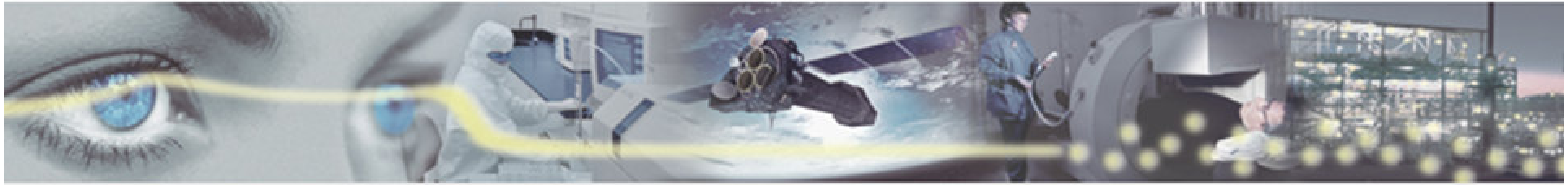
PHOTONIS



# Performance vs cost in the quest for the ideal detector in neutrino experiments

*Bruno Combettes*

*NNN07 Hamamatsu city, 2007 Oct 5*

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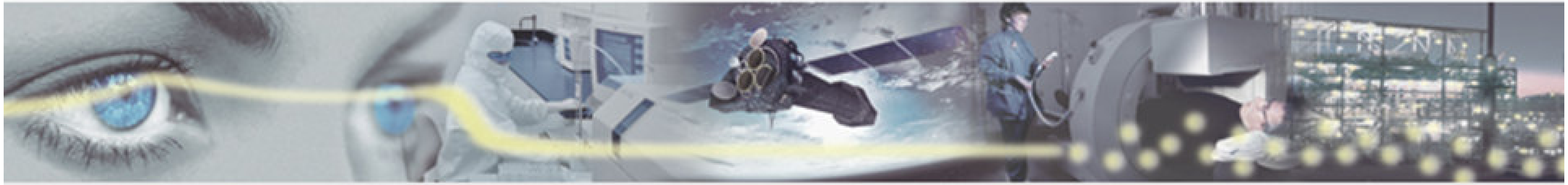


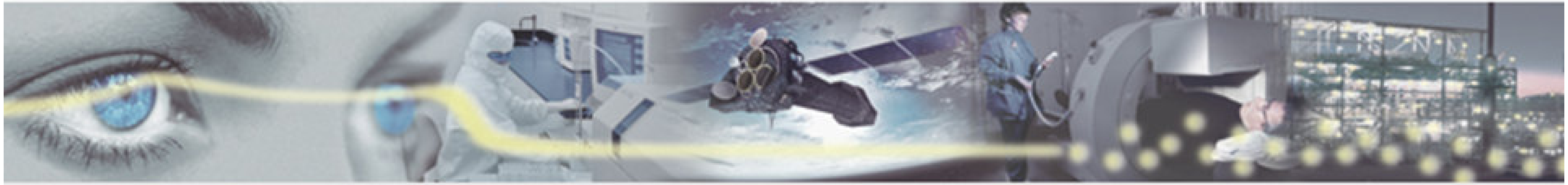

- 2 acquisitions in 2005:

  DEP and BURLE

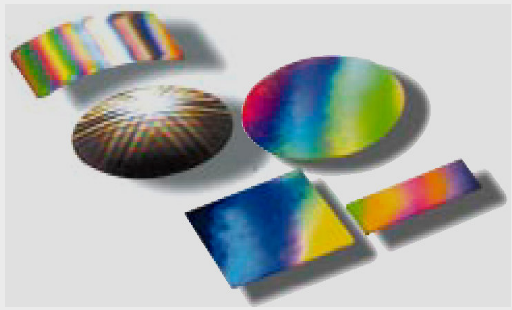
  5 production sites

  over 1200 employees

  total turn-over aro 130 M€



- Photomultipliers from Photonis and Burle
- Image intensifiers
- Streak tubes
- Microchannel plates from Photonis and Burle
- Single-channel electron multipliers from Photonis and Burle
- Neutron & gamma detectors



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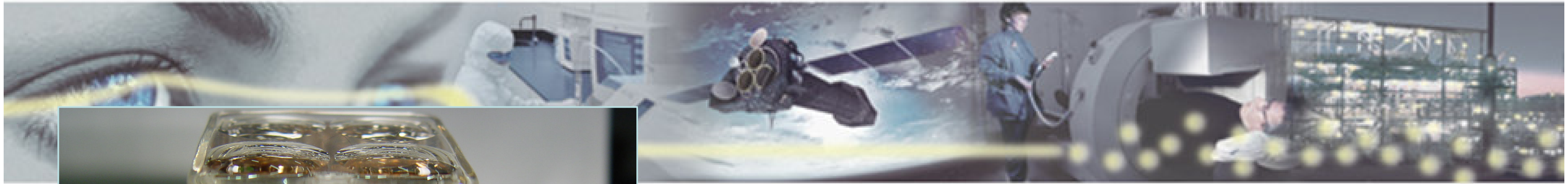
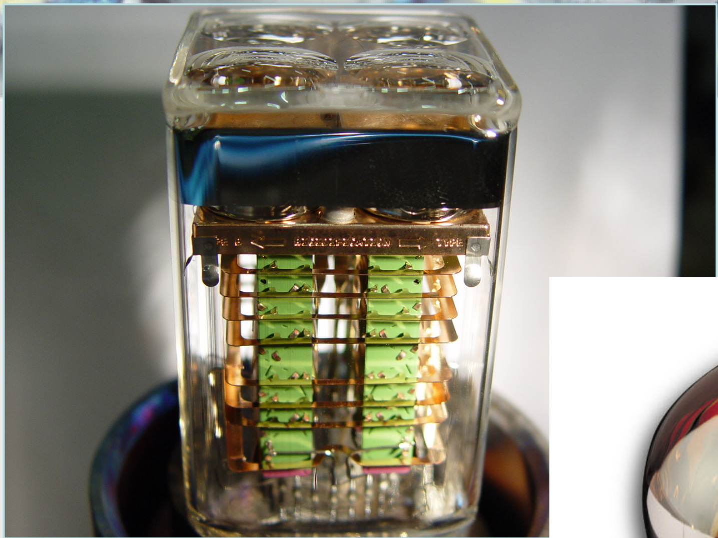
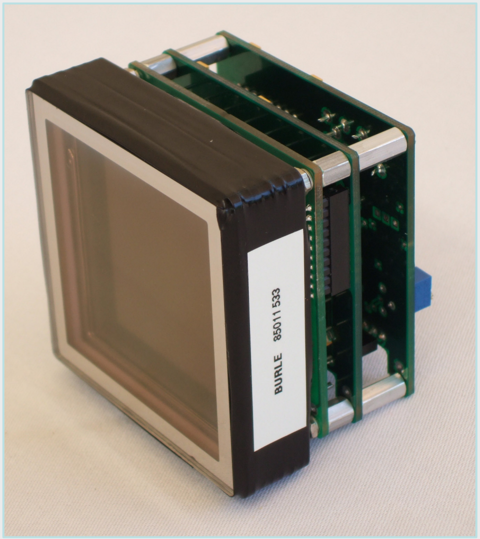
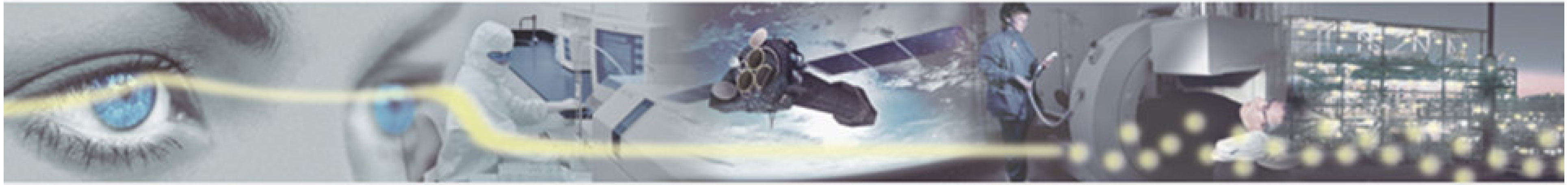
# *PHOTONIS tubes*





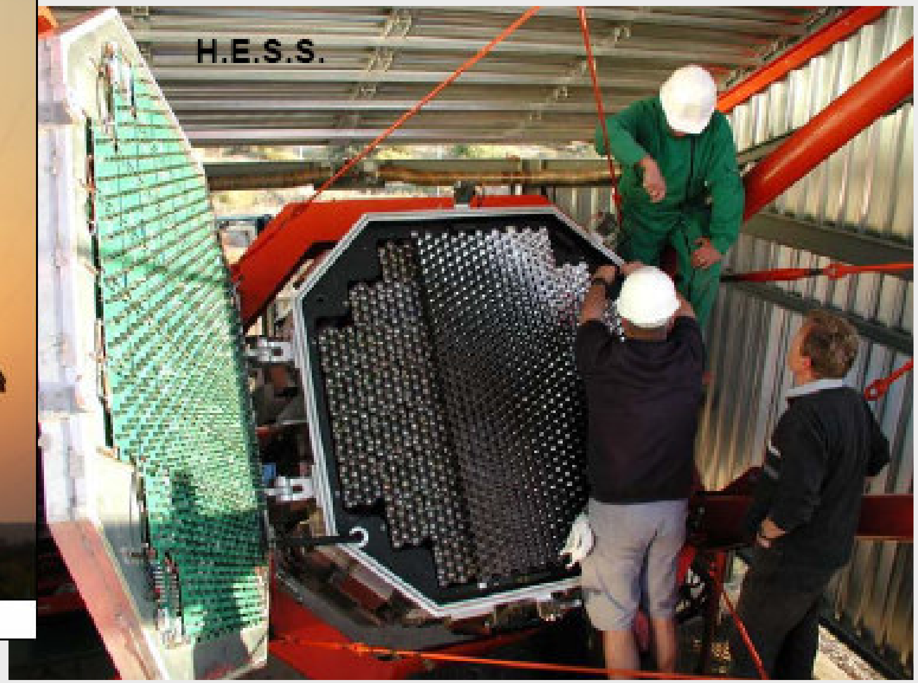


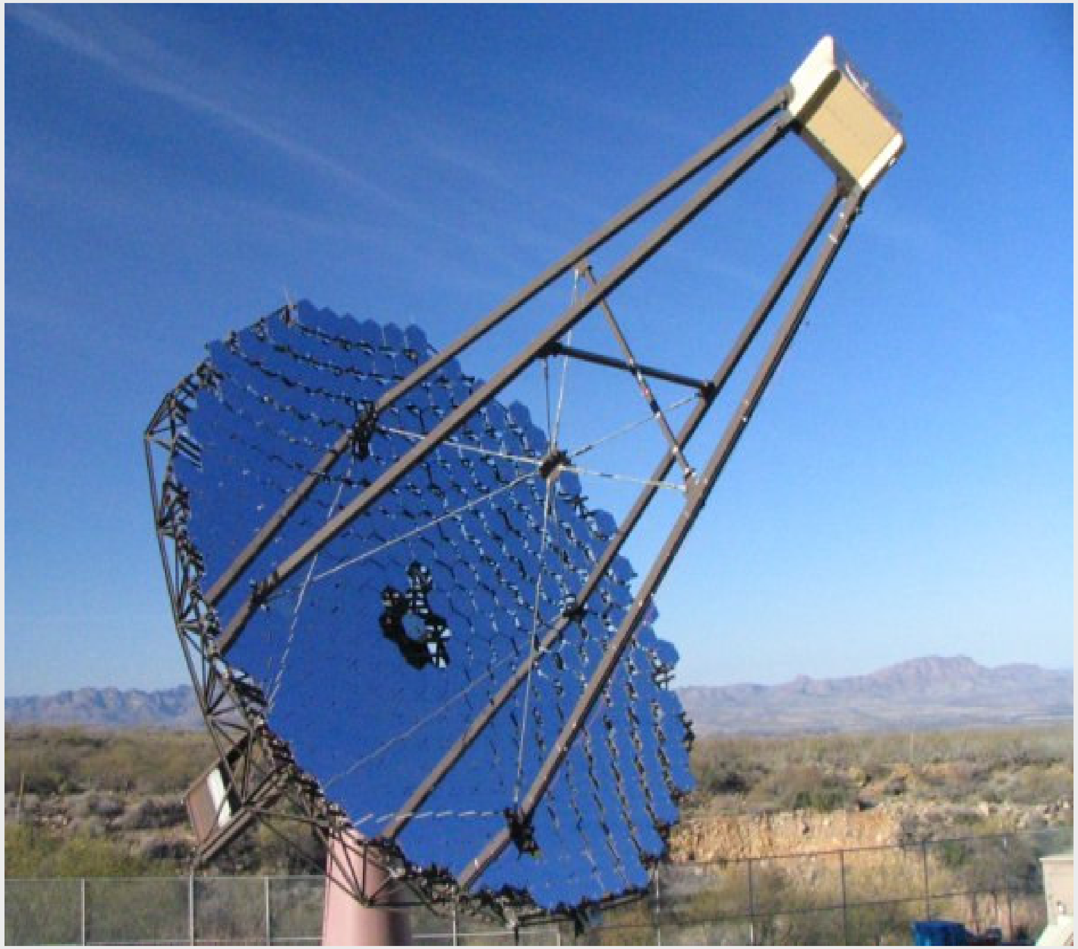
# HESS in Namibia

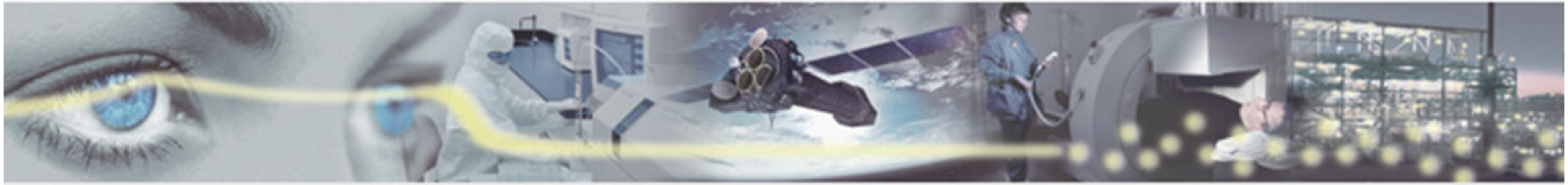
(*XP2960*)

HESS COSMIC-RAY TELESCOPE

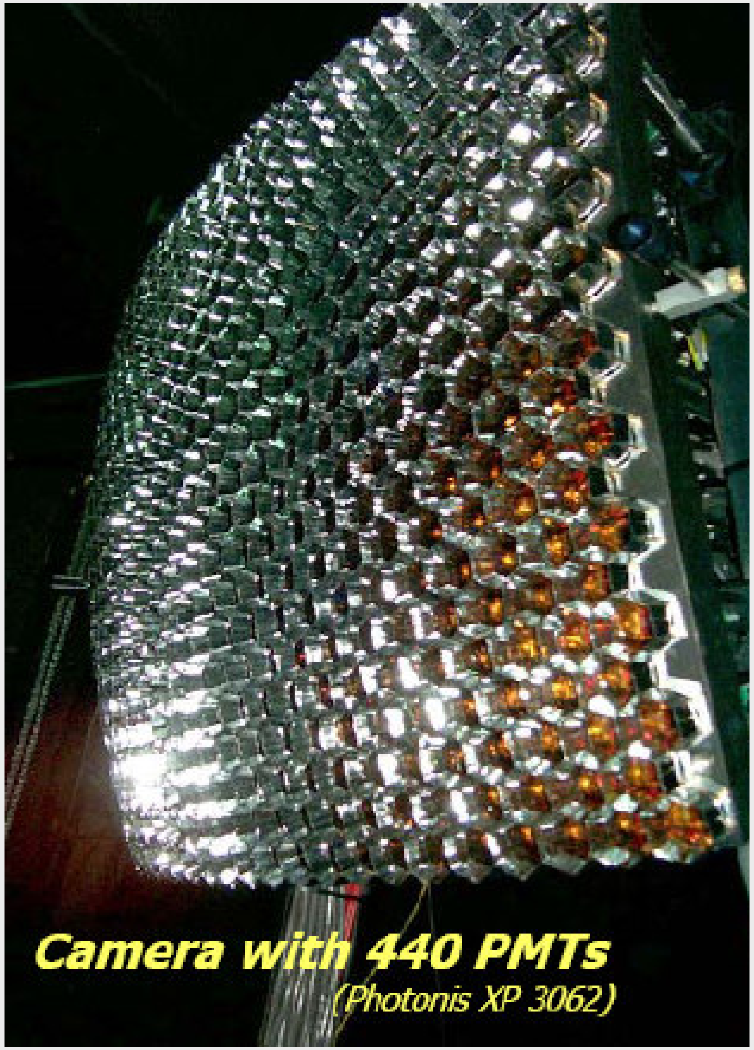


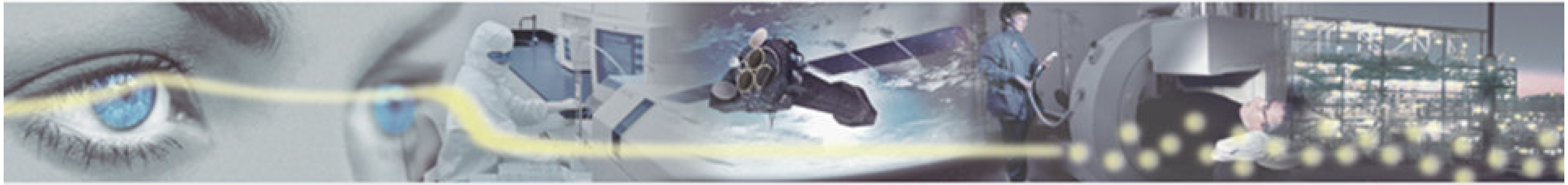
Veritas in Arizona
(XP2970)





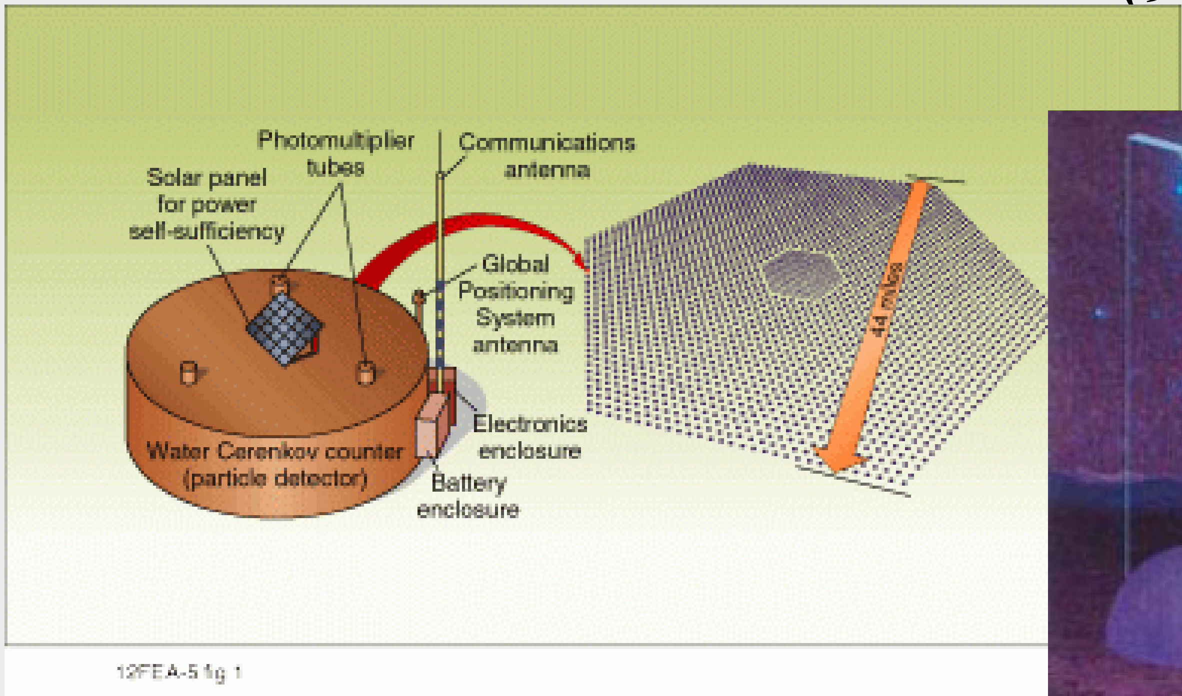
# AUGER in Argentina
## *(hexagonal PMTs)*

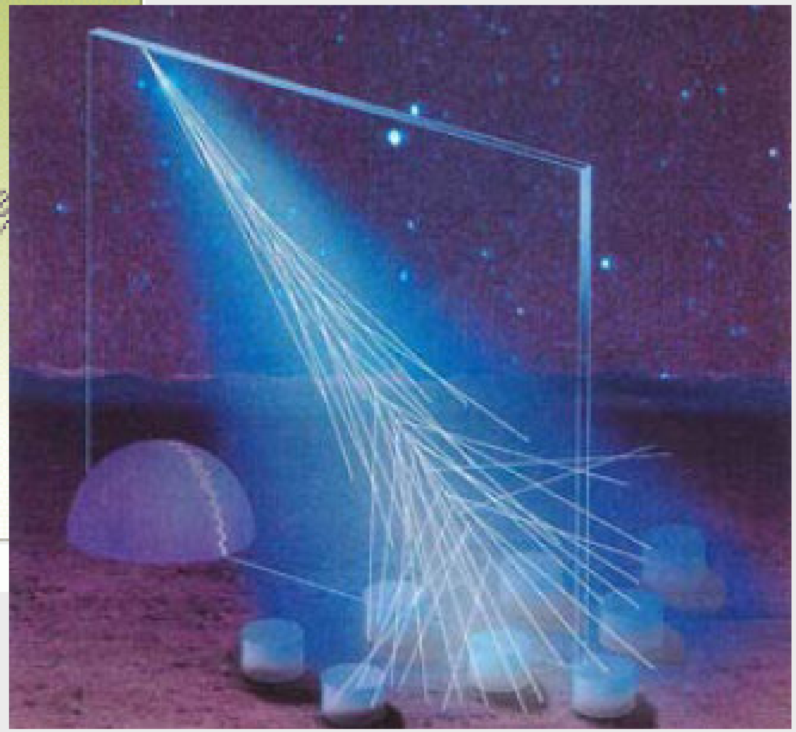


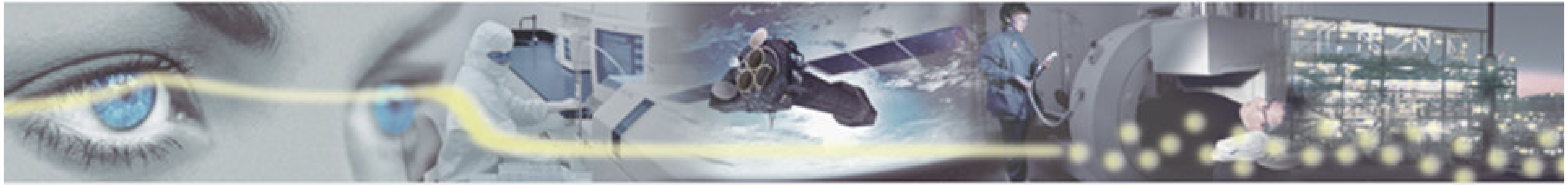



# AUGER in Argentina

*(9-inches PMTs)*





# References of hemispherical tubes from Photonis

- **5’’ tube : XP1803**
- **8’’ tube : XP1806**
- **9’’ tube : XP1805 (Auger Tube)**
- **10’’ tube : XP1804**
- **12’’ tube : XP1807**

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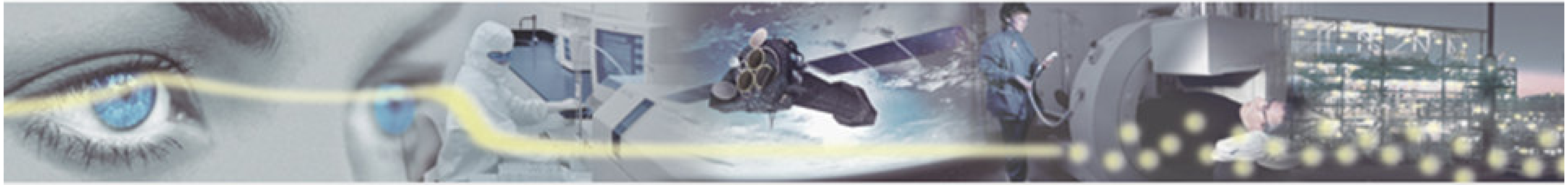
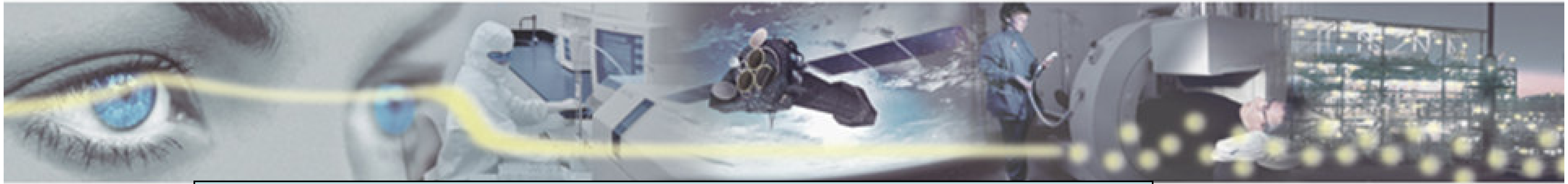
## *Specs for Neutrino detection*



| | |
|---|---|
| dimension | 10-13 inch |
| Spectral response | 300-650 nm |
| Wavelength of maximum response | 420 nm |
| Photocathode material | bialkali |
| Quantum efficiency at maximum | 25% |
| Window material | borosilicate glass |
| Dark counts | < 5 khz (1/3 p.e.) |
| Gain | 5*10exp7 for supply voltage < 1800 V |
| Peak/valley ratio | > 2 |
| Pulse risetime | < 10 ns |
| Pulse transit-time spread | < 3 ns (FWHM) |
| Afterpulse 1 | < 1.0% |
| Afterpulse 2 | < 5 % |
| Delayed pulse | < 5 % |
| Pre pulse | < 1% |

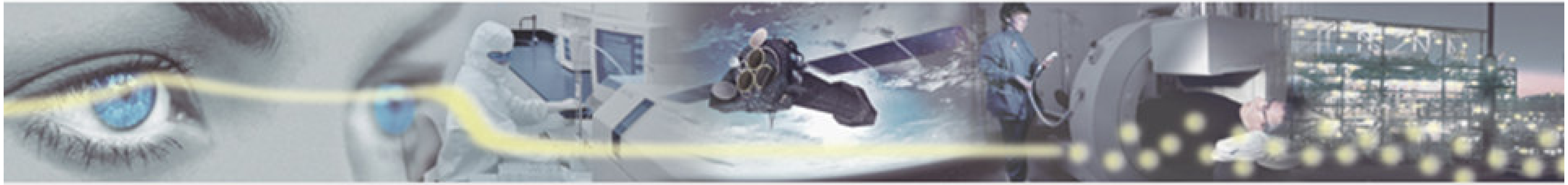
Very Large Volume Neutrino Telescope VLVνT workshop



| | | | |
|---|---|---|---|
| 1 | . | **Quantum efficiency at maximum** | **25%** |
| 2 | . | **Window material** | **borosilicate glass** |
| 3 | . | **Dark counts** | **< 5000 khz (1/3 p.e.)** |
| 4 | . | **Gain** | **5*10exp7 for supply voltage < 1800 V** |
| 5 | . | **Peak/valley ratio** | **> 2** |
| 6 | . | **Afterpulse 2** | **< 5 %** |

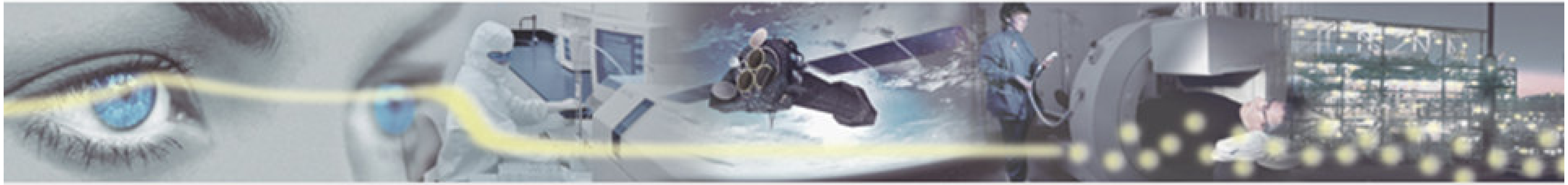
Very Large Volume Neutrino Telescope VLVνT workshop

PHOTONIS



- Improvement work on QE

## *What is Quantum Efficiency ?*



**Definition is easy :**

$$QE \equiv \frac{(\#Emitted\_Photoelectrons)}{(\#Incident\_Photons)} = \frac{N_{pe}}{N_{\gamma}}$$

**Many underlying factors :**

$$QE \approx \left(1 - P_{rob\_of\_refelection}\right)\left(1 - P_{rob\_Absorption\_in\_Window}\right) \times \left(1 - e^{-\frac{d}{2\cos\alpha \cdot L_{photon}}}\right) \cdot P_{rob\_of\_Electron\_Excitation} \times e^{-\frac{d}{2\cos\beta \cdot L_{electron}}} \cdot P_{rob\_of\_Electron\_Emission}$$

*d*: Thickness of Alkali Material
α: Incident Photon Angle
β: Emitted Electron Angle

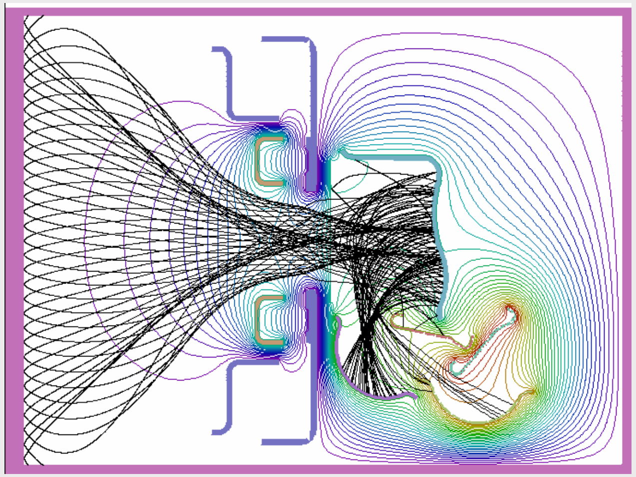
Ref : K. Arisaka (LA)

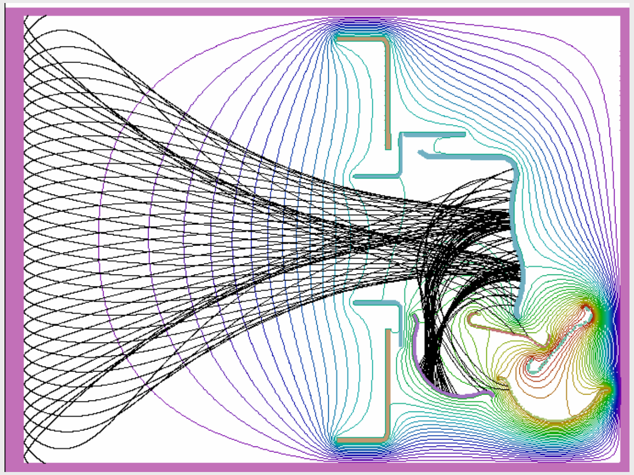
# *QE vs DQE : a key difference*

$$DQE \equiv \frac{(\#PE\_captured\_by\_1st\_Dynode)}{(\#Insident\_Photons)} = QE \cdot CE$$

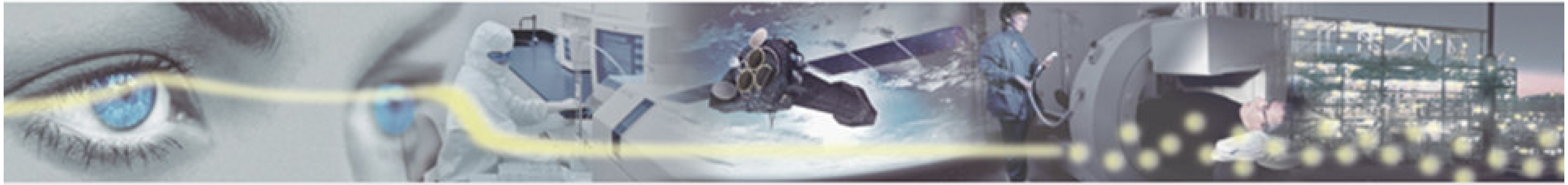
***Detection QE***

It is not only important to convert photons into electrons : QE
but also not to lose them before multiplication effect : Collection Efficiency





Note: there is no longer a mesh in the electron path. We get 10 % improvement.



## What are the key parameters to increase photocathode QE ?

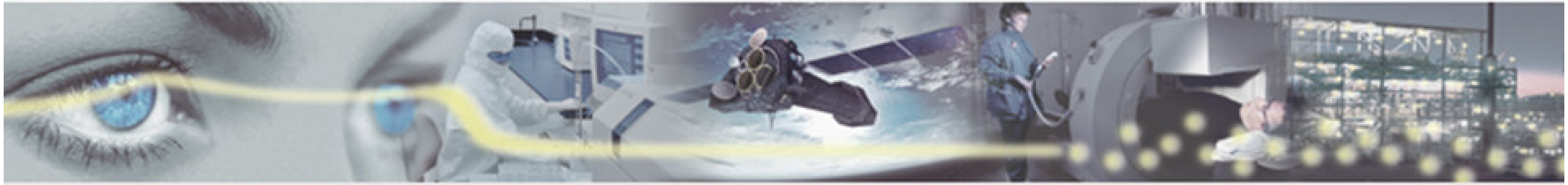
### 1. Surface structure and cleanliness :
Impact on photocathode growth & diffusion of impurities

### 2. Photocathode interface :
Optical coupling with entrance window

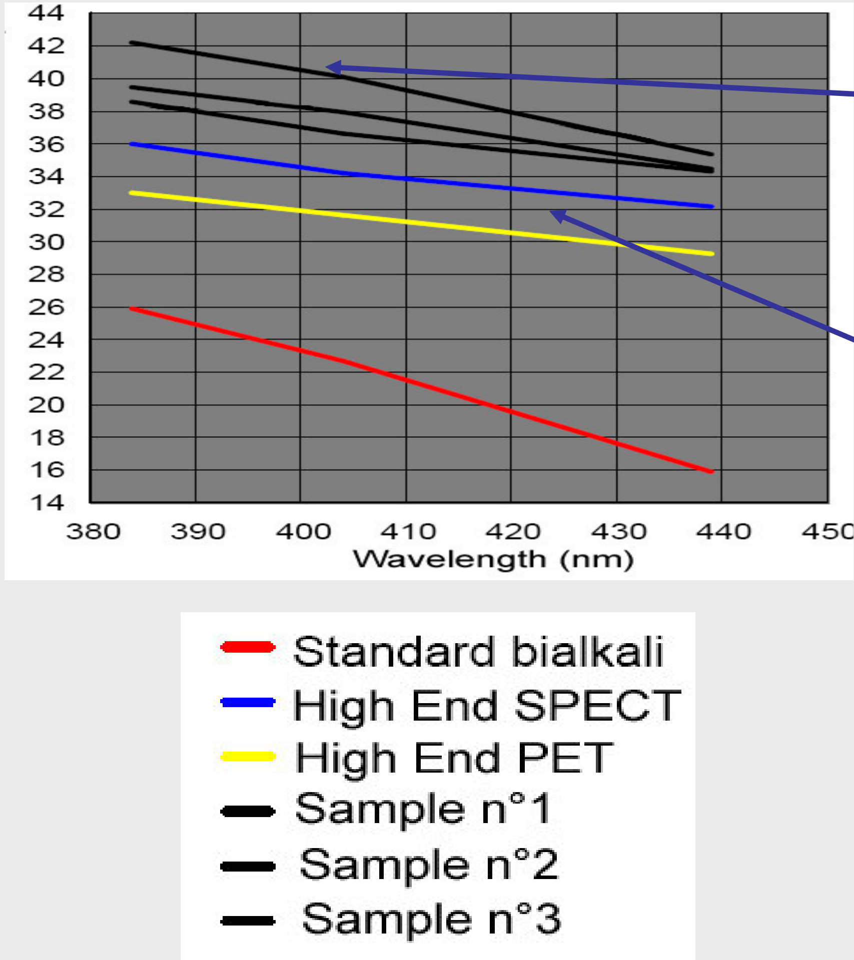
### 3. Photocathode material :
Purity of basic materials (dispensers) - Composition

### 4. Photocathode growth :
Growth defects – Uniformity – Band bending

### 5. Photocathode thickness :
Compromise absorption of photons – recombination of electrons



## Various generations of bialkali PK and related QE performance level




Super² bialkali allow
Above 40% QE at 400 nm

Super bialkali allow
35 – 40% QE at 400 nm

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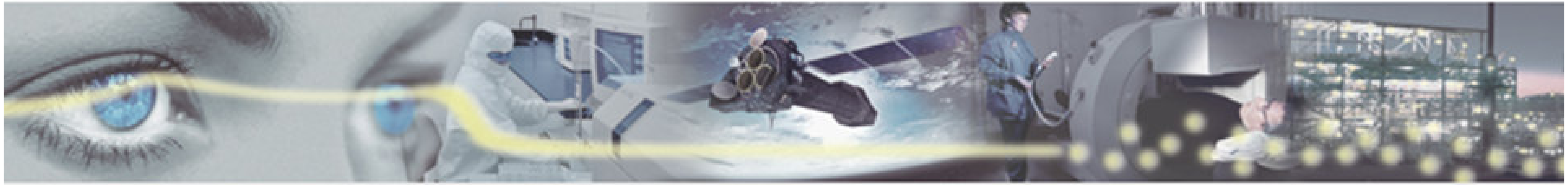
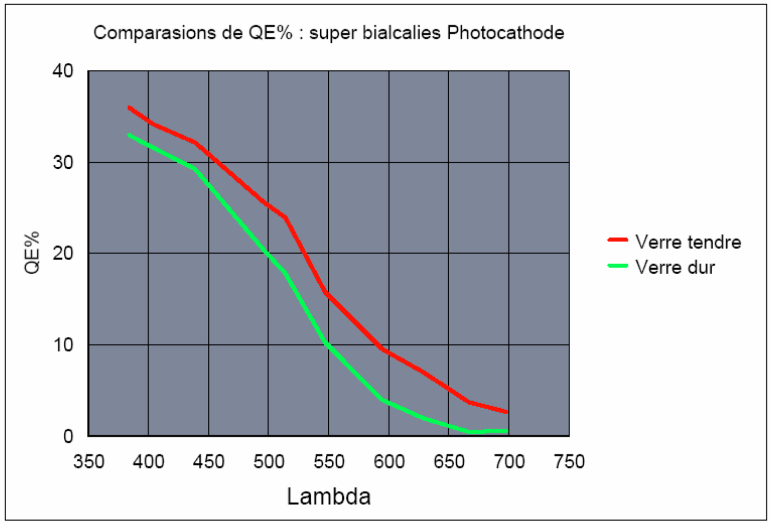
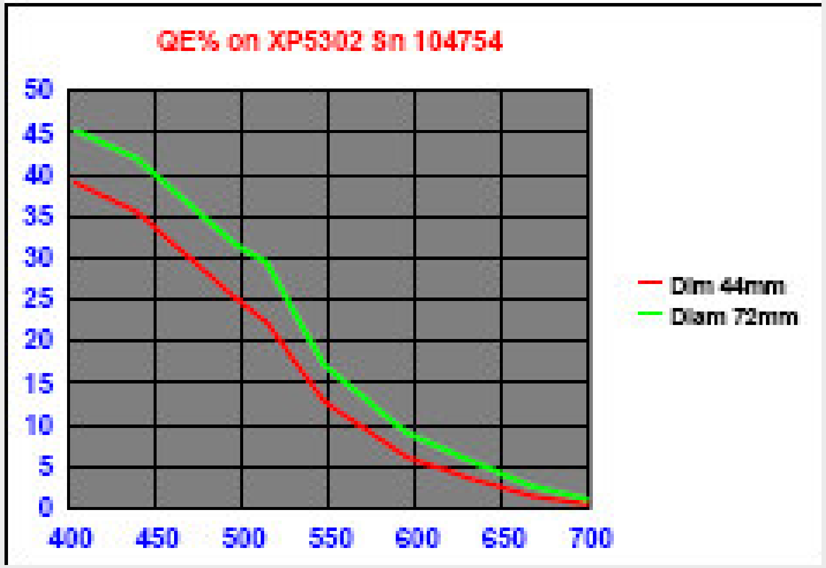
# *New bialkali photocathodes*



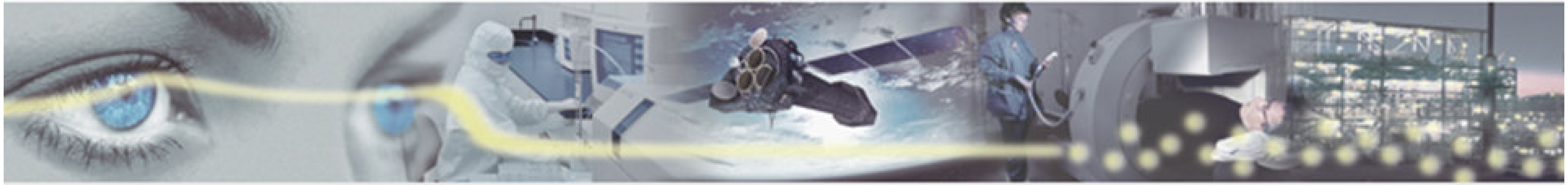
Super bialkali process
(400 nm 30 – 40%)



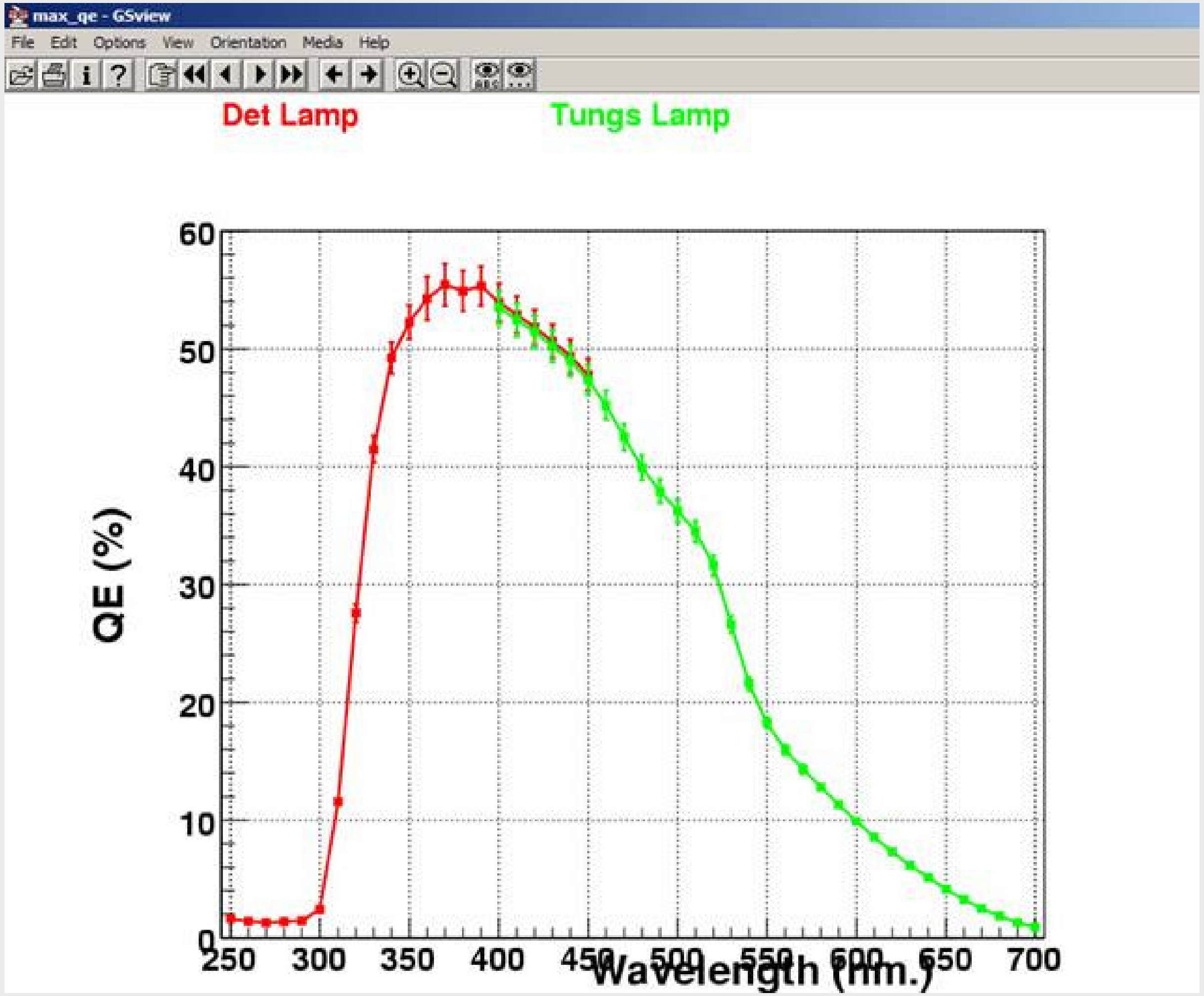

Super$^2$ bialkali process
(400 nm 40 – 50%)



## *Very New bialkali photocathodes*

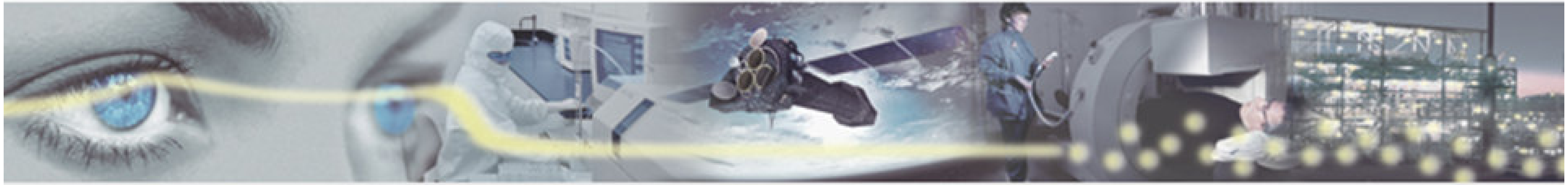


Super³ bialkali process
(400 nm 50 – 60%)




*From R.Mirzoyan, LIGHT07*

## *Drawbacks in high QE*



- Drawbacks of increasing QE

1. Noise : increases with QE

   (not linear function, depending on improvement process)

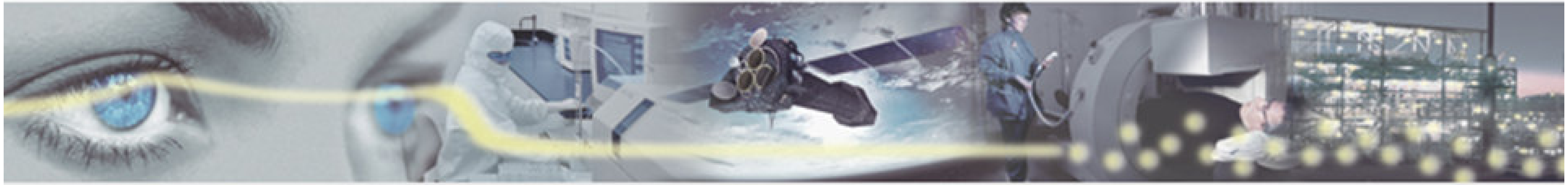
   Resulting S/N ratio should be higher. This is the case with PHOTONIS new process for super3 PC. Leads to much higher S/N ratio.

2. AP : increases a bit with QE

   Which level of AP physicists can tolerate?

3. Stringent specs could lead to low yield and then higher cost.

4. Aging?



- Improvement work on collection

  Good to improve QE, do not forget to look at CE

Two types of traditional tubes available at PHOTONIS:

- **9'' tube** equiped with a first ''foil'' dynode ( XP1805 AUGER tube ).
- **5'', 8'', 10'' and 12''** equiped with a linear focused dynode (10.6'' developped for ANTARES experiment )

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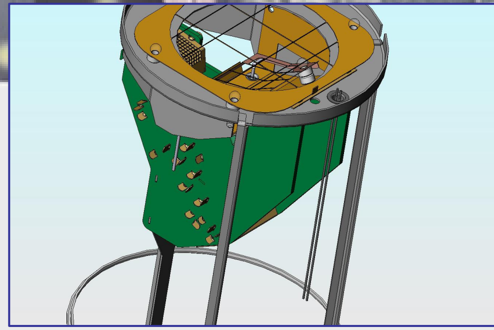
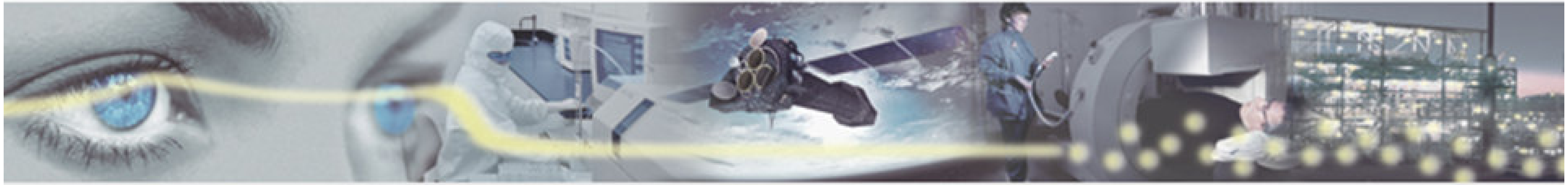
# *Foil vs focused*



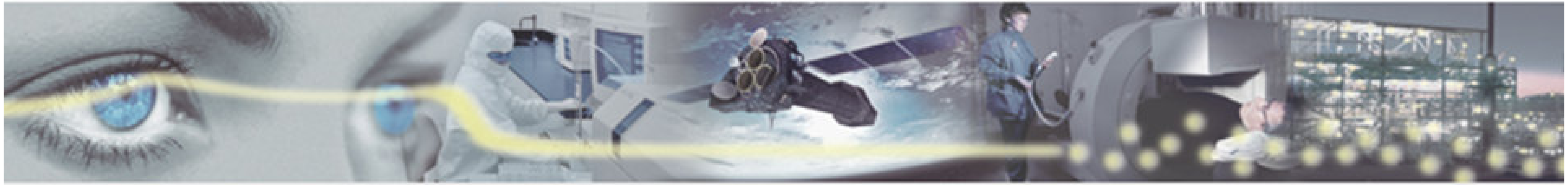
| Multiplier with first dynode | foil | linear focused |
|---|---|---|
| Collection uniformity | +++ | + |
| Pk – D1 isochronism | +++ | + |
| After pulses | <1% | 5% |
| P/V | --<br>aver. 1.4 max. at 1.8 | +++<br>typ. 2.5 (spec min. at 2) |

- Improvement work : mix both concepts

  D1 foil and rest is standard dynodes



Good to improve QE and CE, but do not forget to think of the active surface area, this will give an idea of the instrumentable volume (key parameter for the Physic).



# PMT size <=> cost

| | | | | |
|---|---|---|---|---|
| • Diameter | 20“ | 17“ | 12“ | |
| • projected area | 1660 | 1450 | 615 | $cm^2$ |
| • QE(typ) | 20 | 20 | 24 | % |
| • CE | 60 | 60 | 70 | % |
| • Cost | 2500 | 2200 | 800 | € |

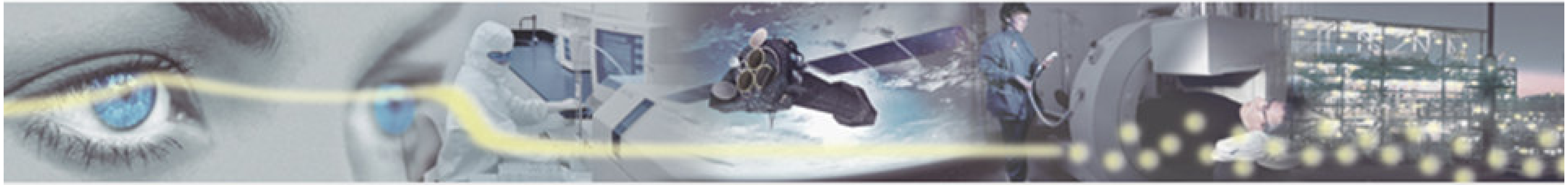
- ***Cost/cm² per DQE* = cost/(cm²*xQExCE*)**

| | | | |
|---|---|---|---|
| **12.6** | **14.4** | **7.7** | **€/DQE/cm²** |

**Optimise !**

***Cost/cm² per useful area***

PHOTONIS talk @ NNN 05 :
Need to invest in high QE tube



- Improvement work on dark noise

  (self $e^-$ emission from photocathode + glass radioactivity)

Parameters which make dark noise high:

. Photocathode surface

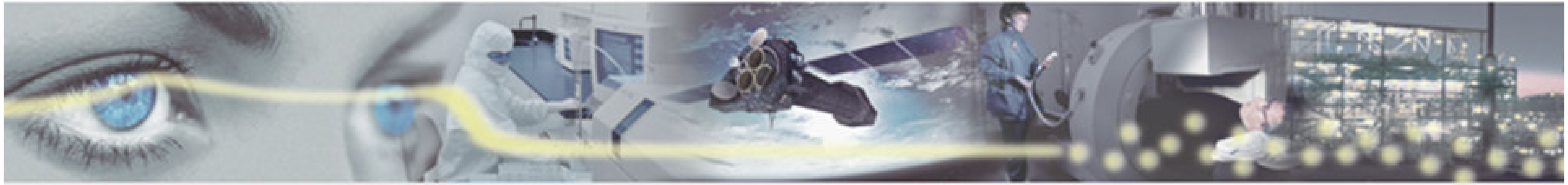
. QE

. HV

. Temperature

We're working on new process to get quiet high QE photocathode (high SNR)

. Glass level in radio elements



- Improvement work on glass

  glass : major point in piece part cost

. If low quality glass: cheap but high radioactivity background

. Very important for excavation experiments

. (Underwater : noise dominated by water $K^{40}$)

. New glass should be consistent with manufacturing constraints (eg dilatation coef when sealing, chemical photocathode processing)

. Compatibility with experimental conditions (eg ultra pure water, water pressure)

. At lowest price

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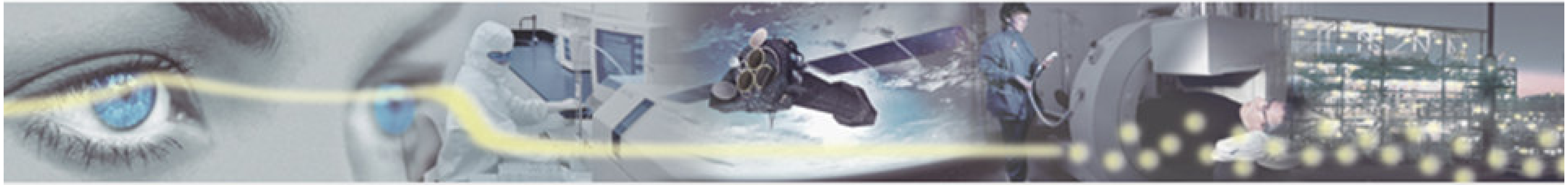
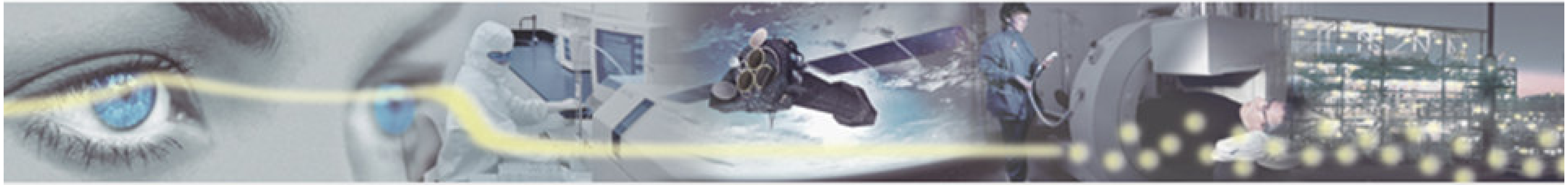
# *PMT glass specifications*



| Sample Bq/kg | P (g) | T (h) | $^{40}$K | $^{137}$Cs | $^{238}$U | $^{226}$Ra | $^{228}$Ra | $^{228}$Th |
|---|---|---|---|---|---|---|---|---|
| **Standard low noise Schott glass** | 170 | 90 | 26 | <0,02 | 9 | 12,6 | 2,3 | 2,6 |
| **Special Optic Schott glass (very low noise)** | 60 | 236 | 1,5 | <0,005 | <0,25 | 0,14 | <0,04 | <0,02 |
| **Low noise glass for general applications at Photonis** | 120 | 166 | 9,7 | <0,008 | 0,9 | 0,84 | 0,45 | 0,51 |
| Specific VERY low noise glass used by Photonis | 33.8 | 92 | <2 | <0.01 | <0.3 | 2 | <0.2 | 0.03 |



- Improvement work on gain

Necessary to have high gain to get a high P/V ratio
(Single Electron Response)

Use of new secondary electron emitting material :

Sb : PK-D1 gain = 30

New : PK-D1 gain = 50

+ very nice SER

- More expensive

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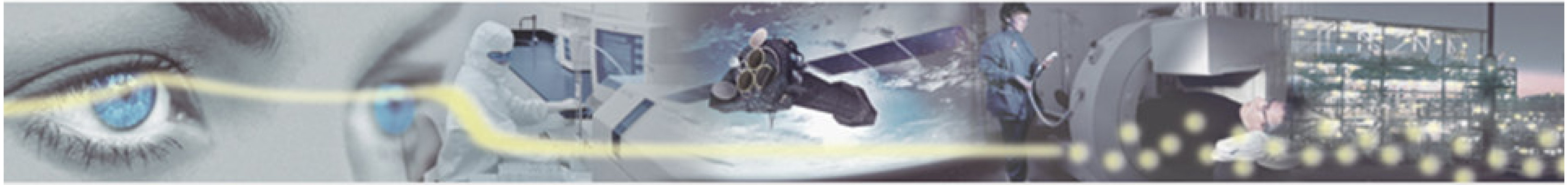

- Improvement work on After Pulses

After Pulses type 2 (in the µsec range) is generated by gas or atome ionization ($X + e^{-} \rightarrow X^{+} + 2\ e^{-}$) in the D1-D2 space. $X^{+}$ positive ions back-hit photocathode (TOF is several µsec) and create a new pulse (delayed).

Improvements could be made by higher vacuuming the tube (less residual gas). Takes longer time, increases costs?

Mesh to trap backing ions (will penalize collection)

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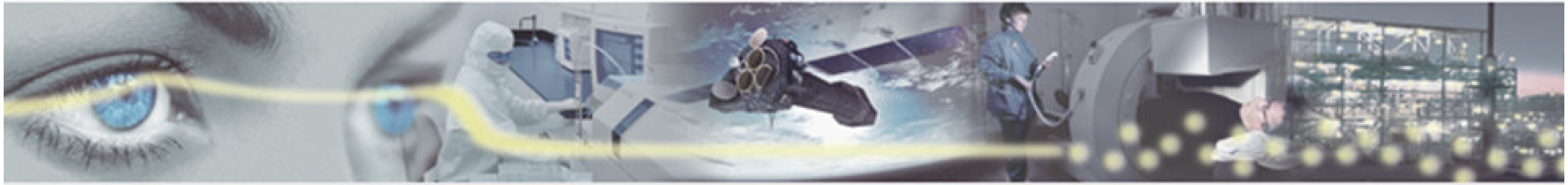
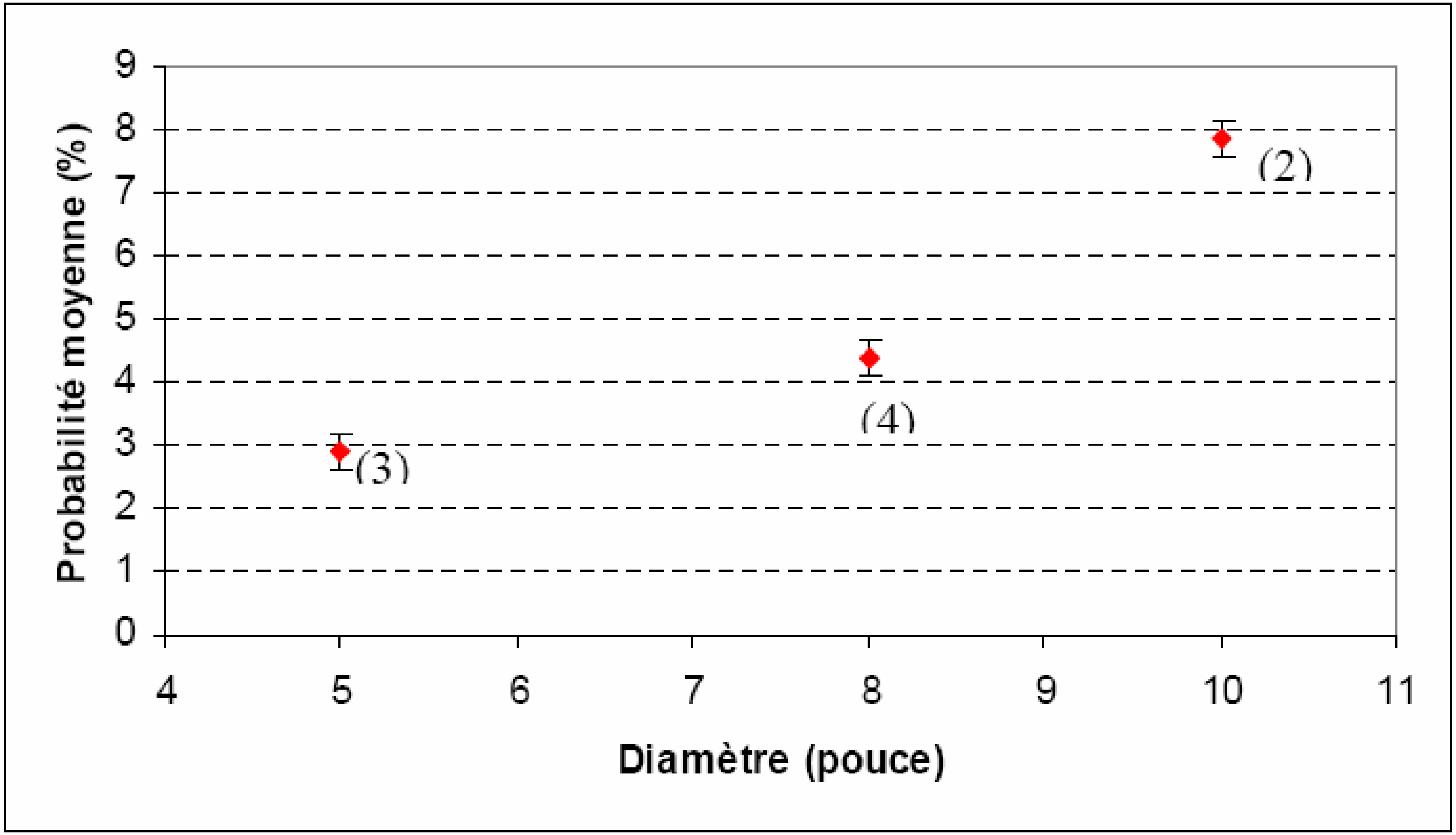
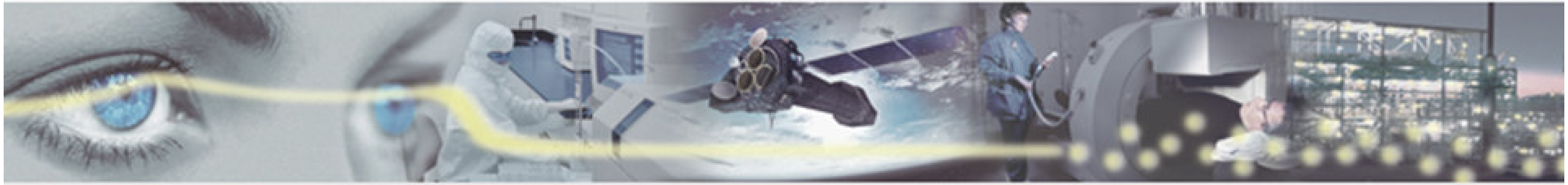
# *AP vs Size*

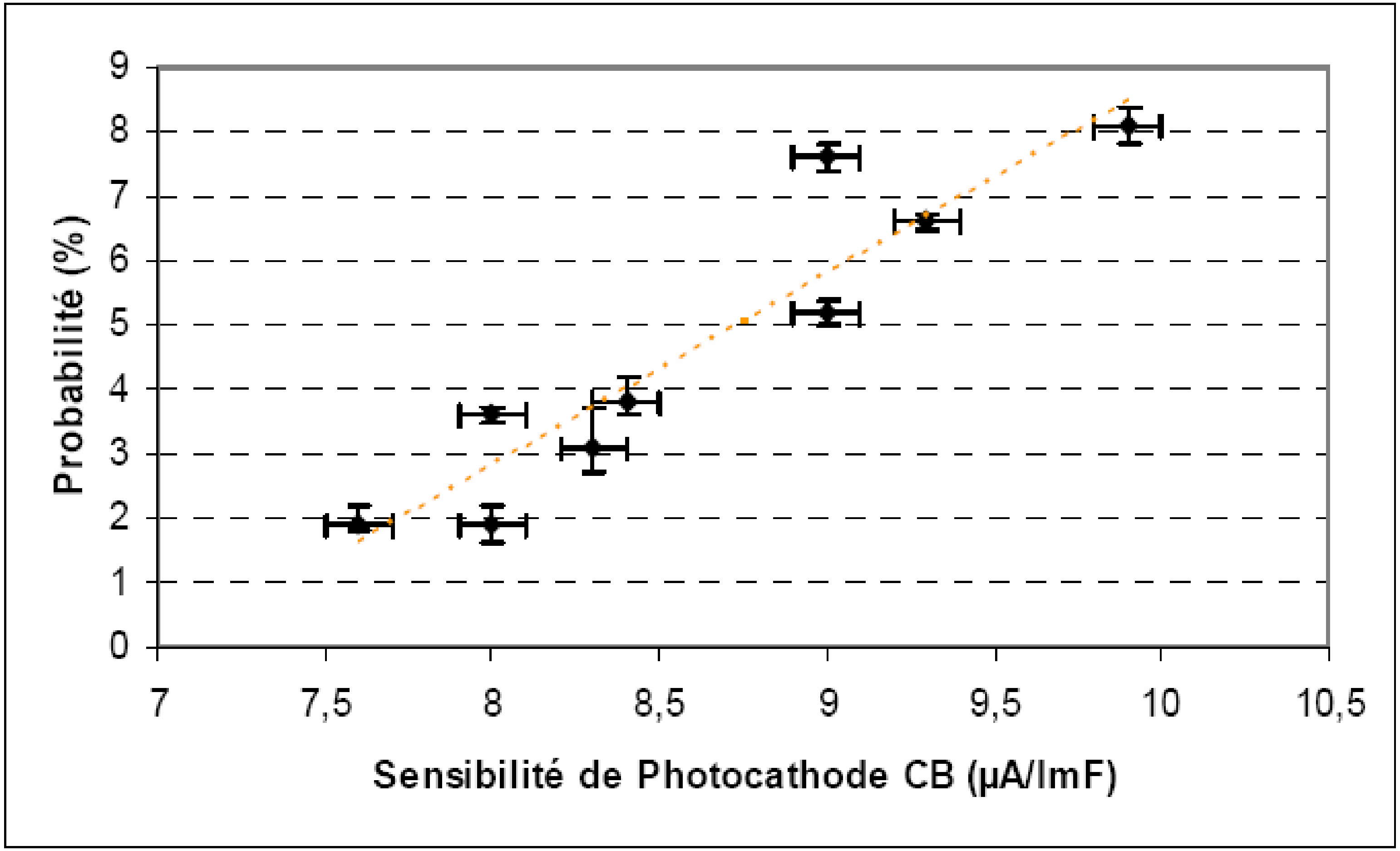





From D. Dornic and J. Pouthas (IPNO, France)

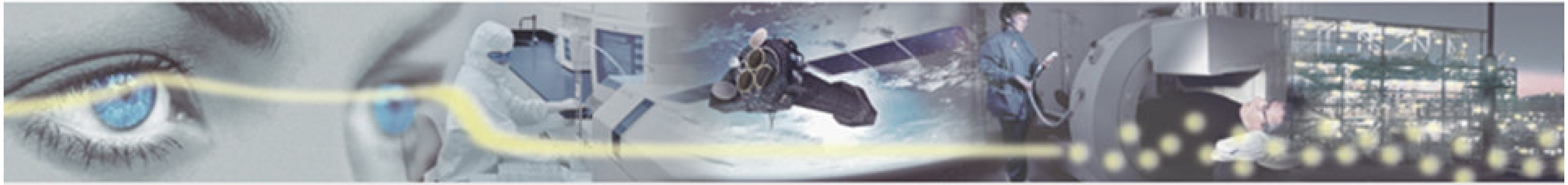
# *AP vs QE*

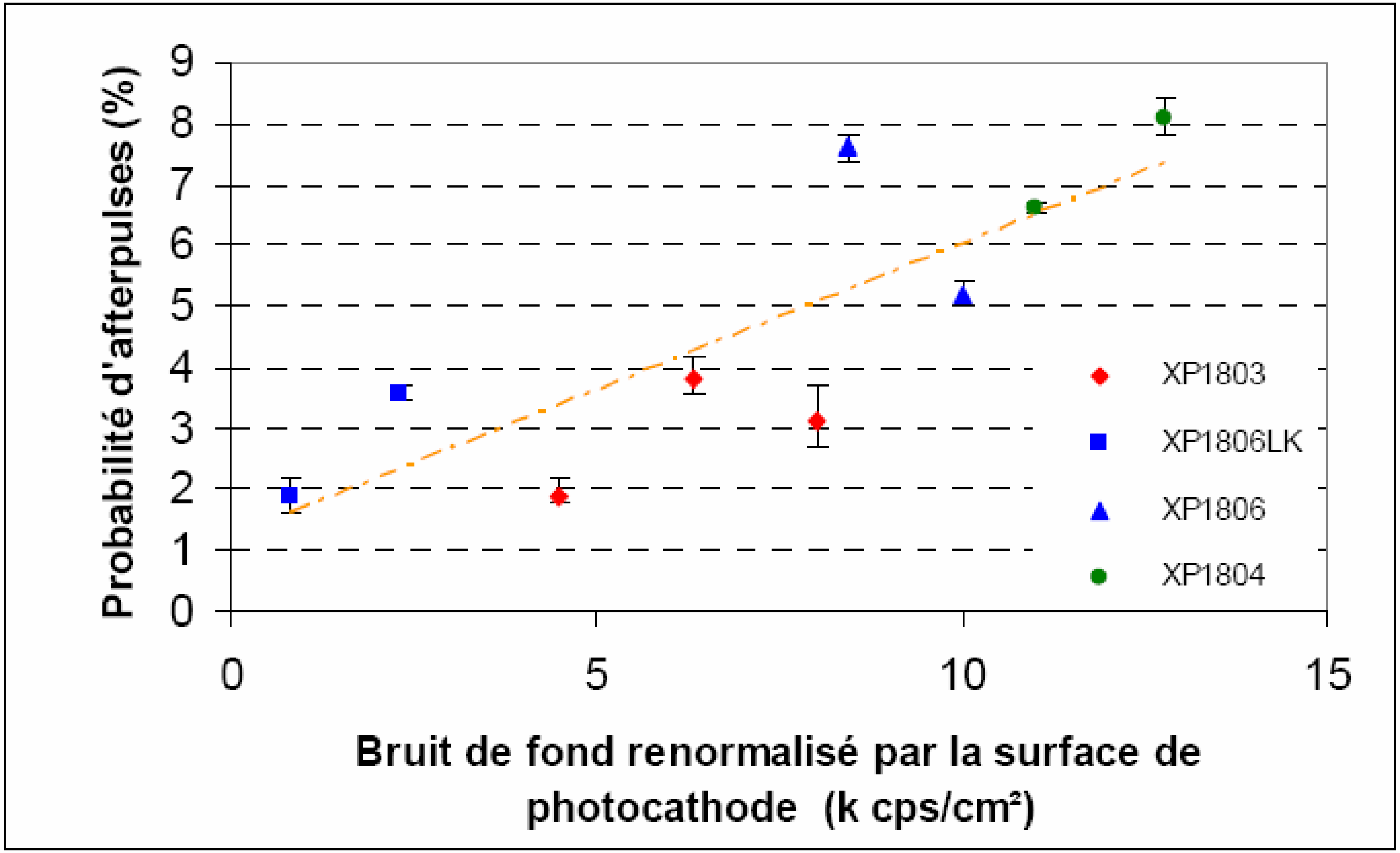





From D. Dornic and J. Pouthas (IPNO, France)

# AP vs Noise






From D. Dornic and J. Pouthas (IPNO, France)

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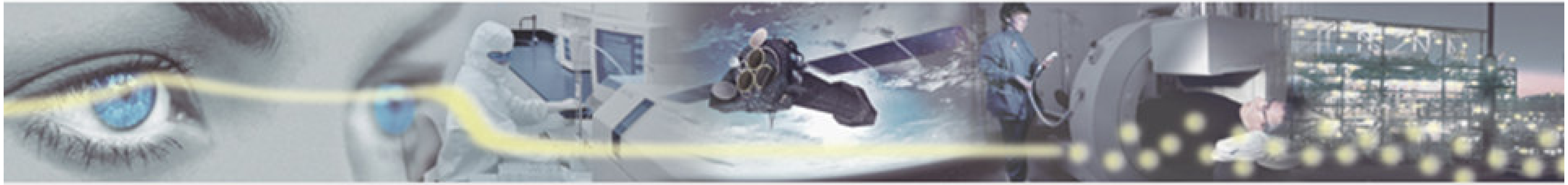
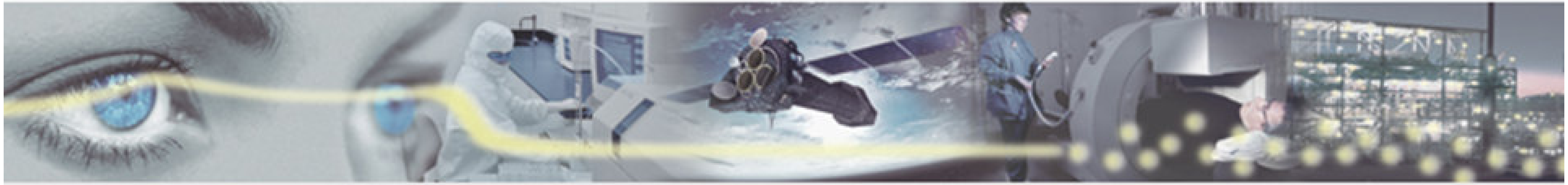
# *Smthg better?*



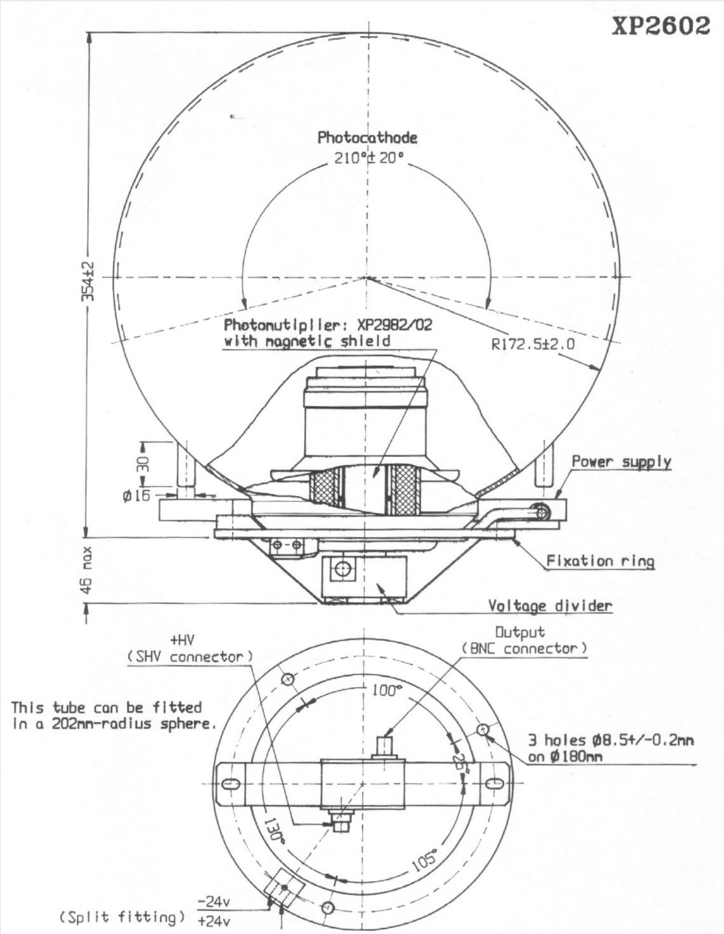
- Taking into account:

1. PMT performances driven by Physic new needs
2. Instrumentable volume driven by cathode surface and DQE
3. Final cost

One could think of a detector with higher performance/cost ratio.



# Improvement work on Crystal Hybrid Photo Detector (XHPD)

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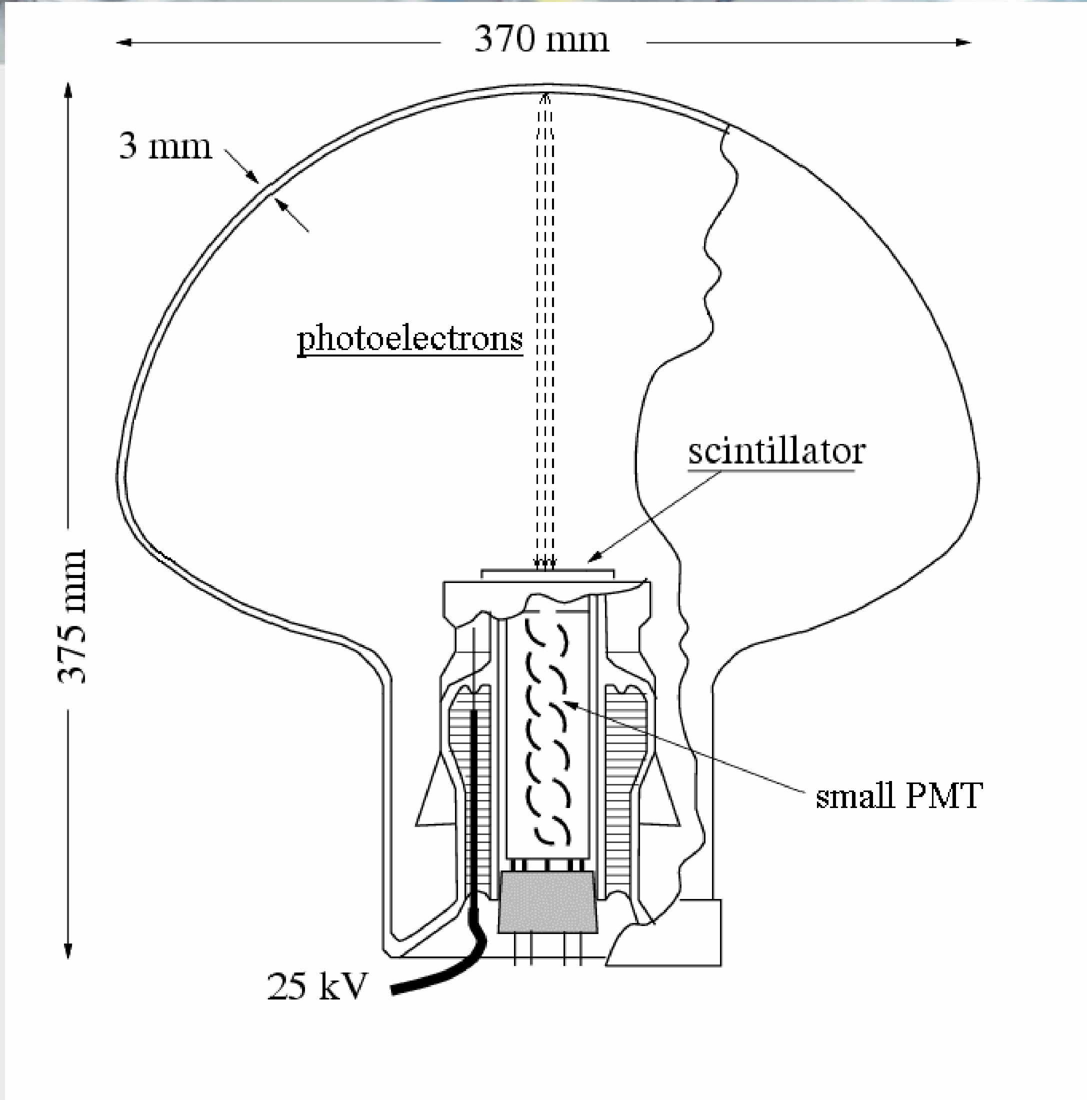
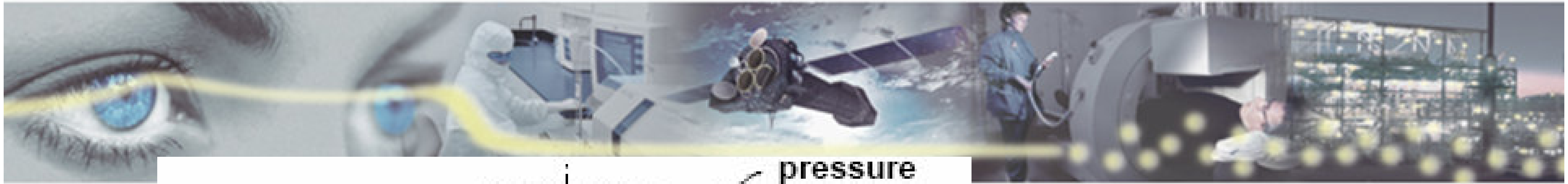
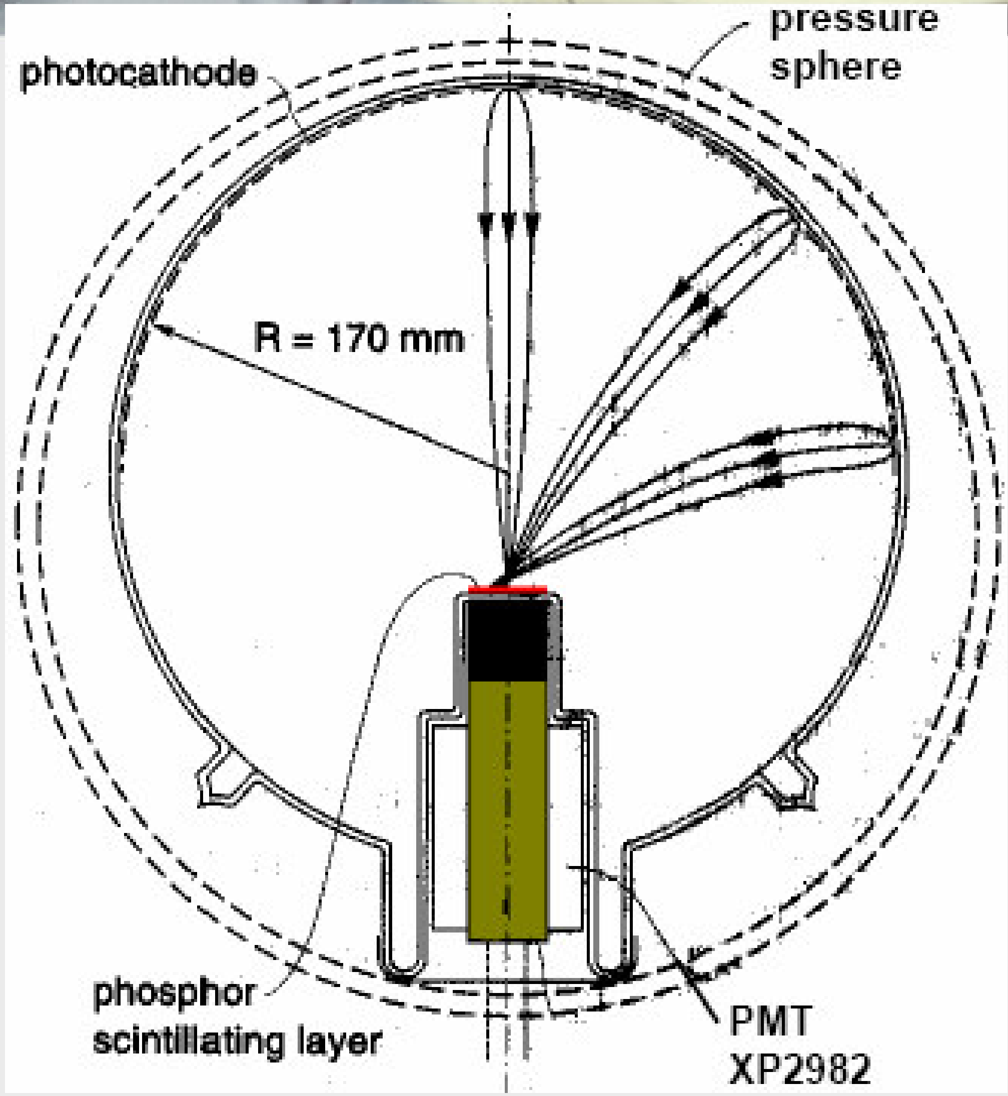
# XP2600 / Quasar-370



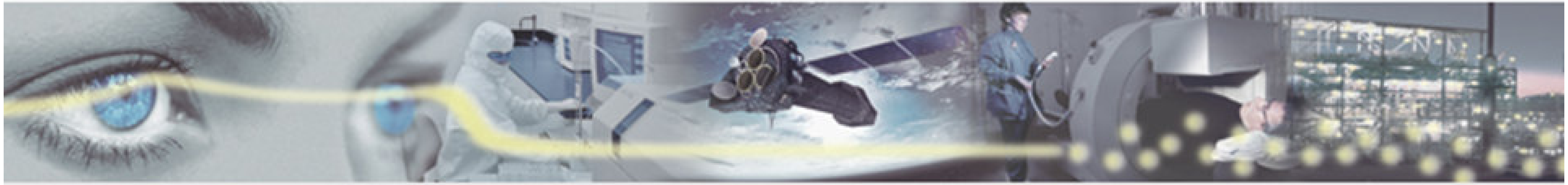

- 37 cm (15”) extended bialkali hemispherical photocathode ($K_2CsSb$)
- $2\pi$ acceptance
- YSO, LSO, YAP, SBO… scintillator (first amplificator)
- Small 6 stages high anode current PMT






*XHPD active surface area is very large. Collection ~100%*

*Cost/cm2 per DQE is optimized*

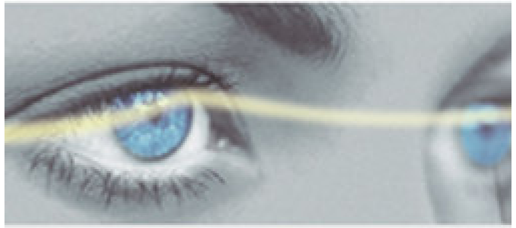


Xtal-HPM tube has excellent timing performances and very good single electron resolution

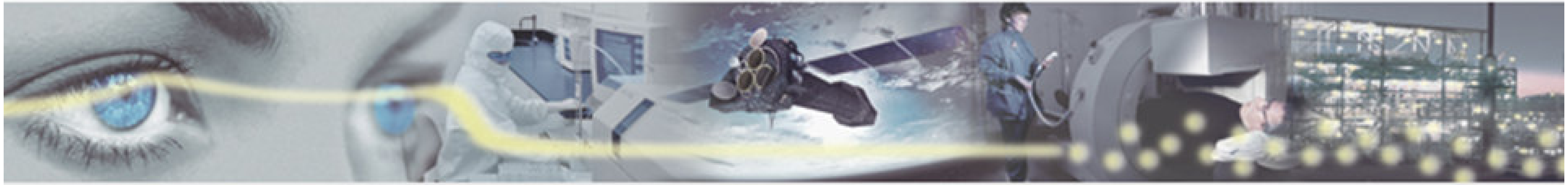
- no prepulses
- no late pulses in TTS
- low level of afterpulses (<1% type II)
- ~100% effective collection effiency
- 1 ns TTS (FWHM)
- very good SER (competitive to HPD)
- immunity to terrestrial magnetic field
- $>2\pi$ sensitivity

***See Combettes, SCINT 2007***

# *Xtal parameters*



| Scintillator | $Z_{eff}$ | D $g/cm^3$ | n | $\lambda_{max}$ nm | Y %(NaI(Tl)) | τ ns | Hyg |
|---|---|---|---|---|---|---|---|
| $Y_2SiO_5$:Ce (YSO) | 33 | 4.45 | 1.8 | 420 | 25 | 30-50 | No |
| $Gd_2SiO_5$:Ce (GSO) | 59 | 6.71 | 1.4 | 440 | 25 | 50-60 | No |
| $LuAlO_3$:Ce (LuAP) | 65 | 8.34 | 1.935 | 360 | 30-40 | 20 | No |
| $Lu_2SiO_5$:Ce (LSO) | 66 | 7.41 | 1.82 | 420 | 75 | 40 | No |
| $Lu_2Si_2O_7$:Ce (LPS) | 64.4 | 6.23 | | 380 | 70-80 | 30 | No |
| $YAlO_3$:Ce (YAP) | 36 | 5.6 | 1.94 | 390 | 40-50 | 25-30 | No |
| ZnO:Ga | 28.4 | 5.61 | | 440 | 40-100 | 0.4 | No |
| $BaF_2$ | 54 | 4.89 | 1.5 | 220 320 330 | 6 23 | 0.8/ 630 | No |
| $LaCl_3$:Ce | 59.5 | 3.86 | | 350 | 120 | 28 | Yes |
| $LaBr_3$:Ce | - | 5.29 | 1.9 | 380 | 160 | 26 | Yes |
| $Lu_2S_3$:Ce | 66.8 | 6.25 | | 590 | 80 | 30 | No |
| CsF | 53 | 4.64 | 2.69 | 390 | 5 | 3-5 | Yes |
| $KMgF_3$ | 13 | 3.2 | | 140 | 5 | 1.3 | Yes |
| $ScBO_3$:Ce | 17.1 | | | 380 | 40 | 30 | No |
| CsI(Tl) | 54 | 4.51 | 1.79 | 550 | 140 | 630 | Yes |
| NaI(Tl) | 51 | 3.67 | 1.85 | 420 | 100 | 230 | Yes |



# Figure of merits – F

$$F = (Y/\tau)\times a\times b$$

Y - light yield, $\tau$ - decay time,

a - detectibility by small PMT

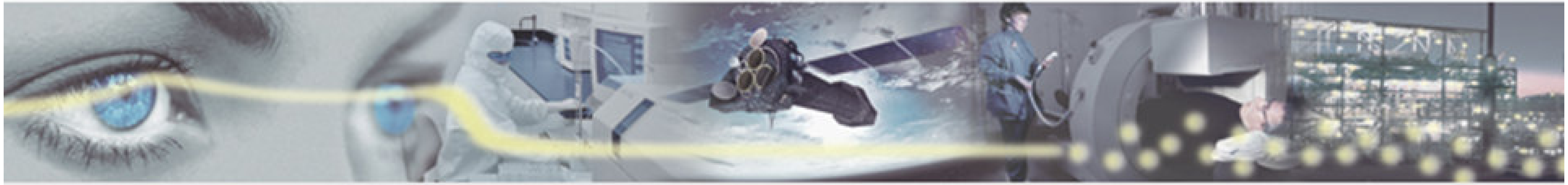
b - compatibility with photocathode manufacturing

| | YSO | YAP | SBO | LSO | LuS | Bril350 | Bril380 |
|---|---|---|---|---|---|---|---|
| F | 1 | 1.3 | 1.3 | 1.8 | 4 | 0.7 | 0.9 |

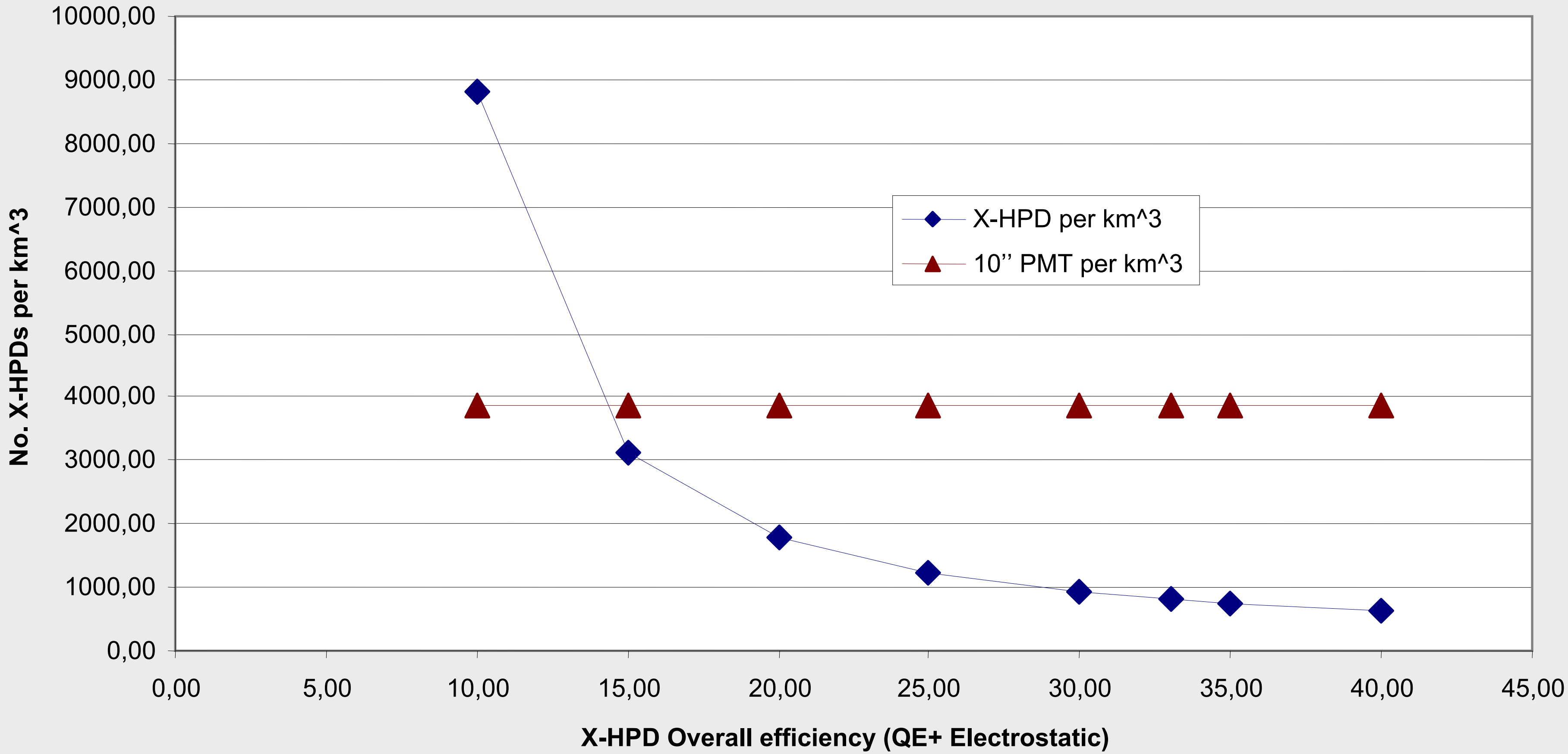
ZnO:Ga F = 250 !

*From Lubsandorzhiev, **INR***

*XHPD vs 10''*



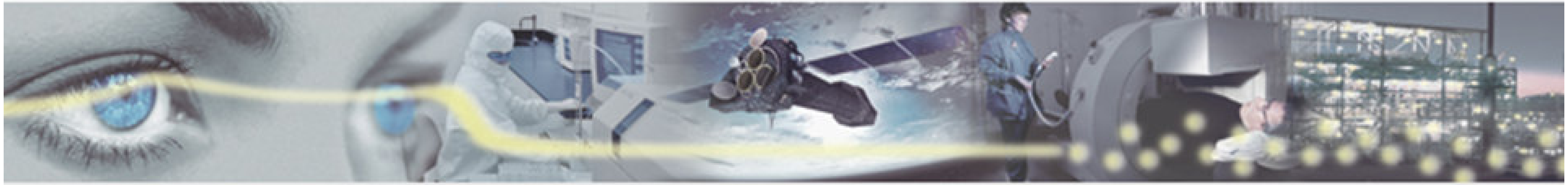
**Comparison of No. 20cm X-HPDs per km^3 vs X-HPD overall efficiency (+/- 120 deg polar angle)**
**Compared to 10''standard PMT with max polar angle +/- 55 deg & 20% overall efficiency**



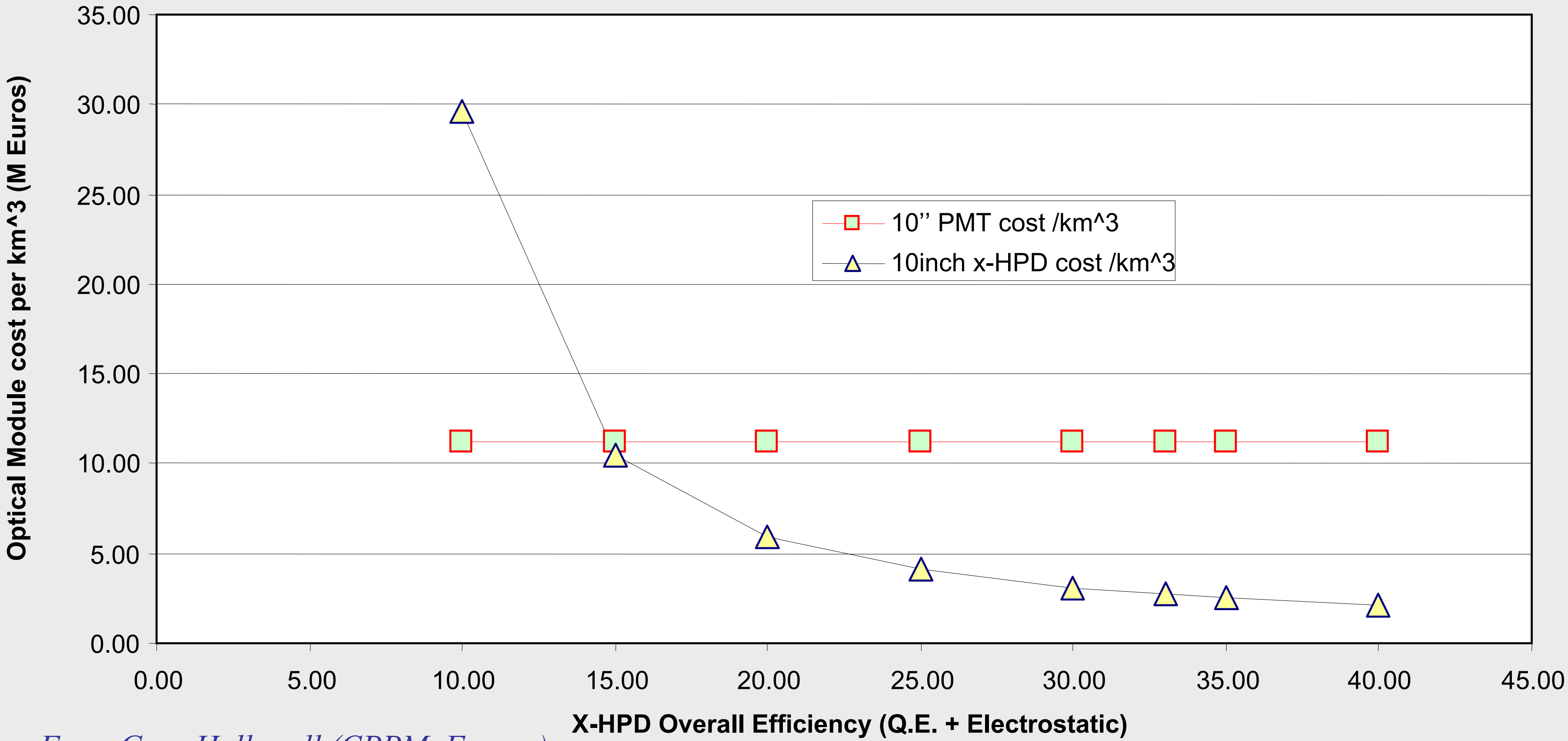

*From Greg Hallewell (CPPM, France)*

PHOTONIS

## *XHPD vs 10''*

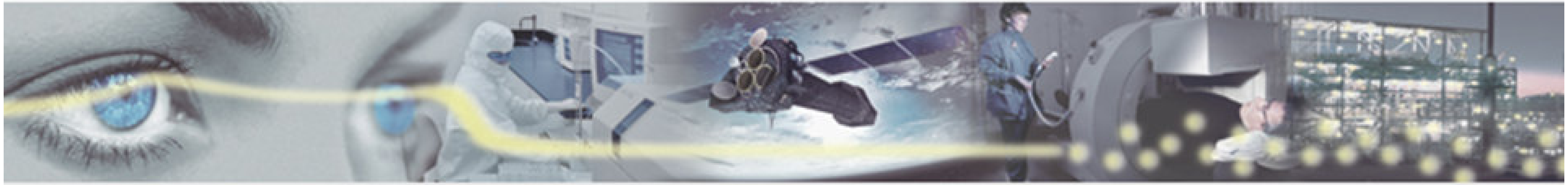


**Comparison of X-HPD Optical Module Cost (inc. sphere, mechanics, electronics) per km^3 vs X-HPD overall efficiency (assumed 22cm photocathode +/-120 deg polar angle:  costed at 150% * 10" standard tube)**

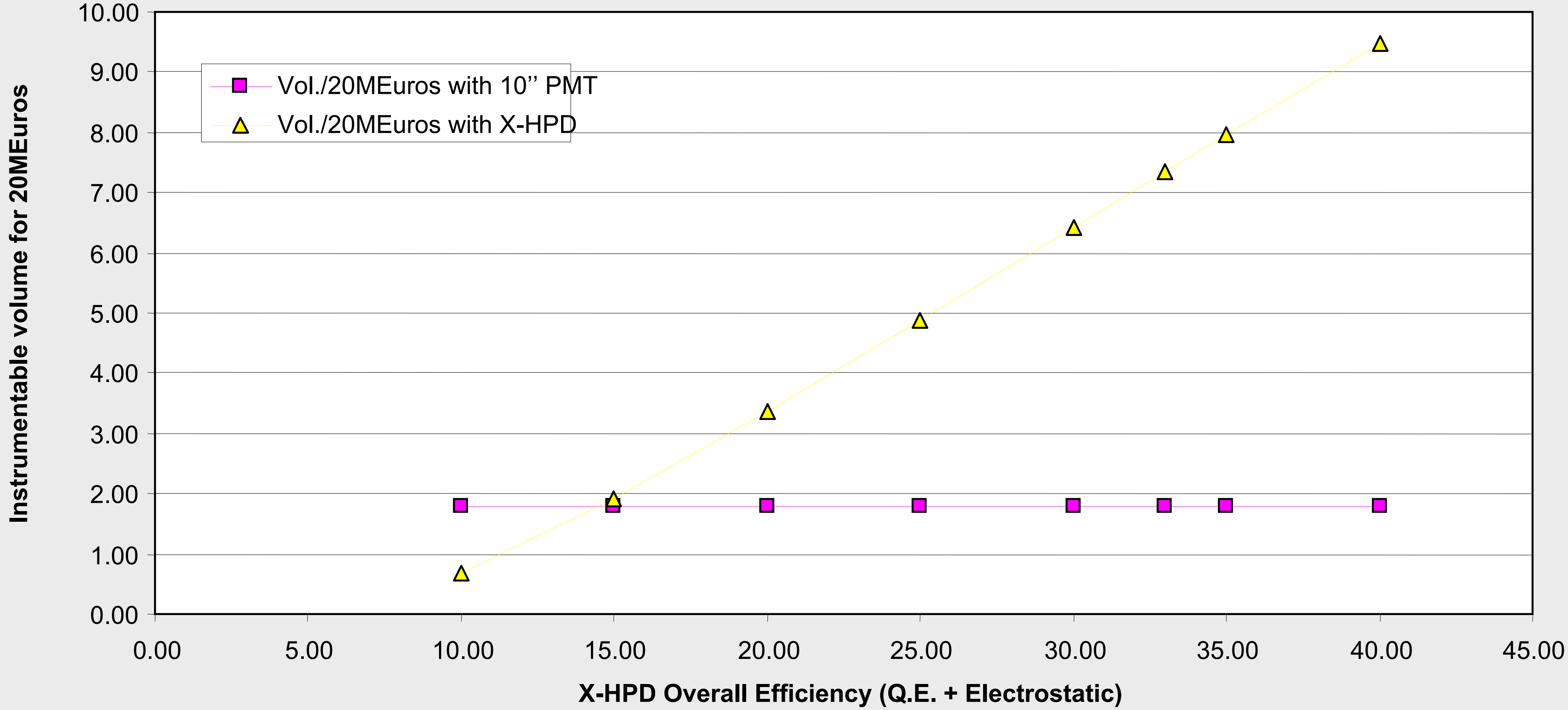



*From Greg Hallewell (CPPM, France)*

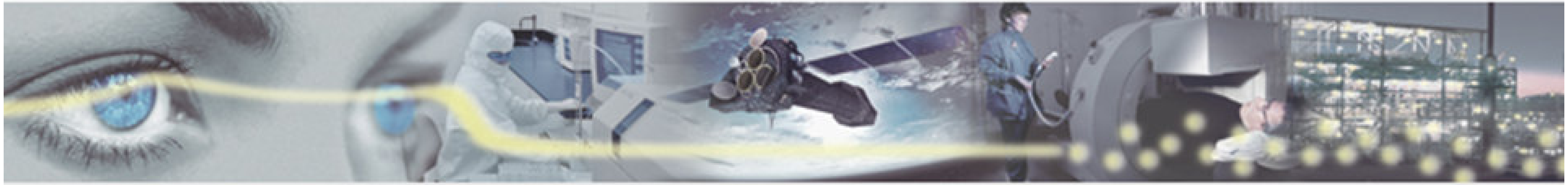
## *XHPD vs 10''*



**Comparison volume instrumentable for 20MEuros with X-HPD Optical Module Cost (inc. sphere, mechanics, electronics) vs X-HPD overall efficiency (assumed 22cm photocathode, +/- 120 deg polar angle costed at 150% * 10" standard PMT)**




*From Greg Hallewell (CPPM, France)*



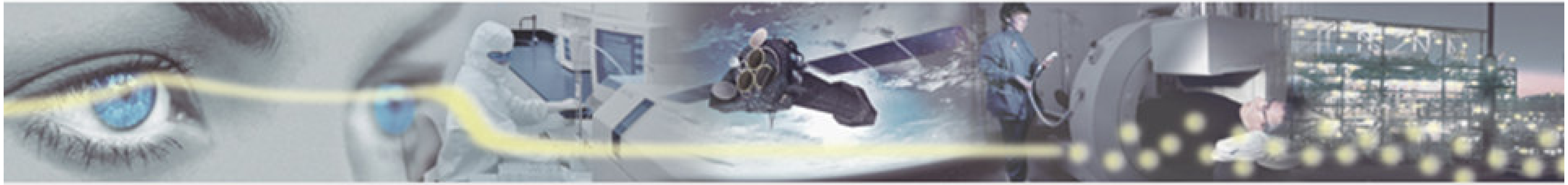
. X-HPD Performances are superior to traditional PMTs on major critical points.

. Manufacturing costs are higher (crystal, extra outer PMT)

. Manufacturing X-HPD is difficult : lower yield

Even if global cost is higher, the ratio Performance/Cost remains by far in favor of X-HPD

# *Money!*



- Improvement work on costs

Hard to keep the cake and eat it…

Always a tradeoff between Physic and budget.

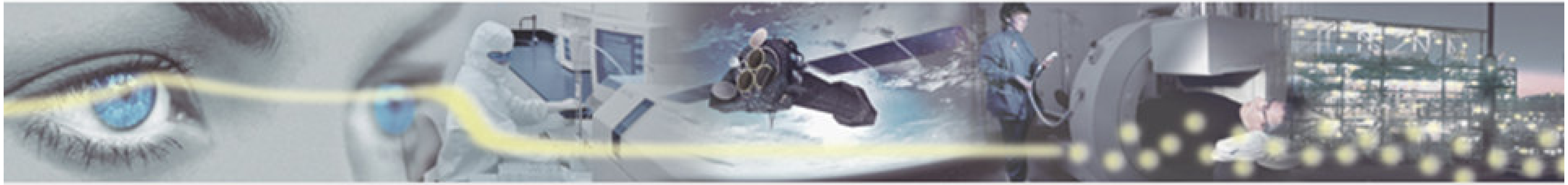
. There are fixed costs (eg human, piece parts, decent margin) : very cramped space to reduce costs.

. Relaxing requested specs: higher yield, lower price

Physic will pay the price.

. Working on higher DQE, low noise and photocathode surface area for a same-price tube: increase detection volume (Physicists will grab nuts from the fire)

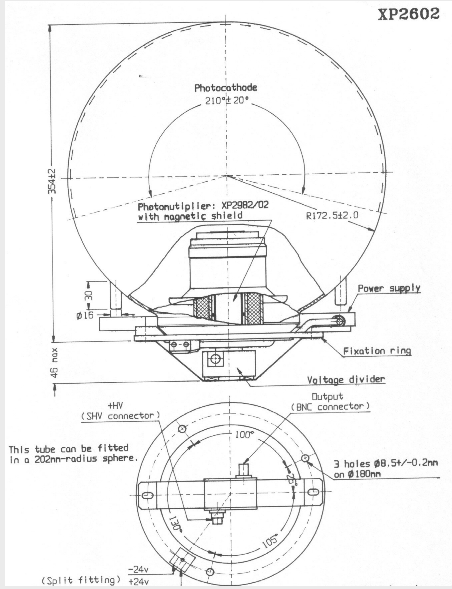
# PHOTONIS Thank you for your attention

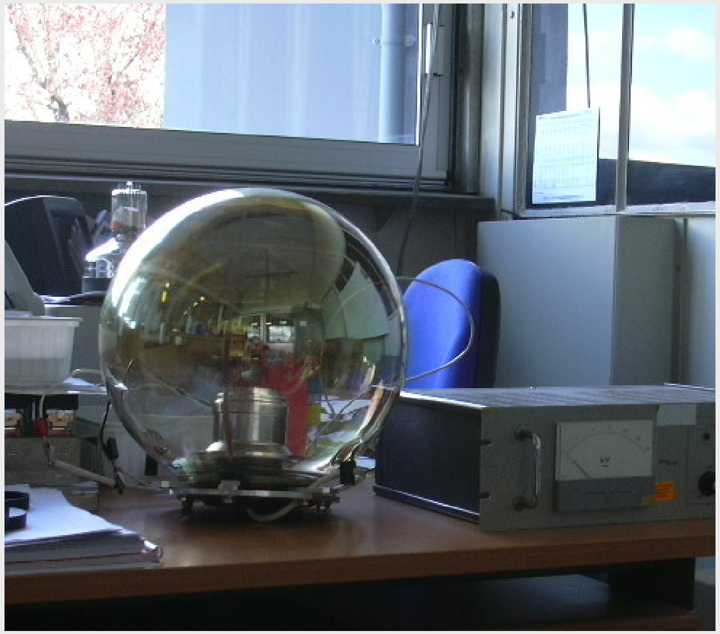


## Bruno COMBETTES

Photonis Group product management

b.combettes@photonis.com



## Japanese distributor :

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Makoto Tada
Sales and Marketing

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