PART 1
PHOTON DETECTION AND IMAGING WITH GASEOUS COUNTERS

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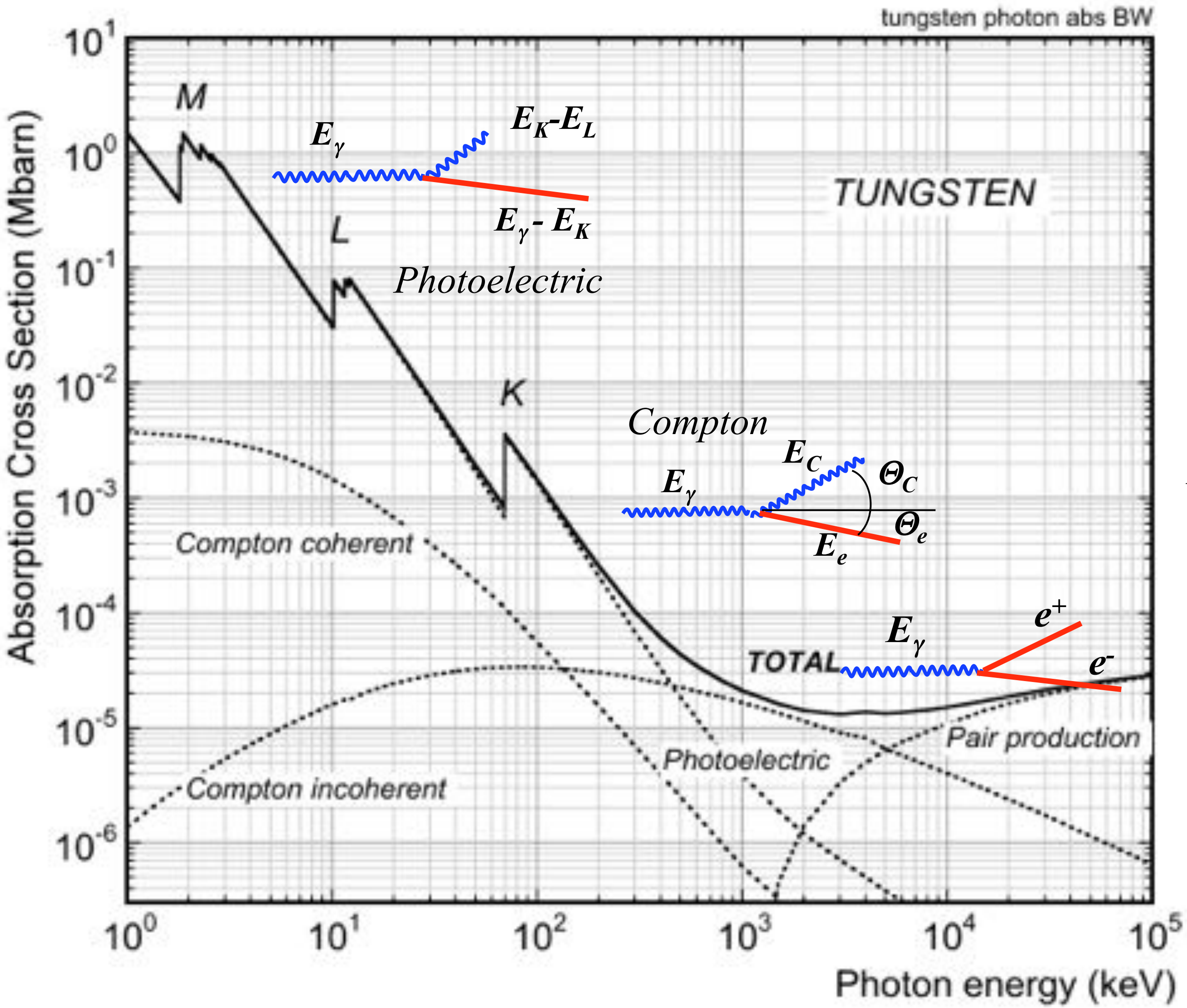
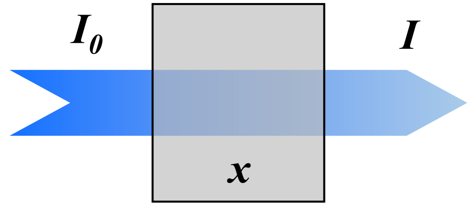
TERA Foundation and CERN

EDIT 2015 Laboratori Nazionali di Frascati, October 20-29, 2015





I_0 *: Incoming flux*
I *: Outgoing flux*

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

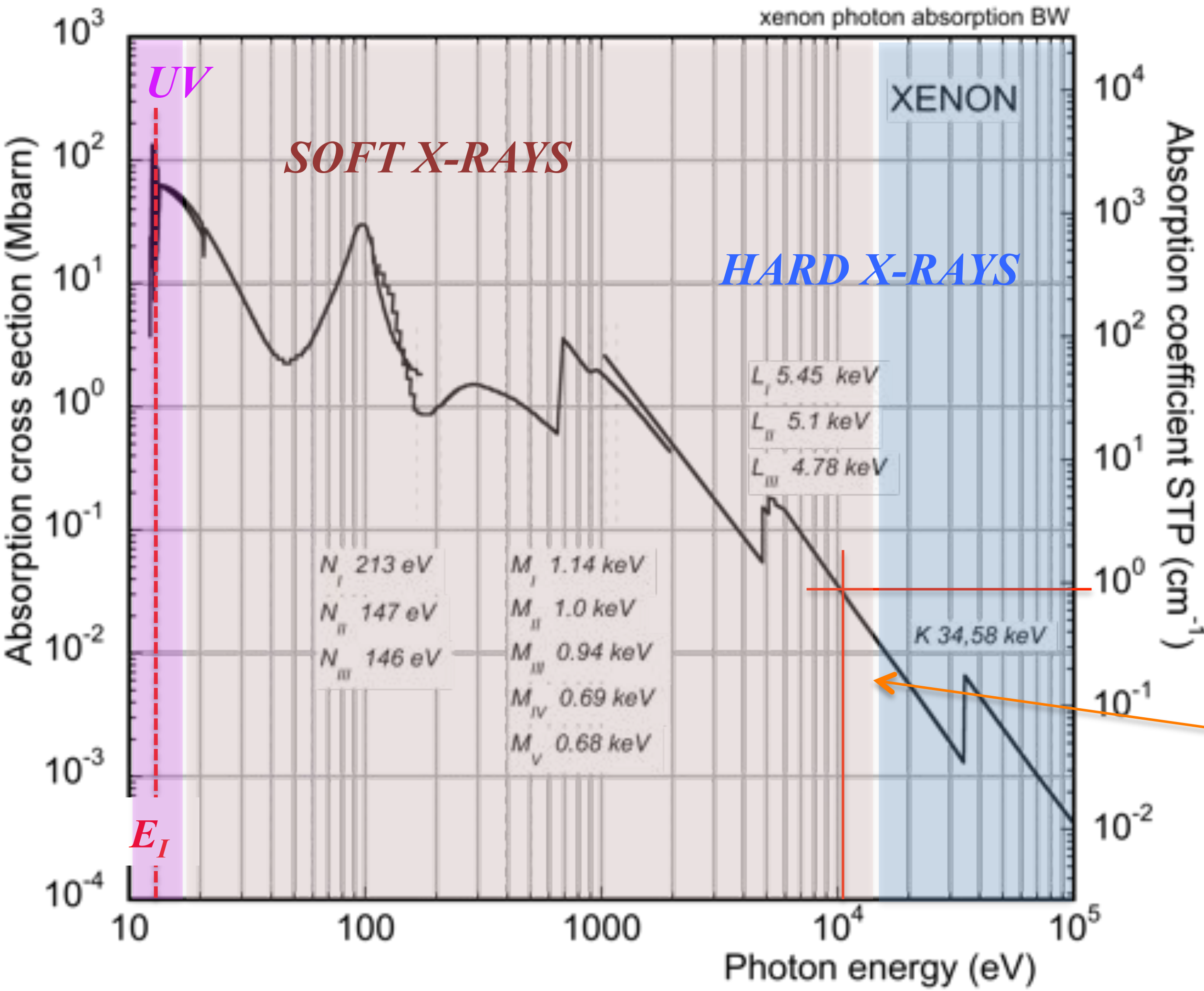
Absorption coefficient (cm^{-1}):

$$\alpha = \frac{N_A \rho}{A} \sigma$$

Absorption length (cm):

$$\lambda = \frac{1}{\alpha}$$

ρ: density ($g\ cm^{-3}$)
N: atoms (molecules) cm^{-3}
σ: absorption cross section (cm^2)
A: Avogadro number



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

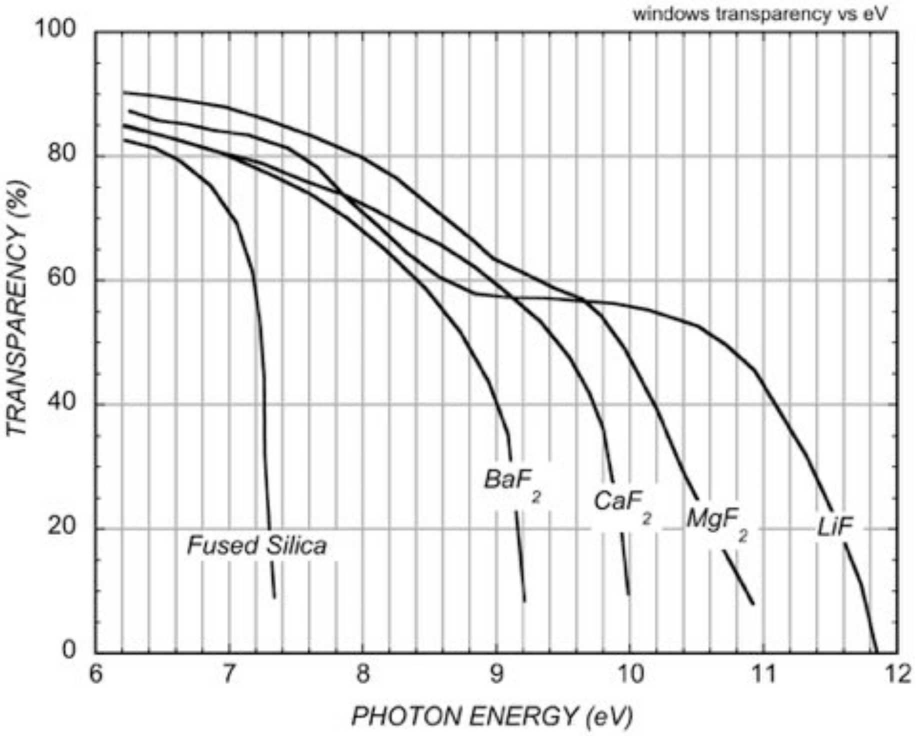
For gases at STP:

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

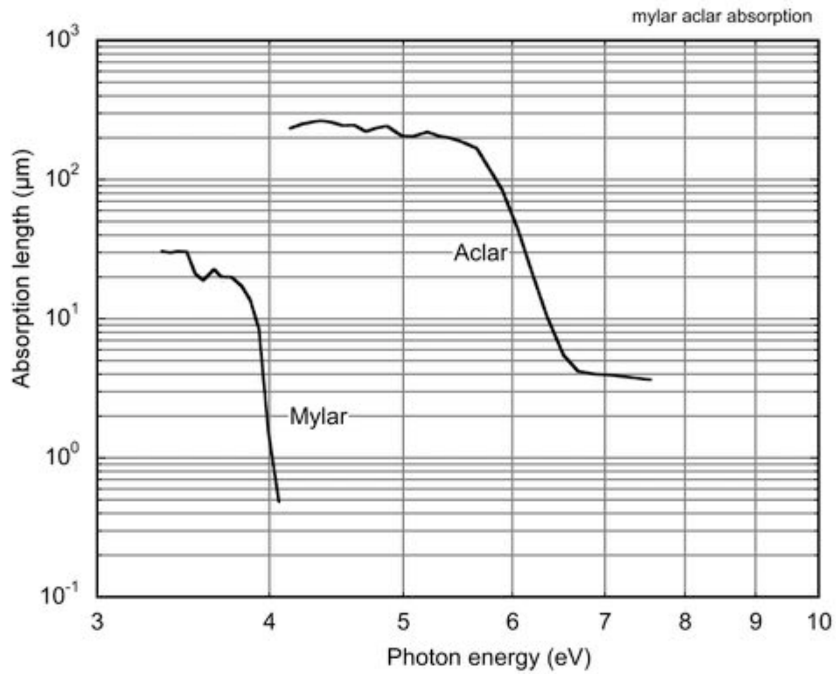
@ E_γ=10 keV
$\lambda \sim 1$ cm (STP)

http://xdb.lbl.gov/
http://henke.lbl.gov/optical_constants/
http://www.nist.gov/pml/data/xraycoef/

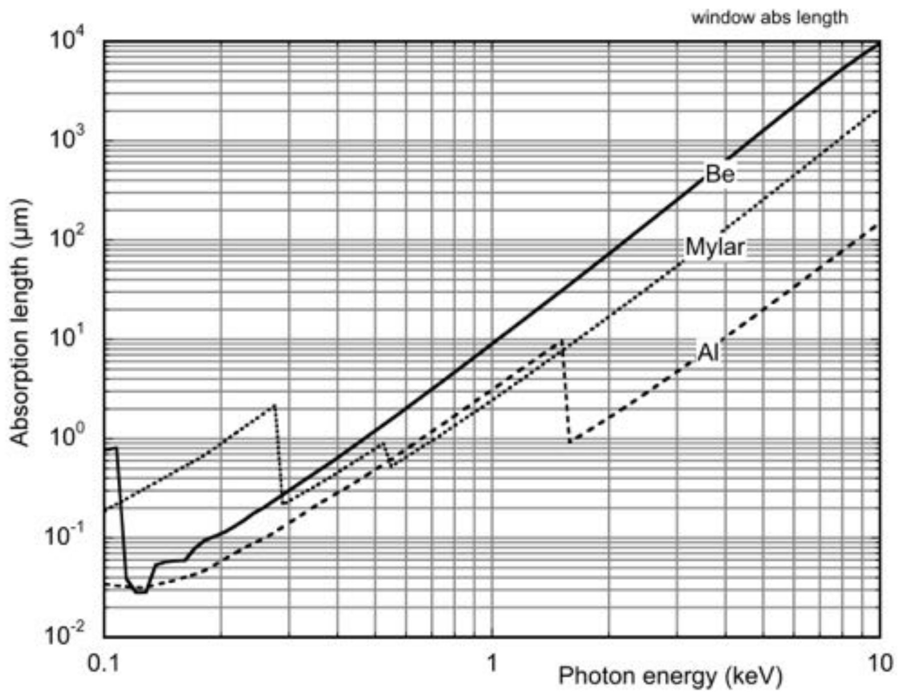
UV GLASS AND FLUORIDE CRYSTALS:



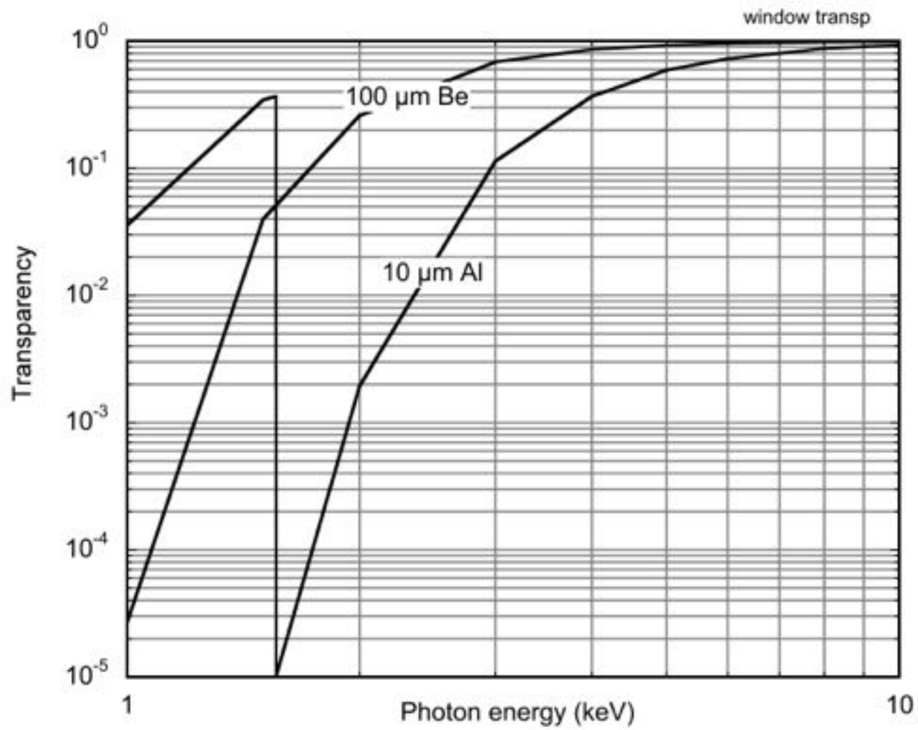
THIN POLYMER FOILS:



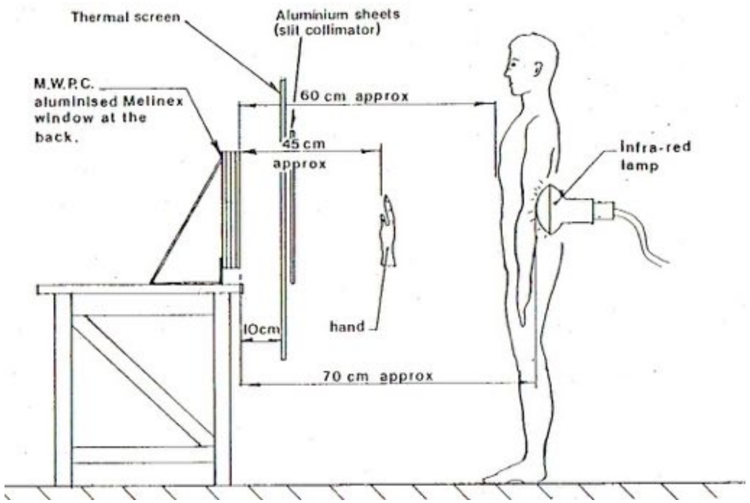
ABSORPTION LENGTH VS ENERGY:



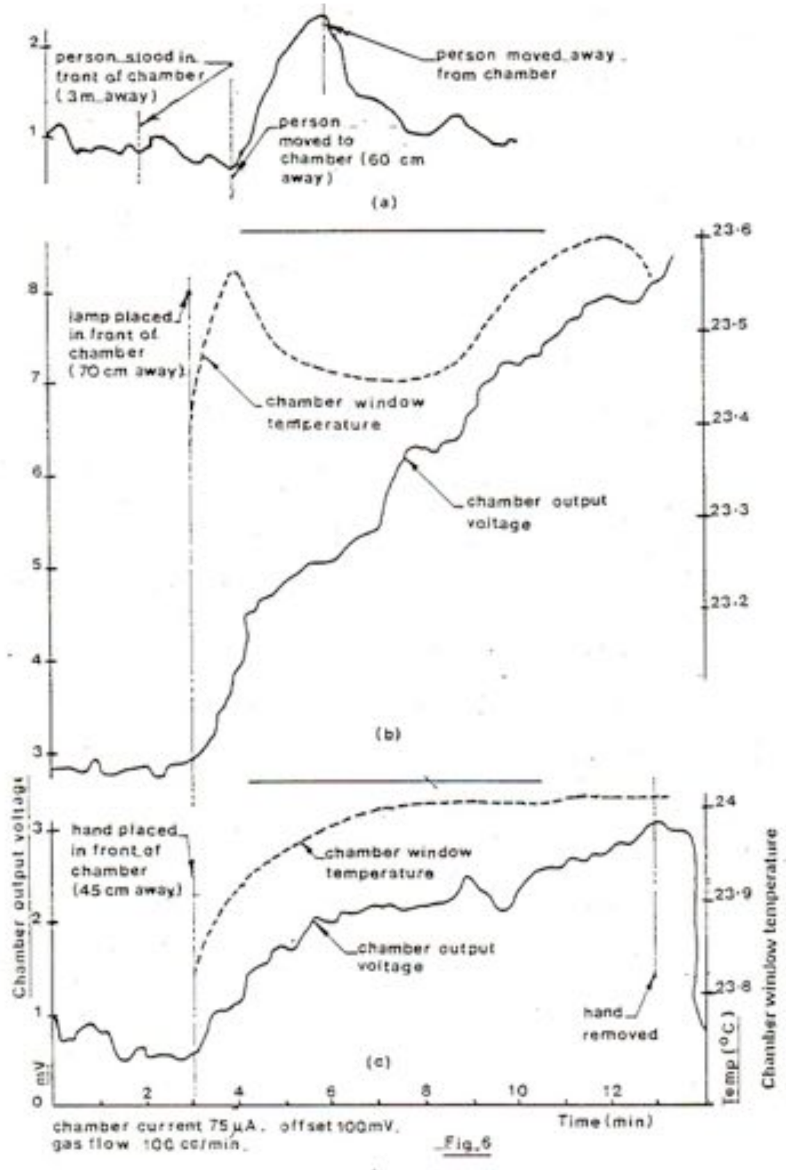
TRANSPARENCY VS ENERGY:



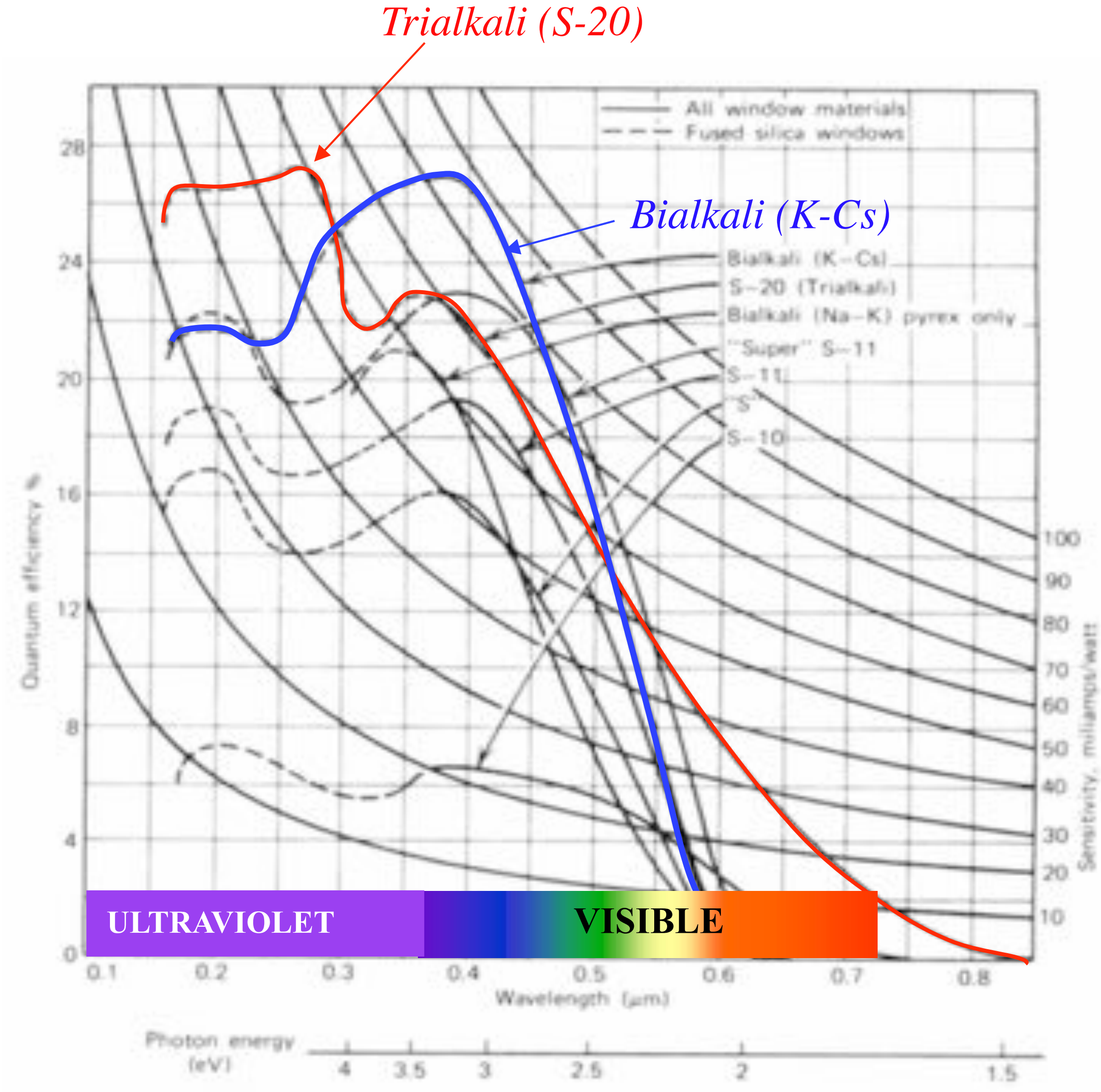
STUDY OF GLOW DISCHARGES IN MWPCs
Rutherford Lab (1979)



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



SPECTRAL RESPONSE OF PHOTOCATHODES (IN VACUUM):

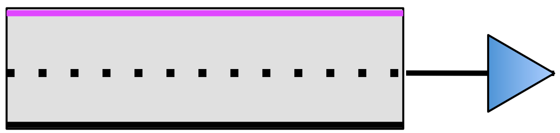


VACUUM PHOTODIODE:

GAS PHOTODIODE:

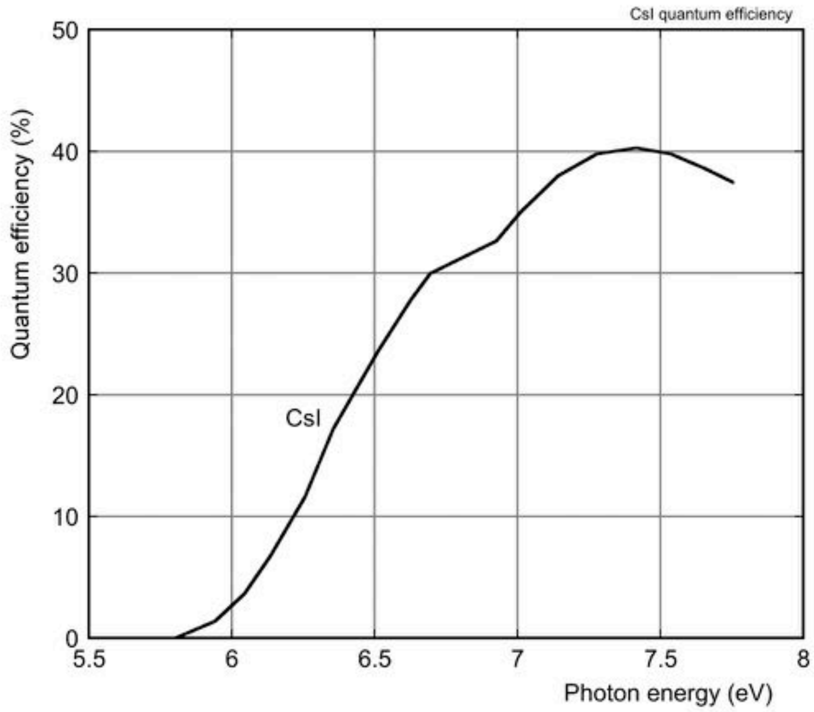
- *Damaged by impurities (O_2, H_2O, …)*
- *Backscattering reduces Quantum Efficiency*

GAS DETECTOR WITH GAIN:



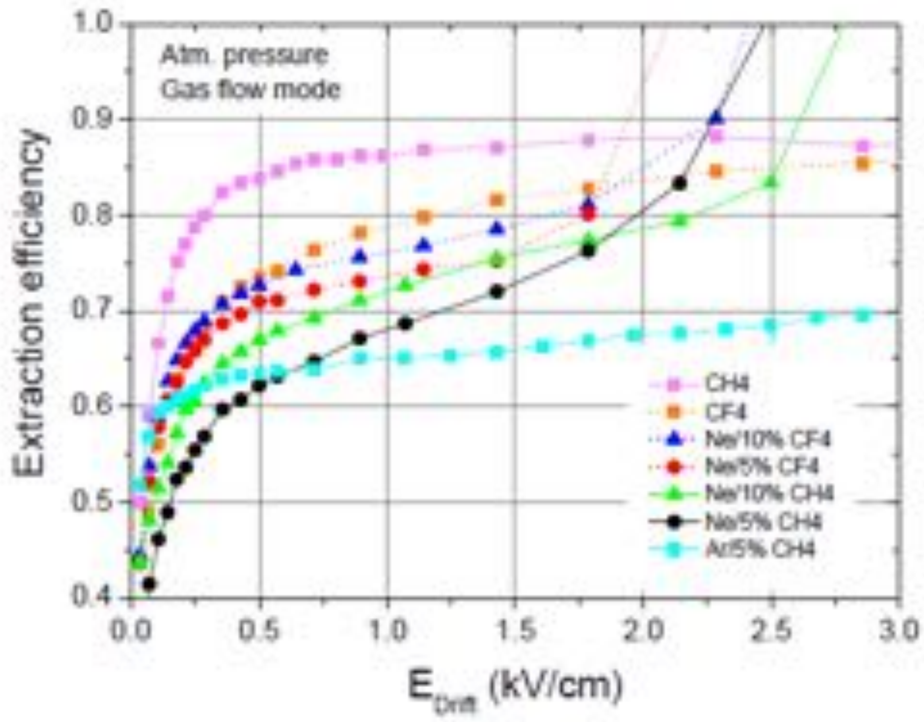
- *Photon feedback*
- *Positive ions damage of photocathode*

CsI QUANTUM EFFICIENCY (IN VACUUM):



J. Seguinot et al, Nucl. Instr. and Meth. 297(1990)133

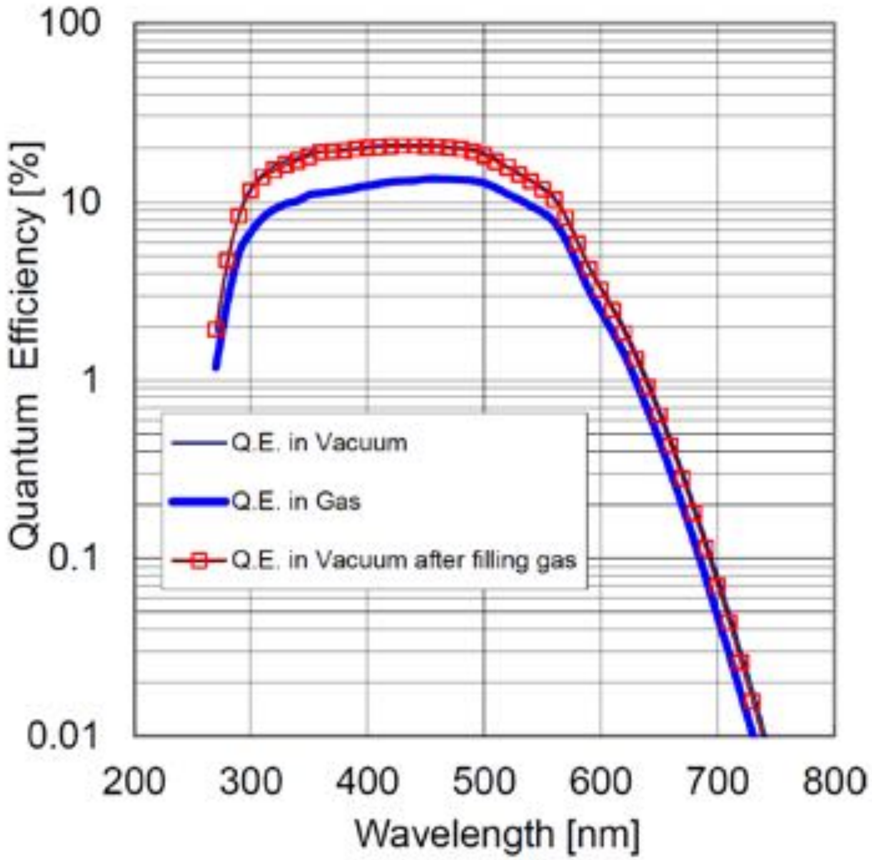
IN GASES:
FIELD DEPENDENCE OF THE PHOTOELECTRON EXTRACTION EFFICIENCY:



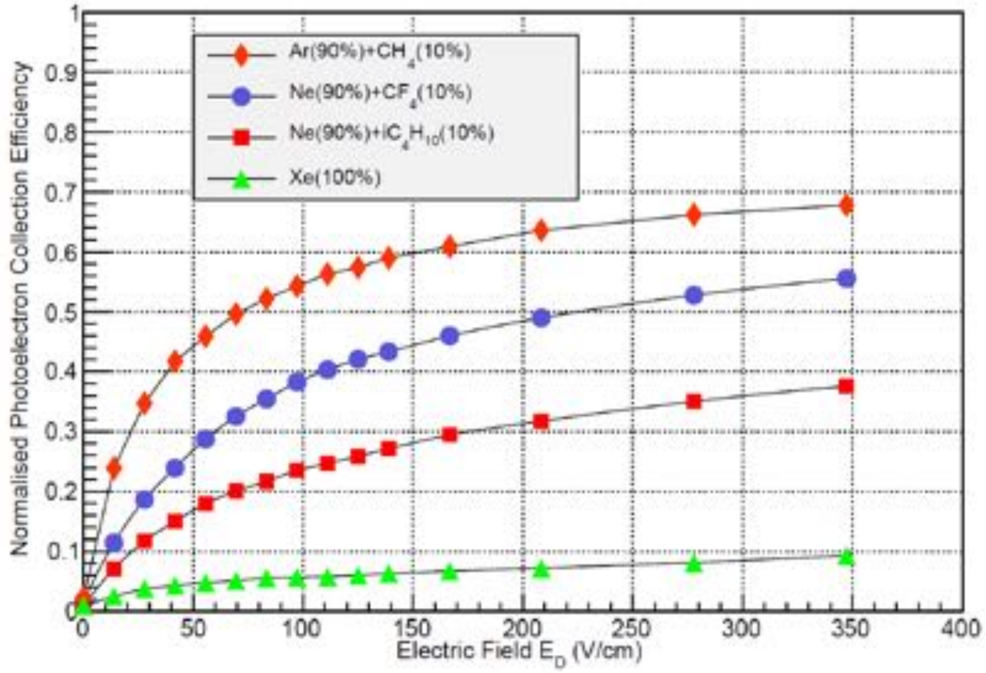
C. D. R. Azevedo et al., 2010 JINST 5 P01002

MICRO-PATTERN GAS DETECTORS: GEM, MICROMEGAS, GLASS CAPILLARY

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

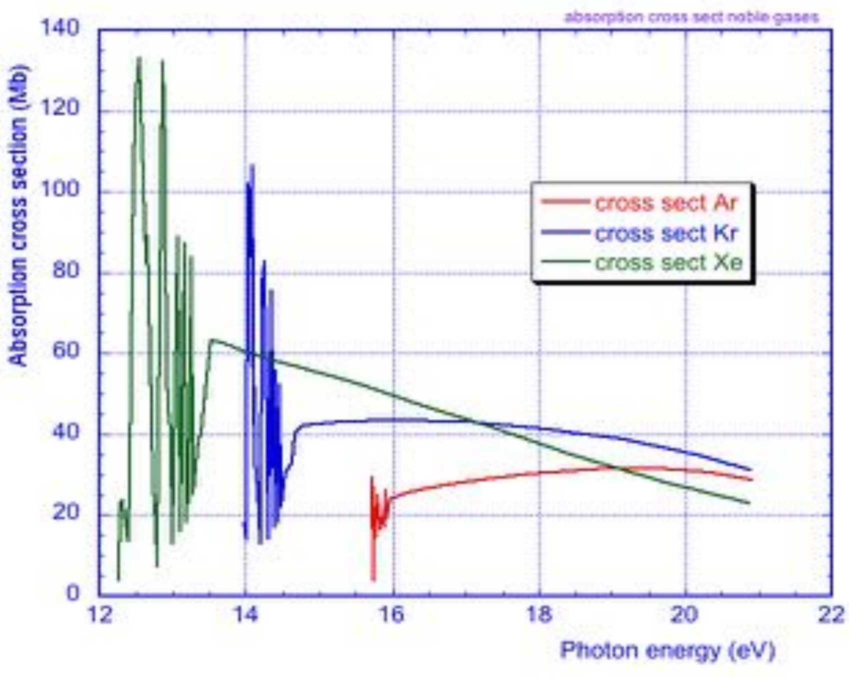


Photoelectron Collection Efficiency in several gases at increasing fields:

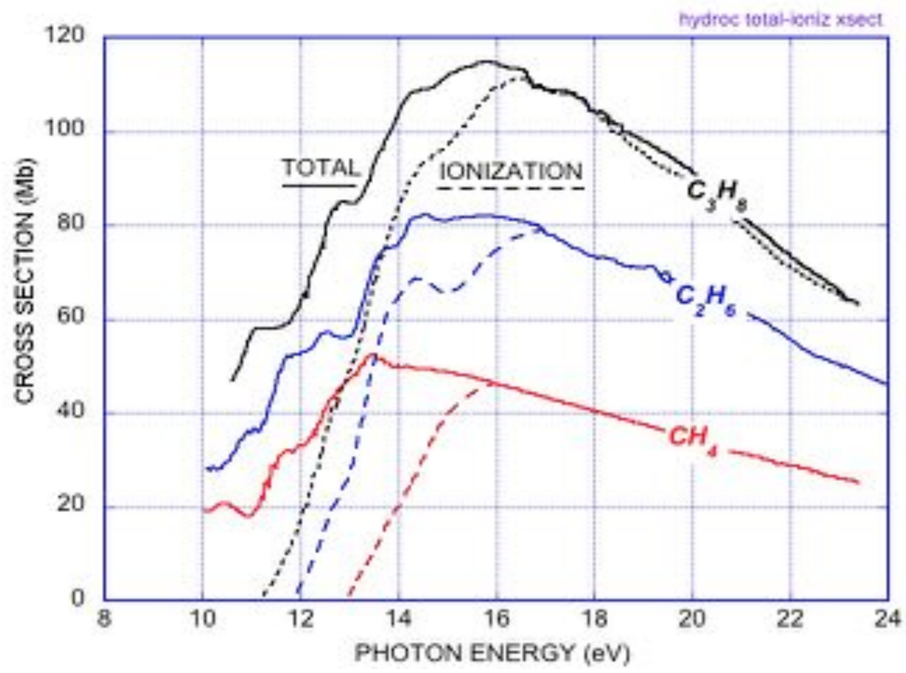


F. Tokanai et al, Nucl. Instr. and Meth. A610(2009)164

NOBLE GASES: PHOTOIONIZATION THRESHOLD



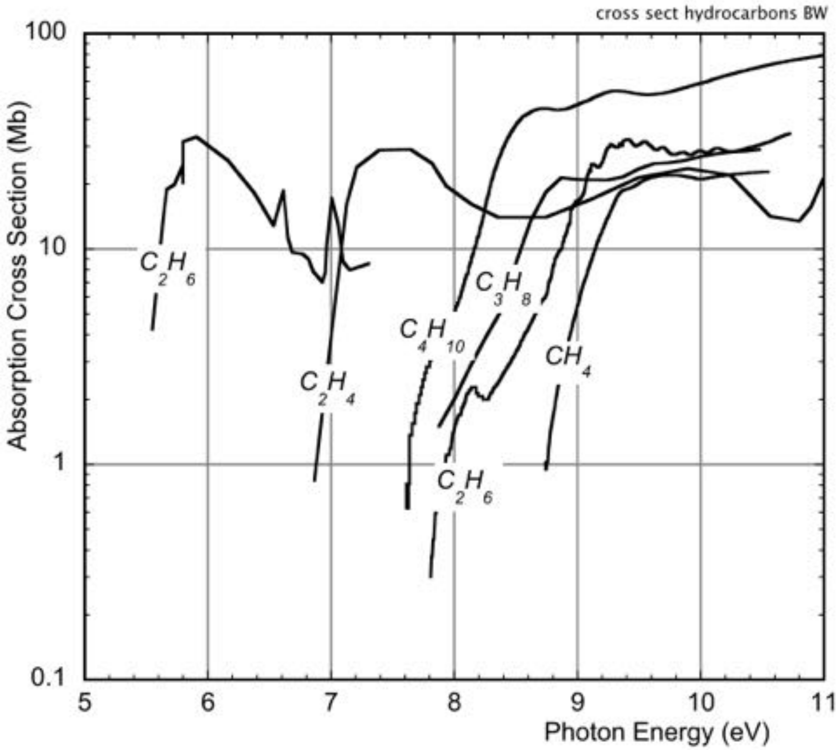
MOLECULAR GASES:
TOTAL AND IONIZATION CROSS SECTIONS:



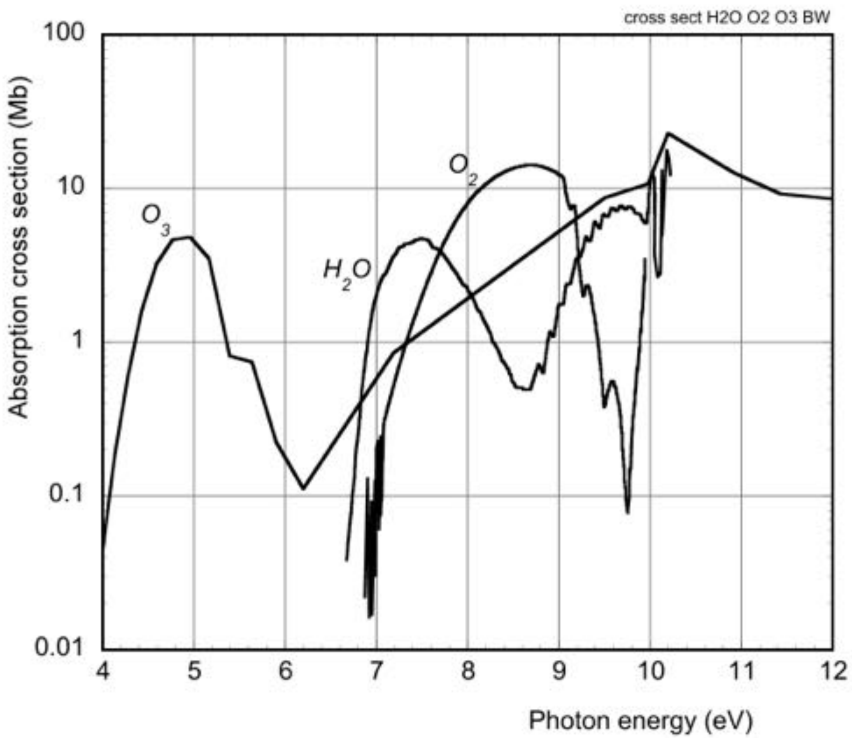
H. S. W. Massey, Electronic and Ionic impact Phenomena (Oxford Press 1969)

G. Marr, Photoionization Processes in Gases (Academic Press NY 1967)

HYDROCARBONS

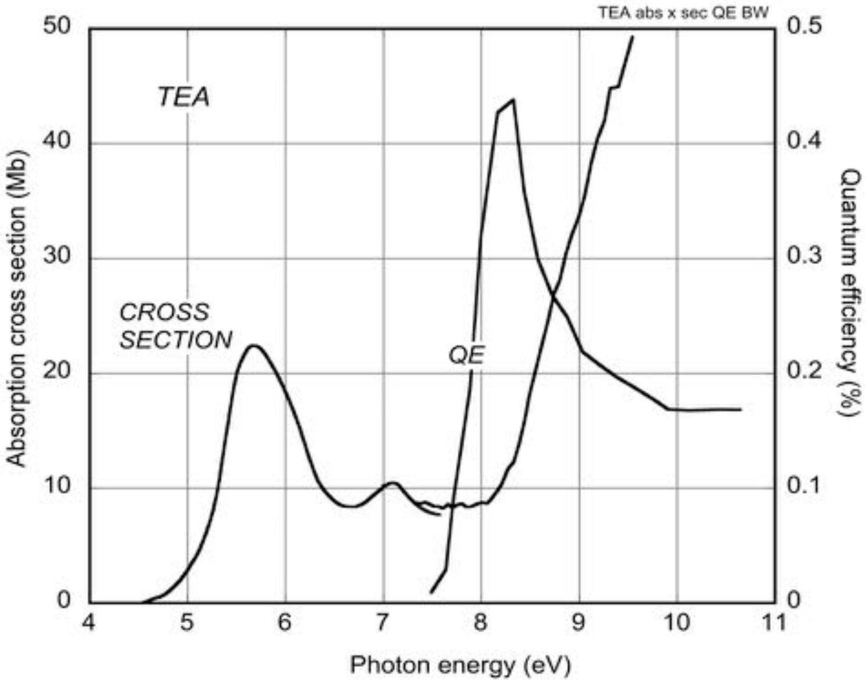


OXYGEN, OZONE, WATER:

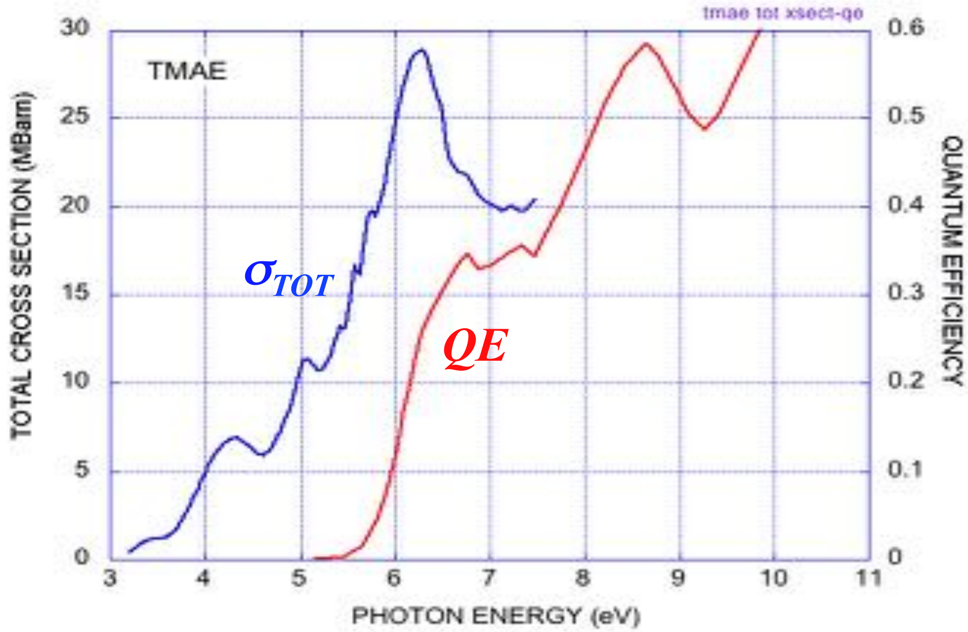


F. Sauli, Gaseous Radiation Detectors
Cambridge University Press (2014)

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

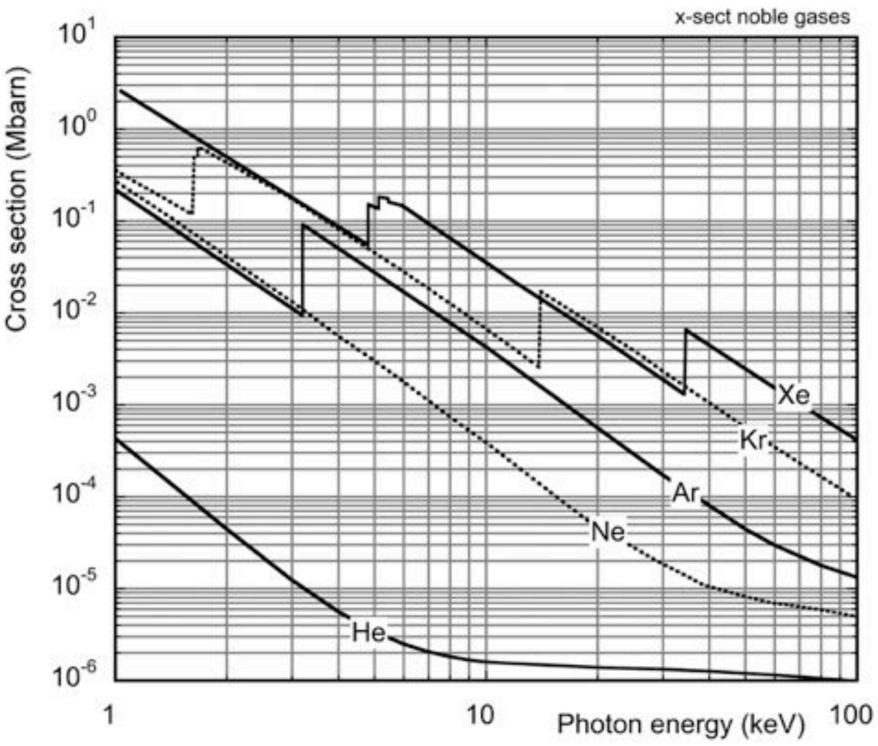


Tetrakis-dimethilamino-ethylene (TMAE)
$C[(CH_3)_2N]_4$
E_i = 5.3 eV

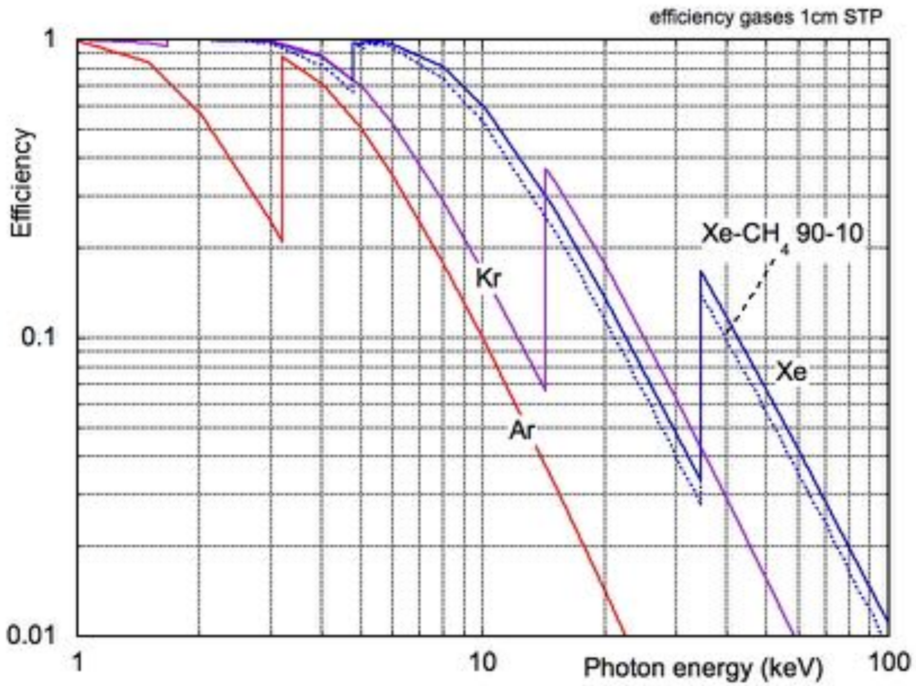


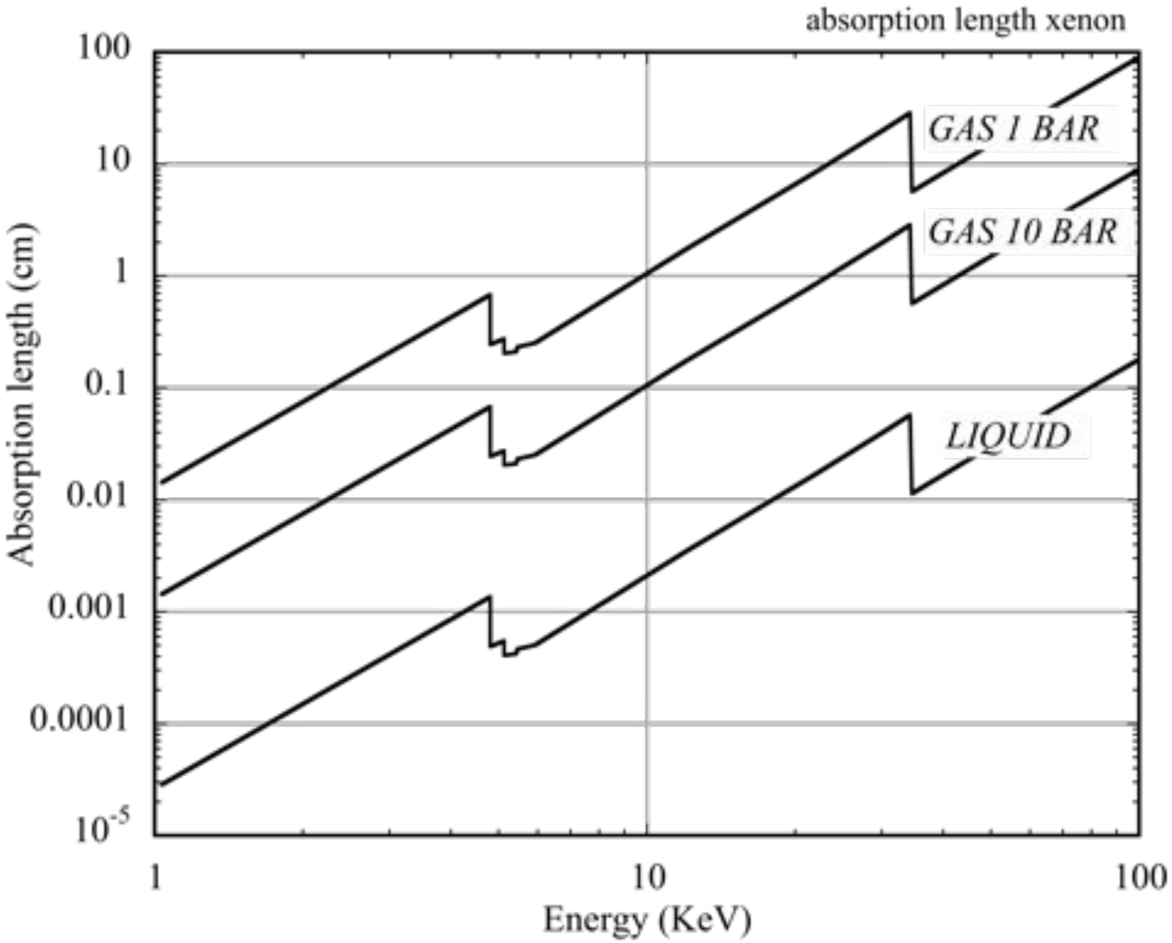
R. Holroyd et al, Nucl. Instr. and Meth.A261(1987)440

ABSORPTION CROSS SECTION:

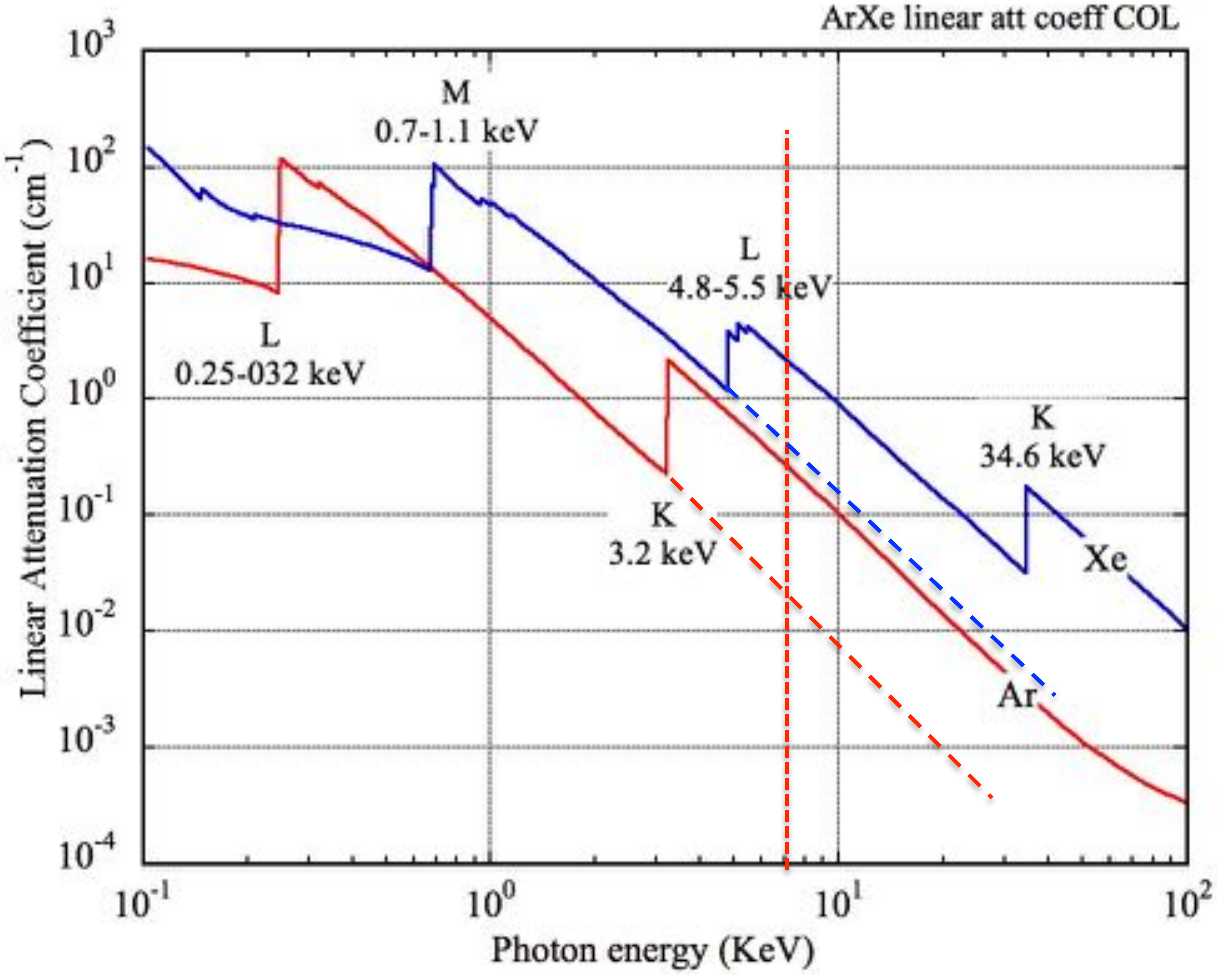


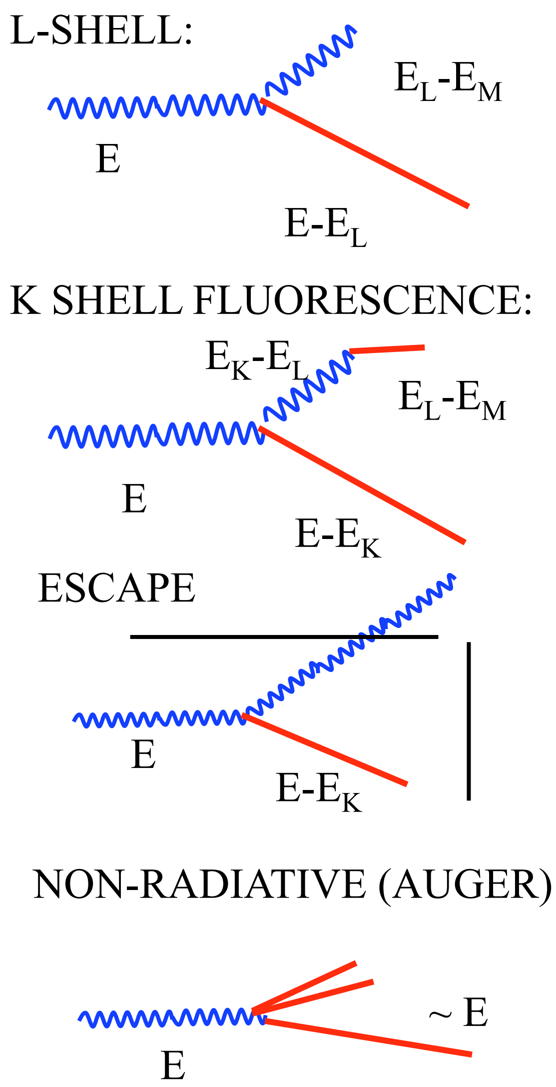
DETECTION EFFICIENCY
1 cm GAS @ STP (0^0C, 1 ATM):



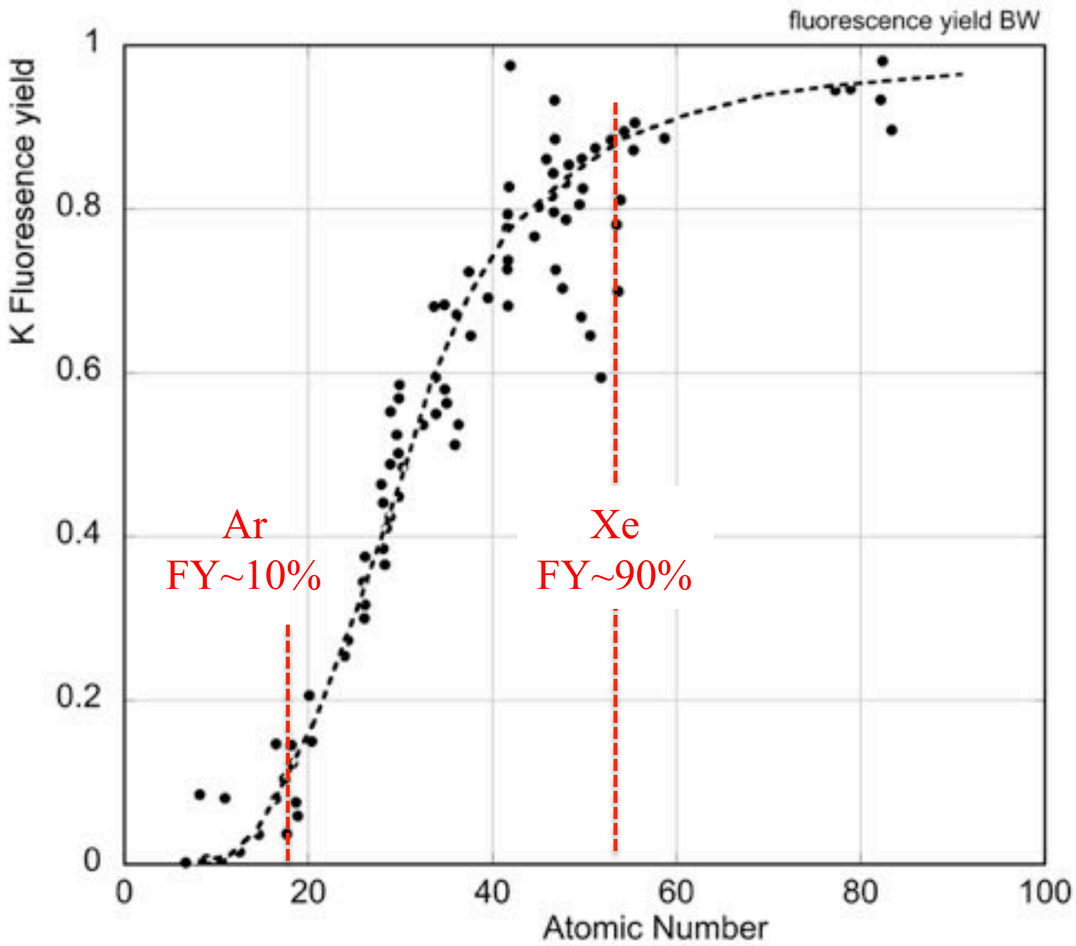

absorption length xenon
100
10
1
0.1
0.01
0.001
0.0001
10^-5
Absorption length (cm)
GAS 1 BAR
GAS 10 BAR
LIQUID
1
10
100
Energy (KeV)

LINEAR ATTENUATION COEFFICIENT (STP):

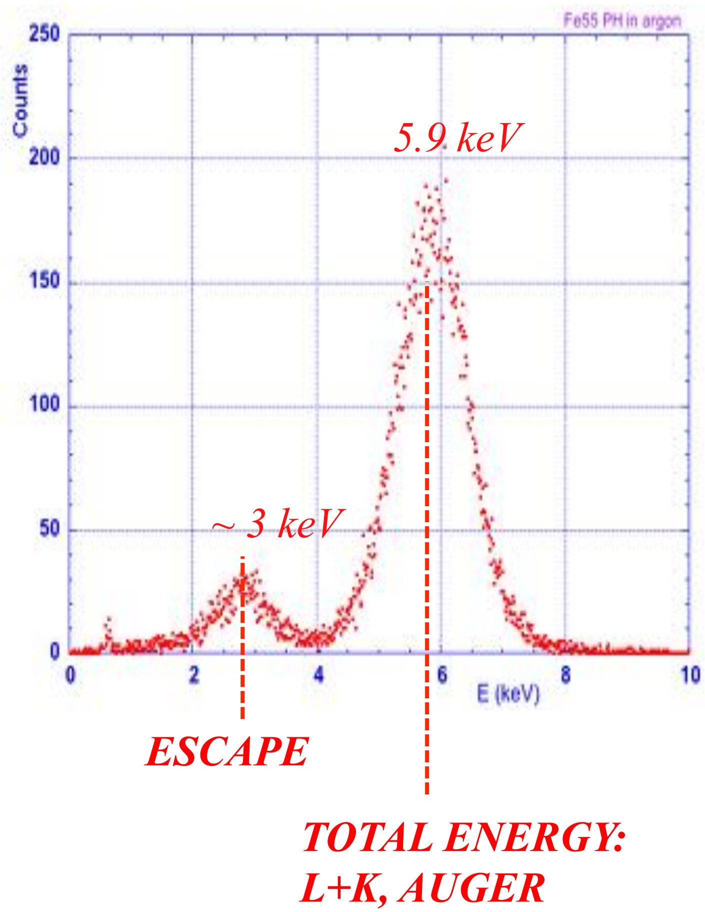




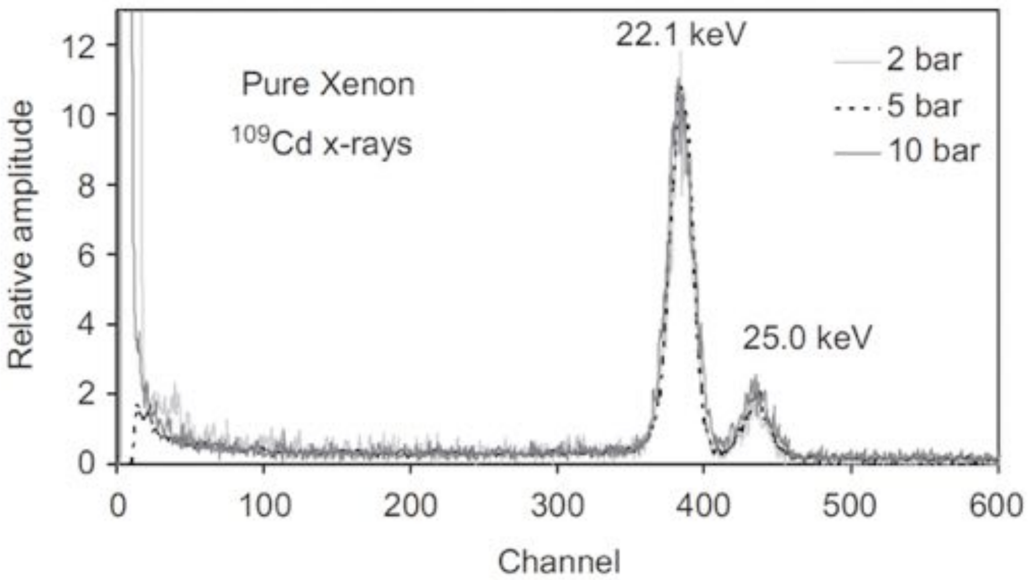
FY = Probability of Fluorescence / Total



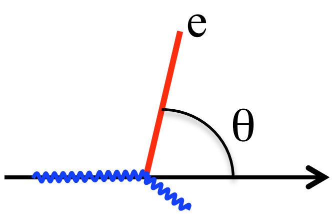
5.9 keV ^{55}Fe SOURCE IN ARGON:



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



PHOTOELECTRON EMISSION ANGLE:



E_γ 5.9 keV

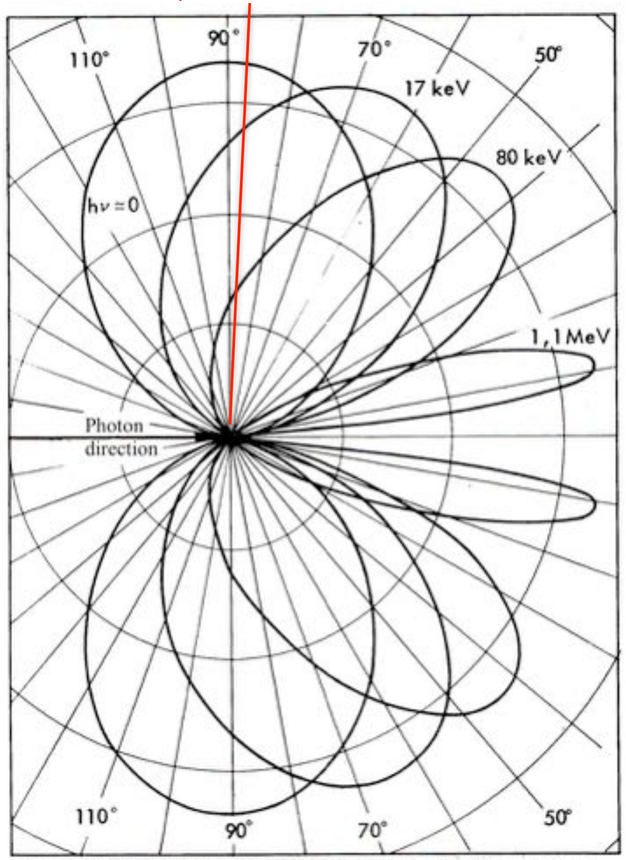
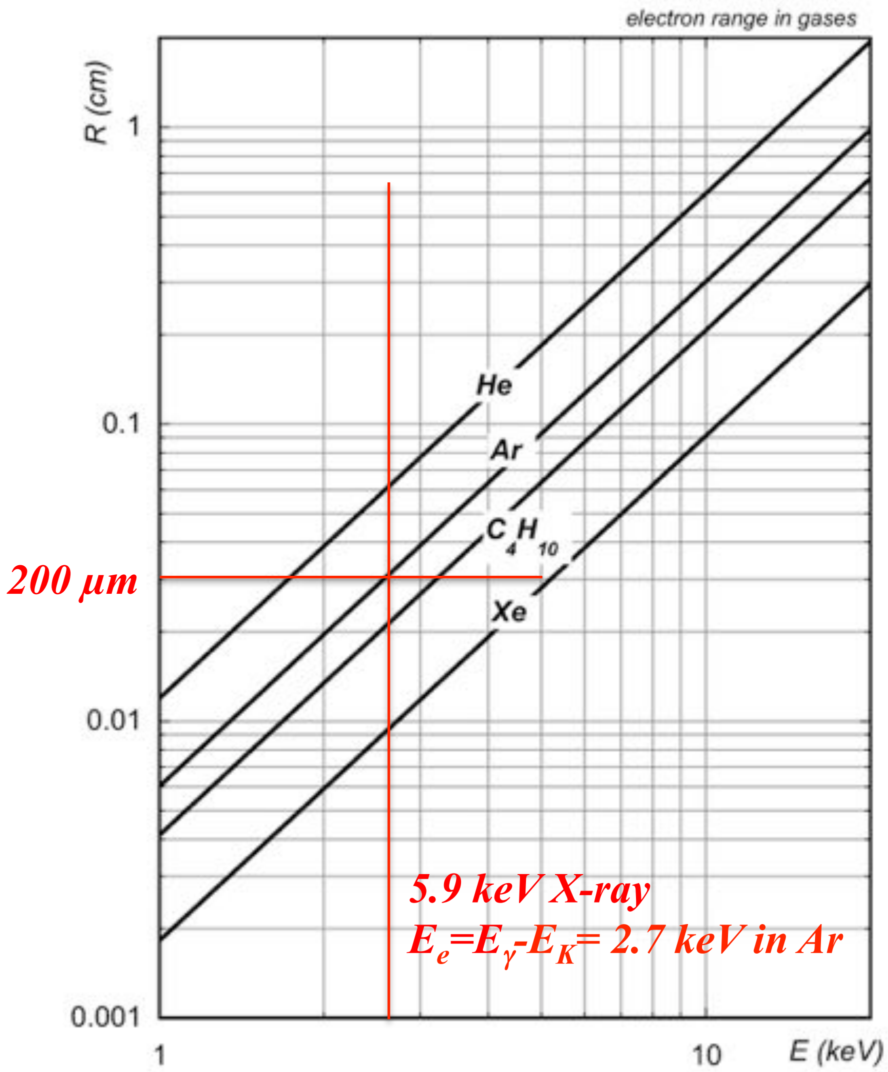
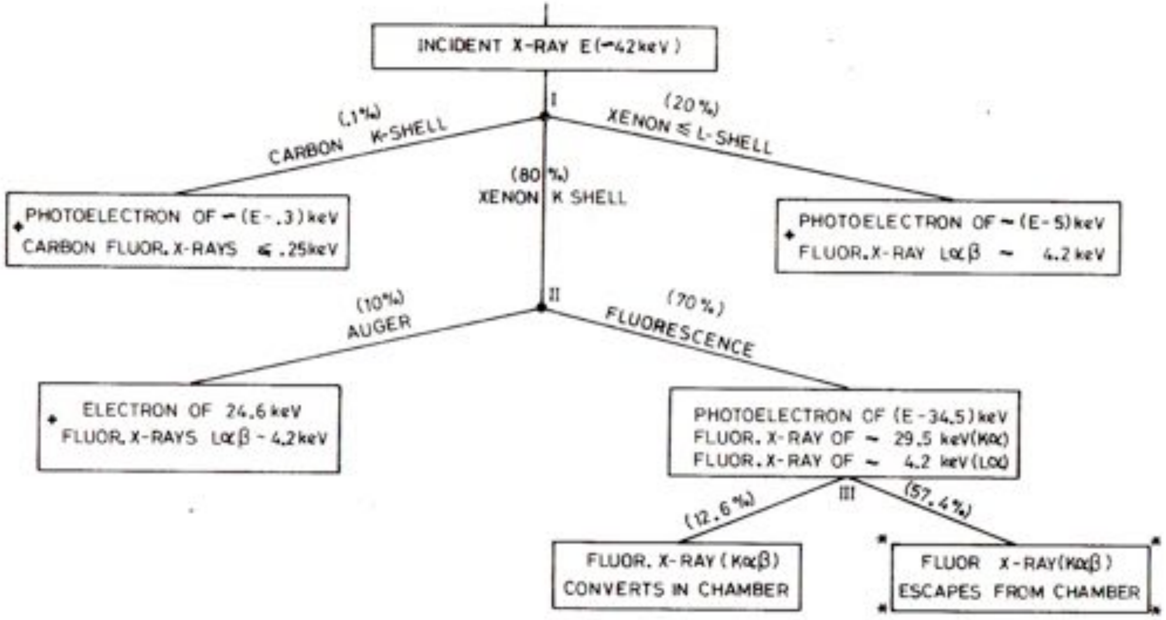


Figura 9.2. Distribuzione angolare dei fotoelettroni; le cur-

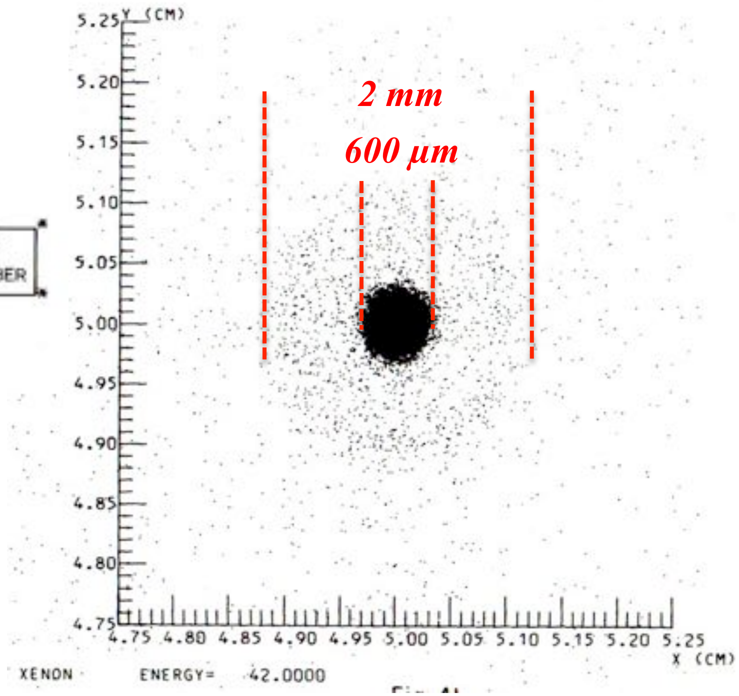
ELECTRON RANGE:



42 keV PHOTONS ON XENON



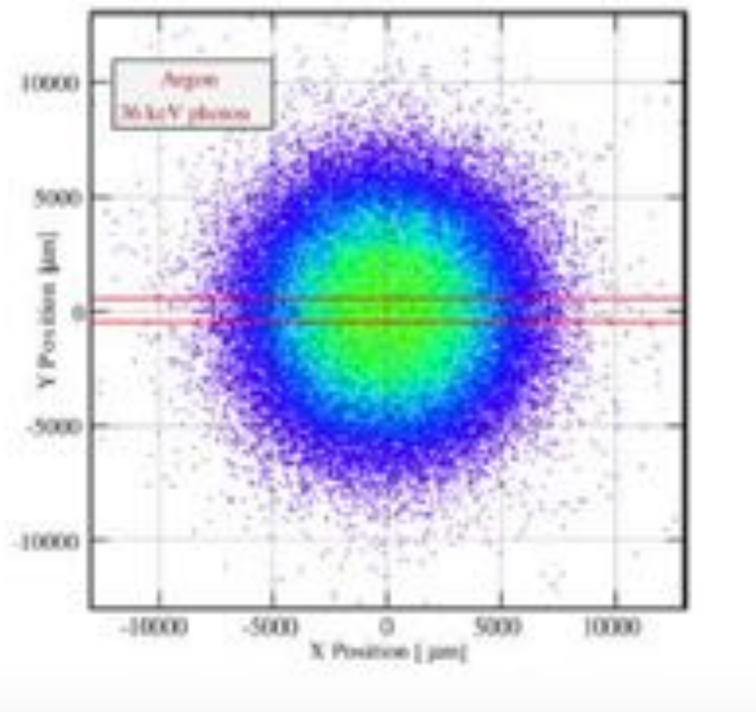
POSITION RESOLUTION FOR A POINT-LIKE COLLIMATED BEAM:

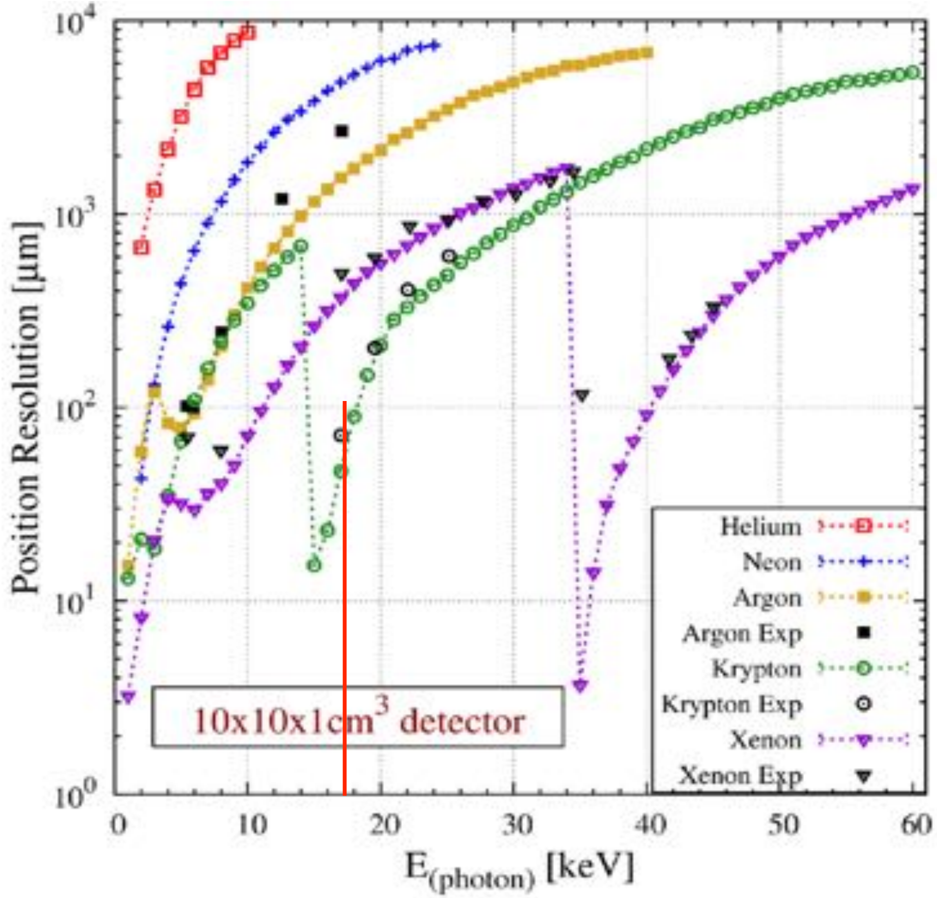


J.E. Bateman et al, RL-75-140

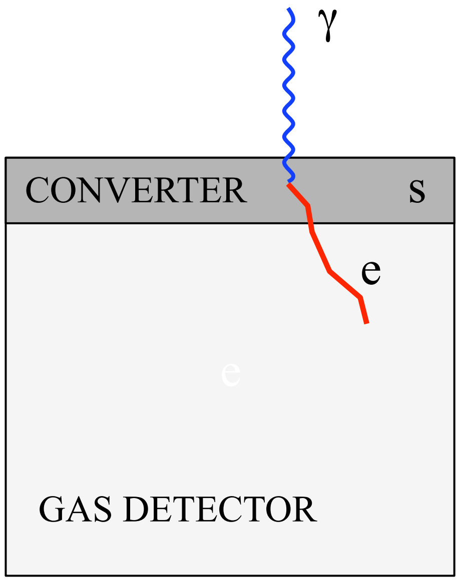
X-Rays in He, Ne, Ar, Kr and Xe AT STP

36 keV in Ar:

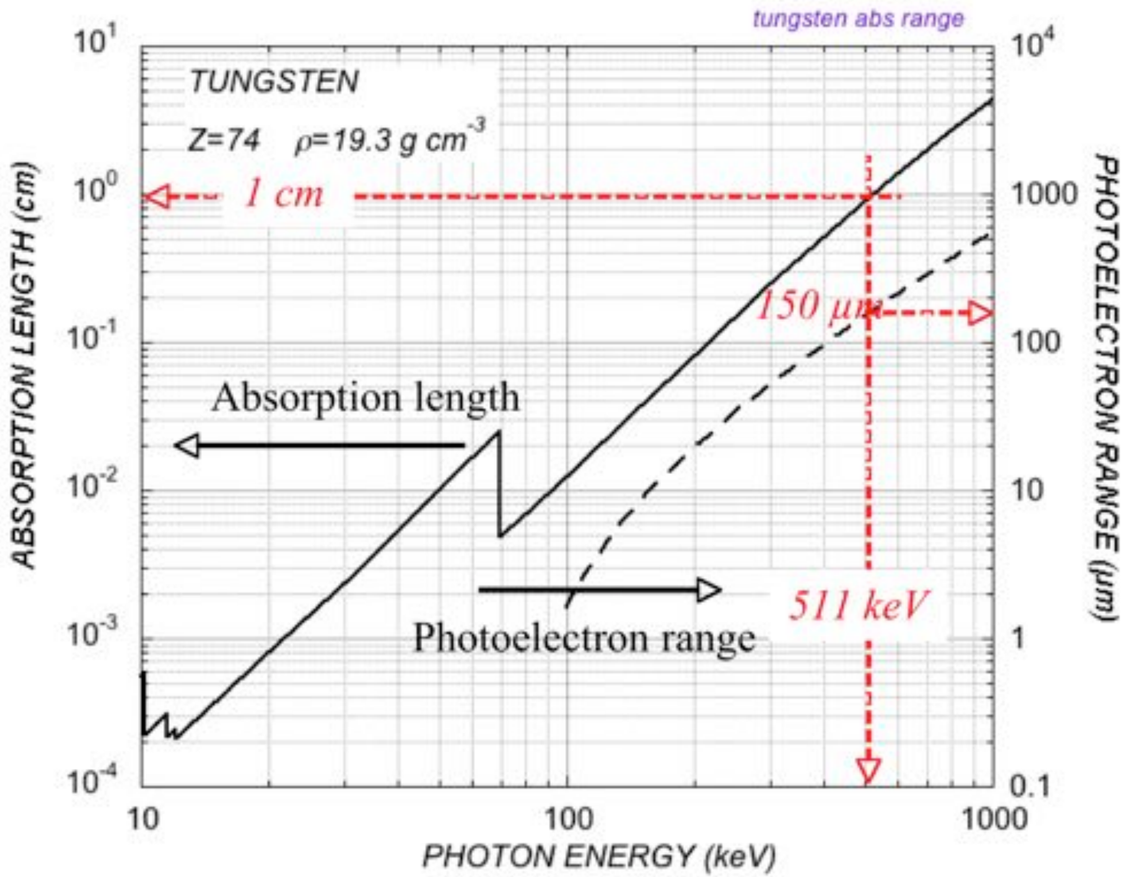




C. Azevedo et al., Phys. Lett. B 741(2015)272



USEFUL CONVERTER THICKNESS AND ELECTRON RANGE



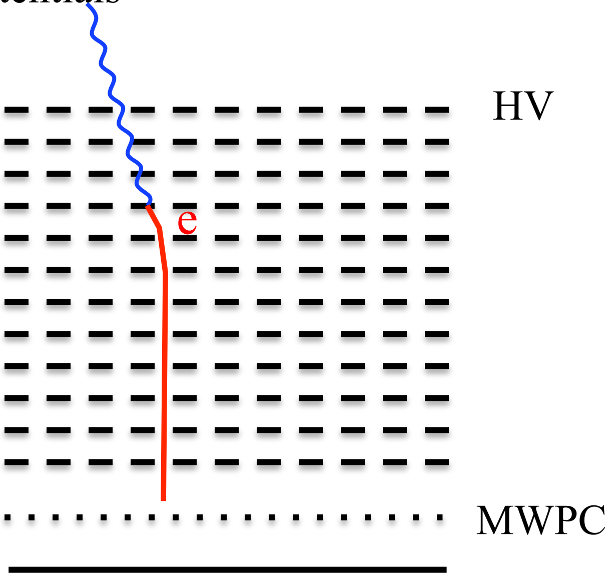
DETECTION EFFICIENCY:

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

s: converter thickness
λ: absorption length

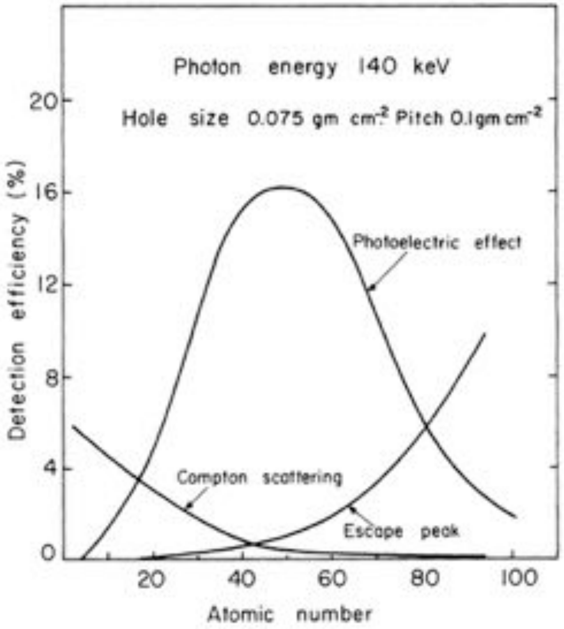
100 µm converter --> ε ~ 1%

HEAVY DRIFT CHAMBER
Stack of converter Grids at graded potentials

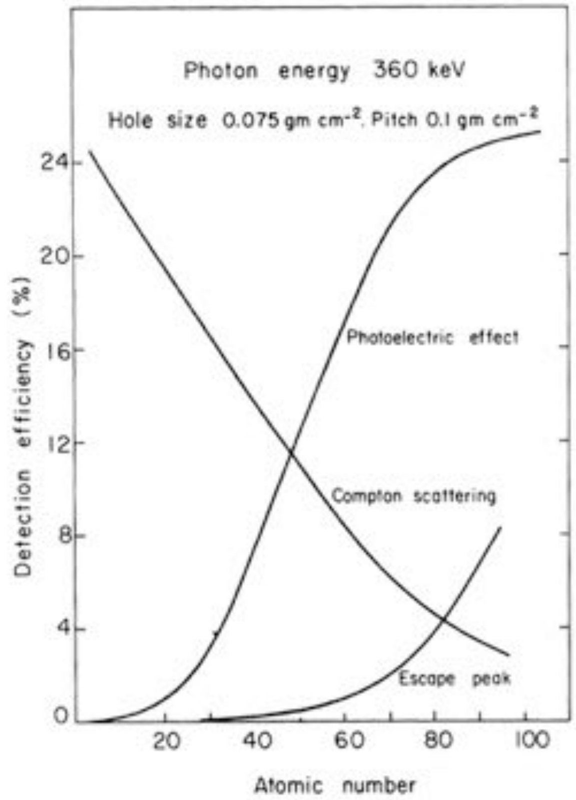


EFFICIENCY vs CONVERTER ATOMIC NUMBER:

140 keV

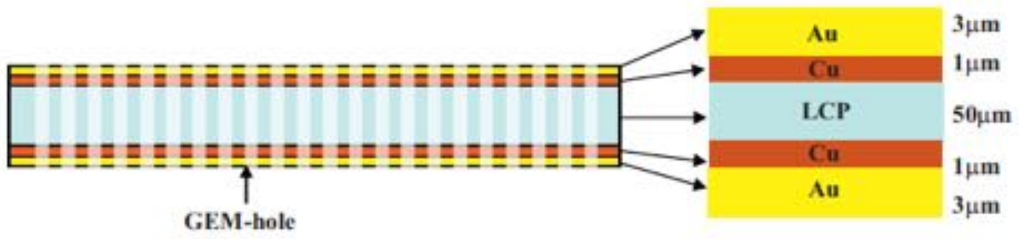


360 keV

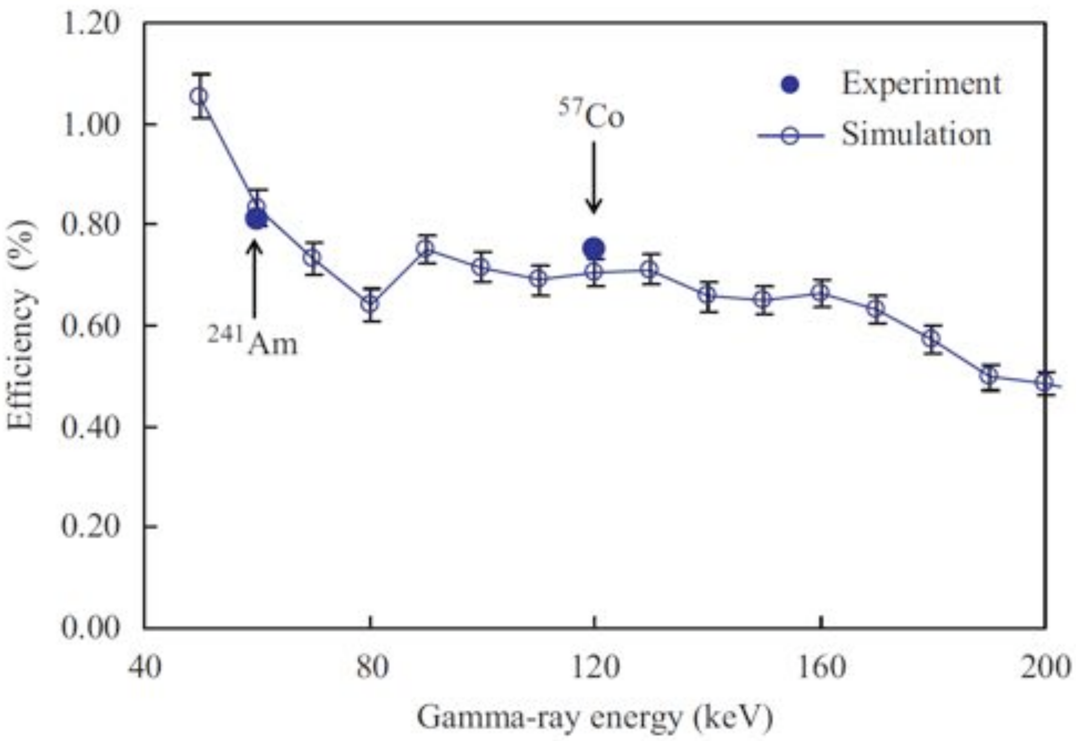


A. Jeavons et al, IEEE Trans. Nucl. Sci. NS-23 (1978)41

GOLD-COATED GAS ELECTRON MULTIPLIER (GEM)



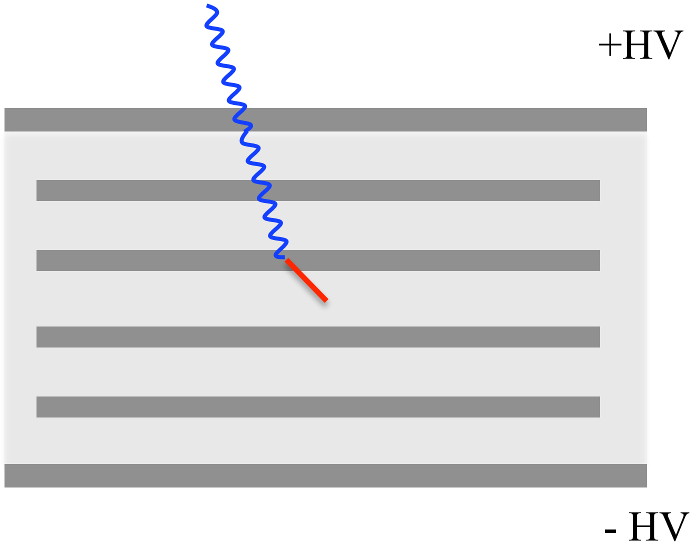
DETECTION EFFICIENCY

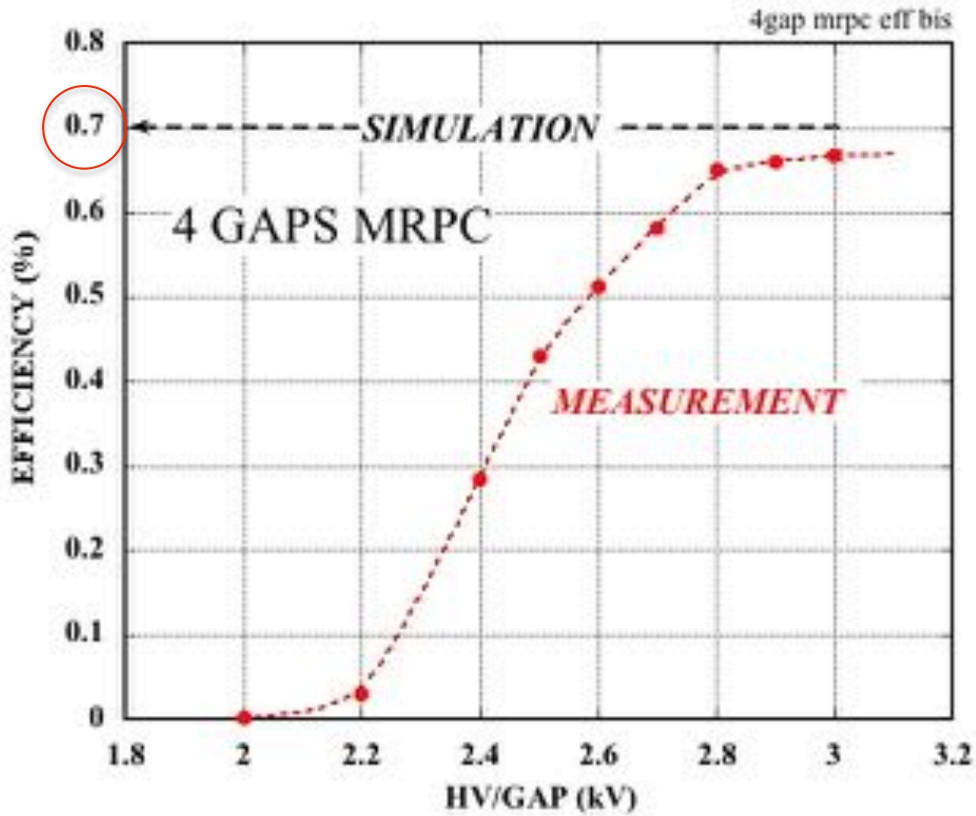


T. Koike et al,
Nucl. Instr. and Meth. A648(2011)180

DETECTION OF 511 keV γ FOR PET
MULTI-GAP RESISTIVE PLATE CHAMBER

400 μm HIGH RESISTIVITY GLASS PLATES





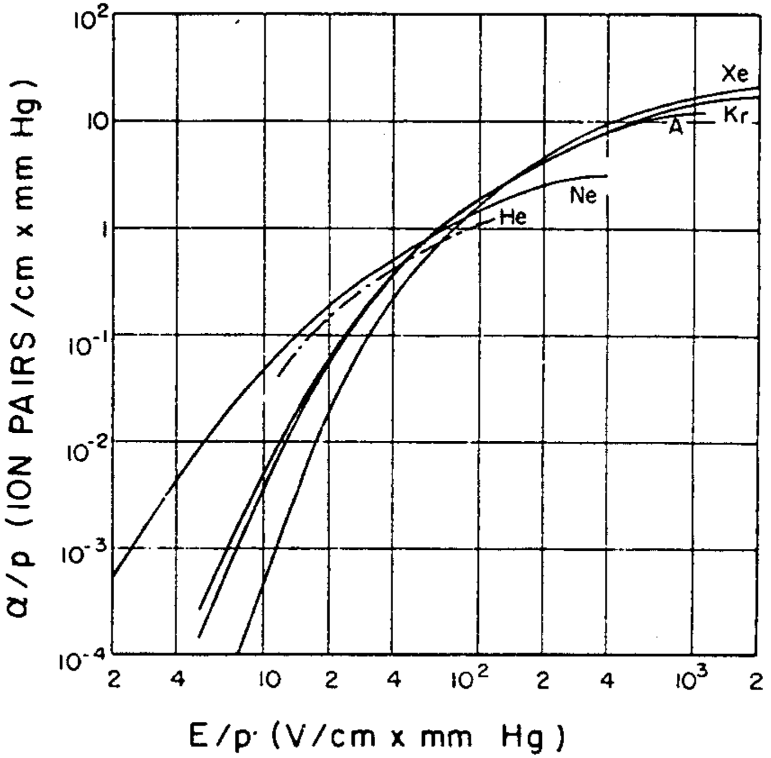
D. Watts et al, J. Rad. Res. 54 (2013)i136

Mean free path for ionization:

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

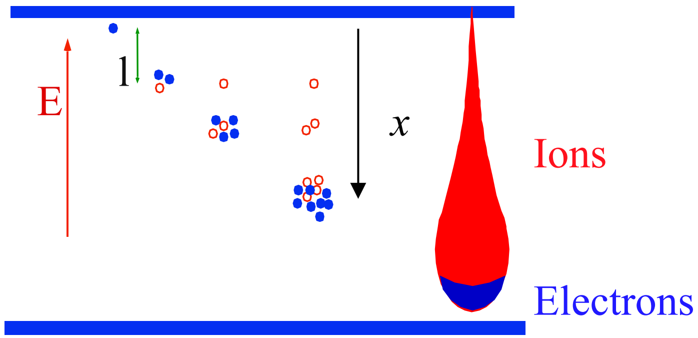
Townsend coefficient:

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



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)

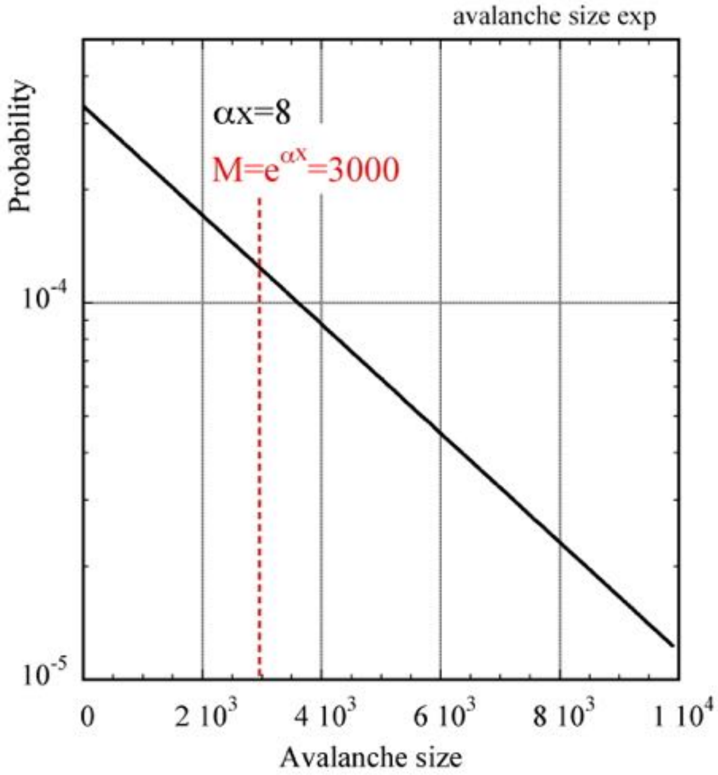
SINGLE ELECTRON
AVALANCHE SIZE DISTRIBUTION

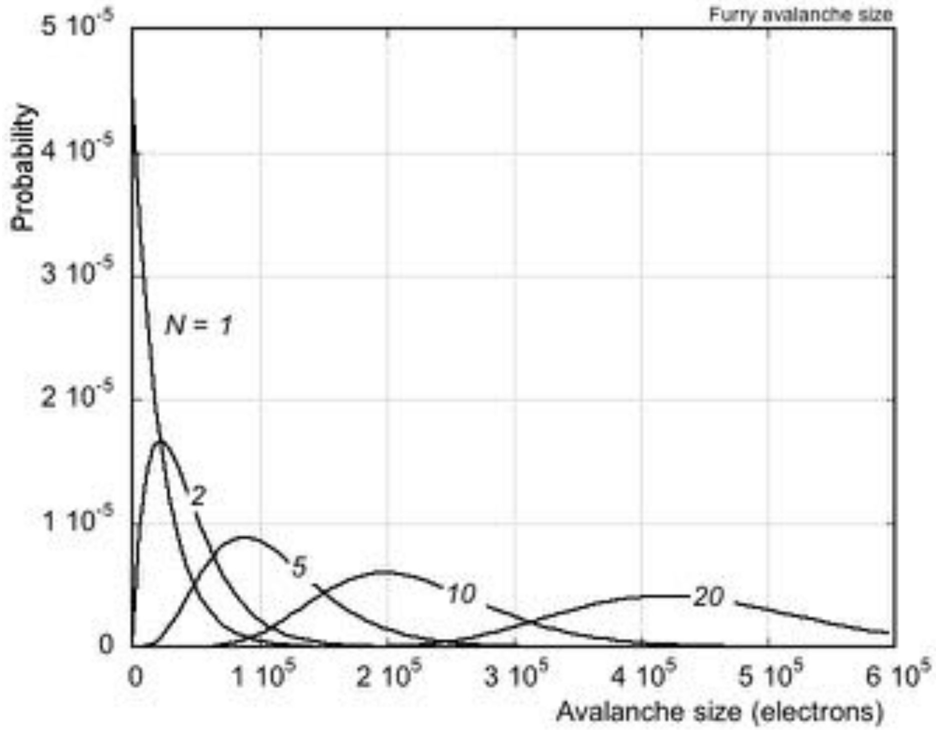
$$P(n) = \frac{e^{-n/\bar{n}}}{\bar{n}} \qquad M = \bar{n} = e^{\alpha x} \qquad \sigma_{\bar{n}} = \bar{n}$$

MAXIMUM PROBABILITY FOR n=1!

N ELECTRONS:

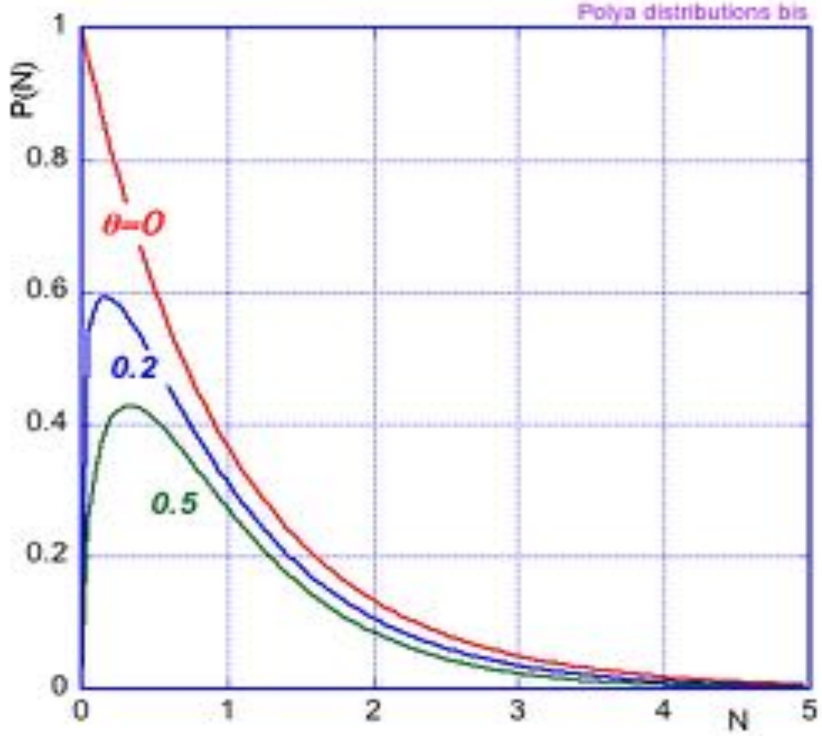
$$P(n,N) = \frac{1}{\bar{n}}\left(\frac{n}{\bar{n}}\right)^{N-1} \frac{e^{-\frac{n}{\bar{n}}}}{(N-1)!}$$





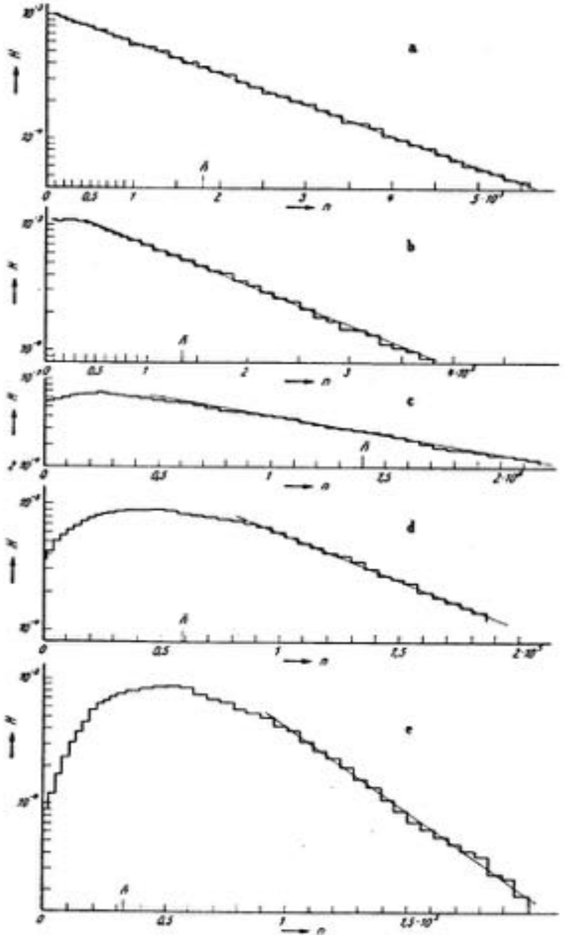
AVALANCHE DISTRIBUTION AT INCREASING GAINS (FIELDS)
POLYA DISTRIBUTION

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

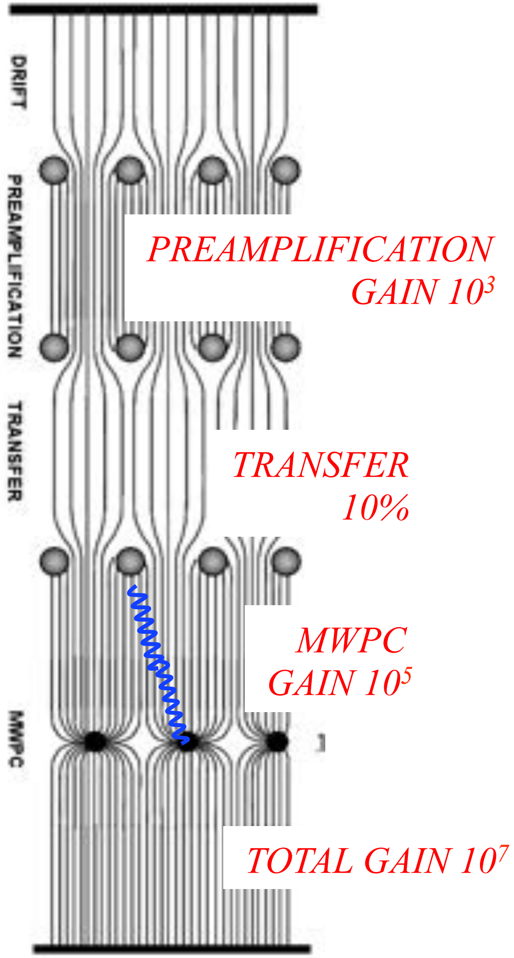


H. Schindler, S.F. Biagi, R. Veenhof
Nucl. Instr. and Meth. A624(2010)78

EXPERIMENTAL:

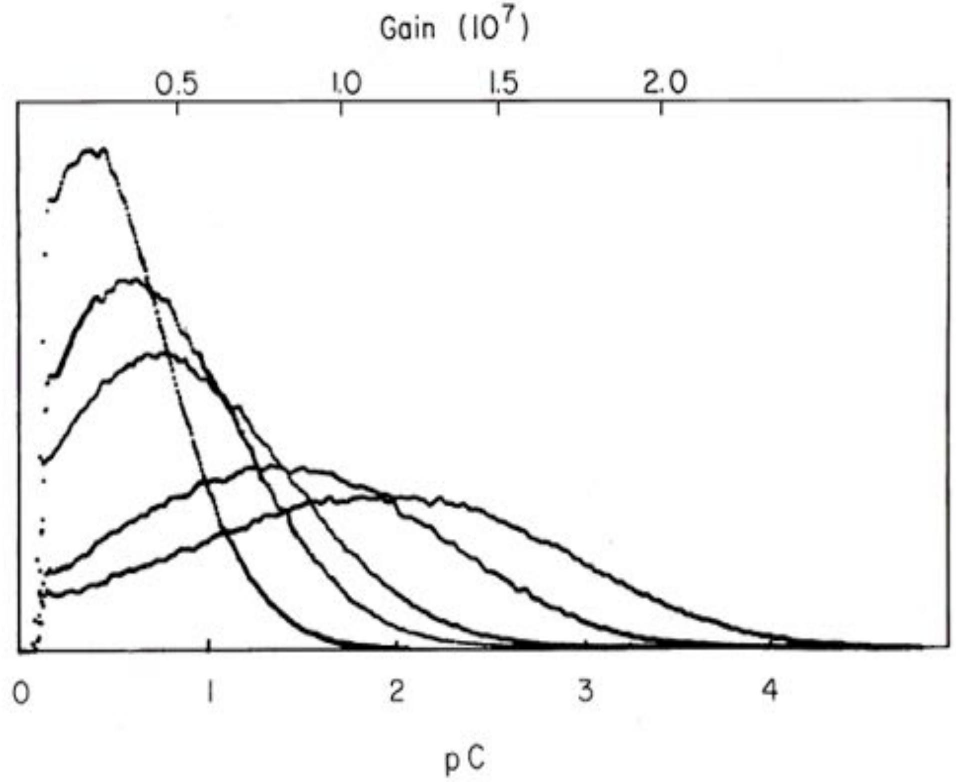


H. Sclumbohm, Zeit. Physik 151(1958)563



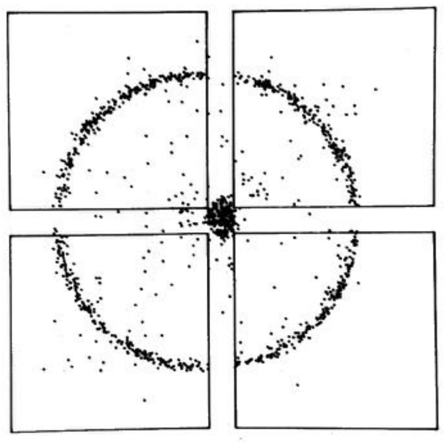
] G. Charpak and F. Sauli, Phys. Letters 78B(1978)523

SINGLE ELECTRON PH
DISTRIBUTIONS:



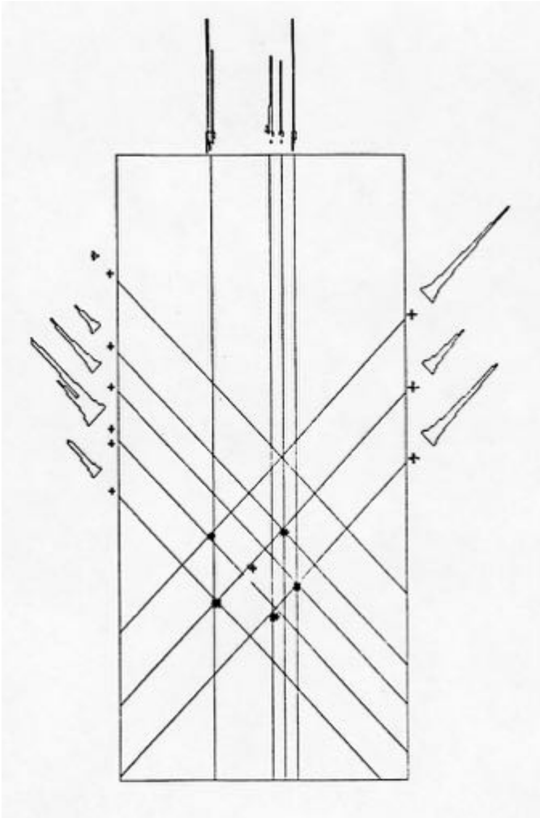
R. Bouclier, et al.,
Nucl. Instr. and Meth. 205 (1983) 403

OVERLAPPING CHERENKOV RINGS
He-CH_4-TEA (92-5-3)

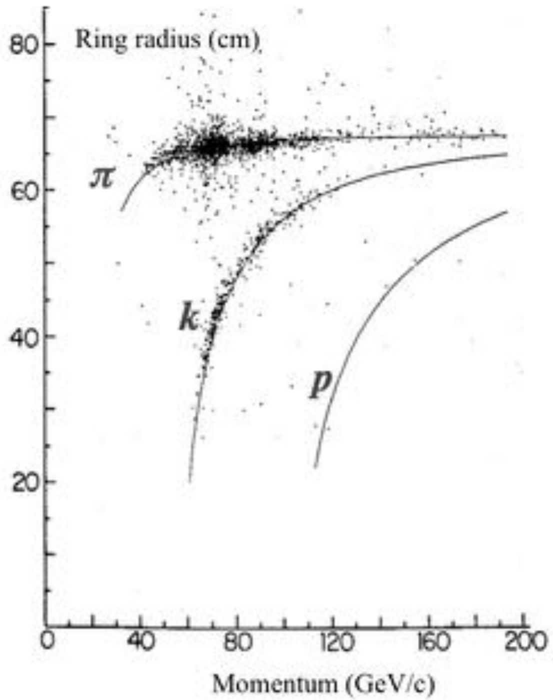


R. McCarty, et al,
Nucl. Instr. and Meth. A248(1986)69

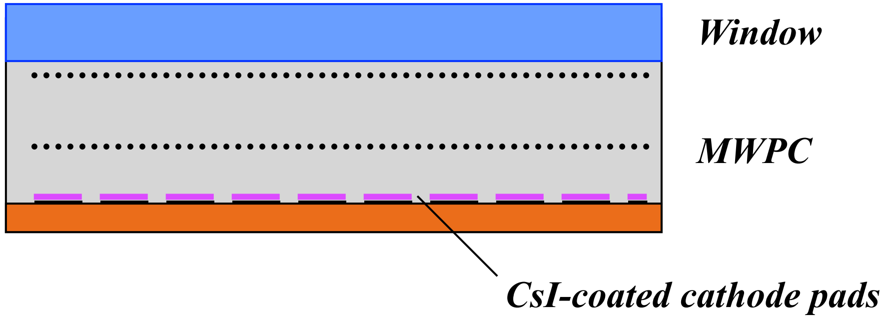
E-605 RICH
5-PHOTONS RING

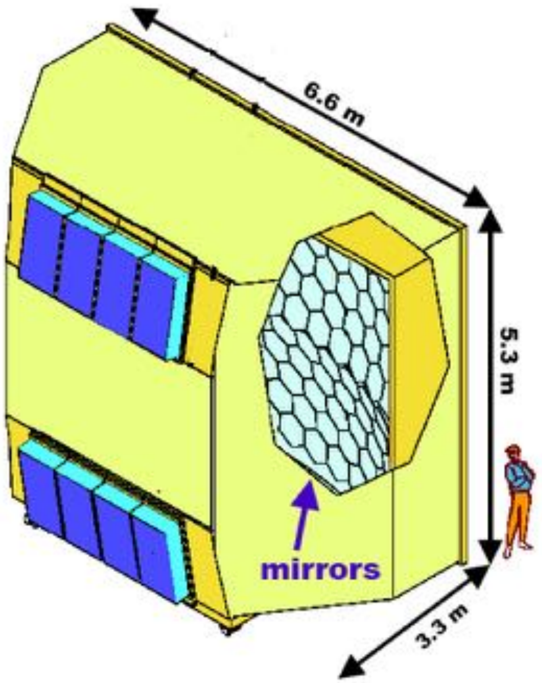


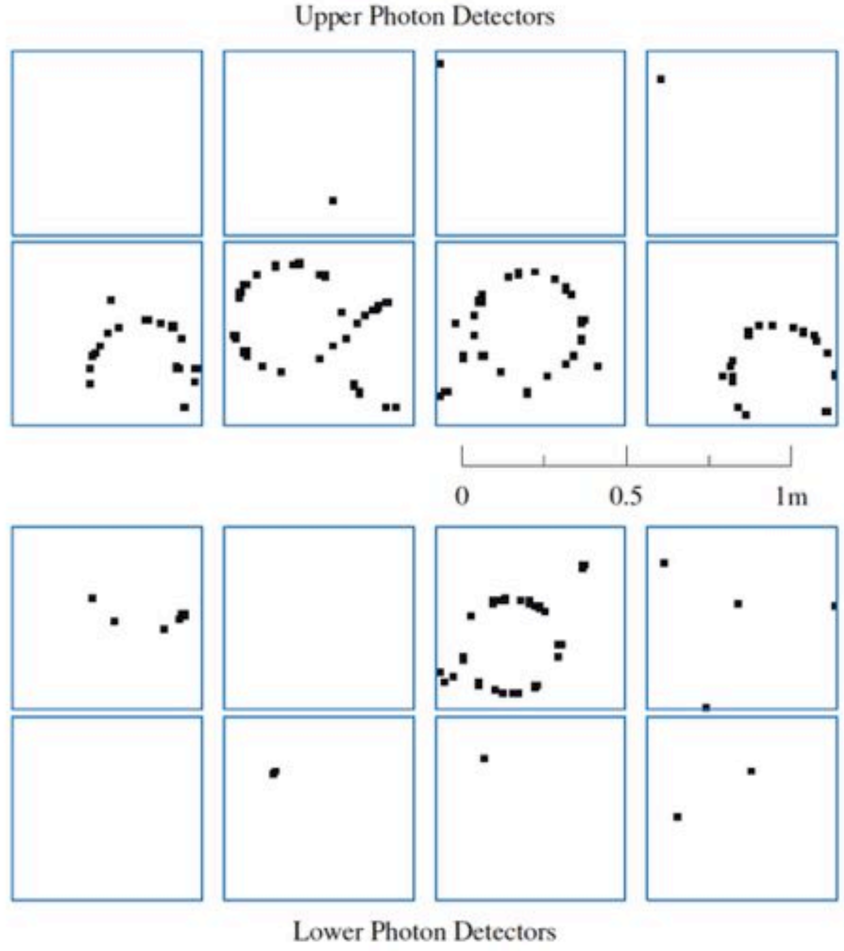
PARTICLE IDENTIFICATION



COMPASS RING IMAGING CHERENKOV COUNTER (RICH)

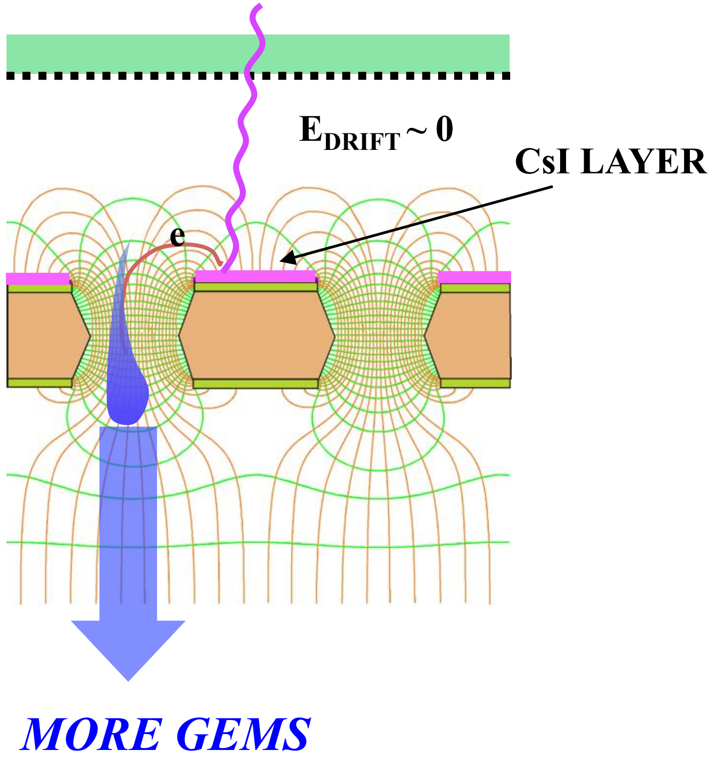


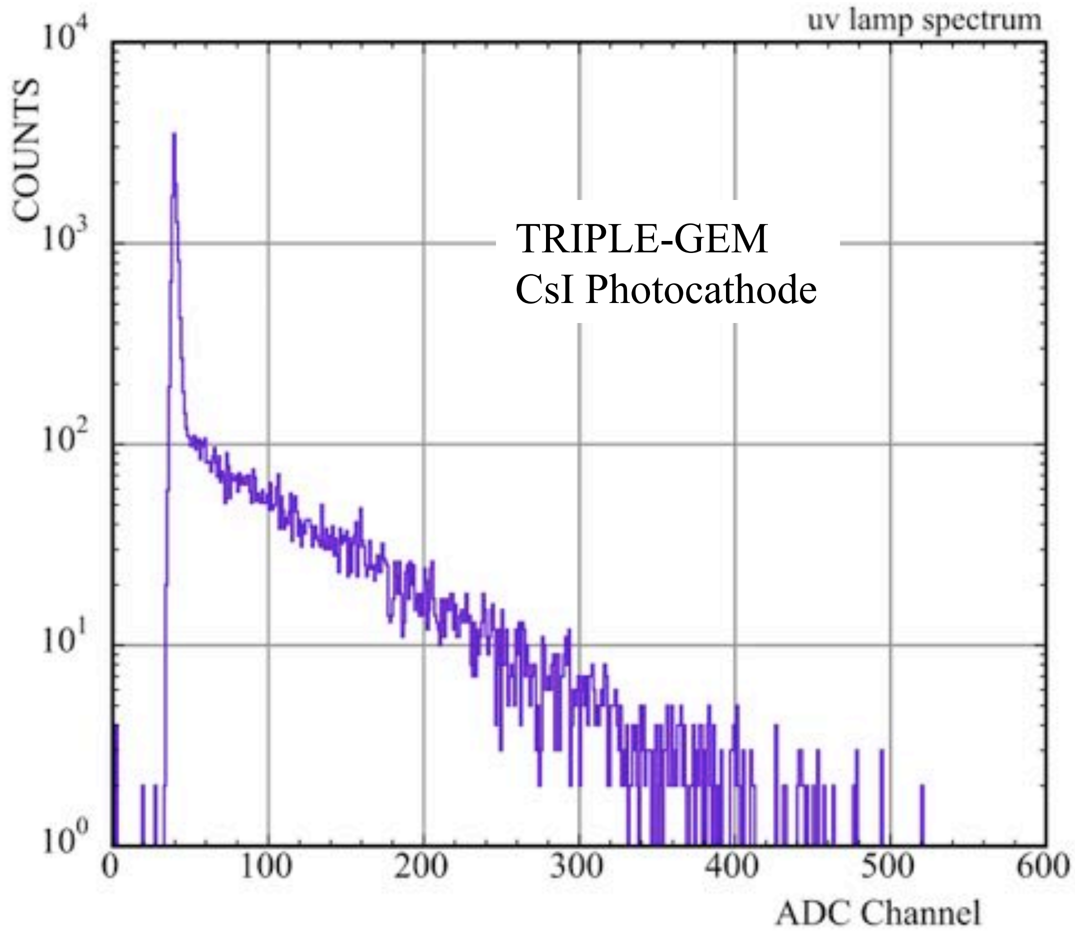




E. Albrecht et al, Nucl. Instr. and Meth. A502(2003)112

GAS ELECTRON MULTIPLIER (GEM)



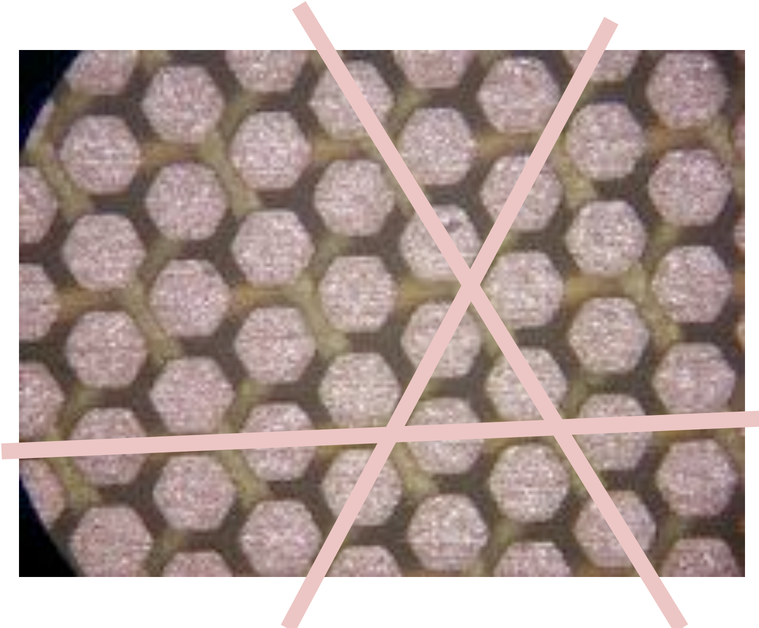


- No photon feedback
- Strong suppression of ions feedback

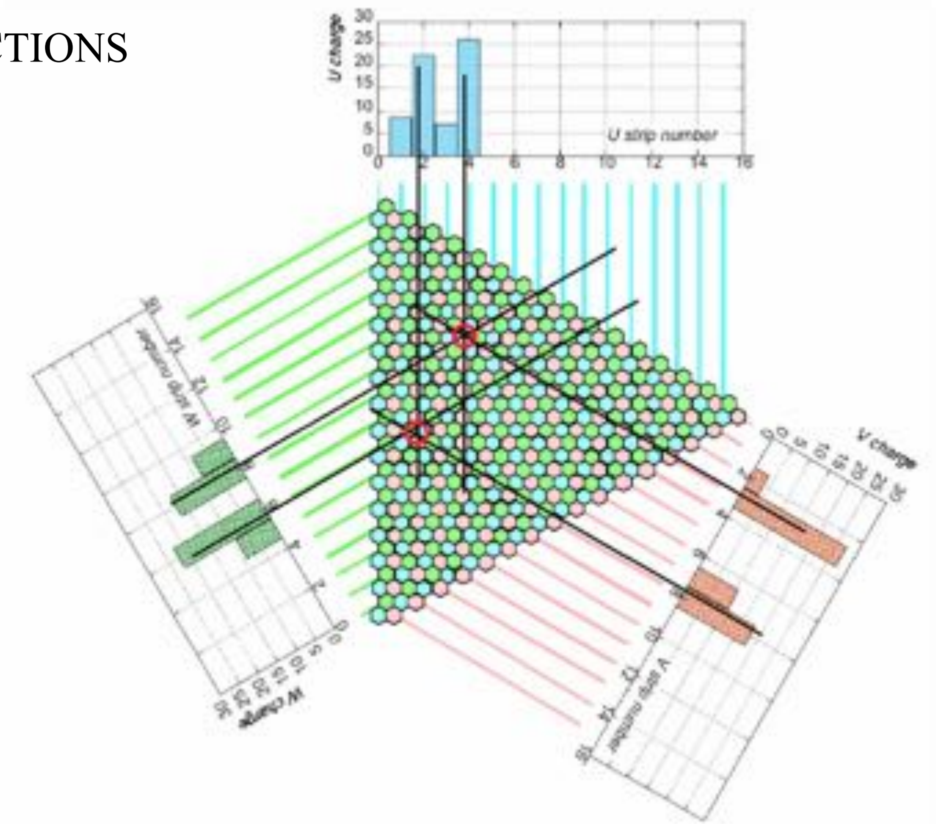
F. Sauli, Nucl. Instr. and Meth. A553(2005)18

TRIPLE GEM WITH HEXABOARD READOUT

MATRIX OF HEXAGONAL PADS
INTERCONNECTED ALONG THREE DIRECTIONS

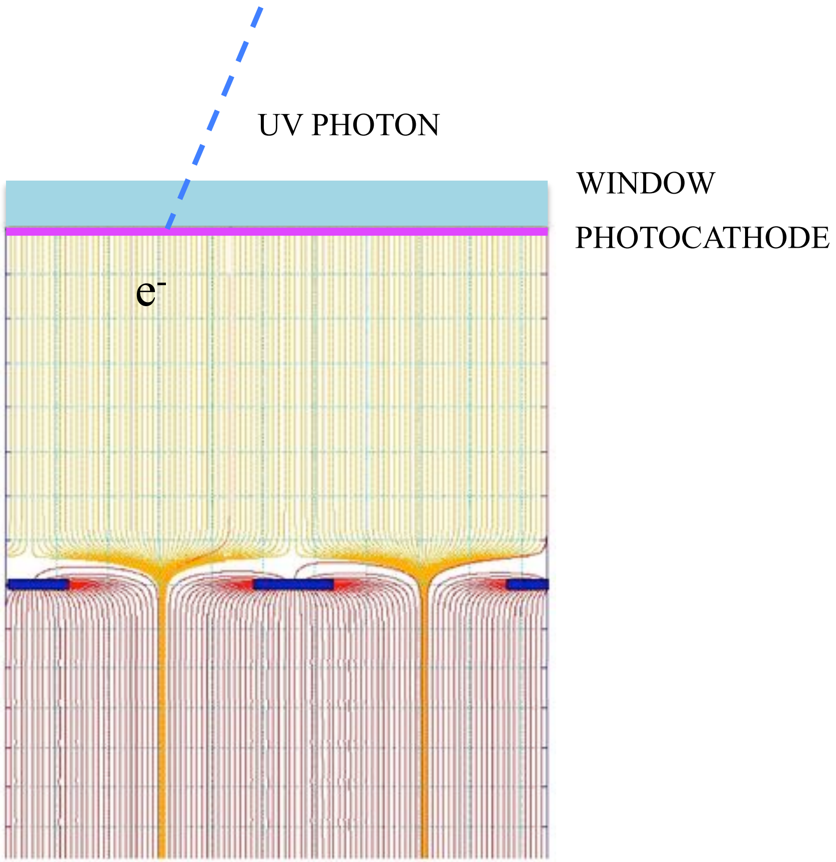


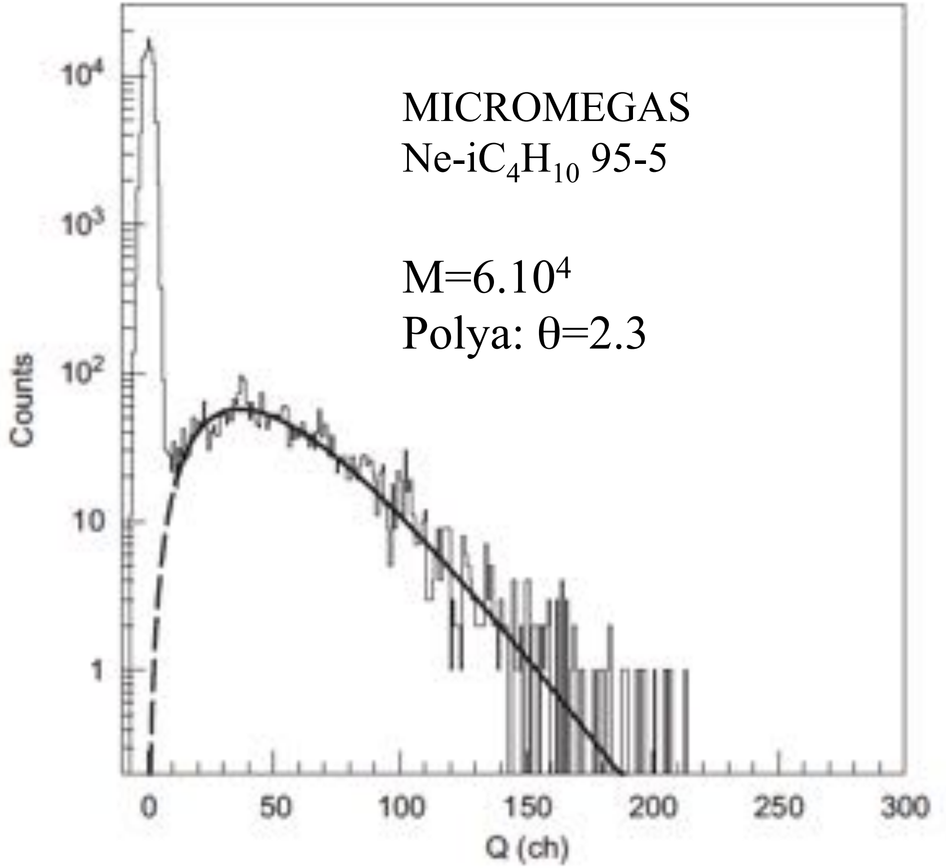
TWO-PHOTONS EVENT:



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

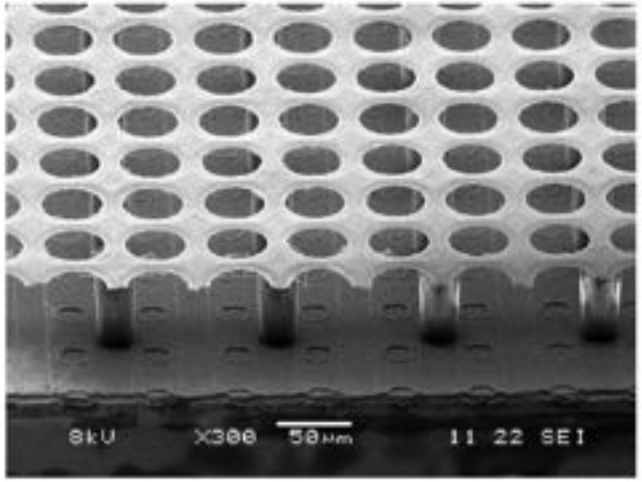
MICROMEGAS

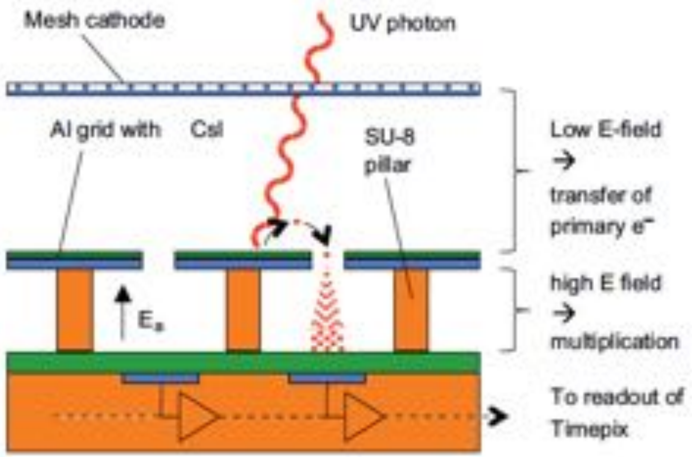


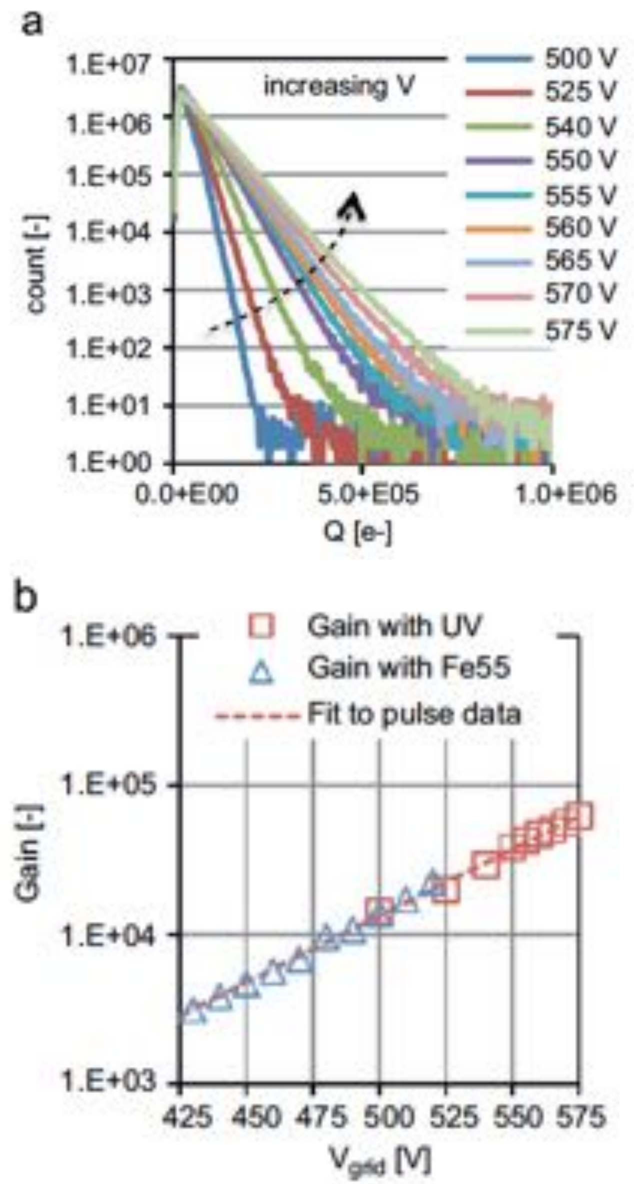


T. Zerguerras et al, Nucl. Instr. and Meth. A608(2009)397

CsI-COATED MICROMEGAS WITH TIMEPIX READOUT



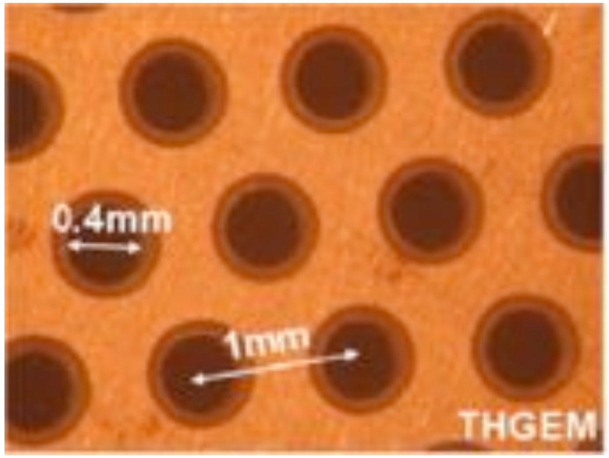




J. Melai et al, Nucl. Instr. and Meth, A628(2011)133

MECHANICAL DRILLING OF METAL-CLAD PC BOARD:

- SELF-SUPPORTING
- HIGH GAIN



R.Chechik et al,
Nucl. Instr. and Meth. A535(2004)303

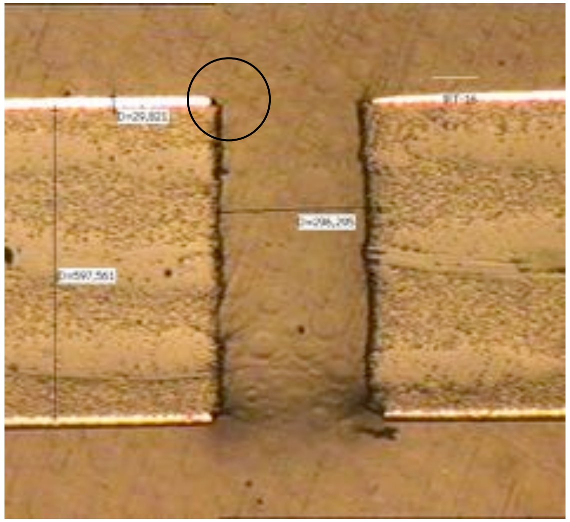
A. Breskin et al,
Nucl. Instr. And Meth. A623(2010)132

ALSO NAMED LARGE ELECTRON MULTIPLIER (LEM)

P. Janneret, Thesis at Neuchatel University (2001)

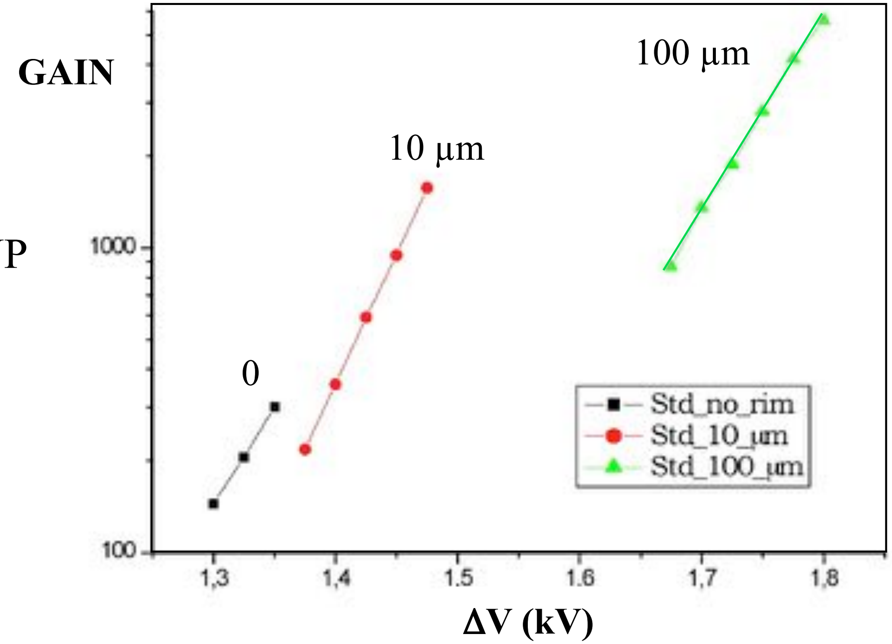
A. Badertscher et al, Nucl. Instr. And Meth. A617(2010)188

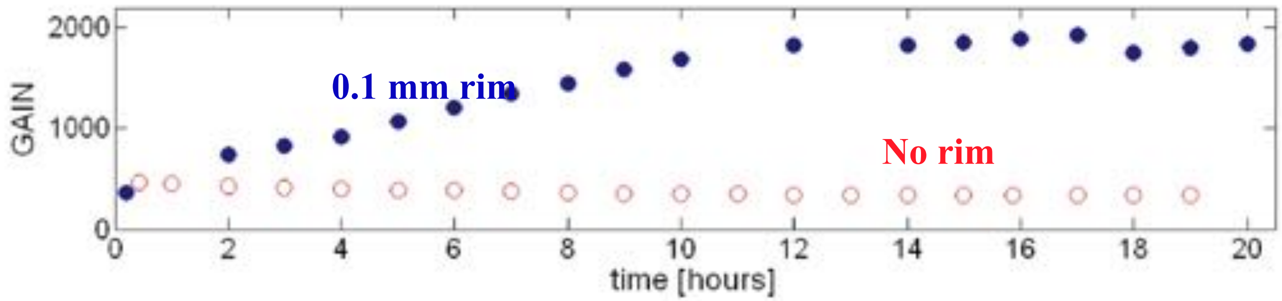
DEVELOPMENT FOR THE COMPASS RICH UPGRADE



LARGE RIM:
- HIGH GAIN
- CHARGING UP

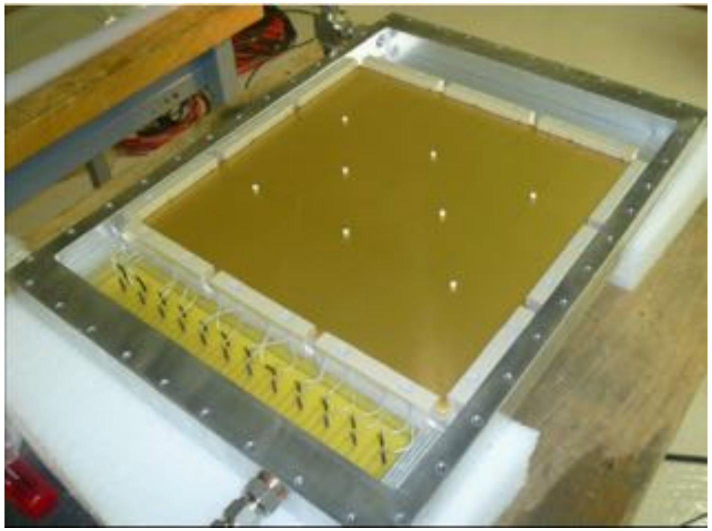
RIMLESS:
- LOW GAIN
- STABLE



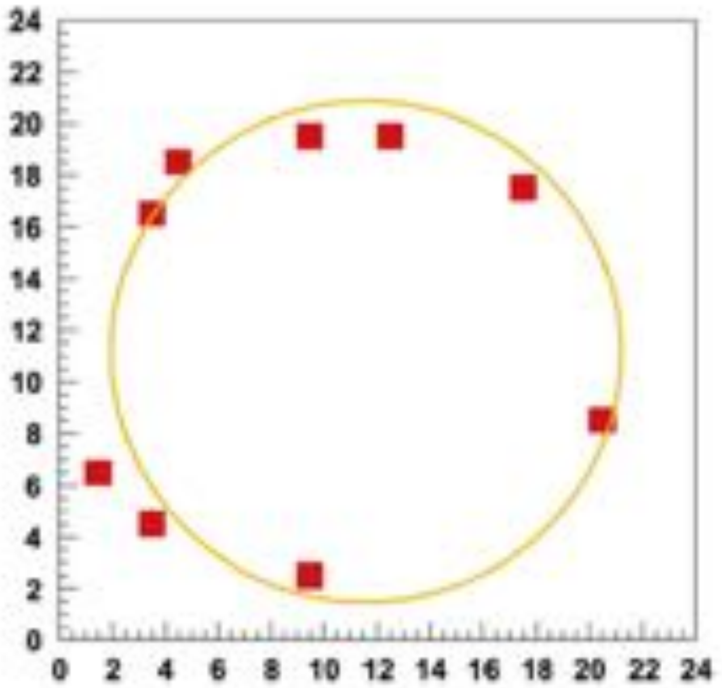


M. Alexeev et al, Nucl. Instr. and Meth. A695(2012)159

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

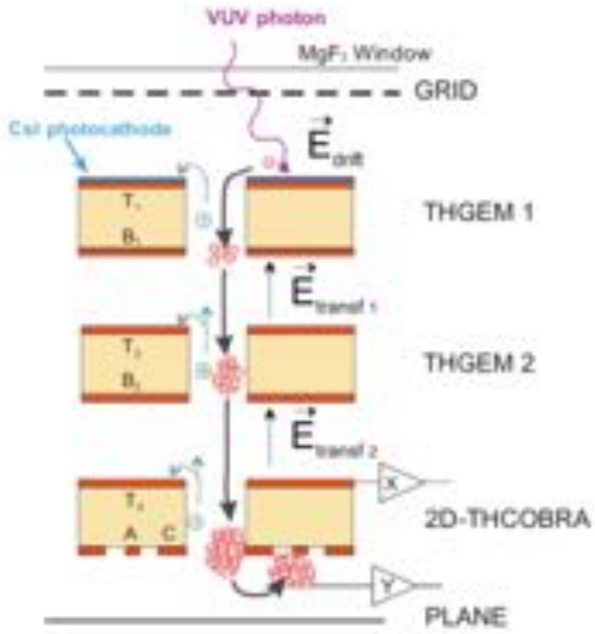


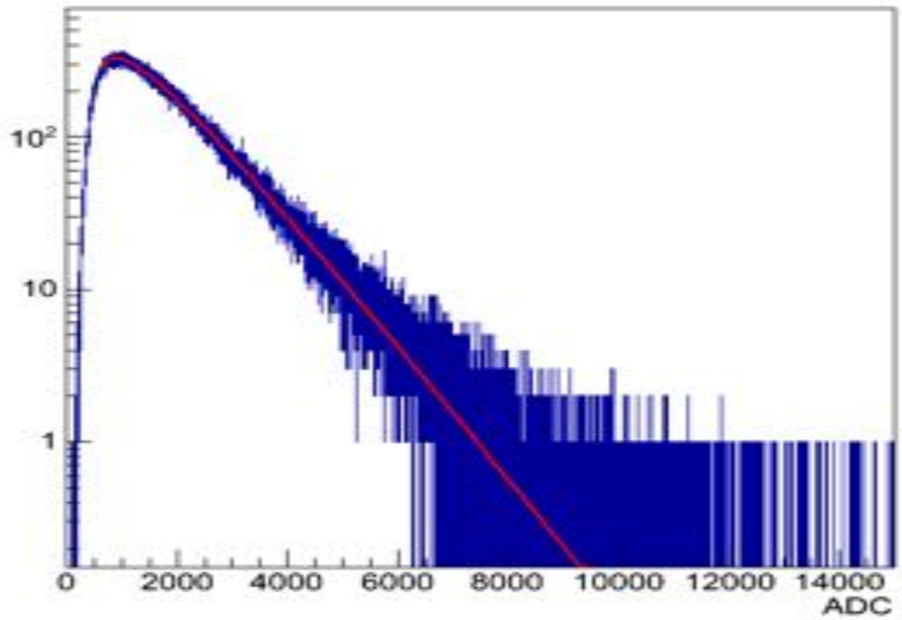
9-PHOTONS RING



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

THICK COBRA





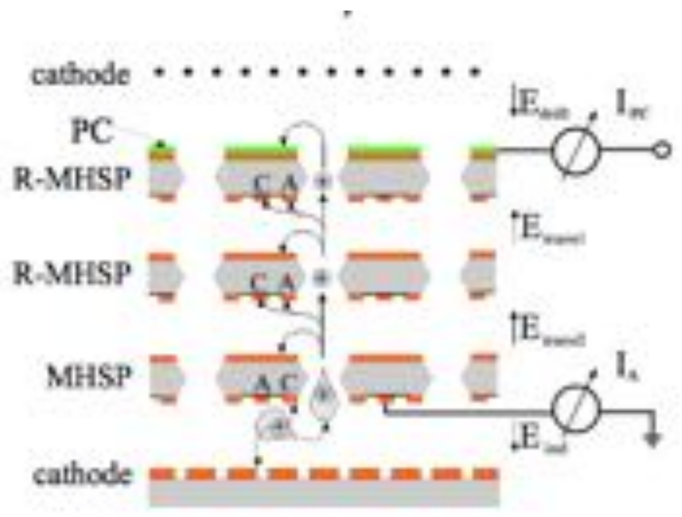
- $G > 10^6$
- collection efficiency ~100%
- $R_{p(\mathrm{anode})} = 60\ \mu\mathrm{m}$
- $R_{p(\mathrm{top})} = 90\ \mu\mathrm{m}$
- only a few discharges for several months even for high photon flux

F. Amaro et an JINST5 (2010)

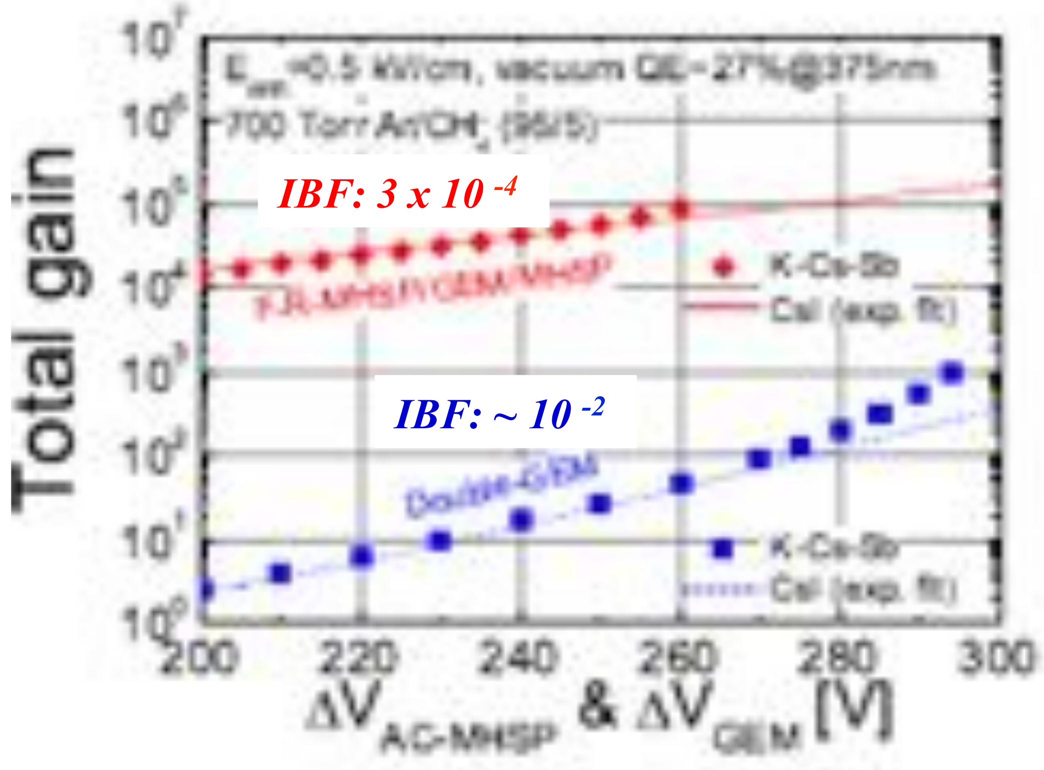
J.F.C.A.Veloso et al
Nucl. Instr. and Meth. A639(2011)

NEW STRUCTURES:
COBRA, MICRO-HOLES AND STRIPS, PACEM….

GEM+MICRO-HOLE AND SRIP PLATE
GEM-MHSP:

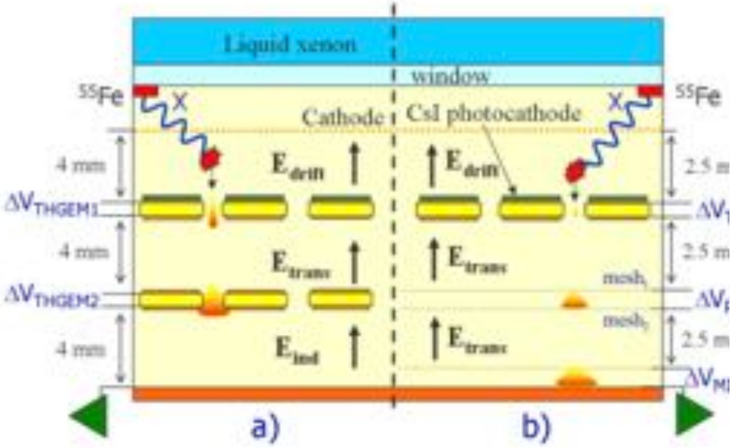


R. Chechik, A. Breskin,
Nucl. Instr. and Meth. A595(2008)116

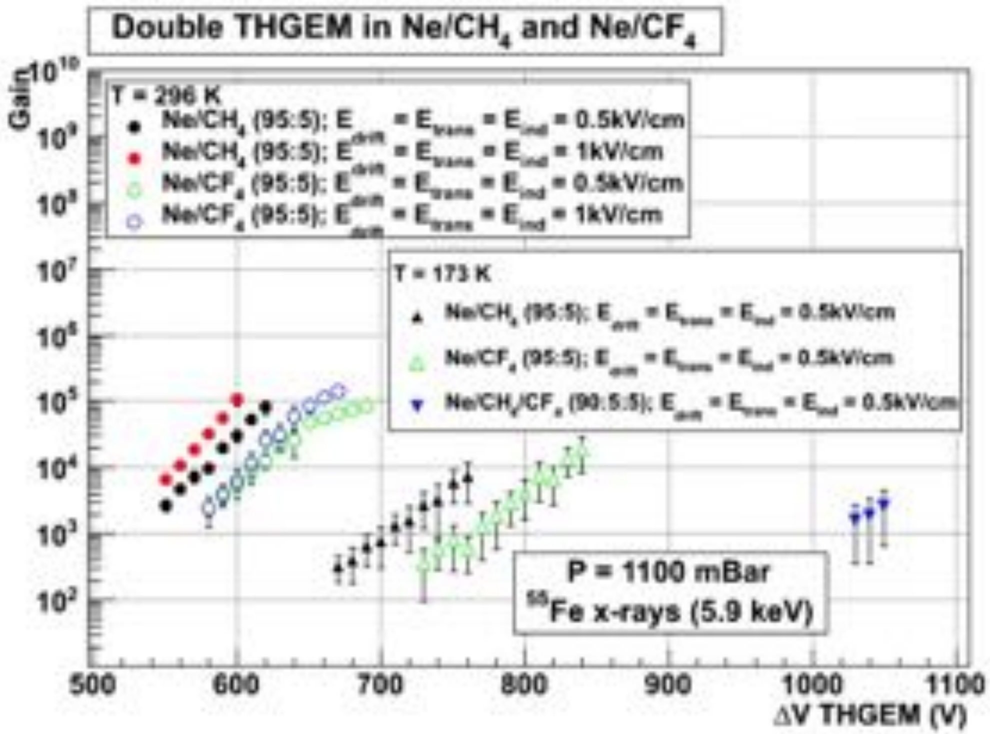


A.V.Lyashenko et al., 2009 JINST 4 P07005

LIQUID XENON
THICK-GEM with CsI Photocathode + MICROMEGAS

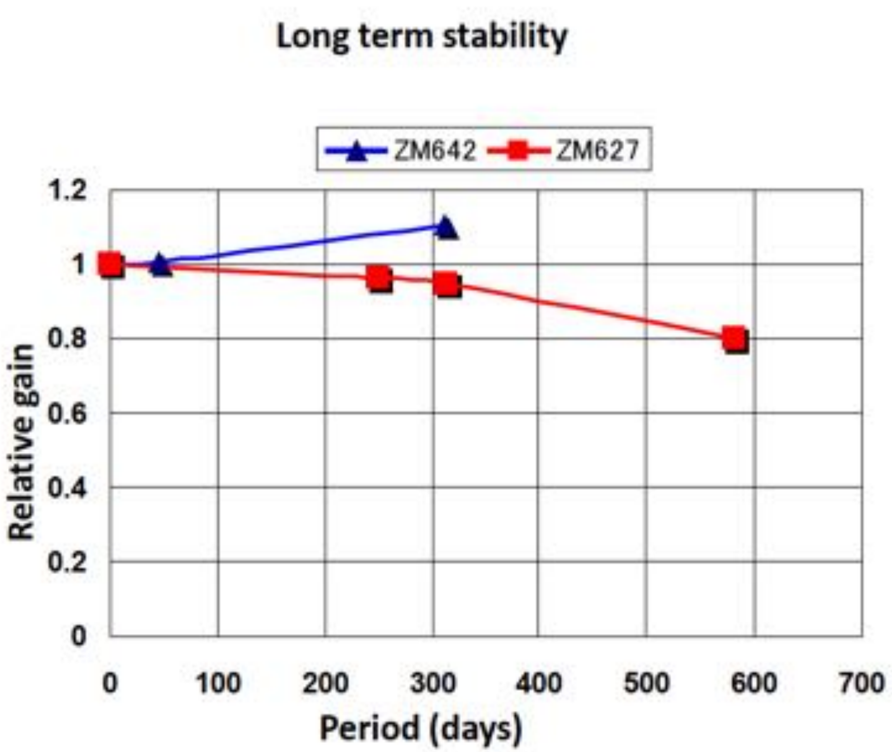


S. Duval et al,. JINST 6(2011)P04007

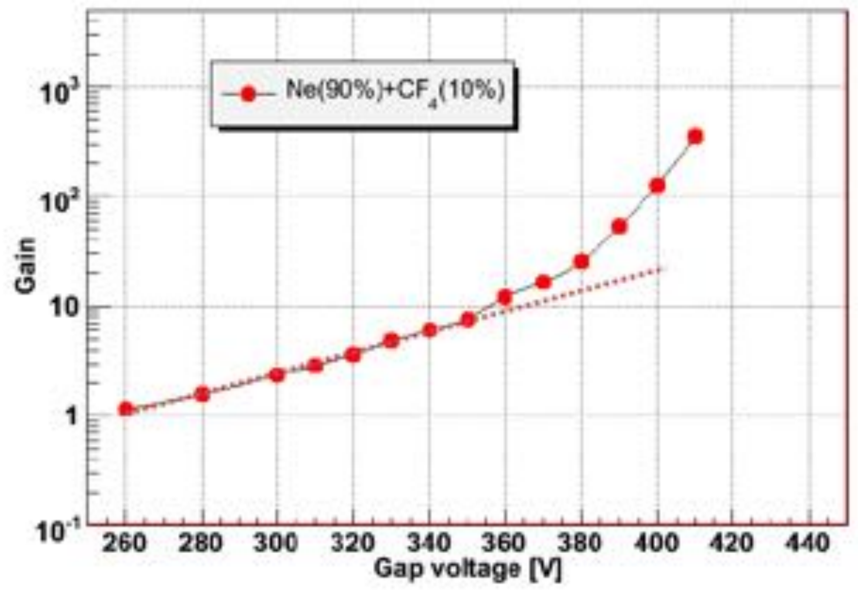


KAPTON AND PYREX GEM DETECTORS

Bi-alkali Photocathode in Ar-CH_4 (90-10)



GAIN VS VOLTAGE
GasPMT with Pyrex glass CP



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

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

Ionization　　Avalanche statistics

Average gain: $$M = \frac{1}{N}\sum_{i=1}^{N} A_i = \overline{A}$$

A_i : single electron avalanche size

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

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

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

Ionization variance: $$\sigma_N^2 = F\,N$$

F: Fano factor

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

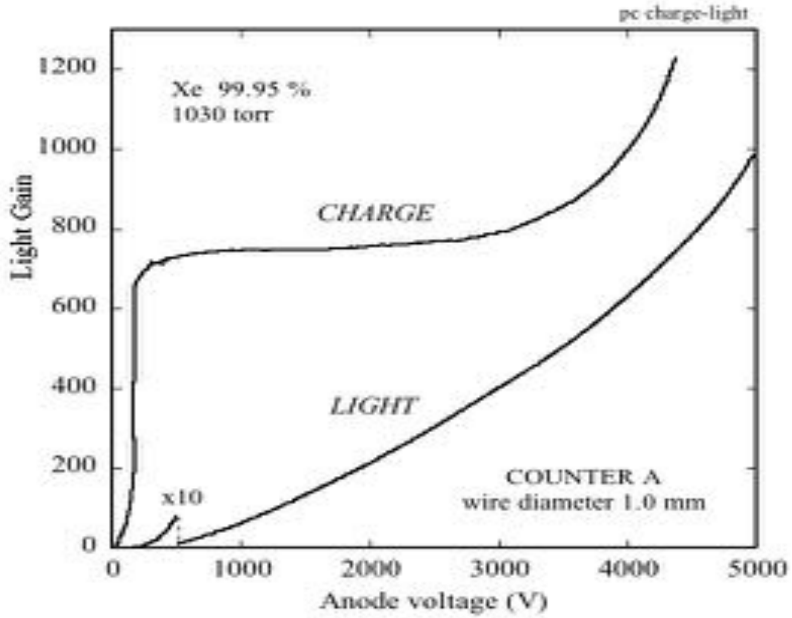
Furry: *b=1*　Polya: $b = 1/(1-\theta)$

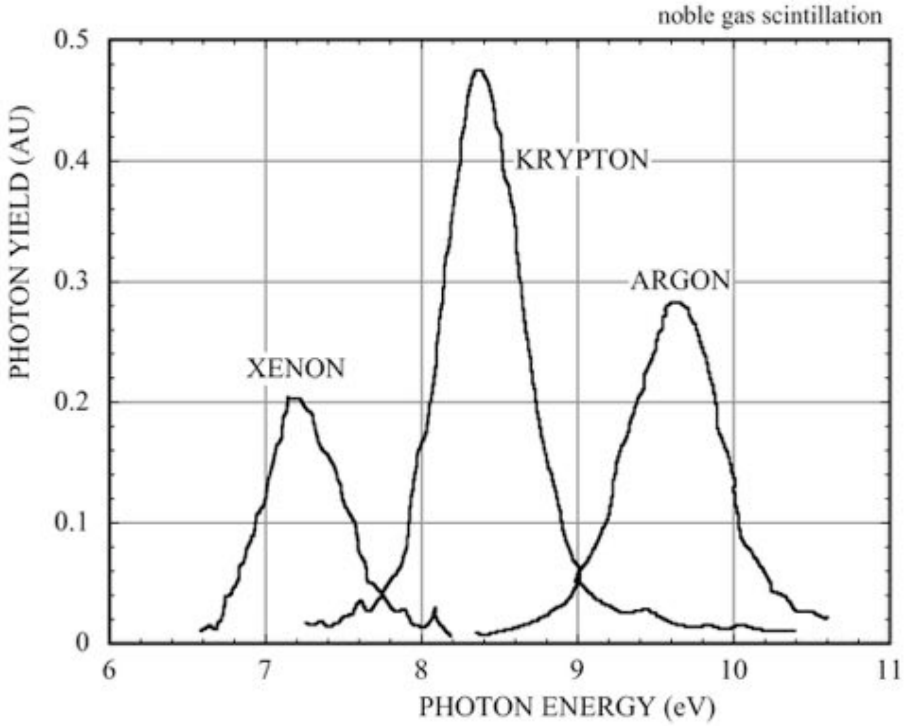
FANO FACTORS

GAS	F
Ar	0.19
Ar-CH_4	0.19
Xe	<0.17
Ne+0.5%Ar	0.05

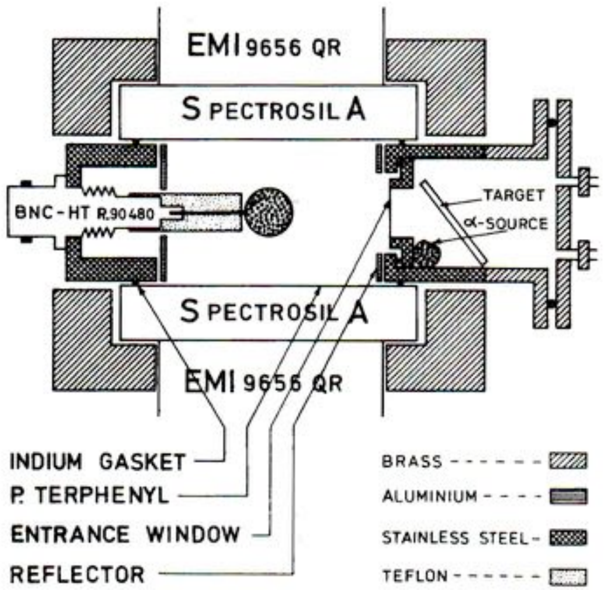
PHOTON EMISSION BEFORE CHARGE MULTIPLICATION:
NO AVALANCHE DISPERSIONS

NOBLE GASES SCINTILLATION SPECTRA ~1bar

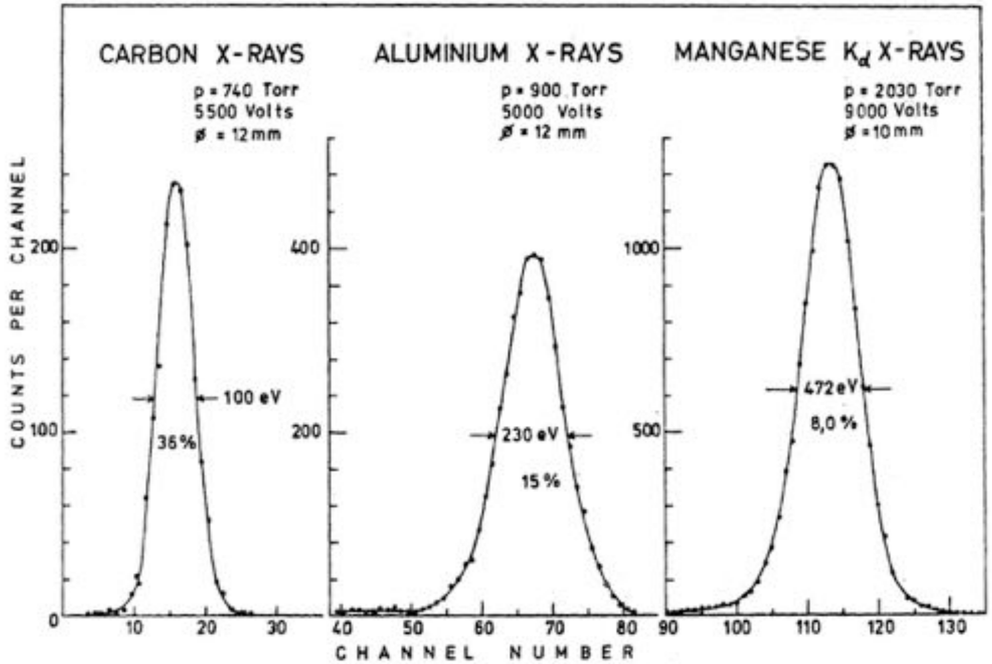




SCINTILLATION COUNTERS

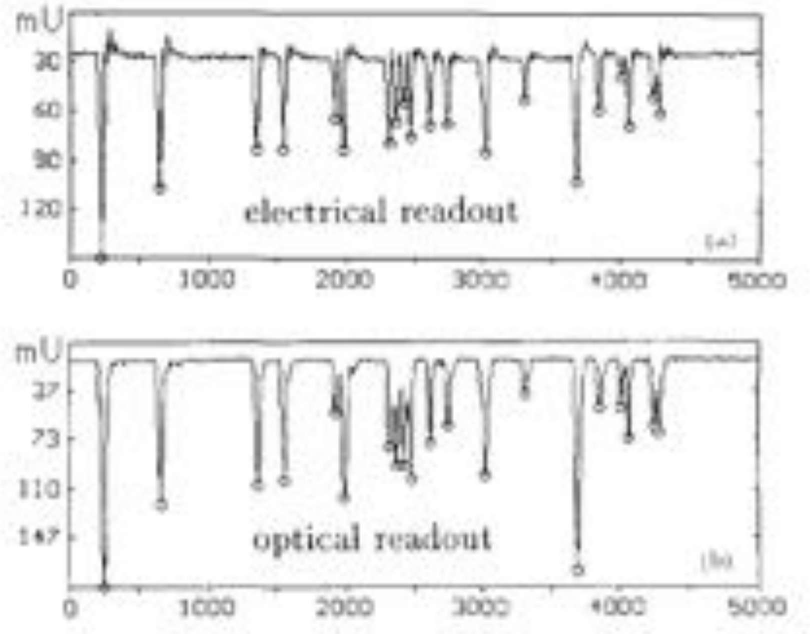


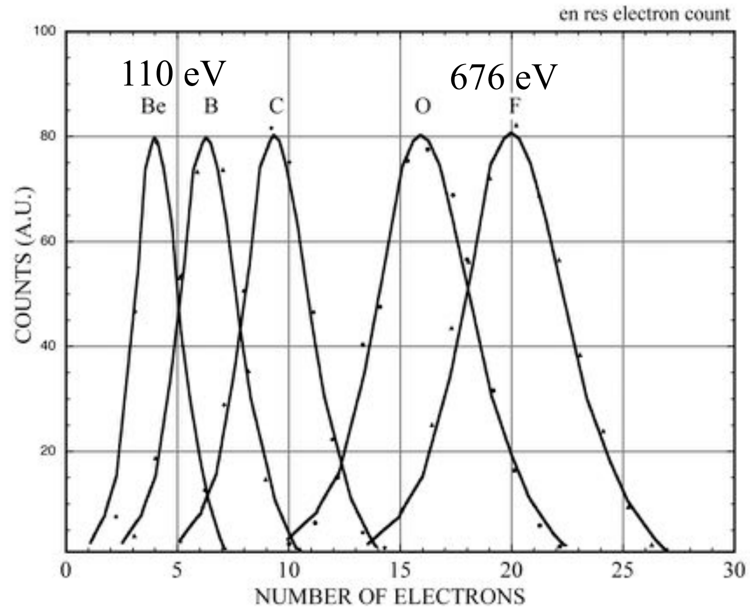
ENERGY RESOLUTION:
CLOSE TO STATISTICAL LIMIT

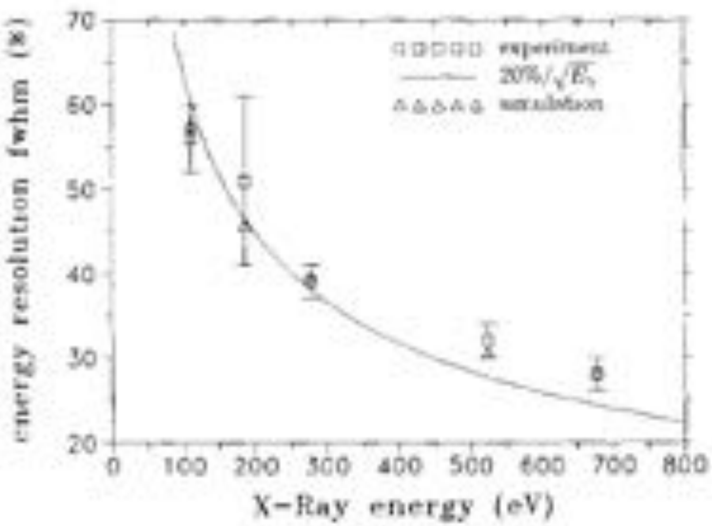


A. Policarpo et al, Nucl. Instr. and Meth. 102(1972)337

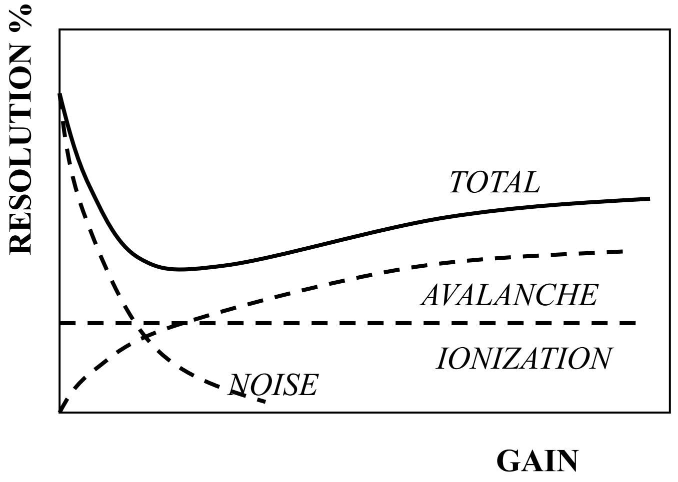
LOW PRESSURE (10 Torr) PROPORTIONAL COUNTER

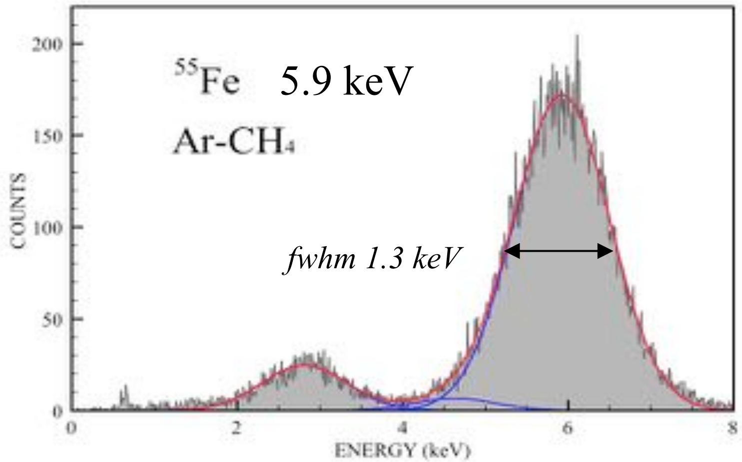


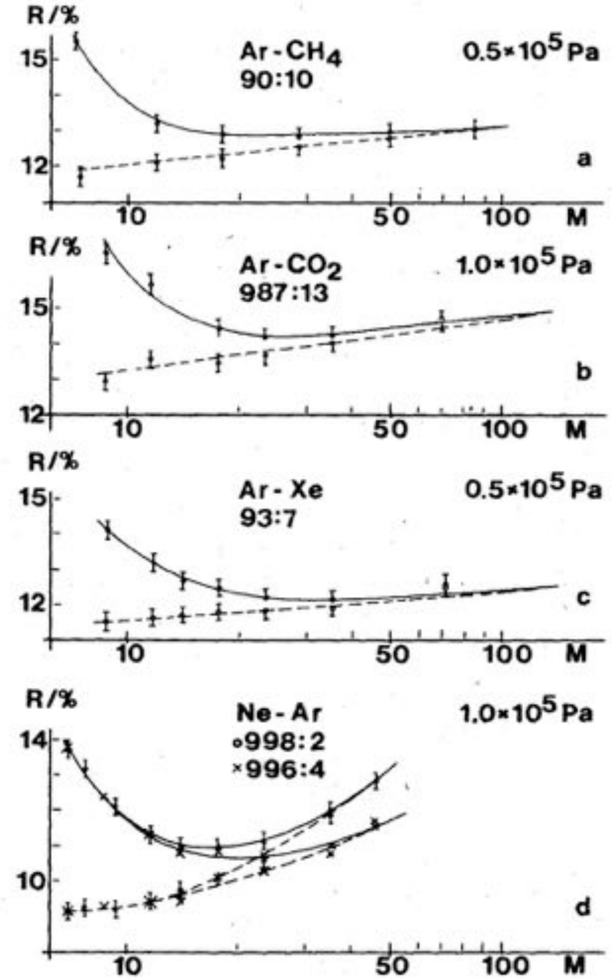




A. Pansky et al, Nucl. Instr. and Meth. A330(1993)150

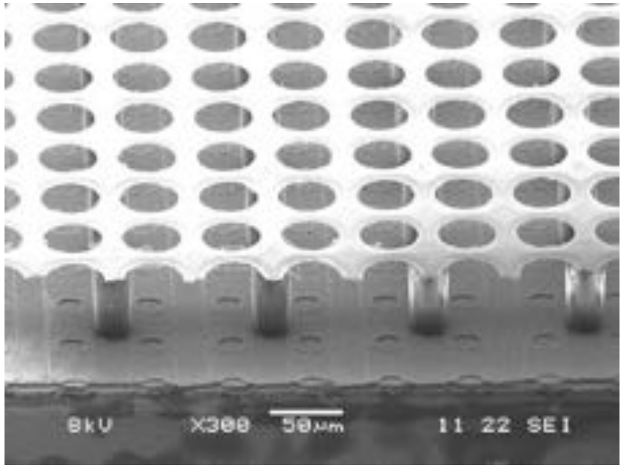




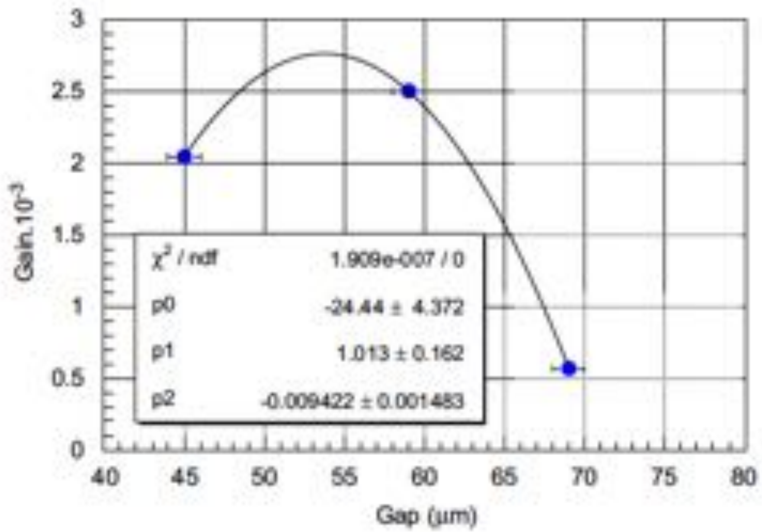


H. Sipilä and E. Kiuru, Adv. X-Ray Analysis 21(1978)

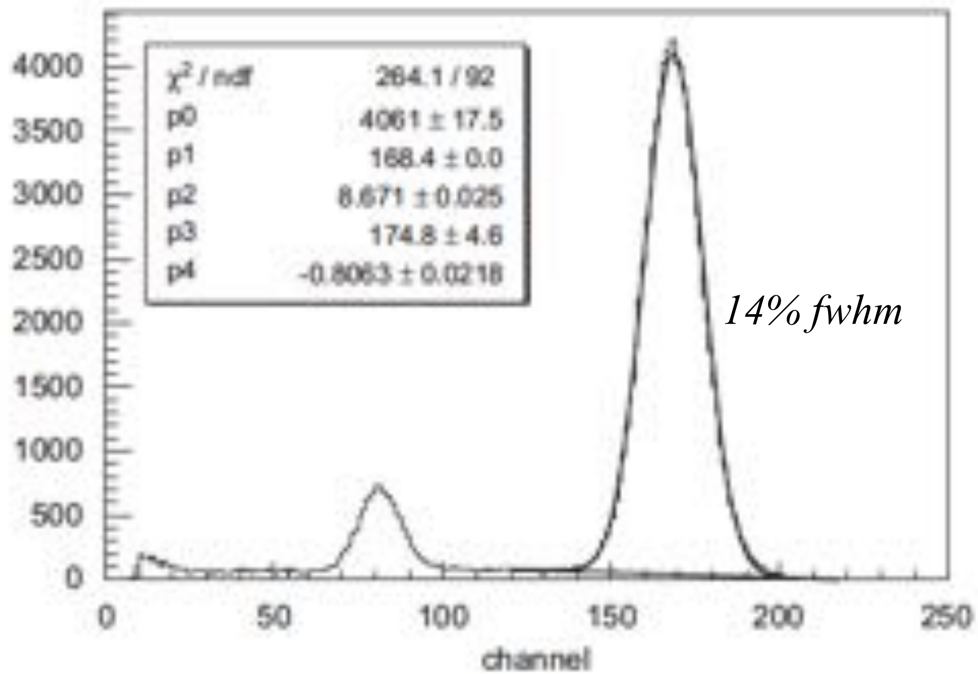
INGRID: MICROMEGAS WITH TIMEPIX READOUT



GAP INDEPENDENCE OF GAIN

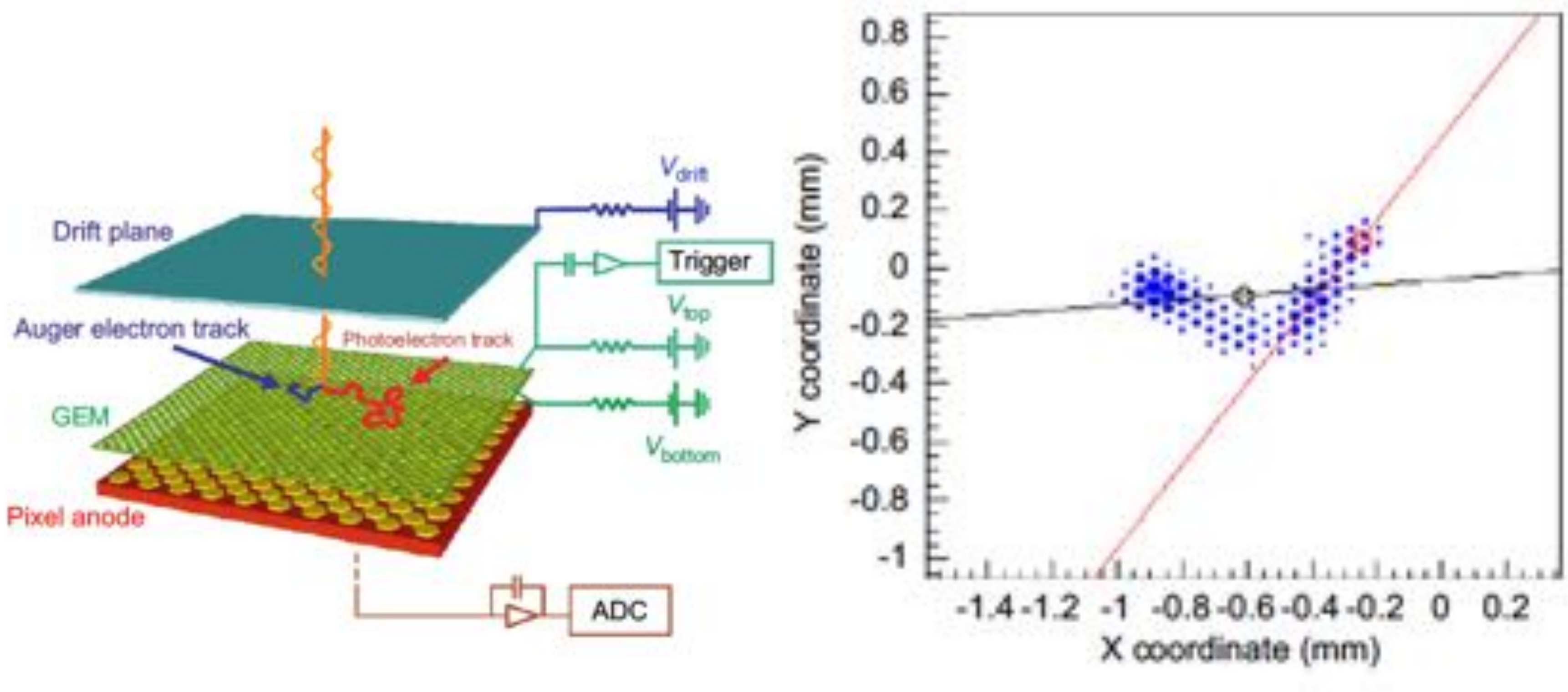


5.9 keV ^{55}Fe in Ar-CH_4 90-10

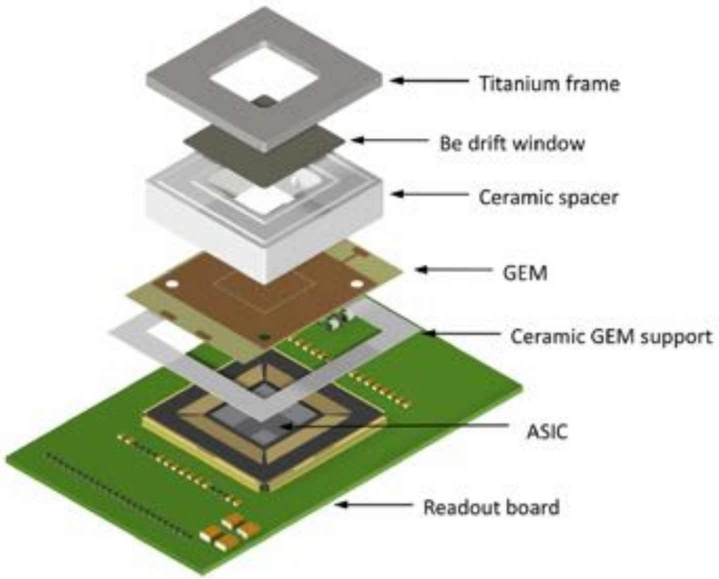


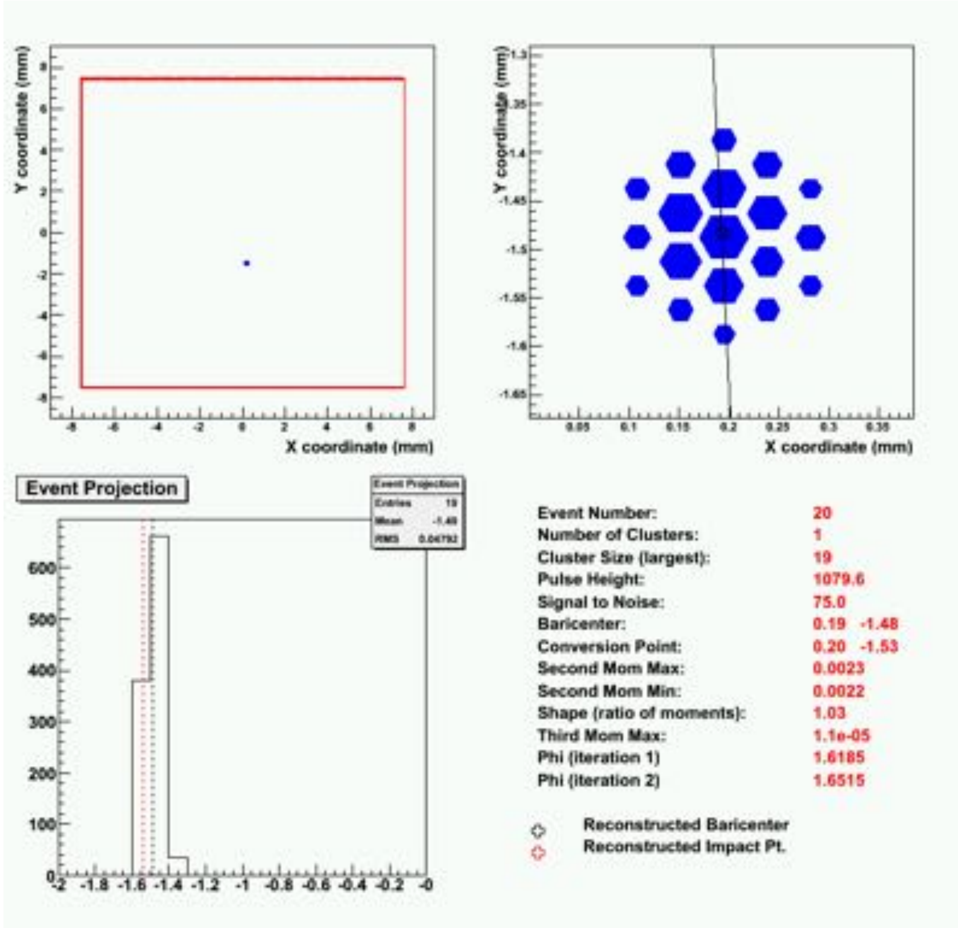
M. Chefdeville et al,
Nucl. Instr. and Meth. A591(2008)147

X-RAY POLARIMETER

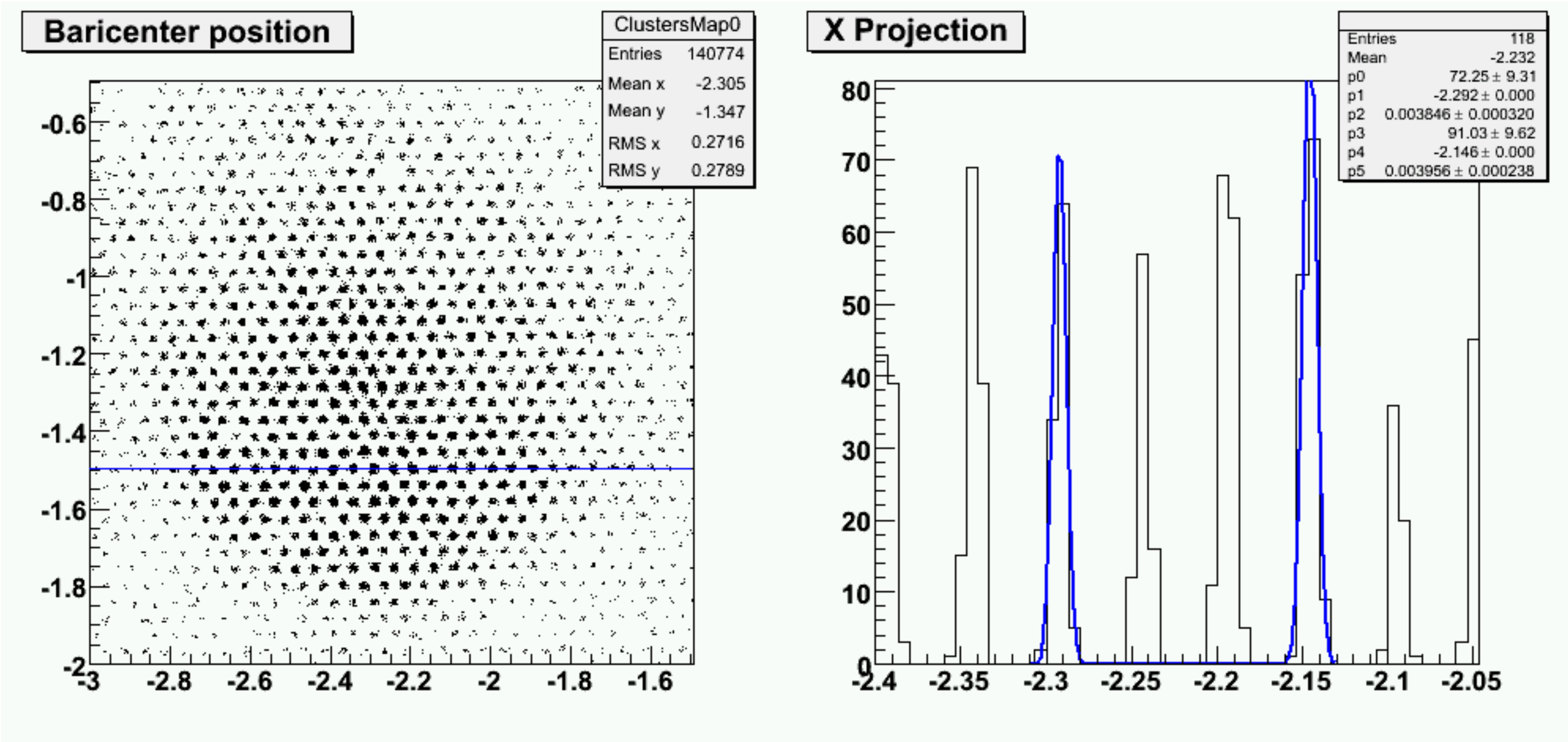


R. Bellazzini et al, Nucl. Instr. and Meth. A623(2010)766





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



$\sigma \sim 4\ \mu m$

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

END OF PART 1