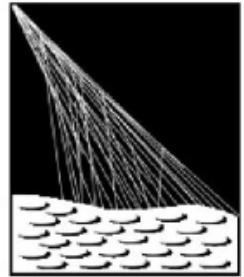
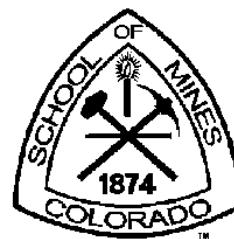


The Auger Raman Lidar: 2013-2022 continuous observations.



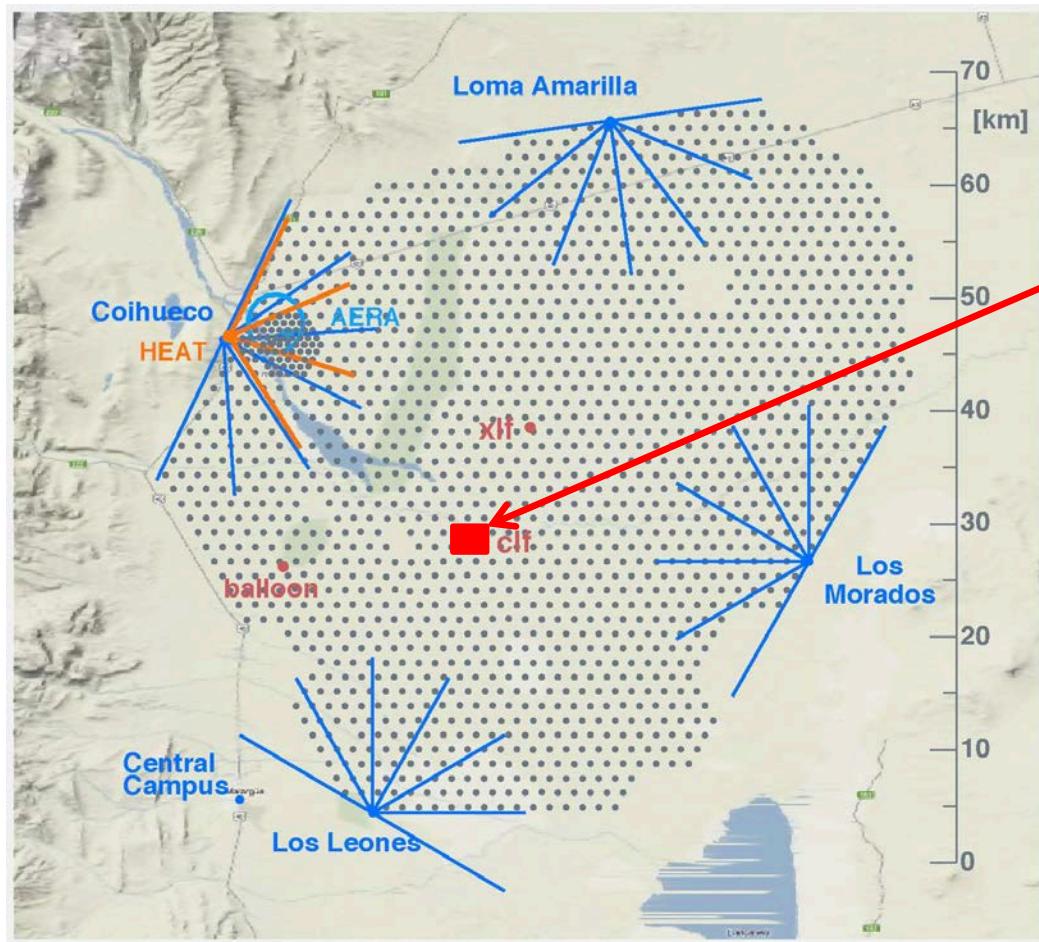
PIERRE
AUGER
OBSERVATORY

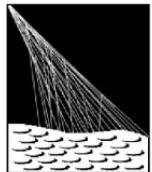
CRLF



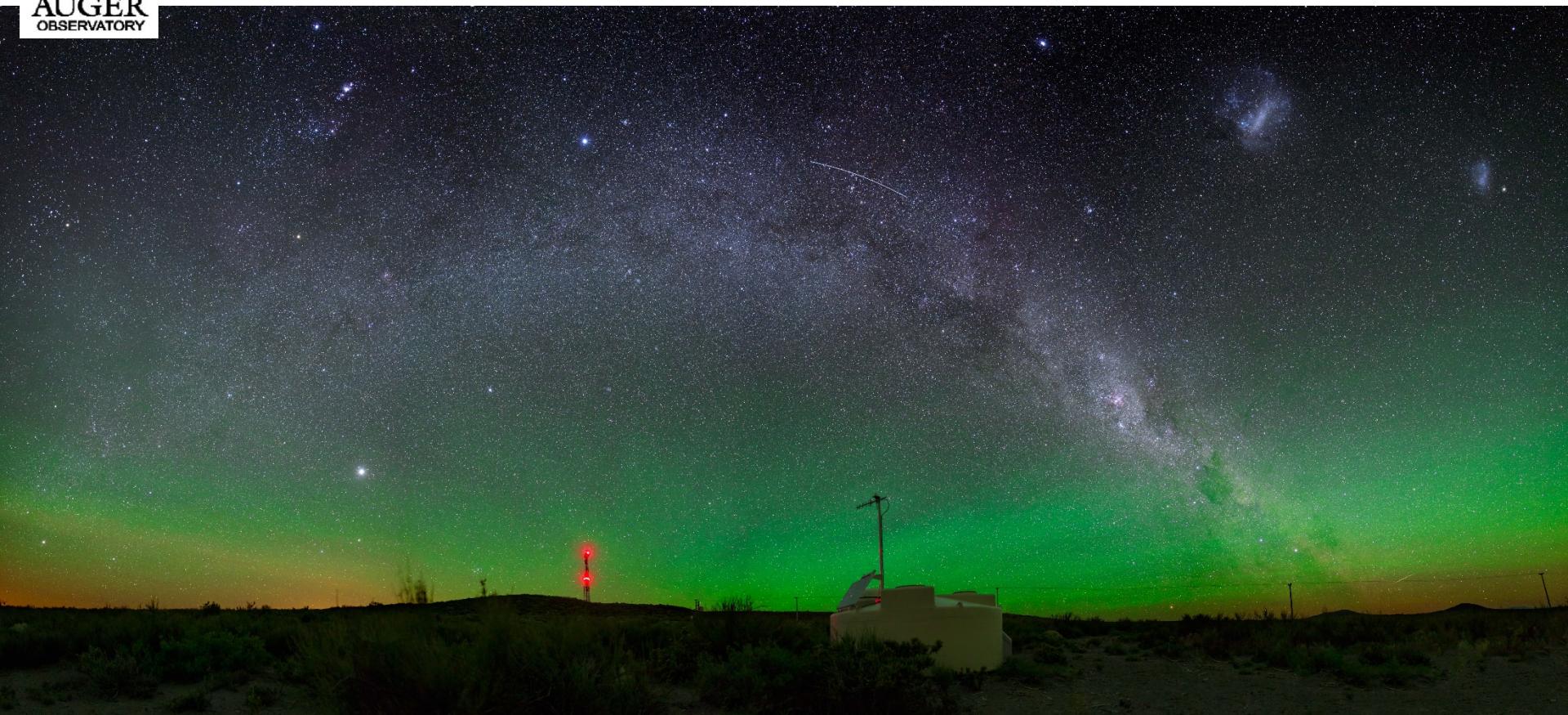
Raman LIDAR (RL)

The RL system samples vertically the part of the atmosphere **above the CRLF site**, and the retrieved VAOD profiles have a **representativeness** of the aerosol optical transmission in the atmosphere over the Observatory.





PIERRE
AUGER
OBSERVATORY



AUGER Observatory



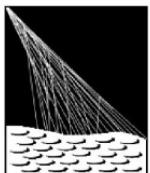
AUGER Observatory



PIERRE
AUGER
OBSERVATORY



AUGER Observatory



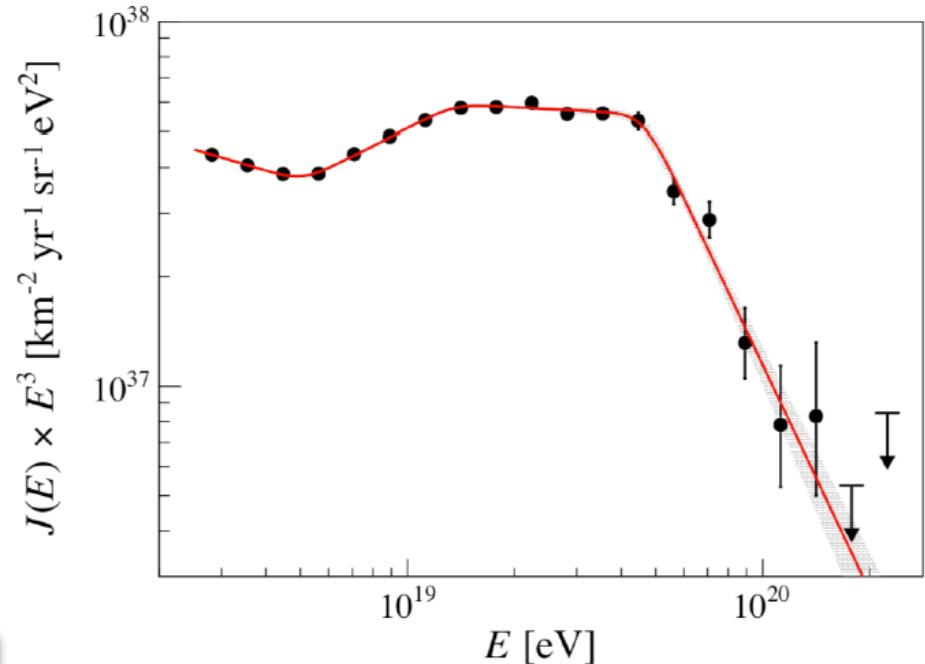
PIERRE
AUGER
OBSERVATORY

ENERGY SPECTRUM

- 215030 events recorded with zenith angle <60 degrees;
- No declination dependence identified;
- Spectral features identified:

parameter	value $\pm \sigma_{\text{stat.}} \pm \sigma_{\text{sys.}}$
J_0 [$\text{km}^{-2} \text{sr}^{-1} \text{yr}^{-1} \text{eV}^{-1}$]	$(1.315 \pm 0.004 \pm 0.400) \times 10^{-18}$
γ_1	$3.29 \pm 0.02 \pm 0.10$
γ_2	$2.51 \pm 0.03 \pm 0.05$
γ_3	$3.05 \pm 0.05 \pm 0.10$
γ_4	$5.1 \pm 0.3 \pm 0.1$
E_{12} [eV] (ankle)	$(5.0 \pm 0.1 \pm 0.8) \times 10^{18}$
E_{23} [eV]	$(13 \pm 1 \pm 2) \times 10^{18}$
E_{34} [eV] (suppression)	$(46 \pm 3 \pm 6) \times 10^{18}$
D/n_{dof}	17.0/12

- Where do the features of the spectrum come from?



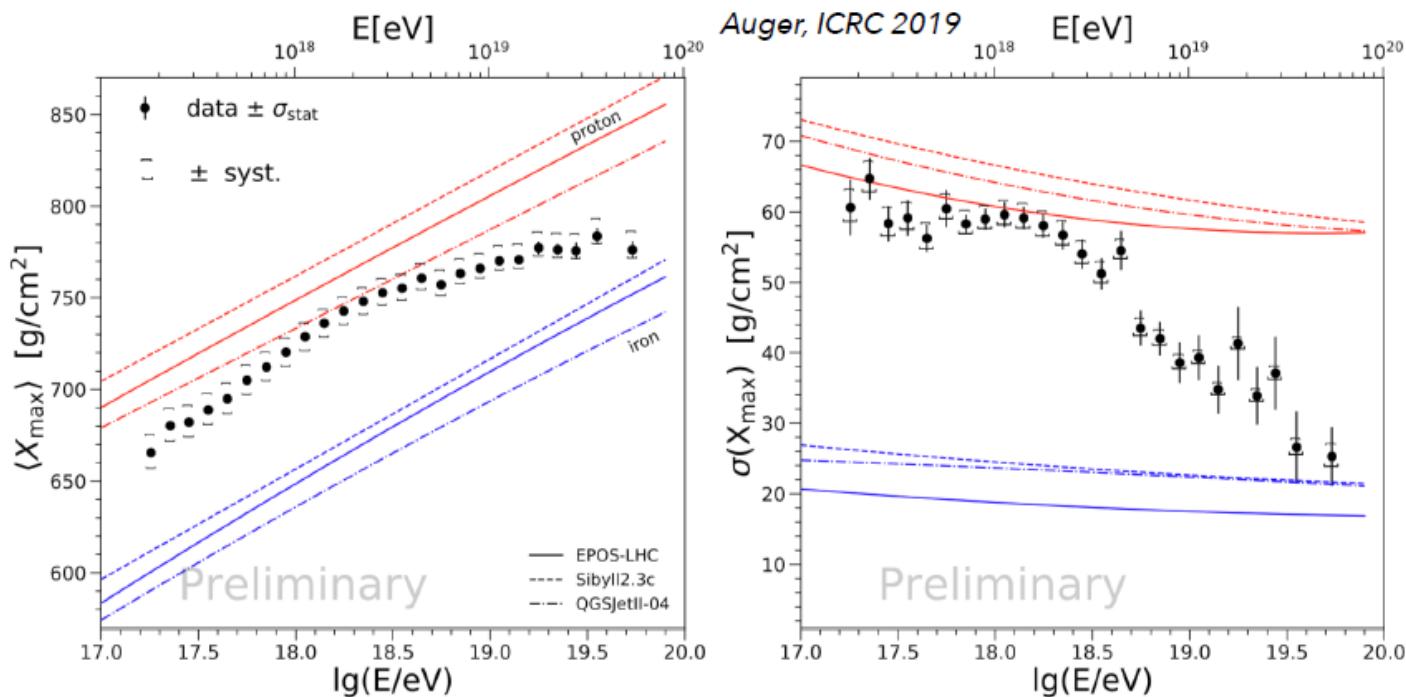
Auger, PRD 2020 & PRL 2020

AUGER results



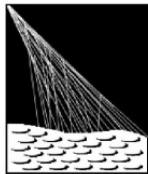
PIERRE
AUGER
OBSERVATORY

MASS COMPOSITION



- Composition information (mainly) from the longitudinal development of the shower
- Break in $\langle X_{\max} \rangle$ at energy of the ankle
- Fluctuations decreasing with increasing energy

AUGER results

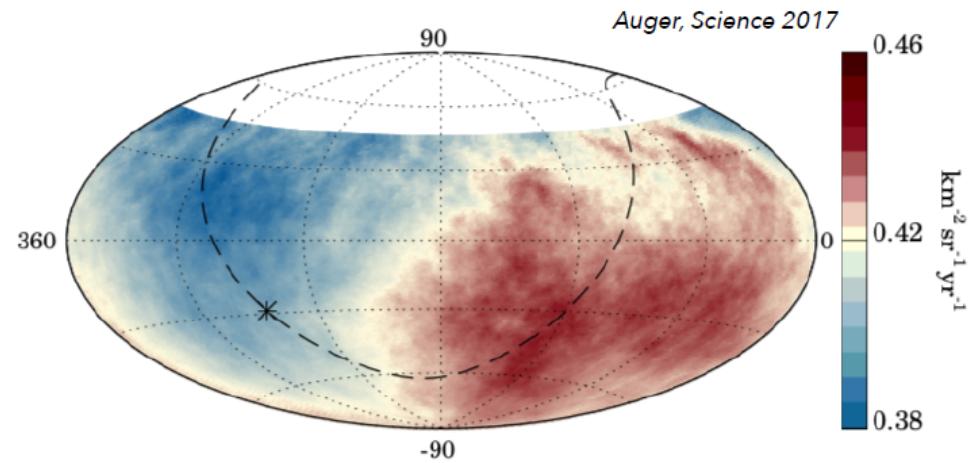


PIERRE
AUGER
OBSERVATORY

ANISOTROPY



- 114000 SD events
- 76800 km² sr yr exposure, 85% sky coverage
- Analysis of first harmonic in right ascension:
 - 4-8 EeV -> compatible with isotropy
 - >8 EeV: 3D dipole of amplitude 6.5% at 5.2 sigma



Magnitude and direction of the anisotropy support the hypothesis of extragalactic origin of UHECRs !

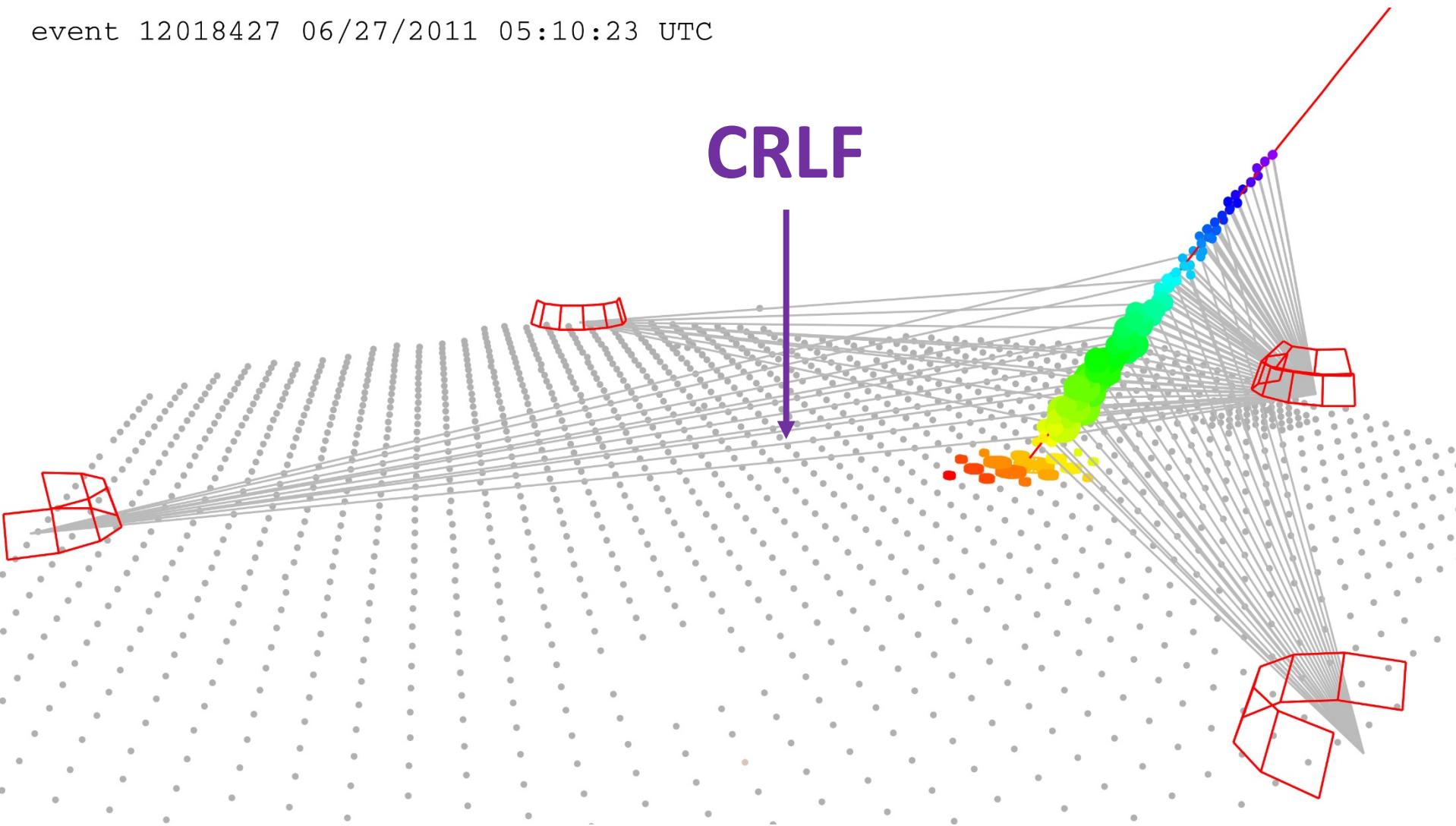
AUGER results

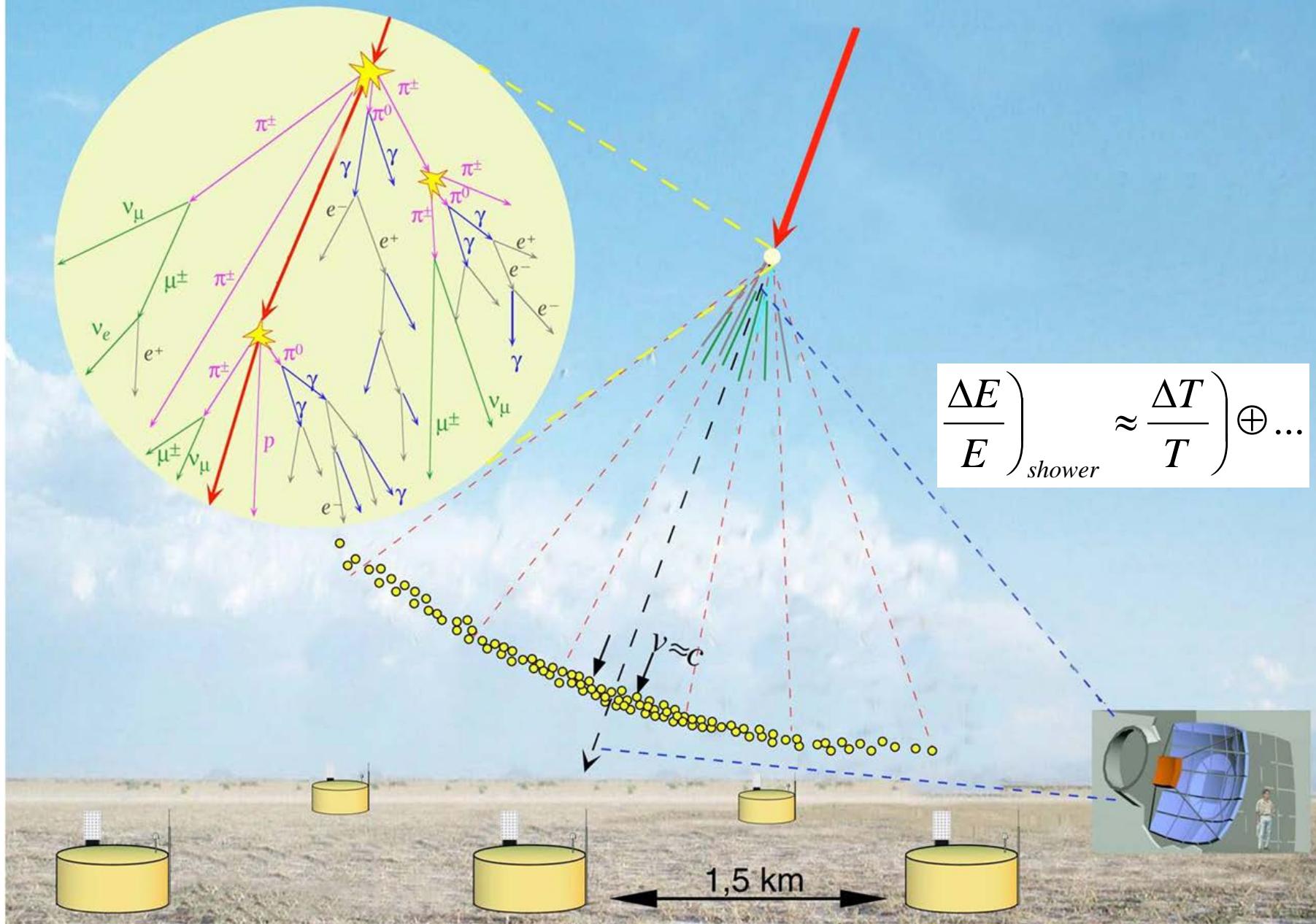
There is an impact of the estimations of the optical and thermodinamical status of the atmosphere on AUGER results.

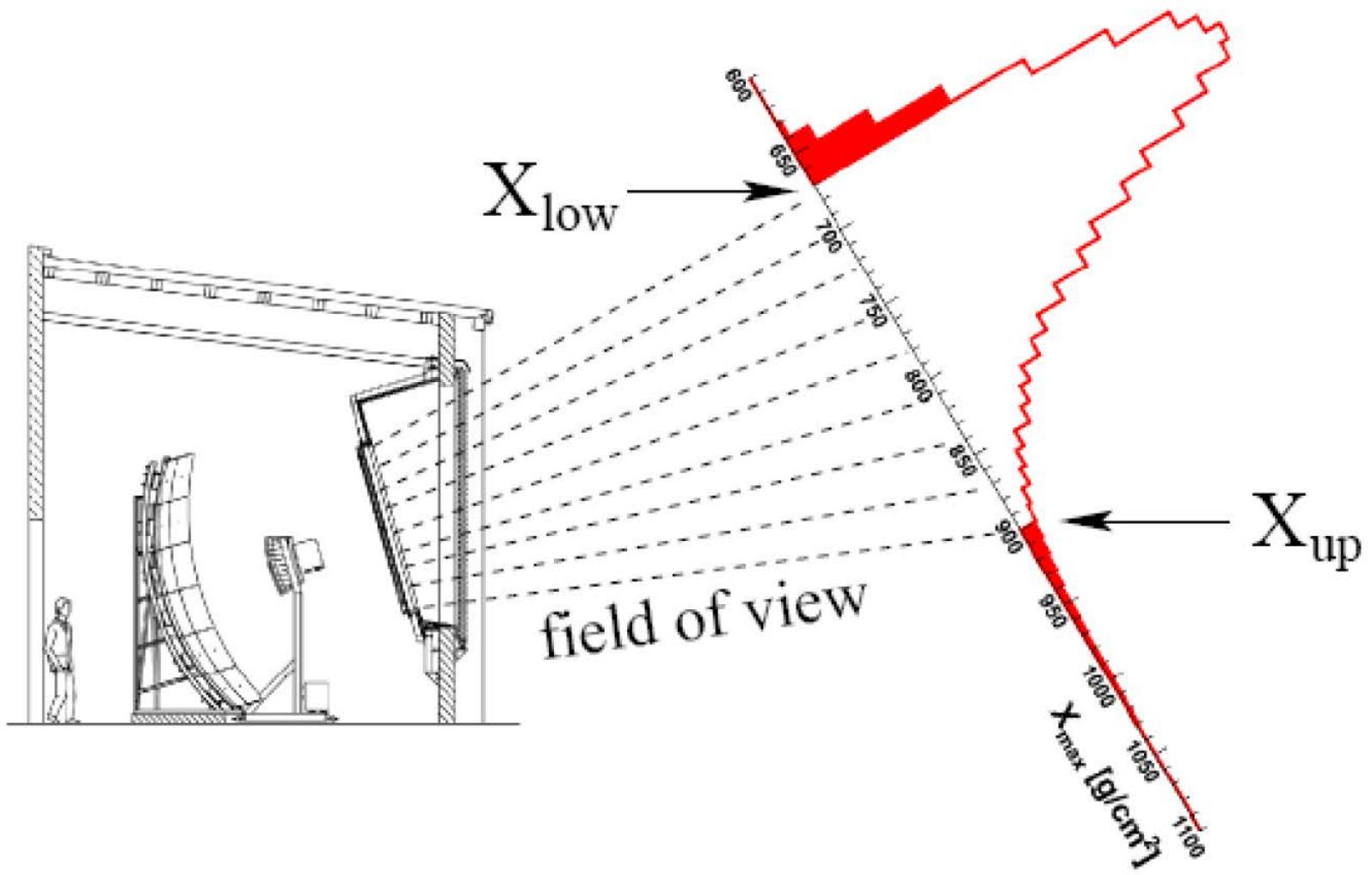
aerosol

event 12018427 06/27/2011 05:10:23 UTC

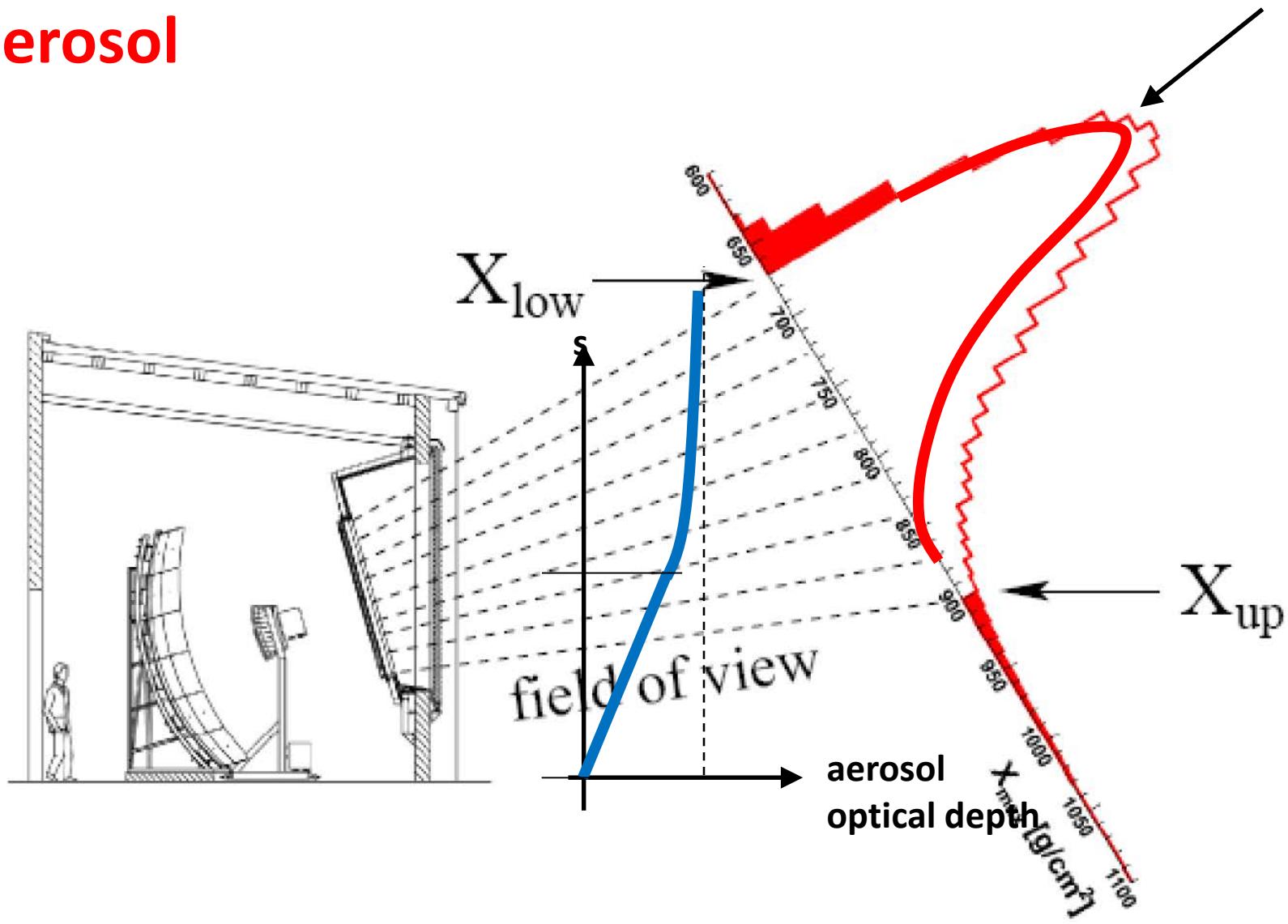
CRLF



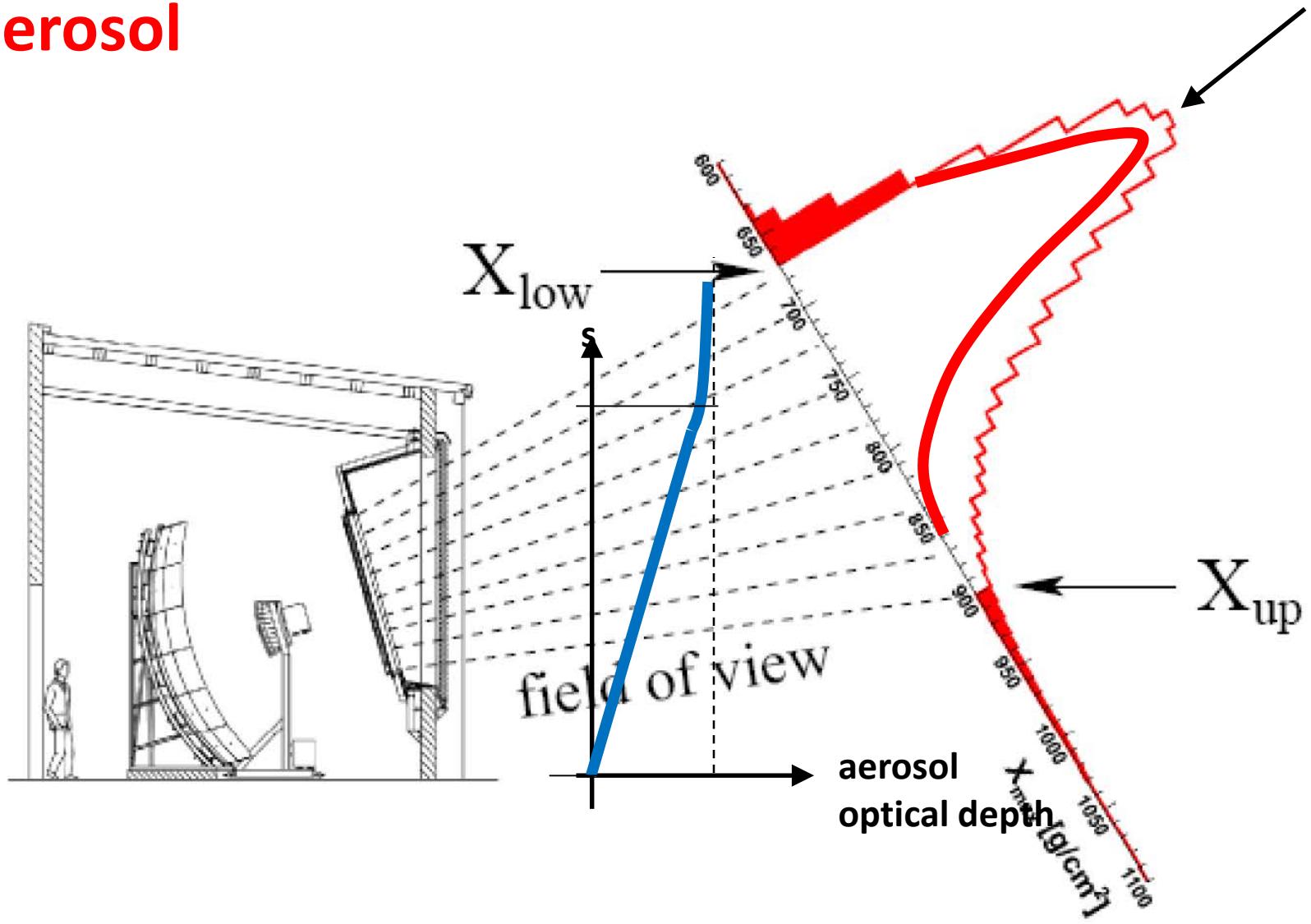




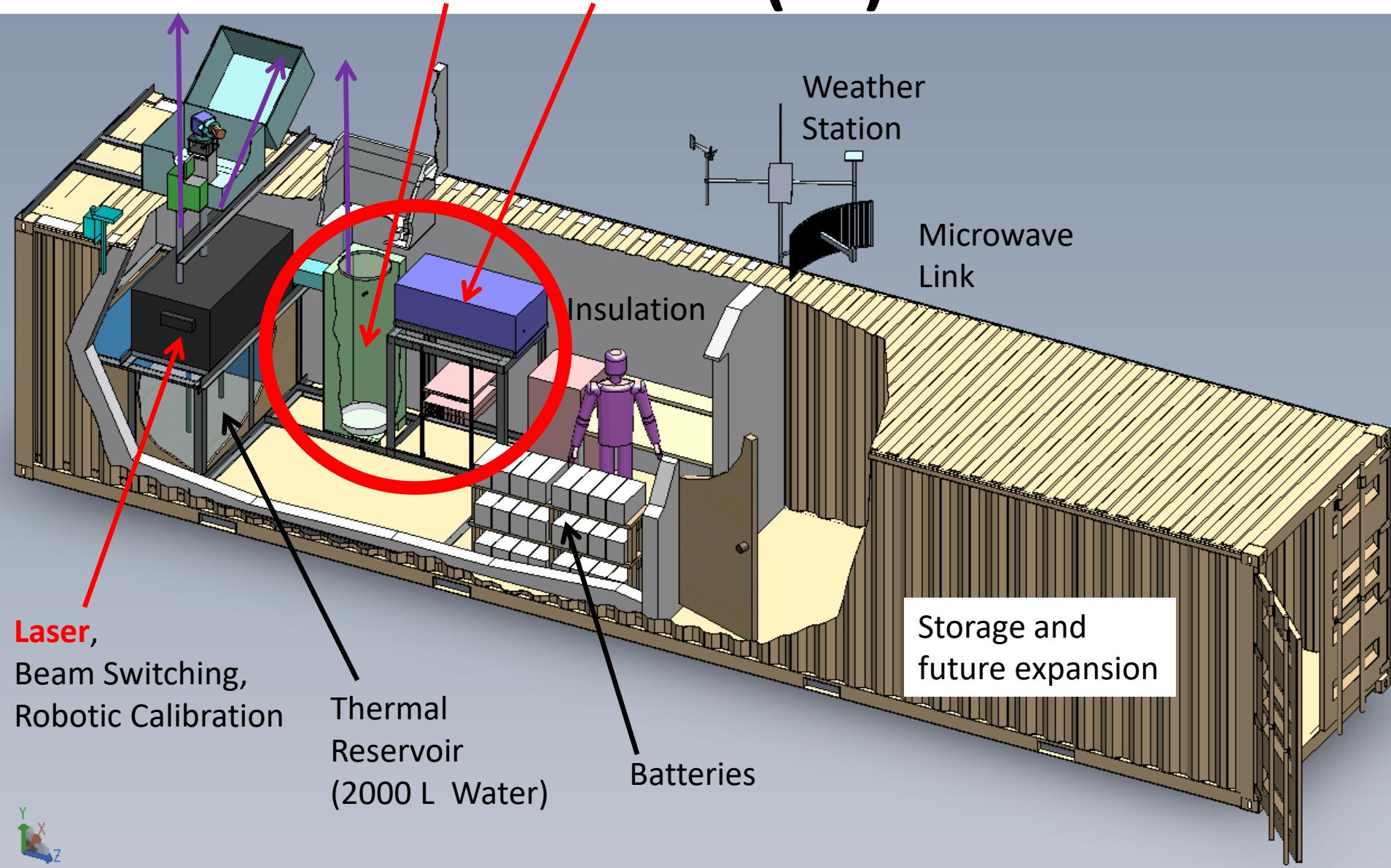
aerosol



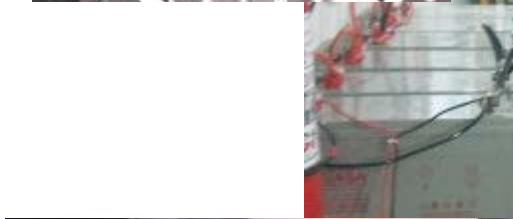
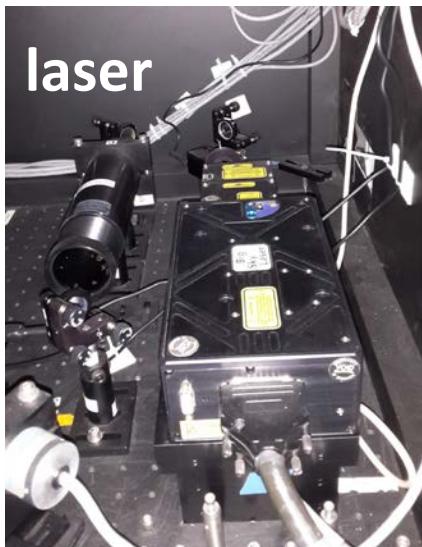
aerosol



Raman LIDAR (RL)



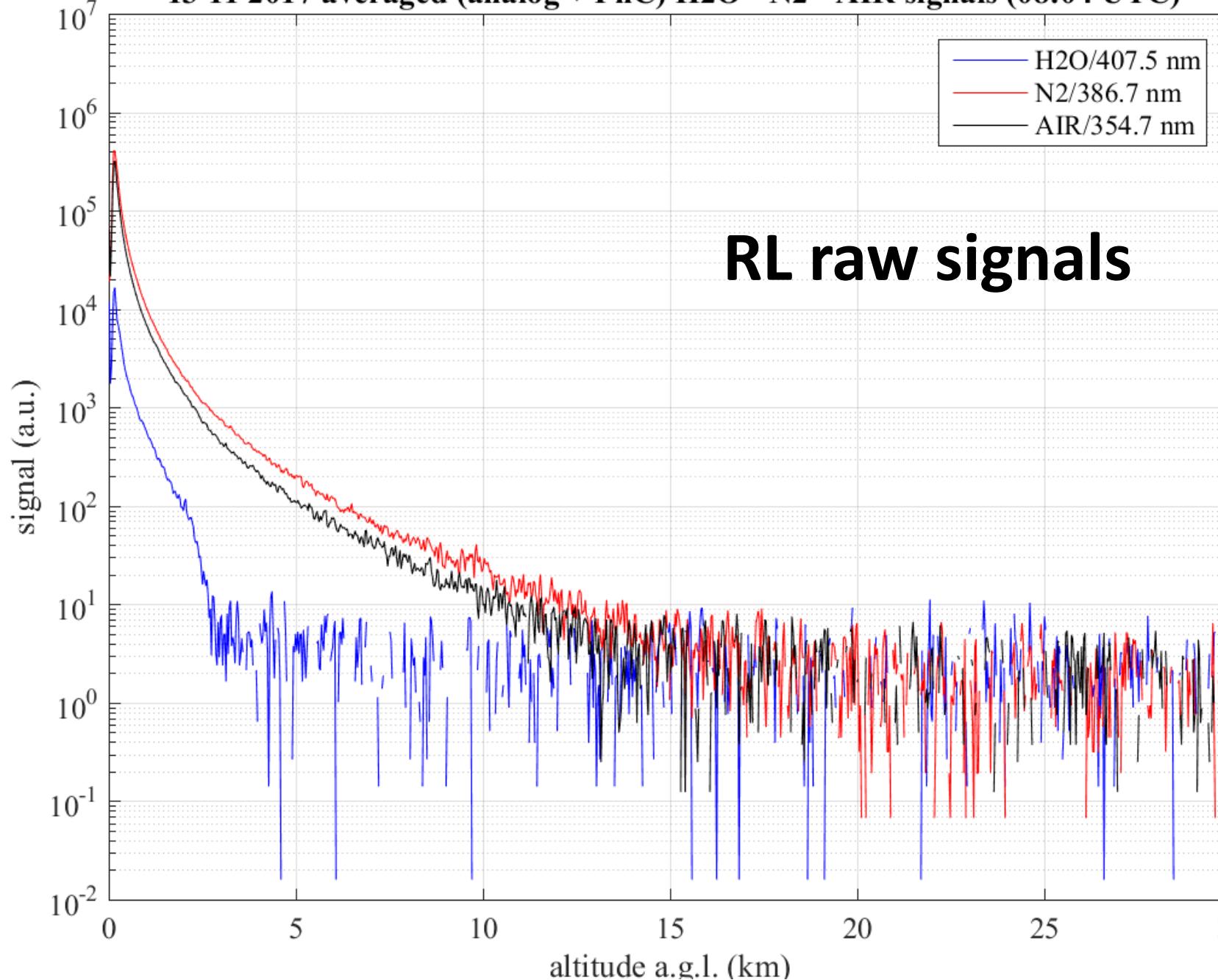
Raman LIDAR (RL)



f/3 Ø 50 cm
telescope



13 11 2017 averaged (analog + PhC) H₂O - N₂ - AIR signals (08:04 UTC)



Outline:

Performance

Cost

Maintenance

Data

~~Technical documentation~~

Science

Some considerations & Summary

Performance

The system is **automatic** and it is run at Central Raman Laser Facility (**CRLF**) during the **FD shift periods** in 3 time windows of about 15 minutes **before**, **during** and **after (BDA)** the daily FD shift.

- RAMAN shots: Next bays need to be close from 1:30 to 1:50 local time:
 - Los Leones: Bay 4
 - Los Morados: Bay 4
 - Loma Amarilla: Bay 3
 - Coihueco: Bay 3

[...]

[...]

The programmed measurements have been regularly taken. The RL database cover a period between September 2013 to present:

- 4885 measurements of vertical aerosol optical depth profile;
- 4713 measurements of the vertical aerosol volume backscatter profile;
- 3674 measurements of the vertical water vapour mixing ratio profile;

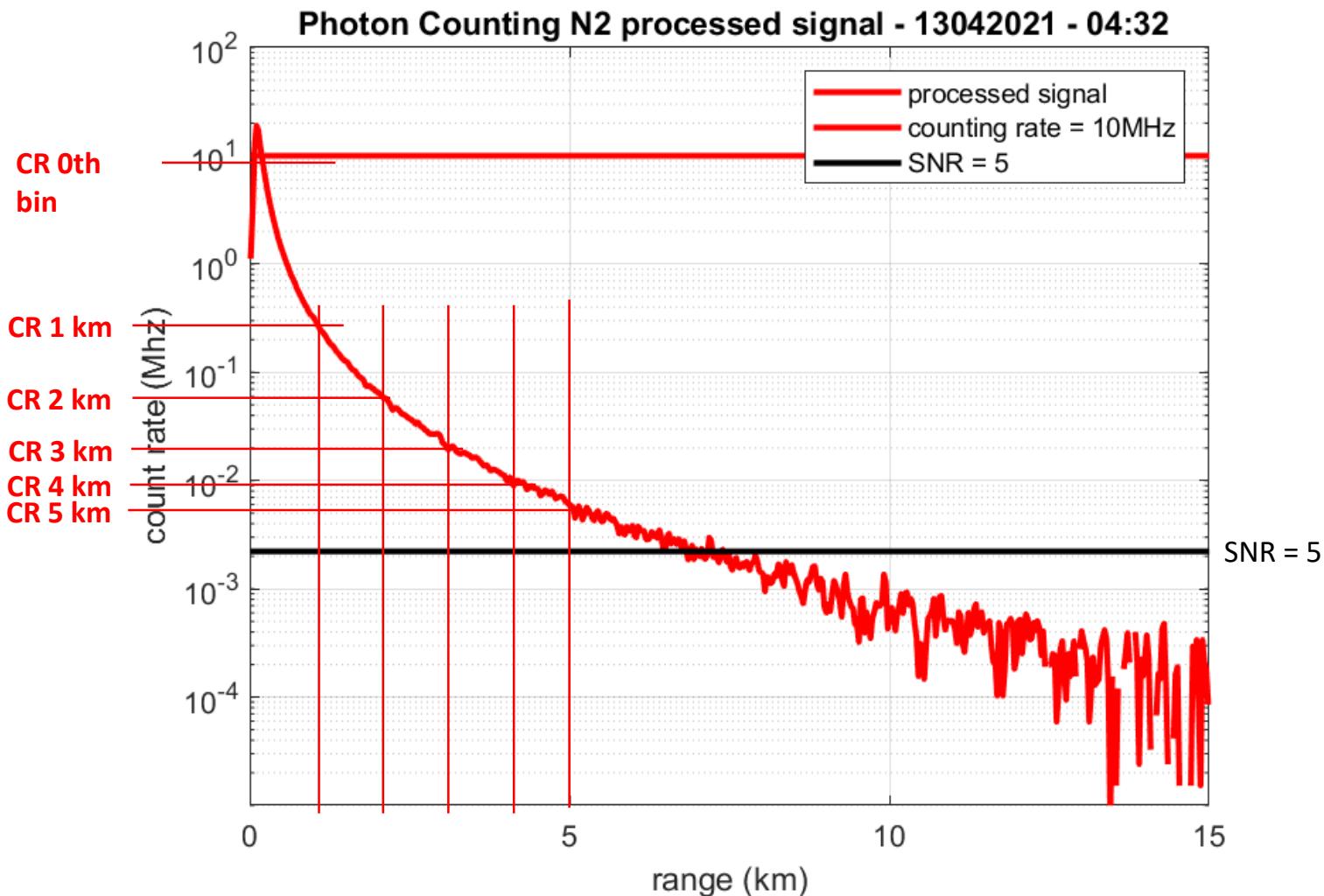
and the current BDA schedule of the observations has started since October 2014.

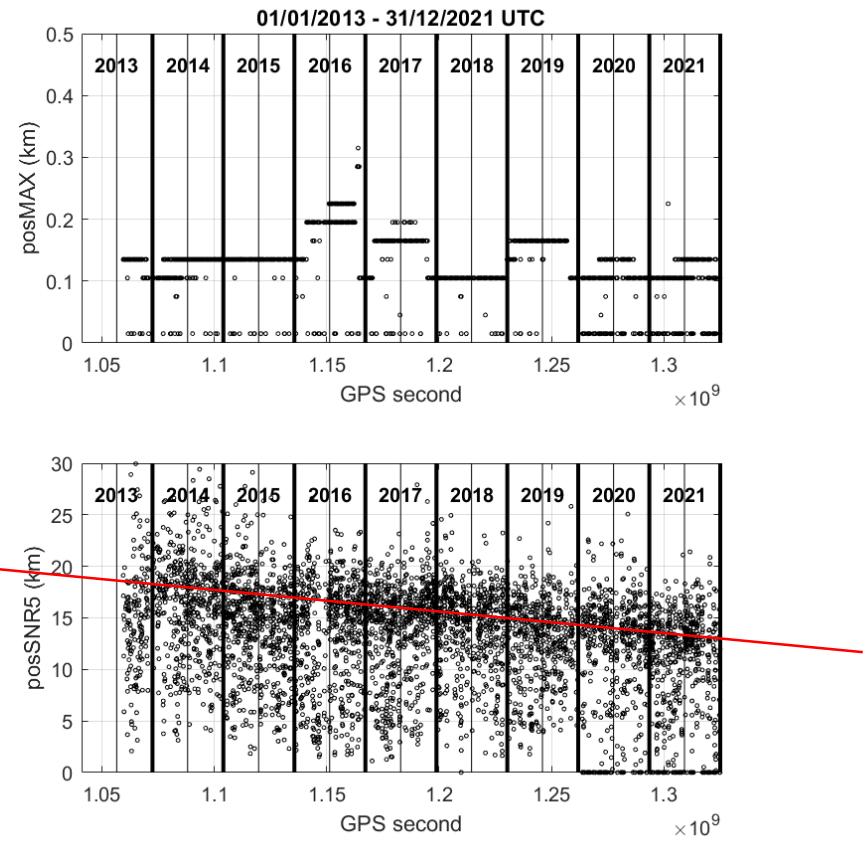
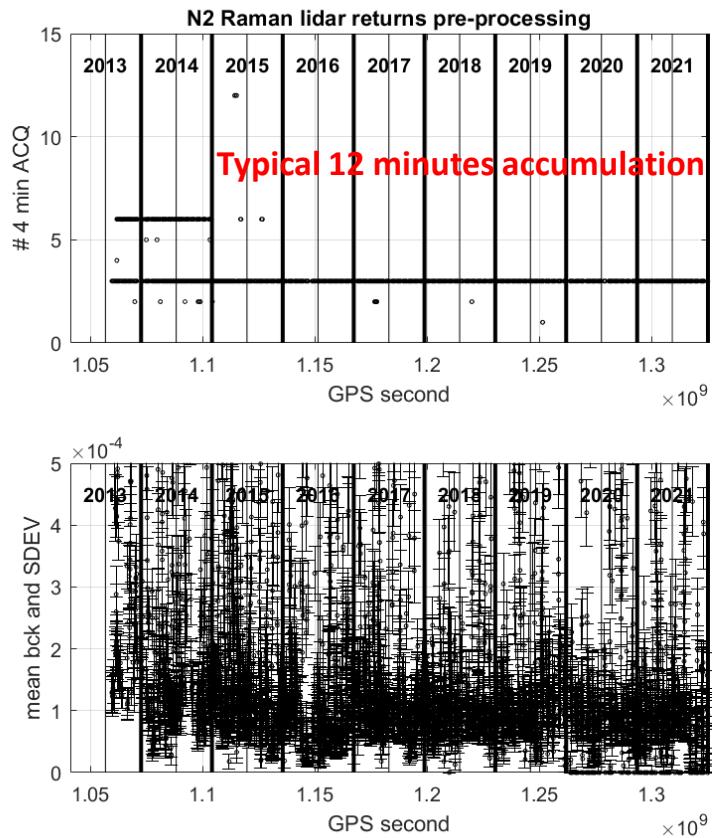
“metrics” confirm good long term performances
September 2013 - December 2021

Resume of N2 signals

2013-2021

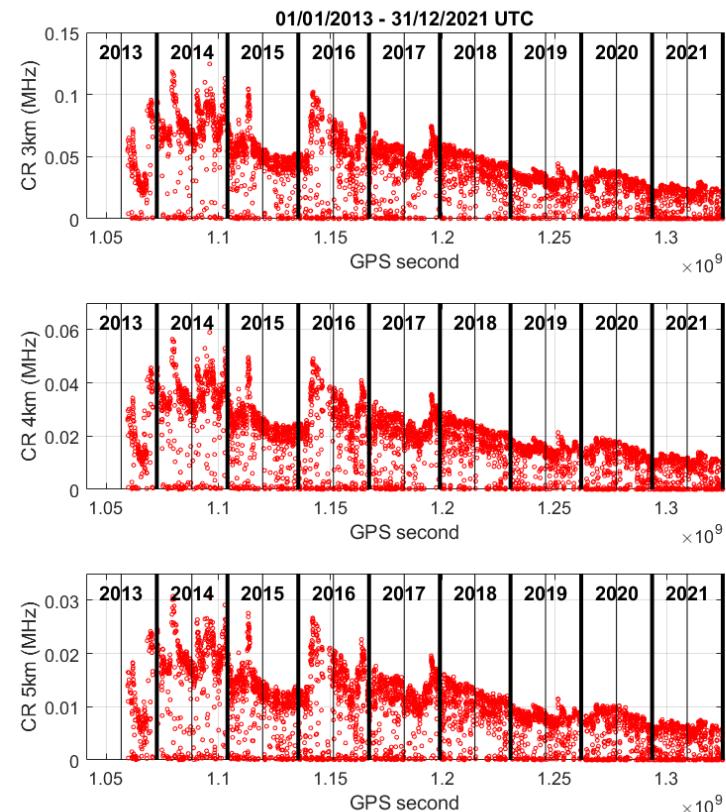
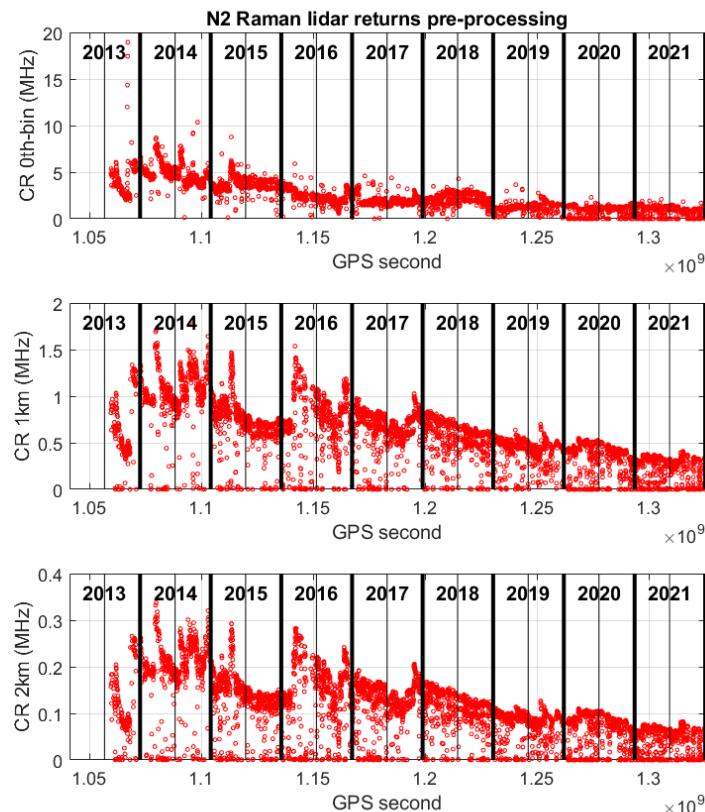
4885 sessions of measurements



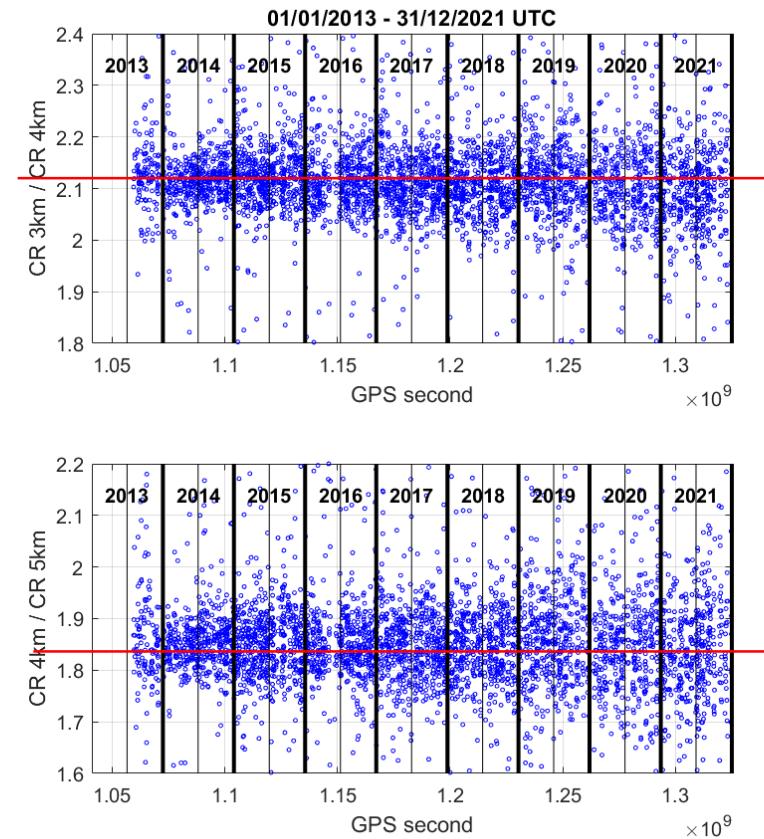
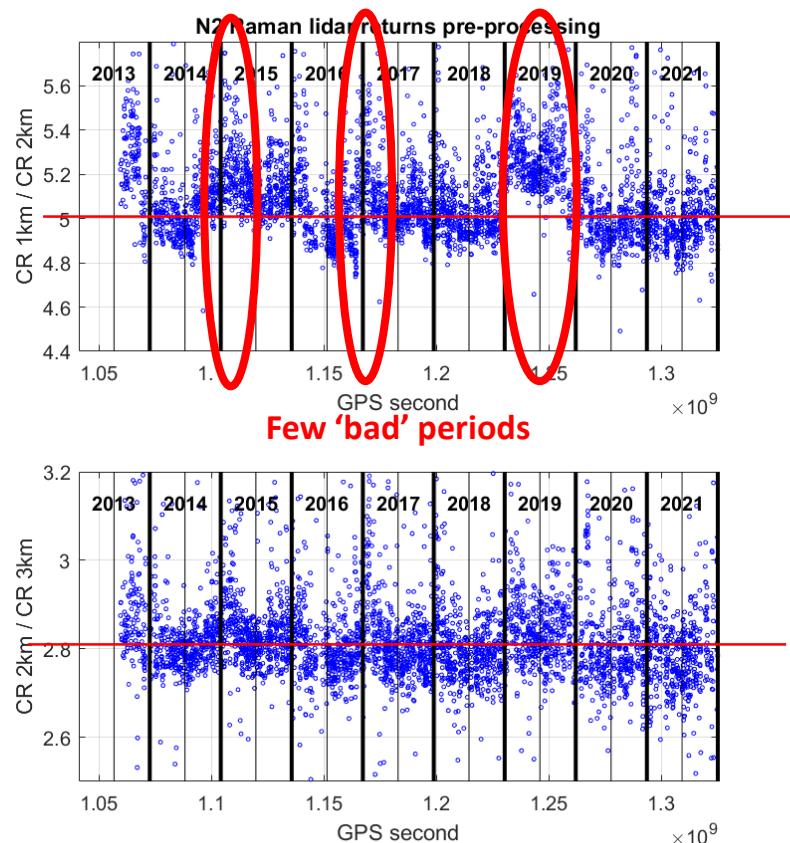


**The position where the signal has
Signal to Noise Ratio = 5 is decreasing**

Count rate (MHz) at 0, 1, 2, 3, 4, 5 km



Ratios of count rates (MHz): 1 km/2 km, 2 km/ 3 km, 3 km/4 km, 4 km/5 km



Conclusions:

- about 80 % of the scheduled observations were successful (recently it has decreased below 50 %);
- proxies of the laser energy indicate a decreasing of $\sim 4.0 \pm 1.0 \text{ \%}/\text{year}$;
- the Raman N2 signals show a season's dependance (due to the variation of aerosol loading);
- few 'bad periods', i.e. end 2014, start 2015, end 2015, all 2016, start 2017, all 2019; due to optical disalignments and/or dirt optics;
- the ratio between the signal level at different ranges show that most of the time the Raman lidar has good optical and mechanical stability, and the alignment problems, if present, are evident below 1.5 km altitude above ground level;
- similar info by the Rayleigh/Mie air/aerosol an Raman H₂O signals.

Data

INFN/L'Aquila is responsible of the analysis of the RL data.

RAW DATA (real-time)

Most of the N2 RL signals are in:

http://cetemps.aquila.infn.it/osservatorio/CLRF_raman_lidar/RL_data/N2_signals/

they are used (usable) to estimate the VAOD profiles

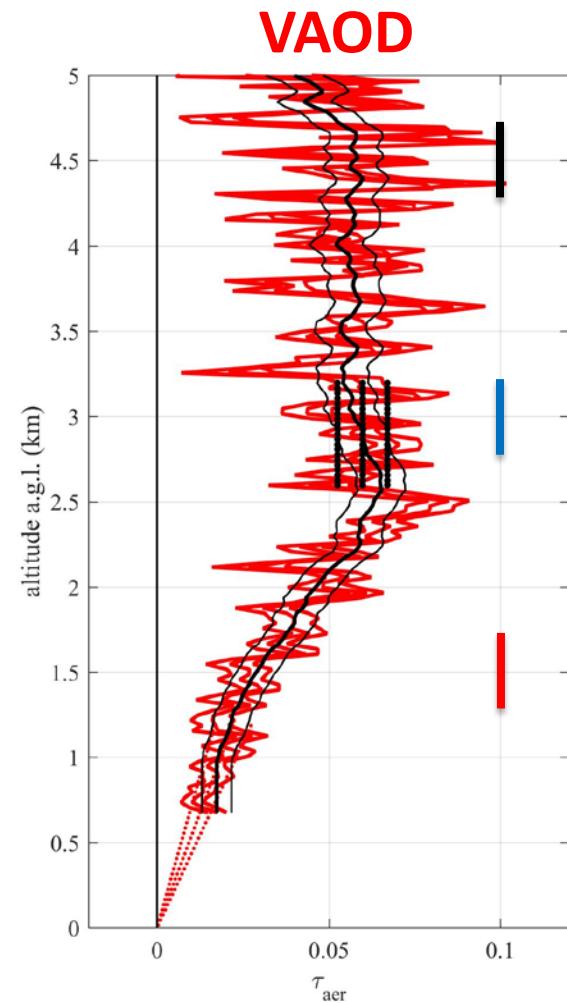
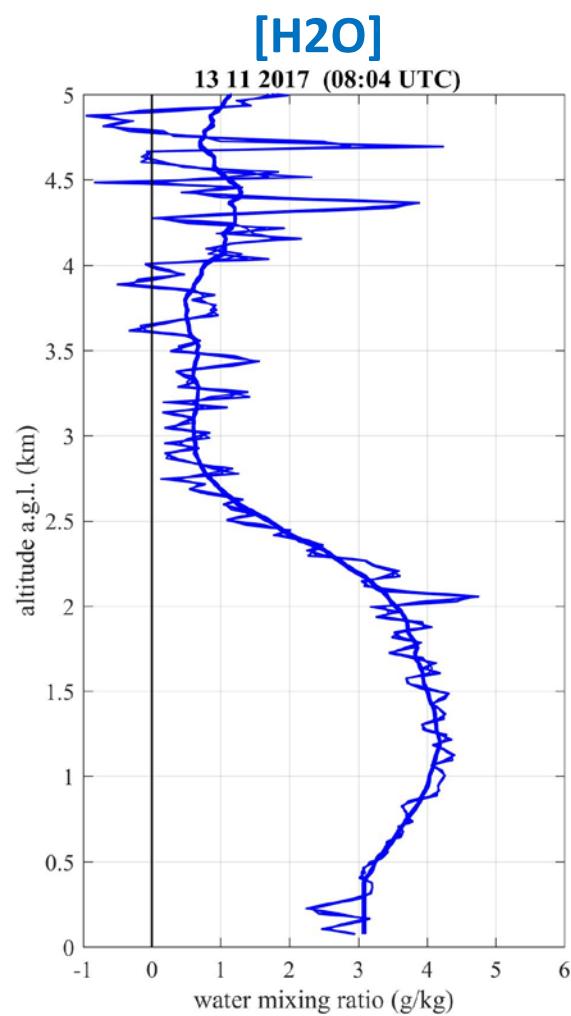
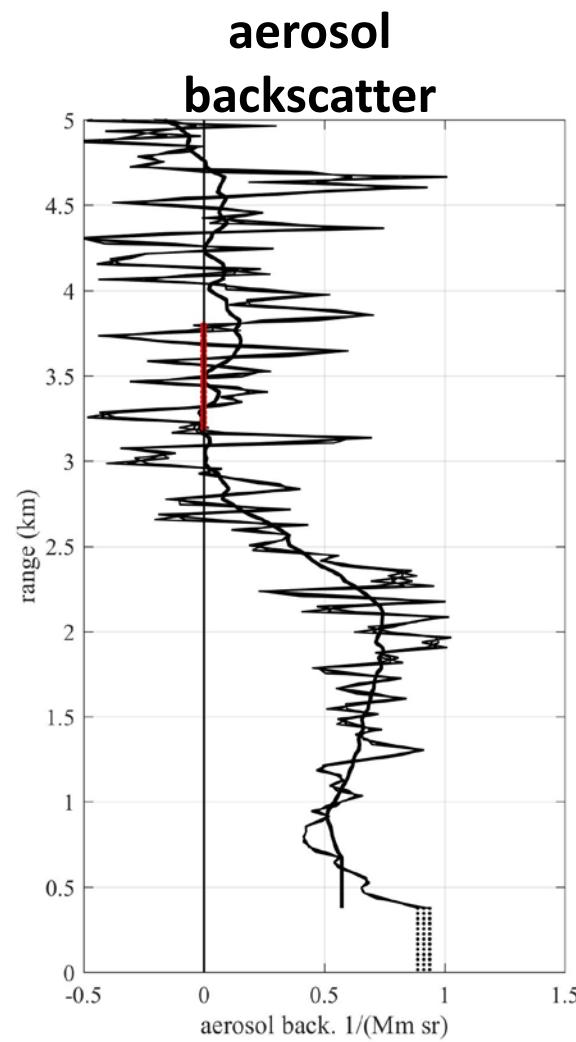
Filenames: L_N2_DDMMYYYY_hhmm.dat or L_N2_GPSsecond.dat (in
.../GPS_second/)

Format: [altitude agl (km)] [pre-processed signal a.u.]

raw vertical resolution: 30 m

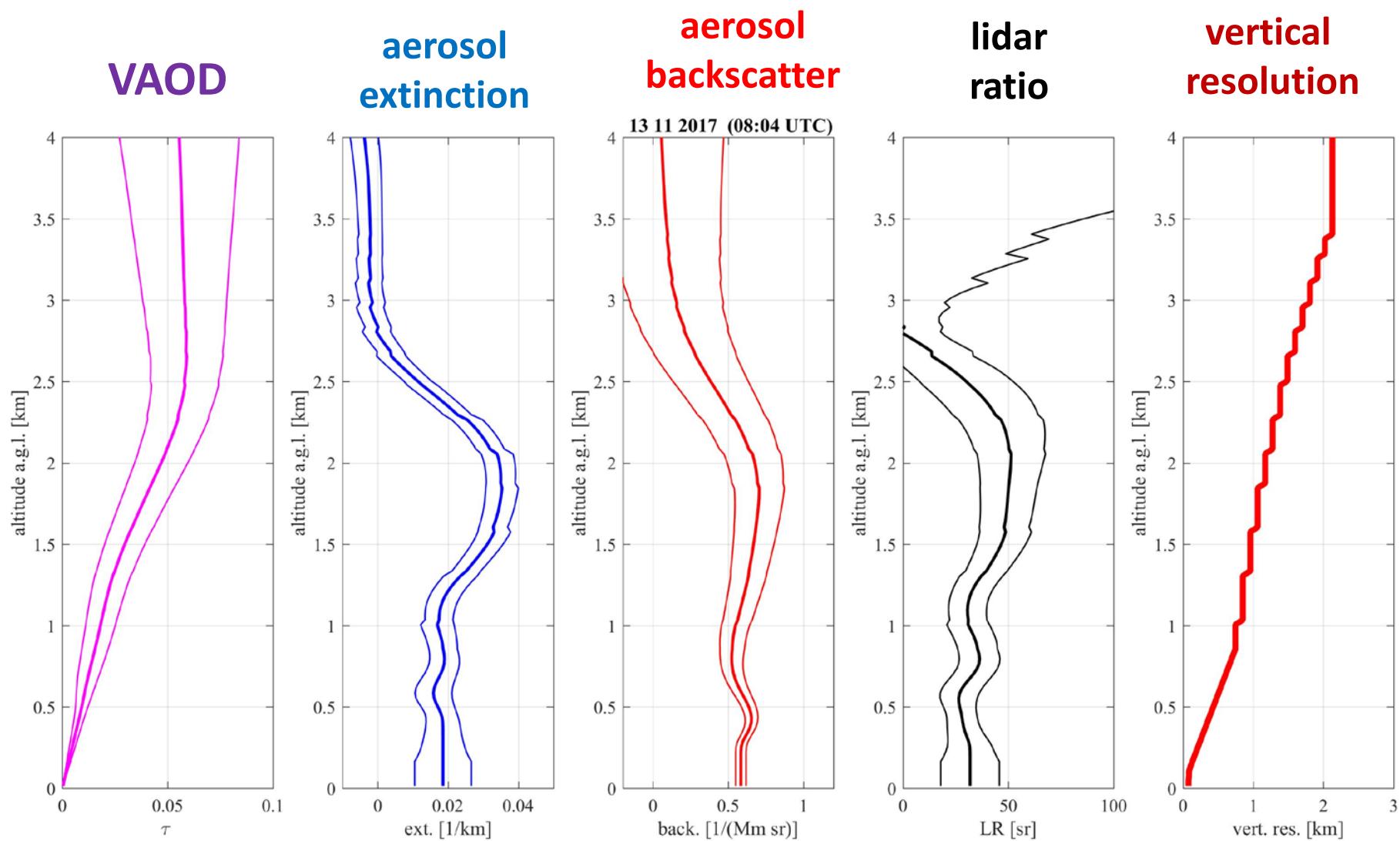
Data period: **2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021
and ...**

12 min run during FD shift



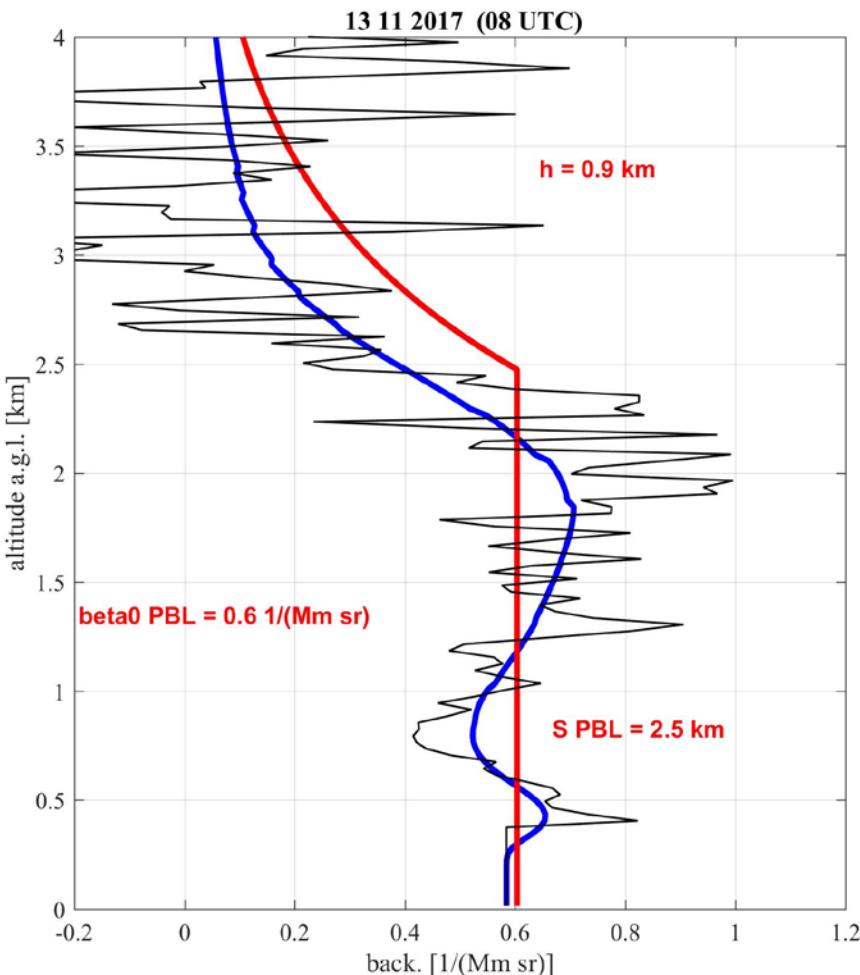
13/11/2017 08:04 – 08:16 UTC

12 min run during FD shift

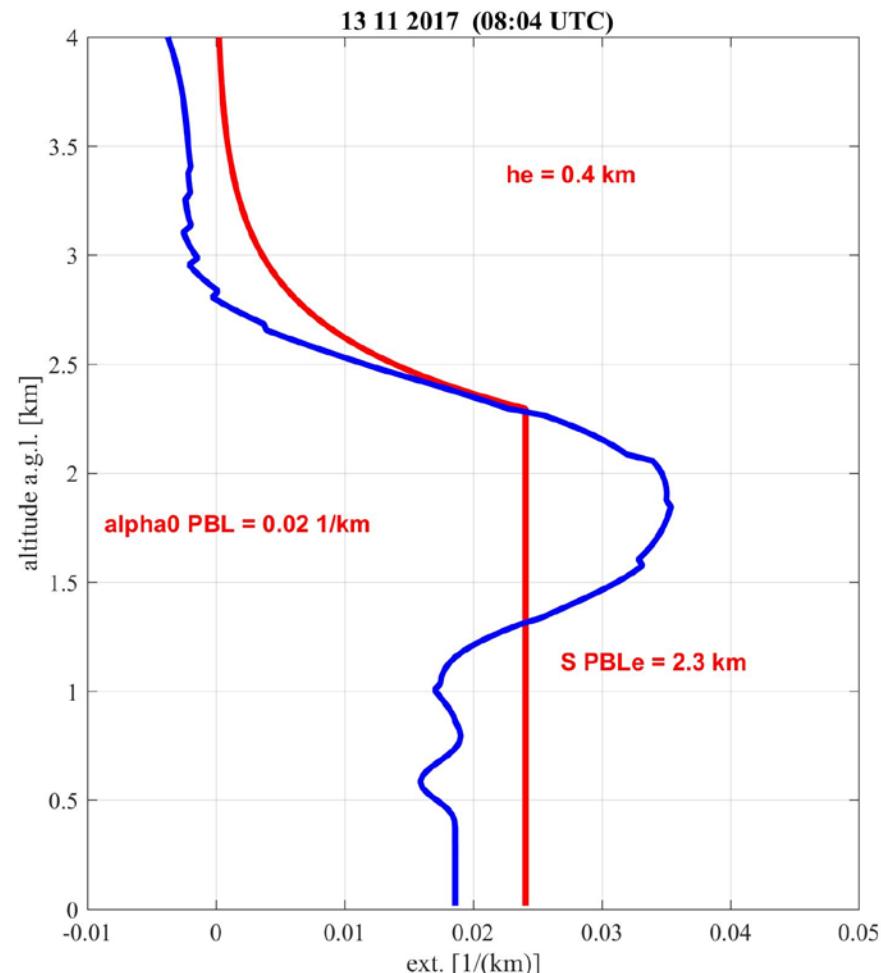


13/11/2017 08:04 – 08:16 UTC

13/11/2017 08:04 – 08:16 UTC



aerosol backscatter



aerosol extinction

aerosol model ...

PBL height and transition zone to free troposphere

data NOV2013-DEC2021

1.5, 3.0, 4.5 KM ALTITUDES ABOVE GROUND LEVEL (a.g.l.)
Aerosol Optical Depth (AOD)

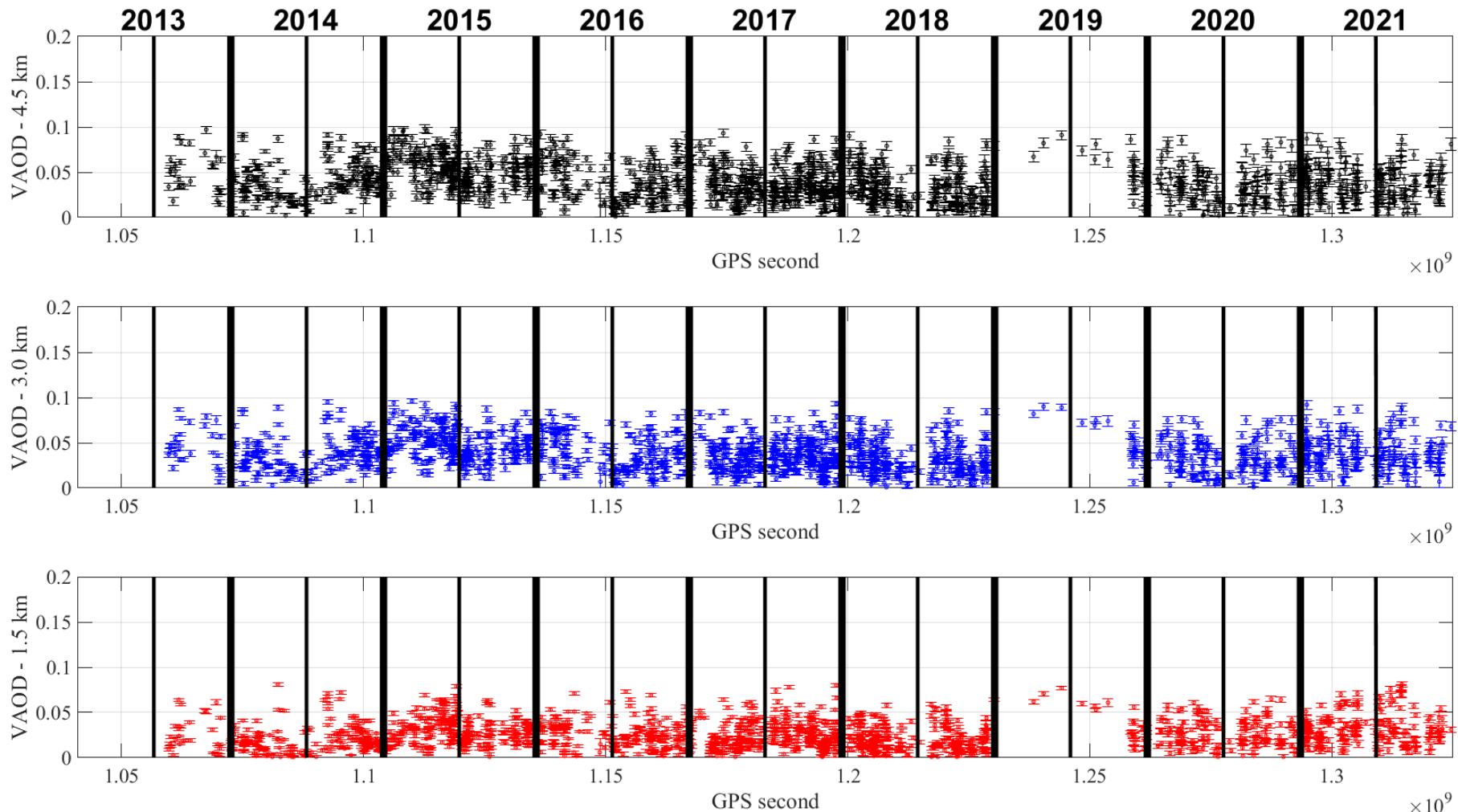
VAOD data selection: simple criteria

$0 < \text{VAODvalue}@1.5\text{km} < 0.05$

$0 < \text{VAODvalue}@3.0\text{km} < 0.10$

$0 < \text{VAODvalue}@4.5\text{km} < 0.10$

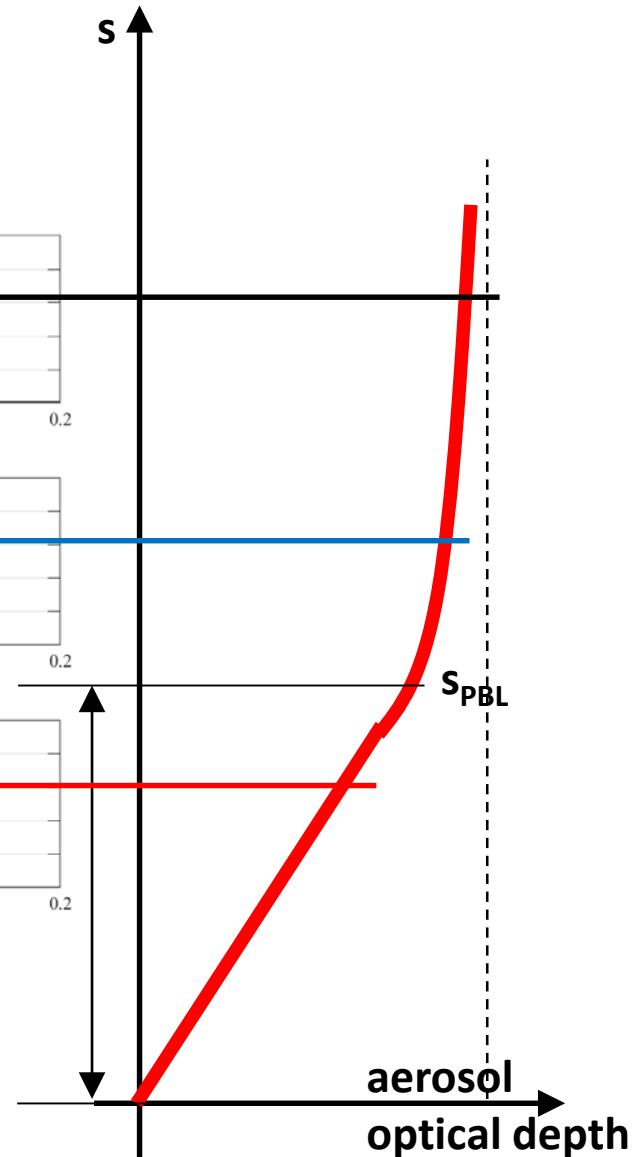
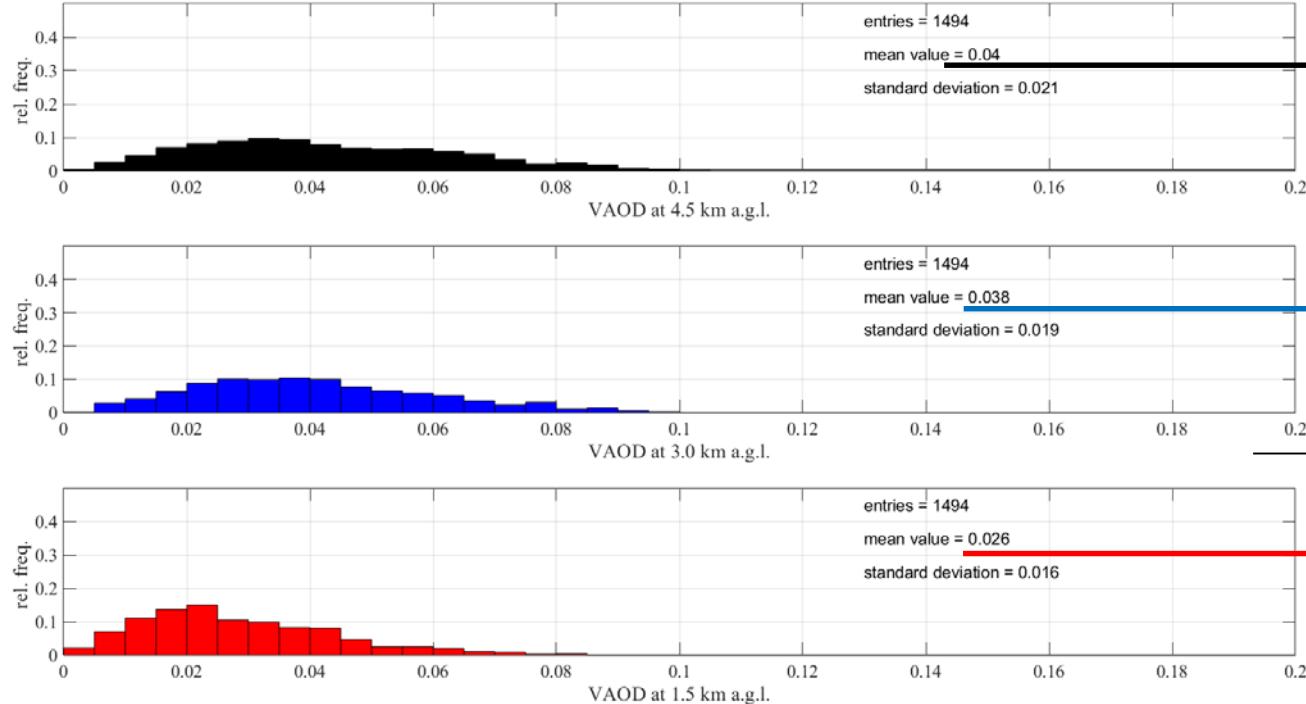
Quality cuts and cloud masking.



VAOD values

Science

1494 profiles

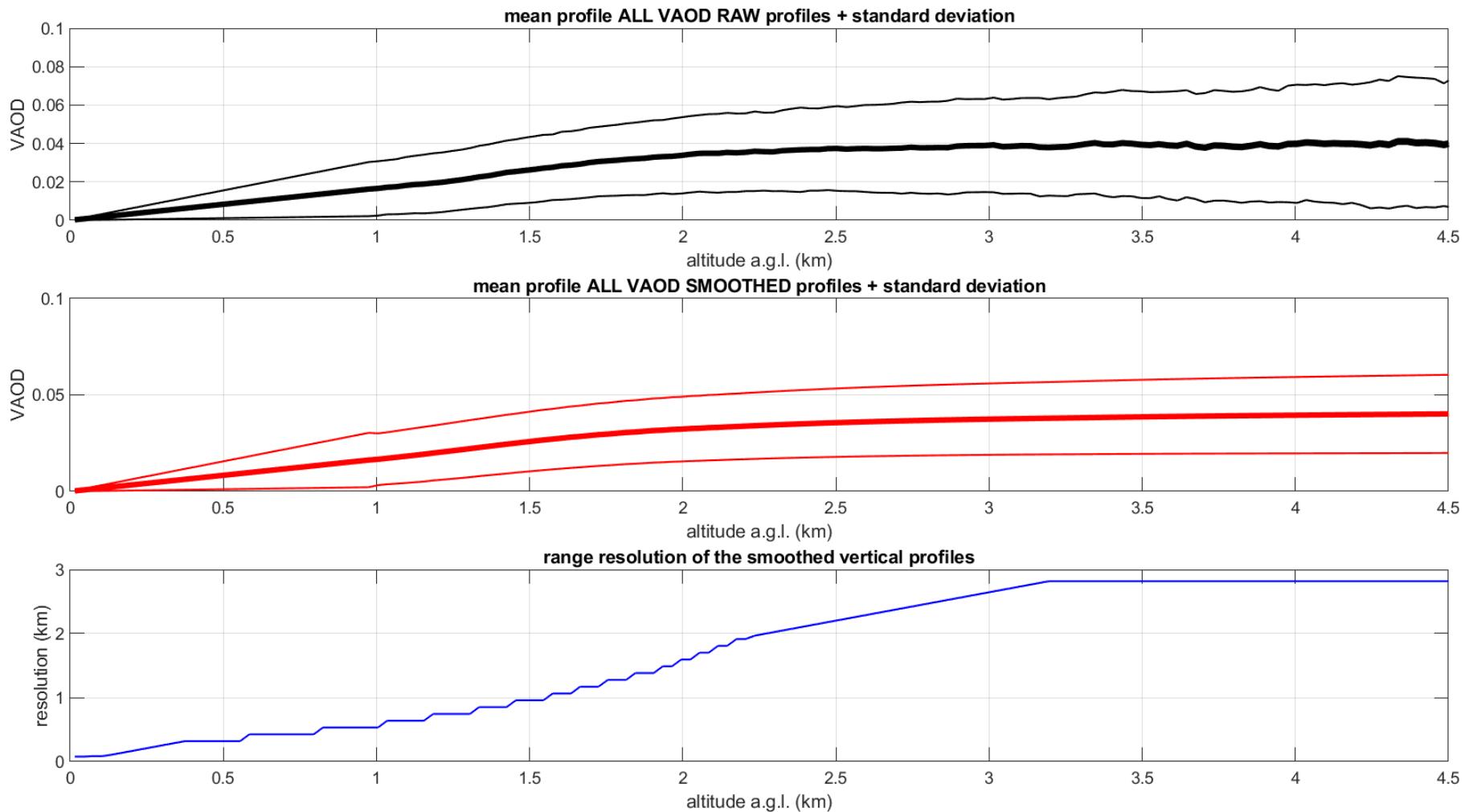


NOV2013-DEC2021

VAOD values

Science

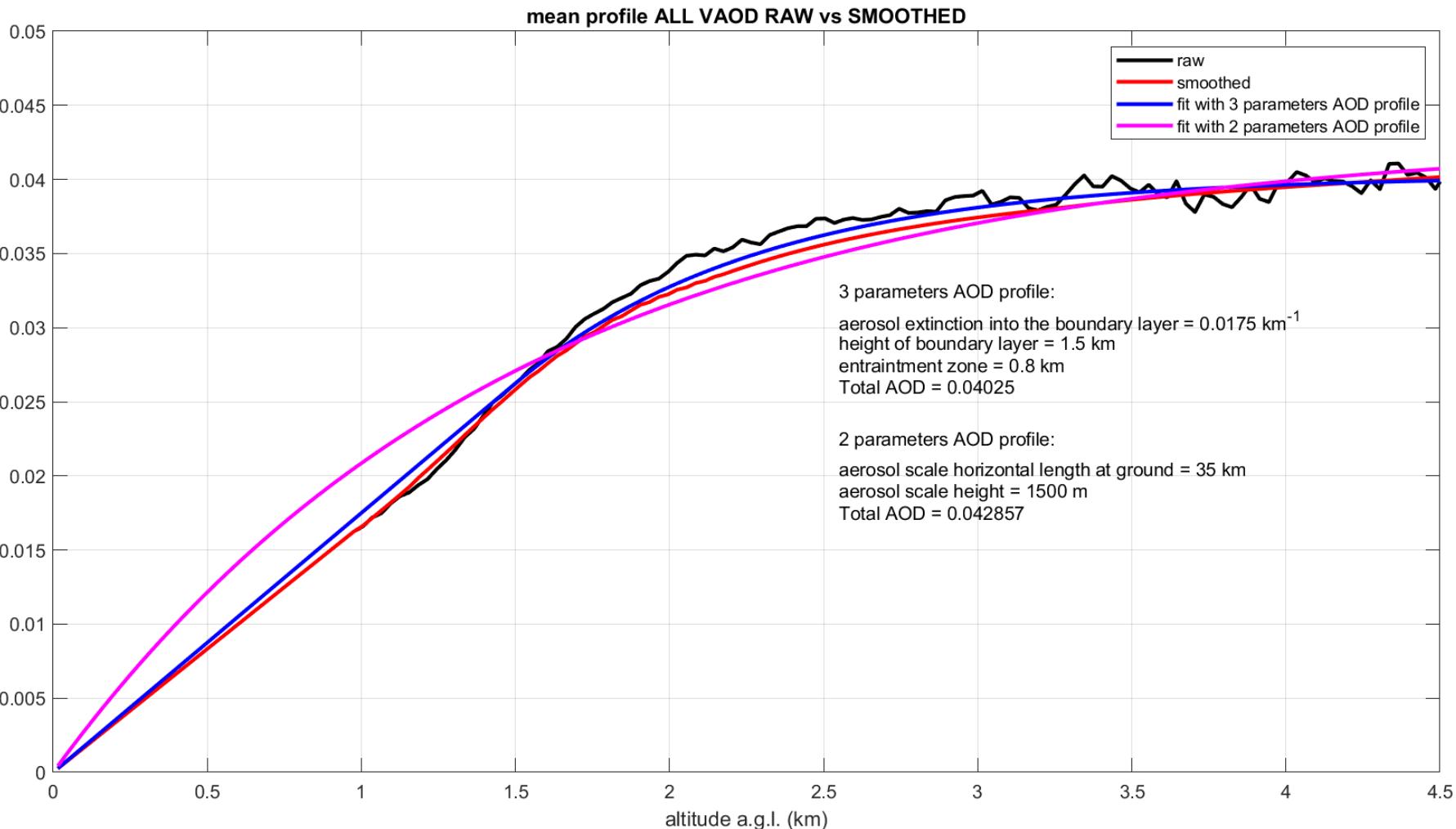
Global mean VAOD profile



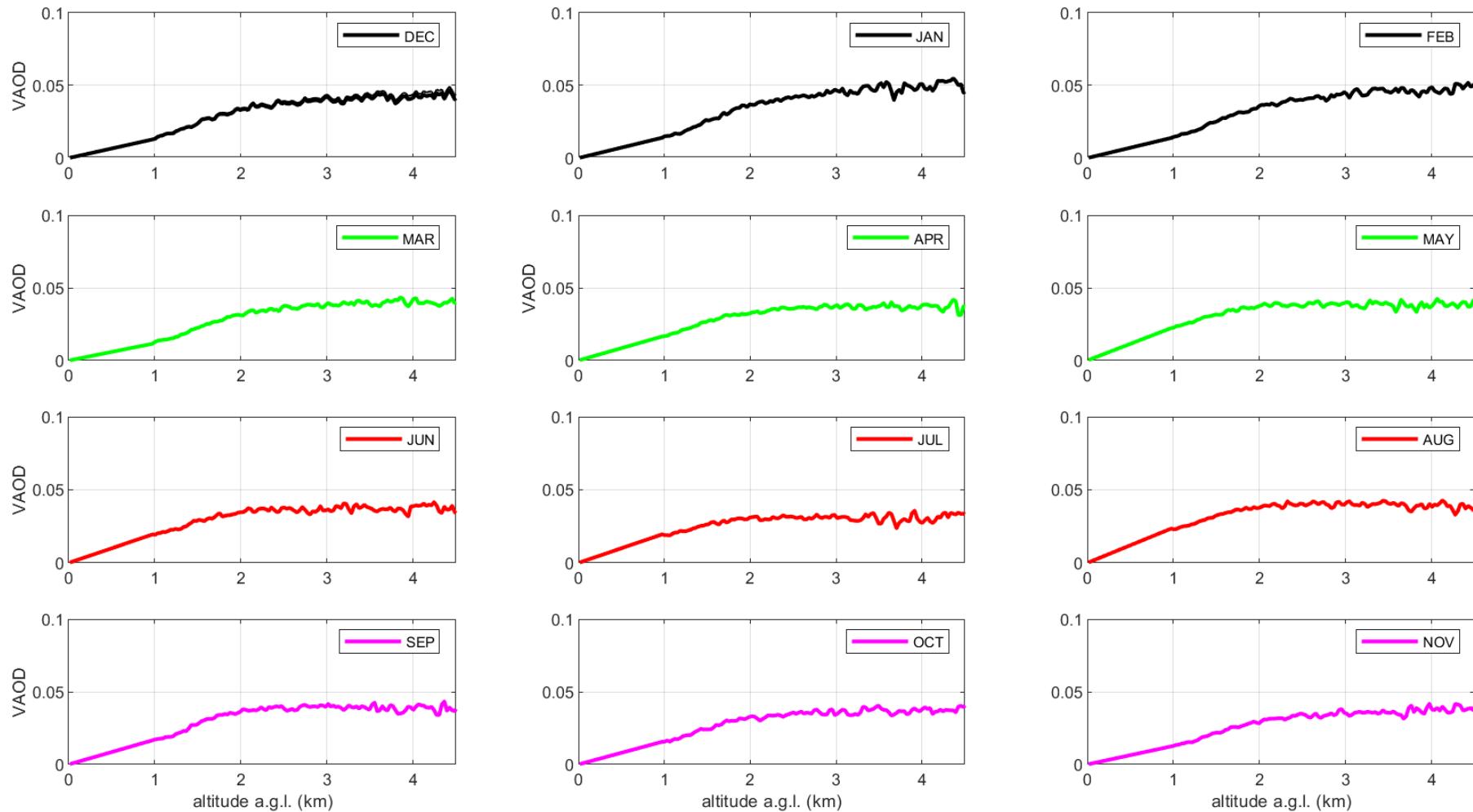
VAOD values

Science

Global mean VAOD profile



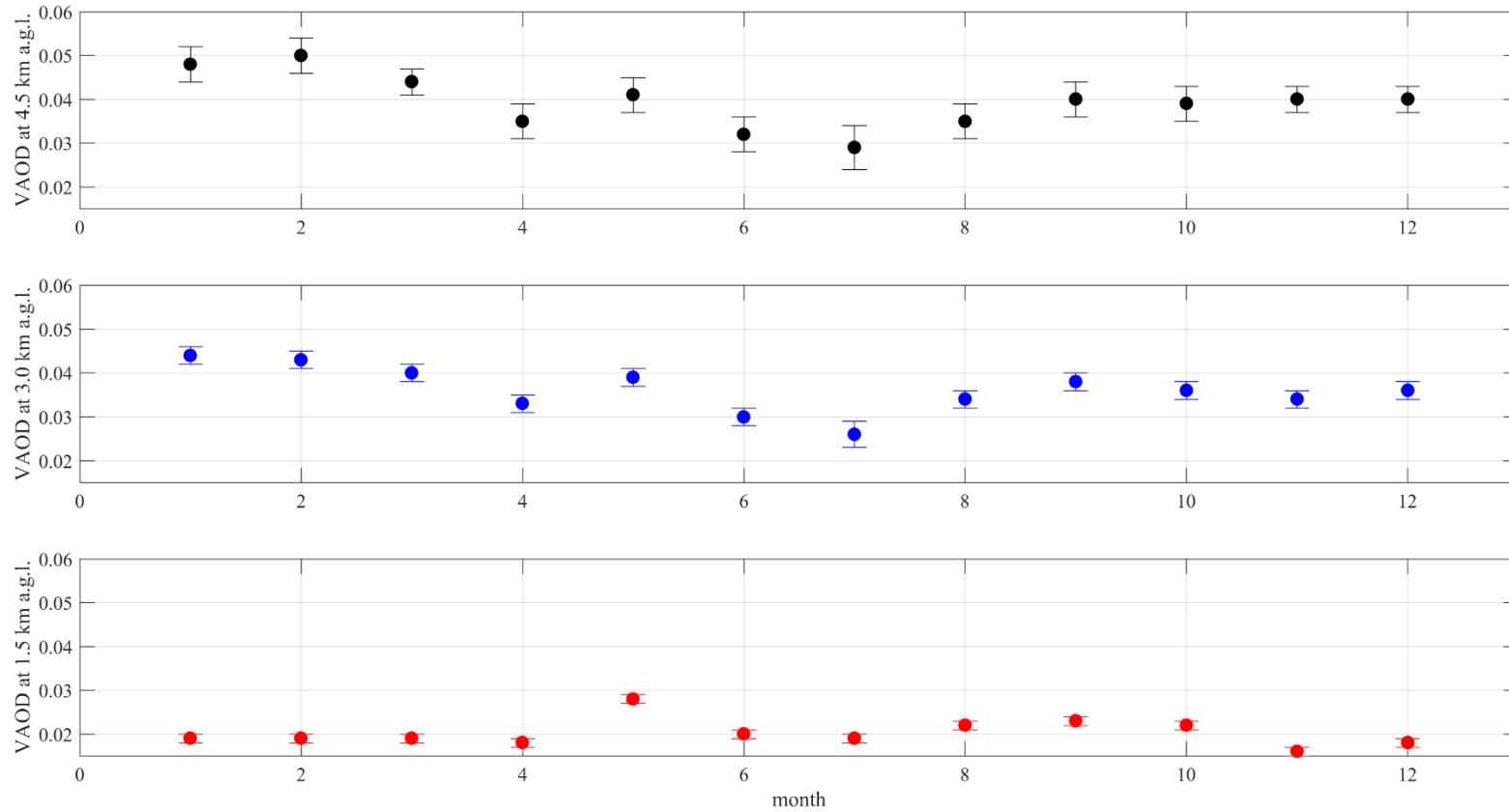
Monthly mean profiles



VAOD values

Science

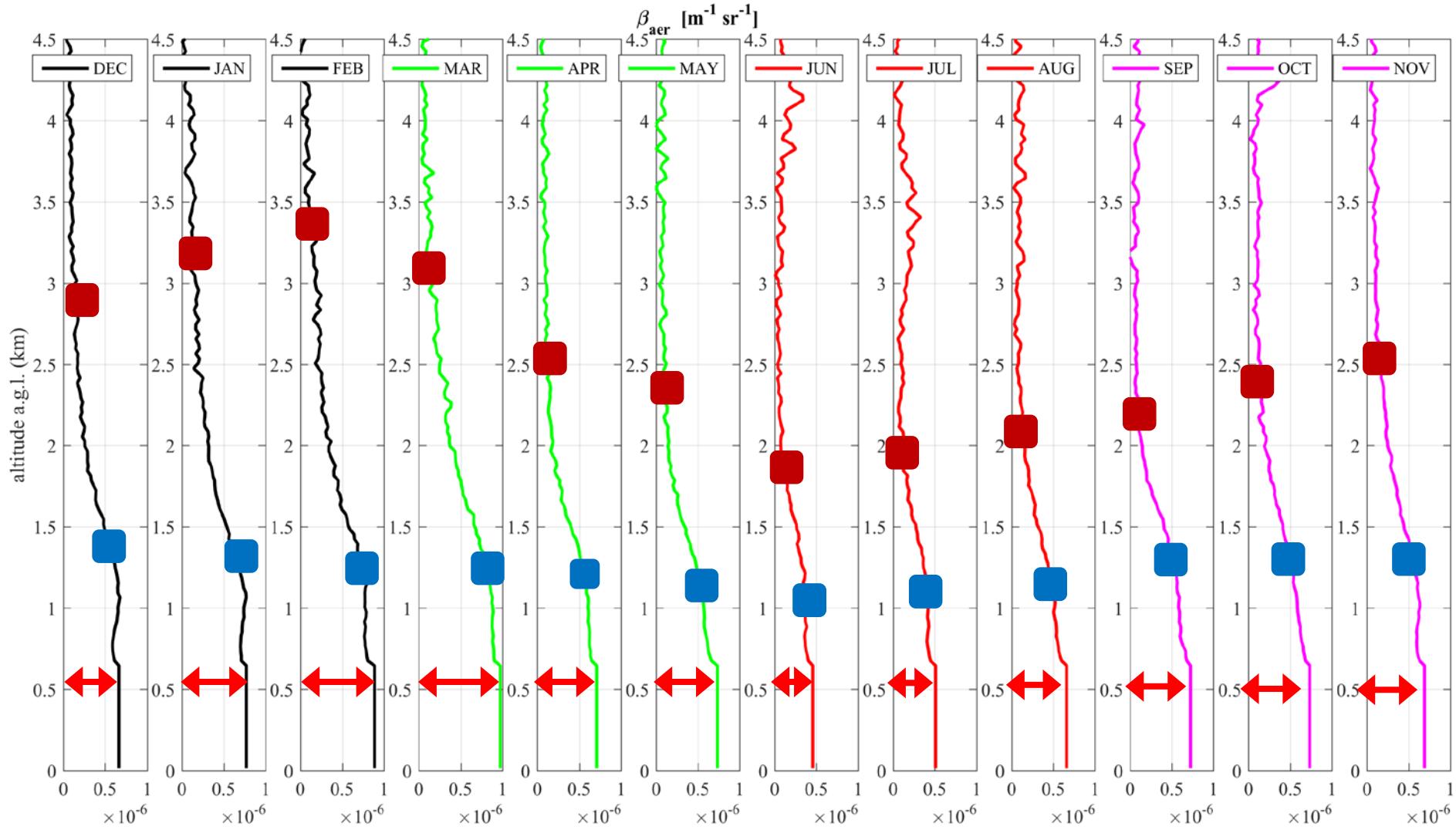
Monthly mean values



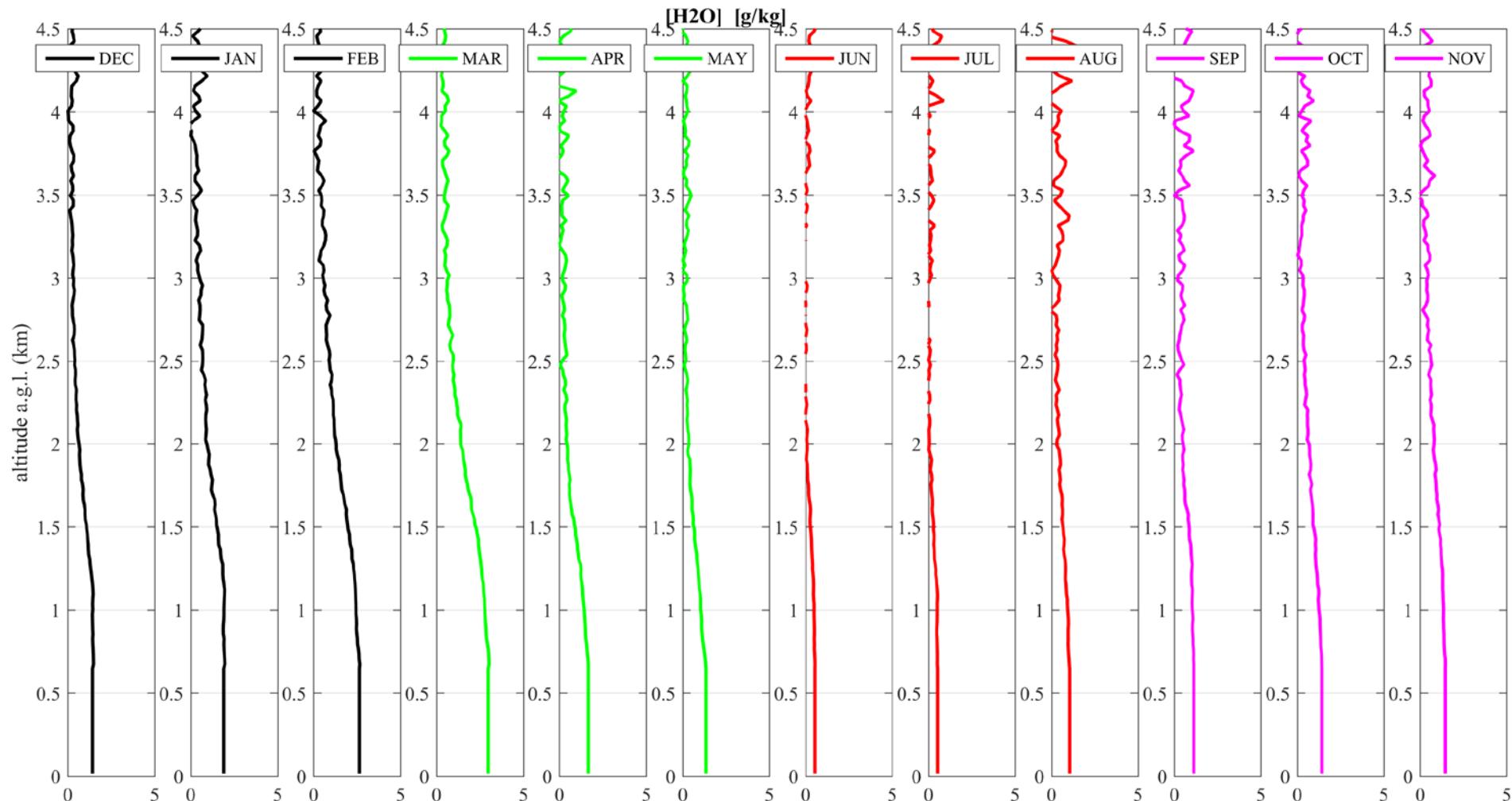
Conclusions:

- masking for clouds, high aerosol content and bad measurements selects 1494 out of 4885 observations;
- the overall mean/stdev AOD values at 4.5 km a.g.l. is 0.039 ± 0.019 ;
- the vertical AOD profile has a monthly variability and its shape can be represented with a 2 parameters (total AOD and scale height) or 3 parameters (boundary layer height, total AOD and entrainment zone extension);
- similar info can be obtained with the estimation of aerosol volume backscatter which is less affected by eventually present optical disalignments.

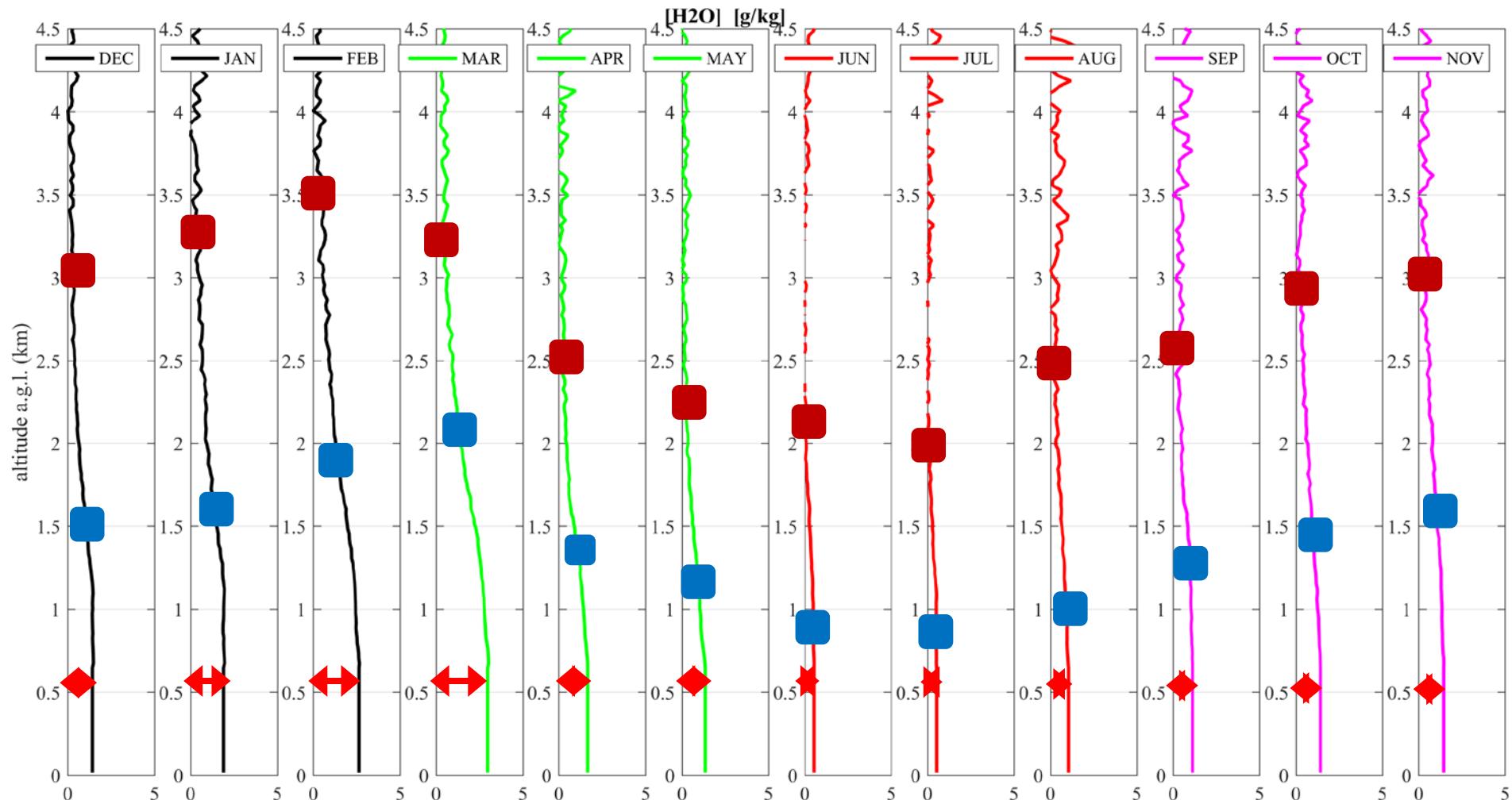
Monthly mean profiles - backscatter



Monthly mean profiles – water vapour



Monthly mean profiles – water vapour



Considerations & SUMMARY

The AUGER RL can continue to run in the present mode, its impact on FD data taking duty cycle seems negligible.

Other strategies of measurements can easily implemented.

Improvements in RL optics

Laser lifetime

Considerations & SUMMARY

RL VAOD database

gpstime

max_quota_db

min_quota_cloud

altitude (a.s.l.)

alfa

alfa_min_uncorrelated

alfa_max_uncorrelated

alfa_min_correlated

alfa_max_correlated

vaod

vaod_min_uncorr

vaod_max_uncorr

vaod_min_corr

vaod_max_corr

data at a resolution of 200 m, up to max_quota_db.

alfa = aerosol extinction coefficient

correlated = systematic

uncorrelated = statistical

Considerations & SUMMARY

- RL is measuring the aerosol optical properties at 355 nm since November 2013;
- the RL data analysis is documented and reproducible;
- the shape of the measured vertical profiles of the aerosol backscatter and extinction suggest a simple model of the aerosol vertical distribution;
- the measured vertical profiles of the aerosol backscatter and extinction show, as expected, a seasonal dependence;
- the database of the raw RL signals, and RL vertical profiles of the aerosol backscatter, VAOD, (and water vapour) will be made available with all the documentations and analysis programs;
- maybe it is time for a paper describing RL data;
- [...] comparison with other techniques;

CTA – INFN Raman lidar @ La Palma - ORM

<https://www.aquila.infn.it/arcade/>



UHECR2022:

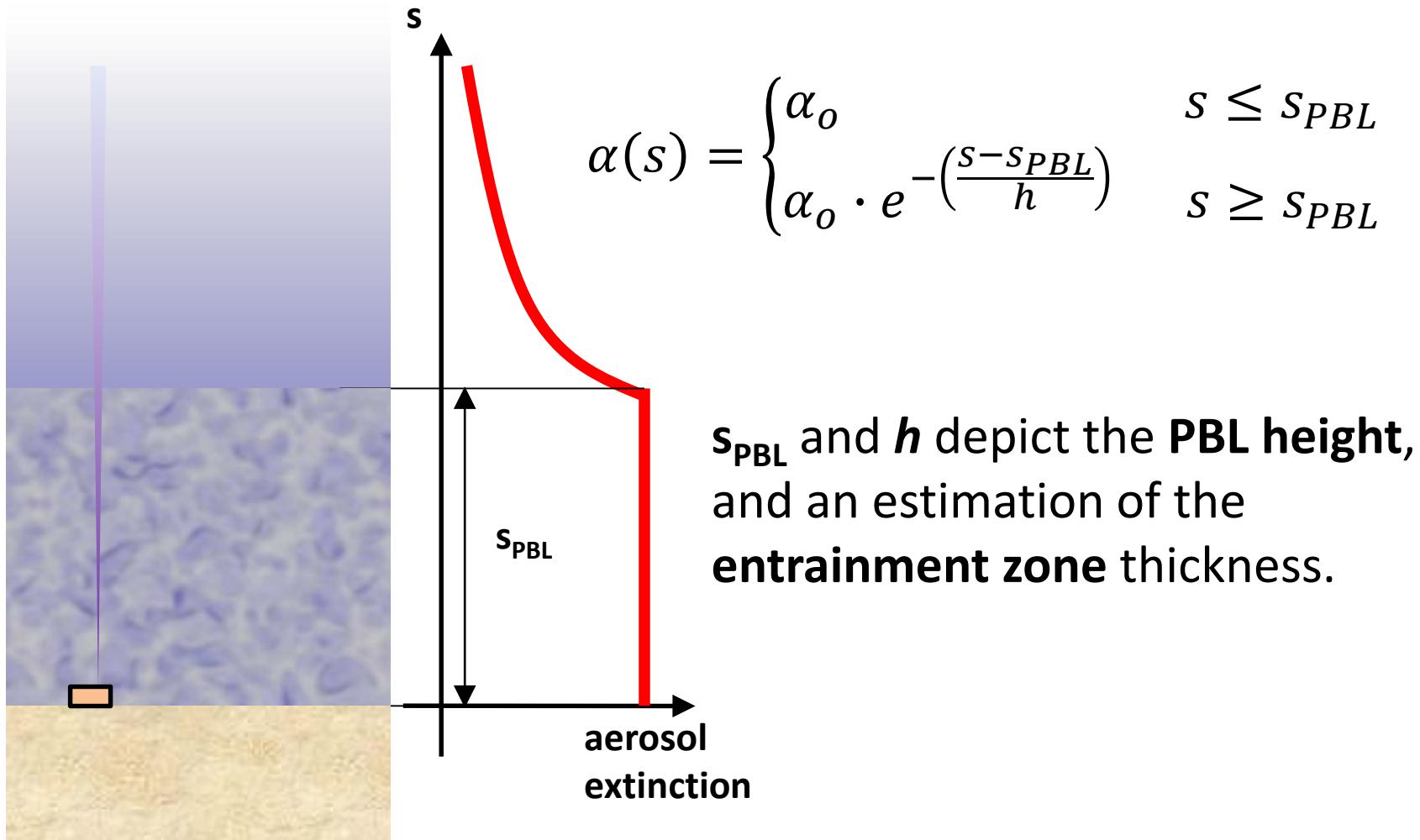
6th International Symposium on Ultra High Energy Cosmic Rays

<https://indico.gssi.it/event/396/>

GRACIAS

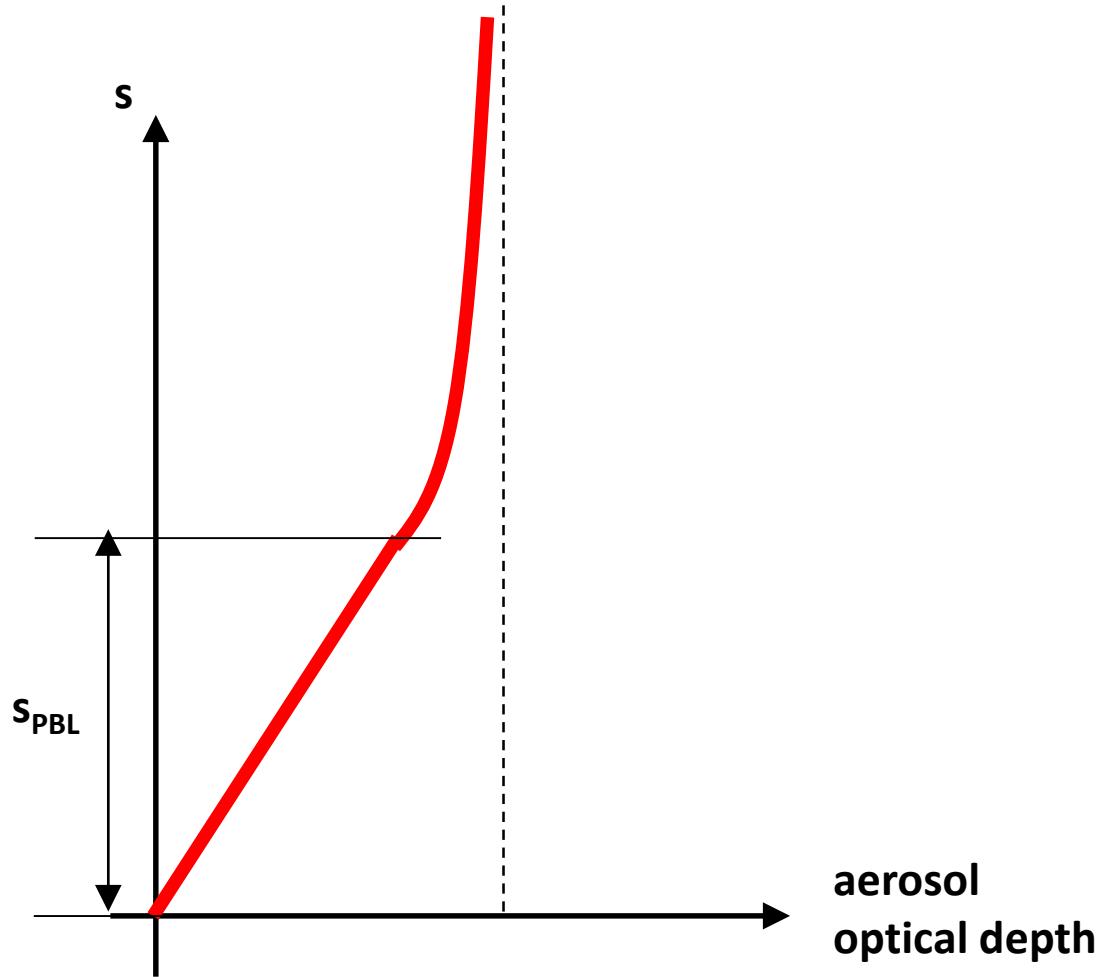
BACKUP slides #1c

3 parameters aerosol model



3 parameters aerosol model

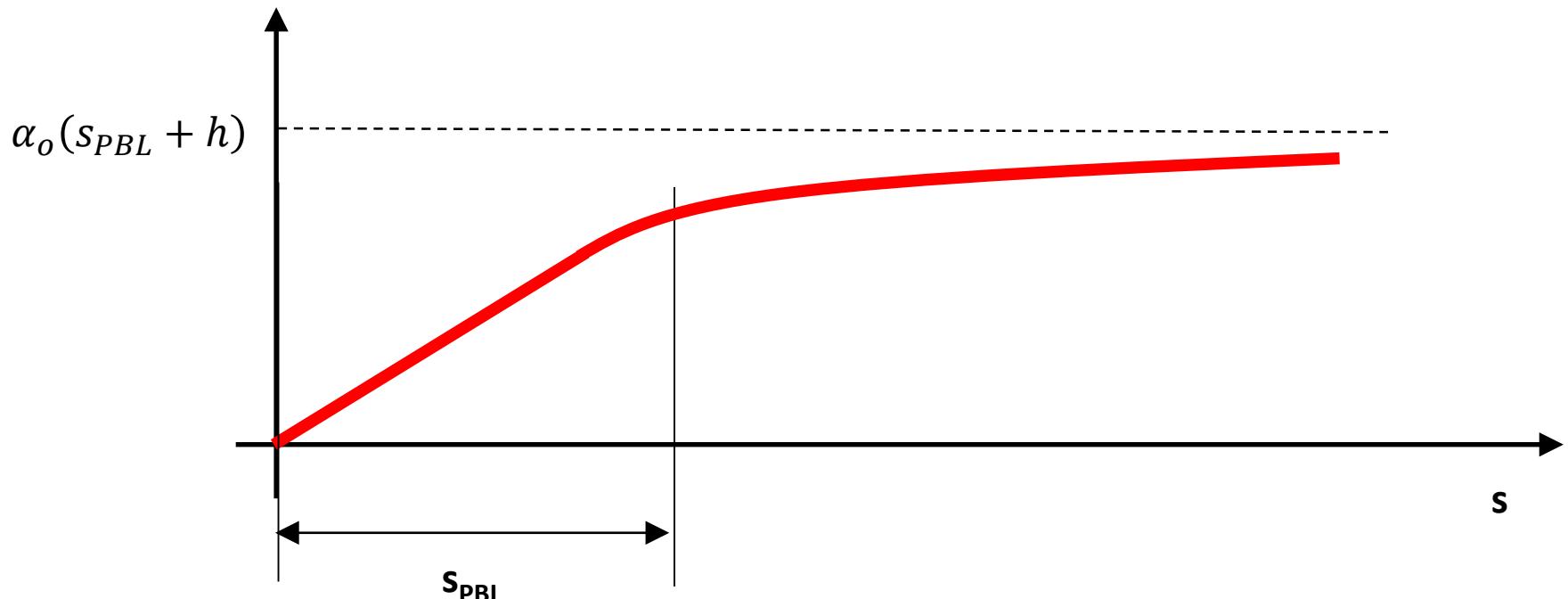
$$\tau(s) = \begin{cases} \alpha_o s & s \leq s_{PBL} \\ \alpha_o(s_{PBL} + h) - \alpha_o h \cdot e^{-\left(\frac{s-s_{PBL}}{h}\right)} & s \geq s_{PBL} \end{cases}$$



3 parameters aerosol model

$$\tau(s) = \begin{cases} \alpha_o s & s \leq s_{PBL} \\ \alpha_o(s_{PBL} + h) - \alpha_o h \cdot e^{-\left(\frac{s-s_{PBL}}{h}\right)} & s \geq s_{PBL} \end{cases}$$

aerosol
optical depth



BACKUP slides #2

Raman LIDAR sensitivity

**Raman LIDAR sensitivity:
minimum measurable VAOD at 355 nm
~ 0.005**

Raman LIDAR sensitivity

Rayleigh night is the night without aerosols!

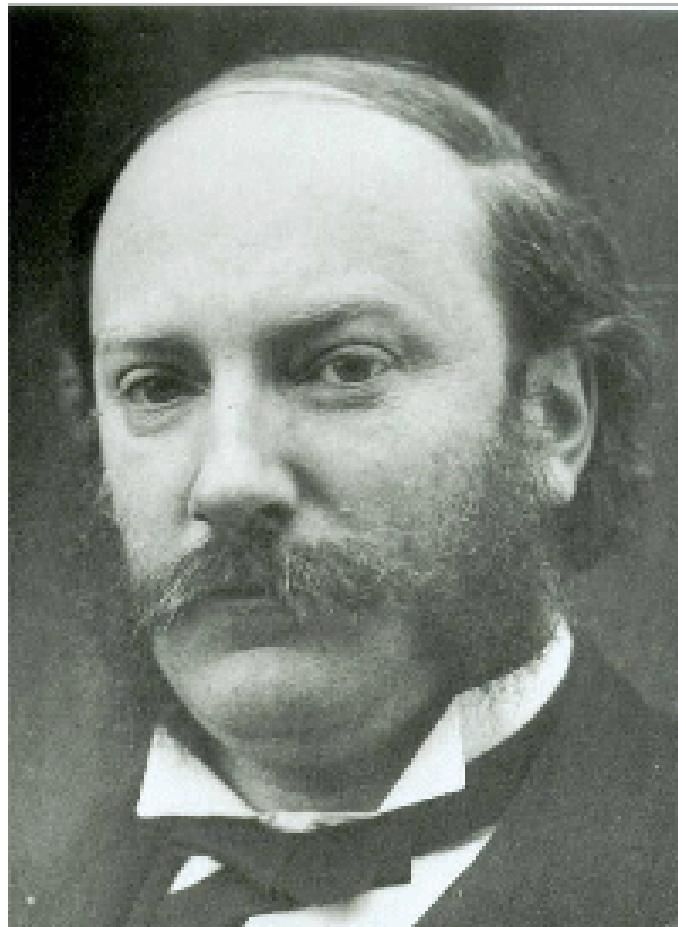


Lord Rayleigh

Raman LIDAR sensitivity

VAOD ~ 0.005

$T = \exp(-\text{VAOD})$

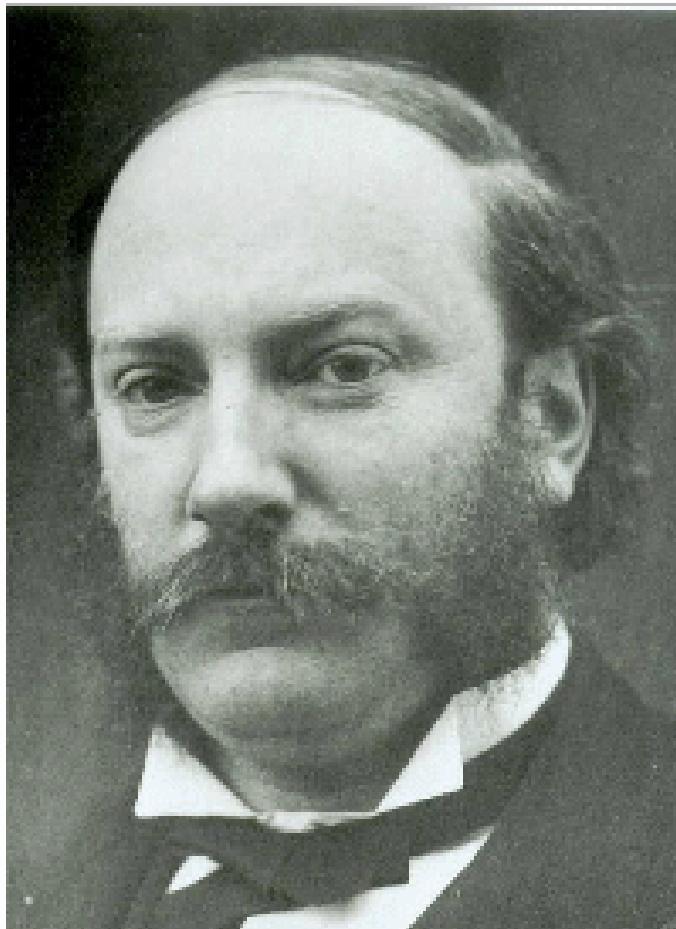


Lord Rayleigh

Raman LIDAR sensitivity

VAOD ~ 0.01

$T = \exp(-\text{VAOD})$

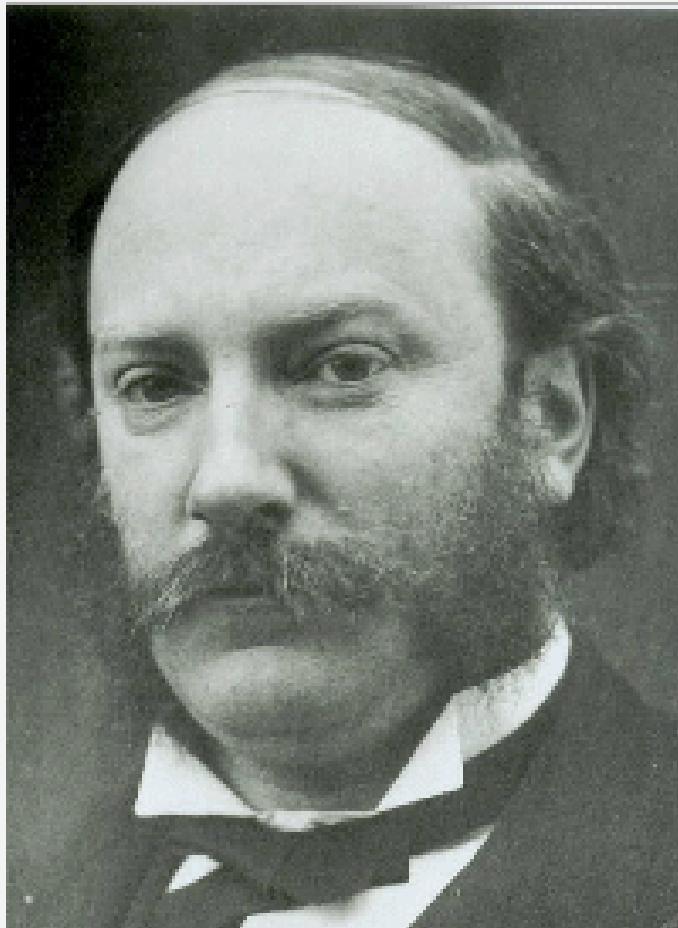


Lord Rayleigh

Raman LIDAR sensitivity

VAOD ~ 0.05

$T = \exp(-\text{VAOD})$

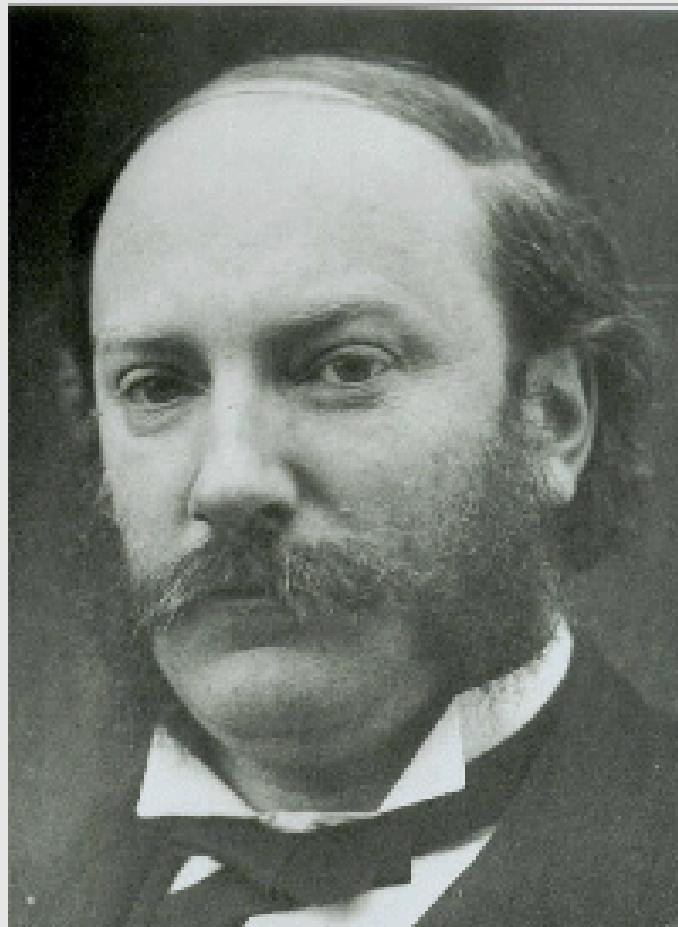


Lord Rayleigh

Raman LIDAR sensitivity

$\text{VAOD} \sim 0.1$

$T = \exp(-\text{VAOD})$

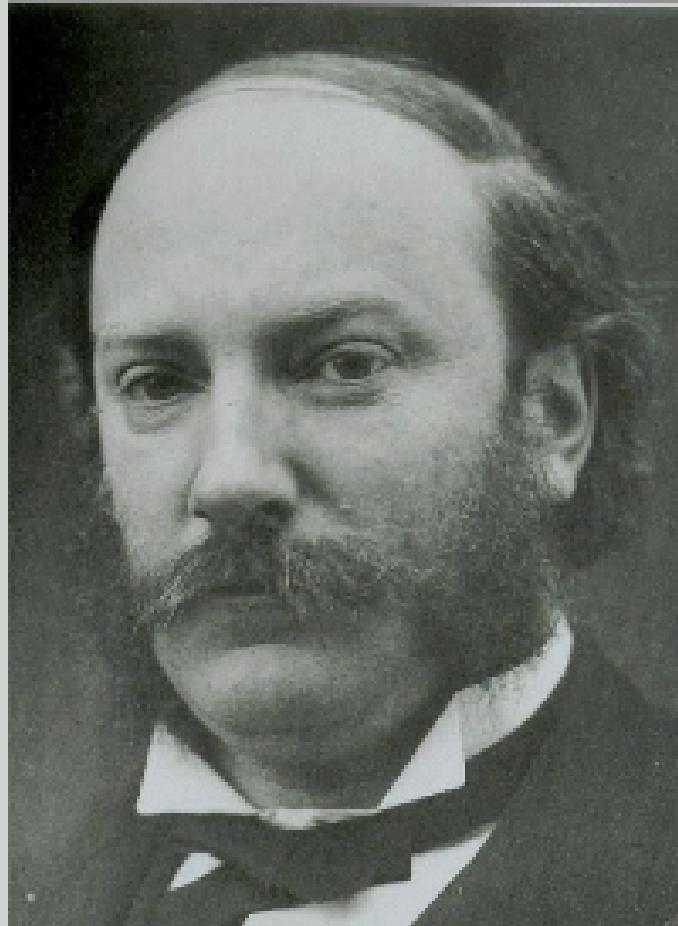


Lord Rayleigh

Raman LIDAR sensitivity

VAOD ~ 0.2

T = exp(-VAOD)

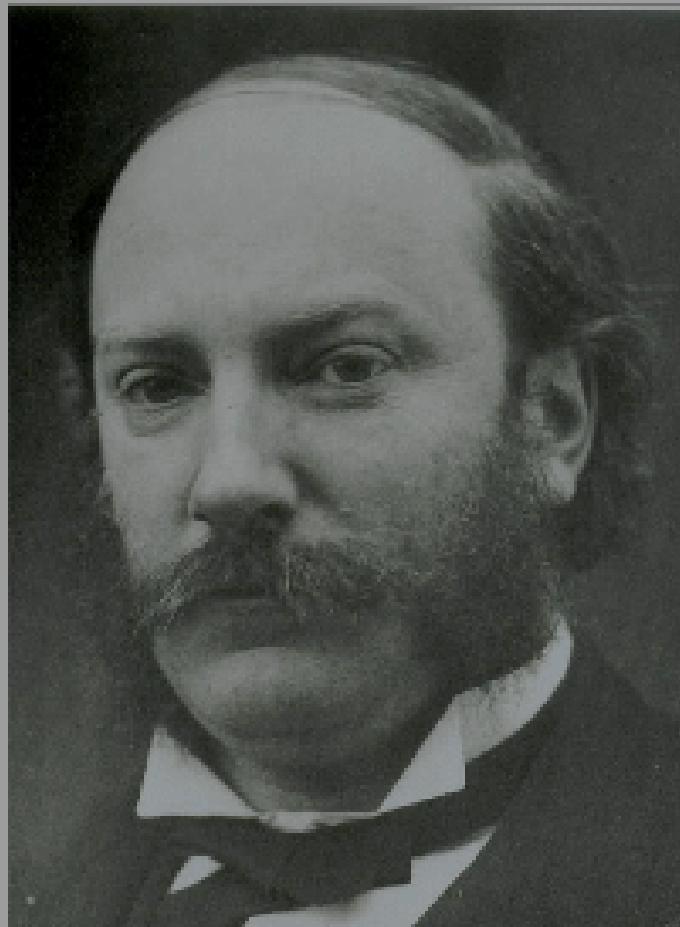


Lord Rayleigh

Raman LIDAR sensitivity

VAOD ~ 0.5

$T = \exp(-VAOD)$



Lord Rayleigh

BACKUP slides #3

Raman LIDAR

Vertical Aerosol Optical Depth $\tau_{aer}(s)$

sources of errors

$$\tau_{aer}(s) = - \frac{\log \left(\frac{C \cdot s^2 L_R(s)}{T_{mol}(s) \cdot T_{mol}^R(s) \cdot n_{mol}(s)} \right)}{1 + \left(\frac{\lambda_o}{\lambda_R} \right)^k}$$

constant

range scale

N_2 Raman backscatter

optical properties of molecular atmosphere

Angstrom exponent

RANDOM/STATISTICAL

SYSTEMATIC

ALL HAVE BEEN ESTIMATED

Raman LIDAR

Vertical Aerosol Optical Depth $\tau_{aer}(s)$

estimations of the errors

12 min standard acquisition: N_{laser} shots ~ 24000 ; $\Delta t_{bin} = 200 \text{ ns}$

RANDOM/STATISTICAL

$$\Delta\tau_{aer}(s) \Big|_{L_R(s)} \leq \pm 0.01 \text{ } (s \leq 3 \text{ km})$$

$$\Delta\tau_{aer}(s) \Big|_B \leq \pm 0.003 \text{ } (s \leq 3 \text{ km})$$

$$\Delta\tau_{aer}(s) \Big|_{calib} \leq \pm 0.004$$

Raman LIDAR

Vertical Aerosol Optical Depth $\tau_{aer}(s)$

estimations of the errors

12 min standard acquisition: N_{laser} shots ~ 24000 ; $\Delta t_{bin} = 200 \text{ ns}$

IMPORTANT SYSTEMATICS

t_o is the delay between the reference trigger pulse and the output of laser pulse.

$\Delta\tau_{aer}(s)|_{t_o}$ it can be important. It has been measured. To be checked periodically;
(laser output jitter) $\Delta\tau_{aer}(s)|_{t_o} \leq \pm 0.001$

Assuming that GDAS is representing well the atmosphere over PAO.

The seasonal and hour to hour variations of the molecular number density is generally larger than its indetermination. We are ready to use the GDAS hourly profiles.

$$\Delta\tau_{aer}(s)|_{mol} \leq \pm 0.005$$

Raman LIDAR

Vertical Aerosol Optical Depth $\tau_{aer}(s)$

estimations of the errors

12 min standard acquisition: $N_{laser} \text{ shots} \sim 24000$; $\Delta t_{bin} = 200 \text{ ns}$

$$\Delta \tau_{aer}(s) \Big|_{L_R(s)} \leq \pm 0.01 \quad (s \leq 3 \text{ km})$$

$$\Delta \tau_{aer}(s) \Big|_B \leq \pm 0.003 \quad (s \leq 3 \text{ km})$$

$$\Delta \tau_{aer}(s) \Big|_{calib} \leq \pm 0.004$$

$$\Delta \tau_{aer}(s) \Big|_{t_o} \leq \pm 0.001$$

$$\Delta \tau_{aer}(s) \Big|_k \leq \pm 0.02 \cdot \tau_{aer}(s)$$

$$\Delta \tau_{aer}(s) \Big|_{mol} \leq \pm 0.005$$

$$\Delta \tau_{aer}(s) \Big|_{tot} \leq \pm 0.012$$

bin to bin

$s \leq 3 \text{ km}$

$\tau_{aer}(s) \sim 0.05$

**It can be lower if a model of VAOD
is fitted to the data.**

BACKUP slides #4

MASS COMPOSITION

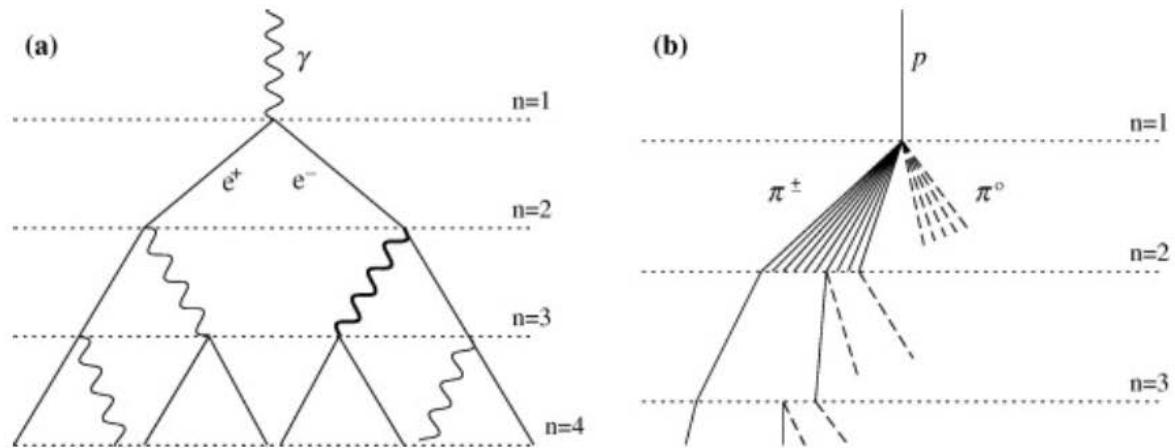
Heitler model for EAS

$$N(X) = 2^{X/\lambda}$$

$$E(X) = \frac{E_0}{N(X)}$$

$$N(X_{\max}) = \frac{E_0}{E_c}$$

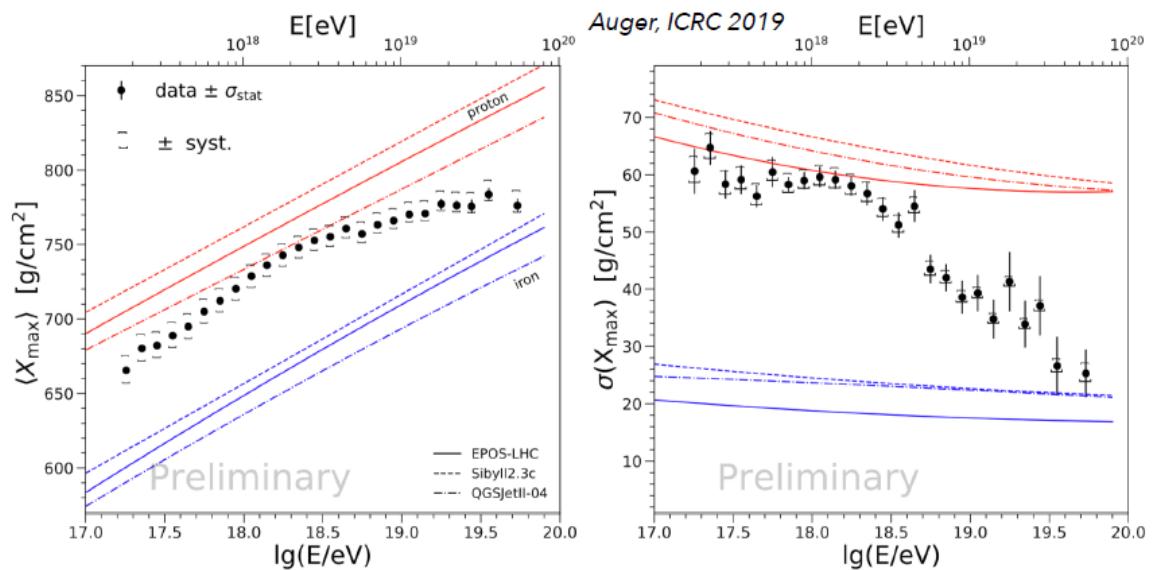
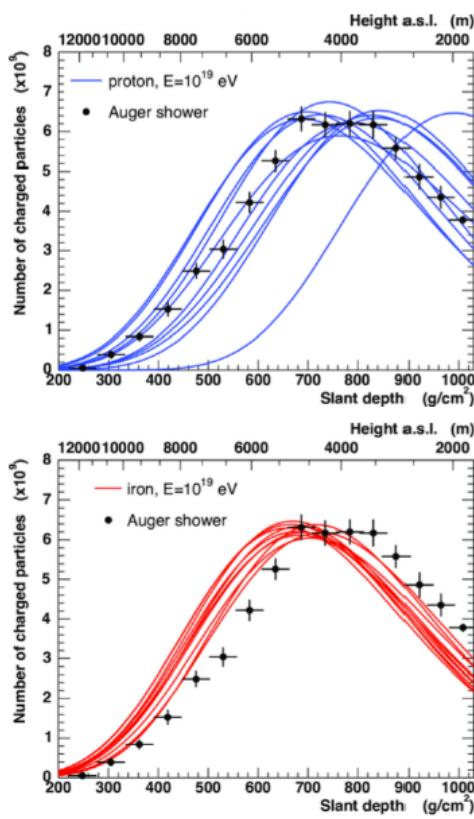
$$X_{\max} \propto \ln(E_0/E_c)$$



Superposition model: ${}^A X, E_0 \leftrightarrow A \times n, E_0/A$

$$X_{\max}^A \propto X_{\max}(E_0/A)$$

MASS COMPOSITION



- Composition information (mainly) from the longitudinal development of the shower
- Break in $\langle X_{\max} \rangle$ at energy of the ankle
- Fluctuations decreasing with increasing energy

Maintenance

Once a month, **a person** of the local staff is taking care of the regular maintenance at CRLF, the cost of such activity is considered in the CRLF costs.

PRE-COVID

In connection with the **Collaboration Meetings**, personnel from L'Aquila and/or Golden, travel to Malargue to support **special** activities on RL system and sub-systems (i.e., the **optical alignments of the laser transmitter and of the receiver bench, and the status of the detectors**).

1.5, 3.0, 4.5 KM ALTITUDES ABOVE GROUND LEVEL (a.g.l.)

Aerosol Optical Depth (AOD)

% selection 2 (masking for clouds, high aerosol content and bad measurements)

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if ( (vaod_1_5 > 0 && vaod_1_5 <0.05) &&
    (vaod_3_0 > 0 && vaod_3_0 <0.10) &&
    (vaod_4_5 > 0 && vaod_4_5 <0.10) &&
    (vaod_6_0 > 0 && vaod_6_0 <0.10) &&
    (vaod_7_5 > 0 && vaod_7_5 <0.10) &&
    (vaod_9_0 > 0 && vaod_9_0 <0.10))
```

Overall Aerosol Optical Depth mean and standard deviation values at 1.5, 3.0, 4.5 km above ground level

Low fit	VAOD mask	# of profiles	AOD@1.5 km mean and stddev	AOD@3.0 km mean and stddev	AOD@4.5 km mean and stddev
0.5-1.0 km	selection 2	1366	0.023/0.012	0.035/0.017	0.037/0.019