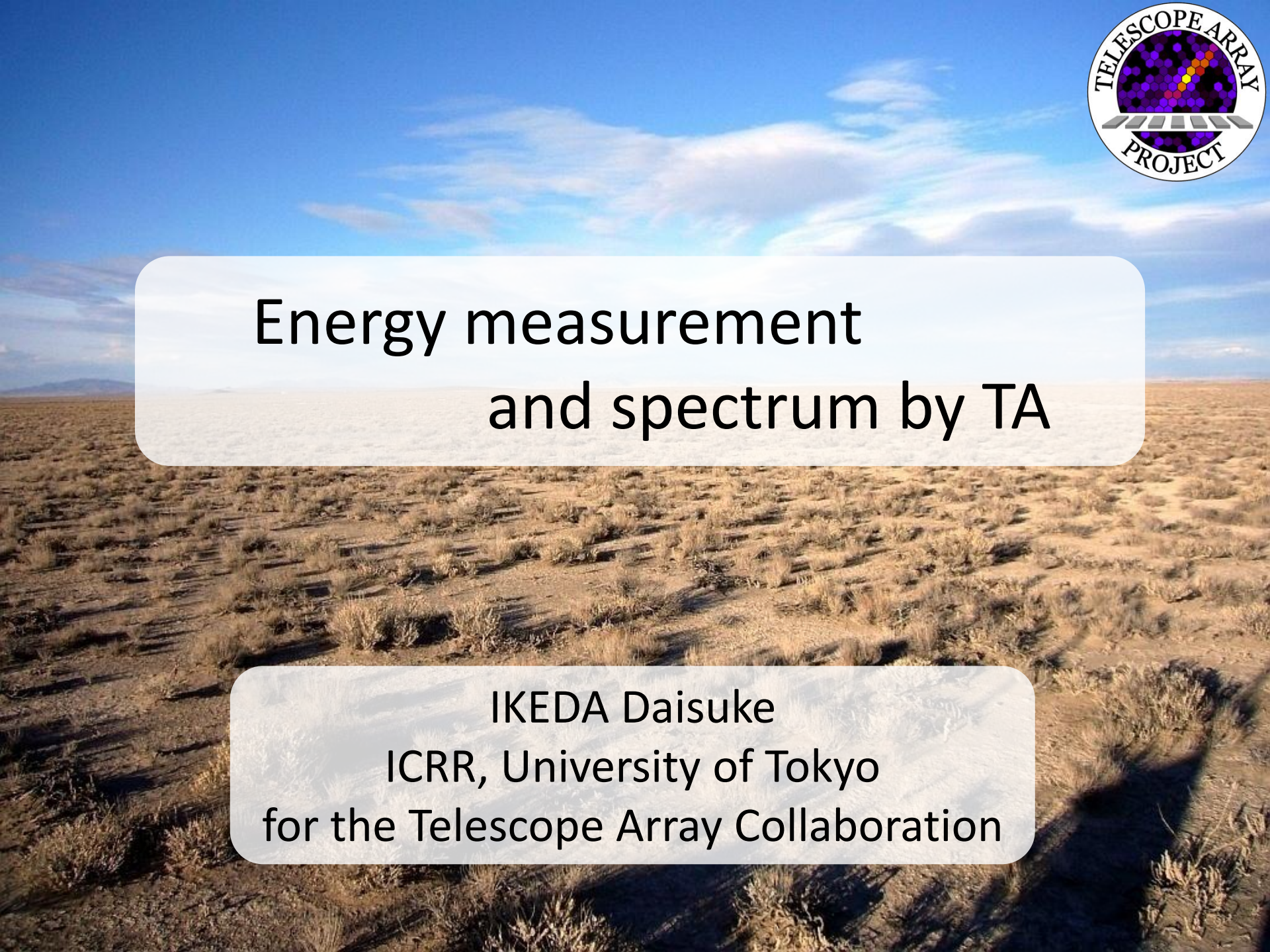


Energy measurement and spectrum by TA

IKEDA Daisuke
ICRR, University of Tokyo
for the Telescope Array Collaboration

Contents

- Introduction
- TA FD
- Calibration
- Monte Carlo
- Data analysis
- Conclusion

Fluorescence Technique

- Energy?
- Composition?

Total ΔE + Missing energy

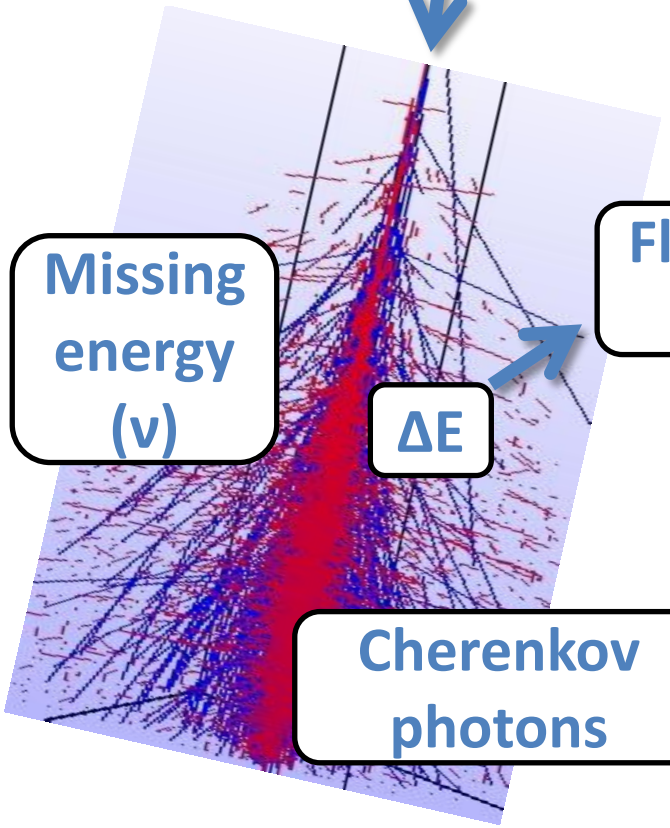
Development of ΔE

We have to understand
- Calibration
- Monte Carlo
- Analysis method

UHECR

Reconstruction

Data



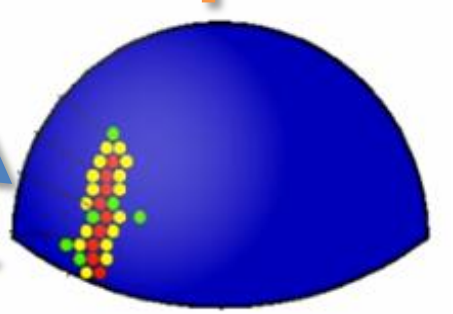
Missing energy (ν)

ΔE

Fluorescence photons

Atmospheric transparency

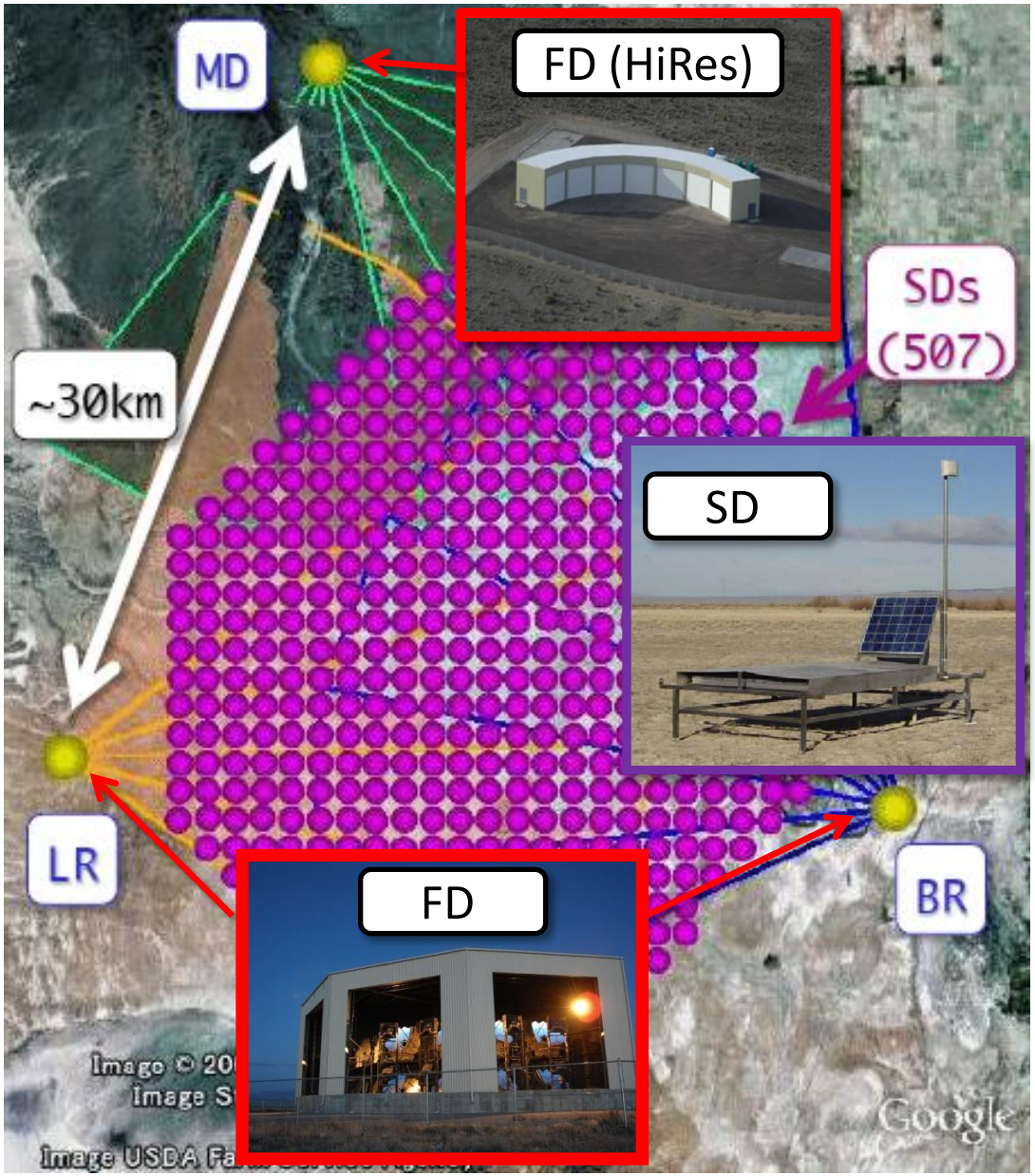
Cherenkov photons



Detector response

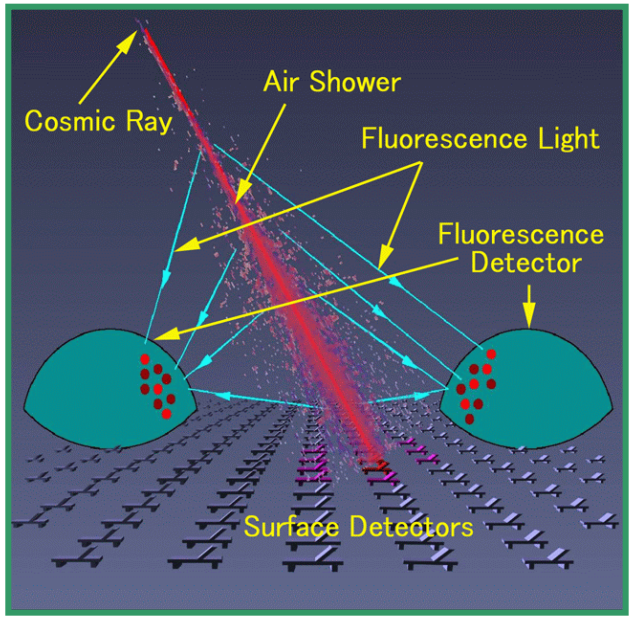
TA Fluorescence Detector

Telescope Array Experiment



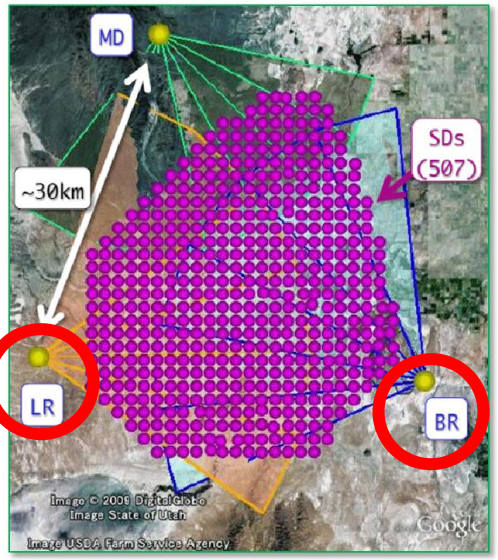
- Desert in Utah, US (1400m a.s.l.)
- 507 Surface Detectors (SDs)
  - 1.2km spacing
  - Two layers of plastic scintillator, $3m^2$, 1.2cm thickness
- 3 Fluorescence Detectors (FDs)
  - Middle Drume (MD) station is transferred from HiRes.

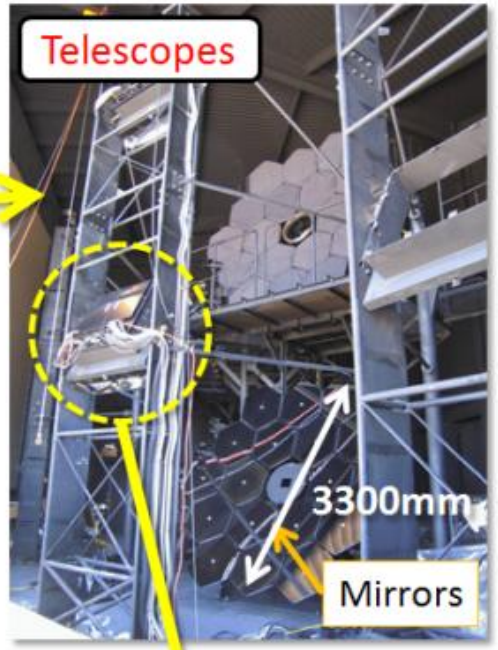
- FD observation : from Nov/2007
- SD observation : from Mar/2008

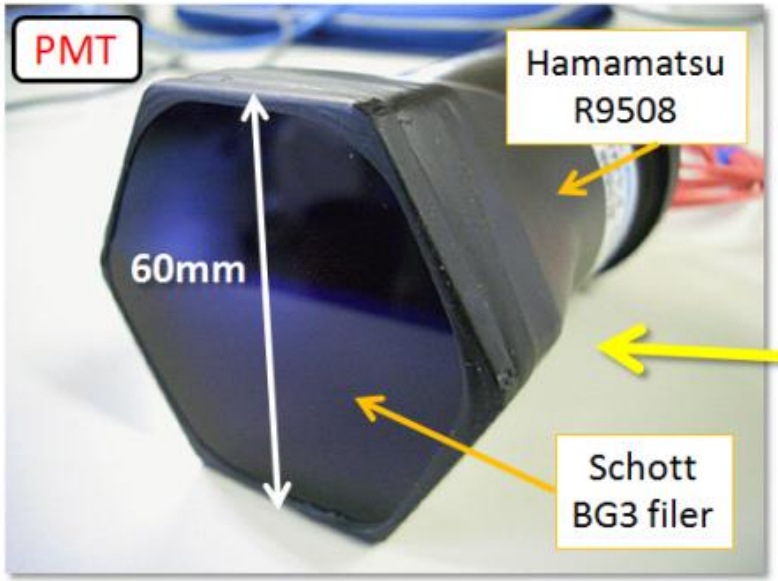


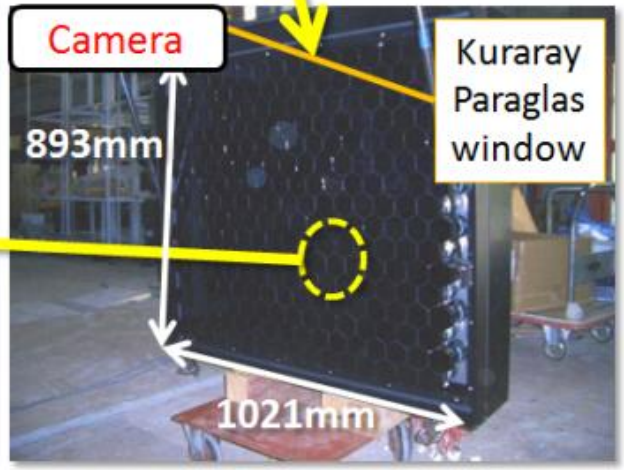
FD at BR/LR station

BR/LR site : new telescopes





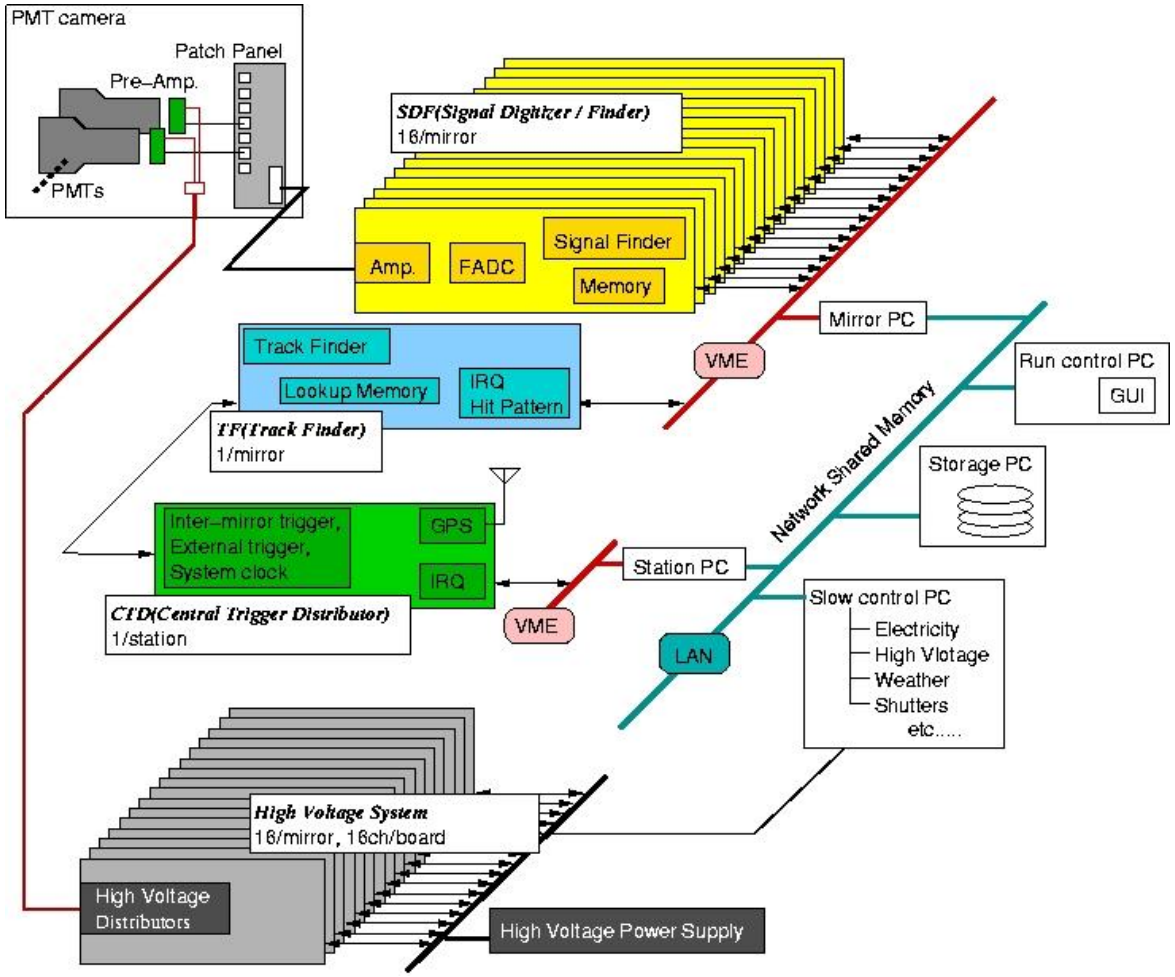




F.O.V of station:

- Elevation:3~33°
- Azimuth: 108°

Electronics (trigger)



Waveform: 10MHz, 14bits

Trigger:

- PMT trigger: >6σ
- Track trigger:
  >5 adjacent triggered PMTs

Time stamp: GPS

All of waveforms are stored when FD is triggered

Calibration

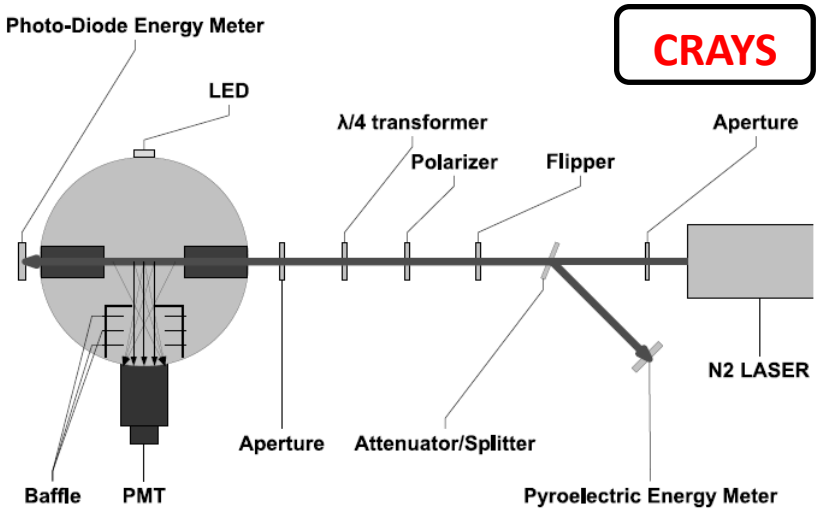
Telescope Calibration (PMT Gain)

•Absolute gain: CRAYS and YAP

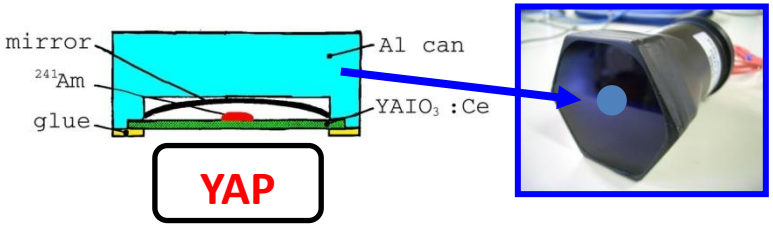
Three PMTs for each camera

Scattered Rayleigh photons as an absolute light source

- 0.508 count / photons (337.1nm) @24degrees
- Systematic error: ~8%



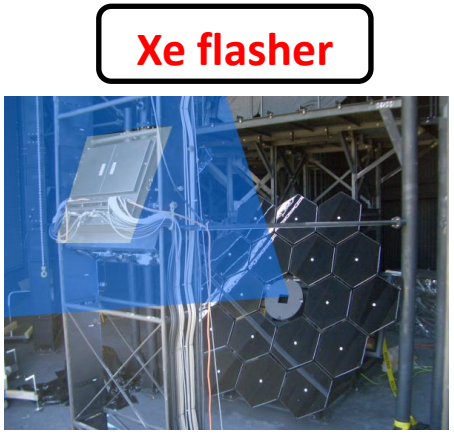
Scintillator and RI as a stable light source

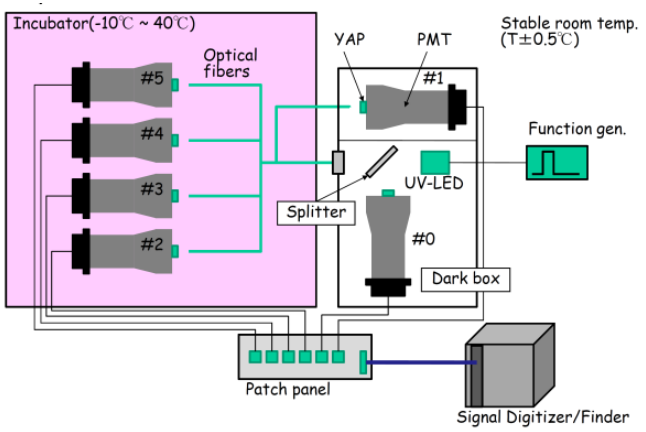


•Relative gain: Xe flasher

Xe discharge flasher as a uniform light source

- Adjusted about 1% for all PMTs
- Monitoring in every 1hour





•Temperature dependence

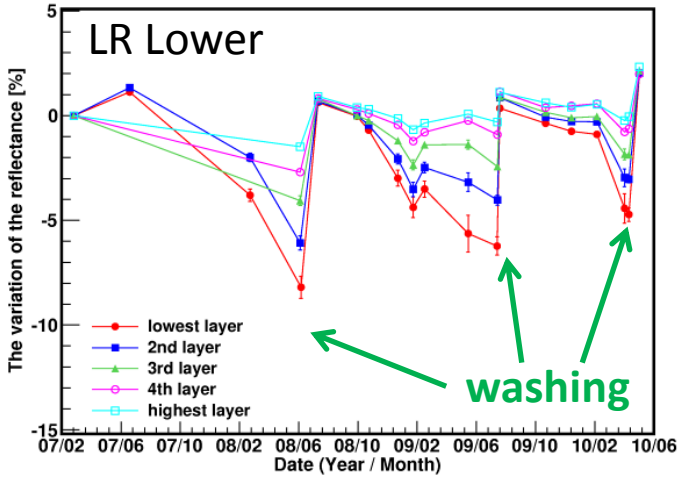
Measured by Incubator and LED

~-0.72%/degree

Telescope Calibration (Other components)

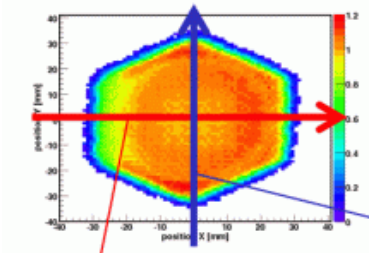
•Mirror reflectance

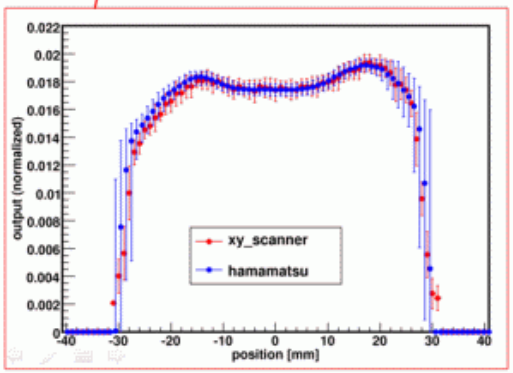
Monitored by handy spectrometer
(KONICA MINOLTA CM-2500d)

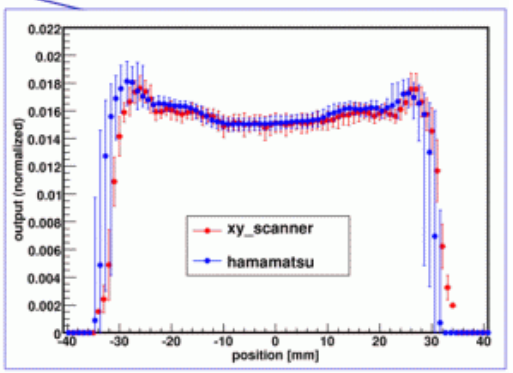


•PMT Uniformity

XY-Scanner (4LEDs, 4mm step)

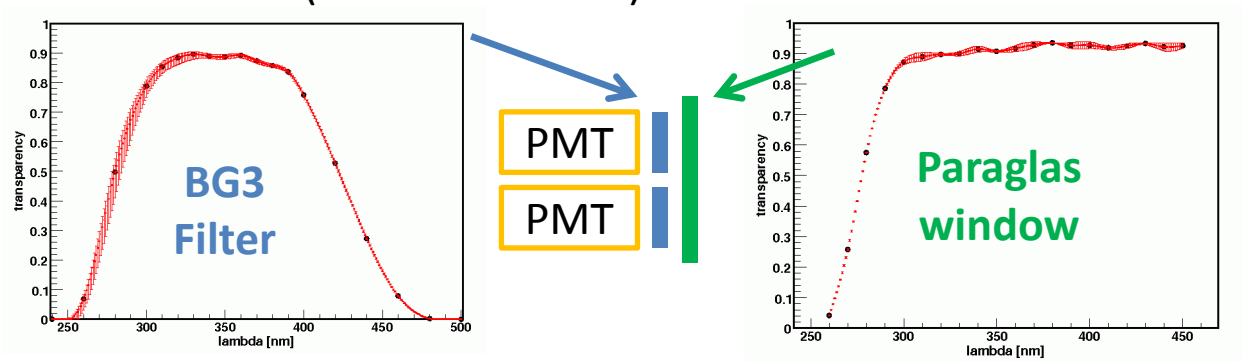






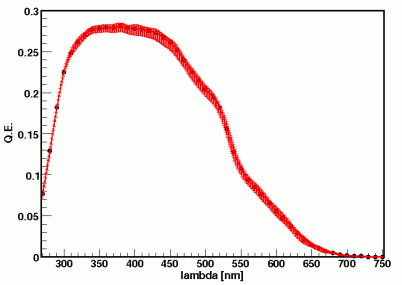
•Filter transparency

Measured by spectrometer
(HITACHI U-1100)



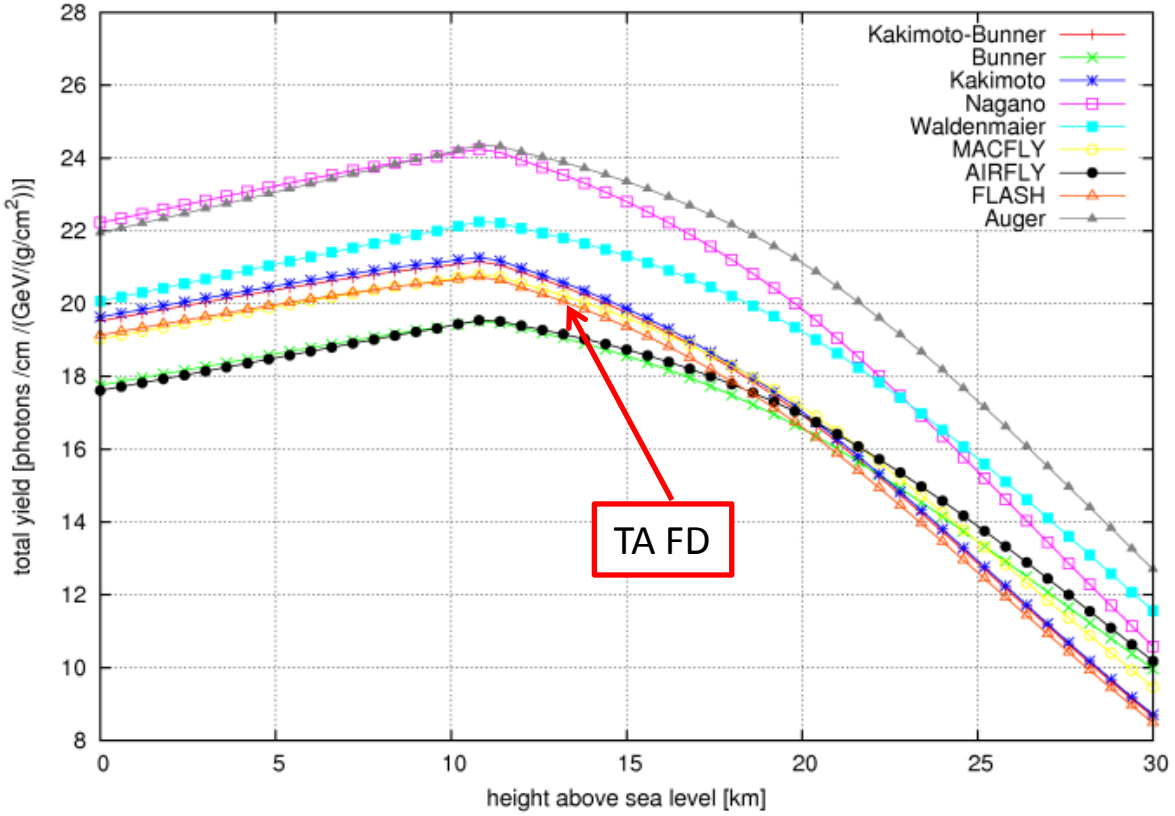
•PMT QE

Measured by HAMAMATSU



Total systematic error in detector:10% (8% of CRAYS, 5% of mirror, 3% of aging)

Fluorescence yield



Currently, we use
FLASH model
scaled by Kakimoto model

- Kakimoto model was used in HiRes experiment
- TA has HiRes refurbished detector (MD station)

Currently, the humidity dependence (~5% near ground) is not corrected.

Total systematic error in FL yield:12% (10% of model, 5% of humidity, 3% of atmosphere)

Atmosphere

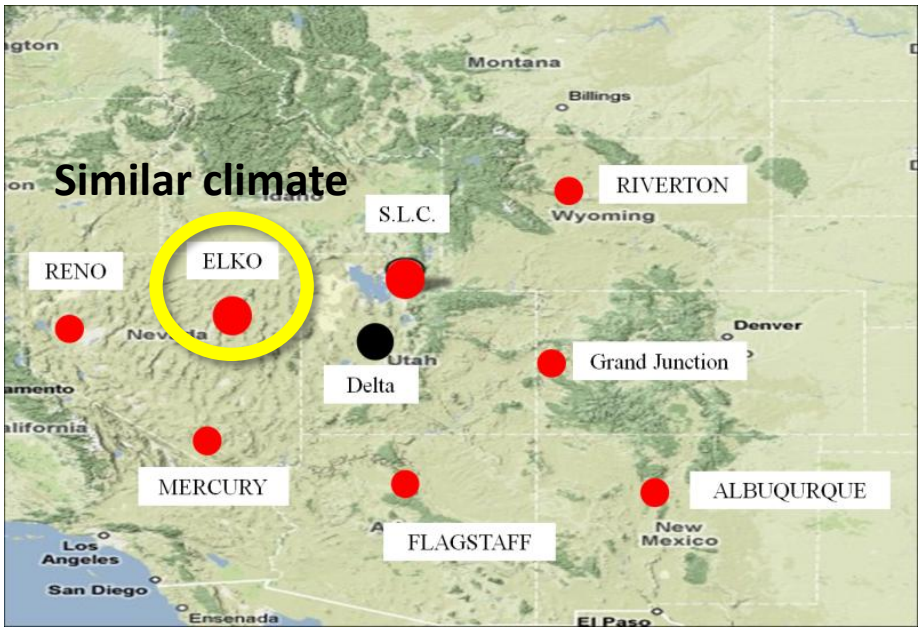
Two components of attenuation: Molecule (Rayleigh) + Aerosol

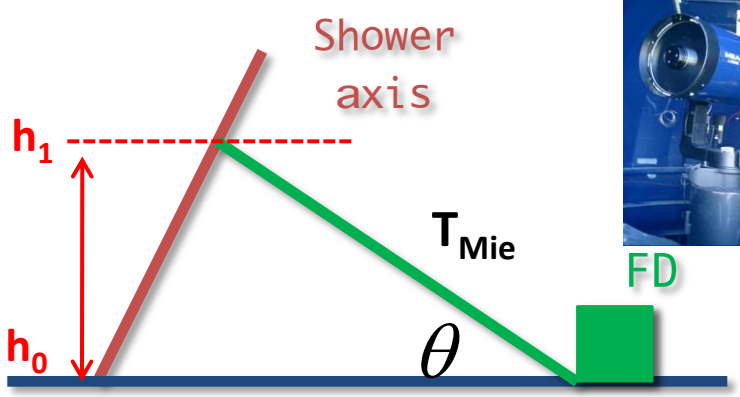
calculation (well known) → Atmospheric parameters

measurement → Aerosol: LIDAR

:Radiosonde

Every 12hours





$$T_{Mie} = \int_{h_0}^{h_1} \exp\{-\alpha_{Mie}(h)\} dh / \sin\theta$$

$$\alpha_{Mie}(h) = \lambda \exp(-h/H)$$

Currently, we use typical value:

- Attenuation length (λ) : 29.4km
- Scale height (H): 1.0km

The details of atmospheric calibration are described in the poster by Tomida(P-102)

Total systematic error in atmosphere:11% (10% of aerosol, 5% of Rayleigh)

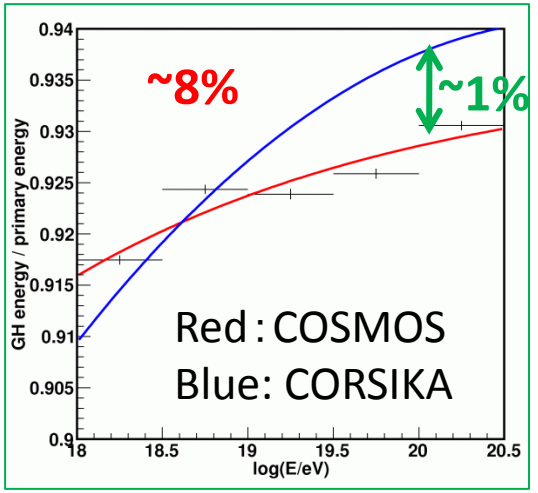
Monte Carlo

Air shower simulation
COSMOS/CORSIKA

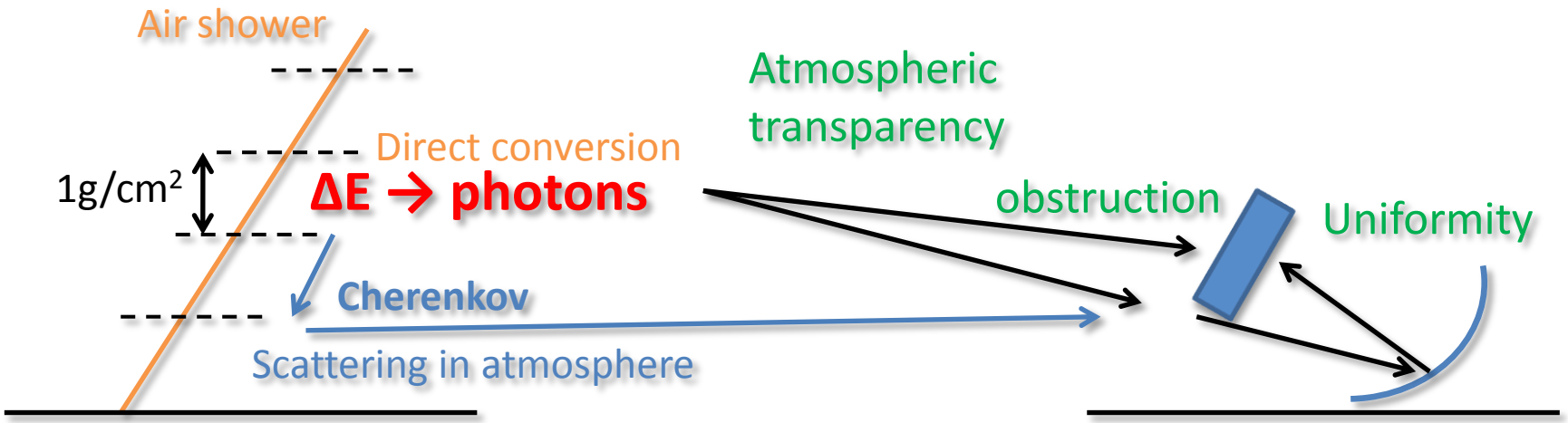
Items	COSMOS	CORSIKA
Primary energy	10^{18}eV ~ $10^{20.5}$eV	10^{18}eV~$10^{19.5}$eV
Zenith angle	cosθ=0.65 (≒50degrees) ~ 1	0~60degrees
Primary particle	Proton	Proton / Iron
Thinning ratio	10^{-4} (< 10^{20}eV), 10^{-5}(≥ 10^{20}eV)	10^{-4}
Interaction model	QGSJET II	QGSJET01, QGSJET-II, SYBYLL
Cut threshold energy	100keV	100keV

Missing energy
- Difference b/w primary energy and integrated energy of fitted G.H. function
  - Muon / Neutrino
  - Difference b/w true development and G.H. function
- Obtained missing energy is ~8%
  - Difference b/w COSMOS and CORSIKA: <1%

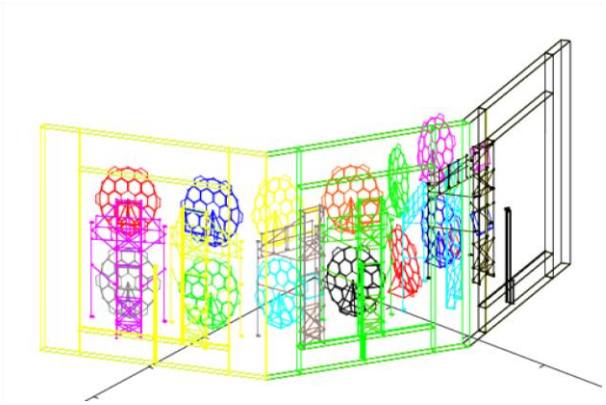
4%



MC Simulations
Detector MC



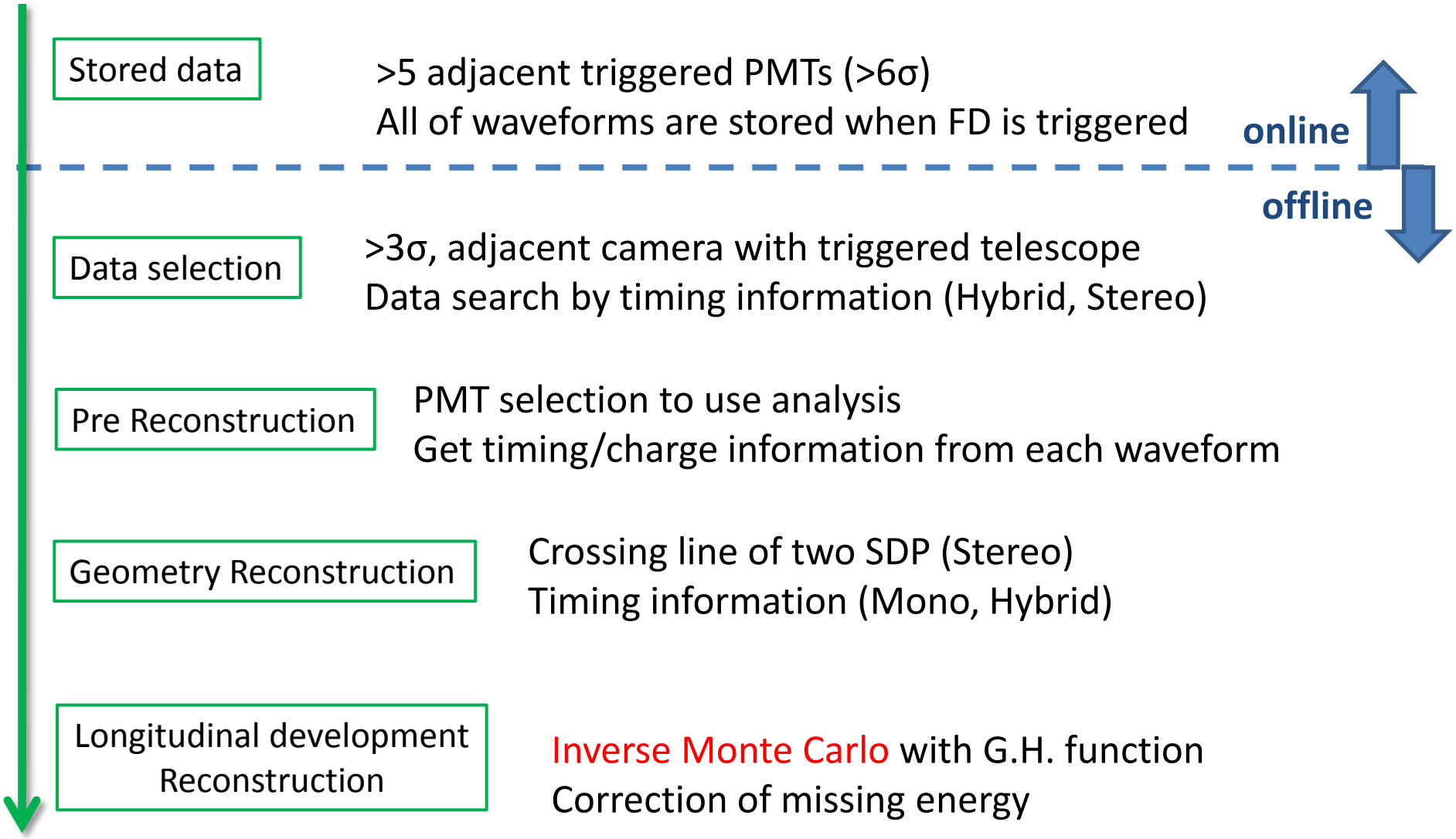
FDMC (JAVA)



- Not only Fluorescence but also Cherenkov (Nerling)
- Calibration factors with time dependence
  - PMT gain, mirror reflectance, back ground...
  - Same as data analysis
- Calibrated geometry of telescopes by star monitoring
  - We can see the star directly from baseline of waveform
    - DC- coupling

Data analysis

Analysis flow



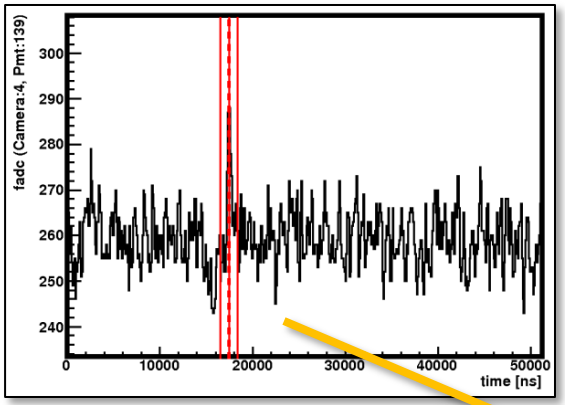
Pre reconstruction

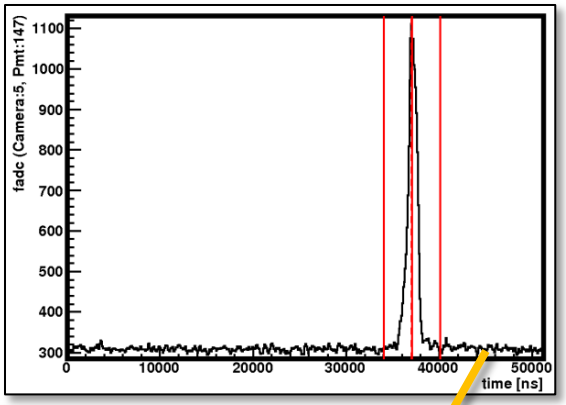
PMT Selection

Data selection

0th selection

- Reject for S/N < 3
- Keep only the neighboring camera by the triggered one.





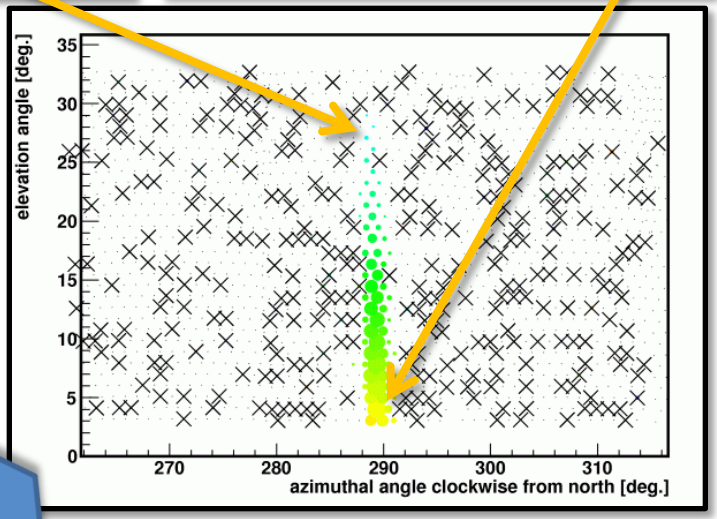
Pre reconstruction (The initial parameters for the 4th selection)

1st selection (waveform analysis)

- The peak, region for the integration is decided by the triangle filter
- Reject for S/N < 6

2nd selection (Track on the camera plane)

3rd selection (Timing)



ITEM	SOFT	HARD
Residual	<1.2μs	<0.8μs
Chi2	<20	<15
SDP beta	<4°	<2°

Final selection (The rejected PMTs is also re-analyzed)

4th selection

- The geometrical reconstruction with the elevation angle and timing.
- Each PMT is judged by the condition. If the selected PMTs are changed, this analysis is done again.

Geometry (Stereo)

Shower-Detector Plane (SDP)

Determination by direction of the selected PMTs

$$\chi^2 = \sum_i w^i (\boldsymbol{n} \cdot \boldsymbol{k}^i)^2$$

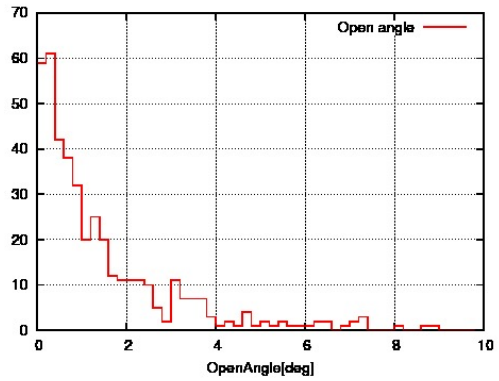
n: Normal SDP vector

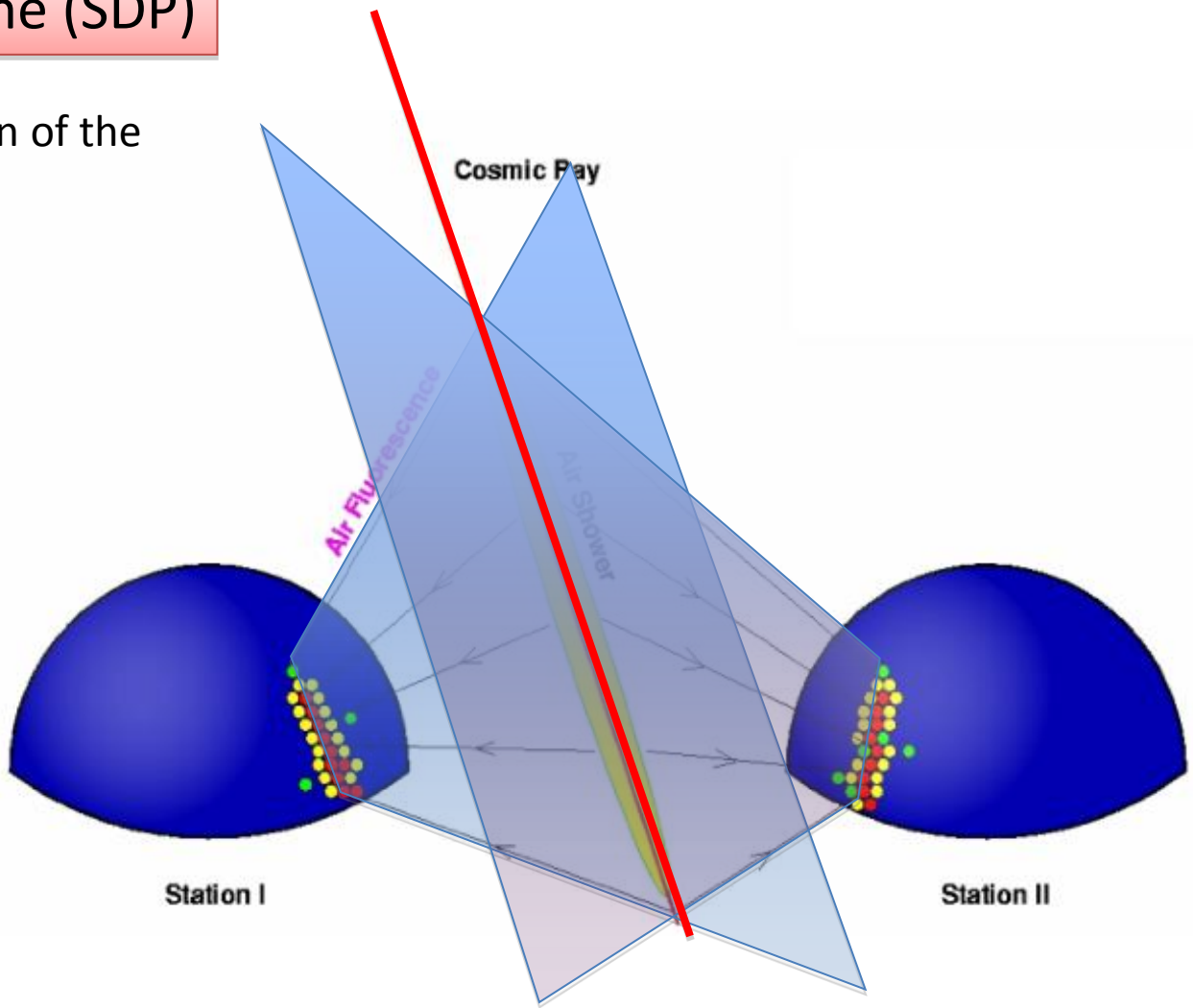
k^i: PMT direction vector

Shower axis

Intersect line of two SDPs

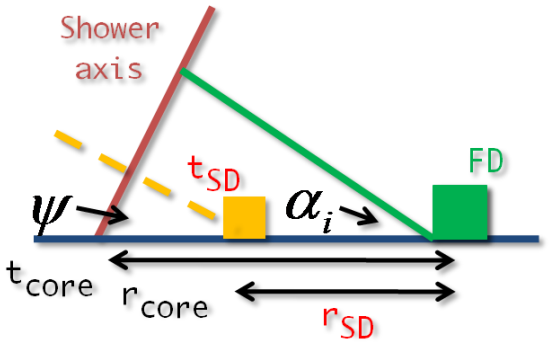
$$\boldsymbol{s} = \boldsymbol{n}_1 \times \boldsymbol{n}_2$$





Geometry (Hybrid)

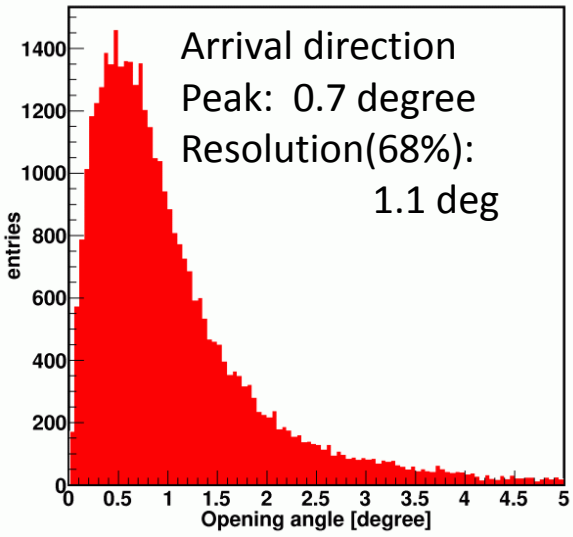
- Geometry is determined by **hybrid information**
  - Traditional analysis of the mono-reconstruction with timing of one SD

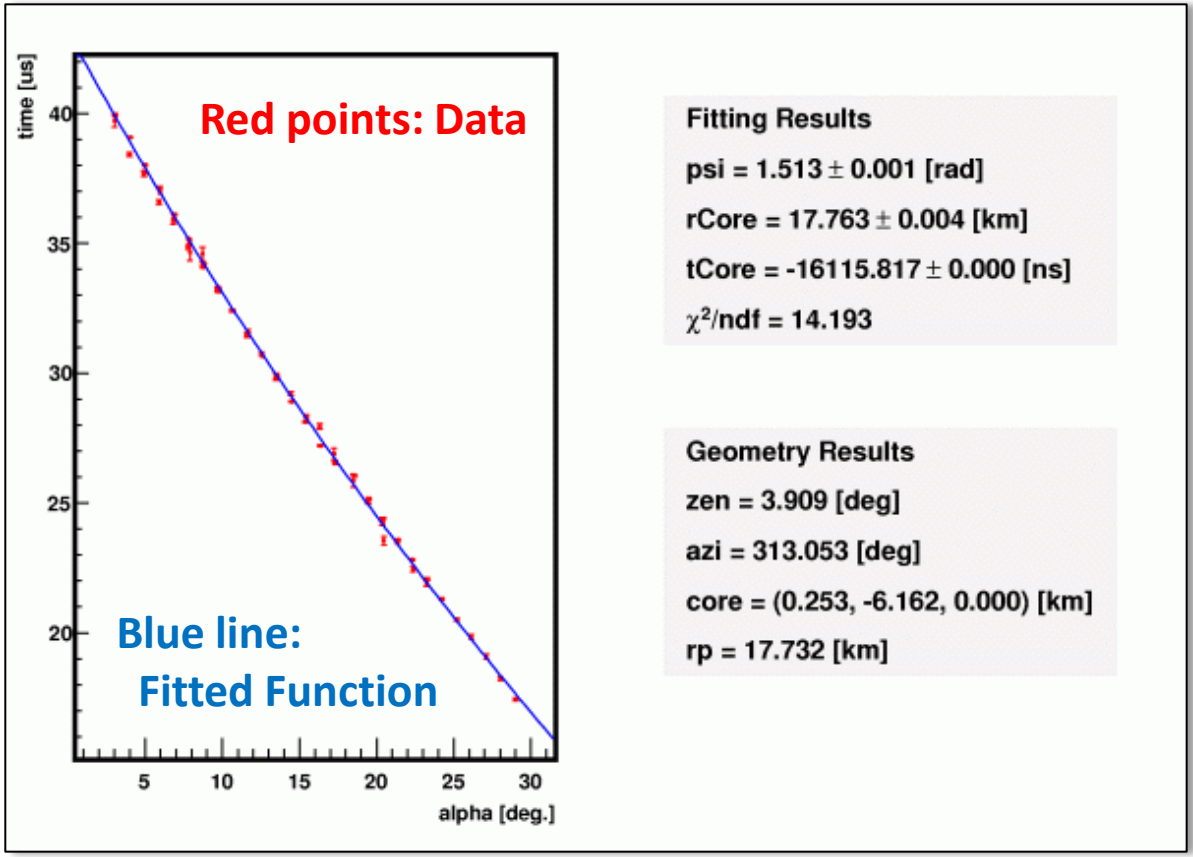


Hybrid reconstruction

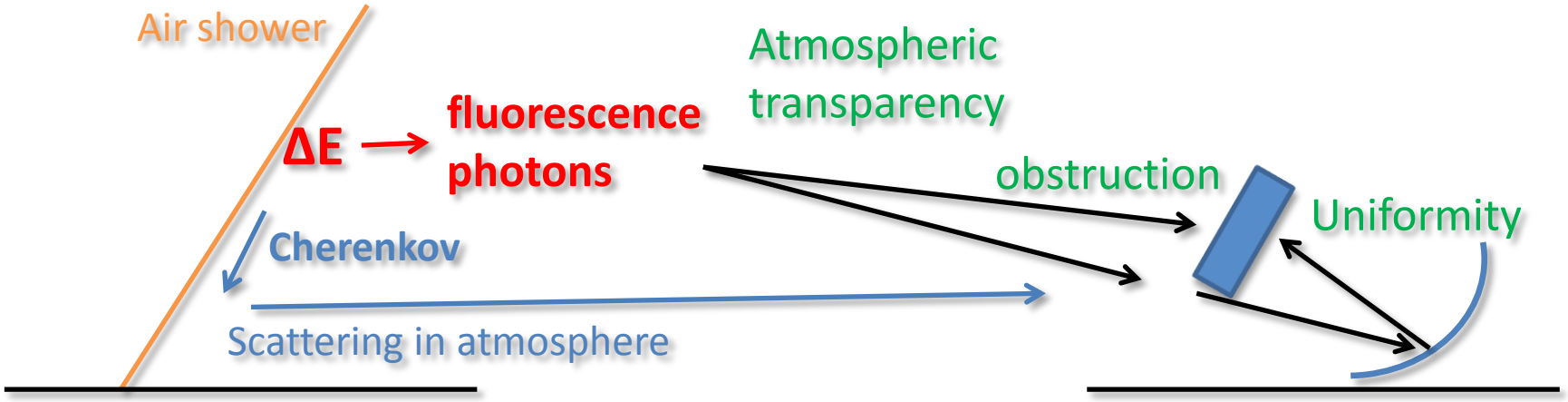
$$t_i = t_{core} + \frac{1}{c}\frac{\sin\psi - \sin\alpha_i}{\sin(\psi+\alpha_i)} r_{core}$$

$$t_{core} = t_{SD} + \frac{1}{c}(r_{core} - r_{SD})\cos\psi$$





Longitudinal development
Inverse Monte Carlo method



The detected photons are not so simple!!

- FL light and Cherenkov light
- Atmospheric transparency
- Obstruction by the telescope structure
- Gap of segment mirrors
- Uniformity on cameras

These factors are irreversible.

Inverse Monte Carlo (IMC)

- Direct comparison b/w data and MC on cameras
- All of effect can be included
- Database of detector response
  - High speed/statistics

How to determine the X_{max} and primary energy ?

1. **Shape of shower development**
2. **Scale factor of G.H. function**
   - Difference of total charge b/w data and MC
3. **Calorimetric energy**
   - Integration of fitted G.H. function
4. **Primary energy**
   - Missing energy correction

Search best X_{max} by IMC method

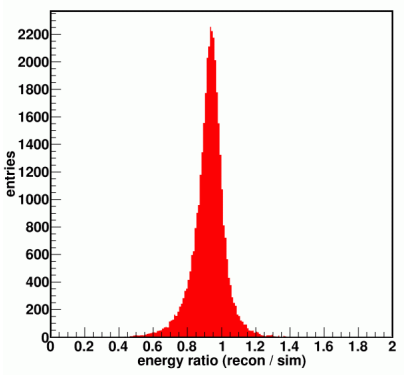
MC (G.H. function with scale factor of 1) # of p.e.

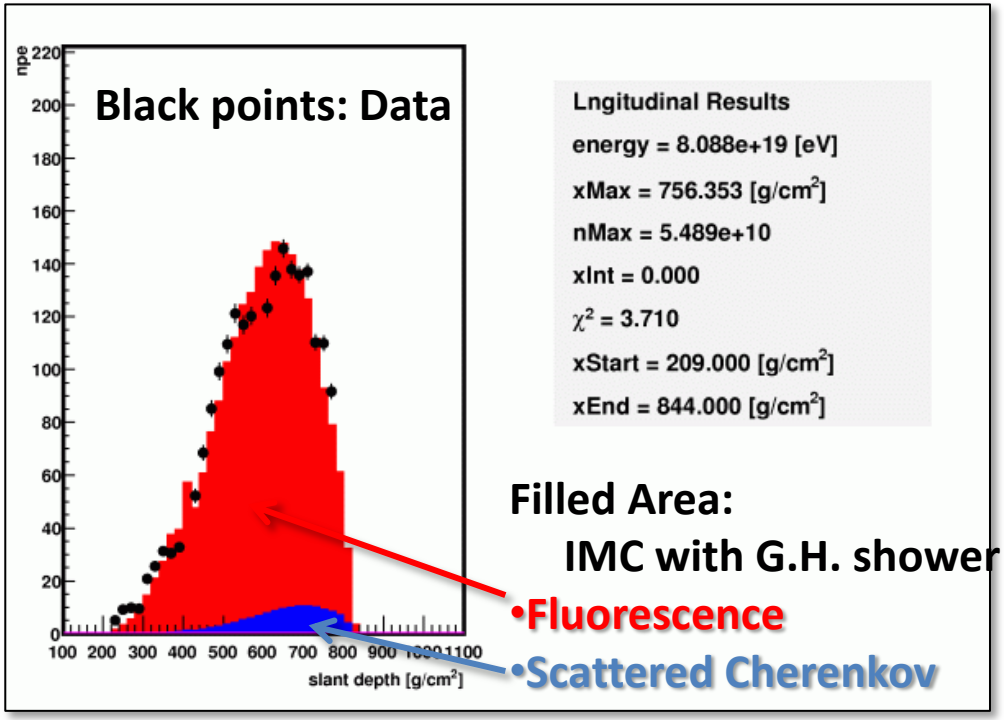
⟺

Data # of p.e.

Comparison
- Relative charge in telescope
- Selected PMTs

Energy Resolution: 8%



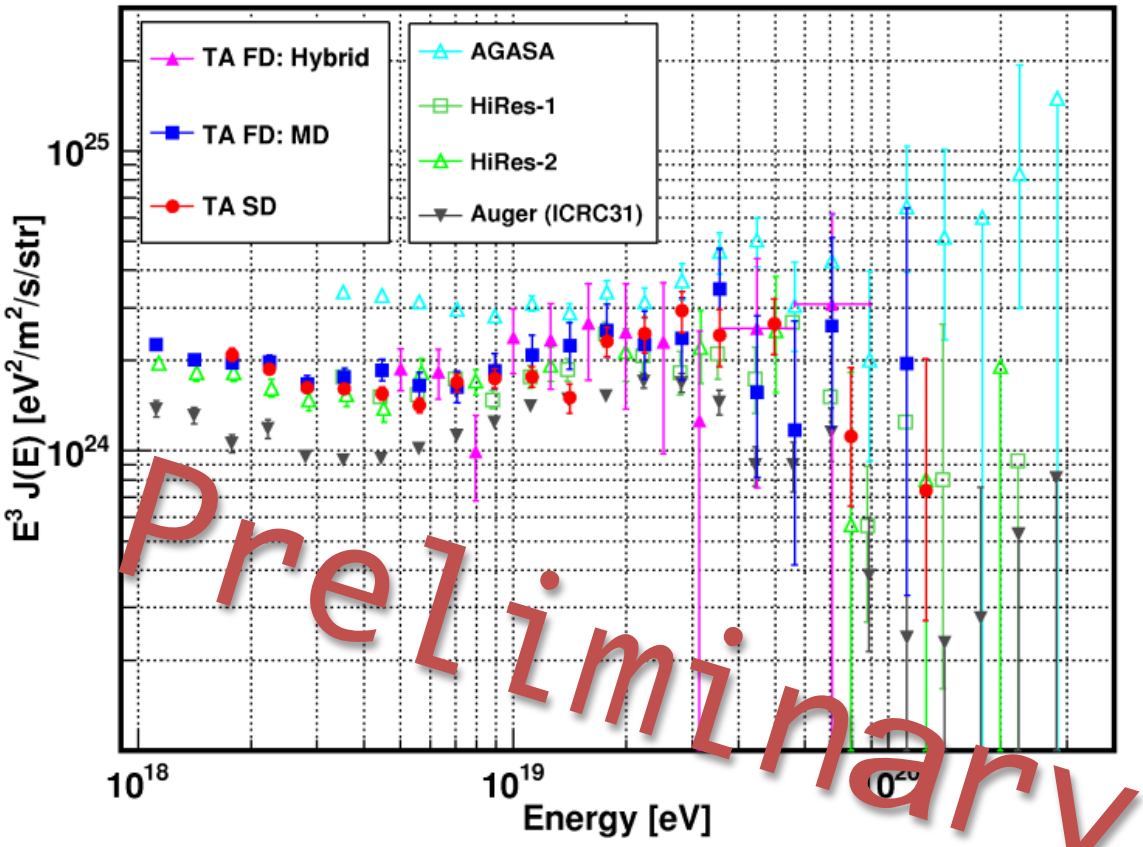


The details of the analysis method are described in the poster by Fujii (P-101)

Results

Energy spectrum

TA 1.5 years of hybrid events on BR and LR station



Systematic errors

Item	Systematic error
Fluorescence yield	12%
Detector	10%
Atmosphere	11%
Primary particle mass	5%
MC correction	3%
Total	19%

The energy scale of TA FD is almost same as HiRes.

In future...

- **Systematic error**

Item	Currently	Future (w/ ELS)
Fluorescence yield	**12%** Measurement(10%), Atmosphere(3%), Humidity(5%)	**8%** ELS (5%), Atmosphere(3%), Humidity(5%)
Detector	**10%** PMT(8%), Mirror(5%), Filter(1%), Aging(3%)	
Atmosphere	**11%** Mie(10%), Rayleigh(5%)	
Primary particle mass	**5%**	
MC correction	**3%**	1%
Total	19%	15%

- Measurement is on going in several experiment
- The dew-points are recorded by Radiosonde.
- Currently, we use one typical value.

Total systematic error will be reduced to 10~15%.

Conclusion

- To determine the UHECR energy, we have to understand
  - Calibration
  - Monte Carlo of Air shower / Detector
  - Analysis method
- Our status was presented
  - Systematic error is ~19%
- Our energy scale is in good agreement with HiRes

- In future, our systematic error will be improved by ELS and atmospheric calibration.