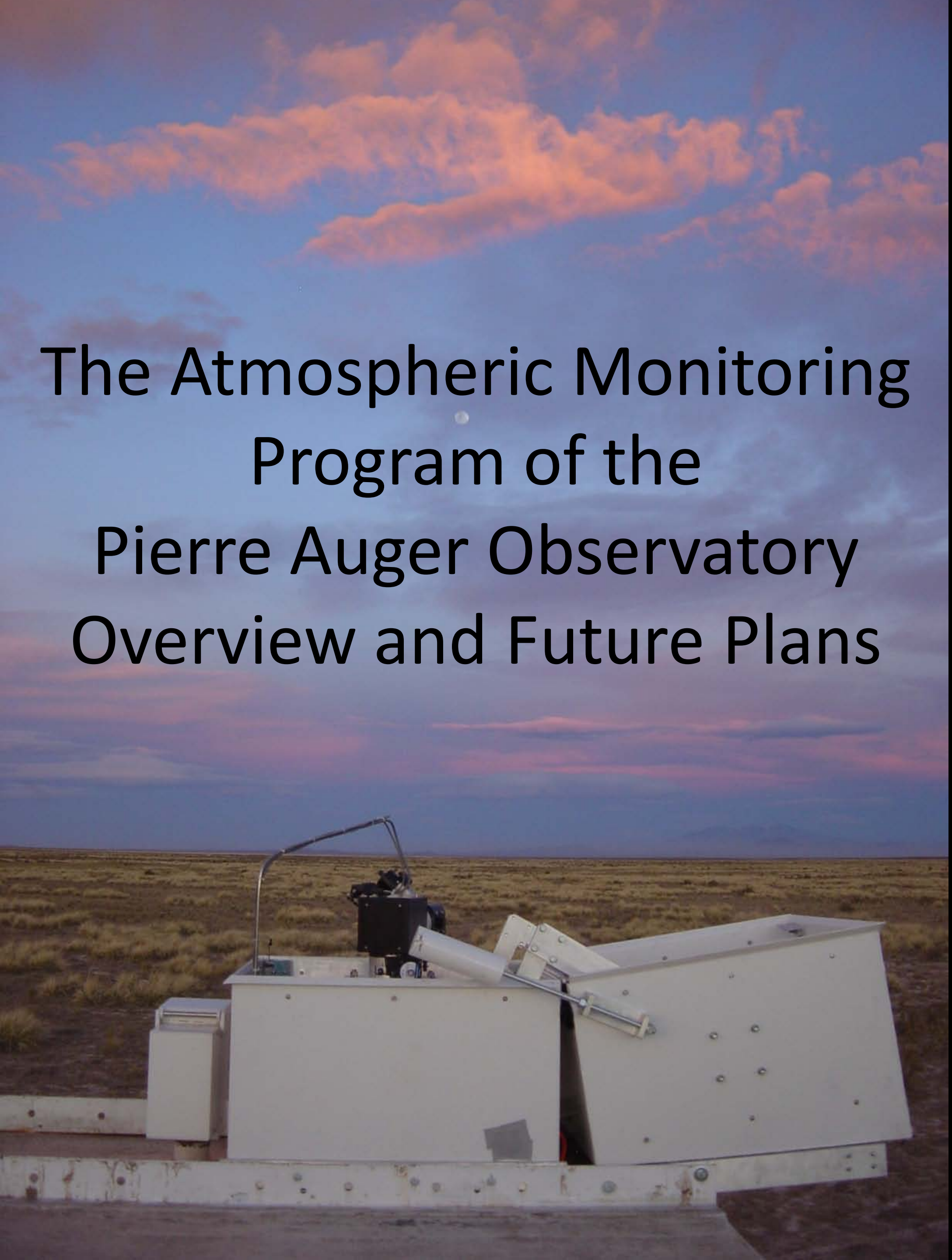
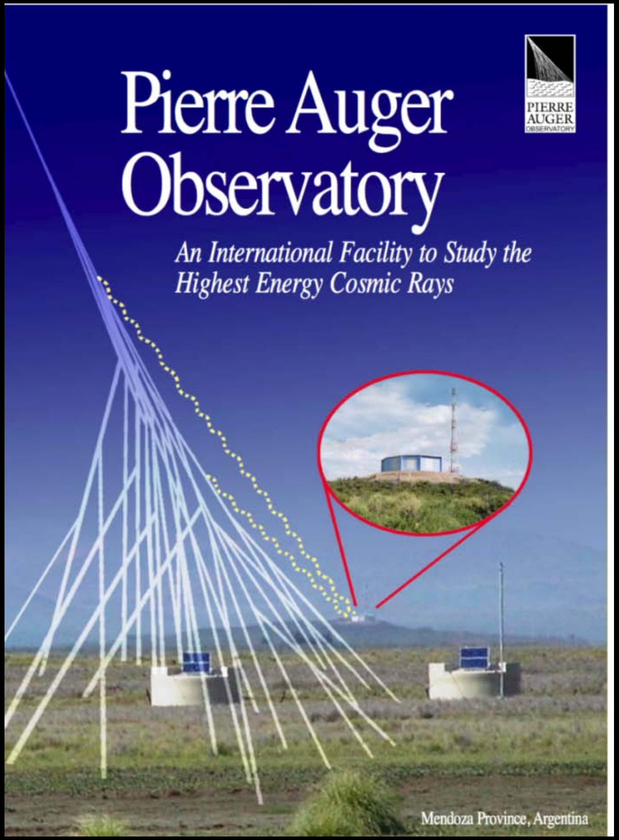
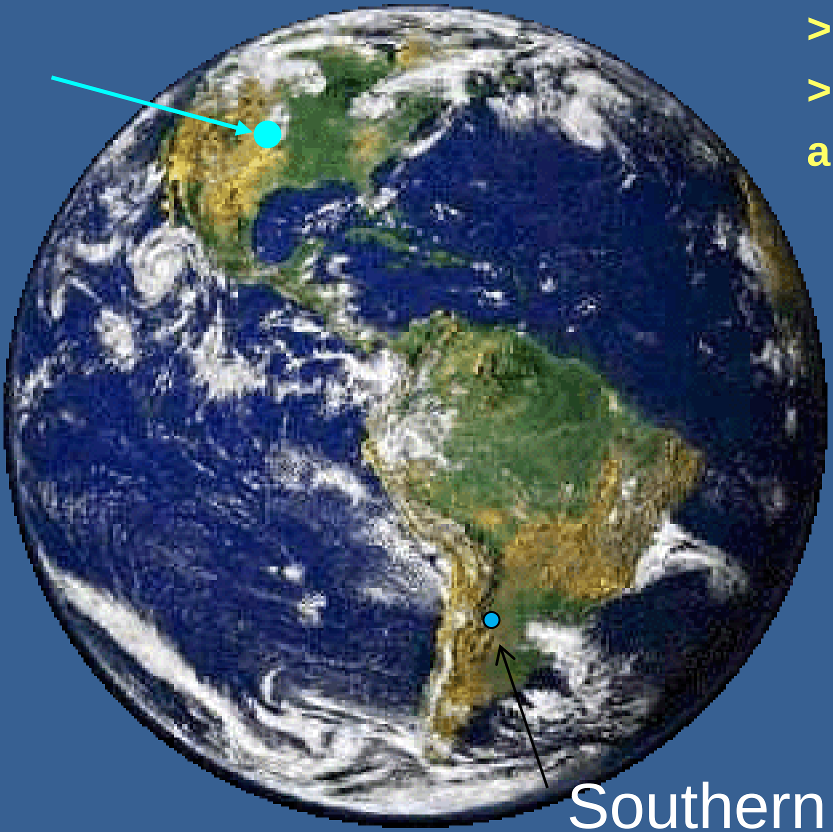
The Atmospheric Monitoring Program of the Pierre Auger Observatory Overview and Future Plans





Lawrence Wiencke
Colorado School of Mines
ATMON 2010
Madison WI Sept. 14 2010

The Pierre Auger Observatory of Ultra-High Energy Cosmic Rays



Northern site : Colorado

21000 km^2

(Planned)

> 400 PhD scientists from

> 80 Institutions

and 16 countries

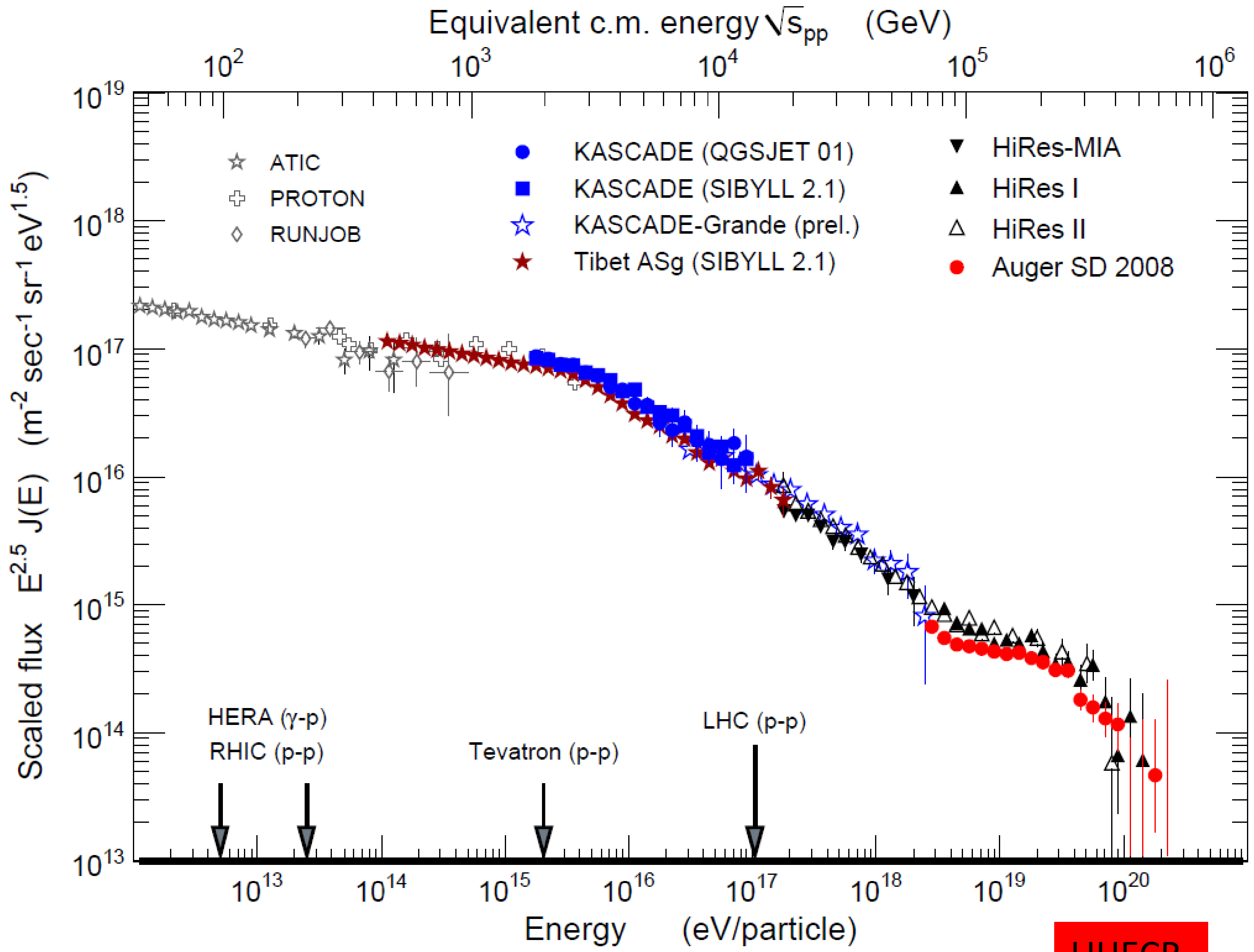
Argentina
Australia
Brazil
Bolivia*
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Slovenia
Spain
UK
USA
Vietnam*

Associate Countries

Southern site: Argentina

3000 km^2

(Operational)



TeV γ-ray

Neutrino Detectors

UHECR
(Auger)

Atmospheric Quantities used in Air Shower Detection

Light Production:

- Fluorescence production: light yield is weather-dependent

$$Y(\lambda, p, T, e)$$

- Collisional quenching N_2-N_2, O_2-O_2: $\sigma_{NN}(T)$, $\sigma_{NO}(T)$
- N_2-H_2O quenching: estimate from vapor pressure e

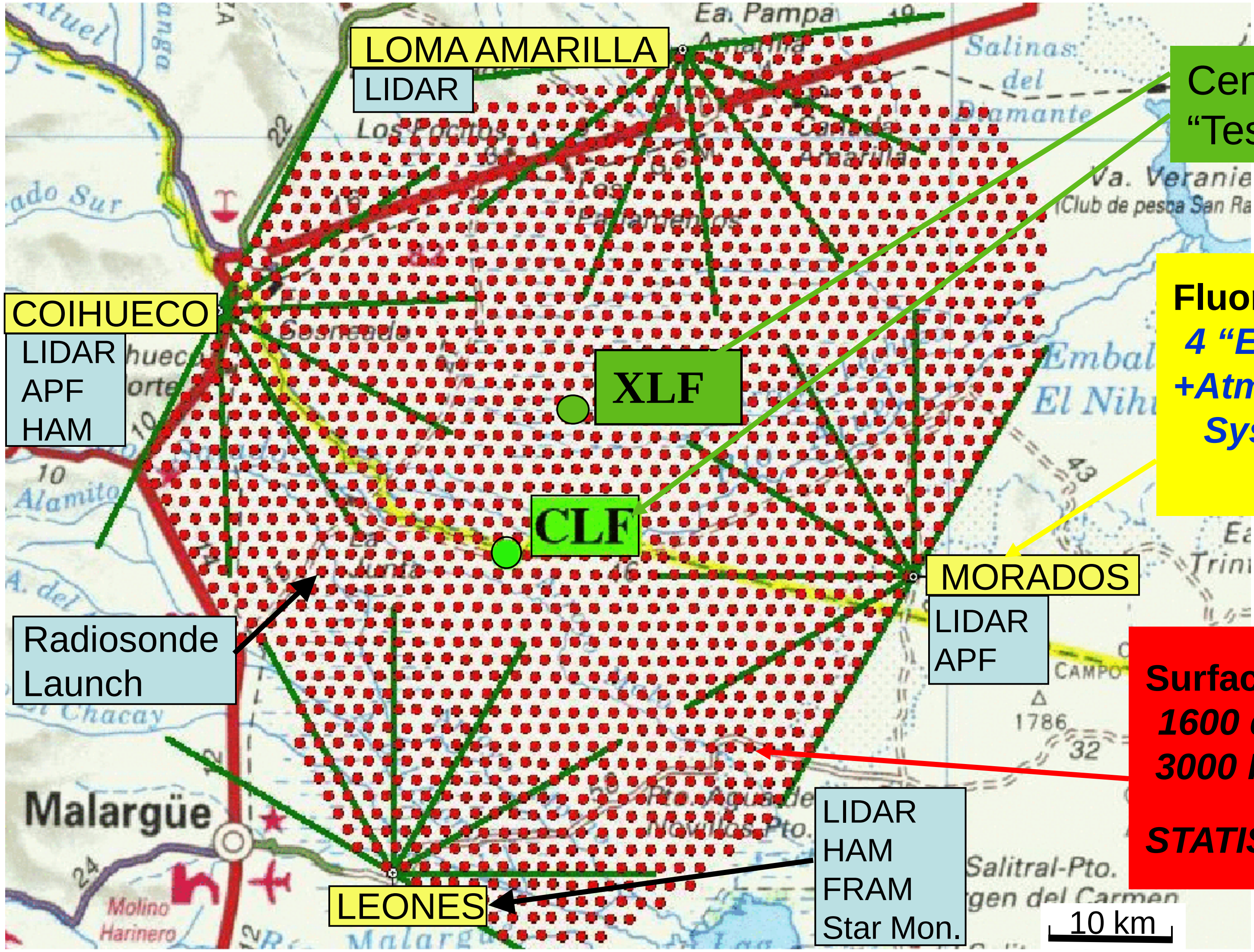
Light Transmission:

$$\mathcal{T}(\lambda, h) = e^{-(\tau_m(\lambda,h)+\tau_a(\lambda,h))/\sin\varphi}\,(1 + H.O.)$$

- τ_m = Molecular Optical Depth: from $p(h)$, $T(h)$, $e(h)$
- τ_a = Aerosol Optical Depth: field measurements with laser shots
- Clouds: measurements with lidar + infrared cameras

S. Benzvi (ICRC 2009)

Auger South: Detector Configuration



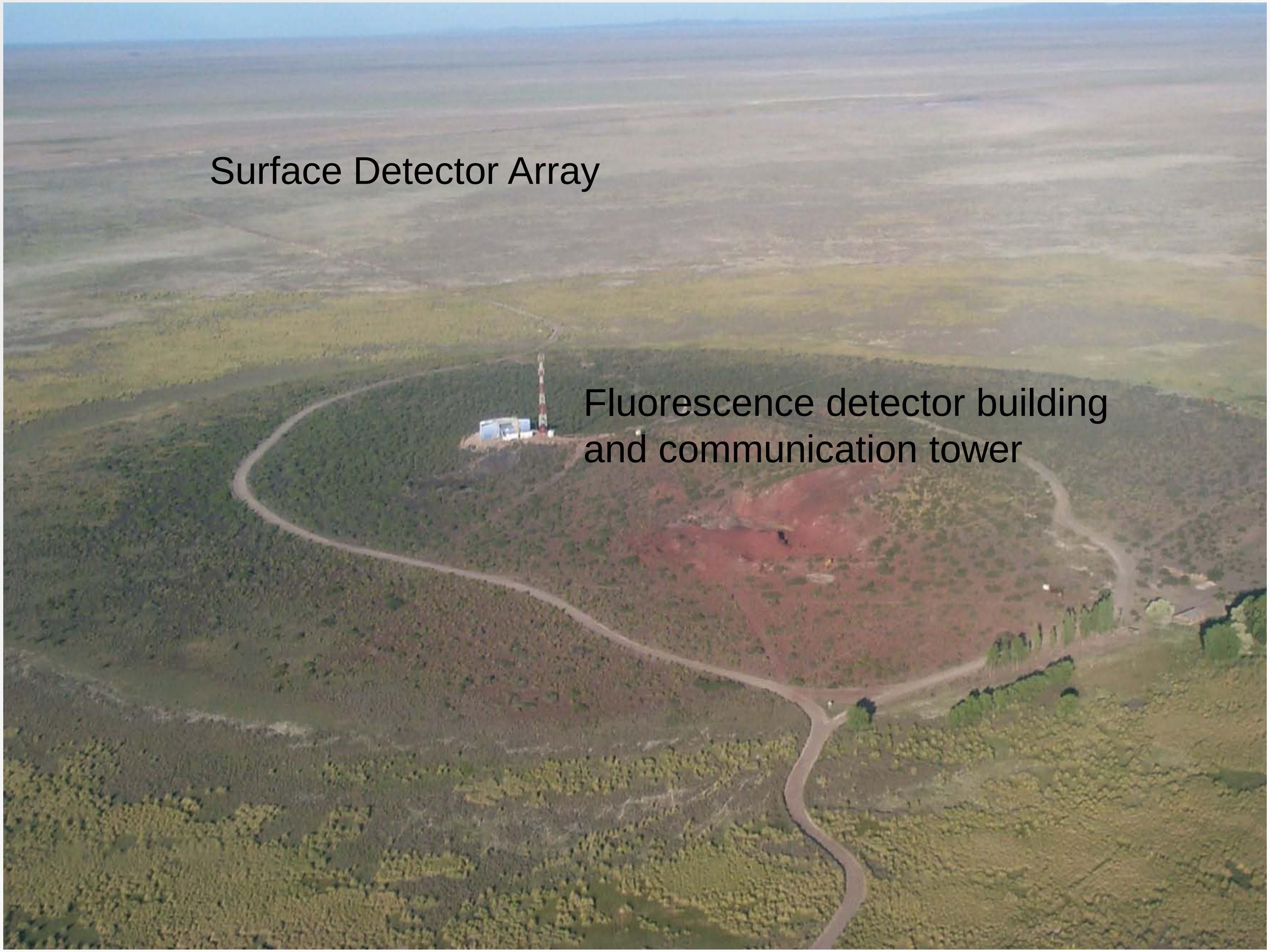
Central Laser Facilities
“Test Beams”

Fluorescence Detectors
4 “Eyes”
+Atmospheric Monitoring Systems

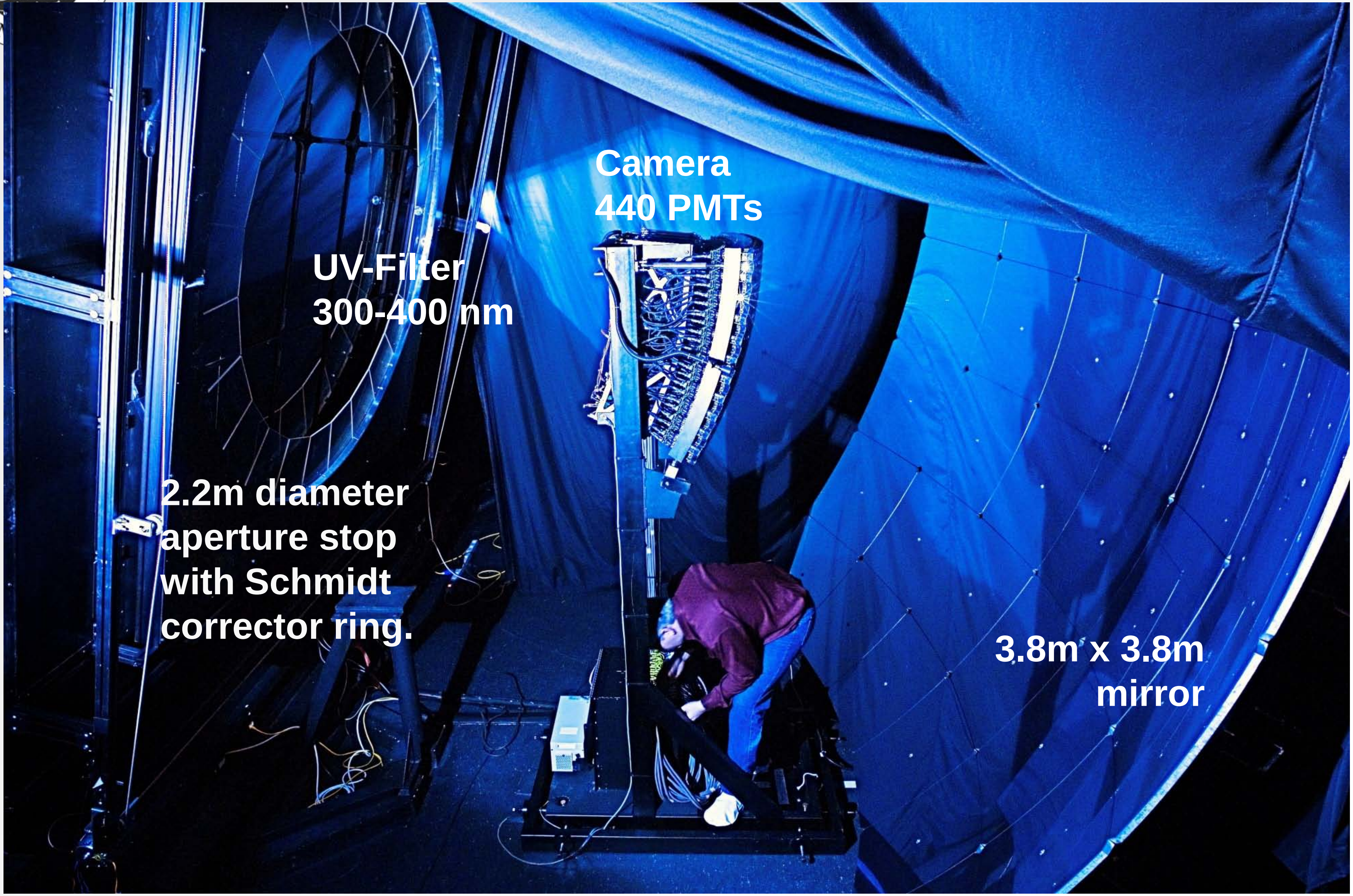
Surface Detector Array
1600 detector stations
3000 Km^2

STATISTICS ENGINE

Los Leones Site



An Air Fluorescence Telescope

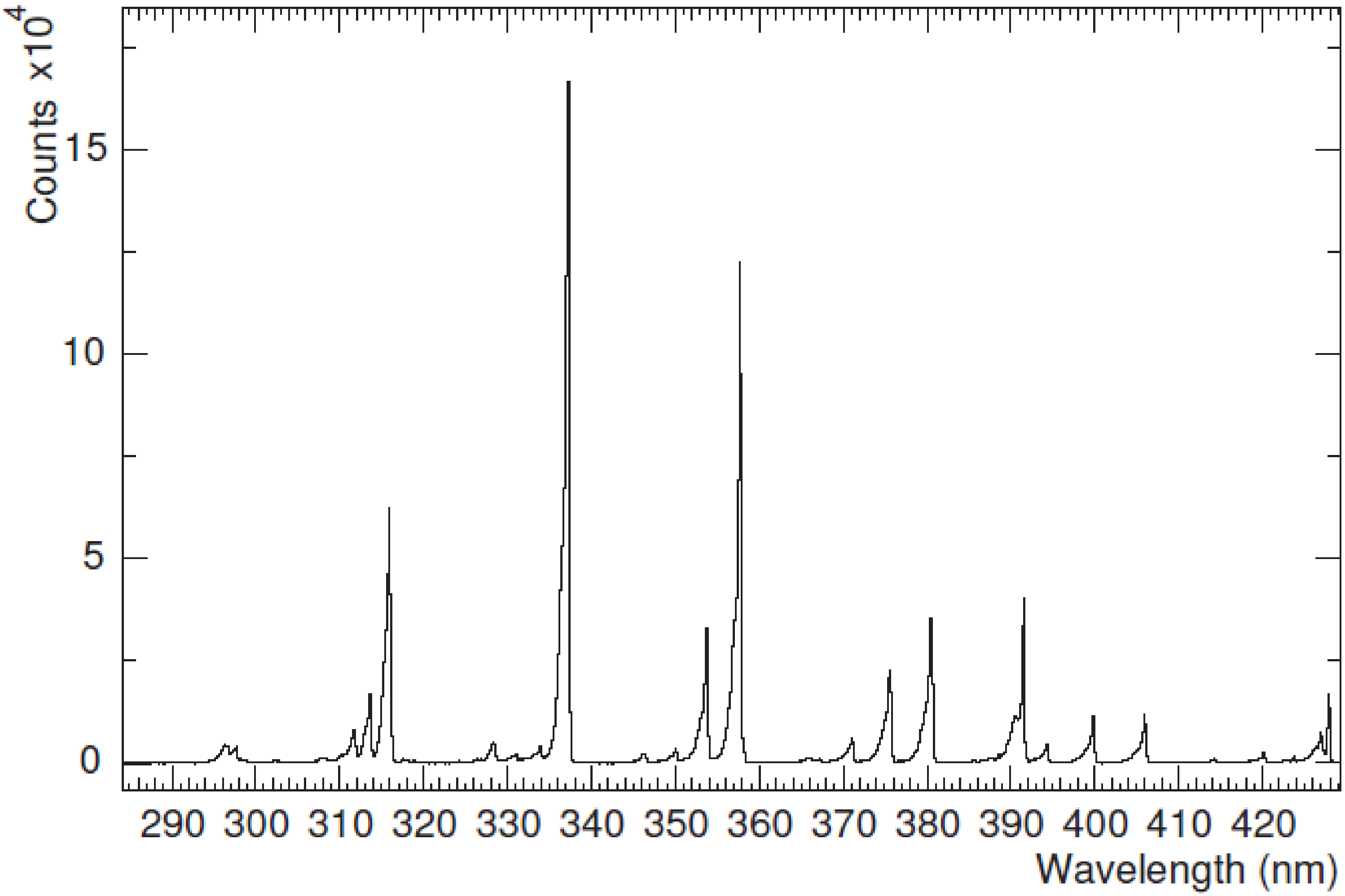


Camera
440 PMTs

UV-Filter
300-400 nm

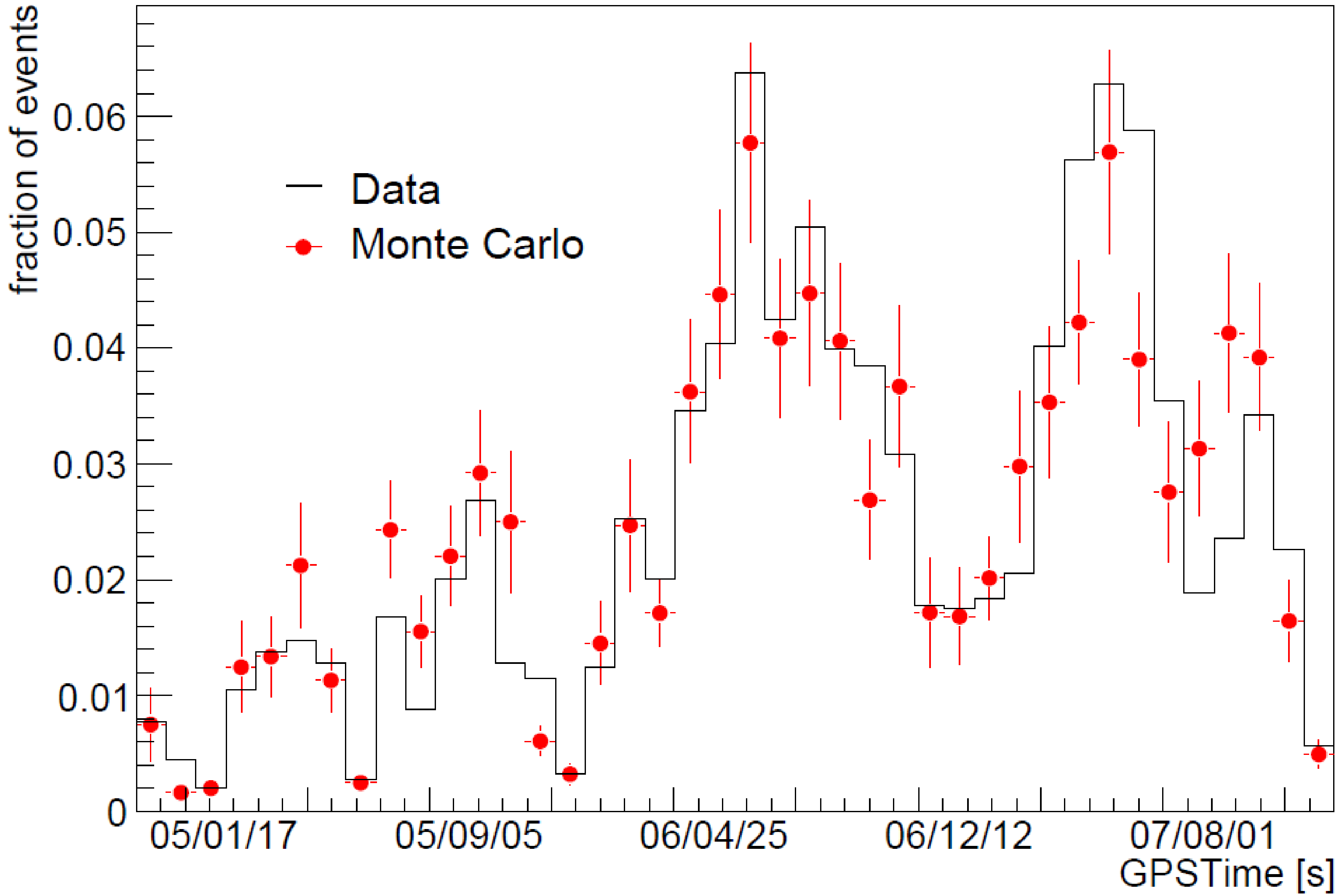
2.2m diameter
aperture stop
with Schmidt
corrector ring.

3.8m x 3.8m
mirror



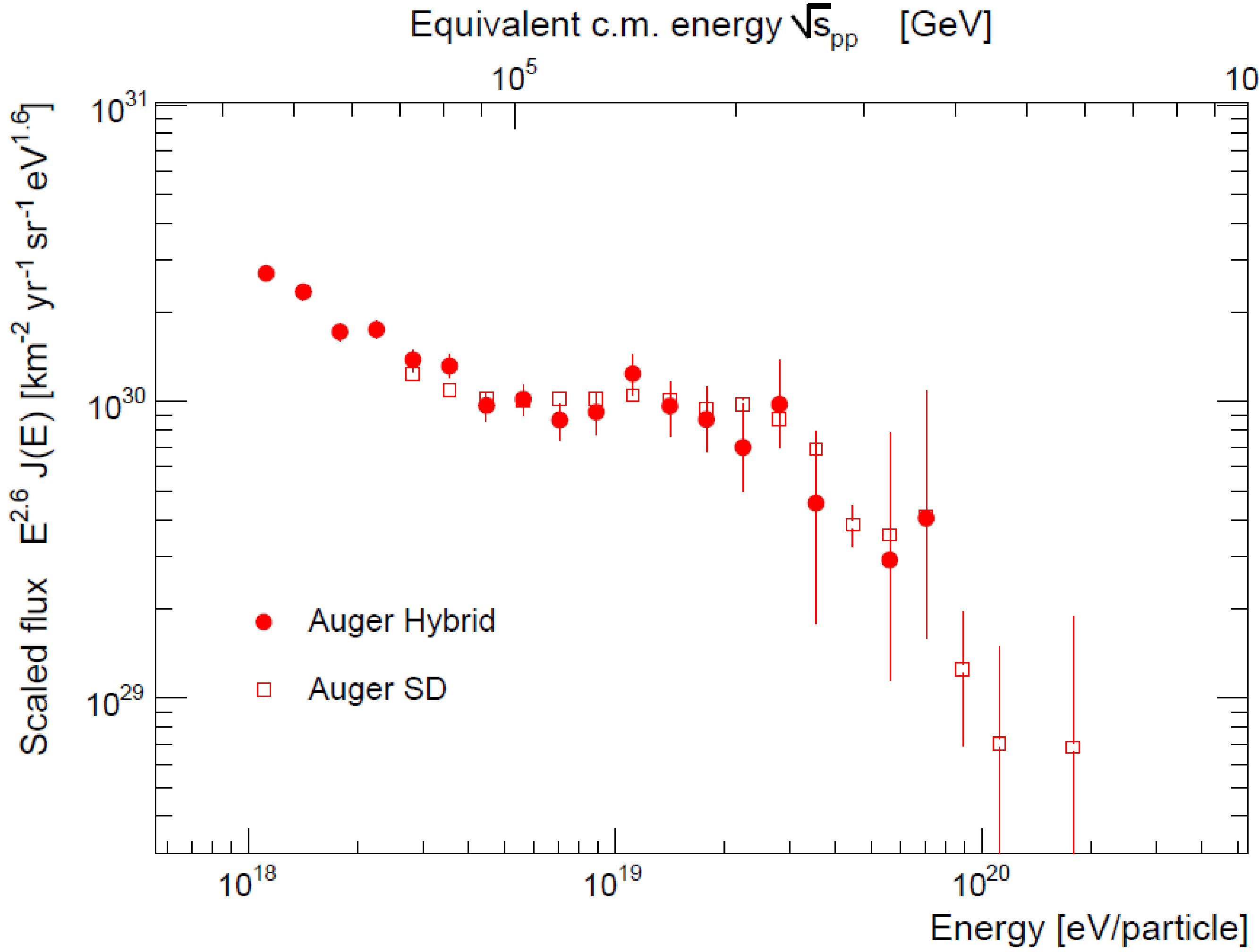
Fluorescence Spectrum (3 MeV electrons in Air at 800 hPa)

M. Ave et al. (AIRFLY) Astropart. Phys **28** 41 (2007).



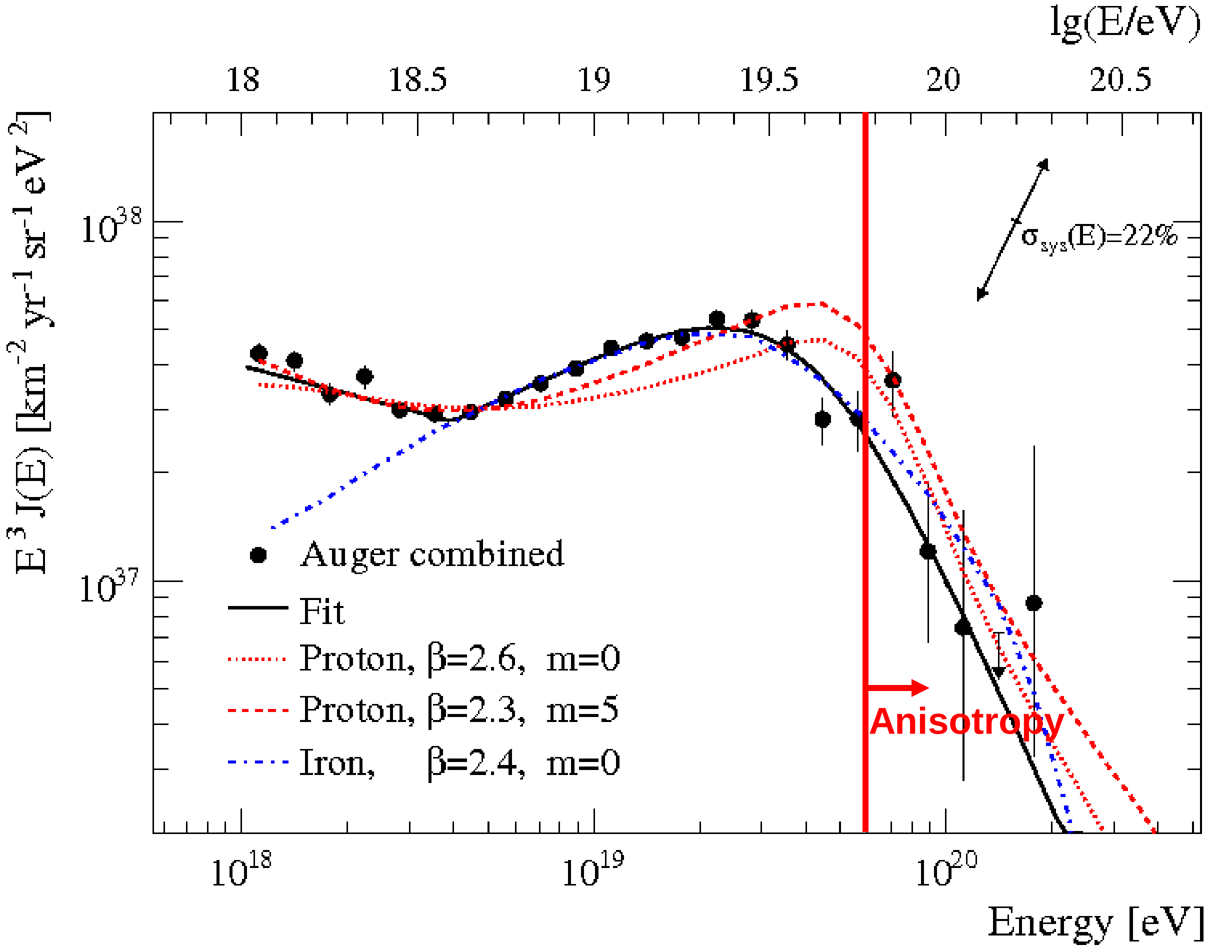
Data-Monte Carlo Comparison: fraction of hybrid events as a function of time starting from November 2005.

Hybrid Spectrum



- agreement with SD spectrum, combination possible

Cosmic Ray Energy Spectrum (Auger South)



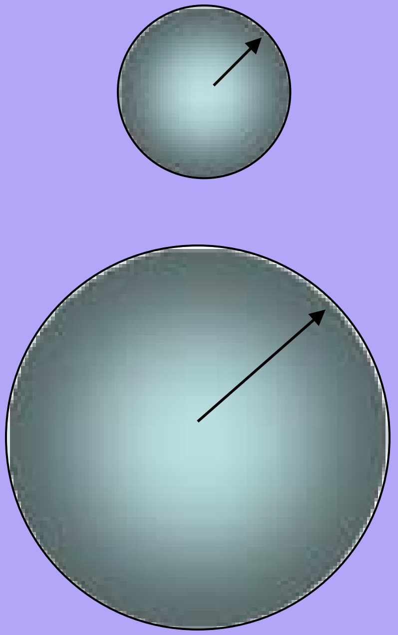
Comparison with models

Motivation for Energy Calibration

$\Delta E/E$ 25%

$\Delta V/V$ >10

(for protons in CMBR)



8×10^{19} eV
90 MPC

6×10^{19} eV
200 MPC

$\Delta E/E$ of 1% corresponds to a change in volume of ~10^6 MPC^3

Our local supercluster of galaxies occupies 10^5 MPC^3

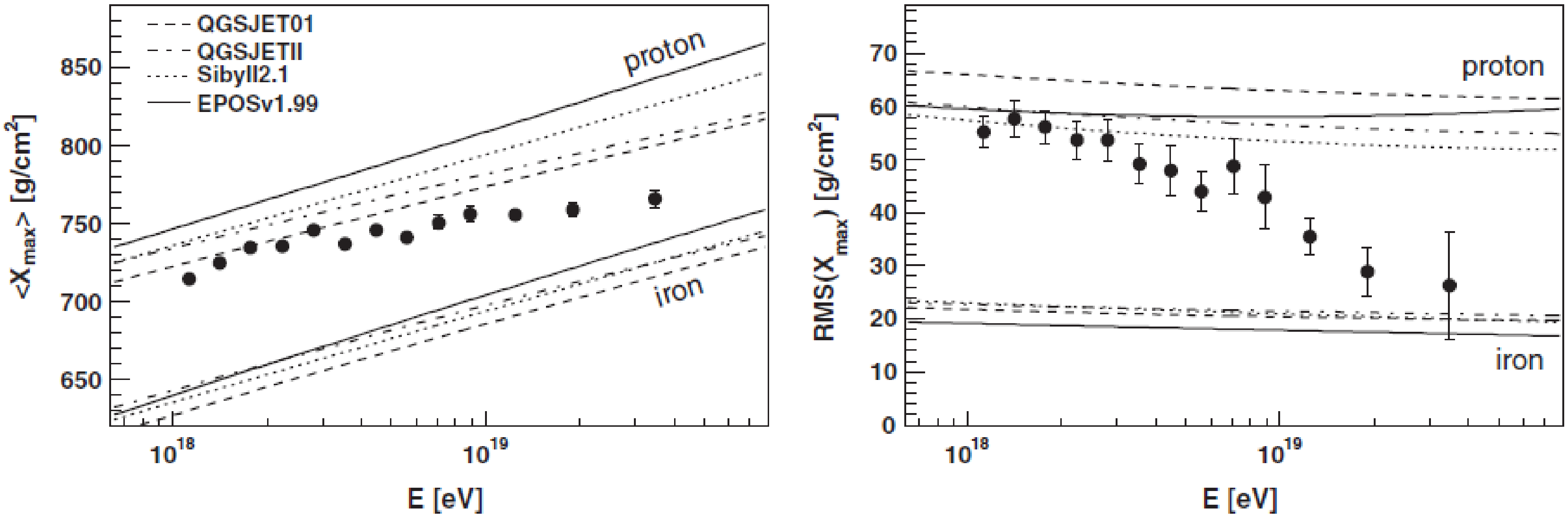
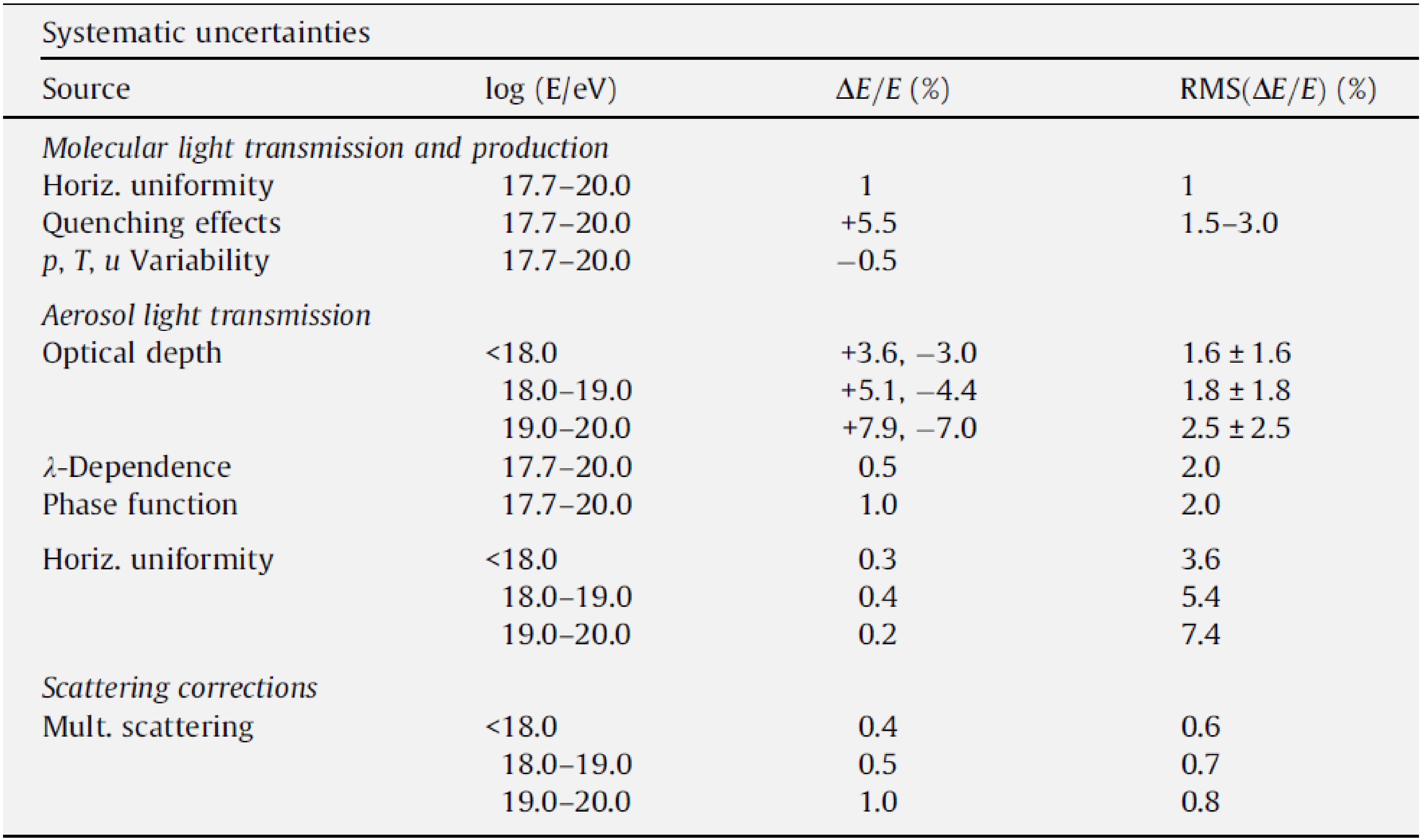


FIG. 3. $\langle X_{\max} \rangle$ and rms($X_{\max}$) compared with air shower simulations [20] using different hadronic interaction models [21].

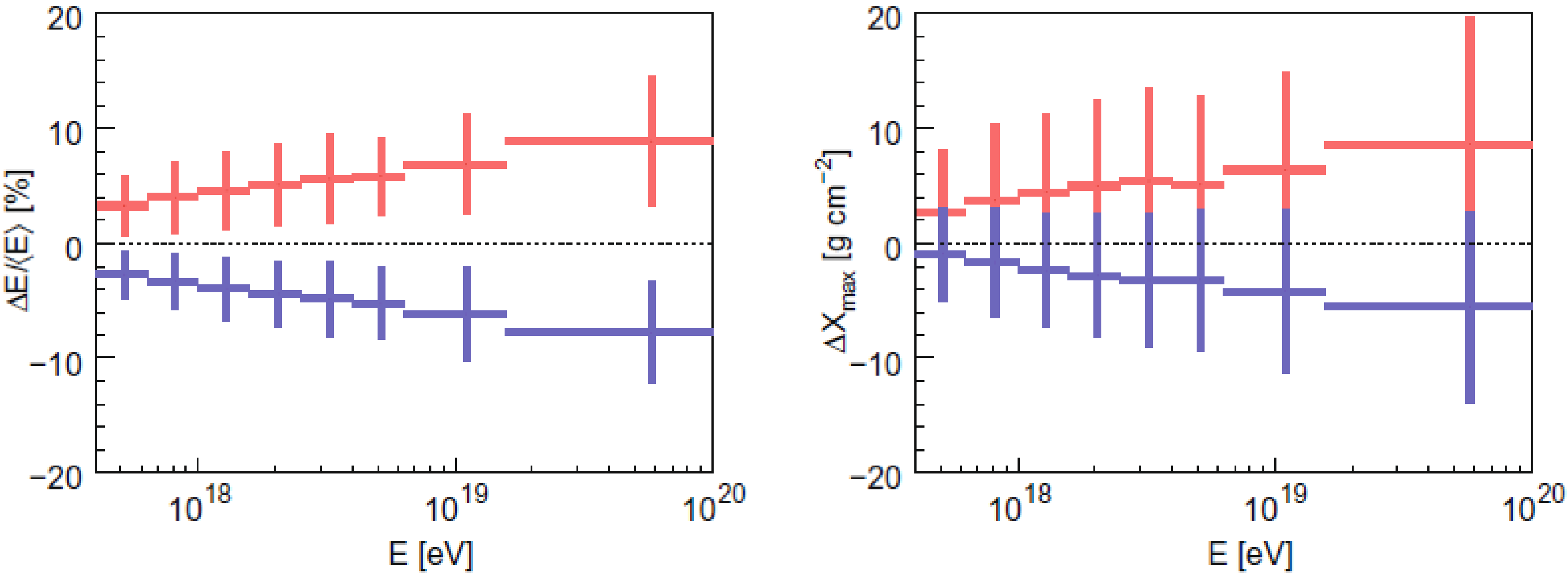


Systematic uncertainties

Source	log (E/eV)	$\Delta E/E$ (%)	RMS($\Delta E/E$) (%)
Molecular light transmission and production			
Horiz. uniformity	17.7–20.0	1	1
Quenching effects	17.7–20.0	+5.5	1.5–3.0
p, T, u Variability	17.7–20.0	−0.5	
Aerosol light transmission			
Optical depth	<18.0	+3.6, −3.0	1.6 ± 1.6
	18.0–19.0	+5.1, −4.4	1.8 ± 1.8
	19.0–20.0	+7.9, −7.0	2.5 ± 2.5
λ-Dependence	17.7–20.0	0.5	2.0
Phase function	17.7–20.0	1.0	2.0
Horiz. uniformity	<18.0	0.3	3.6
	18.0–19.0	0.4	5.4
	19.0–20.0	0.2	7.4
Scattering corrections			
Mult. scattering	<18.0	0.4	0.6
	18.0–19.0	0.5	0.7
	19.0–20.0	1.0	0.8

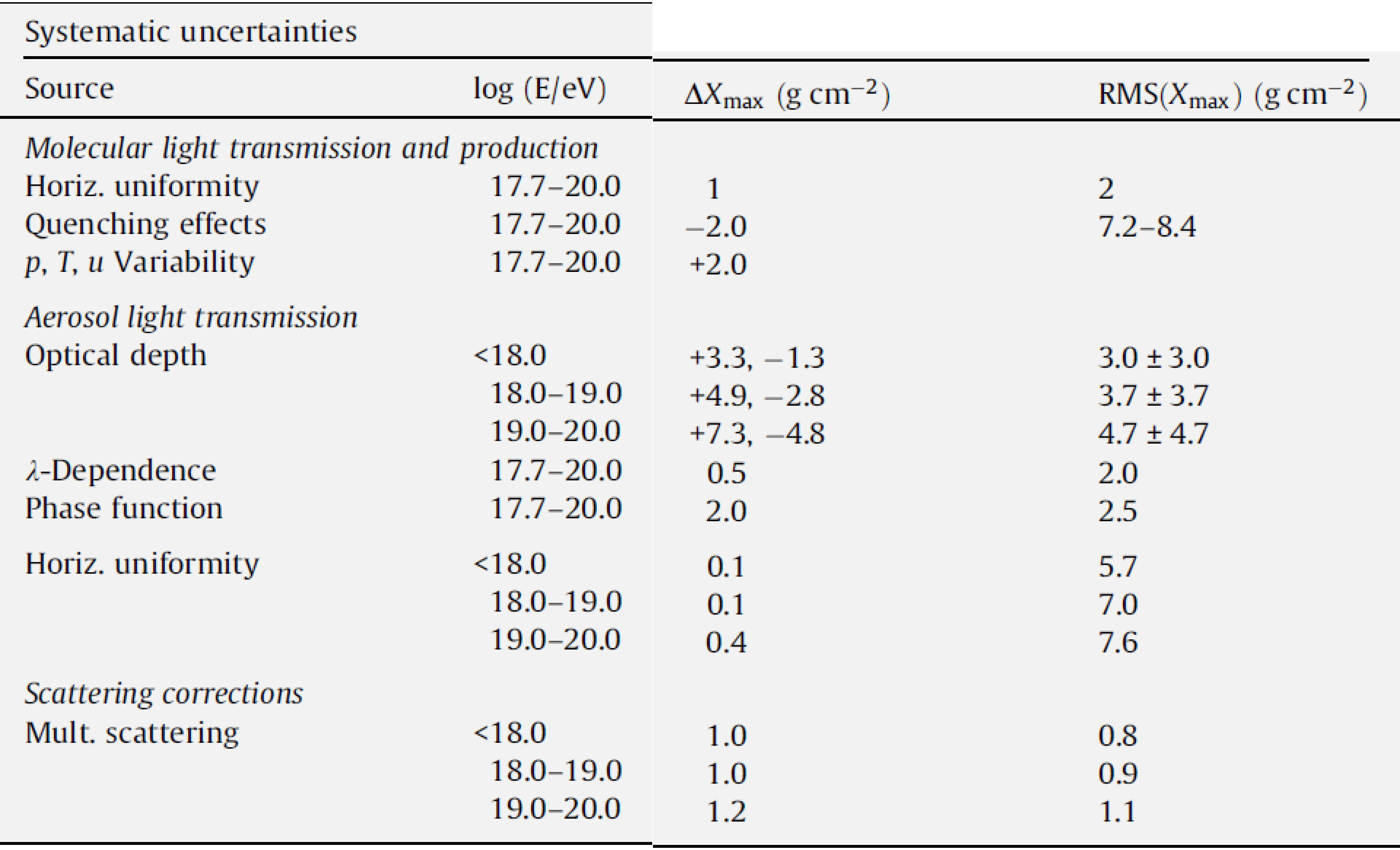
J. Abraham et al./Astroparticle Physics 33 (2010) 108–129

J. Abraham et al. / Astroparticle Physics 33 (2010) 108–129



Shifts in the reconstruction of energy and Xmax when the aerosol optical depth is varied by its +1σ systematic uncertainty (red points) and -1σ systematic uncertainty (blue points).

The dotted line corresponds to the central aerosol optical depth measurement. The uncertainty bars correspond to the sample RMS in each energy bin.

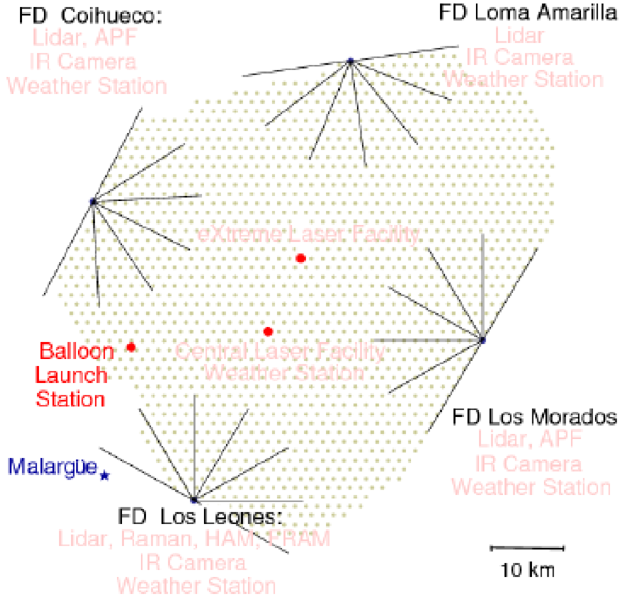


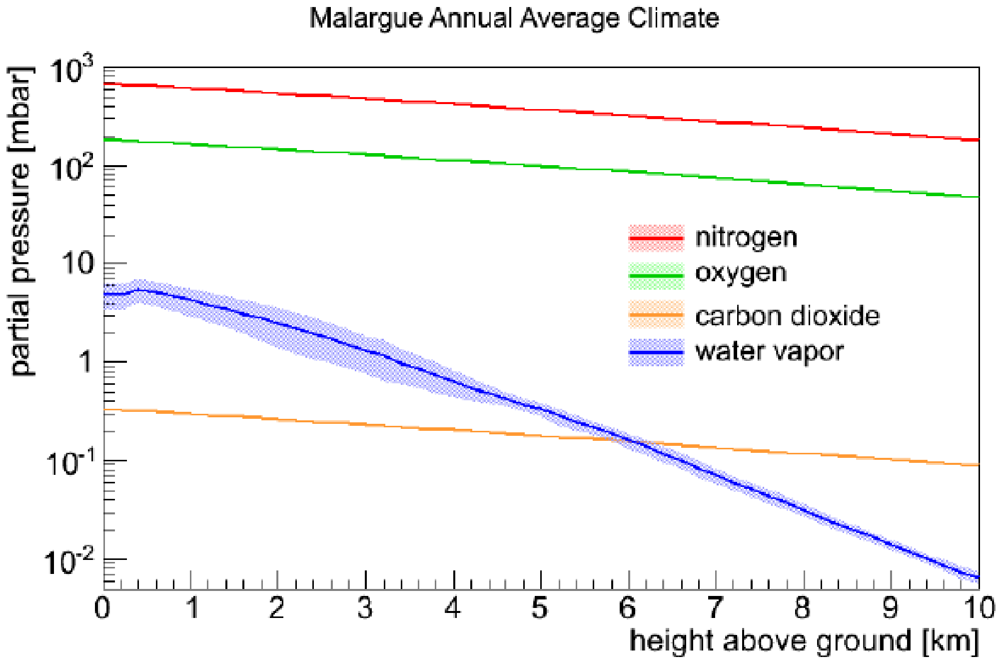
Systematic uncertainties

Source	log (E/eV)	$\Delta X_{\max}$ (g cm^{-2})	RMS($X_{\max}$) (g cm^{-2})
Molecular light transmission and production			
Horiz. uniformity	17.7–20.0	1	2
Quenching effects	17.7–20.0	−2.0	7.2–8.4
p, T, u Variability	17.7–20.0	+2.0	
Aerosol light transmission			
Optical depth	<18.0	+3.3, −1.3	3.0 ± 3.0
	18.0–19.0	+4.9, −2.8	3.7 ± 3.7
	19.0–20.0	+7.3, −4.8	4.7 ± 4.7
λ-Dependence	17.7–20.0	0.5	2.0
Phase function	17.7–20.0	2.0	2.5
Horiz. uniformity	<18.0	0.1	5.7
	18.0–19.0	0.1	7.0
	19.0–20.0	0.4	7.6
Scattering corrections			
Mult. scattering	<18.0	1.0	0.8
	18.0–19.0	1.0	0.9
	19.0–20.0	1.2	1.1

Atmospheric Monitoring at the Pierre Auger Observatory

Molecular Measurements

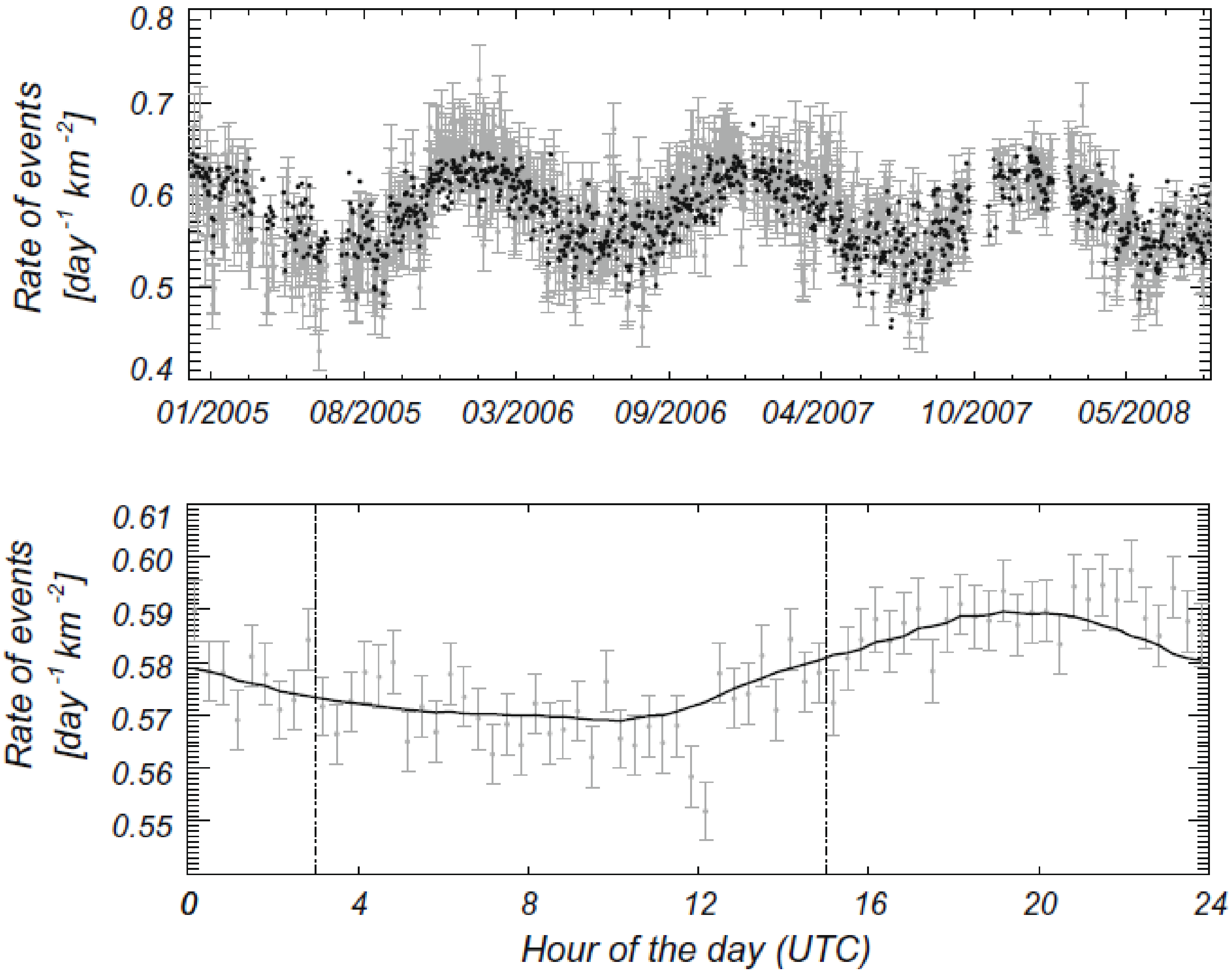




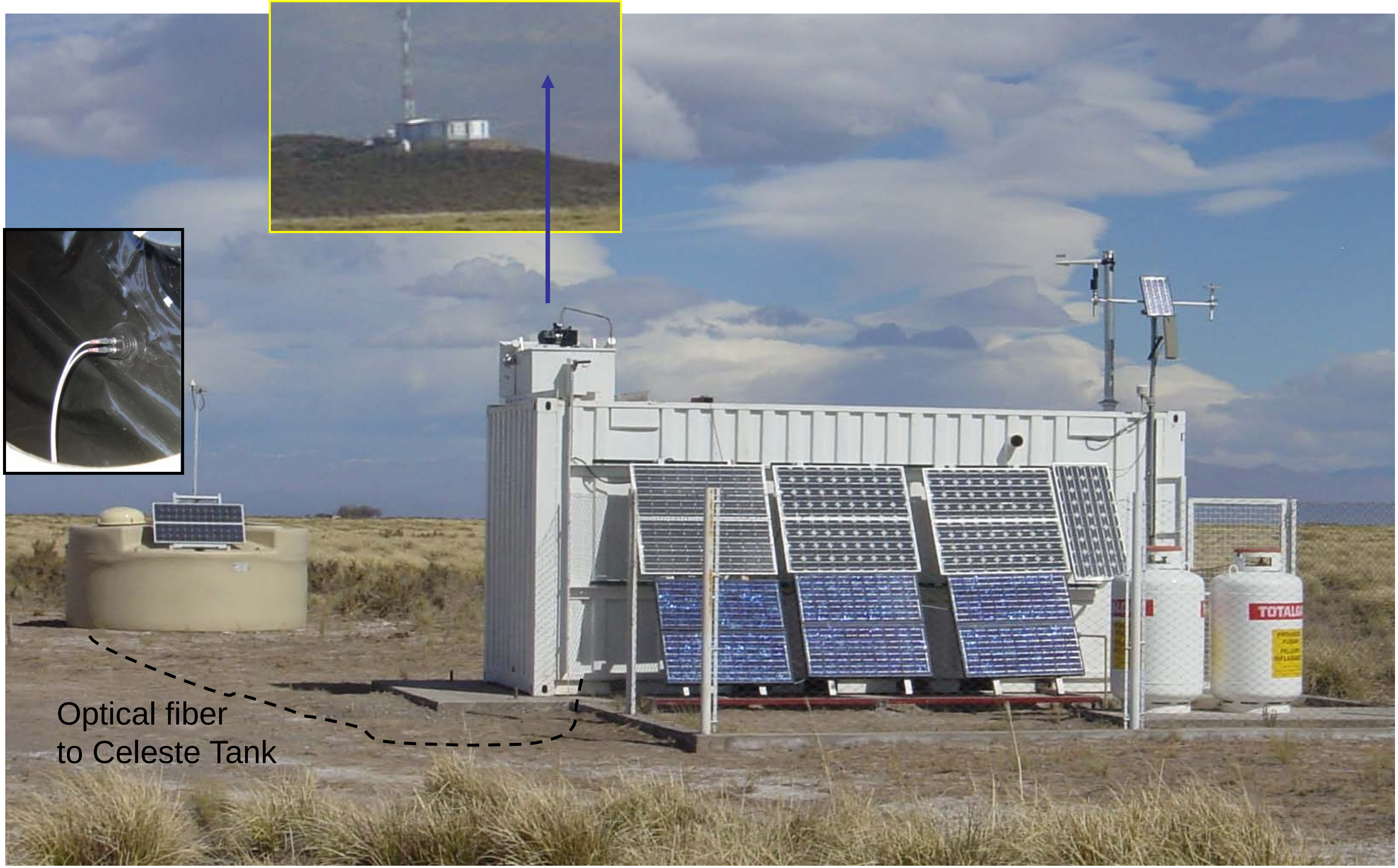
- Measurements of p, T, e up to $\sim$ 23 km with radio soundings
- Launches about every 5 days; 279 flights since 2003
- Monthly average profiles $\langle p \rangle$, $\langle T \rangle$, $\langle e \rangle$ used most nights
- Largest variability: vapor pressure. Significant in austral summer
- Since Jan 2009: launches triggered by high-energy showers

Note: Modulation in the atmosphere density profile has an effect on the Surface Detector Array

J. Abraham et al. / Astroparticle Physics 32 (2009) 89–99



Seasonal (top) and diurnal (bottom) modulation of **Surface Detector** event rate

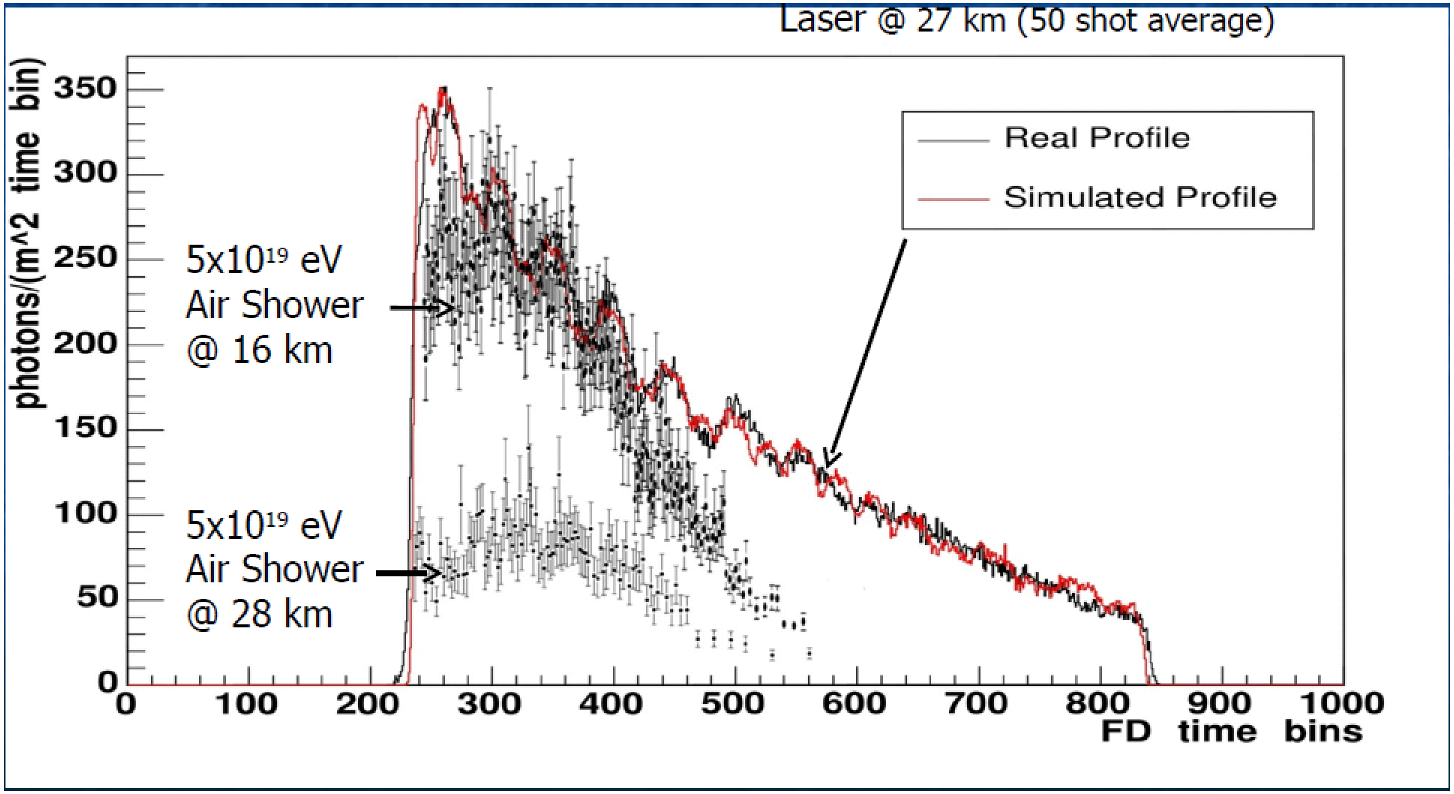


The CLF sends light simultaneously to
the Surface Detector and to the Fluorescence Detector

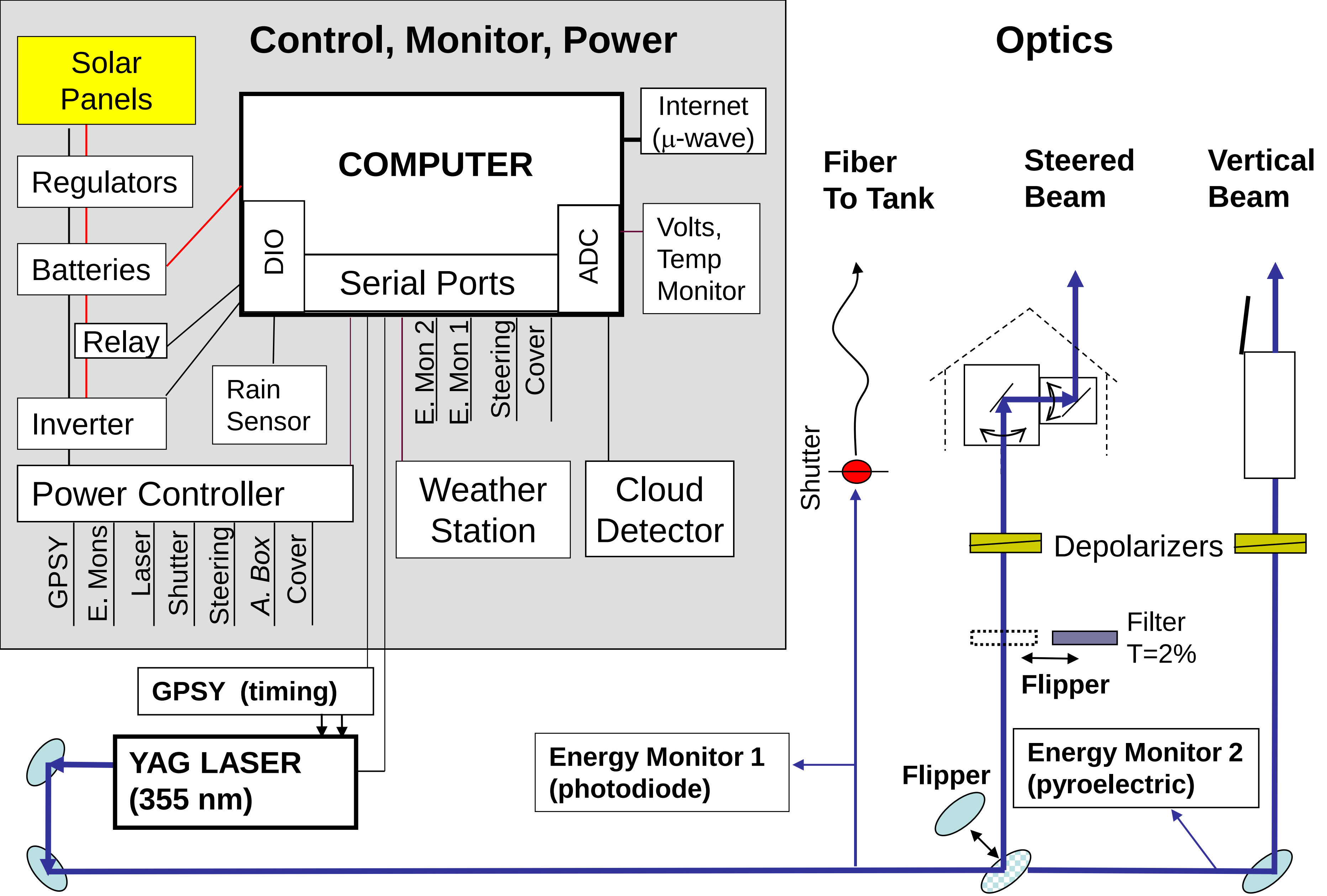
Why use Lasers?

10^{20} eV Cosmic Ray Air Showers are rare ~1/km^2/Century

Pulsed UV Laser provides an optically similar “test-beam”
choose rate, direction, location, energy



Data from Auger South



Control, Monitor, Power

Solar Panels

Regulators

Batteries

Relay

Inverter

Power Controller

GPSY

E. Mons

Laser

Shutter

Steering

A. Box

Cover

COMPUTER

DIO

Serial Ports

ADC

Internet (μ-wave)

Volts, Temp Monitor

Rain Sensor

E. Mon 2

E. Mon 1

Steering

Cover

Weather Station

Cloud Detector

GPSY (timing)

YAG LASER (355 nm)

Optics

Fiber To Tank

Steered Beam

Vertical Beam

Shutter

Depolarizers

Filter T=2%

Flipper

Energy Monitor 1 (photodiode)

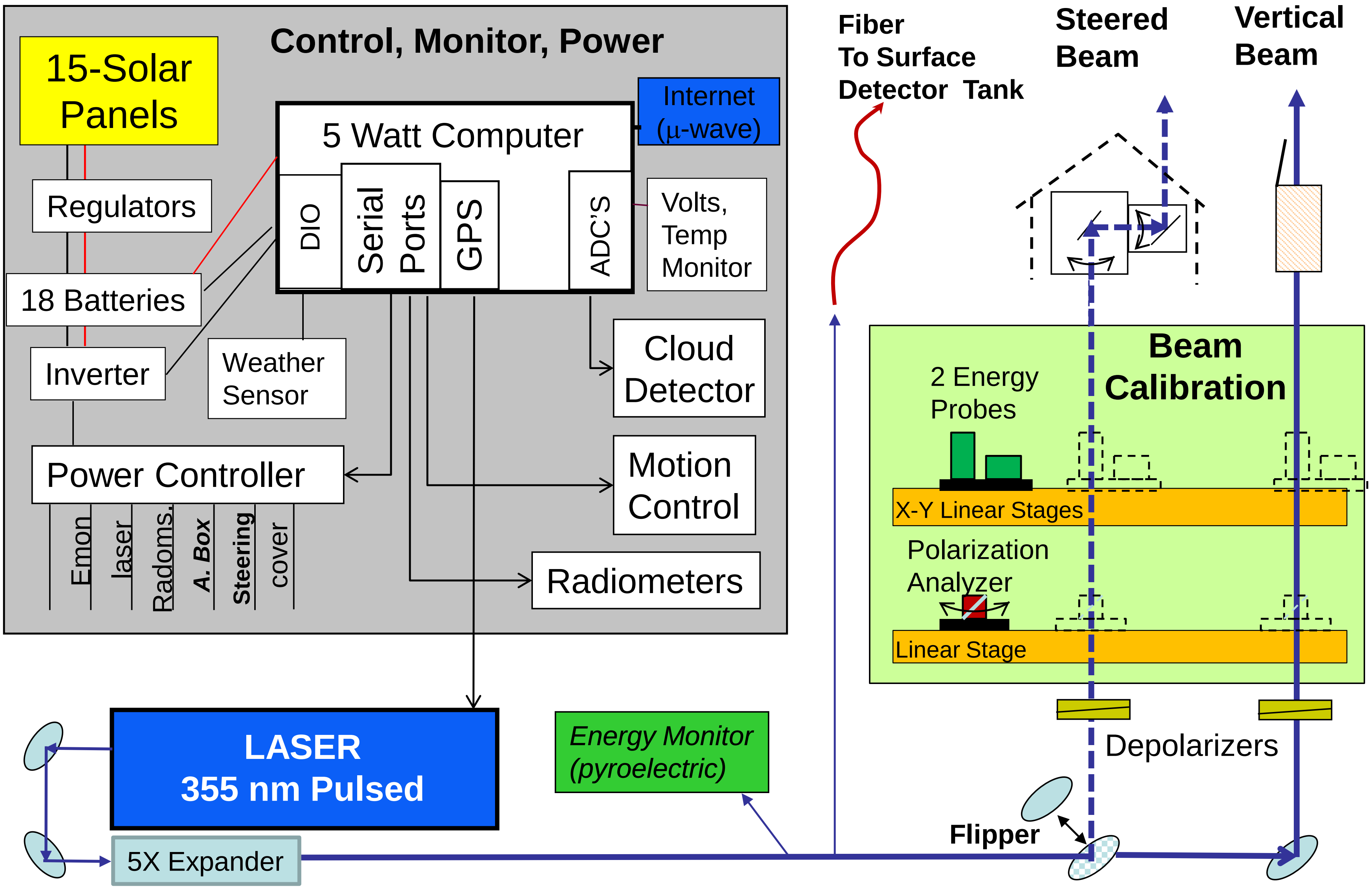
Flipper

Energy Monitor 2 (pyroelectric)

Pierre Auger Observatory Central Laser Facility

JINST 1 P11003 (2006)

Extreme Laser Facility at the Pierre Auger Observatory



Control, Monitor, Power

15-Solar Panels

Regulators

18 Batteries

Inverter

Weather Sensor

Power Controller

Emon

laser

Radoms.

A. Box

Steering

cover

5 Watt Computer

DIO

Serial Ports

GPS

ADC'S

Internet (μ-wave)

Volts, Temp Monitor

Cloud Detector

Motion Control

Radiometers

Fiber To Surface Detector Tank

Steered Beam

Vertical Beam

Beam Calibration

2 Energy Probes

X-Y Linear Stages

Polarization Analyzer

Linear Stage

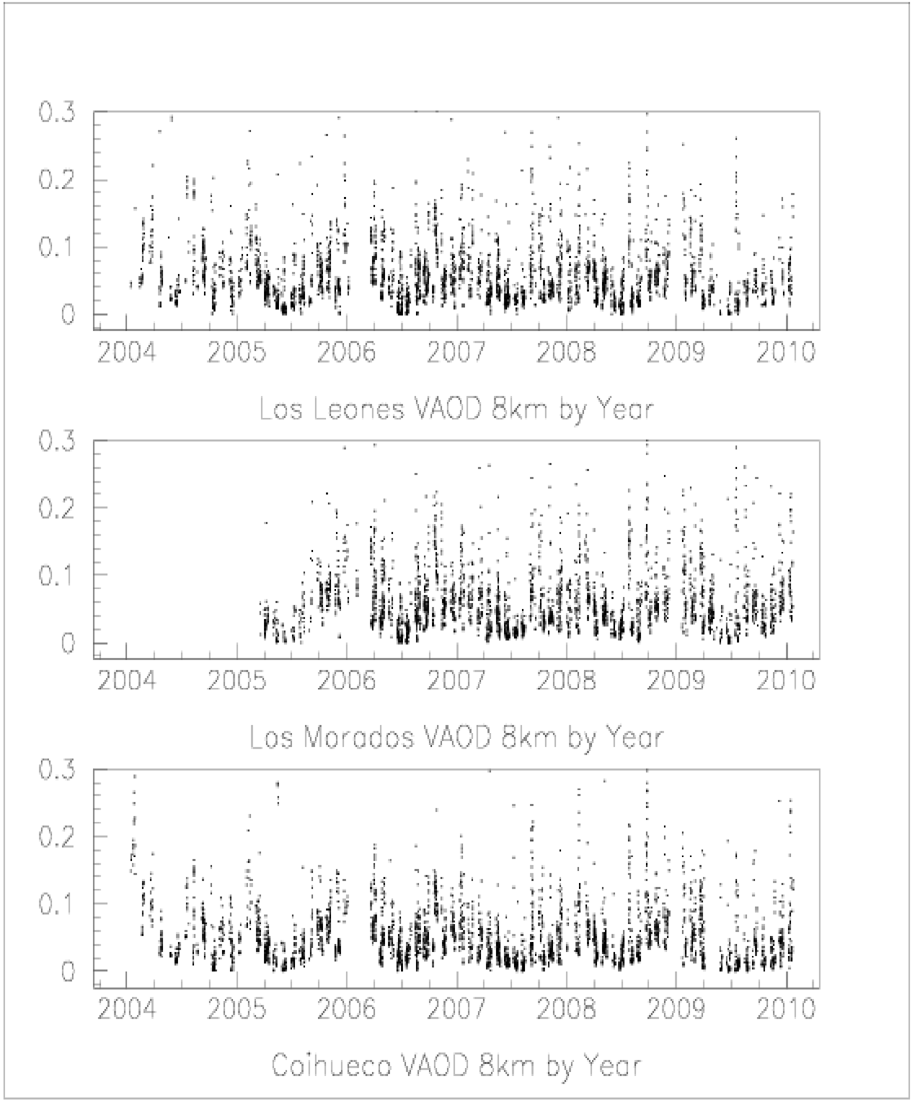
Depolarizers

Flipper

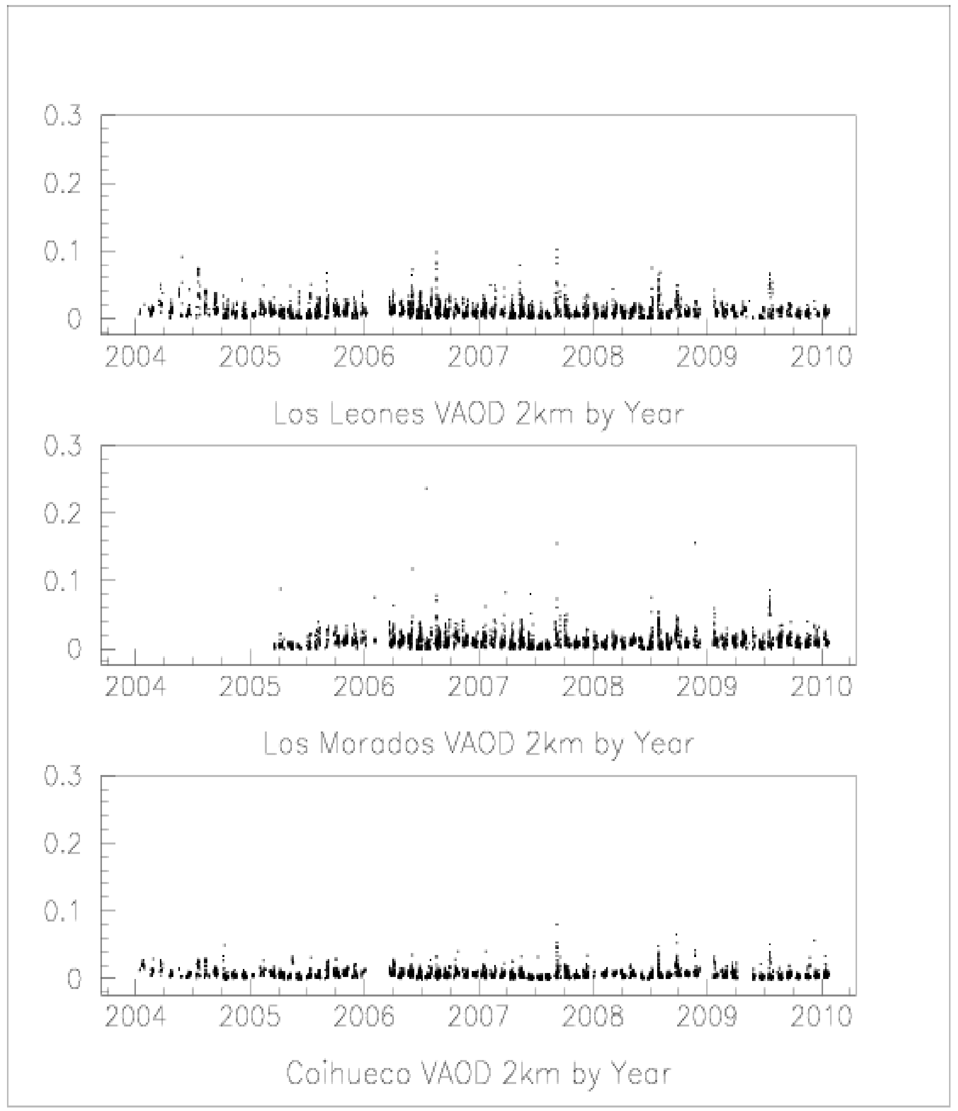
LASER
355 nm Pulsed

Energy Monitor (pyroelectric)

5X Expander



VAOD at 8 km

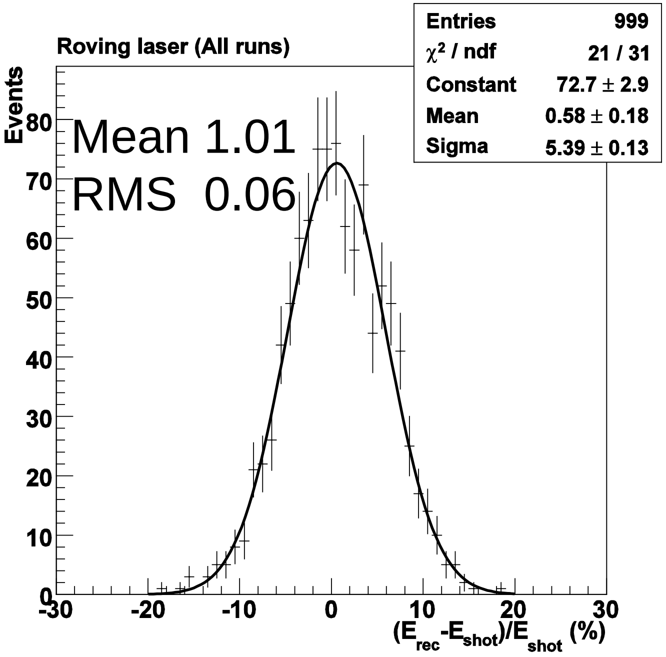


VAOD at 2 km

Laser Tests of Photometric Calibration – *In Progress*

Roving Laser @ 4km

analysis-V. Verzi (Roma)

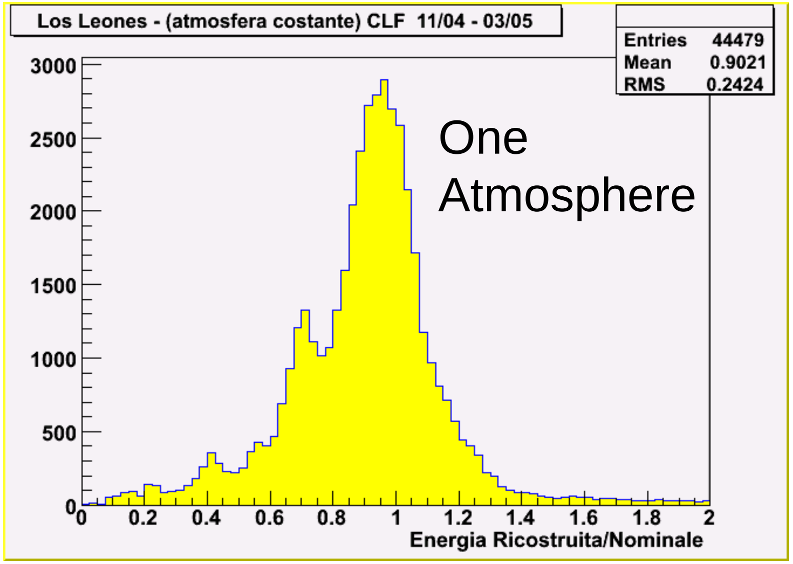


Mean 1.01
RMS 0.06

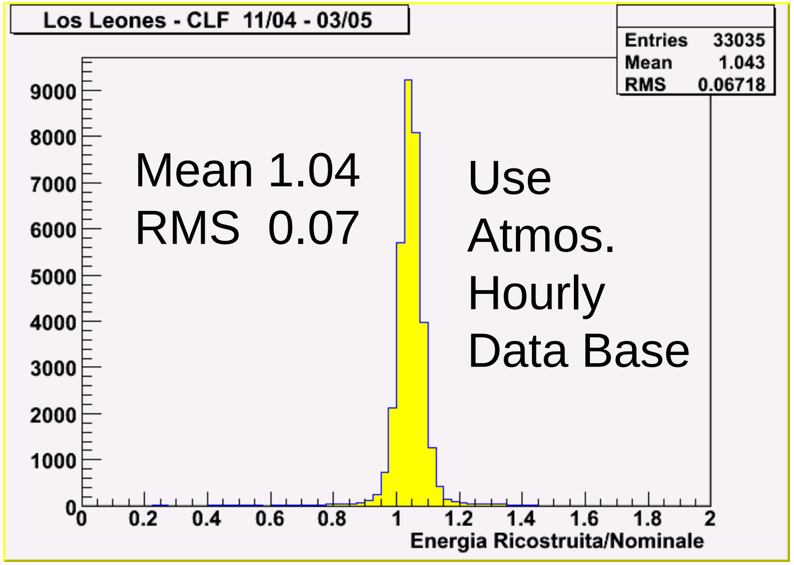
$(E_{rec}\text{-}E_{laser})/E_{laser}$

"CLF @ 27 km"

Analysis -L. Valore (Napoli)



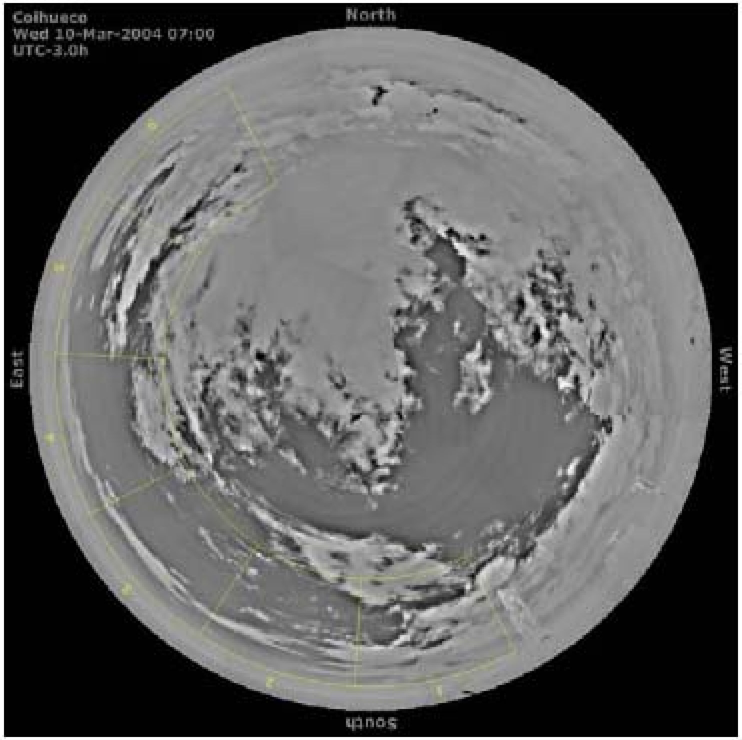
One Atmosphere



Mean 1.04
RMS 0.07

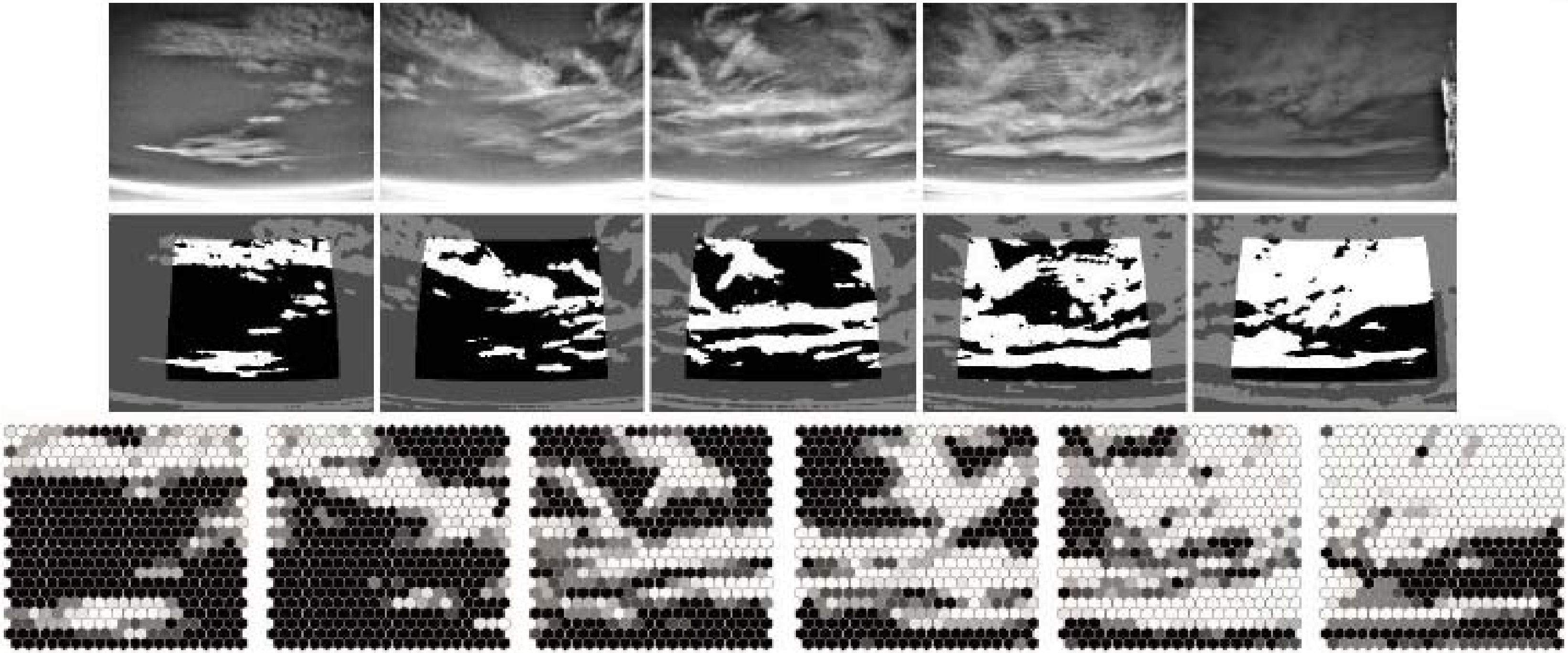
Use
Atmos.
Hourly
Data Base

Bruce Dawson for
Mathew Cooper and Michael Winnick
University of Adelaide



IR Scanning Camera

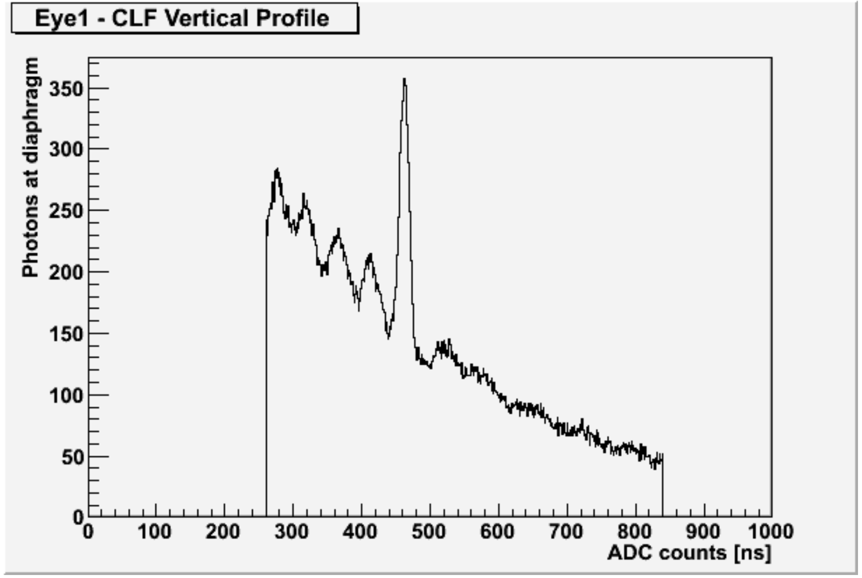
Generation of “cloud masks” for CloudCamera Database

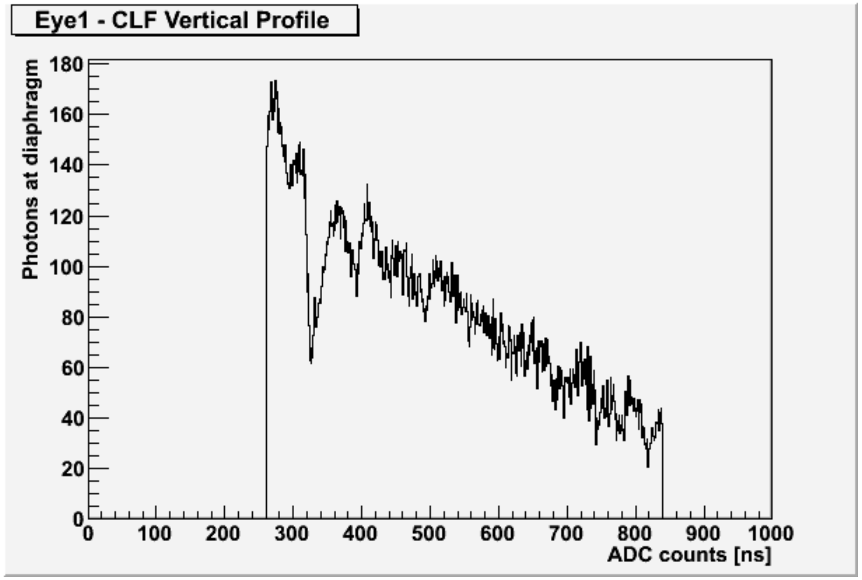


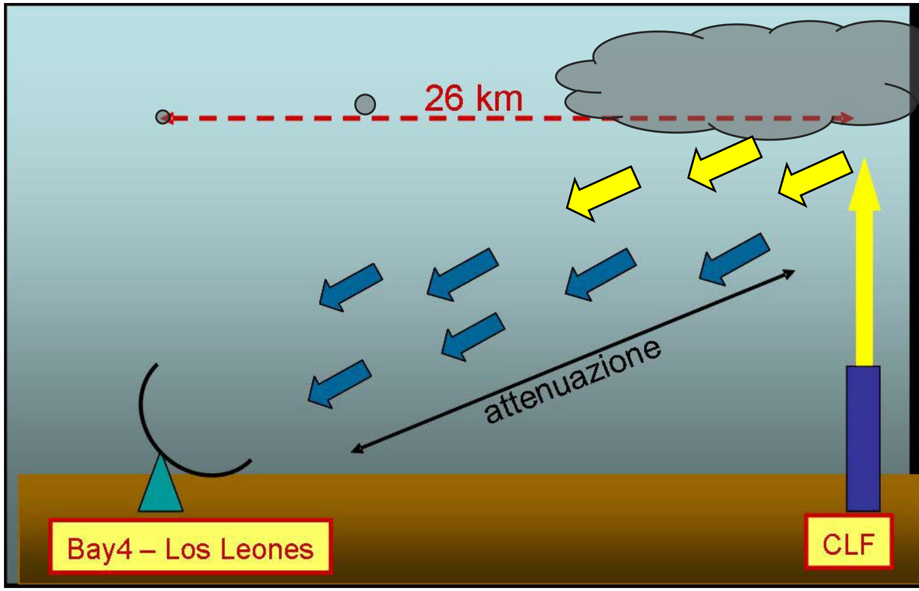
CloudCam cloud index for each FD pixel 0,1,2,3,4,5

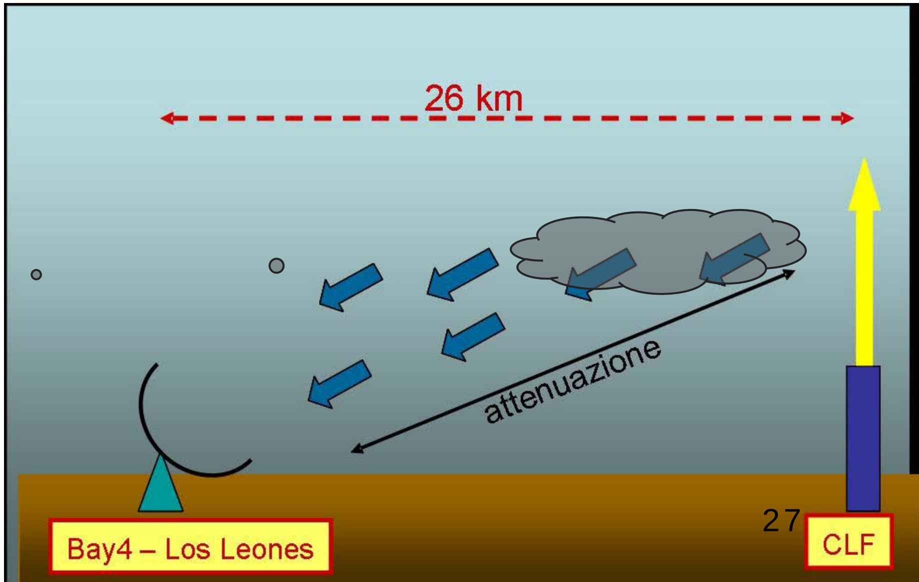
2

Clouds shape in CLF vertical profiles









Elastic Backscatter LIDAR
Cloud detection, Shoot the shower

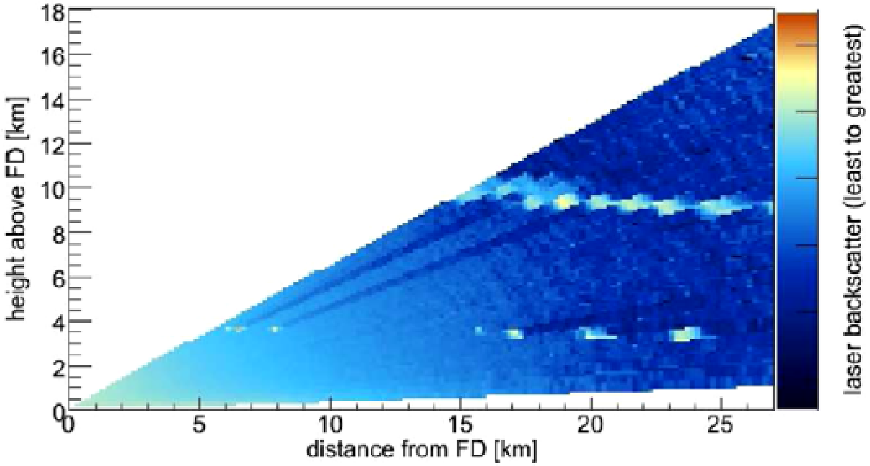
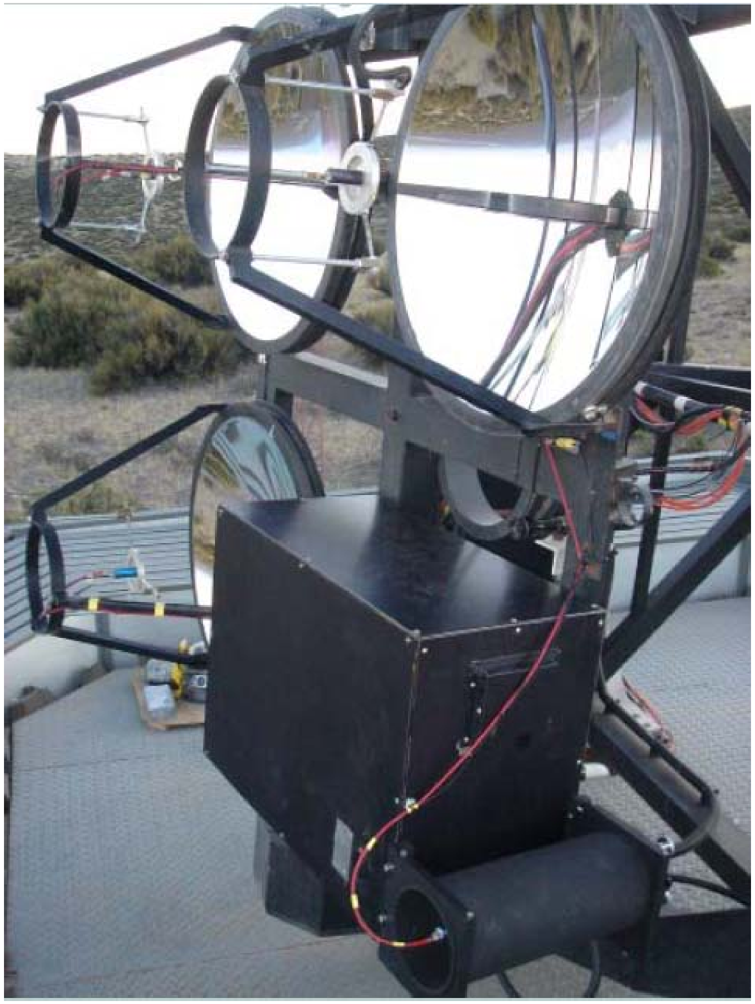
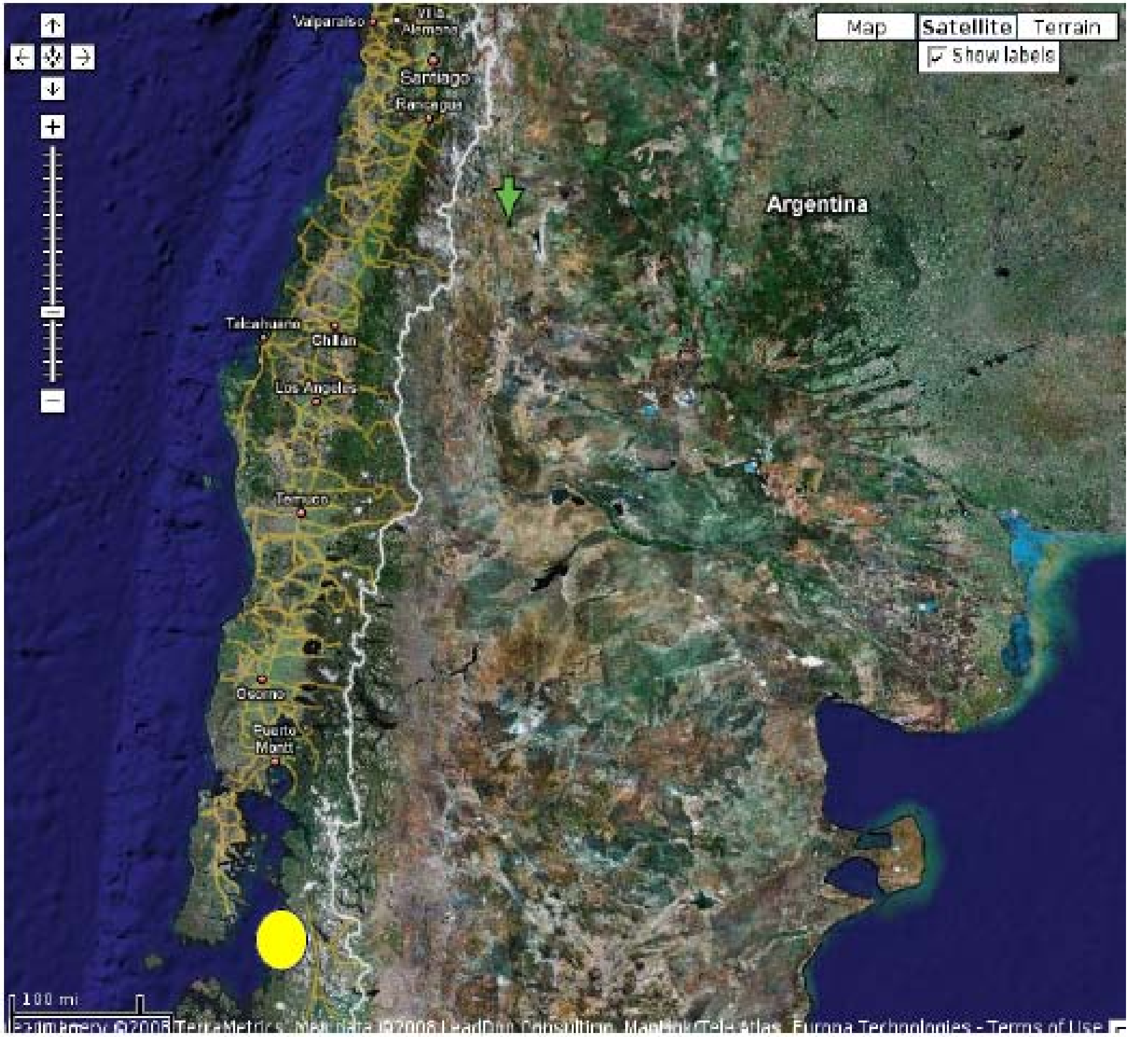


Fig. 25. Lidar sweep of the shower-detector plane for the cloud-obscured event shown in Fig. 23. The regions of high backscatter are laser echoes due to optically thick clouds.



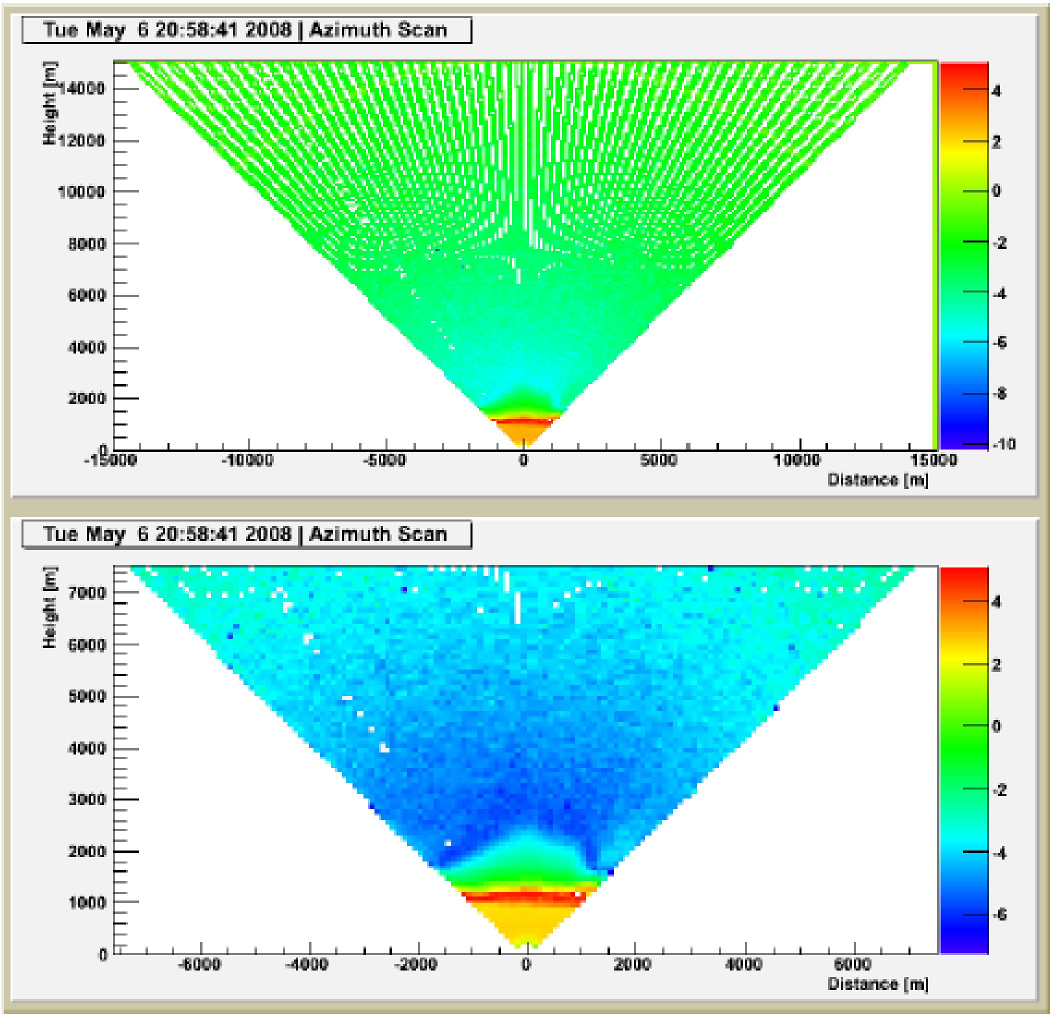
Topinka, USGS/CVO,2000; basemap from:CIA, 1998; volcanoes from: Simkin&Siebert, 1994



Imagery ©2008 TerraMetrics, Map data ©2008 LeadDog Consulting, MapLink/Tele Atlas, Europa Technologies - Terms of Use

Ashes from Chaiten volcano?

A huge cloud of ash spewed from the Chaiten volcano, Chile, May 6, 2008. An evacuation of Chaiten Town and regions around had been underway since the volcano's first eruption on last Friday.

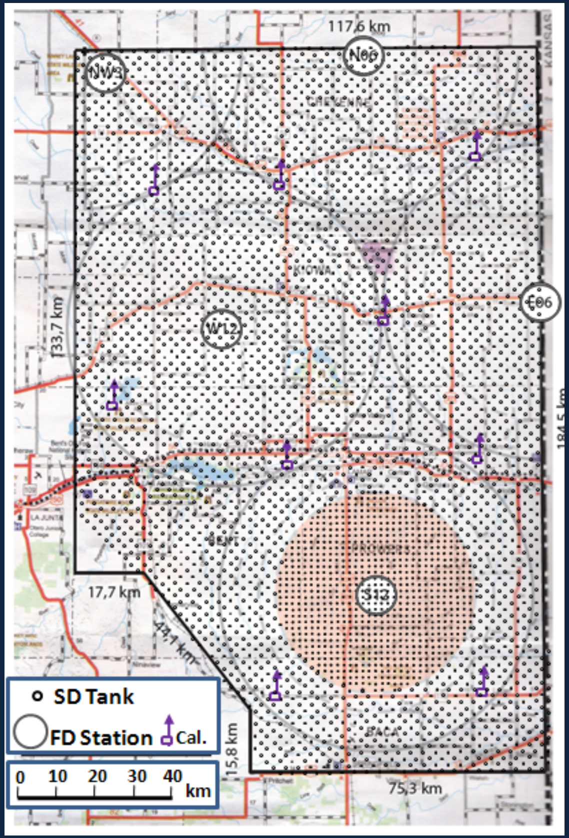


The Pierre Auger Observatory
One observatory in two hemispheres

Northern site: Colorado

21000 square km

(Planned)

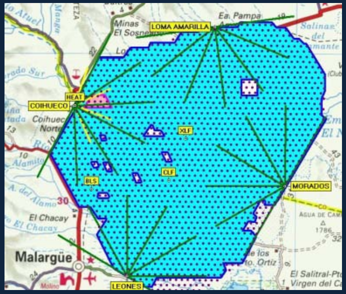


- Argentina
- Australia
- Brasil
- Bolivia*
- Czech Rep.
- France
- Germany
- Italy
- Mexico
- Netherlands
- Poland
- Portugal
- Slovenia
- Spain
- UK
- USA
- Vietnam*

***Assoc. Countries**

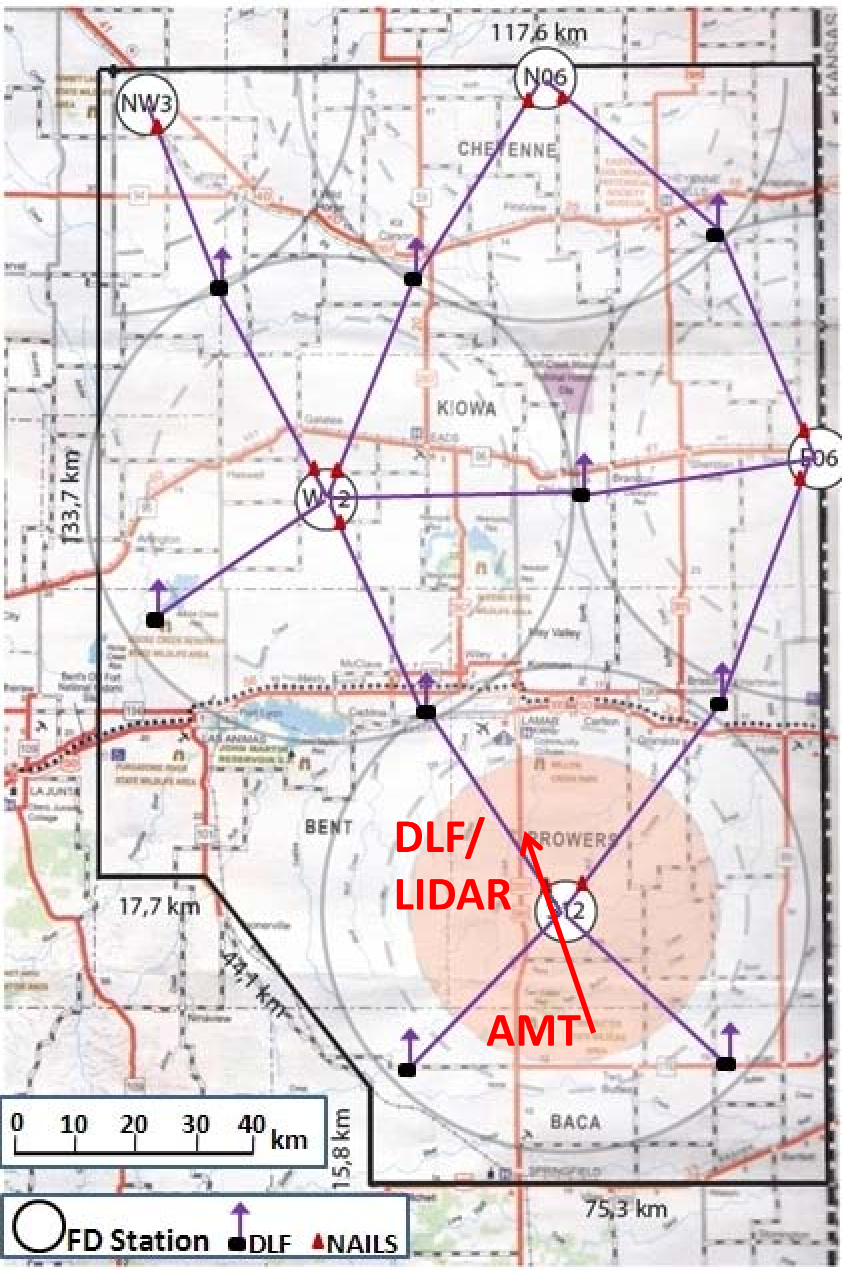
Southern site: Argentina

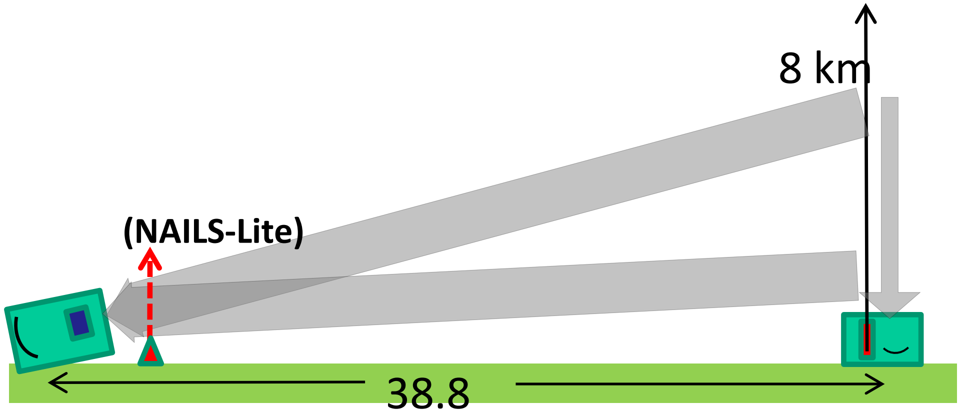
3000 Square km



Auger North Atmospheric R&D

Institution	Country	Contribution
Adelaide	Australia	Cloud Radiometers
CSU	US	AMT-Calibration
CSU-Pueblo	US	Site Prep
CWRU	US	Firewall, GPS
KIT	Germany	AMT-DAQ Radiosondes
Krakow	Poland	Molecular DB analysis
L'Aquila	Italy	Raman LIDAR
Madrid-Cmp	Spain	Laser Calibration
Mines	US	AMT, Site Prep, NAILS-lite
MTU	US	Weather Stations
Napoli	Italy	AMT- DAQ analog
Rosario	Argentina	Raman LIDAR





AMT

3.8m^2 mirror

4 columns of 16 1 degree pixels

External Trigger from GPS

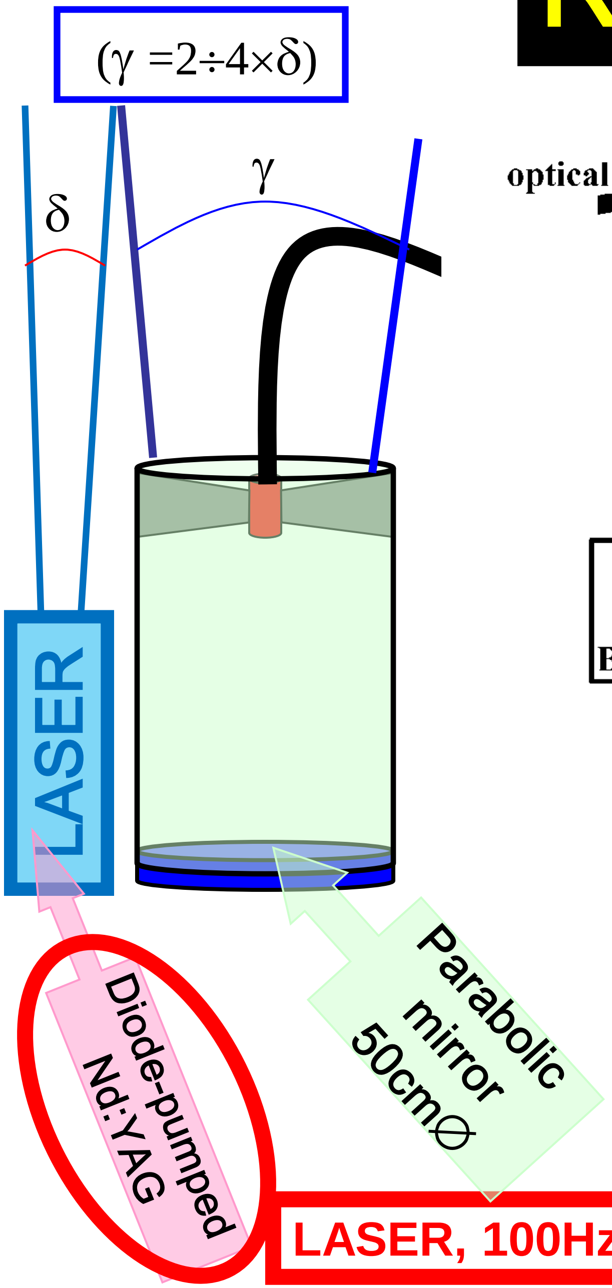
DLF/LIDAR

355 nm Laser

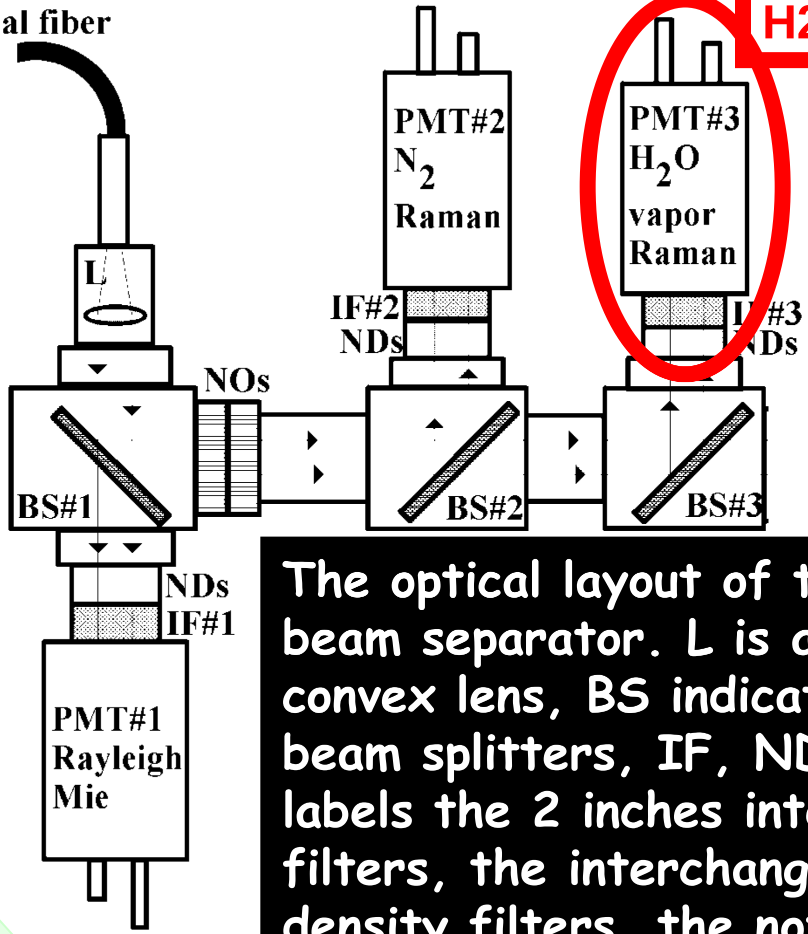
Raman Detector

(L'Aquilla)

Raman LIDAR



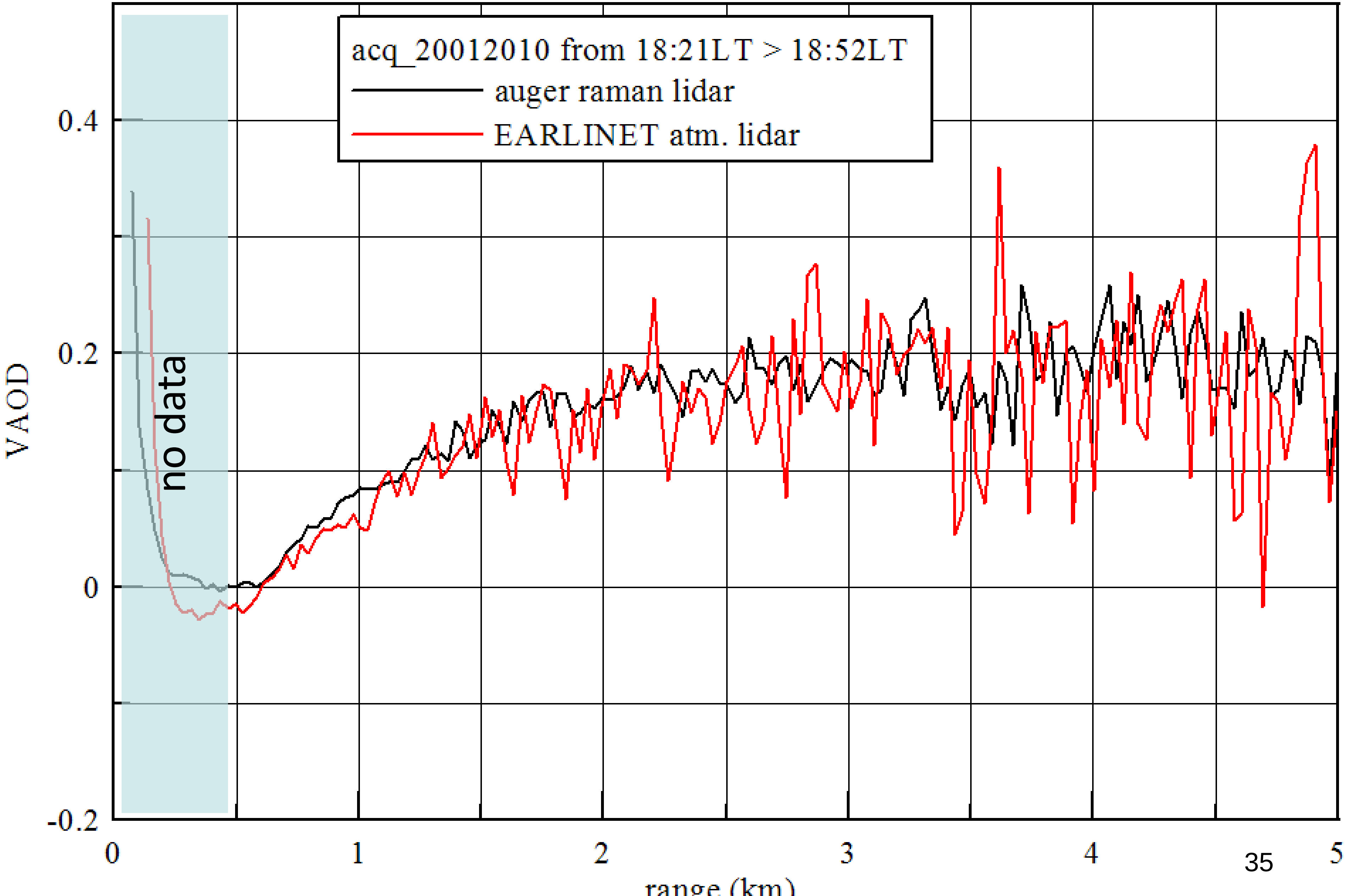
NEW lidar channel, H2O detection



The optical layout of the receiver's beam separator. L is a 1 inch plano-convex lens, BS indicates dichroic beam splitters, IF, ND, NO and PMT labels the 2 inches interference filters, the interchangeable neutral density filters, the notch filters and the photomultipliers, respectively.

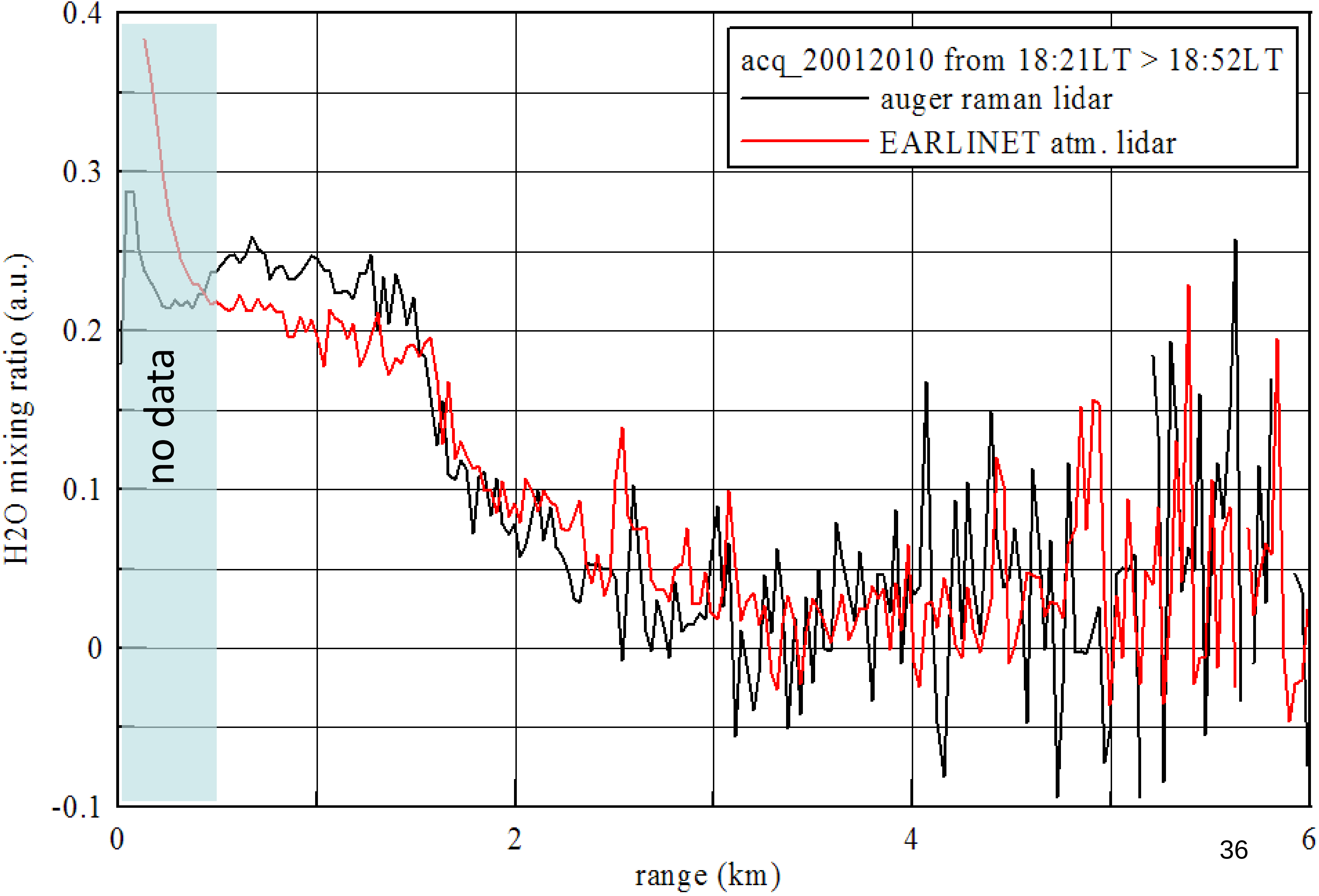
LASER, 100Hz repetition rate, 6mJ/pulse @355nm

Vertical Aerosol Optical Depth 1/20, 2010 L'Aquilla



Water vapor mixing ratio

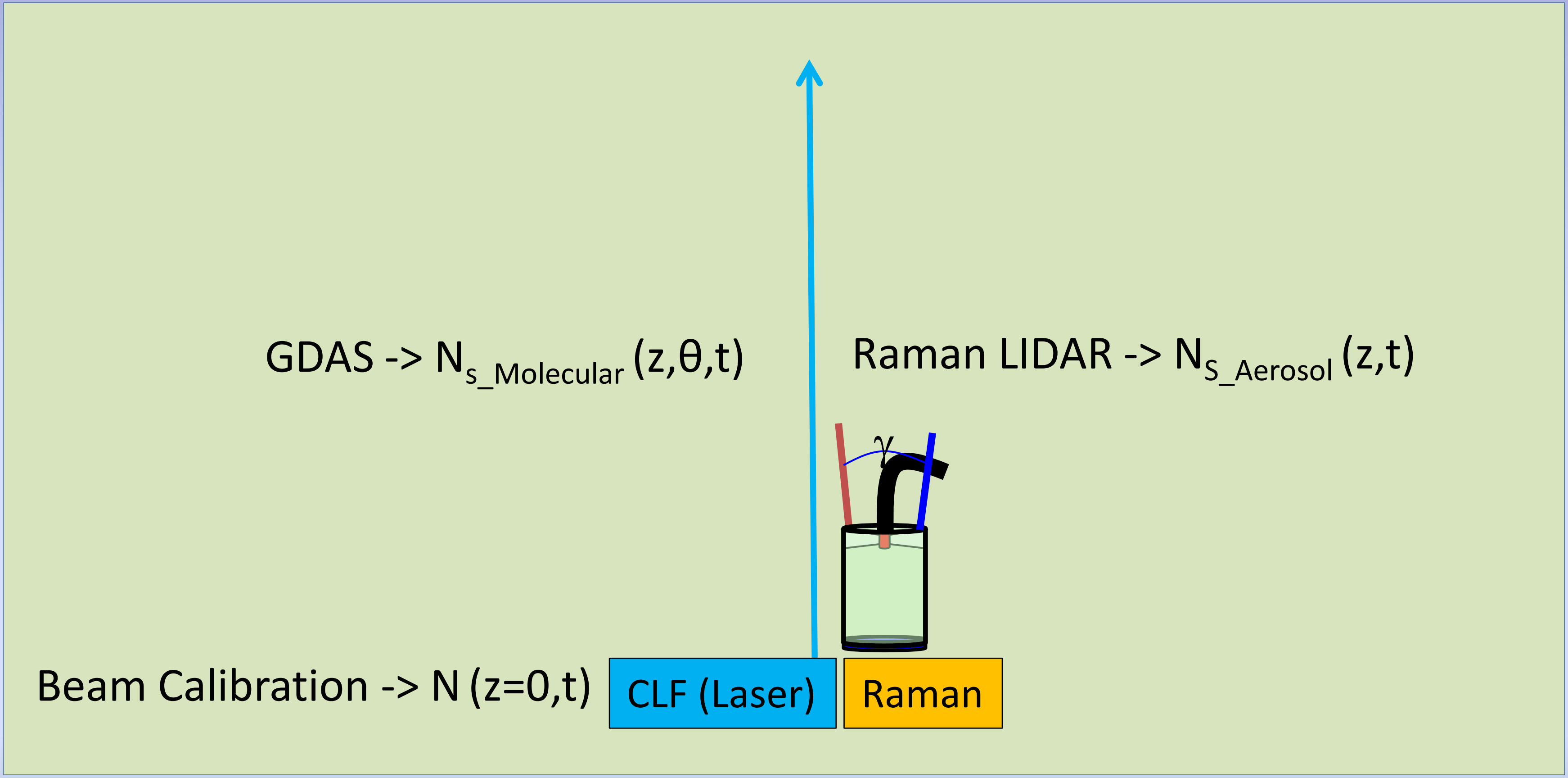
1/20, 2010 L’Aquilla



Looking Ahead… CLF + Raman =Super Test Beam

Calibrated beam as a function of height

$$N_{scatter}=N_{s\_Mol}+N_{S\_Aero}$$



GDAS -> $N_{s\_Molecular}(z,\theta,t)$

Raman LIDAR -> $N_{S\_Aerosol}(z,t)$

Beam Calibration -> $N(z=0,t)$

CLF (Laser)

Raman