Summary of Beaune 2005

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Outline

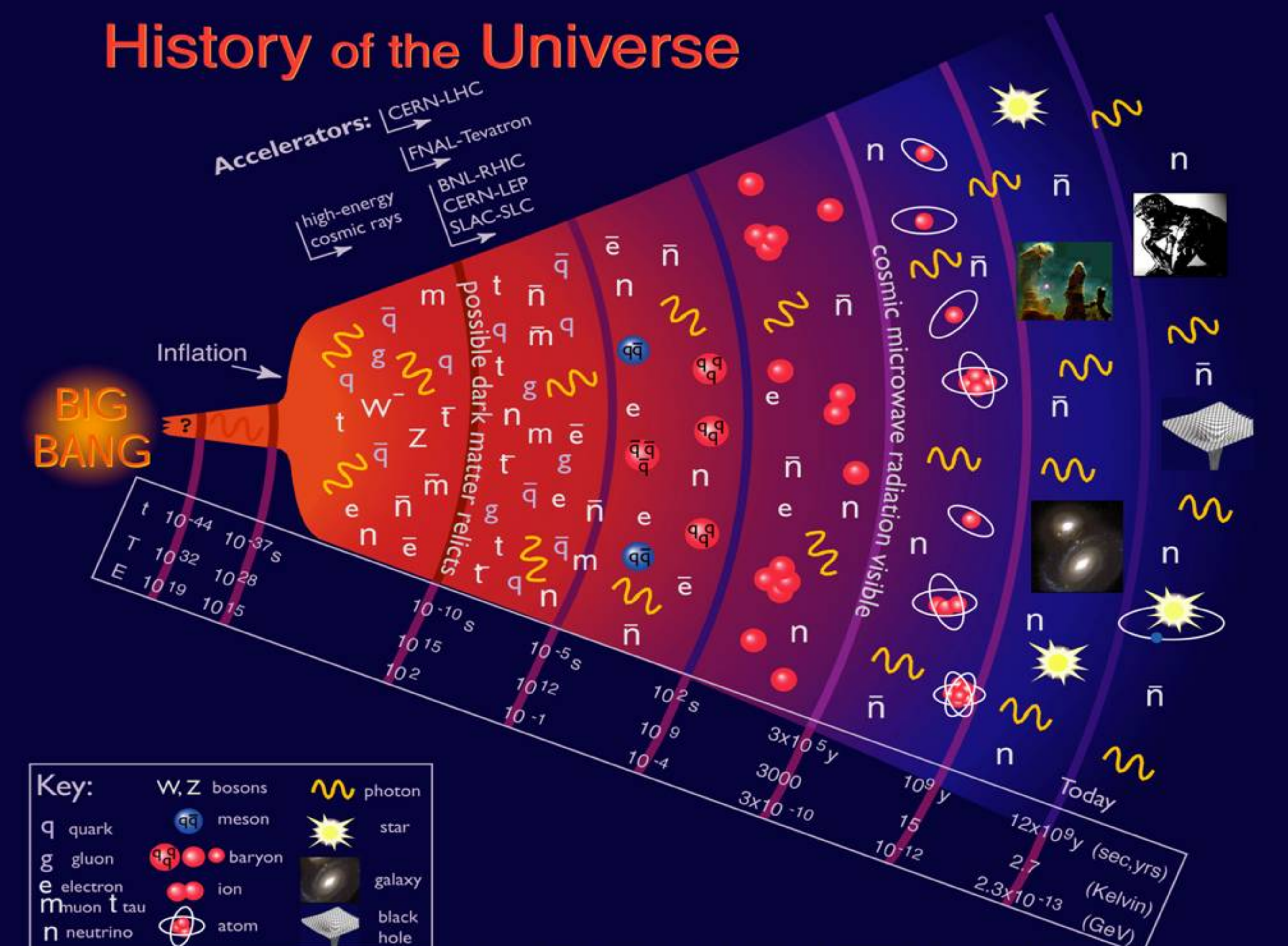
- **Focus on big picture:**
  - New trend on scientific applications
  - Demands, specs on detectors
  - Major new technology
  - Fair comparison of detectors
- **My apologies for not including:**
  - UV, X and direct Gamma detection
  - Readout electronics, systems
  - Friday's talks

Why are we here?

F. Rocard

Are we alone?

F. Rocard



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Science of 21st Century

- **Why are we here?**
  - Origin of Ourselves
  - Origin of Life
  - Origin of the Solar System
  - …
  - Origin of the Universe
- **What is the most fundamental law in nature?**

⇩

- **We rely on weak, fast photon signals.**

Scientifics Applications

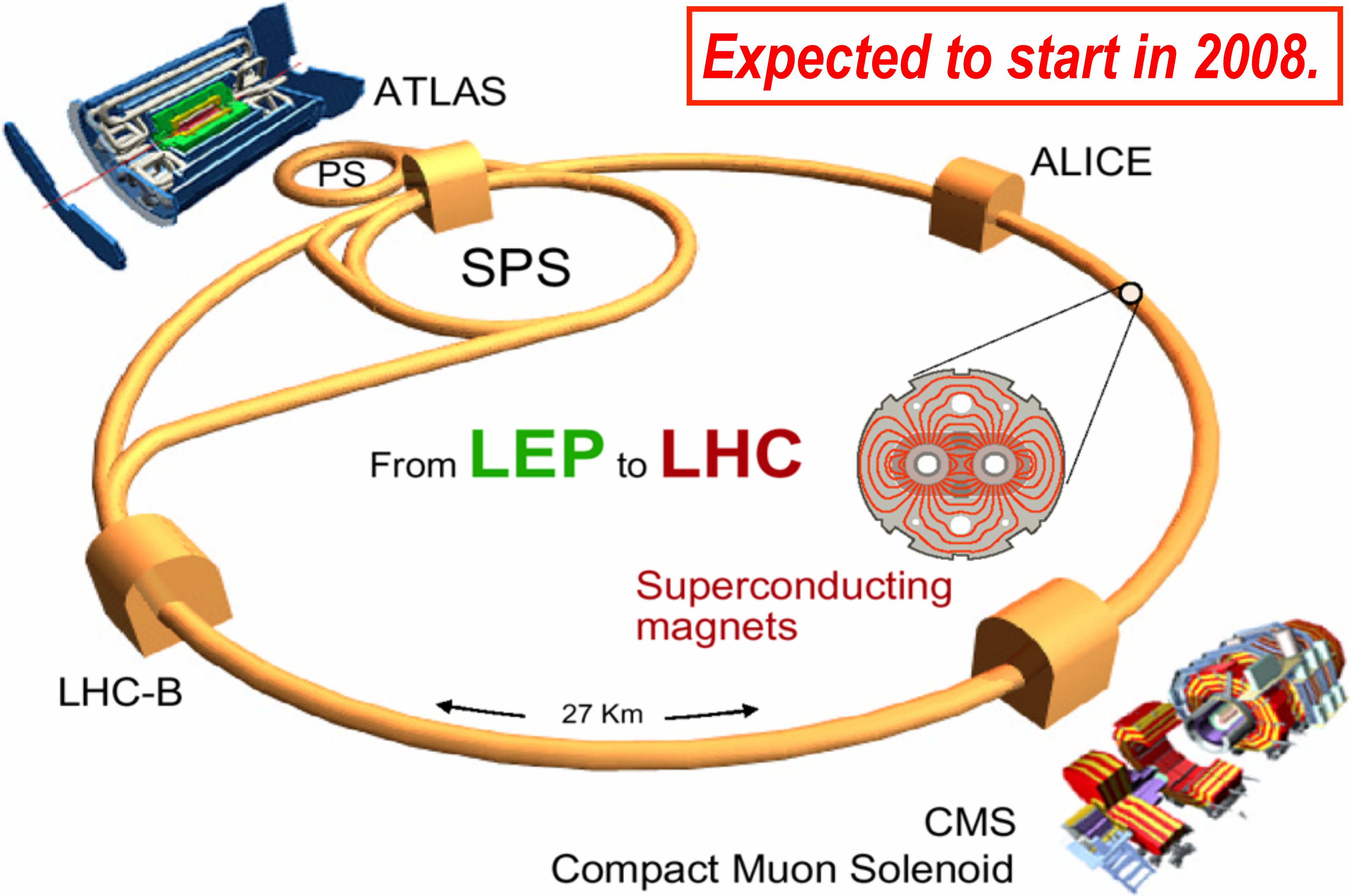
- High Energy
- Particle Astrophysics
- Bio and Medical Imaging

High Energy

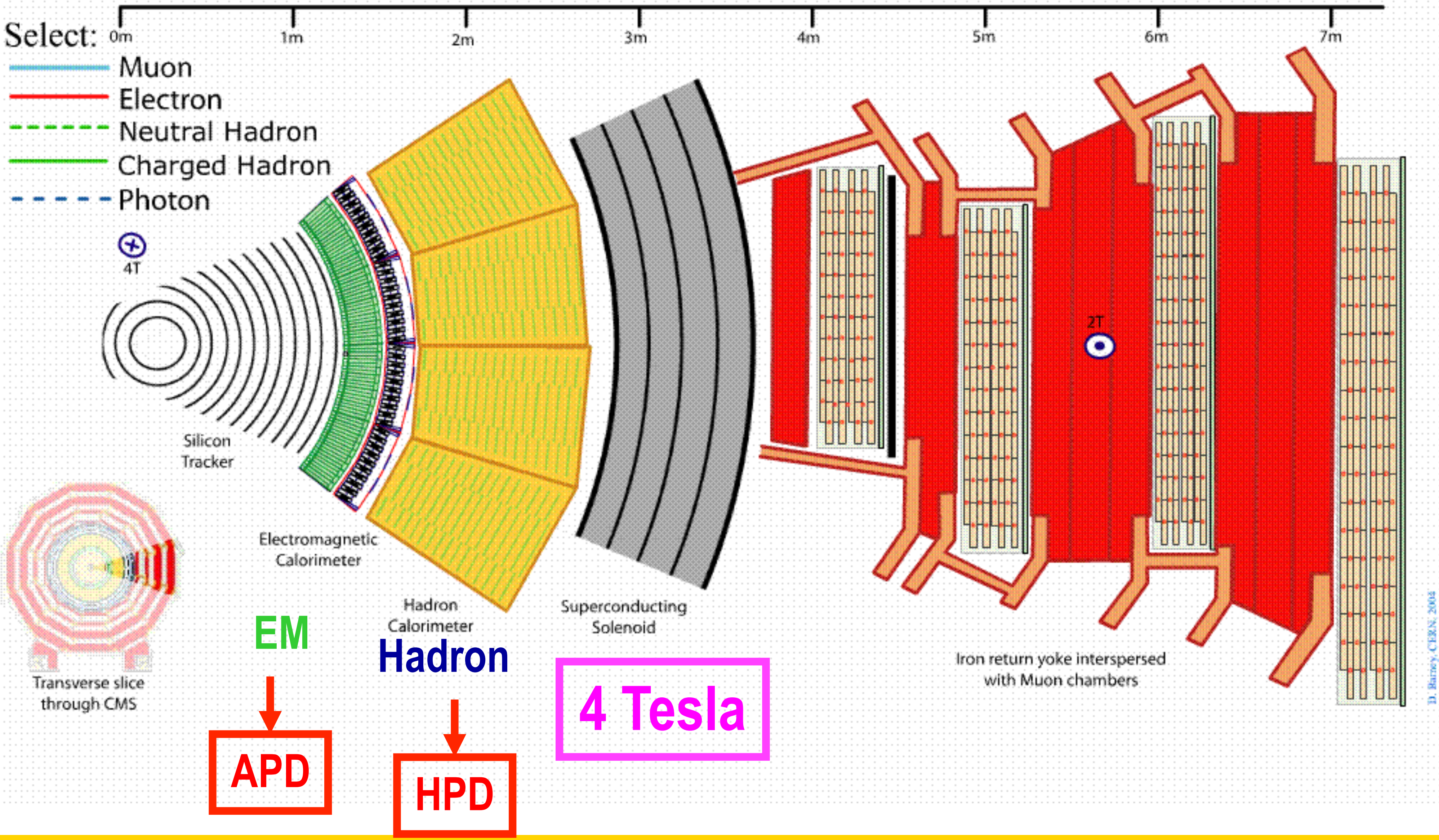
- LHC
- B-Factory etc.
- ILC

Large Hadron Collider (LHC)

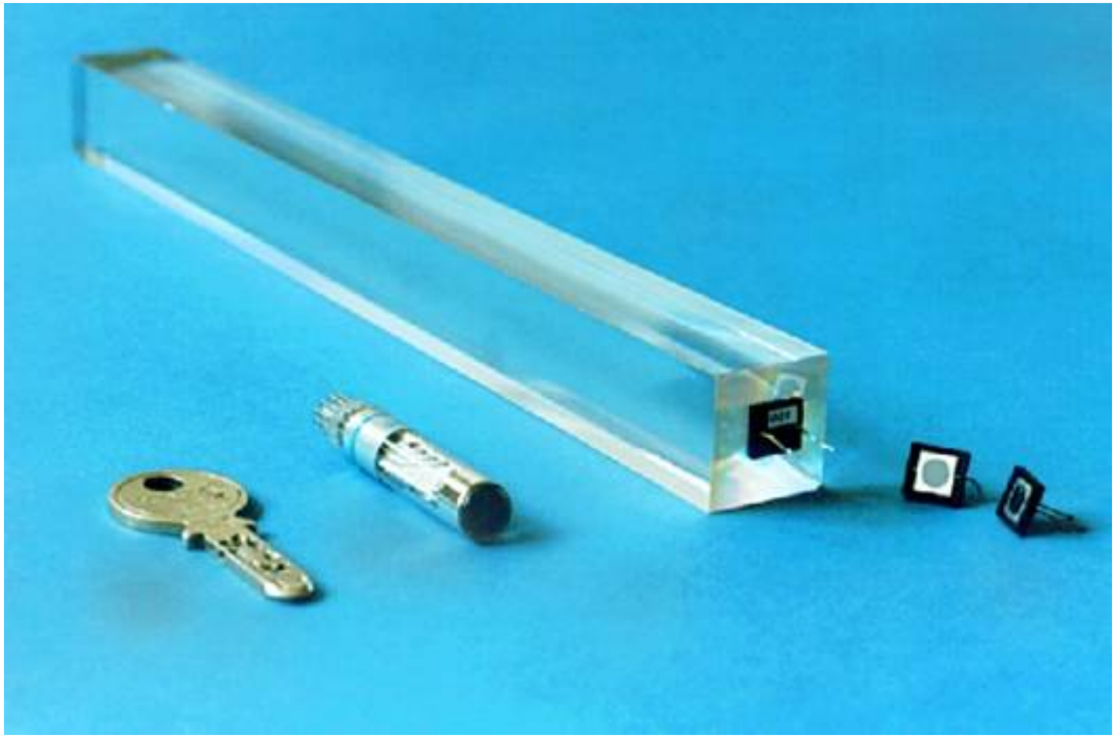
Expected to start in 2008.



CMS Detector under 4 Tesla



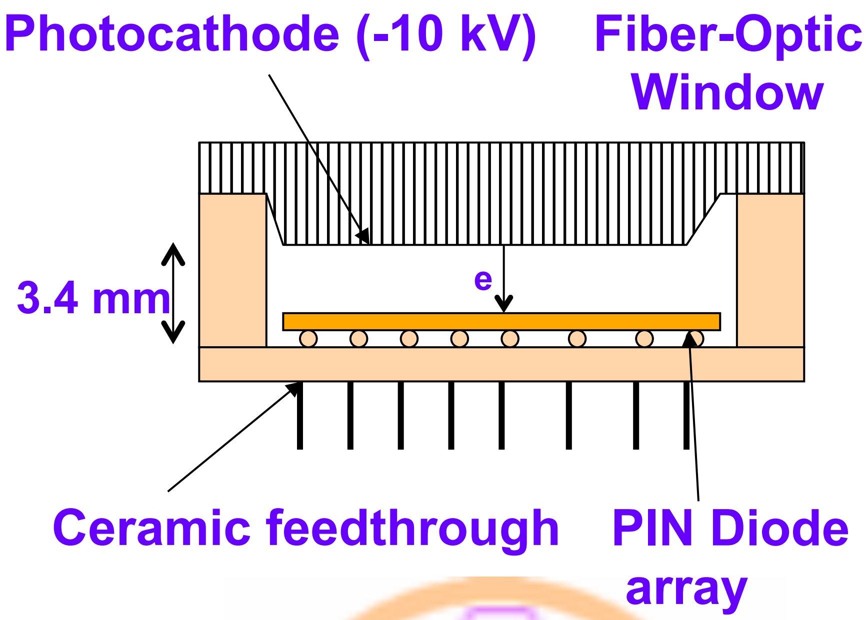
APD's for CMS ECAL (HPK)
(Beaune 2002)

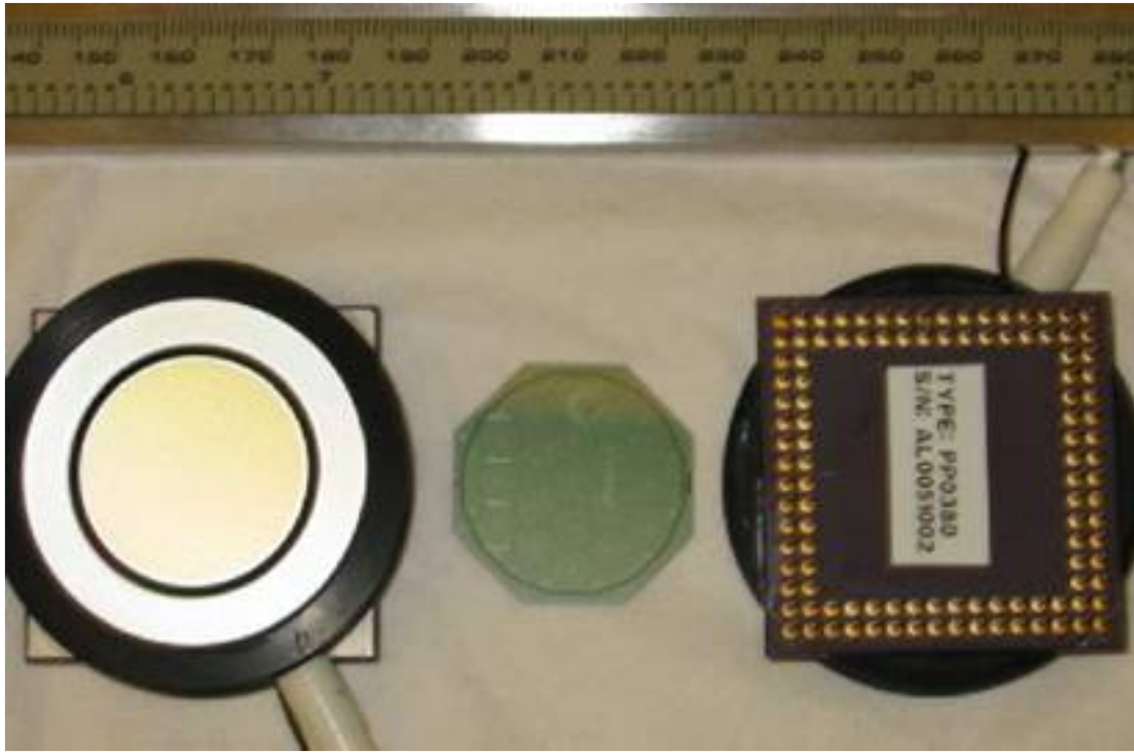


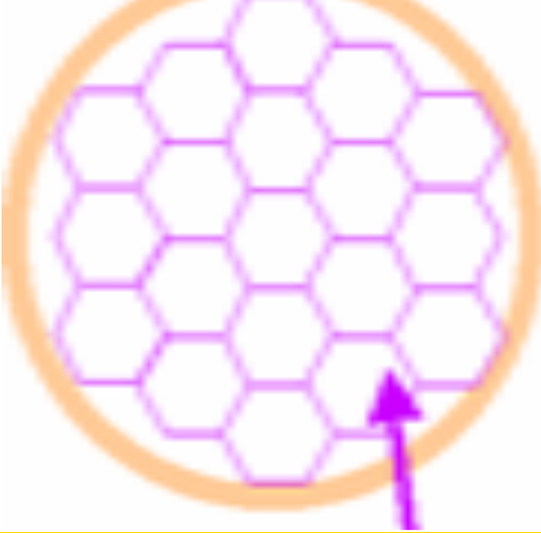
Delivery from Hamamatsu started last year: ~37 000 APD`s delivered so far

Today's APD is a result of about 10 years R&D with (EG&G and) Hamamatsu Photonics KK.

CMS HCAL Multi pixel HPD (DEP)
(Beaune 2002)



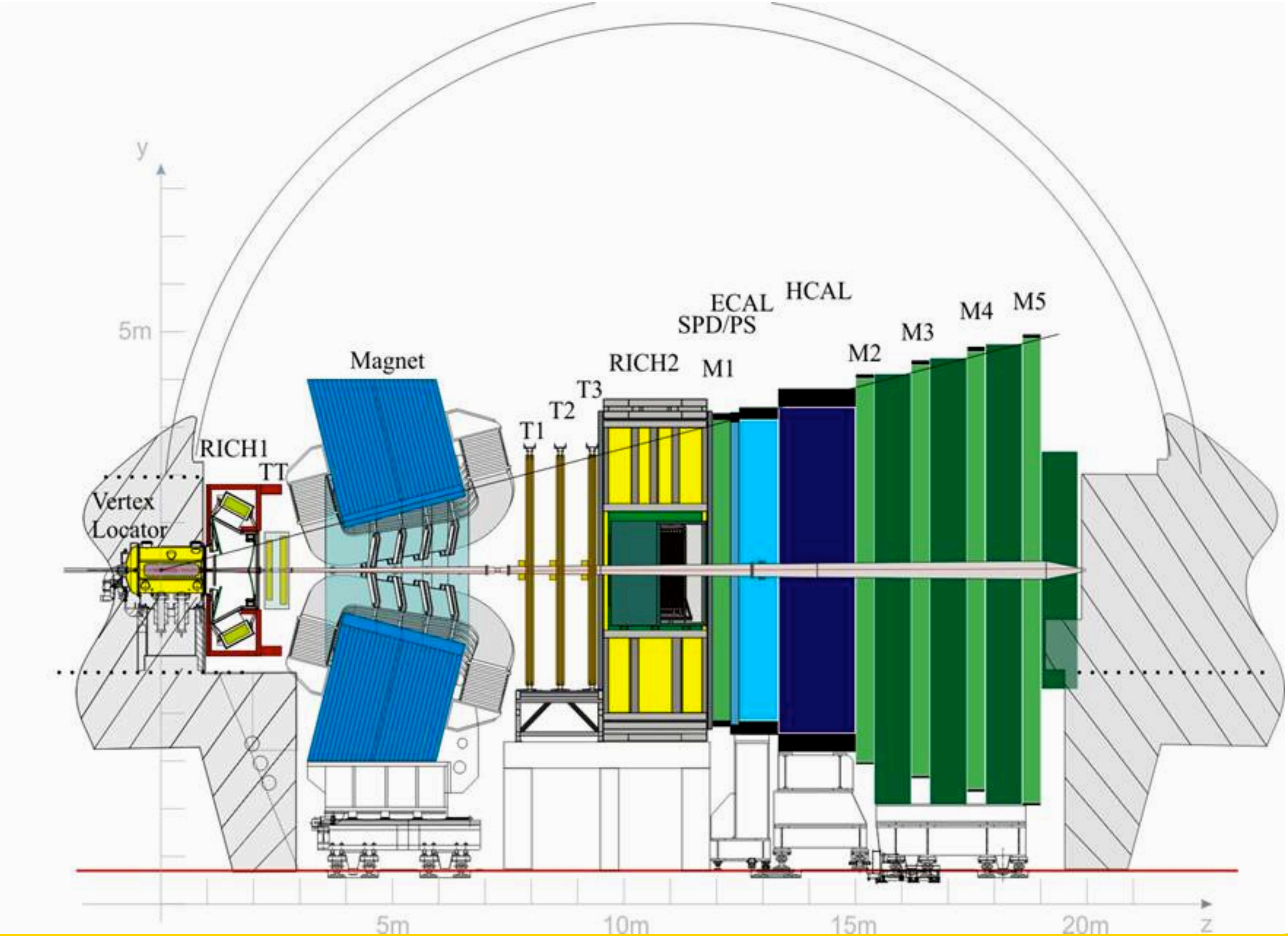




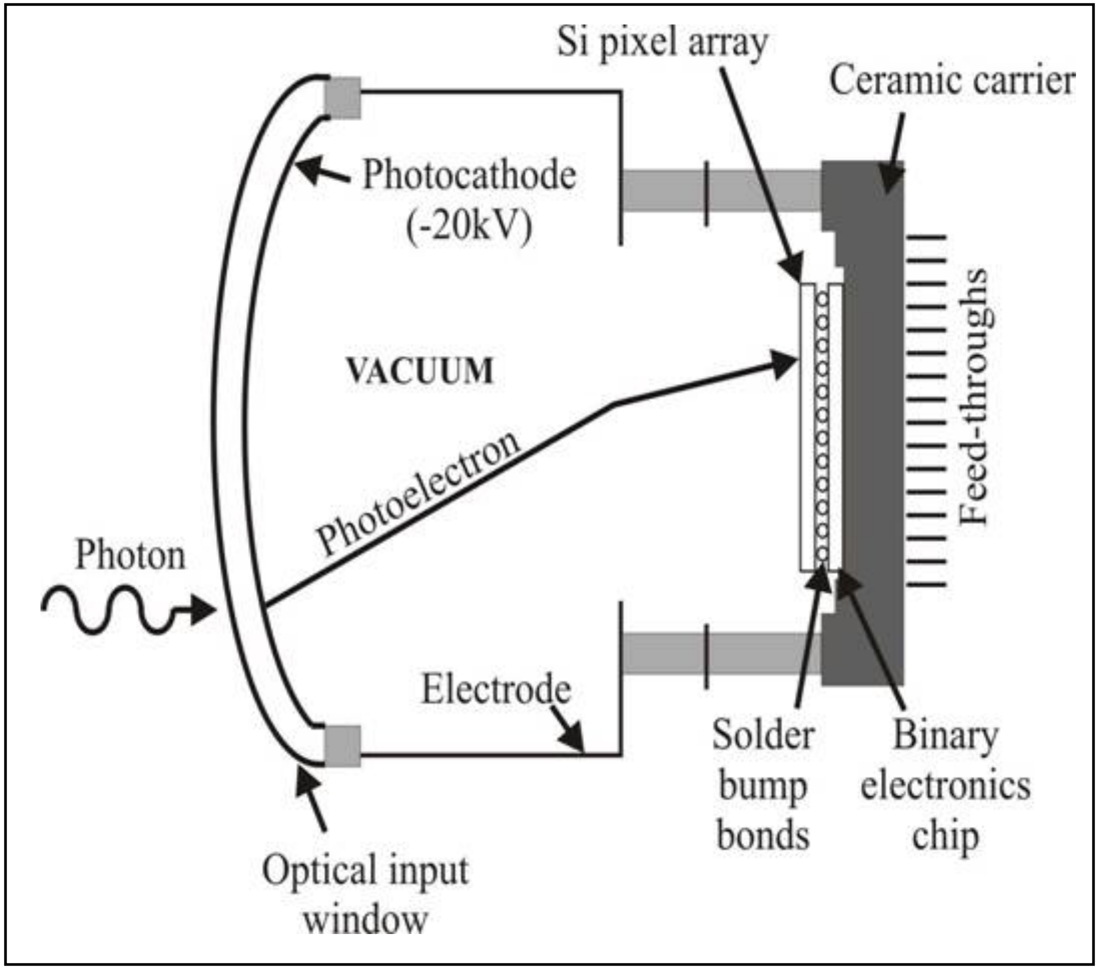
19 channel pixel layout

pixel size: 5.4 mm flat-flat
gap between pixels: 0.04 mm

LHCb experiment



The pixel HPD by DEP



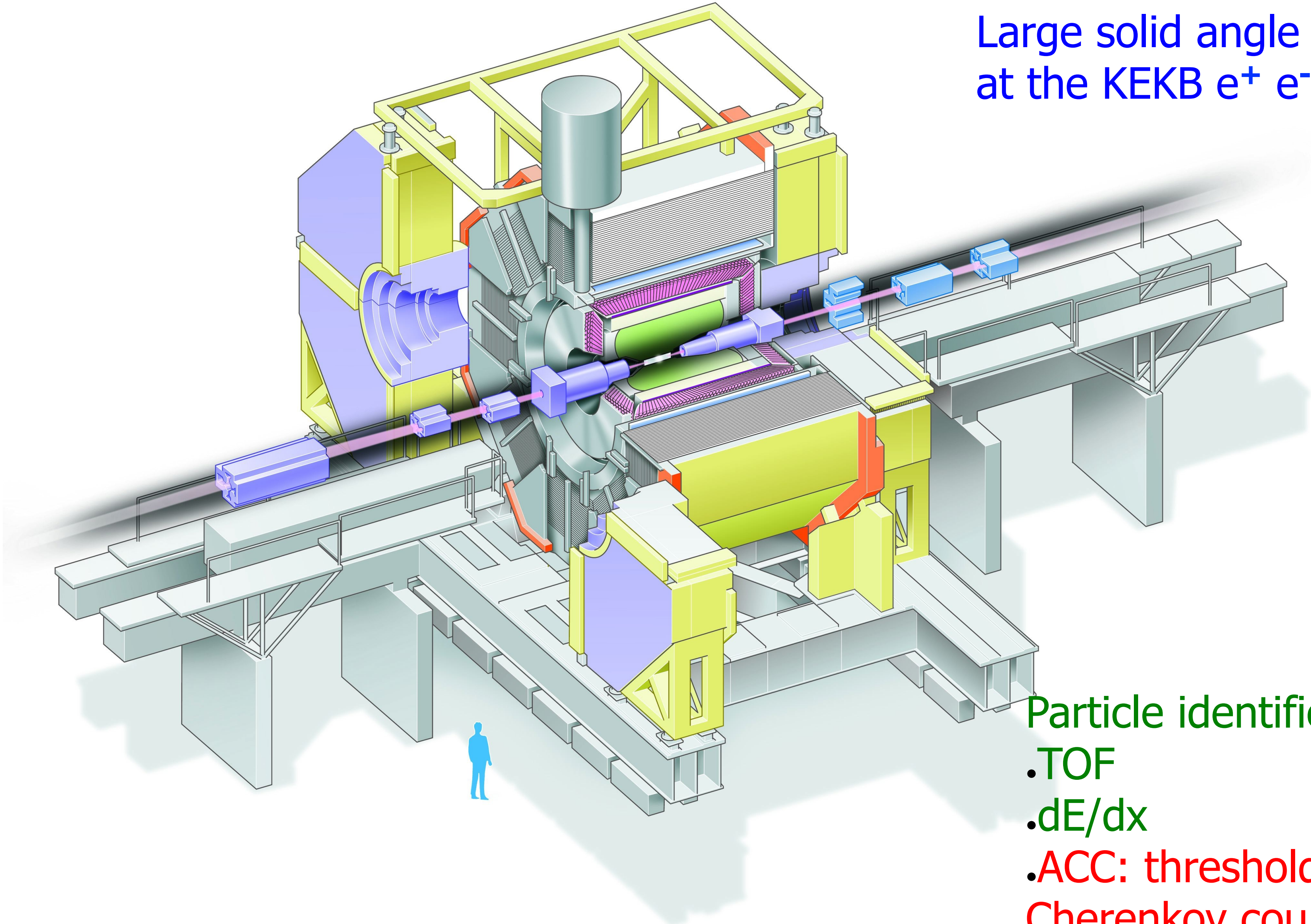
Advantages of this hybrid, pixel structure:

low noise: excellent resolution of single photoelectrons
high channel number/density

DEP, The Netherlands

Belle Spectrometer - PID

Large solid angle detector at the KEKB $e^+ e^-$ collider

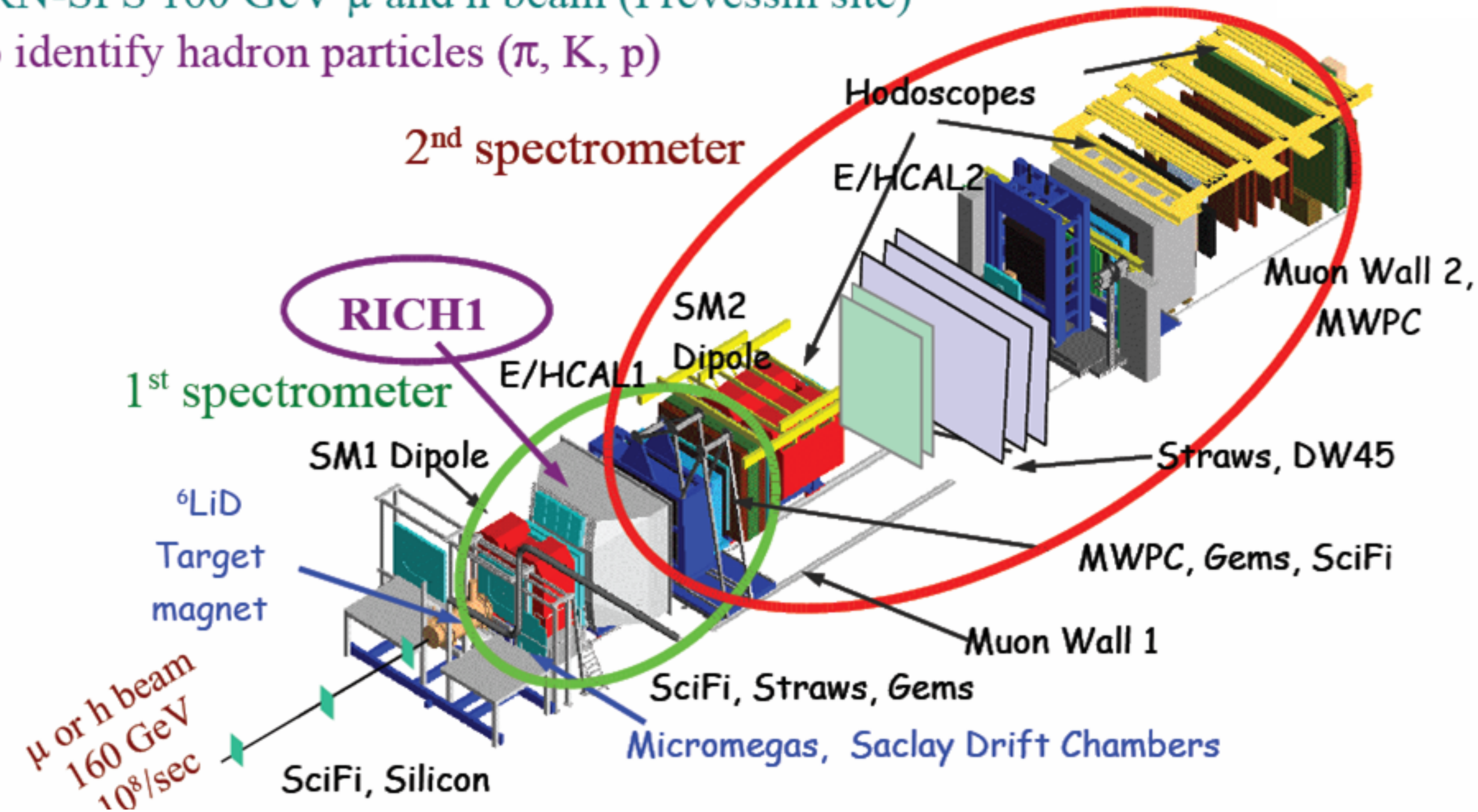


Particle identification:

- TOF
- dE/dx
- ACC: threshold aerogel Cherenkov counter

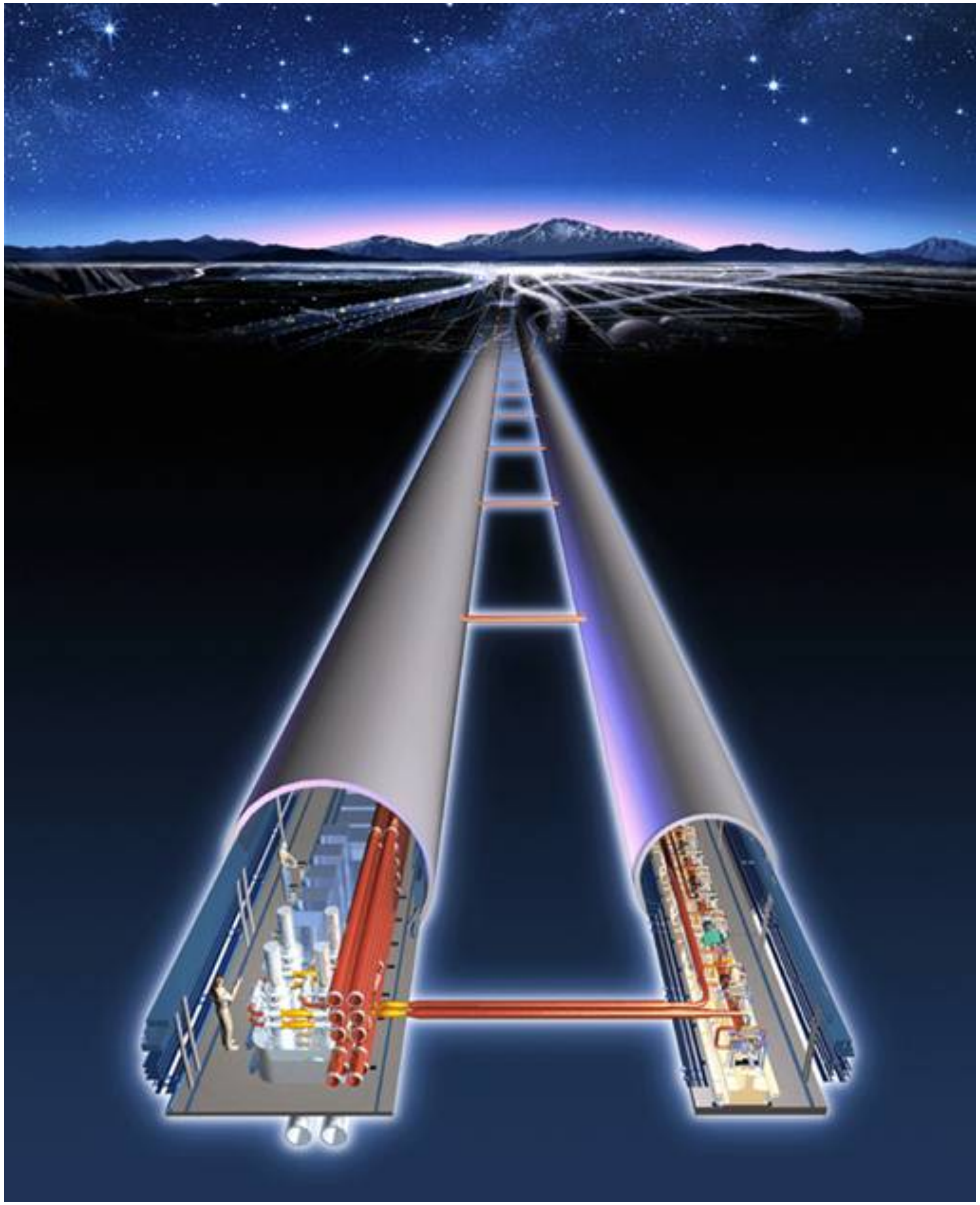
COMPASS at CERN

Dedicated to nucleon structure and spectroscopy studies
On CERN-SPS 160 GeV μ and h beam (Prévessin site)
Need to identify hadron particles (π, K, p)

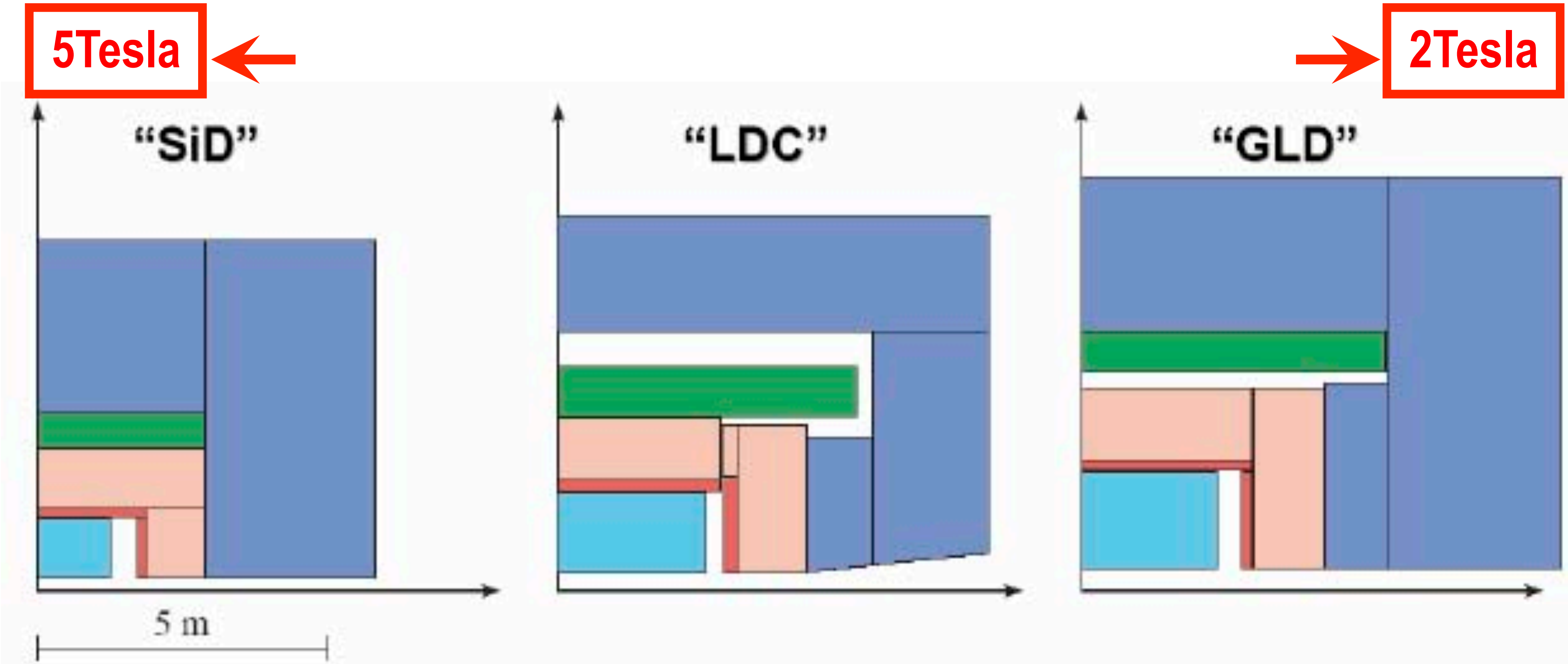


International Linear Collider

- Electron/Positron collider .
- Expandable, energies 0.5TeV to 1.5TeV.
- 10X larger than the Stanford Linear Accelerator.
- Two detectors.



ILC Detector Concepts



- Main Tracker
- EM Calorimeter
- Had Calorimeter
- Cryostat / Solenoid
- Iron Yoke / Muon System

- SiD: Silicon Detector — SiD: **B** R^2
  - Small, 'all' silicon
- LDC: Large Detector Concept — LDC: **B** R^2
  - TPC based
- GLD: Global Large Detector — GLD: **B** R^2

Particle Astrophysics

(Eckart Lorenz)

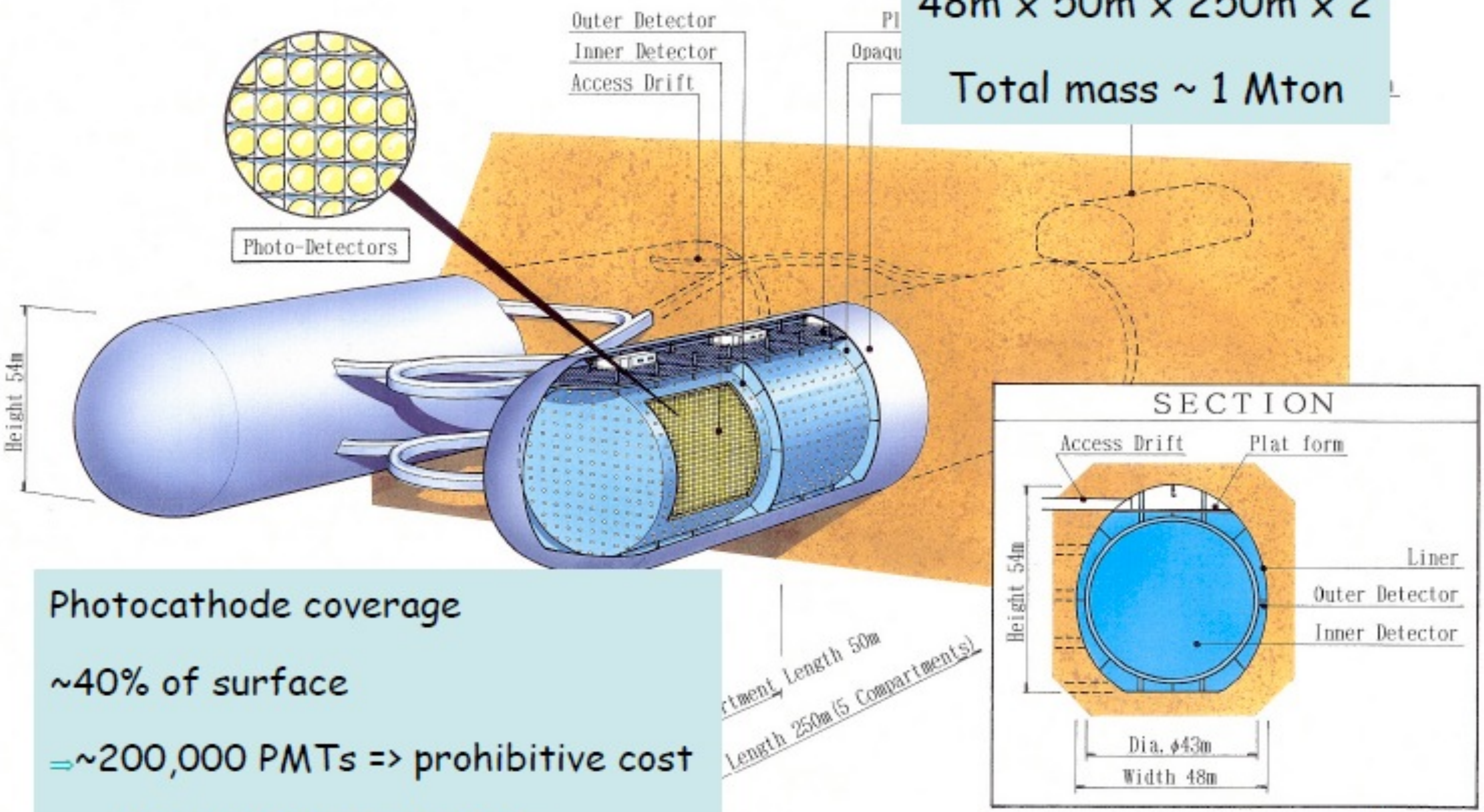
Multi-Messenger Exploration of Energy Frontiers

- Energy Frontier of Particle Physics, Cosmology and Astronomy
  - Earliest Universe: Inflation, Planck Scale …
  - Extreme Universe: AGN, GRB, SN …
- Need for Multi-Messenger Approach
  - Gamma ray Hess, MAGIC, GLAST …
  - Charged Particle Auger, EUSO …
  - Neutrino Super-K, Icecube…
  - Gravitational Wave LIGO, VIRGO, LISA …
  - Anti-Matter AMS, BESS…
  - Dark-Matter CDMS, Edelweiss …

Super-Kamiokande

- 11,200 of 20” PMTs

Hyper Kamiokande, UNO



48m x 50m x 250m x 2

Total mass ~ 1 Mton

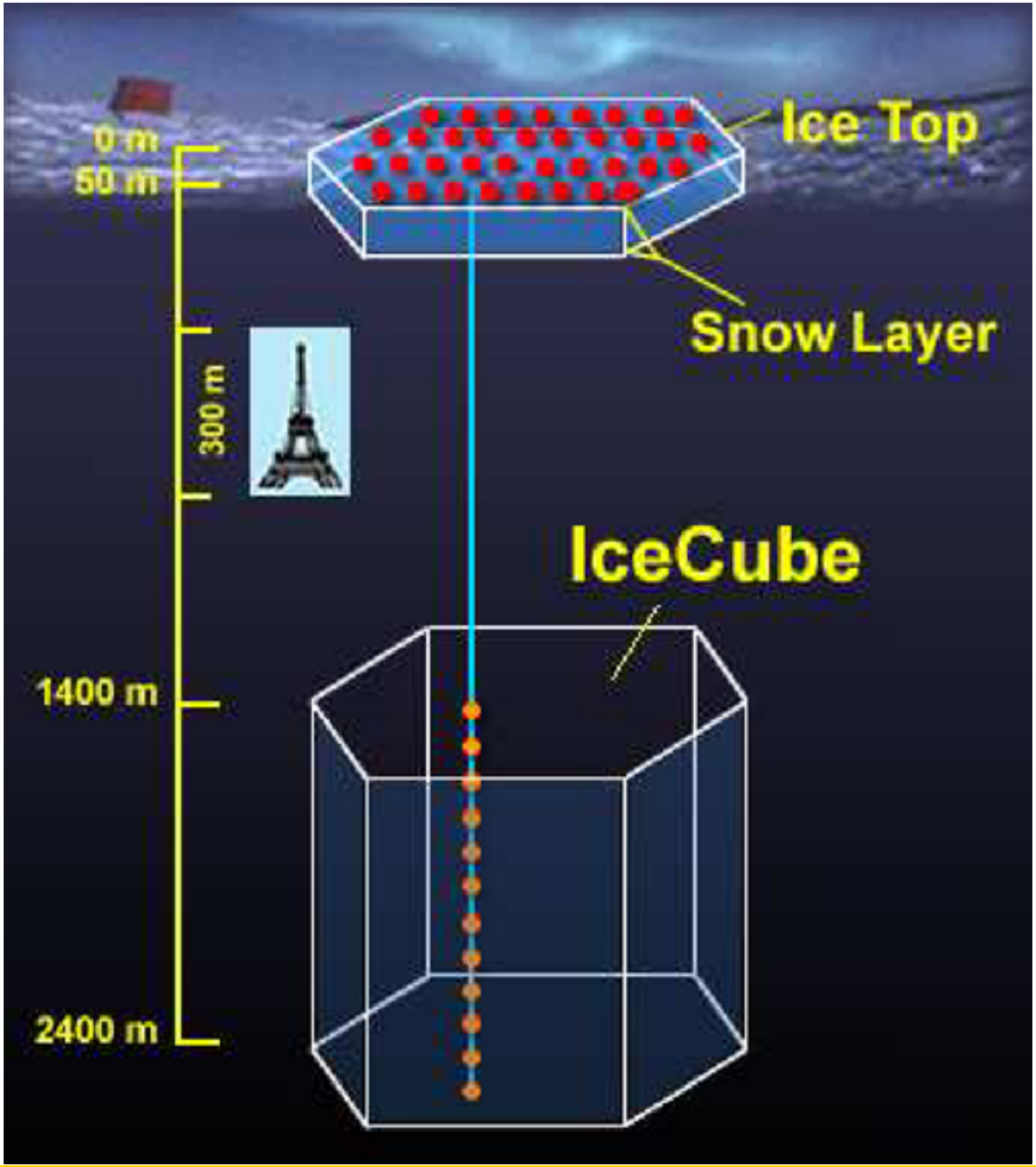
Photocathode coverage

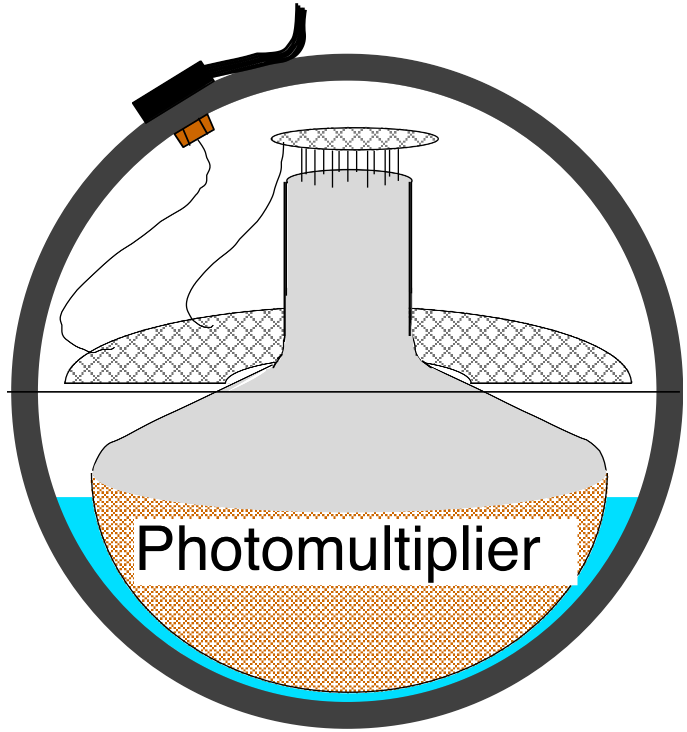
~40% of surface

⇒~200,000 PMTs => prohibitive cost

(~10,000 PMTs for SK)

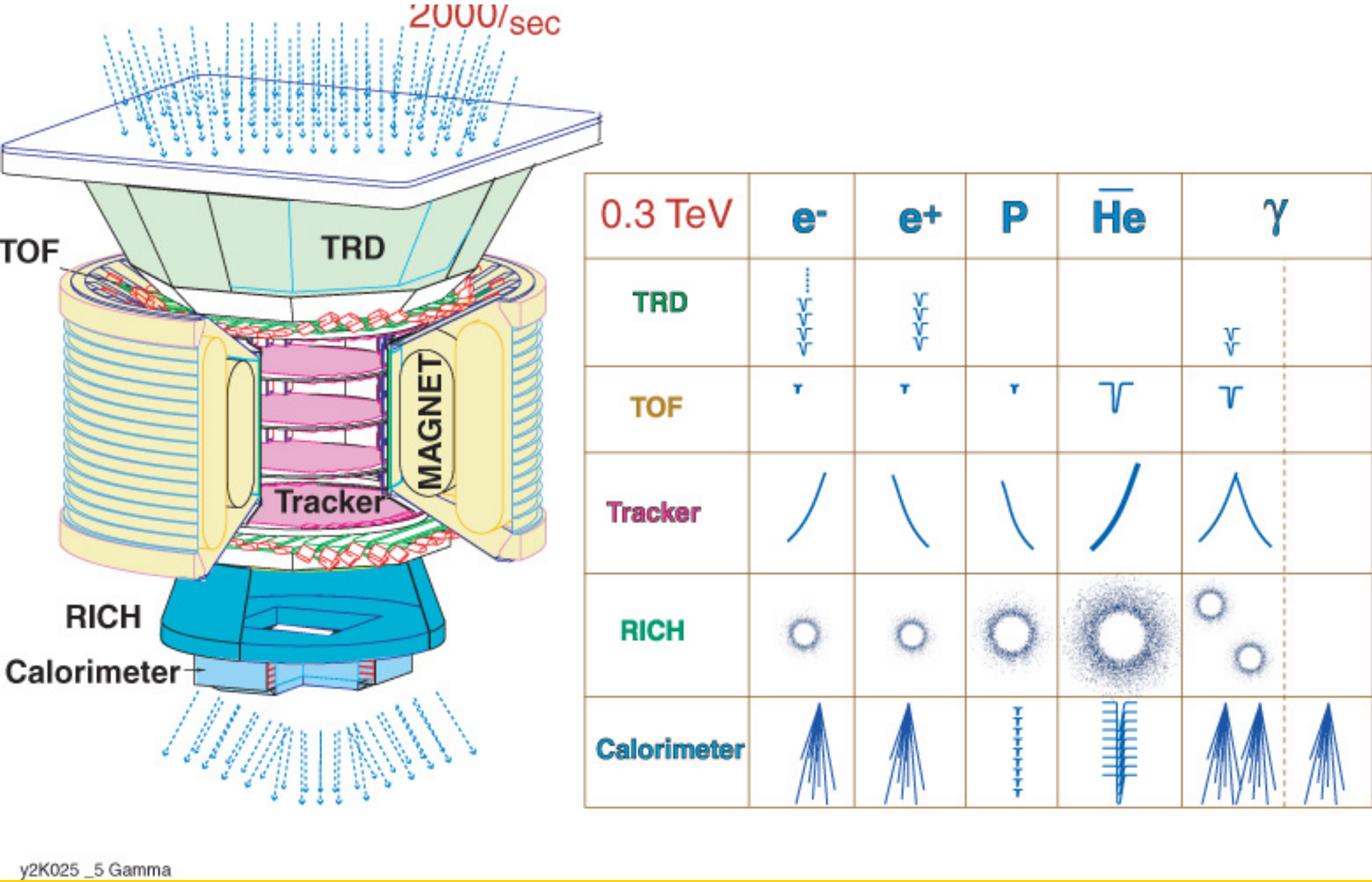
ICECUBE





60 PMTs/string x 80 strings
= 4,800PMTs

AMS - Anti-Matter Search

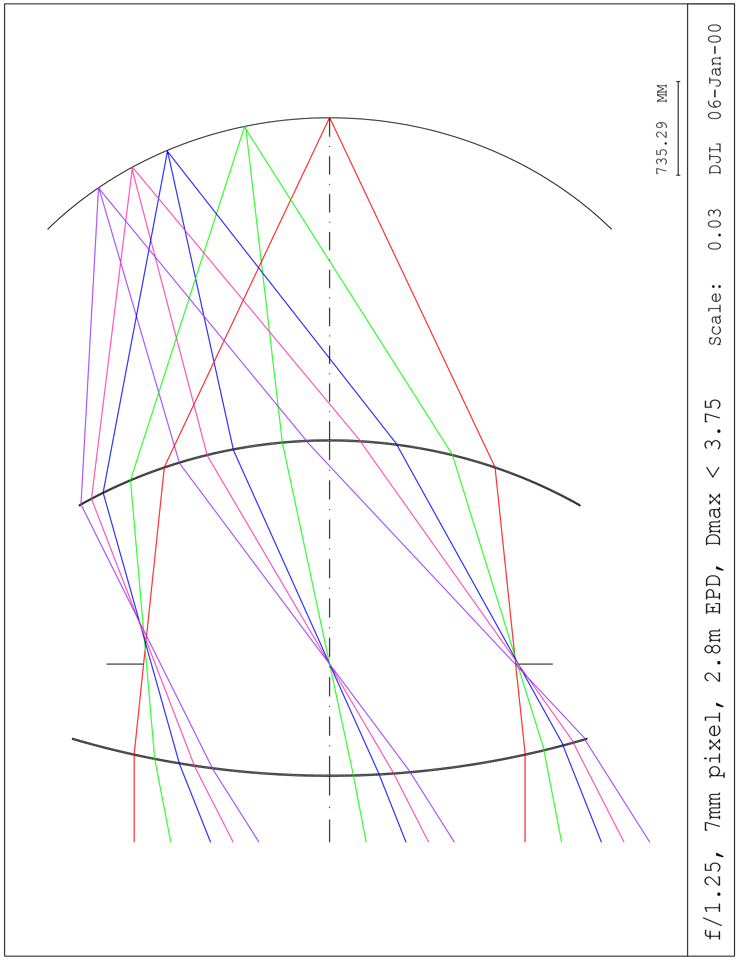


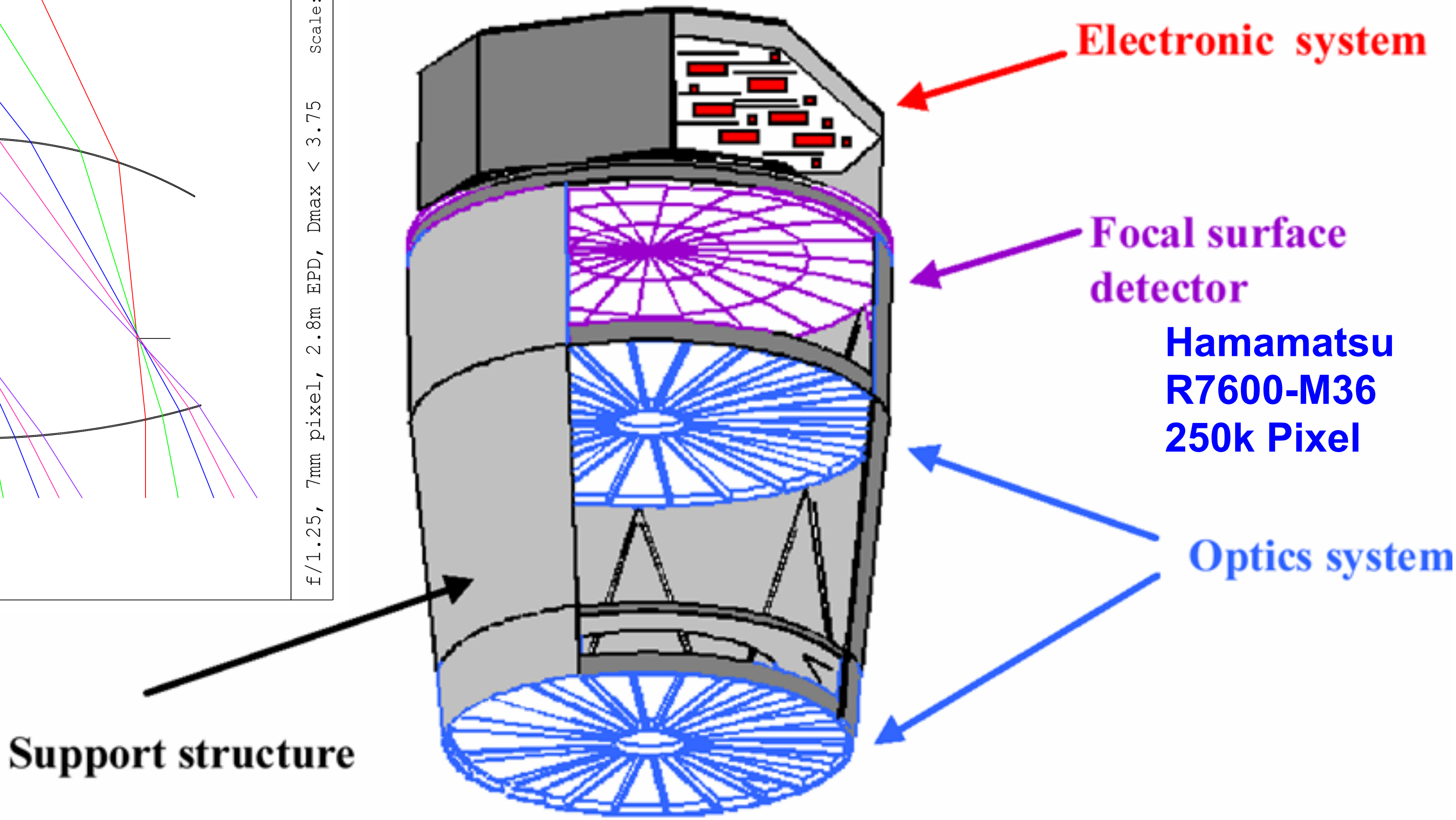
EUSO on International Space Station

A. Petrolini

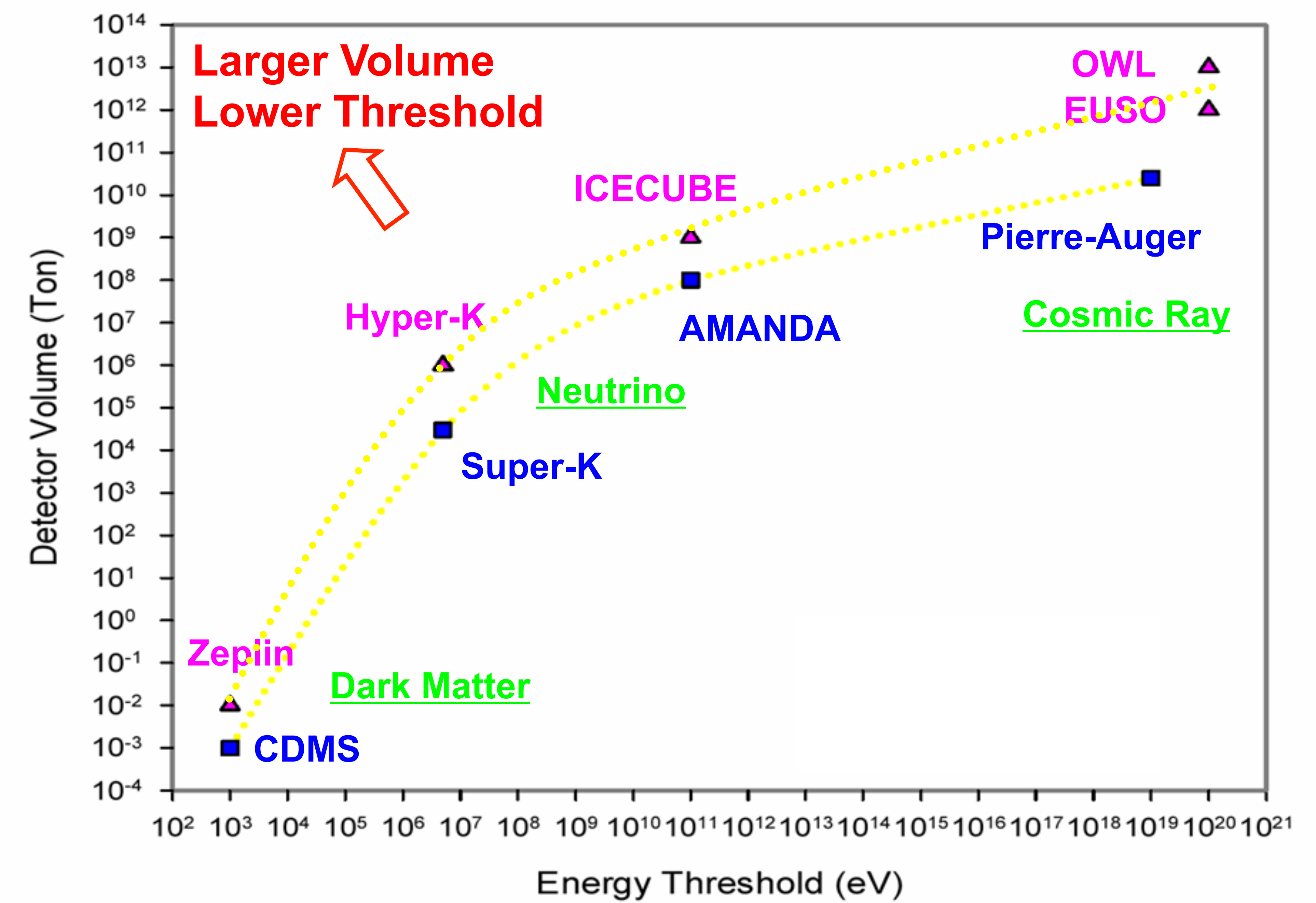
EUSO Detector

- 2.5m Diameter
- 60° FOV
- f/1.25

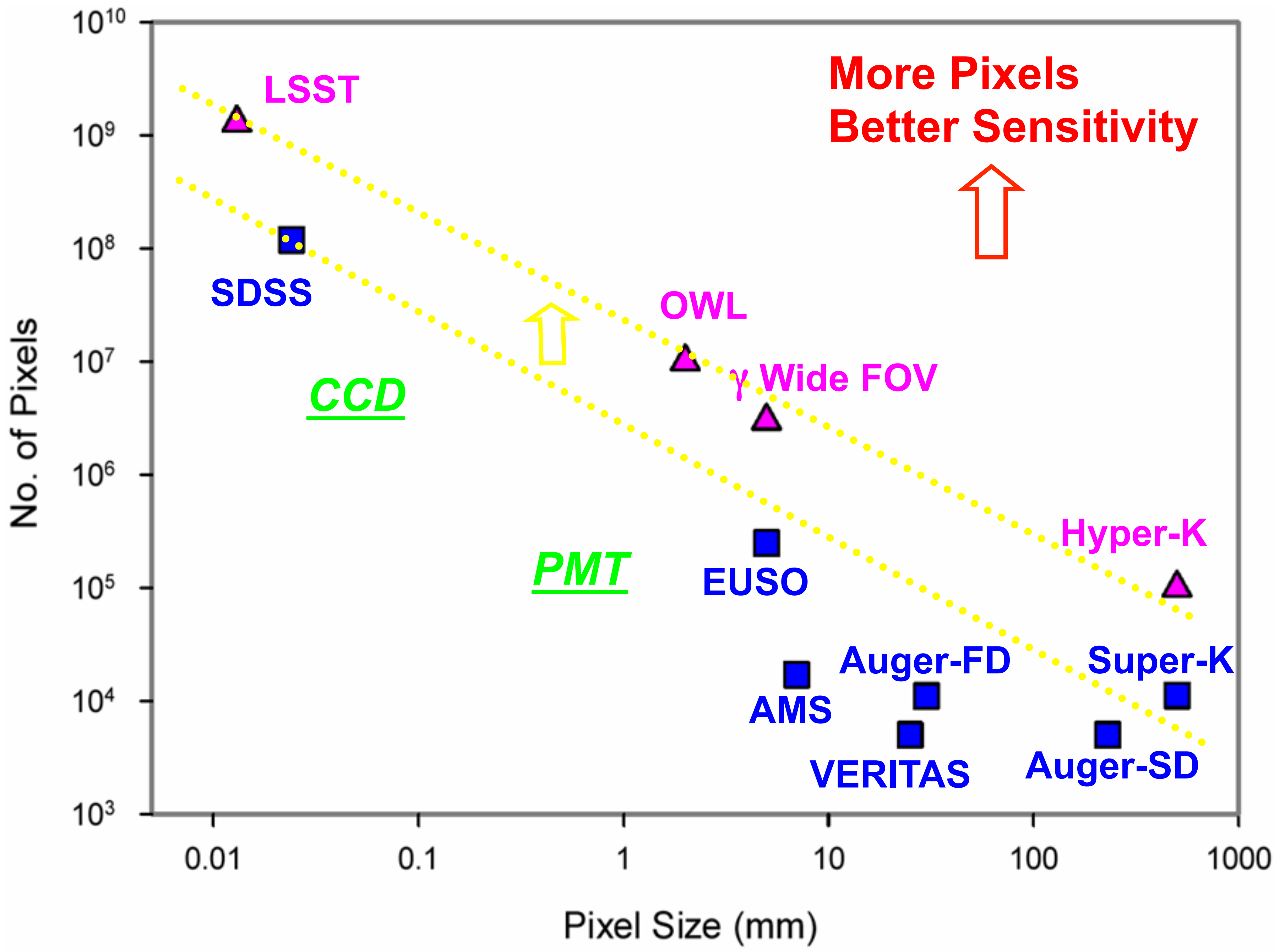




Detection of Cosmic Radiation



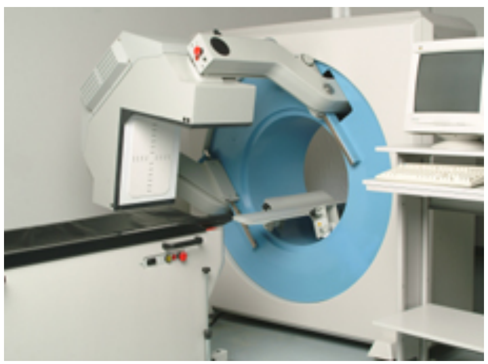
Photon Detector



Bio/Medical Imaging

- SPECT & PET
- Molecular Imaging

γ-Camera Today

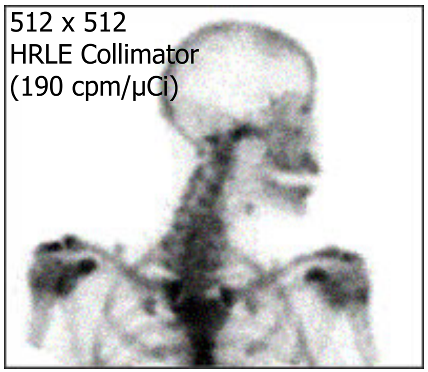


Workhorse of nuclear medicine

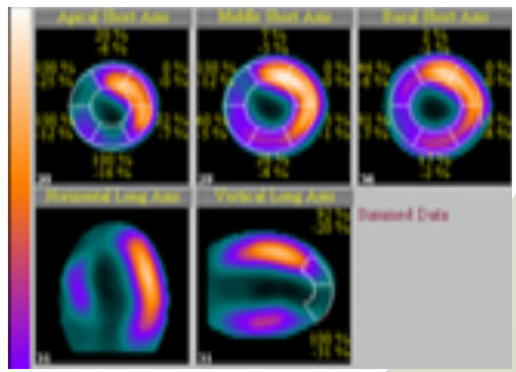
Improvements:

- ✓ **Large imaging area (up to 91 PMTs)**
- ✓ **Square & rectangular imaging FOV**
- ✓ **Variety of configurations for specific needs**
- ✓ **Digital signal processing → improved ΔE & Δx**
- ✓ **Multiple heads**
- ✓ **Rotating gantry for tomography (SPECT)**

Bone scan



Cardiac SPECT imaging



^{99m}Tc Sestamibi
64 × 64 matrix
48 45-sec steps
Gated 8 frames/R-R
HRGP Collimator
(250 cpm/µCi)

http://www.is2research.com/

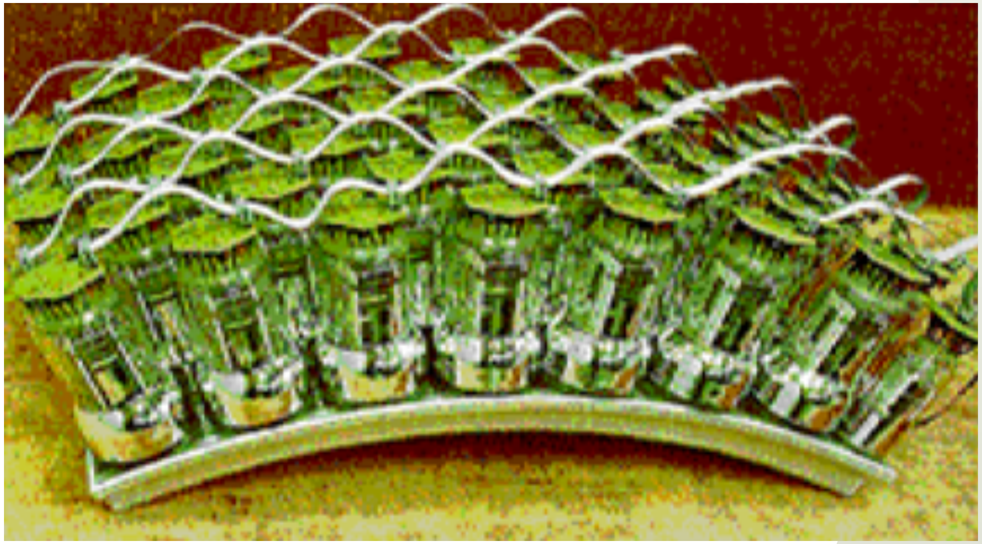
R. Lecomte

Anger Camera

Adam et al, *J Nucl Med* 42:1821-30, 2001

Large continuous NaI(Tl) bars

C-PET Module



- ☺ **Inexpensive**
- ☺ **Isotropic spatial resolution**
  - → **~5 mm FWHM**
- ☺ **High energy resolution**
  - → **Efficient scatter rejection**
- ☹ **Poor stopping power**
- ☹ **Limited count rate / high dead time**

⇒ **Excellent spatial resolution possible by reducing crystal thickness at the expense of sensitivity (*Green et al*)**

⇒ **Count rate performance can be improved by:**

- **Local triggering**
- **Slotted surface / Detector granularity**
- **Faster scintillator**

Crystals

Crystals	Density (g/cm^3)	Light yield (ph/MeV)	Decay time (ns)	Maximum Emission lenght (nm)	ΔE/E (FWHM) PMT read-out	
					662 keV **	140 keV
NaI:Tl	3.67	41000	230	410	5.6 %	8.5 %
CsI: Na	4.51	40000	630	420	7.4 %	9.5 %
CsI:Tl	4.51	66000	$800 \div 6 \times 10^3$	550	6.6 (PMT)/ 4.3 (SDD)	14 %
$LaCl_3$:Ce	3.79	49000	28	350	3.8 %	8.0* %
$LaBr_3$:Ce	5.3	63000	26	380	2.8 %	5.8 %
$Bi_4Ge_3O_{12}$ (BGO)	7.1	9000	300	480	9.0 %	--
Lu_2SiO_5:Ce (LSO)	7.4	26000	40	420	7.9 %	18 %
Gd_2SiO_5:Ce (GSO)	6.7	8000	60	440	7.8 %	22 %
YAl O_3:Ce (YAP)	5.5	21000	30	350	4.3 % (APD)	20 %

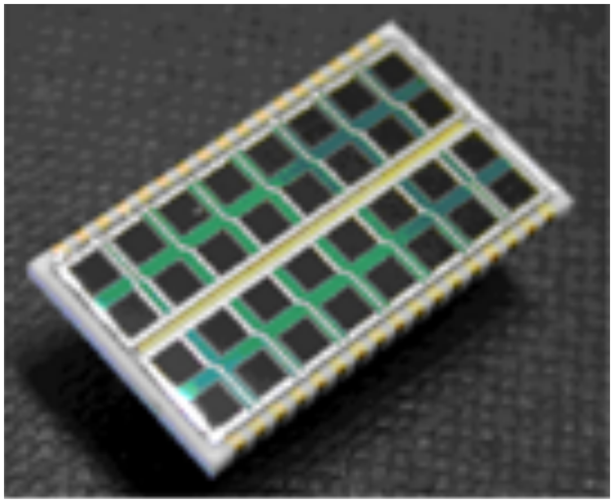
** from C.W.E. van Eijk Phys. Med. Biol. (2002) 85-106
* Expected values

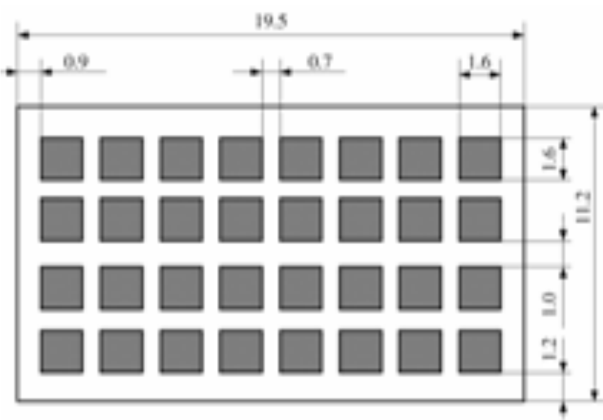
Individual Coupling & Independent Processing

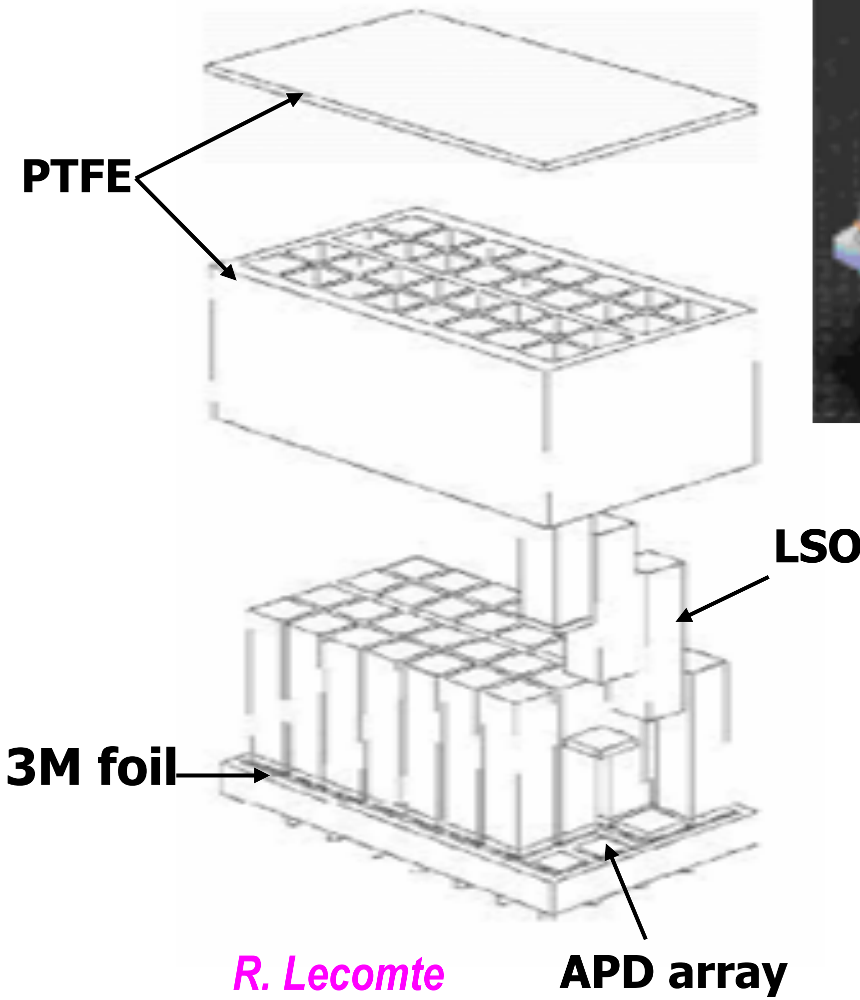
Munich APD PET (MADPET II)

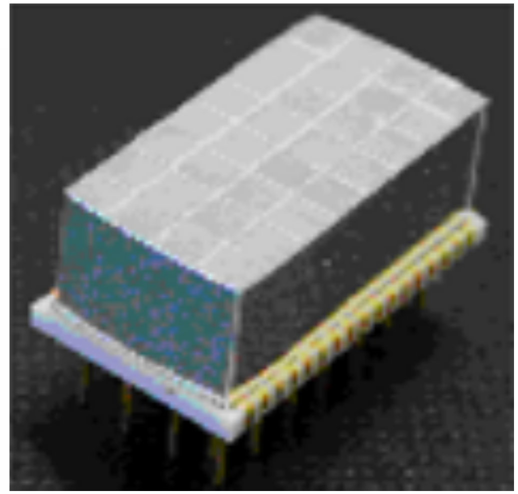
Pichler et al,
IEEE MIC 2000

4 × 8 APD Array (Hamamatsu Photonics)
2 × 2 × 6 mm^3 LSO individually coupled
b ~ 0 mm → Intrinsic FWHM ~ 1.2 mm









√ **Good packing fraction**
• **Poor light collection**

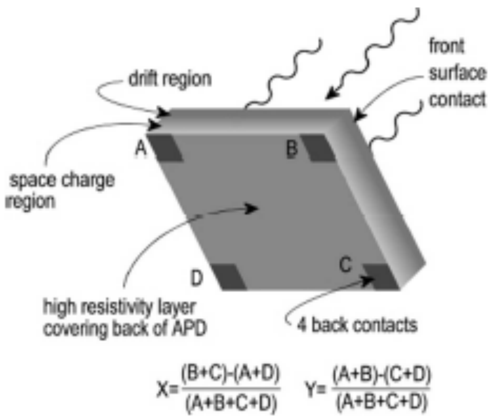
R. Lecomte

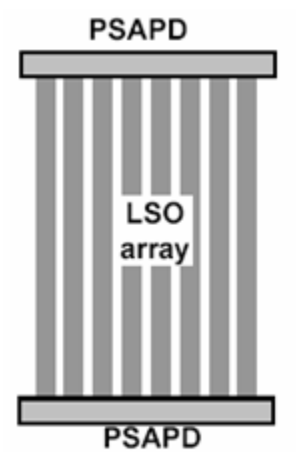
Dual APD Readout

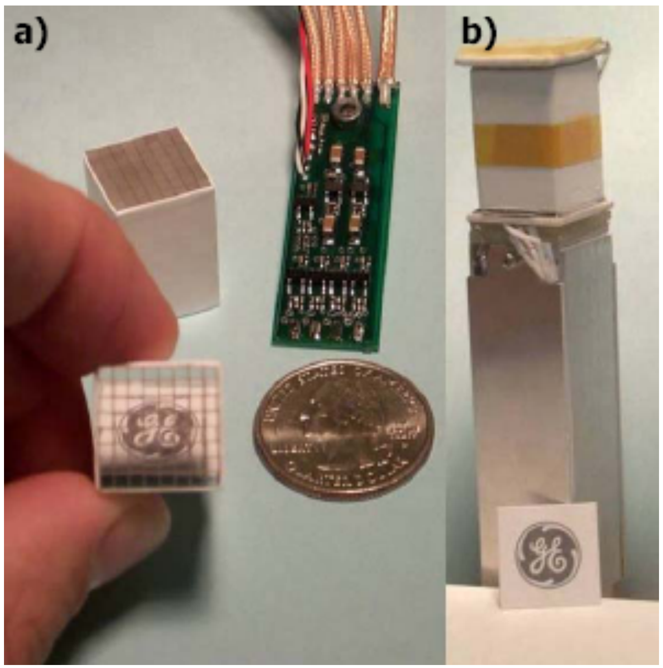
PS-APD Module

Burr et al, *IEEE NSS/MIC* 2003

1.65 × 1.65 × 22 mm^3 MLS crystals
8 × 8 array on dual 14 × 14 mm^2 PS-APDs
~ 3 mm FWHM DOI resolution







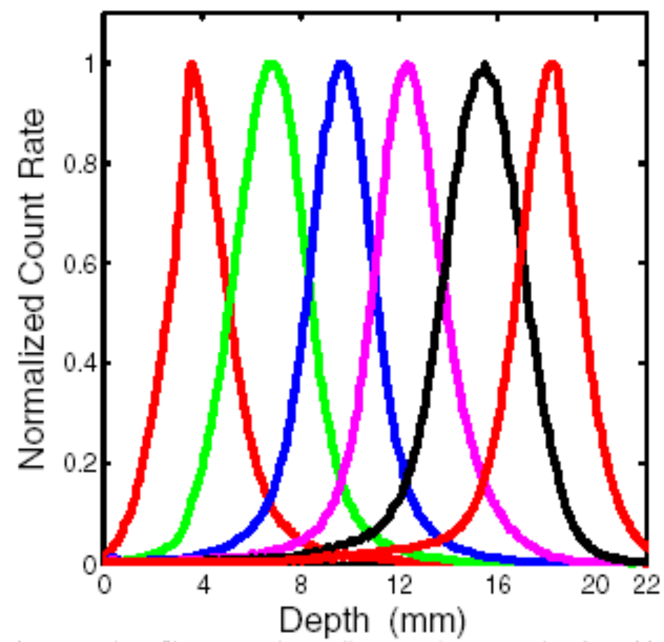
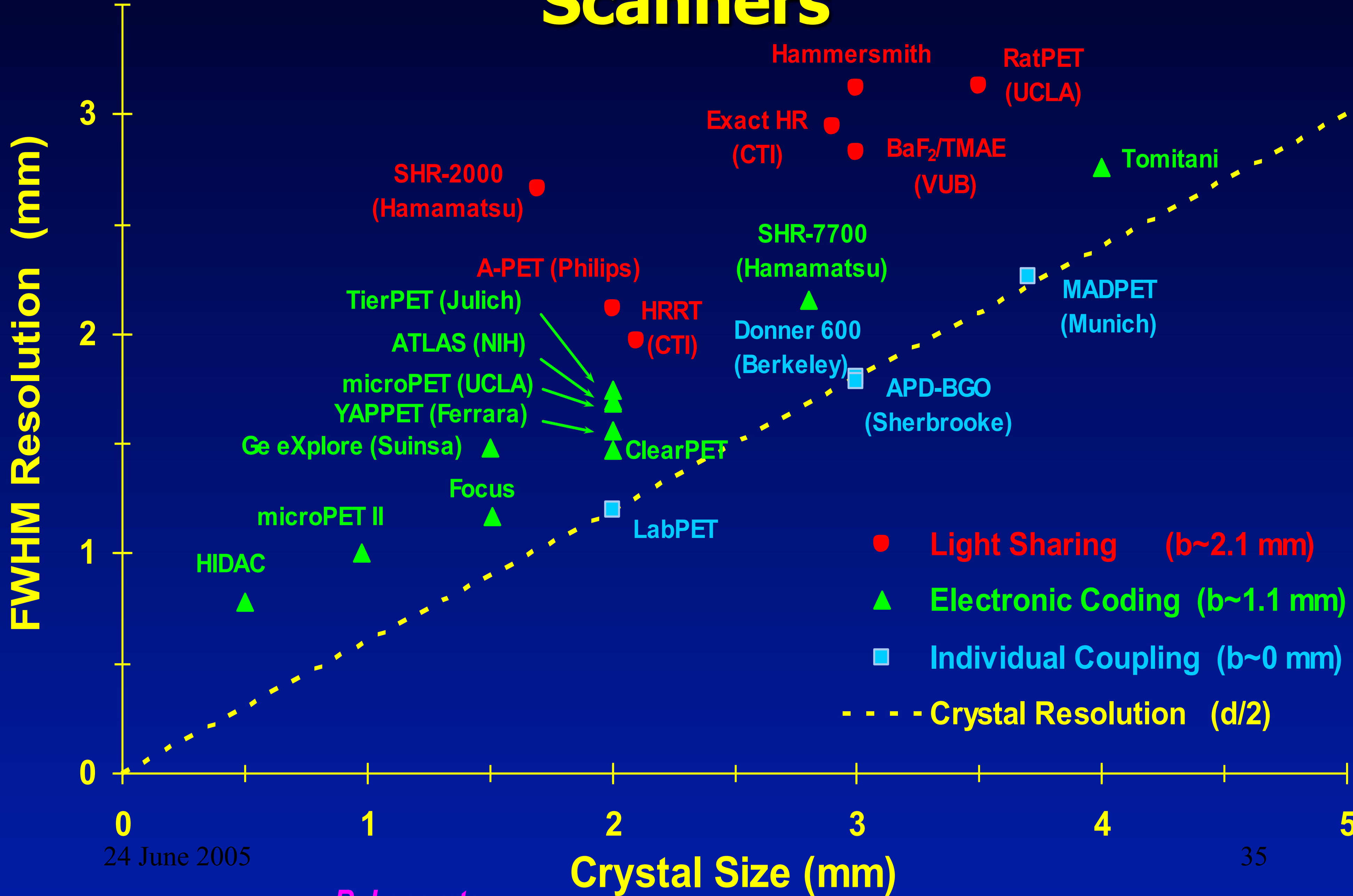


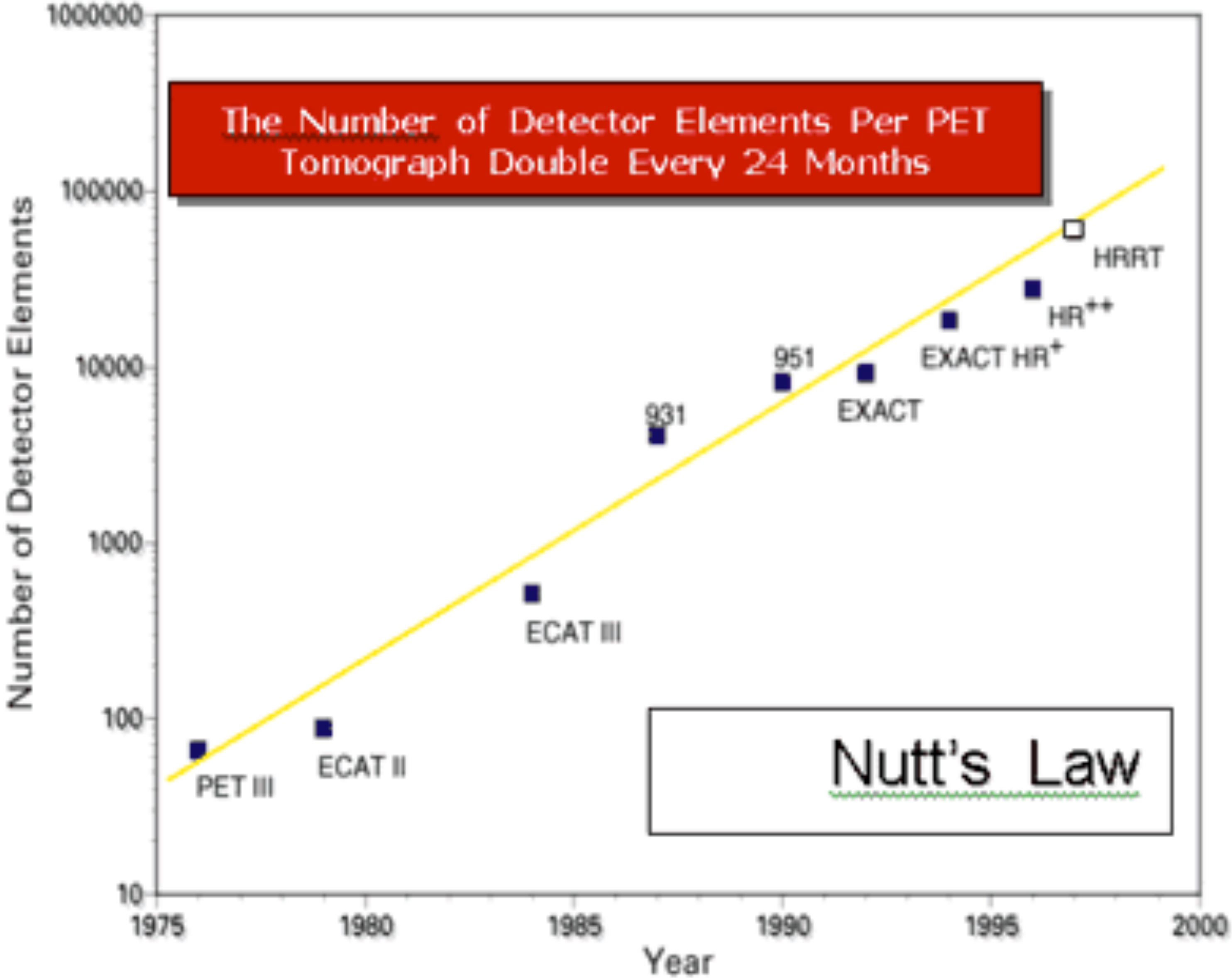
Fig. 3. Depth profiles (summed over all 64 crystals) measured at six positions. The FWHM of the profiles varies from about 3 to 4 mm, and it is dominated by the width of the collimated beam. An energy window of 250 to 650 keV was applied.

Intrinsic Spatial Resolution of PET Scanners



R. Lecomte

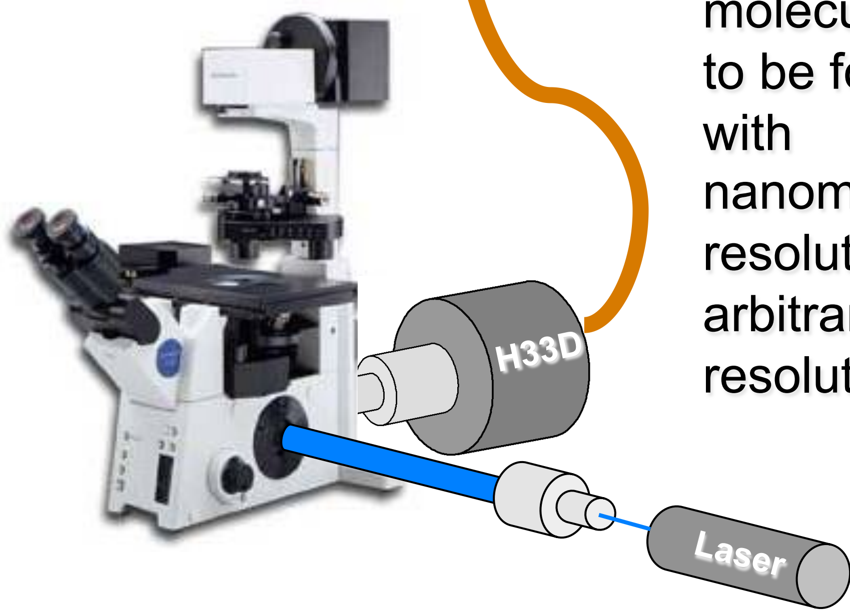
Nutts' Law

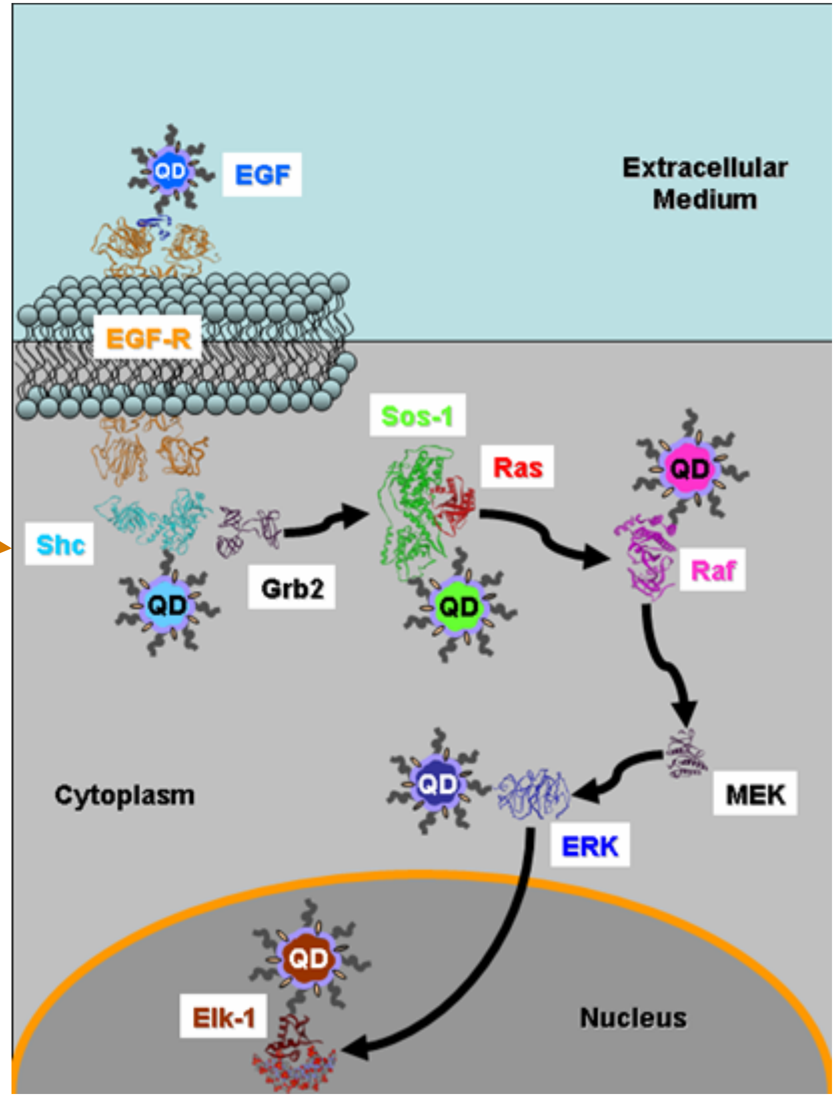


The Number of Detector Elements Per PET Tomograph Double Every 24 Months
Nutt's Law
Number of Detector Elements
Year
1000000
100000
10000
1000
100
10
1975
1980
1985
1990
1995
2000
PET III
ECAT II
ECAT III
931
951
EXACT
EXACT HR+
HR++
HRRT

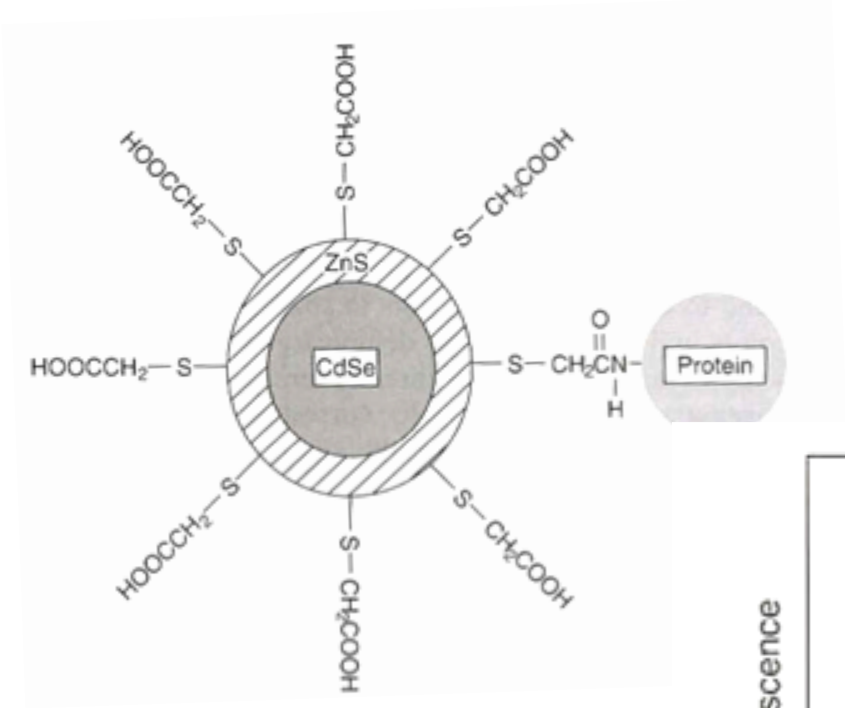
Single Molecule Imaging

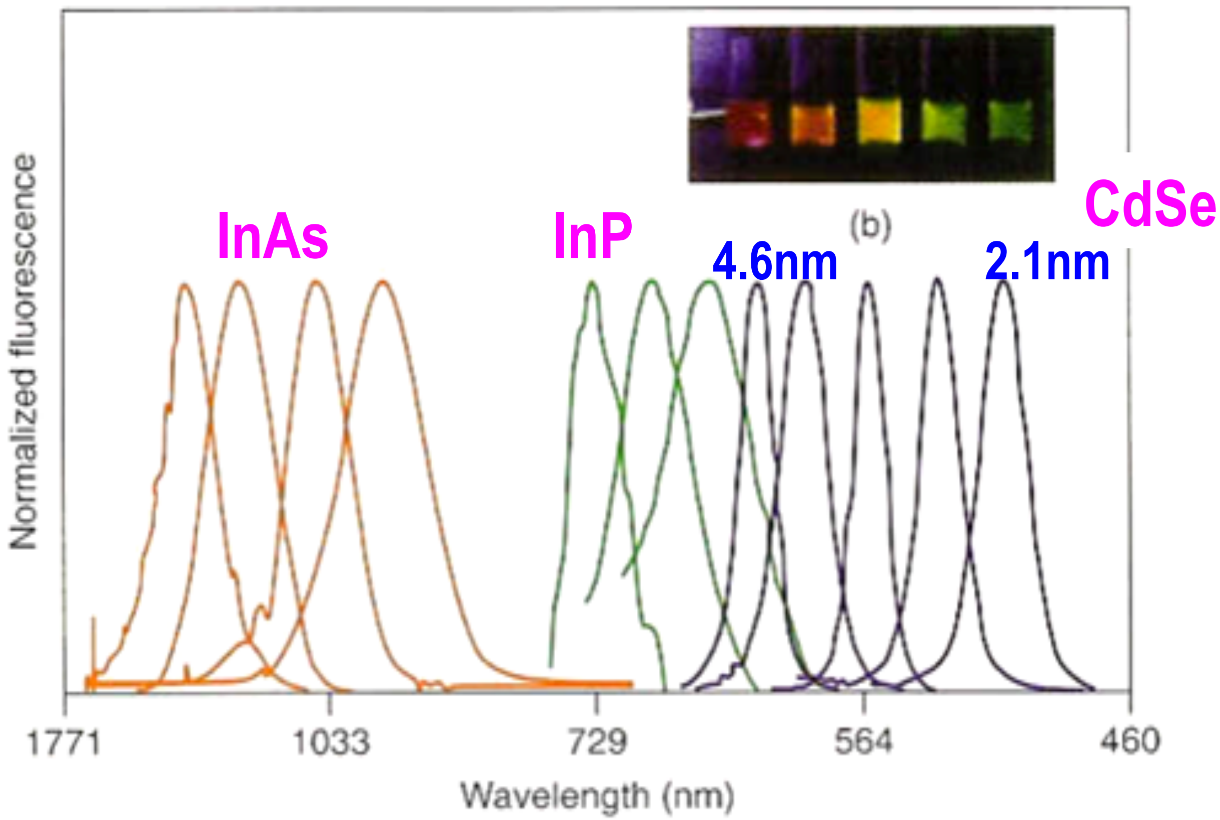
The H33D capabilities will allow protein-protein interaction, protein trafficking at the single-molecule level to be followed with nanometer resolution and arbitrary time-resolution



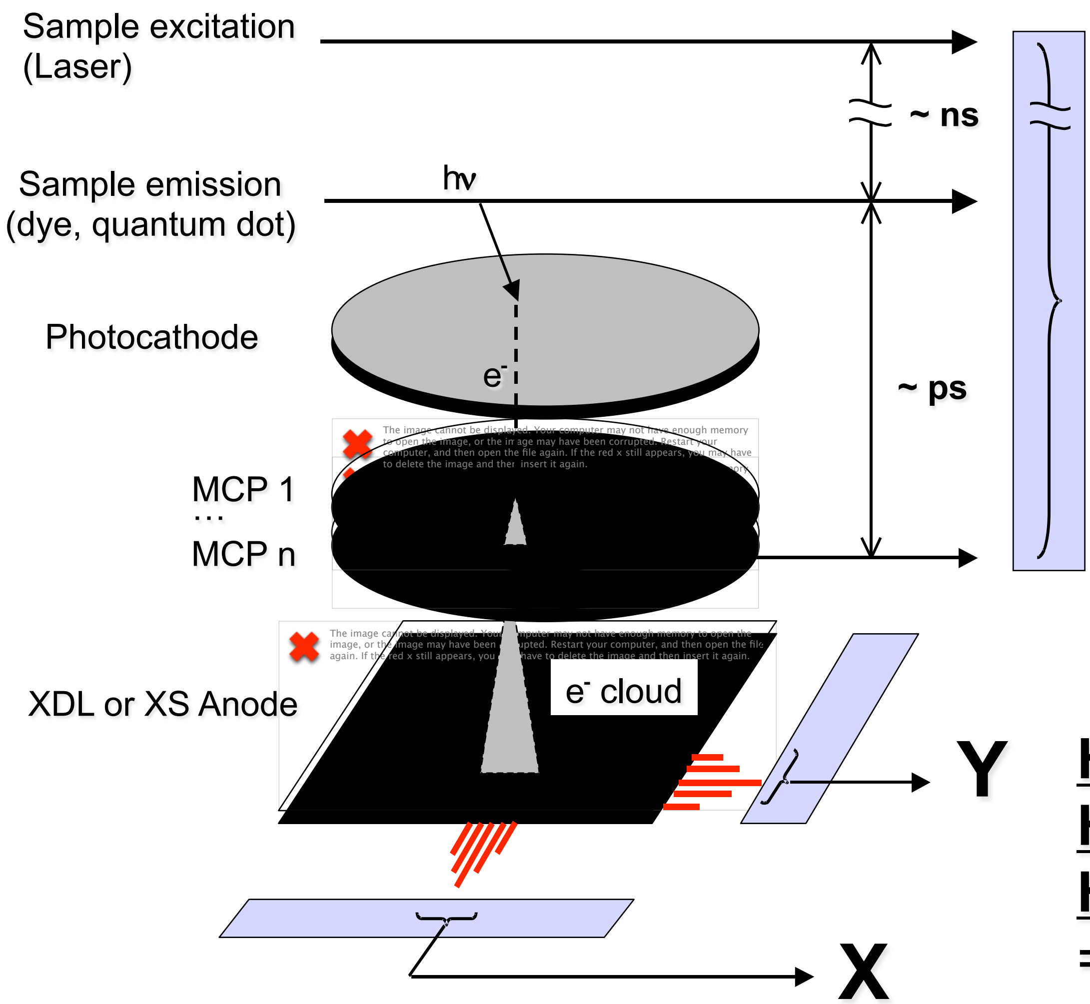


Emission of Quantum Dot





Schematic of the H33D detector



t (100 ps) **+ T** (20 ns)

X + Y + T = **3D**

High spatial resolution: **100 um**
High temporal res. : **100 ps**
High throughput: **50 MHz**
= **H**^{3}

H33D = Heed = Attention, Notice

General Requirements

- Various Sizes
  - Large Area > 30 cm
    - Neutrino, Proton decay…
  - Coarse Pixel 1-5 mm
    - RICH, Tile Calorimeter, EUSO, PET…
  - Imaging < 100 μm
    - Astronomy, Single Molecule…
- High Speed
  - TTS < 1 nsec
  - Rate > 1 MHz
- Single Photon Counting
- (Insensitive to Magnetic Field)
- Los Cost !

New Developments on Detectors

- Gaseous
- PMT
- Hybrid
- Solid State

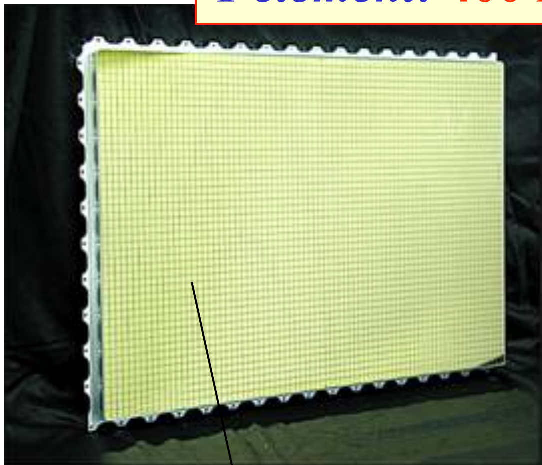
Gaseous Detector

(Amos Breskin)

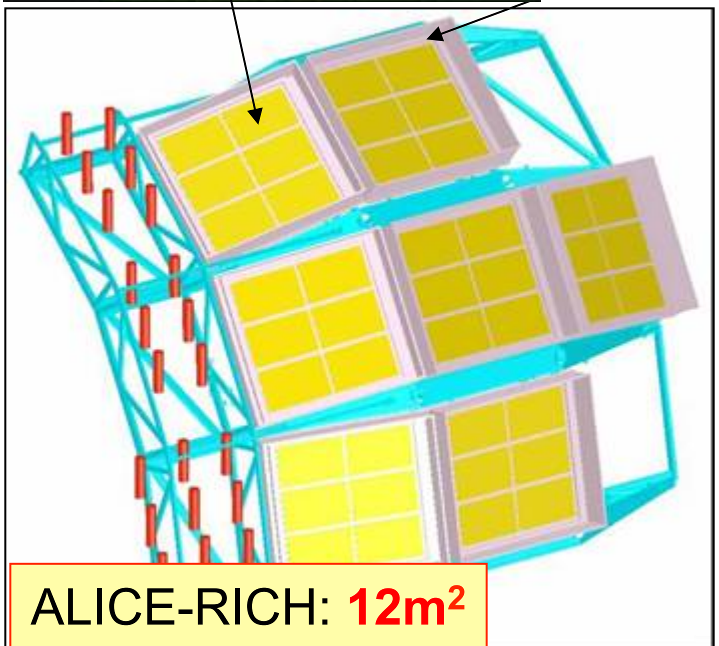
CERN-ALICE CsI-RICH

RICH: Ring Imaging Cherenkov UV-detectors for particle identification

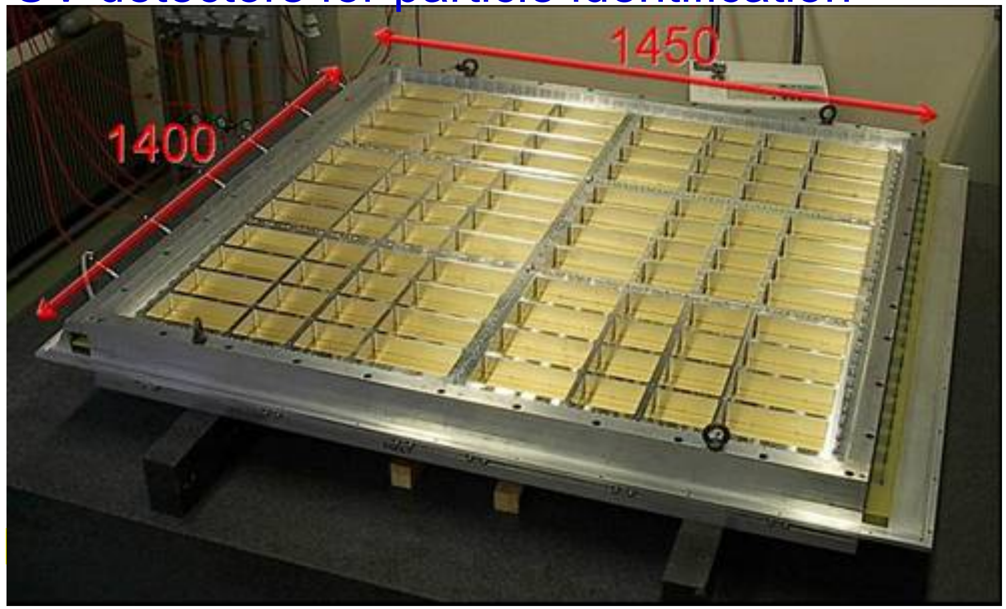
1 element: **400 x 600 mm^2**



~2m^2



ALICE-RICH: **12m^2**

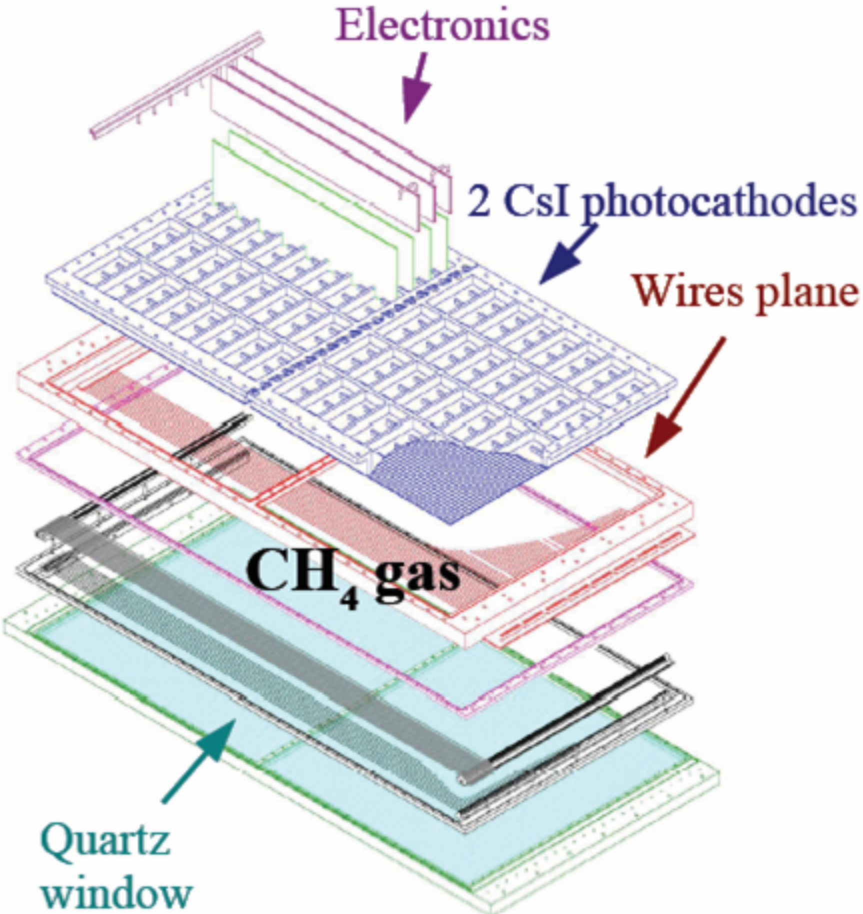


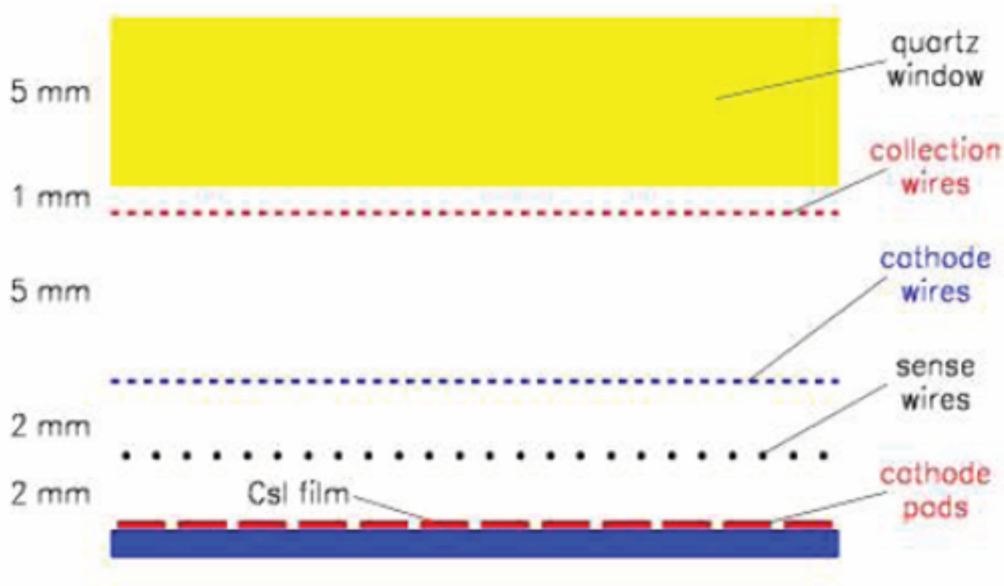
- **Single arm detector, radial distance of 4.9 m**
- **$|\eta| < 0.9$, 5% of barrel acceptance**
- **Proximity focusing (80 mm gap), 15 mm C_6F_{14} radiator, 7 modules each with 6 CsI PC**
- **Total active area ~12 m^2**
- **FEE: Gassiplex 0.7 μ, noise 1000 e$^-$**

<u>CsI-RICH:</u>
ALICE, HADES, COMPASS, J-LAB….

COMPASS RICH

8 chambers with 2 photocathodes each, methane gas





photocathode: 72x72 pads of 8x8 mm²

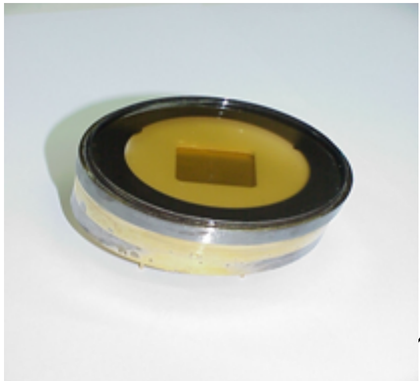
γ detection range 160-200 nm

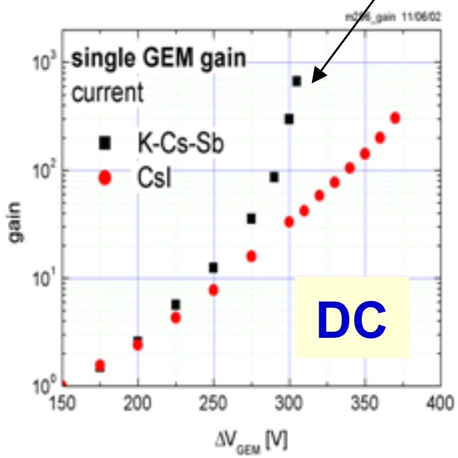
gas gain ~ 3.10^4 at 2000V

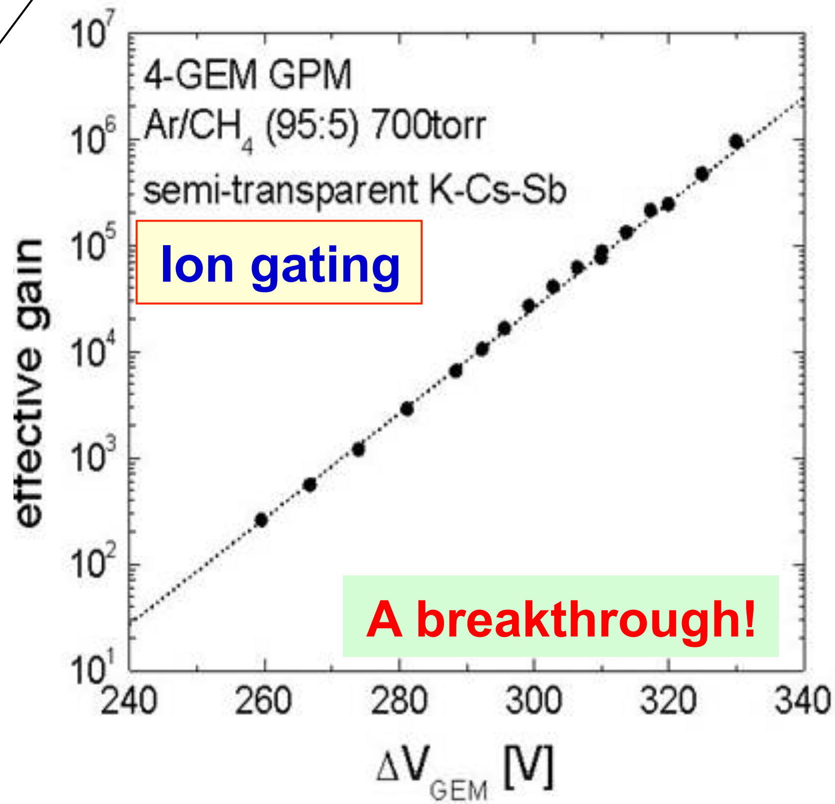
Gated GPM for visible light

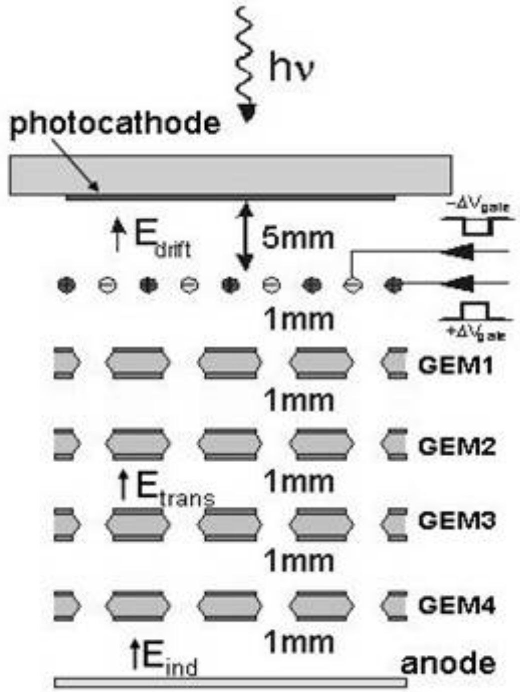
GAIN: 100-1000 in **DC** mode (ion feedback limit)

~10^6 in ion-gating mode





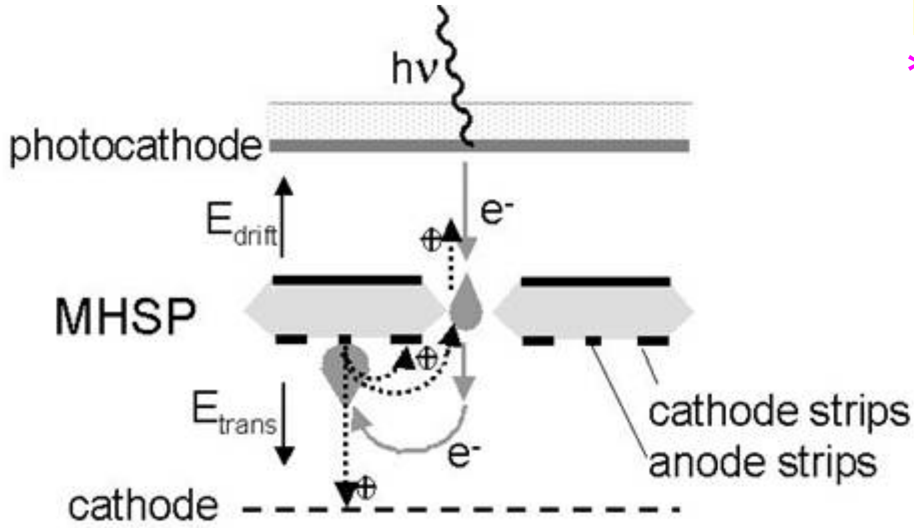




A. Breskin et al. Physics/0502132

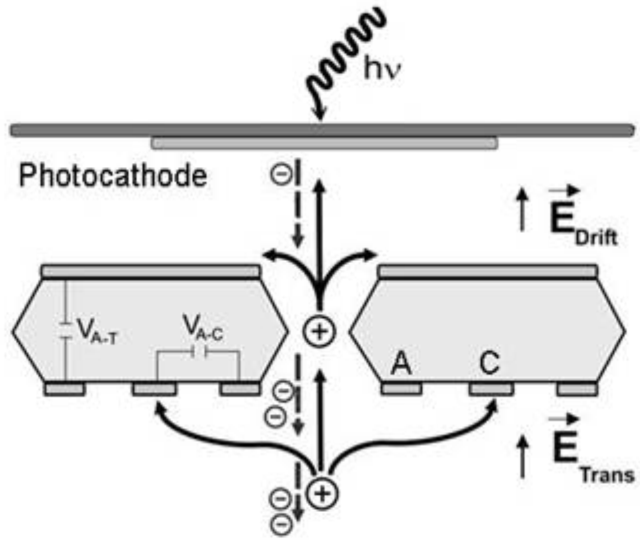
Ion Back-flow Reduction: Reversed-MHSP

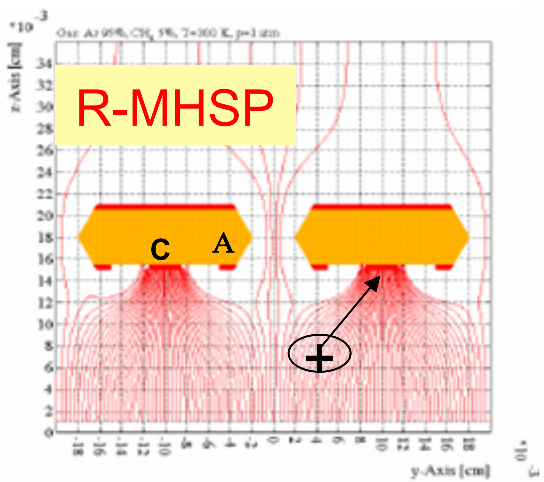
MHSP: 2-step gain & some ion blocking



R-MHSP: hole-gain & ion defocusing from successive multiplier*

* R-MHSP: Roth, Vienna 04

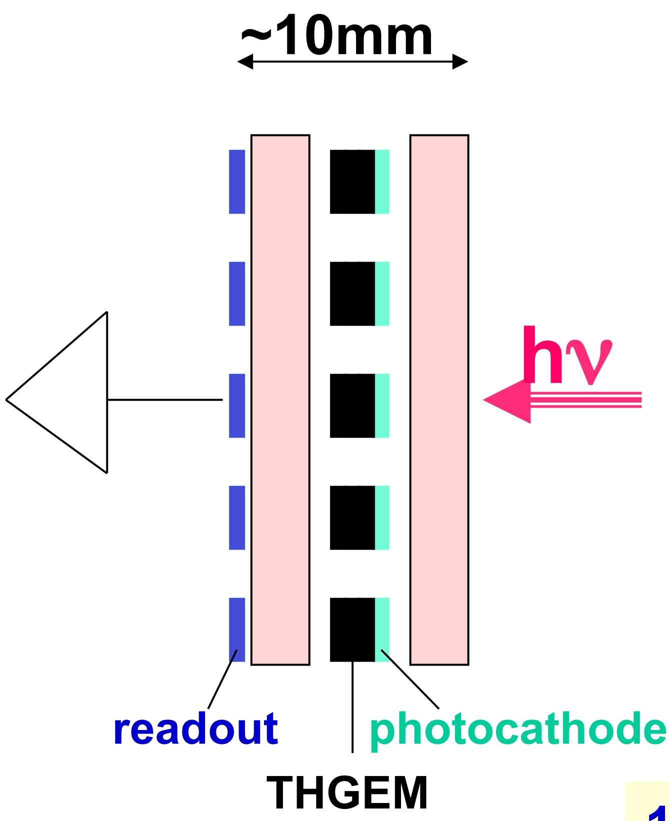


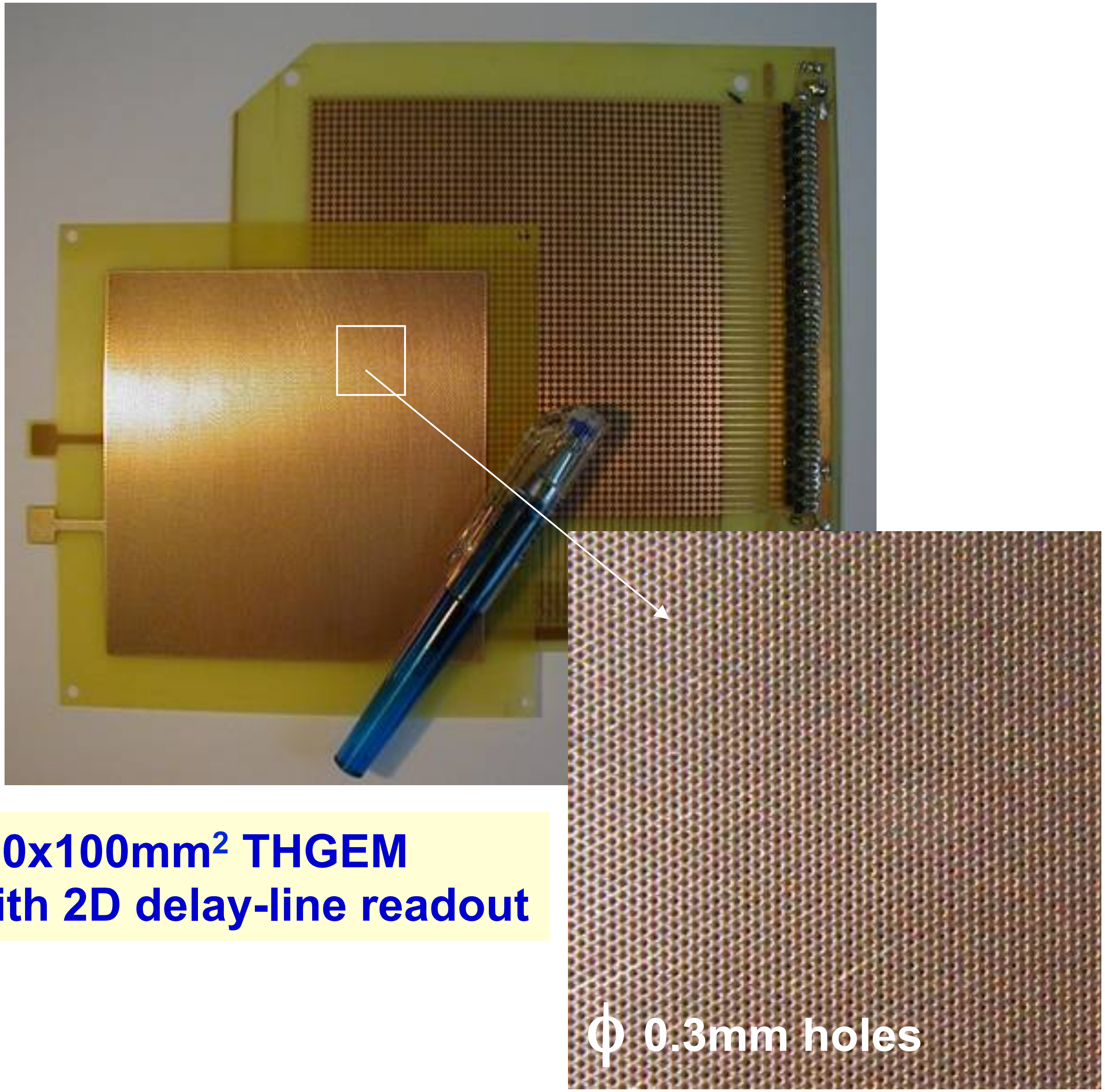


Ion blocking:
Breskin et al. physics/0502132
Veloso et al. physics/0503237

Simulations:Oleg Bouianov

A Very Flat Gaseous Imaging PM



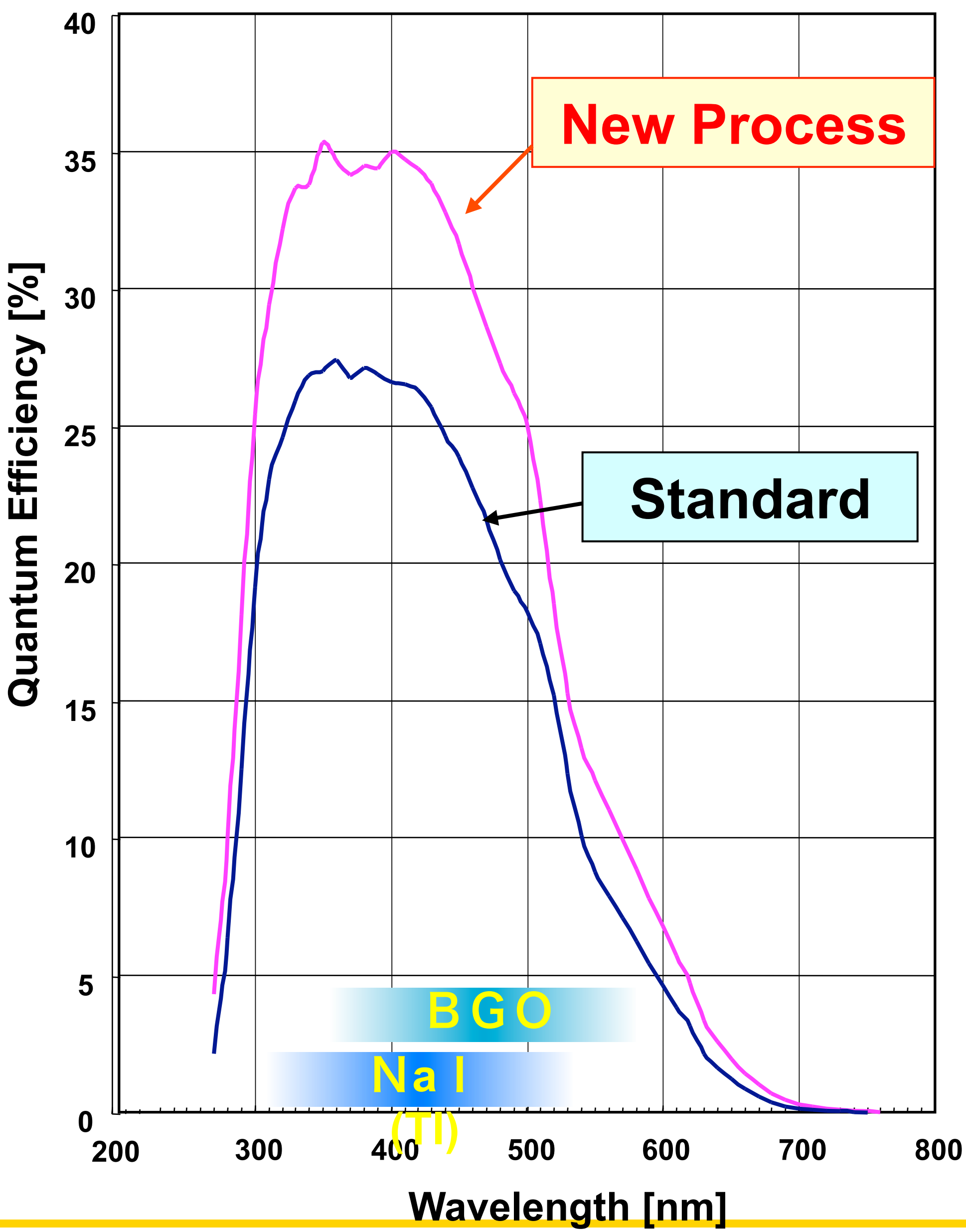


100x100mm^2 THGEM
With 2D delay-line readout

Photomultiplier

- High QE Alkali
- Multi Pixel, Flat PMT

Hamamatsu High QE Photocathode

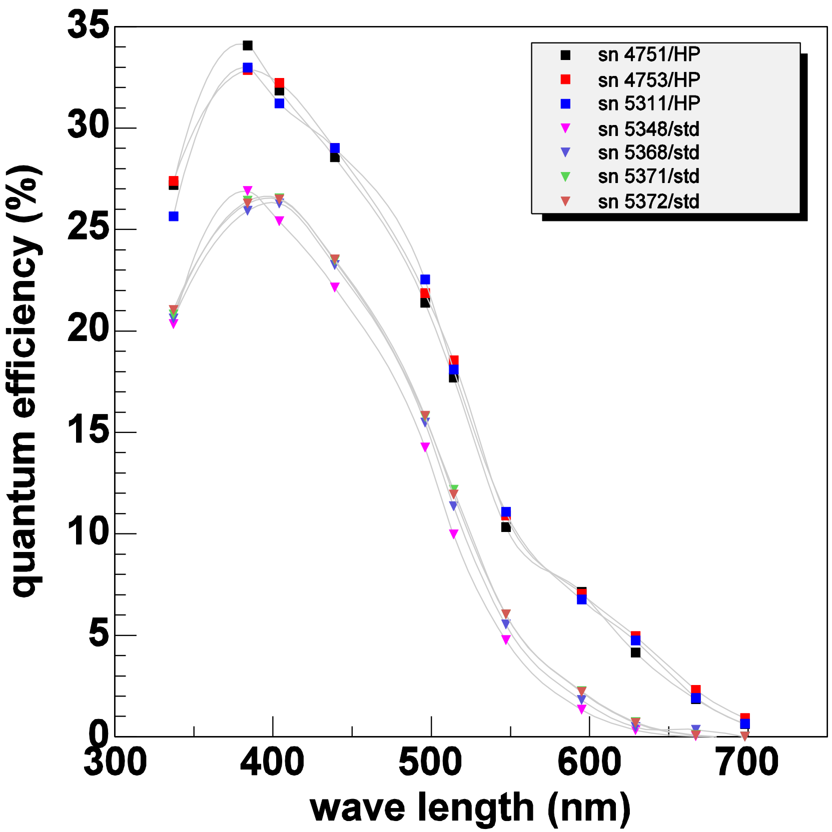


Bialkali Photocathode

new process BEST	37 %
new process TYPICAL	34 %
standard typical	27.5 %

(at 360 nm)

Improved QE of Photonis 9 inch PMT



$$QE(\%) = 124 \frac{S_{k,\lambda}(\mu A / W)}{\lambda(nm)}$$

- <u>Quantum efficiency (400 nm)</u>
  - Standard: ~26%
  - Improved: **~32%**

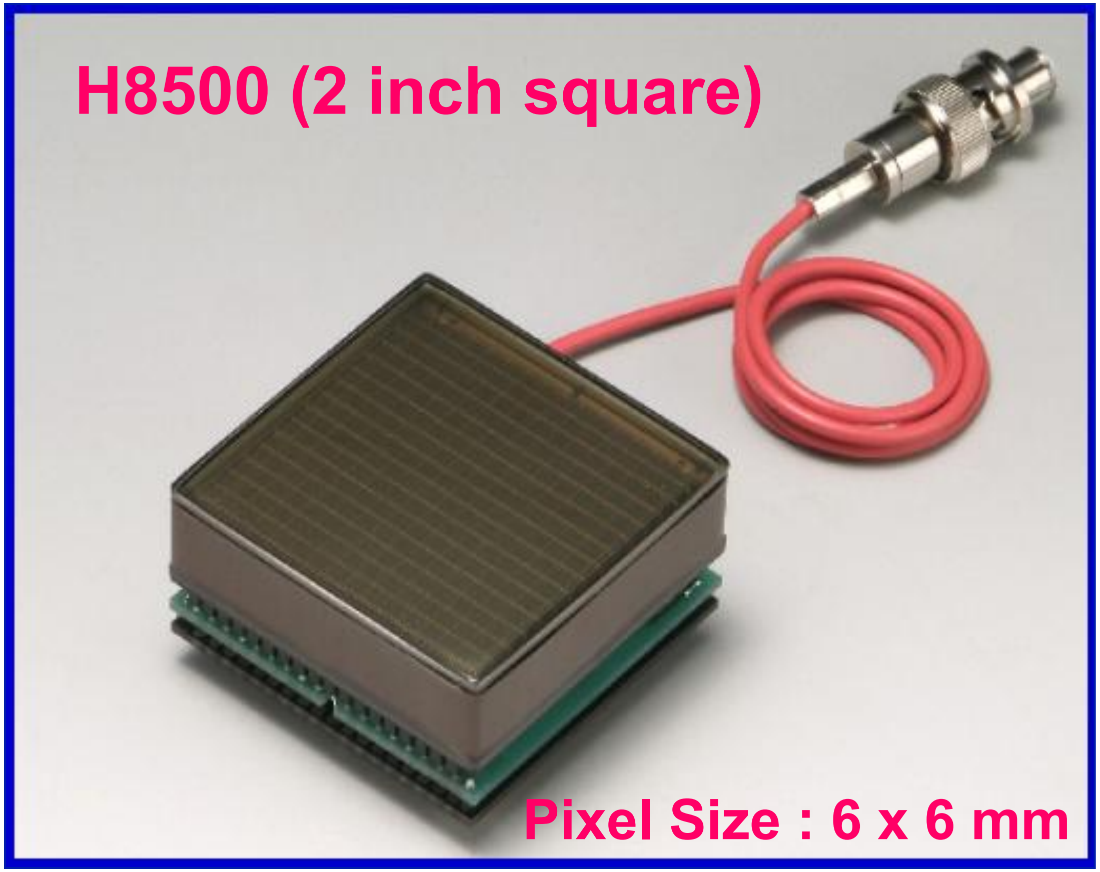
  + 19%

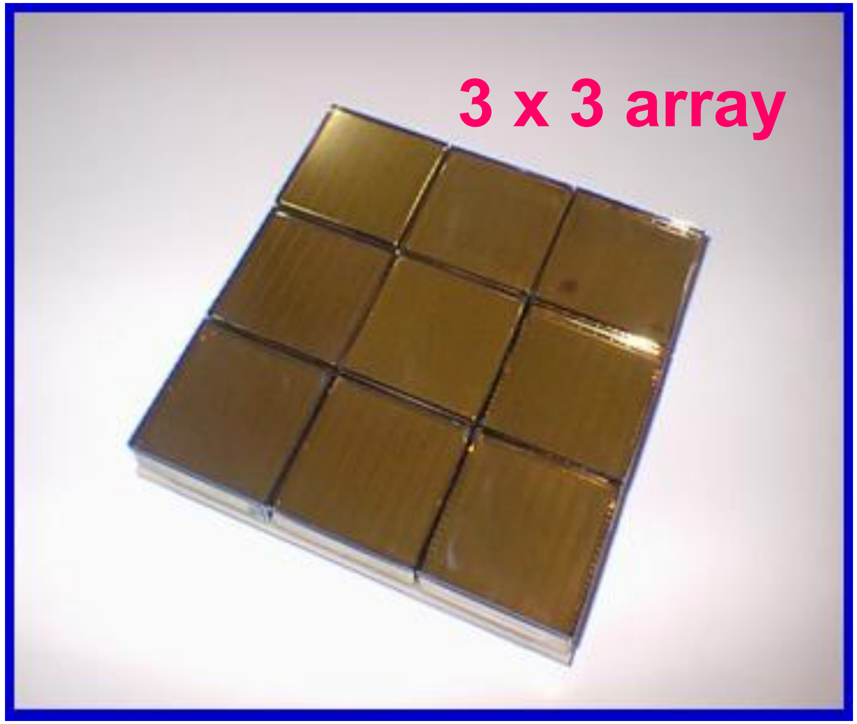
- <u>Quantum efficiency (600 nm)</u>
  - Standard: ~1.6%
  - Improved: **~6.3%**

  + 75%

- Extension of the spectral sensitivity in the red region

Hamamatsu Flat Panel PMT



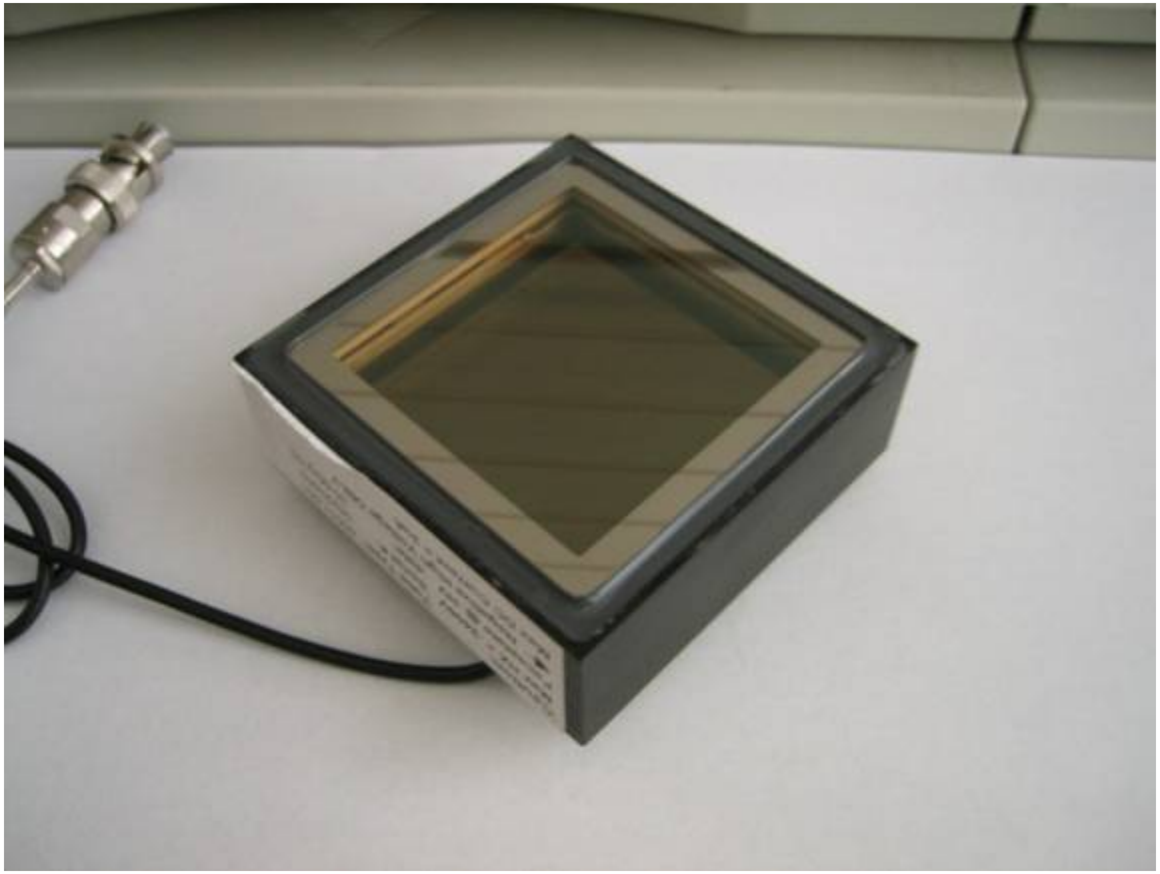


500 tubes were delivered since 2002
for Medical, Radiation monitor and HEP.

Burle Flat MCP PMT

BURLE 85011 MCP-PMT:

- multi-anode PMT with 2 MCPs
- 25 mm pores
- bialkali photocathode
- gain ~ 0.6 x 10^6
- collection efficiency ~ 60%
- box dimensions ~ 71mm square
- 64(8x8) anode pads
- pitch ~ 6.45mm, gap ~ 0.5mm
- active area fraction ~ 52%



Hybrid Detector

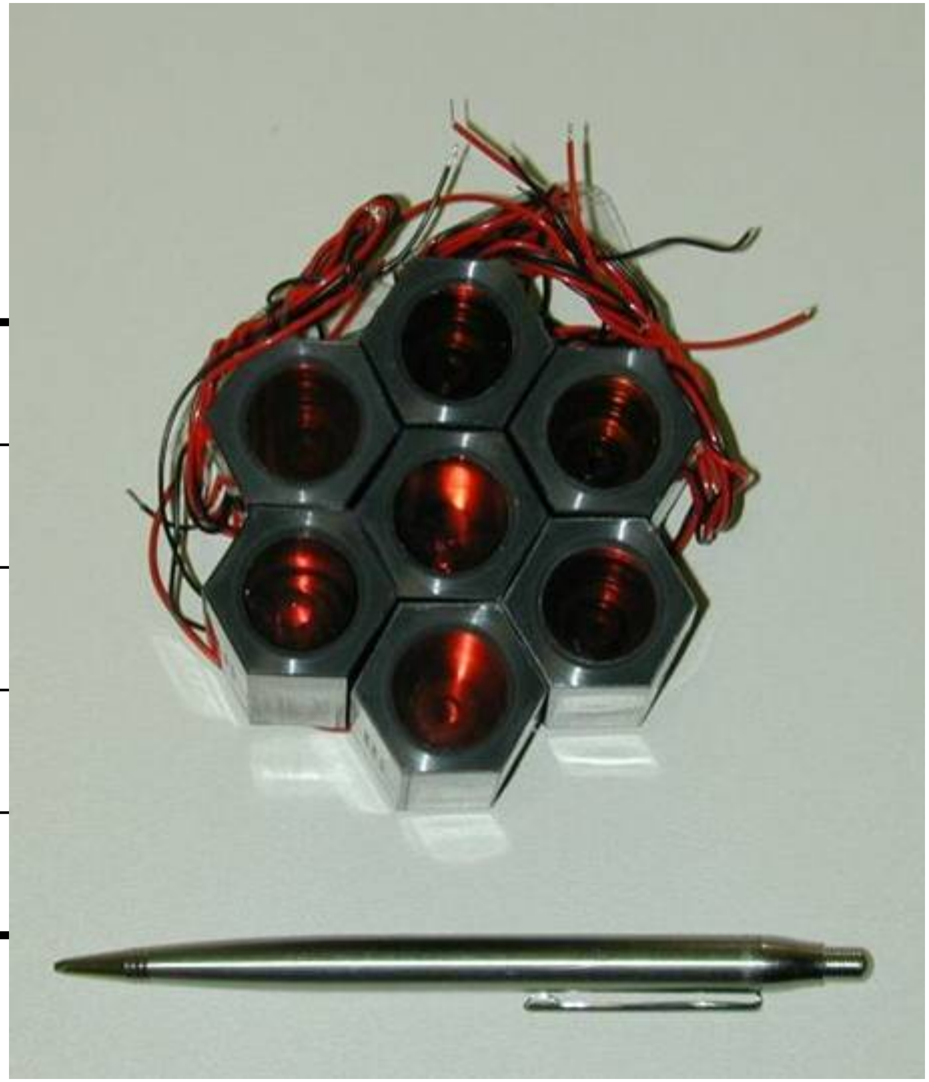
- GaAsP HAPD
- Multi Pixel
- Large Area

HPD with 18-mm GaAsP Photocathode by Hamamatsu

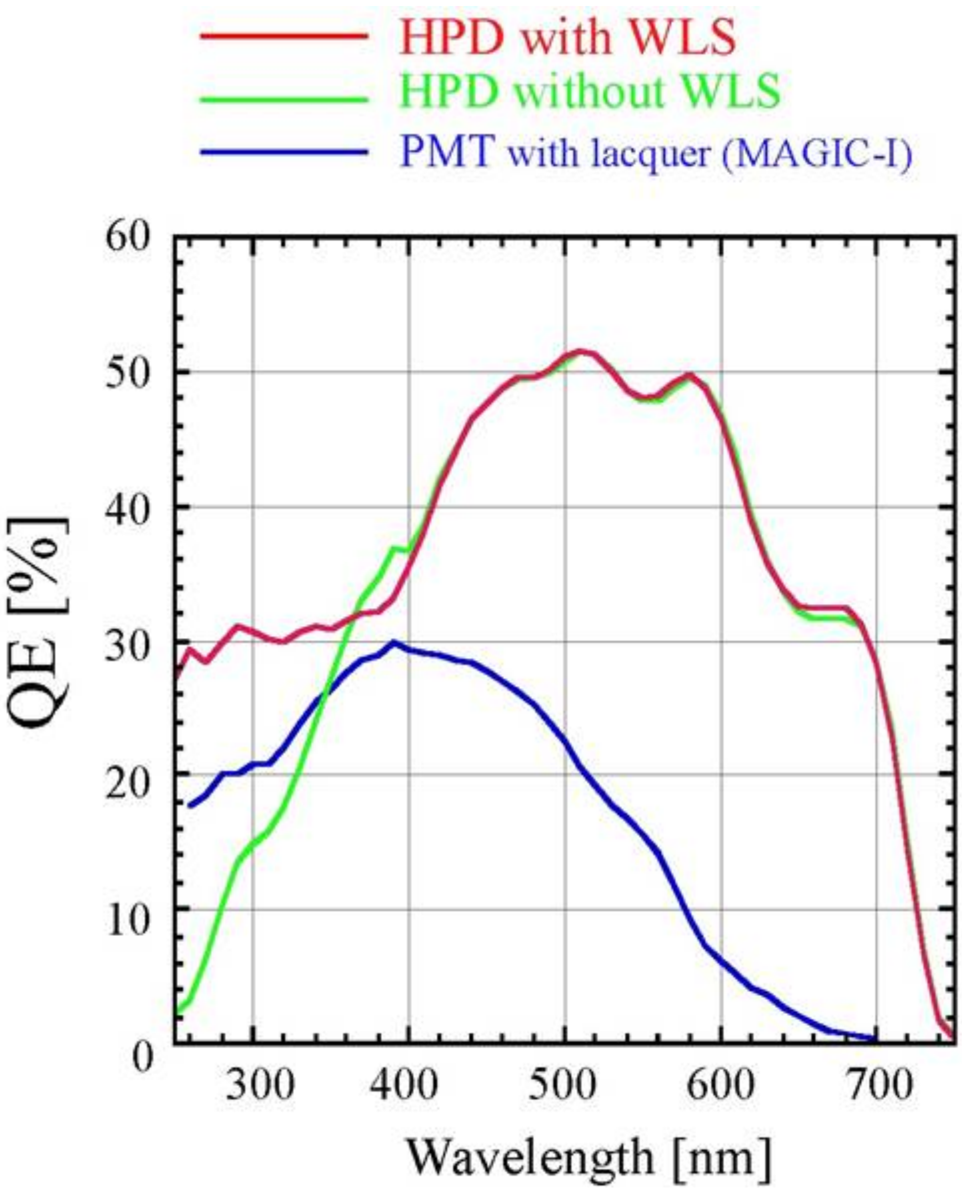
Designed for MAGIC-II camera

<Parameters>

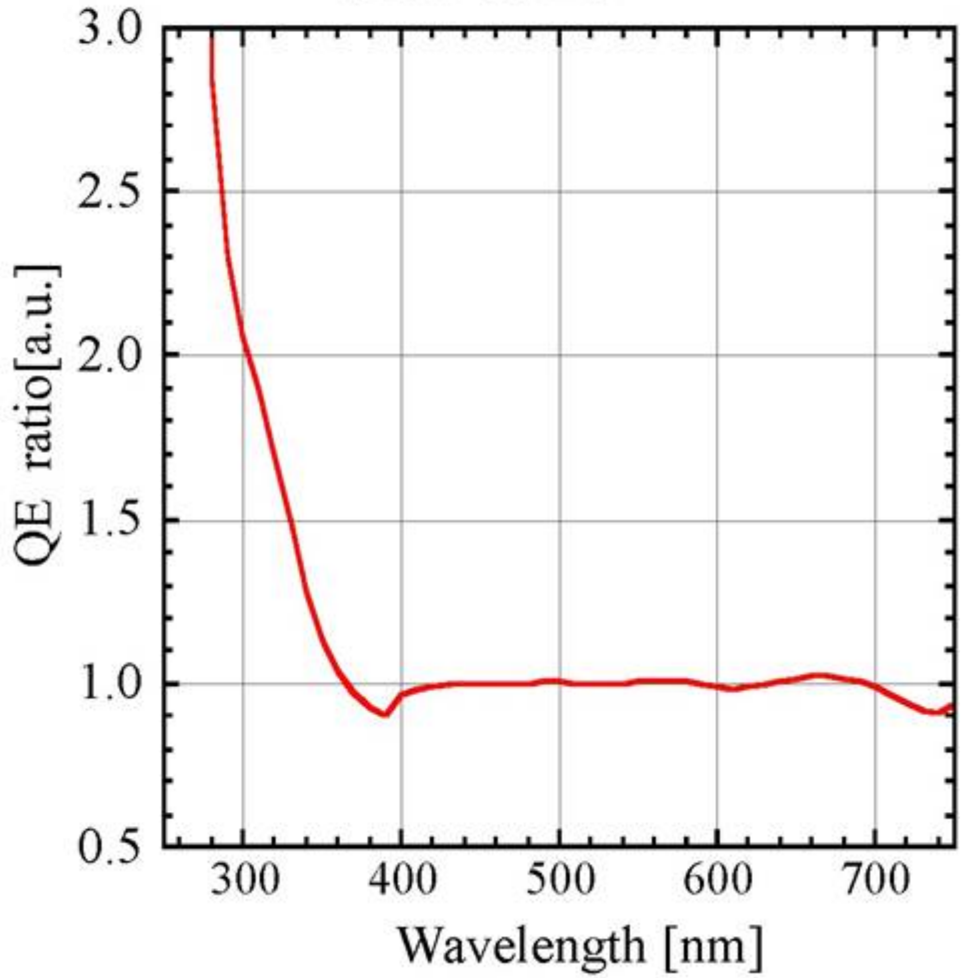
Photocathode	GaAsP (for high QE)
Cathode Size	18 mm [old < 8 mm]
Avalanche Diode	3 mm Silicon
Sensor shape	hexagonal 28 mm
	39 mm height



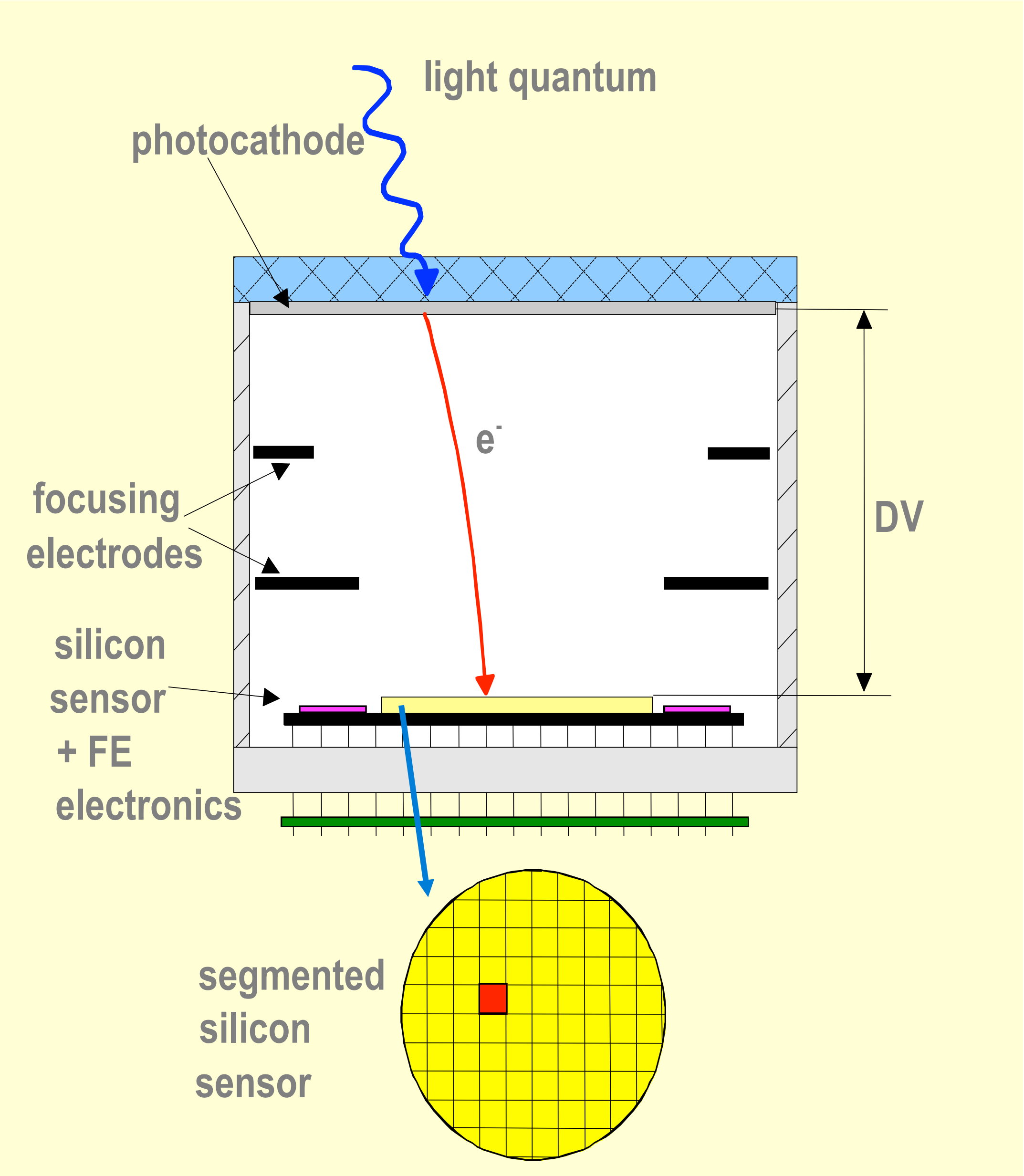
QE of GaAsP + WLS



QE enhancement with WLS



Hybrid Photon Detectors (HPD)



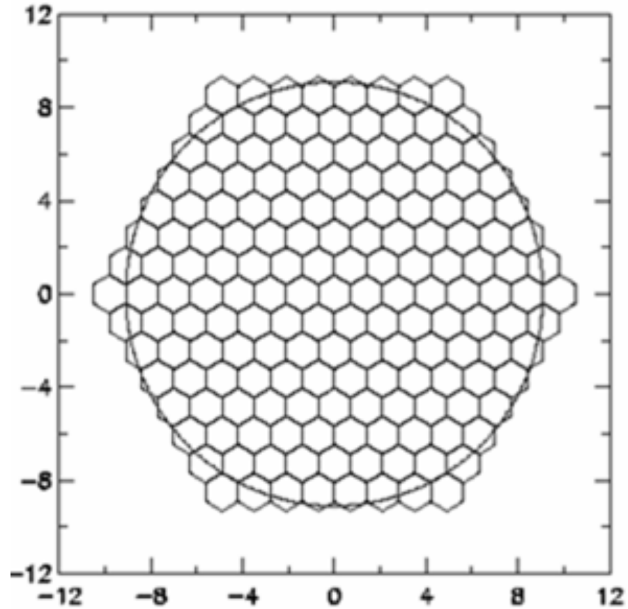
Gain: $$G \approx \frac{e \cdot U_C}{3.6\,\mathrm{eV}}$$

Gain is achieved in a single dissipative step !

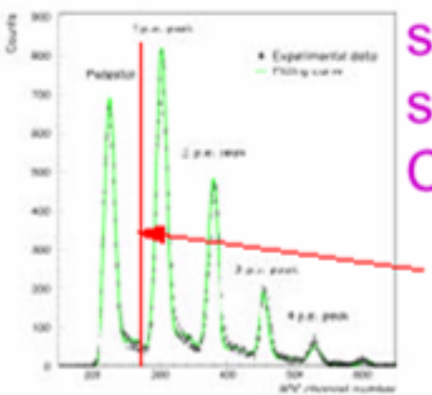
U_C = 20 kV $\rightarrow$ G ~ 5000

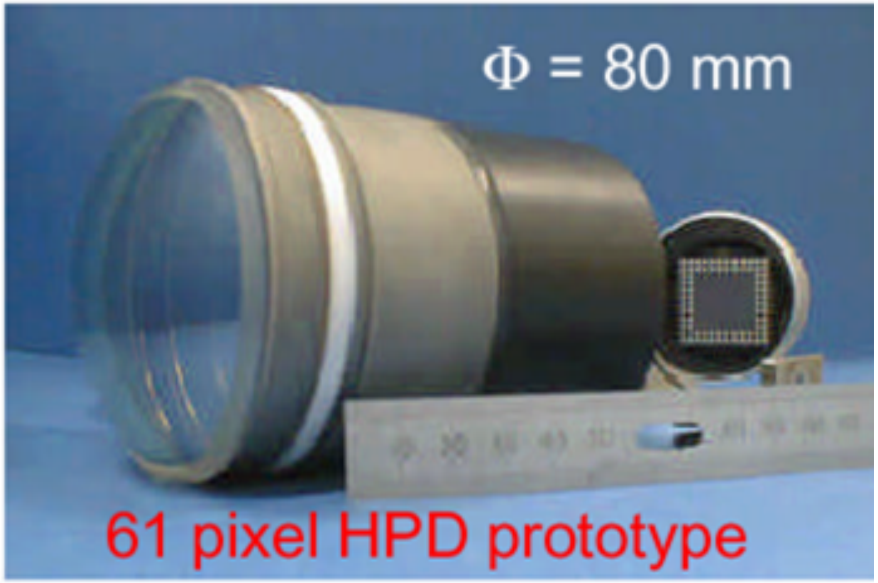
DEP Hybrid Photodiode (HPD)
(Beaune 2002)

- Baseline design for LHC-b RICH
- 8cm diameter
- 61 Pixel, (5mm view)

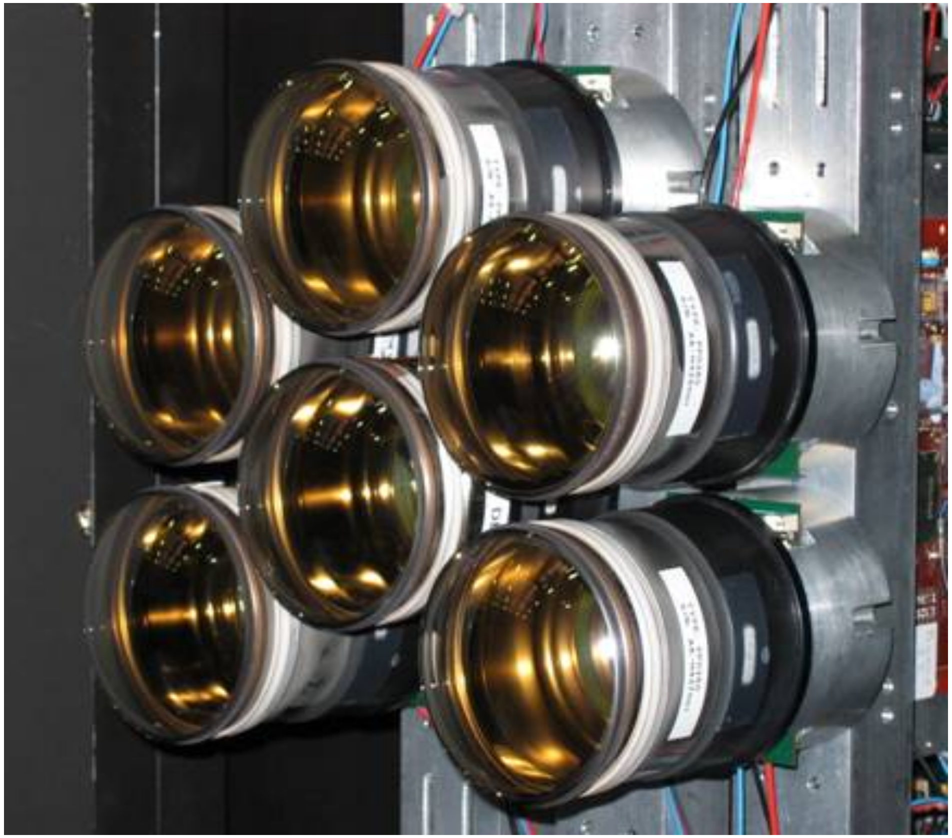


baseline: Hybrid Photo Diodes (HPD)



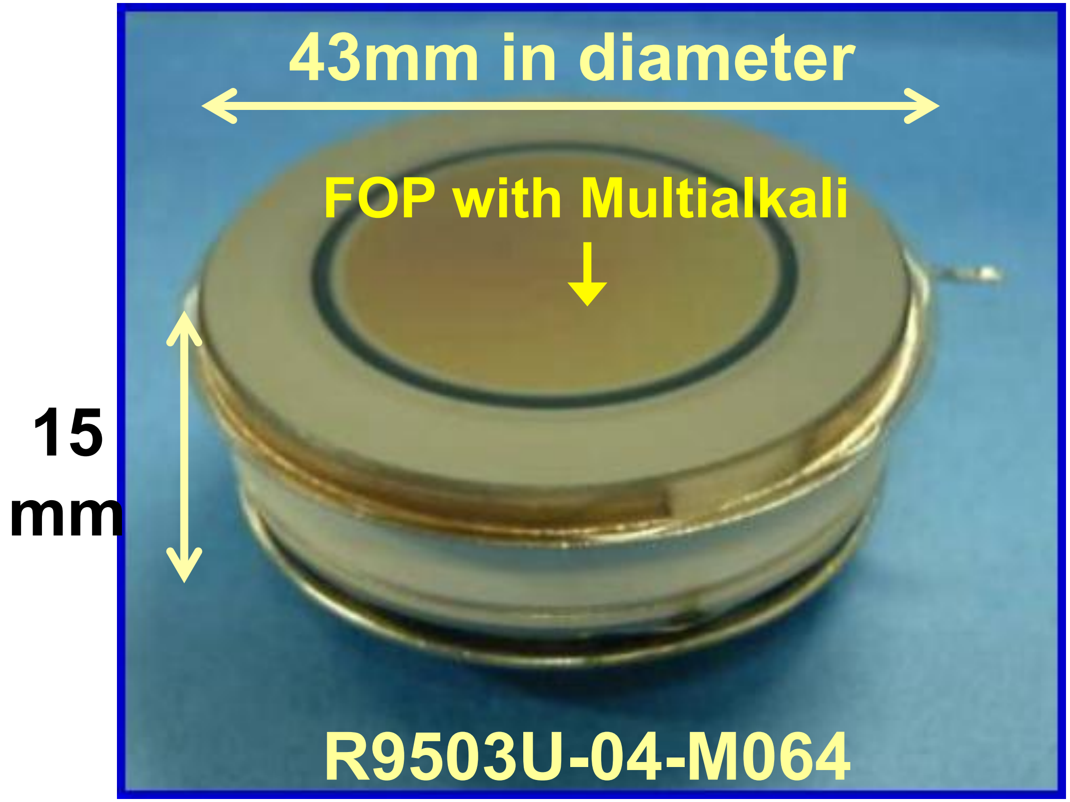


HPD pre-series (9 tubes): performance results

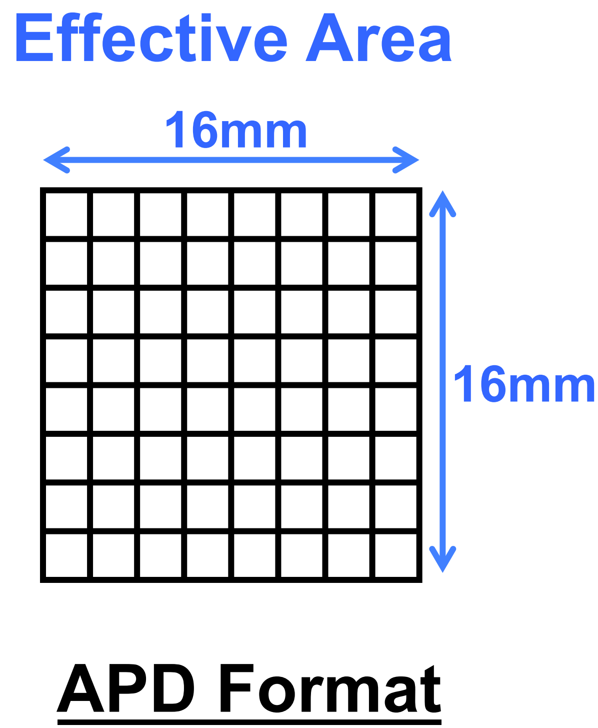


Item	Specification	Results
Pixel response	>95%	>99%
Min. threshold Noise	<2000e- <250e-	Typ. 1200e- Typ. 160e-
Leakage current	Typ. 1uA @ 80V bias	< 1uA
Dark count rate	Max. 5kHz/ cm^2	0.03–3kHz/ cm^2
Ion feedback rate	Max. 10-2 rel. to signal	<10-3
P.e. detection efficiency	Typ. 85%	79-89%
Quantum efficiency	See next picture	Generally well above specs

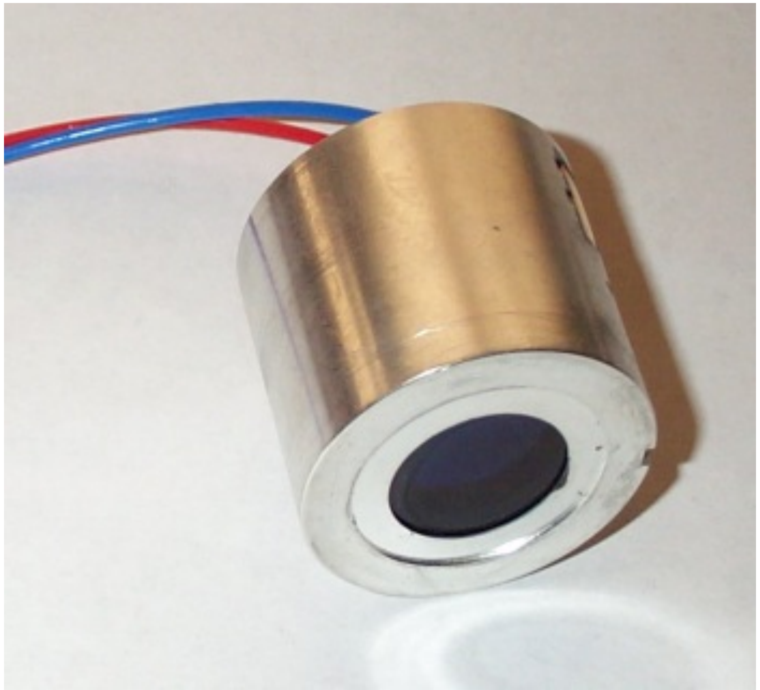
Multi-pixel HAPD (8x8 matrix)

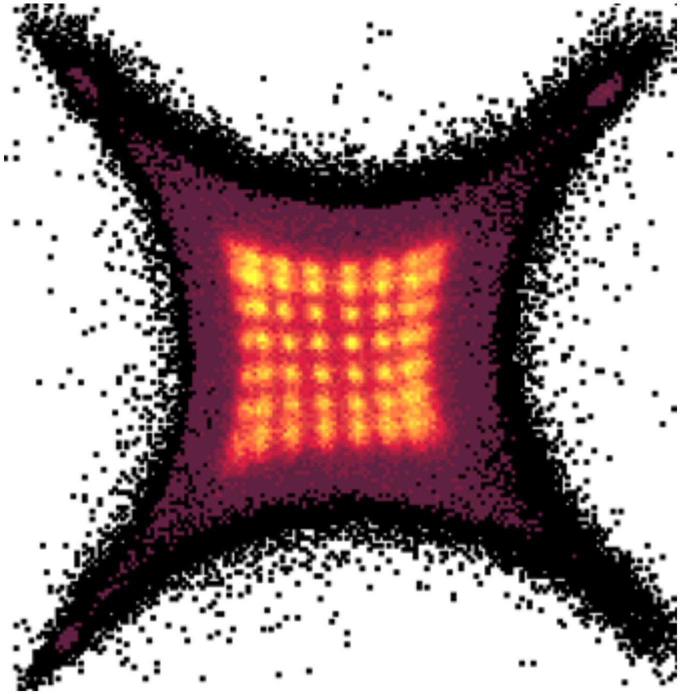


8x8 Matrix (64 Pixels)
2x2 mm / Pixel



RMD Position Sensitive HAPD



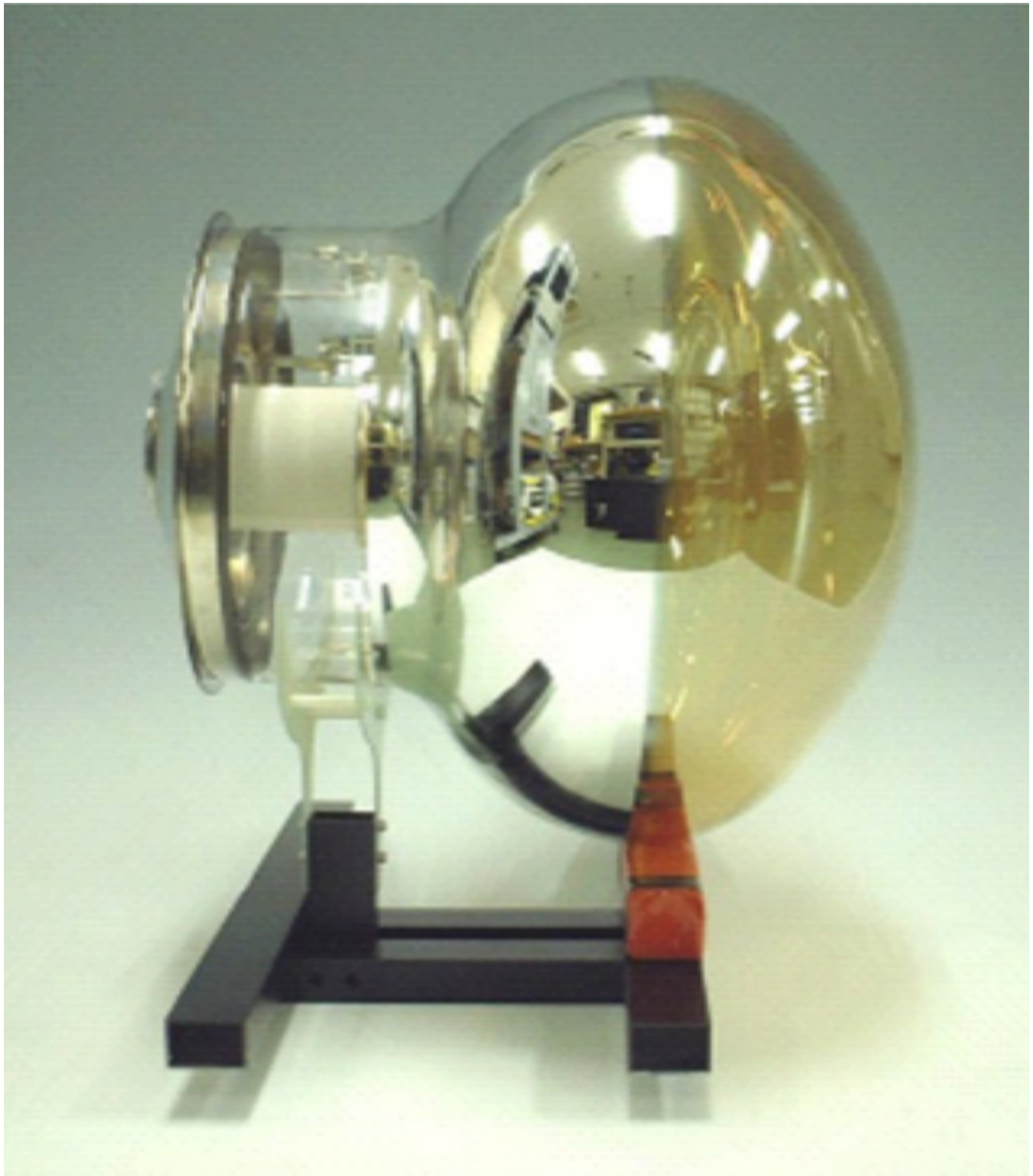


- Proximity design
- 14 x 14 mm^2 PSAPD
- High gain 10^6 to 10^7
- 320 μm with ~5 photons/pulse

8 x 8 CsI:Tl, 1 mm pixel
CsI:Tl imaged at 23 °C with ^{241}Am (60 keV).

M. McClish, K.S. Shah, R. Grazioso, J. Glodo, R. Farrell, E. Karplus, R. Benz, "A hybrid position sensitive avalanche photodiode detector for scintillation spectroscopy and imaging," *IEEE NSS Conf. Rec.* Oct. 19-25, 2003, Portland, OR.

13inch HAPD by Hamamatsu



	13inch	5inch
Diameter	332mm	128mm
Effective area	240mmφ	-
APD size	5mmφ	3mmφ
APD type	Low capacitance (~70pF)	Low capacitanc e (~30pF)
Bias max	370V	350V
HV max	+12kV	-8.5kV

HPD developed and built at CERN

5-inch → 10-inch

127 mm Ø, D ~ 2.5,
2048 channels 1mm^2
bialkali photocathode

NIM A 442 (2000) 128-135

NIM A 478 (2002) 400-403

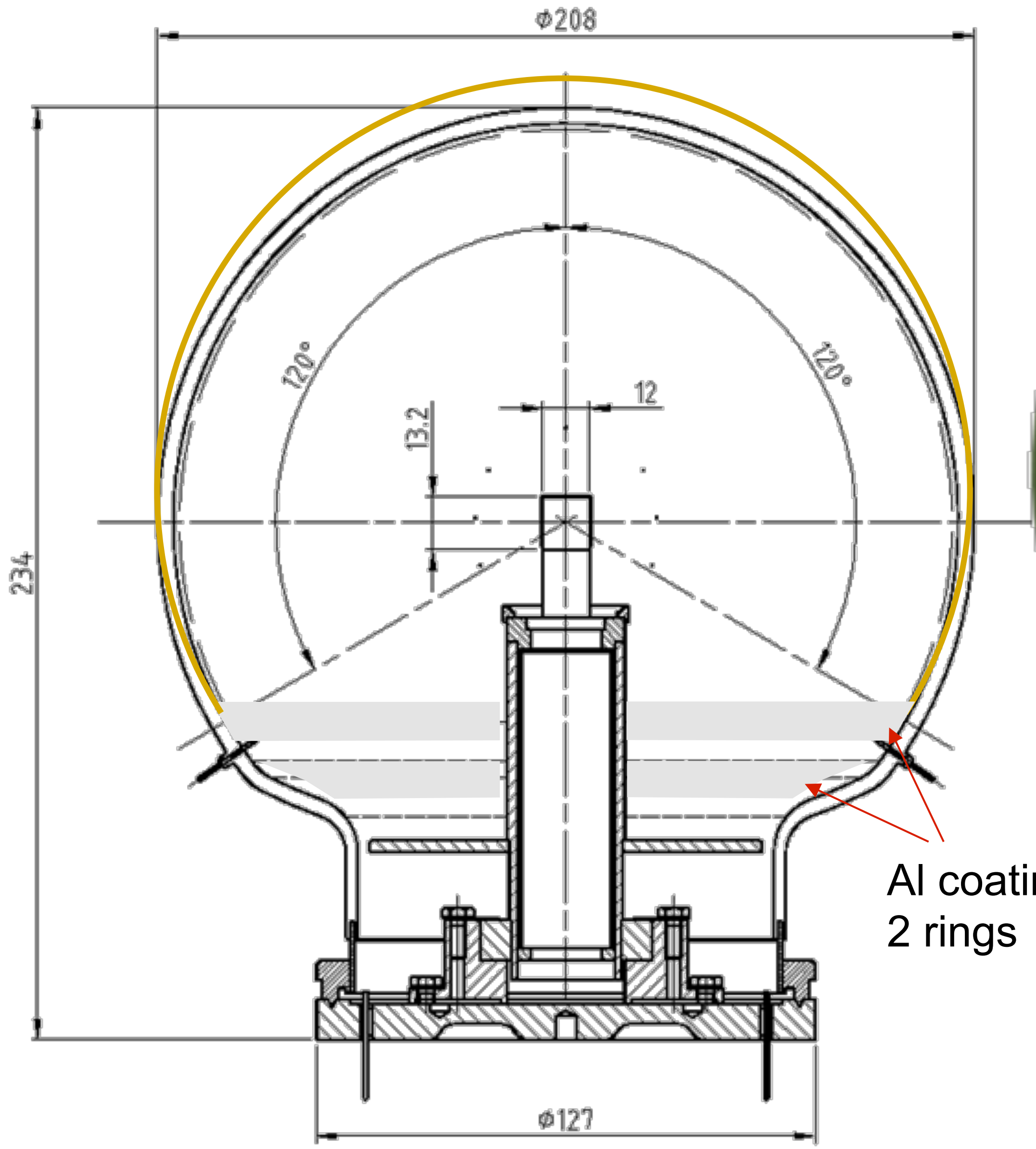
www.cern.ch/ssd/HPD

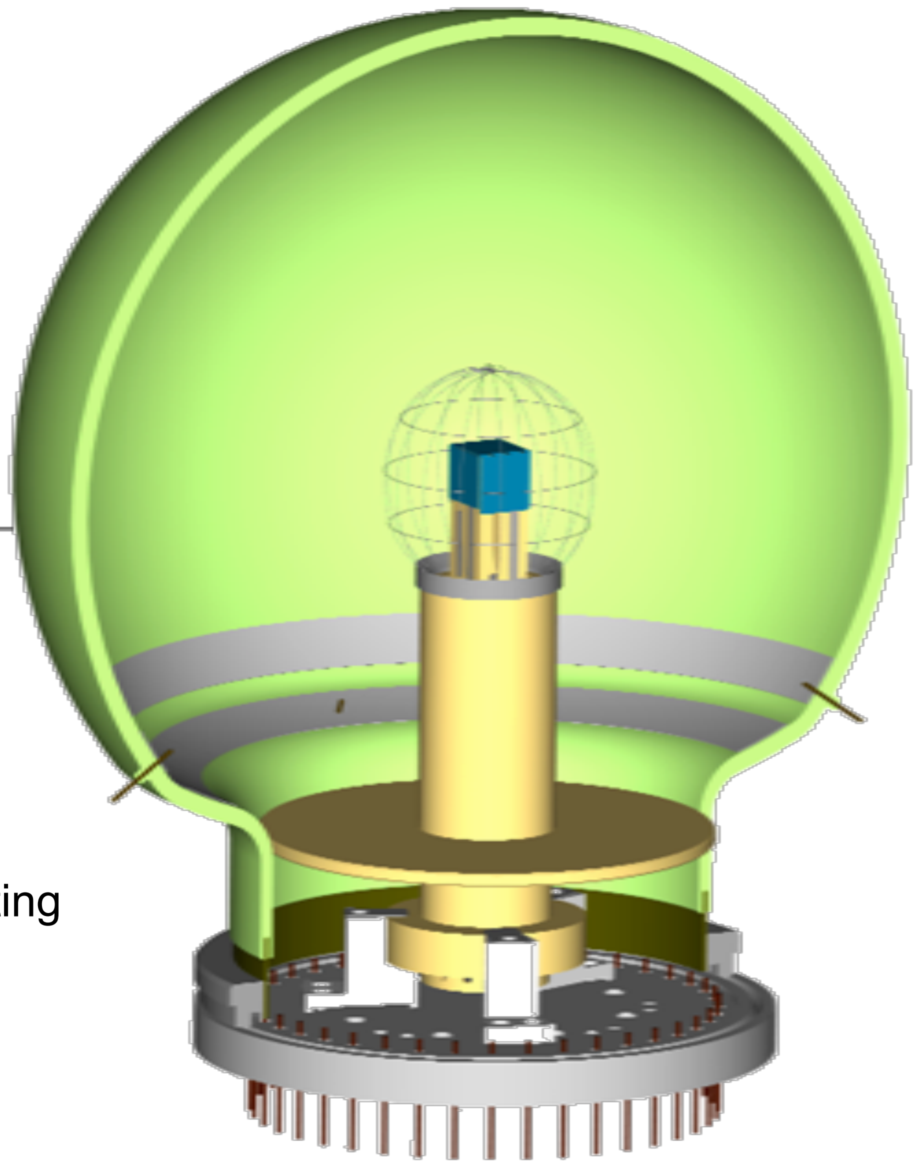
254 mm Ø, D ~ 4,
2048 channels 1mm^2
bialkali photocathode

NIM A 504 (2003) 19

NIM A 518 (2004) 574-578

C2GT Optical Module (38cmϕ)





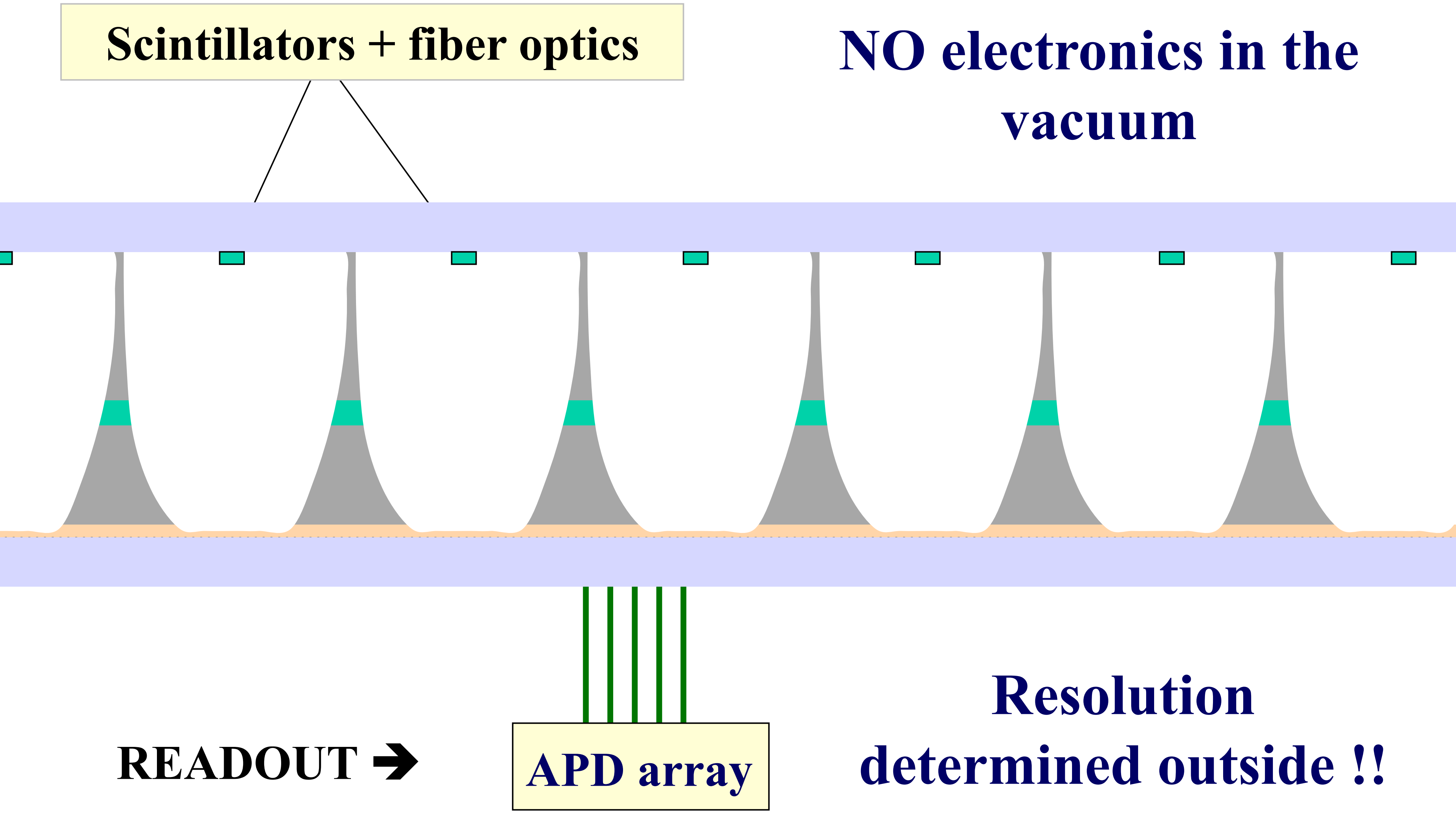
Development of Other Vacuum Devices

~1960

~2000

Production Cost: < $1,000 per m^2

Light Amplifier Concept



NO electronics in the vacuum

READOUT ➔

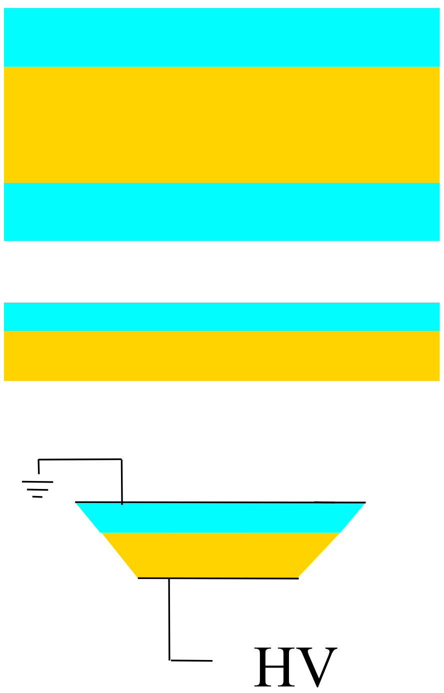
Resolution determined outside !!

Solid State Detector

- APD
- SiPM

Planar Process for APD Fabrication

Standard Wafer

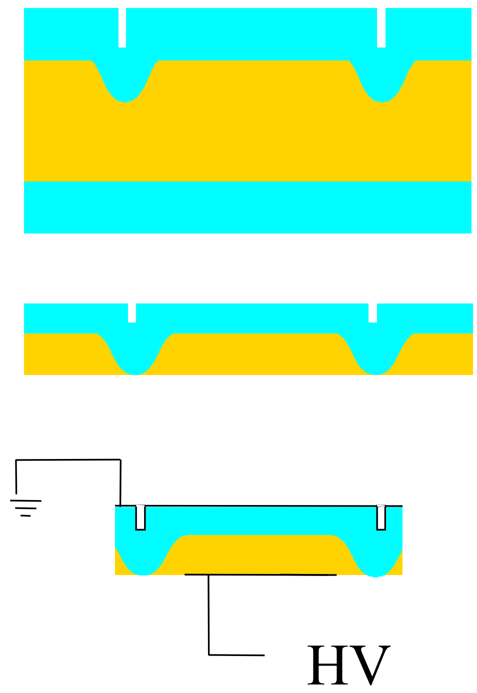


Bevel Formed

Deep Diffusion into Si wafer, p-n-p

Si Removal

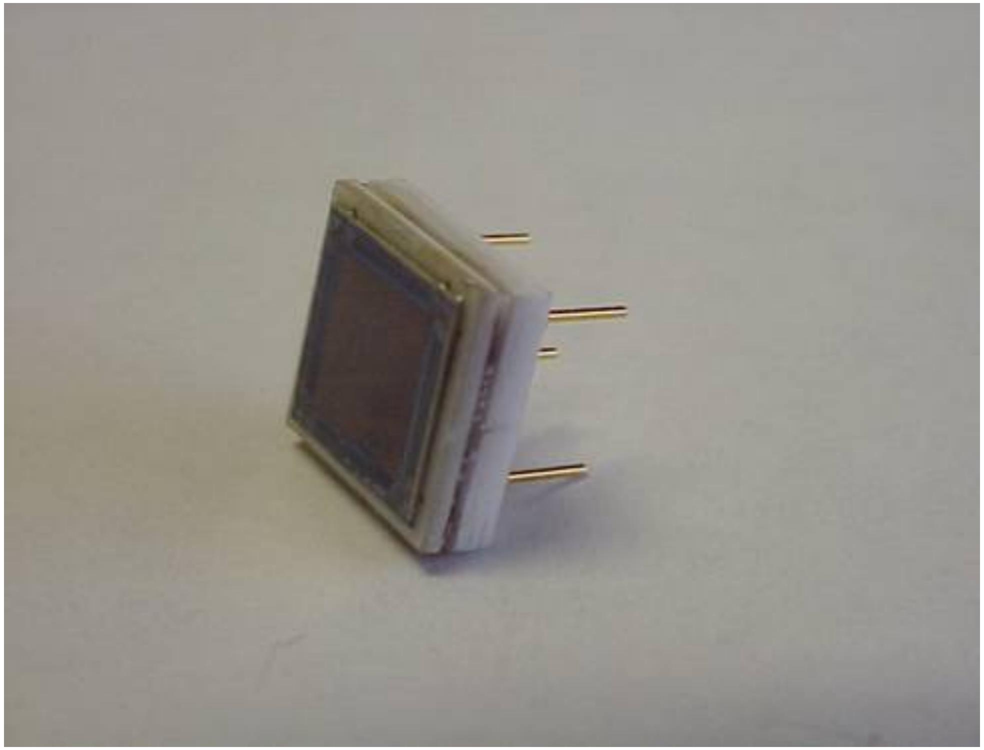
Grooved Wafer



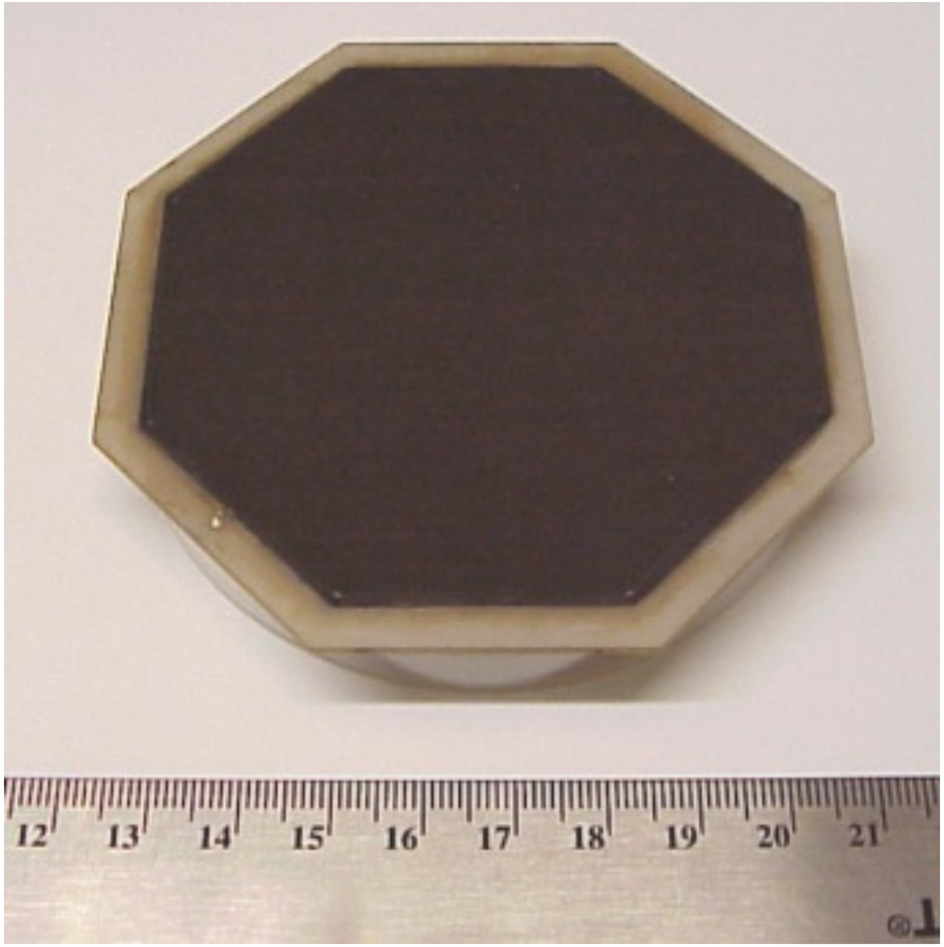
Wafer Diced

R. Farrell, K.S. Shah, K. Vanderpuye, R. Grazioso, R. Myers, G. Entine "APD arrays and large-area APDs via a new planar process," ***Nuc. Inst. Meth. Phys. Res. A*****, Vol. 442, pg. 171, 2000.**

Position Sensitive and Discrete APDs

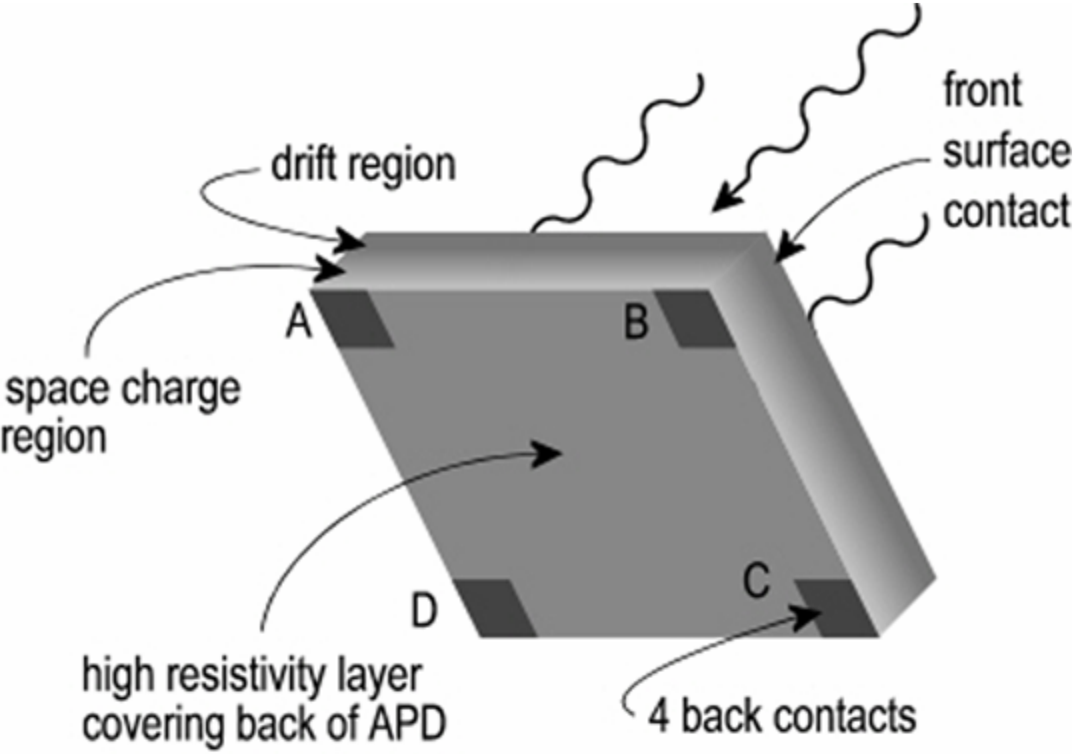


8 x 8 mm^2 PSAPD

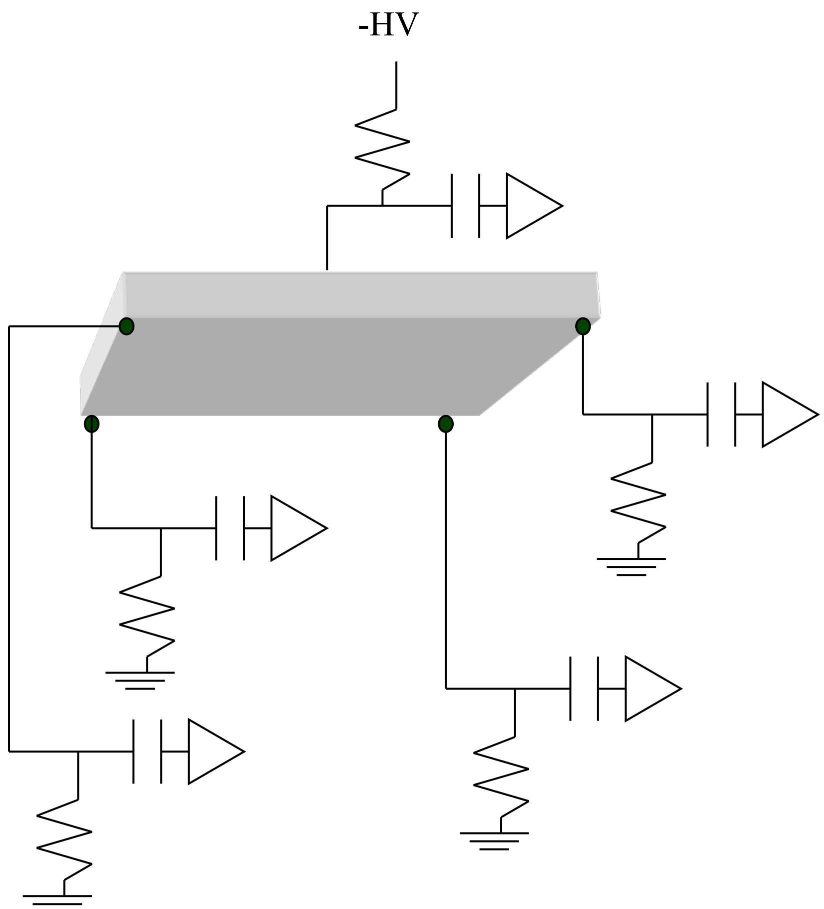


45 cm^2 Planar APD

Fabrication for Position Sensitivity

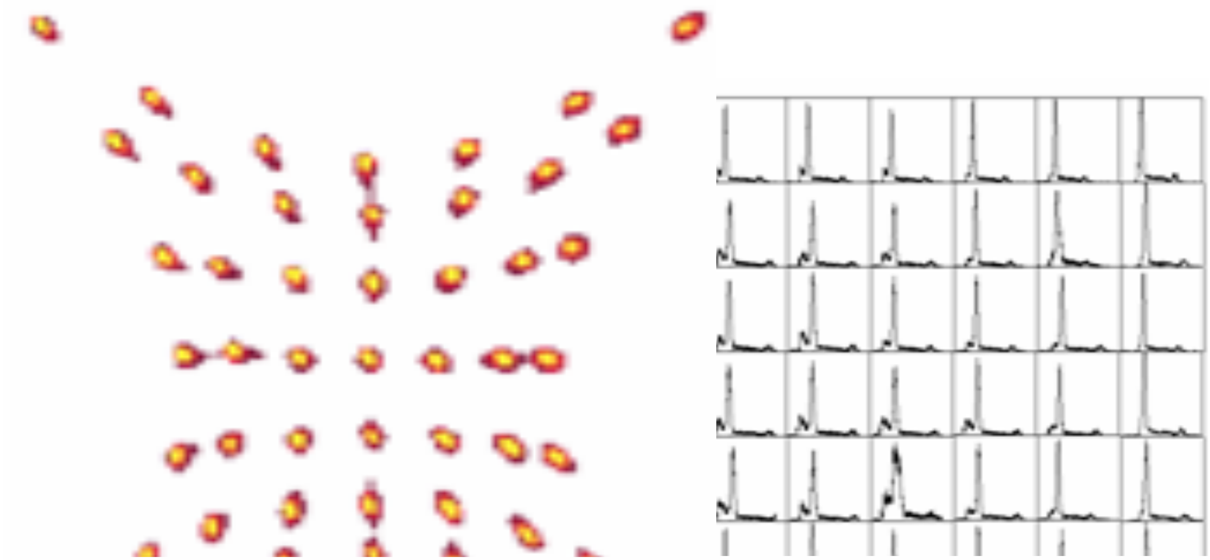


$$X=\frac{(B+C)-(A+D)}{(A+B+C+D)} \qquad Y=\frac{(A+B)-(C+D)}{(A+B+C+D)}$$

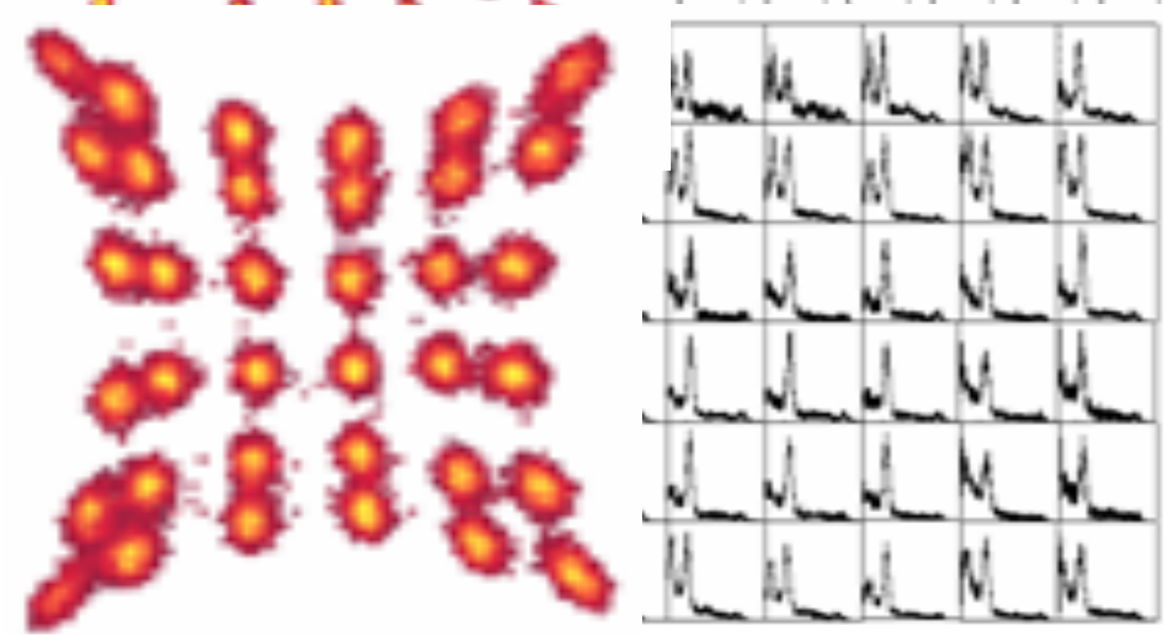


K.S. Shah, R. Farrell, R. Grazioso, E. Harmon, E. Karplus, "Position-sensitive avalanche photodiodes for gamma-ray imaging," ***IEEE Trans. Nuc. Sci.***, **Vol. 49, No. 4, August 2002**

RMD APD for PET Applications



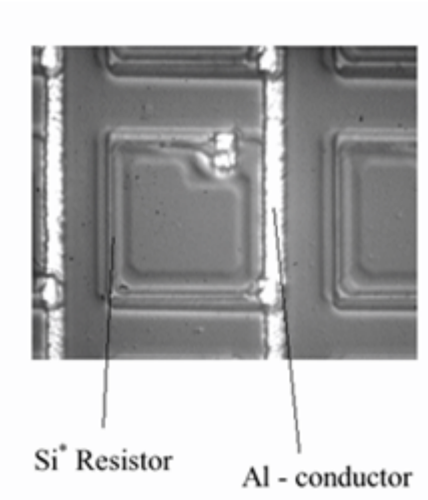
28 x 28 mm^2 PSAPD coupled to 7 x 7 LSO array with 3 mm pixels at –20 °C. Average energy resolution = 15.5% at 511 keV.

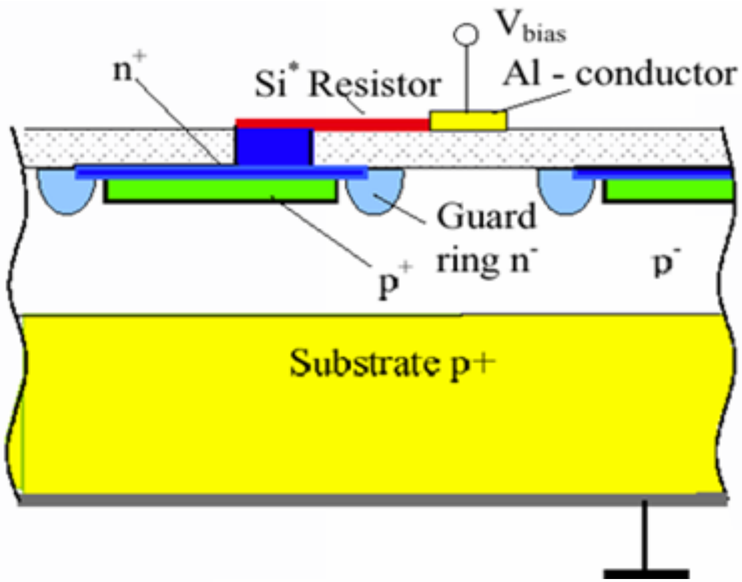


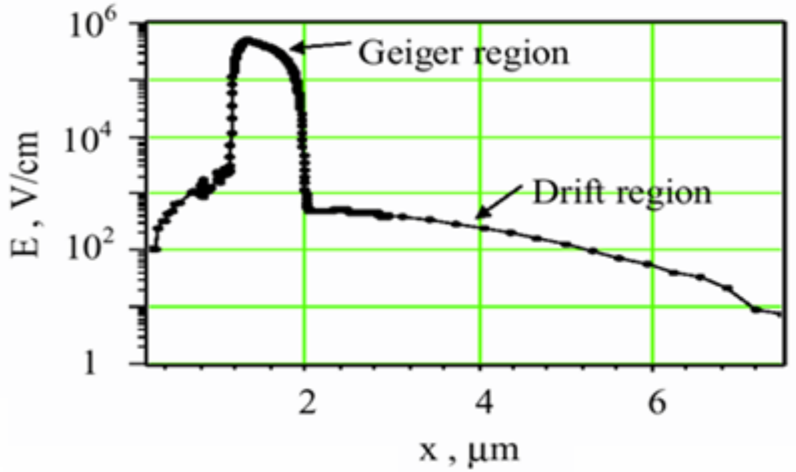
CHANNELS

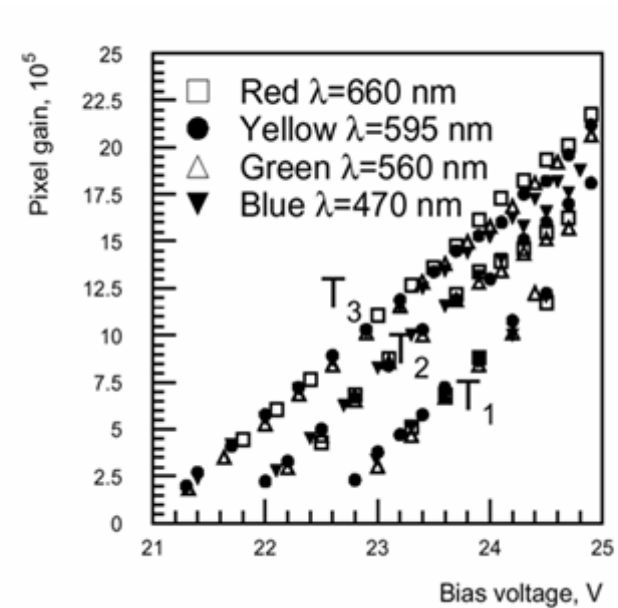
8 x 8 mm^2 PSAPD coupled to 6 x 6 LSO array with 1 mm pixels at 23 °C. Average energy resolution = 16% at 511 keV.

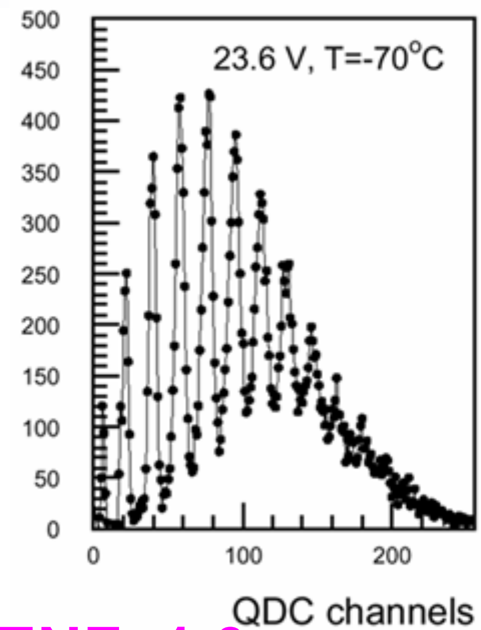
Silicon Photomultiplier
(from Beaune 2002)

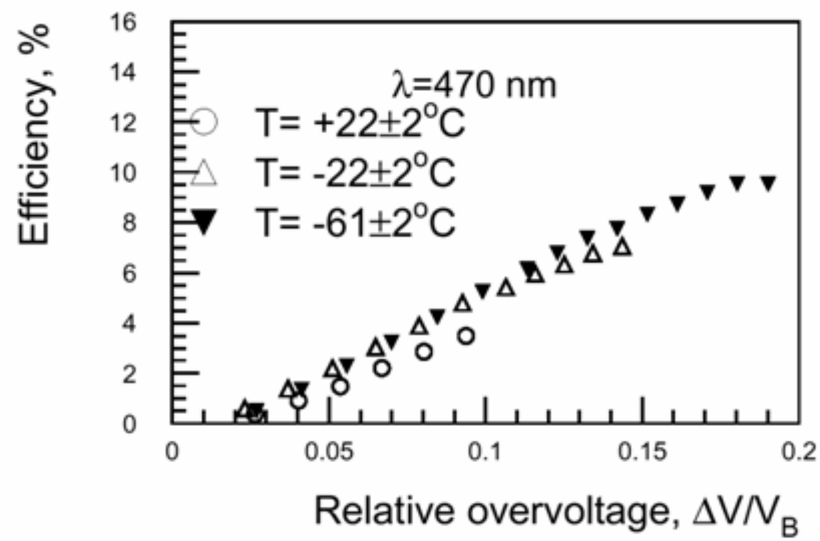








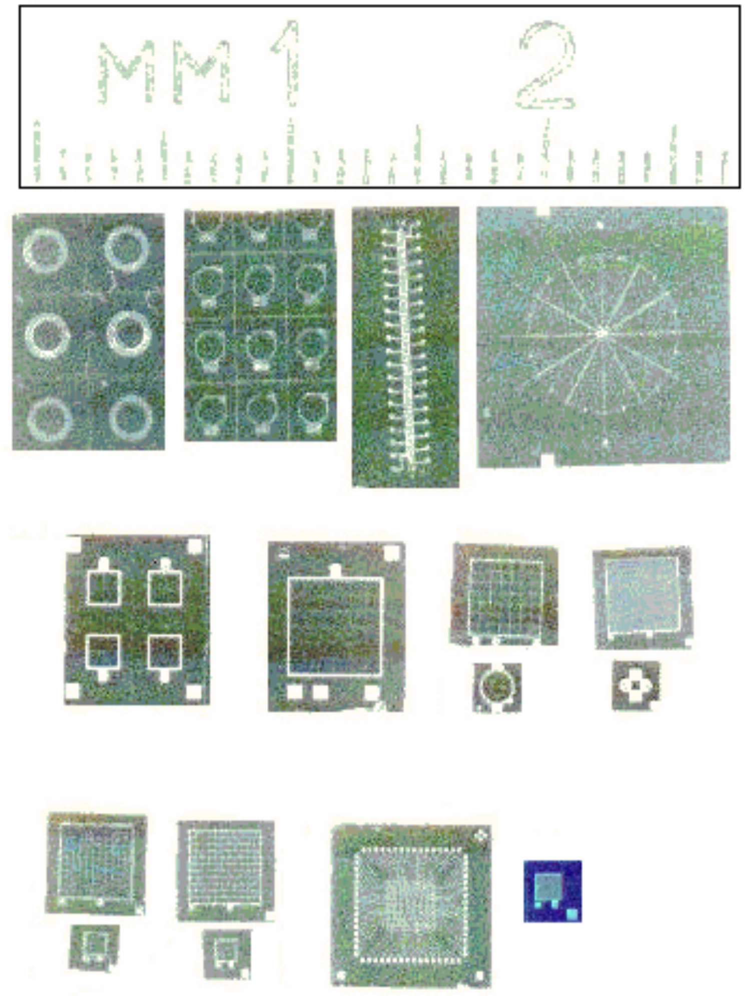




Gain~10^6 **ENF=1.0** **DQE~10%**

Long History of SiPM

At present many people consider that the new APDs with inner microstructures are very easy devices. To my mind, the way to micro-pixel APDs was not easy. This development took about 20 years.



Different generations of silicon avalanche structures produced in 1983-2005.

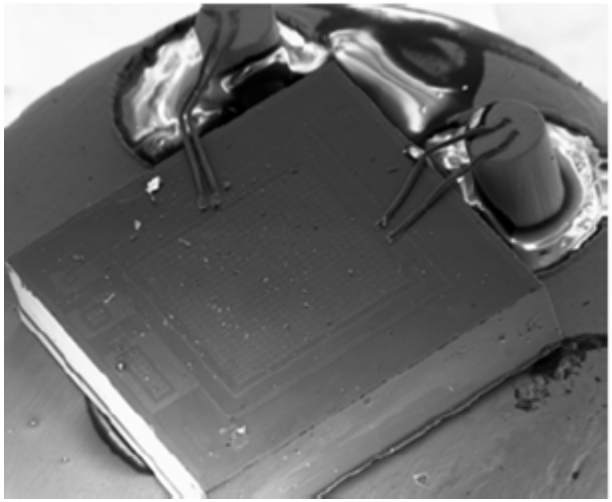
MOS and MRS type APDs. 1983-1993.

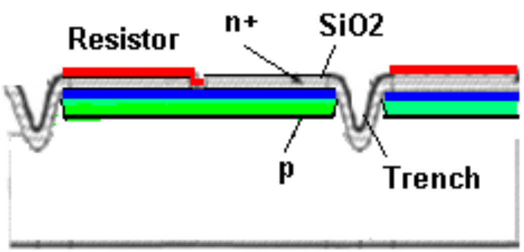
MRS and CCD type APDs. 1994-2001.

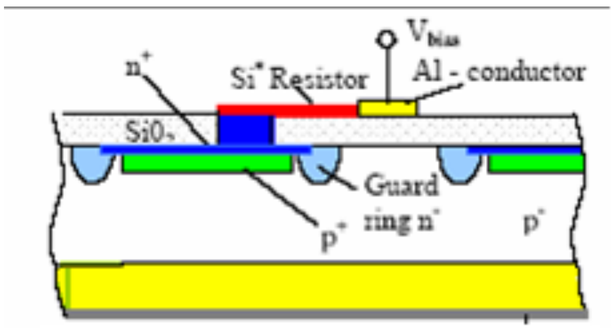
CCD and MW type APDs. 2002- present

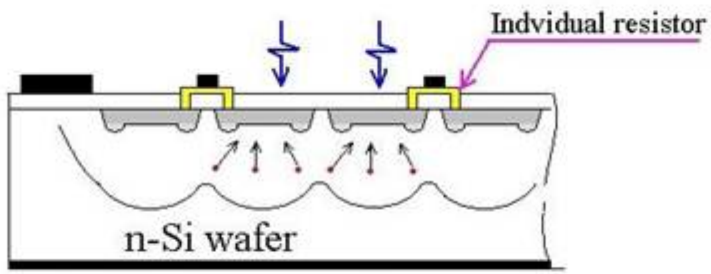
Various SiPM

MPGM name	Area (mm^2)	Number of pixels	Geometric factor [%]	Si substrate type	MPGM source
SSPM (or MRS APD)	1	576	70	p	"Photonique SA" and V. Golovin(CPTA, Moscow)
SiPM	1	556	25	p	B. Dolgoshein and "PULSAR"(Moscow)
R8-type AMPD	0.5	10 000	?	n	Z. Sadygov (JINR, Dubna)

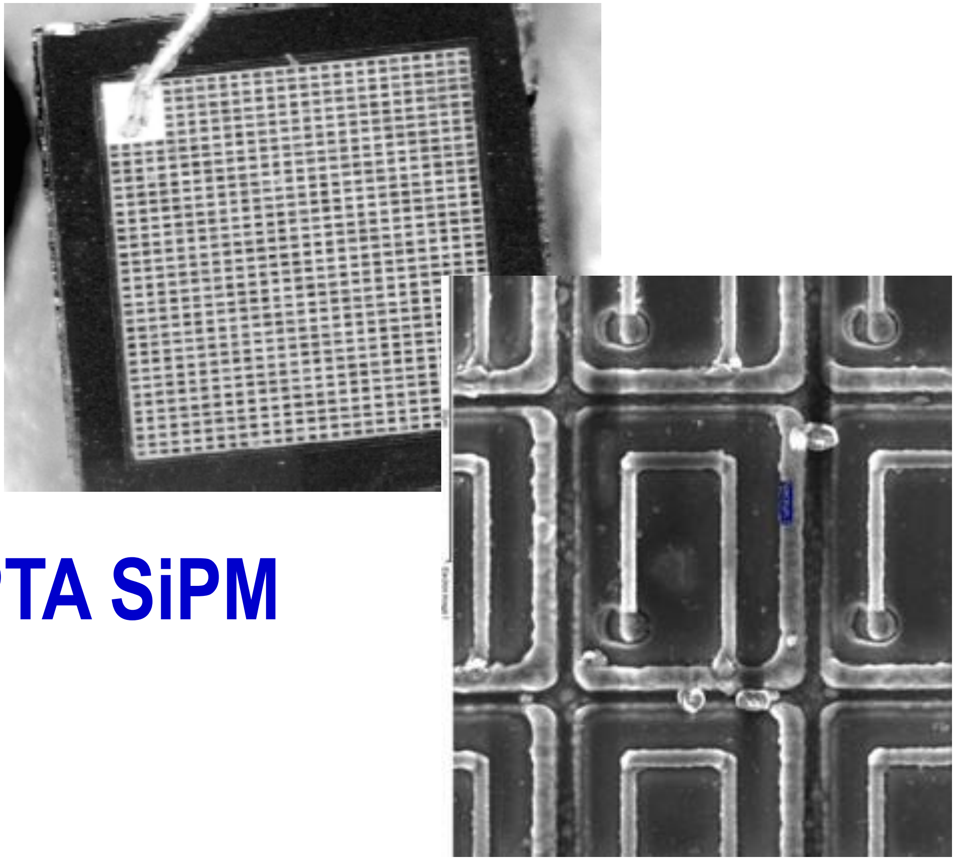




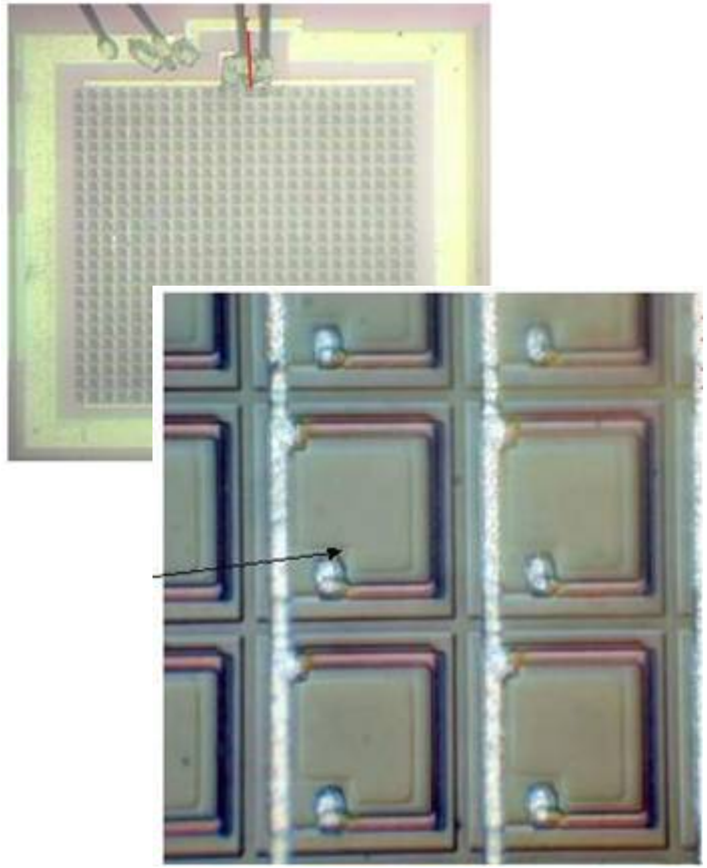




SiPM Layout



CPTA SiPM

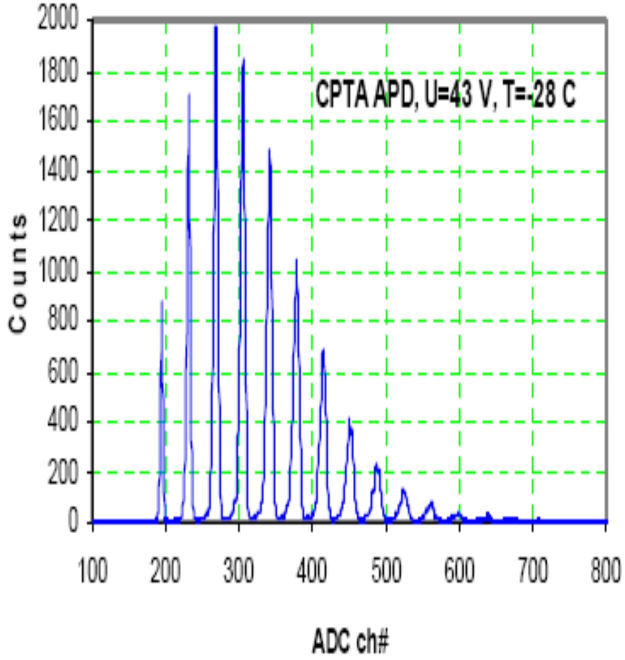


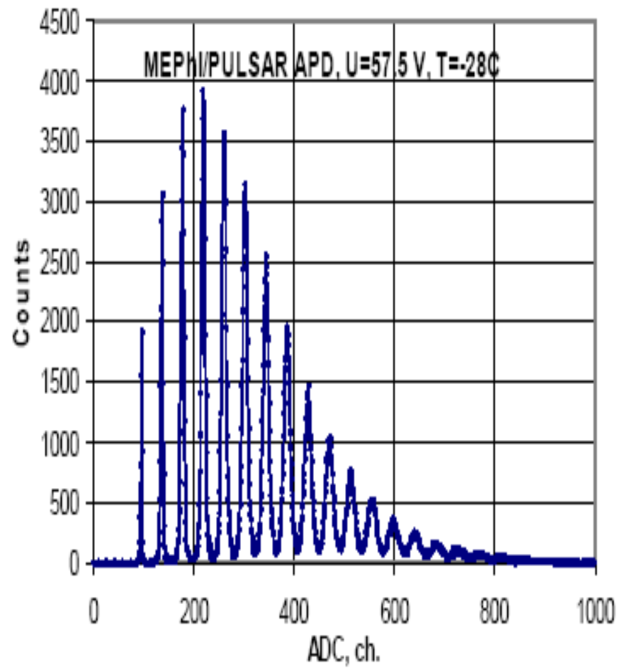
- General view 1x1 mm,
- Common Electrode Layout,
- Microcells with Quenching Mechanism,

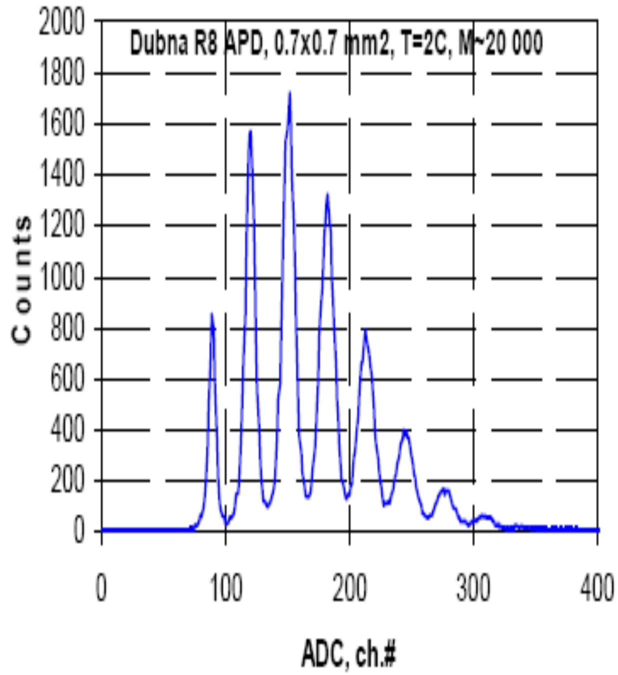
Pulsar SiPM

(LCWS2004, M.Danilov ITEP,Moscow)

PE Distribution of Various SiPM

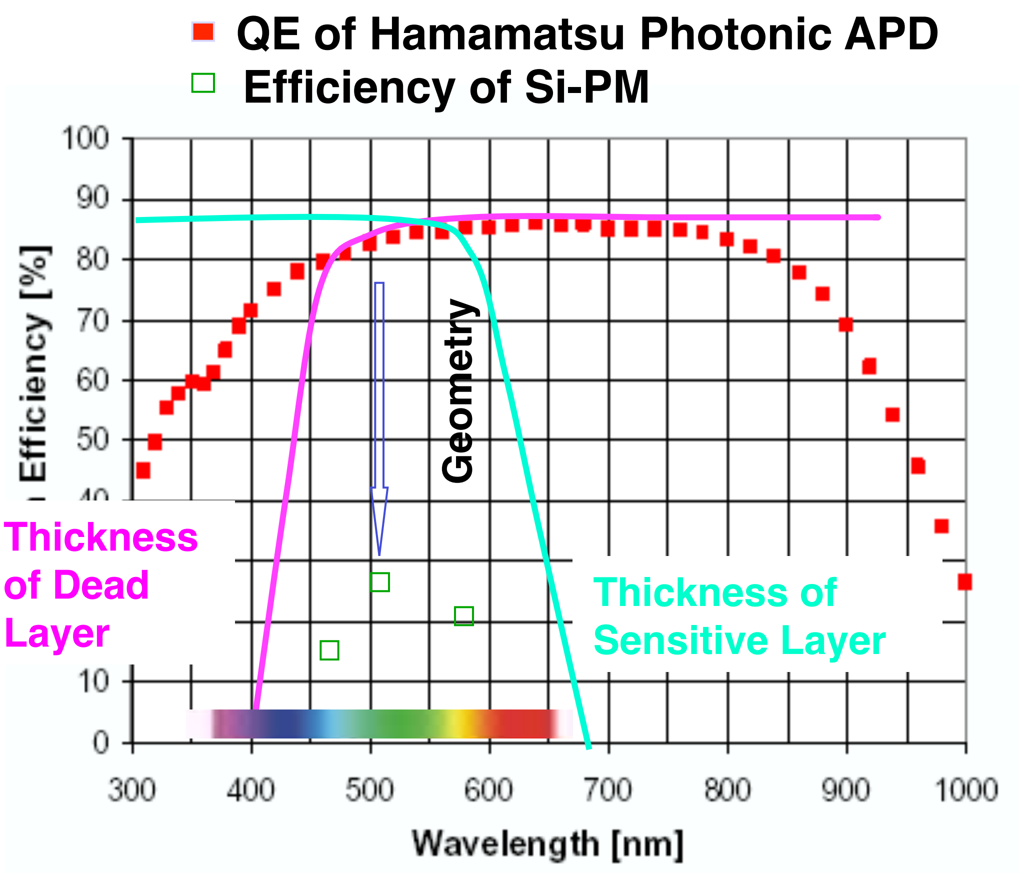






SiPM Performance

Detection Efficiency – Wavelength Dependent:



UV region of SiPM

is limited by **dead layers** on the top of structure

IR region of SiPM

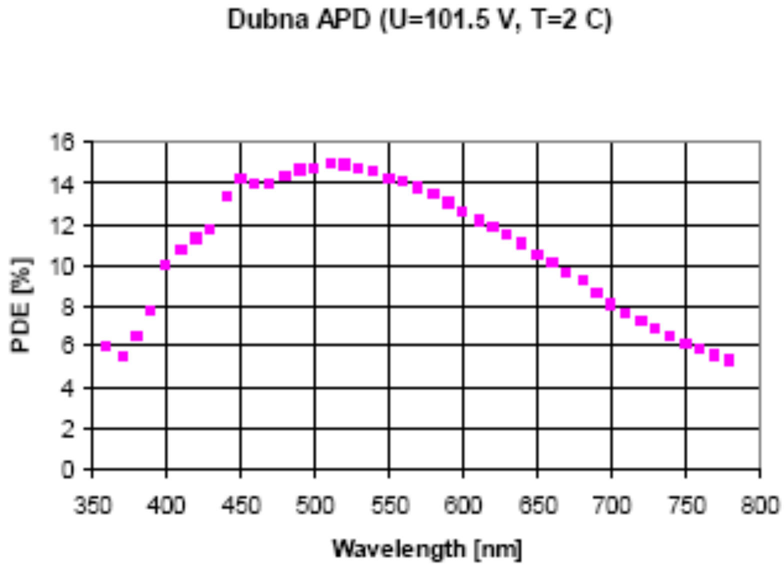
is limited by the thickness of **sensitive layer** of SiPM

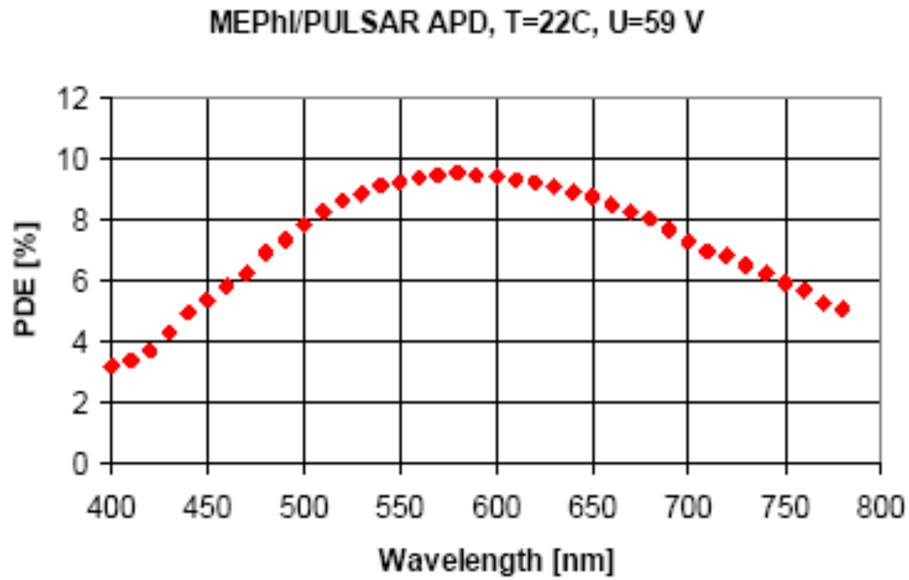
Absolute value scaling

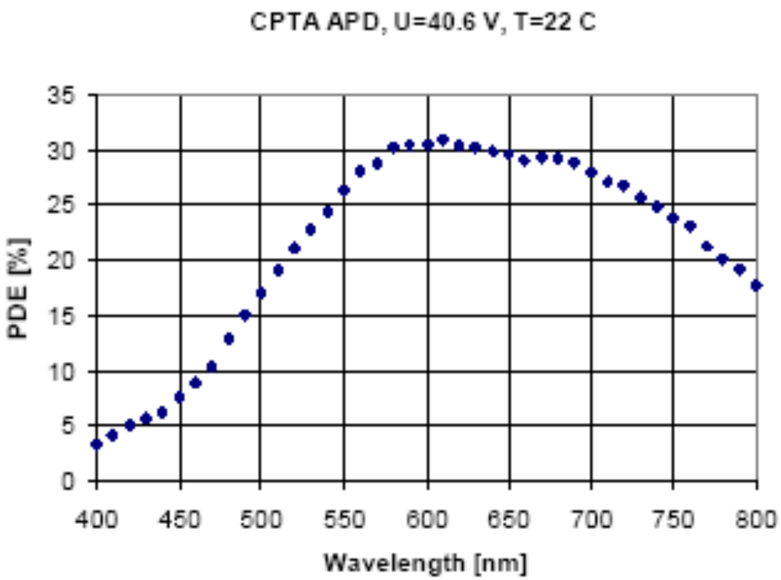
is limited by **geometry factor**

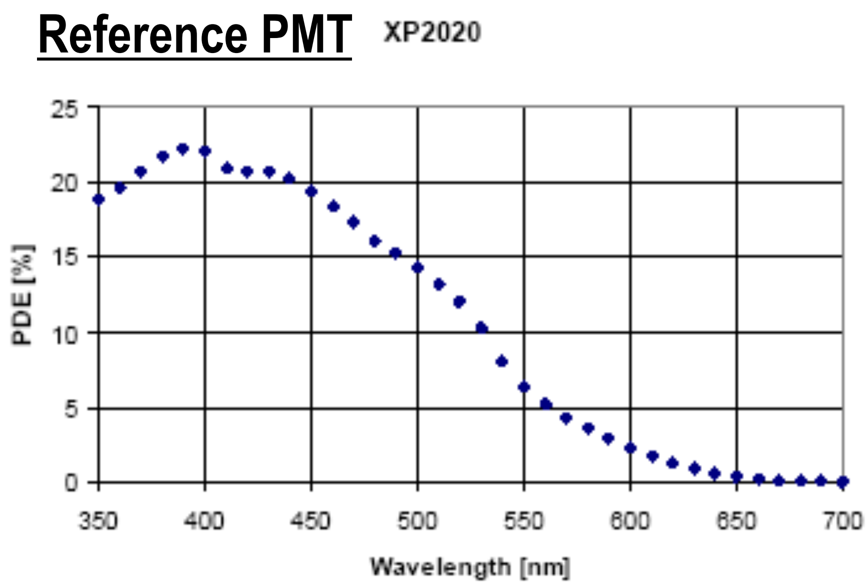
The Si-PM has green light sensitivity
and total Detection Efficiency for green range of light is ~25%

QE of Various SiPM

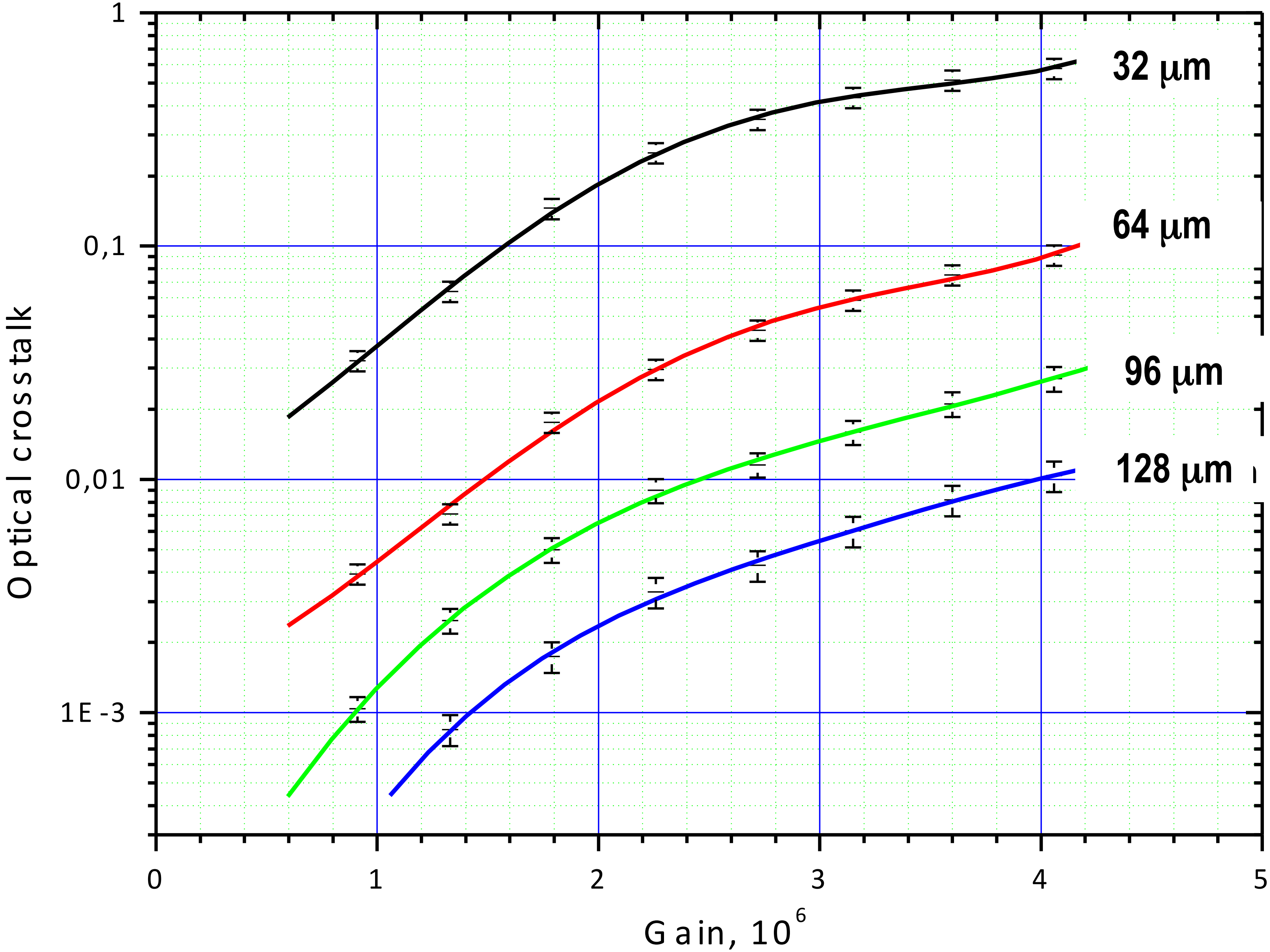






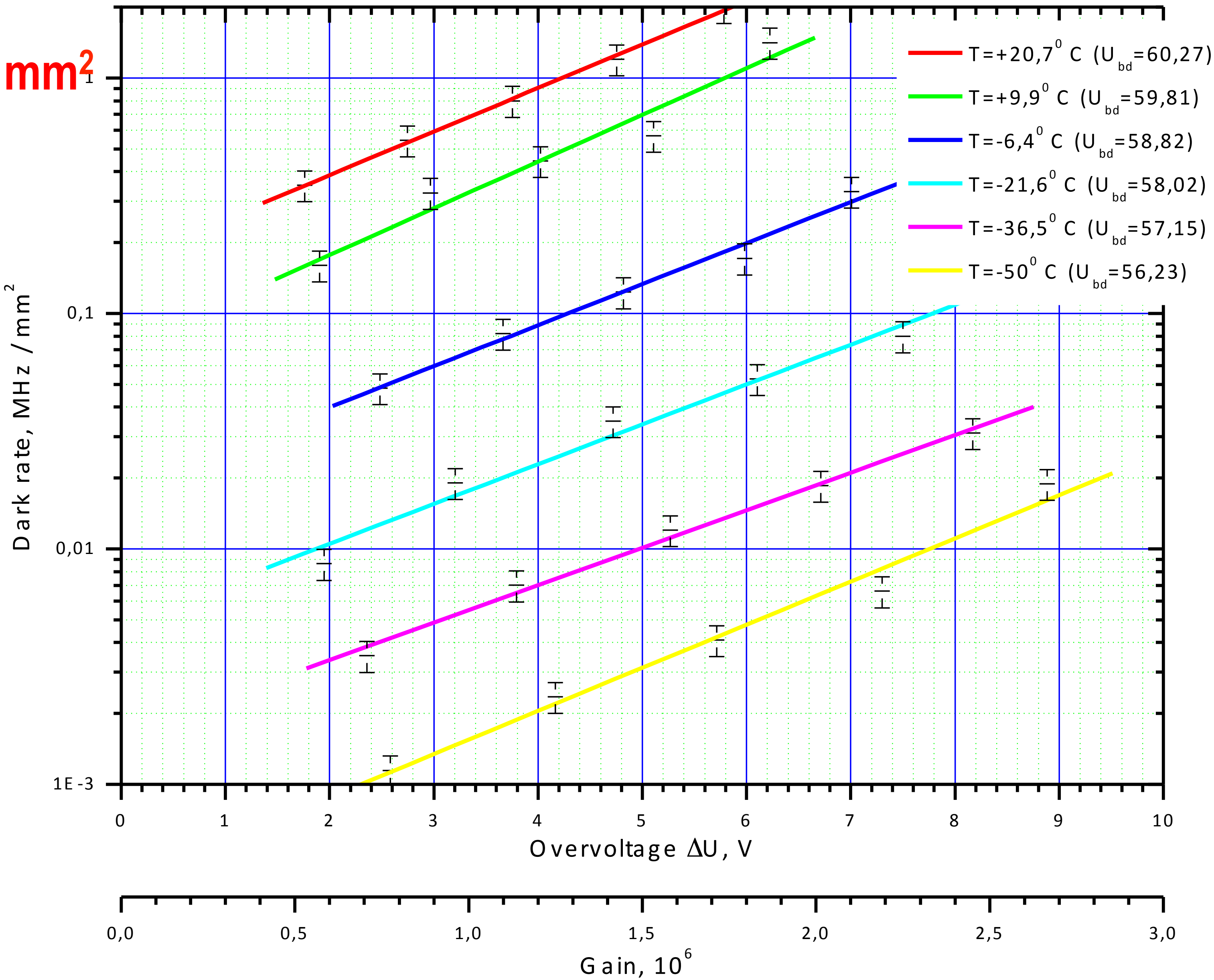


Optical Cross Talk of 1mm^2 SiPM



Dark Rate of 1mm² SiPM

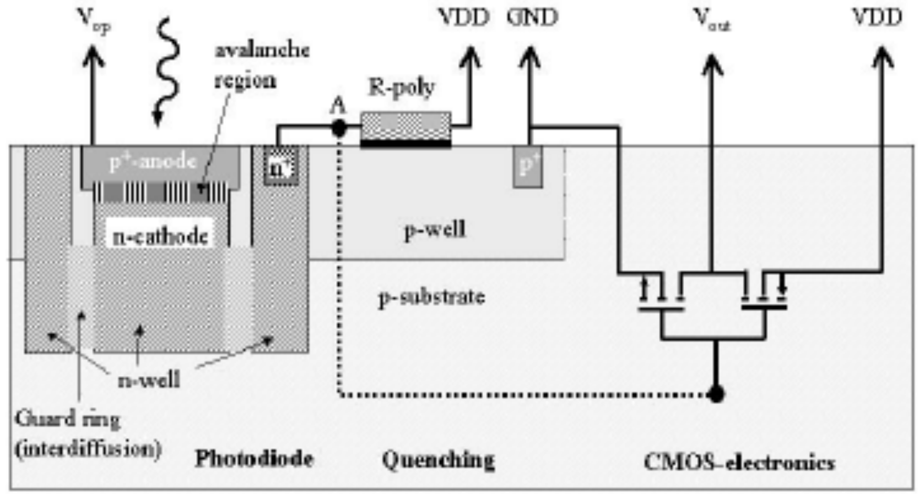
1 MHz / mm²

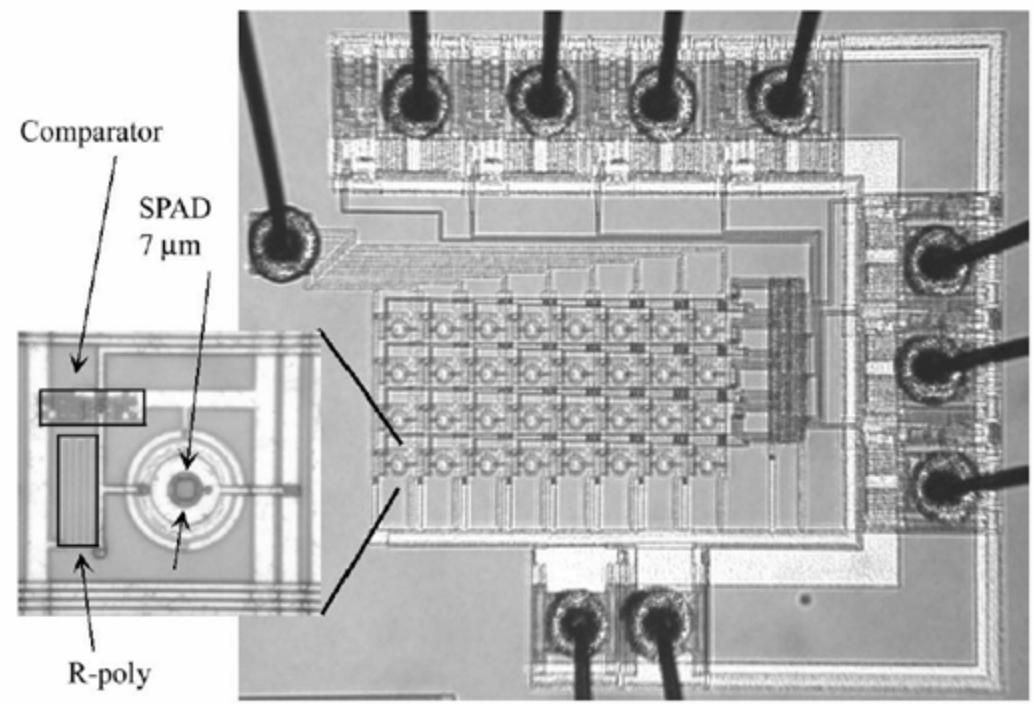


Future of SiPM

- **Combination of the Sensors and FE Electronics in the same technology Process.**

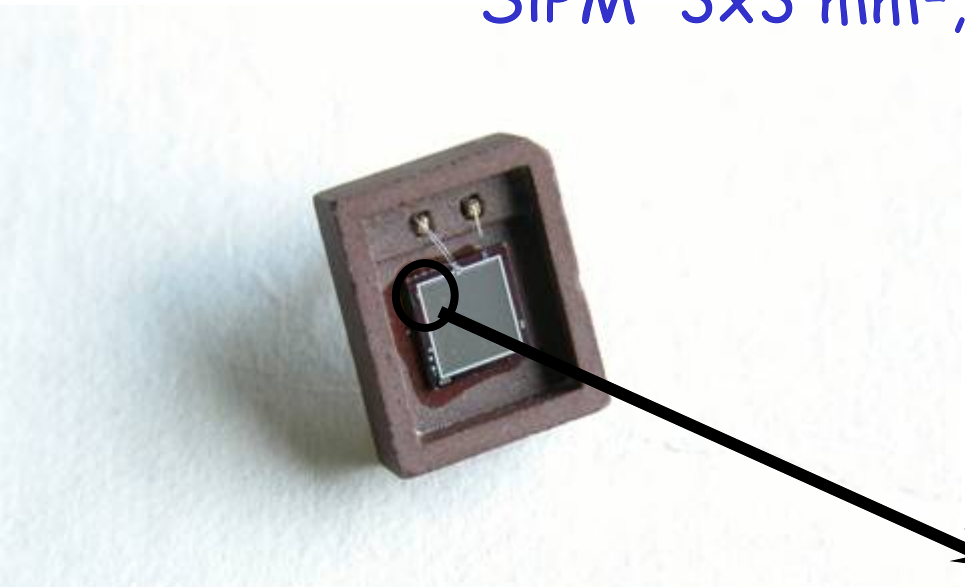
  (IEEE STQE, v10, Jul-Aug, 2004,C.Niclass)

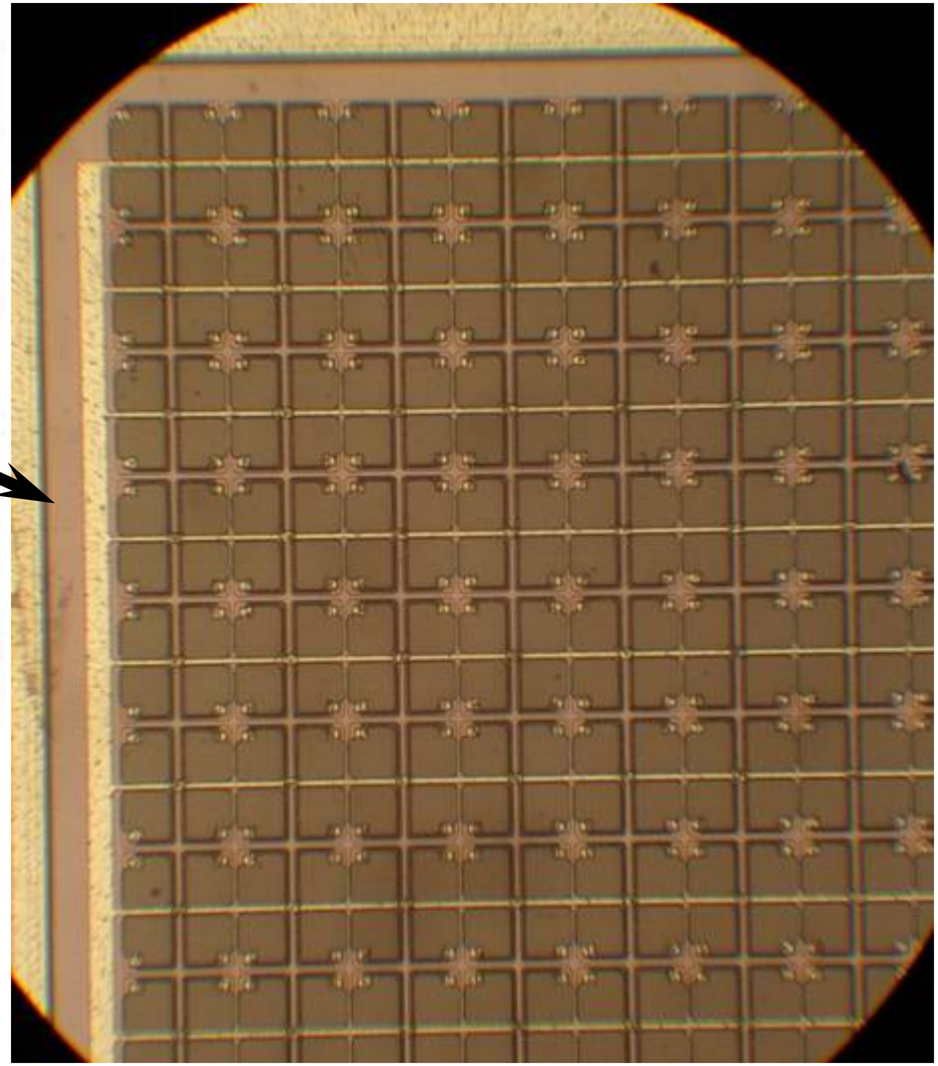




Large Area SiPM

SiPM 3x3 mm^2, 5625 pixels





Larger area (up to 10x10 mm^2) is required for a number of applications:

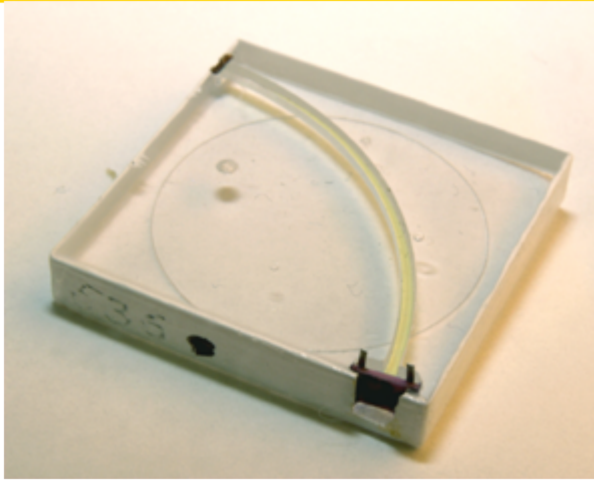
o astroparticle physics

o PET

o Particle physics

o . . .

SiPMs in ILC Tile HCAL Prototype

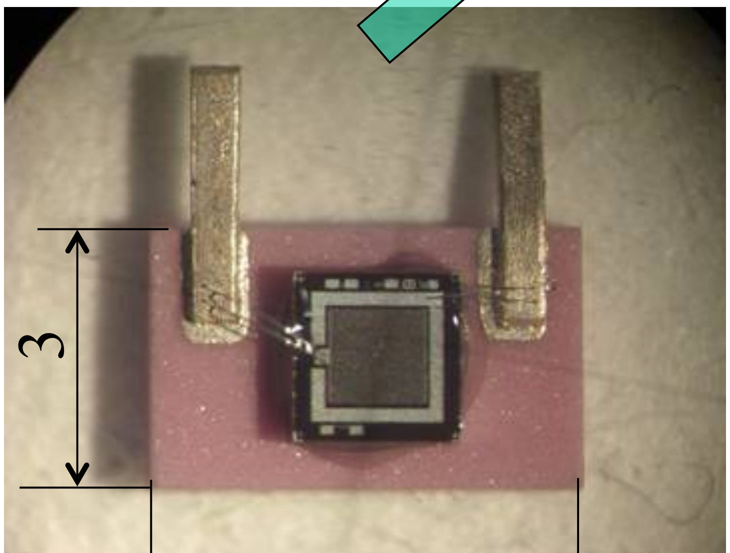


Tile with milled groove for WLS and precise hole for SiPM installation

SiPMs

1156 pixels

1x1 mm^2

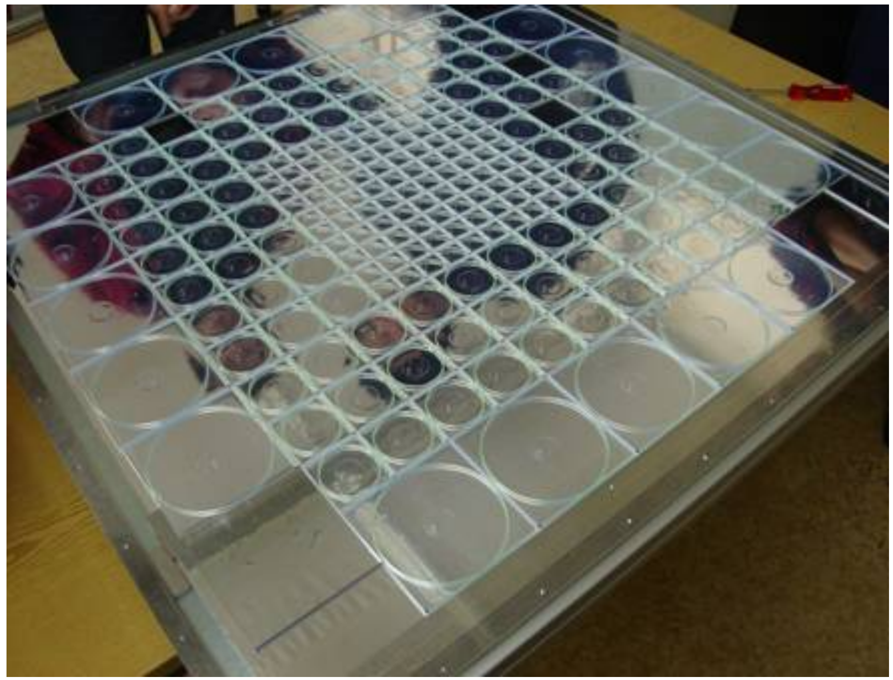


3

5±0.03

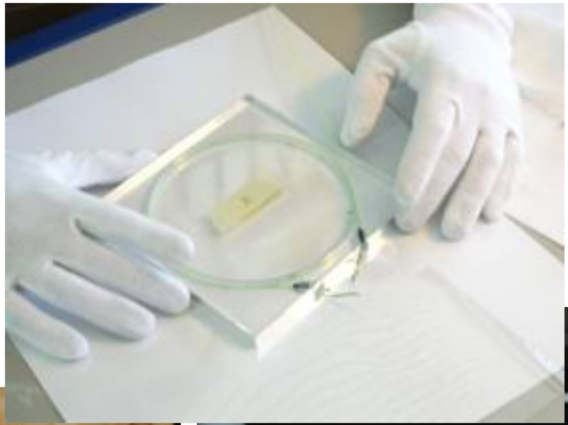
Precise ceramic plate

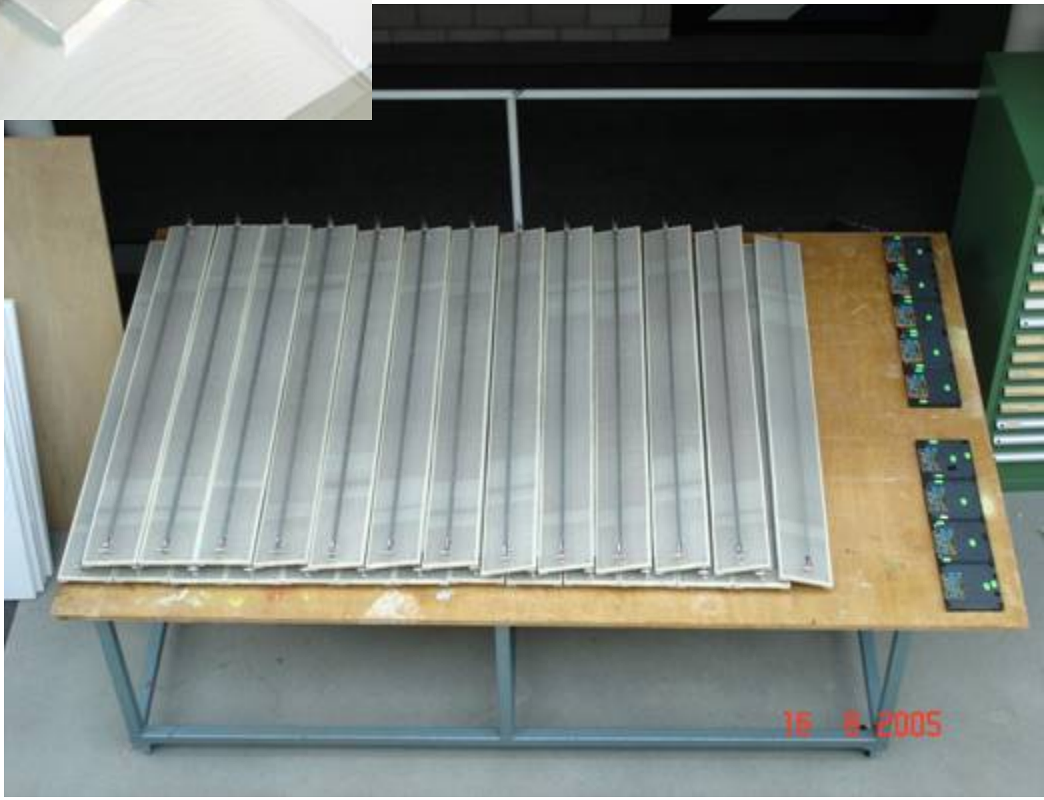
The first HCAL prototype cassette



40 Cassettes will be required

Production for ALICE CRF

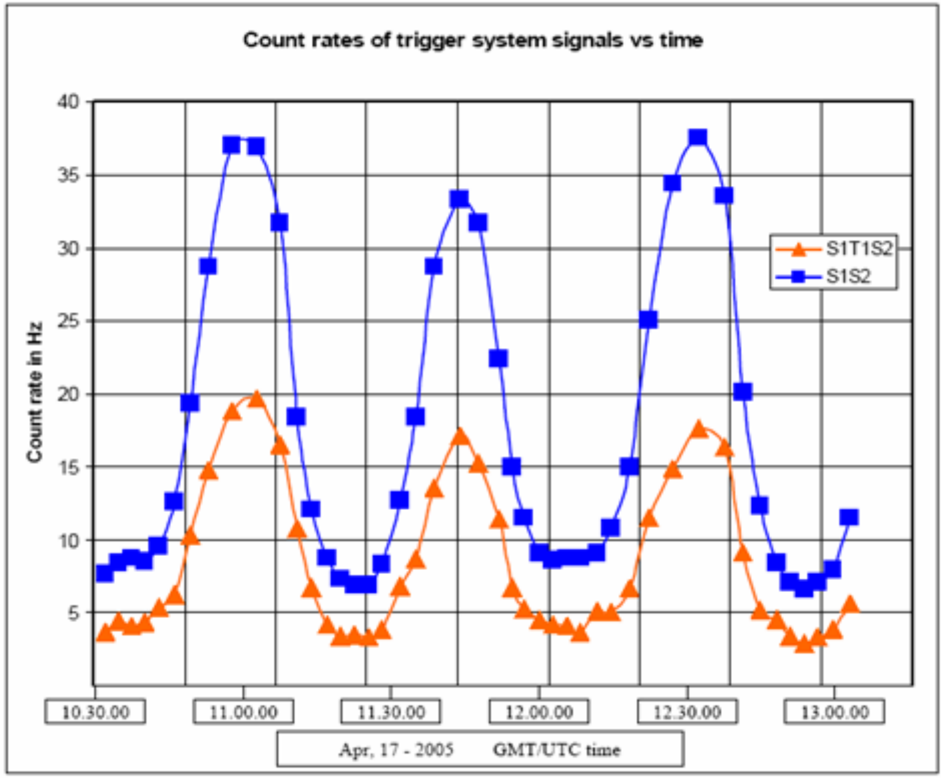




Akindinov et al., High-efficiency and low noise scintillation detector for ionizing particles START (Scintillation Tile with MRS APD Light ReadouT)

SiPM's in space ! International Space Station: launched by 15th of April,2005

Space experiment "LAZIO"(MEPHI-INFN Collaboration)



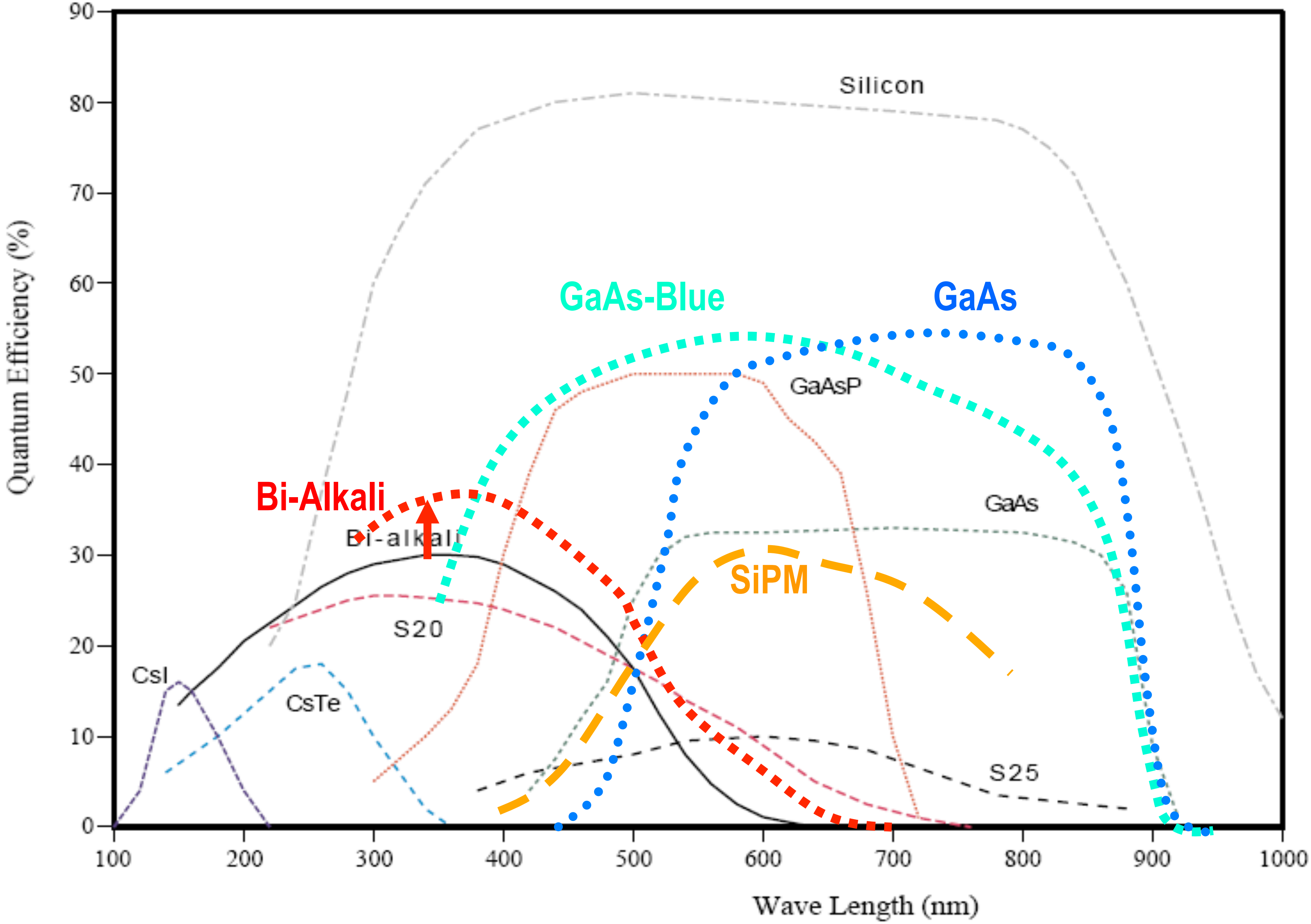
Latitude particle flux dependence

<u>Scientific goal</u>:The measurement of low energy particle fluxes and radiation monitoring by apparatus,including sci tile+WLS fiber+SiPM hodoscope system

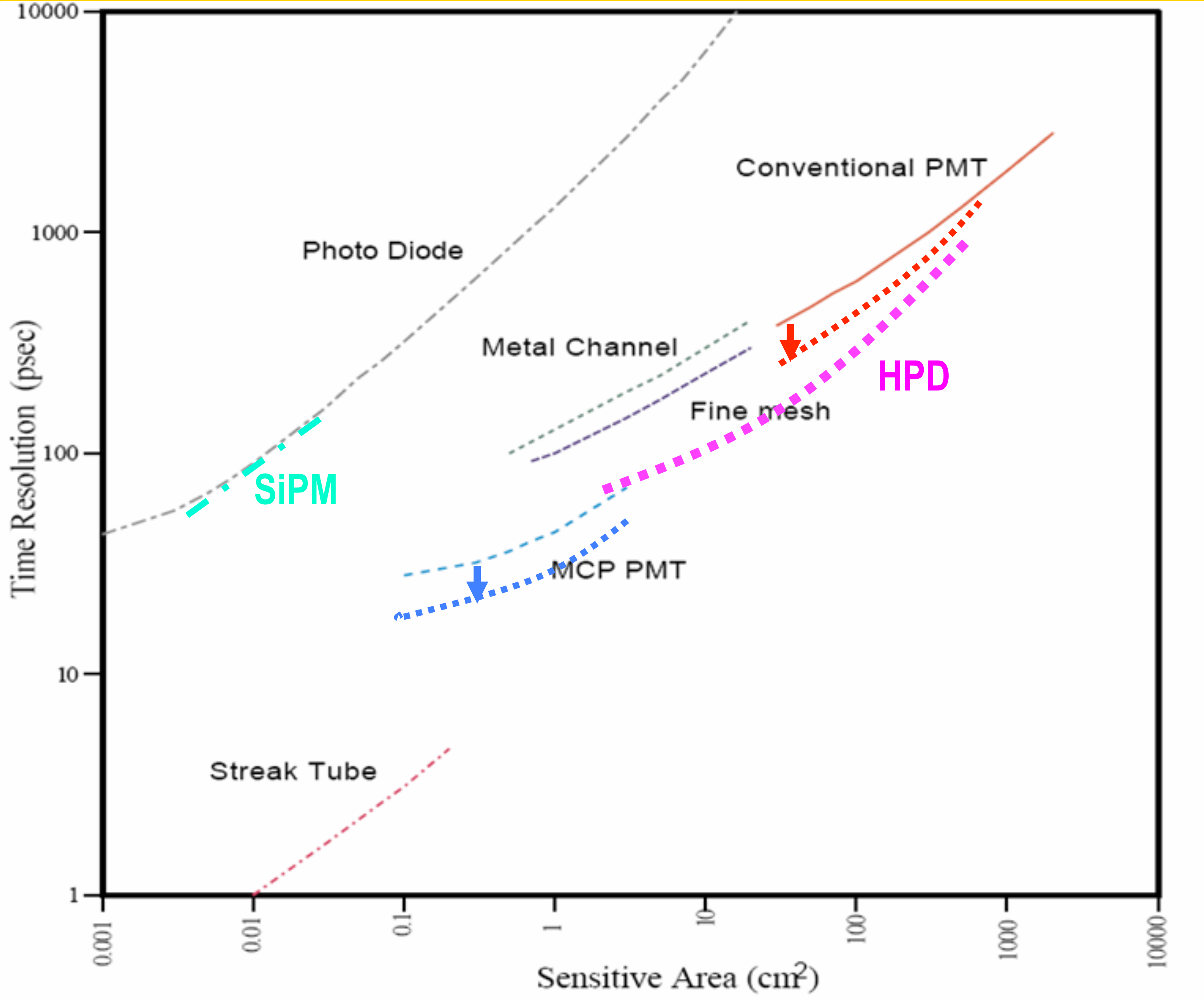
Final Comparisons

- QE
- TTS
- Energy Resolution
- Cost

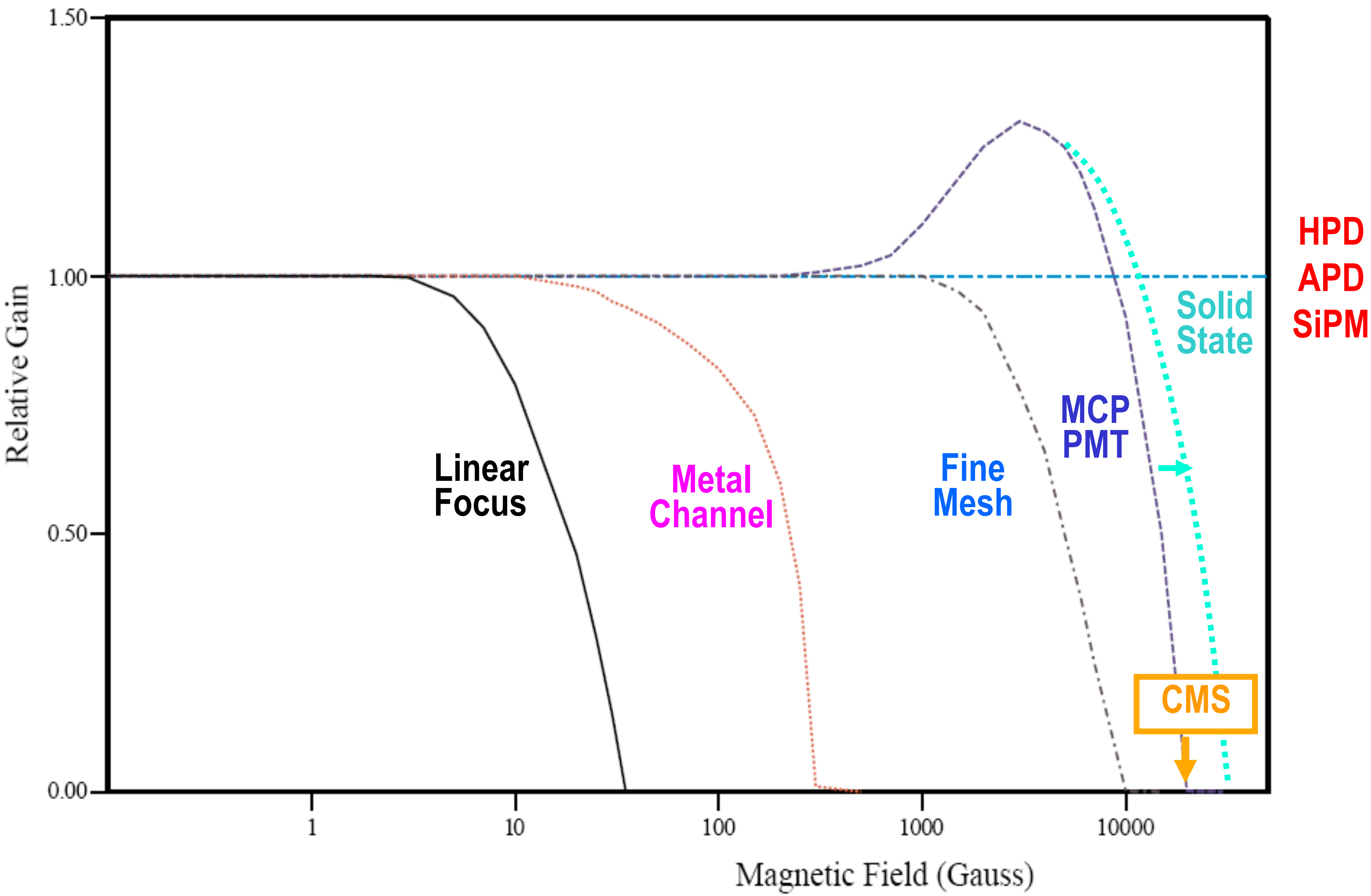
Quantum Efficiency
(Beaune 1999 → 2002 → 2005)



Time Resolution vs. Sensitive Area
(Beaune 1999 → 2005)



Effect of Magnetic Fields
(Beaune 1999 → 2005)



Equivalent Noise Charge (ENC) after CRRC^n

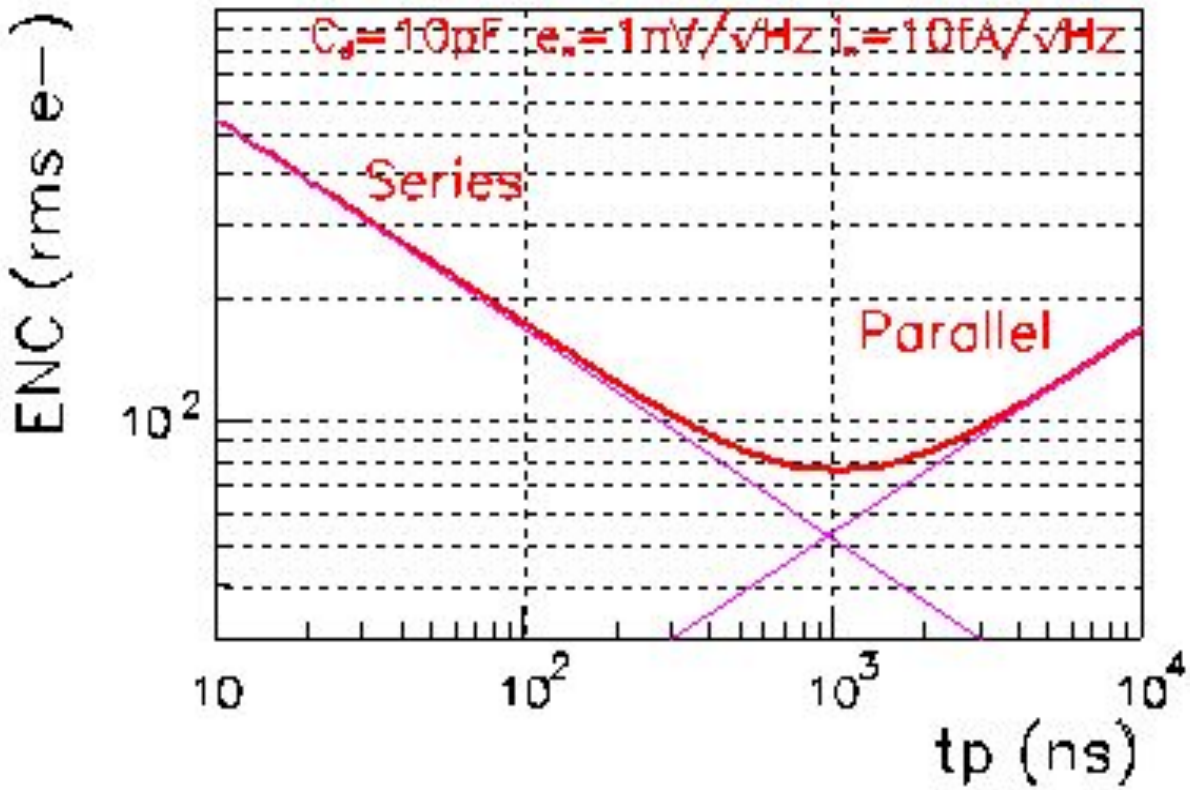
- **A useful formula :** ENC (e- rms) after a CRRC^2 shaper :

$$\boxed{ENC = 174\ e_n C_{tot} / \sqrt{t_p}\ (\delta) \oplus 166\ i_n \sqrt{t_p}\ (\delta)}$$

  - e_n in nV/ √Hz, i_n in pA/ √Hz are the preamp noise spectral densities
  - C_{tot} (in pF) is dominated by the detector (C_d) + input preamp capacitance (C_{PA})
  - t_p (in ns) is the shaper peaking time (5-100%)

- **Noise minimization**
  - Minimize source capacitance
  - Operate at optimum shaping time
  - Preamp series noise (en) best with high trans-conductance (g_m) in input transistor

    => large current, optimal size



Energy Resolution (σ/E)

- In ideal case:

$$\frac{\sigma}{E} = \frac{\sqrt{N_\gamma}}{N_\gamma} = \sqrt{\frac{1}{N_\gamma}}$$

- In reality:

$$\frac{\sigma}{E} = \sqrt{\frac{ENF}{N_\gamma \cdot QE \cdot CE} + \left(\frac{ENC}{N_\gamma \cdot QE \cdot CE \cdot G}\right)^2}$$

– Nγ	Number of incident photons
– QE	Quantum Efficiency
– CE	Collection Efficiency:
– ENF	Excess Noise Factor (from Dynodes)
– ENC	Equivalent Noise Charge (Readout Noise)
– G	Gain

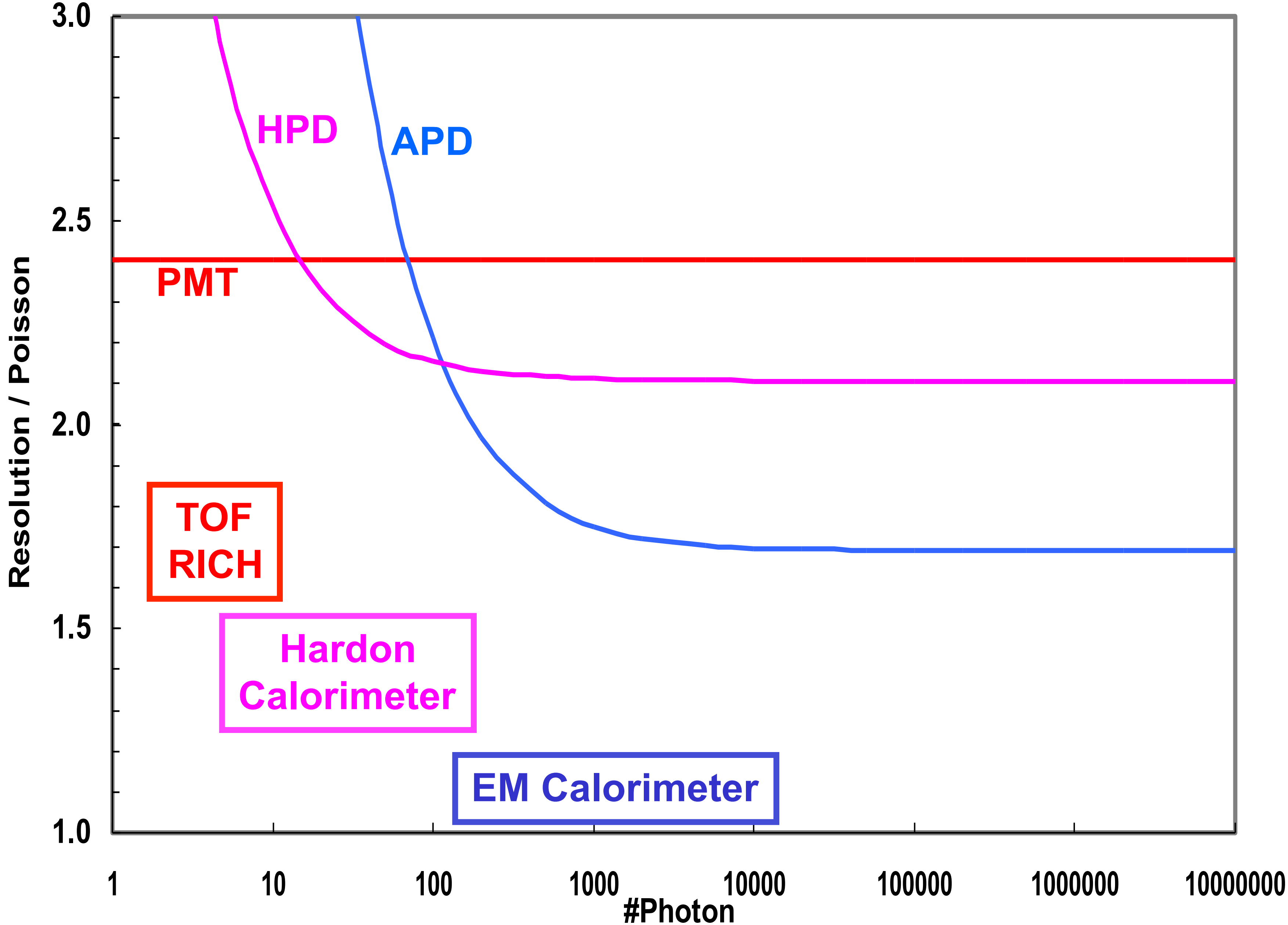
Summary Table
(Beaune 1999)

	QE	CE	δ_i	ENF	G	ENC	σ/E
Ideal	1.0	1.0	1000	1.0	10^6	0	$\sqrt{1/N}$
PMT	0.25	0.9	10	1.3	10^6	1000	$\sqrt{5.8/N}$
PD	0.7	1.0	-	1.0	1	1000	$\sqrt{1.4/N+(1400/N)^2}$
APD	0.7	1.0	2	2.0	100	1000	$\sqrt{2.9/N+(14/N)^2}$
HPD	0.25	0.9	1000	1.0	10^3	1000	$\sqrt{4.4/N+(4.4/N)^2}$
HAPD	0.25	0.9	1000	1.0	10^5	1000	$\sqrt{4.4/N}$
VLPC	0.7	1.0	1000	1.0	10^5	1000	$\sqrt{1.4/N}$

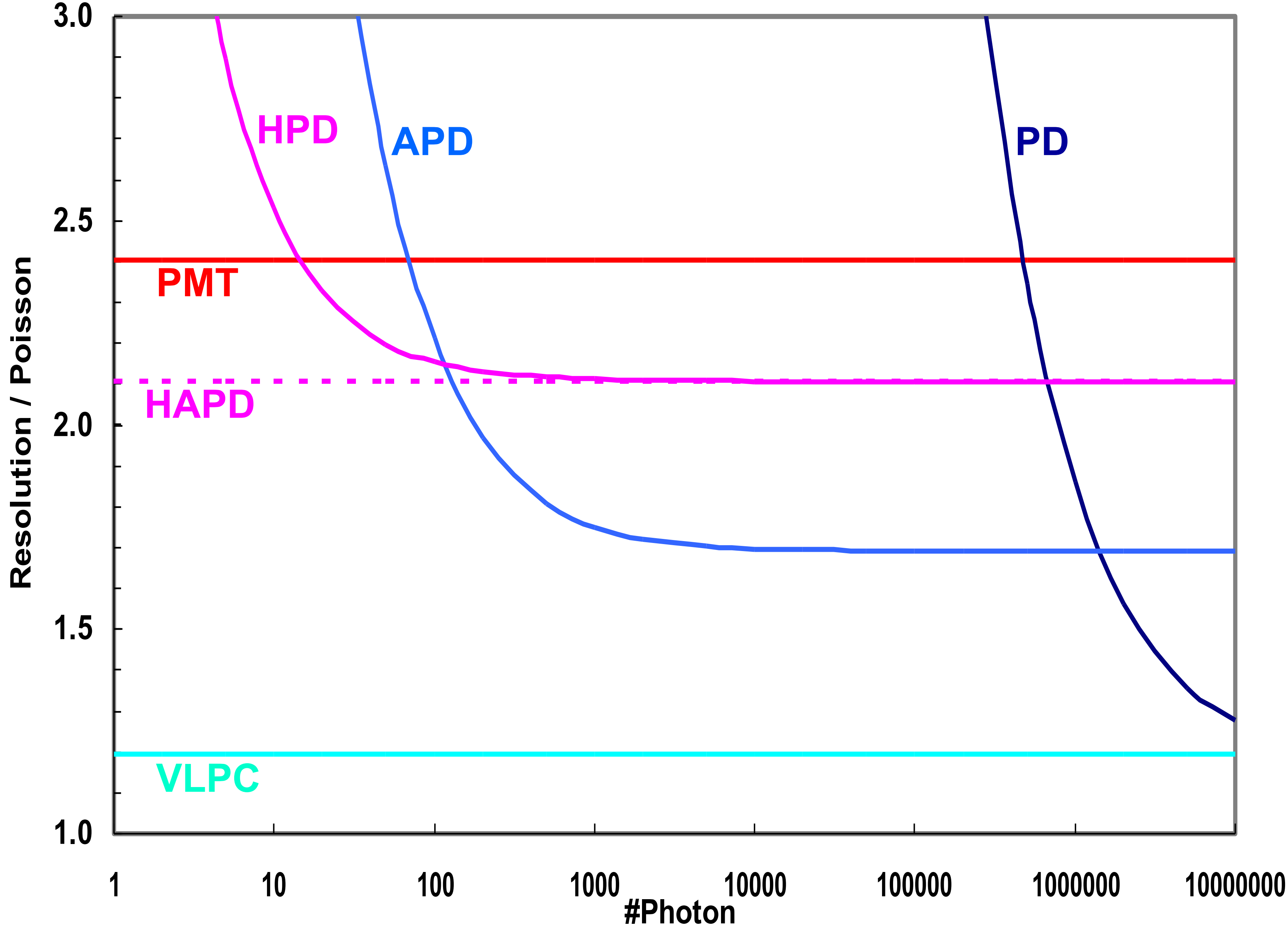
Summary Table
(Beaune 2005)

	QE	CE	δ_i	ENF	G	ENC	σ/E
Ideal	1.0	1.0	1000	1.0	10^6	0	$\sqrt{1/N}$
PMT	0.35	0.9	10	1.3	10^6	200	$\sqrt{3.8/N}$
PD	0.7	1.0	-	1.0	1	200	$\sqrt{1.4/N+(280/N)^2}$
APD	0.7	1.0	2	2.0	100	200	$\sqrt{2.9/N+(2.9/N)^2}$
HPD	0.5	0.9	1000	1.0	10^3	200	$\sqrt{2.2/N+(0.4/N)^2}$
HAPD	0.5	0.9	1000	1.0	10^5	200	$\sqrt{2.2/N}$
SiPM	0.7	0.4	1000	1.3	10^6	1000	$\sqrt{4.3/N}$
VLPC	0.7	1.0	1000	1.0	10^5	200	$\sqrt{1.4/N}$

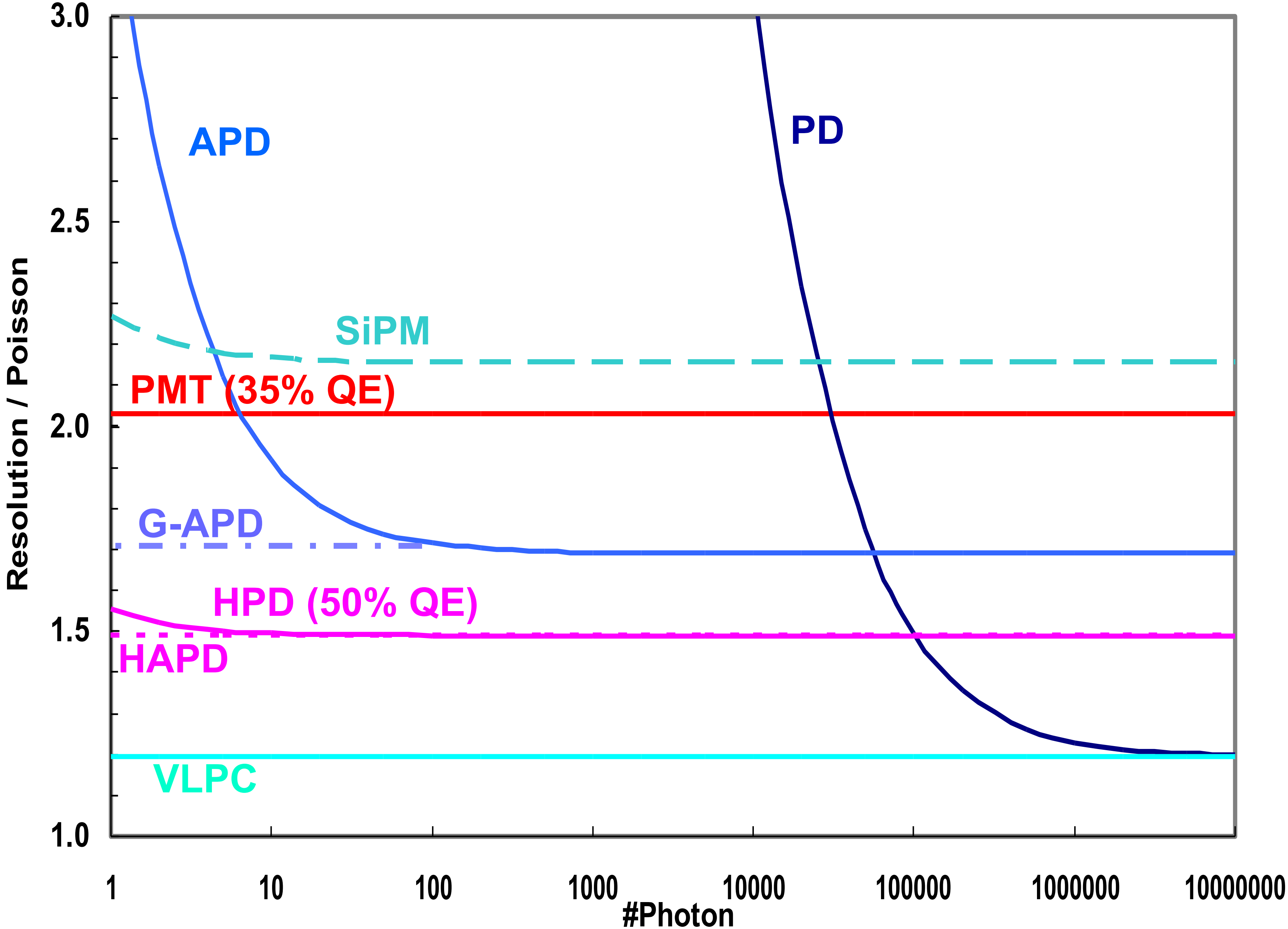
Resolution (over Poisson Limit)
(Beaune 1999)



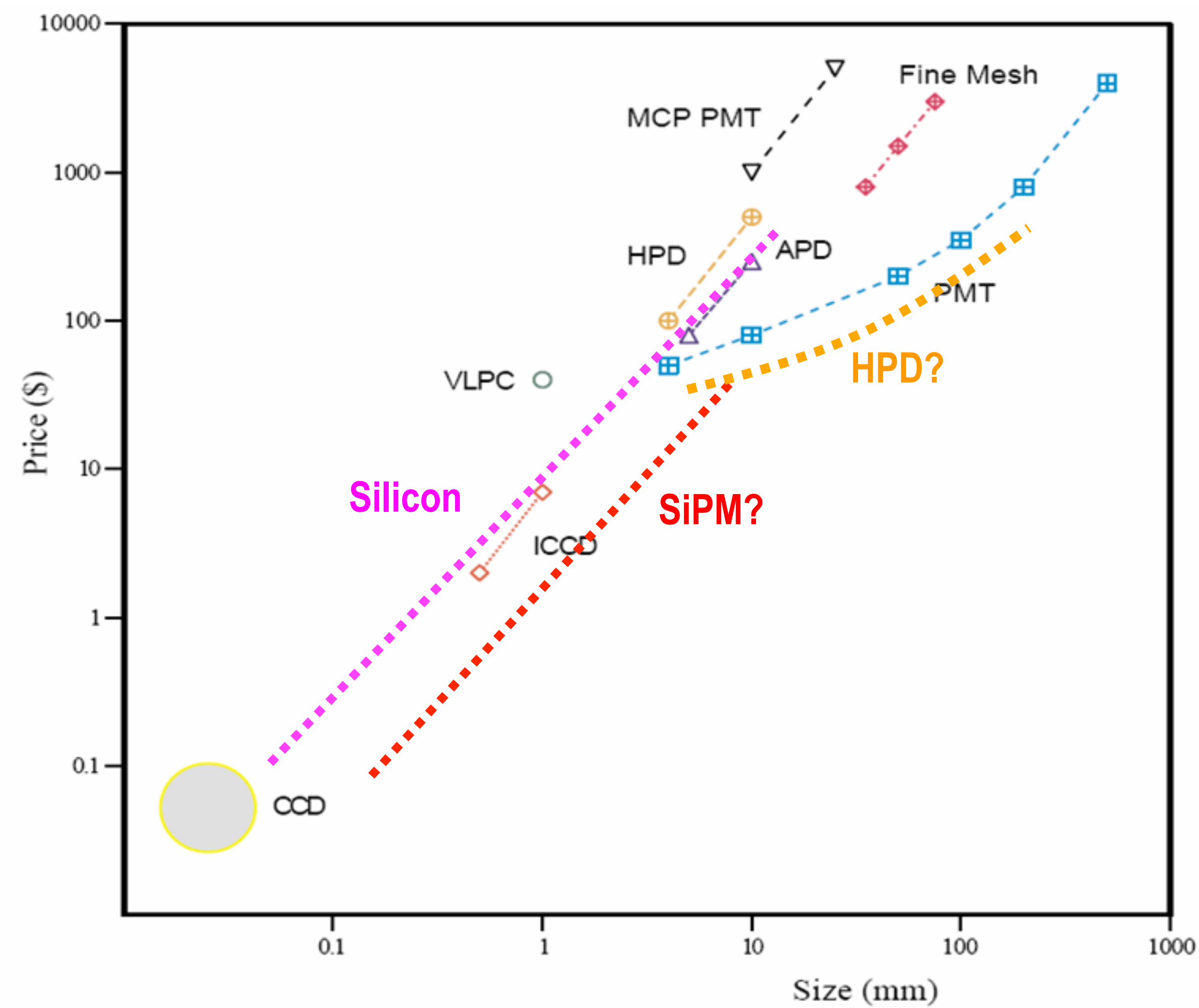
Resolution (over Poisson Limit)
(Beaune 1999)



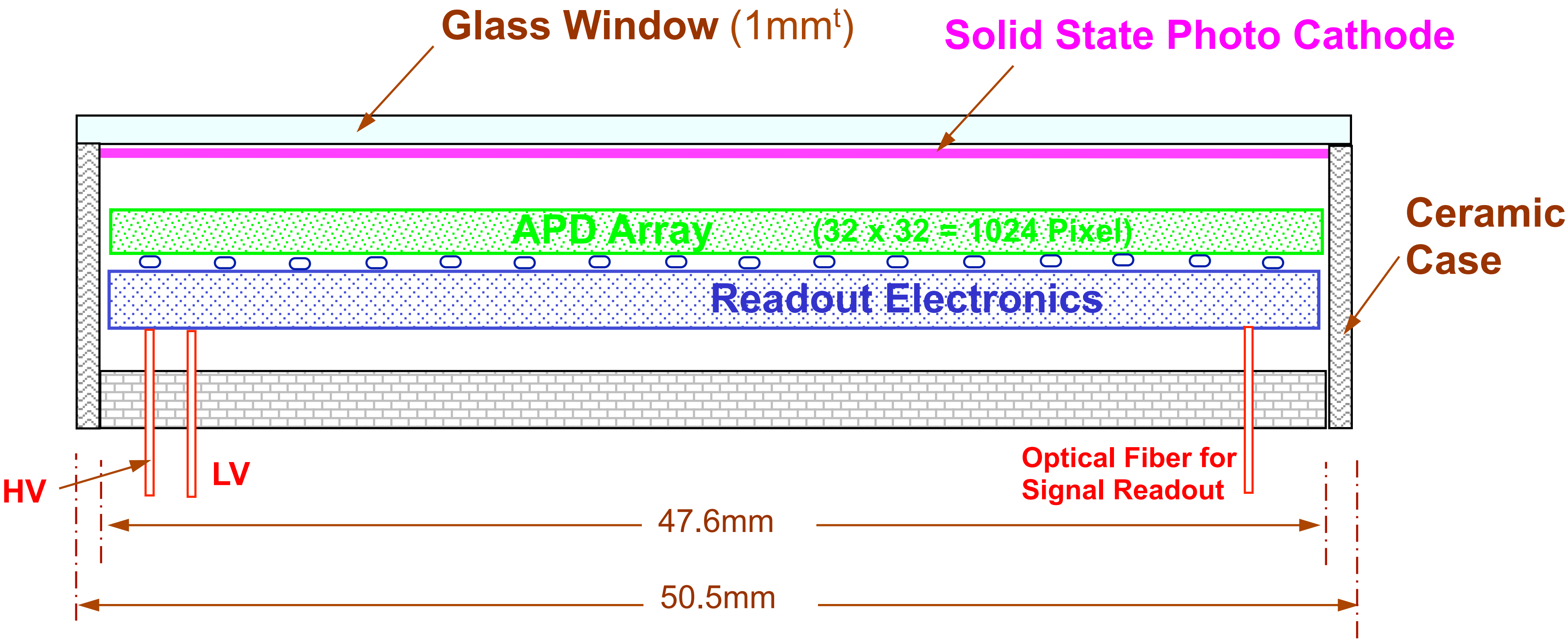
Resolution (over Poisson Limit)
(Beaune 2005)



Market Price
(Beaune 1999 → 2005)

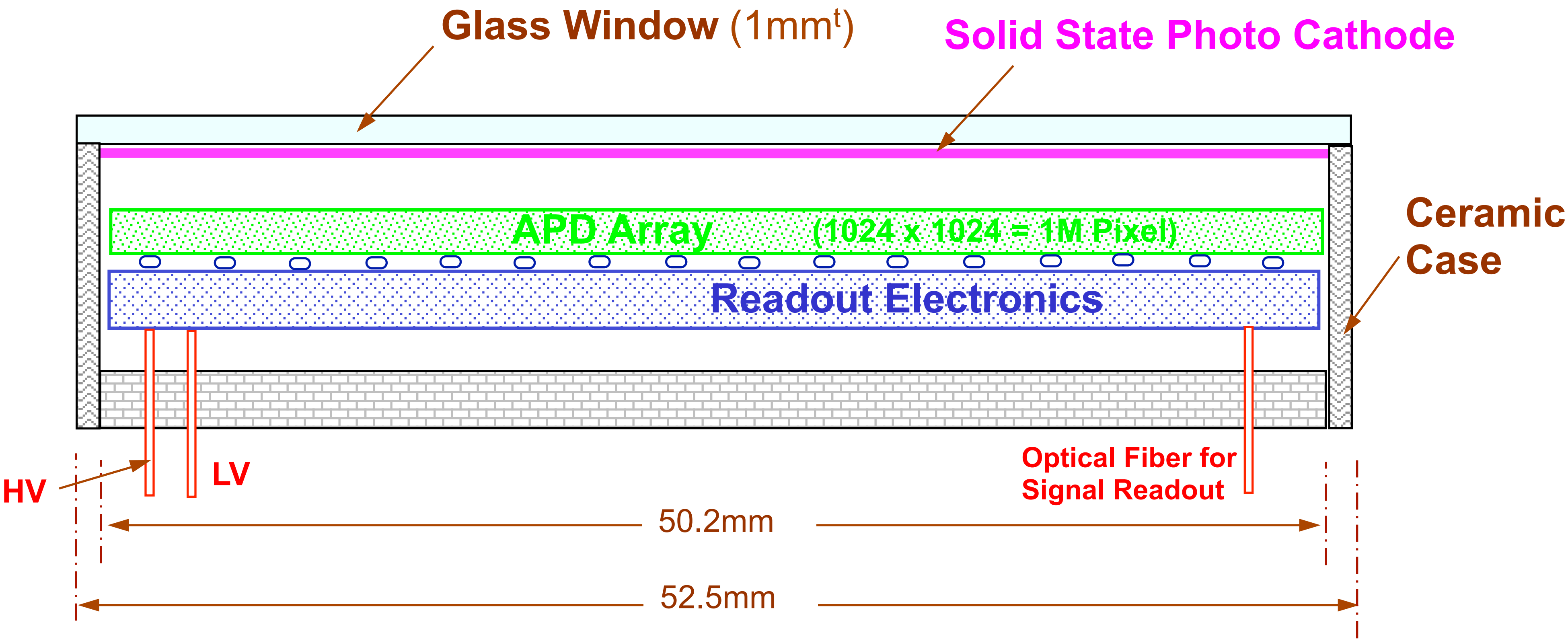


Katsushi' s Dream Detector
(at Beaune 1999, 2002)



- 1.4mm Pixel Size
- 32 x 32 = 1,024 Pixels
- QE ~ 50% at 350 ~ 500nm
- Gain ~10^5

Katsushi's Dream Detector
(at Beaune 2005)



- 50 μm Pixel Size
- 1024 x 1024 = 1M Pixels
- QE ~ 80% at 300 ~ 800 nm
- Gain ~10^5

Concluding Remarks

- **Areas of interests at Beaune 2005:**
  - SiPM
  - Large area HPD
  - Integrated front-end electronics
- **Future direction will be driven by**
  - Broader markets (outside of Physics)
  - Low Costs