# Phase 2: Transport of electrons

- As a result of the charged particle passing through the gas, we have most probably ~40 electrons/cm.

- With these, we've to reconstruct the charged particle.

# Transport of electrons

- As long as they stand still, they are invisible, and they may eventually recombine with an ion.
- By applying an electric field we move them to a readout structure.
- There we multiply them: moving charges induce currents, and these currents can be measured.

# How do electrons move in a gas ?

- We would like to know:
  - How fast are the electrons ?
  - Will they move in a straight line ?
  - Are they absorbed or do they produce showers ?

- To answer these questions, we first look at:
  - Distance between gas molecules;
  - Mean free path of electrons;
  - Interactions between electrons and gas.

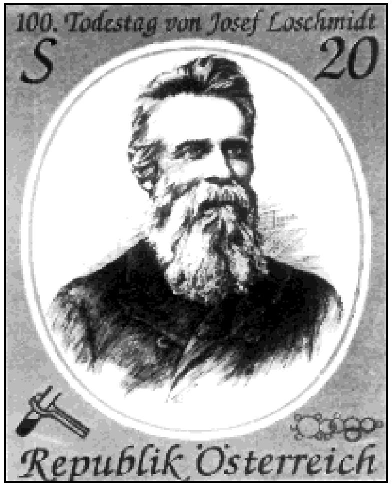
Amedeo Avogadro
(1776-1856)

# Distances in gases

- Number of Ar atoms in a cm³:
- Avogadro's number: $6.022\ 10^{23}$ atoms/mole ÷
- Atomic weight of Ar: 40 g/mole ×
- Density of Ar: $1.662\ 10^{-3}$ g/cm³ =
- ~Loschmidt's number: $2.5\ 10^{19}$ atoms/cm³

- Distance between neighbouring Ar atoms:

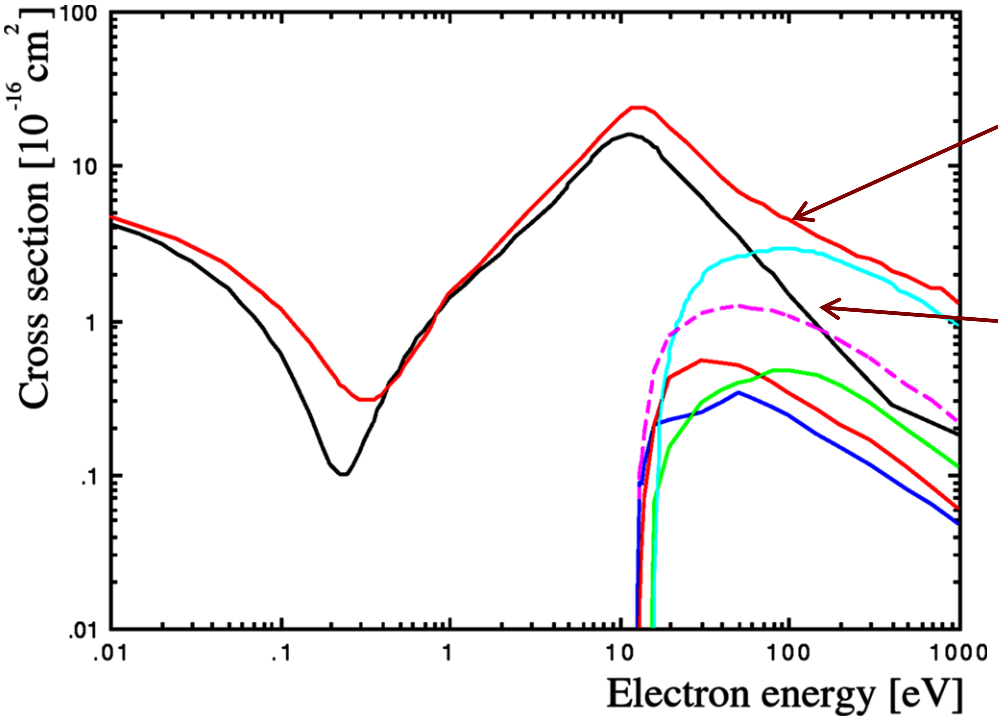
- How about e.g. xenon ?



Josef Loschmidt(1821-1895)

# Cross section of argon

- Cross section in a hard-sphere model:
- Radius: ~70 pm (`http://www.webelements.com`)
- Surface:
- Simplified cross sections used by Magboltz:



Elastic cross section

Excitations, ionisation, attachment

# Mean free path in argon

- We know already that:
  - Cross section of 1 atom: $\sigma \approx 1.5\ 10^{-16}\ \mathrm{cm}^2$
  - Atoms per volume: $\mathcal{L} \approx 2.5\ 10^{19}$ 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 $\mathcal{L}\sigma L$ atoms
  - Hence, the mean free path is $\lambda_e = 1/(\mathcal{L}\sigma) \approx 2.7\ \mu\mathrm{m}$
  - Much larger than the distance between atoms, 0.004 μm !

# Drift velocity in electric fields

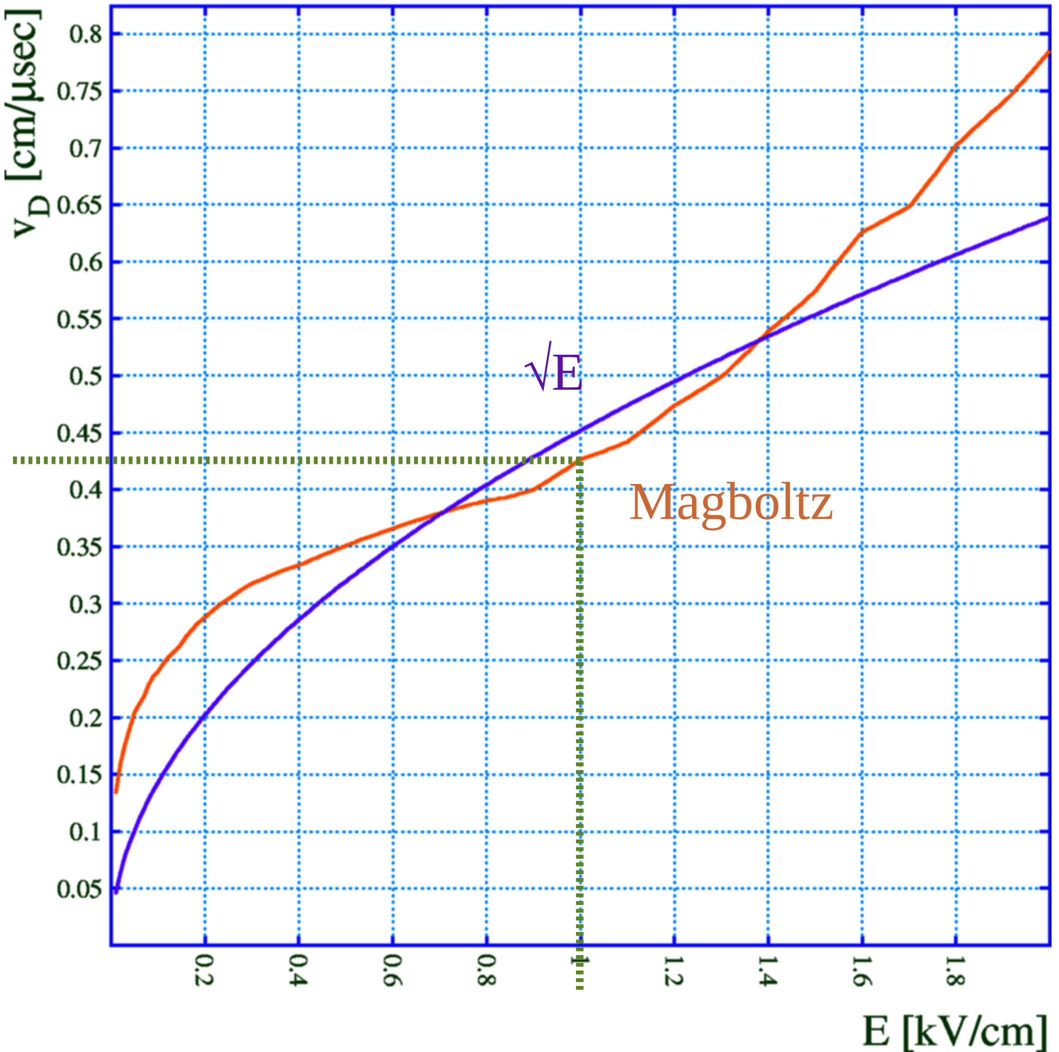
- Imagine that an electron loses all its energy every time it collides with a gas molecule, how fast will it move in a field with strength *E* ?
- To cover a distance , it will need a time *t*:
- For example:

# Drift velocity in argon

- Magboltz calculation for pur argon:

- *E* dependence OK;
  BUT
- Much slower than we estimated: not all energy is lost in each collision.

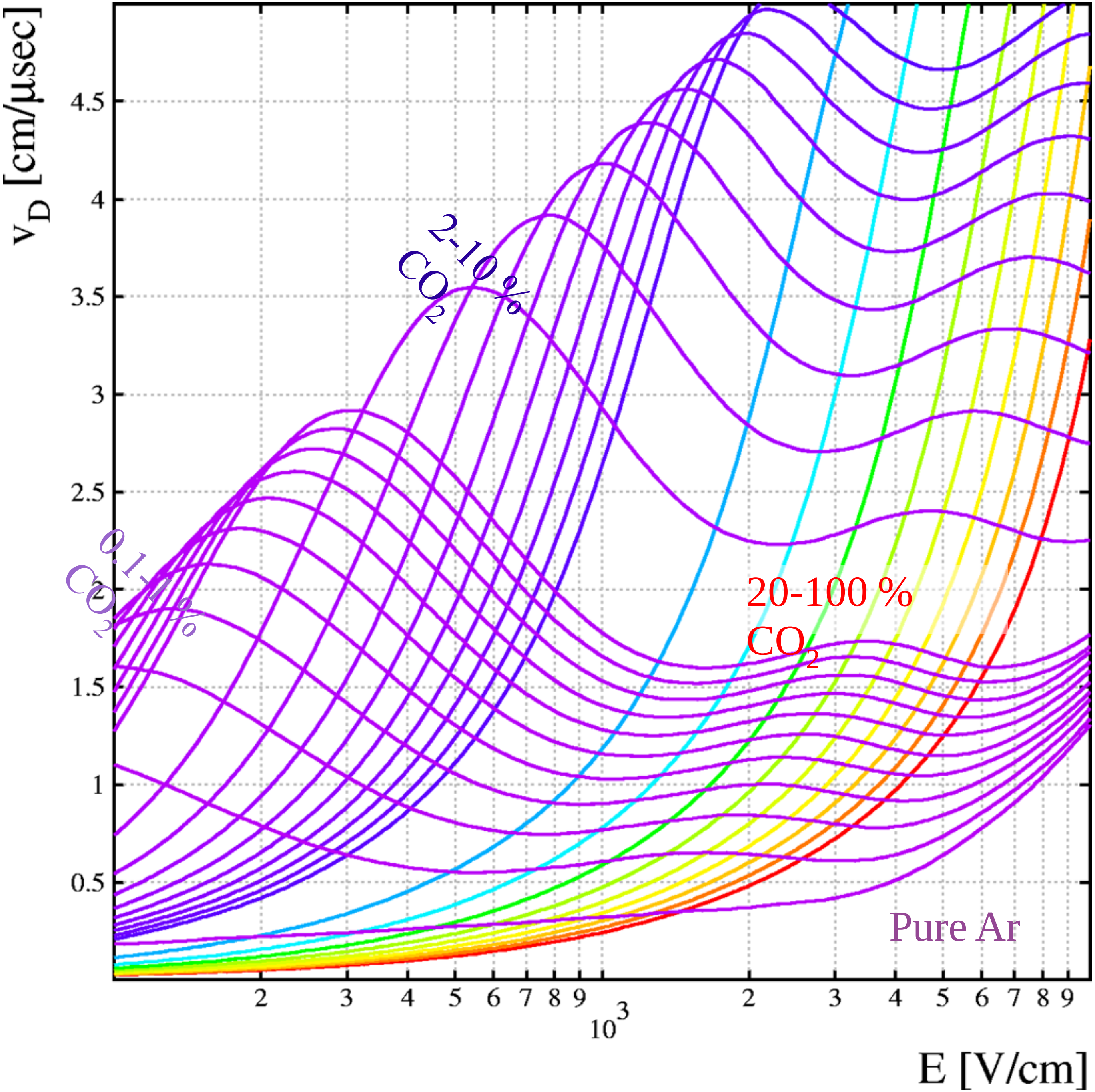
Drift velocity in argon



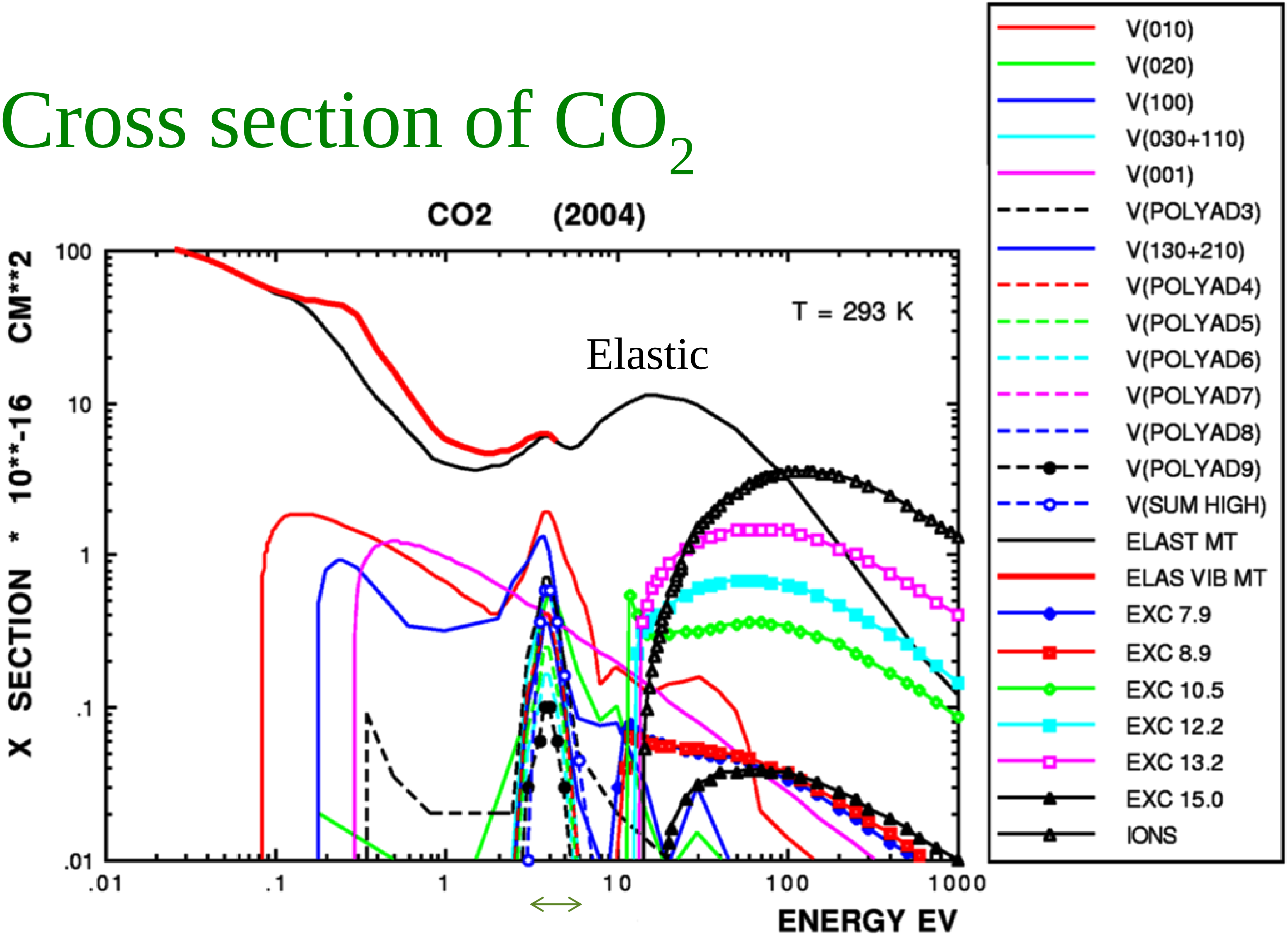
# Ar + $CO_2$

- $CO_2$ makes the gas faster, dramatically.
- Why ?

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



# Cross section of $CO_2$



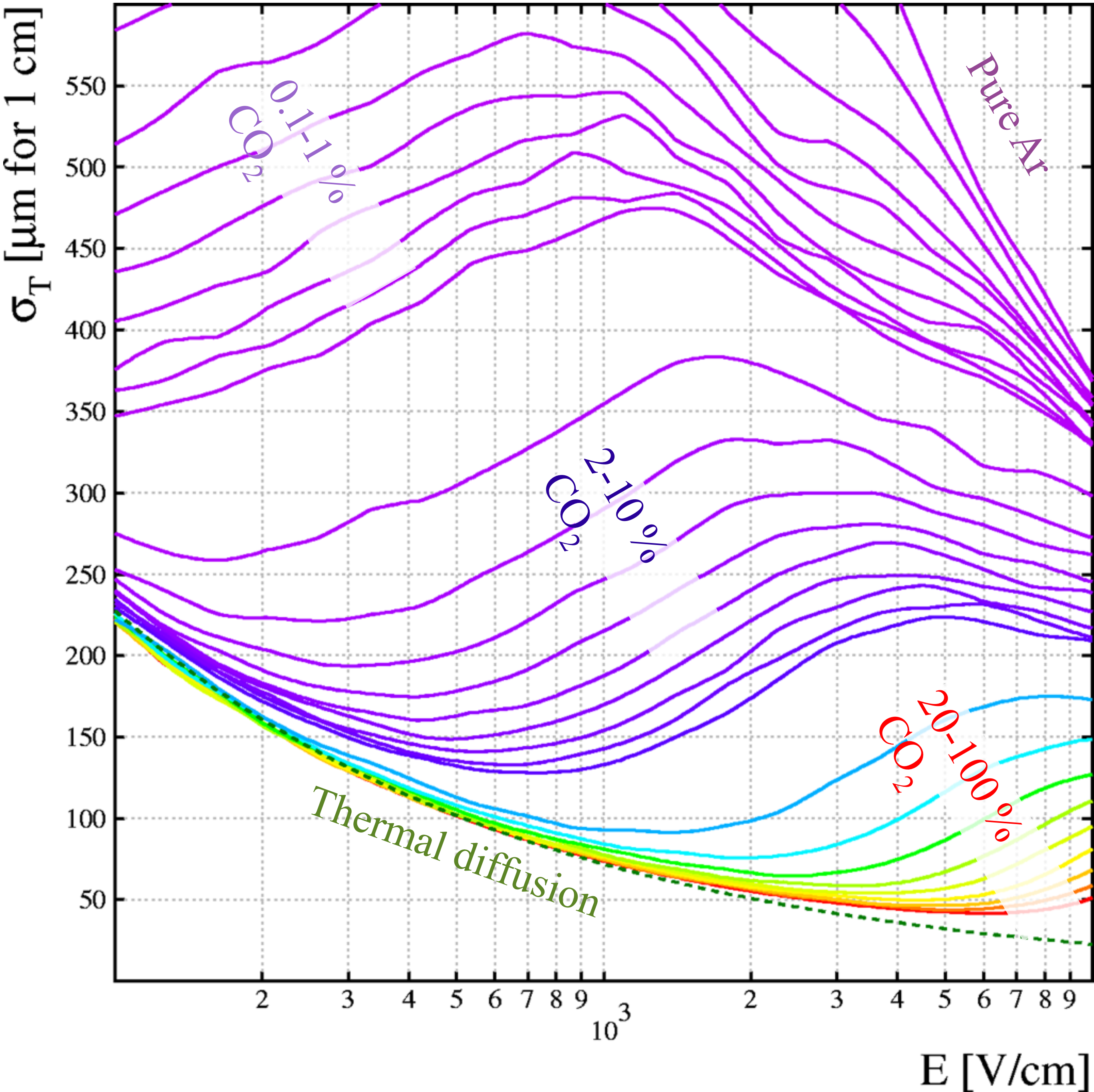
Attachment range:
4 eV < □ < 8 eV

Ionisation threshold:
□ = 13.8 eV

# Ar + $CO_2$

- Transverse diffusion is much reduced by $CO_2$.

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



# Diffusion

- Electrons scatter during transport, in particular in mainly elastic gases.

- A typical value is 200 μm lateral spread after 1 cm. How much would this be after 1 m ?

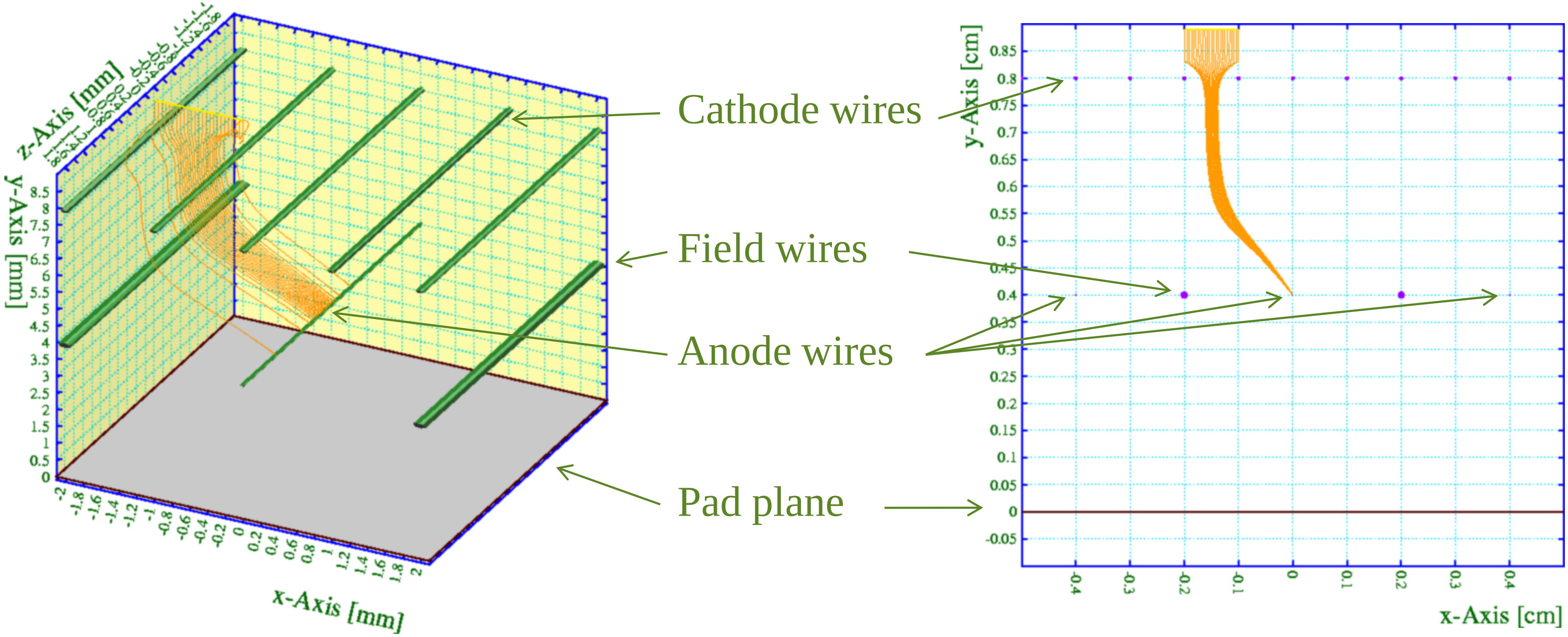
# Scale $\gg$ mean free path (> 1 mm)

- For practical purposes, electrons from a given starting point reach the same electrode – but with a spread in time and gain.

- Electrons transport is treated by:
  - integrating the equation of motion, using the Runge-Kutta-Fehlberg method, to obtain the path;
  - integrating the diffusion and Townsend coefficients to obtain spread and gain.

- This approach is adequate for TPCs, drift tubes etc.

# TPC read-out structure



Cathode wires

Field wires

Anode wires

Pad plane

# Scale > mean free path (100 □m - 1 mm)

- Electrons from a single starting point may end up on any of several electrodes.

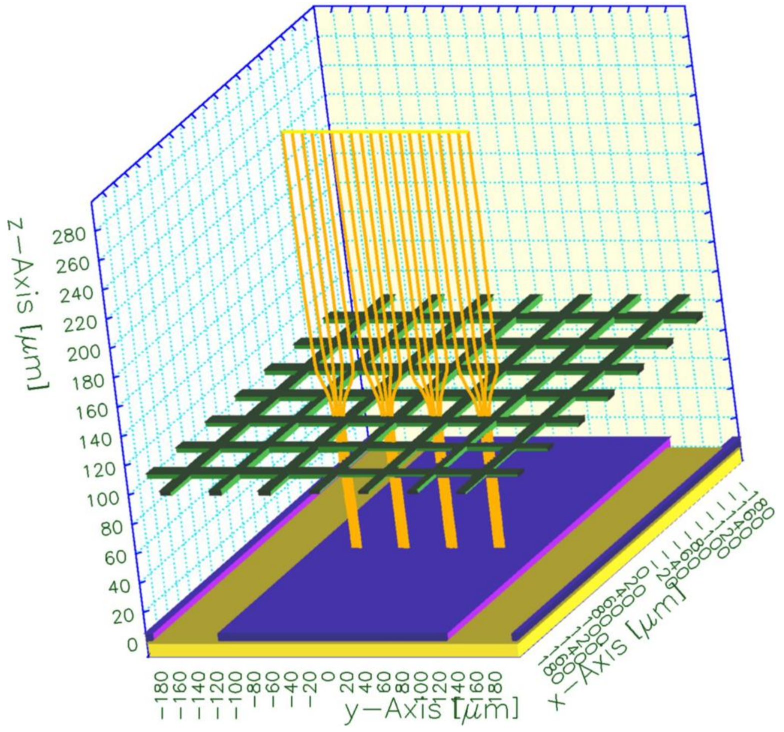
- Calculations use Monte Carlo techniques, based on the mean drift velocity and the diffusion tensor computed by microscopic integration of the equation of motion in a constant field. Gain depends on the path.

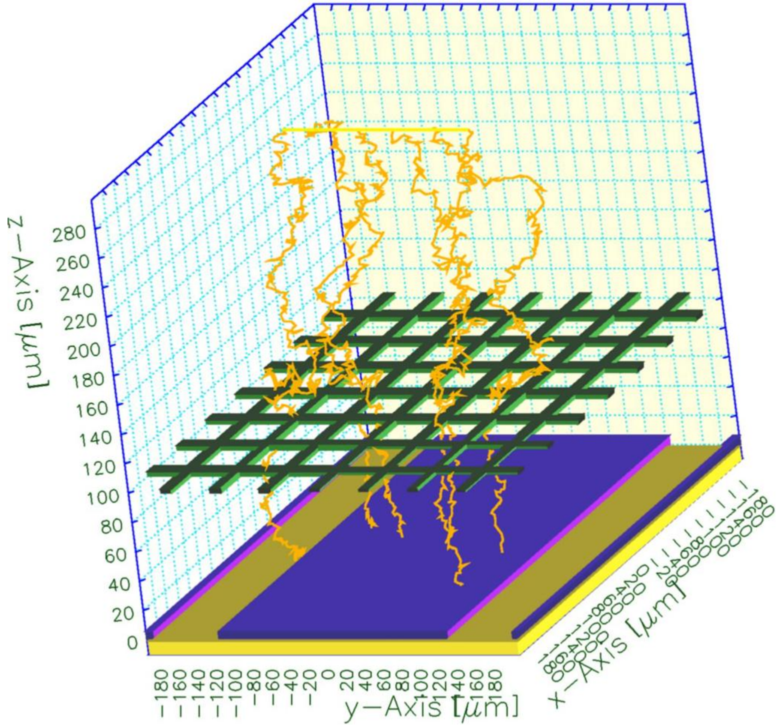
- This approach is adequate as long as the drift field is locally constant – a reasonably valid assumption in a Micromegas but less so in a GEM.

# Micropattern detector

- Analytic integration
  - Runge-Kutta-Fehlberg technique;
  - automatically adjusted step size;
  - optional integration of diffusion, multiplication and losses.

- Monte Carlo integration
  - non-Gaussian in accelerating, divergent and convergent fields;
  - step size to be set by user.





[Figures made by Gilles Barouch, CEA]

# Scale ~ mean free path (1 μm - 1 mm)

- At this scale, where the mean free path approaches the characteristic dimensions of detector elements, free flight between collisions, is no longer be parabolic.

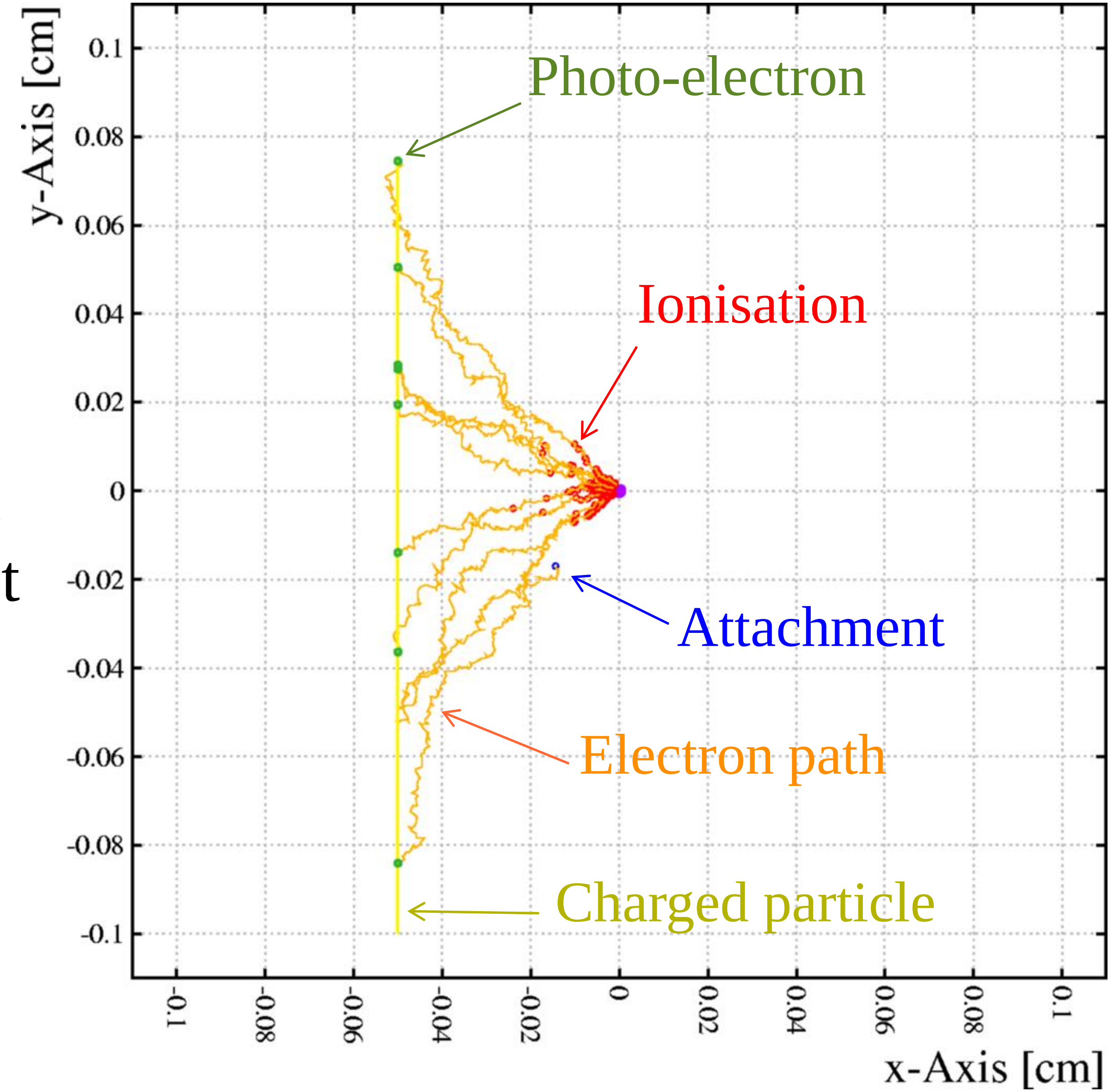
- The only viable approach here seems to be a complete microscopic simulation of the transport processes, taking local field variations into account.

- The method shown here is based on the Magboltz program.

# Molecular tracking

- Example:
- CSC-like structure,
- Ar 80 % $CO_2$ 20 %,
- 10 GeV ▯.

- The electron is shown every 100 collisions, but has been tracked rigourously.



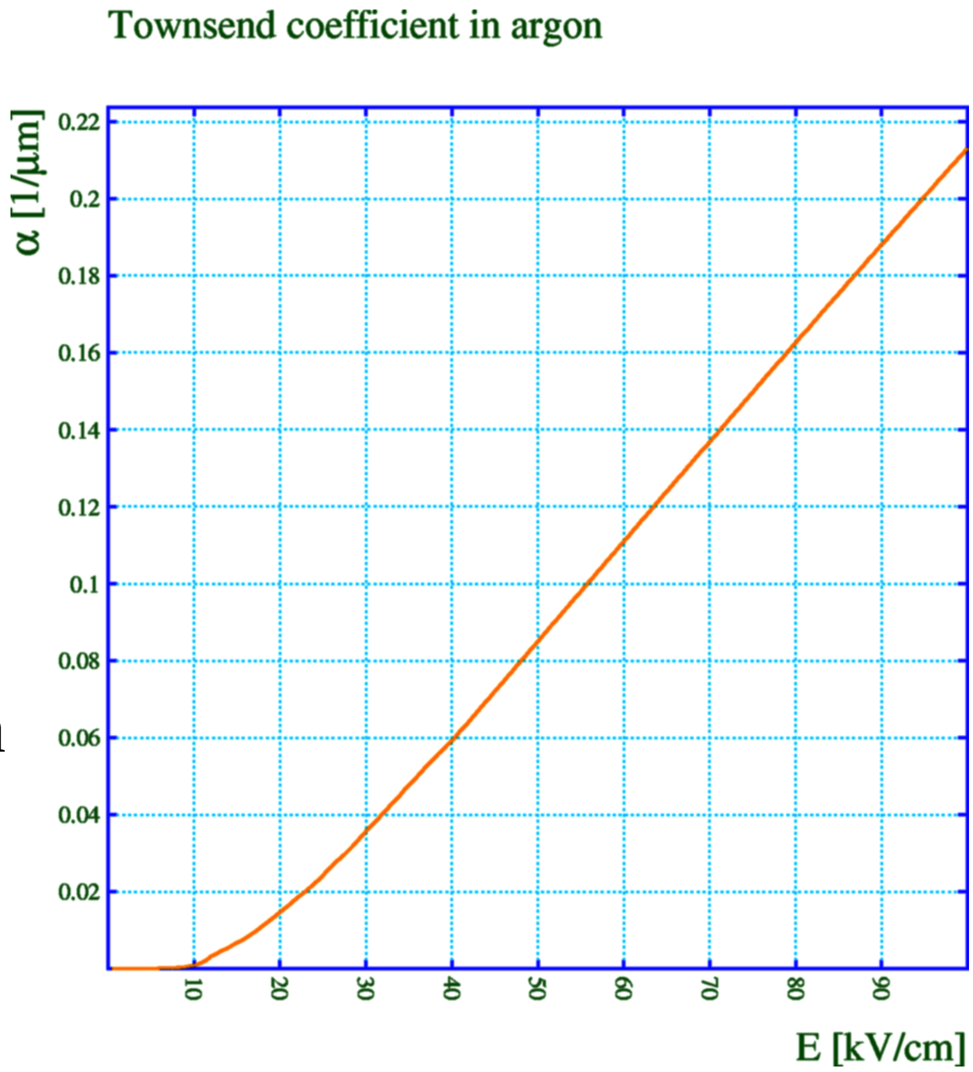
# Phase 3: Gain

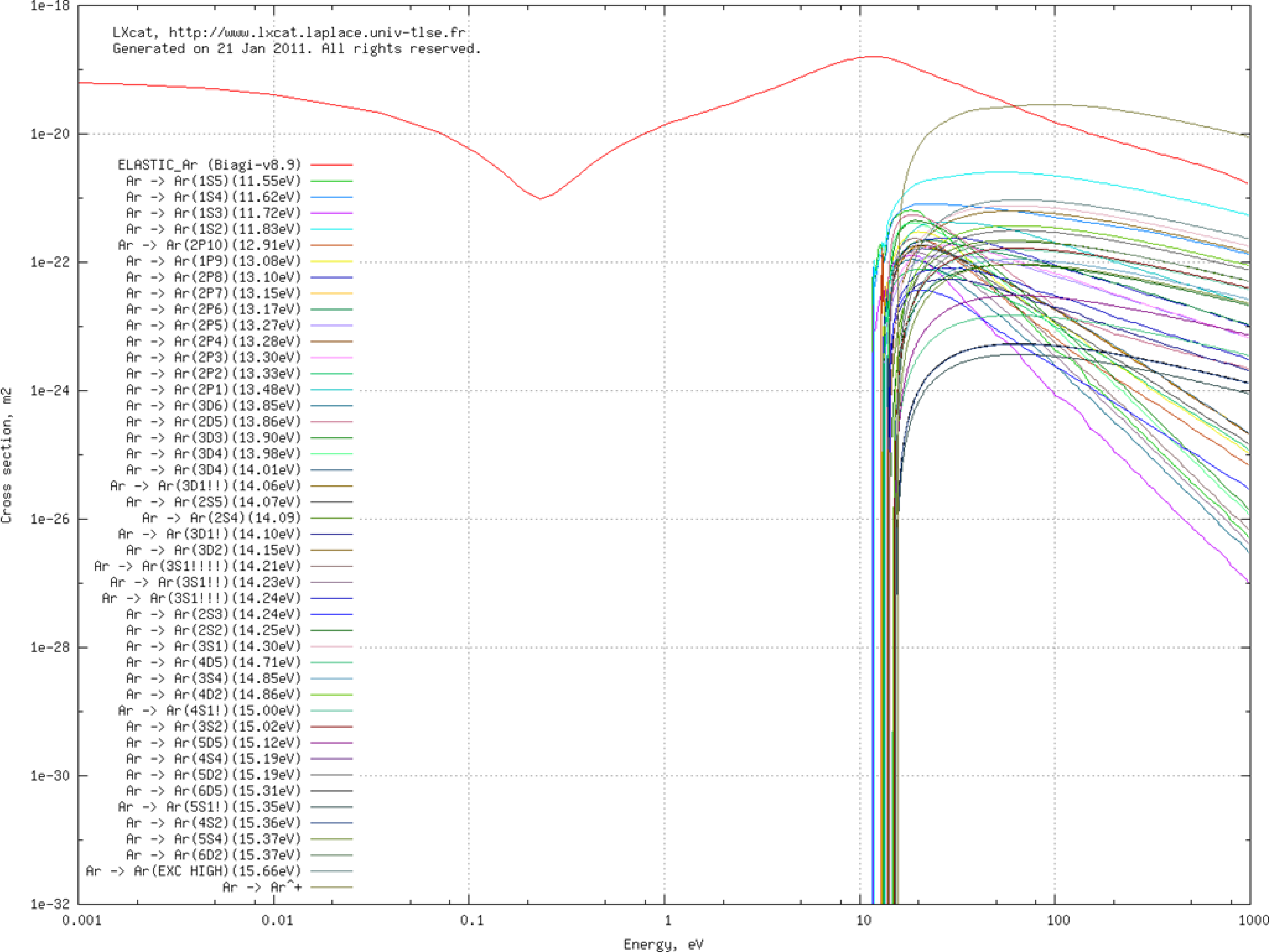
- After transport, we still have most probably 40 electrons per cm of gas. We need to detect them. If we collect them on an electrode over 1 µsec, the current will be:

- Maybe manageable nowadays, but certainly not comfortable. Amplification is required.
- Amplification calls for fields where the energy after a mean free path > ionisation energy.

# Energy after a mean free path

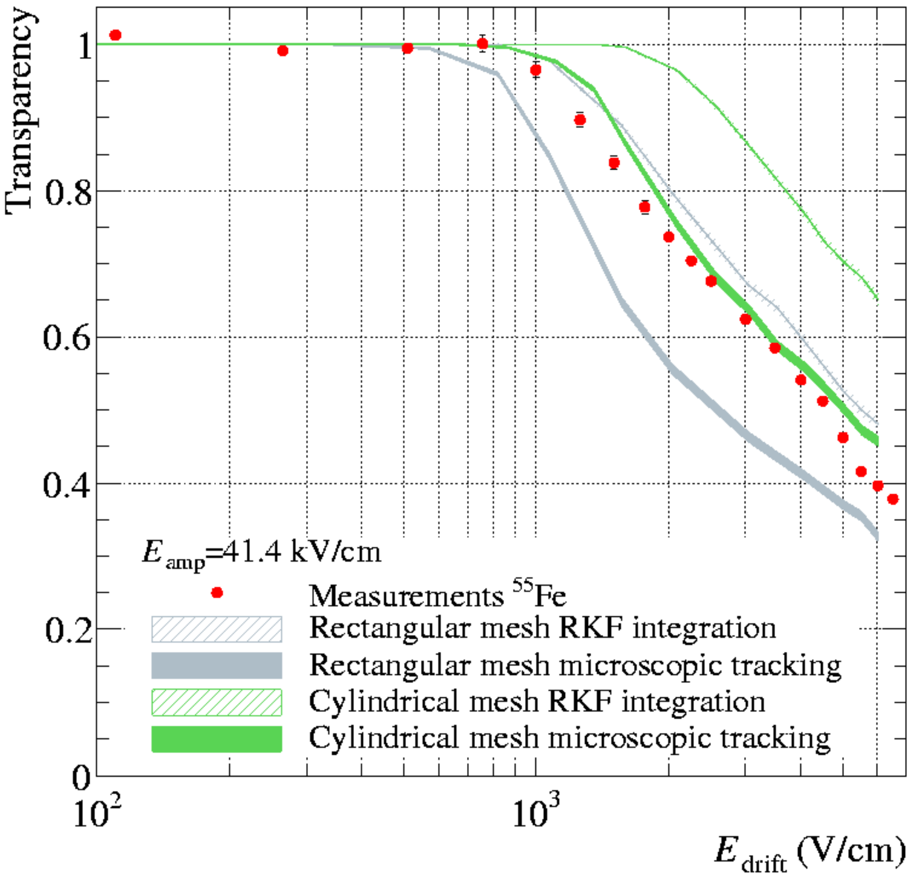
- Energy after a distance :
- Ionisation energy of argon:
- About 15.7 eV
- Ionisation would occur at:
- *E* > 75 kV/cm
- Multiplication indeed occurs at such fields, avalanches start much earlier, though.
- $\alpha$: Townsend coefficient, new $e^-$ per unit length.

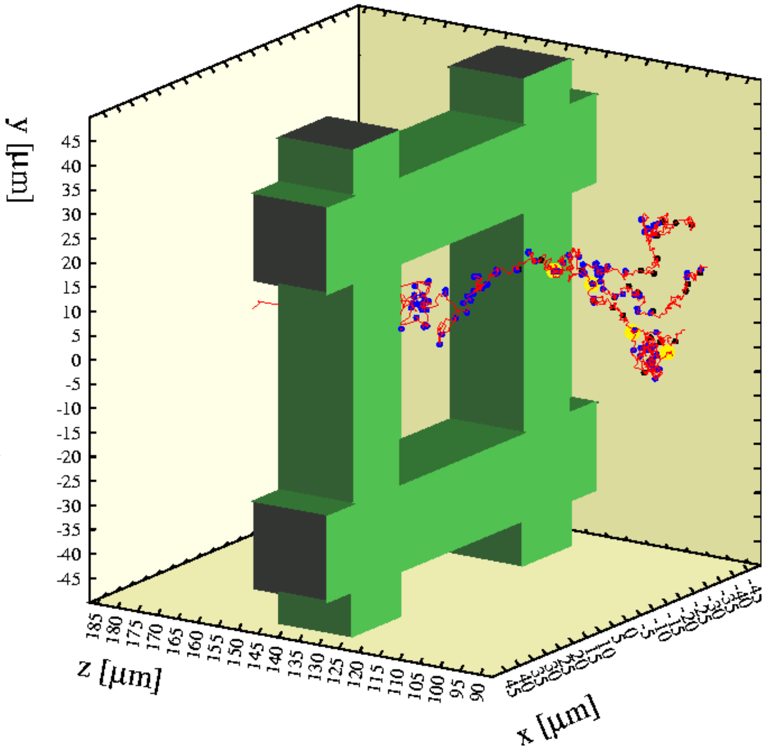


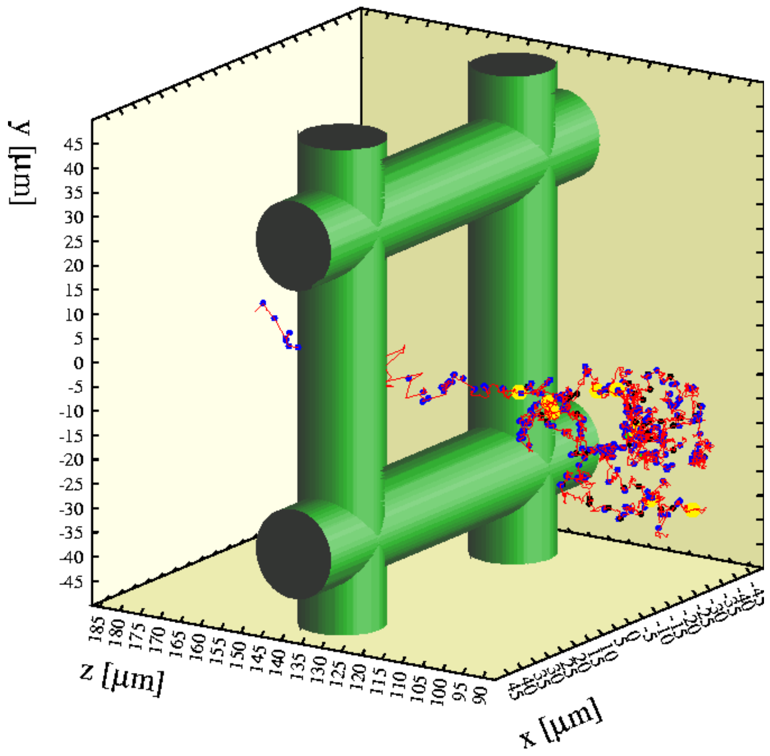

LXcat, http://www.lxcat.laplace.univ-tlse.fr
Generated on 21 Jan 2011. All rights reserved.
ELASTIC_Ar (Biagi-v8.9)
Ar -> Ar(1S5)(11.55eV)
Ar -> Ar(1S4)(11.62eV)
Ar -> Ar(1S3)(11.72eV)
Ar -> Ar(1S2)(11.83eV)
Ar -> Ar(2P10)(12.91eV)
Ar -> Ar(1P9)(13.08eV)
Ar -> Ar(2P8)(13.10eV)
Ar -> Ar(2P7)(13.15eV)
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^+
1e-18
1e-20
1e-22
1e-24
1e-26
1e-28
1e-30
1e-32
Cross section, m2
0.001
0.01
0.1
1
10
100
1000
Energy, eV

# Micromegas avalanches

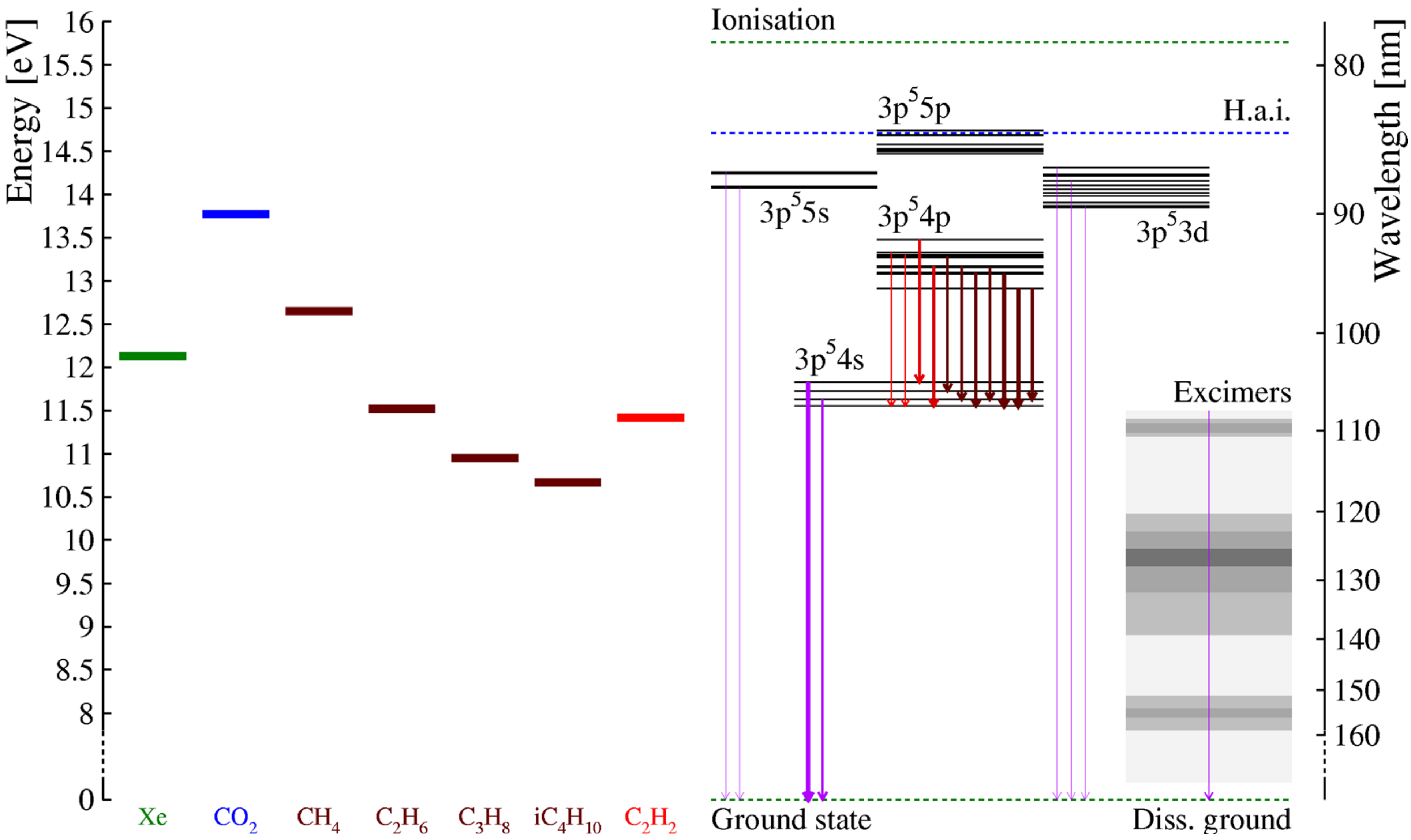
- Part of a study to verify the diffusion spread during avalanches in a Micromegas mesh.





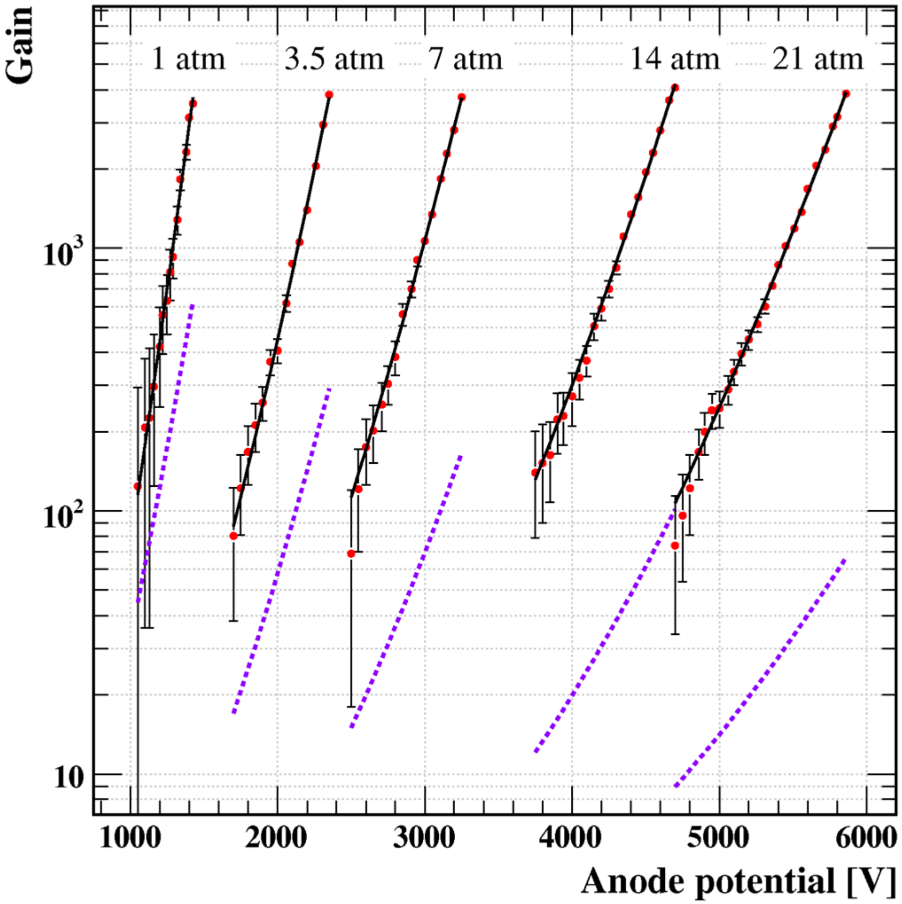


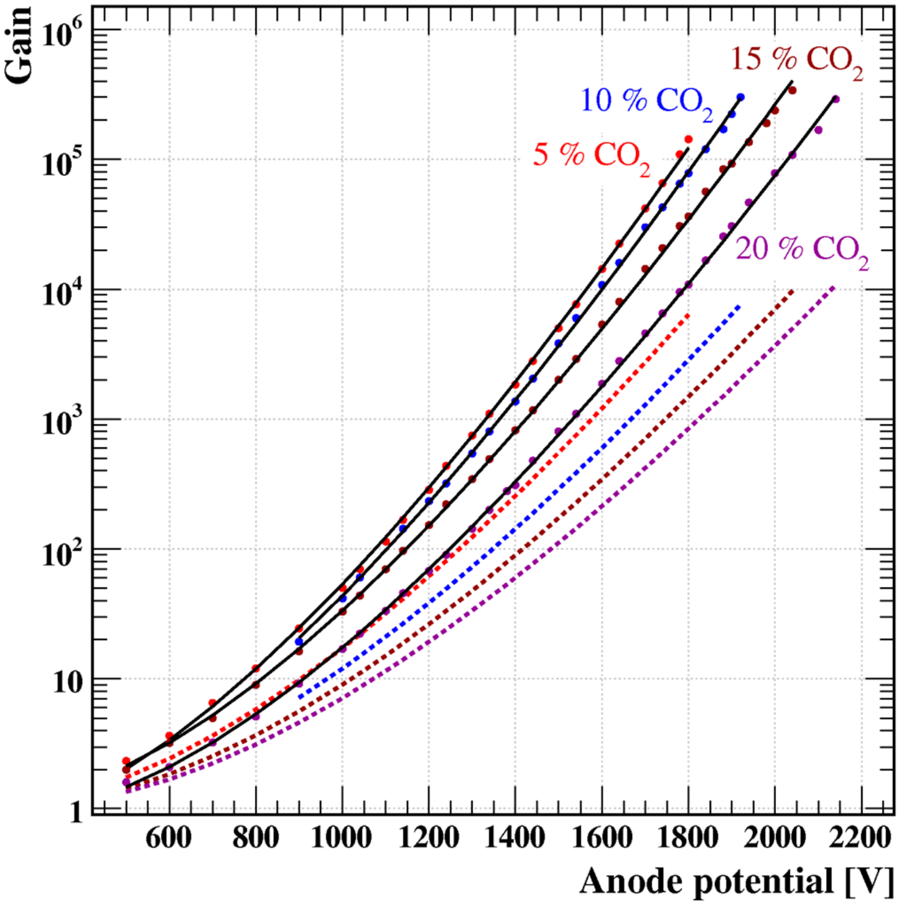
# Level diagram argon and admixtures



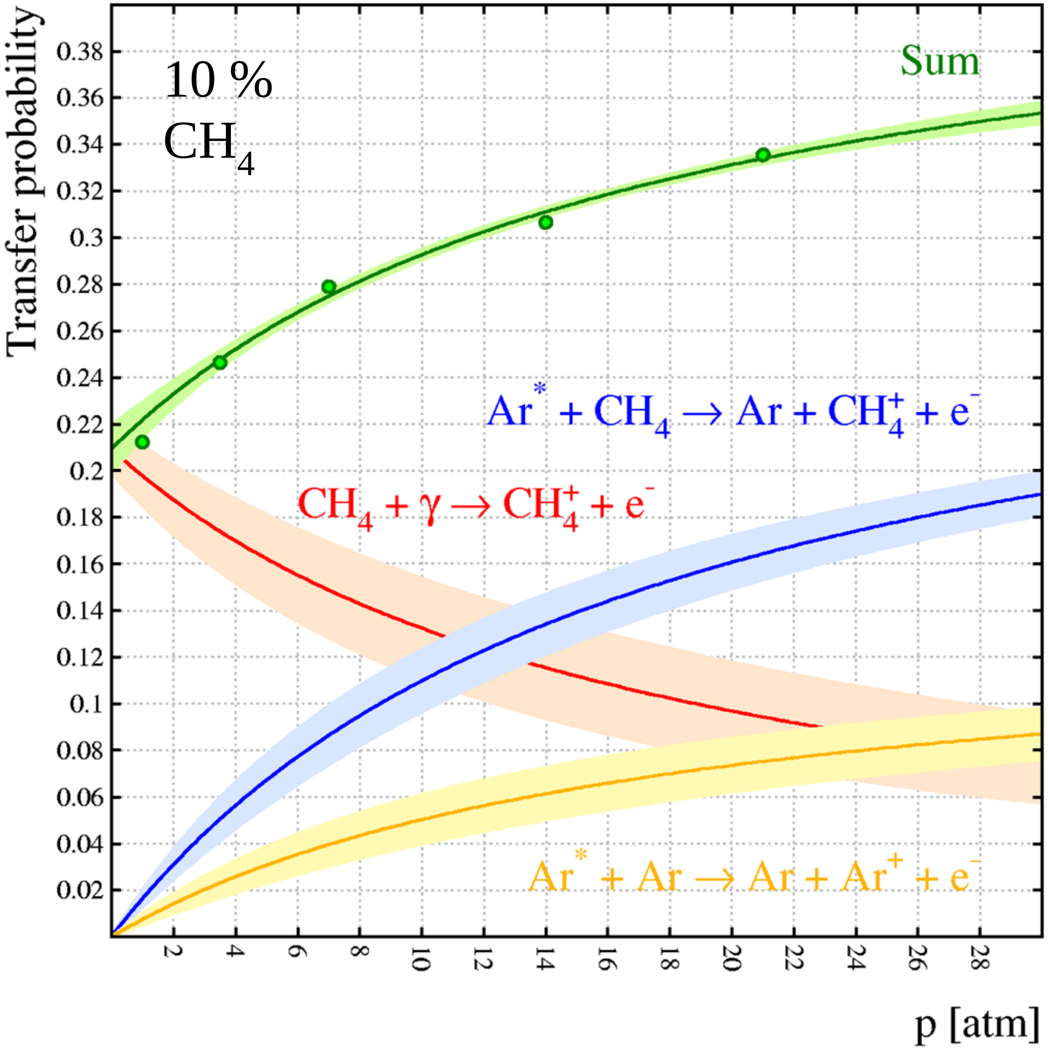
# Importance of Penning transfer

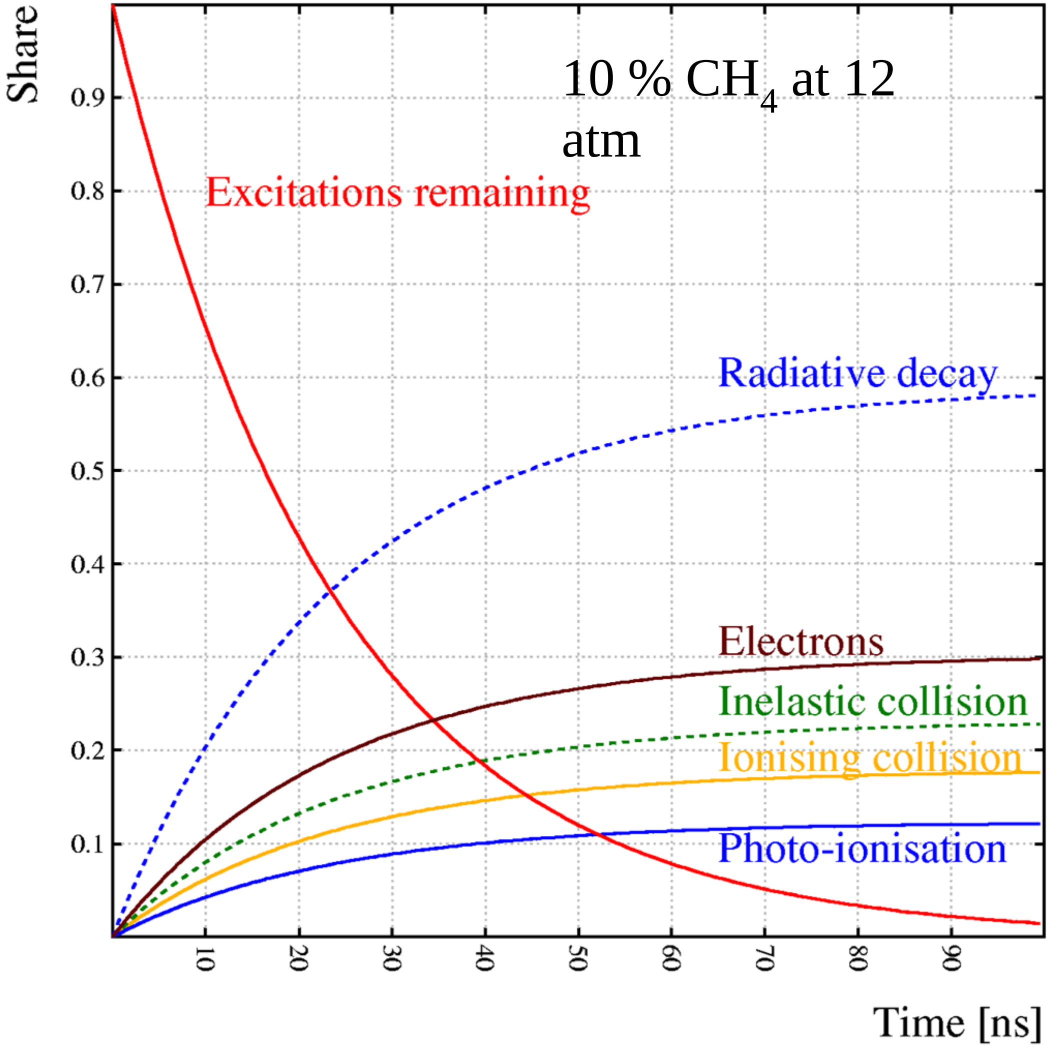
- Ar$^*$ 4p, 3d … $\rightarrow$ $CH_4^+$ + $e^-$
- Ar$^*$ 3d … $\rightarrow$ $CO_2^+$ + $e^-$





# Ar-CH$_4$: processes and timing





# Avalanche growth

- The avalanche size $n(x)$, increased in principle in a very simple manner:

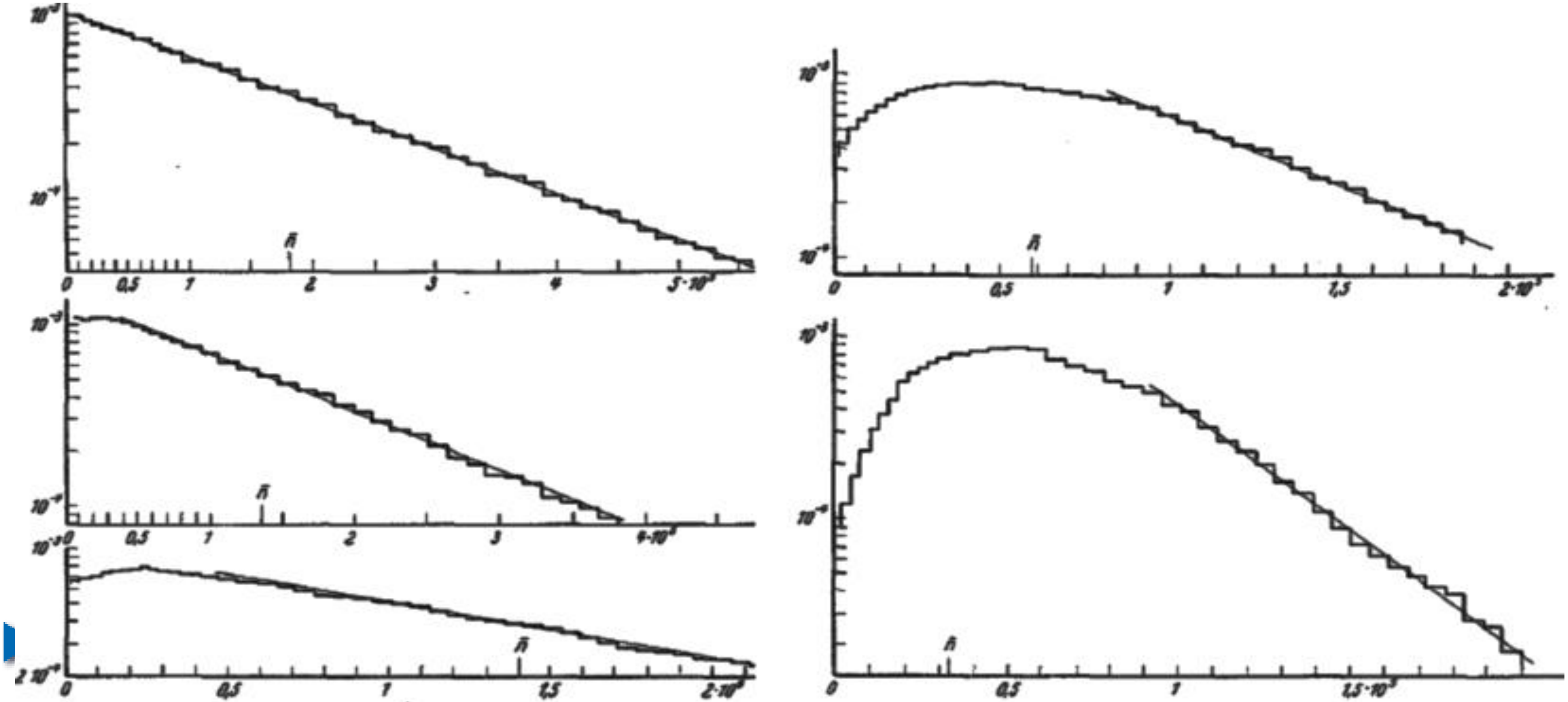
# Avalanche statistics

- Exponentials like each other, and in the simplest models also the size is exponentially distributed.
- This neglects the effects of
  - minimum path length before a new ionisation;
  - energy loss in inelastic collisions;
  - excitations;
  - Penning effect;
  - attachment.

- DOI: `10.1016/j.nima.2010.09.072`

# Avalanche size distributions

- Data for dimethoxymethane at increasing E field:



*Feld*, Z. Phys. **151** (1958) 563-576.

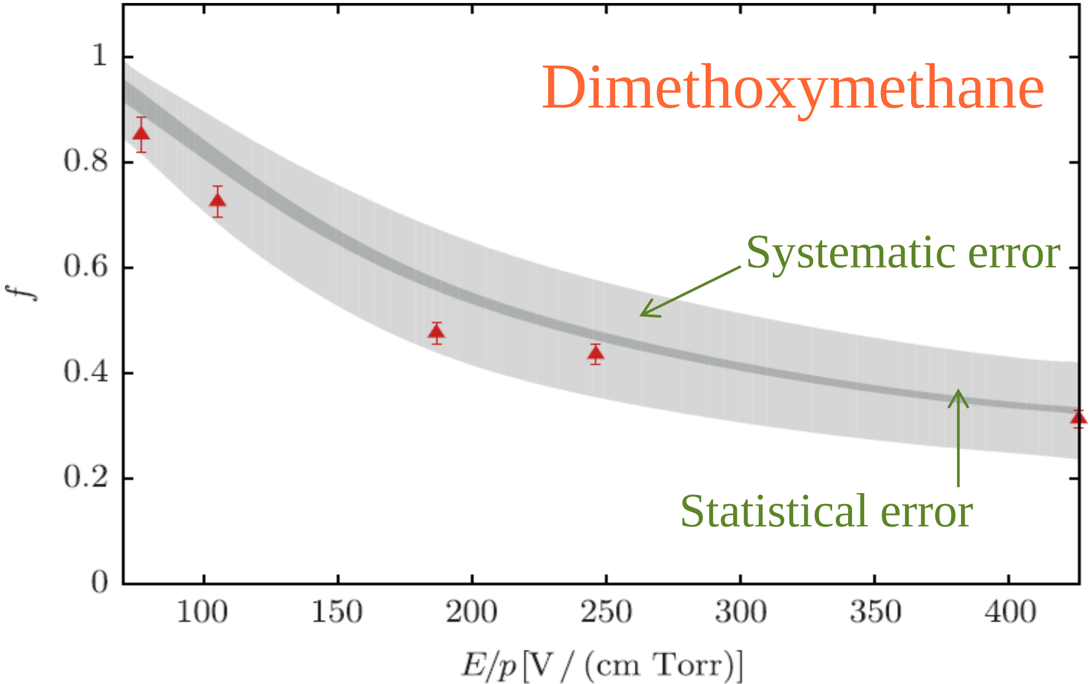
# Relative variance

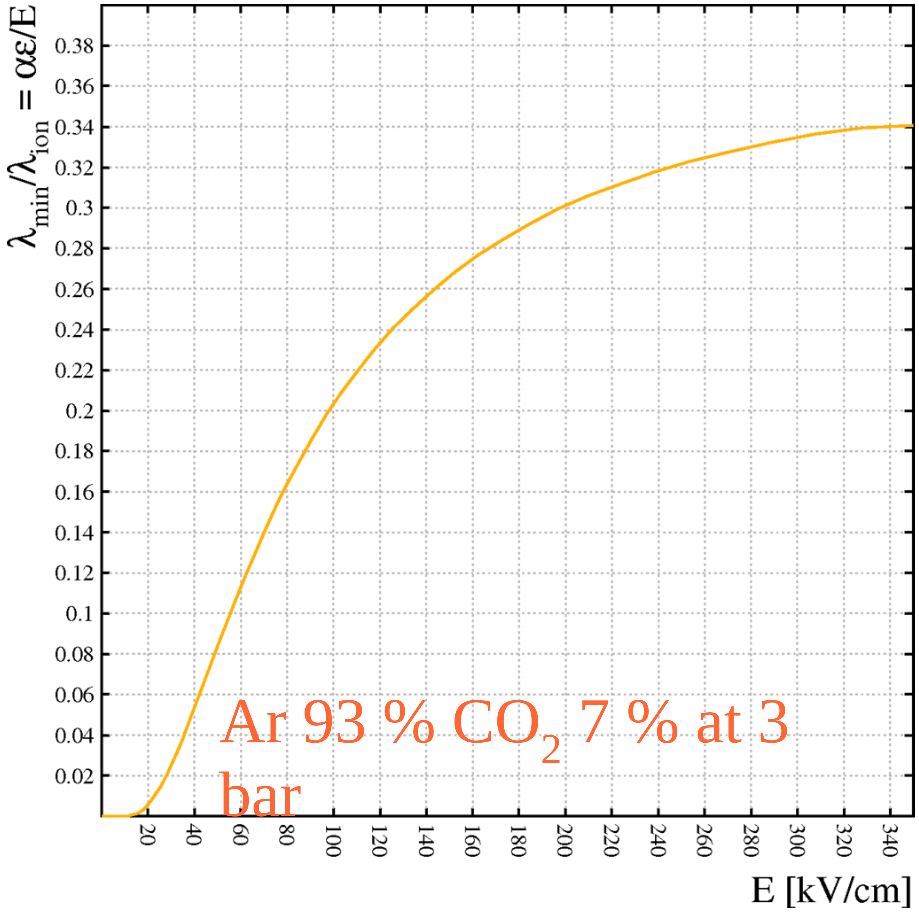
relative variance

▯, no spread

exponential

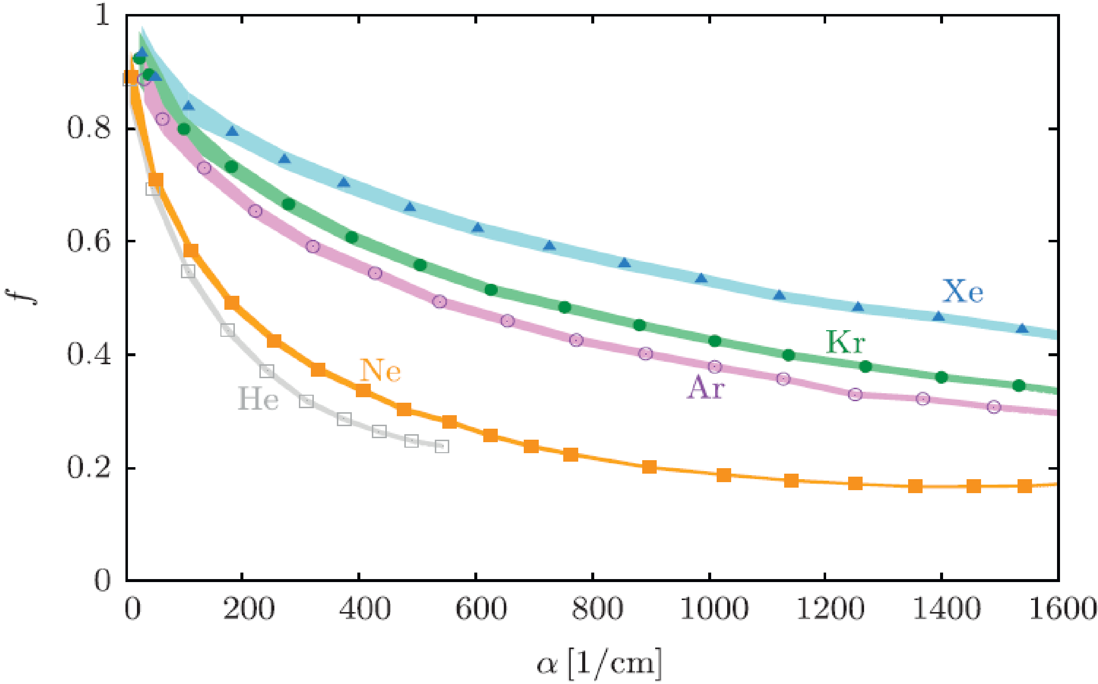
attachment

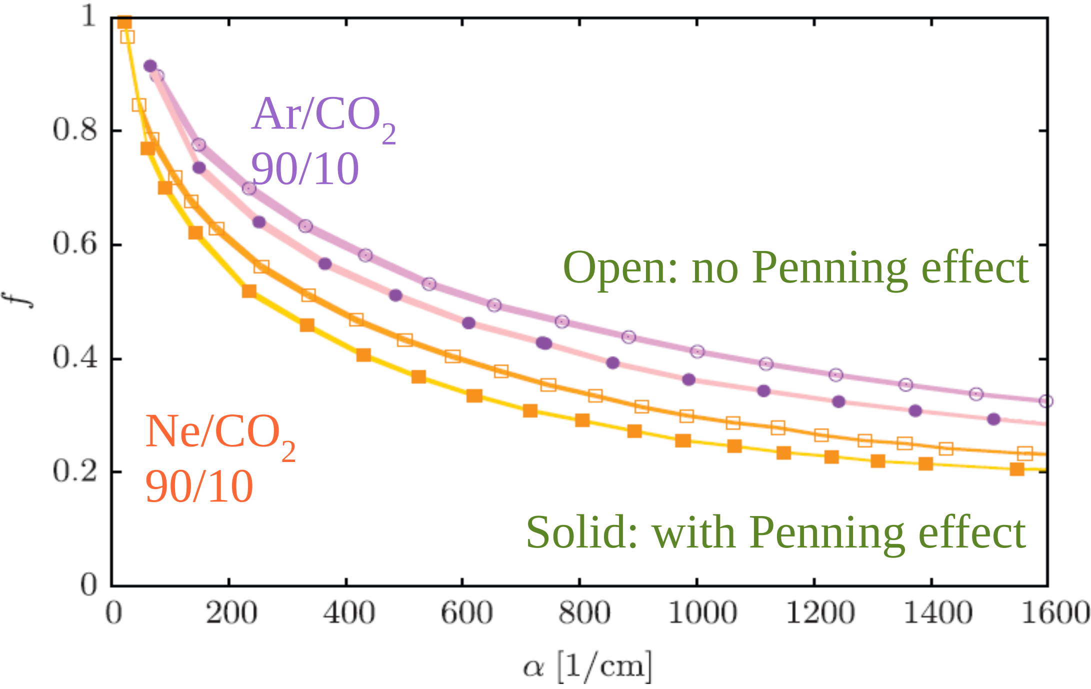


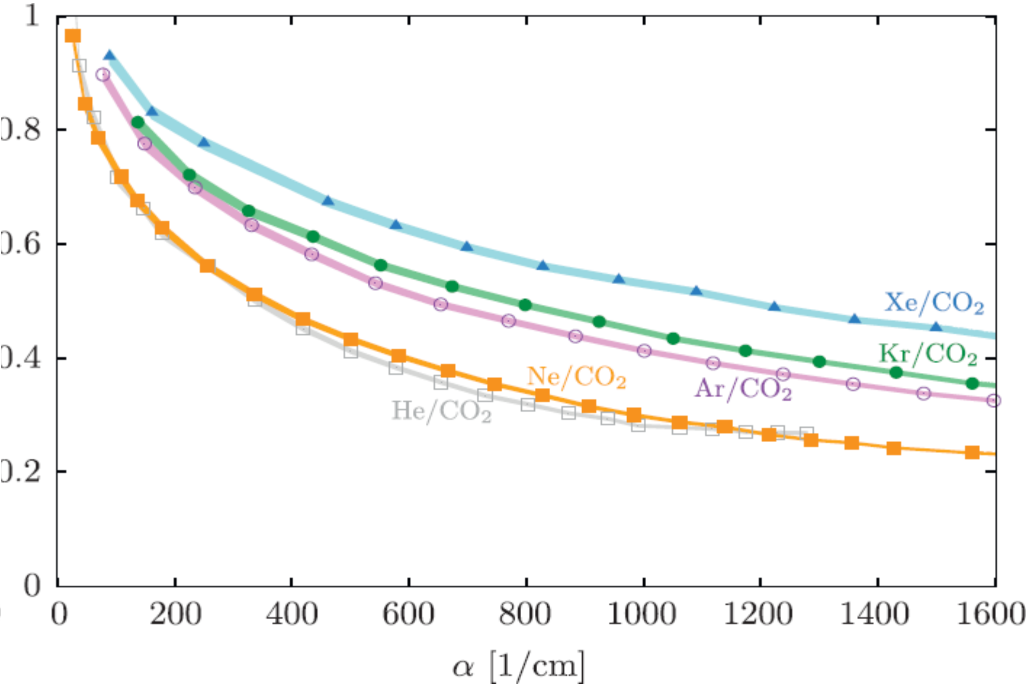


# Minimising *f*

- Quenchers: more inelastic & less ionisation ▯ larger *f* ;
- Penning transforms excitation into ionisation ▯ smaller *f*.





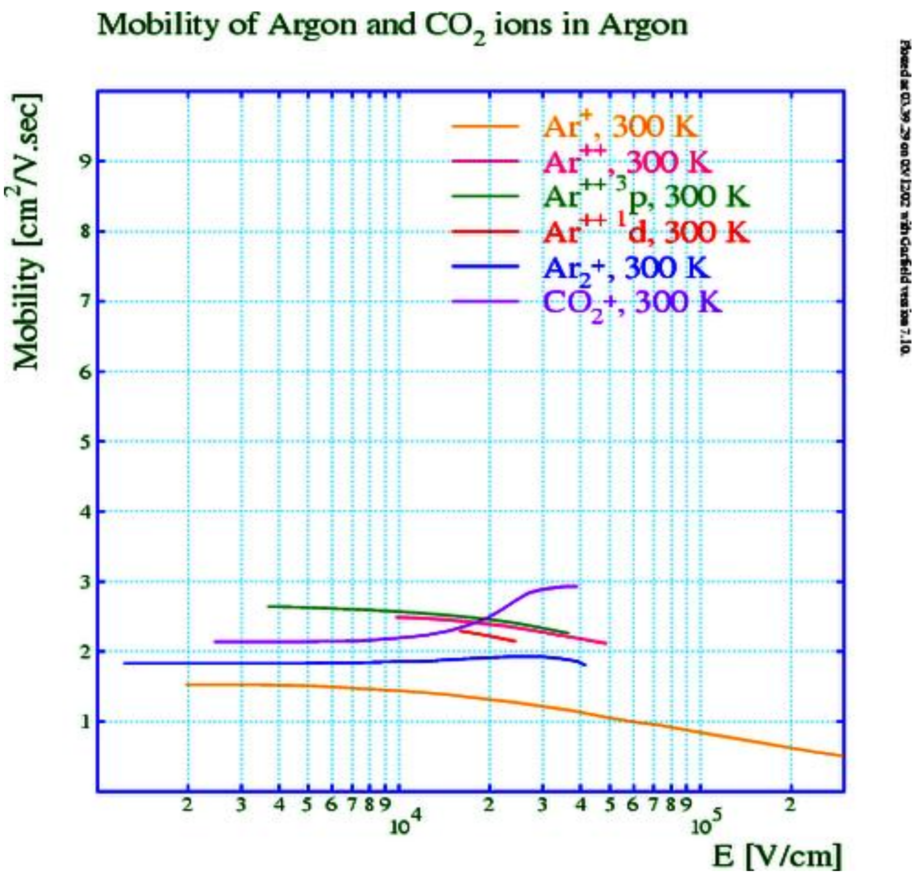


# Ion movement

- Along with the avalanche electrons, we get an equal number of avalanche ions.

- They move in the opposite direction ... and therefore travel much further.

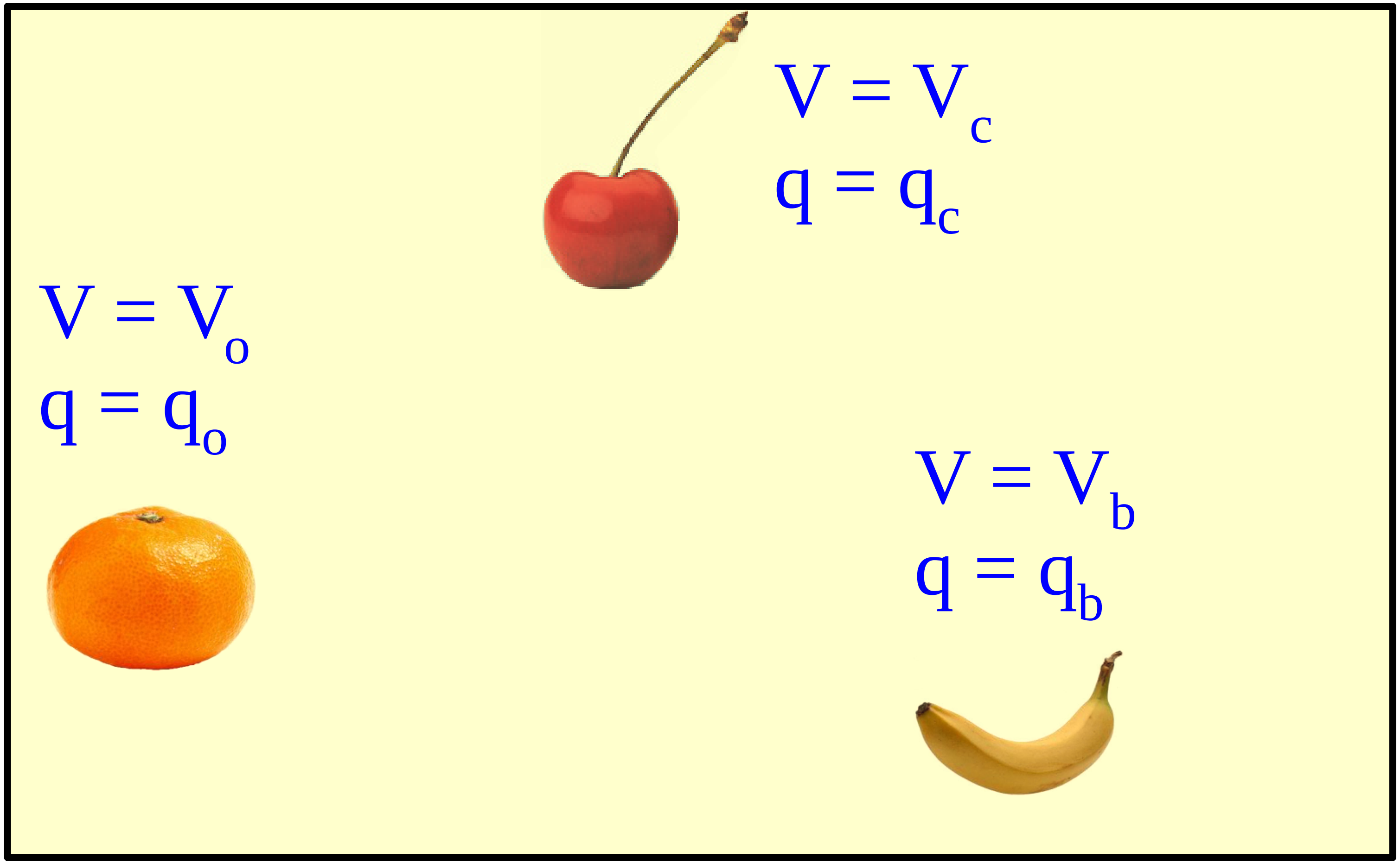
- They are slow: $Ar^+$ in Ar moves at 5 km/h only.



# Phase 4: Signals

- Remains reading the signals induced by the electrons and ions moving around in the chamber.

# Current induction

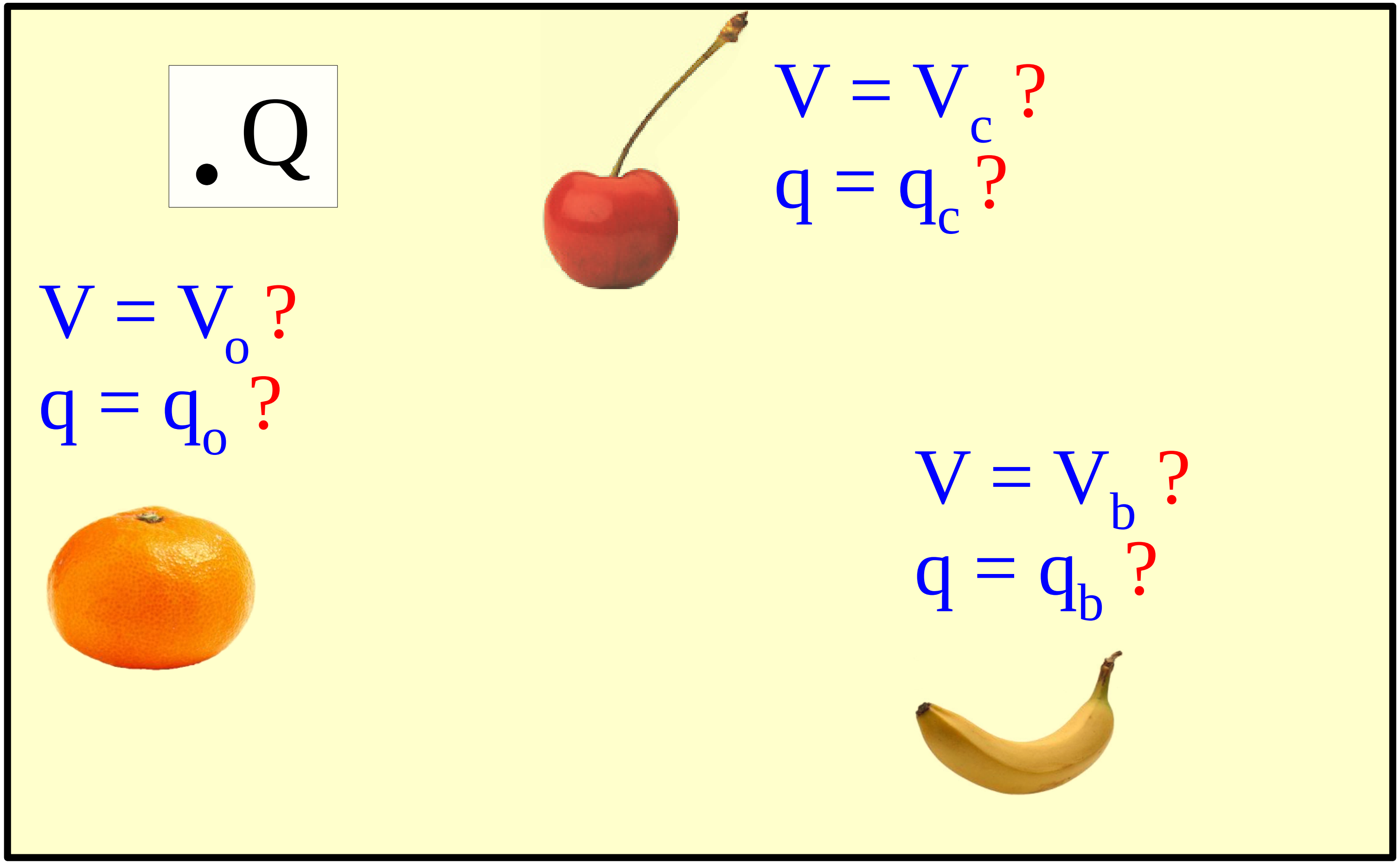


$V = V_c$
$q = q_c$

$V = V_o$
$q = q_o$

$V = V_b$
$q = q_b$

# Current induction



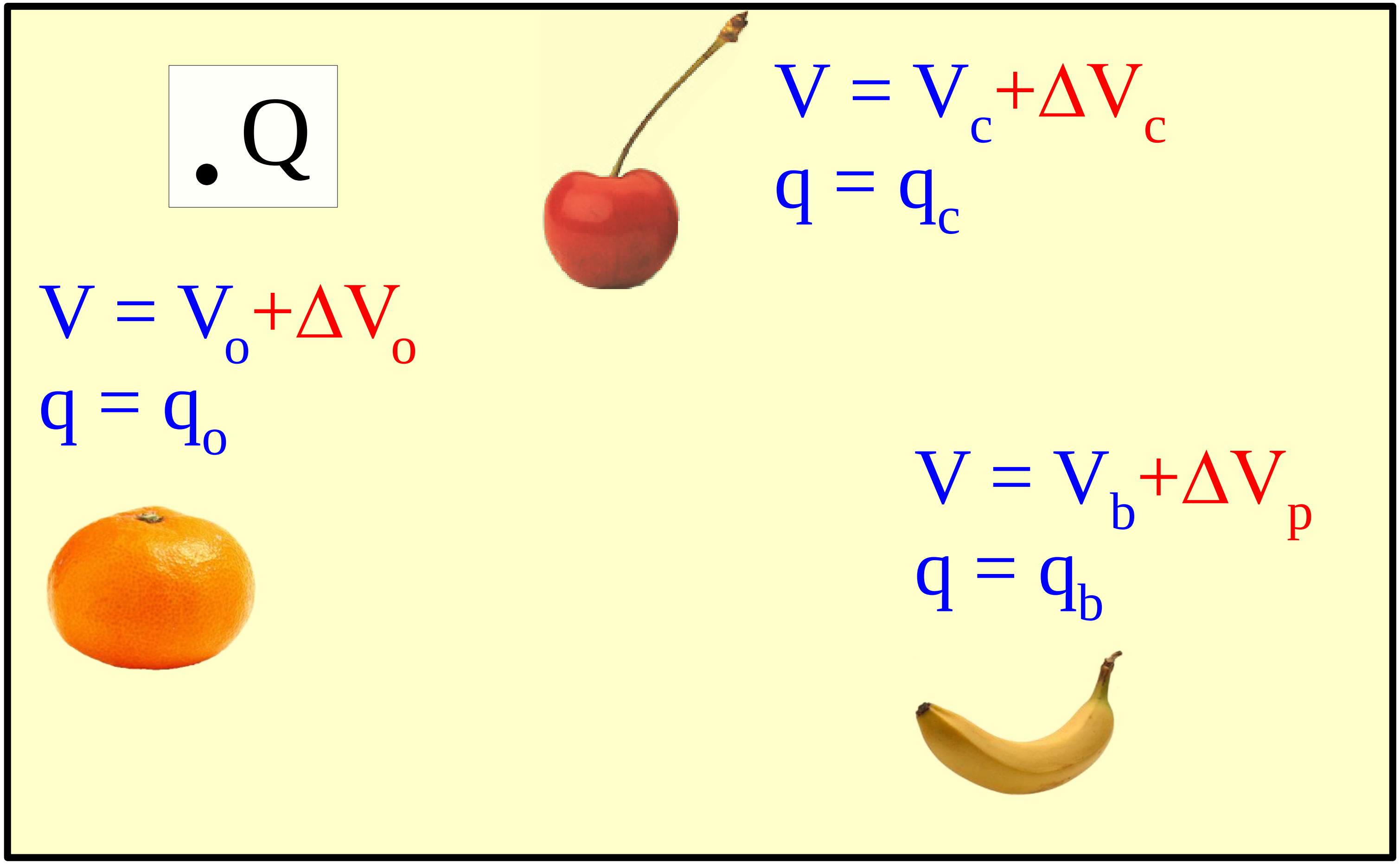
$.Q$

$V = V_c$ ?
$q = q_c$ ?

$V = V_o$ ?
$q = q_o$ ?

$V = V_b$ ?
$q = q_b$ ?

# Current induction



.Q

$V = V_c + \Delta V_c$

$q = q_c$

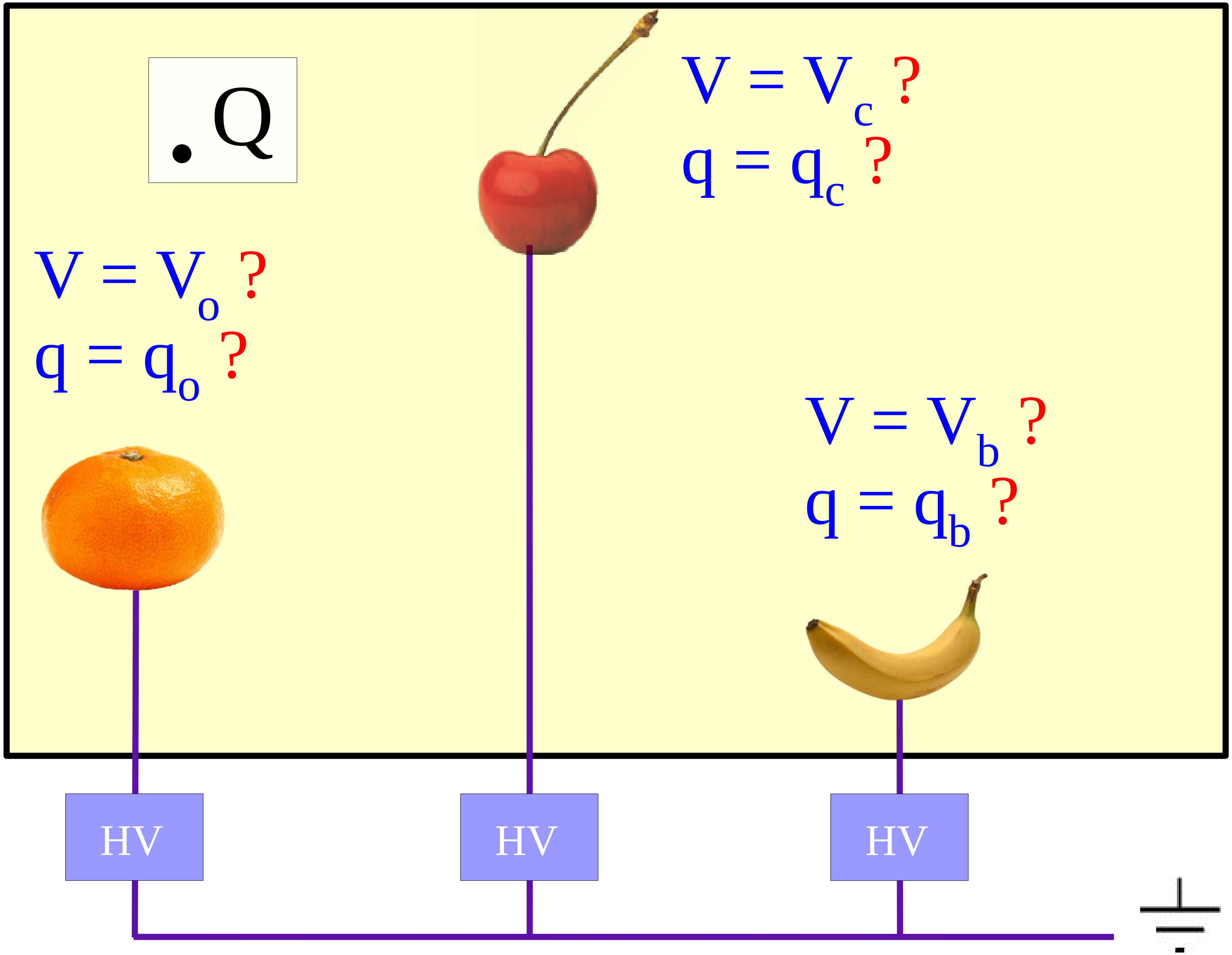
$V = V_o + \Delta V_o$

$q = q_o$

$V = V_b + \Delta V_p$

$q = q_b$

# Current induction



.Q

$V = V_c$ ?
$q = q_c$ ?

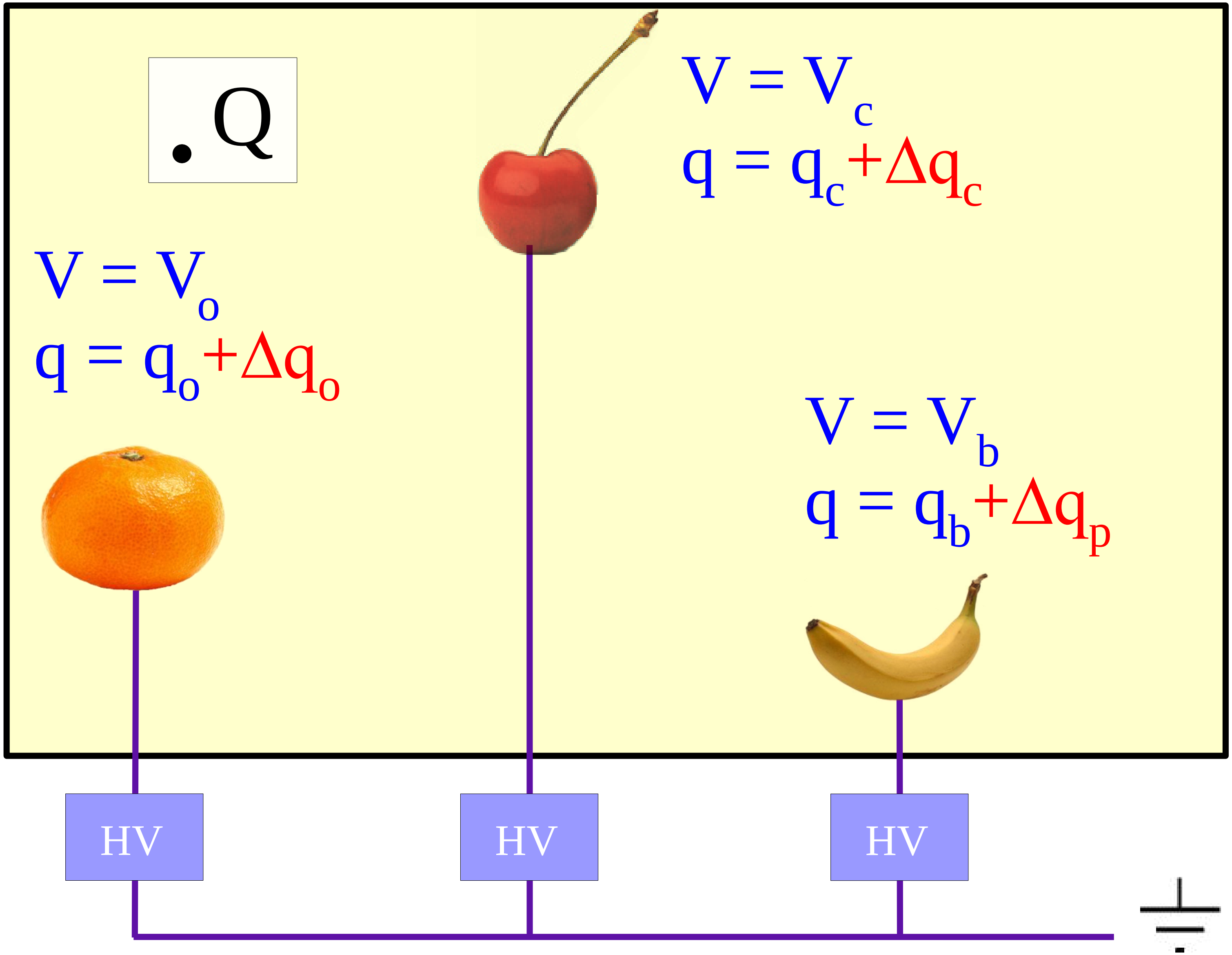
$V = V_o$ ?
$q = q_o$ ?

$V = V_b$ ?
$q = q_b$ ?

# Current induction

No charge creation:

$\Delta q_o + \Delta q_c + \Delta q_p = 0$



.Q

$V = V_c$

$q = q_c + \Delta q_c$

$V = V_o$

$q = q_o + \Delta q_o$

$V = V_b$

$q = q_b + \Delta q_p$

# Signal properties

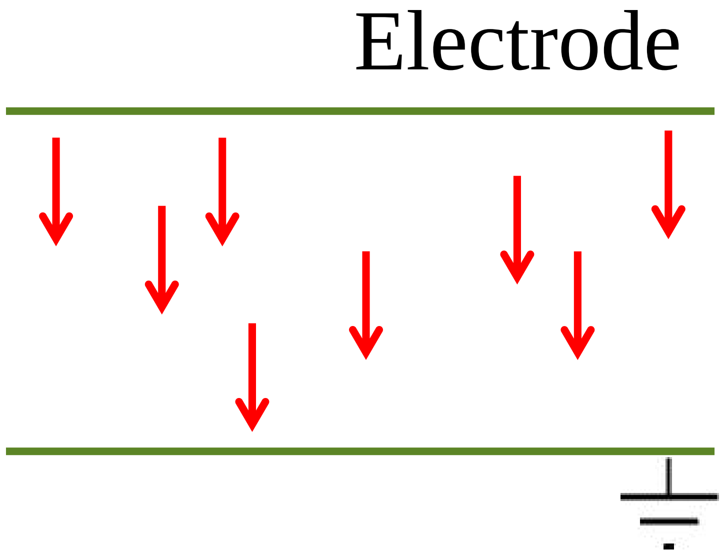
- Properties of the current induced in an electrode:
  - proportional to the charge Q;
  - proportional to the velocity of the charge ;
  - dependent on the electrode and the geometry.

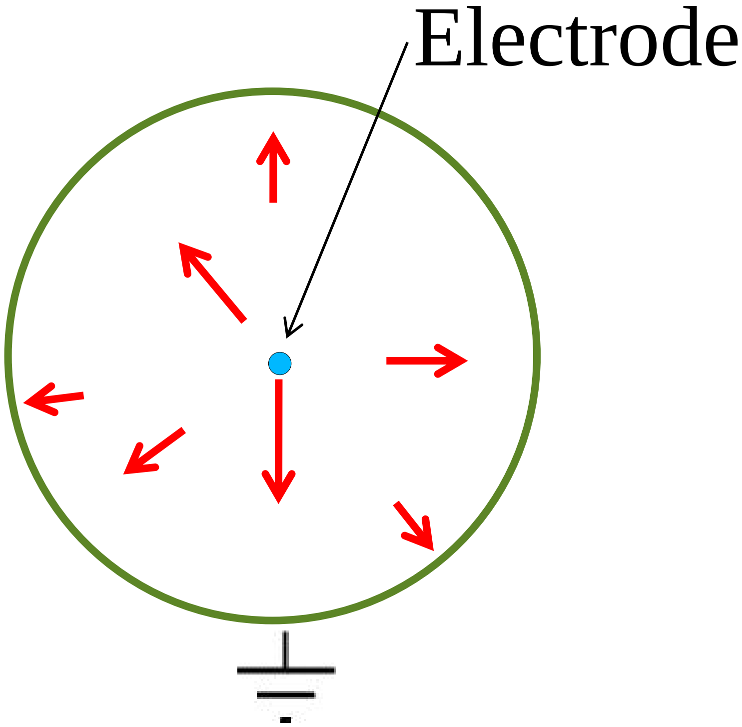
- This leads to the following ansatz:

- The geometry is contained in , necessarily a vectorial quantity, the *weighting field*. Each electrode has its own weighting field.
- The sign is mere convention.

# Weighting field – examples

- The weighting field is often easy to guess:





# Weighting fields

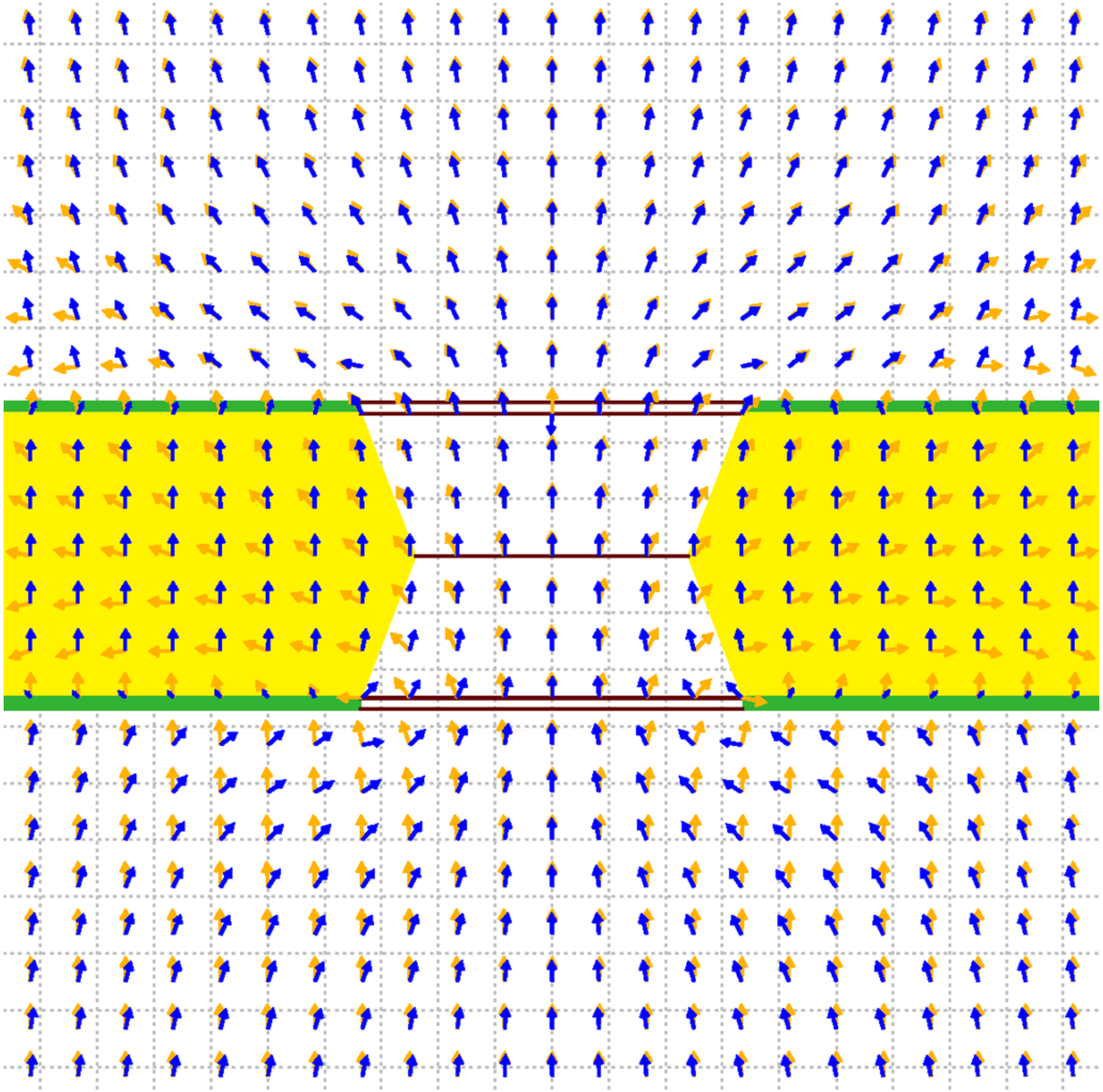
- Claim (without proof): can be computed by setting the potential as follows:
- read-out electrode set to 1,
- all other electrodes set to 0;
- note ... 0 and 1, not 0 V and 1 V !

- This is plausible considering the examples, and
- can be proven using Green's reciprocity. See e.g. George Erskine's paper.

# Weighting field GEM

- Orange:
  weighting field
- Blue:
  electric field
- Yellow:
  plastic
- Green:
  conductors

- The strength of the weighting field is not represented !



# Weighting field Micromegas

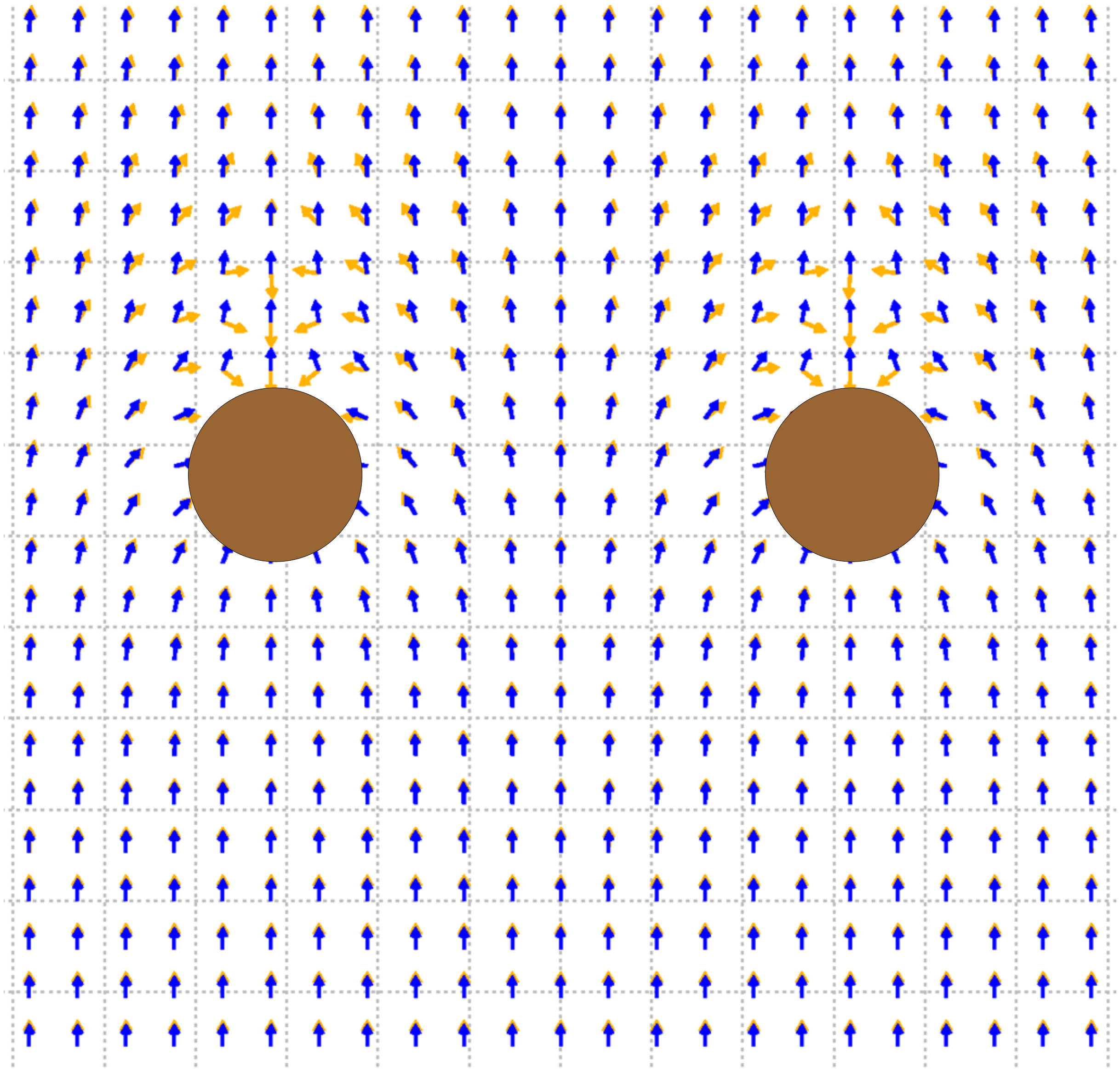
- Orange:

  weighting field
- Blue:

  electric field
- Brown:

  mesh (cut)

- The strength of the weighting field is not represented !



# Summary

- Mechanism:
- charged particles deposit most probably ~40 $e^-$/cm;
- the electrons move with a speed of 1-5 cm/µsec;
- they diffuse during transport, typically 200 µm over 1 cm;
- they multiply near an electrode;
- measurement relies on recording ion + $e^-$ movement.

- Simple arguments, give a feeling for electron and ion transport, but such estimates are not particularly precise.

- Gas-based detectors need to be well-understood, if they are to perform well.