Science using video : what can be done ?

eXtreme Low Light Imaging

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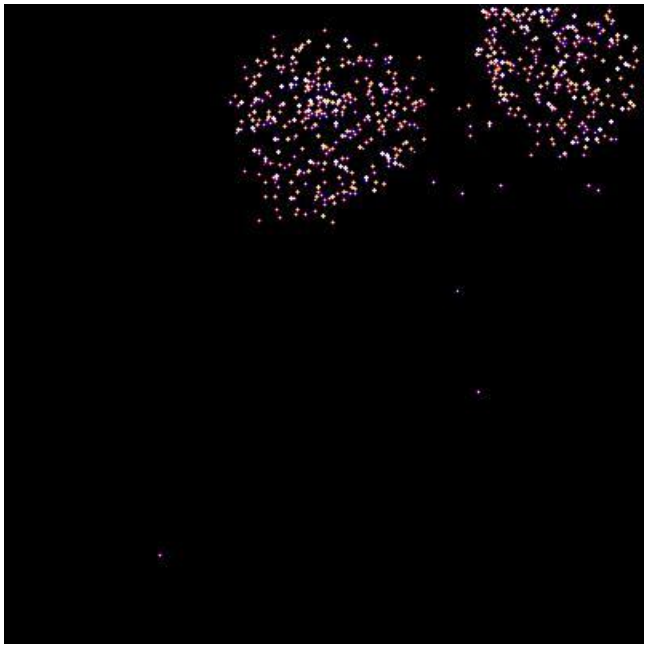


outline

- eXtreme Low Light Imaging ?
  - What is it ?
  - What for ? Science ?
- What has been done ?
  - LuSEApher on the Biocam project
  - Data 2011 : analysis examples
  - Issues raised by this campaign
- What can be done in the future ?
  - General remarks
  - Some serious or crazy idea ?

eXtreme Low Light Imaging : what is it ?

- XLL Imaging in dark conditions:
  - **Fast frame rate** : few milliseconds
  - **Localization accuracy on a large FOV**: Mpixels / micron
  - **Single-photon sensitive** : Gain = electron multiplying strategy x200
  - **Quantification** : Gain linearity to count the number of photon / target !
  - **Smart** : trigger to reduce the initial data rate to the physical information : 24h/24h survey !
  - **Extreme Low Noise**: lowest dark count to push down the threshold !

- The electron-bombarded CMOS photo-detector is one option for XLL

- 8 years R&D project at IN2P3 (IPNL/IPHC/PHOTONIS) on ebCMOS for XLL Imaging: proof of feasibility (ebMIMOSA) & proof of concept

  LUSIPHER = Large-scale Ultra-fast SIngle-PHoton recordER

- One possible application is the **measurement** of bioluminescence in deep Sea : (IPNL/CPPM)

  LuSEApher

Extreme Low Light Imaging : for Science ?

- Deep Sea Light Sources :
  1. Bioluminescence : (stimulated by the camera window or not !)
  2. Fluorescence : excitation + emission (SNR ↗ with filter)
  3. Standard Illumination

- in case of bioluminescence : difference between the light emitting centres and the shape of the whole organism !

- Time scale of observed phenomena
  - From milliseconds to years !
    - Sequence duration from few milliseconds to few seconds ➔ **Identification**
    - Sequence Time Series ➔ **Correlation**

- XXL imaging combines 3 types of information for a better identification of the phenomena :
  - Spatial
  - Time
  - Intensity

What have been done ? : LuSEApher (1/2)

- Bioluminescence Observation (See Juergen Brunner Talk) on ANTARES site SJB – MII module :

First campaign : Oct. 2010 - Now

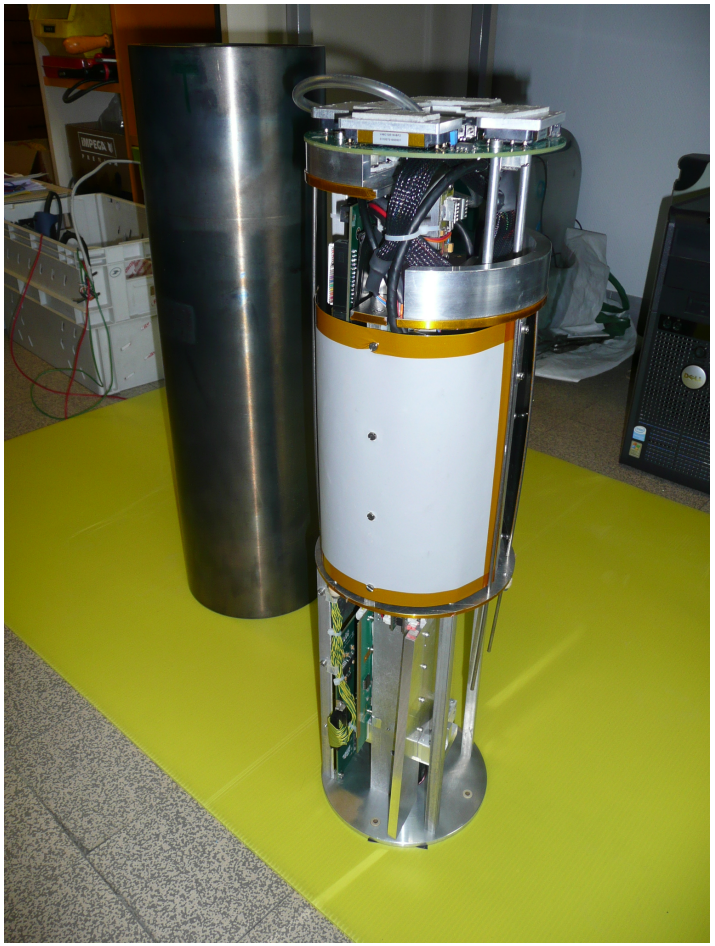
- LuSEApher is an embedded camera system based on :
  - An optical system (unfortunately not optimized !)
  - An ebCMOS sensor sensitive to single-photon 400x400 pixels 16 mm2
  - A Eth DAQ System (Analogue and Digital boards)
  - A Slow-Control system for HV – Cooling - Temp. – Vref – PowSup.
  - An embedded PC board with Eth. Boards and SSD disk
  - A power supply unit
  - 48V/1-2A and an Ethernet Link (100 Mb Ethernet)

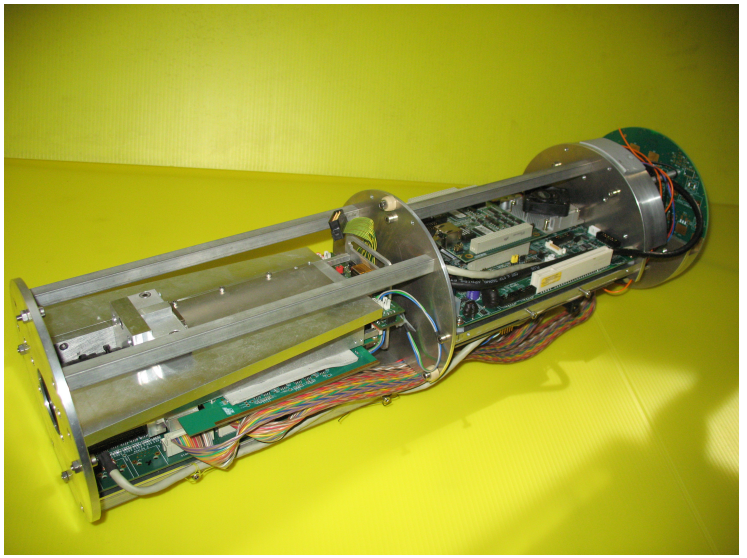
References:

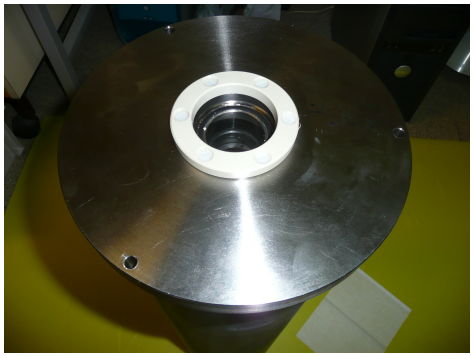
1. Camera Lusipher : Barbier et al. *NIMA 2011*
2. Camera LuSEApher : Dominjon et al. *NIMA 2012*

LuSEApher

- Design to fit the titanium cylinder
- 4 months / 4 engineers: IPNL ebCMOS team & CPPM support







What have been done ? : LuSEApher (2/2)

- **Trigger Strategy: every 16 ms (1 frame at 62 fps)**
  - Raw in a circular buffer
  - Reconstruct the "signal frame" (CDS-PED-Noise compuat-ion)
  - Reconstruct the photon image (0 everywhere except when a photon, a cluster, is found) !
  - Count the photons in the current frame
  - Trigger a sequence on the photon number threshold define T_0
  - Store DATA from the circular buffer to the SSD: take 50 frames **before** T_0 and 300 frames **after** the last frame with more than 15
  - Send RAW DATA to the shore station

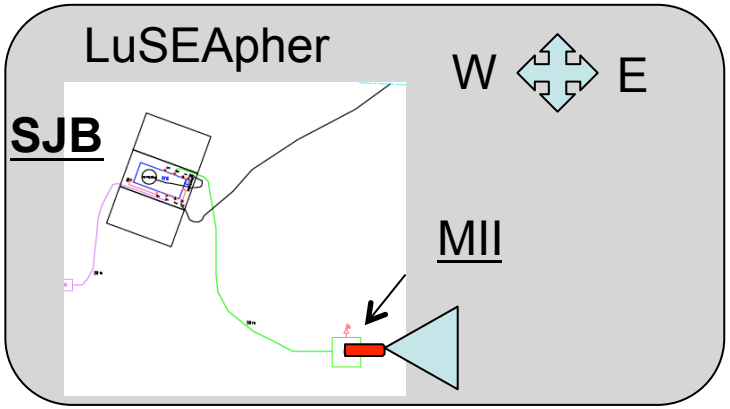
We call a sequence the consecutives frames stored after one trigger :

- **Numbers :**
  - Mean DC rate : 0.8 phe-/16ms (cathode S20 @ 15°C)
  - The trigger threshold is set at 14 phe- (actually du to Ion Feed Back ~14 equ. phe-)
  - 2011 data: more than 8000 events stored (mostly noise above threshold- 400 biolum. events)

What have been done ? LuSEApher Data 2011

- Some examples of data taken during 2011 on the ANTARES Site MII

- **Halo observed with a mean radius 32 pixels !**
- Classification of the sequences (on his way):
  1. Noise = 1 frame with more than 14 ph.e
  2. Single Flash: exponential decays : < 2s
  3. Multiple flash :
     1. Static
     2. Dynamic source
  4. No flash = Light Glow
     1. Static
     2. Dynamic fast (current)



LuSEApher

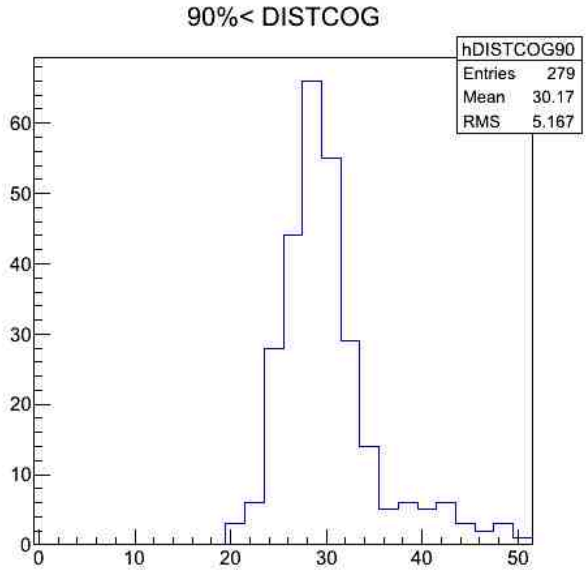
Optical : Lens

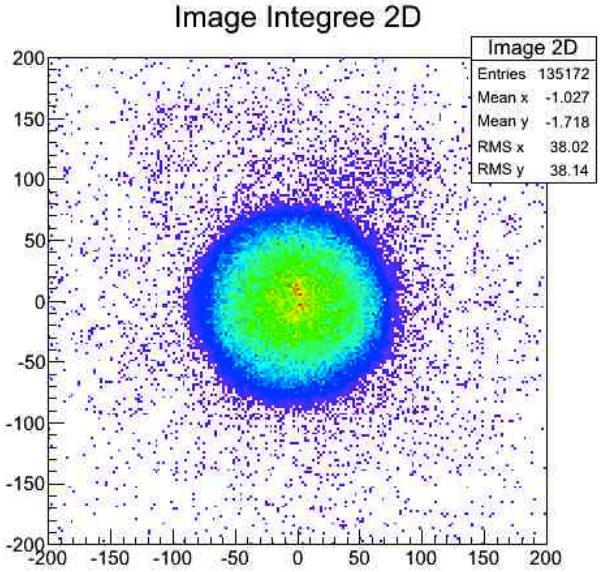
FOV fixed at :
65 cm @ z=1m

Distance Window-Lens
3.3 cm < Minimum Working Distance 30 cm

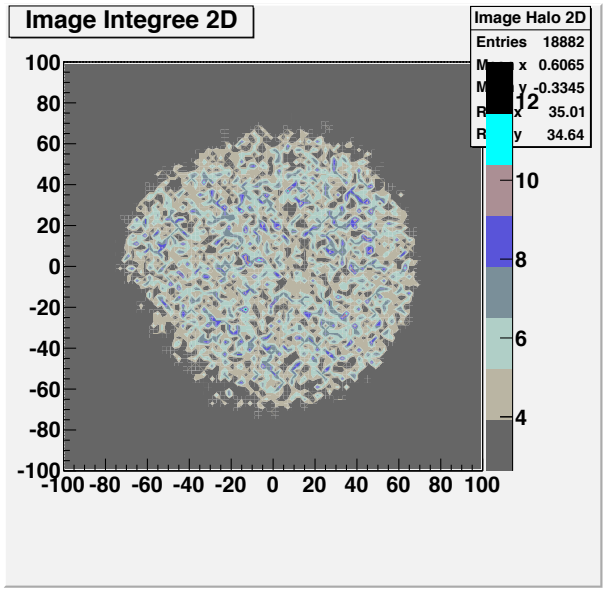
What have been done ? LuSEApher Data 2011

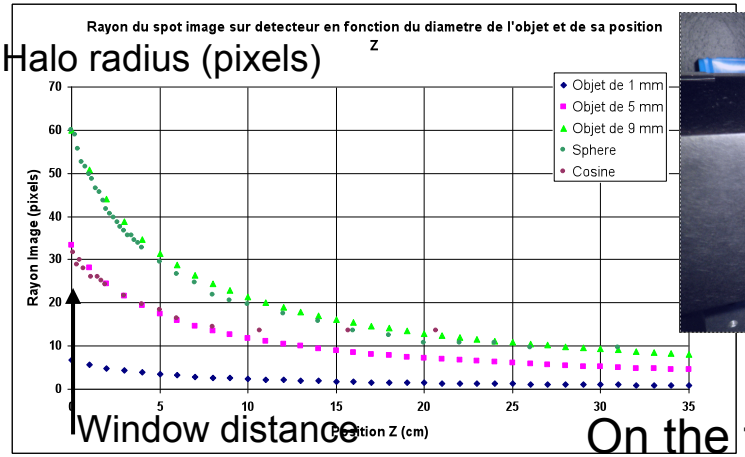
Integrated photon image centred on the COG for each frame :single flash





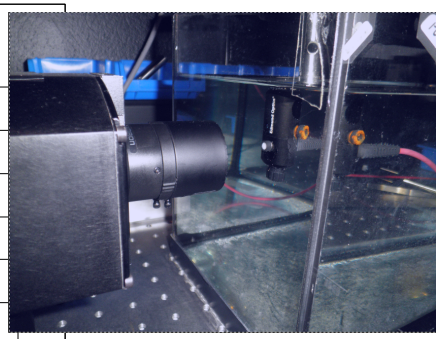
An “artist view” of a bright event !





Halo radius (pixels)

Window distance

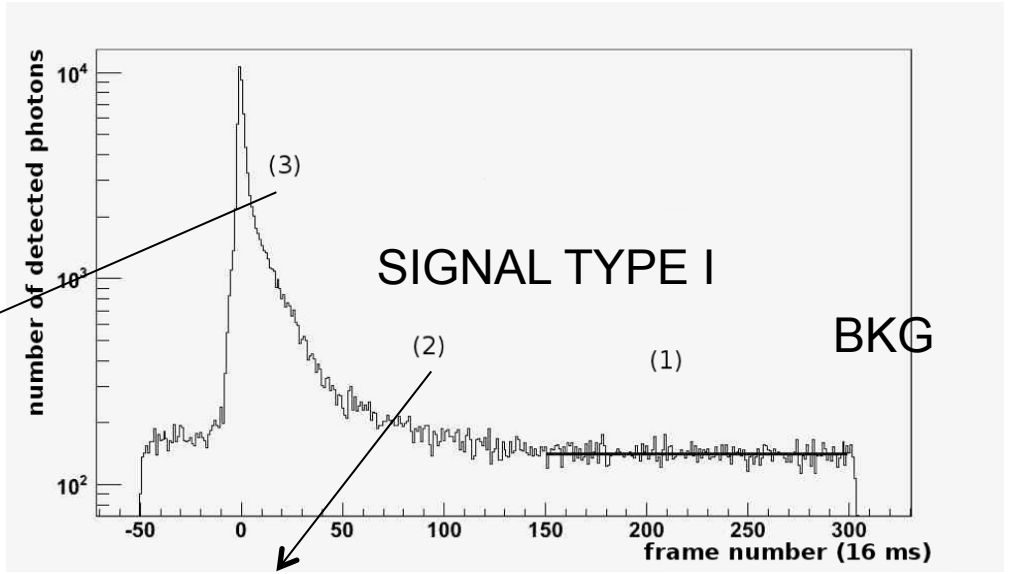


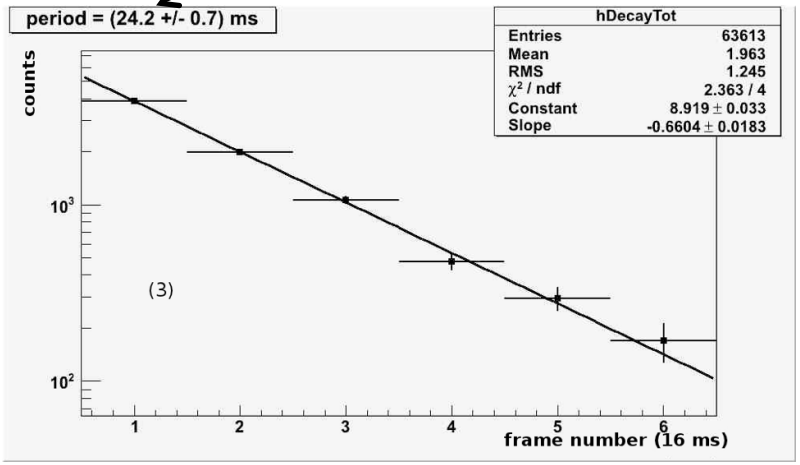
On the test bench

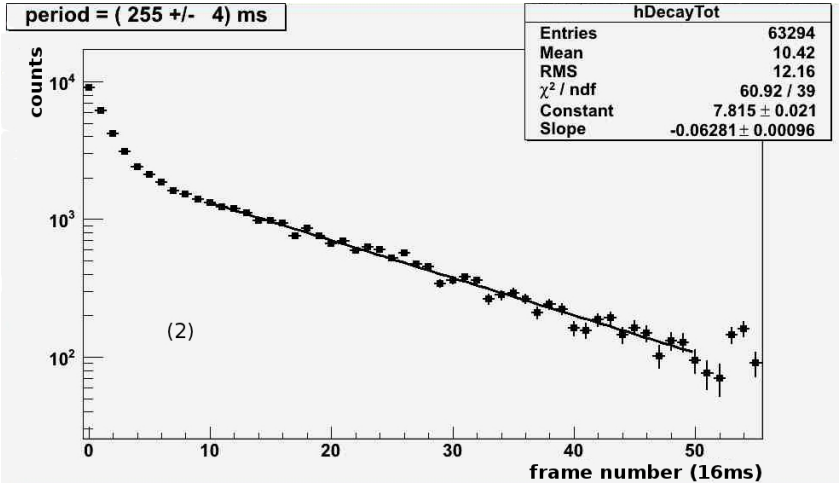
What have been done ? LuSEApher Data 2011

Sum of temporal histograms of Single-flash sequences

BKG 0.78 ph/frame
Fast Decay : tau = 24 ms
Slow Decay : tau = 255 ms





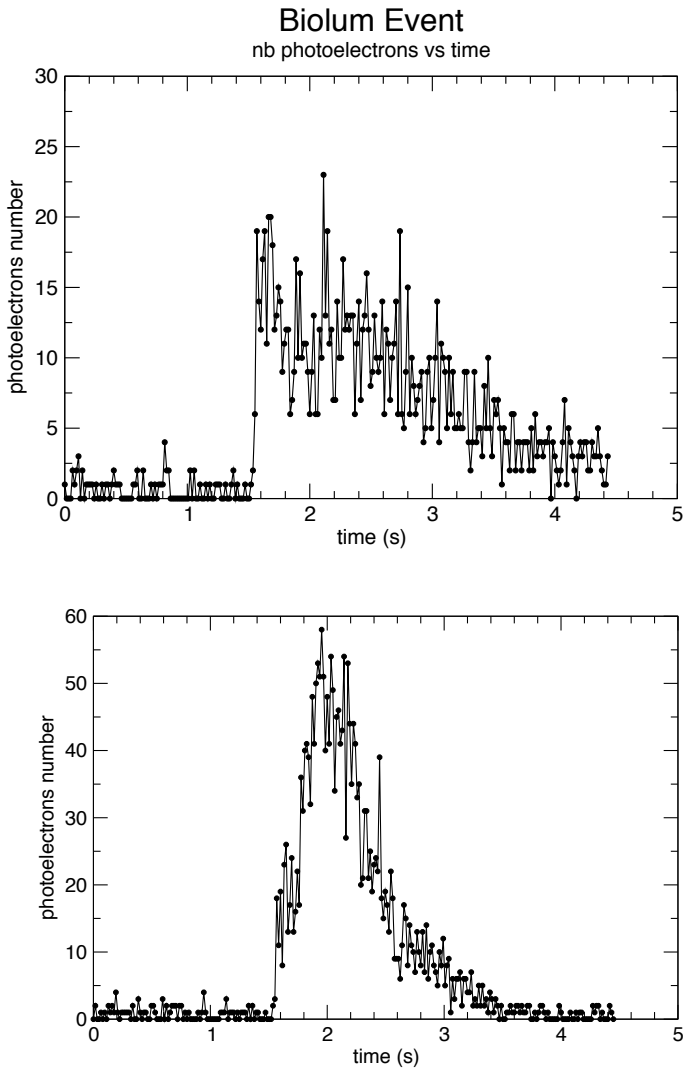


Seq. by Seq. analyse could be performed to cross-check
the homogeneity of the samples : different decay = different species ?

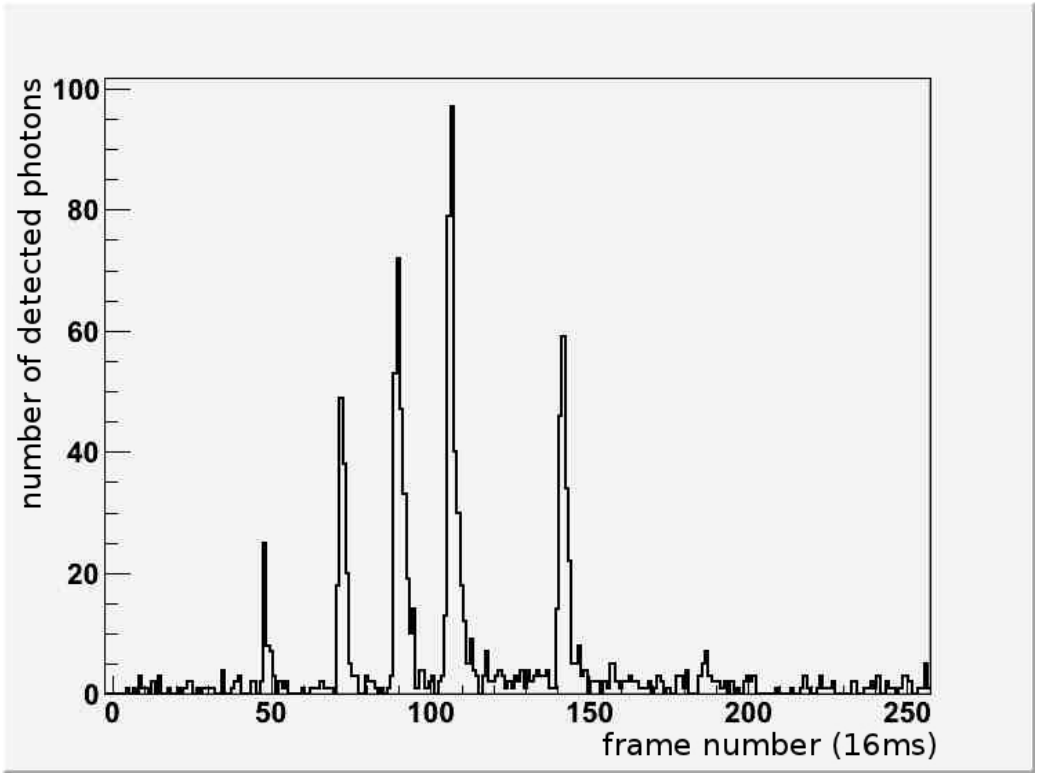
What have been done ? LuSEApher Data 2011

Photon number versus time

Light glow event

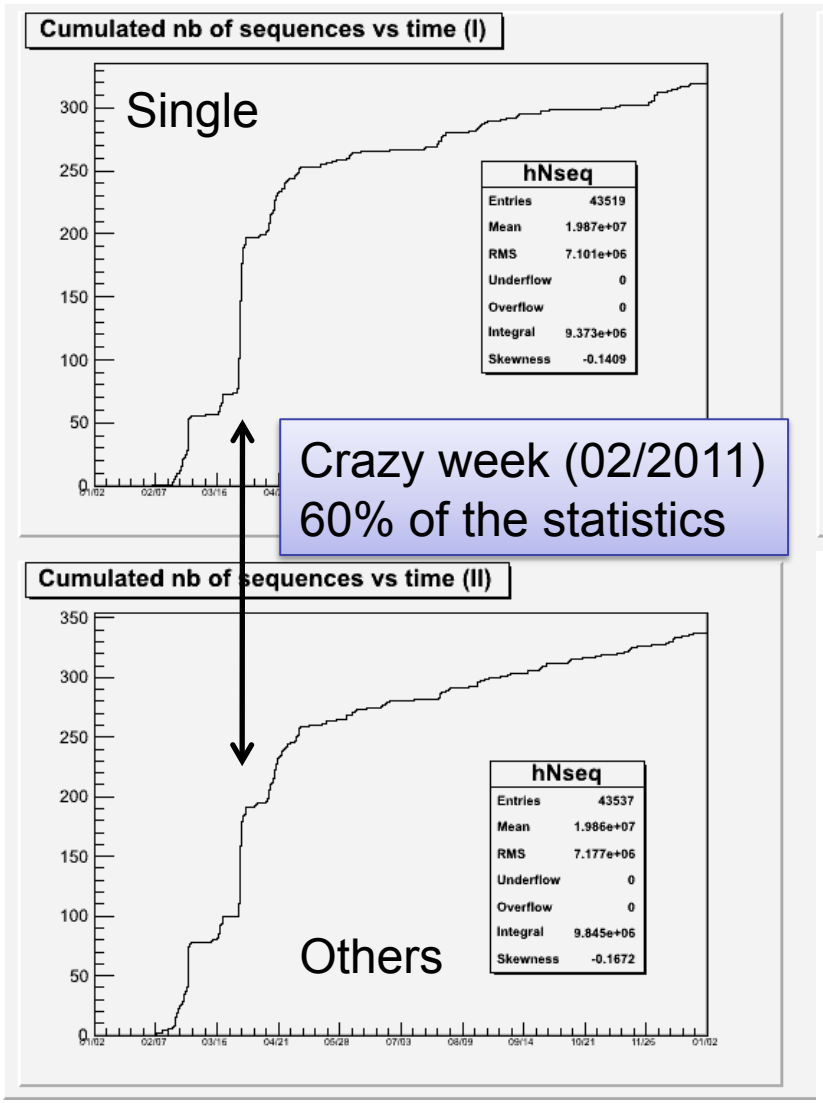


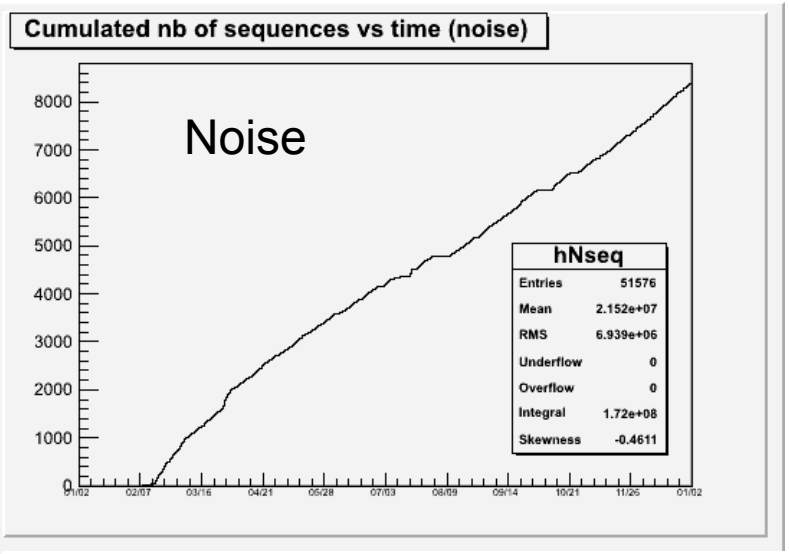
A nice multiple flash event

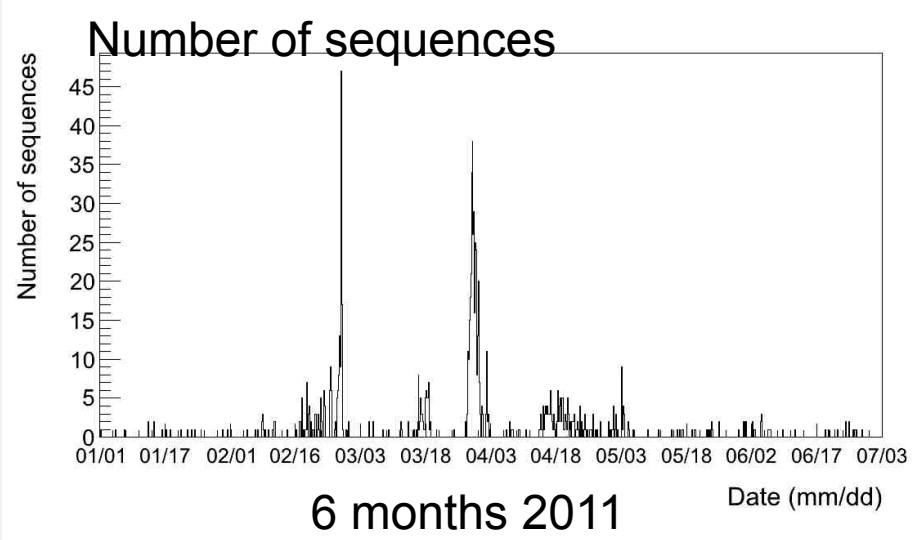


What have been done ? LuSEApher Data 2011

- Cumulative distribution of noise, single flash seq. and others





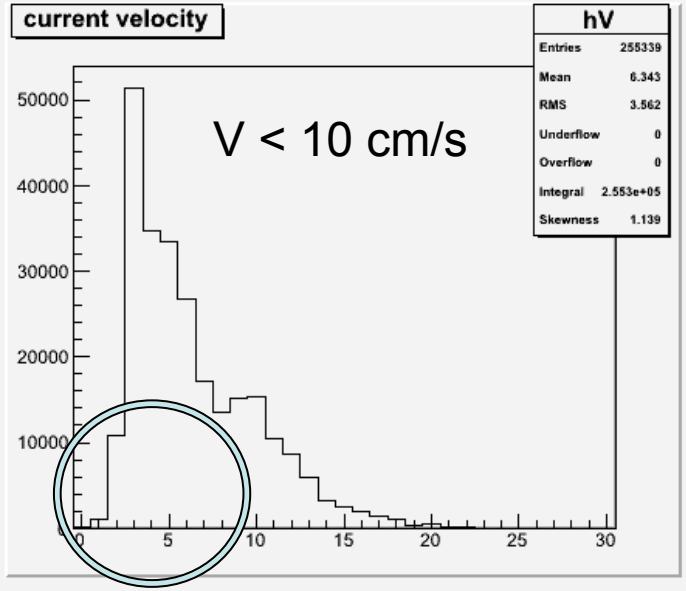


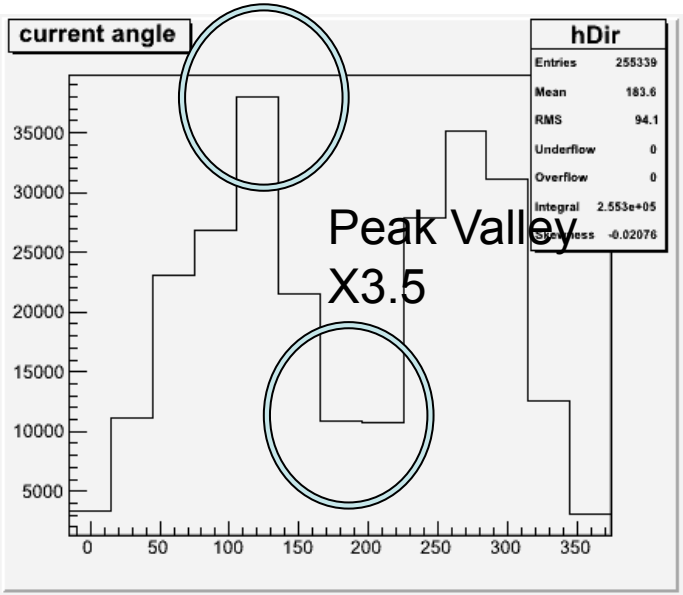
What have been done ? LuSEApher Data 2011

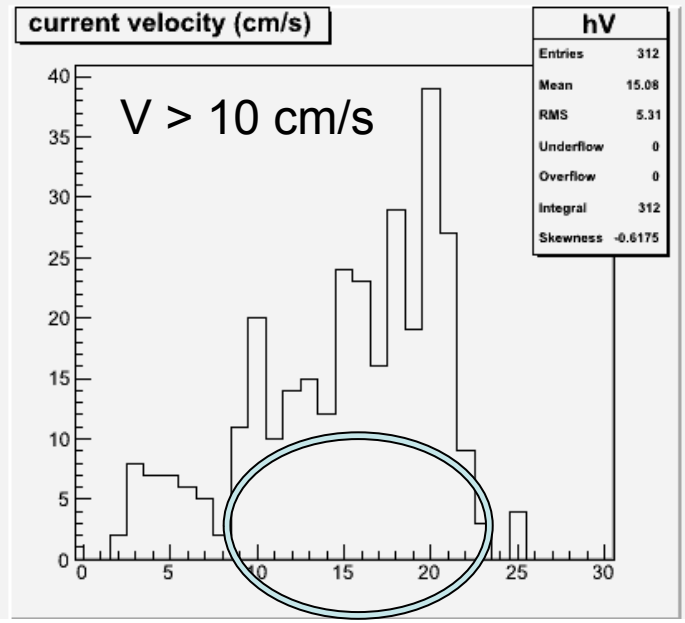
Correlations
Trigger rate /
Current velocity
Current Angle
From ANTARES

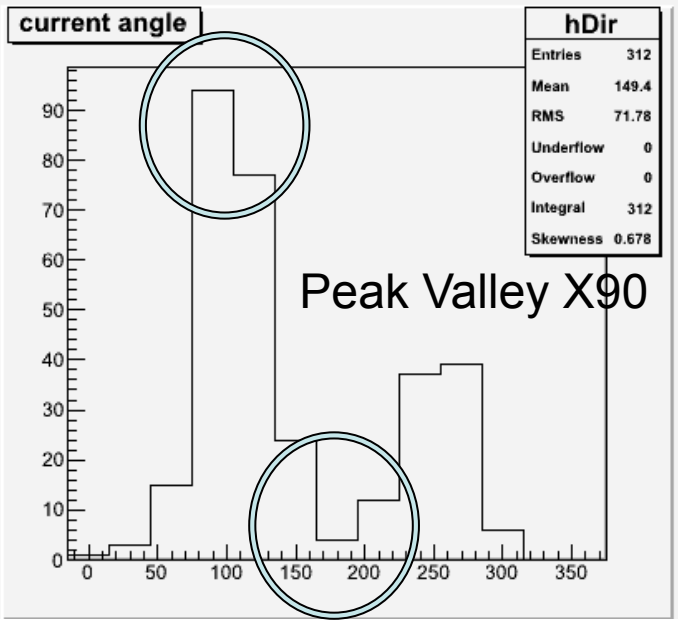
All data 2011
cur. velocity
curr. angle.

Data
corresponding to
single flash event



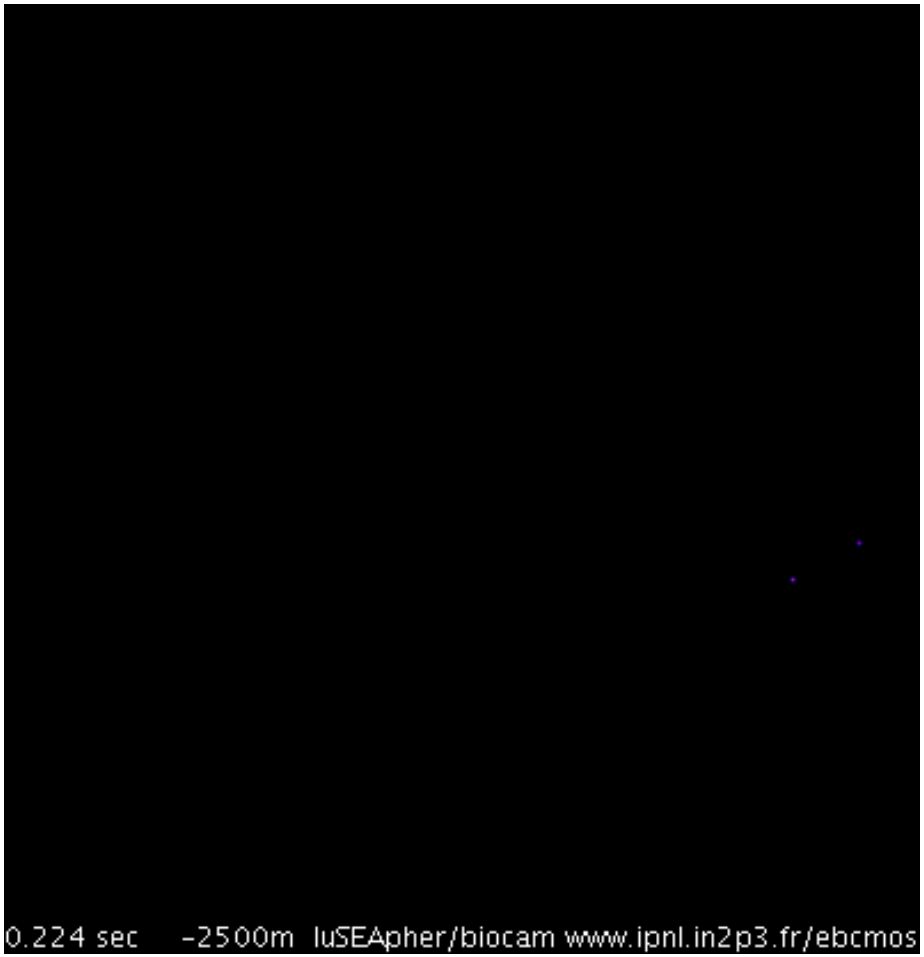


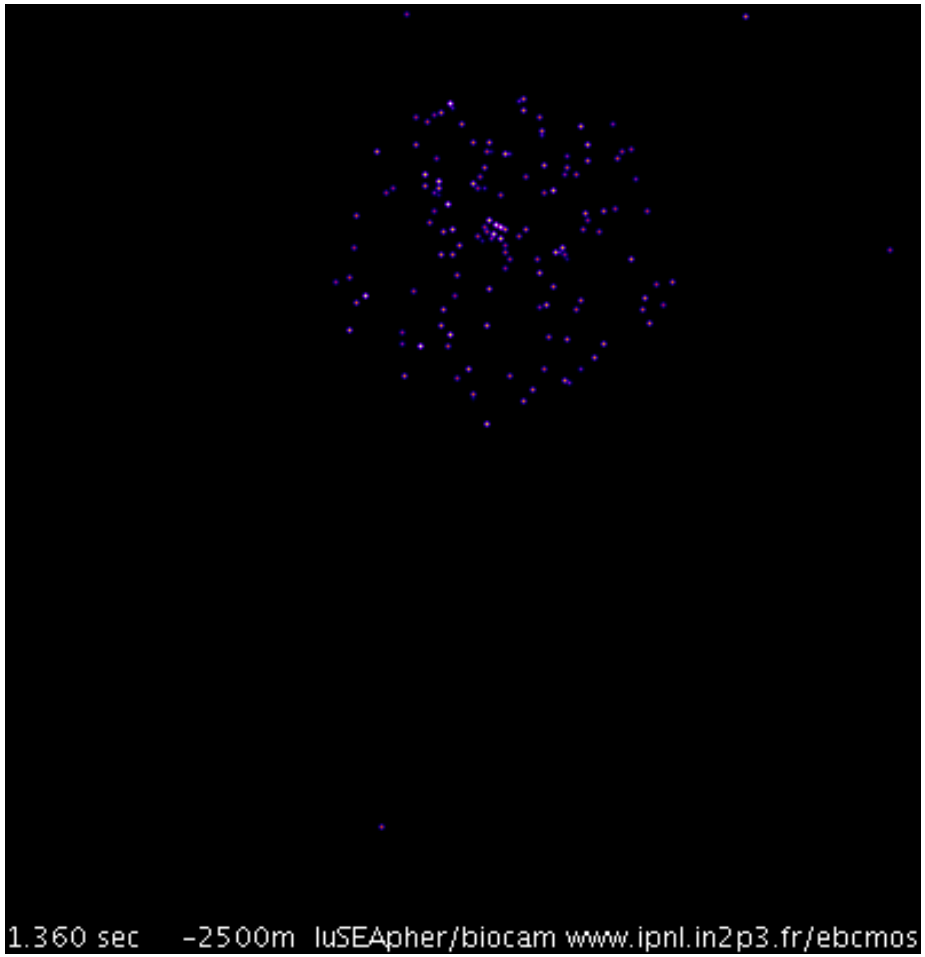




What have been done ? LuSEApher Data 2011

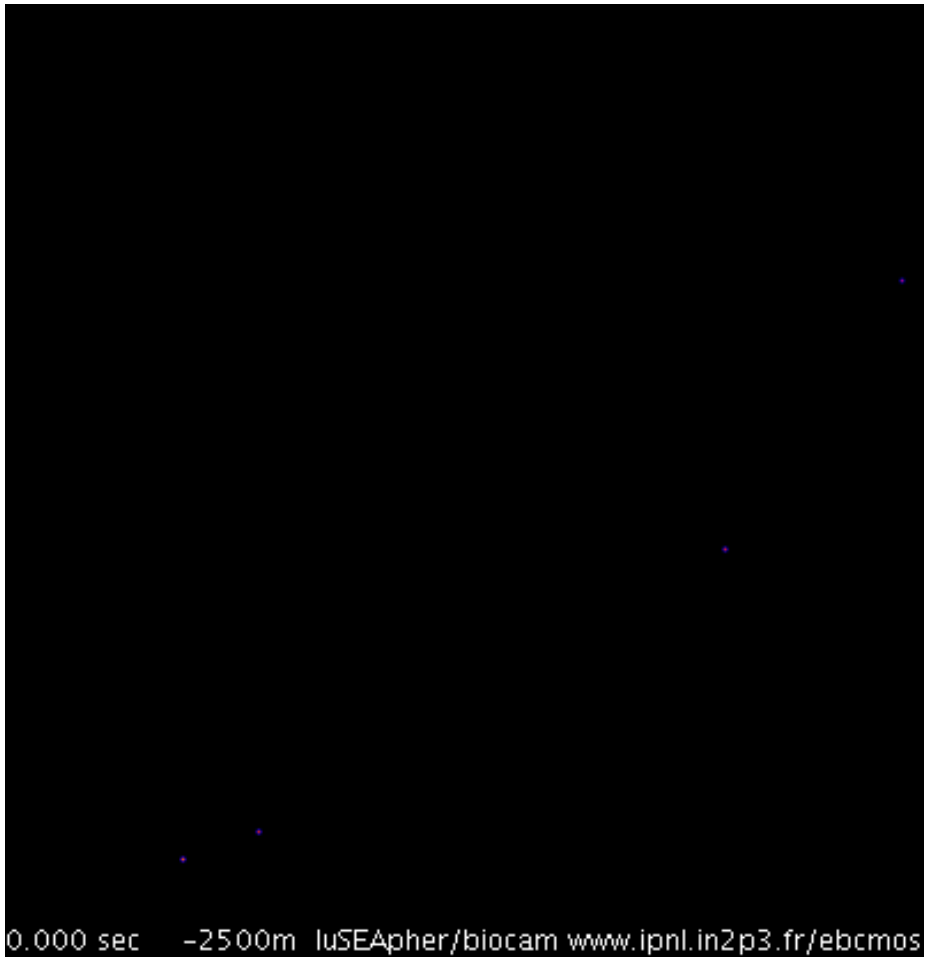
Flashing or not : same nature ?

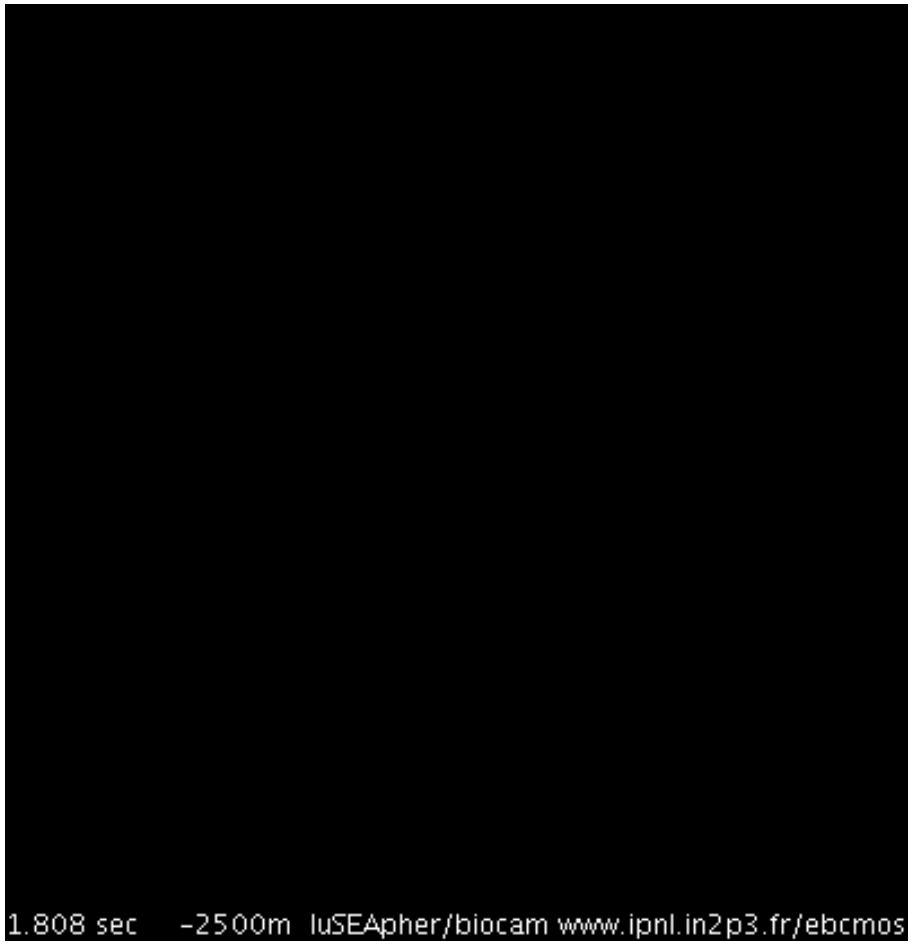




What have been done ? LuSEApher Data 2011

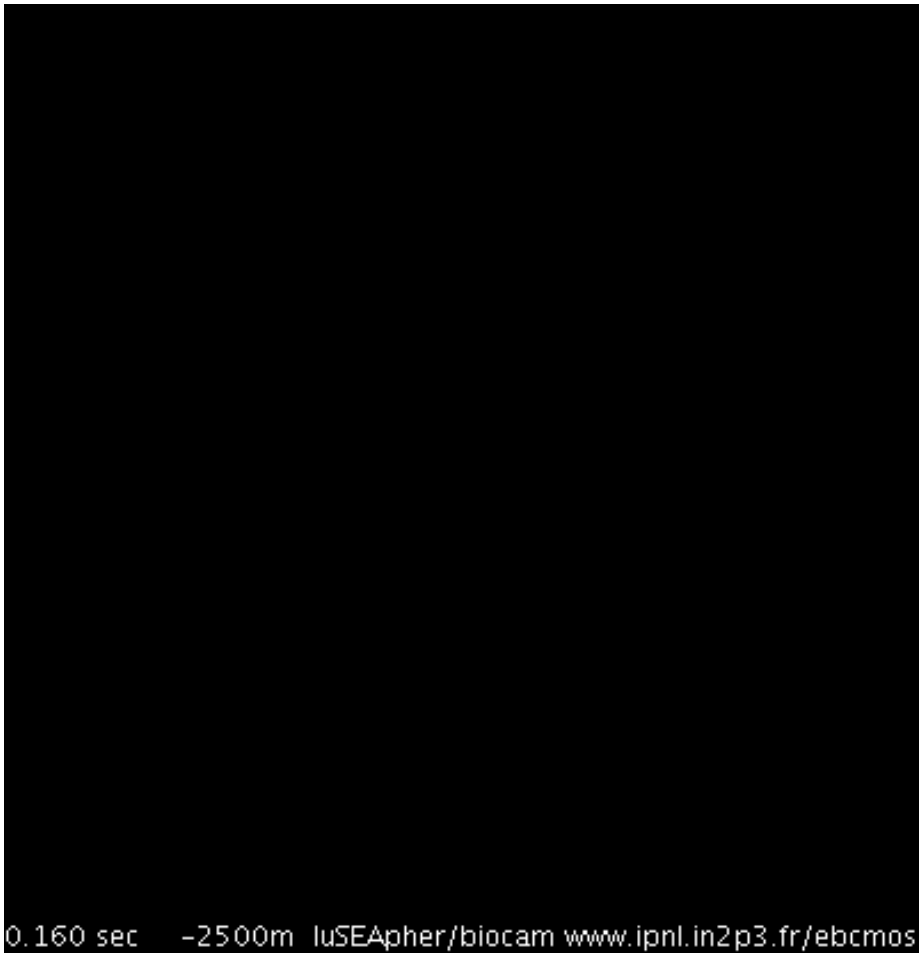
Change the direction, swimming needs tracking

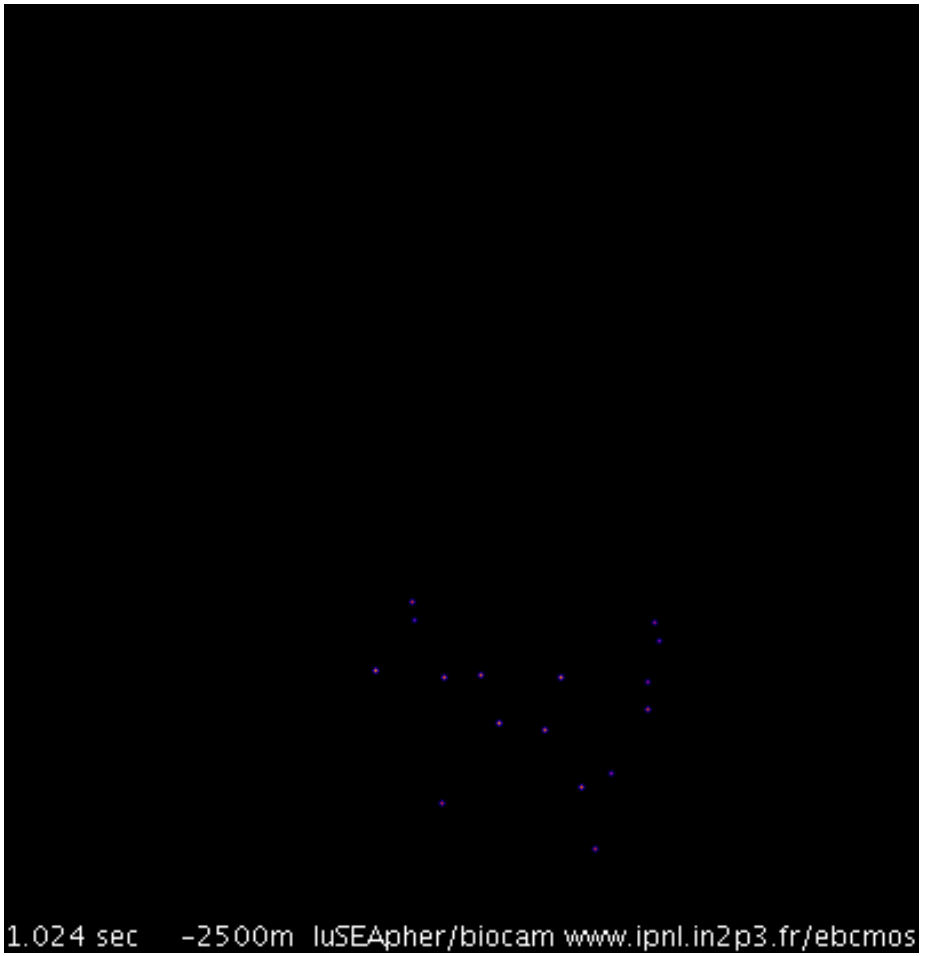




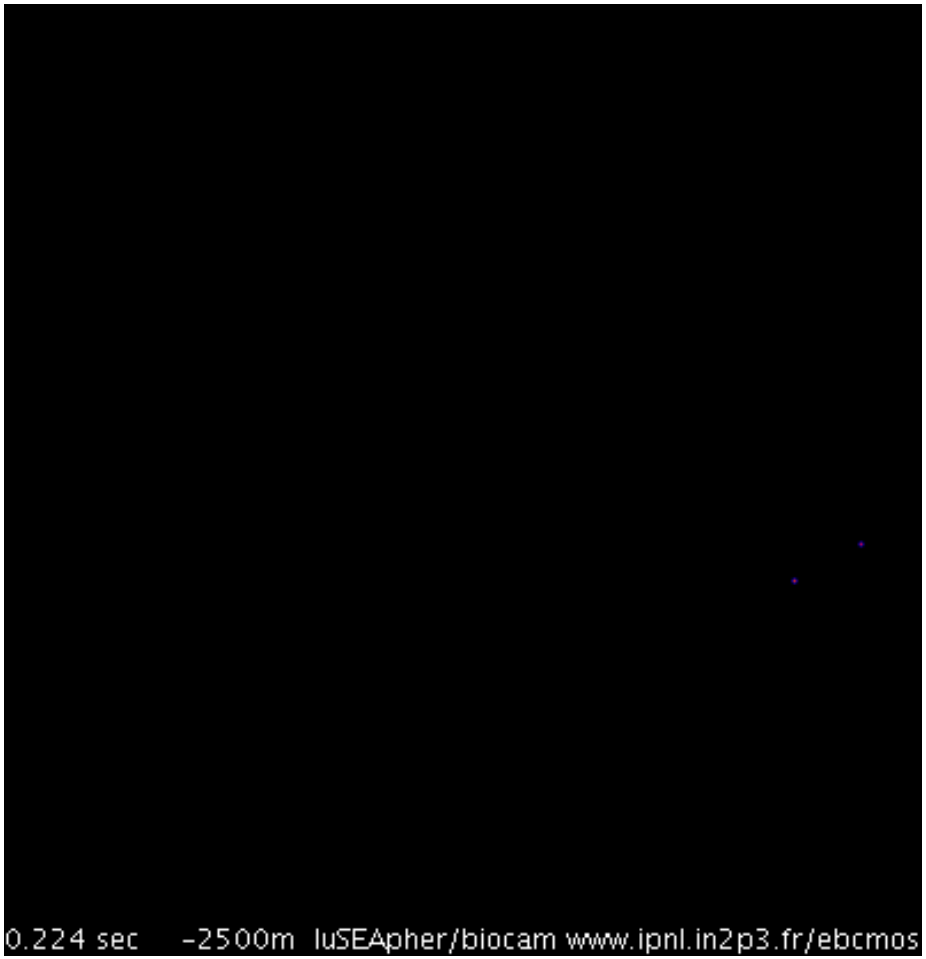
What have been done ? LuSEApher Data 2011

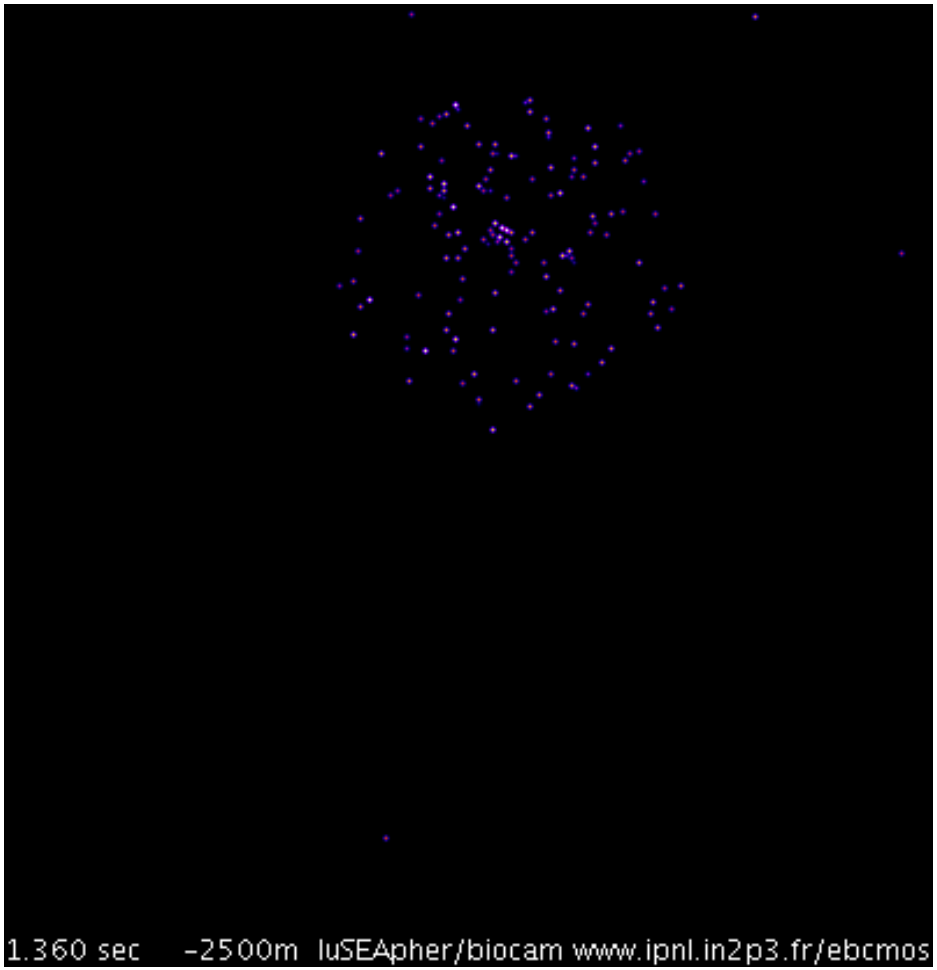
A structure during the bright spot ! How to analyze ?





- FAST or SLOW


0.224 sec -2500m luSEApher/biocam www.ipnl.in2p3.fr/ebcmos


1.360 sec -2500m luSEApher/biocam www.ipnl.in2p3.fr/ebcmos

What have been done ? LuSEApher Data 2011

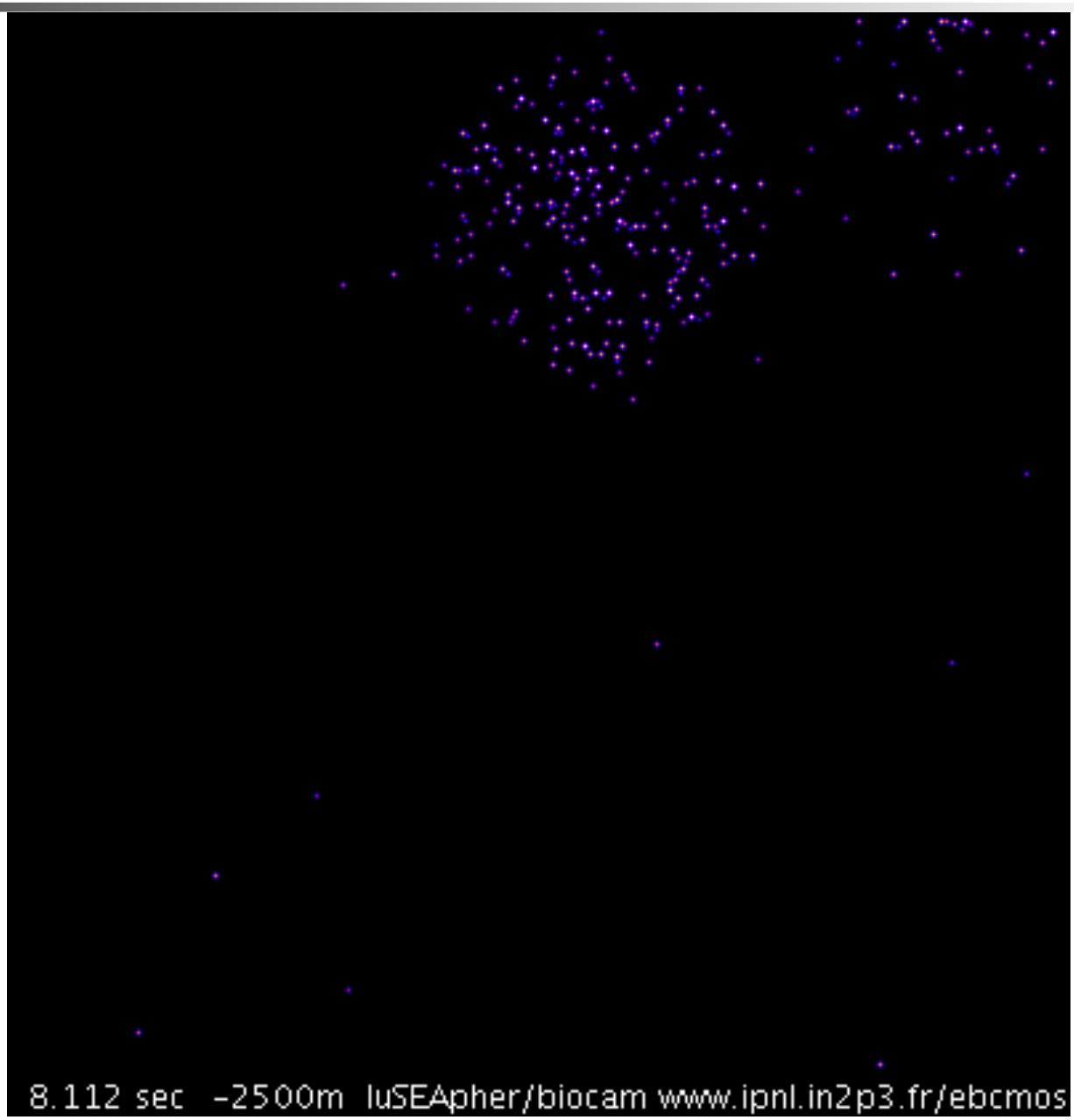
The longest !

More than 12 seconds

….

Because one of them waits for another ?

And saysto the other “Don’t worry they are watching us ! “



What have been done ? LuSEApher Data 2011

See other movies on our website

- http://www.ipnl.in2p3.fr/ebCMOS ➔ bioluminescence

- An event (Seq.) by event (Seq.) analysis is performed : HEP method
  1. Find distribution to classify the sequences
  2. Then correlate with other measurements

Note from this first attempt of XLL imaging

- Optical design not defined for short distance ☹:

- Min focal length 30 cm but window at 3.3 cm

- Conclusion on this first attempt with an **ebCMOS camera** system : **Requirements for the future**
  1. the third dimension to quantify the emission rate in an absolute value
  2. millisecond time scale resolution (flashing events with exponential decay in time have small period 40 ms)
  3. tracking the centre of gravity of photons for moving targets
  4. store with a good time stamping all other possible **local** geophysical parameters with the same DAQ
  5. The low dark count rate is essential for lower the trigger threshold

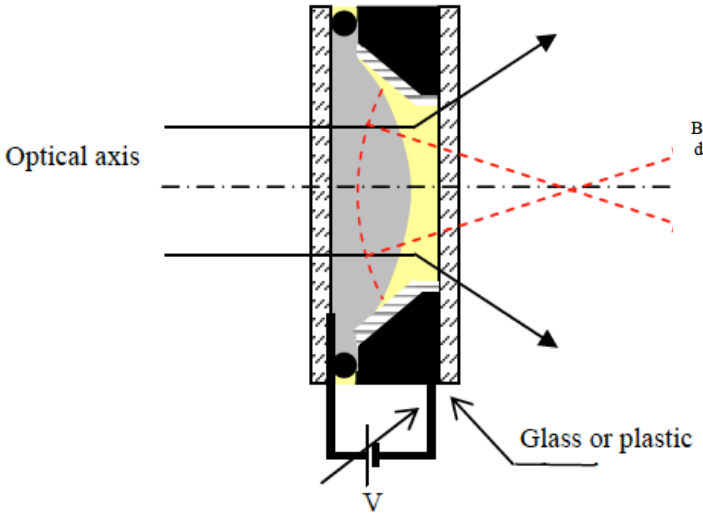
What can be done in the future ?

- **OPTICS**
  - Deep Sea Microscopy: Bacteria …
    - Smaller FOV rare events
    - Current speed to high for big magnification !!!
  - 3D imaging: from 1cm – 50 cm:
    - Stereo
    - Fast auto-focussing
    - Plenoptic camera
    - In-line digital holographic microscopy for terrestrial and exobiological research
  - Increase the FOV : Fisheye Lens 180°
  - ….
- **SENSORS**
  - For me: ebCMOS is the best choice

  but
  - emCCD or sCMOS or ICCD could be used (not discussed here)

3D imaging : auto-focussing

- Auto-focussing with few hundreds of photons in few milliseconds … using liquid lens ?



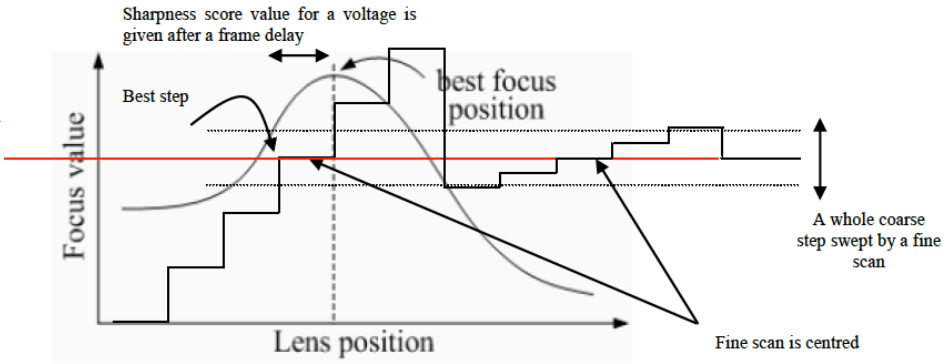
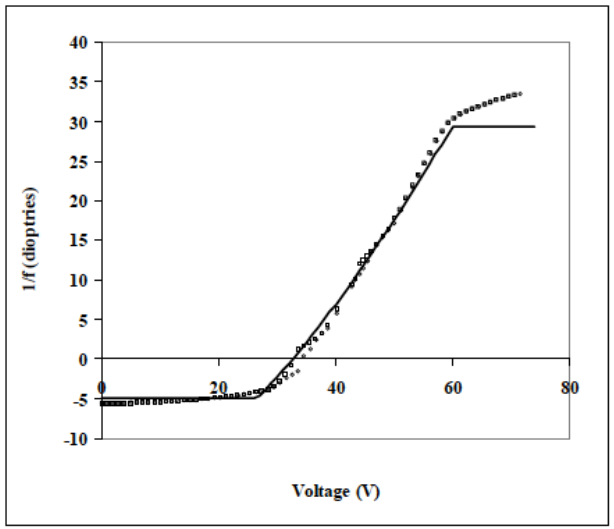


Figure 15 : Fine scan sweep is centred on the coarse best step

Liquid Lens



3D imaging plenoptic camera

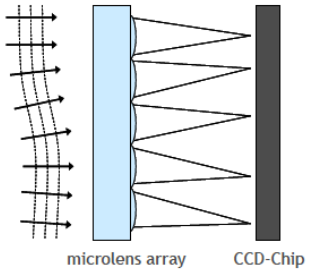
- **Ren Ng** PhD thesis Standford 2006 (M Levoy team)

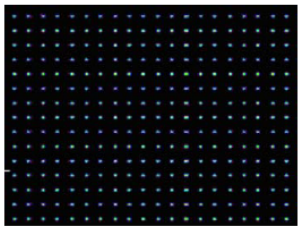
- Now RN is the CTO of LYTRO plenoptic Camera with Digital re-focussing

- **One image all depth of Field !**

- Use Lenses + Micro-lenses 4D Light Field E(u,v,x,y,f)

This could be the solution for XLL 3D Imaging to avoid auto-focus with few photons !




Hartmann pattern

What can be done in the future ?

- **Next STEP on the MII 2013 :**

LuSEApher II targets:

- **A new 1.3 Mpixel ebCMOS** : SXGA 1280x1240 / 100 fps
  - ADC on chip 10 bits
  - GaAs cathode
- **DAQ 10 Gb FPGA Optical-link validated in our LAB with commercial sCMOS 2Kx2K**
- SC monitoring of the ebCMOS but also for the optics
- New optics :
  - XLL Auto-focussing with Liquid length
  - XLL Plenoptic (4D field with microlenses) with digital re-focussing

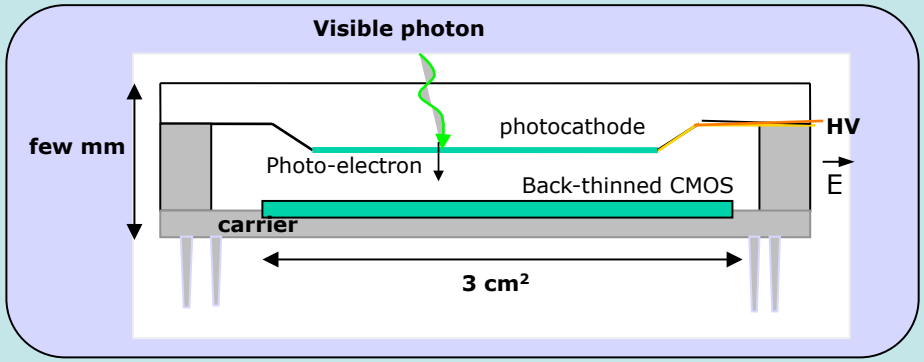
CONCLUSION

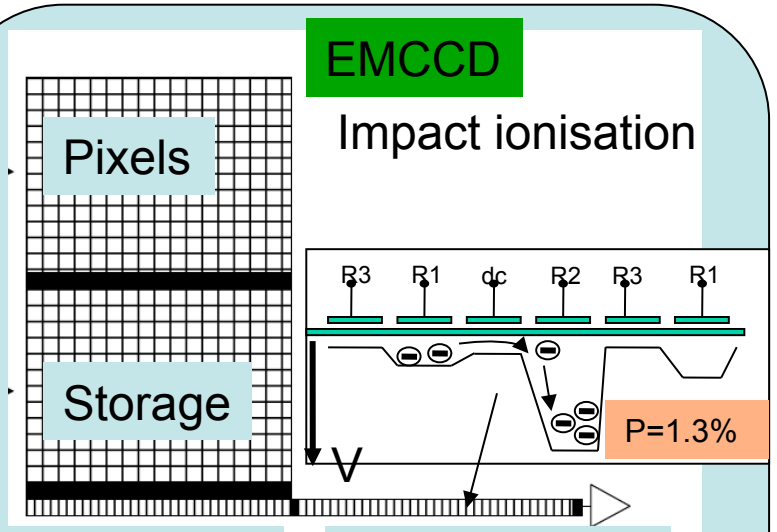
- Many things to do
- exciting challenge : **XLL 3D imaging ! Absolute quantification at millisecond time scale and tracking**
- The next camera will be smart only if collaborators will work together…
- Thx

Back up Slides

ebCMOS = CMOS electro-bombardé

Principe ➔ Techno Vide + Techno CMOS





$G=(1+P)^{512}=1000$

Réalisations ebCMOS @ IPNL

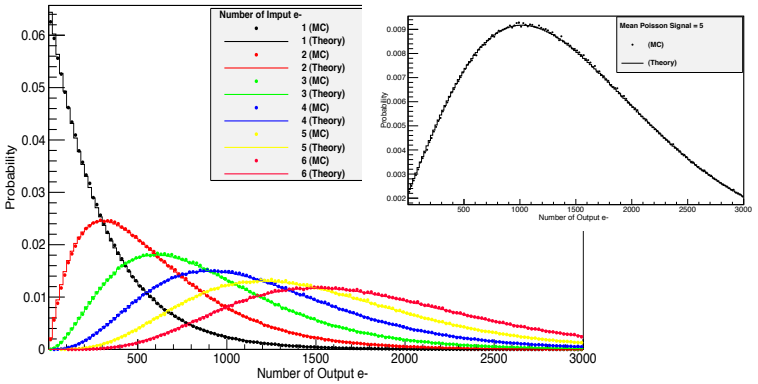
1er Prototype – 2007

➔ Preuve de faisabilité :ebMIMOSA5

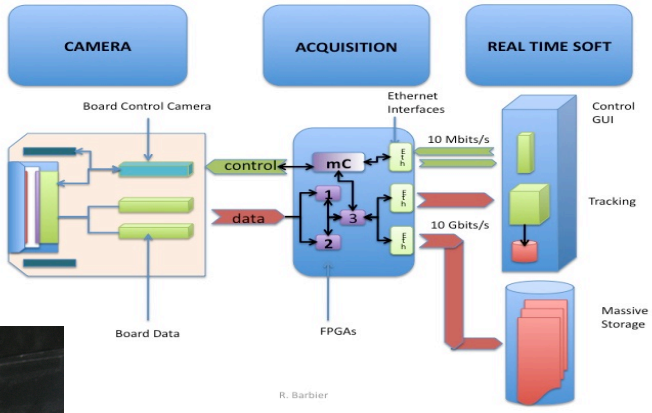
2° Prototype - 2010

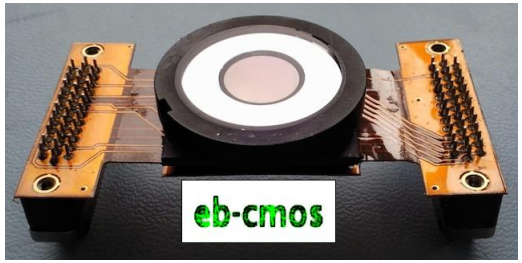
➔ Preuve de concept : LUSIPHER

Large-scale Ultra-fast SIngle PHoton trackER

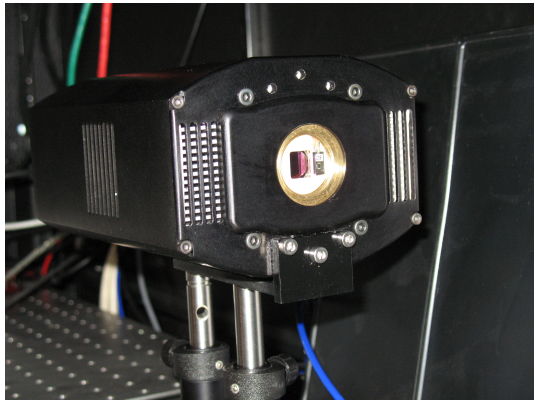


- LUSIPHER

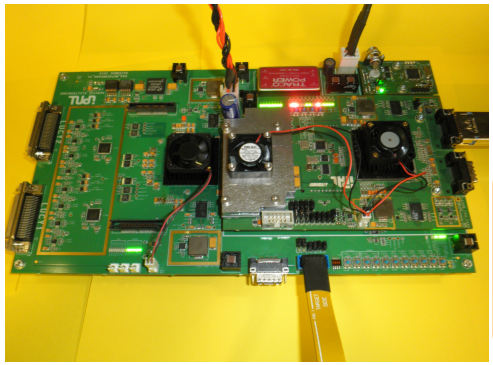




Tube S20
Lusipher 2x(400x800)
500 fps

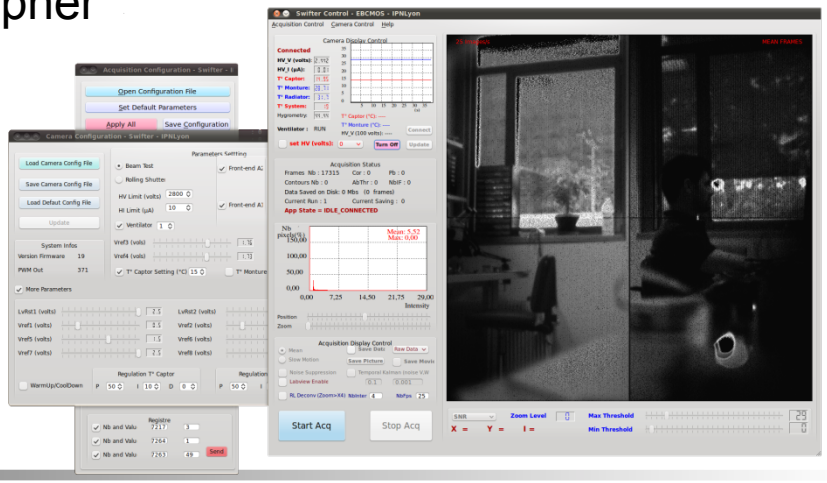


Caméra Lusipher



✓True 10Gbit Ethernet link!

=> 1.2 GB/s



Extreme Low Light Imaging : for Science ?

- Main objectives for science:
  - Identify the phenomena (extract signal from noise)

  ➔ Trigger on physical events

  - Quantify the signal versus time and shape

  ➔ Identify (classify) the emitters

  - Follow the emitter in the Field of View if moving species

  ➔ Track the emitters and compare to current measurement

  - Extract the third dimension to quantify the absolute emission intensity : the "ultimate" identification

  ➔ 3D imaging

  - Times series of classified sequences

  ➔ Make science

  - Correlate with other geo-chemical measurements