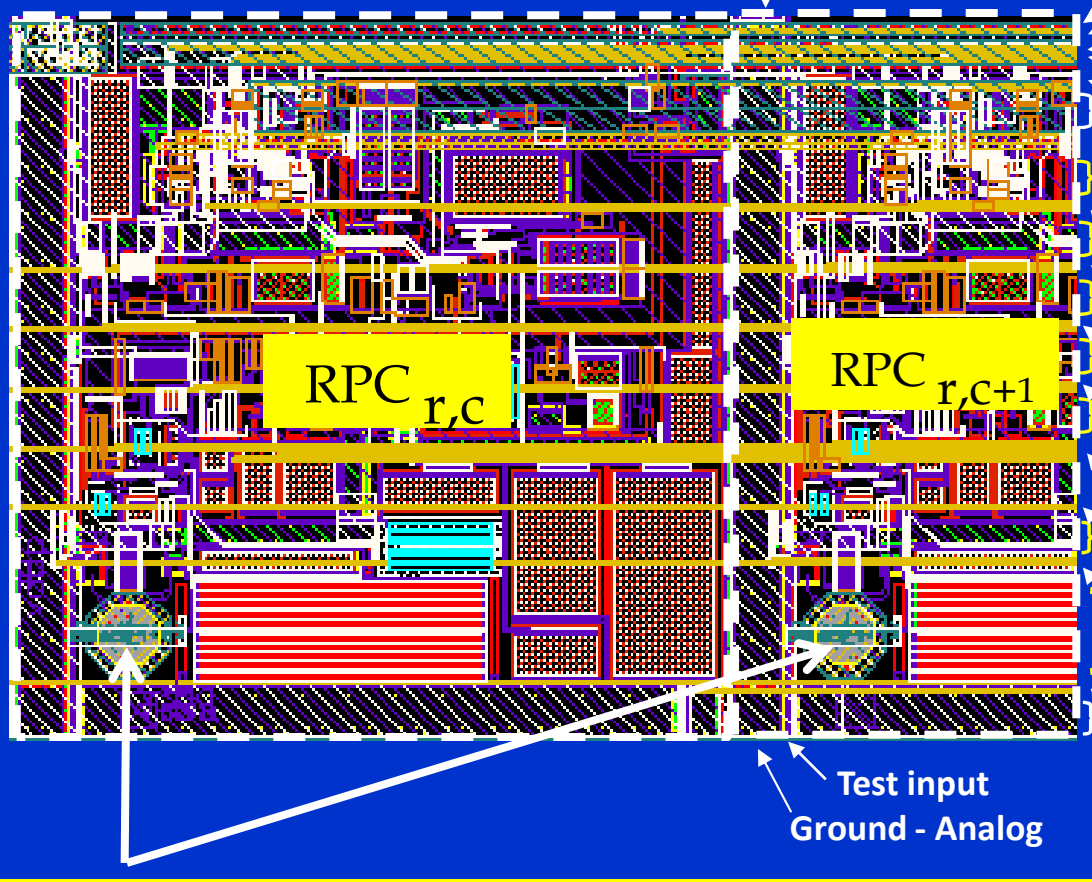


Power supply - Analog 1
Power supply - Analog 2
Analog Output
Start signal
End of Conversion
Output Enable
Trigger output (16 lines)
Power Supply – Digital
Ground - Digital
Disc Disable (16 lines)
Signal Selection
Threshold level
Voltage Reference bus 4
Disc Fine tuning bit (48 lines)
Voltage Reference bus 3
Preamp. disable (16 lines)
Shaping Time (3 lines)
Voltage Reference bus 2
Test Enable bit (16 lines)
Voltage Reference bus1
Input Pads area (no lines)
Pre feedback control
Column select bit (16 lines)
Ground - Analog

Test input
Ground - Analog

Inputs: Charge Sensitive Virtual Ground Node

Power and I/O Lines



Power supply - Analog 1

Power supply - Analog 2
Analog Output
Start signal
End of Conversion
Output Enable
Trigger output (16 lines)
Power Supply – Digital

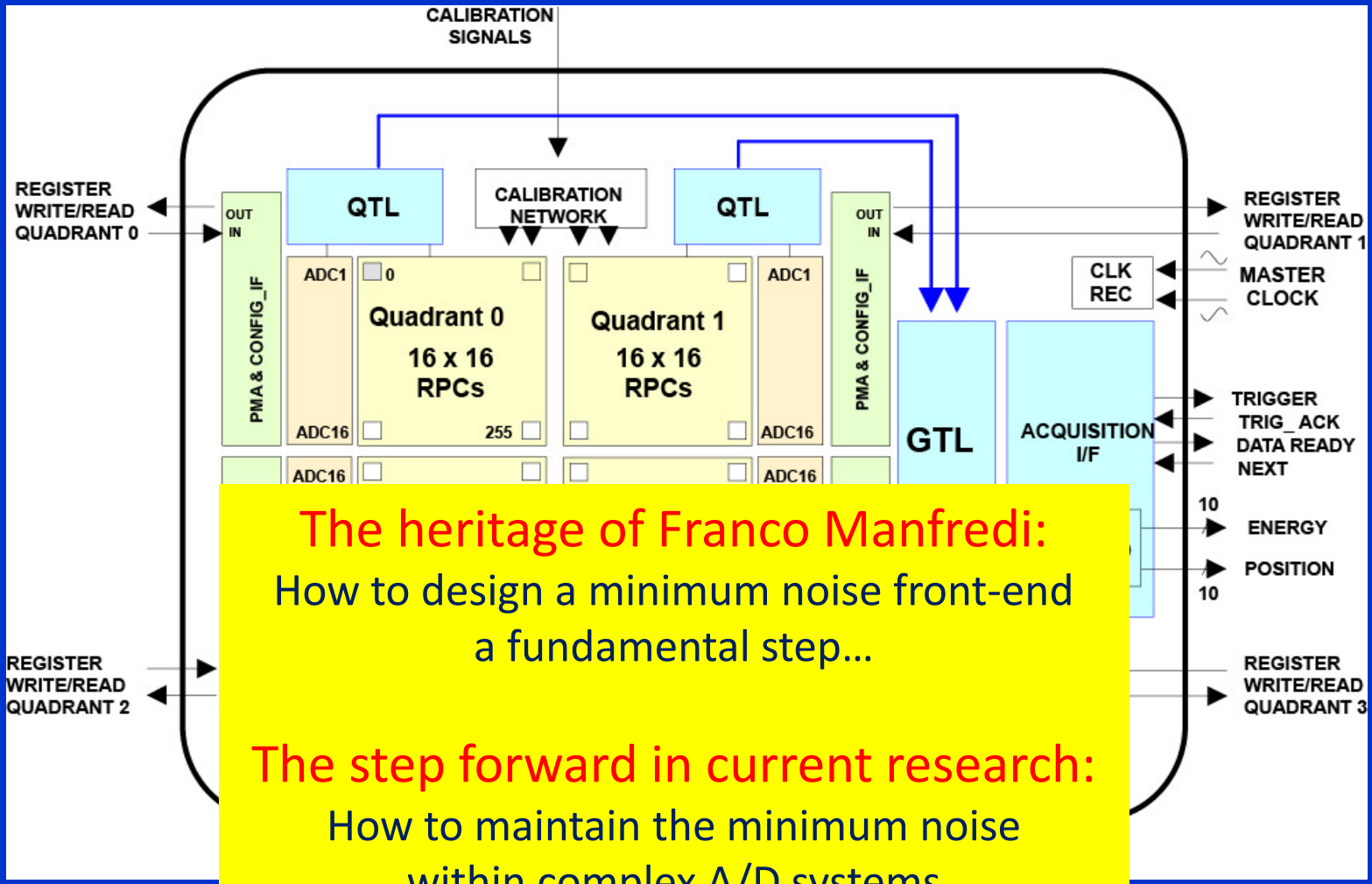
Current mode
Trigger transmission

Threshold level
Voltage Reference bus 4
Disc Fine tuning bit (48 lines)
Voltage Reference bus 3
Preamp. disable (16 lines)
Shaping Time (3 lines)
Voltage Reference bus 2
Test Enable bit (16 lines)
Voltage Reference bus1
Input Pads area (no lines)
Pre feedback control
Column select bit (16 lines)
Ground - Analog

Test input
Ground - Analog

Inputs: Charge Sensitive Virtual Ground Node

STAR-X Architecture



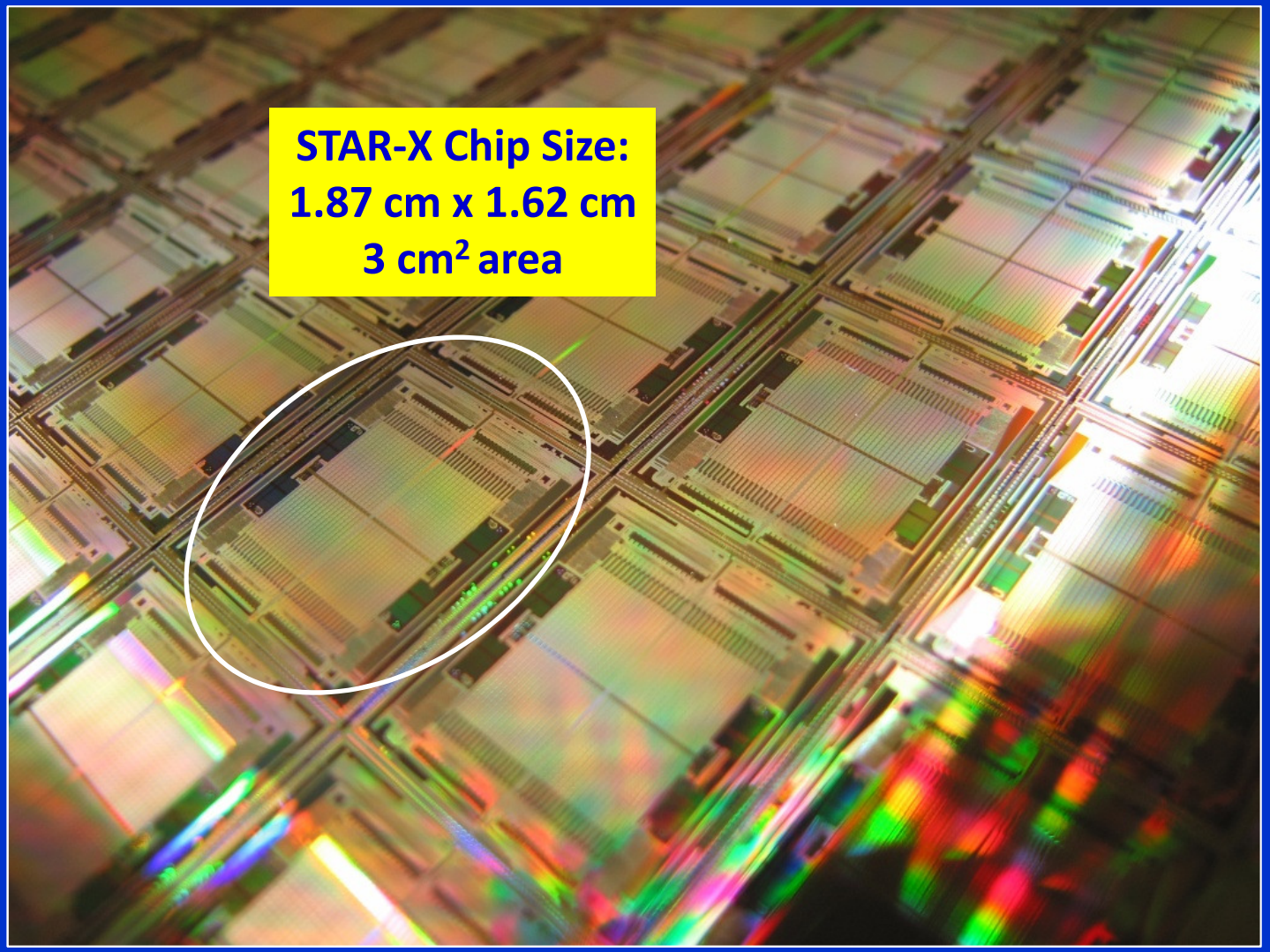
The heritage of Franco Manfredi:

How to design a minimum noise front-end a fundamental step…

The step forward in current research:

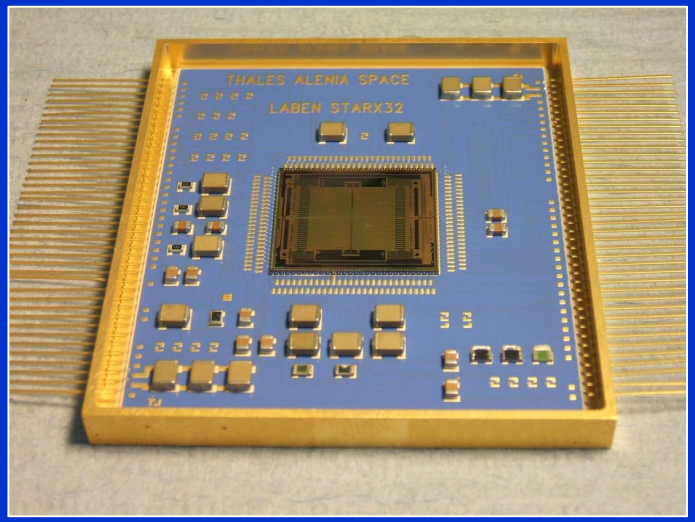
How to maintain the minimum noise within complex A/D systems

Wafer Photo

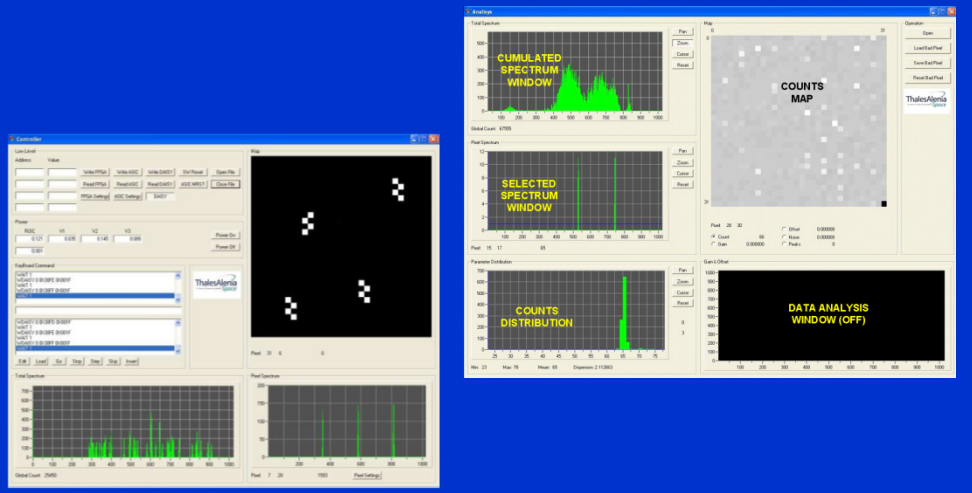


STAR-X DASIC

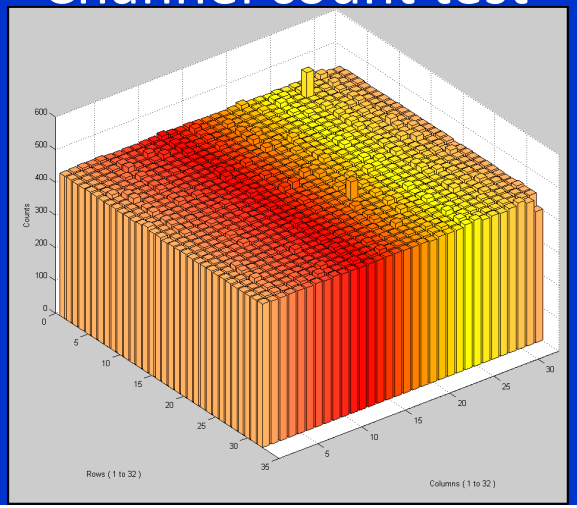
Packaged



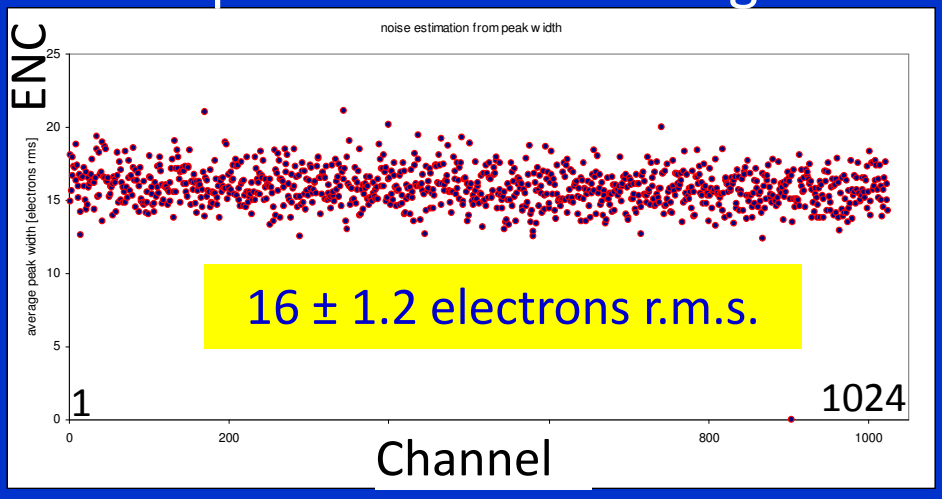
User Interface



Channel count test



Equivalent Noise Charge

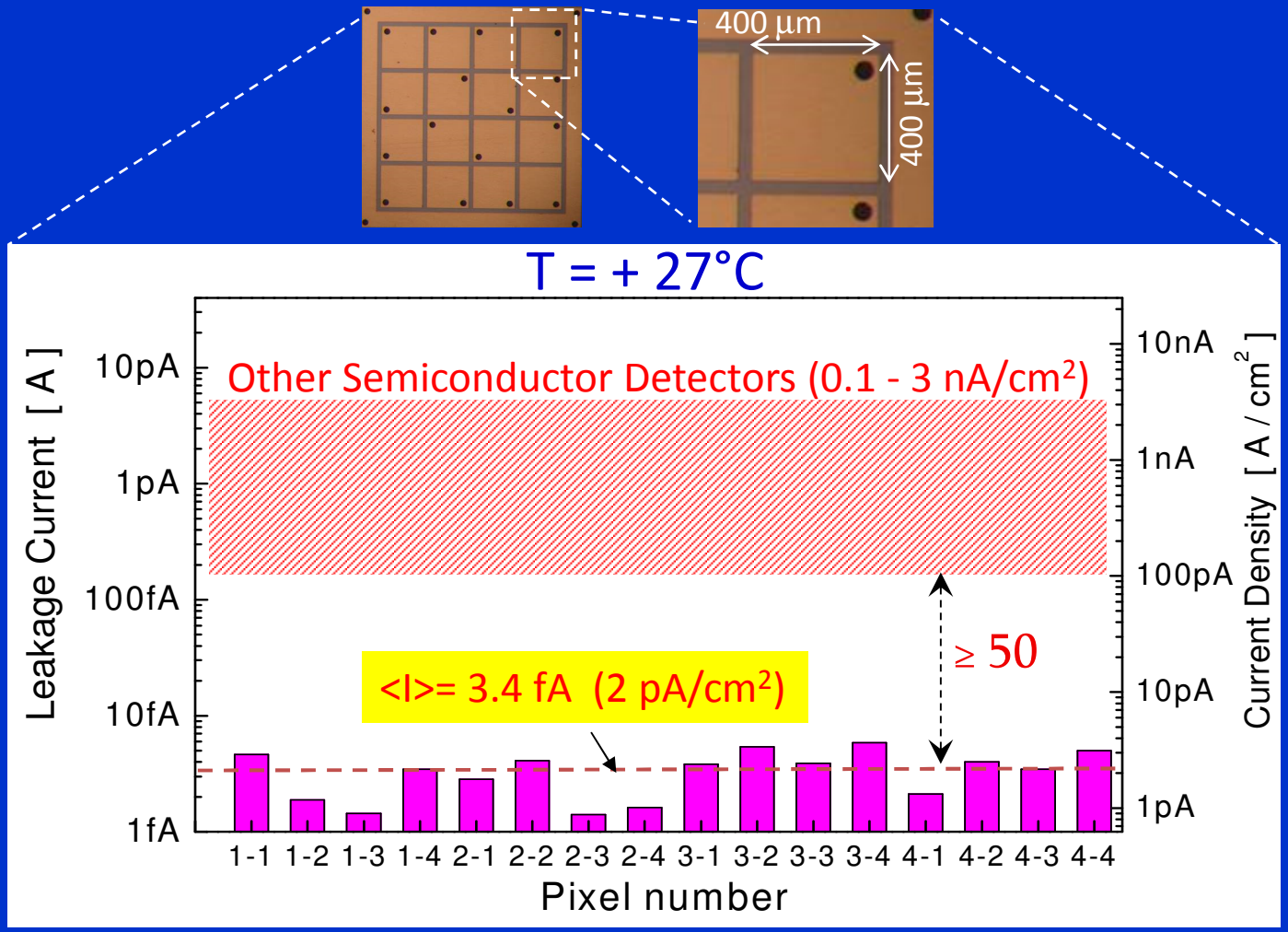


Toward The Ultimate Low-Noise Front-End Electronics

two examples:

- A Complex, High Functionality, Ultra Low-Noise ASIC
- An Ultimate-Low Noise Fully Integrated CMOS Charge Sensitive Preamplifier

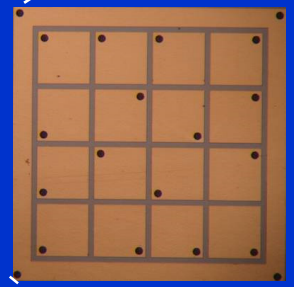
Silicon Carbide Pixel Detector

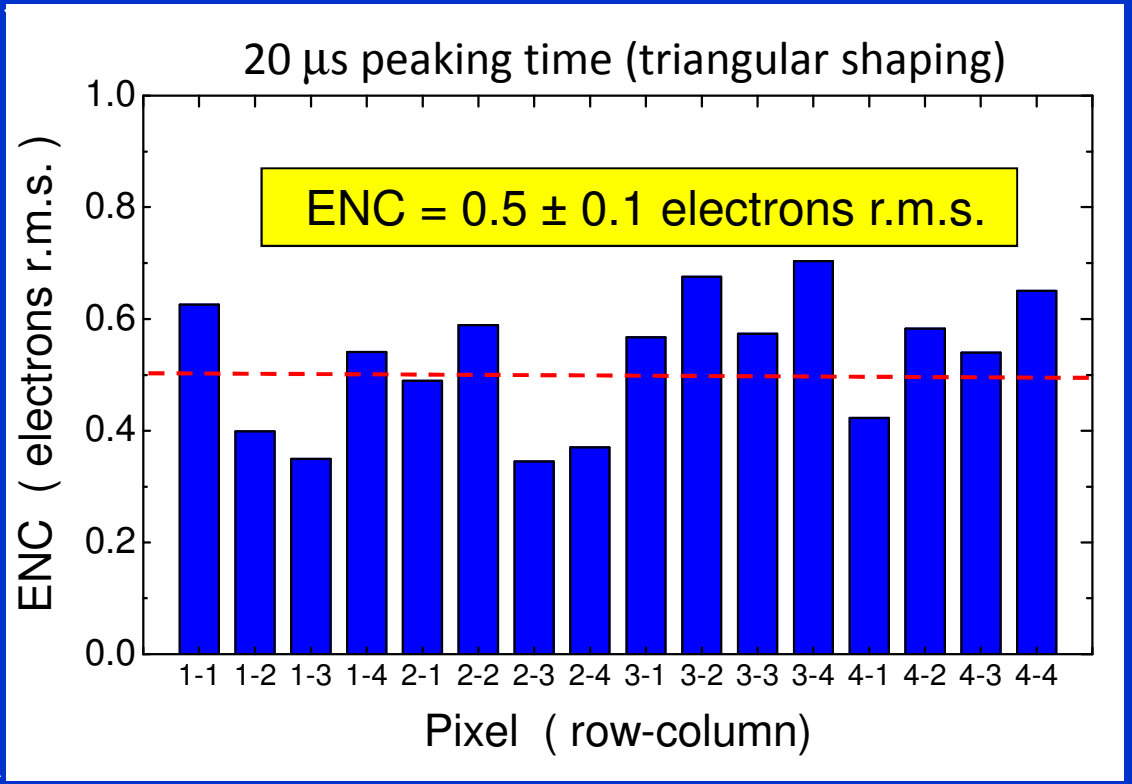


G. Bertuccio et al. IEEE Trans. Nucl. Sci. 53, 2006

The SiC detector's noise

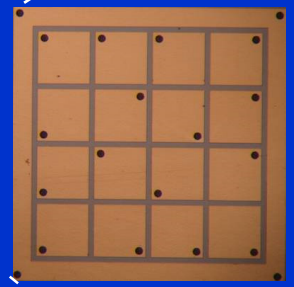
$$ENC(I_{Leak}) \cong 2\sqrt{I_{Leak}\ [pA]}\sqrt{\tau_{\text{peak}}\ \ [\mu s]}\ \ [e^{-}\ r.m.s.]$$

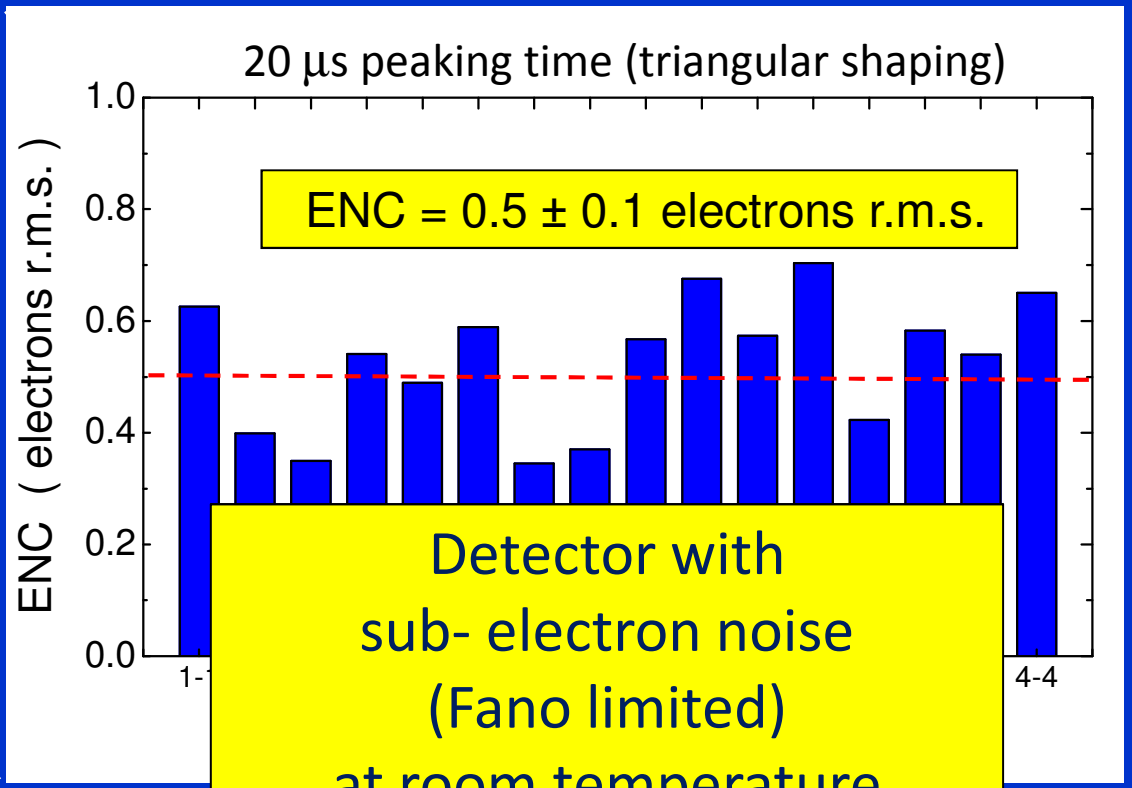




The SiC detector's noise

$$ENC(I_{Leak}) \cong 2\sqrt{I_{Leak}\ [pA]}\sqrt{\tau_{\text{peak}}\ \ [\mu s]}\ \ [e^{-}\ r.m.s.]$$





Detector with
sub- electron noise
(Fano limited)
at room temperature

Ultimate Low Noise Charge Sensitive Amplifier needed!

2007: a breakthrough in CMOS CSA

ELSEVIER

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ScienceDirect

Nuclear Instruments and Methods in Physics Research A 579 (2007) 243–246

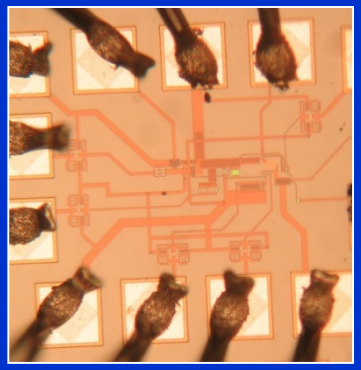
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.com/locate/nima

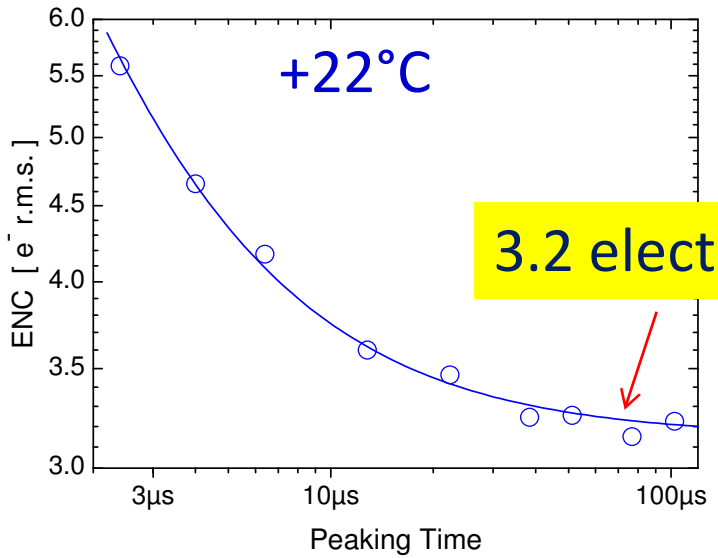
Progress in ultra-low-noise ASICs for radiation detectors

Giuseppe Bertuccio[a,b,*], Stefano Caccia[a,b]

[a]*Politecnico di Milano, Department of Electronics Engineering and Information Science, P.za L. da Vinci 32, 20133 Milano, Italy*
[b]*National Institute of Nuclear Physics, INFN sez., Milano, Italy*



Technology
CMOS 0.35µm (AMS)



3.2 electrons r.m.s.

The ultimate CMOS low noise challenge

Is one electron noise CMOS Charge Amplifier possible ?

from 3 to 1 electron r.m.s.

small numbers, a Big step

The ultimate CMOS low noise challenge

Is one electron noise CMOS Charge Amplifier possible ?

from 3 to 1 electron r.m.s.

small numbers, a Big step

$$ENC_{TOTAL} = \sqrt{ENC_{N1}^2 + ENC_{N2}^2 + ENC_{N3}^2 + ENC_{N4}^2 + ENC_{N5}^2 + ENC_{N6}^2 + ENC_{N7}^2 + ENC_{N8}^2 + ENC_{N9}^2}$$

$$ENC_{TOTAL} = \sqrt{1+1+1+1+1+1+1+1+1} = \sqrt{9} = 3\ electrons\ r.m.s.$$

- 55 %

$$ENC_{TOTAL} = \sqrt{1+1+1+1+\cancel{1+1+1+1+1}} = \sqrt{4} = 2\ electrons\ r.m.s.$$

- 50 %

$$ENC_{TOTAL} = \sqrt{1+1+\cancel{1+1}+\cancel{1+1+1+1+1}} = \sqrt{1} = 1.4\ electrons\ r.m.s.$$

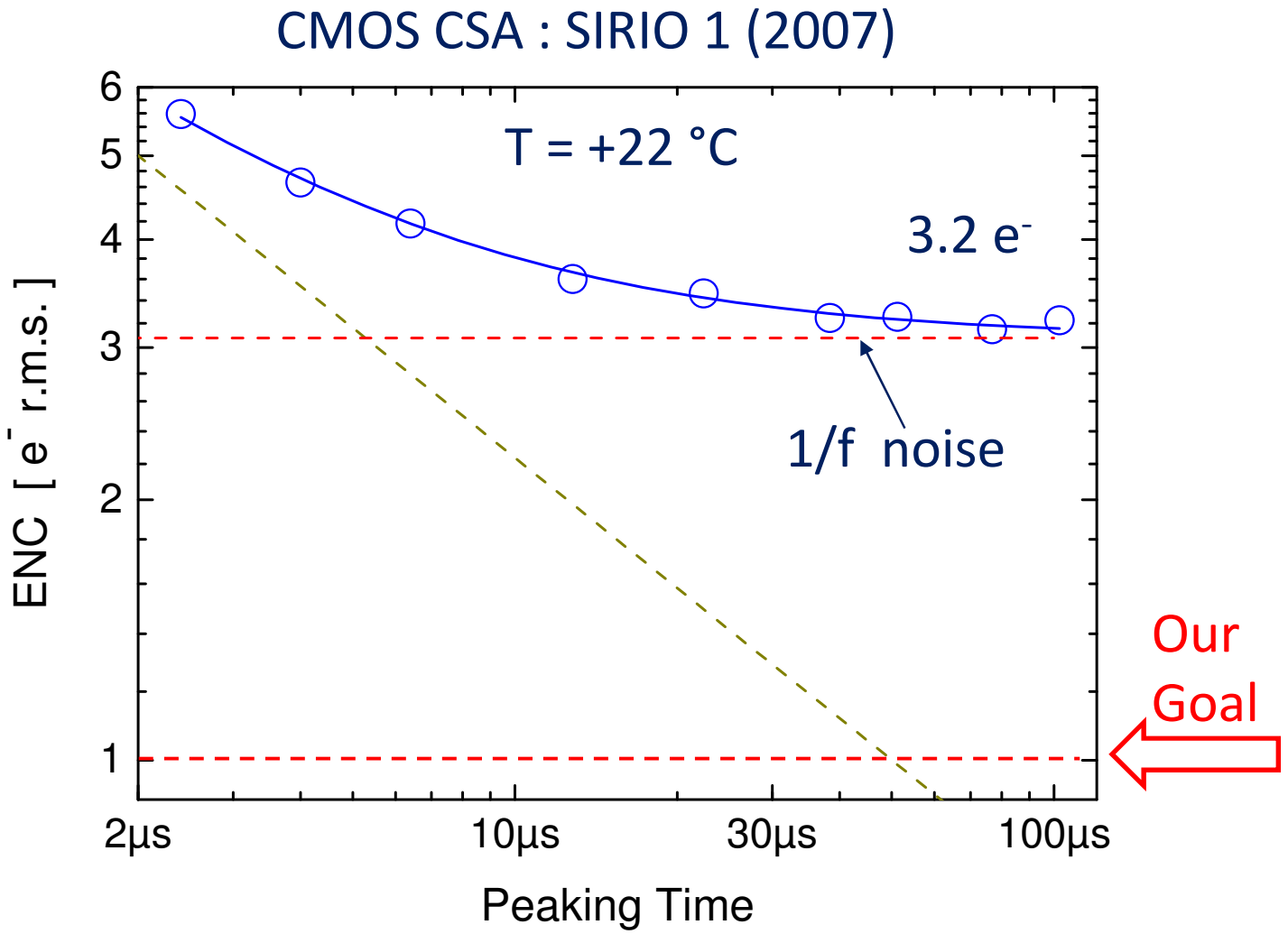
- 50 %

$$ENC_{TOTAL} = \sqrt{1\cancel{+1}+\cancel{1+1}+\cancel{1+1+1+1+1}} = \sqrt{1} = 1\ electrons\ r.m.s.$$

Noise removed

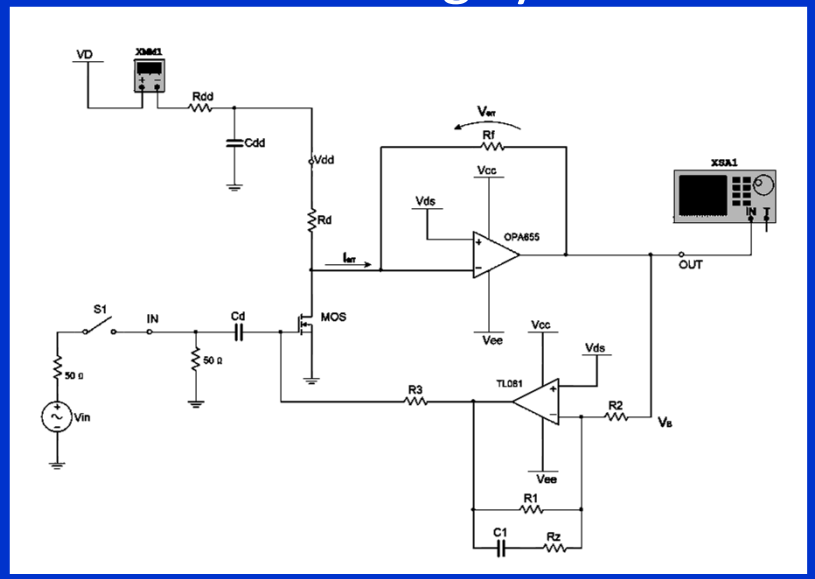
- 90 %

The *1/f* noise limit…

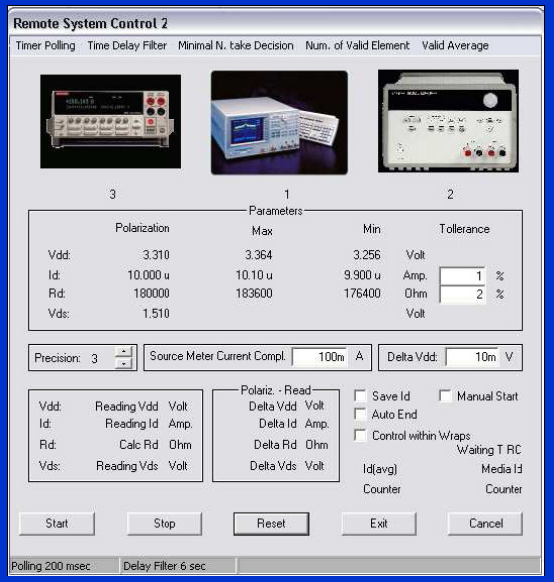


Study of CMOS Low Frequency Noise

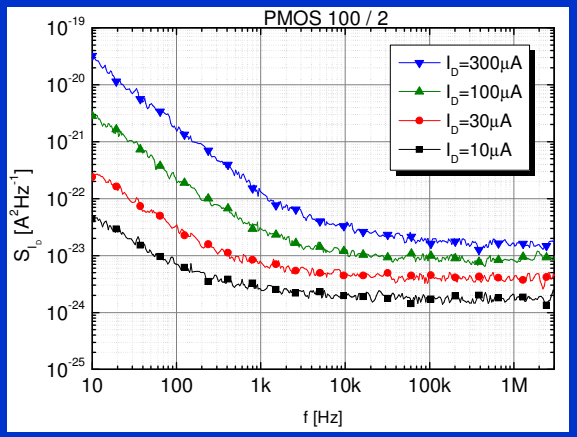
Measuring system

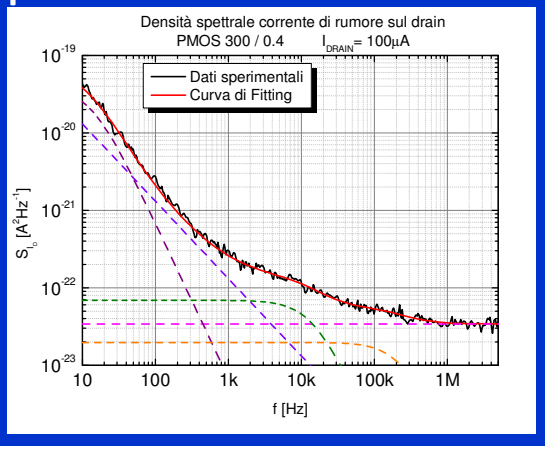


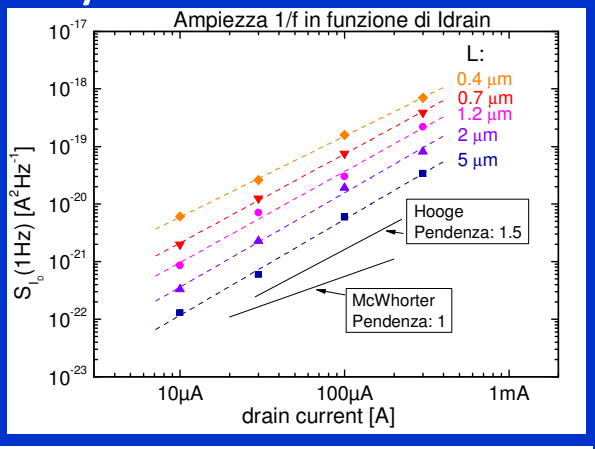
User Interface



Experimental data and analysis







Low Frequency Noise of Transistors

The heritage of Franco Manfredi and of his Research Group: the development of Instrumentation for accurate measurement of the noise spectral density

AIP | Review of Scientific Instruments

Extremely low-noise amplifier for interfacing active devices to instruments for spectral analysis

P. F. Manfredi[1], V. Speziali[1] and F. Svelto[1]

Rev. Sci. Instrum. 65, 3848 (1994); http://dx.doi.org/10.1063/1.1145176

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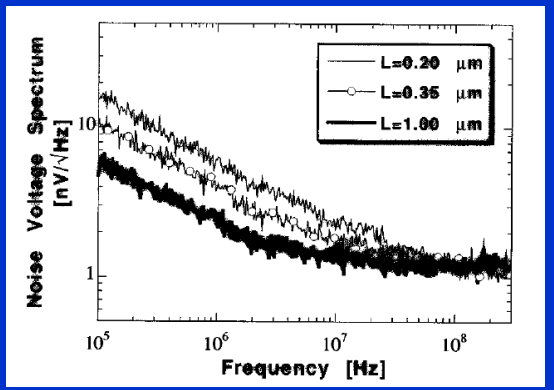
Nuclear Physics B (Proc. Suppl.) 44 (1995) 599–606

NUCLEAR PHYSICS B PROCEEDINGS SUPPLEMENTS

Instrumentation for High Accuracy Noise Characterisation of Front-End Devices in Detector Applications

V. Re and F. Svelto

Dipartimento di Elettronica, Università di Pavia, Via Abbiategrasso 209, 27100 Pavia, Italy, and INFN, Sezione di Milano, Via Celoria 16, 20133 [illegible]



Instrumentation for Noise Measurements on CMOS Transistors for Fast Detector Preamplifiers

M. Manghisoni, L. Ratti, V. Re, and V. Speziali

CMOS CSA: what possible ENC?

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 56, NO. 3, JUNE 2009 1511

Noise Minimization of MOSFET Input Charge Amplifiers Based on $\Delta\mu$ and ΔN $1/f$ Models

Giuseppe Bertuccio and Stefano Caccia

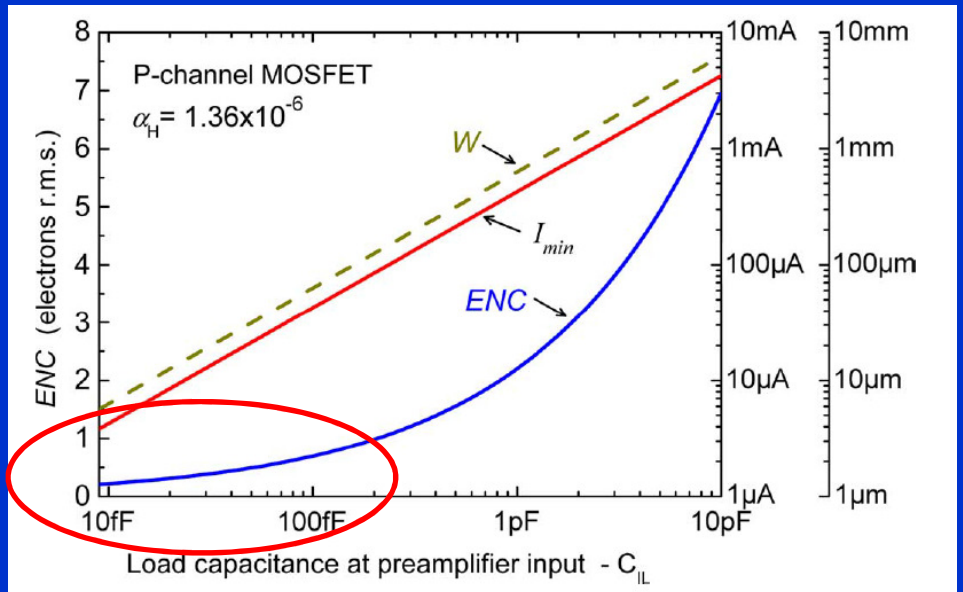


Fig. 8. $\Delta\mu$-type MOSFETs: minimum $\mathrm{ENC}_{1/f}$ calculated as a function of the load capacitance C_{IL} at the preamplifier input (13a). Also, the MOSFETs bias current $I_{\min}$ (13b) and its optimum gate width obtained by setting $C_G = C_{IL}$ are shown . (33). The parameters for the evaluation are shown in Table I.

ENC < 1 e- r.m.s.

Predicted for C_{input} < 100 fF

(Pixel & Drift Detectors)

Prediction based on experimental data

IEEE Trans. Nucl. Science 56, 2009

1/f & white noise optimization

$$ENC^2 = ENC_{ws}^2 + ENC_{1/f}^2 + ENC_{wp}^2$$

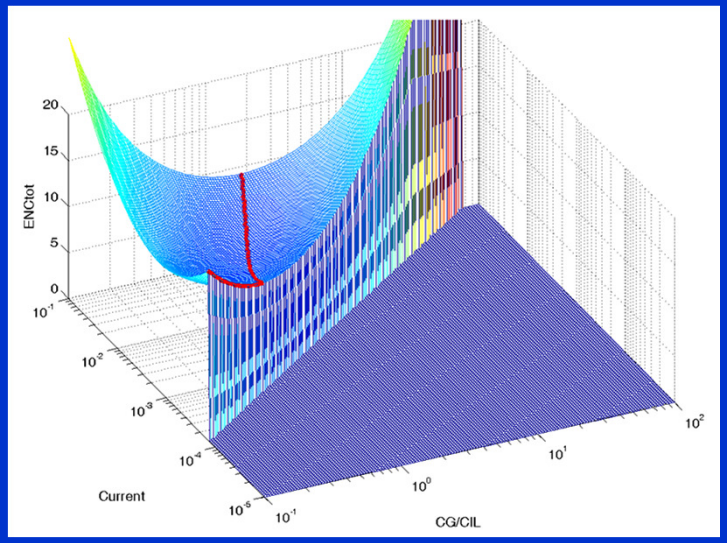
for p-MOSFET input (Δμ *1/f* noise model)

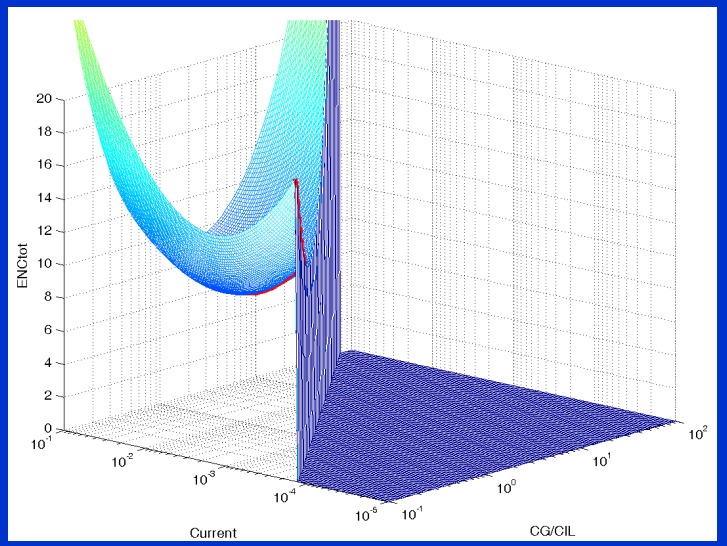
$$ENC_{tot(\Delta\mu)}^2 = k_{ws}\frac{(C_{IL}+C_G)^2}{\sqrt{C_G}}\frac{1}{\sqrt{I}}\frac{1}{\tau} + k_{\Delta\mu}\frac{(C_{IL}+C_G)^2}{\sqrt{C_G^3}}\sqrt{I} + k_{wp}\tau$$

$$k_{ws} = A_1\left(\frac{\beta\, 4kT\, L}{q^2\sqrt{2\mu/n}}\right)$$

$$k_{\Delta\mu} = 2\pi A_2\left(\frac{n\alpha_H L}{q\sqrt{2\mu}}\right)$$

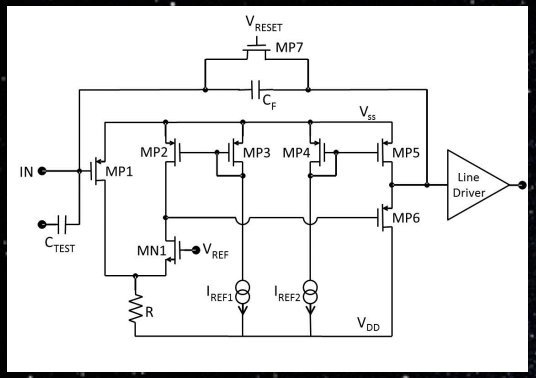
$$k_{wp} = \frac{A_3}{q^2}S_I$$

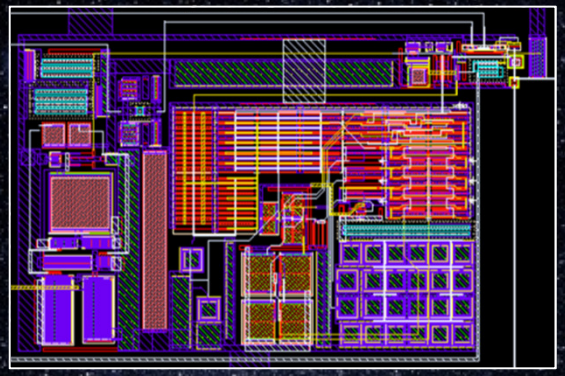




IEEE Trans. on Nuclear Science, Vol. 56, 2009, pp. 1511

SIRIO Charge Sensitive Amplifier





Technology: AMS CMOS 0.35 µm

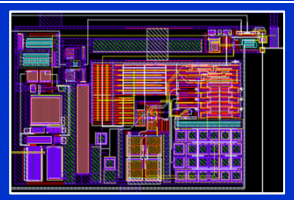
4 metals / 2 Poly / High Resistive Poly

V_{DD} = 3.3V

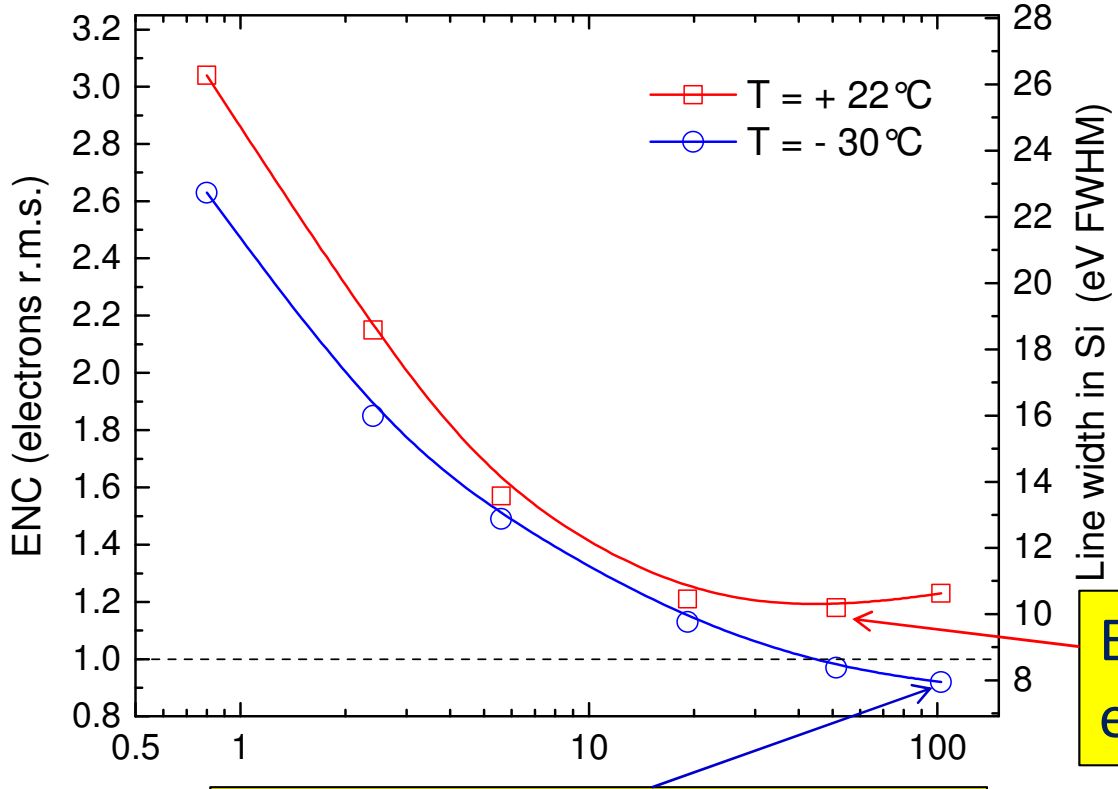
Size: 530 µm x 450 µm

- Optimized for Silicon Drift Detectors ($C_{DET} \leq 0.1$pF)
- Designed for X-ray Spectroscopy: from 50 eV to 50 keV

SIRIO: measured ENC



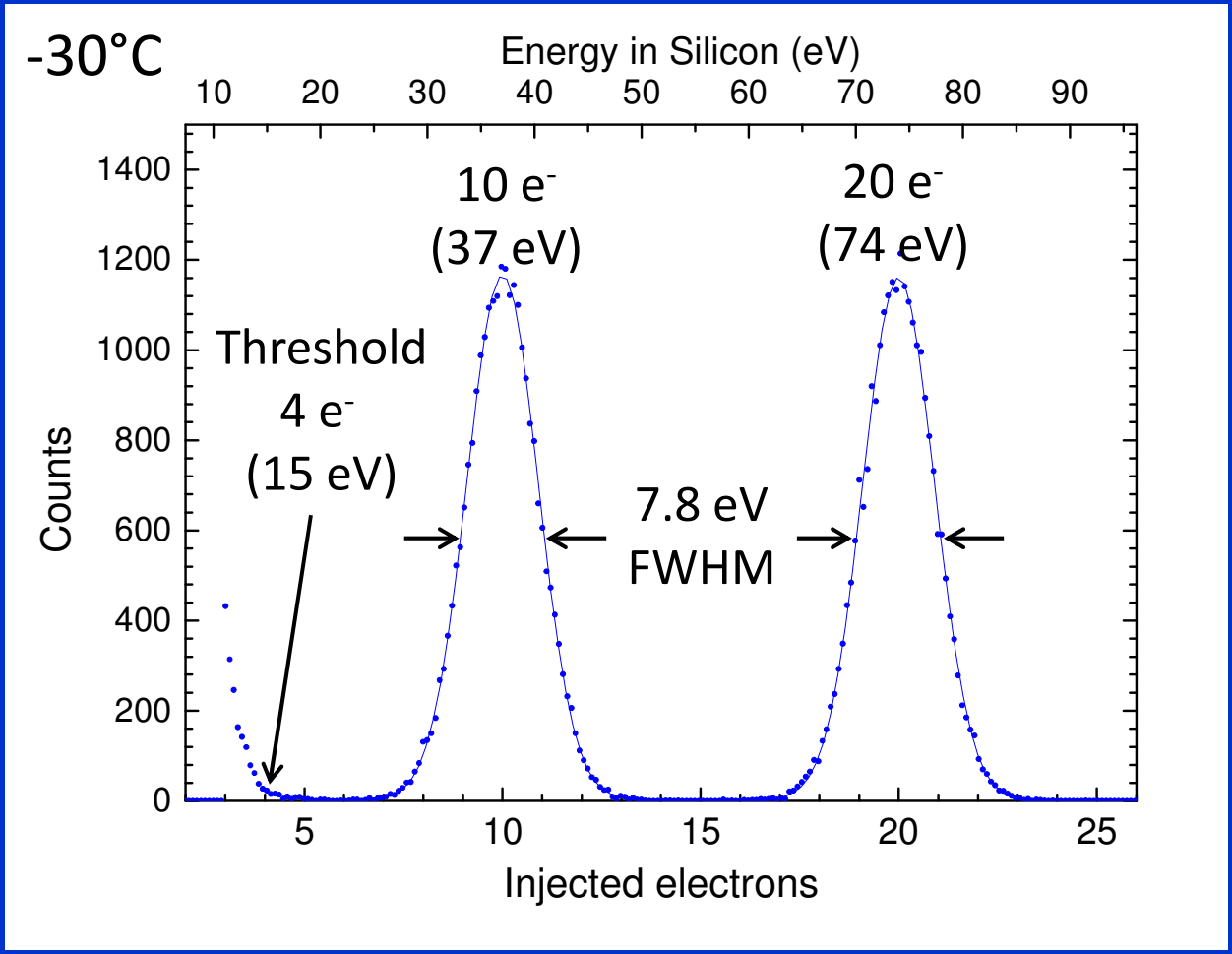
G. Bertuccio et al., 2014 IEEE Nuclear Science Symposium and Medical Imaging Conference



ENC_{min}= 1.18 electron r.m.s.

ENC_{min}= 0.92 electron r.m.s.

Intrinsic noise (no detector) @ -30°C



ENC= 0.89 e⁻ r.m.s.

Franco Manfredi and Emilio Gatti

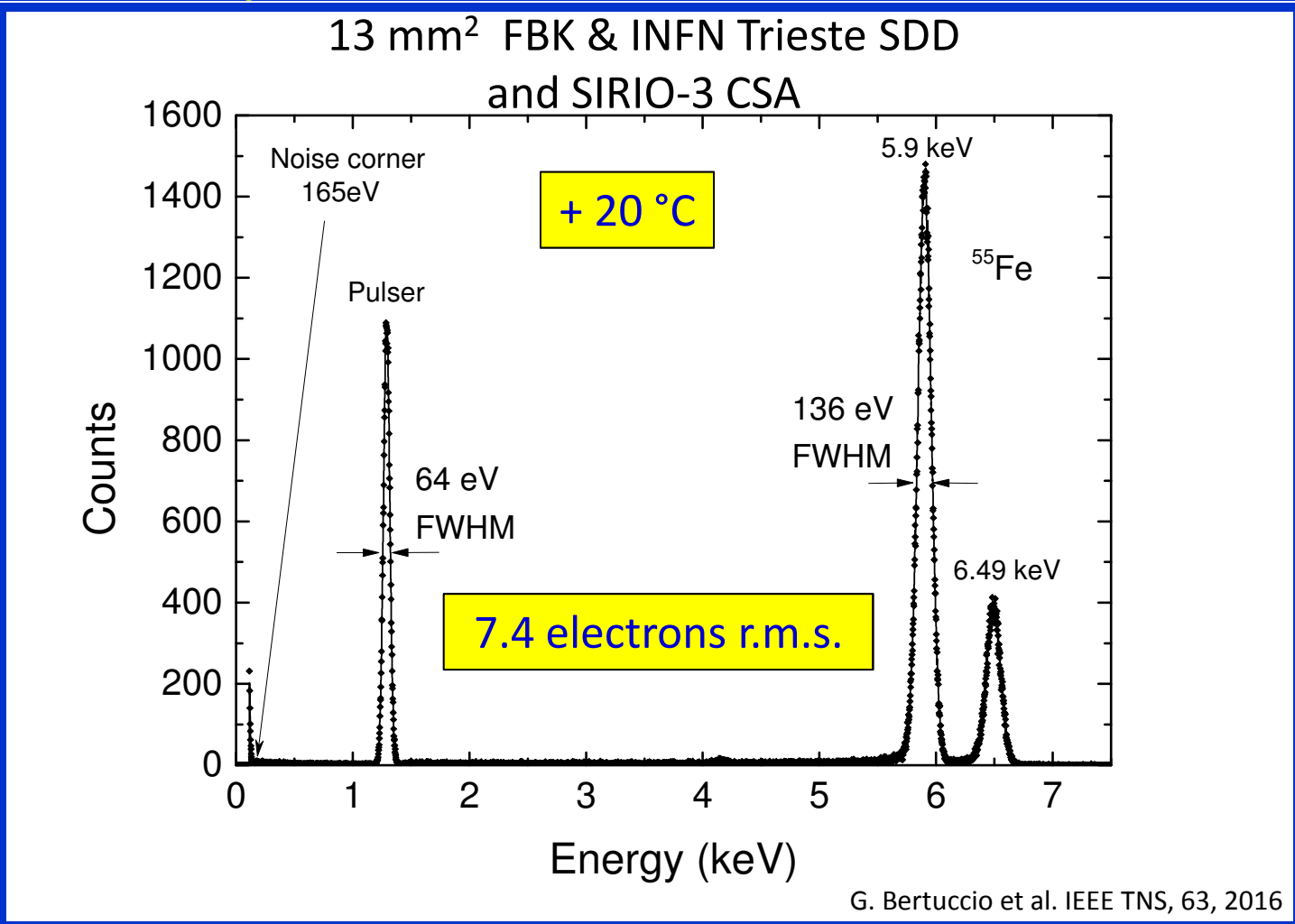
On 8 December 2009, Emilio Gatti and I celebrated the 50 years of scientific cooperation and a very nice friendship.

Politecnico di Milano
4th October 2012

Scientific life dedicated to the design of Low Noise Front-End Electronics for Radiation Detectors

Inventor of the Charge Sensitive Amplifier and of the Silicon Drift Detector

Today 2016: SIRIO and SDD



G. Bertuccio et al. IEEE TNS, 63, 2016

Highest Energy Resolution reached at Room Temperature with a semiconductor detector of large area

Acknowledgements

Ahangarianabhari M., Bastia P., Bellutti P., Caccia S., Cappelluti I.,

Grassi M., Graziani C., Macera D., Malcovati P., Martin D.,

Masci S., Picciotto A., Piemonte C., Rachevsky A., Ratti N.,

Rossi T., Pozzi A., Sampietro M., Shi Y.,

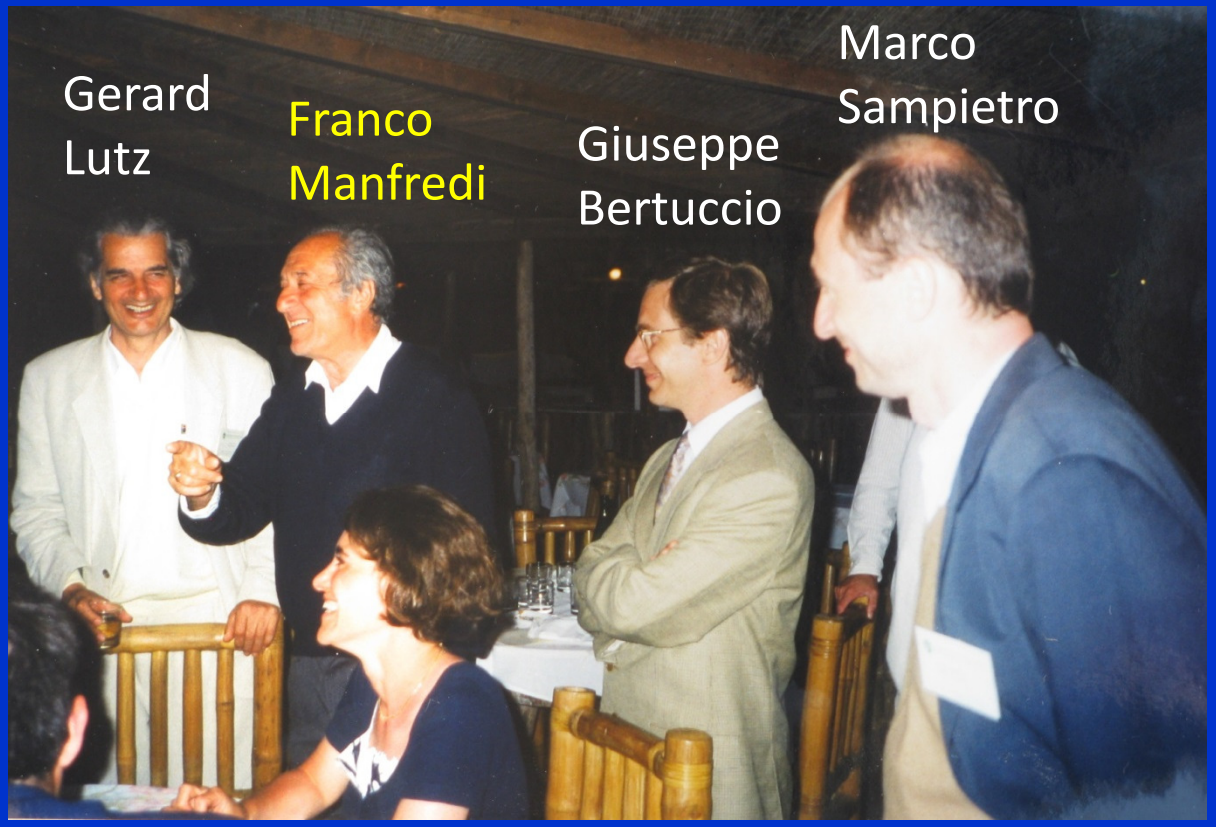
Vacchi A., Zampa G., Zampa N., Zorzi N.

Conclusion

Two examples of results of the research in last years has been shown here…

the cultural heritage of Franco Manfredi is within these results.

At the 7th Pisa Meeting on Advanced Detectors
25 - 31 May 1997, Isola d'Elba, Italy



But the main Heritage which Franco Manfredi trasmitted to all his collaborators is the passion for the design of low-noise front-end electronics for radiation detectors