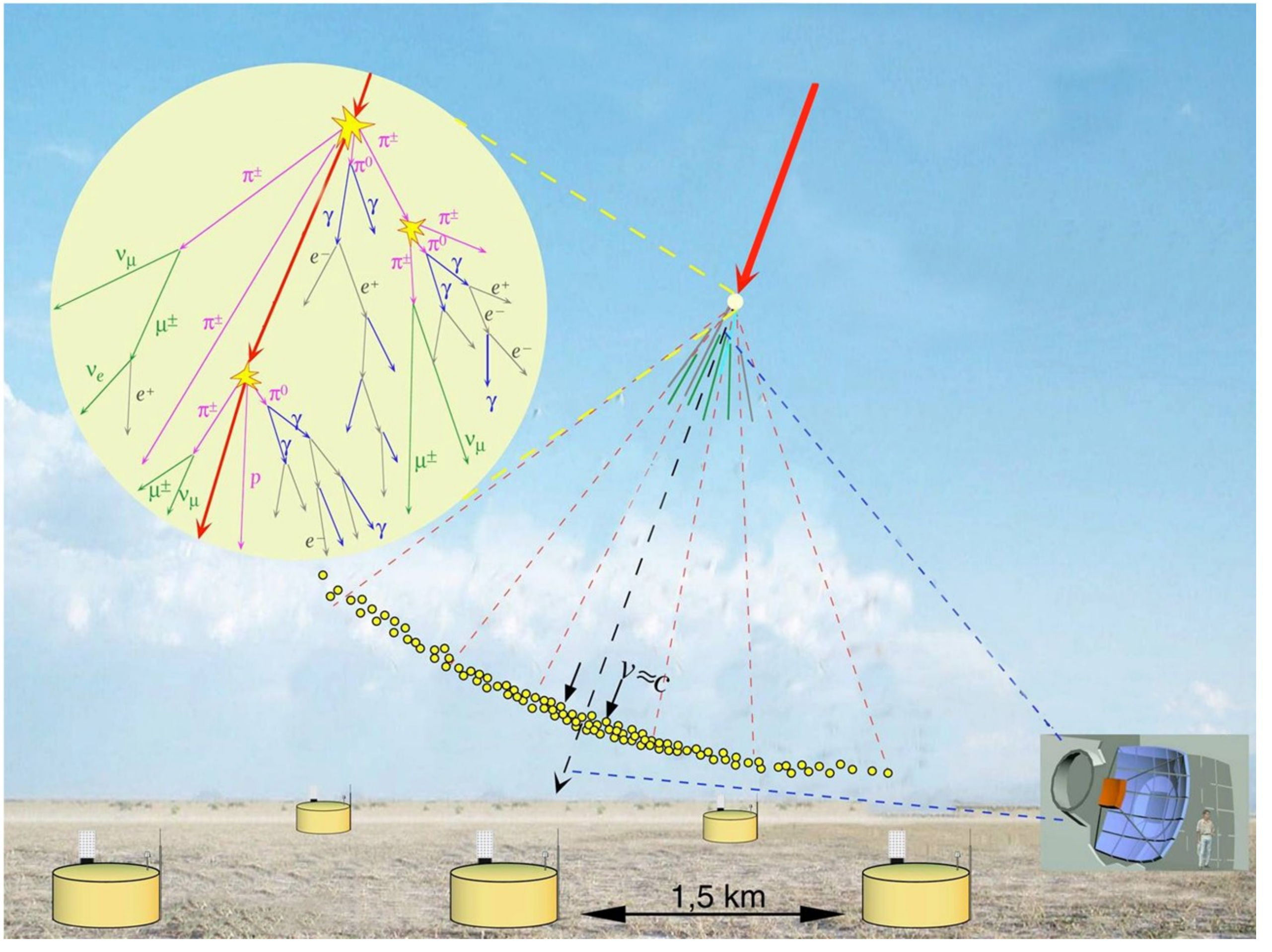
Detection of Ultra High Energy Cosmic Rays

Fluorescence and Microwave technique

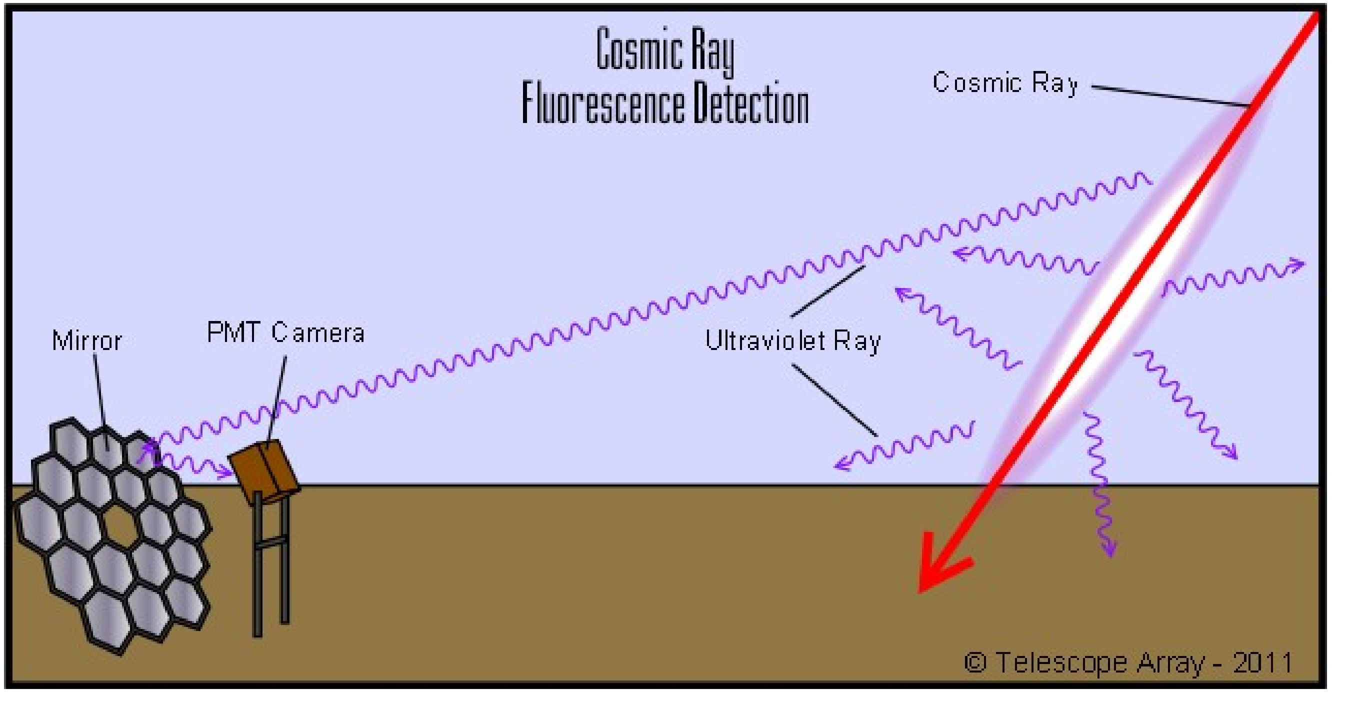


M. Boháčová 12. 12. 2013

Detection techniques at EeV energies

- **surface array** of particle detectors (Čerenkov water tanks, scintillators)
  + 100% duty cycle

- air **fluorescence telescopes**
  + direct observation of longitudinal profile => maximum of the shower development
  -- emission in near UV, limited to dark moonless nights
  15% duty cycle (at most)
  -- faint isotropic emission (~ 5 ph/MeV deposited) => usable above 10^{17} eV



Fluorescence technique

- secondary shower particles interact with nitrogen molecules
- nitrogen de-excites by emitting photons in 300 – 400 nm range
- the amount of emitted light should be proportional to the deposited energy
- dependent on the pressure, temperature and humidity at the production region
- fluorescence model has to be measured in laboratory

Current fluorescence detectors:
AUGER FD, **TA**, (ASHRA)
previous:
Fly's Eye, **HiRes**
future:
JEM-EUSO (ISS) space observation

Disclaimer:
Technically the process should be called **scintillation**, i.e. light emission caused by ionizing particles as opposed to **fluorescence** – light emission induced by absorption of photons at different wavelength

AIR FLuorescence Yield

idea: in 2002, within the Auger community
- available models did not have sufficient precision
- temperature and humidity dependence ignored

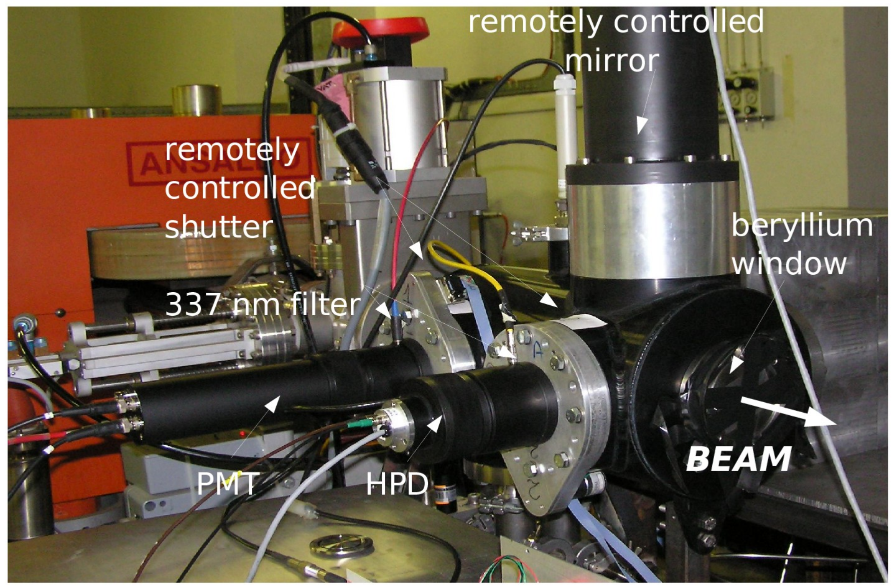
AIRFLY scientific goal:

- energy dependence in wide energy range
- relative pressure, temperature and humidity dependence
- nitrogen emission spectrum with high resolution
- absolute fluorescence yield

The only experiment designed to measure
the complete fluorescence yield model

AIRFLY results

Energy dependence

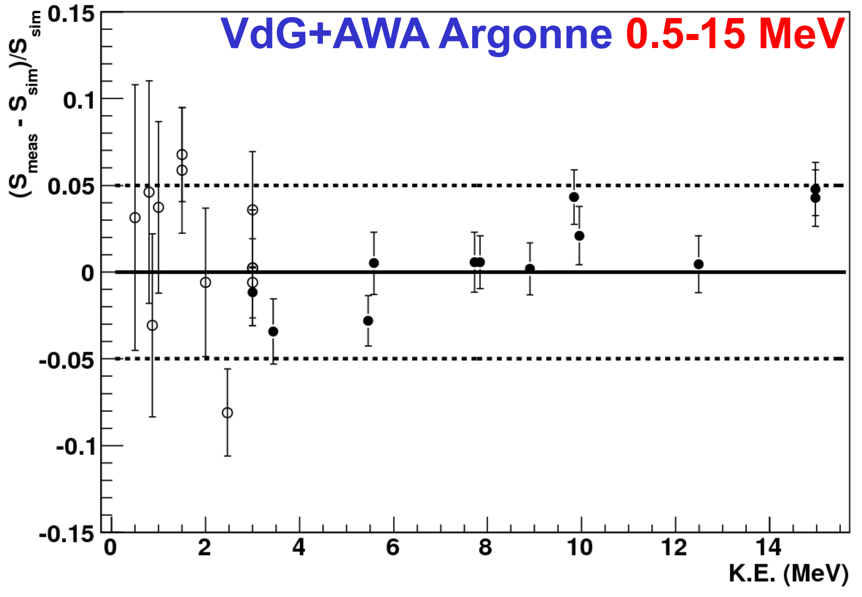


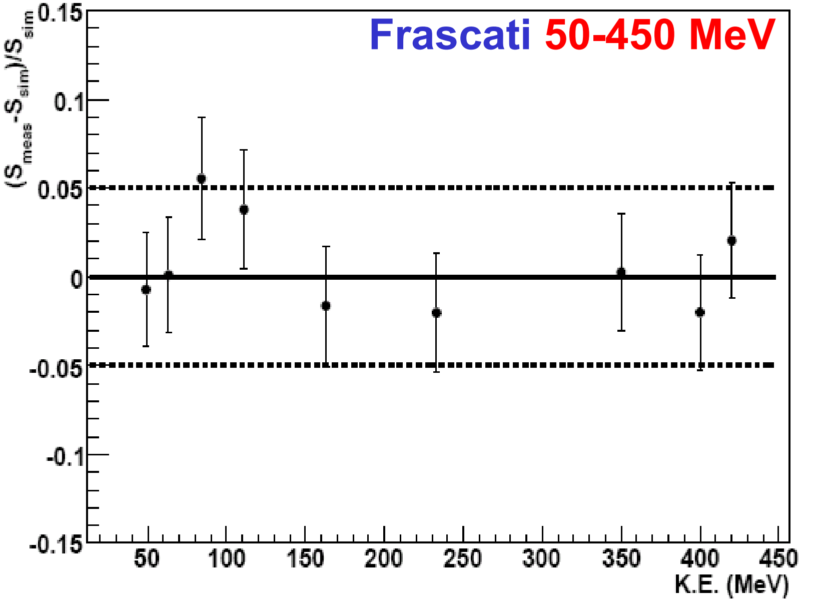
- energy dependence proved in wide energy range
  - BTF (Frascati linac) 50 – 450 MeV
  - AWA (Argonne Wakefield accelerator) 3 – 15 MeV
  - Argonne electron van de Graaff 0.5 – 3 MeV
  - APS (Advanced Photon Source) 6 – 30 keV

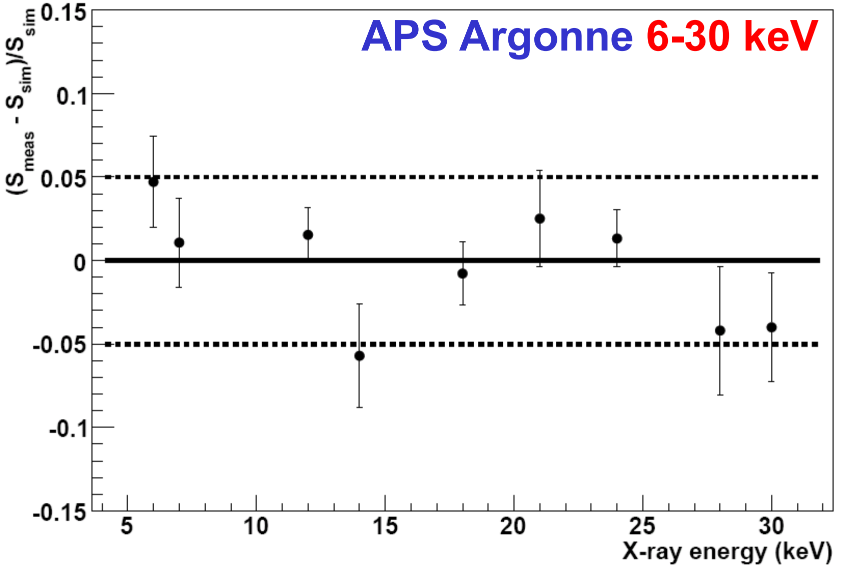
Note: critical energy of electrons in air is ~ 80 MeV => shower maximum

AIRFLY results

Energy dependence





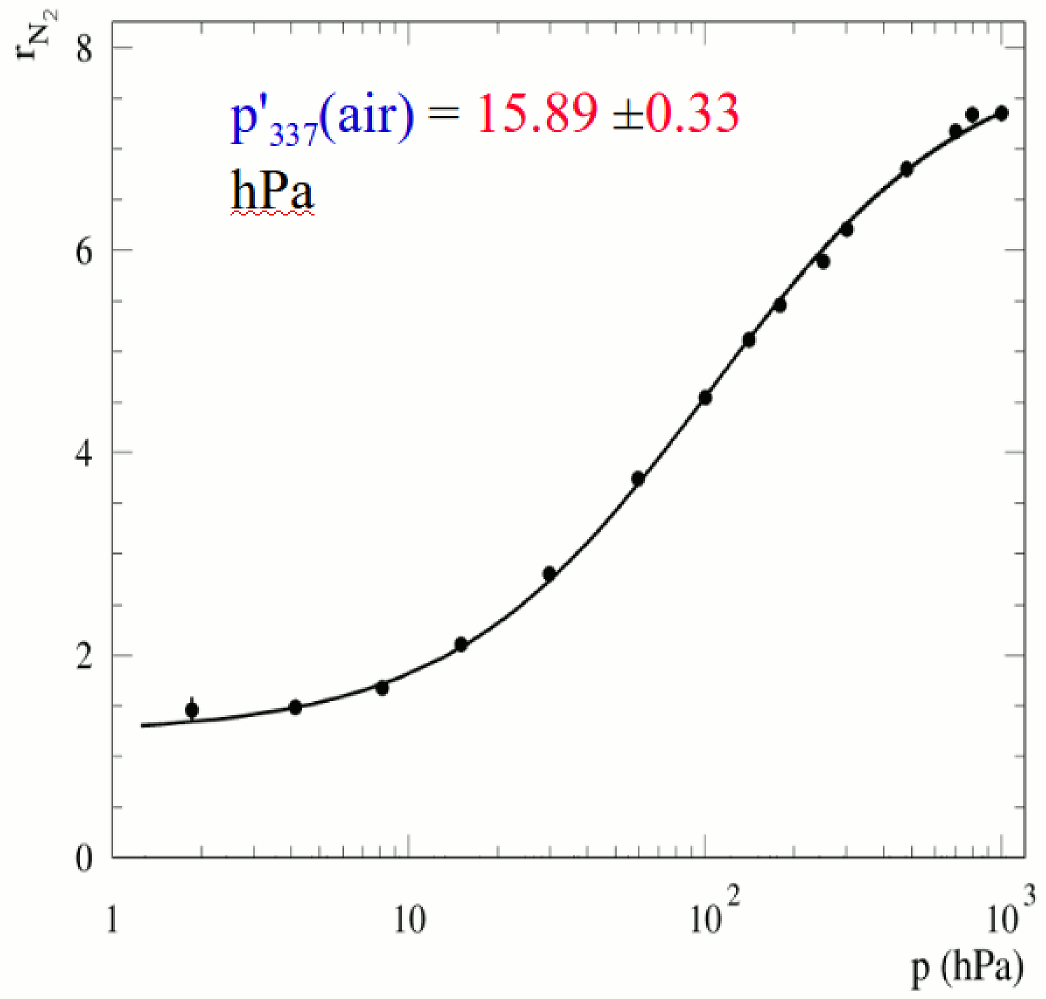


- Proportionality of fluorescence yield to deposited energy at few %

NIM A 597 (2008) 46

AIRFLY results

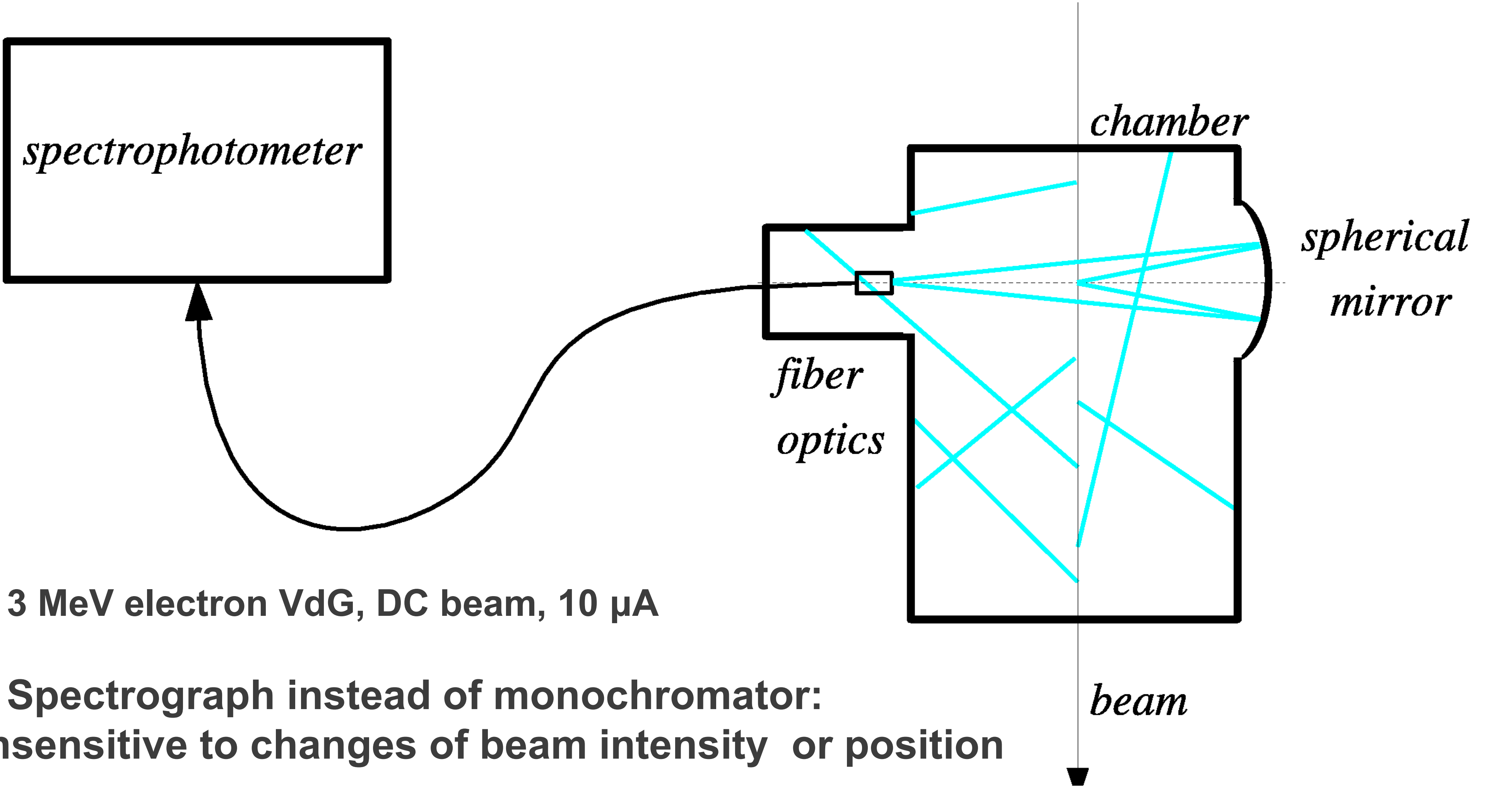
Pressure dependence of 337 nm line



- energy deposit changes with pressure due to particles escaping the field of view
- two methods:
  1. MC simulation of the energy deposit correction
  2. ratio of nitrogen to air yield – energy deposit almost the same => dependence cancels
- previous experiments:
  p'(337) ~ 19 hPa

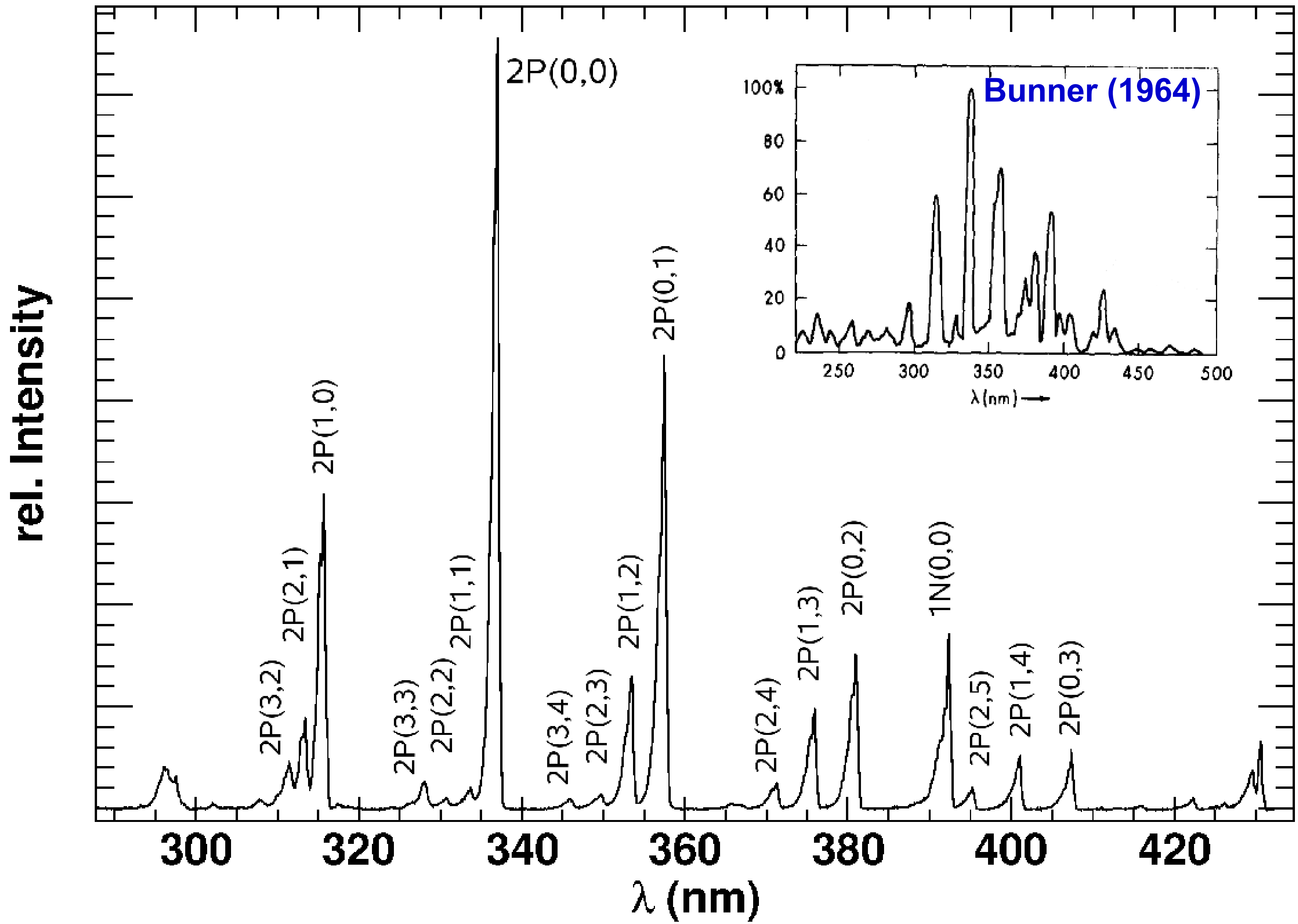
AIRFLY results

Relative pressure dependence of the spectrum



- 3 MeV electron VdG, DC beam, 10 μA
- Spectrograph instead of monochromator:
Insensitive to changes of beam intensity or position
- L.O.T. Oriel MS257, $\Delta\lambda$ = 0.1 nm

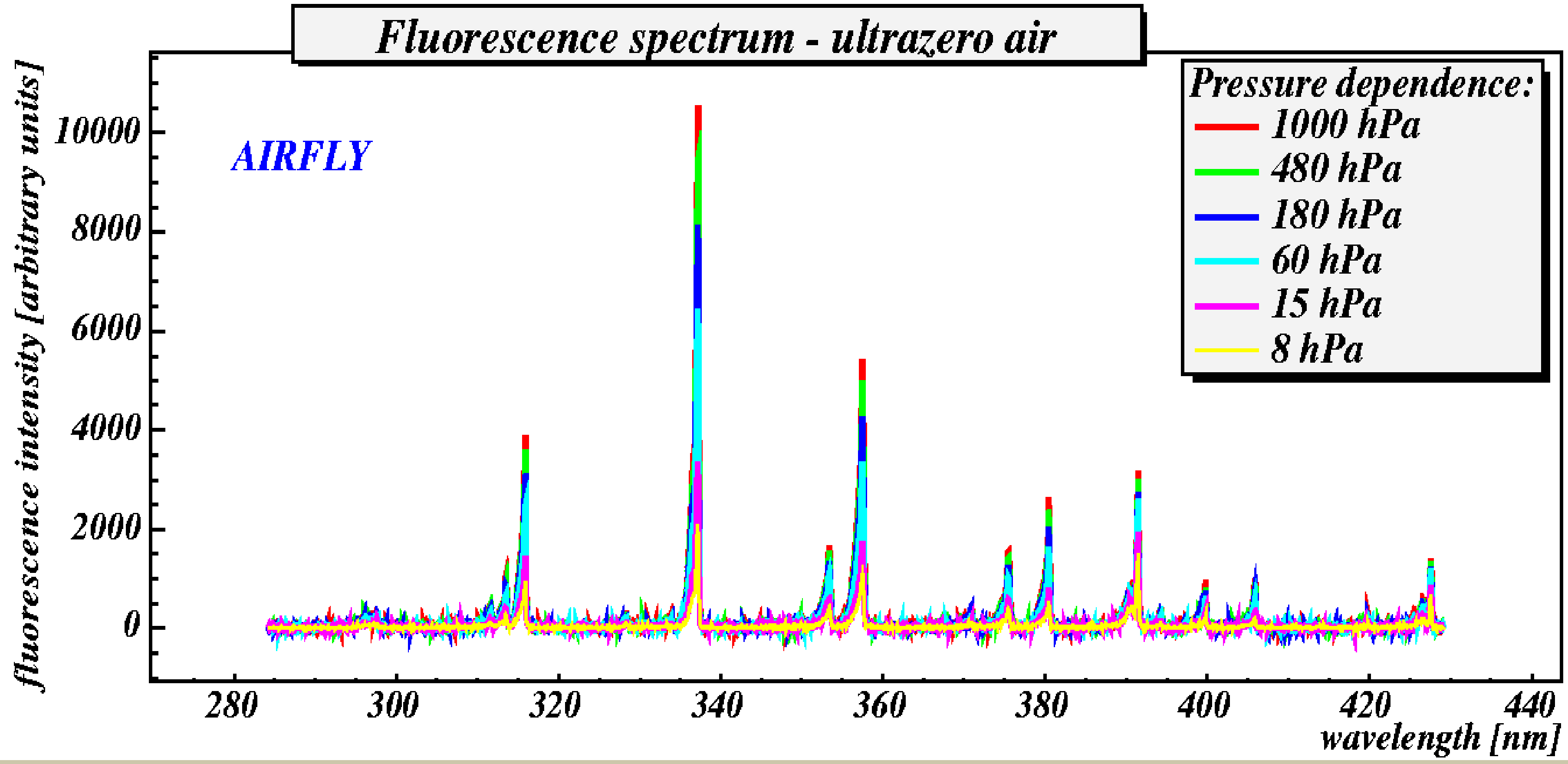
AIRFLY spectrum



➜ **34 band intensities measured (relative to the 337 nm line)**

AIRFLY spectrum

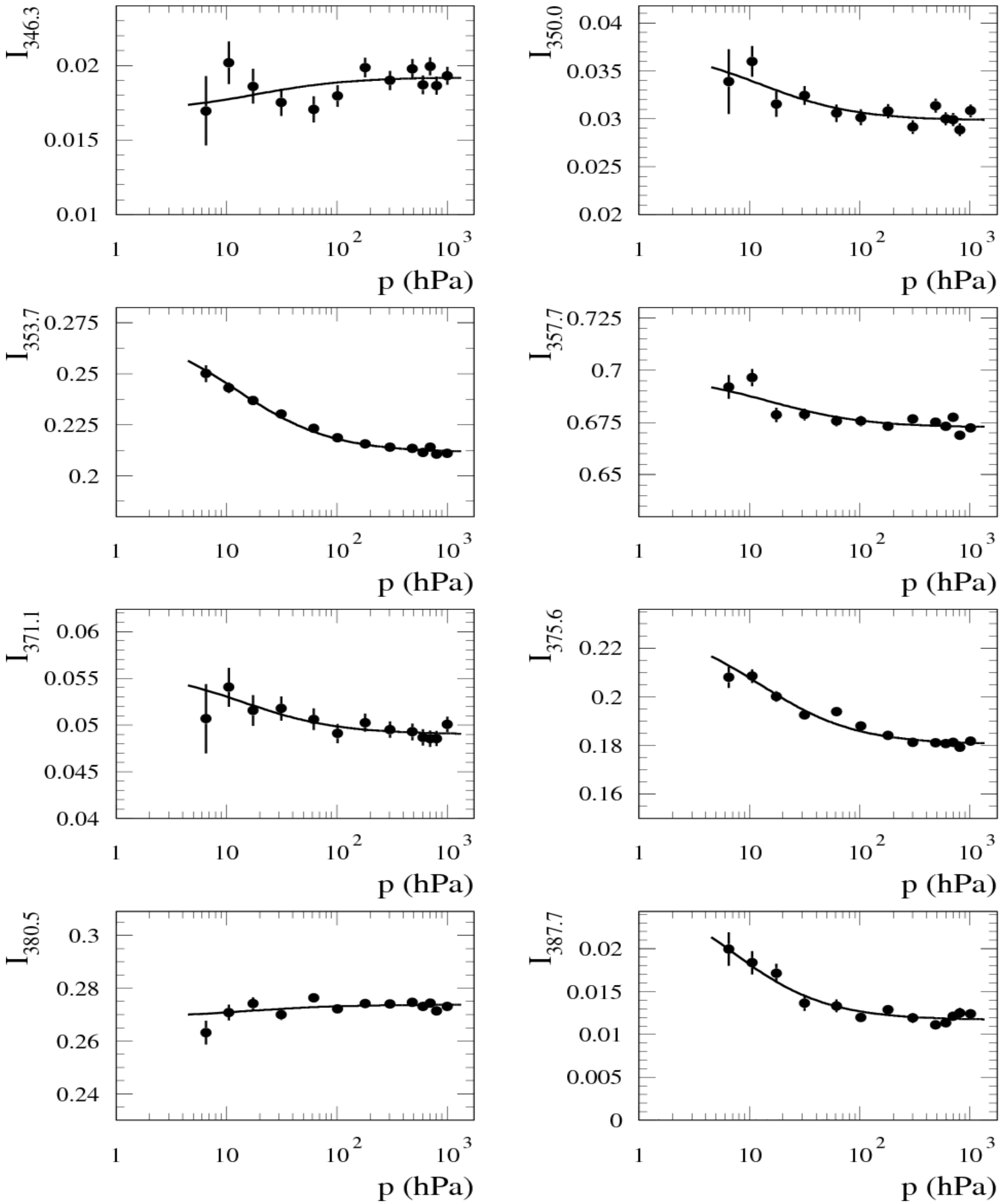
Relative pressure dependence of the spectrum



➜ **34 band intensities measured (<u>relative to the 337 nm line</u>)**

AIRFLY results

Relative pressure dependence

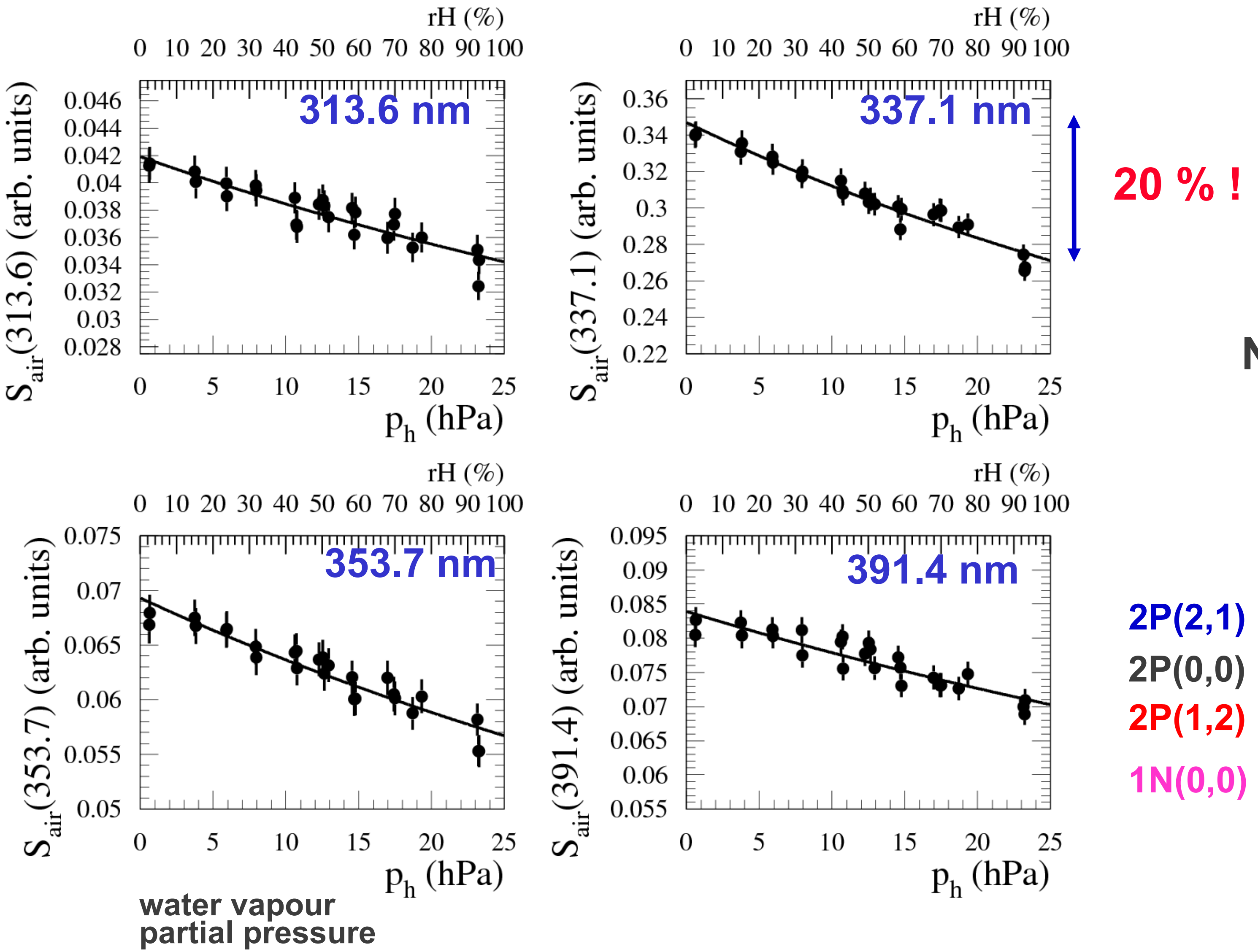


- using p' 337 previously measured
- characteristic pressure of all resolved lines

Astropart. Phys. 28 (2007) 41

AIRFLY results

Relative humidity dependence

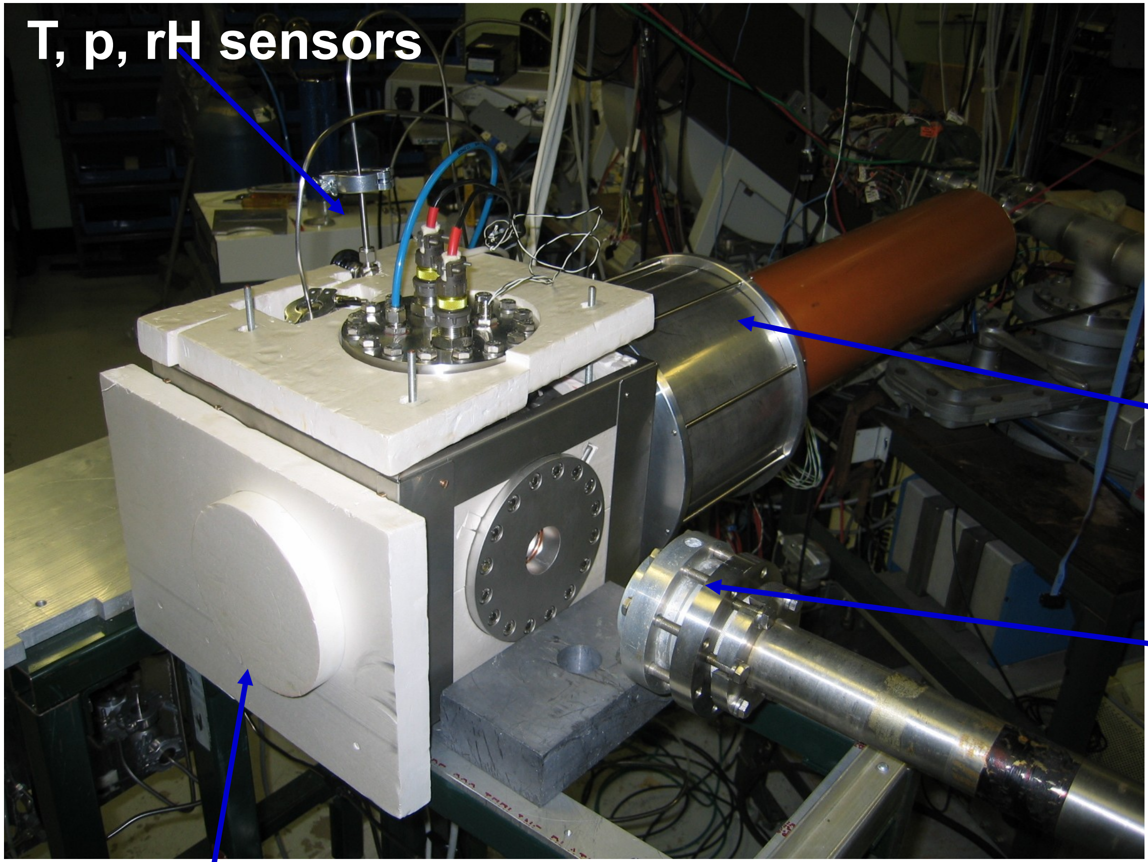


NIM A597 (2008) 50

	λ (nm)	p'_{H_2O} (hPa)
2P(2,1)	313.6	1.21 ± 0.13
2P(0,0)	337.1	1.28 ± 0.08
2P(1,2)	353.7	1.27 ± 0.12
1N(0,0)	391.4	0.33 ± 0.03

AIRFLY results

Relative temperature dependence



Fiber to spectrograph in dry N_2 filled box

VdG beam exit

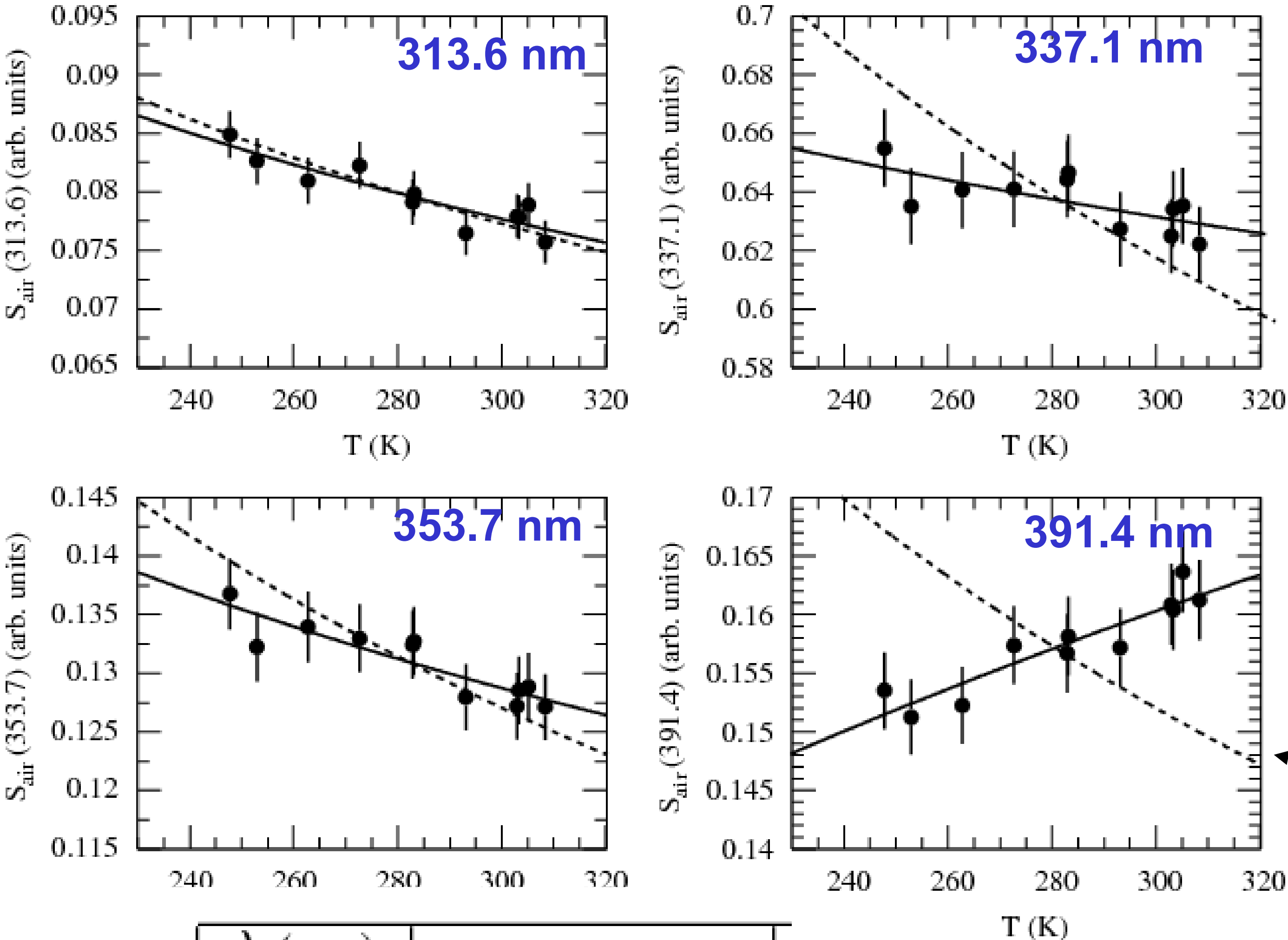
Temperature chamber with dry ice cooling and polystyrene walls - produced in FZU

$$\frac{H_\lambda(T)}{H_\lambda(T_0)} = \left(\frac{T}{T_0}\right)^{\alpha_\lambda}$$

$\alpha = 0$ usual assumption in UHECR
(no T dependence of the collisional cross sections)

AIRFLY results

Relative temperature dependence



RANGE [-40,30] ^{0}C

up to 10 % effect!

$\alpha = 0$

	λ (nm)	α_λ
2P(2,1)	313.6	-0.09 ± 0.10
2P(0,0)	337.1	-0.36 ± 0.08
2P(1,2)	353.7	-0.21 ± 0.09
1N(0,0)	391.4	-0.80 ± 0.09

$\alpha \neq 0$!

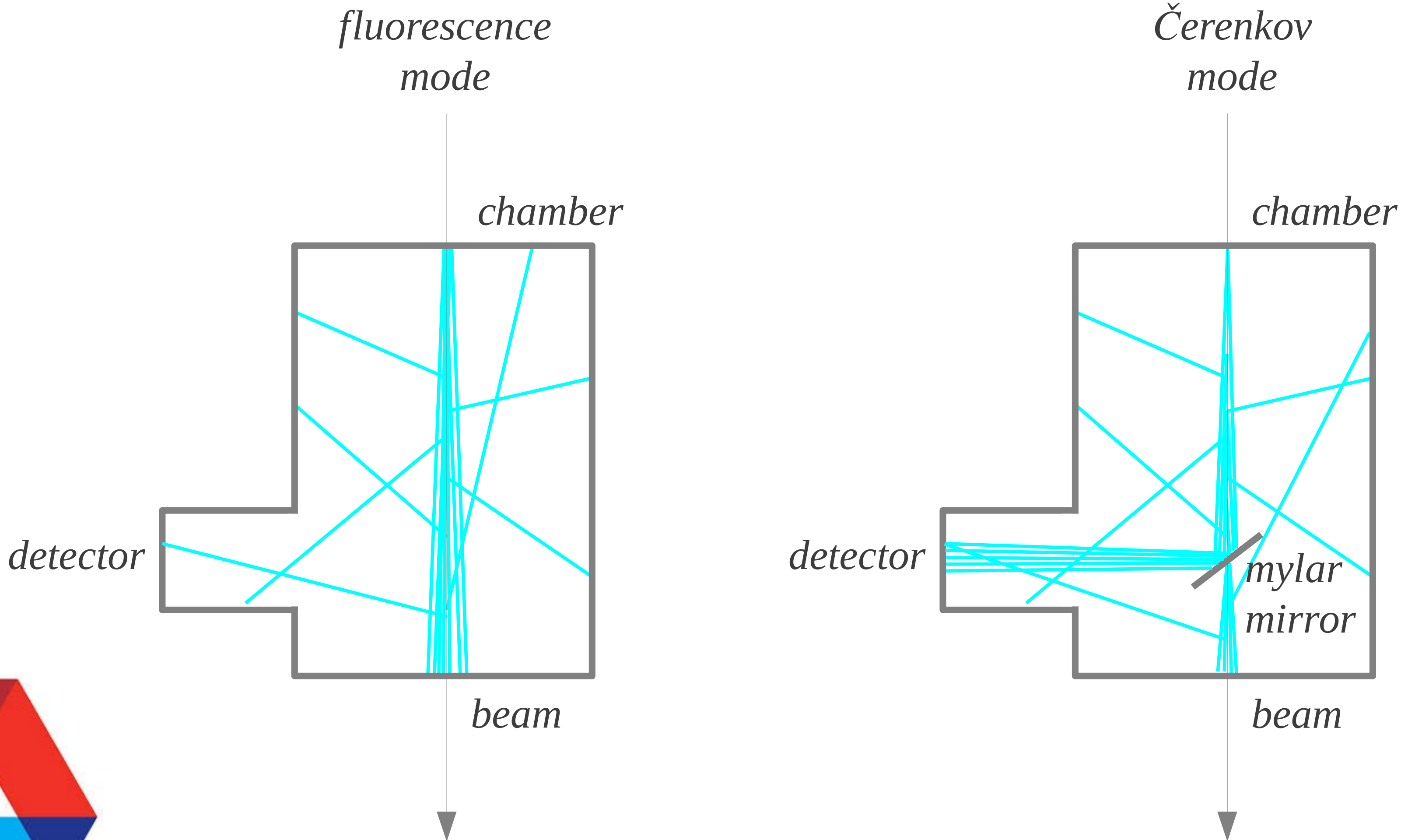
NIM A597 (2008) 50

M. Boháčová 12. 12. 2013

AIRFLY results

Absolute yield of 337 nm line

- new idea: normalize to a well known process - Cerenkov emission
- measure one line and use it to normalize the whole spectrum



AIRFLY results

Absolute yield of 337 nm line

- new idea: normalize to a well known process - Cerenkov emission
- measure one line and use it to normalize the whole spectrum

$$\underbrace{N_{337}(fluo)}_{measured} = \underbrace{Y_{fl}}_{known} \times \underbrace{Geom_{fluo}}_{MC} \times \underbrace{T_{filter} \times QE_{337}}_{\sim cancel} \times \underbrace{N_p}_{relative}$$

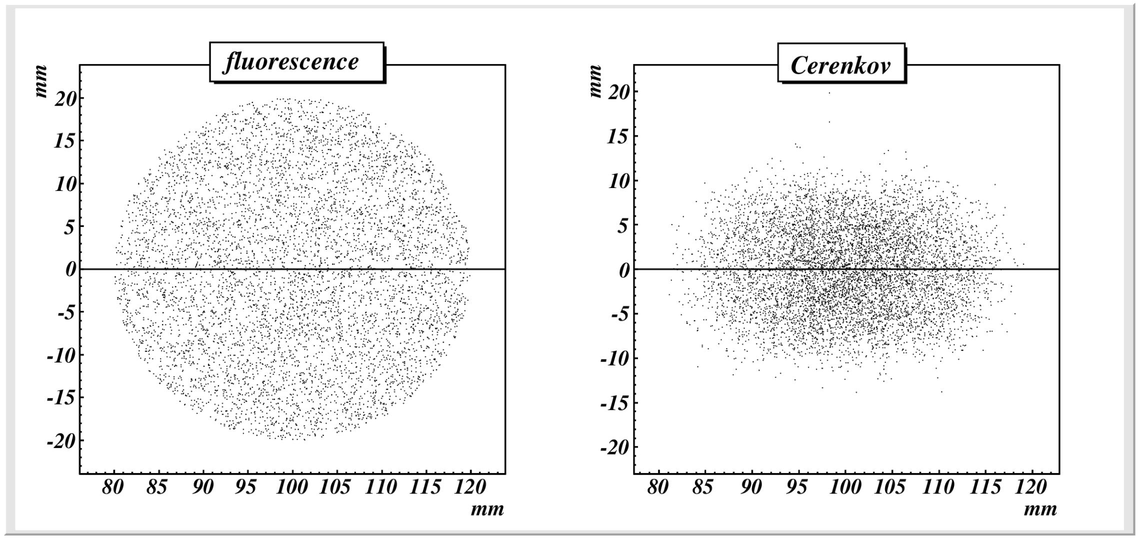
$$\overbrace{N_{337}(cere)} = \overbrace{Y_{cere}} \times \overbrace{Geom_{cere}} \times \overbrace{T_{filter} \times QE_{337}} \times \overbrace{N_p}$$

- Full MC simulation of the ratio with nominal FLY is compared to the ratio measured in laboratory

AIRFLY results

Absolute yield of 337 nm line

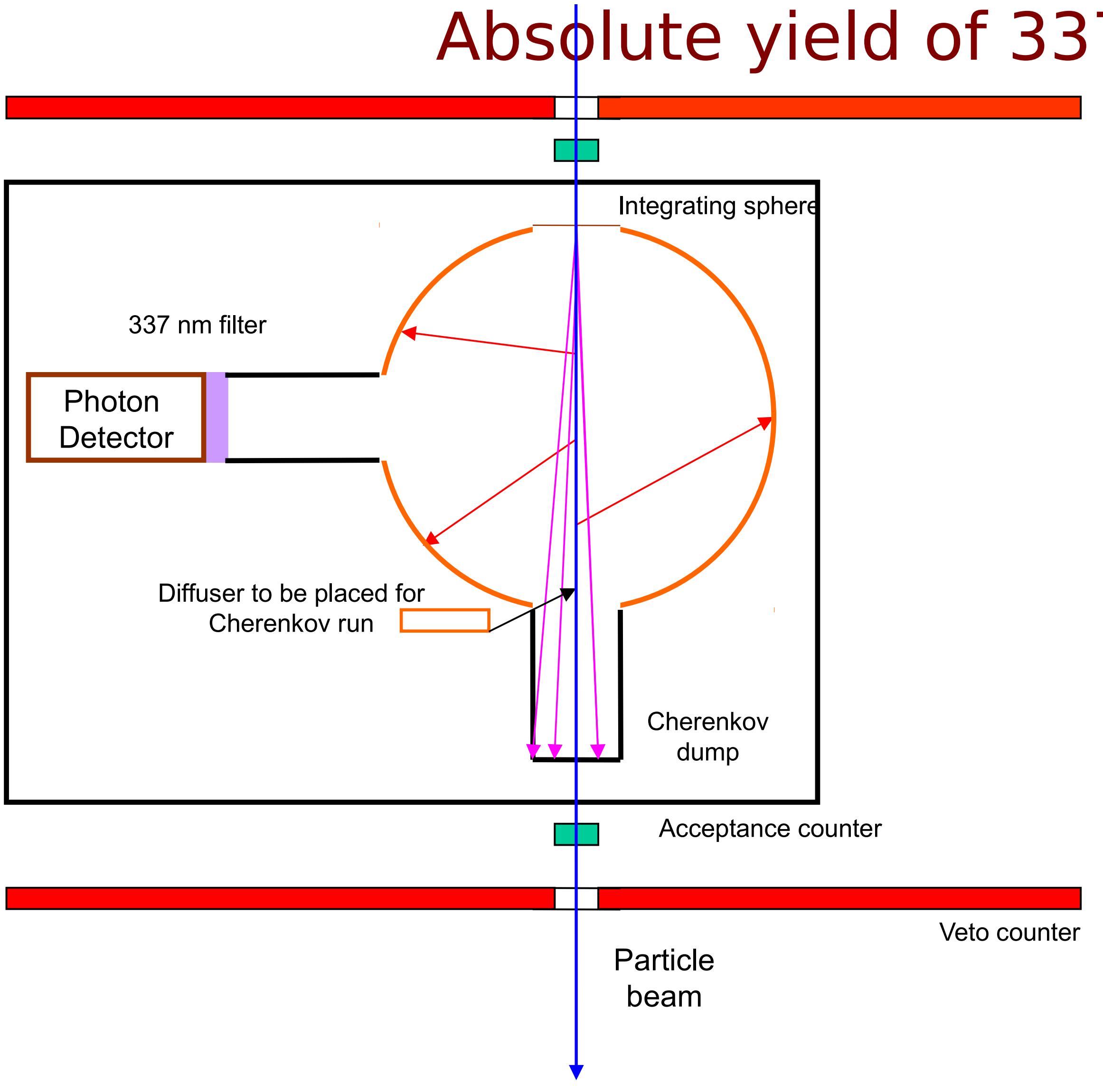
- new idea: normalize to a well known process - Cerenkov emission
- measure one line and use it to normalize the whole spectrum



- photocathode nonuniformity would affect strongly the ratio
 => integrating sphere would eliminate the bias

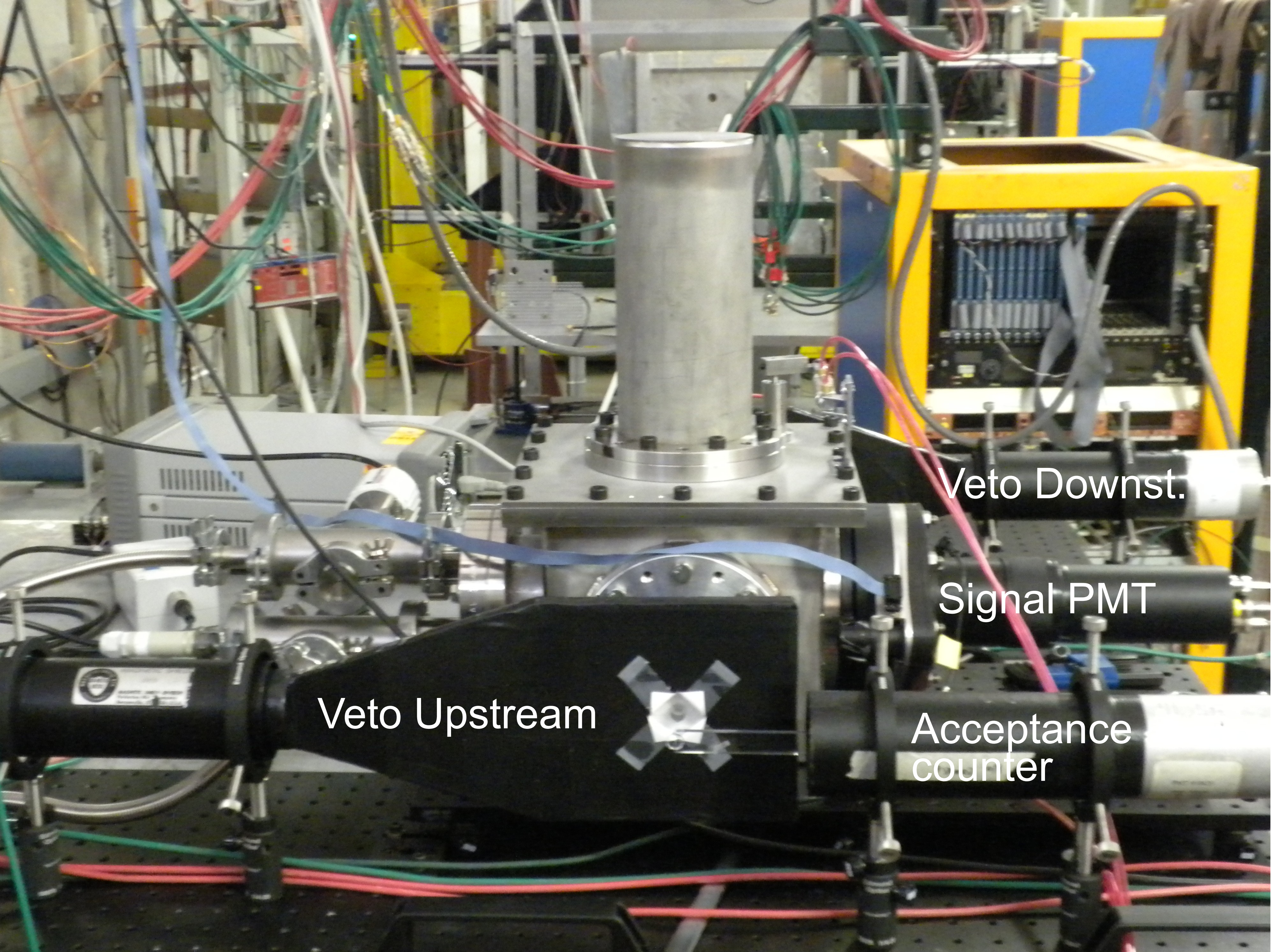
AIRFLY results

Absolute yield of 337 nm line



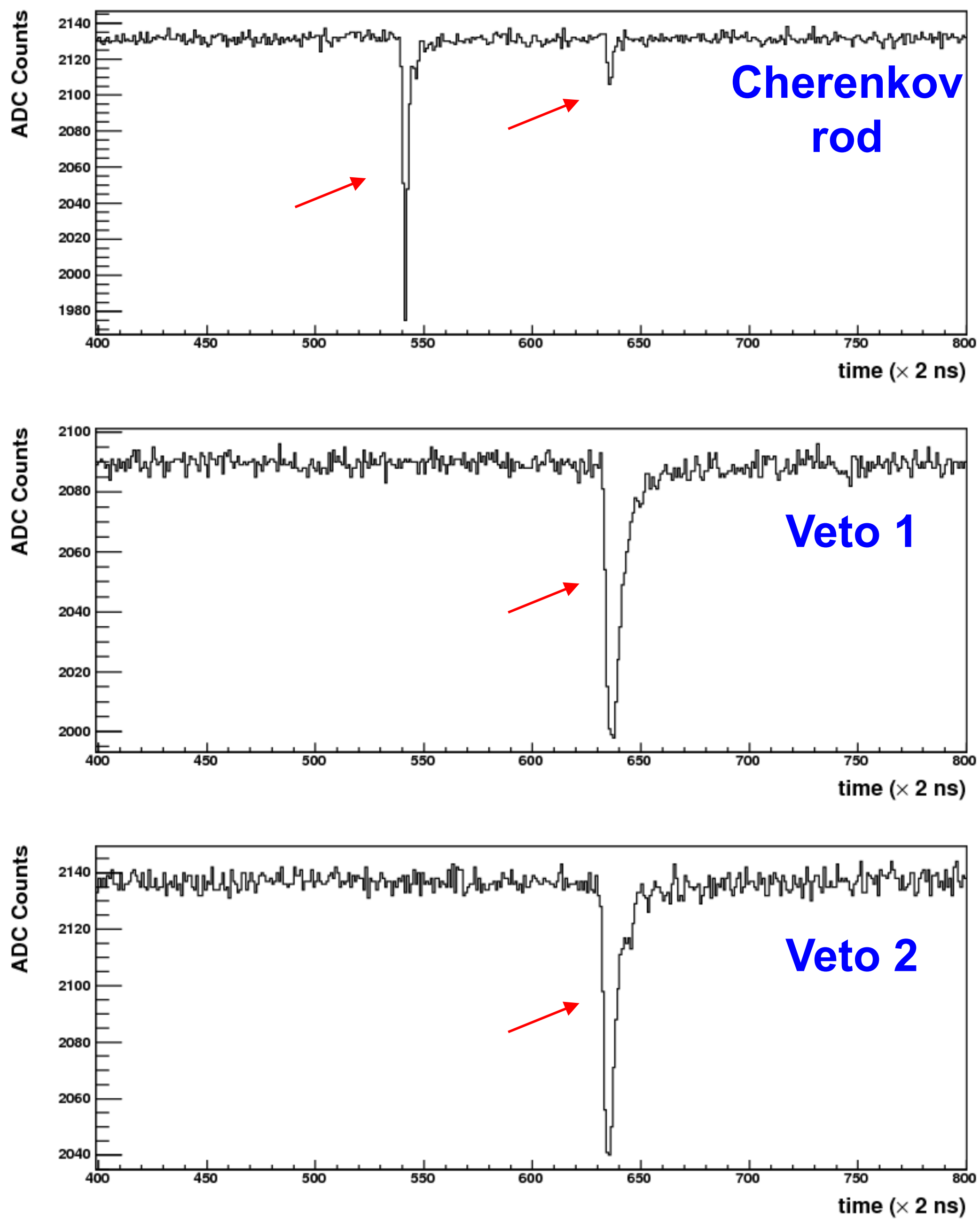
- High energy up to 120 GeV
- Well defined beam: single particle trigger and geometry
- Wide range of particles type and intensity (p, e, μ, π)

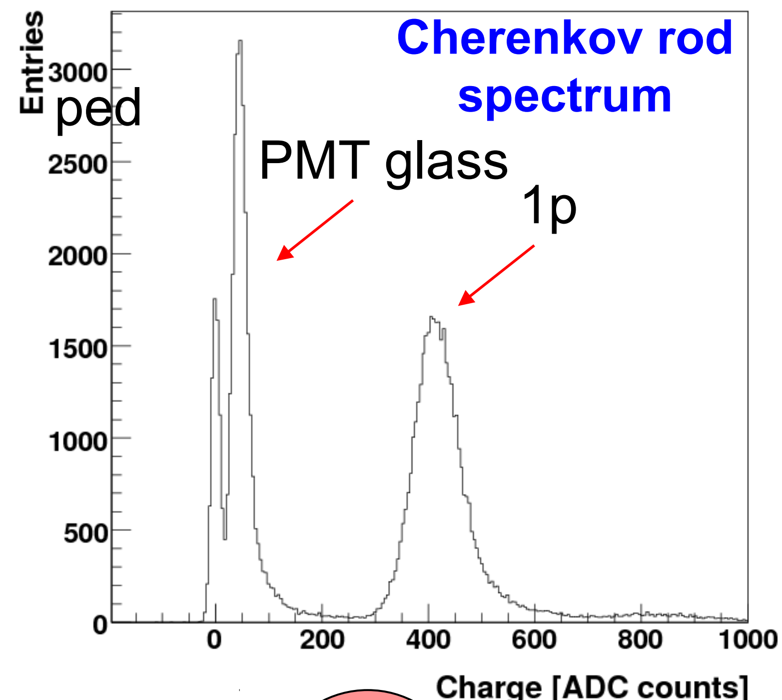
Absolute calibration with two independent methods: Čerenkov and laser light

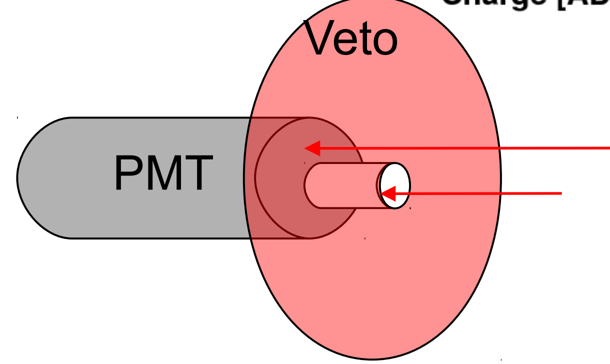

Veto Downst.
Signal PMT
Veto Upstream
Acceptance
counter

AIRFLY results

f 337 nm line







Single particle triggering

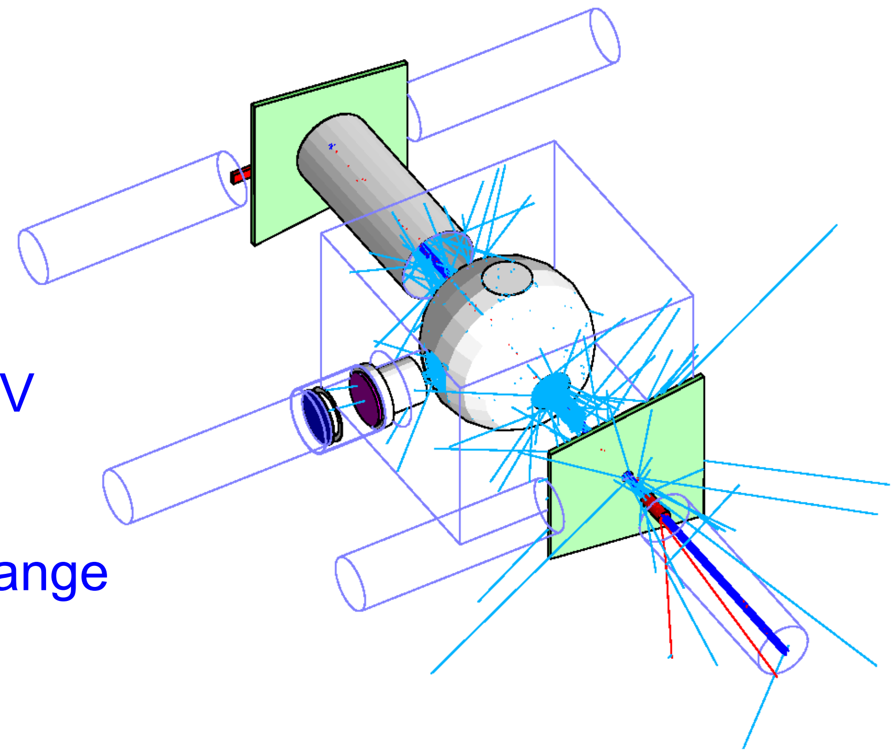
M. Boháčová 12. 12. 2013

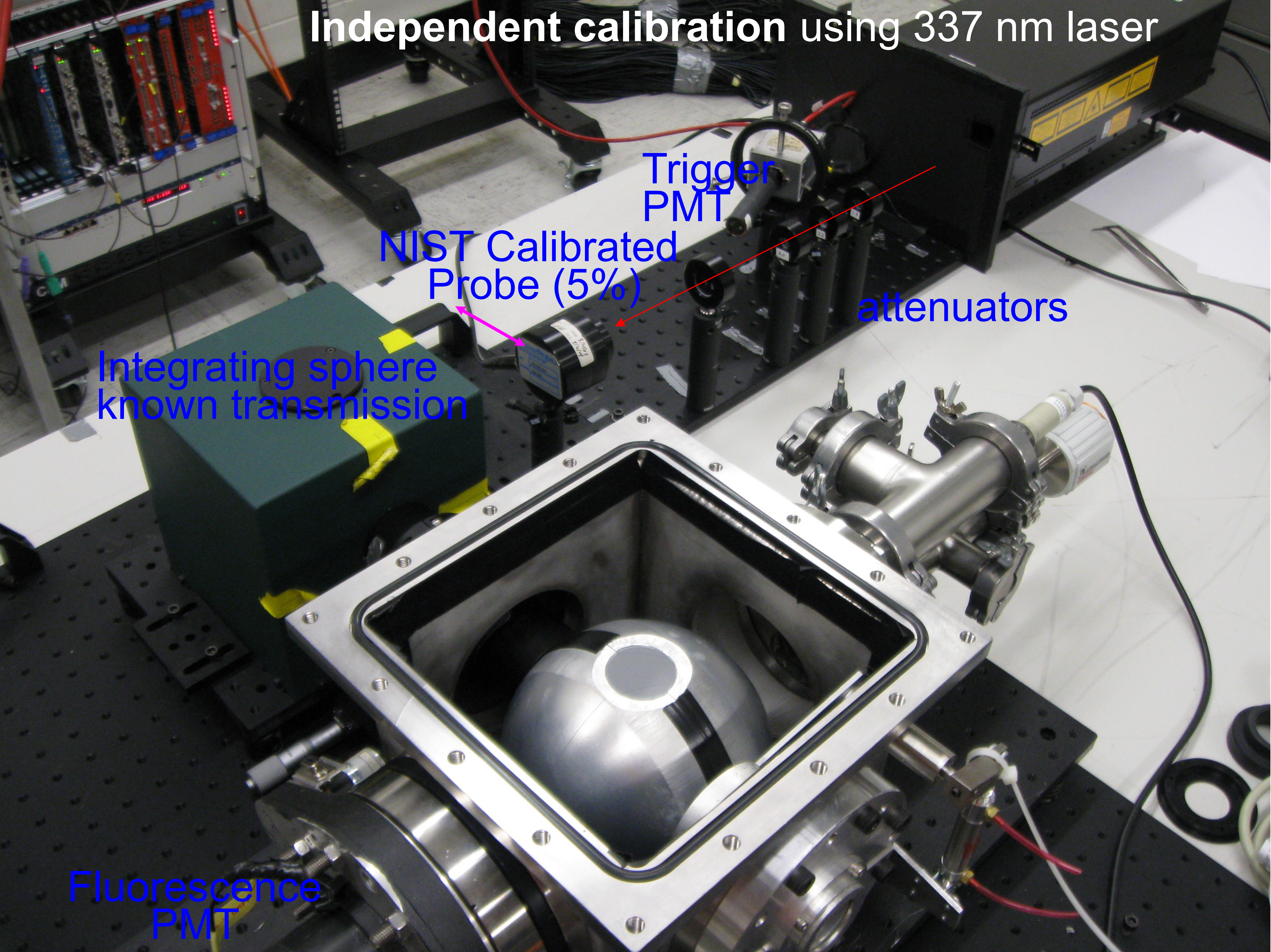
AIRFLY results

Absolute yield of 337 nm line

Total simulation of the experiment

- using version Geant4.9.2.p02
- Standard electromagnetic processes
  (protons 120 GeV)
- Cerenkov process implemented by Geant4
- G4ScintillationProcess simulates
  the fluorescence – nominal yield 20 ph/MeV
  sampled from the AIRFLY spectrum
- 337 nm line forms 25.75% of the spectrum
- Cut in range 1 mm – particles with shorter range
  deposit all their energy on the spot




Independent calibration using 337 nm laser
Trigger PMT
NIST Calibrated Probe (5%)
attenuators
Integrating sphere known transmission
Fluorescence PMT

AIRFLY results

Absolute yield of 337 nm line

- **three different measurements with different statistics**
- **performed in Nitrogen to increase the statistics**
- **Ratio Nitrogen/Air (337nm)**
  - **- Measured at AWA Argonne** **r = 7.35±0.08**
  - **- Confirmed in Fermilab setup**

(dry air, 1013 hPa, 293 K)

$$Y_{air} = \frac{(R_{N2} / r)}{(R_{air})_{MC}}$$

$(Y_{air})_{F/C} = 5.64 \pm 0.12_{stat}$ photons$_{337}$/MeV

2.4 % statistical unc.

Mylar mirror

$(Y_{air})_{F/C} = 5.48 \pm 0.25_{stat}$ photons$_{337}$/MeV

$$Y_{air} = \frac{(L_{N2} / r)}{(L_{air})_{MC}}$$

$(Y_{air})_{LAS} = 5.73 \pm 0.08_{stat}$ photons$_{337}$/MeV

1.3 % statistical unc.

Previously used in Auger: 5.05 photons/MeV

AIRFLY results

Absolute yield of 337 nm line

Systematic uncertainties

Fluo/Cere ratio

- sphere reflectivity	~ 0.9%
- PMT quantum efficiency	~ 1.0%
- Monte Carlo statistics	~ 1.0%
- N_2/Air ratio	~ 1.0%
- sphere λ dependence	~ 1.0%
- filter transmittance	~ 2.0%
- background subtraction	~ 1.0%
- energy deposit	~ 2.0%
Total	3.7%

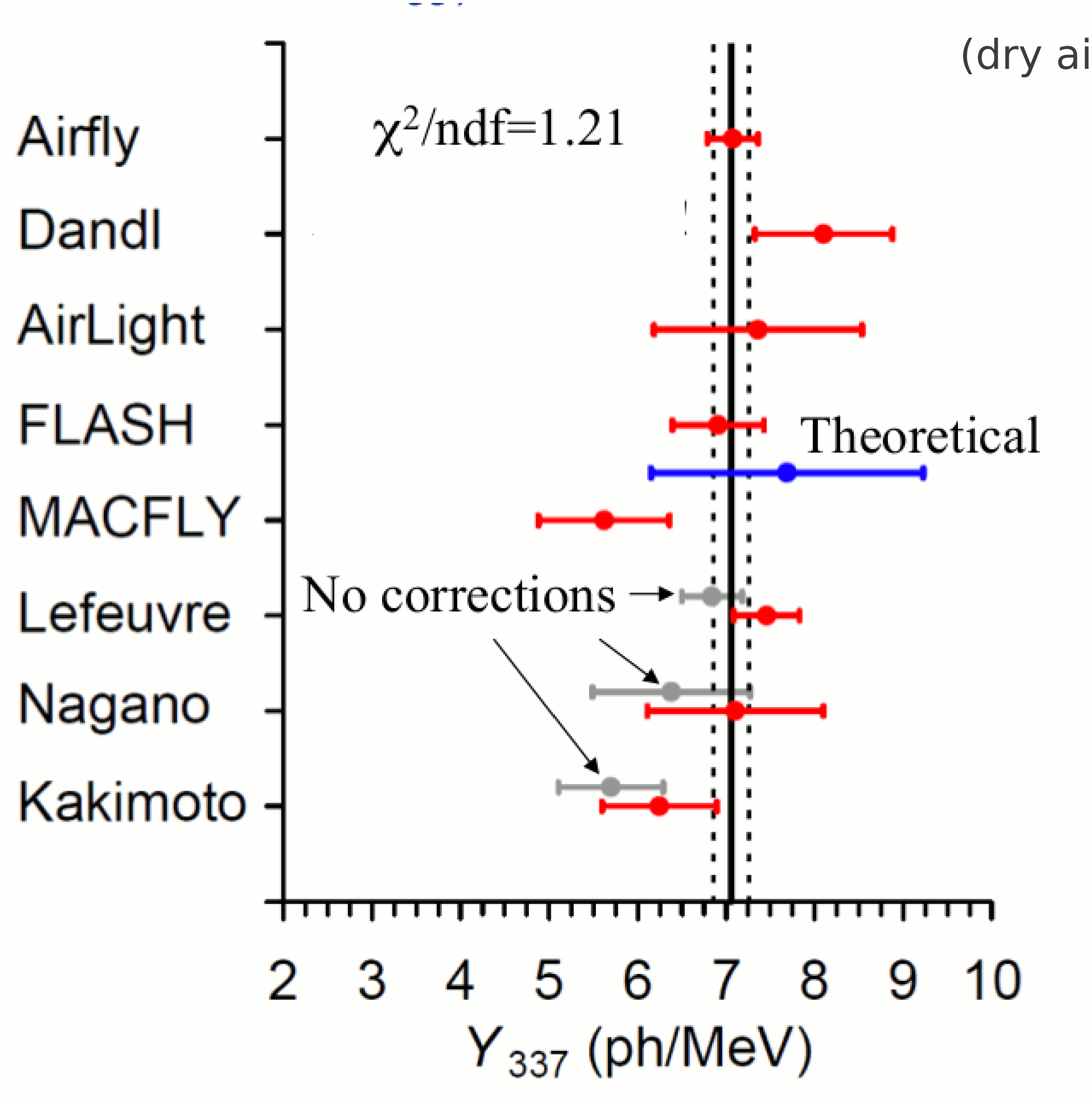
Laser calibration

- laser probe calibration	~ 5.0%
- calibration sphere transmission	~ 0.8%
- integrating sphere efficiency	~ 0.9%
- Monte Carlo statistics	~ 1.0%
- N_2/Air ratio	~ 1.0%
- geometry	~ 0.3%
- background subtraction	~ 1.0%
- energy deposit	~ 2.0%
Total	6%

Astroparticle Physics 42 (2013) 90-102

Comparison to other experiments

(dry air, 800 hPa, 293 K)



Average value:

Y337 = 7.06 ± 0.25 ph/MeV
(3.4% error)

J. Rosado and F. Arqueros
Universidad
Complutense de Madrid
ICRC 2013, Rio de Janeiro

AIRFLY

SYSTEMATIC UNCERTAINTIES OF THE AUGER ENERGY SCALE

		uncertainties on previous energy scale
Absolute fluorescence yield	3.4%	
Fluores. spectrum and quenching param.	1.1%	
Sub total (Fluorescence Yield)	**3.6%**	**14%**
Aerosol optical depth	3% ÷ 6%	
Aerosol phase function	1%	
Wavelength dependence of aerosol scattering	0.5%	
Atmospheric density profile	1%	
Sub total (Atmosphere)	**3.4% ÷ 6.2%**	**5% ÷ 8%**
Absolute FD calibration	9%	
Nightly relative calibration	2%	
Optical efficiency	3.5%	
Sub total (FD calibration)	**9.9%**	**9.5%**
Folding with point spread function	5%	
Multiple scattering model	1%	
Simulation bias	2%	
Constraints in the Gaisser-Hillas fit	3.5% ÷ 1%	
Sub total (FD profile rec.)	**6.5% ÷ 5.6%**	**10%**
Invisible energy	**3% ÷ 1.5%**	**4%**
Statistical error of the SD calib. fit	**0.7% ÷ 1.8%**	
Stability of the energy scale	**5%**	
TOTAL	**14%**	**22%**

improvement in each sector with the exception of FD cal. (largest contribution) work in progress to reduce it

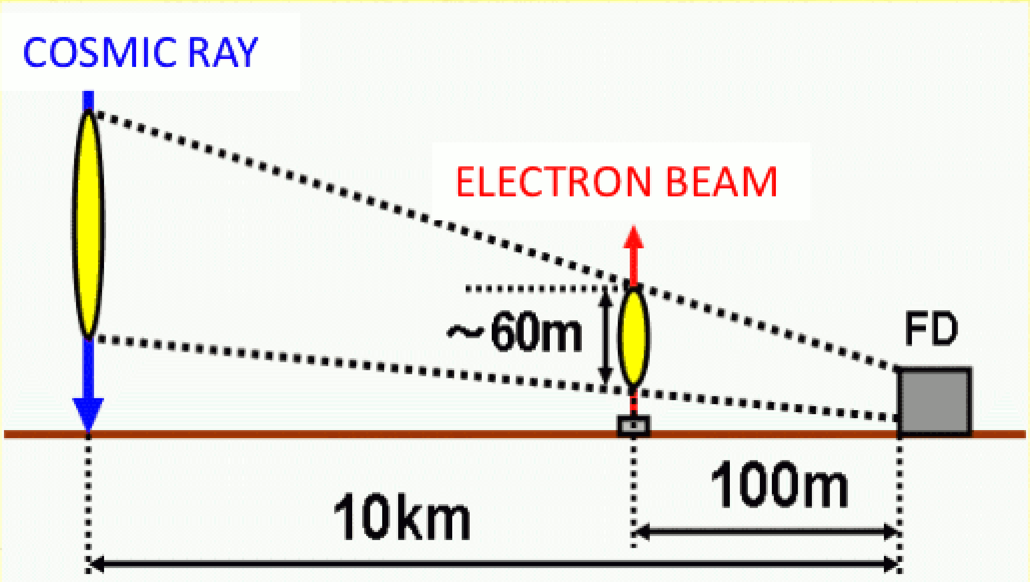
12. 2013

Electron Light Source (ELS)

ICRC 2013

Precise measurement of Energy of UHECR is most important

Proposed a new calibration for Fluorescence Detectors (FD)
of the Telescope Array (TA) = use **Electron Beam from LINAC(ELS)** near FD site

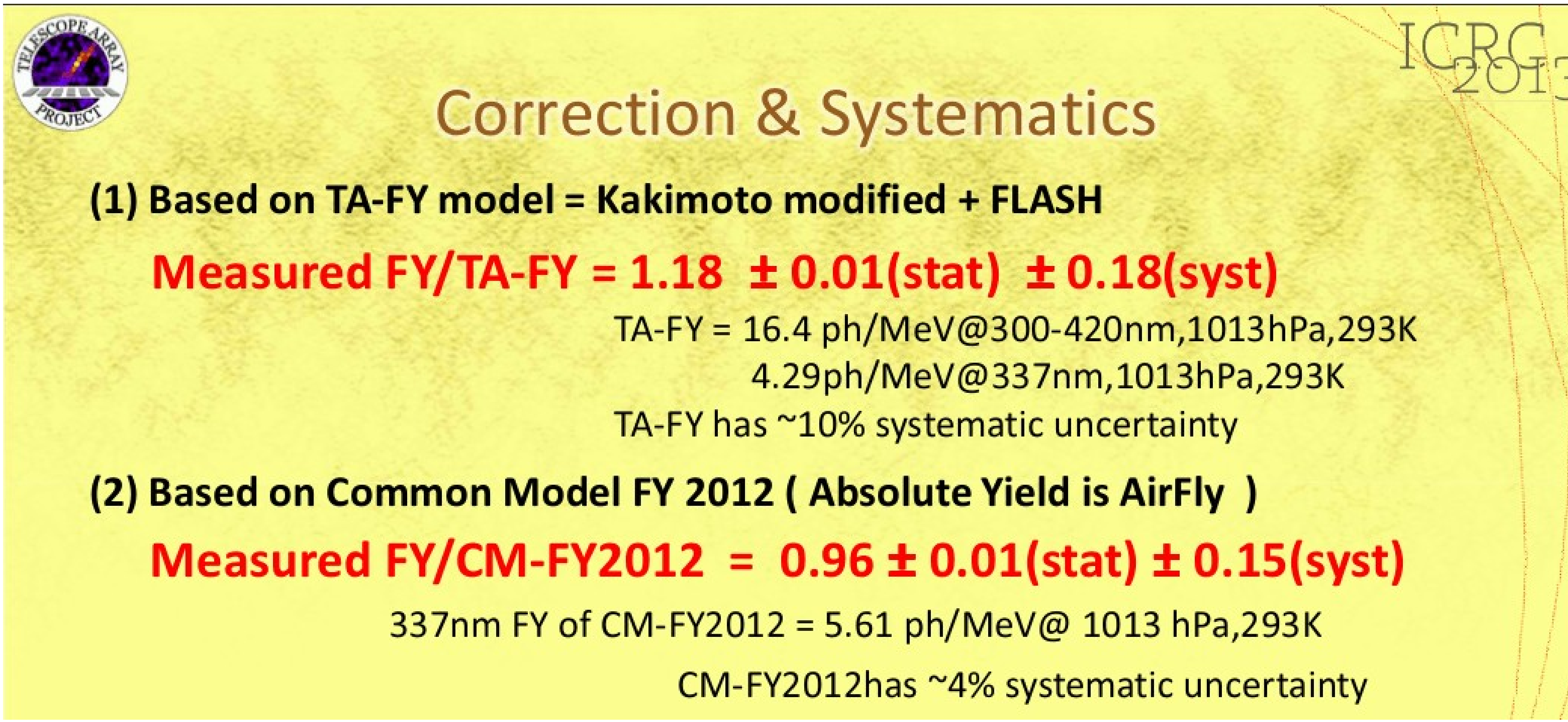


ELS is located at **100m** far from FD

Item	systematic error of FD
Fluorescence Yield	11 %
Detector	10 %
Atmosphere	11 %
Reconstruction	10 %
Total Systematic Error	21 %

Known beam energy and current = We can **calculate energy deposit** in the air
We can calibrate all of FD calibration constant = **End-to-End Calibration**

Telescope Array linac comparison



Tatsunobu Shibata
Institute for Cosmic Ray, University of Tokyo

Air Microwave technique

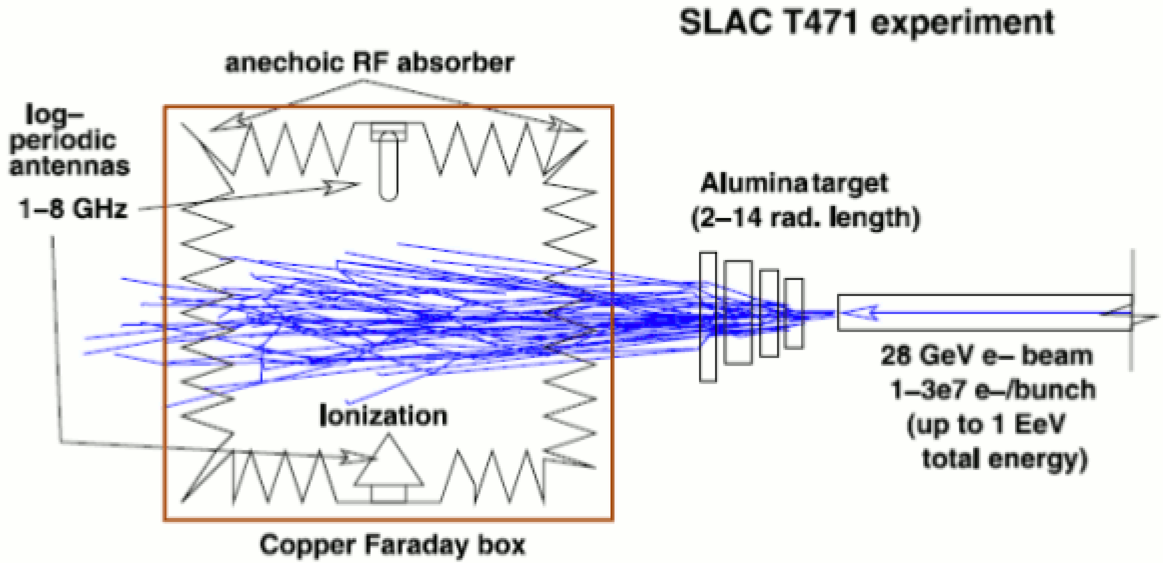
- fluorescence technique have been mastered
- low UHECR flux calls for an improved duty cycle
- detection of showers in another range - e.g. GHz region would not be affected by weather or daylight - much increased duty cycle

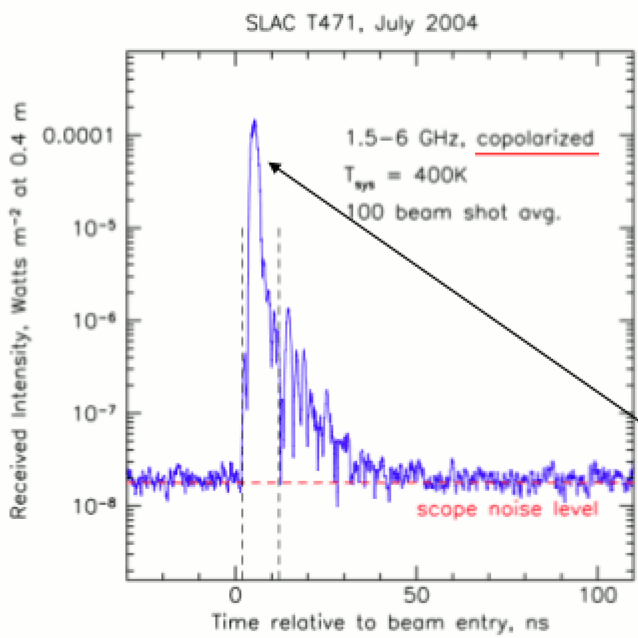
proposed mechanism: Molecular Bremsstrahlung Emission (MBR)

- EAS particles dissipate energy through ionization
- Produces plasma with $T_e \sim 10^4$-10^5K
- Low energy tail of free electrons produce Bremsstrahlung emission in microwave regime from scattering interactions with neutral air molecules
- Trace number of shower particles as in FD
- Emission is unpolarized and isotropic

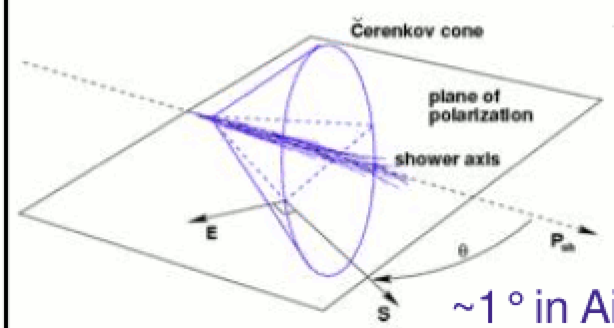
Potential exists for an FD-like detection technique capable of measuring the shower's longitudinal development with nearly 100% duty cycle, limited atmospheric effects and low cost (ability to cover large area)

Previous Beam Measurements





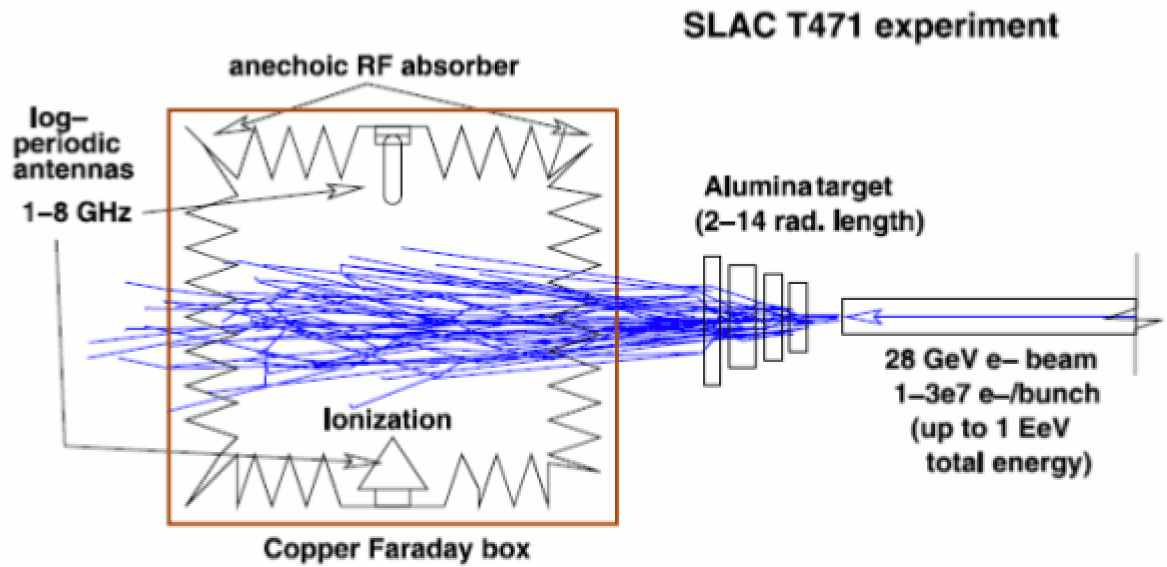
Dense bunch of high energy electrons emit coherently and polarized away from beam axis



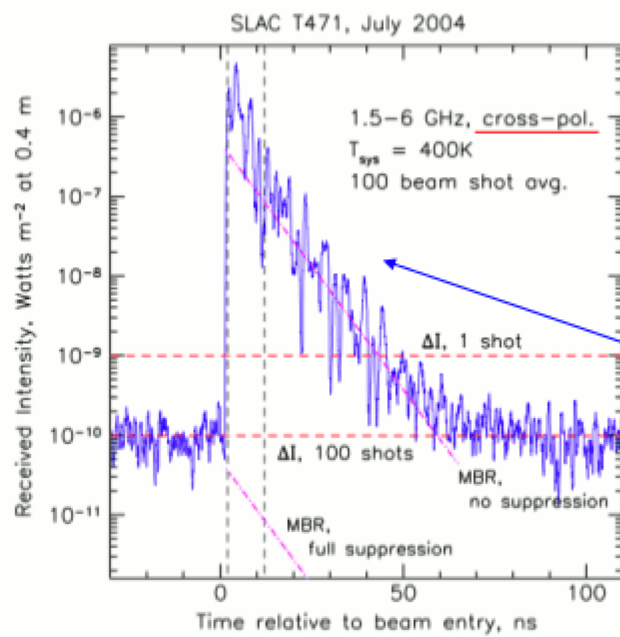
Prompt emission likely Cherenkov signal or Transition radiation at chamber entrance

P.W. Gorham *et al.,* "Observations of microwave continuum emission from air shower plasmas", Phys. Rev .D. **78**, 032007 (2008)

Previous Beam Measurements



Cross polarized orientation should be insensitive to Cherenkov if chamber well shielded



10 ns decay constant, compatible with plasma cooling.

P.W. Gorham *et al.*, “Observations of microwave continuum emission from air shower plasmas”, Phys. Rev .D. **78**, 032007 (2008)

Microwave Detection of Air showers MIDAS

- Use 4.5m dish already installed at University of Chicago
- extended C-band feeds, 1.5° field of view
- 50 channels 15° total field of view
- 100 ns resolution
- FADC acquisition with FPGA trigger

Detection threshold using Gorham et al. flux:

$E_{quad} \sim 2 \times 10^{18}$ eV

$E_{lin} \sim 10^{19}$ eV

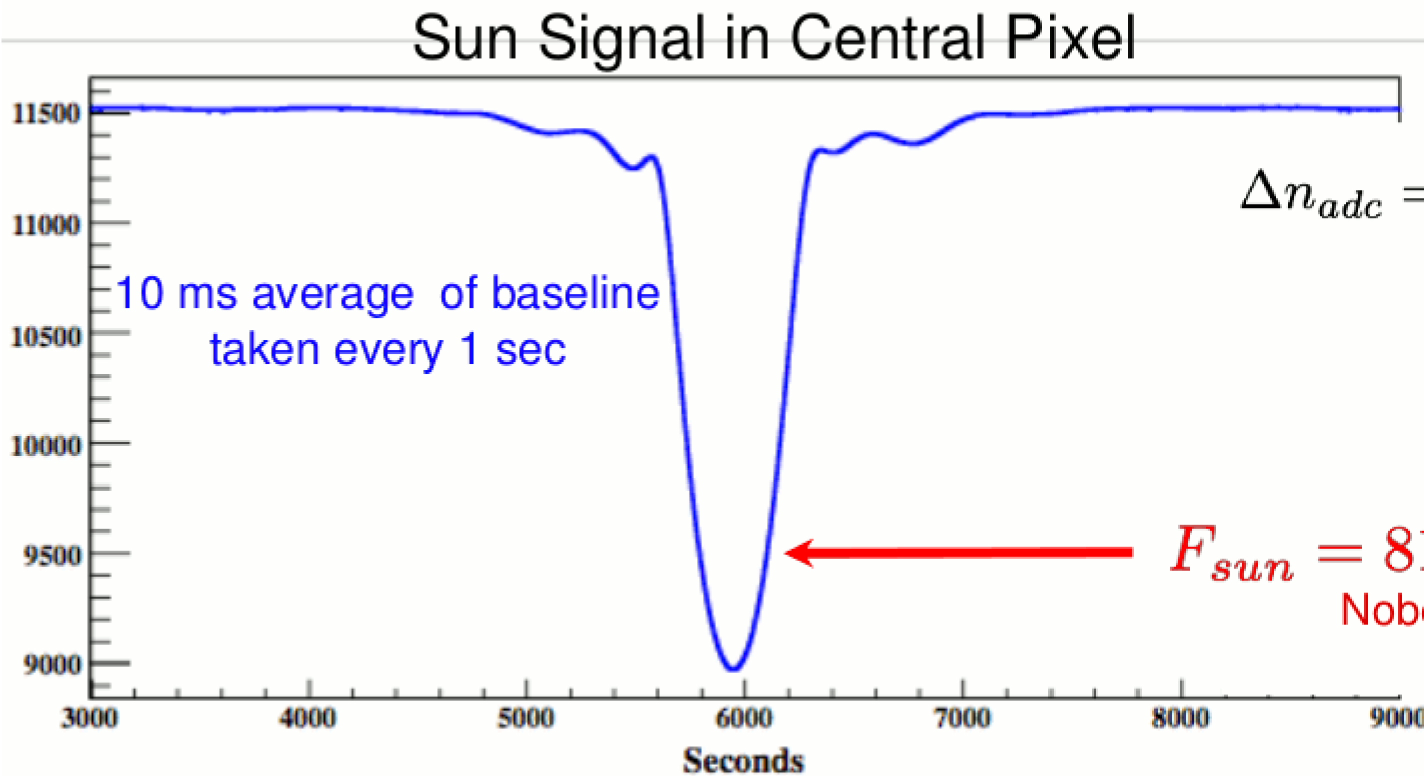
Plasma properties (density) determine level of signal coherence

Fully coherent plasma: $P_{tot}=(N_e)^2 \times P_1$

Incoherent plasma: $P_{tot}=N_e \times P_1$

MIDAS Absolute Calibration

Astrophysical sources provide a calibration of system temperature



$$\Delta n_{adc} = 10\ k\ log(1 + \frac{P_{sun}}{P_{sys}})$$

$$\Delta n_{adc} \simeq 2500$$

$$F_{sun} = 81 \times 10^{-22} W/m^2/Hz$$

Nobeyama Radio Observatory

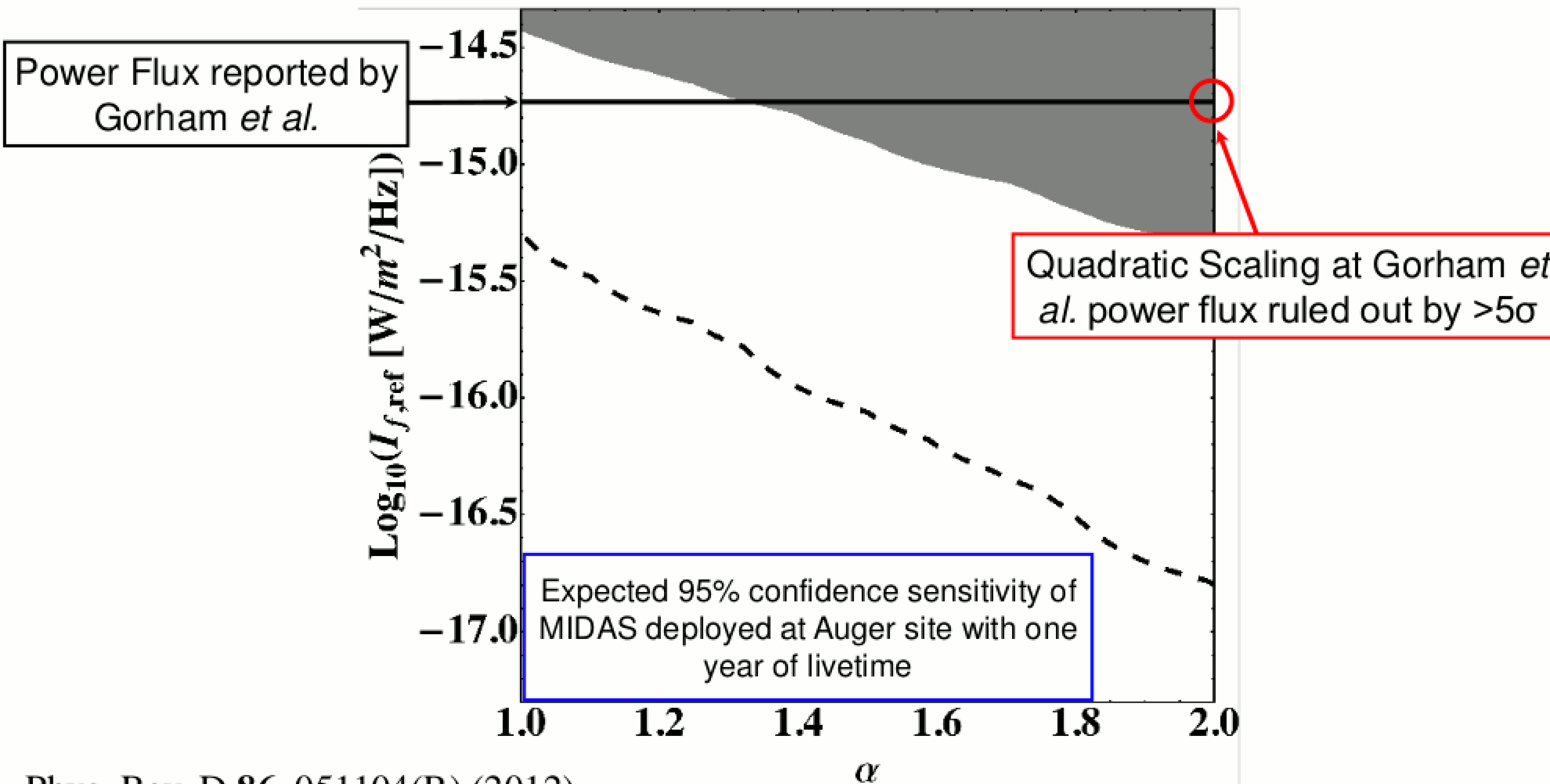
$$F_{sys} \simeq 1.5 \times 10^{-22}\ W/m^2/Hz \longrightarrow T_{sys} \simeq 65\ \mathrm{K}$$

$$F_{sys} = \frac{2k_B T_{sys}}{A_{eff}}$$

also have observed
Moon (Sun/100) and
Crab Nebula (Sun/1000)

Microwave Emission Limits

95% confidence exclusion with 5-pixel search and 61 days of livetime data from University of Chicago campus



Phys. Rev. D **86**, 051104(R) (2012)

Karlsruhe experiment
CROME

Radomír Šmída et al.

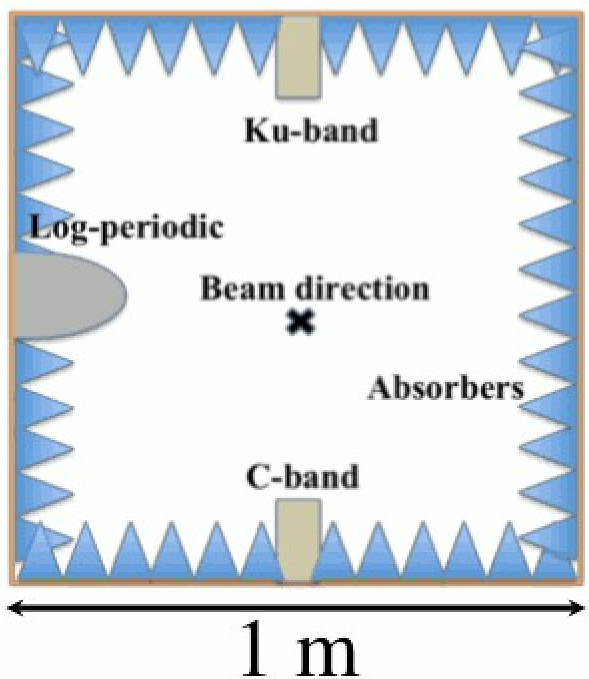
- Segmented 340 cm dish
- Prime focus with 4 receivers
- Vertical orientation
- In the middle of Kascade Grande
- Trigger from KG every 5 minutes

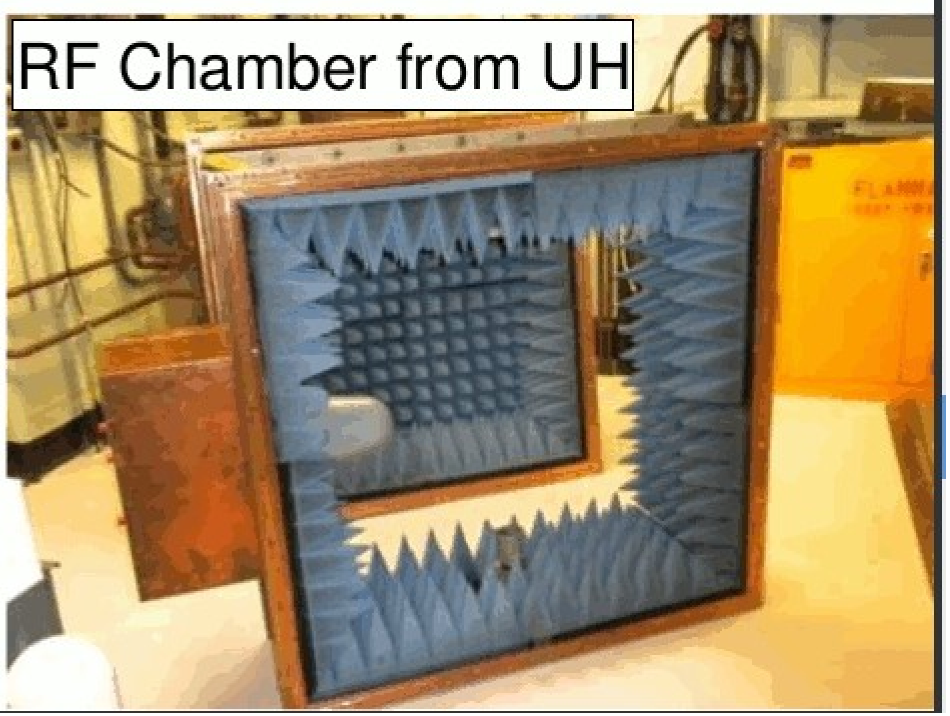
- Several events detected in coincidence with KG
- All compatible with coherent Čerenkov emission
- no isotropic emission observed

MAYBE

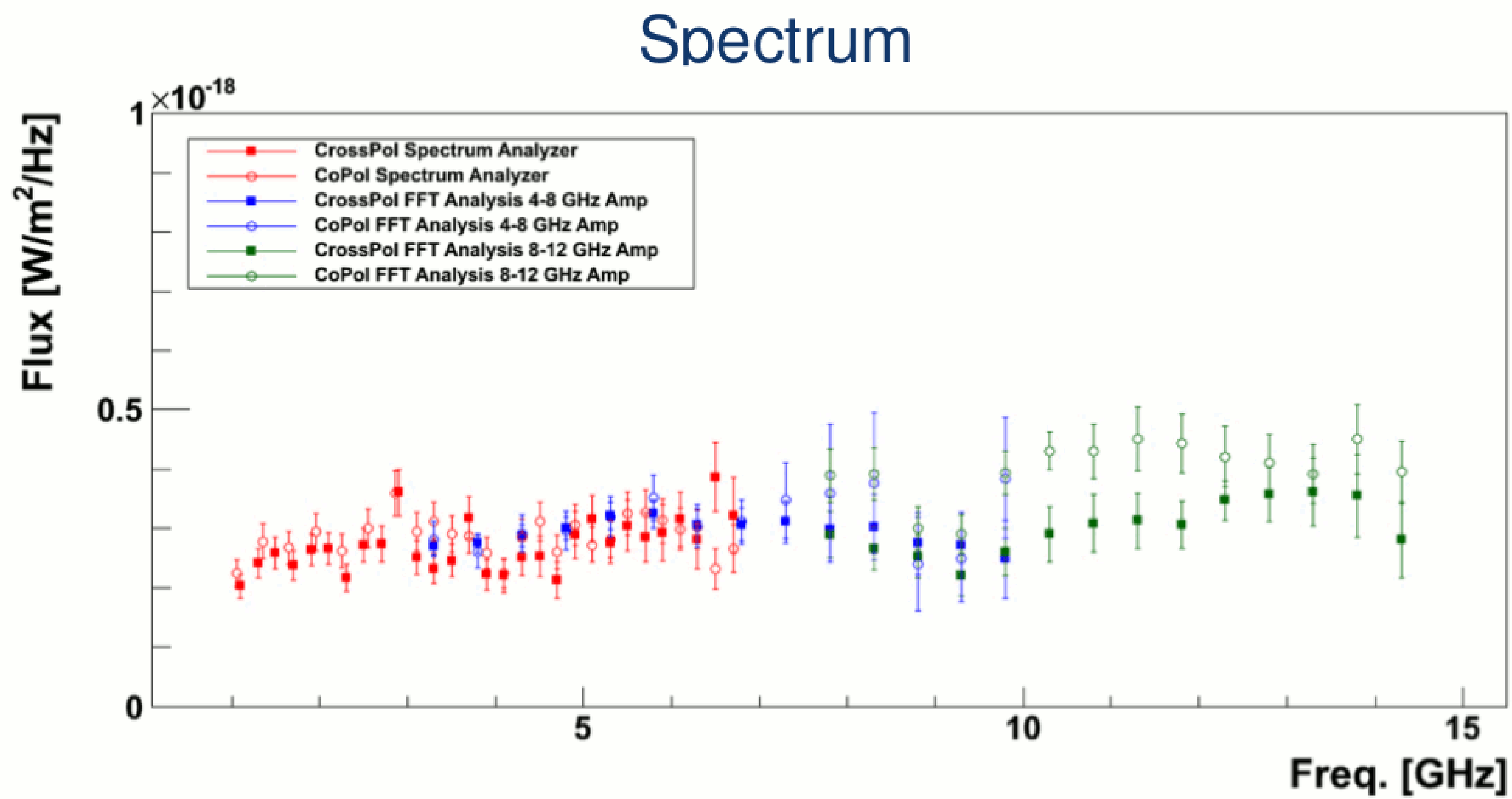
- m3 RF anechoic chamber, Absorber atten. >30 dB above 1 GHz
- Instrumented with three feed horns
- Main Receiver 850 MHz to 26.5 GHz R&S Log Periodic Antenna
- Both Pols accessible through physical rotation of antenna
- 3 Miteq low noise amplifiers and low loss coax cable
- Amplifiers operate well outside stated frequency range

- 3 MeV Van de Graaff at Argonne National Lab, Chemistry Division
- Electrons below Cerenkov threshold
- Pulse length 5 ns to 1 ms
- 1 μs pulse for most data taking





MAYBE



- Emission is unpolarized with a flat spectrum from 1 to 15 GHz
- Consistent with expectations for Molecular Bremsstrahlung emission
- Linear scaling with energy observed

- Several orders of magnitude lower signal than previous measurements

- Possible Cerenkov contamination in Gorham et al. ?

Air Miccrowave Yield
AMY

Measurement of the MBR at the Frascati linac

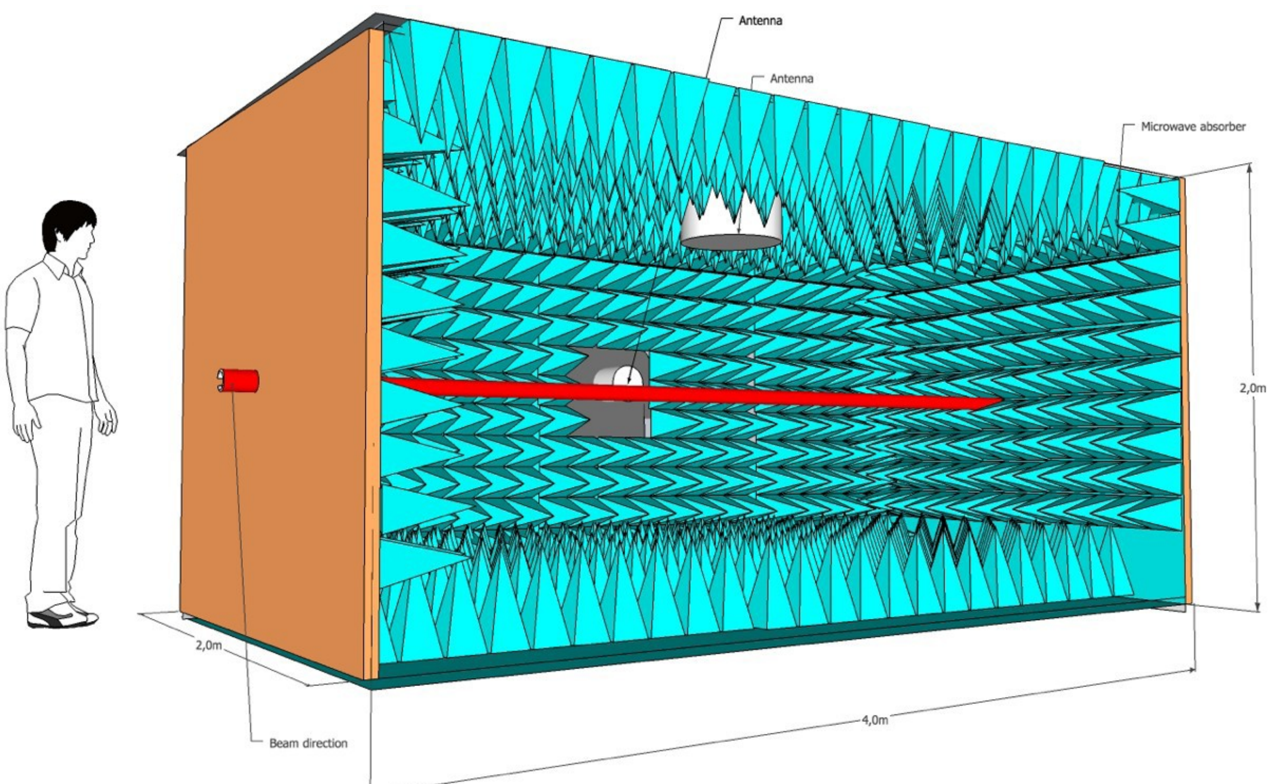
Roma ToV	C. Di Giulio, G. Rodriguez, G. Salina, V. Verzi
Lecce	G. Cataldi, M. R. Coluccia, P. Creti, I. De Mitri, D. Martello, L. Perrone
Aquila	M. Iarlori, S. Petrera, V. Rizi
Genova	R. Pesce
Frascati	B. Buonomo, L. Foggetta, G. Mazzitelli, P. Valente
Prague	M. Bohacova
Chicago	P. Facal, M. Monasor, P. Privitera, C. Williams
Santiago	J. A. Muniz, D. Garcia-Fernandez
Madrid	J. R. Vazquez
Granada	I.C. Maris
IPNO	F. Salamida
LPNHE	M. Blanco, R. Gaior, A. Letessier-Selvon, M. Settimo
LPSC	K. Louedec, S. Le Coz

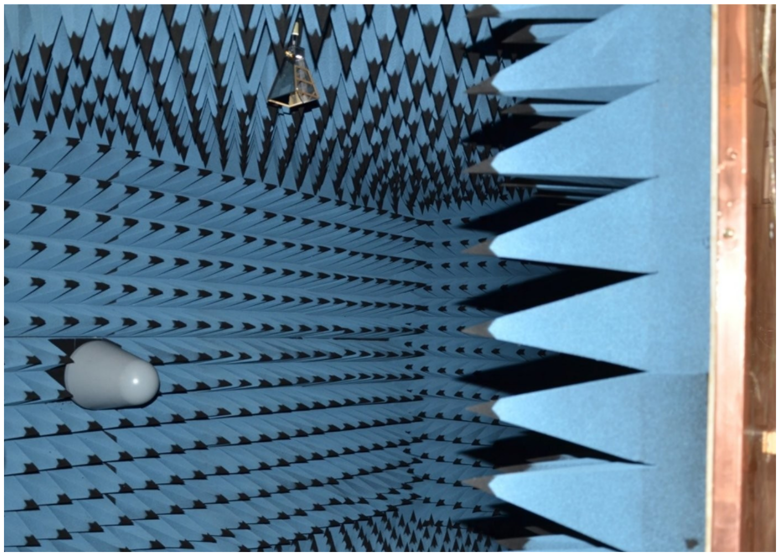
Air Miccrowave Yield
AMY

Measurement of the MBR at the Frascati linac

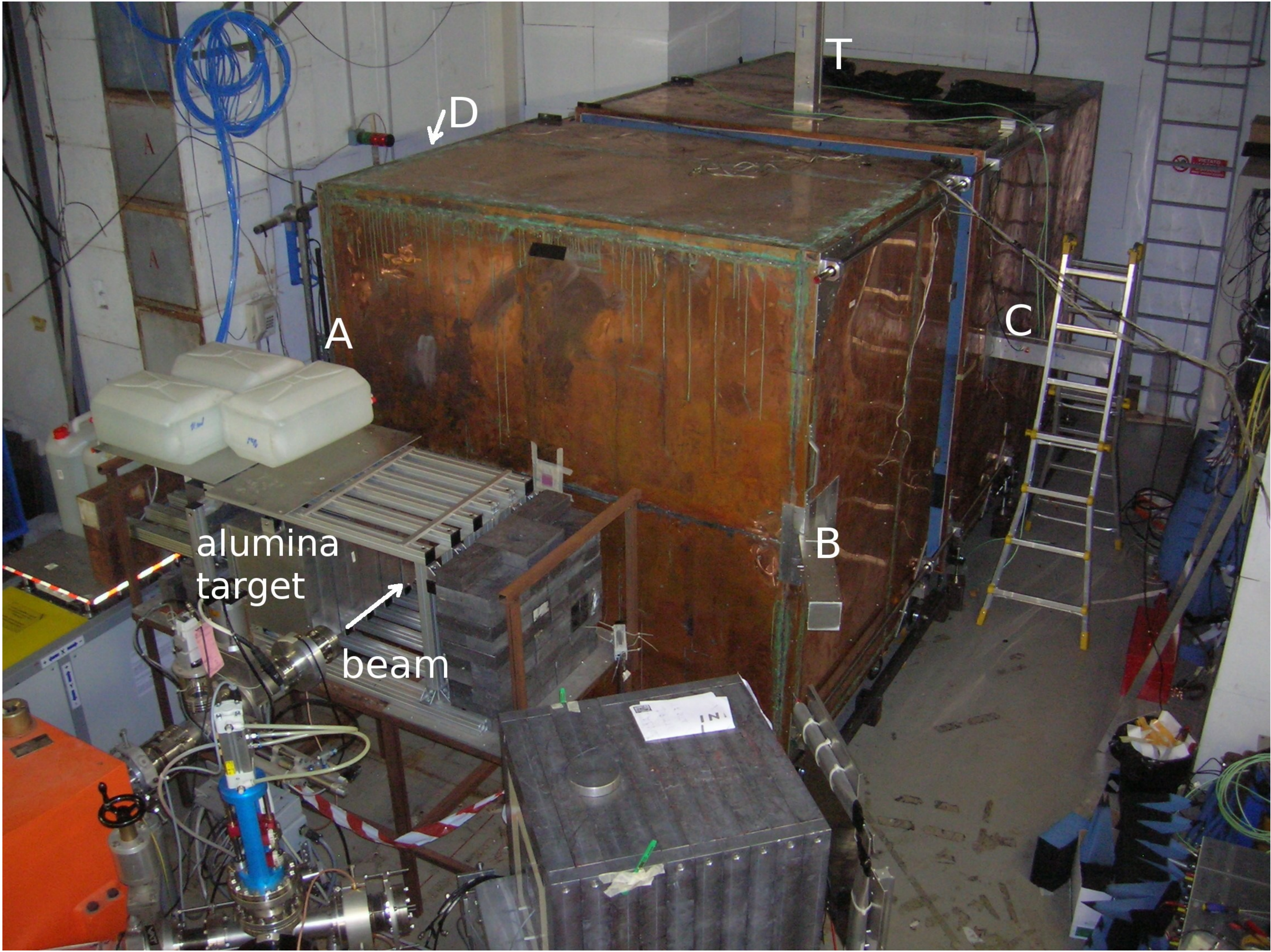
- 510 MeV electrons
- up to 1010 e-/bunch
- 10ns, 3ns, 1.5ns bunches
- 1Hz repetition rate
- LINAC frequency 2.856 GHz

- anechoic Faradaychamber 2m x 2m x 4m
- copper walls
- microwave absorber lining





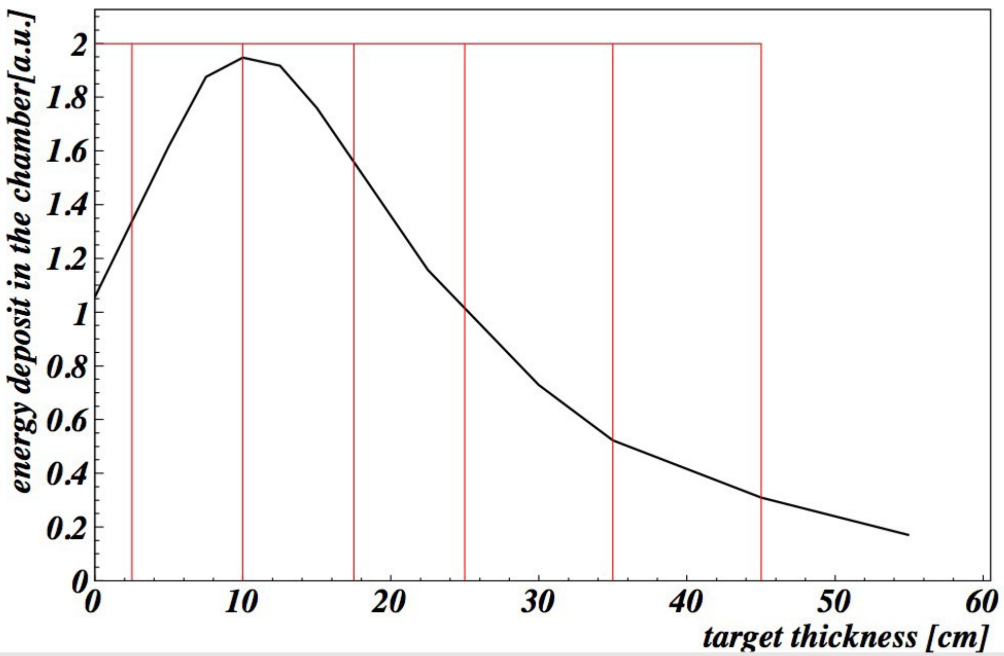
M. Boháčová 12. 12. 2013


T
D
A
C
B
alumina
target
beam

Air Miccrowave Yield
AMY

Interaction target

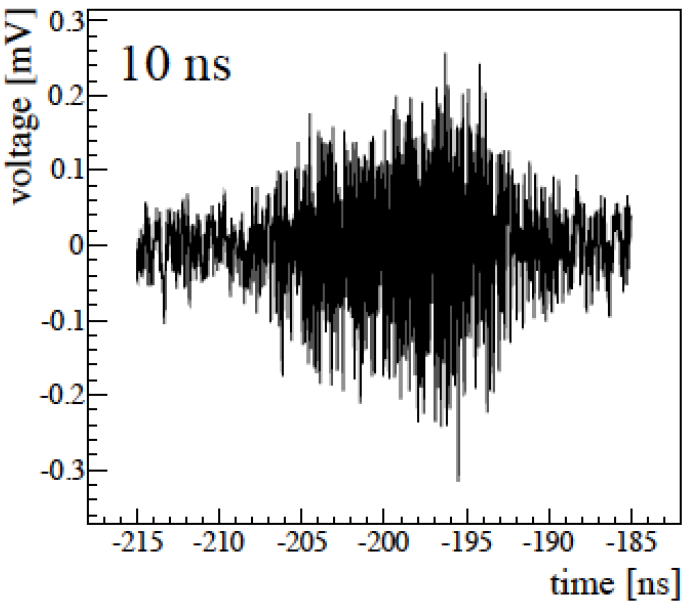
- allows to maximize energy deposit and minimize coherence
- 6 alumina modules – 95% Al_2O_3
- remotely controlled



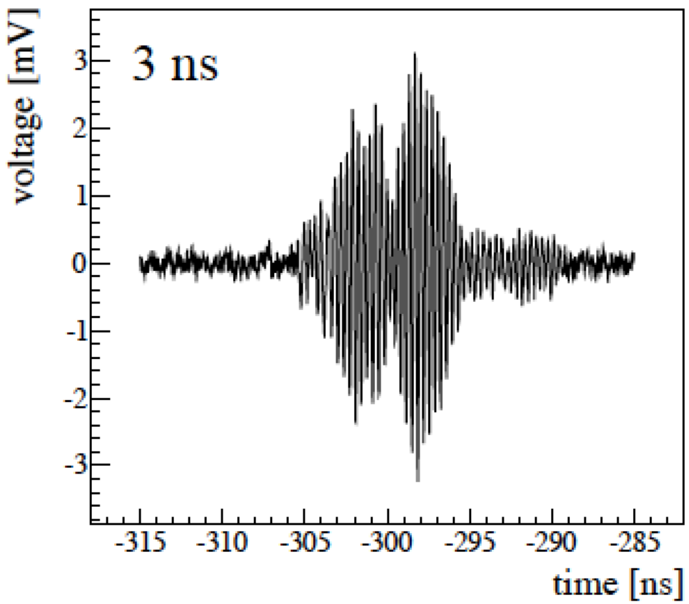
Air Miccrowave Yield
AMY
Bunch length

Oscilloscope traces

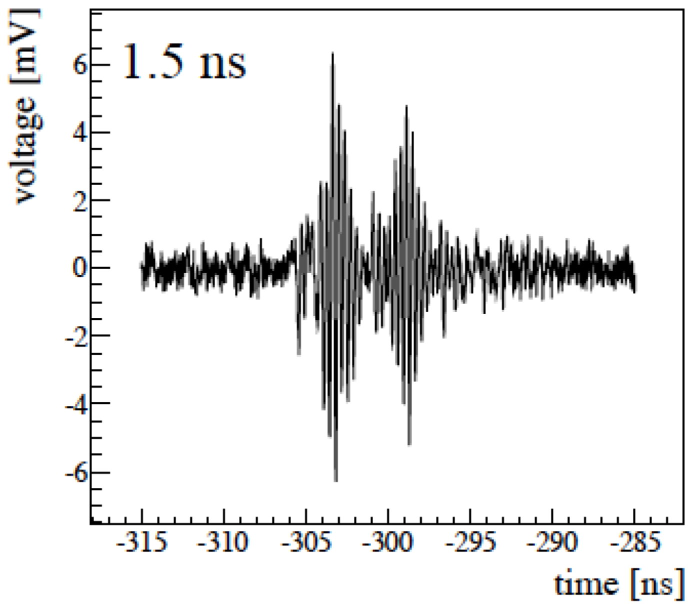
December 2011



May 2012



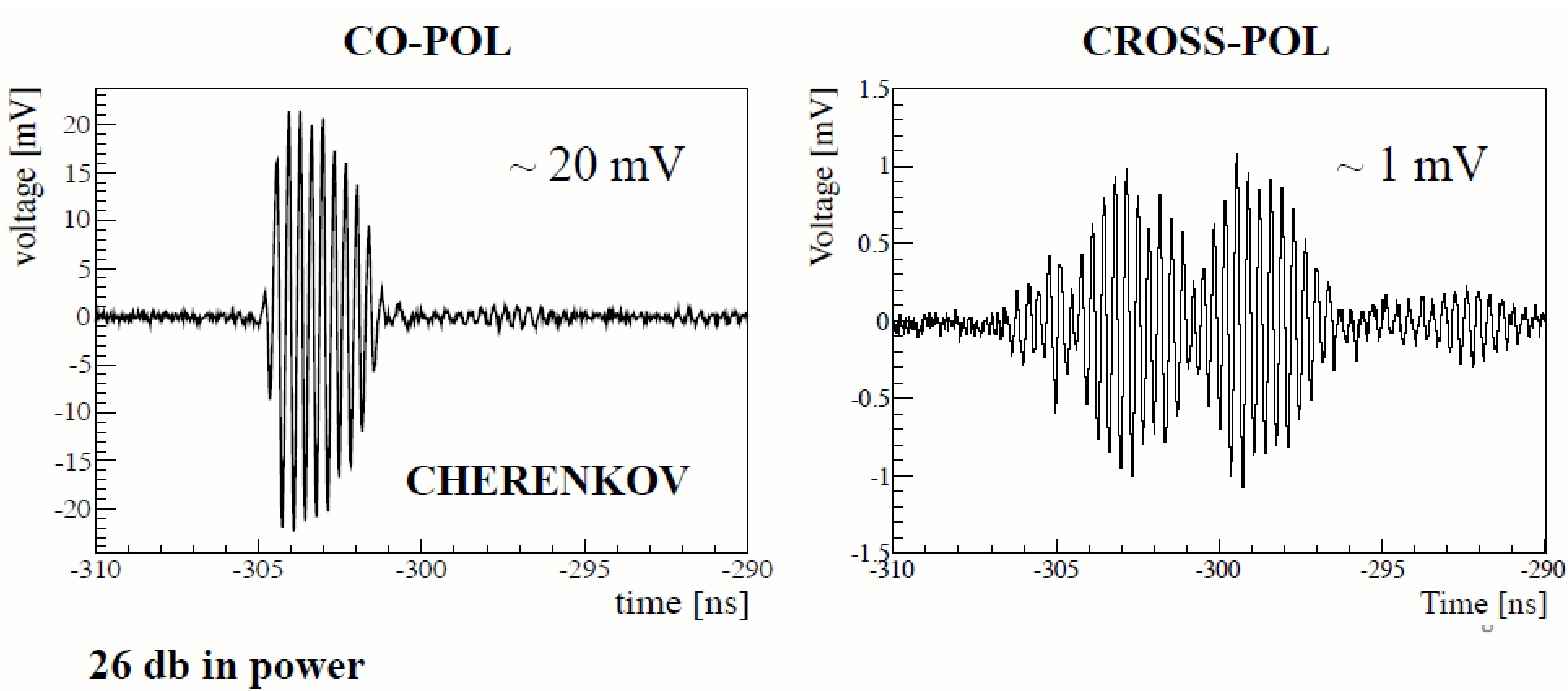
December 2012



Air Miccrowave Yield
AMY

- the Čerenkov radiation is polarized in the plane defined by the Poynting vector and the electron velocity
- antenna polarisation orthogonal to this plane (CROSS-POL) -> minimize Čerenkov
- parallel to this plane (CO_POL) -> maximize Čerenkov

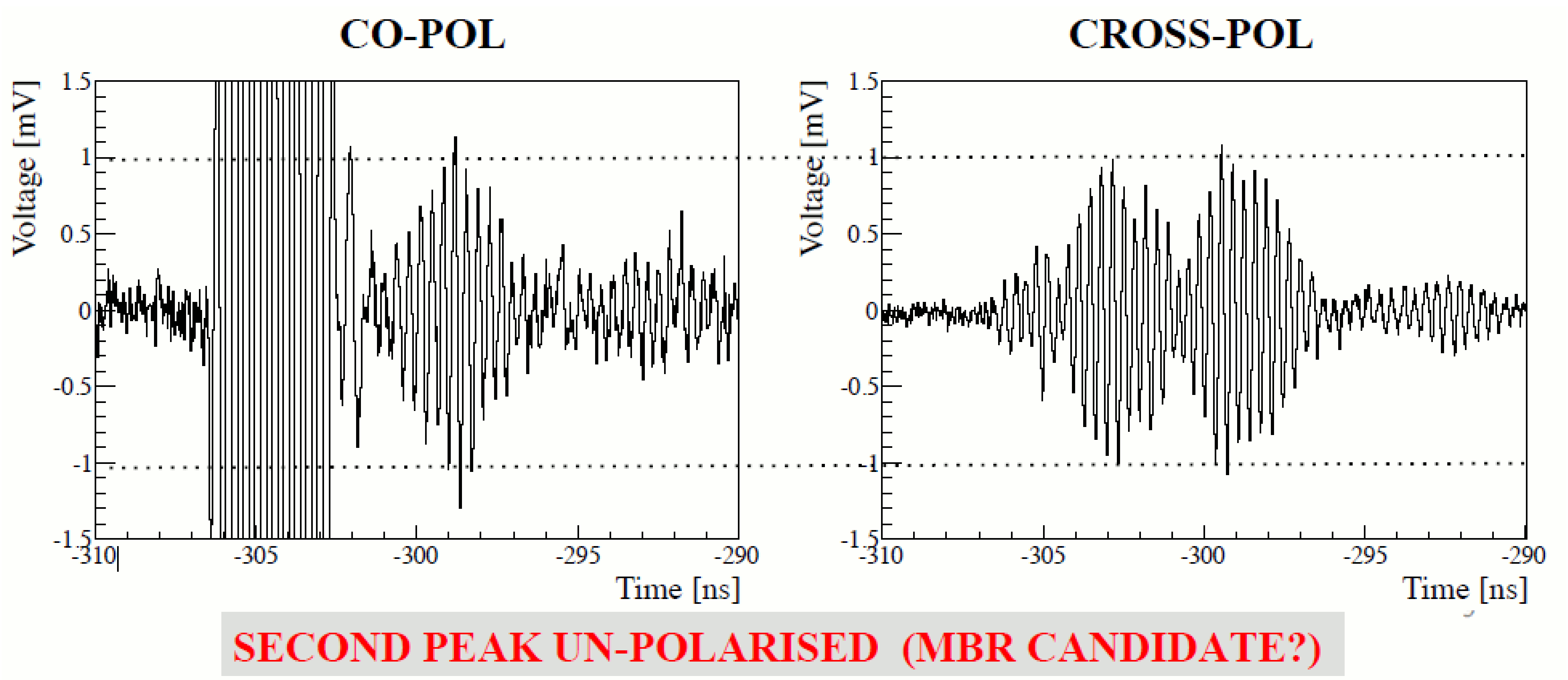
as suggested in the P.Gorham et al. paper



Air Miccrowave Yield
AMY

- the Čerenkov radiation is polarized in the plane defined by the Poynting vector and the electron velocity
- antenna polarisation orthogonal to this plane (CROSS-POL) -> minimize Čerenkov
- parallel to this plane (CO_POL) -> maximize Čerenkov

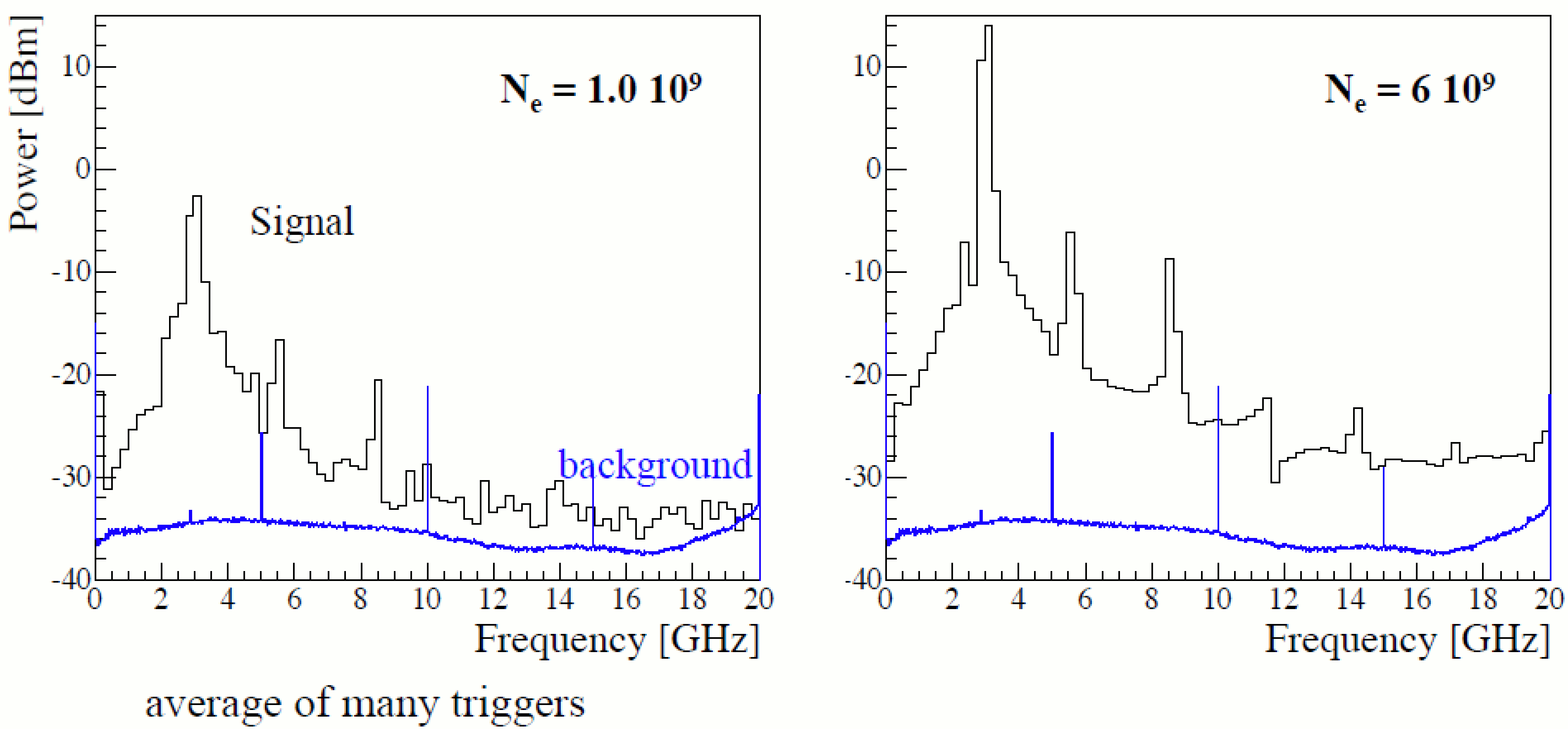
as suggested in the P.Gorham et al. paper



Air Microwave Yield
AMY

FREQUENCY SPECTRUM

FFT of the oscilloscope trace
(dominated by linac frequency and harmonics)



POWER IN DIFFERENT FREQUENCY BANDS