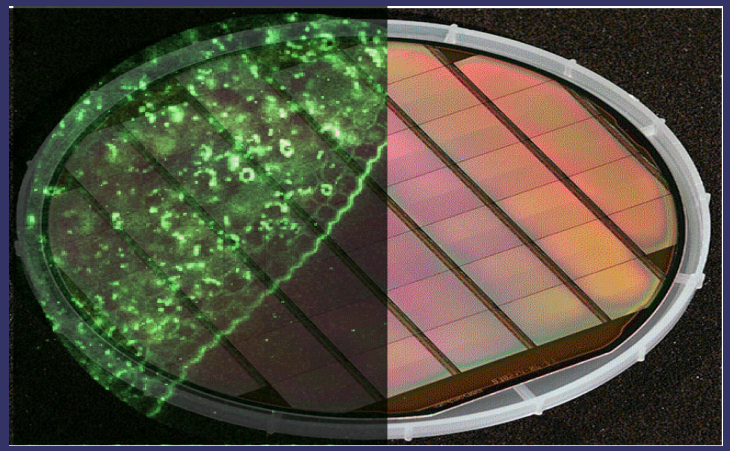
Photon detection with CMOS sensor for fast imaging

PSD 2008, Glasgow, September 1-5



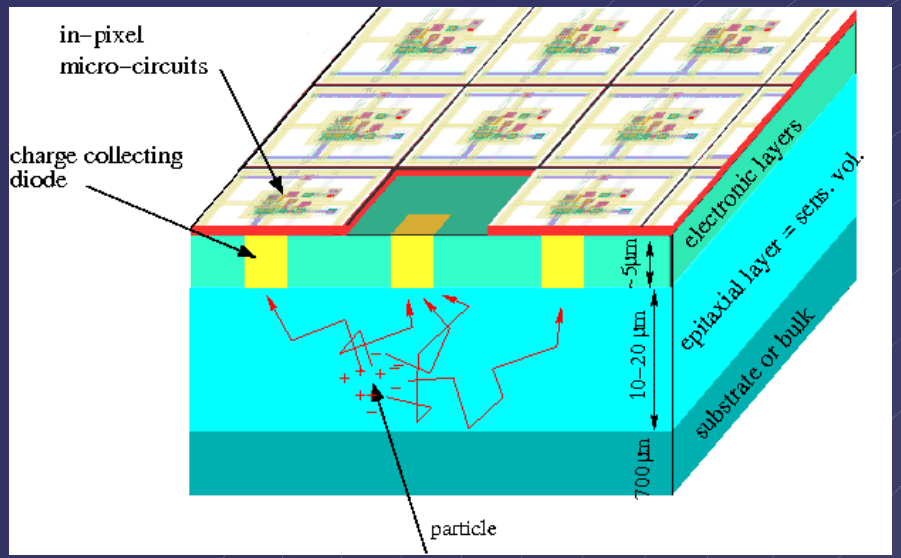
Jerome Baudot, IPHC Strasbourg
in collaboration with IPN-Lyon

R.Barbier, E. Chabanat, P. Depasse,
W. Dulinski, N. Estre, M. Winter

- CMOS sensors for Min.Ion.Part.
- Single photon with EBCMOS
- First tests for biology

Basic principle of CMOS sensors

- Technology
  - Industry standard for ICs
  - Require an “epitaxial layer” 10-20 µm thick
- Monolithic sensors
  - Tow layers in a single object: sensing + reading-out
  - Many integration advantages



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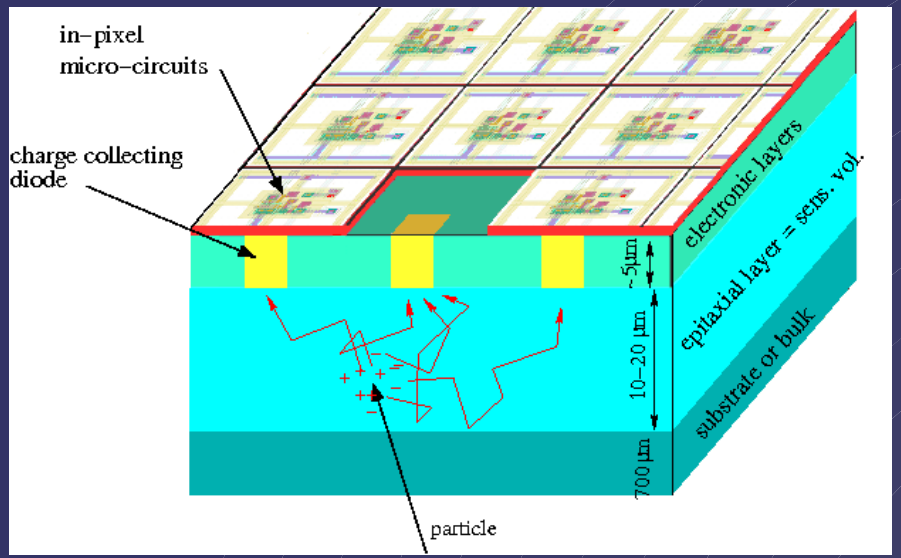
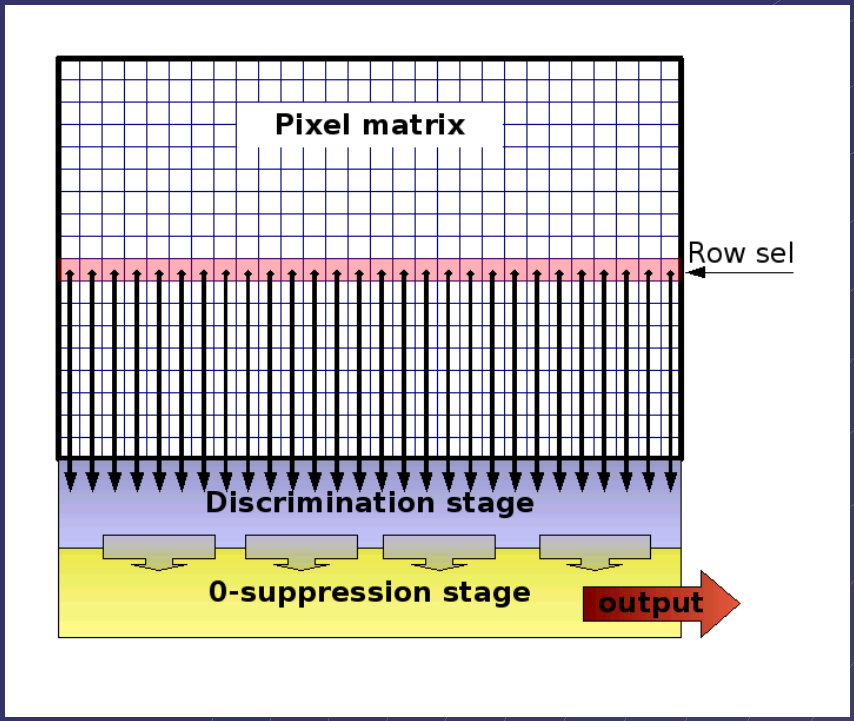


- Developments since 1999
  - Originated in IPHC-Strasbourg
  - >30 sensors produced
  - Including ~MegaPixels sensors of few cm^2
- "Standard" performances for Single charge particle detection
  - Analog readout of each pixel
  - Techno. AMS 0.35 um OPTO
    - Noise ~ 10-15 e-
    - Signal/Noise (MIP) > 15
    - Efficiency ~ 100%, fake rate ~ 10^{-5}/pixel
    - Spatial resolution ~ 1 um (10 um pitch) -> 3 um (40 µm pitch)
  - Room temperature operation

Readout possibilities

- Readout speed
  - Analog readout limited ~ ms for MegaPixels sensors
  - Column parallel readout
    - ~100-200 ns / column
      readout ~100 µs for 1000 rows
    - Requires discrimination/ADC
    - Digital readout



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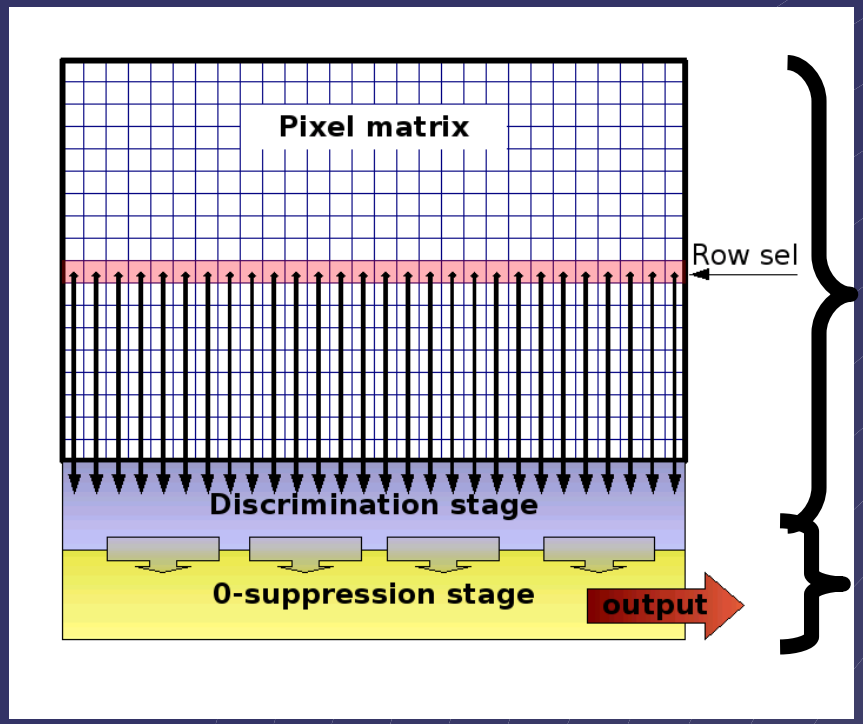
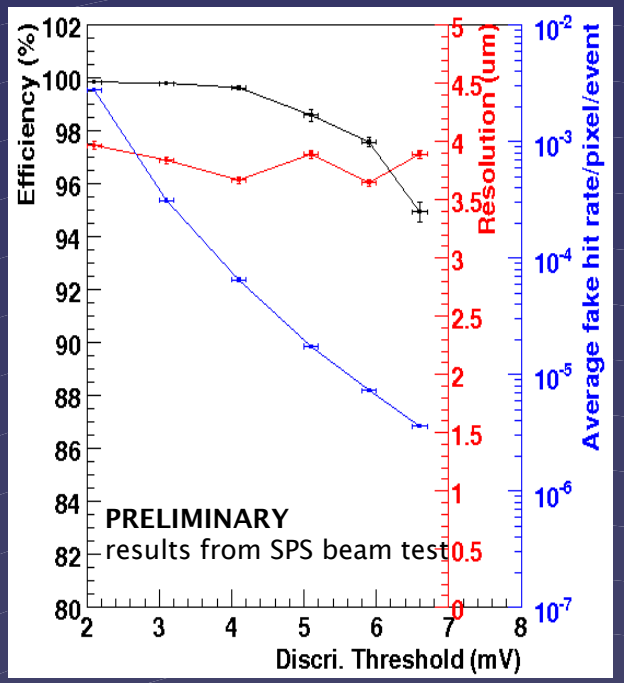


- Digital Mimosa serie: M8, 16, 22
  - Mimosa 22 (2007)
    - 576x128 pixels, 18.4 µm pitch
    - 100 µs readout time

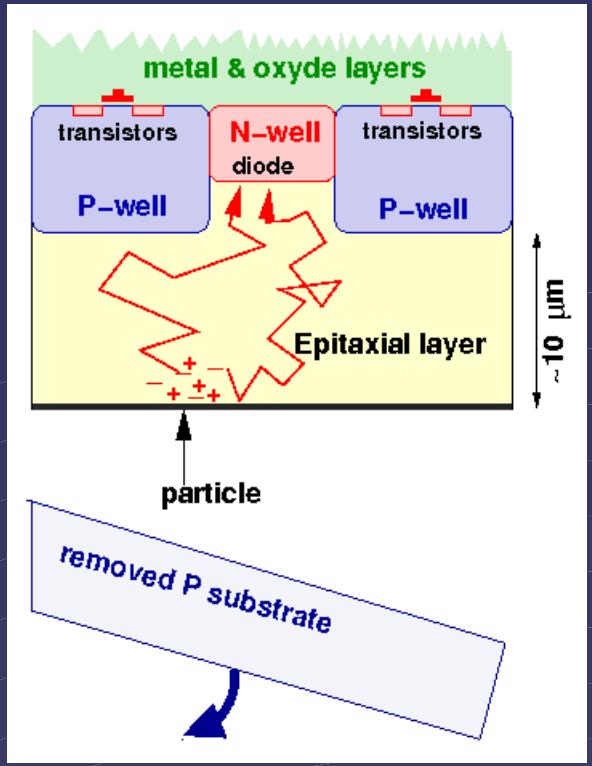


  - Suze 01 (2007)
    - Zero-suppression logic only
    - 64 columns treatment in 160 ns
    - Validated with test patterns

Sensitivity

- Low energy particles
  - Electrons of few keV, Visible photons
  - Short range in IC material: can't reach the sensitive volume !
  - Back-thinning (industrial process) + Post-processing of sensitive volume back-plane

⇨ back-illumination



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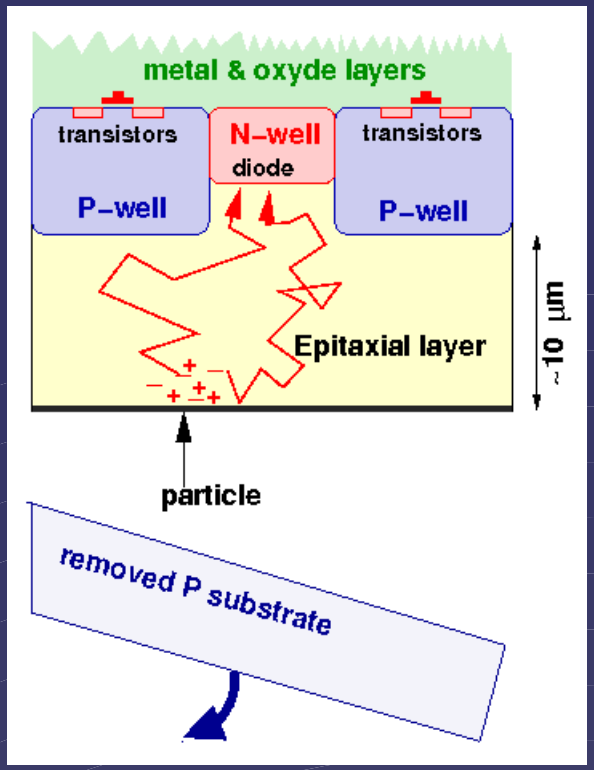
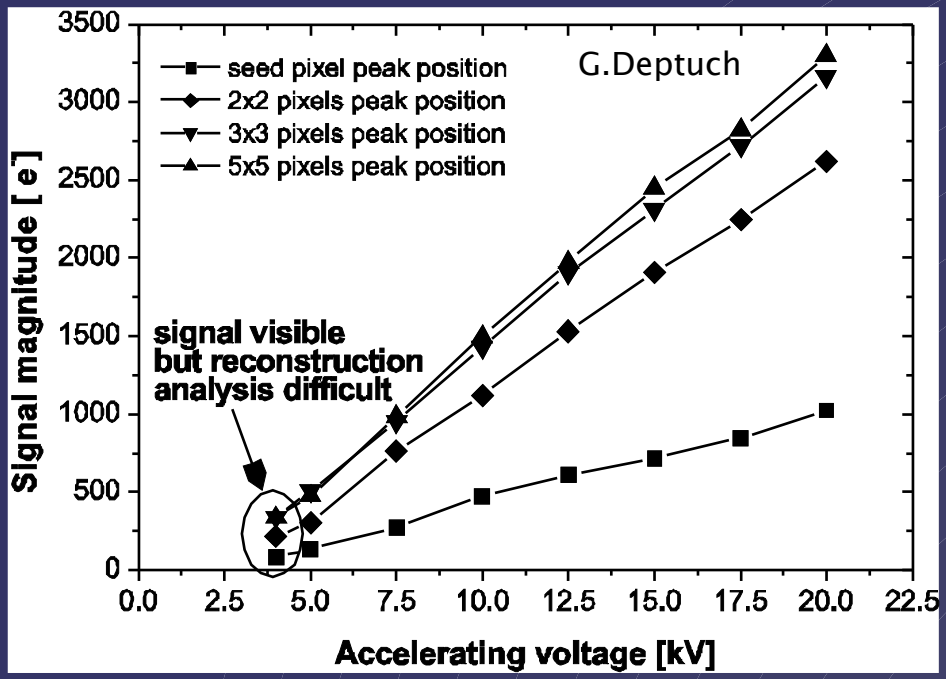
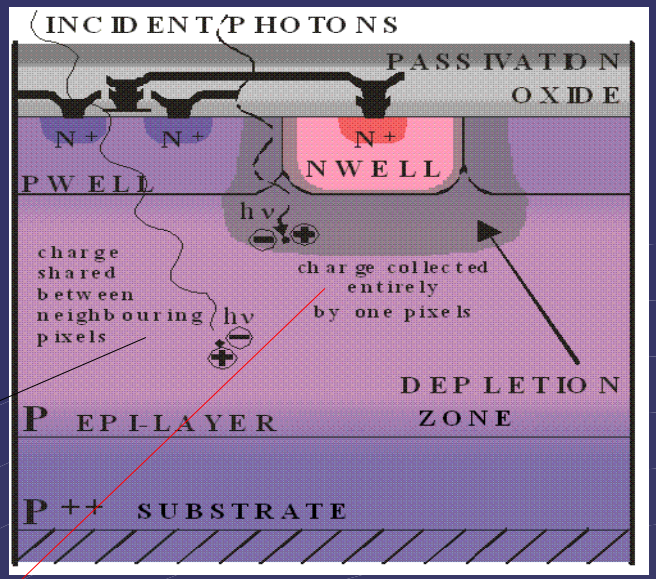


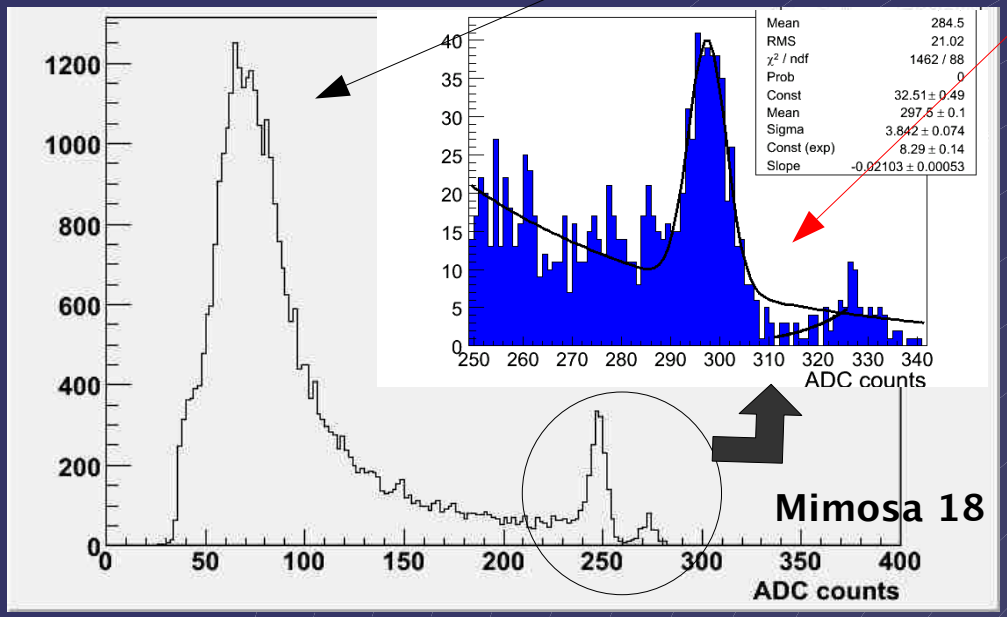


- Back-thinned Mimosa 5
  - MegaPixel sensor with 17 µm pitch
  - Back-tinning within SUCIMA project
  - HV accelerated electrons bombarding
  - applications for electron imaging not covered here

Photon detection

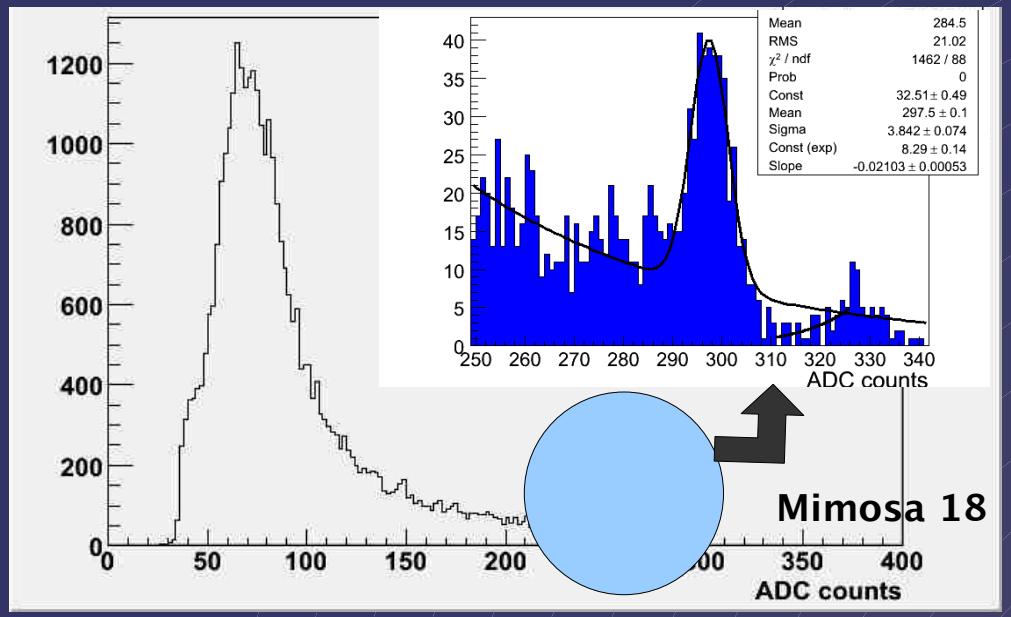
- γ rays
  - No efficiency, bu seeable
- X rays
  - > 10 keV: no efficiency
  - Few keV range
    - % level efficiency
    - Energy resolution ~ %

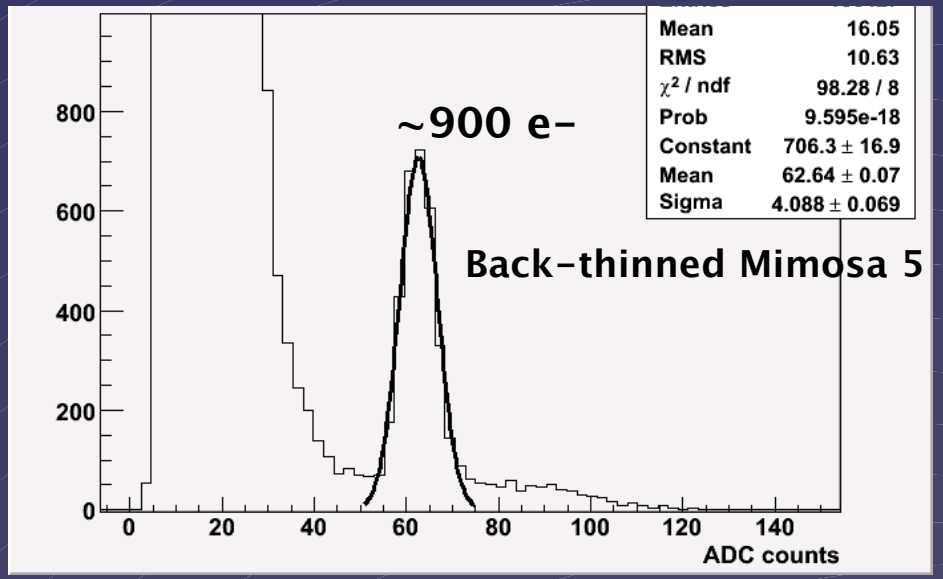




Photon detection

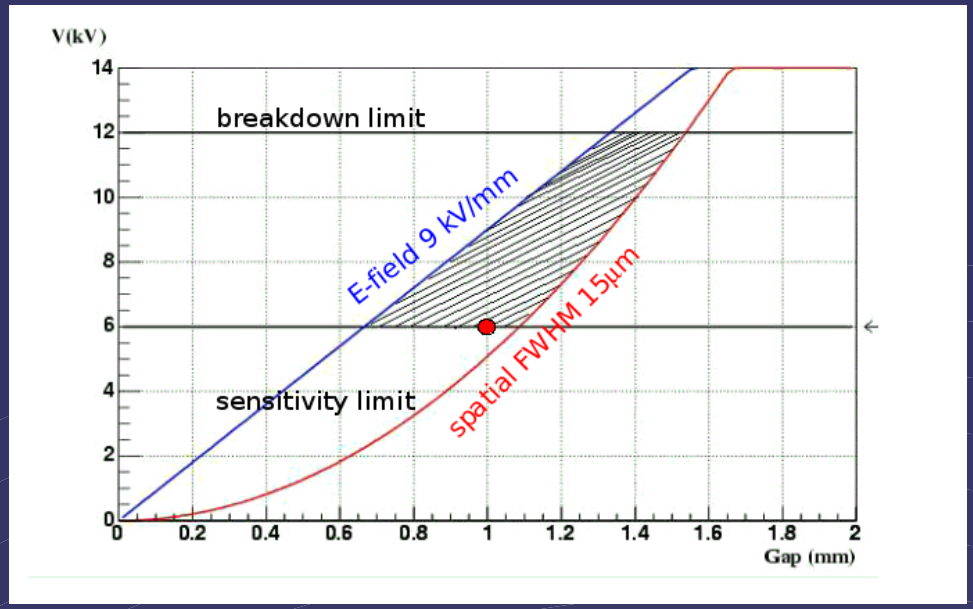
- γ rays
  - No efficiency, bu seeable
- X rays
  - > 10 keV: no efficiency
  - Few keV range
    - % level efficiency
    - Energy resolution ~ %
- Visible photons
  - Std camera applications for visible light
  - For much less intense source: back-illumination
    - Back-thinned Mimosa 5
    - In-pixel focused infrared led (1063 nm)
- Still looking for applications

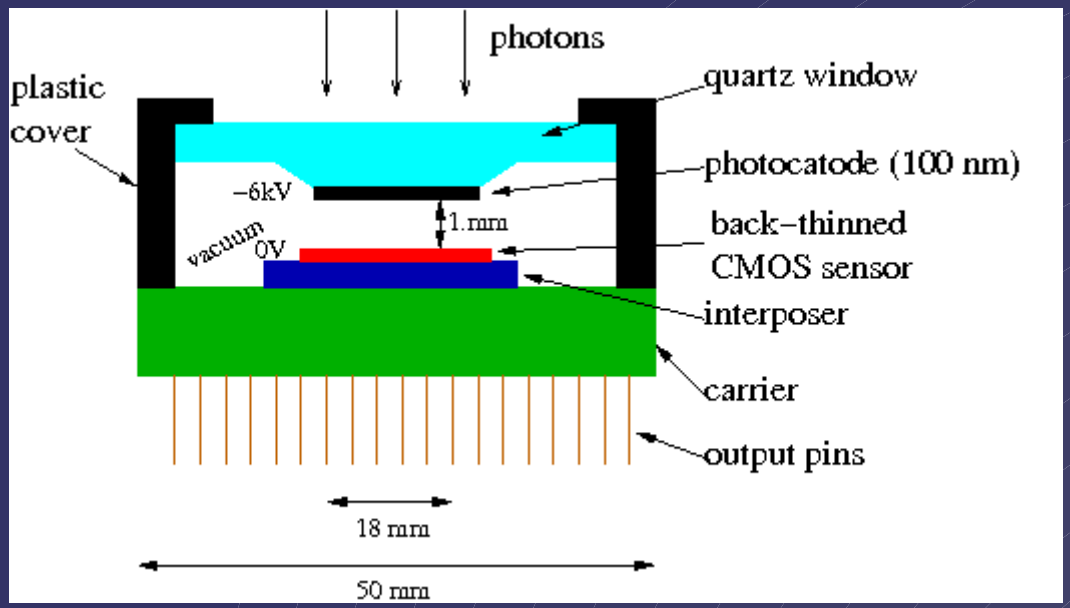




Single photon detection: EBCMOS

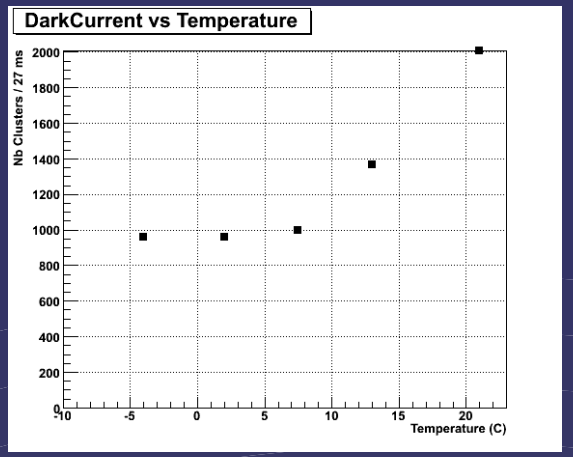
- A new hybrid photo-detector: Electron-Bombarded CMOS Sensor
  - Use back-thinned Mimosa 5
    - 1024x1024 pixels, 17 µm pitch
    - Readout time 27 ms (~30 frames/sec)
  - Combined with photocathode S20-type
    - QE @ 532 nm ~ 15%
  - Vacuum tube integration by PHOTONIS, first prototypes june 2007

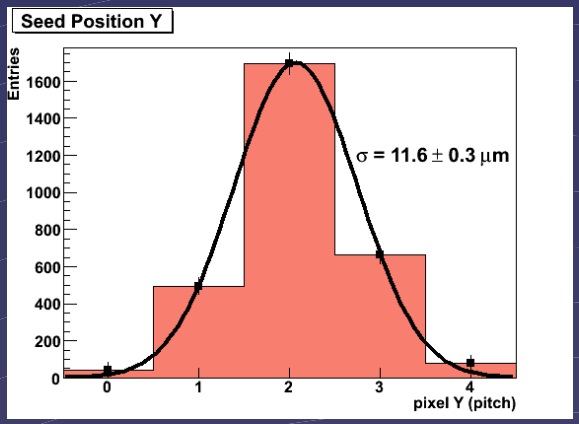


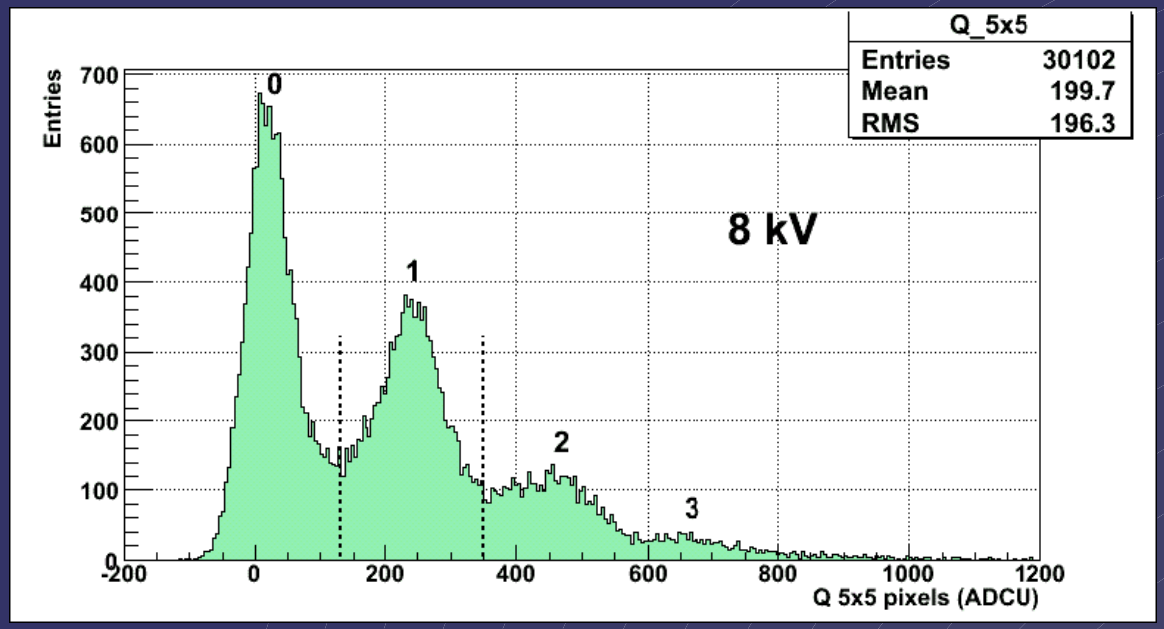


EBCMOS performances

- Characterization @ IPN-Lyon
  - Optical bench: focalized laser diode
  - Photon-counting calibration
  - PSF studies
- Performances
  - Dark count rate 100 Hz/mm @ 10 °C
  - Spatial resolution 11.6 µm (@ 540 nm)
  - Dynamic 1-30 photo-electrons/pixel







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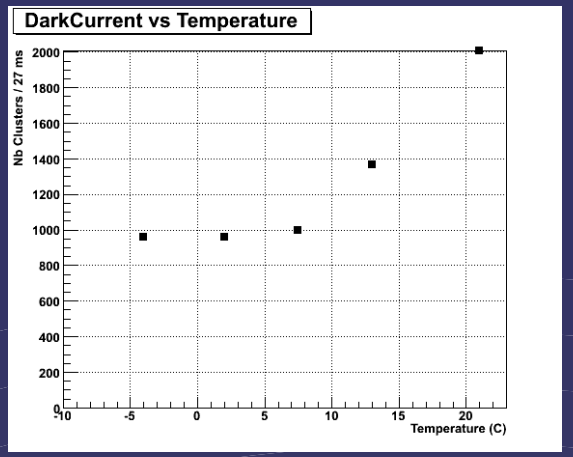
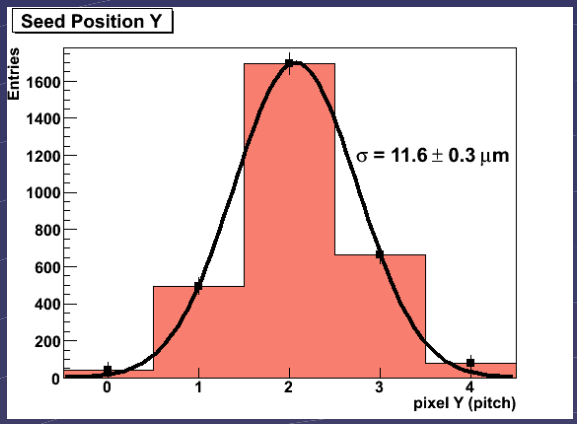
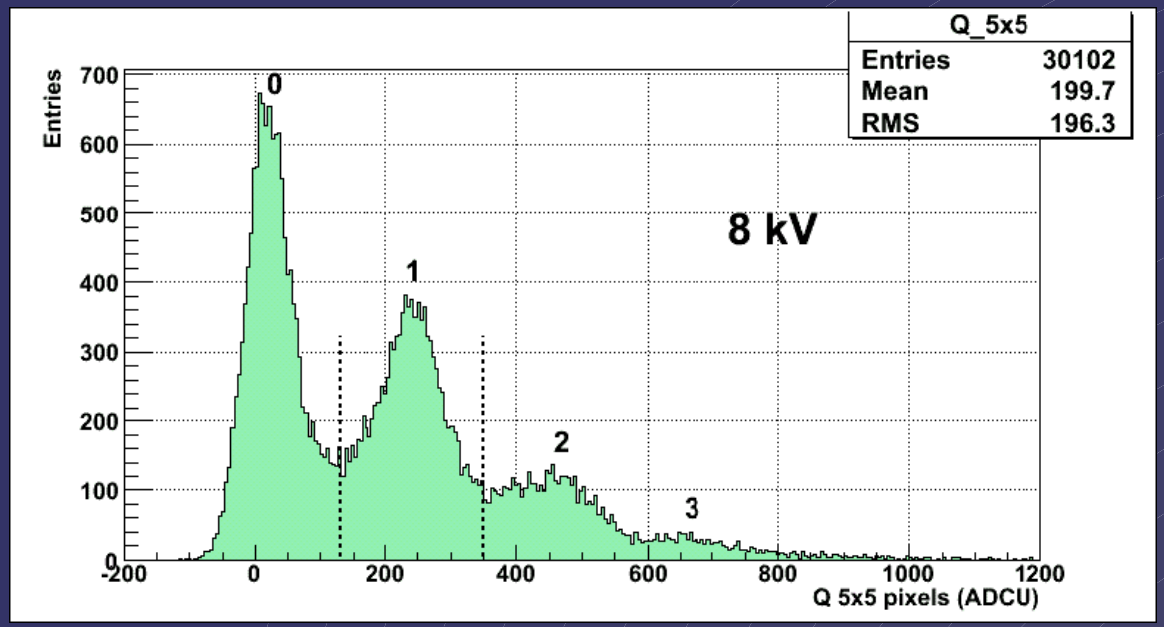
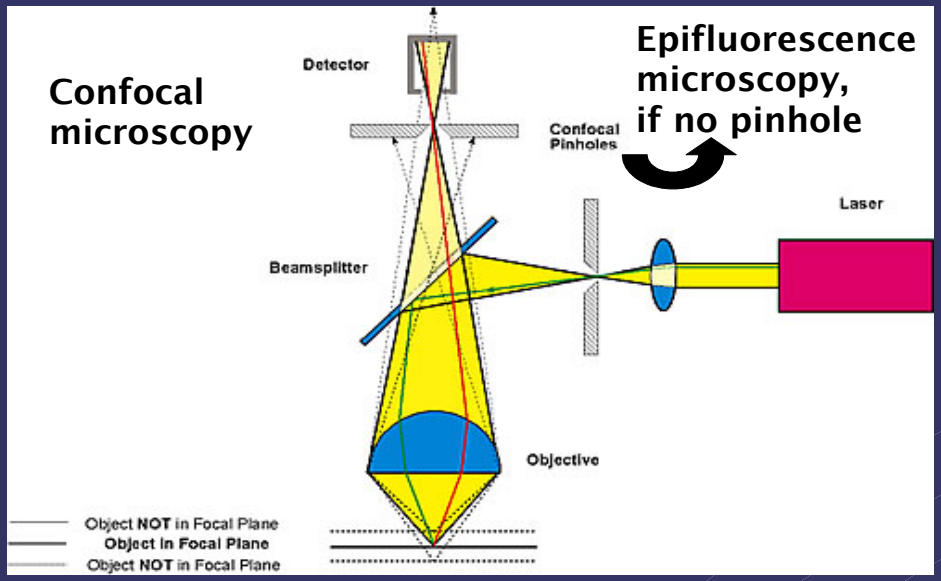






- Known problems
  - Ion feed-back
  - Back-scattering ~ 18%
  - Low to moderate quantum efficiency (restricted wavelength bandwith)

Fluorescence microscopy



- In life sciences
  - Image cells/molecules in 3D+time dynamics
  - Use fluorescent (all colors) proteins on defined targets
  - Detector used:
    - CCD: 2D but sensitivity limited
    - EMCCD: 2D+single photon but speed limited (~30 frames/sec)
    - PMT: single photon but not 2D

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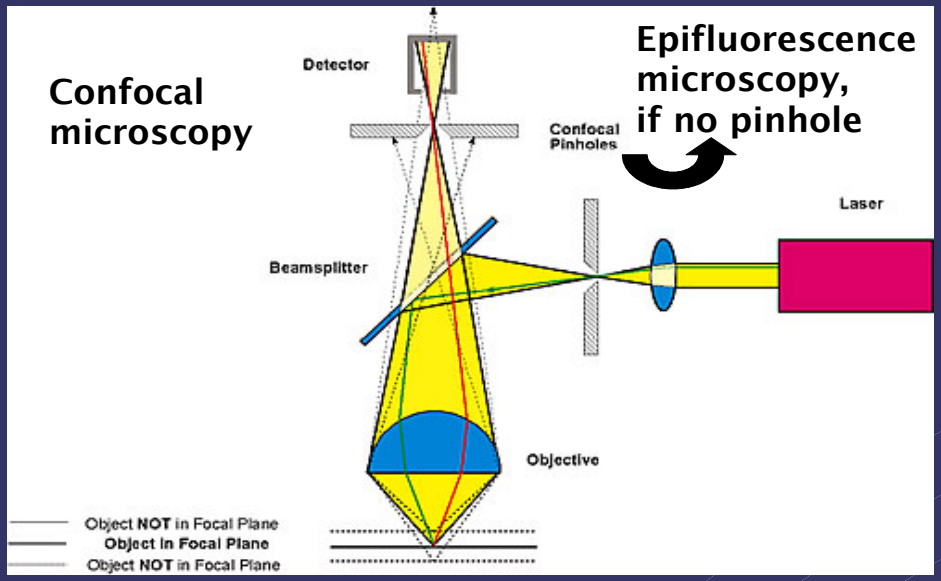

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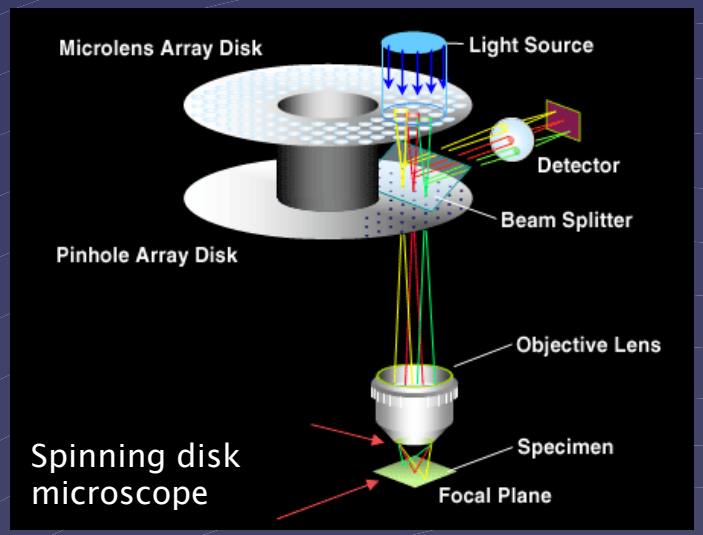
- Where can EBCMOS helps ?
  - for single photon sensitivity
  - for fast 2D imaging from 50 and beyond 1000 images/sec
    - Decrease photodamage & photobleaching
    - Observe a fast dynamic
    - Build real-time 3D pictures



EBMIMOSA-5 tests with biologists

- Biological samples from
  - EBMIMOSA-5 operation by IPNL & IPHC
  - IGBMC-Strasbourg, Angela Giangrande & Jean-Luc Vonesh
    - Lilly root cells
    - Latex beads (⌀~100 nm)
  - ENS-Paris, Maxime Dahan
    - Quantum dots fixed on membranes of hela cells

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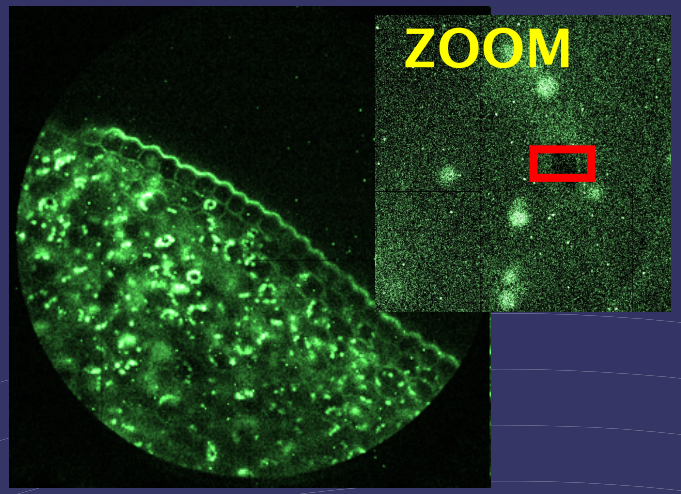
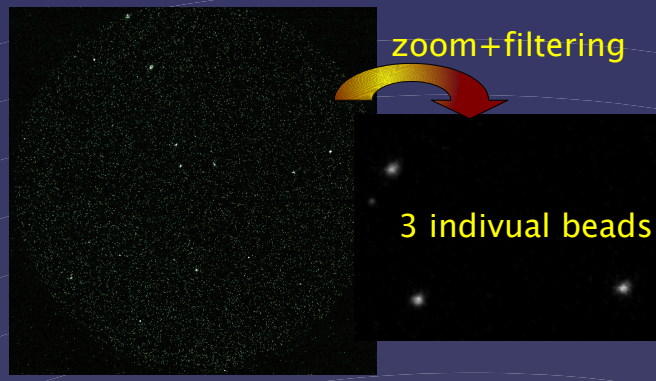
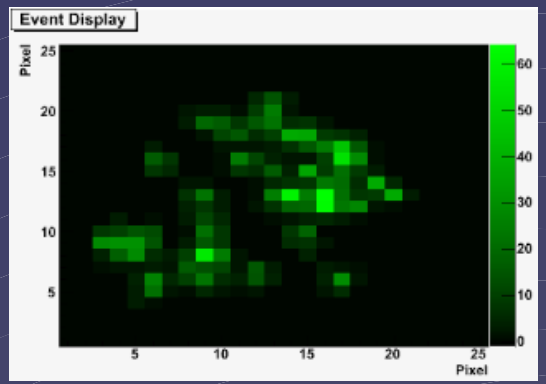
- Sensitivity / contrast
  - Better than CCD
  - Similar to EMCCD (for green fluorescence)
- Spatial resolution
  - σ of distribution after 30 frames and after microscope magnification
  - 275 nm for EBMIMOSA-5
    (145 nm with CCD of 6.5 µm pixel pitch)

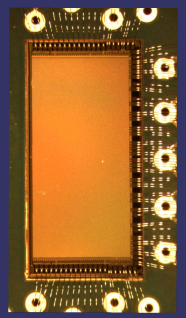






On-going developments

- **CMOS sensor**
  - New chip LUCY fabricated in 2007

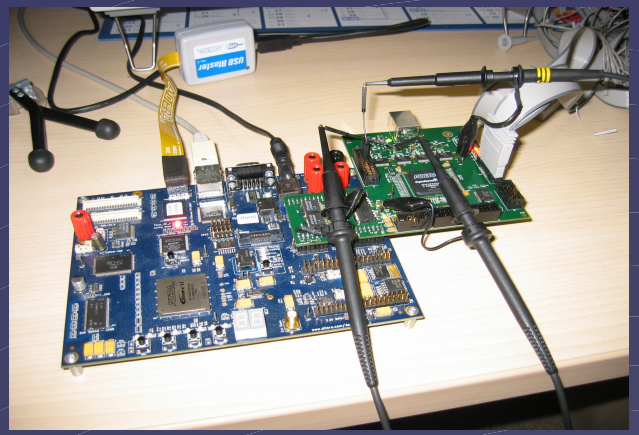


    - 400x800 pixels, 10 µm pitch
    - Analog readout on 8 outputs
      readout time 1 ms (1000 frames/sec)
    - Std version OK (from ^{55}Fe test), noise~8 e-
    - Back-thinned version expected Sept.08

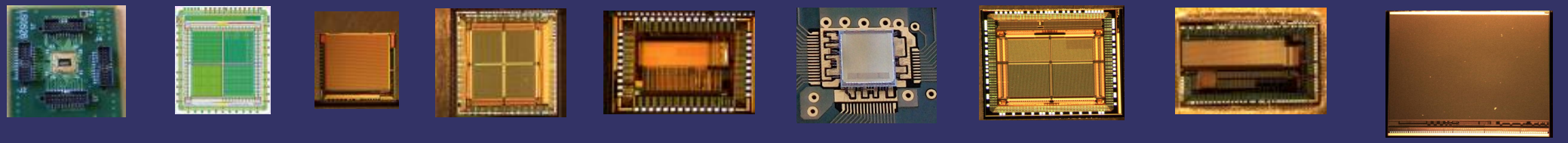
- **Vacuum tube for EBCMOS**
  - Work on photocathode by Photonis to ↗QE
  - Reduced gap ~ 600 µm
    to improve spatial resolution

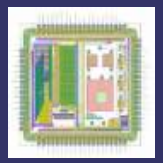
- **Data acquisition**
  - 1 MegaPixels @ 40 frames/sec ~ 300 Mbits/s !
  - IPN-Lyon develops on-board (hit) analysis
    + Gbits/s PC-connection
  - Goal: 1000 frames/sec on 320 kPixels (0.3 cm^2)

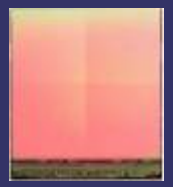
- **Data analysis**
  - Various image treatments
    to be evaluated
    - Filters
    - Tracking

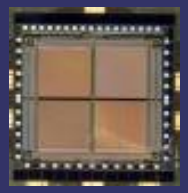


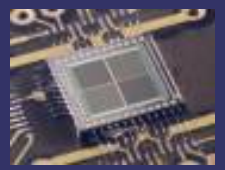
Summary & outlooks



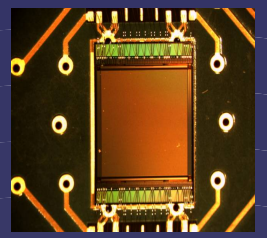


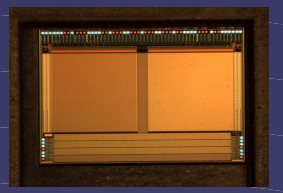




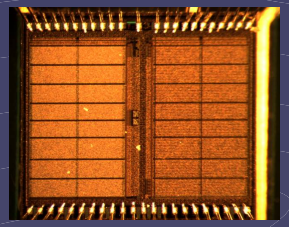


- CMOS sensors from single charged particle tracking
  - Offer various sensitivity for photon imaging
    - Low efficiency for X-rays but few% energy resolution @ few keV
    - Single-photon when back-thinned + hybridized with a photocathode
  - Offer fast readout with on chip signal treatment





- First applications expected:
  - Single photon positionning with EBCMOS for fluorescence microscopy in biology
  - Proof of principle passed
  - Real measurement to come this year

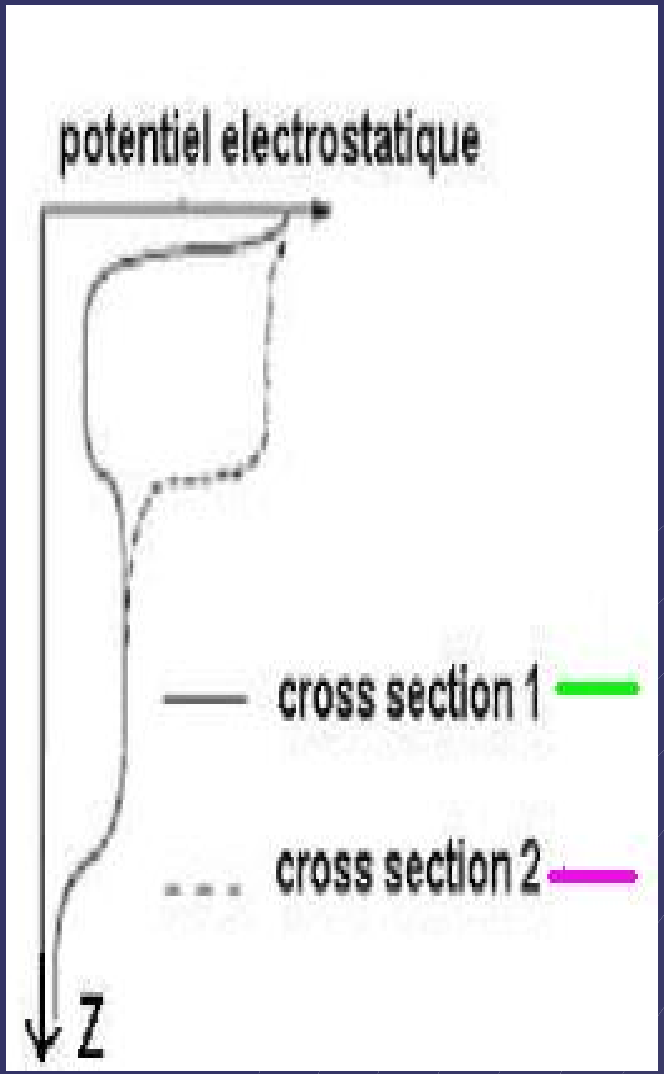


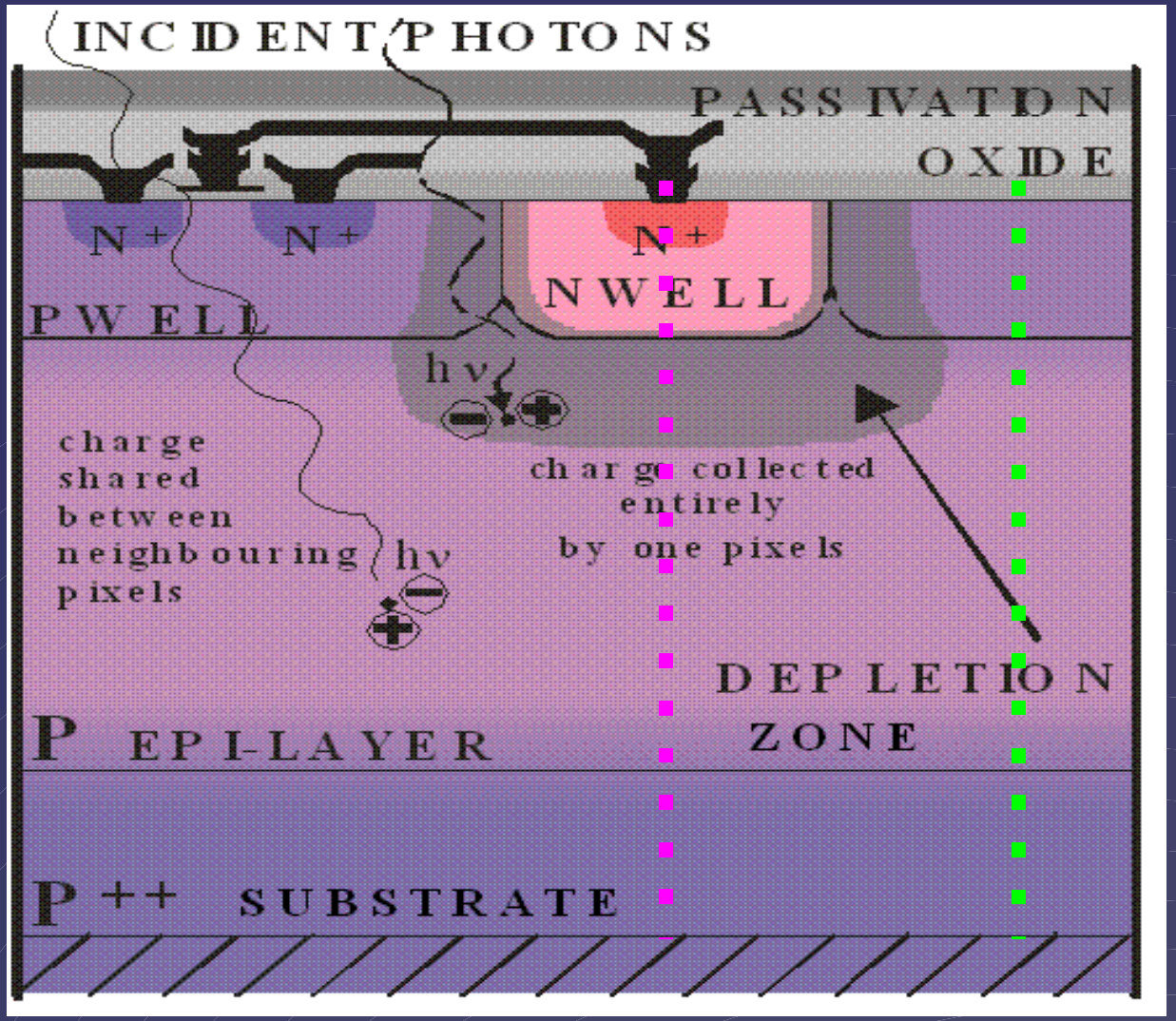
Thanks to

- IPN -Lyon
  - Sylvain Vanzetto / Georges Maurelli / Rodolphe Della Negra / Cyrille Guérin / Didier Bon / Pierre-Yves Solane
- IPHC-Strasbourg
  - Andrea Brognia / Auguste Besson / Claude Colledani / Rita De Masi / Guy Doziere / Christina Dritsa / Andrei Dorokhov / Gilles Clauss / Jean-Charles Fontaine / Mathieu Goffe / Abdelkader Himmi / Christine Hu / Kimo Jaaskelainen / Michal Koziel / Mathieu Goffe / Alexandre Merlin / Frederic Morel / Nicolas Pillet / Alexandre Shabetai
- PHOTONIS SA
  - Henk Verboom / Patrick Clauzel /Carlo Kayser / Nicolas Laurent

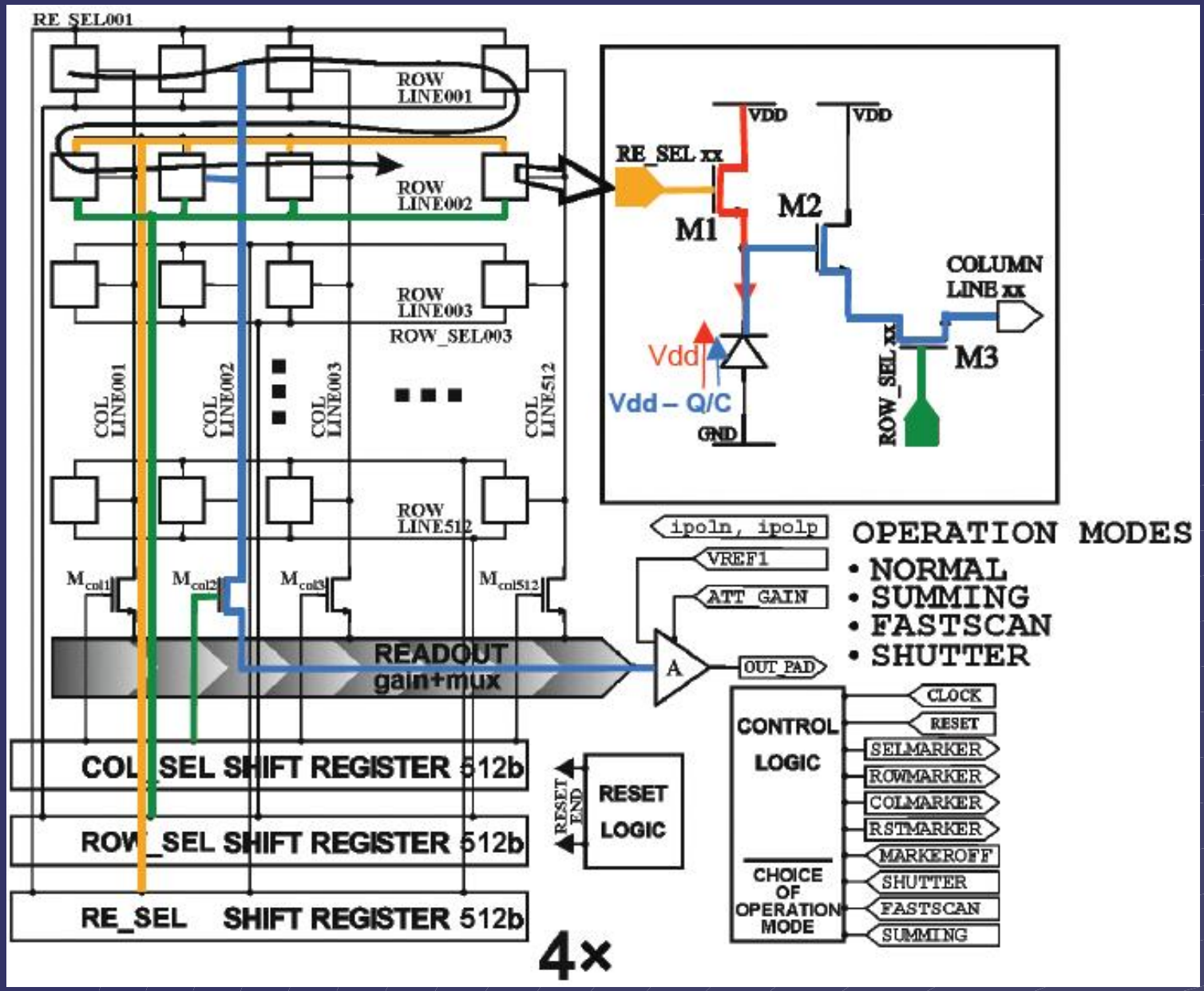
! BACKUP SLIDES !

CMOS charge collection principle

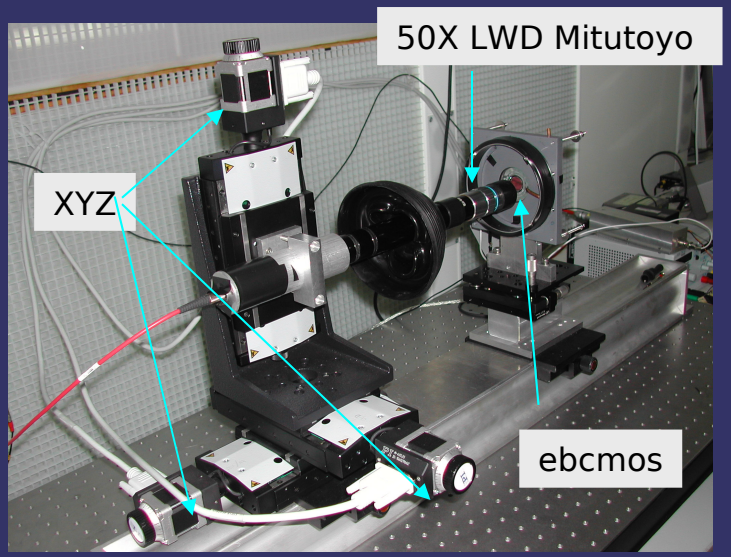


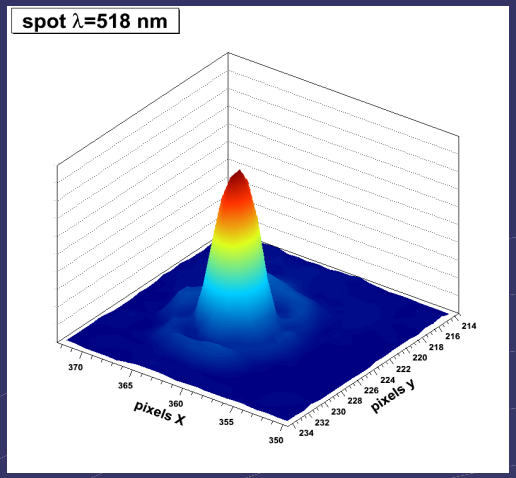


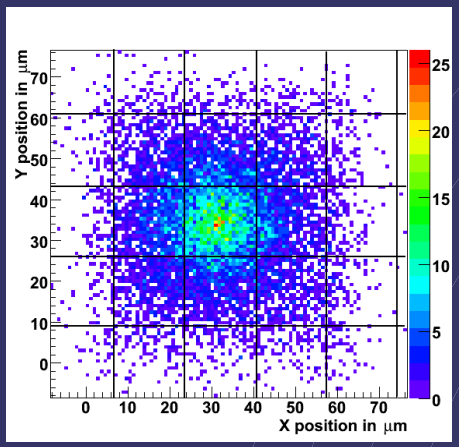
CMOS analog readout principle

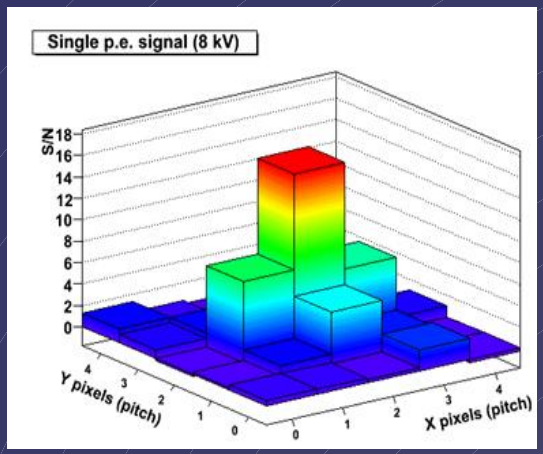


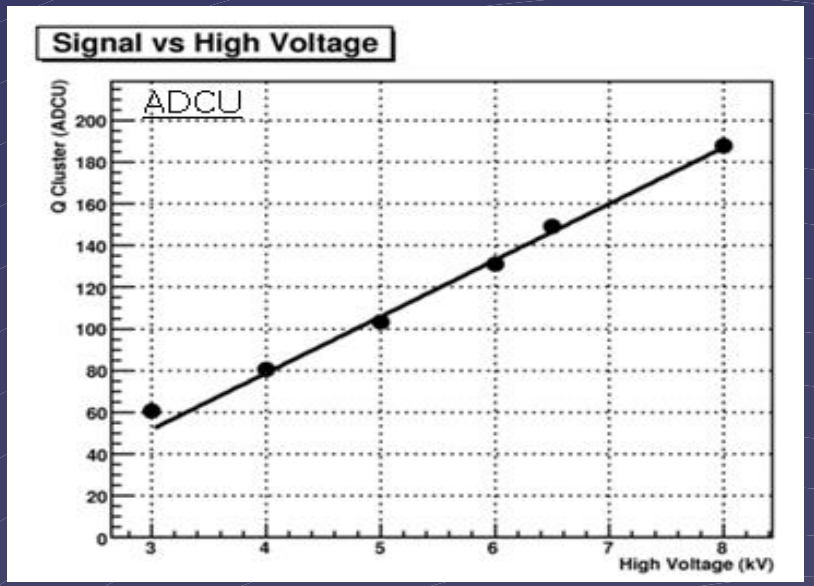
EBCMOS characterization at IPN-Lyon







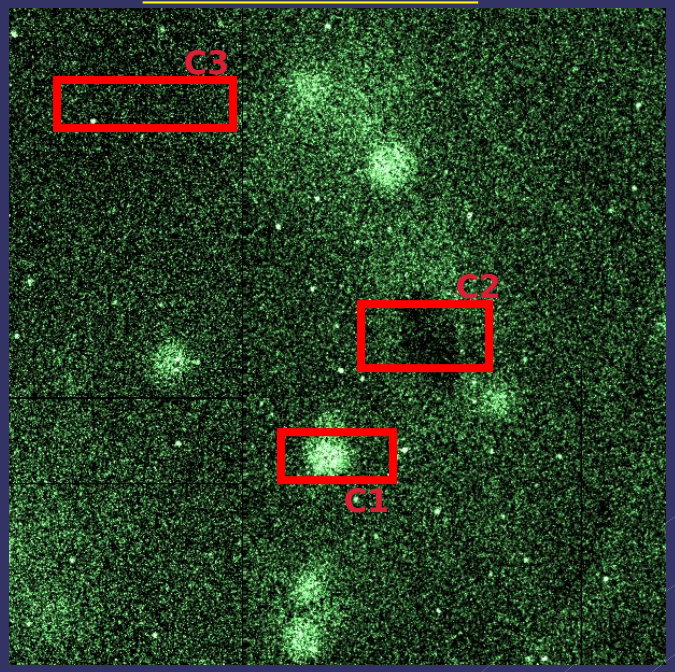




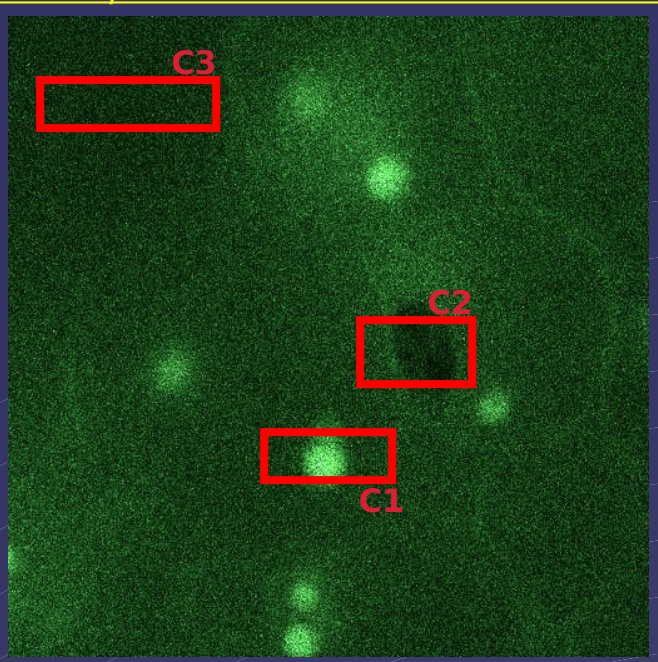
EBCMOS contrast study / EMCCD

From R.Barbier & N.Estre

EBMI5 Tint=27 ms



Cascade 2 / EMCCD Tint=30 ms : Gmax=1000



C= (Imax-Imin)/(Imax+Imin)

C1	SNRmax=175 SNRmin=45 **C= 0,59**	Imax=18000 Imin= 8000 **C= 0,38**
C2	SNRmax=48 SNRmin= 28 **C= 0,26**	Imax=9400 Imin= 7300 C= **0,13**
C3	SNRmean = 30	Imean = 7400

Fluorescence microscopy applications

where 2D localization of single photons is required

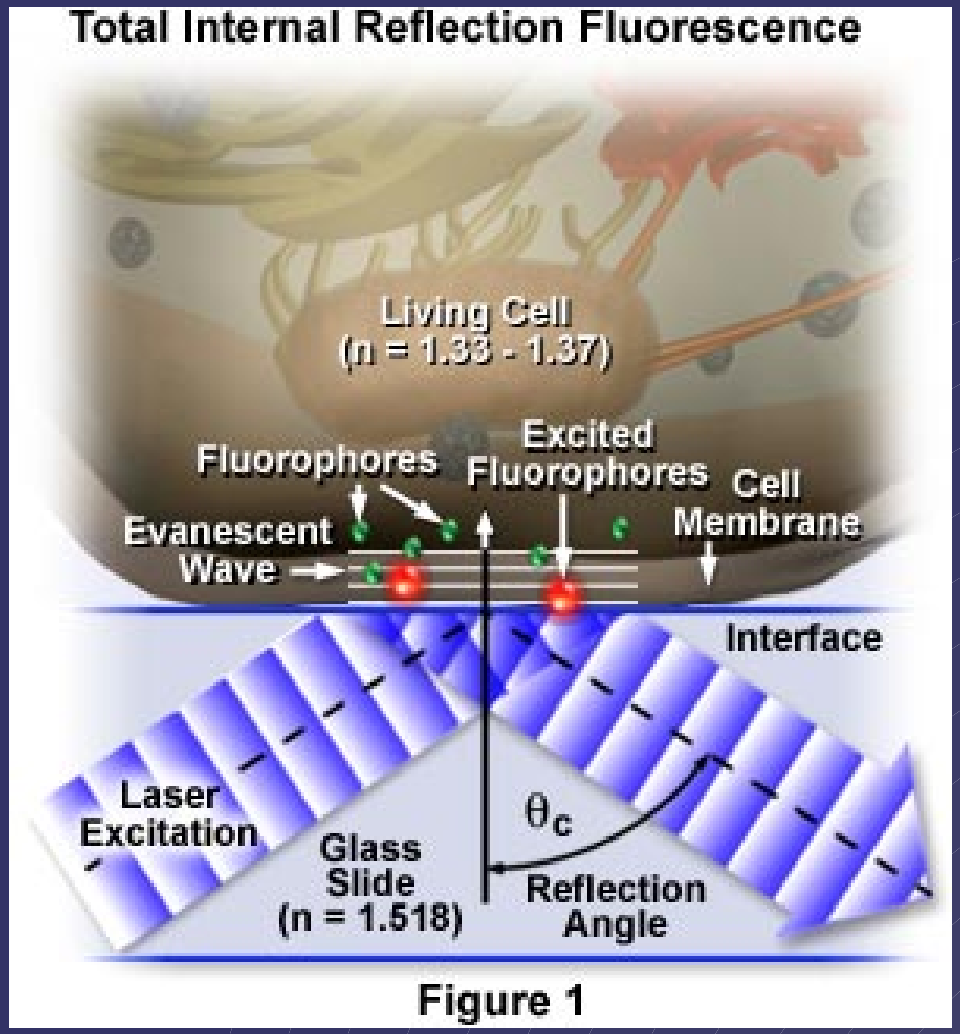
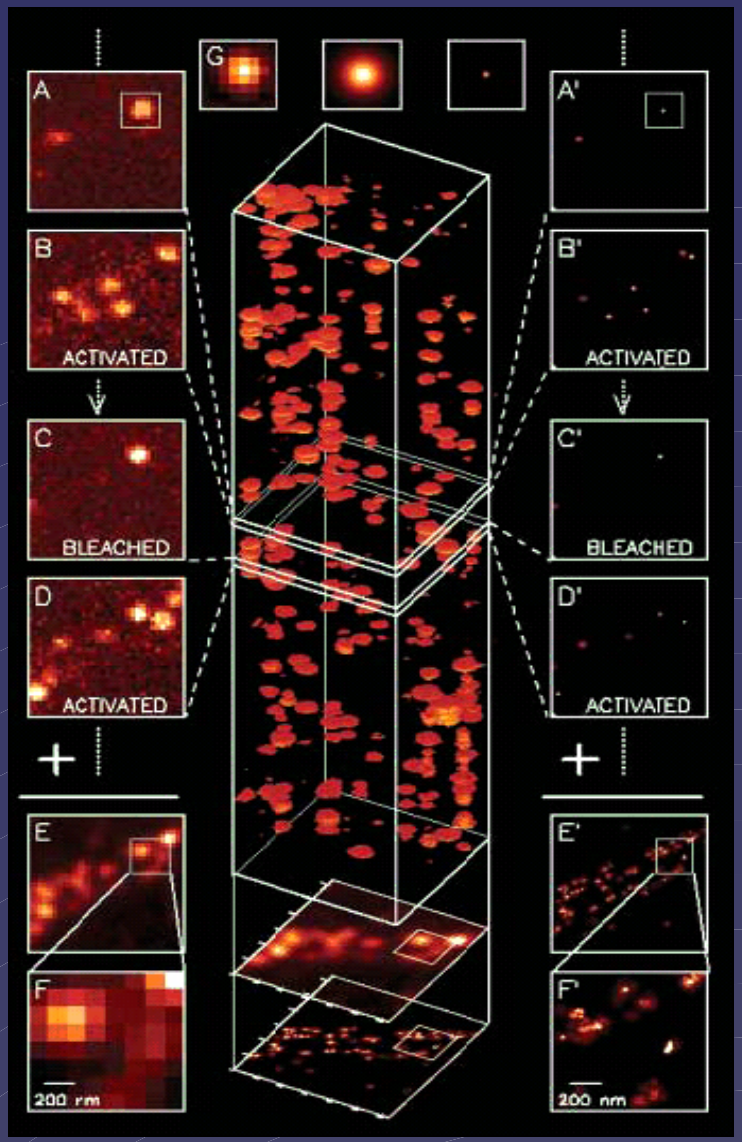


Figure 1



PhotoActivated Localization Microscopy
E.Betzig, Science vol 313, 2006