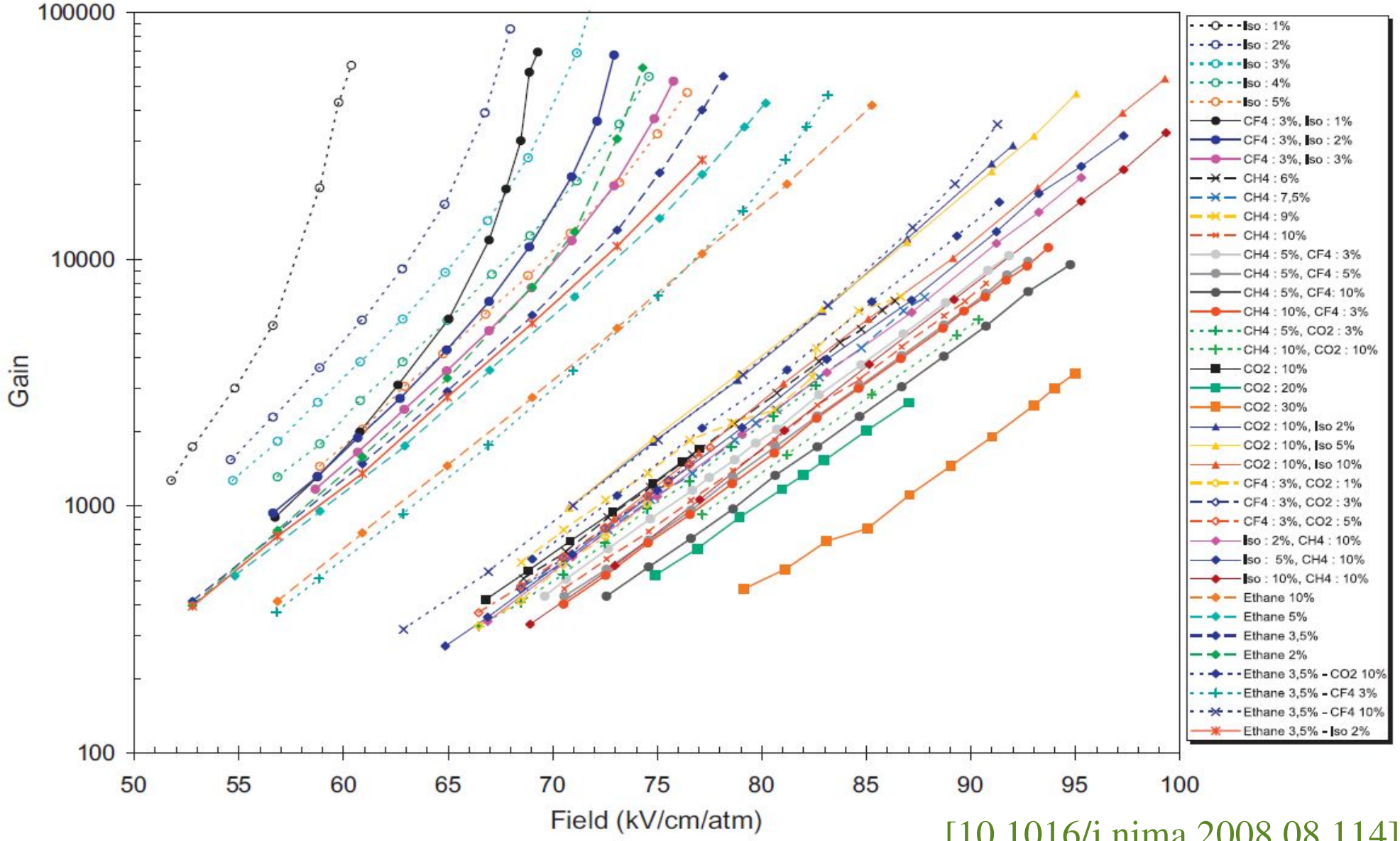
Gain limits

Hints from measurements of Ar mixtures

Saclay Ar compilation



[10.1016/j.nima.2008.08.114]

Saclay compilation

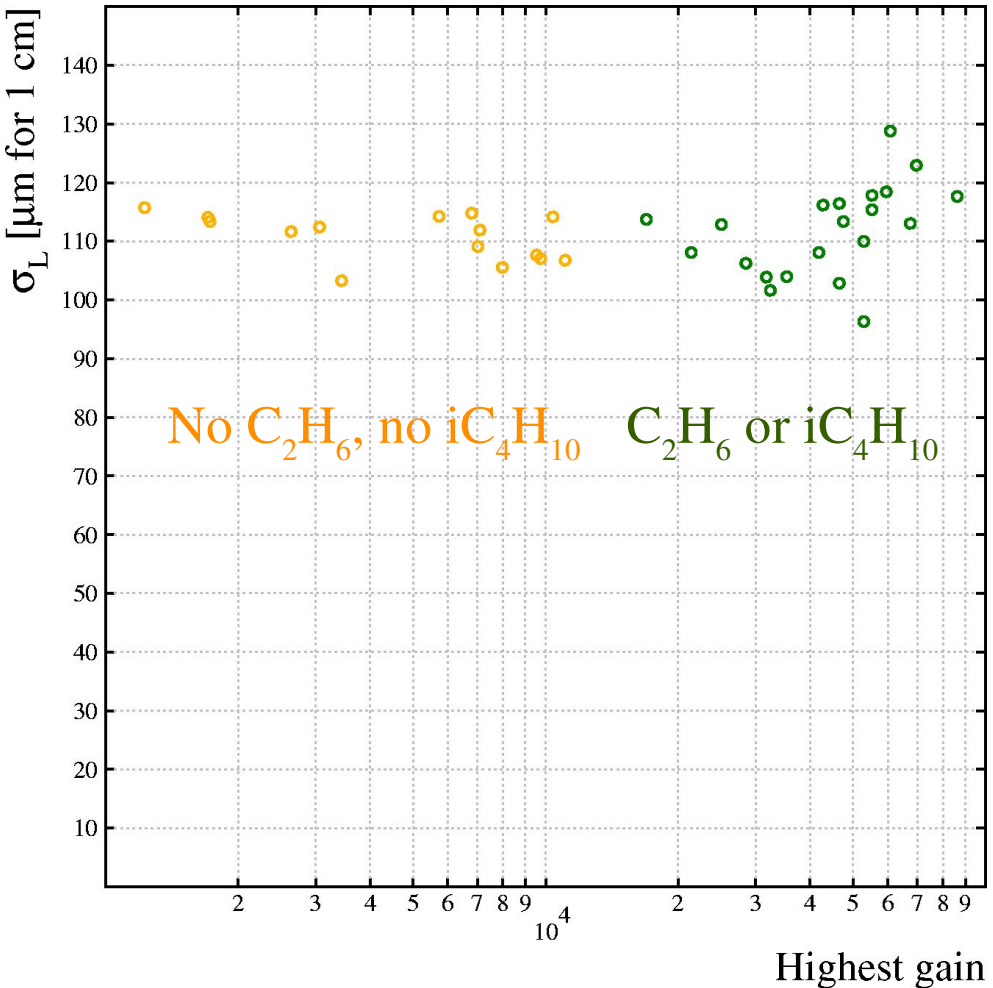
- We take the following elements from the gain curves:
  - the *E*-field at the end-point;
  - the gain at the end-point;
  - the feedback parameter β fitted from the whole gain curve.

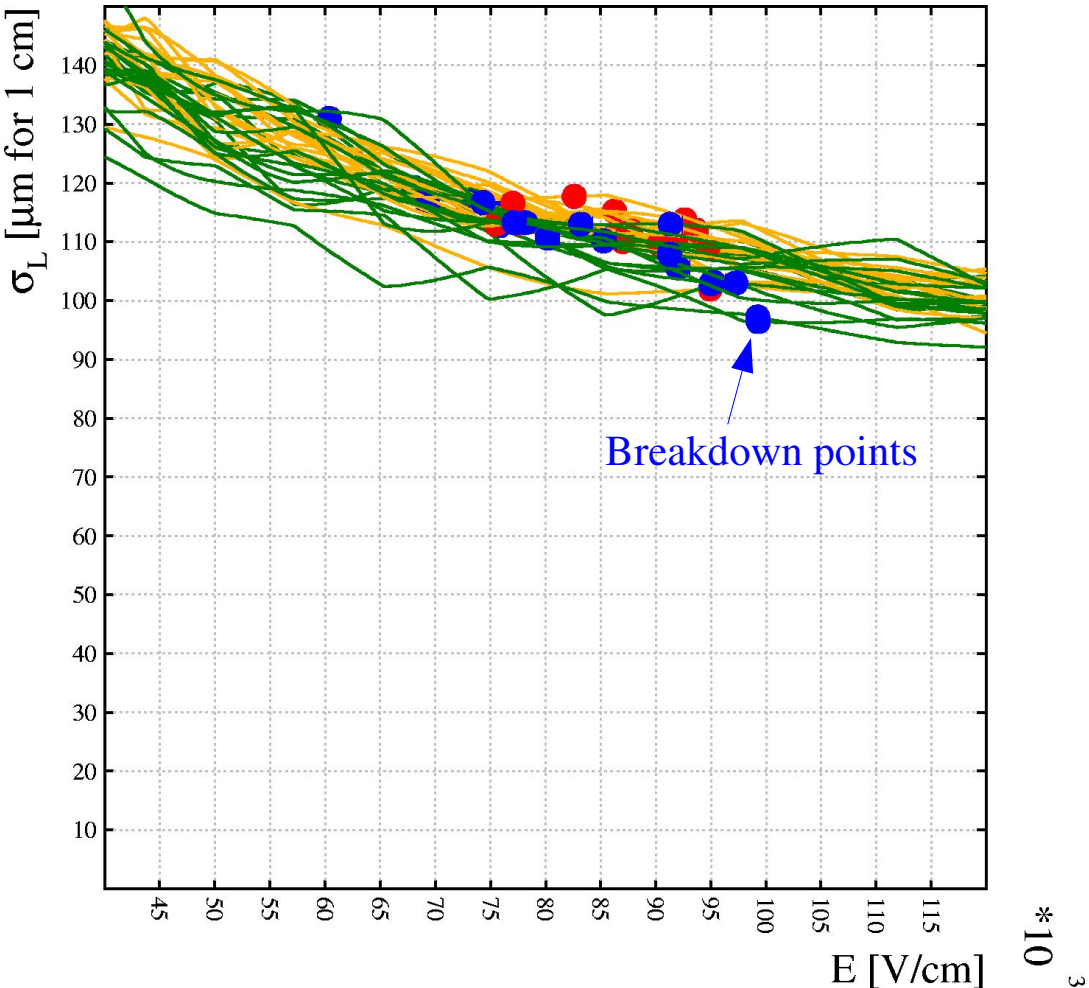
- The end-point corresponds to the onset of discharges:

J'arrêtais les mesures lorsqu'il commençait à claquer. Le taux de claquage n'était pas vraiment fixé, mais l'ordre de grandeur est quelques claquages par minutes. Ces claquages n'avaient jamais lieu au même endroit du détecteur. Ils étaient répartis sur toute la surface (mesh plotée 10×10 cm²). [David Attié, 12 juillet 2010.]

Correlation with σ_L ?

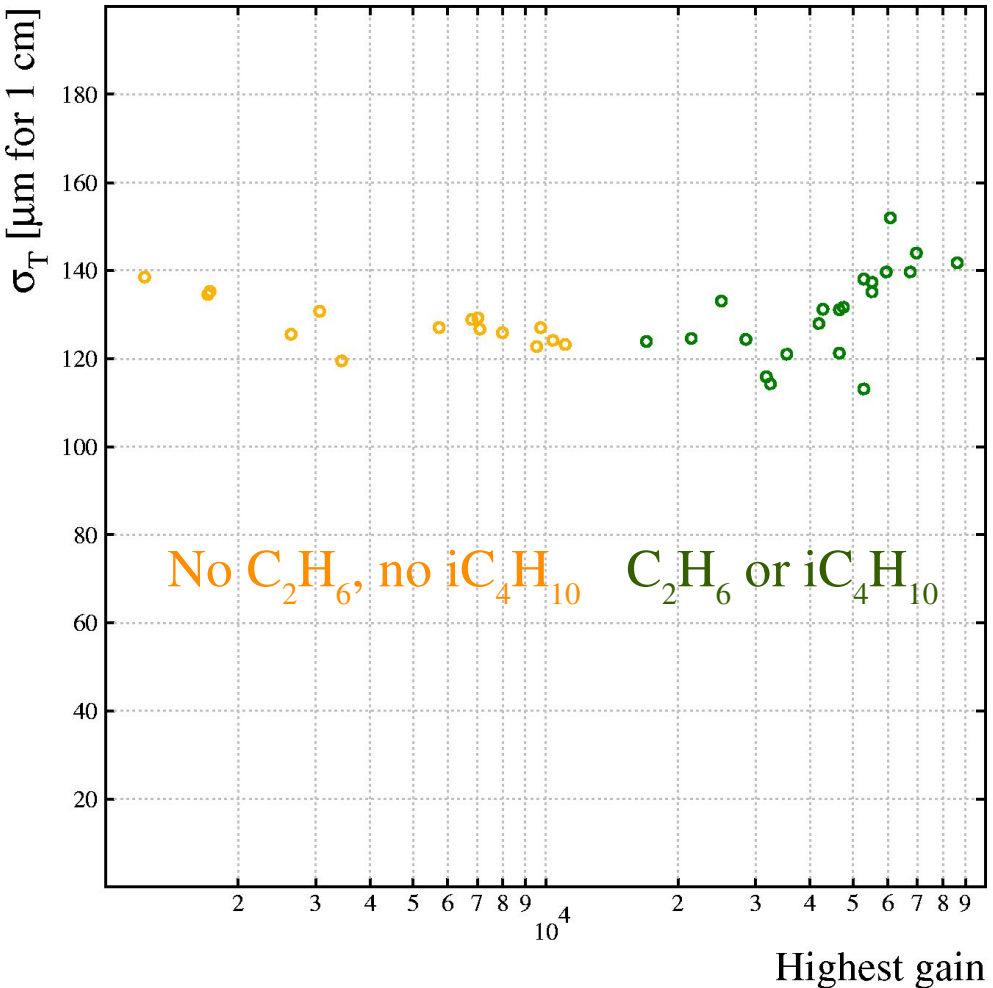
- The mixtures share σ_L at breakdown and $\sigma_L(E)$ dependence.

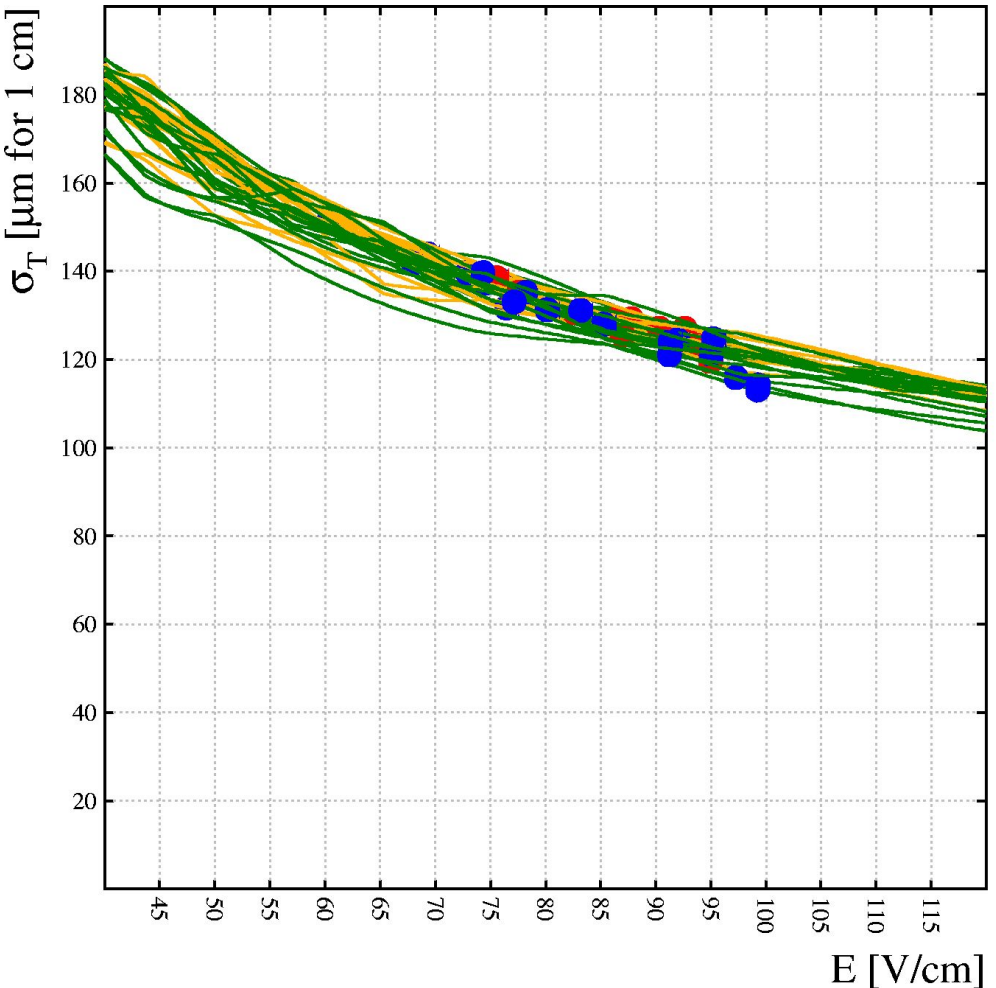




Correlation with σ_T ?

- The mixtures share σ_T at breakdown and $\sigma_T(E)$ dependence.



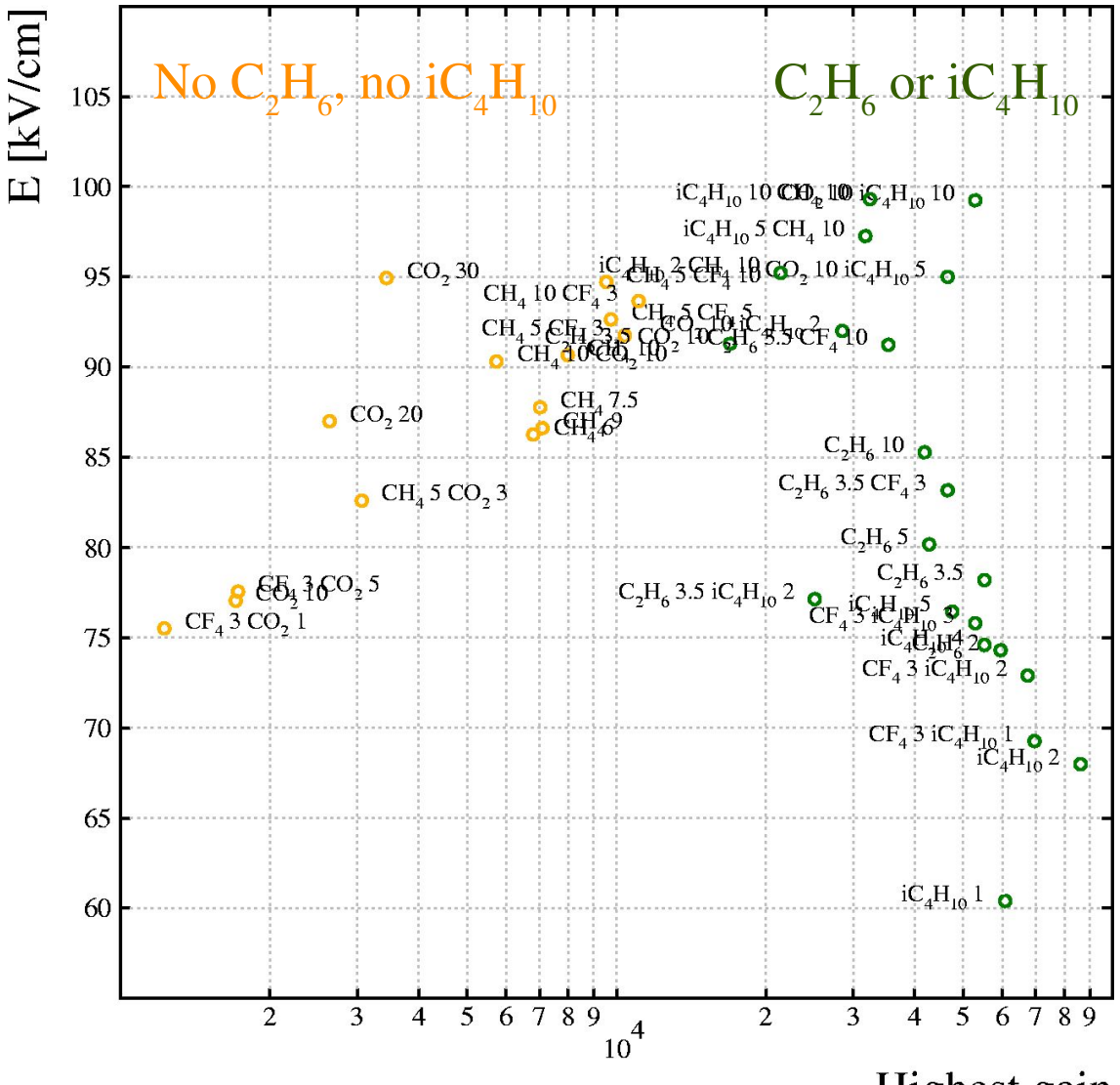


Diffusion

- The $\sigma_L(E)$ and $\sigma_T(E)$ relations are similar for all mixtures considered.
- High gain does not necessarily occur at high E.
- Hence, high gain before breakdown does not seem to correlate with diffusion.

E field at highest achievable gain

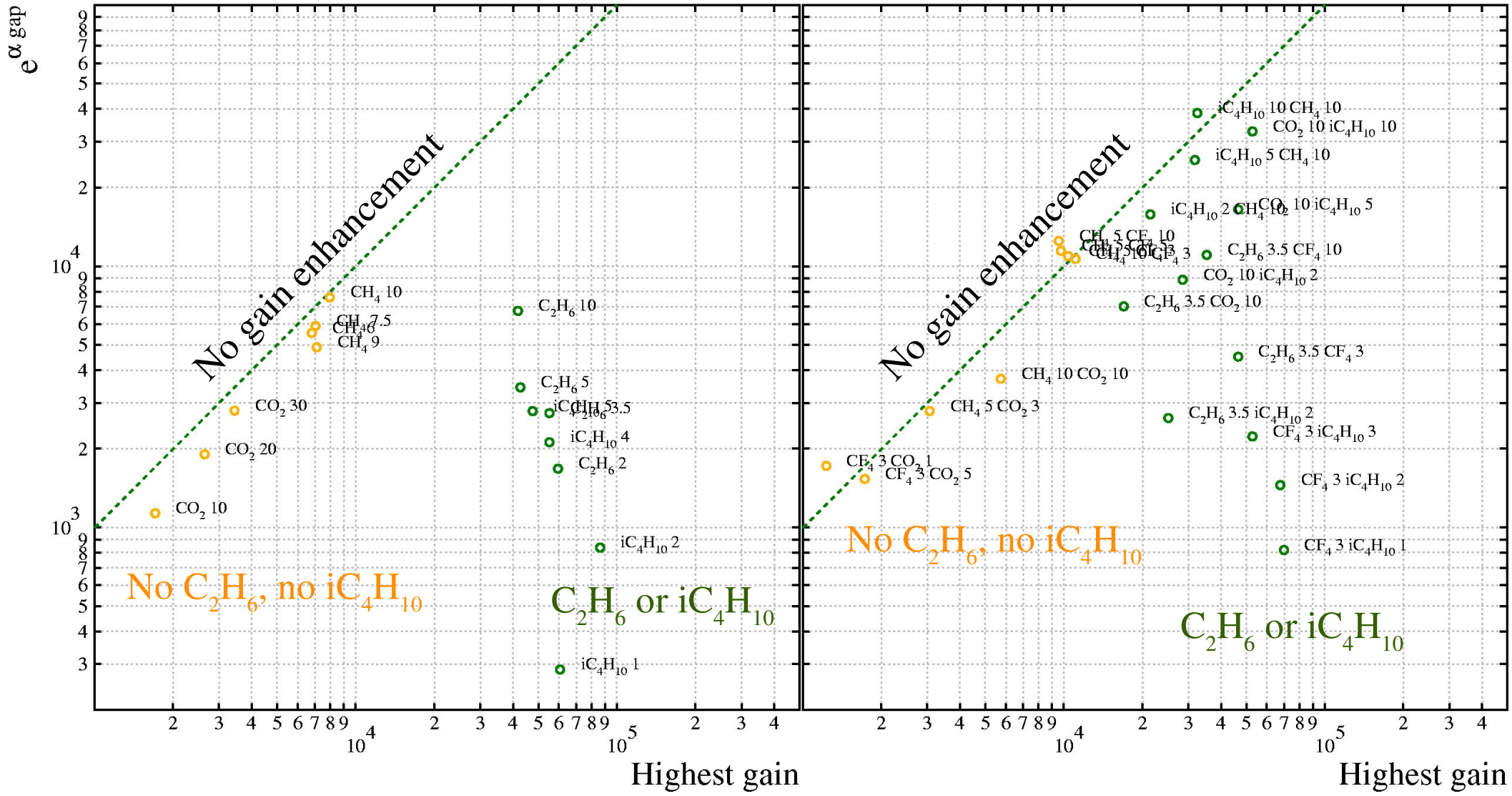
- The highest gains are not necessarily reached at the highest *E* fields.
- *E* ~ 100 kV/cm seems to be a boundary.
- No high gain without C_2H_6 or iC_4H_{10}.



Gain enhancement ?

Binary mixtures

Ternary mixtures



Mechanisms of gain enhancement

- Penning effect – excited Ar^* collide with and ionise admixture molecules Q, gain curves start at lower *E* field:

  $e^- + Ar \rightarrow e^- + Ar^*$

  $Ar^* + Q \rightarrow Ar + Q^+ + e^-$

  e^- becomes part of the avalanche

- Feedback – additional gain from secondary avalanches, visible as over-exponential growth:

  $Ar^* \rightarrow Ar + \gamma$

  $Q + \gamma \rightarrow Q^+ + e^-$ or wall $+ \gamma \rightarrow$ wall $+ e^-$

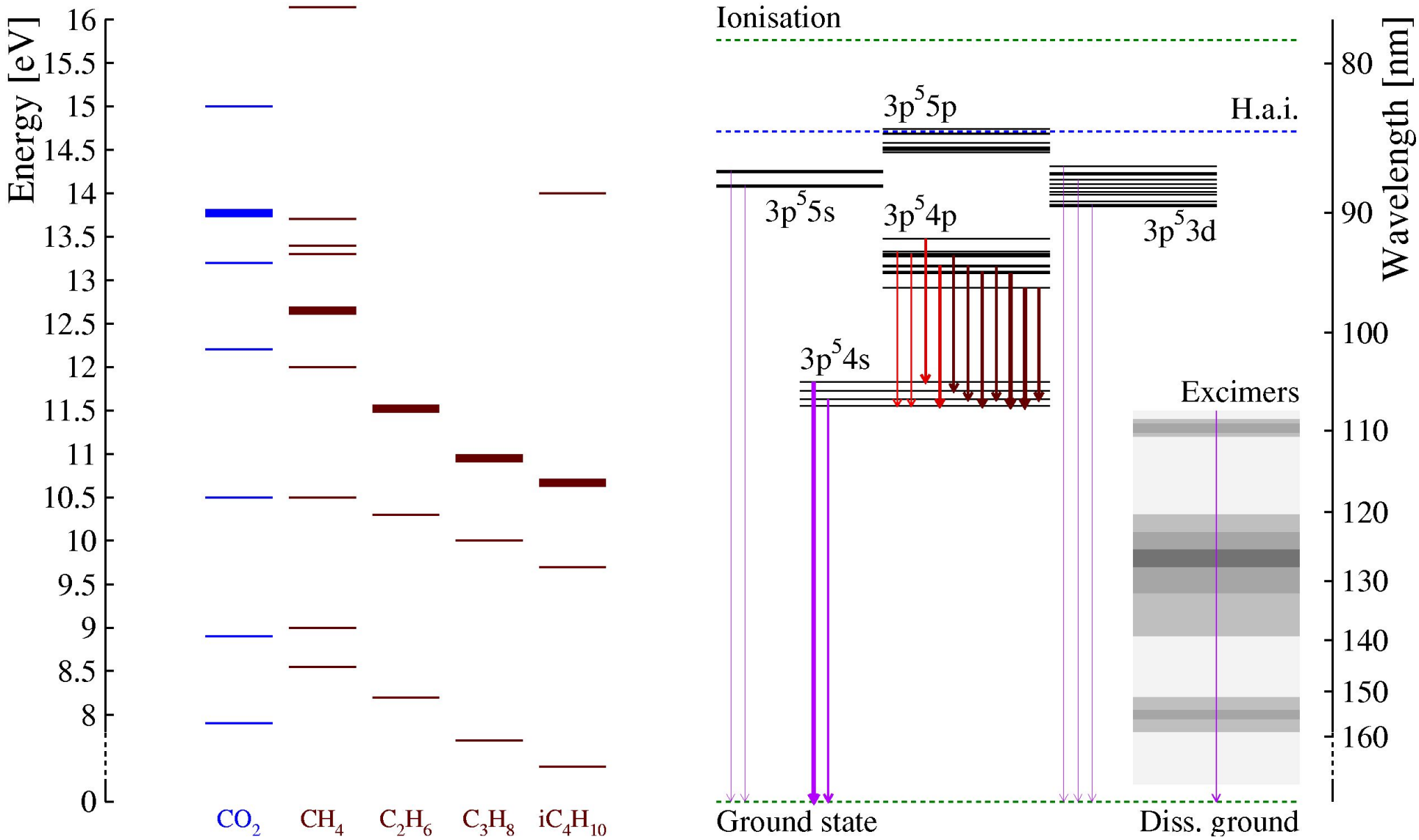
  e^- starts new avalanche

Penning effect ?

- The admixture molecules need to have an ionisation energy below the Ar excitation levels:

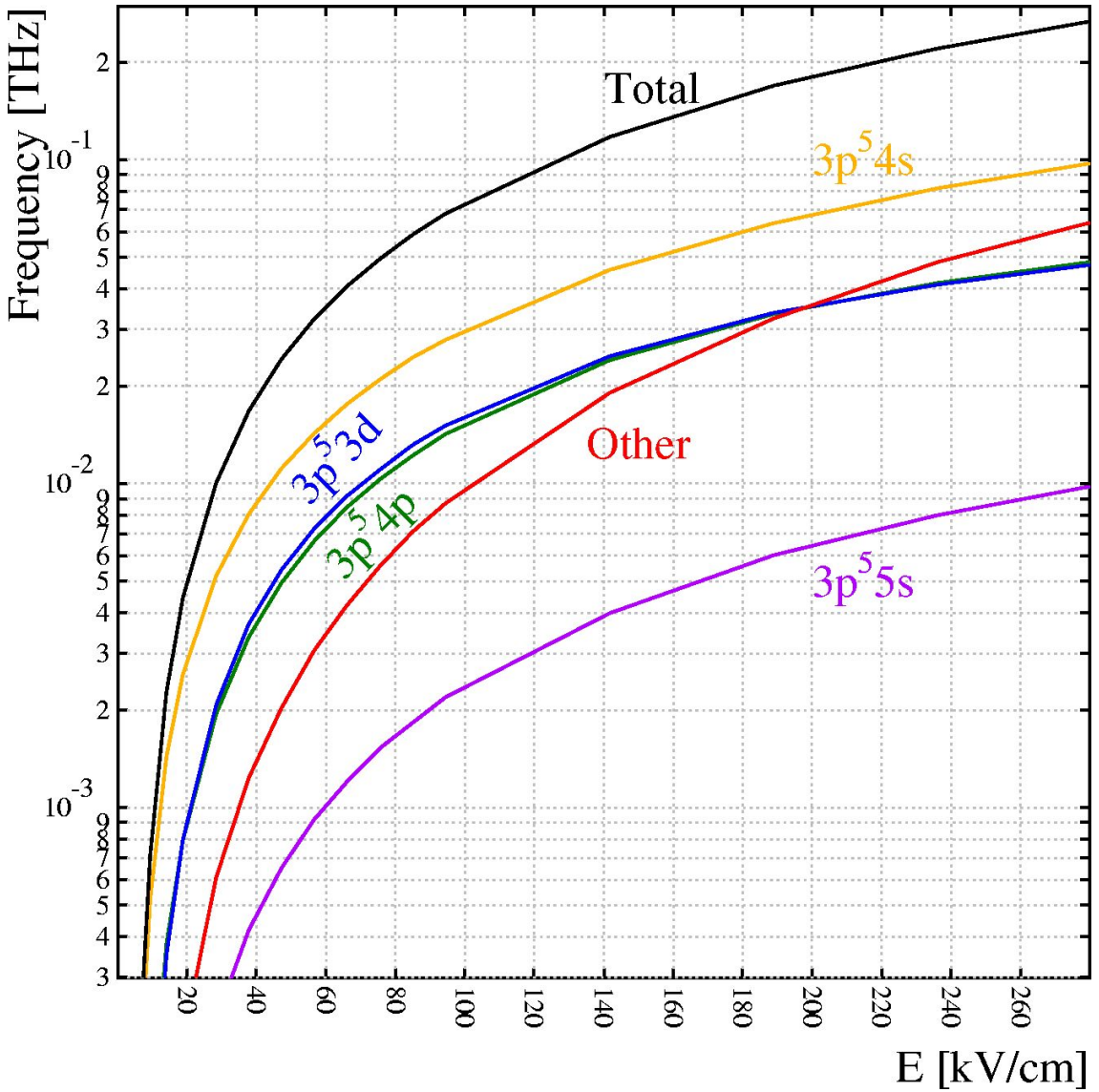
iC_4H_{10}:	10.67 eV	
C_2H_6:	11.52 eV	
Ar^* $3p^5 4s$:		11.55_m, 11.62_r, 11.72_m, 11.83_r eV
CH_4:	12.99 eV	
Ar^* $3p^5 4p$:		~13 eV;
CO_2:	13.77 eV	
Ar^* $3p^5 3d$:		~14 eV;
CF_4:	15.90 eV	

Level diagram argon and admixtures



Excited state rates in Ar mixtures

- Ar^* $3p^54s$ is the dominant source of VUV photons.
- Ar^* $3p^54p$ emits lower-energy photons when decaying to Ar^* $3p^54s$.
- Some of the Ar^* $3p^53d$ emit in the VUV.



Penning effect

- Ar^* $3p^5 4s$ can transfer to iC_4H_{10} and C_2H_6, where one expects the largest effect;
- Ar^* $3p^5 4p$ can ionise both CH_4 and CO_2;
- Ar^* $3p^5 3d$ can transfer to CO_2.

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 absorption in the mesh followed by;
  - e^- extraction to start a new avalanche

Photons emitted by excited Ar*

- VUV radiation results from decay to the ground state:
  - Ar* $3p^5 4s$ levels:
    - 11.62 eV, 11.83 eV;
    - metastable: 11.55 eV, 11.72 eV;
  - Ar* $3p^5 3d$ levels:
    - ~ 13.85 eV;
  - Ar* $3p^5 5s$ and higher levels.
- Lower energy emission from decays between the levels.

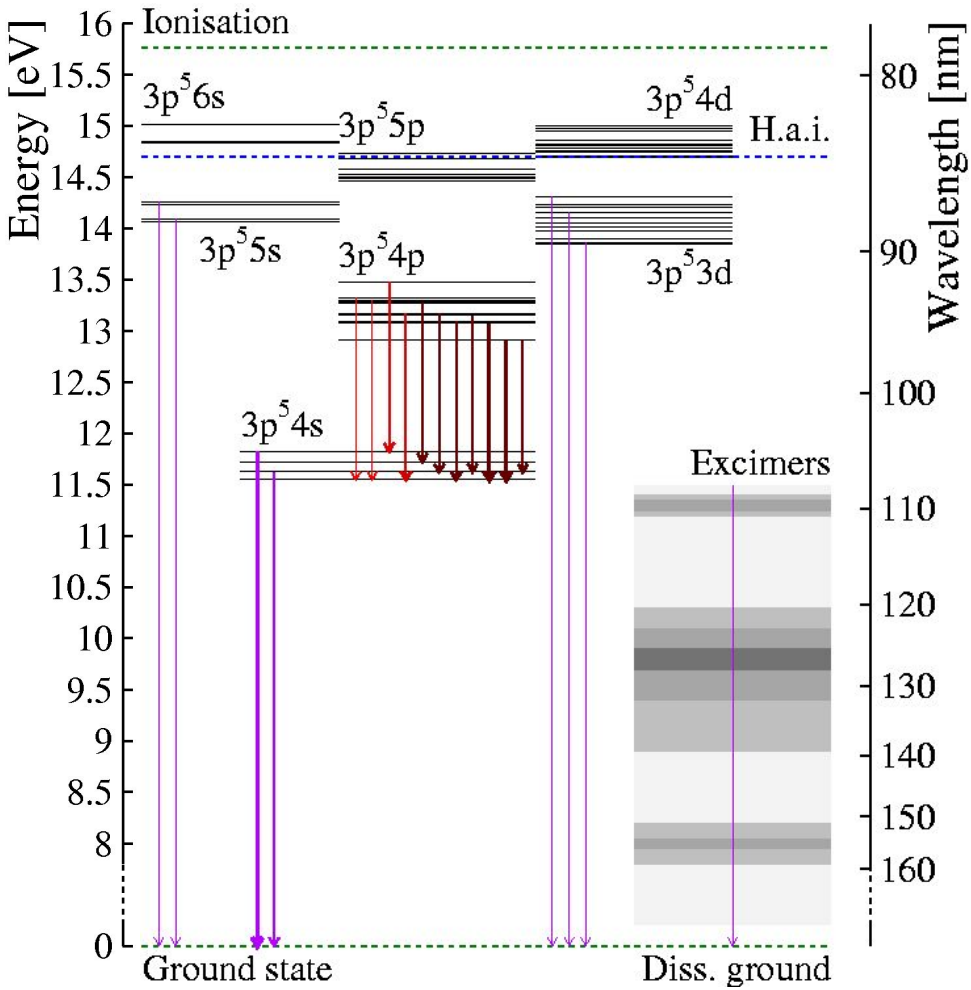
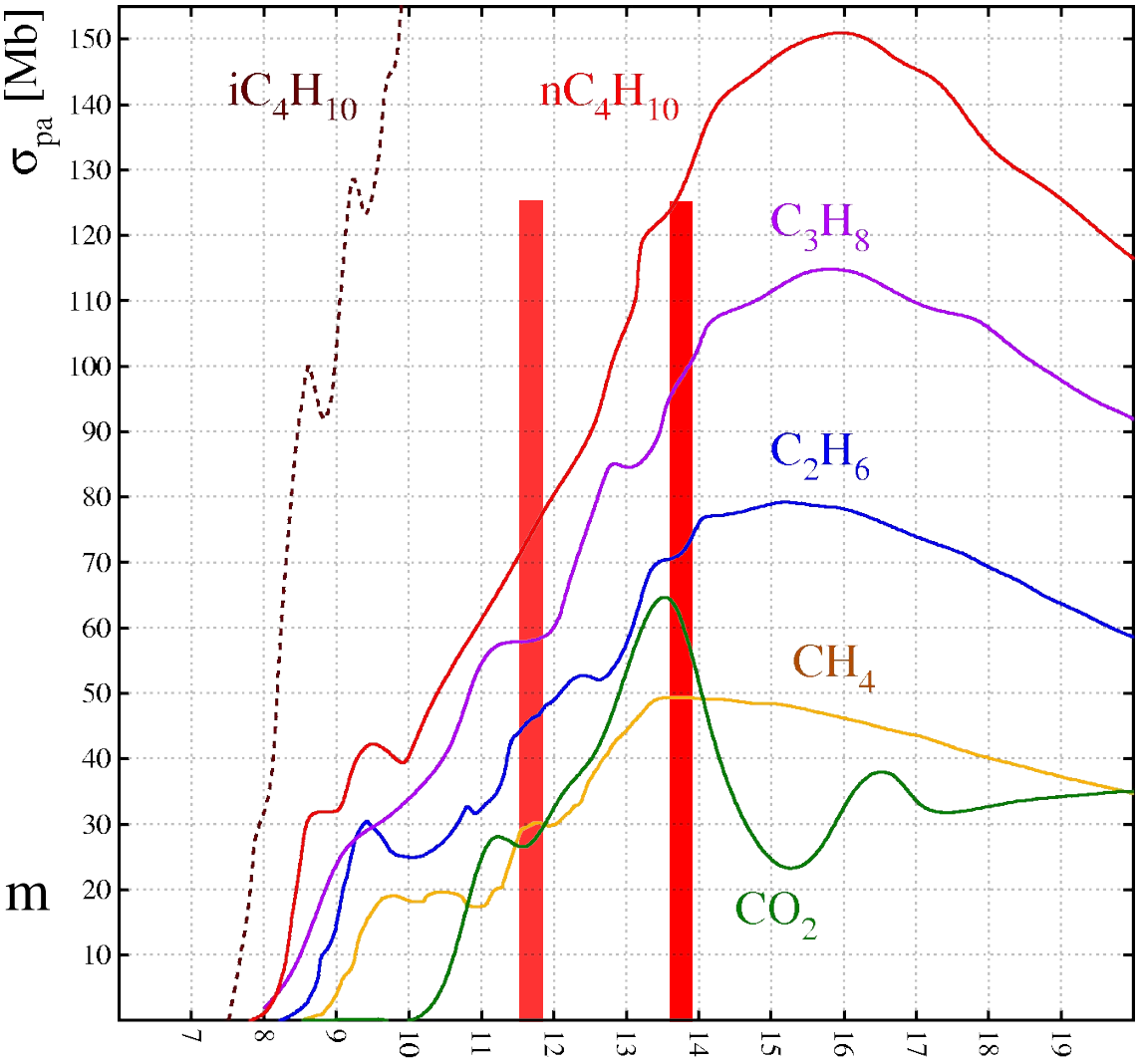


Photo-absorption cross sections

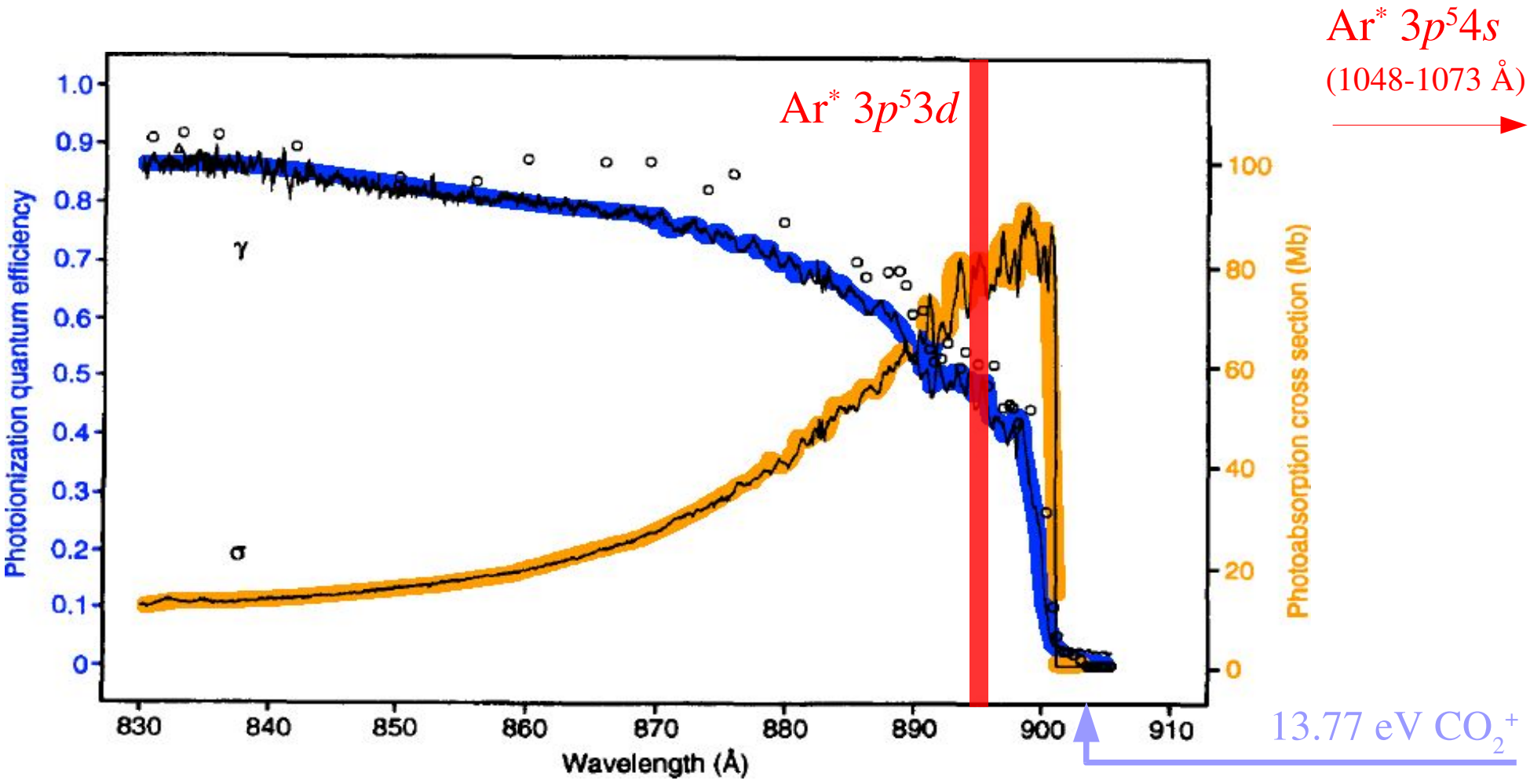
- The photo-absorption cross section of the alkanes increases with the molecular weight.
- Note: the iC_4H_{10} and nC_4H_{10} curves should have the same area on account of the sum rules.

$\lambda = 1/\sigma L$, e.g. $50\,\mathrm{Mb} \sim 7.4\,\mu\mathrm{m}$



[Cross sections compiled from a variety of sources.]

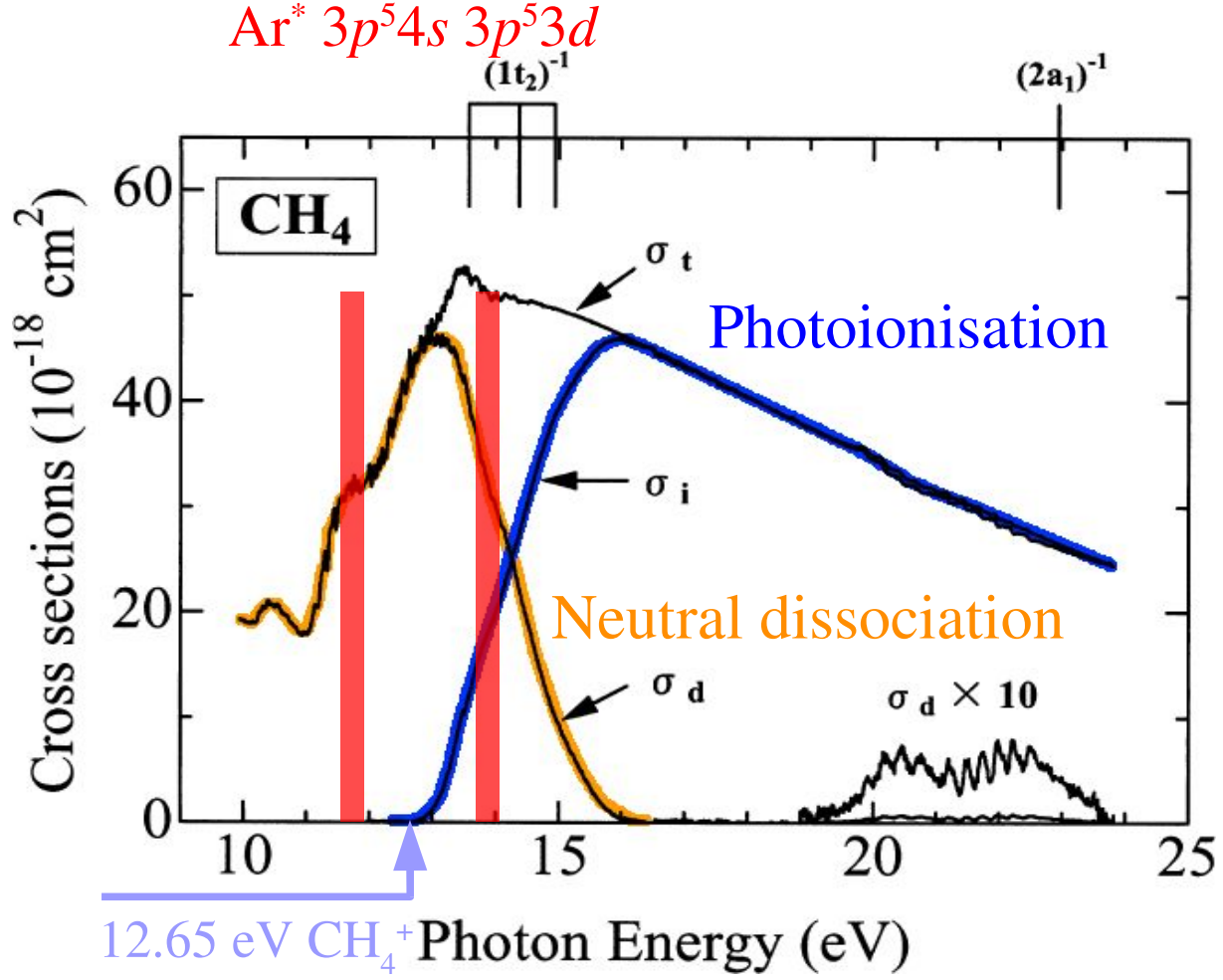
CO_2 photo-ionisation yield



D. A. Shaw *et al*., "*A study of the absolute photoabsorption, photoionisation and photodissociation cross sections and the photoionisation quantum efficiency of carbon dioxide from the ionisation threshold to* 345 Å", Chemical Physics 198 (1995) 381-396.

CH_4 photo cross section terms

- Ar^* 4*s* radiation produces only neutral fragments.



$$\text{yield} \equiv \frac{\sigma_{\text{photoionisation}}}{\sigma_{\text{photoabsorption}}}$$

Reference: Kosei Kameta *et al.*, *Photoabsorption, photoionization, and neutral-dissociation cross sections of simple hydrocarbons in the vacuum ultraviolet range*, Journal of Electron Spectroscopy and Related Phenomena 123 (2002) 225–238.

Terminology

$AB + \gamma$	$\rightarrow$	$AB^+ + e^-$	direct ionisation
	$\rightarrow$	AB^*	excitation
	$\rightarrow$	AB'	super-excitation
		$\hookrightarrow$ $AB^+ + e^-$	autoionisation
		$\hookrightarrow$ $A + B$	(neutral) dissociation
		$\hookrightarrow$ other processes (rare)	

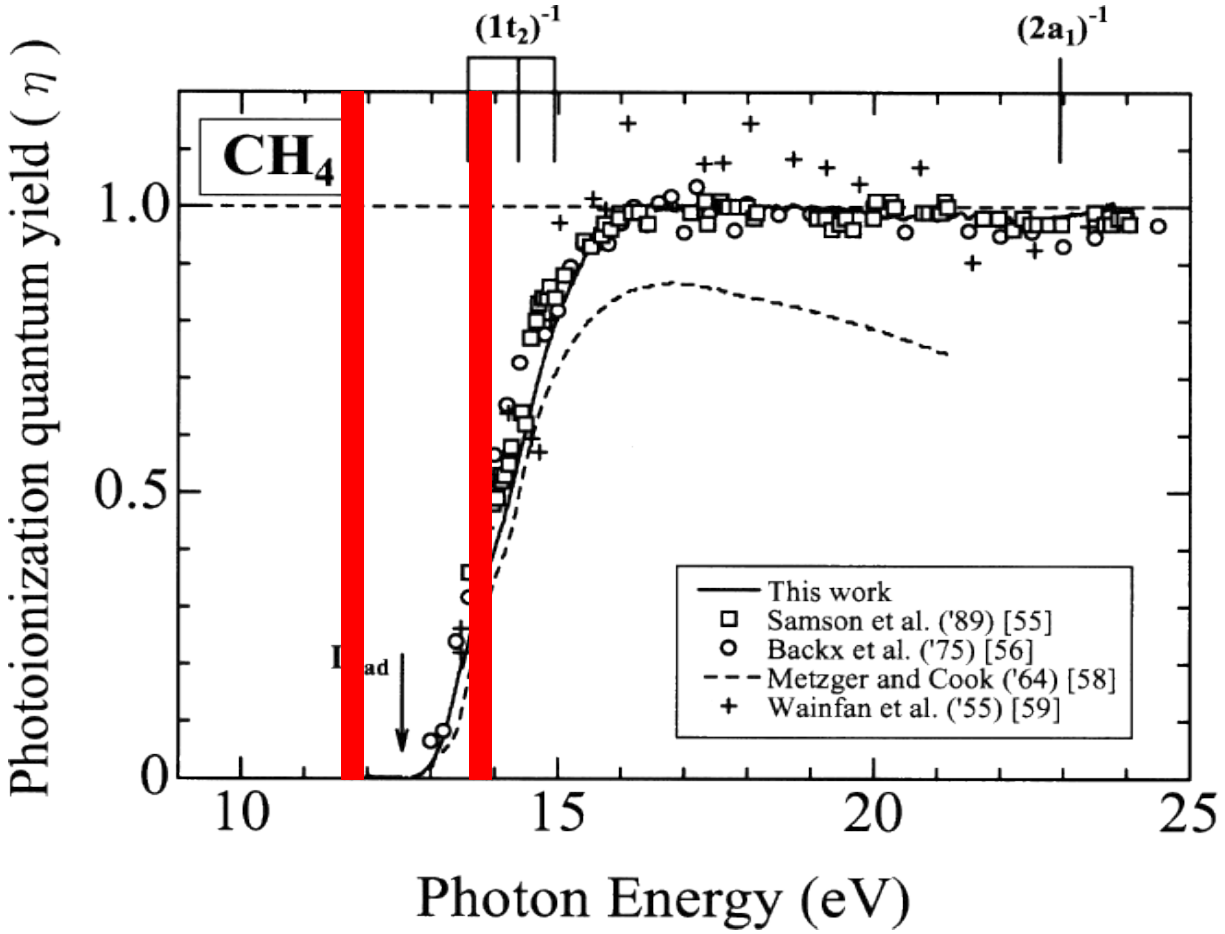
Super-excitation: excited states *above* the ionisation potential.

References:

- Yoshihiko Hatano, *Interaction of vacuum ultraviolet photons with molecules. Formation and dissociation dynamics of molecular superexcited states*, Physics Reports 313 (1999) 109}169.
- Papers referenced therein, in particular those of R.L. Platzman,

CH_4 photo-ionisation yield

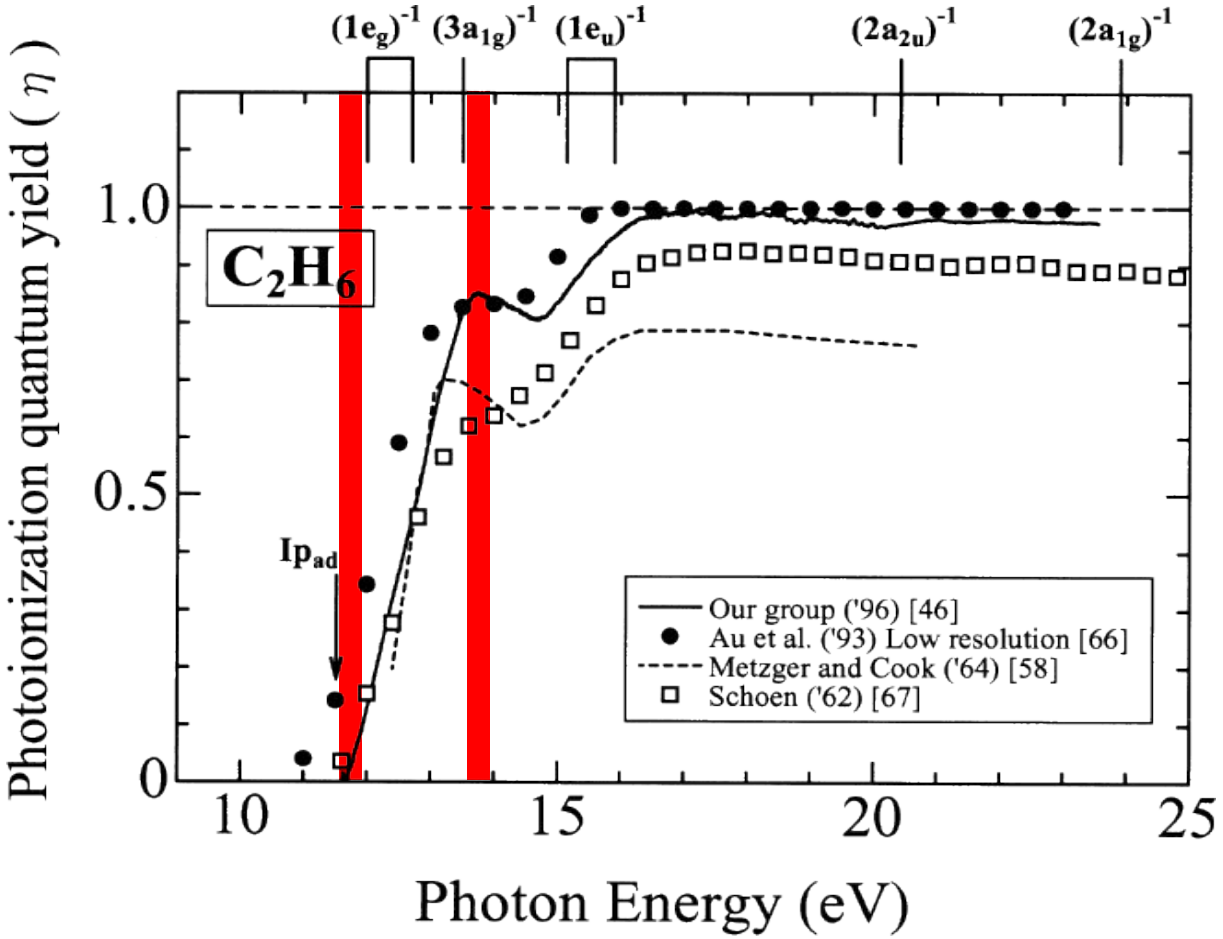
- No photoionisation from Ar^* $3p^5 4s$ radiation:



Reference: Kosei Kameta *et al.*, *Photoabsorption, photoionization, and neutral-dissociation cross sections of simple hydrocarbons in the vacuum ultraviolet range*, Journal of Electron Spectroscopy and Related Phenomena 123 (2002) 225–238.

C_2H_6 photo-ionisation yield

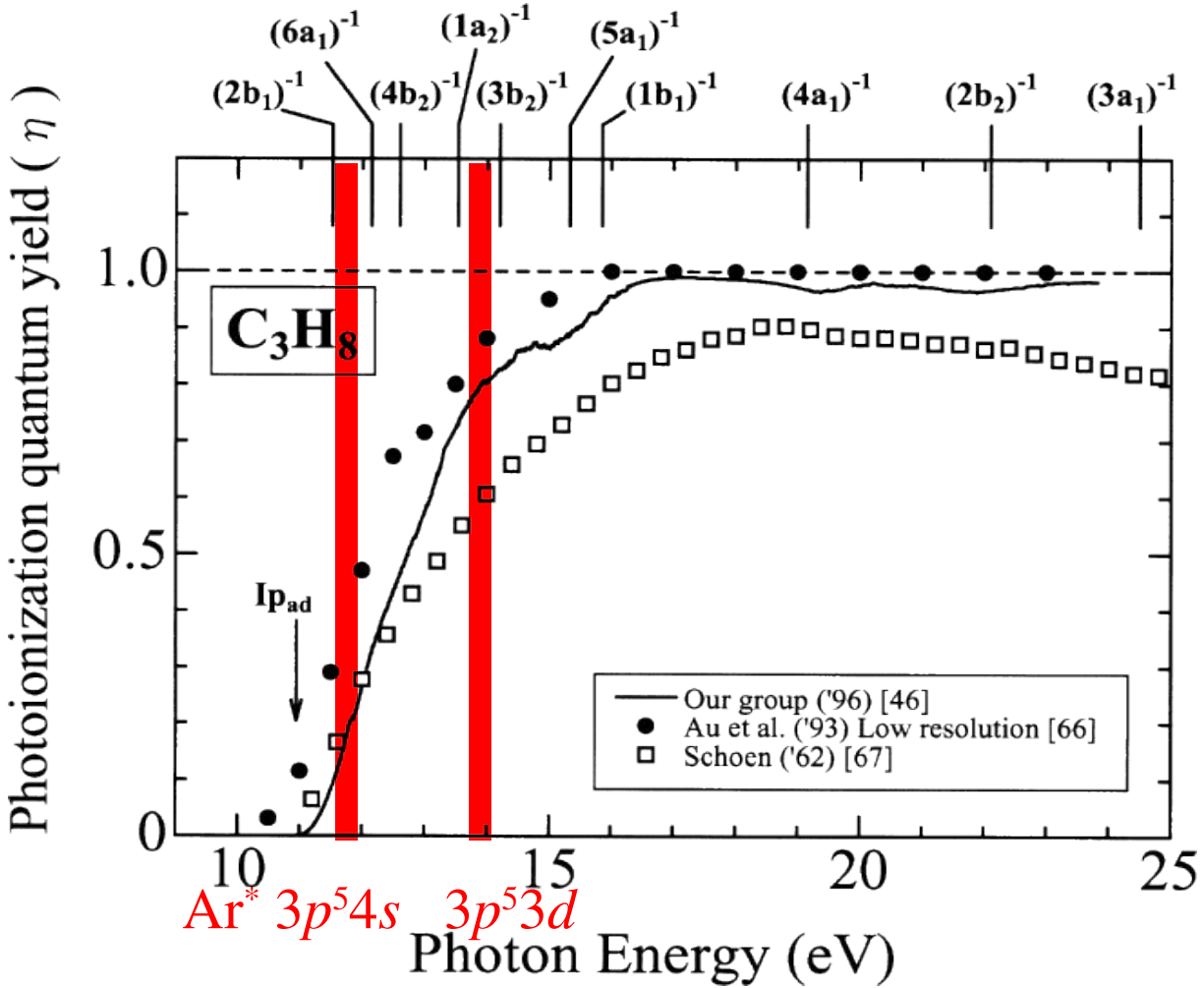
- Onset of photoionisation from Ar^* $3p^5 4s$ radiation:



Reference: Kosei Kameta *et al.*, *Photoabsorption, photoionization, and neutral-dissociation cross sections of simple hydrocarbons in the vacuum ultraviolet range*, Journal of Electron Spectroscopy and Related Phenomena 123 (2002) 225–238.

C_3H_8 photo-ionisation yield

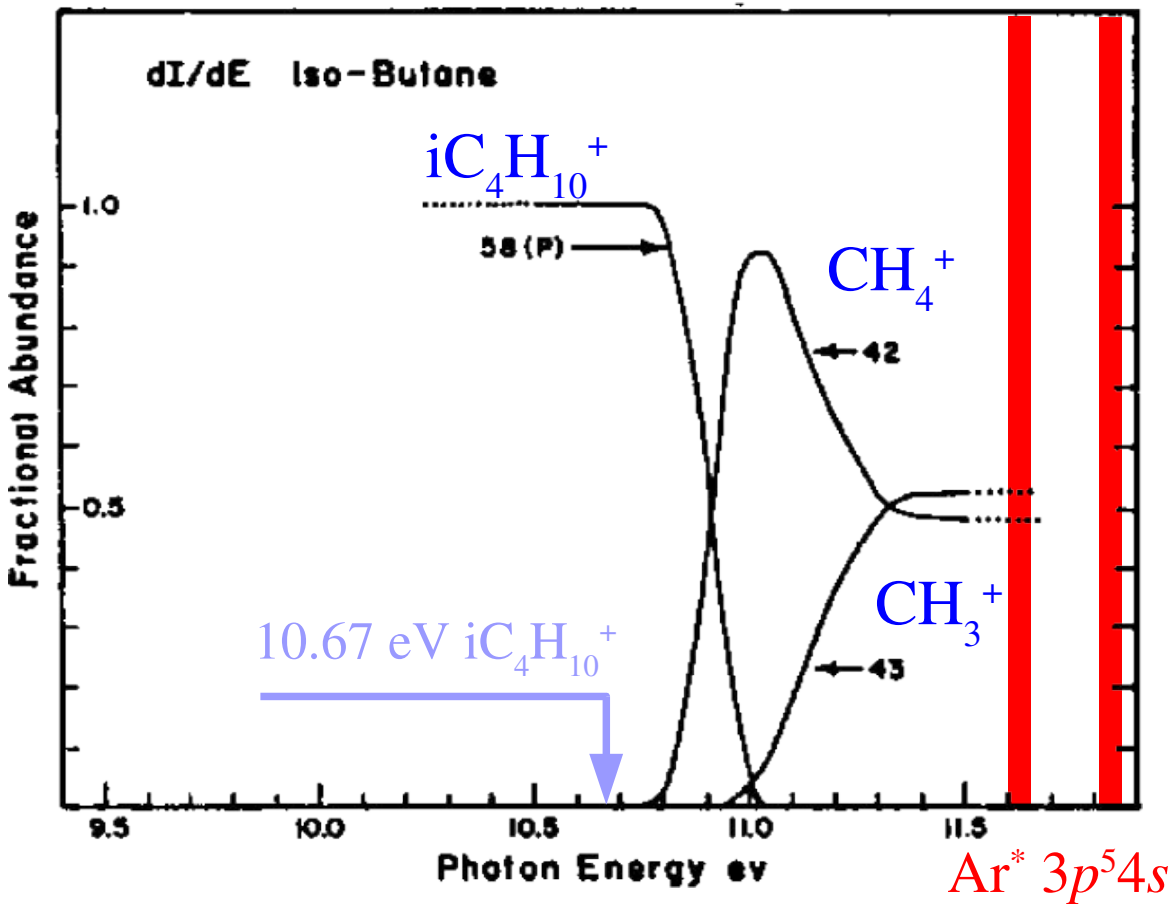
- ~20 % photoionisation from Ar^* $3p^5 4s$ radiation:

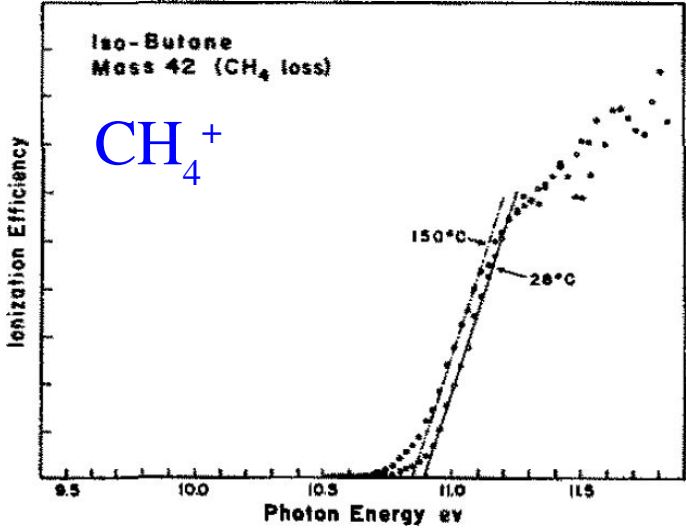


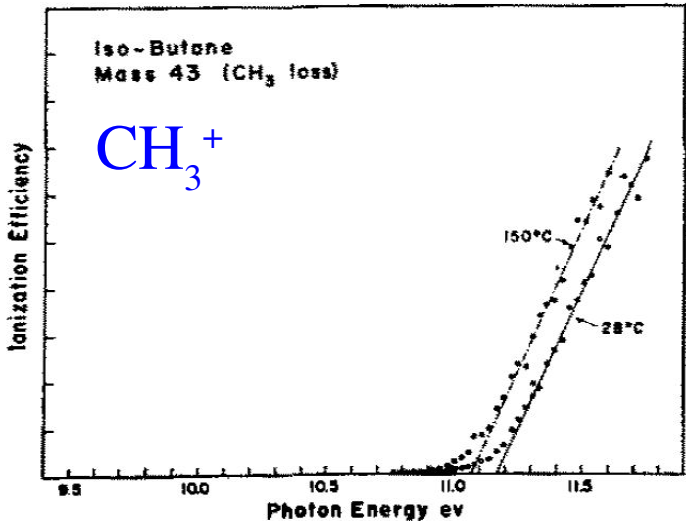
Reference: Kosei Kameta *et al.*, *Photoabsorption, photoionization, and neutral-dissociation cross sections of simple hydrocarbons in the vacuum ultraviolet range*, Journal of Electron Spectroscopy and Related Phenomena 123 (2002) 225–238.

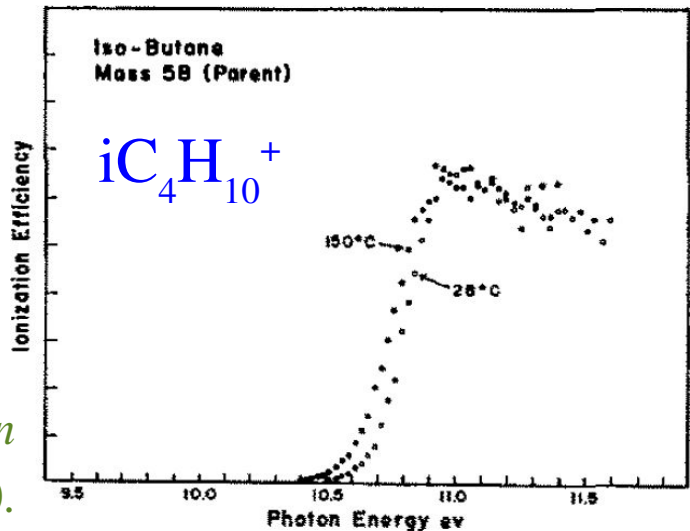
iC_4H_{10} photo-ionisation

- Dominated by CH_3^+ and CH_4^+ loss.









Bruce Steiner *et al.*, *Photoionization of Alkanes. Dissociation of Excited Molecular Ions*, J. Chem. Phys. 34 (1961) 189-220.

Photon properties of admixtures

- Admixtures:

	σ $3p^5 4s$ [Mb]	λ $3p^5 4s$ [μm]	η $3p^5 4s$ [%]	η $3p^5 3d$ [%]
CO_2	28-30	12.8	0	45
CH_4	~30	12.4	0	25
C_2H_6	~45	8.3	~5	80
iC_4H_{10}	? 75-80	? 4.8	large	~100

- Notes:
  - λ: *partial* mean free path for the admixture only;
  - η: photo-ionisation yield;
  - Ar itself absorbs and re-emits photons.

Feedback

- Ar^* $3p^5 4s$ photons can therefore, in virtually all mixtures considered in the compilation, travel a distance larger than the gap width (50 μm) before being absorbed.
- 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.

- (Cathode feedback is not yet discussed here.)

Separating feedback and Penning terms

- Feedback: $g = g'/(1-\beta g')$, $g' = g/(1+\beta g)$

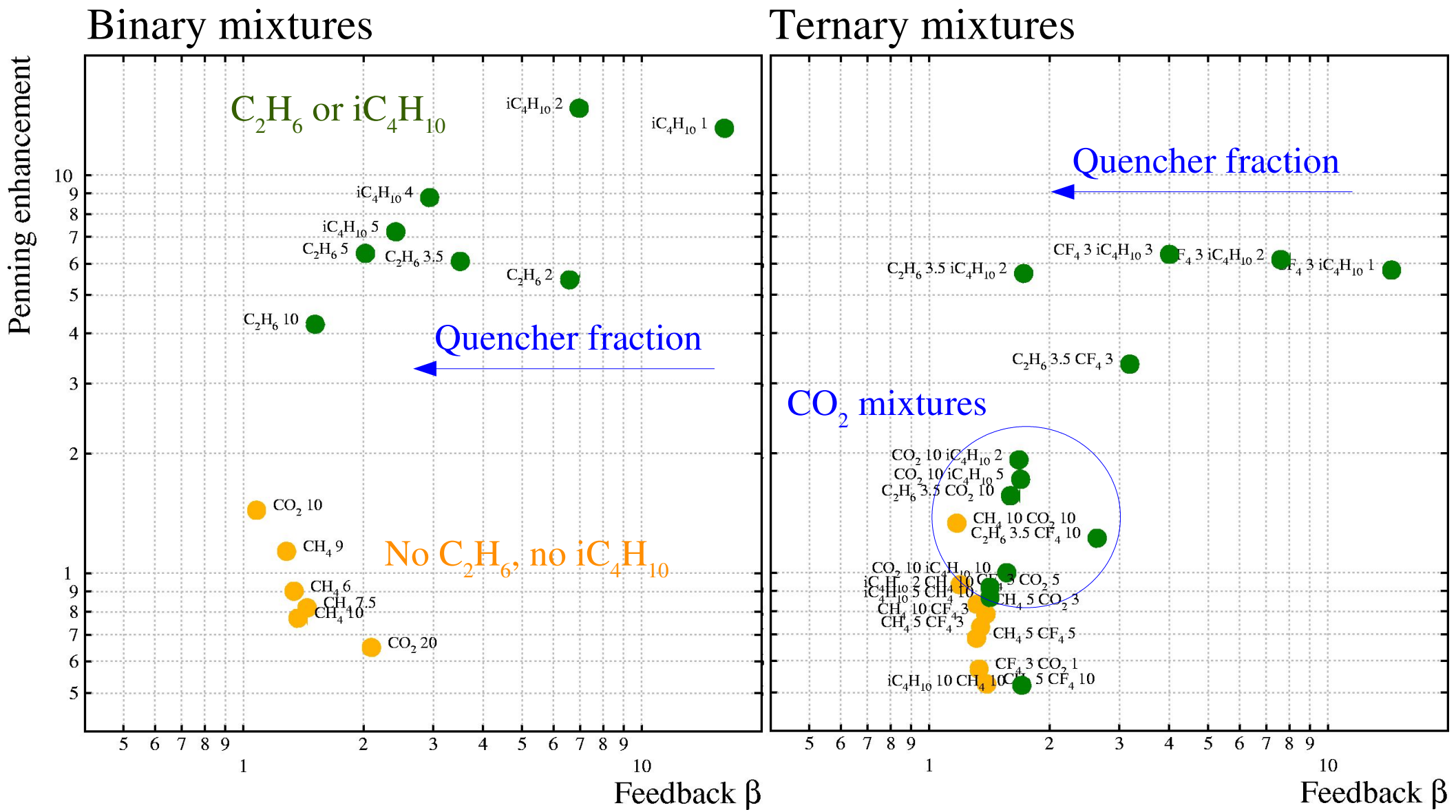
  β can be found by fitting the gain curve.

- Penning transfer: $\alpha = \alpha' \; r_P$, $r_P = (1 + \nu_{exc}/\nu_{ion})$

  the "pure" Townsend coefficient α' is calculated by Magboltz.

- Enhancement factors:
  - Total: $g/\exp(\alpha' \, gap)$
  - Feedback: $1/(1+\beta g)$
  - Penning: $g/(\exp(\alpha' \, gap) \, (1+\beta g))$

Separating the enhancement terms



Origin of the gain

- 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.

Gain limitations

- No relation was found between the breakdown point and the diffusion coefficients.
- iC_4H_{10} mixtures (also with CF_4) are feedback limited.
- The other gases appear to be field-limited, for reasons which are not yet clear.