RD51 open lectures – Tue Dec 12th

9:00 – 10:00 Electron transport
Electron multiplication

coffee

10:15 – 11:00 Electron multiplication fluctuations

coffee

11:15 – 12:00 Ion transport

lunch

Context

- Perhaps surprisingly, gas detectors all work according to much the same principles:
  - a charged particle passing through the gas ionises and excites some 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.

Gas-based detectors

electron transport

How do electrons move in a gas ?

- We'd like to know:
  - how fast the electrons move in the gas;
  - whether they follow the field;
  - whether they are absorbed;
  - how they produce secondaries.

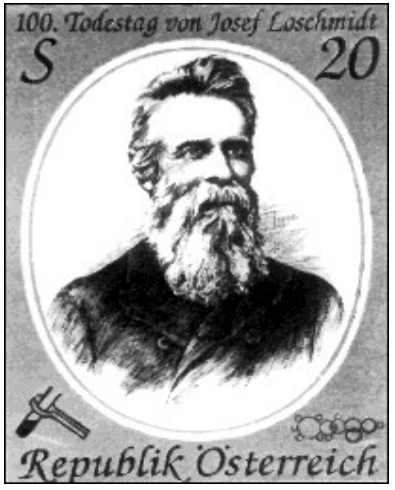
Amedeo Avogadro
(1776-1856)

Atoms per unit volume

- Number of Ar atoms in a cm³:
  - Avogadro's number: $6.022\ 10^{23}$ atoms/mole $\div$
  - atomic weight of Ar: 39.948 g/mole $\times$
  - density of Ar: $1.761\ 10^{-3}$ g/cm³ $\approx$
  - Loschmidt constant n_0: $2.652\ 10^{19}$ atoms/cm³ [CODATA]

[At 273.15 K and 10^5 Pa, IUPAC STP]

Josef Loschmidt
(1821-1895)



Amedeo Avogadro – 1811

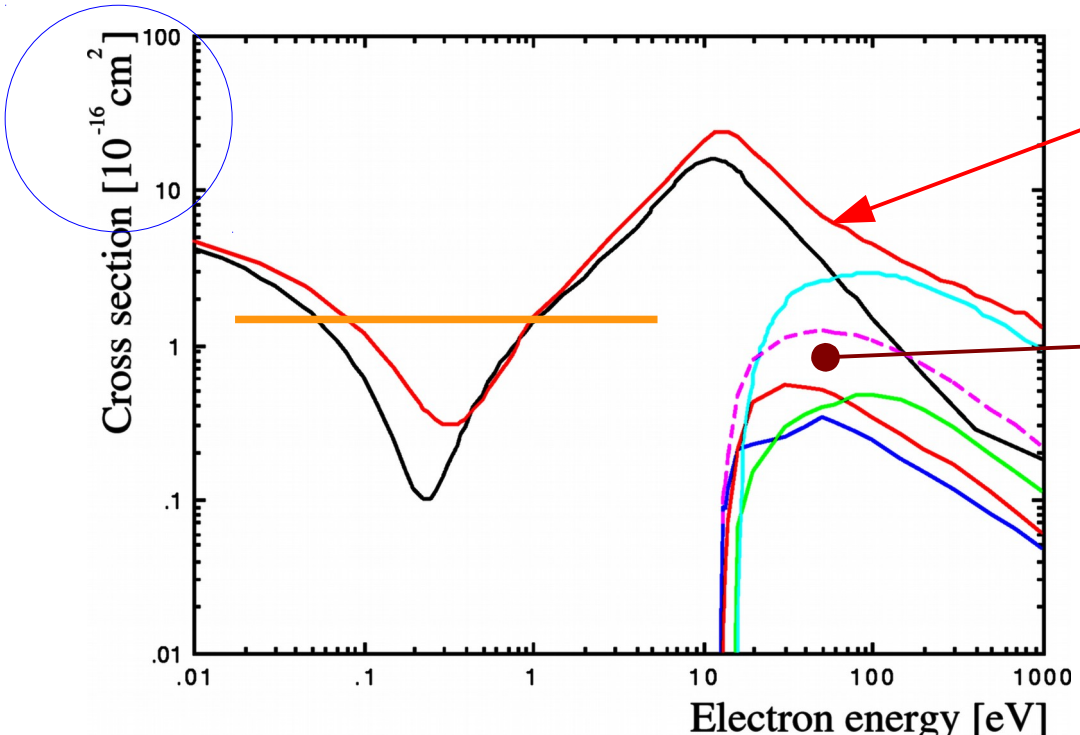
M. GAY-LUSSAC a fait voir dans un Mémoire intéressant (*Mémoires de la Société d'Arcueil*, tome II) que les combinaisons des gaz entre eux se font toujours selon des rapports très-simples en volume, et que lorsque le résultat de la combinaison est gazeux, son volume est aussi en rapport très-simple avec celui de ses composans; mais les rapports des quantités de substances dans les combinaisons ne paroissent pouvoir dépendre que du nombre relatif des molécules qui se combinent, et de celui des molécules composées qui en résultent. Il faut donc admettre qu'il y a aussi des rapports très-simples entre les volumes des substances gazeuses, et le nombre des molécules simples ou composées qui les forme. L'hypothèse qui se présente la première à cet égard, et qui paroît même la seule admissible, est de supposer que le nombre des molécules intégrantes dans les gaz quelconques, est toujours le même à volume égal, ou est toujours proportionnel aux volumes.

A. Avogadro, "Essai d'une manière de déterminer les masses relatives des molécules élémentaires des corps, et les proportions selon lesquelles elles entrent dans ces combinaisons", Journal de Physique, de Chemie et d'Histoire naturelle, LXXIII (1811) 58-76. (courtesy Bibnum)

Cross section of argon

Remember the unit:
1 Mb = 10^{-18} cm^2
100 Mb = 10^{-16} cm^2

- Cross section in a hard-sphere model:
  - Radius: ~70 pm
  - Surface: $\sigma = \pi(70\ 10^{-10}\,\mathrm{cm})^2 \approx 1.5\ 10^{-16}\,\mathrm{cm}^2 = 150\,\mathrm{Mb}$



Elastic cross section (total)

Excitations, ionisation, attachment

[Data: webelements.com
Plot: simplified Magboltz]

Mean free path in argon

- We know already that:
  - Cross section of 1 atom: $\sigma \approx 1.5\ 10^{-16}$ cm^2
  - Atoms per 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 σ 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.

MPGDs and the mean free path

- Recall:
  - Mean free path of electrons in Ar: 2.5 μm,

- Compare with:
  - Micromegas mesh pitch: 63.5 μm
  - GEM polyimide thickness: 50 μm
  - Micromegas wire thickness: 18 μm
  - GEM conductor thickness: 5 μm

- Hence:
  - mean free path approaches small structural elements;
  - such devices should be treated at a molecular level.

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 λ_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:

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

Drift velocity in argon

- Compare with a Magboltz calculation for pure argon:
  - *E* dependence is not too far off (although linear is more common at low fields),

    BUT

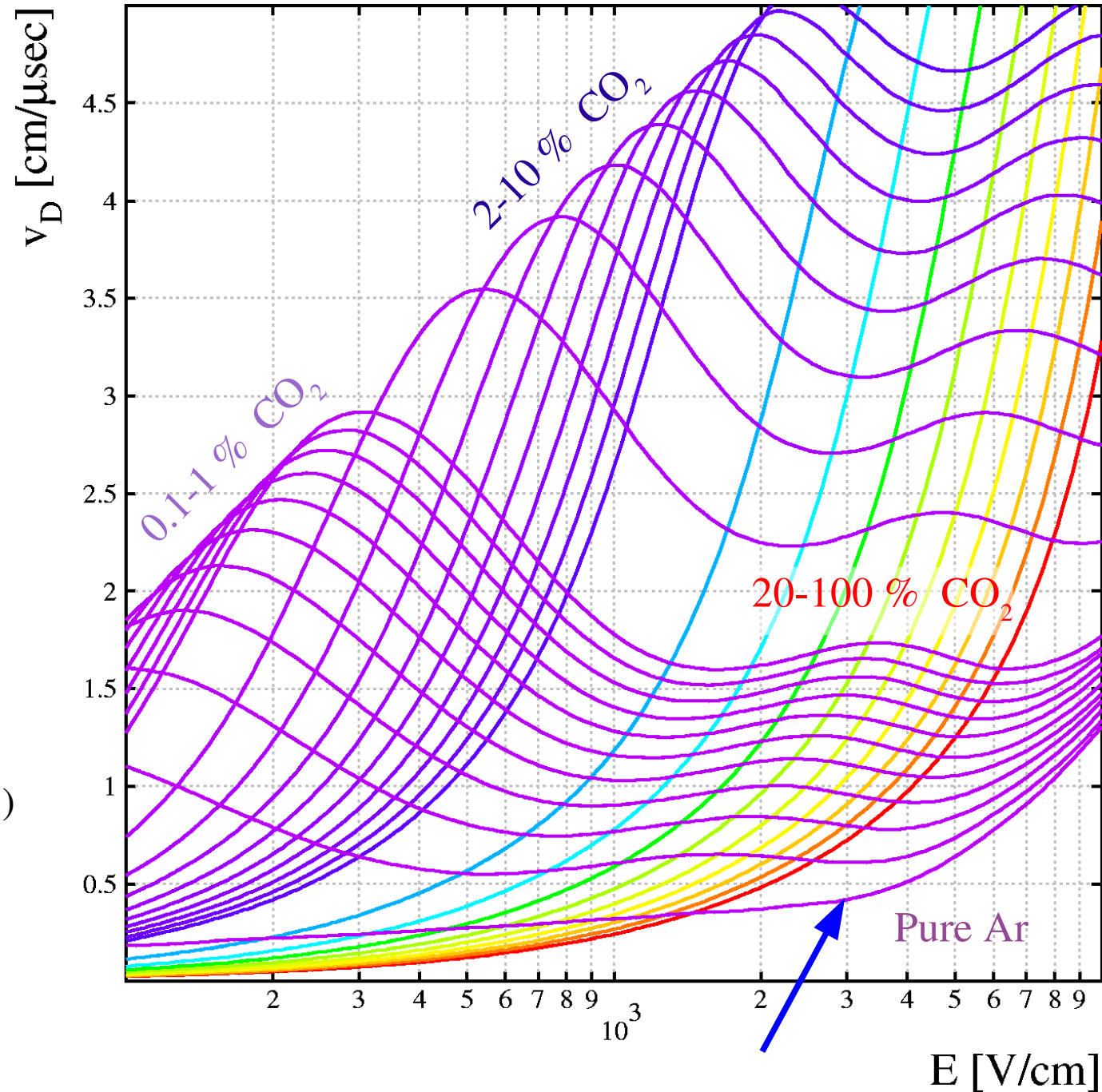
  - the velocity is *vastly* overestimated ! Magboltz finds a velocity that is *30 times* smaller ...

    WHY ?

Adding CO_2

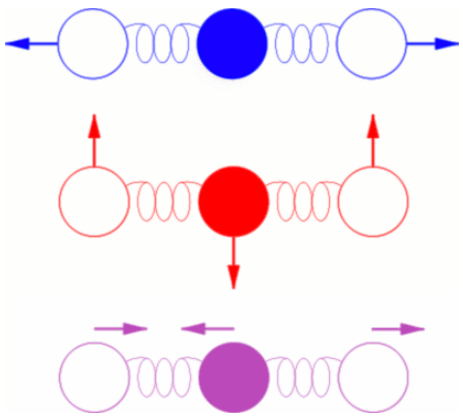
- CO_2 makes the gas faster, dramatically.
- Calculated by Magboltz for Ar/CO_2 at 3 bar.

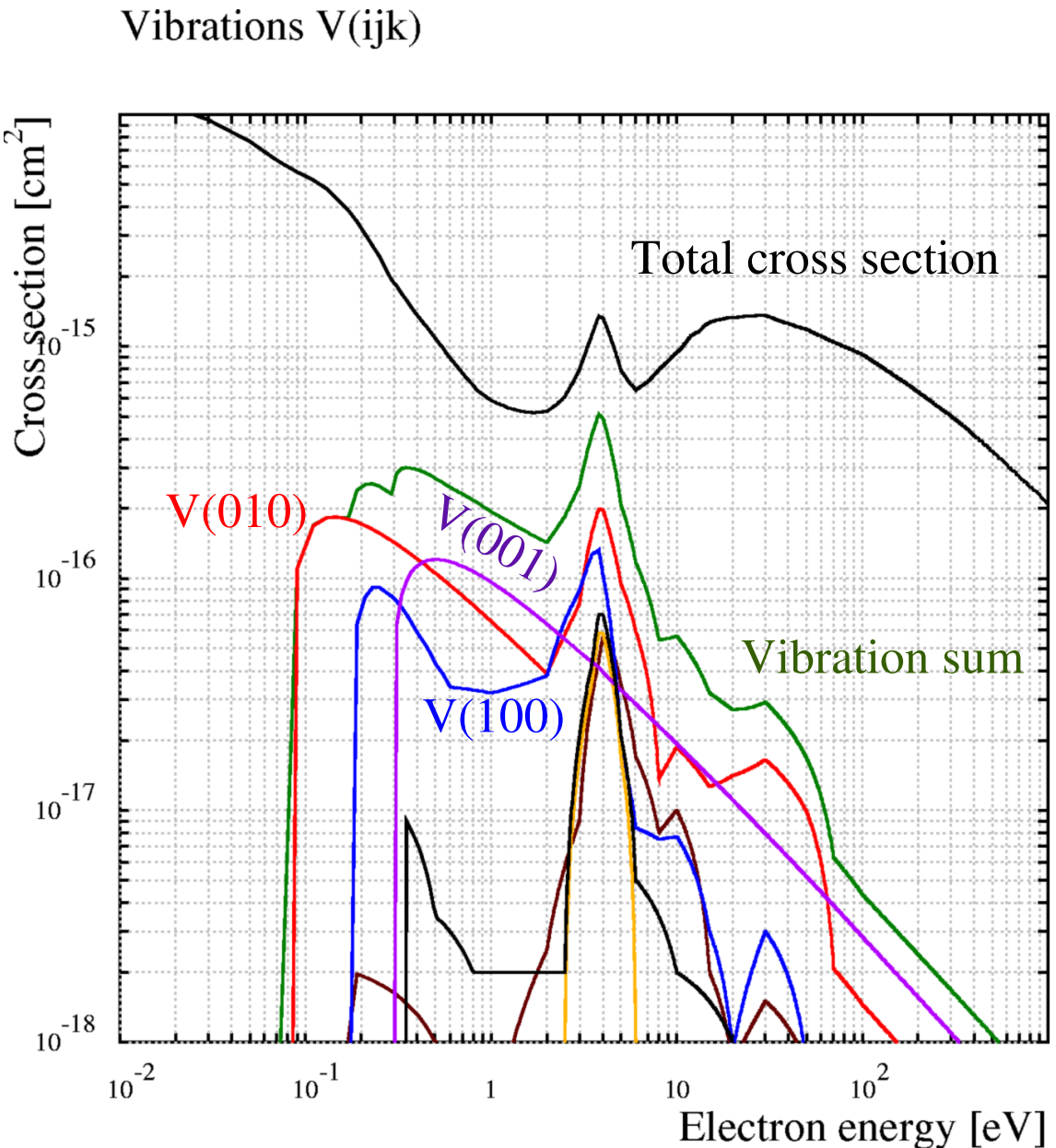
(Note where the arrow is !)



CO_2 – vibration modes

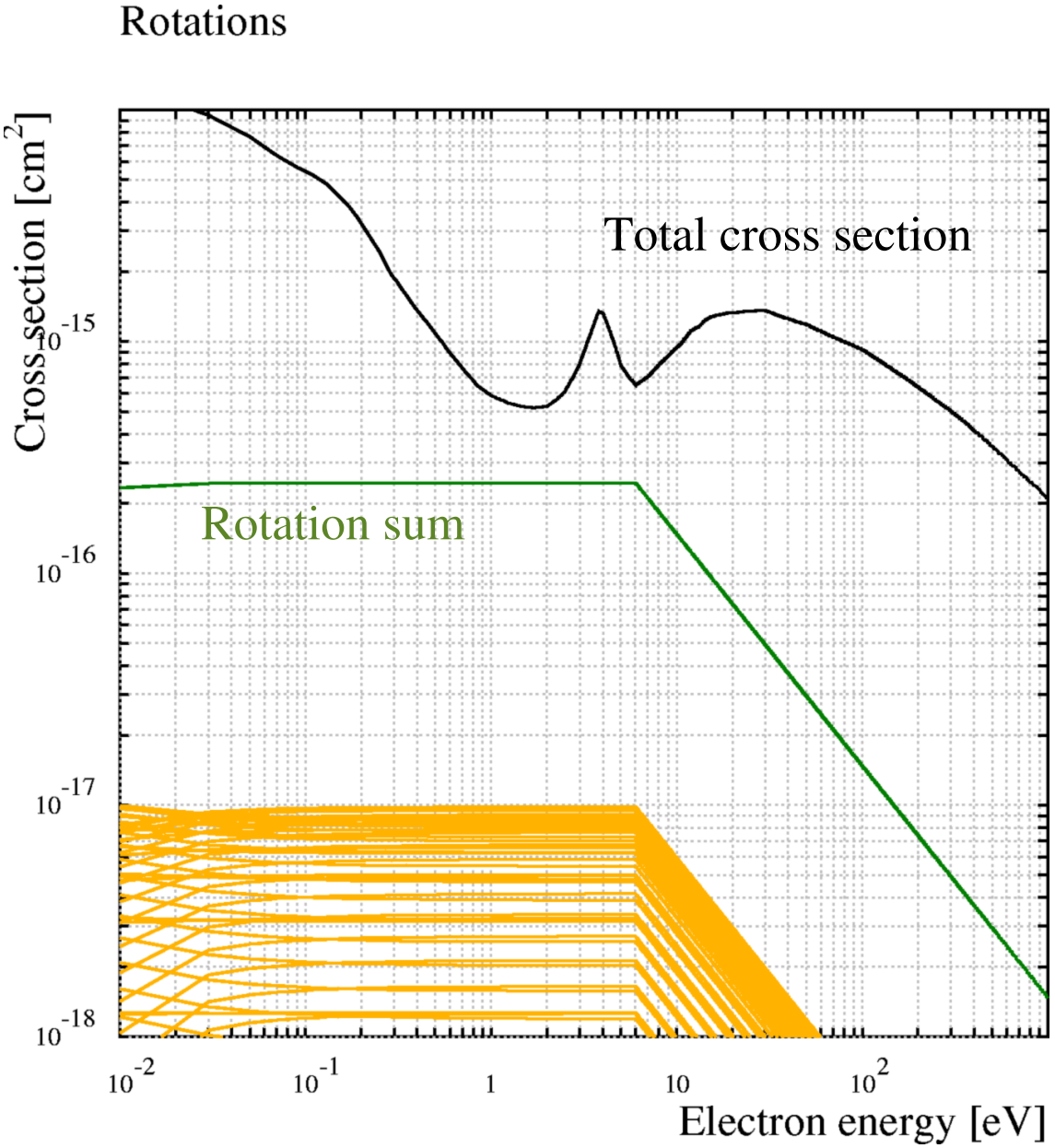
- CO_2 is linear:
  - O – C – O
- Vibration modes are numbered V(*ijk*)
  - *i*: symmetric,
  - *j*: bending,
  - *k*: anti-symmetric.





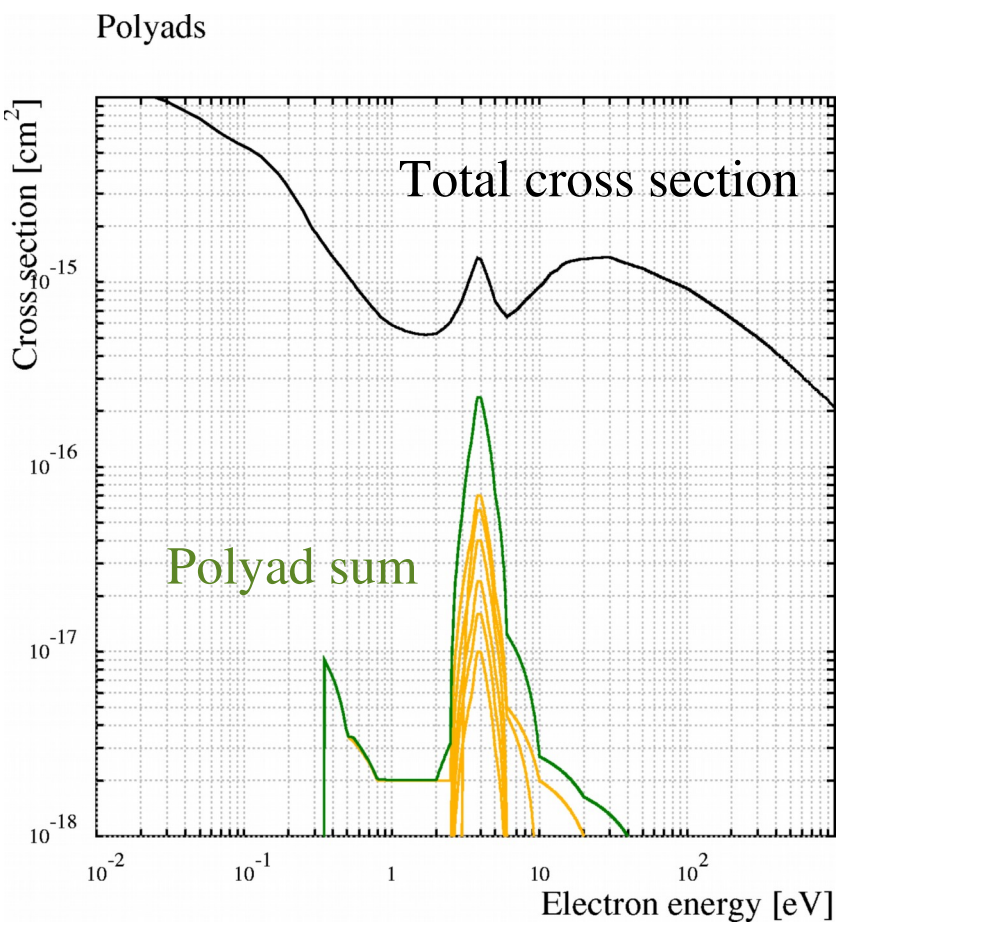
CO_2 – rotational modes

- Major cross section at an energy of ~1 eV.
- Implemented as pairs of inelastic and super-elastic terms.



CO_2 – polyads

- Fermi polyads:
  - Closely spaced vibrational & rotational levels which couple by overlap.
  - Magboltz separates polyads 3-9 and sums the higher ones.
- Cause energy loss.



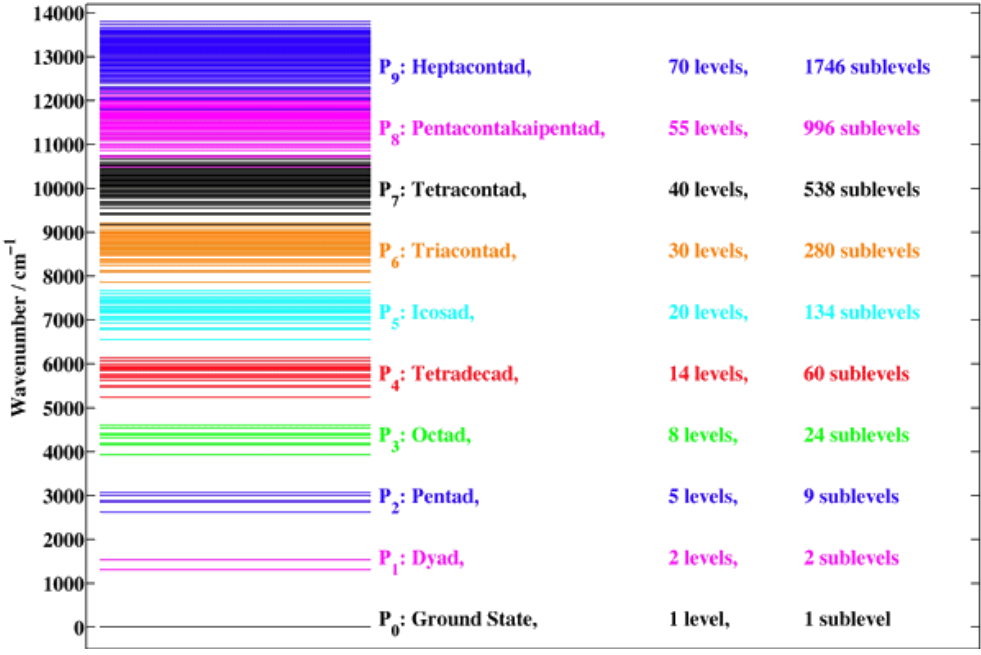
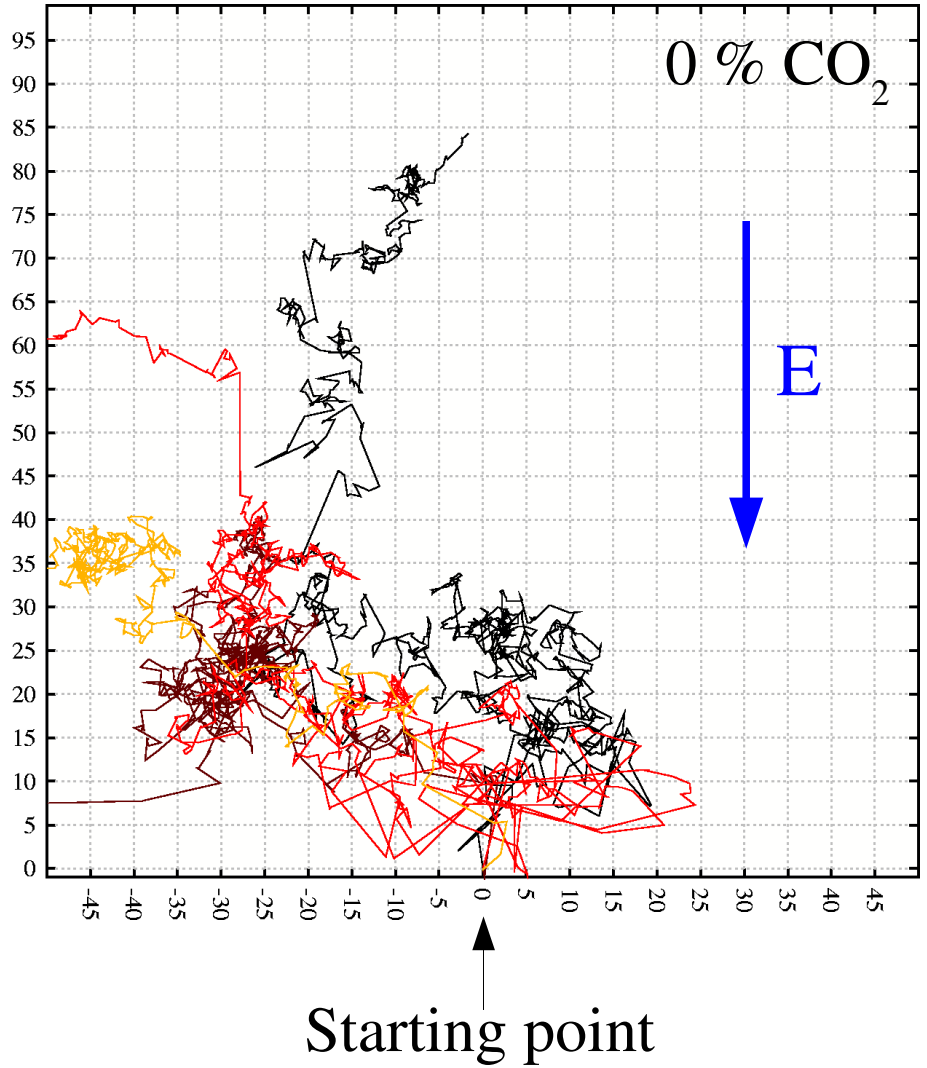
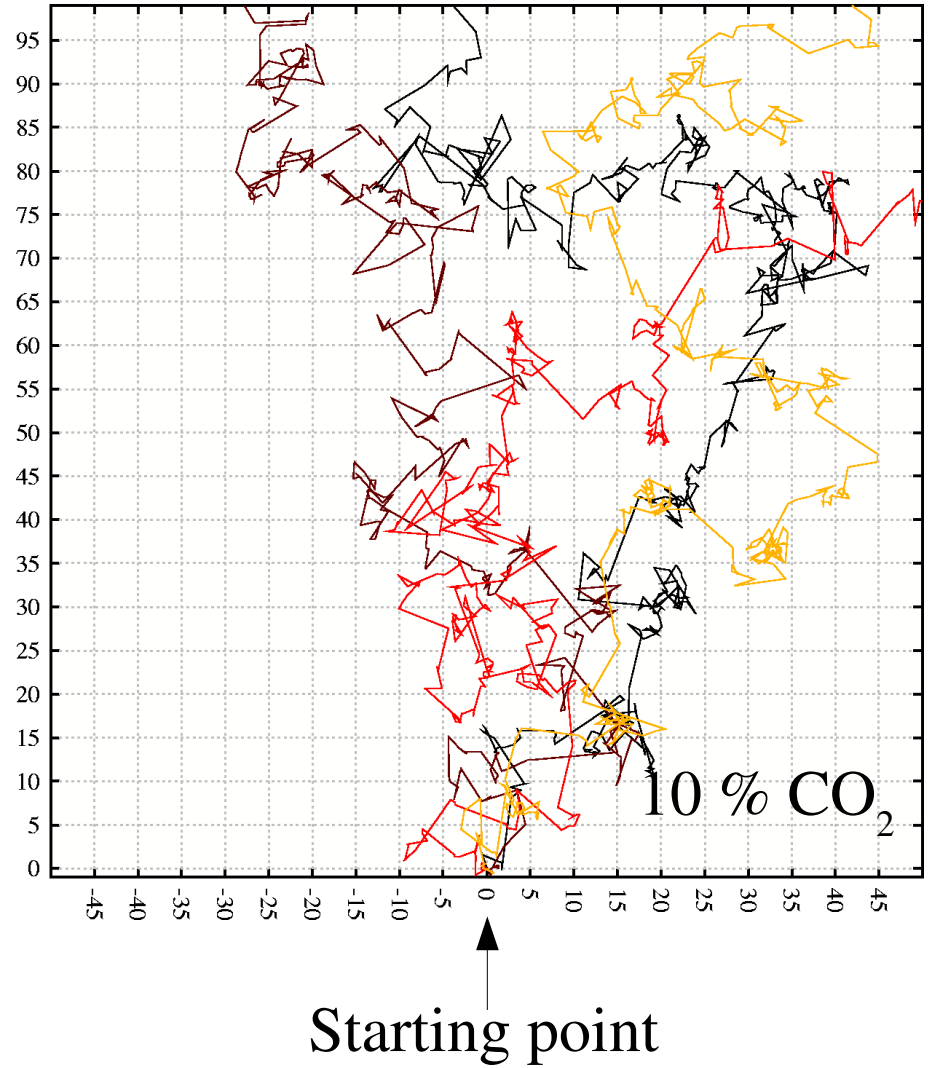


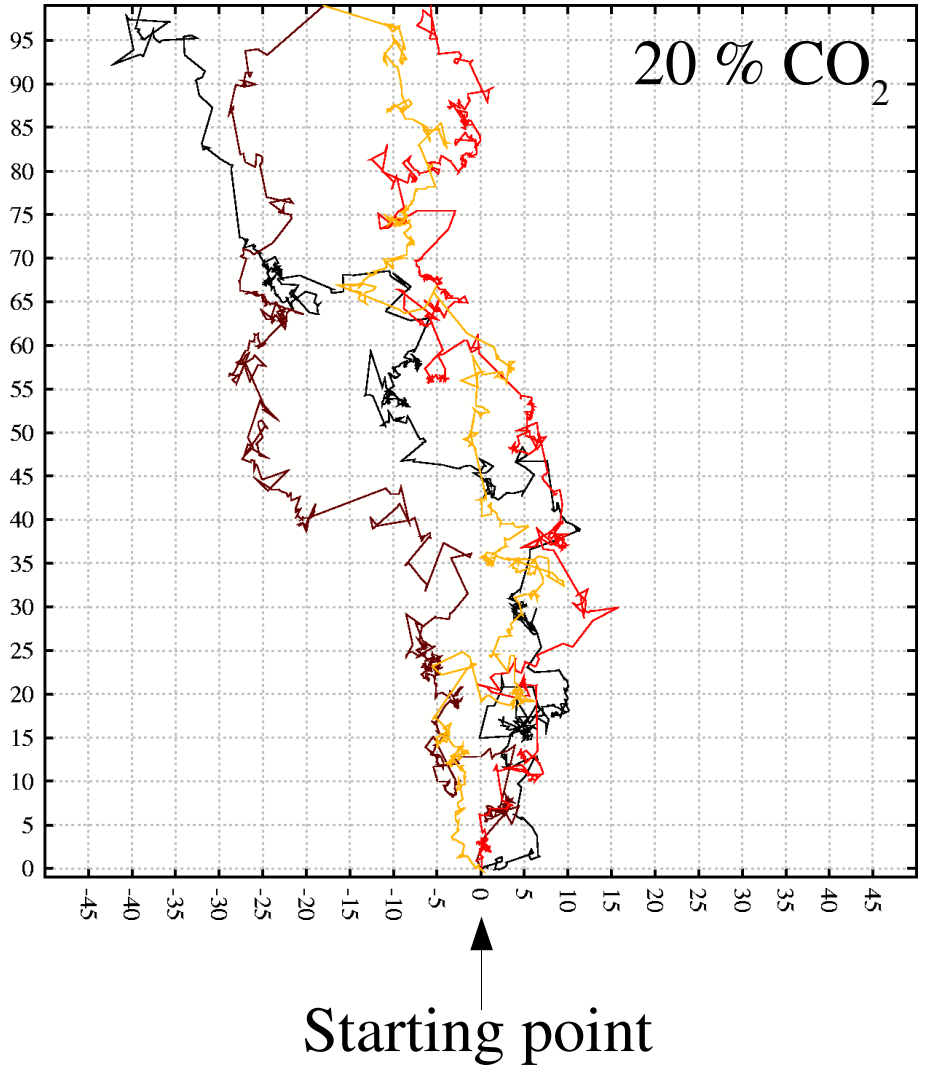
Illustration for CH_4
http://icb.u-bourgogne.fr/OMR/SMA/methane/

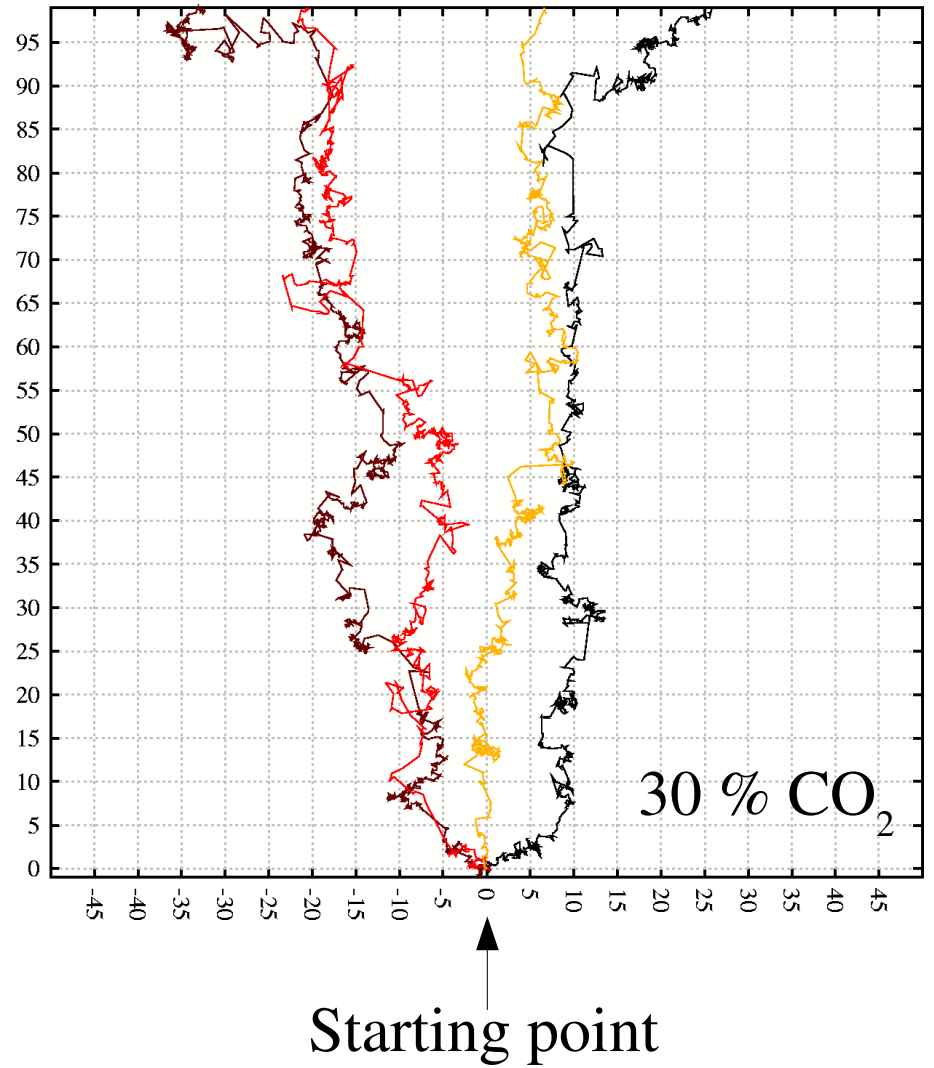
Electrons in Ar/CO_2 at E=1 kV/cm



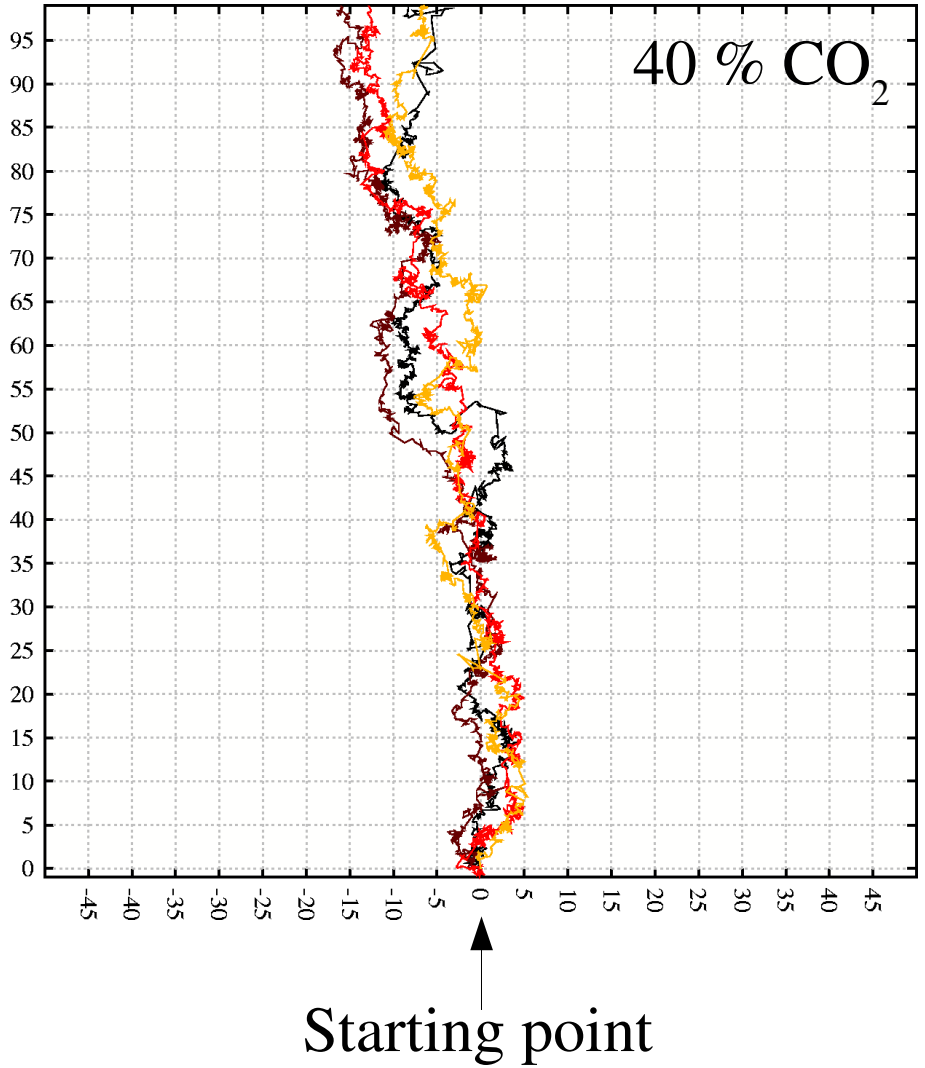


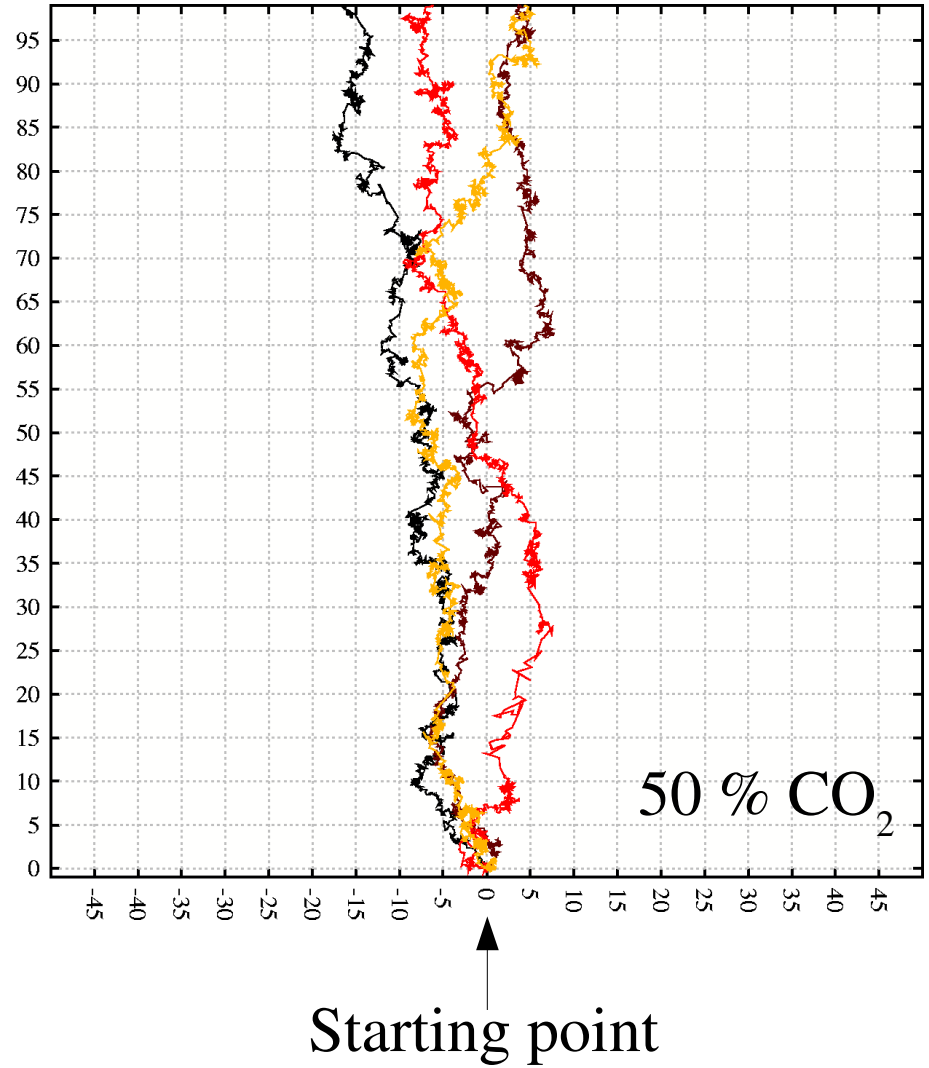
Electrons in Ar/CO_2 at E=1 kV/cm



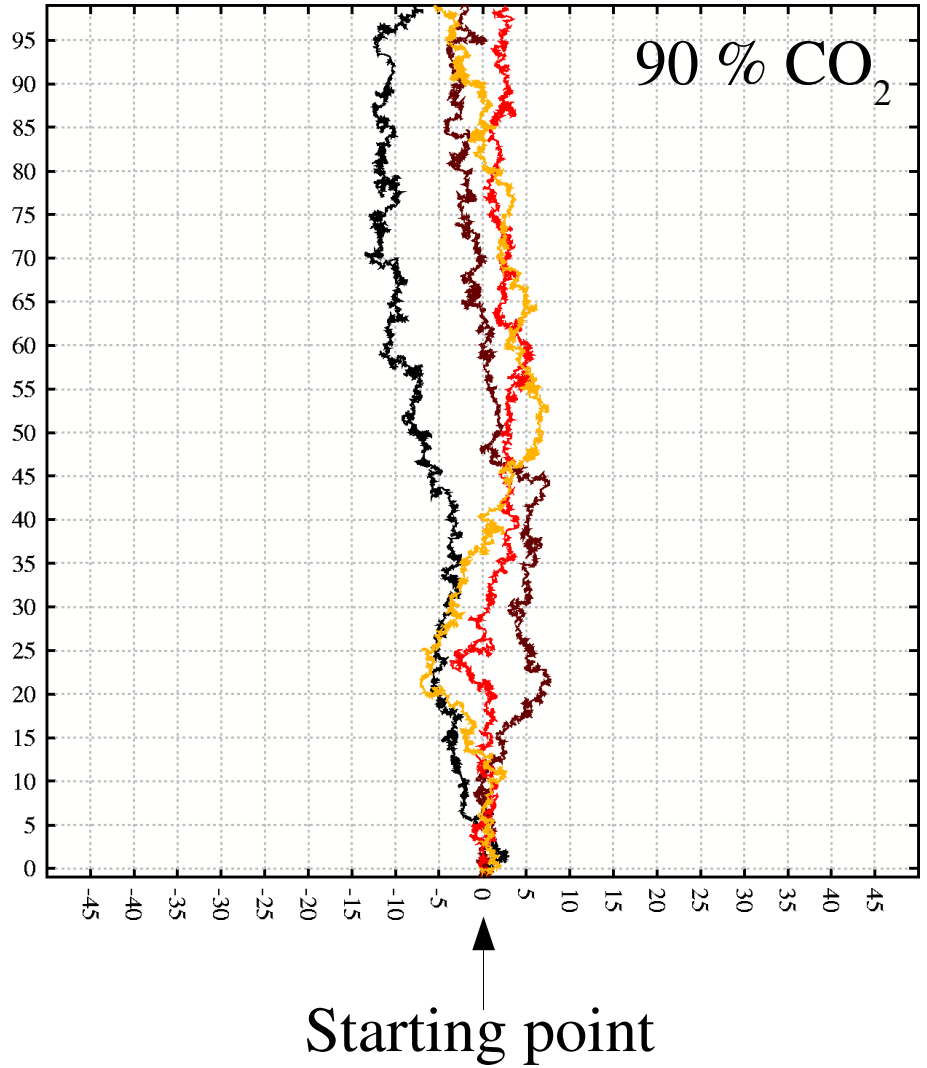


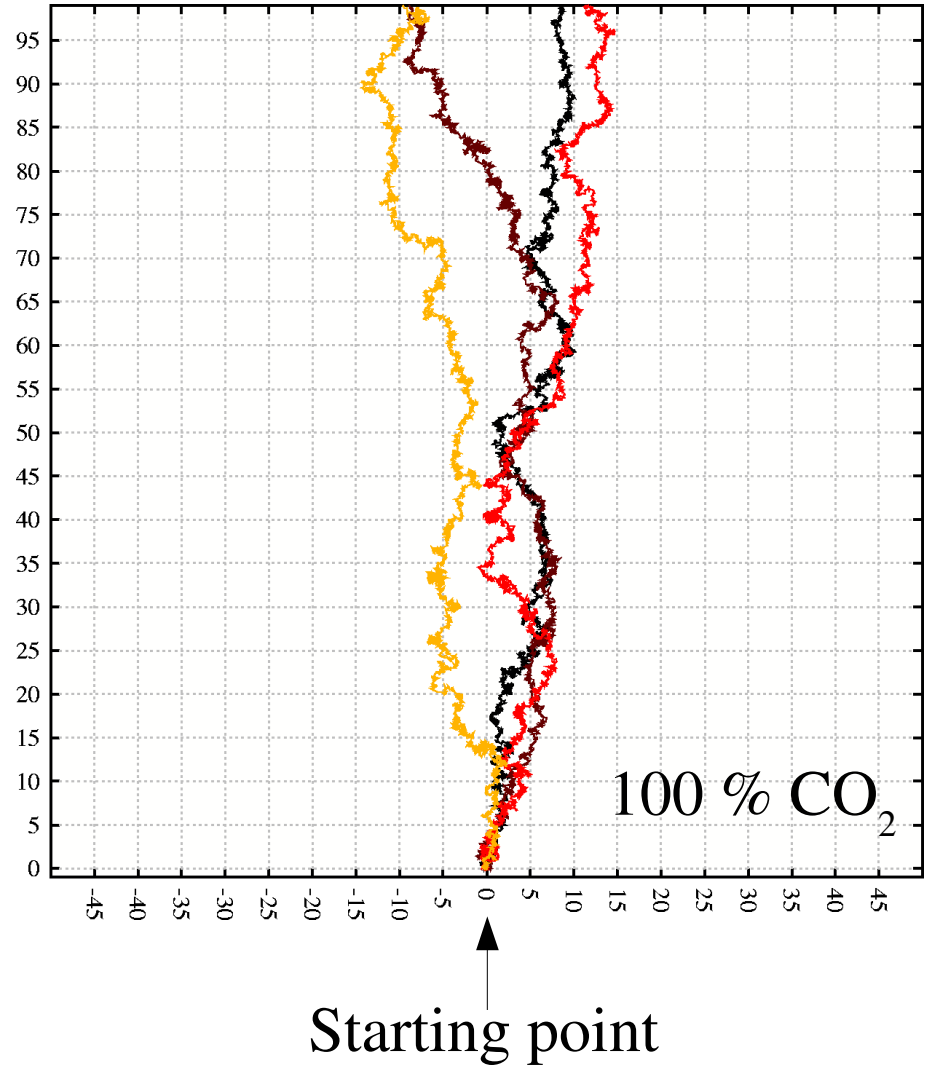
Electrons in Ar/CO_2 at E=1 kV/cm





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





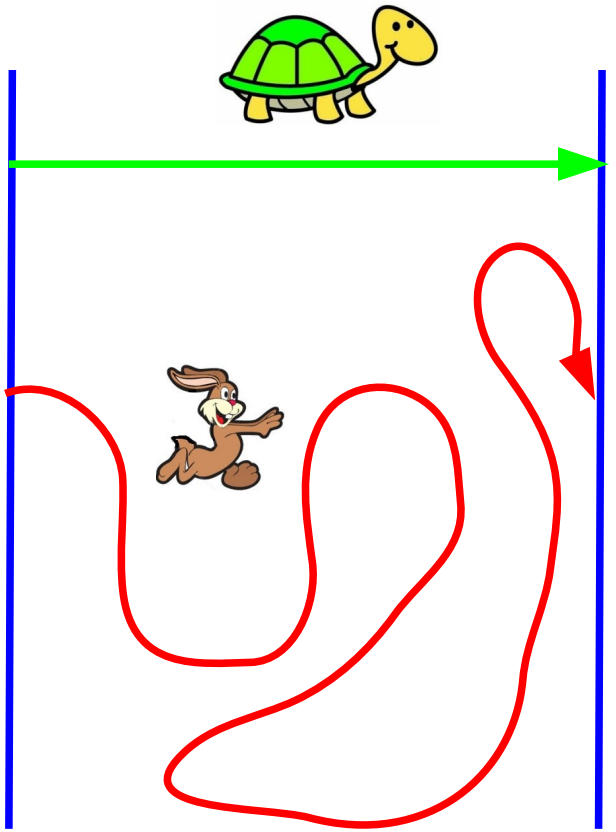
Drift velocity vs Mean velocity

- Drift velocity v_D:
  distance effectively traveled ÷
  time needed.

- Imagine they take equal time:

$$v_D = \bar{v}$$

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

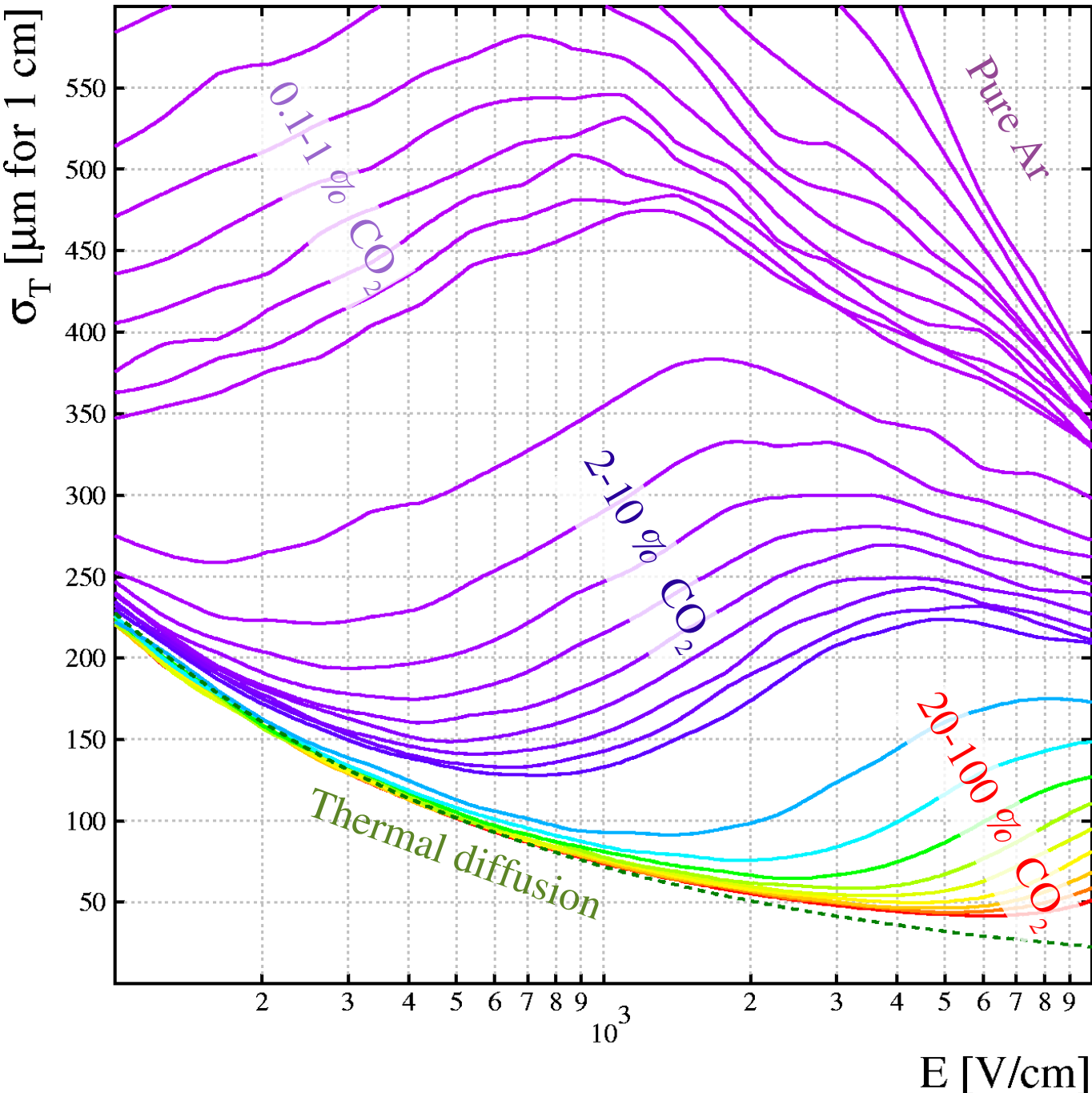


Diffusion

- The combination of a high velocity and low drift velocity implies that the electrons scatter a lot.
- Diffusion = RMS of the difference between the actual and the average movement
- In a homogeneous field, if the diffusion over 1 cm of drift is 200 μm, how large is the diffusion over 1 m ?

Adding CO_2

- Transverse diffusion is much reduced by CO_2.
- Calculated by Magboltz for Ar/CO_2 at 3 bar.

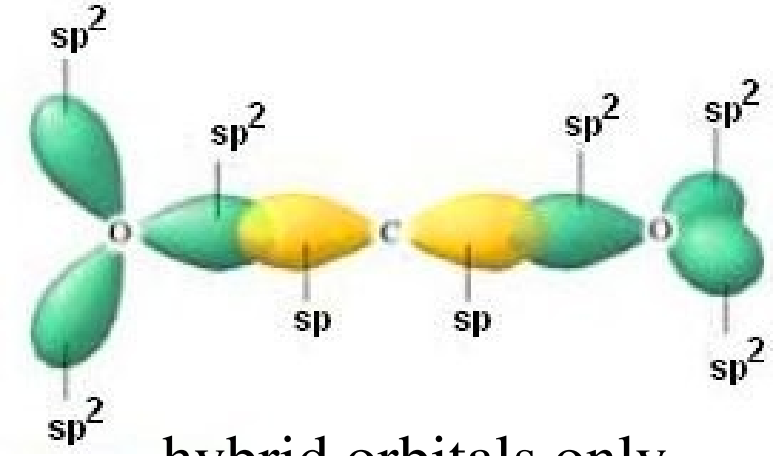


Attachment

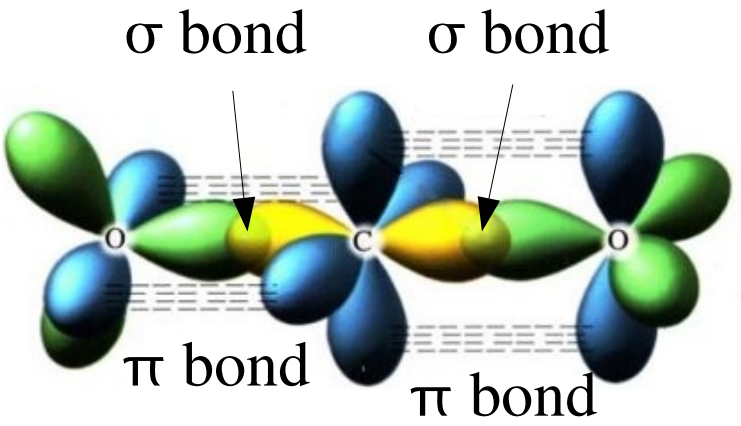
- Some of the quencher gases have the potential of attaching electrons.
- Examples include:
  - O_2: mostly 3-body O_2^- and at higher ϵ 2-body dissociative;
  - H_2O: $[H_2O]_n$ has positive electron affinity, H_2O does not;
  - CF_4: mostly dissociative F^- + CF_3, F + CF_3^- (below 10 eV);
  - SF_6: SF_6^- up to 0.1 eV, $\sigma=10^{-18}$ cm^2, 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



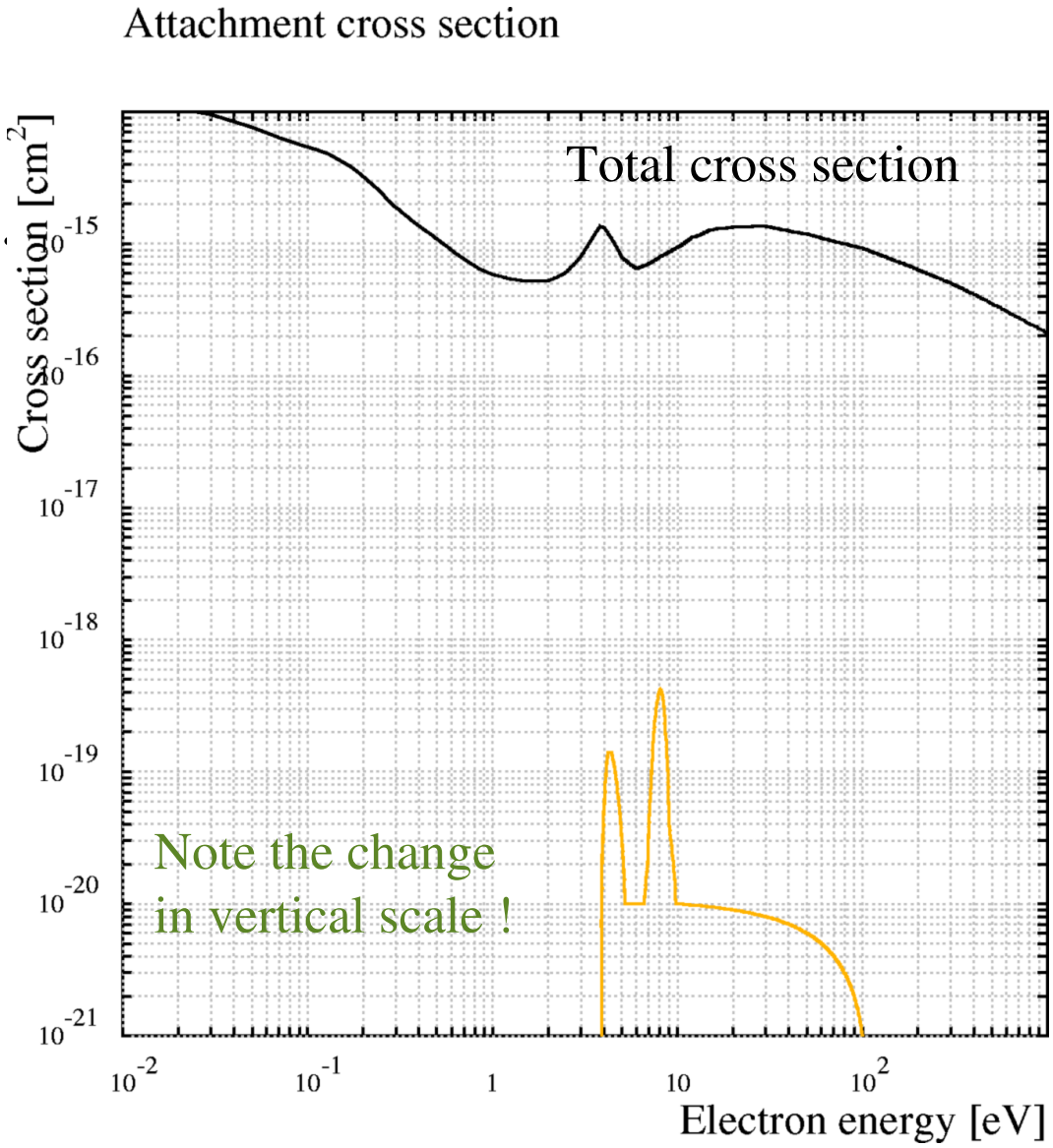
[Source: presumably SS Zumdahl, Chemistry (1983) DC Heath and Company.]

CO_2 – dissociative attachment

- CO_2 has a tiny attachment cross section at low energy.
- The 4 eV peak is linked to a short-lived $^2\Pi_u$ shape resonance which decays $e^- CO_2 \rightarrow CO + O^-$;

[A. Moradmand et al. (2013) 10.1103/PhysRevA.88.032703]

- the 8.2 eV peak is thought to be a Feshbach resonance.



Feshbach and Shape resonances

- Feshbach: e^- attached to electronically excited CO_2^* states of the neutral CO_2 molecule.
- Shape: e^- trapped within barrier.

[E. Leber et al., Eur. Phys. J. D **12** (2000) 125-131]

Calculating transport properties

- One can of course measure every mixture one needs …
- … but it would be far more efficient if one could compute the transport properties of arbitrary mixtures.

1935: Electron energy distribution

- Calculation of the electron energy distribution
  - allowing for energy loss in elastic collisions;
  - detailed balancing of energy and momentum gain (E-field, diffusion) and loss (elastic collision);
  - velocity dependent cross section;
  - use of Legendre expansion (crediting H.A. Lorentz, 1916):

$$f(x, v, \omega) = f_0(x, v) + P_1(\cos\omega) f_1(x, v) + P_2(\cos\omega) f_2(x, v) + \cdots$$
$$= f_0(x, v) + (\xi/v) f_1(x, v) + \cdots .$$

(P_1, P_2: Legendre polynomials)

The function f_0 determines the random distribution in velocity, and f_1 determines the electron drift. The higher terms in the series are nearly always very small and do not correspond to any simple physical property of the distribution, but serve simply to improve the form of the distribution function.

[Philip M. Morse, W.P. Allis and E.S. Lamar, *Velocity Distributions for Elastically Colliding Electrons*, Phys. Rev. **48** (1935) 412–419]

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.]

1980s: Higher moments, high precision

- Expansion in spherical harmonics;
- An accuracy of 1 % (and better) becomes routine.

The starting point for most theoretical work is the Boltzmann equation for the electron velocity distribution function, $f(\mathbf{r}, \mathbf{v}, t)$. The latter is formally expanded in a series of spherical harmonics,

$$f(\mathbf{r}, \mathbf{v}, t) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} f_{lm}(\mathbf{r}, v, t) Y^{\dagger}_{lm}(\hat{\mathbf{v}}), \qquad (1)$$

where $Y_{lm}(\hat{\mathbf{v}}) \equiv Y_{lm}(\theta, \phi) = P_l^{|m|}(\cos\theta)\, e^{im\phi}$, and θ, ϕ denote the polar angles of the unit velocity vector $\hat{\mathbf{v}}$ in some frame of reference.

S.L. Lin, R.E. Robson and E.A. Mason, *Moment theory of electron drift and diffusion in neutral gases in an electrostatic field,* J. Chem. Phys. **71** (1979) 3483-3498 (the "LRM" paper).

R.E. Robson and K.F. Ness, *Velocity distribution function and transport coefficients of electron swarms in gases: Spherical-harmonics decomposition of Boltzmann's equation*, Phys. Rev. A **33** (1986) 2068–2077.

K.F. Ness and R.E. Robson, *Velocity distribution function and transport coefficients of electron swarms in gases. II. Moment equations and applications*, Phys. Rev. A **34** (1986) 2185–2209.

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,
    - 6 excited states and
    - 3 ionisations.
  - noble gases (He, Ne, Ar, Kr, Xe):
    - elastic scattering,
    - 44 excited states and
    - 7 ionisations (Ar^+, Ar^{++}, Ar^{+++}, Ar_{L1}, Ar_{L2}, Ar_{L3}, Ar_K).

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/]

LXcat people

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

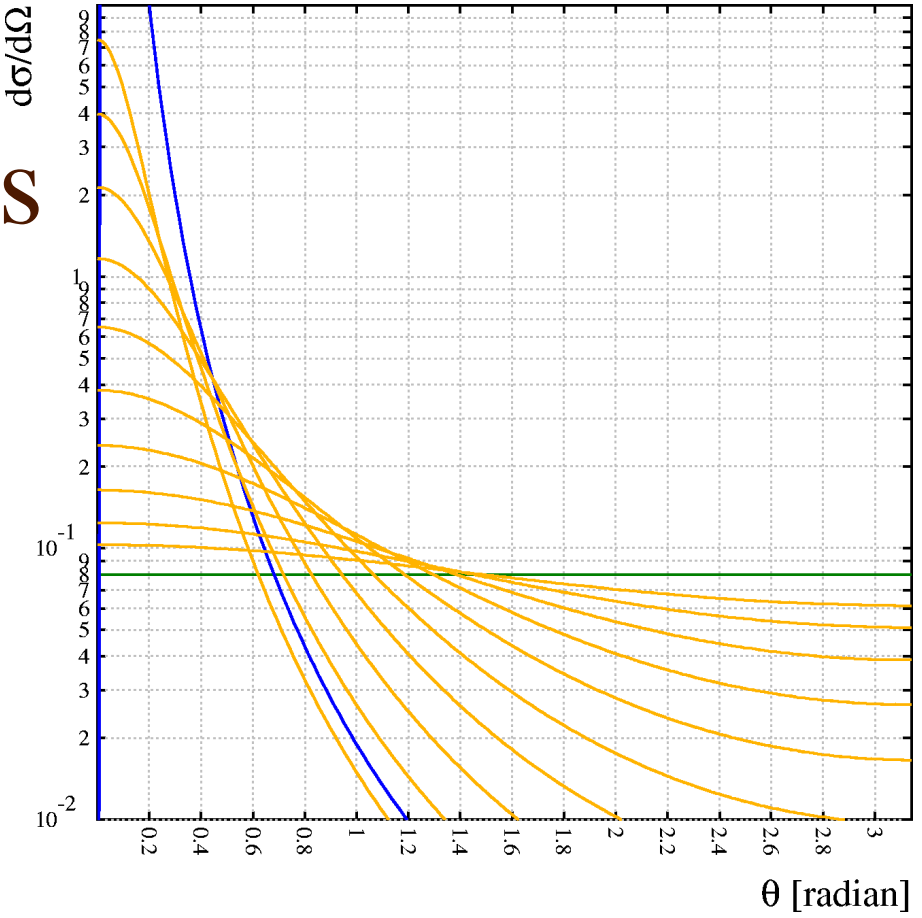
Art Phelps

Leanne Pitchford

Michael Allan

Klaus Bartschat

Simple cross sections



- Hard-sphere scattering:

$$\frac{d\sigma}{d\Omega} = \frac{r^2}{4}$$

- Coulomb scattering:

$$\frac{d\sigma}{d\Omega} = \frac{1}{\sin^4(\theta/2)}$$

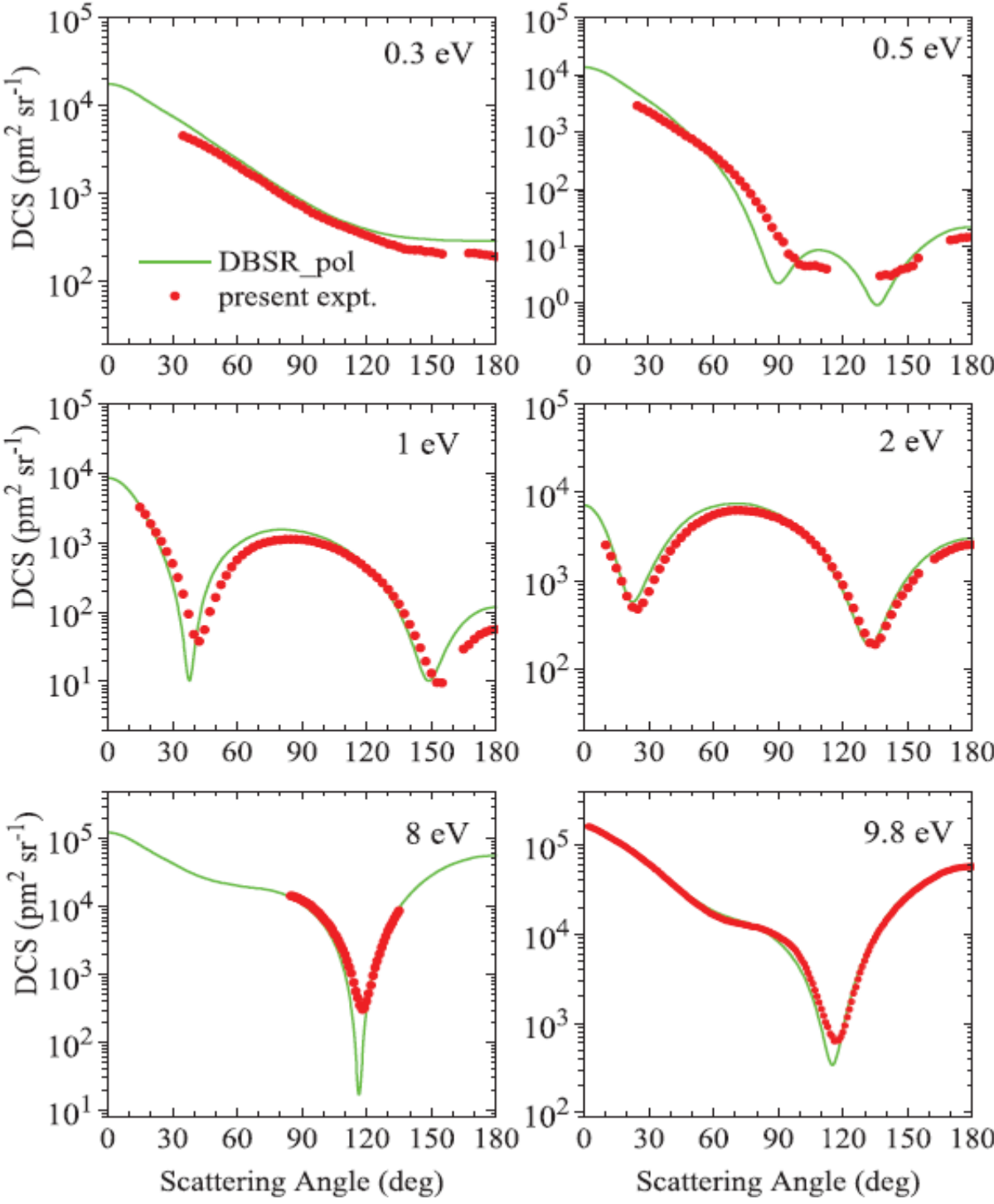
- Screened Coulomb scattering, 1st Born approximation:

$$\frac{d\sigma}{d\Omega} = \frac{1}{4\pi} \frac{1+8\epsilon/\epsilon_0}{(1+4\epsilon/\epsilon_0 - 4\epsilon/\epsilon_0 \cos\theta)^2}, \qquad \epsilon_0 = 27.21\,\text{eV}$$

Krypton data

- From a joint study with high-precision data and a theoretical model.

[O. Zatsarinny et al. (2011) 10.1103/PhysRevA.83.032713]



Reason for structure

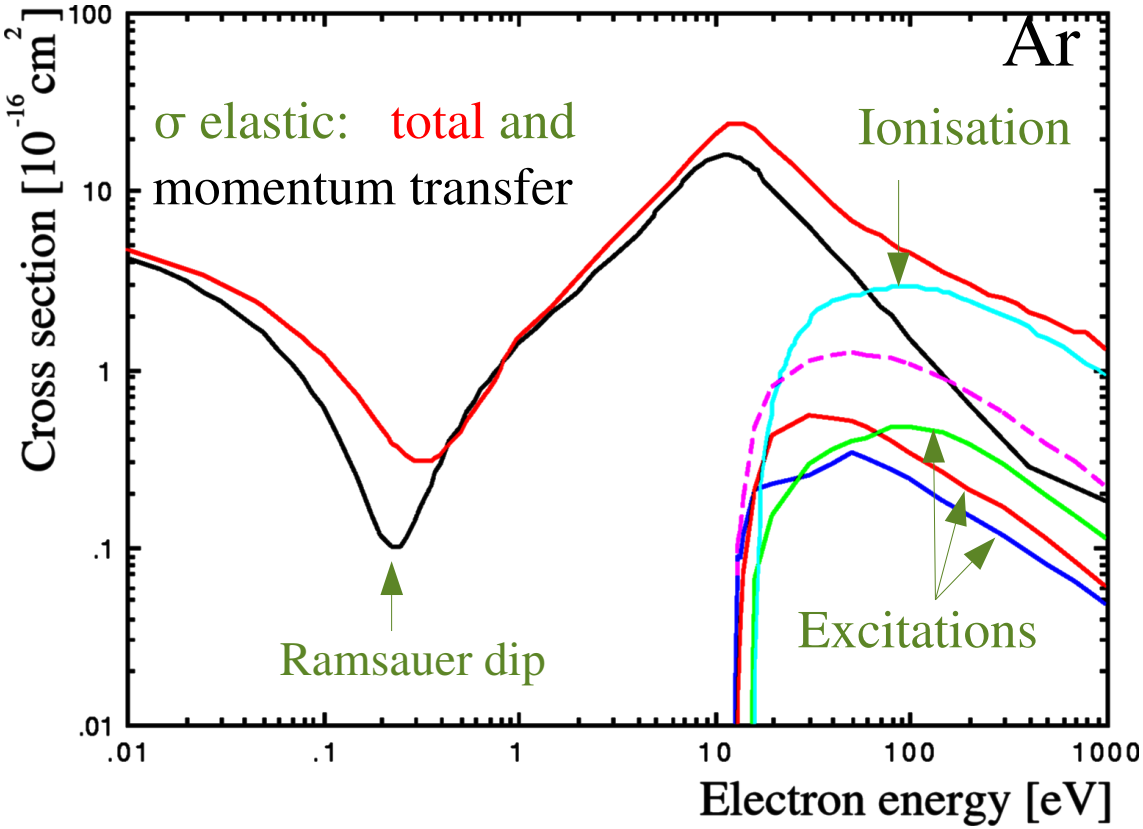
- Elastic Scattering:
  "Away from Feshbach resonances, the most important effect for elastic scattering is the polarization of the target by the projectile."

- "[...] DBSRpol model only included the $4s^2\ 4p^6$ ground state with total electronic angular momentum $J = 0$ and a single pseudostate with $J = 1$ [...]"

[O. Zatsarinny, K. Bartschat and M. Allan 10.1088/1742-6596/388/1/012008]

Energy dependence of e^- scattering

- Elastic scattering:
  - dominant contribution for much of the energy range that concerns us;
  - only term < 15.7 eV (ionisation threshold).
- Non-trivial structure:
  - Ramsauer dip.



Carl Wilhelm Ramsauer
(1879-1955)

Ramsauer effect

- so ist damit bewiesen, daß die Verminderung des Wirkungsquerschnitts mit abnehmender Elektronengeschwindigkeit *eine Erhöhung der völlig freien Durchlässigkeit* des Atoms bedeutet.

  Diese Erscheinung läßt sich in Zusammenhang mit der Quantelung der Energiewirkung des Atoms bringen,

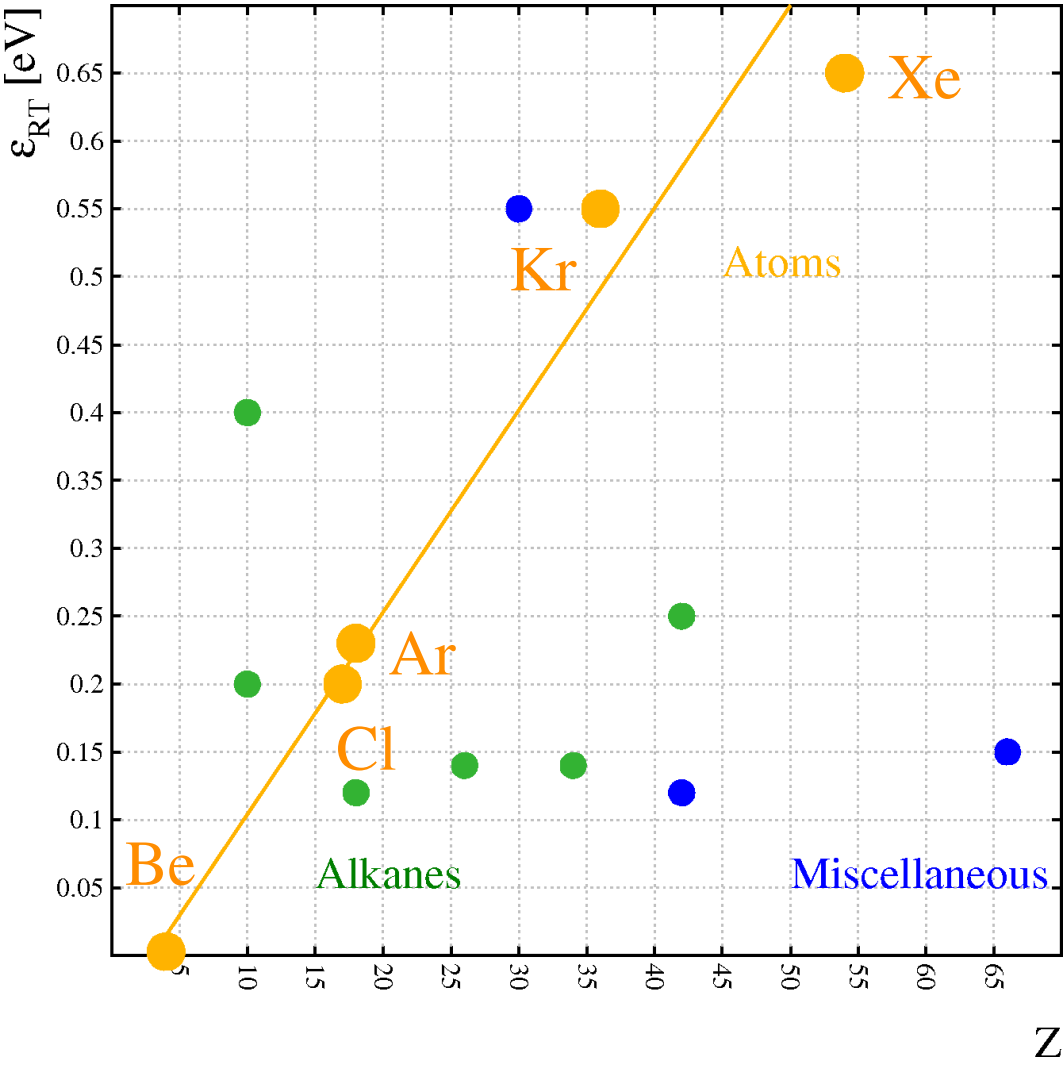
- [Carl Ramsauer, "Über den Wirkungsquerschnitt der Gasmoleküle gegenüber langsamen Elektronen," Annalen der Physik **64** (1921) 513–540. Submitted: 7 September 1920.]

- Bailey & Townsend published similar findings in 1921-1922.

- [J.S. Townsend & V.A. Bailey, "The abnormally long free paths of electrons in argon," Philosophical Magazine Series **43** (1922) 1127-1128.]

Ramsauer minimum

- Heavier gases have a Ramsauer minimum at increasingly high energy.
- He and Ne have no Ramsauer minimum.
- Errors not known, probably ± 10 %.



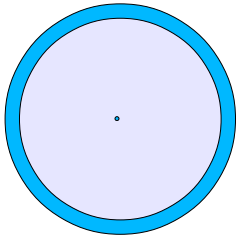
Gas-based detectors

mean multiplication

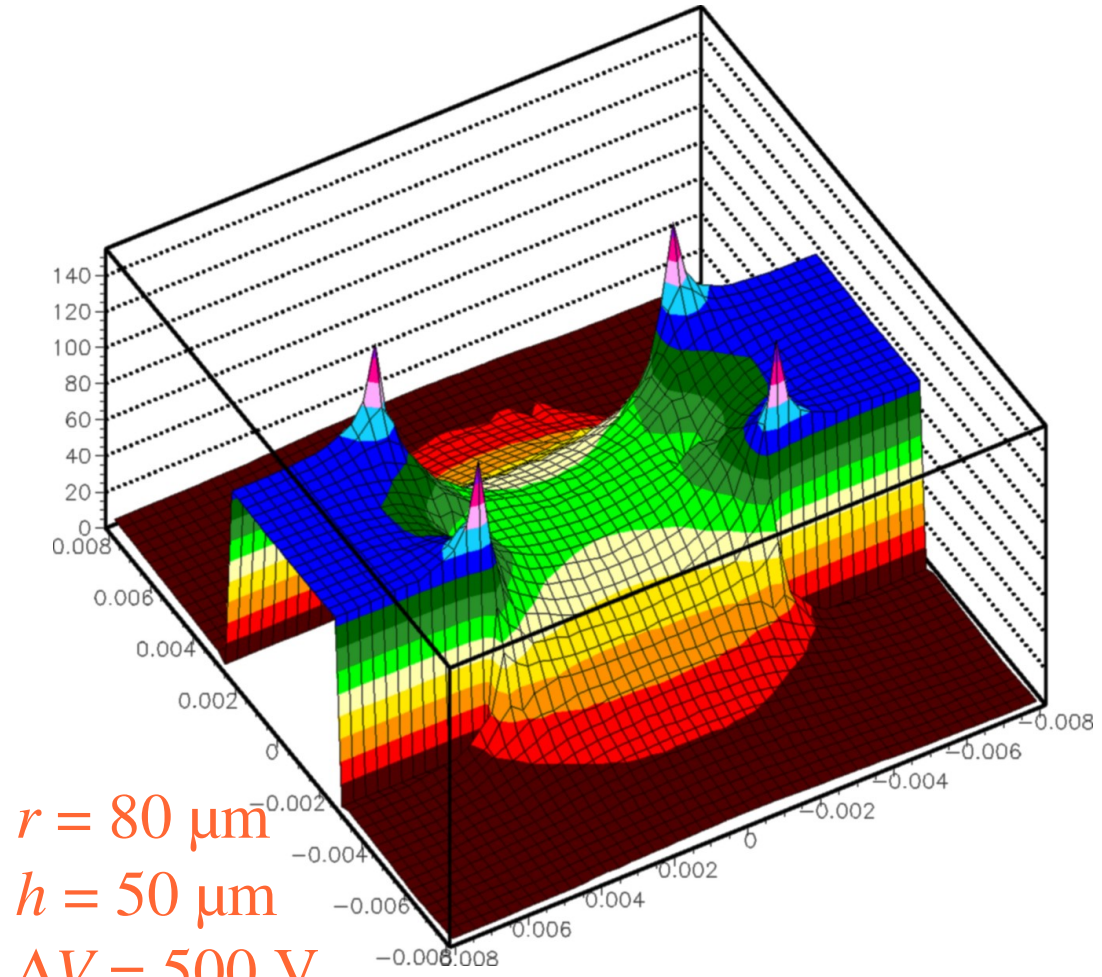
Multiplication

- Ionisation gave us just a few electrons+ions per mm of gas. We have transported them to the read-out, hopefully not losing too many.
- But ... if we collect them directly on a read-out electrode, the current will be tiny.
- We need to multiply them.
- Requires fields where the electron energy occasionally is sufficient to ionise.

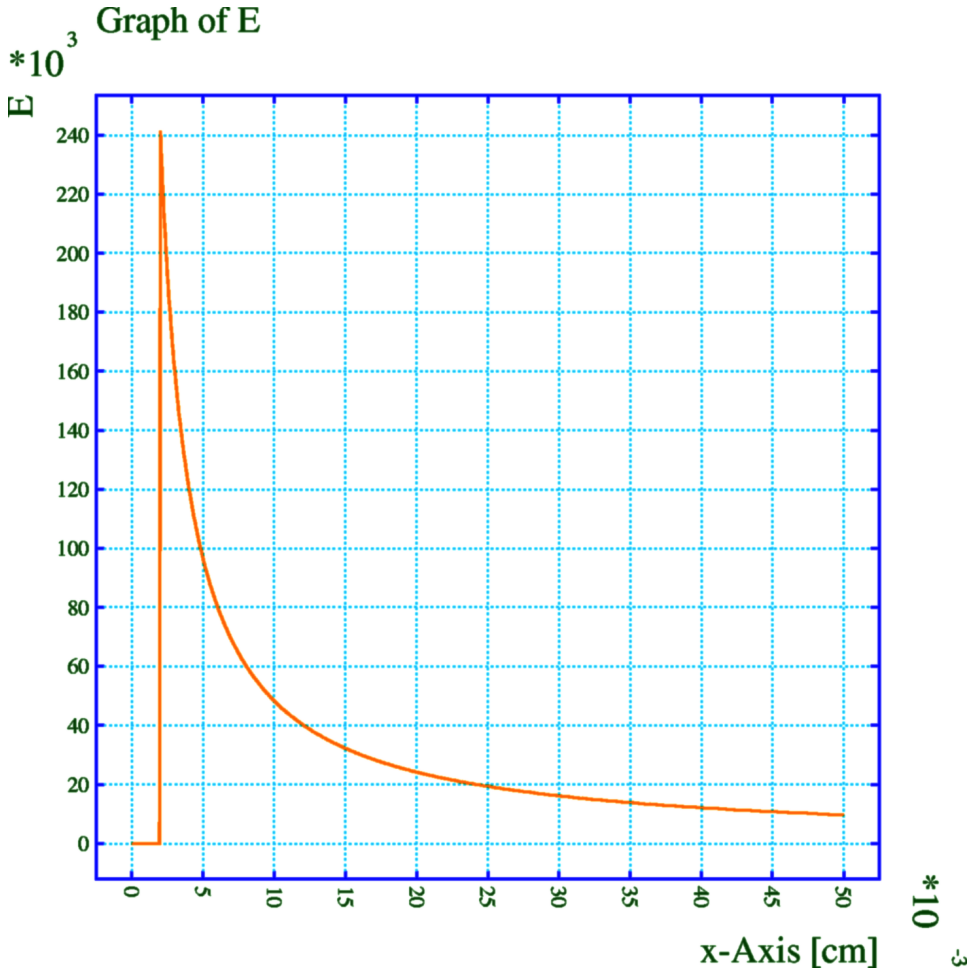
Strong electric fields



- Some ways to generate sufficiently high fields ...



$r = 80$ μm
$h = 50$ μm
$\Delta V = 500$ V



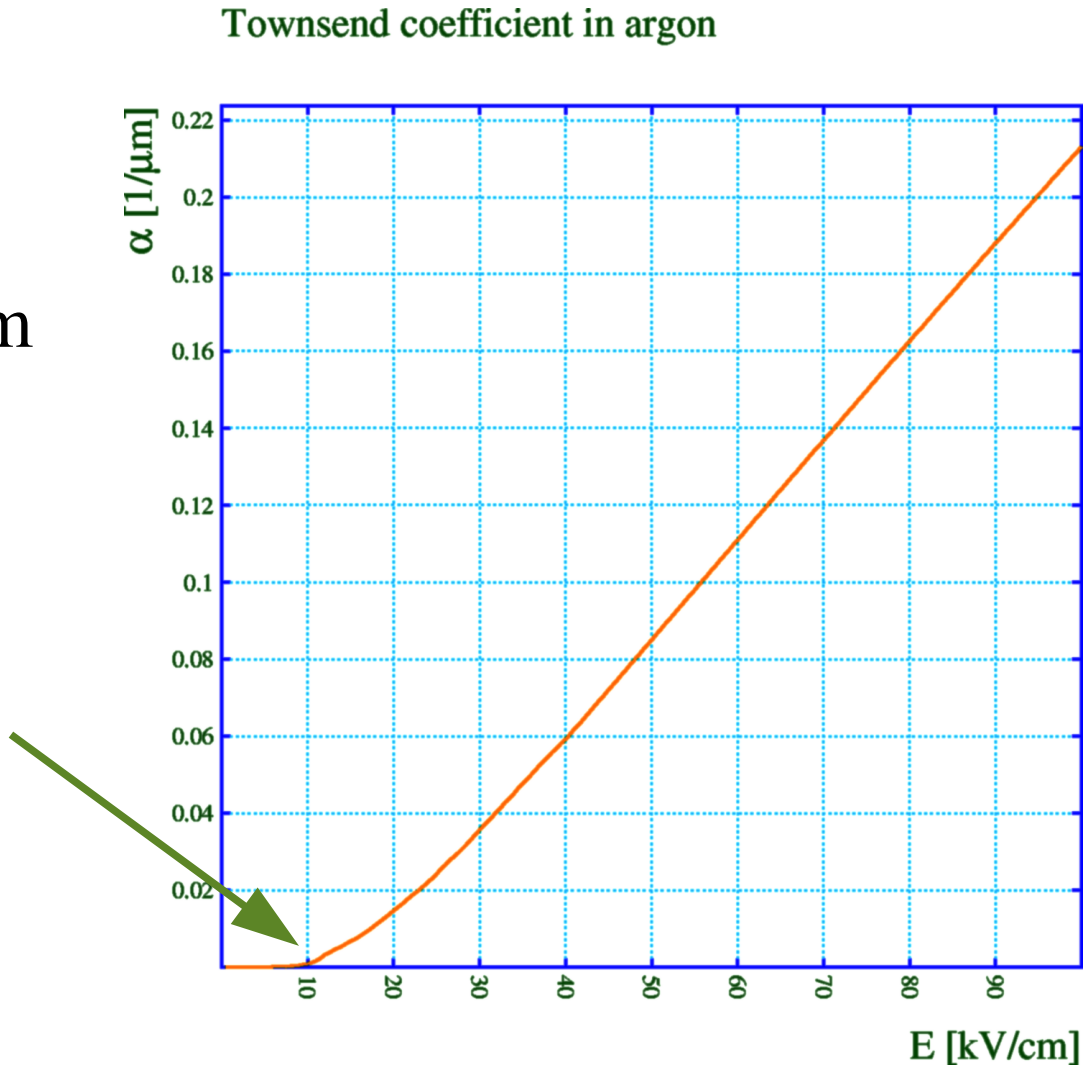
$r = 20$ μm, $d = 1.5$ cm, ΔV=3200 V

Energy after a mean free path

- IP: 15.7 eV
- Ionisation λ_{ion}: ~10 µm
- E = IP / λ_{ion} = 16 kV/cm

- avalanches start earlier

- α: Townsend coefficient,
  # new e^- per unit length.



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 α 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/.]

Mean size of the avalanche

- Townsend coefficient α: probability per unit length that an electron creates an additional electron.

- Avalanches grow proportionally to their size:

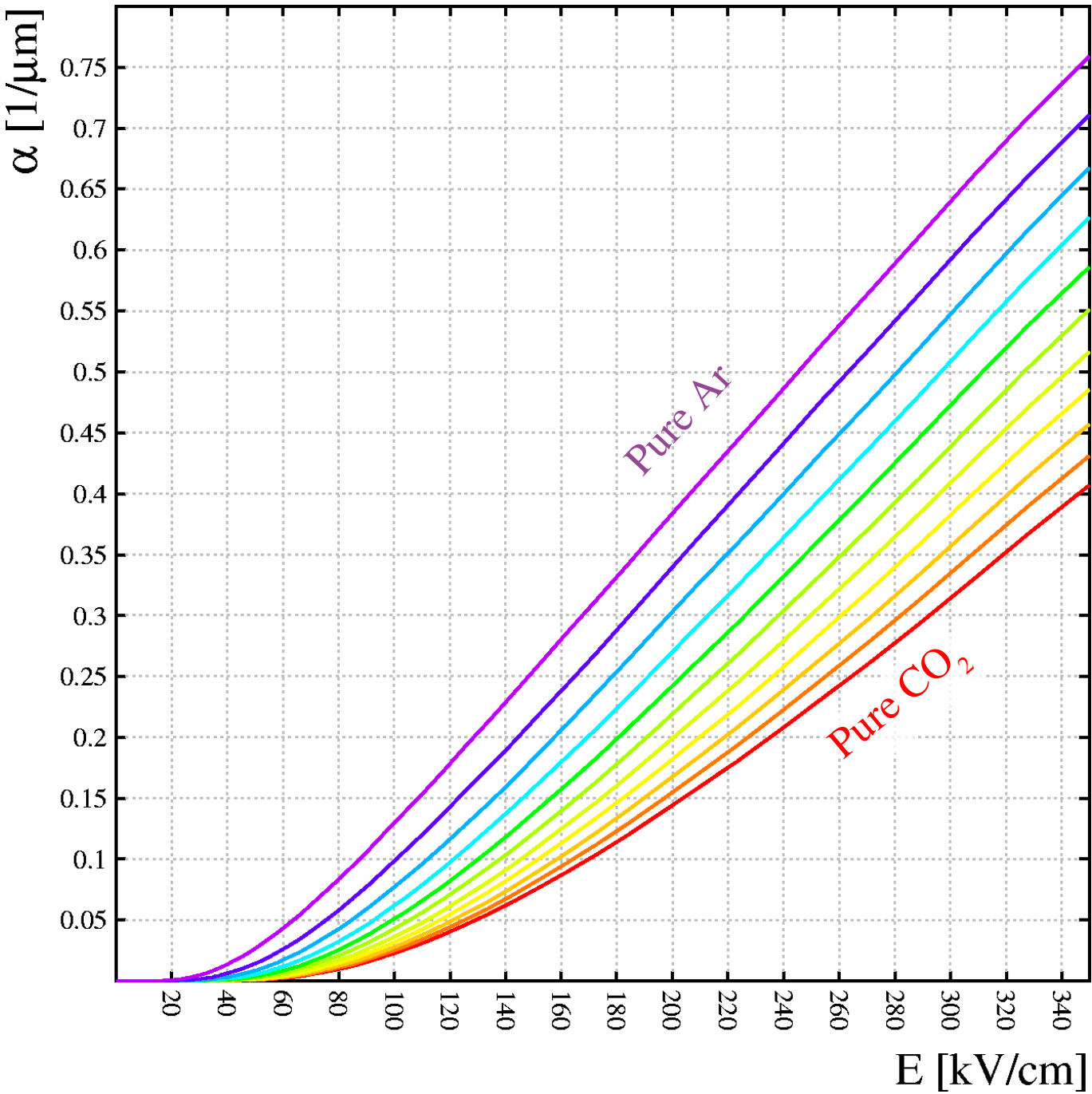
$$\mathrm{d}\, n(x) = n(x)\,\alpha(x)\;\mathrm{d}\, x$$

$$n(x) = n(0)\, e^{\int_0^x \alpha(y)\,\mathrm{d}\, y}$$

- Intuitively, gain is merely a matter of ionisation.

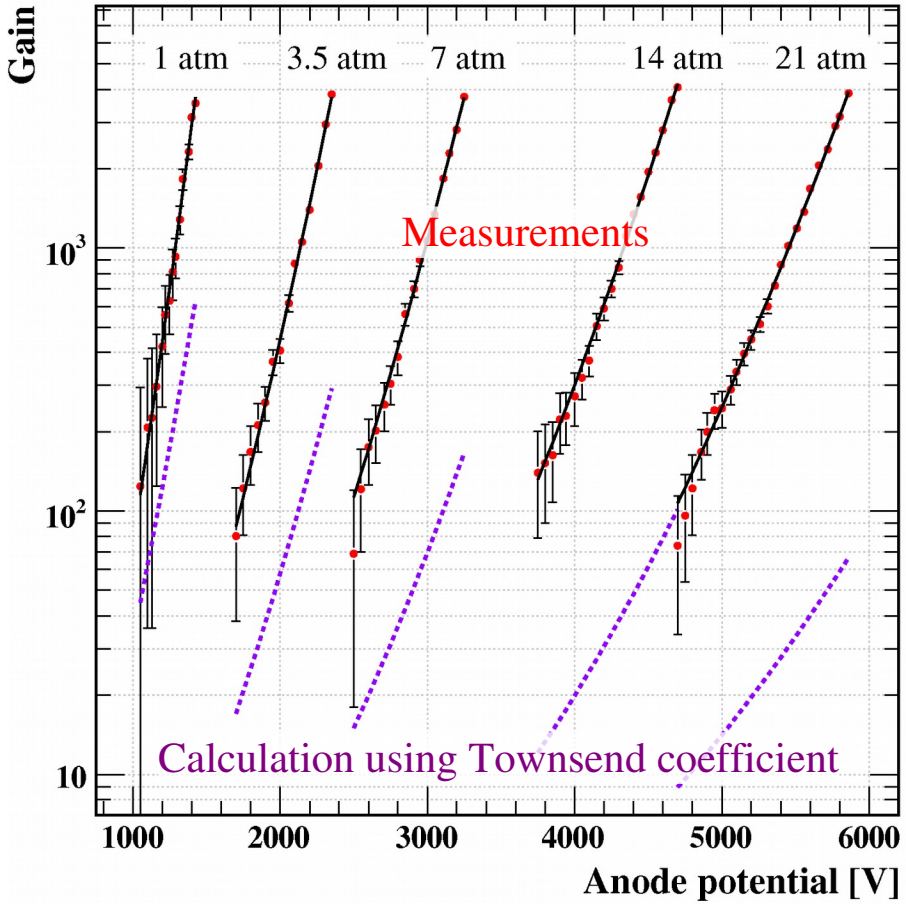
$\alpha(Ar\text{-}CO_2)$

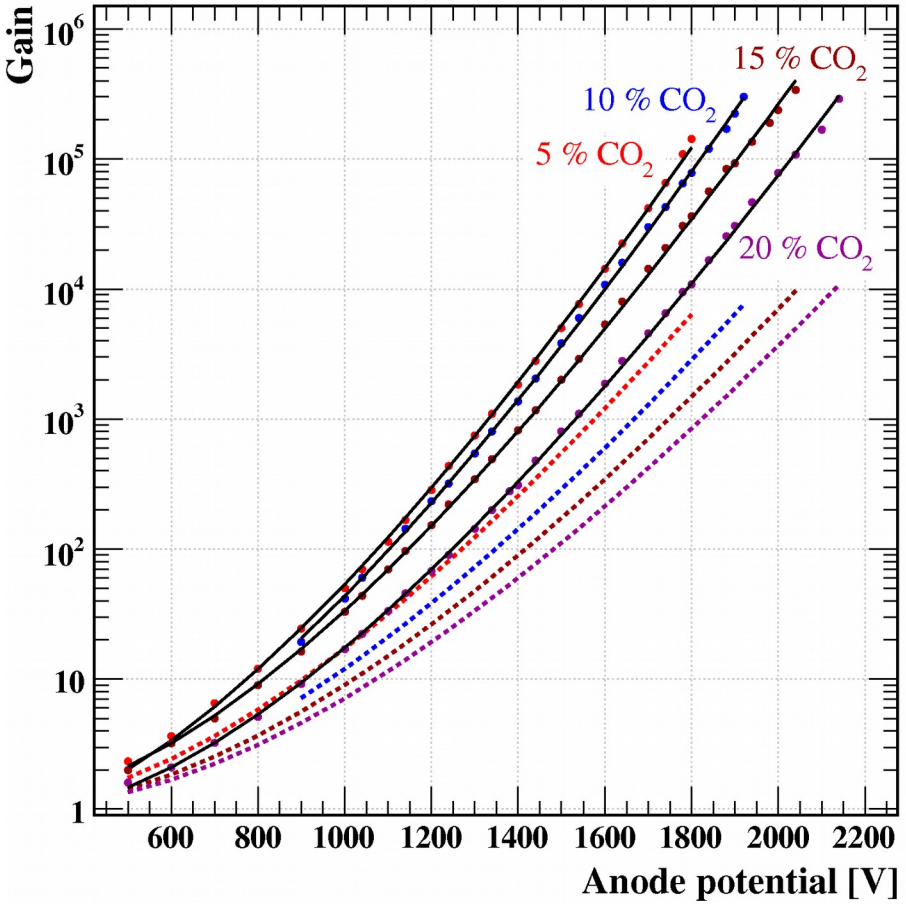
- α = number of e^- an avalanche e^- creates per cm.
- Adding CO_2 reduces the gain.
- Calculated by Magboltz for Ar/CO_2 at 3 bar.

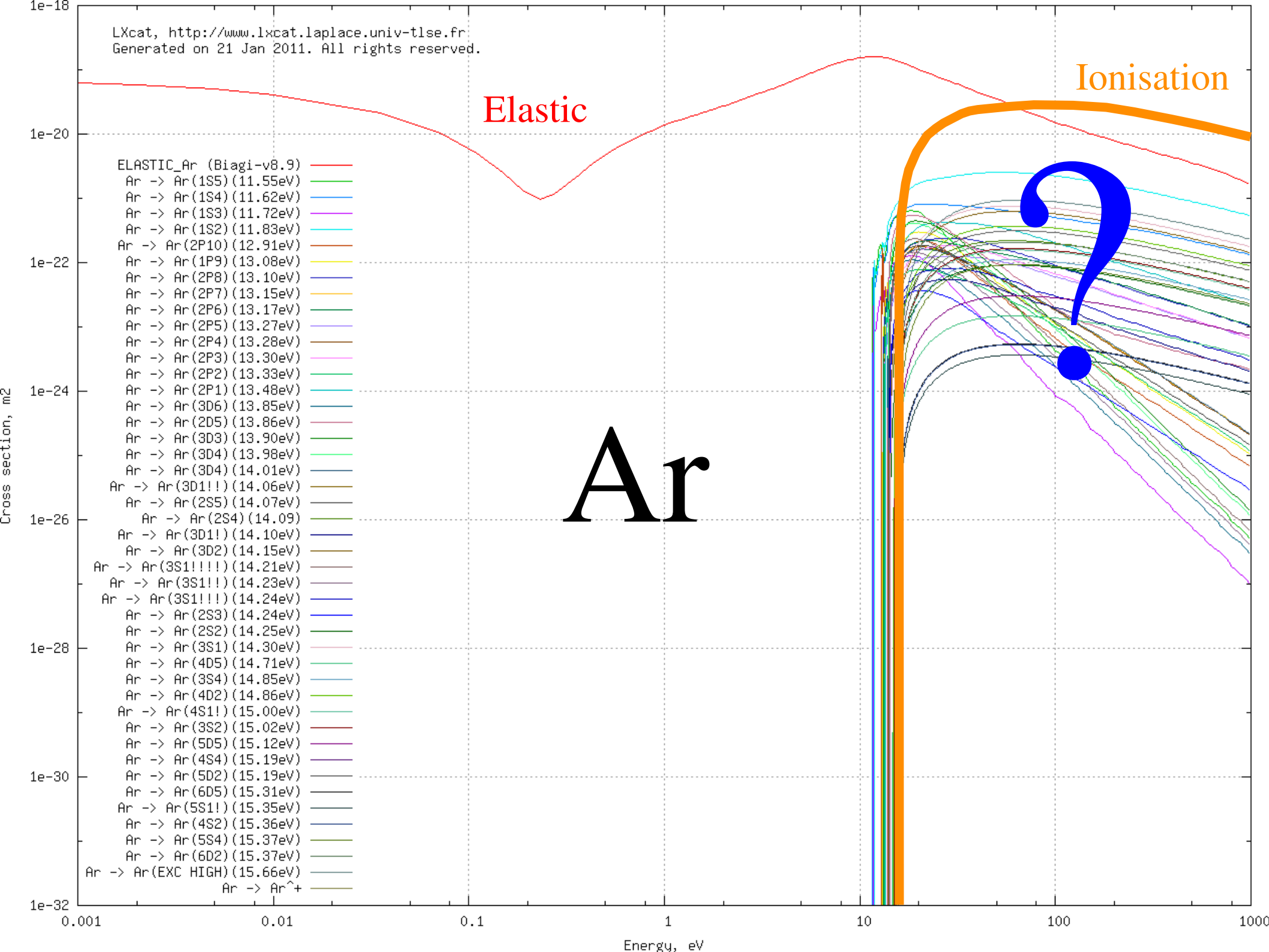


Does this reproduce the measurements ?

- Ar - CH_4
- Ar - CO_2






LXcat, http://www.lxcat.laplace.univ-tlse.fr
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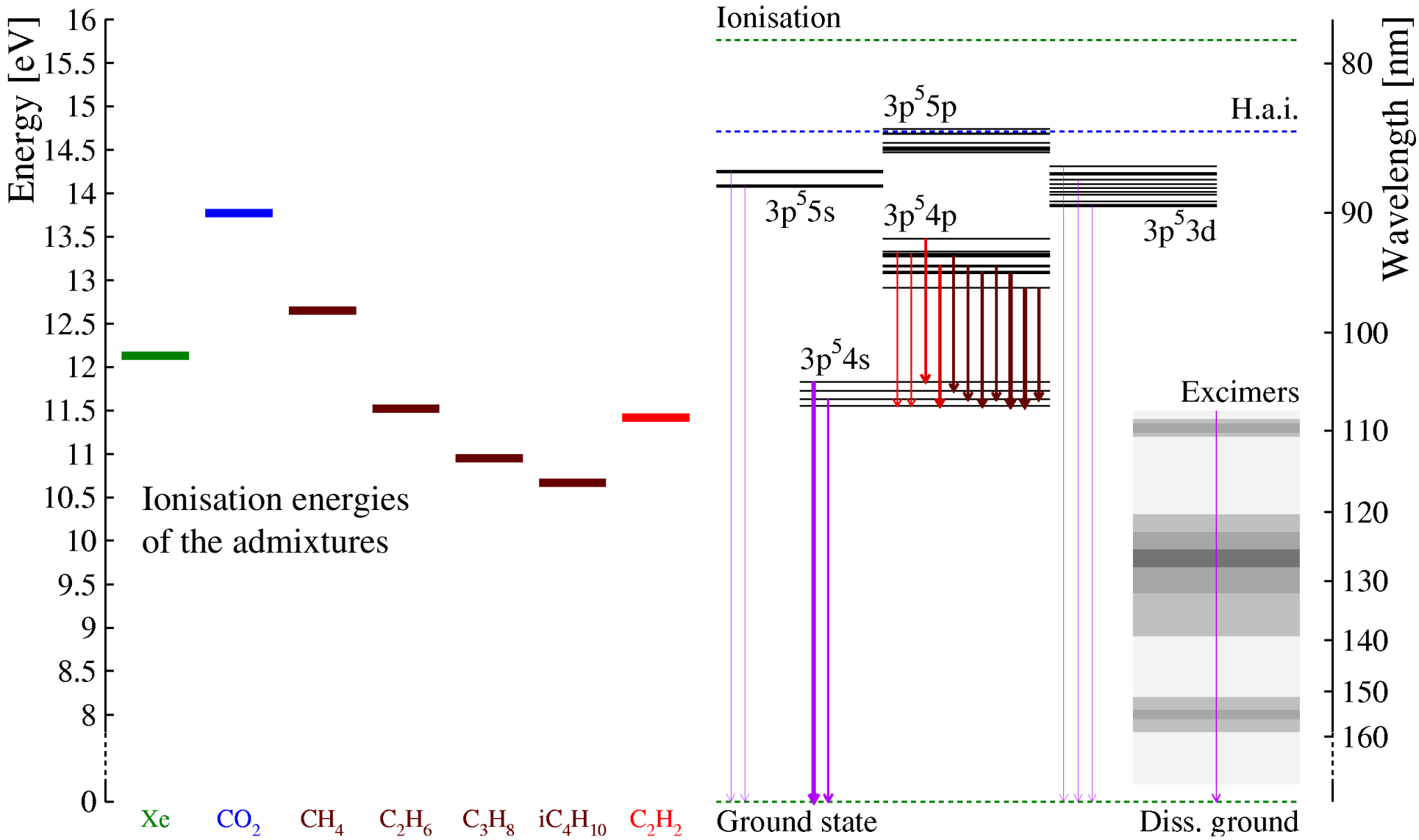
Elastic
Ionisation
Ar
?
ELASTIC_Ar (Biagi-v8.9)
Ar -> Ar(1S5)(11.55eV)
Ar -> Ar(1S4)(11.62eV)
Ar -> Ar(1S3)(11.72eV)
Ar -> Ar(1S2)(11.83eV)
Ar -> Ar(2P10)(12.91eV)
Ar -> Ar(1P9)(13.08eV)
Ar -> Ar(2P8)(13.10eV)
Ar -> Ar(2P7)(13.15eV)
Ar -> Ar(2P6)(13.17eV)
Ar -> Ar(2P5)(13.27eV)
Ar -> Ar(2P4)(13.28eV)
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
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
Energy, eV

Level diagram argon and admixtures

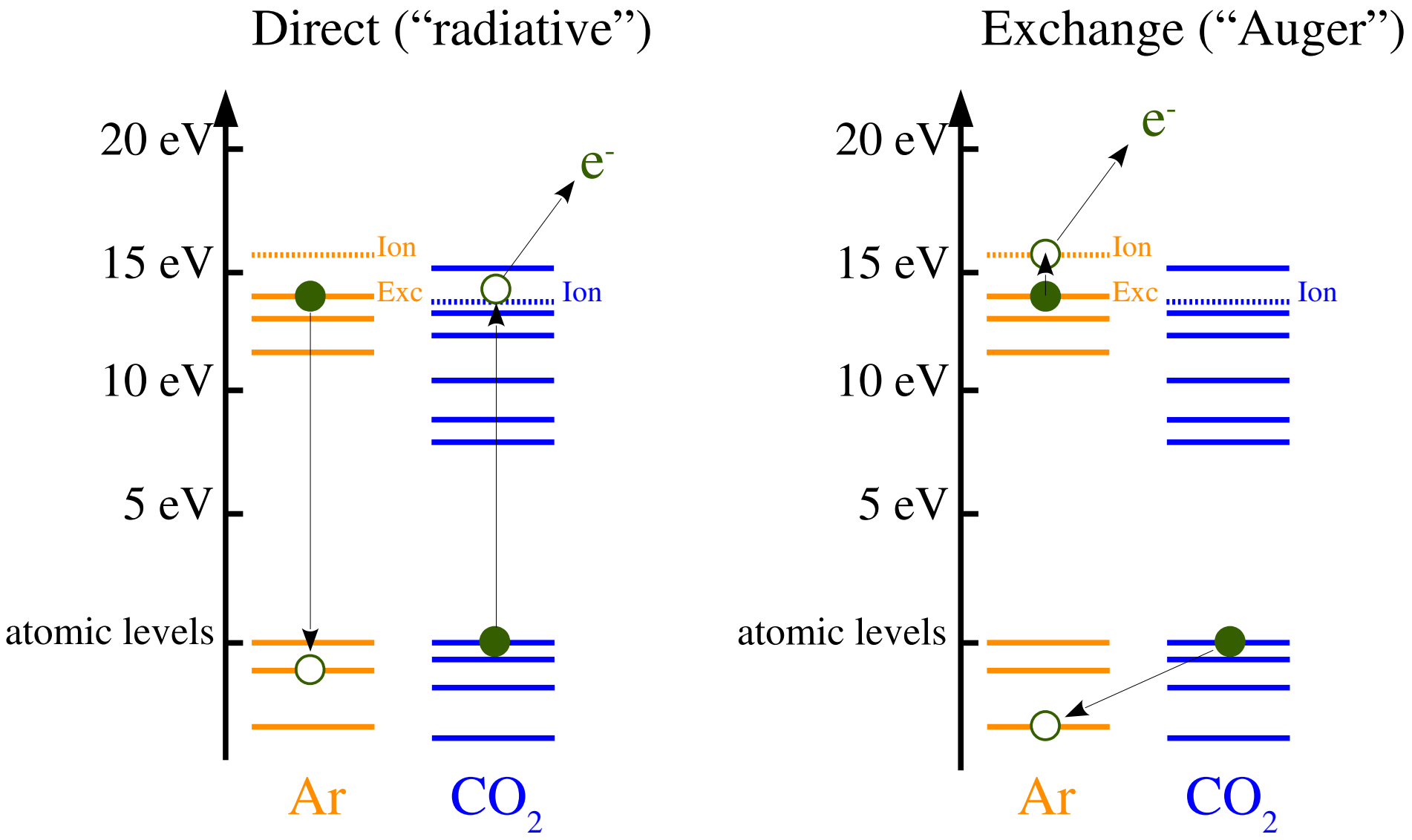


Frans Michel Penning
(1894-1953)

Penning effect

- Ar^* $3p^5 4s$ can transfer to iC_4H_{10}, C_3H_8 and C_2H_6;
  - two 4*s* are metastable, the two others live 2.6 ns and 8.6 ns;
- Ar^* $3p^5 4p$ can also ionise CH_4;
  - 4*p* decays to 4*s* with a lifetime of 20-40 ns;
- Ar^* $3p^5 3d$ can in addtion transfer to CO_2;
  - radiative 3*d* decays take ~3.5 ns, the others ~50 ns.
- Metastables: collision frequencies of Ar^* in pure quencher are ~100 ps.

Direct vs Exchange ionisation

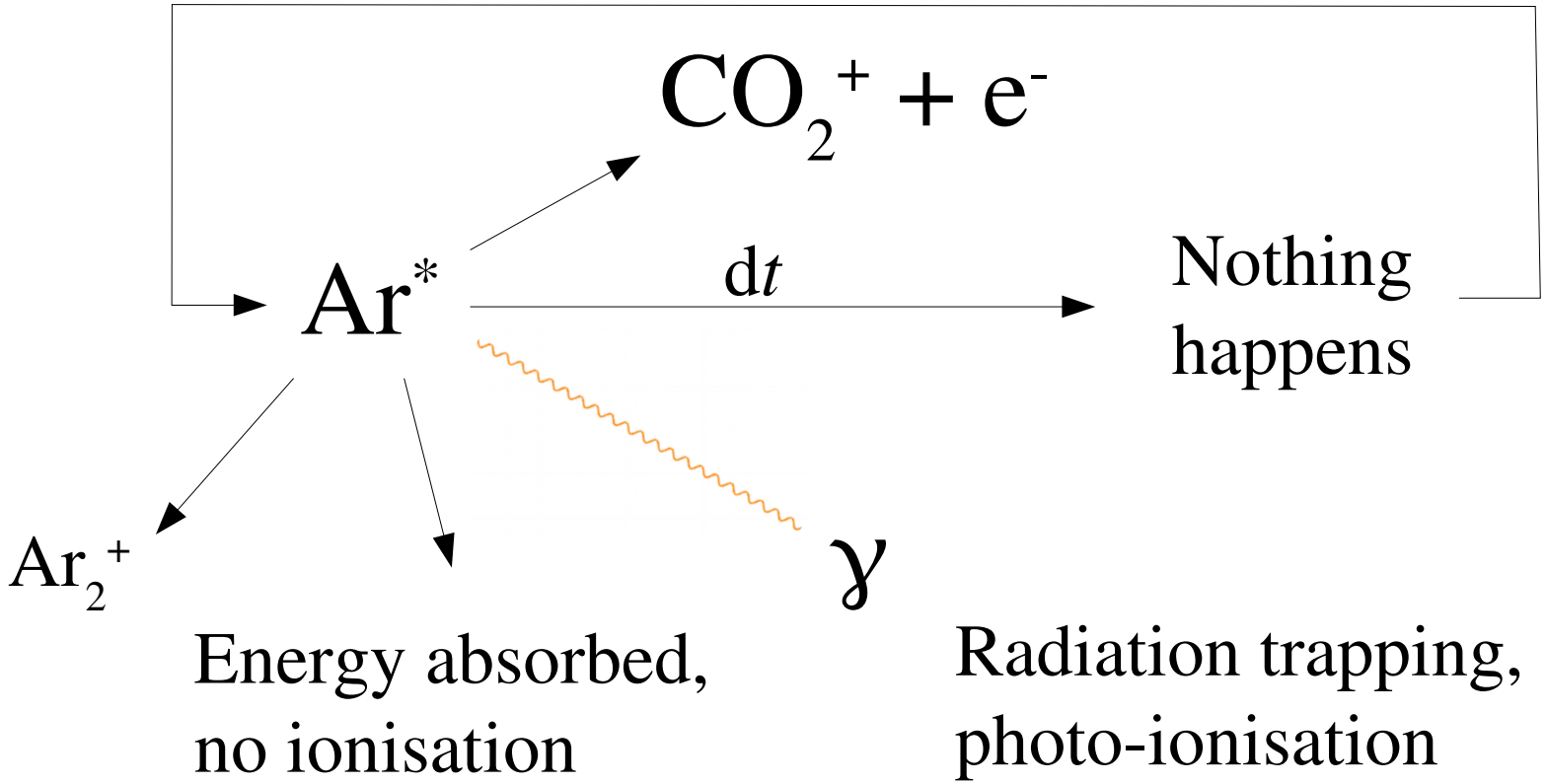


Simplified Penning model

- Reactions of Ar^*:
  - $Ar^* + CO_2 \rightarrow Ar + CO_2^+ + e^-$ Penning transfer,
  - $Ar^* + CO_2 \rightarrow Ar + CO_2^*$ collisional energy loss,
  - $Ar^* + Ar + Ar \rightarrow Ar_2^+ + e^- + Ar$ dimer formation,
  - $Ar^* \rightarrow Ar + \gamma$ radiative decay,
    - $\gamma + Ar \rightarrow Ar^*$ radiation trapping
    - $\gamma + CO_2 \rightarrow CO_2^+ + e^-$ photo-ionisation,
    - $\gamma + metal \rightarrow e^- + hole^+$ ionisation in metal.

Simplified Penning model (cont'd)

- Take small steps until the energy has been used up:



Radiation trapping

- Photons emitted by radiative decay to ground of excited noble gas atoms have a high probability of being re-absorbed and subsequently re-emitted by the noble gas: radiation trapping.

- Eventually, after many absorption/emission cycles, the photons are absorbed by a quencher gas molecule.

- Excited states can effectively have a long lifetime.

Simplified Penning model (cont'd)

- Let A be a noble gas and B a quencher, A^* is excited with excitation energy > ionisation energy of B^+.

- In a step dt, A^* produces n dt electrons:
  - A^* collides with B and transfers its excess energy, or
  - A^* decays and radiatively ionises B

$$n = p c \frac{f_{B^+}}{\tau_{A^*B}} + \frac{f_{\text{rad}}}{\tau_{A^*}}$$

- A^* tries again if it survives, probability:

$$1 - \frac{\mathrm{d}t}{\tau_P}, \qquad \frac{1}{\tau_P} = p c \frac{f_{B^+}}{\tau_{A^*B}} + \frac{1}{\tau_{A^*}}$$

p = pressure
c = quencher fraction
f_{B^+} = transfer probability in collision
f_{rad} = radiative lifetime
τ_{A^*B} = collision time

Simplified Penning model (cont'd)

- Summing to get the number of electrons from A^*:

$$r(p,c) = n\,\mathrm{d}t + n\,\mathrm{d}t\left(1-\frac{\mathrm{d}t}{\tau_P}\right) + n\,\mathrm{d}t\left(1-\frac{\mathrm{d}t}{\tau_P}\right)^2 + \ldots$$

$$= n\,\tau_P$$

Nothing happened in the first step

- $r(p,c)$ is the fraction of the excitation frequency to be added to the ionisation frequency in order to correct the Townsend coefficient for the Penning effect.

- There are only two a priori unknown parameters:
  - f_{rad}: the radiative ionisation probability
  - f_B+: the collisional transfer probability

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Kraków measurement setup

- Single anode, cylindrical counters:
  - r_{anode}: 10-50 μm;
  - $r_{cathode}$: 2 mm (Atlas TRT straws) to 26 mm;
  - p_{gas}: 50 hPa - 0.6 MPa;
  - in some cases, guard rings were added;
  - careful shielding to protect against noise.

  - pA-nA range; usually < 5 nA to avoid space charge;
  - ^{55}Fe, ^{109}Cd and ^{90}Sr sources.

- Available gases: Ar, Xe, Kr, (Ne,) i-C_5H_{12}, C_6H_{12}, C_2H_5OH, C_2H_6, H_2, N_2, CF_4, CO_2, O_2, DME.

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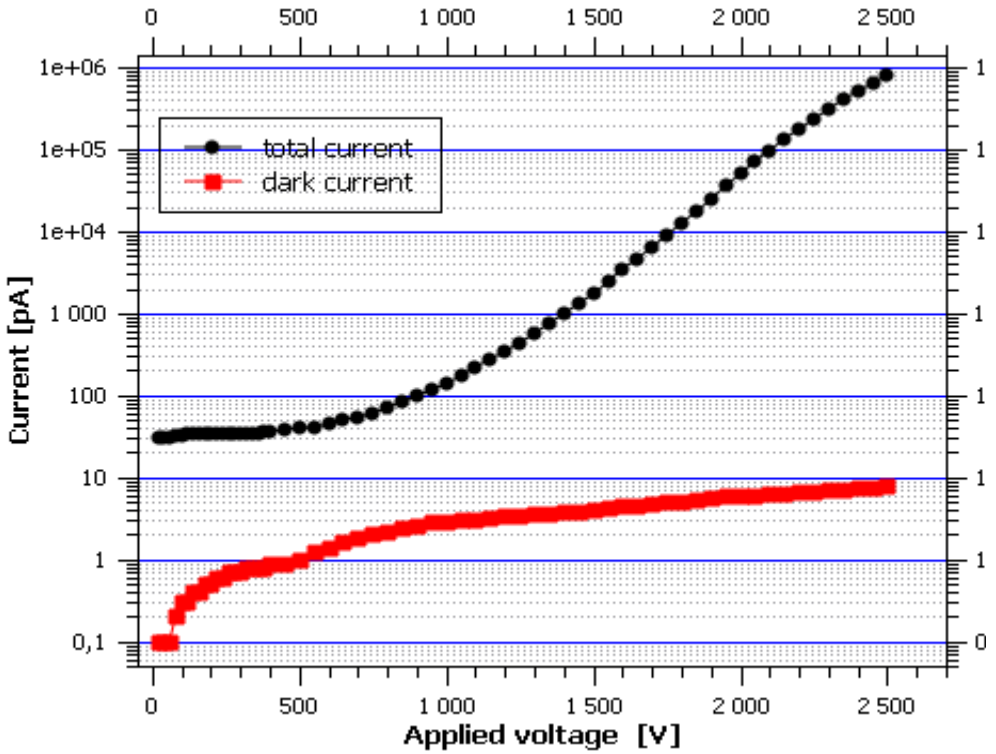
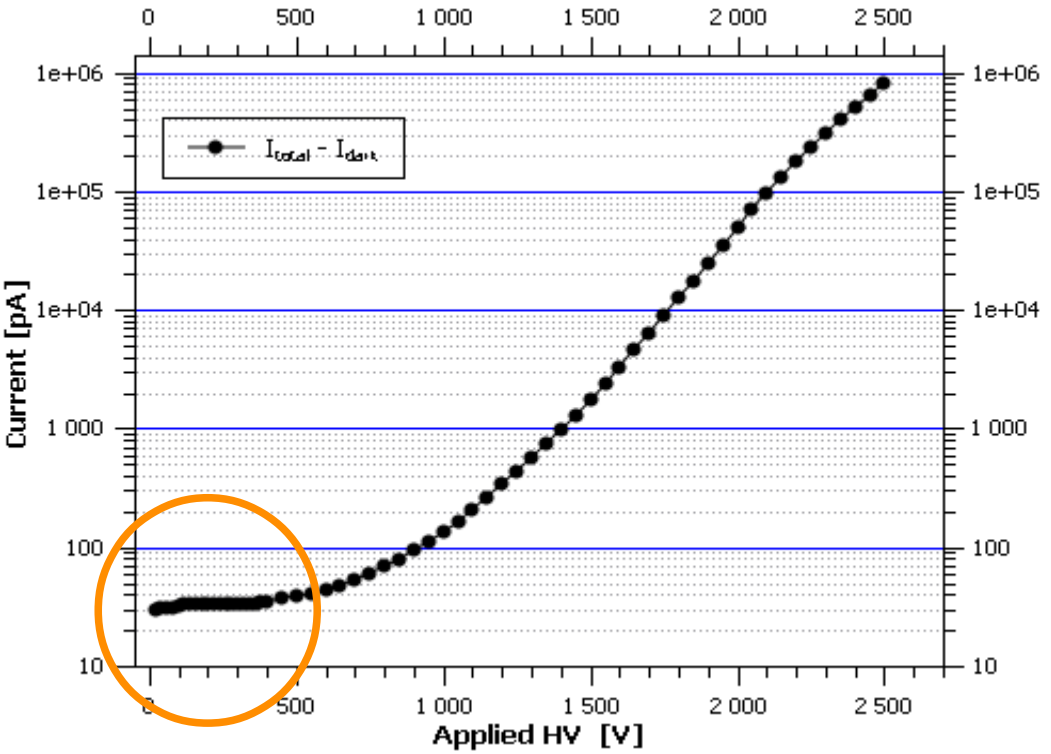
Example of measurements

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





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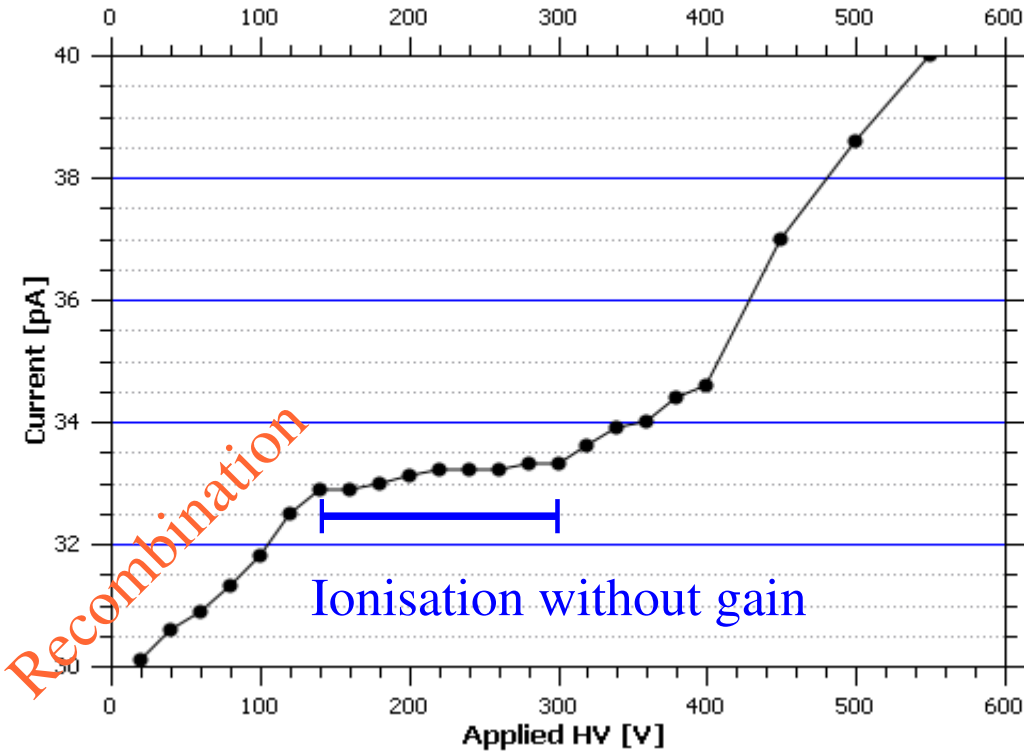
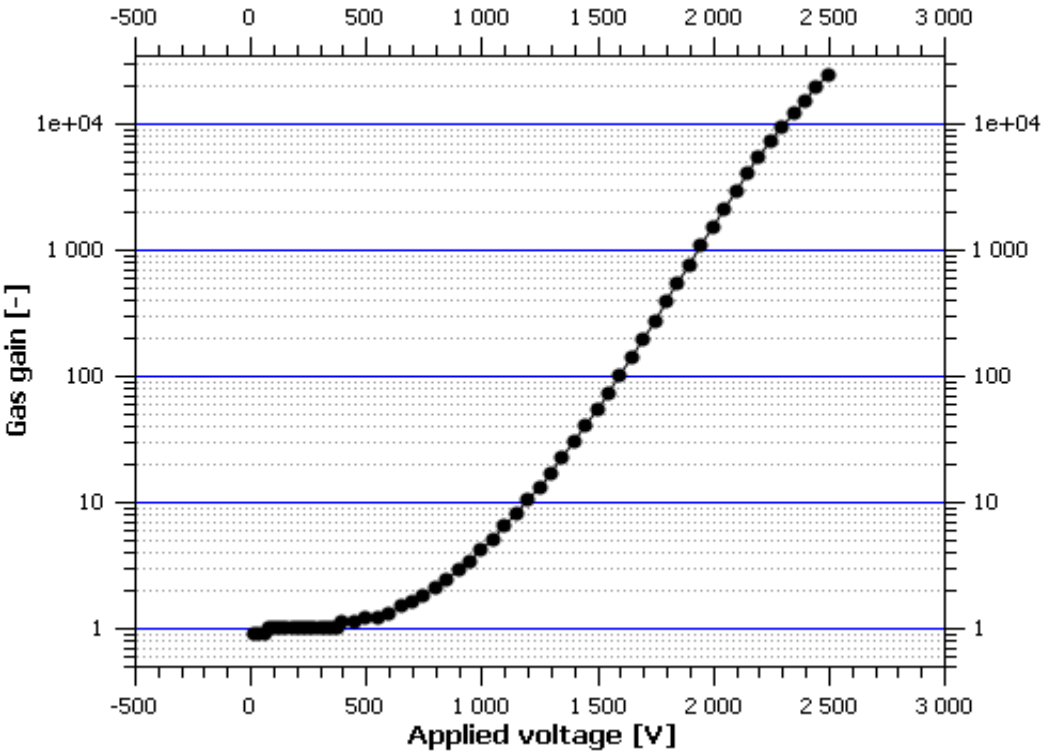
Data covers 5 orders of magnitude !

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





Determining the Penning parameters

- The Penning transfer rate $r(p,c)$ is measured by fitting to experimental data, the fraction of excitations to be added to α that reproduces the measured gain:

$$G = \exp \int \alpha \left(1 + r(p,c) \frac{\nu_{\text{exc}}}{\nu_{\text{ion}}} \right)$$

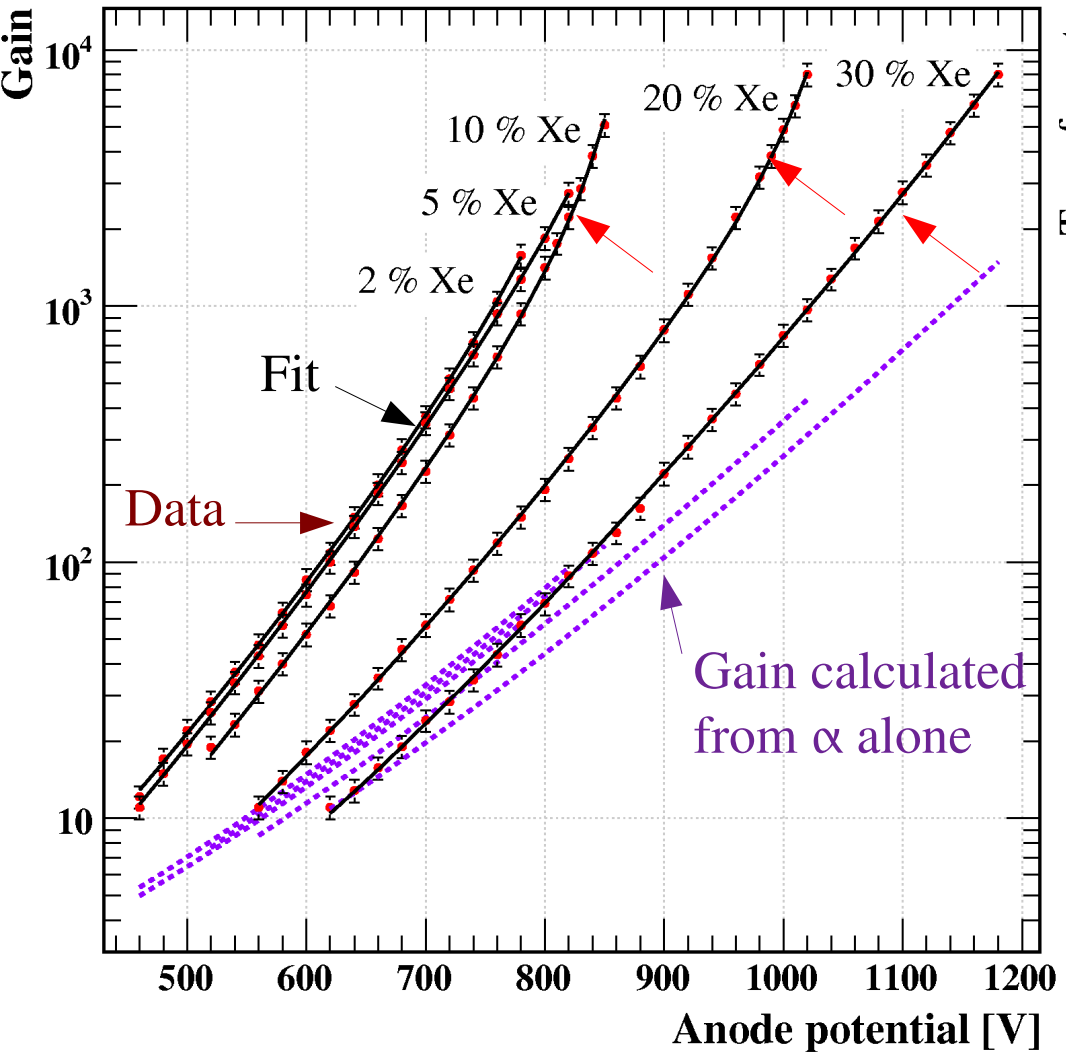
- Model parameters: a subset of

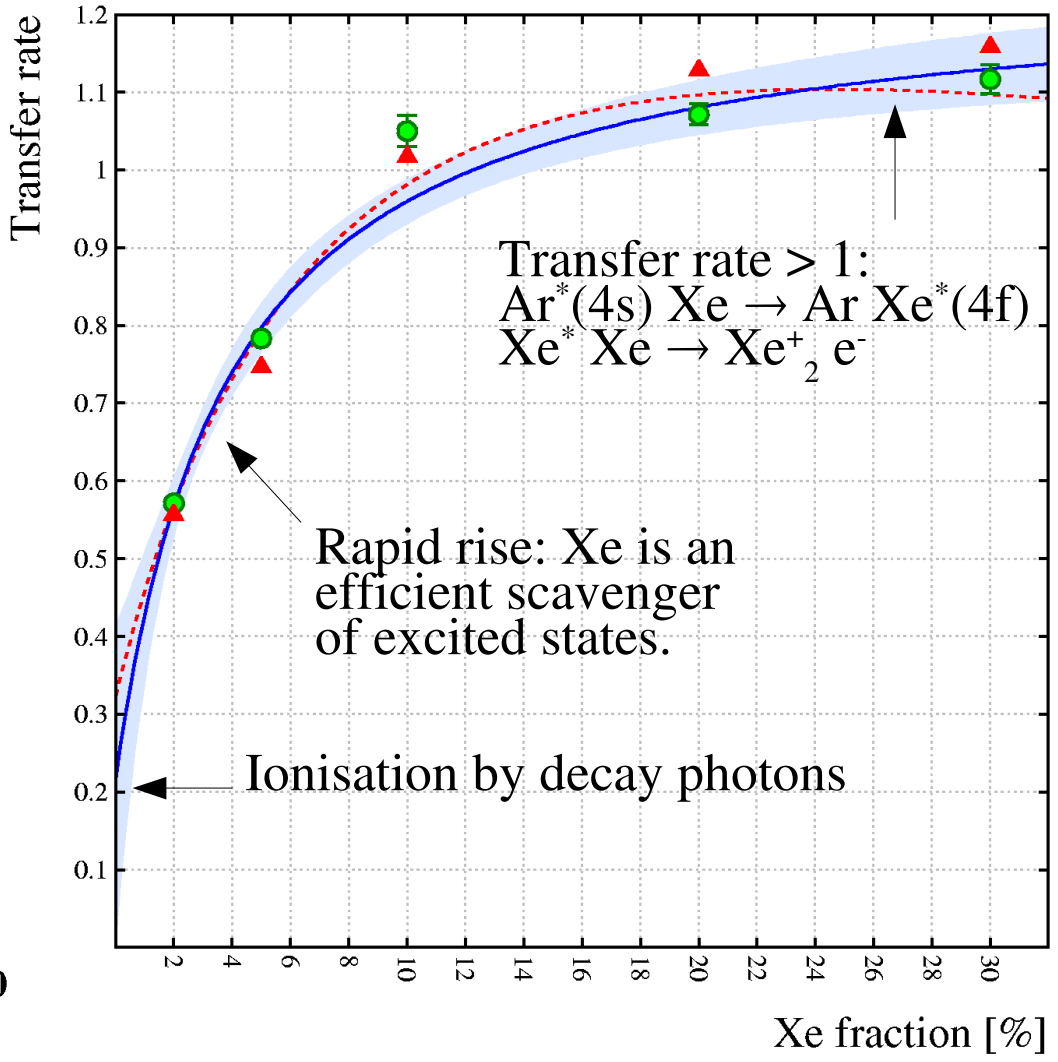
$$r(p,c) = \frac{p\,c\,f_{B^+}/\tau_{AB} + p(1-c)f_{A^+}/\tau_{AA} + f_{\text{rad}}/\tau_{A^*}}{p\,c(f_{B^+} + f_{\bar{B}})/\tau_{AB} + p(1-c)(f_{A^+} + f_{\bar{A}})/\tau_{AA} + 1/\tau_{A^*}}$$

$A^* \rightarrow B^+$ $A^* \rightarrow A^+$ $A^* \rightarrow A\,\gamma$

Penning transfer in Ar-Xe

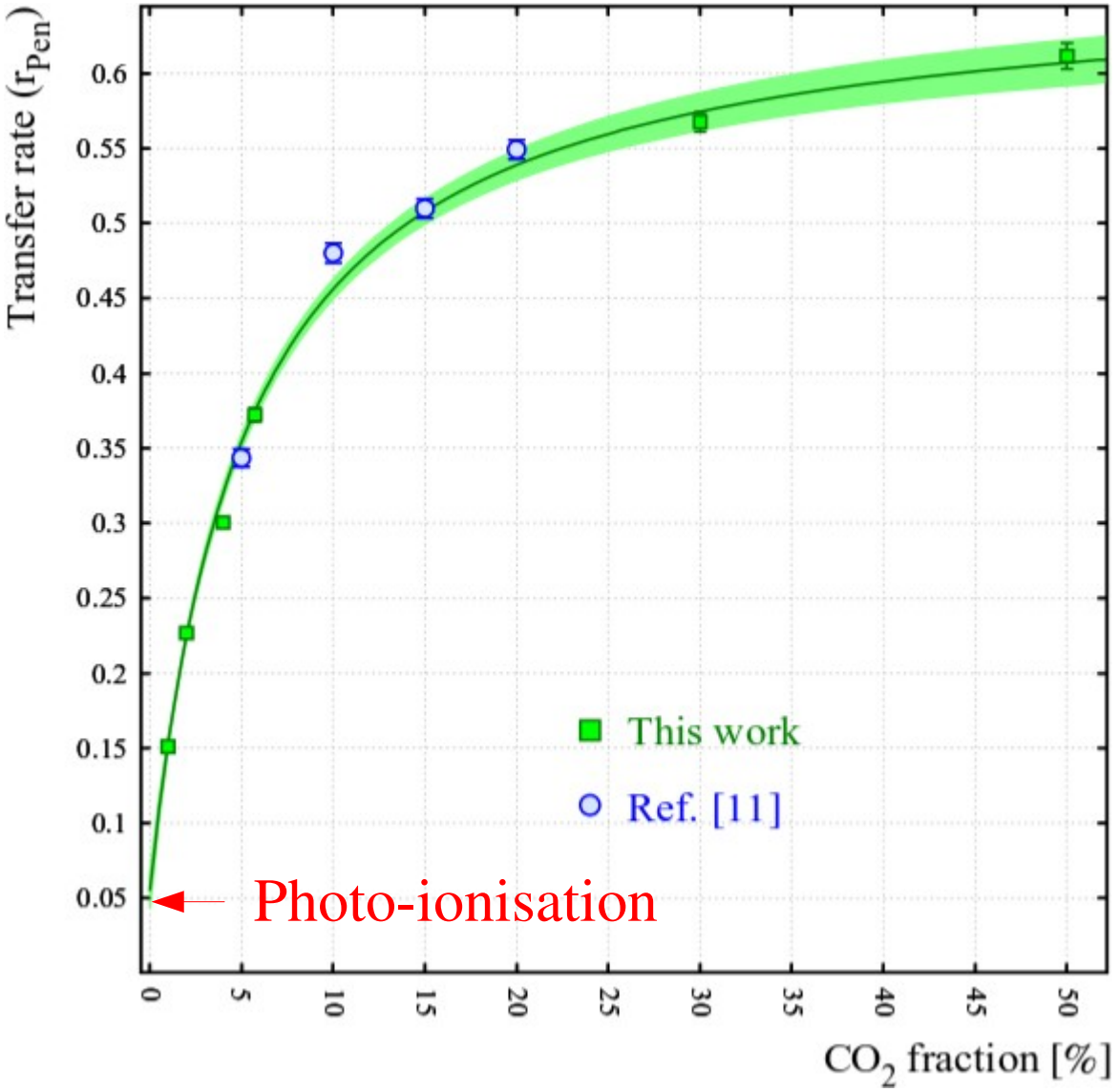
- Ar 4*p*, 3*d* and higher above the Xe ionisation threshold.





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]

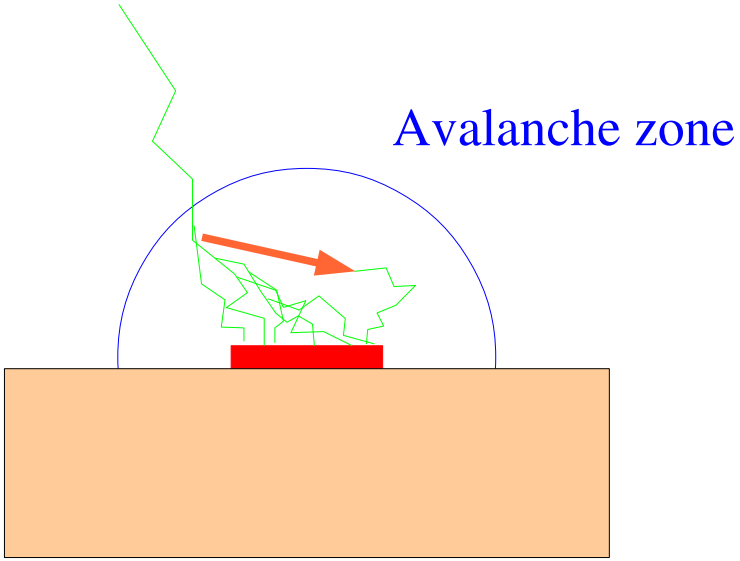
Feedback

- Gas feedback requires:
  - γ emission by the avalanche at an energy above the ionisation potential of the admixture;
  - γ absorption well outside the avalanche;
  - photo-ionisation to produce an e^- starting a new avalanche.

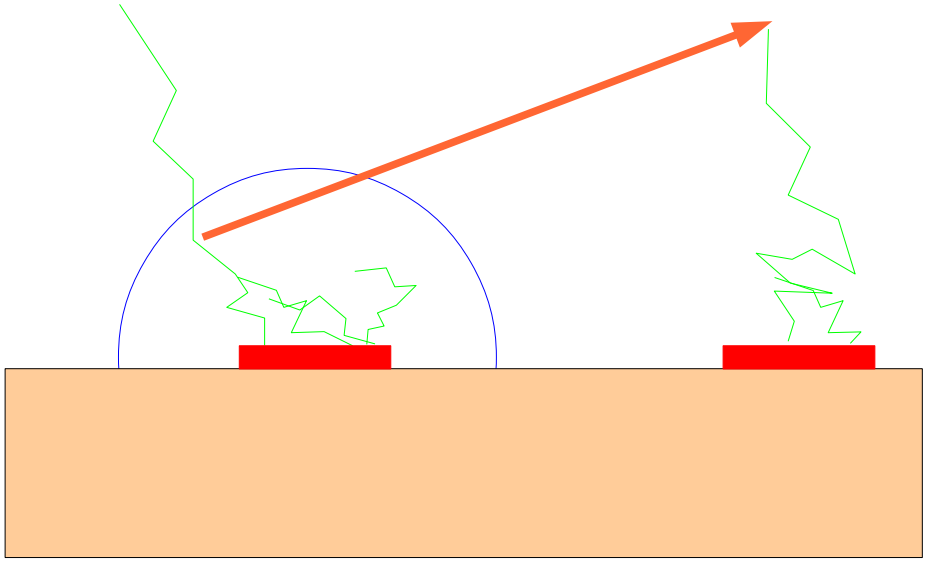
- Cathode feedback requires:
  - γ or ion absorption in the cathode followed by
  - e^- emission to start a new, complete avalanche.

Feedback: in/outside avalanche zone

- A γ absorbed inside the avalanche enhances the gain, similar to Penning transfer:



- A γ leaving the avalanche zone can start a complete new avalanche:



Feedback – summing

- Suppose:
  - an avalanche produces on average G electrons;
  - each produces on average γ fully-fledged secondaries;
- then the size of the 2nd generation is:

$$G^{(1)} = G + \gamma G G$$

Secondaries Multiplication of secondaries

- adding the next generation:

$$G^{(2)} = G + \gamma G G + \gamma(\gamma G G)G$$

- and continuing ...

$$\begin{aligned} G^{\text{tot}} &= G + \gamma G G + \gamma(\gamma G G)G + \gamma(\gamma(\gamma G G)G)G \ldots \\ &= G\left(1+\gamma G+(\gamma G)^2+(\gamma G)^3 \ldots\right) \\ &= G/(1-\gamma G) \end{aligned}$$

Feedback – effect

- As a result of feedback, the gain G is replaced by:

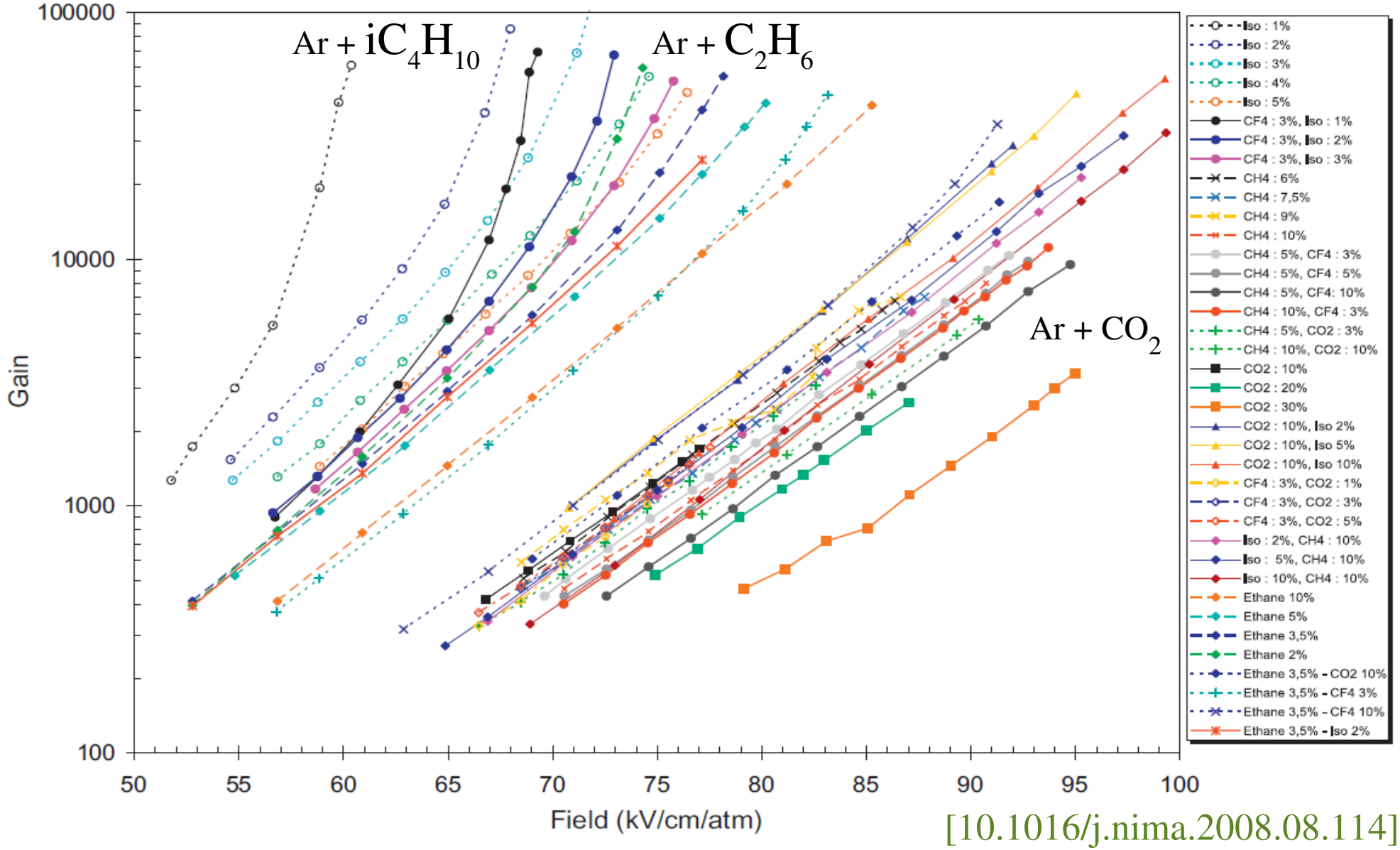
$$G := \frac{G}{1 - \gamma G}$$

- Small gains not affected, high gains become even larger. Sometimes called “over-exponential” avalanche growth.

- Breakdown occurs when:

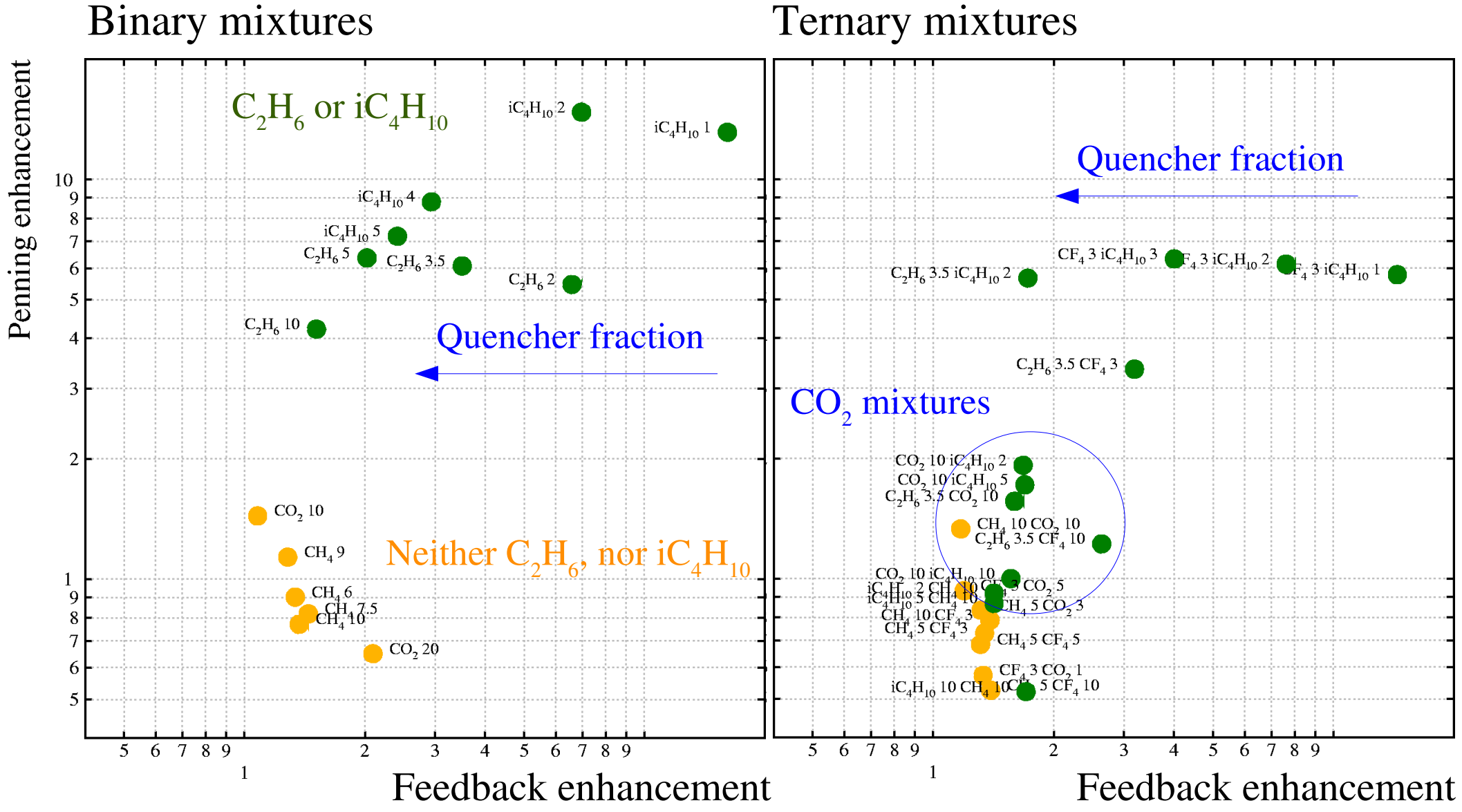
$$\gamma G > 1$$

Saclay Ar compilation



[10.1016/j.nima.2008.08.114]

Penning vs feedback enhancement



Origin of the gain

- Photo-ionisation of the admixture by Ar^{*} $3p^{5}4s$ photons occurs with iC_4H_{10}, is marginal with C_2H_6 and should not occur with e.g. CO_2 and CH_4.
- The C_2H_6 and iC_4H_{10} mixtures owe their high gain to the Penning effect and, at small C_2H_6 and iC_4H_{10} percentages, to gas feedback.
- Feedback is suppressed and the Penning effect is reduced in the presence of CO_2.

Summary of transport

- Quenchers are required because:
  - energy loss makes electrons drift faster;
  - energy loss reduces diffusion;
  - they can contribute directly + indirectly to the gain;
  - they absorb photons and limit discharge.

- Excitations of noble gases play a major role:
  - gain is not only a matter of direct ionisation;
  - they can enhance the gain together with the quencher.