Electronics for ultra high energy gamma rays telescopes

DE LA RECHERCHE À L'INDUSTRIE

E. DELAGNES
eric.delagnes@cea.fr

ESIPAP school of detectors
2021 Feb 16th

www.cea.fr
Irfu.cea.fr

OUTLINE

1. A practical case

2. How an electronics engineer try to understand physics :

   * for his own motivation : « curiosity should be the main driver of scientist »

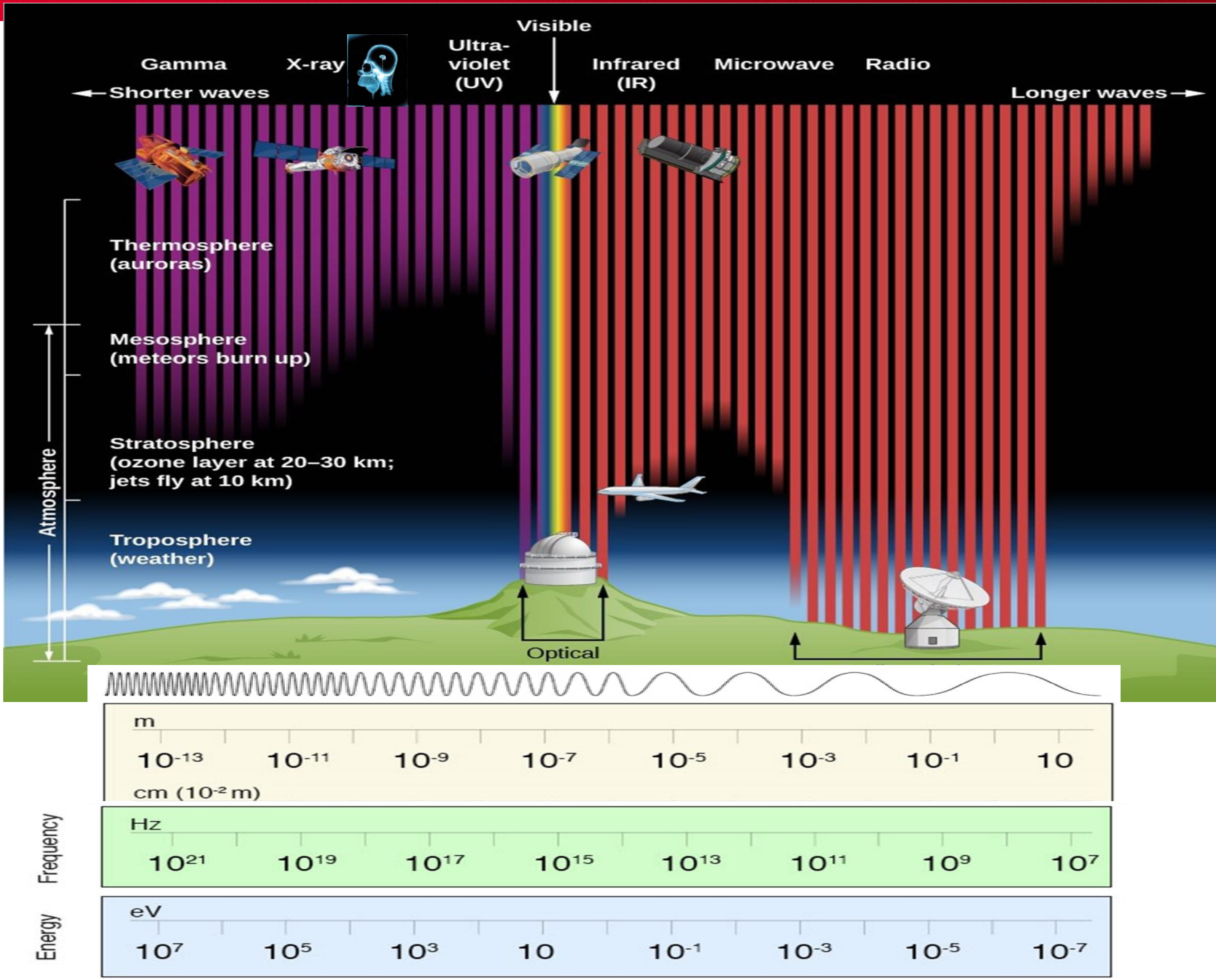
   * to build the best possible instrument

   * to understand it (and its performance)

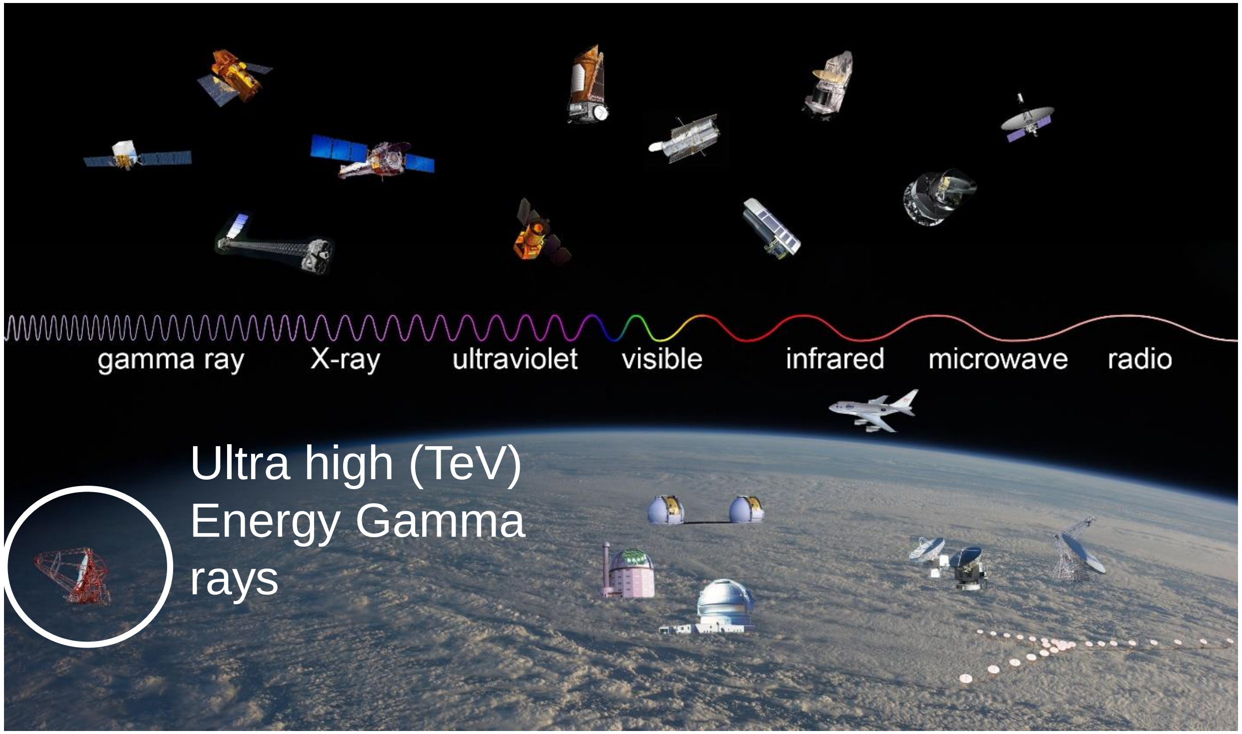
2. Introduction to few technical concepts

3. A great adventure !

THE ATMOSPHERE : THE ENEMY OF ASTRONOMERS ?



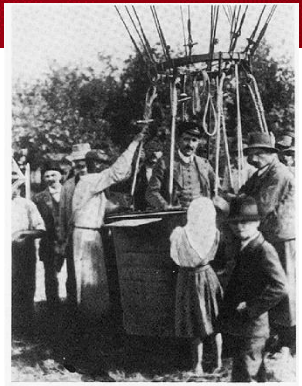
IS THE ATMOSPHERE AN ENEMY FOR ASTRONOMERS ?



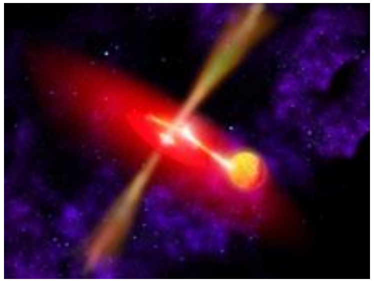
- Largest part of the Spectrum observed by satellite
- Expensive (Billions of euros)
- High cost of operation
- Low detection effective surface and photons becomes rarer at high energy

- But there is a miracle for ultra high energies photon

WHY IS THE UHE RANGE IS SO INTERESTING



- Study of cosmic rays
- Most violent phenomena in the universe :
  - Supernovae
  - Relativistic jets and Blackholes
  - Proimordial black holes
  - Red shifted Extragalactic sources
  - Neutron stars
  - Gamma ray bursts



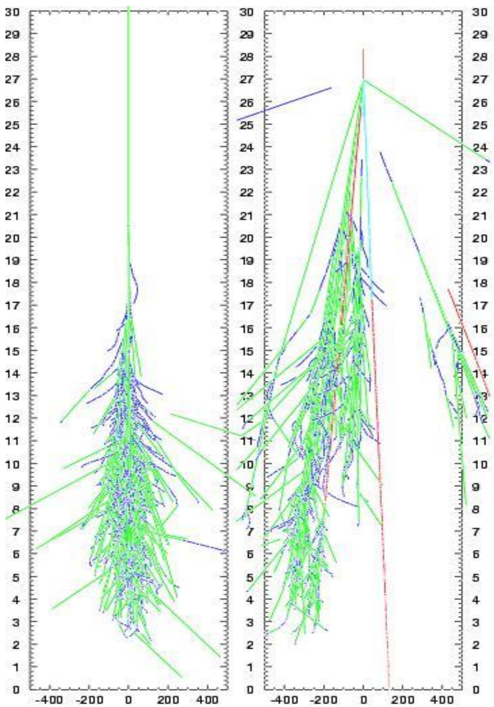
- « cosmic » acceleration gives access to energy impossible to reach on earth (PeV !)

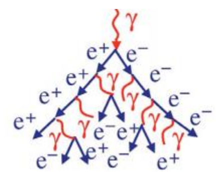
- Dark matter and dark energy (indirect, axion-like)

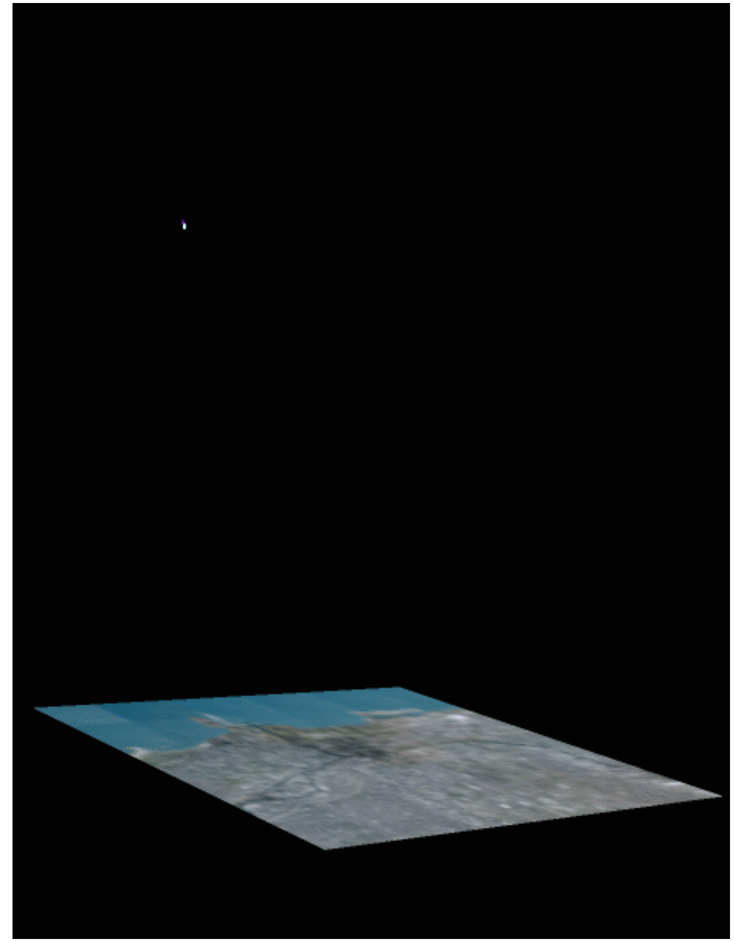
- Test the law of physics (Lorentz invariance…)

NEW WINDOW on the universe:
only very few sources were known 20 years ago…

How to detect UHE gamma rays







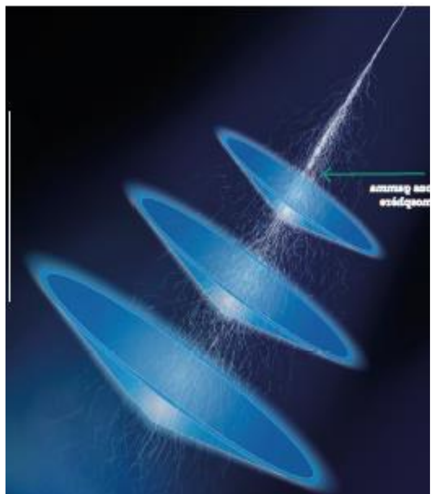
- @10 km altitude. Gamma photons interacts with the atmosphere to produce relativistic cascade/showers of particules as in HEP calorimeters

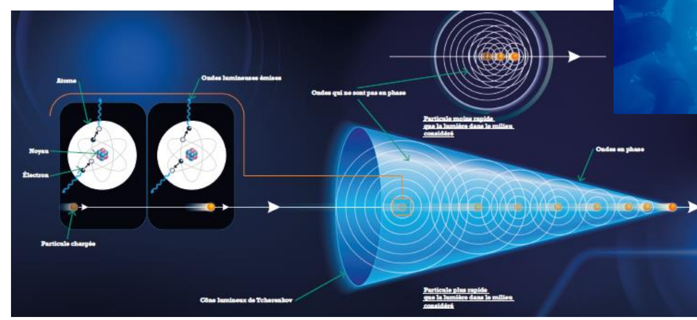
- For E>10 GeV the shower axes follows the gamma direction

CERENKOV LIGHT

- Each relativistic CHARGED particles from the shower are travelling at a speed higher than the speed of light in air (dielectric medium)

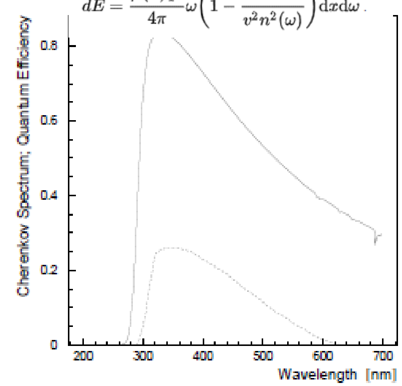
➔ produce Cerenkov light

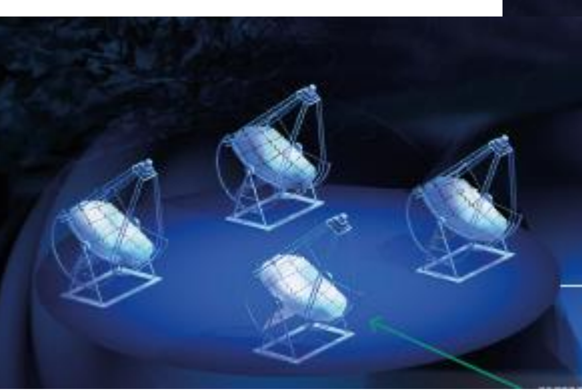




1° light cone: lightfront

$$dE = \frac{\mu(\omega)q^2}{4\pi}\omega\left(1 - \frac{c^2}{v^2n^2(\omega)}\right)\mathrm{d}x\mathrm{d}\omega\,.$$





faint light spot (few photons few ns long) collected by giant telescopes (d=10-30 m) on ground

…equiped by photodetectors optimized for the Cerenkov light (peak in blue)

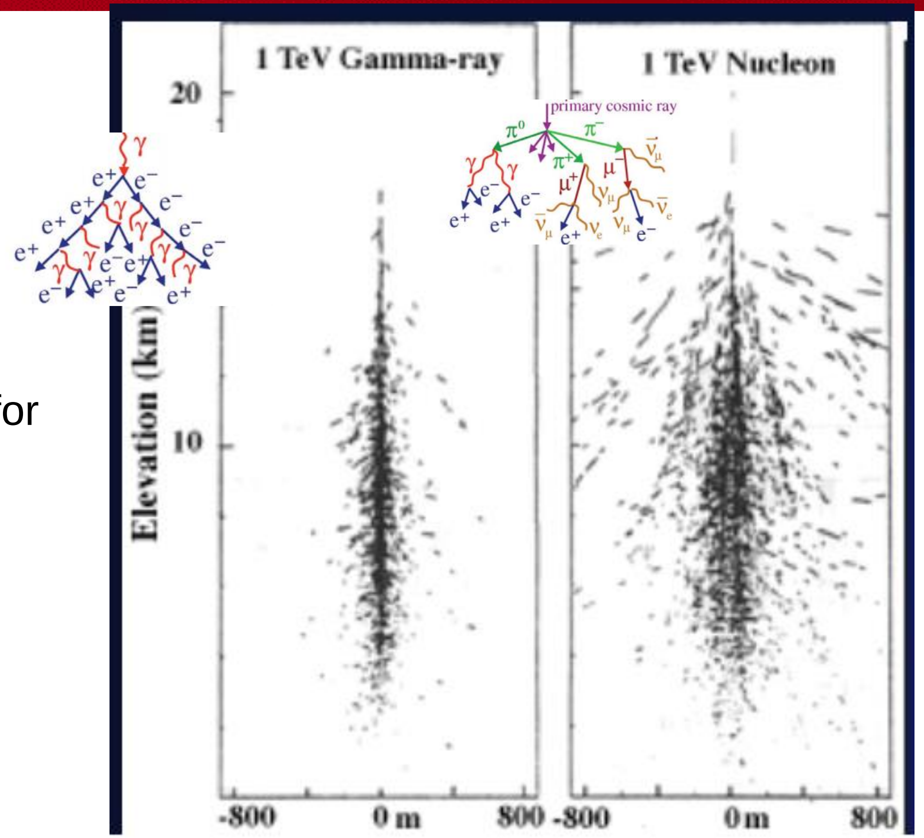
How to detect and measure UHE gamma rays

1. Detect few Cerenkov photons within a Night Sky background Light (1/10000):
   high sensitivity an high speed

2. Discriminate for other particles (proton, muons) interracting with air and producing light (=noise). Only 1/1000 is a gamma:
   Imaging capability allows recognizing shapes for various particle

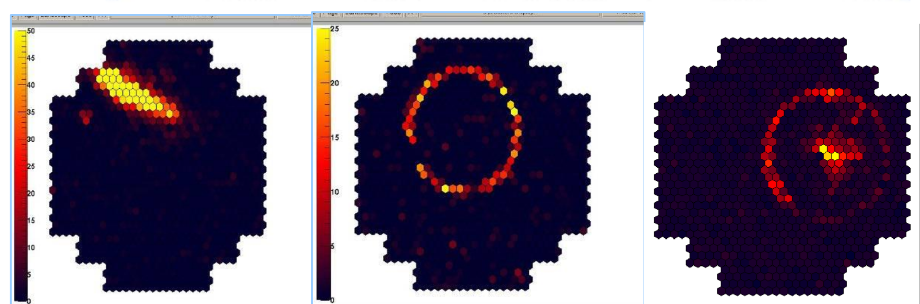
3. Image the shower
=> axis will give direction of the photon

4. Measure precisely the light intensity
 =>proportional to the energy of the photon



Need for ultra high high speed ultra sensitive camera with high dynamic range

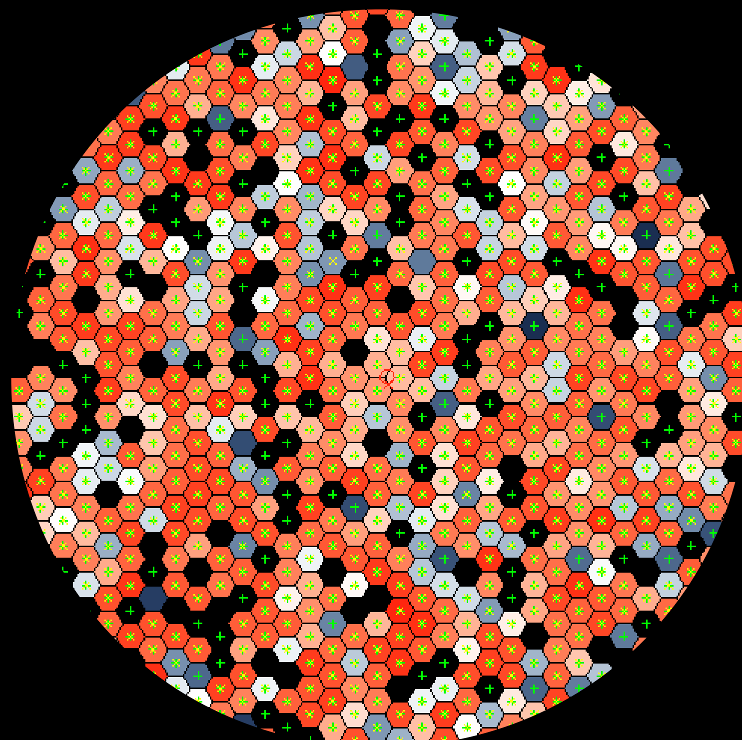
The atmosphere **is** the detector: very large sensitive surface: several 100m^2
=> from enemy it becomes our friend !!!



Gamma Muon Hadron

The need of a very short exposure time

Contamination : Night sky background (NSB)



© W. Hofmann

1/10000
(100 μs)

1/100000
(10 μs)

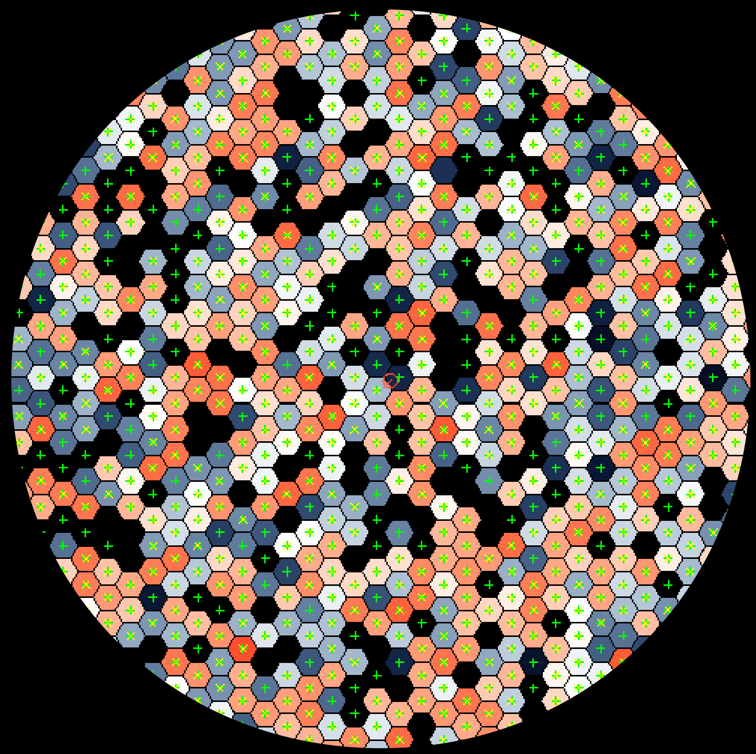
1/1000000
(1 μs)

1/10000000
(100 ns)

1/100000000
(10 ns)

The need of a very short exposure time

Contamination : NSB



1/10000
(100 µs)

1/100000
(10 µs)

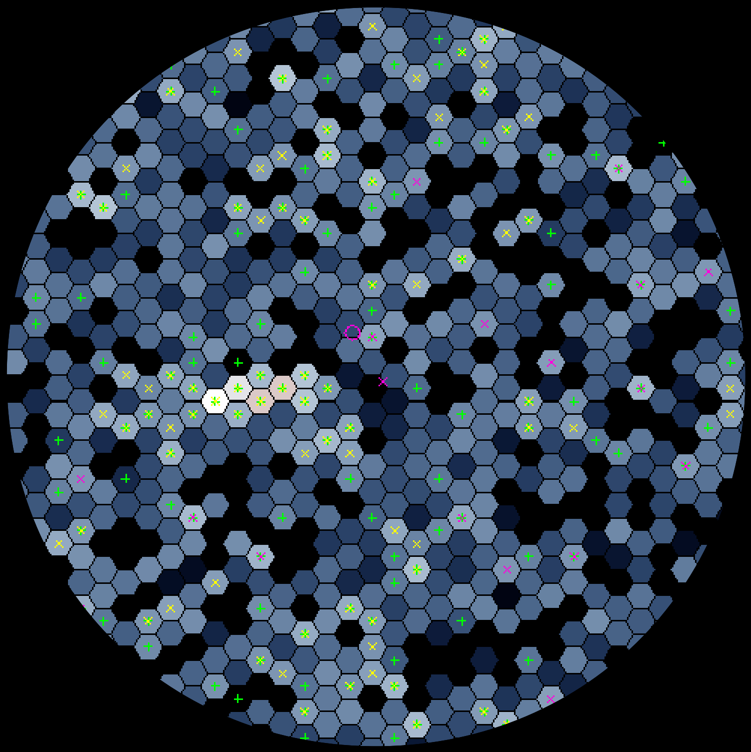
1/1000000
(1 µs)

1/10000000
(100 ns)

1/100000000
(10 ns)

The need of a very short exposure time

Contamination : NSB



© W. Hofmann

1/10000
(100 μs)

1/100000
(10 μs)

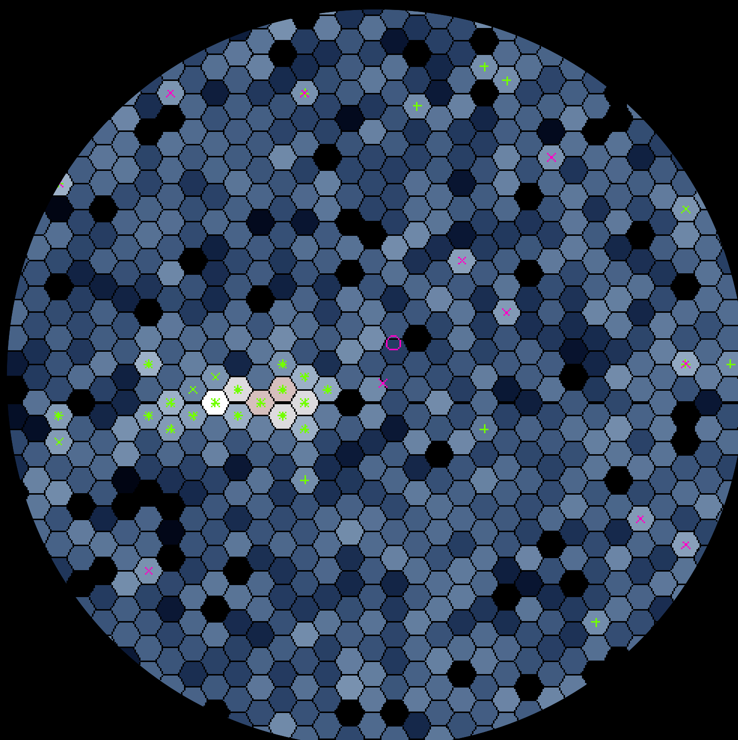
1/1000000
(1 μs)

1/10000000
(100 ns)

1/100000000
(10 ns)

The need of a very short exposure time

Contamination : NSB



© W. Hofmann

1/10000
(100 μs)

1/100000
(10 μs)

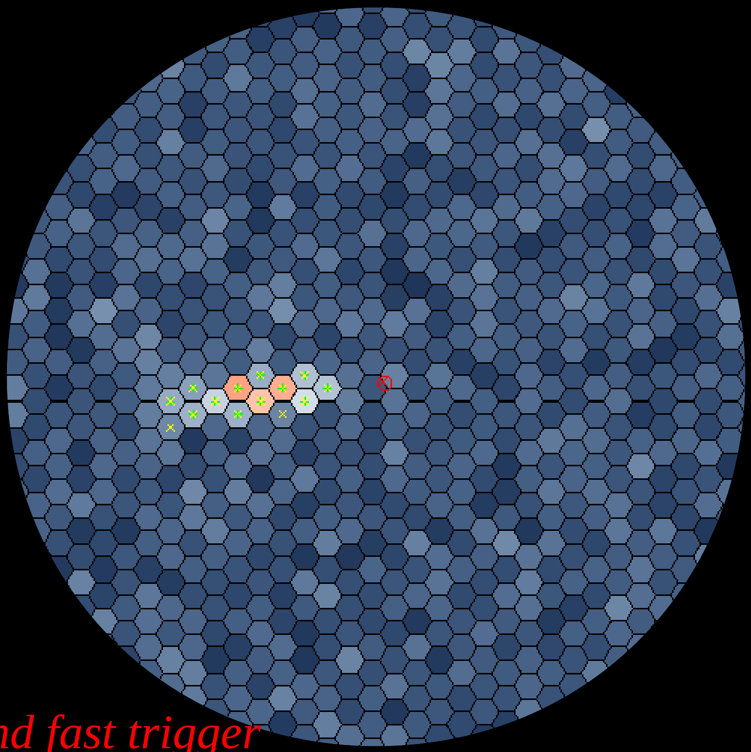
1/1000000
(1 μs)

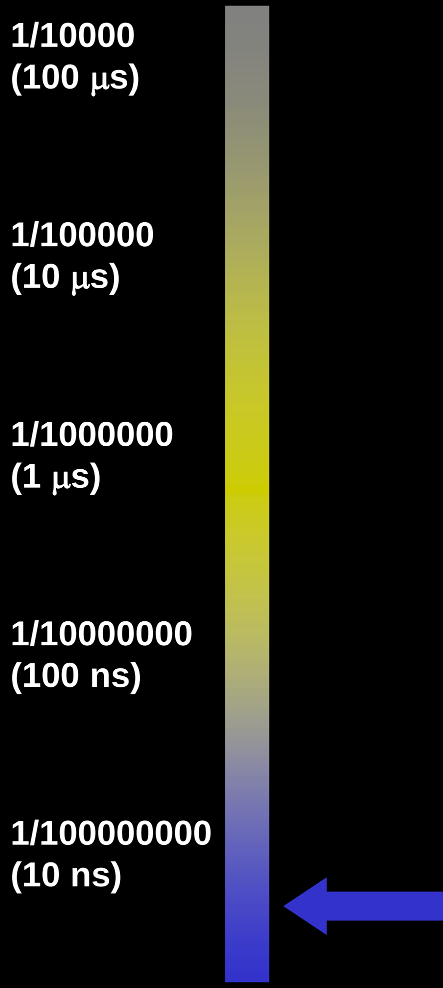
1/10000000
(100 ns)

1/100000000
(10 ns)

The need of a very short exposure time

Contamination : NSB

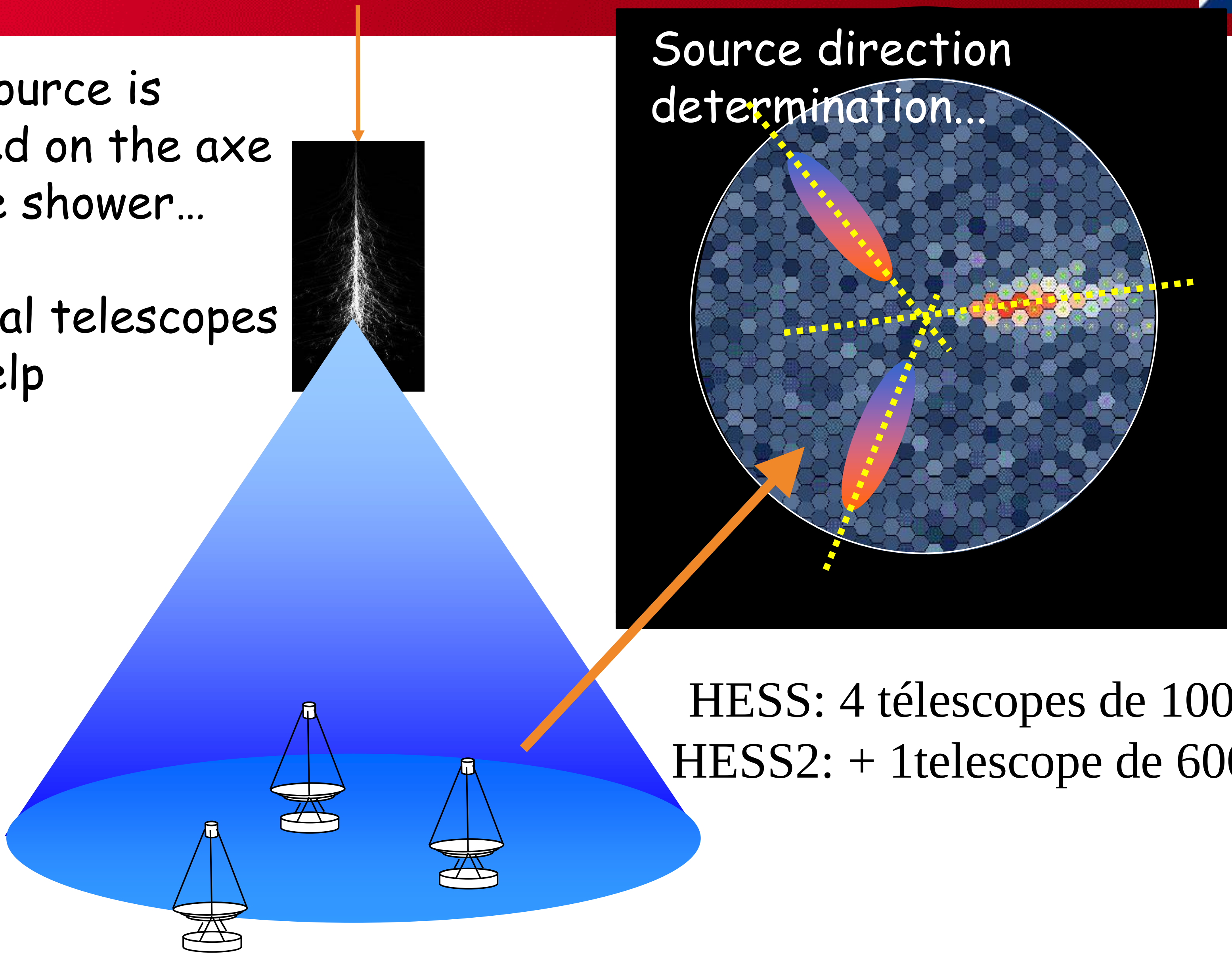




Short exposure time and fast trigger detecting online such pattern are the key ingredients

The source is located on the axe of the shower…

Several telescopes will help



HESS: 4 télescopes de 100m^2
HESS2: + 1telescope de 600m^2

So what do we need

1. A good observational site

2. Array of telescopes to capture the maximum amount of light :
   ⇒ High surface required to reach lower energy
   ⇒ But background incresases for low energy => practical threshold ~30GeV

A high speed camera located @ the focal point of the telescopes with :

3. Good photodectors (sensitive (few Photons) and high speed(ns-scale))

4. High-end electronics: high speed, high dynamic range and low power to be located in the camera

5. Computing power

6. Motivated students and scientists

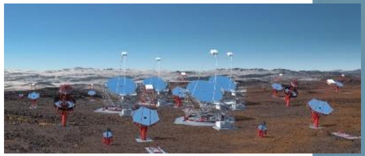
EXISTING AND FUTURE IACT ARRAYS

CTA North (Canary islands) (Project)
4 large telescopes (24m) + 5-10
Medium (12m)

Veritas Arizona
4x10m

MAGIC(Canary islands)
2 x 17m

HESS(Namibia)
4 x 12m: HESSI
+ 1 x 28m: HESS II

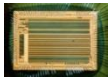


CTA South (Chile) (Project)
30 telescopes
(12m + 6m)

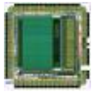
TIMESCALE OF HESS AND CTA

The presentation will now focus on our more recent developments : HESS and CTA

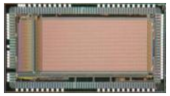
2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	...



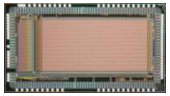
ARS



SAM



NECTAR

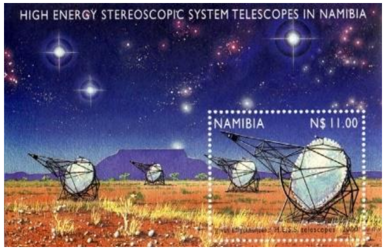


NECTAR2

HESS-I

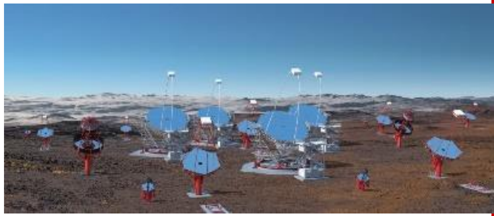
HESS-II

Lower deadtime



HESS-I upgrade

Lower deadtime
Photodetector unchanged

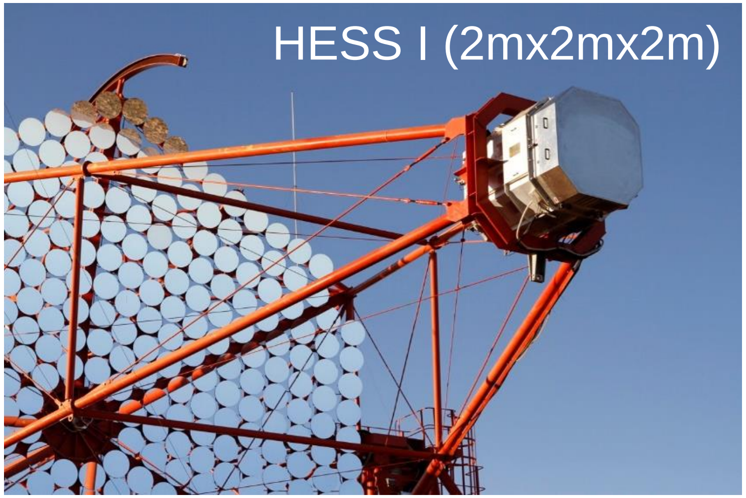


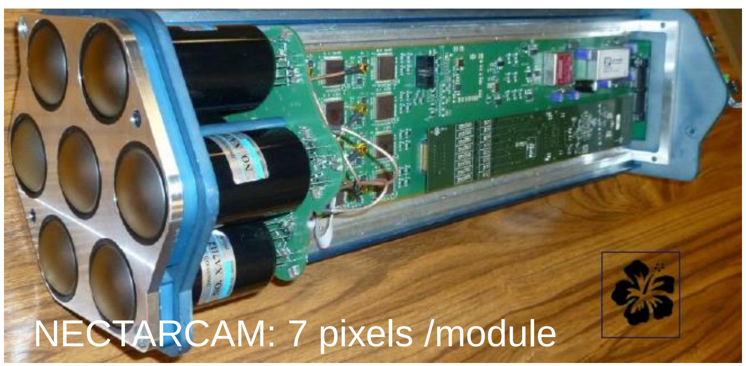
CTA NECTARCAM

Lower deadtime
Faster & more efficient Photodetectors

This talk

What a camera looks like (HESS-I et NectarCAM (CTA))





Module = PMTs + HV + FEB (front end board)

Modules are interfaced to Data Acquisition through ETHERNET.
They are similar to a computer

VERY large device (> 3m x 3m x 2m), 2.5 Tonnes

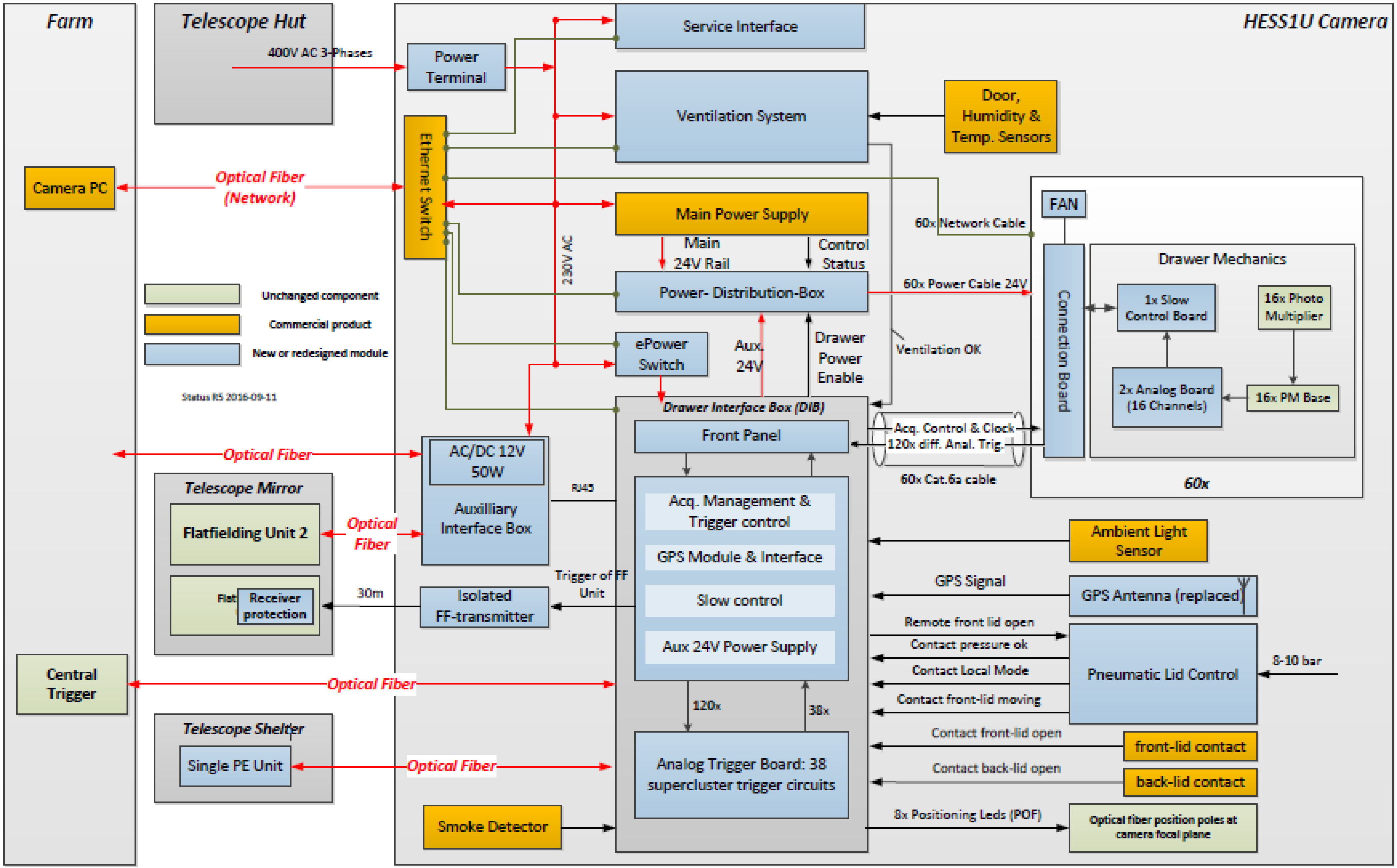
2000 « eyes »

Modular design to **make the maintenance easier** with embeded electronics to reduce number of cables and connectors

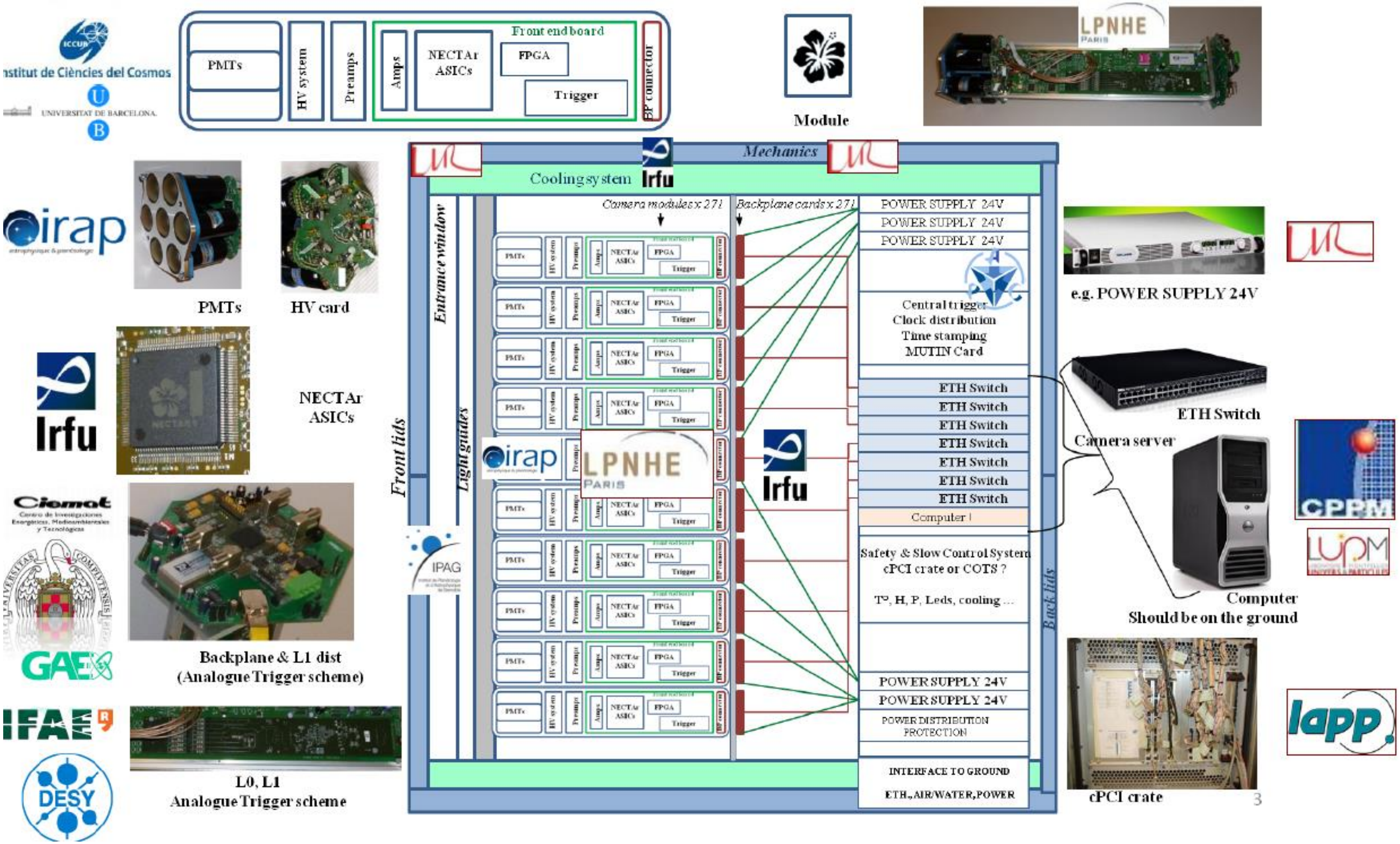
A lot of anciliary functions (HV,LV power supplies, cooling, calibration, synchronisation….)

Reliability is one of the key parameter

A CAMERA SEEN AS A SYSTEM (HESS-I UPGRADED)

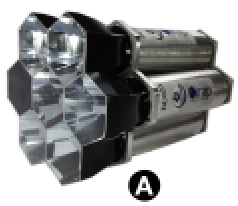


NECTARCAM DATA PATH

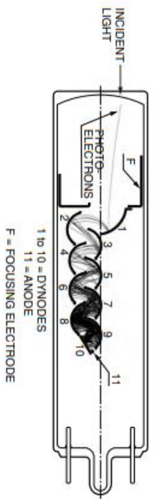


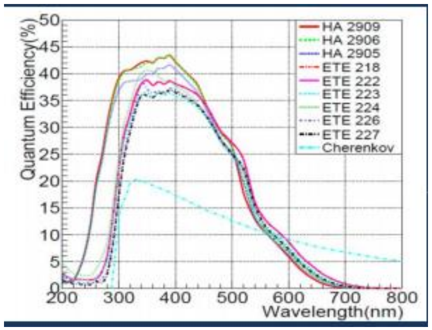
PHOTODETECTORS (1000-2000 PIXELS/ CAMERA)

Winstone cones improve light collection



Photomultipliers

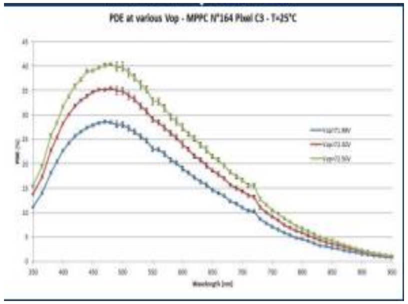




Fast 1-2ns
Good timing precision (1.5ns)
High linear dynamic range (1->4000PE)
Up to 40% detection efficiency.
Response match well Cerenkov spectrum
Low « dark count »
Need a High Voltage
High gain (tuned by HV)
Few providers, still « artisanal » production

The signal from a detected photon is called a « Photoelectron »: PE

Silicon « PMs »

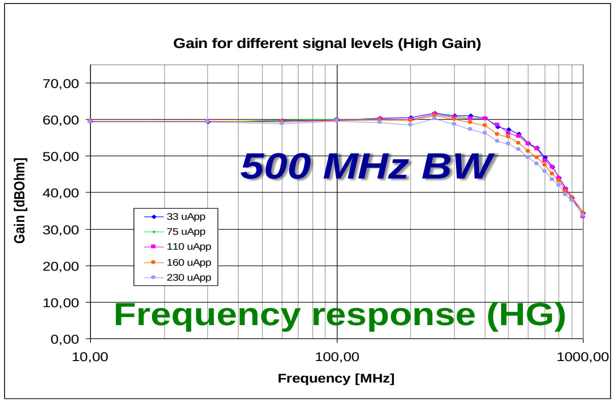


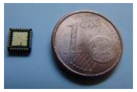
Matrix of avalanche photodiodes, no HV
Now Fast 1-2ns, good timing precision
Moderate linear dynamic range (qq 100 PE)
<30% detection (High QE but low fill factor)
High « dark count » (~100kHz/cm^2)
High T° sensitivity
Semiconductor industry but still expensive

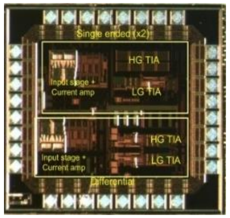
Well suited for small-size focalplanes. Probably the best solution for the future

VERY FRONT-END

- Transfrom the signal from the photodetector (current) in someone we can convert to digital (voltage)
- Could be a simple resistor U=RI !! :
  - Must be small to avoid integration (prop to RC) but must be large to get a large transfer function
  - Used in the past, but low gain : requires high gain operation of the PMT => Ageing
- Provide low active input impedance, then amplify the signal from the photodetector:
  - Example of the PACTA ASIC [Gascon 2011]
  - Allows operation of PMT at low gain (4.10^4) to avoid ageing
  - High Speed (500MHz BW) , Low power Low noise
  - Bi gain (x20,X1) outputs to split the Dynamic range.



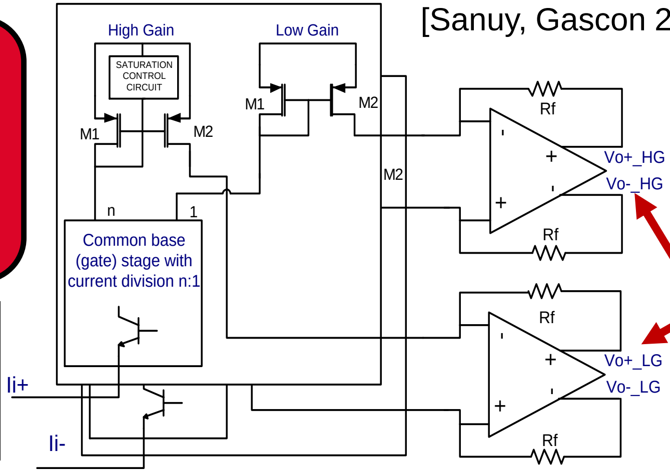




PACTA 2 mm²
BiCMOS SiGe 0.35 um AMS
QFN32 package

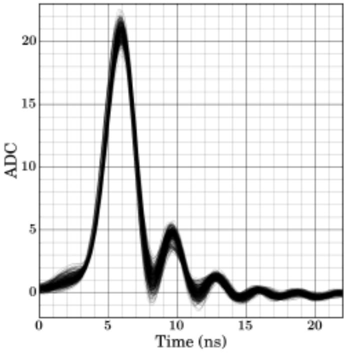
Super common base input: low impedance: optimal and fast current transfer

Current mirror to amplify the current



[Sanuy, Gascon 2012]

Differential drivers



SPLIT OF THE DYNAMIC RANGE

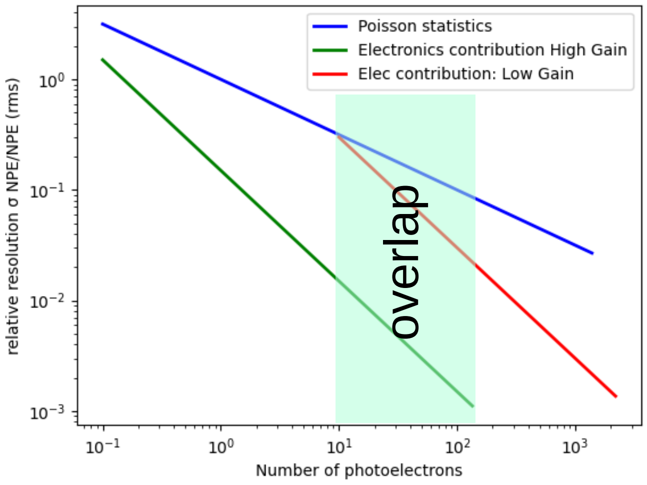
- We have to cover 0.3 to 2000 PE range
- We don't need the same resolution over all the dynamic range.
- For calibration purpose , we need a $\boldsymbol{\sigma_{elec}} \sim 0.15$ PE
- Resolution of the light measurement is limited by the Poisson statistics:

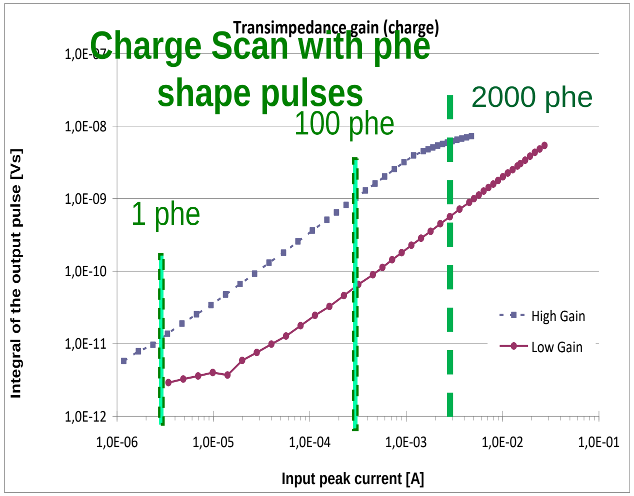
$$\frac{\sigma_{NPE}}{NPE} > \mathbf{1/\sqrt{NPE}}\ \textbf{rms}$$ where NPE is the number of photo electrons

➔ For 100 Photo electrons we only needs a resolution of 10%.

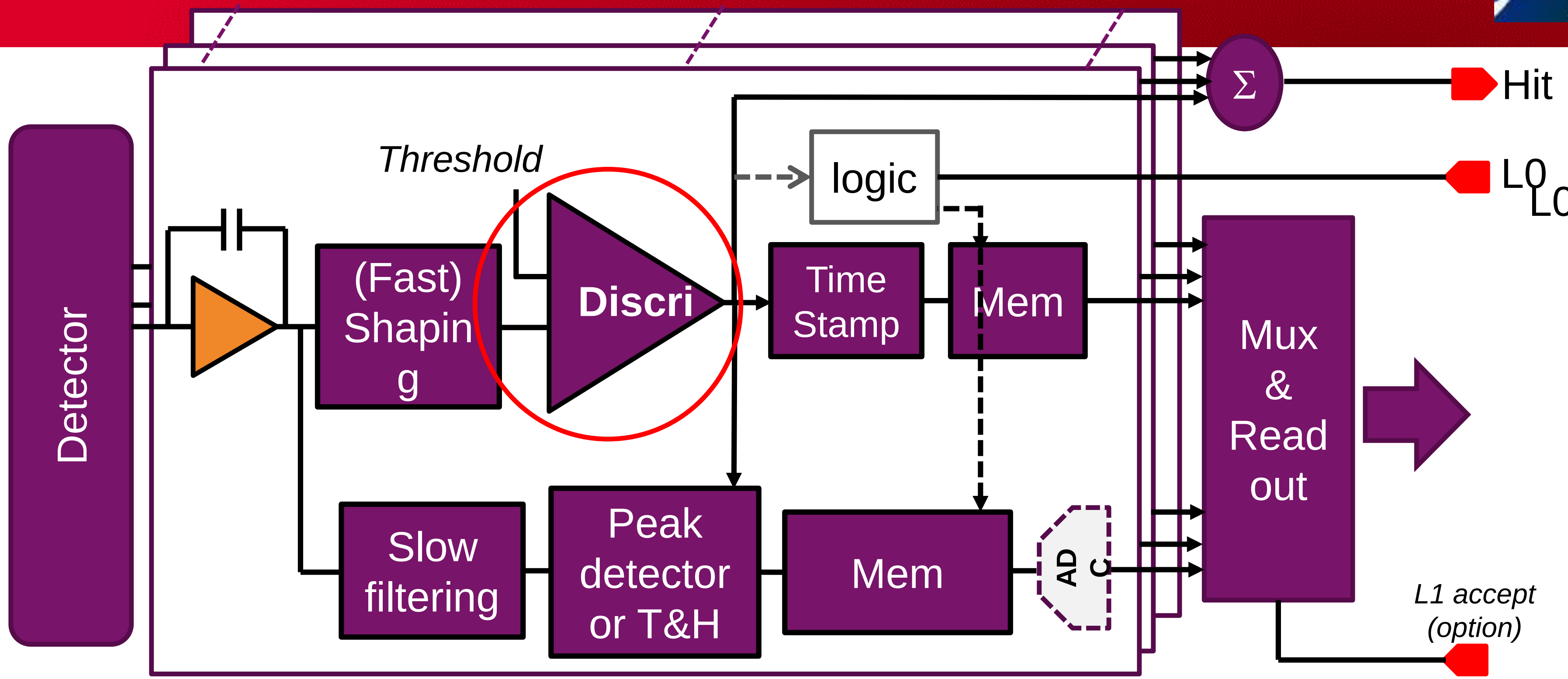
This allows to split the range in 2 parts with lower dynamic => 2 gains with a factor 20

Overlap zone ➔ intercalibration



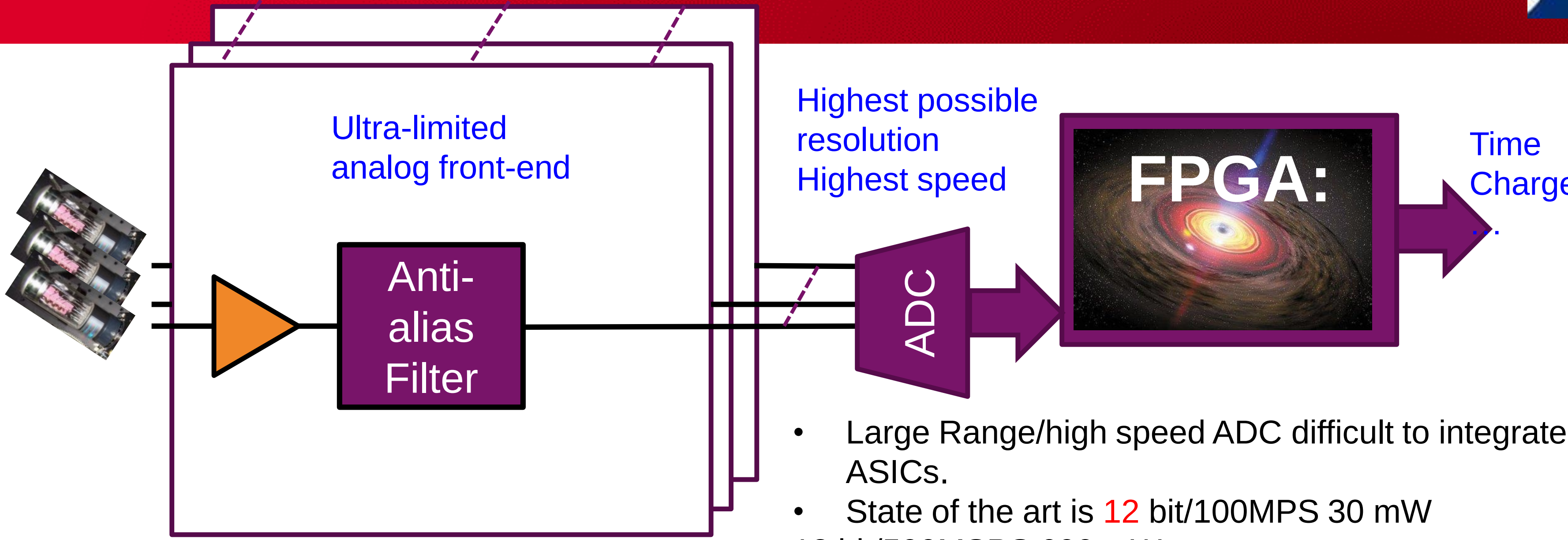


ACQUISITION: THE ANALOG APPROACH



- Optimal data reduction: only the data over the threshold are stored
- Large dynamic range achievable (up to ~14bit with single gain)
- DeadTime depends on the structure of the memories
- Final decision taken very early in the chain by the discriminator
- When threshold is low: - « HIT » rate very sensitive to the noise (power & spectrum
- Pick-up or common mode noise can kill the acquisition
- Low versatility The measurement is done once for all in predefined conditions (shaping)

Acquisition: Go Digital As Soon As Possible



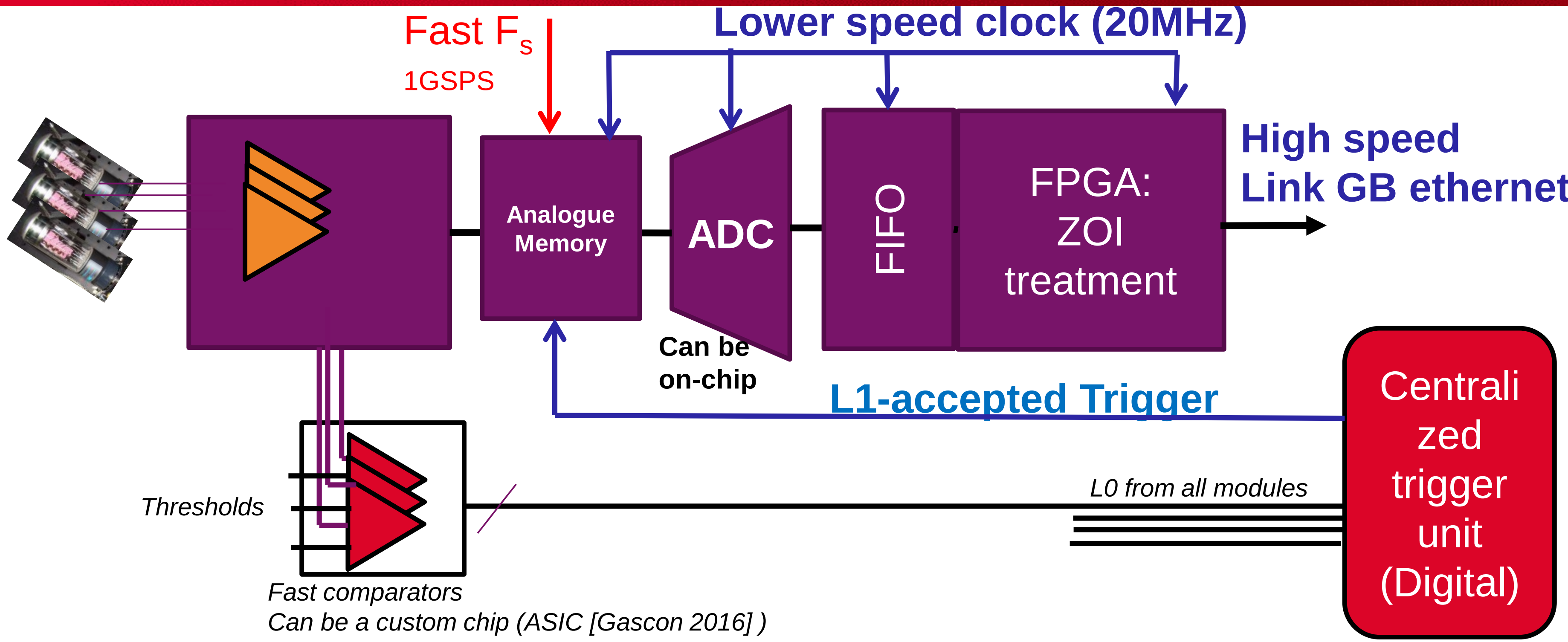
- Large Range/high speed ADC difficult to integrate in ASICs.
- State of the art is 12 bit/100MPS 30 mW

12 bit/500MSPS 600 mW

- **Pro:** **FPGA:** Versatility. Reusability. Ethernet available
  Possible digital filtering before discrimination.
  Optimal filtering for Q and T.
  Digital data available to build complex triggers.
  No limitations for trigger latency: just a matter of memory sizing
- **Con:** Cost of high-end ADC and FPGAs, Power consumption.
  Difficult to reach the ns range

Becomes more and more realistic with the technology evolution
➔ VERITAS & FLASHCAM concept for CTA MST

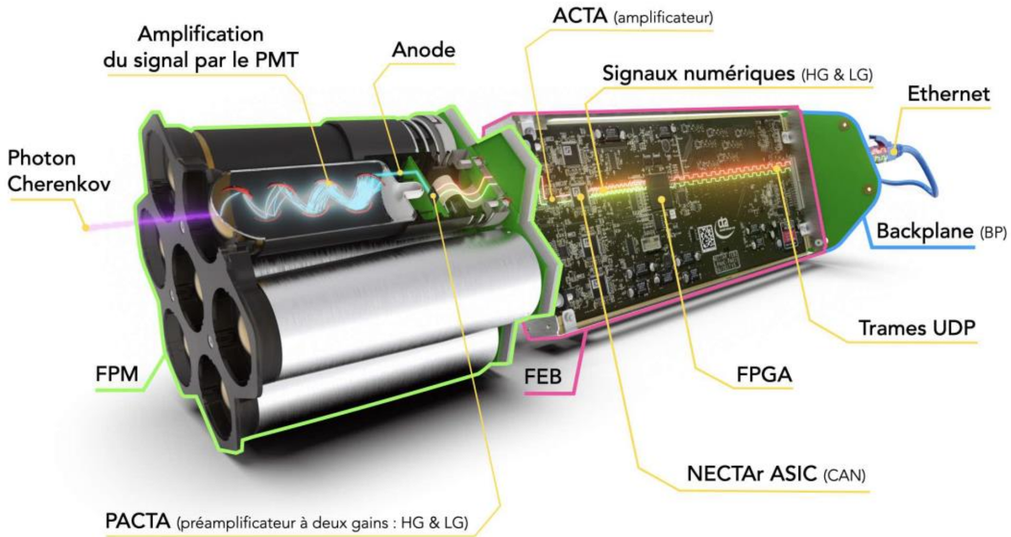
ACQUISITION: THE (SCA) ANALOGUE MEMORY APPROACH

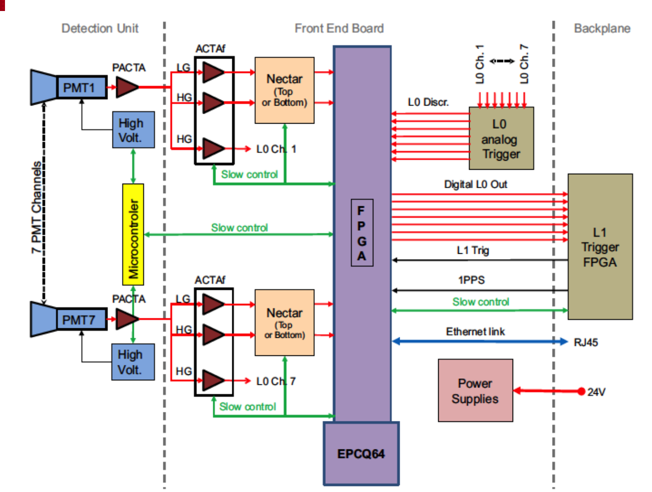


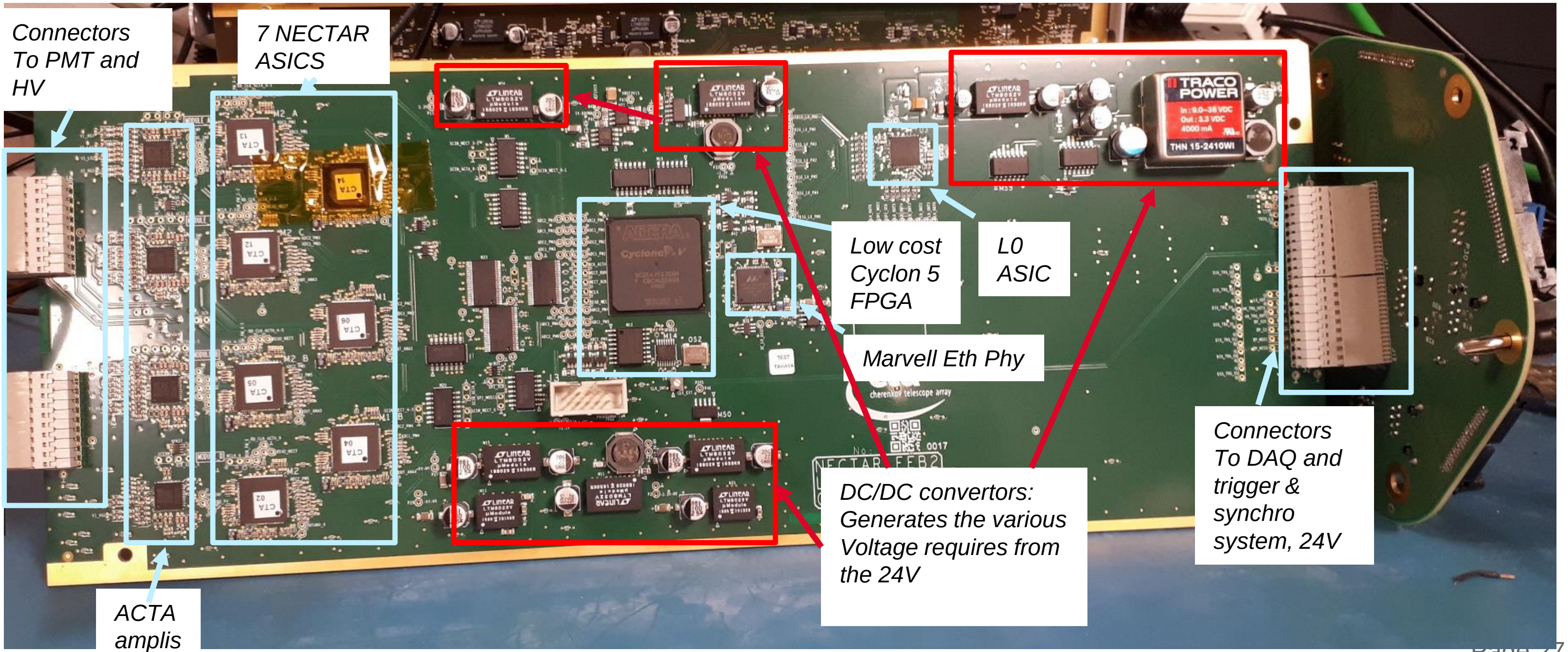
- Analog signal stored at high frequency in an analog memory made of capacitors.
- Read Back on request (trigger) slowly.
- Requires an external path for the trigger: i.e. discriminator (comparators) + trigger unit: can be very fast and versatile. Can also be analog (but more complex)
- Data is available for any possible Digital Treatment ➔ versatile
- Low power ADC & low cost FPGA. Very high sampling frequencies available
- **Complex, deadtime (in the simplest implementation)**

HESS (initial & upgrade 2017), NECTARCAM, LSTCAM

THE REAL FRONT-END BOARD



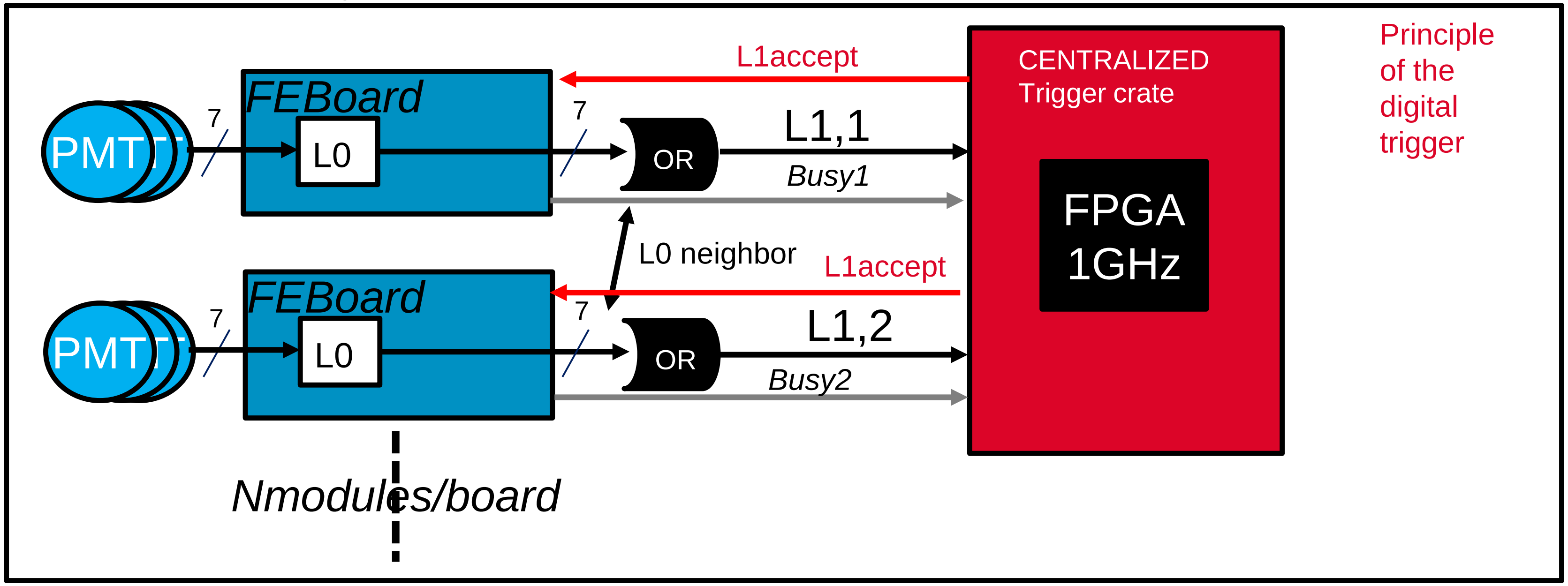




CAMERA TRIGGER

- Goal : detect the events on line in real time
- Detect that several pixel as been touched at the same time
- To be efficient must be fast: (ns range)
- Use simplified information from the camera
- **Require a centralization of the decision: L1 accept**
- **Accept only triggers if all the board are available (note busy) ➔ common deadtime**
- Can be digital (simpler) or analog

- To be used with analog memory : the return time (=trigger latency to return the L1 trigger accept):
  - Must be fast (including the “cabling delays) ➔ can be done in 200ns
  - Must be reproducible at the ns level

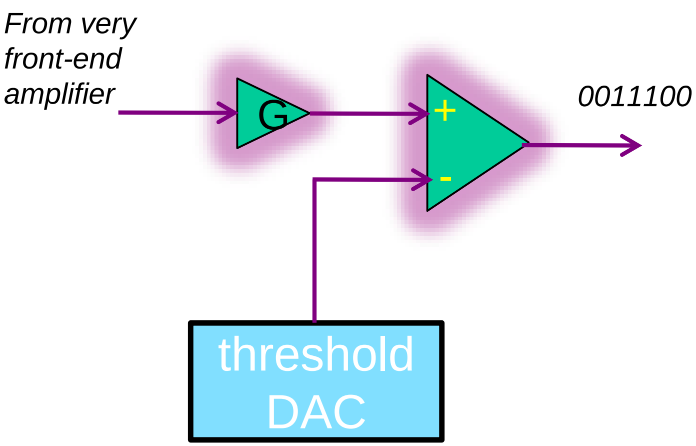


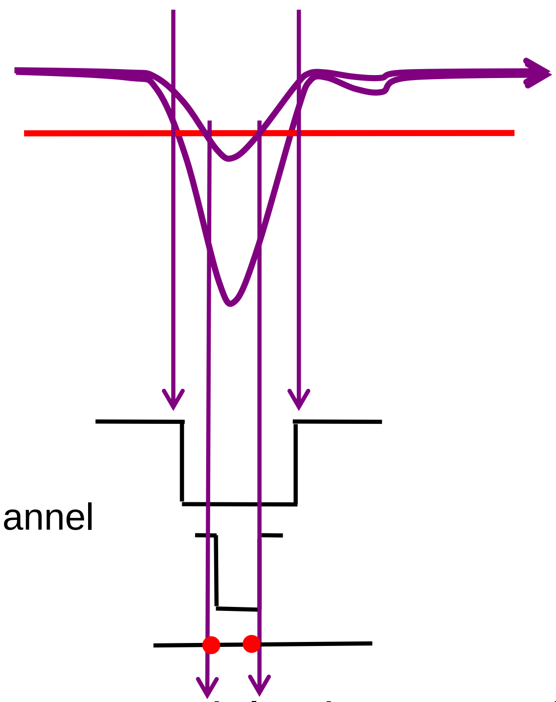
Principle of the digital trigger

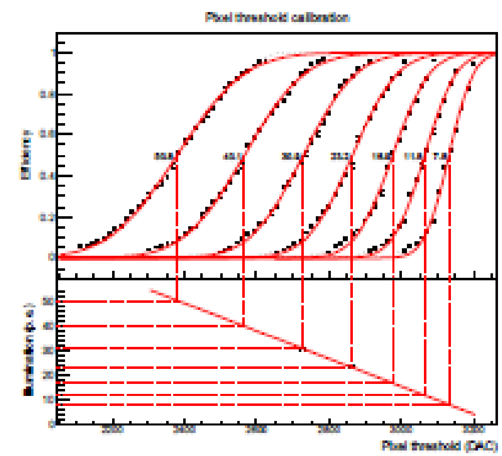
Camera Trigger
First stage

For each pixel : gain + discriminator.

Suffers from “time walk”: triggering time depends on overdrive







Threshold calibration
Using S-curve
(Fit of an erf function)

1. input signal must be as fast as possible
2. Need for sub ns comparators
3. Thresholds must be adjusted channel by channel (gain and offset spread)

   ➔ 1 threshold DAC/channel

Delays must be adjusted channel by channel

Done in FPGA

Low power solution: multichannel integrated in ASICs

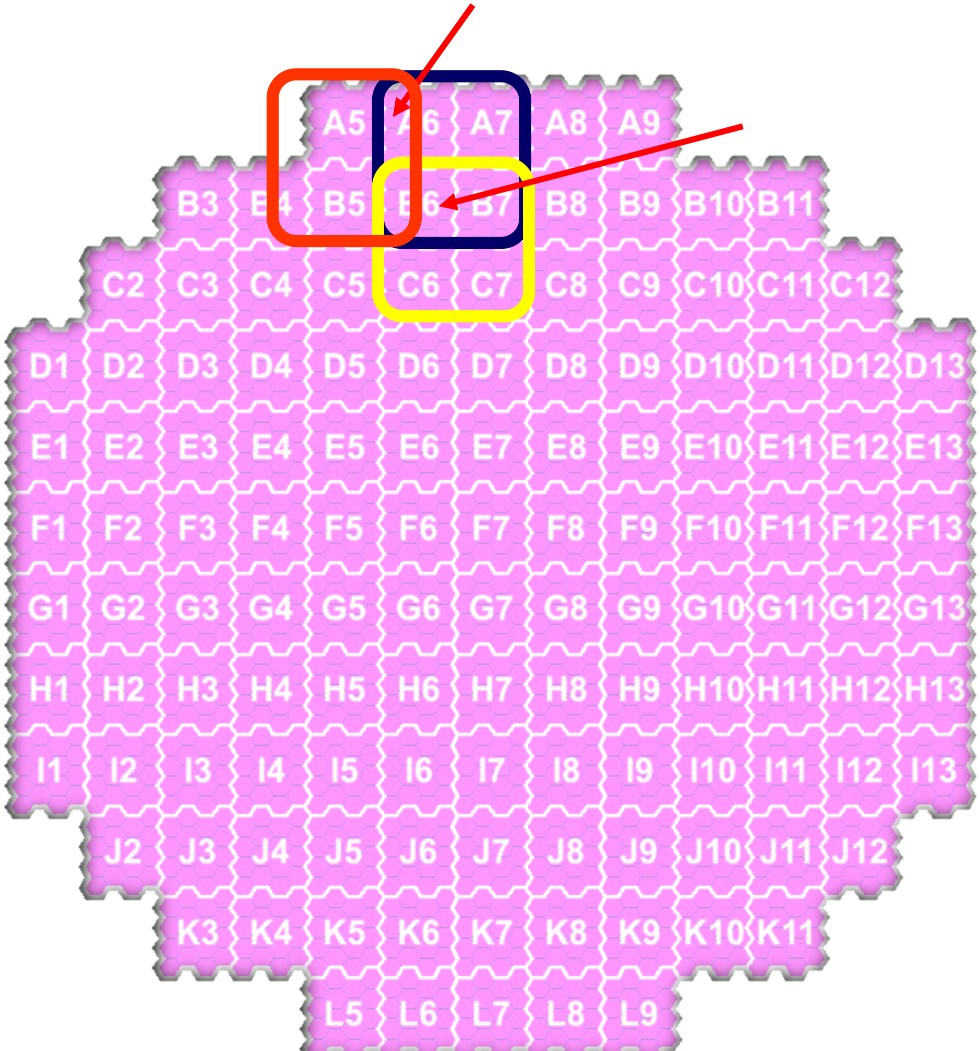
delay is ~proportional to the energy signal above the threshold

DIGITAL (SECTORING) TRIGGER

Very fast logic timing

Sliding Windows

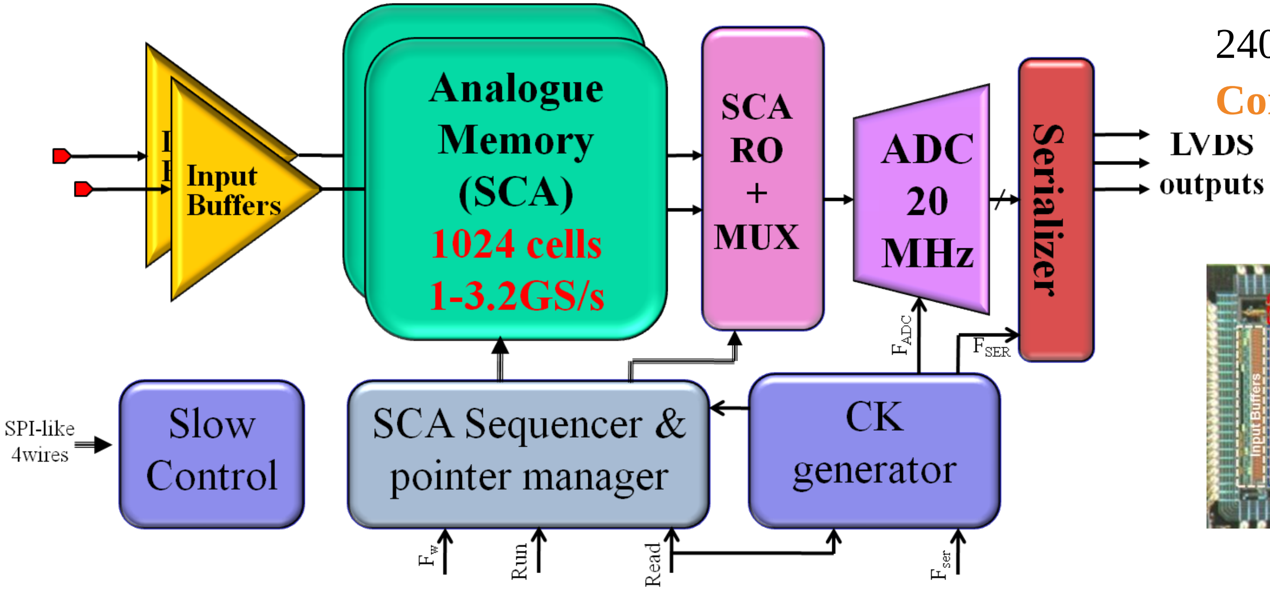
…and expect a minimum energy deposit



So we program:
- **#pe/pixel (Front-End Boards)**
- **#pixels in sectors**

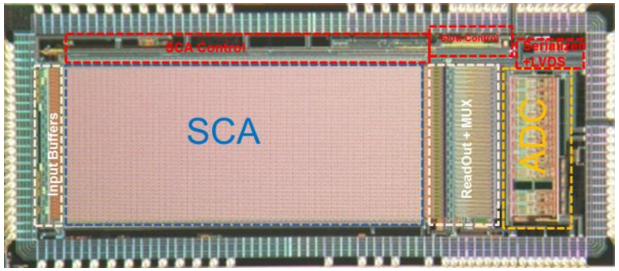
The NECTAR chip

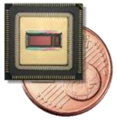
[Naumann,Delagnes 2012]



240Mbit/s LVDS serial output

Compatible with low cost FPGA

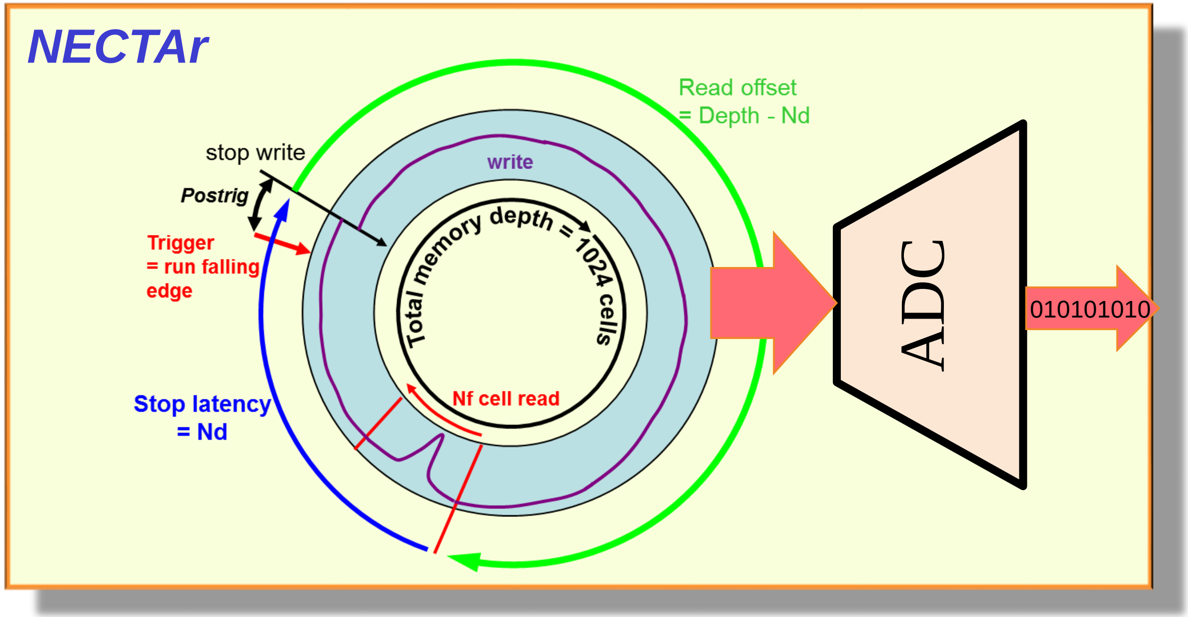




3mm x 7mm
AMS CMOS 0.35µm
QFP128 14 × 14 mm² package

- **4** SCA channels **=> 2** fully differential channels
  => **1 PMT channel in BiGain operation**
- **1024** cells/SCA channel **(1µs max latency @ 1GSPS, 0.5µs @ 2GSPS)**
- Output data directly usable for calculation (without pedestal/gain spread correction)
- Low input capacitance < 5pF including package thanks to input buffers
- Power management: write part powered down during RO/digitizing & vice versa

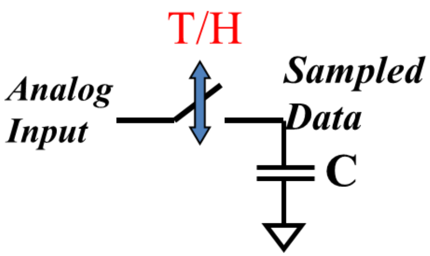
SCA used as Level1 latency buffer : back in the history

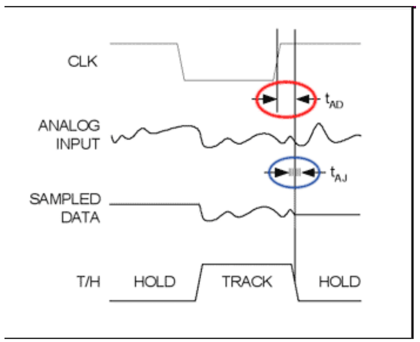


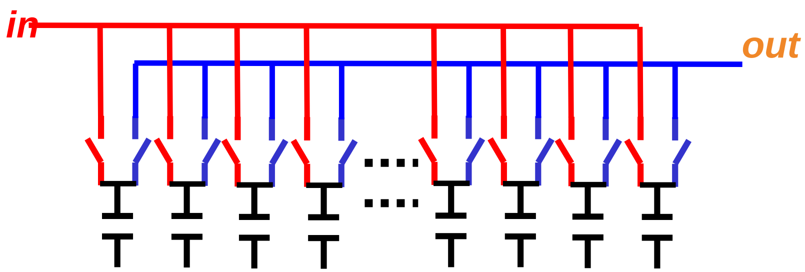
- Signal continuously sampled @ FS (0.5 – 3 GSPS) rate in the memory use as a circular buffer of 1024 cells
- When trigger arrives (after a fix latency): Sampling is stopped & position of the trigger is marked
- Start readout and conversion (@20MSPS) of a ZOI of NF cells (16 to 60) starting from a the trigger cell + ND (corresponding to the trigger latency modulo 1024)
- Readout takes 2(8)µs for 16(64) cells: during this time the system is “dead”

INTRODUCTION TO SWITCHED CAPACITOR ARRAYS

- **Introduction of Analog Memories for HEP experiments at the end of the 80's by S. Kleinfelder.**
- **Principle: Sample & Store an incoming signal in an array of capacitors (SCA), waiting for (selective) readout and digitization= bank of Track & Holds**



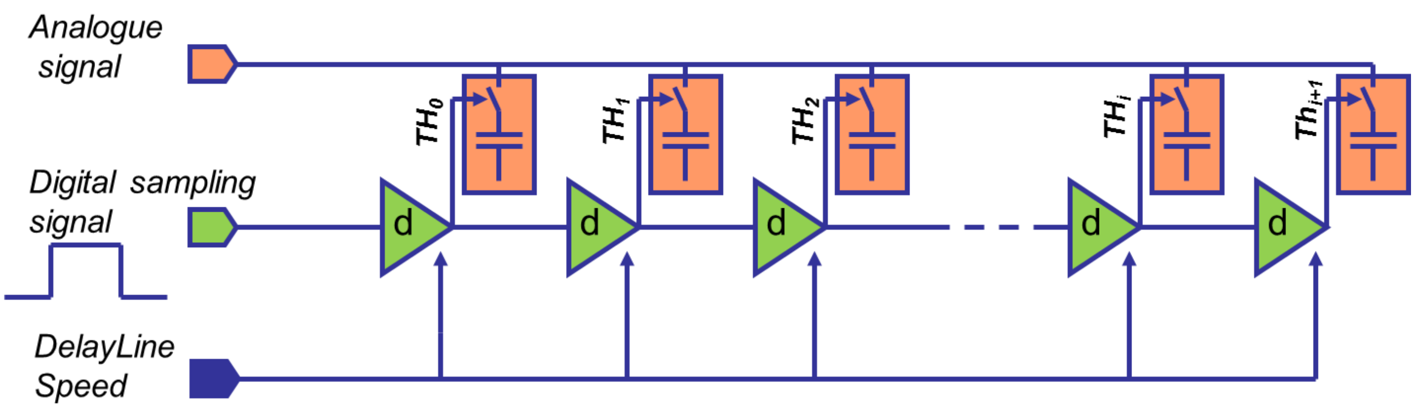




- **High integration: 12 to 128 channels, depth of few hundred cells.**
- **Naturally compatible with CMOS technology.**
- **High dynamic range possible.**
- **Low power (few 100µW/ch).**
- **In first designs Sample & Hold commands generated by shift registers clocked in the 10-100 MHz range => Sampling frequency limitation.**

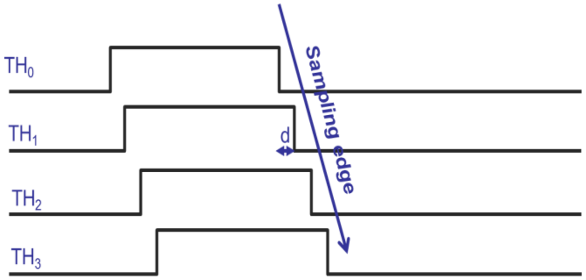
SCA 1.0

- Introduced in 1990's again by **S. Kleinfelder** (ATWR, ATWD chips).
- The Sample & Hold commands are now generated using a pulse propagating through a delay line with $\mathbf{N_{TAP}}$: $F_s = 1/d$ => multiGSPS operation possible even in ~1µm technologies.



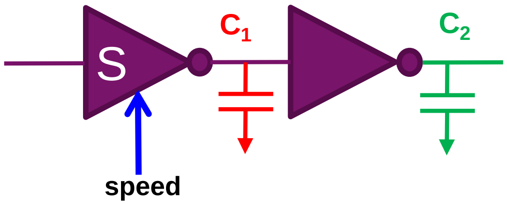
- F_s tunable through an analogue command
- In the early designs:

The digital sampling signal input was a single pulse = trigger => need for an analogue delay (cable) on the analogue signal path to generate the "Pretrig" (delay > latency).

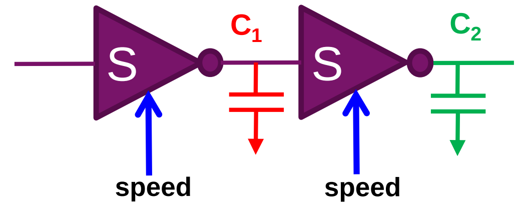


Delay element zoology

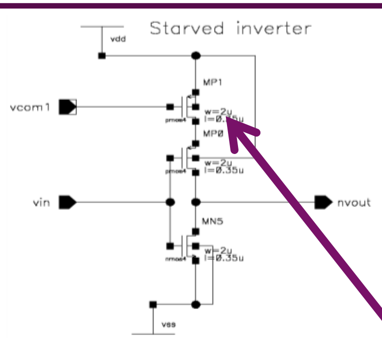
Basically the same as those used in digital TDCs, cascade of **inverting** cells :



Fast.
2nd inverter reshapes the signal => sampling edge always sharp

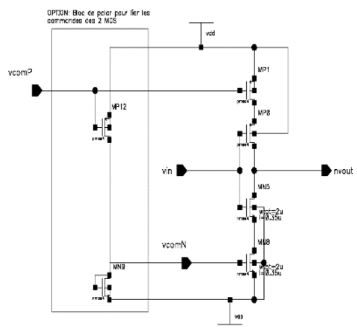


Slower
Symetrical egdes if C1=C2

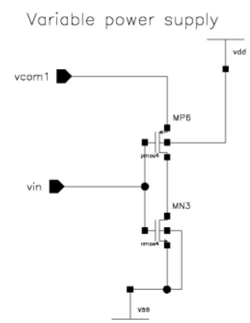


$$t_p \propto t_r = 2.C_l.Vdd.\frac{L_{MP1}}{W_{MP1}.K_{MP1}.(V_{GS\,MP1} - V_{TH})^2}.$$

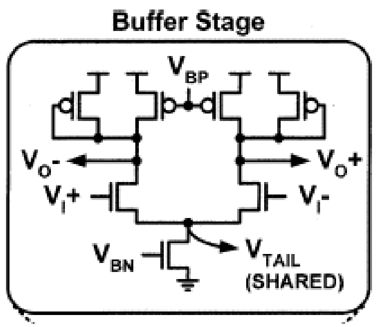
Only the rising edge is slowed down



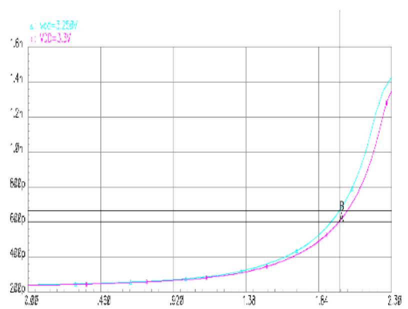
More symetric output



Highest speed, but requires low impedance command



Differential. Low jitter. But Static power.



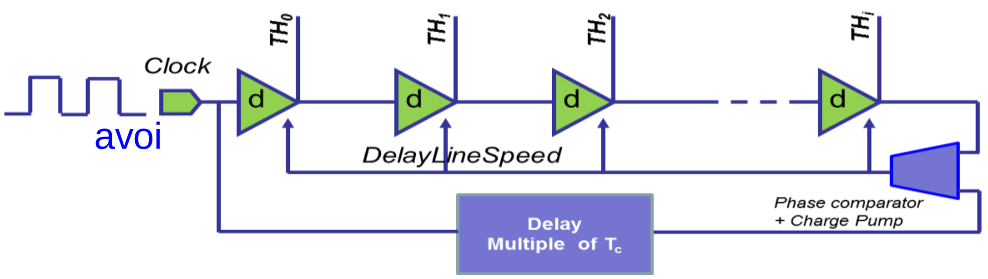
Modulate PMOS conductance is better for low jitter.
$\Rightarrow$ Separate Vdd for DLL only.
$\Rightarrow$ Vdd – Vcommand easy to filter

SERVO CONTROL

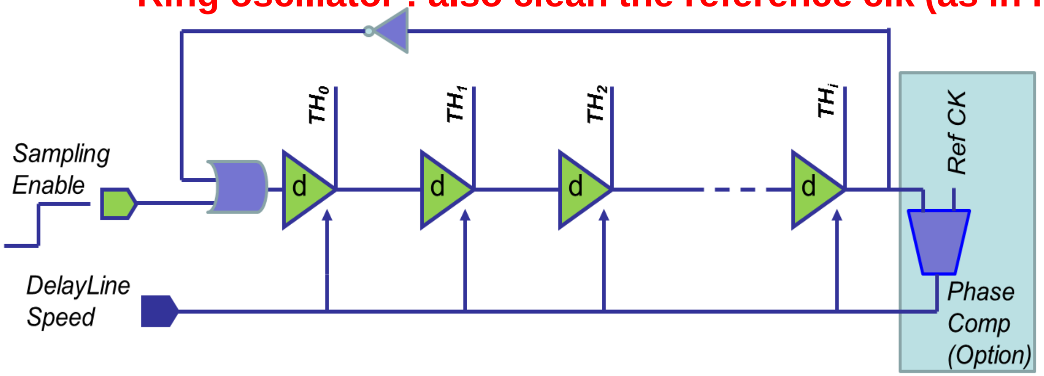
- To avoid the delay cable: generation of a continuous clock (virtual multiplication)
- A rotating sampling pulse is required. Several designs proposed
  - **Pulse regeneration**

    - A new pulse is generated at input with a $d.N_{TAP}$ periodicity

    => $d.N_{TAP} = N.T_c$ period of an external clock.: servo-control with phase comparator



  - **Ring oscillator : also clean the reference clk (as in PLL)**



Servo-control using a phase comparator

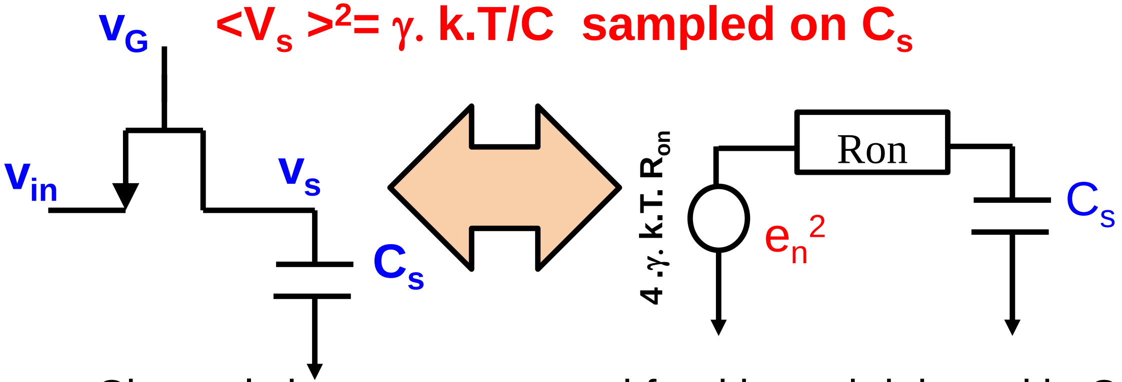
avoids drifts due to temperature, change in power supply

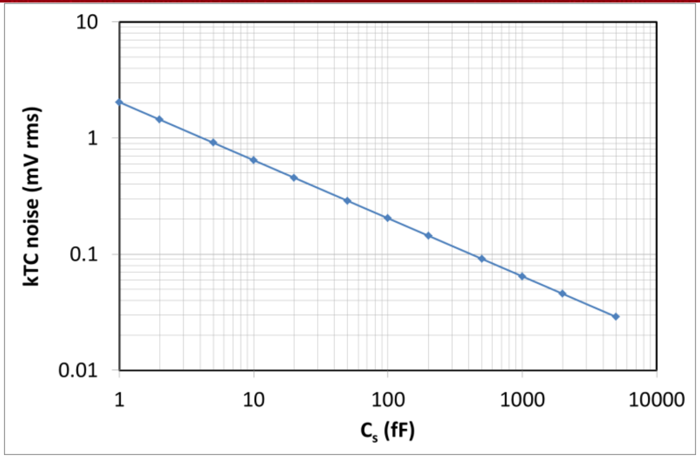
➔ Allows to reach ~10-20ps jitter/ stability without correction

How to design the Storage cell: noise

- Noise: absolute noise limite = kTC noise

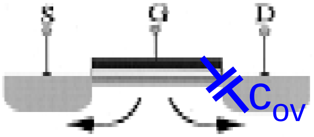
$<V_s>^2 = \gamma . k.T/C$ **sampled on C_s**





- Channel charge + command feedthrough injected in Cs when sampling:

$$\Delta v_s = \frac{k.W.L.Cox.(VG - Vin - VT)}{2.Cs} + \frac{(VDD - VSS).Cov}{C_{ov} + Cs}$$

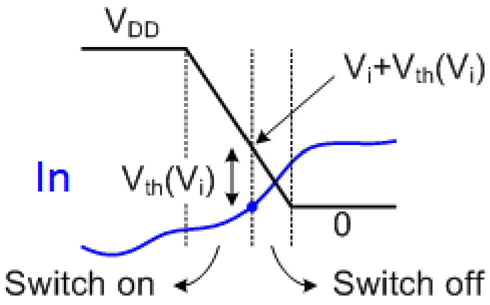


  - First term dominant
  - ~ proportional to $1/C_s$ and to the R_{on} of the switch (if L min)
  - At first order: constant + a term proportional to V_{in} =>Offset + gain different of 1.
  - But transistors mismatches => Offset & gain spread along the SCA.

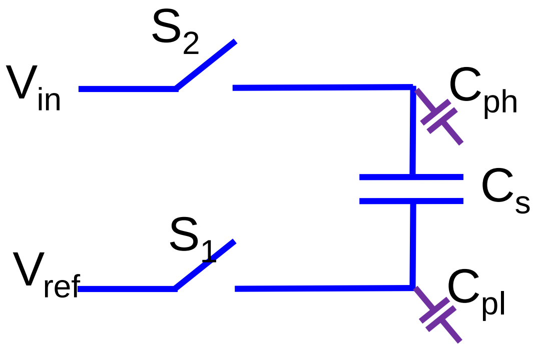
    => Possible calibration & correction
  - “Dummy switch” technique inefficient => increase of the spread.

Large C_s is good for noise & uniformity !

BOTTOM PLATE SAMPLING



- Edges of the switch command is not infinitely fast.
- Transistor cutoff at $V_G = V_{in} + V_T$
  - =>Dependency of the sampling time with Vin
  - => Distortion, Jitter.
- For a 100ps edge => 50ps error possible !
- Solutions: Bottom plate Sampling :

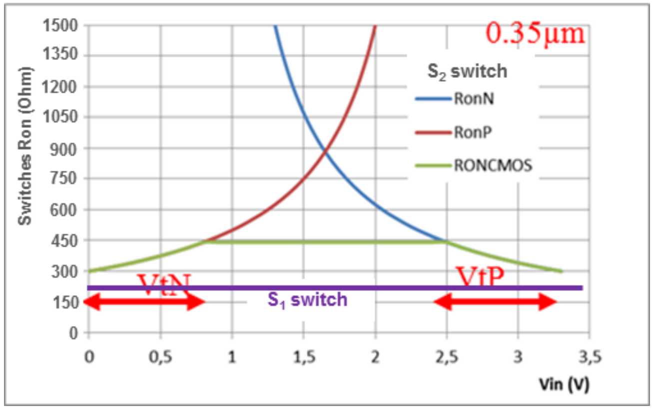


- S_1 has a constant source voltage
  - S_1 opened before S_2 => sample
  - Aperture time now independent of V_{in}
  - If “flip around” readout, the charge injected by S_2 is cancelled
    - => Charge injection does not depend on V_{in} .

- **Drawbacks:**
  - => S_1 added in serie => lower BW.
  - => generation of S_1 command
  - => Less compact cell => more parasitic capacitance

HOW TO DESIGN THE STORAGE CELL: BANDWIDTH

Cell BW set by Rswitch x Cs

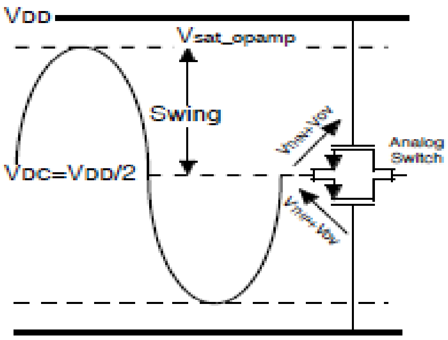


- Minimum L for max Ron with smaller parasitics.
- Ron highly non-linear for a single NMOS and PMOS transistor
- BW_{cell} vary with Vin => distortion.
- BW_{cell} is affected by transistor mismatch

To limit these effect BW_{cell} should be >> system BW

- Possible strategies to limit distortion:

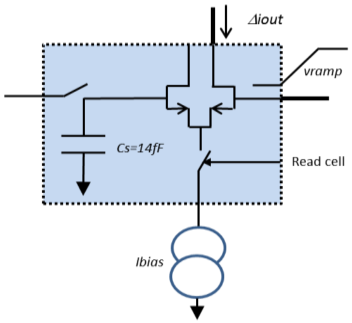
  use NMOS + PMOS in //



NECTAR: S_1 & S_2 switches
$R_{S1}+R_{S2}$ = 600 Ohms
BW_{Cell}= 820 MHz (300fF)

small C_s is good for high BW: tradeoff with noise => Cs =300 fF

Cell readout

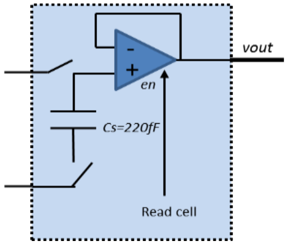


Current discharge Wilkinson readout

The cell is discharged at a constant current. Measure of the time of discharge with a counter ➔ conversion to digital

Counters & ramp generators can be inside or outside the chip

Parallel digitization of several cells. Need for one offset & one gain/cell

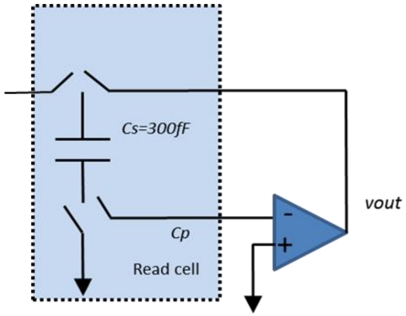


Voltage readout

1 buffer/cell (cut when not used) => low power

Multiplexing toward an external ADC

Need for one offset/cell (gain/cell)



« Flip Around » Readout:

cancels injected charge

Very well defined gain

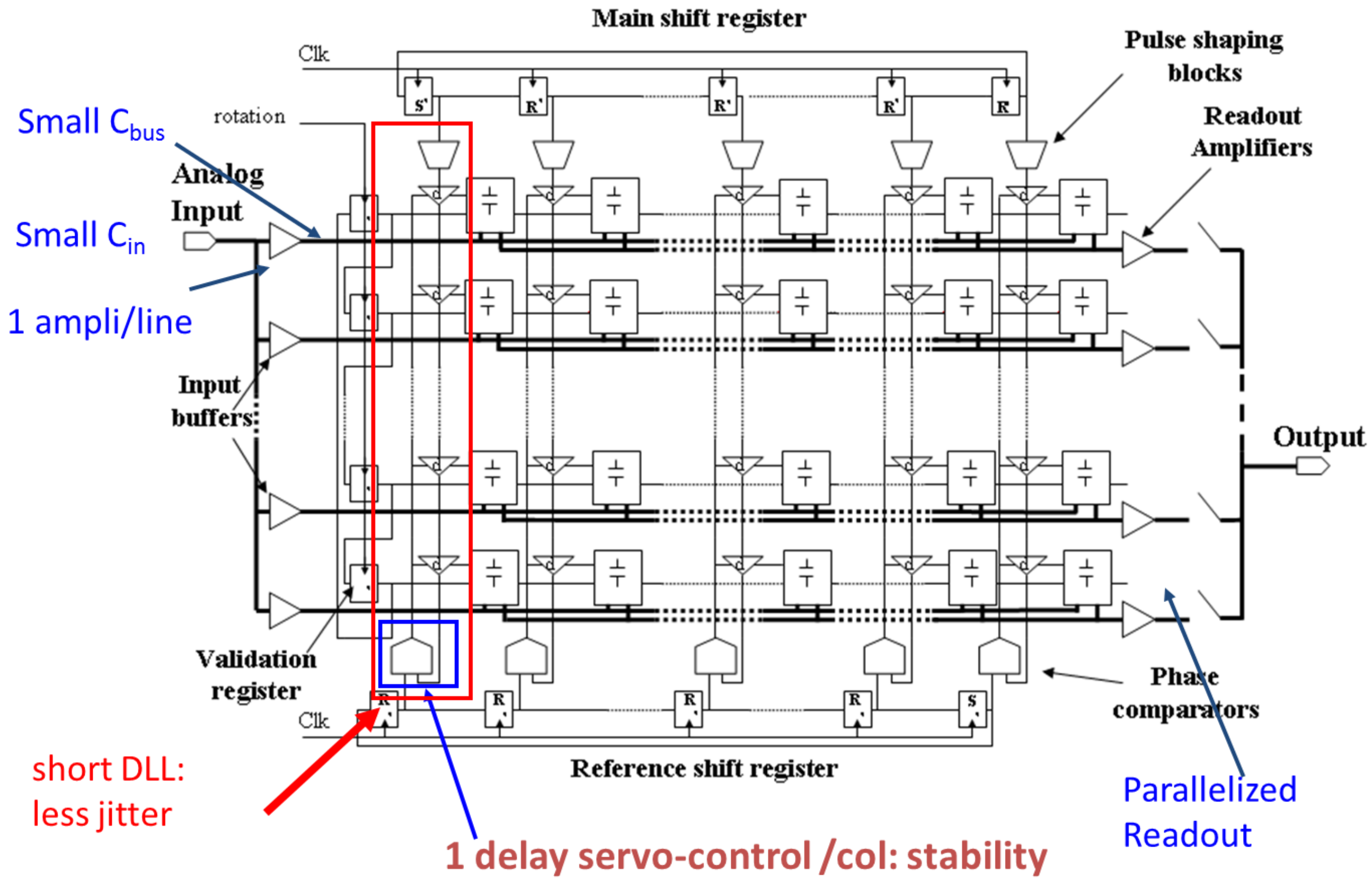
1 ampli/ line of cells => critical design very sensitive to C_p

=> speed

=> noise (amplified by $(C_p+C_s)/C_s$

Multiplexing toward an ADC (on-chip in NECTAR)

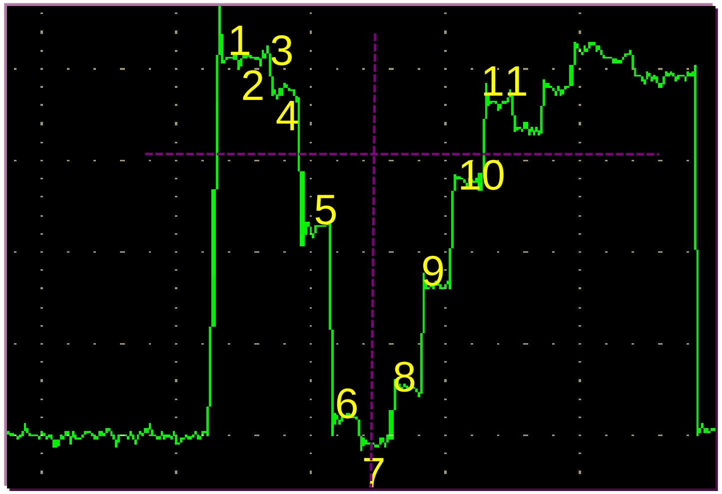
THE FINAL STRUCTURE OF THE NECTAR SCA: 16 LINES OF 64 CELLS X 2 (DIFF) X 2 CHANNELS

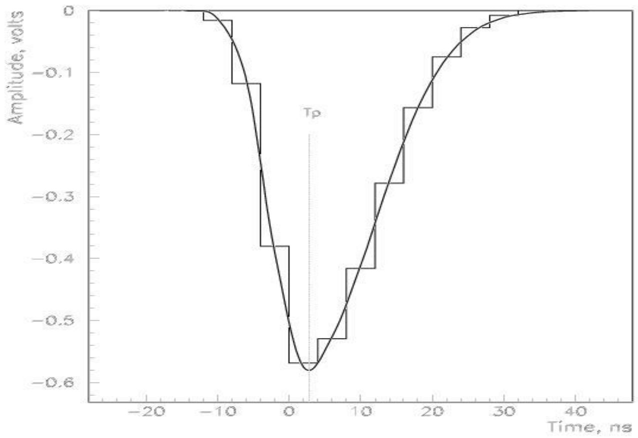


Advantages: robustness => only 1 pedestal/Line to calibrate.
good timing (18ps rms) even with no calibration.

Drawbacks: complexity . Not scalable to a large number of channels/chip

AT THE OUTPUT OF THE SCA





ANALOGUE FRAME

Digital FRAME

Need to be converted to digital by an ADC (analogue to digital converter)
Choosen architecture : PIPELINE ADC

well suited for the resolution/speed/power consumption requirements

(12 bit /20MHz/ 30 mW) in the CMOS 0.35µm technology

PRINCIPLE OF THE PIPELINE ADC

F. Rarbi, D. Dzahini, L. Gallin-Martel, *"A power efficient 12-bit and 25-MS/s pipelined ADC for the ILC / Ecal integrated readout"*, IEEE Transactions on Nuclear Science, vol. 57, n°5, Oct. 2010

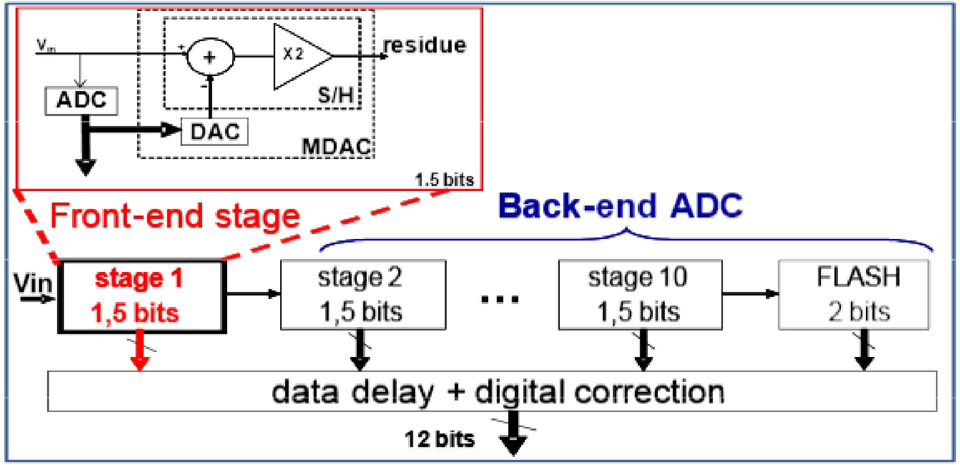
- Fully differential design, 2V full scale
- Cascad of :

 -10 1.5 bit-MDAC stages

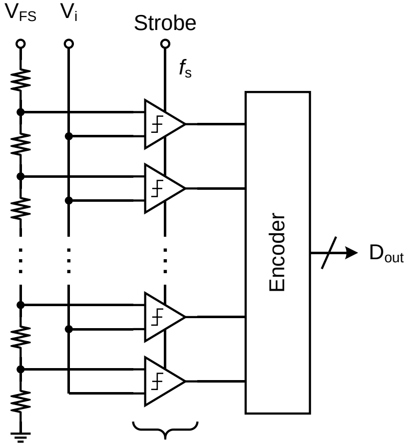
 - 2 bit flash ADC

Even and odd stages operated on oposite clock edge

⇒ Low latency : 6 clock periods to convert



EXCELLENT LINEARITY (INL+4 LSB, DNL=1 LSB)



Less significant bits extracted by a flashADC = 4 comparators + encoding logic

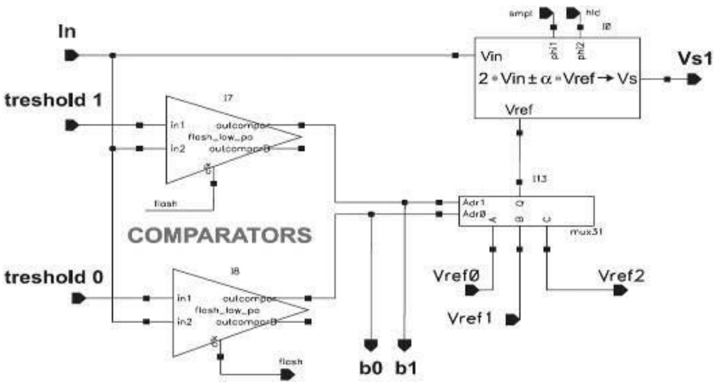
Flash requires 2^N -1 comparators to extract B bits

➔ impossible for 12 bits (would required 4095 comparators)

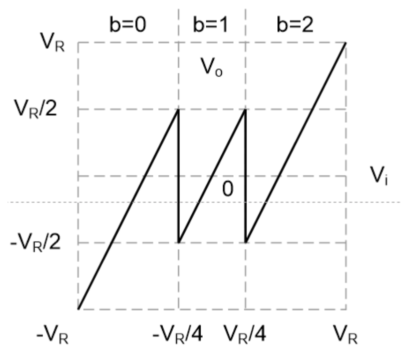
➔ Use of pipeline based on Multiplying DACs (MDACs)

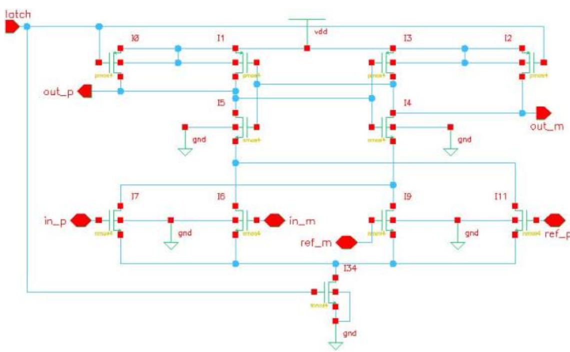
1.5 MDAC:

- Compare the input to 2 thresholds => 3 values of **b**
- Depending on **b** subtract 0, a + reference or a – reference
- Multiply the result by 2 to obtain the residue sent to the next stages



1.5 bit MDAC





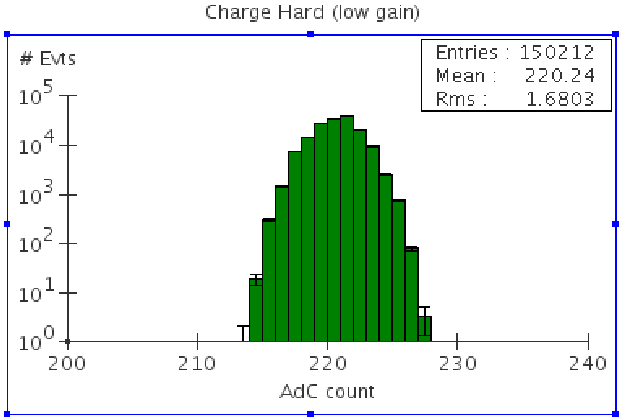
Dynamic comparator

Extract 1.5 bit offers redundancy (range of consecutive stages are overlapping)

If a stage makes an error it can be corrected digitally => allow the use of low precision (low power) comparators

NECTAR CHIP PERFORMANCES

- All the results obtained in nominal conditions include limitations due to external components (ampli, DC-DC…)



- Chip power consumption =210mW
- Behaves has expected for 0.5 - >2 GSPS
- ADC range = 2V /12bits => ADC LSB=0.49mV
- Noise for one sample (random position in the matrix):

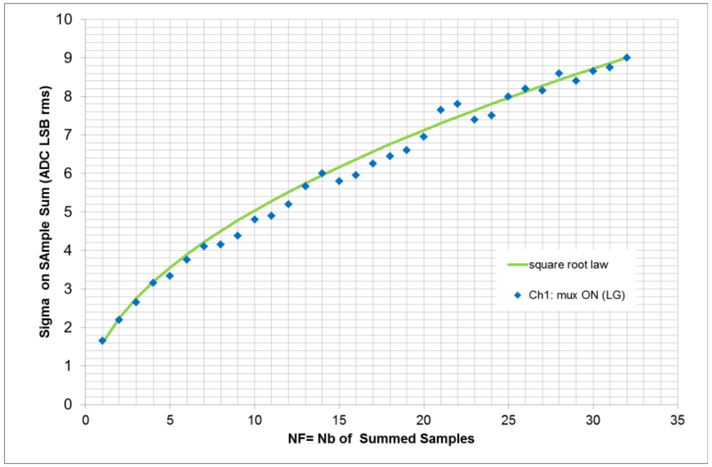
0.8mV rms (1.7LSB) (no offline correction)

=> 11.25 bit rms Dynamic Range

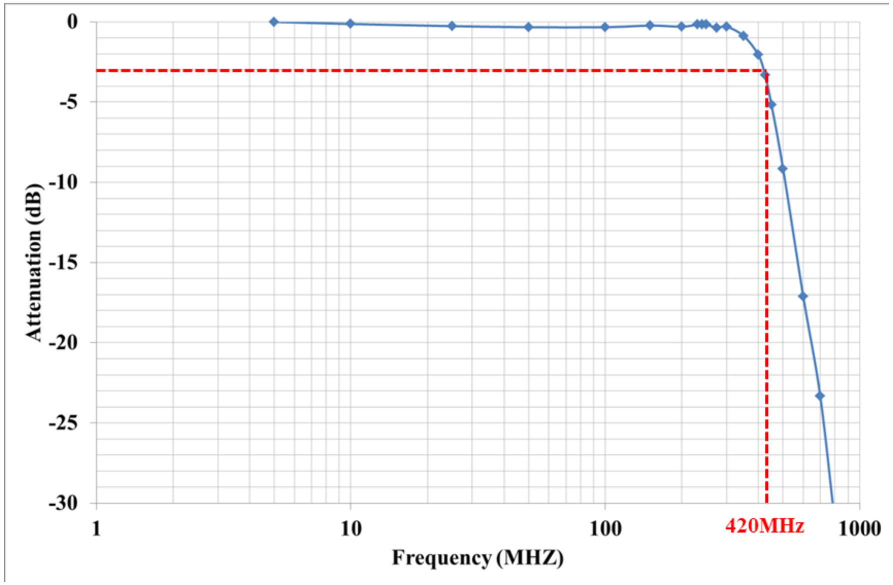
Sigma(Sum) follows square root law

$\Rightarrow$ No noise correlation between samples

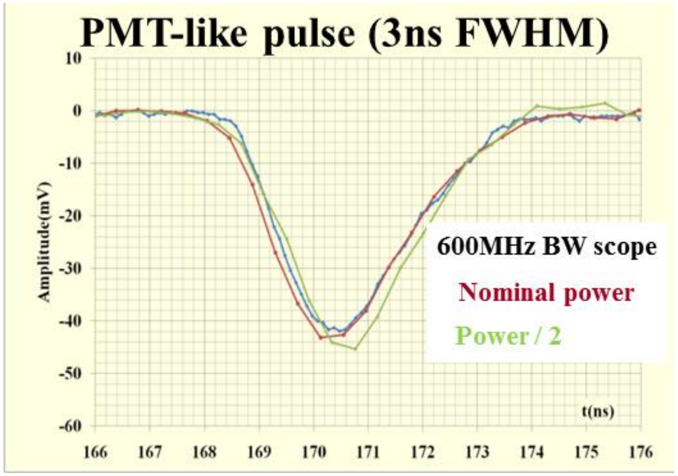
$\Rightarrow$ Important for charge calculation



NECTAR: FREQUENCY RESPONSE



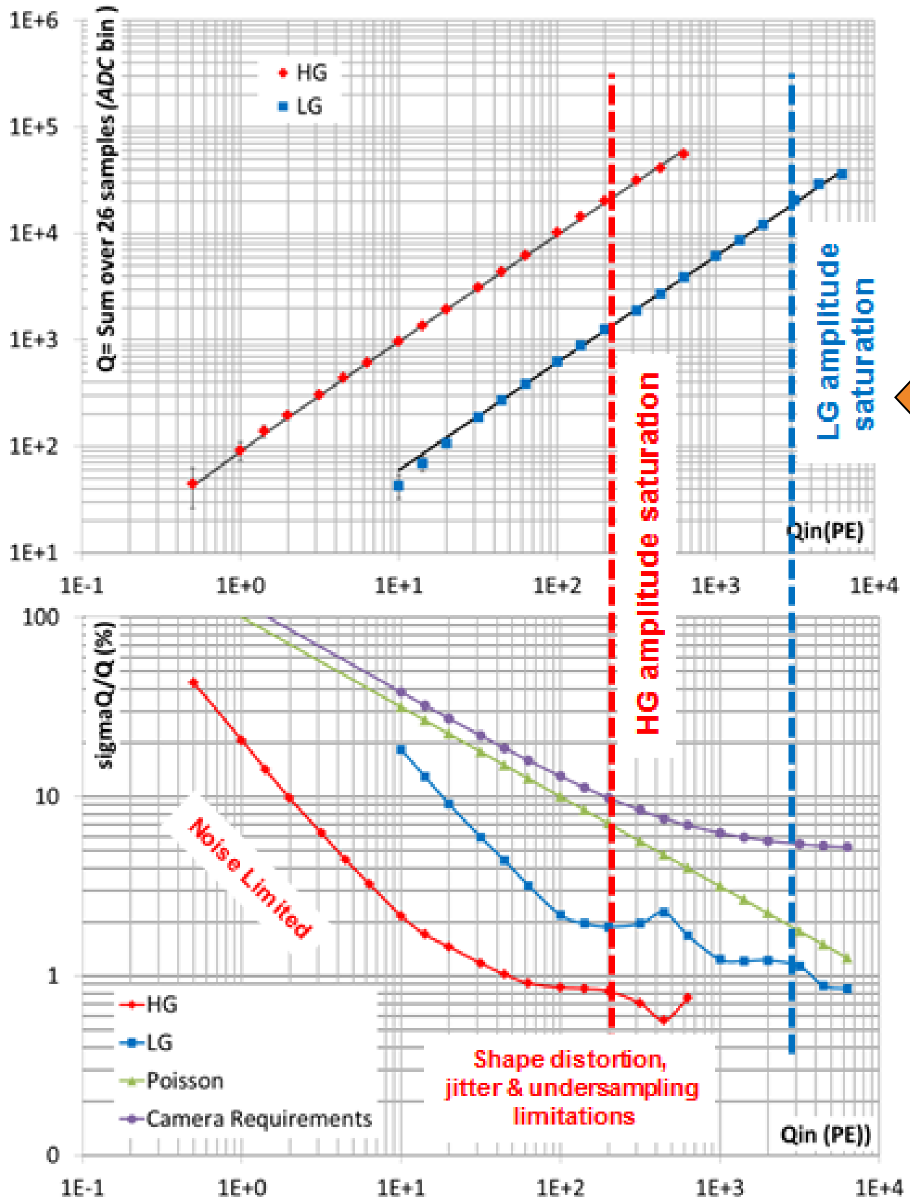
- 800 mV Peak-Peak sinewave input
- Very flat response
- -3dB Bandwidth > 400 MHz
- Remains >300MHz for 2V pp



<=Template signal used for NECTAR characterization

<= NECTAR response (nominal and /2 power) compared with 600MHz BW oscilloscope

NECTAR0: Charge Linearity Scan with PMT-like Electrical Signals



Charge calculated over 26 samples (13ns)

HG saturates in amplitude @ 200 PE
LG saturates in amplitude @ 3000 PE.

INL<3% up to 6000 PE

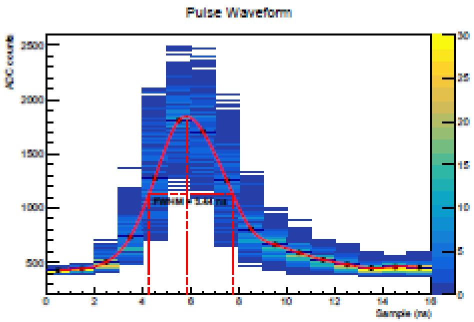
resolution on PE

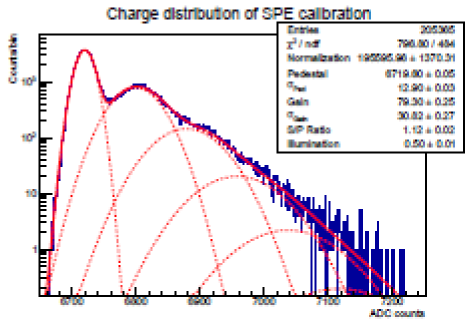
- 0.8% Floor resolution for large signals on HG consistant with sampling jitter < 40ps rms
- Q resolution far better than fluctuations of Poisson statistics (and requirements)

PERFORMANCE SUMMARY

	NECTAr Features or Performance	Requirements	Unit
Number of Channels	2		Differential channels
Memory depth	1024		Cells
Power Consumption	< 210	<300	mW
Sampling Freq. Range	0.5 - 3.2	0.5-2	GS/s
Analogue Bandwidth	400	>300	MHz
Read Out deadtime time for an event (2 gains 16 cells)	2	5	µs
Deadtime @ 10 kHz trigger rate	<2%	<5%	
ADC LSB	0.5	0.5	mV
Total noise (unchanged with frequency)	< 0.8	<0.8	mV rms
Maximum signal (limited by ADC range)	2	2	V
Dynamic Range	>11.3	> 11	bits
Crosstalk	0.4		%
Relative non linearity (integral)	<3%	<3	%
Sampling Jitter	< 40 (from Q resolution)	<50	ps rms

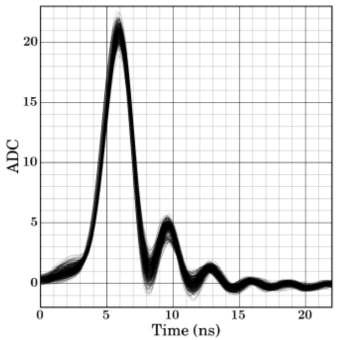
SINGLE PHOTO ELECTRON SPECTRA



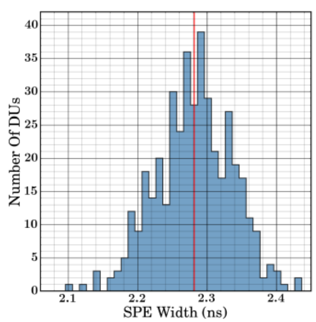


[Ashton, Klepser 2020]

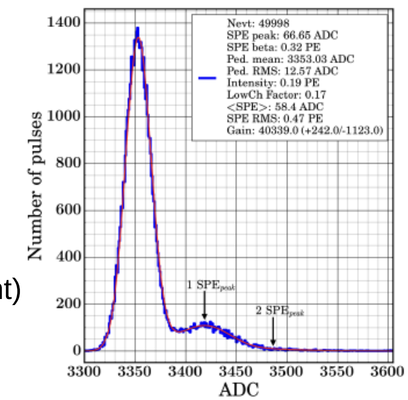
- **HESS upgrade**
- **High PMT gain: 2.7 10^5**
- 1GS/s, 13ns Integration Window
- 1 PE peak – baseline =80 ADC count
- Noise: σ on Baseline = 0.16 PE



Mean SPE waveform (50kevent)



SPE width (1850 channels)



[Tsiahana PhD's 2020]

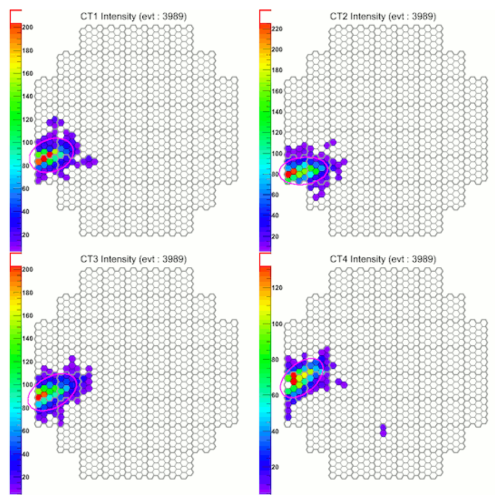
- **CTA Low PMT gain= 5 10^4 +PACTA transimpedance amplifier**

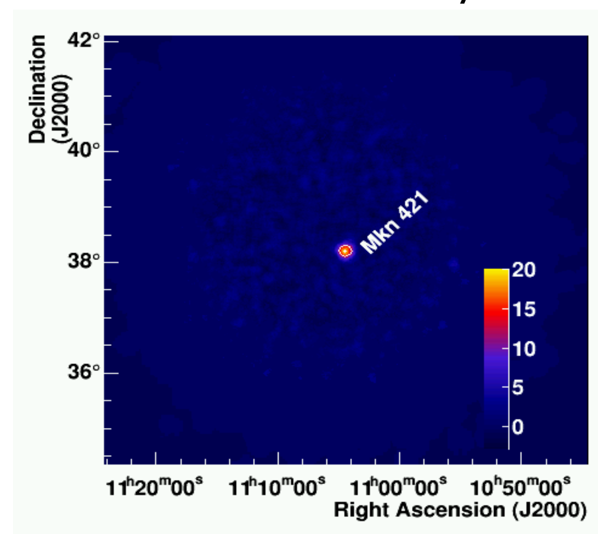
- 1GS/s, 14ns Integration Window
- 1 PE peak – baseline =67 ADC count
- Noise: s on Baseline = 0.19 PE

=>Both Spectra are compatible with in-run camera calibration

2017: FIRST OBSERVATION WITH THE UPGRADED HESS-I CAMERA

- 2017 : end of the refurbishing of the HESS-I camera (with NECTAR electronics)
- 4 avril 2017, during the commissioning phase
- Alert from the Hawk detector (another high energy experiment in Mexico)
  - ➔ Increase of activity of MKN 421
  - ➔ A well known variable source (blazar) located in Ursa Minor (North hemisphere)
- Even if the experiment was not fully commissioned , the collaboration decides to observe it ➔ first successful operation showing the robustness of the system.





Gamma-ray sky image of Markarian 421 as seen with the new H.E.S.S. cameras

- Since this time, the cameras are perfectly working
- Since the COVID crisis, they are now operated by Nabimian scientists/students

THE ISSUE OF DEADTIME (1)

- During readout, that lasts $\boldsymbol{\tau}$, NECTAR cannot accept new events
- For random (Poisson process with mean rate R) events the accepted event rate is given by:

$$F_{mes} = R\,(1 - DTF) = \frac{R}{1 + R \cdot \tau}$$

ie : A fraction DTF = 5% is lost for R=110Hz and τ = 450µs

As the input frequency drastically increase when we lower the threshold, deadtime (and its stability) becomes a problem.

1. This deadtime must be taken into account (measured) to estimate the real activity of the source
2. If N telescopes operates in stereo, their global deadtime will be given by :

$$GDTF = 1 - (1 - DTF)^N$$

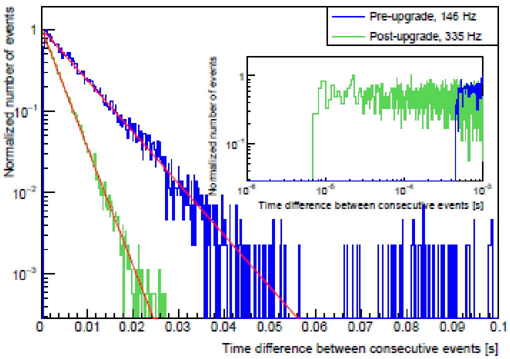
(this is also the reason why we prefer a common DT for all pixels of the camera)

➔For 3 telescopes with DTF=5%, the global deadtime = 14.2% that becomes not negligible.

This was the main motivation for the HESS-I upgrade, $\boldsymbol{\tau}$ was decreased from 450 µS to 7µs

➔ decrease by the 64 of the DTF or possibility to operate up to 5kHz (as HESS2)

Distribution of time difference between consecutive events before and after upgrade (with slightly different input rate) .
It is exponential as expected.
The lower bound give τ

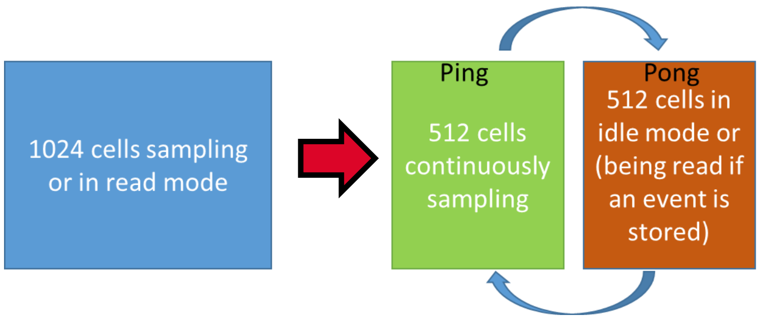


THE ISSUE OF DEADTIME (2) : BUFFERING

- to decrease the deadtime without decreasing τ, we can « derandomize » the input events using buffers with several (=K) « cells » :

then $F_{mes} = R\,(1 - DTF) = \frac{R\cdot(1-(R\cdot\tau)^K)}{1-(R\cdot\tau)^{K+1}}$

➔ an infinite buffering will give a 0 deadtime for $R < 1/\tau$



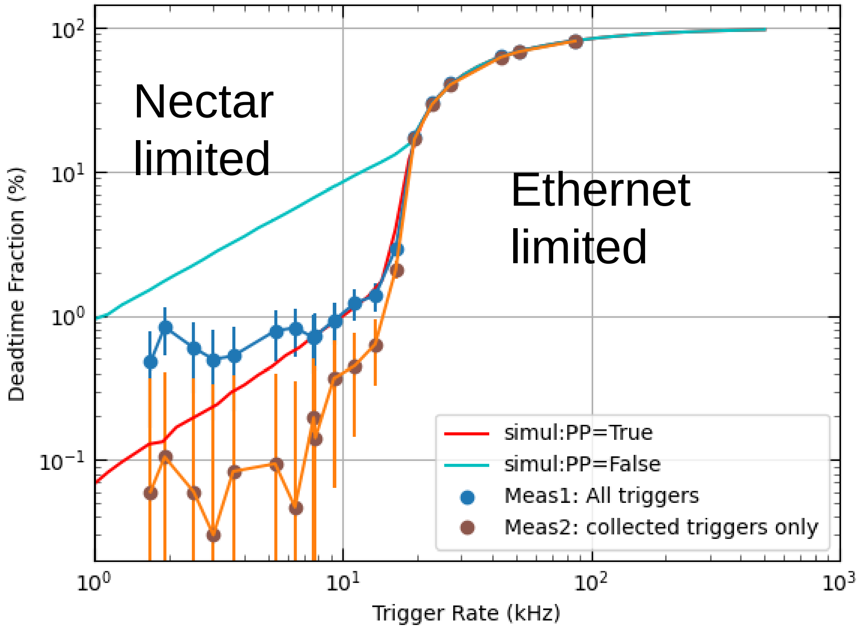
- The simpliest way to do it is K=2 : ping-pong mode:

Integrated in NECTAR2 for CTA

When a subarray is read after a trigger, we write in the 2nd….

- In the CTA condition (τ = 8µs) as expected the deadtime is divided by 10 up to 15kHz and remains below 1%.

- For higher input rate, the deatime is now limited by the ethernet transmission rate

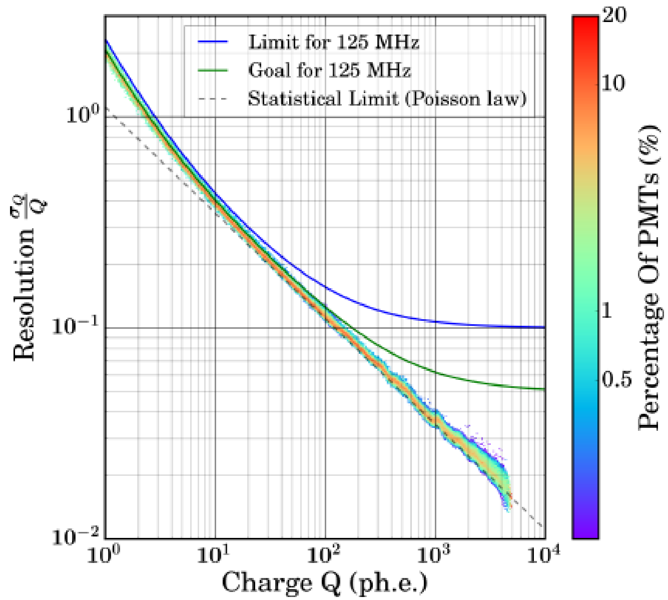


NECTARCAM IN REAL CONDITIONS

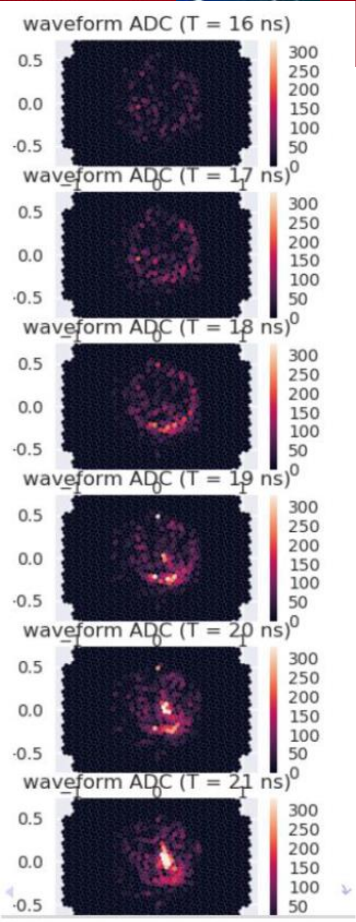
Actually modules

NectarCAM detectors performances

INLAB measurements simulating NSB



[Tsiahana PhD's 2020]

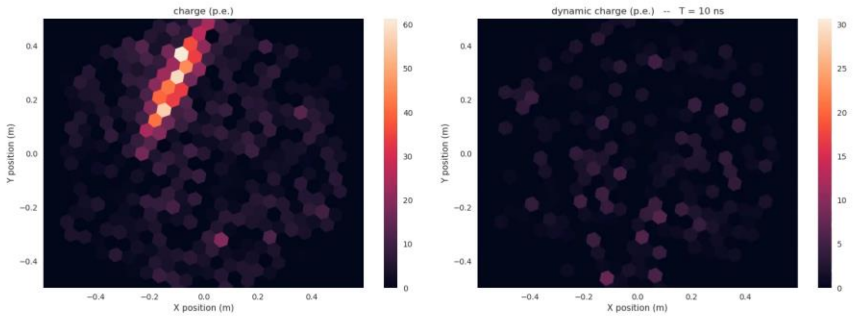


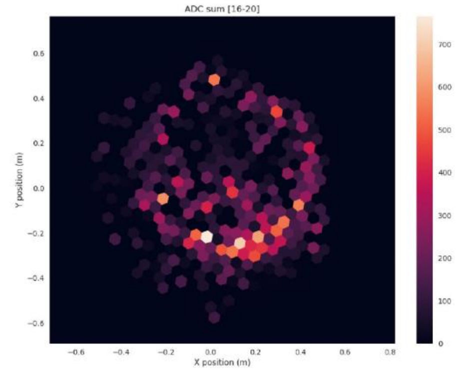
Tests in Berlin (2019)
NECTARCAM ¼ equiped

New: Movie

Detection of a muon

Random "atmospheric" events in Berlin

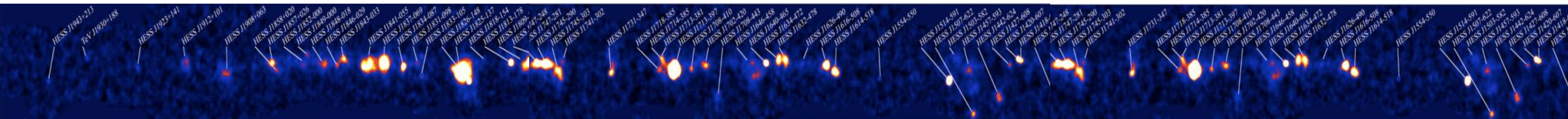




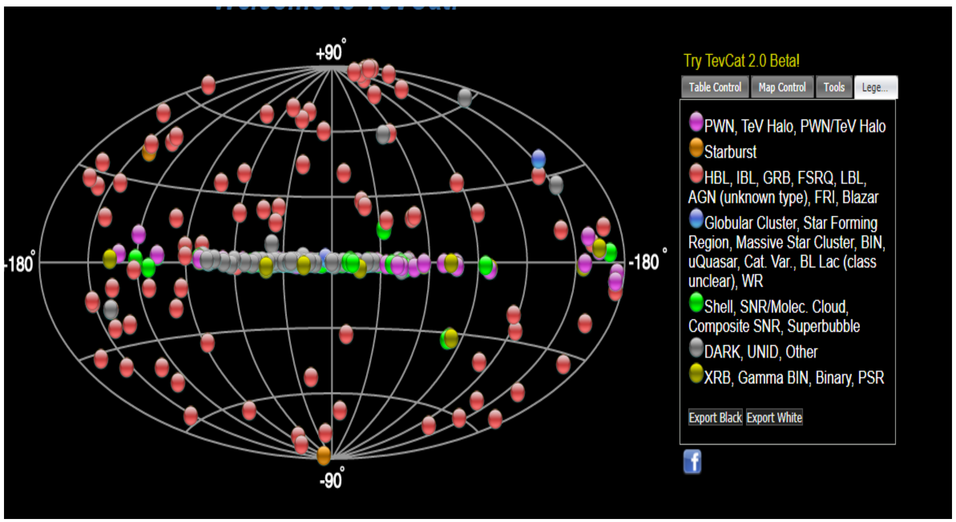
Picture (5ns exposure)

https://www.youtube.com/watch?v=BhKM5NgvBJo

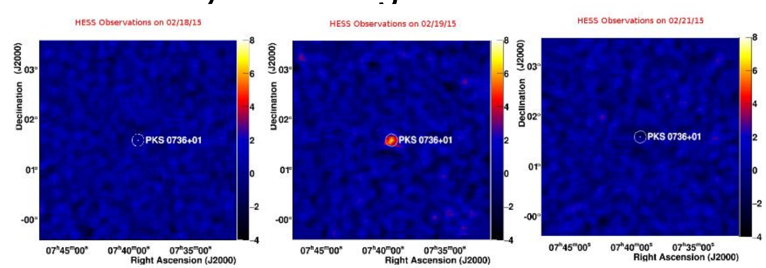
FEW RESULTS FROM HESS



The galactic plane @ TeV by H.E.S.S.

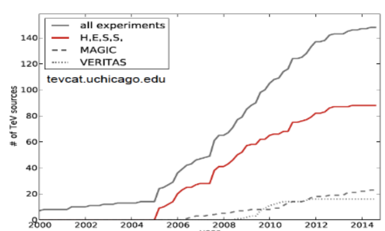


- Discovery of a PeVatron (cosmic accelerator up to PeV energy)
- Limits for dark matter models,
- test of physics laws
- Discovery of variable sources
- Multi-observatory/ multimessenger astronomy
- Discovery/following of variable sources



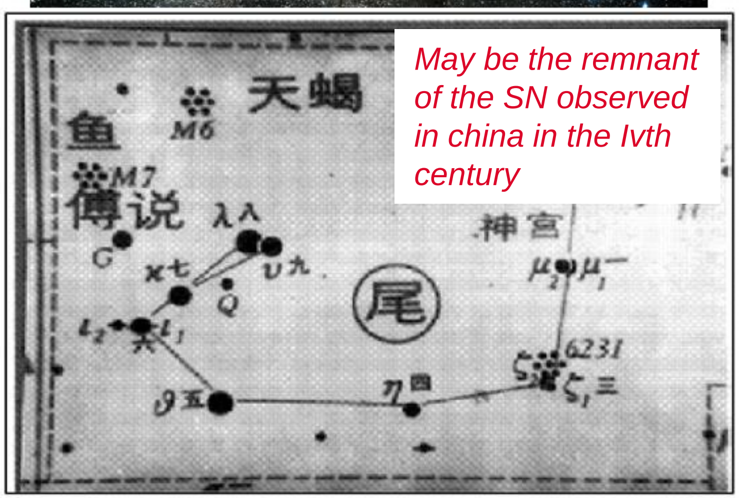
- … hundreds of papers

>50% of TeV sources have been observed by HESS for the first time

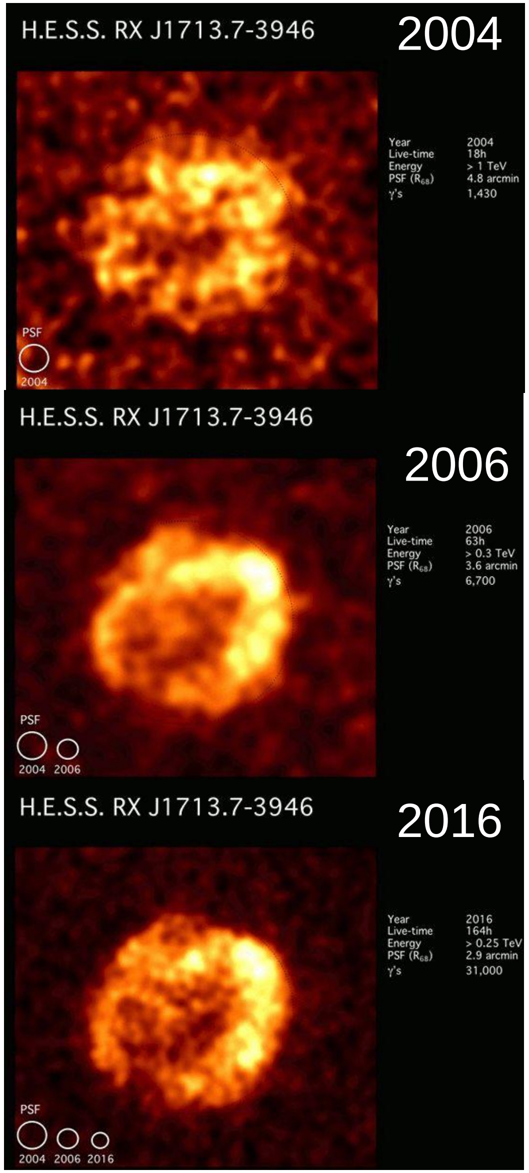


CONCLUSION: PHYSICISTS CAN DO MIRACLE

RX J1713.7: supernovae remnant in Scorpius constellation



May be the remnant of the SN observed in china in the Ivth century



Improvement from 2004 to 2016:
NO MAJOR HARDWARE CHANGE

- Calibration
- Better knowledge of the Instrument
- New reconstruction methods

GREAT WORK OF YOUNG PHYSICISTS !!!