Time structure analysis of extensive air showers using Telescope Array data

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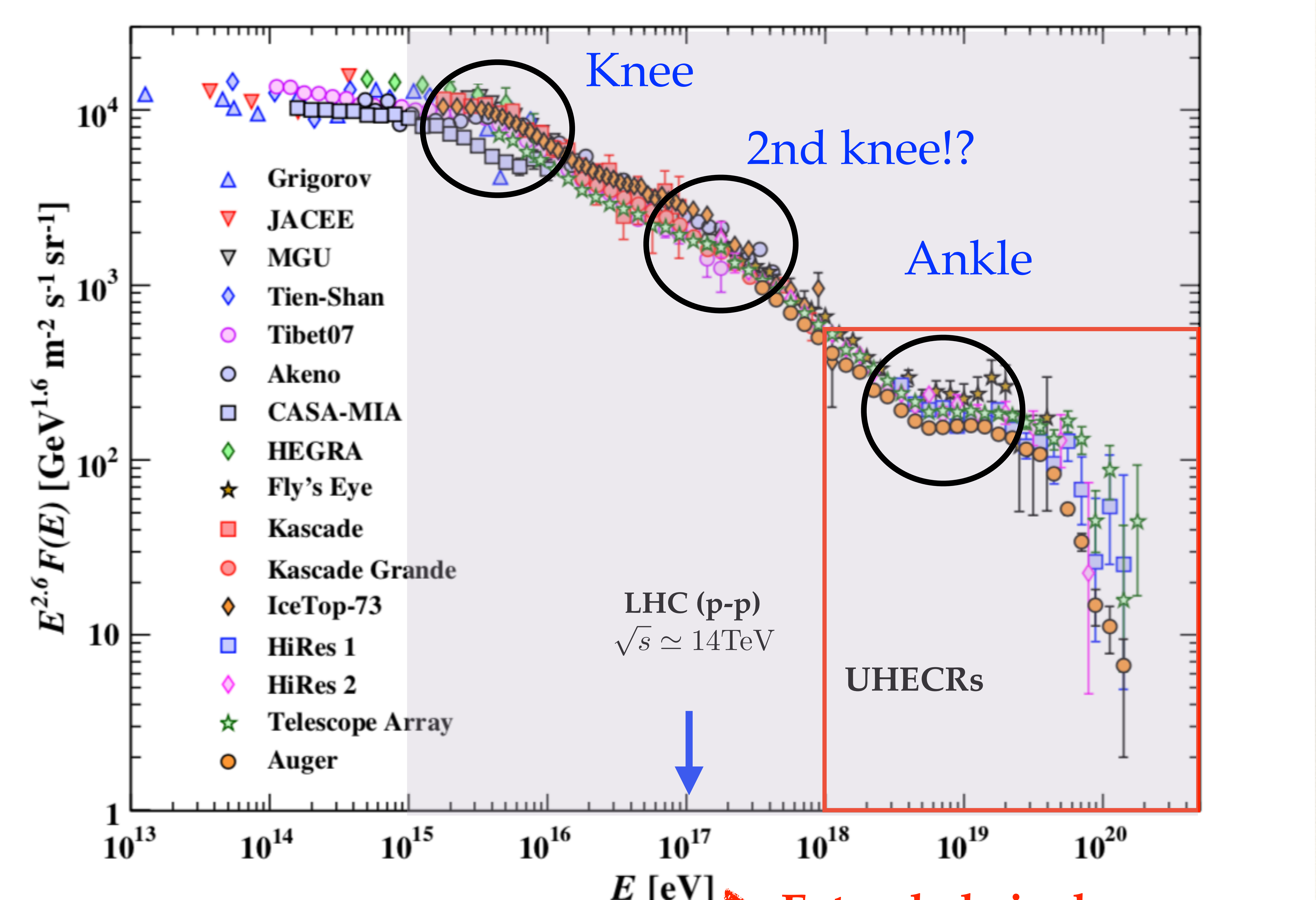
Contents

- **Ultra High Energy Cosmic Rays**
  - Energetic particle from the Universe ($E > 10^{18}$ eV)
- **Telescope Array**
  - A huge observatory for UHECR in northern hemisphere
    - Surface detector array(SDs), Fluorescence Detector (FD)
- **Data Analysis of Time profile**
  - Shower front
  - Thickness of shower disk

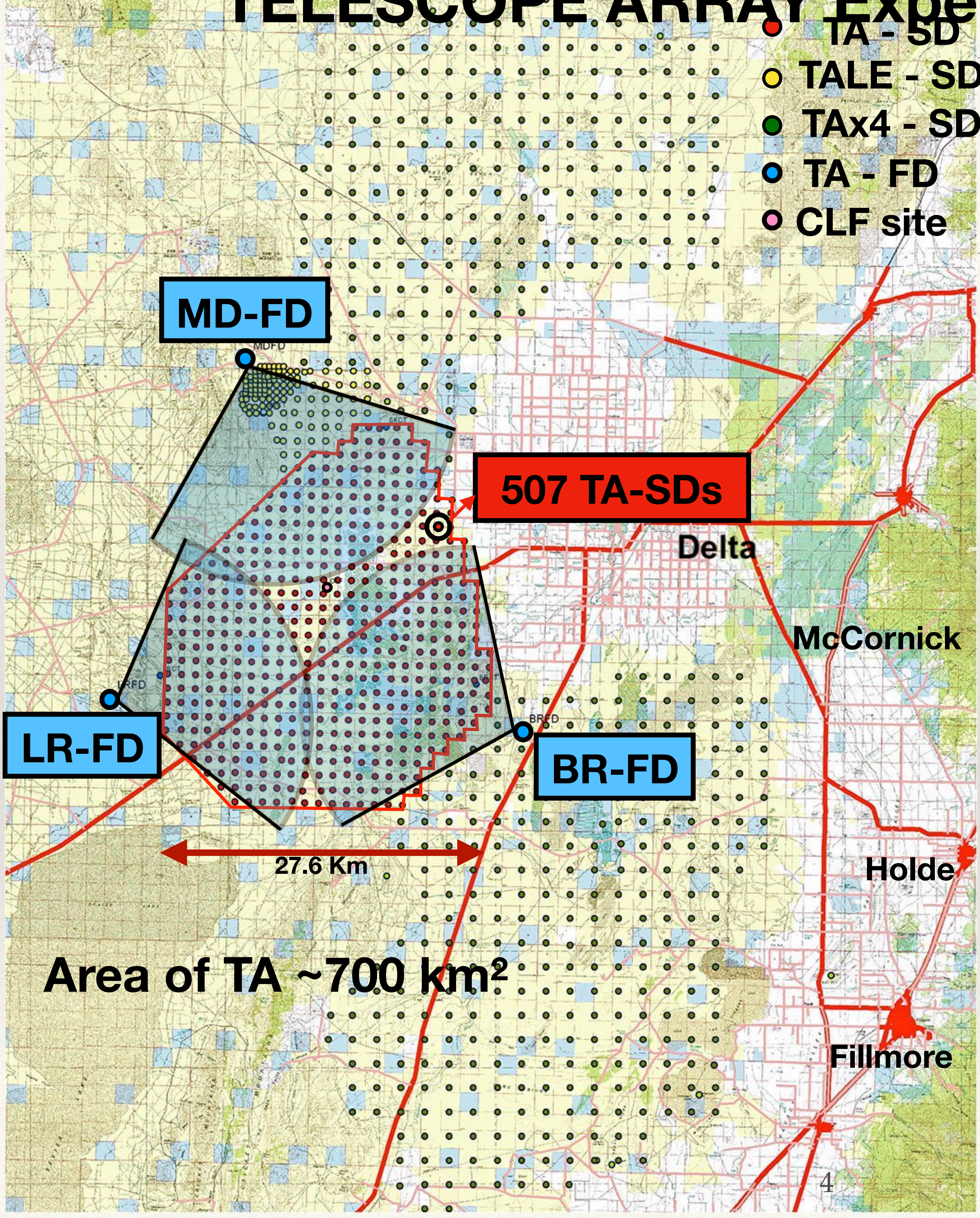
Cosmics Rays

$$\frac{dN}{dE} \propto E^{-\alpha}$$



Extended air showers

TELESCOPE ARRAY Experiment

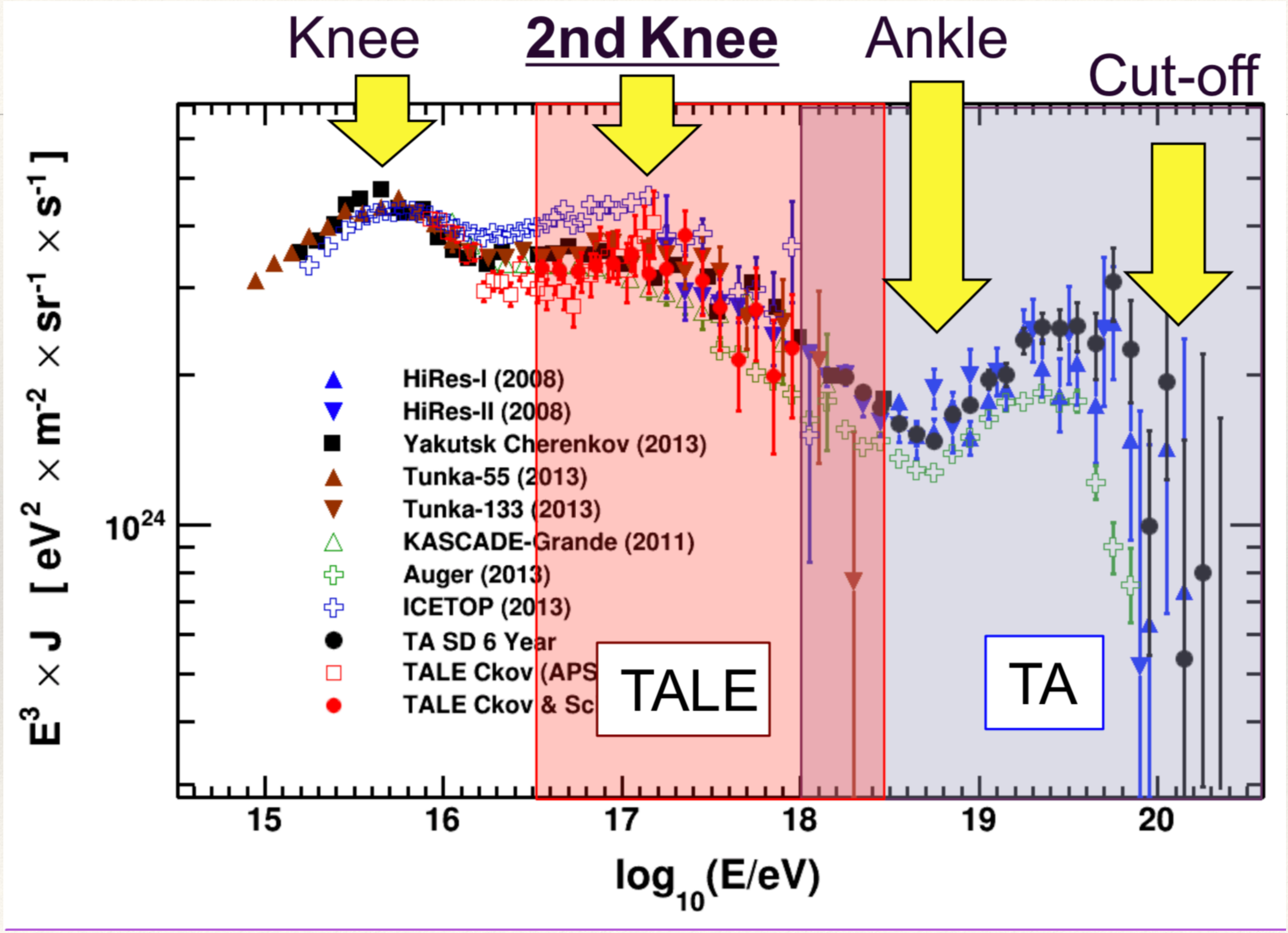


Hybrid Experiment

SD- Surface Detector

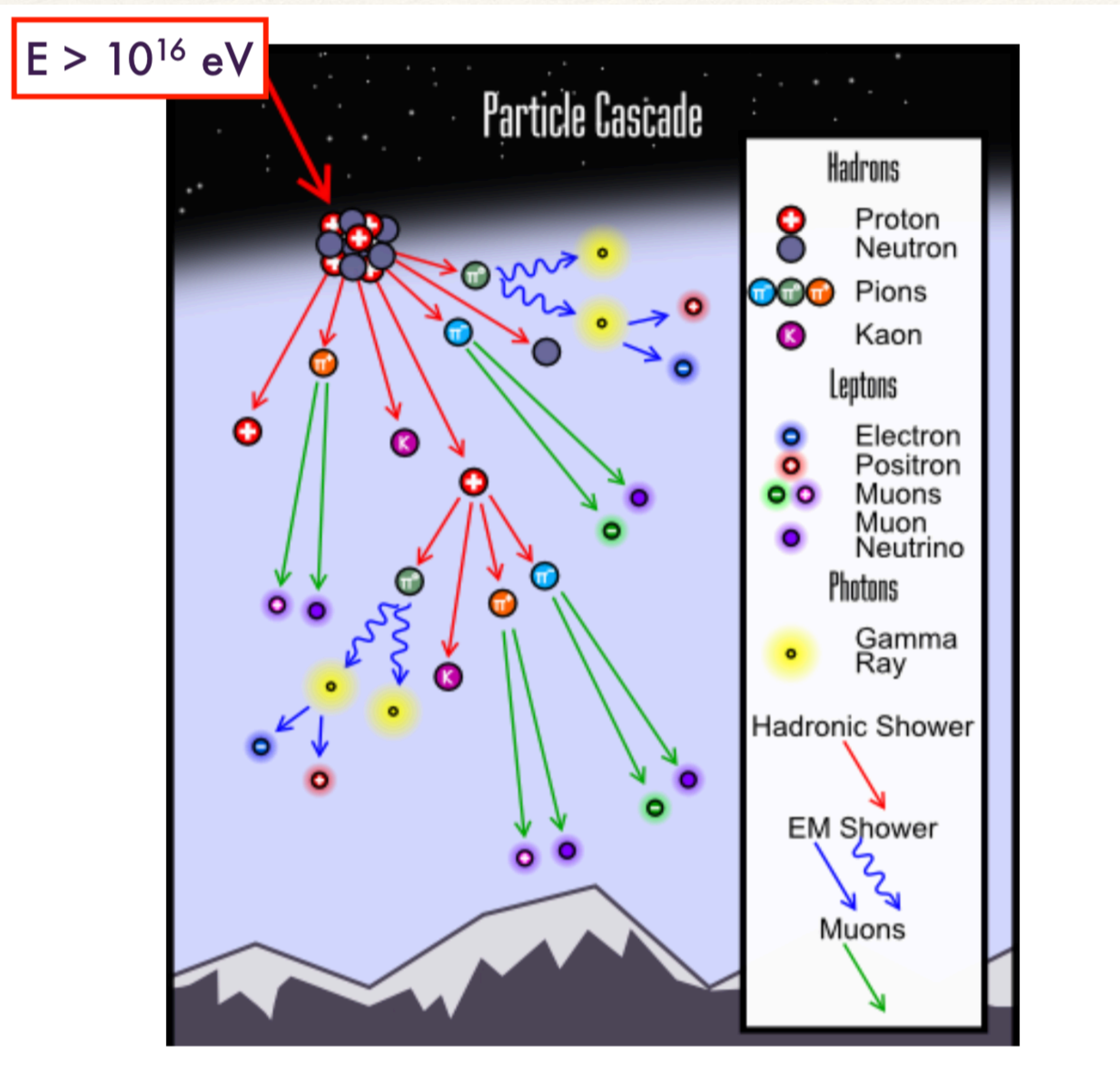
FD- Fluorescence Detector

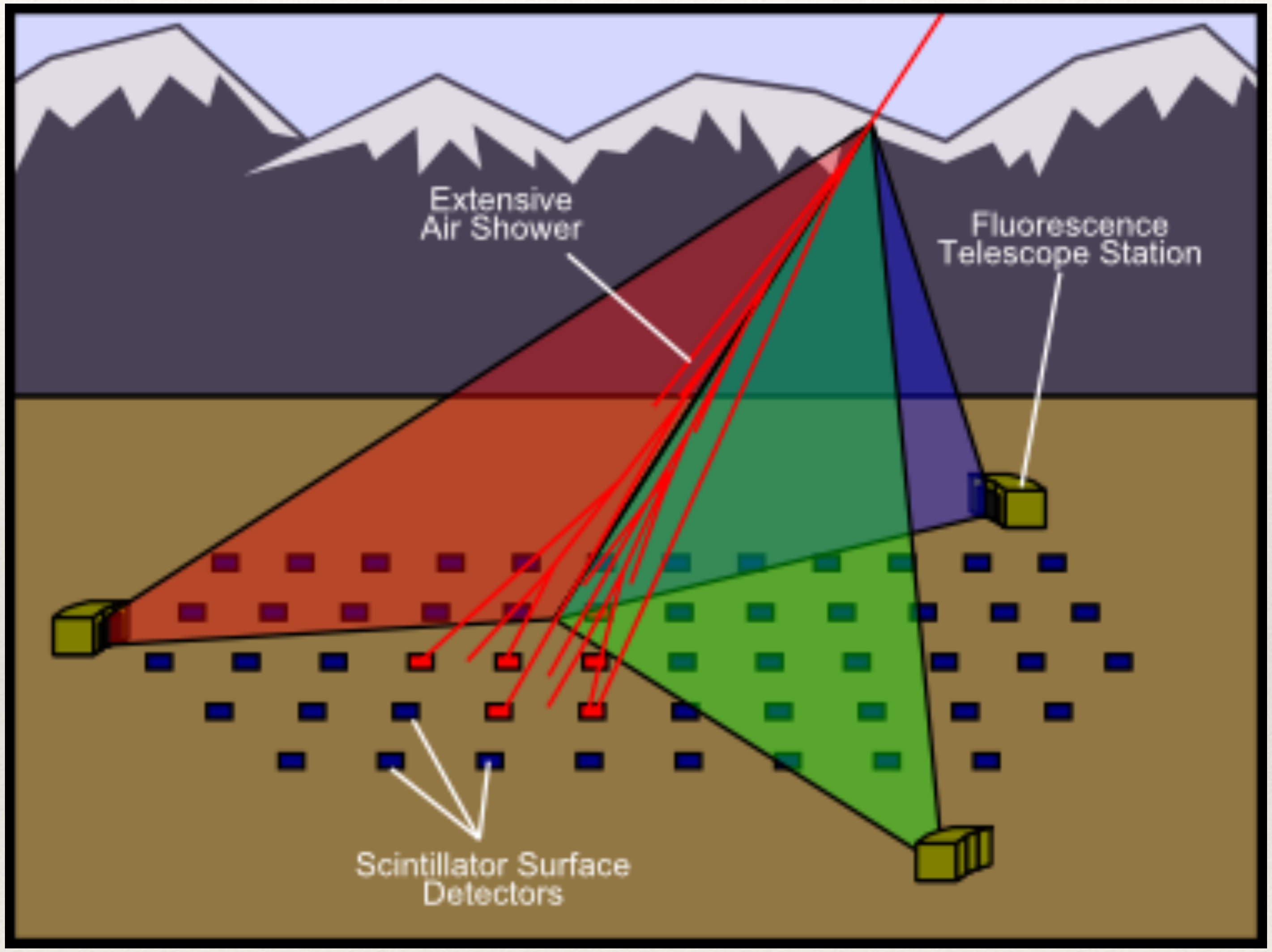
Cosmic rays: TA



UHECR phenomenology

Detection



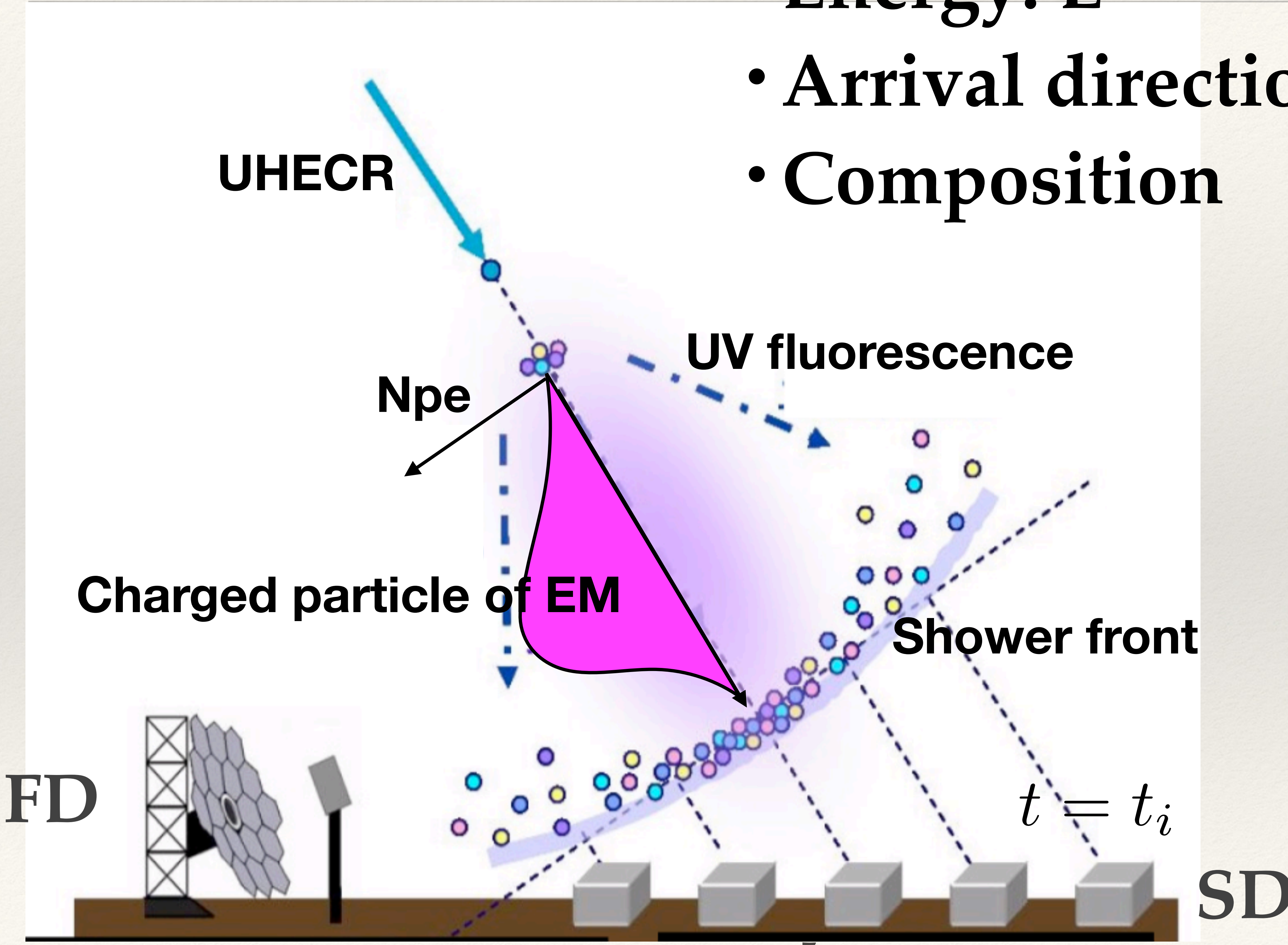


- **Telescope Array**
- **Pierre Auger Observatory**

UHECRs phenomenology

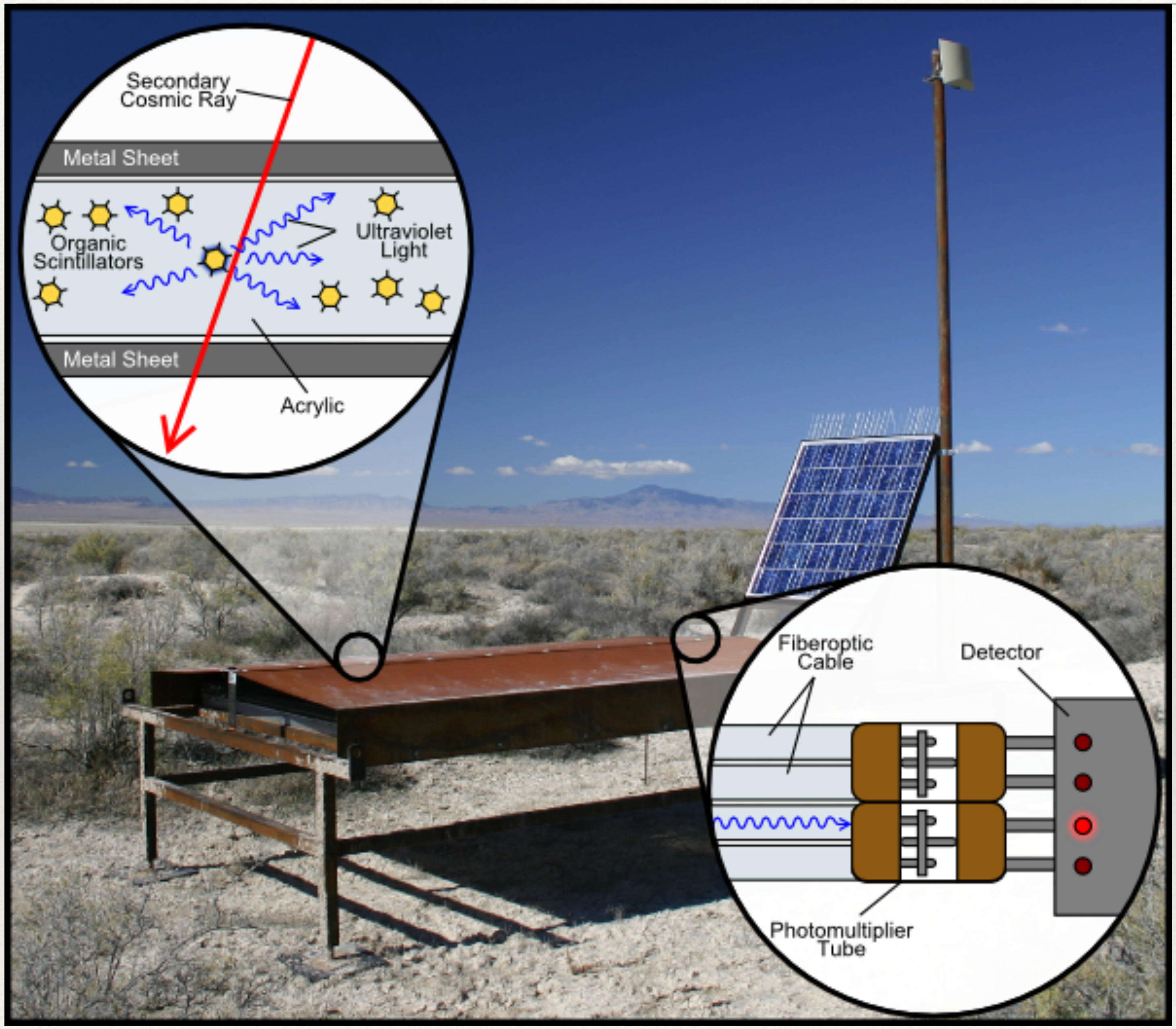
Reconstruction

- **Energy: E**
- **Arrival direction ()**
- **Composition**

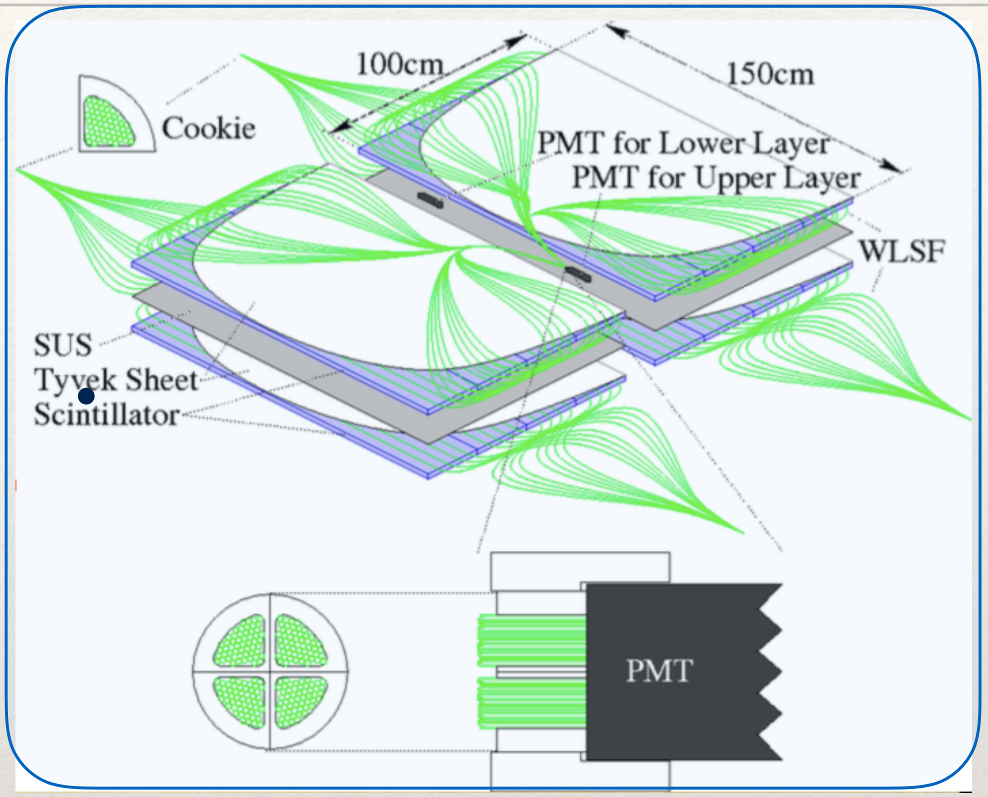


Time structure with SD data

Surface detector

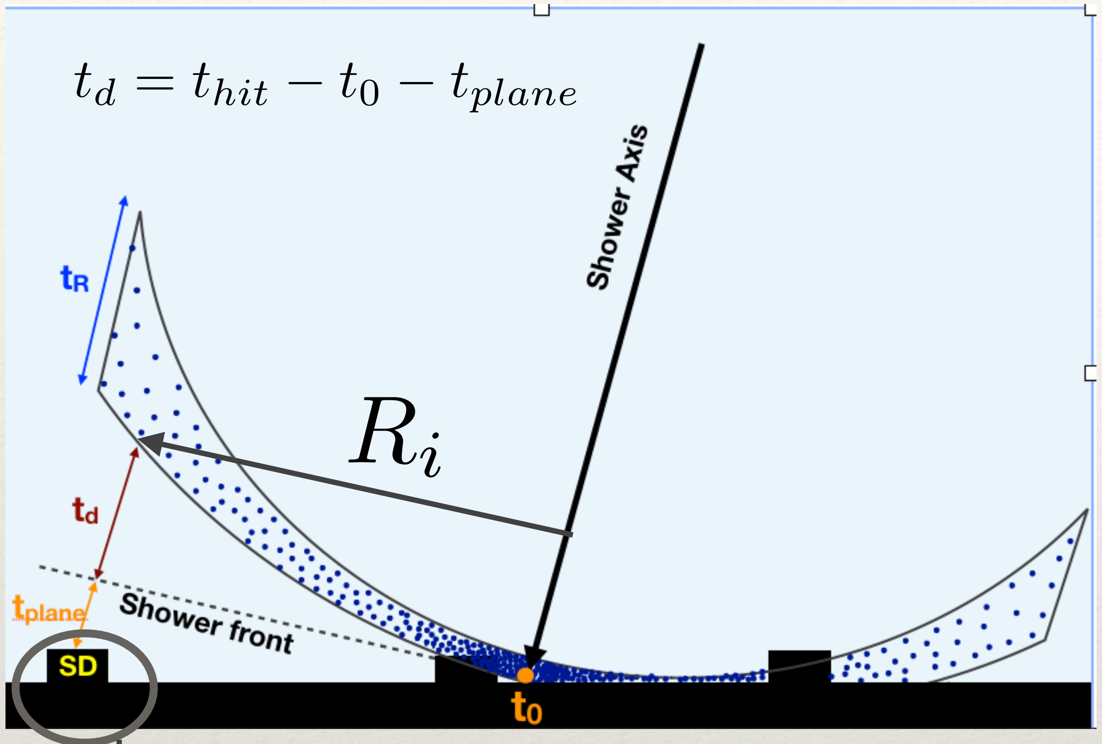


Scintillator Box



- SD: 507 scintillation Counters
  - 1.2 km spacing
  - 2 layers of plastic scintillation (3m²)
- 2 FADC counters UP/LO
  - Resolution: 20ns
  - Window gate: 2.56 μs

Time Structure

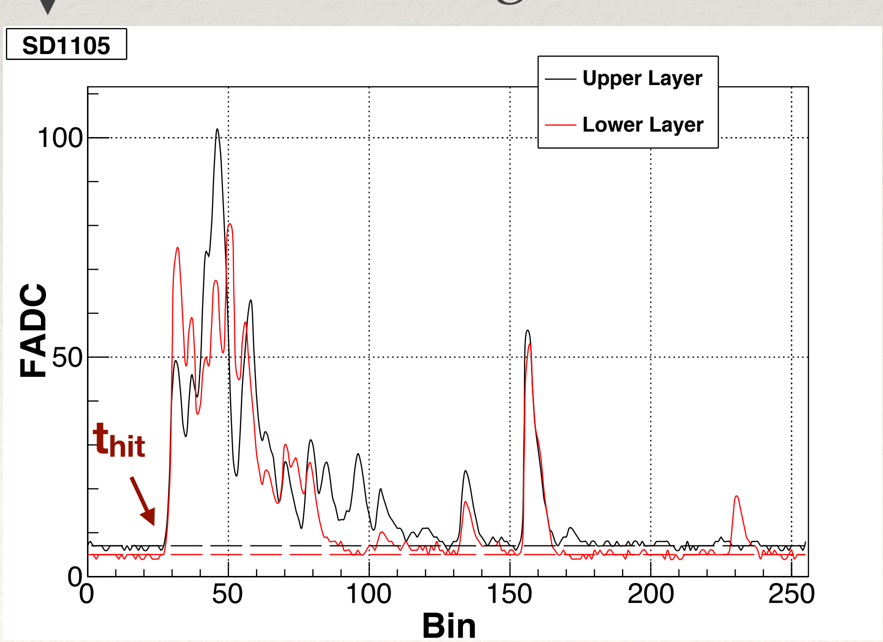


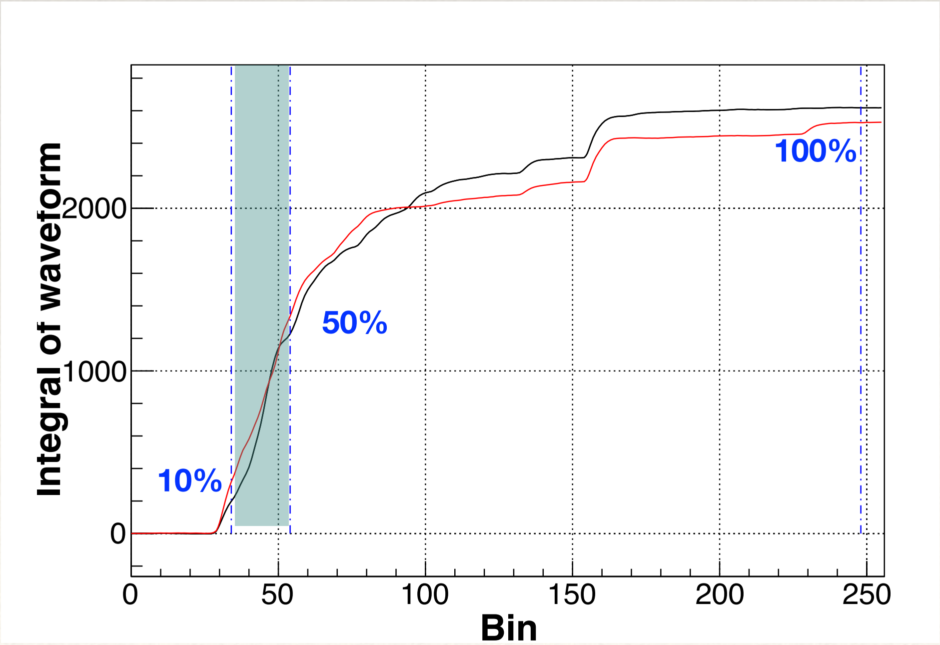
The air shower structure depends on energy, arrival direction, primary mass and on the interaction mechanism with air nuclei.

1) the curvature of the shower front by using the definition of residual time t_d with respect to the shower plane by using t_{hit}.

2) the thickness of the shower disk by analyzing the observable rise time based on the accumulated waveforms t_R.

SD Signal





Curvature front

Obtention of time at core location

t_0

$$\chi^2_{\mathrm{G}} = \sum_{i=0}^{N} \frac{(t_i - t_i^{\mathrm{FIT}})^2}{\sigma^2_{t_i}} + \frac{(\mathbf{R} - \mathbf{R}_{\mathrm{COG}})^2}{\sigma^2_{\mathbf{R}_{\mathrm{COG}}}}$$

$$\chi^2_{\mathrm{LDF}} = \sum_{i=0}^{N} \frac{(\rho_i - \rho_i^{\mathrm{FIT}})^2}{\sigma^2_{\rho_i}} + \frac{(\mathbf{R} - \mathbf{R}_{\mathrm{COG}})^2}{\sigma^2_{\mathbf{R}_{\mathrm{COG}}}}$$

$$\tau = (8 \times 10^{-4} \mu\mathrm{S})\, a(\theta) \left(1.0 + \frac{s}{30\mathrm{m}}\right)^{1.5} \rho^{-0.5}$$

$$\sigma_\tau = (7 \times 10^{-4} \mu\mathrm{S})\, a(\theta) \left(1.0 + \frac{s}{30\mathrm{m}}\right)^{1.5} \rho^{-0.3}$$

$$a(\theta) = \begin{cases} 3.3836 - 0.01848\,\theta & \theta < 25^o \\ c_3\,\theta^3 + c_2\,\theta^2 + c_1\,\theta + c_0 & 25^o \leq \theta < 35^o \\ \exp(-3.2 \times 10^{-2}\,\theta + 2.0) & \theta > 35^o \end{cases}$$

$$c_0 = -7.76168 \times 10^{-2},\ c_1 = 2.99113 \times 10^{-1},$$

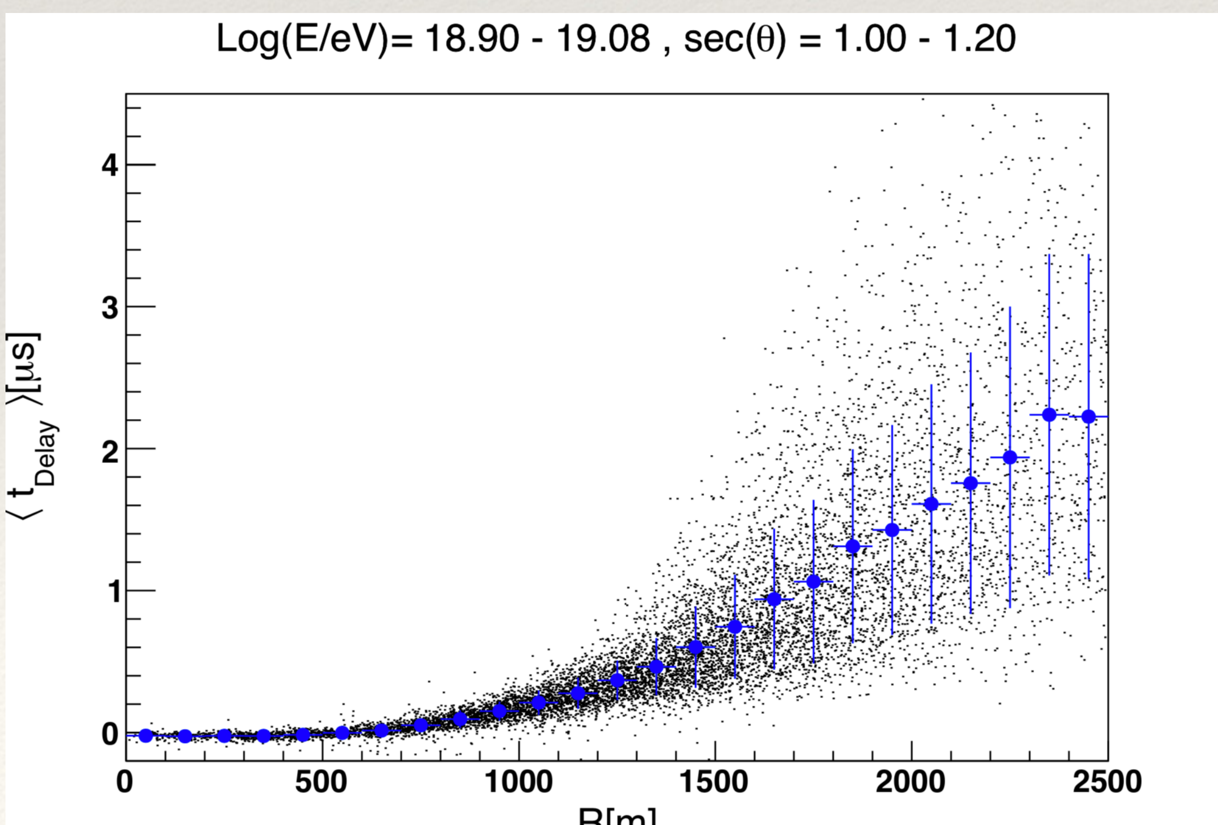
$$c_2 = -8.79358 \times 10^{-3},\ c_3 = 6.51127 \times 10^{-5}$$

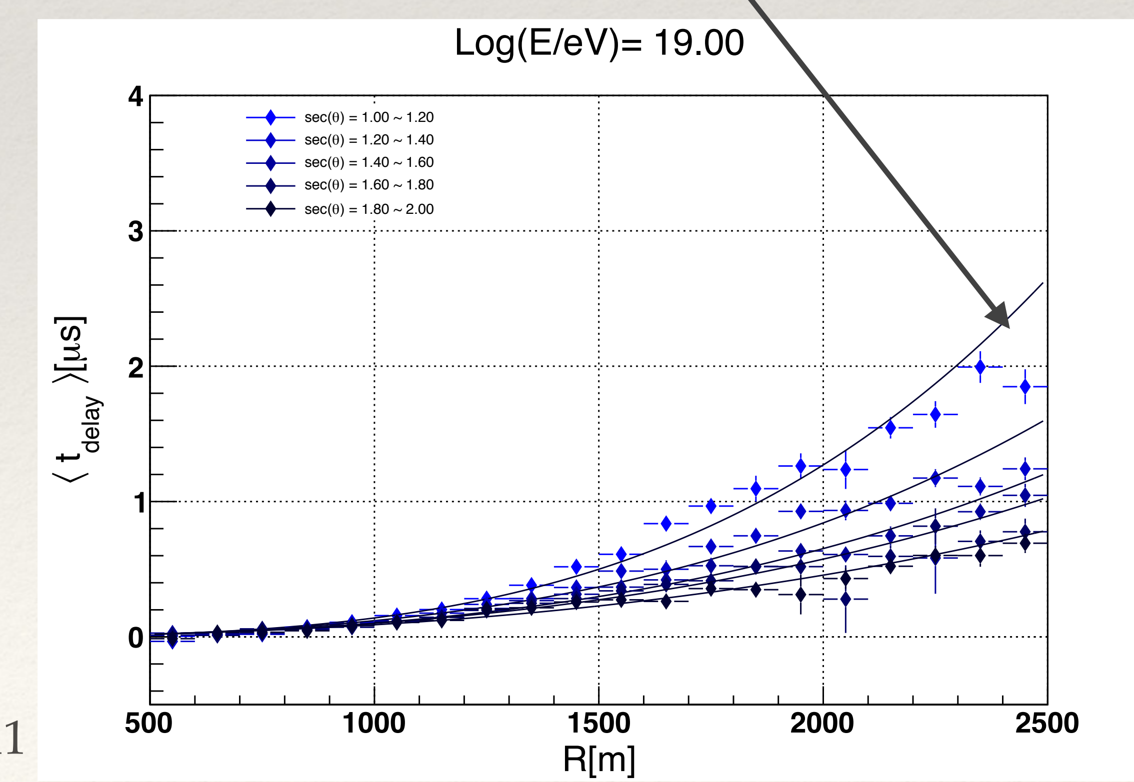
Residual time

$$t_d = t_{hit} - t_0 - t_{plane}$$

Zenith: 0-33.6 [deg]

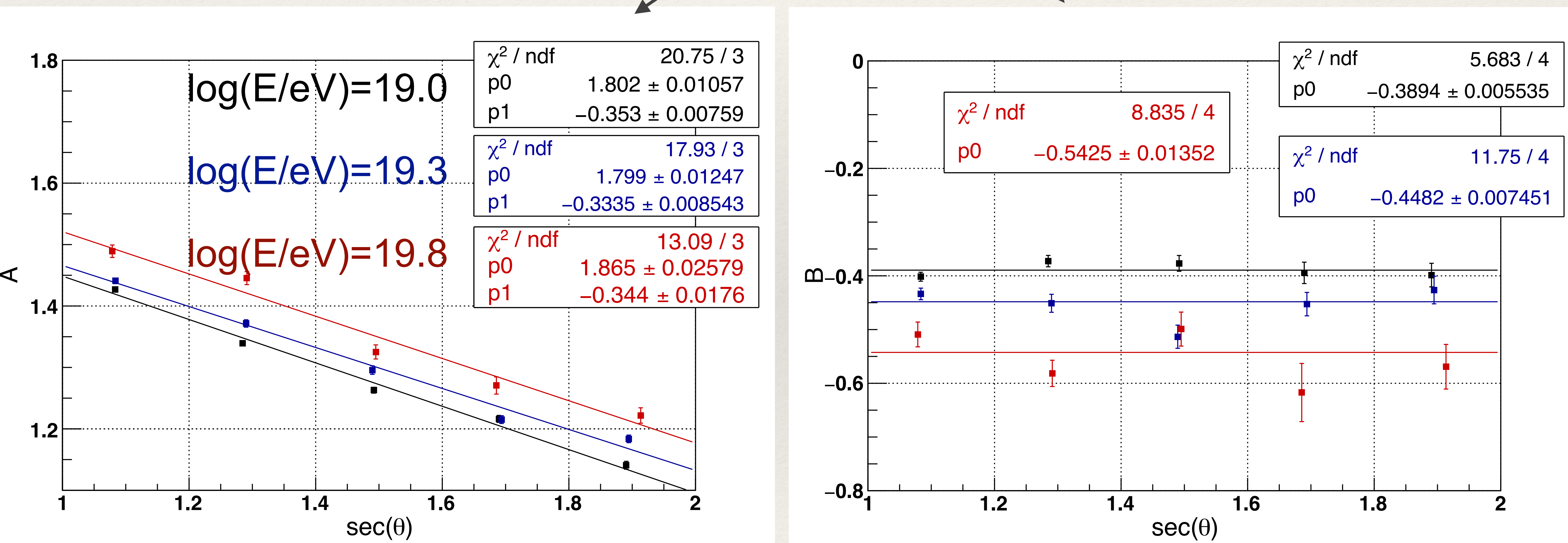
$$\langle t_d \rangle = 2.6 \times \left(1 + \frac{R}{30\mathrm{m}}\right)^A \times \rho^B [m^{-2}][ns]$$





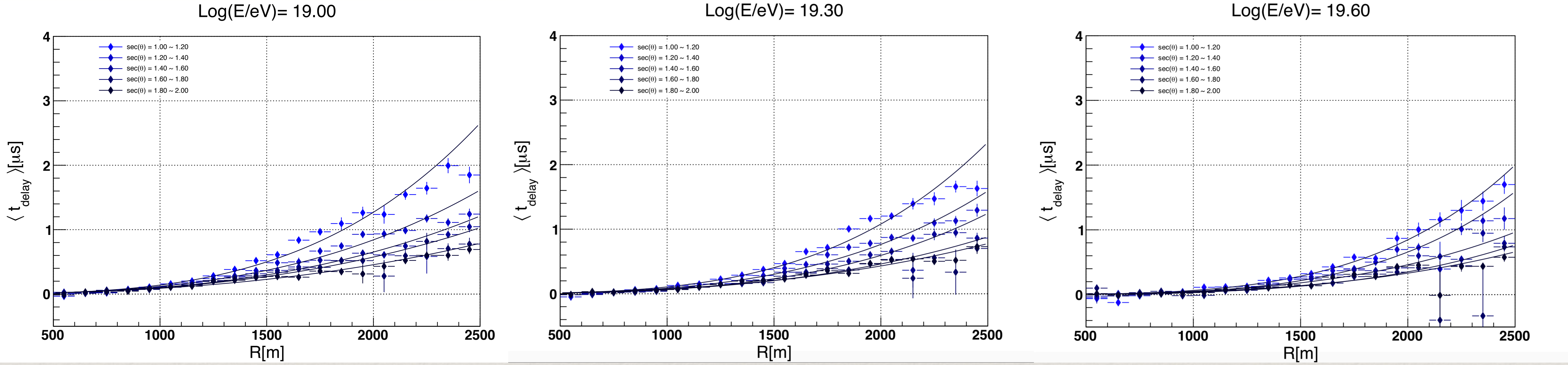
Residual time parameters: A & B

$$\langle t_d \rangle = 2.6 \times \left(1 + \frac{R}{30\mathrm{m}}\right)^{A} \times \rho^{B} [m^{-2}][ns]$$



A & B parameters has dependence on Energy

Shower front for late showers

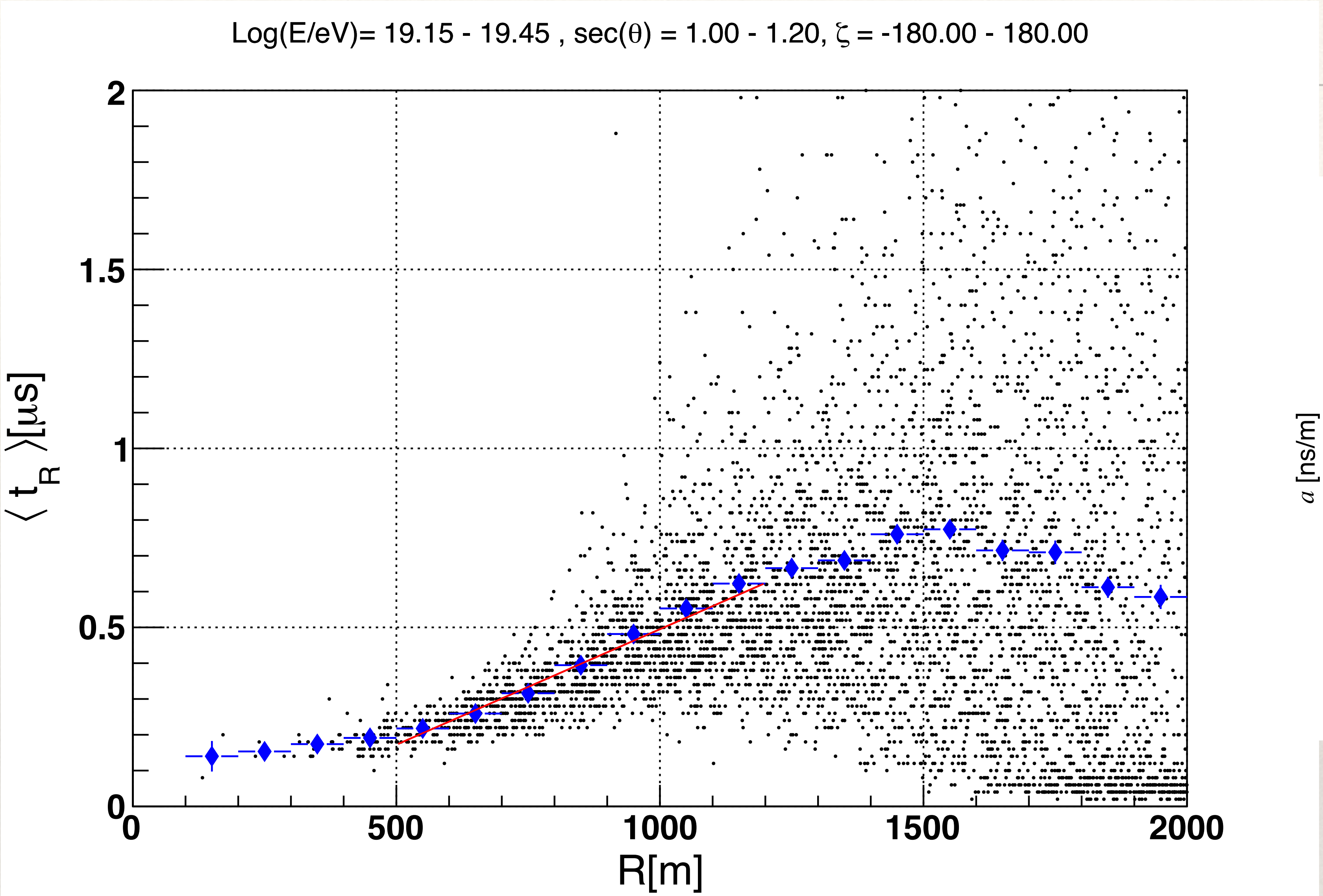


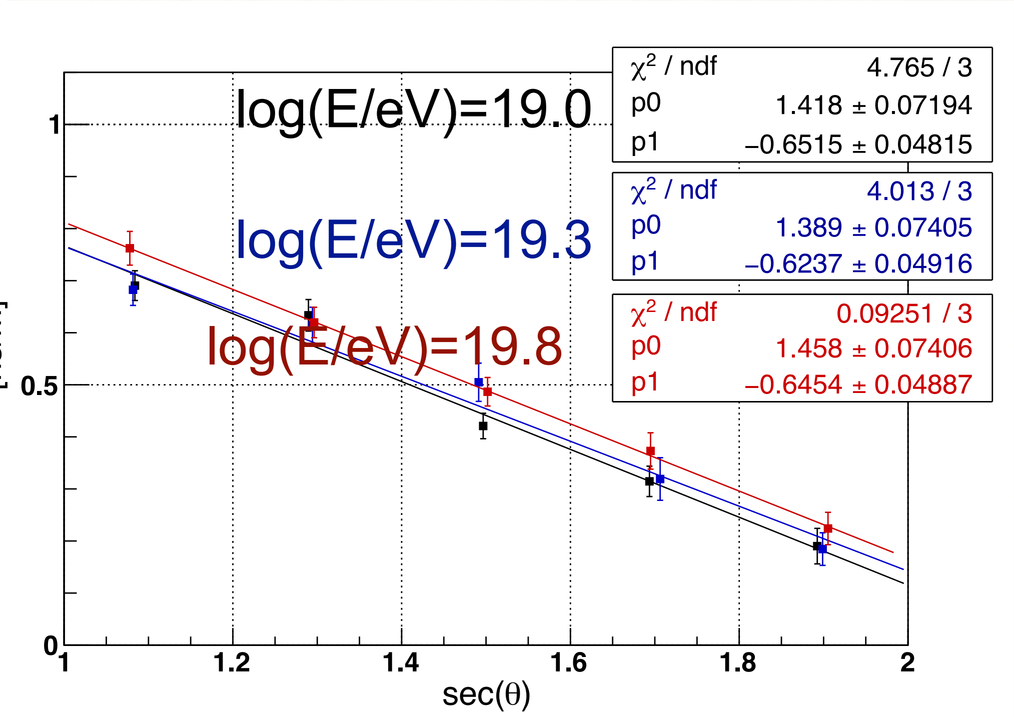
$$t_{delay} = 2.6 \times (1 + \frac{R}{30\text{m}})^{((1.80\pm0.01)-(0.35\pm0.01)\times\sec\theta)} \times \rho^{-0.39\pm5.55\times10^{-3}}[m^{-2}][ns]$$

$$t_{delay} = 2.6 \times (1 + \frac{R}{30\text{m}})^{(1.80\pm0.01)-(0.33\pm0.01)\times\sec\theta)} \times \rho^{-0.45\pm7.45\times10^{-3}}[m^{-2}][ns]$$

$$t_{delay} = 2.6 \times (1 + \frac{R}{30\text{m}})^{(1.86\pm0.02)-(0.34\pm0.02)\times\sec\theta)} \times \rho^{-0.54\pm0.01}[m^{-2}][ns]$$

Thickness of shower disk



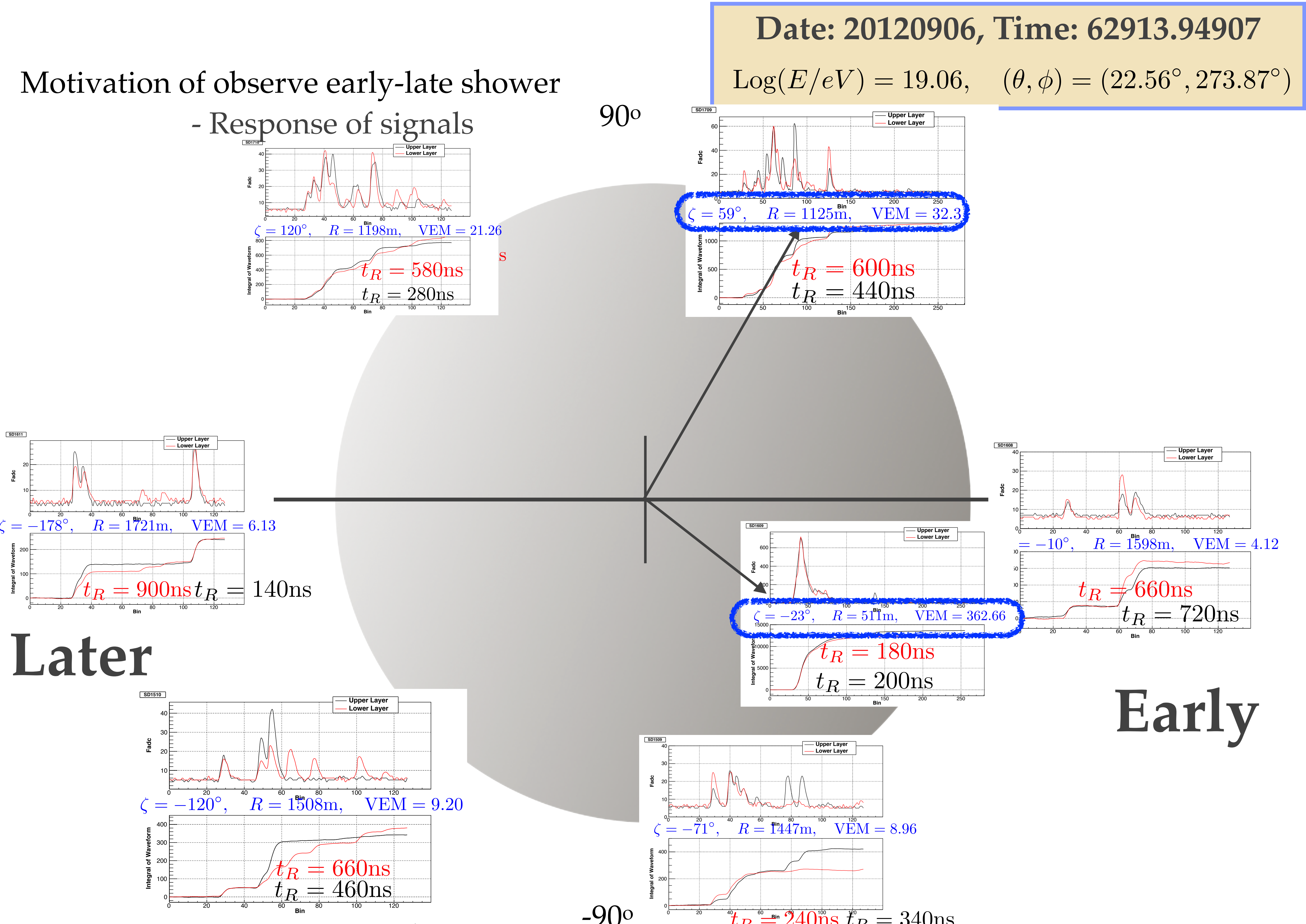


$$\langle t_R \rangle = (a \times R + b)[ns]$$

The slope(a) is considered as factor of thickness of shower

Motivation of observe early-late shower

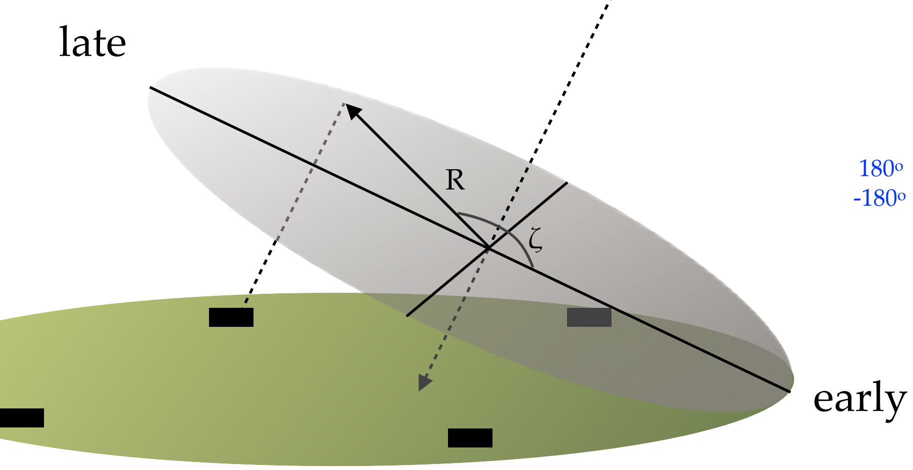
- Response of signals

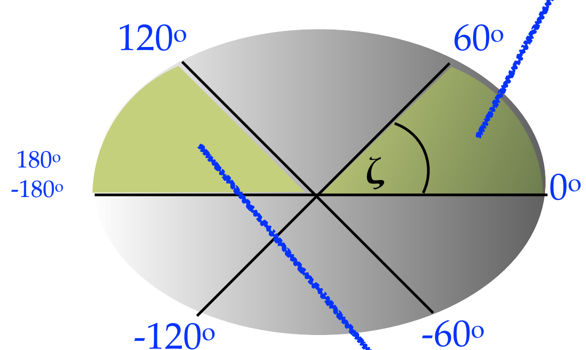


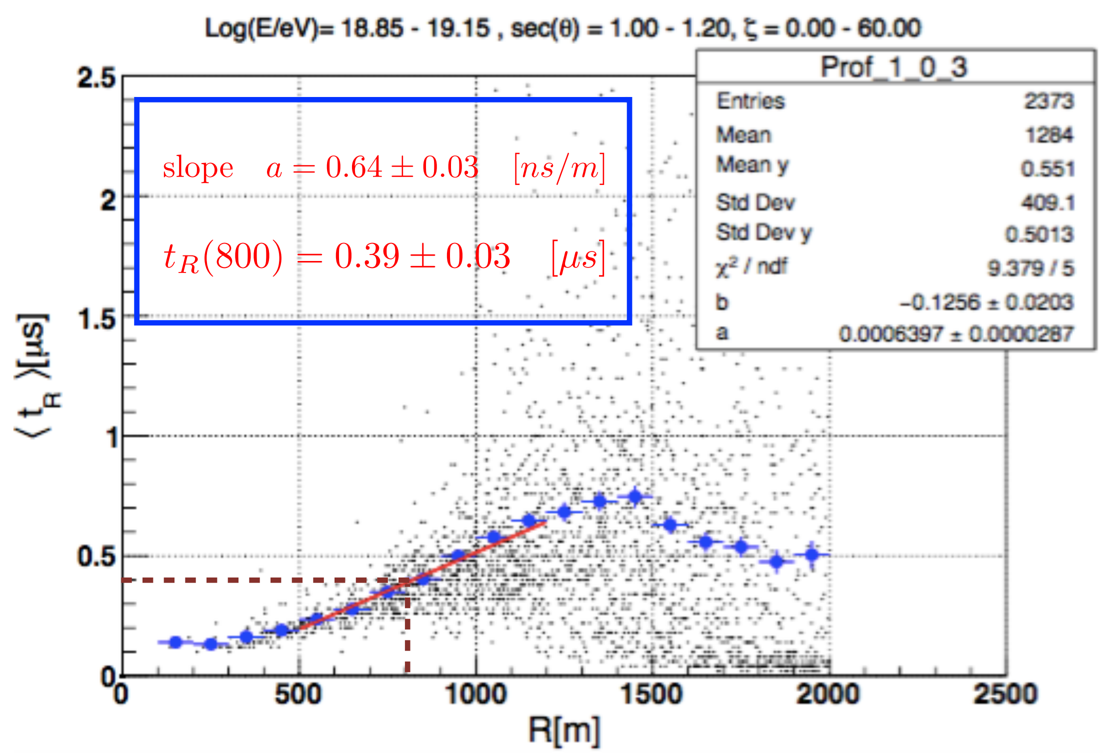
- Early shower: Upper layer all charged
- Later shower: muonic component

Azimuthal (Zeta) Dependency

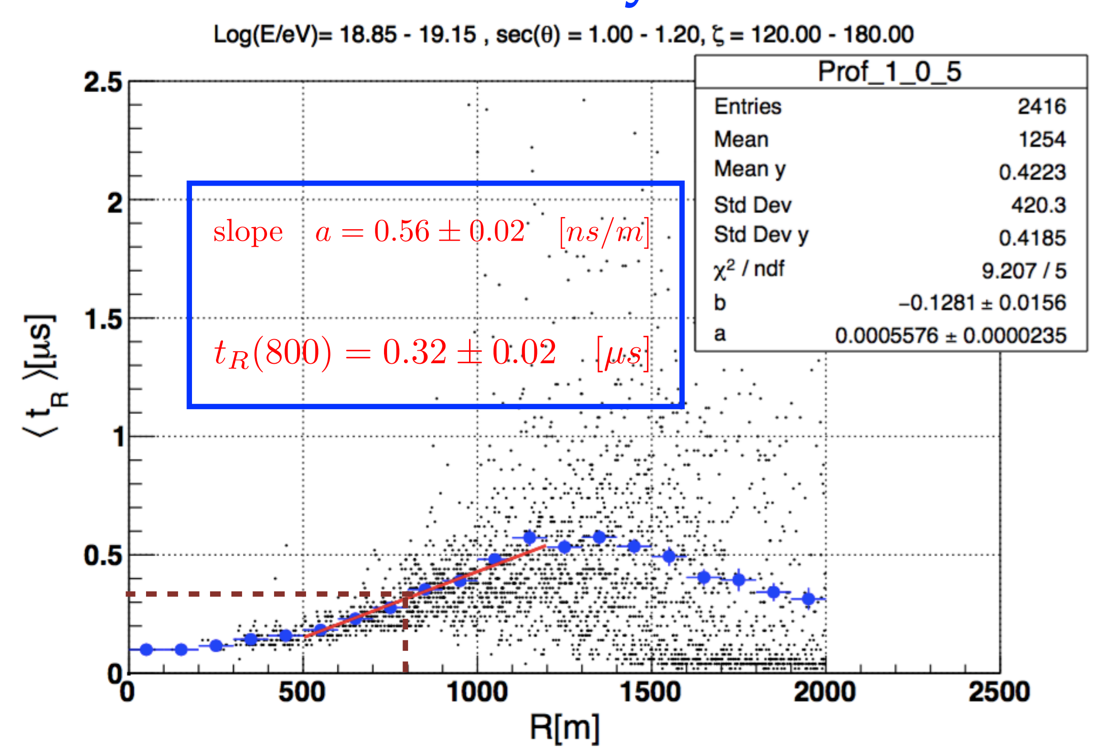
zeta (ζ): azimuthal angle from Shower







Early

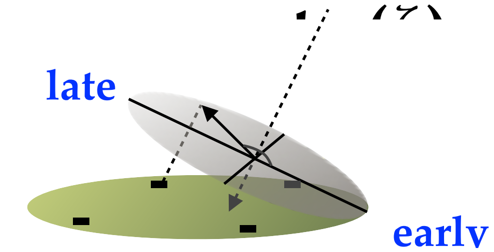


ENERGY	ZENITH (θ)
Log(E/eV): 18.85-19.15 Log(E/eV): 19.15-19.45 Log(E/eV): 19.45-20.00	sec(θ): 1.0~2.0 in Step 0.2

Late

The slope(a) is considered as factor of thickness of shower disk

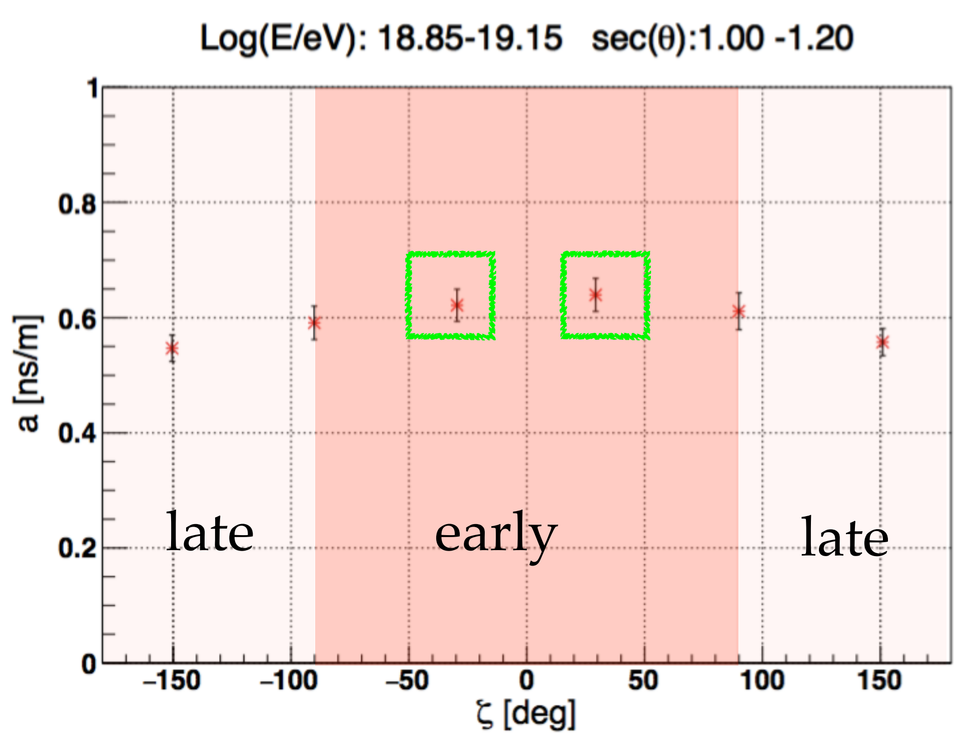
Zeta Vs Slope angle (1)

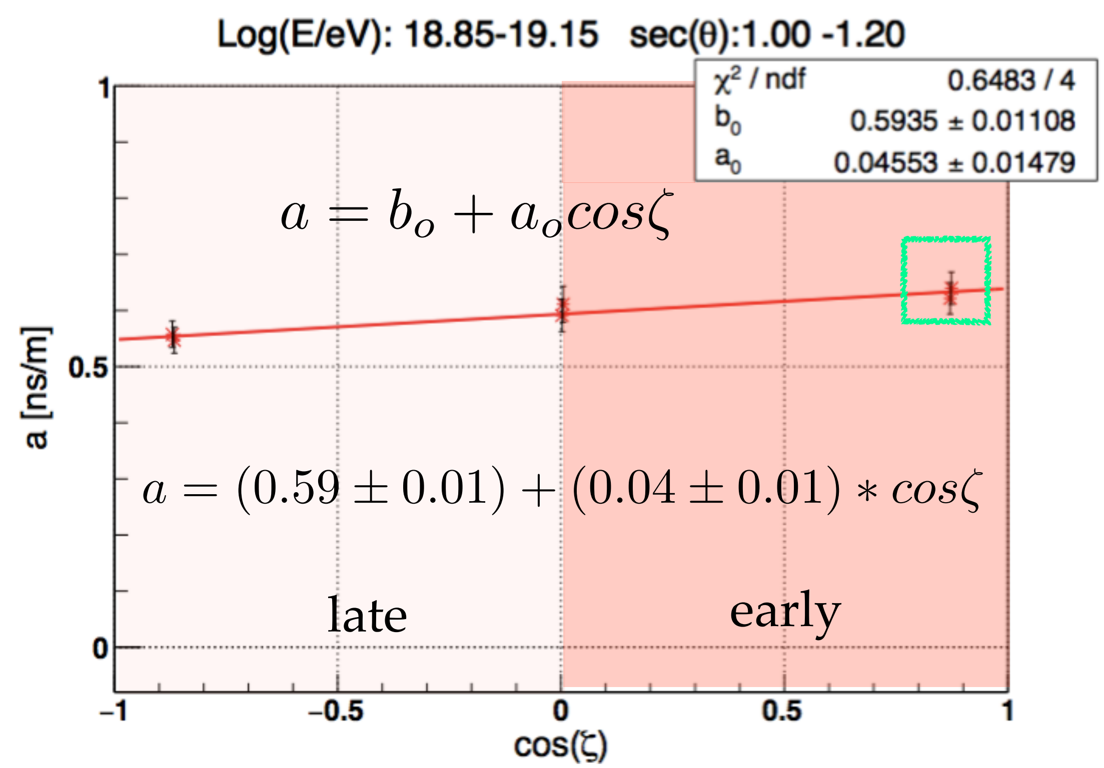


Fix Log(E/eV) : 18.85 - 19.15

Fix R range: 500 - 1200 [m]

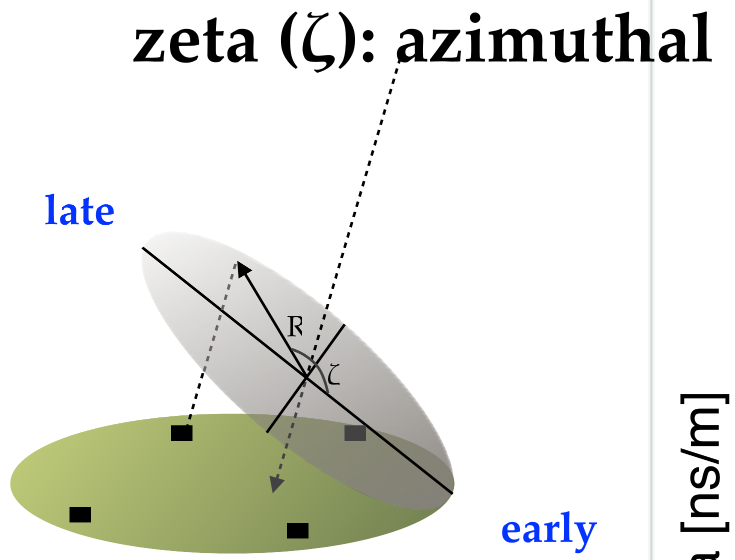
Fix sec(θ) : 1.0 - 1.2

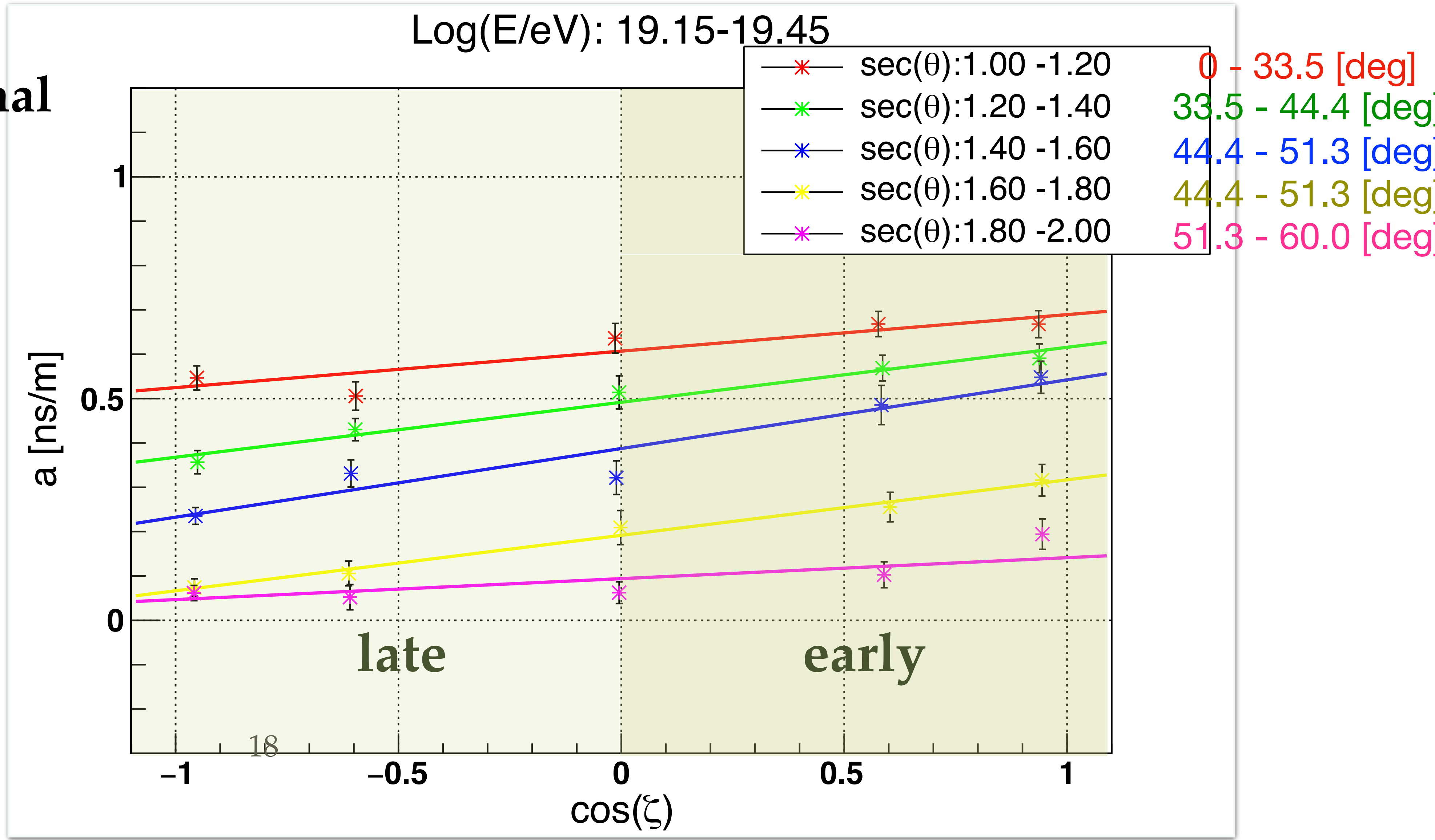




- The thickness of particles is slightly ticker for "early" detectors than for "late"

Zeta Vs Slope angle (2)



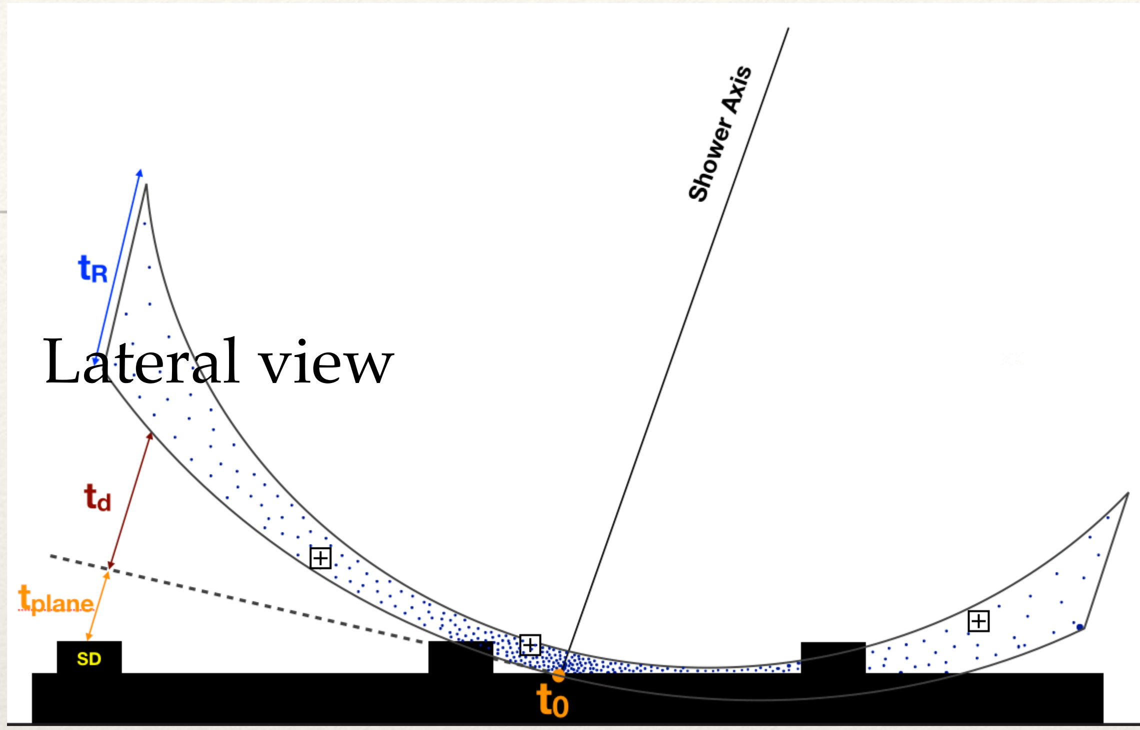


$$a = b_o + a_o cos\zeta$$

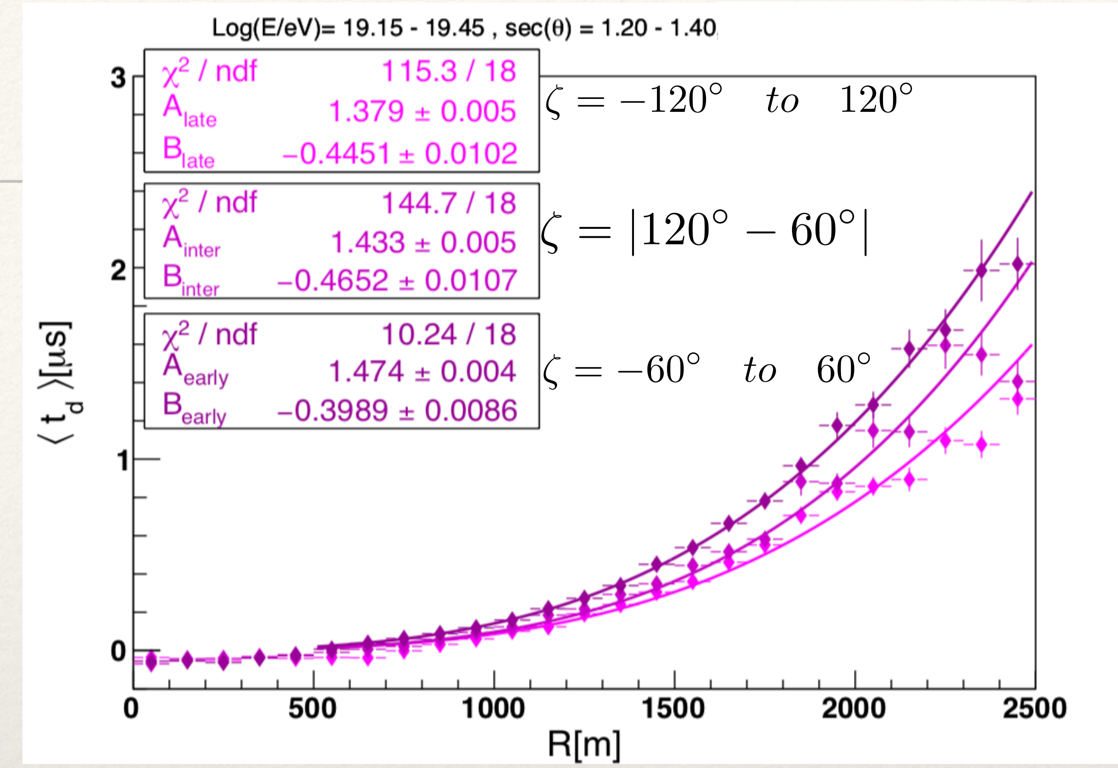
$$a = (0.60 \pm 0.01) + (0.08 \pm 0.02) * cos\zeta$$
$$a = (0.49 \pm 0.01) + (0.12 \pm 0.02) * cos\zeta$$
$$a = (0.39 \pm 0.01) + (0.15 \pm 0.02) * cos\zeta$$
$$a = (0.19 \pm 0.01) + (0.12 \pm 0.02) * cos\zeta$$
$$a = (0.09 \pm 0.01) + (0.05 \pm 0.01) * cos\zeta$$

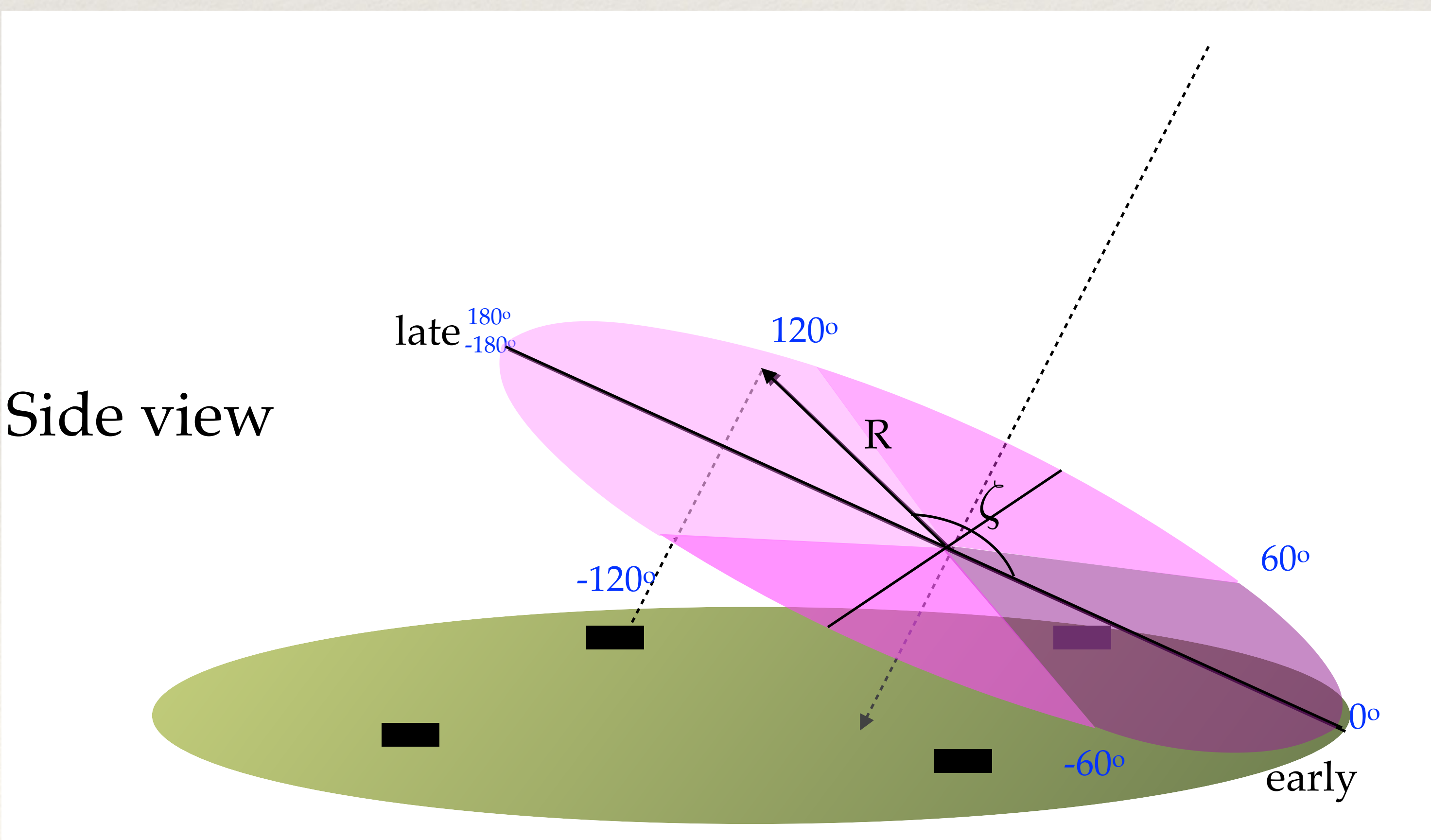
For intermediate zenith angles the thickness of air shower is thicker than vertical/ inclined

Time structure: Asymmetry in ζ angle

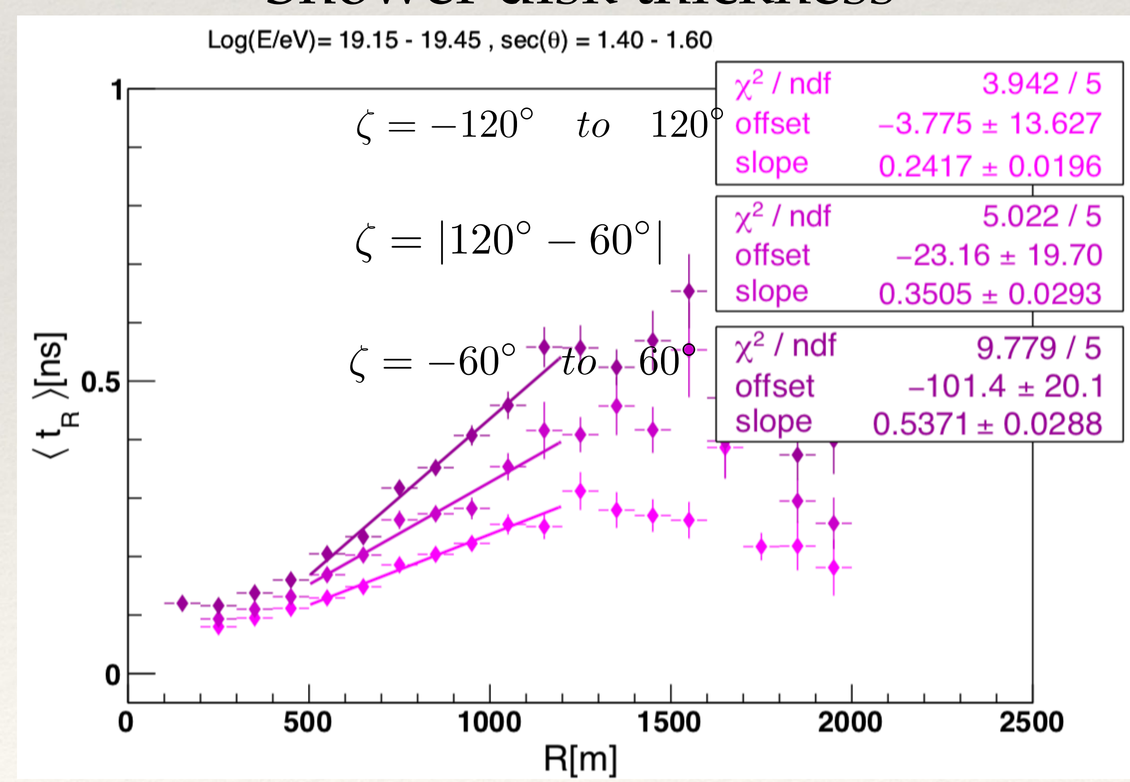


Shower front





Shower disk thickness



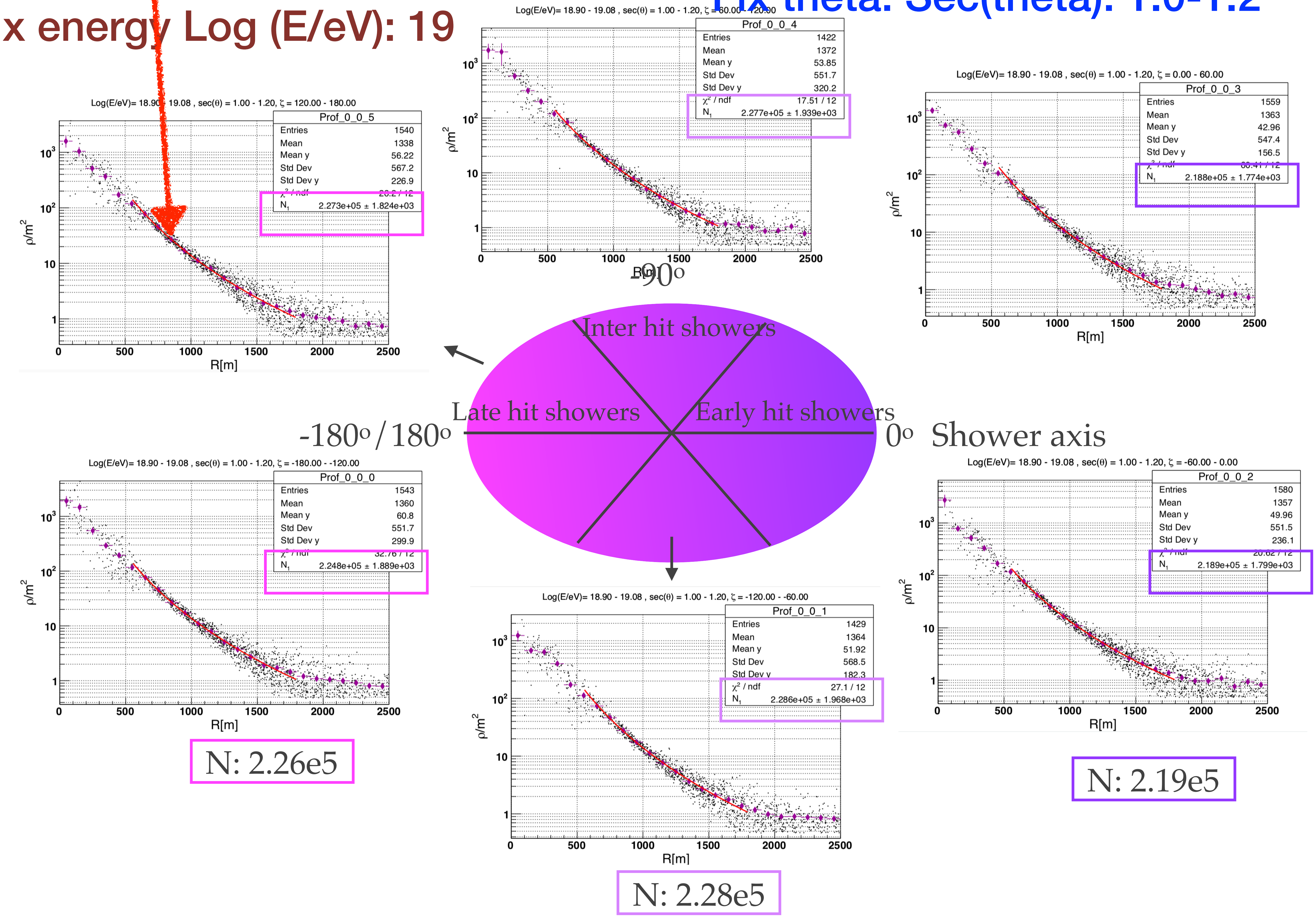
Density vs R

$$\rho(\theta) = N\left(\frac{R}{91.6\mathrm{m}}\right)^{-1.2}\left(1+\frac{R}{91.6\mathrm{m}}\right)^{-(\eta(\theta)-1.2)}\left(1+\left[\frac{R}{1000\mathrm{m}}\right]^{2}\right)^{-0.6}$$

$$t_{delay} = 2.6 * (1+\frac{R}{30})^{A} \times \rho^{B}[m^{-2}][\mathrm{ns}]$$

Fix energy Log (E/eV): 19

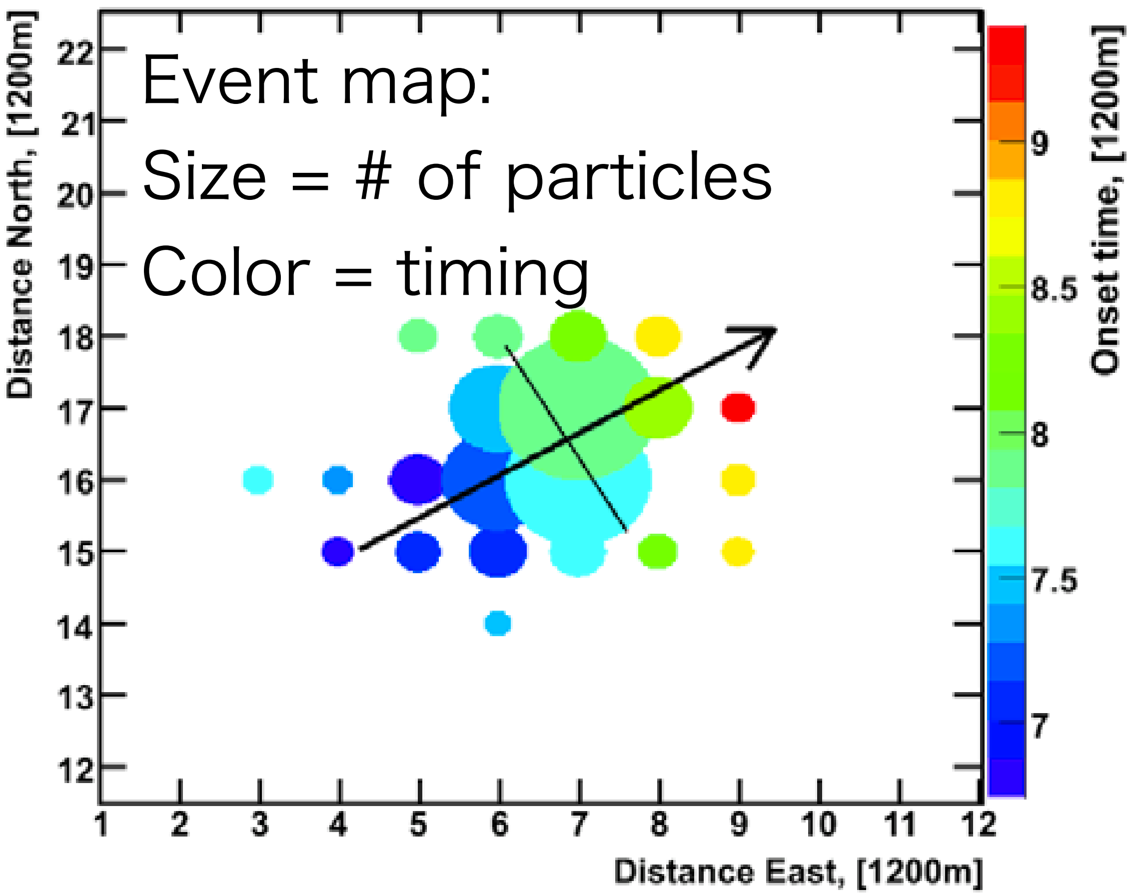
Fix theta: Sec(theta): 1.0-1.2

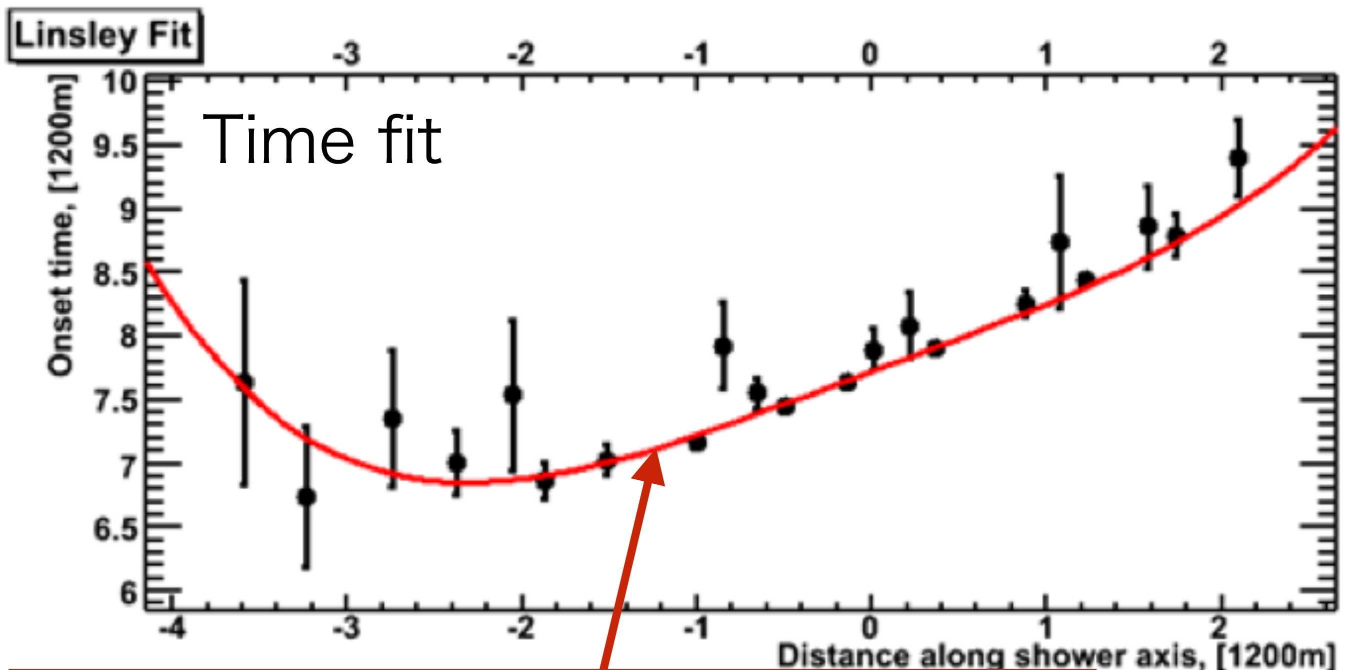


Summary

- TA-SD data of (11 years observed) was used to study air shower structure using waveforms.
- It was studied shower front by time delay:
  - Fit AGASA function time delay —> $\langle t_d \rangle = 2.6 \times (1 + \frac{R}{30\mathrm{m}})^A \times \rho^B [m^{-2}][ns]$
    - Parameter A has dependance on zenith
    - A and B has not Energy dependance
- It was analyzed risetime(t_R) to understand air shower:
  - Using information of risetime from (10-50)% of total wf.
  - It is proposed a linear function in R range (500-1200) m —> $\langle t_R \rangle = (a \times R + b)[ns]$
  - The offset(b) and slope (a) has dependance on zenith
  - It was analyzed slope(a) to observe dependences:
    - It could see tendency on azimuth angle and energy dependance.

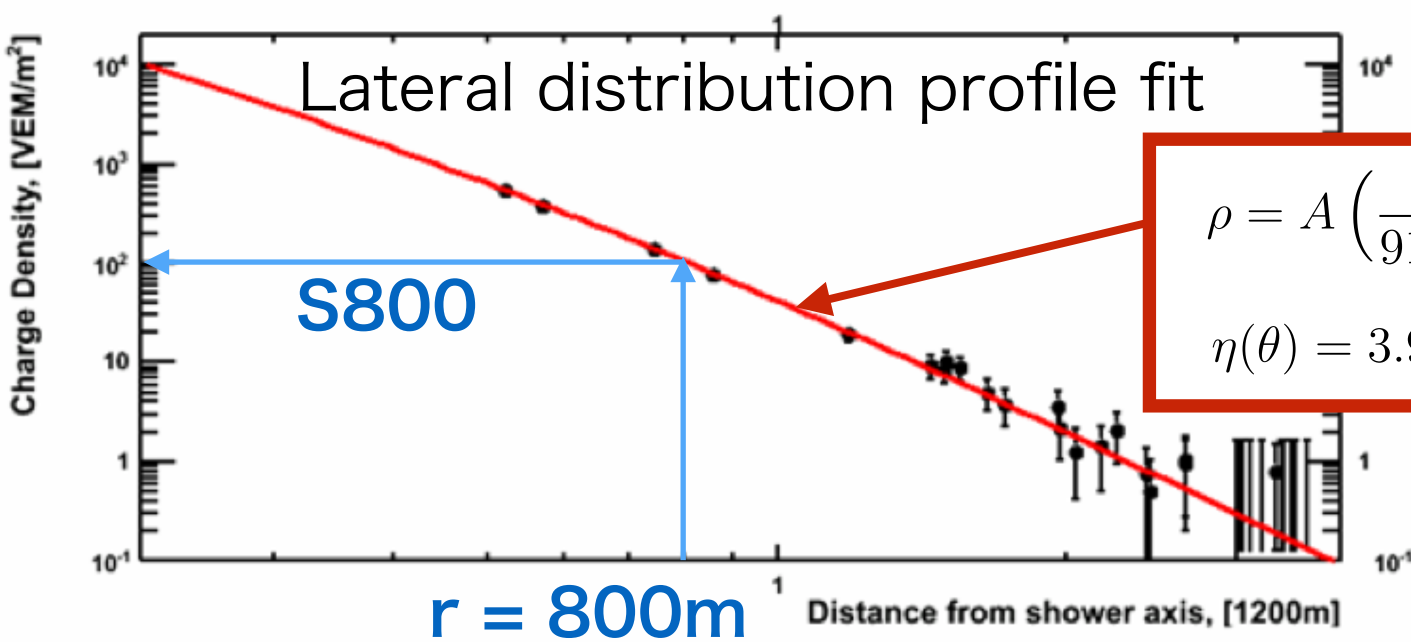
Event reconstruction





$$\tau = a\left(1 - \frac{l}{12\times 10^3\mathrm{m}}\right)^{1.05}\left(1.0 + \frac{s}{30\mathrm{m}}\right)^{1.35}\rho^{-0.5}$$

Modified empirical formula in AGASA



$$\rho = A\left(\frac{s}{91.6\mathrm{m}}\right)^{-1.2}\left(1+\frac{s}{91.6\mathrm{m}}\right)^{-(\eta(\theta)-1.2)}\left(1+\left[\frac{s}{1000\mathrm{m}}\right]^2\right)^{-0.6}$$

$$\eta(\theta) = 3.97 - 1.79\,[\sec(\theta) - 1]$$

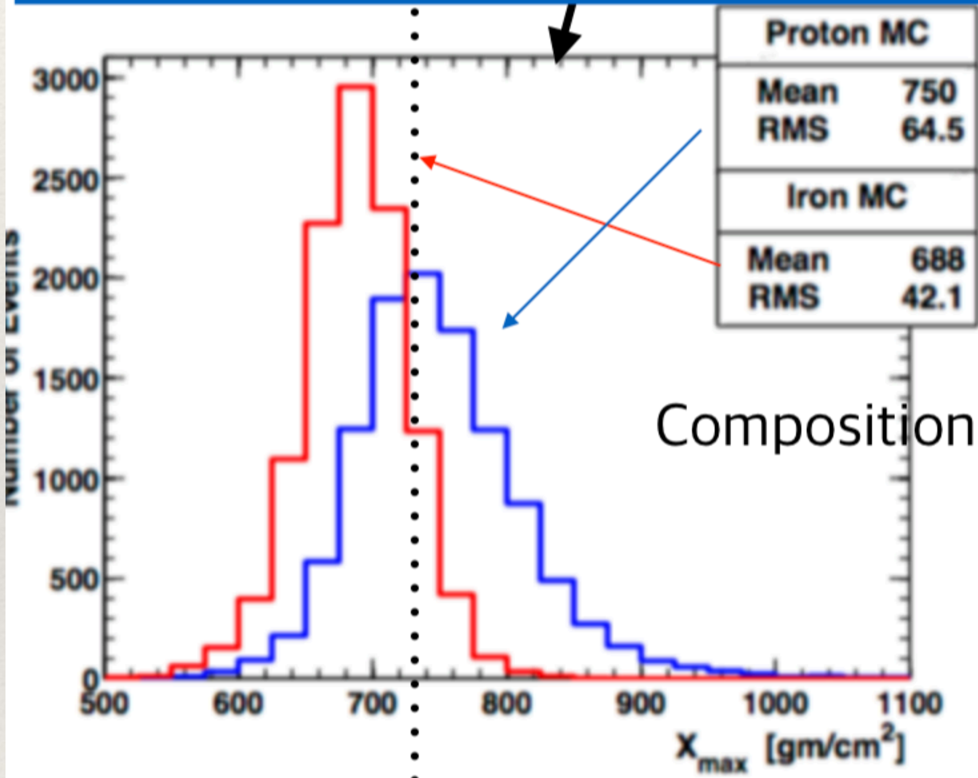
Empirical formula used by AGASA

S800 -> primary energy

Extensive Air Shower (EAS)

Gaisser-Hillas (G-H) formula

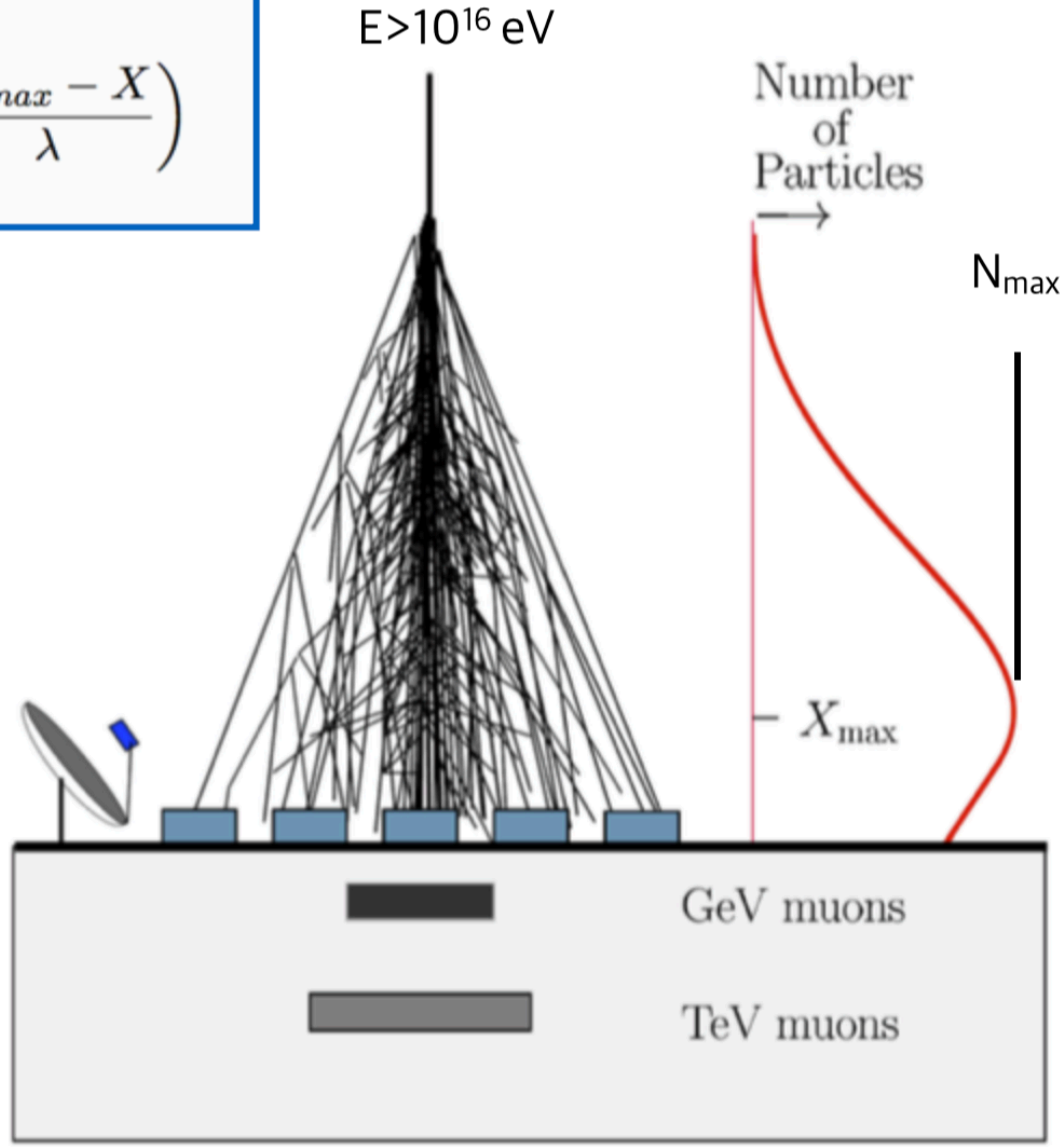
$$N(X) = N_{max}\left(\frac{X - X_0}{X_{max} - X_0}\right)^{\frac{X_{max}-X_0}{\lambda}} exp\left(\frac{X_{max} - X}{\lambda}\right)$$



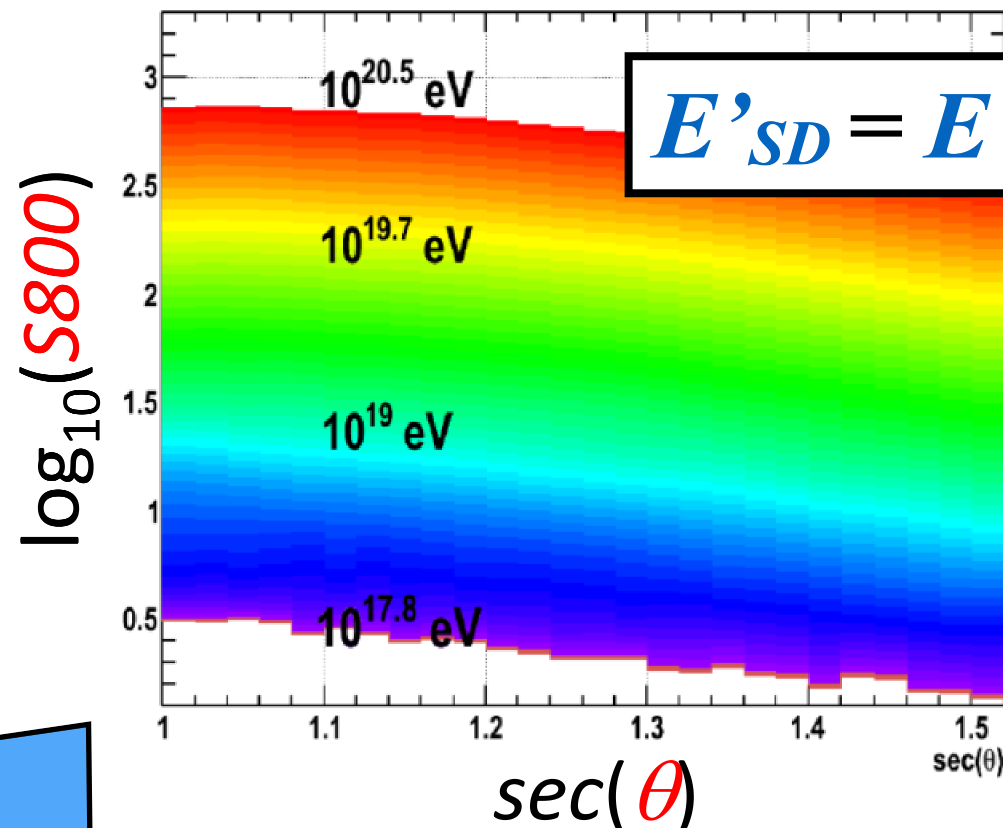
Composition study

Energy Reconstruction

$$E = \lambda N_{max} \frac{d\bar{E}}{dX}\left(\frac{e}{\epsilon}\right)^{\epsilon}\Gamma(\epsilon + 1)$$



Primary energy determination



$$E'_{SD} = E'_{SD}(S800, \theta)$$

Scale to FD energy

$$E_{SD} = E'_{SD} / 1.27$$