Atmospheric Monitoring
for Ground-Based Astroparticle Detectors

MPI Workshop,
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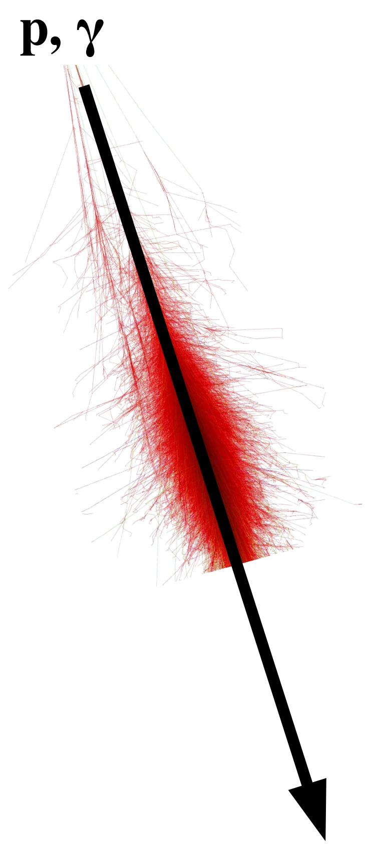
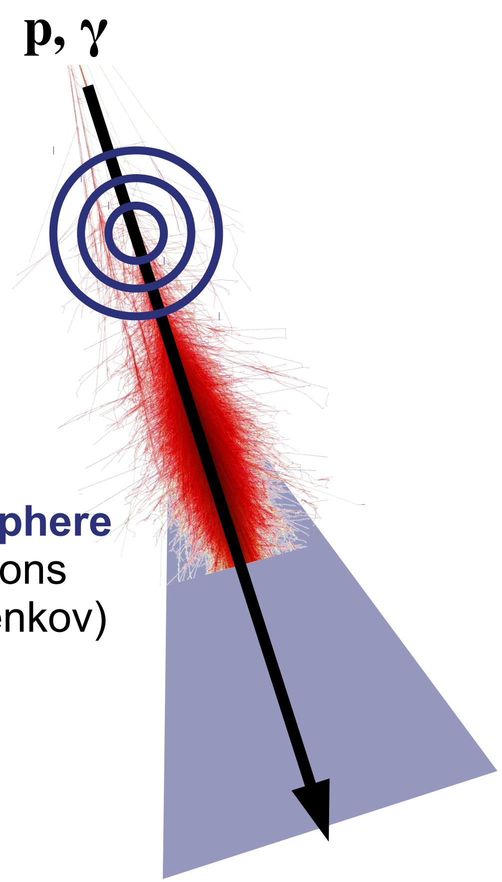
Detection Principle

Development of Air Shower
depends on density profile

$$\rho_{air} = \frac{m_{air}}{V} = \frac{p \cdot M_{air}}{R\,T}$$



Detection Principle



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Interactions with Atmosphere
cause emission of photons
(Fluorescence and Cherenkov)

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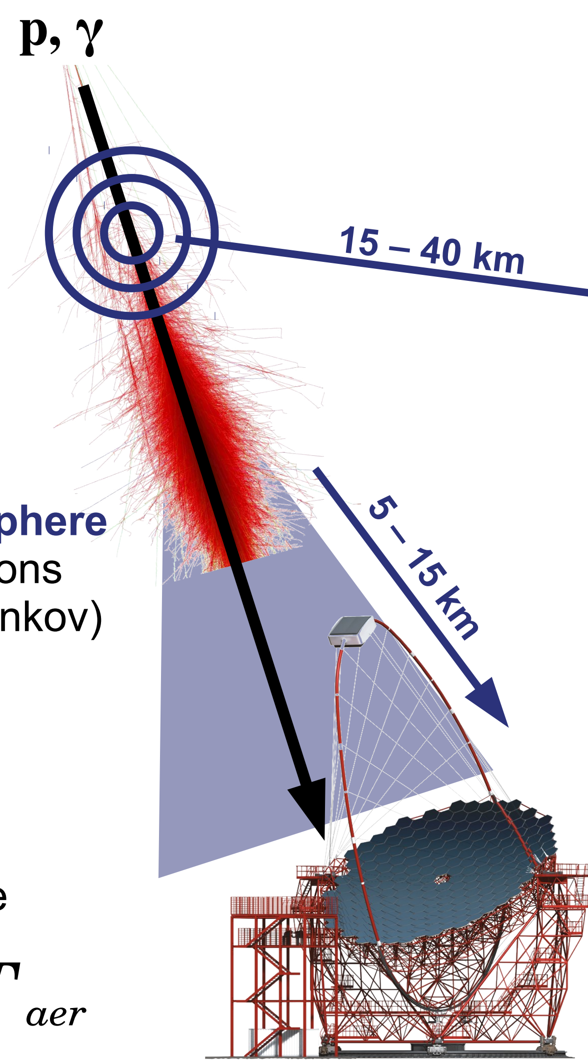
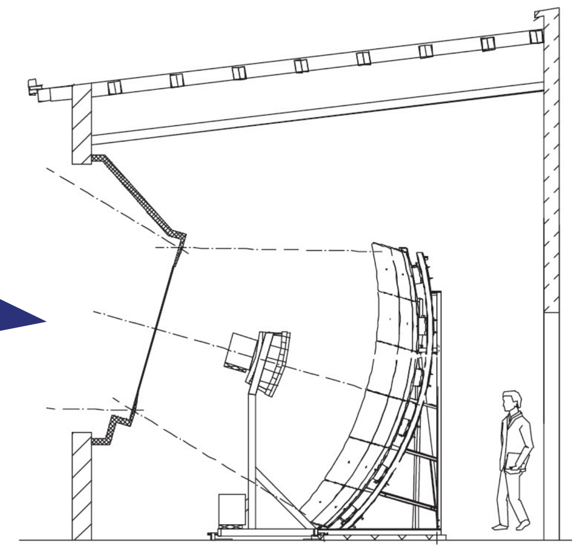
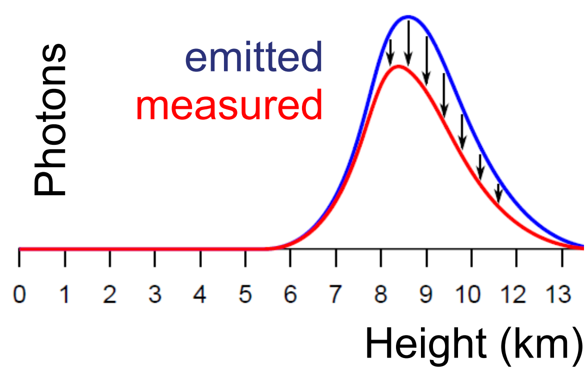




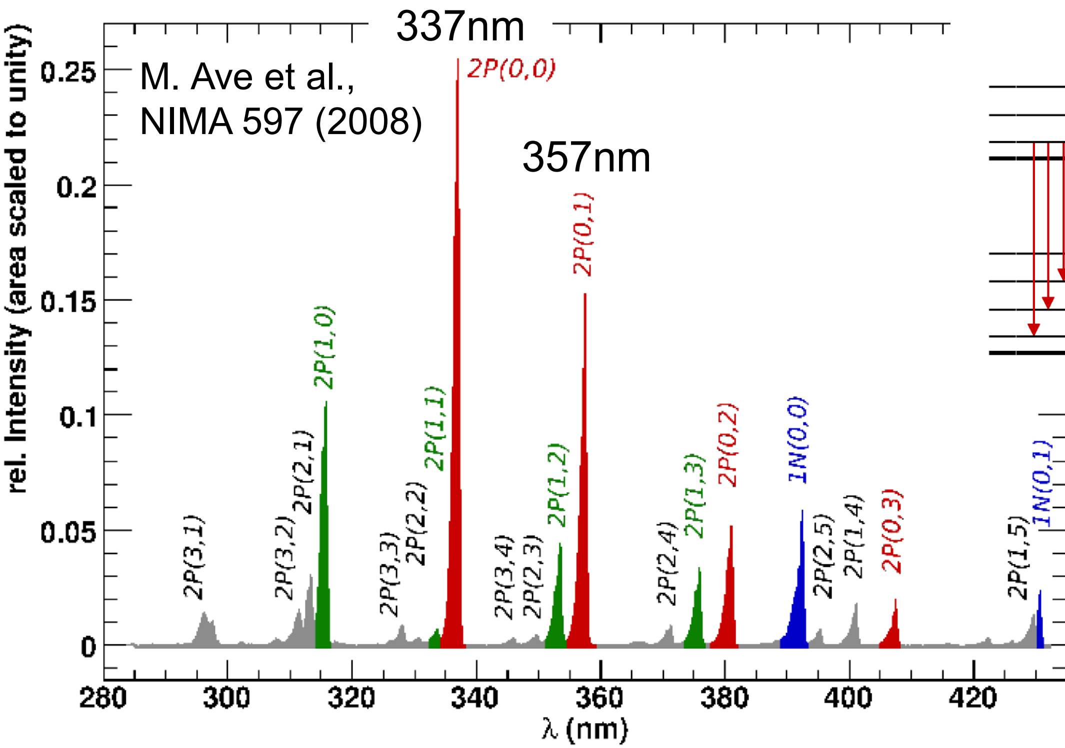
Interactions with Atmosphere
cause emission of photons
(Fluorescence and Cherenkov)

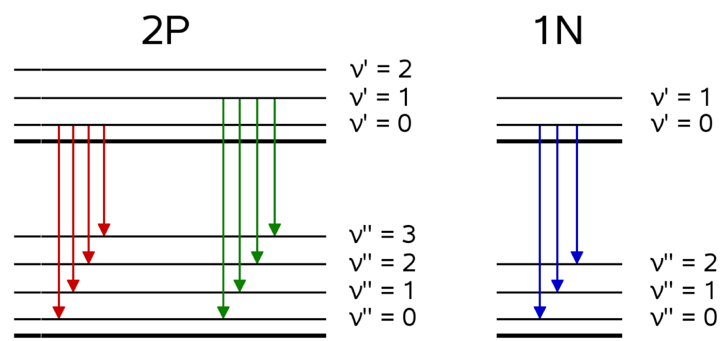
Attenuation (scattering)
depends on aerosols
and molecular atmosphere

$$I_{det} \propto I_{emit} \cdot T_{mol} \cdot T_{aer}$$



Fluorescence Light





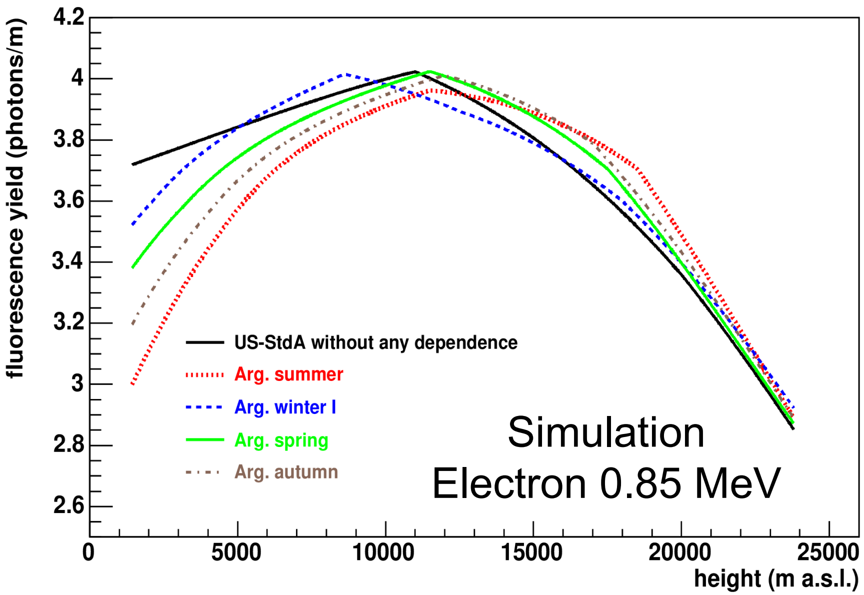
- Particles excite nitrogen vibrational and/or rotational states

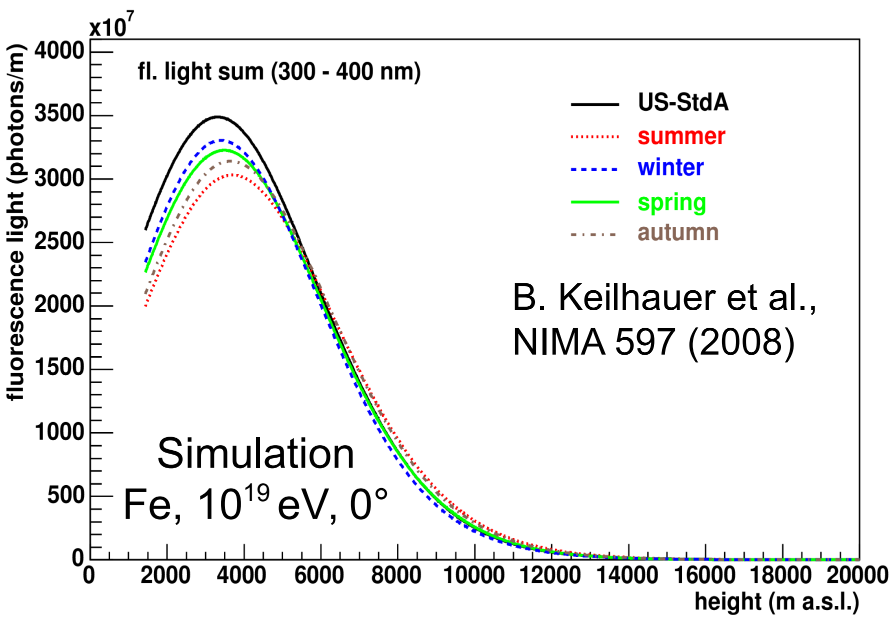
- Radiative transitions to lower states
  → **Isotropic emission of UV fluorescence light**
- Non-radiative transition through collisions with (water) molecules
  → **Vapor quenching**

Fluorescence Yield

$$\frac{dN_\gamma}{dX} = \frac{dE_{dep}^{tot}}{dX} \int FY(\lambda, p, T, e) \cdot \tau_{atm}(\lambda, p, T, e) \cdot \epsilon_{FD}(\lambda)\ d\lambda$$

- Reduction of emitted light due to humidity up to 7 km a.s.l.
- Reconstructed energy without consideration of humidity too low
- Small change in shower maximum (dependent on zenith angle)





Cherenkov Photons

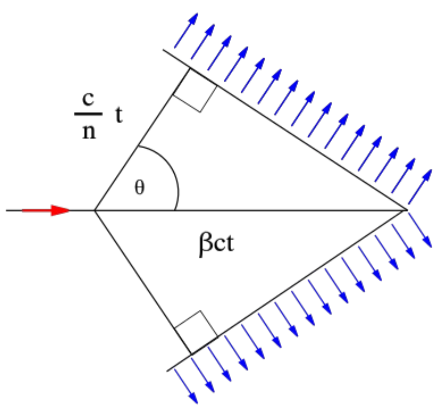
Number of Cherenkov photons per charged particle

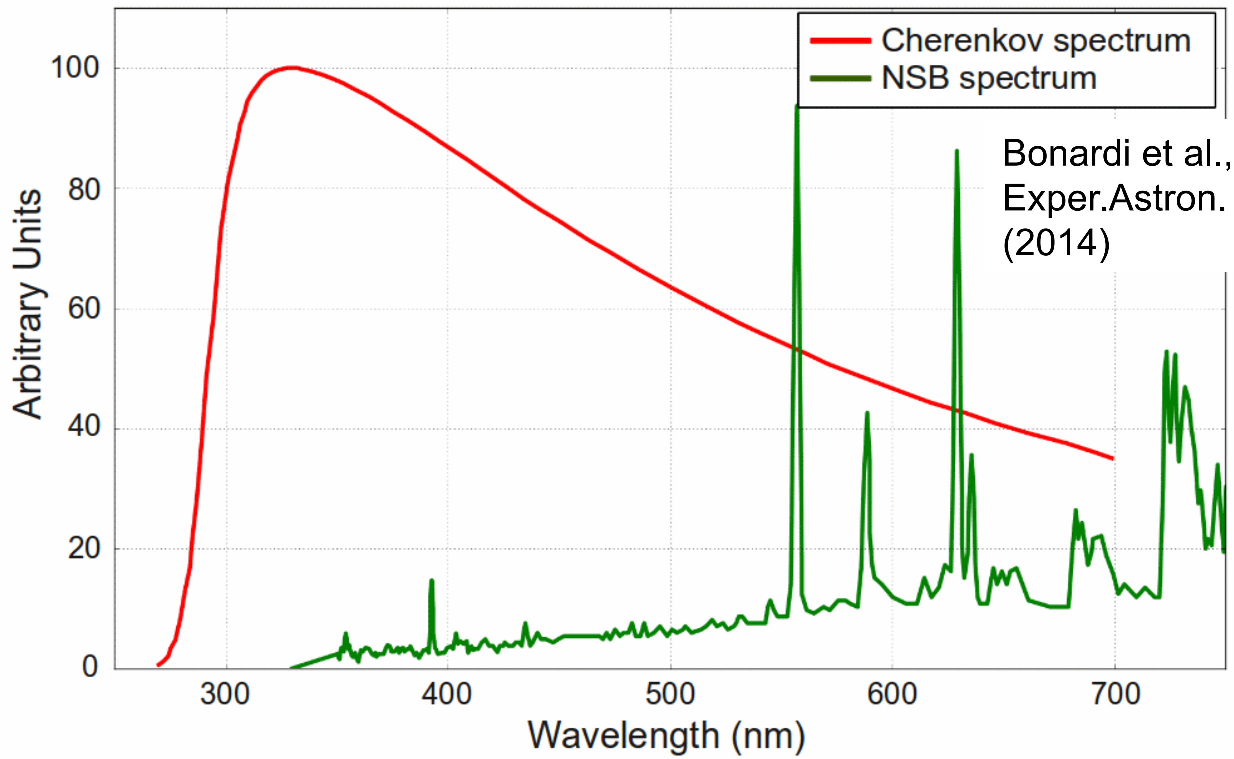
$$\frac{dN_\gamma}{dX}(h,E) = \frac{2\pi\alpha}{\rho_{air}(h)} \int \left(1 - n^{-2}\beta^{-2}\right)\lambda^{-2}\, d\lambda$$

Cherenkov threshold

$$E_{thr}(h) = \frac{mc^2}{\sqrt{2(n-1)}}$$

- Shower particles exceed speed of light in air

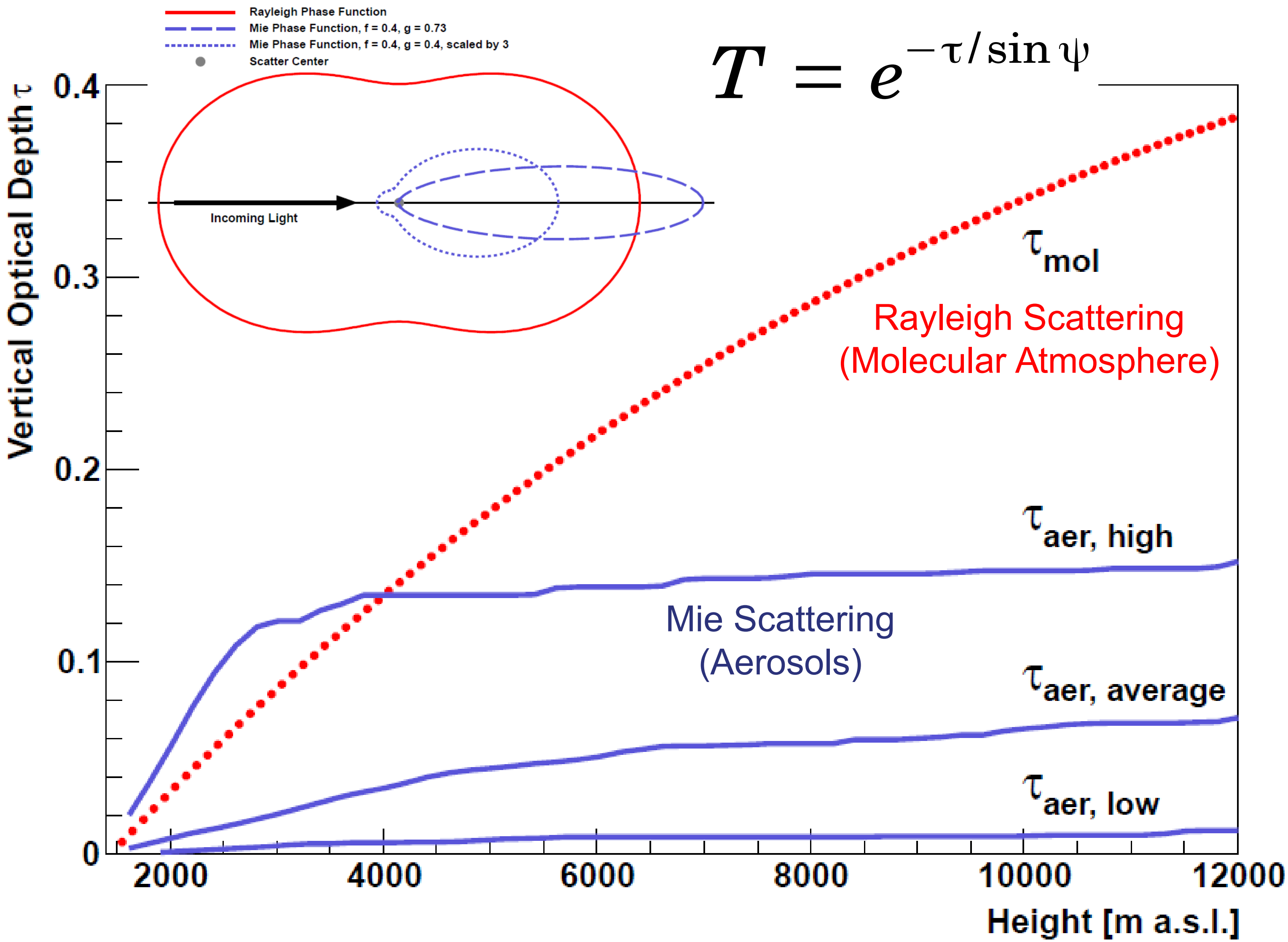




Bonardi et al., Exper.Astron. 38 (2014)

Scattering

$$T = e^{-\tau/\sin\psi}$$



Molecular Atmosphere

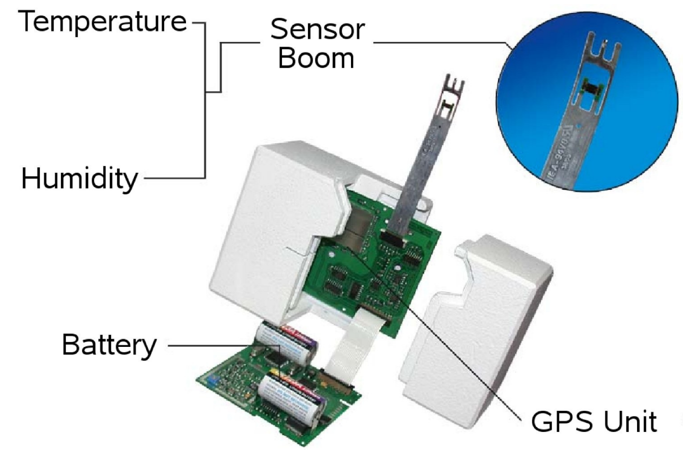
- Effect on produced light
  - Shower development depends on density
  - Number of Cherenkov photons, Cherenkov threshold
  - Fluorescence Yield
- Transmission to detector

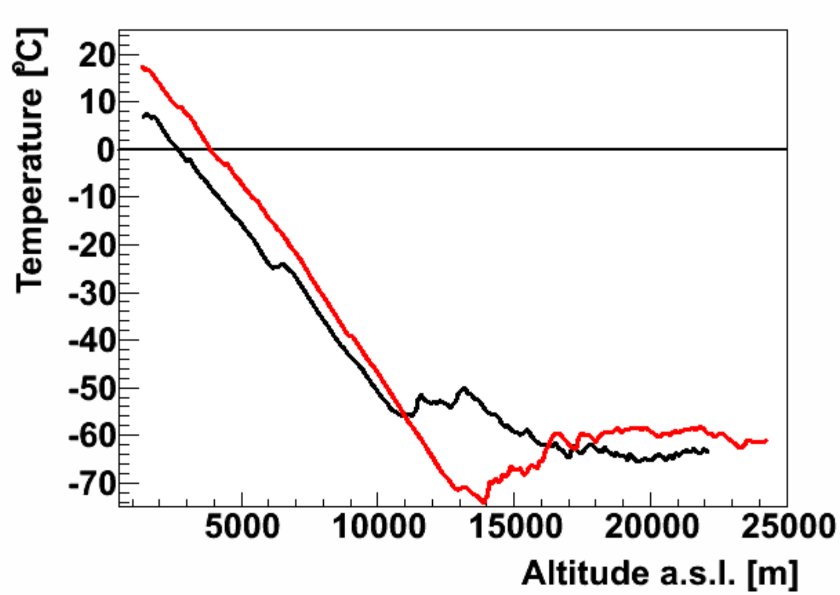
$$I_{det} \propto I_{emit} \cdot T_{mol} \cdot T_{aer}$$

- Reconstructed energy scales with optical transmission

Molecular Atmosphere

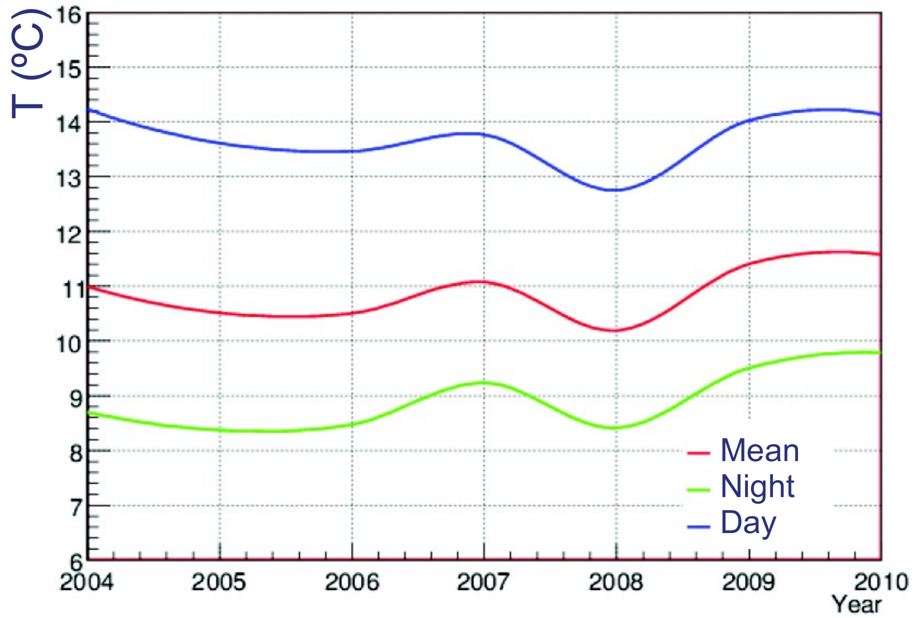
Weather Balloon



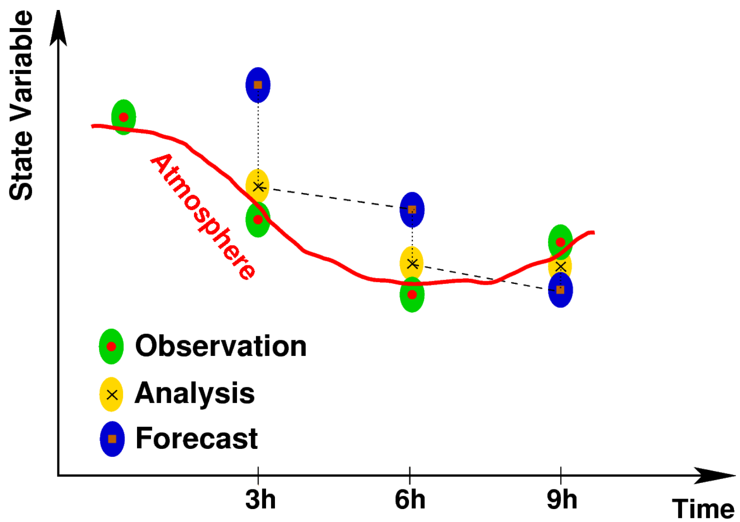


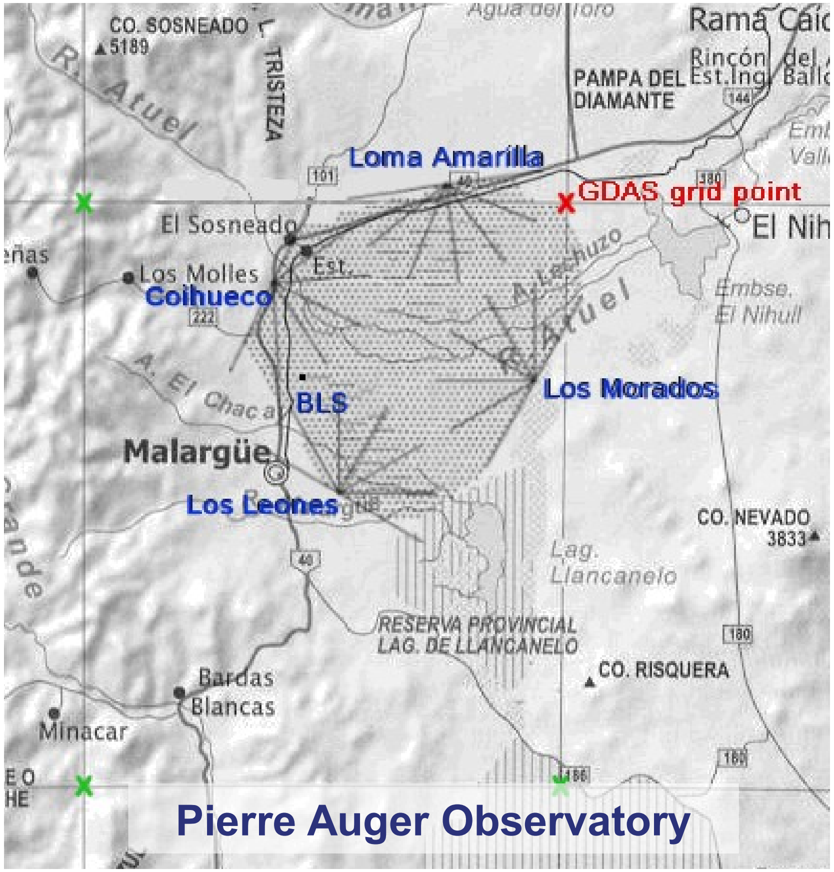
Weather Station

- Ground Measurements
  - Temperature
  - Pressure
  - Relative humidity
  - Wind speed and direction



Global Data Assimilation System



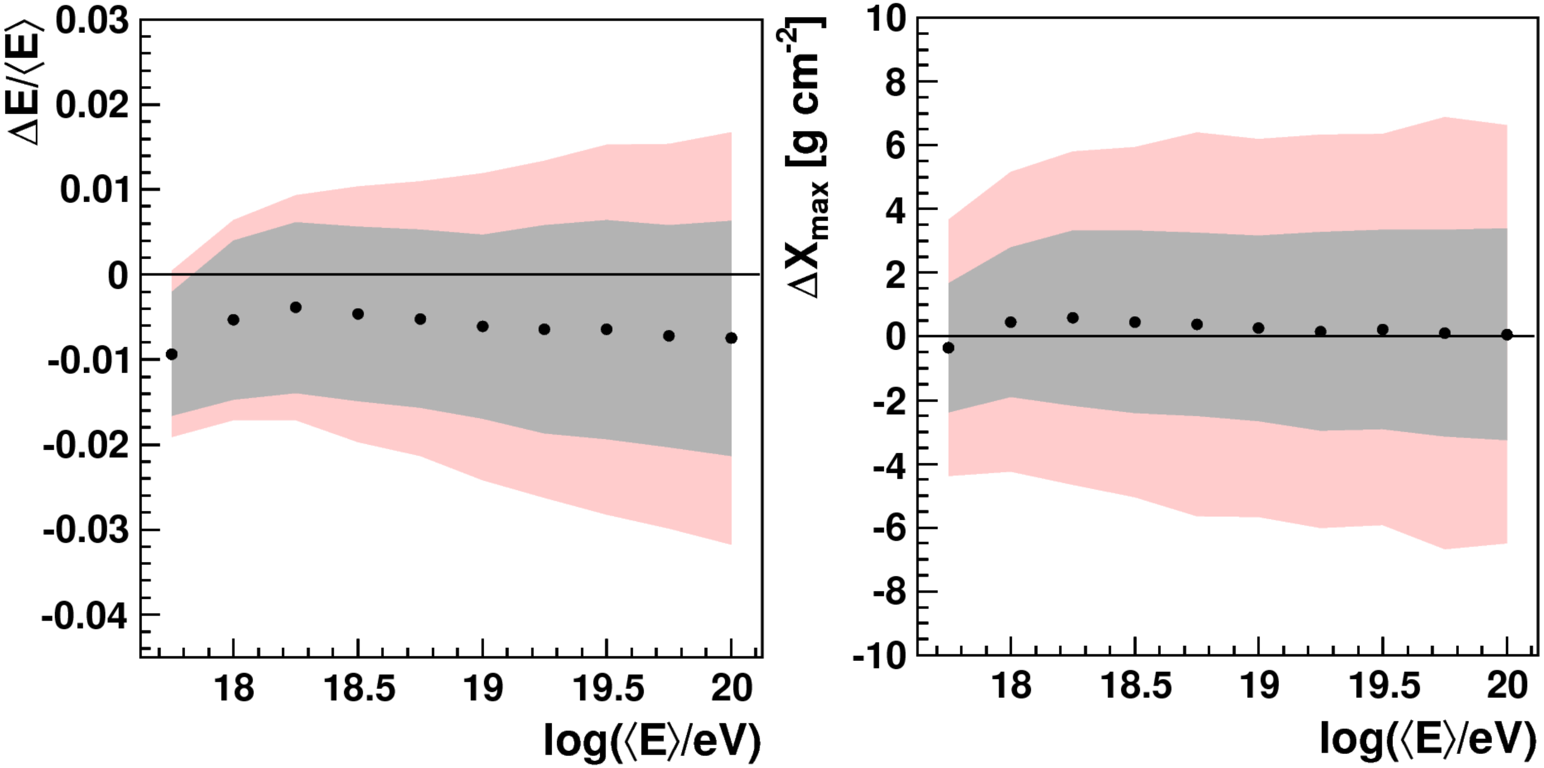


- Global measurements and numerical weather prediction

- GDAS data available
  - for whole earth
  - 1° grid (180° x 360°)
  - every 3 hours

- Comparison with balloon data validates GDAS for Auger site

GDAS Advantages



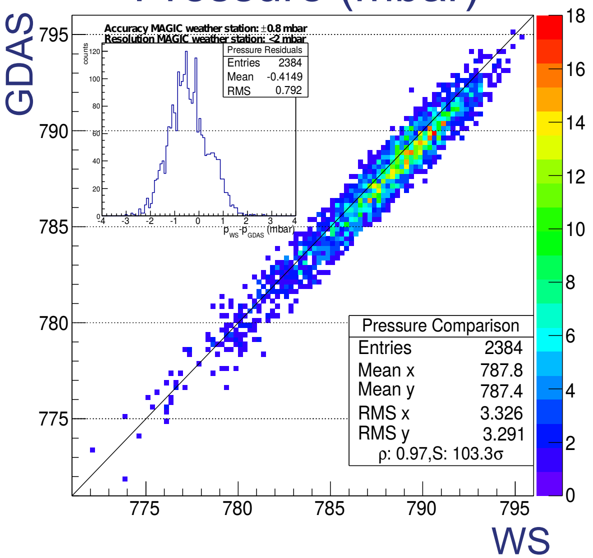
Balloon – Monthly Model

Balloon – GDAS

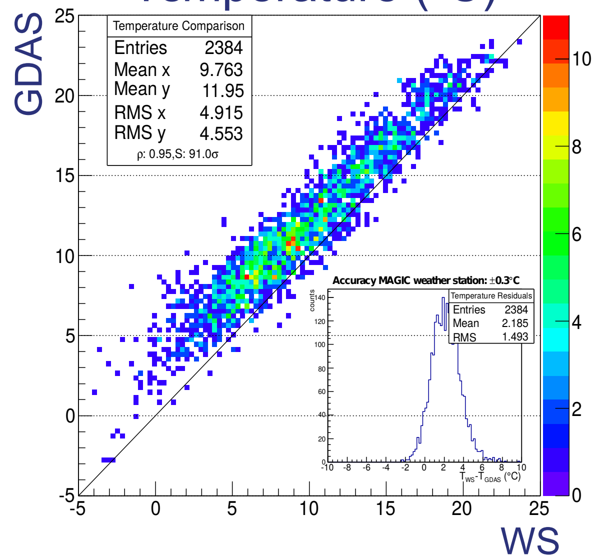
- Improved systematic uncertainty compared to other models
- Replacement for balloon launches
  → **Save money for equipment and personnel**

GDAS in La Palma

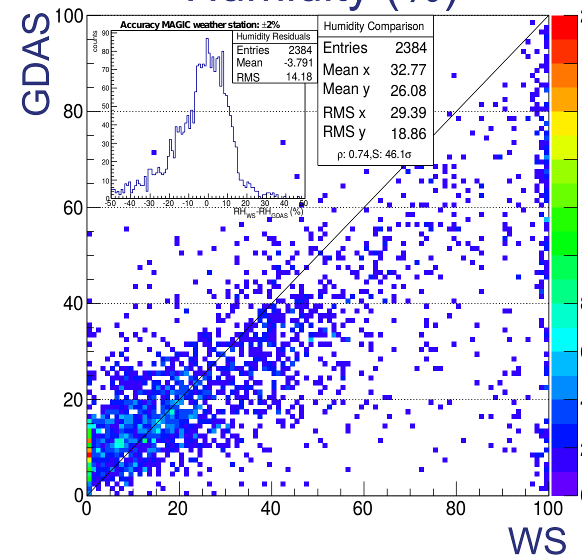
Pressure (mbar)



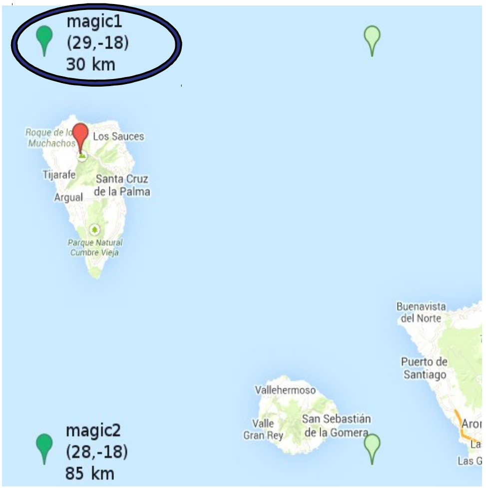
Temperature (ºC)



Humidity (%)



- Comparison with MAGIC weather station
  - Agreement in pressure
  - Sys. offset in temperature (~ 2ºC ground effects)
  - Humidity very dependent on location
- Cheap and reliable data source for CTA

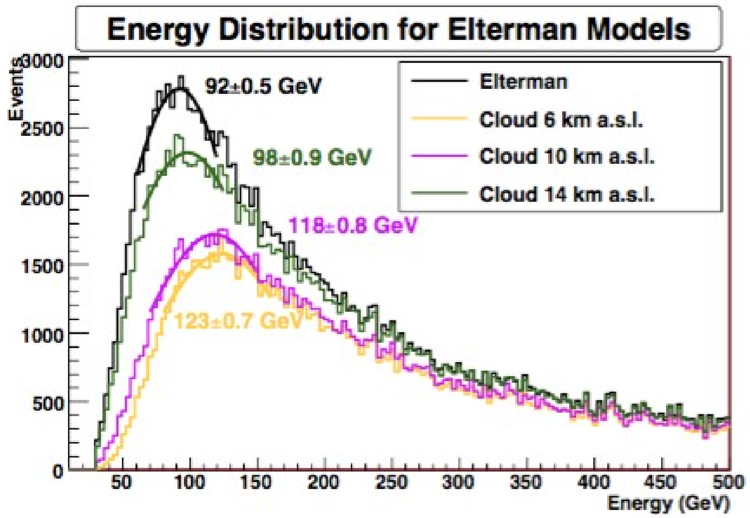


Aerosols

- Aerosol enhancements close to ground and clouds
- Highly variable in altitude and time, scale of hours
- Transmission to detector

$$I_{det} \propto I_{emit} \cdot T_{mol} \cdot T_{aer}$$

- Strong energy dependence on cloud height



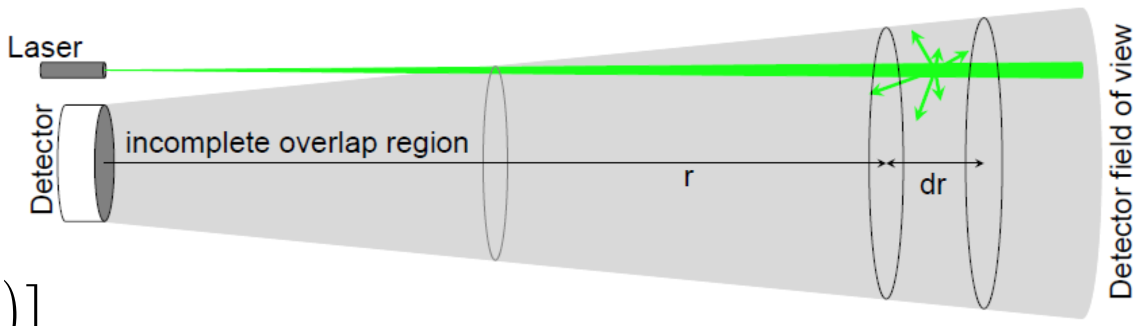
Aerosol Transmission and Clouds

$$I_{det} \propto I_{emit} \cdot T_{mol} \cdot T_{aer}$$

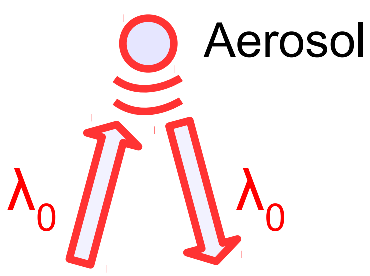
- Measuring instrument: LIDAR
- Light Detection and Ranging ("Light Radar")
- Different kind of LIDARs
  - Wavelength of scattered light (scatter center, scattering process)
  - Location of laser and detector (collocated or separated)
  - Each with advantages and disadvantages

Theory: Elastic LIDAR

- Light reaching detector



$$L = C \cdot G \cdot L_0 \cdot T_{mol} \cdot T_{aer} \cdot [\beta_{mol}(\pi) + \beta_{aer}(\pi)] \cdot T_{mol} \cdot T_{aer}$$

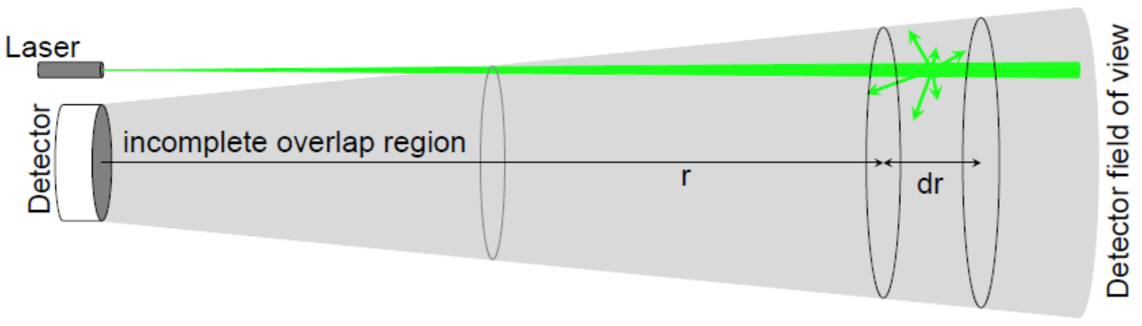


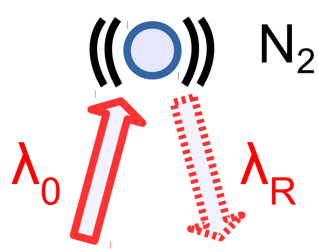
- Aerosol backscattering unknown
  - Size and number of aerosols unknown
  - Need assumptions or scanning

Theory: Raman LIDAR

- Light reaching detector

$$L = C \cdot G \cdot L_0 \cdot T_{mol} \cdot T_{aer} \cdot \beta^R_{N_2}(\pi) \cdot T^R_{mol} \cdot T^R_{aer}$$



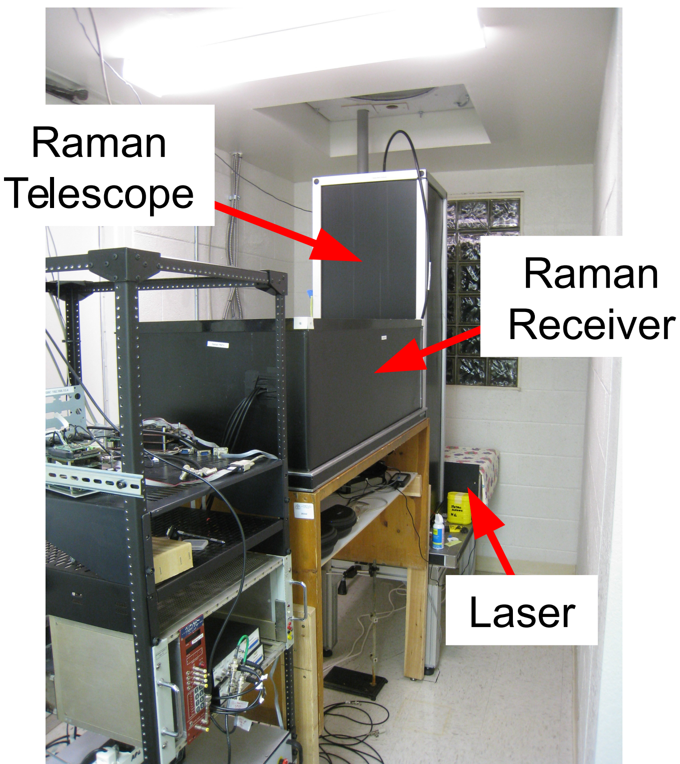


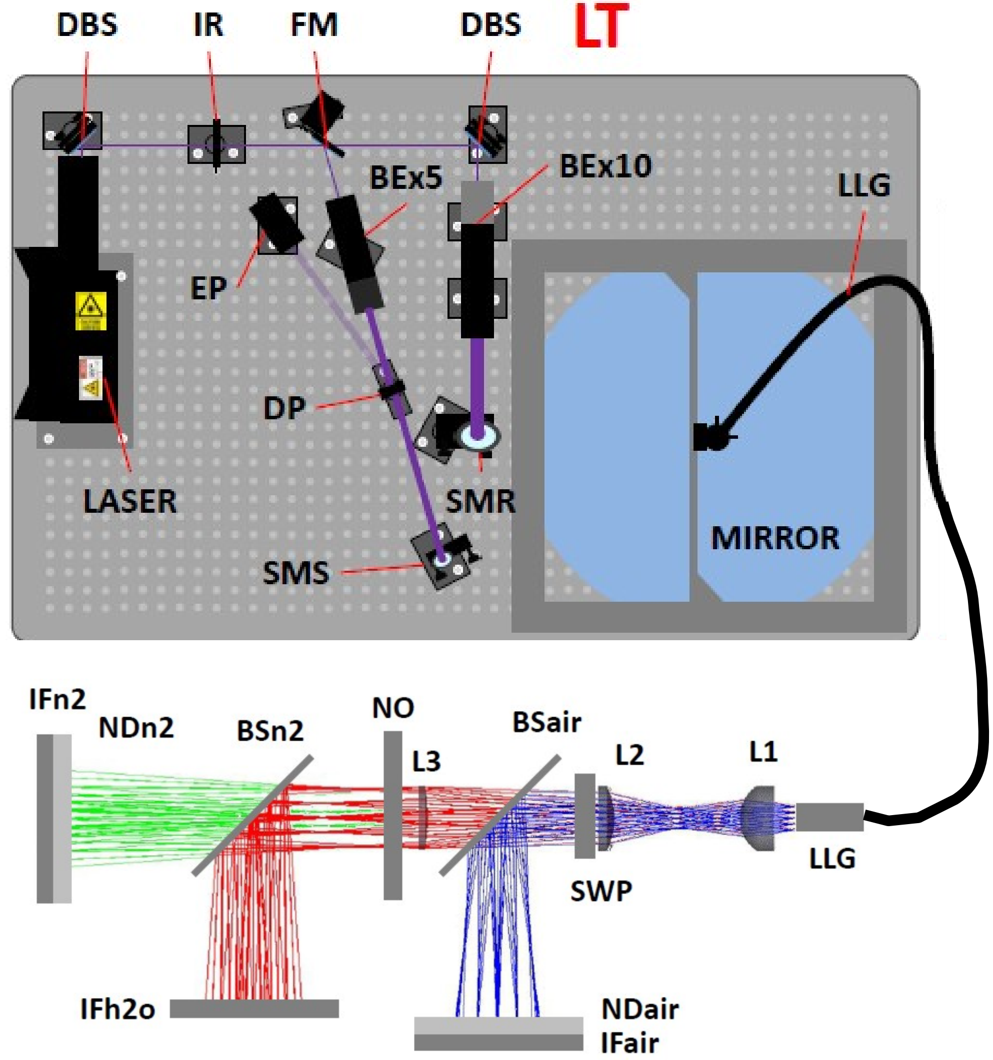
- Nitrogen backscattering
  - Number density known
  - Low Raman cross section
  - Large amount of light needed

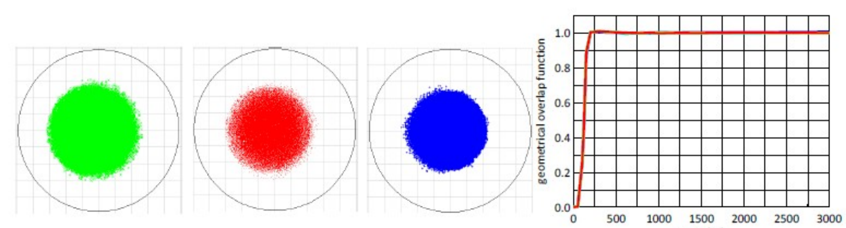
Raman LIDAR

- R&D system commissioned in SE Colorado

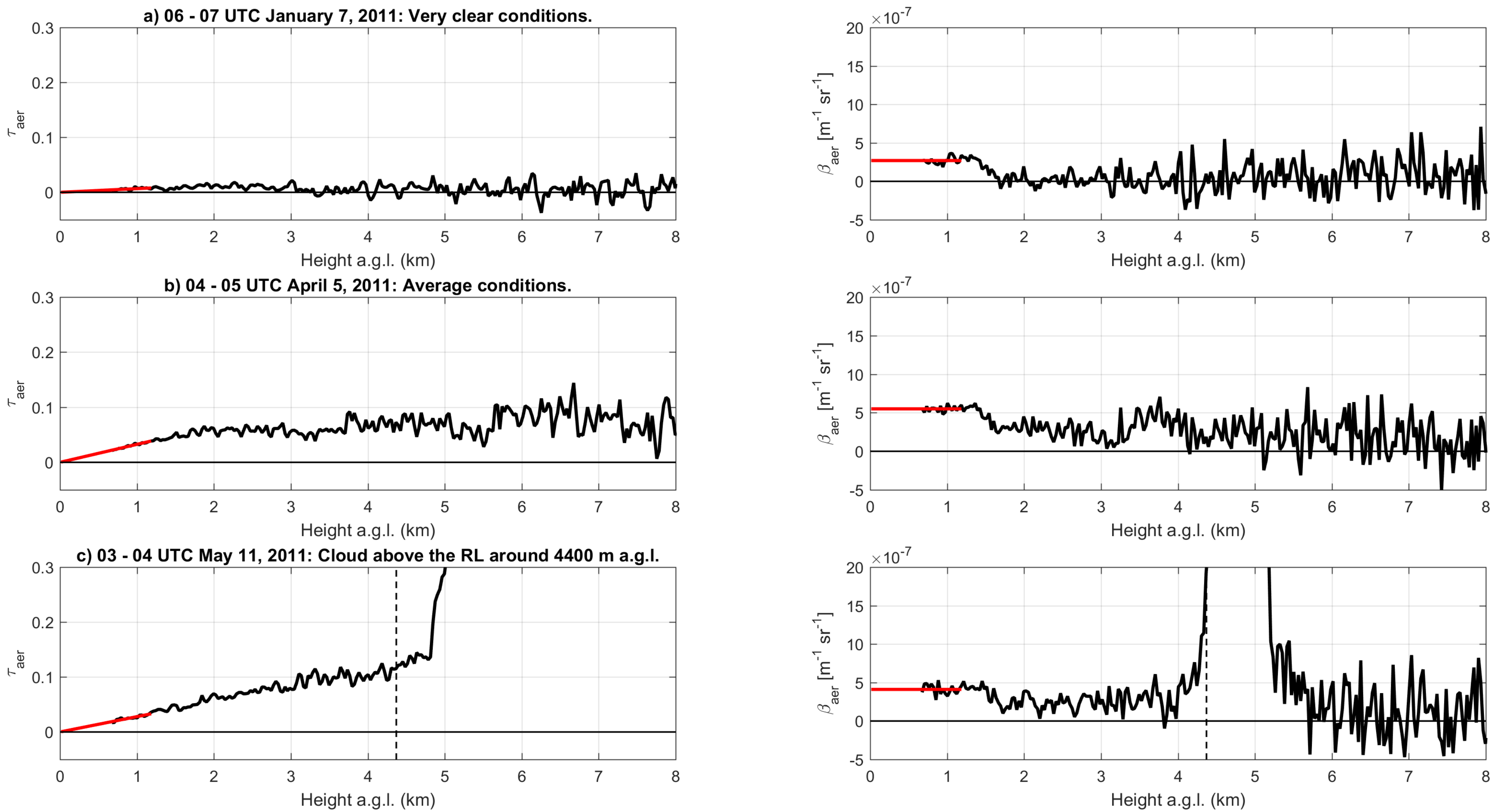
Nd:YAG
355 nm
5–10 mJ







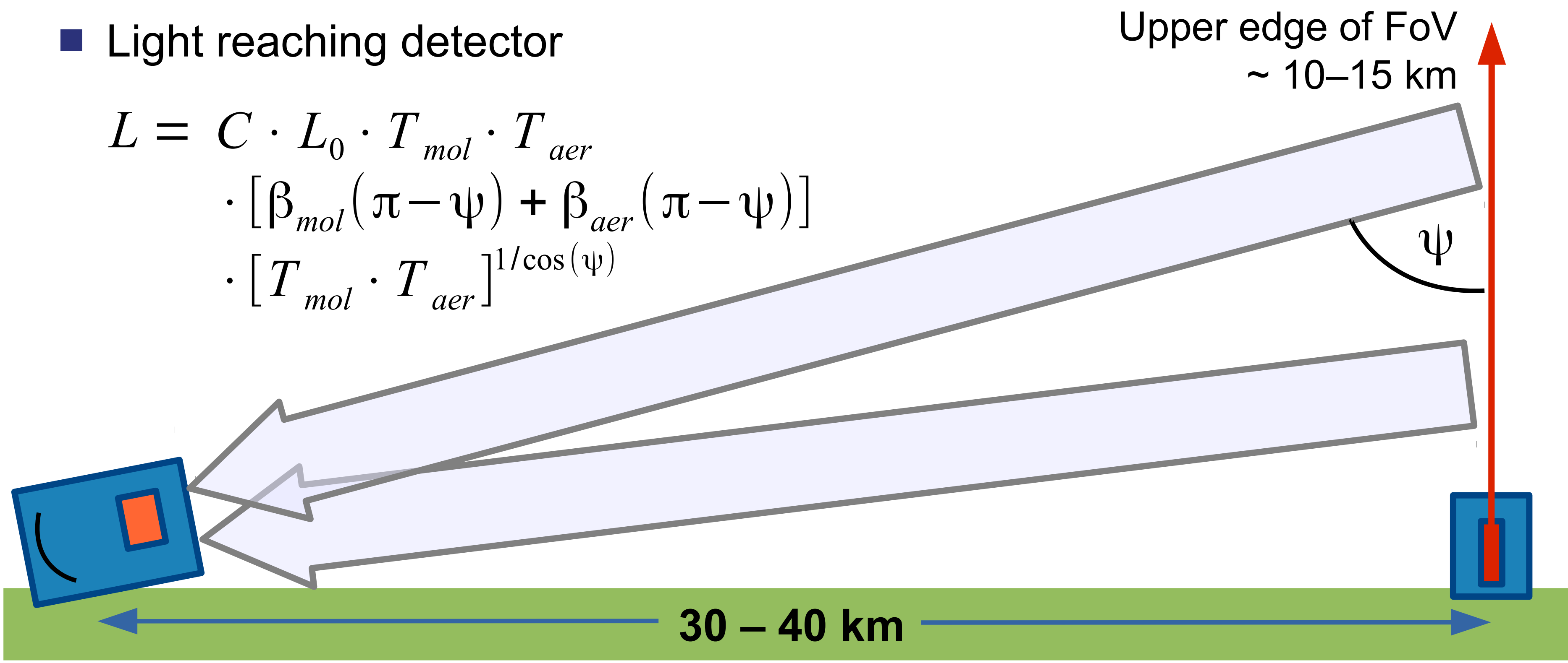
Raman LIDAR Data



Theory: Bi-static LIDAR

- Light reaching detector

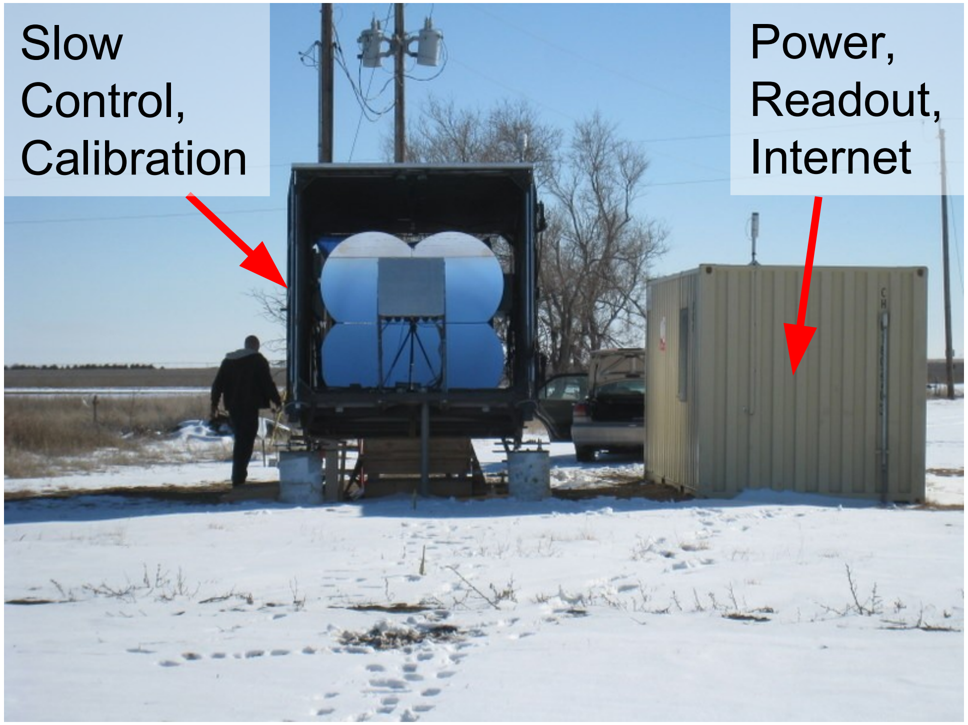
$$L = C \cdot L_0 \cdot T_{mol} \cdot T_{aer} \cdot \left[\beta_{mol}(\pi-\psi) + \beta_{aer}(\pi-\psi)\right] \cdot \left[T_{mol} \cdot T_{aer}\right]^{1/\cos(\psi)}$$

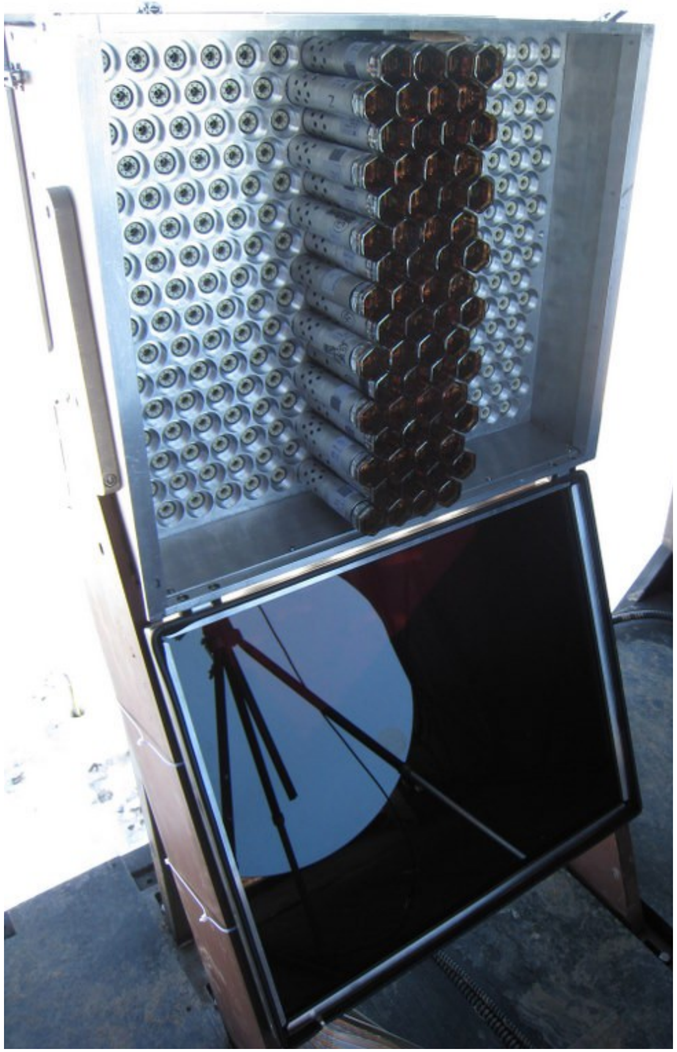


Nd:YAG
355 nm
5–10 mJ

Bi-static LIDAR (Receiver)

- 4 vertical columns, 16 PMTs each
- 1° FoV per pixel (old HiRes-II camera)
- UV bandpass filter

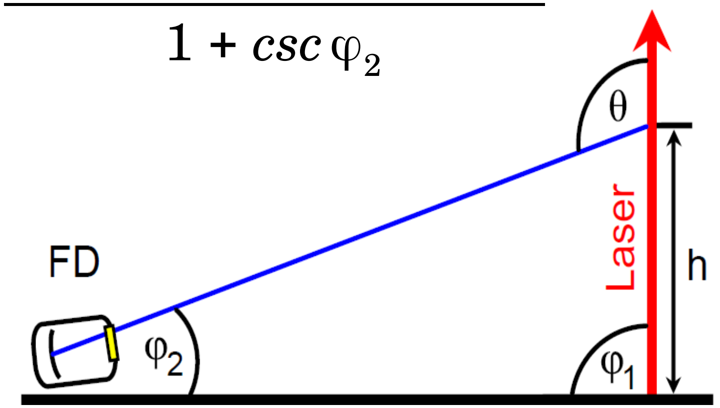


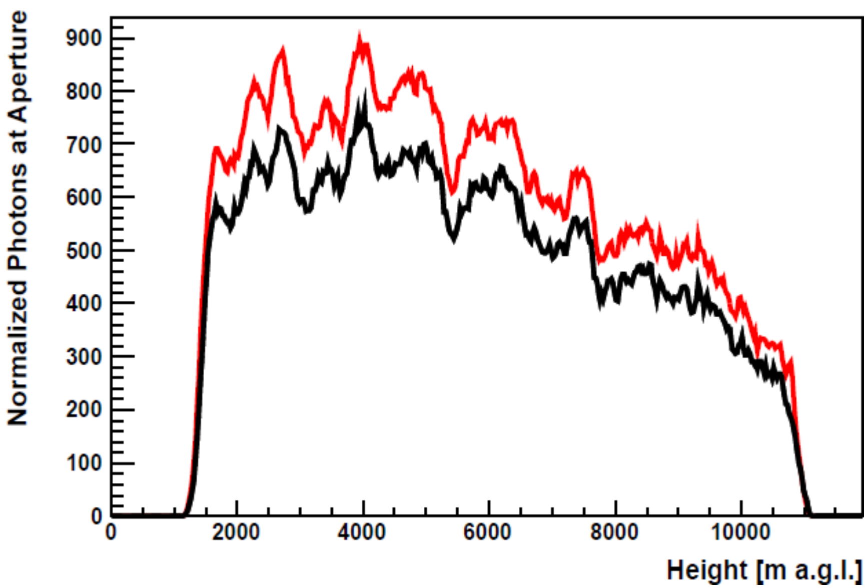


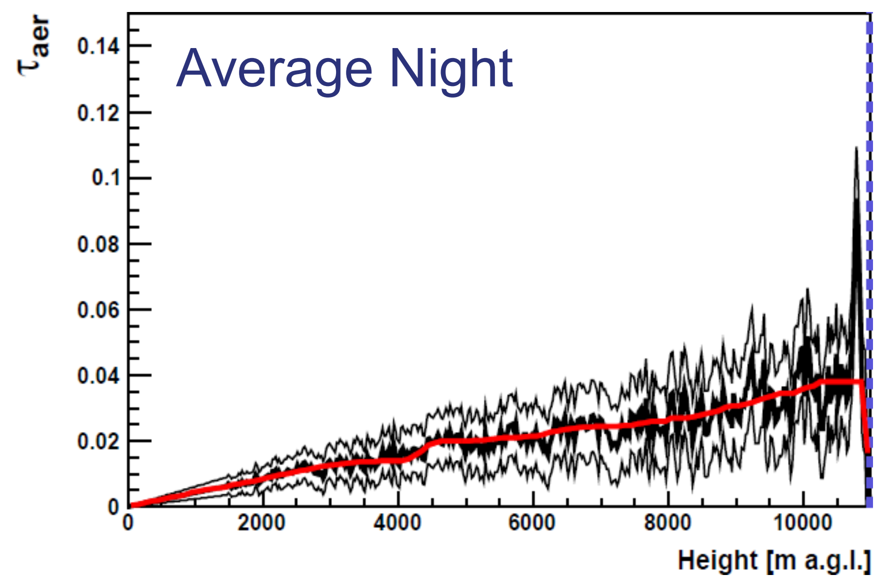
Bi-static LIDAR

$$\tau_{aer}(h) = \frac{\ln N_{ref}(h) - \ln N_{obs}(h)}{1 + \csc\varphi_2}$$

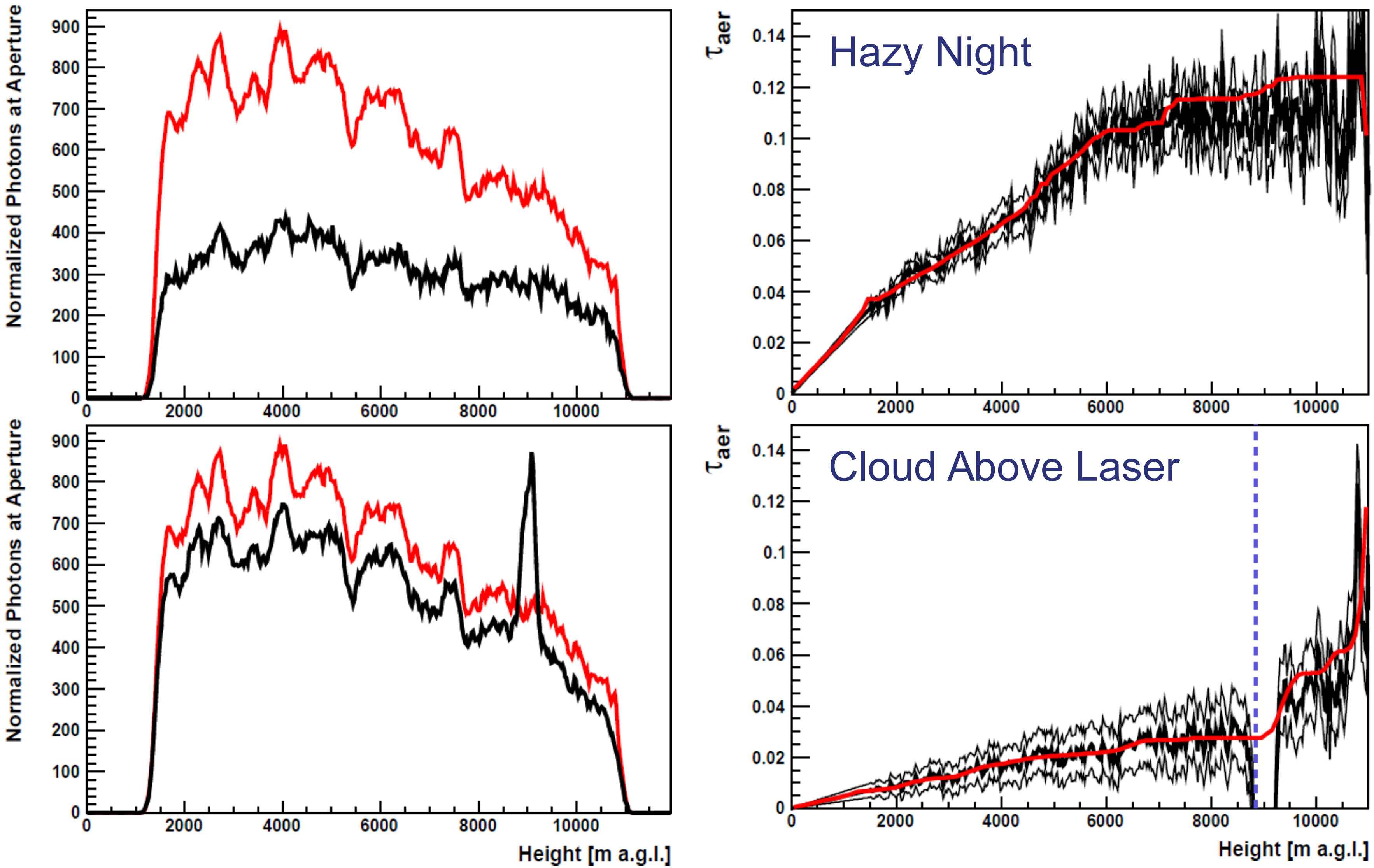
- Main assumptions
  - Reference night clear of aerosols
  - Scattering out of beam is dominated by Rayleigh scattering
  - Atmosphere horizontally uniform between laser and FD



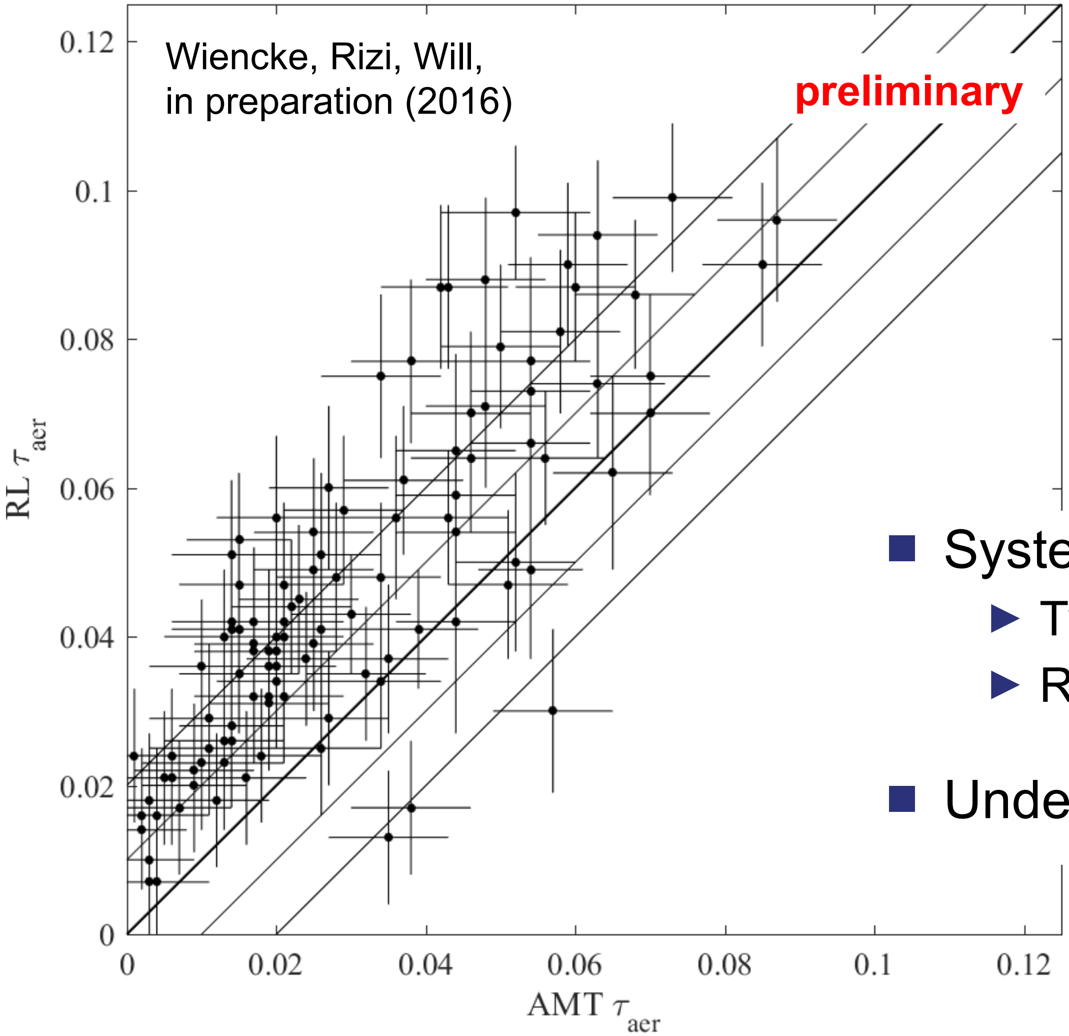




Bi-static LIDAR Data

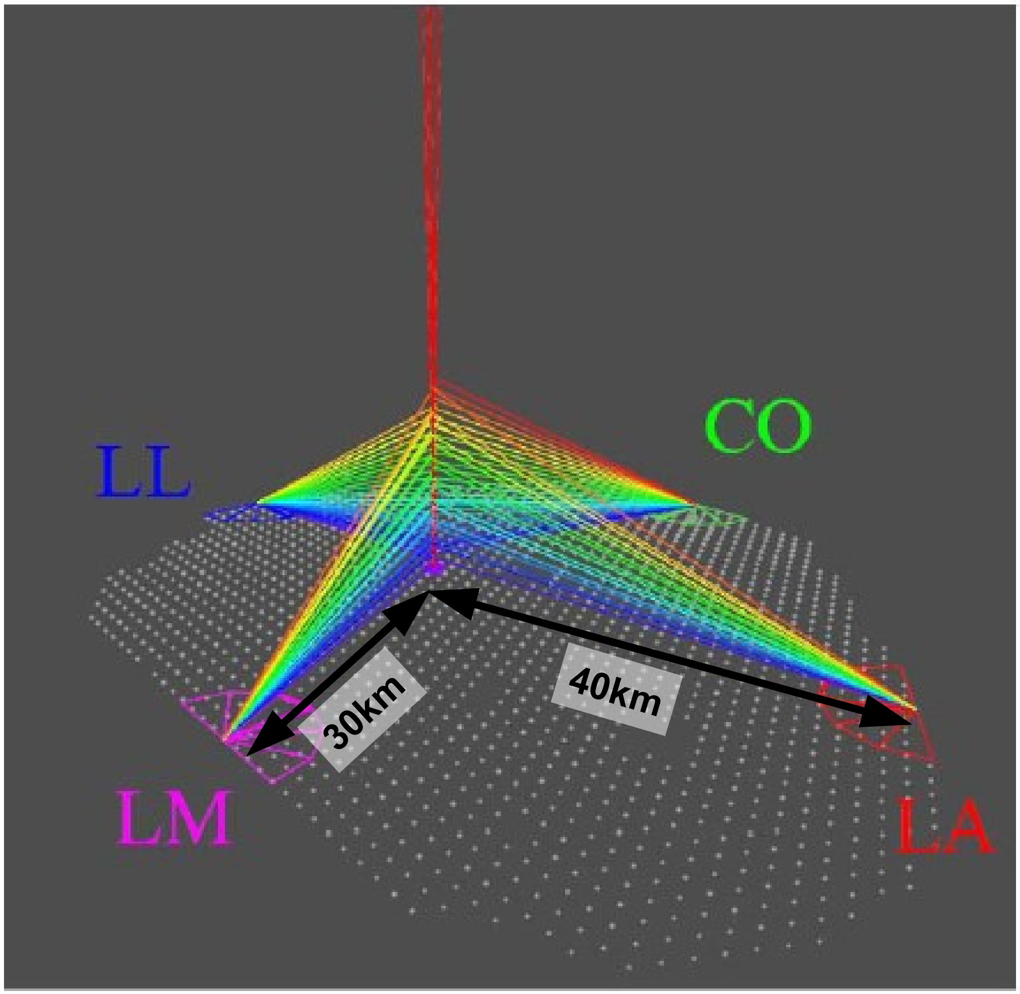


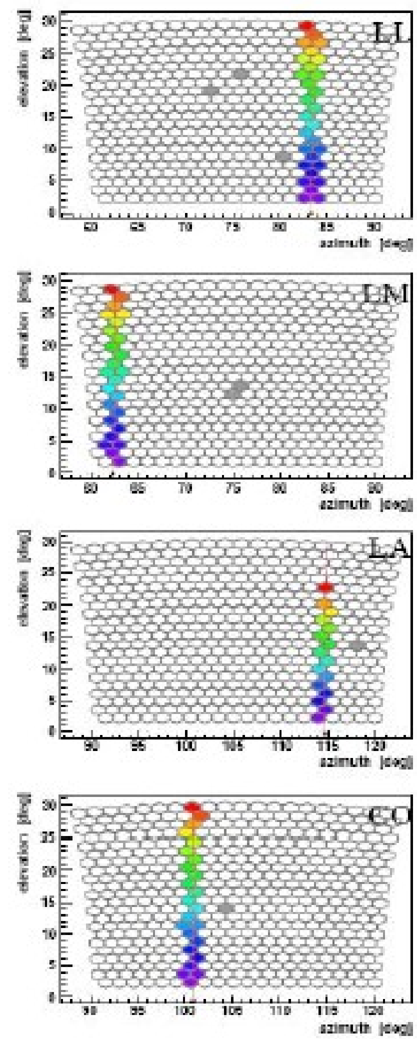
Comparison Raman / Bi-static



- Systematic difference
  - Type of aerosols
  - Reference night not clean
- Under investigation

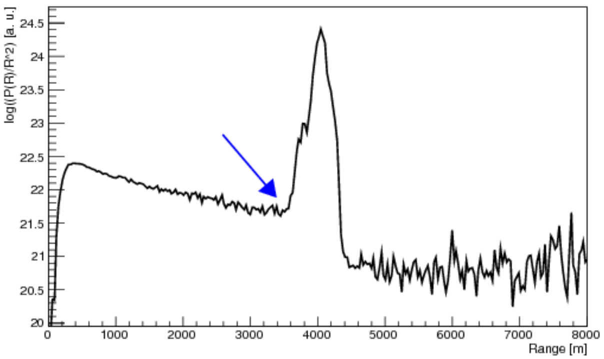
Raman / Bi-static LIDAR at Auger

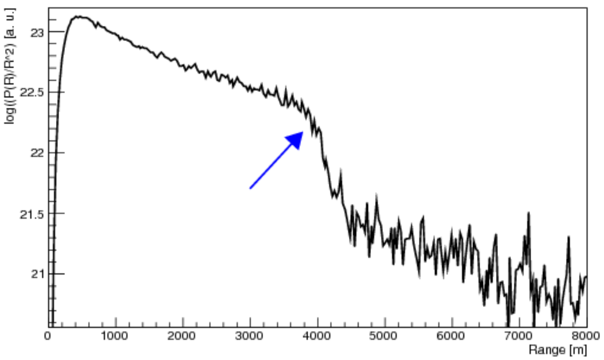




CTA Raman LIDAR

- Upgrade of Colorado system
  - Continue measurements
  - Characterize site
- Integrate into CTA
  - Move to La Palma 2017
  - Later to southern site
- Minimize impact on CTA measurements

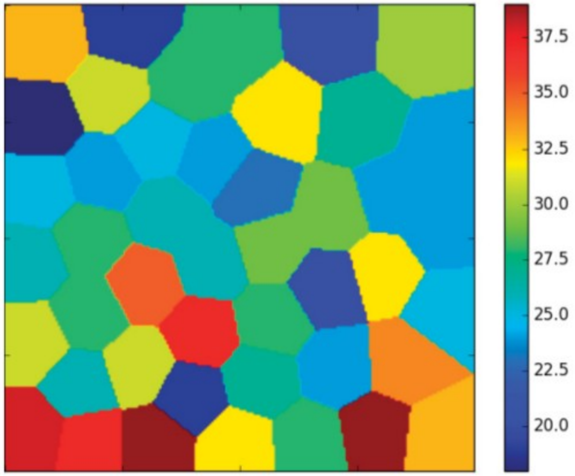




FRAM (Fotometric Robotic telescope for Atmospheric Monitoring)

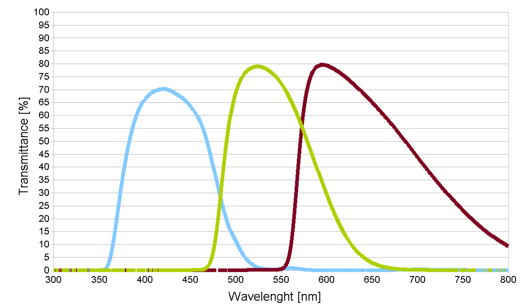
- Passive measurement
  - Stellar photometry
  - 15°×15° FoV, several 100 stars
  - Integral extinction
  - 10 years experience from Auger

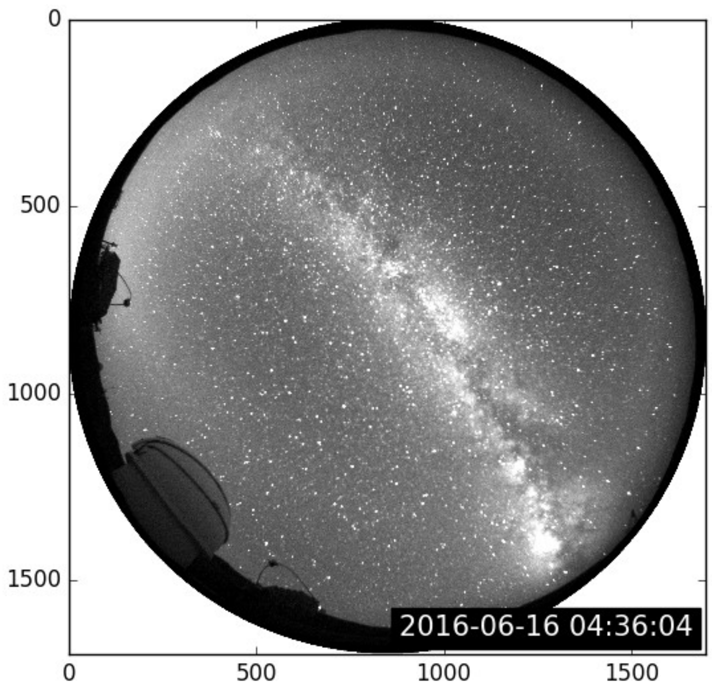
- FRAM for CTA
  - Prototype deployment in La Palma
  - Aerosol maps in fixed FoV
  - Altitude scans for aerosol profiles
- 11 inch MPI telescope for MAGIC
  - Similar characteristics, spectrograph
  - Transmission from spectrum differences of stars
  - Deployed in La Palma before FRAM

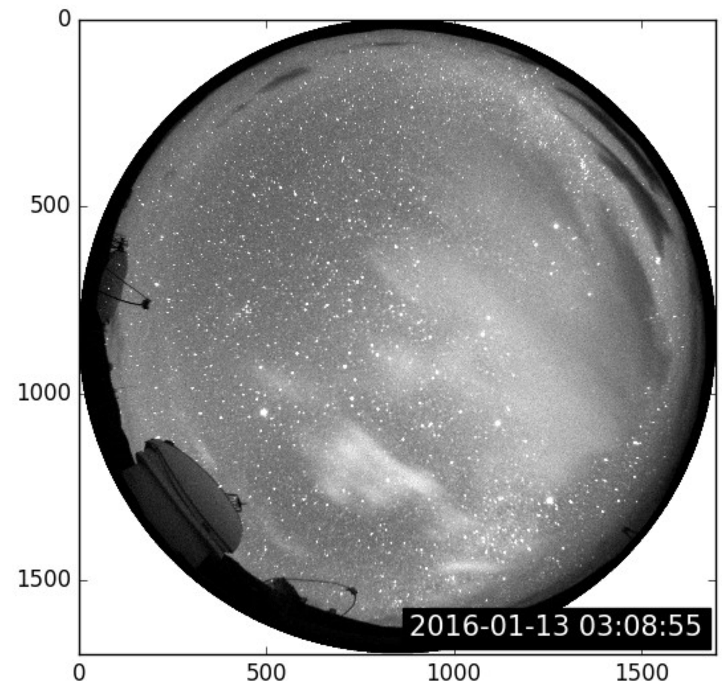


CTA AllSky Camera

- AllSky camera on MAGIC counting house roof
  - Czech construction (also used at Auger)
  - 3 different filters (plus no filter)
  - 60 seconds exposure

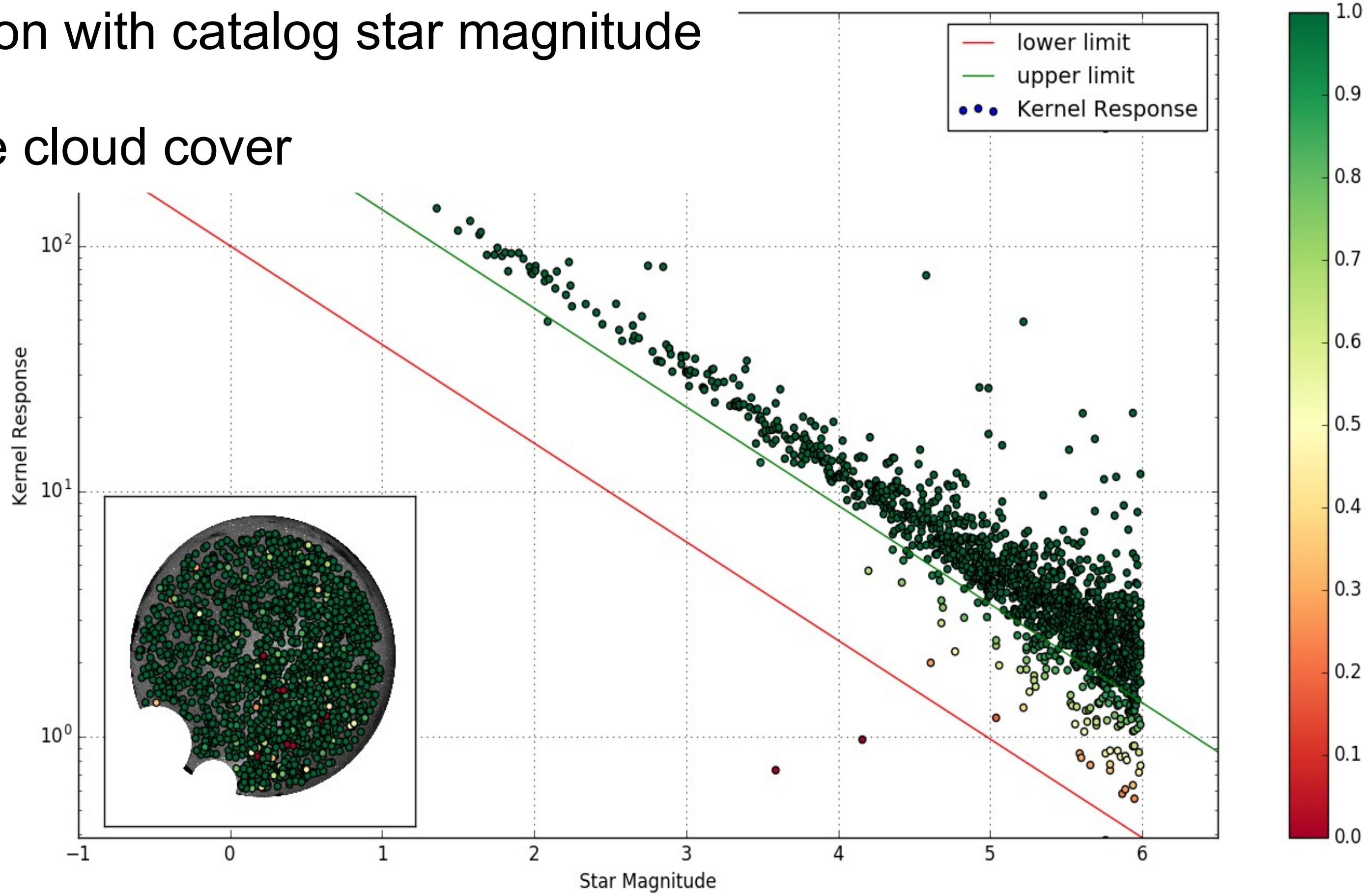






Cloud Detection

- Star detection with image filter
- Comparison with catalog star magnitude
- Determine cloud cover



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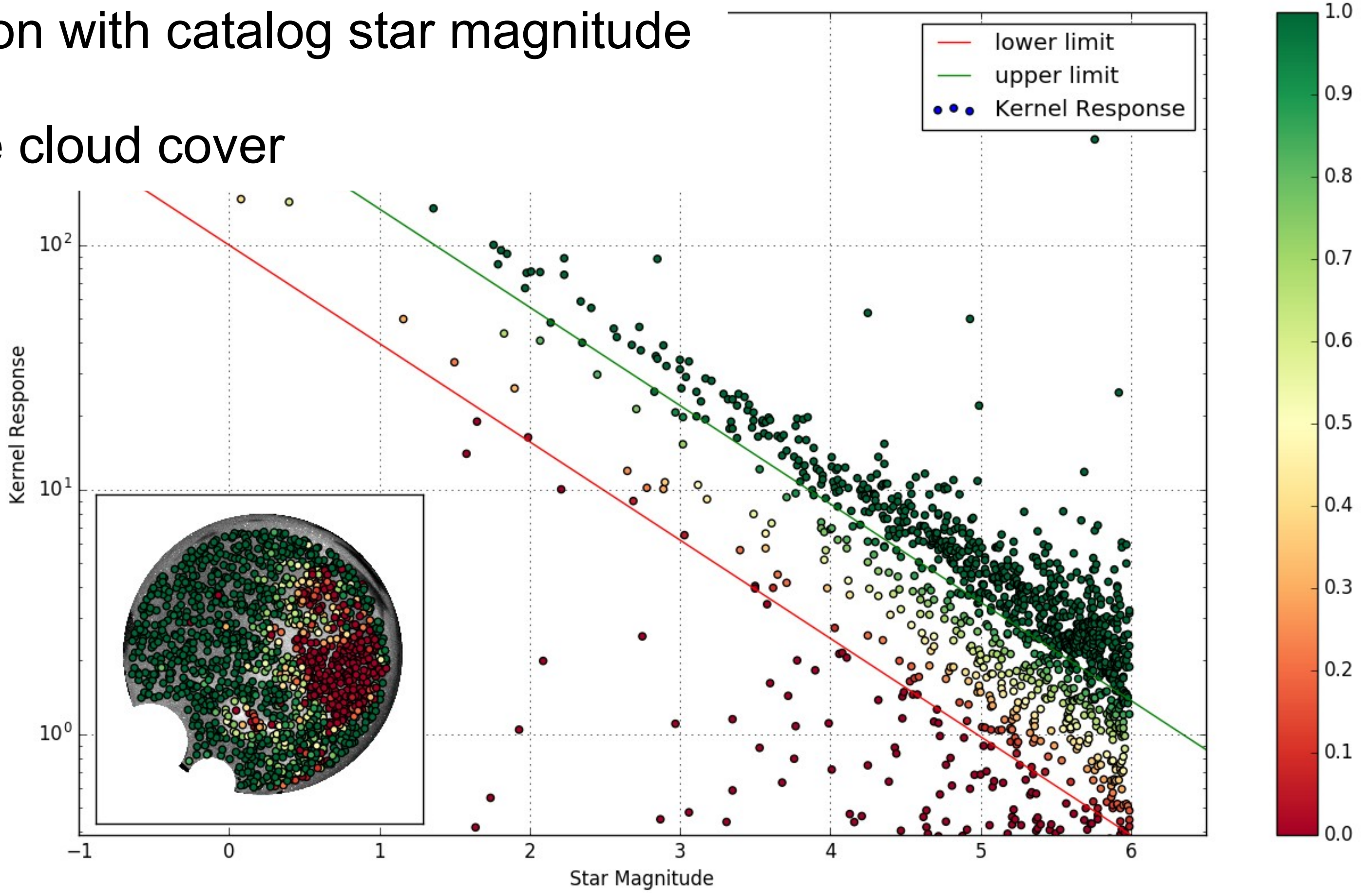
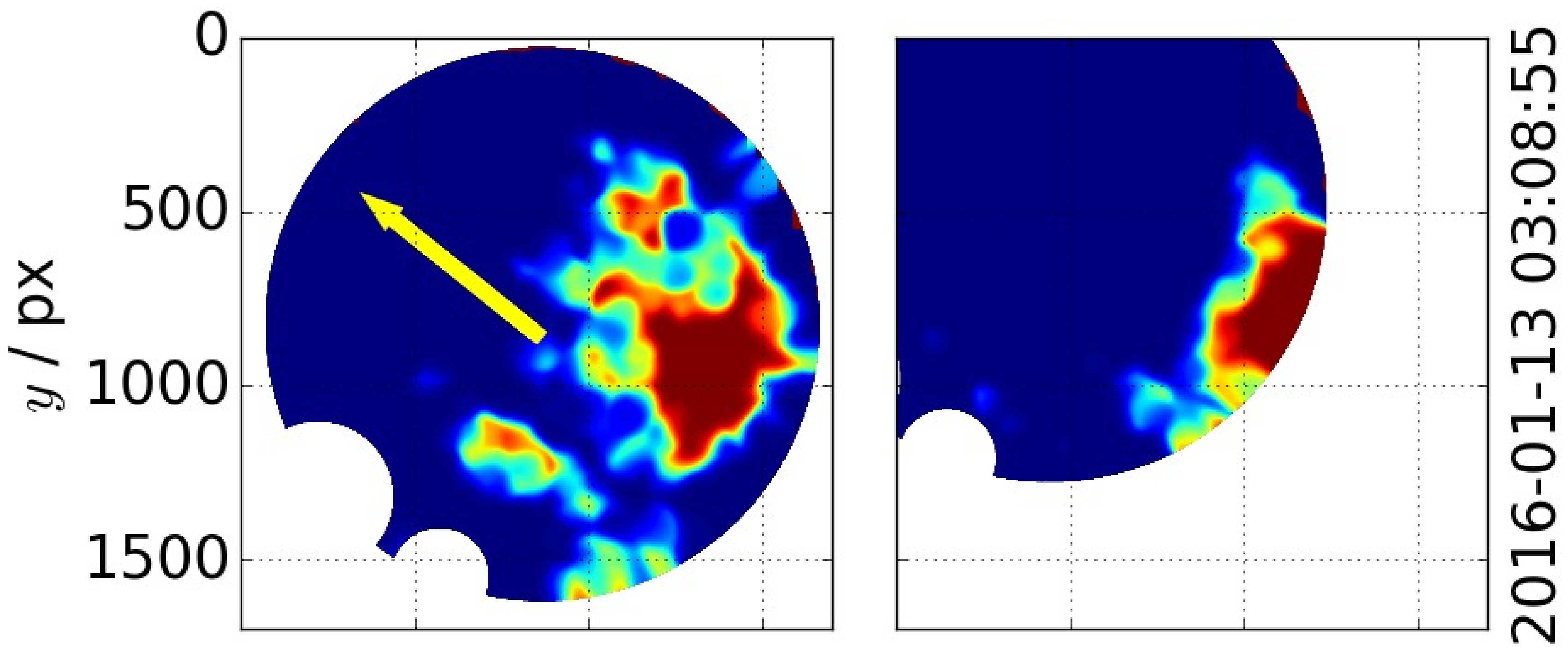


Cloud Tracking

- Identify single clusters in cloud maps
- Compare position of clusters between images
- Difference is direction movement of clouds



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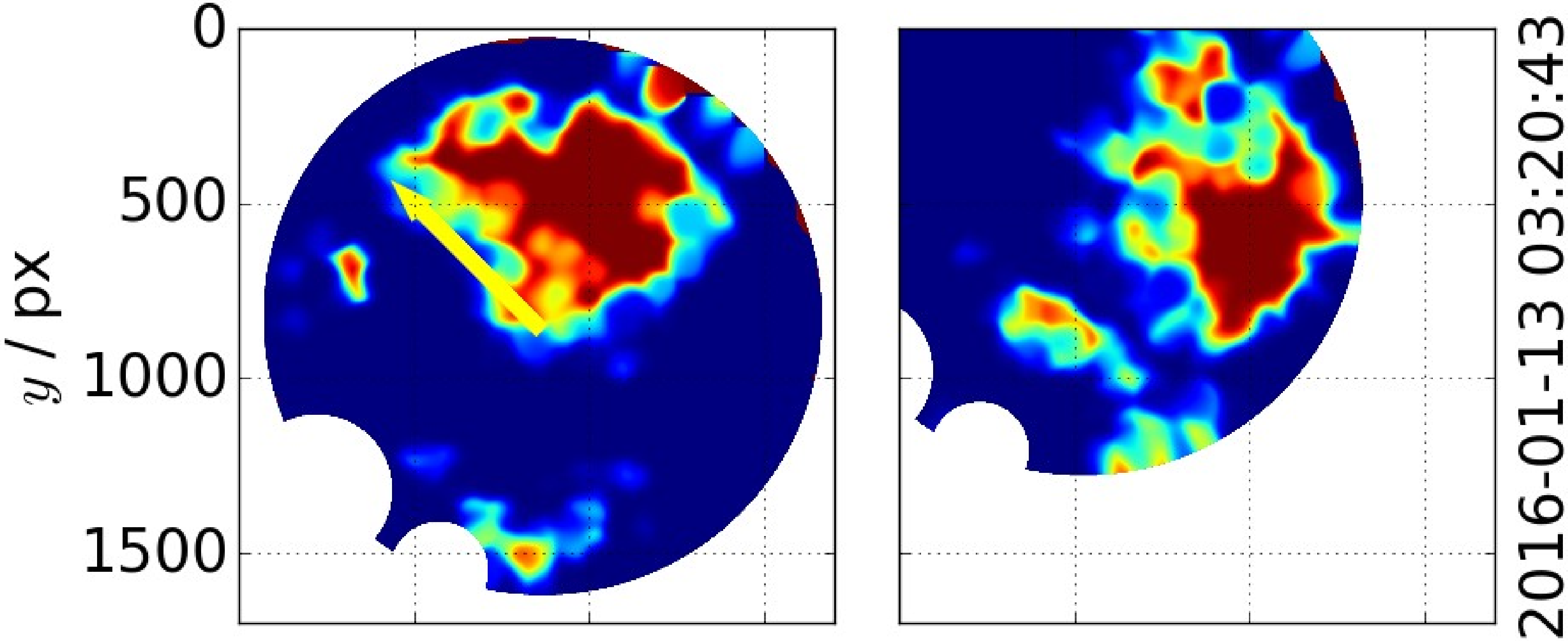

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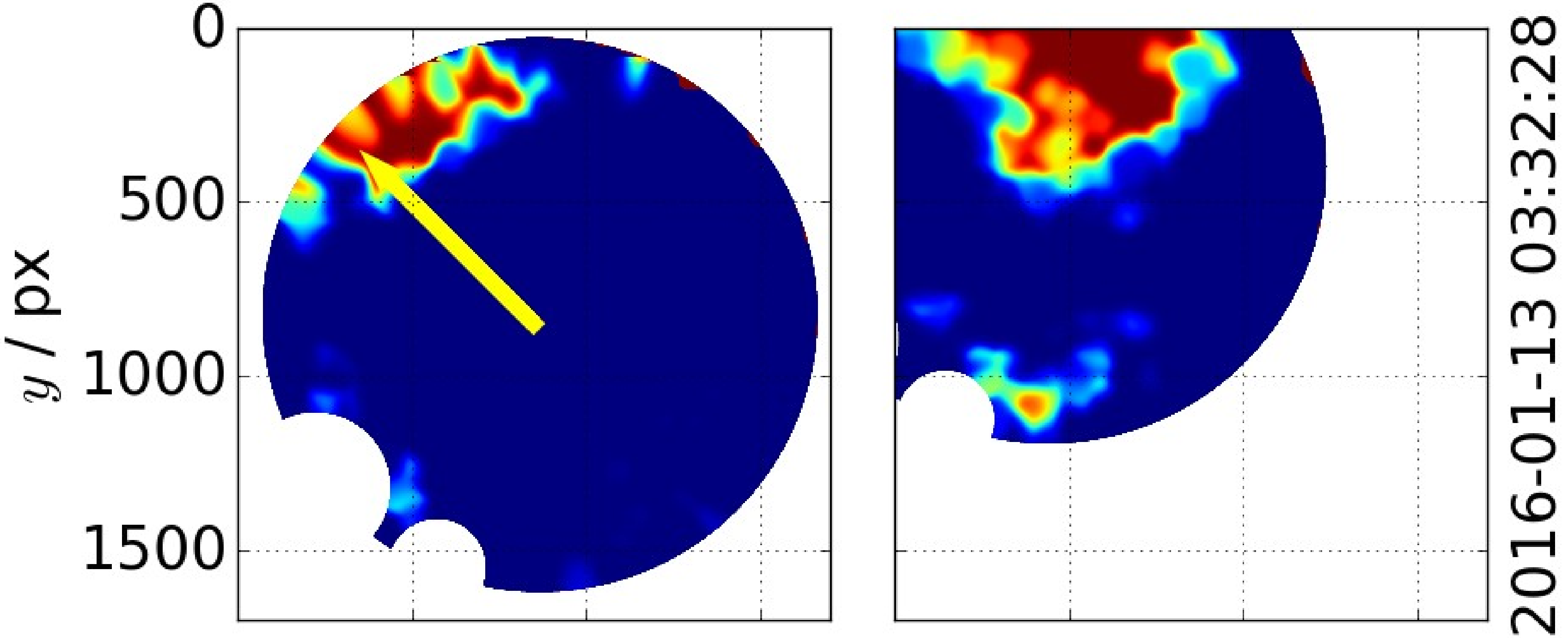
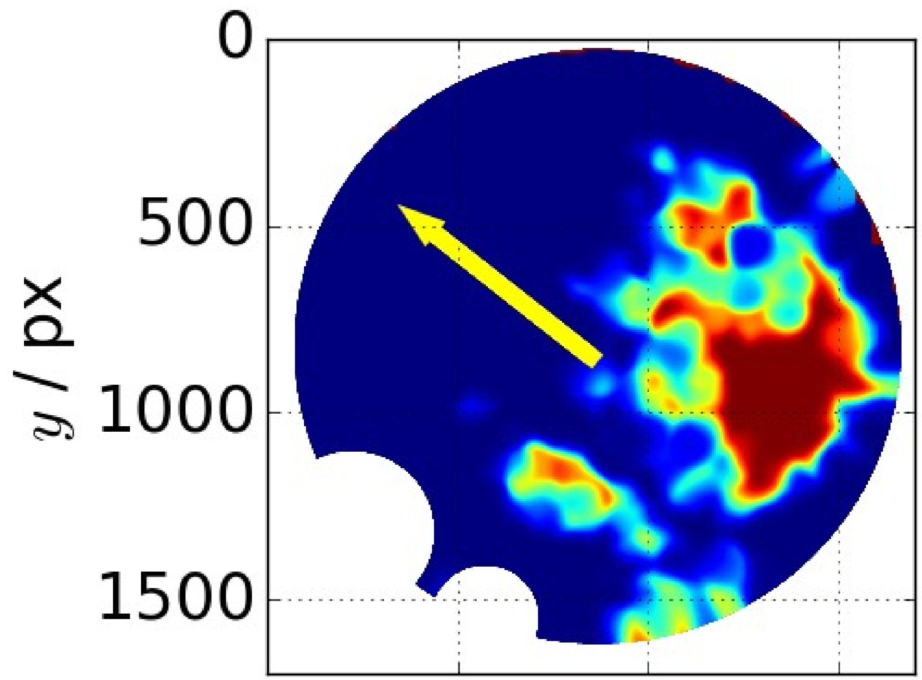


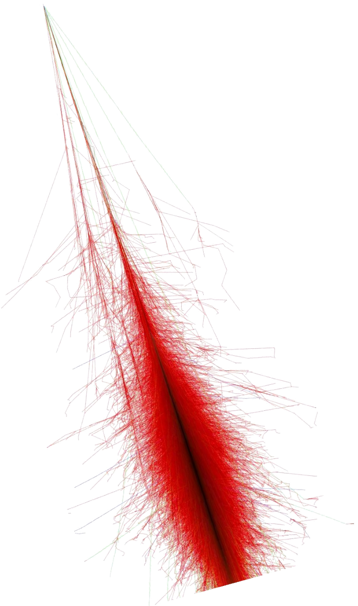
Cloud Tracking

- Identify single clusters in cloud maps
- Compare position of clusters between images
- Difference is direction movement of clouds
- Potential problems
  - Clouds can change shape
  - Clouds can split or merge
  - Clouds can disappear
- Further improvement
  - Wind speed from GDAS
  - Cloud properties from LIDAR



CTA Air Shower Simulations

- Systematic uncertainties in CTA must not exceed 10%
  - MAGIC: 11% due to atmosphere
  - Auger: 6–7% due to atmosphere (14% total)
- Simulated response functions
  - Need input from atmospheric measurement instruments
  - Fast for online analysis
  - Reliable and precise for offline analysis
- Instrumentation at Northern CTA site
  - Weather stations, wind sensors, rain sensors, …
  - Dust counters, electric field mill, ...
  - LIDARs, FRAM, ...



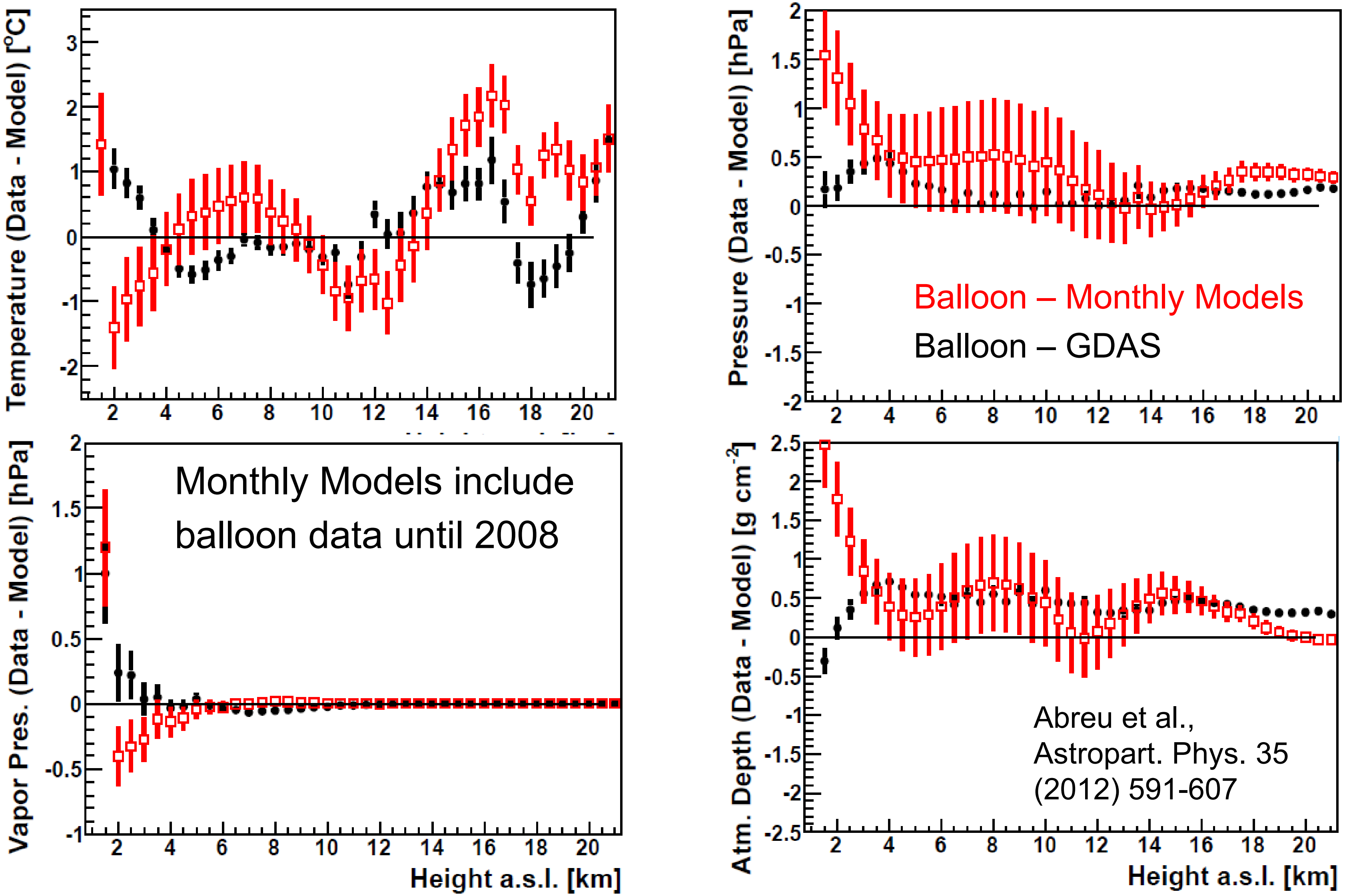
Summary

- Atmospheric parameters influence air shower detection
  - Density profile influences development
  - Cherenkov and fluorescence light production
  - Transmission depends on molecular and aerosol scattering

- Measurement of atmospheric parameters
  - Balloons, weather stations, model data for profiles
  - LIDARs and passive photometry for transmission
  - Cloud detection using AllSky cameras

- Apply lessons learned for CTA
  - Combination of instruments to keep sys. uncertainties at 10%
  - New models and unexplored sources for atmospheric data

GDAS Data Comparison



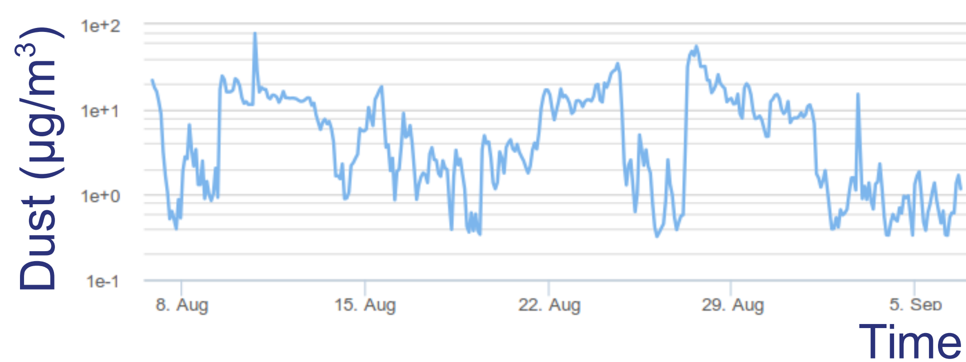
Other Data Sources

20:01 UT	Temp. °C	Hum. %	Wspd km/h	Wdir dir.	Press. mb	See.* "
LT	17.1	9	5.3	NW	779.0	
MT	16.9	9	6.1	NW	778.3	
INT	16.1	9	10.4	WNW	779.6	
JKT	16.4	9	9.4	WNW	776.8	
SWASP	16.6	9	5.0	NNW	761.6	
WHT	16.4	7	0.0	WNW	779.9	n.a.
NOT	14.2	3	9.3	W	774.4	
TNG	16.7	8	6.4	N	776.6	0.6
GTC	17.2	7	2.2	ENE	782.4	
IAC	PWV (mm):			7.0	MORADAS	0.9
MAGIC	15.8	11	4.0	SE	790.7	

*: WHT, TNG, MORADAS

- Dust measurement at TNG
  - Automatic particle counter *Lasair II 310B*
  - Particle concentration from laser scattering
  - Size sensitivity 0.3, 0.5, 1.0, 3.0, 5.0, 10.0 μm
  - 2h cumulative density in μg/m³

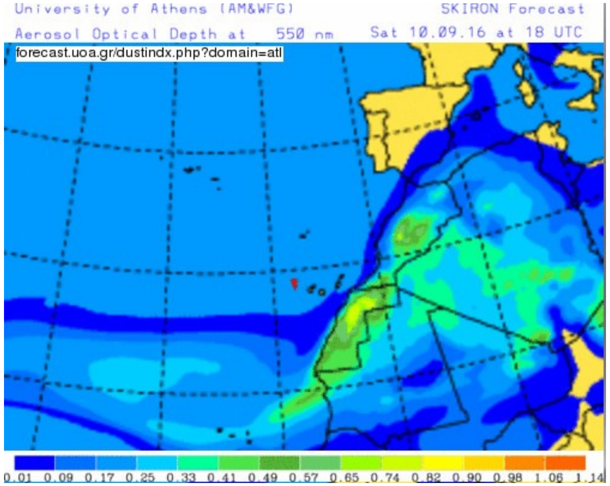
- Other ORM telescopes
  - Weather station data
  - Seeing
  - Dust concentration



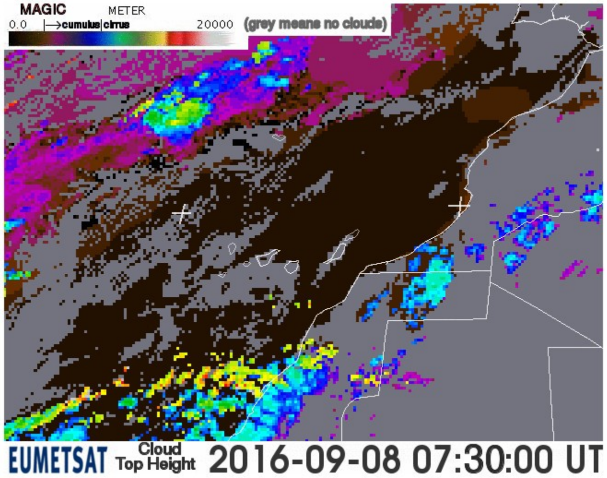
Satellite Data and Forecasts

- Data available for La Palma site
  - Weather forecasts
  - Cloud satellite images
  - Aerosol optical depth forecast

SKIRON AOD Forecast



EUMETSAT Cloud Image

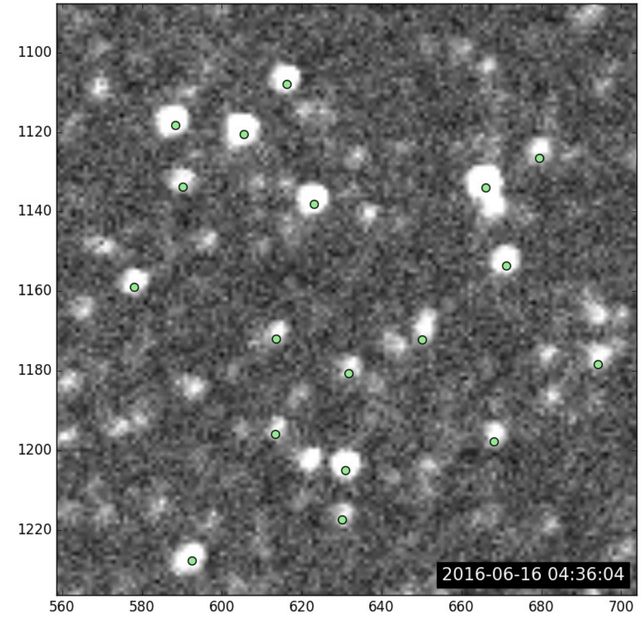


Roque de los Muchachos Mountain Forecast

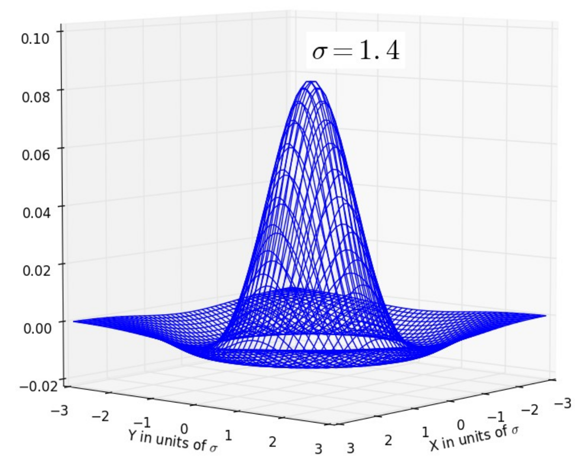
Wind (km/h)	5	10	10	15	10	10	10	10	15	15	5	10	10	10	15	20	20	20
Summary	rain shwrs	clear	clear	clear	clear	clear	clear	clear	clear	clear	clear	rain shwrs	clear	clear	clear	rain shwrs	clear	rain shwrs
Snow (cm)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Rain (mm)	2	-	-	-	-	-	-	-	-	-	-	1	-	-	-	1	-	1
High °C	16	16	16	15	14	14	13	12	12	11	11	11	10	11	11	12	12	12
Low °C	16	16	15	15	14	13	12	12	10	11	10	10	10	11	11	11	12	11
Chill °C	16	16	15	14	13	14	12	11	10	9	10	10	9	10	9	10	10	10
Freezing level (m)	4800	4900	4850	4750	4800	4700	4650	4650	4600	4500	4450	4450	4400	4450	4450	4550	4650	4700

Star Detection

- Blob detection with image filter
  - Applied to each pixel
  - Summing up all neighbor pixels
  - Filter mask as weight matrix
  - Returned value is filter response



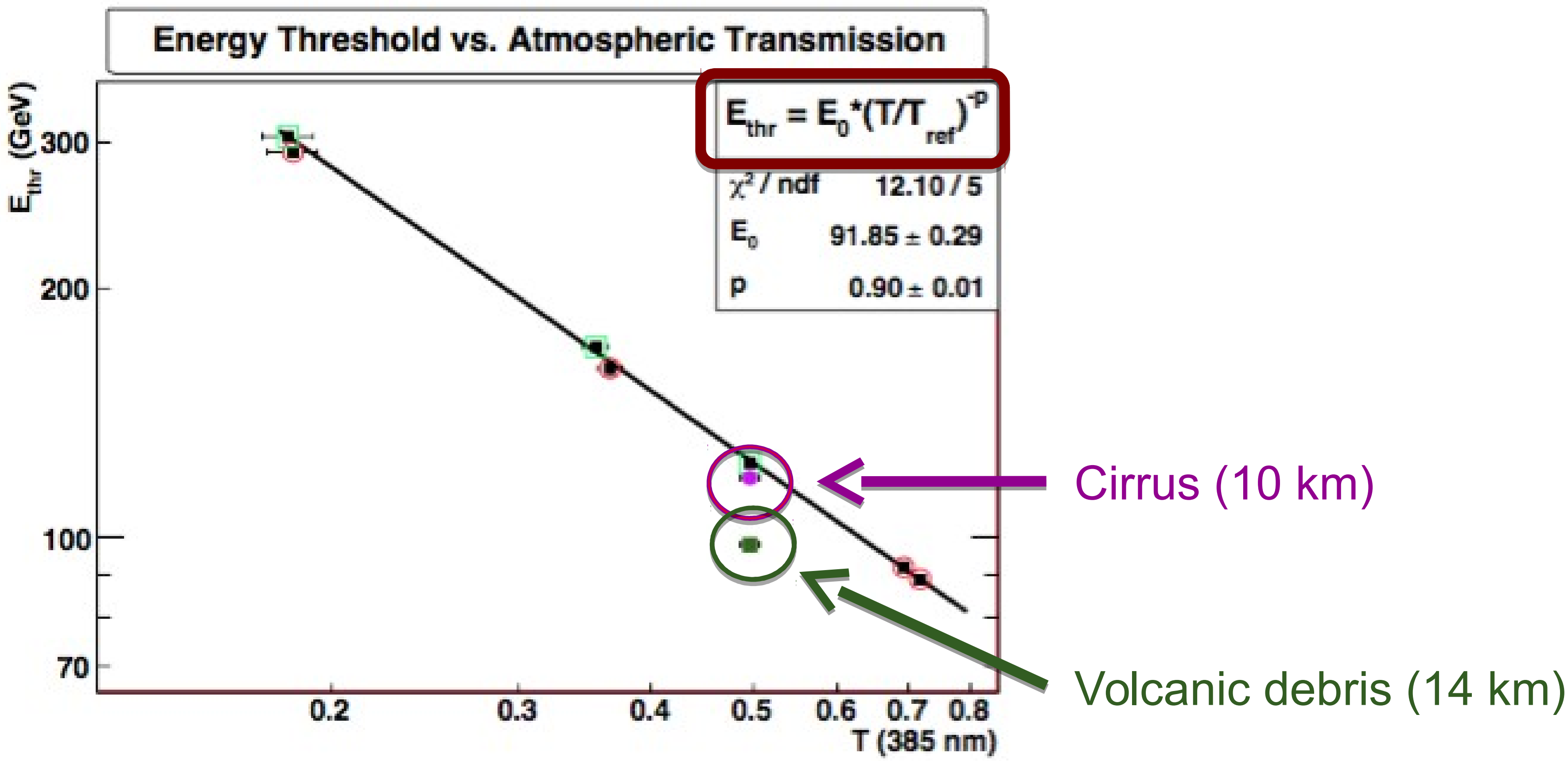
- Chosen filter: Laplacian of Gaussian (LoG)
  - Reduce noise by smoothing with Gaussian
  - Laplacian filter: adjustable blob size, rotation invariant, fast computing speed, insensitive to linear brightness gradients



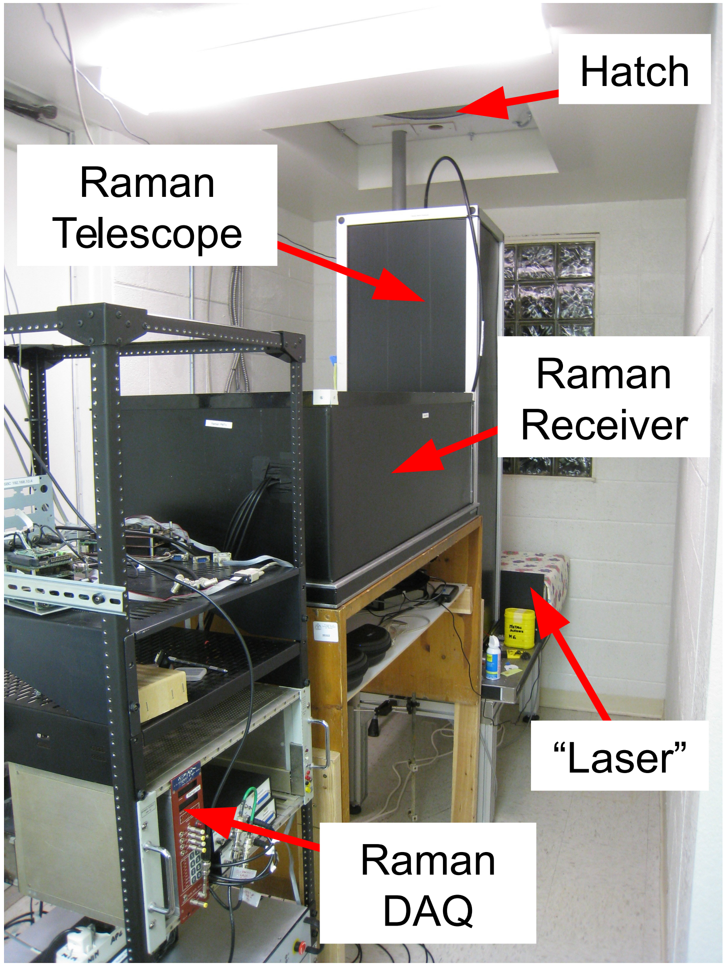
- Apply kernel for each star in catalog
  - Avoid hot pixels
  - Chose magnitude limit

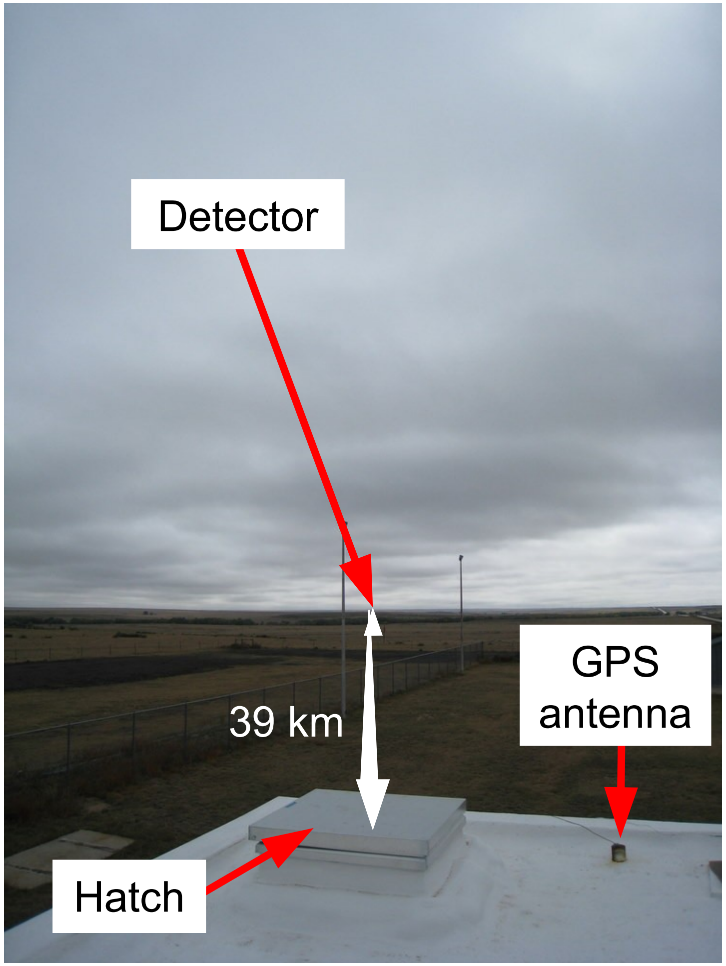
- Take into account exposure, atm. absorption, lens distortions

Energy Threshold

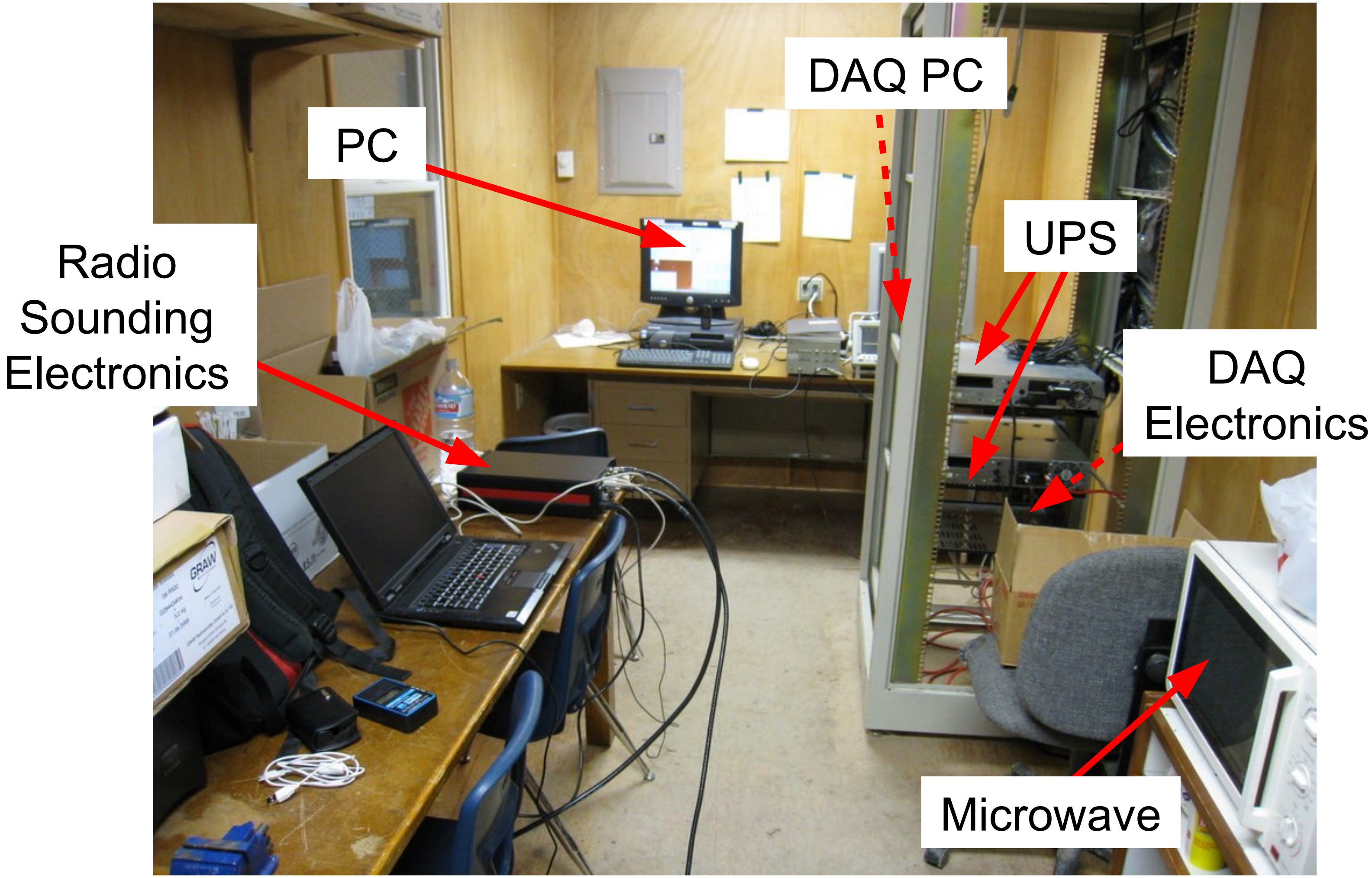


Raman LIDAR

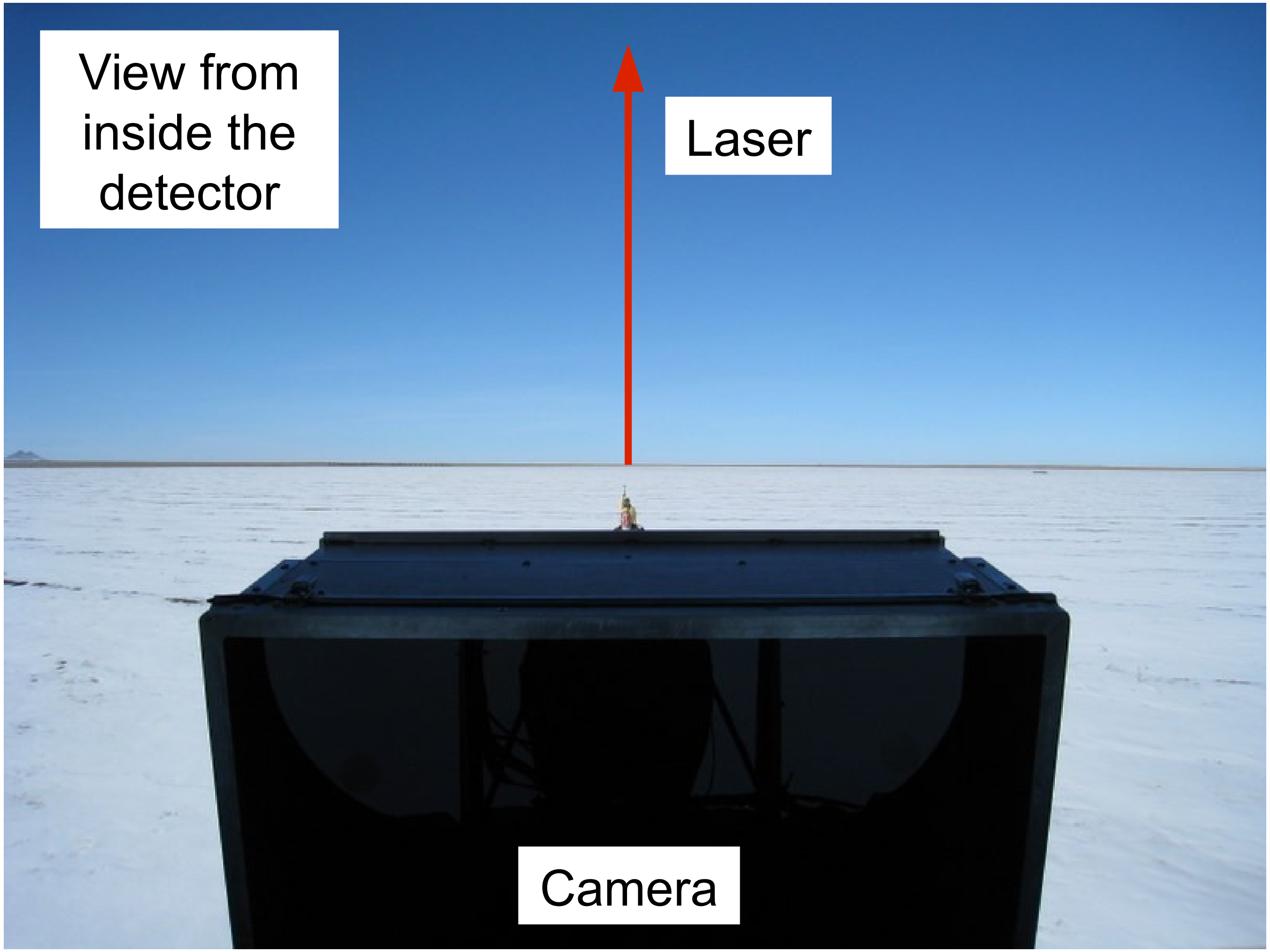

Hatch
Raman
Telescope
Raman
Receiver
"Laser"
Raman
DAQ


Detector
39 km
GPS
antenna
Hatch

Bi-static LIDAR



Bi-static LIDAR



Bi-static LIDAR