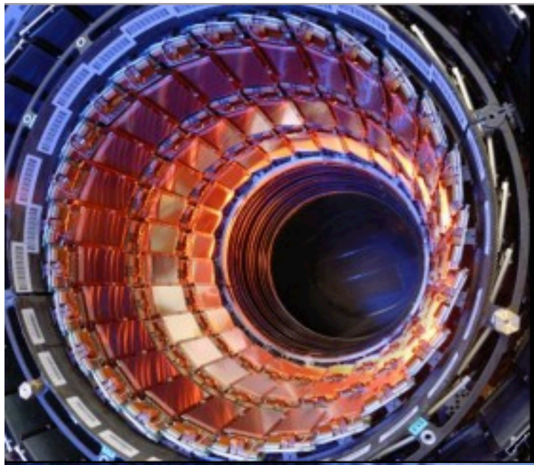


XXV GIORNATE DI STUDIO SUI RIVELATORI
Scuola F. Bonaudi

23-26 Febbraio
Villaggio dei Minatori - Cogne (AO)

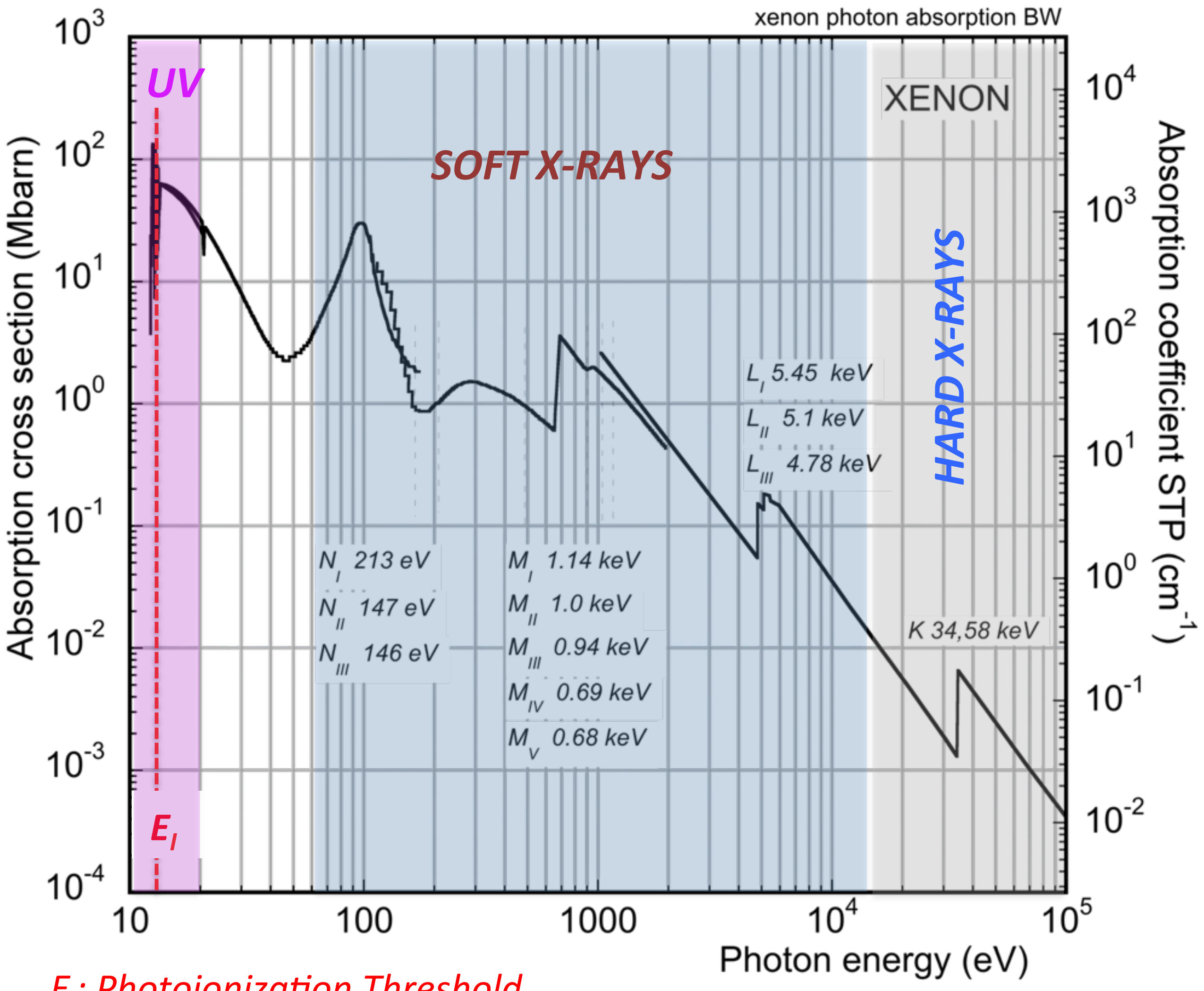
Fabio Sauli
TERA Foundation
CERN

PART 1

PHOTON DETECTION AND IMAGING WITH GASEOUS COUNTERS

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

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

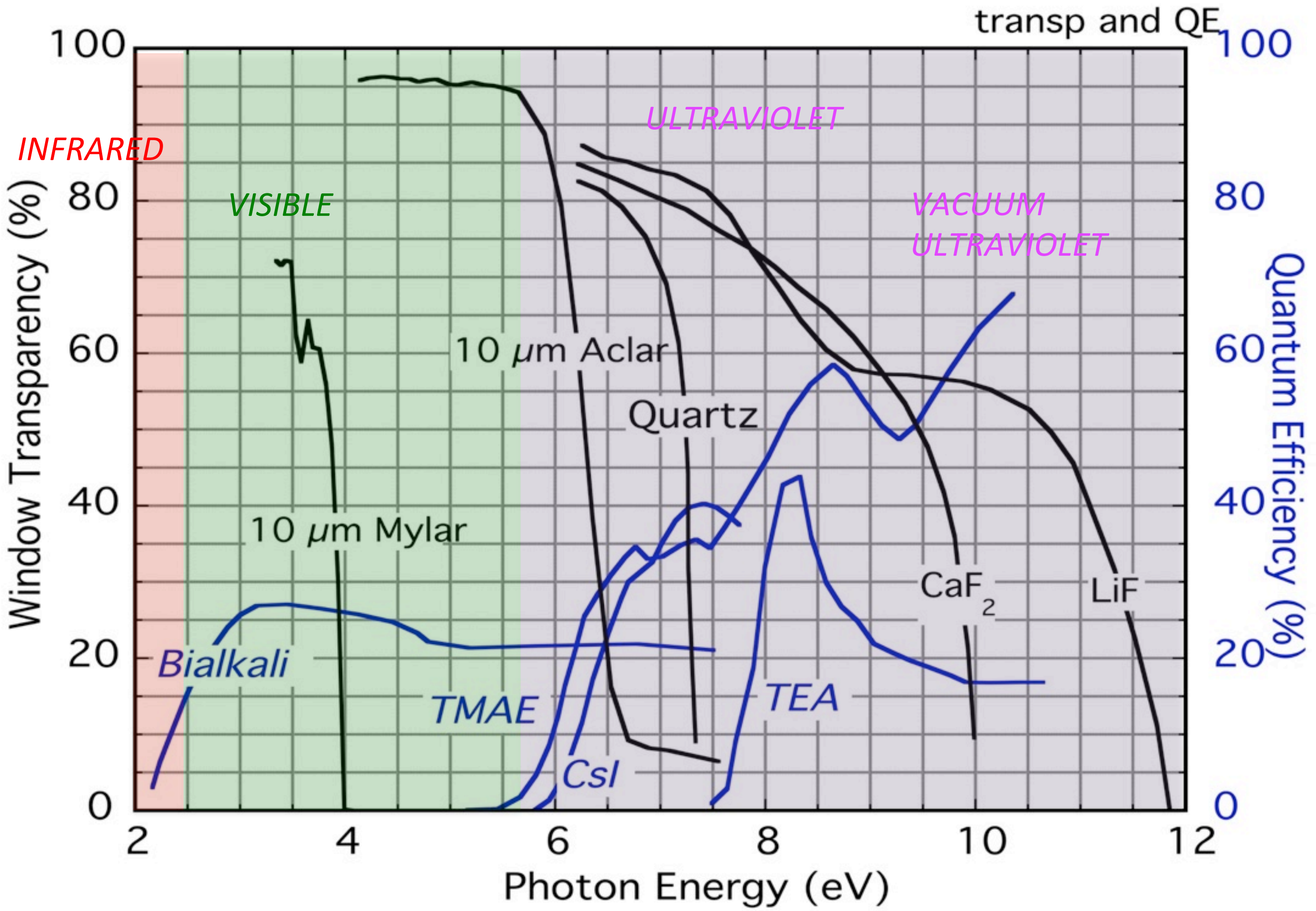
α: absorption coefficient
x: layer thickness
λ: absorption length

For gases at STP:

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

1 Mbarn=10^{-18} cm^2

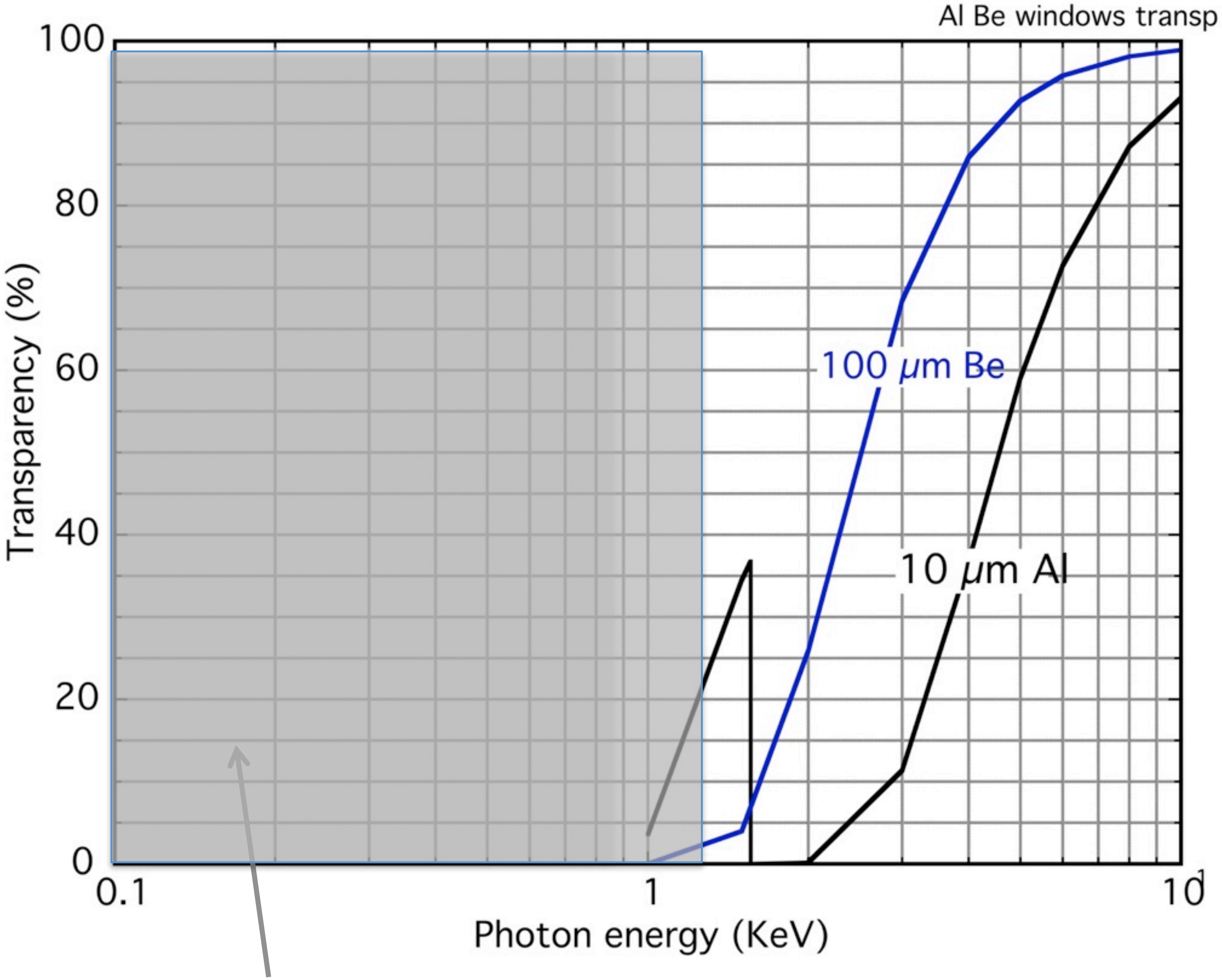
QUANTUM EFFICIENCY AND WINDOW TRANSPARENCY-VISIBLE TO UV



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

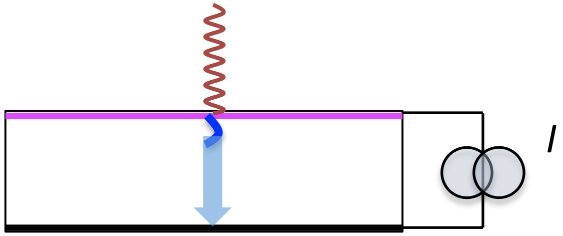
Bialkali: K-Cs Photocathode E_I = 2.2 eV
CSI: Caesium iodide E_i = 5.8 eV
TMAE: Tetrakis-dimethilamino-ethylene $C[(CH_3)_2N]_4$ E_i = 5.3 eV
TEA: Triethylamine $(C_2H_5)_3N$ E_i = 7.5 eV

WINDOWS TRANSPARENCY – SOFT X-RAYS



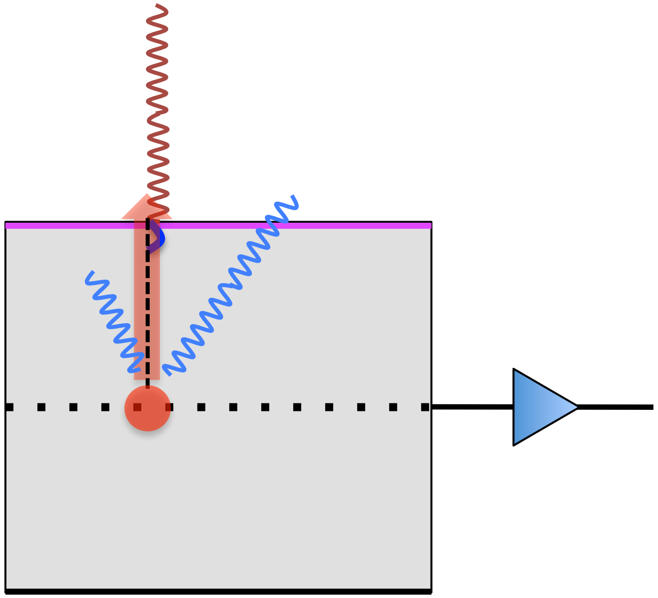
Windows cutoff between ~ 12 eV and ~ 1 keV

VACUUM PHOTODIODE: NO GAIN, NO FEEDBACKS



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

GASEOUS PHOTON DETECTORS:



- Very sensitive to impurities (O_2, H_2O,…)
- Backscattering reduces Quantum Efficiency

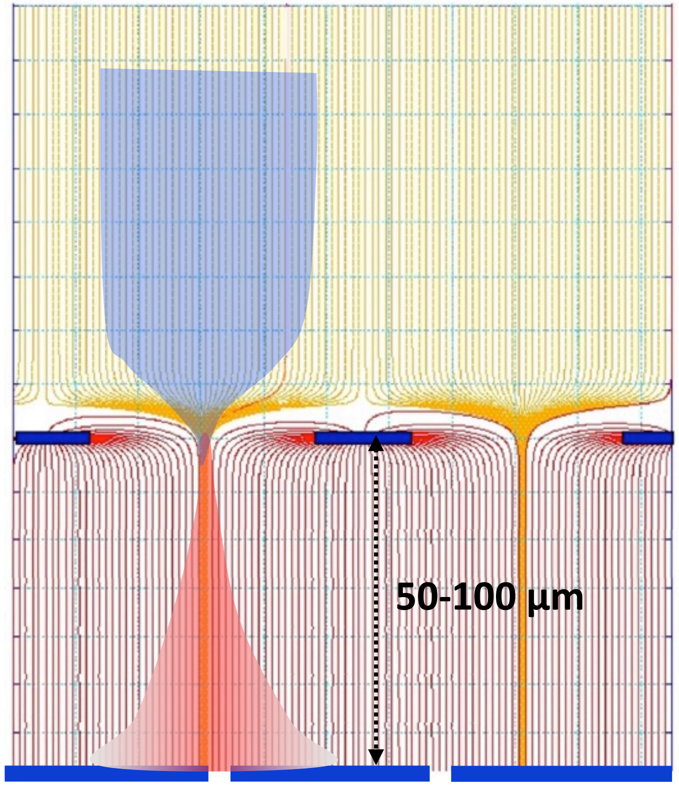
- Drift to anode and multiplication
- High gains (10^5-10^6)

- Photon feedback (secondary ionization)

- Positive ions damage the photocathode

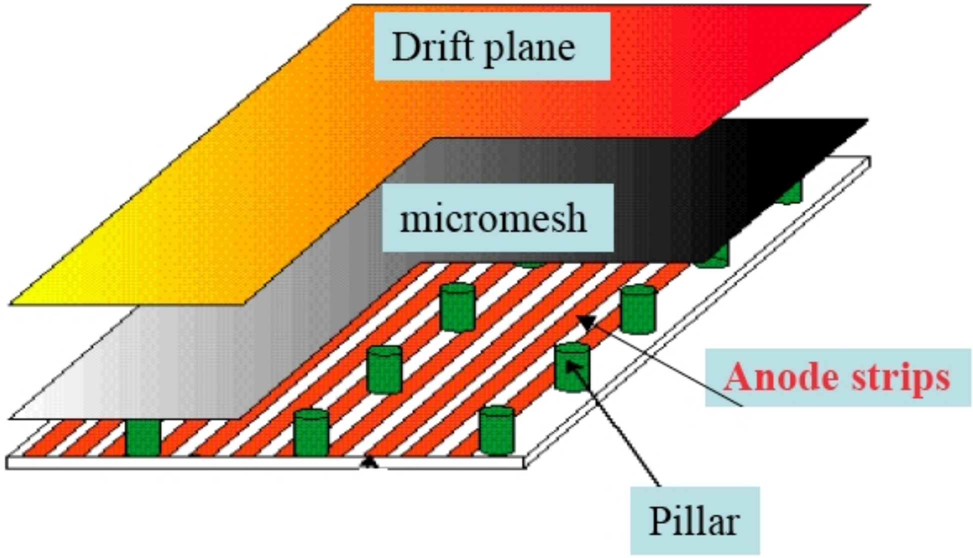
MICRO-PATTERN GAS DETECTORS (MPGD)

MICROMEGAS:
MICRO-Mesh GAseous Structure



Y. Giomataris et al,
Nucl. Instr. and Meth. A376(1996)29

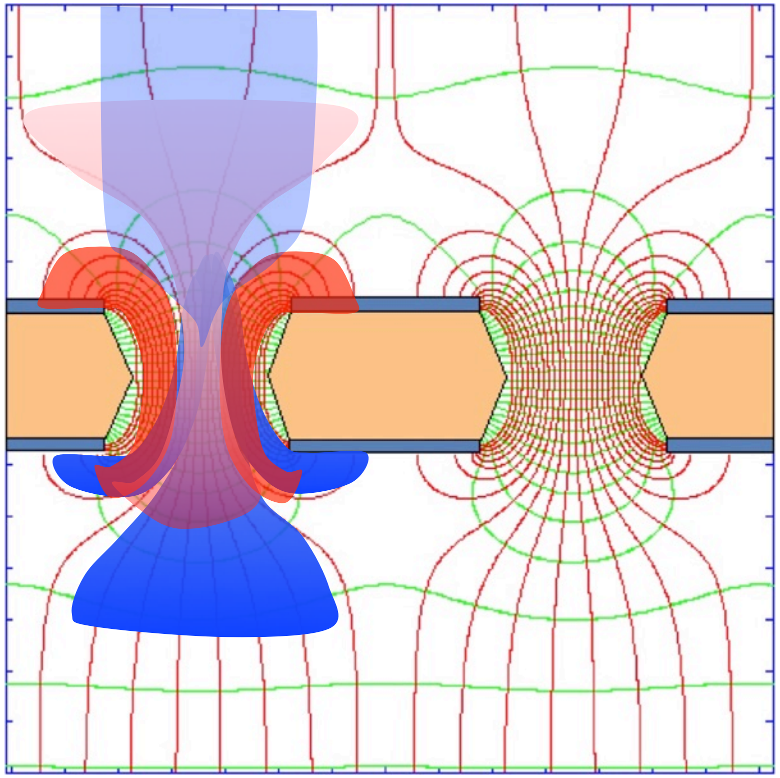
GAP RESTORERS: INSULATING PILLARS



Y. Giomataris,
Nucl. Instr. and Meth. A419(1998)239

MICRO-PATTERN GAS DETECTORS (MPGD)

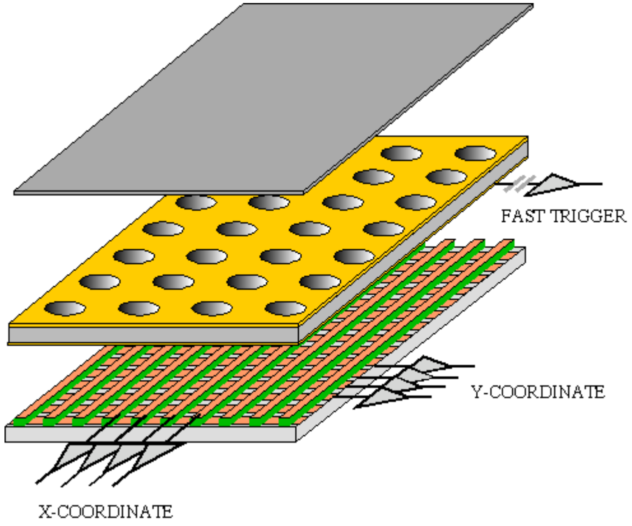
GEM: GAS ELECTRON MULTIPLIER
THIN (50 µM) METAL-COATED POLYMER FOIL
WITH HIGH DENSITY OF HOLES



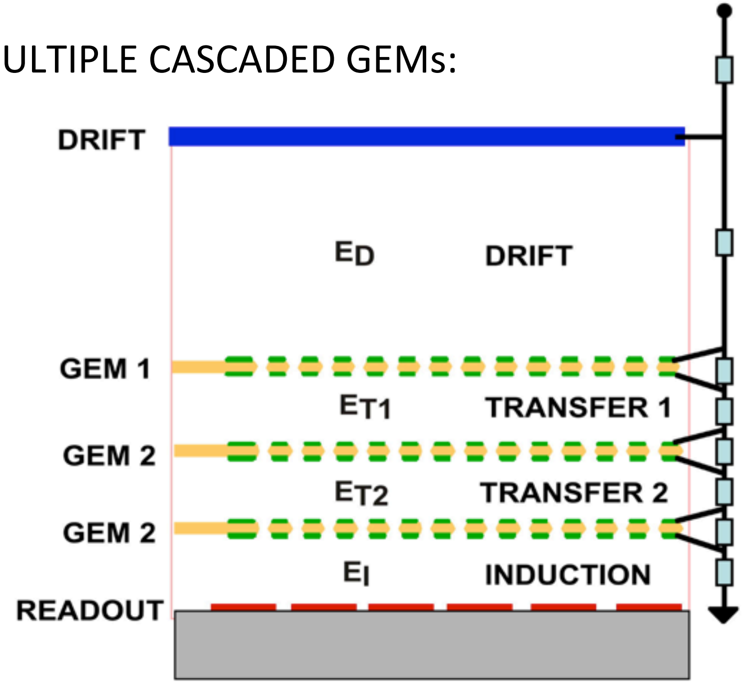
F. Sauli, Nucl. Instr. and Meth. A386(1997)531

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

SINGLE GEM WITH 2-D READOUT BOARD:



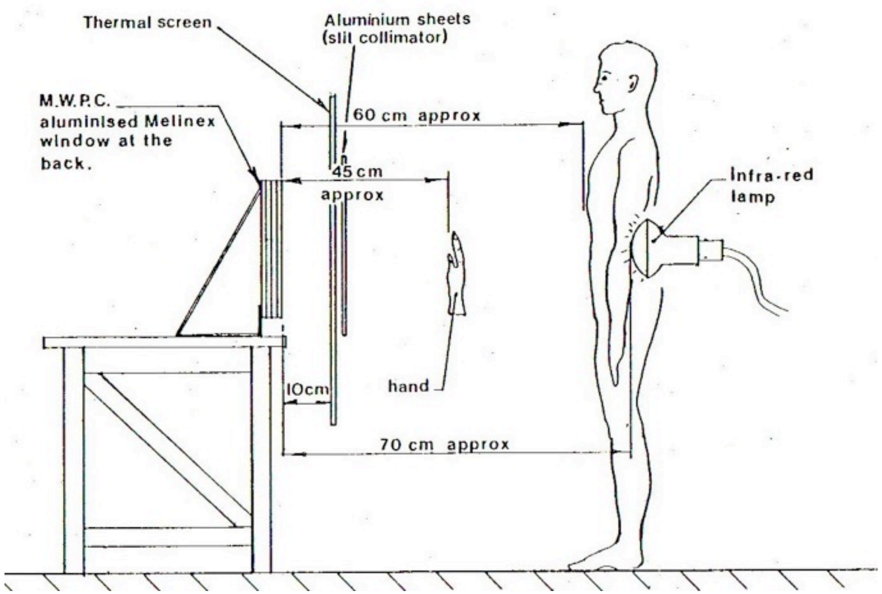
MULTIPLE CASCADED GEMs:

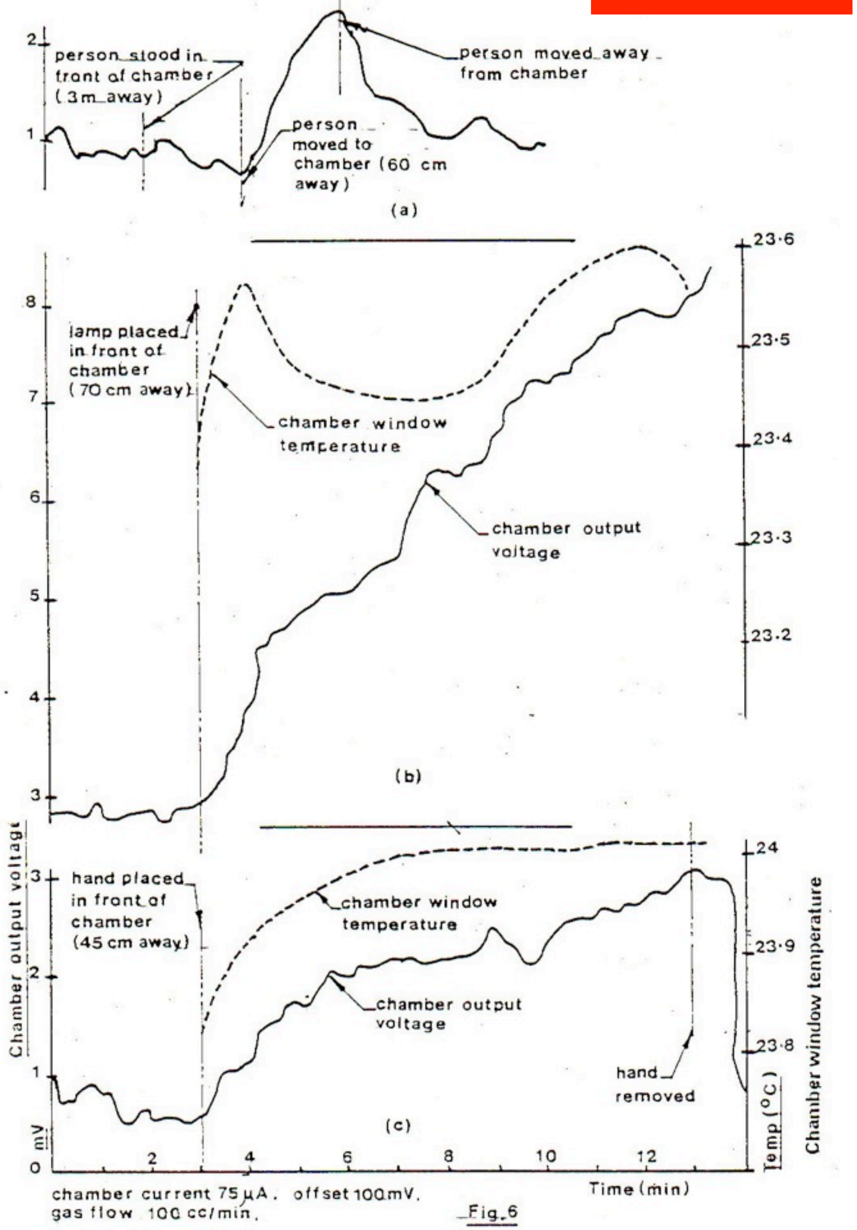


A CURIOUS OBSERVATION: MWPC INFRARED SENSITIVITY?

INFRARED?

STUDY OF GLOW DISCHARGES IN MWPCs
Rutherford Lab (1979)



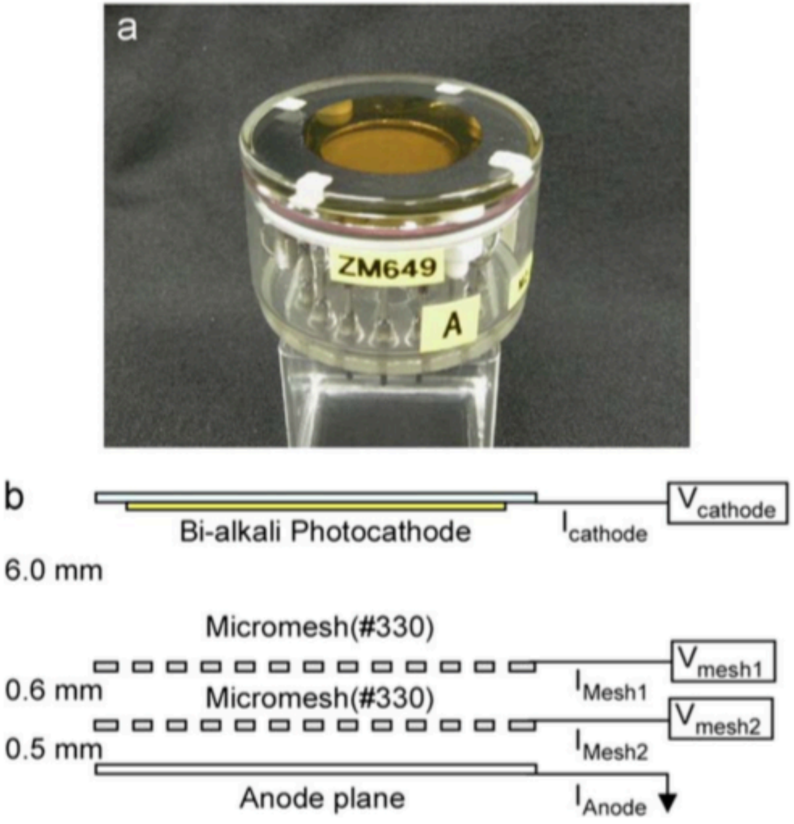


J.B. Marsh, K.H. Souten and B. O'Hagan RL-79-038 (1979)

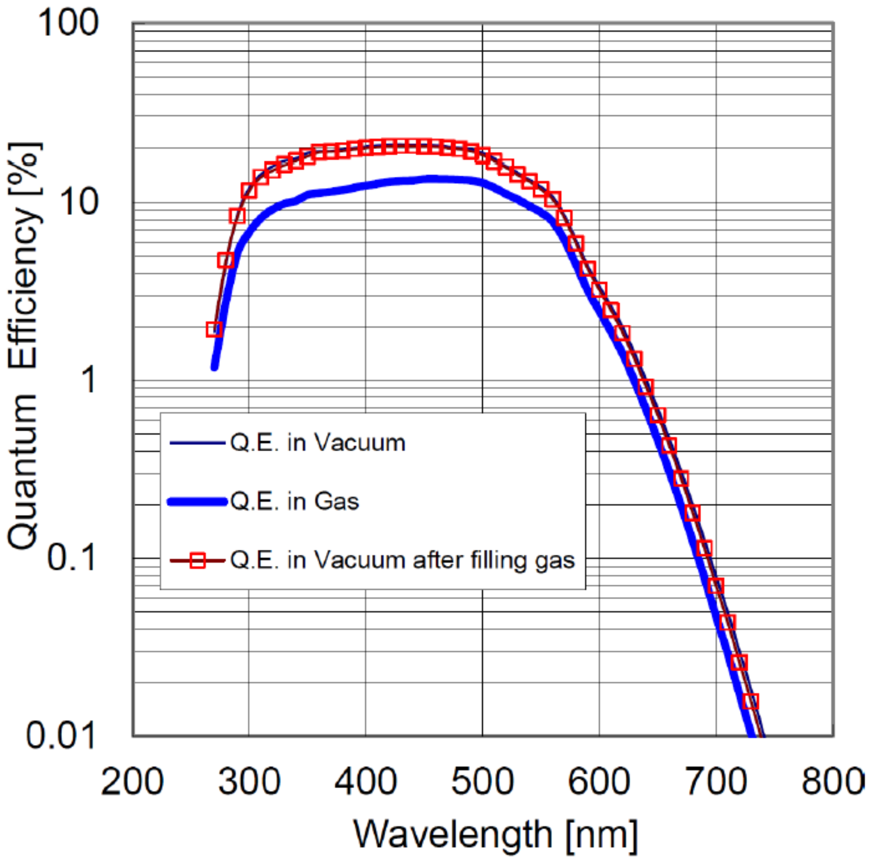
GAS MICRO-PATTERN PHOTON DETECTORS

VISIBLE

SEALED TUBE WITH MICROMEGAS MULTIPLIERS
GAIN ~ 10^3



Quantum Efficiency of Bi-alkali Photocathodes in Ar-CH_4 (90-10):

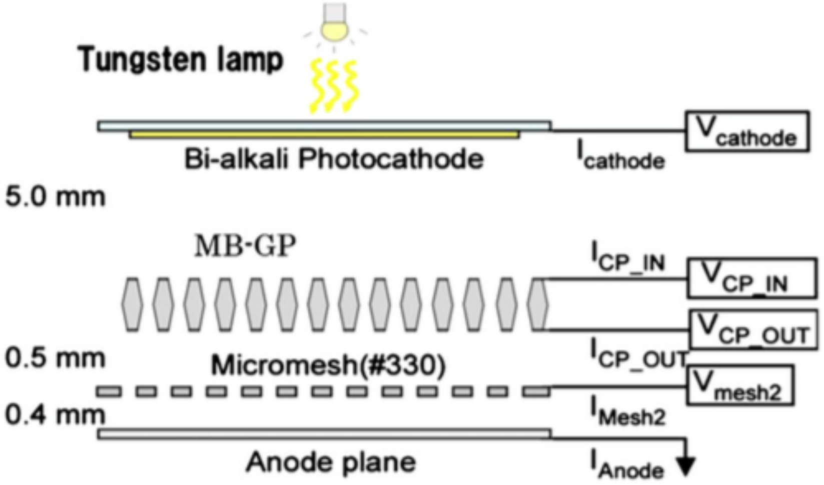


F. Tokanai et al, Nucl. Instr. and Meth. A610(2009)164

KAPTON- AND PYREX-GLASS BASED GEM DETECTORS

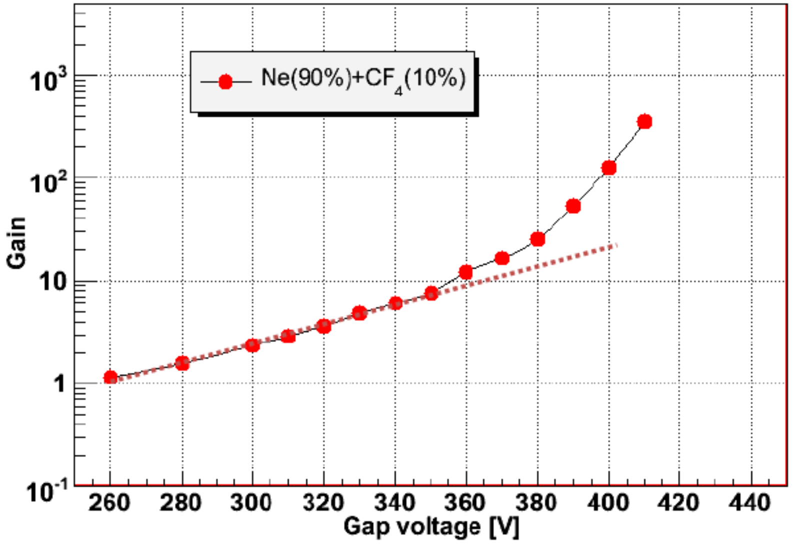
VISIBLE

Bialkali photocathodes
MB-GP: Micro-Blasting Pyrex GEM
Micromegas

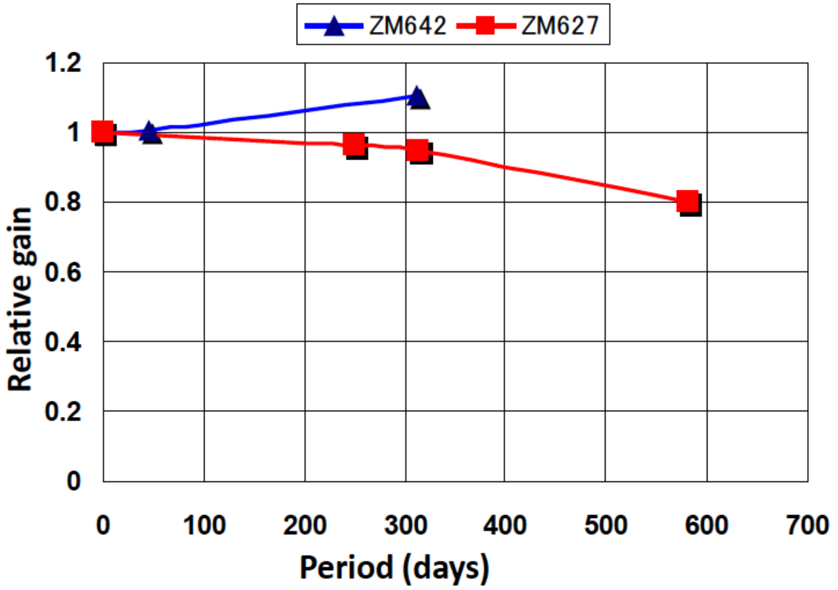


T. Sumiyoshi et al
Nucl. Instr. and Meth. A639(2011)121

GAIN VS VOLTAGE:

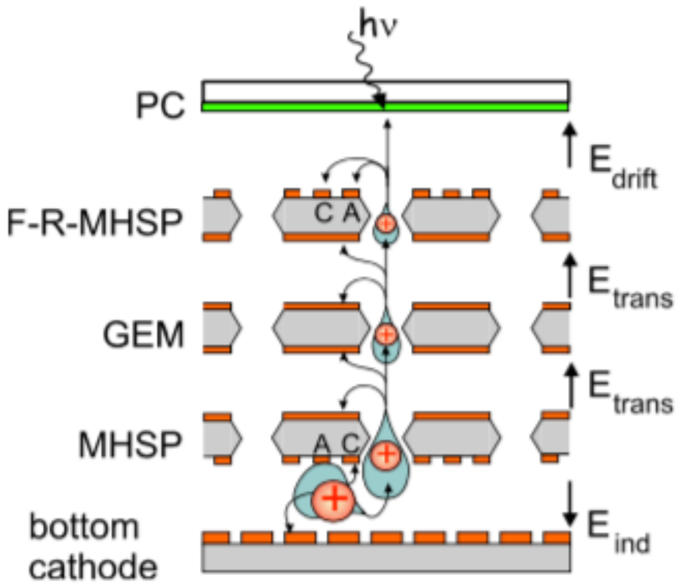


LONG-TERM STABILITY (Ar-CH$_4$ 90-10):



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

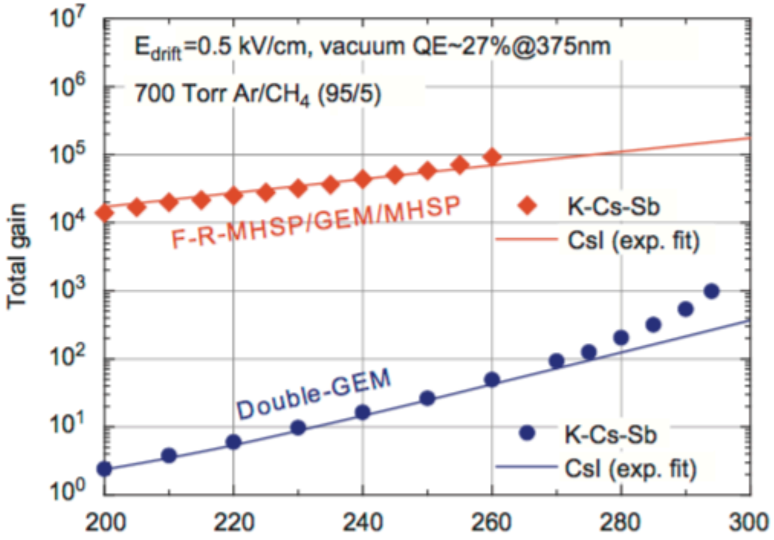
VISIBLE



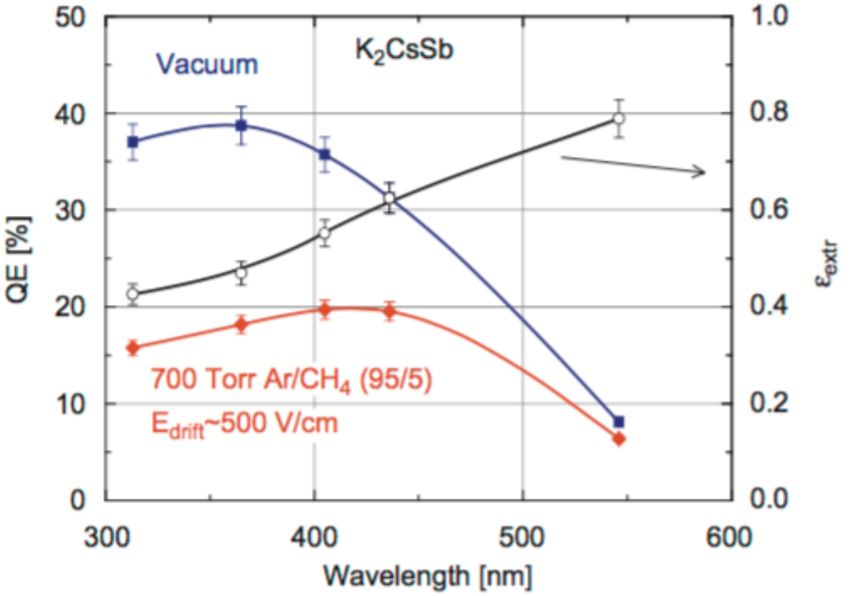
MHSP GEMs for ion backflow reduction

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

Gain:

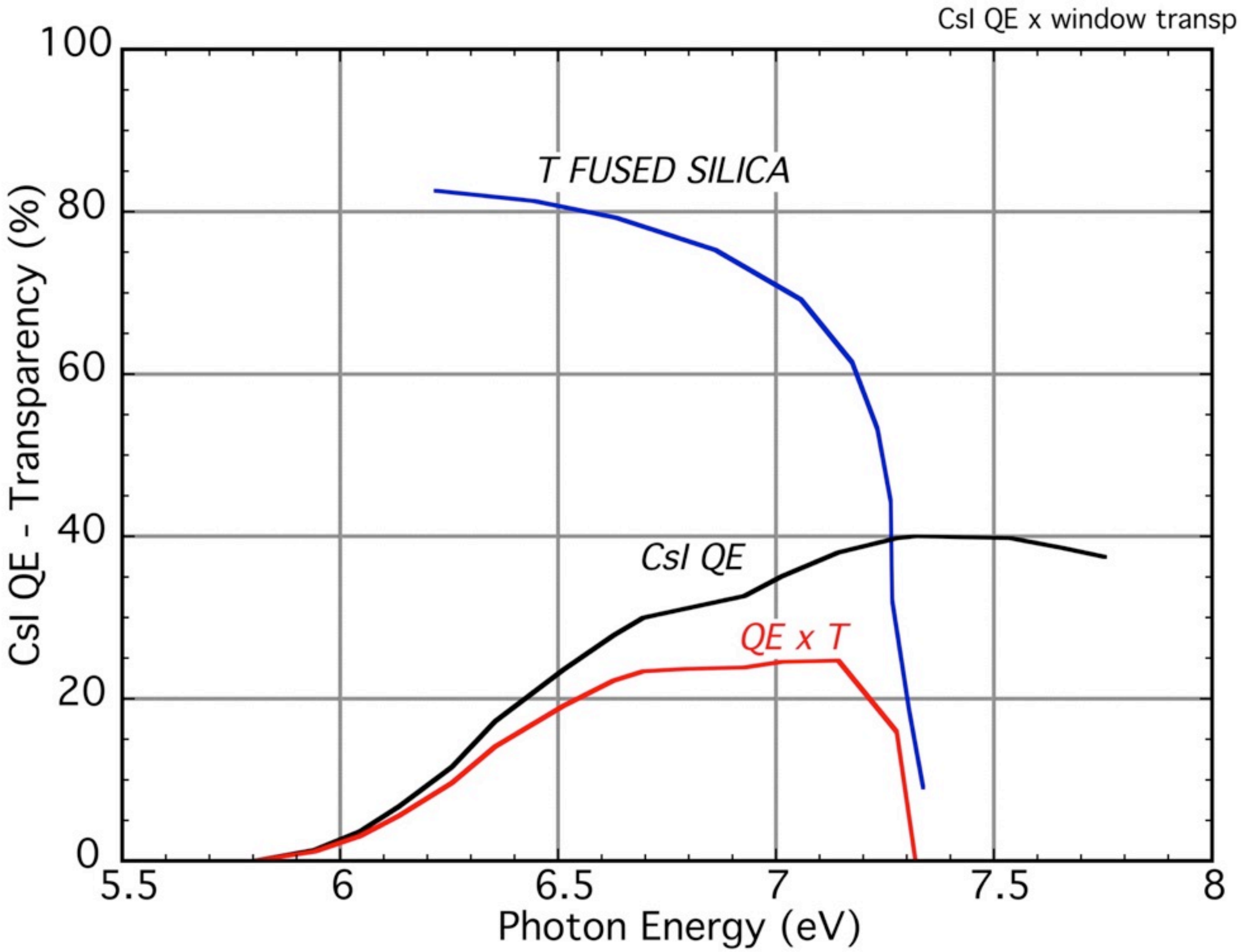


Quantum and Photoelectron extraction efficiency:



SENSITIVITY RANGE: FUSED SILICA WINDOW AND CsI PHOTOCATHODE

ULTRAVIOLET

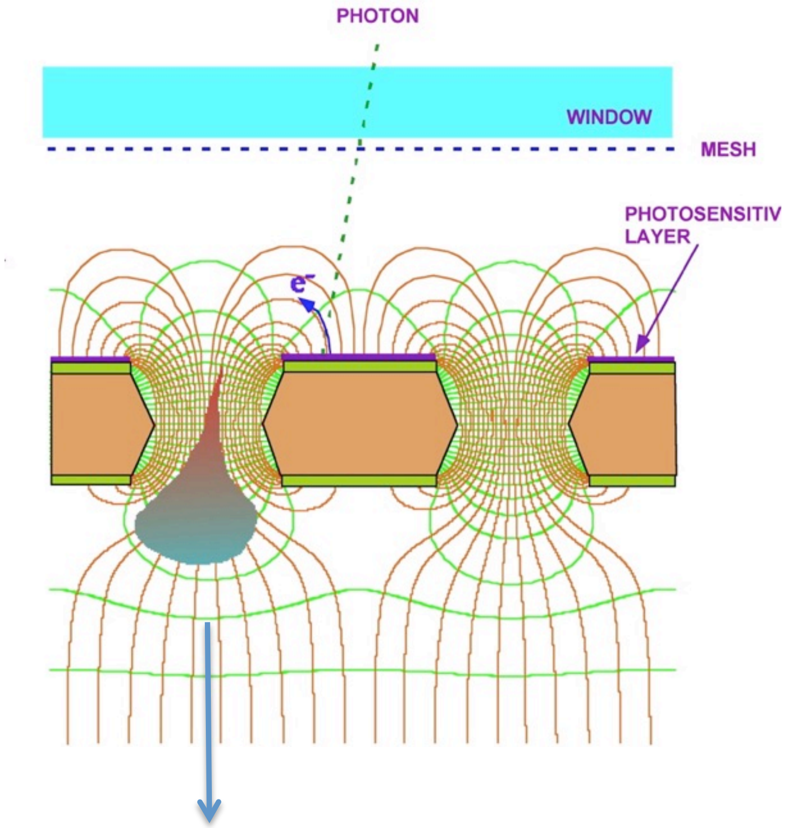


APPLICATIONS:

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

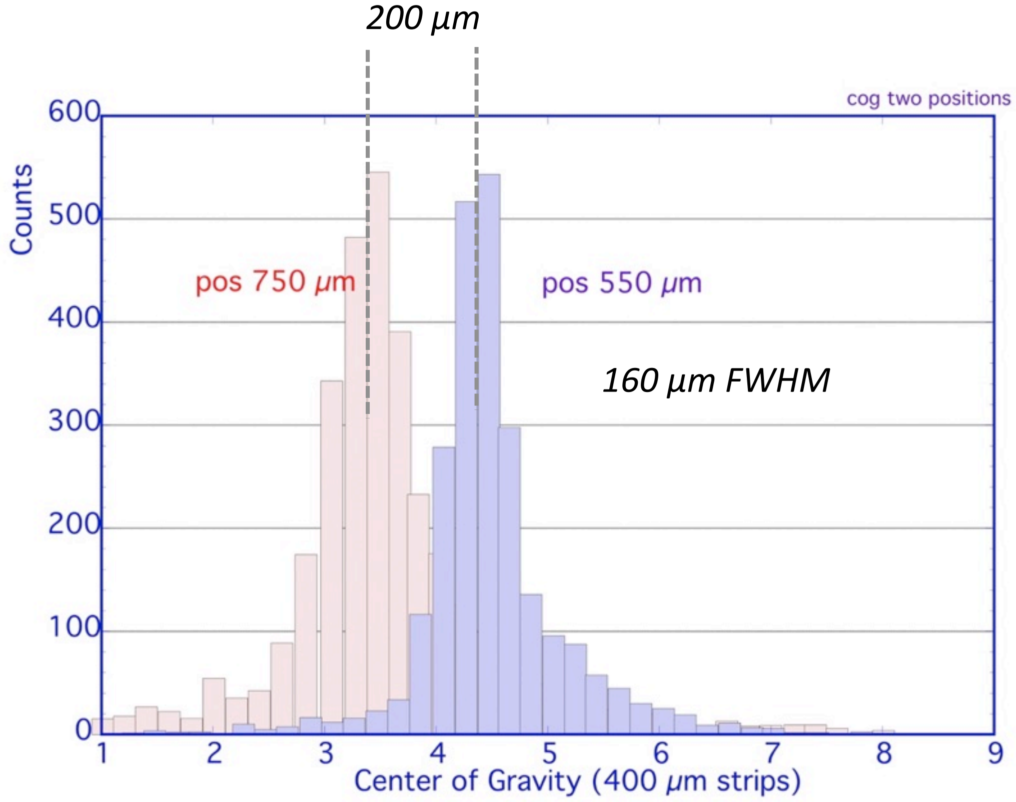
GEM WITH REFLECTIVE CsI PHOTOCATHODE

ULTRAVIOLET



Further amplification

POSITION ACCURACY WITH COLLIMATED PHOTON BEAMS

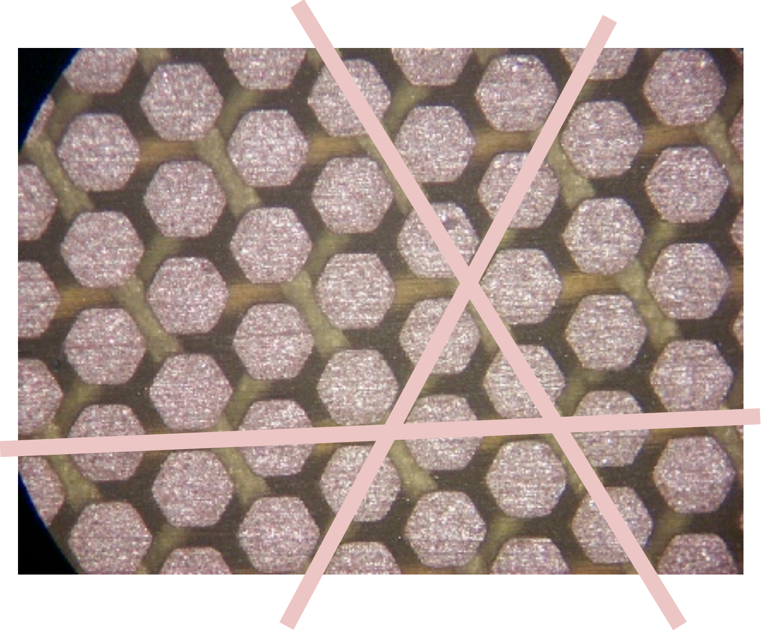


T. Meinshad et al, Nucl. Instr. and Meth. A535(2004)324

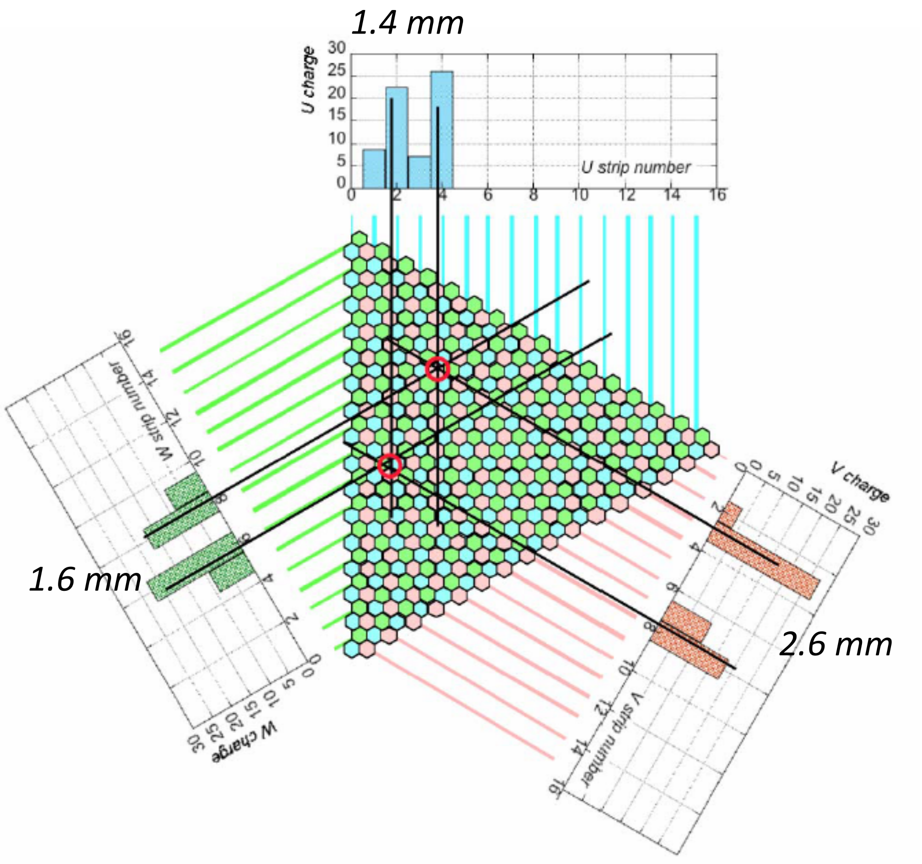
UV PHOTONS DETECTION AND LOCALIZATION

TRIPLE GEM WITH HEXABOARD READOUT

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



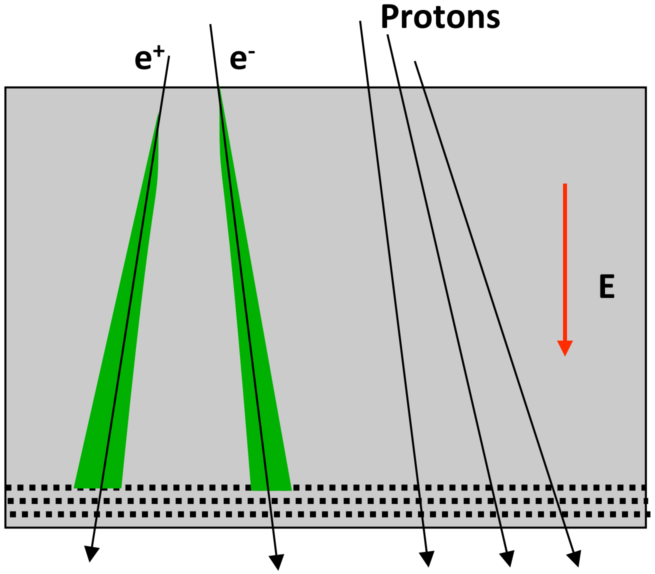
TWO-PHOTONS EVENT:

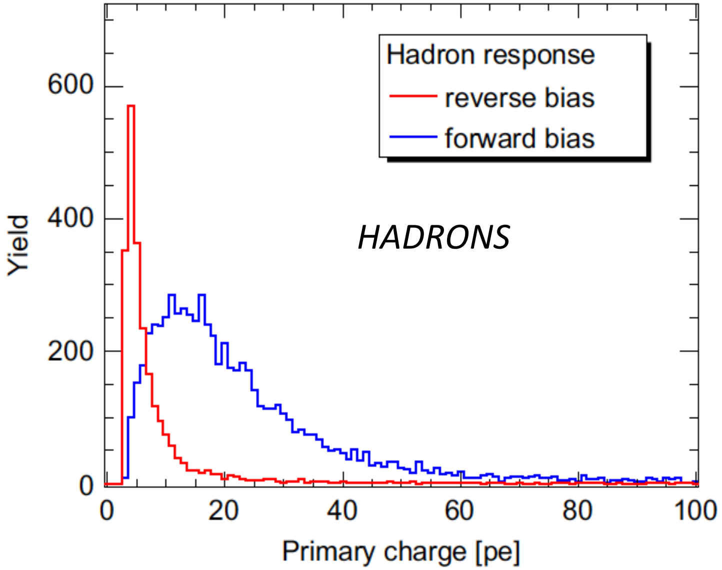


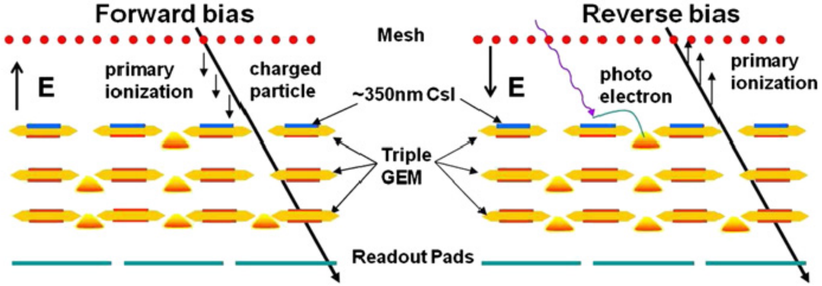
F. Sauli et al, IEEE NSSS 2004 Conf. Rec.Vol. 1, 12

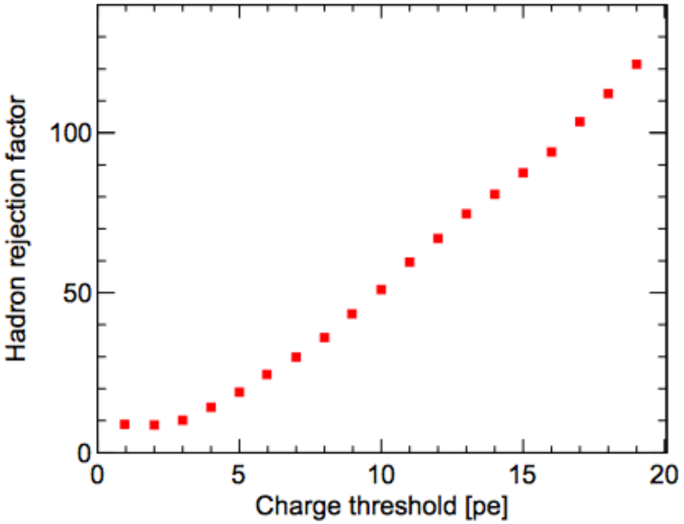
PHENIX HADRON BLIND DETECTOR

ULTRAVIOLET









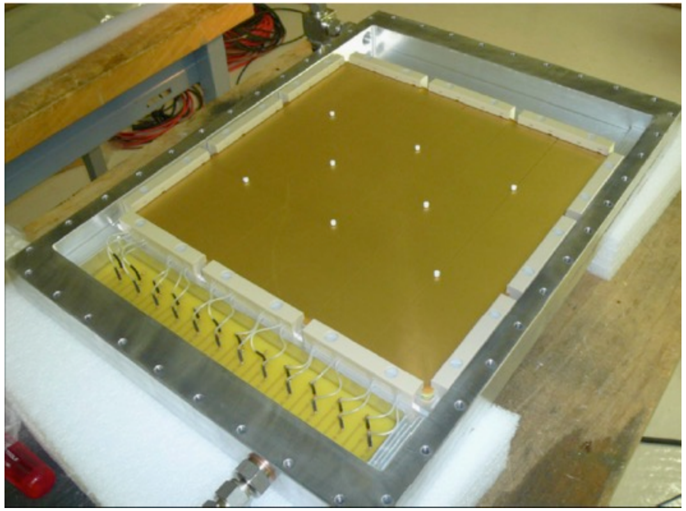
C. Aidala et al, Nucl. Instr. and Methods A502(2003)200

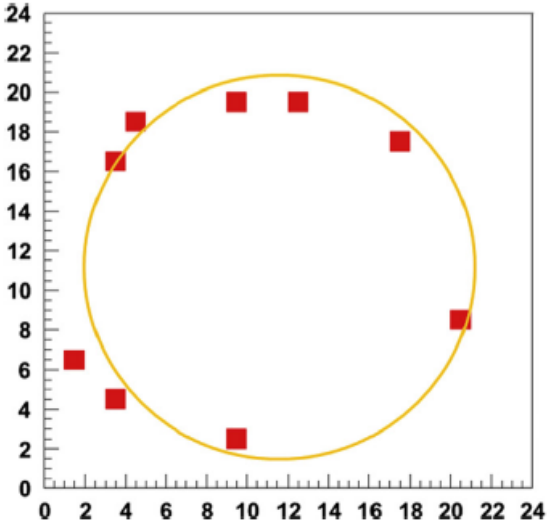
W. Anderson et al, Nucl. Instr. and Meth. A645(2011)35

CHERENKOV RING IMAGING (RICH)

ULTRAVIOLET

COMPASS RICH-1 UPGRADE
THICK GEM CsI-COATED 30x30 cm^2

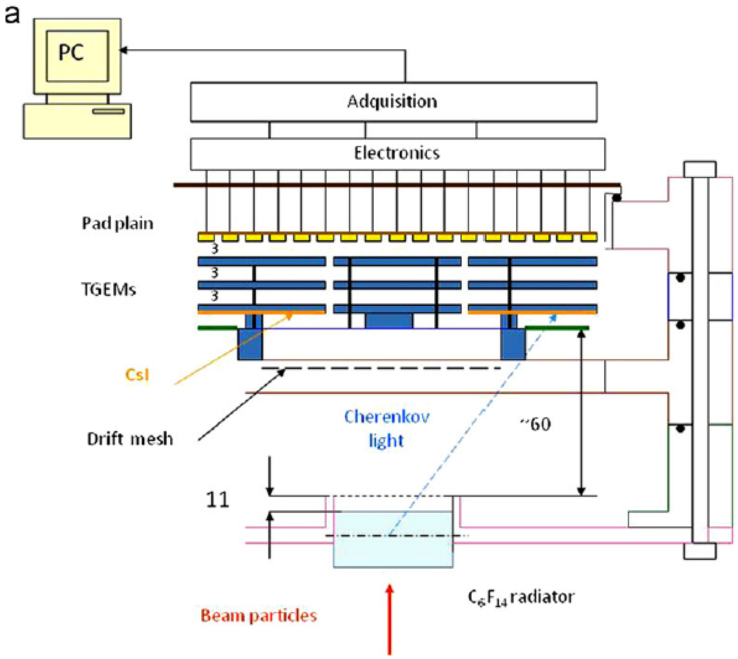




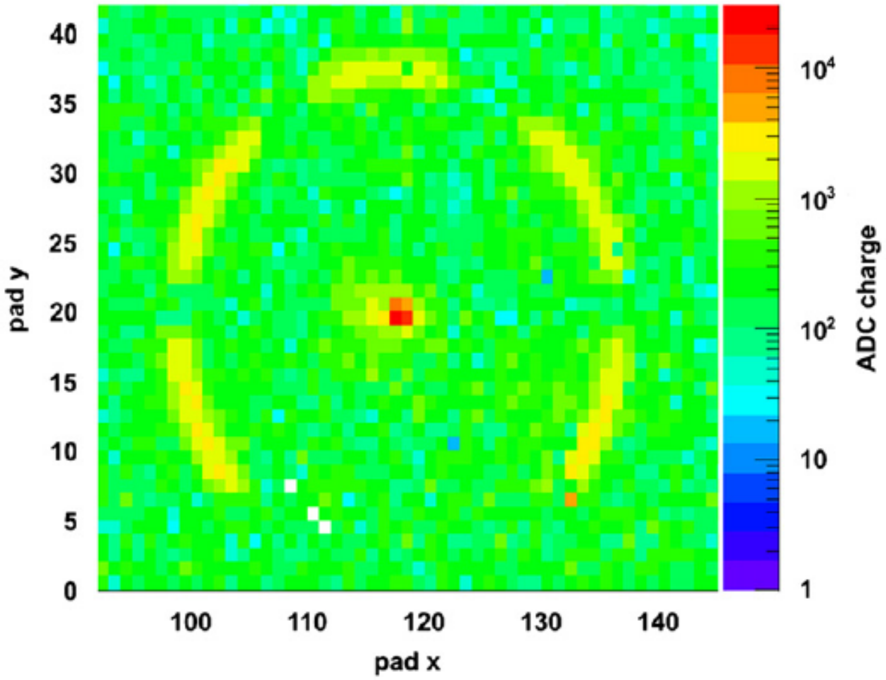
M. Alexeev et al, Nucl. Instr. and Meth. A732(2013)264

ALICE UPGRADE STUDIES

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



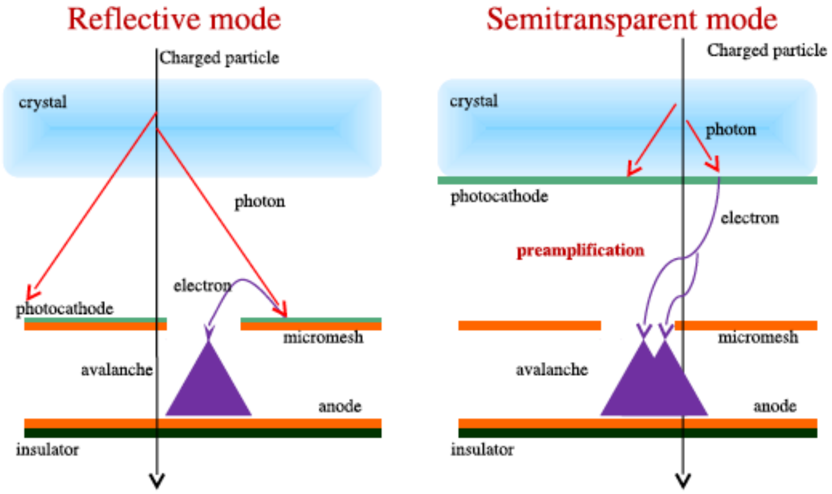
INTEGRATED CHERENKOV RING (6 GeV π):



V. Peskov et al, Nucl. Instr. and Meth. A695(20120154

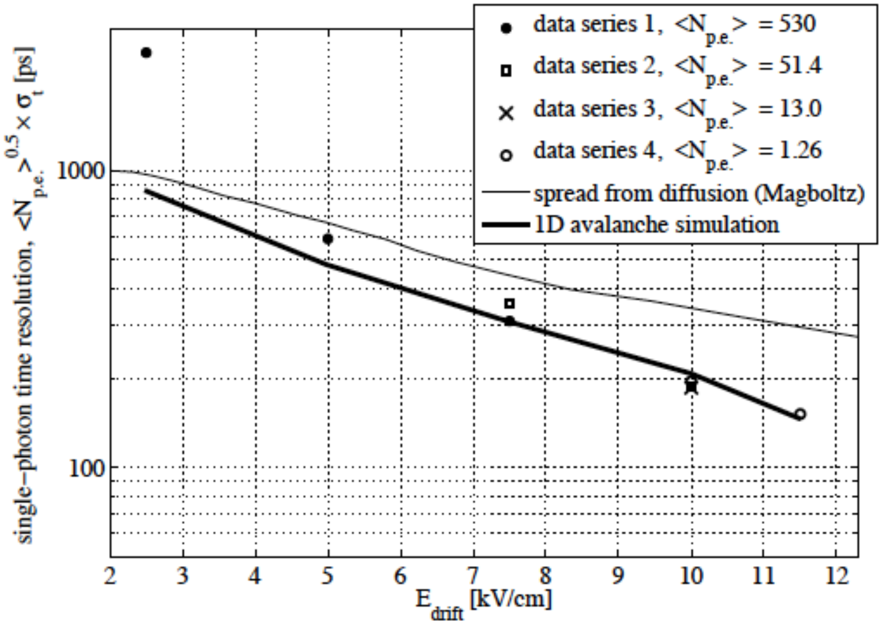
FAST TIMING WITH MPGDs

DETECTION OF CHERENKOV PHOTONS EMITTED IN A CRYSTAL RADIATOR



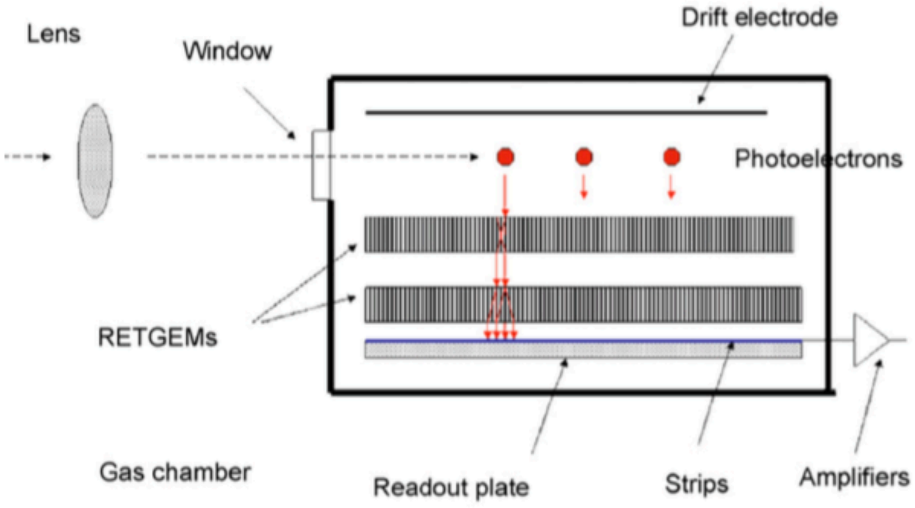
T. Papaevangelu et al, MPGD2015

SINGLE PHOTON TIME RESOLUTION:



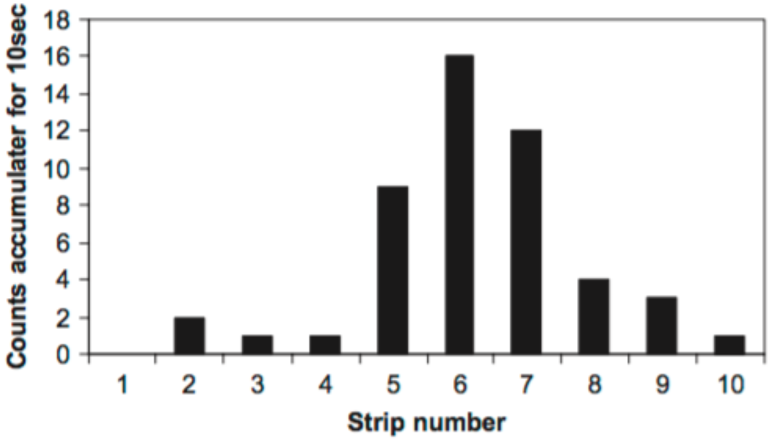
FLAME DETECTION (UV)

ULTRAVIOLET



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

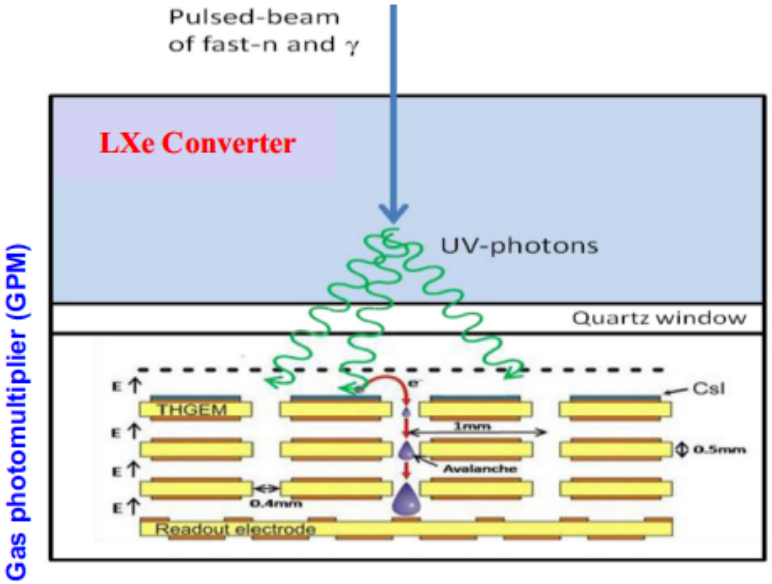
TRANSVERSE IMAGE OF ALCOHOL FLAME 70 m FROM THE DETECTOR IN AMBIENT LIGHT

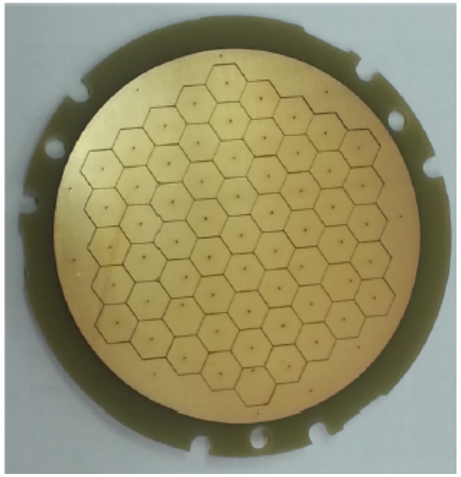


G. Charpak, et al., JINST 4 (2009) P12007.

LIQUID XENON GAS PHOTOMULTIPLIER

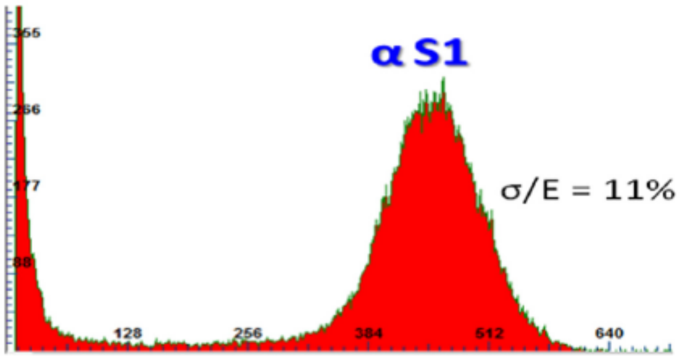
ULTRAVIOLET



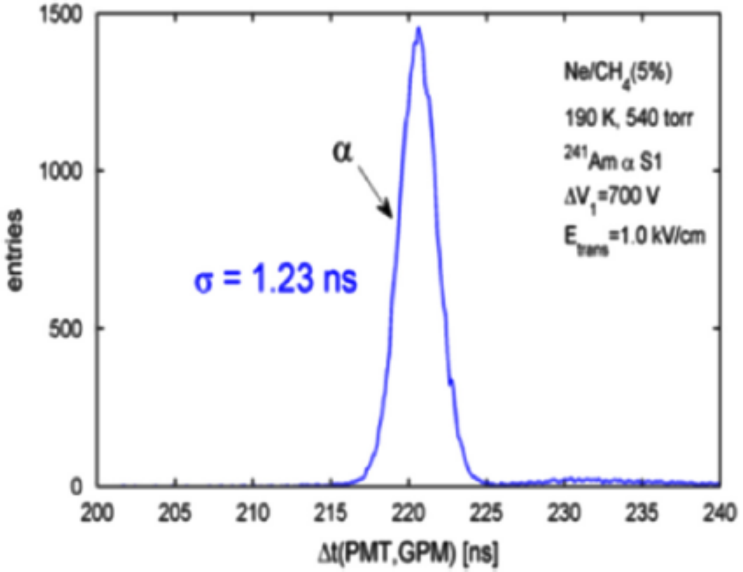


D. Vartski et al, Nucl. Instr. and Meth. in press (2016)

ENERGY RESOLUTION ON ^{241}Am α SOURCE:



TIME RESOLUTION ON ^{241}Am α SOURCE:

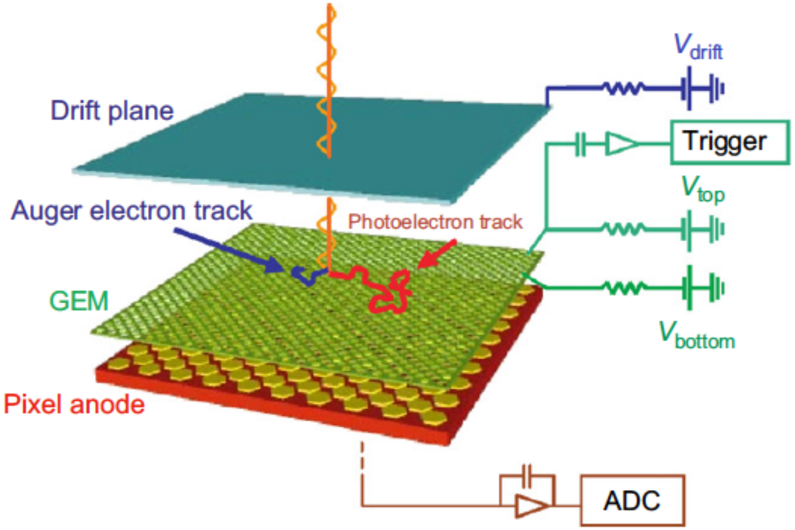


GEM WITH SILICON PIXEL READOUT

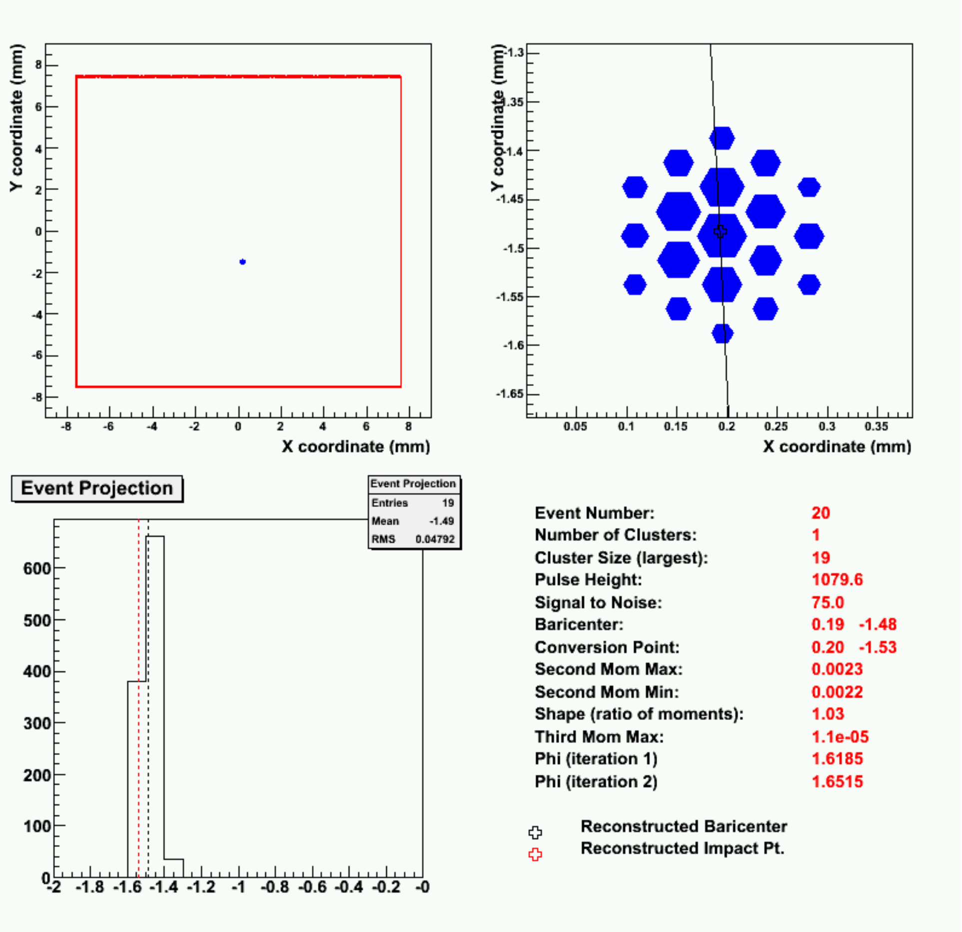
ULTRAVIOLET

X-RAY POLARIMETER

SINGLE PHOTOELECTRONS IMAGING



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



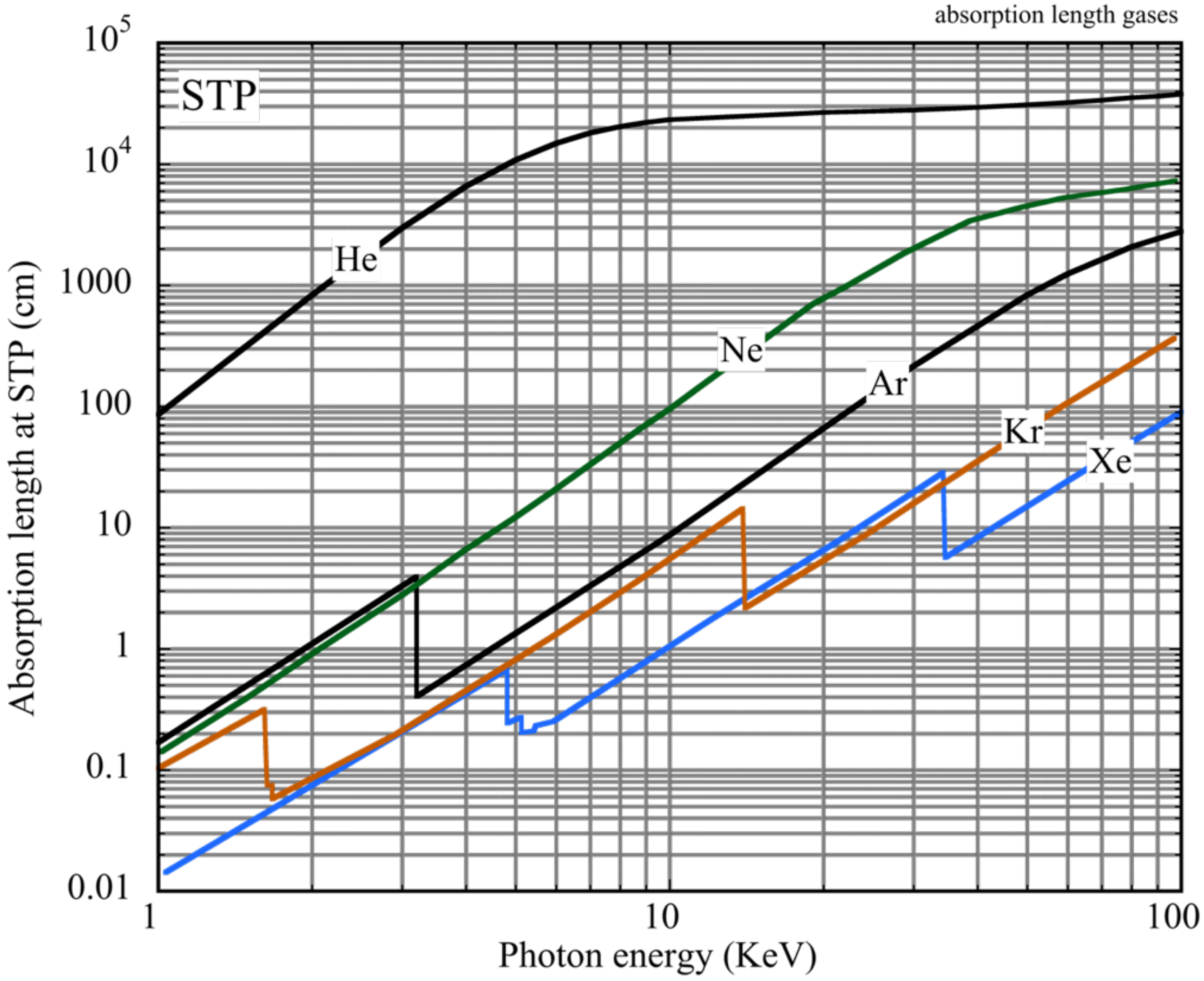
```
Event Number:                  20
Number of Clusters:            1
Cluster Size (largest):        19
Pulse Height:                  1079.6
Signal to Noise:               75.0
Baricenter:                    0.19   -1.48
Conversion Point:              0.20   -1.53
Second Mom Max:                0.0023
Second Mom Min:                0.0022
Shape (ratio of moments):      1.03
Third Mom Max:                 1.1e-05
Phi (iteration 1)              1.6185
Phi (iteration 2)              1.6515

✣      Reconstructed Baricenter
✣      Reconstructed Impact Pt.
```

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

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

SOFT X-RAYS

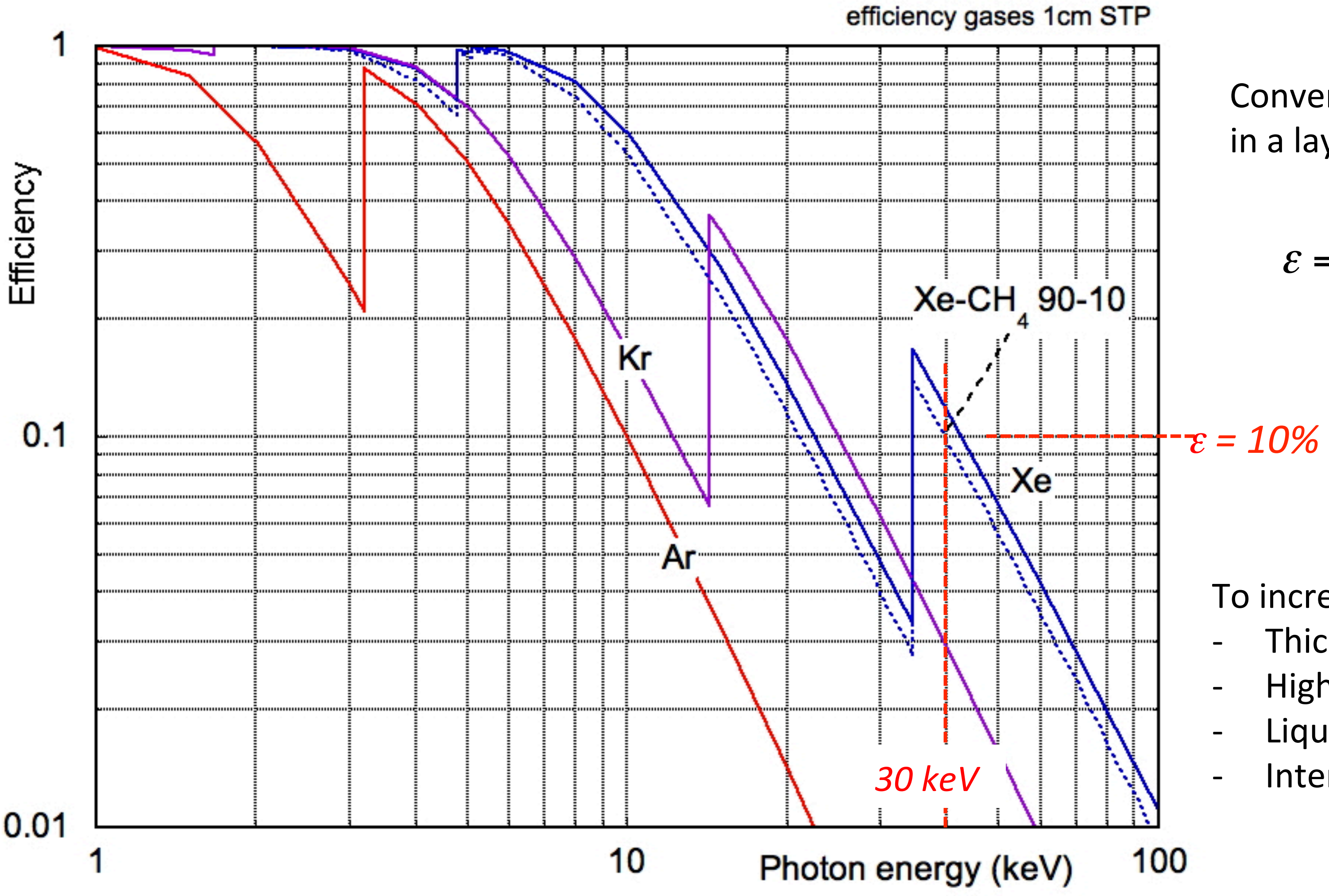


ABSORPTION LENGTH(STP):

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

(MAXIMUM) DETECTION EFFICIENCY, 1 cm GAS AT STP

SOFT X-RAYS



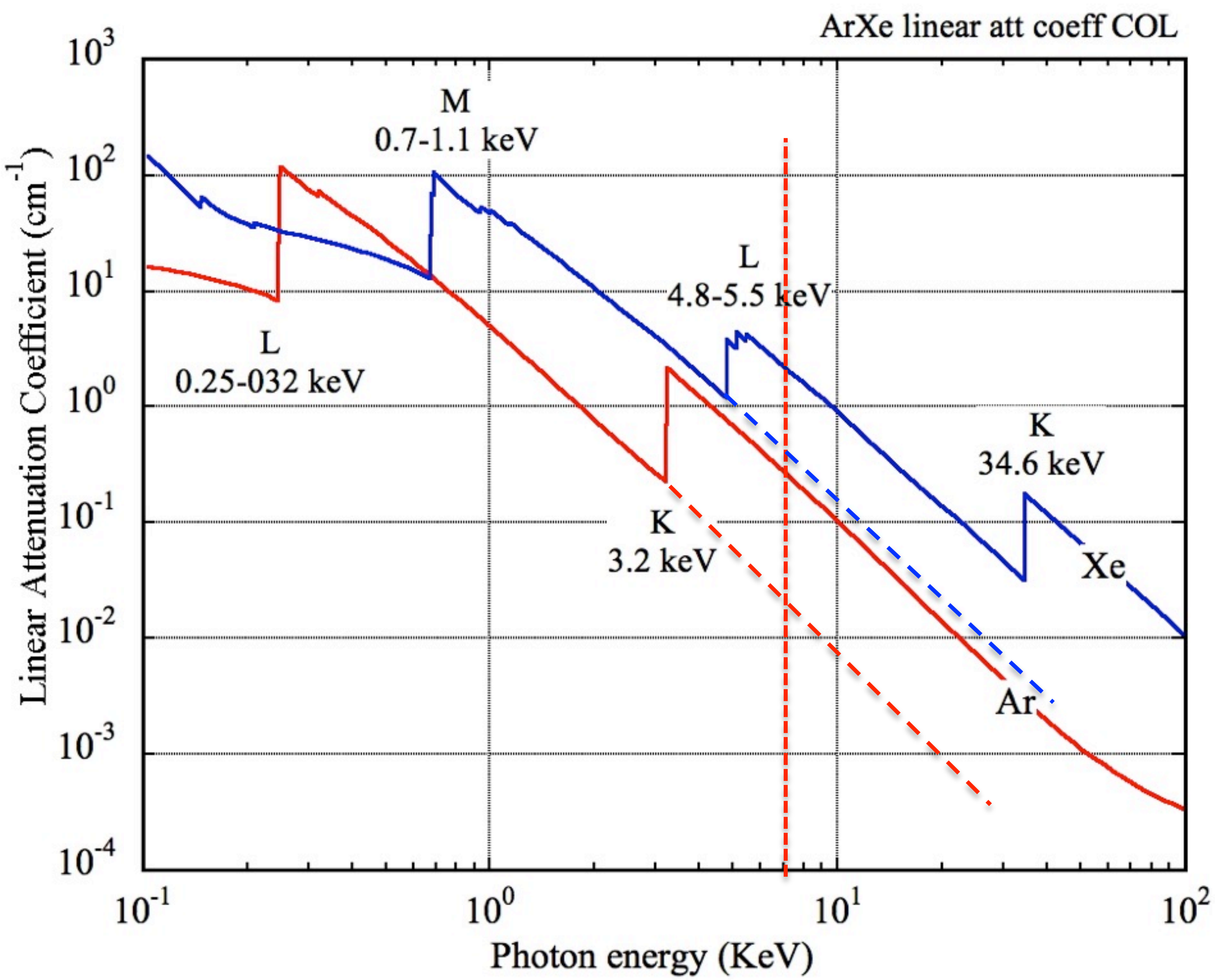
Conversion efficiency in a layer x:

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

To increase efficiency:
- Thicker layers
- Higher pressures
- Liquid noble gas
- Internal converters

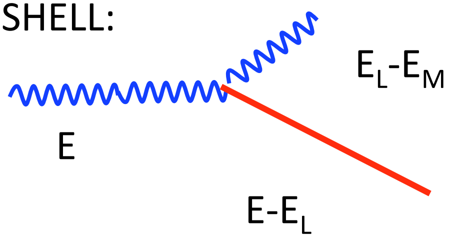
SOFT X-RAYS: PHOTOELECTRIC EFFECT

LINEAR ATTENUATION COEFFICIENT (STP):

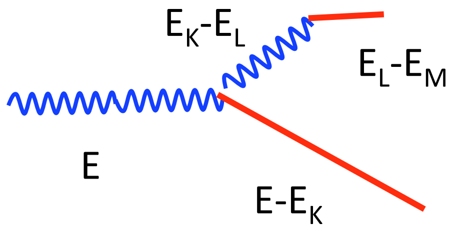


PROCESSES FOR ARGON:

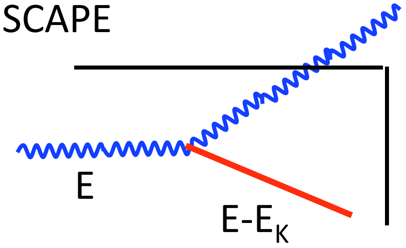
L-SHELL:



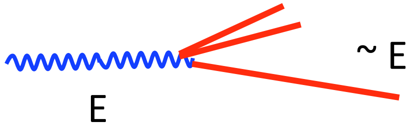
K SHELL FLUORESCENCE:



ESCAPE

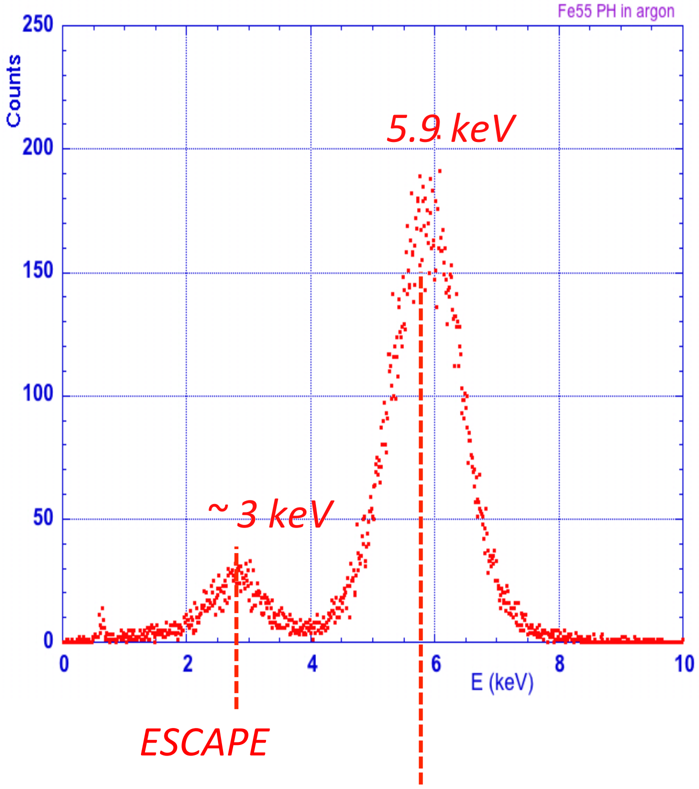


NON-RADIATIVE (AUGER)



SOFT X-RAYS: FLUORESCENCE YIELD AND ESCAPE PEAKS

5.9 keV ^{55}Fe SOURCE IN ARGON:



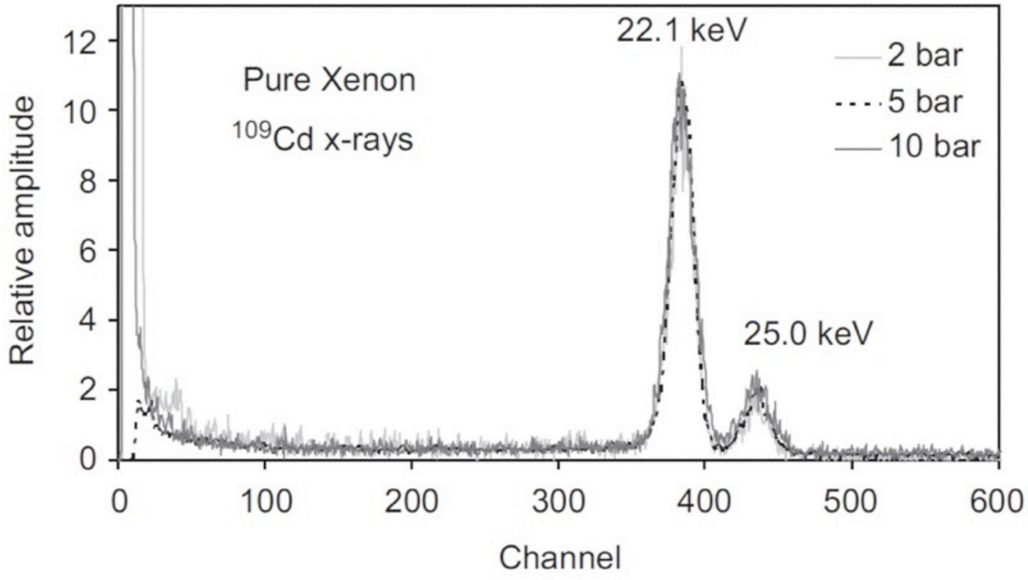
5.9 keV

~ 3 keV

ESCAPE

TOTAL ENERGY:
L+K, AUGER

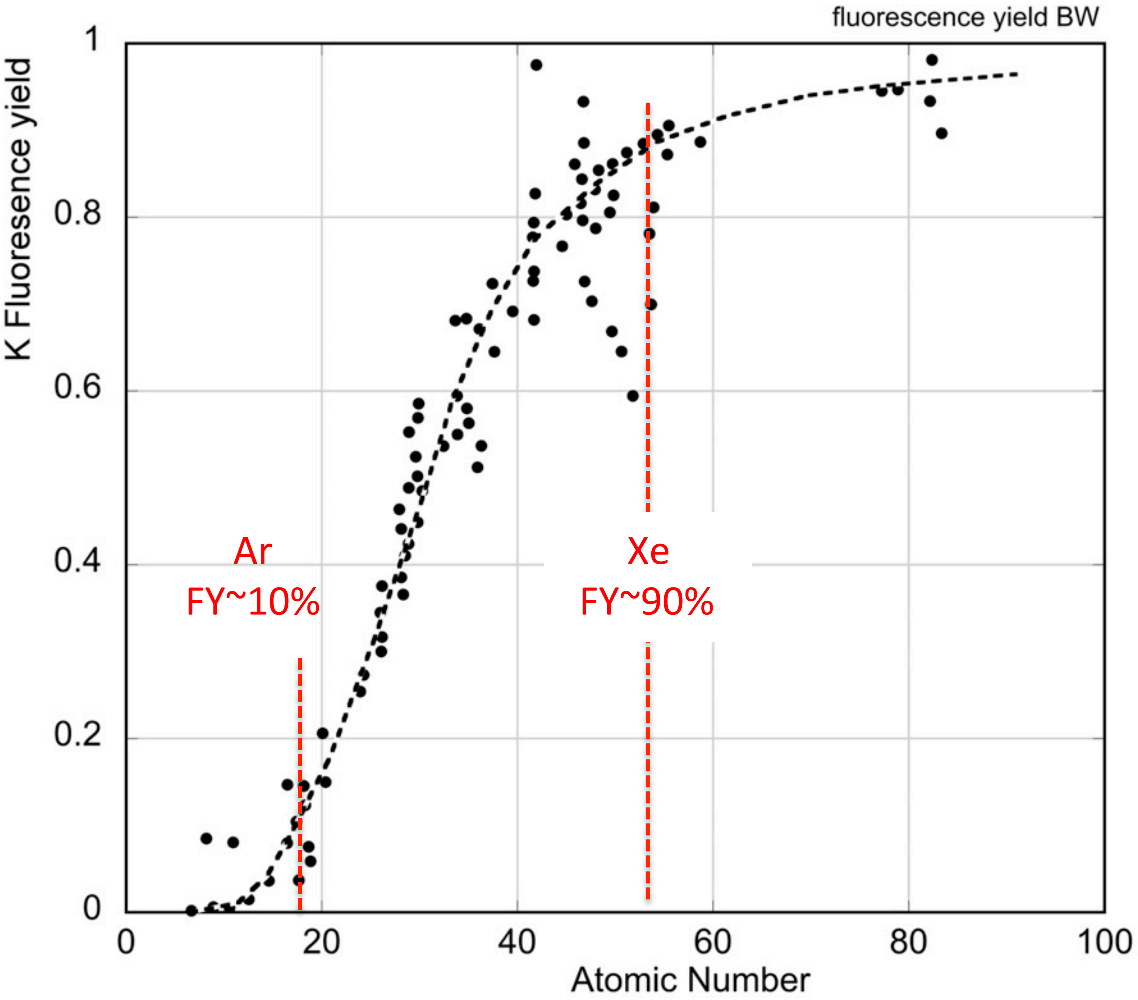
22-25 keV ^{109}Cd SOURCE IN XENON:



FLUORESCENCE YIELD

SOFT X-RAYS

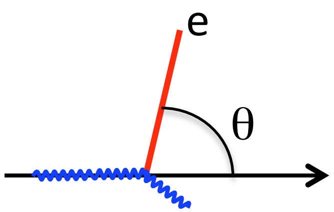
FY = Probability of Fluorescence / Total



ANGULAR DISTRIBUTION AND RANGE OF PHOTOELECTRONS

SOFT X-RAYS

PHOTOELECTRON
EMISSION ANGLE:



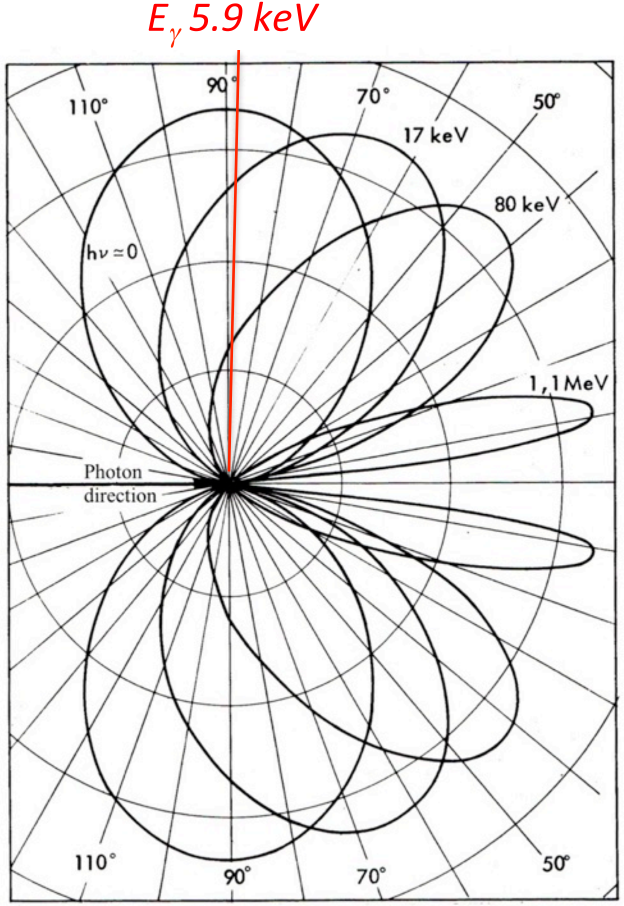
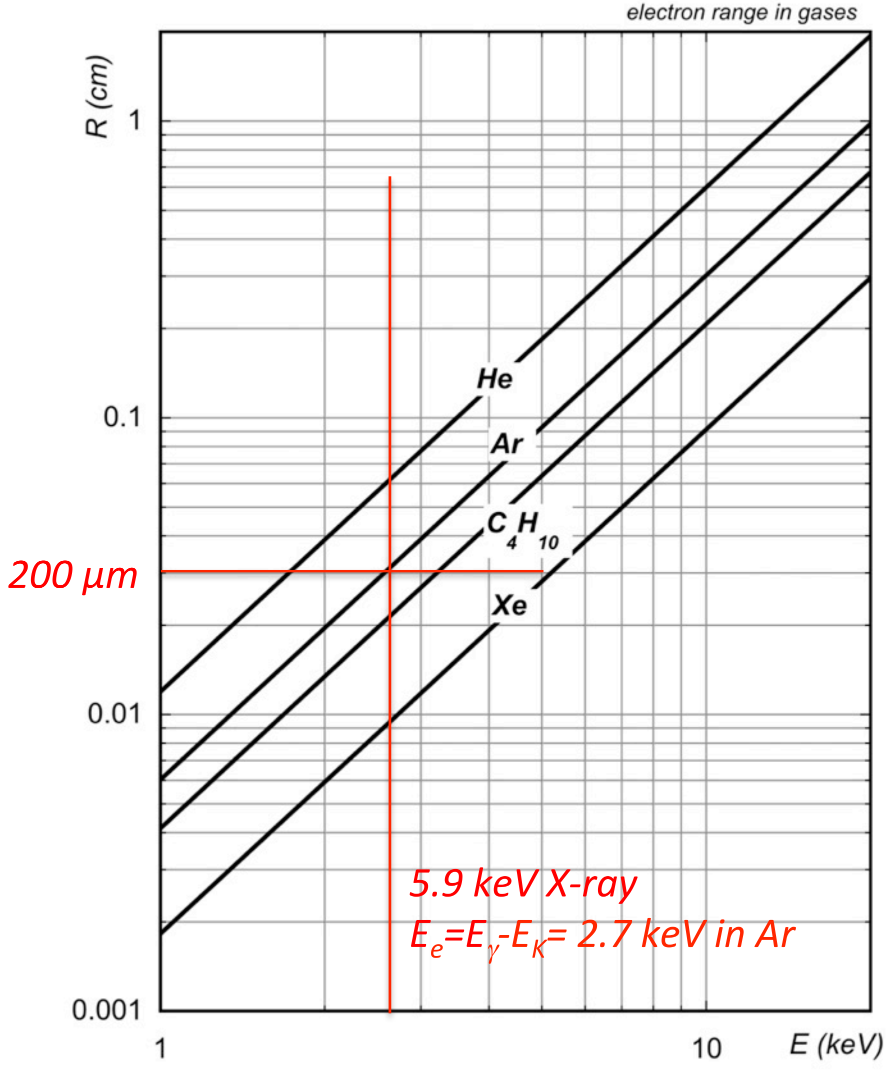


Figura 9.2. Distribuzione angolare dei fotoelettroni; le cur-

ELECTRON RANGE:



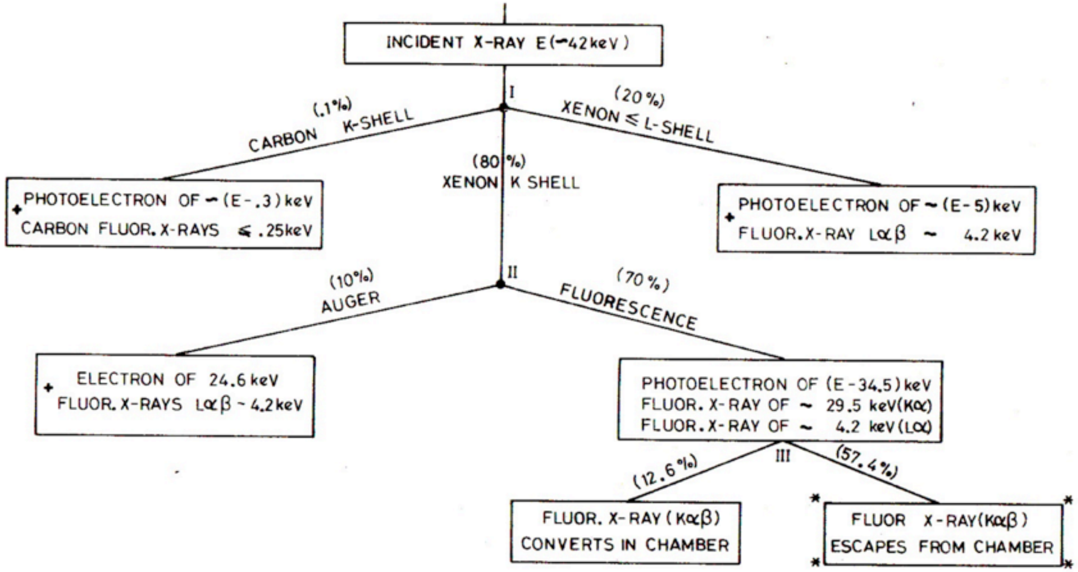
5.9 keV X-ray

$E_e = E_\gamma - E_K = 2.7$ keV in Ar

COMPUTED POSITION RESOLUTION LIMITS

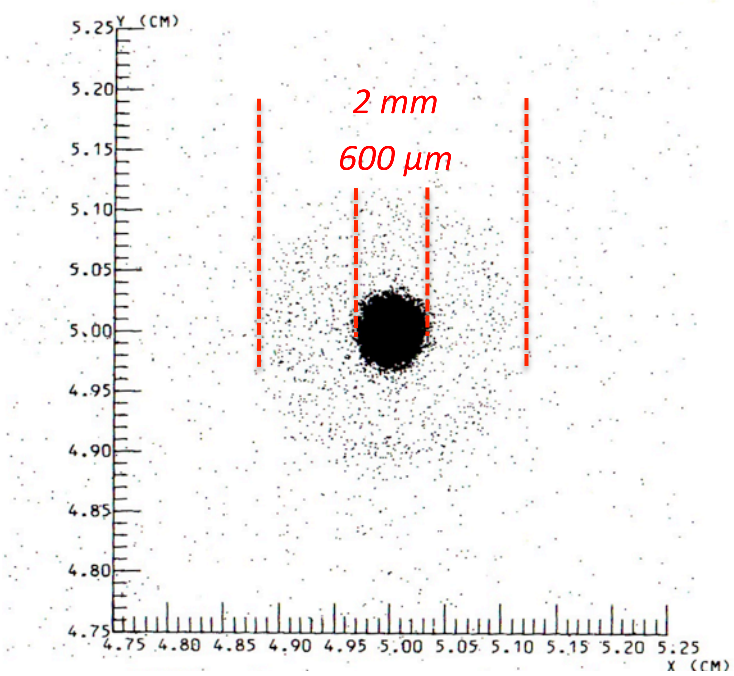
SOFT X-RAYS

42 keV PHOTONS ON XENON



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

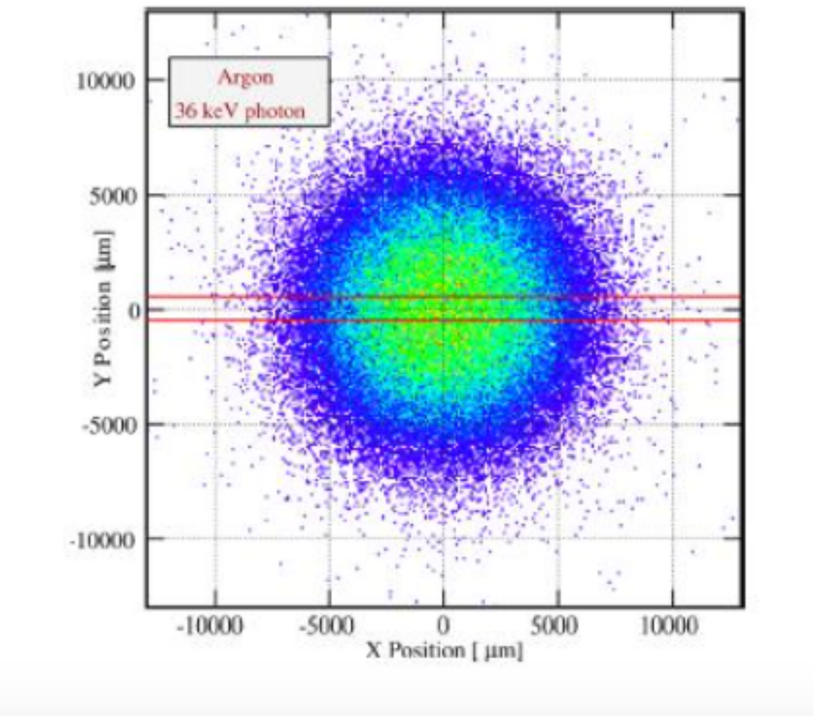
POSITION RESOLUTION FOR A POINT-LIKE COLLIMATED BEAM:

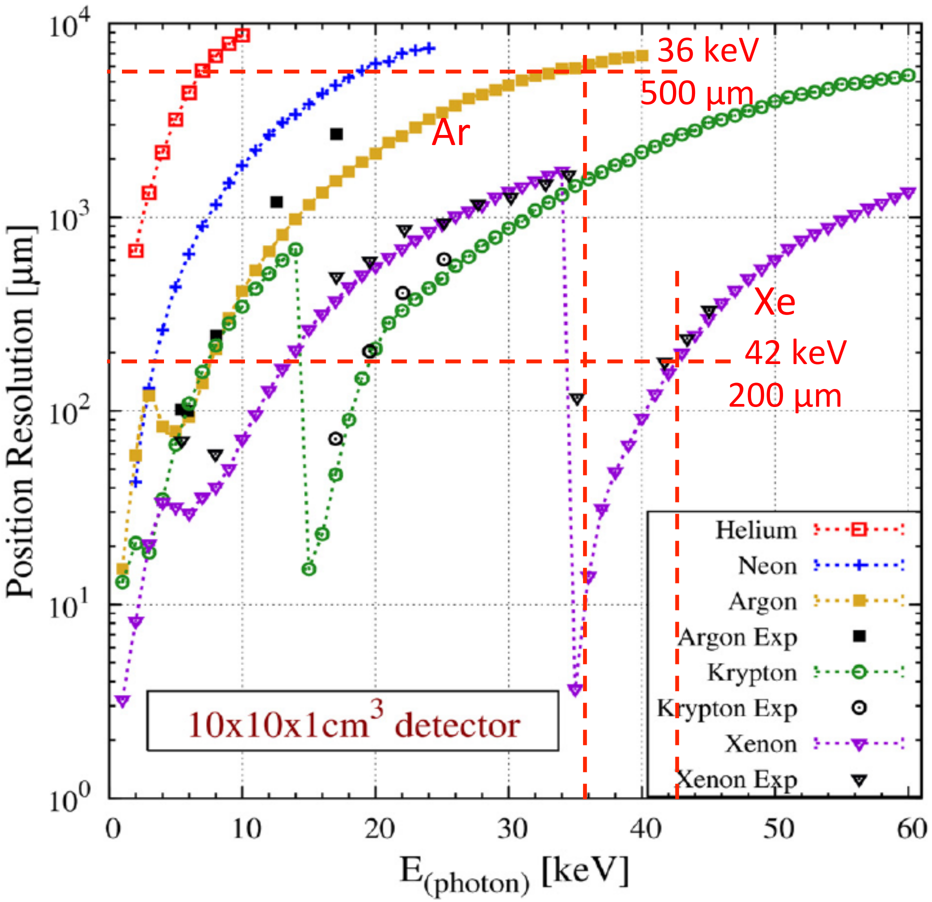


COMPUTED POSITION RESOLUTION LIMITS

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

36 keV in Ar:



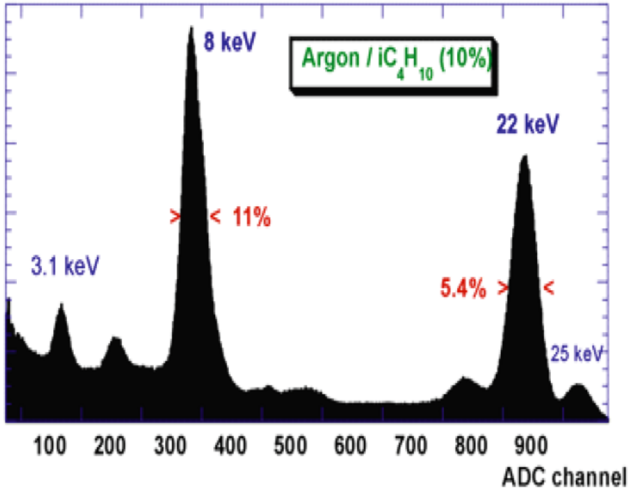


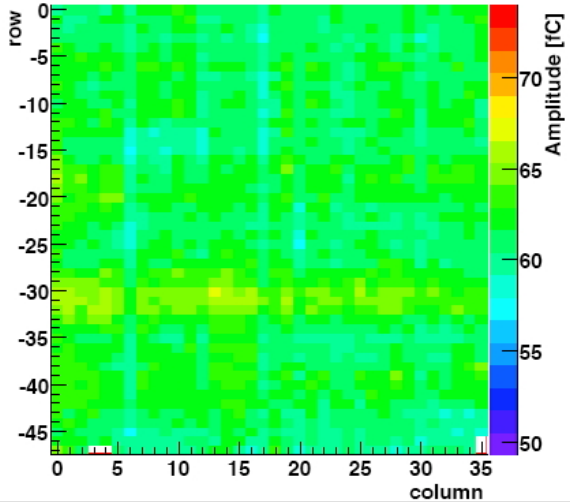
C. Azevedo et al., Phys. Lett. B 741(2015)272

SOFT X-RAY DETECTION WITH MICROMEGAS

SOFT X-RAYS

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

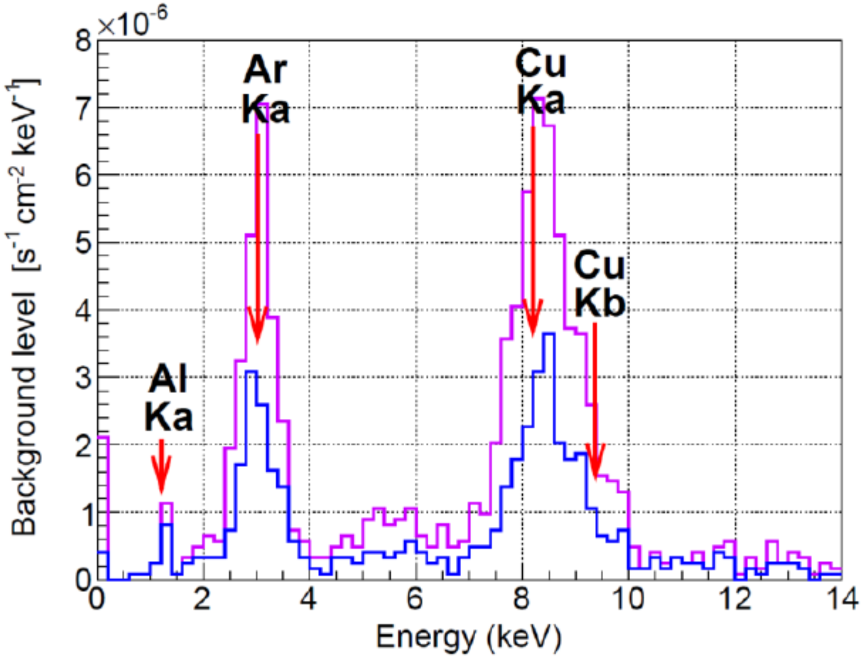




N. Abragall et al, Nucl. Instr. and Meth. A637(2011)25

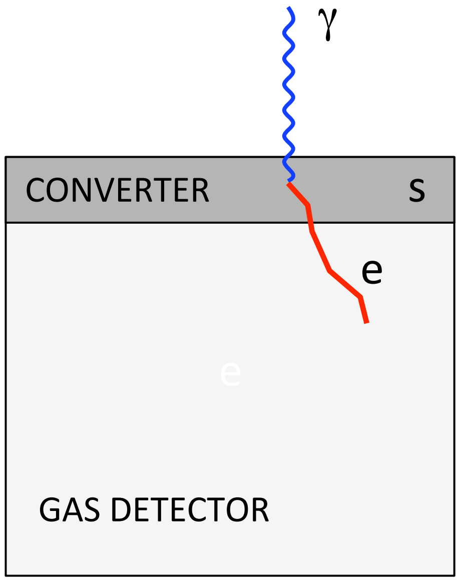
DARK MATTER SEARCH
CERN AXION SOLAR TELESCOPE (CAST)

X-RAYS BACKGROUND SPECTRUM:



J. C. Garza et al, MPGD2015

HARD X-RAYS AND GAMMA RAYS: INTERNAL CONVERTERS

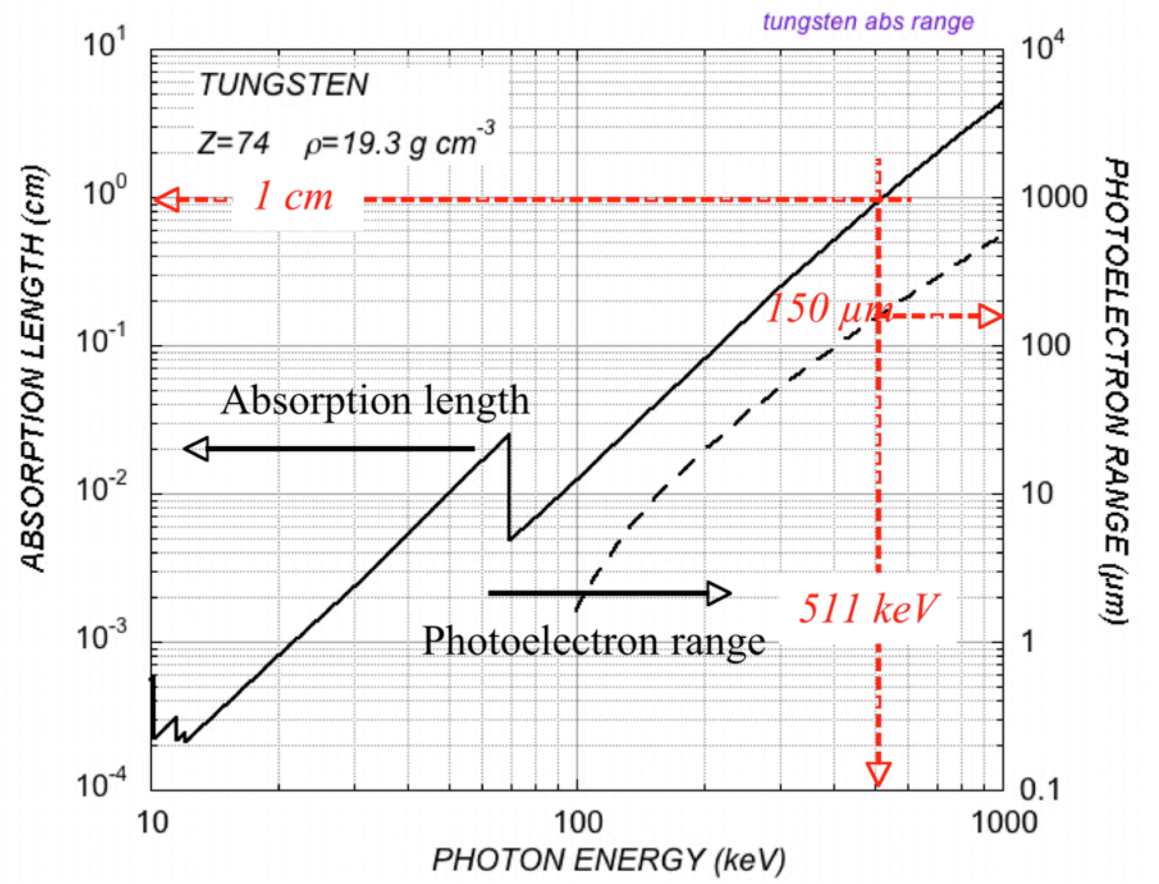


DETECTION EFFICIENCY:

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

s: converter thickness
λ: absorption length
P_{ej}: photoelectron ejection probability

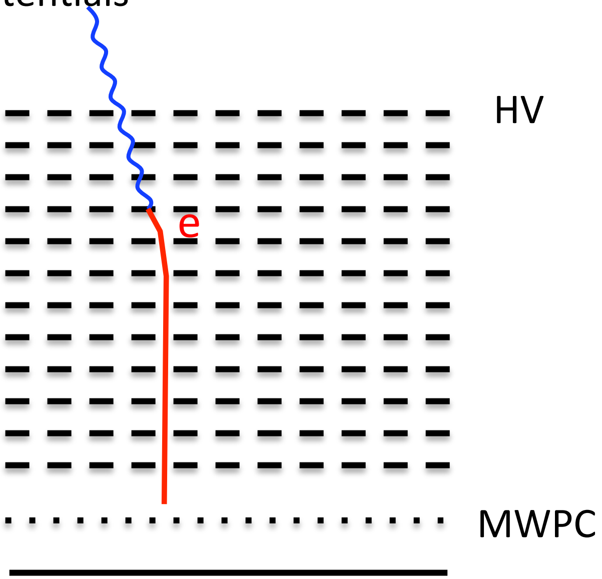
USEFUL CONVERTER THICKNESS AND ELECTRON RANGE



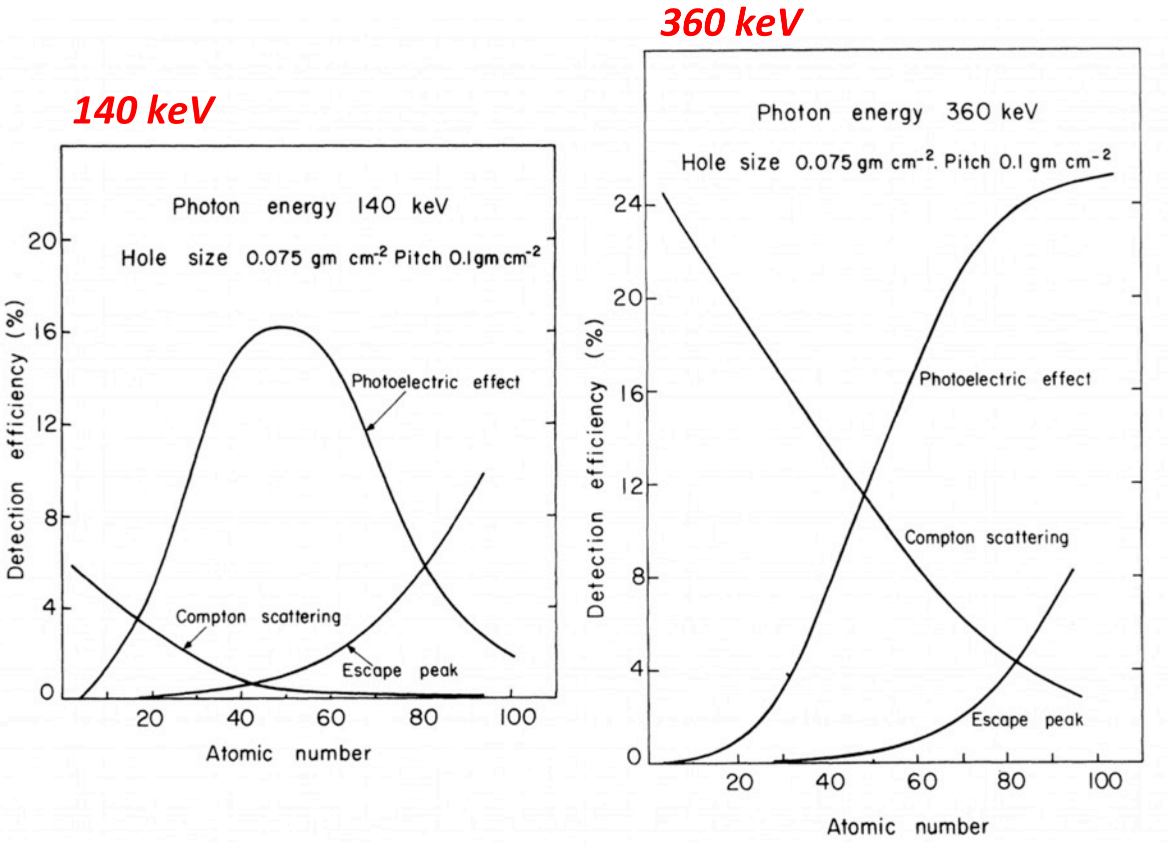
100 µm converter --> $\varepsilon \sim 1\%$

MULTI-CONVERTERS

HEAVY DRIFT CHAMBER
Stack of converter Grids at graded potentials



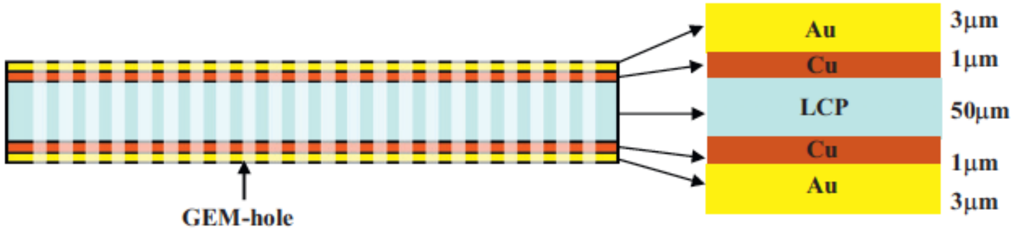
EFFICIENCY vs CONVERTER ATOMIC NUMBER:



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

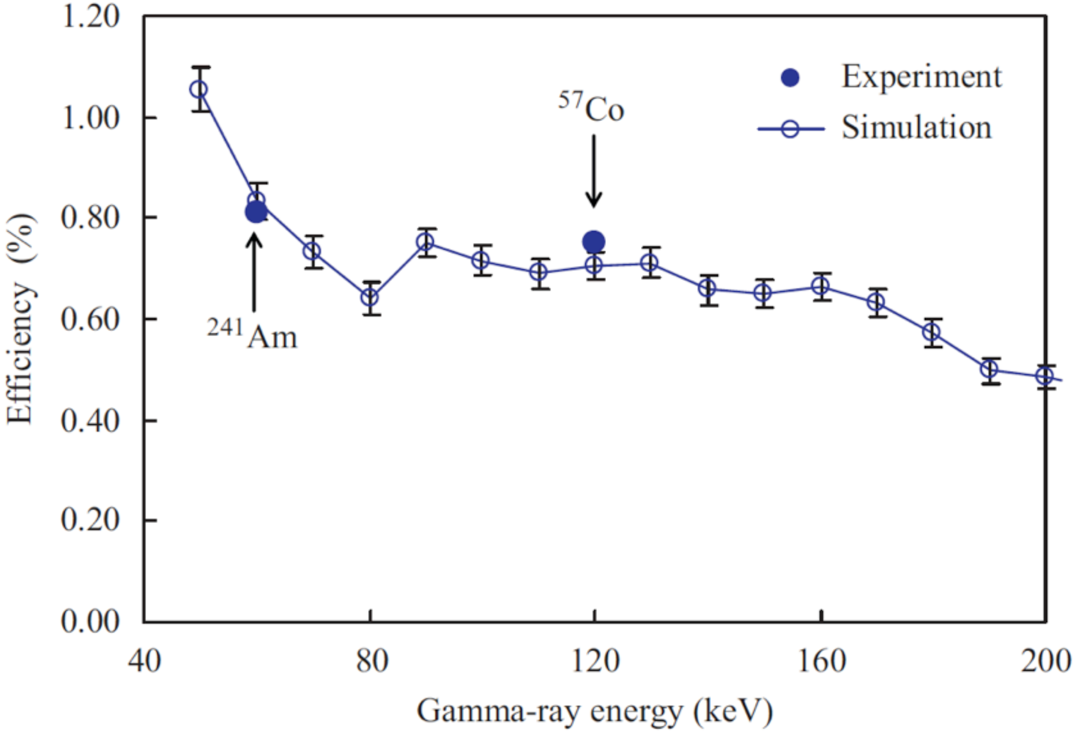
GOLD-COATED GAS ELECTRON MULTIPLIER (GEM)

HARD X-RAYS

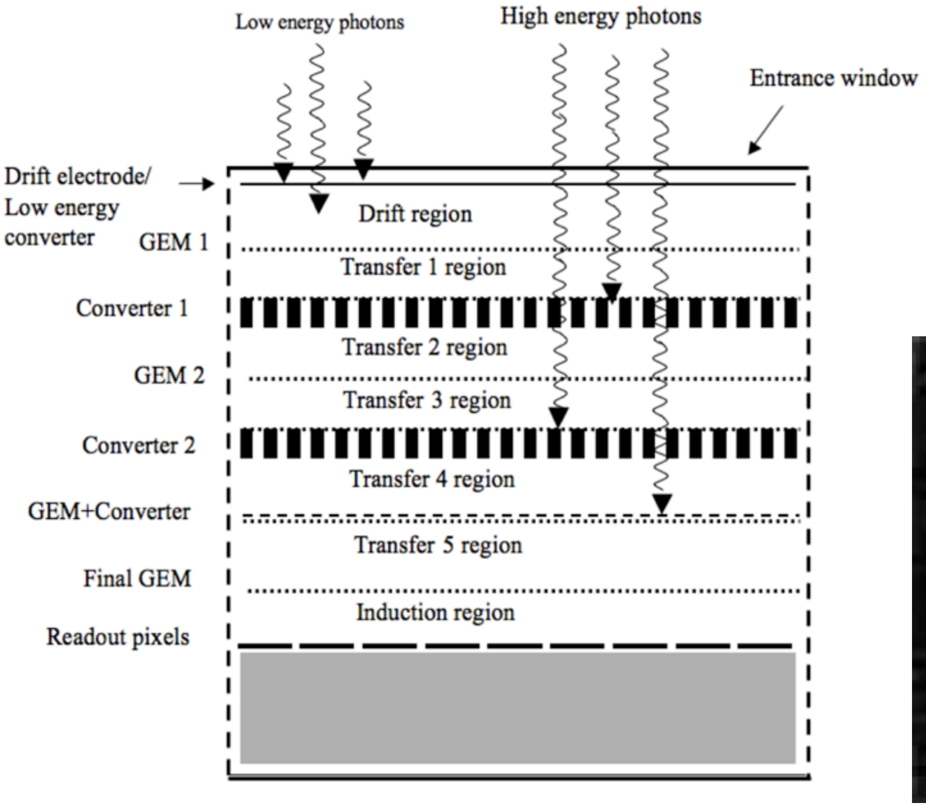


T. Koike et al,
Nucl. Instr. and Meth. A648(2011)180

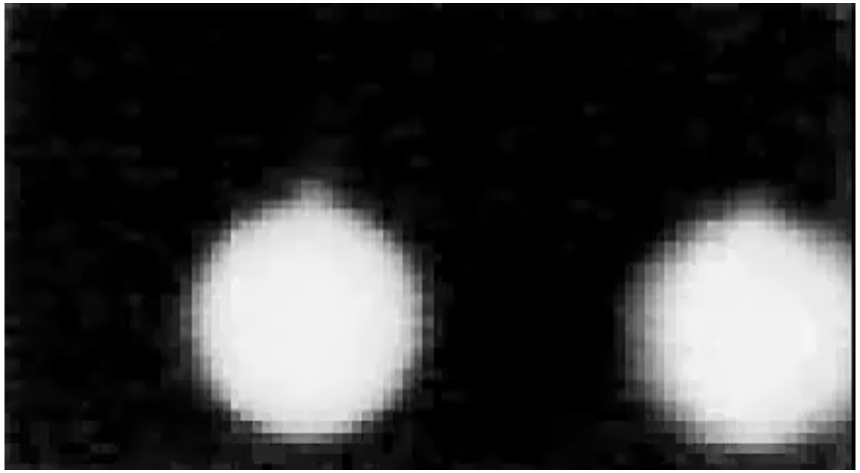
DETECTION EFFICIENCY:



MULTI-GEM FOR PORTAL IMAGING



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

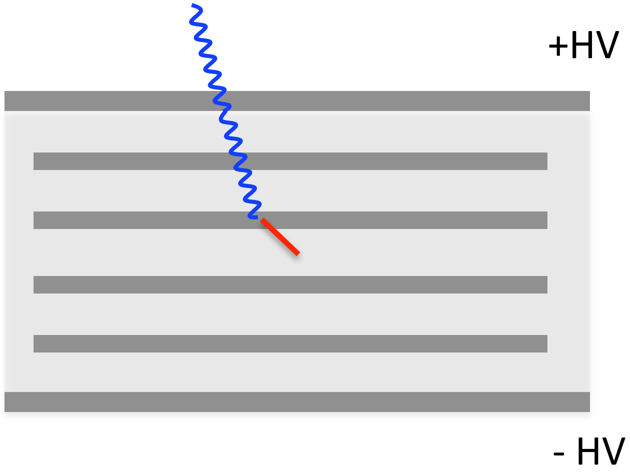


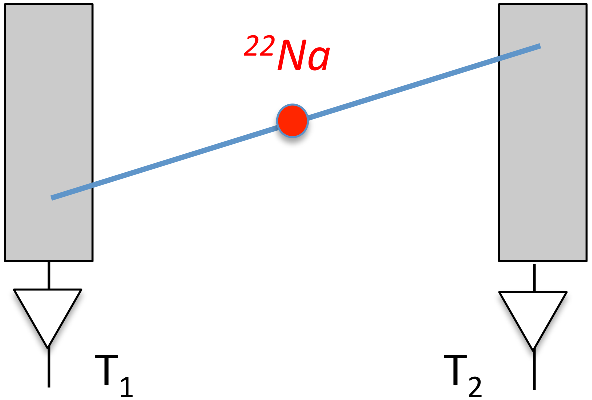
J. Ōstling, New Efficient Detector for Radiation Therapy Imaging using Gas Electron Multipliers. Thesis at Karolinska Institutet Karolinska Institutet (2006)

FAST TIMING PET

DETECTION OF 511 keV γ
MULTI-GAP RESISTIVE PLATE CHAMBER

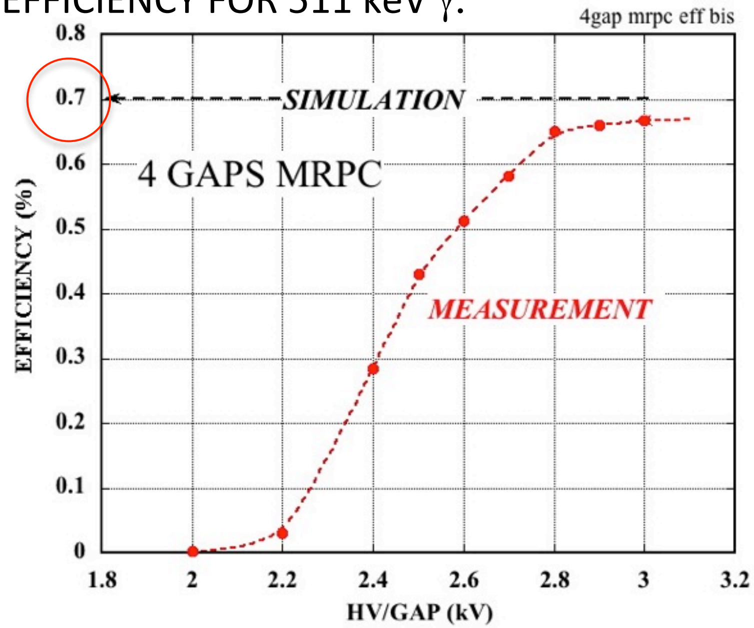
400 μm THICK HIGH RESISTIVITY GLASS PLATES



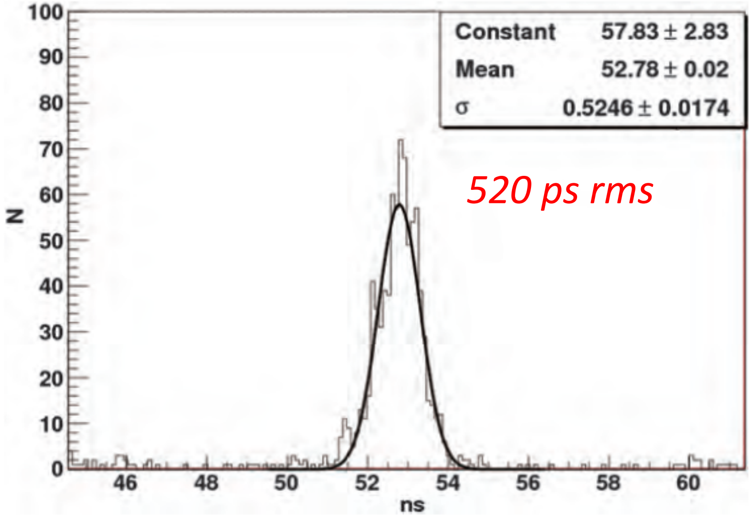


D. Watts et al, J. Rad. Res. 54 (2013)i136

EFFICIENCY FOR 511 keV γ:



TIME RESOLUTION (T_1-T_2):



520 ps rms

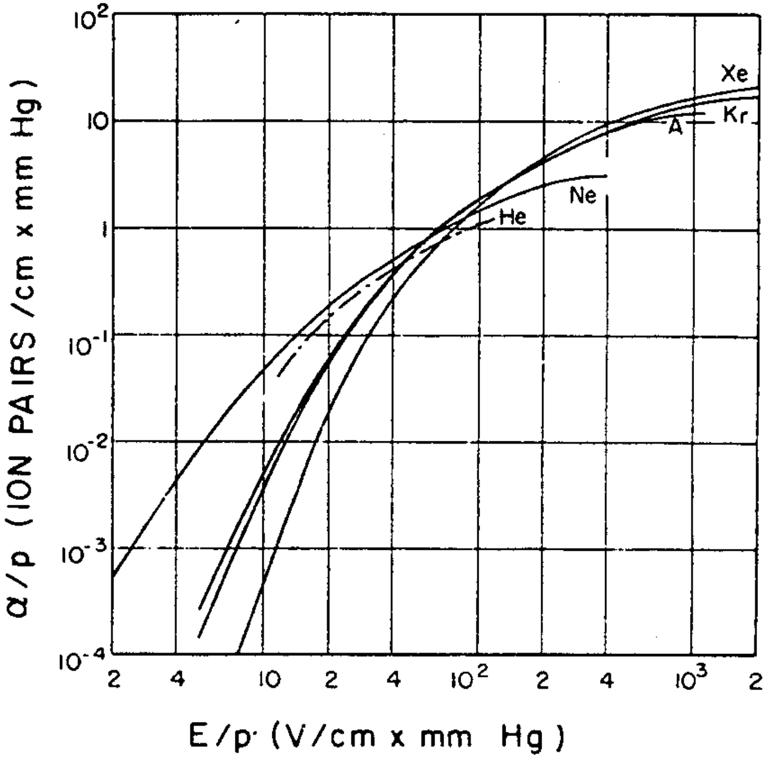
AVALANCHE CHARGE MULTIPLICATION

Mean free path for ionization:

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

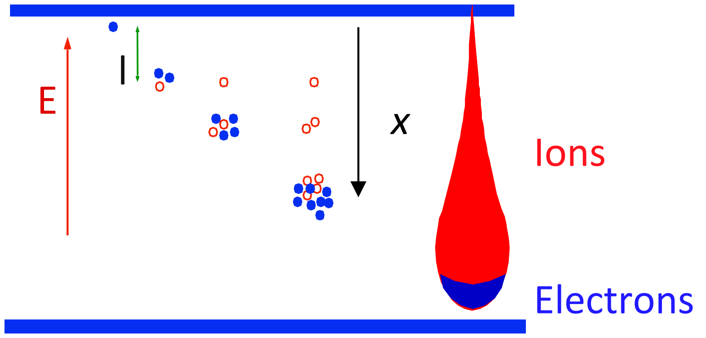
Townsend coefficient:

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



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):

$Q_{MAX} \approx 10^7$ e ⇨ **(PART 2)**

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

SINGLE ELECTRON AVALANCHE: FURRY STATISTICS

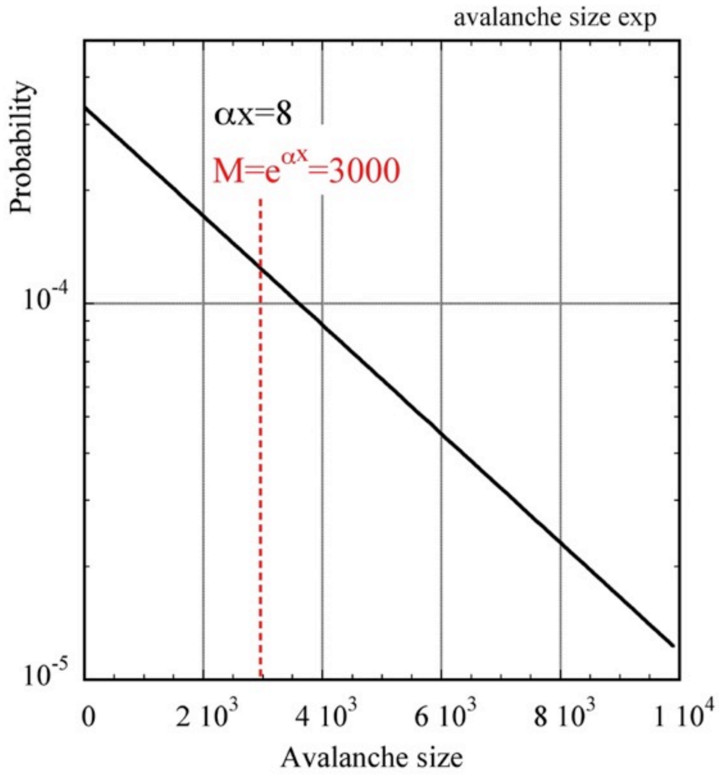
AVALANCHE SIZE DISTRIBUTION:

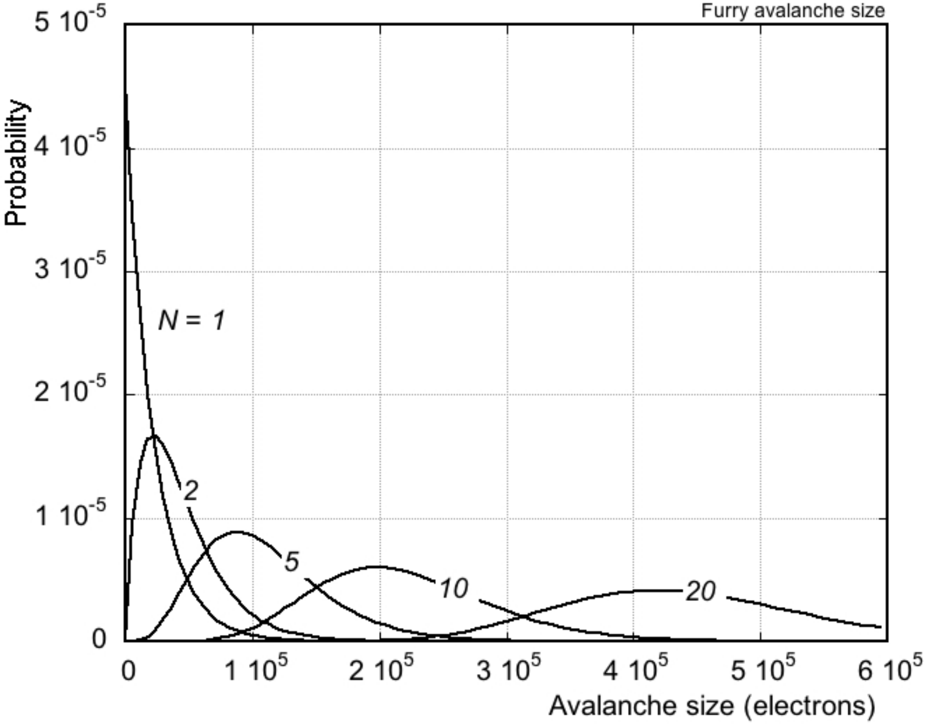
$$P(n) = \frac{e^{-n/\overline{n}}}{\overline{n}} \qquad M = \overline{n} = e^{\alpha x} \qquad \sigma_{\overline{n}} = \overline{n}$$

FOR N INITIAL ELECTRONS:

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

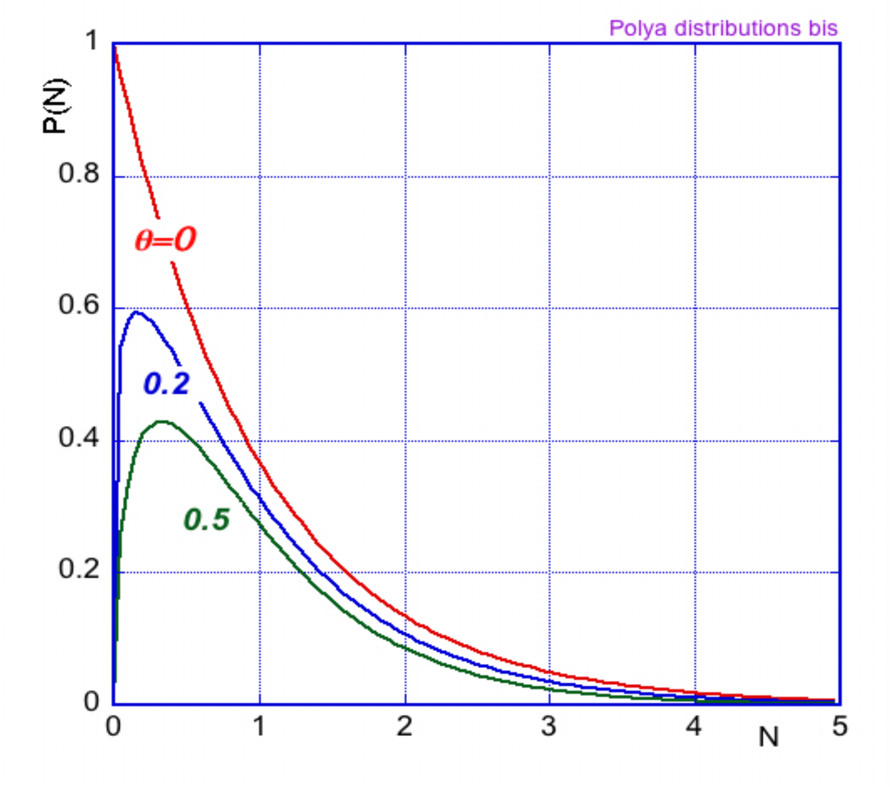
MAXIMUM PROBABILITY FOR n=1!





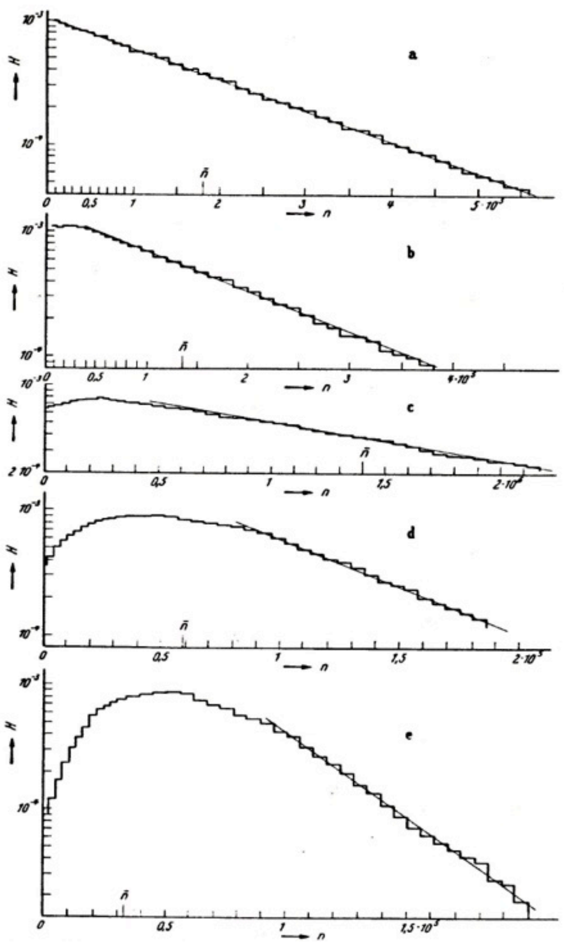
SINGLE ELECTRON AVALANCHE AT HIGH GAINS: POLYA DISTRIBUTION

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



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

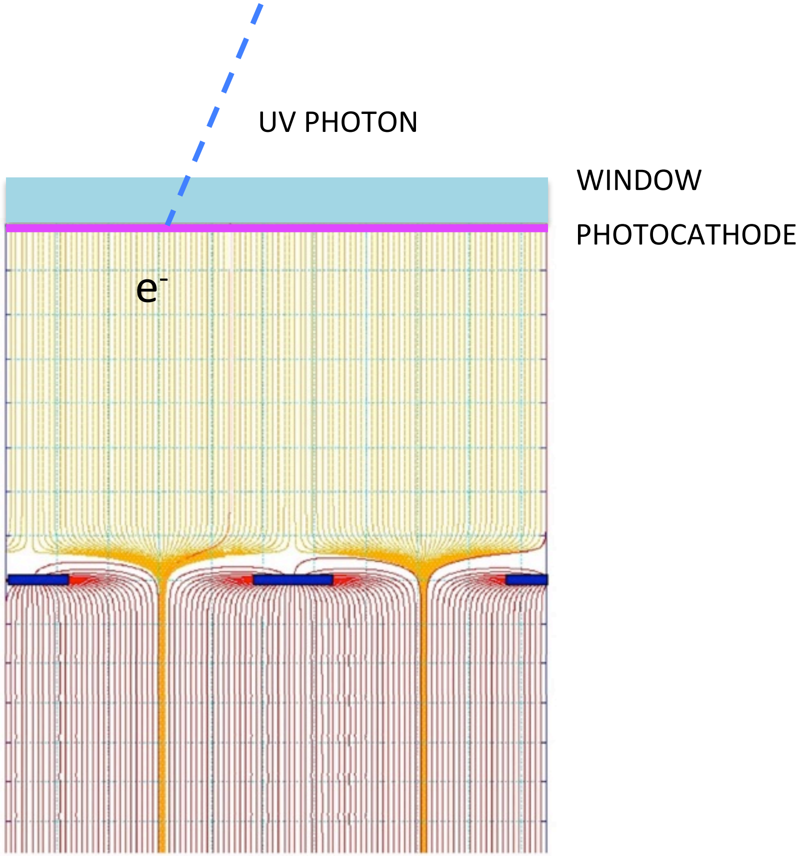
EXPERIMENTAL:

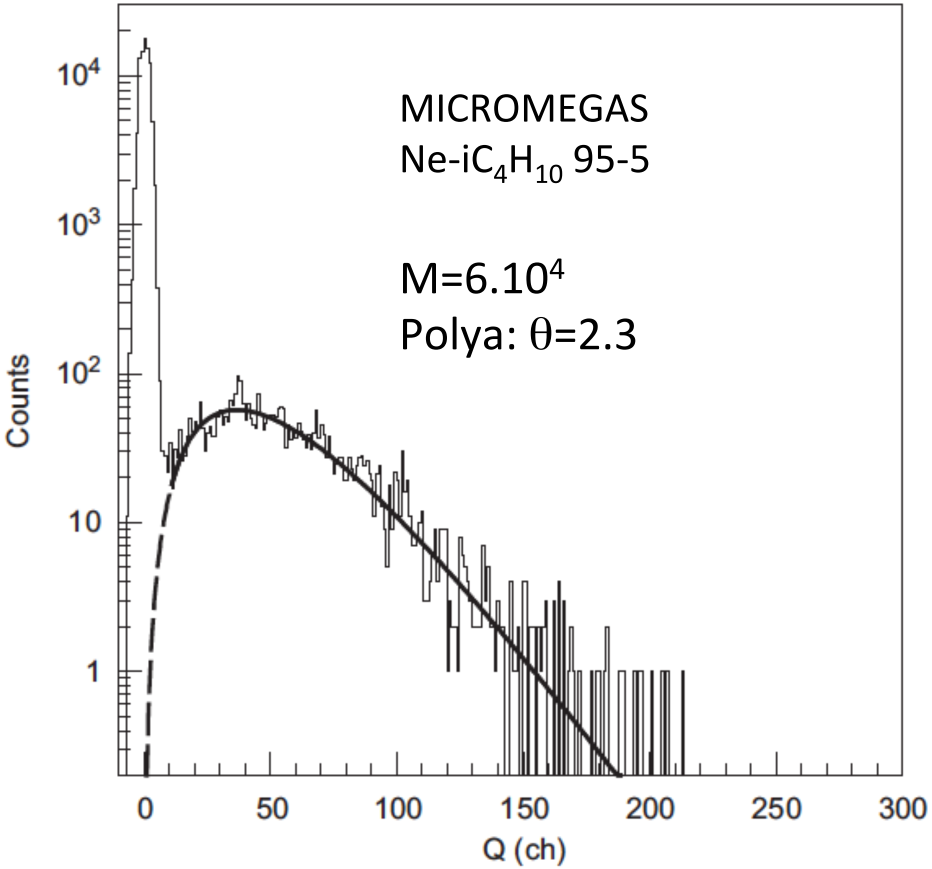


H. Sclumbohm, Zeit. Physik 151(1958)563

SINGLE ELECTRON AVALANCHE DISTRIBUTION IN MPGDs

MICROMEGAS WITH SEMITRANSPARENT PHOTOCATHODE

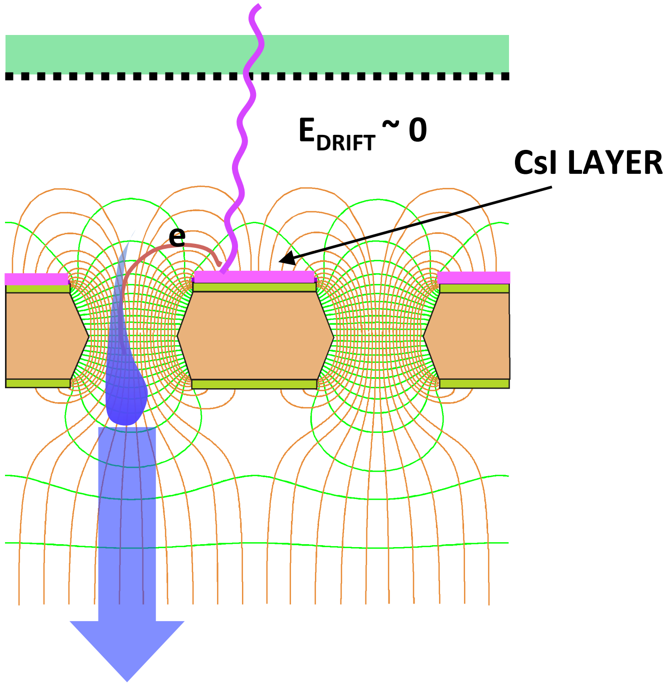




T. Zerguerras et al, Nucl. Instr. and Meth. A608(2009)397

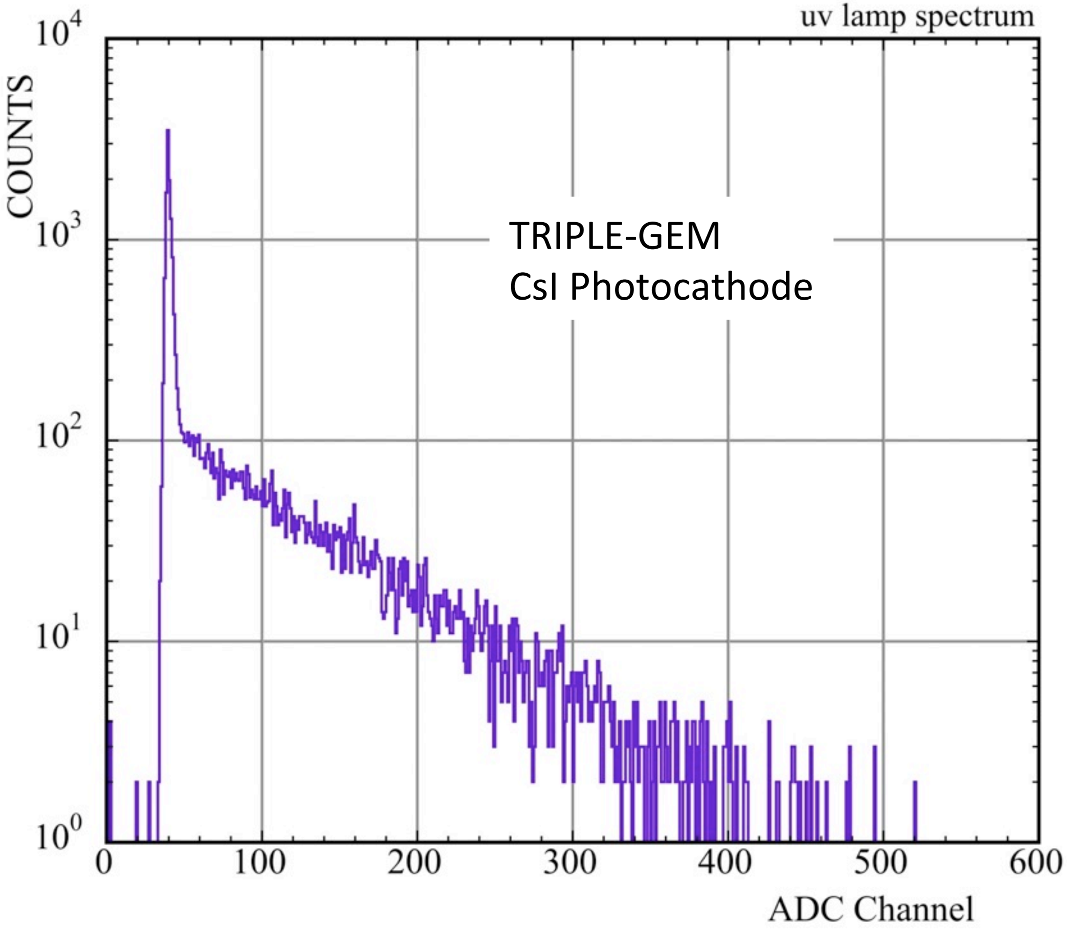
SINGLE ELECTRON AVALANCHE DISTRIBUTION IN MPGDs

GEM WITH REFLECTIVE PHOTOCATHODE:



MORE GEMS

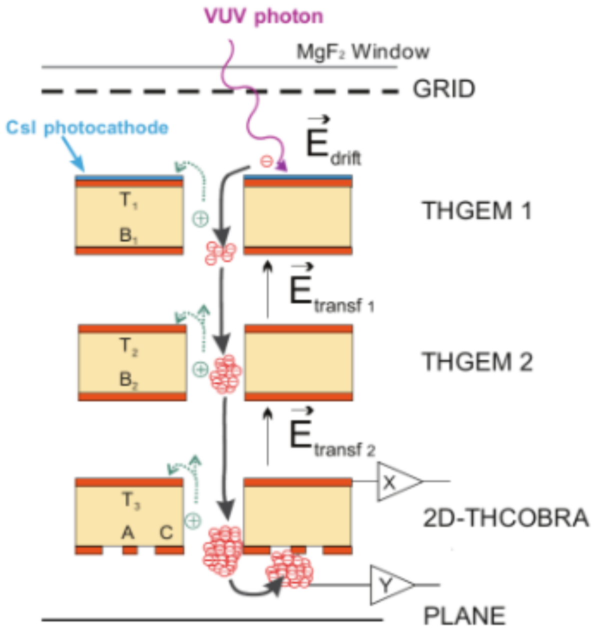
- No photon feedback
- Strong suppression of ions feedback

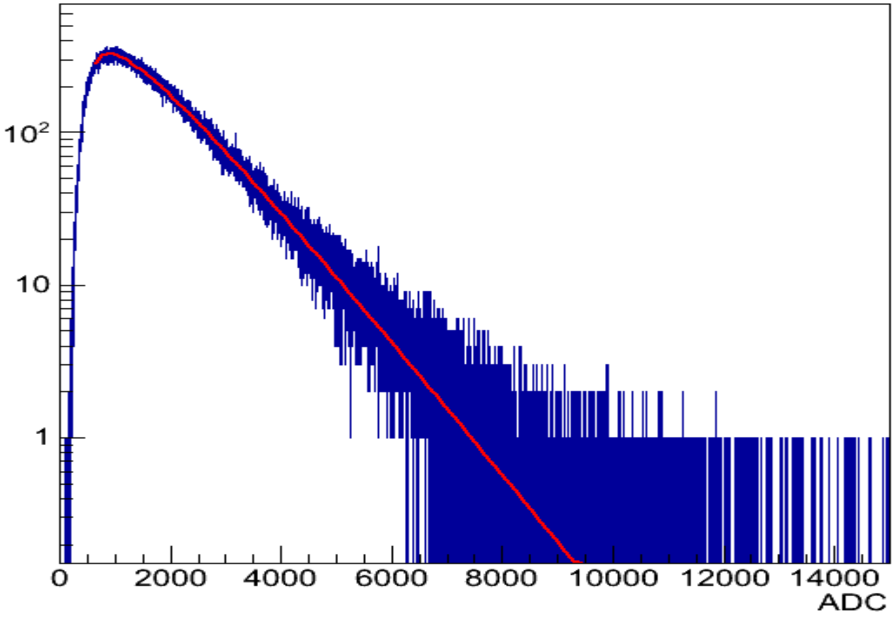


F. Sauli, Nucl. Instr. and Meth. A553(2005)18

SINGLE ELECTRON AVALANCHE WITH IMPROVED ION BACKFLOW SUPPRESSION

THICK COBRA





F. Amaro et an JINST5 (2010)

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

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

END OF PART 1

EXTRAS

SOFT X-RAYS: ENERGY RESOLUTION

Energy resolution:

$$\left(\frac{\sigma_E}{E}\right)^2 = \underset{\underset{\text{Ionization}}{\uparrow}}{\left(\frac{\sigma_N}{N}\right)^2} + \underset{\underset{\text{Avalanche statistics}}{\uparrow}}{\left(\frac{\sigma_M}{M}\right)^2}$$

Average gain:

$$M = \frac{1}{N}\sum_{i=1}^{N} A_i = \bar{A}$$

A_i : single electron avalanche size

Gain variance:

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

Furry statistics:

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

Polya statistics:

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

Ionization variance:

$$\sigma_N^2 = F\,N$$

F: Fano factor

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

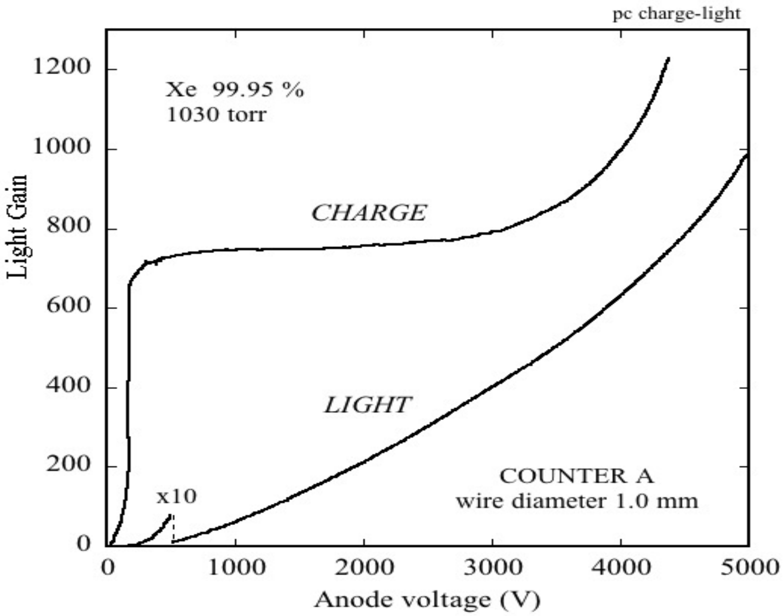
Furry: *b=1* Polya: $b = 1/(1-\theta)$

FANO FACTORS

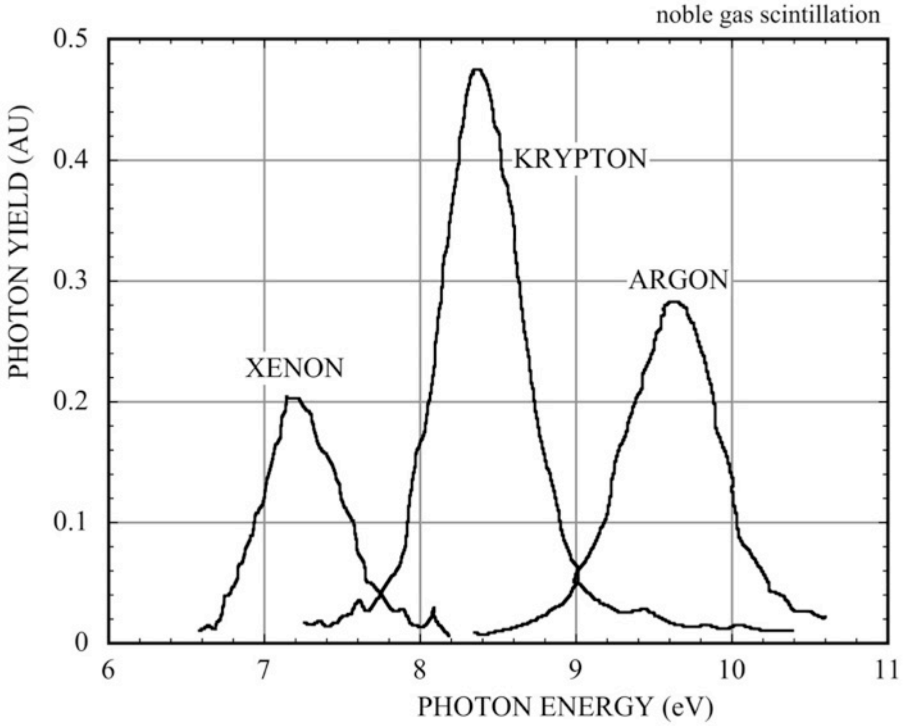
GAS	F
Ar	0.19
Ar-CH$_4$	0.19
Xe	<0.17
Ne+0.5%Ar	0.05

SCINTILLATION PROPORTIONAL COUNTERS

PHOTON EMISSION BEFORE CHARGE MULTIPLICATION:
NO AVALANCHE DISPERSIONS

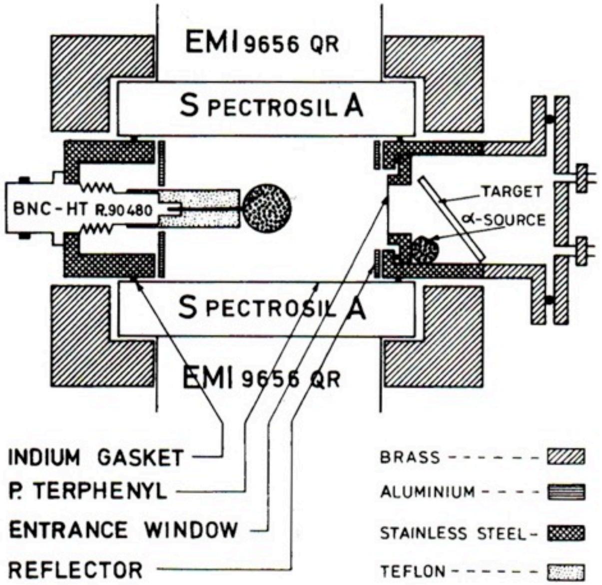


NOBLE GASES SCINTILLATION SPECTRA ~1bar

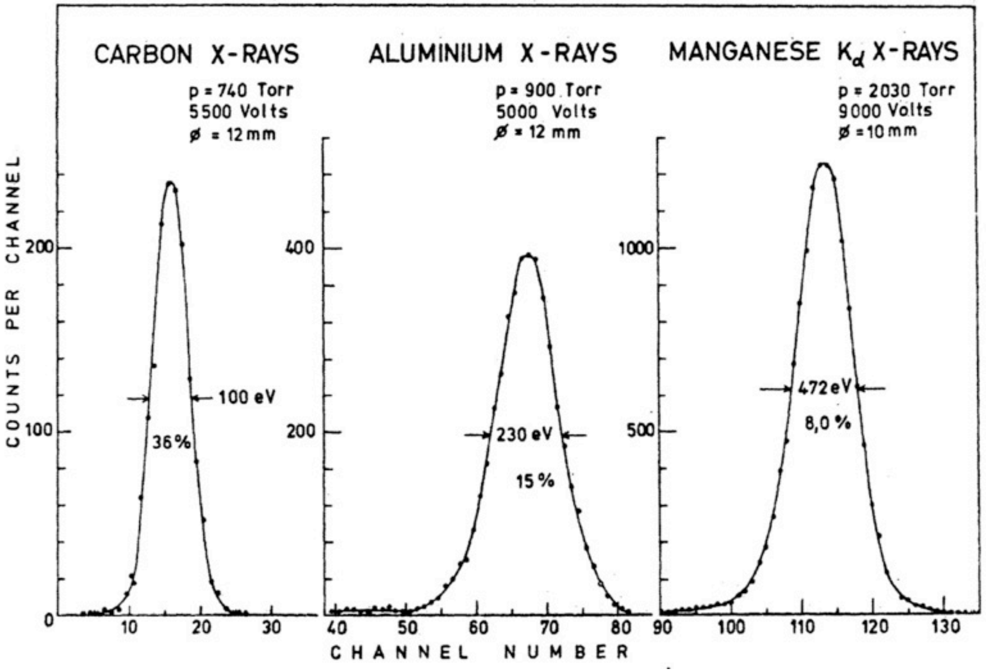


SCINTILLATION PROPORTIONAL COUNTERS

SCINTILLATION COUNTERS



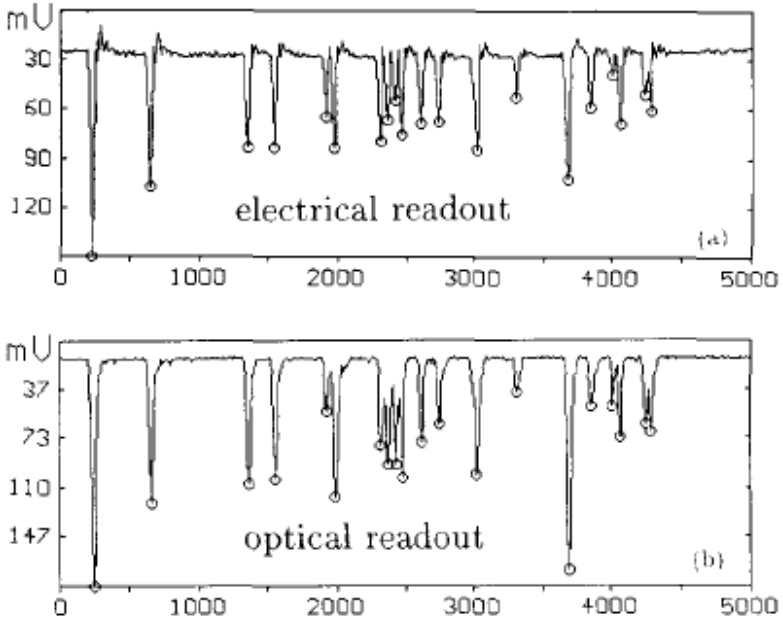
ENERGY RESOLUTION:
CLOSE TO STATISTICAL LIMIT

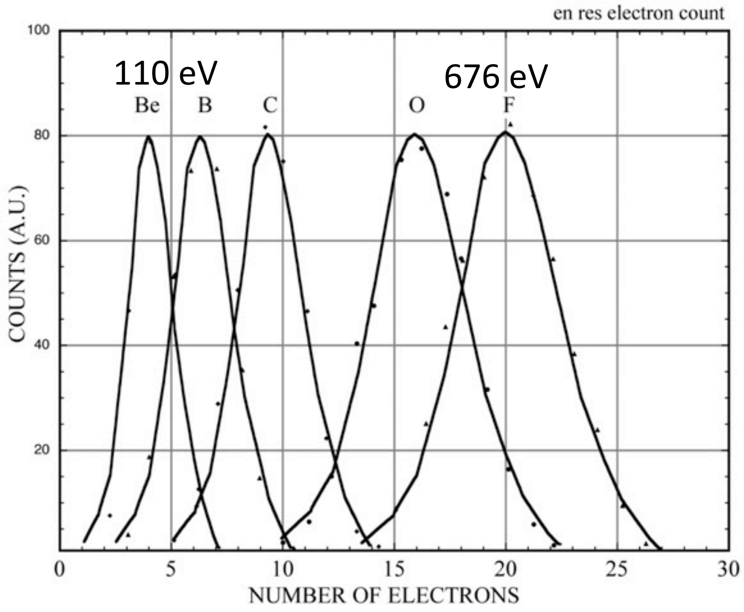


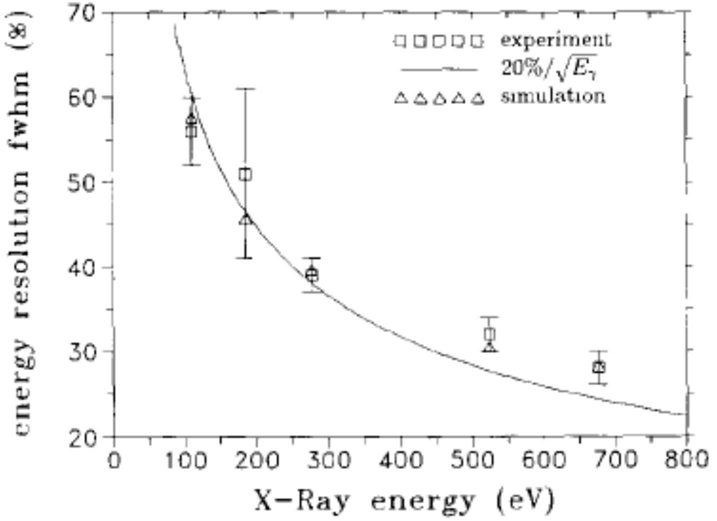
A. Policarpo et al, Nucl. Instr. and Meth. 102(1972)337

ELECTRON COUNTING

LOW PRESSURE (10 Torr) PROPORTIONAL COUNTER

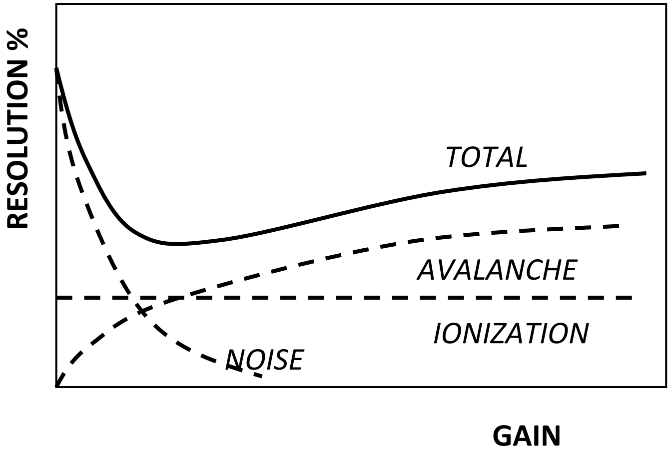


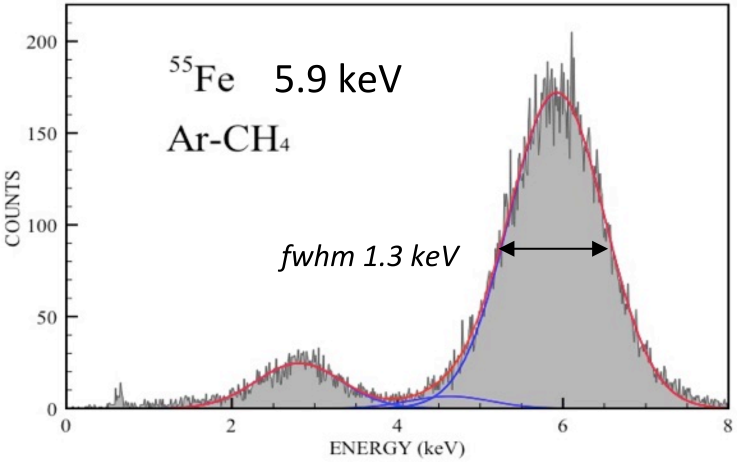


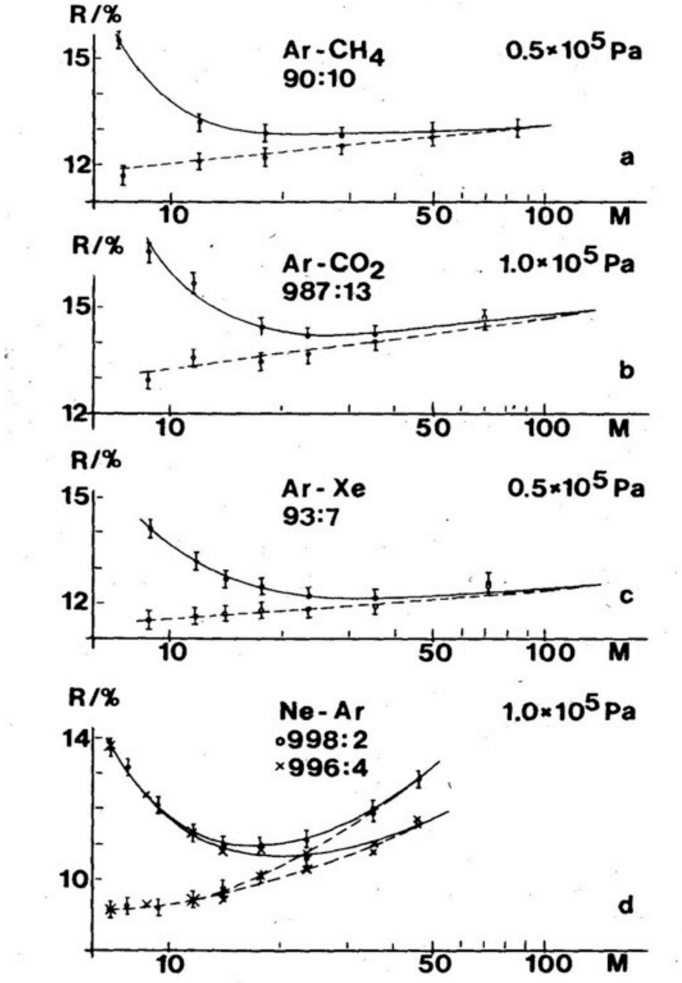


A. Pansky et al, Nucl. Instr. and Meth. A330(1993)150

SOFT X-RAYS ENERGY RESOLUTION



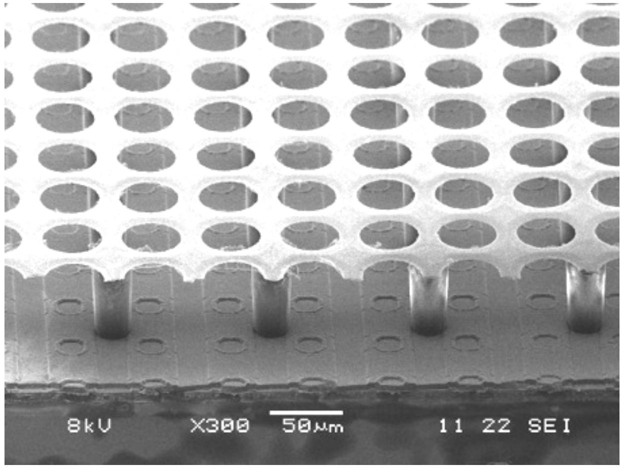




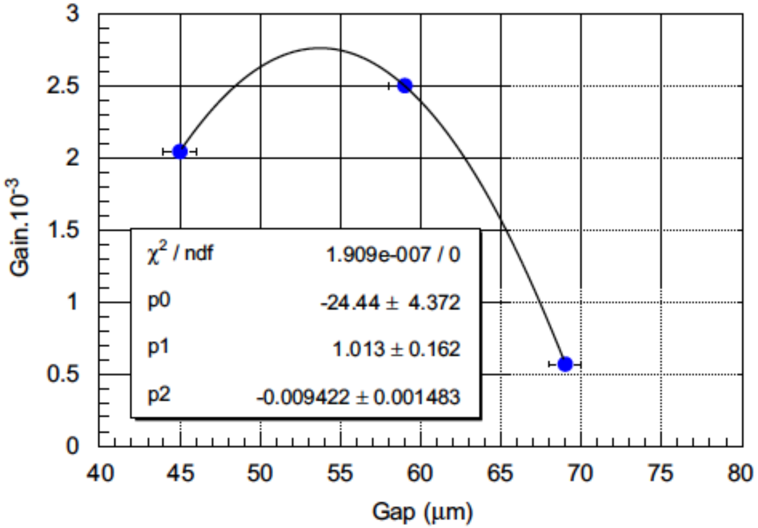
H. Sipilä and E. Kiuru, Adv. X-Ray Analysis 21(1978)

SOFT X-RAYS ENERGY RESOLUTION

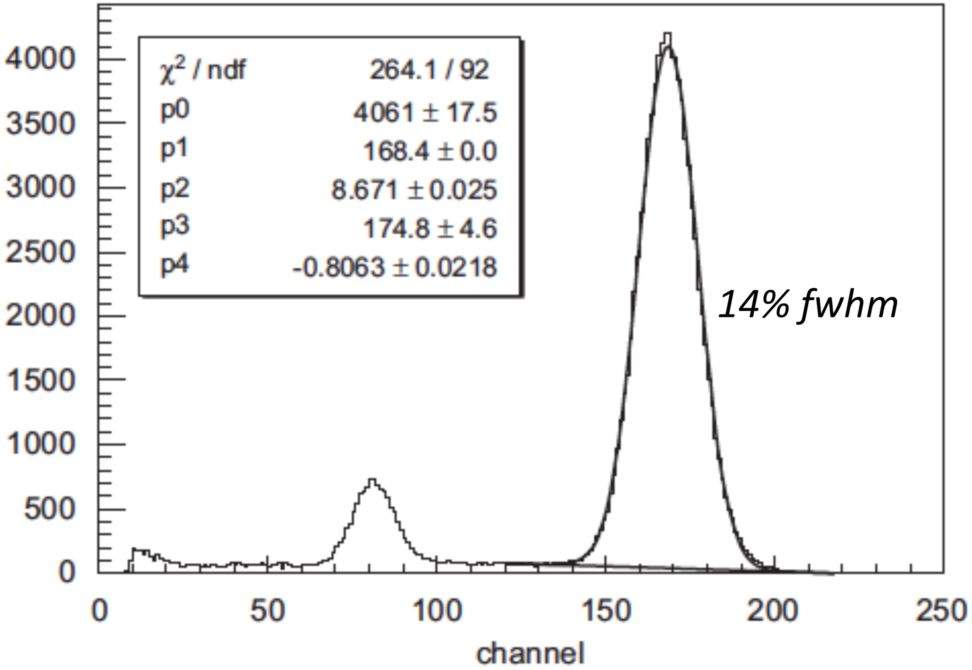
INGRID: MICROMEGAS WITH TIMEPIX READOUT



GAP DEPENDENCE OF GAIN:



5.9 keV ^{55}Fe in Ar-CH_4 90-10



14% fwhm

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