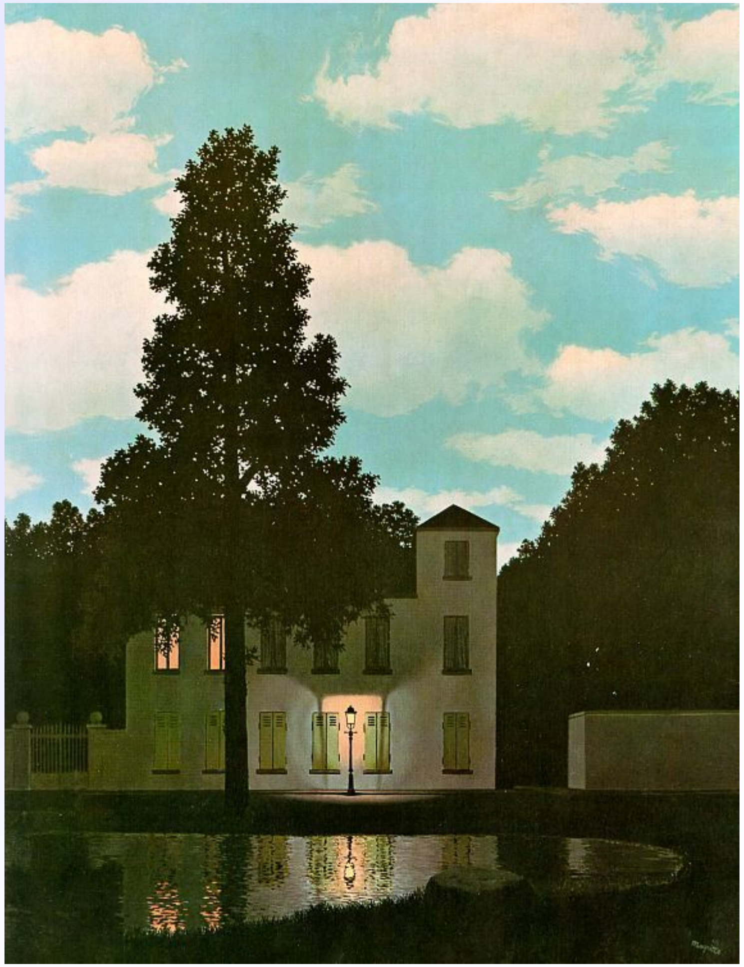
Particle Detectors – Principles and Techniques (3/5)

Lecture 3b – Photo-detection

Speaker: Thierry GYS (CERN–PH/DT2)



The Empire of Lights (René Magritte, Lessines 1898 – Brussels 1967)

(1954, Canvas, 146 x 114 cm, Brussels, Royal Museums of Fine Arts of Belgium, © SABAM 2001)

CERN Academic Training Programme 2004/2005

General outline

- **Lecture 1 - Introduction** C. Joram, L. Ropelewski
- **Lecture 2 - Tracking Detectors** L. Ropelewski, M. Moll
- **Lecture 3 - Scintillation and Photo-detection** C. D'Ambrosio, T. Gys
  - **3a) Scintillation**
  - **3b) Photo-detection** **Thierry Gys (CERN - PH/DT2)**
    - Photon detectors: purpose, basic principle and general requirements
    - Vacuum photon detectors
    - Solid-state photon detectors
    - Hybrid photon detectors
    - Literature
- **Lecture 4 - Calorimetry, Particle ID** C. Joram
- **Lecture 5 - Particle ID, Detector Systems** C. Joram, C. D'Ambrosio

extra slide
not shown

Detailed outline

- **Photon detectors**
  - Purpose, basic principle and general requirements
- **Vacuum photon detectors**
  - The photoelectric effect, photo-cathodes and optical windows
  - Photomultipliers:
    - Basic principle and gain fluctuations
    - Dynode configurations: traditional and position-sensitive
  - Image intensifiers: principles, generations and Micro Channel Plates
- **Solid-state photon detectors**
  - Basic principle, PIN and avalanche diodes, light absorption
  - A detailed example of CCD optimization for astronomy
- **Hybrid photon detectors**
  - Basic principle and gain fluctuations
  - Description of various HPD types
- **Literature**

Photon detectors

Purpose:

- Convert light into detectable (electronic) signal

Principle:

- Use photoelectric effect to convert photons (γ) to photoelectrons (pe)

Standard requirements:

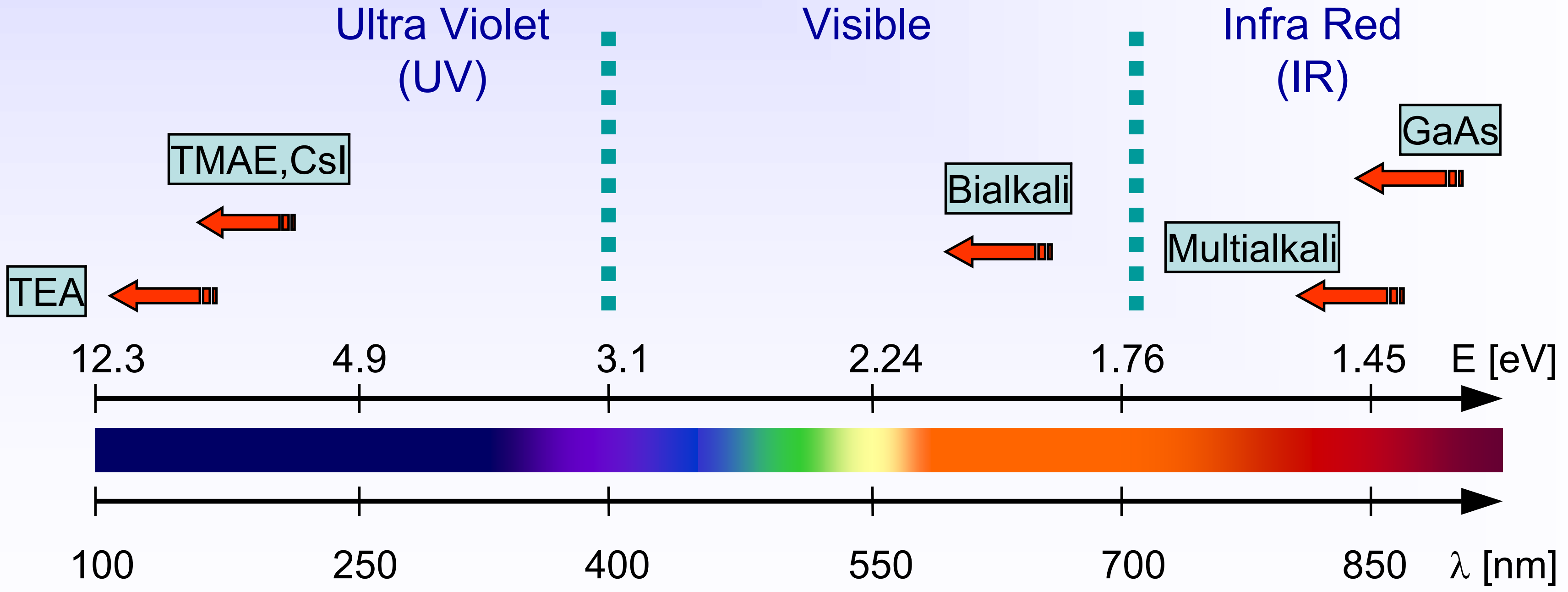
- High sensitivity, usually expressed as:
  - quantum efficiency: $\boxed{QE(\%) = \frac{N_{pe}}{N_\gamma}}$
  - radiant sensitivity S(mA/W) with: $\boxed{QE(\%) \approx 124 \cdot \frac{S(mA/W)}{\lambda(nm)}}$
- Low intrinsic noise
- Low gain fluctuations
- High active area

Photon detectors

Main types of photon detectors:

- gas-based (not covered in this lecture, see lecture 2a)
- vacuum-based
- solid-state (see also lecture 2b)
- hybrid

Photoemission threshold W_{ph} of various materials

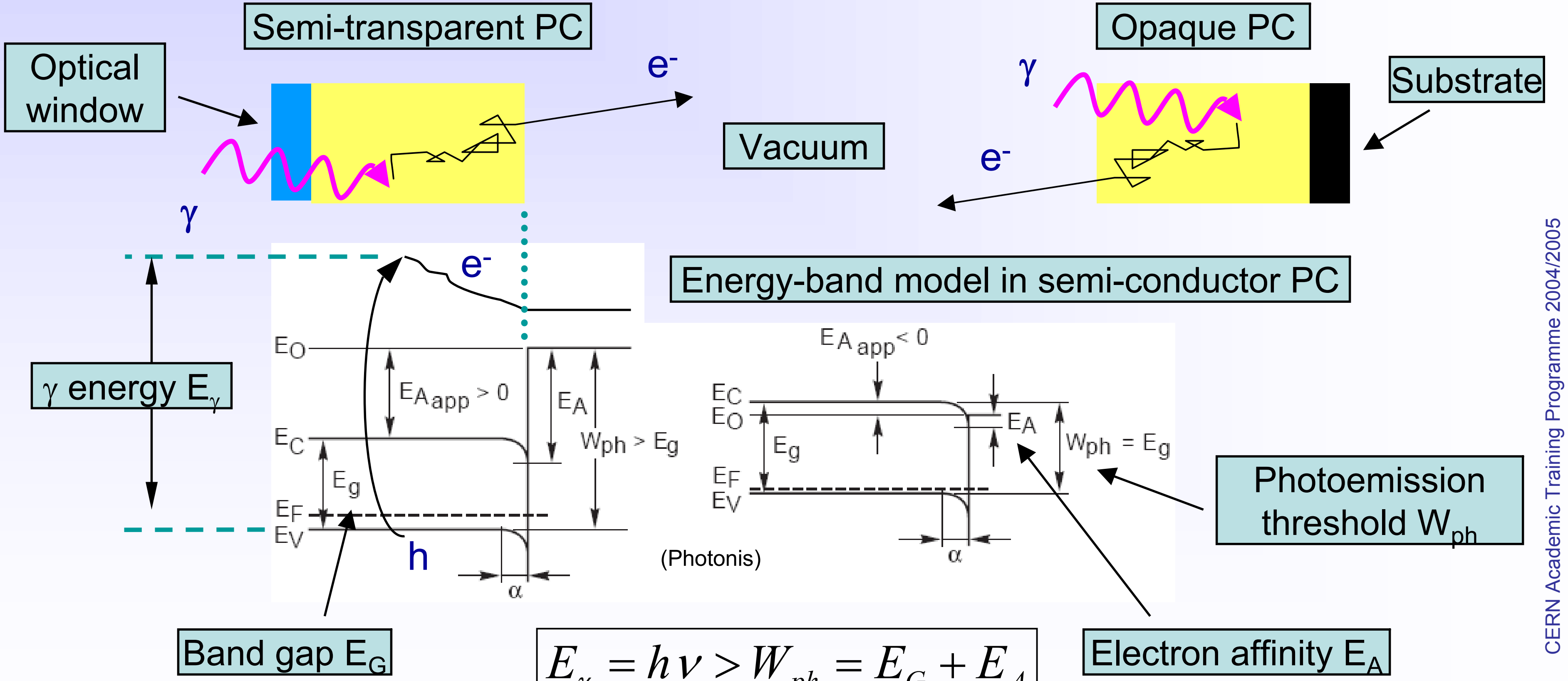


The photoelectric effect

3-step process:

- absorbed γ's impart energy to electrons (e) in the material;
- energized e's diffuse through the material, losing part of their energy;
- e's reaching the surface with sufficient excess energy escape from it;

$\Rightarrow$ ideal photo-cathode (PC) must absorb all γ's and emit all created e's



Semi-transparent PC

Optical window

Vacuum

Opaque PC

Substrate

Energy-band model in semi-conductor PC

γ energy E_γ

Photoemission threshold W_{ph}

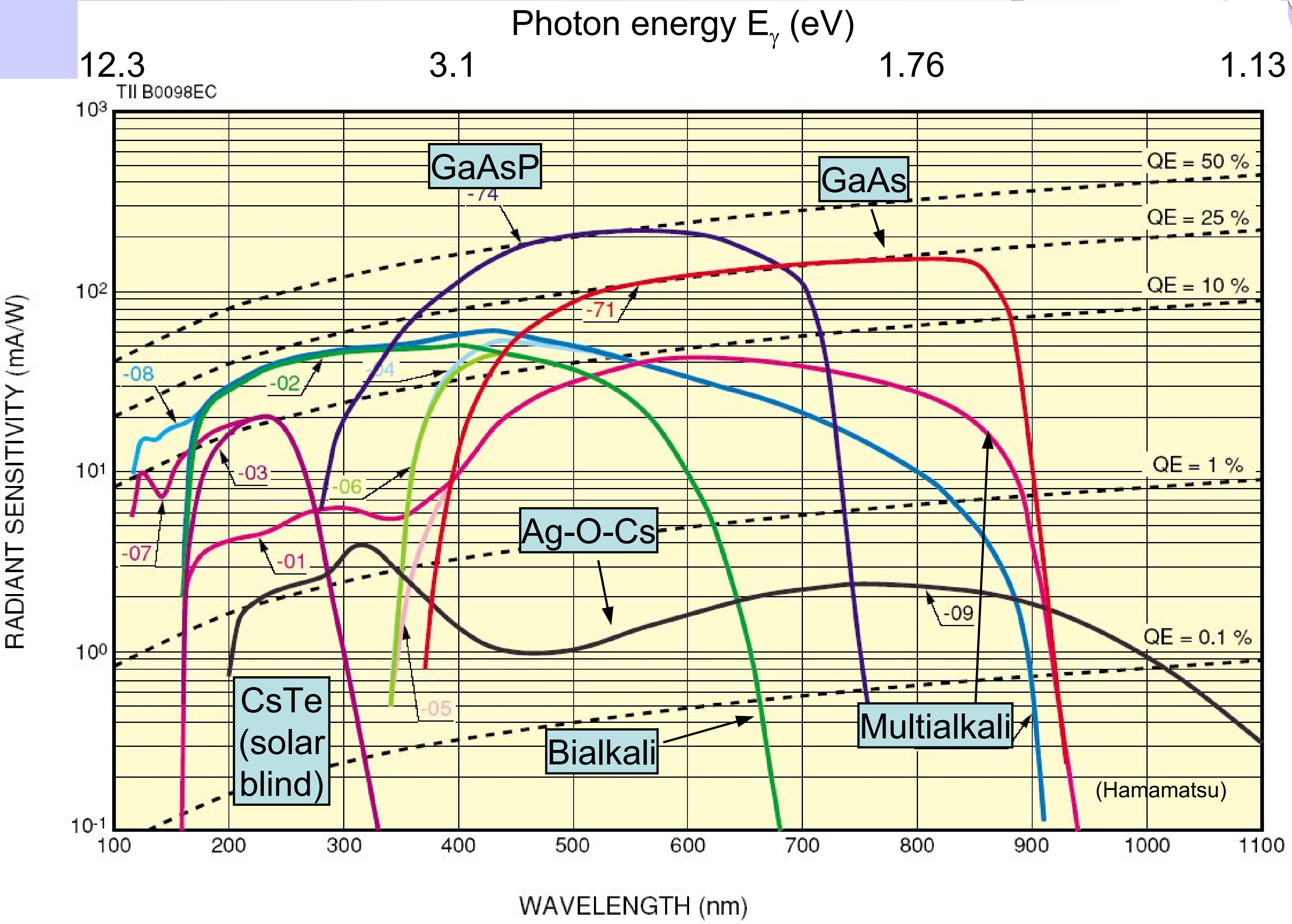
Band gap E_G

Electron affinity E_A

(Photonis)

$$E_\gamma = h\nu > W_{ph} = E_G + E_A$$

QE's of typical photo-cathodes



Bialkali: SbKCs, SbRbCs Multialkali: SbNa$_2$KCs (alkali metals have low work function)

Transmission of optical windows

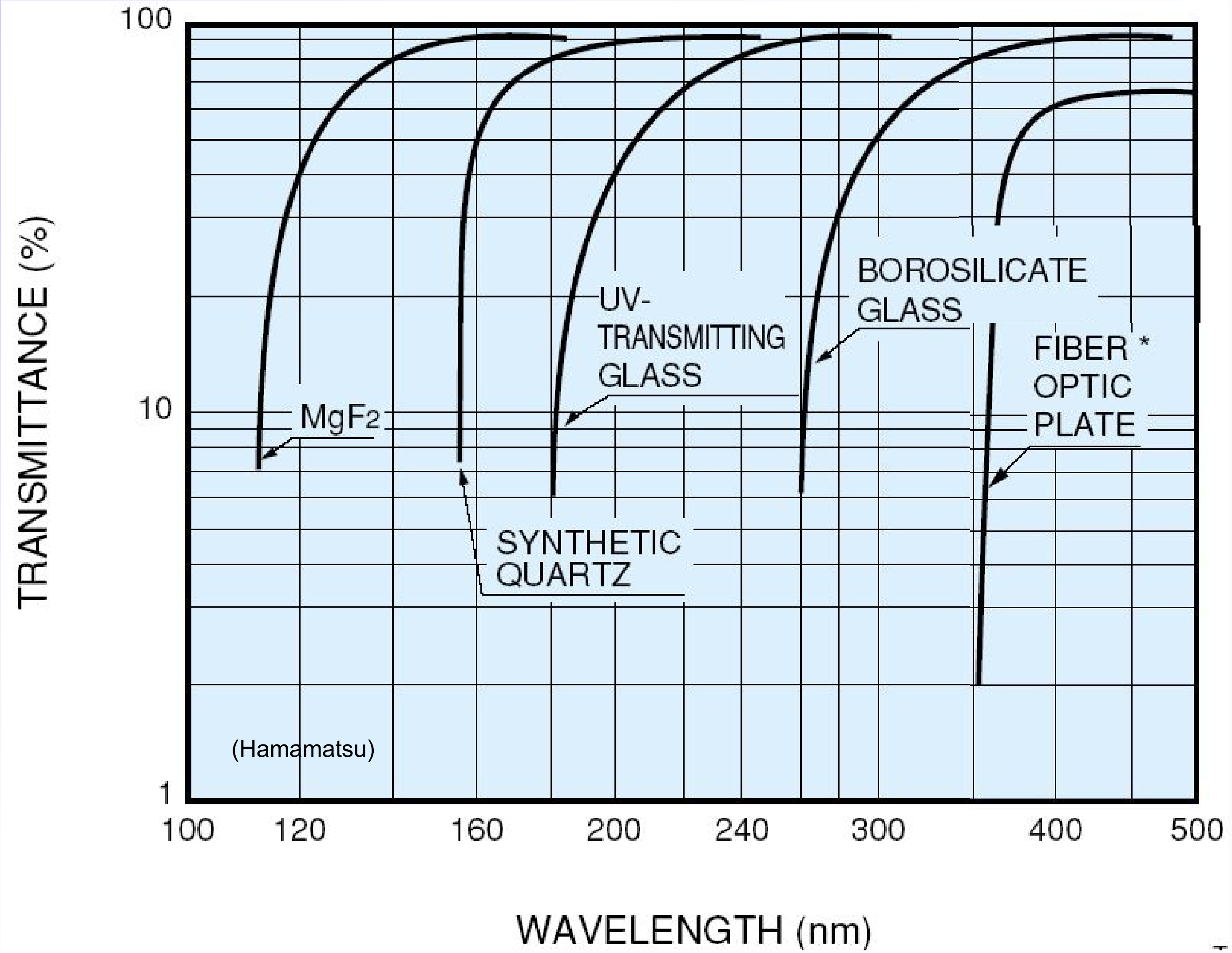


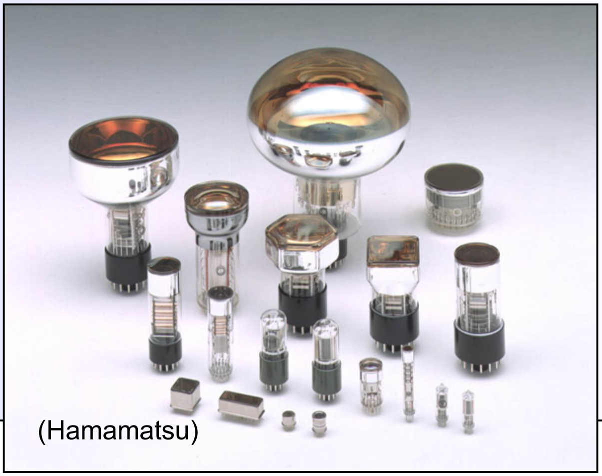
Photo-multiplier tubes (PMT’s)

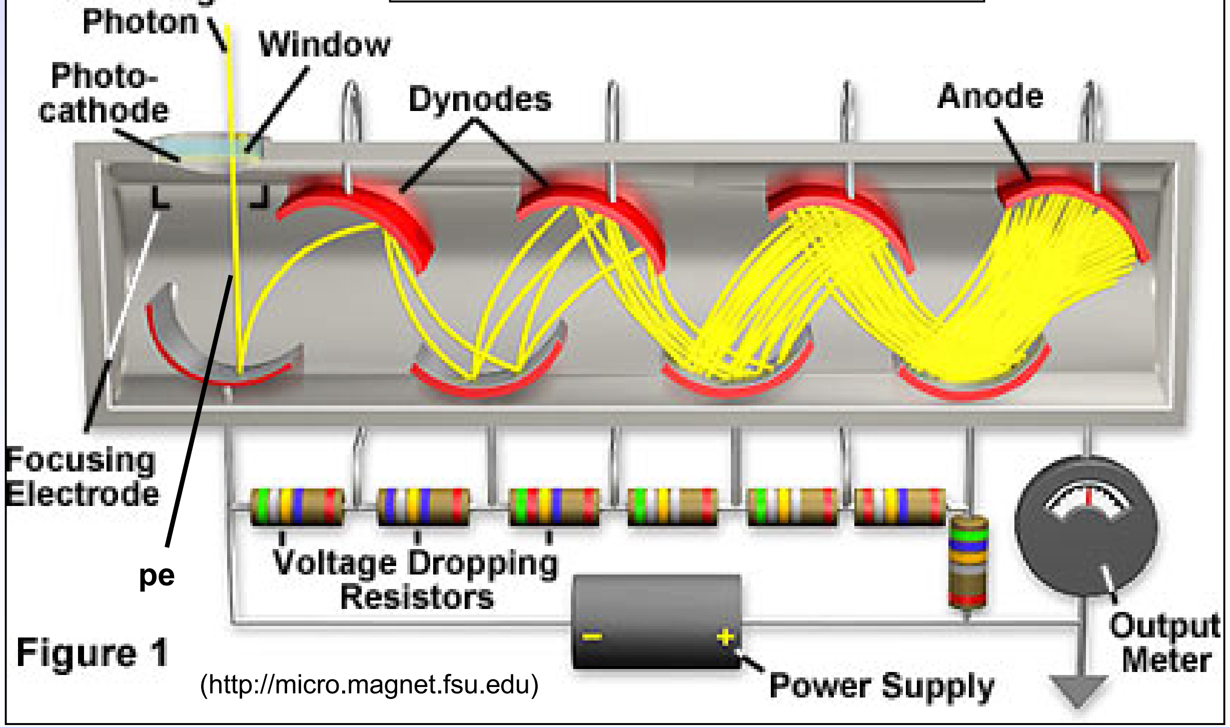
Basic principle:

- Photo-emission from photo-cathode
- Secondary emission (SE) from N dynodes:
  - dynode gain g≈3-50 (function of incoming electron energy E);
  - total gain *M*:

$$M = \prod_{i=1}^{N} g_i$$

- Example:
  - 10 dynodes with g=4
  - $M = 4^{10} \approx 10^6$


(Hamamatsu)

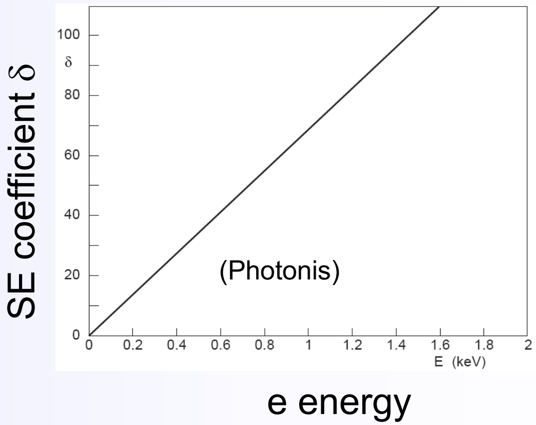


(http://micro.magnet.fsu.edu)

Gain fluctuations of PMT's

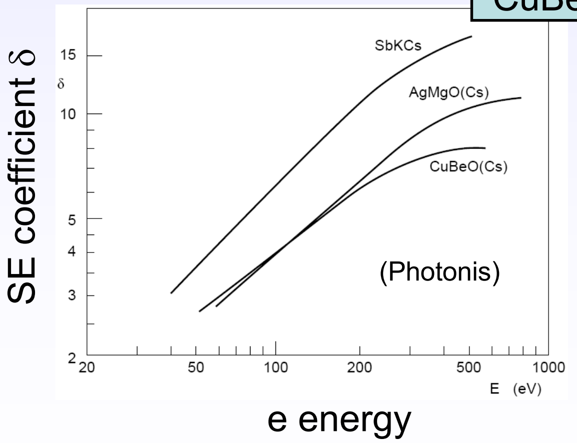
- Mainly determined by the fluctuations of the number m(δ) of secondary e's emitted from the dynodes;
- Poisson distribution: $$P_\delta(m) = \frac{\delta^m e^{-\delta}}{m!}$$
- Standard deviation: $$\frac{\sigma_m}{\delta} = \frac{\sqrt{\delta}}{\delta} = \frac{1}{\sqrt{\delta}}$$

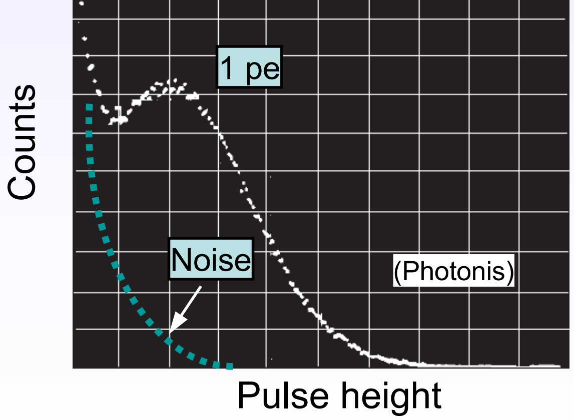
⇒ fluctuations dominated by 1st dynode gain;

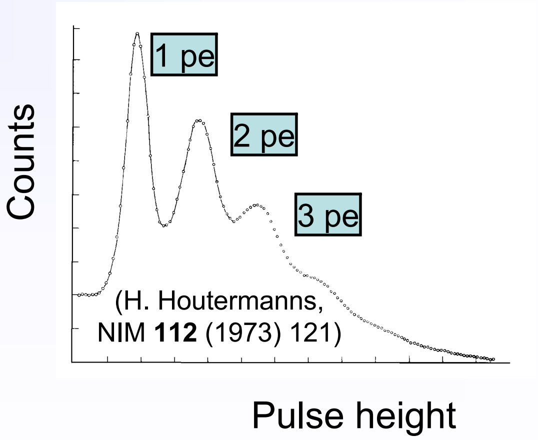


GaP(Cs) dynodes E_A<0

CuBe dynodes E_A>0



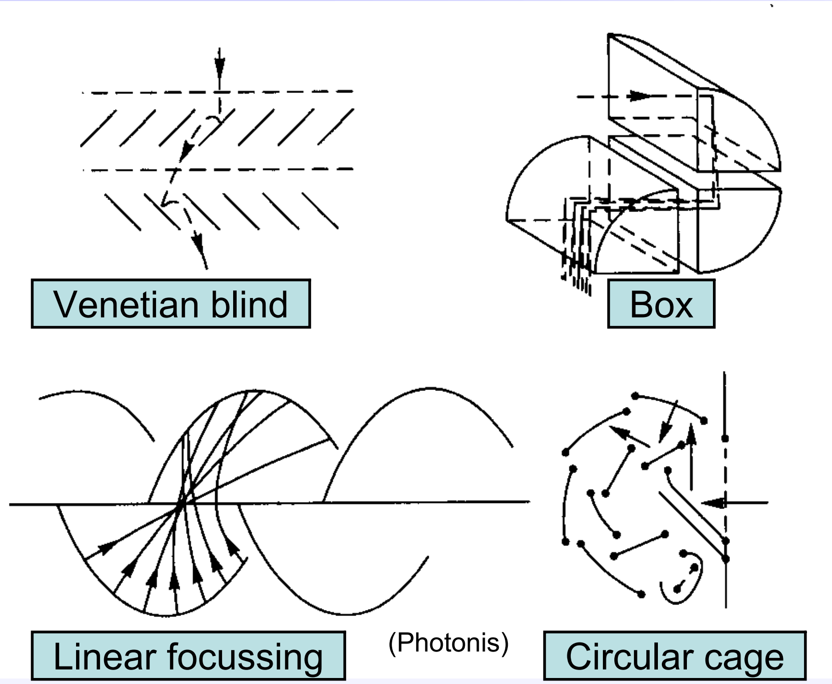




(H. Houtermanns, NIM **112** (1973) 121)

Dynode configurations of PMT's

Traditional



Venetian blind

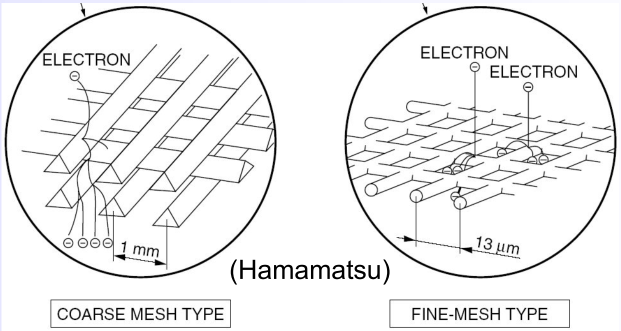
Box

Linear focussing

(Photonis)

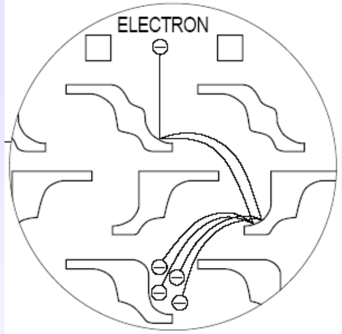
Circular cage

Position-sensitive



(Hamamatsu)

Mesh

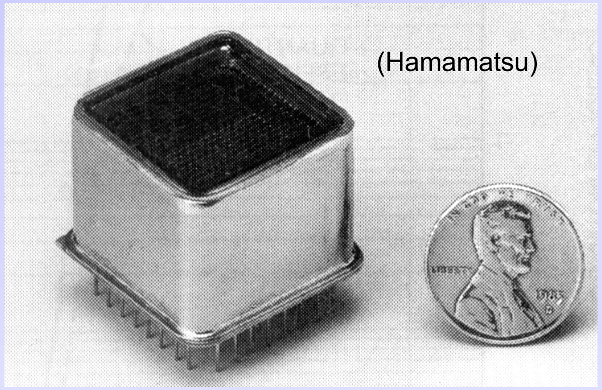


Metal-channel (fine-machining techniques)

(Hamamatsu)

- "Fast" PMT's require well-designed input electron optics to limit (e) chromatic and geometric aberrations → transit time spread < 200 ps;
- PMT's are in general very sensitive to magnetic fields, even to earth field (30-60 μT). Magnetic shielding required.

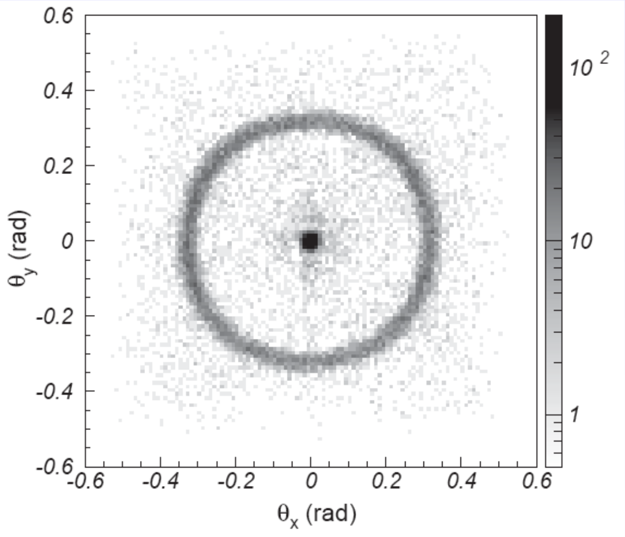
Multi-anode and flat-panel PMT's



Multi-anode (Hamamatsu H7546)

- Up to 8 × 8 channels (2 × 2 mm^2 each);
- Size: 28 × 28 mm^2;
- Active area 18.1 × 18.1 mm^2 (41%);
- Bialkali PC: QE ≈ 20% @ λ_{max} = 400 nm;
- Gain ≈ 3 10^5;
- Gain uniformity typ. 1 : 2.5;
- Cross-talk typ. 2%

Cherenkov rings from 3 GeV/c π^- through aerogel



(T. Matsumoto et al., NIMA **521** (2004) 367)

Flat-panel (Hamamatsu H8500):

- 8 x 8 channels (5.8 x 5.8 mm^2 each);
- Excellent surface coverage (89%)

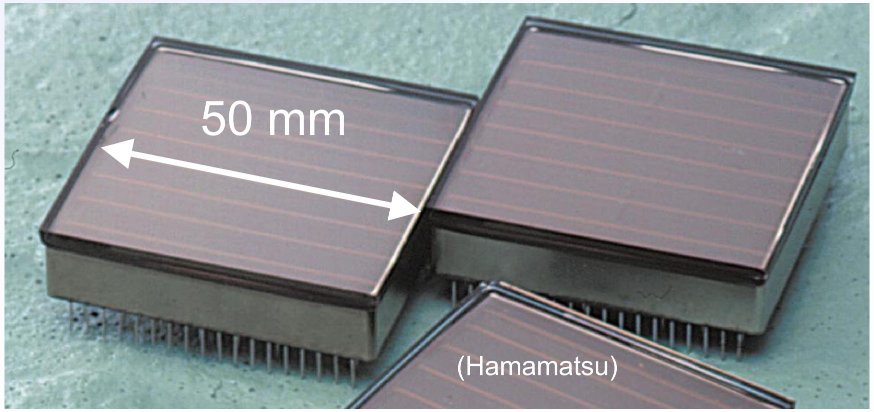


Image intensifiers

Basic principle:

- Vacuum photon detectors amplifying low light-level *image* to observable levels;
- Input: collection lens, optical window, photo-cathode;
- Gain: achieved by high voltage and possibly by additional imaging electron multiplier;
- Output: phosphor on optical window, ocular, observer (eye, CCD)

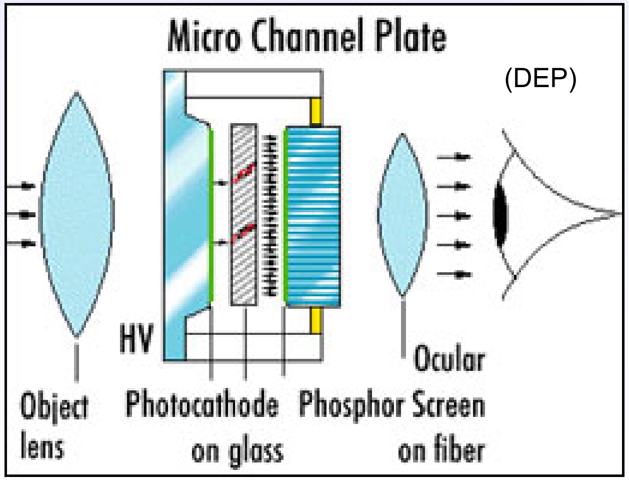
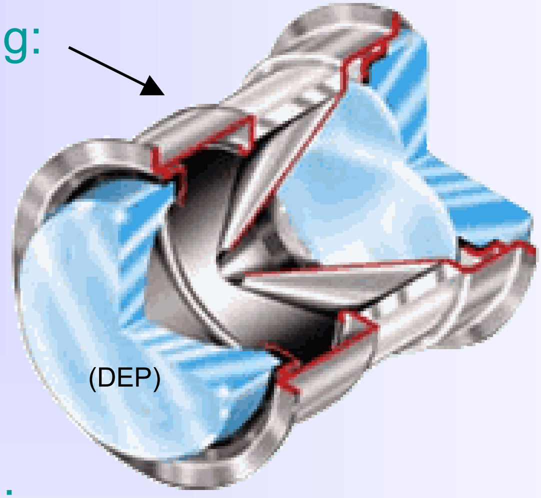
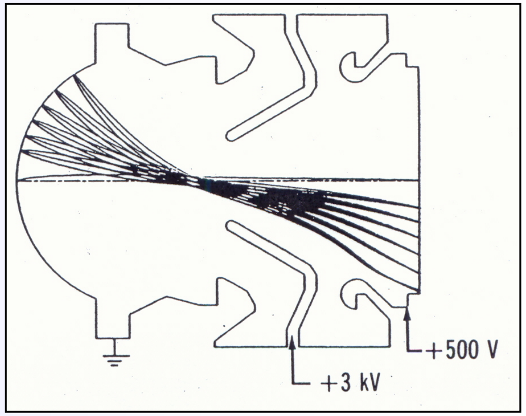


Image intensifier generations

Gen. I - electrostatic focussing:

- high image resolution;
- wide dynamic range;
- low noise;

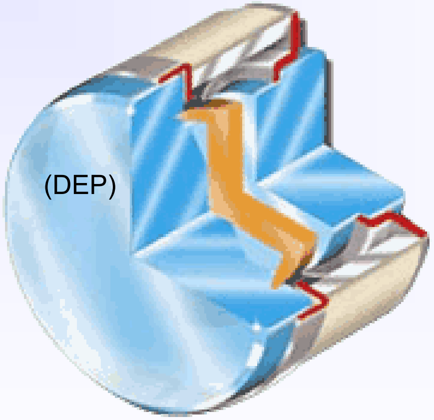




(I. P. Csorba, Image Tubes, Sams (1985))

Gen. II - Micro Channel Plate:

- worse resolution;
- much higher gain;



Gen. III – GaAs photo-cathode;

- enhanced sensitivity in near infrared;

Phosphor screens

extra slide
not shown

Principle:

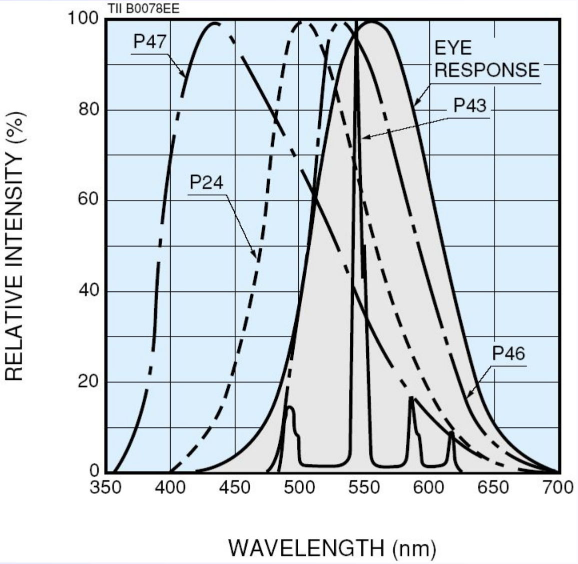
- absorb electrons;
- emit light on a characteristic λ of their material;

Spectral response:

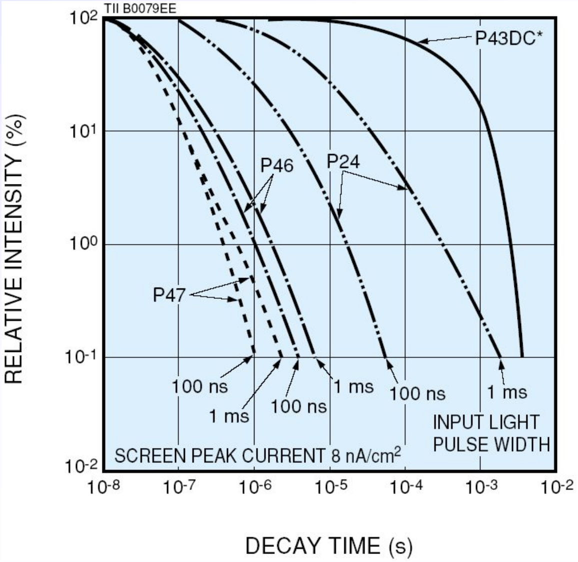
- originally adapted to human eye response;
- must now match solid-state sensor response (e.g. CCD's);

Decay time:

- short (<100ns) for e.g. high-speed CCD's to minimize afterglow;
- long (~1ms) for night-vision and surveillance to minimize flicker;

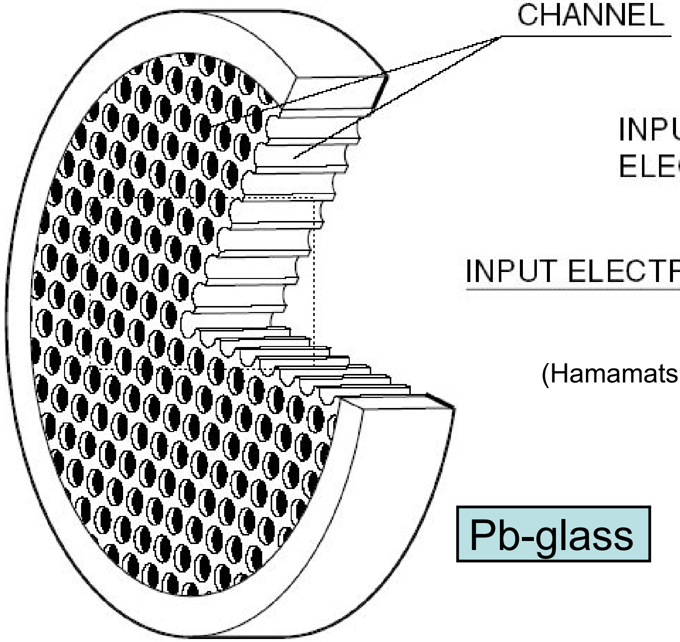


(Hamamatsu)

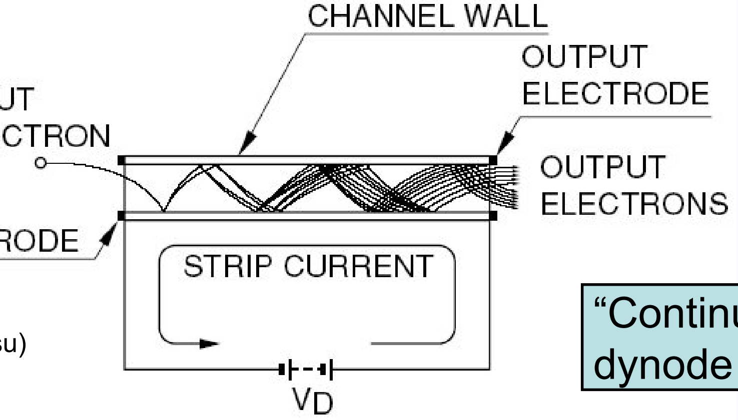


(Hamamatsu)

The Micro Channel Plate (MCP)

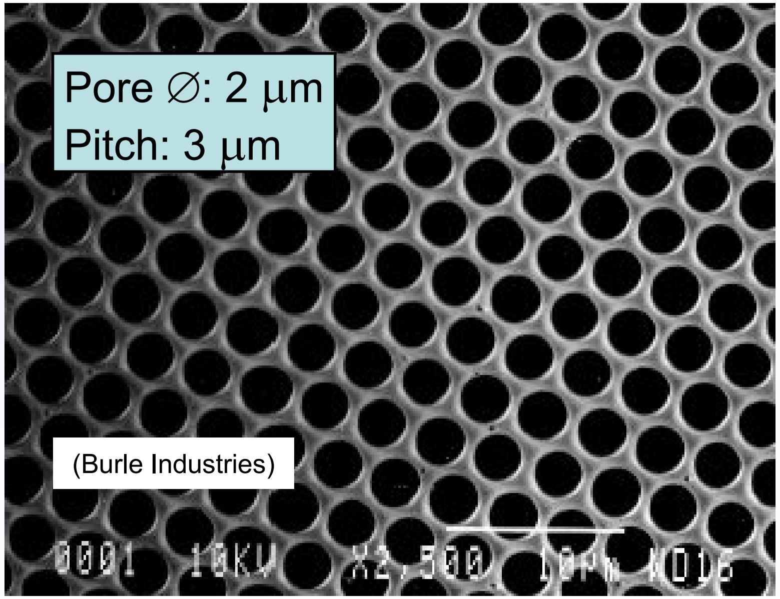


Pb-glass



(Hamamatsu)

“Continuous” dynode chain



Pore ∅: 2 μm
Pitch: 3 μm

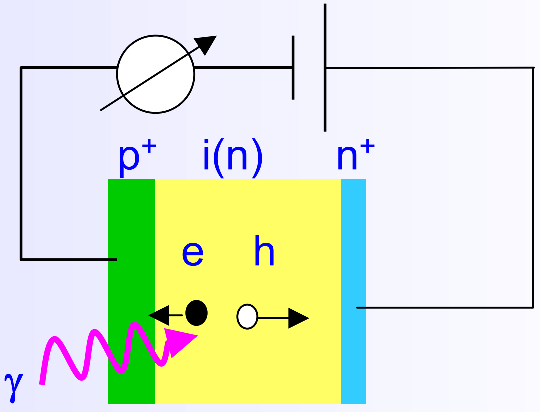
(Burle Industries)

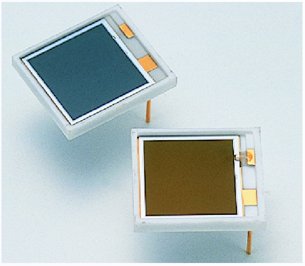
Kind of 2D PMT:
+ high gain up to 5 10^4;
+ fast signal (transit time spread ~50 ps);
+ less sensitive to B-field (0.1 T);
- limited lifetime (0.5 C/cm^2);
- limited rate capability (μA/cm^2);

Solid-state photon detectors

Photodiodes:

- P(I)N type (see lecture 2b);
- p layer very thin (<1 μm), as visible light is rapidly absorbed by silicon (see next slide);
- High QE (80% @ $\lambda \approx$ 700nm);
- No gain: cannot be used for single photon detection;



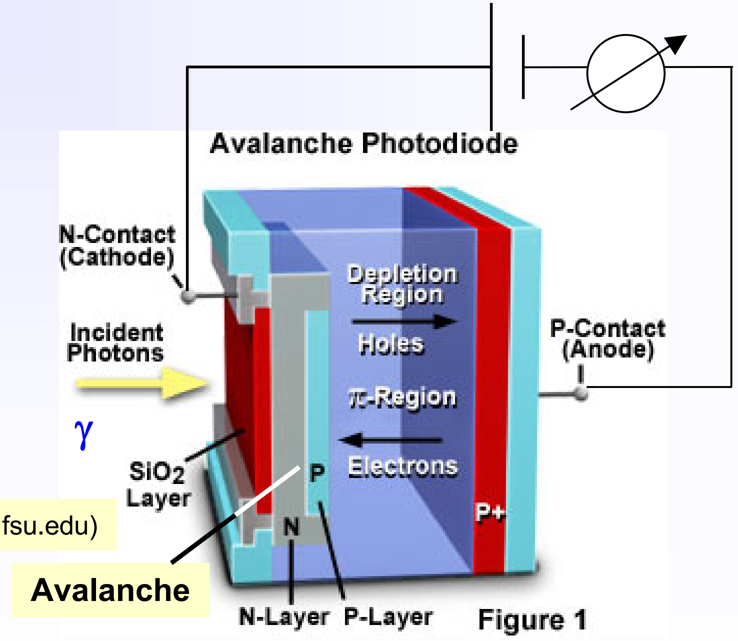


Avalanche photodiode:

- High reverse bias voltage: typ. 100-200 V

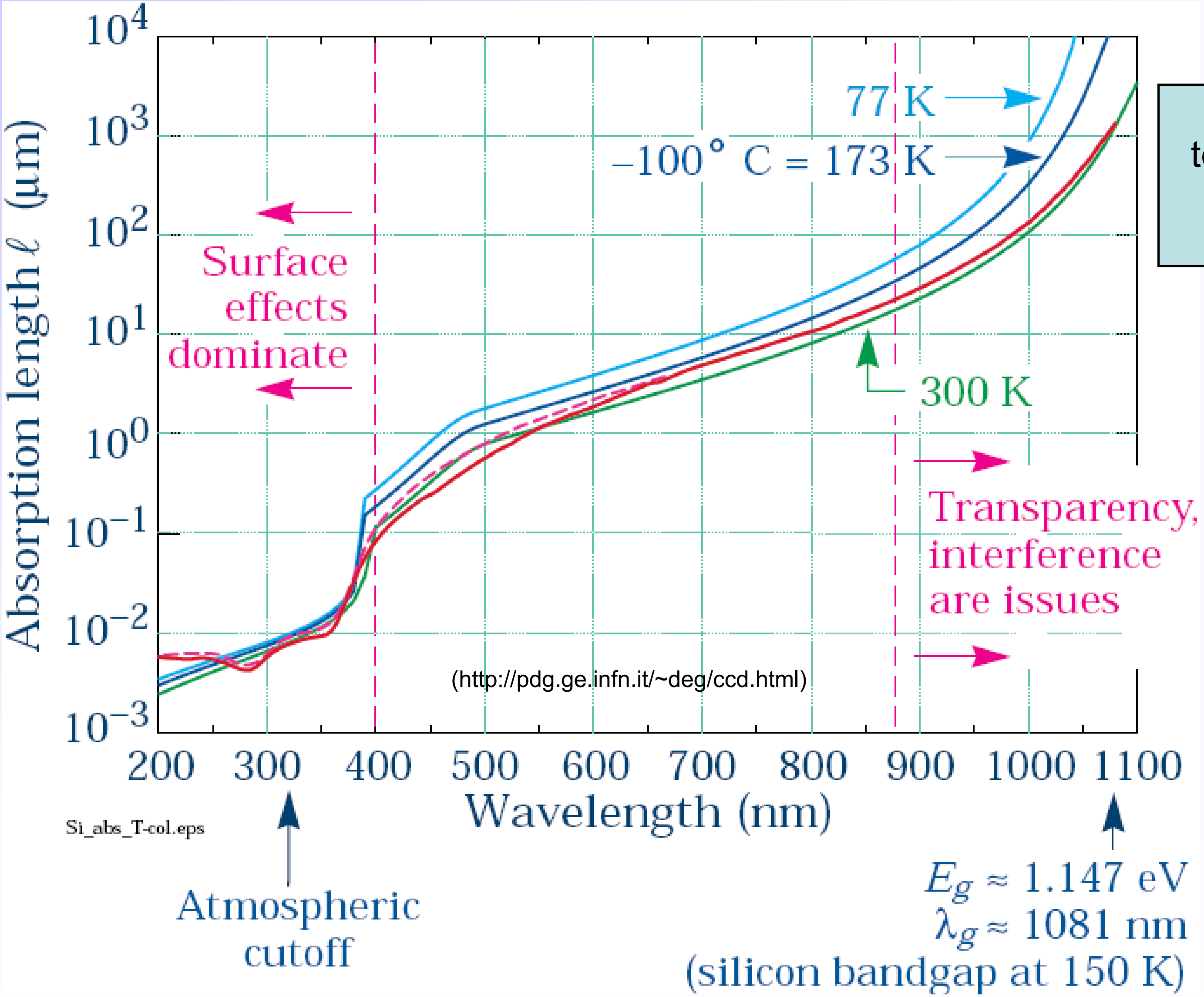
⇒ due to doping profile, high internal field and avalanche multiplication;

- High gain: typ. 100-1000;
- Used in CMS ECAL;



(http://micro.magnet.fsu.edu)

Light absorption in Silicon



(http://pdg.ge.infn.it/~deg/ccd.html)

At long λ, temperature effects dominate

Many more types exist ...

Non-exhaustive list:

- Visible Light Photon Counter (VLPC);
- Silicon Photo-Multiplier (Si-PMT);
- Strip, pad and pixel arrays;
- CCD's:
  - conventional, front-illuminated;
  - thinned, back-illuminated;
  - fully-depleted, back-illuminated;

(see a detailed example of the latter 2 for astronomical applications in the next slides)

Visible Light Photon Counter

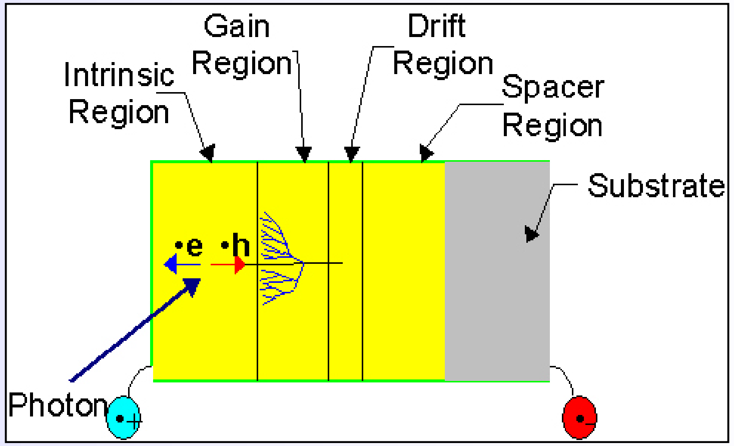
extra slide not shown

Visible Light Photon Counter (VLPC):

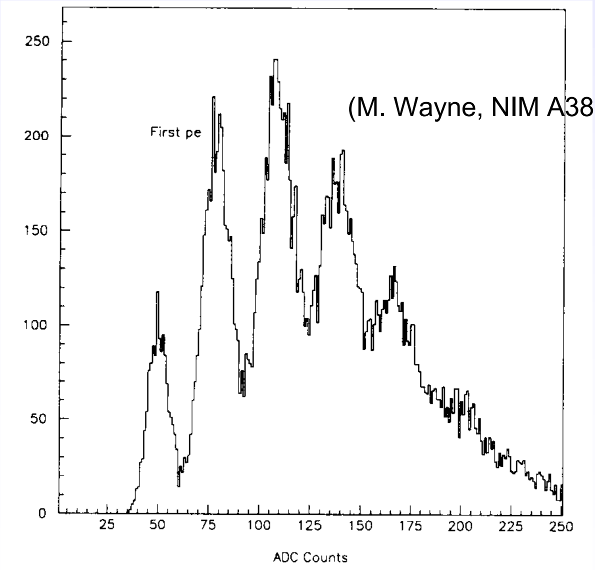
- Originally developed by Rockwell;
- Operation at low bias voltage (7V);
- High IR sensitivity:

$\Rightarrow$ *requires cooling at liquid He T° (7K)!*

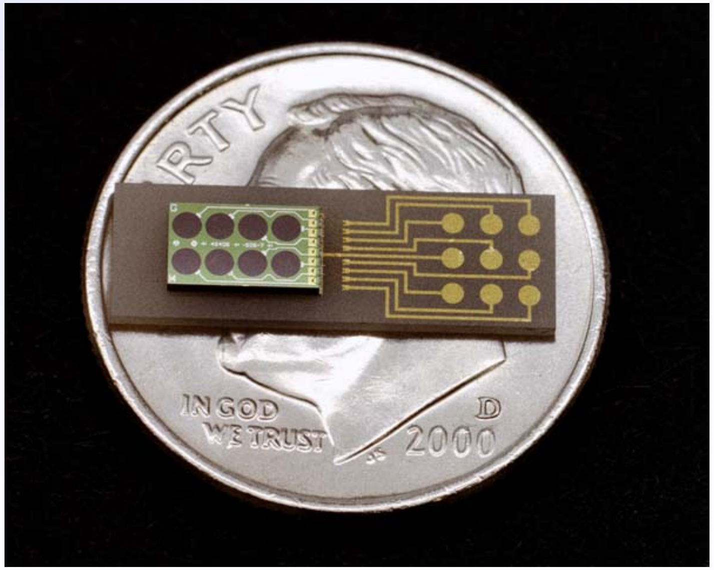
- Q.E. ≈ 70% around 500 nm;
- Gain up to 50.000 !
- used in the D0 Central Scintillating Fibre Tracker



(http://d0server1.fnal.gov/projects/scifi/pictures/vlpc_related.html)



(M. Wayne, NIM A387 (1997) 278)



Silicon Photo-Multiplier

extra slide
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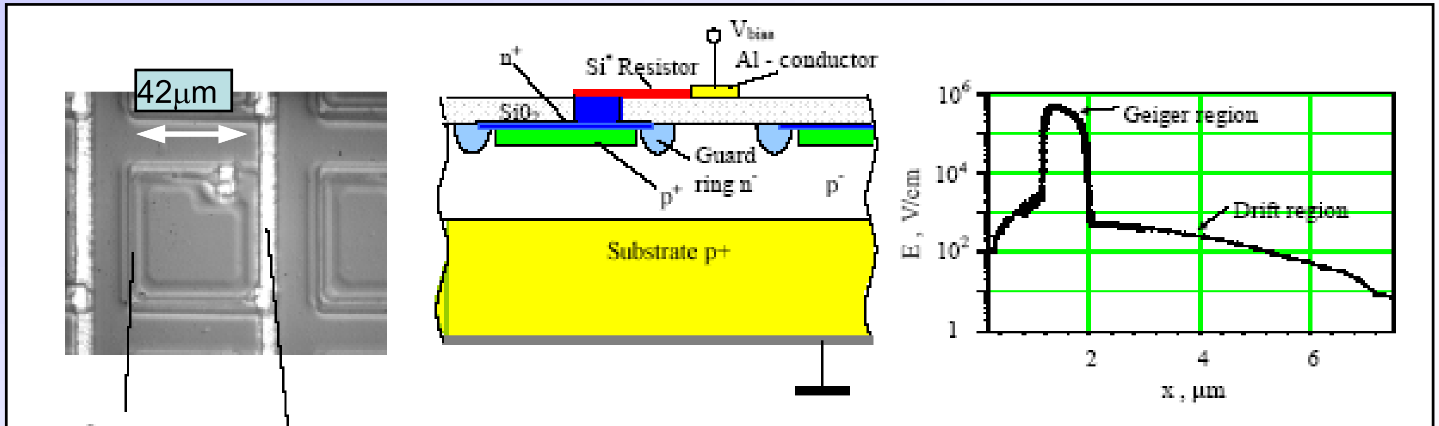
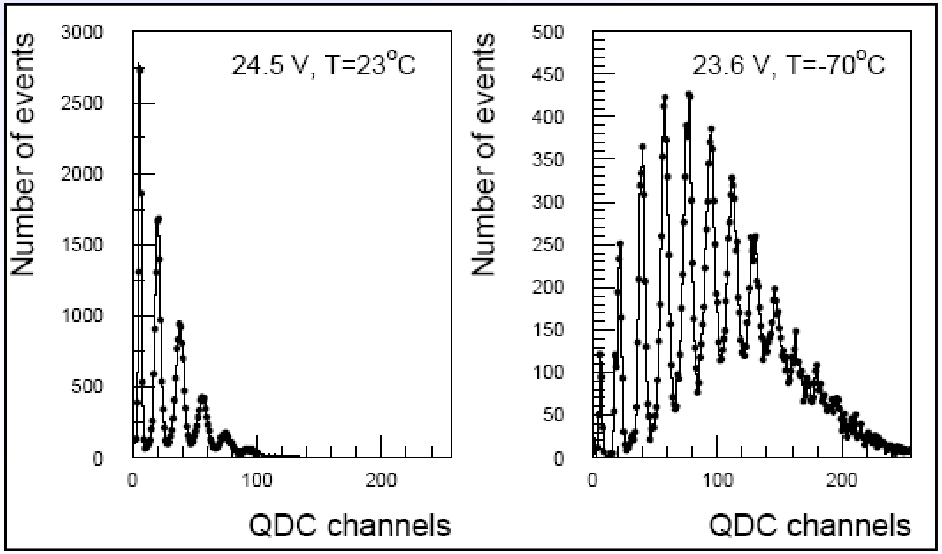


(P. Buzhan et al., ICFA Instrumentation Bulletin Vol. 23 (2001))

Kind of APD array operating in Geiger mode

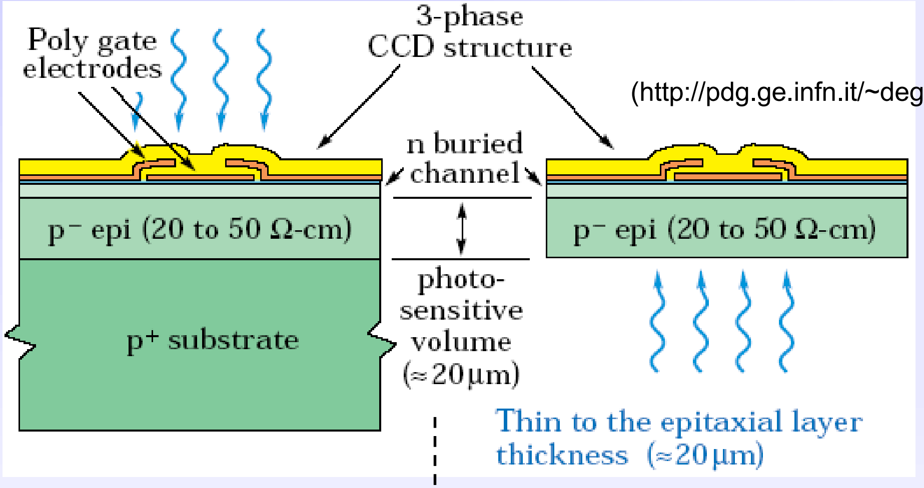


Back-illuminated fully depleted CCD

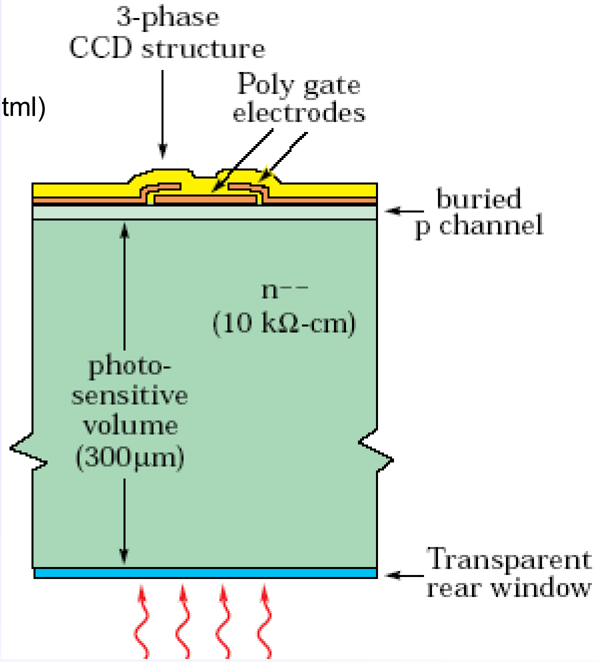
Front-illuminated CCD

Back-illuminated thinned CCD

Back-illuminated fully depleted CCD



(http://pdg.ge.infn.it/~deg/ccd.html)

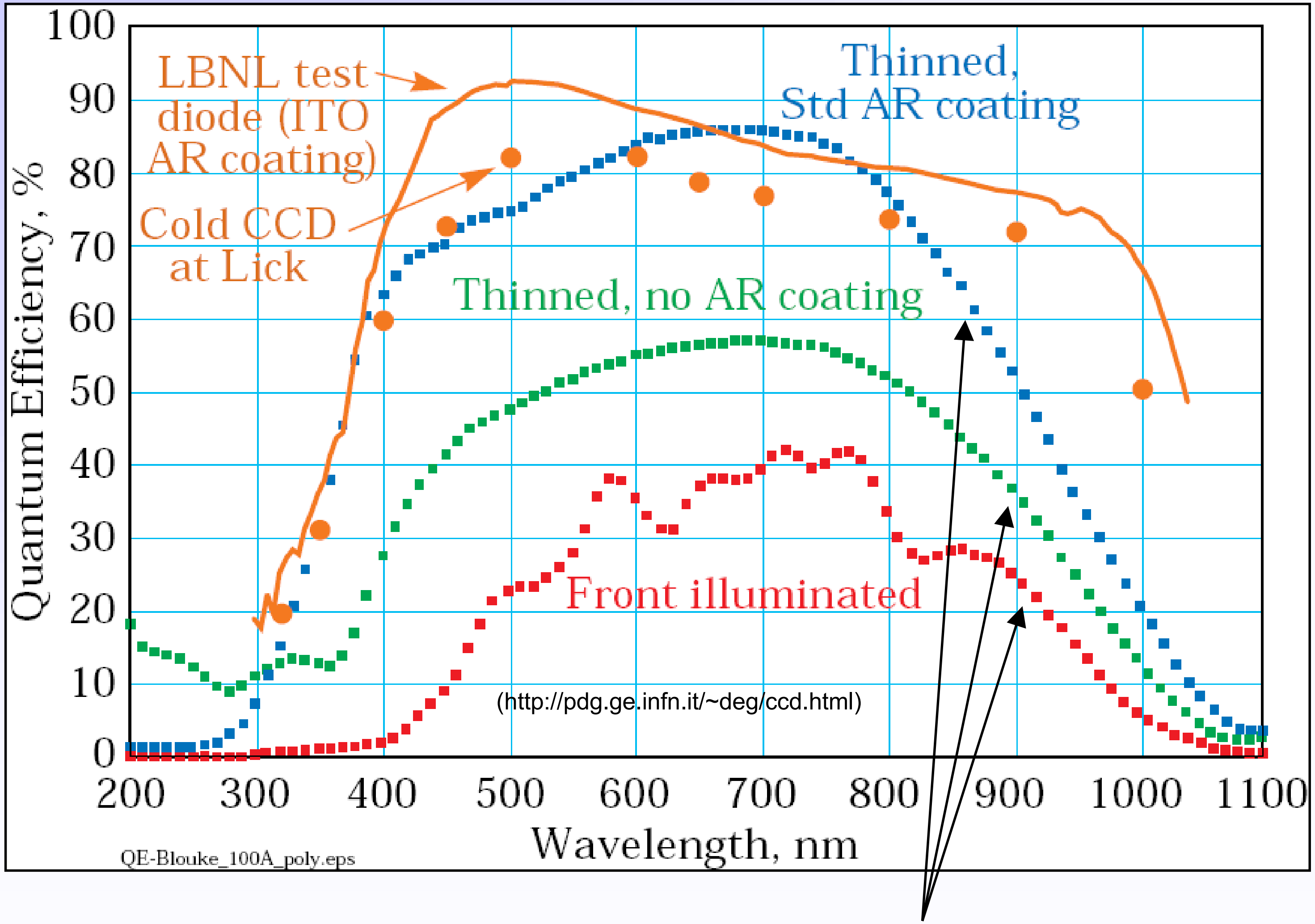


-poor response in blue (poly-Si) and IR (thin epitaxial layer);
-interference (gate);

-thinning difficult, expensive and not flat;
-poor IR response;
-fringing;
-lateral diffusion ⇒ degraded PSF;
-charge build-up at rear surface;

+conventional MOS process;
+full QE up to λ=1µm, (no fringing);
+good blue response;
-enhanced sensitivity to radiation

Measured QE curves



(http://pdg.ge.infn.it/~deg/ccd.html)

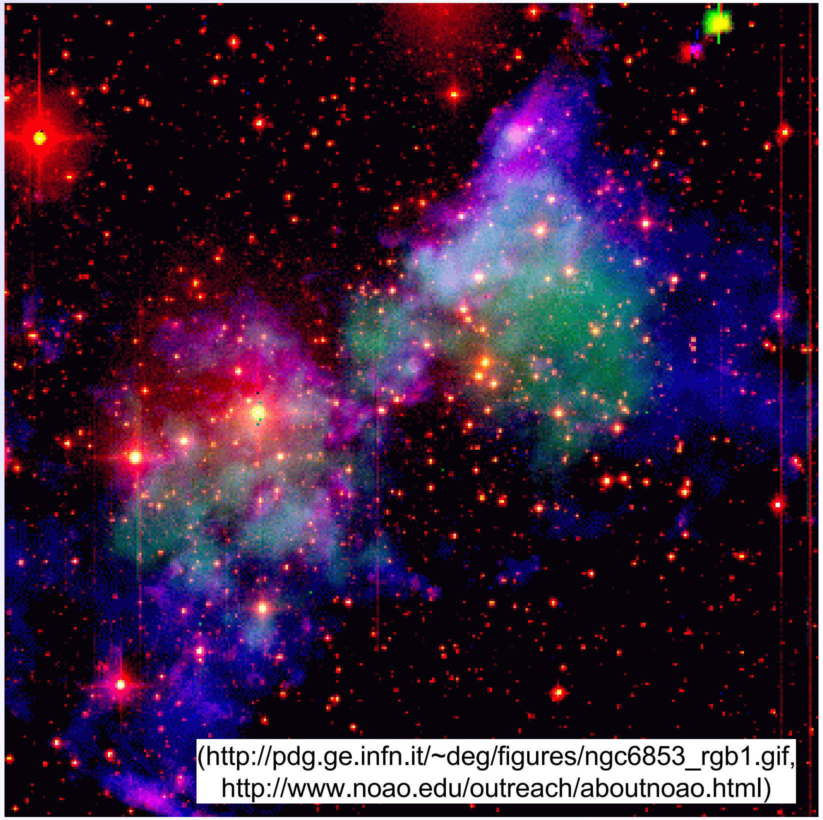
(M. Blouke and M. Nelson, SPIE **1900** (1993), 228-240)

And the result is ...

Dumbbell Nebula in Vulpecula (M27, NGC 6853)

(http://antwrp.gsfc.nasa.gov/apod/ap981009.html)

FORS false color image using a Tektronix back-illuminated 2k×2k CCD with 24μm pixels thinned and anti-reflection coated.
This image was obtained on ESO 8.2-m VLT Unit Telescope (UT) 1 on September 28, 1998.



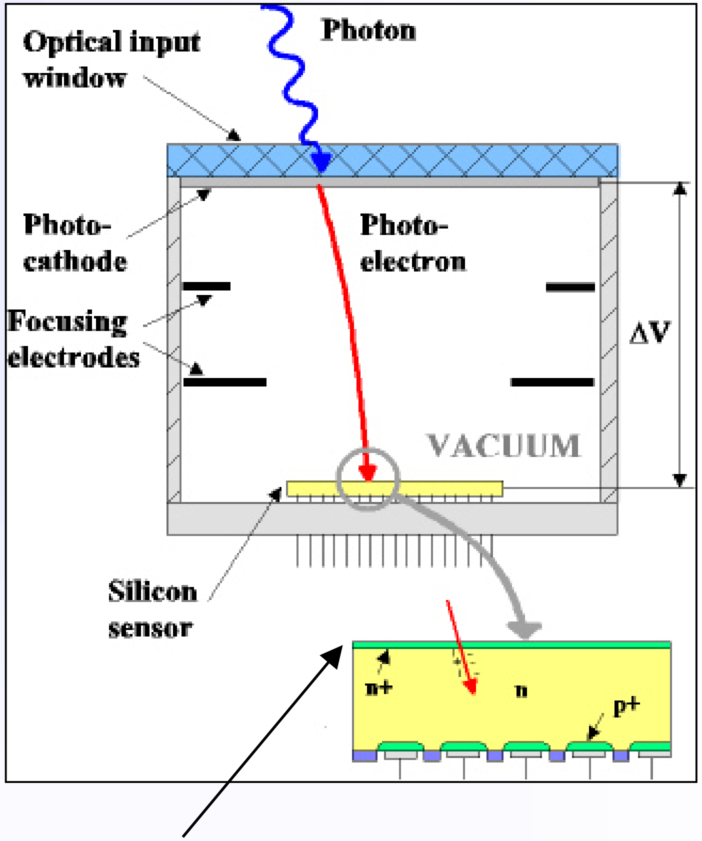
(http://pdg.ge.infn.it/~deg/figures/ngc6853_rgb1.gif, http://www.noao.edu/outreach/aboutnoao.html)

NOAO false color image using a back-illuminated fully depleted 2k×2k CCD with 15μm pixel.
This image was obtained on WIYN 3.5-m Telescope on June 7, 2001.

Hybrid Photon Detectors (HPD's)

Basic principle:

- Combination of vacuum photon detectors and solid-state technology;
- Input: collection lens, (active) optical window, photo-cathode;
- Gain: achieved *in one step* by energy dissipation of keV pe's in solid-state detector anode; this results in low gain fluctuations;
- Output: direct electronic signal;
- Encapsulation in the tube implies:
  - compatibility with high vacuum technology (low outgassing, high T° bake-out cycles);
  - internal (for speed and fine segmentation) or external connectivity to read-out electronics;
  - heat dissipation issues;



Energy loss eV_{th} in (thin) ohmic contact

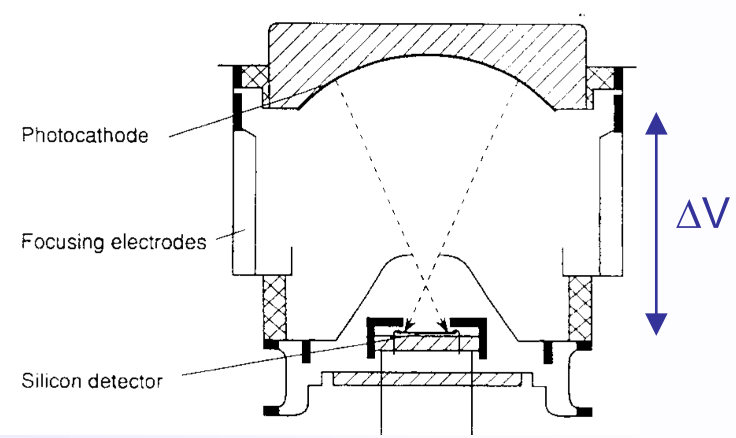
Energy resolution of HPD's

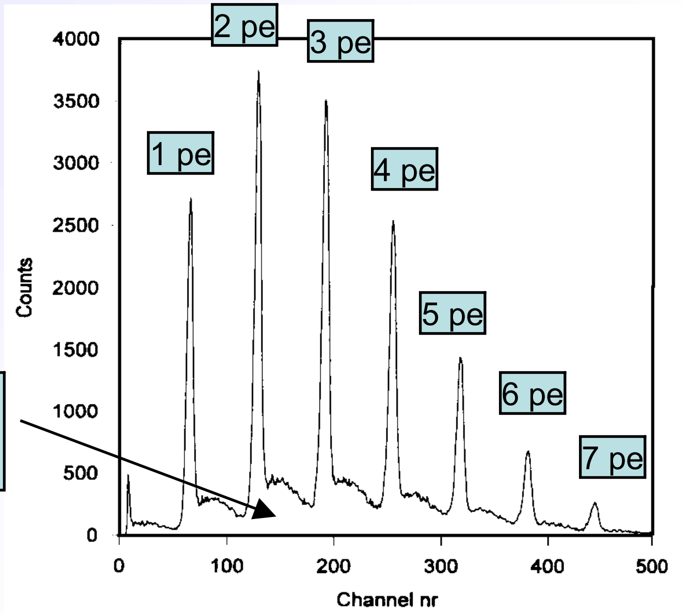
Basic properties:

- Photo-emission from photo-cathode;
- Photo-electron acceleration to $\Delta V \approx$ 10-20kV;
- Energy dissipation through ionization and phonons (W_{Si}=3.6eV to generate 1 e-h pair in Si) with low fluctuations (Fano factor F $\approx$ 0.12 in Si);
- Gain *M*: $$M = \frac{e(\Delta V - Vth)}{W_{Si}}$$
- Gain fluctuations σ_M: $$\sigma_M = \sqrt{F \times M}$$

  $\Rightarrow$ dominated by electronics
- Example: ΔV = 20kV

  $\Rightarrow$ *M* $\approx$ 5000 and $\sigma_M \approx$ 25
- suited for single photon detection with high resolution;



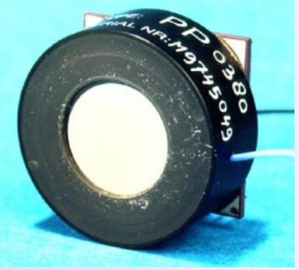


Background from electron back-scattering at Si surface

(C.P. Datema et al., NIM A 387(1997) 100)

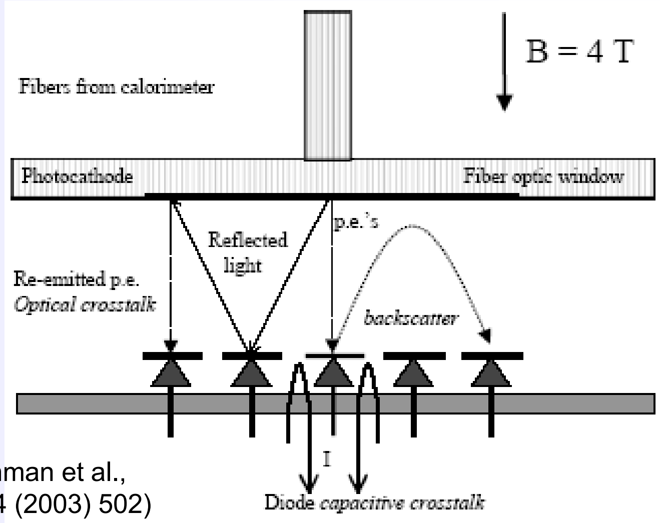
Multi-pixel proximity-focussed HPD

DEP-CMS HCAL example:

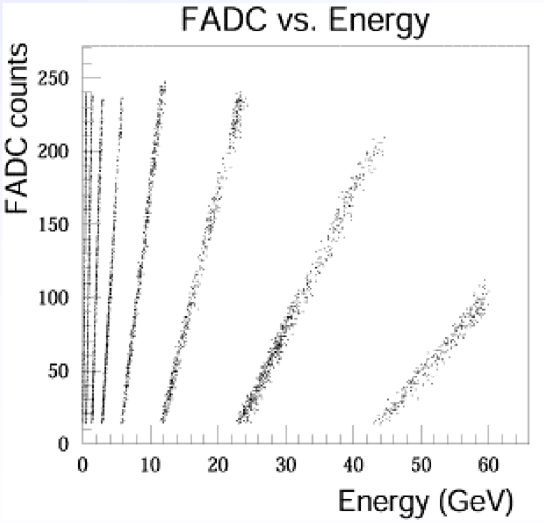


- B=4T ⇒ proximity-focussing with 3.35mm gap and HV=10kV;
- Minimize cross-talks:
  - pe back-scattering: align with B;
  - capacitive: Al layer coating;
  - internal light reflections: a-Si:H AR coating optimized @ λ = 520nm (WLS fibres);
- Results in linear response over a large dynamic range from minimum ionizing particles (muons) up to 3 TeV hadron showers;

Possible cross-talks



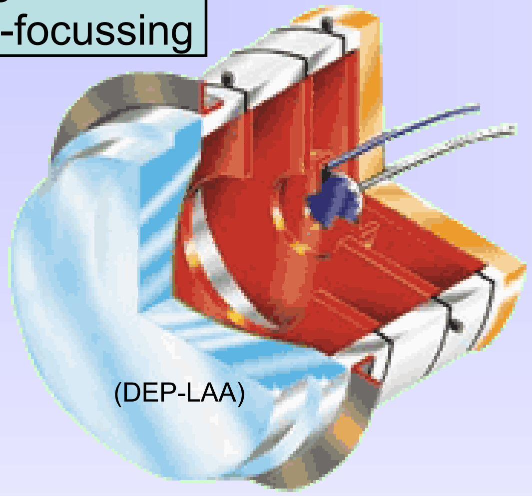
(P. Cushman et al., NIM A 504 (2003) 502)



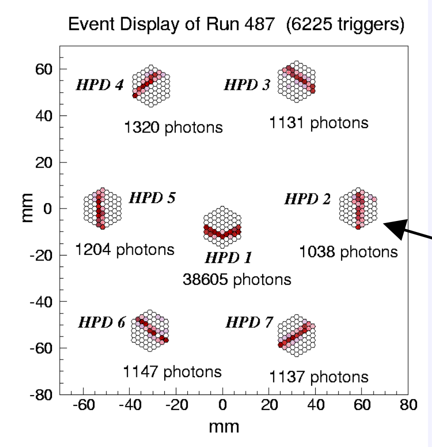
http://cmsinfo.cern.ch/Welcome.html/CMSdetectorInfo/CMShcal.html extra slide not shown

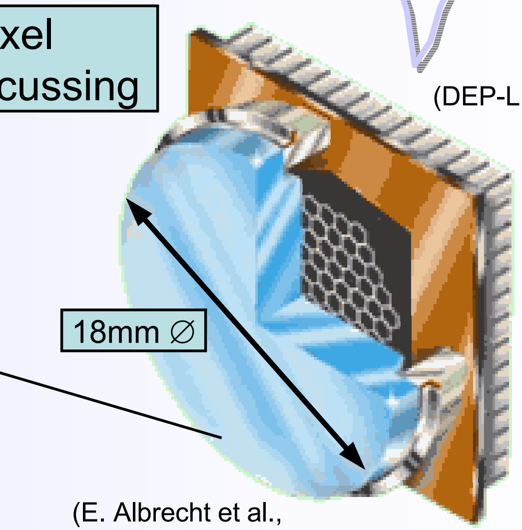
Various kinds of commercial HPD’s

Single-diode cross-focussing


(DEP-LAA)

Multi-pixel proximity-focussing

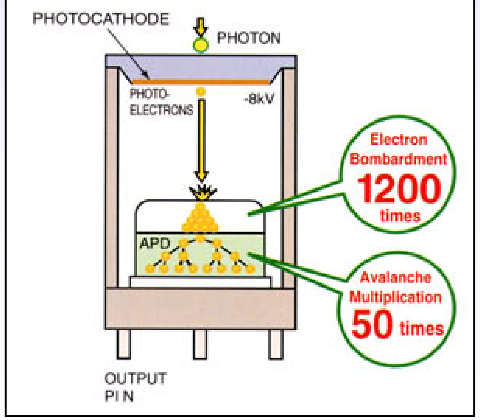




(DEP-LHCb)

(E. Albrecht et al., NIMA A 411 (1998) 249-264)

Single avalanche diode HPD



(Hamamatsu)

DEP-LHCb development:

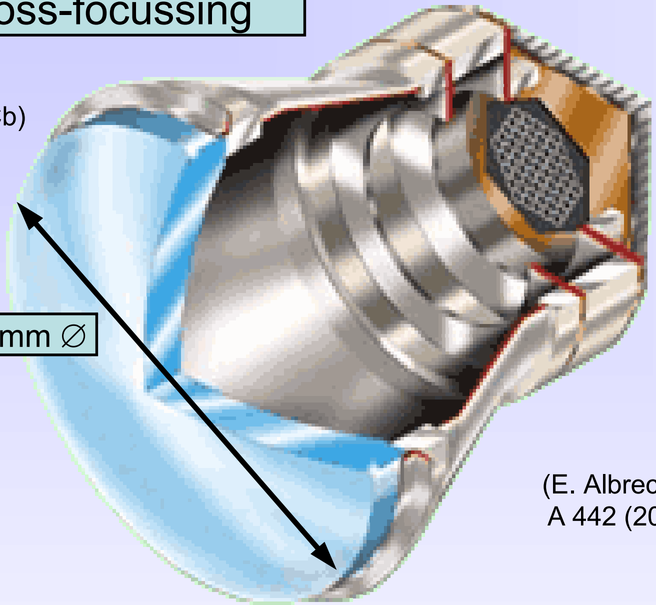
- Multi-alkali photo-cathode;
- Commercial anode with 61 2mm-pixels; vacuum feed-throughs to external analog (VA2) readout electronics;
- Proximity-focussing electron optics;
- Poor intrinsic active area coverage (~50%);

CERN Academic Training Programme 2004/2005

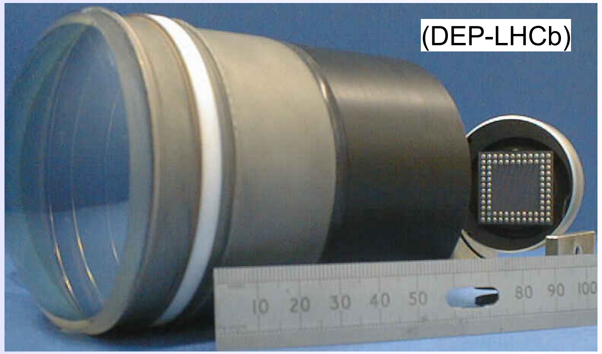
extra slide not shown

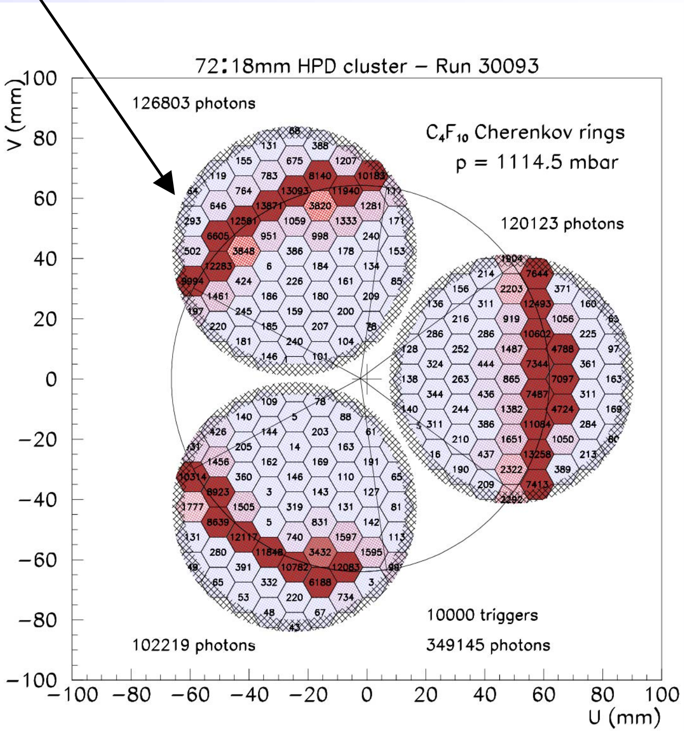
Various kinds of commercial HPD's

Multi-pixel, cross-focussing



(DEP-LHCb)





(E. Albrecht et al., NIMA A 442 (2000) 164-170)

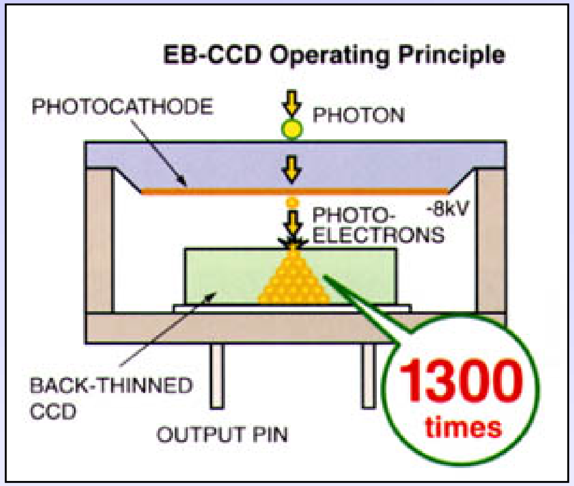
DEP-LHCb development:

- Commercial anode;
- Cross-focussing electron optics (de-magnification by ~5);
- High intrinsic active area coverage (83%);

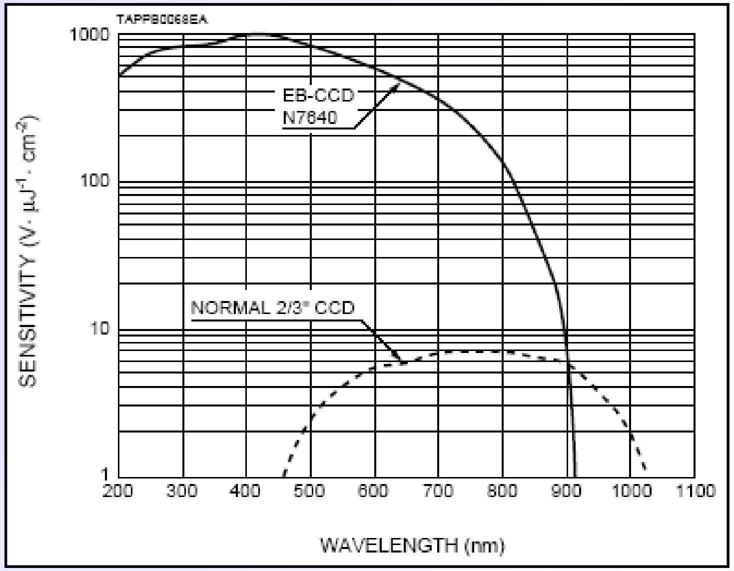
CERN Academic Training Programme 2004/2005

Electron-bombarded CCD (EBCCD)

EBCCD
proximity-focussed

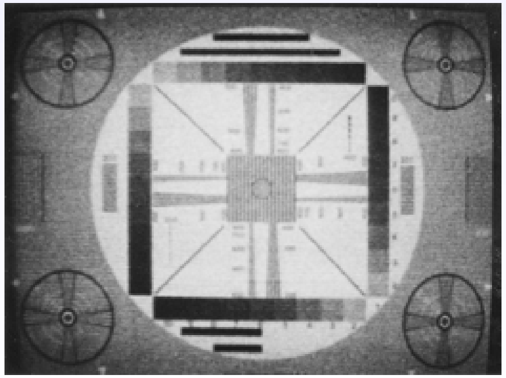


(Hamamatsu)



Commercial 2/3”
CCD

Hamamatsu N7640
EB-CCD

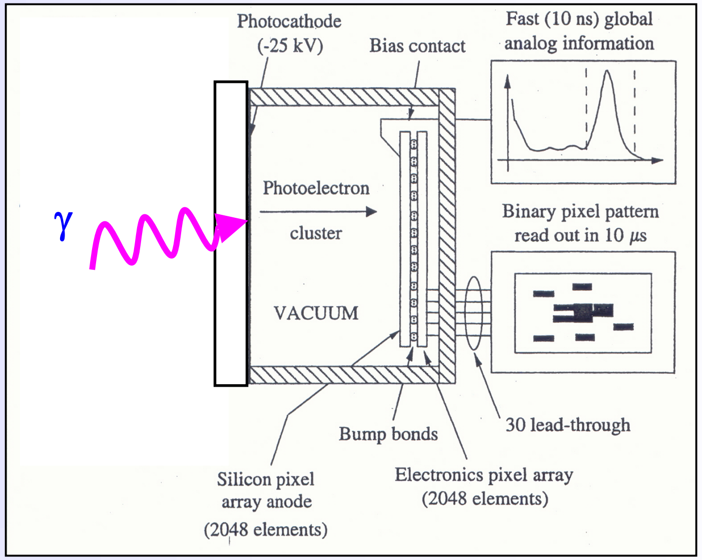


Object illuminance: 0.1lx

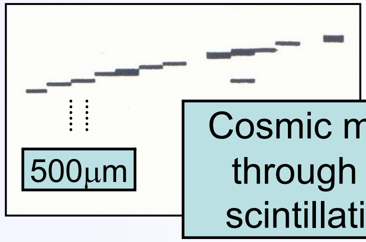
ISPA-tube

Imaging with Silicon Pixel Array:

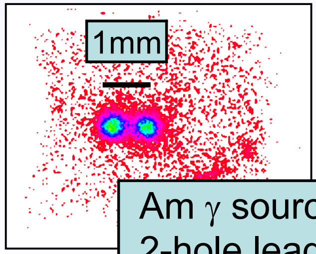
- Pixel array sensor bump-bonded to binary electronic chip, developed for tracking (CERN-RD19);
- Flip-chip assembly encapsulated inside vacuum tube using standard parts, commercial ceramic carriers and packaging techniques;
- First ISPA prototype (1994) used to read small-diameter scintillating fibres developed for tracking (CERN-RD7);
- Spin-off applications for beta- and gamma-detection (quartz and YAP-crystal windows)



(T. Gys et al., NIMA 355 (1995) 386-389)



Cosmic muon track through 60µm ∅ scintillating fibres



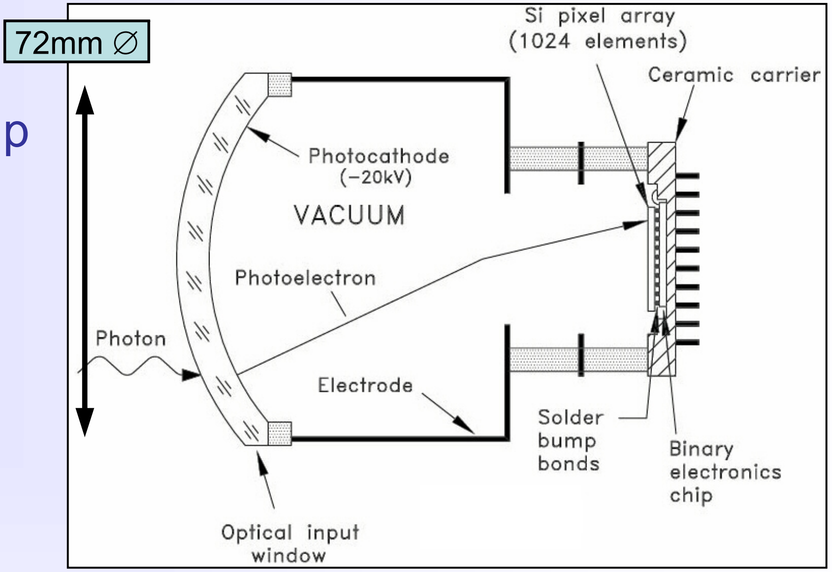
Am γ source through a 2-hole lead collimator

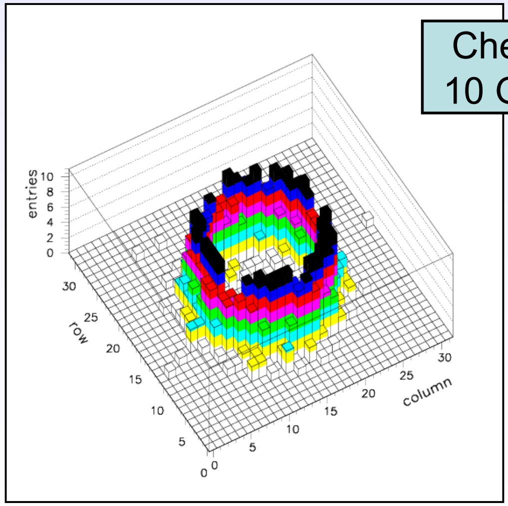
(F. Cindolo et al., IEEE TNS , Vol. 50, No. 1, February 2003, 126-132)

Pixel-HPD's for LHCb RICH's

Industry-LHCb development:

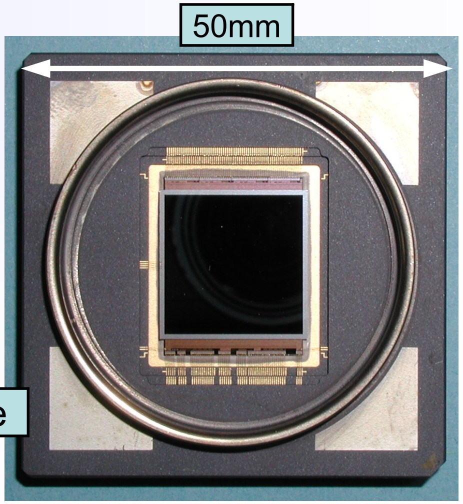
- LHCb-dedicated pixel array sensor bump-bonded to binary electronic chip (in coll. w. ALICE-ITS), specially developed high T° bump-bonding;
- Flip-chip assembly encapsulated inside vacuum tube using full-custom ceramic carrier;





Cherenkov rings from 10 GeV/c π^- through air

(M. Moritz et al., IEEE TNS Vol. 51, No. 3,, June 2004, 1060-1066)



Pixel-HPD anode

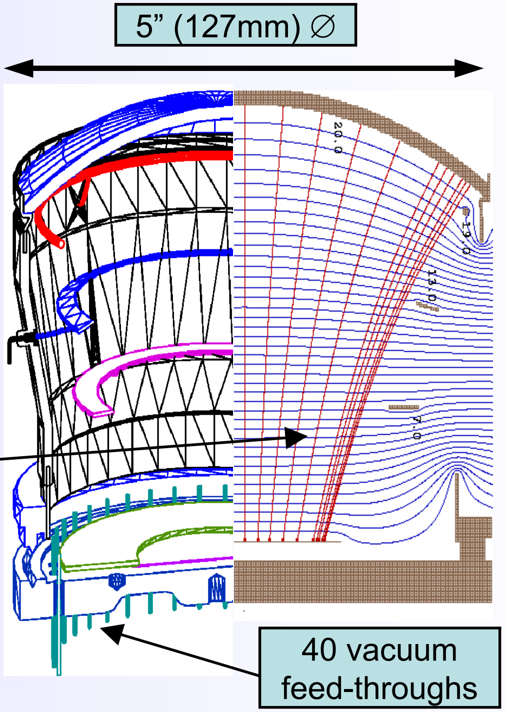
The pad HPD for RICH detectors

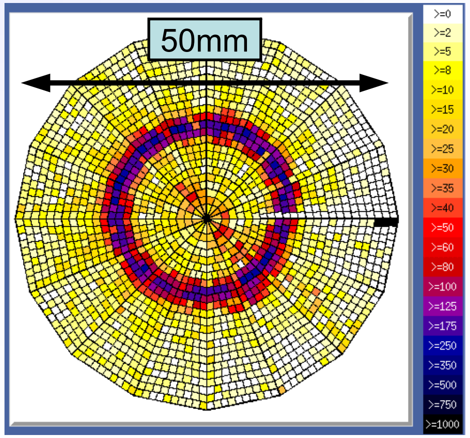
extra slide not shown

Full in-house (LHCb, CERN, Bologna, CdF) development:

- Aim for active area > 80%;
- Bi-alkali photo-cathode;
- “Fountain” focussing electron optics (de-magnification ~2.4);
- Si detector: 16 × 128 = 2048 pads (~1 × 1 mm^2 each);
- Analogue electronics (16 VA3 chips) encapsulated inside vacuum tube;
- Standard Al wedge bonding;

(LHCb 98-007, RICH)



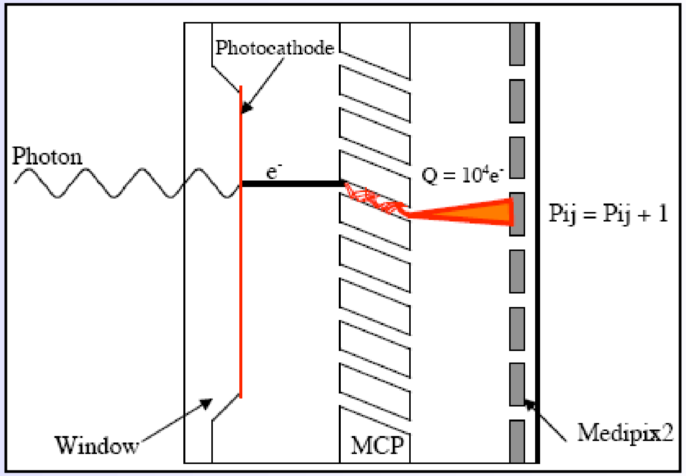


Hybrid MCP for adaptive optics (AO)

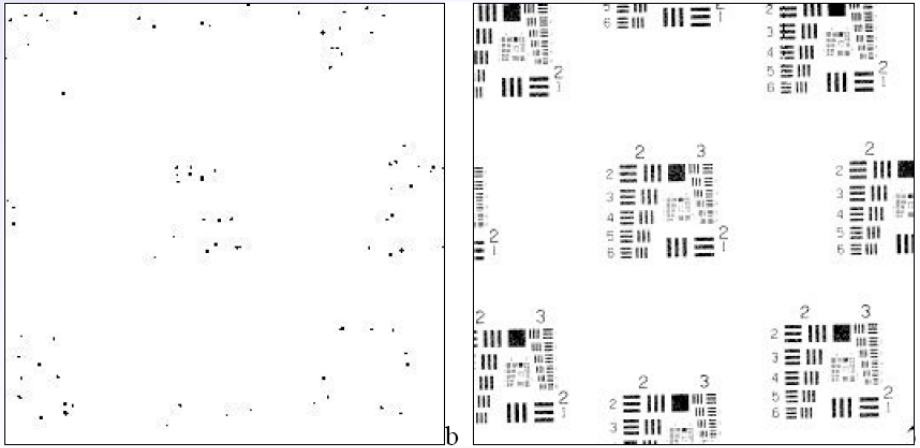
extra slide
not shown

Development of next-generation astronomical AO:

- Alternative to replace more conventional high-speed CCD’s;
- Aim for IR response, ultra-low noise and several kHz frame-rates;
- GaAs photo-cathode;
- Proximity-focussing electron optics;
- High-gain wide dynamic range MCP;
- Anode: Medipix2 photon-counting chip used both as direct electron detector (55μm pixels) and FE readout electronics;



(J. Vallerga et al., Proc. SPIE, vol. 5490 (2004) 1256-1267)



Images of USAF test pattern,
100ms (left) and 100s (right) exposures,
50k MCP gain

Literature

Non-exhaustive list:

- www.photonis.com: "Photomultiplier tubes, principles and applications";
- www.hamamatsu.com;
- www.dep.nl;
- A.H. Sommer, "Photoemissive materials", J. Wiley & Sons (1968);
- H. Bruining, "Physics and Applications of Secondary Electron Emission", Pergamon Press (1954);
- I. P. Csorba, "Image Tubes", Sams (1985);
- Proceedings of the Beaune Conferences (1996-1999-2002) on "New Developments in Photo-detection", published in NIMA;