The air-fluorescence yield

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Introduction

• Several experiments (plan to) measure the energy spectrum of Ultra High Energy Cosmic Rays UHECRs: Auger, HiRes, TA.

• UHECRs generate extensive air showers in the atmosphere. Most of the CR energy is delivered to the EM component of the shower.

- Air-shower electrons generate fluorescence (registered at ground with a telescope). Fluorescence intensity provides a measured of the deposited EM energy

Fluorescence yield = number of fluorescence photons / unit of deposited energy

Problem:

The accuracy in the CR energy (spectrum) measured by the fluorescence technique is presently limited by the uncertainty in the fluorescence yield.

A world-wide campaign to determined the fluorescence yield accurately

5th Fluorescence Workshop, El Escorial, Madrid (2007)

http://top.gae.ucm.es/5th_FW/

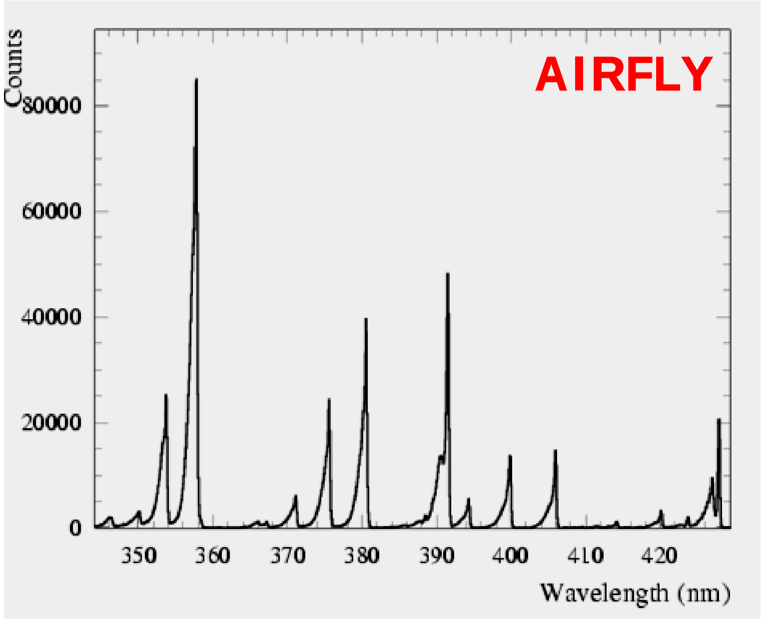
Wavelength spectrum of air fluorescence

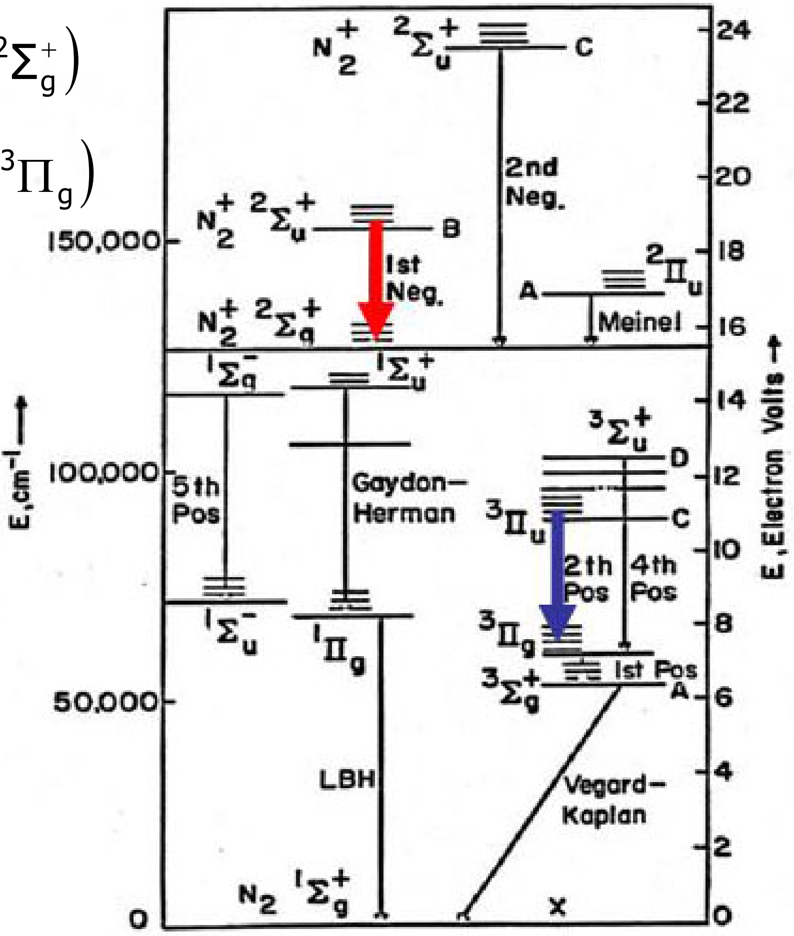
- Range of fluorescence telescopes ≅ 300 – 400 nm

- Air fluorescence basically produced by molecular nitrogen

First Negative System $N_2^+ \left(B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+\right)$

Second Positive System $N_2 \left(C^3\Pi_u \rightarrow B^3\Pi_g\right)$





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The fluorescence technique

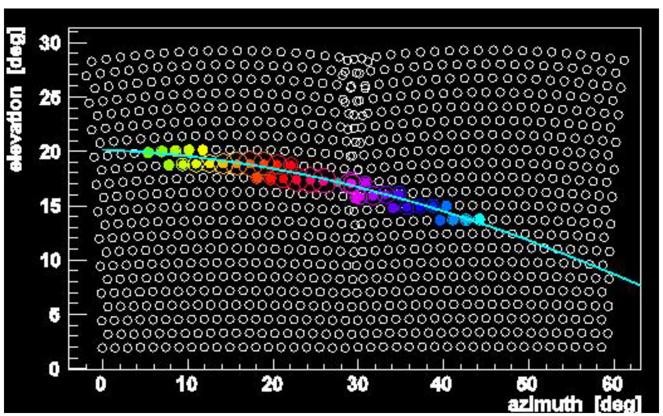
Fluorescence photons Deposited energy

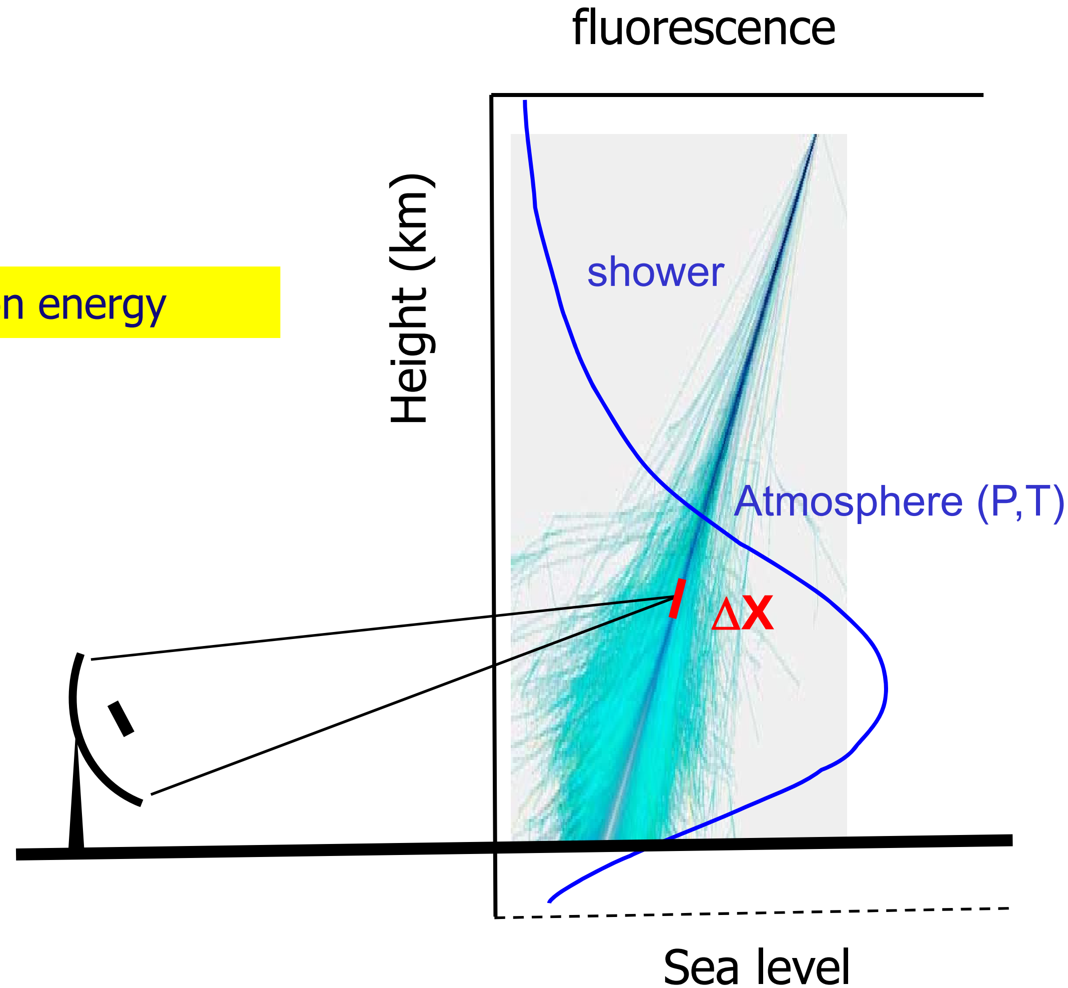
$$\frac{dN_\gamma}{dX} = Y(P,T)\,\frac{dE_{dep}}{dX}$$

Fluorescence yield (photons / MeV)

Assumption: Y independent on electron energy

$$E_{dep} = \int dX \,\frac{1}{Y(P,T)}\,\frac{dN_\gamma}{dX}$$





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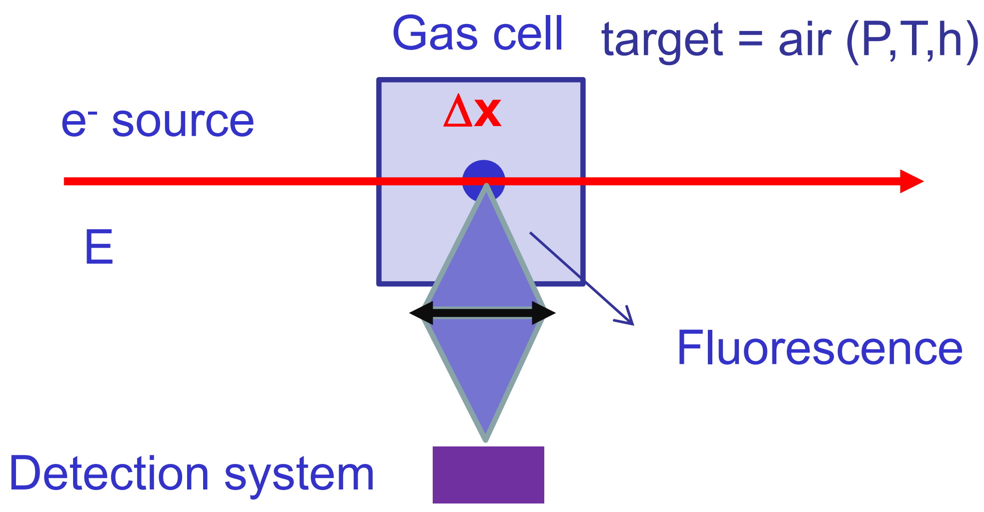
Tools for the FY measurement

- Laboratory techniques I: electron beam
  - accelerators
  - radioactive sources (^{90}Sr, ^{241}Am)
  - low energy beams

- Laboratory techniques II: fluorescence measurement
  - Monochromators, filters
  - Photon counting: PMTs, HPDs

- Laboratory techniques III: Techniques for the absolute calibration of the experimental set-up (photons, electrons..).

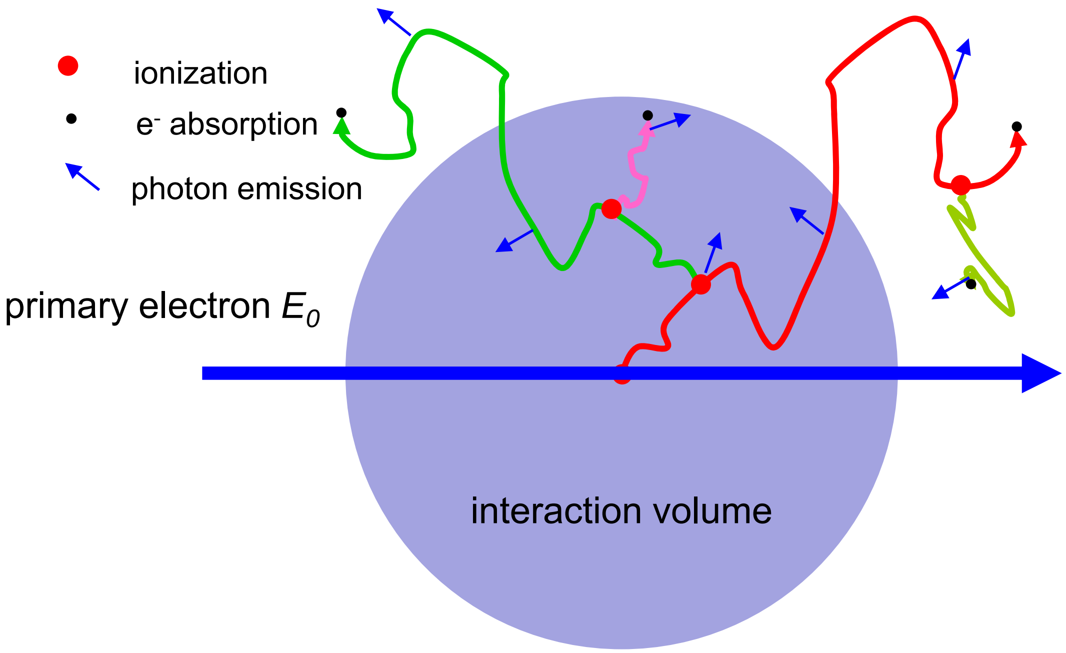


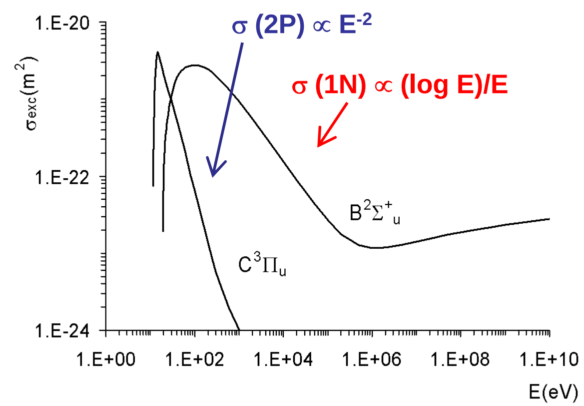
FY groups / experiments

Group	Accelerator	Radioactive Source	Low E beam	Theory
AIRFLY	6 – 30 keV 0.5 – 15 MeV 50 – 420 MeV			
FLASH	28.5 GeV			
MACFLY	20 GeV 50 GeV	^{90}Sr		
Nagano et al.		^{90}Sr (3.7 MBq)		
Karlsruhe		^{90}Sr (37 MBq)		X
Gorodetzky et al.		^{90}Sr (370 MBq)		
Fraga et al.		^{241}Am		
UCM			30 keV	X
Ulrich et al.			12 keV	X

Secondary electrons

Fluorescence is mainly produced by secondary electrons ejected in ionization processes.





Observed fluorescence depends on the experiment FOV !!

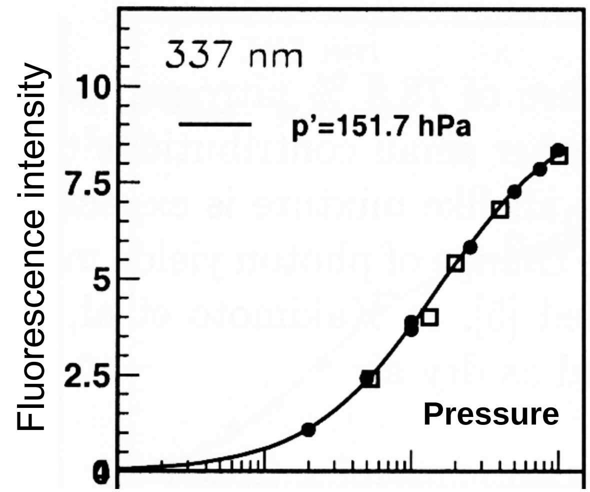
Both fluorescence and deposited energy must be measured/computed in the same volume

F. Blanco and F. Arqueros, Phys. Lett. A 345 (2005) 355
F. Arqueros et al. Astropart. Phys. 26 (2006) 231

Fluorescence Yield vs Pressure (quenching)

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

Collisional de-excitation

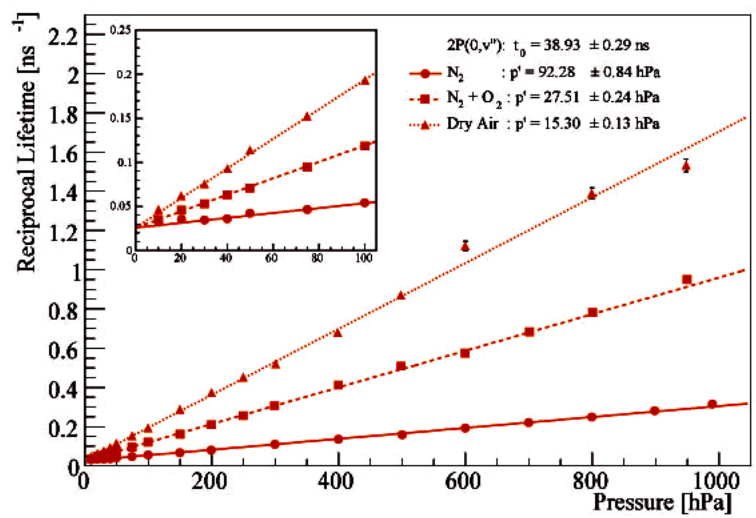


Nagano et al. (2004)

P' = characteristic pressure

P = P' → collisional rate = radiative rate

$$\frac{1}{\tau_v(P)} = \frac{1}{\tau_v}\left(1 + \frac{P}{P_v'}\right)$$



AIRLIGHT (5th FW, El Escorial 2007)

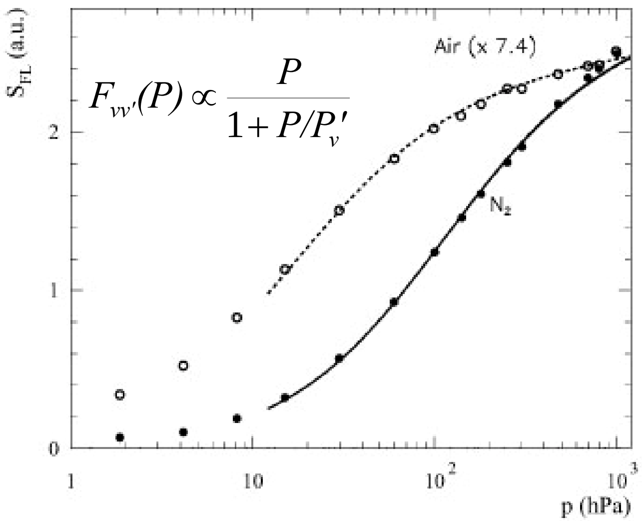
Photons g^{-1} cm^2 (P=0)

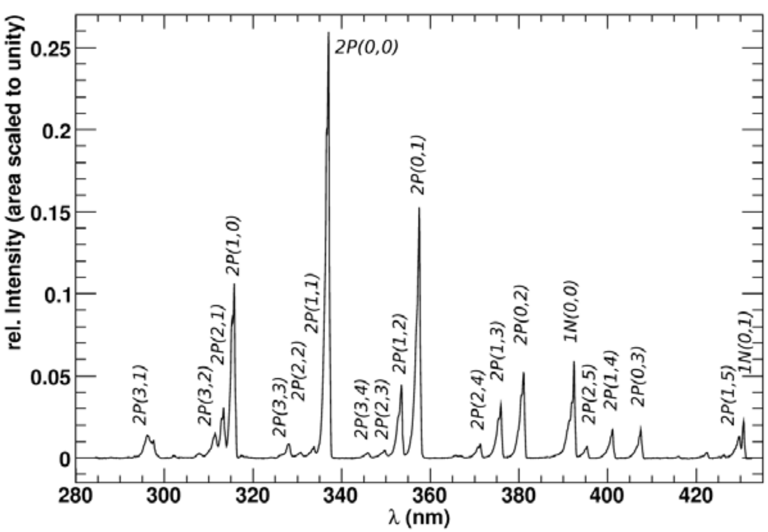
FY (P=0) $$Y_\lambda{}^0 = \frac{A_\lambda}{(dE/dX)_{dep}};$$

dep. energy (P=0)

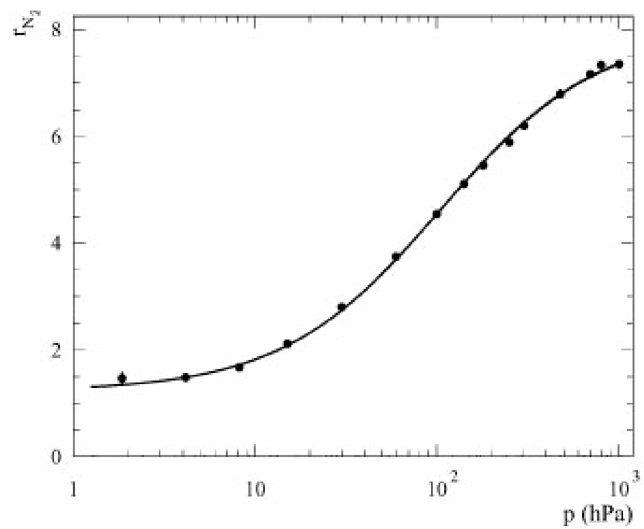
AIRFLY (Astropart. Phys. 2007, 5th FW, El Escorial 2007)

Fluorescence intensity (P)





Novel procedure



I_{N2} / I_{air} effect of secondaries cancels out

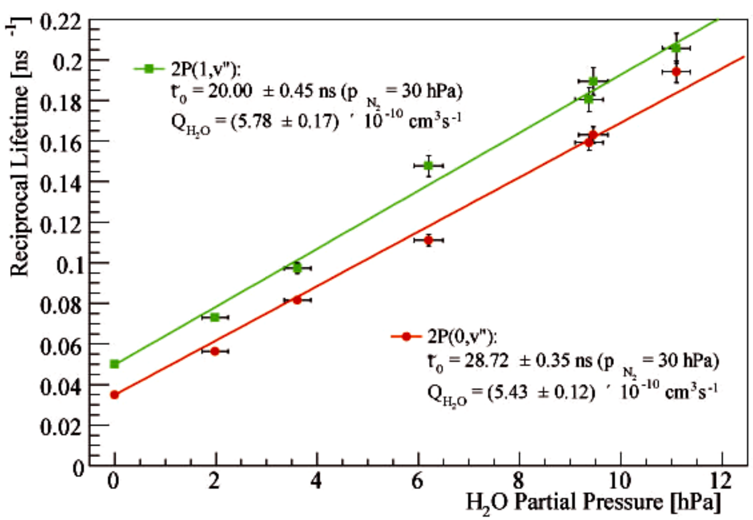
- High resolution spectrum
- Accurate values of P'v

Humidity effect

Air components
N_2, O_2, **H_2O**, Ar, ..

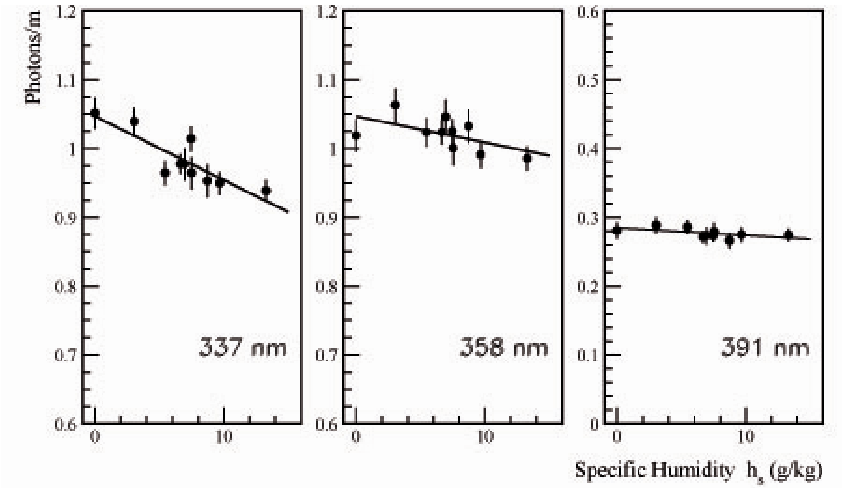
$$\frac{1}{P'} = \sum_i \frac{f_i}{P'_i}; \qquad P'_i = \frac{kT}{\tau}\,\frac{1}{\sigma_{Ni}\,\bar{v}}$$

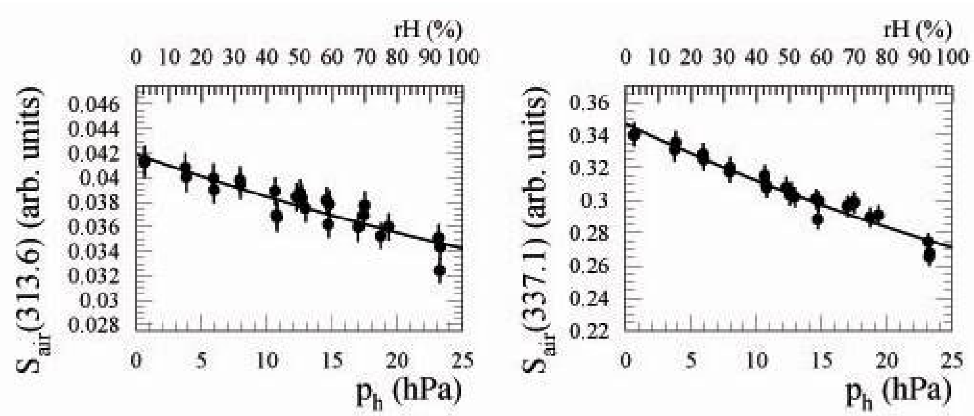
Assuming a given v upper level



AIRLIGHT (5th FW, El Escorial 2007)

Nagano et al (5th FW, El Escorial 2007)





AIRFLY (5th FW, El Escorial 2007)

Temperature effect

$$P_i' = \frac{kT}{\tau}\frac{1}{\sigma_{Ni}\bar{v}} \propto \sqrt{T}\frac{1}{\sigma_{Ni}(T)}$$

lifetime

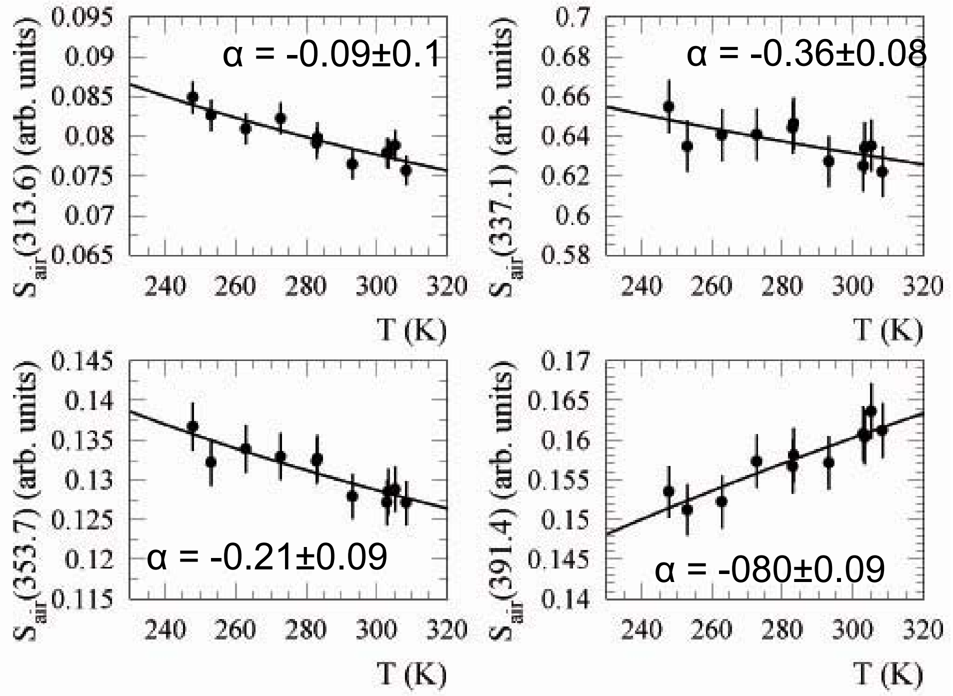
mean velocity

$$\bar{v} = \sqrt{\frac{16kT}{\pi M}}$$

collisional cross section

$$\sigma_{Ni}(T) \propto T^{\alpha}$$

AIRFLY (5th FW, El Escorial 2007)



Fluorescence yield versus electron energy

Assumption: Fluorescence yield is independent on electron energy,

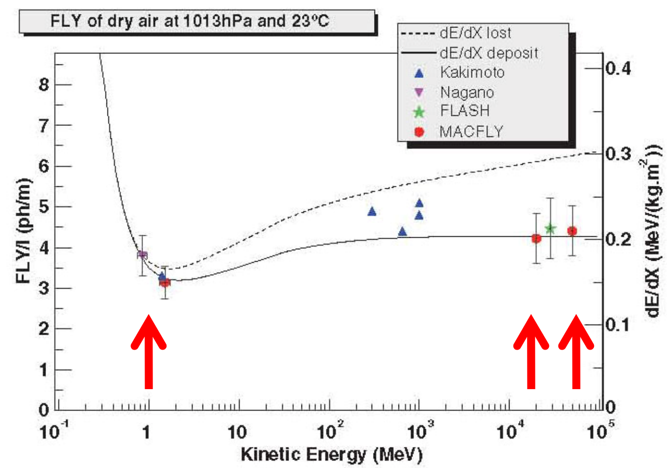
Not evident from a theoretical point of view. It has to be proved.

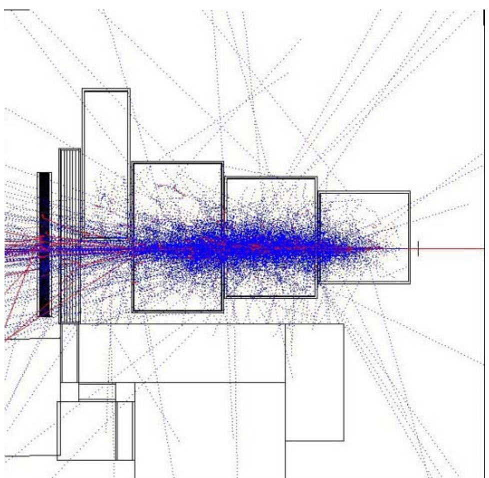
AIRFLY (5th FW, El Escorial 2007)

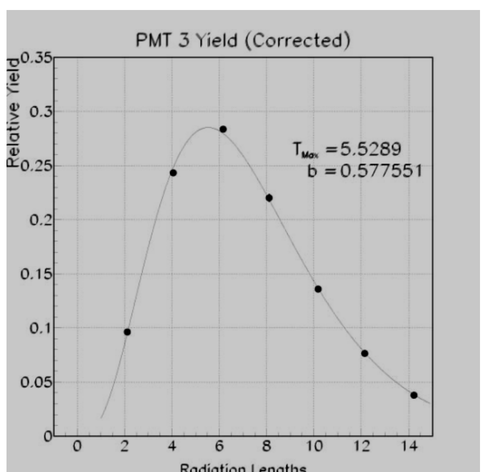
APS	6 – 30 keV
Argonne Wakefield Accelerator + Van de Graaff	0.5 – 15 MeV
BTF Frascati	50 – 420 MeV

Proportionality (± 5%) inside E intervals.
Relative calibration

MACFLY Astropart. Phys. (2007)





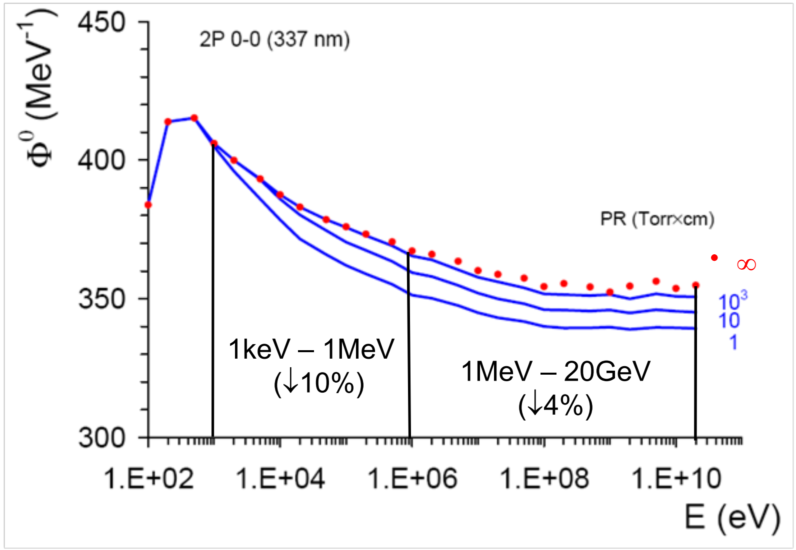


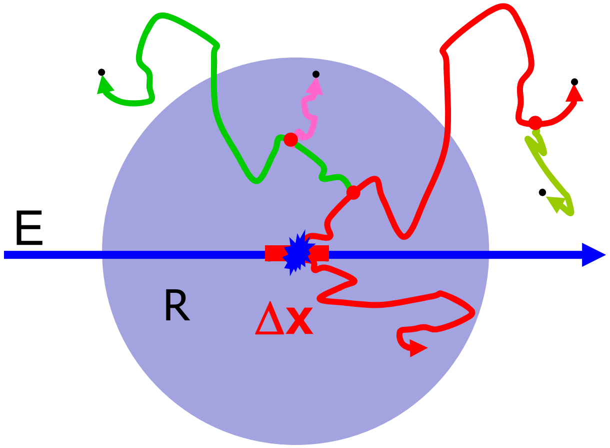
FLASH (THICK TARGET)
Astropart. Phys. (2006)
5th FW, El Escorial 2007

Fluorescence yield versus electron energy

UCM (5th FW, El Escorial 2007)

- Theoretical model including a detailed microscopic simulation.
- Accurately accounts for the contribution of secondary electrons and deposited energy (independent on GEANT, EGS,..)



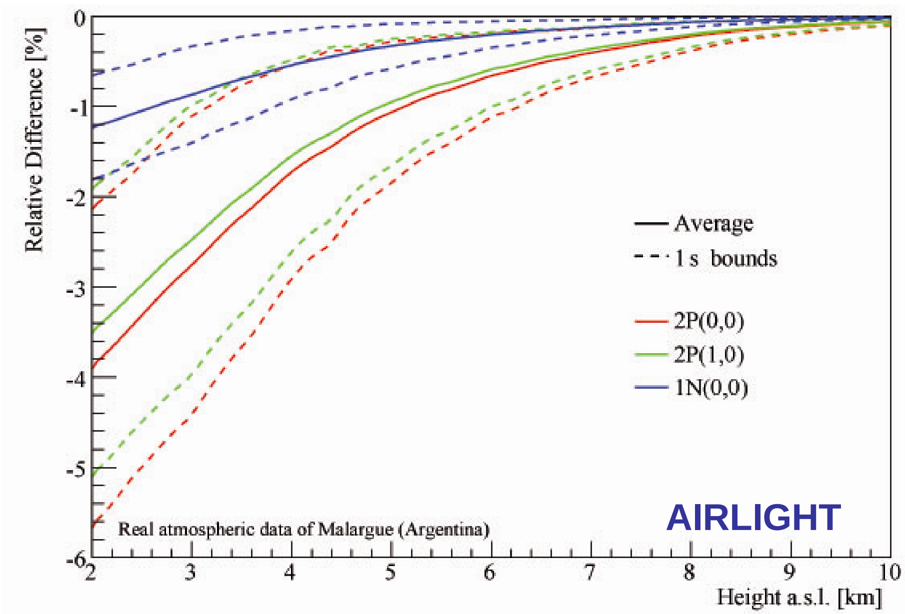


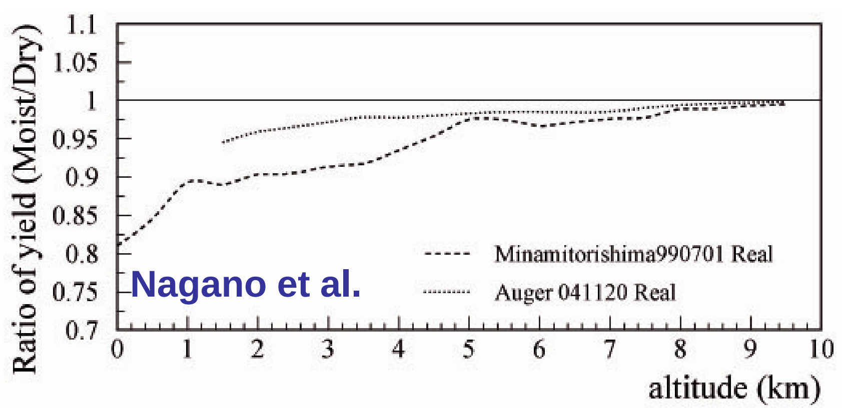
Result of the model:

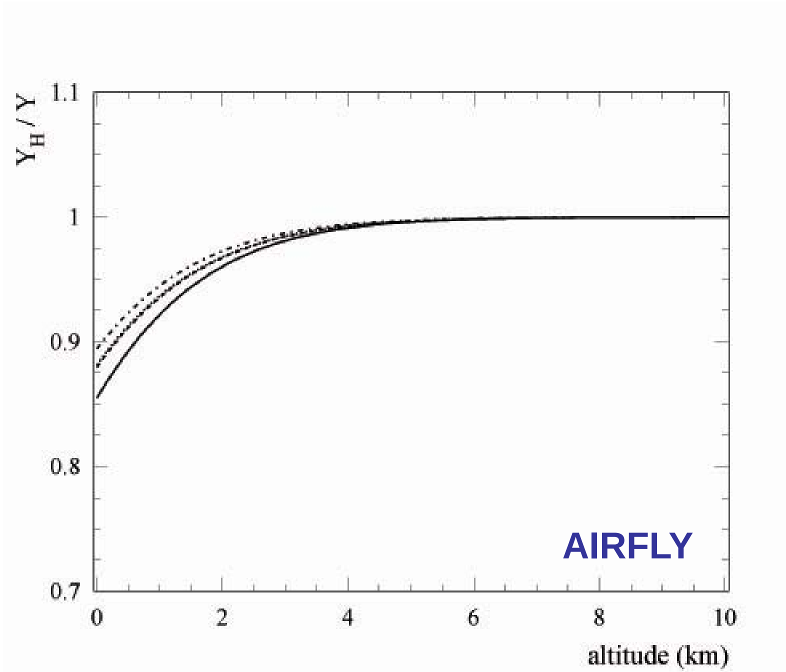
Smooth dependence of FY on electron energy.
No impact for telescope calibration.

Impact of new results on the energy reconstruction of UHECR

Humidity effect

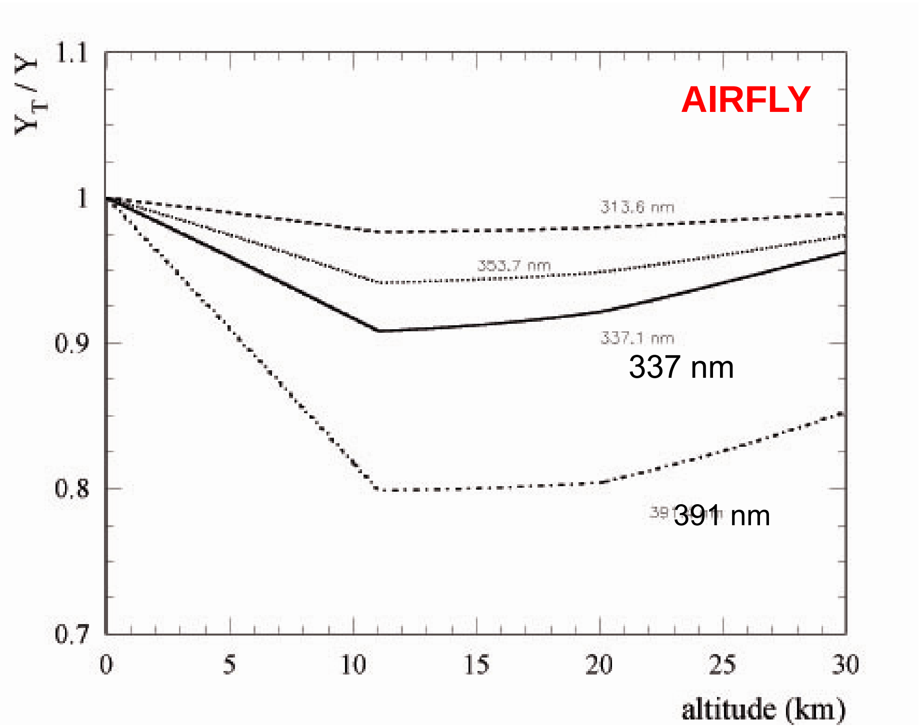






Impact of new results on the energy reconstruction of UHECR

Temperature: Sizable effect which has to be taken into account



Deviations up to 10% (20 %) for 337 nm (391nm) at high altitude

Absolute value of the Fluorescence yield

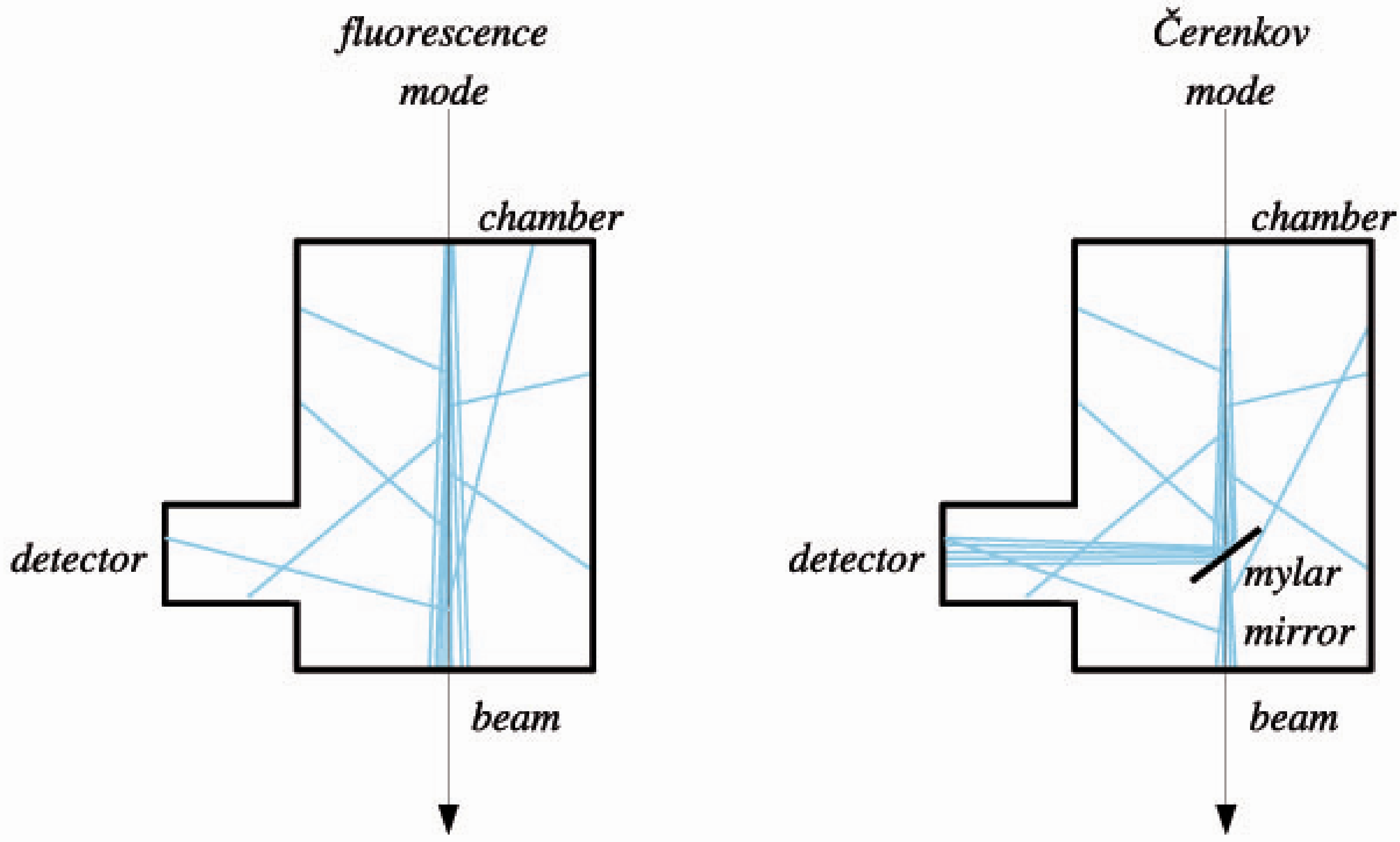
Techniques for absolute calibration:

- Measure the various efficiency factors: geometry, QE of PMT,….
  (Gorodetzky et al., Nagano et al.)

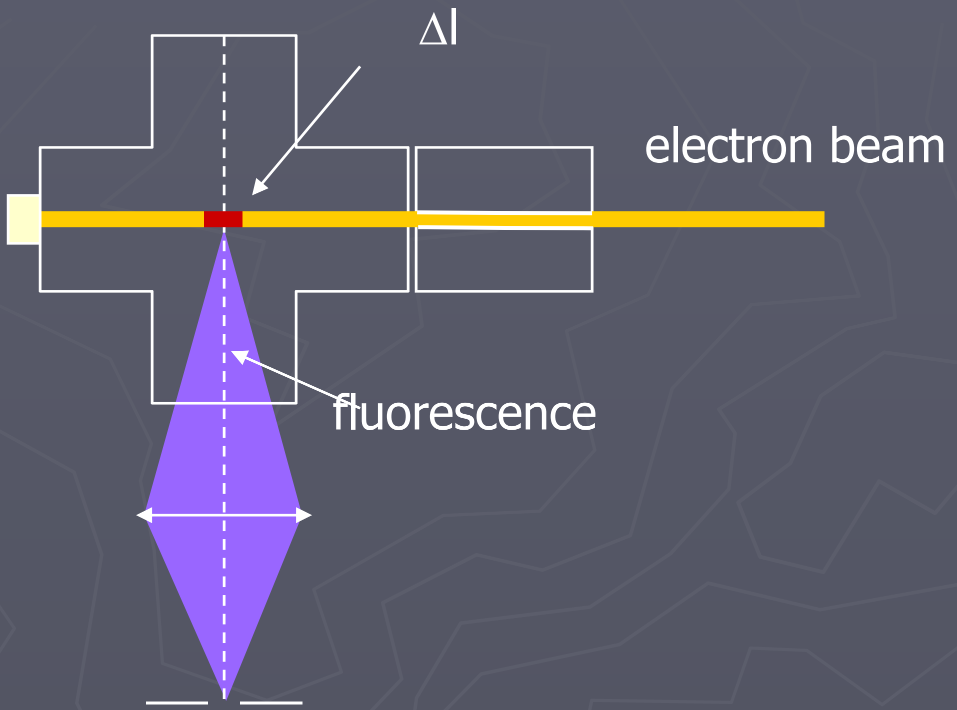
- Compare with a well known emission process (efficiency factors cancel out)
    - Rayleigh scattering (FLASH, AIRLIGHT, UCM)
    - Cherenkov emission (AIRFLY)

Absolute calibration with Cherenkov radiation

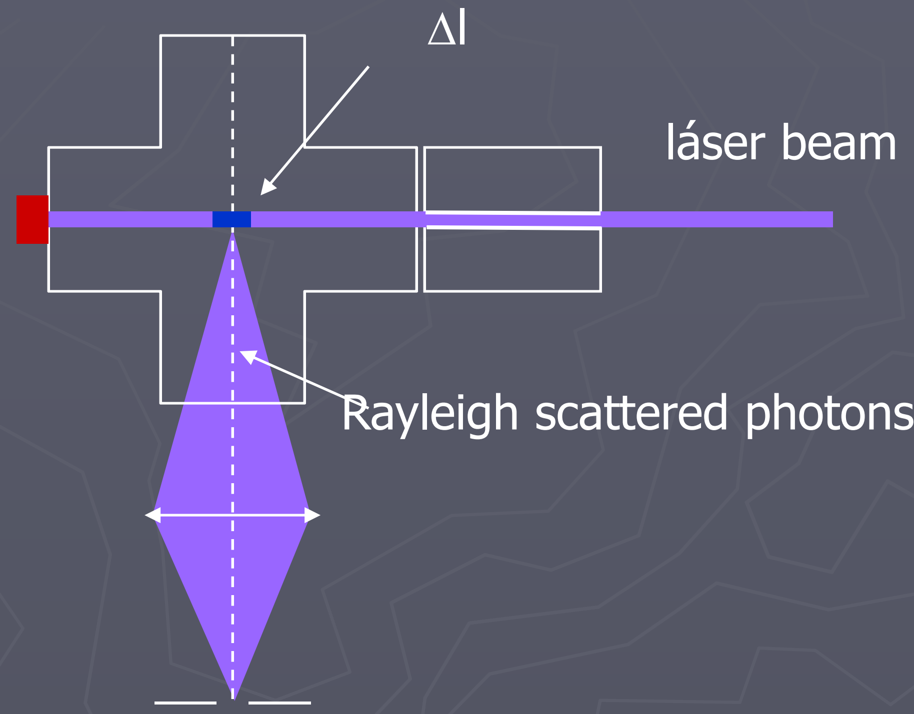
AIRFLY



Absolute calibration with Rayleigh scattering



Absolute calibration with Rayleigh scattering



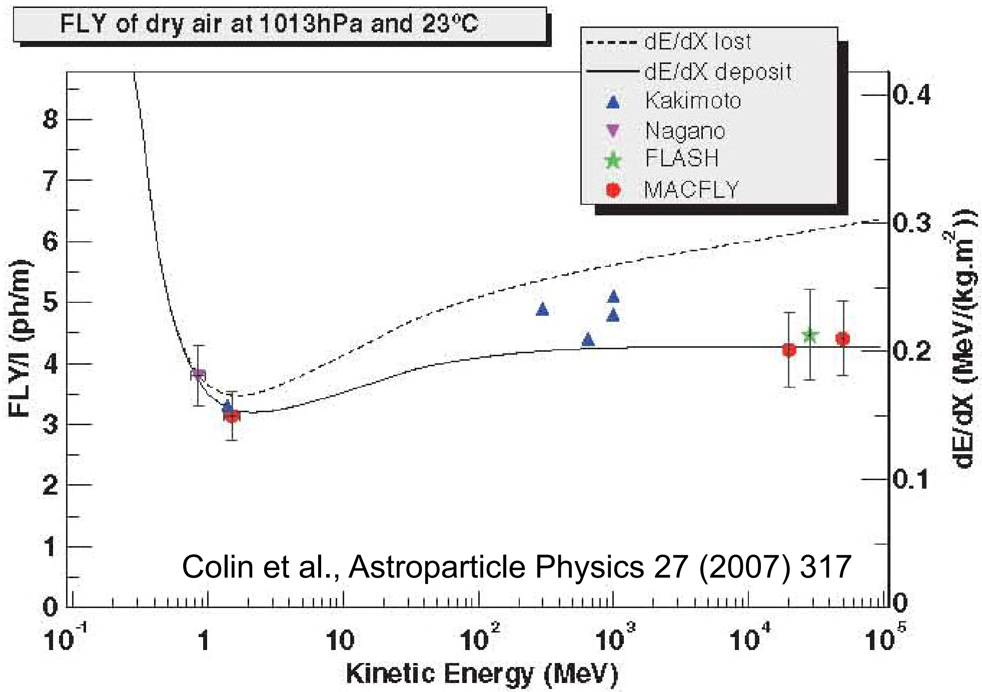
Absolute value of the Fluorescence Yield

	337 nm (atm.)		Wide spectrum (atm.)		337 nm (P=0)		P'_{337} (hPa)
	m^{-1}	MeV^{-1}	m^{-1}	MeV^{-1}	m^{-1}	MeV^{-1}	
AIRFLY (Preliminary)		4.12					**15.9**
FLASH_07 (7.5%)			5.06	20.8			
MACFLY (13%)				17.6		170	**25.8**
Nagano et al. (13%)	1.021		4.05				**19.2**
Godoretzky et al. (5%)			4.23				
AIRLIGHT (15%)						384	**15.0**
Pancheshnyi et al.							**13.1**

Comparison not easy:

- Wavelength interval: narrow (337 nm) or wide.
- Procedure/units: photons/MeV or photons/m.
- Geometrical features

- General agreement within 15% of FY(photons/m) at atmospheric pressure
- Discrepancies in the pressure dependence (P'_{337} = 26 -- 15 hPa)
- Therefore large discrepancies in FY (P=0)



Fluorescence Yield parameters used in UHECRs experiments

HiRes

A set of FY data (photons/m) for the main molecular bands consistent with:

- Relative intensities of the spectrum as predicted by Bunner (Ph.D. thesis Cornell University 1967)
- Absolute values as given for some main bands by Kakimoto et al. NIM A (1996)

Auger

- Absolute value of the main 337 nm band given by Nagano et al. (2004)
- Relative intensities and pressure dependence (P' values) from AIRFLY (2007).

The difference in reconstructed energy (taking into account the HiRes filter) Nagano (absolute value + pressure dependence) vs Kakimoto is of about 5%

Conclusions

- Our knowledge on the processes leading to the generation of fluorescence emission has increased substantially in the last 3 years.
- Better understanding of systematic errors.
  e.g. secondaries outside the field of view
- Fluorescence emission proportional to deposited energy.
- Improved values of quenching parameters in dry air. **Still large discrepancies!!**
- Strong evidences of the dependence of collisional quenching on T. **Caution!!**
- General agreement on the humidity effect. **Small correction.**
- General **agreement** between experimental results at high pressure within **15%**
- Absolute values with an uncertainty below 10% are already being published.
  More experimental results needed.

Proceedings of the 5th Fluorescence Workshop will be published in a dedicated volume of NIM A

http://top.gae.ucm.es/5th_FW/