# Simulating gas-based detectors

Rob Veenhof

RD51 collaboration and Uludağ university, Bursa, Turkey

# Operating principles:

- The charged particle or photon we want to observe passes through the gas and ionises molecules;
- the electric field in the gas volume transports the ionisation electrons and ions;
- electrons multiply in high field areas;
- moving electrons and ions induce currents in electrodes.

# 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:

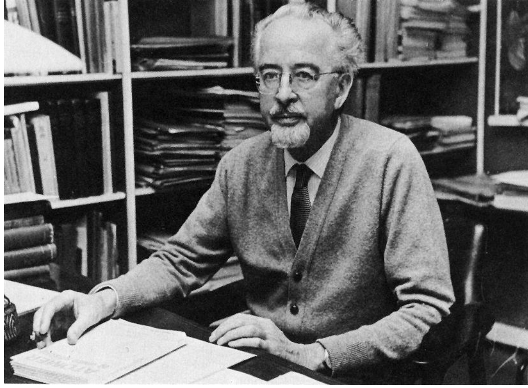
" Becquerel discovered in 1896 the special radiating properties of uranium and its compounds. Uranium emits very weak rays which leave an impression on photographic plates. These rays pass through black paper and metals; they make air electrically conductive. "

[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]

Christian Møller
(1904-1980)



# 1930-1933: EM energy loss

- 1930 - Hans Bethe, non-relativistic quantum calculation:

The loss in kinetic energy per centimeter path is

$$-\frac{dT}{dx} = N E = \frac{4\pi e^4 z^2 N}{m v^2} \ln \frac{(2)\, m v^2}{c R h} .$$

*Z*: “hidden in *N*”
(2): only for electrons
*R*: Rydberg constant

- 1931 - Christian Møller solves relativistic $e^-$ scattering.
- 1932 - Hans Bethe, relativistic quantum calculation:

Ein Teilchen der Ladung $e z$ möge sich mit der Geschwindigkeit $v$ durch eine Substanz hindurchbewegen, welche in der Volumeneinheit $N$ Atome der Ordnungszahl $Z$ enthält. Dann verliert das Teilchen pro Zentimeter Weg die Energie

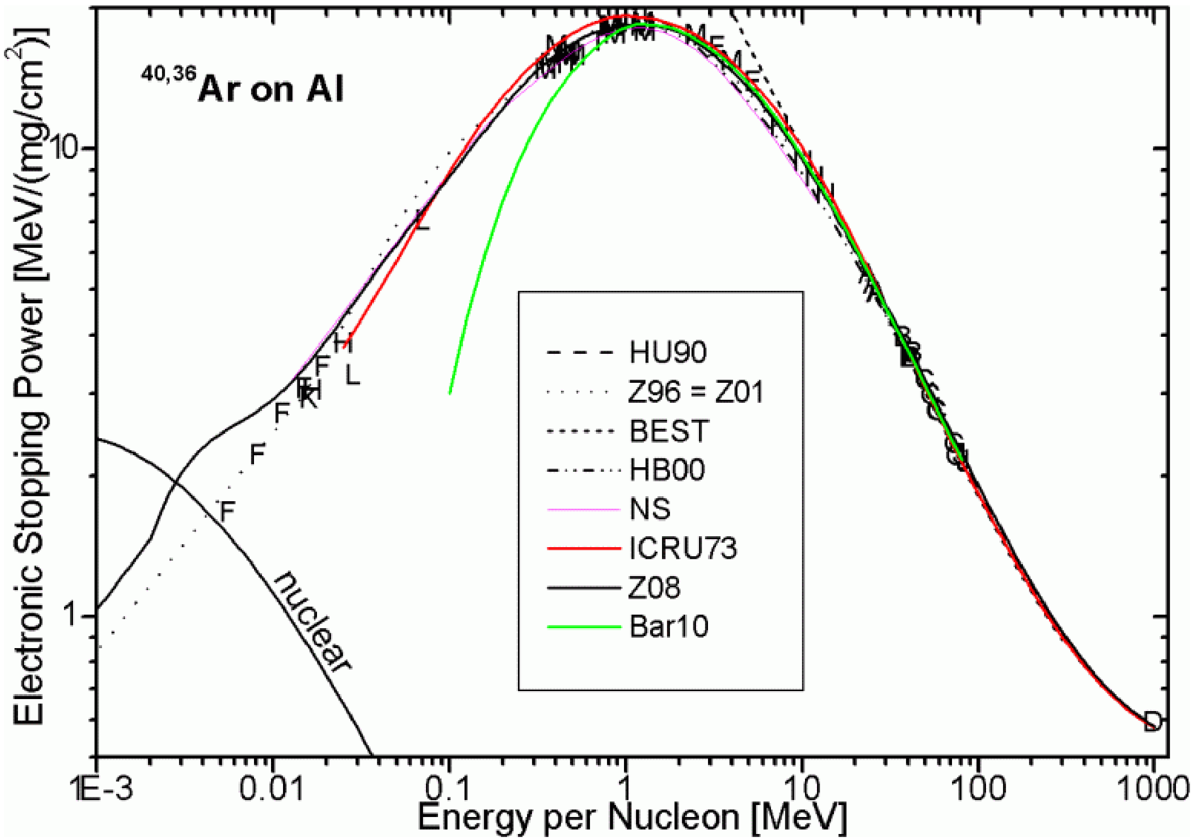
$$-\frac{dT}{dx} = \frac{2\pi e^4 N Z z^2}{m v^2}\left(\lg \frac{2 m v^2 W}{\bar{E}^2 \left(1 - \frac{v^2}{c^2}\right)} - \frac{v^2}{c^2}\right),$$

falls wir nur den Energieverlust durch solche Stöße ins Auge fassen, bei denen im einzelnen höchstens die Energie $W$ auf das Atom übertragen wird[3]).

$\bar{E}$: average atomic ionisation energy
*W*: largest energy transfer per collision

# Electromagnetic losses at low energy

- Nuclear effects abound at low energy.
- Numerous models: SRIM, MSTAR, CasP, PASS ...




- Ref: Helmut Paul, http://www.exphys.uni-linz.ac.at/Stopping/

Лев Давидович Ландау
(1908-1968)

# 1944: Energy loss fluctuations

- Given a single-collision energy loss distribution $w(\epsilon)$, the distribution $f(s)$ of the energy loss $s$ after many collisions is *schematically* given by the Laplace transform:

$$L\, f(x,s) = \bar{f}(x,p) = \mathrm{e}^{-x\int_0^\infty (1-\mathrm{e}^{-p\epsilon})\, w(\epsilon)\, \mathrm{d}\epsilon}$$

*x*: direction of travel

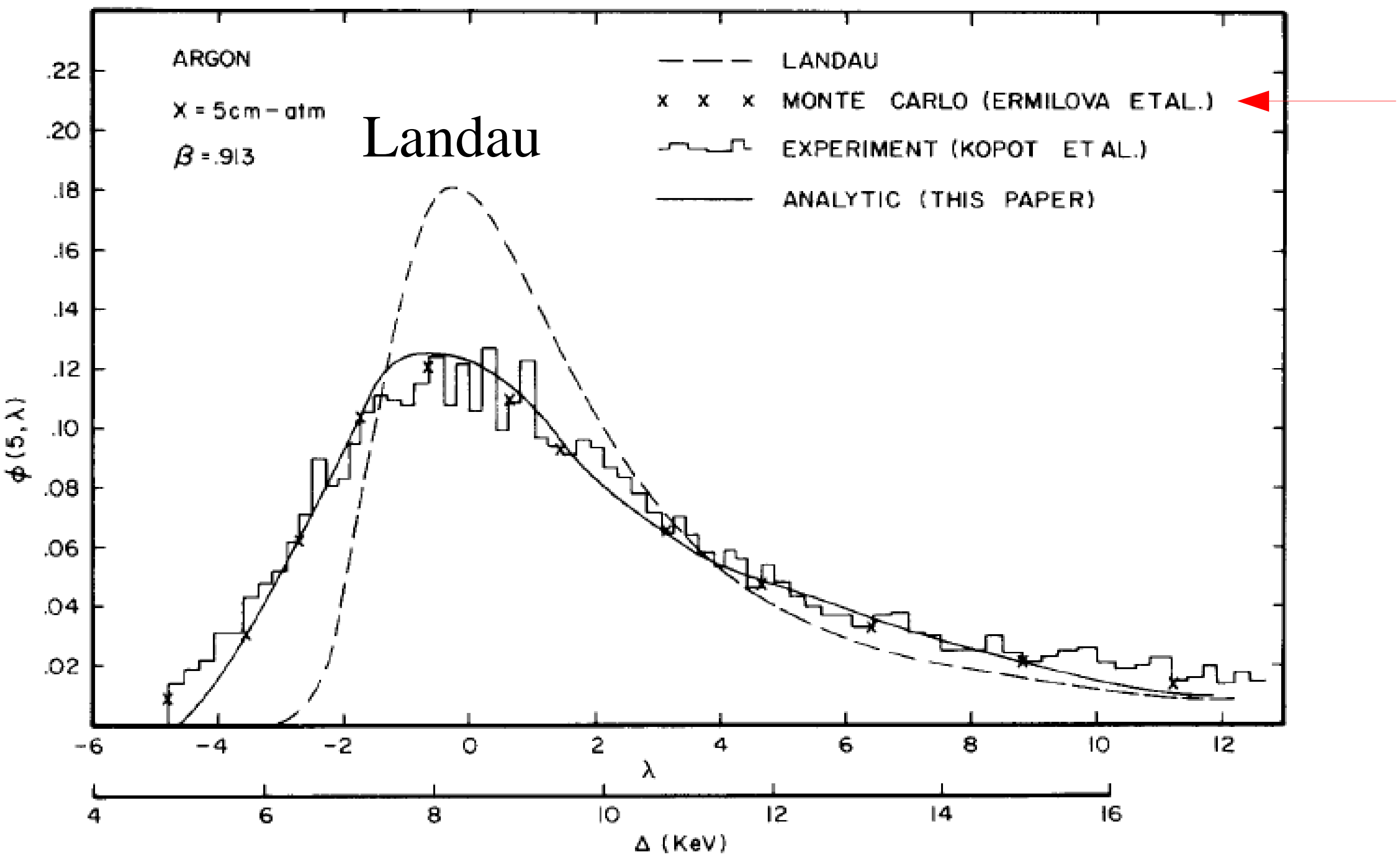
$s \leftrightarrow p$: total energy loss

- Landau showed (1944), assuming in particular:
  - thick layers: numerous small energy losses;
  - Rutherford-inspired energy loss distribution $w(\epsilon) \sim 1/\epsilon^2$;
  - neglect of the atomic structure:

$$L\, f(s) \approx s^s$$

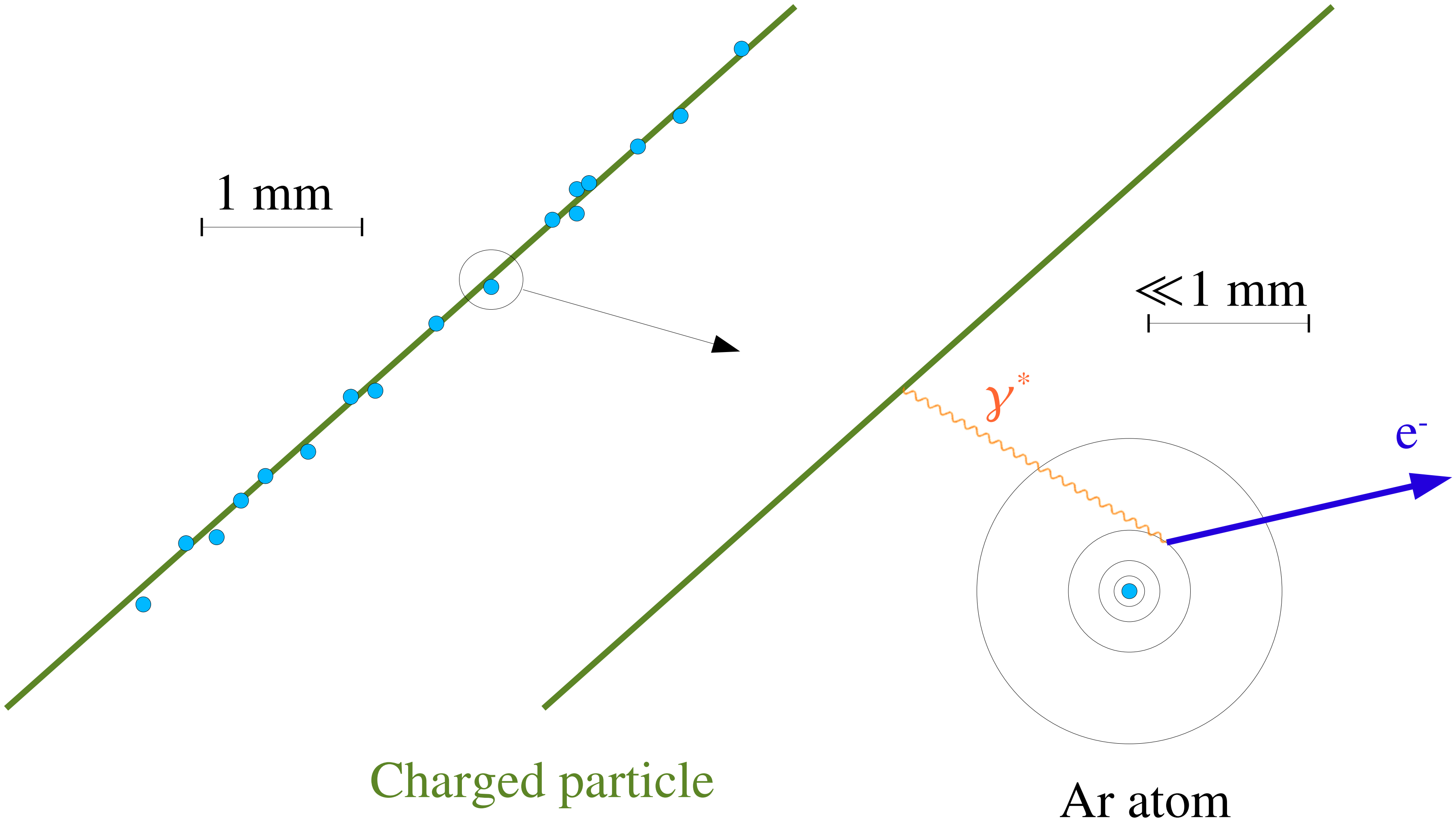
# Landau: too narrow for thin layers

- 2 GeV protons on an (only !) 5 cm thick Ar gas layer:

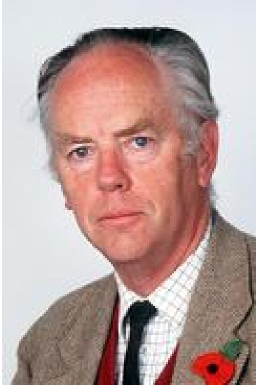



[Diagram: Richard Talman, NIM A **159** (1979) 189-211]

# Virtual photon exchange model



# PAI model



Wade Allison

John Cobb

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

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

Relativistic rise

Cross section to transfer energy $E$

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

Čerenkov 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

With:

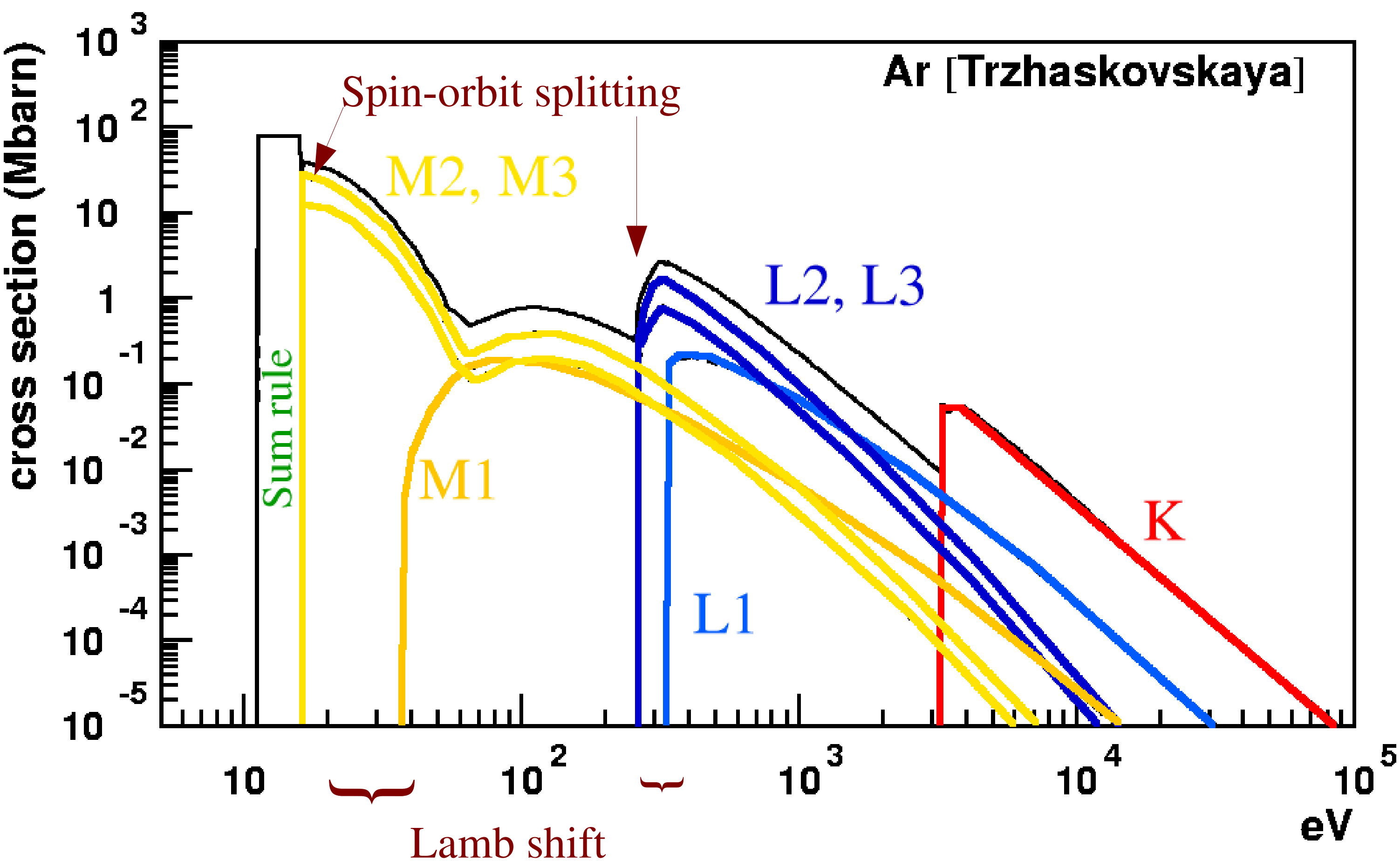
$$\epsilon_2(E)=\frac{N_e\hbar c}{EZ}\sigma_\gamma(E)$$

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

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

# Photo-absorption in argon

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




K = 1s

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

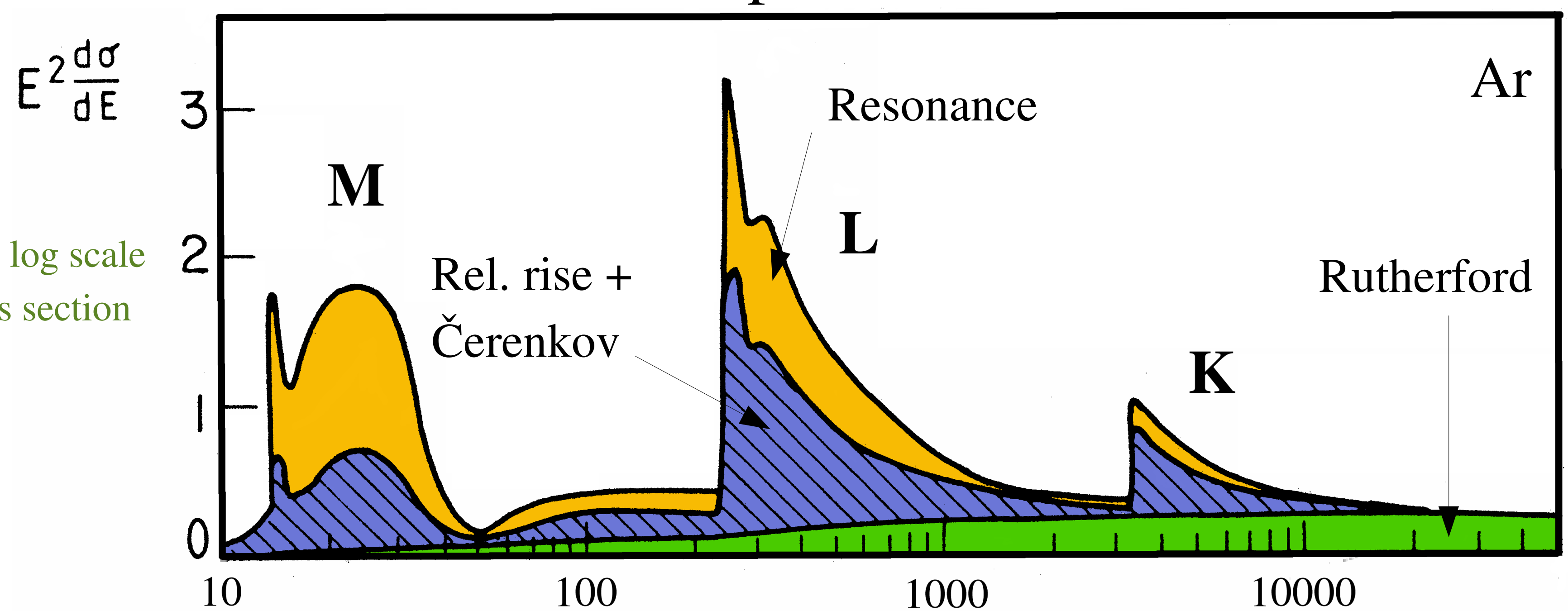
M1 = 3s
M2 = 3p 1/2
M3 = 3p 3/2

[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.

Scaling with $E^2$:
equal areas on log scale
weighing cross section




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

# Heed – computer model

Igor Smirnov

- PAI model or absorption of real photons:

$\text{Atom} + \pi^- \rightarrow \text{Ion}^{+*} + \pi^- + e^-$ (photo-electric effect,

$\text{Atom} + \gamma \rightarrow \text{Ion}^{+*} + e^-$ real or virtual photon)

- Decay of excited states:

$\text{Ion}^{+*} \rightarrow \text{Ion}^{++} + e^-$ (Auger)

$\text{Ion}^{+*} \rightarrow \text{Ion}^{+} + \gamma$ (fluorescence)

$\text{Ion}^{+*} \rightarrow \text{Ion}^{+*}$ (Coster-Kronig)

- Treatment of:
  - secondary photons, returning to the PAI model,
  - ionising photo-electrons and Auger-electrons, collectively known as $\delta$-electrons:

$e^- + \text{Atom} \rightarrow \text{Ion}^{+} + 2\,e^-$ (absorption of high-energy electrons)

# Degrad – Steve Biagi

- Auger cascade model for electron thermalisation in gas mixtures produced by photons or particles in electric and magnetic fields.

- Applications:
  - Work function and Fano factor (including shape)
  - Cloud size after $\beta$-decay
  - Cluster size & density distribution for charged particle tracks

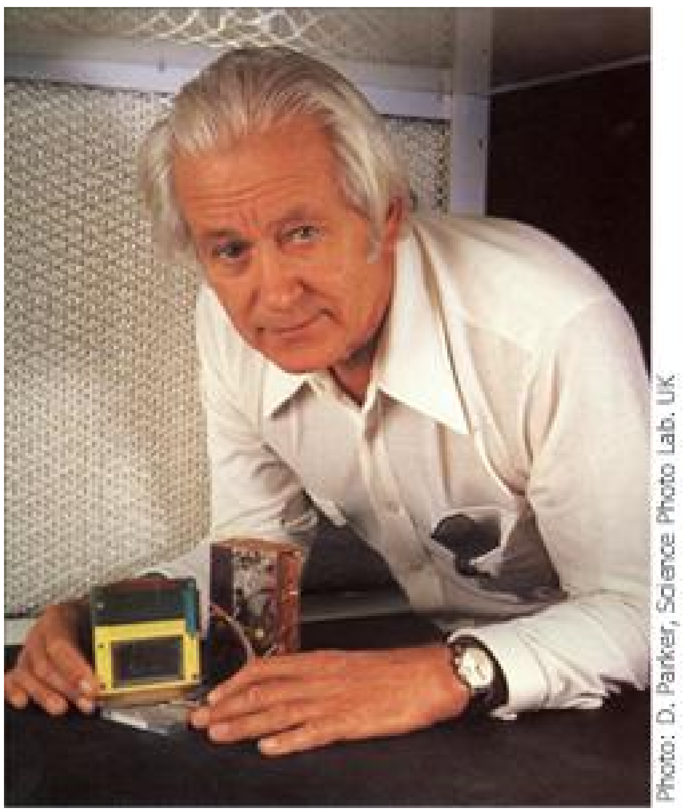
- Degrad shares its electron impact cross sections with Magboltz and is a successor to MIP.

# Fields

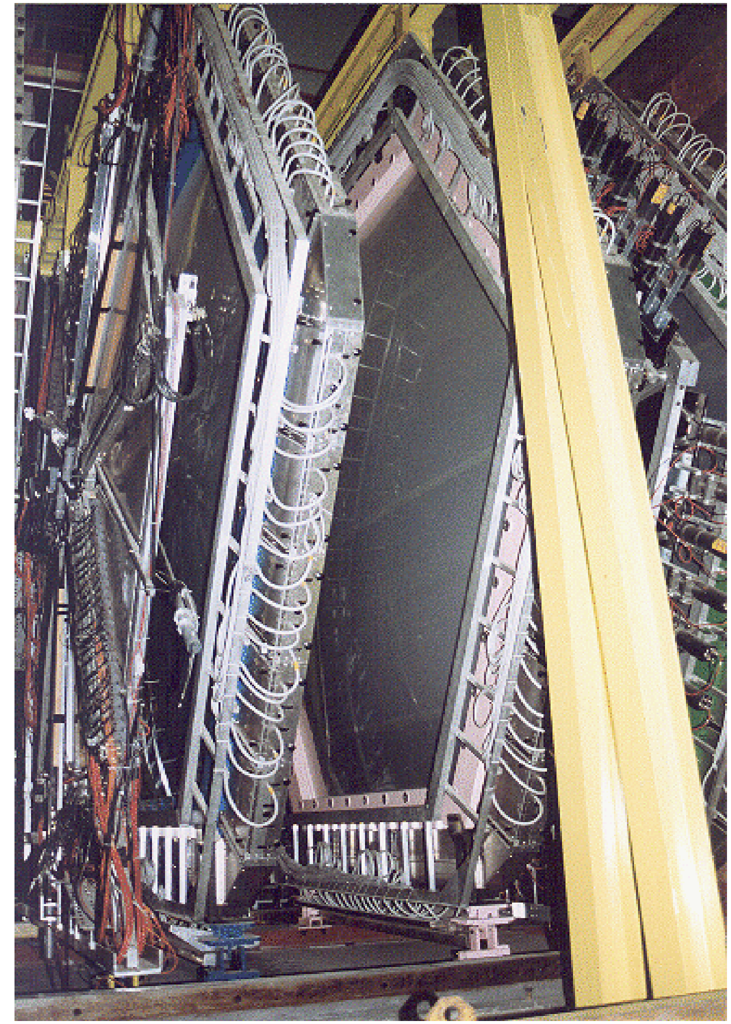
- “Classic” devices – metal wires and planes – 2d:
  - elegant, closed expressions.
- MPGDs – dielectric media – 3d:
  - finite elements;
  - boundary elements.

# MWPC

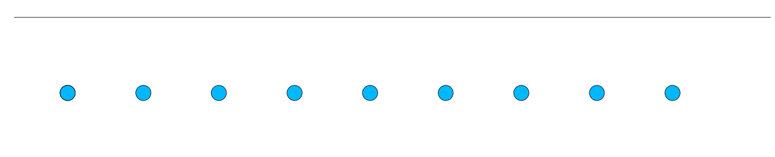
- First gaseous tracking device
- 1968: Georges Charpak




Georges Charpak



One of the NA60 muon chambers



# TPC

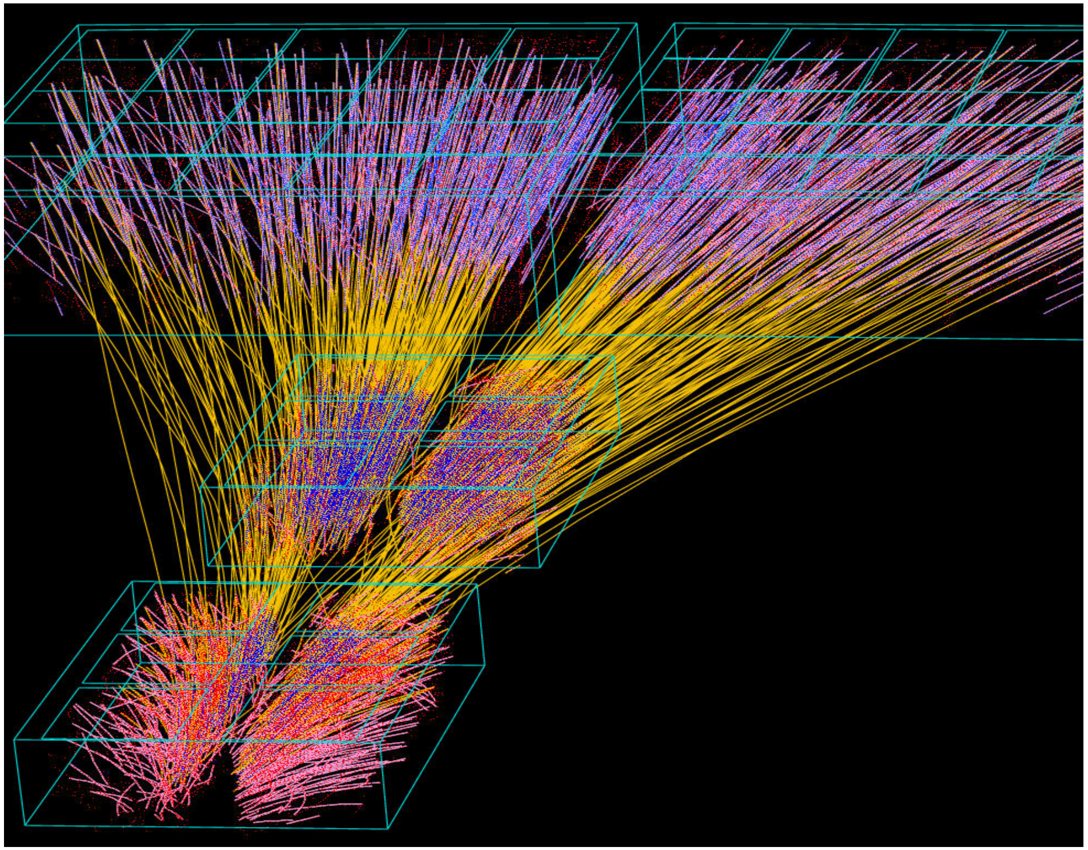
- Typically very large
- Almost empty inside
- Excellent for dealing with large numbers of tracks

- 1976: David Nygren (for PEP4)

David Nygren

Alice

Star



NA49

# 1749: Cauchy-Riemann equations

Jean le Rond d'Alembert
(Nov 16th 1717 –Oct 29th 1783)

- Core of the complex potential method.

- Existence of a derivative of a complex analytic function $f = u + \mathrm{i}\, v$

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

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

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

- implies that Re(*f*) is harmonic:

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

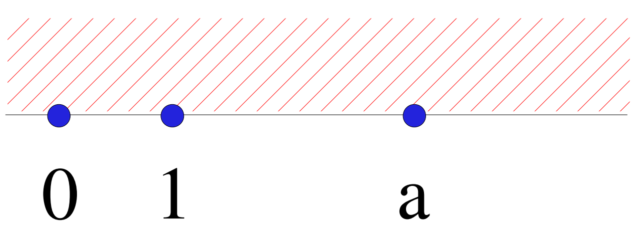
Georg Friedrich Bernhard Riemann
(Sep 17st 1826 – Jul 20th 1866)

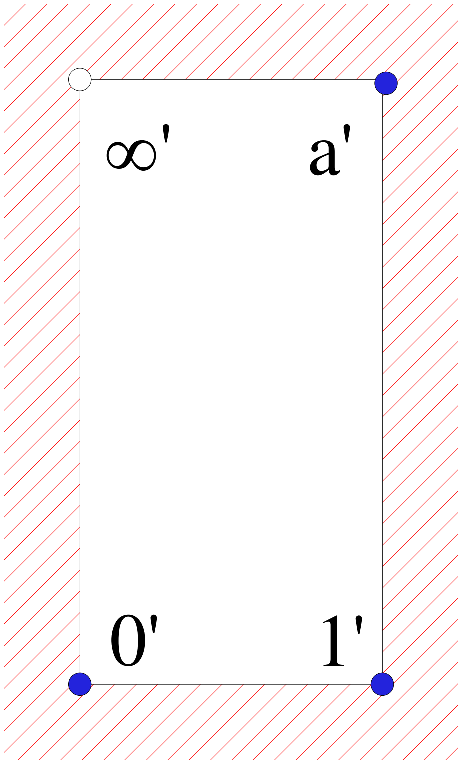
# Conformal mappings – an example

- Schwartz-Christoffel transformation of a half-plane to the external part of a rectangle:

$$z \to \int_0^z \frac{d\xi}{\sqrt{\xi(\xi-1)(\xi-a)}}$$

$$= \frac{2}{\sqrt{a}} \operatorname{sn}^{-1}\left(\sqrt{z}, \frac{1}{\sqrt{a}}\right)$$



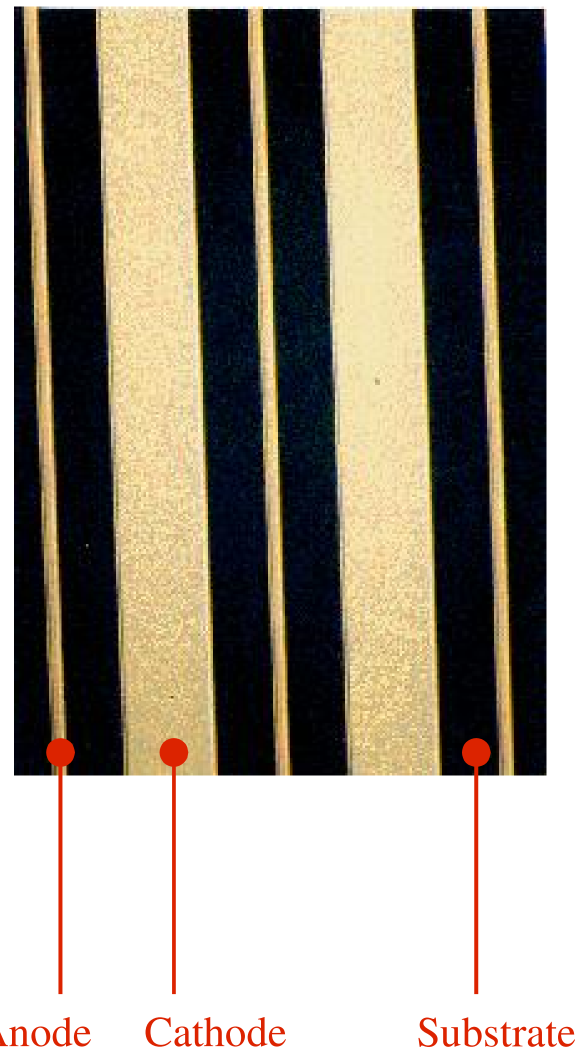
# MPGD

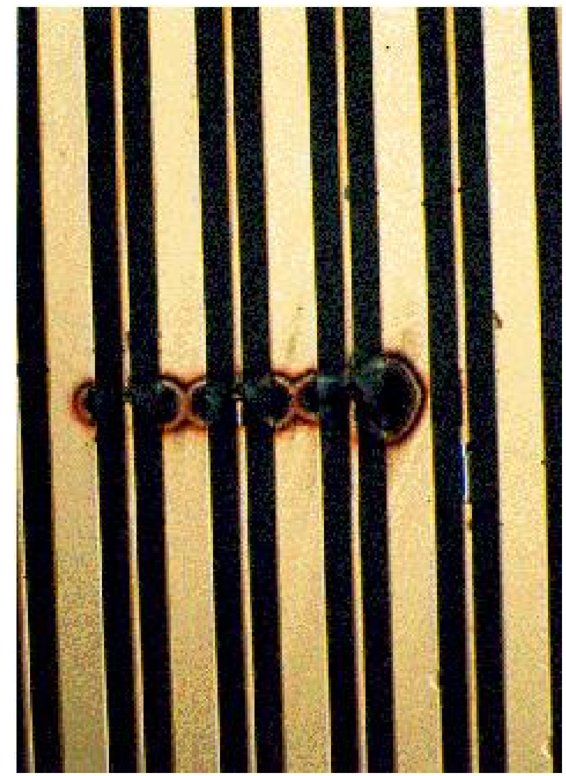
- Micro-Pattern Gas-based Detectors
    - have small structural elements
    - use 3d electrodes to generate electric fields.

# MSGC: an early MPGD

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

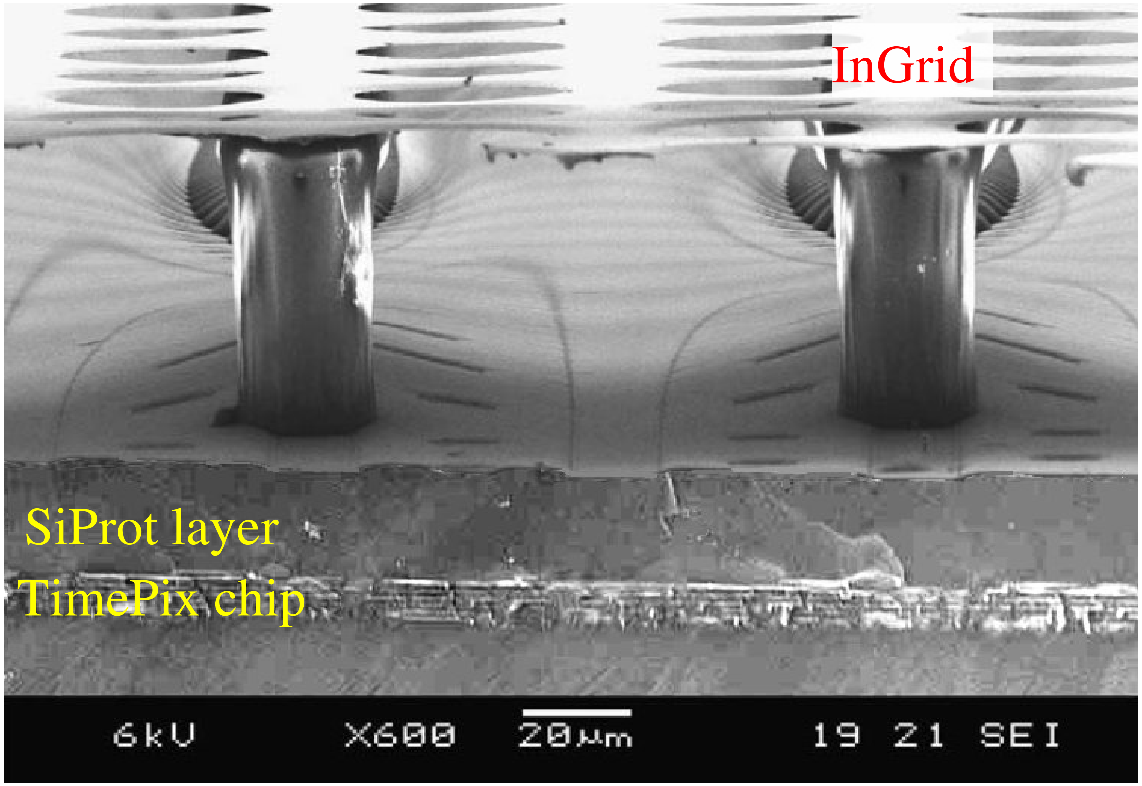
- 1988: Anton Oed



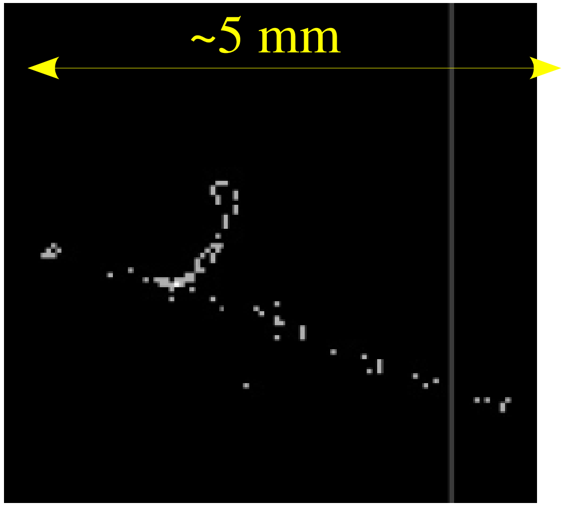



# Gossip

- The “electronic bubble chamber”.



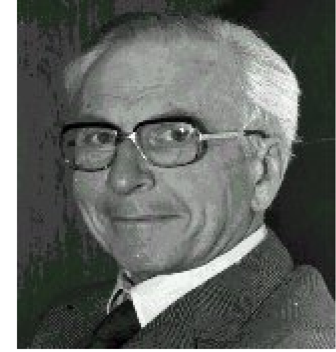

Harry van der Graaf (r)




$\delta$-electrons made visible in He/i$C_4H_{10}$, using a modified MediPix, ~2004.

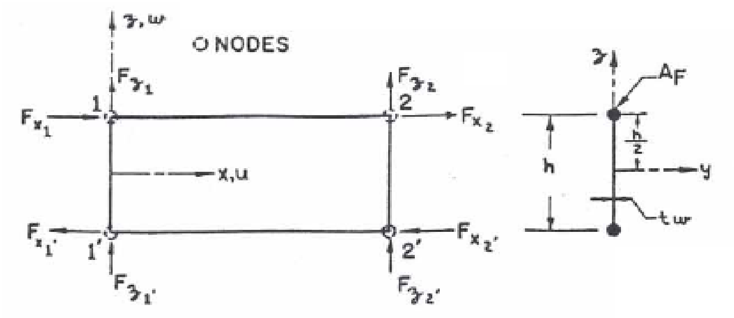
Ιωα'ννης Αργυ'ρης

(1913-2004)

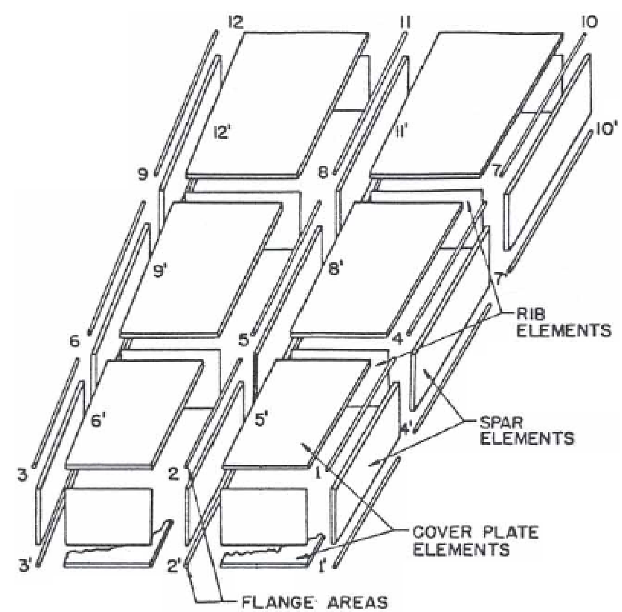


# Aircraft wings – finite elements

- "*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.




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



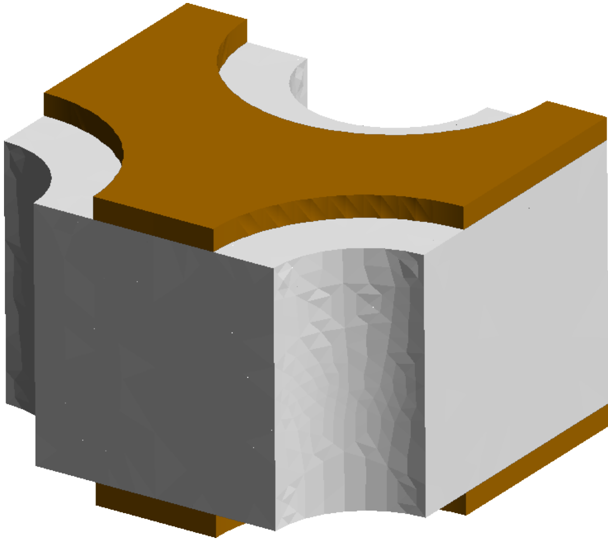

[M.J. Turner, R.W. Clough, H.C. Martin and L.J. Topp, *Stiffness and Deflection Analysis of Complex Structures*, J. Aero. Sc. **23** (1956), 805-824. MJT & LJT with Boeing.]

# FEM – the price to pay

- Finite element programs are flexible but they focus on the wrong thing: they solve $V$ well, but we do not really need it:
  - quadratic shape functions do a fair job at approximating $V \approx \log(r)$ potentials;
  - potentials are continuous;
  - potentials and fields are not Maxwell compliant.

- $E$ is what we use to transport charges, but:
  - gradients of quadratic shape functions are linear and not suitable to approximate $E \approx 1/r$, left alone $E \approx 1/r^2$ fields;
  - electric fields are discontinuous at element boundaries;
  - a local accuracy of ~50 % in high-field areas is not unusual.

# Open source finite elements

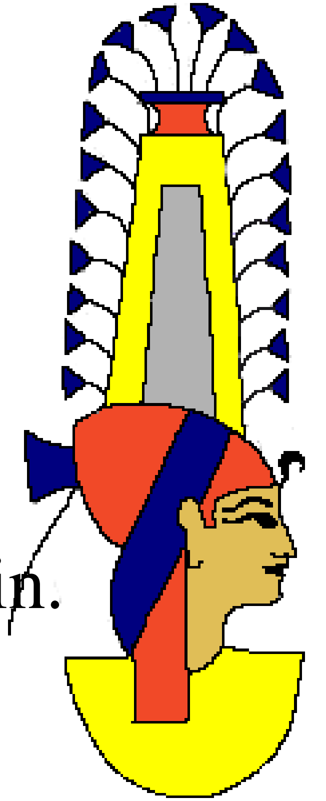


- Finite element programs are widely used in engineering and nearly always commercial.
- A rare exception is Gmsh/Elmer. Josh Renner (Berkeley) has written a Garfield++ interface.


C. Geuzaine and J.-F. Remacle, *Gmsh: a three-dimensional finite element mesh generator with built-in pre- and post-processing facilities,* http://geuz.org/gmsh/.

CSC – IT Center for Science, *Elmer: Open Source Finite Element Software for Multiphysical Problems*, http://www.csc.fi/english/pages/elmer.

# Boundary element methods



- Contrary to the finite element method, the elements are on the boundaries, not inside the problem domain. Charges are computed for the boundary elements.
- The field in the problem domain is calculated as the sum of Maxwell-compliant field functions, each extending over the entire problem domain. There are no discontinuities.
- But ... the method poses substantial numerical challenges: large non-sparse matrices and inherent singularities. The technique is time consuming.

# neBEM – the price to pay

- For computing the field at any point, neBEM sums the fields due to each element on that point.
- Evaluating the Green's functions, especially the one for triangular elements, is costly.
- For a modest doubly-periodic 1000-element model there would be ~$10^8$ function evaluations. For an avalanche study we would love to have 1000. We then need to compute the field at ~$10^7$ points.

# Electron transport

- Interaction of electrons up to a few eV with gas.

# LXcat

Leanne Pitchford

- Art Phelps,
- Leanne Pitchford – Toulouse,
- Klaus Bartschat – Iowa,
- Oleg Zatsarinny – Iowa,
- Michael Allan – Fribourg,
- Steve Biagi

Michael Allan

Klaus Bartschat

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. [...]"

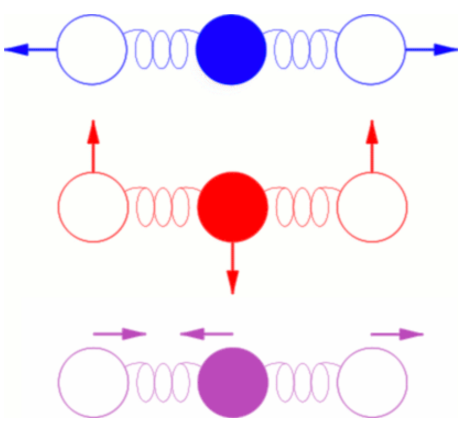
`http://www.lxcat.laplace.univ-tlse.fr/`

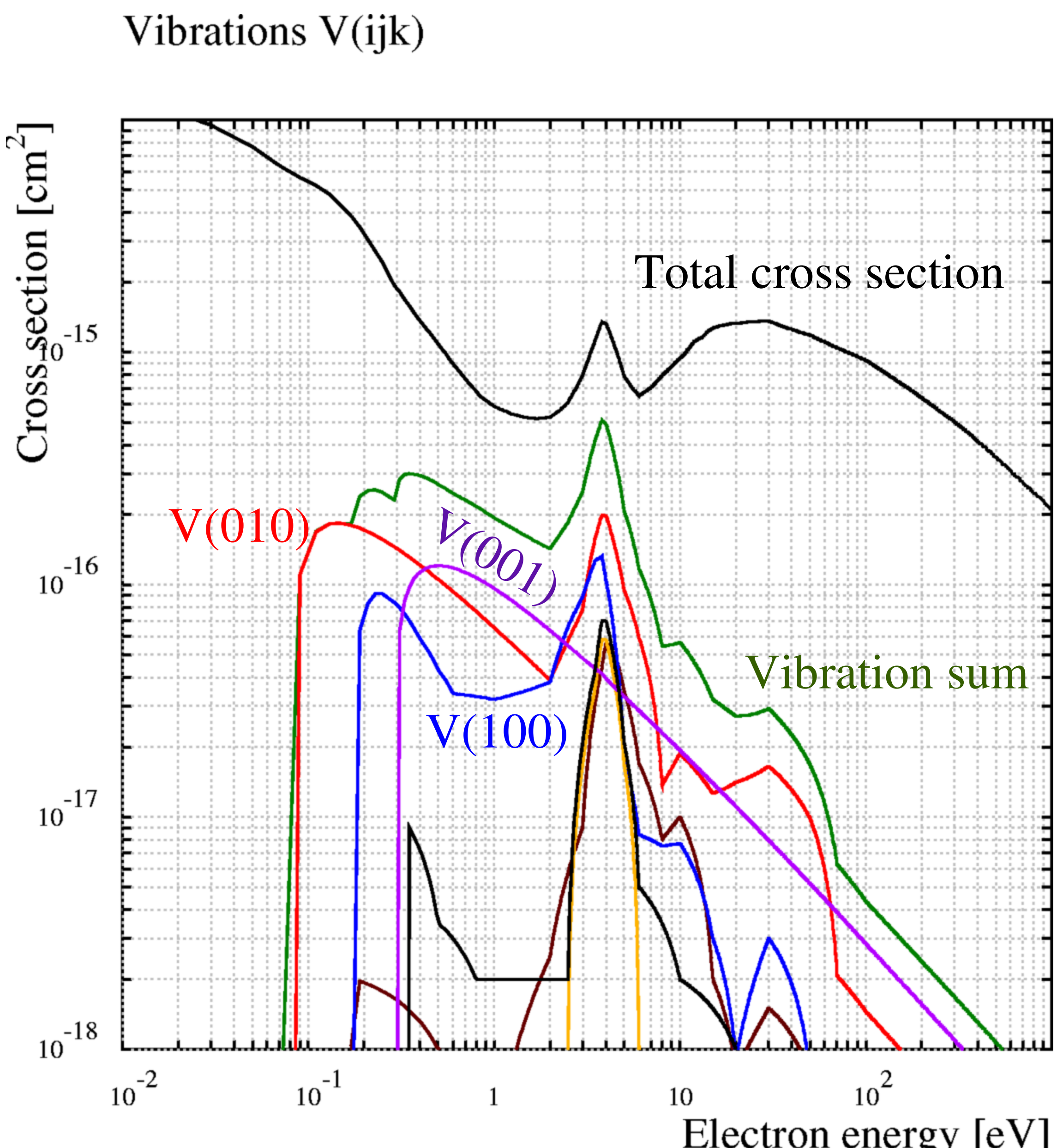
# Magboltz

- A large number of cross sections for 60 molecules...
  - Noble gases (He, Ne, Ar, Kr, Xe):
    - elastic scattering,
    - 44 excited states (Ar) and
    - 7 ionisations (Ar);
  - 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,
    - 6 excited states and
    - 3 ionisations.

# $CO_2$ – vibration modes

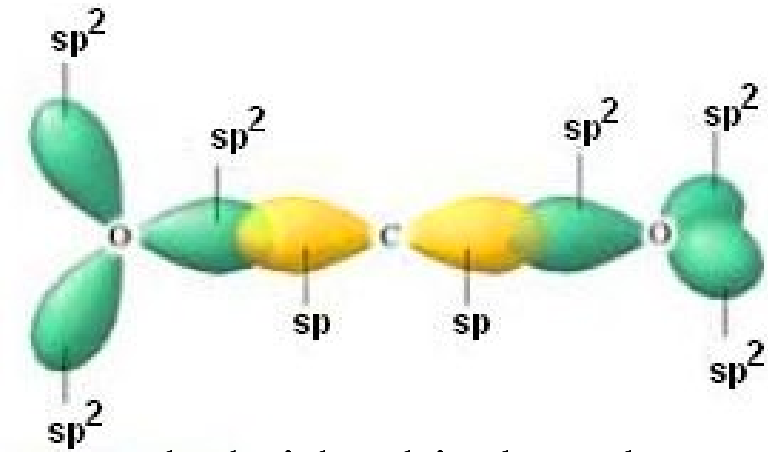
- $CO_2$ is linear:
  - O – C – O
- Vibration modes are numbered V(*ijk*)
  - *i*: symmetric,
  - *j*: bending,
  - *k*: anti-symmetric.





# Attachment in $CO_2$

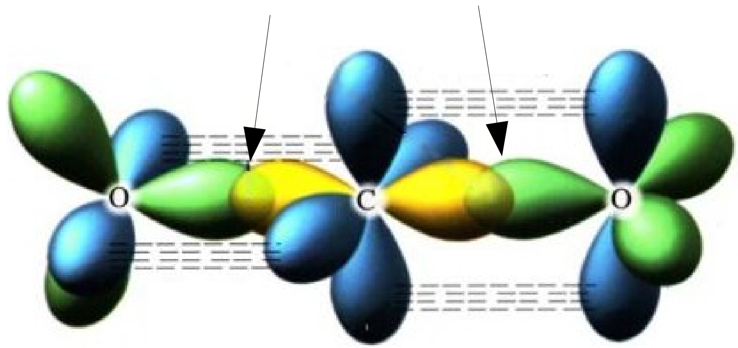
- $CO_2$ is a linear molecule:




hybrid orbitals only,
p-orbitals not shown

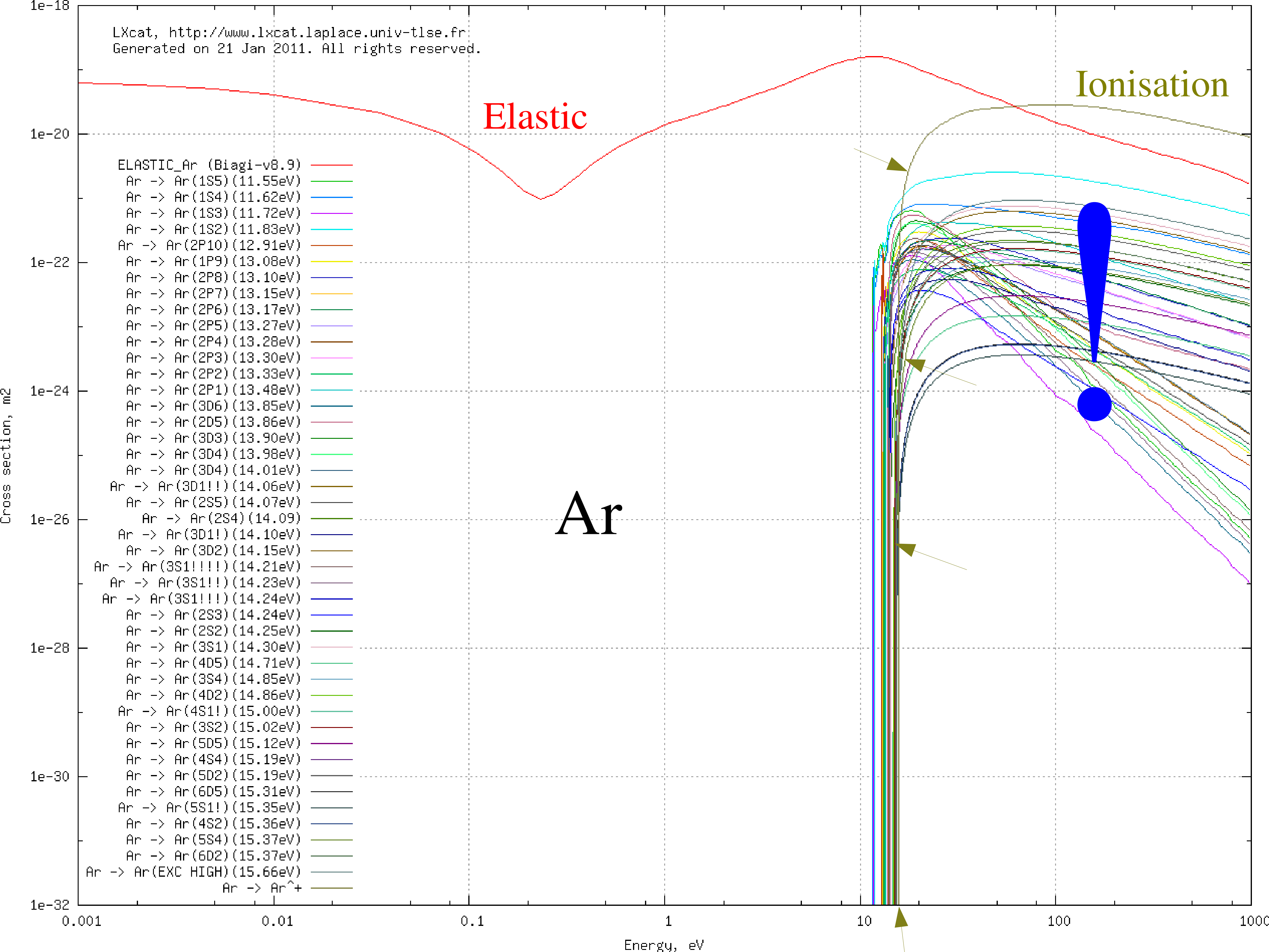
- $CO_2$ with an extra $e^-$: instable ($\tau \ll 1$ ps, $\epsilon_{VEA} \approx$ -3.8 eV). Low energy $e^-$ collisions produce $O^-$, not $CO_2^-$.
- With an $e^-$ added, a bent structure (134°) is favoured. Long lifetime ($\tau \approx 90$ µs) but still *negative* electron affinity ($\epsilon_{AEA} \approx$ -0.6 eV). metastable.
- Attachment works in $[CO_2]_n$ clusters: vibration and rotation modes absorb excess energy.

$\sigma$ bonds (2 times)




$\pi$ bonds (2 times)

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

Sir John Sealy Edward Townsend
(1868-1957)

# Electron multiplication (1901)

- John Townsend "*The conductivity produced in gases by the motion of negatively charged ions*":

> Negative Ionen erzeugen bei ihrer Wanderung durch Berührung neue Ionen. Die Anzahl der negativen Ionen in einer Entfernung $x$ vom Punkte der Entstehung ist deshalb durch die Exponentialfunktion in der Form $N = N_0 e^{\alpha x}$ gegeben. Diese Formel wird durch Versuche bestätigt. Dabei ist $\alpha$ eine Größe, die außer von der Temperatur noch von der Größe der die Ionen bewegenden Kraft $X$ und dem Druck $p$ abhängt, und zwar ergibt sich diese Abhängigkeit in der Form $= pf(X/p)$.

[JS Townsend, "*The conductivity produced in gases by the motion of negatively charged ions*", Phil. Mag. **6-1** (1901) 198-227. Access to Phil. Mag is restricted. The above German-language abstract is available at `http://jfm.sub.uni-goettingen.de/`.]

# “Yule - Furry” model (1924 - 1937)

- The exponential avalanche size disttribution was found by WH Furry, independently by RA Wijsman and others.

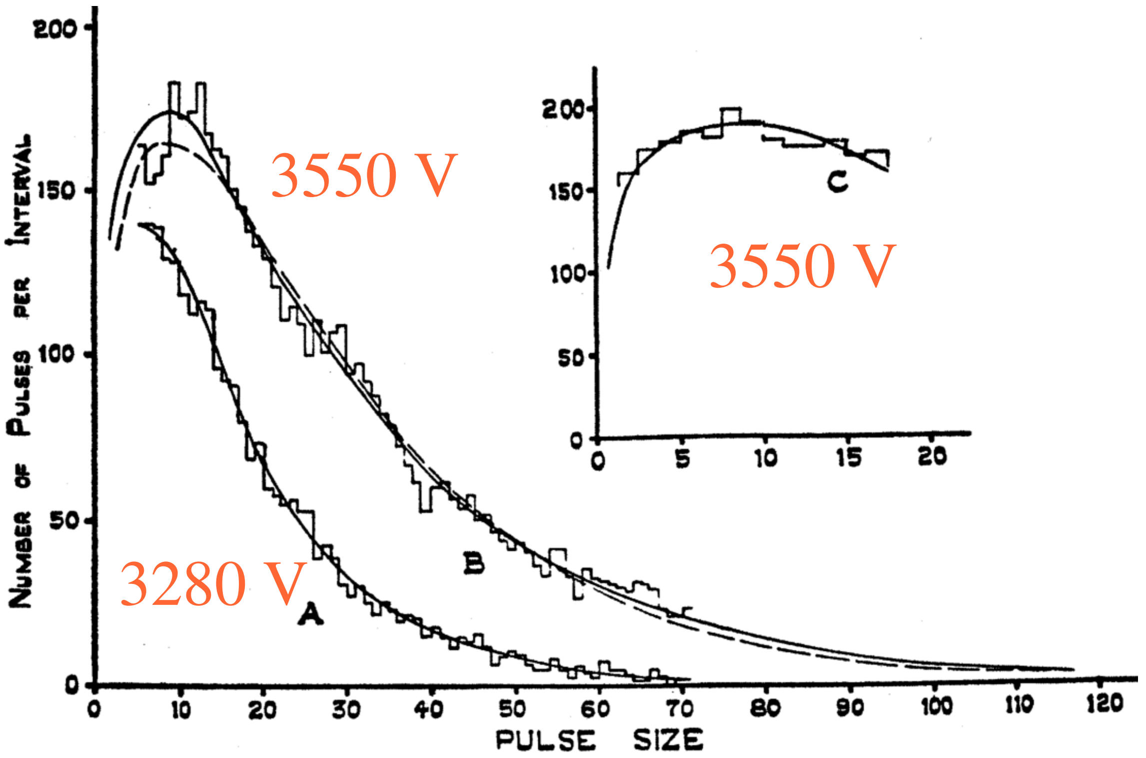
$$p(n) = \frac{1}{\bar{p}}\left(1-\frac{1}{\bar{p}}\right)^{n-1} \approx \frac{e^{-n/\bar{p}}}{\bar{p}} \quad \text{when} \quad \bar{p} \gg 1$$

$$\text{mean}: \ \bar{p}, \qquad \text{width}: \ \bar{p}\sqrt{1-\frac{1}{\bar{p}}}$$

- Assumptions:
  - probability to ionise over a distance $\delta$ is $\delta\alpha$;
  - Townsend coefficient $\alpha$ is constant;
  - further development is independent of history.

# SC Curran (1949)

- SC Curran *et al*. measure the pulse height distribution in a cylindrical counter ($d$ = 150 $\mu$m wire, Ar 50 % $CH_4$ 50 %, $p$ = 670 mbar) at $G \sim 10^4$-$10^5$:




Fit curve:

$$p(n) = \sqrt{n}\, e^{-n}$$

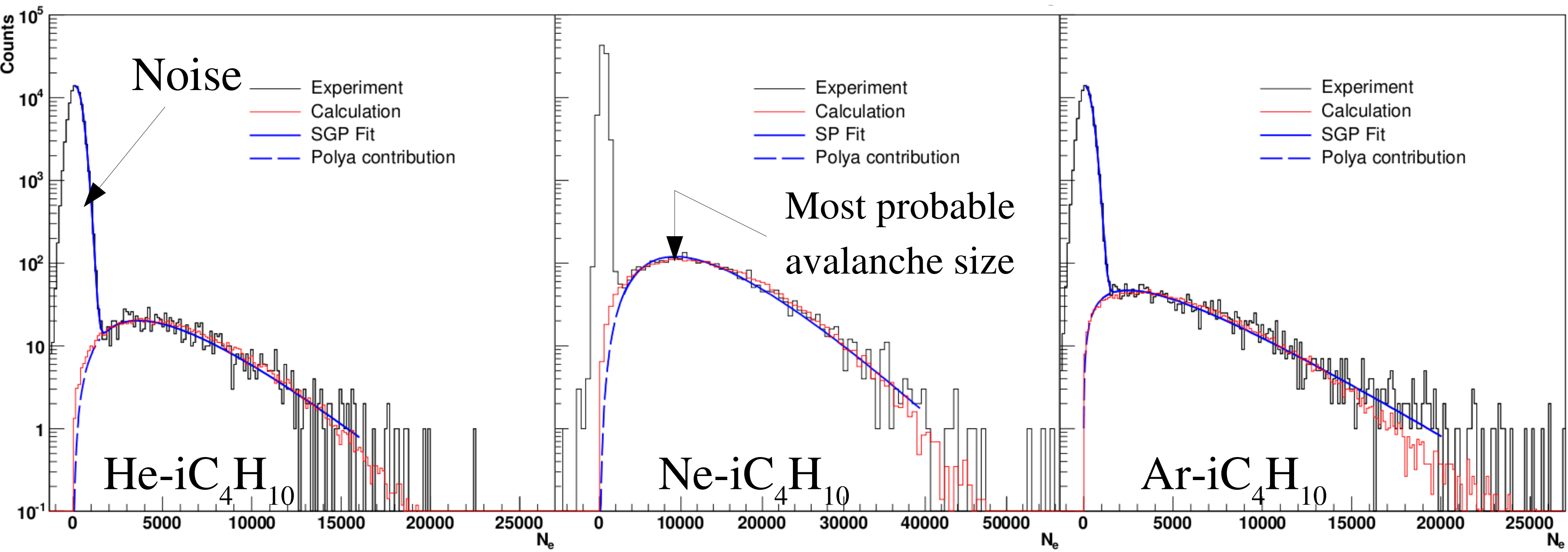
$$\left(\frac{\sigma}{\mu}\right)^2 \approx \frac{2}{3}$$

# Heinz Raether's group (Hamburg)

- Stress that electrons have to travel a minimum distance before their energy exceeds the ionisation potential $U$.
- The parameter $\kappa = E/\alpha U$ is found to be an indicator of the extent to which the Furry distribution applies.
  - Lothar Frommhold (1956):
    - $\kappa$ = 12-110:exponential
  - Hans Schlumbohm (1958):
    - $\kappa > 23$: exponential
    - $23 > \kappa > 10$: levels off towards small sizes
    - $10 > \kappa$: a maximum appears
- Werner Legler's model (1961) for any $\kappa$.

# Avalanche size fluctuations

- Distribution of the size of avalanches triggered by a single electron: measurements and microscopic simulation.




- [Measurements: Thomas Zerguerras *et al.*, calculations Fabian Kuger]

# Ionisation: direct & through excitation

- Electron impact on atoms:
  - $Ar + e^- \rightarrow Ar + e^-$ (in)elastic scattering
    $\rightarrow Ar^* + e^-$ excitation
    $\rightarrow Ar^+ + 2\,e^-$ ionisation

    $e^-$ Energy

- Interaction of excited noble gas and quencher:
  - $Ar^* + CO_2 \rightarrow Ar + CO_2^+ + e^-$

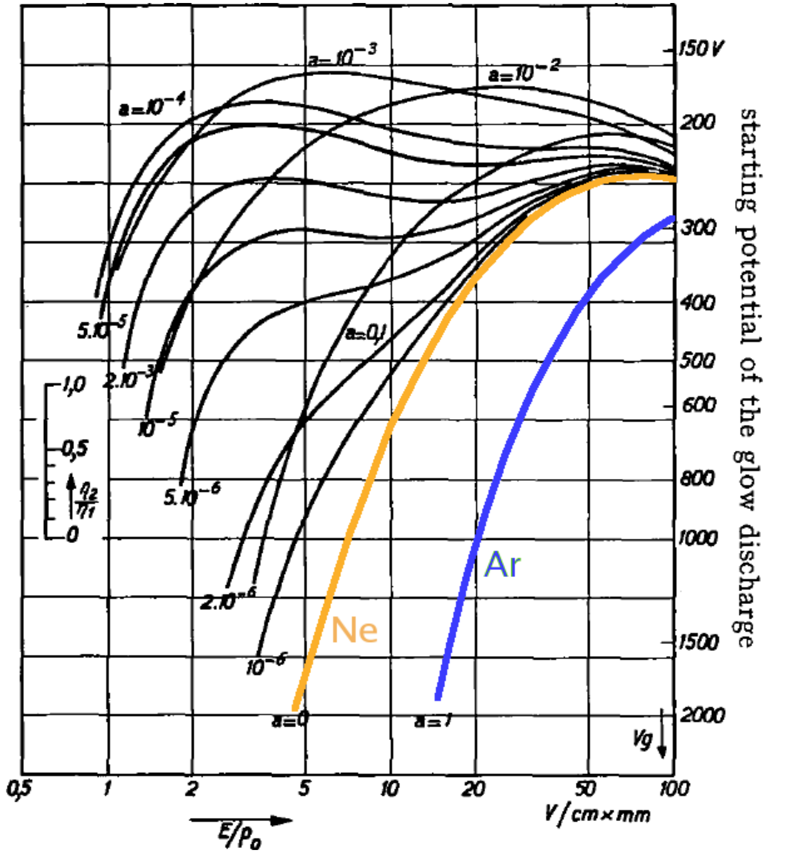
    provided $Ar^*$ excitation energy $>$ $CO_2^+$ ionisation energy;
  - quenching rate constants are comparable to hard-sphere scattering, i.e. faster than radiative decay of (esp. higher) excited states.

Frans Michel Penning,
photo taken around 1921
(1894-1953)

# 1928: Ar-Ne-Hg Penning effects

- Frans Michel Penning worked from 1924 on gas discharges at the Philips Natuurkundig Laboratorium.

Der Einfluß sehr geringer Beimischung von Hg und Ar auf die Zündspannung $V_z$ des Neons wurde quantitativ bestimmt. Die Erklärung wurde gefunden in der Ionisierung der Fremdatome durch die metastabilen Atome des Neons. Die notwendige Bedingung für diesen Vorgang: $V_i' < V_{\text{met.}}$ wurde geprüft bei Ne, Ar und He als Hauptgasen mit verschiedenen anderen Gasen als Beimischung und stets bestätigt gefunden. Andererseits erniedrigten immer Beimischungen, wobei $V_i' < V_{\text{met.}}$ die Zündspannung; nur NO in Ar machte eine Ausnahme von dieser Regel, was aber auf Grund des Termschemas von NO nicht zu verwundern braucht.



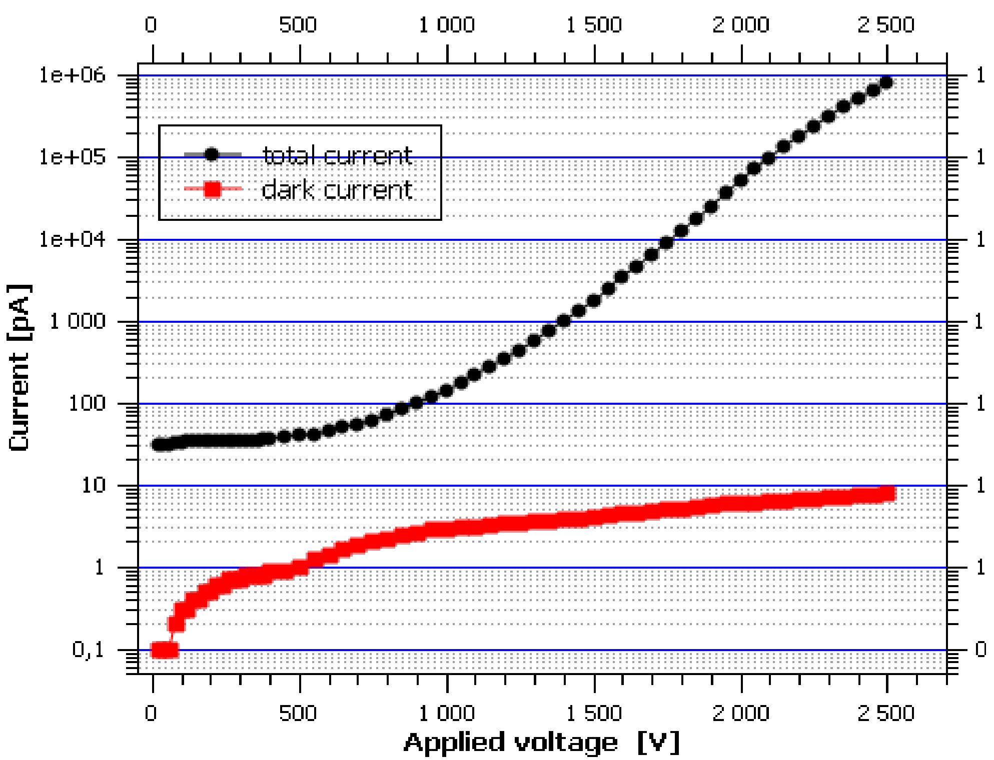

F. M. Penning, *Über den Einfluß sehr geringer Beimischungen auf die Zündspannung der Edelgase*, *Z. Phys.* **46** (1928) 334-348.

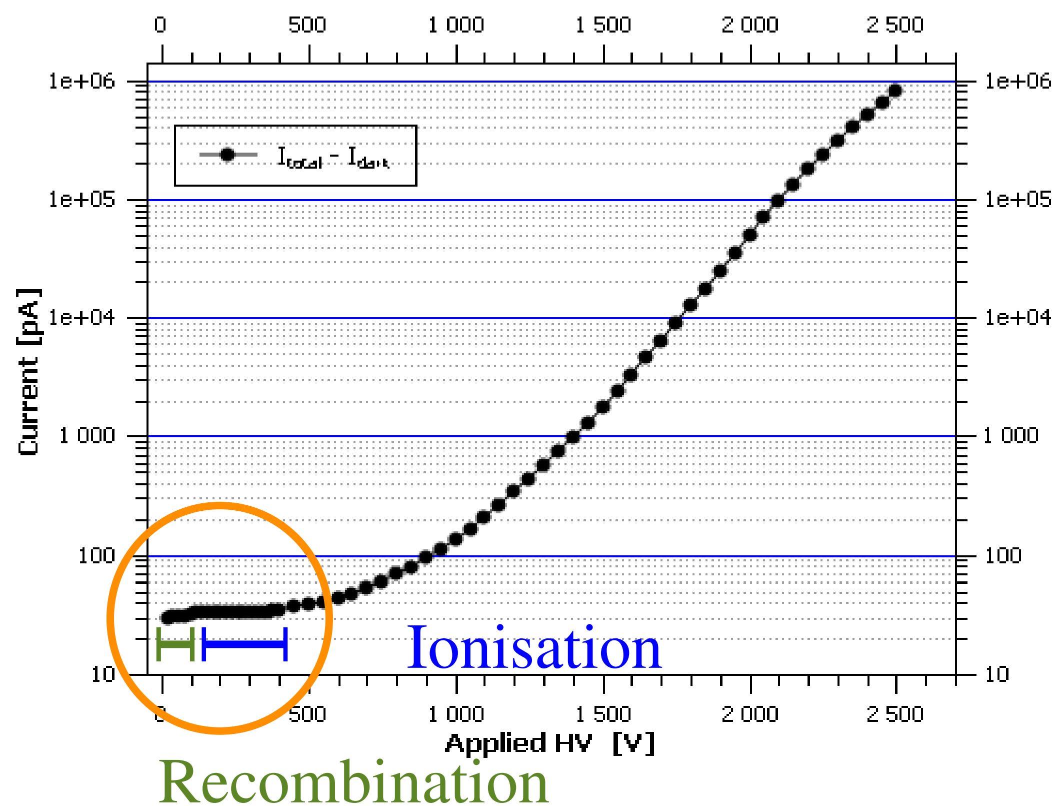
F.M. Penning, *The starting potential of the glow discharge in neon argon mixtures between large parallel plates: II. Discussion of the ionisation and excitation by electrons and metastable atoms*, Physica **1** (1934) 1028-1044.

F.M. Penning, Electrische gasontladingen, Philips Technische Bibliotheek (posthumous, 1955). Translated in various languages.

# Example of gain measurements

- Ar-$CO_2$-$N_2$ [91.1-6.4- 2.5] at $p$ = 0.2 MPa;
- dark current measurement and subtraction:

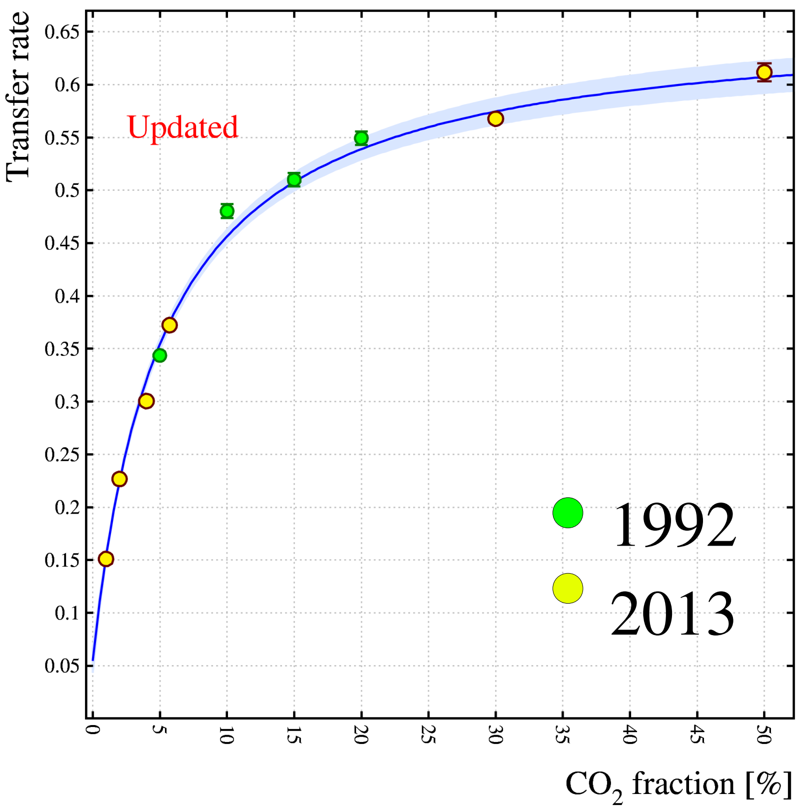


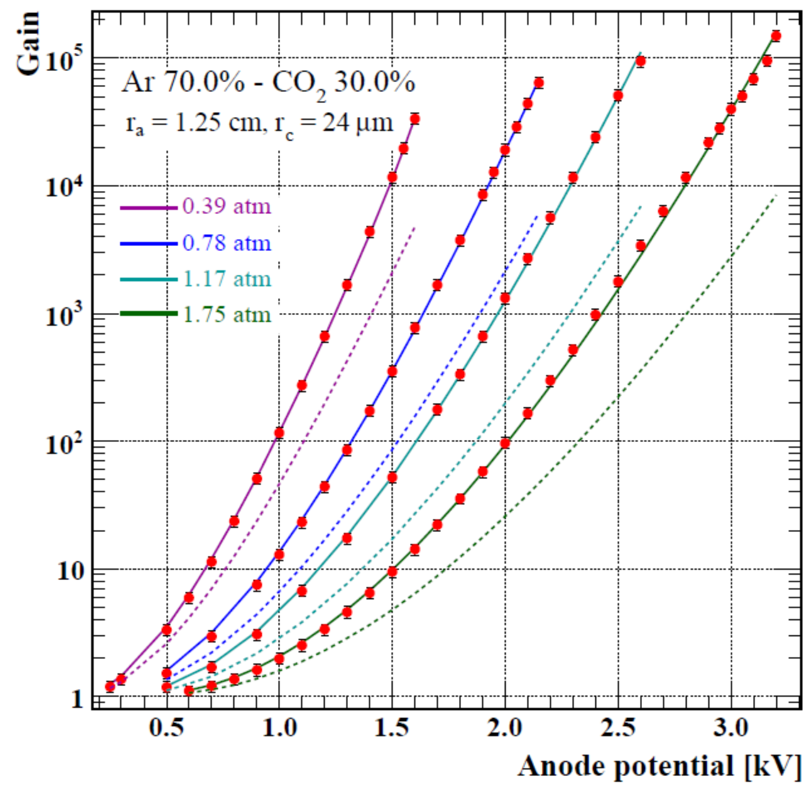



# Ar-$CO_2$

- Reproduce the gain curves by:
  - ionisation rates + $r_P$ excitation rates.
  - $r_P$ is called the Penning or transfer rate.
- Measurements: Tadeusz Kowalski *et al.* AGH Kraków.

  Fits: Özkan Şahin, Uludağ.



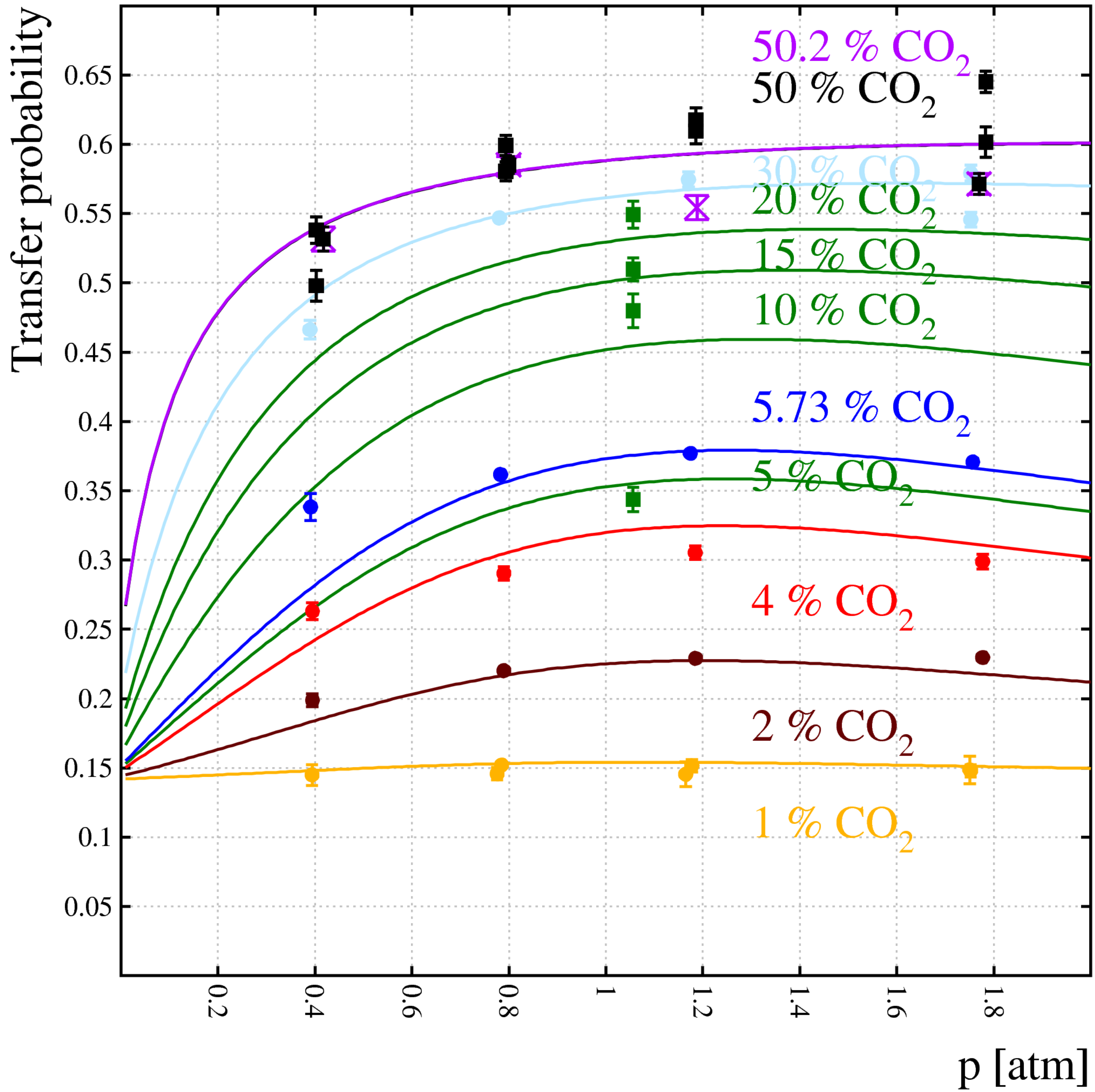



# Pressure

- Transfer rates for Ar-$CO_2$, from experimental gain curves

- Hint of 3-body interactions.

[Tadeusz Kowalski and Özkan Şahin]

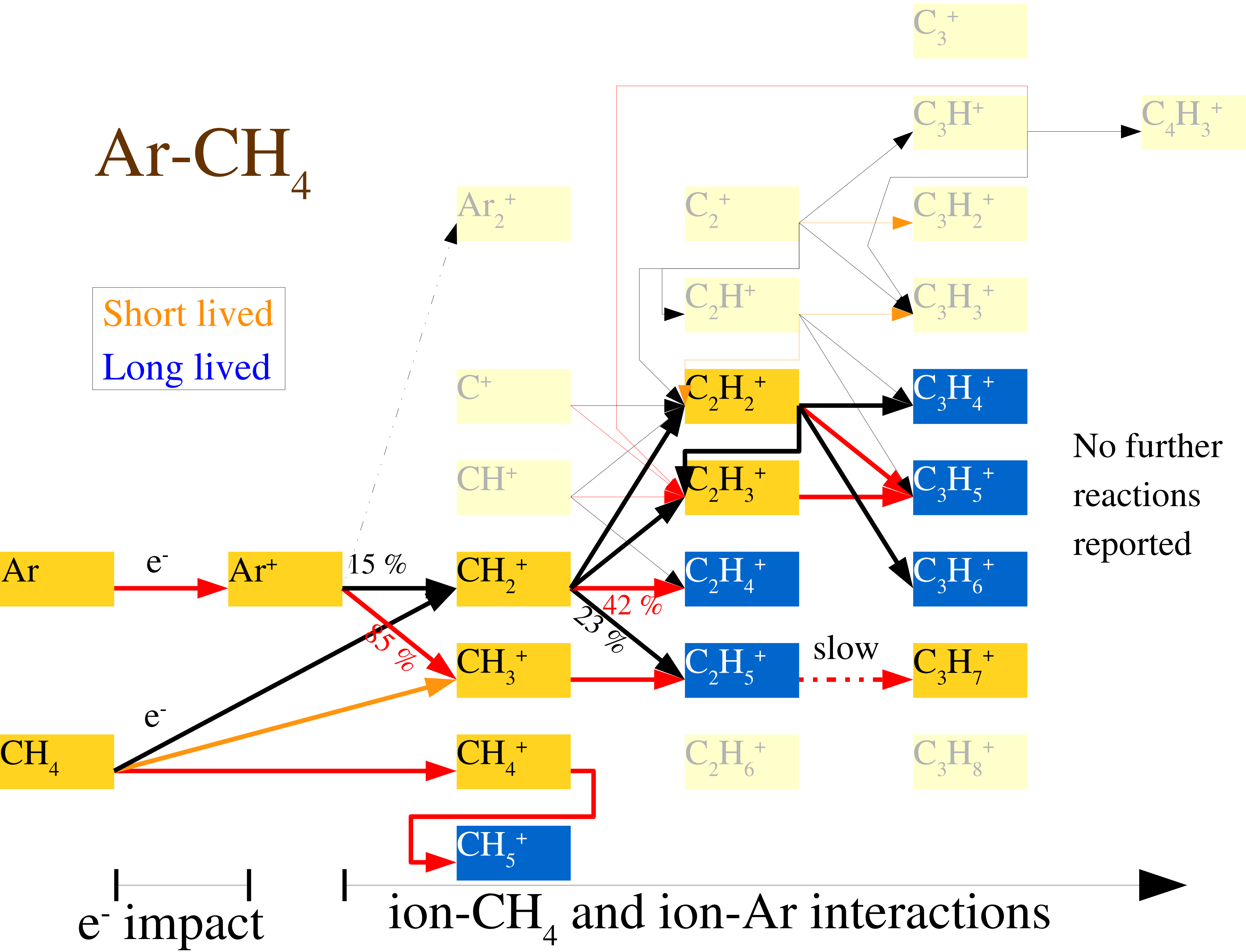


# Ion transport

- If electrons seemed complicated ...

# Ion chemistry – rate constants

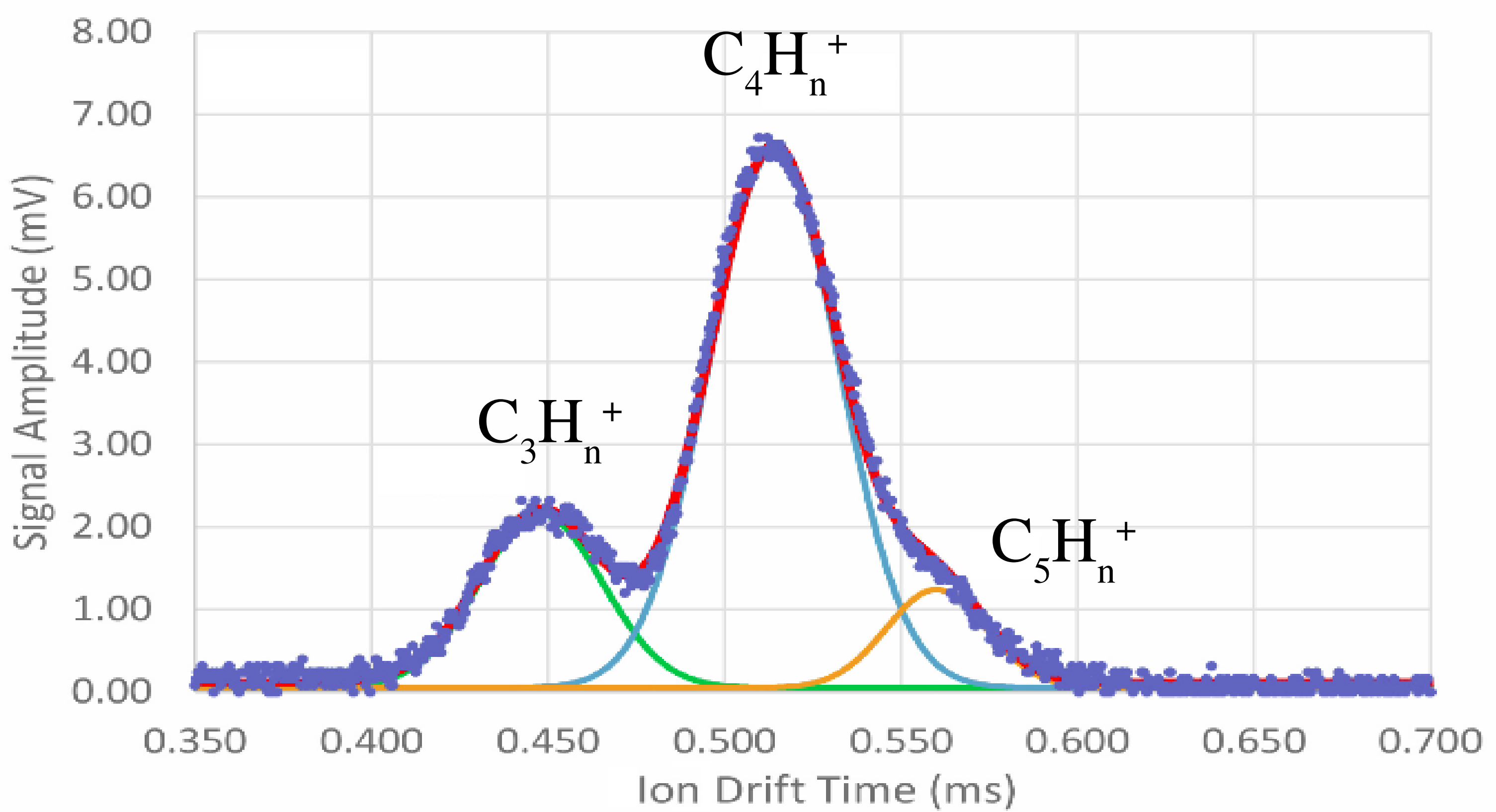
- Ions react with the gas in which they move:
  - proton exchange: $AH^+ \; B \rightarrow A \; BH^+$
  - charge transfer: $A^+ \; B \rightarrow A \; B^+$
  - condensation reactions: new C-O and C-C bonds
  - molecular ion formation $Ar^+{}_2$
  - ...
- Rate constants range from $10^{-9}$ to $10^{-14}$ $cm^3/s$. At atmospheric pressure, in a pure gas, this corresponds to characteristic times of 40 ps to 4 µs.



Ar-$CH_4$
Short lived
Long lived
$C_3^+$
$C_3H^+$
$C_4H_3^+$
$Ar_2^+$
$C_2^+$
$C_3H_2^+$
$C_2H^+$
$C_3H_3^+$
$C^+$
$C_2H_2^+$
$C_3H_4^+$
$CH^+$
$C_2H_3^+$
$C_3H_5^+$
No further reactions reported
Ar
$e^-$
$Ar^+$
15 %
$CH_2^+$
$C_2H_4^+$
$C_3H_6^+$
42 %
23 %
85 %
$CH_3^+$
$C_2H_5^+$
slow
$C_3H_7^+$
$e^-$
$CH_4$
$CH_4^+$
$C_2H_6^+$
$C_3H_8^+$
$CH_5^+$
$e^-$ impact
ion-$CH_4$ and ion-Ar interactions

# Ion transport

- Ar 90 % - $C_2H_6$ 10 %, at low pressure

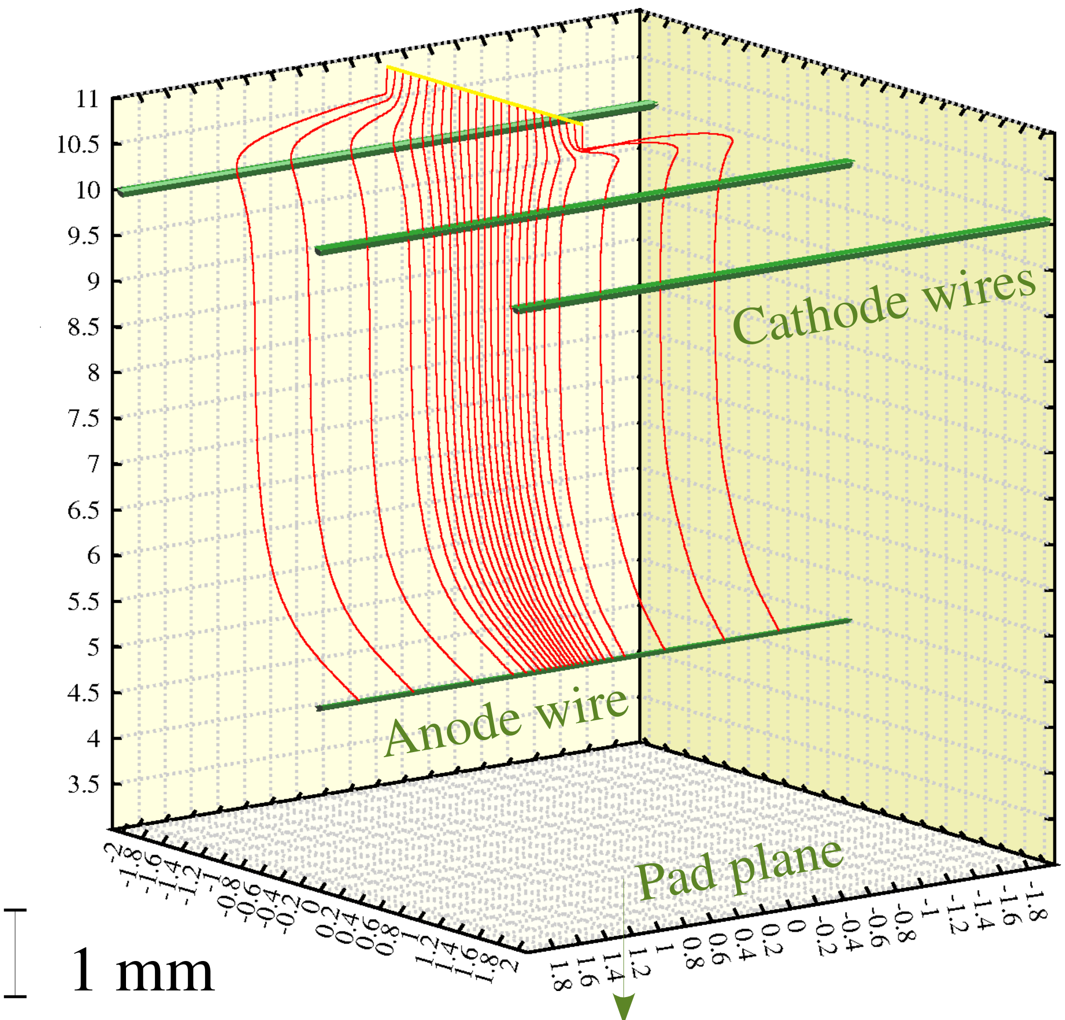


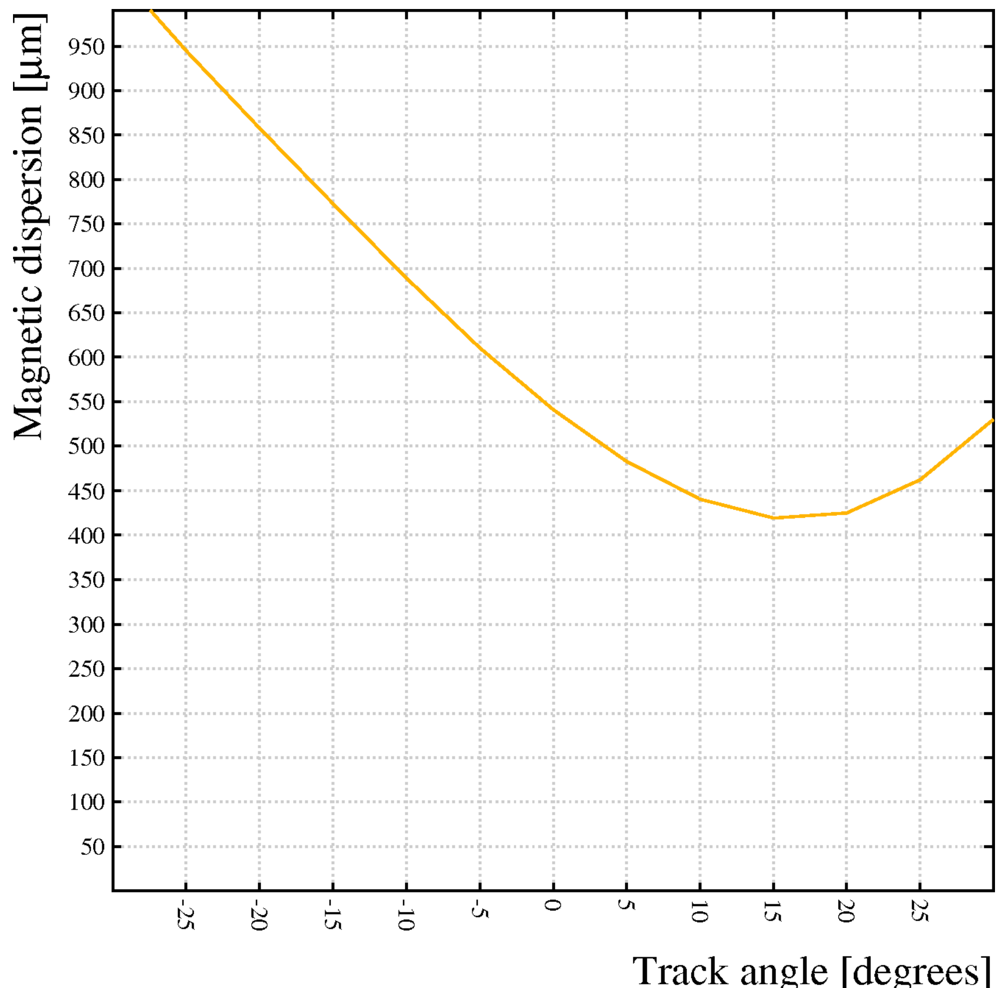

[André Cortez et al. 10.1088/1748-0221/8/12/P12012]

# Putting it together

# Classic: e$^-$ and ion$^+$ trajectories

- Example (Harp): E×B effect in an enlarged ℵ read-out cell.

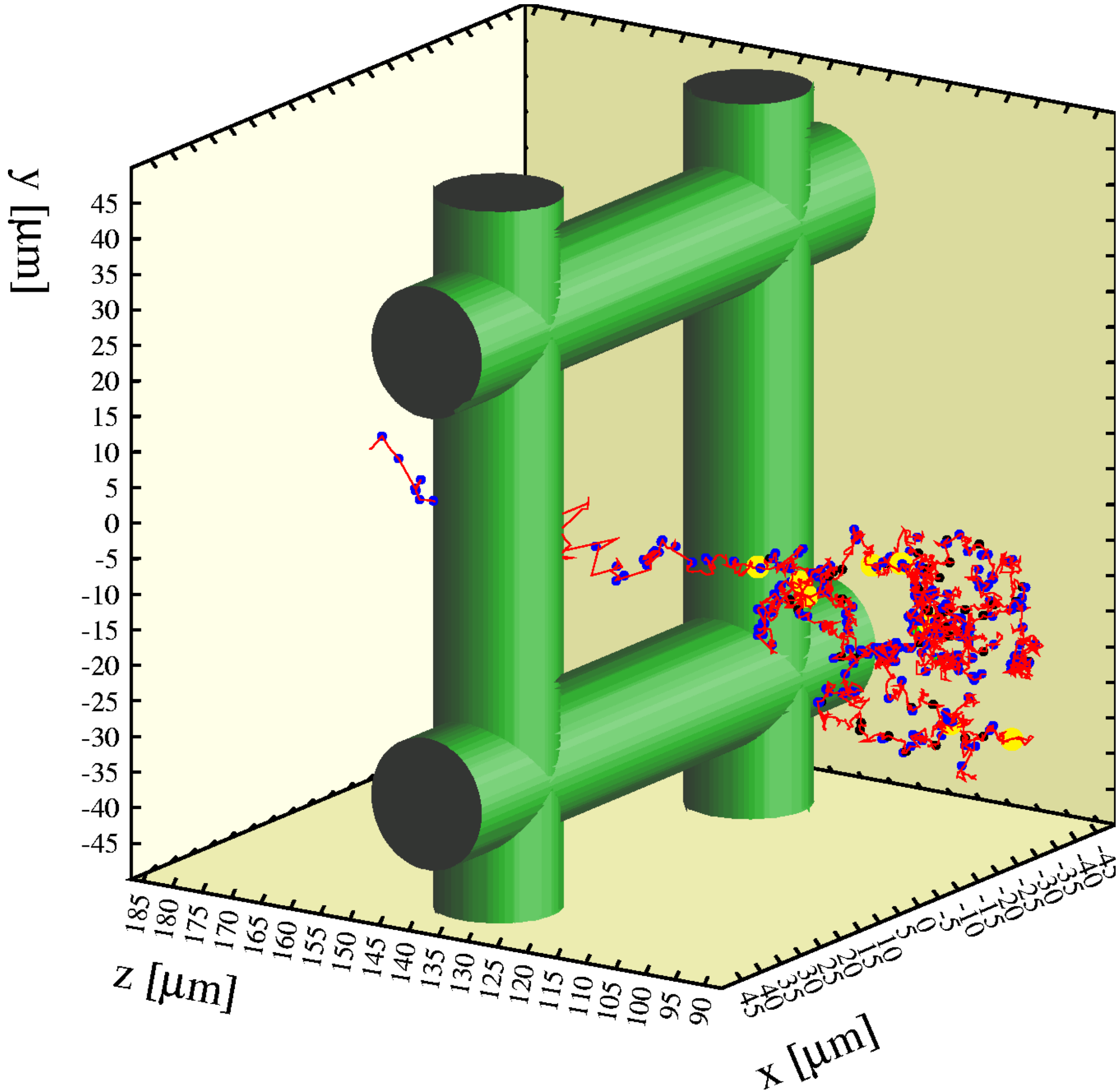


# Scale

- Recall:
  - Mean free path of $e^-$ in argon: 2-5 μm,
  - diffusion: ~80 μm for 1 mm.
- Compare with:
  - Micromegas mesh pitch: 63.5 μm
  - GEM polyimide thickness: 50 μm
  - Micromegas wire thickness: 18 μm
  - GEM conductor thickmess: 5 μm
- Hence:
  - mean free path approaches small structural elements;
  - diffusion is not likely to be Gaussian.

# Microscopic Micromegas

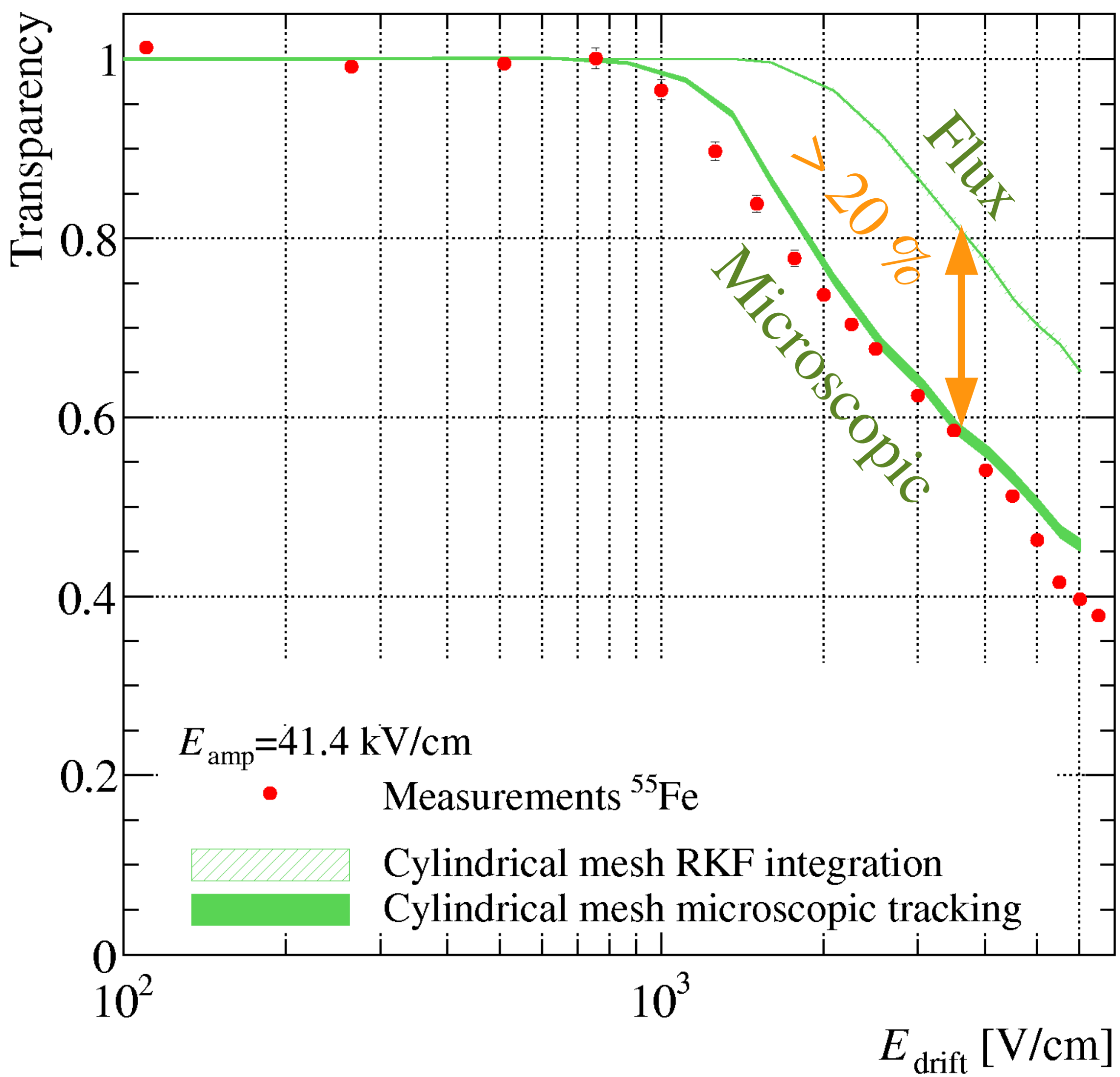



- Legend:
  - – electron
  - ○ inelastic
  - ○ excitation
  - ○ ionisation

# Flux vs microscopic ?

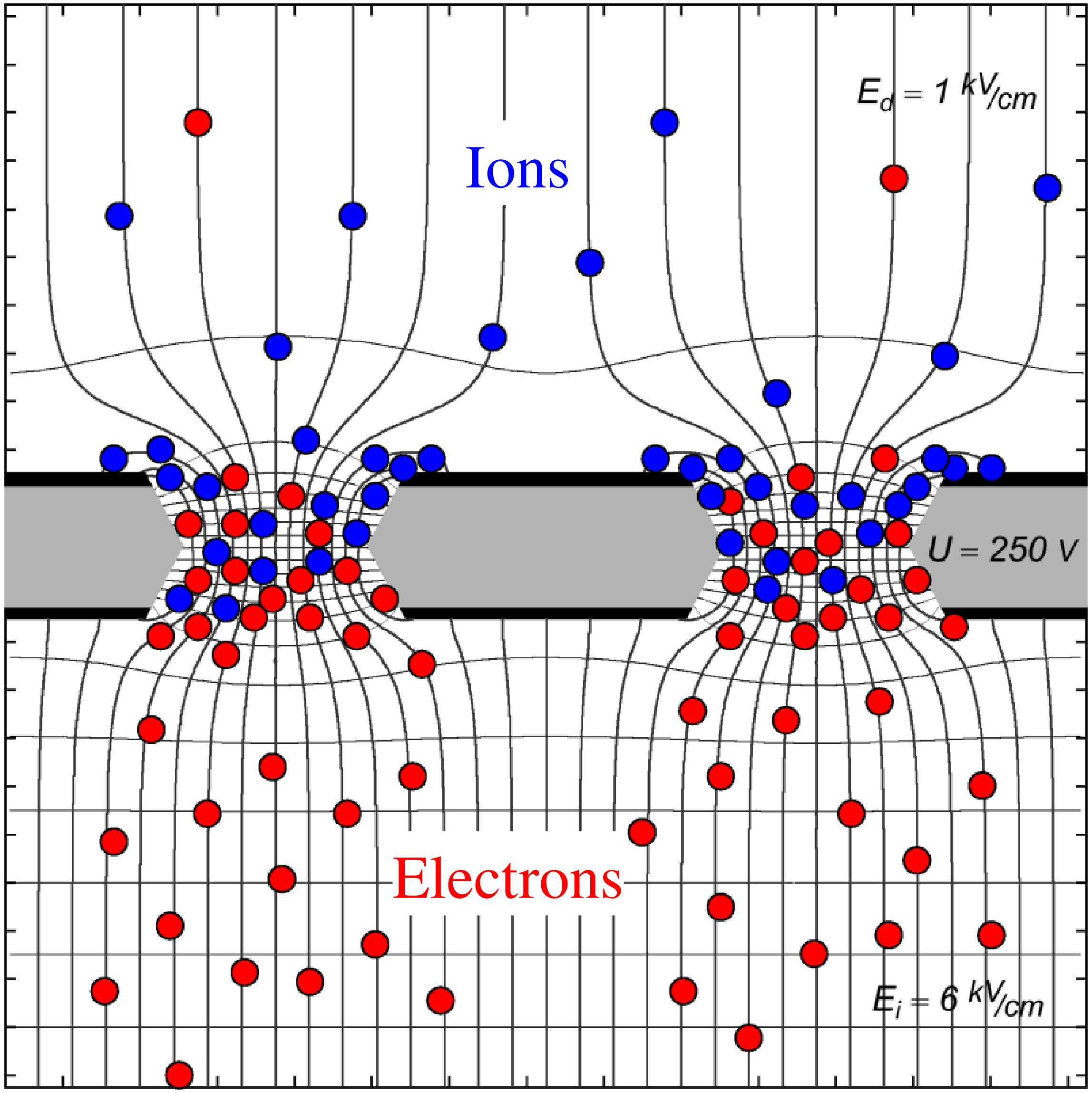
- A diffusion-free flux argument does not reproduce the data ...
- but the microscopic approach works.

Field calculations: finite elements.



# GEM, textbook

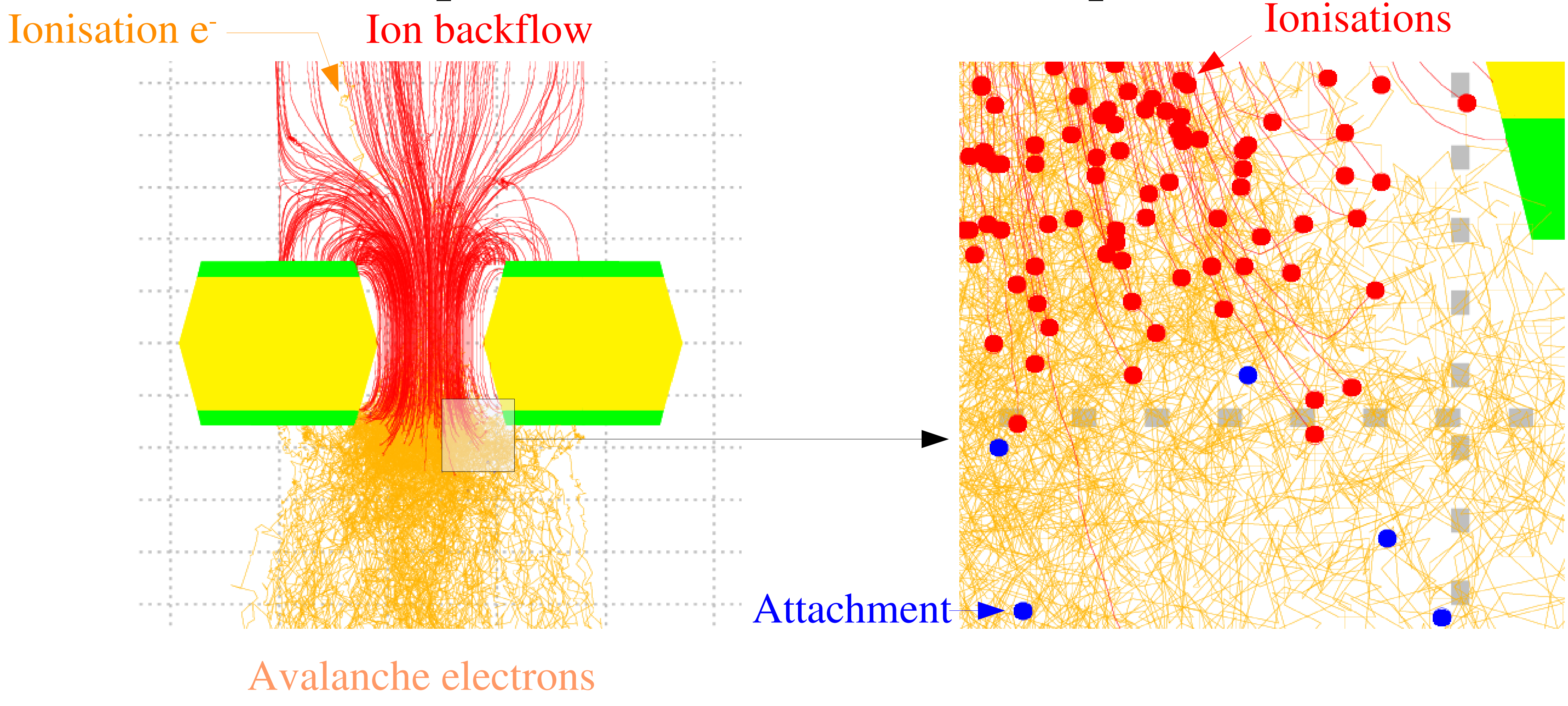
- $e^-$ & $ion^+$ follow the “field lines”




[DESY FLC/TPC, based on a CERN GDD drawing]

# GEM, microscopic view

- Micropattern devices have characteristic dimensions that are comparable with the mean free path.

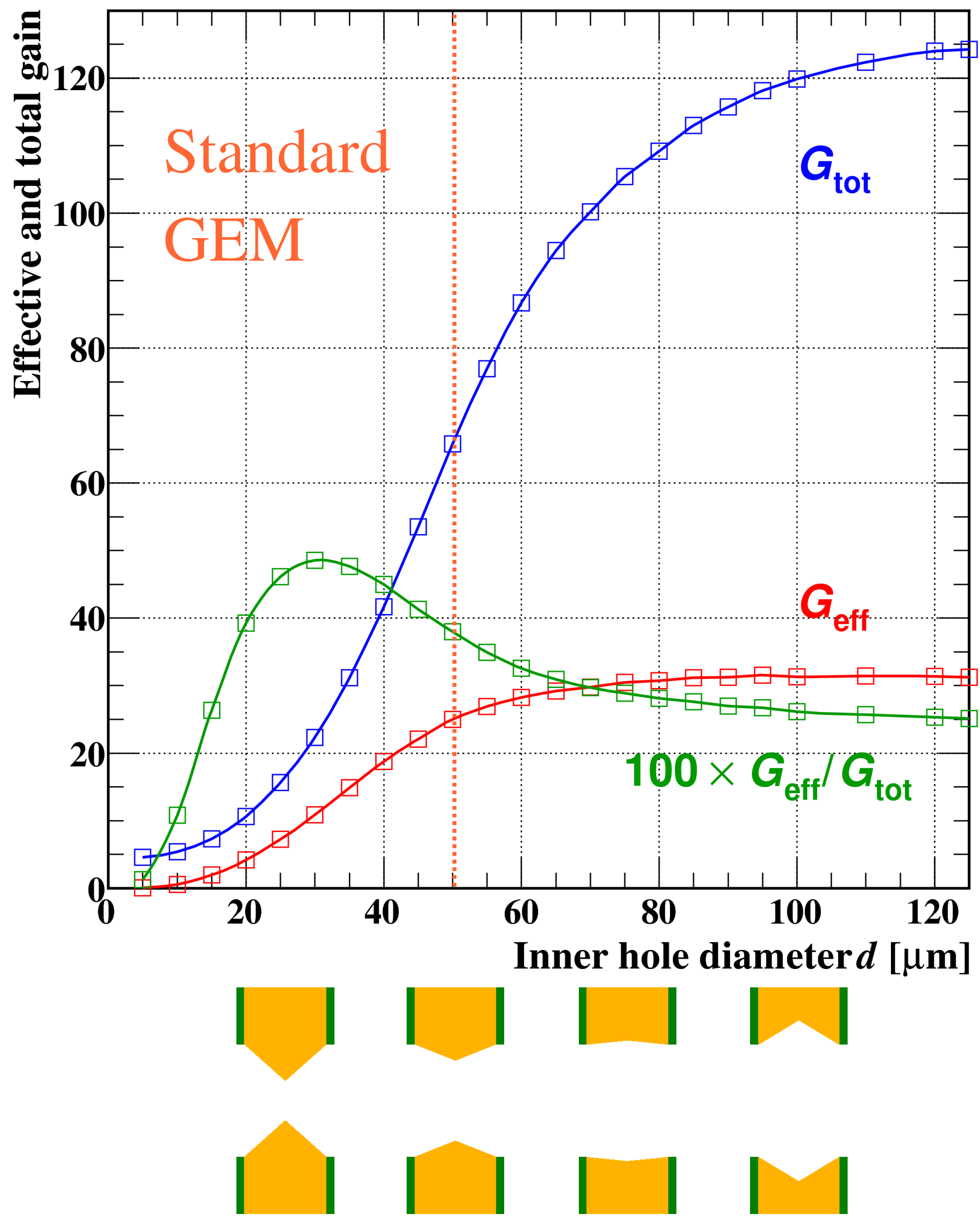



[Plot by Gabriele Croci and Matteo Alfonsi]

# Gain calculations in a pristine GEM

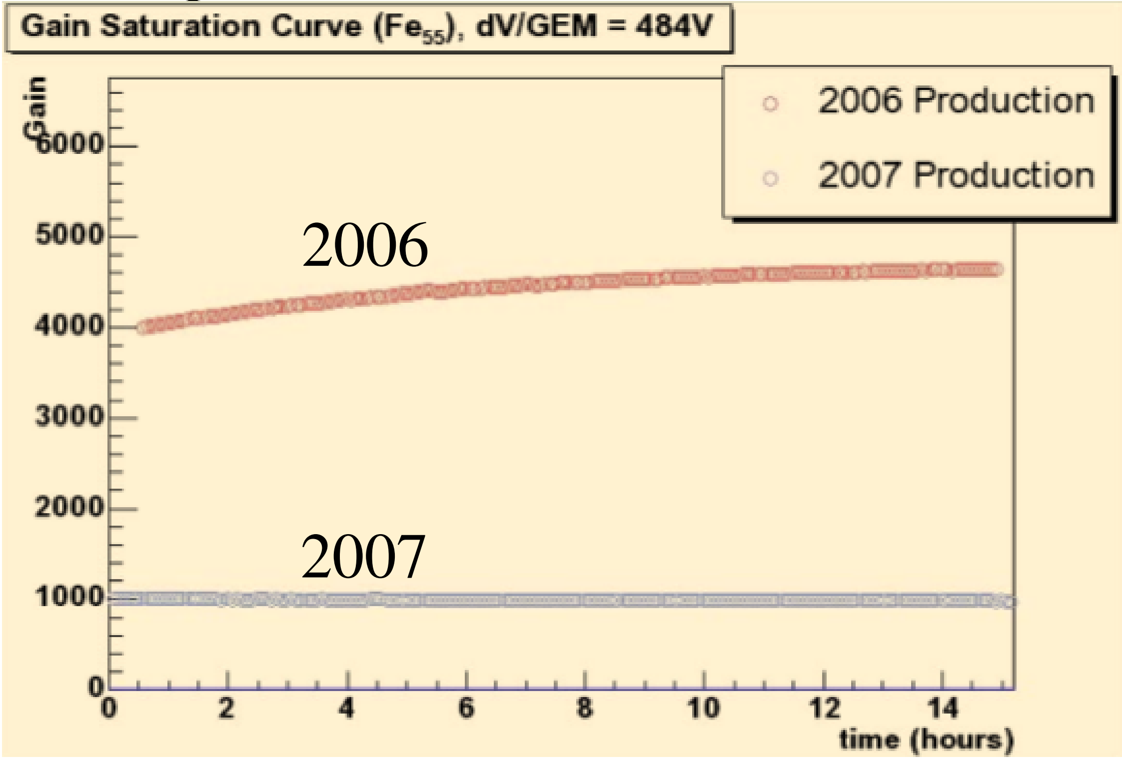
- Calculations predict that $G_{tot}$ and $G_{eff}$ rise with increasing inner hole diameter.

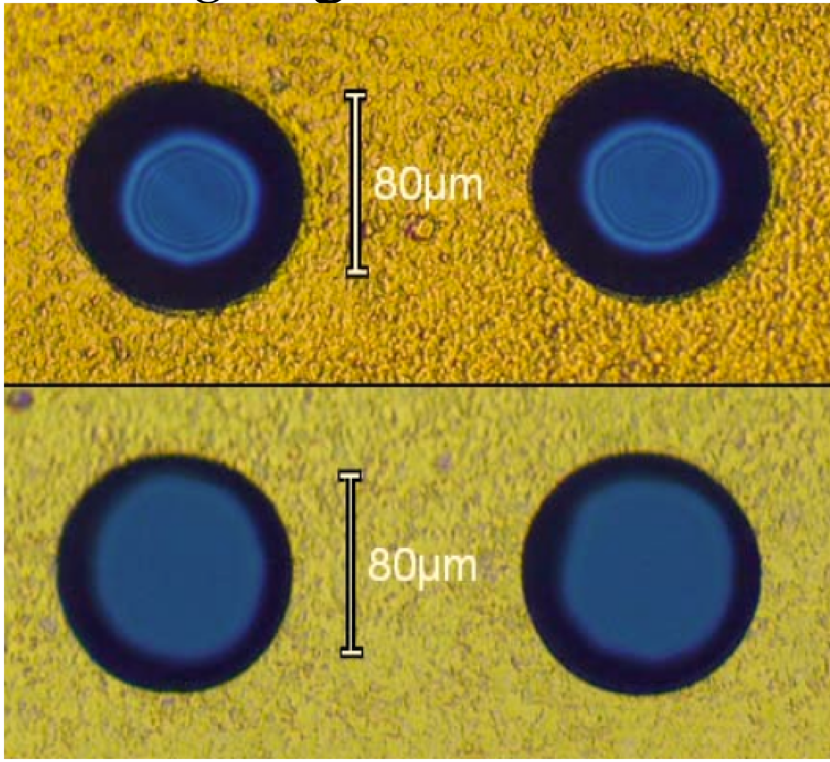
- $G_{eff}$ rises mainly because the losses of incoming electrons diminish;
- $G_{tot}$ rises because the exit electrode becomes more accessible.



# HBD data

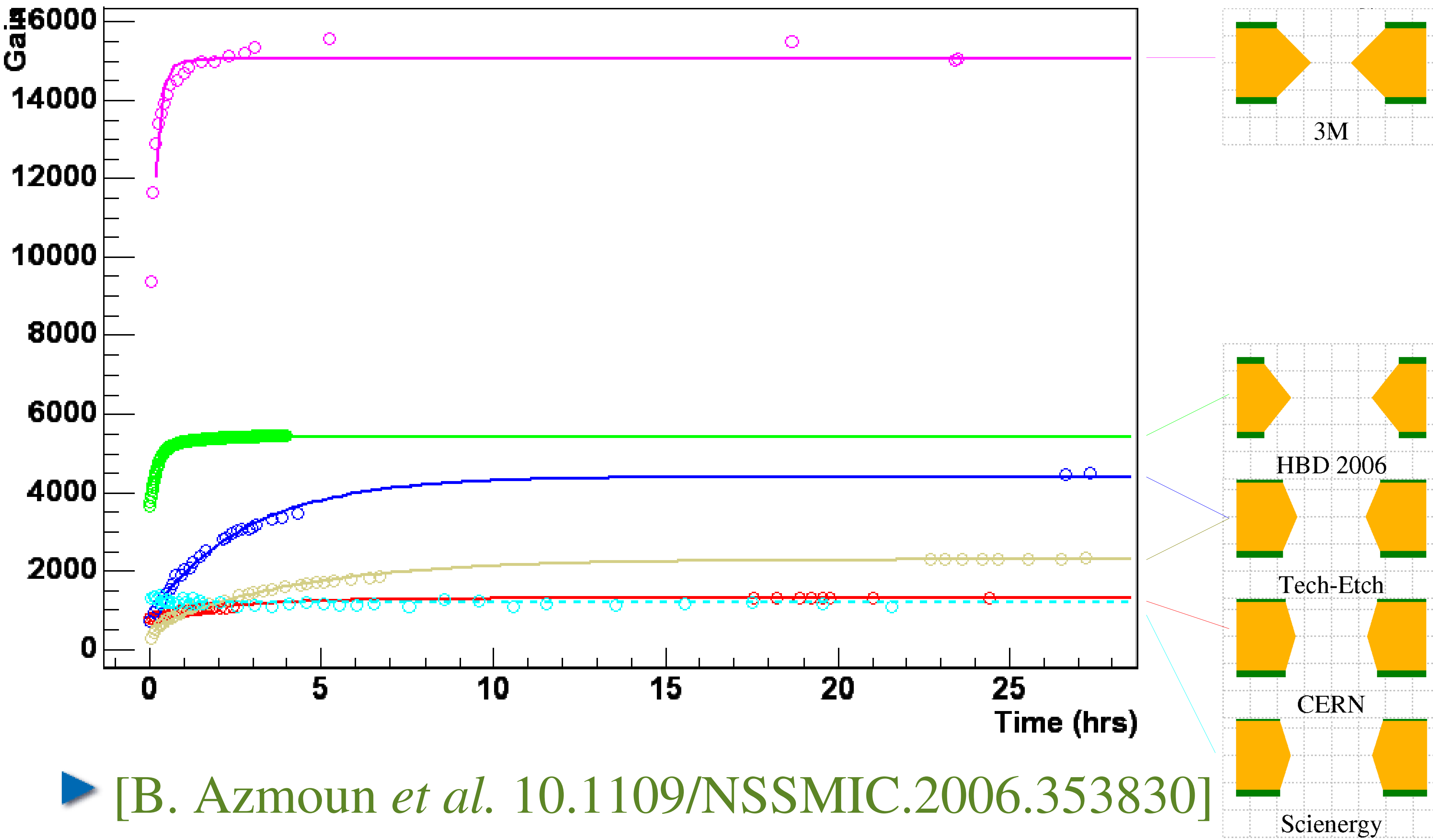
- Measurements for 2 triple GEMs with different hole shape shows that smaller holes lead to *larger* gain !




- [W. Anderson *et al.* 10.1109/NSSMIC.2007.4437147]

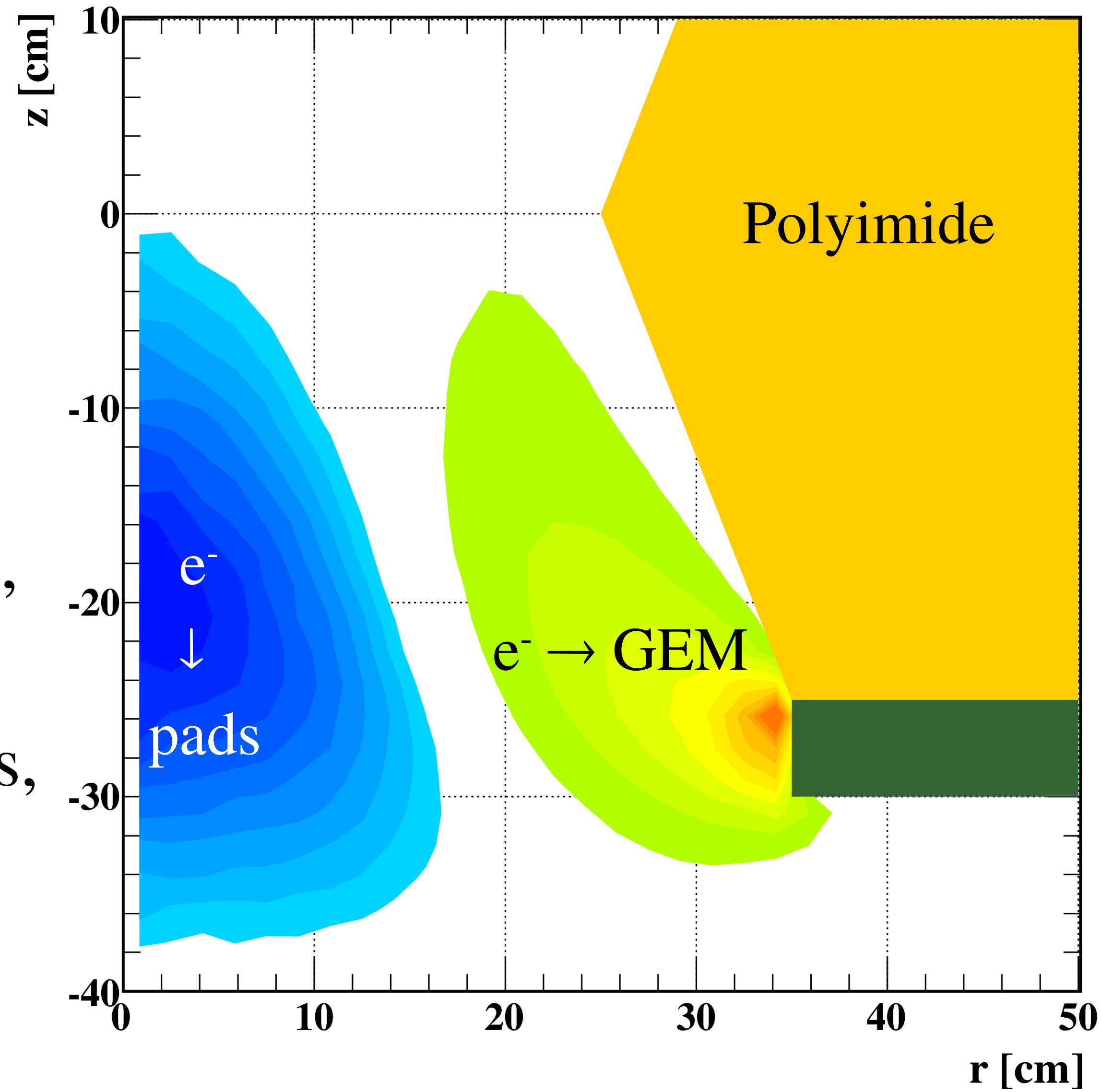
# GEMs of various manufacturers




- [B. Azmoun *et al.* 10.1109/NSSMIC.2006.353830]

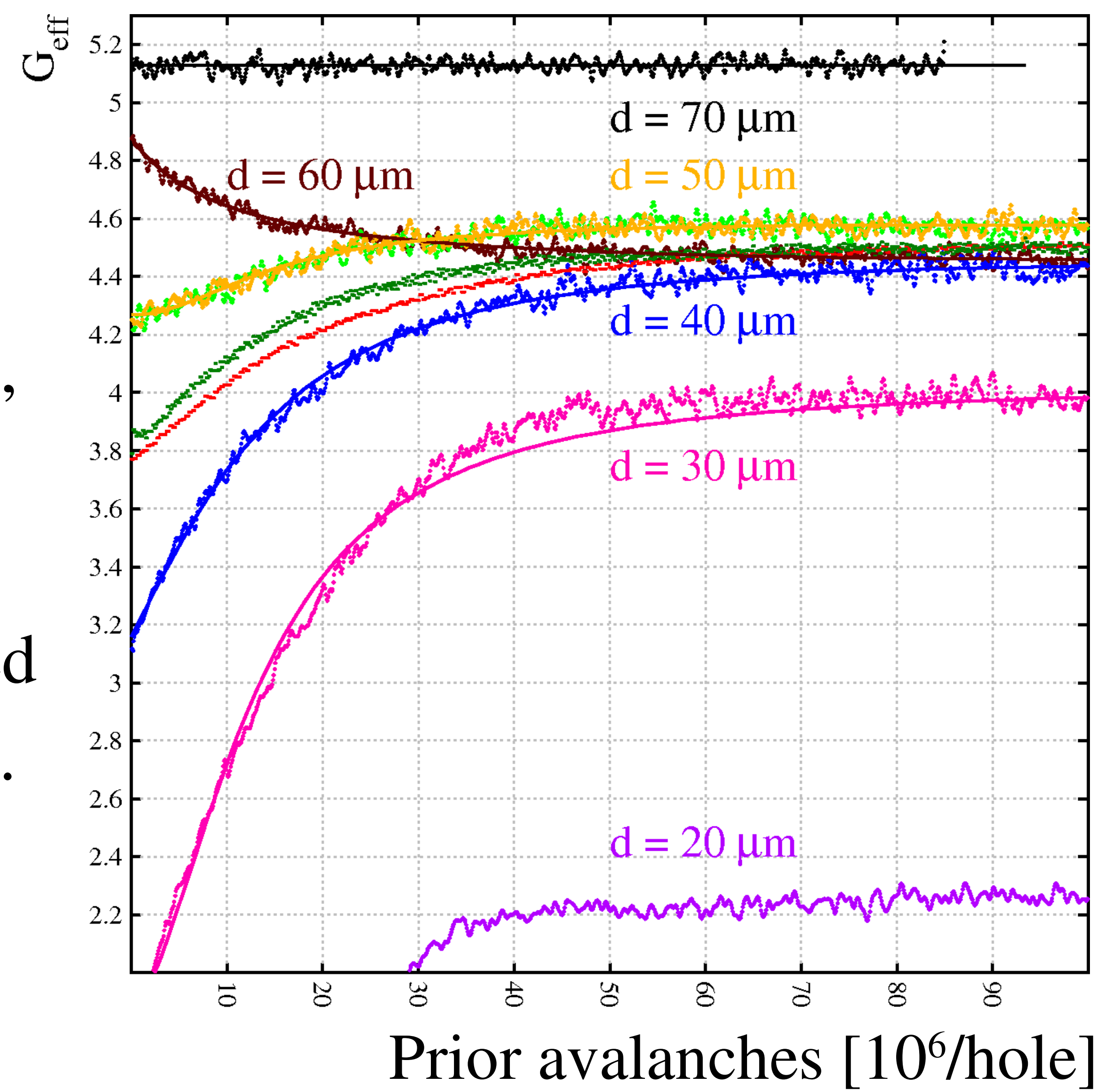
# Avalanche regions

- Vicinity GEM anode: large multiplication,
  e$^-$ → GEM anode, polyimide,
  ion$^+$ → polyimide, GEM cathode, drift region.
- Hole centre: lower fields, less multiplication,
  e$^-$ → pad plane,
  ion$^+$ → drift region.

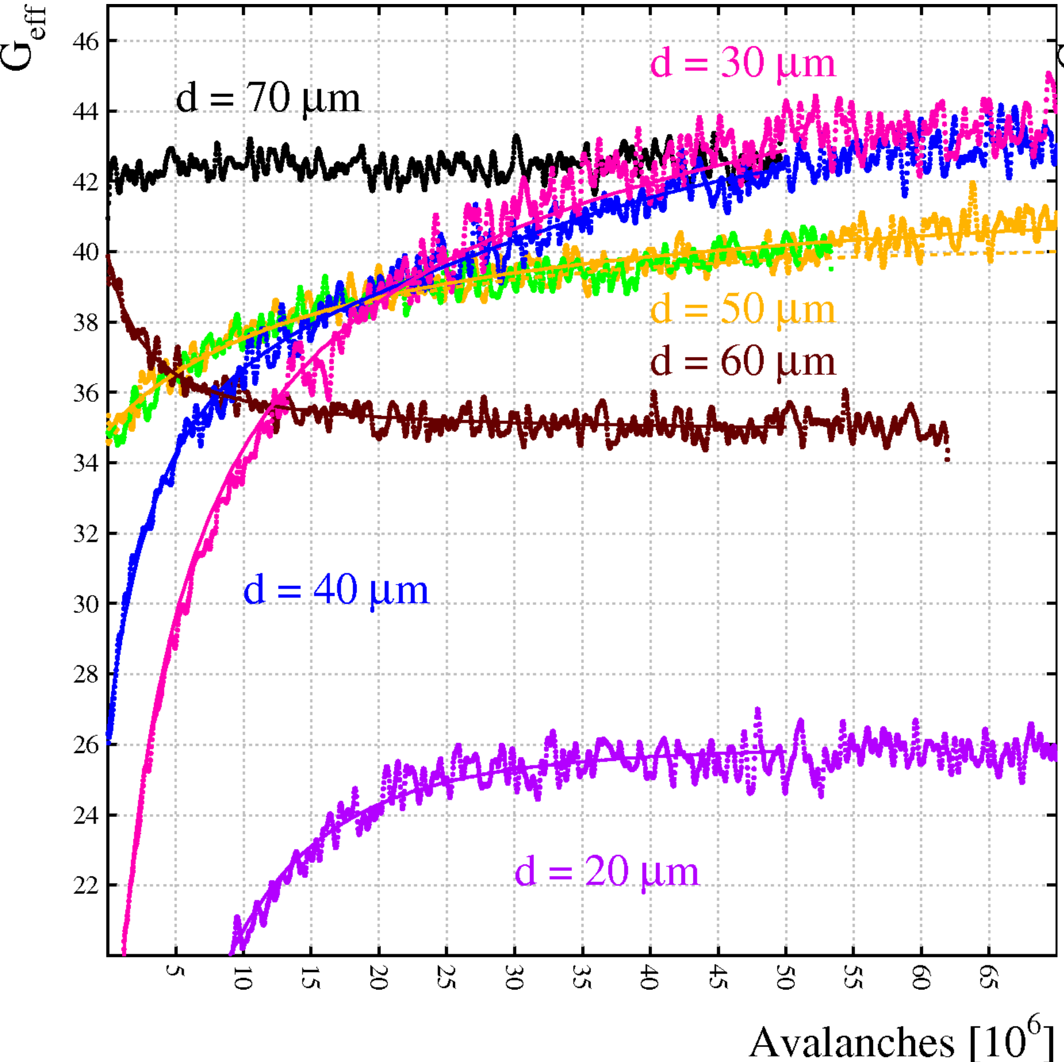


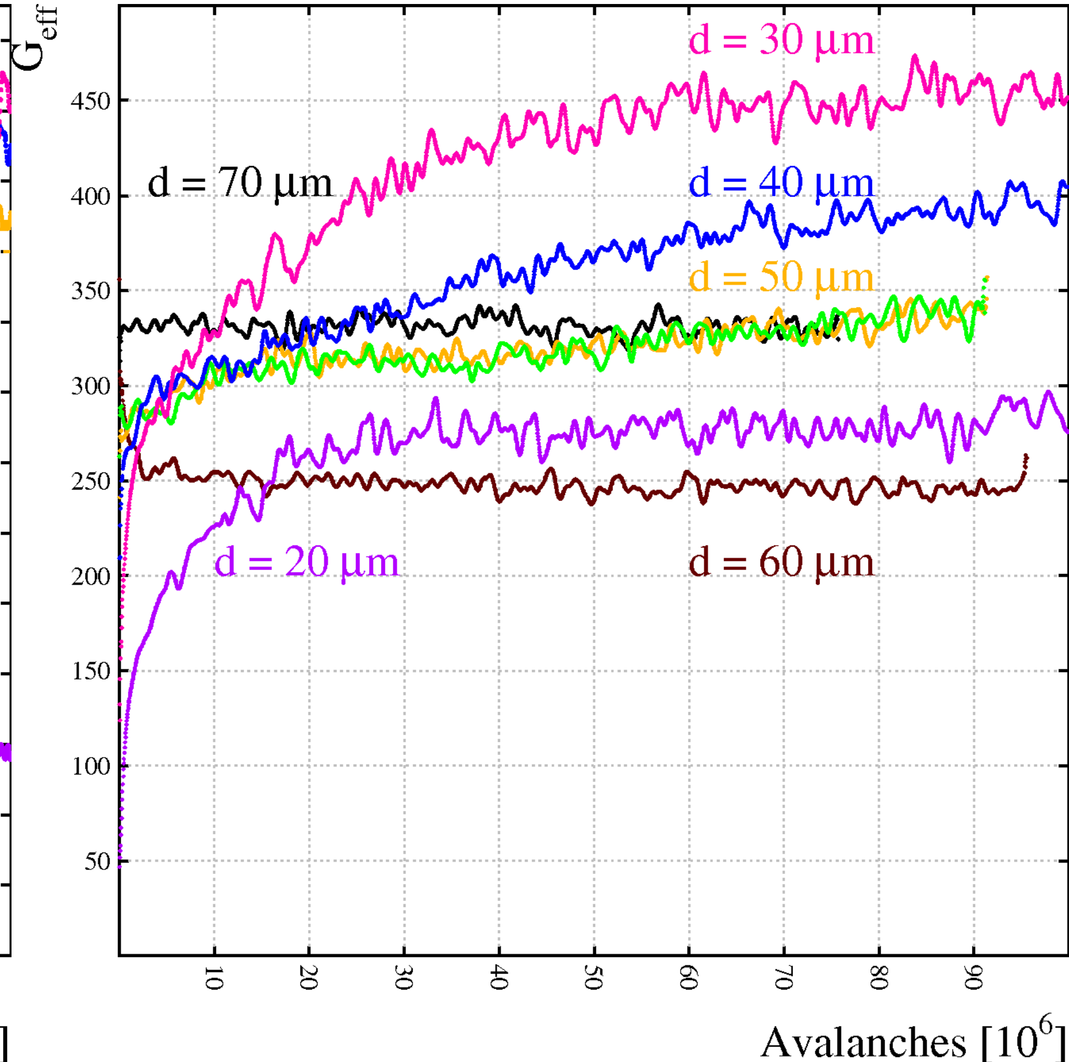
# Effect of surface charge ($V_{GEM}$ = 300 V)

- In a clean GEM, small holes give lower gain.
- As charge accumulates, the gain curves cross.
- Effect more pronounced at higher GEM voltage.



# $V_{GEM}$ = 400 V and $V_{GEM}$ = 500 V



# Trends

- Wires have fallen out of favour:
  - finite element and boundary elements.
- Electron transport:
  - integrated transport and fields for small structures;
  - role of excited noble gas atoms, transfer measurements;
  - charges in dielectrics, surface charge, space charge.
- Ion transport:
  - understanding ion chemistry;
  - measurement of ion transport.
- Current activities
  - semi-conductive layers.

# Backup slides

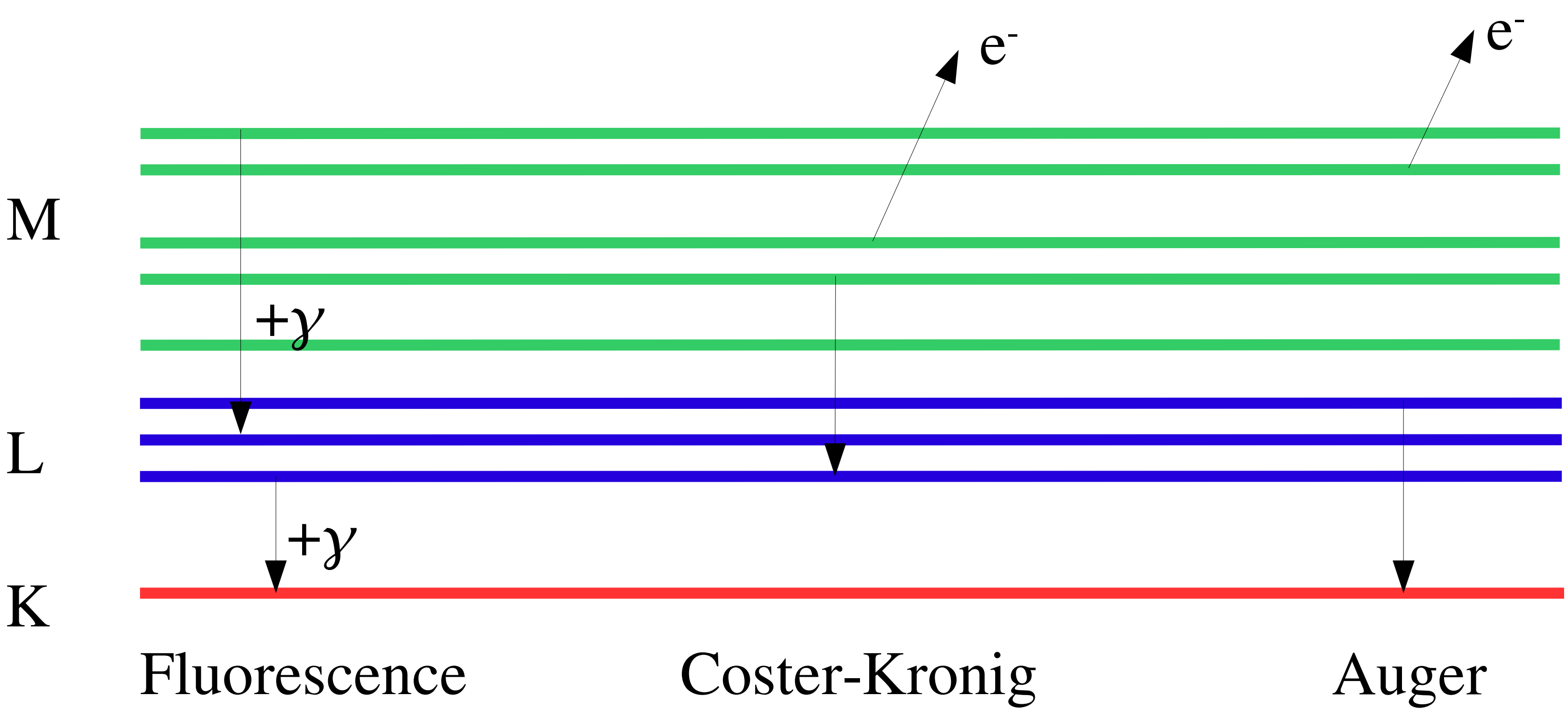
# De-excitation

Ralph de Laer Kronig
(1904-1995)

Dirk Coster
(1889-1950)

Lise Meitner
(1878-1968)

Pierre Victor Auger
(1899-1993)




References:

D. Coster and R. de L. Kronig, Physica **2** (1935) 13-24.

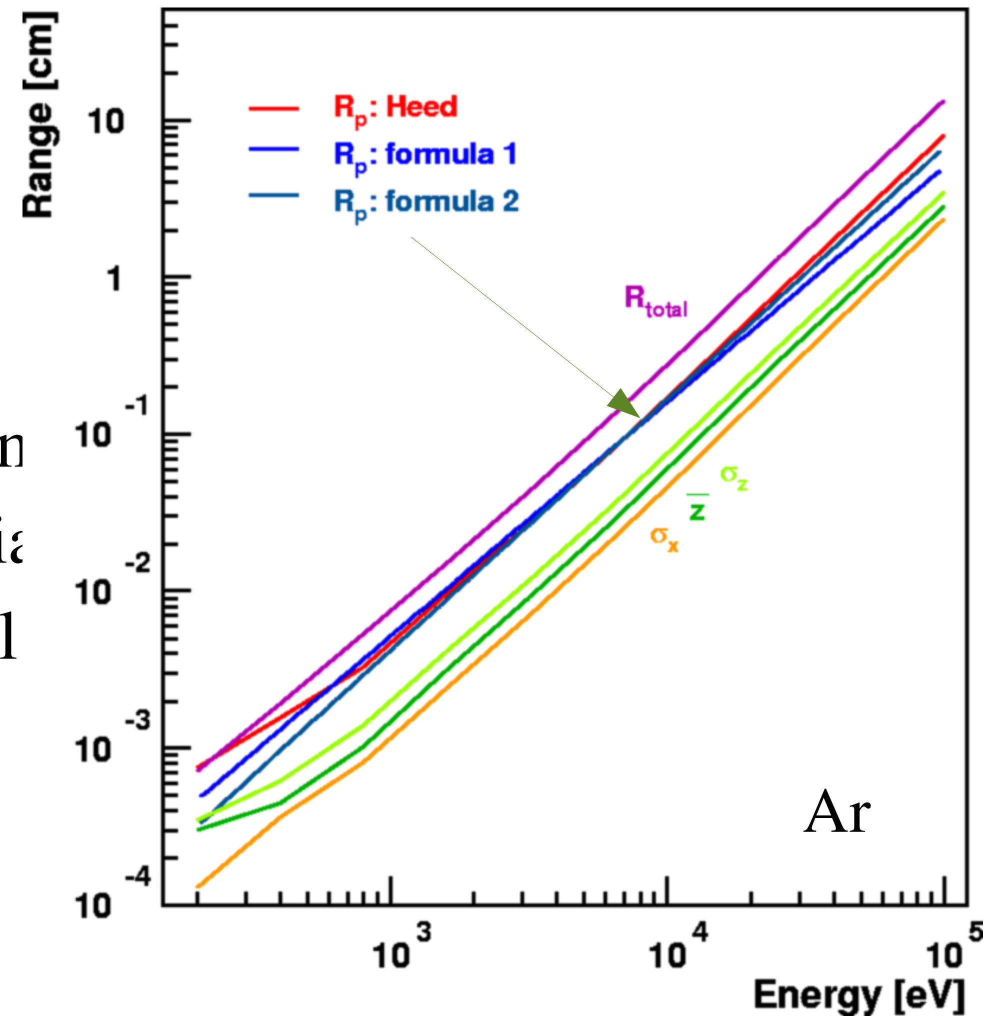
Lise Meitner, *Über die β-Strahl-Spektra und ihren Zusammenhang mit der γ-Strahlung*, Z. Phys. **11** (1922) 35-54.

L. Meitner, *Das β-Strahlenspektrum von $UX_1$ und seine Deutung*, Z. Phys. **17** (1923) 54-66.

P. Auger, J. Phys. Radium **6** (1925) 205.

# Range of photo- and Auger-electrons

- Electrons scatter in a gas.
- Measures of the range:
  - $R_{total}$ : total path length
  - $R_p$ : practical range
  - $\overline{z}$ : cog in direction of initial n
  - $\sigma_x$: RMS in direction of initia
  - $\sigma_z$: RMS transverse to initial



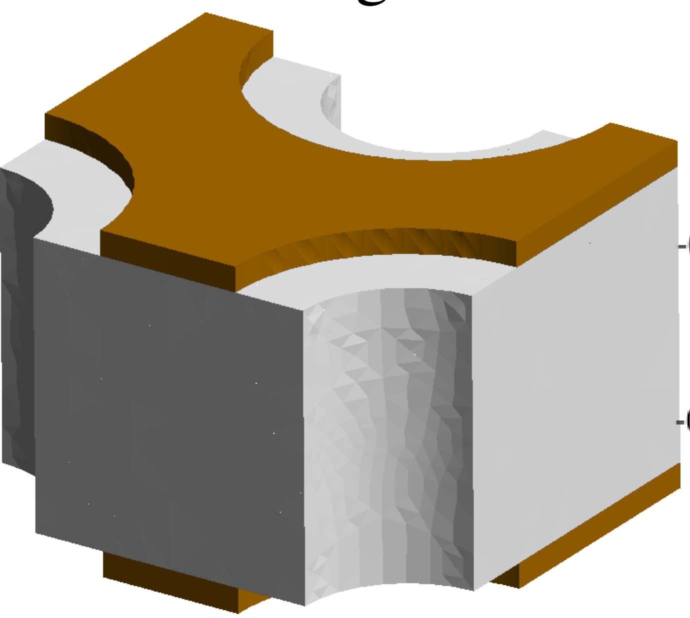

Practical range: distance at which the tangent through the inflection point of the descending portion of the depth- absorbed dose curve meets the extrapolation of the Bremsstrahlung background (ICRU report 35, 1984)

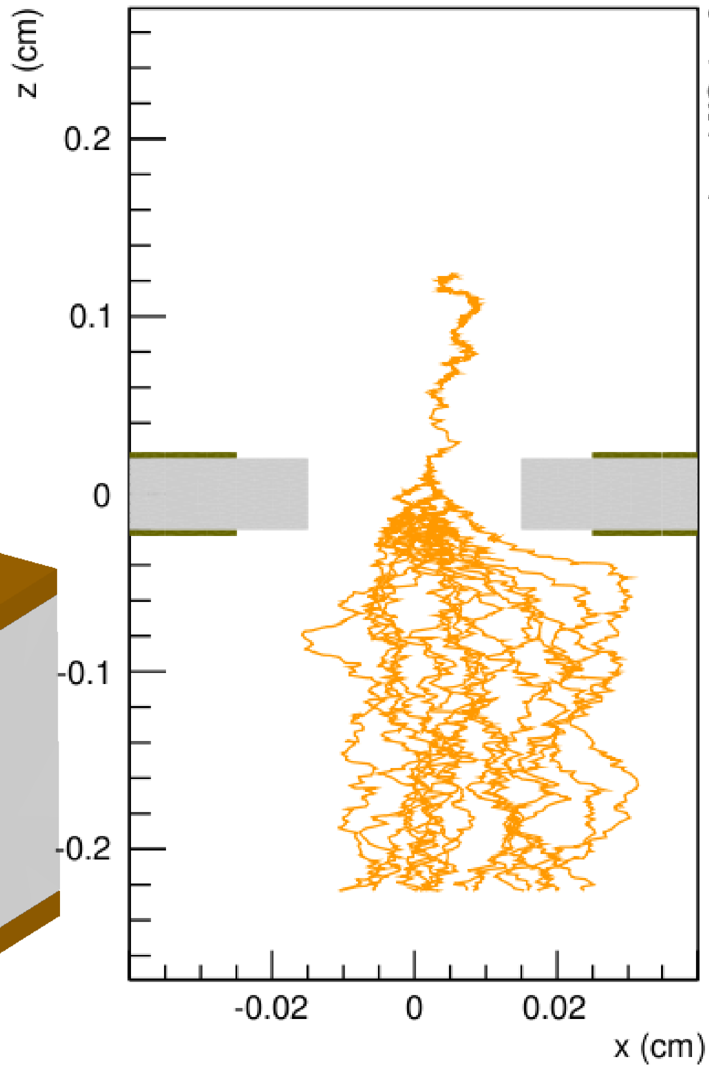
# Field calculation techniques

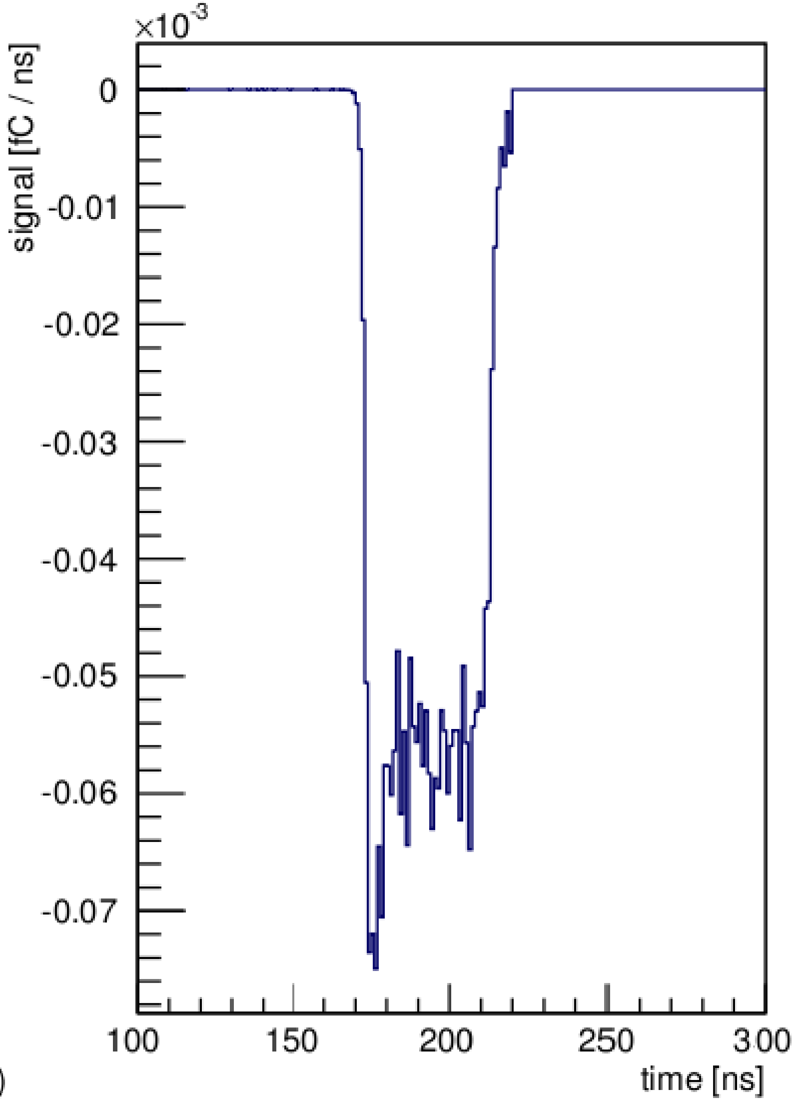
- Closed expressions:
  - almost all 2d structures of wires, planes + periodicities;
  - dielectrics and space/surface charge are laborious;
  - fast and precise, if applicable – not suitable for MPGDs.
- Finite elements:
  - 2d and 3d structures, with or without dielectrics;
  - several major intrinsic shortcomings.
- Integral equations or Boundary element methods:
  - equally comprehensive without the intrinsic flaws;
  - technically challenging and emerging.
- Finite differences:
  - used for iterative, time-dependent calculations.

# Gmsh/Elmer example

- Thick GEM
  - unit cell,
  - avalanche,
  - signal.





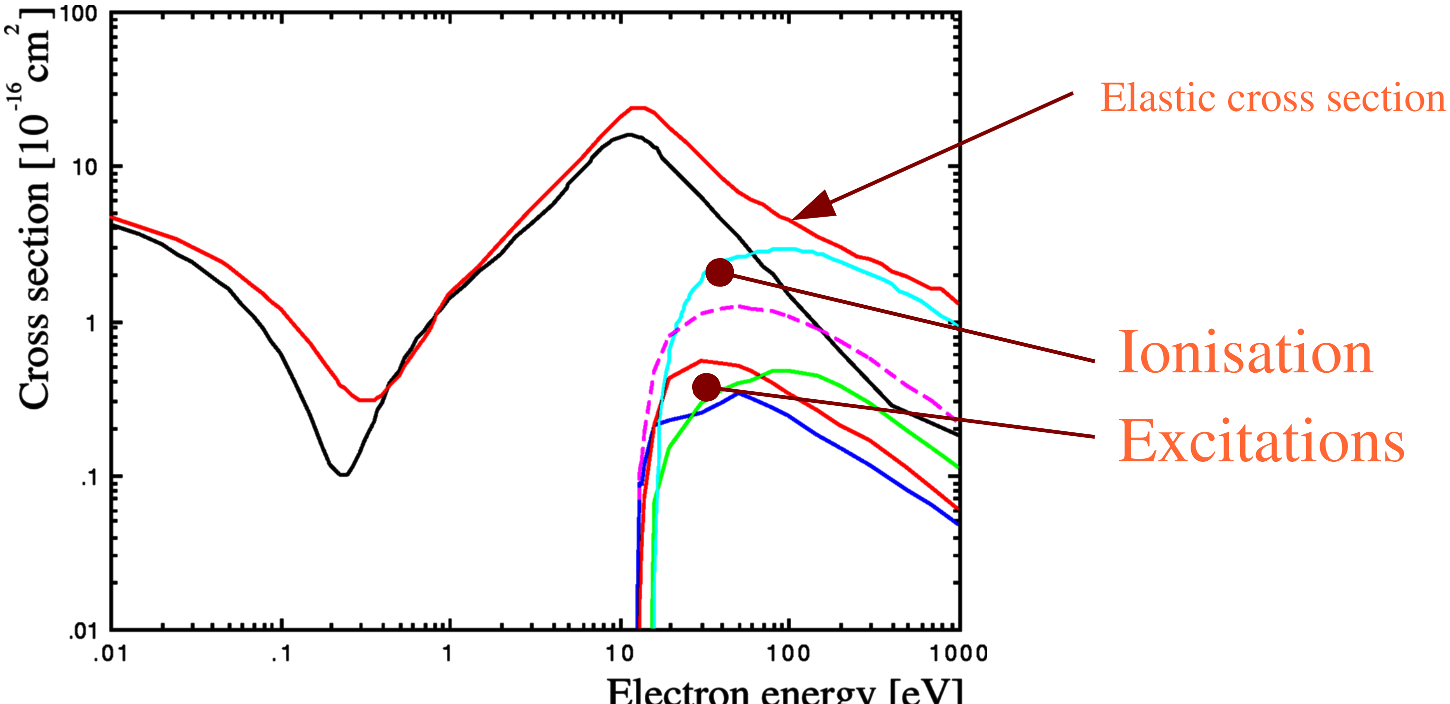

Josh Renner: http://cern.ch/garfieldpp/examples/elmer/

# The Degrad model

- Atomic/molecular cascade:
  - Auger and Coster-Kronig decay; Xe: innermost 17 shells
  - fluorescence;
  - outer shell electron shake off.
- Photon absorption:
  - photoelectric effect;
  - Compton scattering.
- Electron scattering:
  - rotational, vibrational, excitation and ionisation scattering.
- Atomic de-excitation:
  - Penning; $Ar^* + CO_2 \rightarrow Ar + CO_2^+ + e^-$.
  - Hornbeck-Molnar. $Ar^* + Ar \rightarrow Ar_2^+ + e^-$.
- Not included:
  - Bremsstrahlung, pair production.

# Cross section of argon

- Cross section in a hard-sphere model:
  - Radius: ~70 pm (`http://www.webelements.com`)
  - Surface: $\sigma = \pi (70\ 10^{-10}\ \mathrm{cm})^2 \approx 1.5\ 10^{-16}\ \mathrm{cm}^2$
- Simplified cross sections used by Magboltz:



# Mean free path in argon

- Given:
  - Cross section of 1 atom: $\sigma \approx 1.5\ 10^{-16}\ \mathrm{cm}^2$
  - Atoms per volume: $\mathscr{L} \approx 2.5\ 10^{19}$ atoms/cm$^3$

- Mean free path for an electron ?
  - An electron hits all atoms of which the centre is less than a cross section radius from its path
  - Over a distance $L$, the electron hits $\mathscr{L} \sigma\ L$ atoms
  - Hence, the mean free path is $\lambda_e = 1/(\mathscr{L}\sigma) \approx 2.7\ \mu\mathrm{m}$
  - Much larger than the distance between atoms, 3.5 nm and typical gas molecule diameters, 140-600 pm.

# 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*:

$$\frac{1}{2}\frac{qE}{m_e}t^2=\lambda_e, \quad i.e. \quad t=\sqrt{\frac{2\lambda_e m_e}{qE}}, \quad i.e. \quad \bar{v}=\frac{\lambda_e}{t}=\sqrt{\frac{\lambda_e qE}{2m_e}}$$

- For example:

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

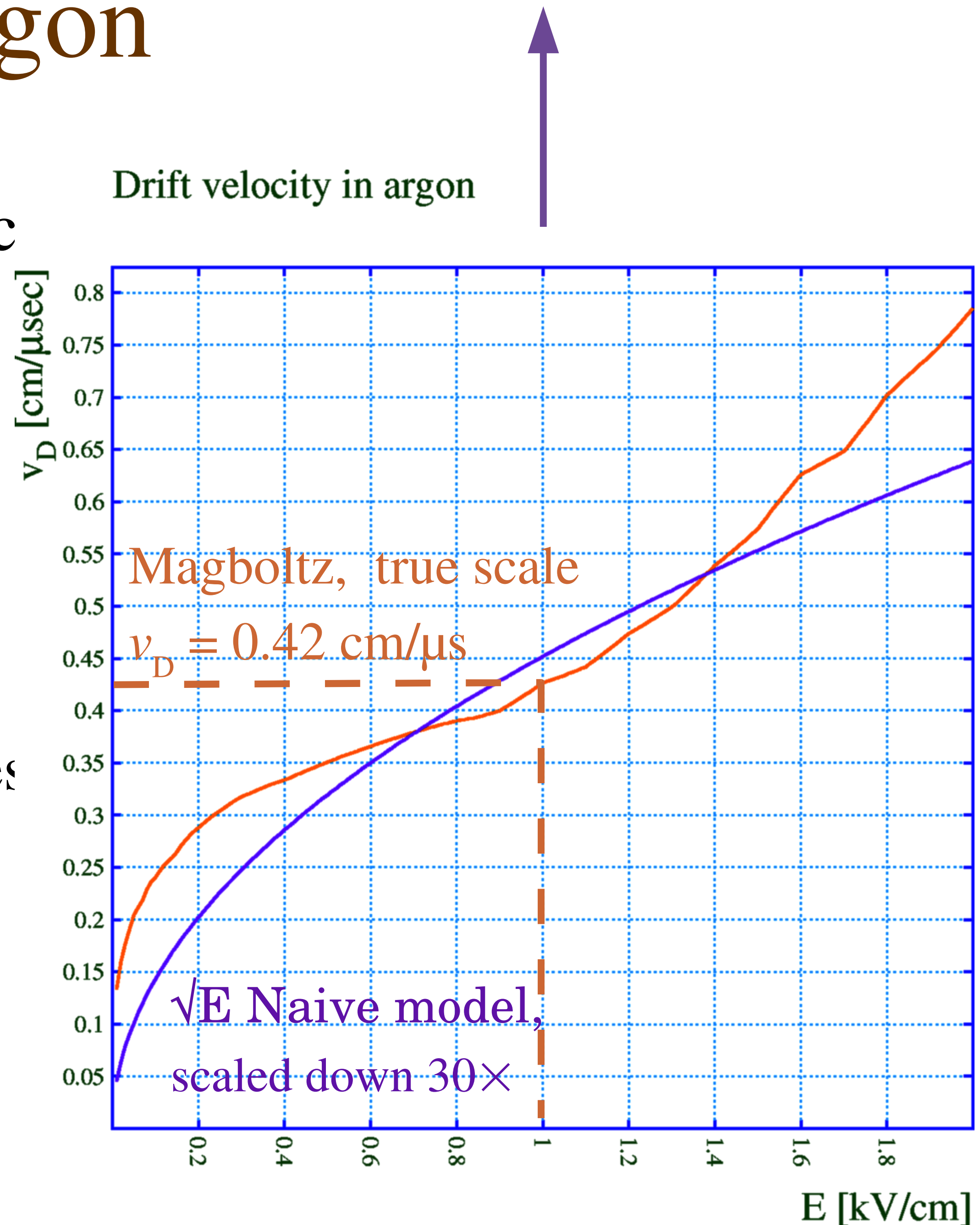
# Drift velocity in argon

- Compare with a Magboltz c
  - $E$ dependence is OK;

BUT

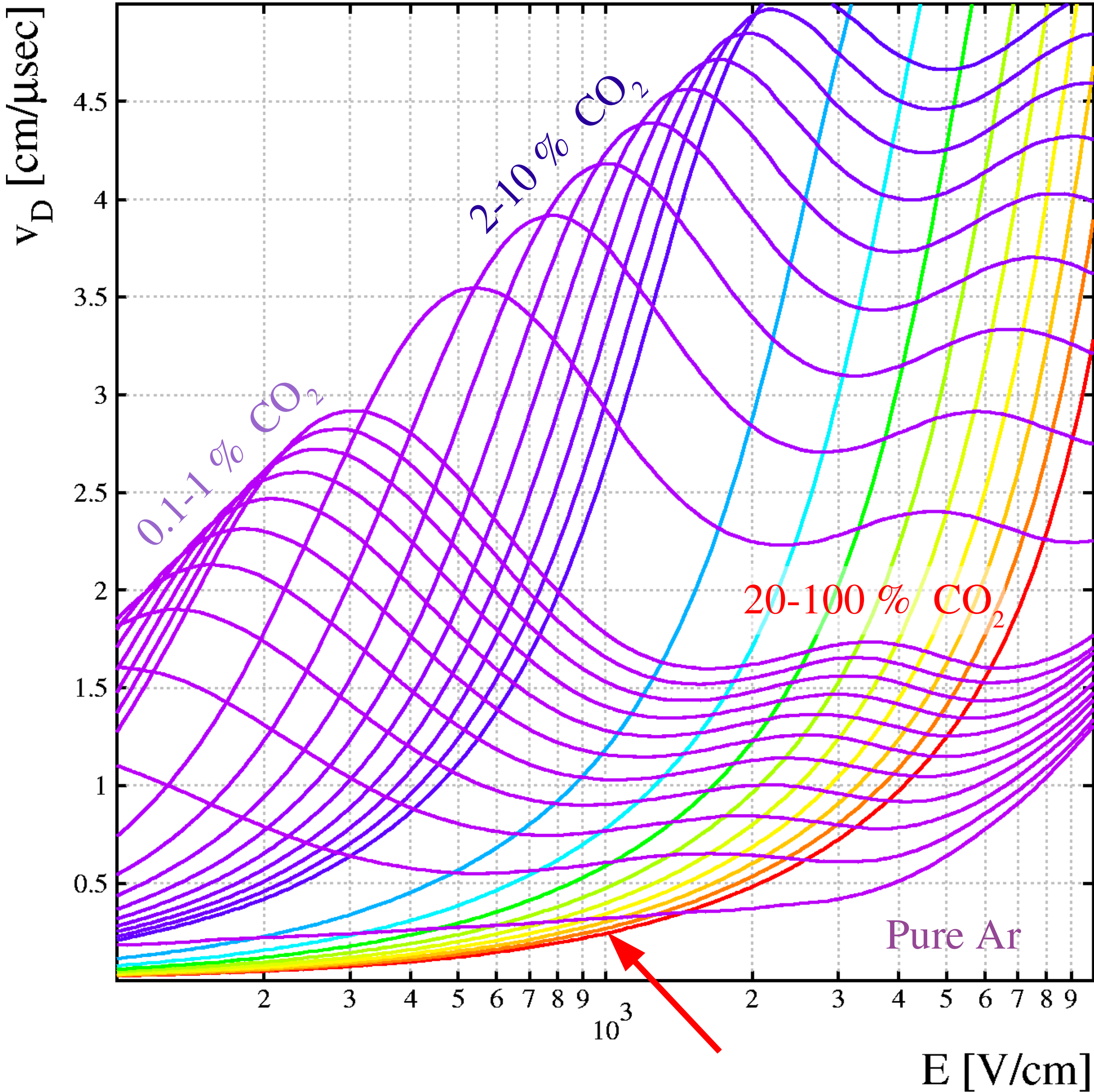
  - the velocity is *vastly* overes

$\bar{v} = 13\,\mathrm{cm}/\mu\mathrm{s}$

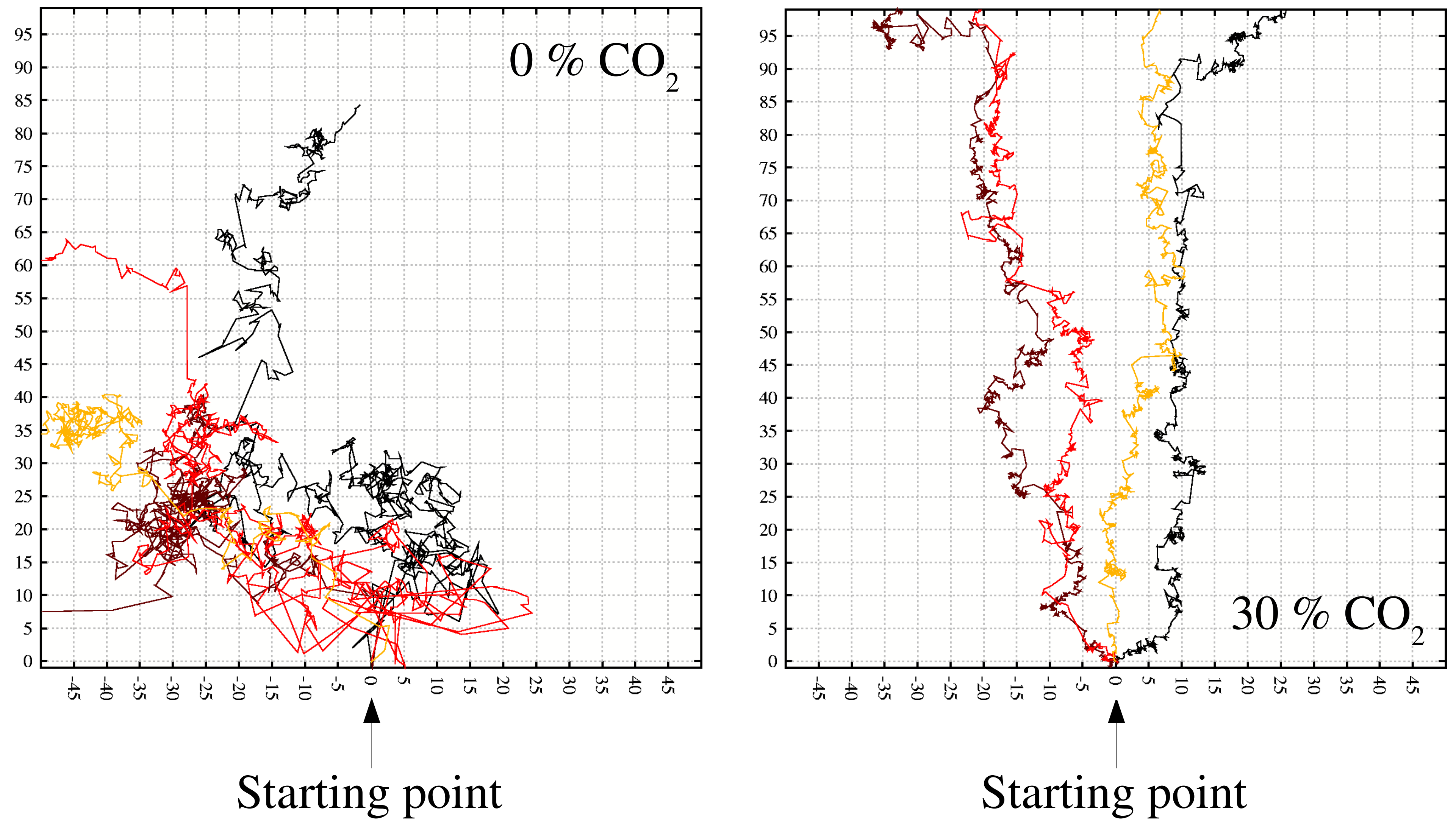


# Adding $CO_2$

- $CO_2$ makes the gas faster, dramatically.
- Calculated by Magboltz for $Ar/CO_2$ at 3 bar.



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

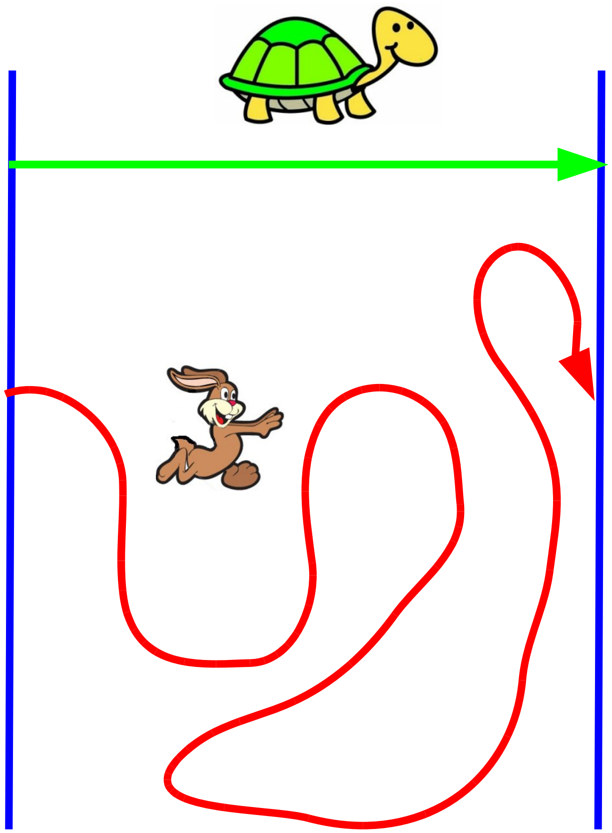


# Drift velocity vs Mean velocity

- Drift velocity: distance effectively travelled divided by time needed.
- Imagine they take equal time:

$$v_D = \bar{v}$$

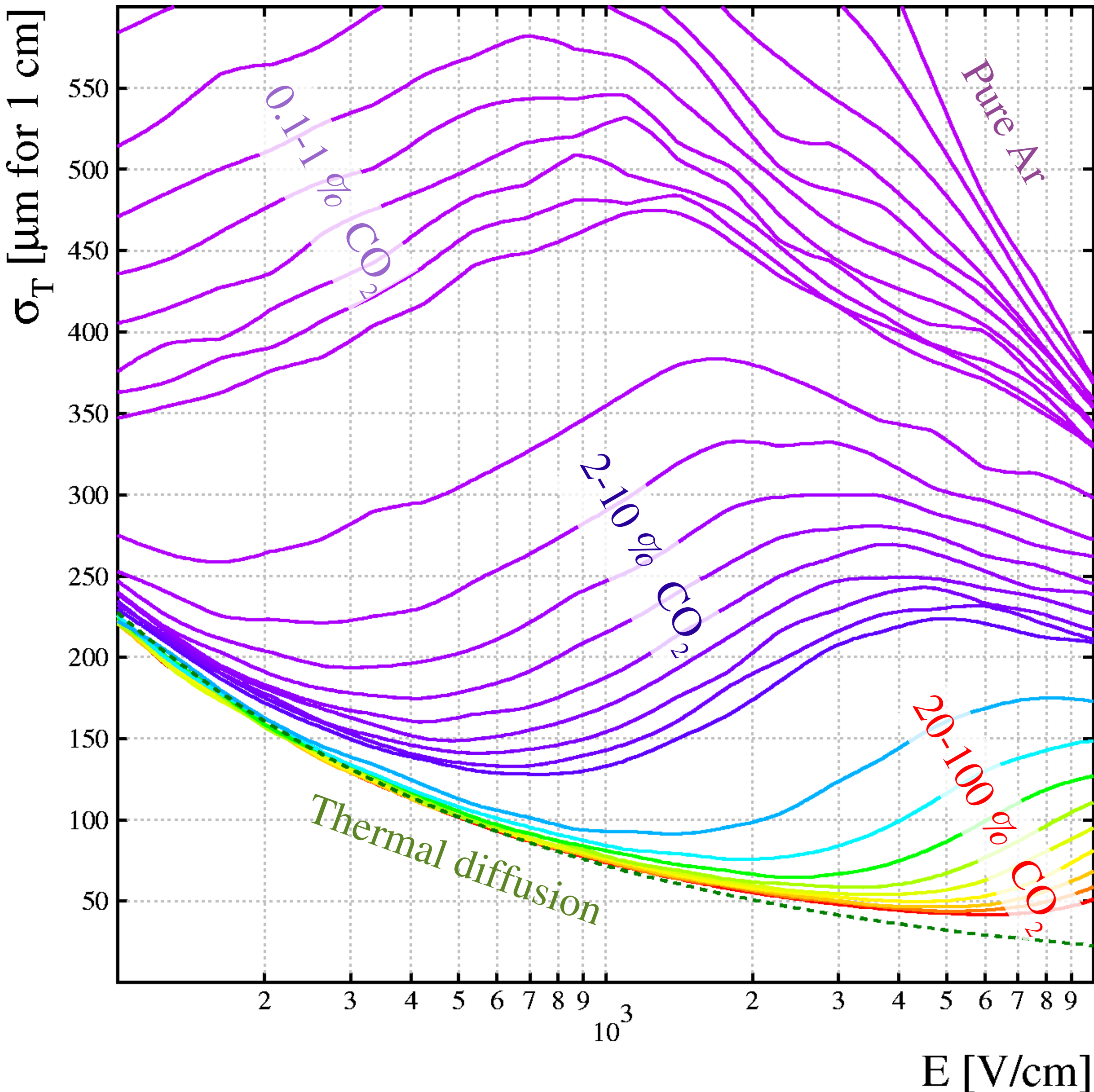
$$v_D \ll \bar{v}$$



# Adding $CO_2$

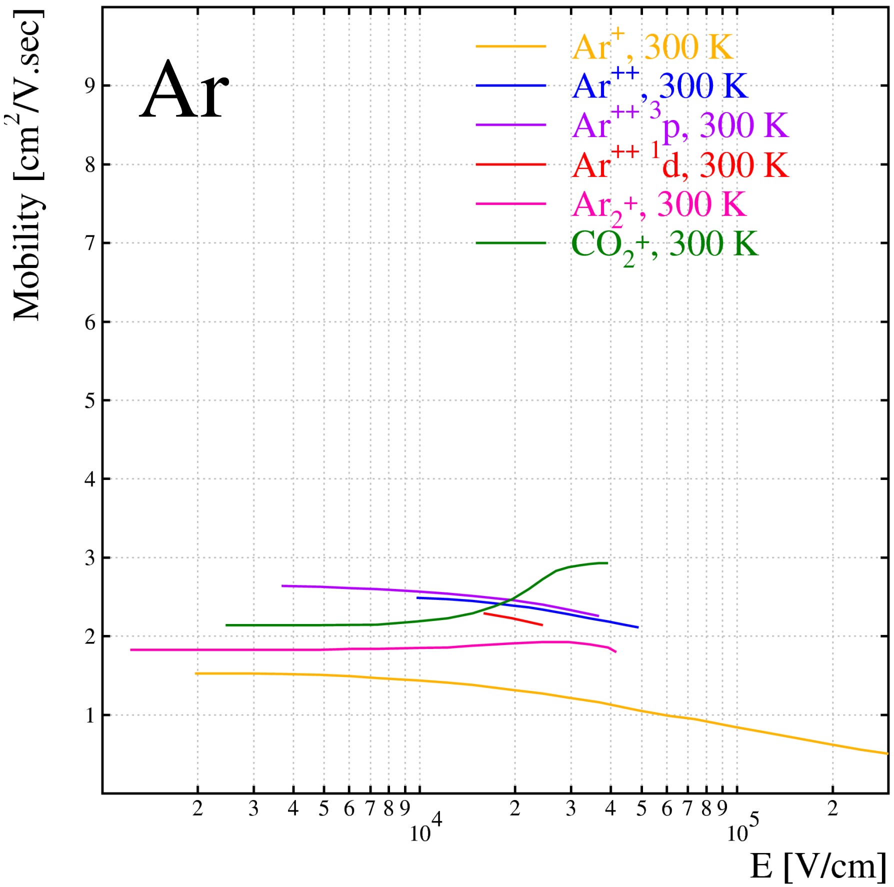
- Transverse diffusion is much reduced by $CO_2$.

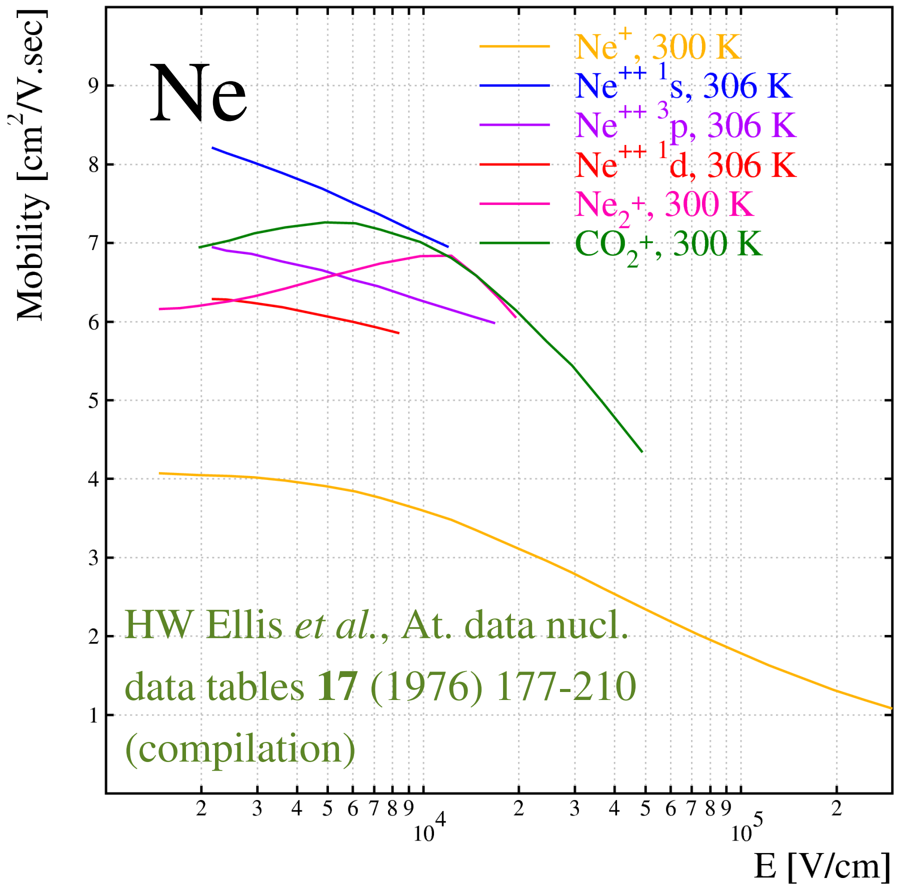
- Calculated by Magboltz for $Ar/CO_2$ at 3 bar.



# $Ar^+$ and $Ne^+$ mobility

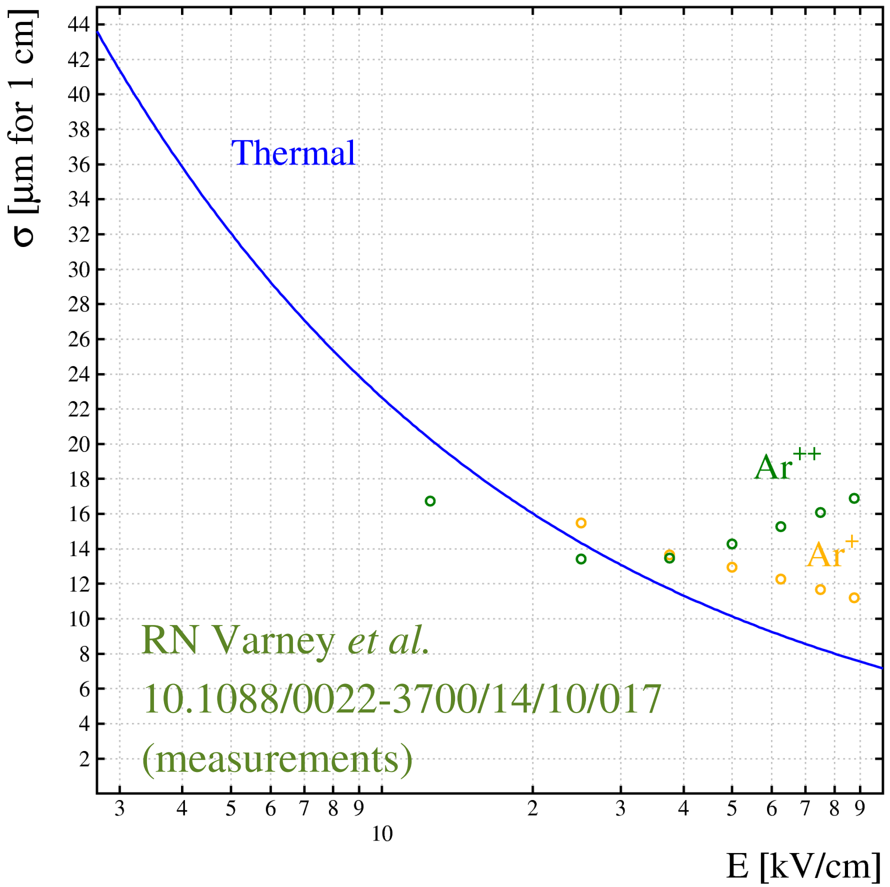
- Avalanches take a few ns: http://cern.ch/garfieldpp/examples/gemgain
- Ion velocity at 3 kV/cm: Ar: ~20 μs/mm, Ne: ~8 μs/mm

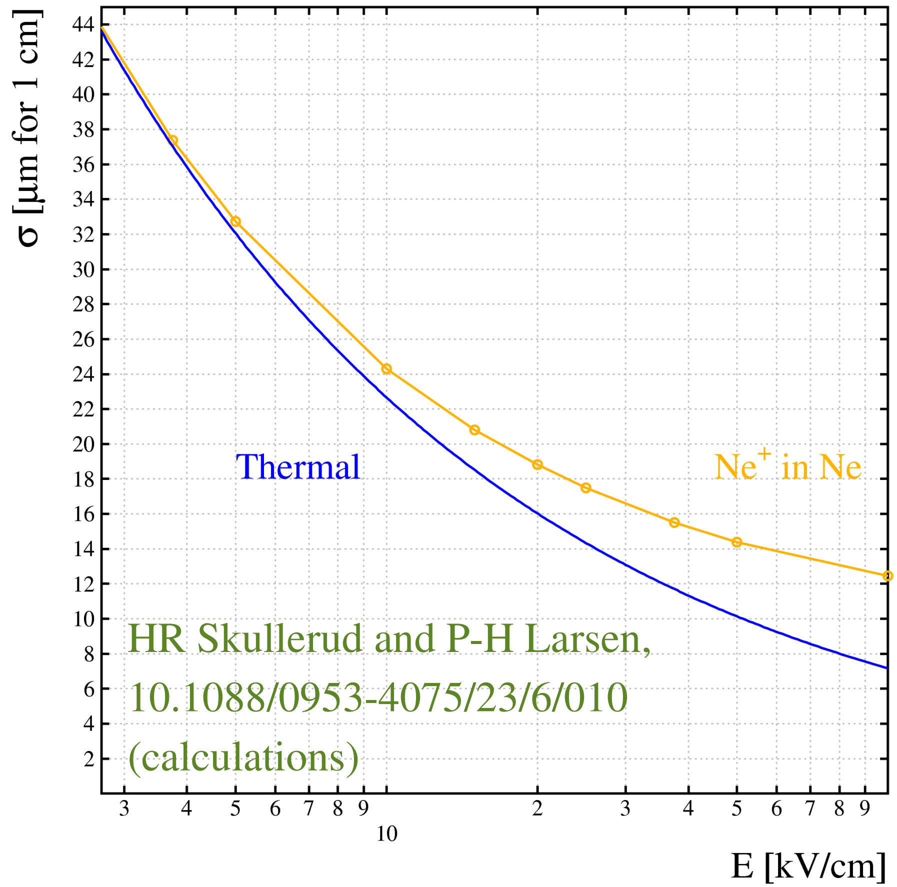


# Diffusion of $Ar^+$ in Ar and $Ne^+$ in Ne

- Little experimental data, in particular at low fields.
  extrapolated from higher fields: ~10 µm for 1 mm

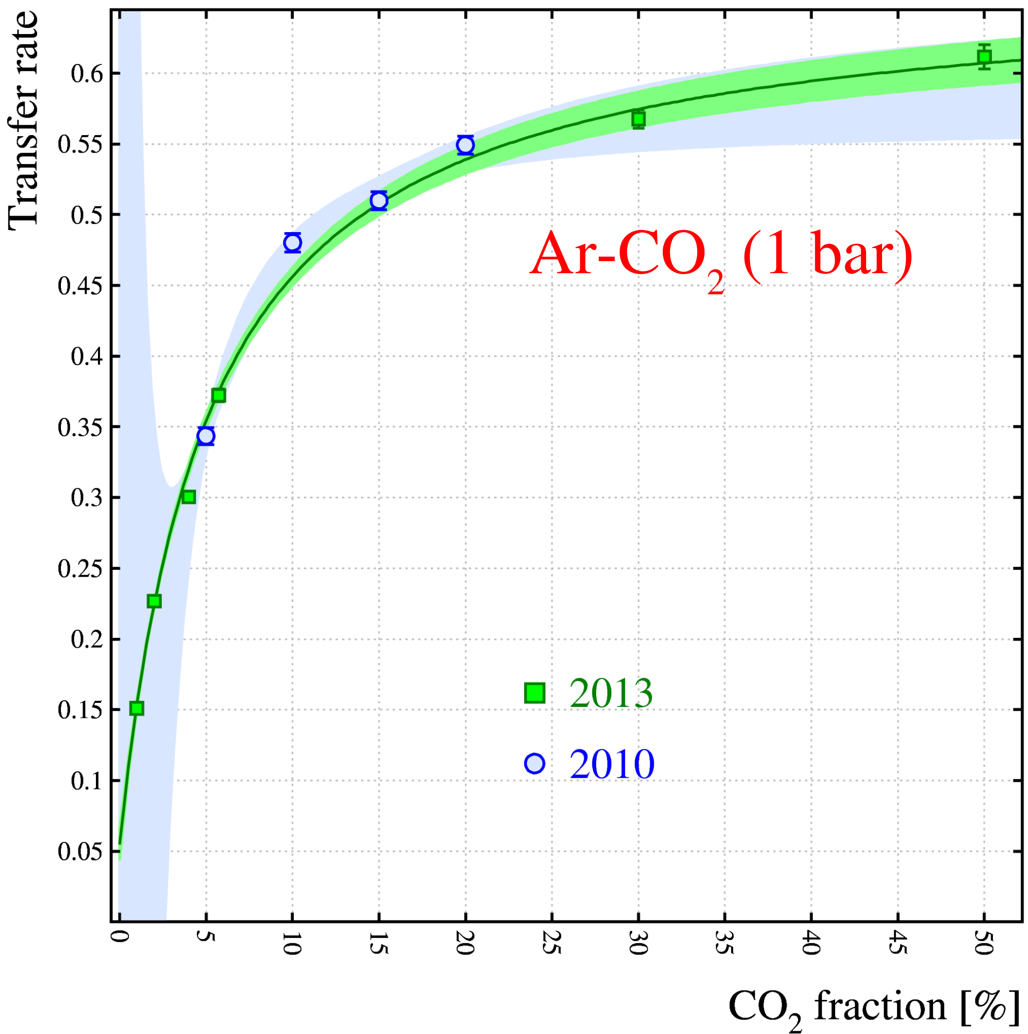


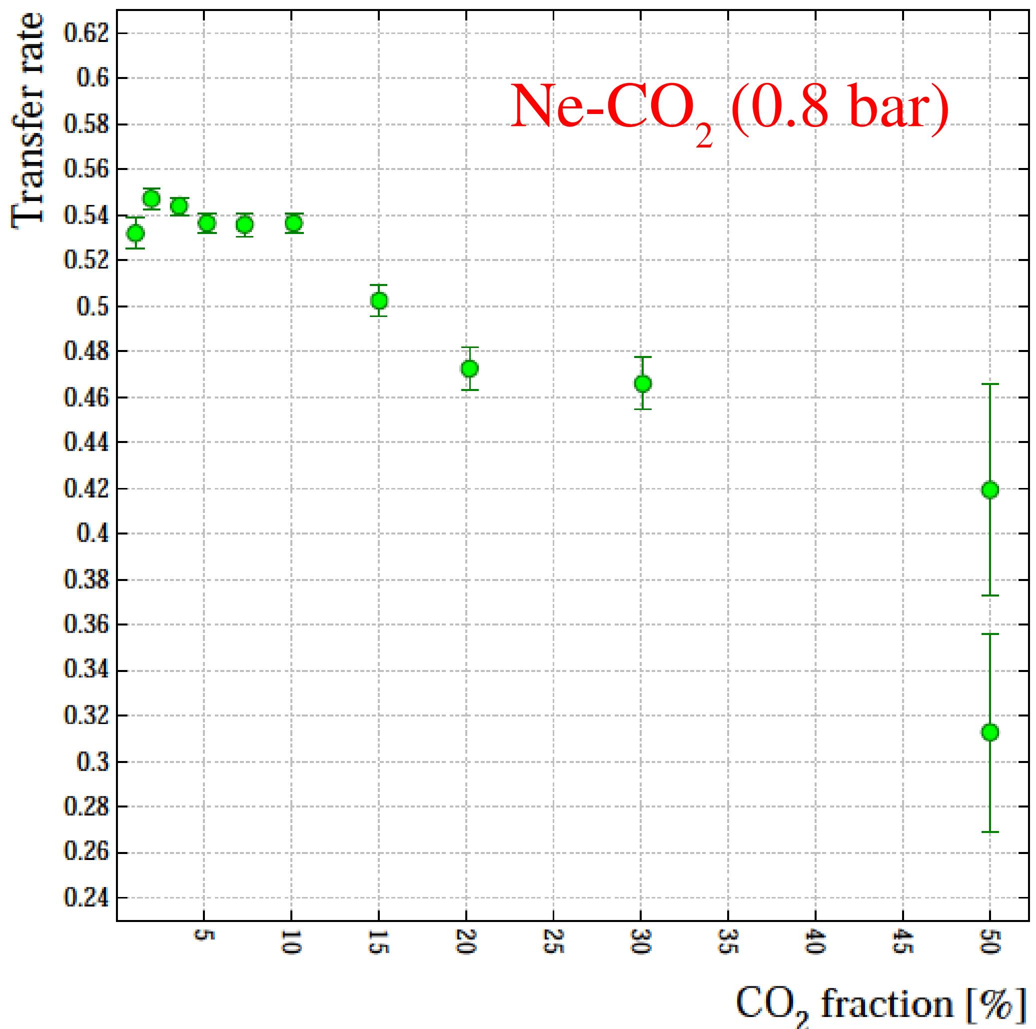



PhD students: solve this puzzle and win a fondue during your next visit to CERN.

# Why does the rate fall in Ne-$CO_2$ ?

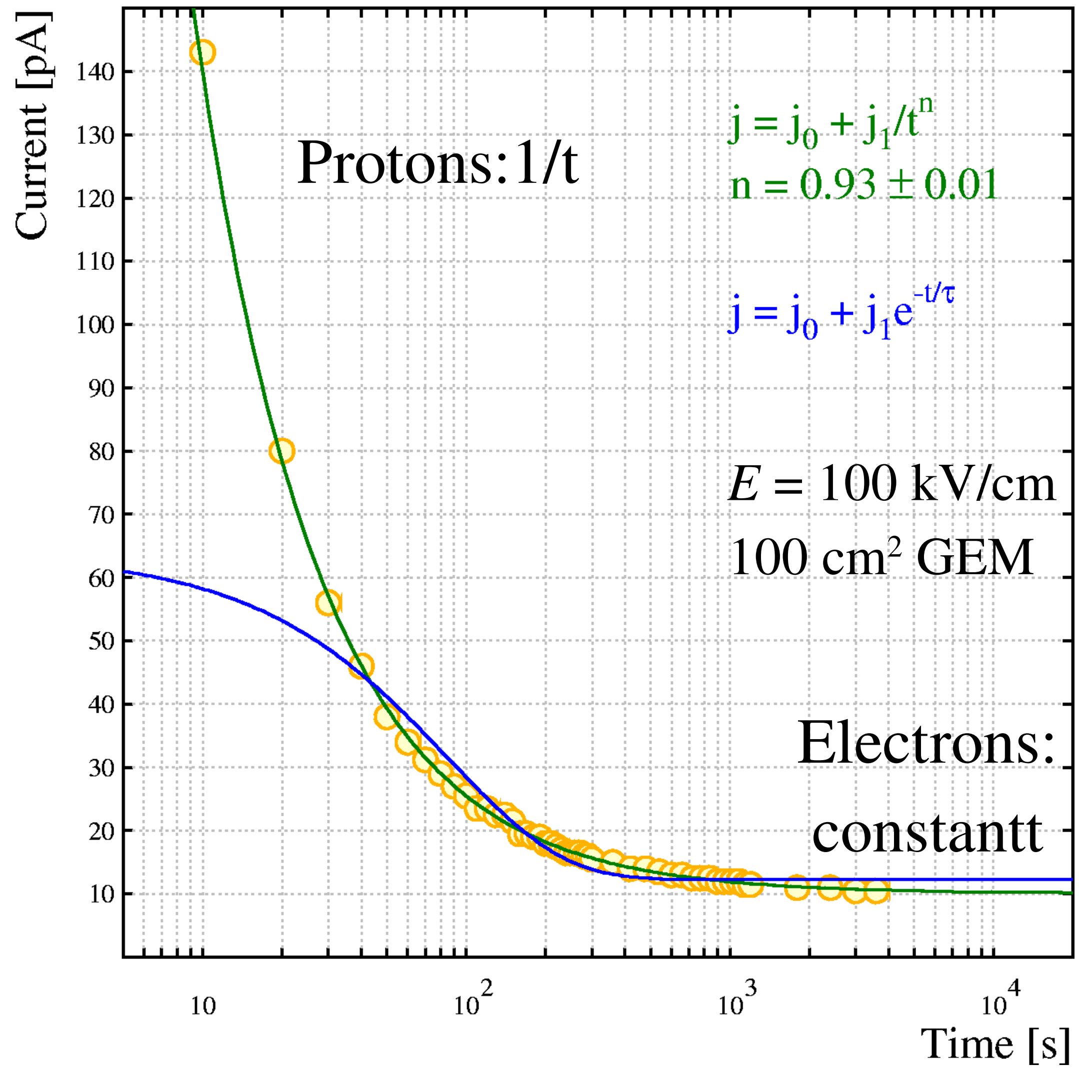
- Ar-$CO_2$ is best studied mixture



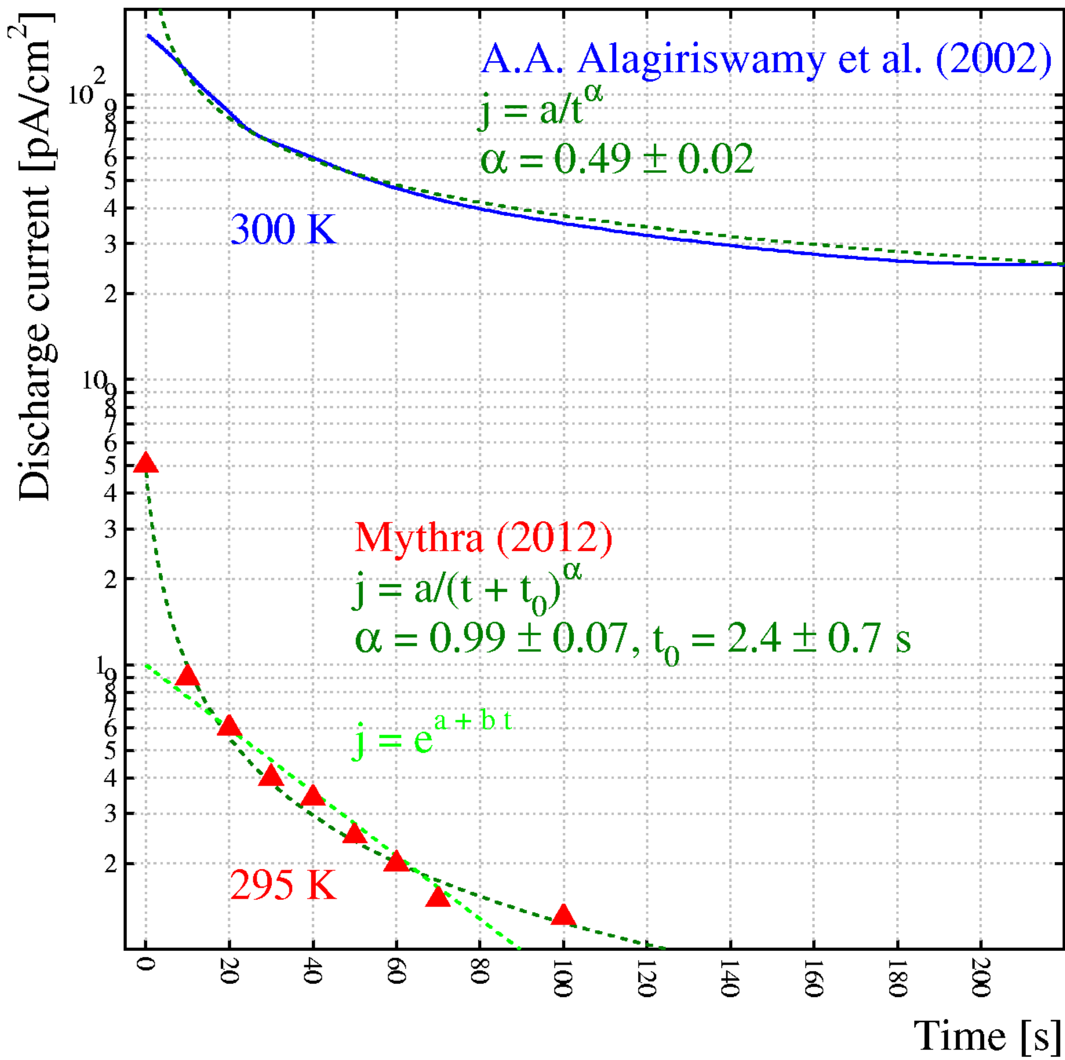
# Charging-up current

- When applying voltage across a new GEM, a current flows:
    - *not* constant (i.e. not a resistor)
    - decay is *not* exponential (i.e. not a capacitor);
    - decay is *not* linear (i.e. not evacuation);
    - but a *power law*.



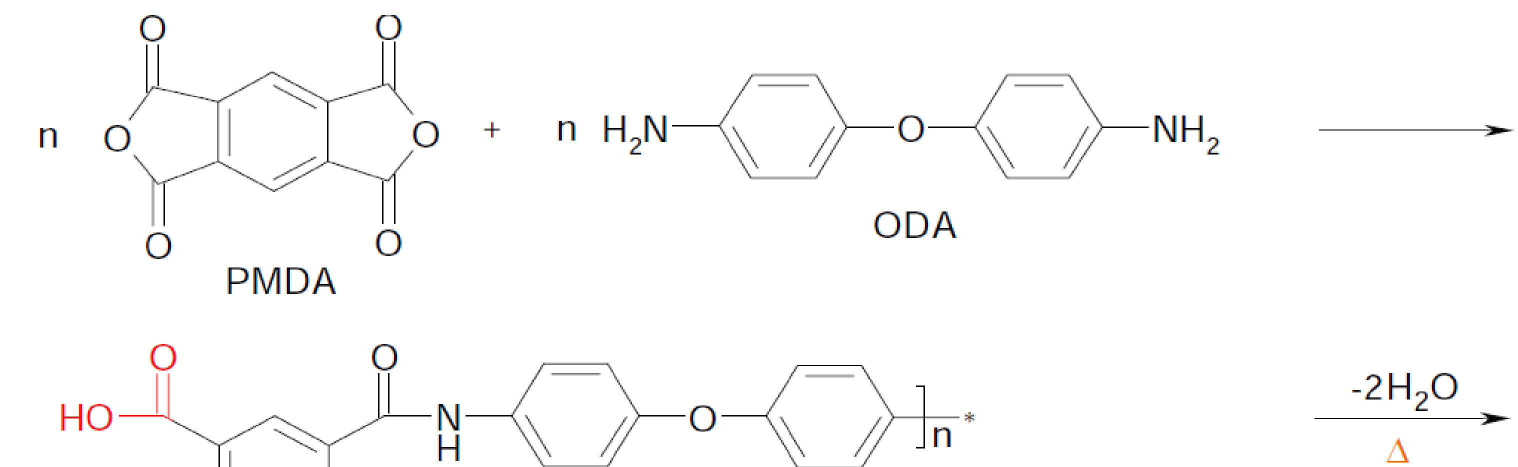
# Discharge current

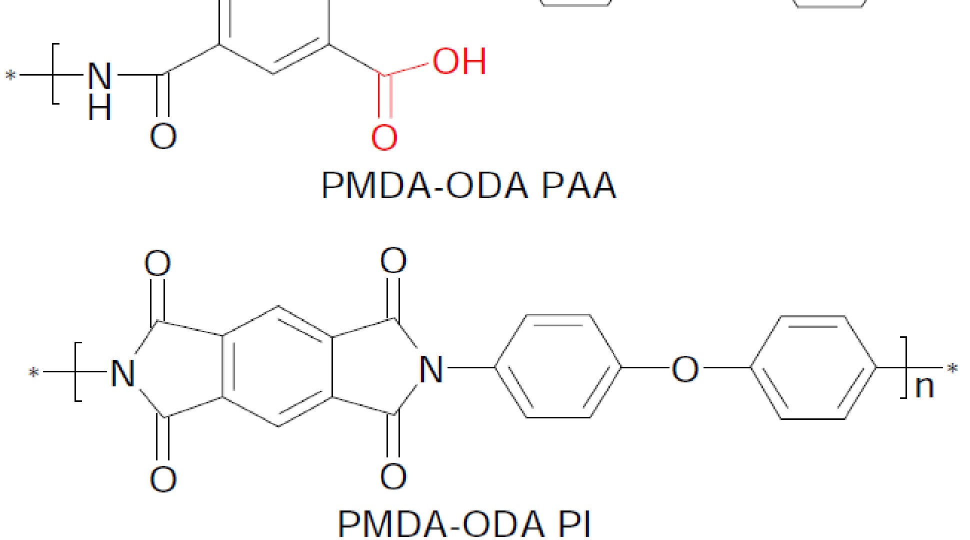
- The initial charge carriers stay in the polyimide, as can be seen by switching off the HV.
- The discharge current has reverse polarity and obeys a Kohlrausch law.



# Protons: polyamic acid (PAA)

- Note the intermediate acid, i.e. an $H^+$ donor:

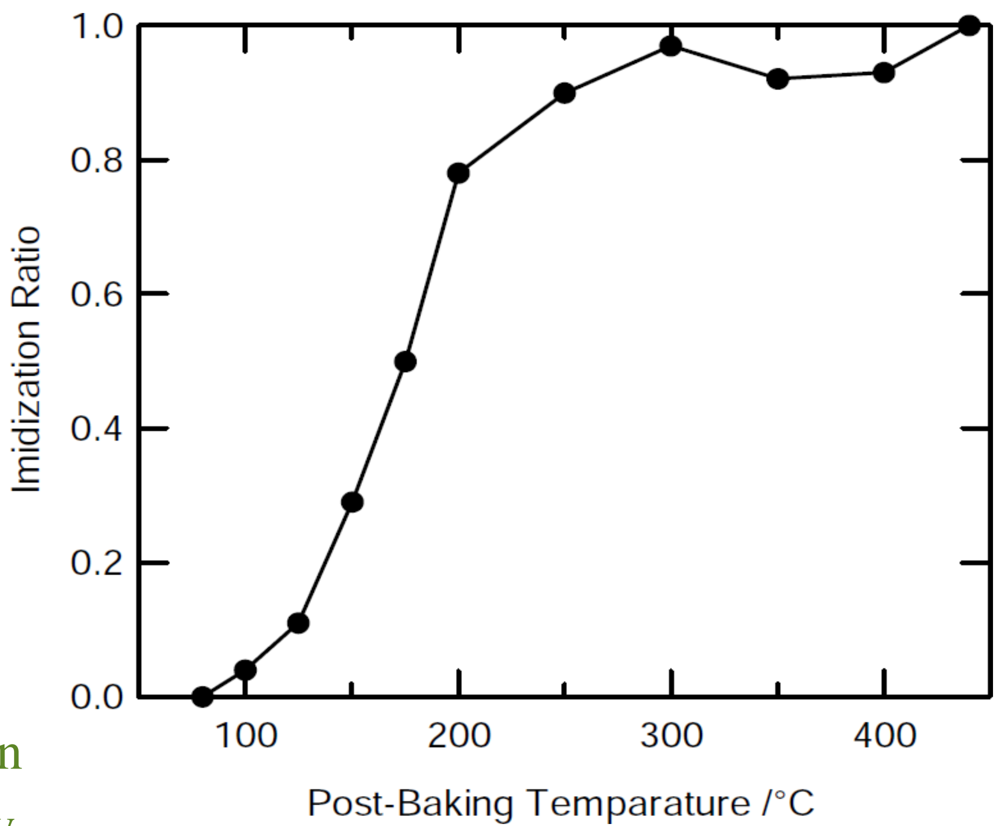



This only happens if heat is provided.

# PAA → PI vs baking temperature

- The quantity of remaining PAA depends on the baking temperature.
- The proton density therefore also varies.
- [H. Oji *et al.*, Memoirs of the Synchrotron Radiation Center, Ritsumeikan University, Kyoto, Japan **8** (2006) 187-188.]



Rudolf Hermann Arndt Kohlrausch (November 6th 1809, Göttingen - March 8th 1858, Erlangen)

# Kohlrausch relaxation

- This time dependence is known since 1854 at least. Also known as Curie-von Schweidler behaviour.

- Numerous models have been proposed
  - H. Kliem, *Kohlrausch relaxations: new aspects about the everlasting story*, doi: 10.1109/TDEI.2005.1511096.

- One of the simplest models specifically assumes ions (e.g. protons, not electrons) as charge carriers and has thin insulating barriers between dielectric medium and electrodes.

# Charges in GEMs

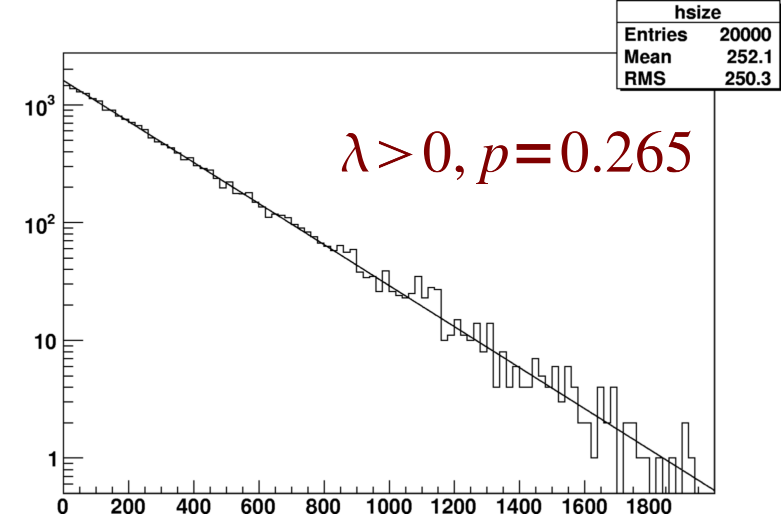
- In GEMs, active gas comes in contact with dielectrics; in breach of a fundamental law of gas-based devices. This results in charge accumulations on the plastic which distort the field.

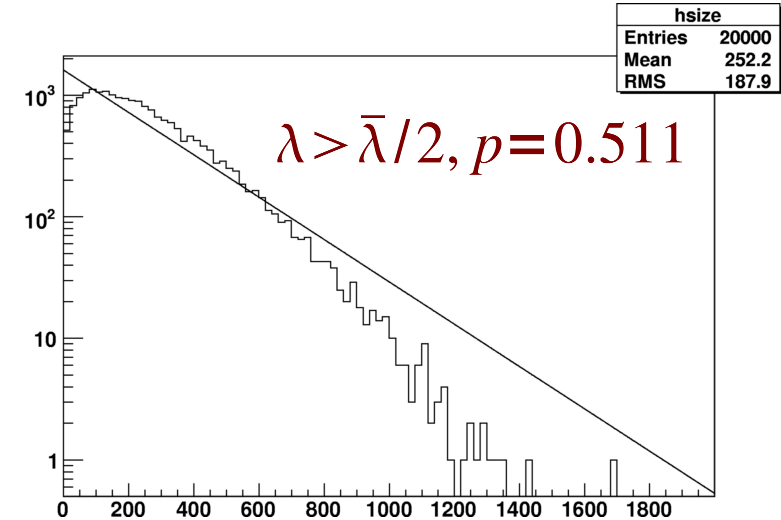
- Space charge affects ion back flow.

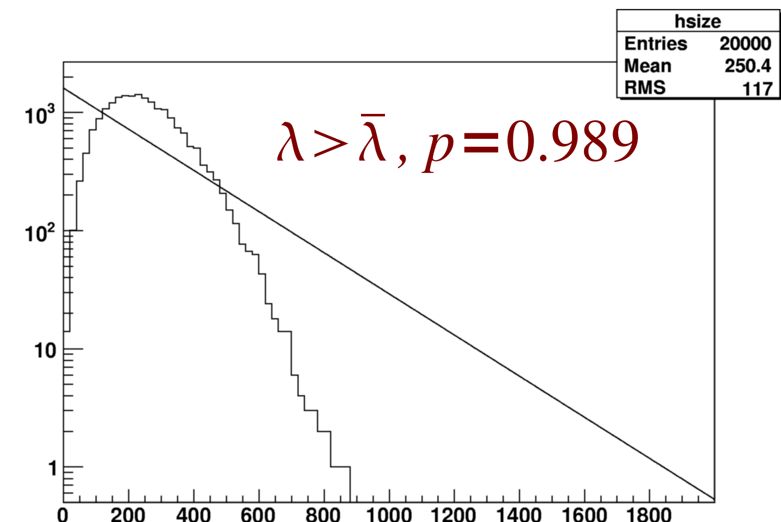
- Polyimide can contain mobile charges. These migrate through the plastic and modify the field.

# Minimum step length

- Exponential not affected by:
  - steps with an exponentially distributed length, nor
  - ionisation probability proportional to the length of the step,
- But ... a minimum step length for ionisation leads to radical changes.
- Illustrated here for a drift path with only 20 steps, $d = 20\bar{\lambda}$.

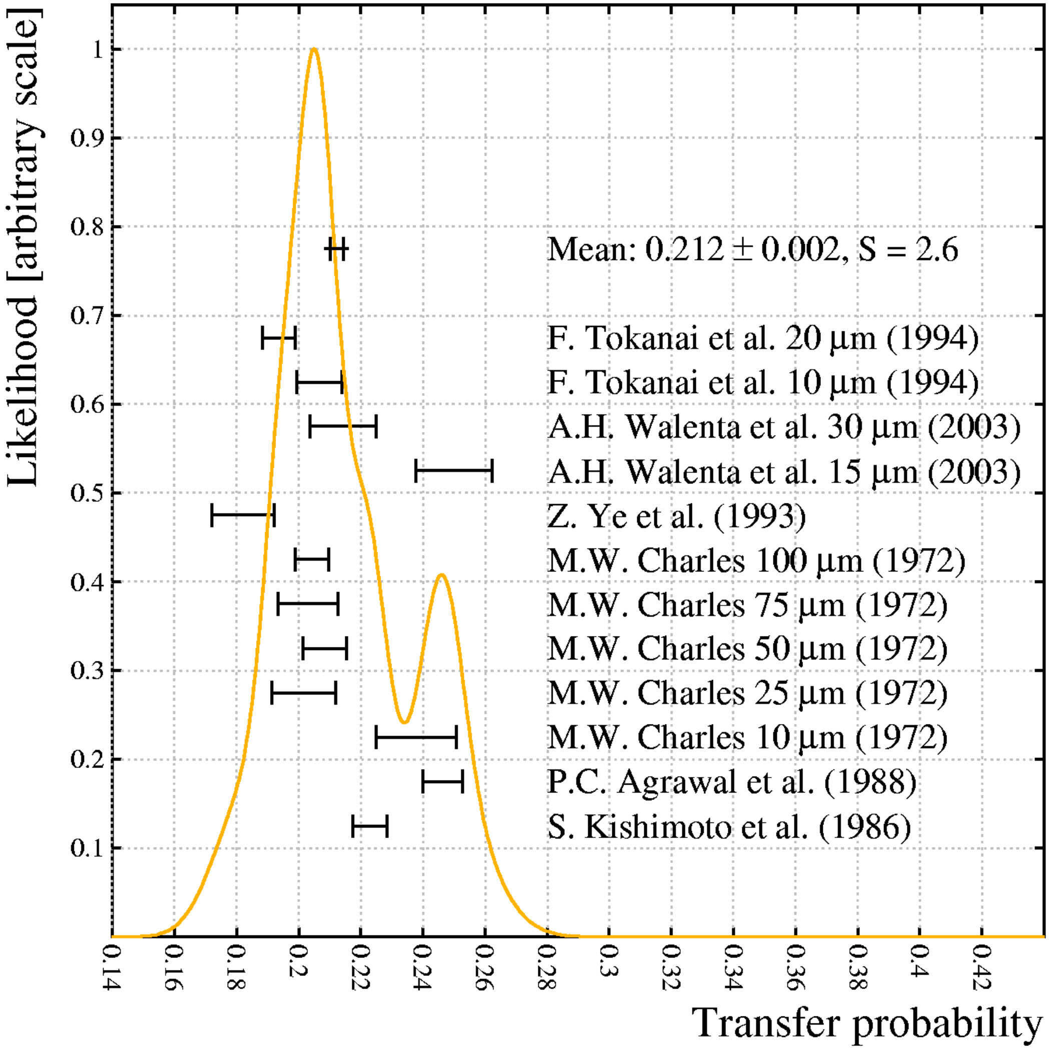


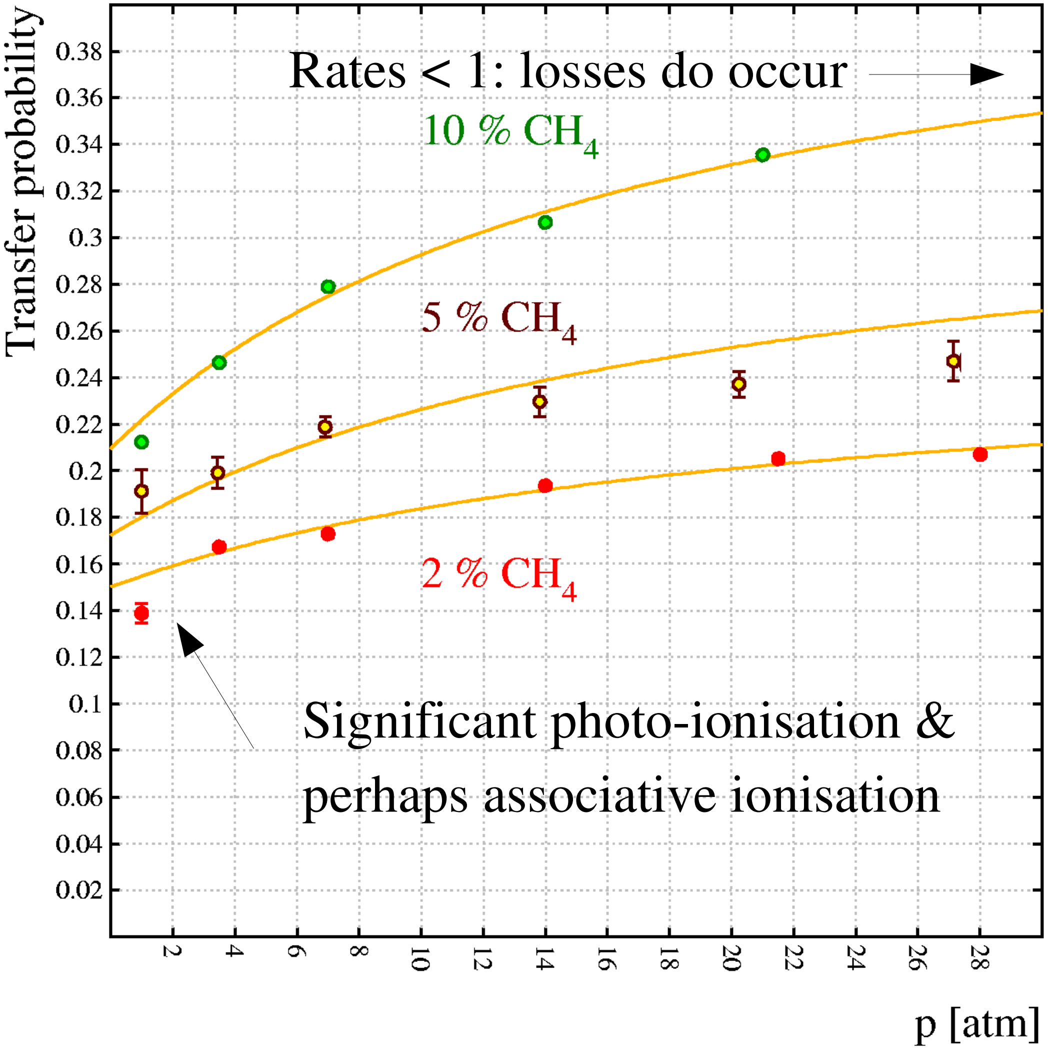



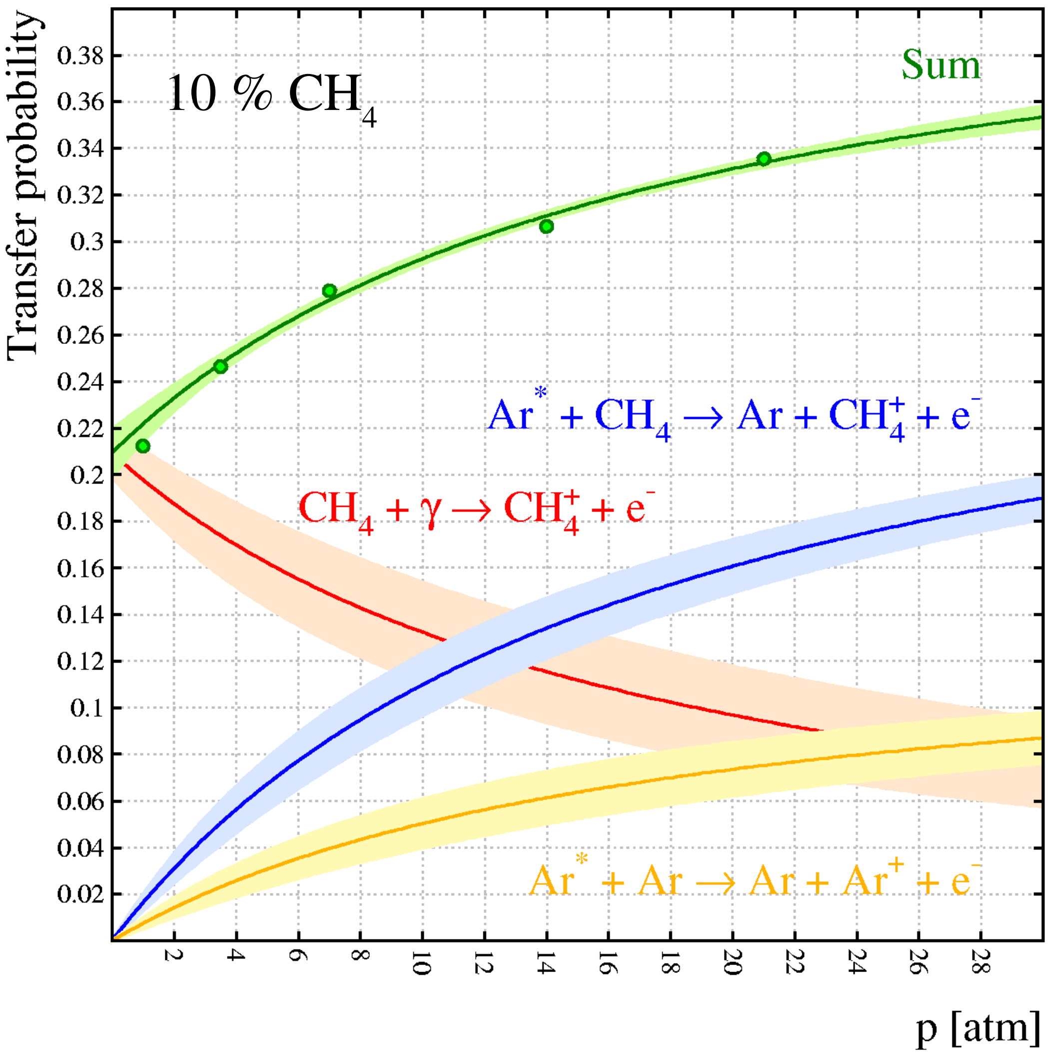
# Ar-$CH_4$

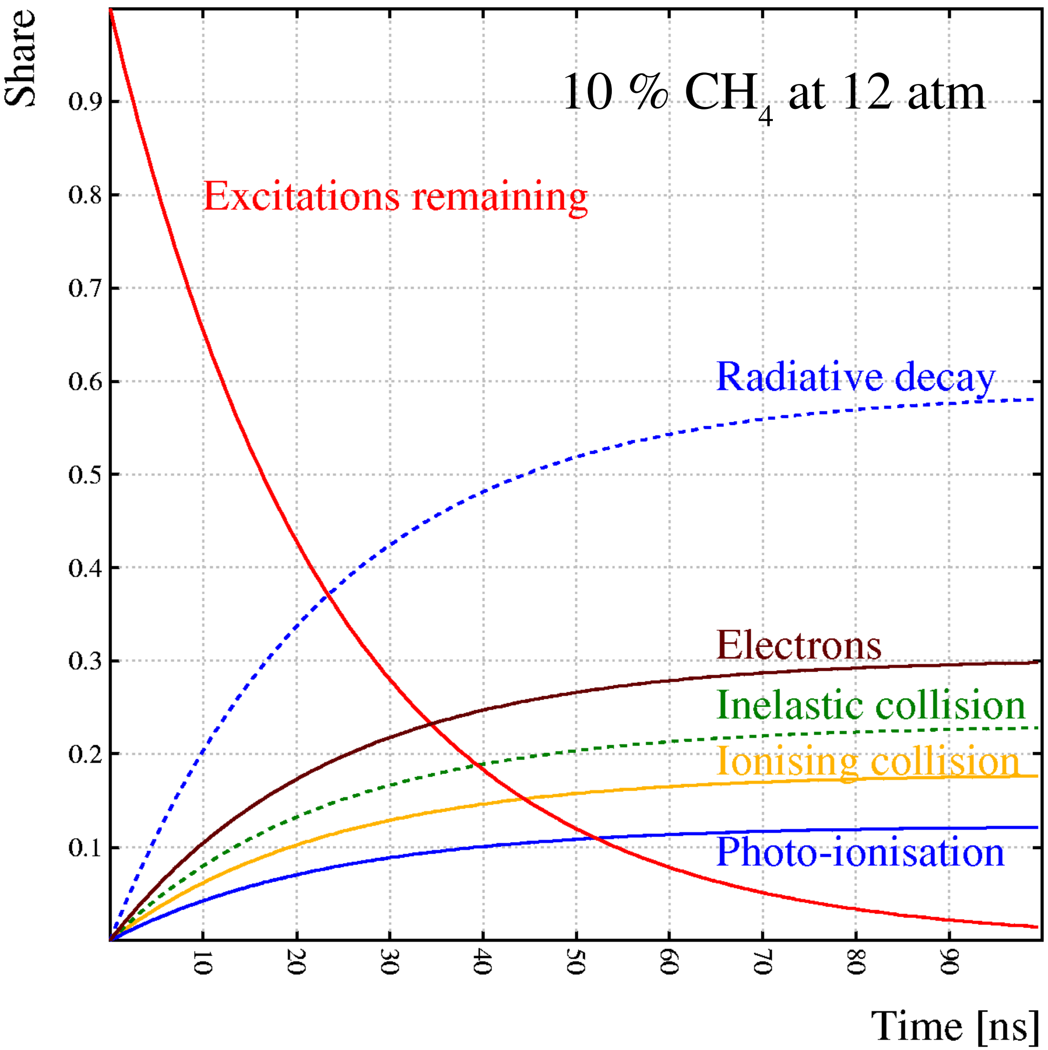
- Large numbers of gain curves are available.



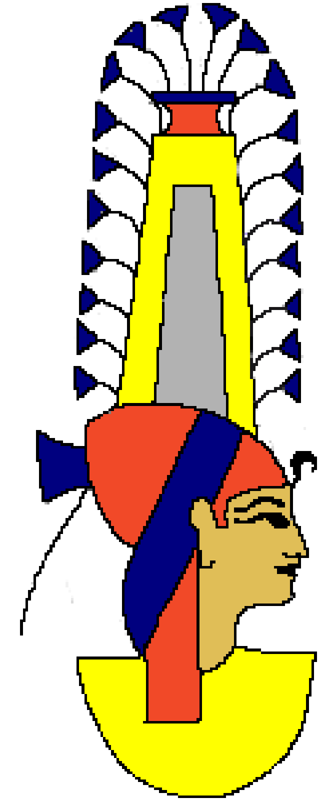



# Ar-$CH_4$: processes and timing



# Towards a faster neBEM



- Optimisation has made the program 75 % faster.
- Introduction of a “fast volume” where the field is
  - pre-computed on a mesh;
  - interpolated (finite element style).
- Outside, the field is computed as is done now.

| Drift field (V/cm) | Transparency Exact computation | Transparency Fast algorithm | Gain (RKF) Exact Computation | Gain (RKF) Fast algorithm |
|---|---|---|---|---|
| 200 | 99.835 | 99.864 | 250.133 | 250.139 |
| 400 | 99.669 | 99.471 | | |
| 750 | 96.364 | 95.774 | | |
| 1500 | 70.248 | 71.214 | | |
| 2000 | 59.669 | 58.791 | | |
| | Time taken for 500 electrons ~150 hours | Time taken for 20,000 electrons ~ 25 hours | Time ~ 40 minutes | Time ~ less than a minute |

# Level diagram argon and admixtures