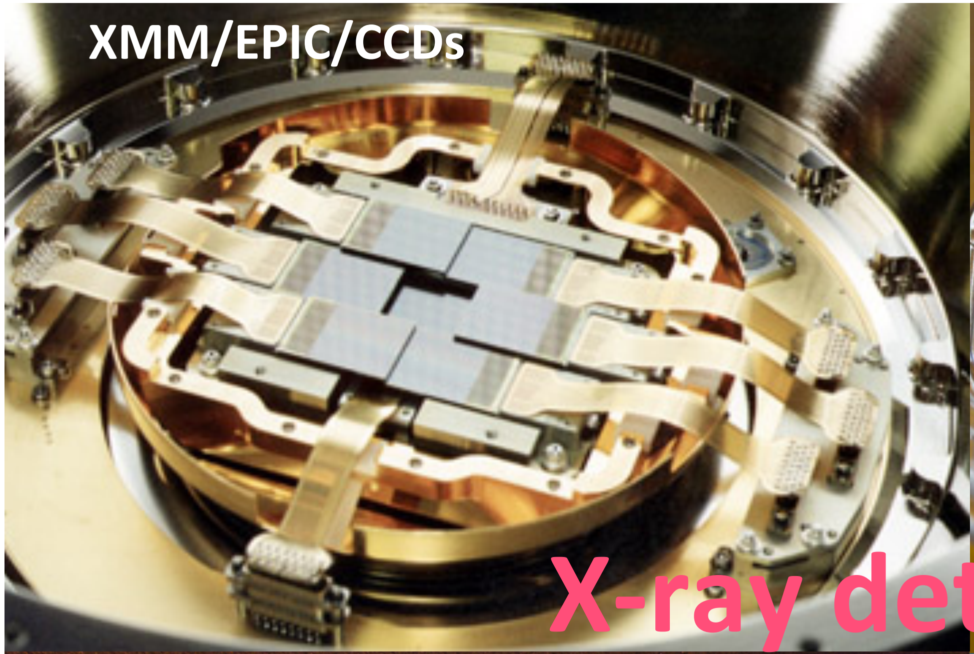
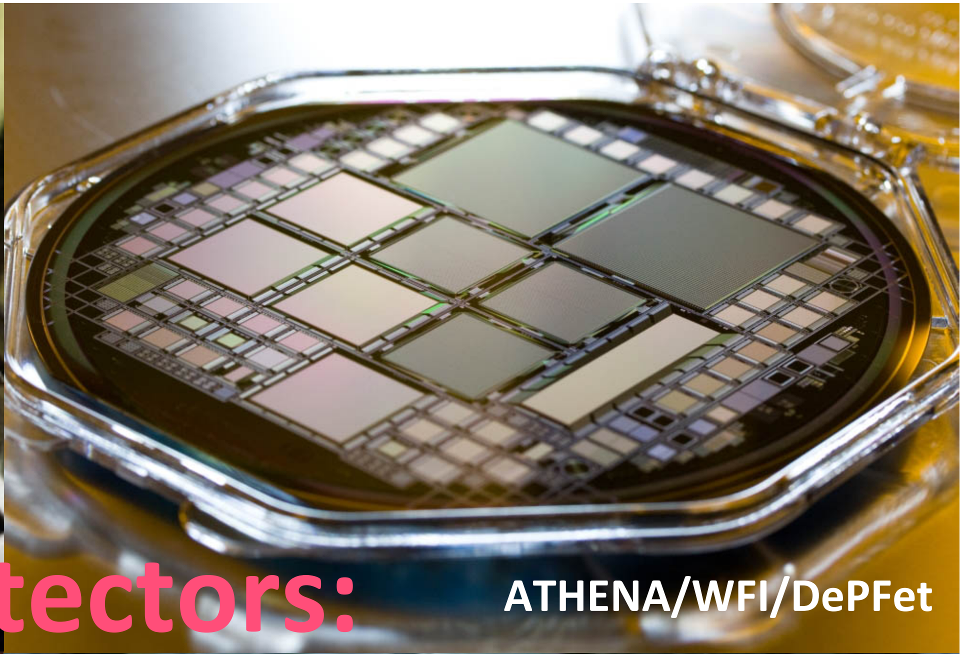
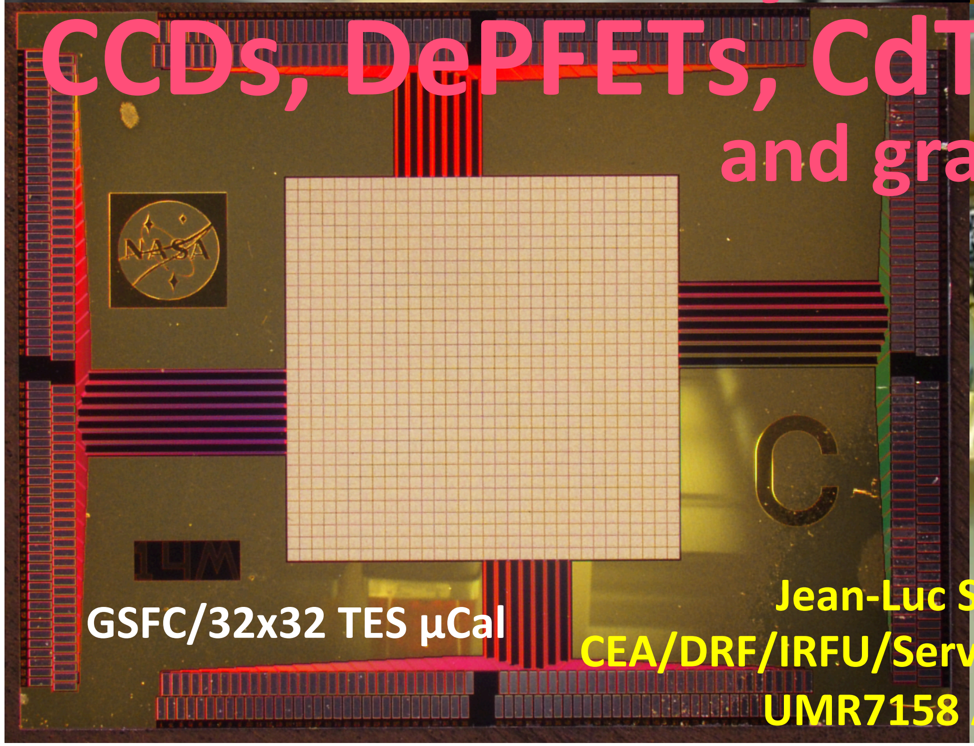
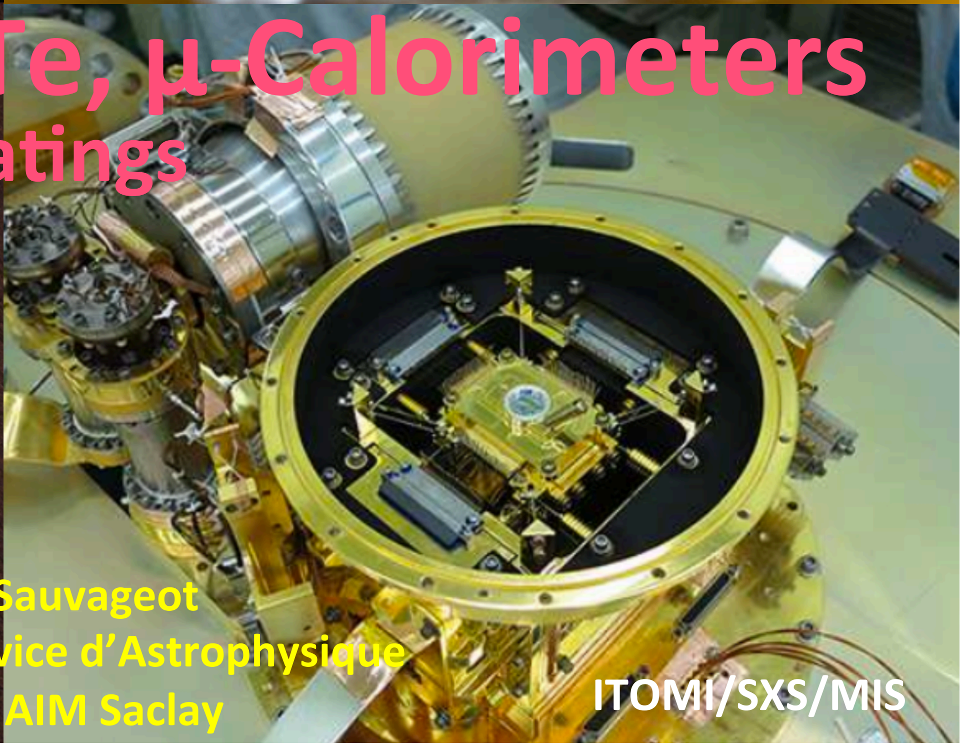
X-ray detectors:
CCDs, DePFETs, CdTe, μ-Calorimeters
and gratings


XMM/EPIC/CCDs


ATHENA/WFI/DePFet


GSFC/32x32 TES μCal


ITOMI/SXS/MIS

Jean-Luc Sauvageot
CEA/DRF/IRFU/Service d'Astrophysique
UMR7158 AIM Saclay

I. CCDs in X-Rays or how do we use CCDs to obtain X-ray Photon List?

II. How DePFETs array improve onto the CCDs observations?

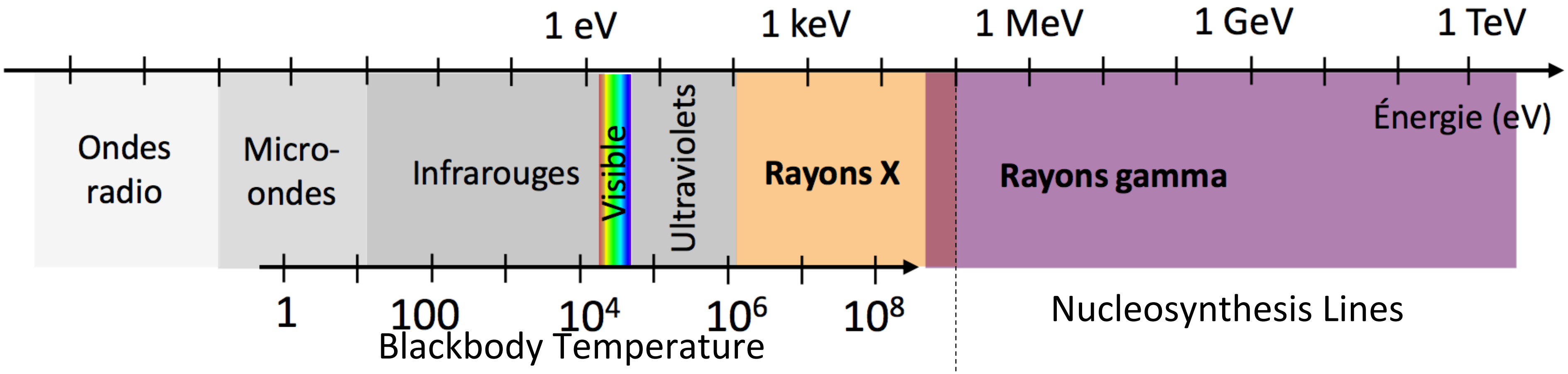
III. The CdTe at higher Energies.

IV. Gratings: Wavelength dispersive spectroscopy against Fano factor.

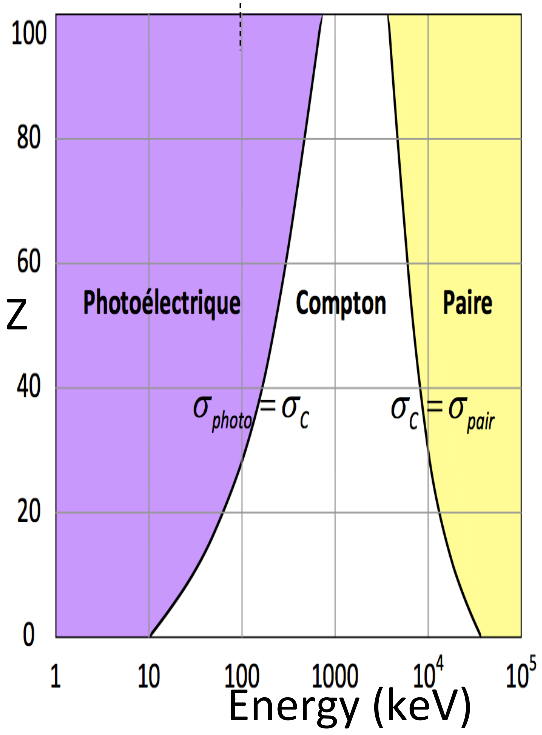
V. The µ-Calorimeters & their exquisite spectral resolution.

I + II ~50min, III 10min, IV 2min & V 50min

X-ray and Matter



Nucleosynthesis Lines



Photoelectric Effect
Compton Effect
Pairs

X-ray range

200ev <E<100keV

dominated by **PhotoElectric Effect**

X-rays & Astronomy

- Large Mirror ?

ATHENA : $S_{eff} \leq$ 1m^2 @ 1keV & $S_{eff} \leq$ 0.1m^2 @ 10keV

Not so « Large »

- Celestial Sources are relatively weak in X-rays photon flux…

- Thus, as long as the detector is fast enough (≤ 1ms)

X-ray observations are always in photon by photon Mode

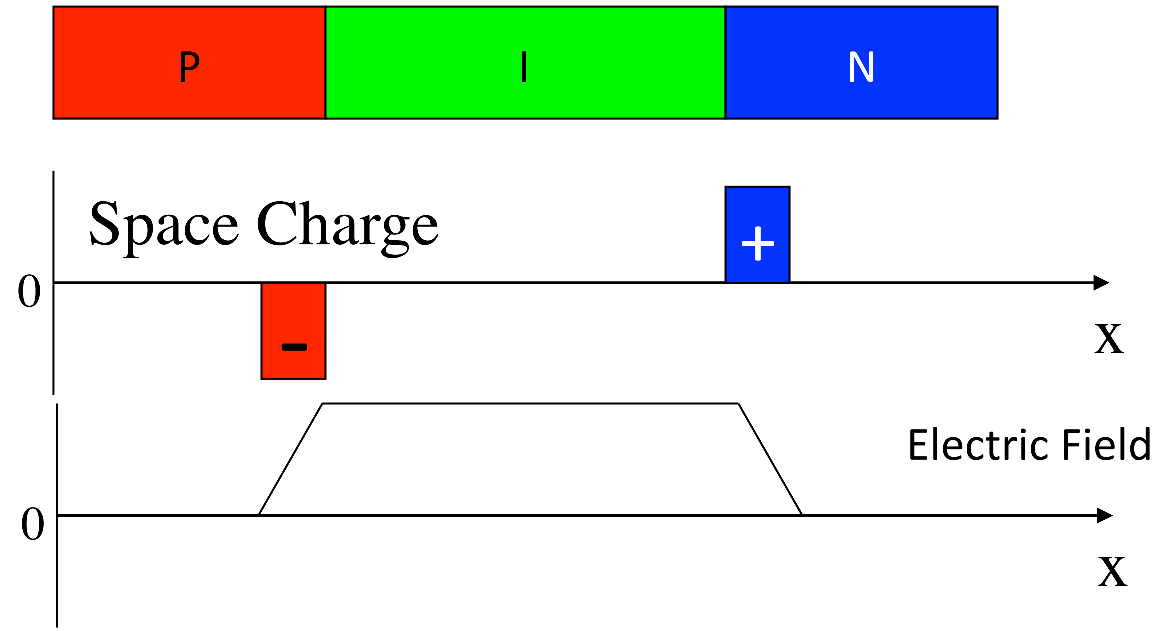
⇒ A spectro-imagery X-ray observation in Astronomy is a photon list with X,Y,En, Arrival Time.

« Historic » X-rays detector

X-ray Astronomy began in the 60 ‘s …

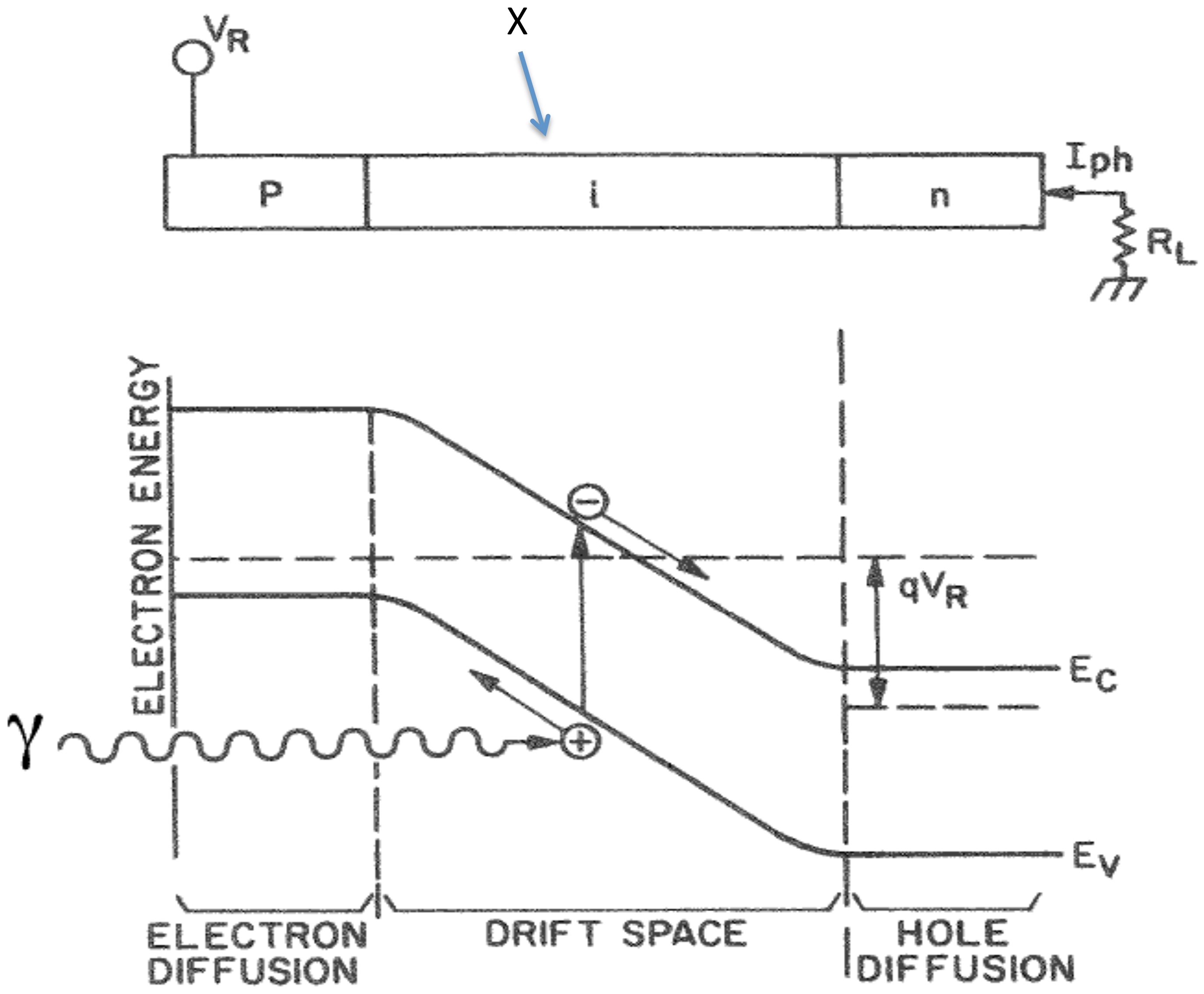
- Gaz Counter (~1960)
- Chanel Multiplier Array
- Gas Scintillating Proportional Counter (1970-1990)
- Solid State Spectrometer (1985)
- Charge Coupled Device (1990-2016)

I.PN-CCDs are p-i-n reversed biased diode



Reverse biased diode & Low Temperature
allow to have very small leakage current.
Leakage current << 1pA

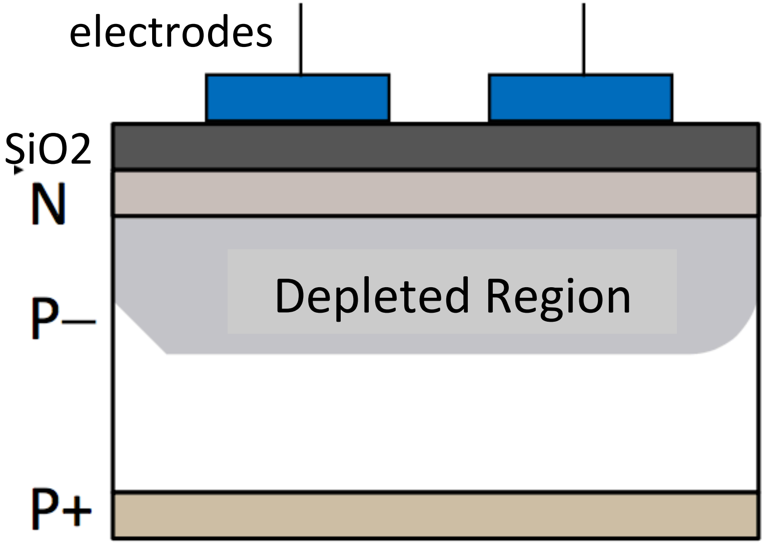
I. CCDs e^- -hole drift



I. CCDs Internal Structure

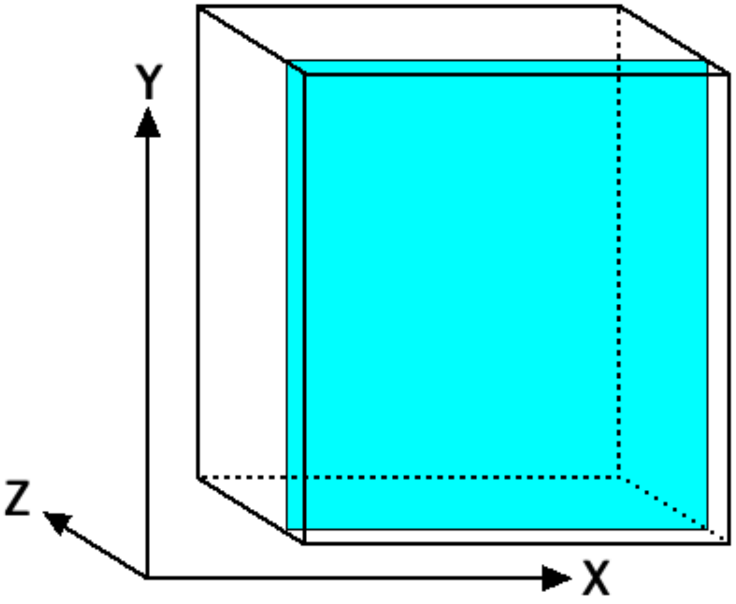
- X-ray detection by Semi-Conductors
- Band-Structure Conduction & Valence Band

1. Photons ➔ PhotoElectric Effect
2. Charges accumulated in the depleted region



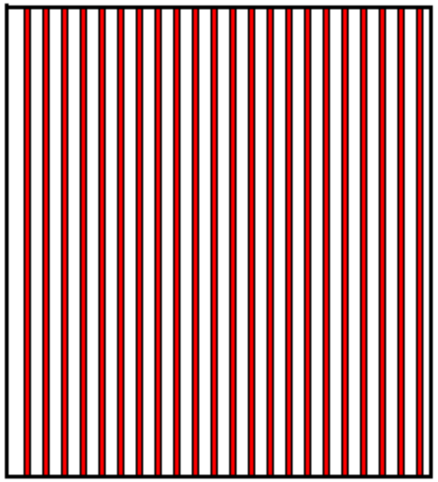
Each X interacting in the depleted region will create e^--hole pairs that will be separated by the electric field

I. CCDs in 3 steps !



1

n+ (P)
dopped layer
Homogeneous
potential
well

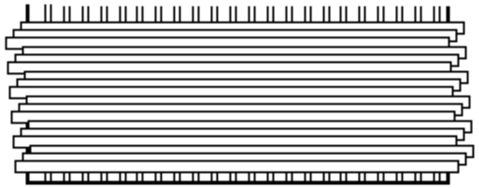


2

p+ (B)
dopped thin
strips
Minimum
potential
well defining
column

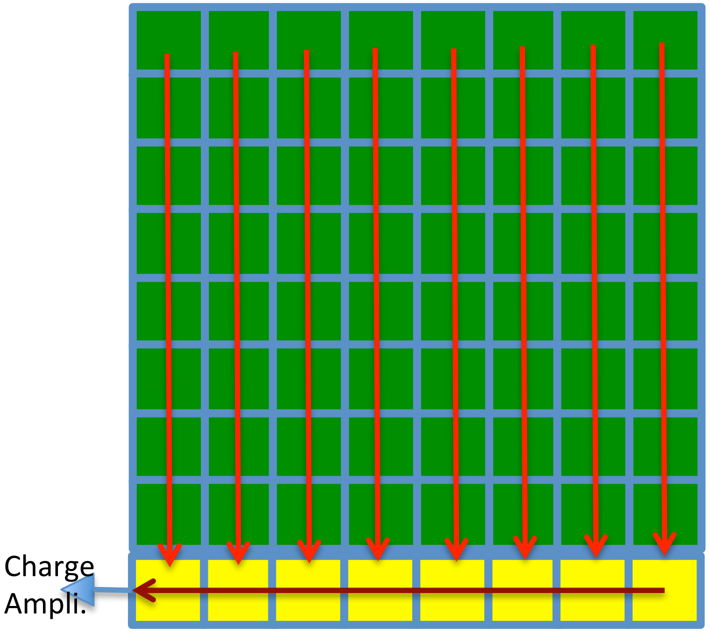
3

Metallic
Surface
Electrode.
Potential
well
underneath



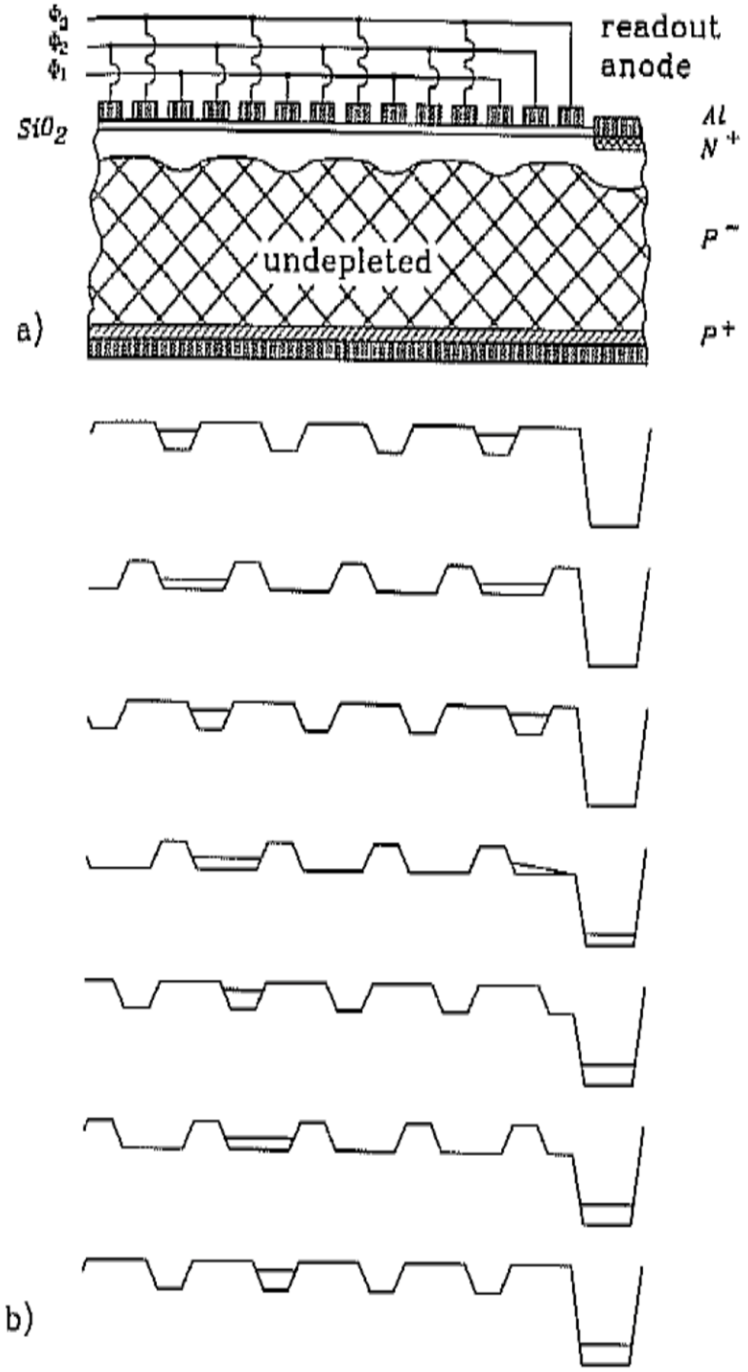
I. CCDs Readout

3/4 electrodes / pixels
(1 collection and 2 fences
+ 2 channel stops (P doped) perpendicular

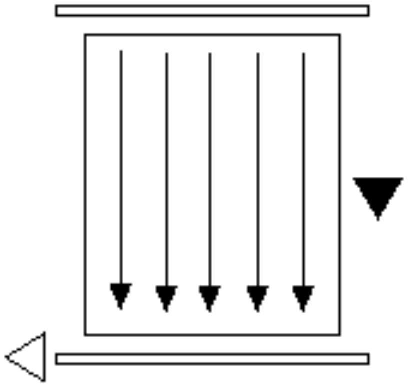


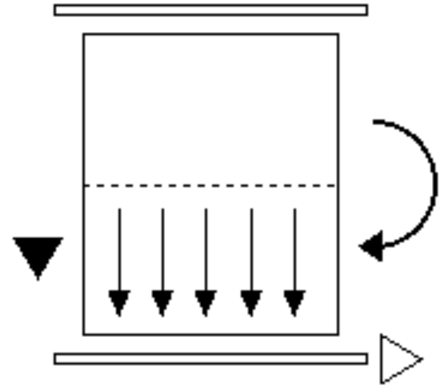
1. Readout by transfer from one pixel to its neighbour.
2. Each Charge is measured by a charge amplifier

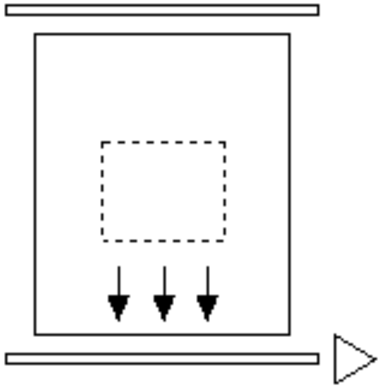
Transfer Efficiency=1 -((N$_{n+1}$ -N$_n$)/N$_n$) = 0.999999 !

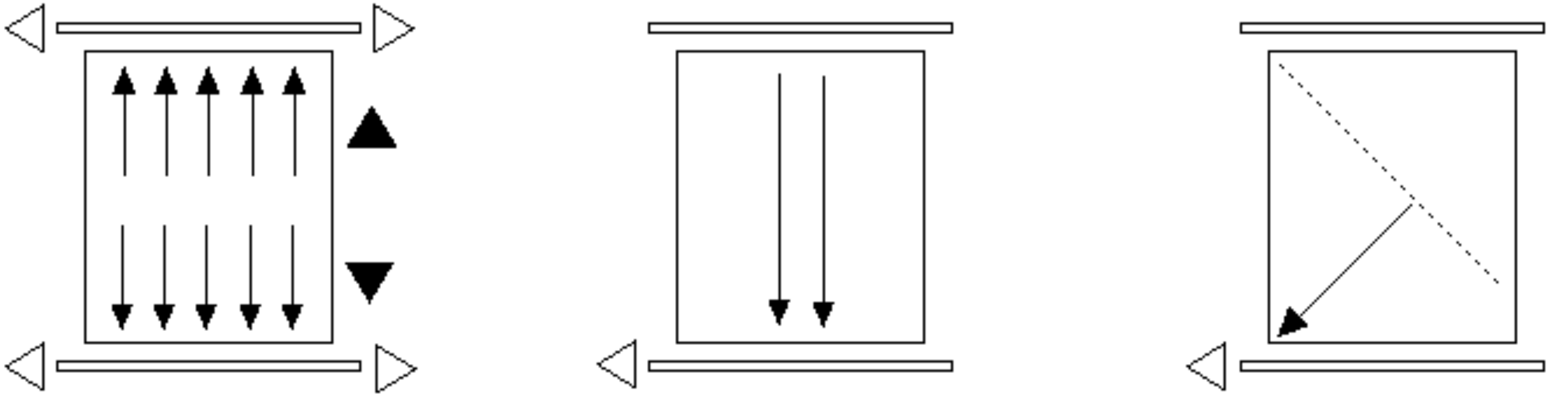


I. CCDs Modes


Full Frame


Frame Store


Window



I. CCDs in X-Rays

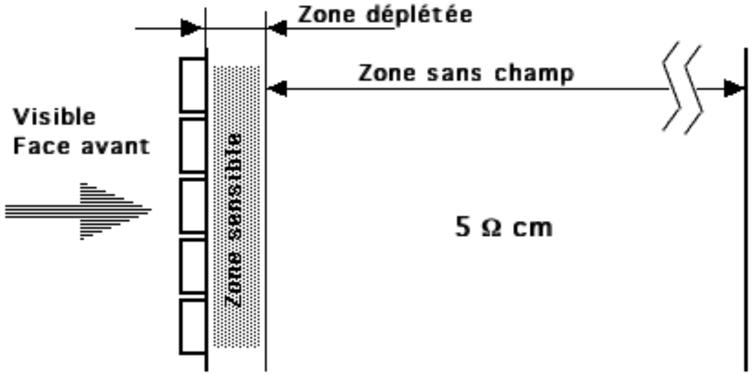
Xrays interaction → one photo-electron produced → ionisation →e$^-$-hole pairs produced by photoelectric Effect.

CCDs are pixelated → X,Y information
Arrival Time is known through Frame time
Spectral resolution is obtain by counting the holes or e$^-$

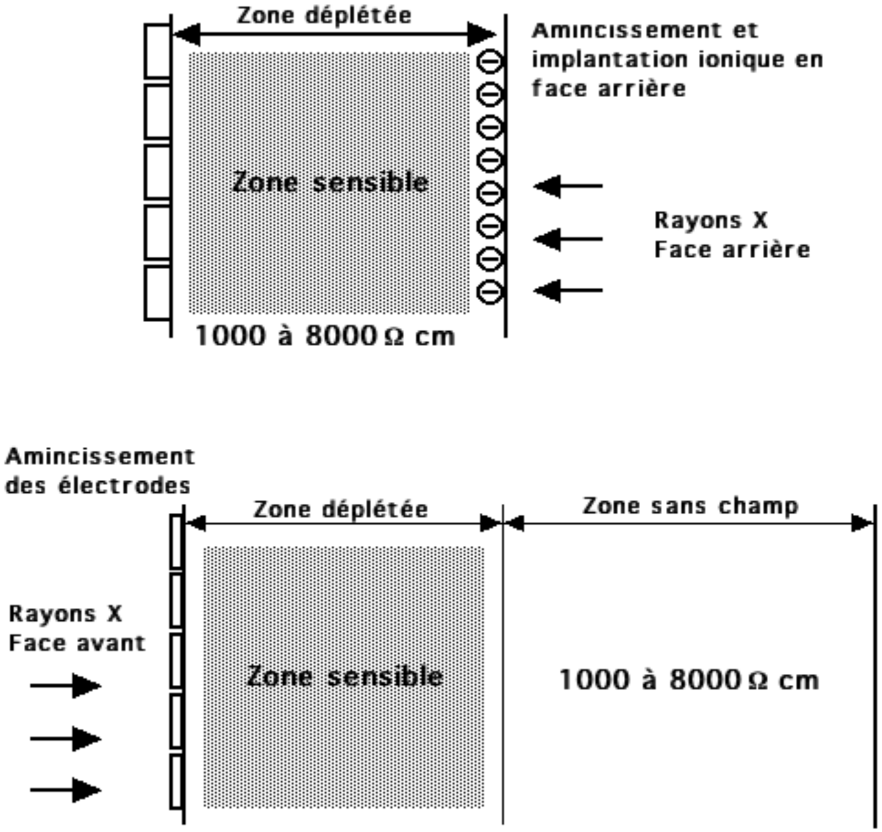
To have spectral information, one needs not to have 2 photons on the same pixel in the same frame

→CCDs are read as fast as possible to avoid Pile-up

Visible vs X-rays CCDs



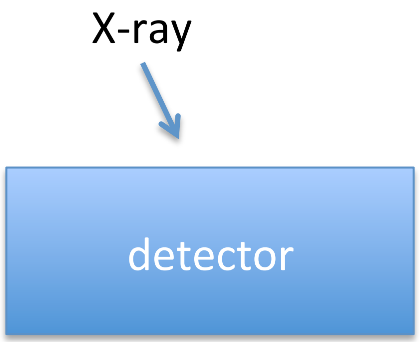
CCD Optique



CCD pour le rayonnement X

I. CCDs Spectral Resolution

E_x -> n e^- + Heat


X-ray

detector

For monochromatic X-rays, the exact number of electrons produced depend on the way the primary photo-electron loose its energy…

Each e^- in the conduction band carry ~E_{gap} energy

$$\Delta E\ (\mathrm{FWHM}) = 2.36\ \varepsilon\ (\sigma_{readout}^2 + \sigma_{coll}^2 + F_{SI}\ E_x/\varepsilon)^{1/2}$$

$\sigma_{readout}$: Readout Noise (in e^-)

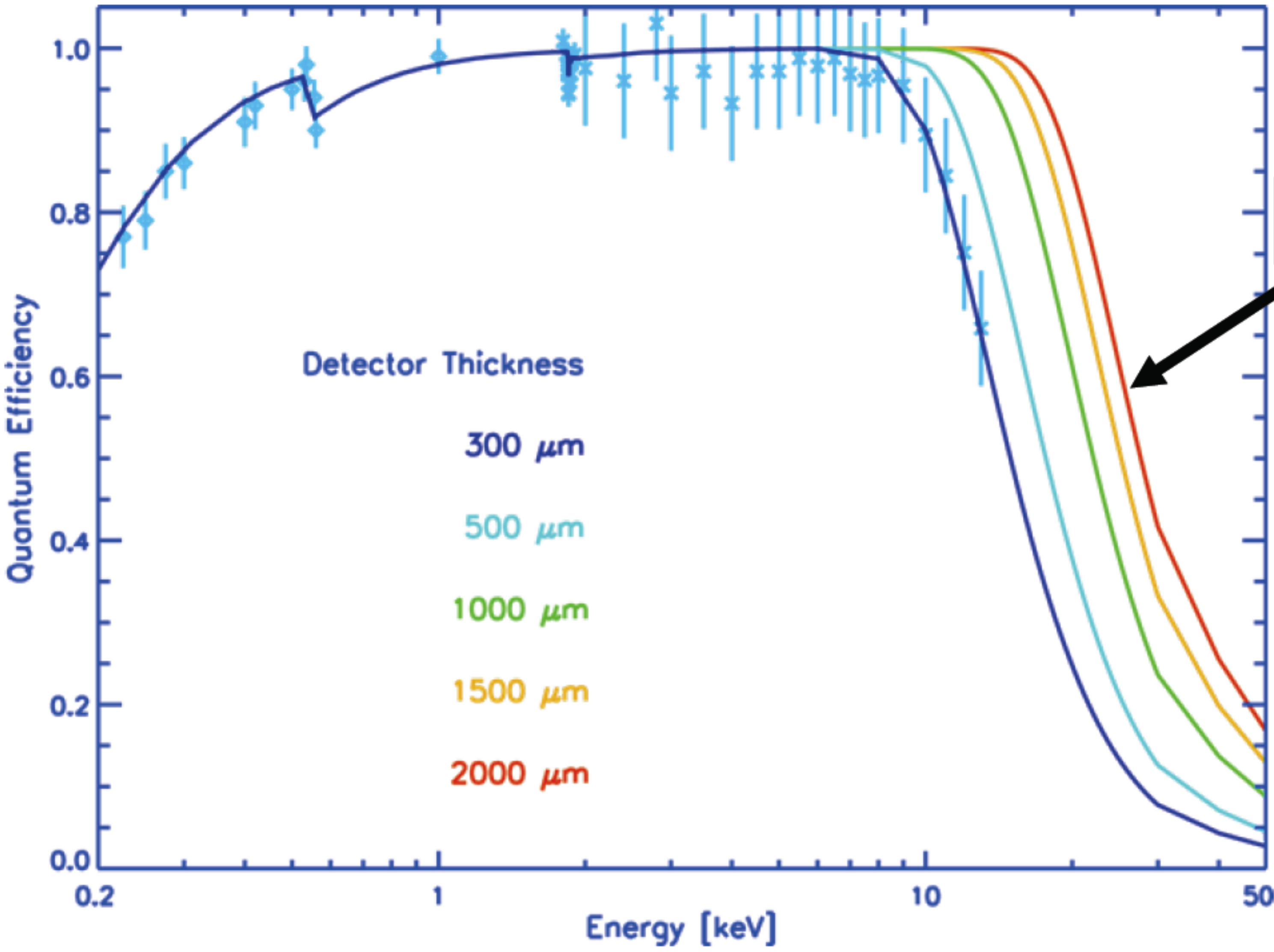
σ_{coll} : Noise from incomplete collection (in e^-)

F_{si} : Fano Factor (~0.11)

ε : Energy to create a pair (~3.65eV)

➔ **ΔE =120 eV @ 6keV**

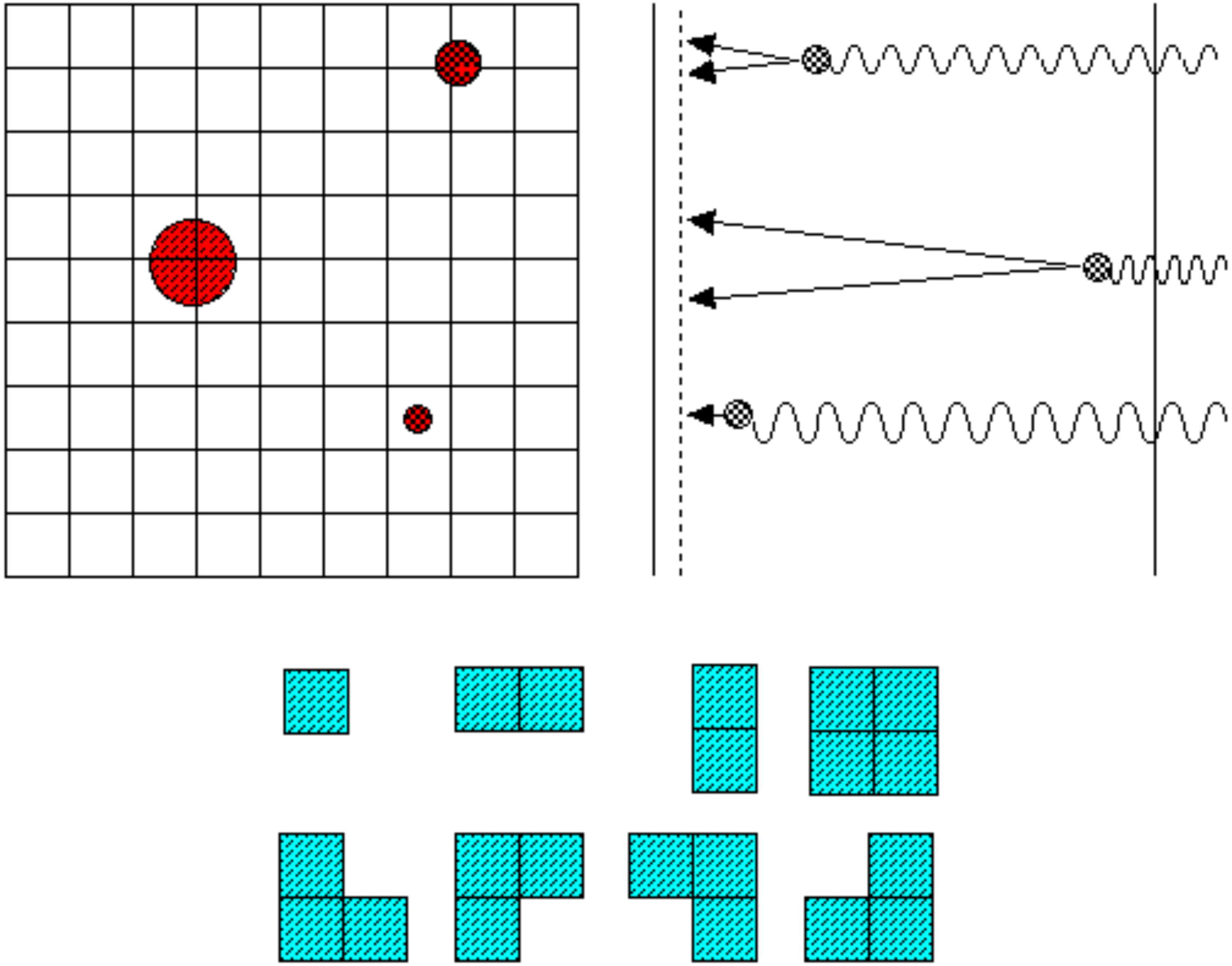
I. CCDs Quantum Eficiency



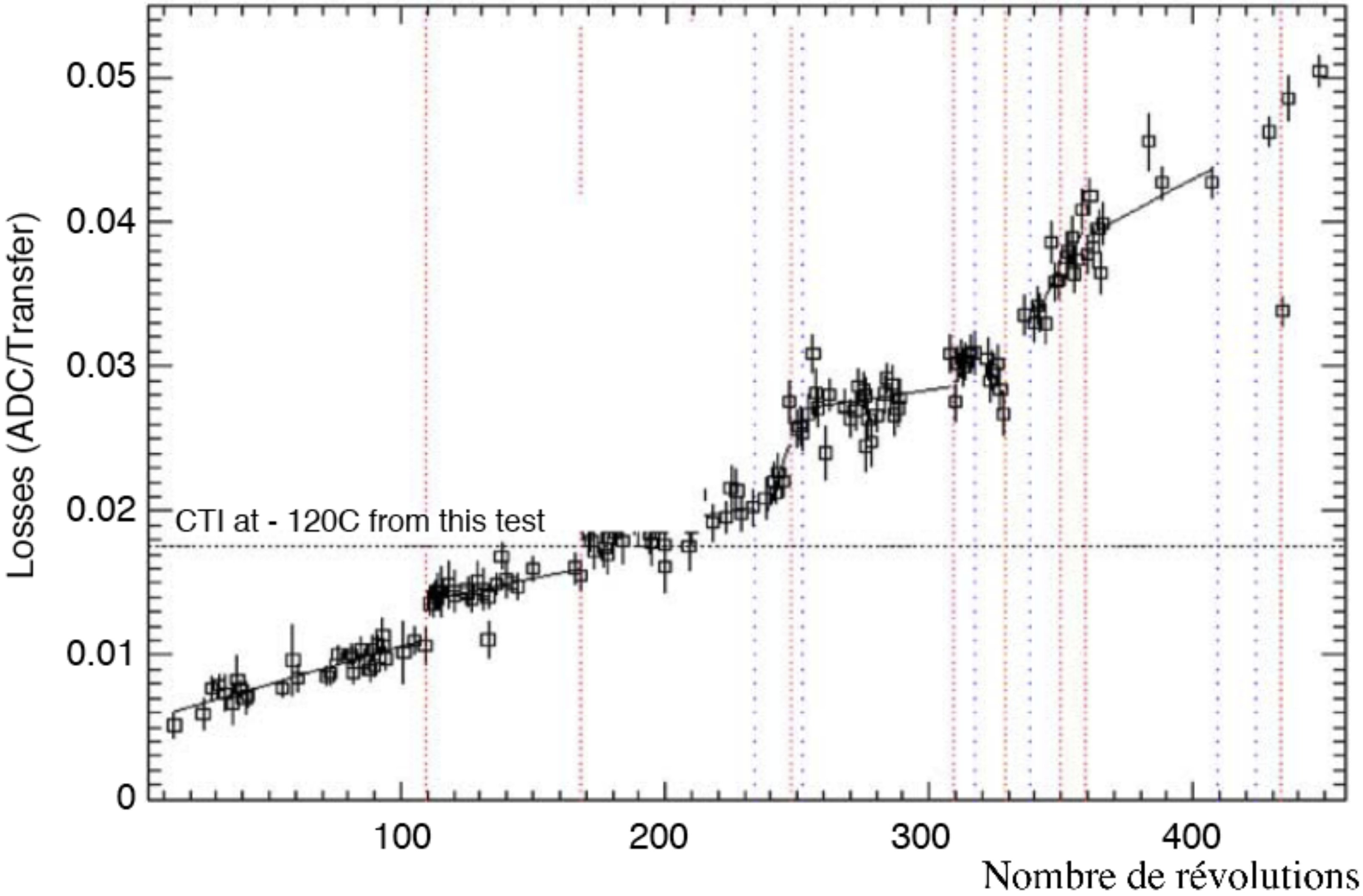
Q.E.

60 % @ 24 keV

Spatial data flow optimized for X-rays CCDs: The Event Detection Unit

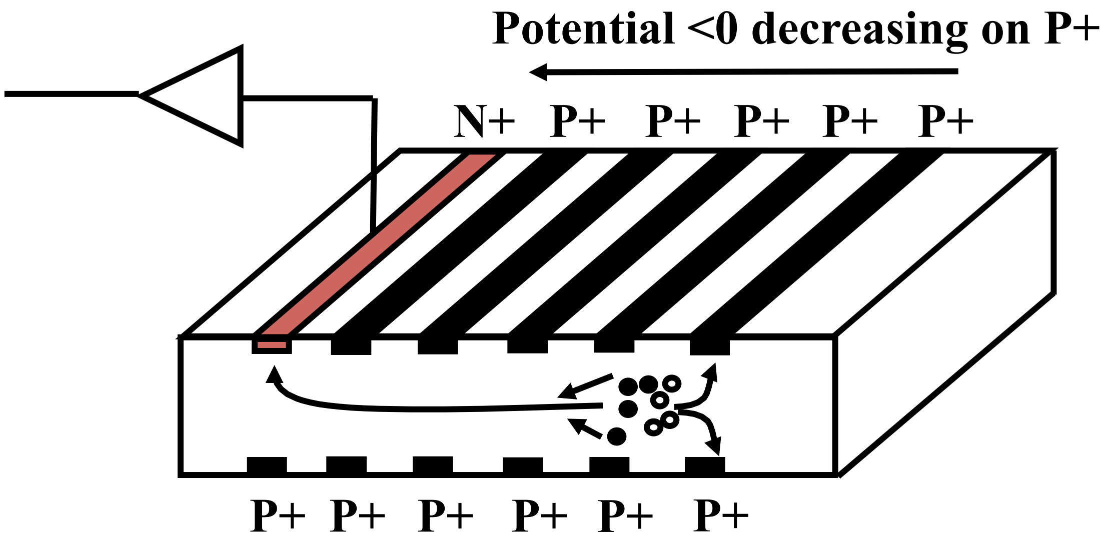


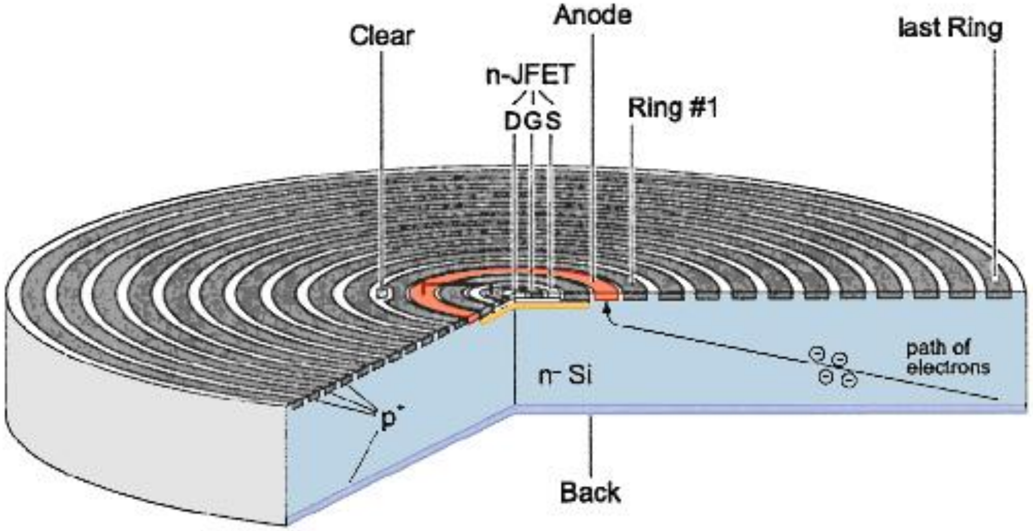
Charge Transfert inefficiency



Degradation of the charge transfert efficiency of the XMM/EPIC_MOS CCDs
Onboard XMM-Newton

II. Silicon Drift Detector (SDD)





II. SDD DEPFET

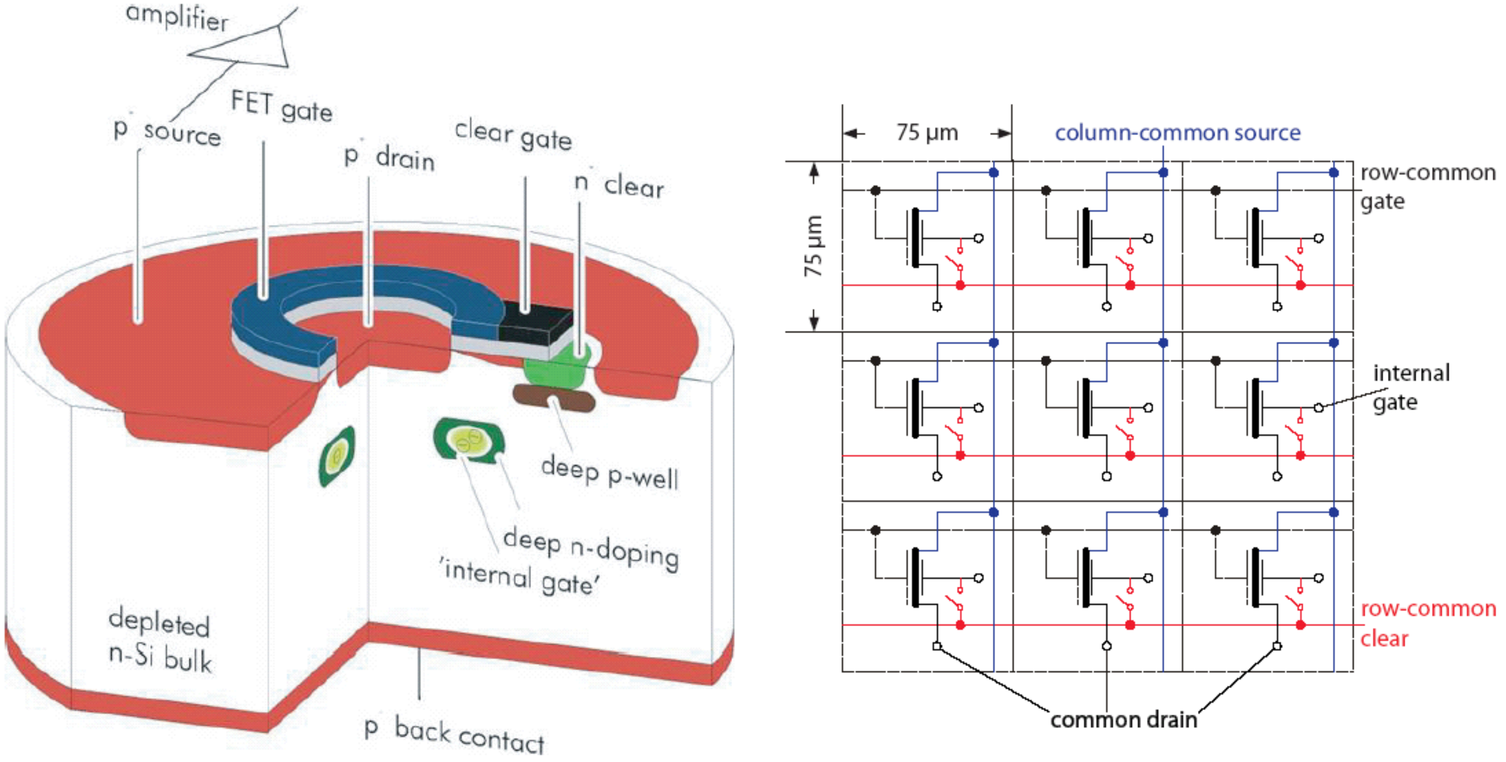
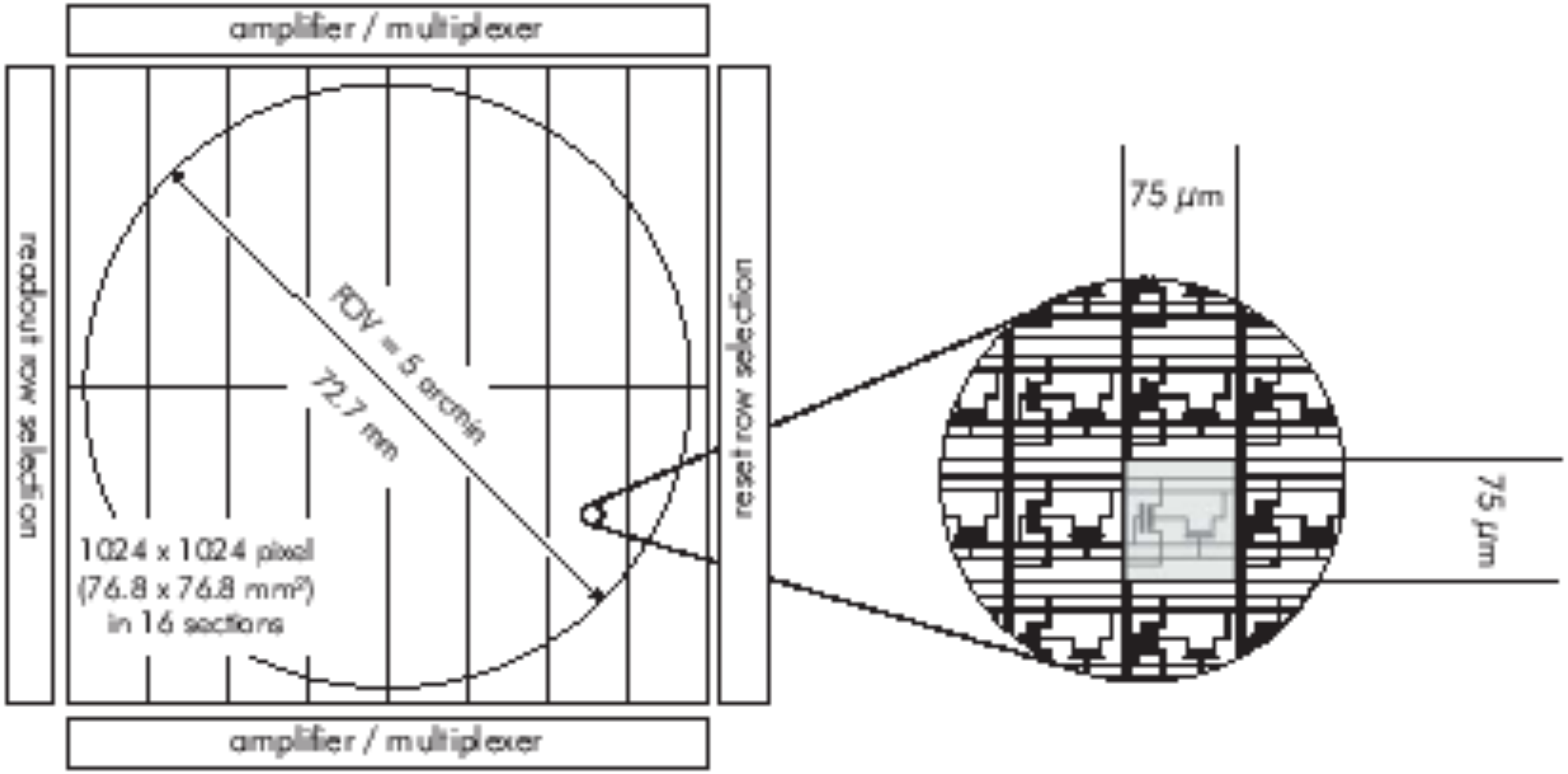


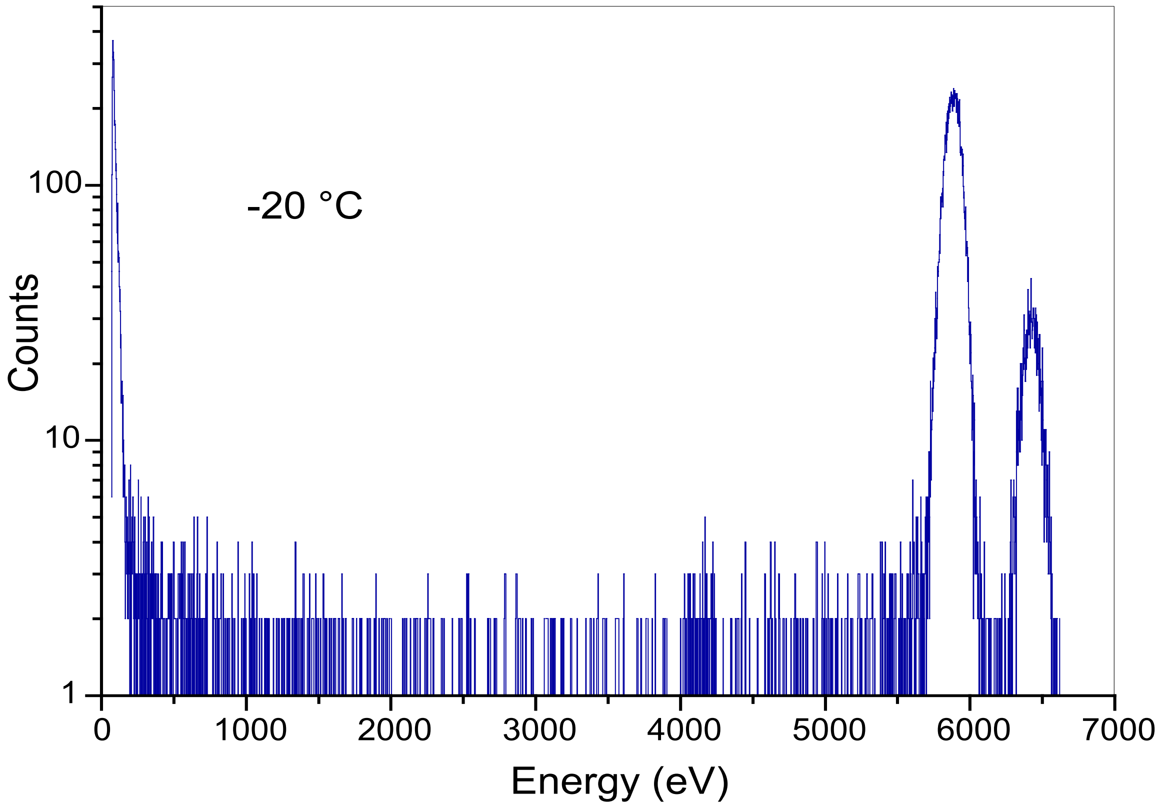
Figure 1, Left: Schematic view of a circular DEPFET pixel. X-ray photons enter through the p back contact. Signal charges are stored close to the opposite (top) side. Right: A 3 × 3 pixel circuitry visualizes how DEPFET pixels are interconnected in an APS matrix.

II. SDD **XEUS / IXO/ATHENA**



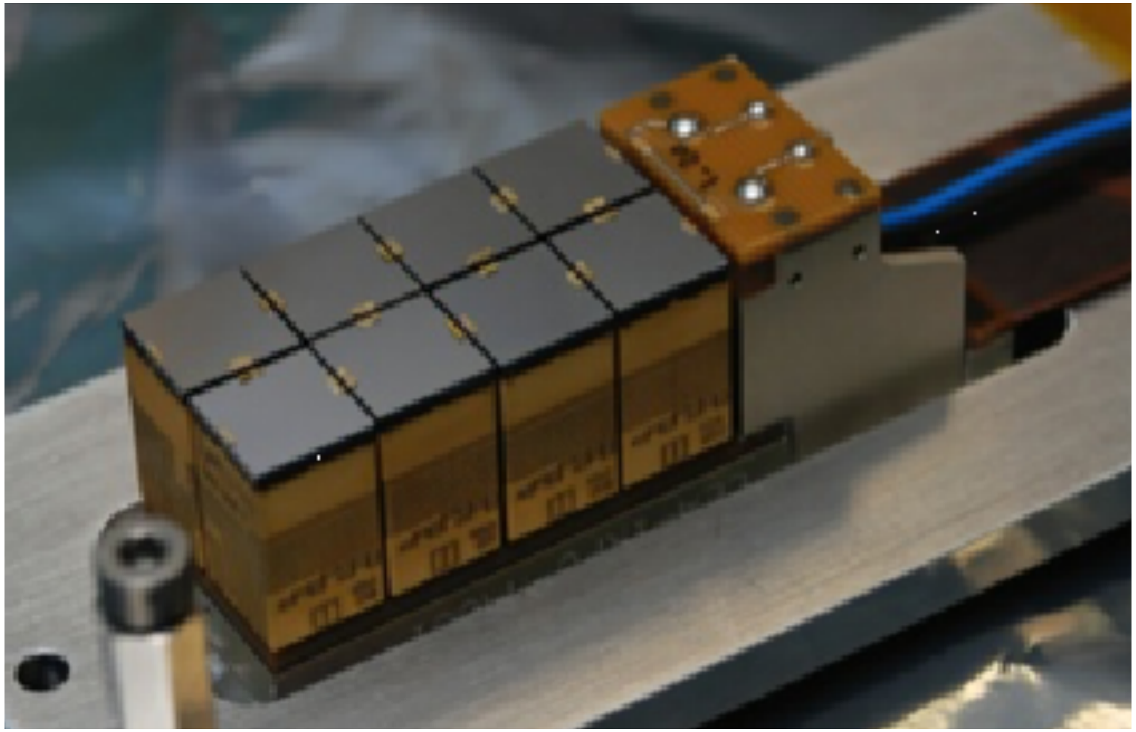
II. SSD Matrix with integrated DEPFet

- **Active Pixel Sensor Matrix Low Power Consumption**
- **working @ room Temperature**
- **Filling Factor ~100 %**
- **Fast Readout (4 μs/pixel, @ ms / matrice)**
- **NO transfert -> Robustness under irradiation**
- **Silicon Spectral Resolution**



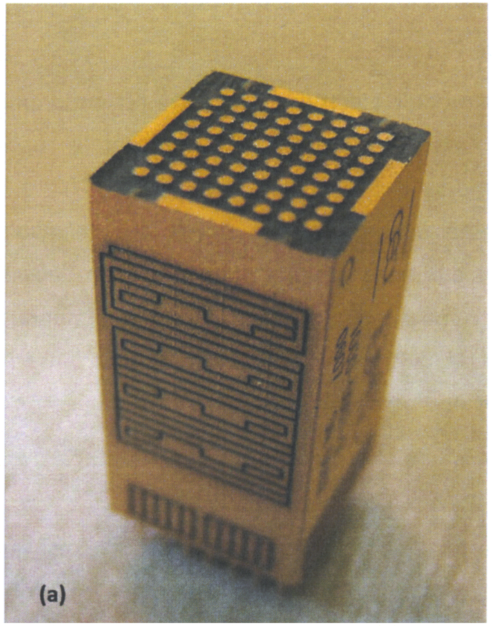
III. CdTe

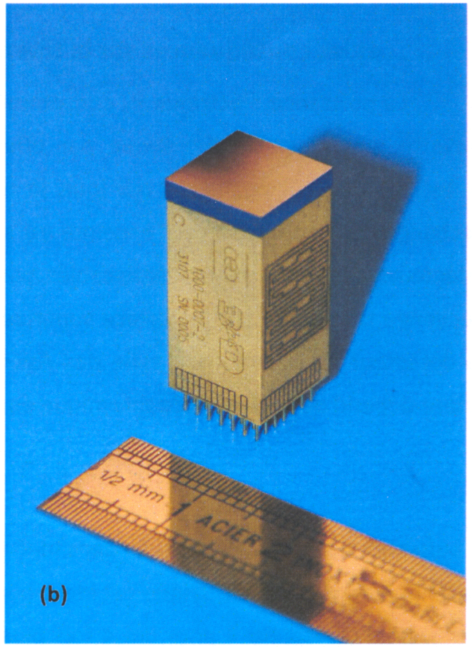
- CdTe & CdZnTe have a larger gap & higher Z than Si
- Thus work @300K and absorb X-rays up to higher E



MACSi: 2048 pixels
8 HD-modules
With 1cm^2 CdTe

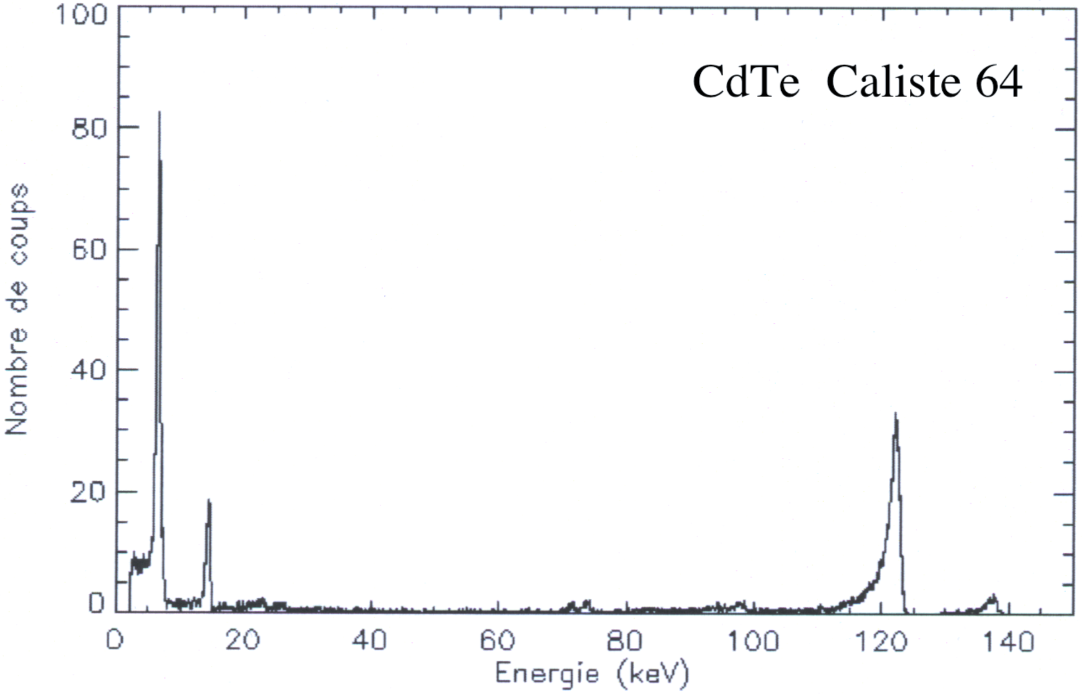
III. Cd Te
Caliste 64





(b) Détecteur intégré au module électrique

Detector with
integrated electronic

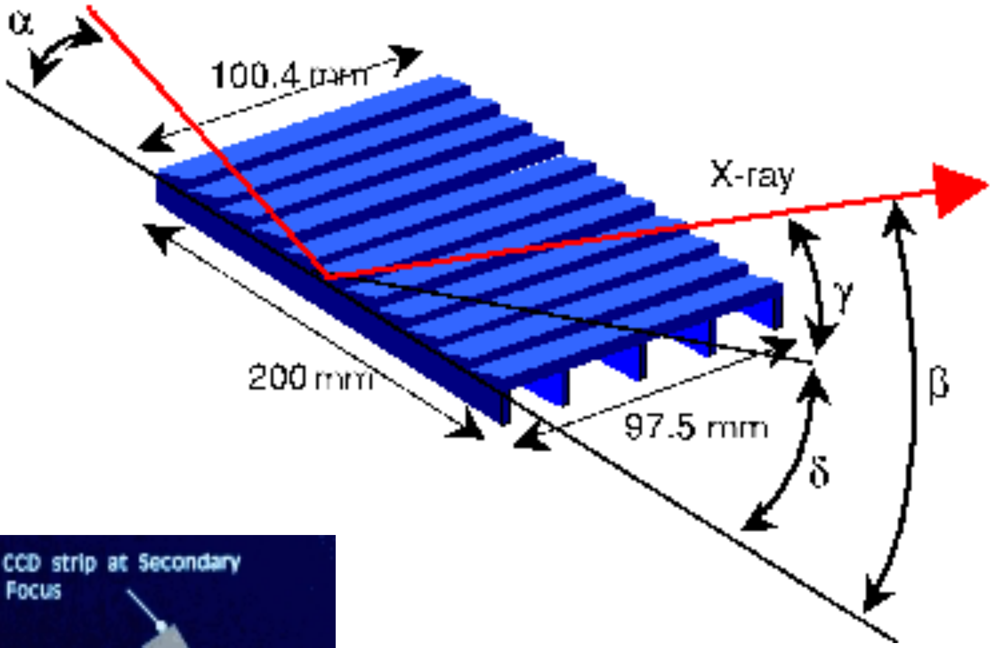


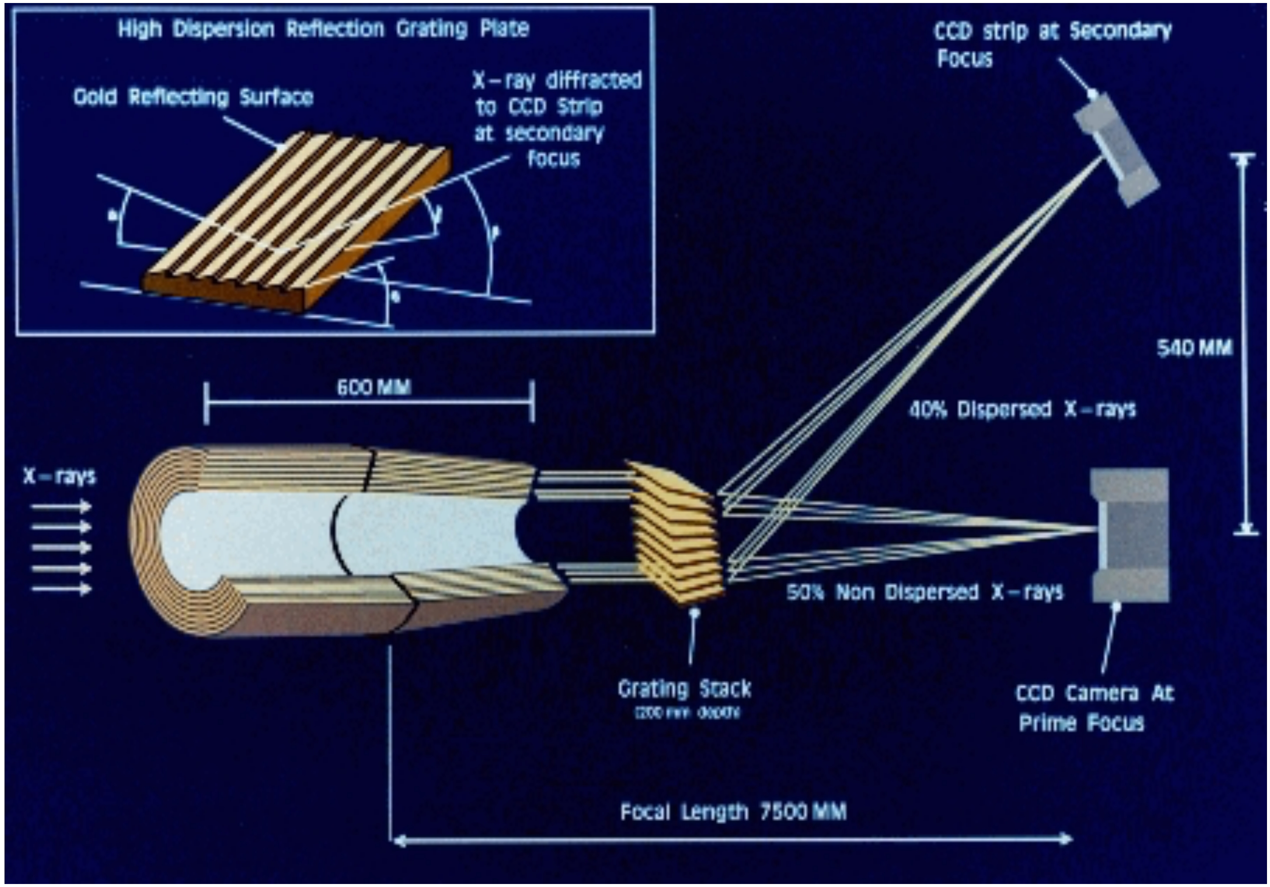
Spectre (Co57), résolution spectrale: 820 eV à 14.4 keV

Comparison of Semi-Conductors for X-rays

	Silicon	**Germanium**	**CdTe**
Atomic Number	**14**	**32**	**48,52**
En. forbidden band(eV)	1.12	0.67	1.42
En. Pair Creation (eV)	3.62	2.96 (@77K)	4.42
Density	2.33	5.33	5.85
Q.E. (@100keV, 5mm)	19%	77%	99%
ρ (Ω.cm)	$2.3\ 10^{5}$	47	10^{9}
Spatial Inst.	EPIC(XMM)	SPI(INTEGRAL)	ISGRI(INTEGRAL)
e^- Mobility(cm^{2}V^{-1}s)	1400	3900	1350
Hole mobility(cm^{2}V^{-1}s)	1900	1900	120
e^- Lifetime	>1ms	>1ms	1µs
Hole Lifetime	1ms	2ms	0.05 µs

IV. Gratings





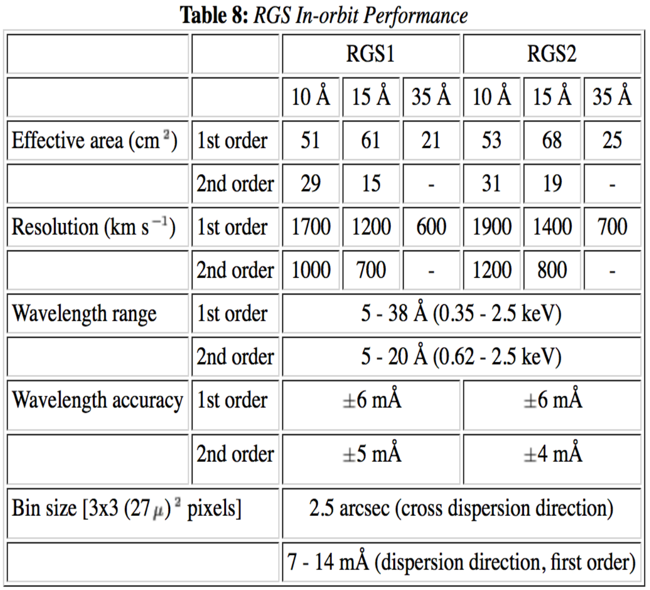
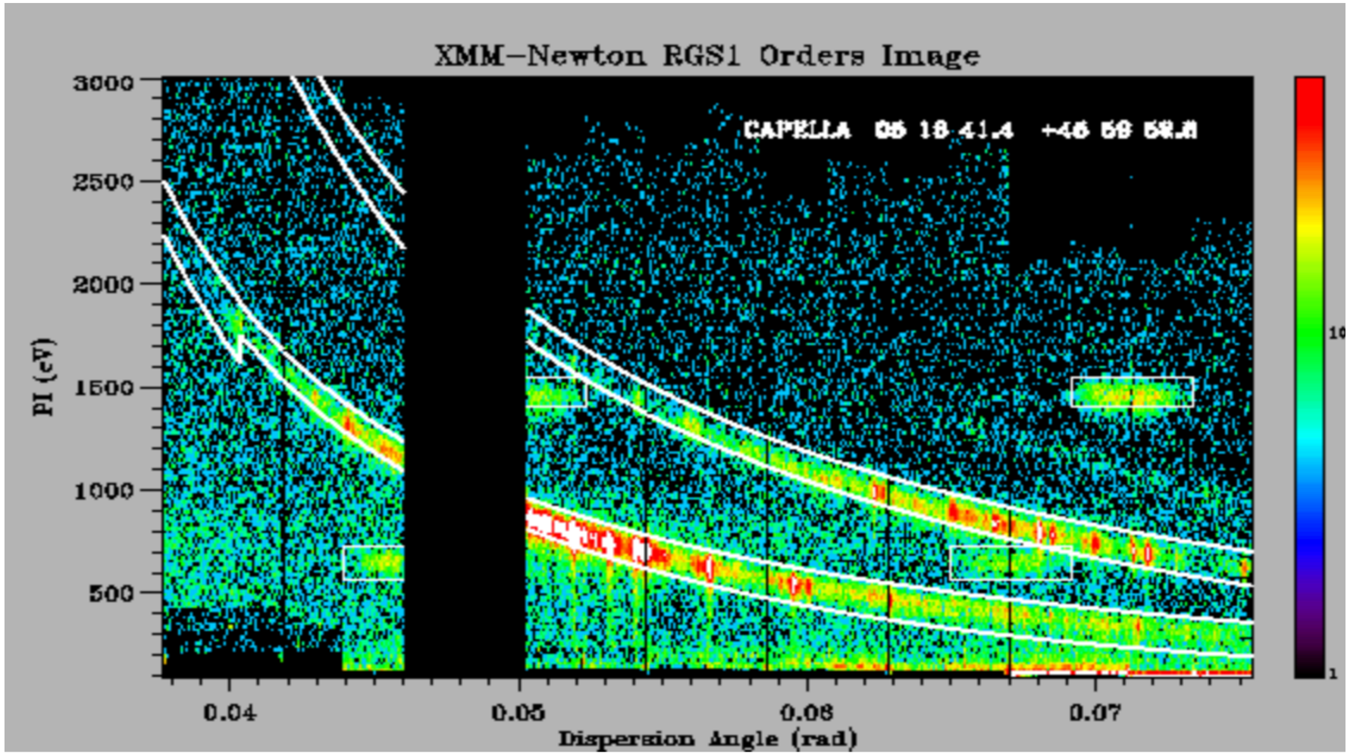
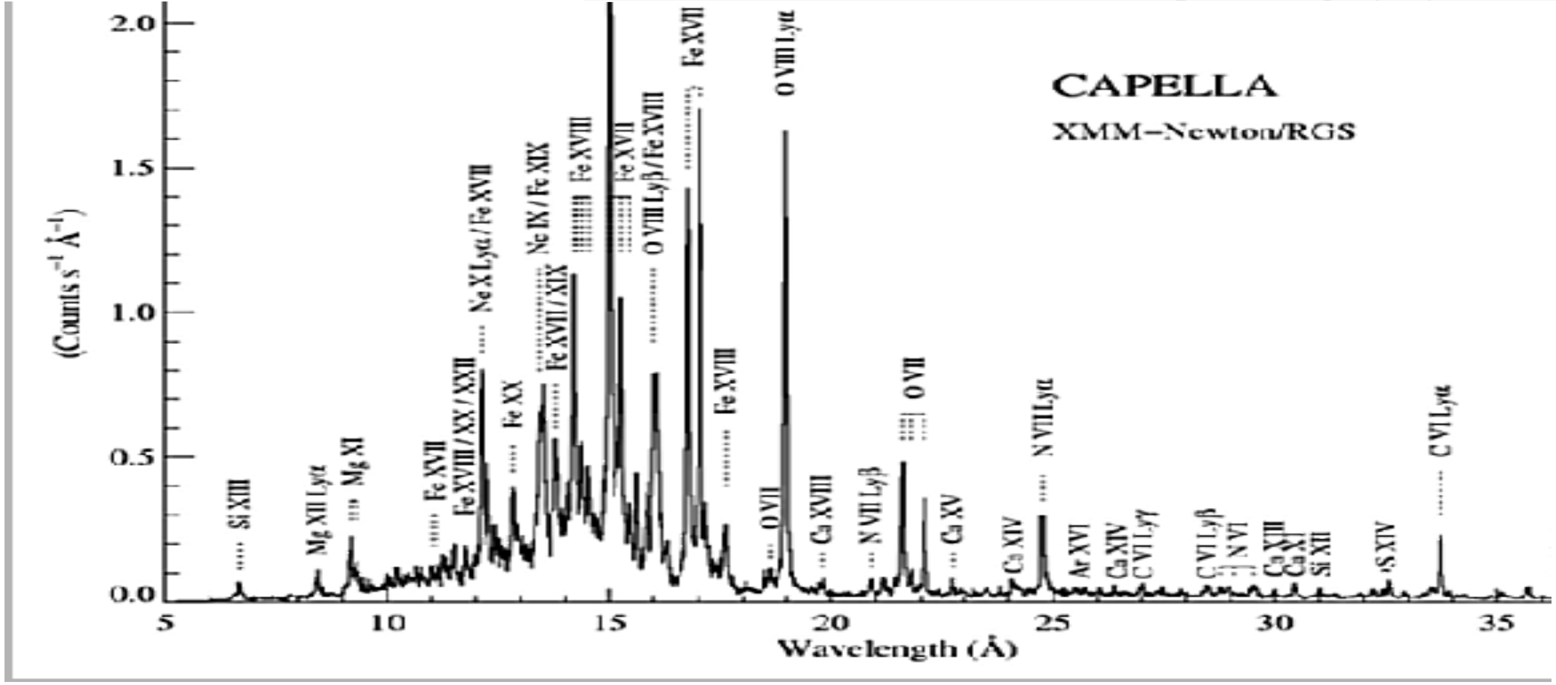


Table 8: *RGS In-orbit Performance*

		RGS1			RGS2		
		10 Å	15 Å	35 Å	10 Å	15 Å	35 Å
Effective area (cm ^{2})	1st order	51	61	21	53	68	25
	2nd order	29	15	-	31	19	-
Resolution (km s $^{-1}$)	1st order	1700	1200	600	1900	1400	700
	2nd order	1000	700	-	1200	800	-
Wavelength range	1st order	5 - 38 Å (0.35 - 2.5 keV)					
	2nd order	5 - 20 Å (0.62 - 2.5 keV)					
Wavelength accuracy	1st order	±6 mÅ			±6 mÅ		
	2nd order	±5 mÅ			±4 mÅ		
Bin size [3x3 (27 μ) ^{2} pixels]		2.5 arcsec (cross dispersion direction)					
		7 - 14 mÅ (dispersion direction, first order)					

IV. Gratings


XMM−Newton RGS1 Orders Image
CAPELLA 05 16 41.4 +45 59 52.8
PI (eV)
3000
2500
2000
1500
1000
500
0.04
0.05
0.06
0.07
Dispersion Angle (rad)
10
1


CAPELLA
XMM−Newton/RGS
(Counts s^{-1} Å^{-1})
2.0
1.5
1.0
0.5
0.0
5
10
15
20
25
30
35
Wavelength (Å)
Si XIII
Mg XII Lyα
Mg XI
Fe XVII
Fe XVIII / XX / XXII
Ne X Lyα / Fe XVII
Fe XX
Fe XVII / XIX
Ne IX / Fe XIX
Fe XVIII
Fe XVII
O VIII Lyβ / Fe XVIII
Fe XVII
Fe XVIII
O VIII Lyα
O VII
Ca XVIII
N VII Lyβ
O VII
Ca XV
Ca XIV
N VII Lyα
Ar XVI
Ca XIV
C VI Lyγ
C VI Lyβ
N VI
Ca XIII
Ca XI
Si XII
S XIV
C VI Lyα

Semi-conductors
Energy Resolution Limitation

$E_x \text{ -> } n\, e^- + \text{Heat}$

Some energy coming from the X-ray is degraded in heat which is NOT measured in ionisation detector such as CCDs

Since Heat formation is inescapable

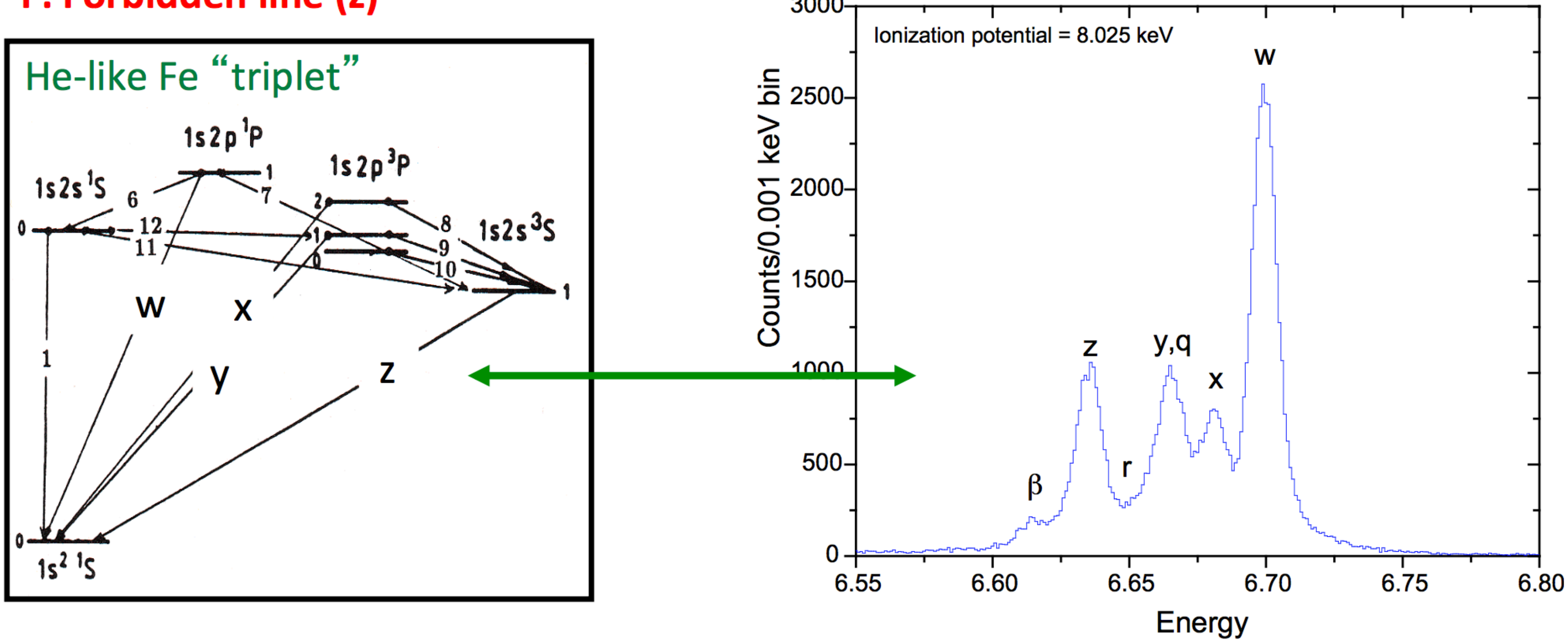
⇒ Let's all the X-ray energy convert in Heat and measure it

Thus build a micro-calorimeter ...

What to learn with very high spectral resolution?

- Emission line ratios provide density & temperature diagnostics
- Emission and absorption line energies identify ions
- Line shapes can be used to study velocities
  - e.g. within galaxy clusters or environment around a supermassive black hole

R: Resonance line (w)
I: Intercombination line (x+y)
F: Forbidden line (z)



V. μ-Calorimeters

- Principle
- Sensors
  - Transition Edge Sensors
  - Metal-Insulator Sensors
- Readout Electronic
- Conclusion

μ-Calorimeters Principle (1)

Two definitions:

- μ-Calorimeters measure Energy pulse issued from the interaction of a high energy photon with an absorber.

- μ-bolometers are designed to be sensitive to an Energy flux as in sub-mm Astronomy

Calorimeters Basis:

-I- The Heat capacity decrease to small value when temperature decrease

$$C = \alpha T + \beta(T/\theta_D)^3 \qquad (\theta_D : \text{Debye temperature })$$

Small deposit of energy will enhance the temperature of the system:

$$\Delta T = E_x / mC$$

-II- There are sensors able to measure such temperature @ very low T.

μ-Calorimeters Principle (2)

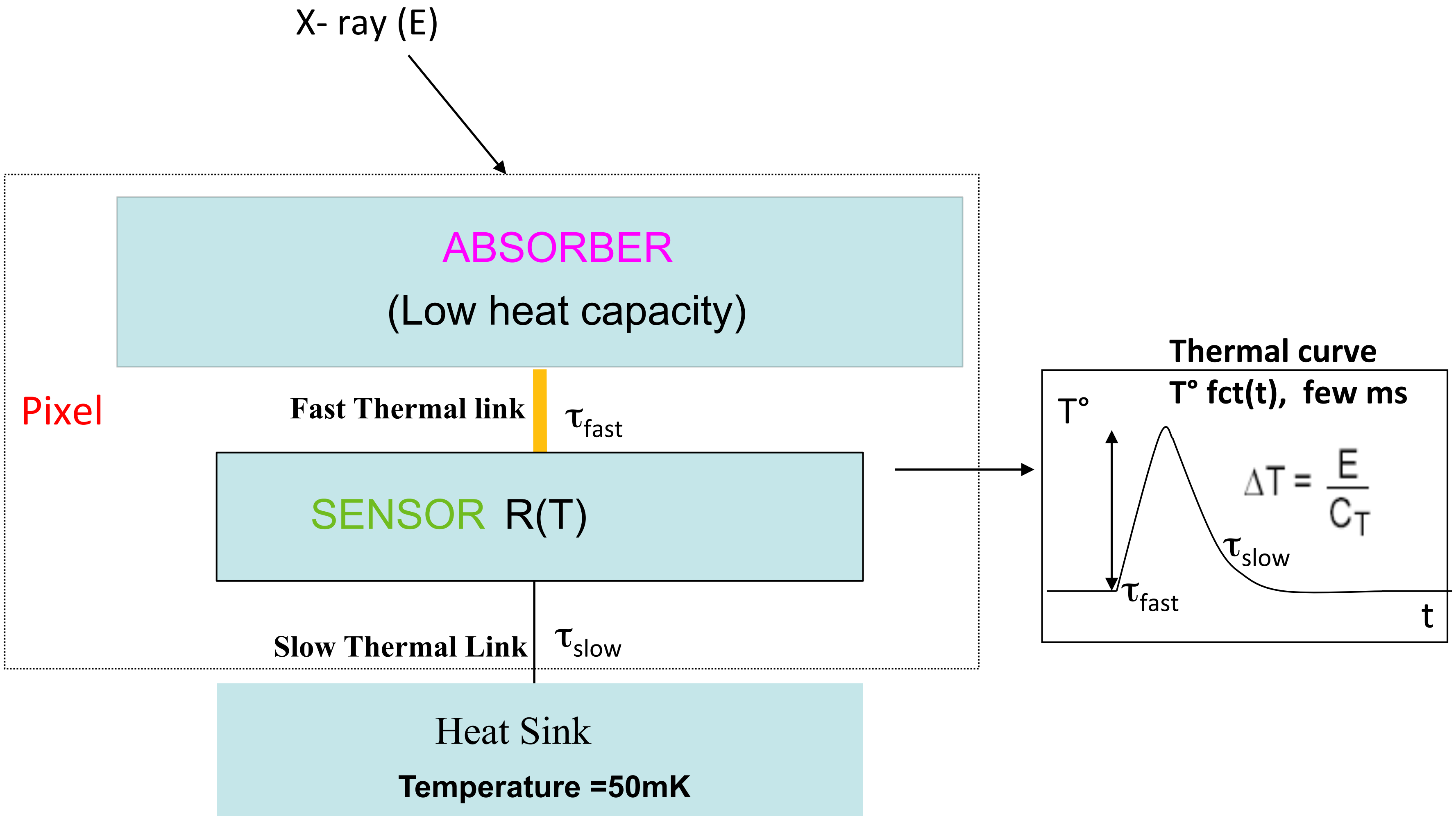
Main Elements of a μ-Calorimeter
An Absorber of the x-ray photons linked through a thermal impedance to a sensor (thermometer). This sensor is itself linked to a cold bath through an another thermal impedance.

The thermal impedance Sensor-Cold Bath should be adapted to have enough time to measure the temperature elevation but not too much so that the pixel is ready for a new interaction.
The signal will be a thermal curve vs Time.
From the curve parameter, one can deduce the X-ray energy.

Since we measure a temperature, (i.e. a phonon bath in thermal equilibrium), there is no partition in energy (like e^- -hole pair and heat a in semi-conductor)...

Thus no Fano Factor Limitation

μ-Calorimeters Principle (3)



Rule of Thumb: $\tau_{slow} \geq 10^* \tau_{fast}$

μ-Calorimeters Principle (4)

$$\Delta T = E_X / M\, C(T)$$

E_X : Energy of incoming photon
M : Pixel Mass
C(T) : heat Capacity @ T
ΔT : Temperature Elevation

$$C = \alpha T + \beta (T/\theta_{Debye})^3$$

e^- contribution
Phonon contribution

To have good μ-Cal ⇒ Enhance ΔT
thus minimize M : smaller pixels
for given X-ray : minimize C & T
for a given T : minimize α & β
To kill α ⇒ choose material with NO free e^-
To minimize phonon Contrib., maximize θ_{debye}

Minimizing M ⇒ smaller pixel size (what about FOV or complexity …)
Minimizing T ⇒ Good but STRONG Spatial CryoCooler Limitations (1μW@50mK)
Minimizing C ⇒ efficiency will depend on the pixel technology & choices

Signal to Noise Ratio

C. Enss and D. McCammon

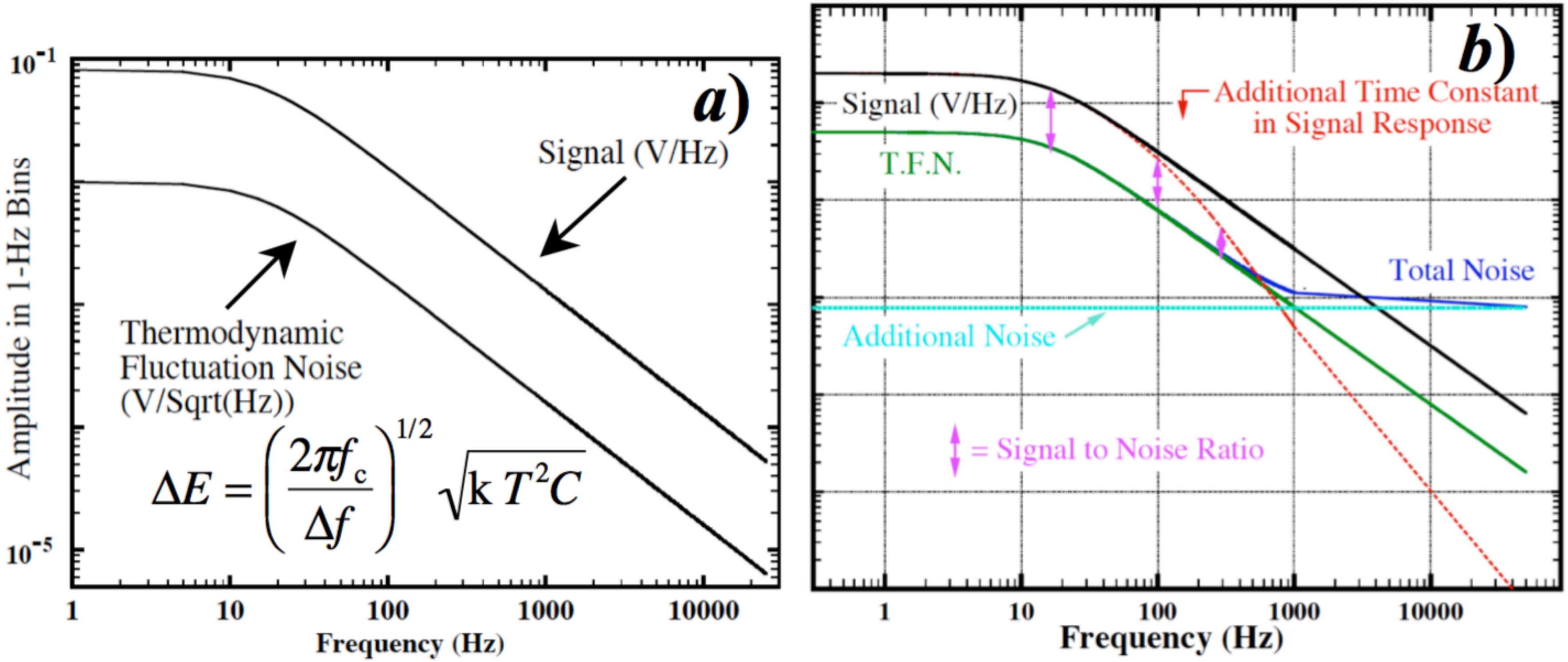


Fig. 4. *a*) Constant ratio of signal to TFN allows signal amplitude to be measured with arbitrarily high accuracy as the bandwidth Δf goes to infinity. *b*) Usual limitation is that either an additional noise source or an additional pole in the signal response causes the signal to total noise ratio to drop above some frequency.

μ-Calorimeters Absorber (1)

Good Qualities for X-ray Absorber:

- High Stopping Power ⇒ High Z material
- Heat Capacity as low as possible
- Fast Thermalization

Those 3 properties are more or less antonymous

μ-Calorimeters Absorber (2)

Resistive Material (Au Bi,…):

Very Good Thermalization (no Energy Trapping)

But Heat Capacity α T ⇒ Dominant Component @ Low T

$$C = \alpha T + \beta (T/\theta_{Debye})^3$$

Superconducting Materials (Sn, Ta):

Heat Capacity depends only of phonon Contribution when $T \ll T_c$.(very small).

X-ray break Cooper Pairs, producing quasi-particles that trap Energy.

If these QPs are slow to recombine ⇒ Slow Thermalization

Insulators & Large Gap SemiConductors (Si, Ge):

Heat Capacity depend only of phonon Contribution & θ_{Debye} is High (⇒ Very Small Heat Capacity) but X-ray produce e^- -Hole pairs that trap Energy for a while in impurities or defects thus Slow Thermalization

Small Gap SemiConductors: HgTe HgZnTe) :

Small Gap ⇒ Good Thermalization but θ_{Debye} is low thus Heat Capacity not so small

Sensors (1)

There are 3 main sensor types:

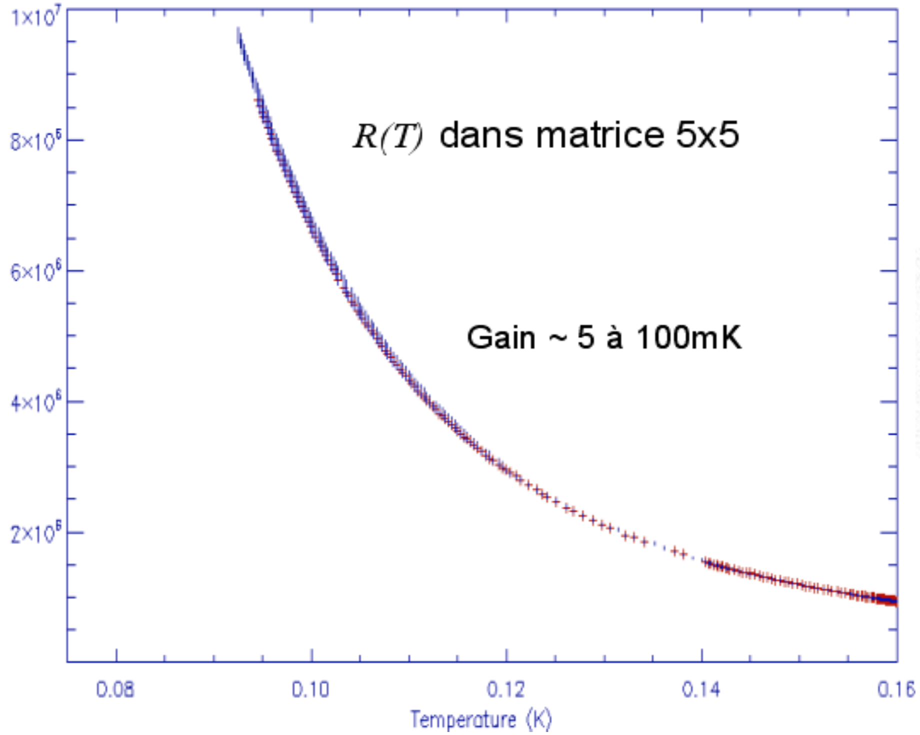
- **TES** (Transition Edge Sensor)
- **MIS** (Metal-Insulator Sensor)
- MMC (Metallic Magnetic Calorimeter)

α is the log derivative of R/T

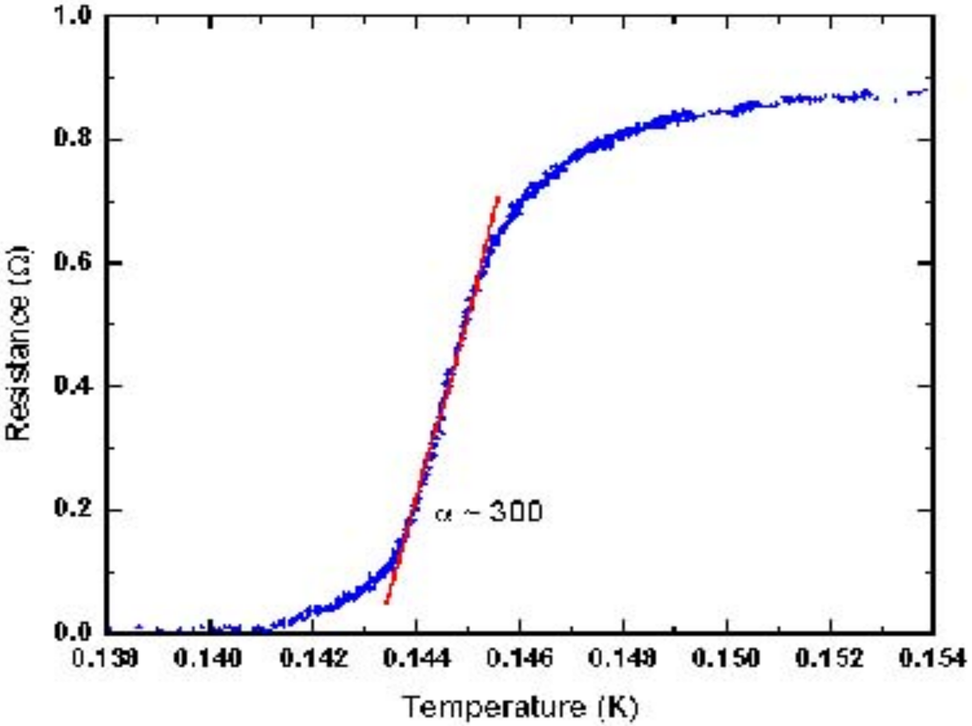
$$\alpha = d(\mathrm{Log}\ R)/d(\mathrm{Log}\ T) = T/R\ dR/dT$$

Sensors (2)

MIS



TES



Sensors (3)

- Sensors polarised in order to create an electro-thermal feedback:
- MIS polarized in current ⇒ Energy dissipation ($P=R\ I^2$) decreases when T increase (since R decrease)
- TES polarized in voltage ⇒ Energy dissipation ($P=U^2/R$) decreases when T increase (since R increase)

- In both cases, the Electro-Thermal Feedback speed up the return to thermal equilibrium and thus the energy dynamic.

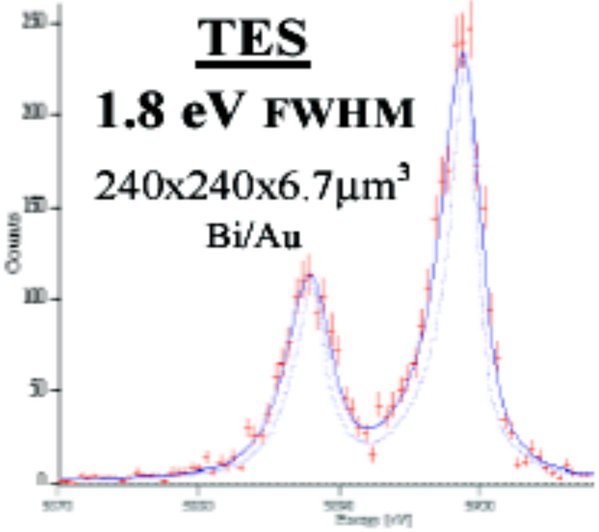
Sensors (4)

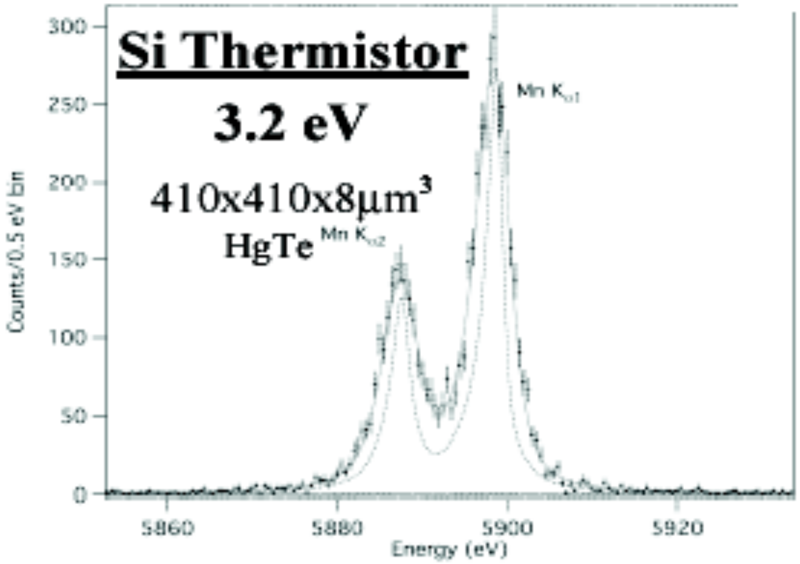
MIS Sensors follow $R=R_0\ e^{\surd(T0/T)}$ Efros & Shklovskii Law

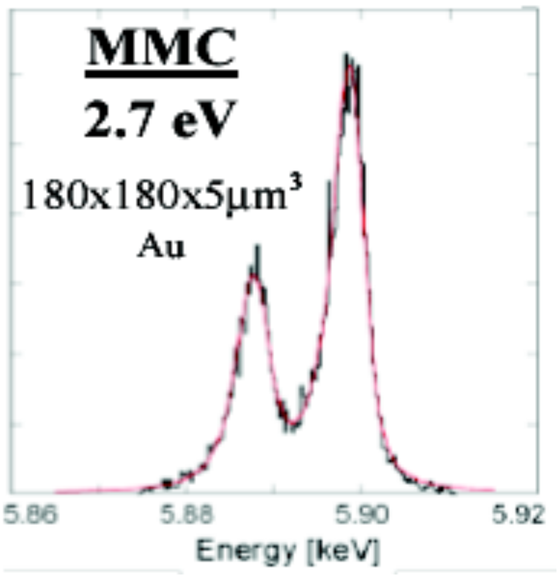
T_0 & R_0 are doping dependant. Small $\alpha \approx$ 5-10 & R ≈ 1 -10 MΩ
R quite high ⇒ Relatively slow sensors
But MIS are sensitive over a large range of E (even in not strictly linear)

TES :Superconductor goes from ZERO ohm to normal resistor (R ≈1 mΩ) in a mK interval thus sensitivity is excellent ($\alpha \geqslant 100$) ⇒ One can use metallic absorber with excellent thermalization & high stopping power (Gold). Fast system but suffer saturation effect.

Spectral Resolution







$$\Delta E_{FWHM} = 2.35\xi\sqrt{KT^2C}$$

Spécifications
ATHENA+ :
2eV @ 6 keV

Readout Electronics

- Need of cryo-electronics

TES : mΩ impedance ⇒ very weak current

MIS : MΩ signal ⇒ Short Connections

- Both have to minimize the thermal load onto the coldest part (50mK)
- If Large Matrices ⇒ Multiplexing is Mandatory

What kind of Electronics could be used ?

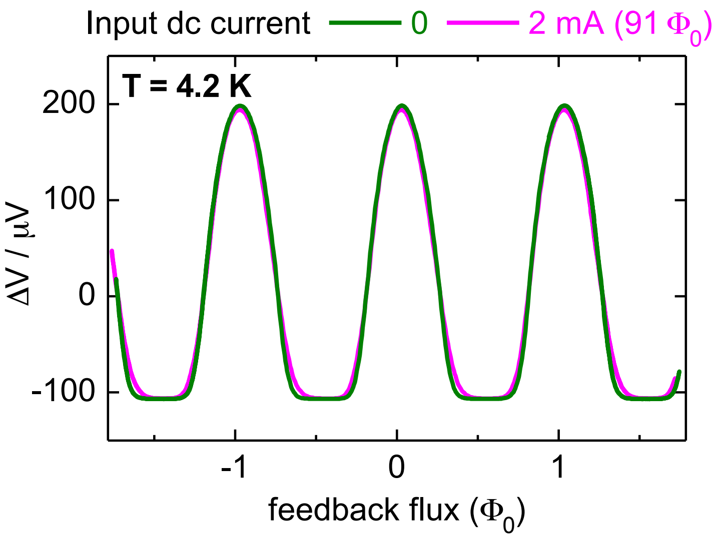
TES Readout Electronics (1)

- TES : mΩ impedance ⇒ very weak current

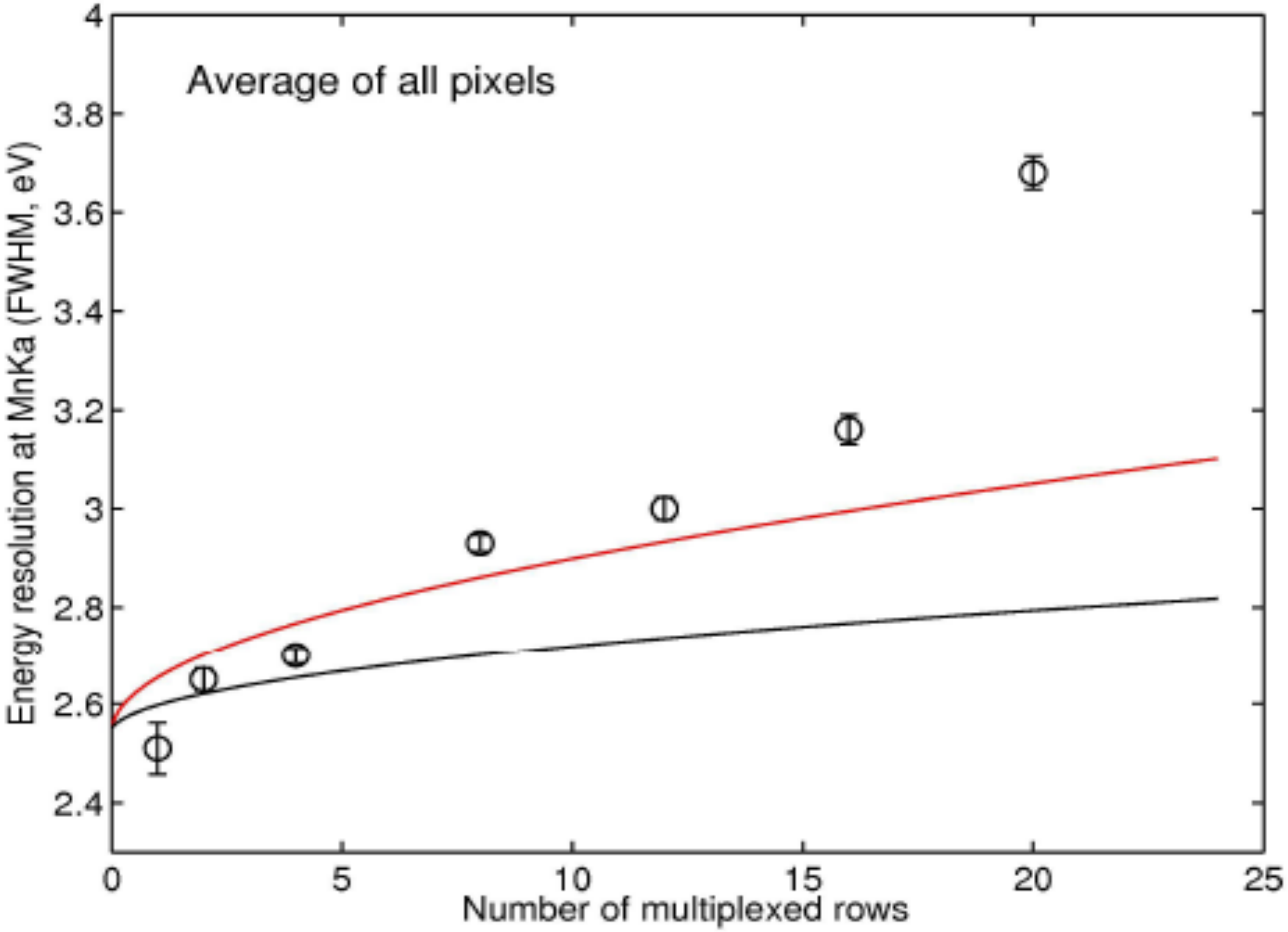
⇒ SQUID @ the lowest temperature.

OK for one detector but in Large Matrix, SQUID power consumption will become the dominant contribution.

Due to cyclic response, SQUID are **very difficult to multiplex**



TES Readout Electronics (2)



Energy resolution degradation with the number of multiplexed pixels

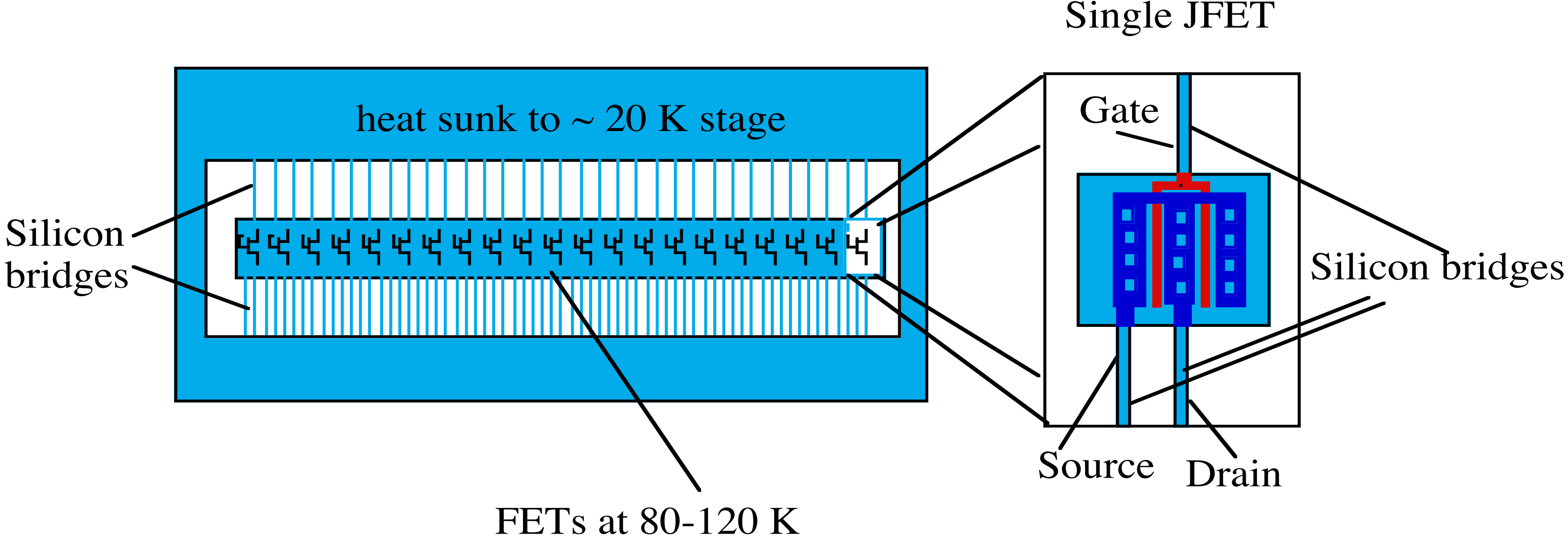
GSFC TES arrays

MIS Readout Electronics (1)

Astro-H/ITOMI MIS Matrices (GSFC)

60 µW/ JFET. JFETs @ 20 K.

JFETs have optimal noise @130 K ⇒ Self-Heating !



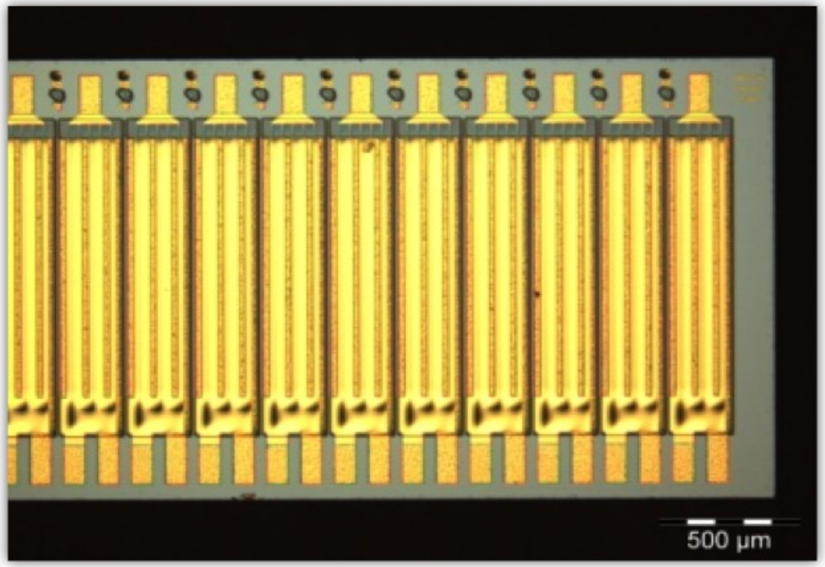
Si-MOSFET OK for very high impedances : 100 GΩ

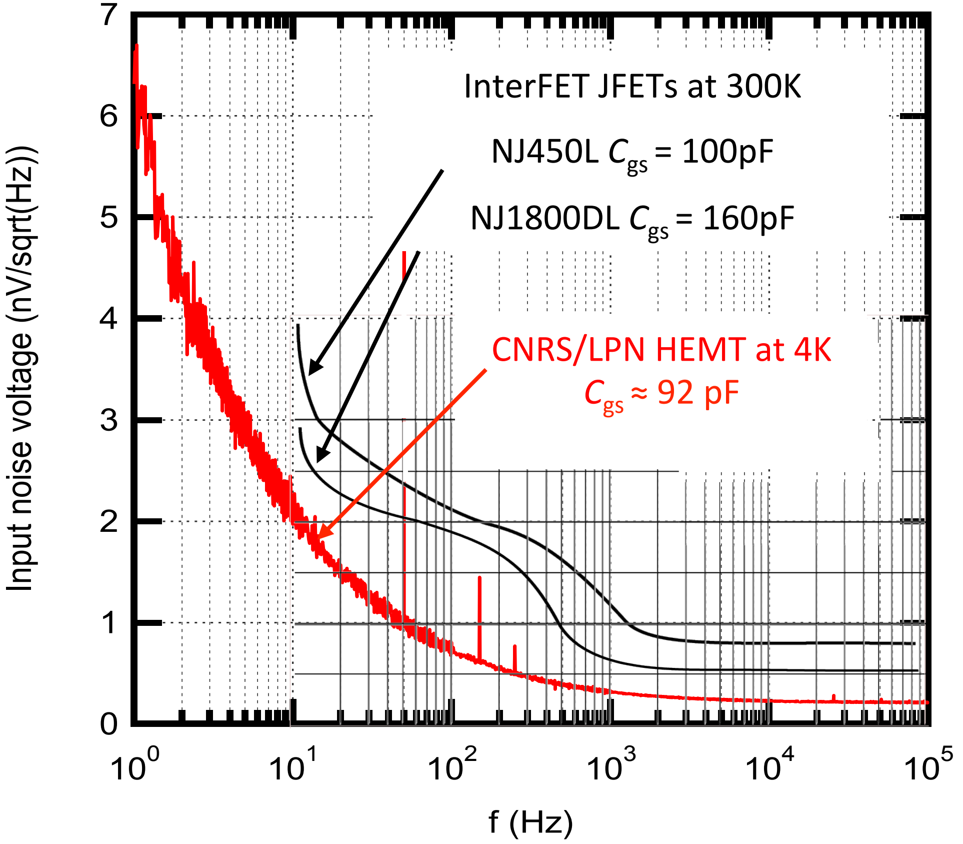
For intermediate sensor impedances (100 kΩ - 100 MΩ) :
GaAs/GaAlAs HEMT possible (work @ very low T)
Bipolar Electronic SiGe @2- 4 K for Low(1kΩ-10kΩ) impedances

MIS Readout Electronics (2)

GaAs/GaAlAs HEMTs
LPN (Laboratoire de Photonique et nanostructures)

17 HEMTs ASIC

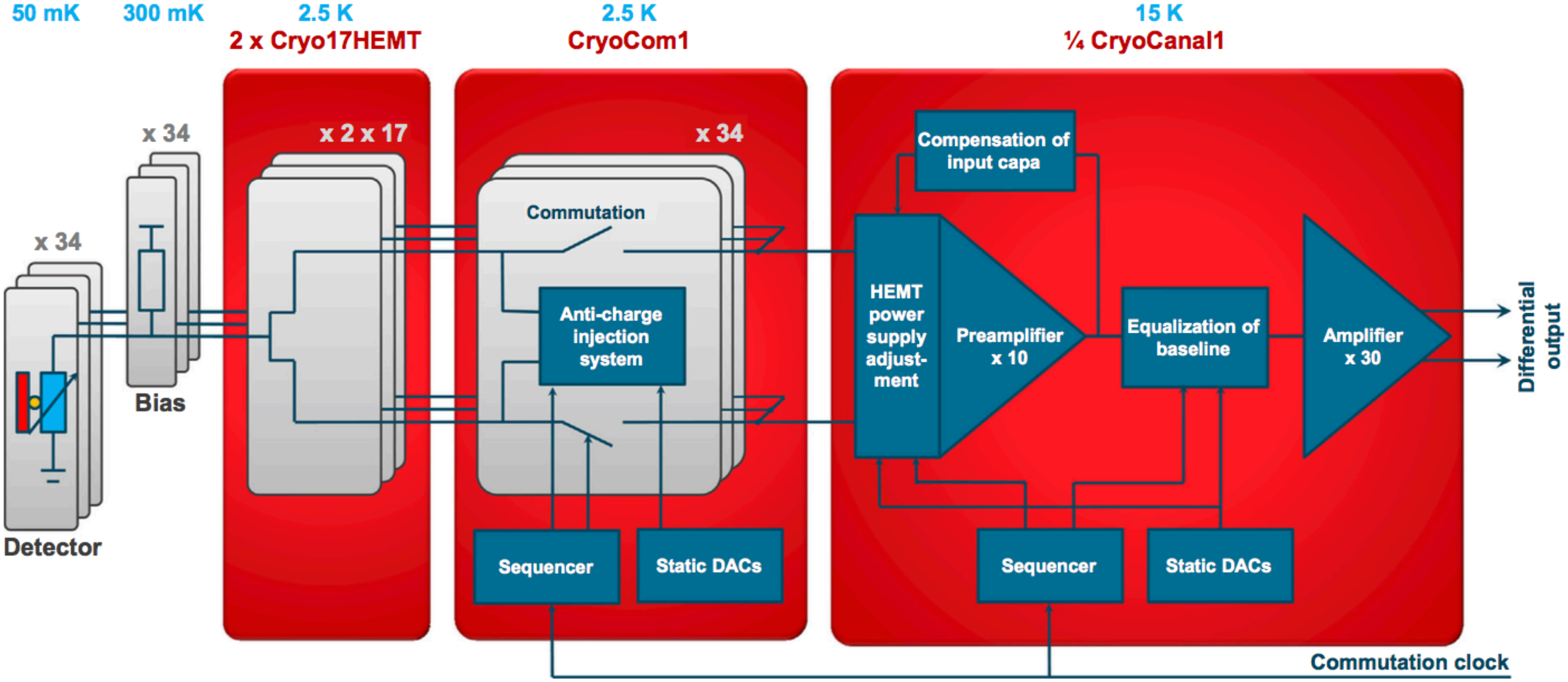




Noise voltage: comparison with Si JFET

HEMT with C_{gs} = 92 pF

MIS Readout Electronics (3)

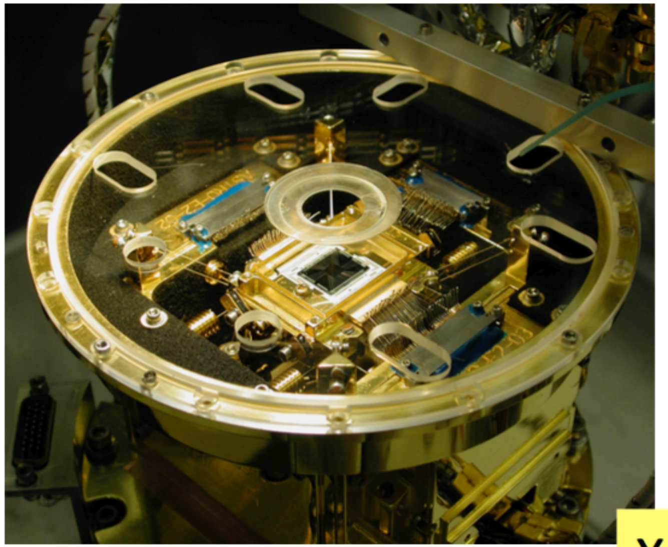


Complete schematic of MIS large array Cryo-Electronics
With HEMTs, MUX and Amplification

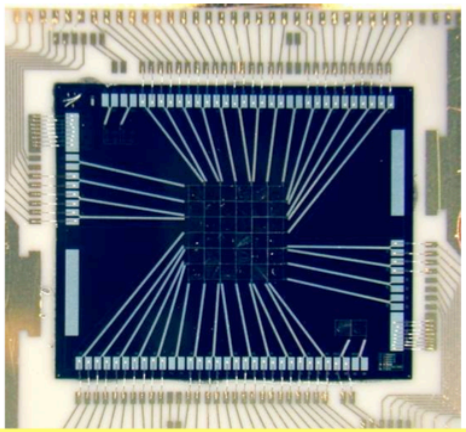
TES/MIS Comparizon

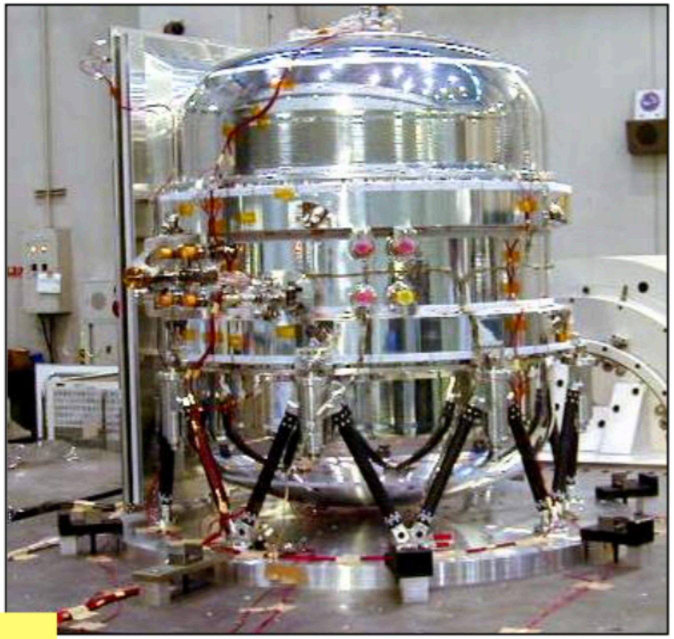
Red=Difficult **Blue=Easy**	**TES**	**MIS**
Fabrication	**Few Steps(~10)**	**Difficult (~120 steps)**
Heat Capacity per Pixel	0.8 pJ/K	0.04 pJ/K
Sensitivity(sensor)	**α=75 (1/F noise)**	**a= -5 -10**
Speed	**25 cp/s (goal)**	**~3-4 cp/s**
Saturation in E	**Yes (Limited by ETF & stifness of transition)**	**No ; $R=R0\ \exp(TO/T)^{0.5}$**
Magn. Field Senssitivity	**Very sensitive TES & SQUIDs**	NO
Sensor Impedance	mΩ	MΩ
Cryogenic Electronic	**SQUIDS (difficult)**	**HEMT/SiGe (~Classical)**
MUX	**VERY Difficult**	**~classical**
Filling Factor	Small (Deposited Absorber)	Very good (sticked Absorber)
P (4000p+Readout) @ 50mK	**SQUIDs ⇒ >1µW**	**Very Low @50mK**

Itomi: MIS State of the art

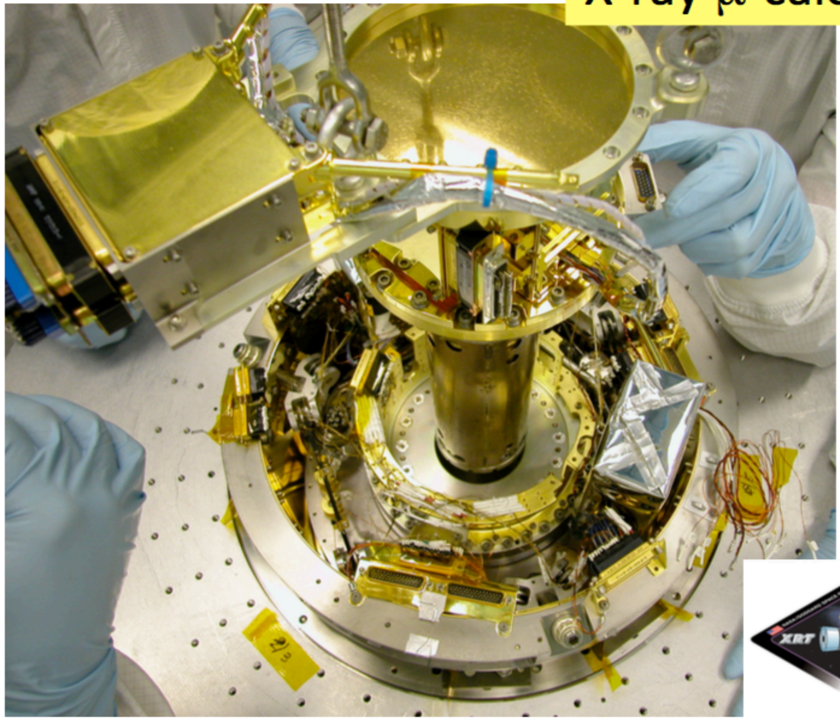


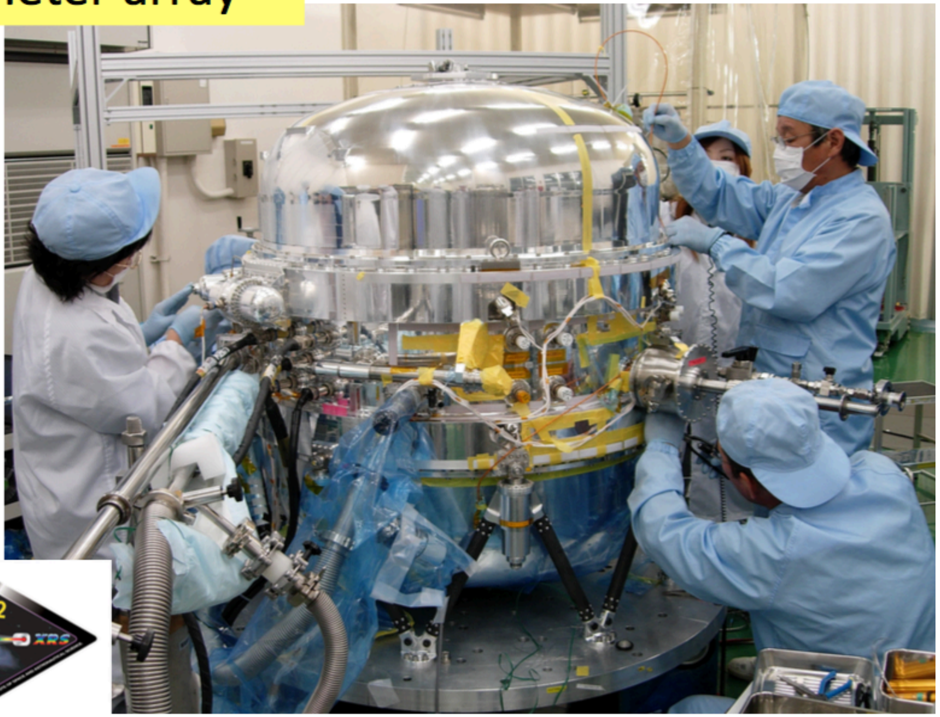
SXS 6x6 matrix





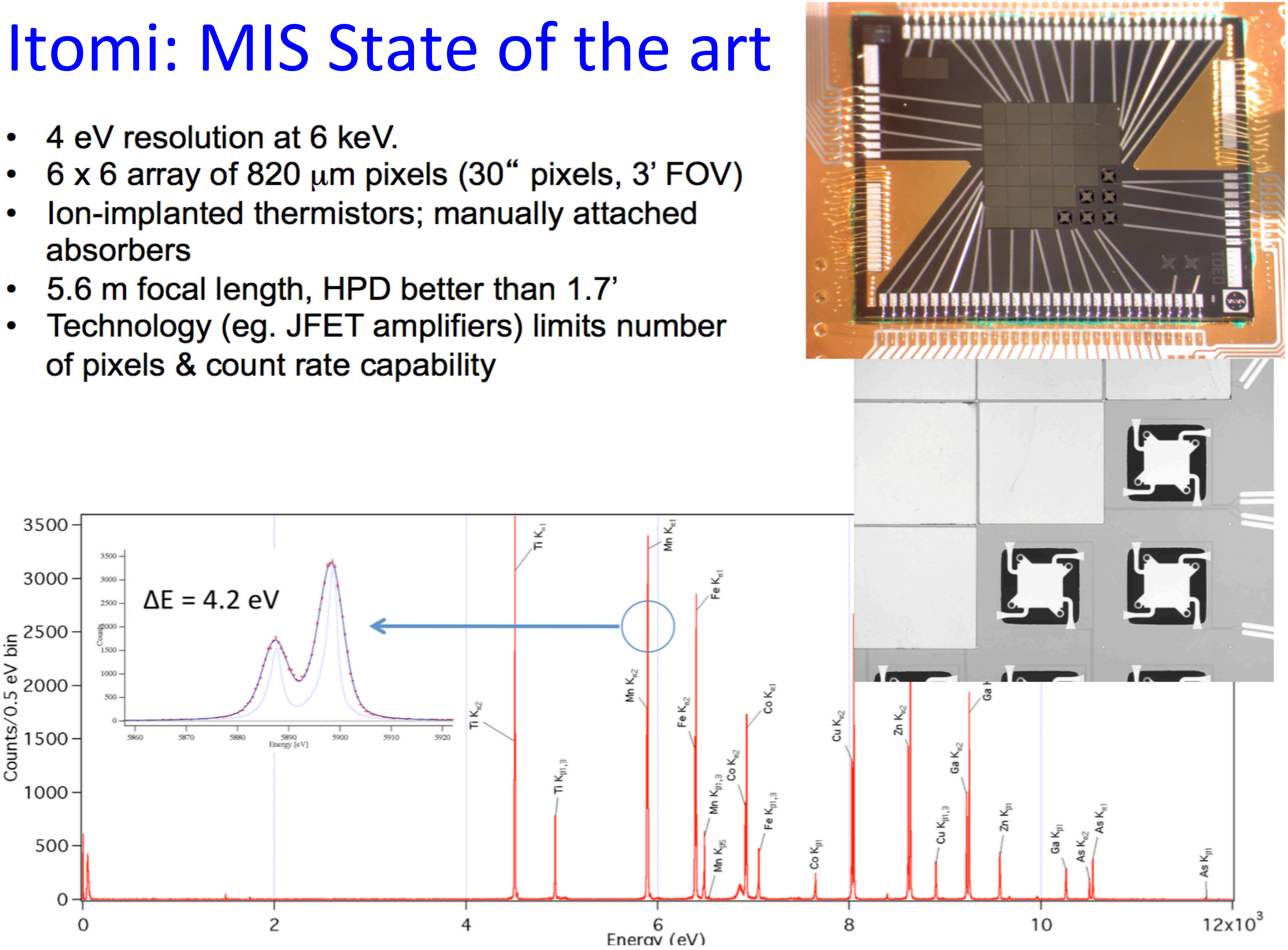
X-ray μ-calorimeter array





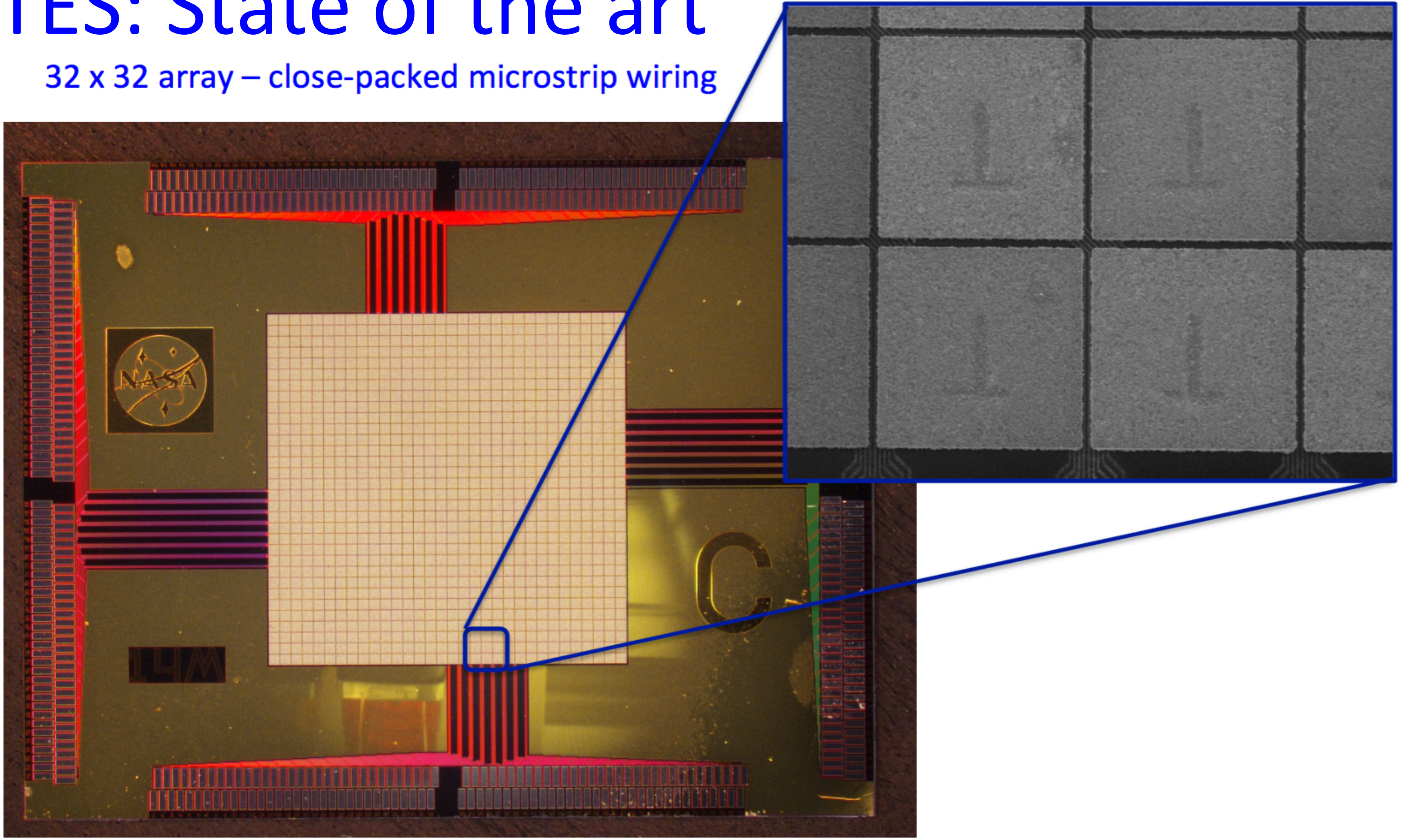
Itomi: MIS State of the art

- 4 eV resolution at 6 keV.
- 6 x 6 array of 820 μm pixels (30“ pixels, 3’ FOV)
- Ion-implanted thermistors; manually attached absorbers
- 5.6 m focal length, HPD better than 1.7’
- Technology (eg. JFET amplifiers) limits number of pixels & count rate capability


ΔE = 4.2 eV

TES: State of the art

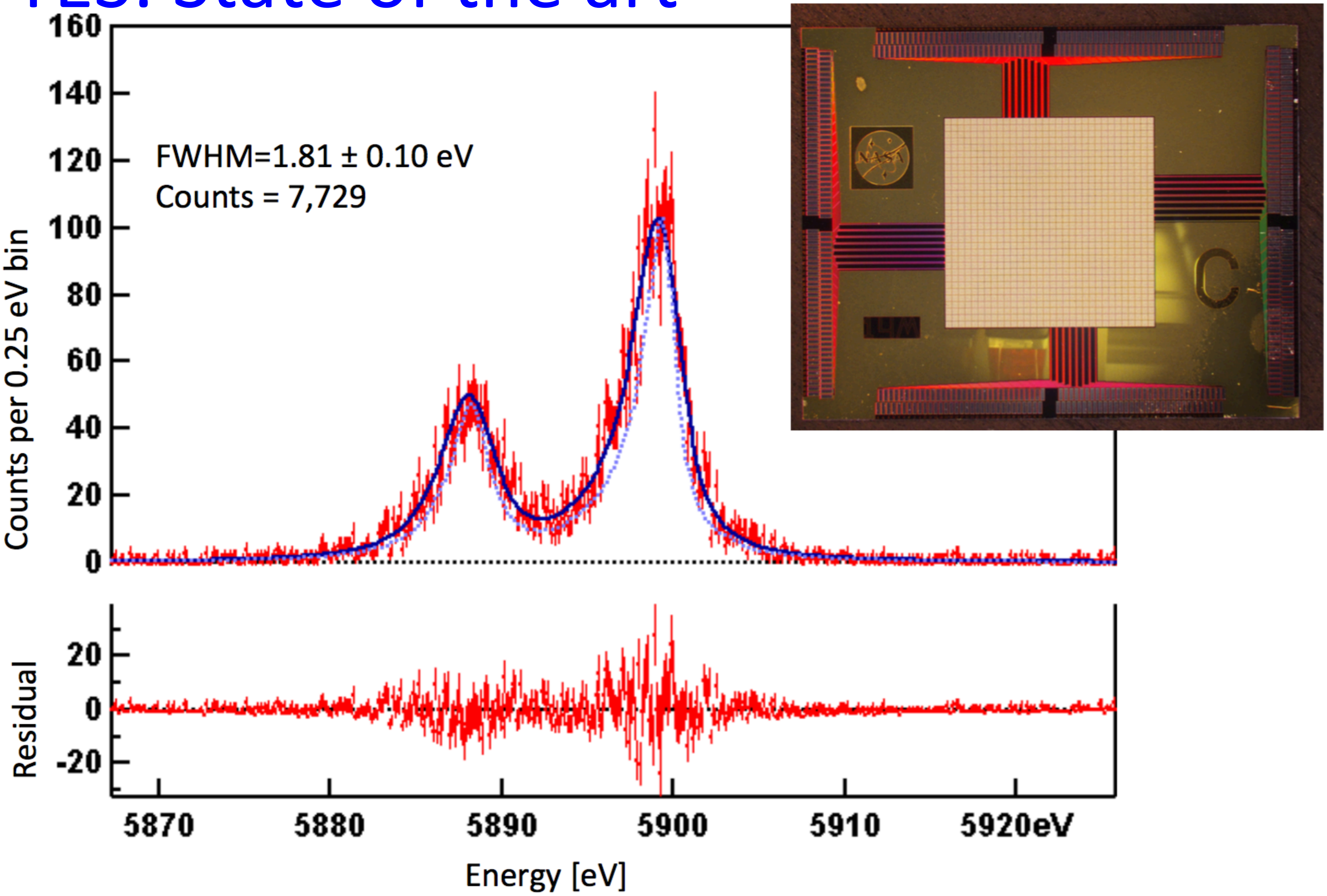
32 x 32 array – close-packed microstrip wiring



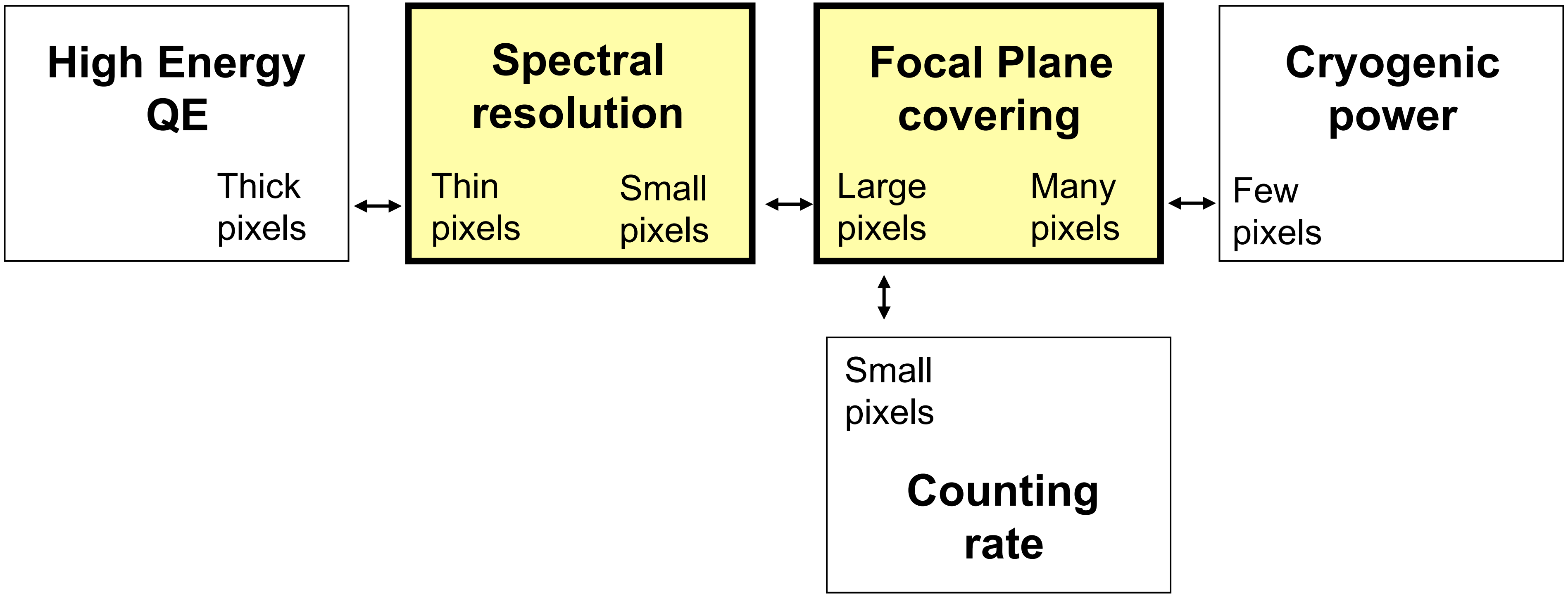
Absorbers:

- 242 x 242 μm on 250 μm pitch
- Au: 1.5 μm, Bi: 3.0 μm – electroplated
- >90% QE at 6 keV

TES: State of the art



Microcalorimeters Trade-offs



High Energy QE

Thick pixels

Spectral resolution

Thin pixels

Small pixels

Focal Plane covering

Large pixels

Many pixels

Cryogenic power

Few pixels

Small pixels

Counting rate

Conclusion

- CCDs were the first real spectro-imagers in X-rays Astronomy (2000-2016). DEPFets present excellent improvement.
- CdTe are THE semiconductors for high energies
- µ-Calorimeters will be THE next generation Low-Energy instruments … Very demanding in Spatial instrument budgets (Thermic, Power, weight…)