Digital Pulse Shape methods with Silicon Detectors

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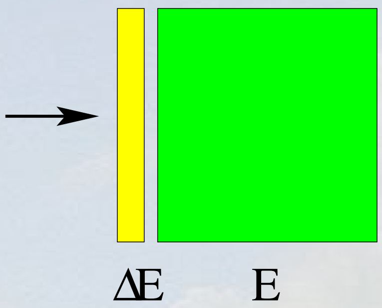
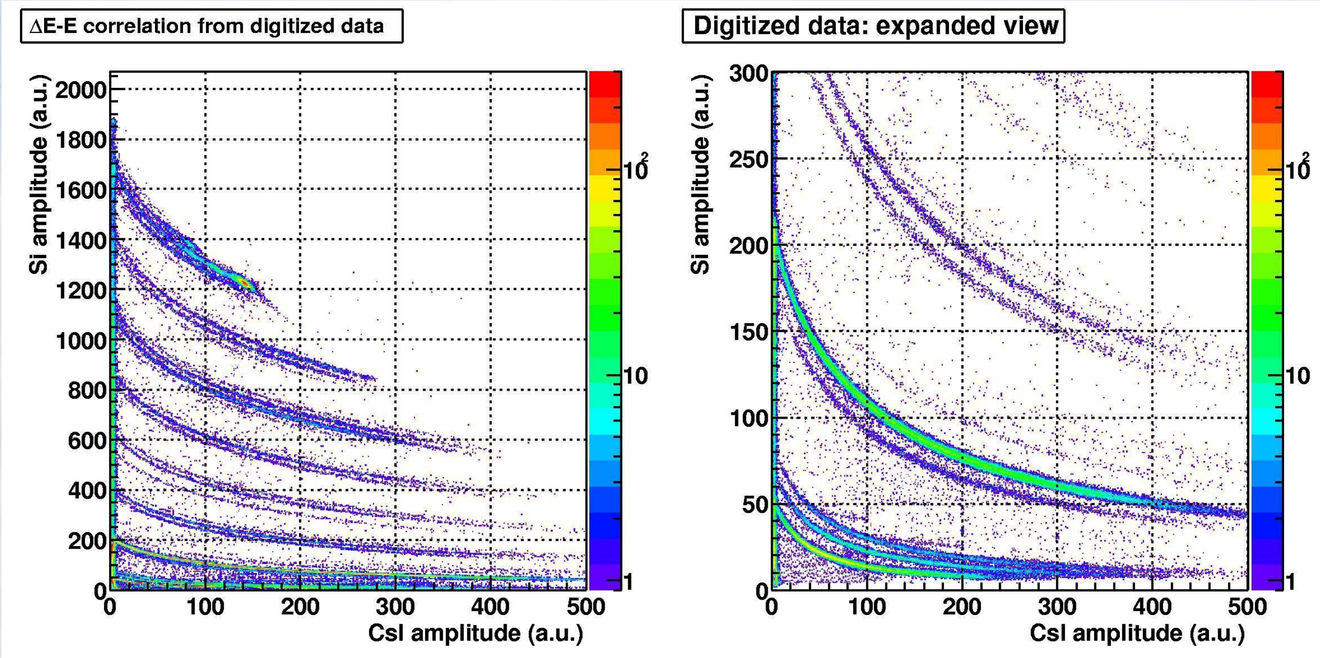
for the NUCL-EX and FAZIA collaborations

Outline

- Why Pulse Shape in Silicon – comparison with ΔE–E
- Experimental results with analog methods
- Digital signal processing:
  - Energy measurements
  - Timing and Time of Flight measurements
  - Pulse Shape Analysis
- Key factors affecting PSA
- Current research topics within FAZIA
- Conclusions

The ΔE–E method is a very common particle identification solution:





L.Bardelli *et al.*, Nucl.Phys. **A**746 (2004) 272.

Problem: high thresholds ↔ punch through ΔE

Some estimates about thresholds and isotopic identification properties for a ΔE–E detector, taking into account energy straggling and homogeneity ($\pm 0.5\mu$m):

300 μm detector:

Ion	Threshold	Near punch through:	
		ΔE(Z,A+1)-ΔE(Z,A)	δE(stragg+unif)
^{1}H	6.2 AMeV		
^{4}He	6.2 AMeV		
^{6}Li	7.8 AMeV		
^{8}Be	9.1 AMeV		
^{10}B	10.3 AMeV		
^{12}C	11.4 AMeV		

Using Hubert eloss tables and Wang/Yang straggling parametrization

Some estimates about thresholds and isotopic identification properties for a ΔE–E detector, taking into account energy straggling and homogeneity ($\pm 0.5\mu$m):

300 μm detector:

Ion	Threshold	Near punch through: ΔE(Z,A+1)-ΔE(Z,A)	Near punch through: δE(stragg+unif)
^{1}H	6.2 AMeV	2.0 MeV	0.5 MeV
^{4}He	6.2 AMeV	2.4 MeV	0.9 MeV
^{6}Li	7.8 AMeV	3.0 MeV	1.4 MeV
^{8}Be	9.1 AMeV	3.6 MeV	1.9 MeV
^{10}B	10.3 AMeV	4.0 MeV	2.4 MeV
^{12}C	11.4 AMeV	4.5 MeV	3.1 MeV

Using Hubert eloss tables and Wang/Yang straggling parametrization

Some estimates about thresholds and isotopic identification properties for a ΔE–E detector, taking into account energy straggling and homogeneity ($\pm 0.5\mu$m):

100 μm detector:

Ion	Threshold	Near punch trought: ΔE(Z,A+1)-ΔE(Z,A)	δE(stragg+unif)
^{1}H	3.2 AMeV	1.0 MeV	0.3 MeV
^{4}He	3.2 AMeV	1.1 MeV	0.5 MeV
^{6}Li	4.0 AMeV	1.4 MeV	0.8 MeV
^{8}Be	4.7 AMeV	1.7 MeV	1.0 MeV
^{10}B	5.2 AMeV	1.8 MeV	1.4 MeV
^{12}C	5.8 AMeV	1.8 MeV	1.7 MeV

Some estimates about thresholds and isotopic identification properties for a ΔE–E detector, taking into account energy straggling and homogeneity ($\pm 0.5\mu$m):

50 μm detector:

Ion	Threshold	Near punch trought:	
		ΔE(Z,A+1)-ΔE(Z,A)	δE(stragg+unif)
^{1}H	2.1 AMeV	0.6 MeV	0.2 MeV
^{4}He	2.1 AMeV	0.5 MeV	0.3 MeV
^{6}Li	2.6 AMeV	0.8 MeV	0.6 MeV
^{8}Be	3.0 AMeV	0.9 MeV	0.7 MeV
^{10}B	3.4 AMeV	1.0 MeV	0.9 MeV
^{12}C	3.7 AMeV	1.1 MeV	1.2 MeV

It is not possible to lower the identification thresholds by simply using thinner ΔE detectors, due to various experimental effects (mainly energy straggling and detector inhomogeneities).

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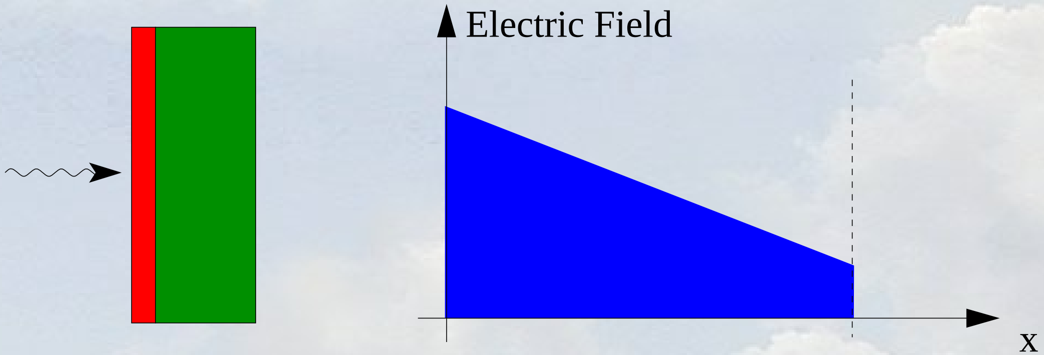
A more effective method: Pulse Shape in Silicon

PSA properties are due to two main effects:

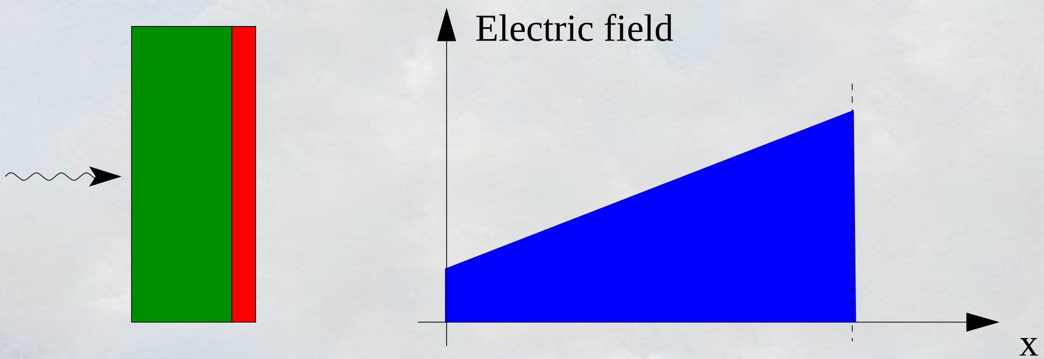
Electric field particles that explore high-electric-field regions will have shorter collection times

Plasma effects signals from high ionization-density tracks (heavy ions with small range) have a longer collection time (due to a "space-charge" effect)

Standard configuration



Reverse configuration



reverse mount Silicon detector

Increased **Pulse Shape** capabilities due to a combination of **charge collection** and **plasma** effects.

Some groups (ChimeraPS) are also investigating PSA in front mount Si

Ions with different ranges in silicon will explore different regions of the detector, i.e. the charge collection time will vary.

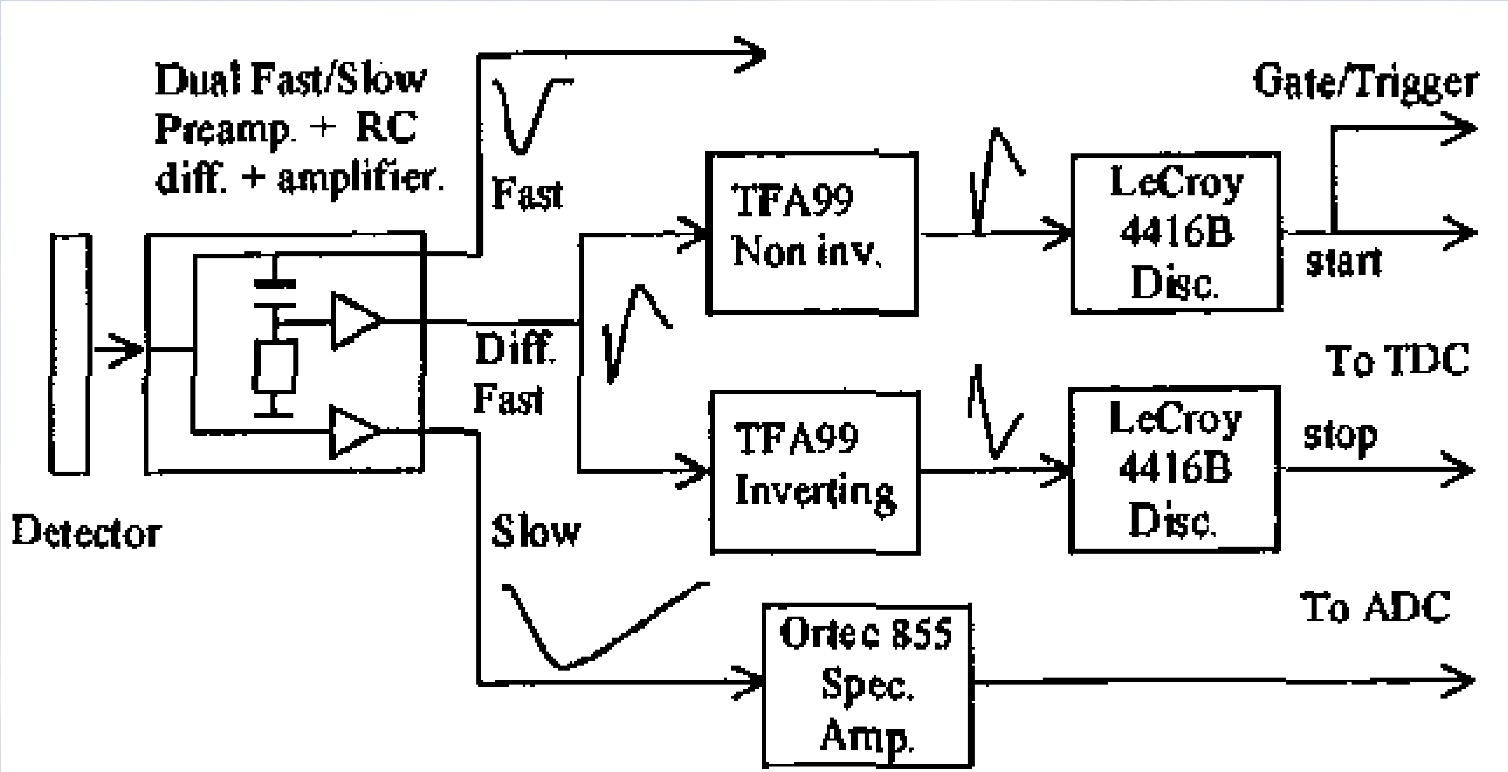
For reverse mount silicon:

Long range $\rightarrow$ Short collection time
Short Range $\rightarrow$ Long collection time

Idea: look an Energy vs "RiseTime" plot.

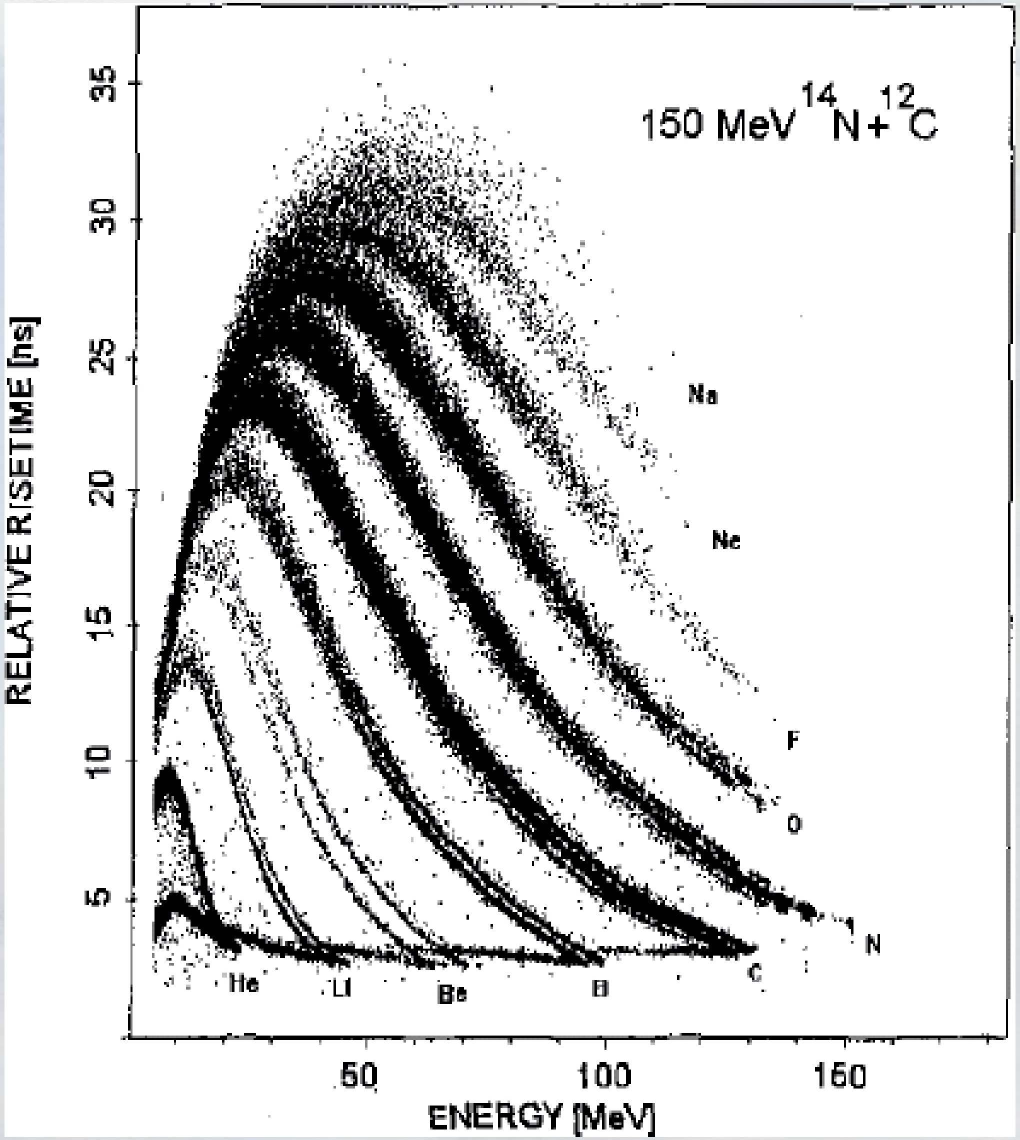
Some results with analog methods:

Example of an analog chain employing energy and risetime measurements:



M.Mutterer *et al.*, IEEE Trans. Nucl. Science, vol.47, no.3, June 2000

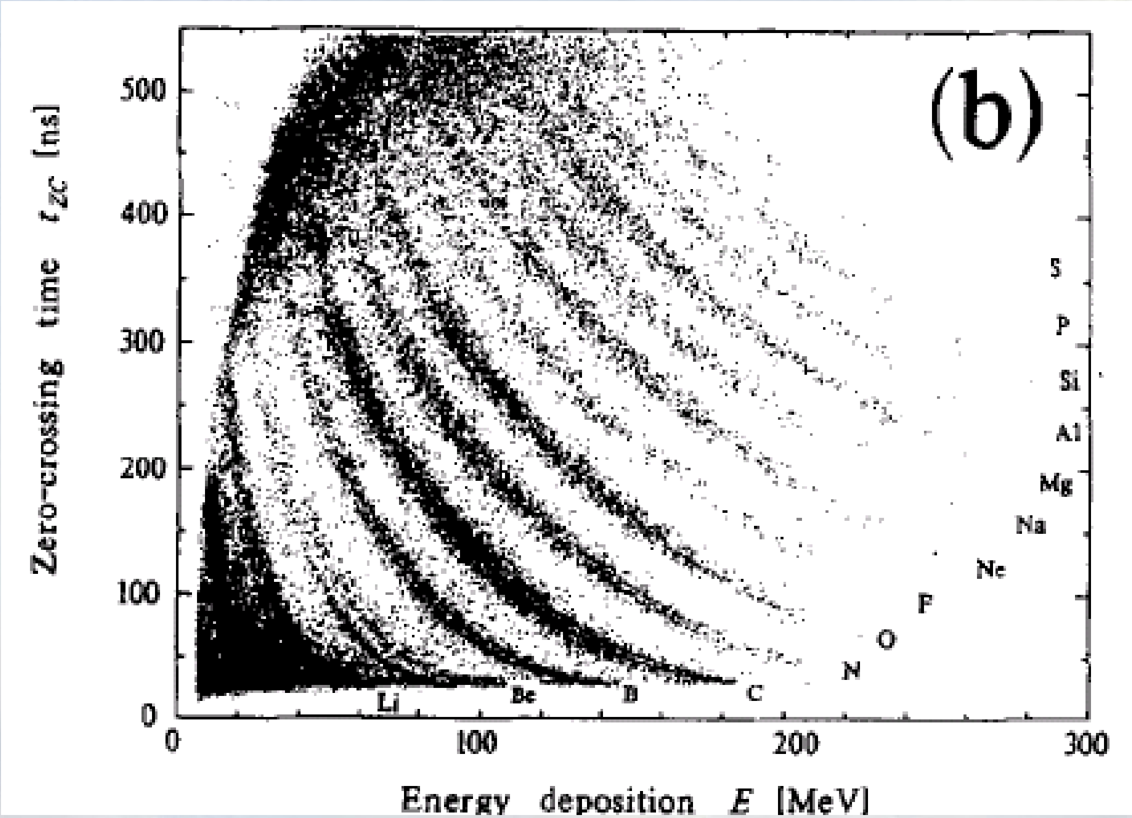
PSA with analog methods (2)



250 μm NTD detector
100 mm^2
Depletion: 45 V
Bias: 140 V

M.Mutterer *et al.*, IEEE Trans. Nucl. Science, vol.47, no.3, June 2000

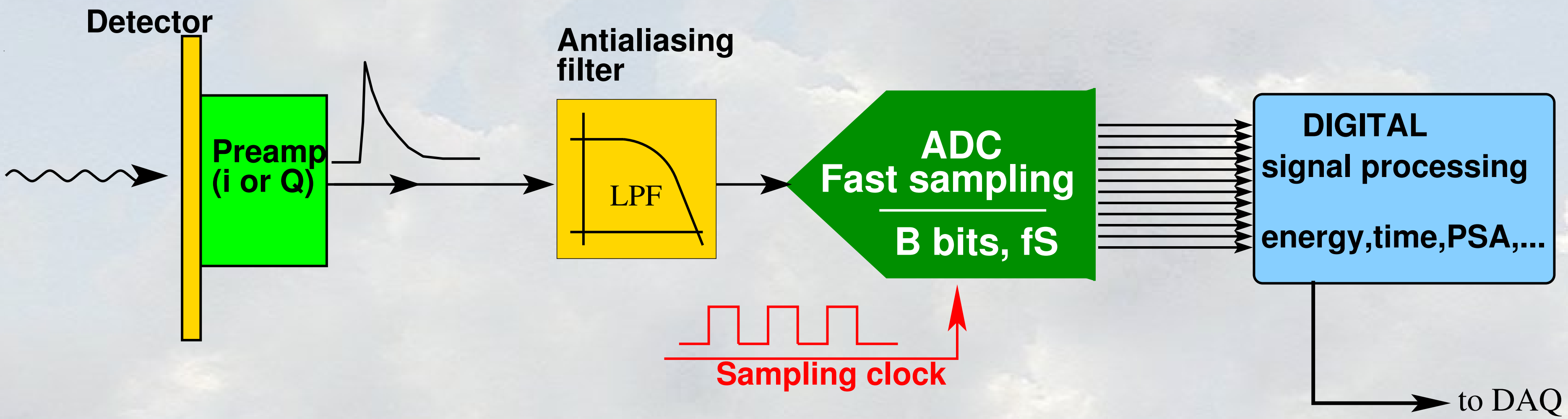
PSA with analog methods (3)



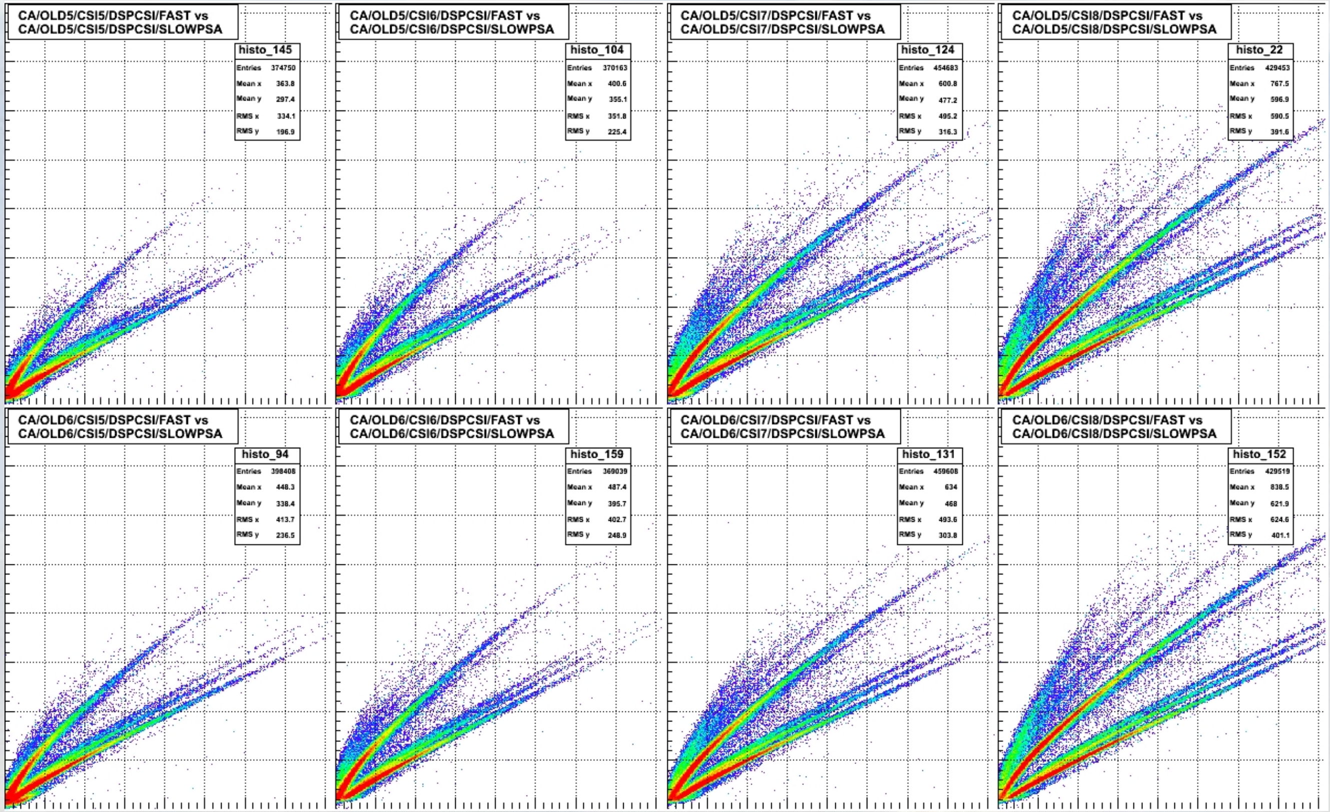
500 μm detector
750 mm^2
Depletion: 62 V
Bias: 80 V

G.Pausch *et al.*, Nucl. Instr. and Meth. **A365** (1995) 176

Typical configuration employing digital sampling and processing:



Example of a digital online analysis



Fast-Slow correlations in CsI, GARFIELD experiment @ LNL
Custom digitizer 12 bit–125 MS/s, about 180 channels installed and tested, ∼200 in construction

G.Pasquali *et al.*, NIMA 570 (2007) 126

What do we need to perform Nuclear Physics experiments with such digitizers?

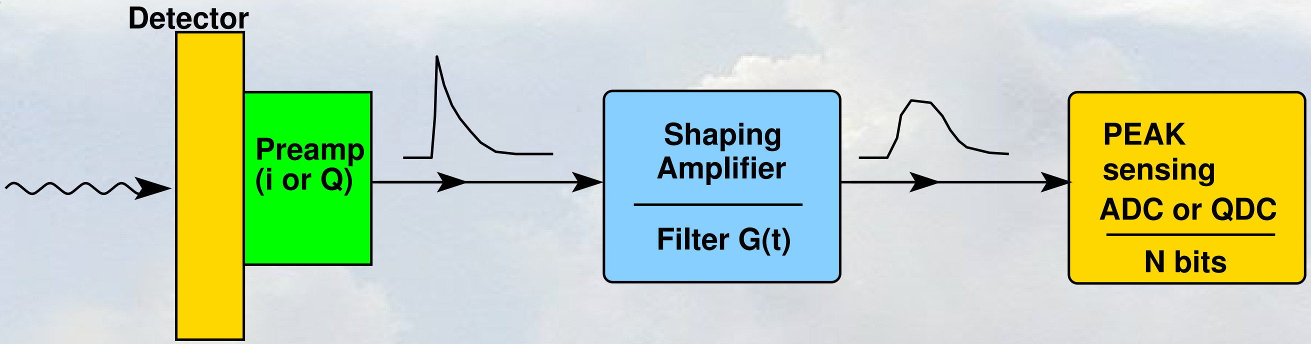
A wide class of detectors can be handled with:

- Signal Amplitude measurement ($\Longrightarrow$ energy)
- Timing measurement ($\Longrightarrow$ CFD, rise time)
- Inter-channel time synchronization ($\Longrightarrow$ ToF)
- Pulse Shape (often a combination of Amplitude and Timing)

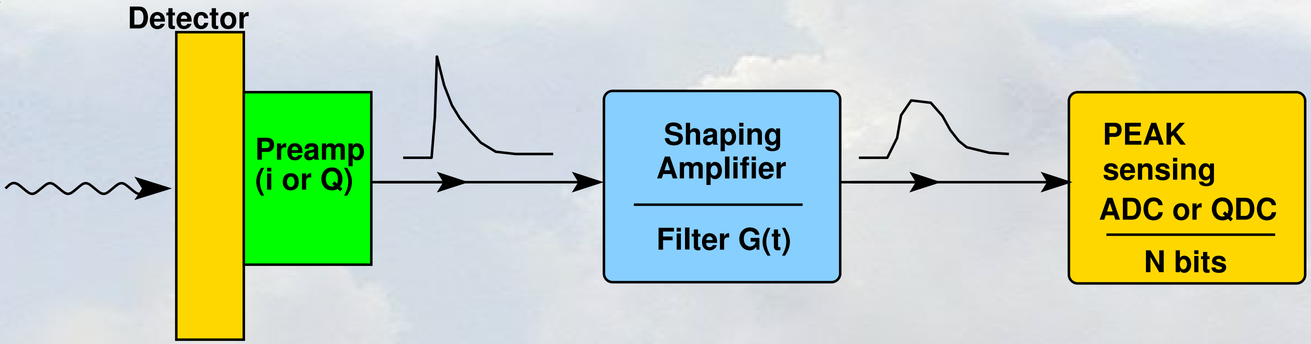
Let's see some examples...

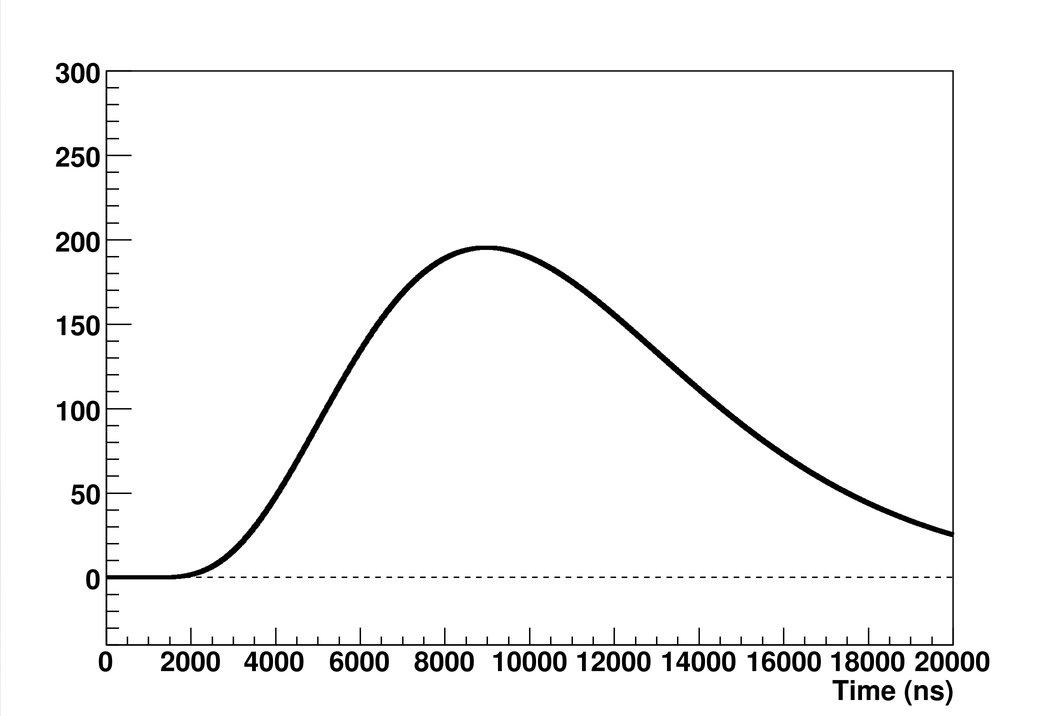
energy

Energy measurements (analog world)



Energy measurements (analog world)





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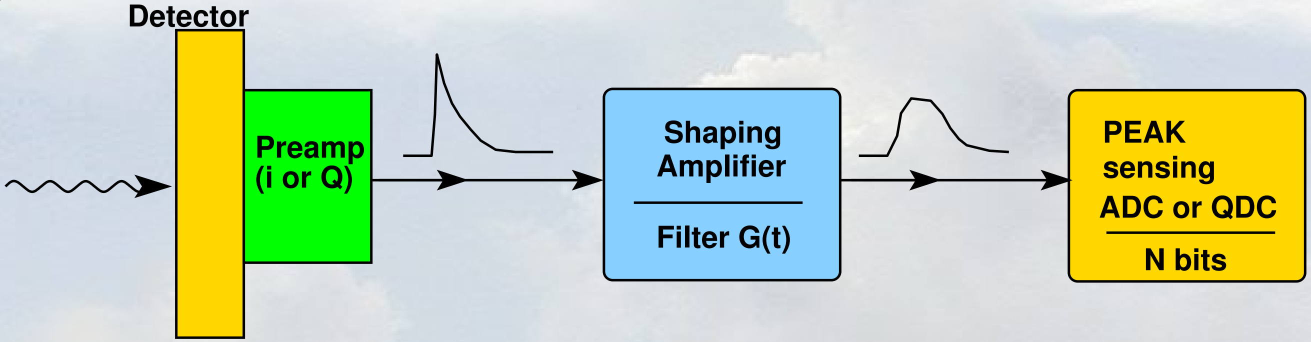

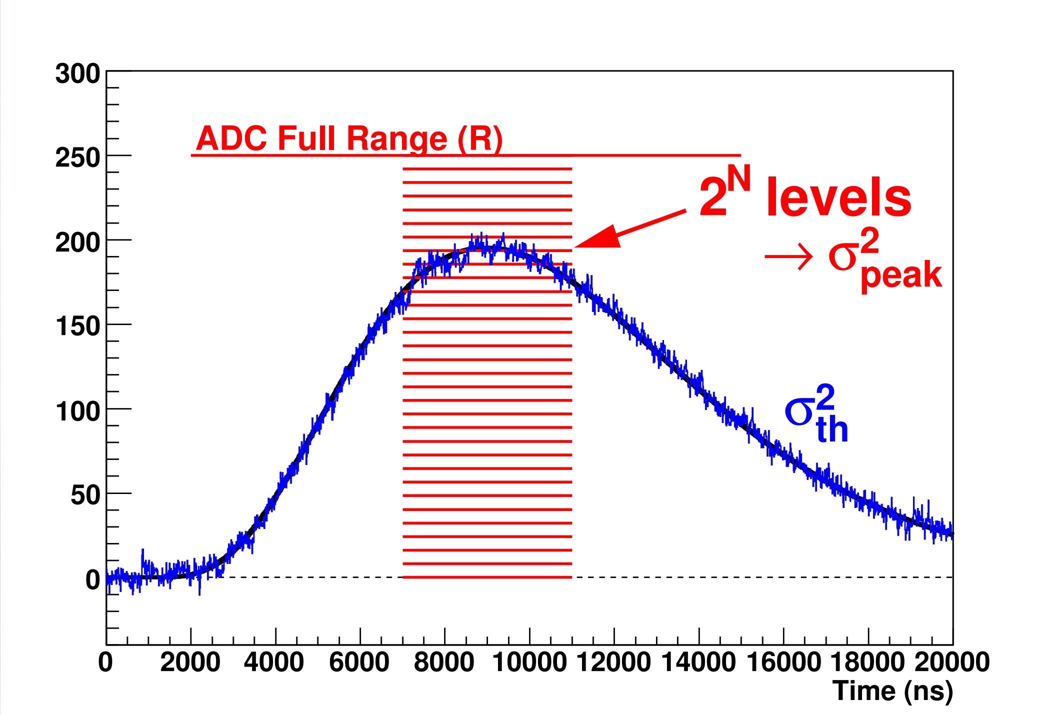

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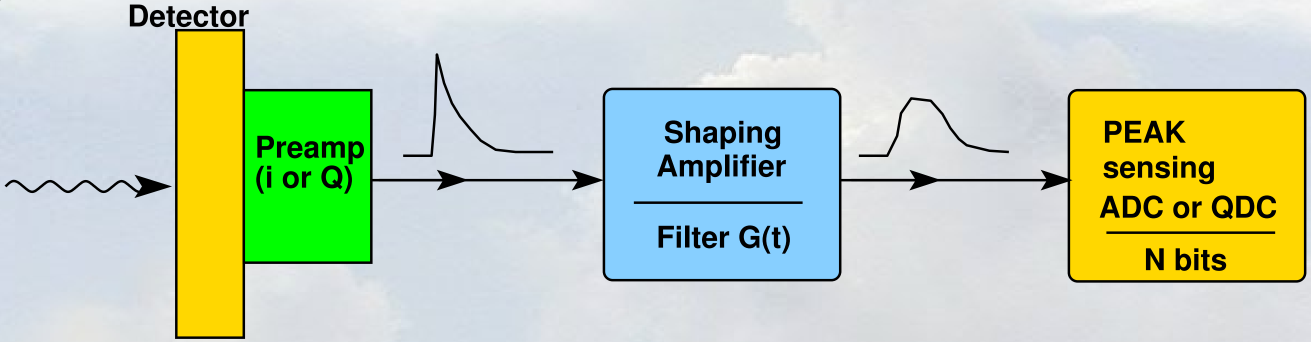
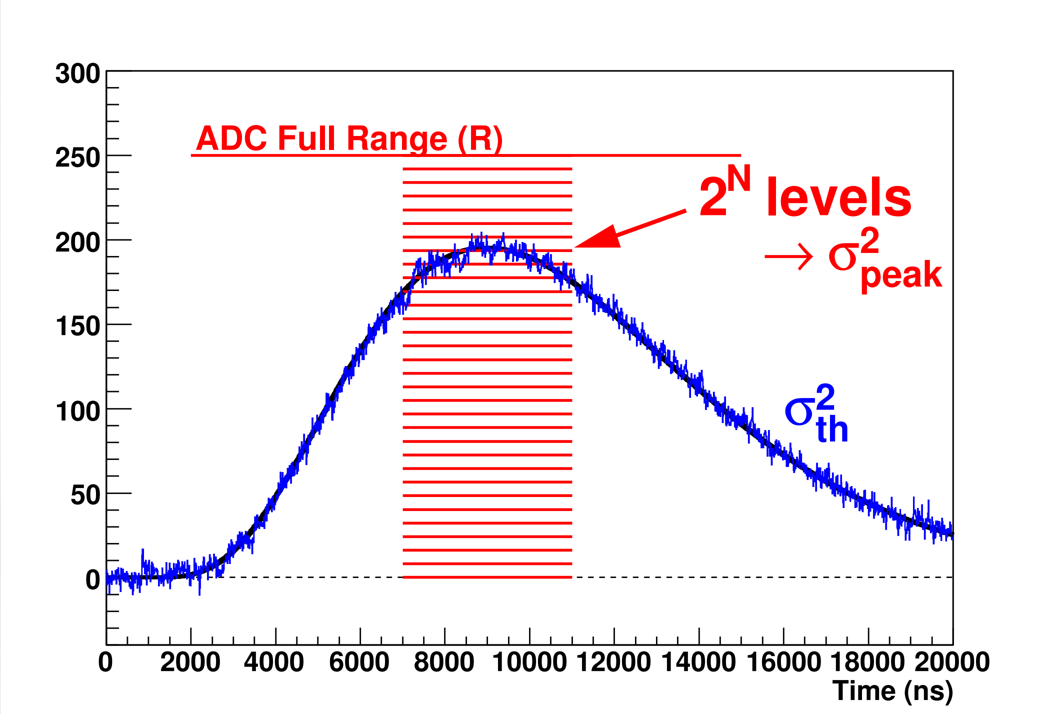
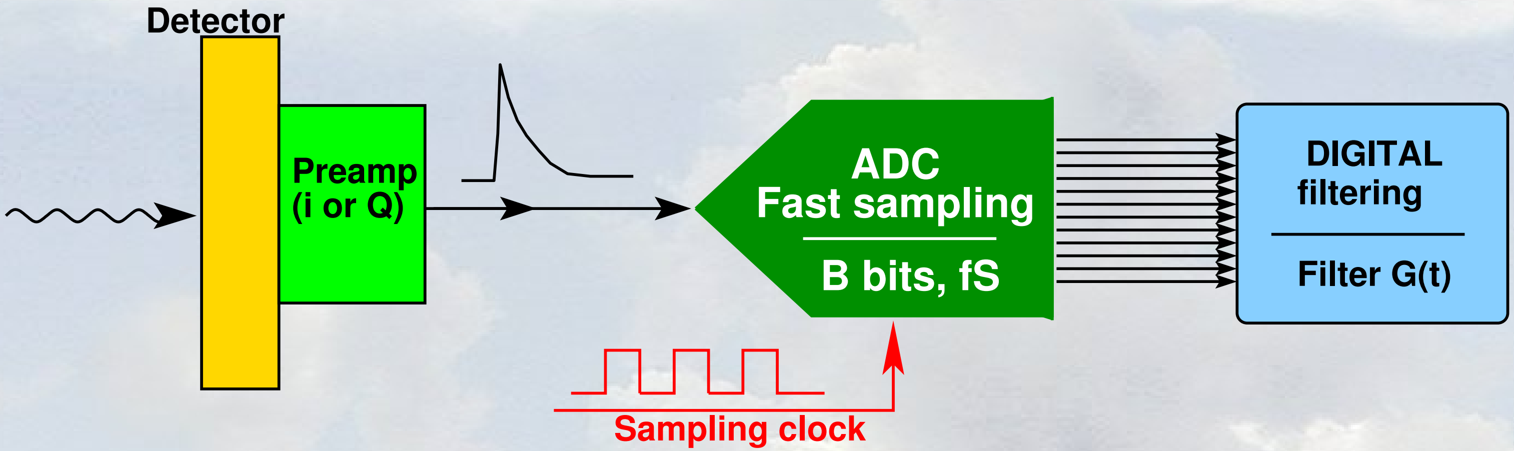




$$\sigma^2_{exp} = \sigma^2_{th} + \sigma^2_{peak}$$

PEAK-sensing contribution to the resolution:

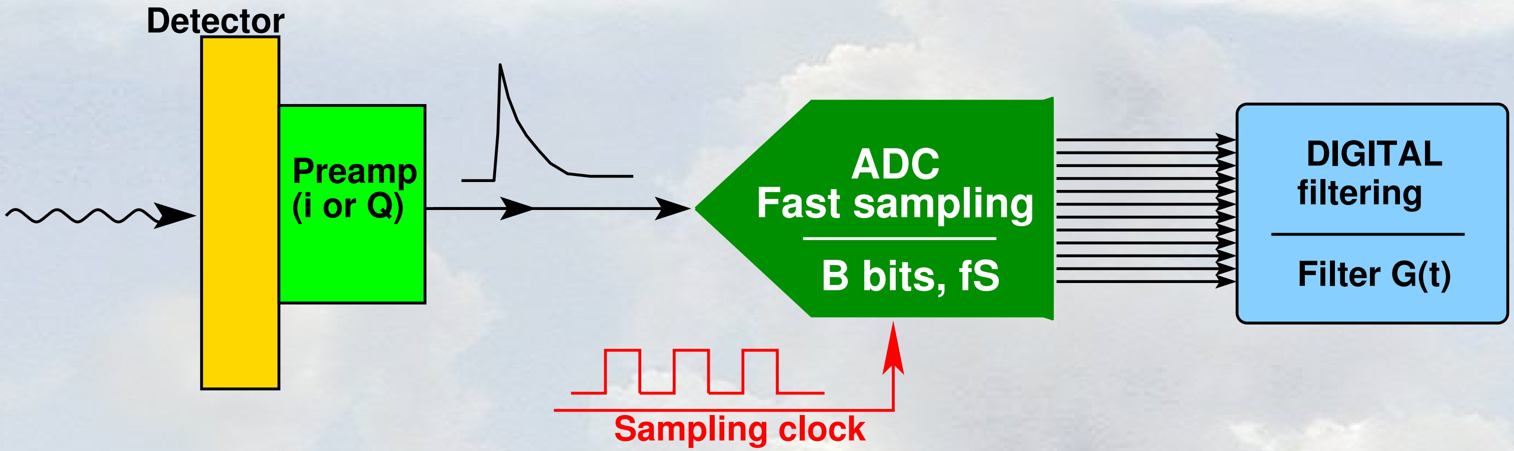
$$\frac{\sigma^2_{exp}}{\sigma^2_{th}} = 1 + \frac{9}{12} \cdot \left(\frac{R}{3\sigma_{th}}\right)^2 \frac{1}{4^N}$$

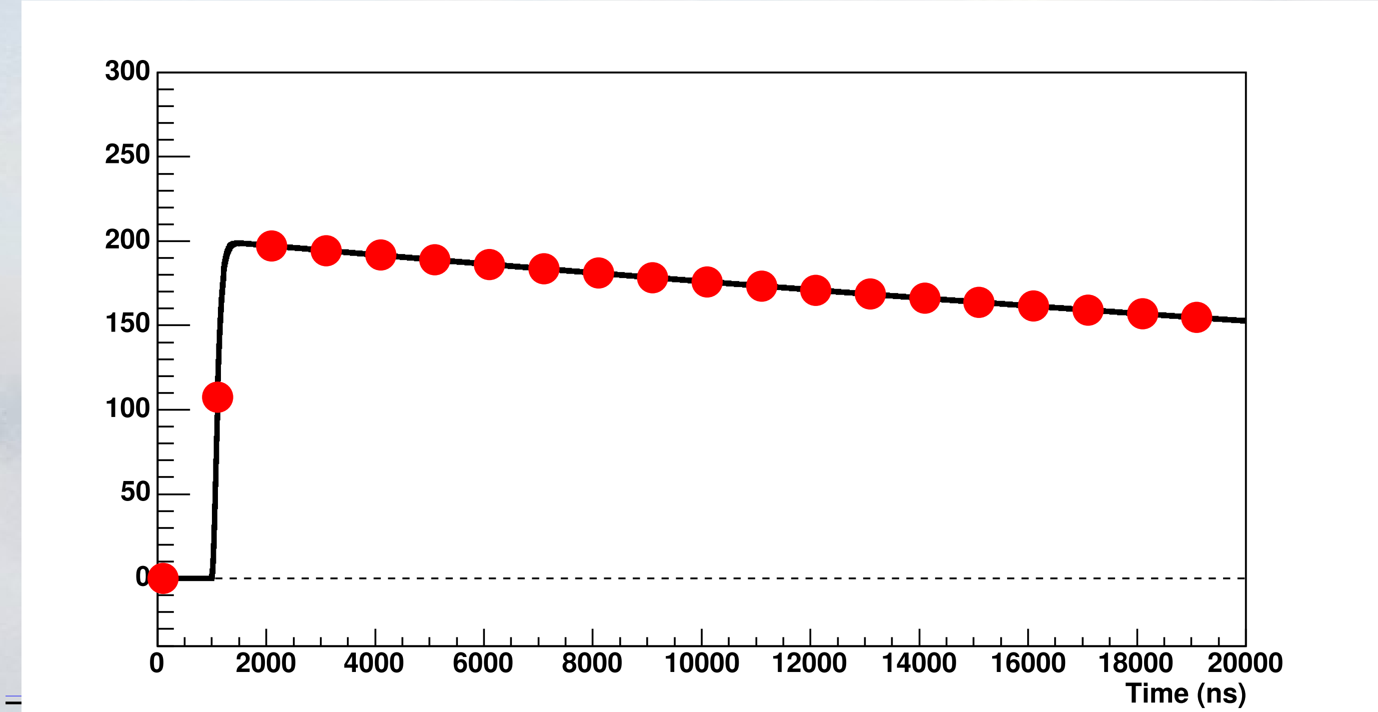


Which resolution with an
B-bits, f_S-MSamples/s fast AD converter
?

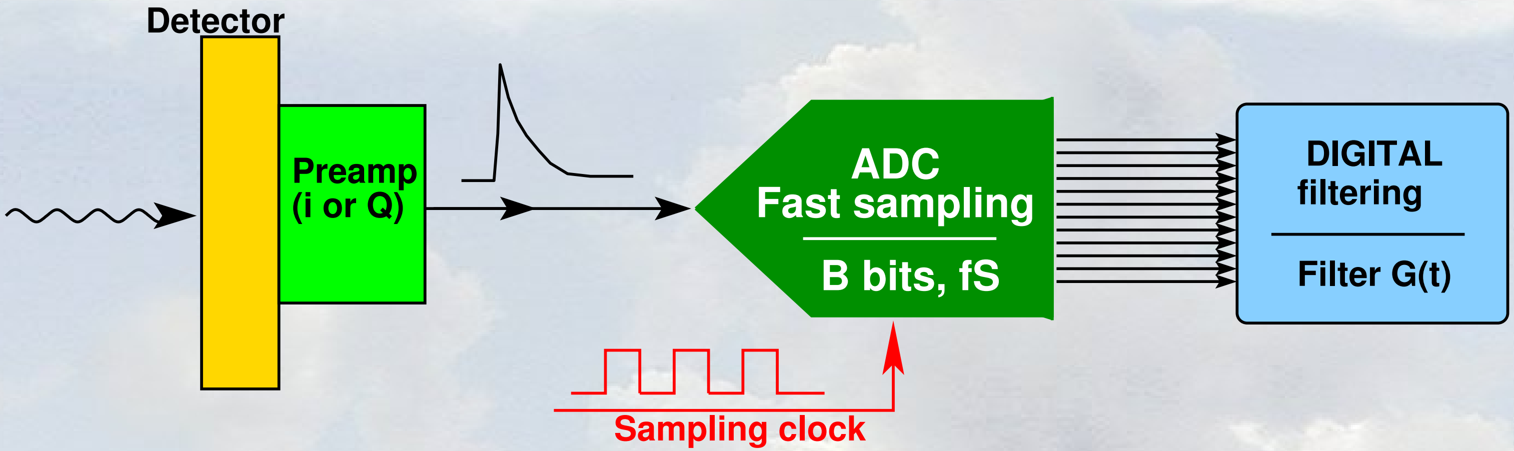
(direct comparison with peak-sensing ADCs?)

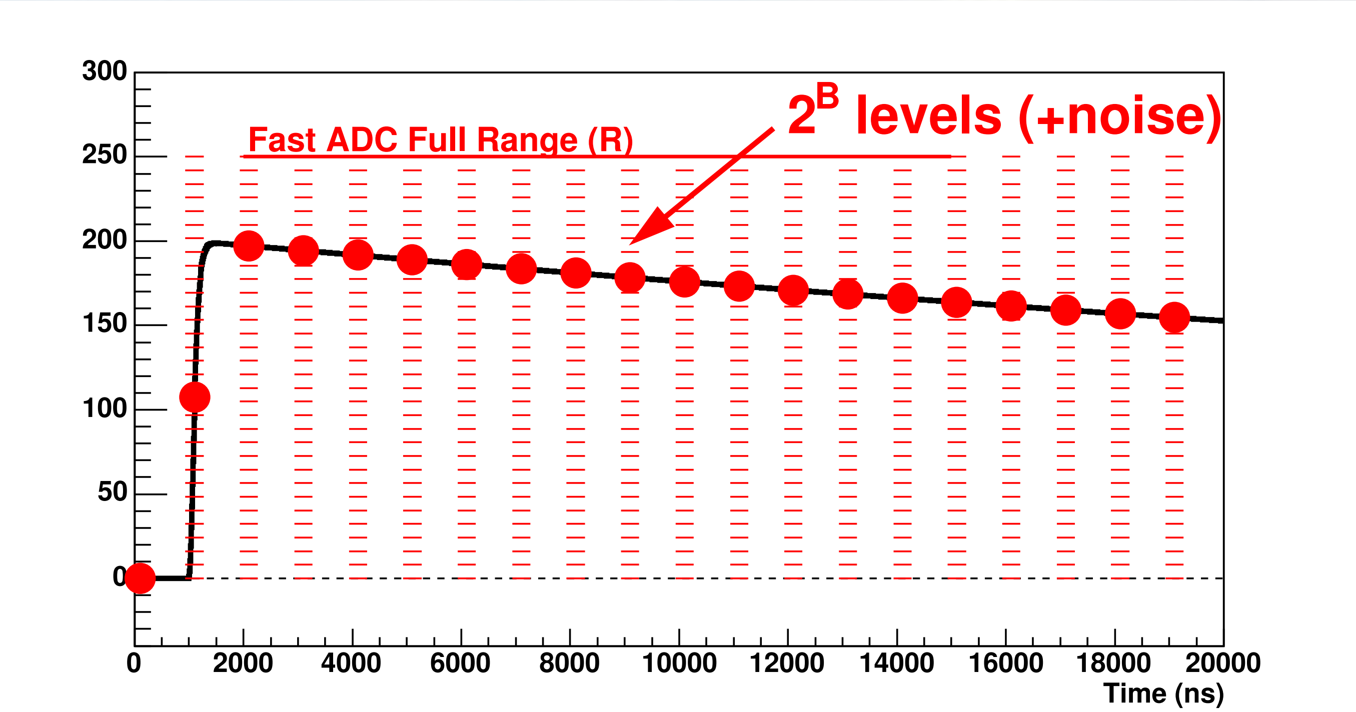
Energy measurements with digital systems

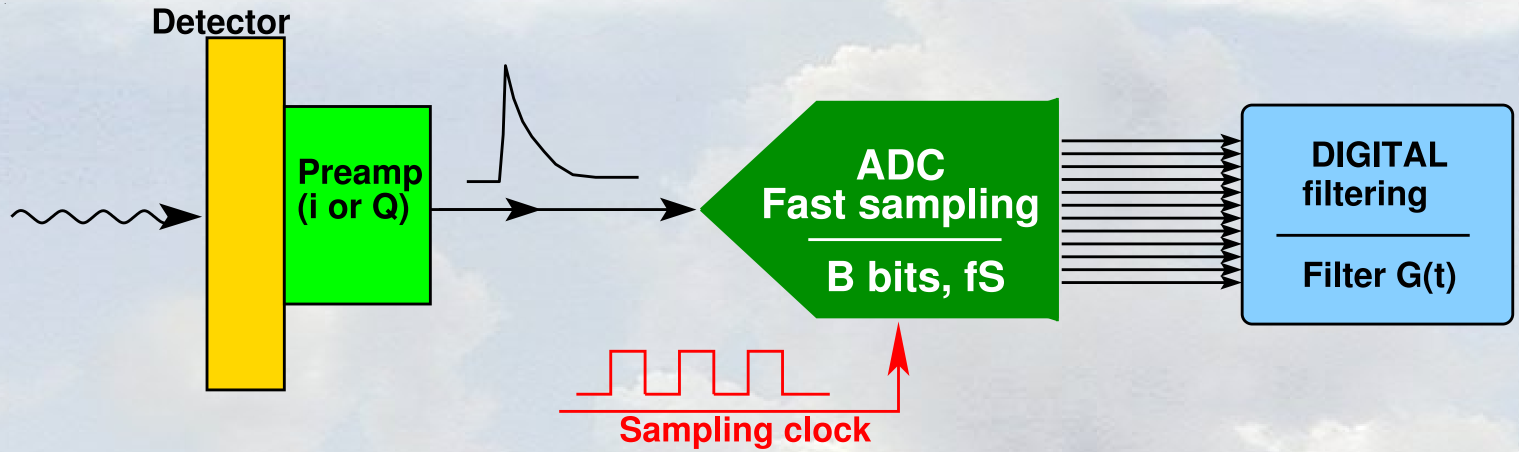


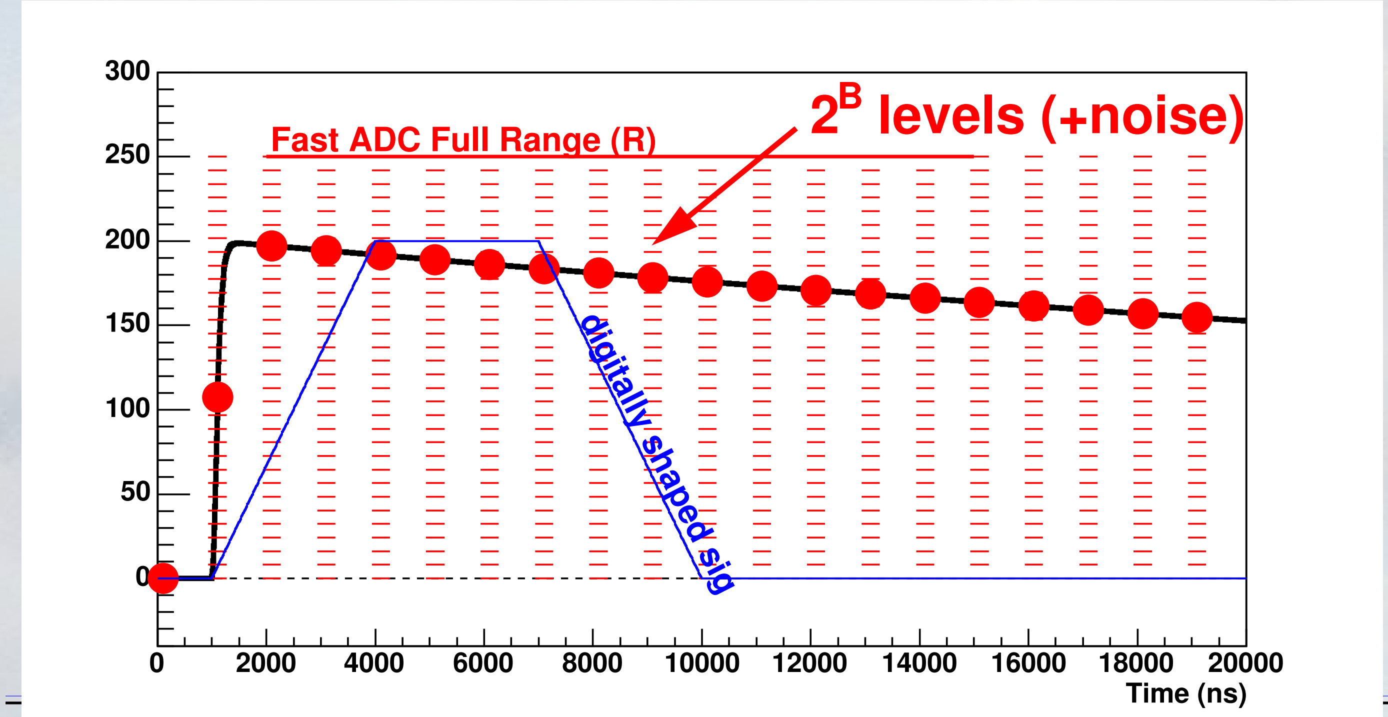


Energy measurements with digital systems







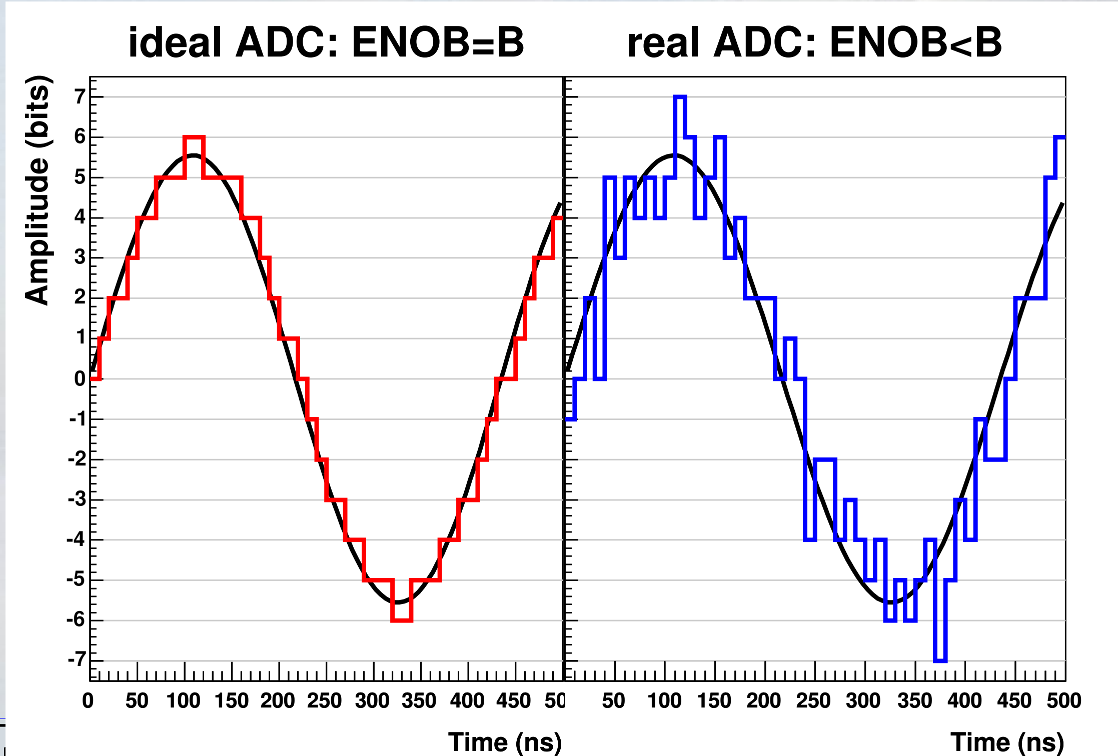


digital filter:
semigaussian,
trapezoidal,
triangular,
optimal. . .

Sampling frequency “f_S” Limits the bandwidth of the system

Number of bits “B” quantization level

Effective number of bits “ENOB” Real ADCs have thermal noise,. . .
ENOB gives the ADC noise performances in terms of an equivalent “ideal” ADC:



The **same quantization** level, but much more noise

In the figure:

$$\begin{aligned} \mathbf{B} &= \mathbf{12} \\ \mathbf{ENOB} &= \mathbf{10.6} \end{aligned}$$

(typical values)

One can carry out the computation and compare the result with the peak-sensing expression:

$$\frac{\sigma^2_{\text{exp}}}{\sigma^2_{\text{th}}} = 1 + \frac{9}{12}\left(\frac{R}{3\sigma_{\text{th}}}\right)^2 \cdot \frac{1}{4^{\textbf{PSENOB}}}$$

with the definition

$$\textbf{PSENOB} = \textbf{ENOB} + \frac{1}{2}\log_2\left(\frac{f_S \tau_C}{k_G^2}\right) - \frac{1}{2}$$

Peak-**S**ensing-**E**quivalent **N**umber **o**f **B**its

- depends on the ADC ENOB value
- depends logarithmically on $f_S \cdot \tau_C$ (detector corner time)
- depends on the used filter G with k_G ($\simeq$1 for common filters)

details in: L.Bardelli and G.Poggi, NIM A560 (2006) 517 and 524

$$\textbf{PSENOB} = \textbf{ENOB} + \frac{1}{2}\log_2\left(\frac{f_S\tau_C}{k_G^2}\right) - \frac{1}{2}$$

Some numerical examples (using $\tau_C = 5\mu s$):

ENOB	Bits	f_S (MS/s)	PSENOB
12.0	14	100	16.2
10.0	12	400	15.3
10.8	12	100	15.0
10.0	12	200	14.7
7.0	8	2000	13.4

Modern fast sampling ADCs $\rightarrow$ **wide dynamic ranges!**
details in: L.Bardelli and G.Poggi, NIM A560 (2006) 517 and 524

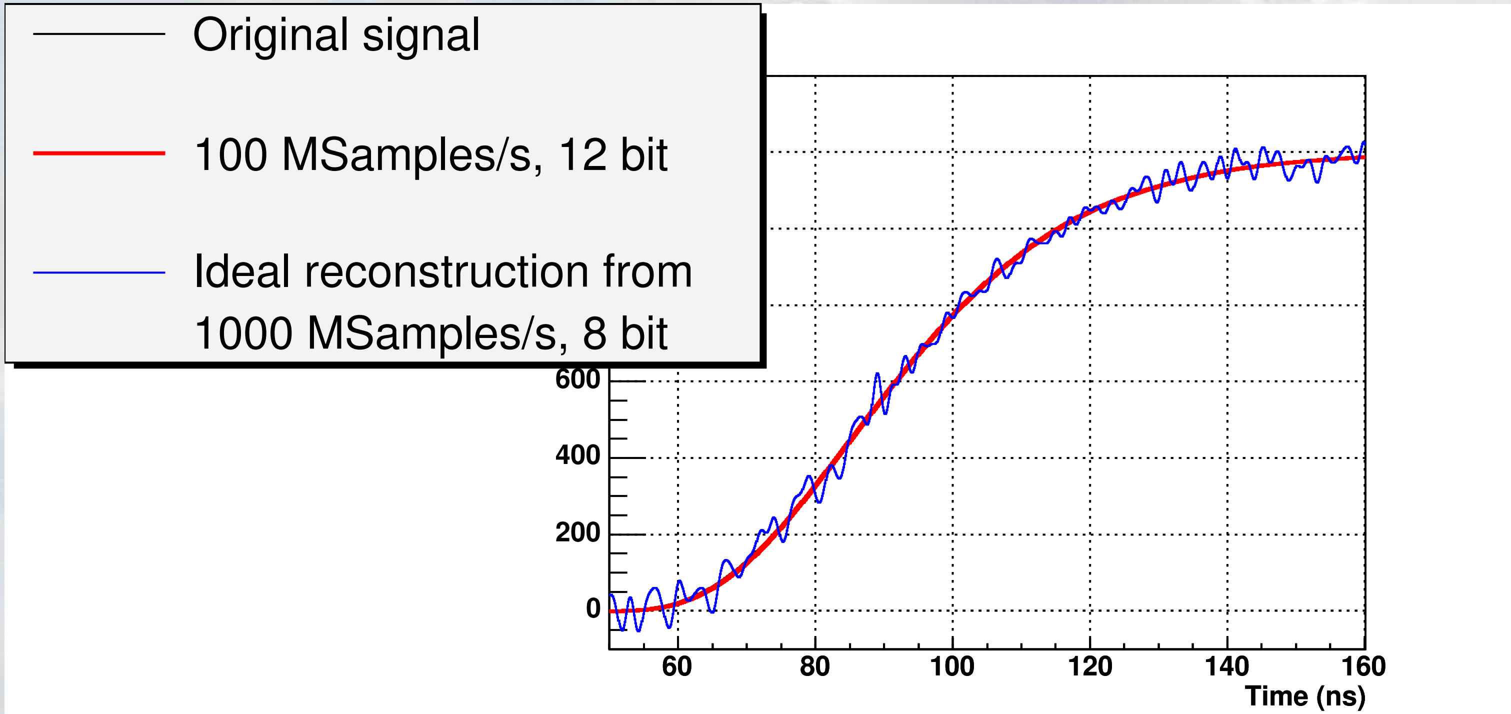
timing

High resolution or High speed Sampling ADC?

High resolution or High speed Sampling ADC?

Timing measurements: in practice obtain the time t_0 where $S(t_0) = S_0$

⇒ good timing possible with good signal reconstruction!



Key points for good signal reconstruction:

low noise

Higher speed = wider bandwidth = higher noise.

$f_{\text{sampling}} \approx f_{\text{Nyquist}}$ is enough. . .

good interpolation

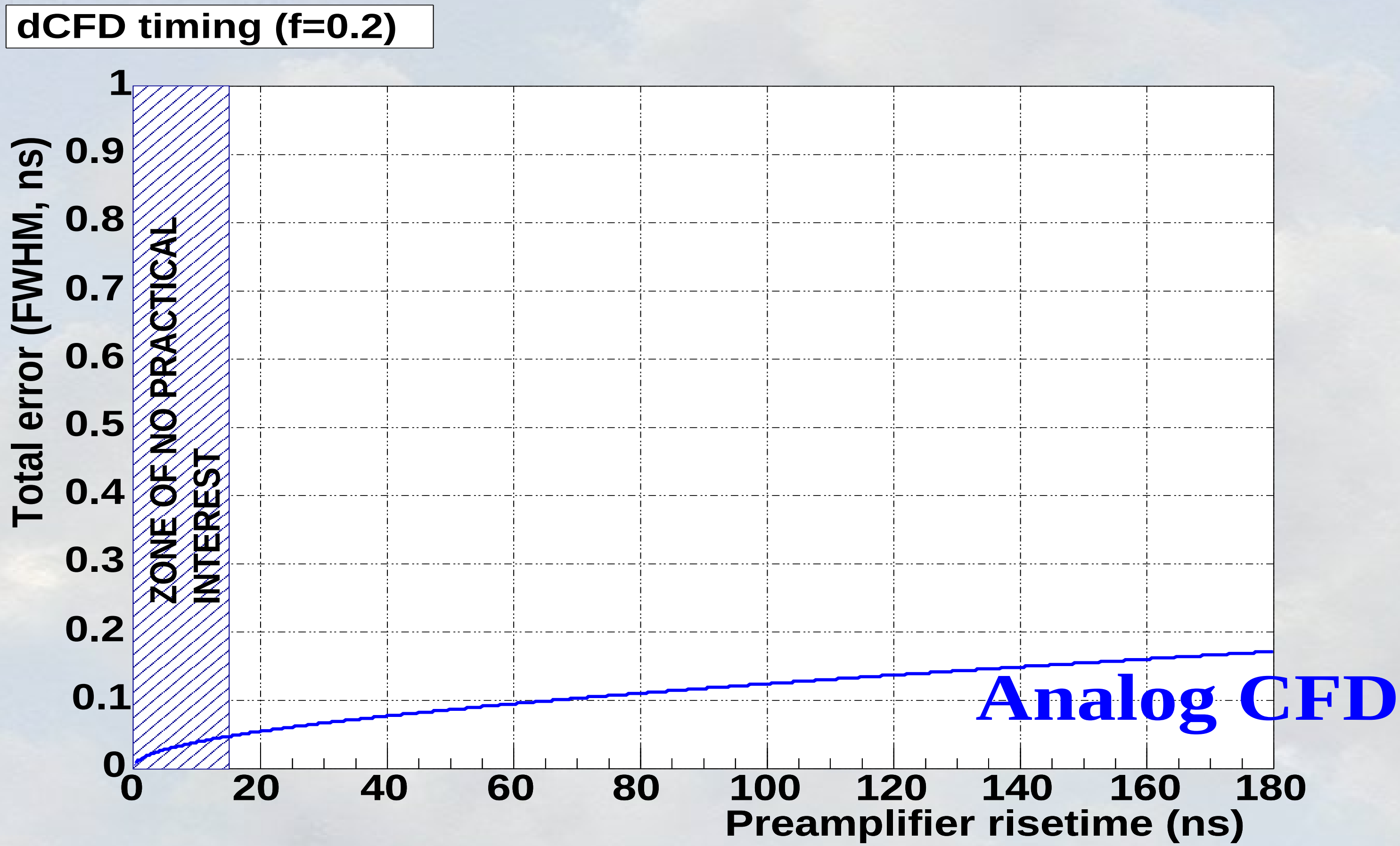
linear interpolation gives more error/noise

⇒ at least **cubic** is needed

Low noise + Good interpolation =
= Good Signal reconstruction = Good Timing!

Which AD converter ? L.Bardelli *et al.*, NIM **A521** (2004)

realistic simulations, **fixed shape** signals, **cubic interpolation**:



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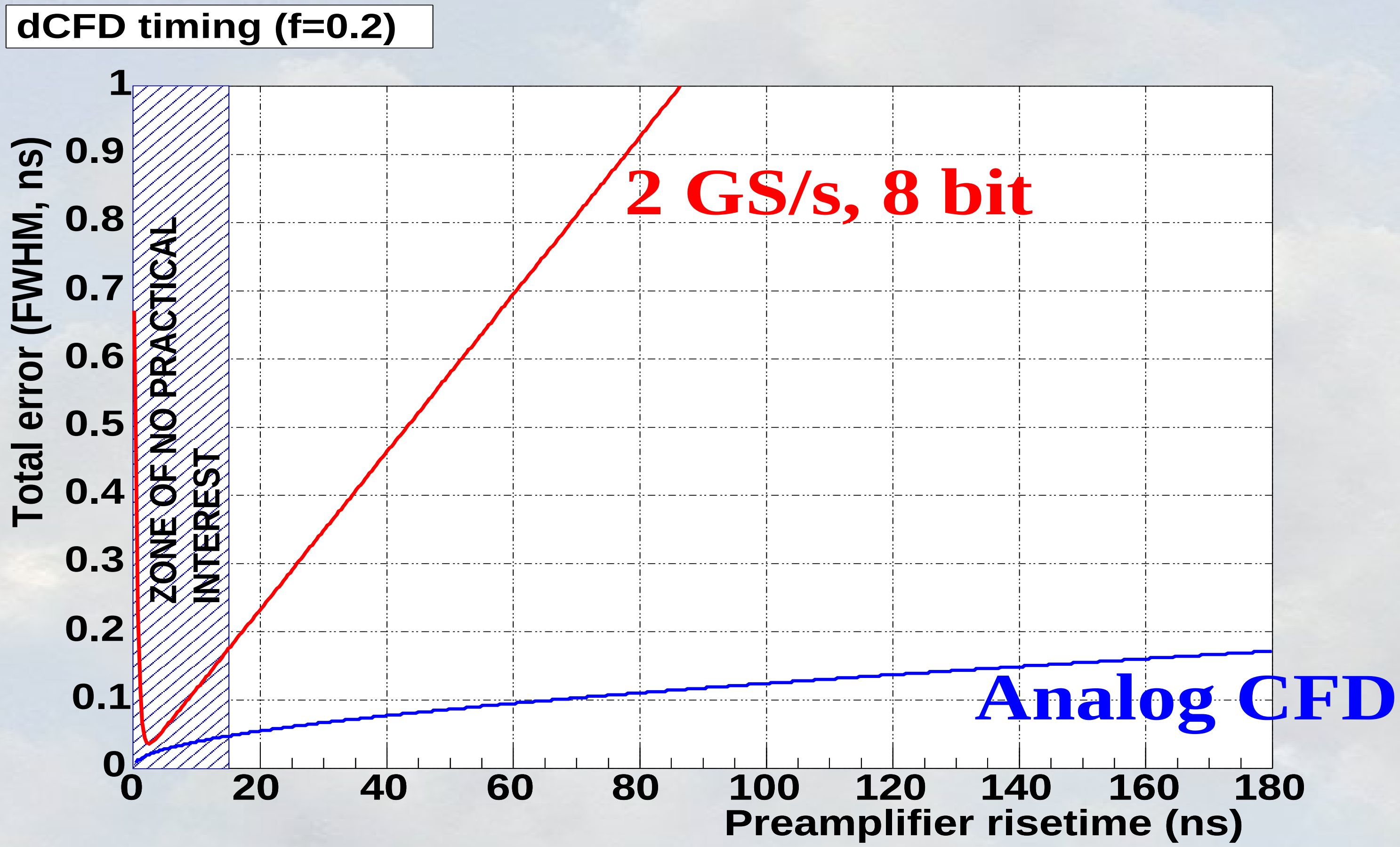

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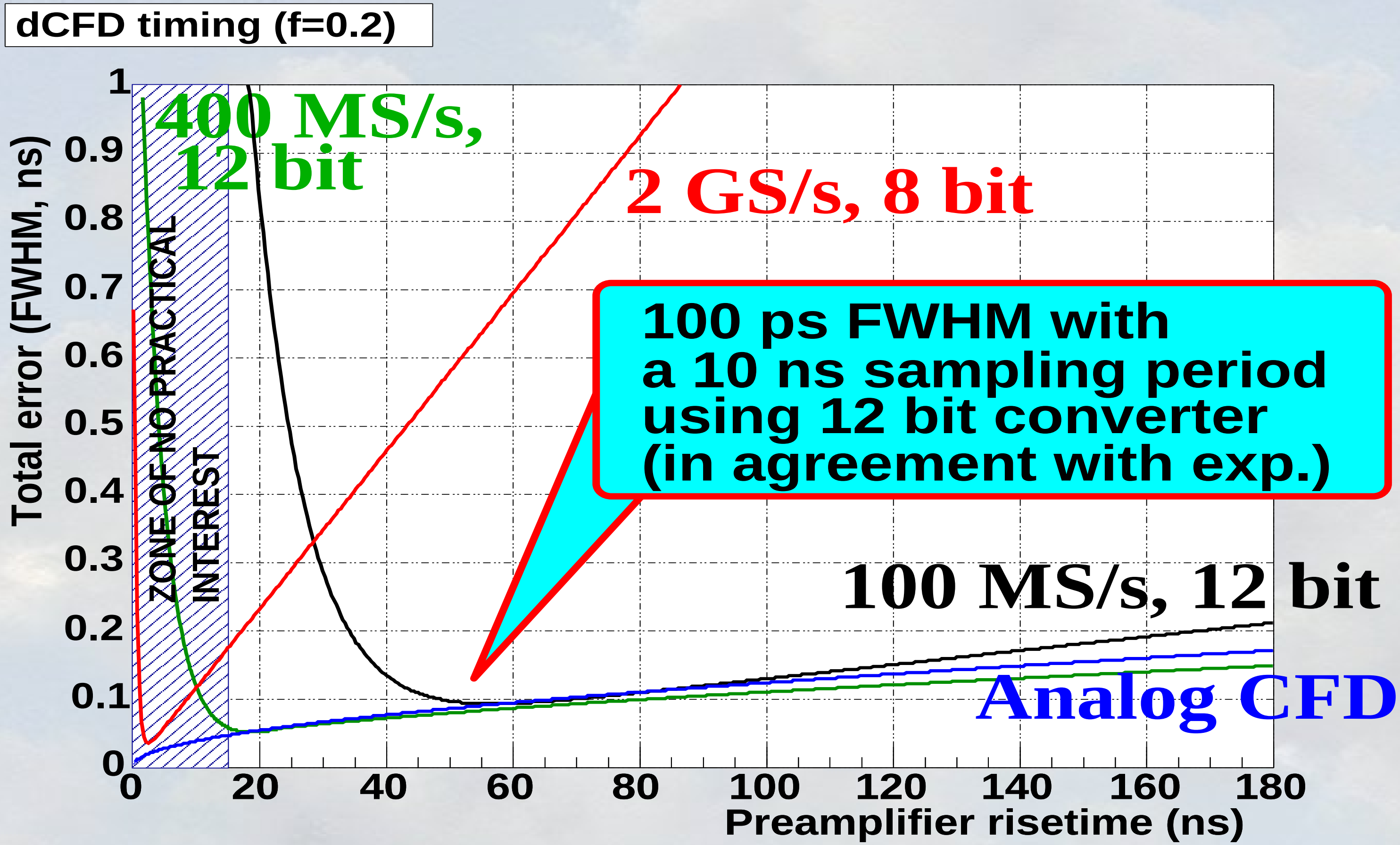
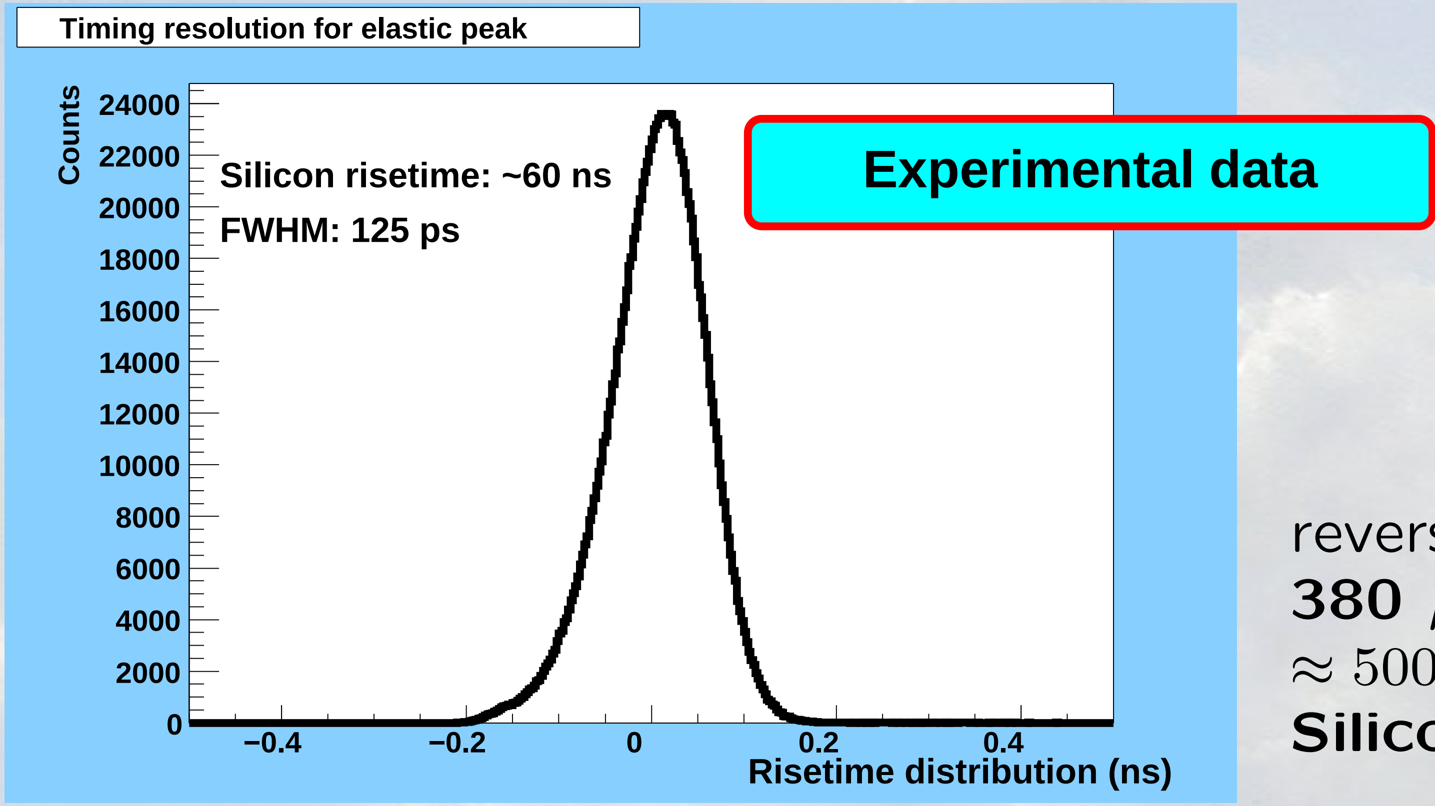


12 bit $\Rightarrow$ FWHM resolution 100 times smaller than sampling period

Rise-time analysis: differences between two **dCFDs**.
250 MeV Oxygen elastic peak using a Si detector (test at LNL)



reverse
380 μm,
≈ 500 **mm^2**
Silicon

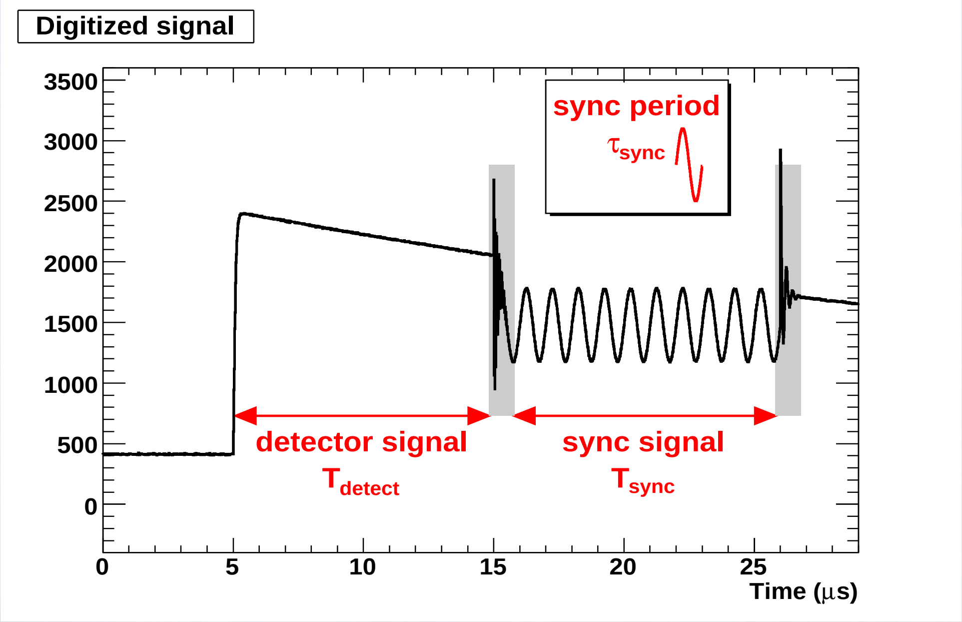
Time difference between 90% and 10% dCFDs
Cubic interpolation with 100 MS/s ADC
L.Bardelli *et al.*, NIM **A521** (2004)

time of flight

Time of Flight or coincidence measurements?

Time of Flight or coincidence measurements?

Time-stamped clock or **mix a common time reference signal with the preamplifier output**:



Time of Flight or coincidence measurements?

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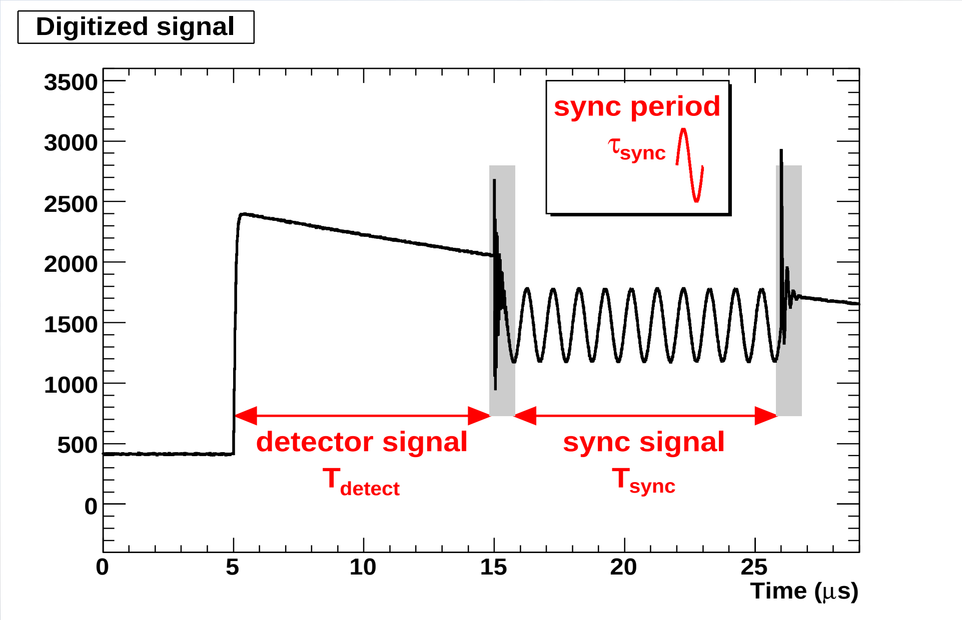


The DSP software can separate the "true" signal from the "reference" one and compute the time difference.

Using a train of pulses as reference the resolution can be significantly improved, down to **1 – 5 ps FWHM**

This allows for **synchronization** between many channels: **coincidence** measurements possible.

L.Bardelli *et al.*, NIM **A**, 572 (2007) pag 882

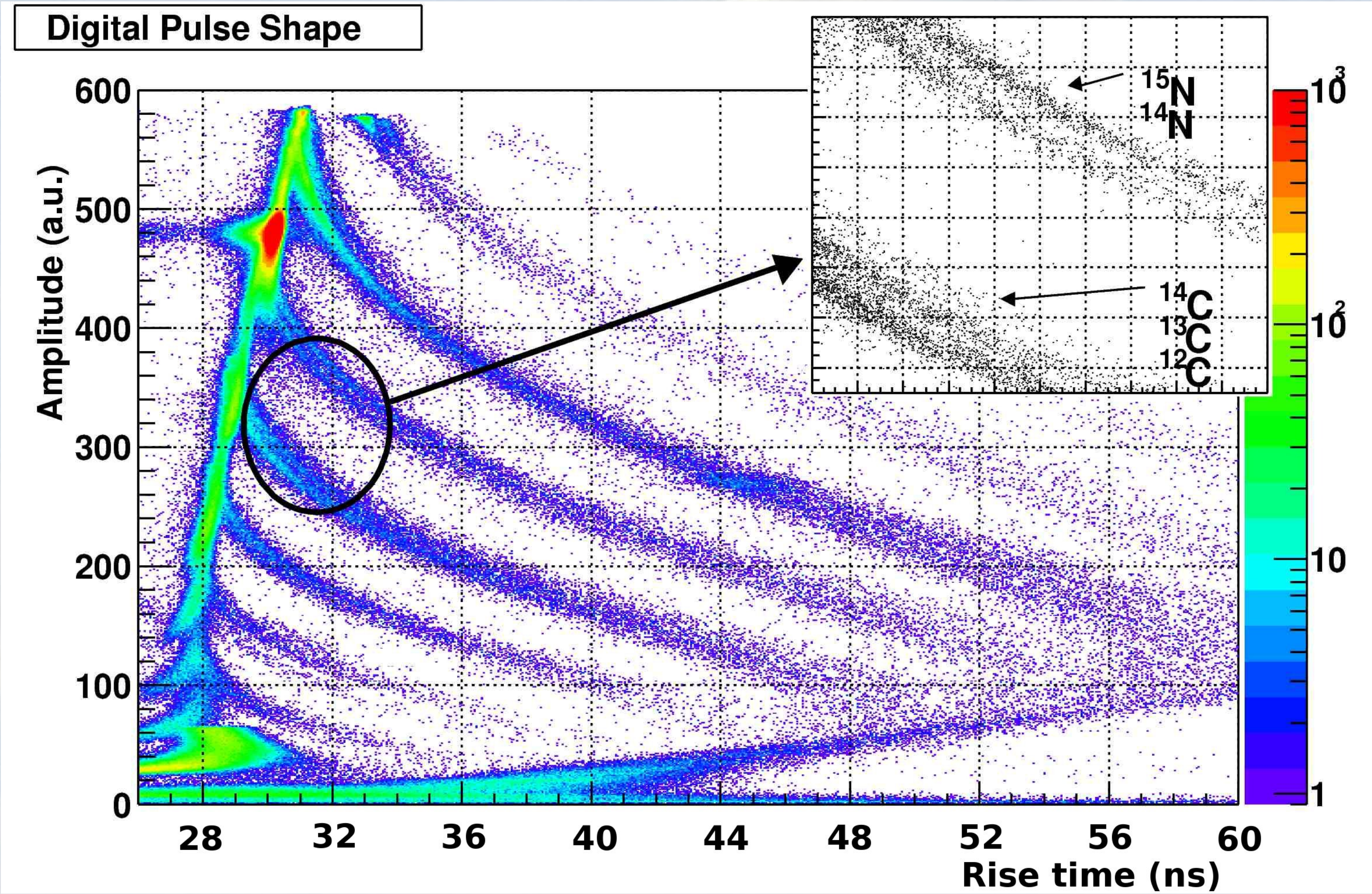
L.Bardelli *et al.*, NIM **A**, 521 (2004) pag 480

We have seen DIGITAL examples of:

- Signal Amplitude measurement ($\Longrightarrow$ energy)
- Timing measurement ($\Longrightarrow$ CFD, rise time)
- Inter-channel time synchronization ($\Longrightarrow$ ToF)

Now we can try an Energy vs "RiseTime" plot for a Silicon detector:

Digital Amplitude vs. **Digital Zero Crossing** time:



reverse **380 μm,**
≈ 500 **mm^2**
Silicon

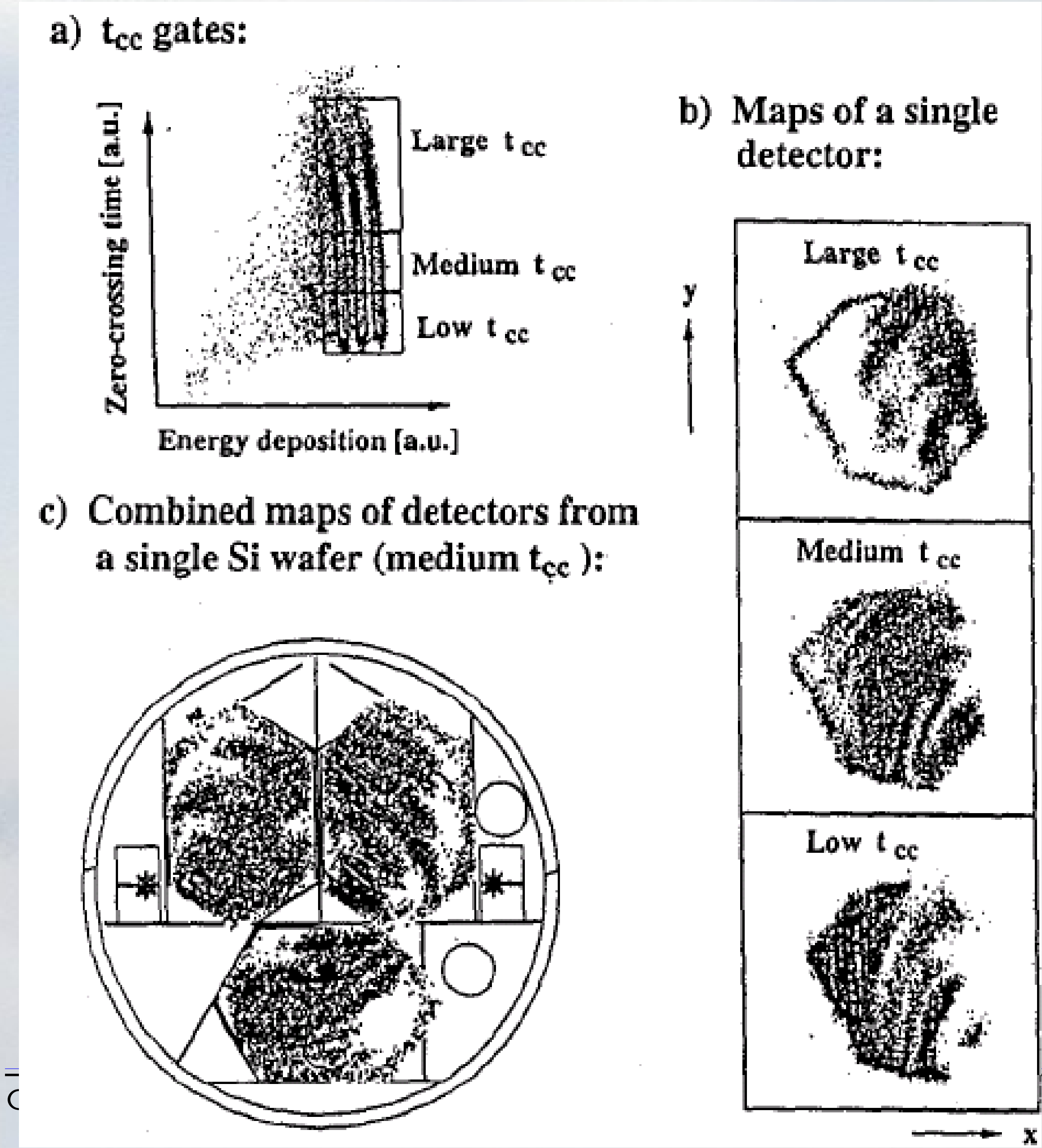
12bit
100 MS/s
digitizer

L.Bardelli *et al.*, NIM **A521** (2004)

Regardless of the analysis method, various factors may limit the achievable identification performances, like:

- Detector thickness inhomogeneities
- Detector bias voltage
- Thresholds
- Channeling effects

. . . let's see some examples

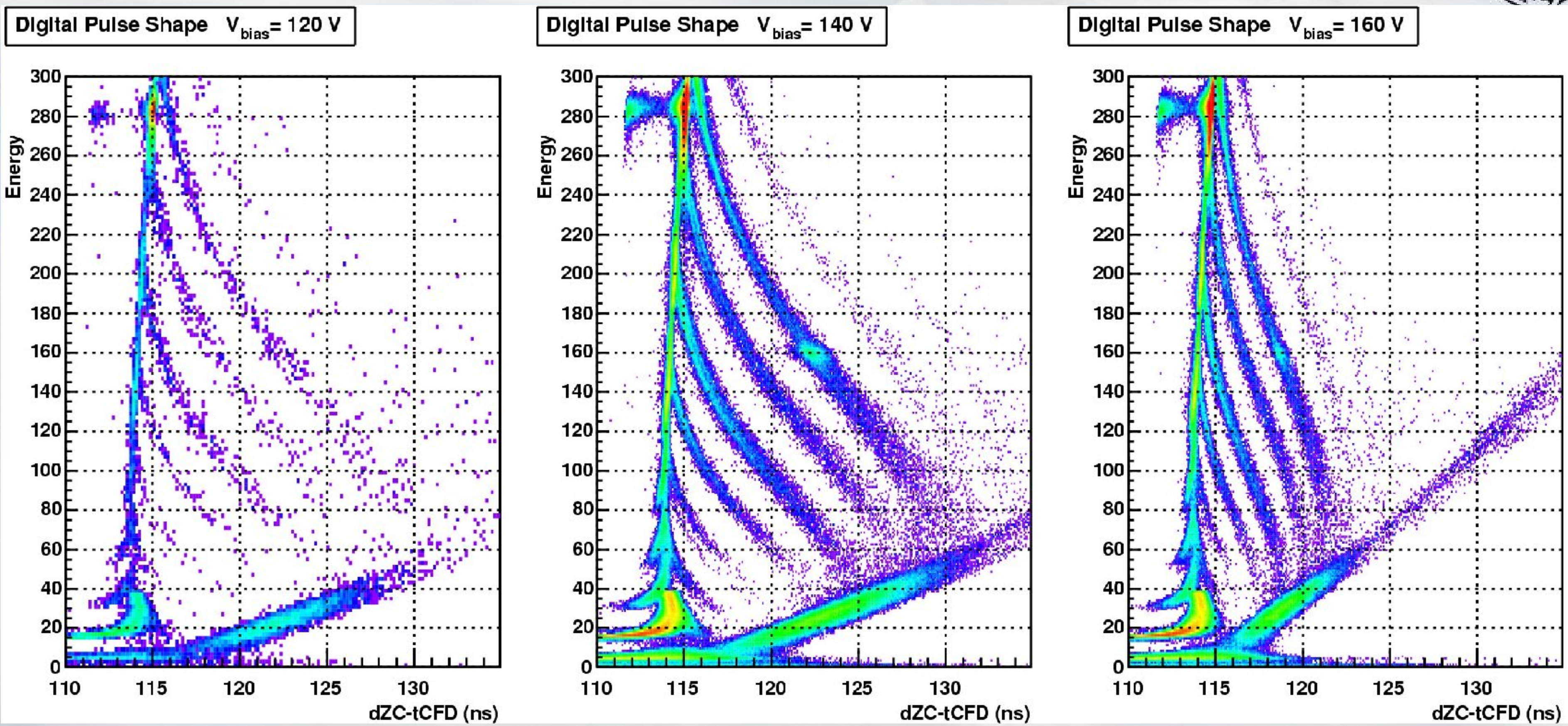


G.Pausch *et al.*, IEEE Trans. Nucl. Science, vol.44, no.3, June 1997

the detector area and uniformity are important!

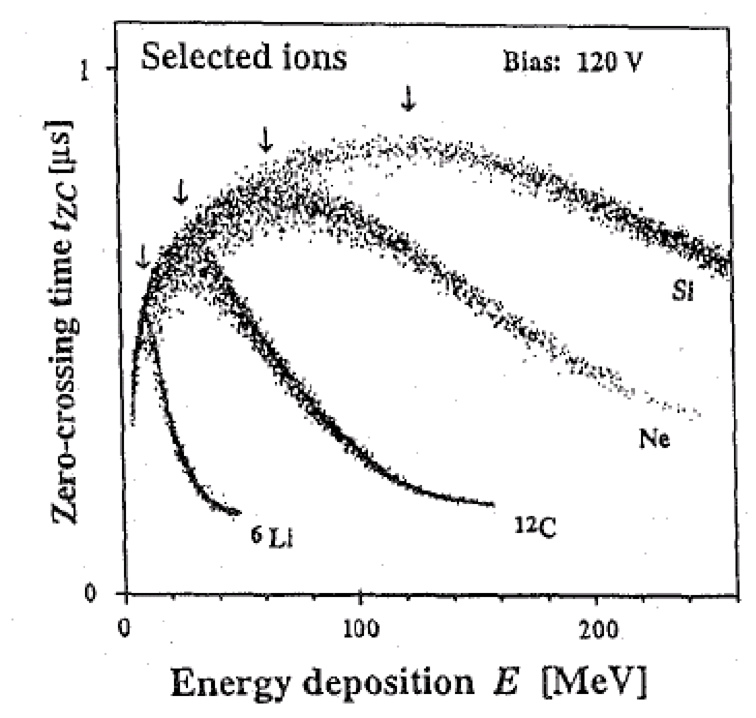
Additional tests will be performed by the FAZIA collaboration at LNL in the first week of June.

Detector Bias Voltage



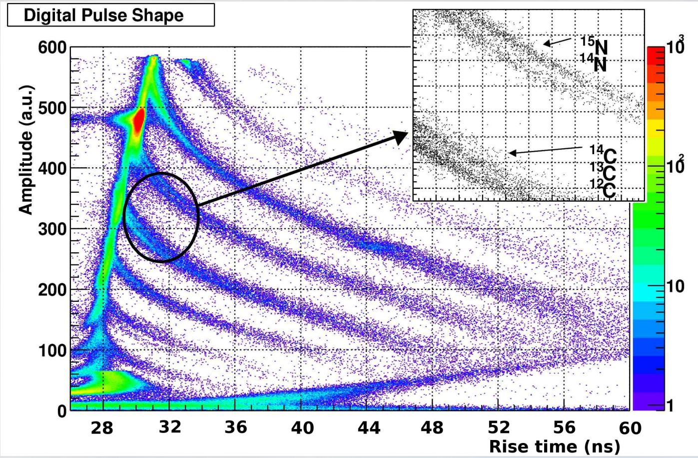
- detector bias/depletion voltage need careful optimization
- during experiment the detector bias must be monitored

L.Bardelli, PhD Thesis, Florence, 2005



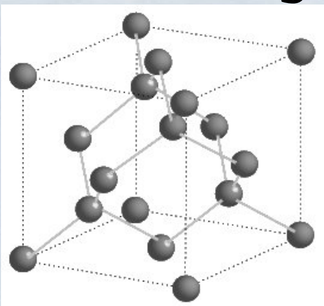
G.Pausch *et al.*, IEEE Trans. Nucl. Science, vol.44, no.3, June 1997

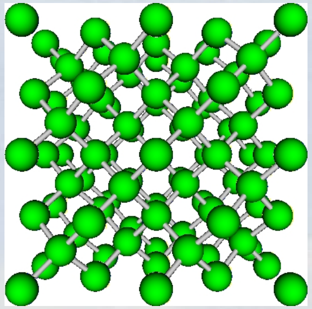
All the “identification” lines merge into a single line: this effect can be explained in terms of “plasma” effects, see L.Bardelli et al, Proc. of IWM2005 conf., ISBN 88-7438-029-1

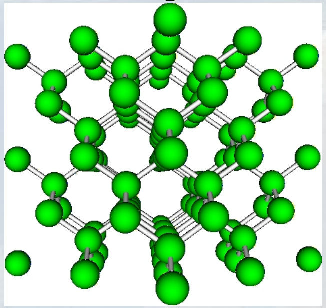


About **30 μm** Si-equivalent for LNL2002 dataset.

Channeling effects can destroy the PSA resolution:

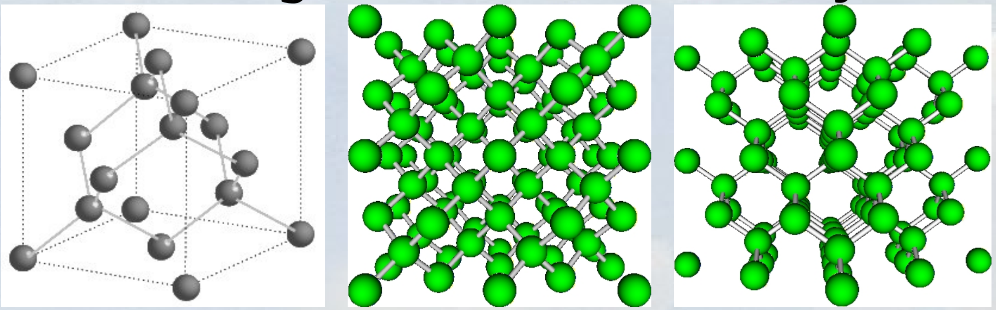




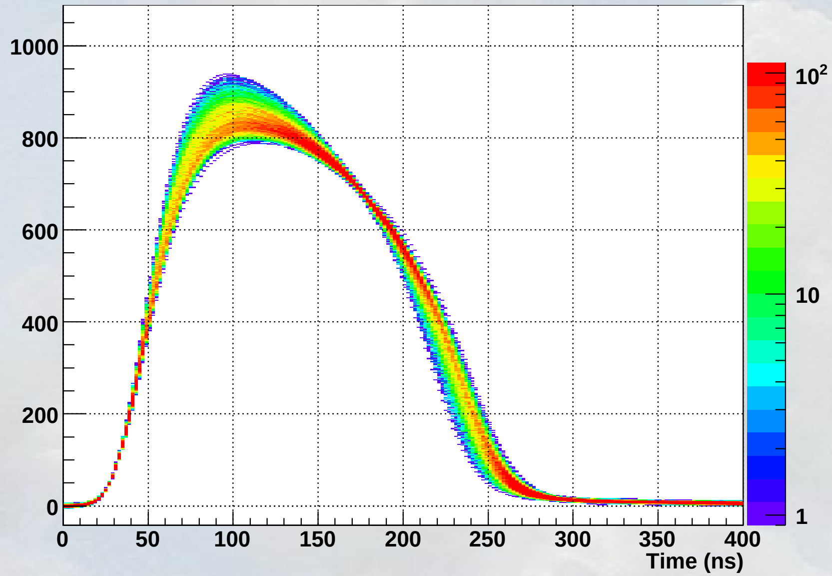


→ our detectors??

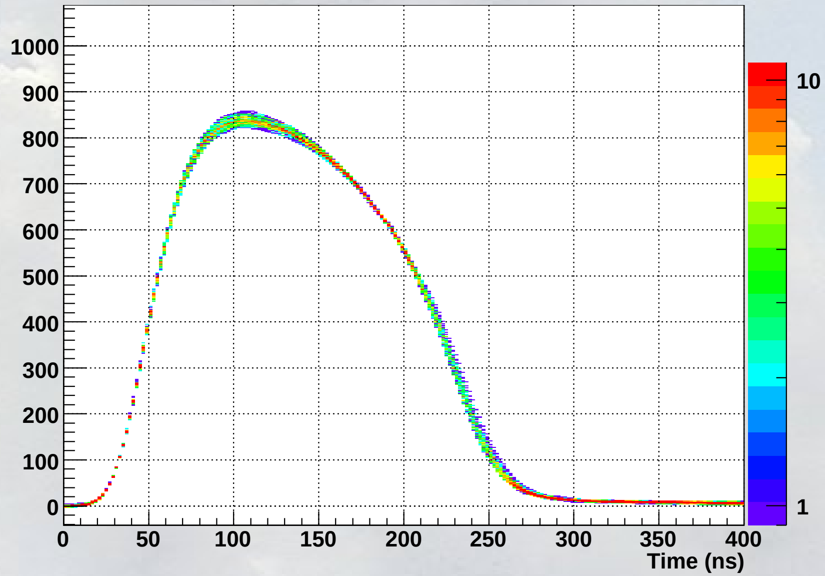
Channeling effects can destroy the PSA resolution:



→ our detectors??



Channeled



Random (∼9°)

$i(t)$, **^{80}Se @ 408 MeV,** $\langle 100 \rangle$

L.Bardelli et al., LNL Ann.rep.2006 & in preparation

The FAZIA collaboration is currently performing an R&D activity on digital pulse shape analysis in Silicon Detectors:

1. dedicated working group (WG1)

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1. dedicated working group (WG1)
2. a number of experimental tests for building a signal database (mainly for heavy ions)
3. PACI preamp to compare $q(t)$ and $i(t)$ $\rightarrow$ H.Hamrita et al.

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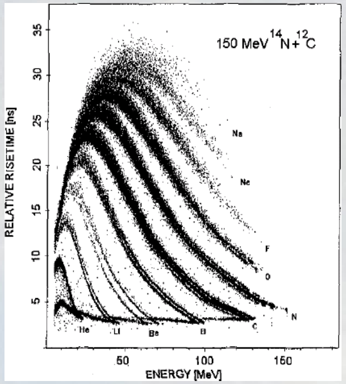
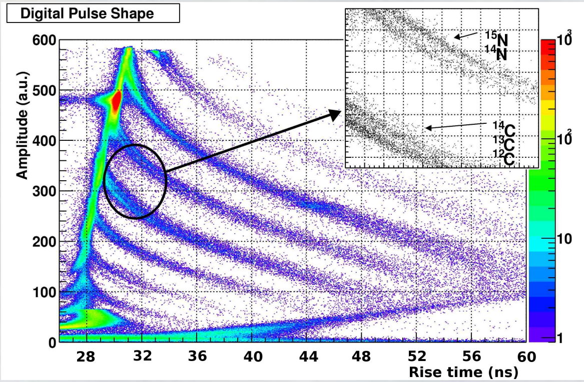
Conclusions

- PSA in silicon detectors may be used to significantly lower the detection and particle identification thresholds
- Digital sampling methods offer a powerful and compact way to realize such systems
- Proper algorithms make high-resolution digital energy and timing measurements possible
- PSA resolution may be limited by detector properties





Some references: M.Mutter, IEEE.T.N.S.47, L.B. NIMA572, G.Pasquali NIMA570, L.B. NIMA560, L.B. NIMA521, L.B. NPA746, L.B. NIMA491, http://fazia.in2p3.fr

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