Theoretical evaluation of fluorescence emission and energy deposition in air generated by electrons

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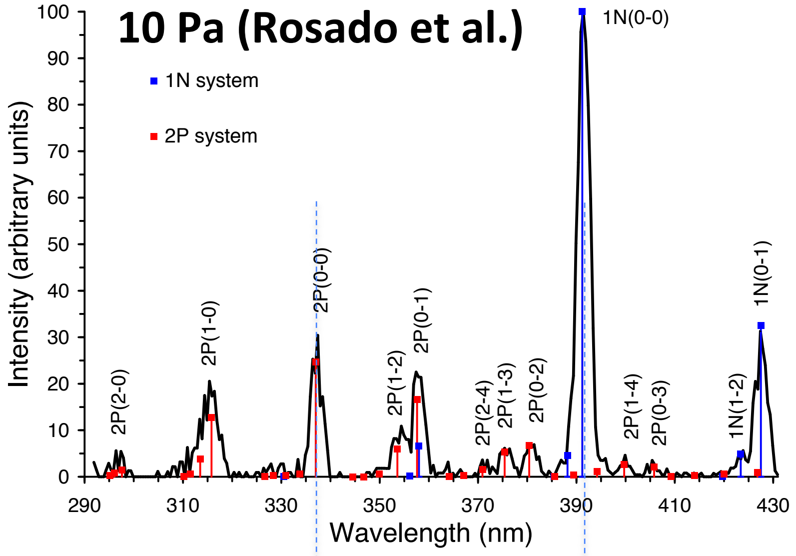
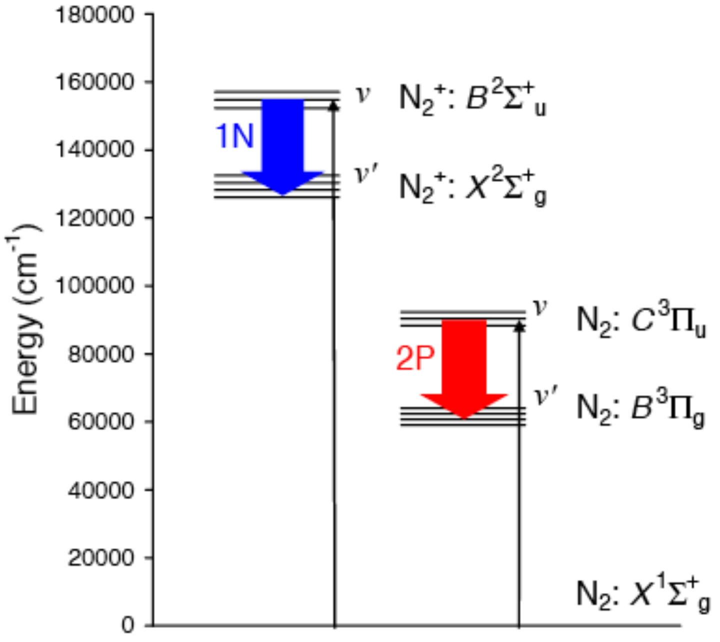
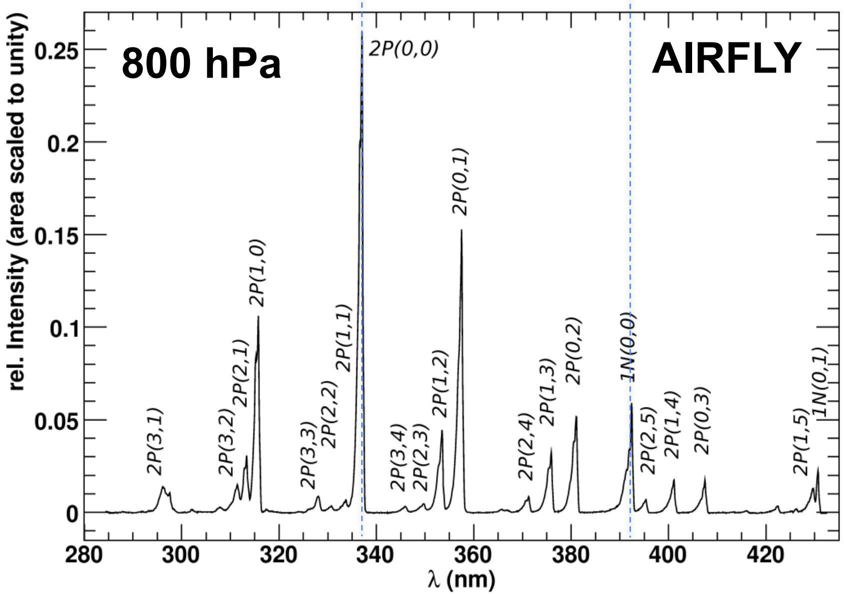
Outline

- Introduction
- Relative intensities
- The role of secondary electrons
- MC simulation
- Results
  - Energy deposition
  - Fluorescence emission
  - Remarks on P' measurements
  - Fluorescence yield vs. E and PR
  - Absolute Fluorescence yield
- Conclusions

- Air-fluorescence induced by electrons.
- Spectrum: 2P and 1N systems







- **Fluorescence yield Y** (# photons/unit deposit energy): parameter to convert the telescope signal in shower energy.

- Fluorescence is quenched by collisional de-excitation and thus, the FY depends on atmospheric parameters (P, T, h).

$$Y_\lambda = \frac{Y_\lambda^0}{1+P/P'_\lambda}; \qquad P'_\lambda(T,h)$$

- The fluorescence yield is NOT a "name" (e.g. Nagano, Kakimoto, ..) but a set of parameters:

1) Absolute value (e.g. Y_{337}, $Y_{\Delta\lambda}$) → **Main source of uncertainty**

2) Wavelength spectrum
3) Pressure dependence in dry air (P'_λ)
4) Humidity dependence (P'_w)
5) Temperature dependence (α)

Non-negligible contribution

Relative intensities

- Common upper level v: proportional to Einstein coefficients

$$I_{vv'} \propto A_{vv'}$$

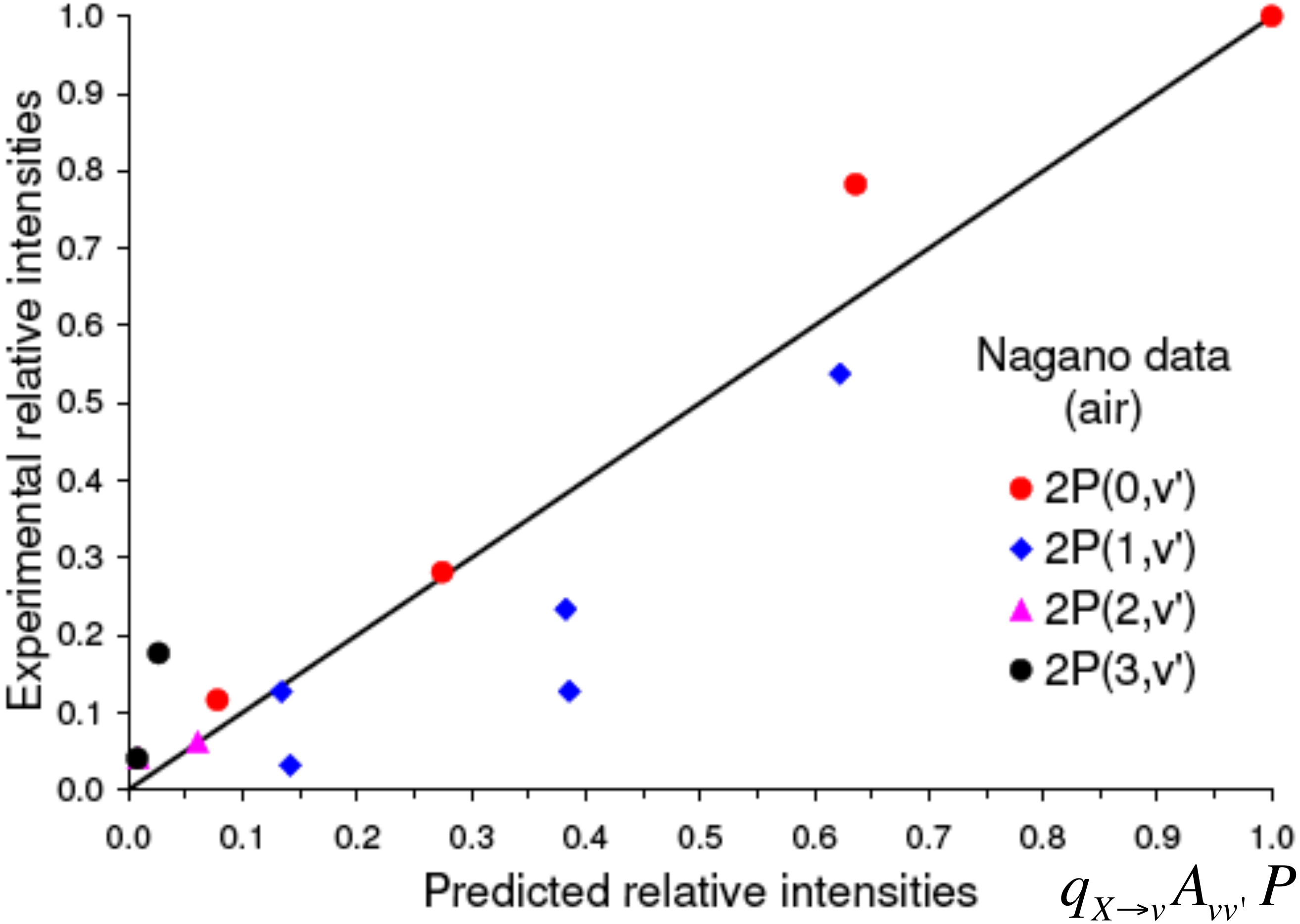
- Different upper levels: Franck-Condon coefficients $q_{X\to v}$

$$\frac{I_{vv'}}{I_{00}} = \frac{q_{X\to v}A_{vv'}}{q_{X\to 0}A_{00}}\frac{1+P/P'_0}{1+P/P'_v} \overset{P>>P'}{\approx} \frac{q_{X\to v}A_{vv'}}{q_{X\to 0}A_{00}}\frac{P'_v}{P'_0}$$

independent of P

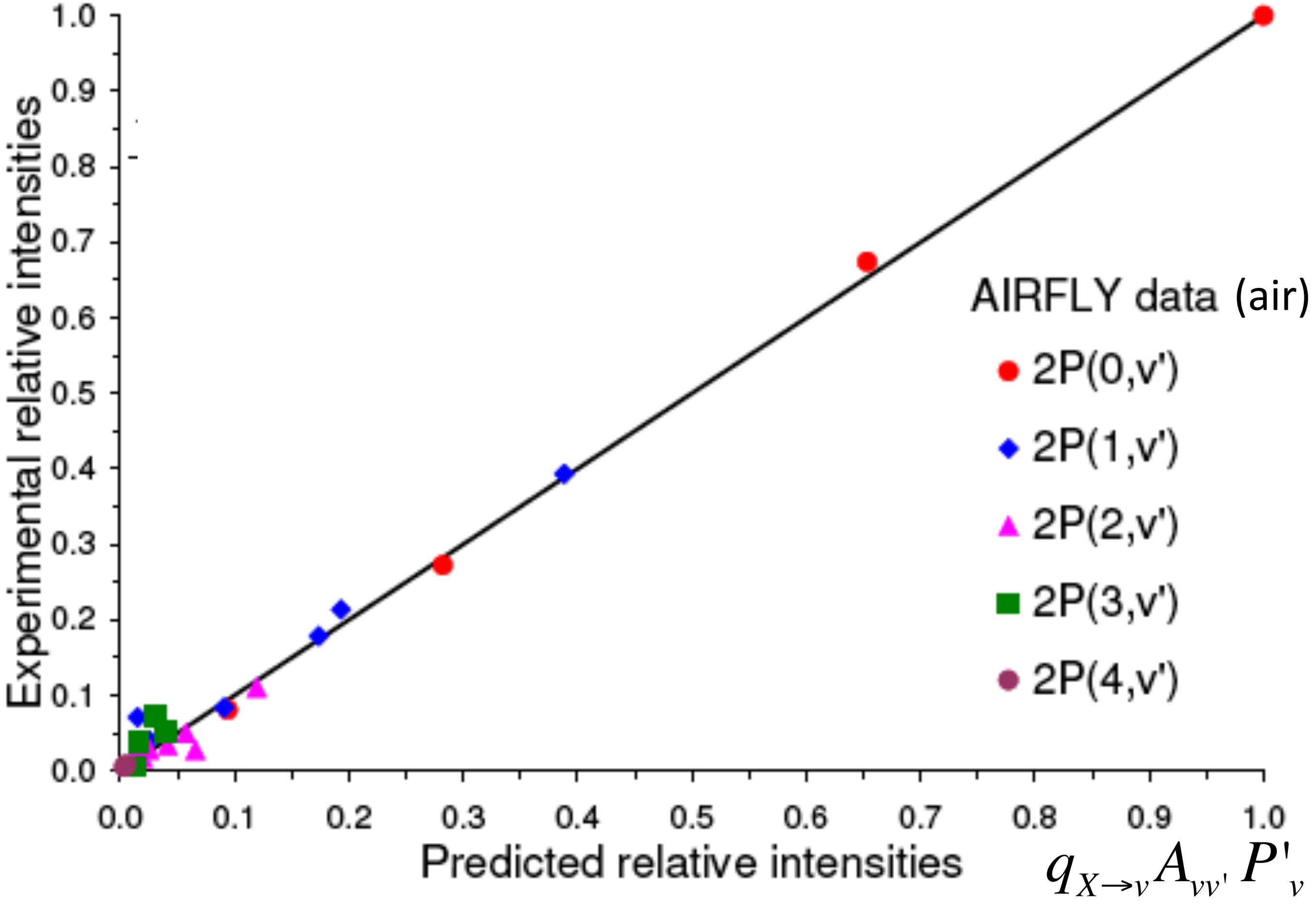
Applicability of F-C principle is not expected *a priori* because fluorescence is induced by low-energy secondaries, nevertheless …

Relative intensities



$$q_{X\rightarrow v} A_{vv'} P'_v$$

Relative intensities



$$q_{X\rightarrow v}A_{vv'}P'_{v}$$

Relative intensities

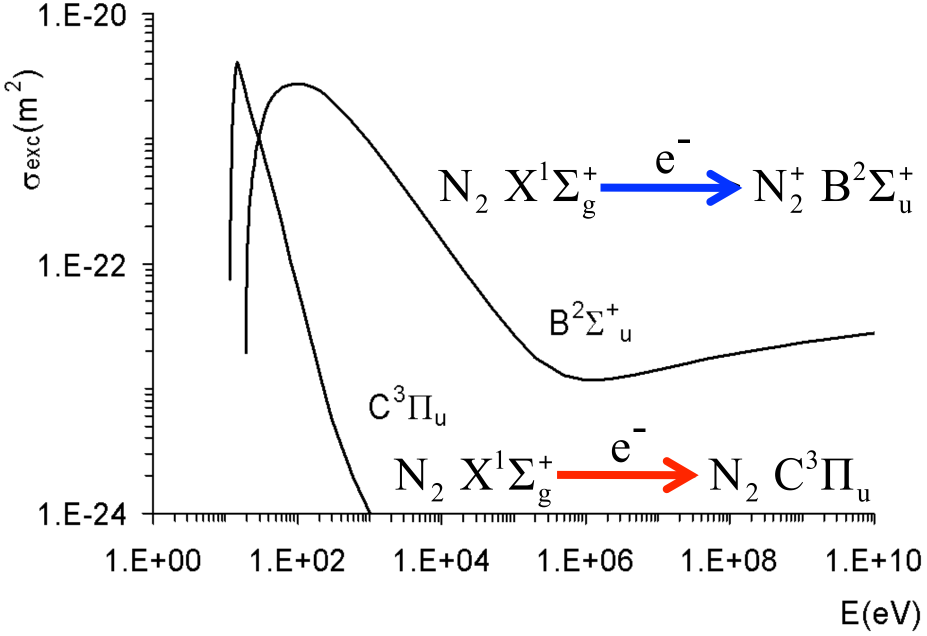
$$\frac{I_{vv'}}{I_{00}} = \frac{q_{X\to v} A_{vv'}}{q_{X\to 0} A_{00}} \frac{1+P/P'_0}{1+P/P'_v} \overset{P>>P'}{\approx} \frac{q_{X\to v} A_{vv'}}{q_{X\to 0} A_{00}} \frac{P'_v}{P'_0}$$

independent of P

Applicability of F-C principle is not expected *a priori*, nevertheless … **it works** for 2P(0-v') and 2P(1-v') bands (90% contribution) and also for weaker bands when taking into account experimental uncertainties.

- Accurate I_λ within 290 – 430 nm from AIRFLY
- Beyond this interval (small contributions), the above formula can be used safely.

Seconday electrons

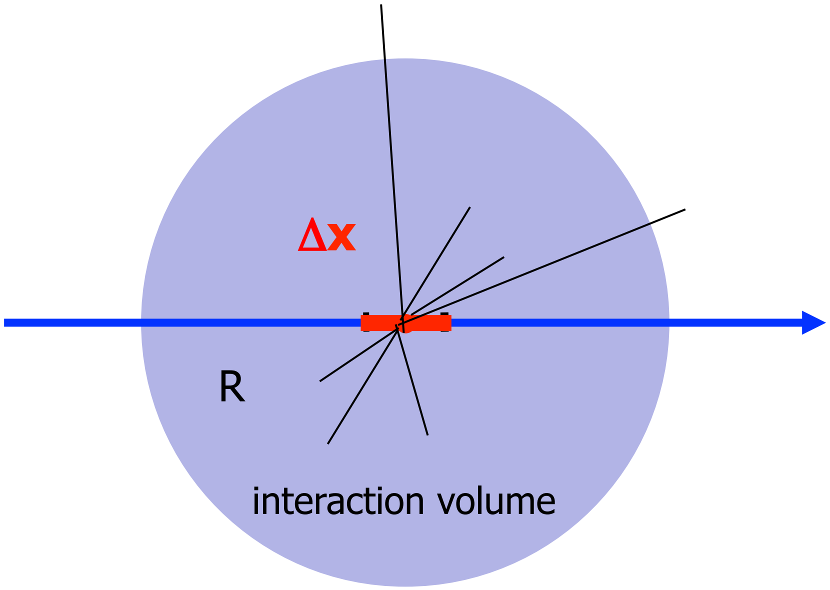


Excitation cross section of the 2P system peaked at few eVs → High energy electrons cannot produce 2P fluorescence (dominant at high pressure)

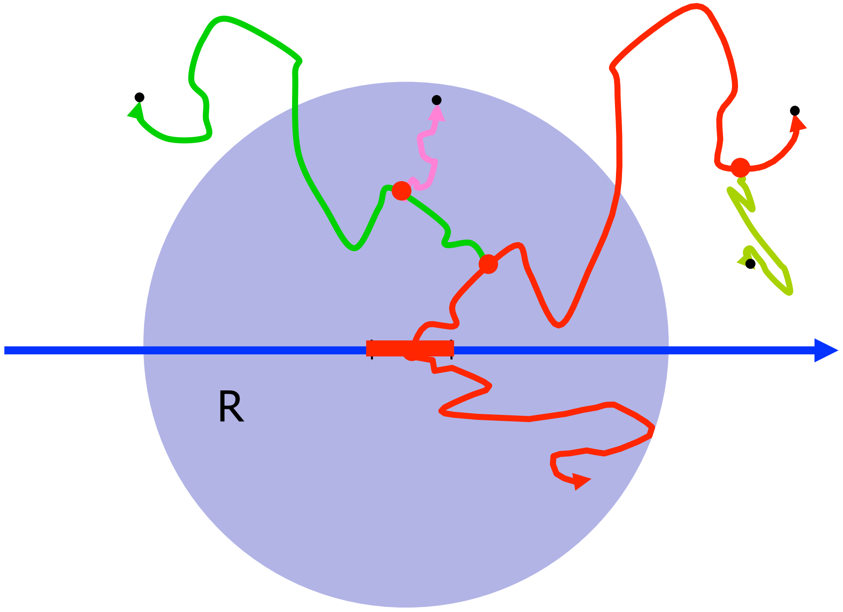
2P fluorescence is generated by low energy electrons from ionizations.

- Suggested by Bunner (PhD thesis 1967).
- First detailed calculation up to GeVs:
  F. Blanco and F. Arqueros Phys. Lett. A 345 (2005) 355

Secondary electrons



A simple analytical model



MC simulation

ph/m

$$\varepsilon_{vv'}(E) = N\,\frac{1}{1+P/P_v'}\left\{\sigma_{vv'}(E) + \underbrace{\left\langle\frac{\sigma_{vv'}}{\sigma_{inel}}\right\rangle\left(1-\overbrace{e^{-N<\sigma_{inel}>R}}^{\text{Probability to escape the observation region}}\right)\sigma_{ion}(E)}_{\text{Secondary electrons contribution}}\right\}$$

Direct excitation

ph/m

$$\varepsilon_{vv'}(E) = N\,\frac{1}{1+P/P_v'}\left\{\sigma_{vv'}(E) + \overbrace{\alpha_{vv'}(E,P,R)}^{\text{Average \#ph per secondary electron}}\,\sigma_{ion}(E)\right\}$$

Direct excitation

Phys. Lett. A 345 (2005) 355

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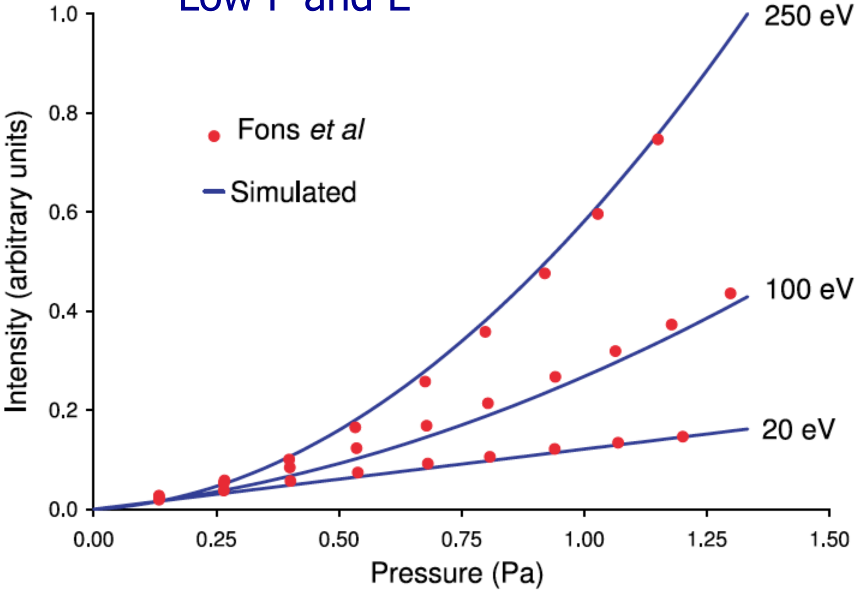
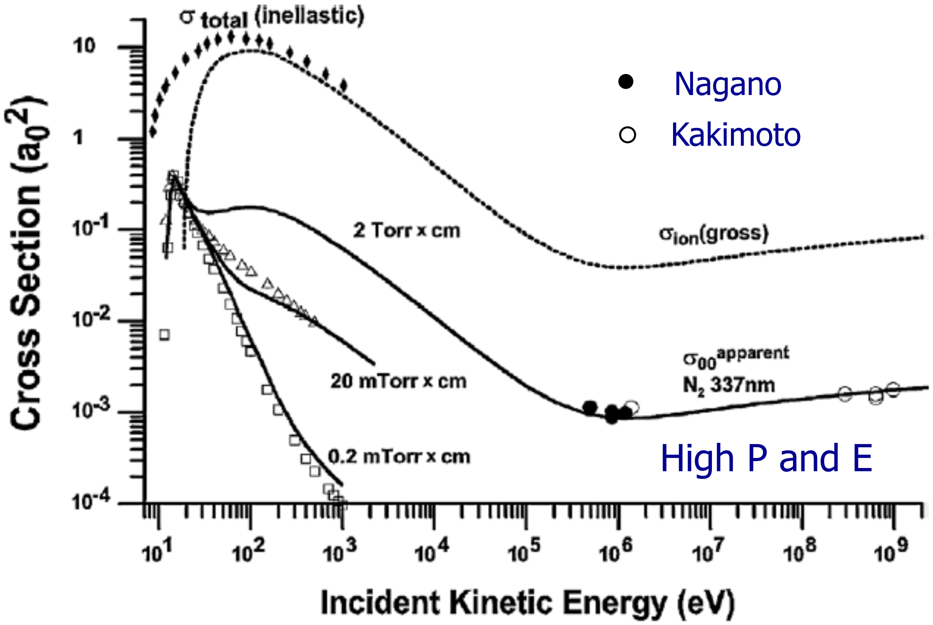
Low P and E



Fluorescence intensity vs pressure

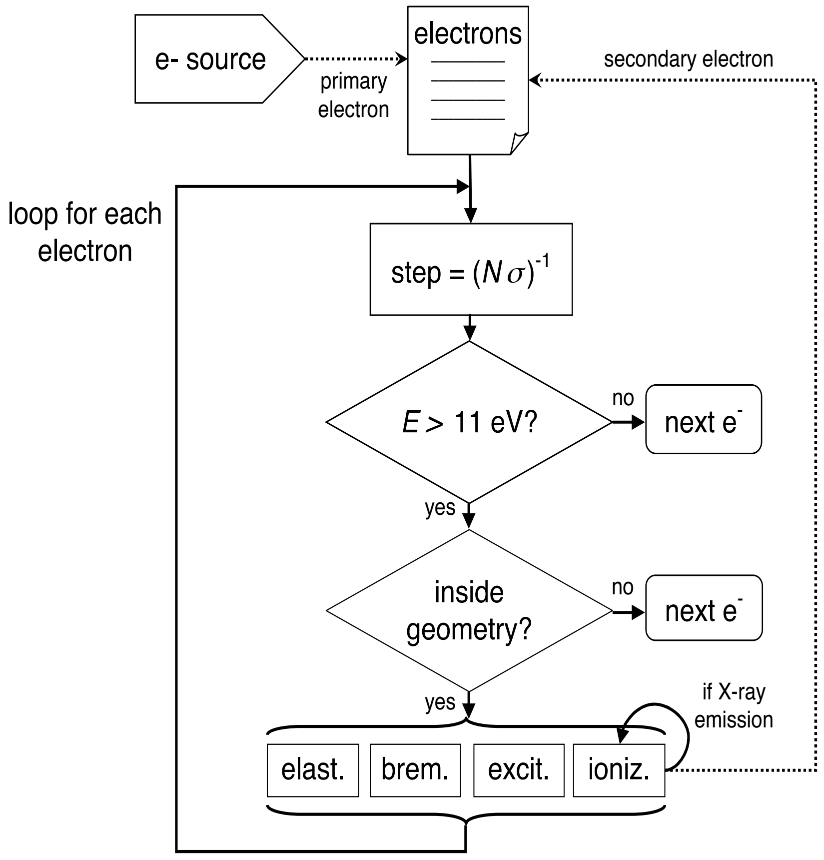


High P and E

Fluorescence intensity vs energy

The model accounts for experimental results previously not well understood

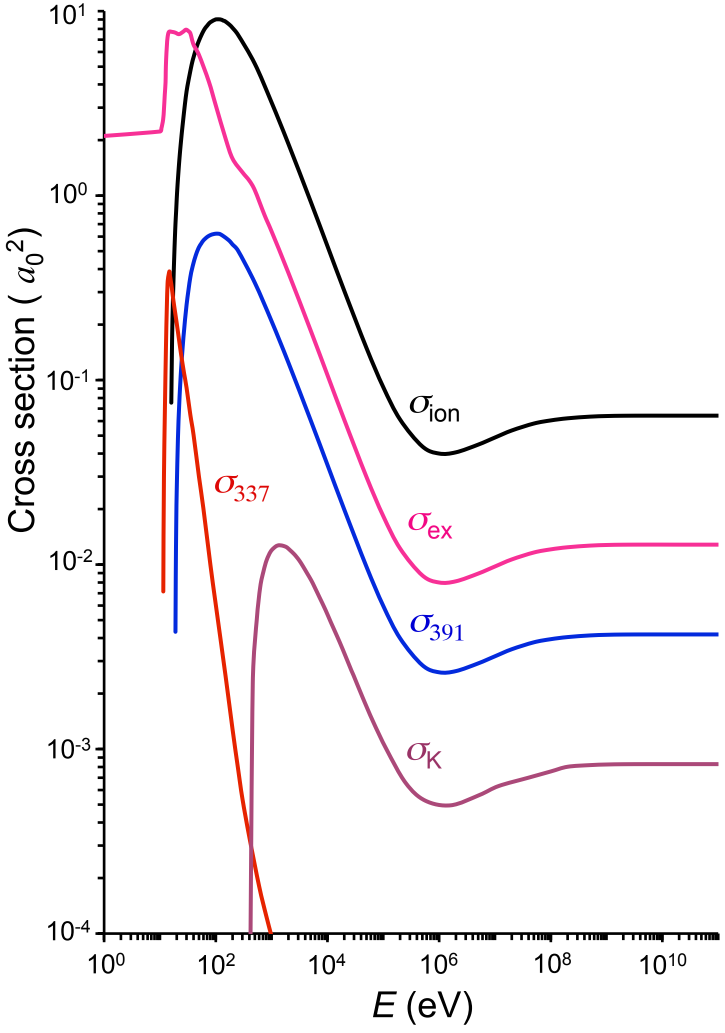
MC simulation*



- Elastic scattering
  - Individual e^- - molecule collision
- Excitation
  - $E = E - \langle E_{exc} \rangle$
  - $n_{337} = \sigma_{337}/\sigma_{exc}$
- Ionization
  - e^- ejected with E_s
  - $E = E - \langle E^{ion}{}_{exc} \rangle - E_s$
  - $n_{391} = \sigma_{391}/\sigma_{ion}$
  - K-shell ionization (410 eV).
- Bremsstrahlung
  - 3% of E converted in γ-ray.
- Energy cutoff
  - $E_{cut} = 11$ eV

* F. Arqueros et al. New J. Phys. 11 (2009) 065011
updated details in J. Rosado Ph.D. thesis (in press)

MC simulation*



- Elastic scattering
  - Individual e^- - molecule collision
- Excitation
  - $E = E - \langle E_{exc} \rangle$
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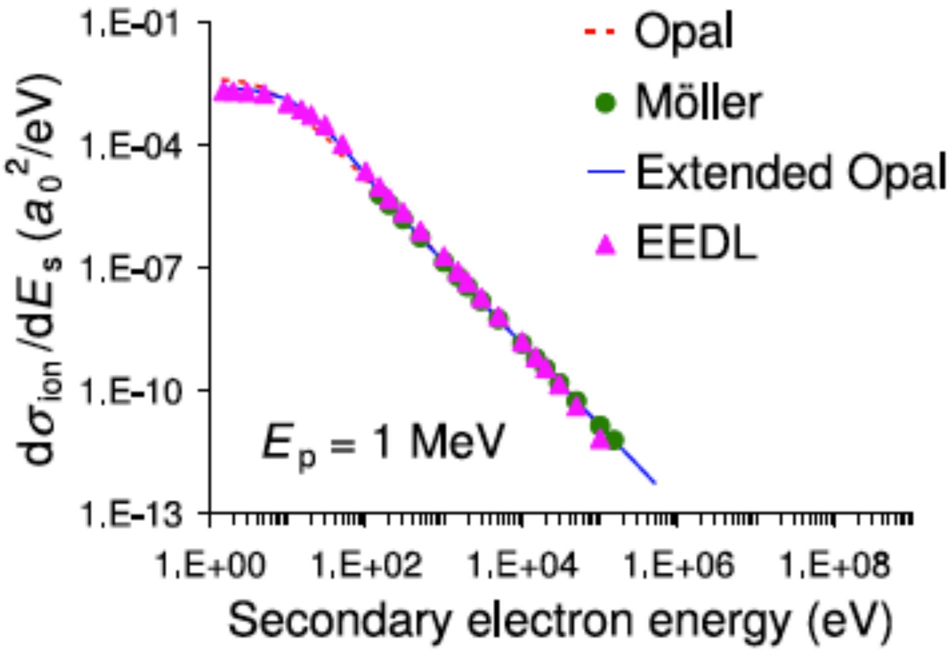
Novel parameterization of the energy spectrum of secondaries

$$\frac{d\sigma_{ion}}{dE_s} = \begin{cases} \dfrac{4\pi\, Z\, Ry}{E_p^{'}} \dfrac{1 + C(E_p)\exp\{-E_s / E_k\}}{E_s^2 + w^2} & for\ E_s \leq (E_p - I) \\ 0 & for\ E_s > (E_p - I) \end{cases}$$

$$E_p^{'} = \frac{1}{2} m_e \beta^2 c^2$$

Fully consistent with:

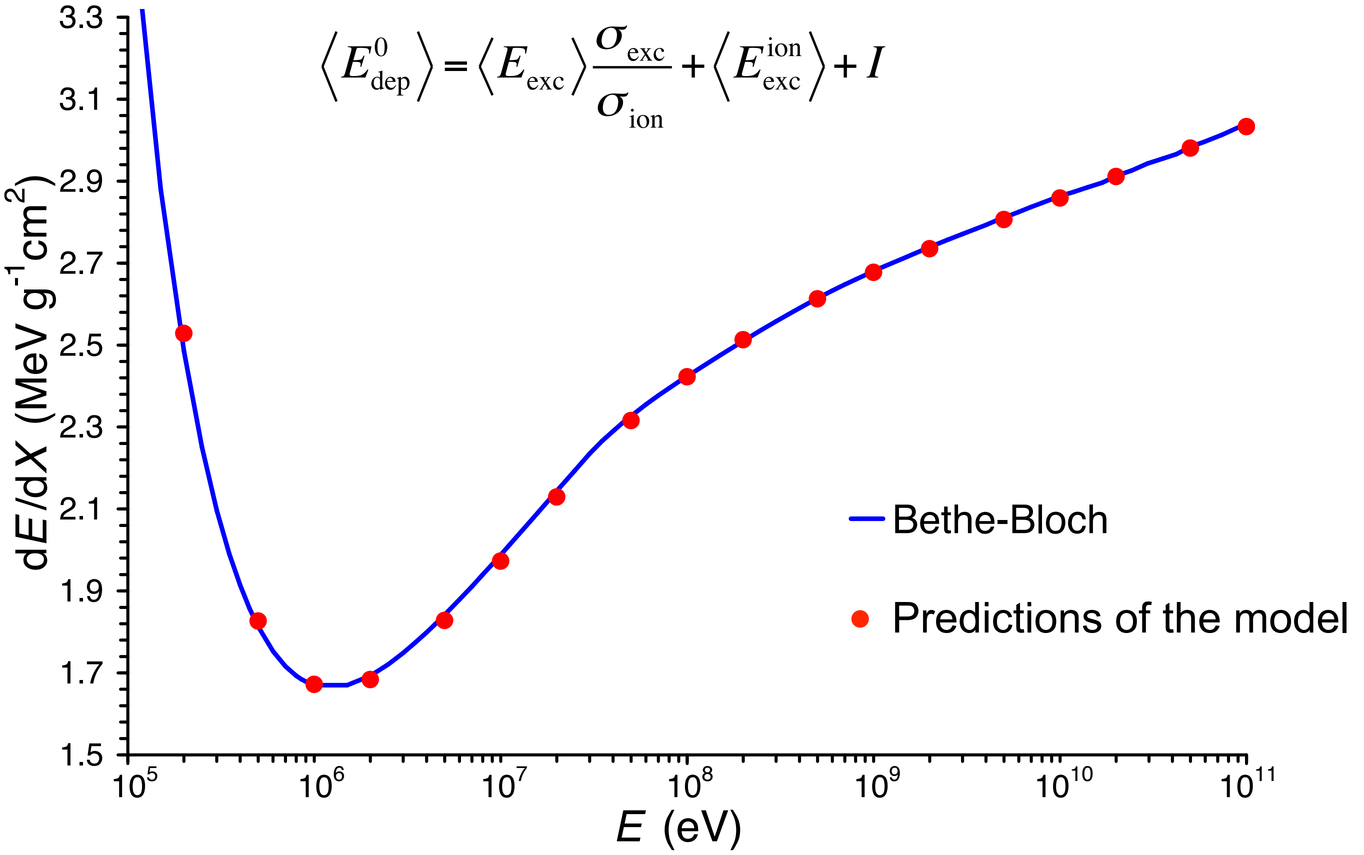
- EEDL – Møller at high E_s
- Opal (exp.) at low E_s
- $\sigma_{ion}(E_p)$
- Bethe - Bloch



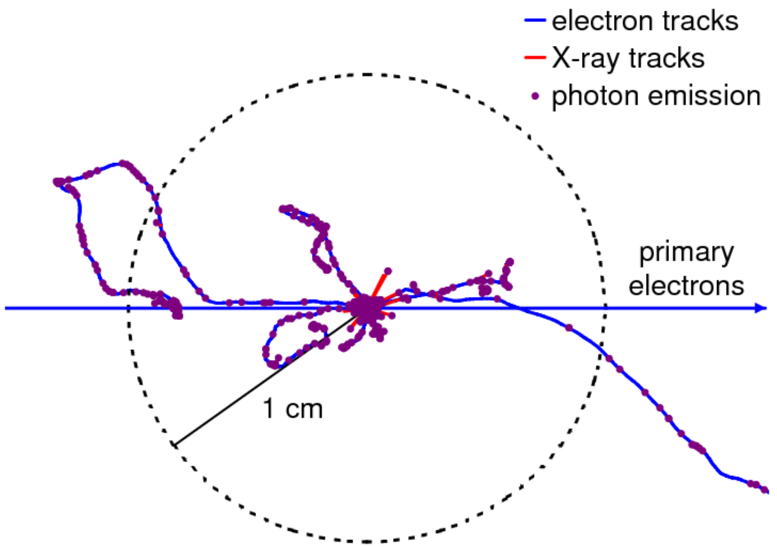
Parameterization of the energy spectrum of secondaries consistent with Bethe-Bloch

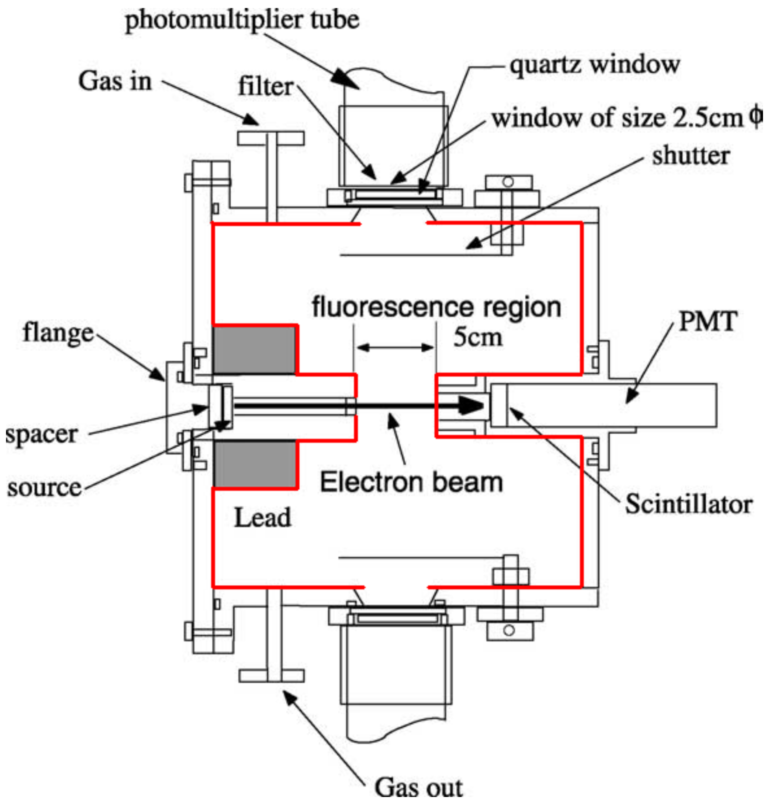
$$\frac{\mathrm{dE}}{\mathrm{dx}} = \mathrm{N}_{\mathrm{air}}\left\{\left\langle E^{0}_{\mathrm{dep}}\right\rangle + \left\langle E_{s}\right\rangle\right\}\sigma_{\mathrm{ion}}(\mathrm{E}_{0})$$

$$\left\langle E^{0}_{\mathrm{dep}}\right\rangle = \left\langle E_{\mathrm{exc}}\right\rangle\frac{\sigma_{\mathrm{exc}}}{\sigma_{\mathrm{ion}}} + \left\langle E^{\mathrm{ion}}_{\mathrm{exc}}\right\rangle + I$$



Geometry





Generic simulation:

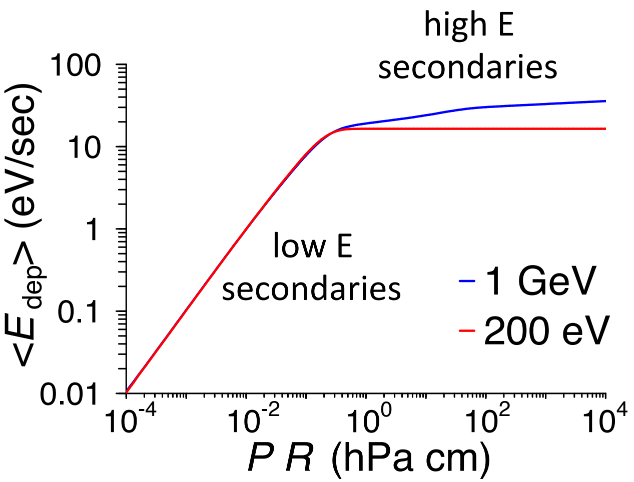
- Medium: sphere R of air (P, T)
- Primary electron forced to interact at the center

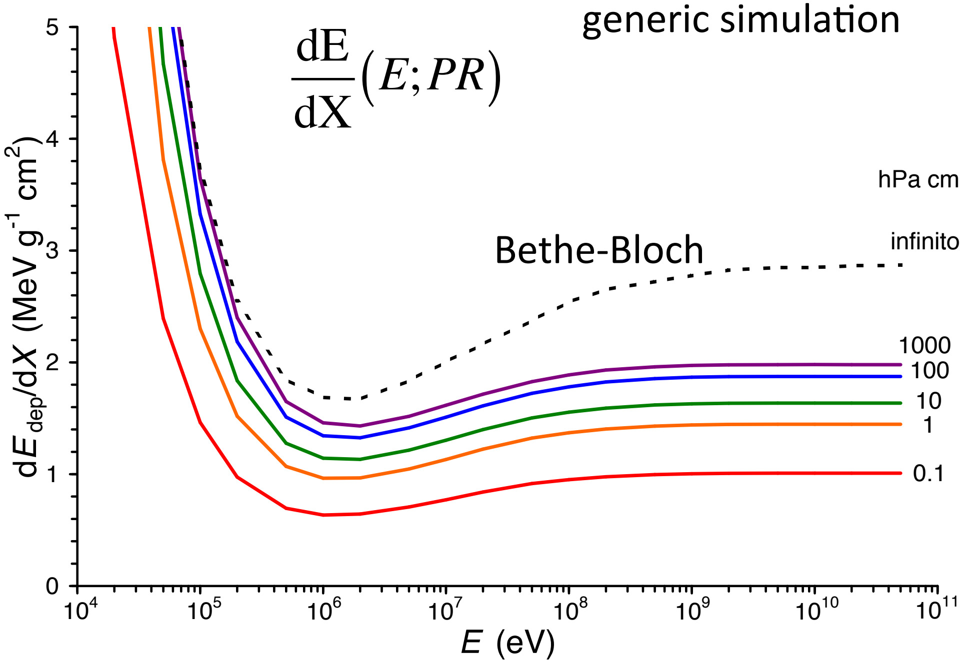
Detailed simulation:

- Geometry
- e^- beam features
- Field of view

Results: Energy deposition

$$\frac{\mathrm{dE}}{\mathrm{dx}} = \mathrm{N}_{\mathrm{air}}\left\{\left\langle E^{0}_{\mathrm{dep}}\right\rangle + \left\langle E_{\mathrm{dep}}\right\rangle\right\}\sigma_{\mathrm{ion}}(\mathrm{E}_0)$$





<u>Generic simulations</u>:

E_{dep} weakly dependent of PR.

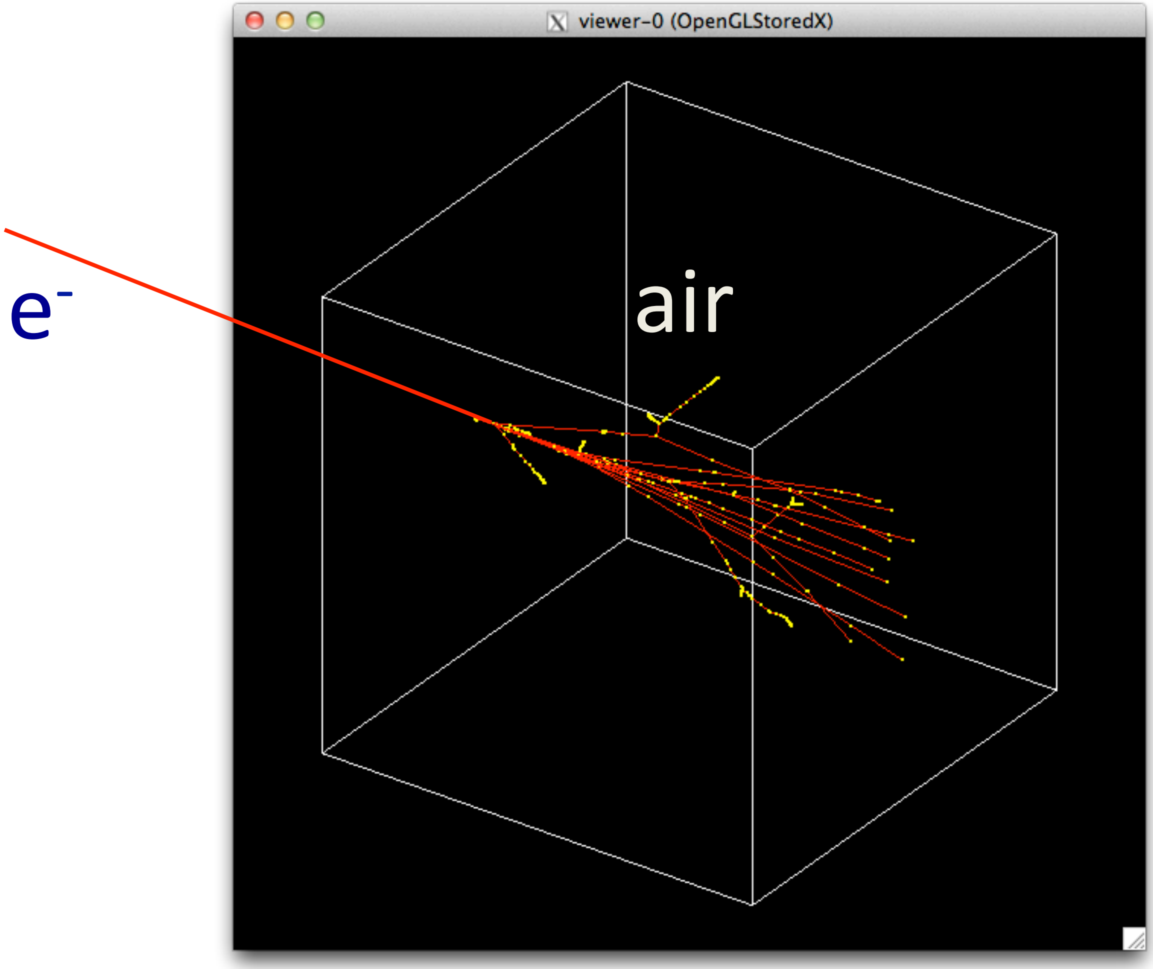
<u>Detailed simulations</u>:

E_{dep} weakly dependent of fine geometrical details.

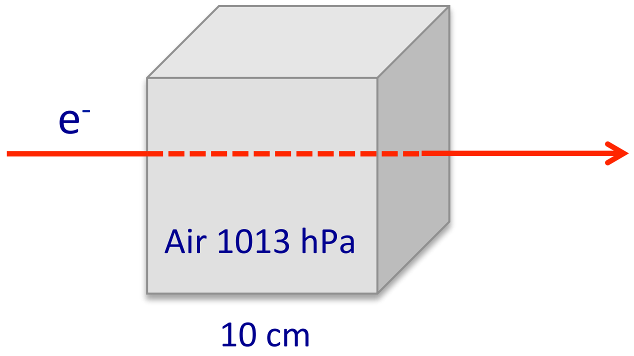
E_{dep} from generic simulations equals those of detailed simulation for R ≈ size of the collision chamber

Energy deposition – cross check

GEANT4 has been implemented for comparisons with our MC simulation using simple geometries



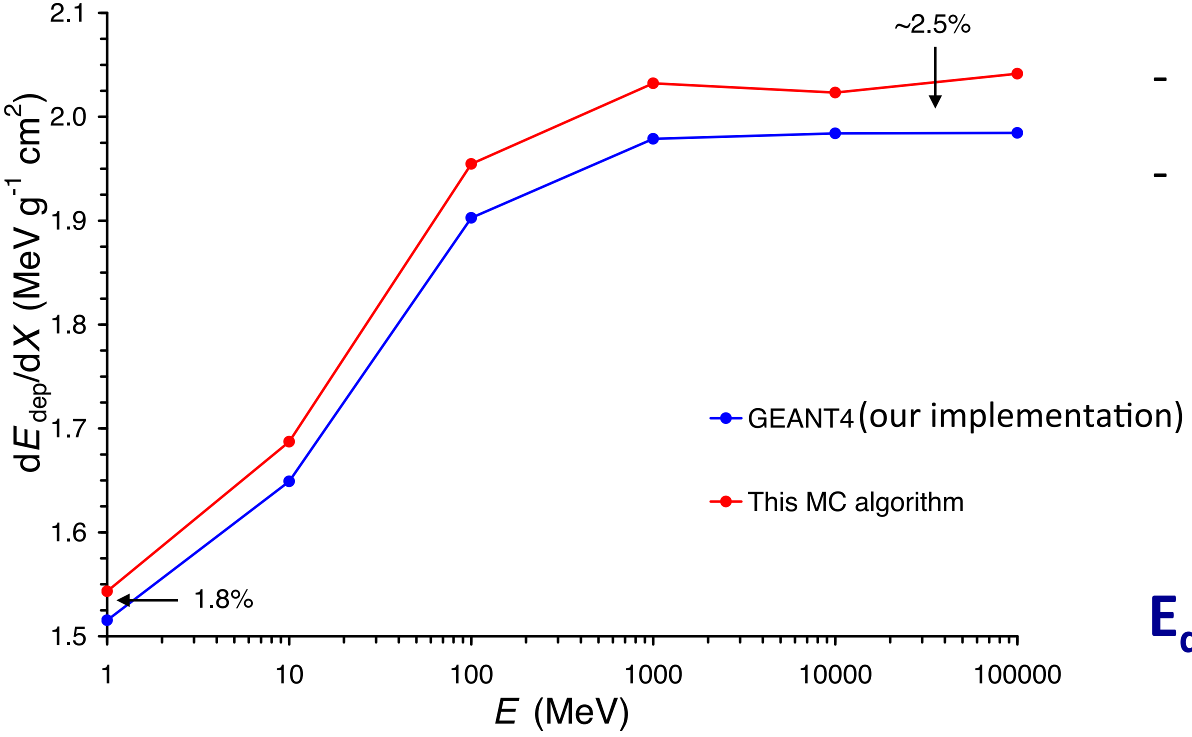
Energy deposition – cross check



$$\frac{dE_{dep}}{dX} \text{ versus } E$$

Comparison of our detailed MC with other simulations

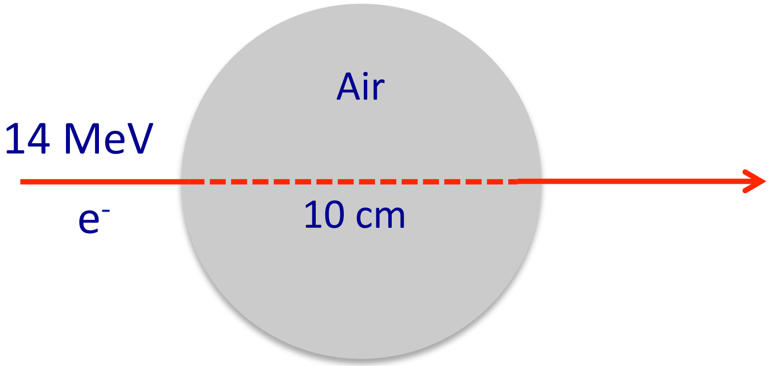
- GEANT4 (our implementation)
- GEANT4 (MACFLY)
- GEANT4 (AIRFLY – electrons)



Systematic difference:

$$E_{dep}(MC) - E_{dep}(GEANT4) \approx 2\%$$

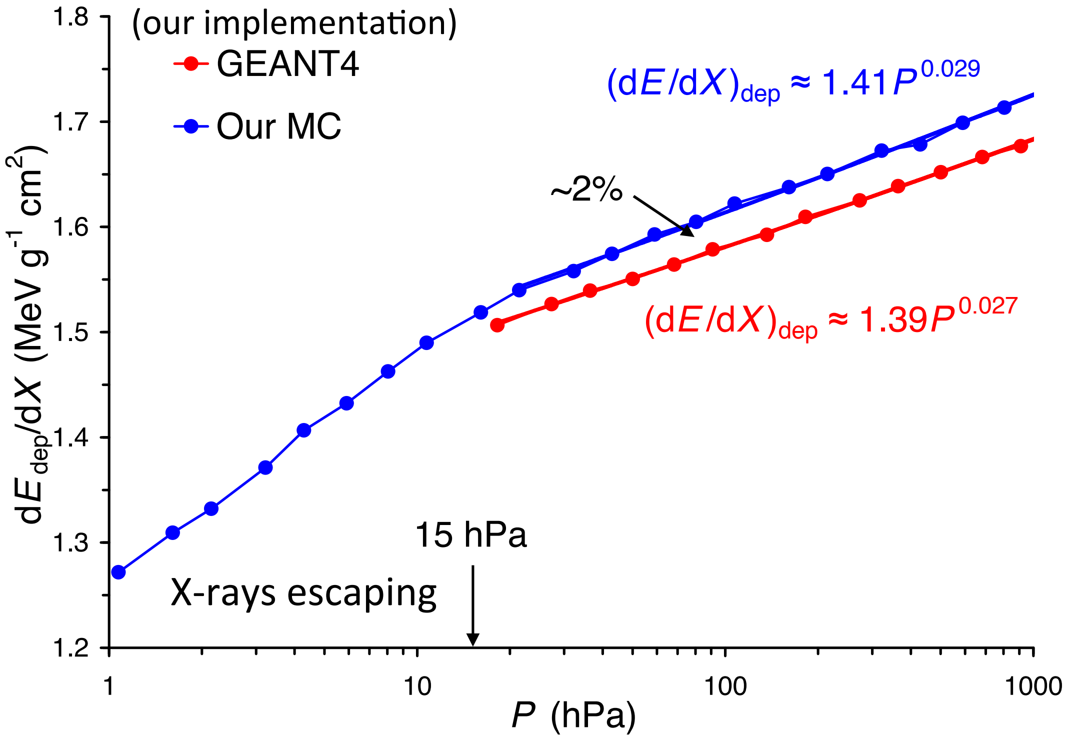
Energy deposition – cross check



$$\frac{dE_{dep}}{dX} \text{ versus } P$$

Comparison of our detailed MC with other simulations:

- GEANT4 (our implementation)
- GEANT4 (AIRFLY*)



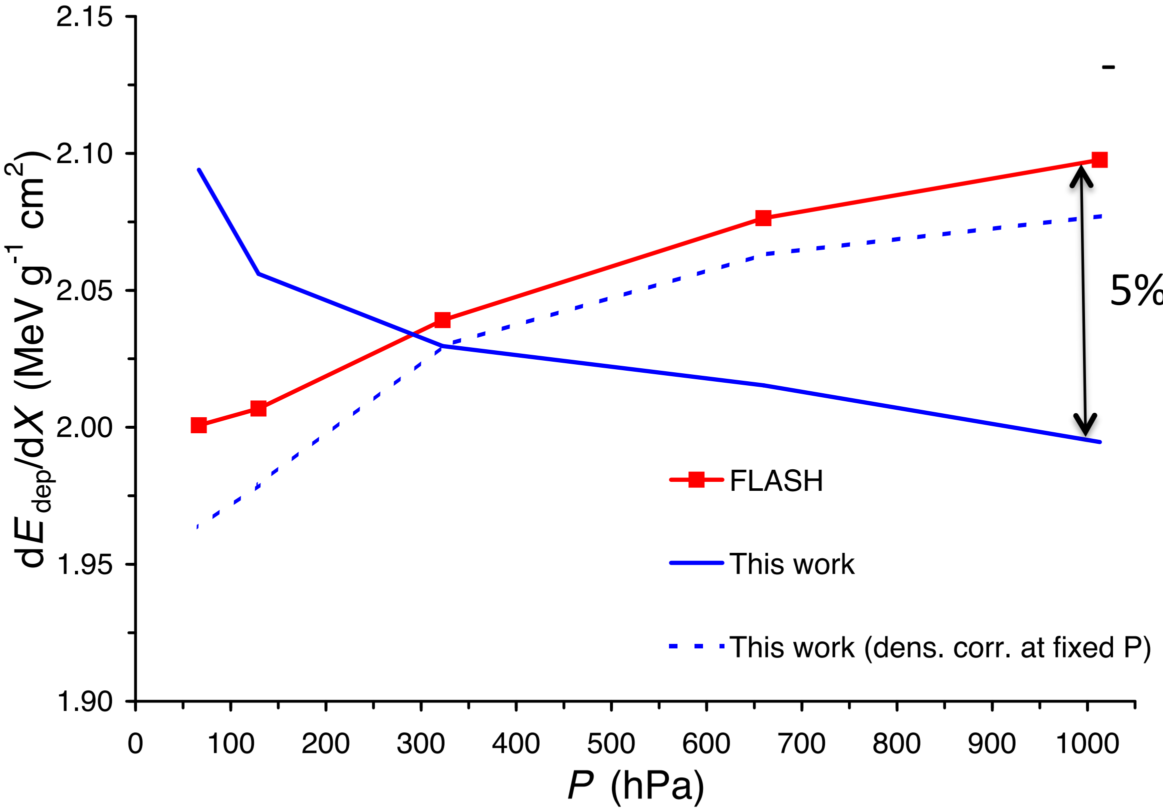
Very good agreement in 15 – 1000 hPa

* Astropart Phys. 28 (2007) 41

Energy deposition – cross check

$$\frac{dE_{dep}}{dX} \text{ versus } P$$

FLASH collision chamber
E = 28.5 GeV



Comparison of our detailed MC with other simulations:

- EGS4 (FLASH*)

Some discrepancy < 5%

* Astropart Phys. 29 (2008) 77

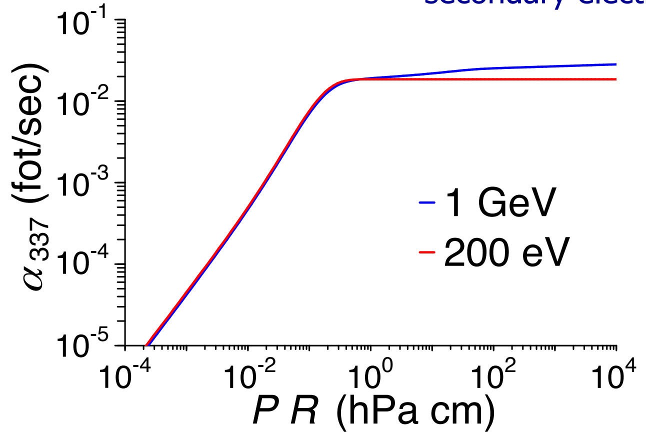
Results: Fluorescence

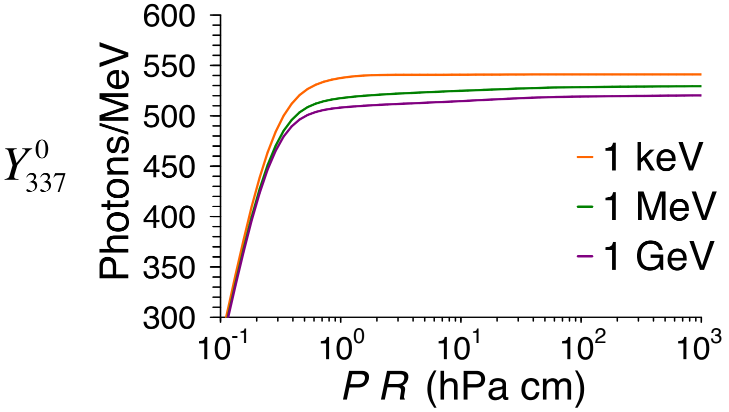
Photons (vv’) per meter without quenching

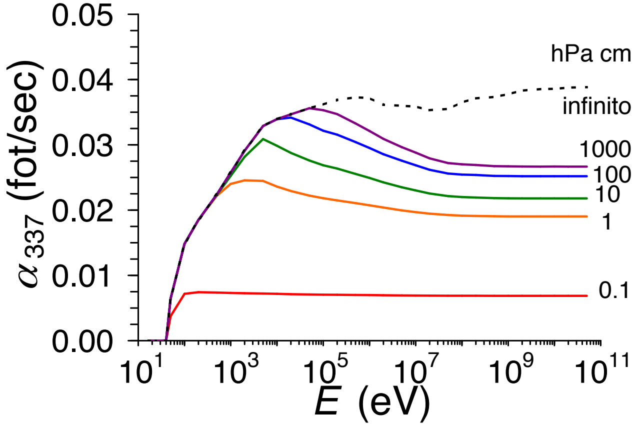
$$\varepsilon^0_{vv'}(E) = N\left\{\sigma_{vv'}(E) + \underbrace{\alpha_{vv'}(E,P,R)}_{\text{Average \#ph per secondary electron}}\,\sigma_{ion}(E)\right\}$$

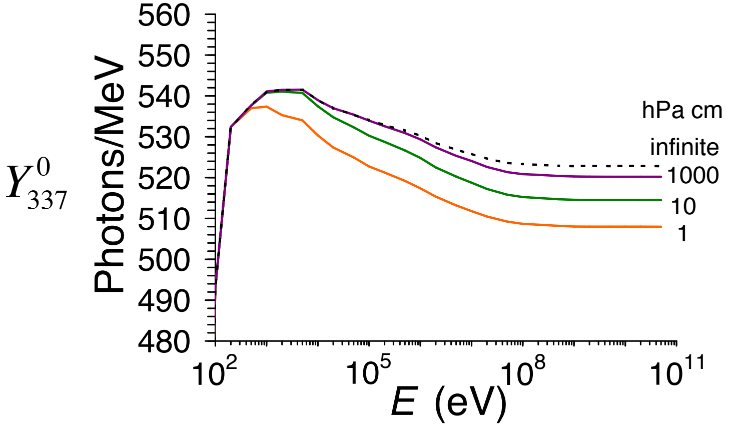
Fluorescence yield without quenching

$$Y^0_{vv'} = \frac{\varepsilon^0_{vv'}}{\mathrm{d}E/\mathrm{d}X}$$

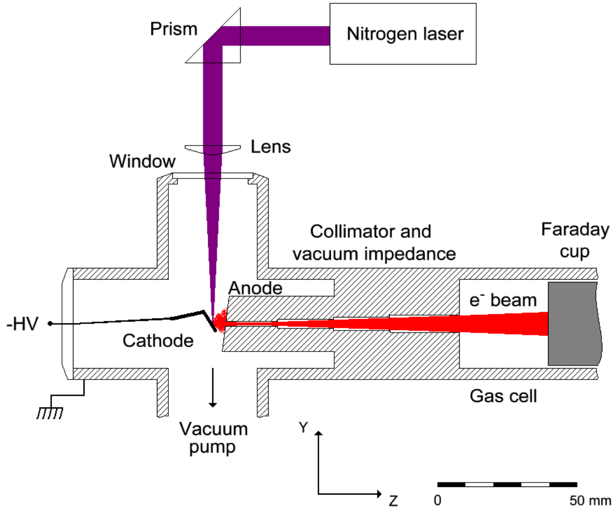






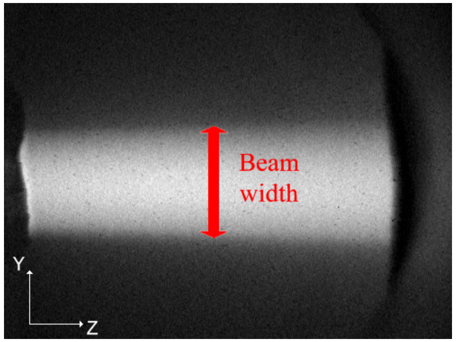


Fluorescence emission cross-check

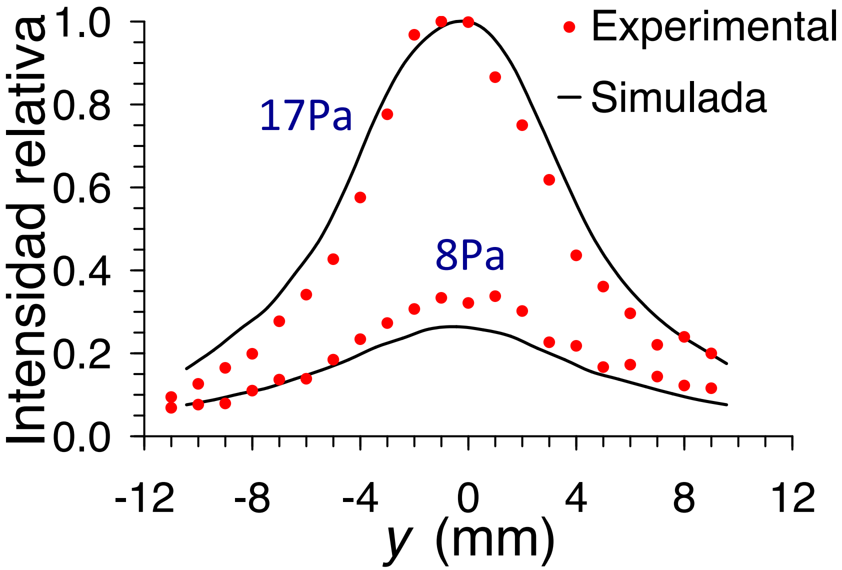


20 keV
low pressure

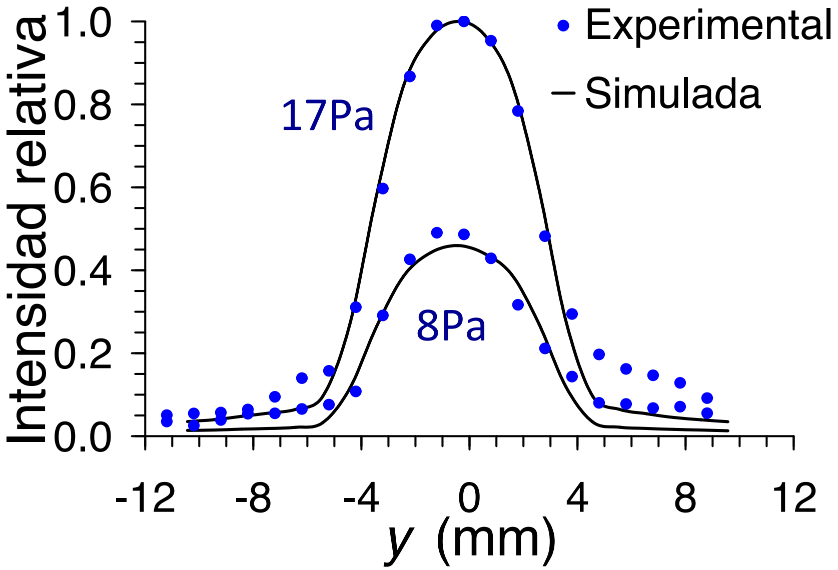
Rosado et al.



337 nm

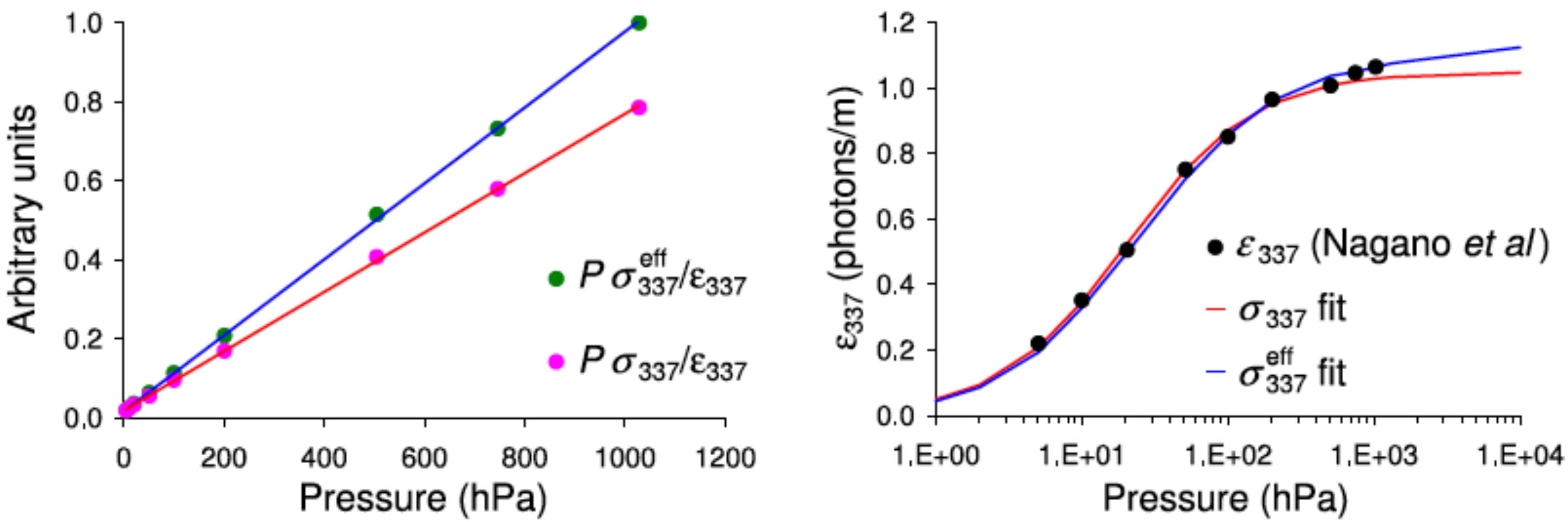


391nm



Fluorescence intensity vs. pressure P' measurement*

$$\varepsilon_{vv'}(E) = N\,\frac{1}{1+P/P_v'}\left\{\,\sigma_{vv'}(E)+\underbrace{\alpha_{vv'}(E,P,R)}_{\text{additional P dependence}}\,\sigma_{ion}(E)\,\right\}$$

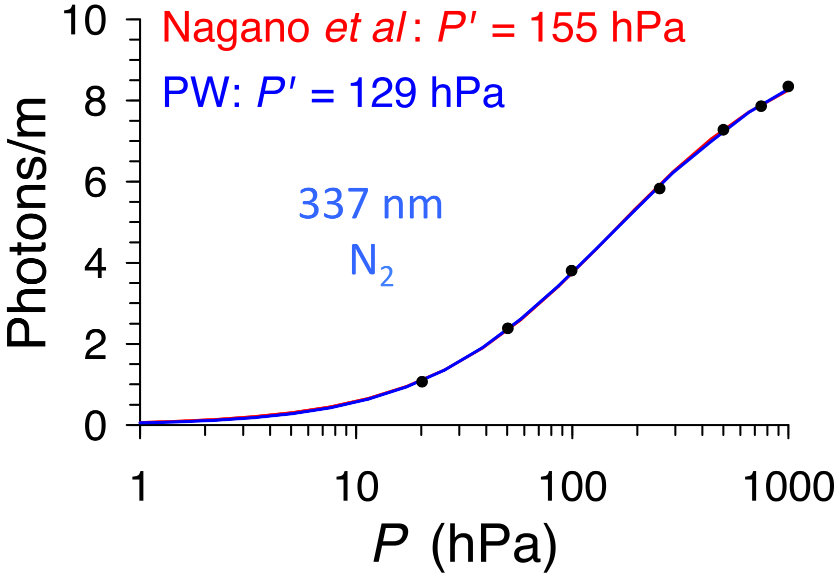


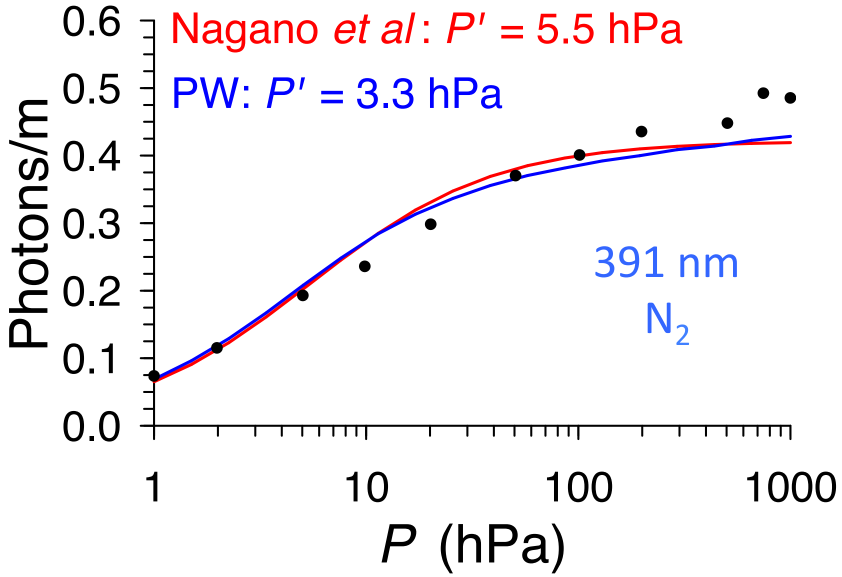
Neglecting the effect of secondary electrons in $\varepsilon_{vv'}$ give rise to systematic errors in the measurement of P'

* F. Arqueros et al. New J. Phys. 11 (2009) 065011

Fluorescence intensity vs. pressure P’ measurement*

$$\varepsilon_{vv'}(E) = N \frac{1}{1+P/P_v'}\left\{ \sigma_{vv'}(E) + \underbrace{\alpha_{vv'}(E,P,R)}_{\text{additional P dependence}} \sigma_{ion}(E) \right\}$$

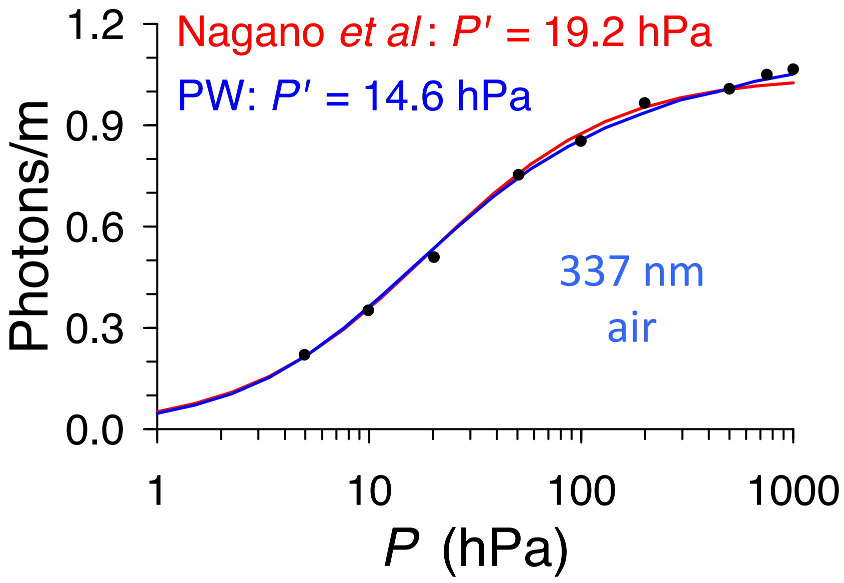


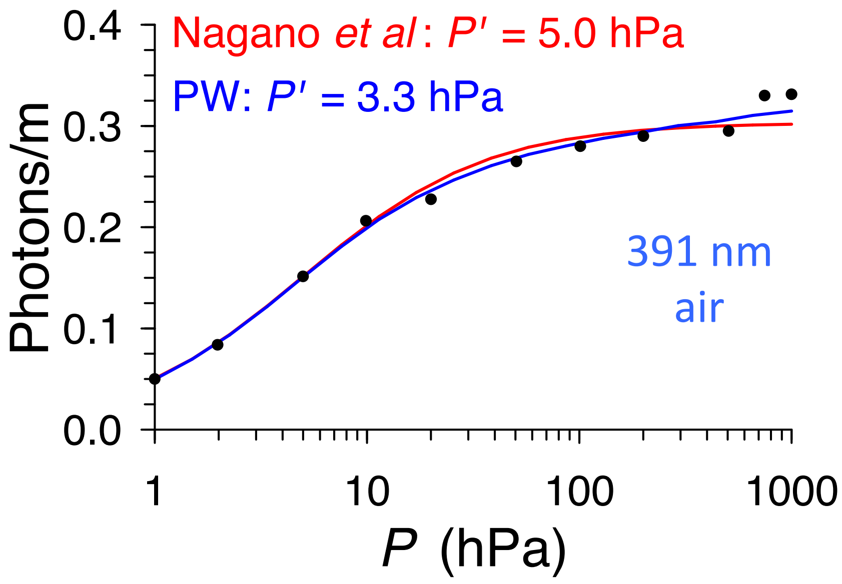


Nagano’s data of $\varepsilon_{vv'}$ (P) have been re-analyzed including the $\alpha_{vv'}$(P) dependence from our MC

*updated results in J. Rosado Ph.D. thesis (in press)

Fluorescence intensity vs. pressure P' measurement*



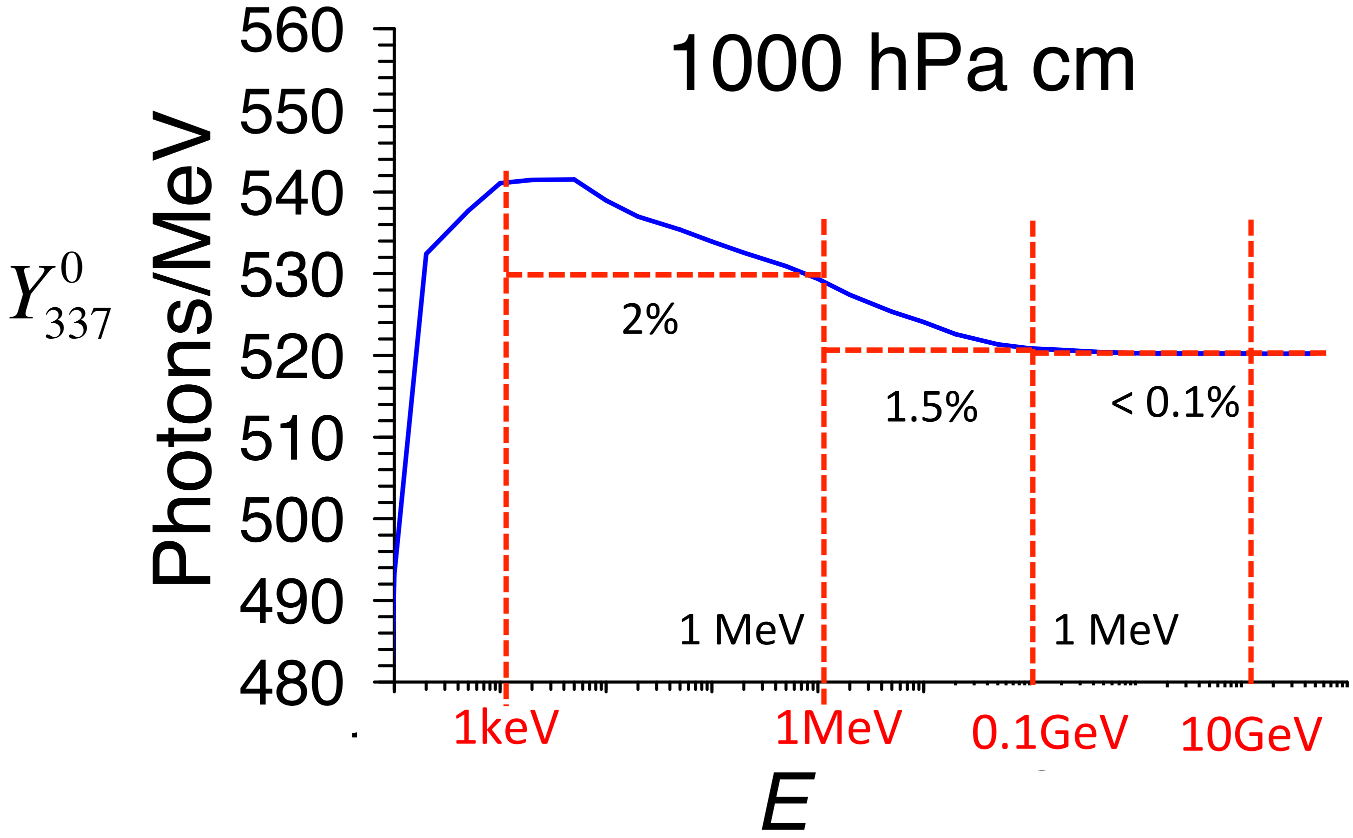


AIR	**P'$_{337}$ (hPa)**	**P'$_{391}$ (hPa)**
Nagano	19.2	5.02
AIRFLY	15.9	2.94
Nagano corrected	14.6	3.3

Discrepancies between Nagano and AIRFLY are reduced significantly when corrected for this effect

*updated results in J. Rosado Ph.D. thesis (in press)

Fluorescence yield versus Energy

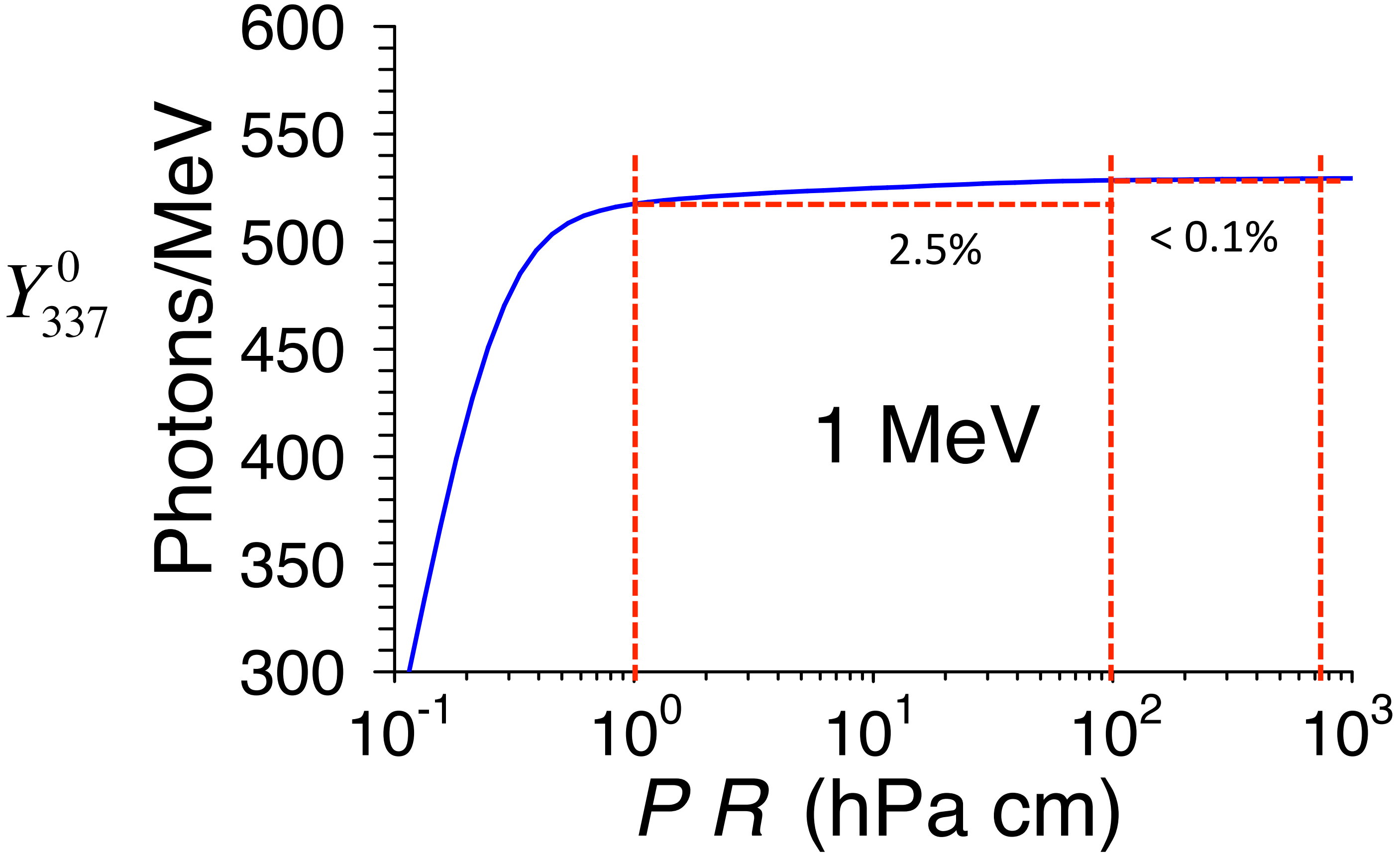


Y ≈constant for
E > 1 keV

Y dependence
is even smaller
for Y_{391}

Experimental tests show Y independent of E within < 5 %

Fluorescence yield versus PR



Y strongly dependent on PR in the vicinity of the electron track (PR < 100 hPa × 100 μm)

Theoretical value of the air-fluorescence yield

$$Y_{337} = \frac{1}{1 + P / P'_{337}} Y^0_{337} = \boxed{6.3\ \mathrm{ph/MeV}}$$

1013 hPa 293K

P'_{337} from AIRFLY*

Y^0_{337} from our MC simulation

Uncertainties in our calculations:

Energy deposit ≈ 2%

Fluorescence emission ≈ 20 %

Fluorescence yield ≈ 20 %

Average value of experimental results**

$$Y_{337} = \boxed{5.57\ \mathrm{ph/MeV}}$$

* Astropart Phys. 28 (2007) 41

** talk of J. Rosado

Conclusions

- Fluorescence emission and energy deposition in air is reasonably well understood.
- Our simulation in agreement with GEANT4 (2%). Some disagreement (< 5%) with EGS4-FLASH.
- FY independent of E supported by theory at the level of < 1.5% (1MeV – 100 GeV).
- Theoretical absolute FY in good agreement with experiments.
- Systematic errors when the effect of secondaries is neglected.
- Detailed simulations provide the necessary correction factors. When applied, agreement between experiments improves:
  - Energy deposition/absolute FY (see talk of J. Rosado)
  - P’ values in ε(P) measurements, e.g., Nagano vs AIRFLY

Thanks