# ESIPAP 2021

Simulation of gas-based detectors, introduction

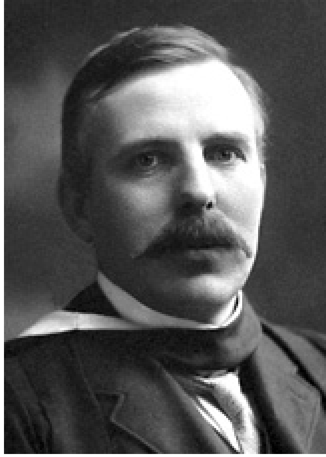
course 1, laboratory 4

Friday February 5th 14h00-14h30

video-only

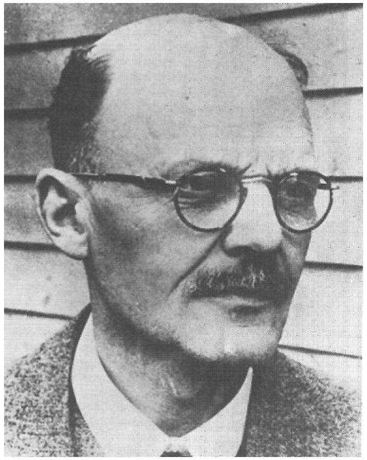
# Gas-based detectors, a brief history

E(a)rnest Rutherford
(1871-1937)

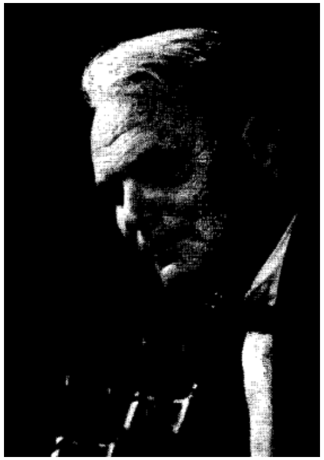


# Geiger counter

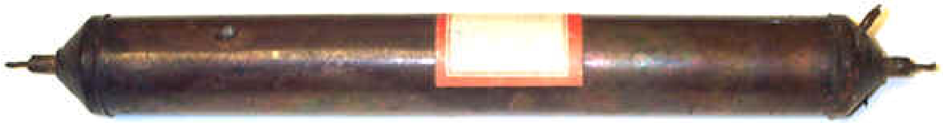
- Detects radiation by discharge;
- can count α, β and γ particles (at low rates ...);
- no tracking capability.
- 1908: Ernest Rutherford and Hans Geiger
- 1928: Hans Geiger and Walther Müller



Hans Geiger
(1882-1945)



Walt(h)er Müller
(1905-1979)



A Geiger-Muller counter built in 1939 and used in the 1947-1950 for cosmic ray studies in balloons and on board B29 aircraft by Robert Millikan et al.

Made of copper, 30 cm long

# MWPC

- First gaseous tracking device
- 1968: Georges Charpak

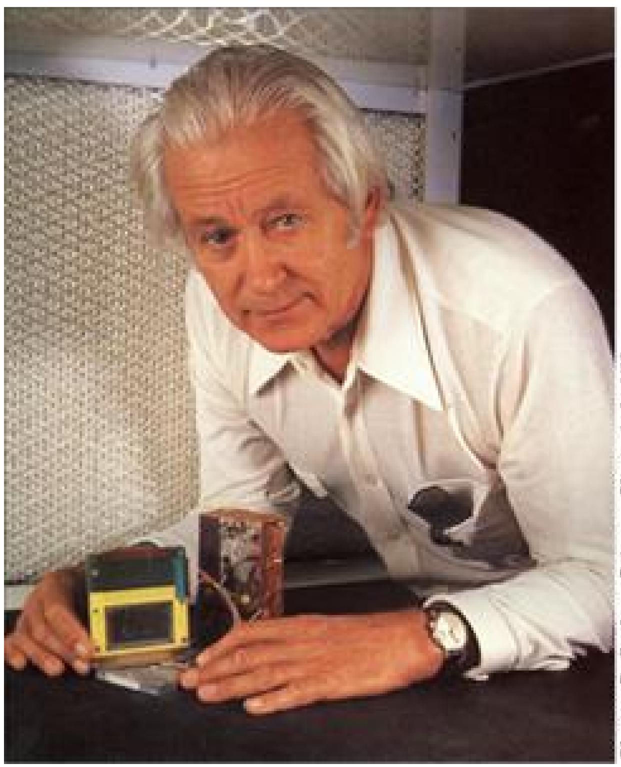
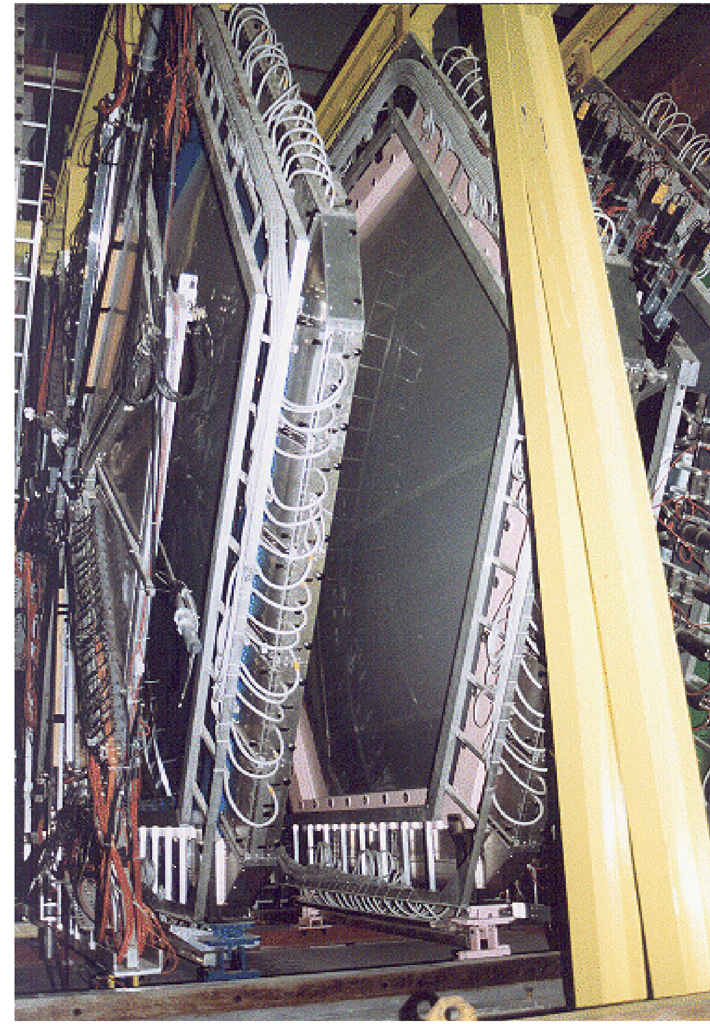


Photo: D. Parker, Science Photo Lab. UK

Georges Charpak
(1924-1992-2010)

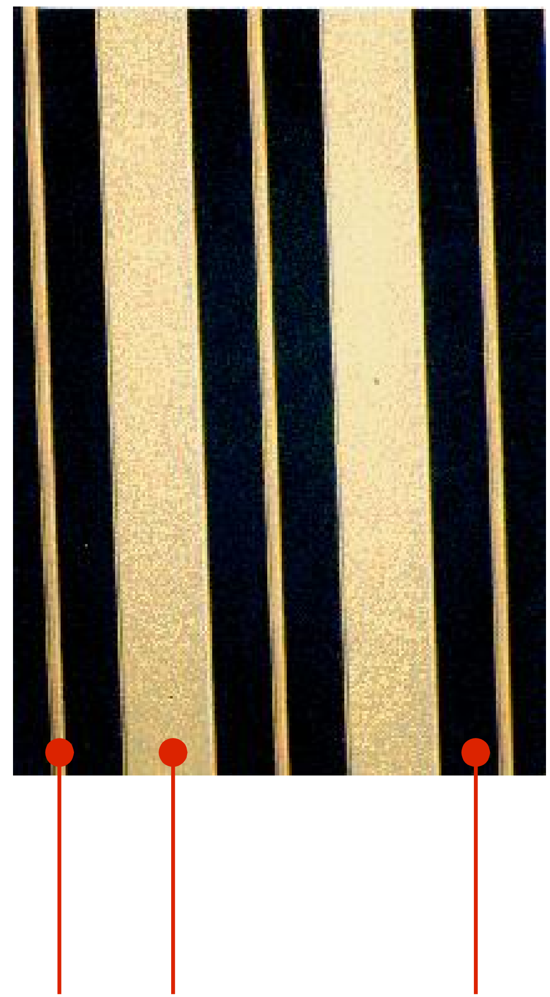


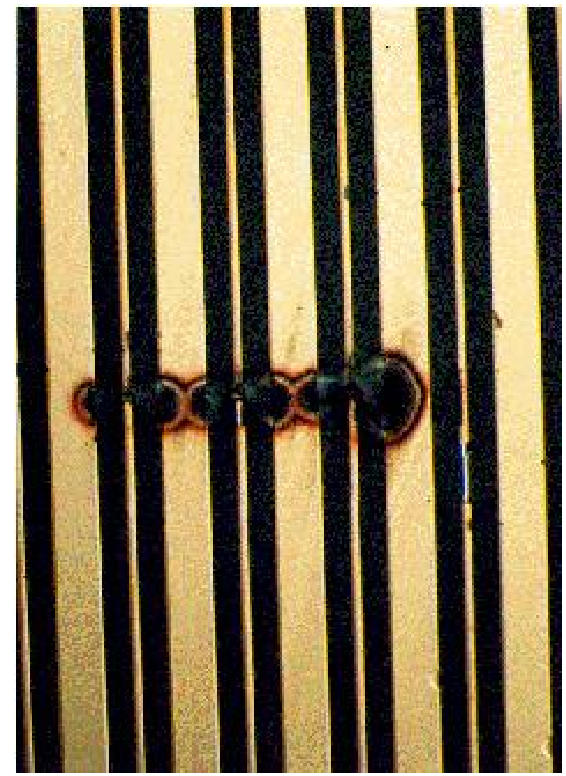
One of the NA60 muon chambers

# MSGC: an early MPGD

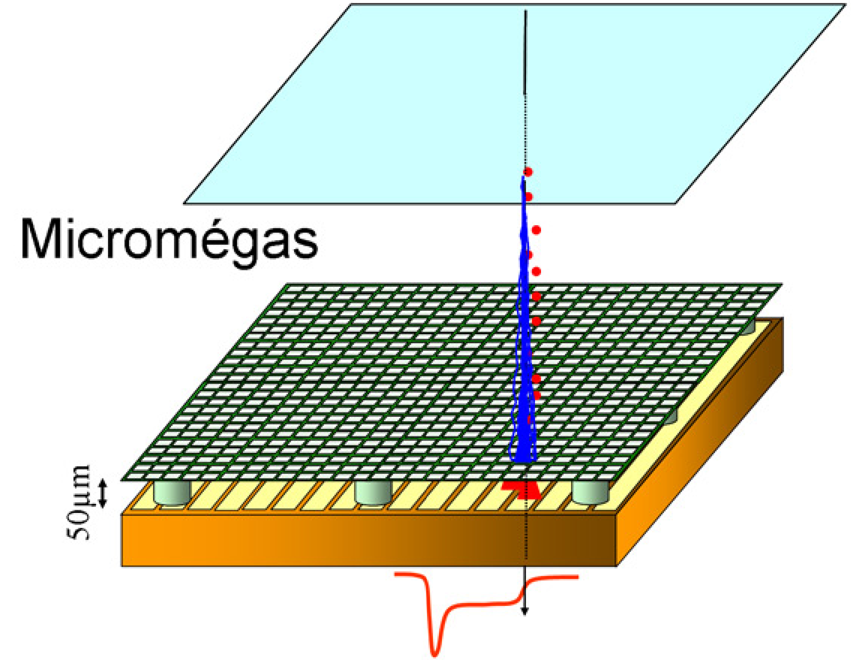
- Built using solid-state techniques;
- good resolution;
- poor resistance to high rates.

- 1988: Anton Oed

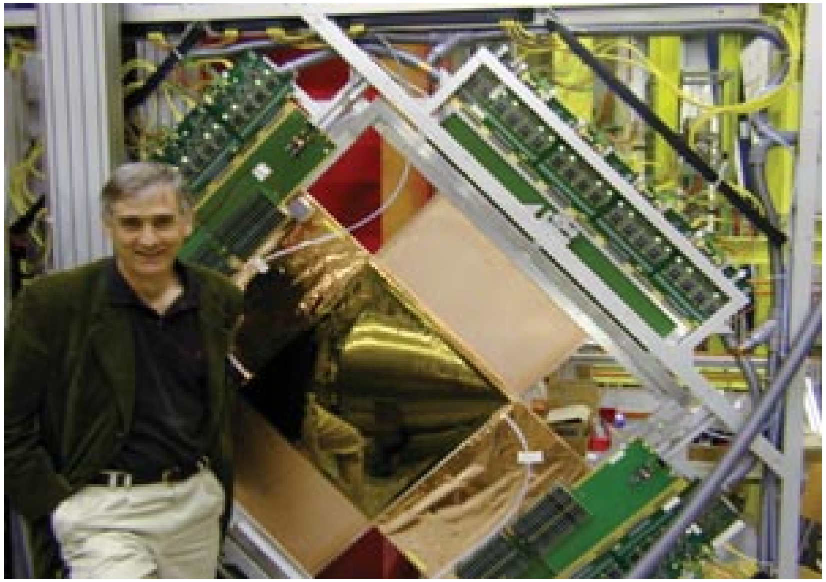


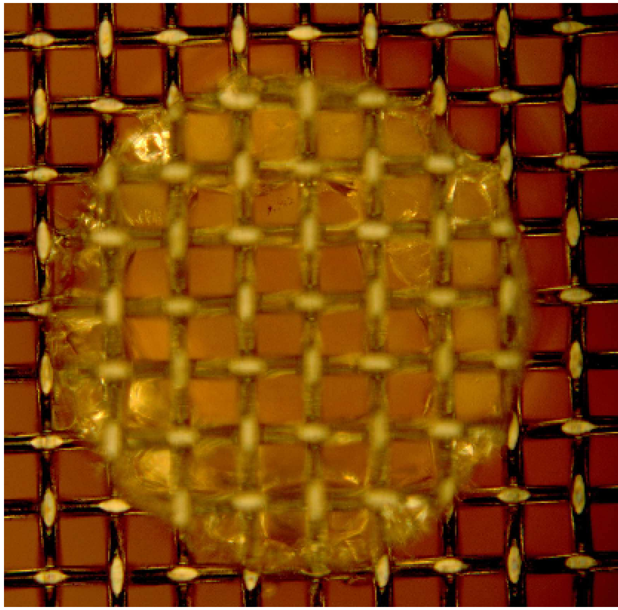
# Micromégas




- Fast, rate tolerant tracking device.
- 1994: Yannis Giomataris and Georges Charpak.



Yannis Giomataris

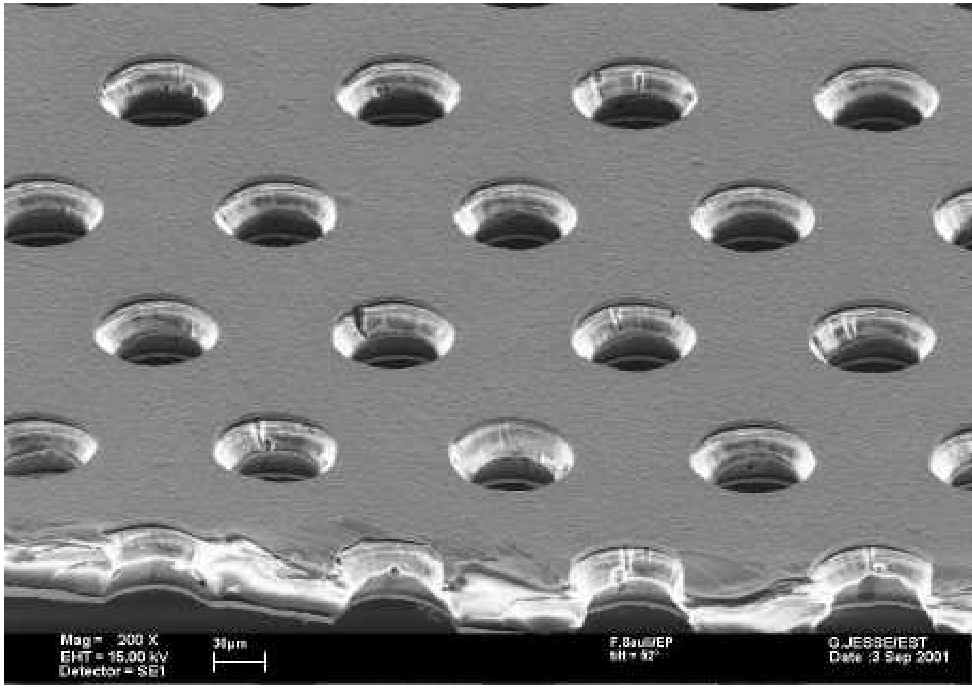


Wire diameter: 18 µm,
Pitch: 63 µm, Gap: 192 µm

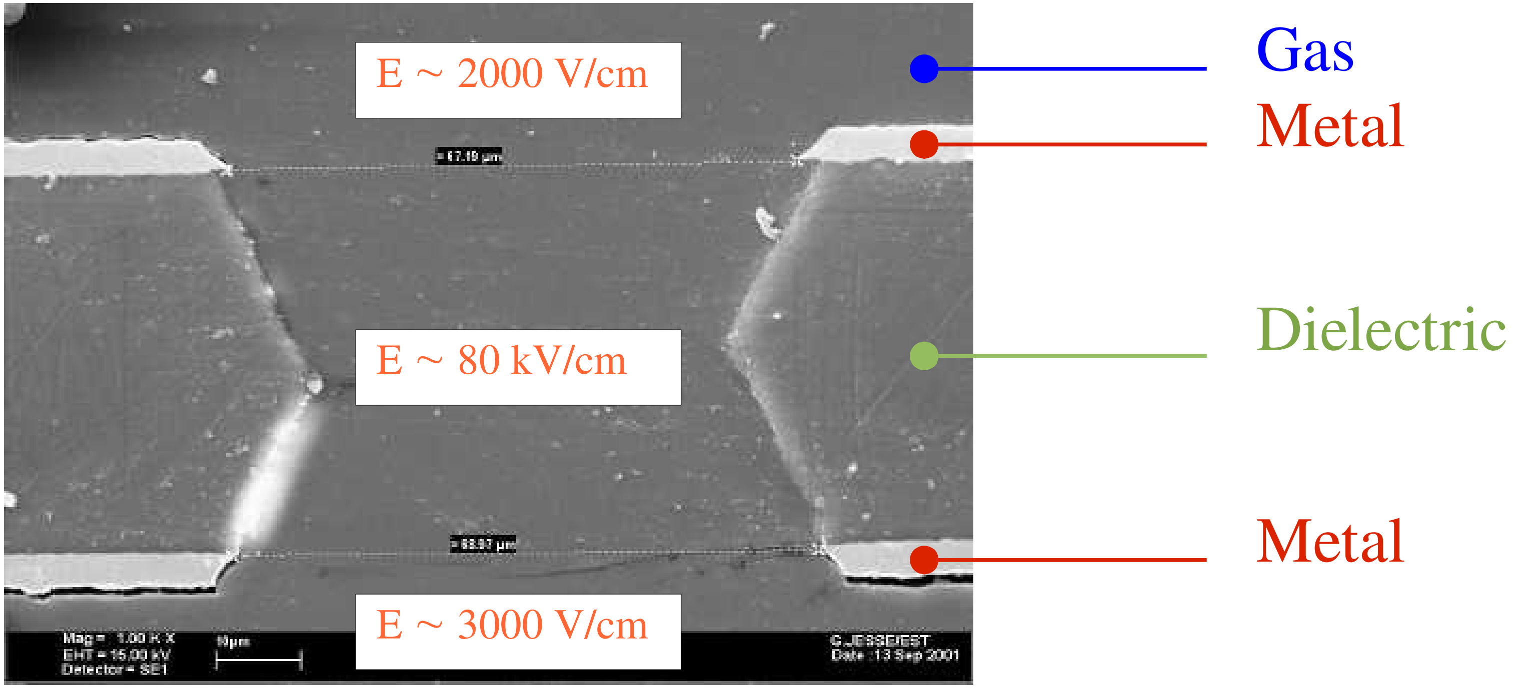
[Purba Bhattacharya et al., 10.1016/j.nima.2013.07.086; ILC NewsLine]

# GEM

- Originally, a “pre-amplifier”.
- 1996: Fabio Sauli



A few electrons enter here

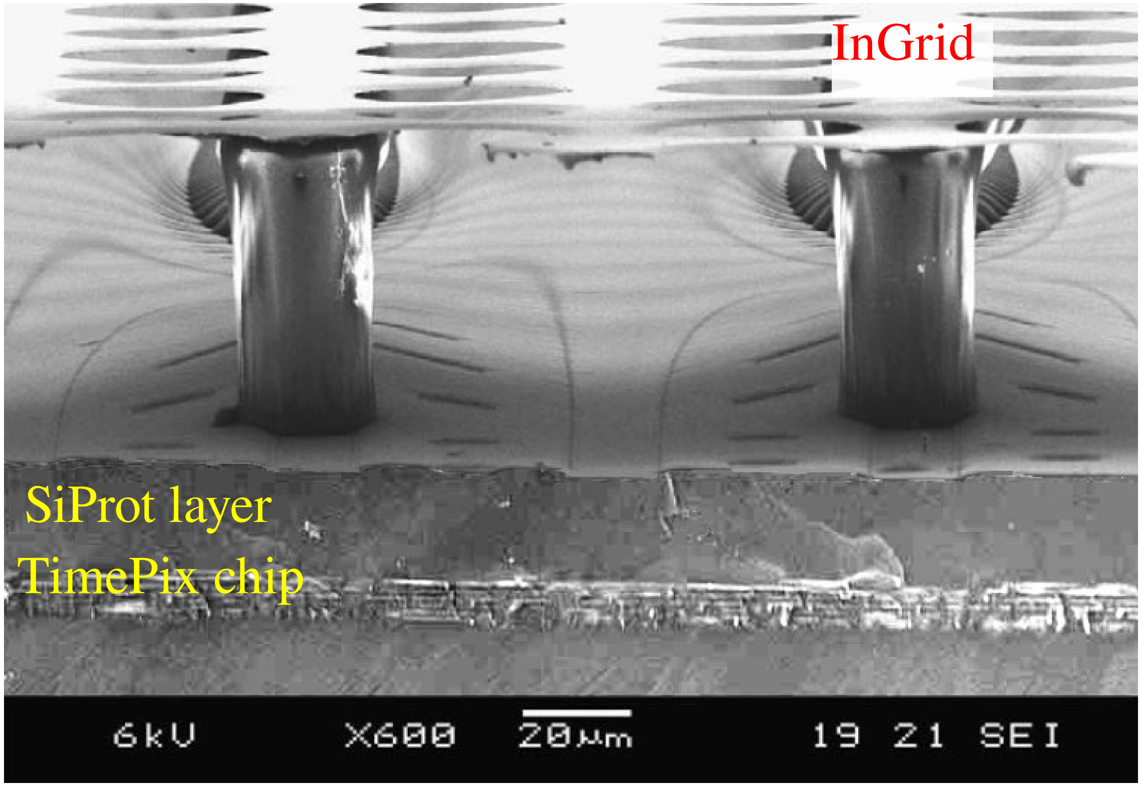



Many electrons exit here

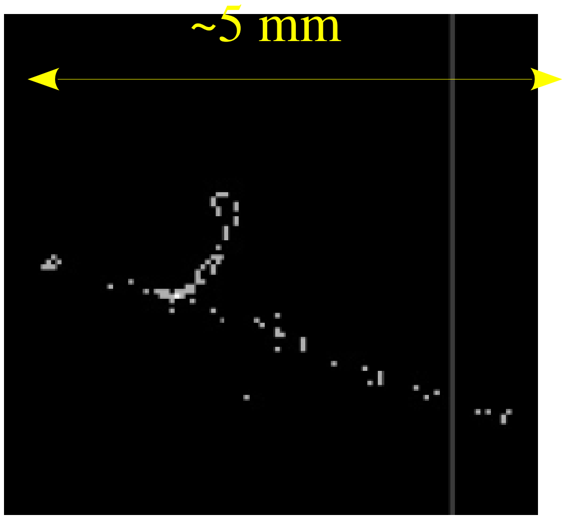
Fabio Sauli

# Gossip

- The "electronic bubble chamber".




Harry van der Graaf (r)



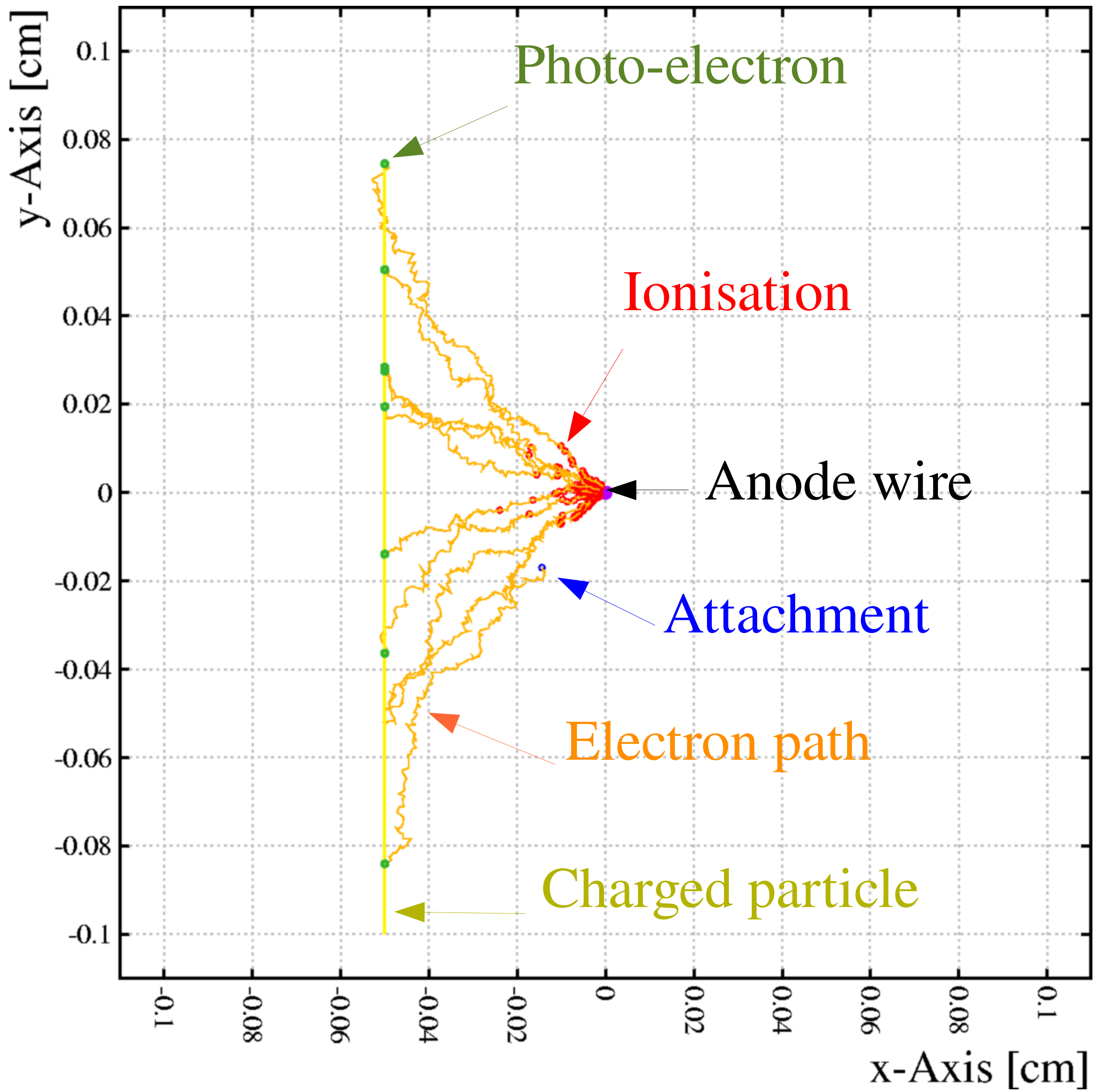

δ-electrons made visible in $He/iC_4H_{10}$, using a modified MediPix, ~2004.

# How they work

- Gas-based detectors all work according to much the same principles:
  - a charged particle passing through the gas ionises a few gas molecules;
  - the electric field in the gas volume transports the ionisation electrons and provokes multiplication;
  - the movement of electrons and ions leads to induced currents in electrodes;
  - the signals are processed and recorded.

# At the 100 μm scale

- Example:
  - CSC-like structure,
  - Ar 80 % $CO_2$ 20 %,
  - 10 GeV μ.
- Electron are shown every 100 collisions, but have been tracked rigorously.
- Ions are not shown.



# Ionisation

[Four Curies: Pierre, Marie, Irène and Pierre's father, around 1904 at the BIPM]

# 1896: Ionisation by radiation

- Early in the study of radioactivity, ionisation by radiation was recognised:

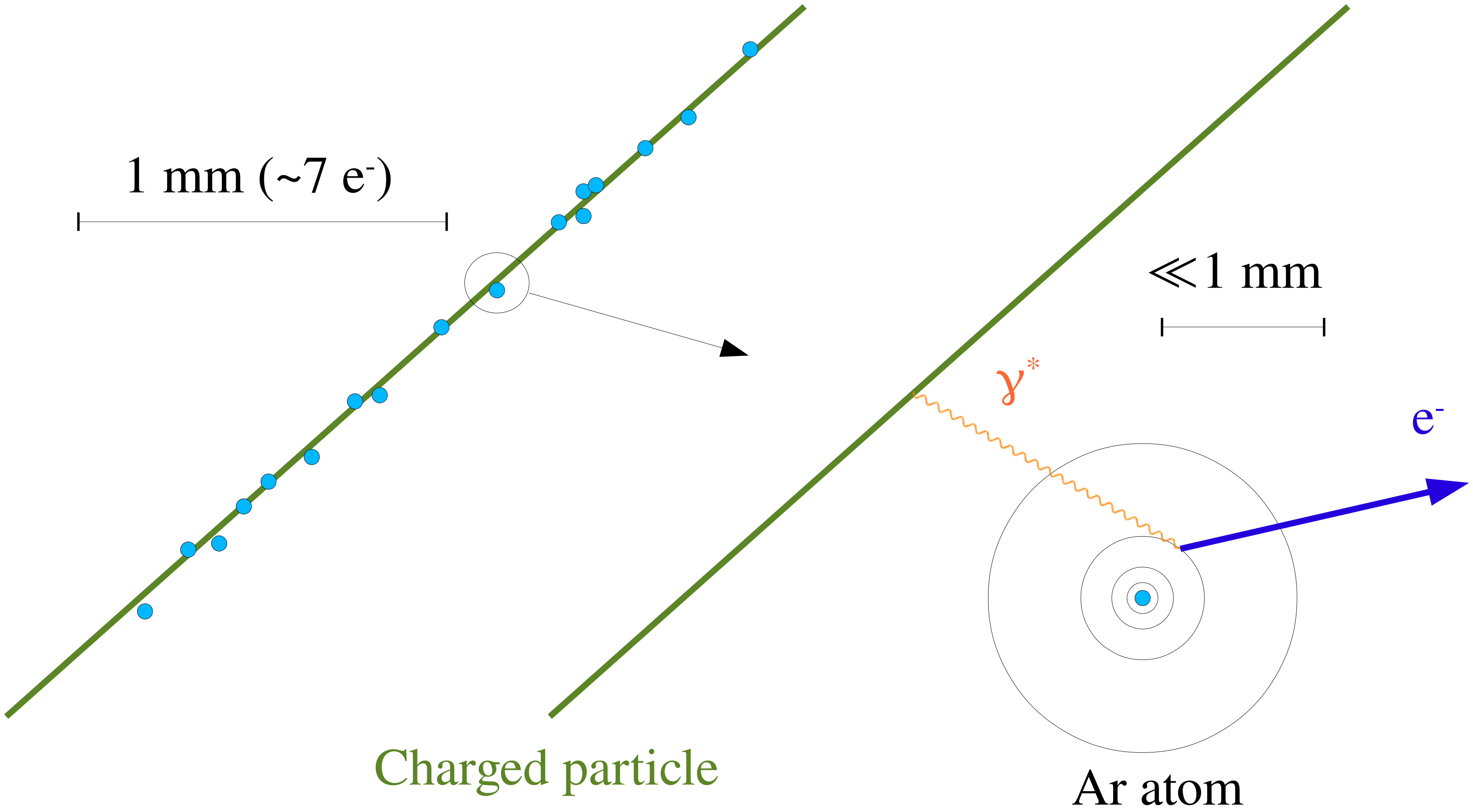
” Becquerel discovered in 1896 the special radiating properties of uranium and its compounds. Uranium emits very weak rays which leave an impression on photographic plates. These rays pass through black paper and metals; they make air electrically conductive. “

[Pierre Curie, Nobel Lecture, June 6th 1905]

“A sphere of charged uranium, which discharges spontaneously in the air under the influence of its own radiation, retains its charge in an absolute vacuum. The exchanges of electrical charges that take place between charged bodies under the influence of the new rays, are the result of a special conductivity imparted to the surrounding gases, a conductivity that persists for several moments after the radiation has ceased to act.”

[Antoine Henri Becquerel, Nobel Lecture, December 11th 1903]

# Virtual photon exchange



Wade Allison

John Cobb

# Core formulae PAI model

- Key: photo-absorption cross section $\sigma_\gamma(E)$

$$\frac{\beta^2\pi}{\alpha}\frac{d\sigma}{dE} = \frac{\sigma_\gamma(E)}{E}\log\left(\frac{1}{\sqrt{(1-\beta^2\epsilon_1)^2+\beta^4\epsilon_2^2}}\right) +$$

Relativistic rise

$$\frac{1}{N\hbar c}\left(\beta^2 - \frac{\epsilon_1}{|\epsilon|^2}\right)\theta +$$

Черенков radiation

$$\frac{\sigma_\gamma(E)}{E}\log\left(\frac{2m_e c^2\beta^2}{E}\right) +$$

Resonance region

$$\frac{1}{E^2}\int_0^E \sigma_\gamma(E_1)\, dE_1$$

Rutherford scattering

Cross section to transfer an energy $E$ in a single collision of an incident charged particle with an atom.

With:

$$\epsilon_2(E) = \frac{N_e\hbar c}{E Z}\sigma_\gamma(E)$$

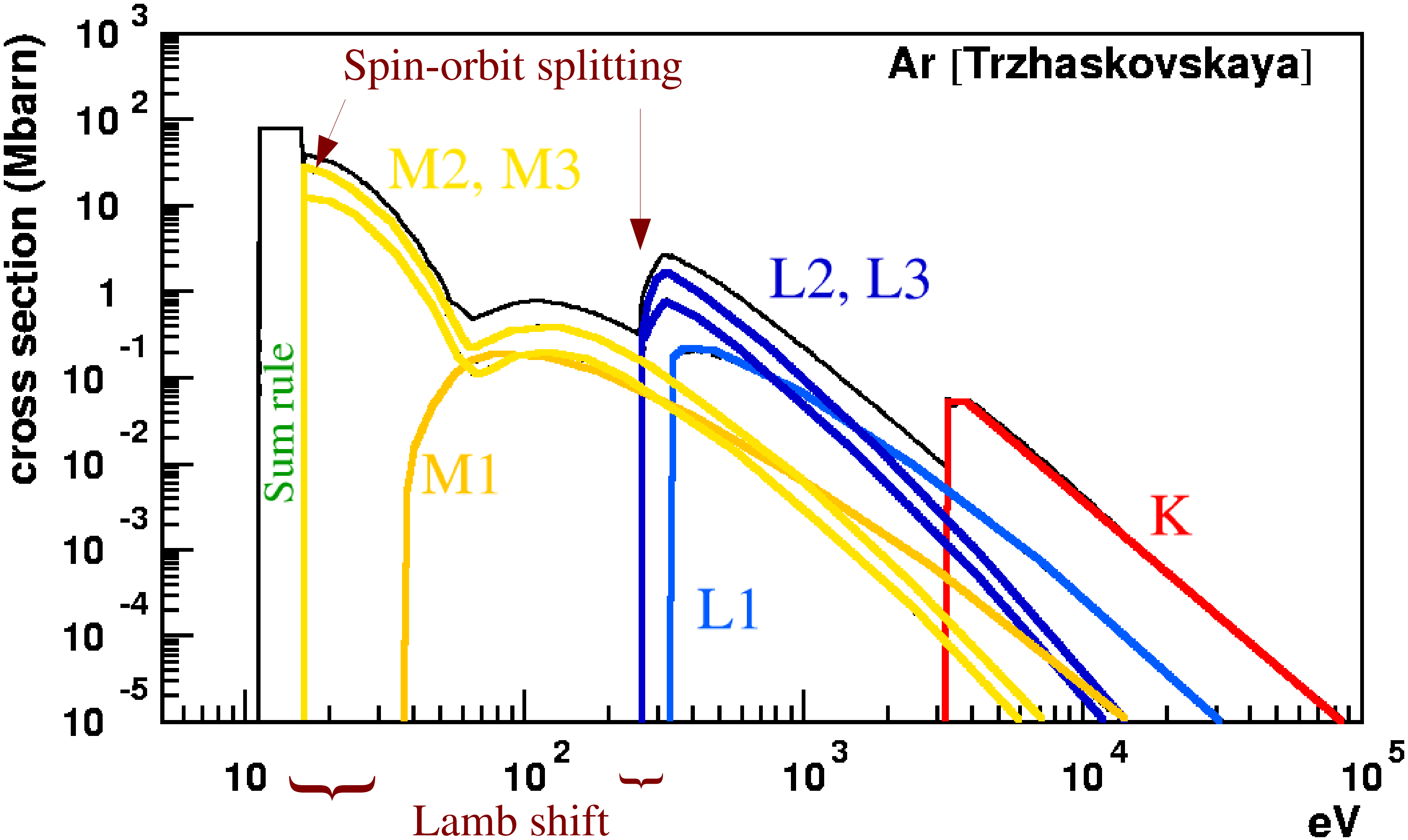
$$\epsilon_1(E) = 1 + \frac{2}{\pi}\mathrm{P}\int_0^\infty \frac{x\,\epsilon_2(x)}{x^2-E^2}\,dx$$

$$\theta = \arg(1-\epsilon_1\beta^2 + i\,\epsilon_2\beta^2) = \frac{\pi}{2} - \arctan\frac{1-\epsilon_1\beta^2}{\epsilon_2\beta^2}$$

# Photo-absorption in Ar (Heed)

Igor Smirnov

- Argon has 3 shells, hence 3 groups of lines:




K = 1s

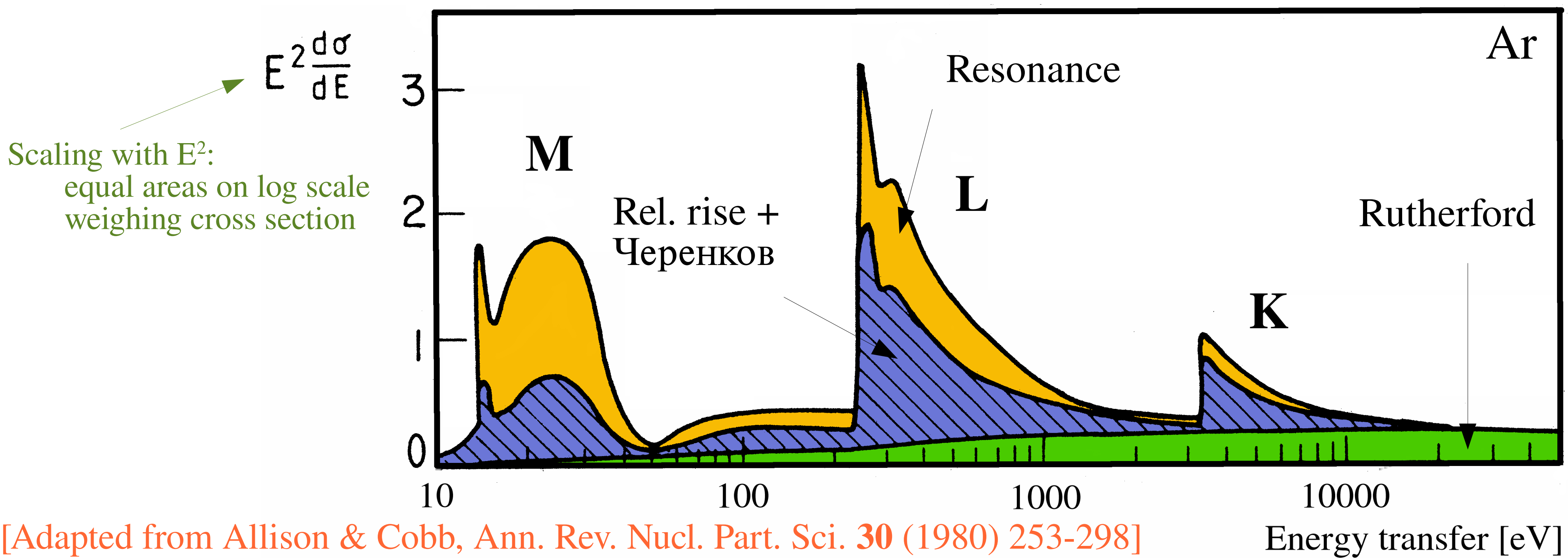
L1 = 2s
L2 = 2p 1/2
L3 = 2p 3/2

M1 = 3s
M2 = 3p 1/2
M3 = 3p 3/2

[Plot from Igor Smirnov]

# Importance of the PAI model terms

- All electron orbitals (shells) participate:
  - outer shells: frequent interactions, few electrons;
  - inner shells: few interactions, many electrons.
- All terms in the formula are important.




[Adapted from Allison & Cobb, Ann. Rev. Nucl. Part. Sci. **30** (1980) 253-298]

# Electric fields

William Gilbert
(1544-1603)

# 1600: "Electric force"

- 1544: William Gilbert born in Colchester
- 1600: De magnete, magneticisque corporibus, et de magno magnete tellure.
- Concluded that the Earth is a magnet; and he is credited with the first use of the term "electric force":

> vim illam electricam nobis placet appellare quæ ab humore prouenit

- 1601: Physician to Elizabeth I and James I.

[Guilielmi Gilberti, *De magnete* ..., excudebat Petrus Short anno MDC, Londini, courtesy Universidad Complutense de Madrid and Google books]

# Field calculation techniques

- Closed expressions, "analytic method":
  - almost all 2d structures of wires, planes + periodicities;
  - dielectrics and space/surface charge are laborious;
  - fast and precise, if applicable.
- Finite element method:
  - 2d and 3d structures, with or without dielectrics;
  - several major intrinsic shortcomings.
- Integral equations or Boundary element methods:
  - equally comprehensive as FEM, without the intrinsic flaws;
  - technically challenging and emerging;
  - consumes more CPU time than FEM, but catching up.
- Finite differences:
  - used for iterative, time-dependent calculations.

# 1814: Cauchy-Riemann equations

Augustin Louis Cauchy
(Aug 21st 1789 – May 23rd 1857)

- Express the existence of a derivative of a complex analytic function $f = u + \mathrm{i}\, v$:

$$f'(z) = \frac{\partial f}{\partial x} = \frac{\partial u}{\partial x} + \mathrm{i}\frac{\partial v}{\partial x}$$

$$= \frac{\partial f}{\partial \mathrm{i}\, y} = -\mathrm{i}\frac{\partial u}{\partial y} + \frac{\partial v}{\partial y}$$

Georg Friedrich Bernhard Riemann
(Sep 17st 1826 – Jul 20th 1866)

- implies that the real part $u$ is harmonic:

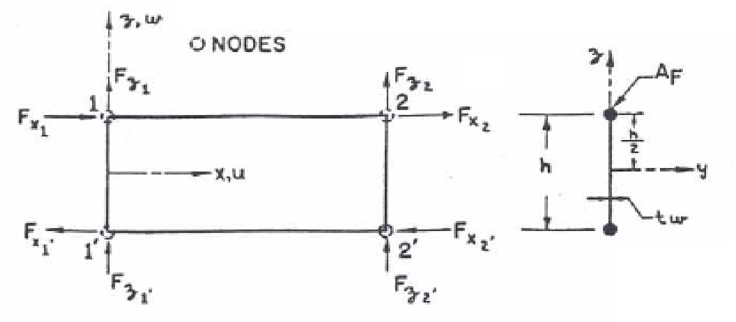
$$\frac{\partial^2 u}{\partial x^2} = \frac{\partial^2 v}{\partial x \partial y} = \frac{\partial^2 v}{\partial y \partial x} = -\frac{\partial^2 u}{\partial y^2} \quad \rightarrow \quad \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = \nabla^2 u = 0$$

Reference: A.L. Cauchy, *Sur les intégrales définies* (1814). This *mémoire* was read in 1814, but only submitted to the printer in 1825. Riemann was born a year later.

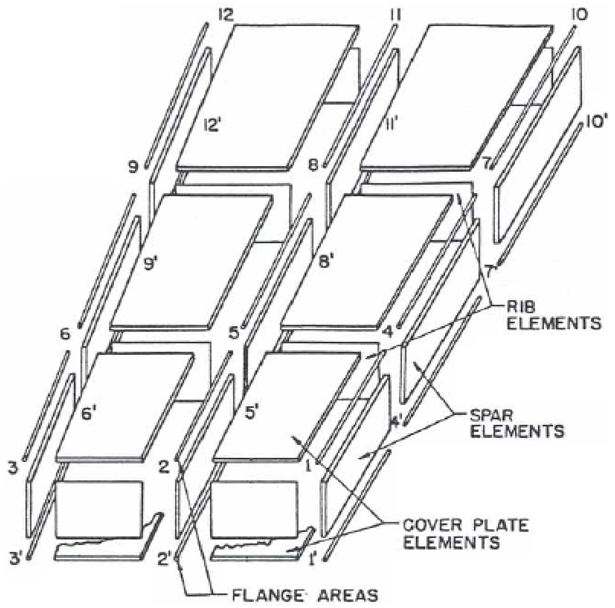
Ιωάννης Αργύρης
(1913-2004)

# Aircraft wings – finite elements

- "*Stiffness and Deflection Analysis of Complex Structures*", a study in the use of the finite element technique (then called "direct stiffness method") for aircraft wing design.



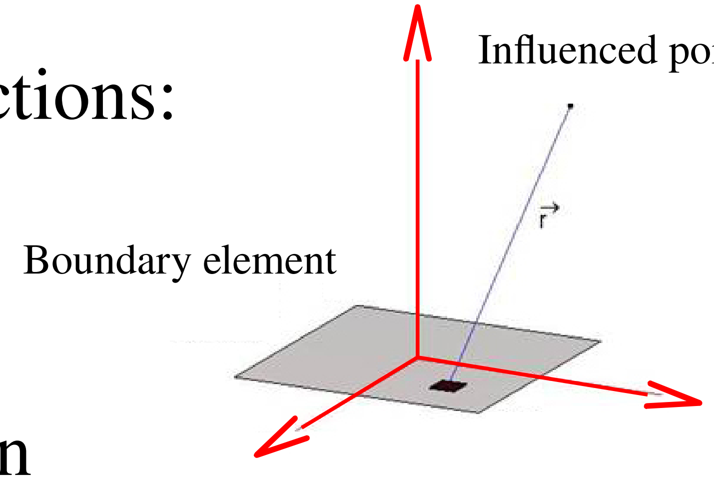

$$[K] = \frac{6EI}{Lh^2(1+4n)} \begin{array}{c} \begin{array}{cccccc} u_1 & v_1 & w_1 & u_2 & v_2 & w_2 \end{array} \\ \begin{bmatrix} (4/3)(1+n) & & & & & \\ 0 & 0 & & & & \\ -(h/L) & 0 & h^2/L^2 & & & \\ (2/3)(1-2n) & 0 & -(h/L) & (4/3)(1+n) & & \\ 0 & 0 & 0 & 0 & 0 & \\ h/L & 0 & -(h^2/L^2) & h/L & 0 & h^2/L^2 \end{bmatrix} \end{array}$$




[M.J. Turner, R.W. Clough, H.C. Martin and L.J. Topp, *Stiffness and Deflection Analysis of Complex Structures*, J. Aero. Sc. **23** (1956), 805-824. MJT & LJT with Boeing.]

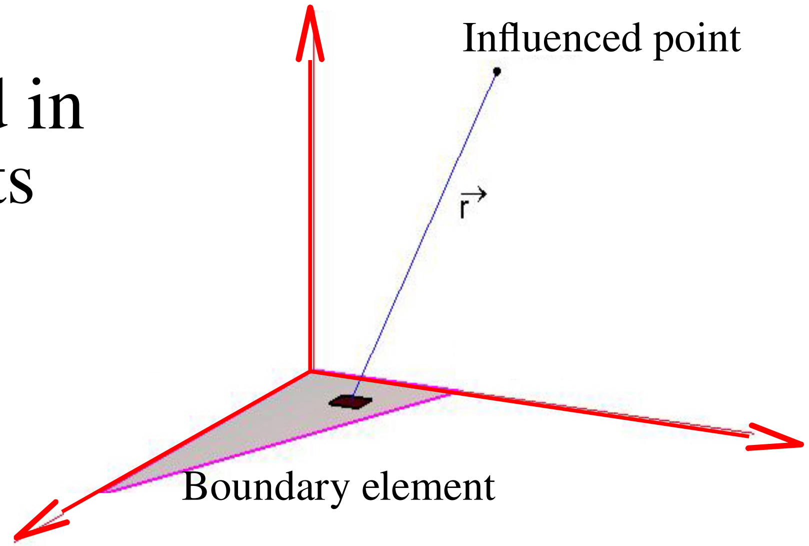
# neBEM's Green's functions

- neBEM has only 3 Green's functions:
  - rectangle;
  - right-angled triangle;
  - line segment.




- The Green's functions have been computed by integrating a uniform charge distribution across the element.

- This avoids the nodal charges found in several BEM methods. But the joints between elements still have a jump.



# Electron transport

# Mean free path in argon

- Literature will tell you:
  - $e^-$ cross section Ar atom: $\sigma \approx 1.5\ 10^{-16}$ $cm^2$
  - atoms per unit volume: $n_0 \approx 2.7\ 10^{19}$ $atoms/cm^3$
- Mean free path for an electron ?
  - An electron hits all atoms of which the centre is less than a cross section $\sigma$ radius from its path;
  - over a distance $L$, the electron hits $n_0\ \sigma\ L$ atoms;
  - mean free path = distance over which it hits 1 atom;

$$\lambda_e = 1/(\sigma\ n_0) \approx 2.5\ \mu m$$

  - much larger than:
    - 4 nm — distance between atoms, and
    - 140-600 pm — typical gas molecule diameters.

# Drift velocity in electric fields

- Imagine that an electron stops every time it collides with a gas molecule and then continues along *E*.

- To cover a distance $\lambda_e$ it will need a time *t*:

$$\frac{1}{2}\frac{qE}{m_e}t^2 = \lambda_e, \qquad t = \sqrt{\frac{2\lambda_e m_e}{qE}}, \qquad \bar{v} = \frac{\lambda_e}{t} = \sqrt{\frac{\lambda_e qE}{2m_e}}$$

- which gives:

$$\bar{v} \approx 13\,\mathrm{cm}/\mu\mathrm{s} \quad \text{for} \quad E = 1\,\mathrm{kV/cm}$$

# Drift velocity in argon

- Compare with a Magboltz calculation for pure argon:
  - $\sqrt{E}$ dependence is not too far off, although linearly proportional is more common at low field,

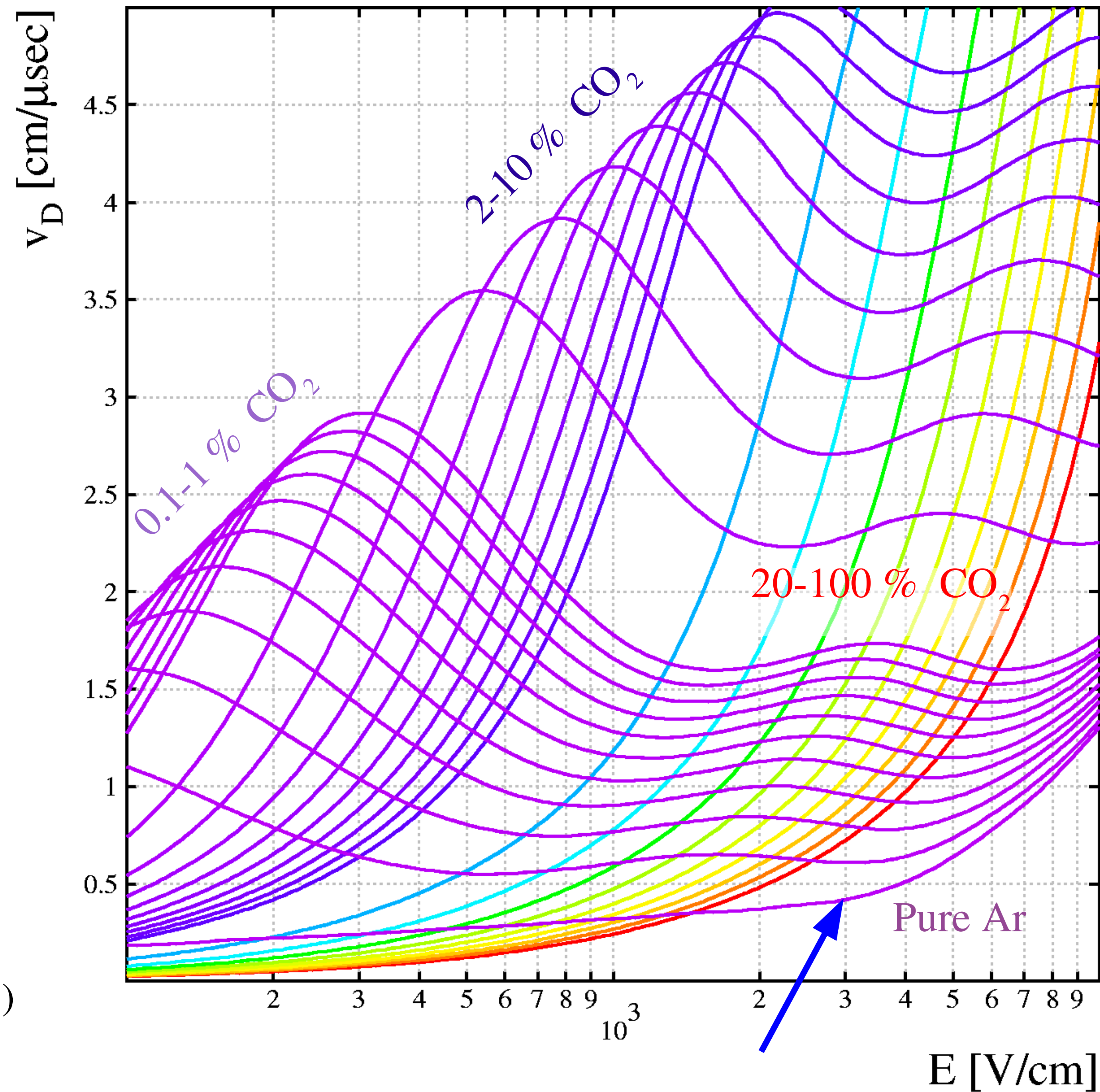
    BUT

  - the velocity is *vastly* overestimated ! Magboltz finds a velocity that is *30 times* smaller ...

    WHY ?

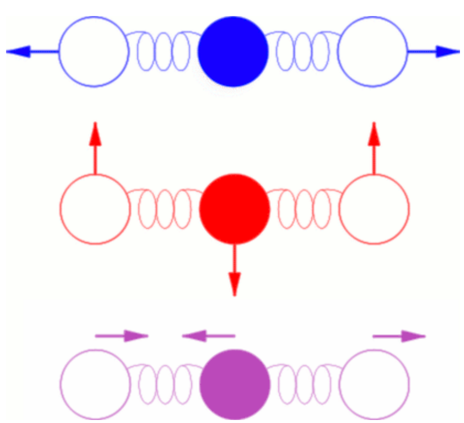
# Adding $CO_2$

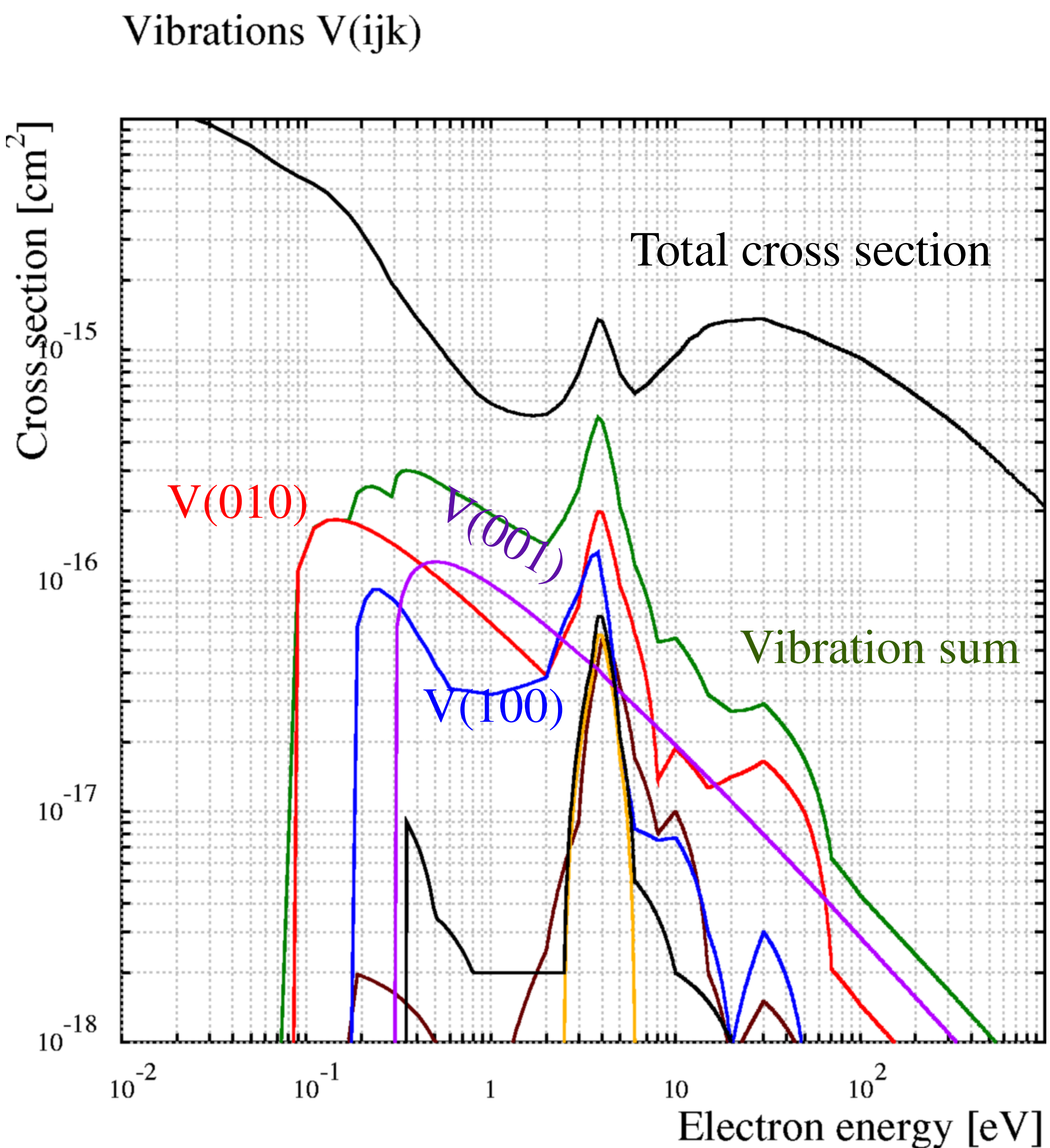
- $CO_2$ makes the gas faster, dramatically.
- Additives like $CO_2$ are called “quenchers” or admixtures.
- Drift velocities calculated by Magboltz for Ar/$CO_2$ at 3 bar.
  (Note where the arrow is !)



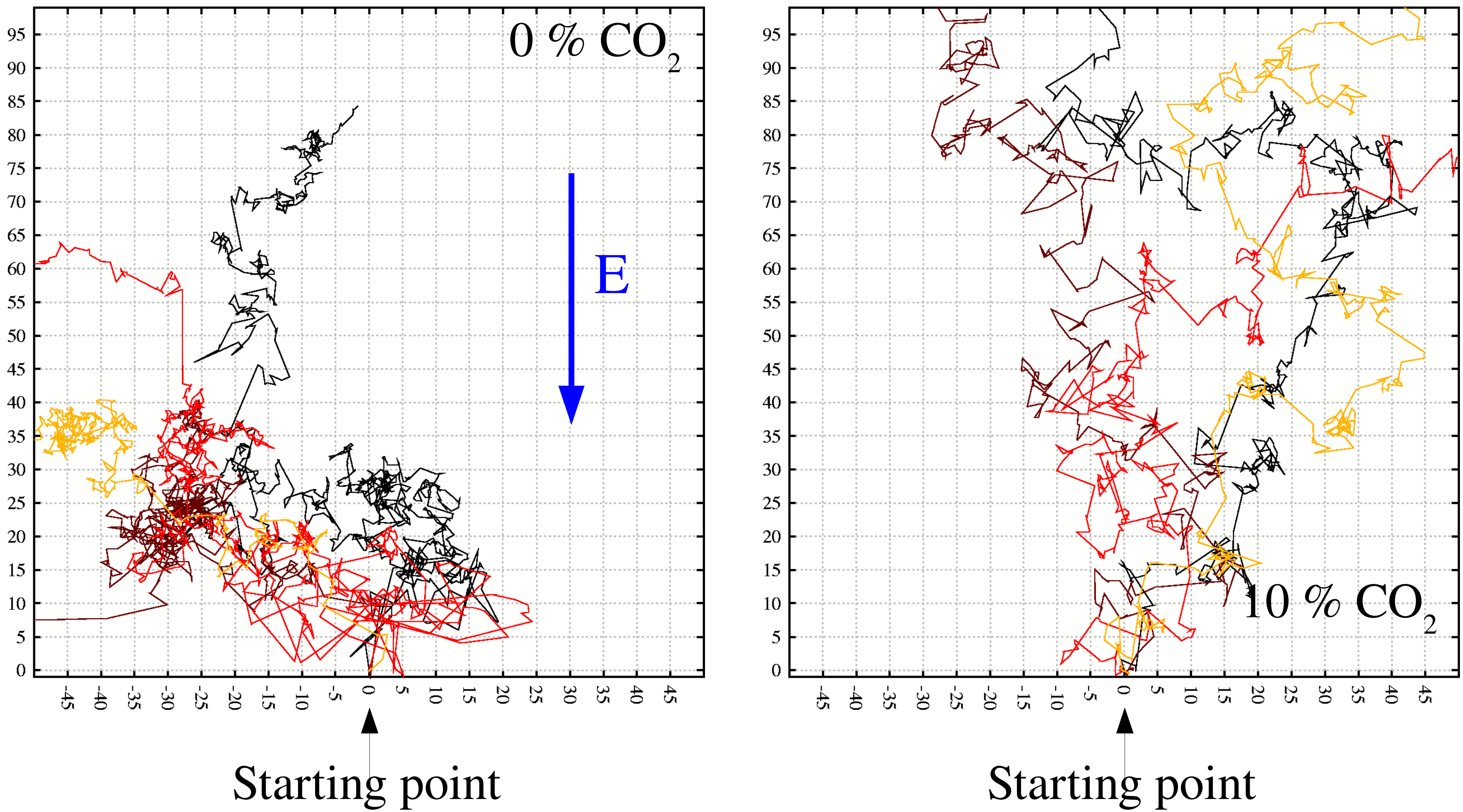
# $CO_2$ – vibration modes

- $CO_2$ is linear:
  - O – C – O
- Vibration modes are numbered V(*ijk*)
  - *i*: symmetric,
  - *j*: bending,
  - *k*: anti-symmetric.

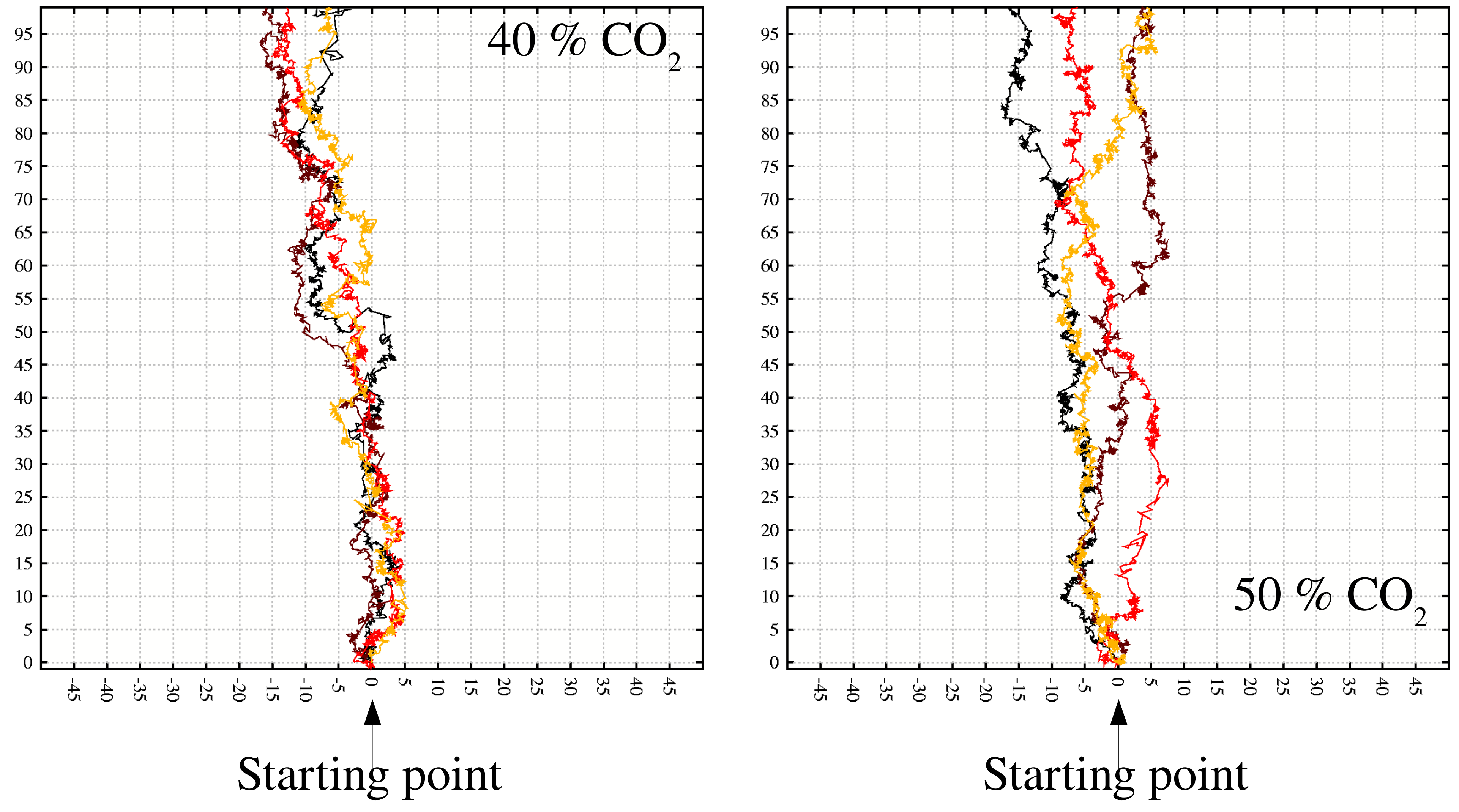




# Electrons in Ar/$CO_2$ at $E$=1 kV/cm



# Electrons in Ar/$CO_2$ at $E$=1 kV/cm



# Attachment

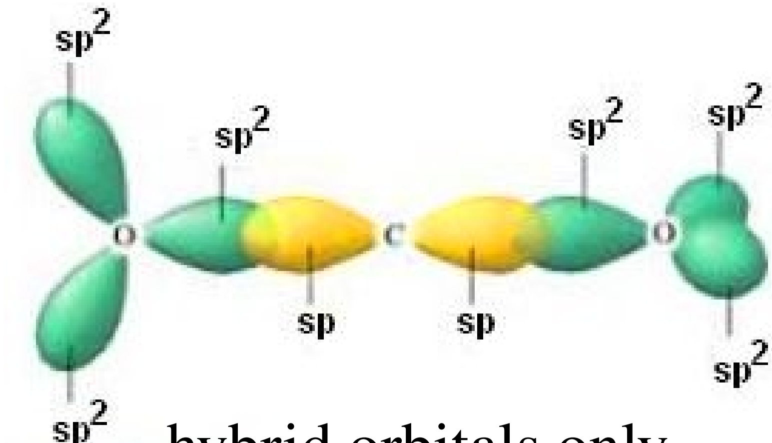
- Some quencher gases can attach electrons.

- Energy-momentum conservation:
  - 3-body interaction or
  - dissociation.

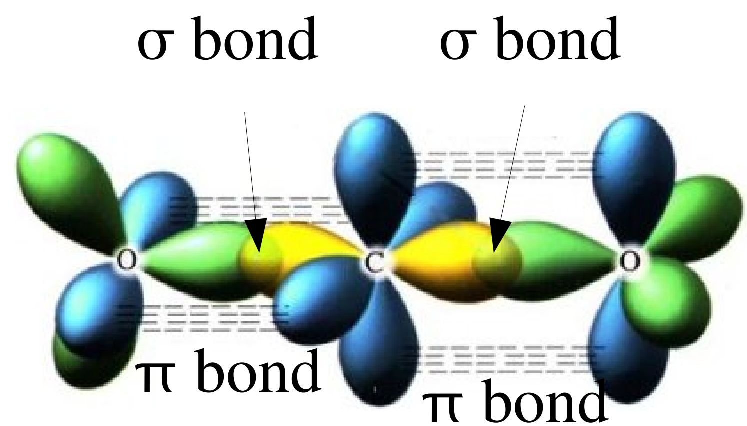
- Examples:
  - $O_2$: mostly 3-body $O_2^-$ and at higher $\epsilon$ 2-body dissociative;
  - $H_2O$: $[H_2O]_n$ has positive electron affinity, $H_2O$ probably not;
  - $CF_4$: mostly dissociative $F^- + CF_3$, $F + CF_3^-$ (below 10 eV);
  - $SF_6$: $SF_6^{-*}$ < 0.1 eV, then $F^- + SF_n^-$ (n=3, 4, 5)
  - $CS_2$: negative ion TPC;
  - $CO_2$: $O^-$, $[CO_2]_n^-$ but no $CO_2^-$ (4 eV and 8.2 eV).

# Attachment in $CO_2$

- $CO_2$ is a linear molecule:




hybrid orbitals only,
p-orbitals not shown




[Source: presumably SS Zumdahl, Chemistry (1983) DC Heath and Company.]

Arthur V. Phelps
(1923 - 2012)

# 1962: Numerical $e^-$ transport

- Iterative approach, allowing for inelastic cross section terms:
  - educated guess of cross sections (elastic & inelastic);
  - numerically solve the Boltzmann equation (no moments);
  - compare calculated and measured mobility and diffusion;
  - adjust cross sections.

"… more than 50,000 transistors plus extremely fast magnetic core storage. The new system can simultaneously read and write electronically at the rate of 3,000,000 bits of information a second, when eight data channels are in use. In 2.18 millionths of a second, it can locate and make ready for use any of 32,768 data or instruction numbers (each of 10 digits) in the magnetic core storage. The 7090 can perform any of the following operations in one second: 229,000 additions or subtractions, 39,500 multiplications, or 32,700 divisions. " (IBM 7090 documentation)

[L.S. Frost and A.V. Phelps, *Rotational Excitation and Momentum Transfer Cross Sections for Electrons in* $H_2$ *and* $N_2$ *from Transport Coefficients*, Phys. Rev. **127** (1962) 1621–1633.]

# Magboltz: microscopic $e^-$ transport

- A large number of cross sections for 60 molecules...
  - Numerous organic gases, additives, *e.g.* $CO_2$:
    - elastic scattering,
    - 44 inelastic cross sections (5 vibrations and 30 rotations + super-elastic and 9 polyads),
    - attachment,
    - 67 excited states and
    - 11 ionisations.
  - noble gases (He, Ne, Ar, Kr, Xe):
    - elastic scattering,
    - 44 excited states and
    - 7 ionisations.

# LXcat

- LXcat (pronounced *elecscat*) is an open-access website for collecting, displaying, and downloading ELECtron SCATtering cross sections and swarm parameters (mobility, diffusion coefficient, reaction rates, etc.) required for modeling low temperature plasmas. [...]”

[http://www.lxcat.laplace.univ-tlse.fr/]

# Gas gain

Sir John Sealy Edward Townsend
(1868-1957)

# 1901: Gas multiplication

- John Townsend:

Let a force X be applied to $N_0$ negative ions in a gas at pressure $p$ and temperature $t$. Let N be the total number of negative ions after the $N_0$ ions have travelled a distance $x$. The new negative ions travel with the same velocity as the original $N_0$ ions, so that all the negative ions will be found together during the motion. The number of negative ions produced by N ions travelling through a distance $dx$ will be $\alpha N dx$; where $\alpha$ is a constant depending on X, $p$, and $t$.

Then

$$dN = \alpha N dx.$$

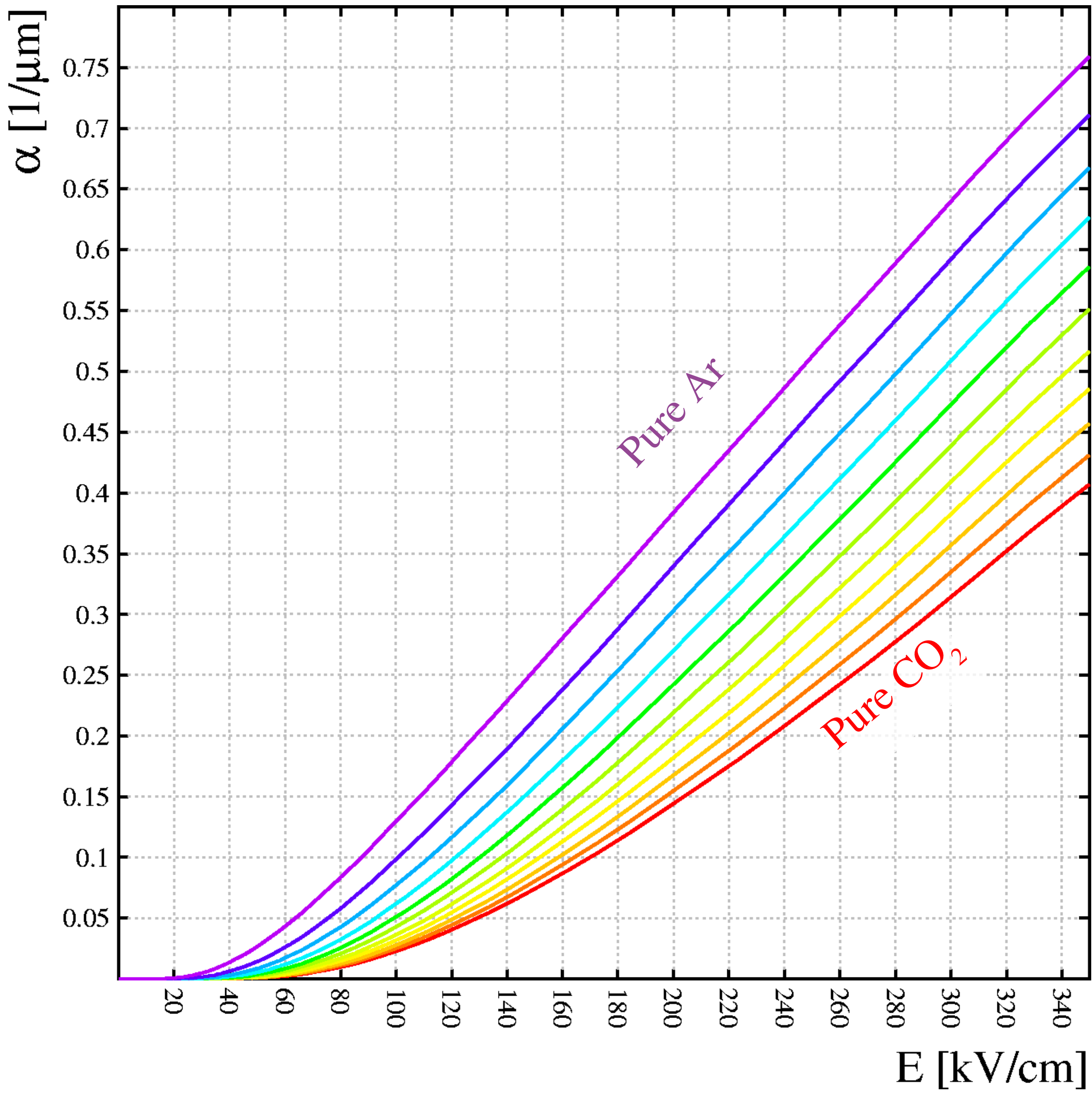
Hence

$$N = N_0 \epsilon^{\alpha x}$$

[J.S. Townsend, "*The conductivity produced in gases by the motion of negatively charged ions*", Phil. Mag. **6-1** (1901) 198-227. If access to the Philosophical Magazine is restricted, then consult a German-language abstract at http://jfm.sub.uni-goettingen.de/.]

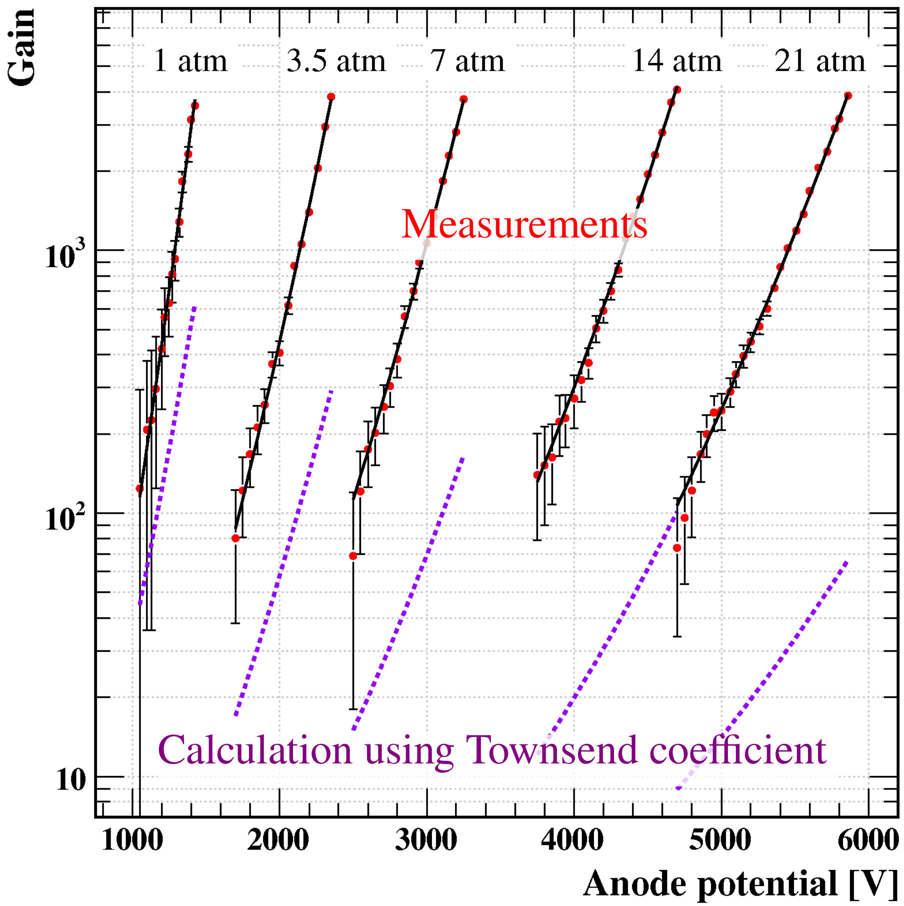
# $\alpha(Ar\text{-}CO_2)$

- $\alpha$ = number of $e^-$ an avalanche $e^-$ creates per cm.
- Adding $CO_2$ reduces the gain.
- Calculated by Magboltz for $Ar/CO_2$ at 3 bar.

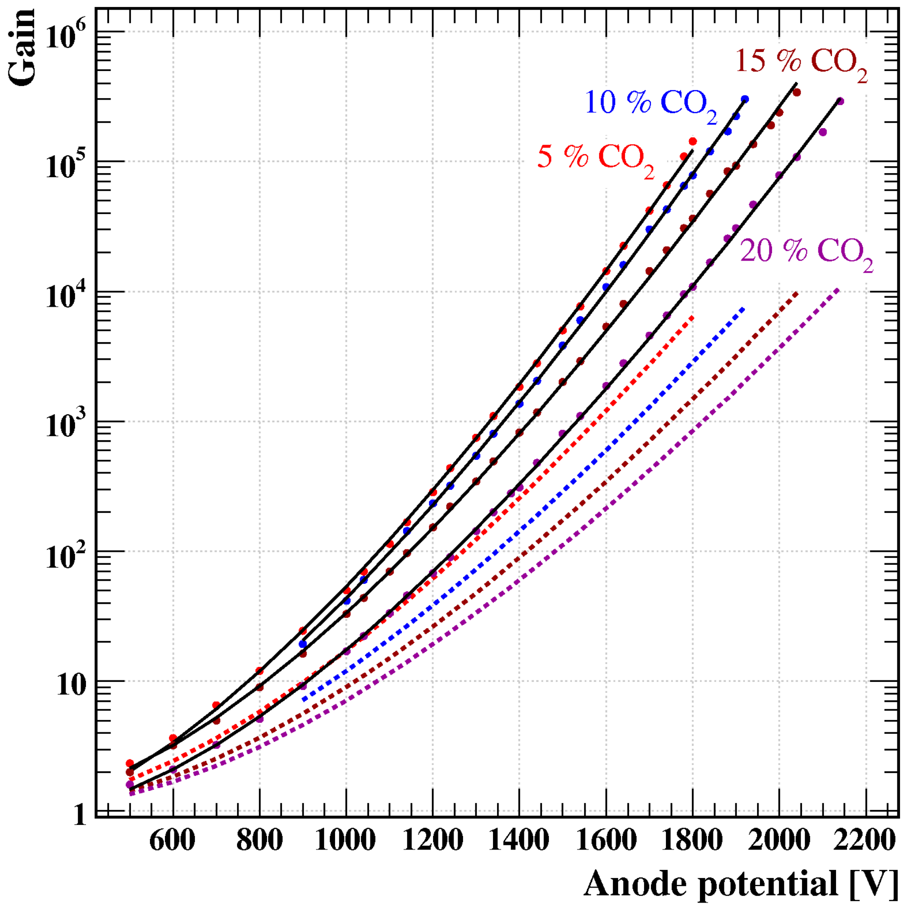


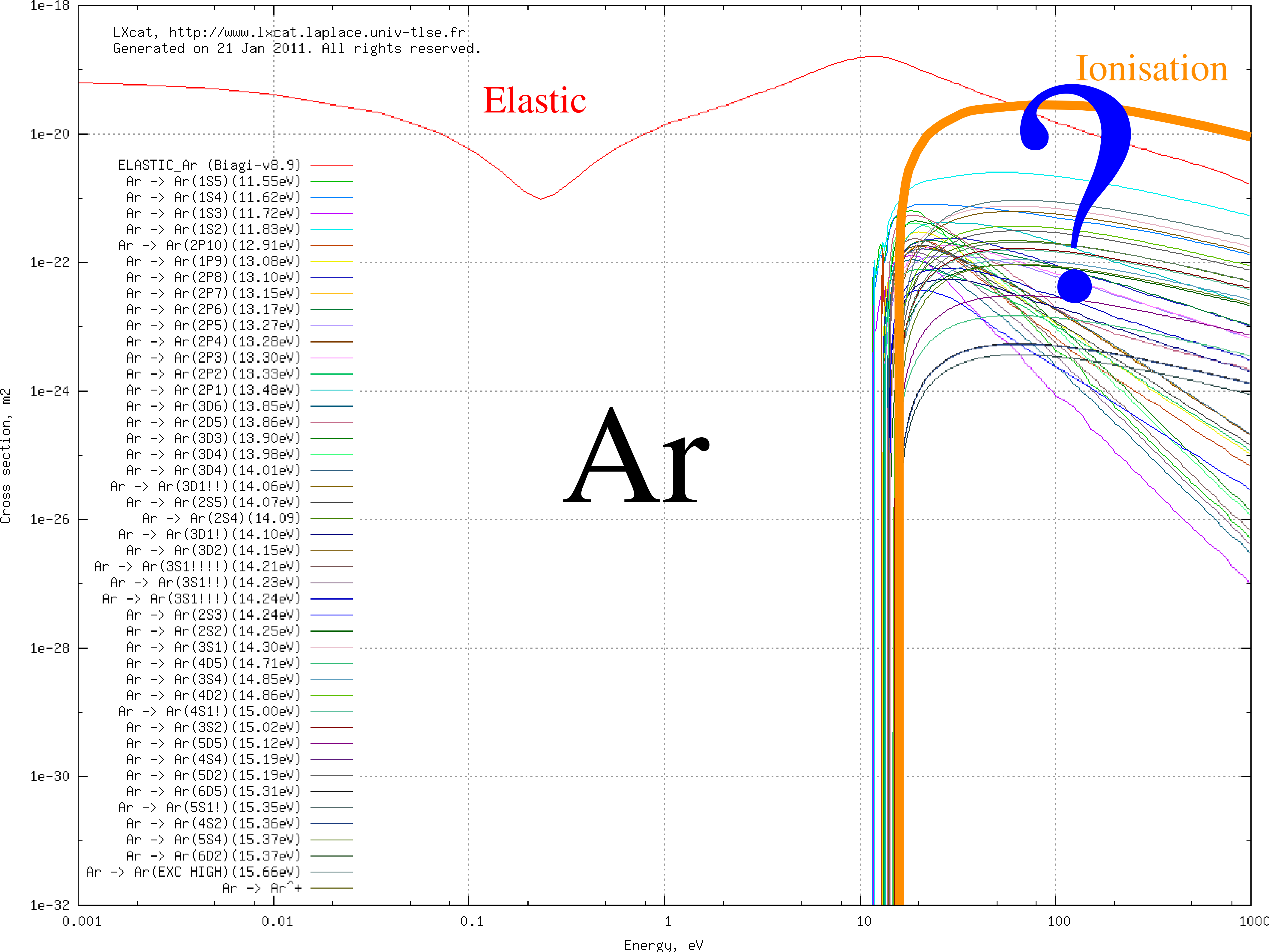
# Does this reproduce the measurements ?

- Ar - $CH_4$




- Ar - $CO_2$




LXcat, http://www.lxcat.laplace.univ-tlse.fr
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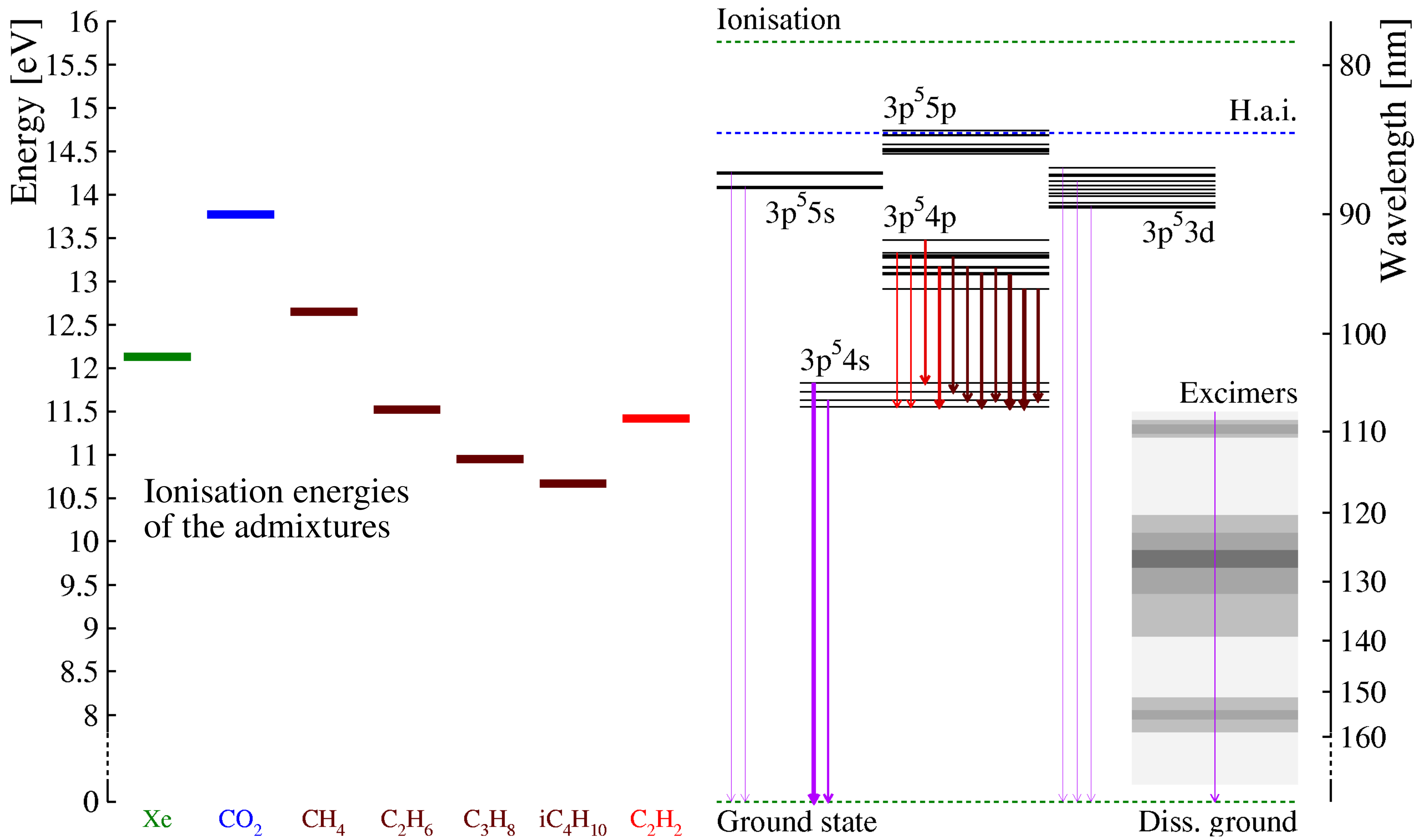
Elastic
Ionisation
?
Ar
ELASTIC_Ar (Biagi-v8.9)
Ar -> Ar(1S5)(11.55eV)
Ar -> Ar(1S4)(11.62eV)
Ar -> Ar(1S3)(11.72eV)
Ar -> Ar(1S2)(11.83eV)
Ar -> Ar(2P10)(12.91eV)
Ar -> Ar(1P9)(13.08eV)
Ar -> Ar(2P8)(13.10eV)
Ar -> Ar(2P7)(13.15eV)
Ar -> Ar(2P6)(13.17eV)
Ar -> Ar(2P5)(13.27eV)
Ar -> Ar(2P4)(13.28eV)
Ar -> Ar(2P3)(13.30eV)
Ar -> Ar(2P2)(13.33eV)
Ar -> Ar(2P1)(13.48eV)
Ar -> Ar(3D6)(13.85eV)
Ar -> Ar(2D5)(13.86eV)
Ar -> Ar(3D3)(13.90eV)
Ar -> Ar(3D4)(13.98eV)
Ar -> Ar(3D4)(14.01eV)
Ar -> Ar(3D1!!)(14.06eV)
Ar -> Ar(2S5)(14.07eV)
Ar -> Ar(2S4)(14.09)
Ar -> Ar(3D1!)(14.10eV)
Ar -> Ar(3D2)(14.15eV)
Ar -> Ar(3S1!!!!)(14.21eV)
Ar -> Ar(3S1!!)(14.23eV)
Ar -> Ar(3S1!!!)(14.24eV)
Ar -> Ar(2S3)(14.24eV)
Ar -> Ar(2S2)(14.25eV)
Ar -> Ar(3S1)(14.30eV)
Ar -> Ar(4D5)(14.71eV)
Ar -> Ar(3S4)(14.85eV)
Ar -> Ar(4D2)(14.86eV)
Ar -> Ar(4S1!)(15.00eV)
Ar -> Ar(3S2)(15.02eV)
Ar -> Ar(5D5)(15.12eV)
Ar -> Ar(4S4)(15.19eV)
Ar -> Ar(5D2)(15.19eV)
Ar -> Ar(6D5)(15.31eV)
Ar -> Ar(5S1!)(15.35eV)
Ar -> Ar(4S2)(15.36eV)
Ar -> Ar(5S4)(15.37eV)
Ar -> Ar(6D2)(15.37eV)
Ar -> Ar(EXC HIGH)(15.66eV)
Ar -> Ar^+
Cross section, m2
Energy, eV
1e-18
1e-20
1e-22
1e-24
1e-26
1e-28
1e-30
1e-32
0.001
0.01
0.1
1
10
100
1000

# Level diagram argon and admixtures



# Determining the Penning parameter

- The Penning transfer rate $r_P$ is measured by finding, the fraction of the excitations to be added to $\alpha$ so that the measured gain is reproduced:

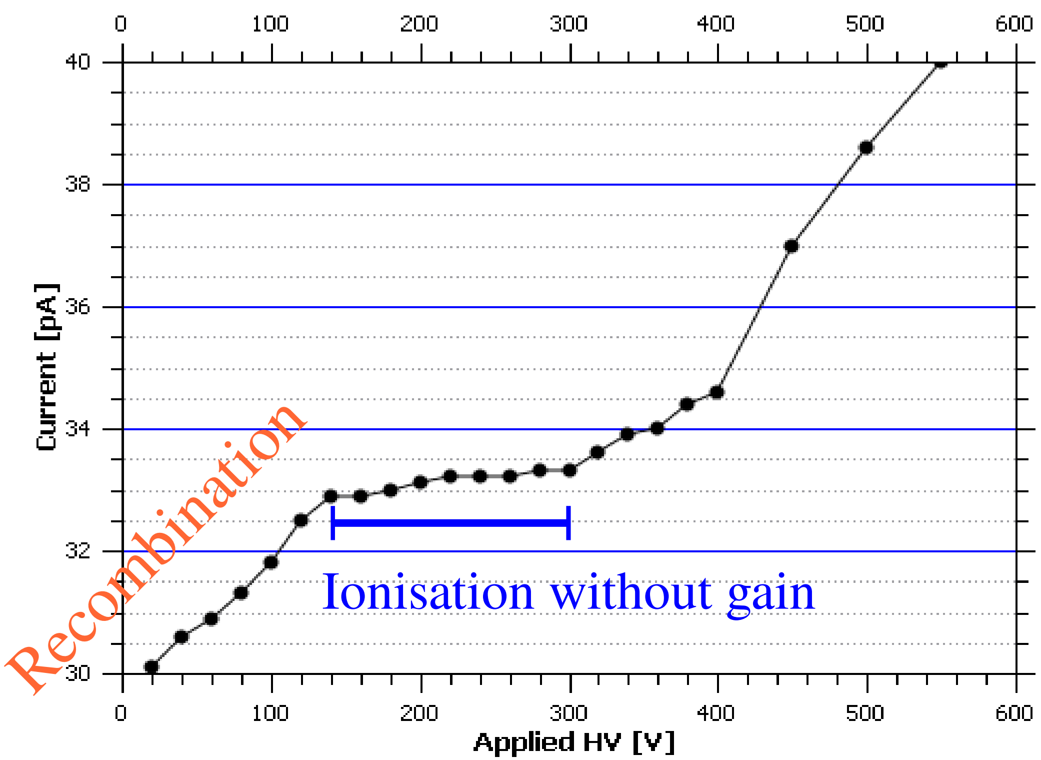
$$G = \exp \int \alpha \left( 1 + r_P \frac{\nu_{\mathrm{exc}}}{\nu_{\mathrm{ion}}} \right)$$

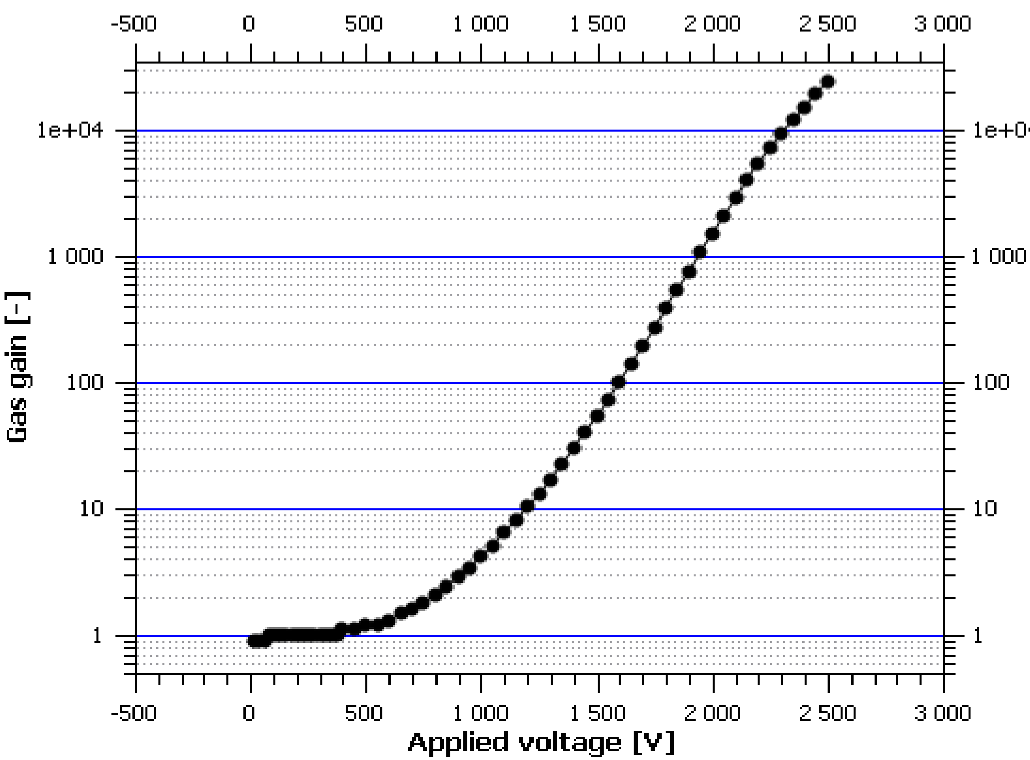
- $r_P$ depends on gas choice, quencher fraction and density.

- Ideally, one would like to determine a separate $r_P$ for each excitation, but for now, we do not have the data for that.

# Data covers 5 orders of magnitude !

- Current reference is taken at the ionisation level.
- Main source of error: ~5 %.

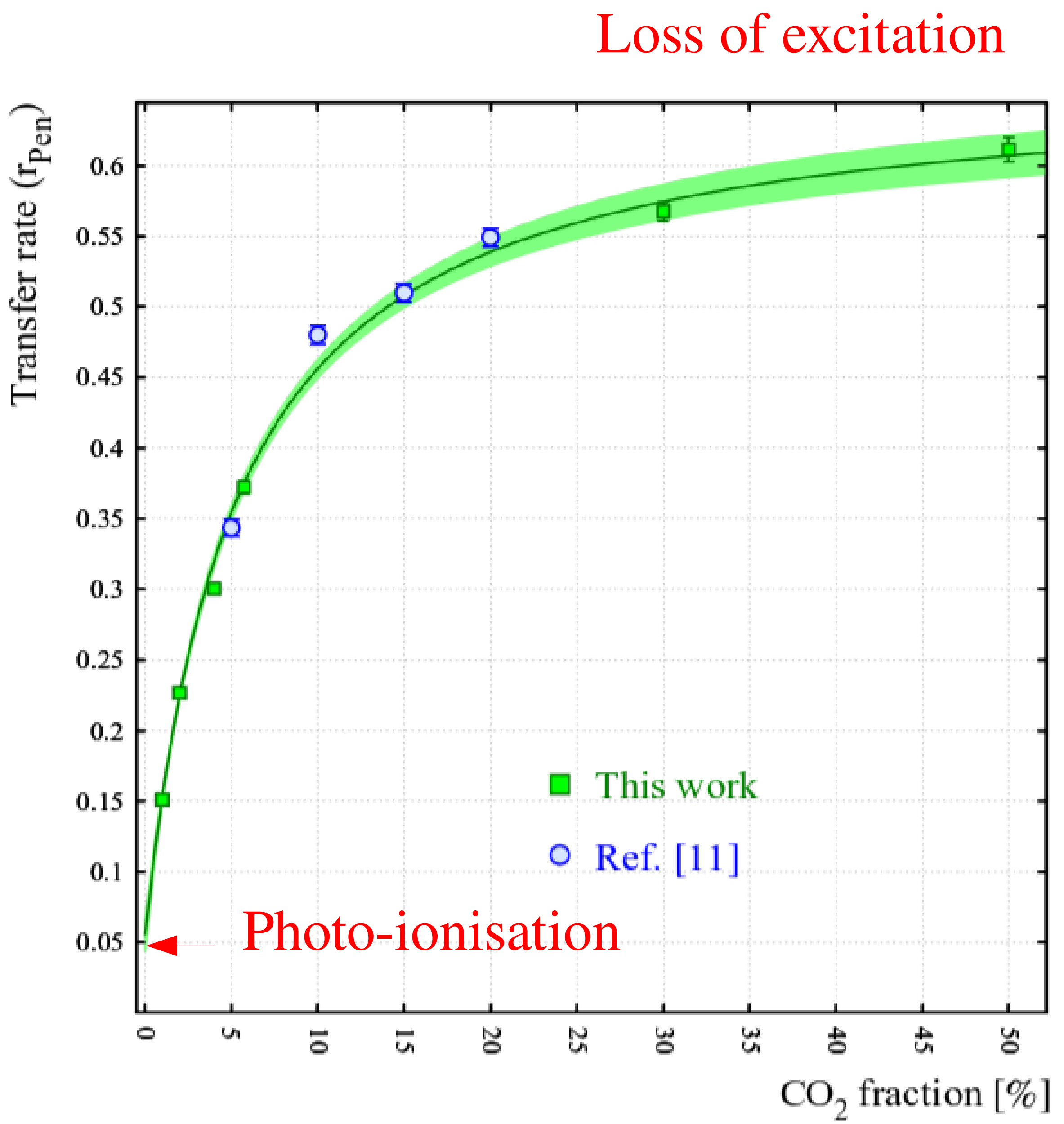


# Ar-$CO_2$ transfer rates

- Penning parameter fits with data from Tadeusz Kowalski et al. 1992 and 2013.
- At $p$ = 1070 hPa.

[10.1016/0168-9002(92)90305-N, 10.1016/j.nima.2014.09.061]



# Gain calculations

# Total gain vs effective gain in a GEM

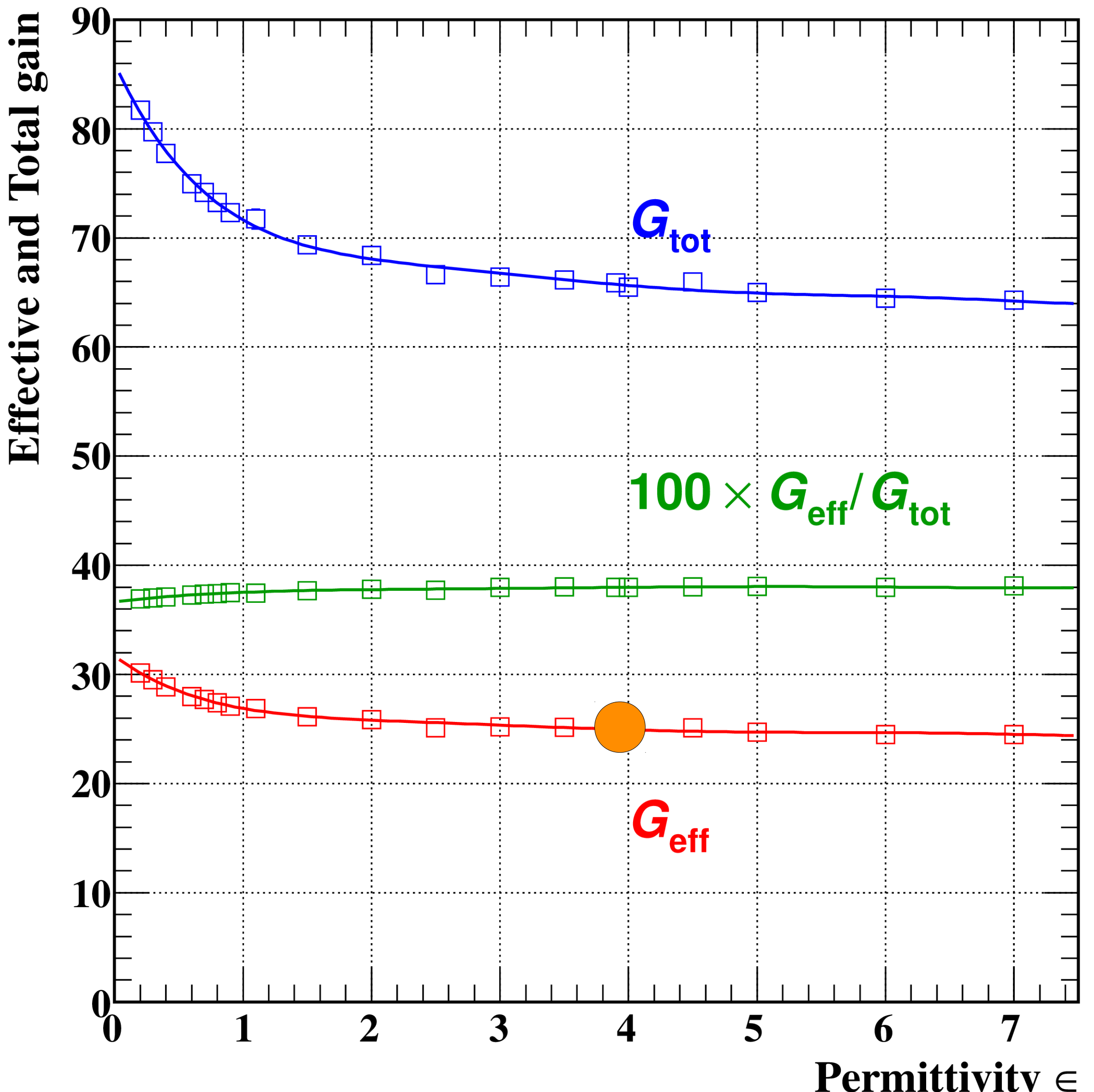
- Total gain: $G_{tot}$
  - total number of electrons produced by the average avalanche

- Effective gain: $G_{eff}$
  - number of electrons produced by the average avalanche and that reach the GEM read-out structure

  - the other electrons land on the PI, modifying the field, or on the bottom GEM electrode.

# Varying the permittivity

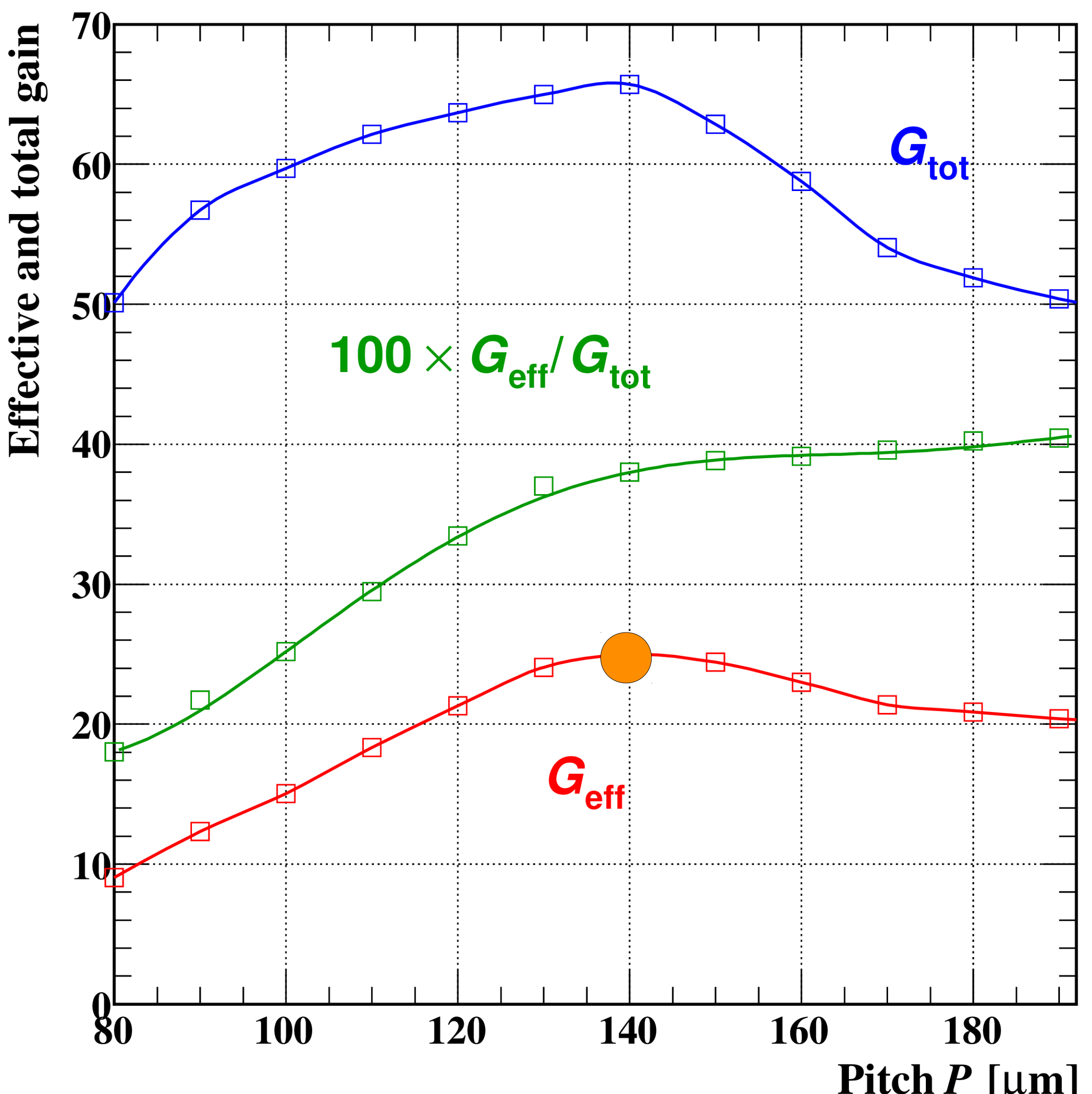
- Reference geometry:
  - inner diam $d = 50$ µm,
  - outer diam $D = 70$ µm,
  - pitch $T = 140$ µm,
- Material reference:
  - permittivity $\varepsilon = 3.9$.
- Permittivity affects the gain at low $\varepsilon$.



# Varying the pitch

- Reference geometry:
  - inner diam $d = 50$ µm,
  - outer diam $D = 70$ µm,
  - pitch $T = 140$ µm,
- Material reference:
  - permittivity $\varepsilon = 3.9$.

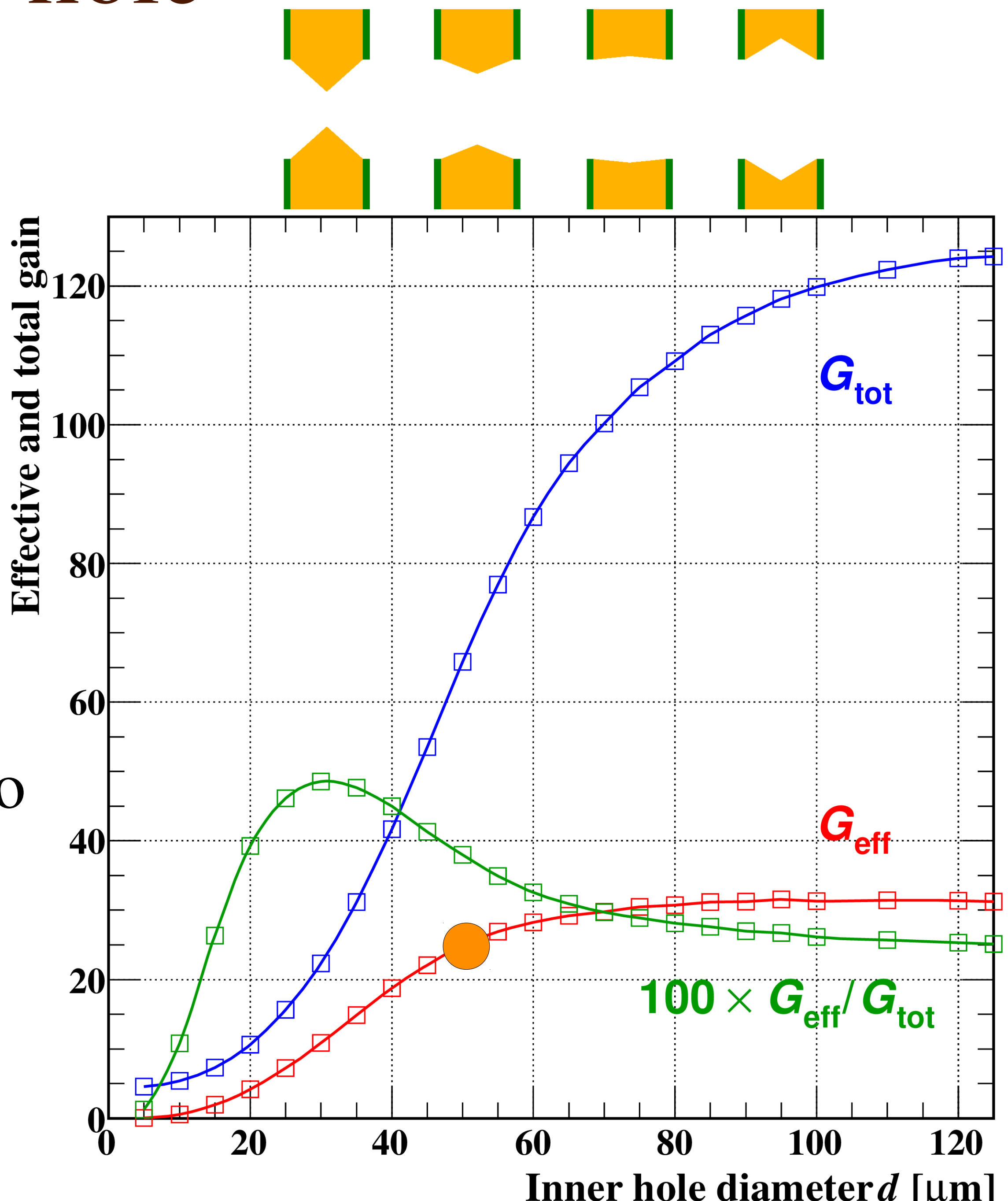
- Usual pitch maximises the gain.



# Varying the inner hole diameter

- Reference geometry:
  - inner diam $d$ = 50 µm,
  - outer diam $D$ = 70 µm,
  - pitch $T$ = 140 µm,
- Material reference:
  - permittivity ε = 3.9.

- At small d, electrons hit the PI near the tip;
- $G_{eff}$ increases with $d$ up to cylindrical, then flattens;
- over-etching does cause $G_{tot}$ to keep increasing.



# Ion Transport

# Ion transport

- In this laboratory, we look into electron transport, but not into ion transport.
- We do this because electrons are responsible for the signals in GEMs.
- Beware though that the signals in
  - wire chambers,
  - Micromegas
  - and others,
- are generated by ion movement
- Ion transport is a rich field which we can discuss in a small group if desired: ion reactions, cluster formation ...

# Next

- Josh Renner has prepared exercises to simulate a LEM.
- Beware … GEM and LEM look similar at first sight, but there are important differences !