8th Air Fluorescence Workshop, Karlsruhe Germany
12 - 14 September 2011

Calibration methods in the Fluorescence Yield measurement

Paolo Privitera

THE UNIVERSITY OF CHICAGO
PHYSICAL SCIENCES

Fluorescence Yield measurement

$$N_{p.e.} = N_{part} \cdot E_{dep} \cdot FY \cdot \varepsilon_{PMT} \cdot \varepsilon_{filter} \cdot \varepsilon_{geom}$$

$N_{p.e.}$ N. measured photoelectrons

N_{part} N. of particles passing through gas

E_{dep} Energy deposited by the particle in the gas in the fov of the PMT

$FY(\lambda)$ Fluorescence Yield (photons/MeV)

$\varepsilon_{PMT}(\lambda,\theta)$ PMT detection efficiency (QE•CE)

$\varepsilon_{filter}(\lambda,\theta)$ Filter efficiency (10 nm or 100 nm bandwidth)

$\varepsilon_{geom}(\lambda)$ geometrical efficiency (may include mirrors, etc.)

All of them contribute to the systematic uncertainty of the FY measurement

Calibration strategy

- “Piece-by-piece” calibration

Kakimoto et al, Nagano et al, MACFLY, AIRLIGHT, Lefeuvre et al, FLASH

Measure each factor of detection efficiency independently

$$N_{p.e.} = N_{part} \cdot E_{dep} \cdot FY \cdot \underbrace{\varepsilon_{PMT} \cdot \varepsilon_{filter} \cdot \varepsilon_{geom}}$$

- “End-to-end” calibration

Calibrate the detection efficiency at once, AIRFLY

(CRAYS, end-to-end calibration of the Fluorescence Detector!)

Calibration of PMT efficiency

Major systematic uncertainty of the FY measurement

- "Standard" calibration

  Rely on the manufacturer calibration: uncertainty ≈10%

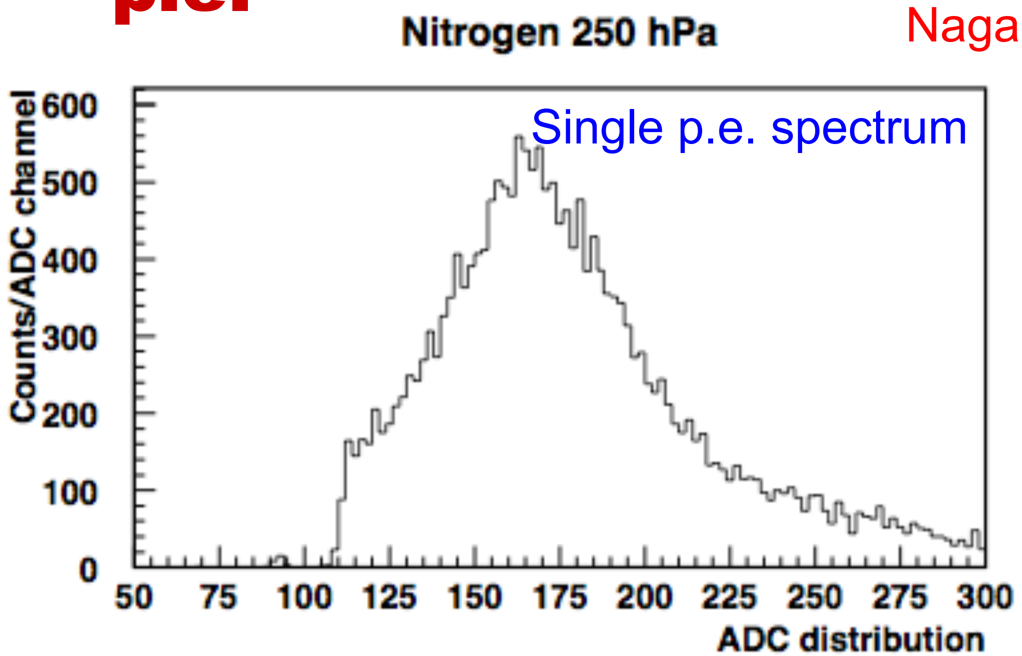
  Kakimoto et al, Nagano et al, MACFLY, AIRLIGHT

- "Ad hoc" calibration

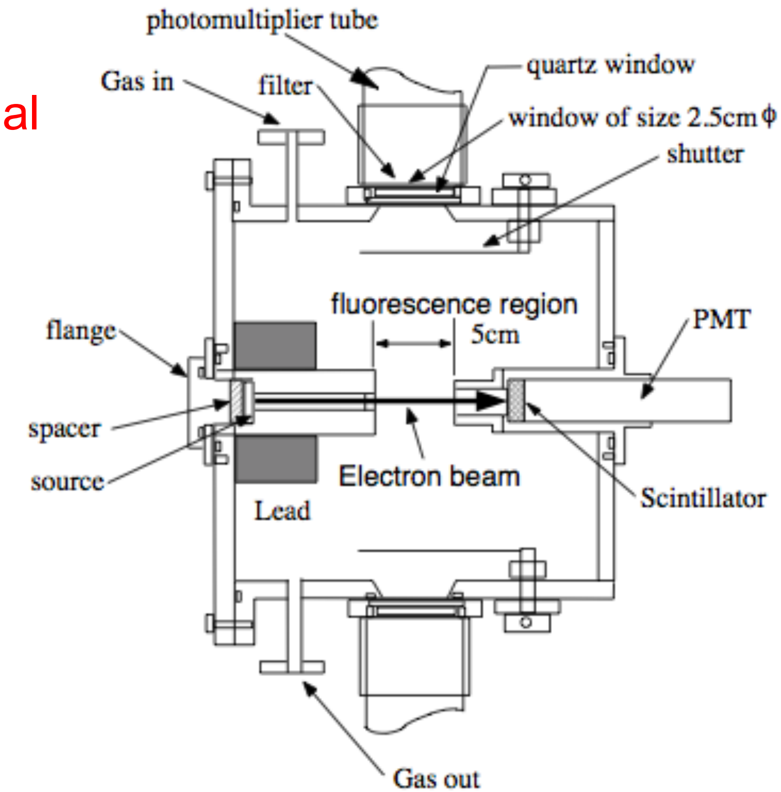
  Use specifically developed calibration techniques: uncertainties 2.2% to 7.5%

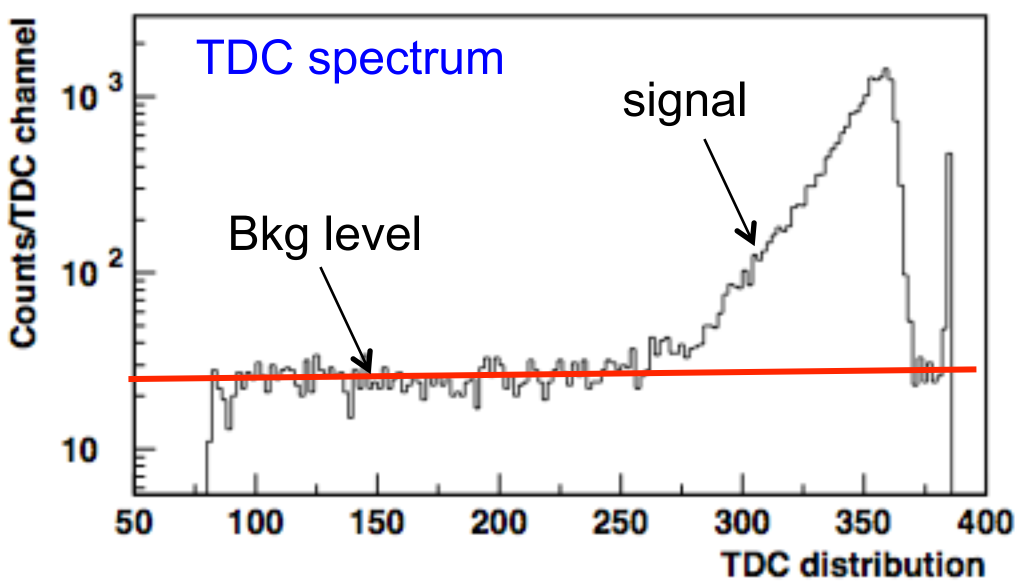
  Lefeuvre et al 377 nm Integrating sphere + NIST
  FLASH Rayleigh scattering of 337 nm laser
  AIRFLY Cherenkov light and 337 nm laser

$N_{p.e.}$



Nagano et al





- Radioactive source measurement

Discriminator set on valley of single p.e. spectrum

scintillator – p.e. time coincidence

Bkg extrapolated from TDC spectrum

$N_{p.e.}$ (counting p.e.)

Correction for n. of p.e. below threshold

- Kakimoto et al

  Fit single p.e. distribution with a model

  (CE) systematic unc. 5%

cathode. The factory collection efficiency measurement was done by counting a known intensity photon beam at a PMT gain setting of 5 x 10^6 and with a discriminator setting at 1/3 of the single photon peak.

Since we used a higher gain setting, 2 x 10^7, and a lower discriminator threshold, 1/10 of the observed single photon peak, we evaluated the collection efficiency for this experiment. Fitting our observed single photon spectrum to a first dynode and second dynode gain model with our gain and bias settings, we obtained a collection efficiency of 90% with a 5% uncertainty. This model also

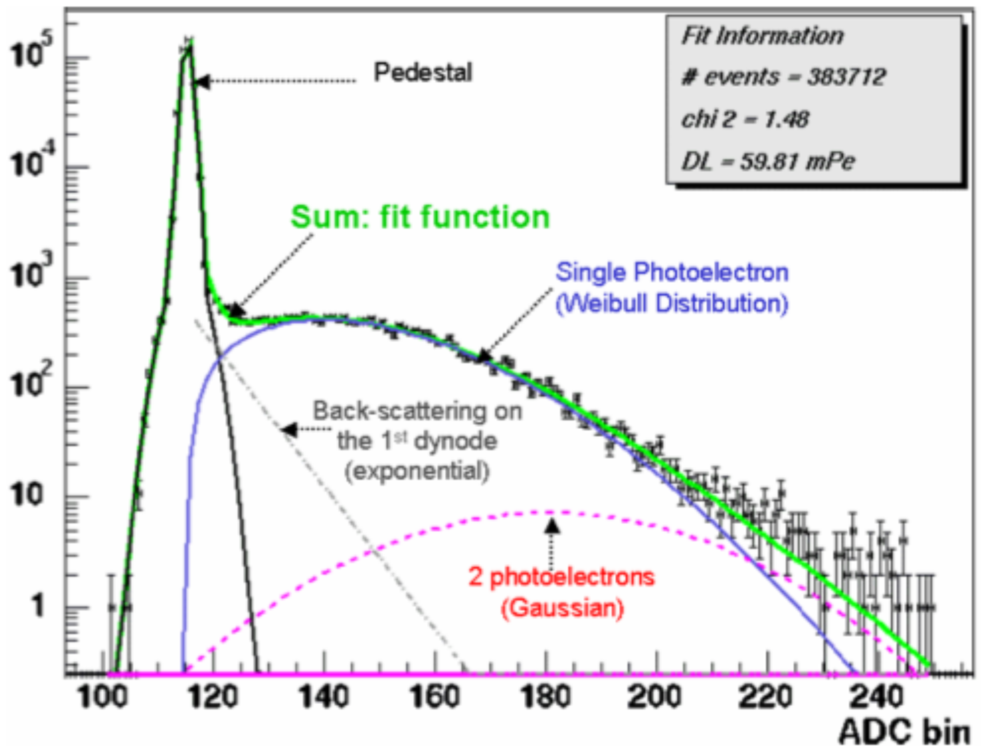
- Nagano et al

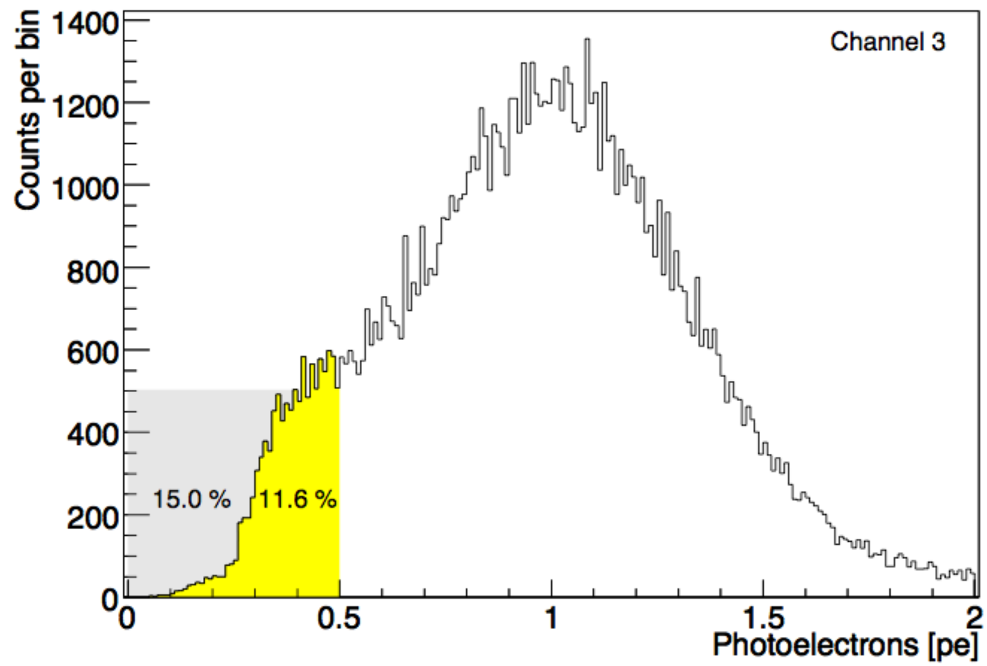
  Use single p.e. threshold as calibrated by factory. No systematic from single p.e. threshold

  (CE systematic unc. 10%)

The main uncertainty is due to the PMT calibrations (QE and CE), which were provided by the manufacturer (Hamamatsu Photonics). The CE is defined by Hamamatsu as the counts at the anode divided by the number of photo-electrons emitted from the photocathode. In this measurement the factory used a 25mm diameter area centered on the photocathode, at a PMT gain setting of 5×10^6 and with a discriminator setting at $\frac{1}{3}$ of the single photon peak. These conditions are also used in the present experiment. The number of photo-electrons was estimated in DC mode in a separate measurement.

$N_{p.e.}$





- MACFLY

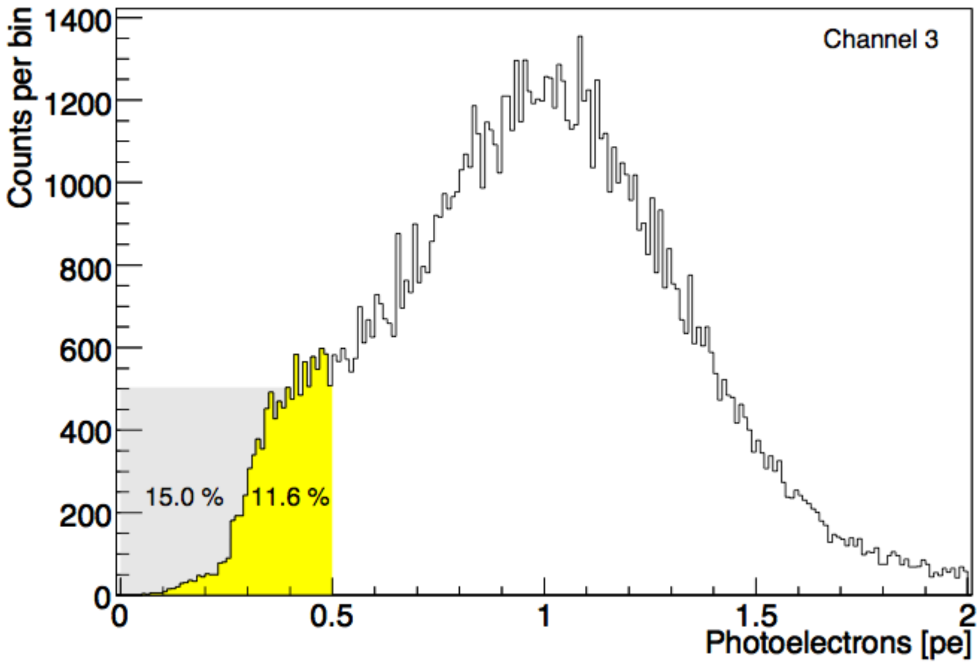
  Fit single p.e. distribution with a model

systematic unc. 4%

- AIRLIGHT

  Count single p.e.above 0.5 p.e. threshold. Then correction of +12% + 7.5% ± 7.5%

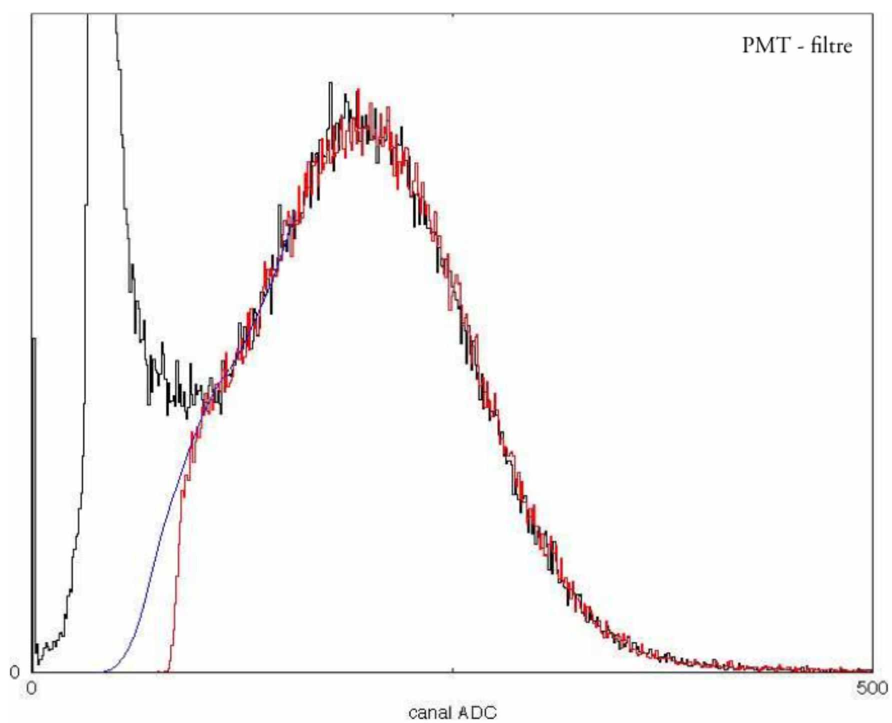
systematic unc. 7.5%



- AIRLIGHT
  Count single p.e.above 0.5 p.e. threshold. Then correction of +12% + 7.5% ± 7.5%

  systematic unc. 7.5%

$N_{p.e.}$



- Lefeuvre et al
  Correction estimated to be only 3.8%

  systematic unc. negligible

Significant differences in the estimates of uncounted p.e., with systematic uncertainty varying over a large range:

Negligible to 7.5 % !?!

$N_{p.e.}$

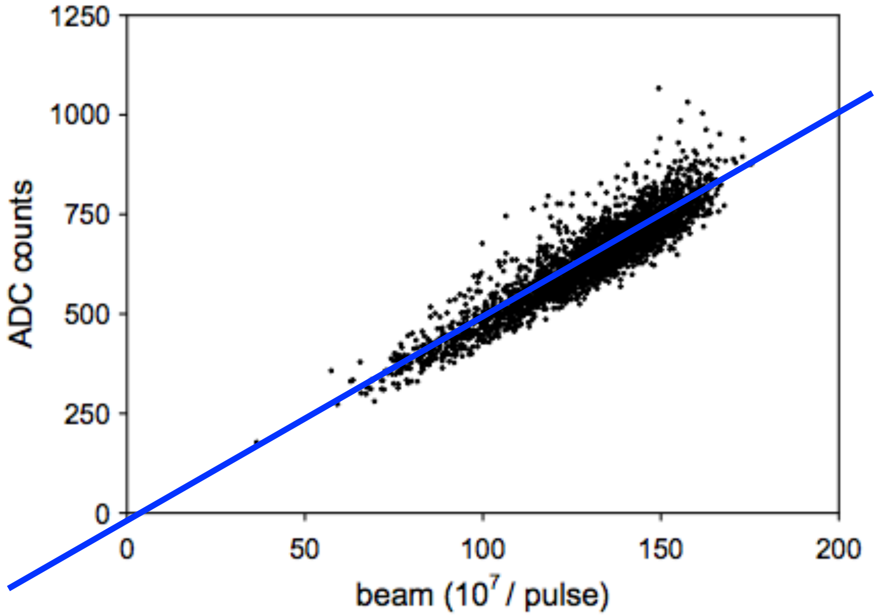
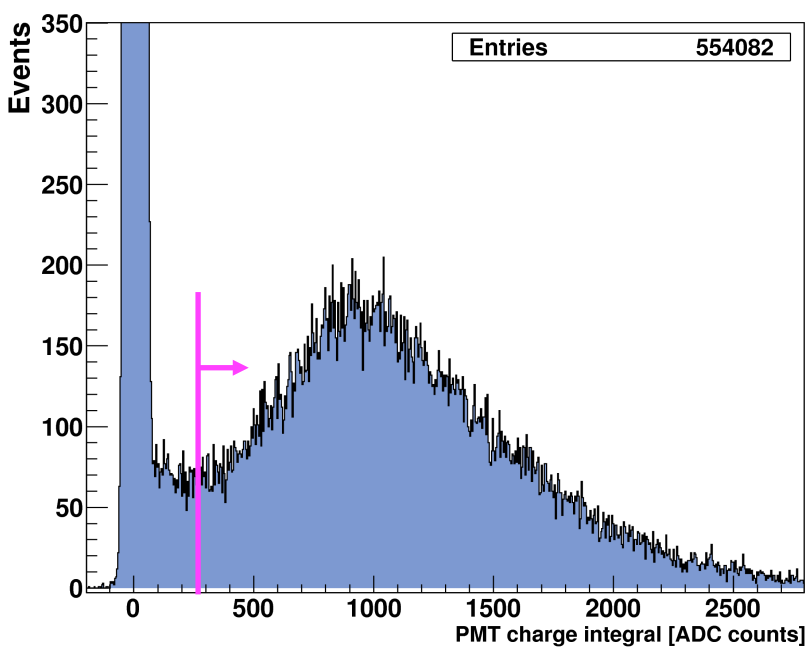


Fig. 4. Fluorescence signal plotted pulse-by-pulse against beam intensity at 750 torr, using the HiRes filter.

- FLASH

  Many p.e. per beam pulse. Systematic arise from absolute calibration of ADC counts to n. of photons.

  Zero constraint of fits, syst. unc. 1%



- AIRFLY

  Same threshold for single p.e. used for fluorescence and calibration runs (Cherenkov and laser). Systematic cancel

  Systematic unc. (including bkg subtraction) 1%

$N_{p.e.}$ (rate effects)

	electron rate (kHz)
Nagano et al	1.5
AIRLIGHT	15
Lefeuvre et al	10^3
Kakimoto et al	$6\ 10^3$ (beam)

Accidentals and pile-up

Lefeuvre et al

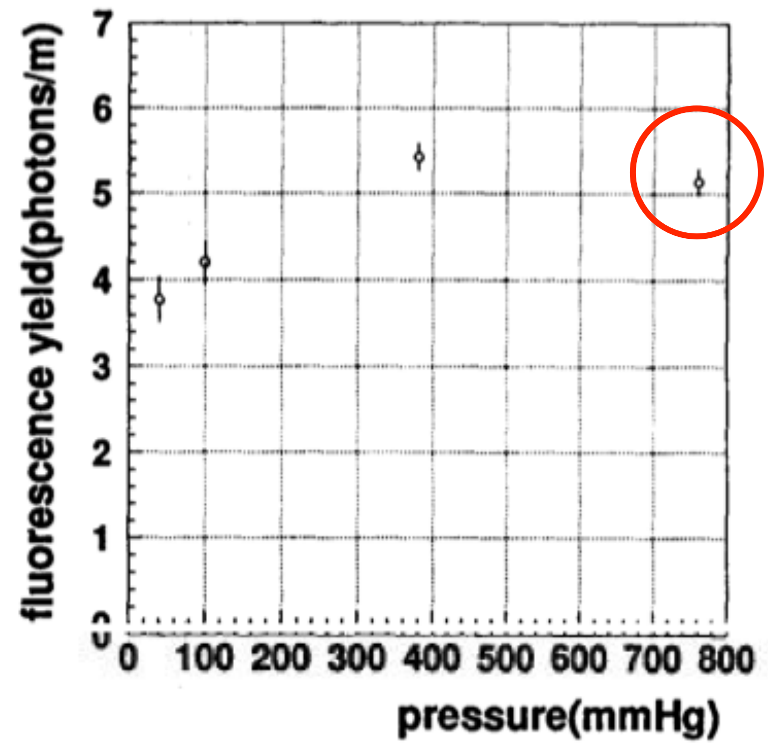
Systematic errors are presented in table 1. The main uncertainty of this experiment is due to the high counting rate of the electrons, leading to a non-linear dead time dependence in the TDC module. This effect, which varies from channel to channel, depends on the internal TDC time constants and is not fully understood. It has been evaluated by using all the module's channels, and another TDC module (CAEN V1290N, multihit) to compare their results. All values are found equal within 4% (at 1σ) and this uncertainty has been chosen in a conservative way. In the future, to further reduce this uncertainty, fast flash ADCs will be used, allowing to discriminate pulses with and without pile-up on an event per event basis.

4% (out of total syst. unc. of 4.7%)

Kakimoto et al

displayed on the right hand side. A typical fluorescence yield as a function of pressure with 1000 MeV electrons is shown in Fig. 8 which is similar to those obtained with 1.4 MeV electrons. All uncertainties shown include statistics, deadtime, multiple counts in a single rf bucket, and calibration uncertainties.

≈3%



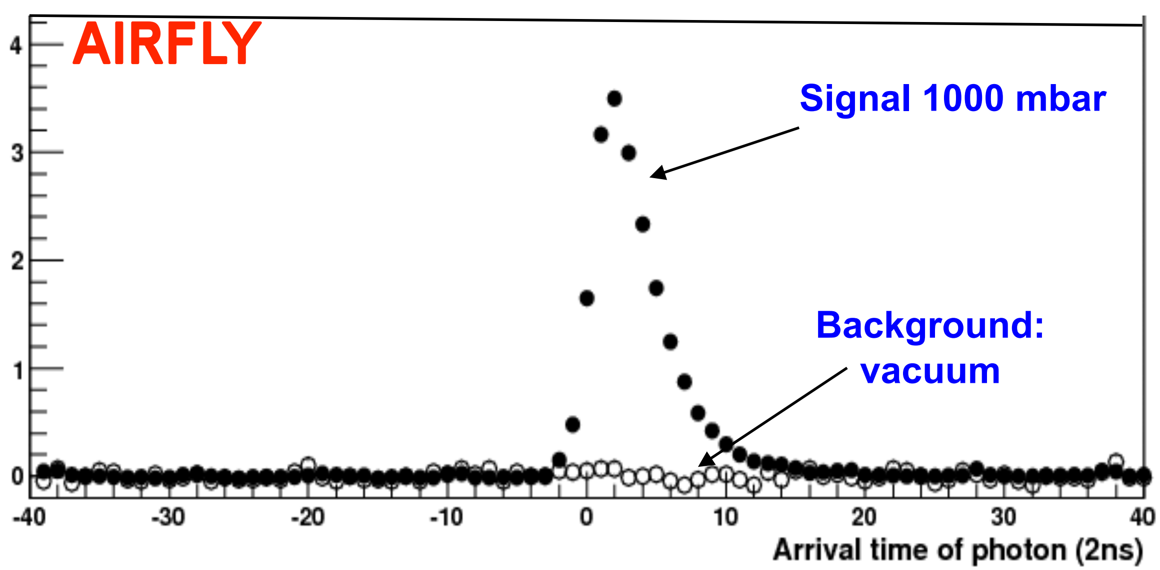
$N_{p.e.}$ (backgrounds)

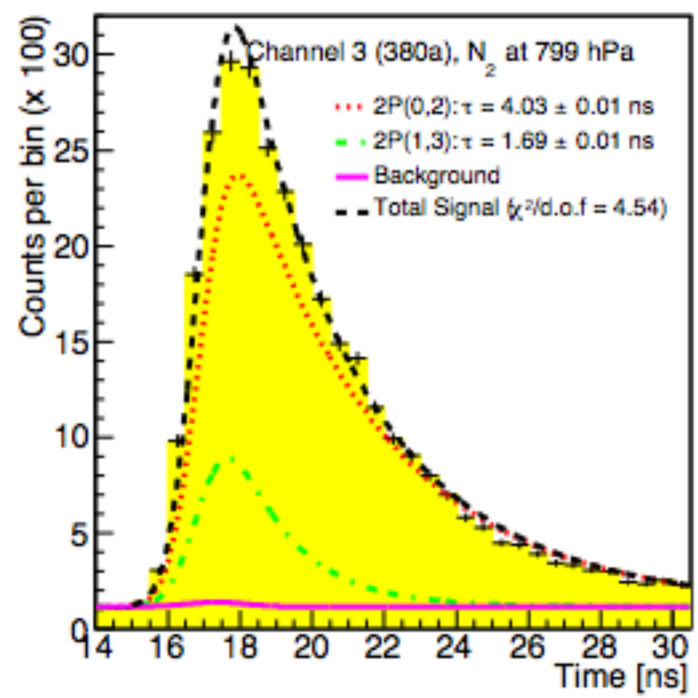
- Background level

Vary from a few % (AIRFLY, FLASH) to several tens of % in radioactive source experiments. Estimated from the TDC spectrum, vacuum measurements, shutter closed measurements, non-fluorescing gas.

Expect a small systematic unc.; few experiments quote a value (≈1%)

AIRLIGHT





N_{part}

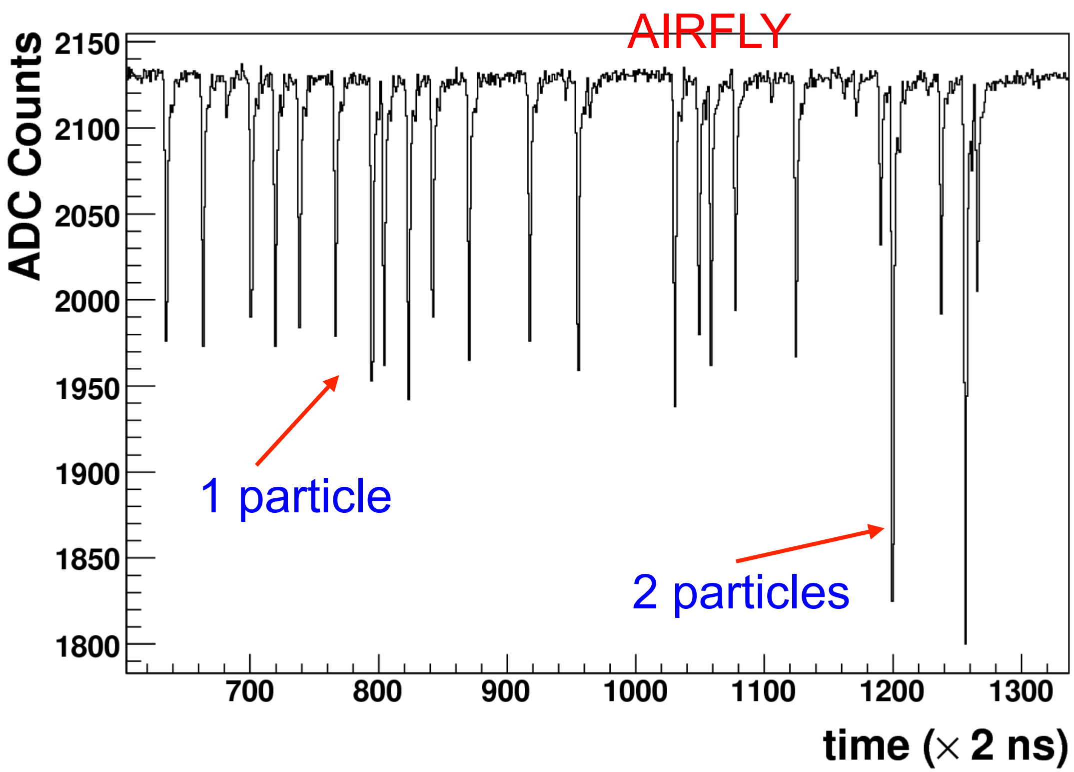
• Radioactive source experiments

Small corrections due to deadtime in Kakimoto et al and Lefeuvre et al.

• Beam experiments

FLASH: 10^9 electrons/pulse; beam current measurement syst. unc. 2.7%

AIRFLY: single particle measurement, all spill particles recorded in FADC memory, no correction needed. Same for fluorescence and Cherenkov runs, systematic cancel in ratio. Selection of single particles, n. of p.e. and bkg. subtraction give a syst unc. 1%

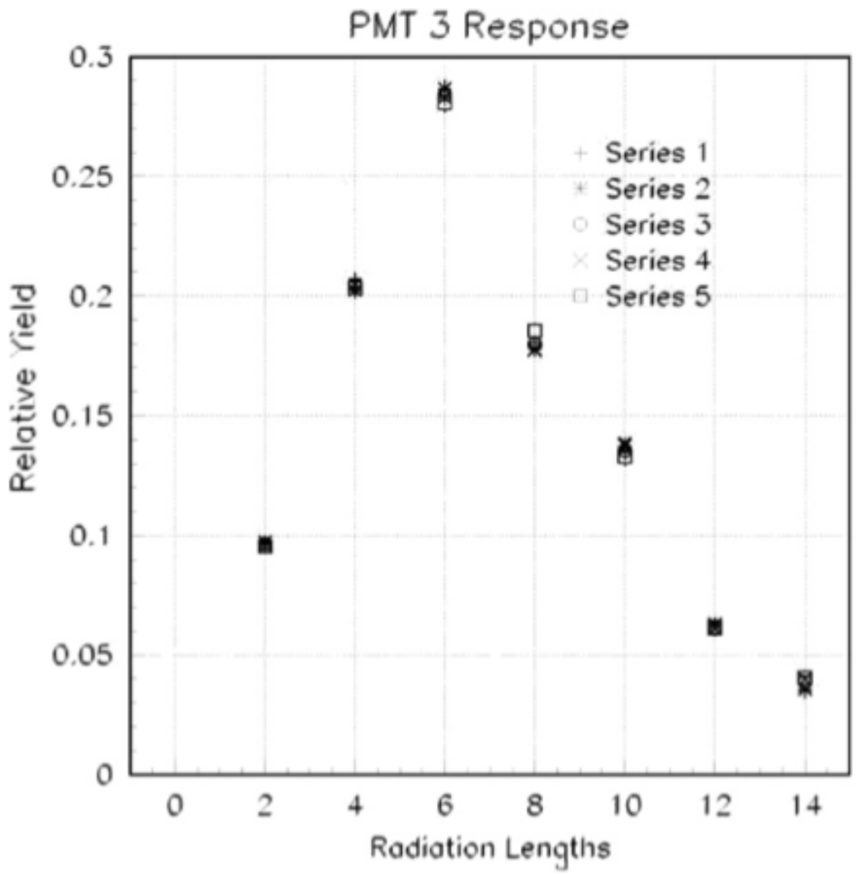


E_{dep}

- Beam experiments

FLASH, MACFLY: compare FY emission with longitudinal development of shower (integrate over energy spectrum of shower electrons)

FLASH



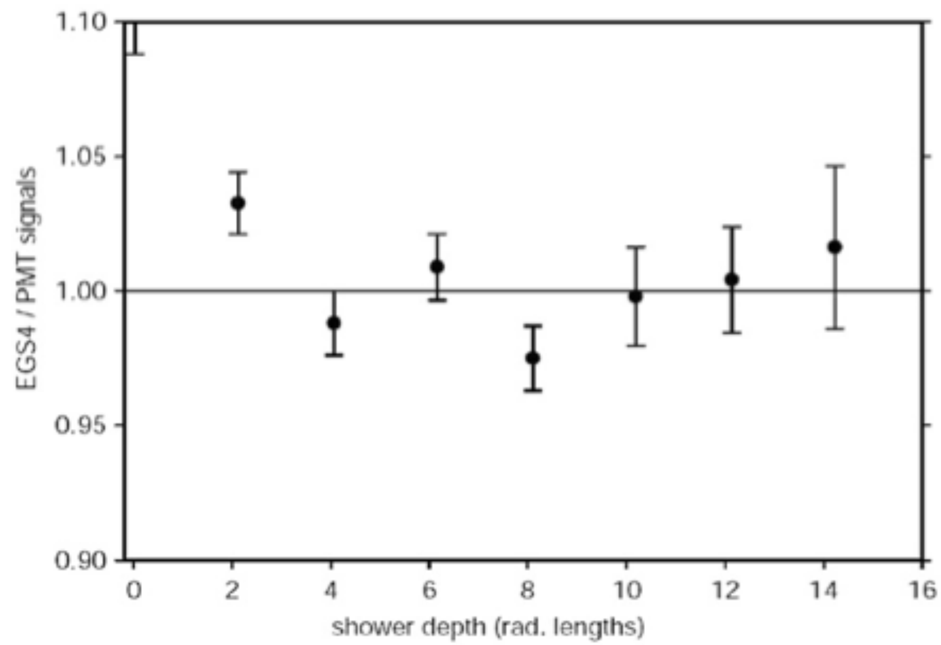
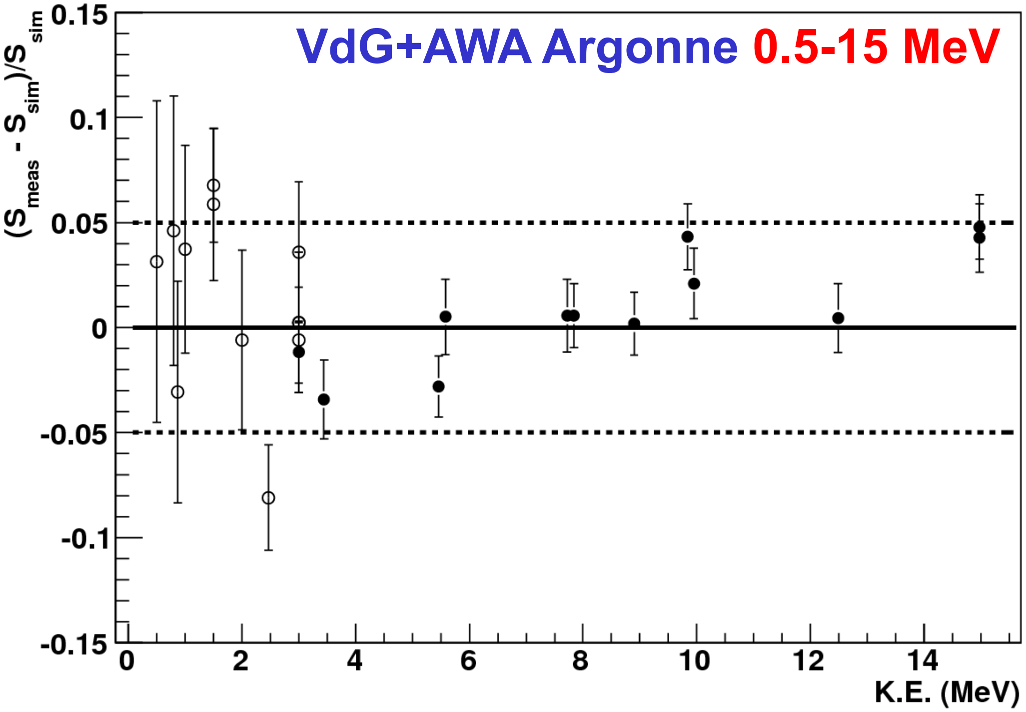
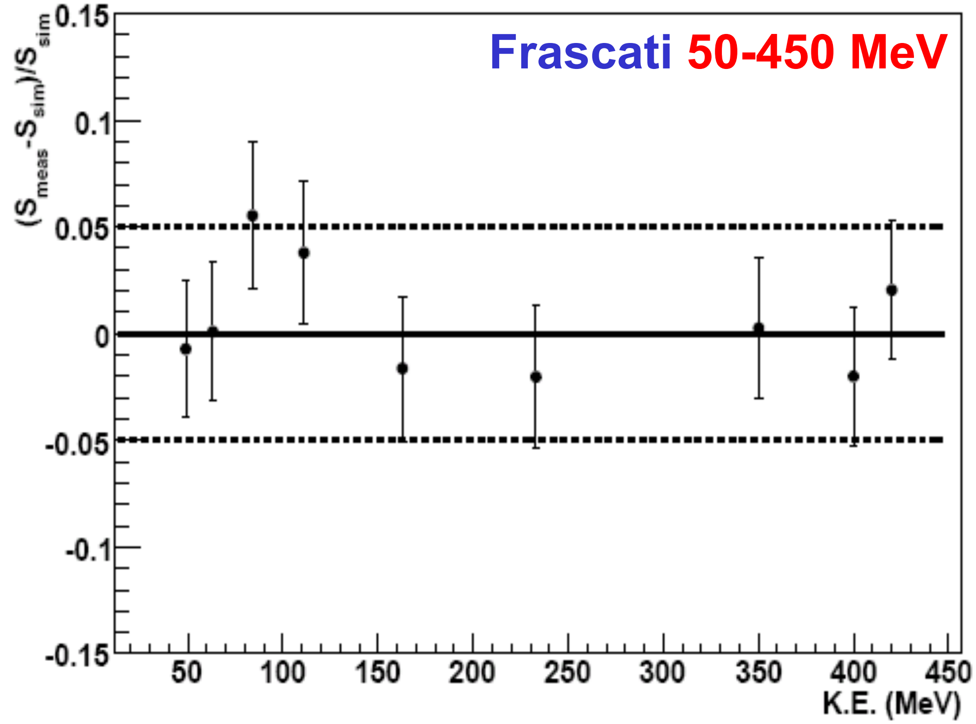
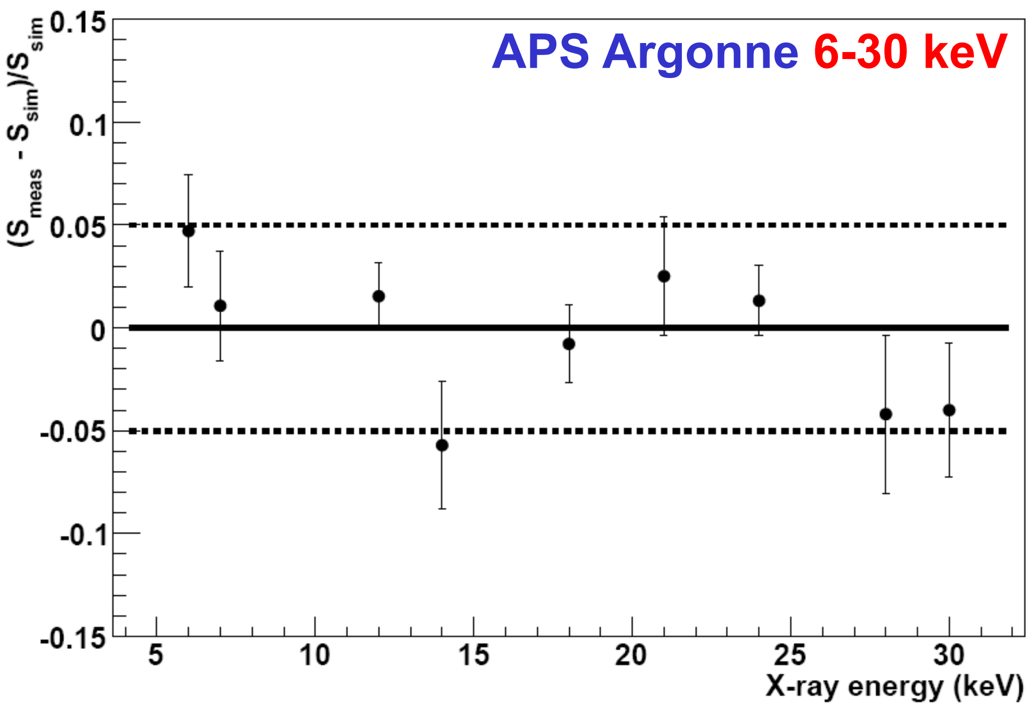


Fig. 6. Ratio of EGS4 results to weighted average of PMT signals versus shower depth.







AIRFLY E_{dep}

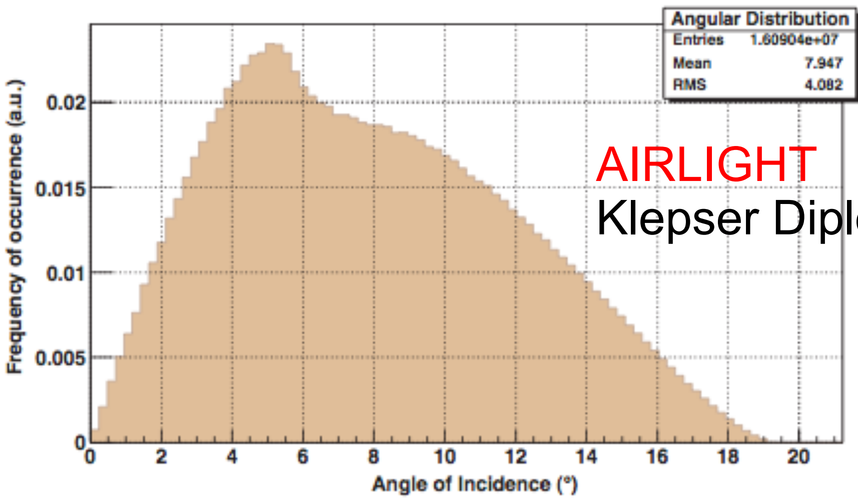
FY vs primary electron energy keV to GeV. Also, FY induced by protons, positrons, pions.

From these complementary approaches, proportionality of fluorescence yield to E_{dep} verified to ≈1%

ε_{filter} (transmission)

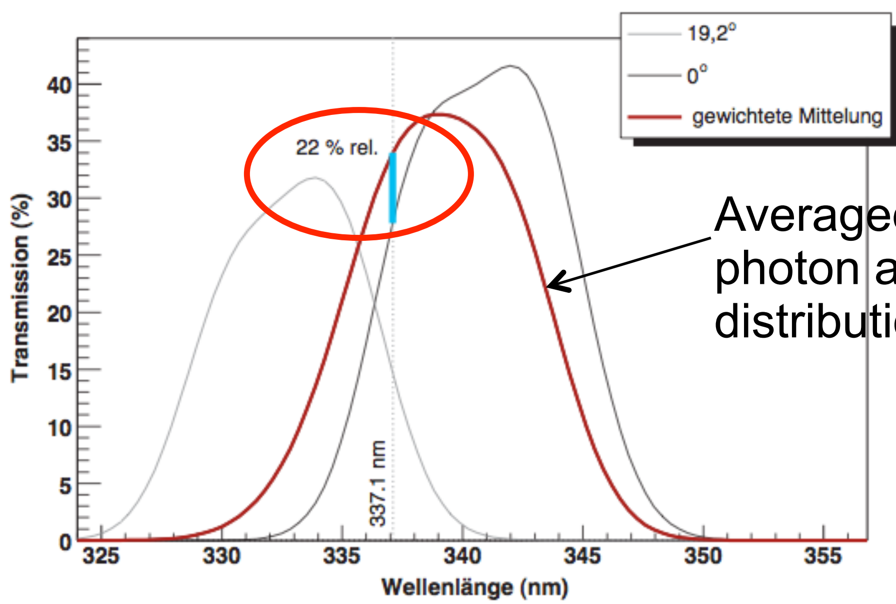
• Interference filters angular dependence (line measurement)

Significant angular dependence. Must measured and introduced in the simulation to take into account photon directions

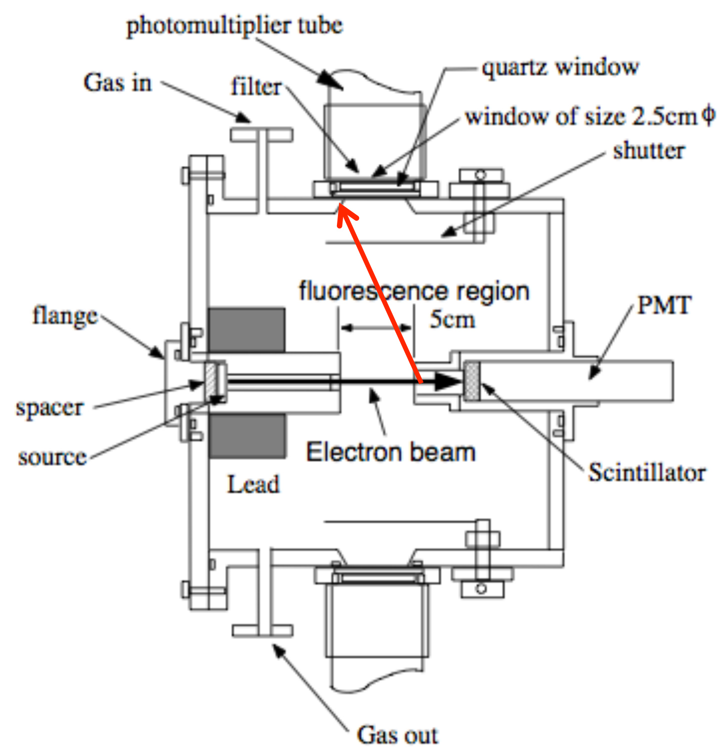


AIRLIGHT

Klepser Diploma thesis



Averaged over the photon angular distribution



Nagano et al

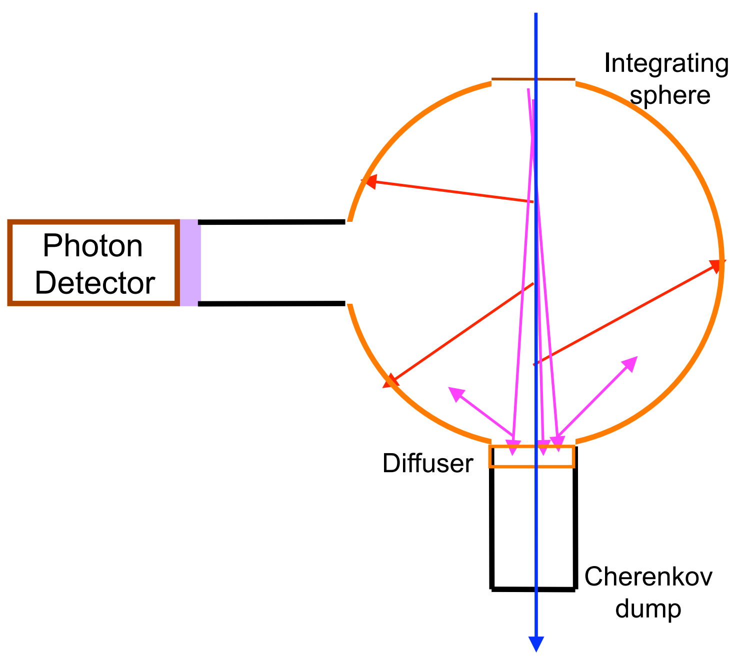
up to 20°

Syst. unc. 5%

ε_{filter}

- Interference filters angular dependence (line measurement)

In AIRFLY, fluorescence photons and calibration photons (Cherenkov or laser) have the same angular distribution at the PMT thanks to the diffusion inside the integrating sphere. In the ratio Calibration/Fluorescence, systematic cancel



AIRFLY

	Systematic unc.
Cherenkov	2%
337 nm laser	-

ε_{filter}

- Wideband filter (300-430 nm)

Most experiments measure the FY integrated over ≈300-430 nm with a wideband filter (Hires, BG3,M-UG6), which does not have the strong angular dependence of the interference filters; transmission mostly taken from manufacturer (e.g. Lefeuvre et al). But few % differences between nominal transmission and in situ transmission may arise from angular distribution, positioning of filters, etc.

FLASH

(0.2%). Measurements were also made with the HiRes wide-band filter in place. The ratio of signals with: without filter gave a value for its transmission at the 337 nm laser wavelength. This was also measured using a spectrophotometer, and the discrepancy between the results of the two methods, ±1.8%, may be taken as an indication of the repeatability uncertainty.

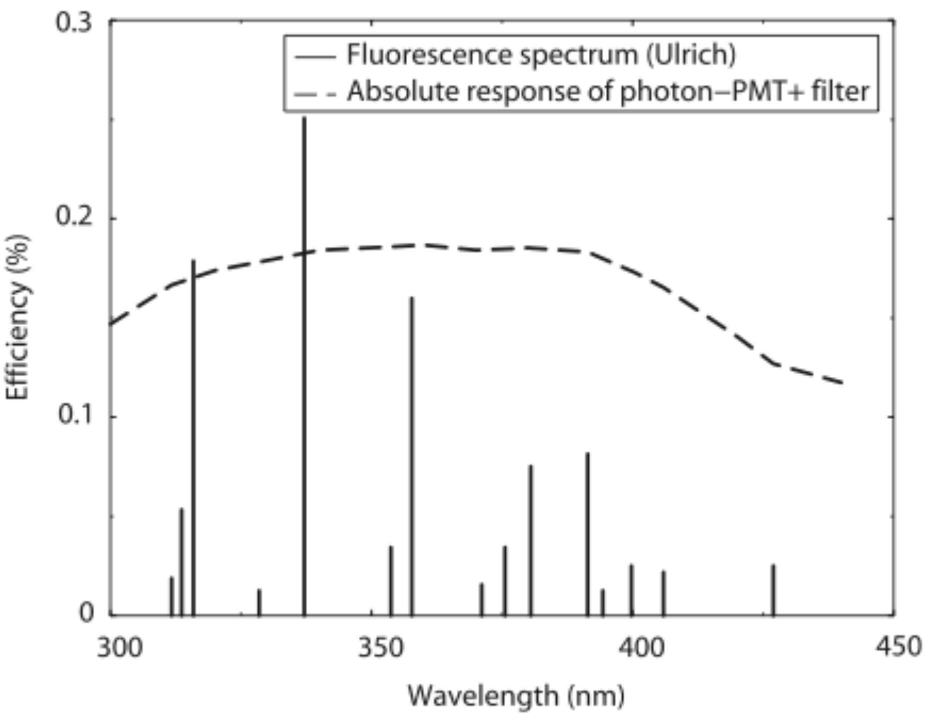
ε_{filter} (FY spectrum)

- Fluorescence yield spectrum

All fluorescence lines within the filter contribute to the measured signal. To derive a measurement, a fluorescence spectrum must be assumed. Experiments use different measured spectra.

Lefeuvre et al

Syst. unc. 0.5%+1%

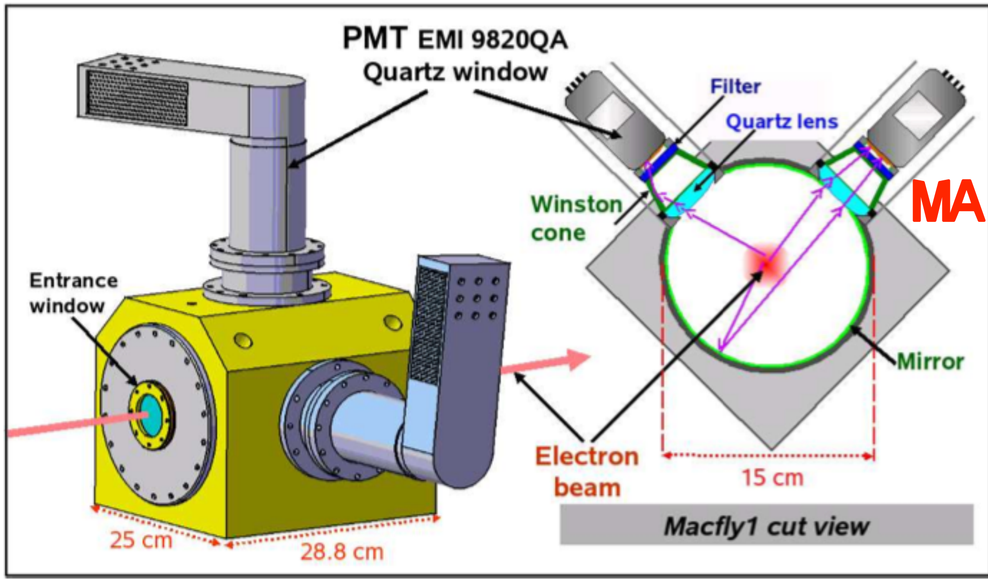


has been extended using manufacturer's data. The overall sensitivity to the air fluorescence spectrum has been computed using two examples of measured spectra. One was that reported by the Airfly collaboration [23], and the second, from this experiment, is discussed below. In both cases, the spectrum was extended over the weak emission range to 600 nm, using the visible wavelength results from Davidson and O'Neil [17]. The results of the average response calculation for the two spectra agree within 0.1% where a HiRes filter is used, and within 3% for the case with no filter. Relative to the 337 nm light, for air fluores-

FLASH

Spectrum sensitivity, open filter	1.5%
Spectrum sensitivity, HiRes filter	1.0%

ε_{geom}



MACFLY

Uncertainty sources	MF1-lab	MF1-beam
Electron position	5%	6%
Mirror	4%	4%
Winston cone	2%	2%
Row aluminum	3%	3%
Cherenkov catcher	0%	1%
Others (lens, filter ...)	< 2 %	< 2%
Geometrical Acceptance	**7.5%**	**8.2%**

cal acceptance systematic uncertainties for both experimental configura-
F1-lab (with ^{90}Sr source) and MF1-beam (CERN test beam)

for both experimental configurations (MF1-lab and MF1-beam). The main contributions come from the electron track position uncertainty (delay chamber/MF1 alignment and multiple-scattering in the chamber), from the internal surfaces reflective properties and from the mirror inhomogeneity. The overall

Nagano et al: Electron path, PMT solid angle, window transmission 4%

AIRFLY: Syst. cancel in ratio of calibration to fluorescence signals. Uncertainty from beam particle path (for laser calibration only) 0.3%

ε_{PMT}

- Quantum efficiency (QE) and Collection efficiency (CE)

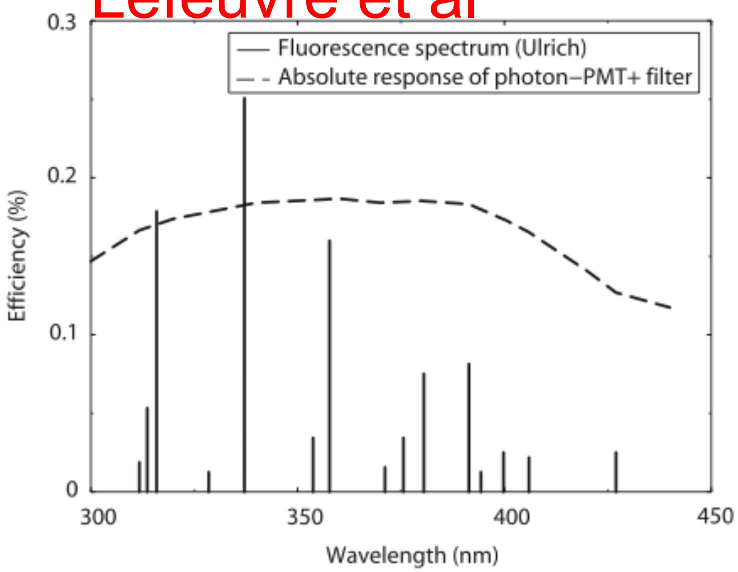
  Rely on the manufacturer calibration

Kakimoto et al	8%	(QE, Hamamatsu-Utah measurement)
Nagano et al	11%	(QE 5%, CE 10%)
AIRLIGHT	11%	(QE 5%, CE 10%)
MACFLY	10%	

- Wavelength dependence of QE

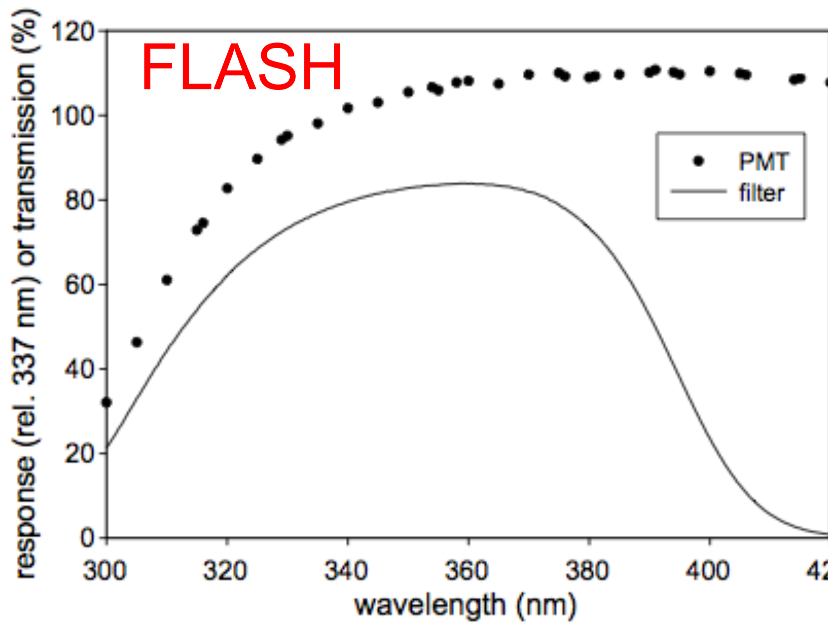
  More important for wideband filter measurements

Lefeuvre et al



From manufacturer   Syst. unc. 0.5%

FLASH



Measured by FLASH   Syst. unc. 1.2%

ε_{PMT}

- "Ad hoc" calibration

Goal: reduce systematic uncertainty due to PMT absolute calibration to better than factory standard (10%)

Three independent approaches for a calibrated light source:

FLASH: Rayleigh scattered nitrogen laser light

Lefeuvre et al: 377 nm LED and integrating spheres

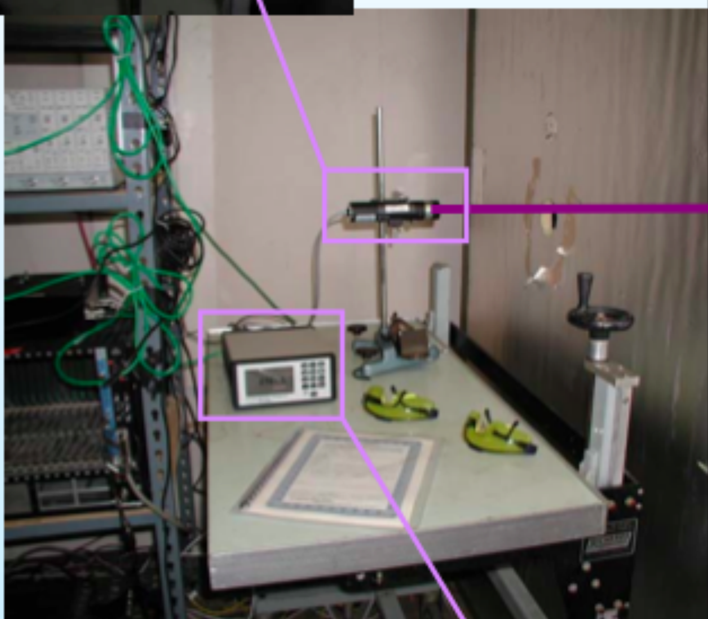
AIRFLY: Cherenkov light and nitrogen laser in the AIRFLY apparatus

FLASH

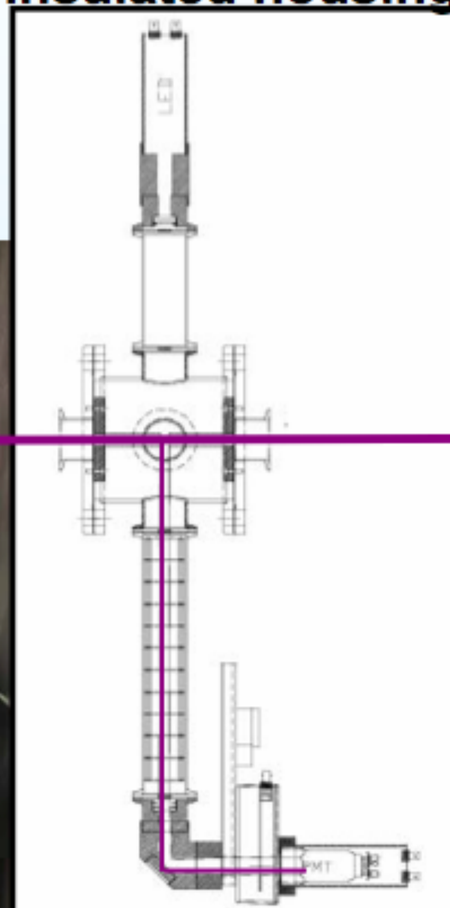
Optical Calibration

RjP-734 Energy probe

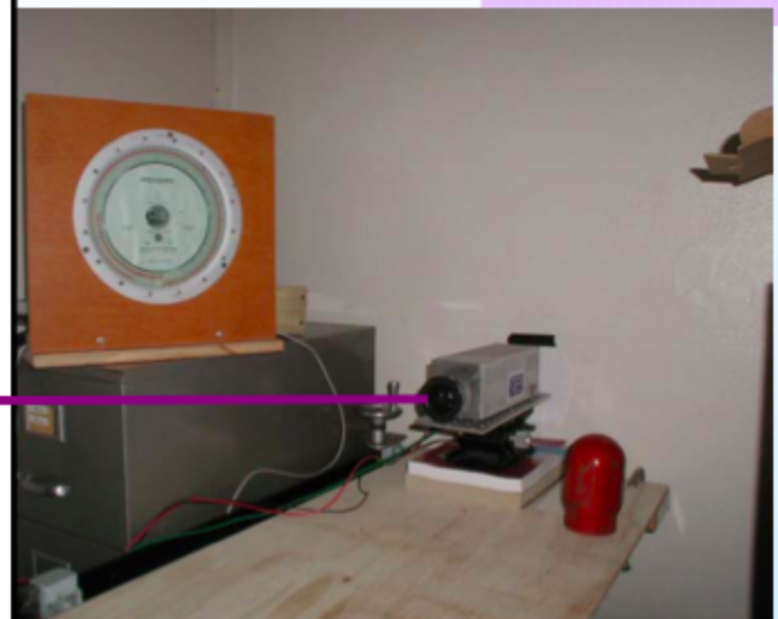
σ=5%



insulated housing



Nitrogen laser
337 nm, 160 μJ



Rayleigh Scattering
→calculation based on Bucholtz, Appl. Opt. Vol. **34**, 2765-2773 (1995)

Radiometer →

FLASH calibration

$$\frac{N_{ADC} - N_{ped}}{E} = G \cdot F \frac{SP}{T} + k_0$$

Rayleigh

pressure

temperature

Filter transm.

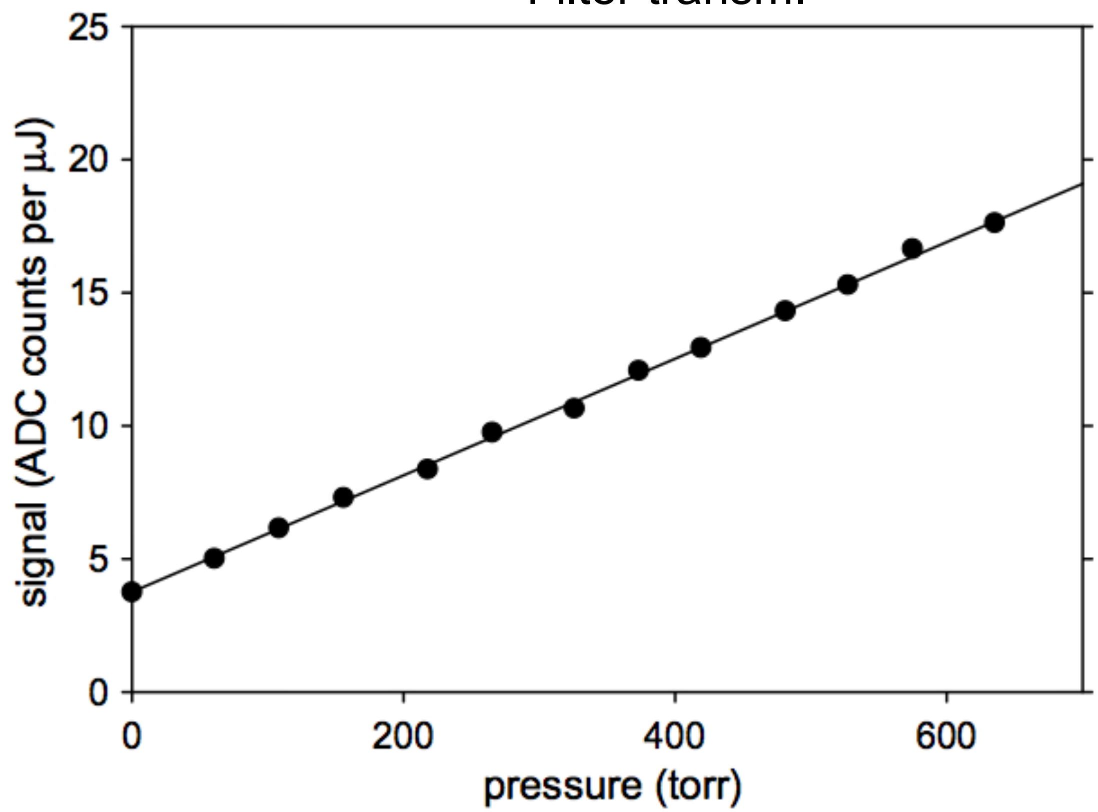


Fig. 2. PMT response to Rayleigh-scattered laser light in air at various pressures. Each PMT pulse is normalized to 1 µJ laser pulse energy, and

FLASH calibration systematic uncertainties

Table 2
Contributions, in units of percent, to the overall 7.5% uncertainty on the photon yield

Uncertainty contribution	%
Beam calib.	2.7
Signal splitter	1
Zero constraint of fits	1
Run-to-run stability	1
Laser vs. e-beam light source shape	0.4
Simulation	1
Spectrum sensitivity, open filter	1.5
Spectrum sensitivity, HiRes filter	1
Beam line vs. lab stability	2.5
2003 data calib.	2
Filter consistency checks	1.8
PMT relative spectral response	1.2
Rayleigh scattering:	
Laser power	5
Gas density for laser scattering	1.1
Theoretical calculations	0.2
Fit slope	0.2

Spatial distribution of light emission

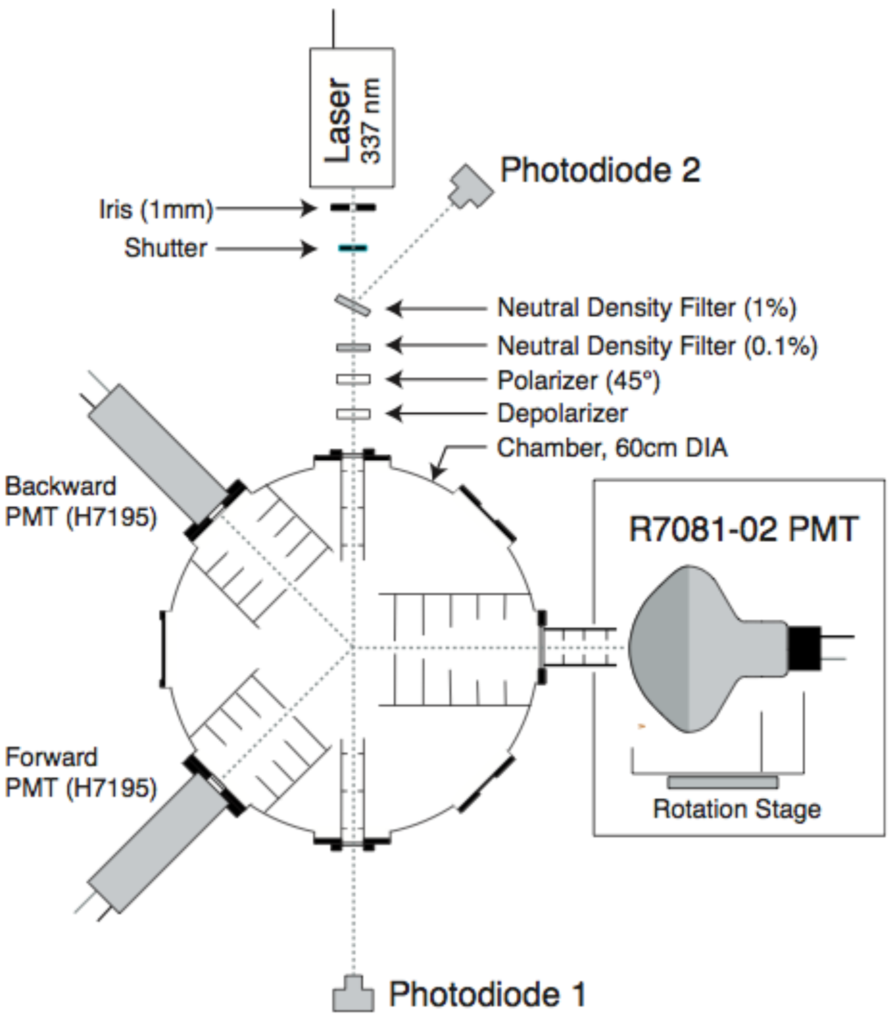
Calibration performed in lab, not in situ

P, T

Rayleigh

A very careful study of systematic uncertainties

IceCube Rayleigh scattering calibration

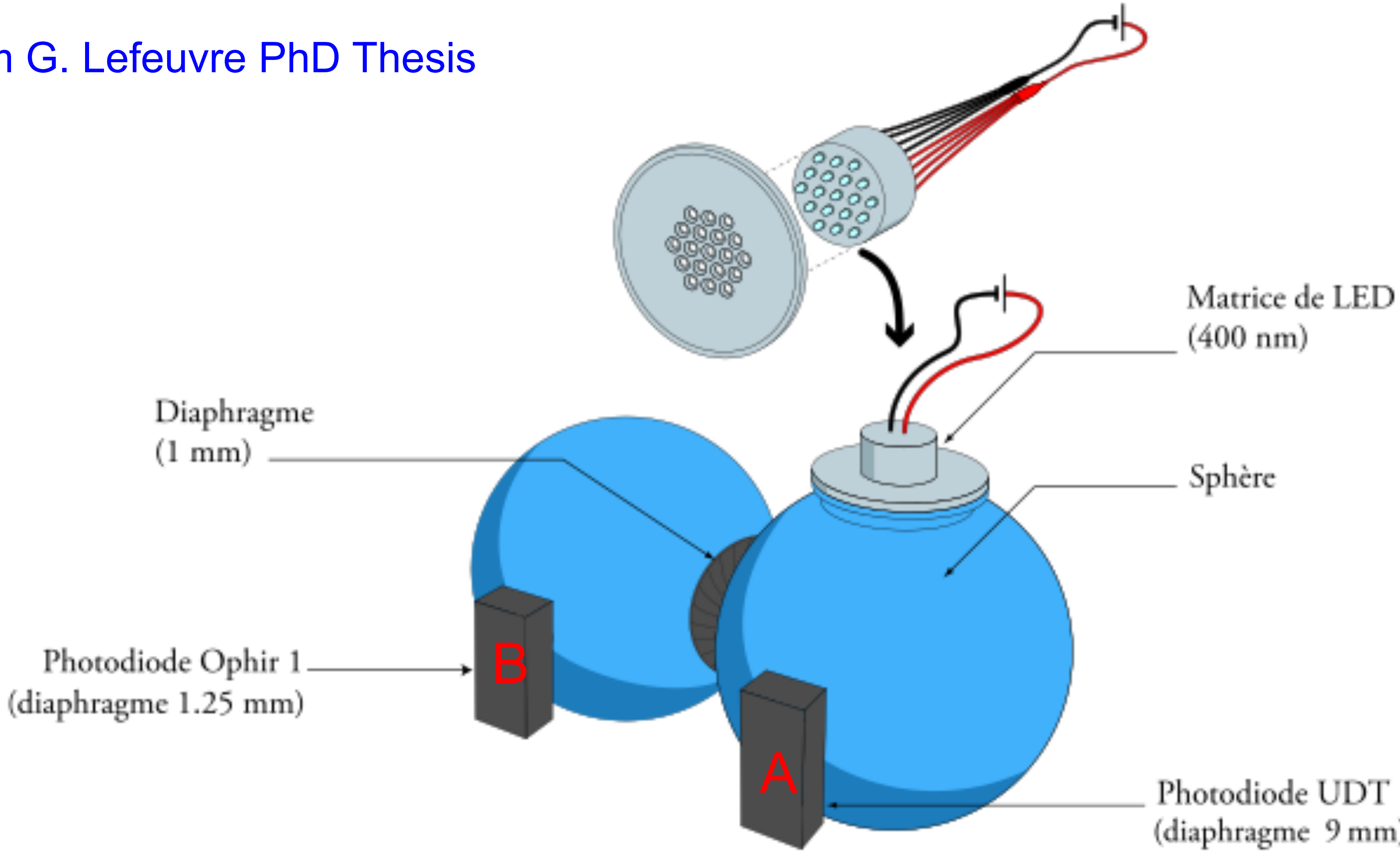


ystematic error budget for the PMT efficiency calibration.

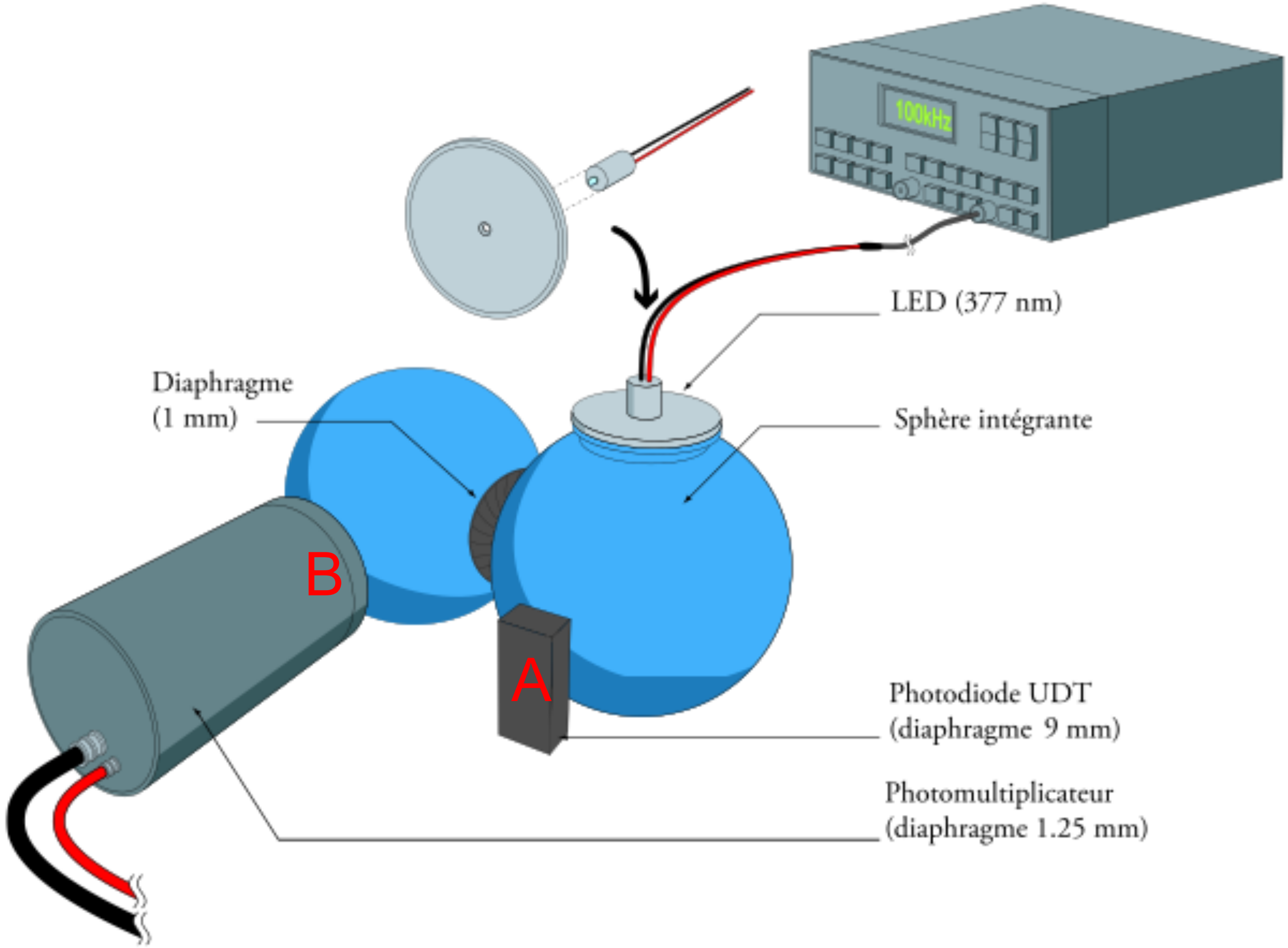
Source	$\Delta\eta/\eta$
Laser beam energy	5 %
Aperture	4 %
Ambient magnetic field	4 %
Pressure and temperature	1 %
Polarization	1 %
Rayleigh cross section	0.5 %
Dark noise / cosmic rays	0.2 %
Overall	7.7 %

Lefeuvre et al

From G. Lefeuvre PhD Thesis

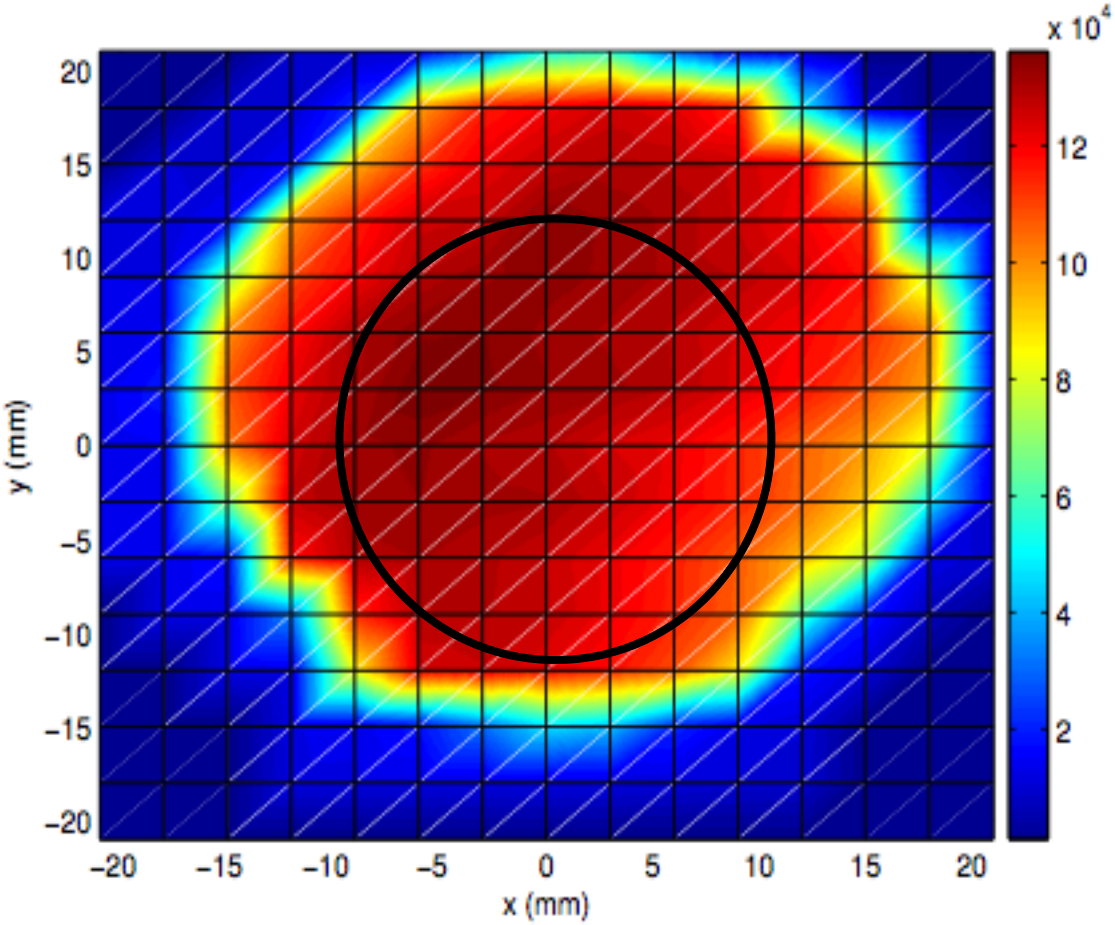


(1) Correlate absolute photon flux at B (measured with a NIST calibrated photodiode) with the signal measured at A



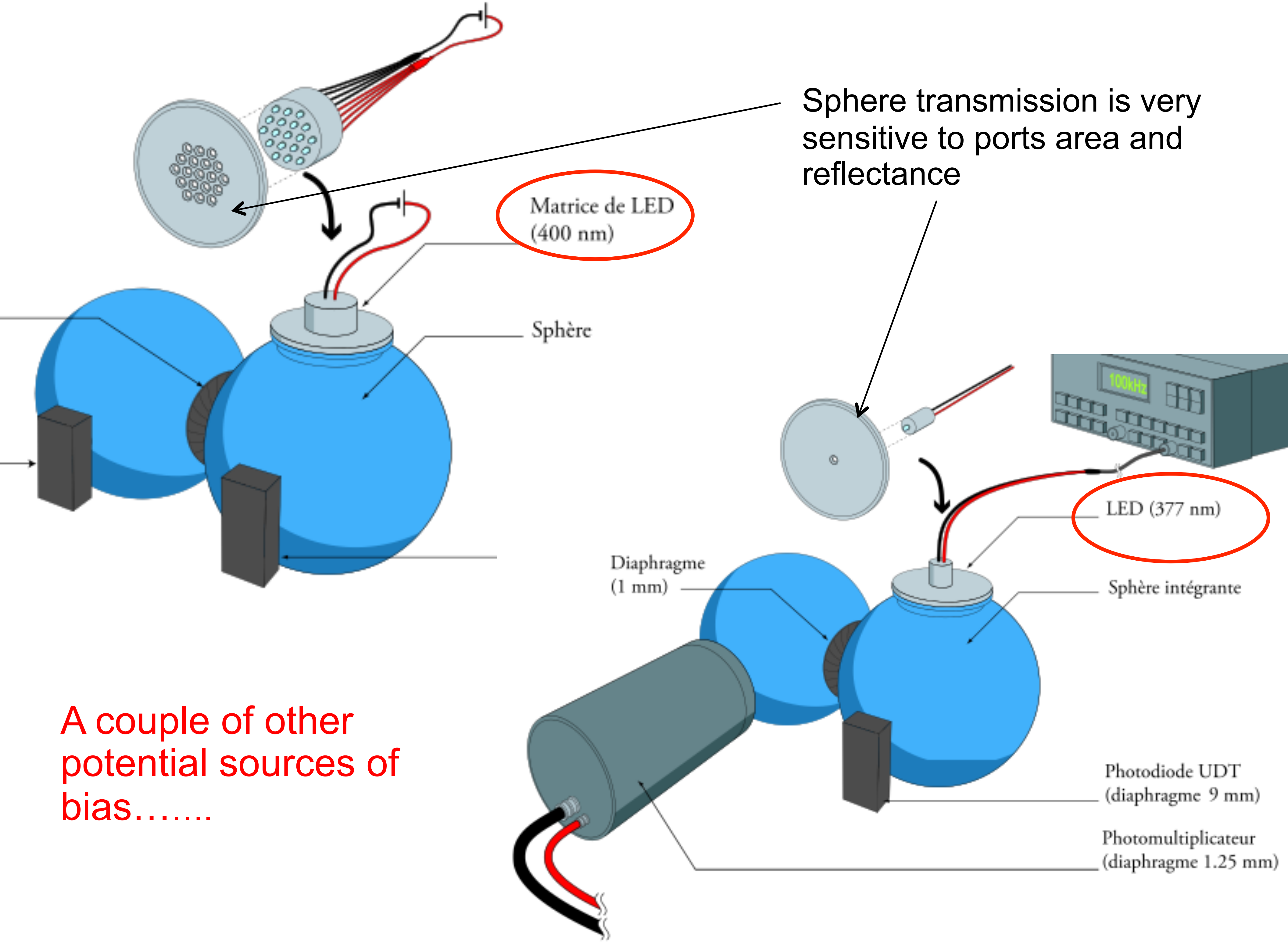
(2) From the signal measured at A (reduced by a factor of 10^{-7} with respect to (1)), one knows how many photons/s arrive at B. By measuring the PMT single p.e. rate, the PMT is calibrated (the 1.5 mm diameter portion of the photocathode)

(3) A precise X-Y scan of the PMT photocathode is performed, thus allowing the calibration of (2) to the entire photocathode. A 20 mm diaphragm is used for the FY measurement, selecting the uniform area of the photocathode



	Systematic unc.
NIST calibration	1.7%
XY scan	0.5%

Given these small uncertainties (<2%!), all aspects of the calibration must be under control to <1%. E.g. uncertainty on linearity of photodiode (10^7 dynamic range used…)



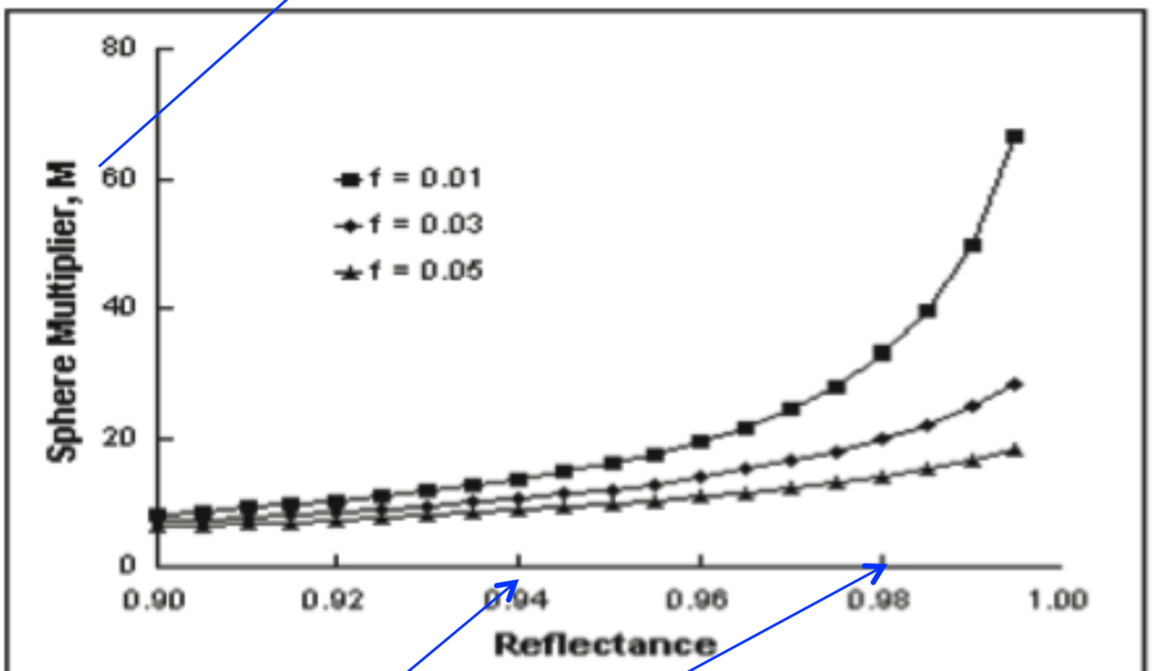
A couple of other potential sources of bias…....

Integrating Sphere

$$L_s = \frac{\Phi_t}{\pi A_s} \frac{\rho_w}{1-\rho_w(1-f)}$$

reflectance

fraction of ports' area
(0.06 in Lefeuvre et al)



Sphere transmission is very sensitive to ports area and reflectance

From G. Lefeuvre PhD Thesis

Le matériau réflecteur qui tapisse leur paroi interne est du Spectraflect©, optimisé pour l'utilisation dans le visible et l'ultraviolet proche. Entre 300 et 400 nm, sa réflectivité varie entre 0.94 et 0.98. Étant donné le grand nombre de réflexions auxquelles sont soumis les photons dans une sphère, il y aura une atténuation non négligeable. Mais nous n'avons pas besoin de connaître cette atténuation : il suffit de savoir qu'elle est constante.

Integrating Sphere wavelength dependence

Le matériau réflecteur qui tapisse leur paroi interne est du Spectraflect©, optimisé pour l'utilisation dans le visible et l'ultraviolet proche. Entre 300 et 400 nm, sa réflectivité varie entre 0.94 et 0.98. Étant donné le grand nombre de réflexions auxquelles sont soumis les

$$\frac{\rho_w}{1-\rho_w(1-f)}$$

ρ(377) = 0.97 → 11.00

ρ(400) = 0.98 → 12.44

13%

In AIRFLY, we have measured the integrating sphere wavelength dependence, which is still sizeable even if Gore has a much better reflectance than Spectraflect.

It may be an important effect O(10%) for the Lefeuvre et al measurement. Must be checked

AIRFLY systematic uncertainties

Cherenkov calibration

data selection and background subtraction	1.0%
r_{N_2}	1.0%
integrating sphere efficiency	0.9%
integrating sphere wavelength dependence	1.0%
PMT quantum efficiency	1.0%
filter transmittance	2.0%
simulation of energy deposit	2.0%
Monte Carlo statistics	1.0%
Total	3.7%

Nitrogen laser calibration

data selection and background subtraction	1.0%
r_{N_2}	1.0%
integrating sphere efficiency	0.9%
geometry	0.3%
laser probe calibration	5.0%
calibration sphere transmission	0.8%
simulation of energy deposit	2.0%
Monte Carlo statistics	1.0%
Total	5.8%

- Main aspects of the calibration

Two independent methods; *in situ* calibration; same geometry and detection efficiency for fluorescence and calibration light, thus many systematic cancel; Cherenkov light spectrum vs 337 nm laser: different systematic

Simulation of energy deposit

- An important effect (according to F. Arqueros et al)

Shift measurements of 0.5 to 3 times the systematic unc.

Experiment	$\Delta\lambda$ (nm)	P (hPa)	T (K)	E (MeV)	Experimental result	Error (%)	$I_{337}/I_{\Delta\lambda}$	Y_{337} (ph/MeV)	Correction (%)
Kakimoto [1]	337	800	288	1.4	5.7 ph/MeV	10	1	4.55 / **4.81**	6
	300 - 400	1013	288	1.4 300 650 1000	3.3 ph/m 4.9 ph/m 4.4 ph/m 5.0 ph/m	10	0.279	4.54 / **4.80** 4.44 / **5.53** 3.80 / **4.85** 4.28 / **5.51**	6 25 27 29
Nagano [2]	337	1013	293	0.85	1.021 ph/m	13	1	5.05 / **5.35**	6
Lefeuvre [3]	300 - 430	1005	296	1.1 1.5	3.95 ph/m 4.34 ph/m	5	0.262	5.15 / **5.52** 5.63 / **6.10**	7 8
MACFLY [4]	290 - 440	1013	296	1.5 $20 \cdot 10^3$ $50 \cdot 10^3$	17.0 ph/MeV 17.4 ph/MeV 18.2 ph/MeV	13	0.255	4.32 / **4.35** 4.42 / **4.34** 4.62 / **4.53**	1 -2 -2
FLASH [6]	300 - 420	1013	304	$28.5 \cdot 10^3$	20.8 ph/MeV	7.5	0.272	5.55 / **5.65**	2
AirLight [5]	337	-	-	0.2 - 2	$Y^0 = 384$ ph/MeV[a]	16	1	5.83 / **5.40**	-7
AIRFLY[b] [7]	337	1013	293	$120 \cdot 10^3$	5.6 ph/MeV	$\lesssim 5\%$	1	5.6 / **-**	-

Uncertainty quoted by AIRFLY (2%, GEANT4) and FLASH (1%, EGS)

Conclusions

- The uncertainty on the absolute fluorescence yield has been significantly reduced (≈ a factor 3) during the last decade. The level we have reached (<5%) should be enough for the purpose of UHECR physics

- The measurements, which employ different calibration methods, are consistent between themselves. A few aspects of the systematic uncertainty should still be looked into with open mind, and clarified. It may need additional work (simulation or systematic checks) from the different experiments, particularly if we would like to properly combine the results.

- I wish to thank all the organizers and participants of the Fluorescence Workshops, which have provided a stimulating forum to present and discuss our work during the last ten years. It has been a truly rewarding experience.