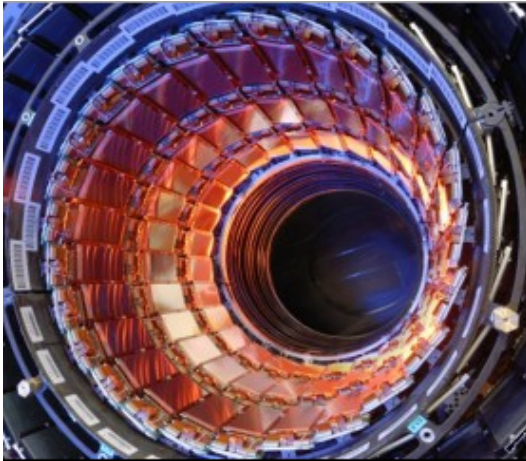




XXV GIORNATE DI STUDIO SUI RIVELATORI

Scuola F. Bonaudi

23-26 Febbraio

Villaggio dei Minatori - Cogne (AO)

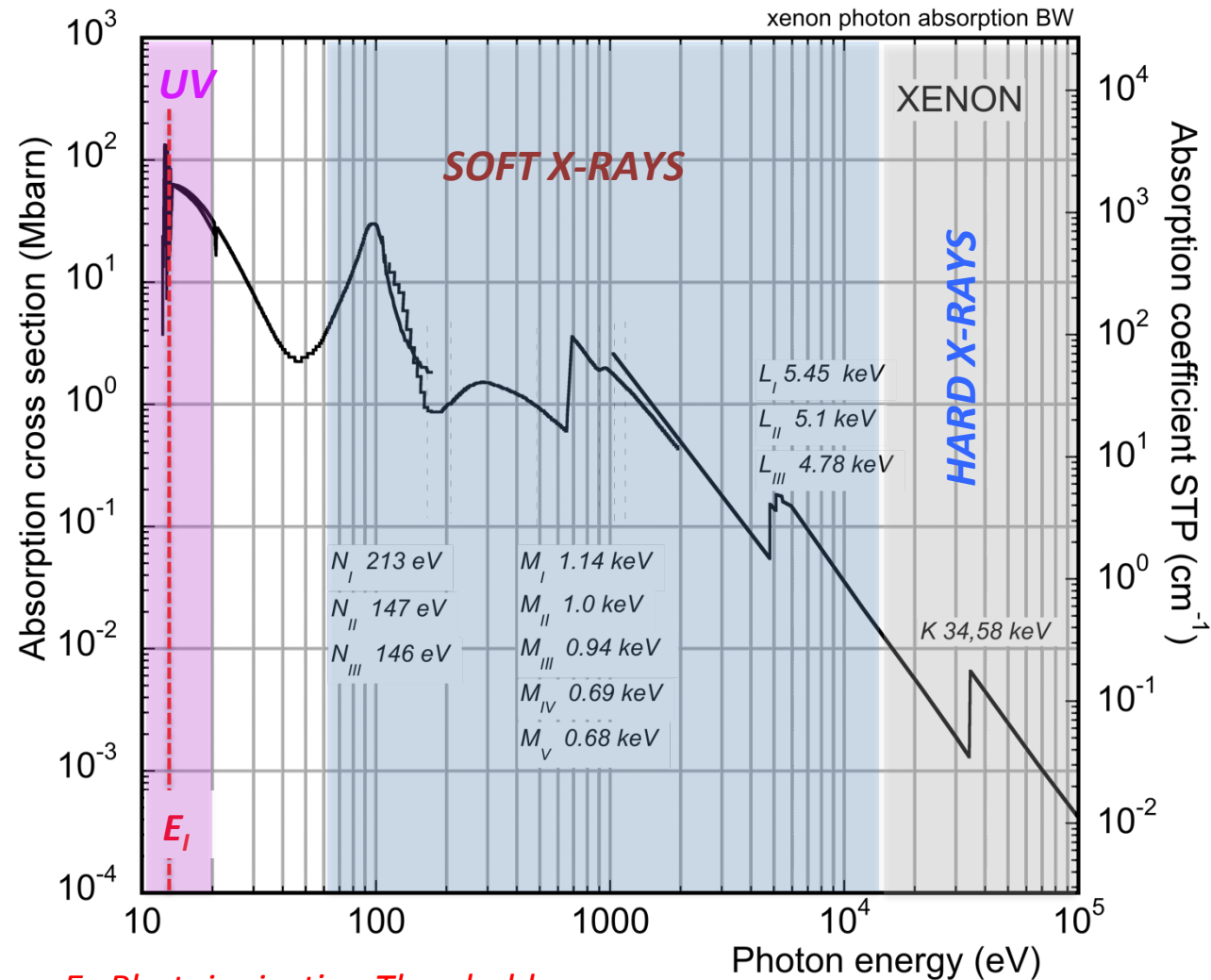
Fabio Sauli
TERA Foundation
CERN



PART 1
PHOTON DETECTION AND IMAGING WITH
GASEOUS COUNTERS

PHOTON ENERGY	RANGE	PROCESS	APPLICATIONS
1 eV	INFRARED	CATHODE FIELD EMISSION?	
	VISIBLE		IMAGE INTENSIFIERS
	NEAR UV	INTERNAL PHOTOCATHODES	FLAME DETECTION
10 eV	VACUUM UV	GAS PHOTOELECTRIC	CHERENKOV RING IMAGING
100 eV	NO WINDOWS		
1 keV		GAS PHOTOELECTRIC	PROPORTIONAL COUNTERS SPECTROSCOPY
10 keV			CRISTALLOGRAPHY FLUORESCENCE ANALYSIS
100 keV		INTERNAL CONVERTERS	RADIOGRAPHY CAT
511 keV			PORTAL IMAGING PET
1 MeV			

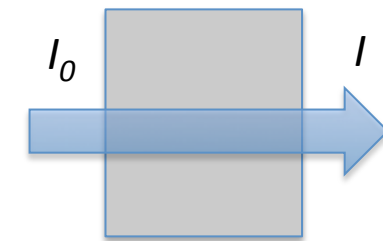
XENON PHOTON ABSORPTION CROSS SECTION AND ABSORPTION COEFFICIENT



E_i : Photoionization Threshold

<http://xdb.lbl.gov/>

<http://www.nist.gov/pml/data/xraycoef/>



$$I = I_0 e^{-\alpha x} = I_0 e^{-\frac{x}{\lambda}}$$

α : absorption coefficient

x : layer thickness

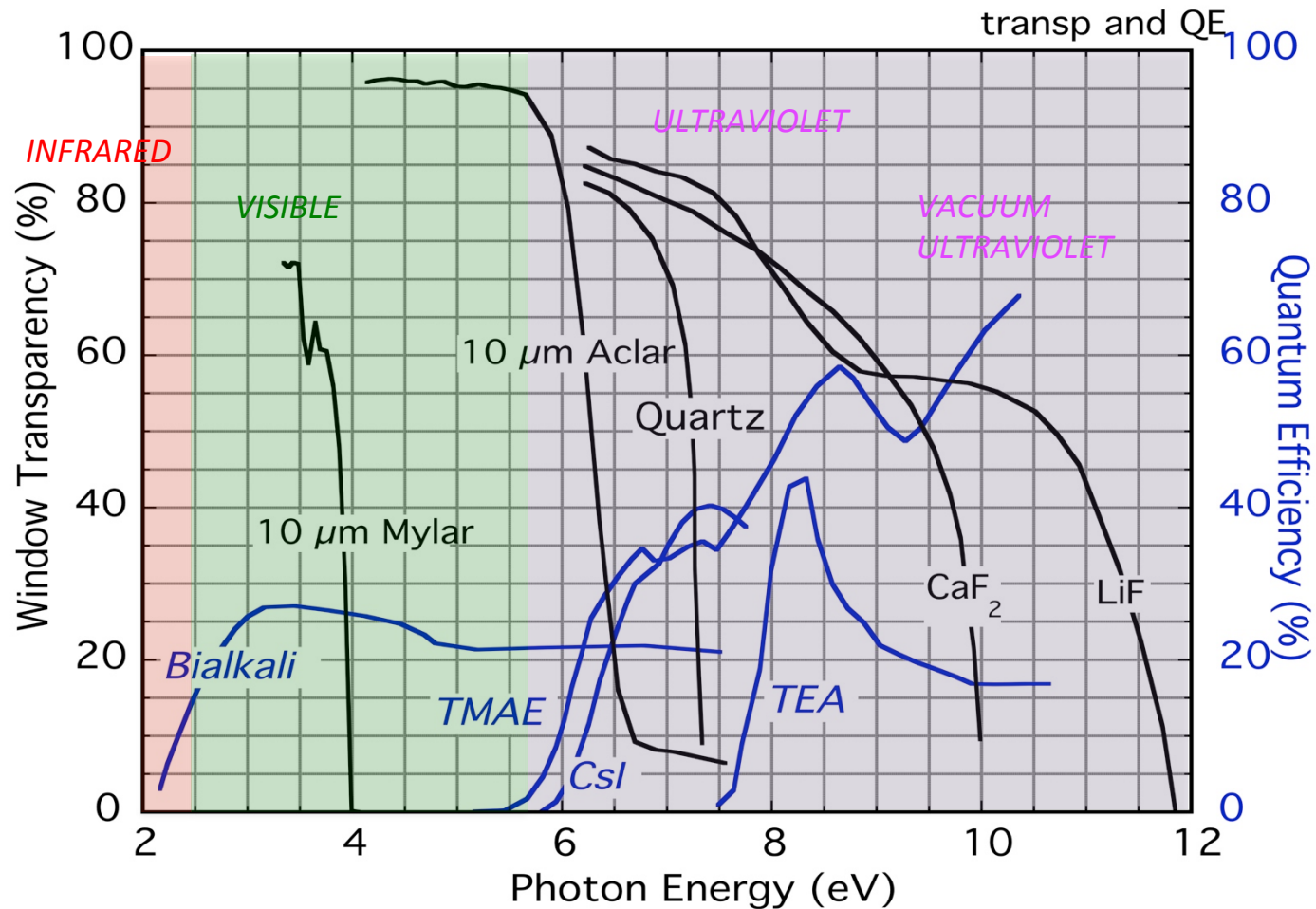
λ : absorption length

For gases at STP:

$$\alpha_{STP} (cm^{-1}) = 26.87 \sigma (Mbarn)$$

$$1 \text{ Mbarn} = 10^{-18} \text{ cm}^2$$

QUANTUM EFFICIENCY AND WINDOW TRANSPARENCY-VISIBLE TO UV



Mylar: cut UV from external sources, hygroscopic
 Aclar: non-hygroscopic, transparent to UV

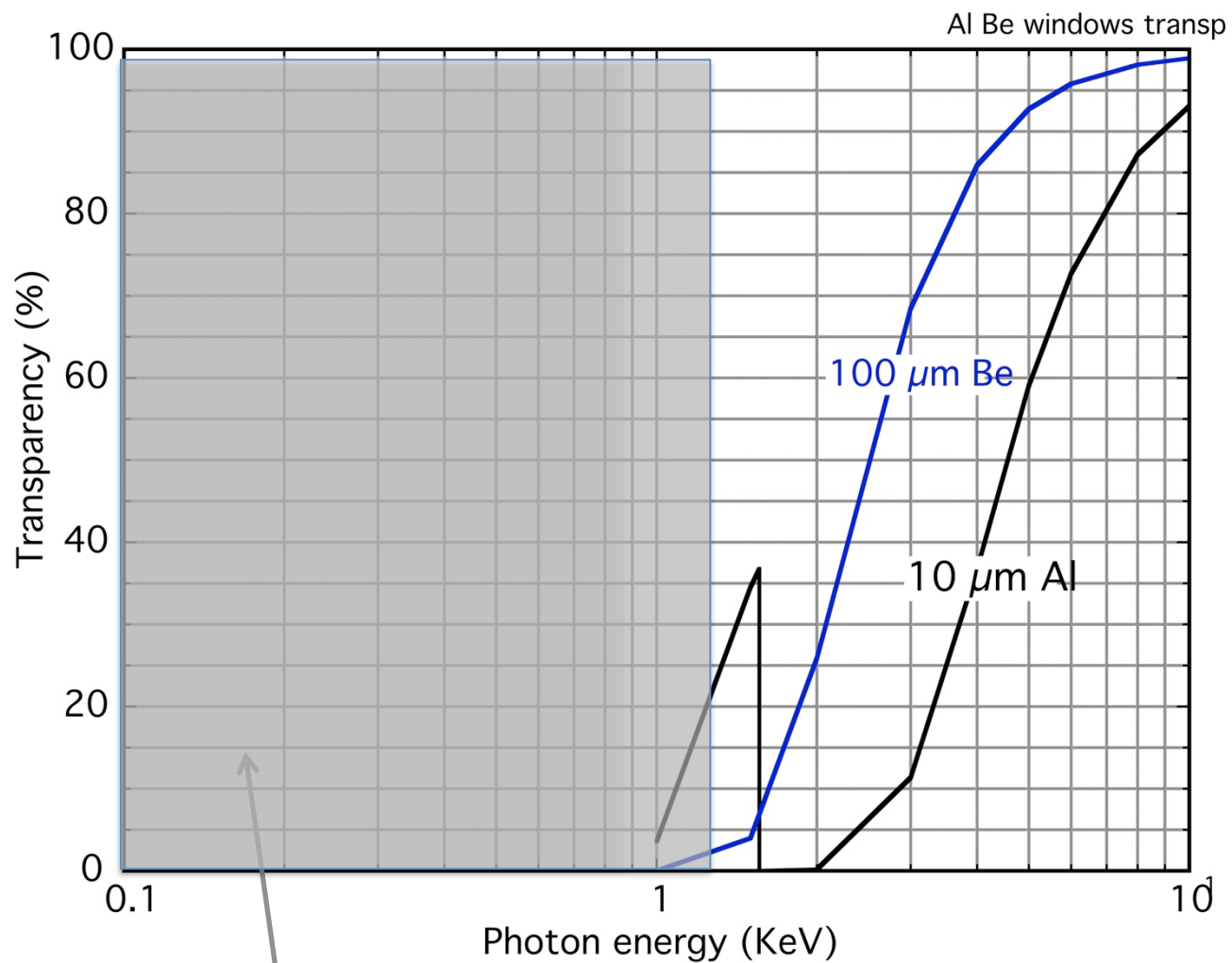
Bialkali: K-Cs Photocathode $E_i = 2.2$ eV

CSi: Caesium iodide $E_i = 5.8$ eV

TMAE: Tetrakis-dimethylamino-ethylene $C[(CH_3)_2N]_4$ $E_i = 5.3$ eV

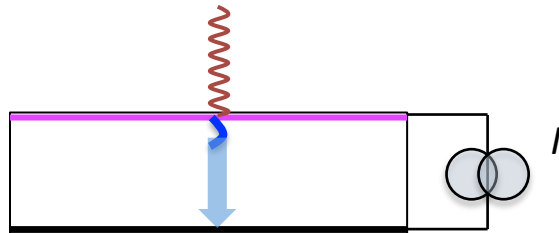
TEA: Triethylamine $(C_2H_5)_3N$ $E_i = 7.5$ eV

WINDOWS TRANSPARENCY – SOFT X-RAYS



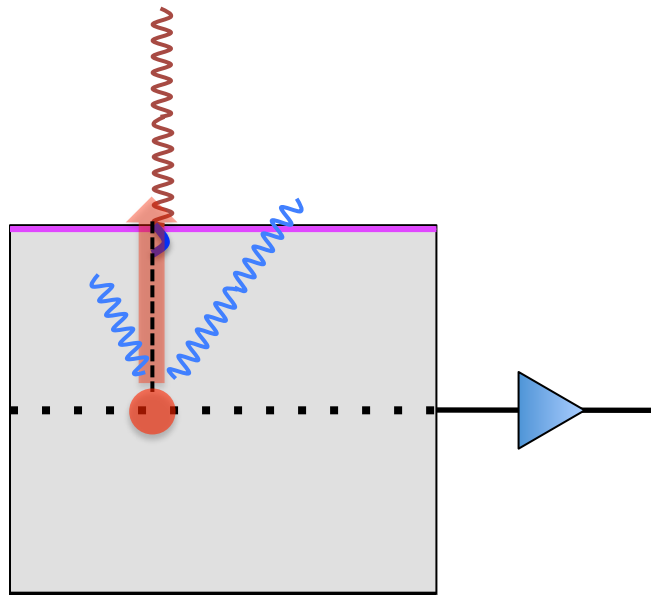
Windows cutoff between ~ 12 eV and ~ 1 keV

VACUUM PHOTODIODE: NO GAIN, NO FEEDBACKS



- No gain,
- Uniform and stable response
- No secondary processes

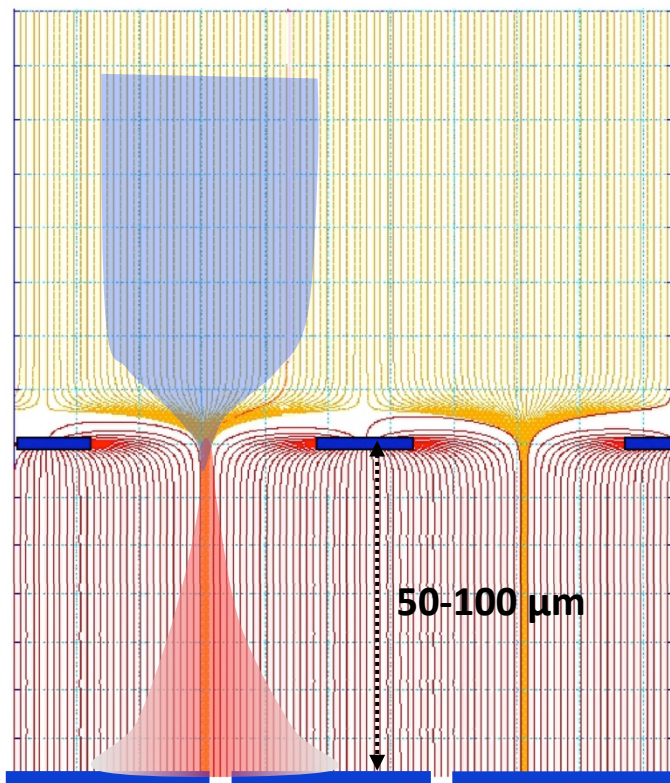
GASEOUS PHOTON DETECTORS:



- Very sensitive to impurities (O_2 , H_2O ,...)
- Backscattering reduces Quantum Efficiency
- Drift to anode and multiplication
- High gains (10^5 - 10^6)
- Photon feedback (secondary ionization)
- Positive ions damage the photocathode

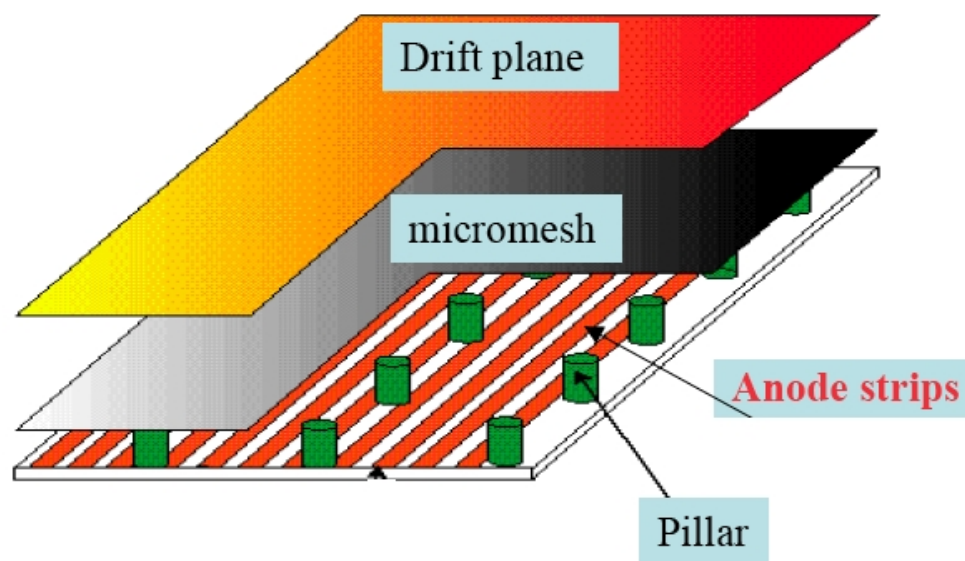
MICRO-PATTERN GAS DETECTORS (MPGD)

MICROMEGAS:
MICRO-Mesh Gaseous Structure



Y. Giomataris et al,
*Nucl. Instr. and Meth. A*376(1996)29

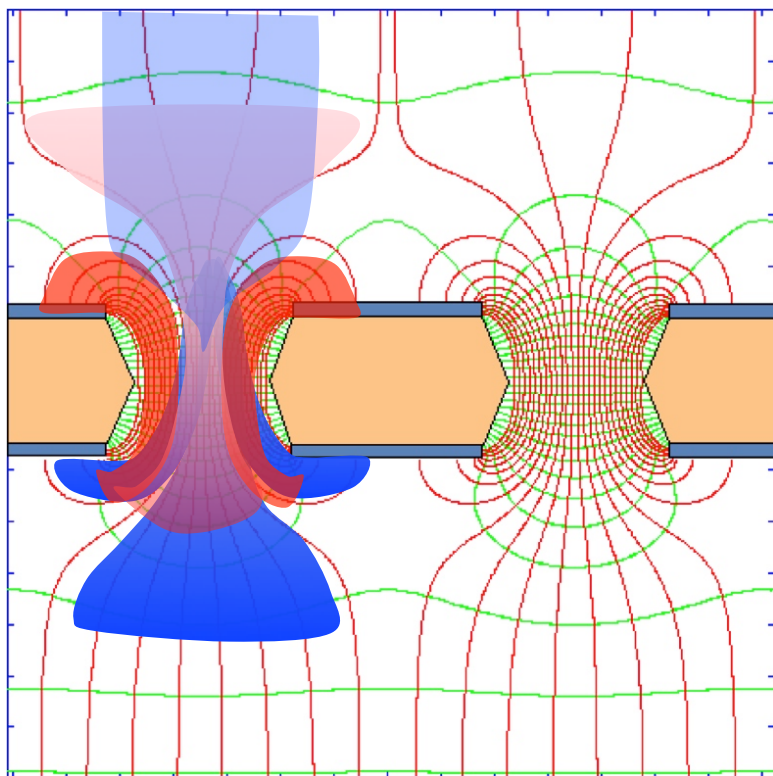
GAP RESTORERS: INSULATING PILLARS



Y. Giomataris,
*Nucl. Instr. and Meth. A*419(1998)239

MICRO-PATTERN GAS DETECTORS (MPGD)

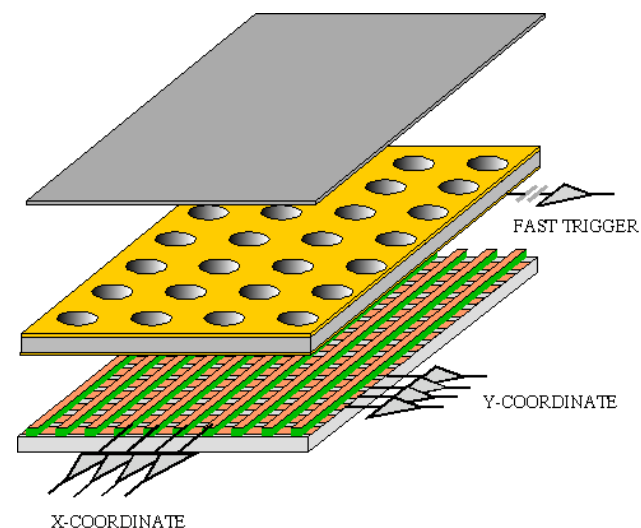
GEM: GAS ELECTRON MULTIPLIER
THIN (50 μM) METAL-COATED POLYMER FOIL
WITH HIGH DENSITY OF HOLES



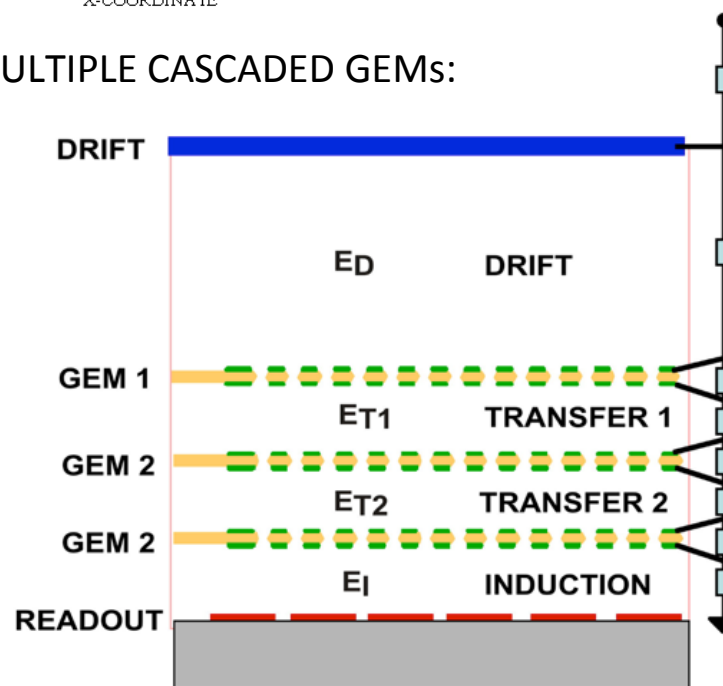
F. Sauli, Nucl. Instr. and Meth. A386(1997)531

A. Bressan et al, Nucl. Instr. and Meth. A425(1999)254

SINGLE GEM WITH 2-D READOUT BOARD:



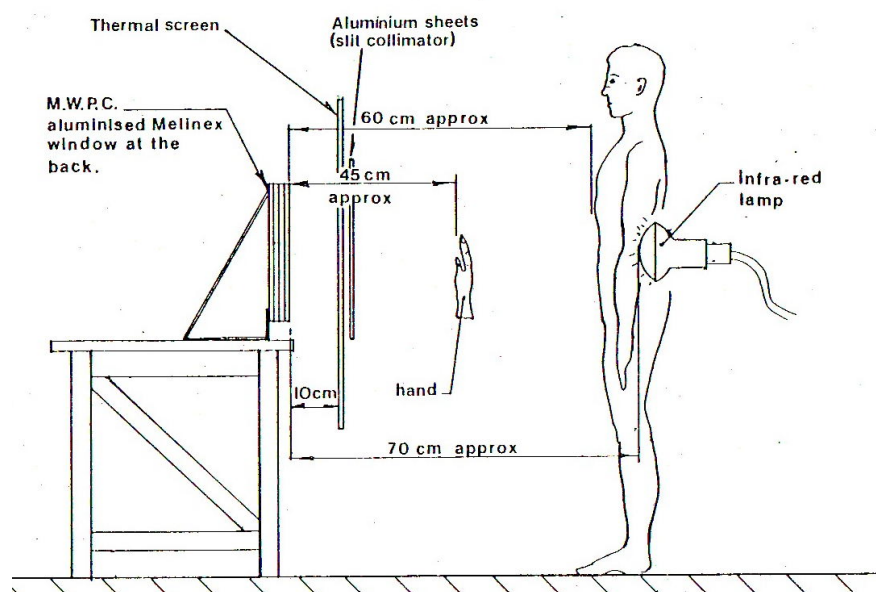
MULTIPLE CASCADED GEMs:



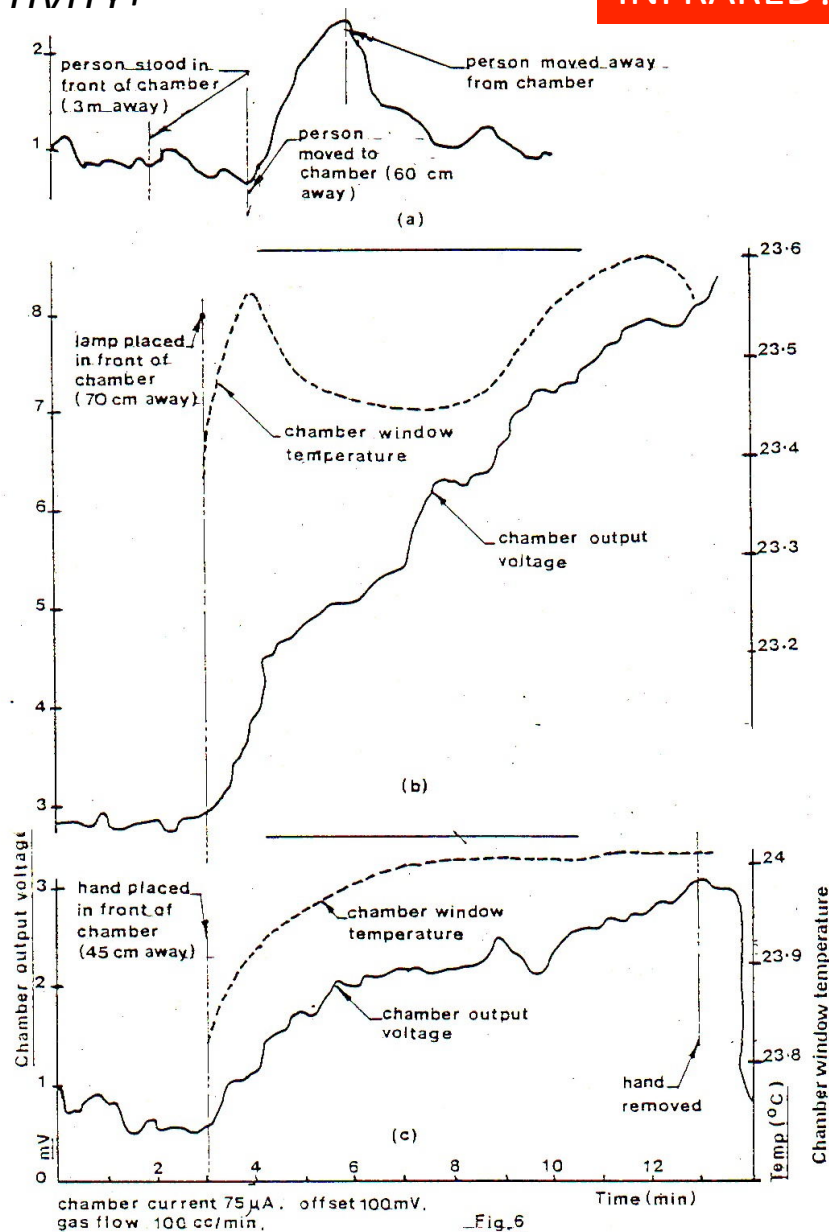
A CURIOUS OBSERVATION: MWPC INFRARED SENSITIVITY?

INFRARED?

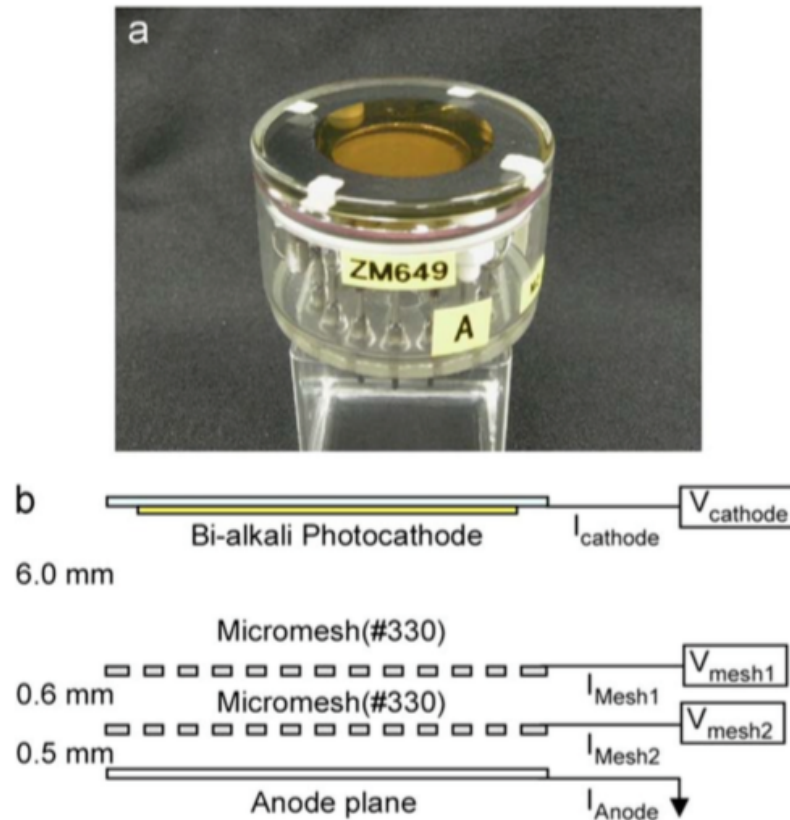
STUDY OF GLOW DISCHARGES IN MWPCs Rutherford Lab (1979)



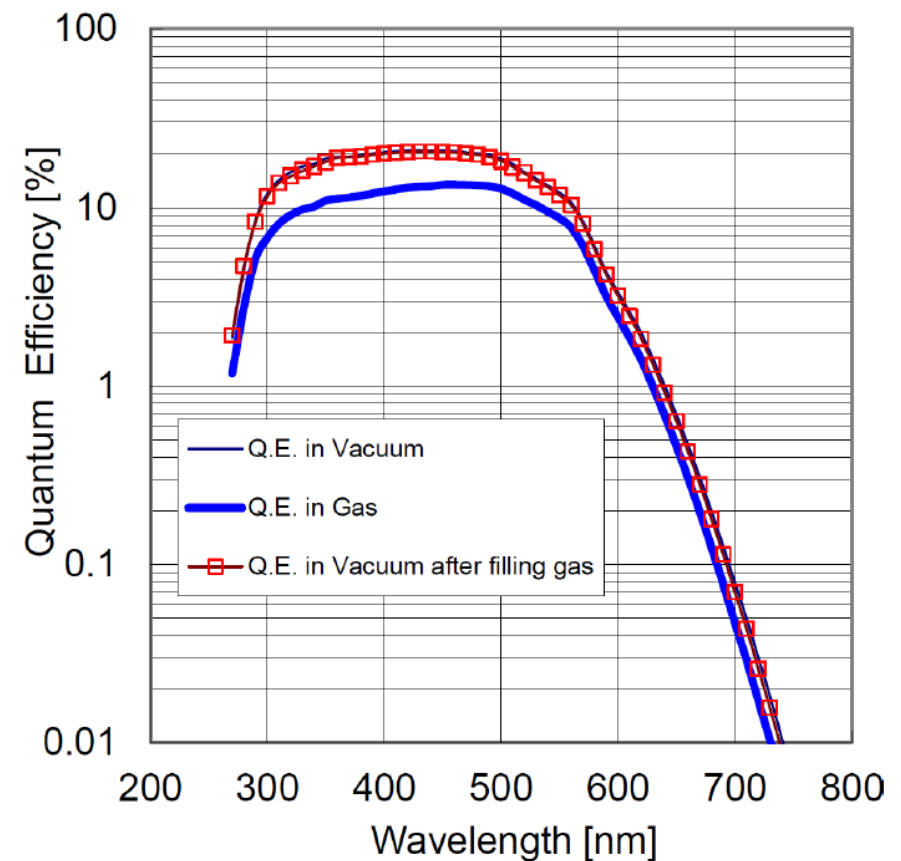
J.B. Marsh, K.H. Souten and B. O'Hagan RL-79-038 (1979)



SEALED TUBE WITH MICROMEGAS MULTIPLIERS
GAIN $\sim 10^3$



Quantum Efficiency of Bi-alkali Photocathodes
in Ar-CH₄ (90-10):

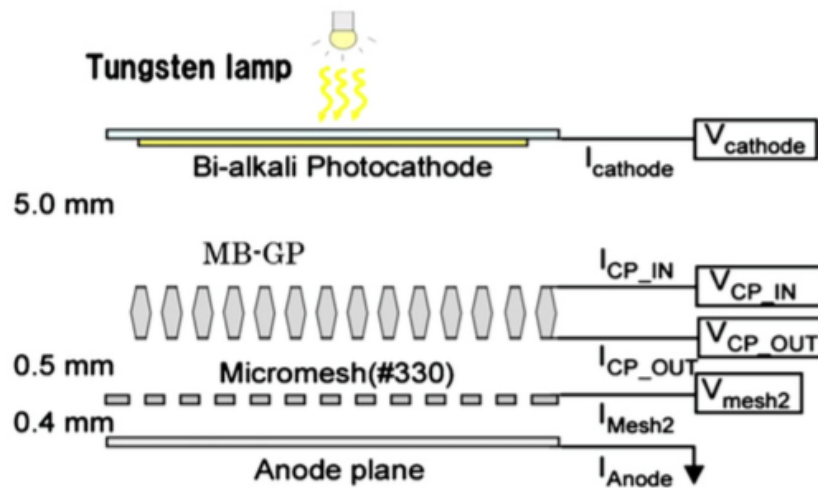


F. Tokanai et al, Nucl. Instr. and Meth. A610(2009)164

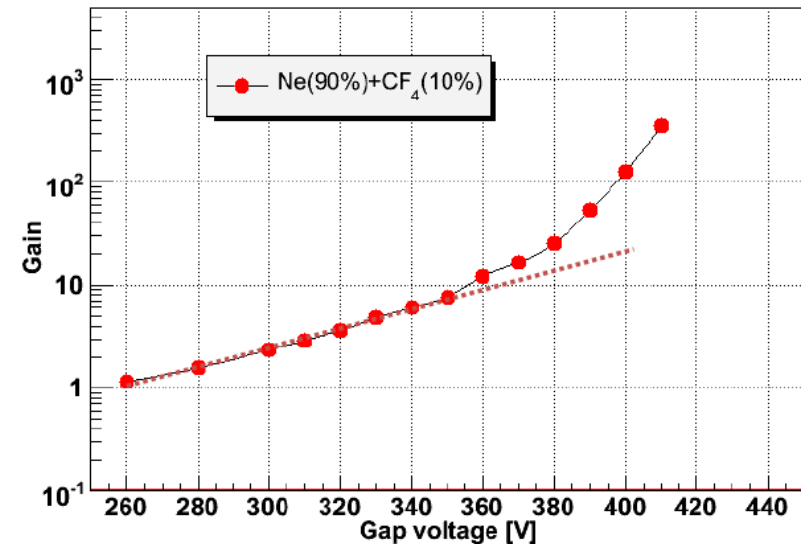
Bi-alkali photocathodes

MB-GP: Micro-Blasting Pyrex GEM

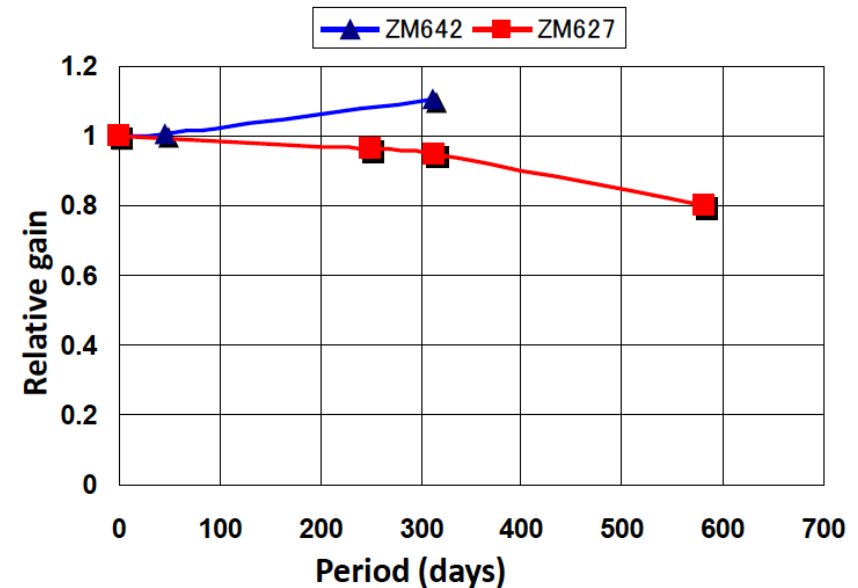
Micromegas



T. Sumiyoshi et al
Nucl. Instr. and Meth. A639(2011)121

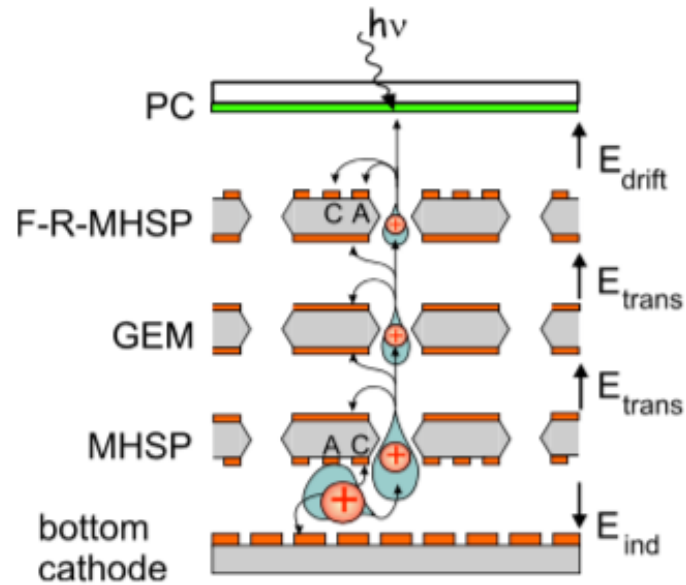


LONG-TERM STABILITY (Ar-CH₄ 90-10):



GAS ELECTRON MULTIPLIER (GEM)+MICRO-HOLE AND STRIP PLATE (MHSP)

VISIBLE

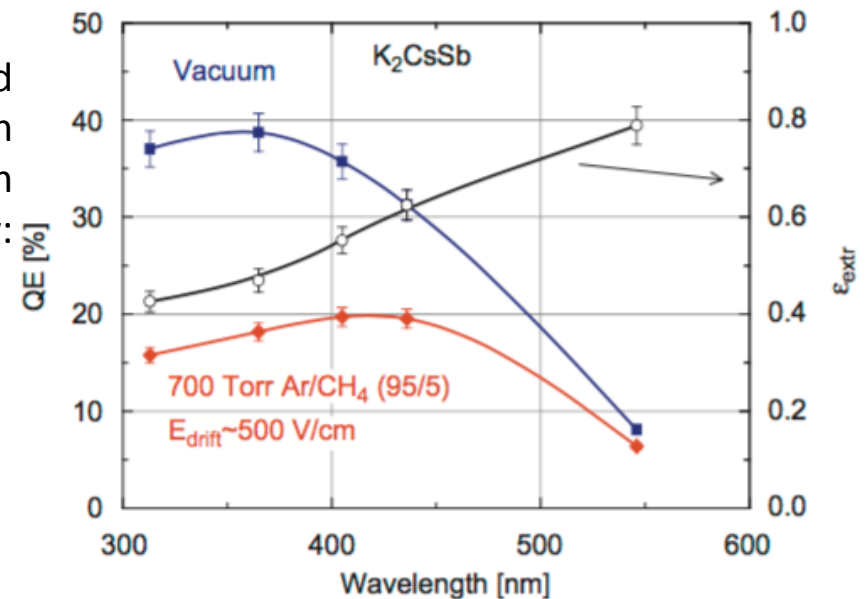
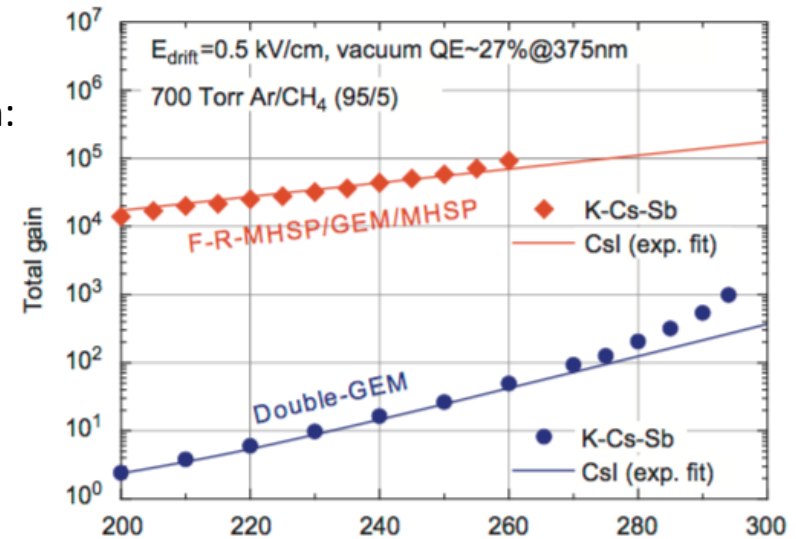


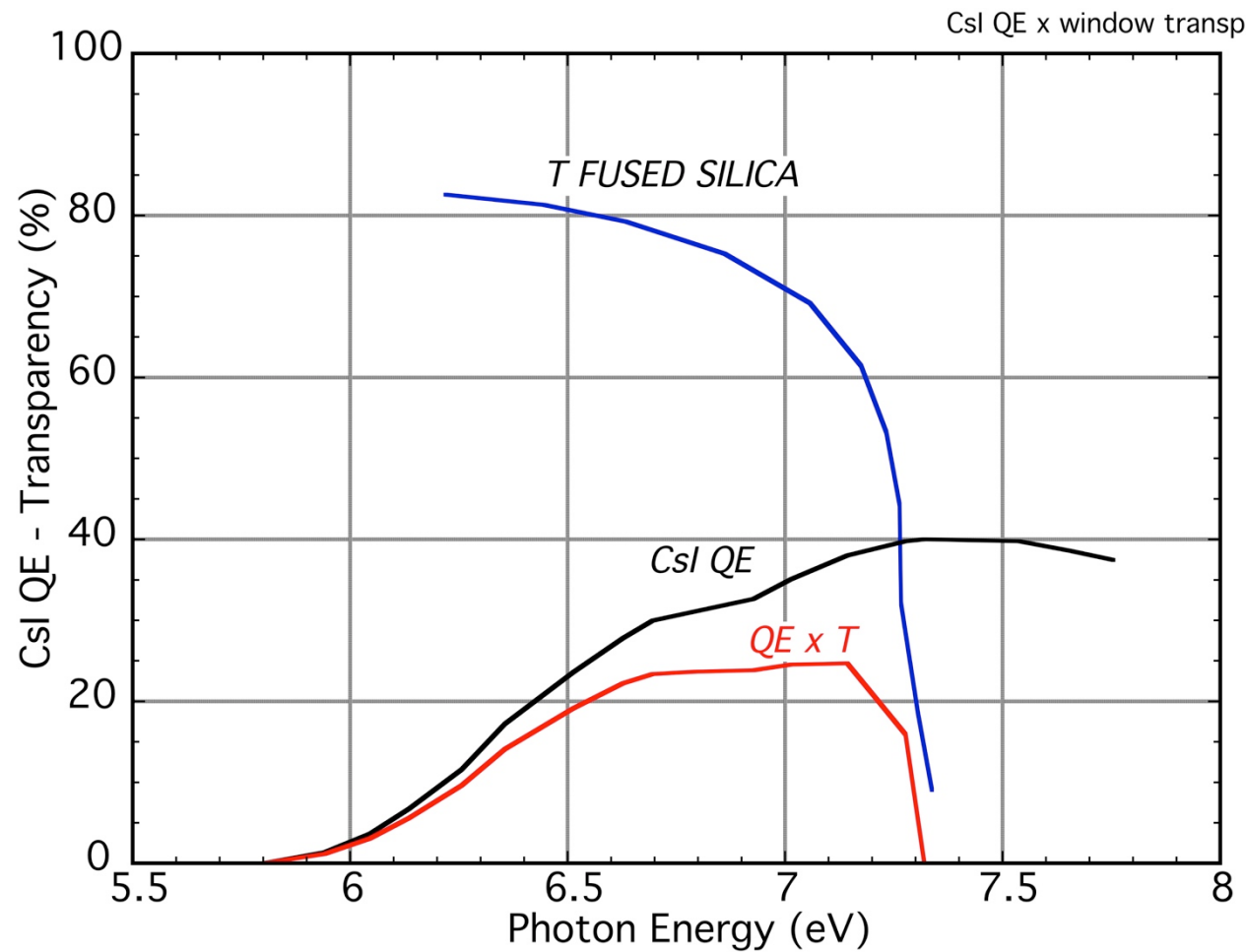
MHSP GEMs for ion backflow reduction

Quantum and
Photoelectron
extraction
efficiency:

A. Breskin et al, Nucl. Instr. and Meth. A623(2010)318

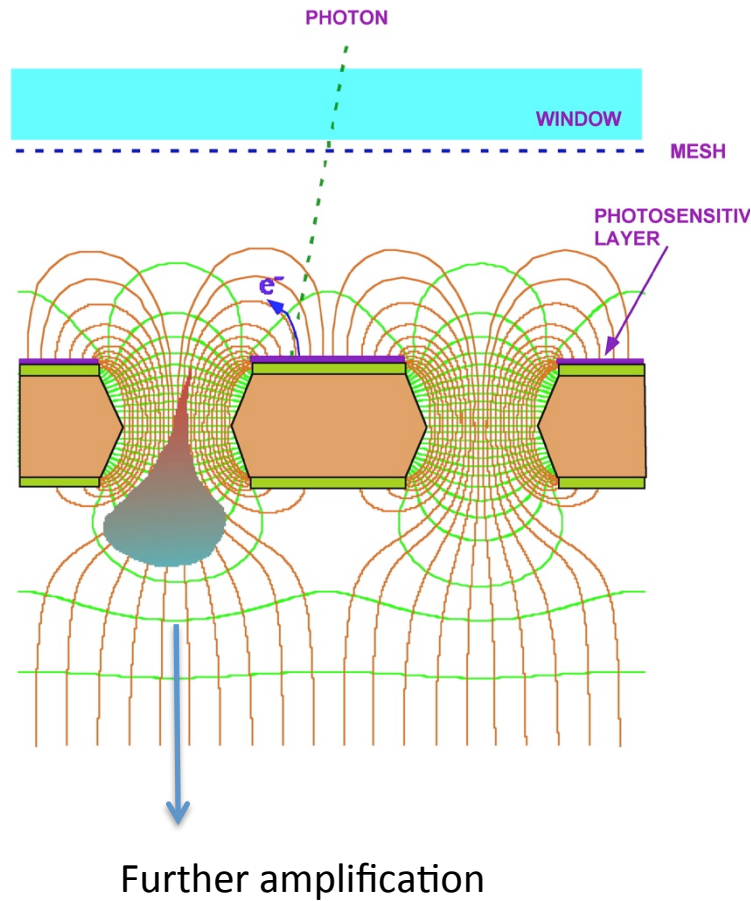
Gain:



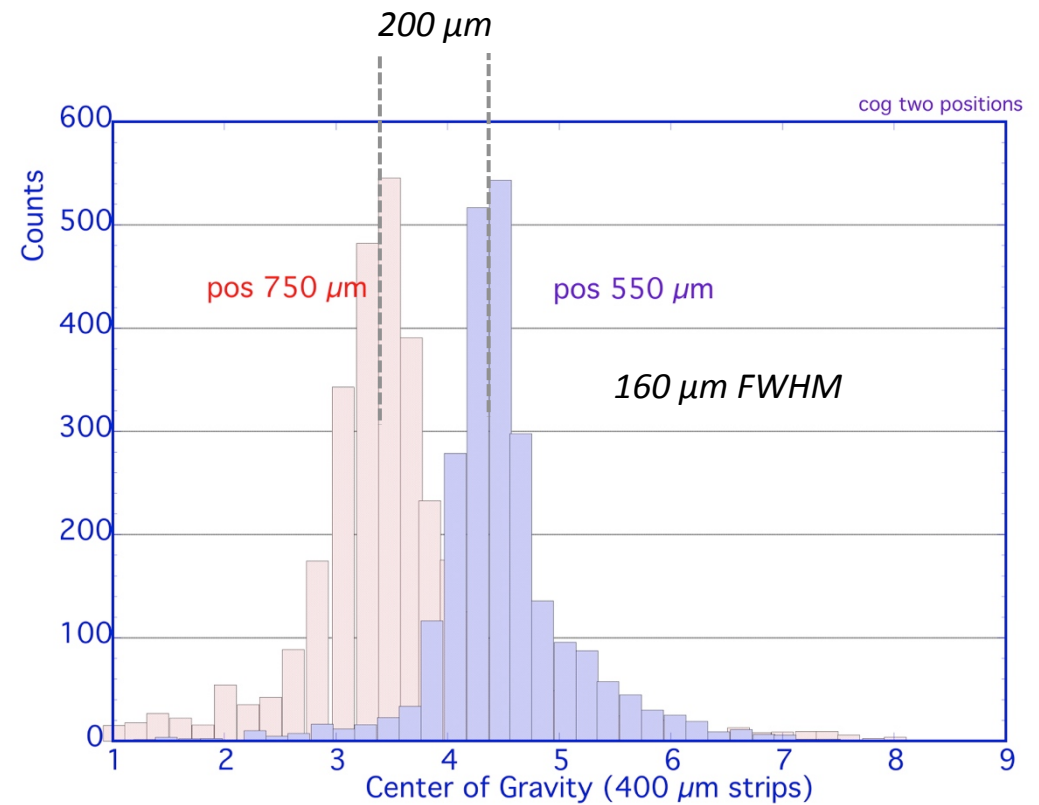


APPLICATIONS:

CHERENKOV RING IMAGING
 RADIATION IMAGING
 SCINTILLATION DETECTION
 FLAME DETECTION
 DARK MATTER SEARCH
 X-RAY IMAGING



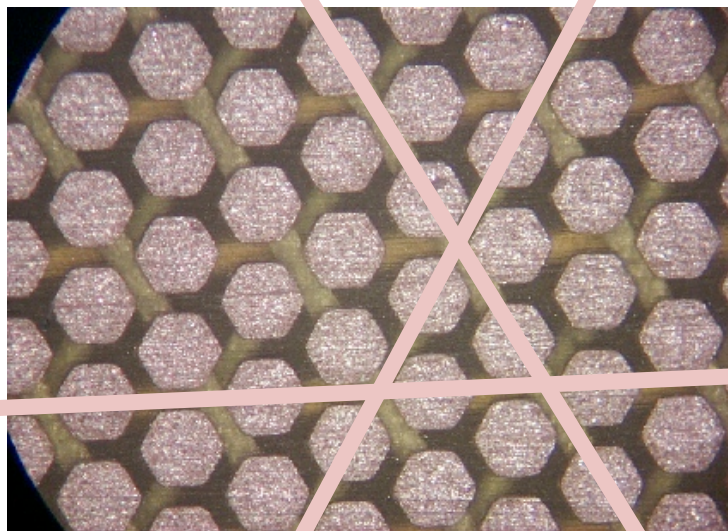
POSITION ACCURACY WITH COLLIMATED PHOTON BEAMS



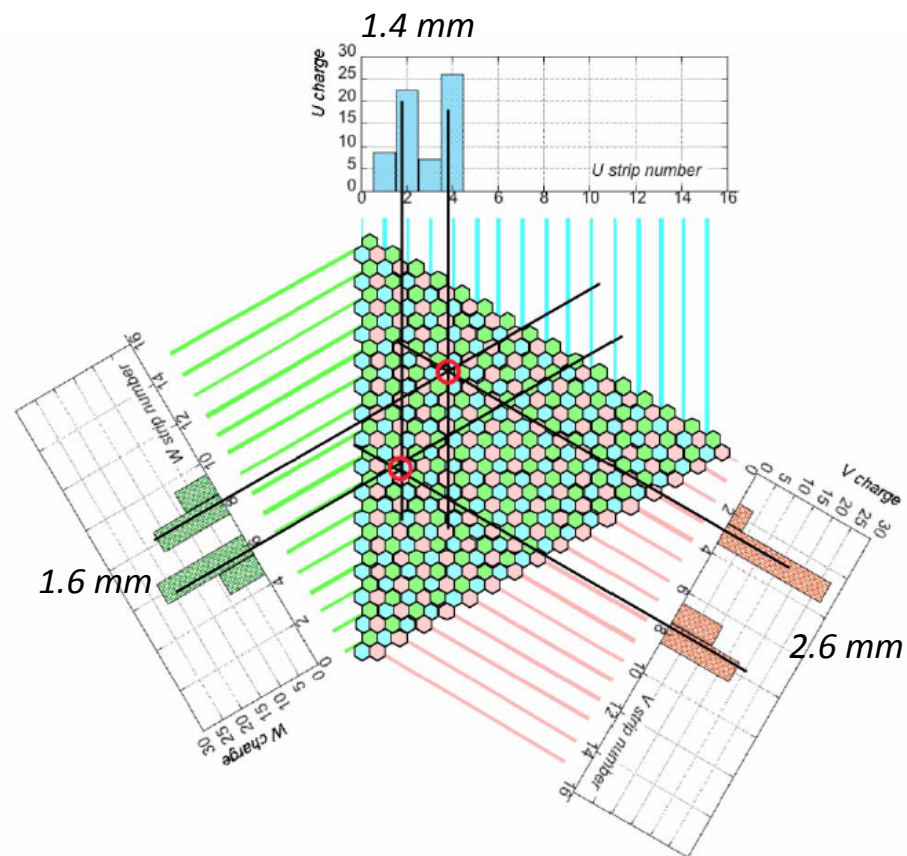
T. Meinshad et al, Nucl. Instr. and Meth. A535(2004)324

TRIPLE GEM WITH HEXABOARD READOUT

MATRIX OF HEXAGONAL PADS
INTERCONNECTED ALONG THREE DIRECTIONS
ON STRIPS AT 520 μm PITCH



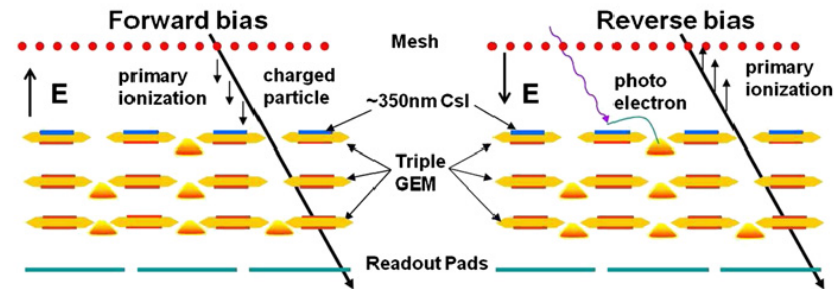
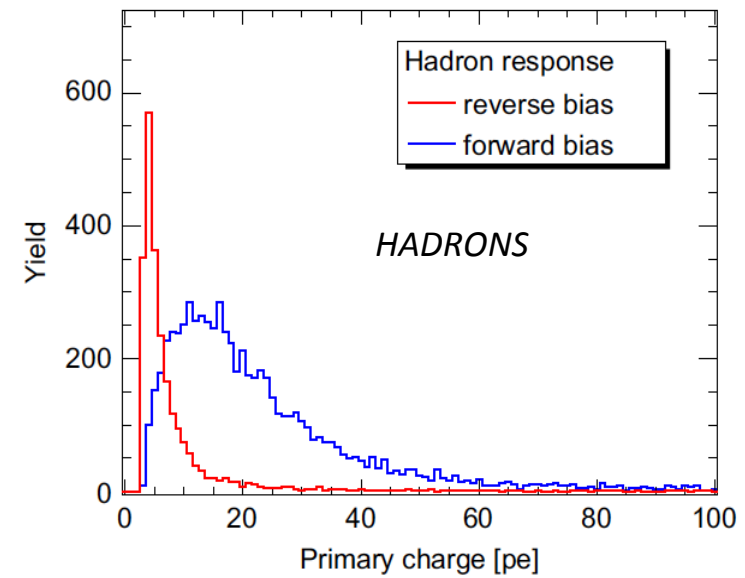
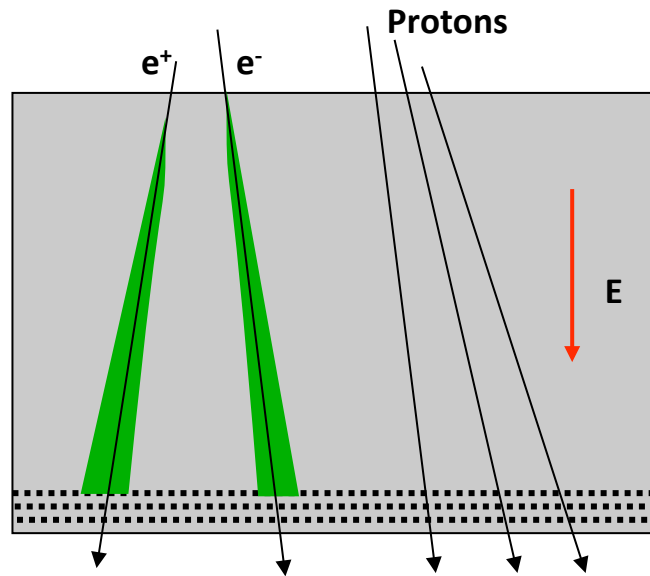
TWO-PHOTONS EVENT:



F. Sauli et al, IEEE NSSS 2004 Conf. Rec. Vol. 1, 12

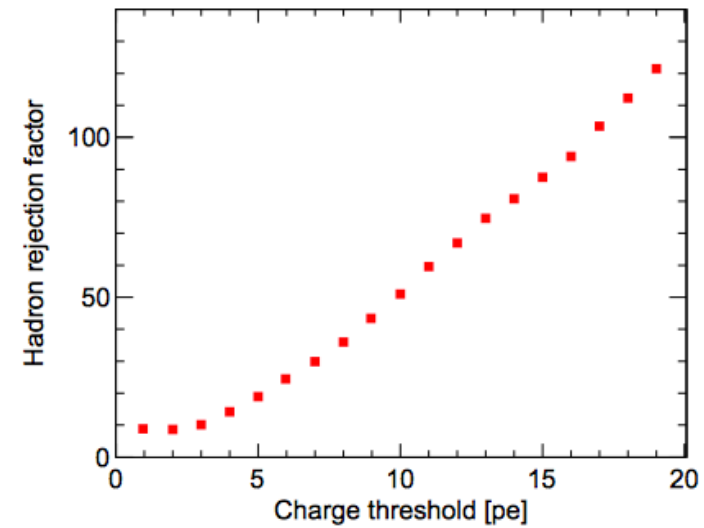
PHENIX HADRON BLIND DETECTOR

ULTRAVIOLET



C. Aidala et al, Nucl. Instr. and Methods A502(2003)200

W. Anderson et al, Nucl. Instr. and Meth. A645(2011)35



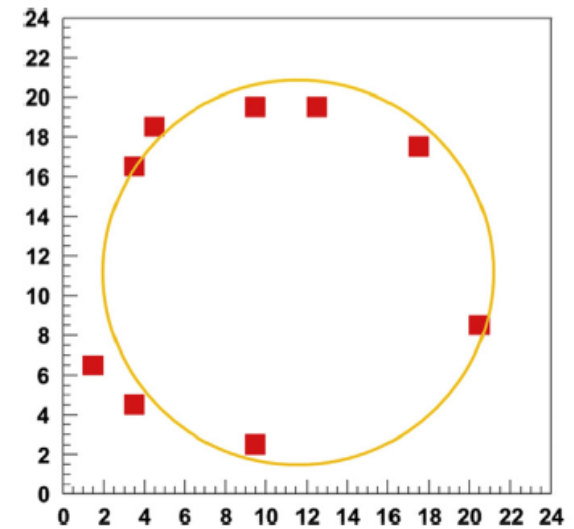
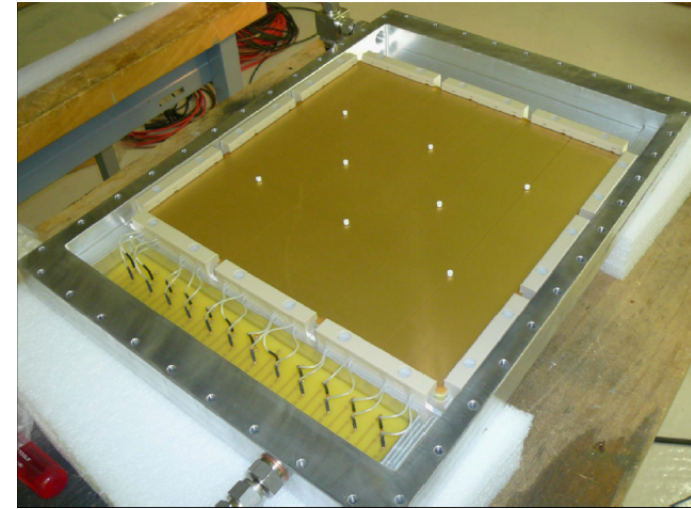
CHERENKOV RING IMAGING (RICH)

ULTRAVIOLET

COMPASS RICH-1 UPGRADE
THICK GEM Csi-COATED 30x30 cm²

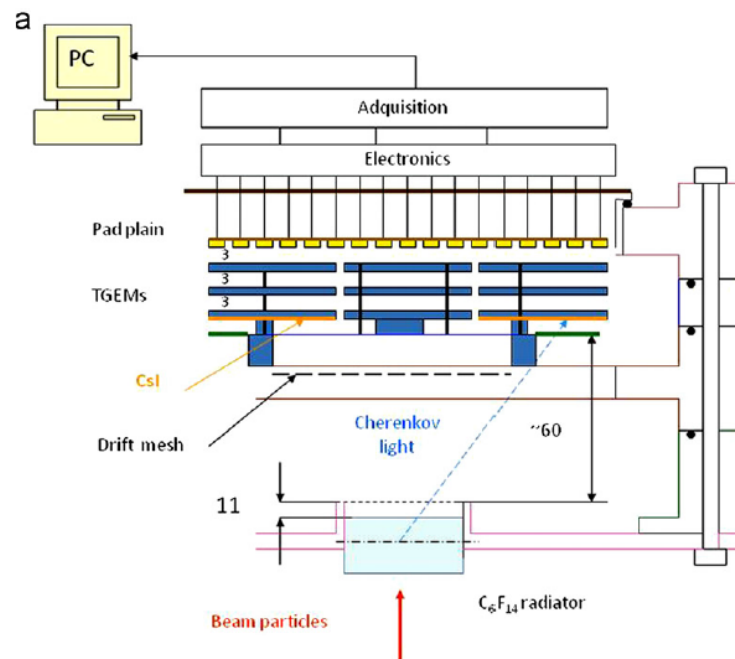


M. Alexeev et al, Nucl. Instr. and Meth. A732(2013)264

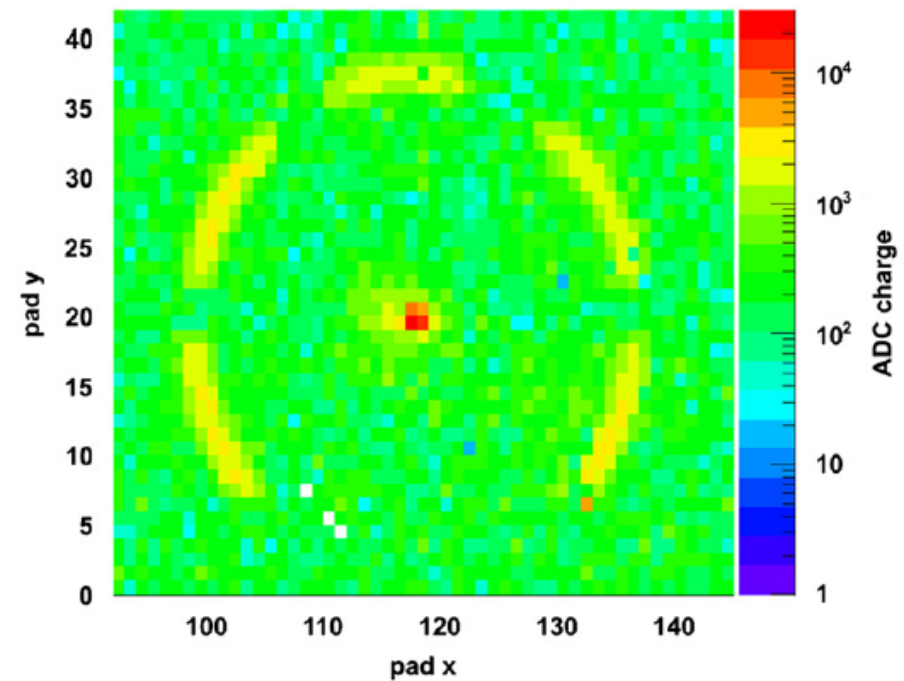


ALICE UPGRADE STUDIES

C_6F_{14} Radiator with Triple CsI-ThickGEMs with Pad Readout



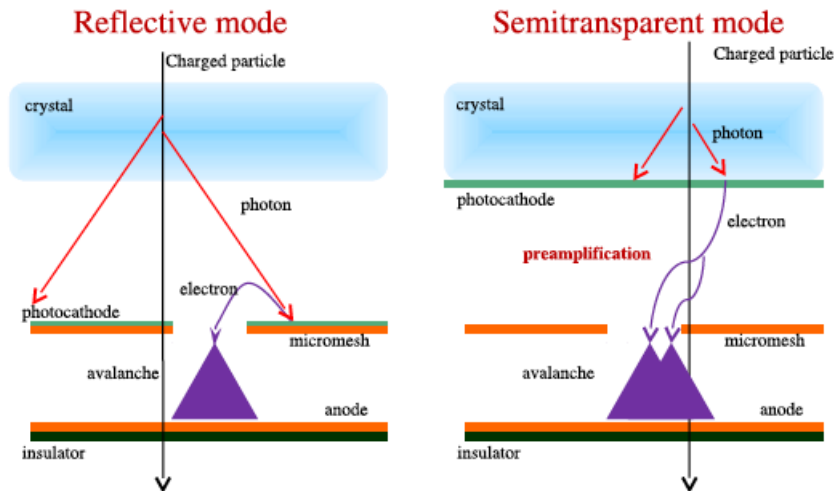
INTEGRATED CHERENKOV RING (6 GeV π):



V. Peskov et al, Nucl. Instr. and Meth. A695(2012)0154

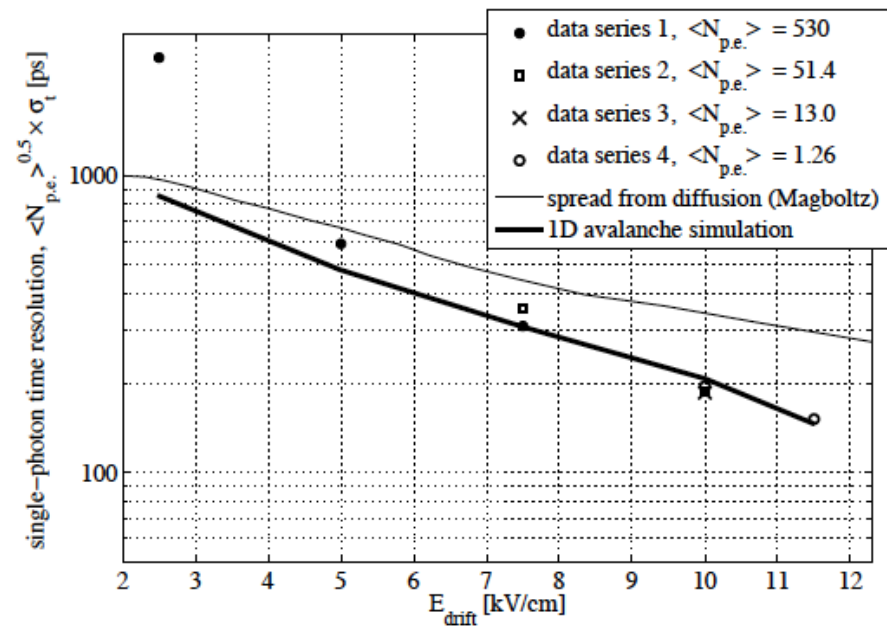
FAST TIMING WITH MPGDs

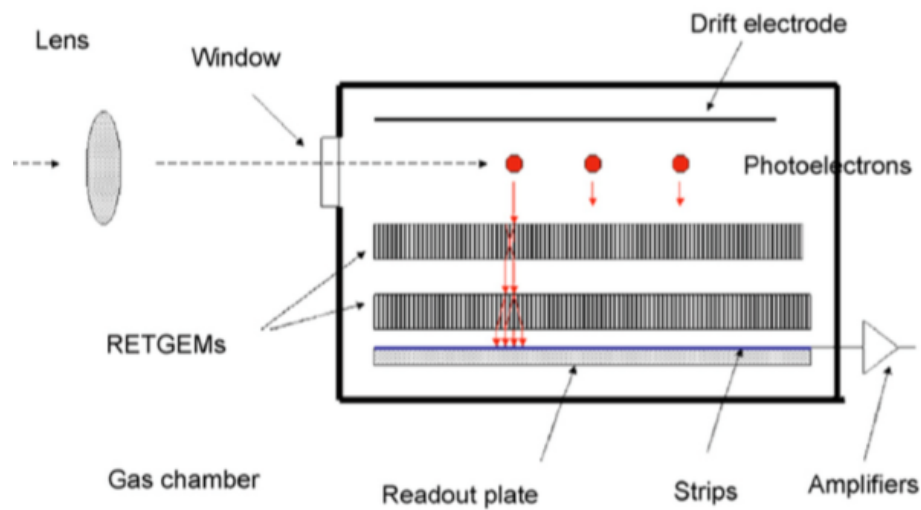
DETECTION OF CHERENKOV PHOTONS EMITTED IN A CRYSTAL RADIATOR



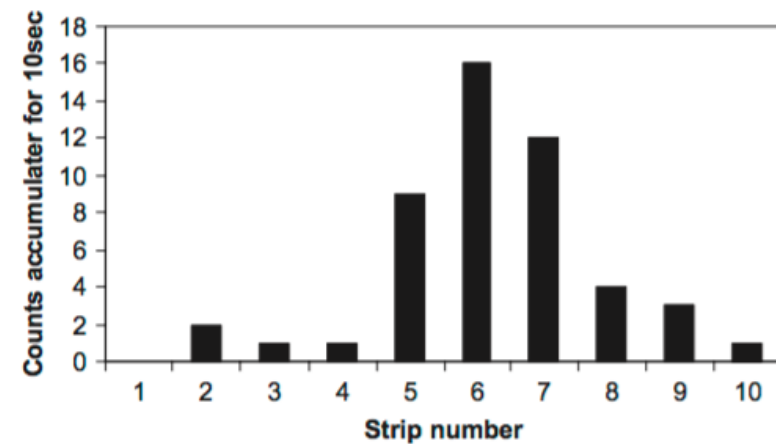
T. Papaevangelu et al, MPGD2015

SINGLE PHOTON TIME RESOLUTION:





TRANSVERSE IMAGE OF ALCOHOL FLAME 70 m FROM THE DETECTOR IN AMBIENT LIGHT

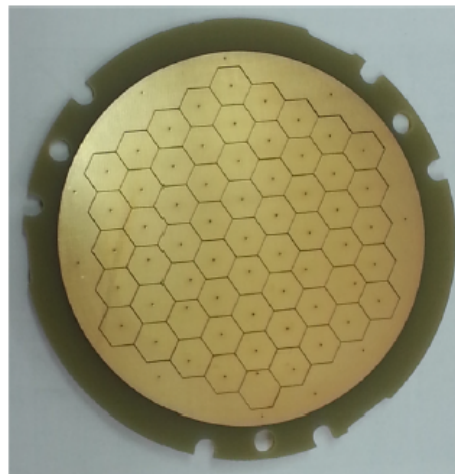
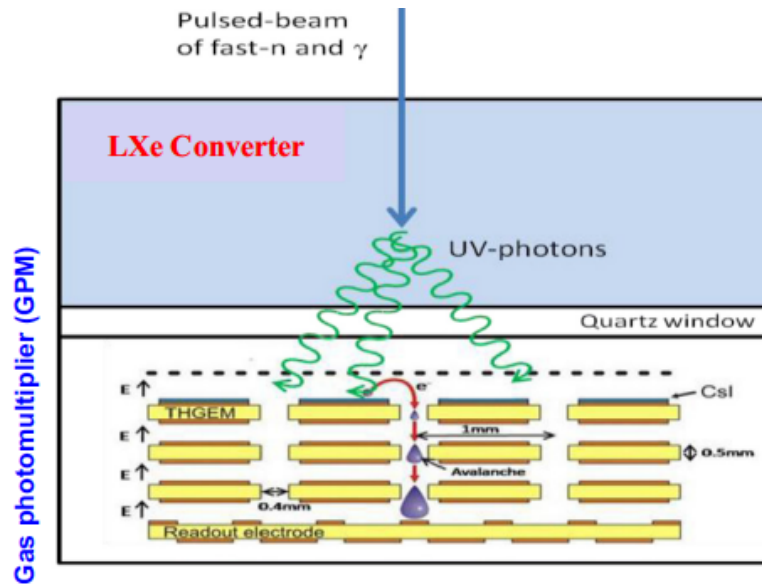


J.M. Bidault et al, Nucl. Instr. and Meth. A580(2007)1036

G. Charpak, et al., JINST 4 (2009) P12007.

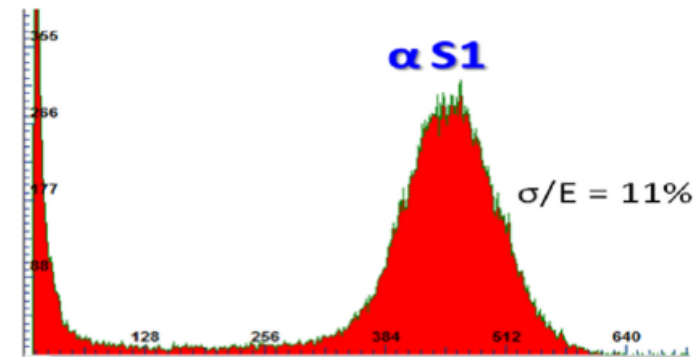
LIQUID XENON GAS PHOTOMULTIPLIER

ULTRAVIOLET

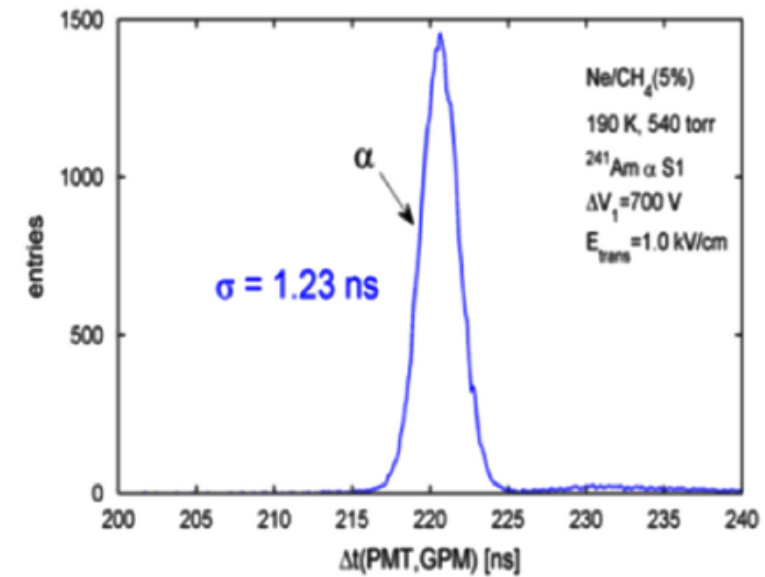


D. Vartski et al, Nucl. Instr. and Meth. in press (2016)

ENERGY RESOLUTION ON ^{241}Am α SOURCE:

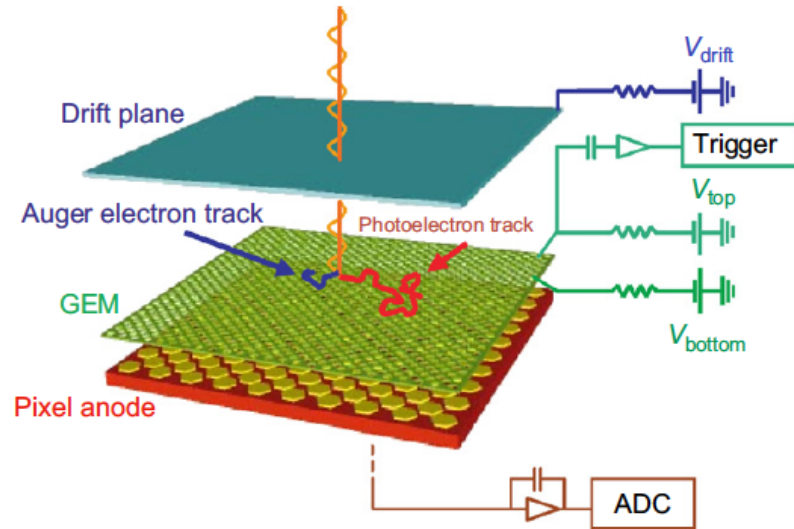


TIME RESOLUTION ON ^{241}Am α SOURCE:



GEM WITH SILICON PIXEL READOUT

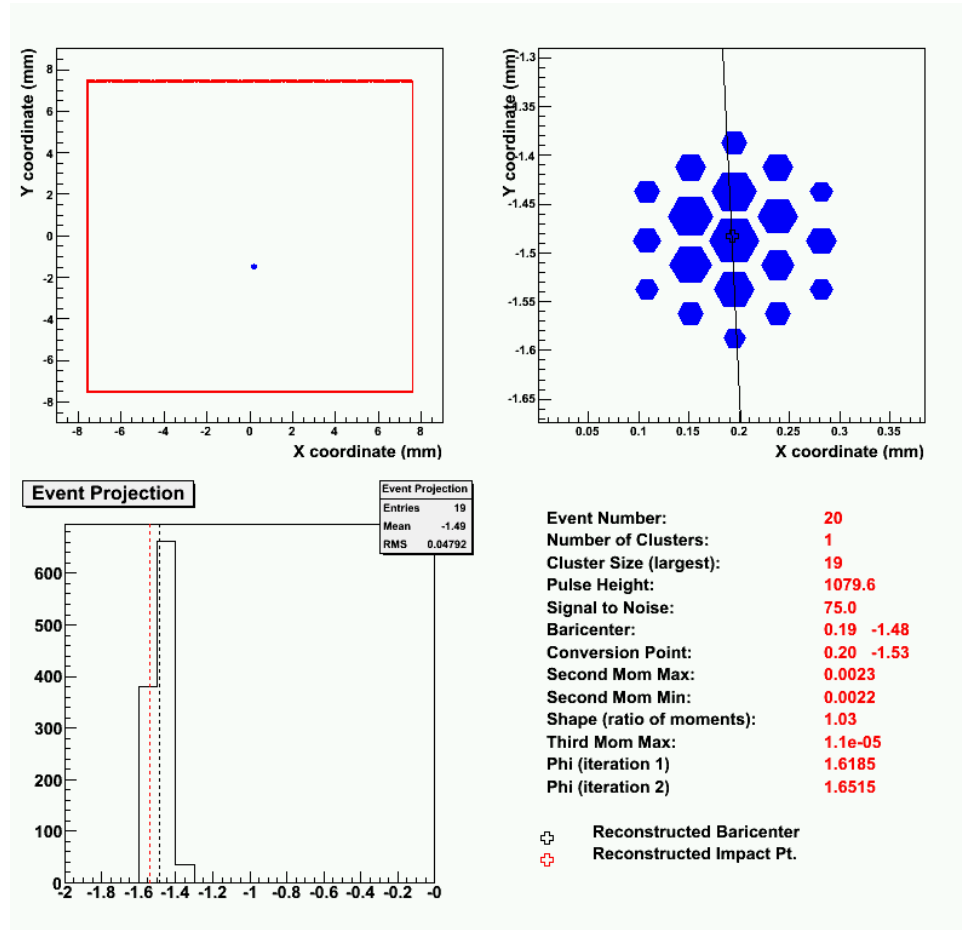
X-RAY POLARIMETER



*R. Bellazzini et al,
Nucl. Instr. and Meth. A623(2010)766*

ULTRAVIOLET

SINGLE PHOTOELECTRONS IMAGING



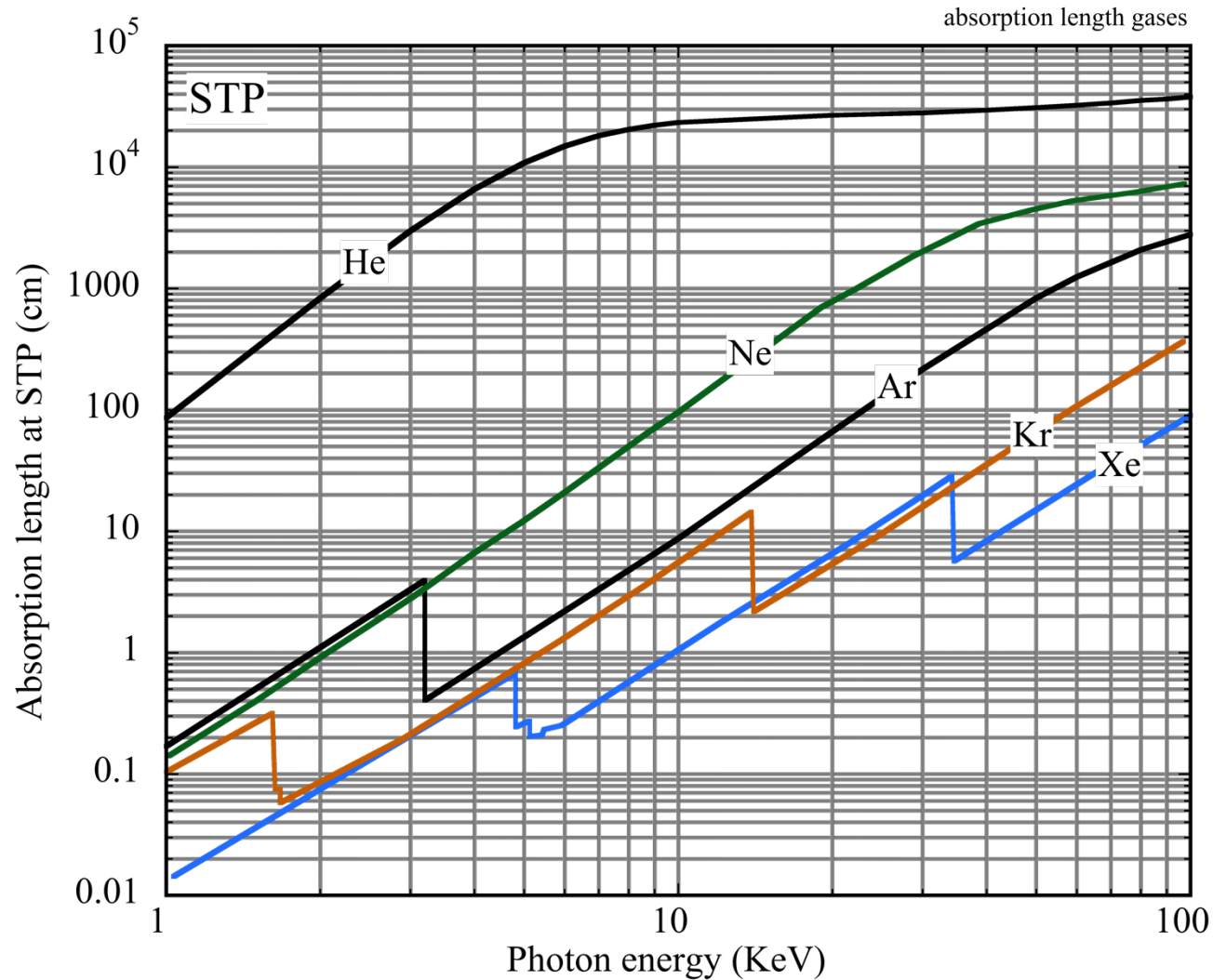
R. Bellazzini et al, Nucl. Instr. and Meth. A581(2007)246

PHOTON ABSORPTION LENGTH – SOFT X-RAYS NOBLE GASES AT STP

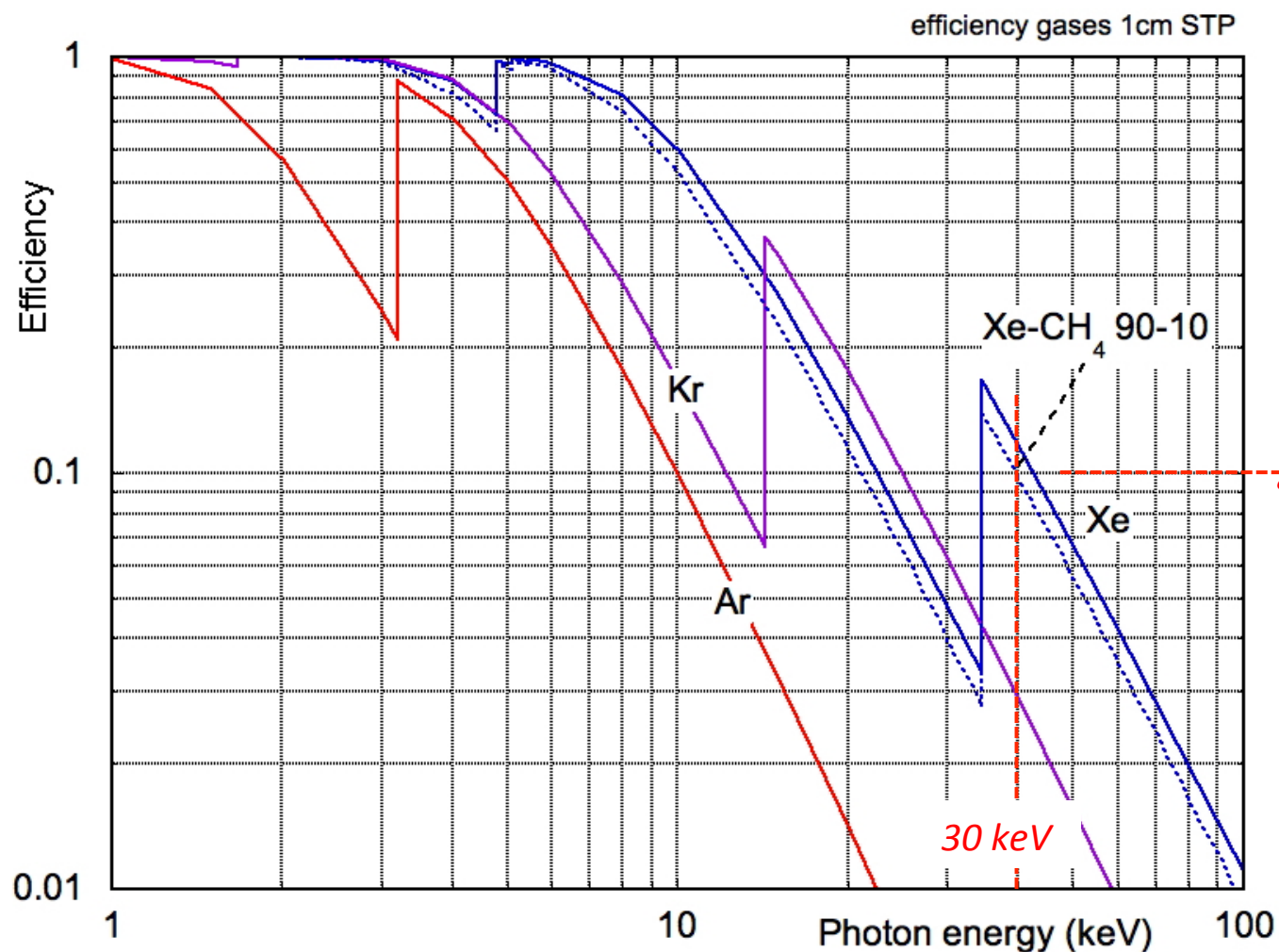
SOFT X-RAYS

ABSORPTION LENGTH(STP):

$$\lambda(cm) = \frac{1}{26.87 \sigma(MB)}$$



(MAXIMUM) DETECTION EFFICIENCY, 1 cm GAS AT STP



Conversion efficiency
in a layer x:

$$\epsilon = 1 - e^{-\frac{x}{\lambda}}$$

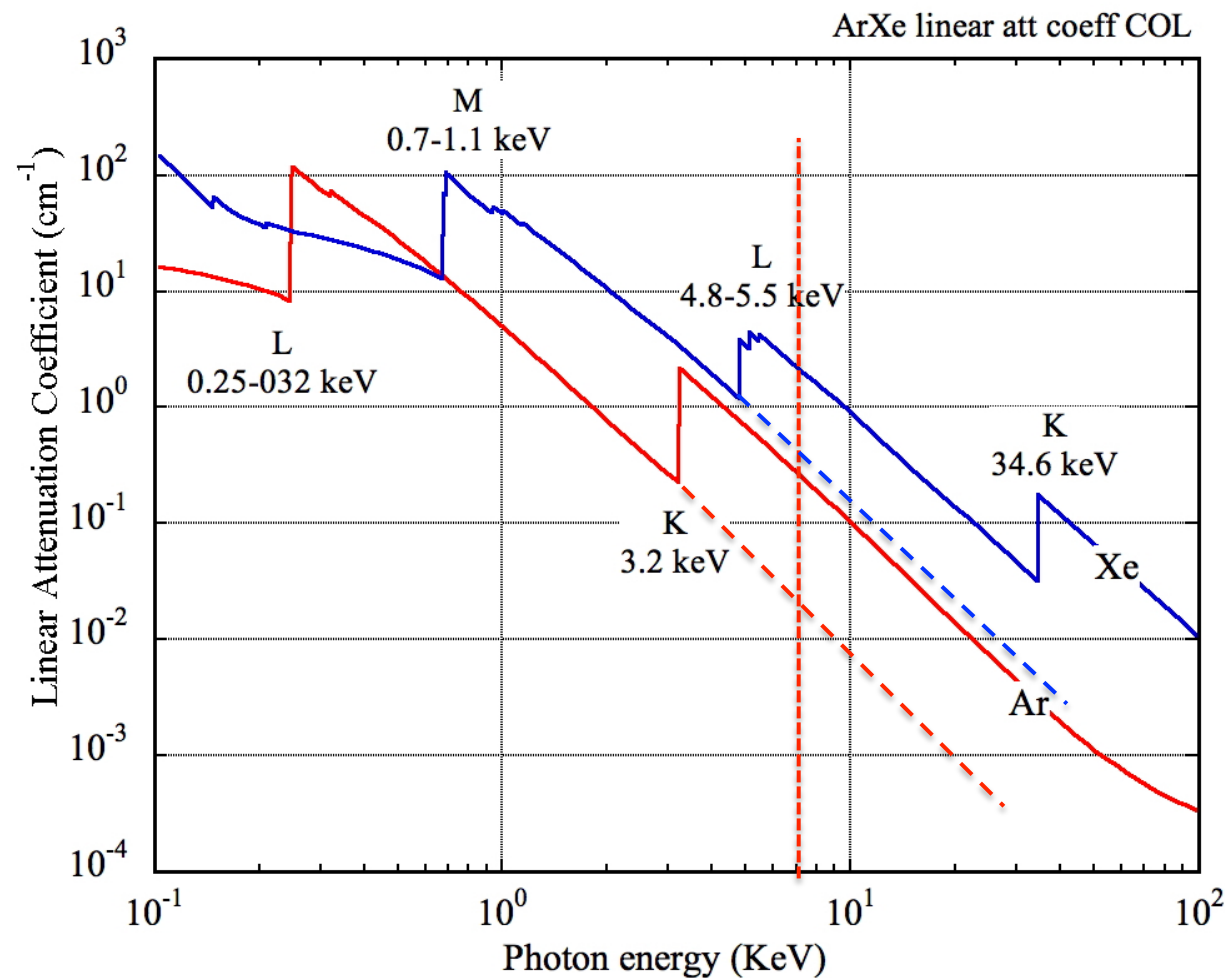
To increase efficiency:

- Thicker layers
- Higher pressures
- Liquid noble gas
- Internal converters

SOFT X-RAYS: PHOTOELECTRIC EFFECT

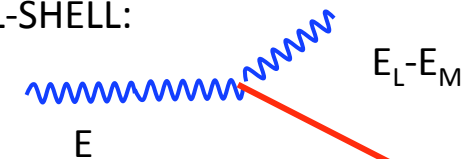
SOFT X-RAYS

LINEAR ATTENUATION COEFFICIENT (STP):

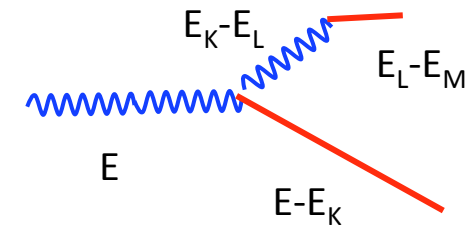


PROCESSES FOR ARGON:

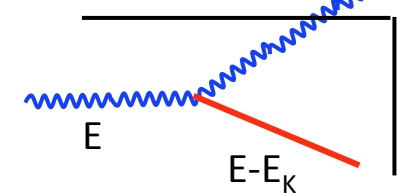
L-SHELL:



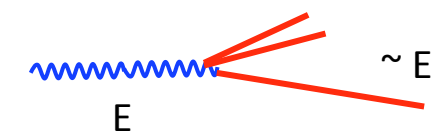
K SHELL FLUORESCENCE:



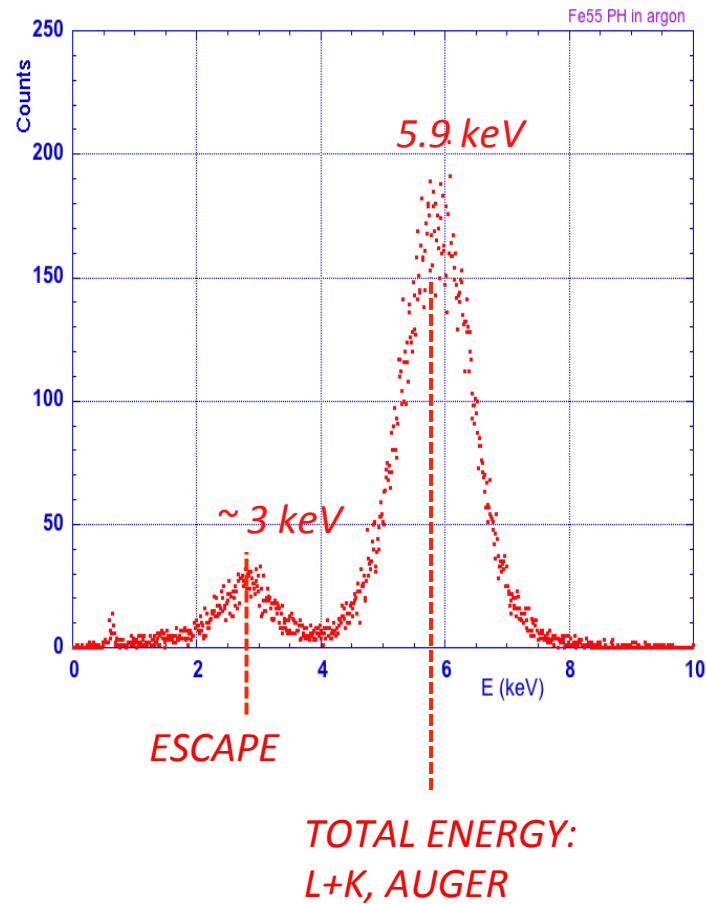
ESCAPE



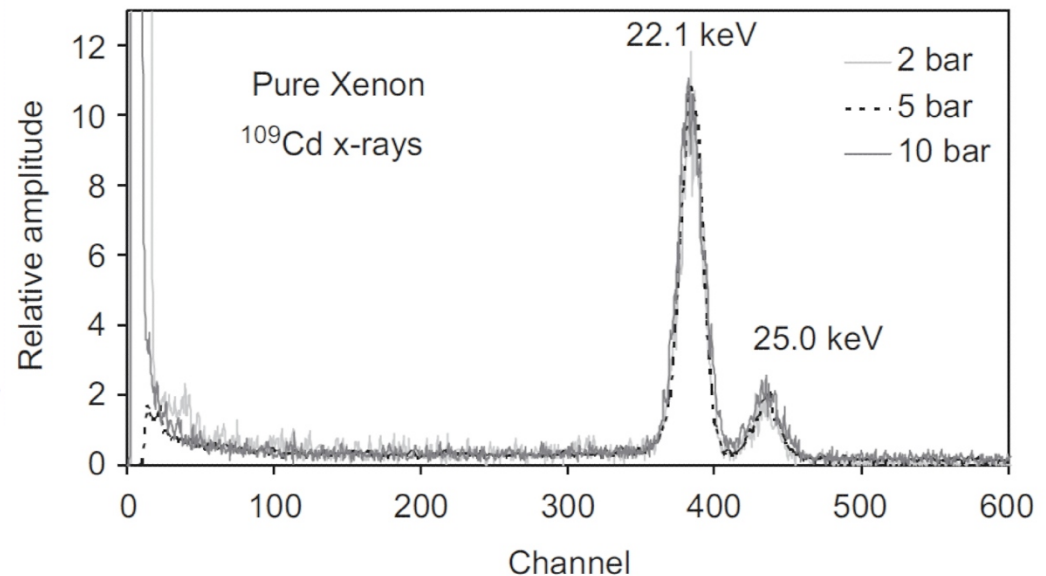
NON-RADIATIVE (AUGER)



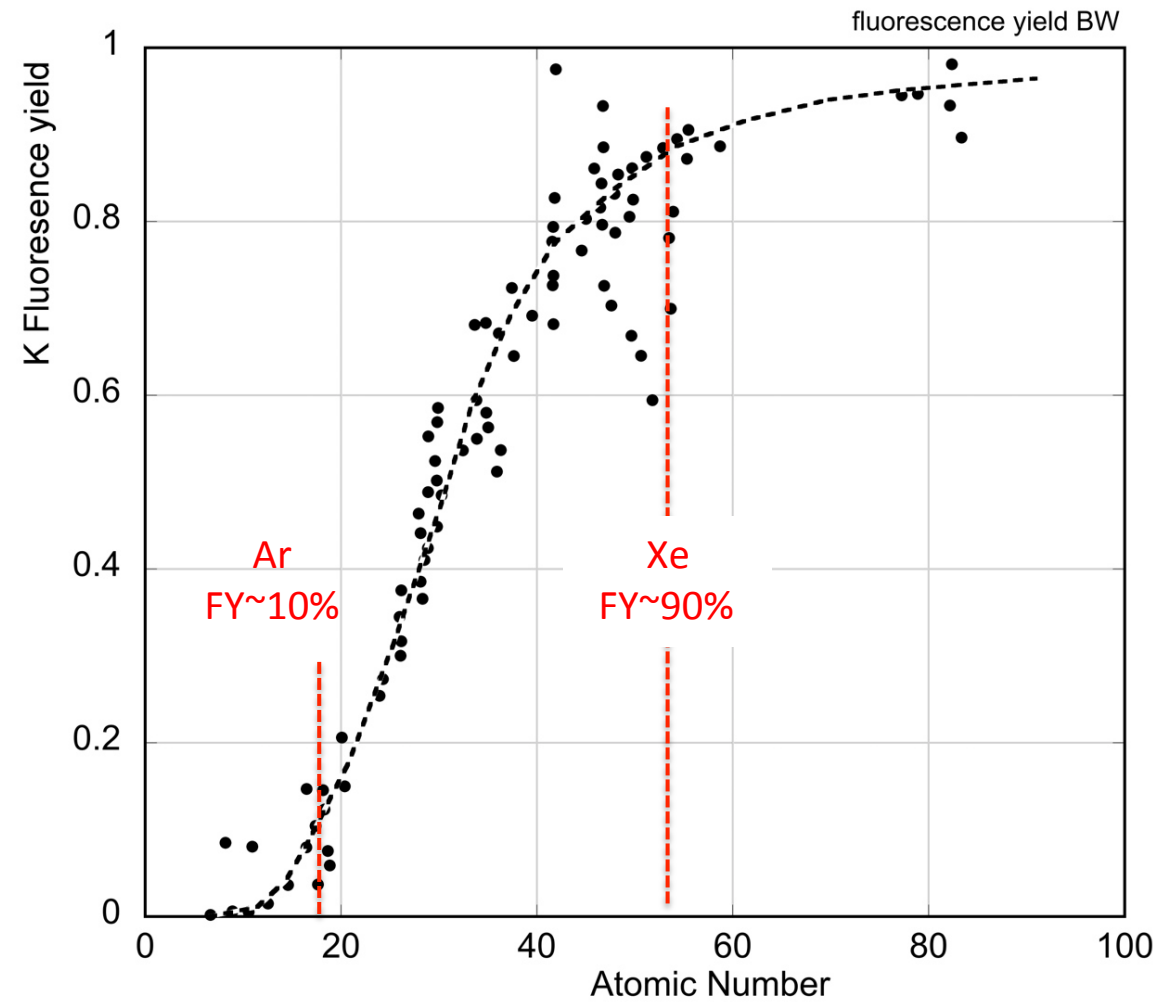
5.9 keV ^{55}Fe SOURCE IN ARGON:



22-25 keV ^{109}Cd SOURCE IN XENON:



FY = Probability of Fluorescence / Total



PHOTOELECTRON
EMISSION ANGLE:

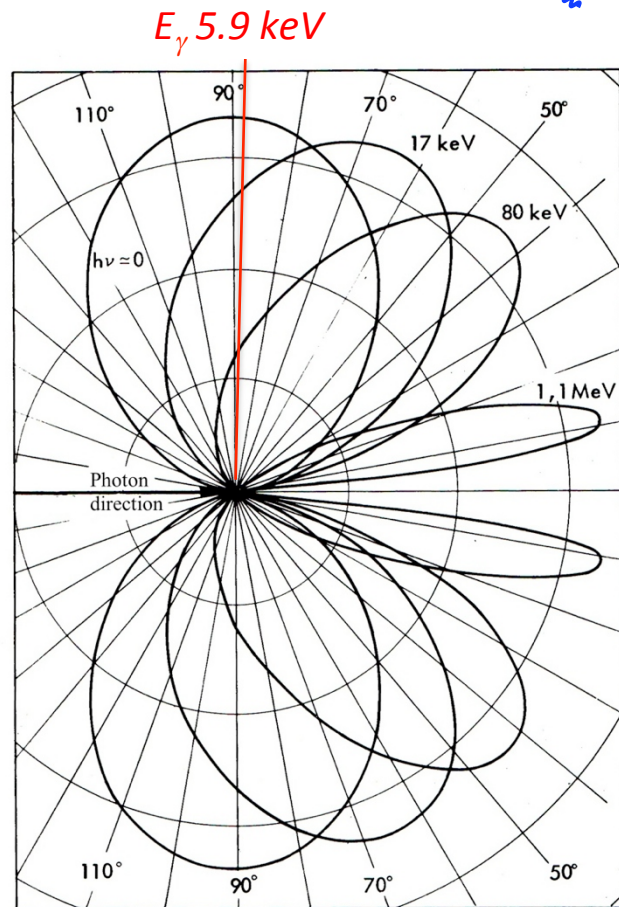
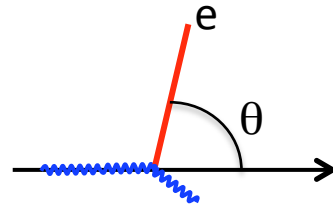
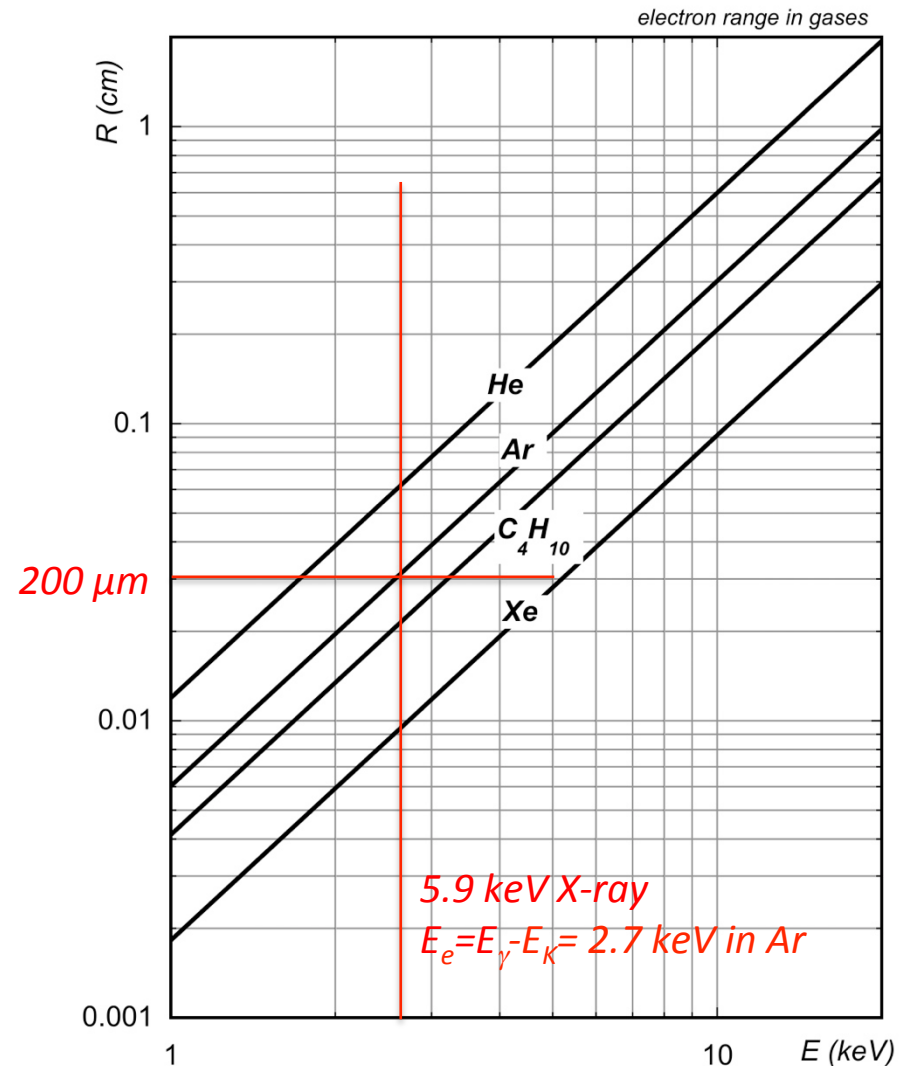
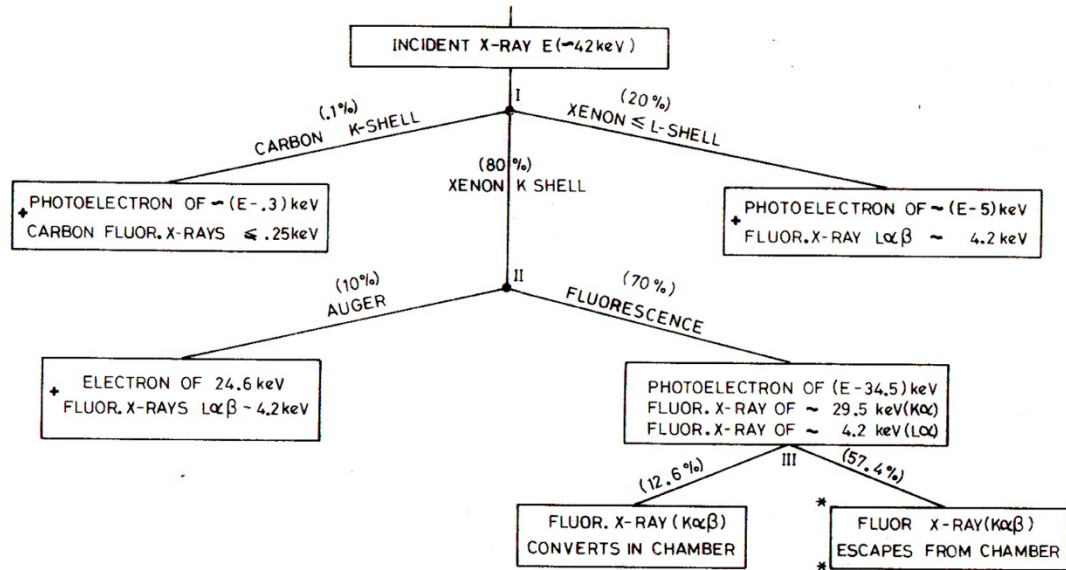


Figura 9.2. Distribuzione angolare dei fotoelettroni; le cur-

ELECTRON RANGE:

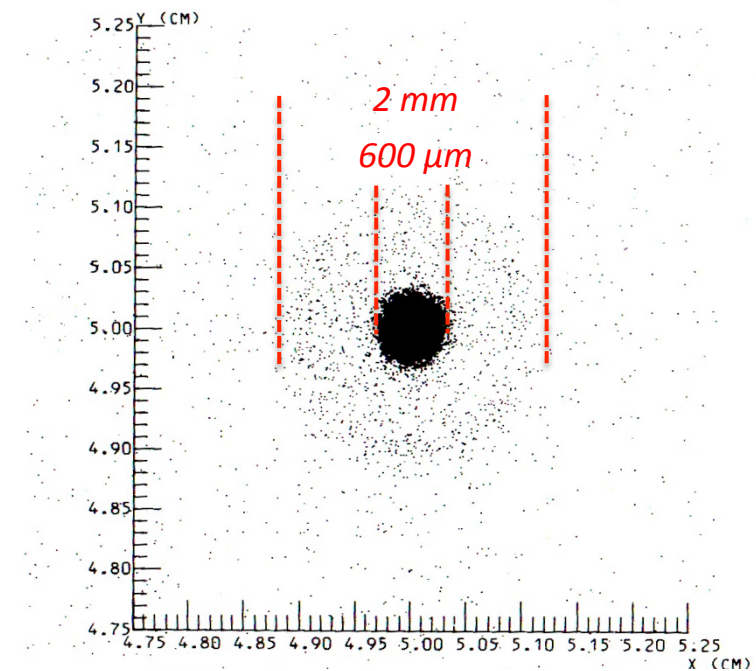


42 keV PHOTONS ON XENON



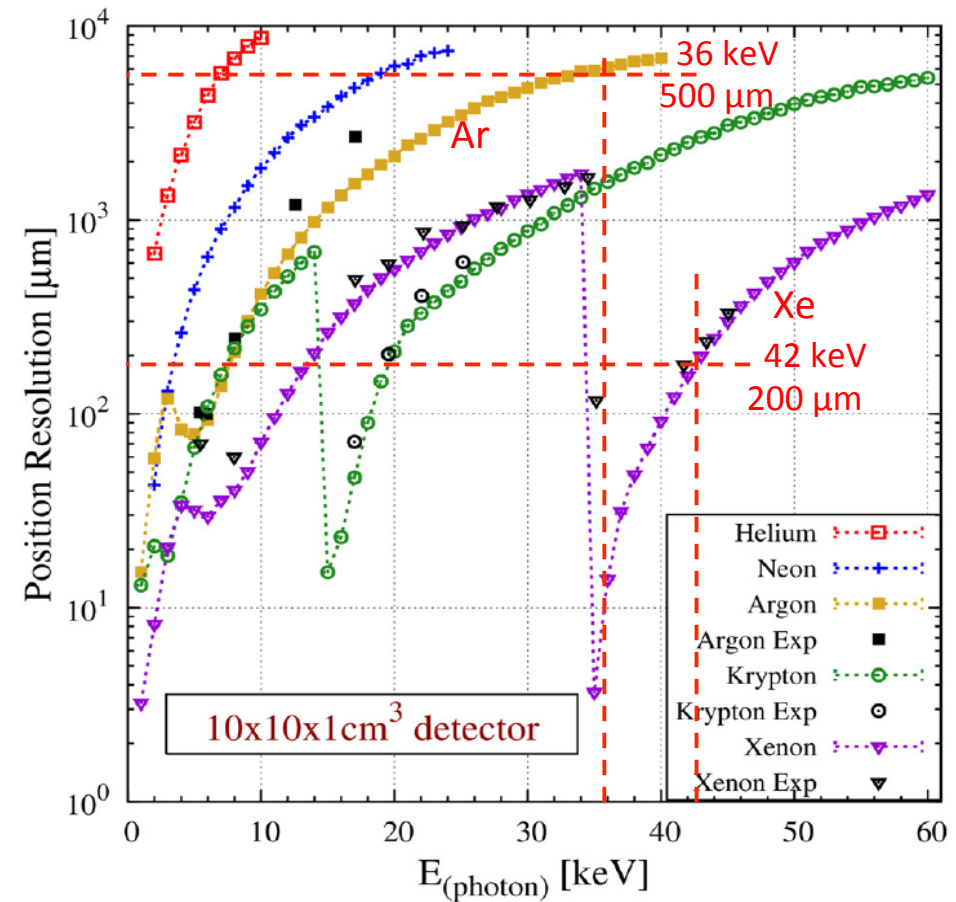
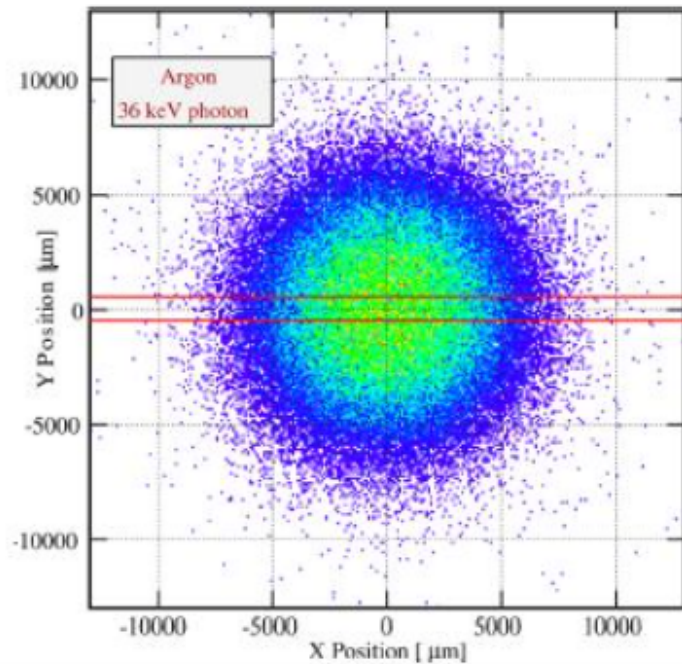
J.E. Bateman et al, RL-75-140

POSITION RESOLUTION FOR A POINT-LIKE COLLIMATED BEAM:



X-Rays in He, Ne, Ar, Kr and Xe AT STP

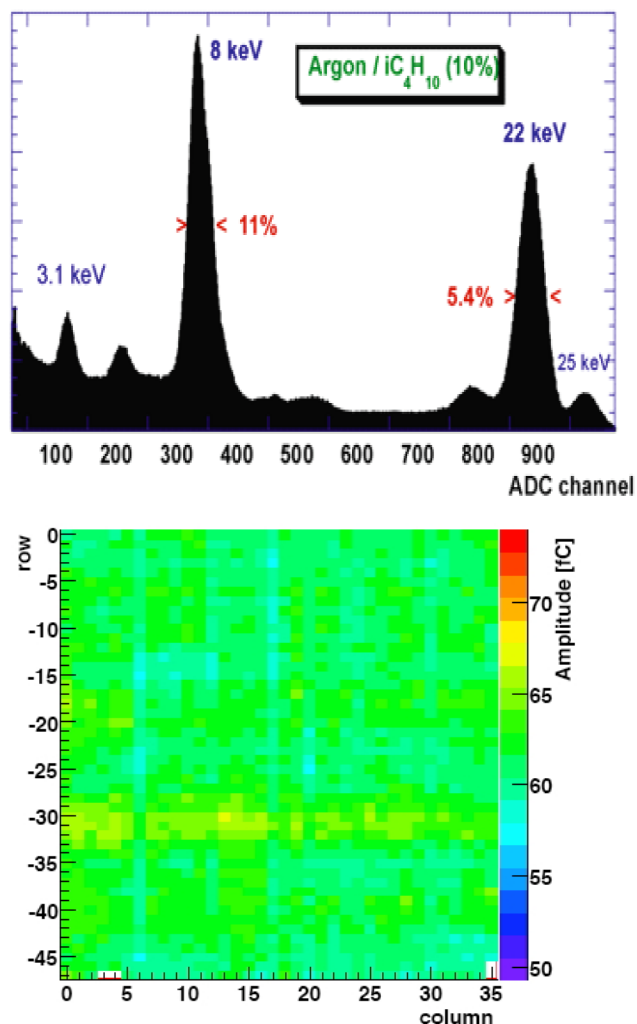
36 keV in Ar:



C. Azevedo et al., Phys. Lett. B 741(2015)272

SOFT X-RAY DETECTION WITH MICROMEGAS

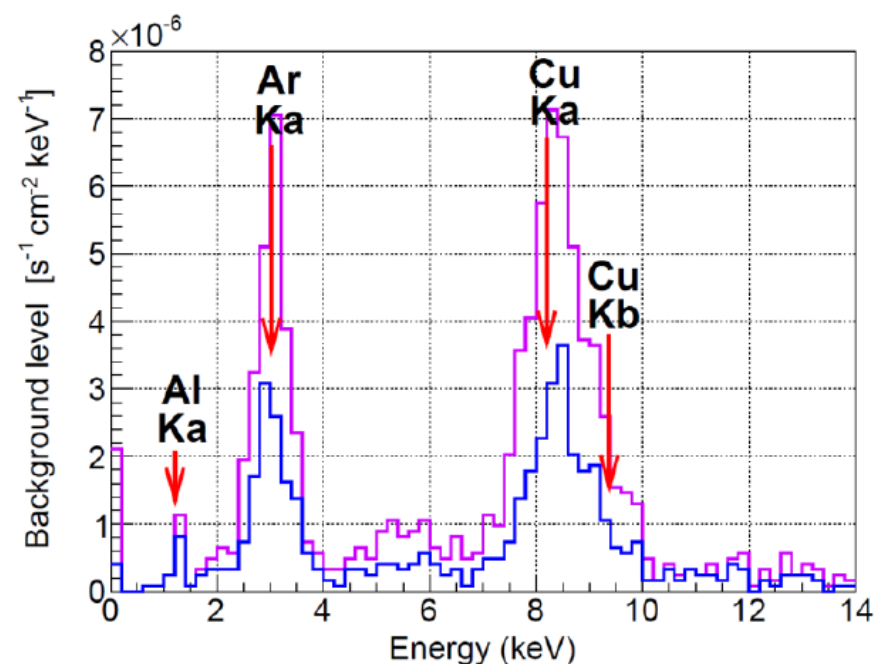
AS PARALLEL PLATE COUNTER, MICROMEGAS HAS
GOOD ENERGY RESOLUTION AND GAIN UNIFORMITY:



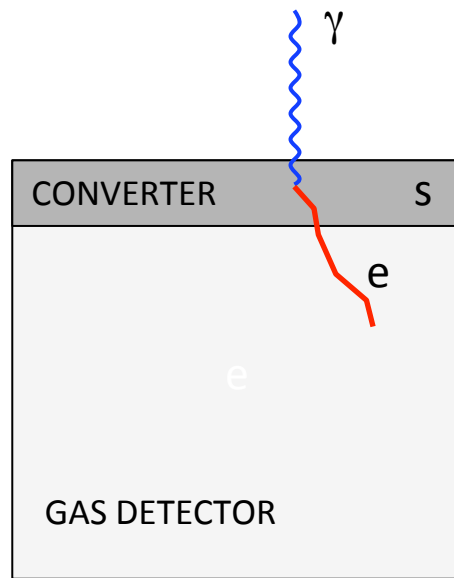
N. Abragall et al, Nucl. Instr. and Meth. A637(2011)25

DARK MATTER SEARCH
CERN AXION SOLAR TELESCOPE (CAST)

X-RAYS BACKGROUND SPECTRUM:



J. C. Garza et al, MPGD2015



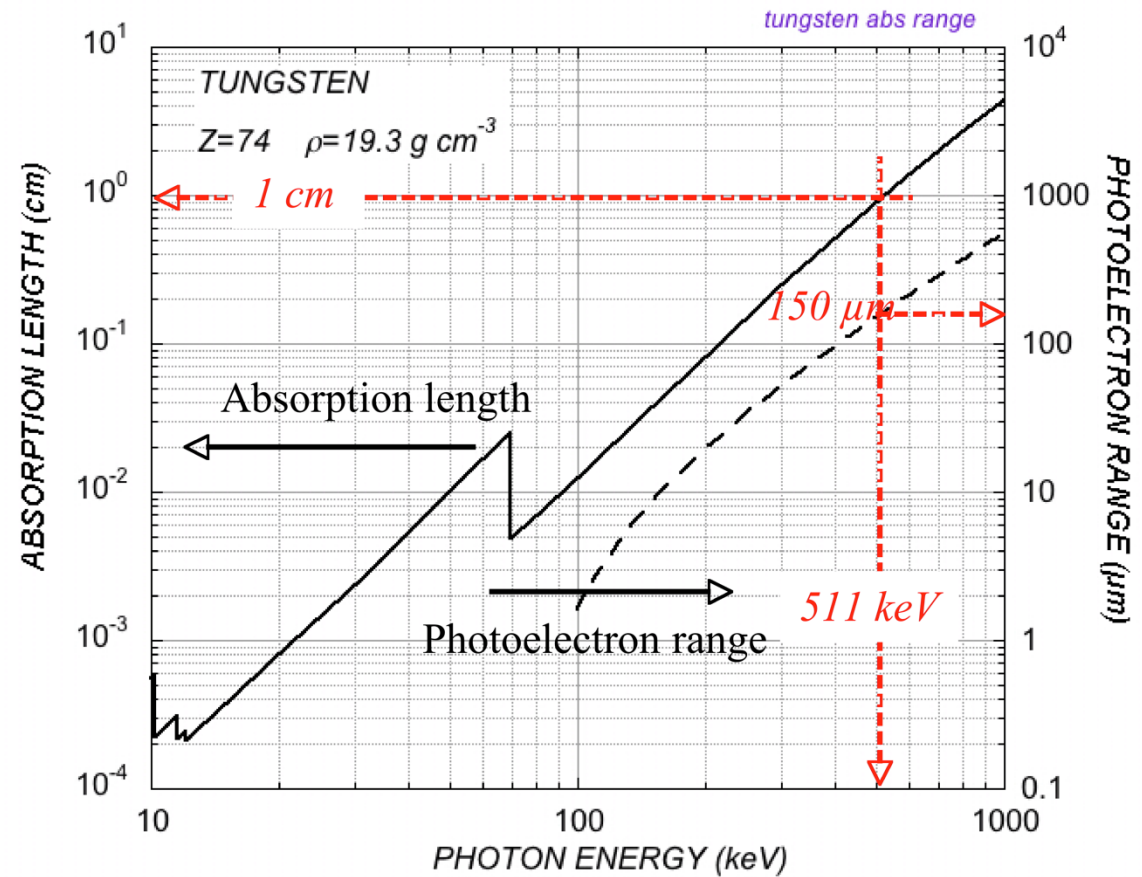
DETECTION EFFICIENCY:

$$\varepsilon = \left(1 - e^{-\frac{s}{\lambda}}\right) P_{ej}$$

s: converter thickness

 λ : absorption length P_{ej} : photoelectron ejection probability

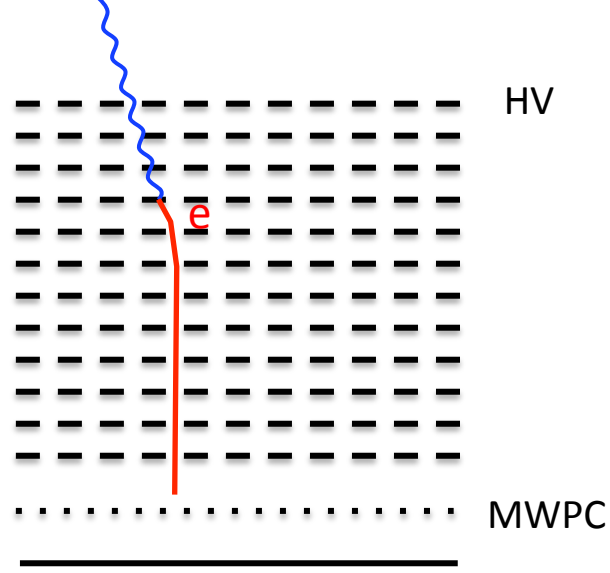
USEFUL CONVERTER THICKNESS AND ELECTRON RANGE

100 μm converter $\rightarrow \varepsilon \sim 1\%$

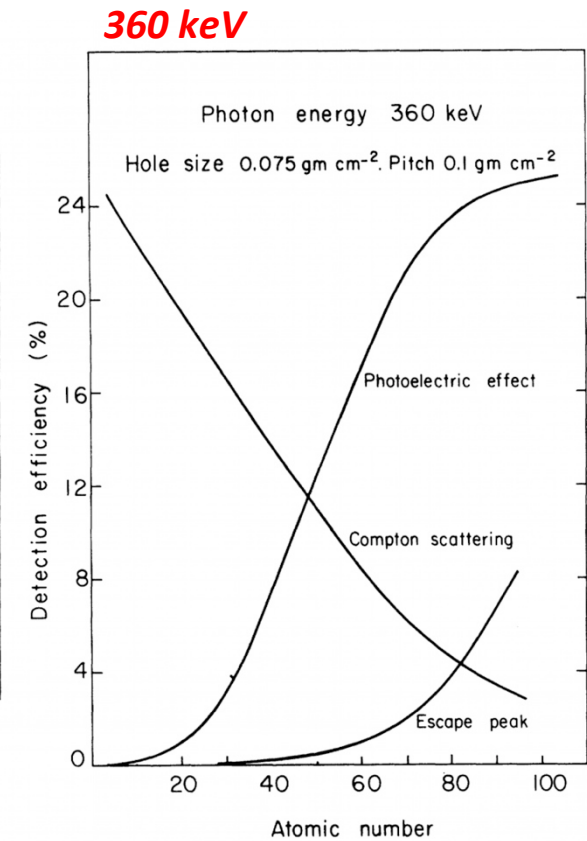
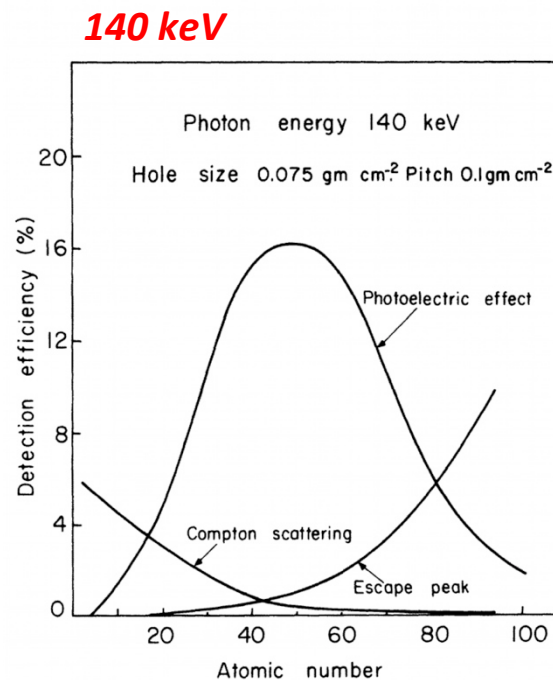
MULTI-CONVERTERS

HEAVY DRIFT CHAMBER

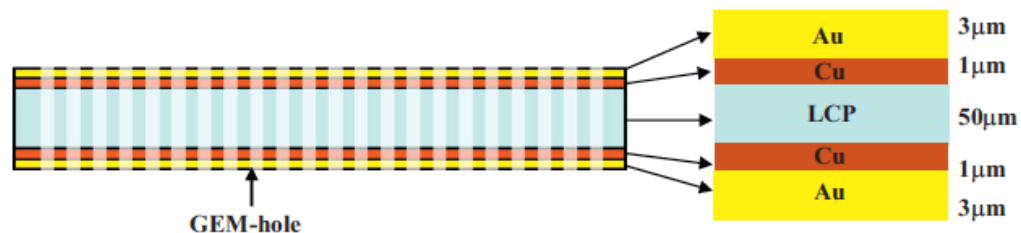
Stack of converter Grids at graded potentials



EFFICIENCY vs CONVERTER ATOMIC NUMBER:

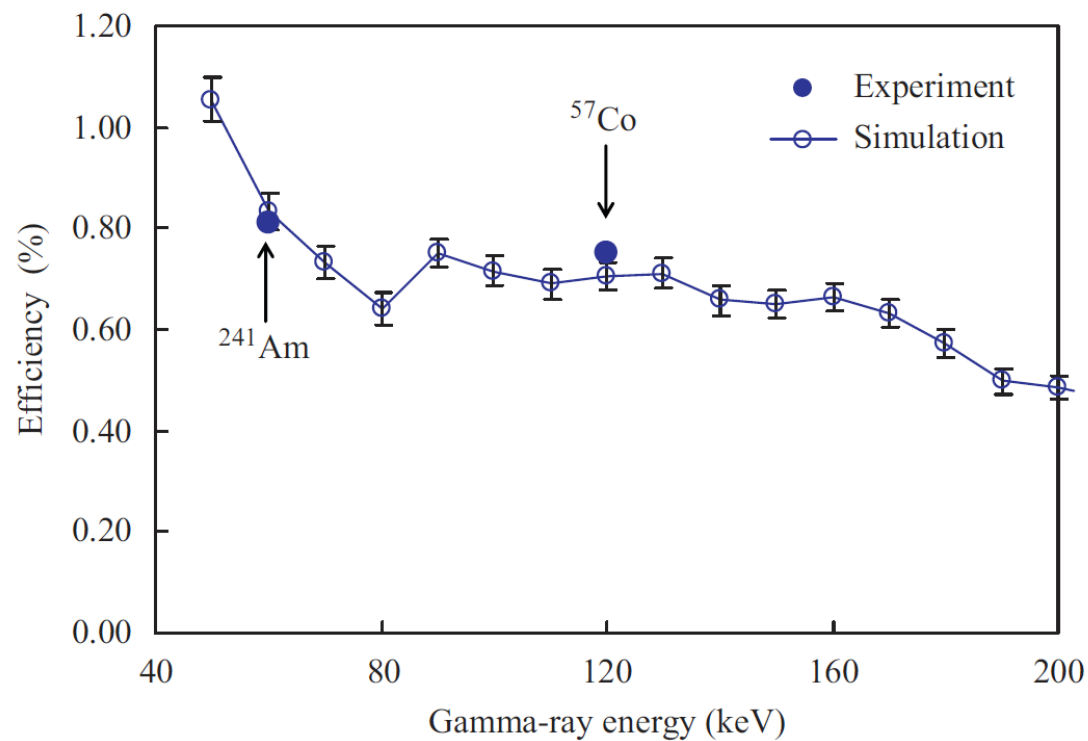


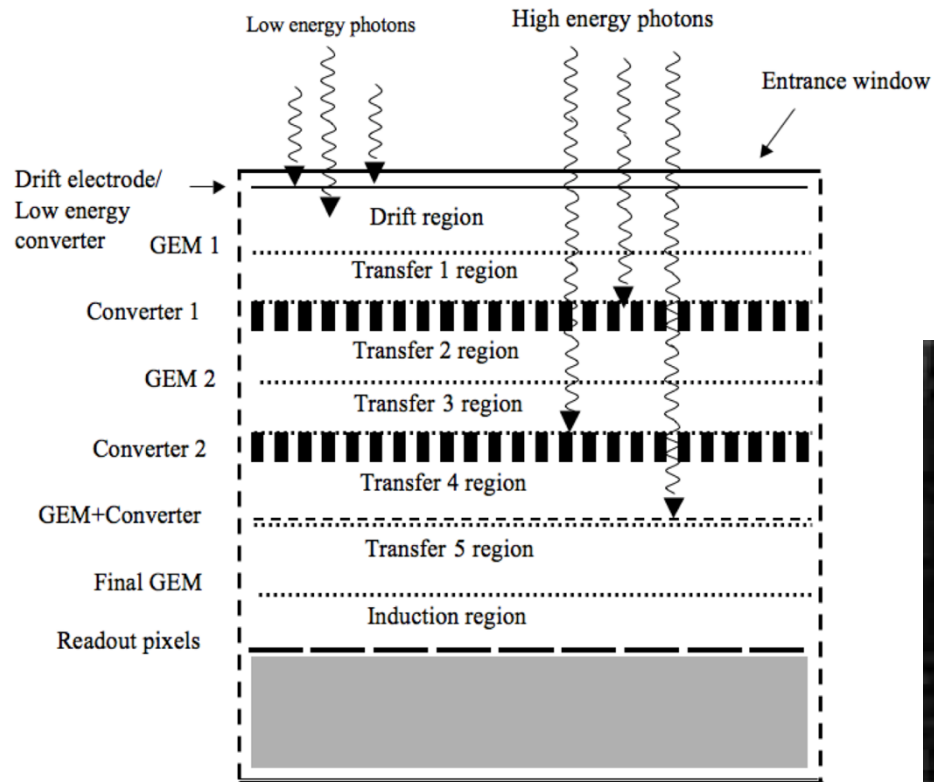
A. Jeavons et al, IEEE Trans. Nucl. Sci. NS-23 (1978)41



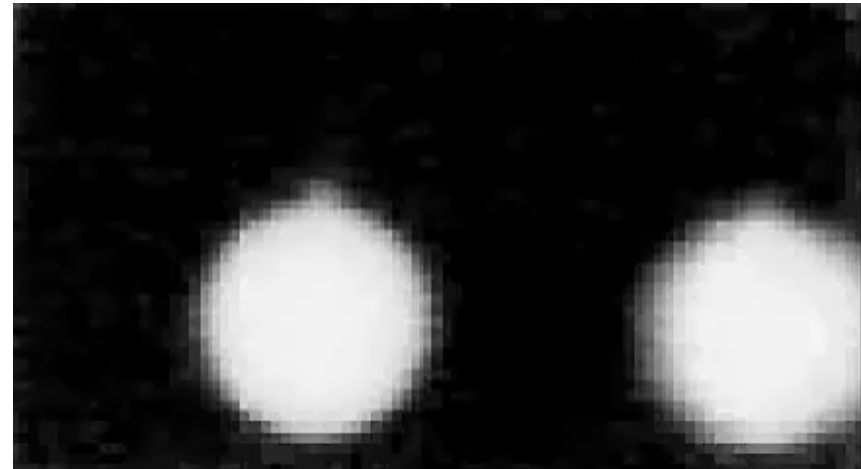
*T. Koike et al,
Nucl. Instr. and Meth. A648(2011)180*

DETECTION EFFICIENCY:





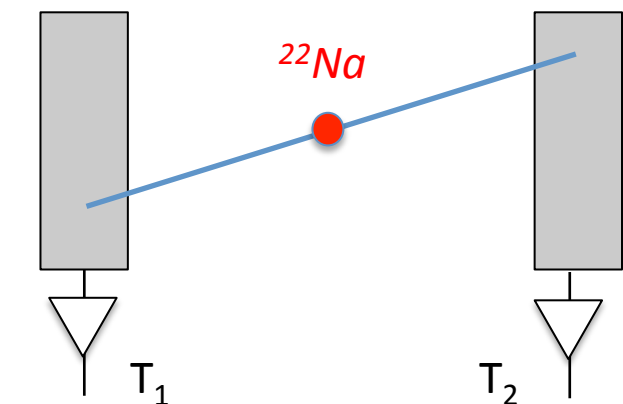
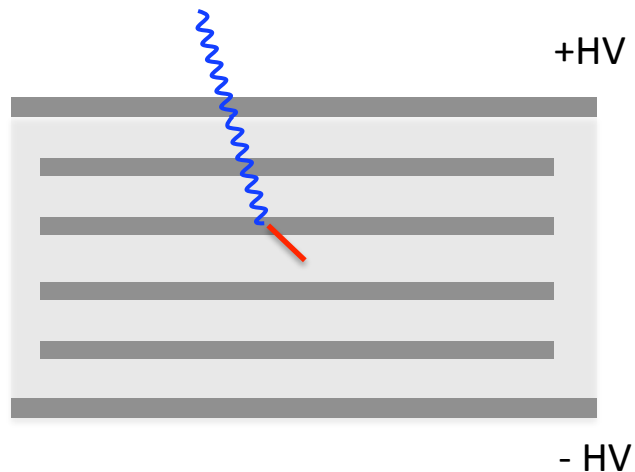
70 Hz TIME-RESOLVED IMAGE OF A NEWTON PENDULUM AT 40 keV



J. Östling, New Efficient Detector for Radiation Therapy Imaging using Gas Electron Multipliers. Thesis at Karolinska Institutet Karolinska Institutet (2006)

FAST TIMING PET

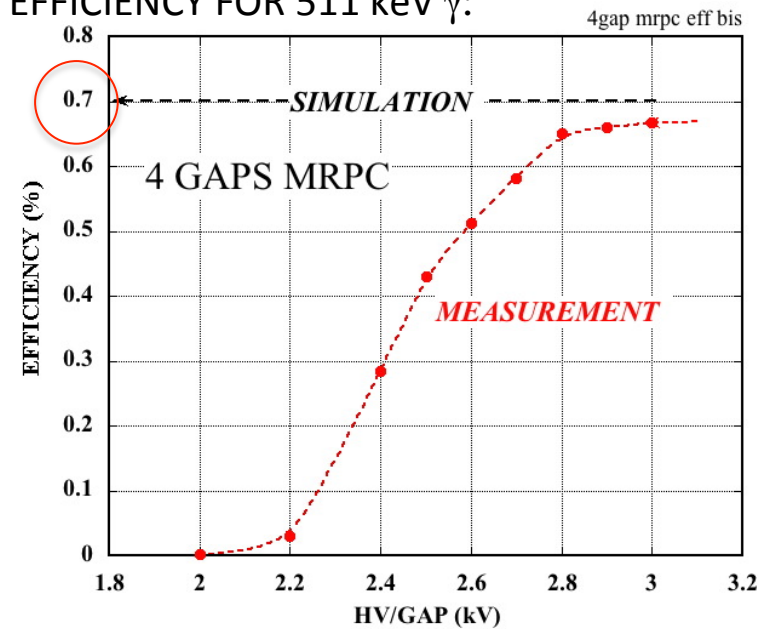
DETECTION OF 511 keV γ
 MULTI-GAP RESISTIVE PLATE CHAMBER
 400 μm THICK HIGH RESISTIVITY GLASS PLATES



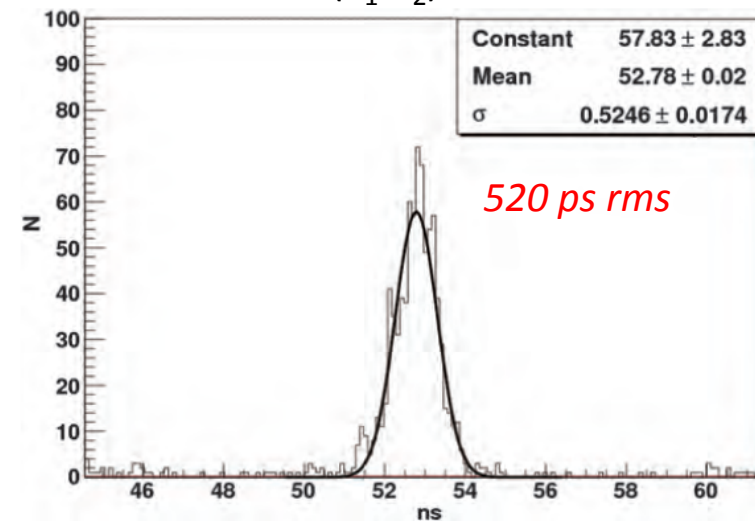
D. Watts et al, J. Rad. Res. 54 (2013)i136

GAMMA RAYS

EFFICIENCY FOR 511 keV γ :



TIME RESOLUTION ($T_1 - T_2$):



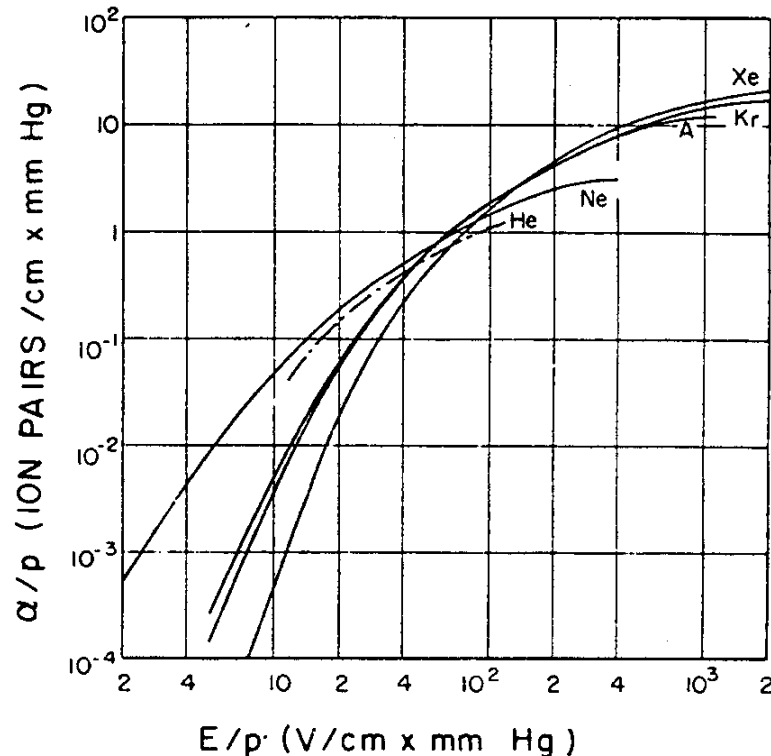
AVALANCHE CHARGE MULTIPLICATION

Mean free path for ionization:

$$\lambda = \frac{1}{N\sigma} \quad N: \text{molecules/cm}^3$$

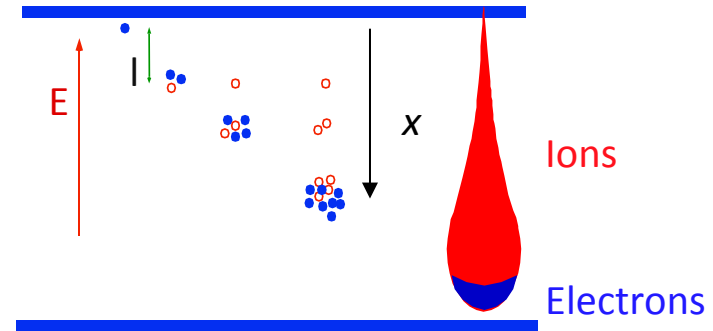
Townsend coefficient:

$$\alpha = \frac{1}{\lambda} \quad \text{Ionizing collisions/cm} \quad \frac{\alpha}{P} = f\left(\frac{E}{P}\right)$$



S.C. Brown, Basic Data of Plasma Physics (MIT Press, 1959)

CHARGE MULTIPLICATION IN UNIFORM FIELD



Incremental increase of the number of electrons in the avalanche:

$$dn = n \alpha dx$$

Multiplication factor or Gain: $M(x) = \frac{n}{n_0} = e^{\alpha x}$

Maximum avalanche size before discharge
(Raether limit):

$$Q_{\text{MAX}} \approx 10^7 e \rightarrow \text{(PART 2)}$$

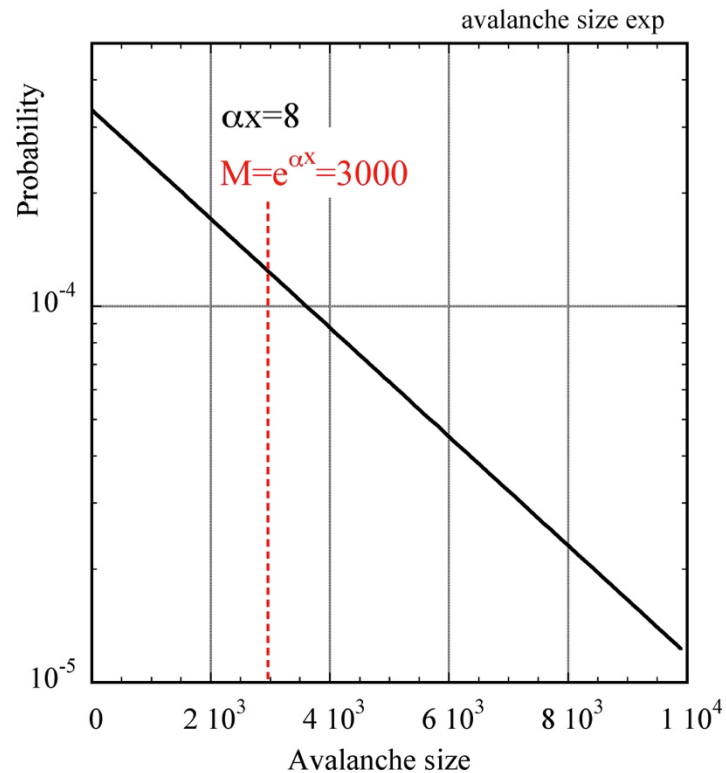
H. Raether, Electron Avalanches and Breakdown in Gases (Butterworth 1964)

SINGLE ELECTRON AVALANCHE: FURRY STATISTICS

AVALANCHE SIZE DISTRIBUTION:

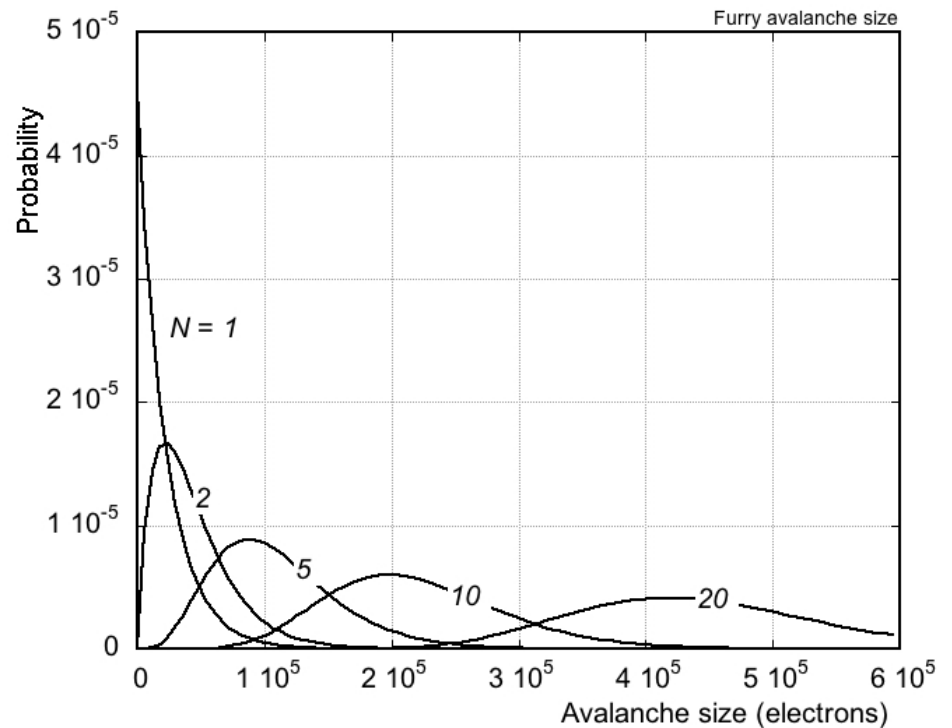
$$P(n) = \frac{e^{-n/\bar{n}}}{\bar{n}} \quad M = \bar{n} = e^{\alpha x} \quad \sigma_{\bar{n}} = \bar{n}$$

MAXIMUM PROBABILITY FOR $n=1$!



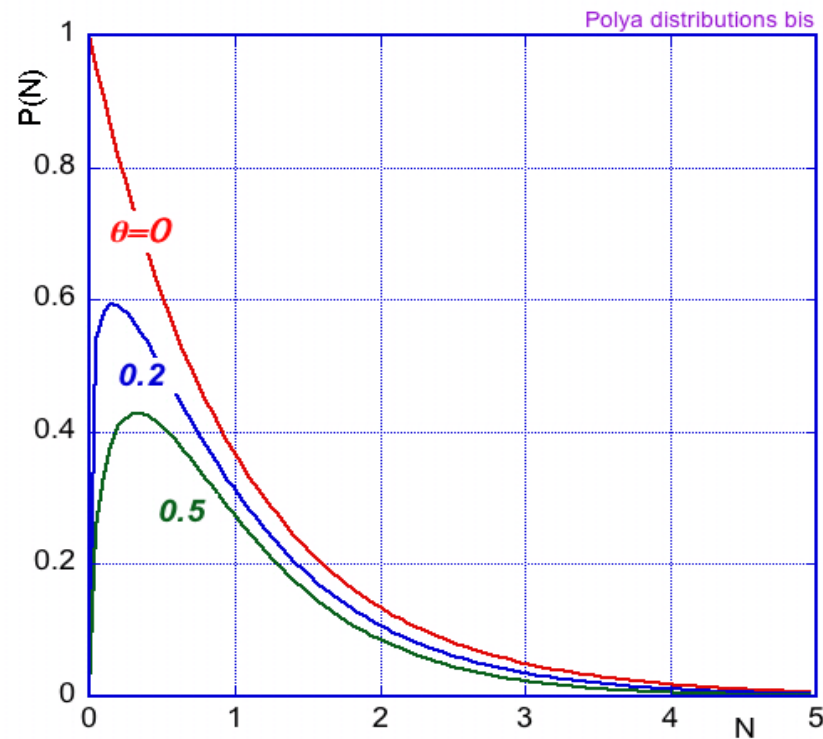
FOR N INITIAL ELECTRONS:

$$P(n, N) = \frac{1}{\bar{n}} \left(\frac{n}{\bar{n}} \right)^{N-1} \frac{e^{-\frac{n}{\bar{n}}}}{(N-1)!}$$



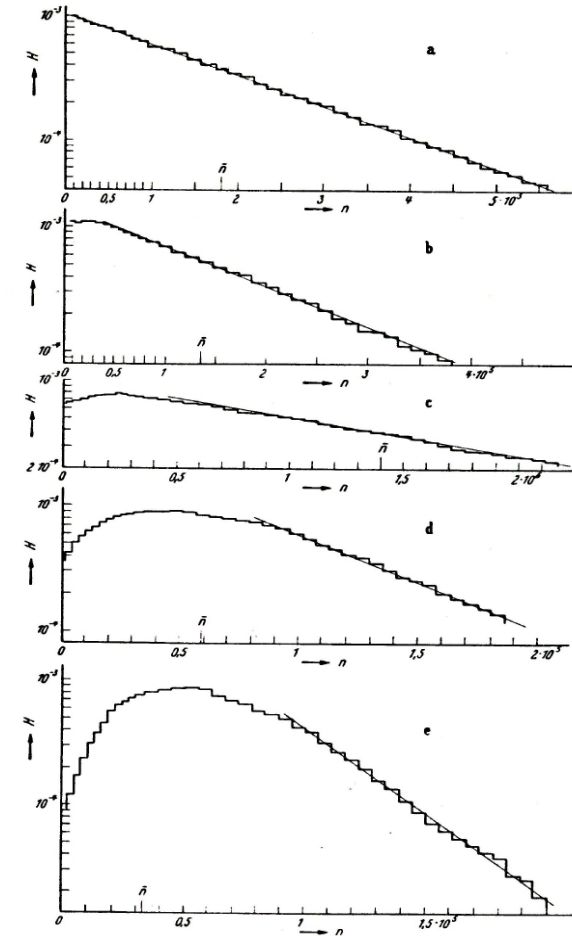
SINGLE ELECTRON AVALANCHE AT HIGH GAINS: POLYA DISTRIBUTION

$$P(N) = \left[\frac{N(1+\theta)}{\bar{N}} \right]^\theta e^{-\frac{N(1+\theta)}{\bar{N}}} \quad \left(\frac{\sigma_A}{A} \right)^2 = \frac{1}{A} + \frac{1}{1-\theta} \cong \frac{1}{1-\theta}$$



H. Schindler, S.F. Biagi, R. Veenhof
Nucl. Instr. and Meth. A624(2010)78

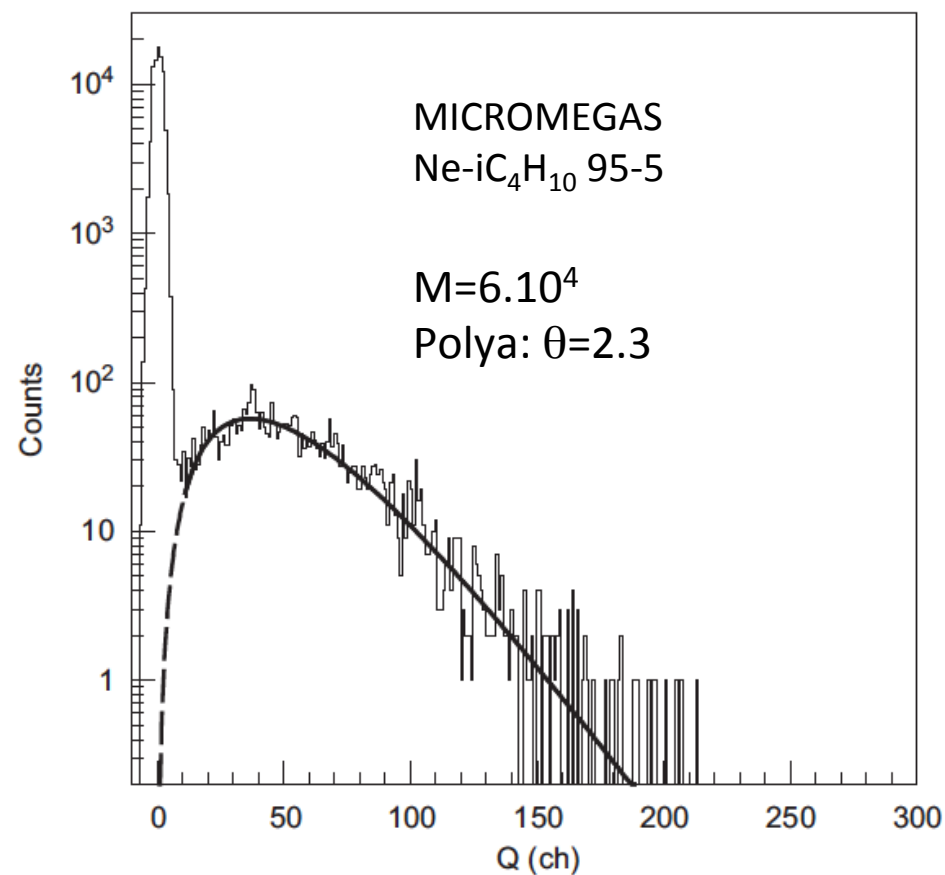
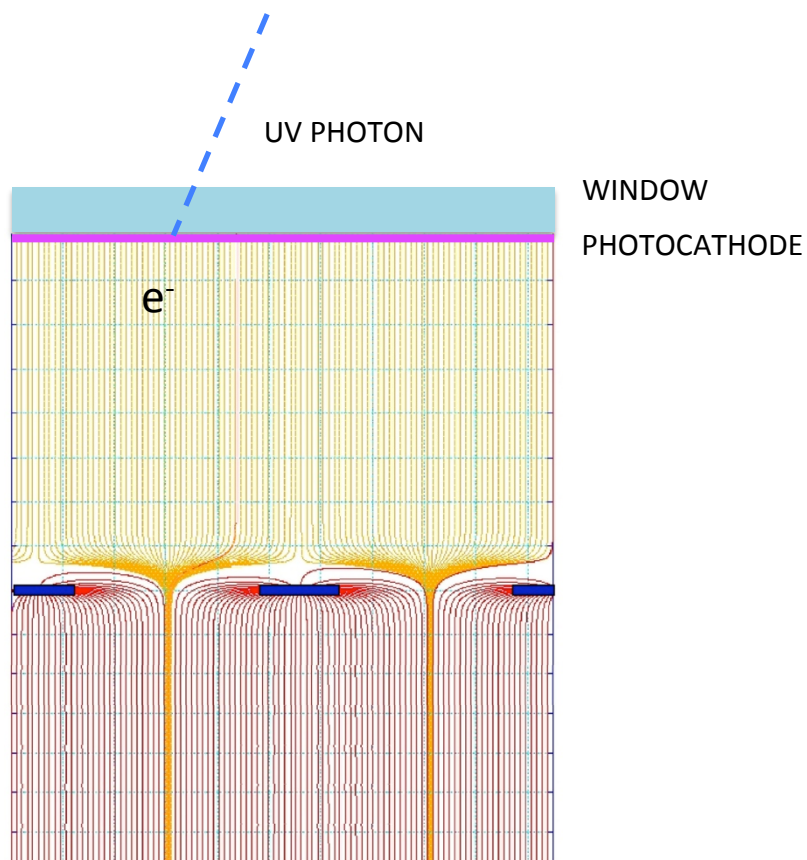
EXPERIMENTAL:



H. Schlumbohm, Zeit. Physik 151(1958)563

SINGLE ELECTRON AVALANCHE DISTRIBUTION IN MPGDs

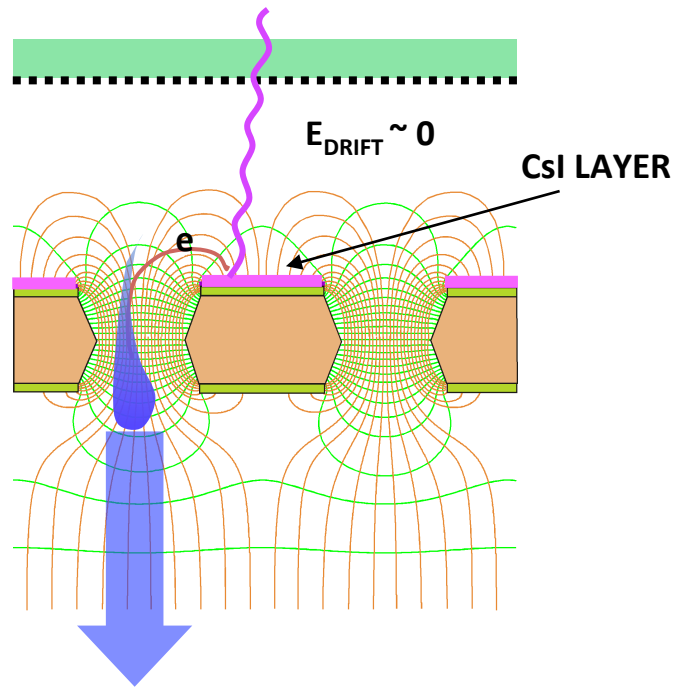
MICROMEGAS WITH SEMITRANSSPARENT PHOTOCATHODE



T. Zerguerras et al, Nucl. Instr. and Meth. A608(2009)397

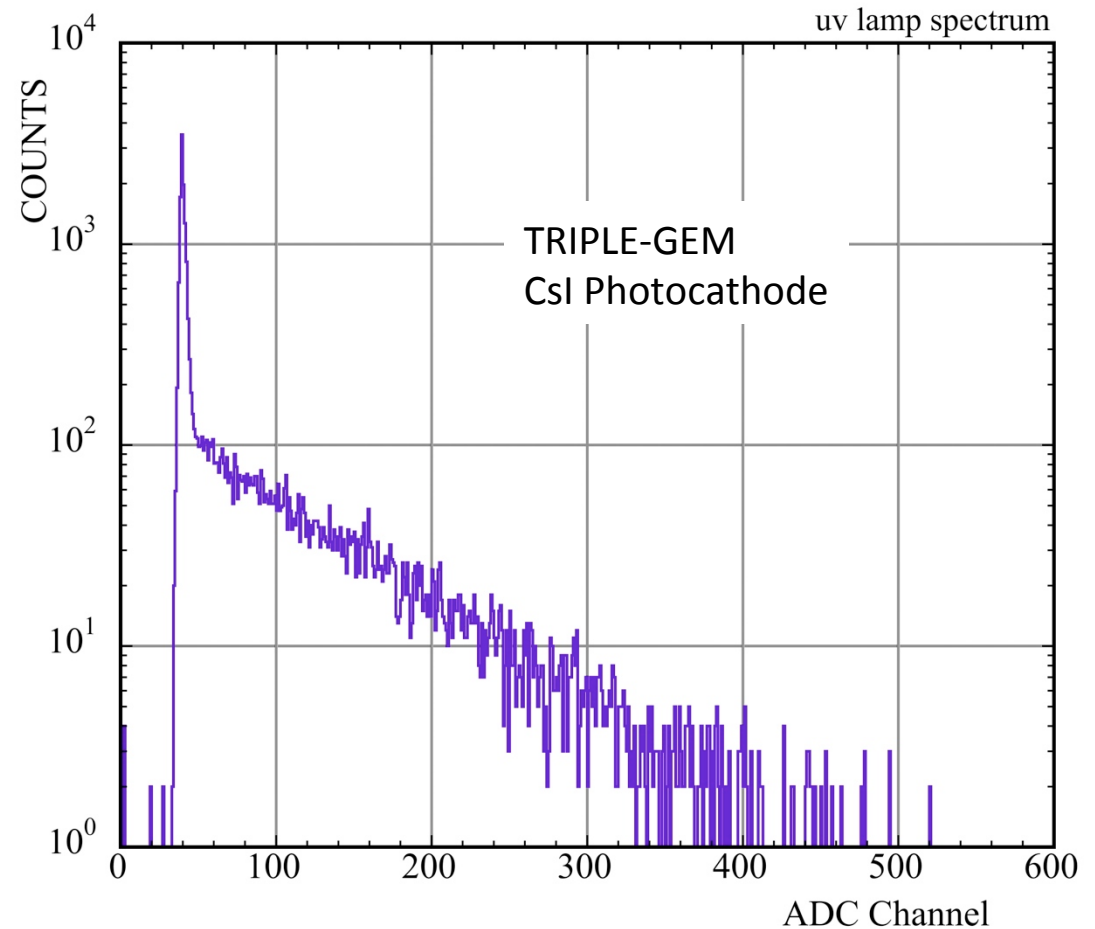
SINGLE ELECTRON AVALANCHE DISTRIBUTION IN MPGDs

GEM WITH REFLECTIVE PHOTOCATHODE:



MORE GEMS

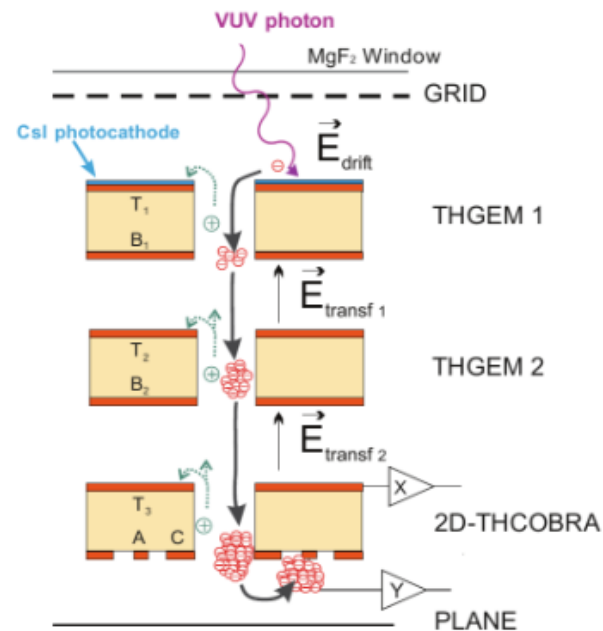
- No photon feedback
- Strong suppression of ions feedback



F. Sauli, Nucl. Instr. and Meth. A553(2005)18

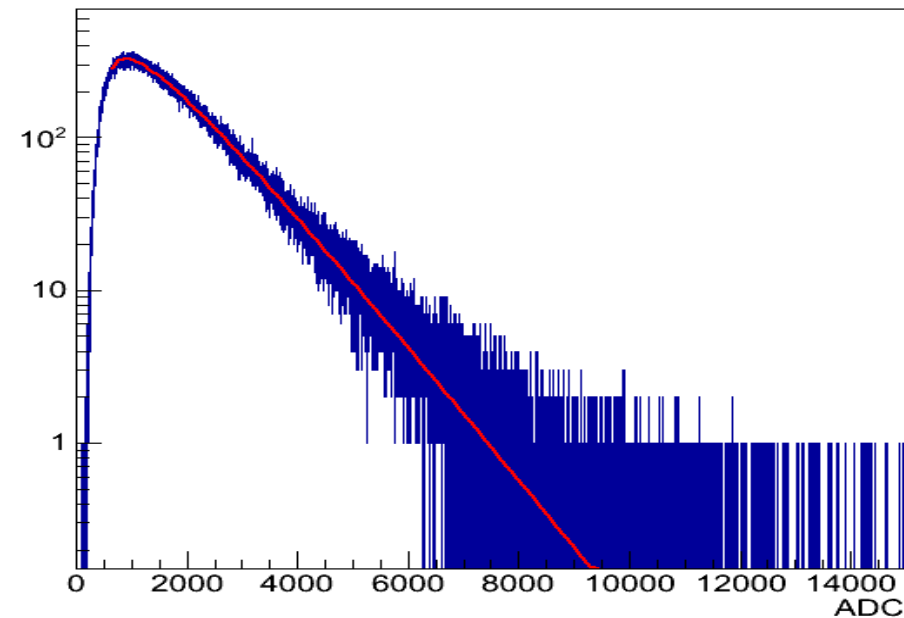
SINGLE ELECTRON AVALANCHE WITH IMPROVED ION BACKFLOW SUPPRESSION

THICK COBRA



F. Amaro et al JINST5 (2010)

*J.F.C.A.Veloso et al
Nucl. Instr. and Meth. A639(2011)*



- $G > 10^6$
- collection efficiency $\sim 100\%$
- $R_{p(\text{anode})} = 60 \mu\text{m}$
- $R_{p(\text{top})} = 90 \mu\text{m}$
- only a few discharges for several months even for high photon flux

END OF PART 1



EXTRAS

SOFT X-RAYS: ENERGY RESOLUTION

Energy resolution: $\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{\sigma_N}{N}\right)^2 + \left(\frac{\sigma_M}{M}\right)^2$

$\uparrow$ Ionization $\uparrow$ Avalanche statistics

Average gain: $M = \frac{1}{N} \sum_{i=1}^N A_i = \bar{A}$ A_i : single electron avalanche size

Gain variance: $\sigma_M^2 = \left(\frac{1}{N}\right)^2 \sum_{i=1}^N \sigma_A^2$ $\left(\frac{\sigma_M}{M}\right)^2 = \frac{1}{N} \left(\frac{\sigma_A}{\bar{A}}\right)^2$

Furry statistics: $\sigma_A = \bar{A}$ $\left(\frac{\sigma_A}{\bar{A}}\right)^2 = 1$

Polya statistics: $\left(\frac{\sigma_A}{\bar{A}}\right)^2 = \frac{1}{\bar{A}} + b$ $b = \frac{1}{1 + \theta}$

Ionization variance: $\sigma_N^2 = F N$ F: Fano factor

$$\left(\frac{\sigma_E}{E}\right)^2 = \frac{1}{N} (F + b)$$

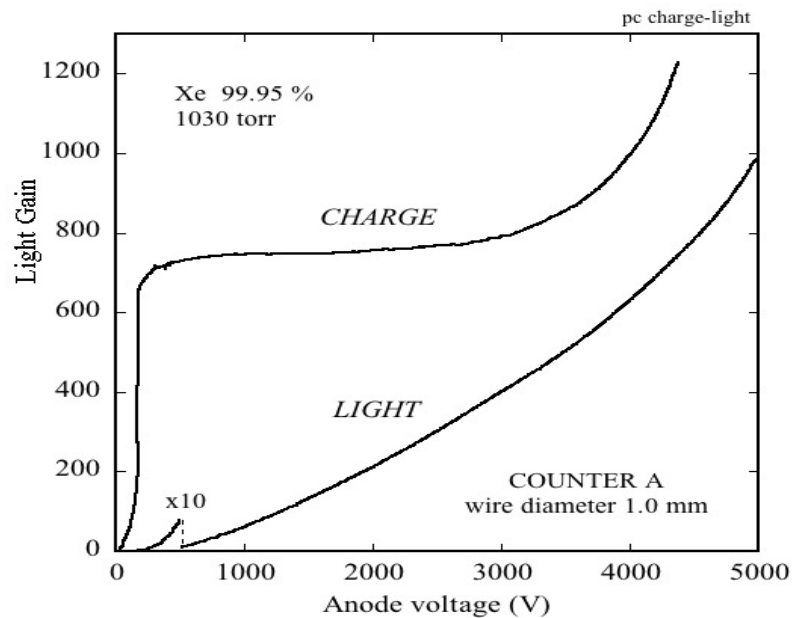
Furry: $b=1$ Polya: $b = 1/(1 - \theta)$

FANO FACTORS

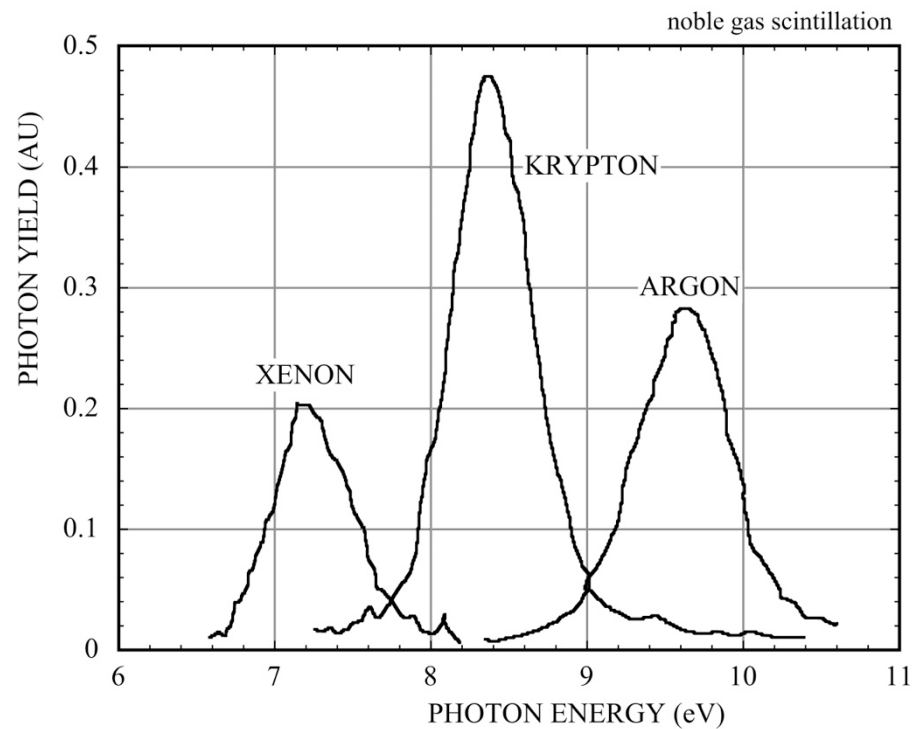
GAS	F
Ar	0.19
Ar-CH ₄	0.19
Xe	<0.17
Ne+0.5%Ar	0.05

SCINTILLATION PROPORTIONAL COUNTERS

PHOTON EMISSION BEFORE CHARGE MULTIPLICATION:
NO AVALANCHE DISPERSIONS

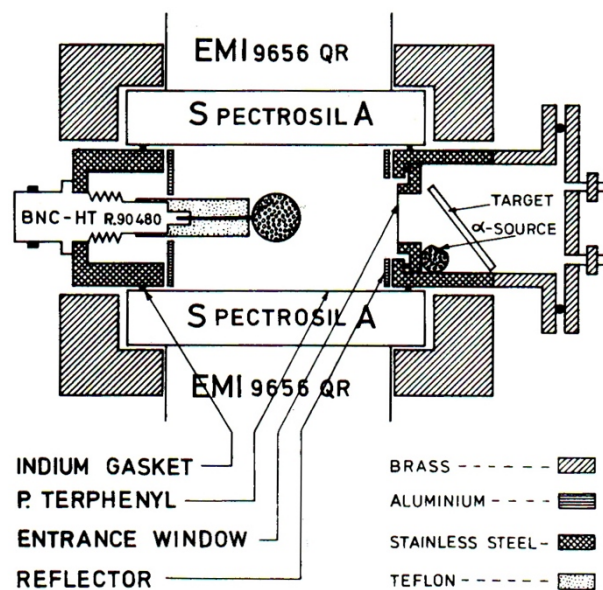


NOBLE GASES SCINTILLATION SPECTRA ~1bar

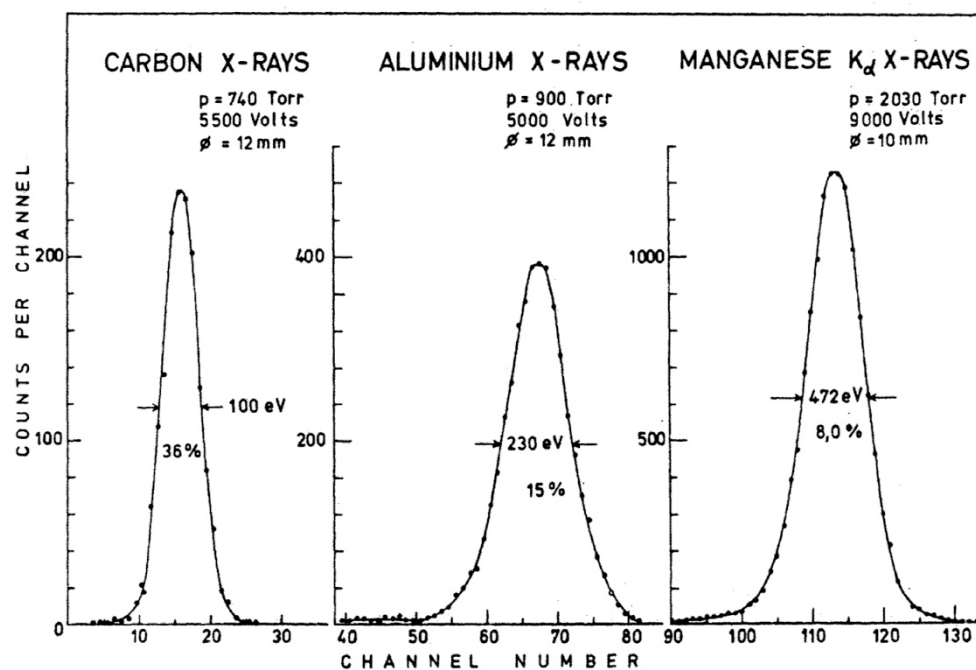


SCINTILLATION PROPORTIONAL COUNTERS

SCINTILLATION COUNTERS



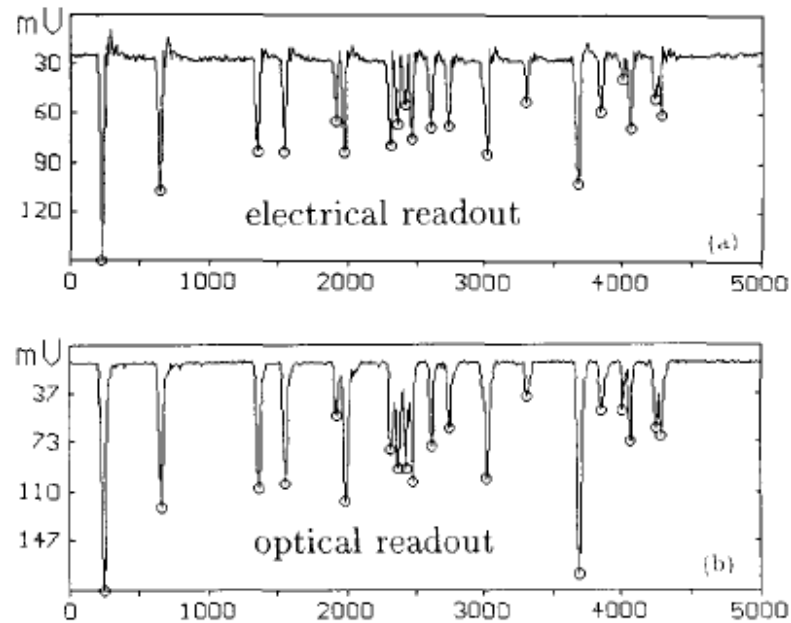
ENERGY RESOLUTION:
CLOSE TO STATISTICAL LIMIT



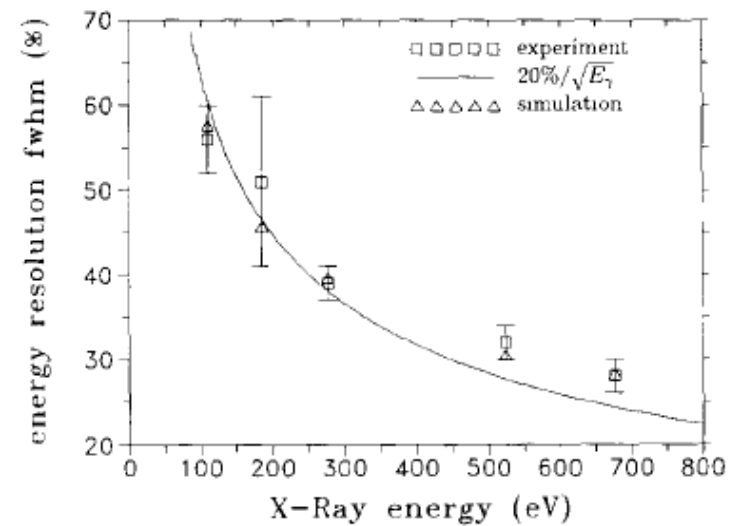
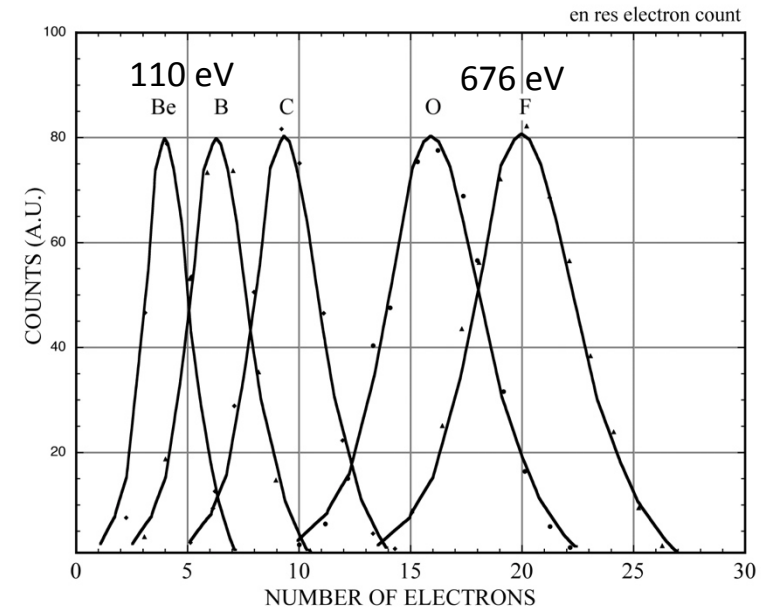
A. Policarpo et al, Nucl. Instr. and Meth. 102(1972)337

ELECTRON COUNTING

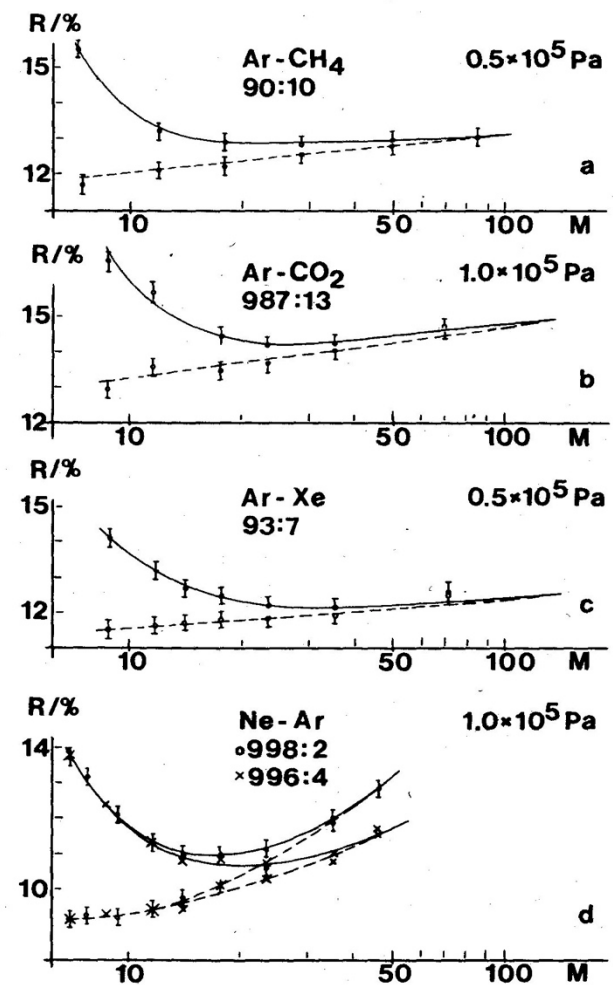
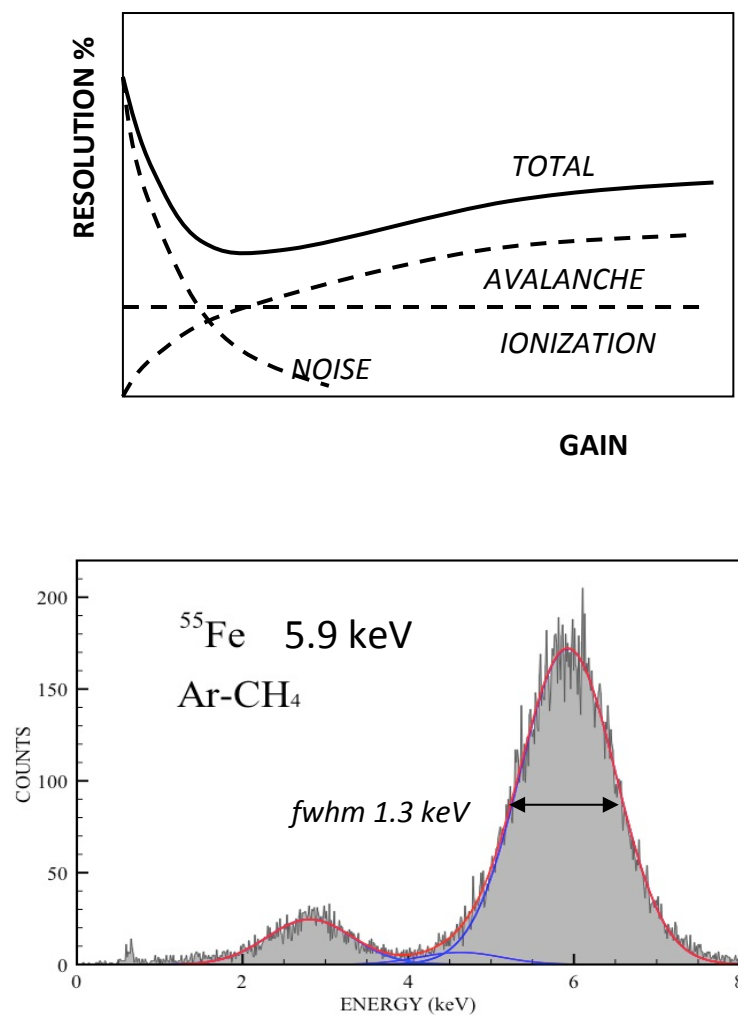
LOW PRESSURE (10 Torr) PROPORTIONAL COUNTER



A. Pansky et al, Nucl. Instr. and Meth. A330(1993)150



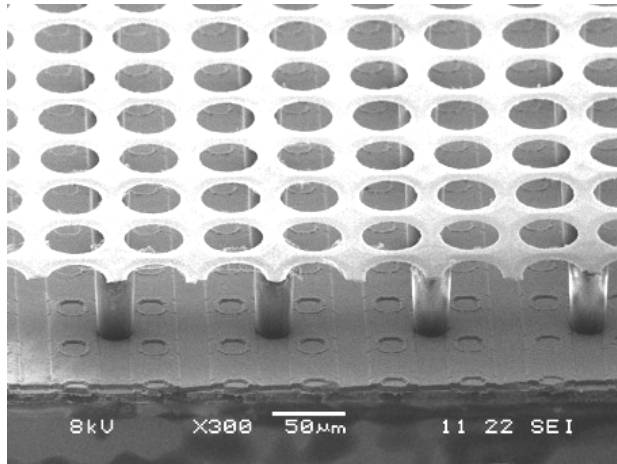
SOFT X-RAYS ENERGY RESOLUTION



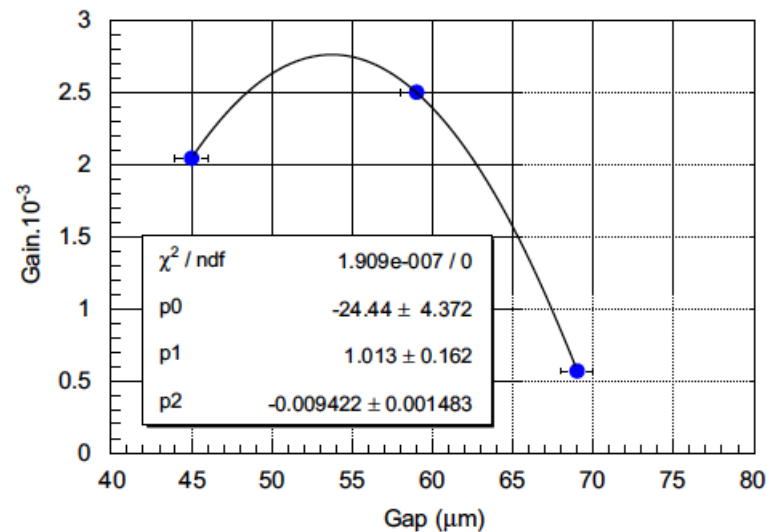
H. Sipilä and E. Kiuru, *Adv. X-Ray Analysis* 21(1978)

SOFT X-RAYS ENERGY RESOLUTION

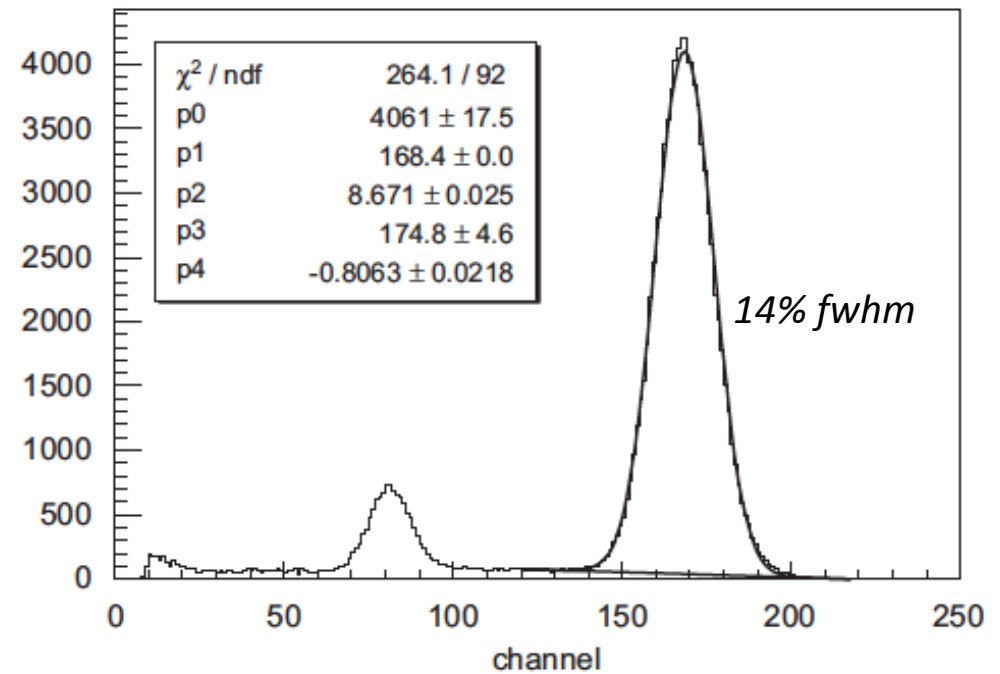
INGRID: MICROMEGLAS WITH TIMEPIX READOUT



GAP DEPENDENCE OF GAIN:



5.9 keV ⁵⁵Fe in Ar-CH₄ 90-10



M. Chefdeville et al,
Nucl. Instr. and Meth. A591(2008)147