Cosmic-ray physics (II)
- What have been and will be discovered by cosmic rays? -

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Telescope Array Collaboration

April 4, 2015
@BINP

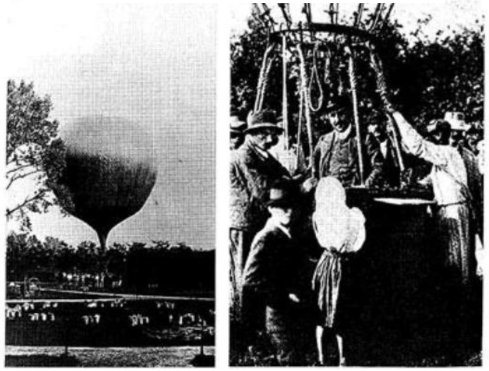
Outline

- Multi-messenger observation
- Telescope Array (TA)
  - Physics motivation/TA detector
- Recent preliminary TA results
  - Energy spectrum
  - Anisotropy of arrival directions: hotspot
  - Composition
- TA Extension proposal
  - TAx4, TALE
- Others
- Summary

Cosmic Rays

- High-energy elementary particles that travel the universe
- Main component is proton. Others are nuclei and electrons
- They arrive at the earth uniformly (~0.1% level anisotropy)

Hess who boarded a heat-air balloon



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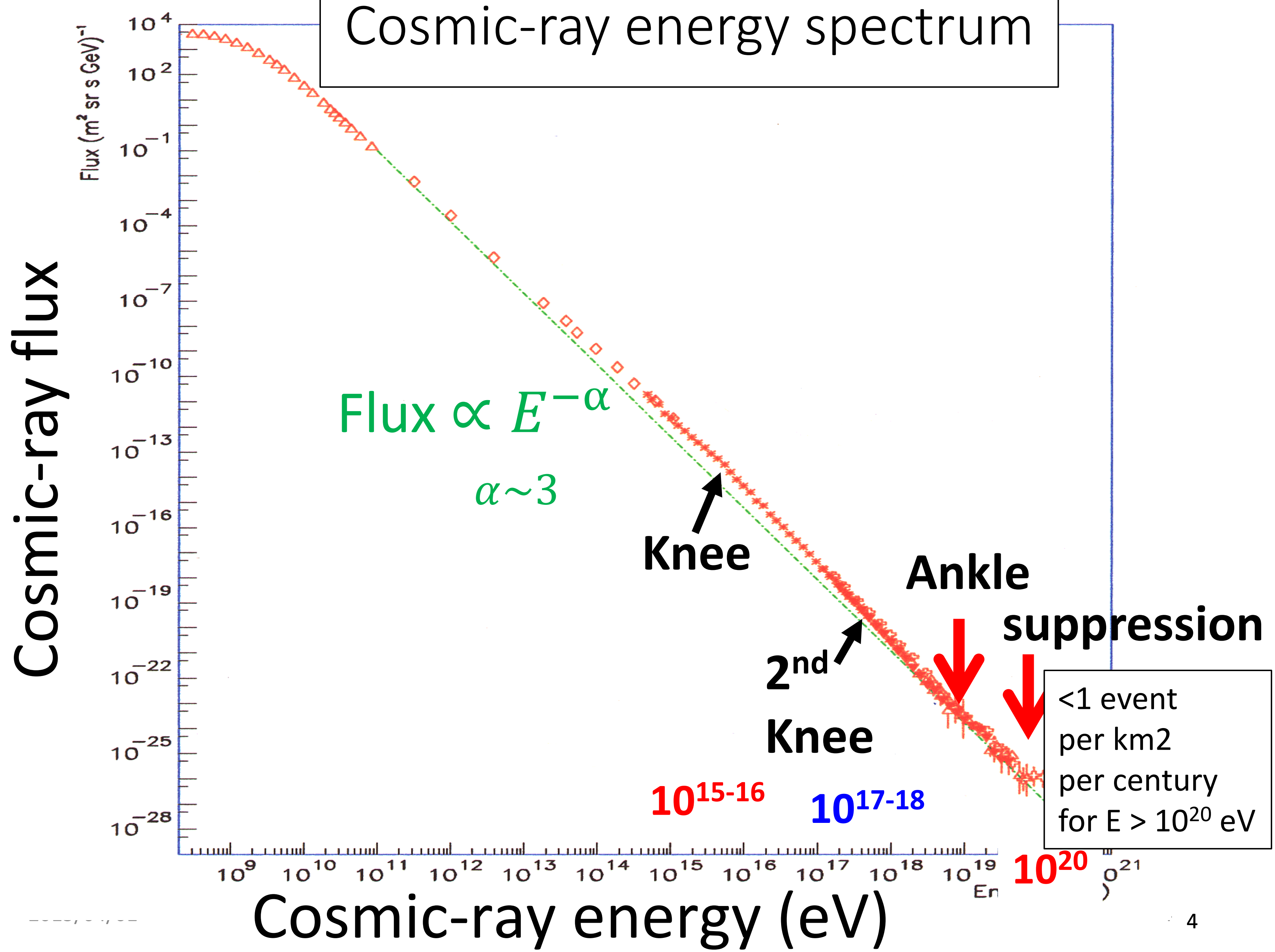
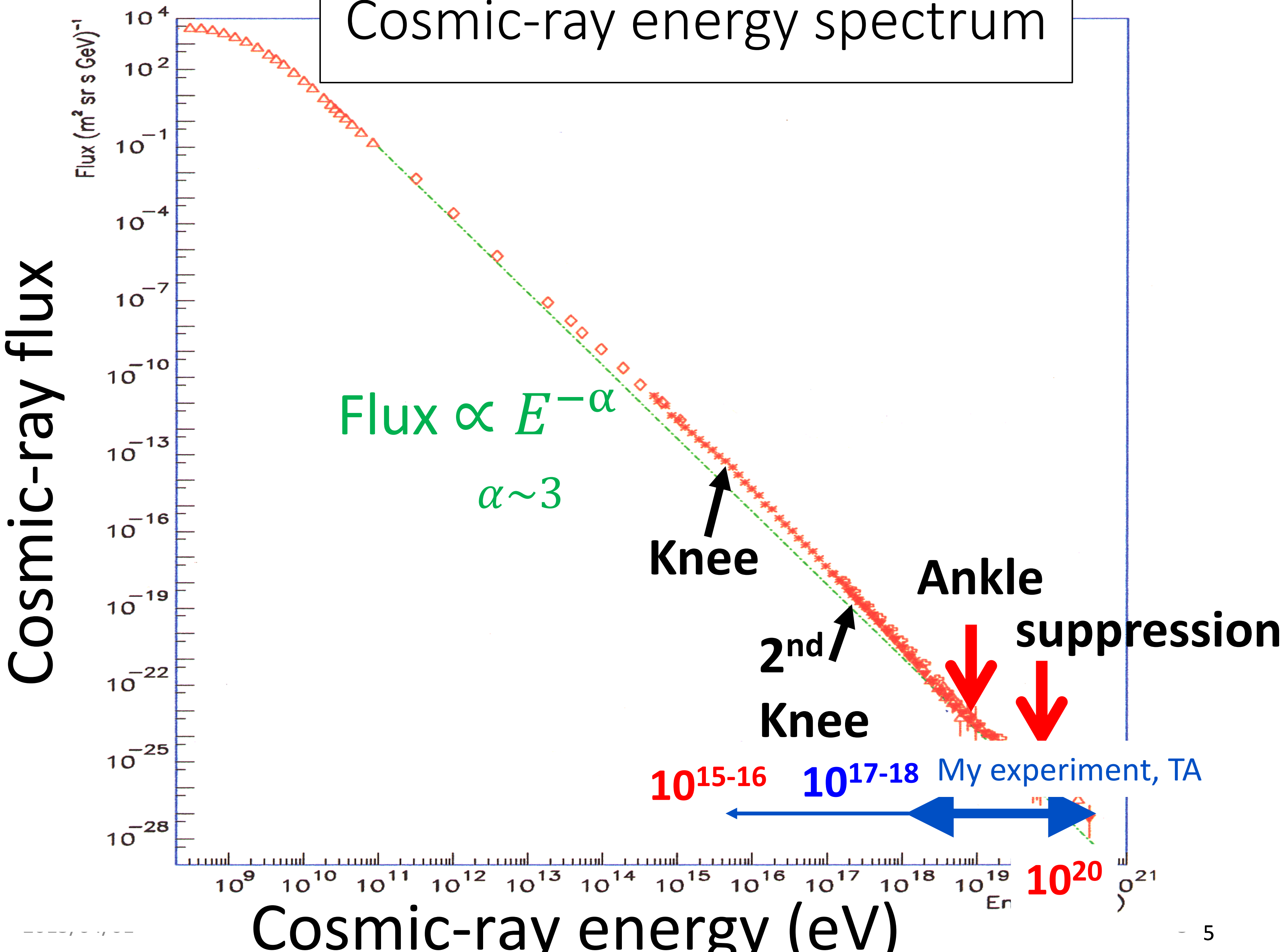
- 1930s～1940s Elementary particles were discovered using cosmic rays
  - Positrons, muons, pions …
- 1938 Pierre Auger discovered extensive air showers
- 1950s～
  - The mission of the discovery of elementary particles moved to particle accelerator experiments
  - The mission of cosmic rays moved to the subjects such as observations of the universe
- 1962 J.D. Linsley observed a first highest-energy (10^{20} eV) cosmic rays
- Since 2008, Telescope Array experiment has been taking data of 10^{20} eV.

Cosmic-ray energy spectrum

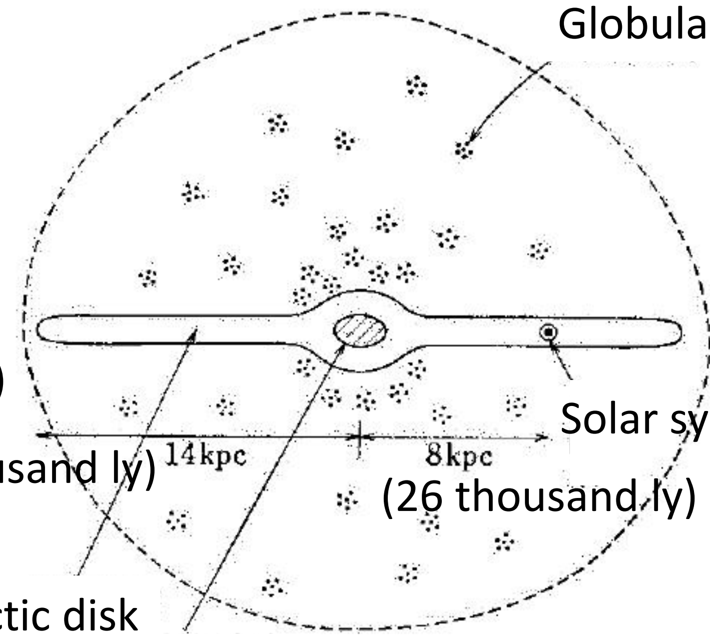


Cosmic-ray energy spectrum



the Milky way (the Galaxy)

- Galaxy that includes our solar system



Our galaxy

1pc = 3.26 ly

ly= light year

Balance of cosmic-ray energy

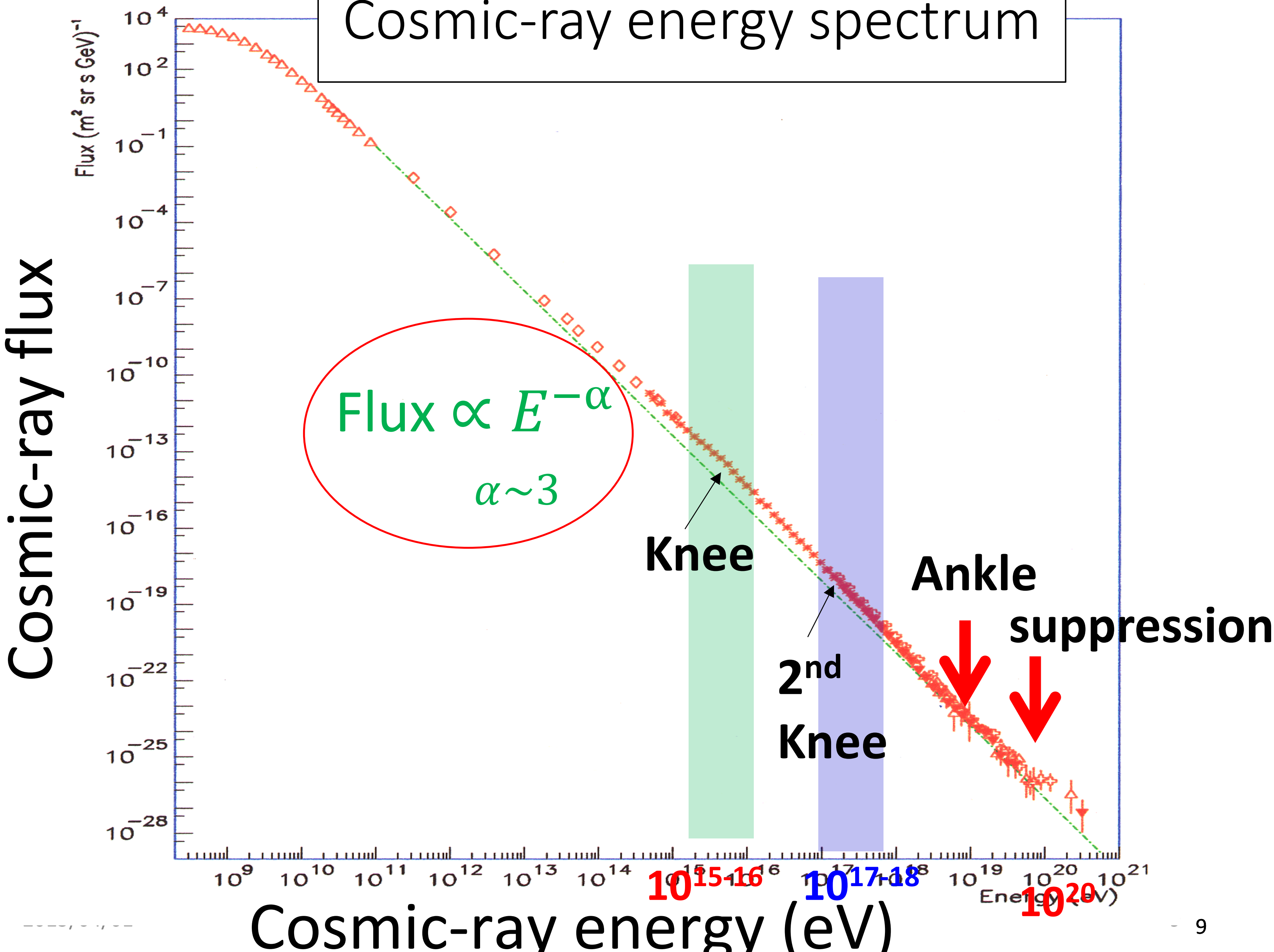
- The structure of our glaxy
  - Total energy of cosmic rays in the galactic disk Ecr = ρcr x V $\approx 10^{54\sim55}$ erg
    - Volume V = $10^{66\sim67}$ cm^3
      - Radius of about 10 kpc
      - Thickness of about a few hundred pc
    - Galactic magnetic field of about 1 μG
  - Leakage of cosmic-ray energy from the galaxy Ecr/τ = ρcr x V/$\tau \approx 10^{40}$ erg/s
    - Time during which cosmic rays are confined: $\tau \approx 10^7$ yr $10^{14\sim15}$ s

Balance of cosmic-ray energy

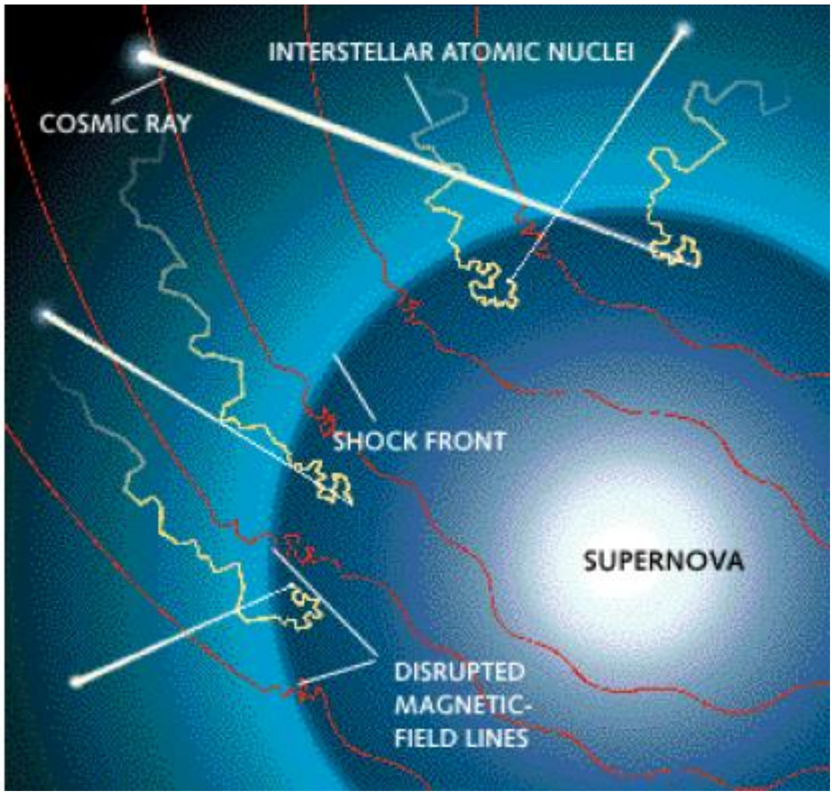
- The rate of energy generation by supernova $R_E \sim 10^{42}$ erg/s
  - Release of energy by a supernova explosion Esn 10^{51} erg
  - The number of supernova explosions in the galaxies 1/(30 yr)
- Supply of energy to cosmic rays by supernova explosion $E \sim 10^{40}$ erg/s $\approx Ecr/\tau$
  - Assuming that 1% of energy is used for particle acceleration

Balance of energy between supply and loss of cosmic rays in the galaxy
Intensity of cosmic rays in the galactic disk is constant

Cosmic-ray energy spectrum



Acceleration of cosmic rays shock-wave acceleration



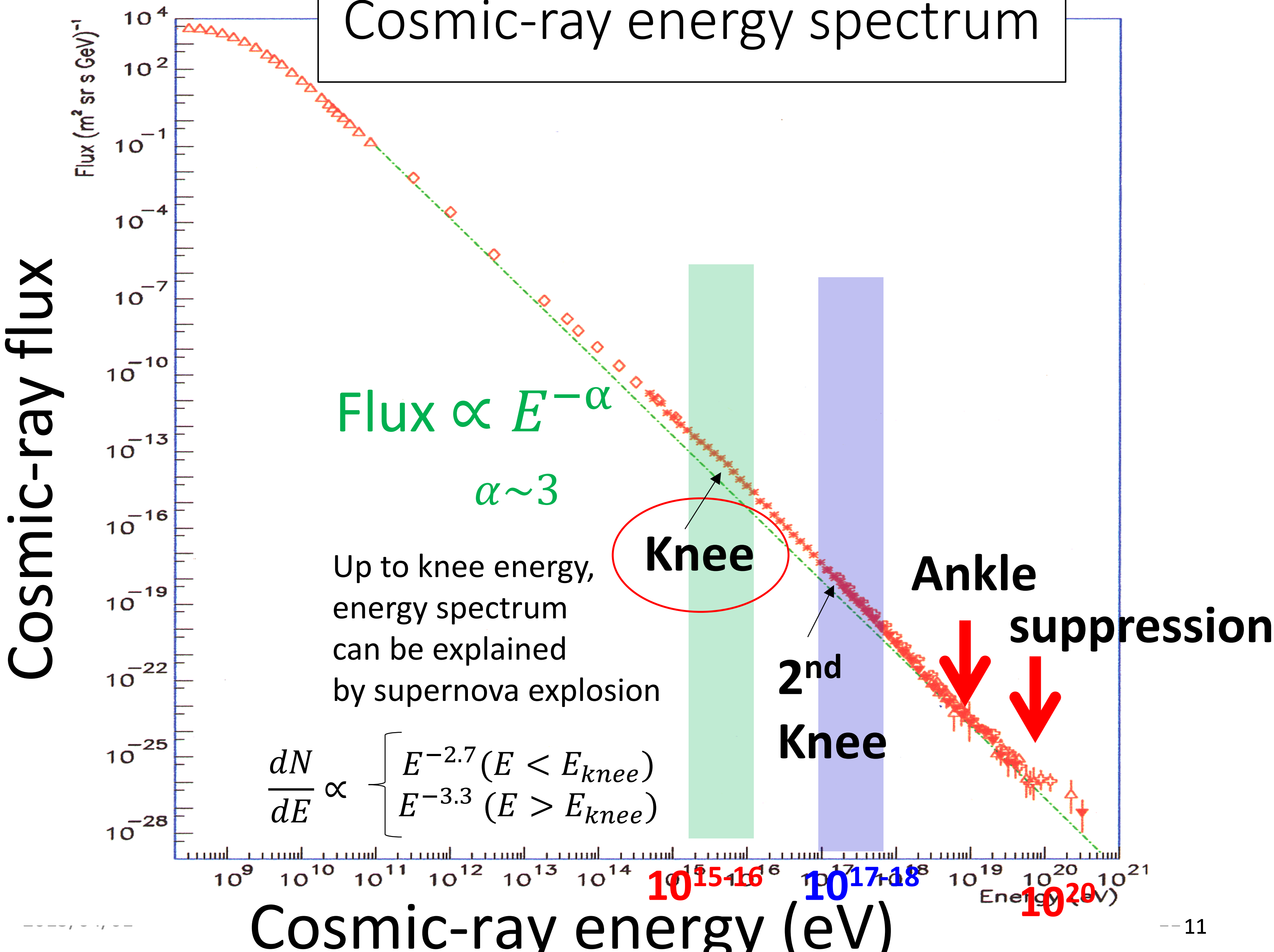
Supernova explosion
Shock wave
Cosmic ray acceleration

- Energy spectrum of cosmic rays at the source
  - $N(E) \propto E^{-2}$
    - Observed cosmic-ray spectrum may be explained
- Maximum energy for proton
  - $E_{max} \sim 10^{14}$eV

  can be possible
- Early stage of neutron stars
  - $E_{max} \sim 10^{16}$eV

  can be expected

Cosmic-ray energy spectrum

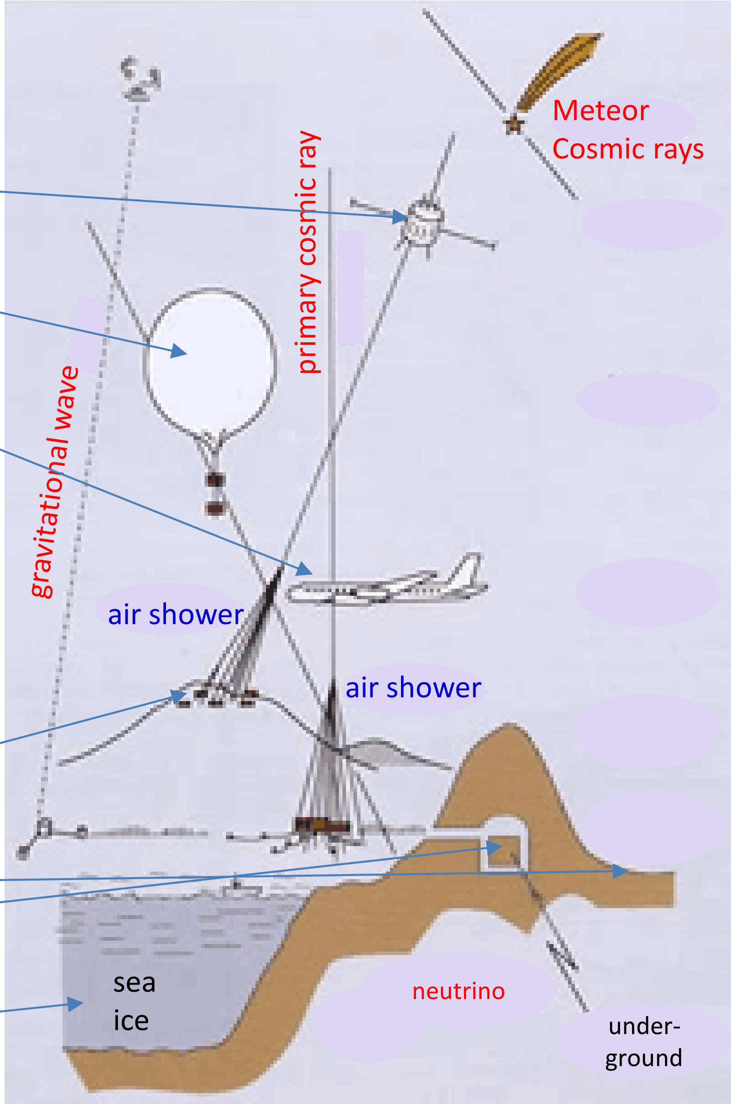


Multi-messenger observation

- High-energy electromagnetic waves
- Particles
- Gravitational waves

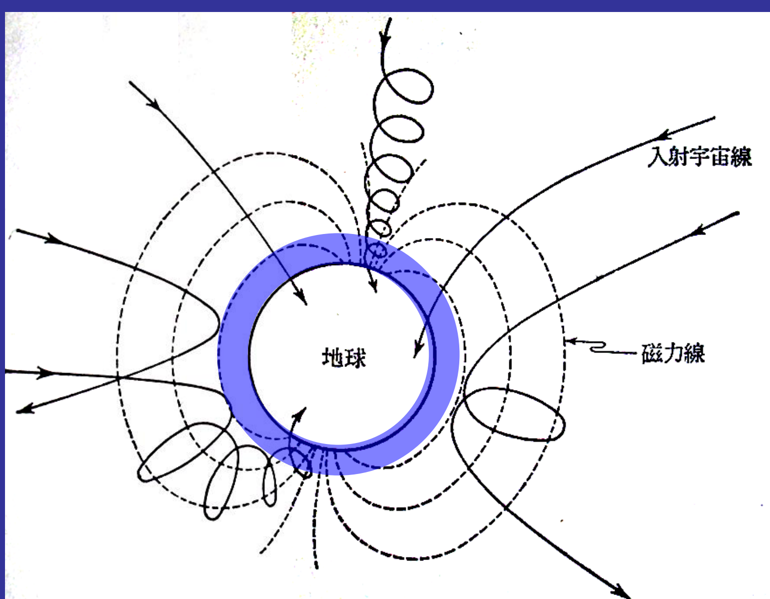
Observation of cosmic rays

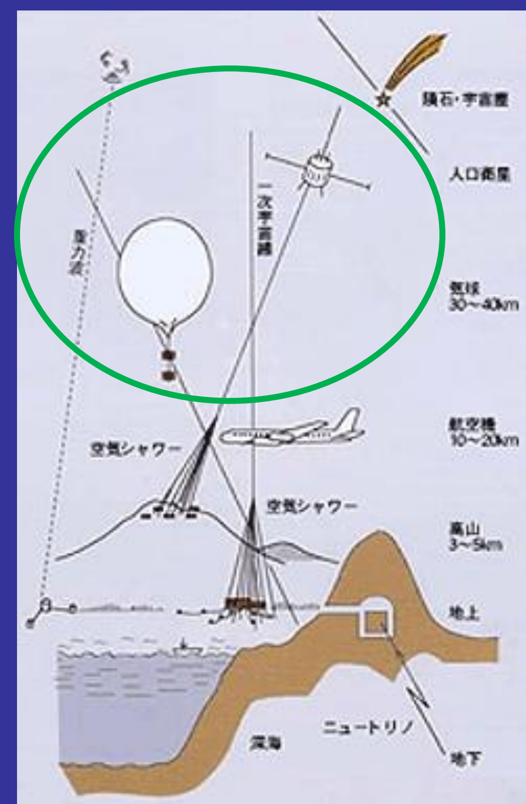
- Primary cosmic rays
  - Satellite
  - Balloon (30~40km)
  - Airplane (10~20km)
- Secondary cosmic rays
  - Radiation produced by primary cosmic rays when they enter the atmosphere
  - High mountain (3~5km)
  - Ground (~0km)
  - Underground
  - deep sea, ice



Detection below 10^{14} eV

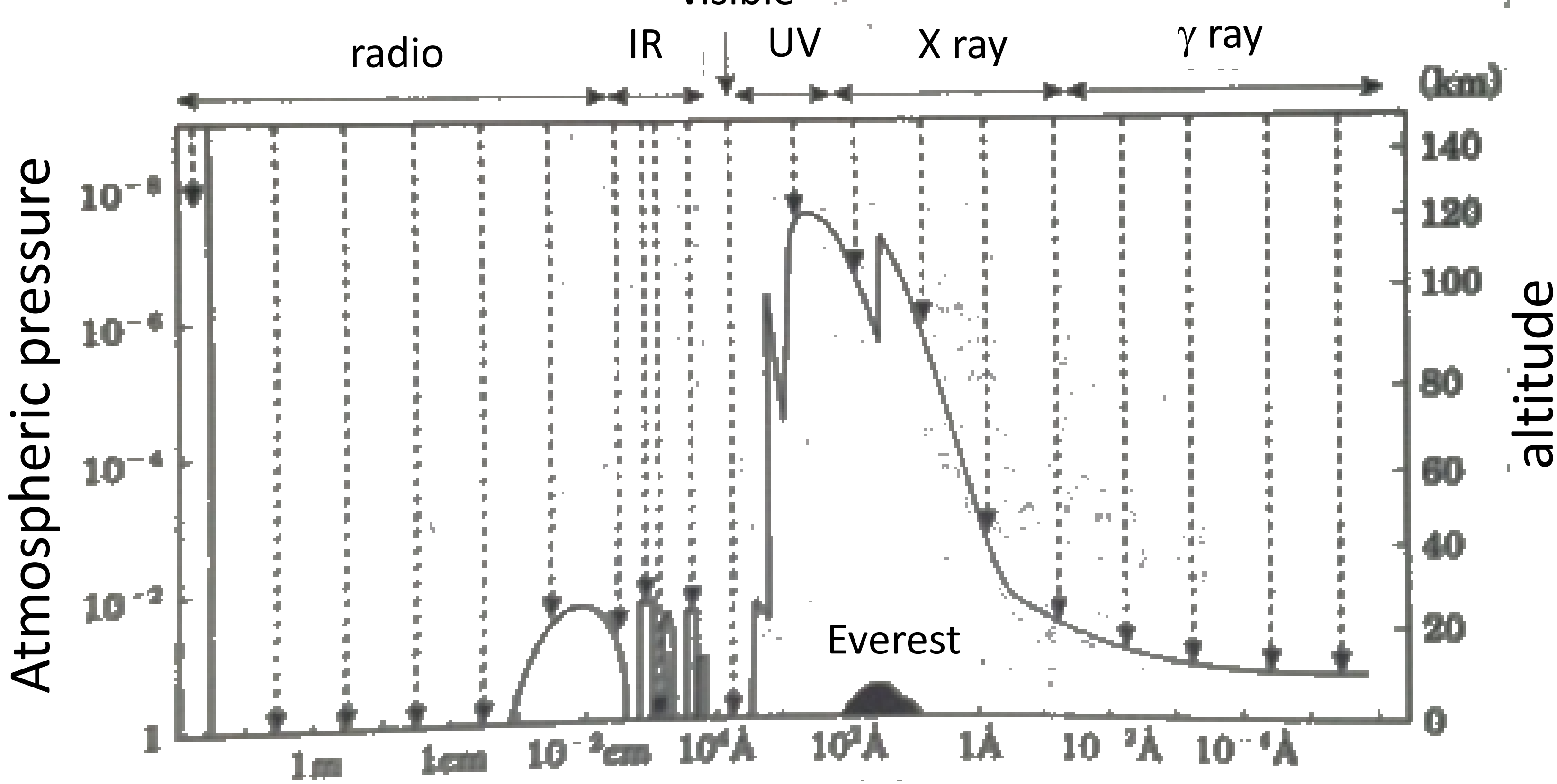
- Direct detection by Satellite / balloon
  - limit of weight of detector
  - Low-energy CRs do not reach the ground because of geomagnetic field and atmosphere.





Electromagnetic waves

Altitude to which electromagnetic waves can arrive



Wavelength of electromagnetic waves

longer ⟷ shorter

Electromagnetic waves except radios, part of IR and visible light can not arrive at the ground

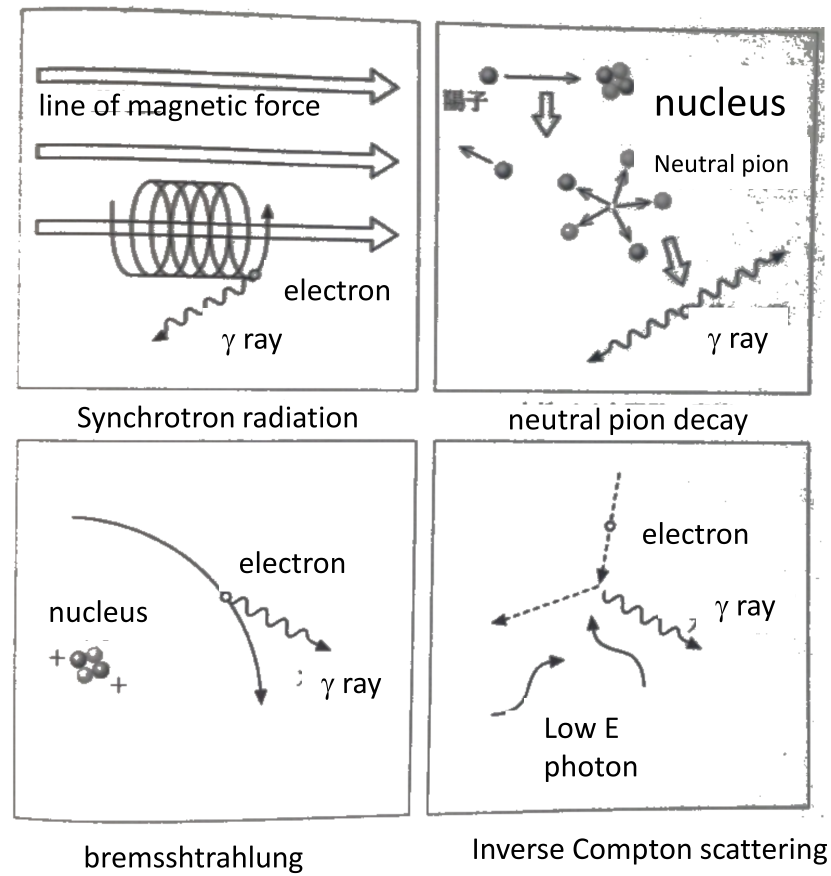
⟶ Rockets, satellites, balloons

Electromagnetic waves X rays

- Items that were found by X-ray astronomy
  - Many objects in the universe emit X rays
  - Objects for which X-ray intensities vary irregularly within very short time
  - Existence of gases of ultra-high temperature
  - Ultra-high energy phenomena to accelerate electrons close to light velocity
- Relation to black holes, clusters of galaxies, objects with huge explosion

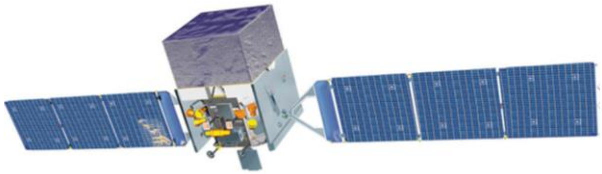
Electromagnetic waves
γ rays

- X ray
  - Radiation from high-temperature plasma
- Gamma ray
  - Mainly radiation related to charged particles accelerated to relativistic energy
  - Subjects
    - Supernova explosion
    - e+e- annihilation from galactic center
    - Cosmic-ray acceleration in supernova explosion
    - Black hole using γ ray
    - Gamma-ray burst

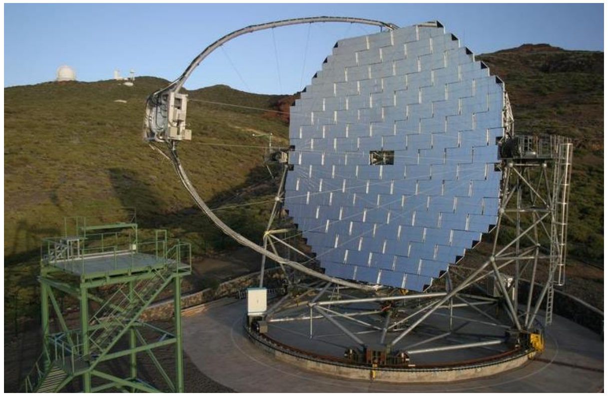


Electromagnetic waves
γ rays

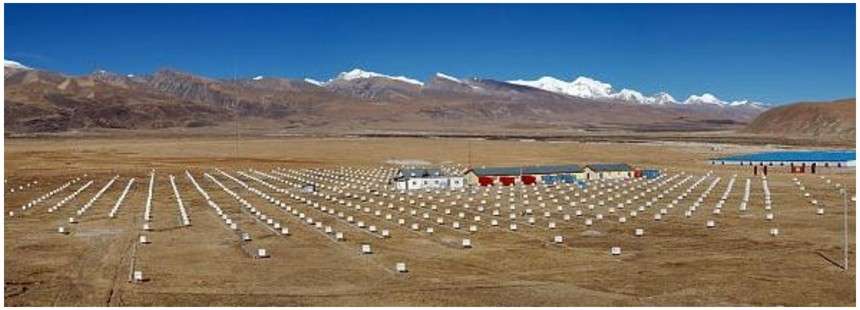
- Methods of measurement
  - Hard X ray and gamma ray
    - Detectors with satellite
  - TeV gamma ray
    - Atmospheric Cherenkov telescope
    - Air shower detector



(ex) Fermi space craft



(ex) MAGIC Cherenkov telescope

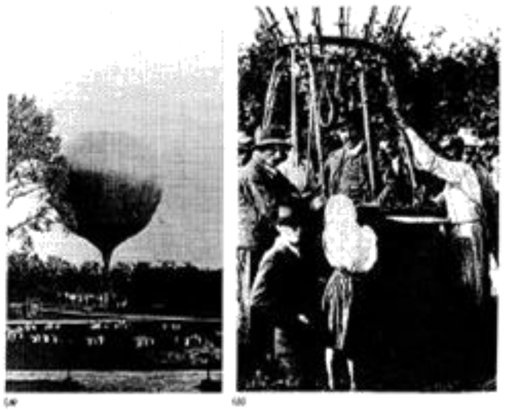


(ex) Tibet Air Shower

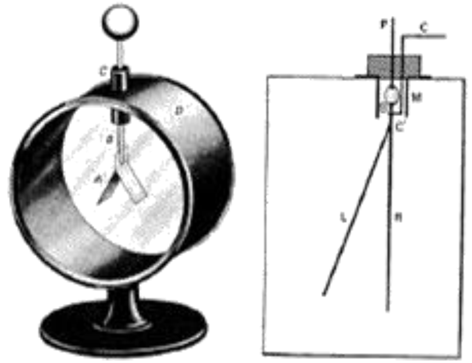
Cosmic Ray

- 1900-1926 the twilight
  - 1896 radiation from Uranium by A.H.Becquerel
  - 1896 X ray by W.C.Rontgen
  - 1898 radiation from Thorium, Polonium, Radium etc. by M.Curie and G.Schmidt
  - 1900~ alpha ray, beta ray, gamma ray
  - 1908 alpha ray = Helium nucleus – 2 electrons
  - 1911-1912 discovery of cosmic rays by V.Hess

Cosmic rays by V.Hess



Balloon



electroscope

Cosmic ray

- 1926-1933 establishing the concept of cosmic rays
  - Particle ray or gamma ray?
    - The intensity depends on latitude → particle ray
      - (geomagnetic field strength depends on latitude)
  - Charge of cosmic ray?
    - East-west effect
      - More come from west

Cosmic ray

- 1933- era of discovery of elementary particles
  - 1932 discovery of positron with cloud chamber by C.D.Anderson
  - 1936 discovery of muon by C.D.Anderson and S.H.Neddermeyer
  - 1947 discovery of pion by C.F.Powell
  - 1947 discovery of V particle (K meson) by G.D.Rochester and C.C.Butler

Cosmic ray

- 1941- era of studies of the universe
  - 1948 study of cosmic-ray composition with balloon by P.Freier et al.
  - Study of energy spectrum
  - 1955~ existence of magnetic field of the universe was known
    - Study of sources of cosmic rays
      - Cosmic rays of higher energy
      - Neutral particles

neutrino

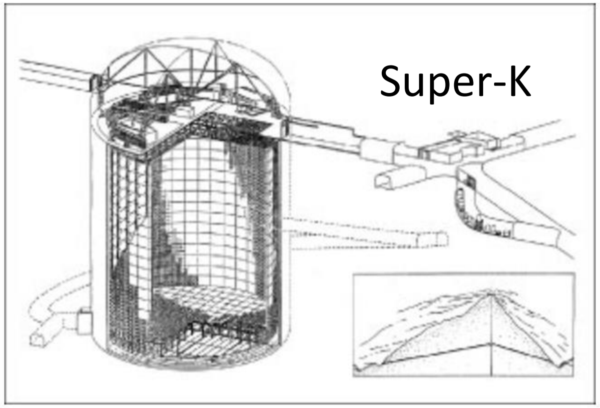
Leptons and quarks

- Electrons belong to lepton category
- Leptons are the group of elementary particles that do not undergo strong interaction
- Quarks and leptons

		1st generation	2nd generation	3rd generation
	quark	u, d	s, c	b, t
lepton	electron-type	e (1897)	μ (1937)	τ (1975)
	neutrino-type	ν_e (1956)	ν_μ (1962)	ν_τ (2000)

neutrino

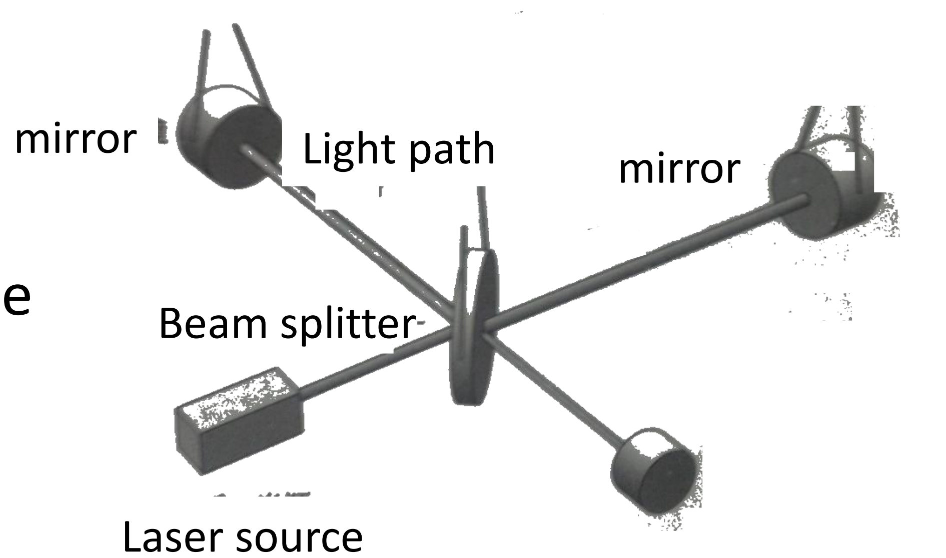
- Solar neutrino (to study nuclear fusion, oscillation) ~MeV
  - Homestake (C_2Cl_4), SAGE, GNO (gallium)
  - Kamiokande, SuperKamiokande, SNO (Water Cherenkov)
- Neutrino from supernova 10~20 MeV
  - Baksan, LSD, KamLAND (Liq. Scintillator)
  - Kamiokande, SuperKamiokande, SNO etc. (Water Cherenkov)


Super-K

- Atmospheric neutrino
  - Study of neutrino oscillation
- High-energy neutrino from the universe $E > 10^{15}$ eV
  - IceCube at the Antarctic
  - ANTARES in the deep sea

Gravitational wave detection

- Expected from the general theory of relativity
- Direct measurement of gravitational wave
  - Binary stars of high density
  - Explosion of supernova
- Detector type
  - Resonance-type
  - Laser interferometer-type



Next-generation gravitational wave detectors

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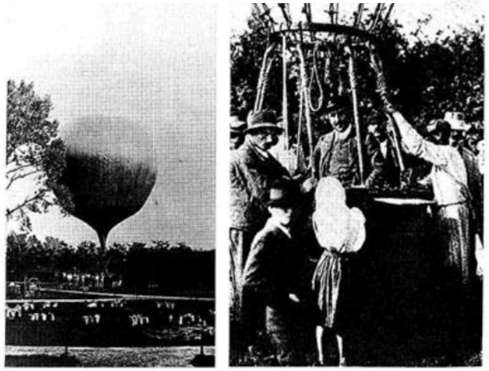
Hess who boarded a heat-air balloon



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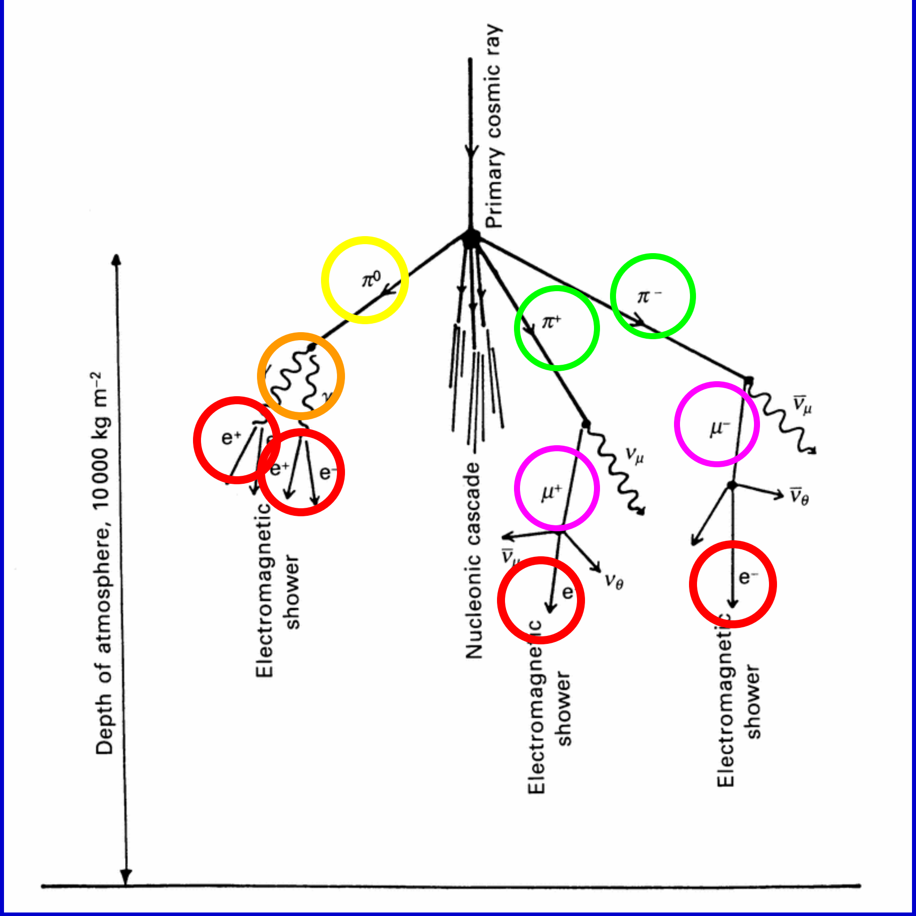
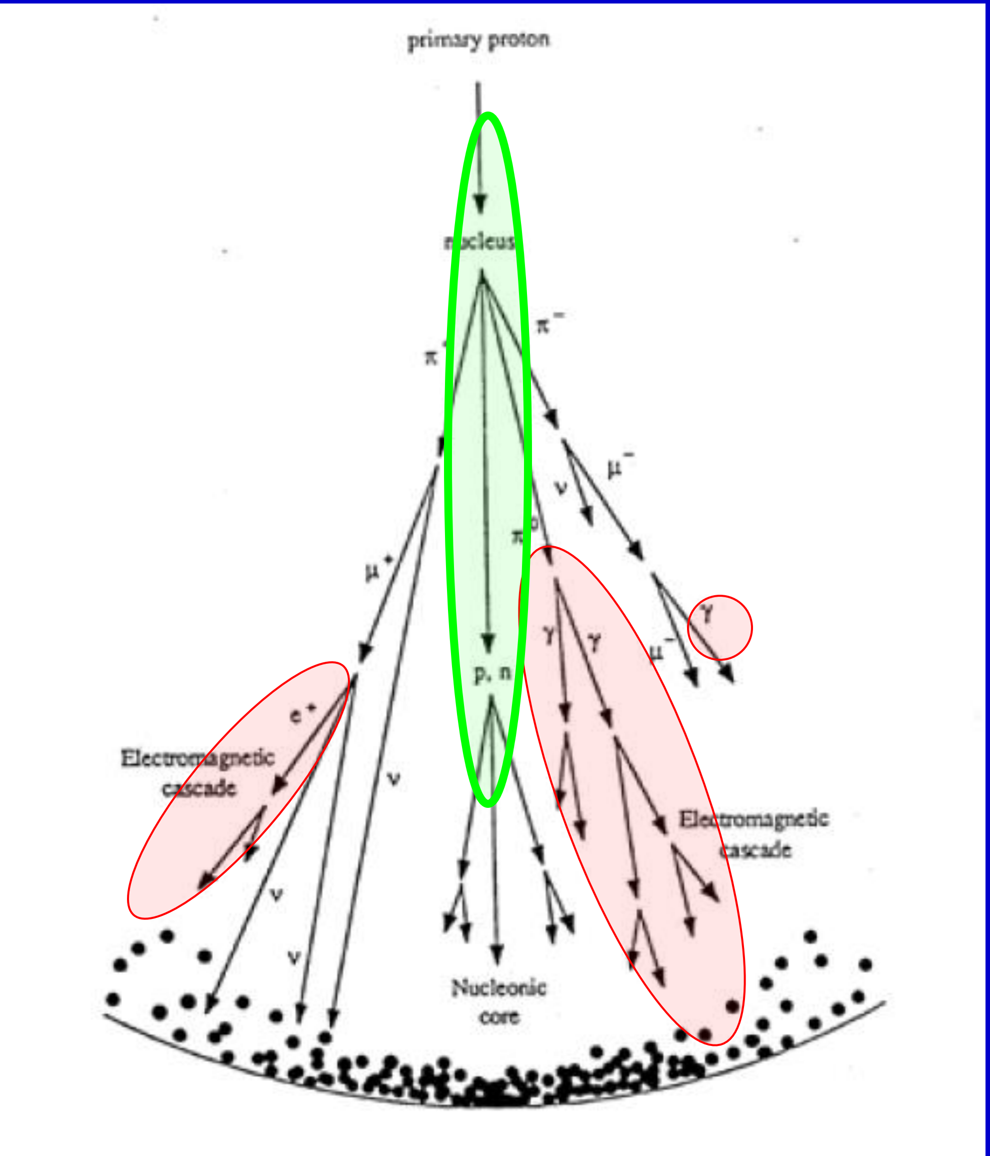
Theory of Cosmic-ray Shower

- **Gamma ray** and **electron** are known.
- Positrons is known in 1932.
- Bhabha,Heitler,Carlson,Oppenheimer proposed **cascade-shower theory in 1937**.
  - Bremsstrahlung of electrons, and then electron-positron pair creation from gamma rays occur.→Many electrons are created.
- Schein found that primary CRs are protons in 1941.
- By the collision of proton with air nucleus, π mesons are produced and decay.
  - $\pi^{\pm} \rightarrow \mu$(discovered in 1947)
  - $\pi^{0} \rightarrow \gamma$ rays



Air shower



- nuclear cascade shower

nucleus

$$p + A \rightarrow p + \pi^+ + \pi^- + \pi^0 + \ldots,$$

$$\pi^\pm + A \rightarrow \pi^\pm + \pi^+ + \pi^- + \ldots,$$

- electromagnetic shower

$$\pi^0 \rightarrow 2\gamma,$$

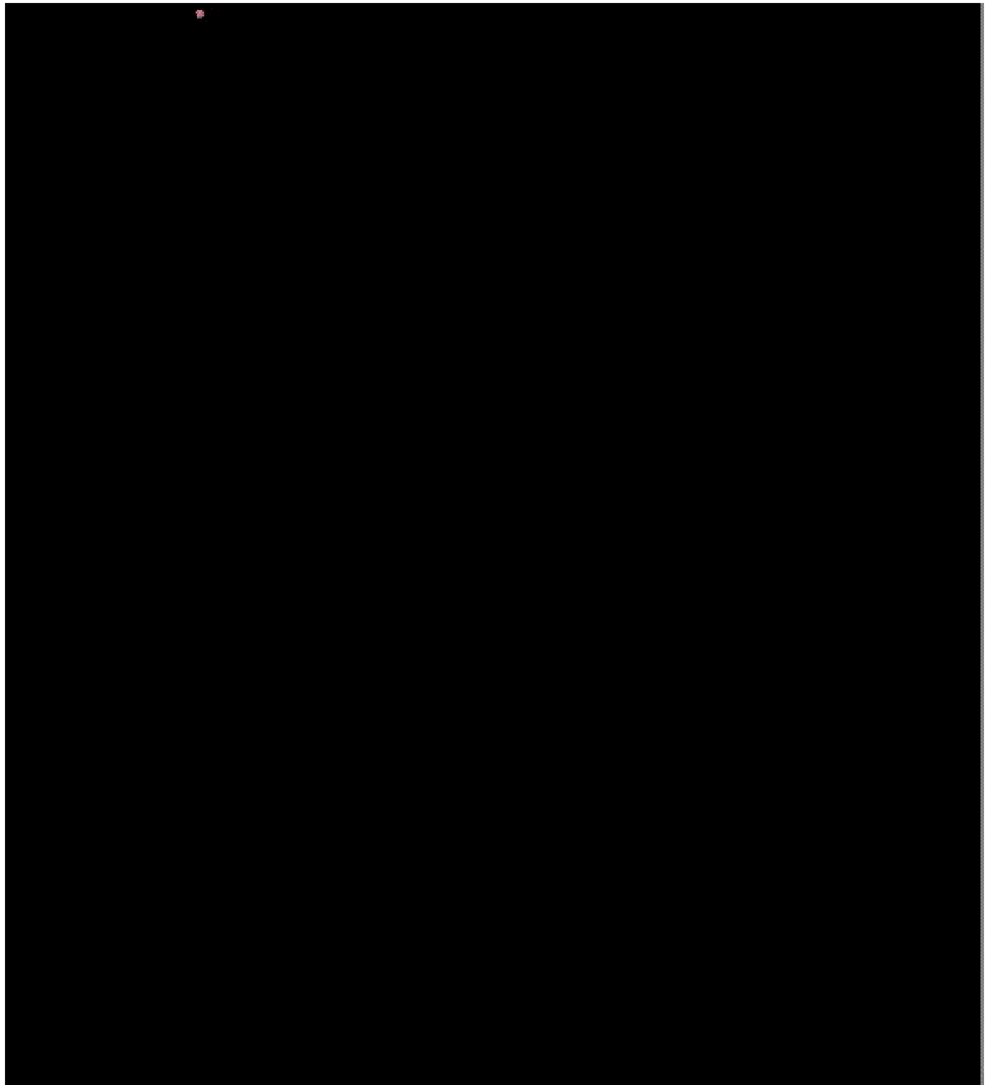
$$\gamma \rightarrow e^+ + e^-,$$

$$e^\pm \rightarrow e^\pm + \gamma$$

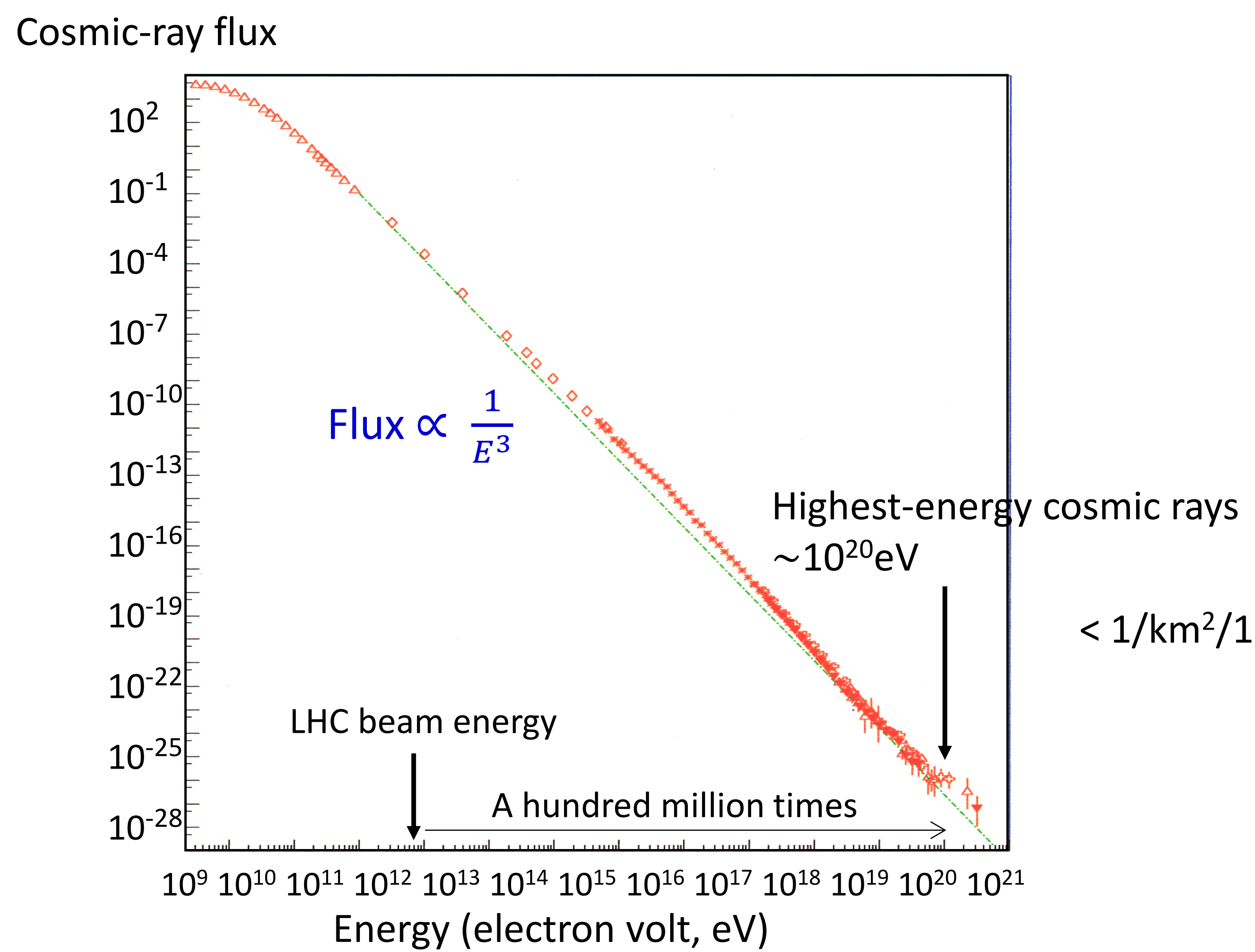
$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu$$

$$\mu^\pm \rightarrow e^\pm + \nu_\mu + \nu_e$$

Air shower simulation



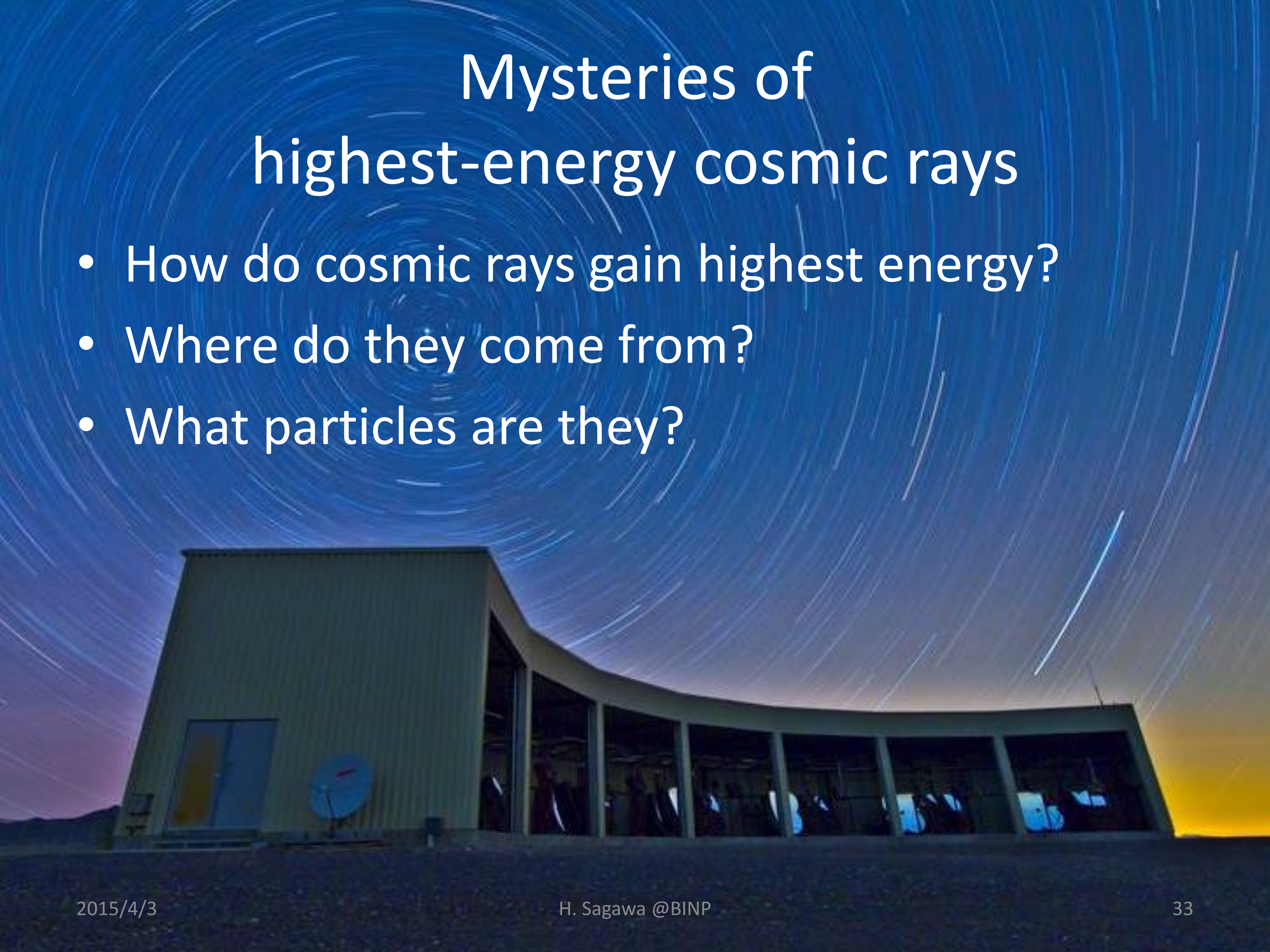
Energy spectrum of cosmic rays



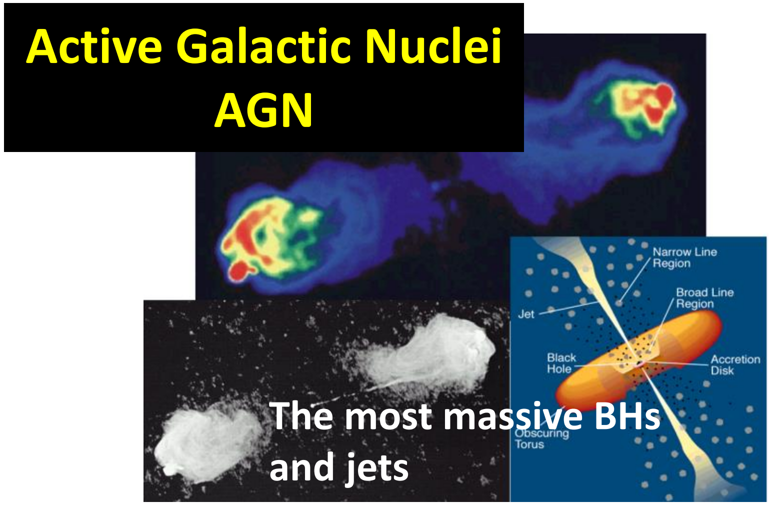
< 1/km²/100years

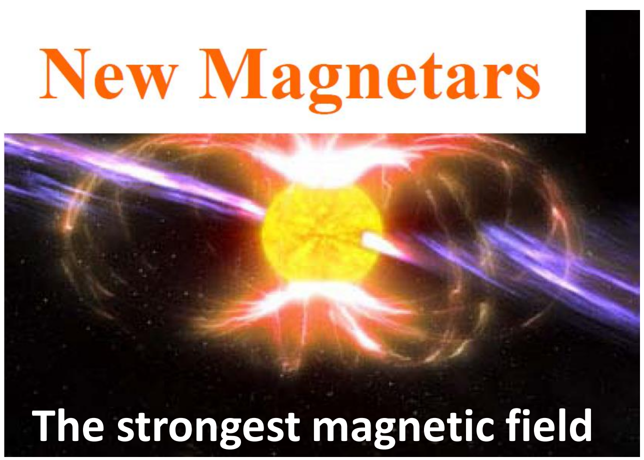
Mysteries of highest-energy cosmic rays

- How do cosmic rays gain highest energy?
- Where do they come from?
- What particles are they?

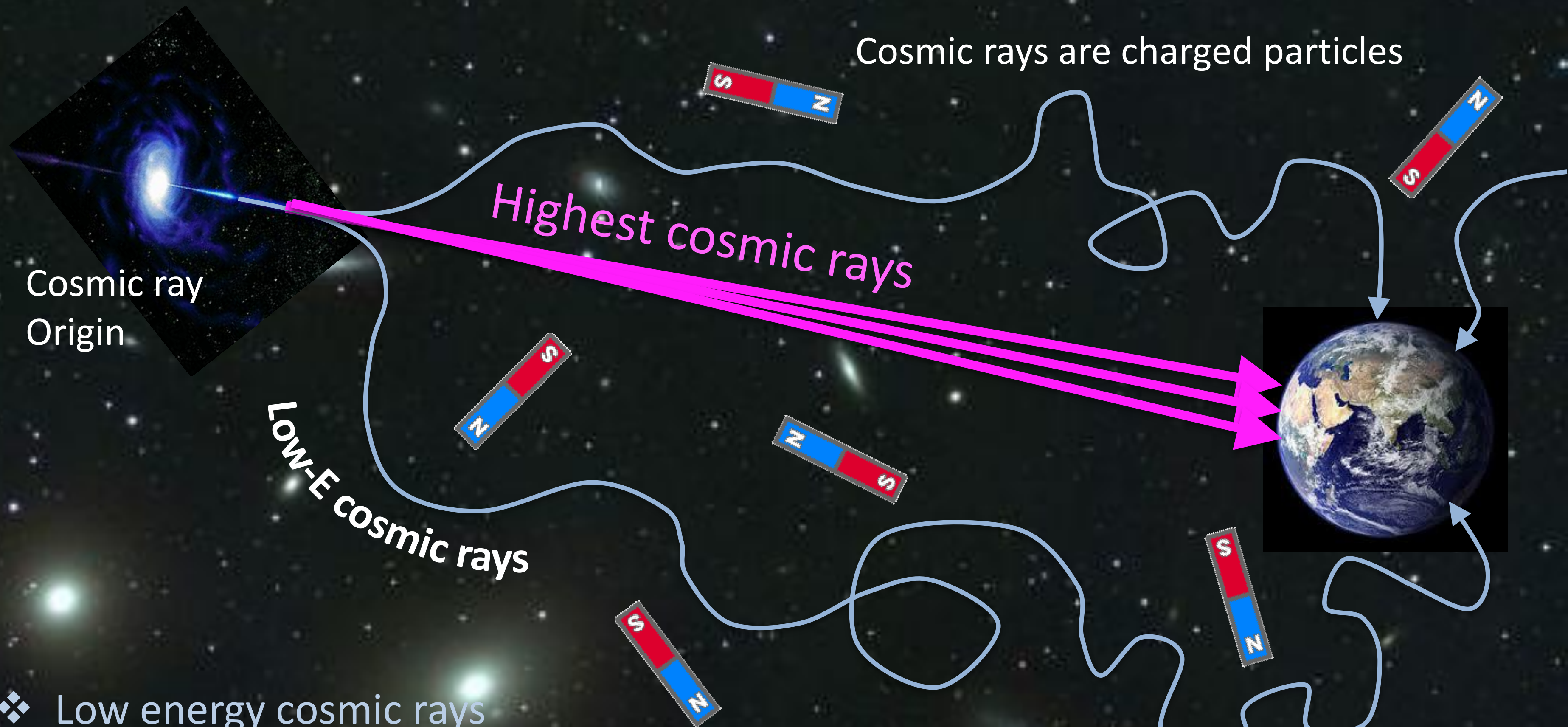


UHE accelerators in the universe
(Candidates of highest-energy CR origin)



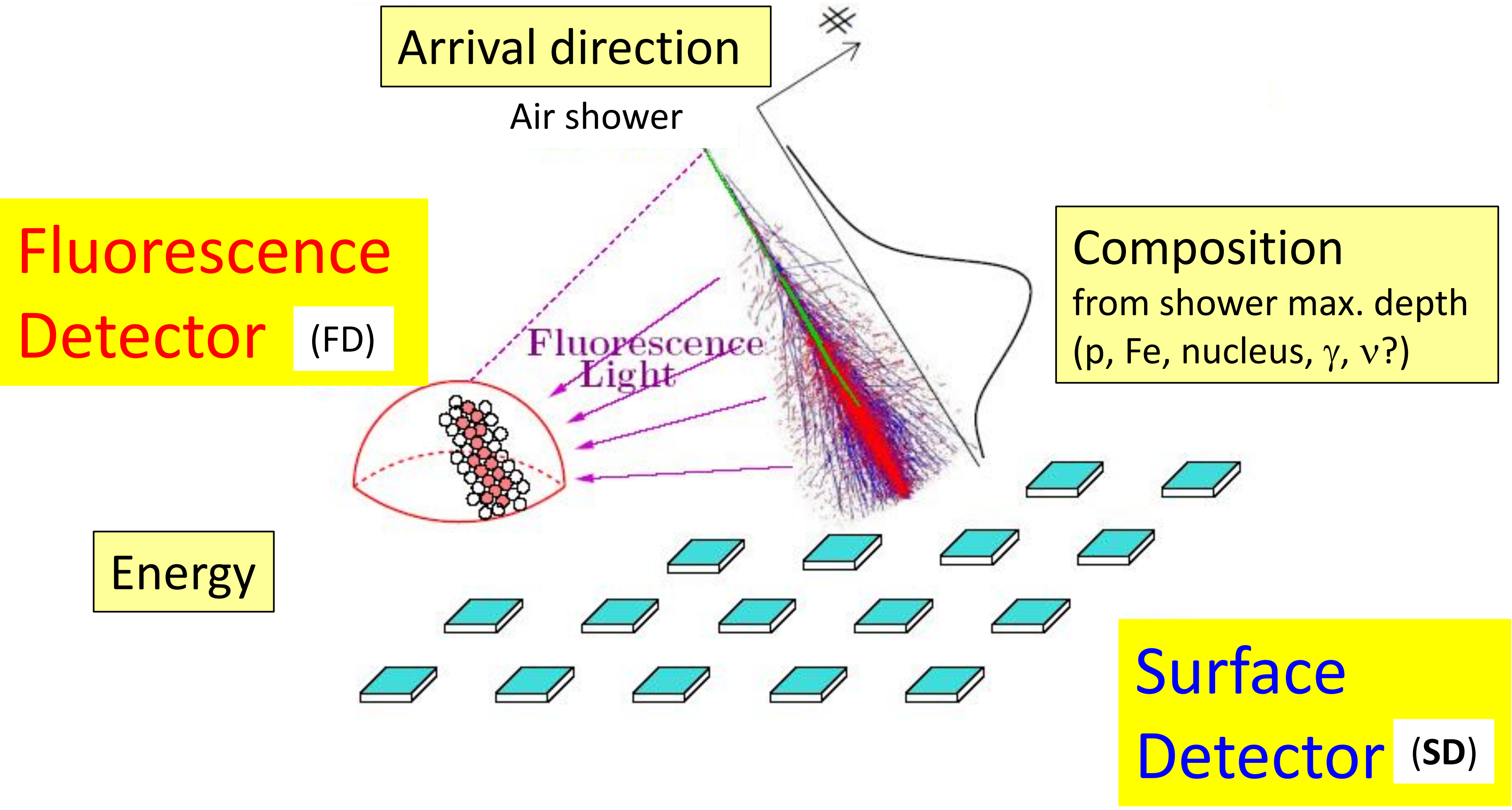


Why highest energy cosmic rays?



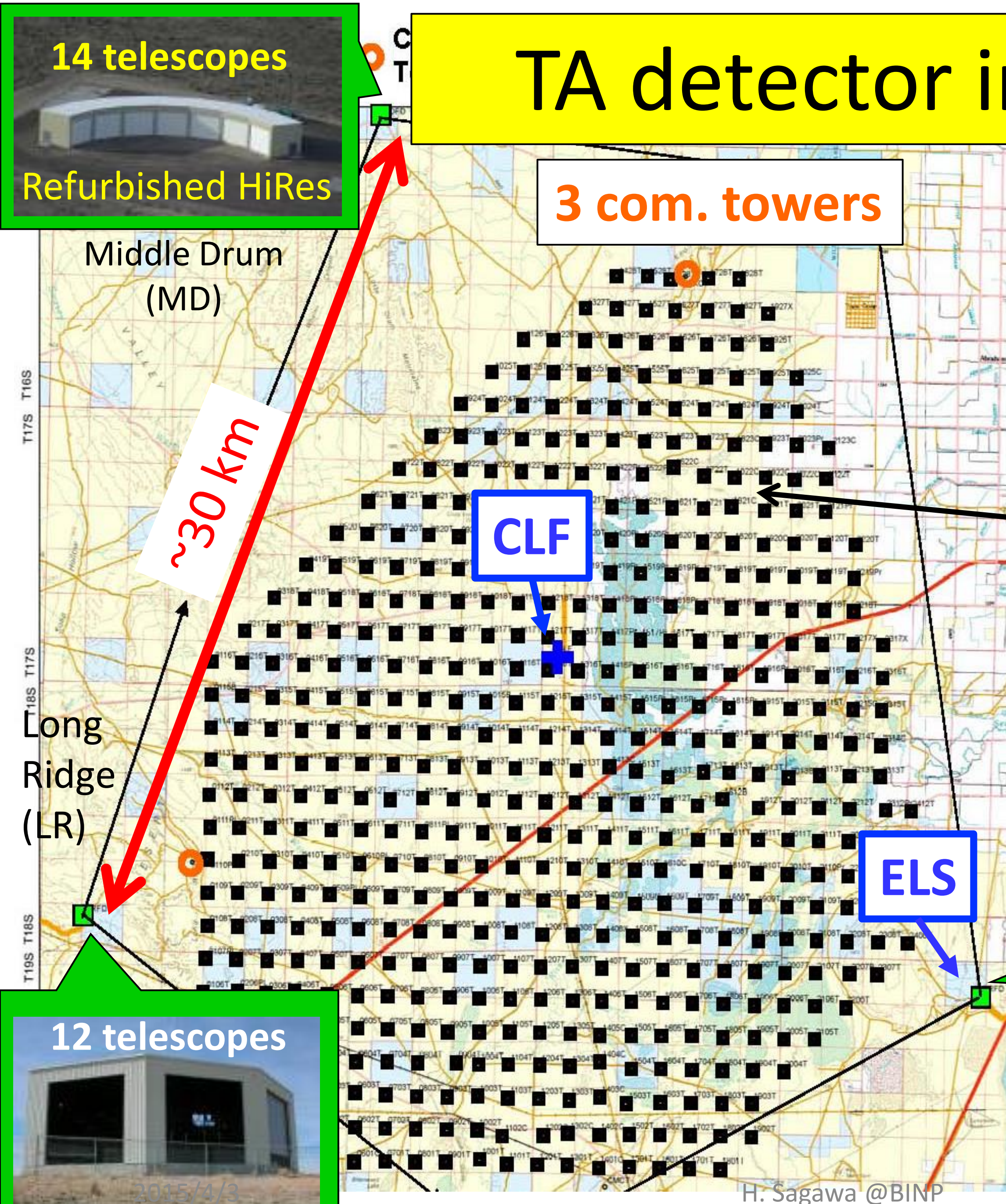
- Low energy cosmic rays
  - → bend by the magnetic field
  - → Isotropy at the Earth
- Highest energy cosmic rays
  - → Almost go straight against magnetic field
  - → Possible to find cosmic-ray hotspot

Detectors of highest energy cosmic rays



TA detector in Utah

39.3°N, 112.9°W
~1400 m a.s.l.



Surface Detector (SD)

507 plastic scintillator SDs

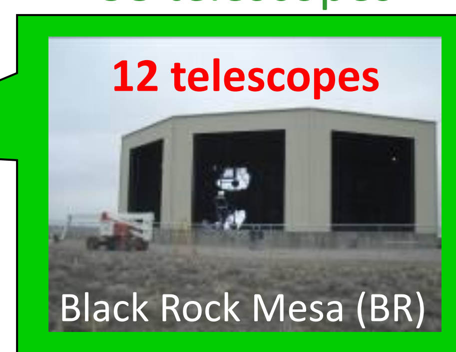
1.2 km spacing

~700 km²

Fluorescence Detector(FD)

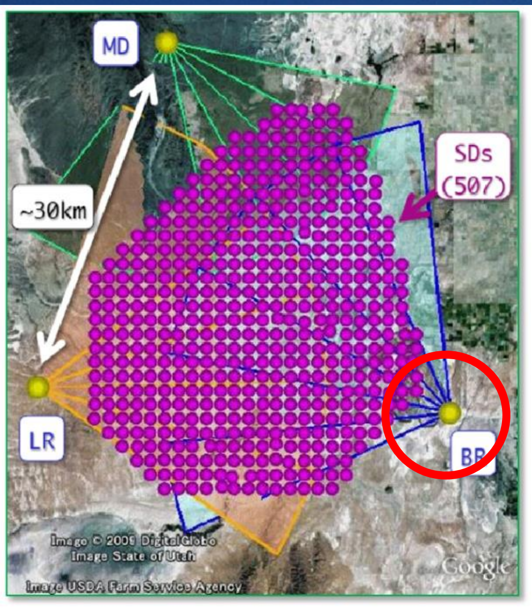
3 stations

38 telescopes



FD and SD: fully operational since 2008/May

Fluorescence Detector stations

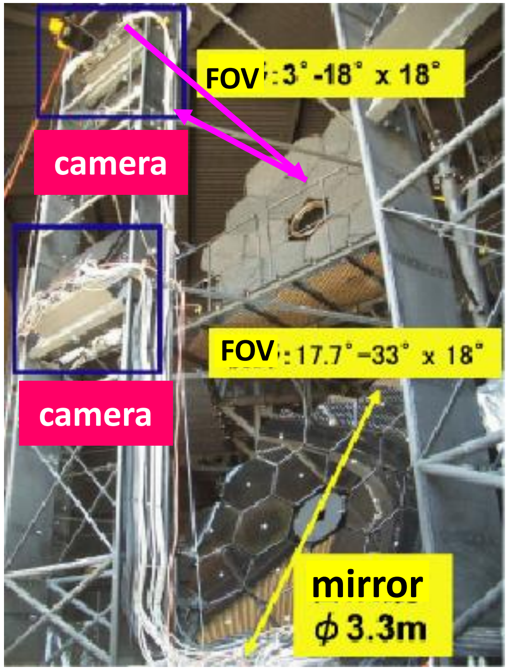


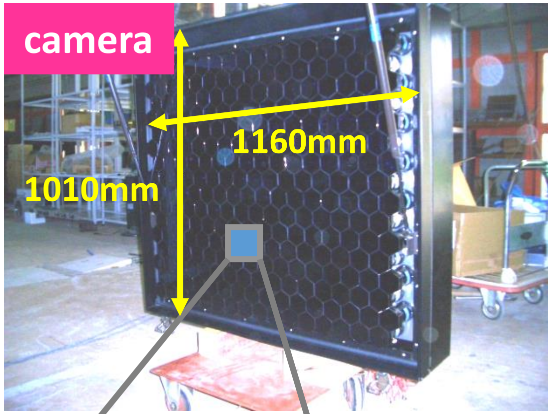
Field of View
3 – 33^{o} in zenith
108^{o} in azimuth

Observation
moonless, clear night
duty cycle ~10%

All three stations: observation since Nov., 2007

FD: mirrors & cameras



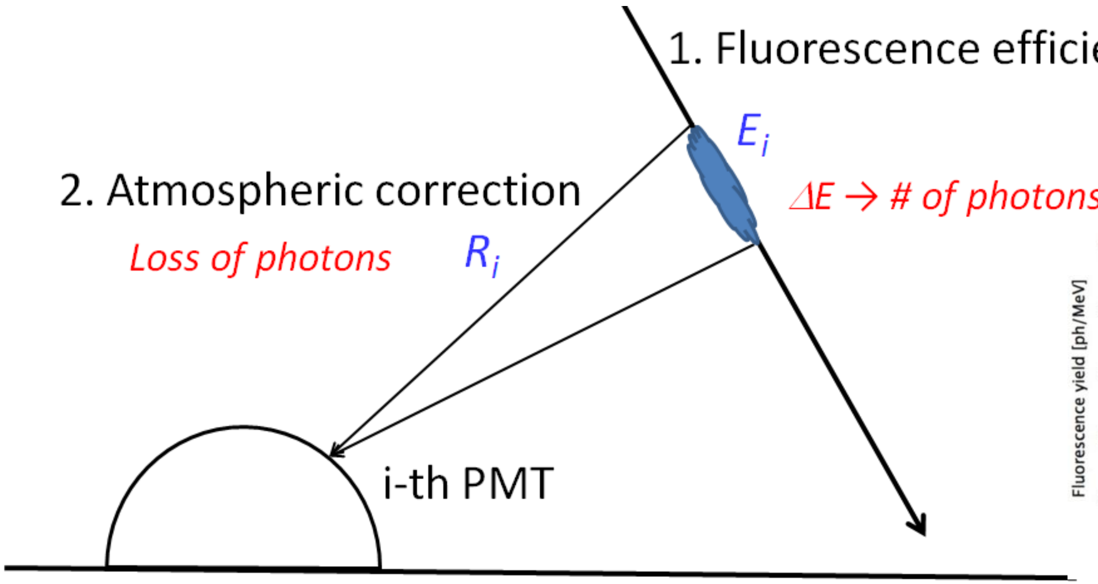


256PMTs

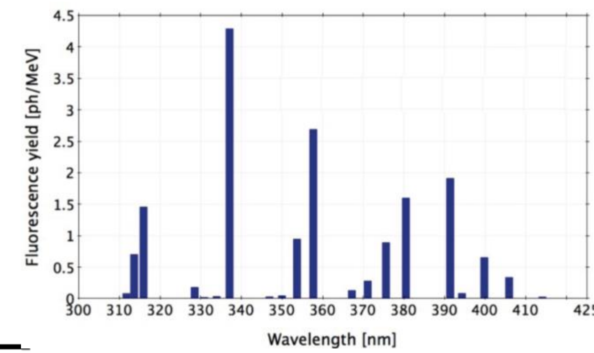
Hexagonal PMT

~1º FOV/PMT

FD as an absorption calorimeter

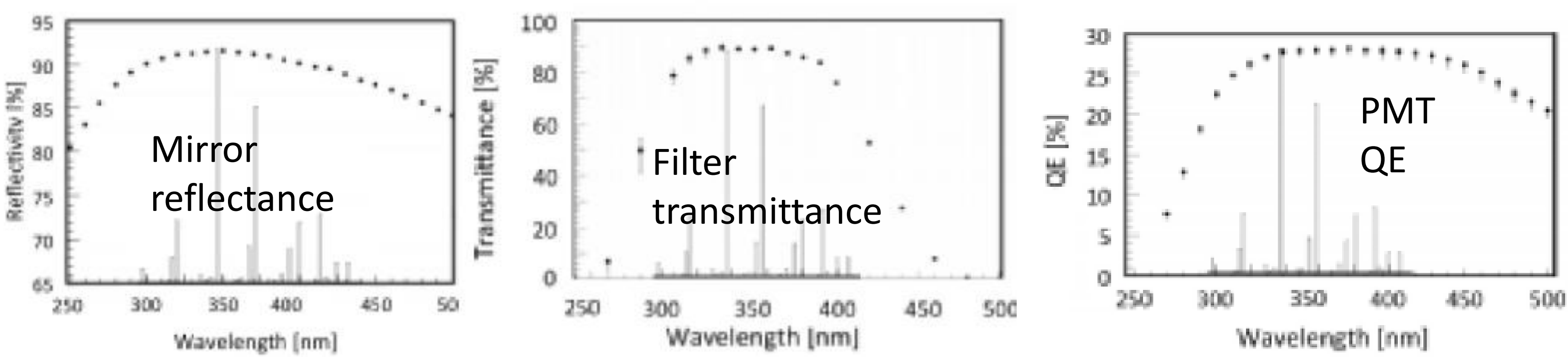


Fluorescence yield



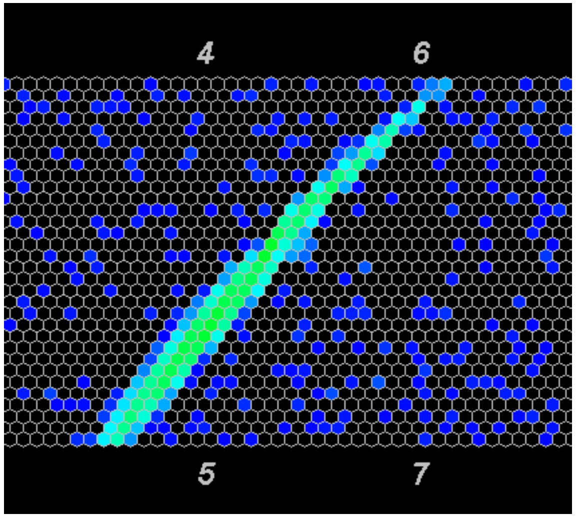
3. Telescope calibration

# of photons → ADC channels

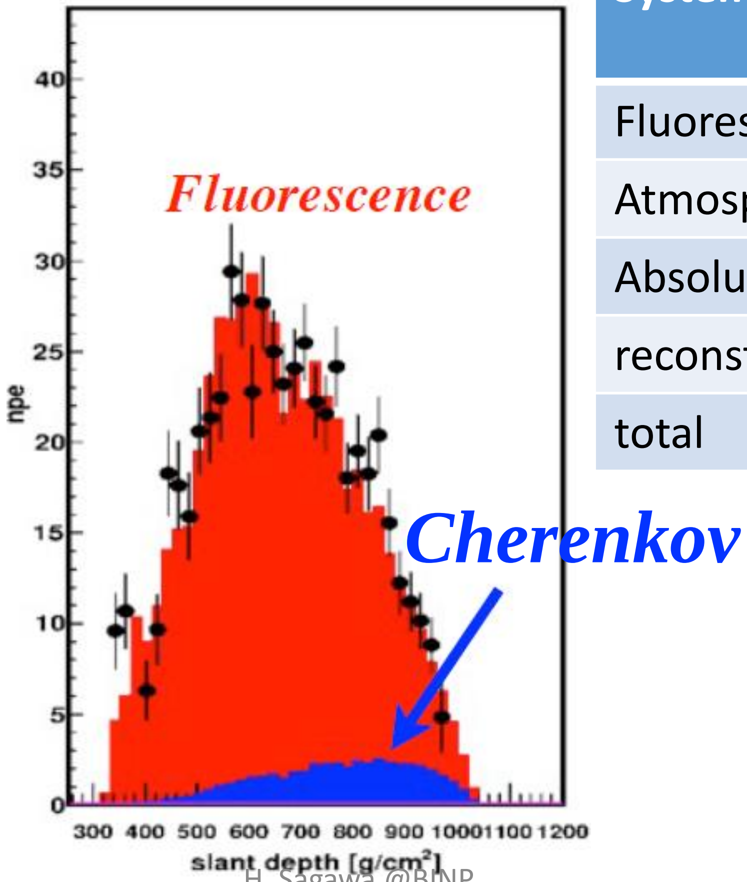


TA shower analysis with FD

An example of an air shower
the camera view

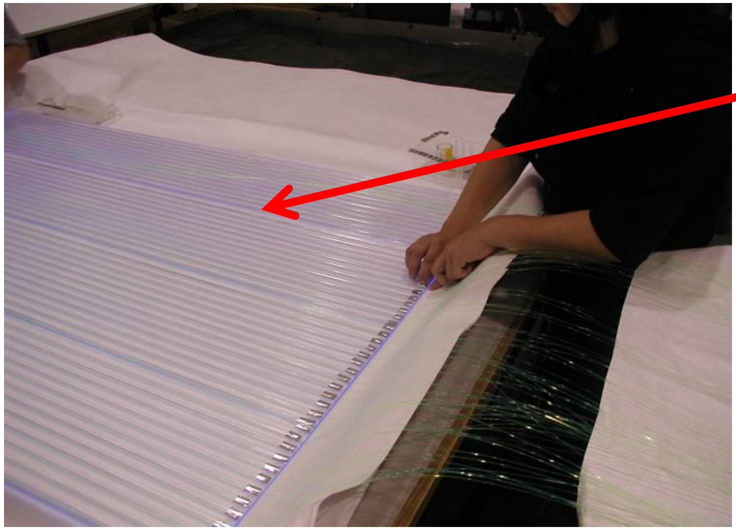


Longitudinal shower profile



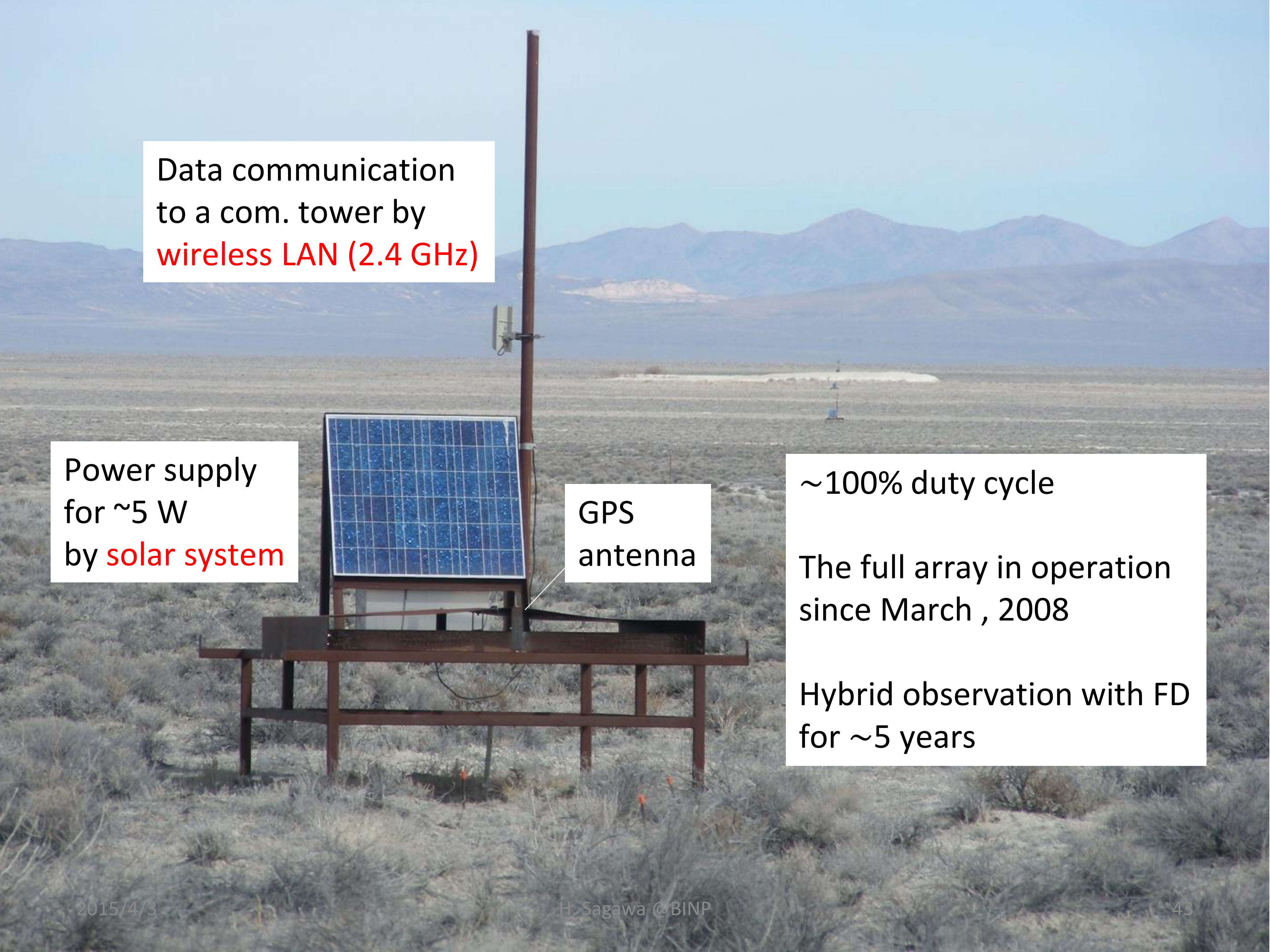
Systematic uncertainty in energy determination	
Fluorescence yeild	11%
Atmospheric attenuation	11%
Absolute detector calib.	10%
reconstruction	10%
total	21%

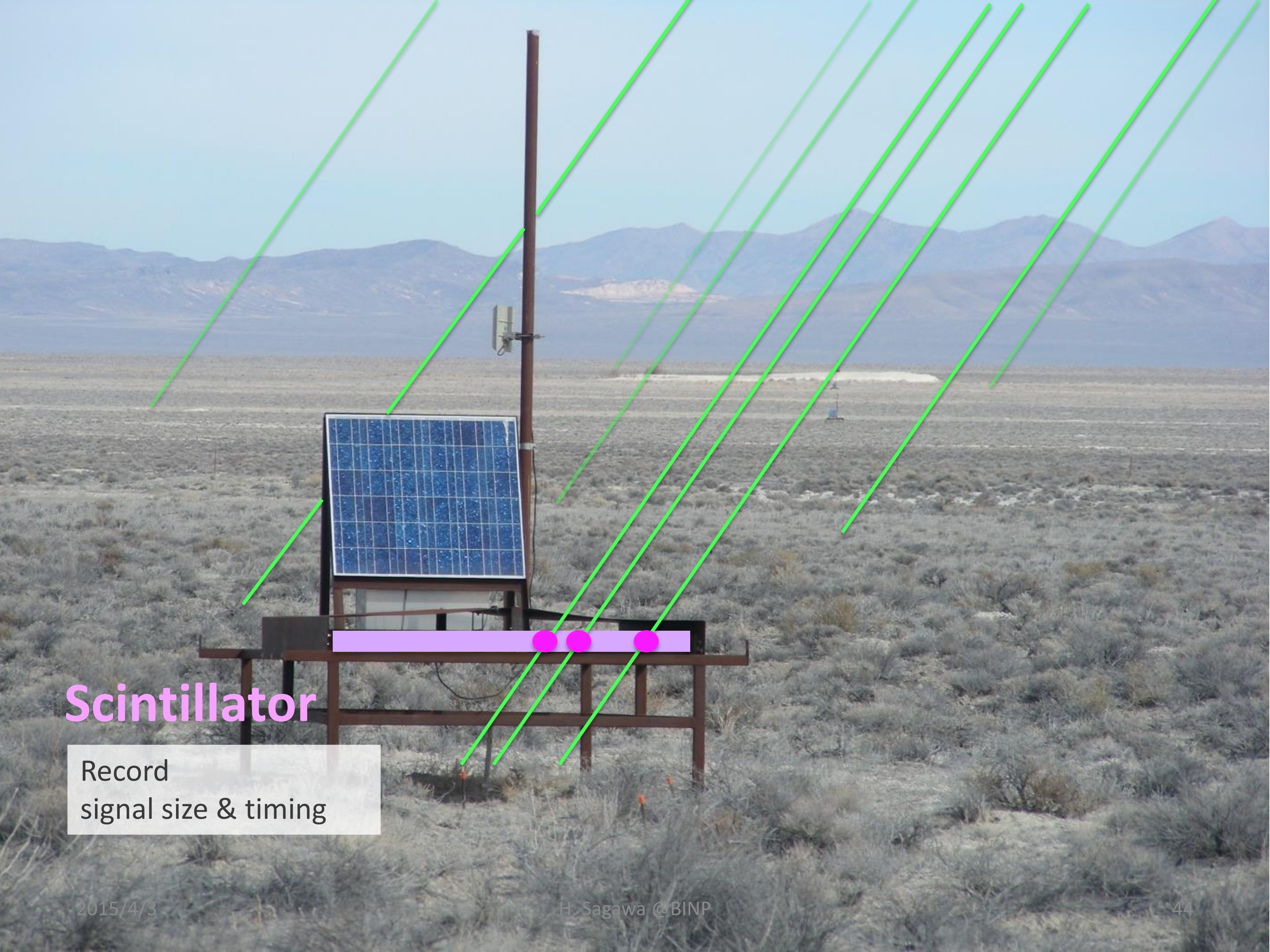
Surface Detector (SD)



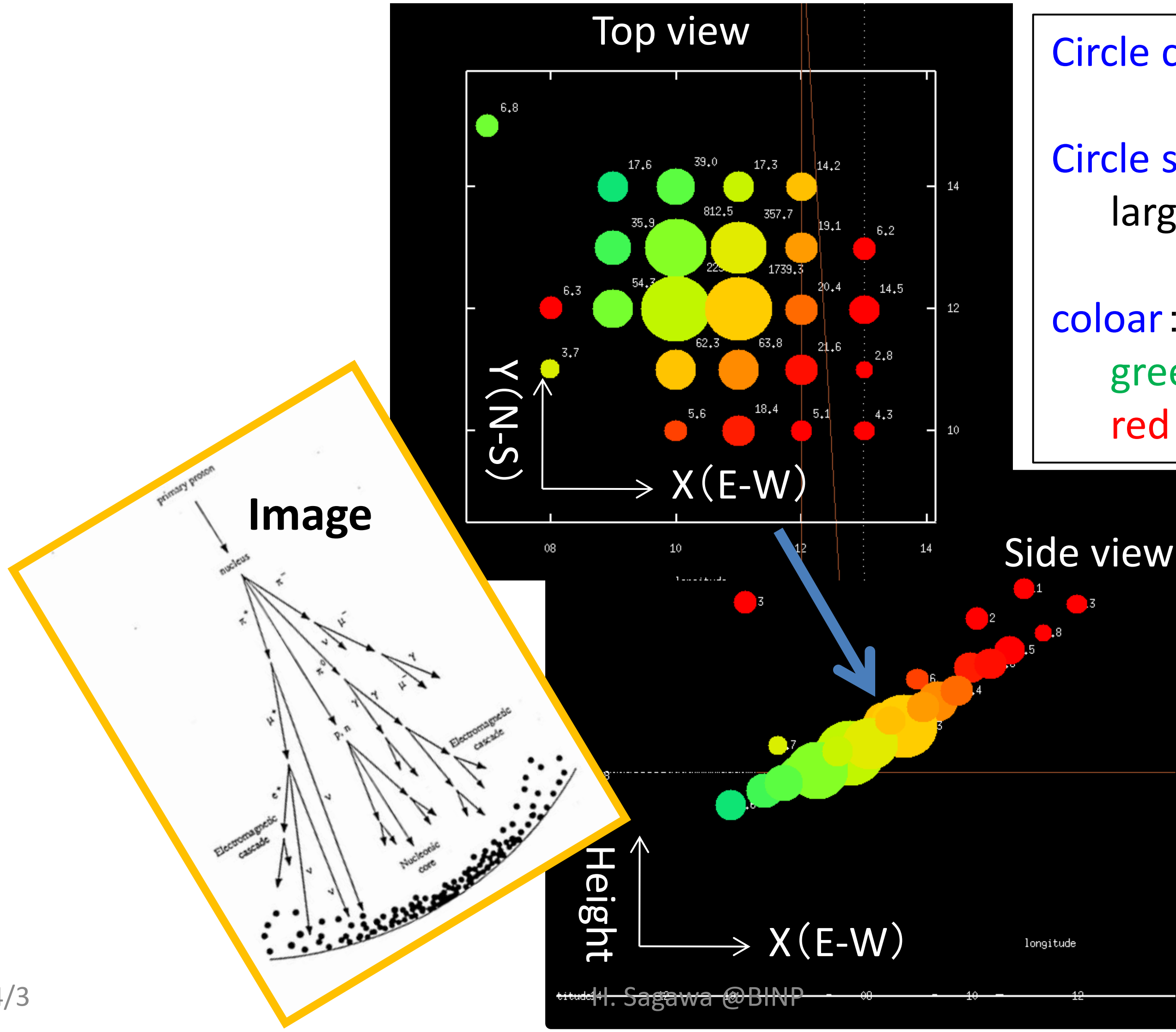
WLS fibers

- 2 layers of
  plastic scintillator
  - 3 m^2 /layer
  - 1.2 cm thick/layer
- WLS fibers
  - 1 mm ϕ
  - ~100 fibers/layer
- 1 PMT for 1 layer
  - 1-inch ϕ
- 50 MHz FADC readout


Data communication to a com. tower by wireless LAN (2.4 GHz)
Power supply for ~5 W by solar system
GPS antenna
∼100% duty cycle
The full array in operation since March , 2008
Hybrid observation with FD for ∼5 years


Scintillator
Record
signal size & timing

Example of air shower by TA SD



Circle center : SD position

Circle size :
larger size → larger signal

coloar : particle arrival time
green : early
red : late

The Telescope Array Collaboration

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M. Fukushima[8,9], T. Goto[10], W. Hanlon[1], Y. Hayashi[10], N. Hayashida[11], K. Hibino[11], K. Honda[12], D. Ikeda[8],
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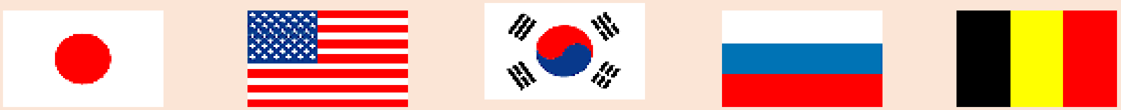
S. Tro … mane[10],
H. Yamaoka[20], K. Yamazaki[10], J. Yang[3], K. Yashiro[5], Y. Yoneda[10], S. Yoshida[19], H. Yoshii[30], R. Zollinger[1], Z. Zundel[1]

~120 collaborators from 30 institutes in 5 countries

Japan, USA, Korea, Russia, Belgium

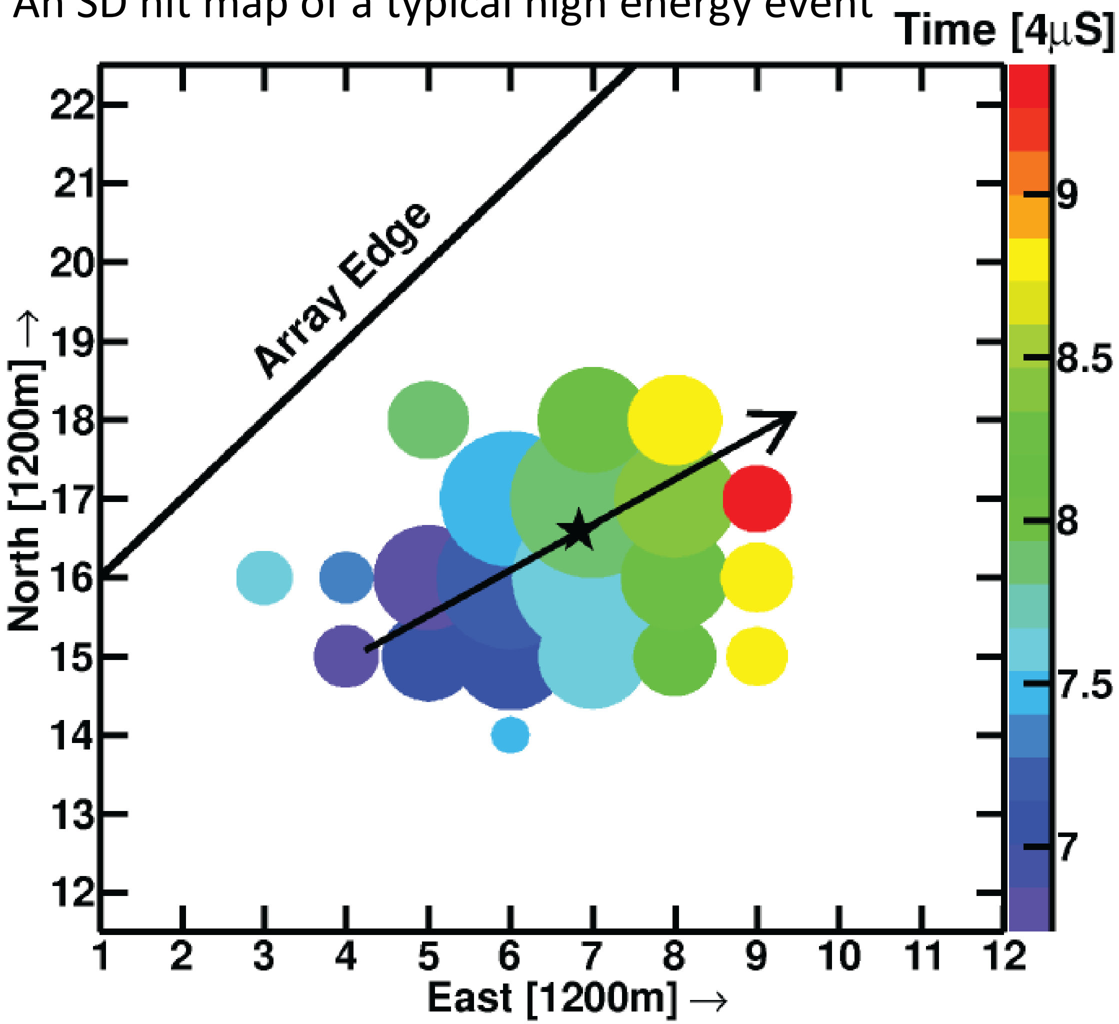


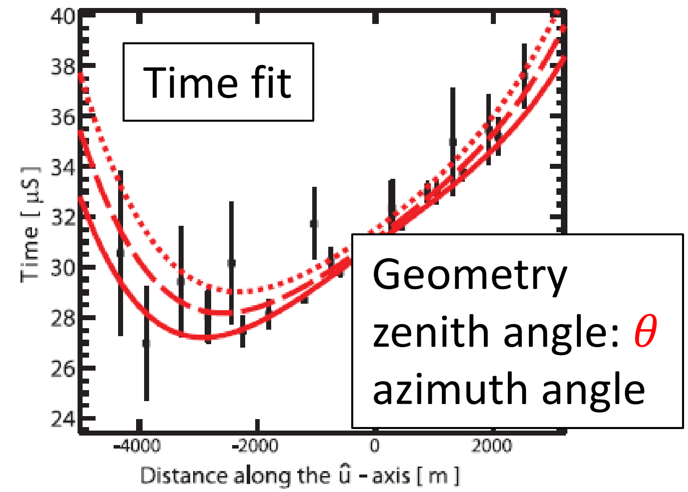
1 University of Utah 2 Tokyo Institute of Technology 3 Ewha Womans University 4 Hanyang University
5 Tokyo University of Science 6 Kinki University 7 Yonsei University 8 ICRR, University of Tokyo
9 IPMU, the University of Tokyo 10 Osaka City University 11 Kanagawa University 12 University of Yamanashi
13 Saitama University 14 Astrophysical Big Bang Laboratory RIKEN, Wako 15 Rutgers University
16 Tokyo City University17 INR of the Russian Academy of Sciences 18 Waseda University
19 Chiba University 20 KEK 21 Kochi University 22 Ritsumeikan University 23 Sungkyunkwan University
24 Universite de Libre de Bruxelles 25 Ulsan National Institute of Science and Technology
26 ERI, University of Tokyo 27 Hiroshima City University 28 Advanced Science Institute, RIKEN
29 National Institute of Radiological Science 30 Ehime University

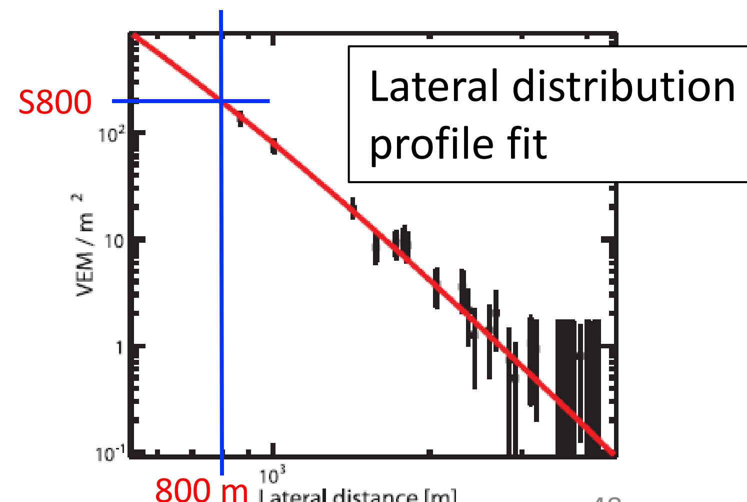
Energy spectrum

TA shower analysis with SD

An SD hit map of a typical high energy event

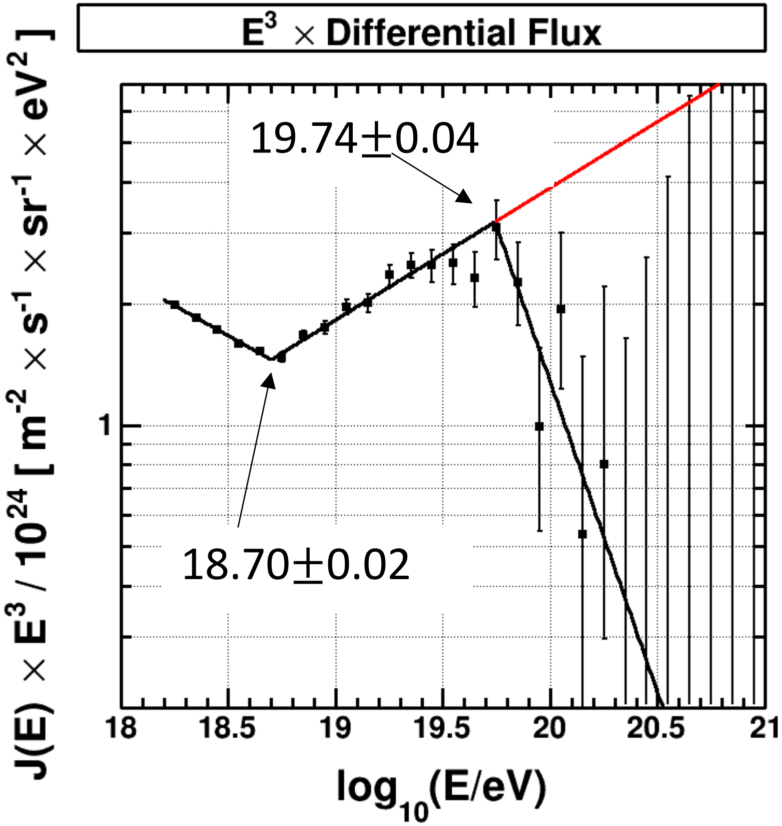






TA energy spectrum

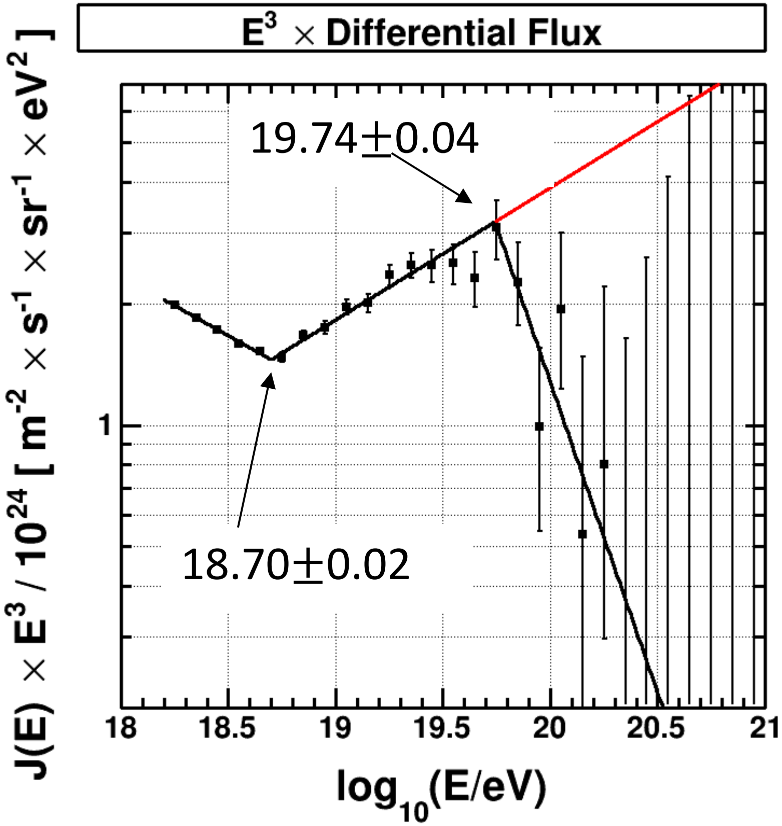
- SD data：2008/May～2014/May (6 years)



What can be these two breaks?

TA energy spectrum

- SD data：2008/May～2014/May (6 years)

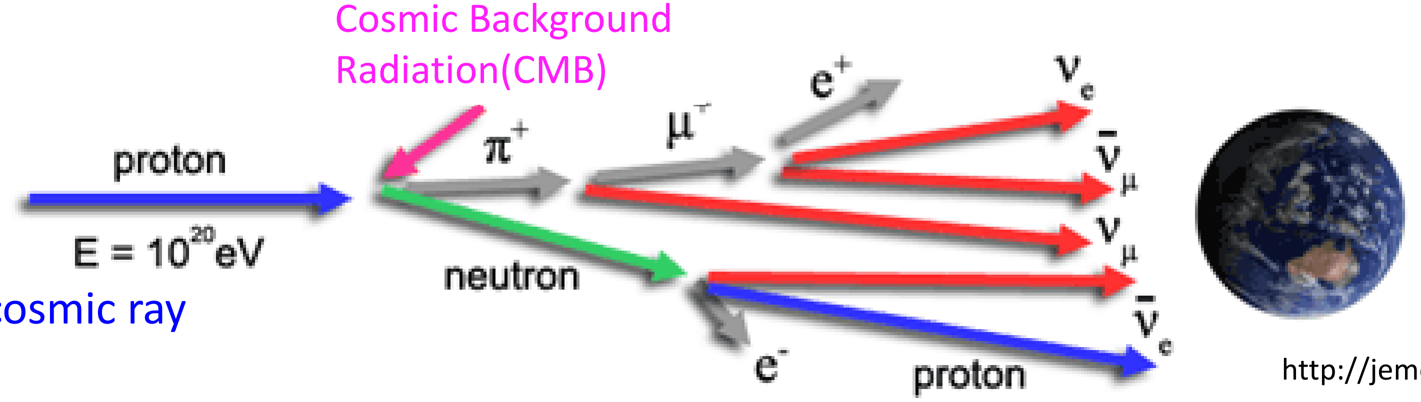


ankle
Cutoff consistent with GZK cutoff

$E > 10^{19.8}$eV
Expected (no cutoff) = 85.93
observed = 32
Cutoff chance prob. = 6.59σ

Distance to the Origin

Advantage of highest-E cosmic ray (>5.7×10^{19}eV)



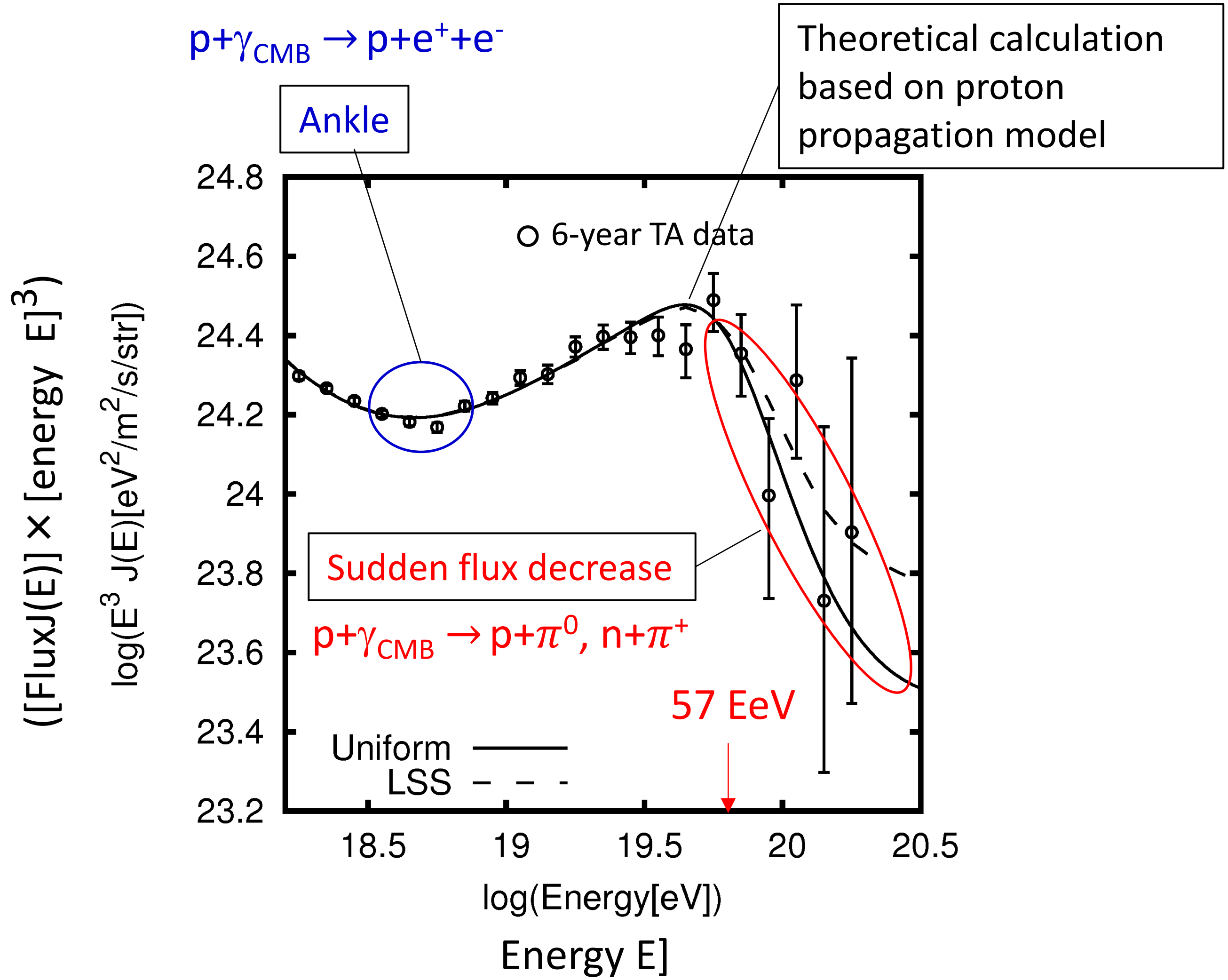
http://jemeuso.riken.jp

<u>Highest energy region</u> (Size of Universe: ~14000 million light years)

❖ Highest-E cosmic rays come beyond 150 million light years (ly) rapidly loss their energy by interaction with the cosmic microwave background (relic radiation of the Big Bang). → GZK limit

Highest-E cosmic rays can not reach the Earth from the distant universe. Therefore, Origin of cosmic rays should be limited to local universe.

TA energy spectrum at highest energy region



1 EeV = 10^{18}eV

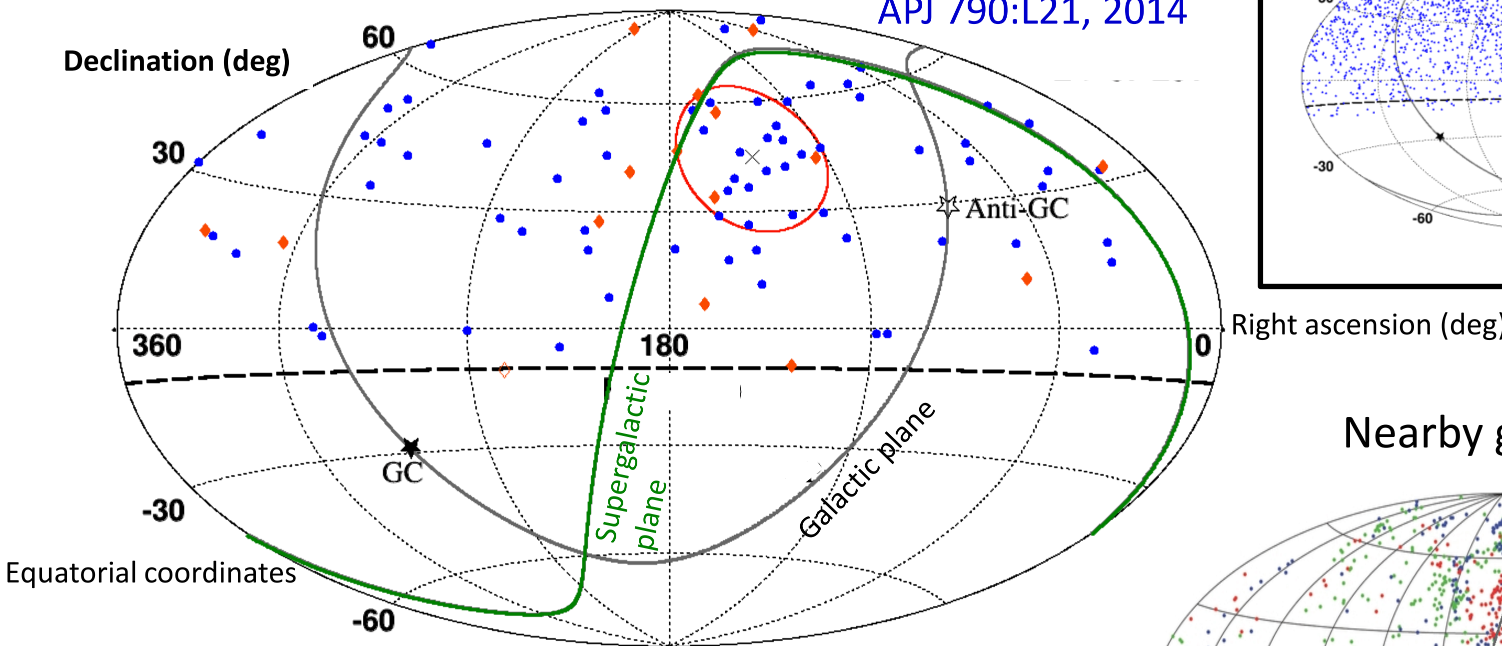
Anisotropy

TA 5-year SD data

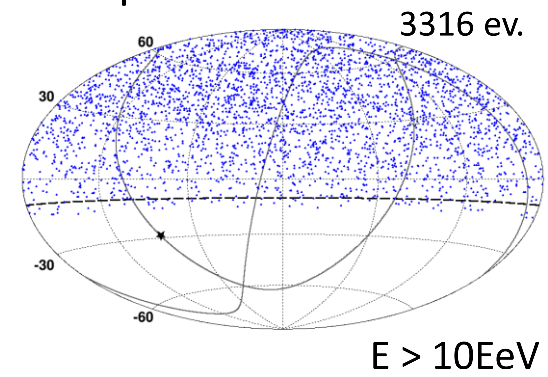
Arrival directions of highest-energy cosmic rays

- 6-year TA SD data
- 87 events (E > 57EeV)

Blue points：
5-year data
APJ 790:L21, 2014



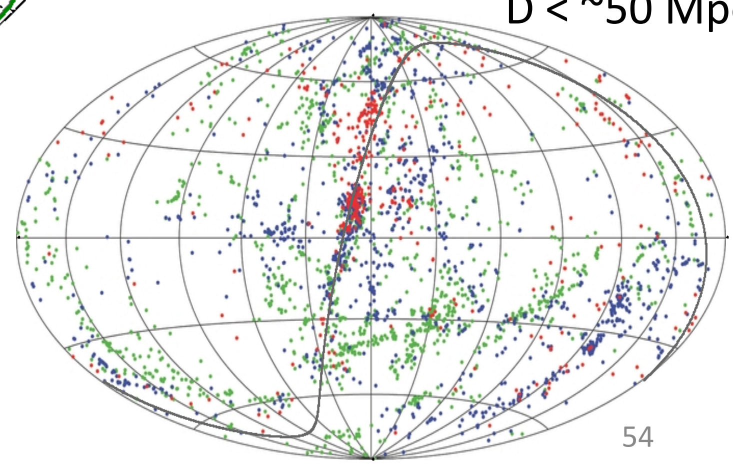
Events of ~10^{19}eV (10EeV)
Isotropic



- In the red circle with 20-deg. Radius
  - Expectation from isotropic distribution：5.5
  - observation：23

    23/5.5: ~400% flux excess

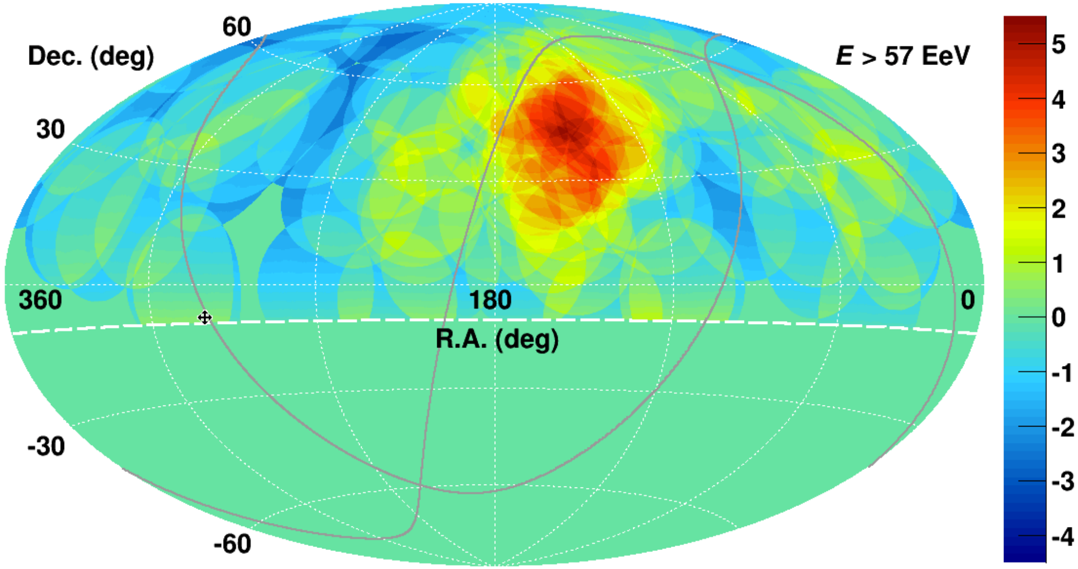
Nearby galacies
D < ~50 Mpc



Anisotropy of arrival directions of highest-energy cosmic rays (TA hotspot)

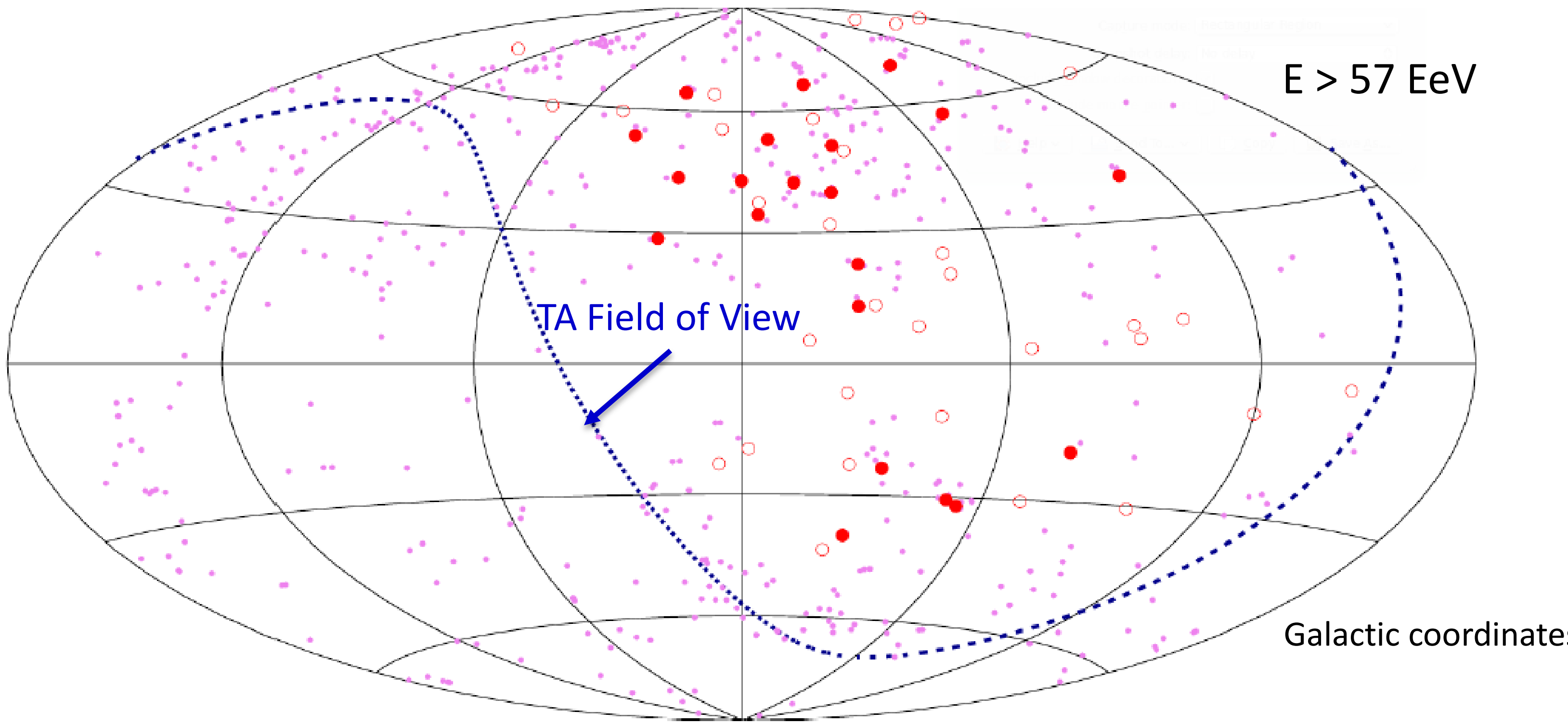
Anisotropy significance map

Maximum significance 5.55σ



- Chance probability to obtain maximum significance greater than 5.5σ was $\sim 3\times10^{-5}$ (4σ)
- Large anisotropy of cosmic rays was first found above the cutoff energy

Correlation of cosmic rays above 57 EeV with Active Galactic Nuclei （AGN）



- AGN ($z < 0.018$)
- No. of TA events correlated with AGNs within 3.1 deg. (21) 40%

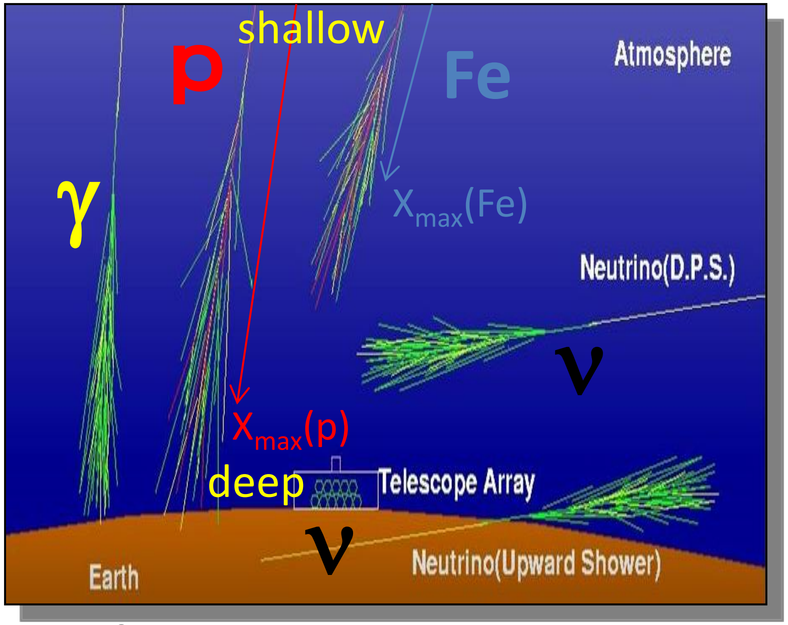
  Background (isotropy) (12.5) 24%

  P-value 0.7% (2.7σ)
- TA events without correlation (32)

Mass Composition

Nuclear interaction

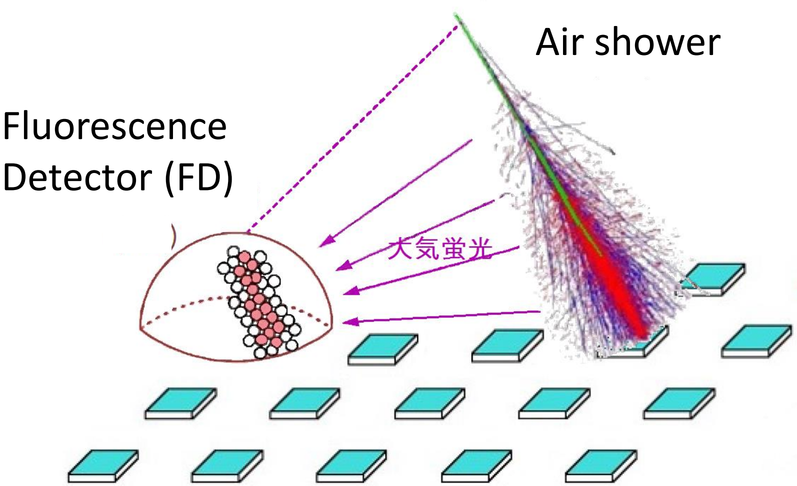
- A: mass number of incident nucleus
- Nuclear radius: r
  - $r \propto A^{1/3}$
- Cross section: σ
  - $\sigma \propto A^{2/3}$
- Mean free path: λ
  - $\lambda \propto A^{-2/3}$
- Interaction depth vs. heavy nuclei
  - Shallower for heavier composition

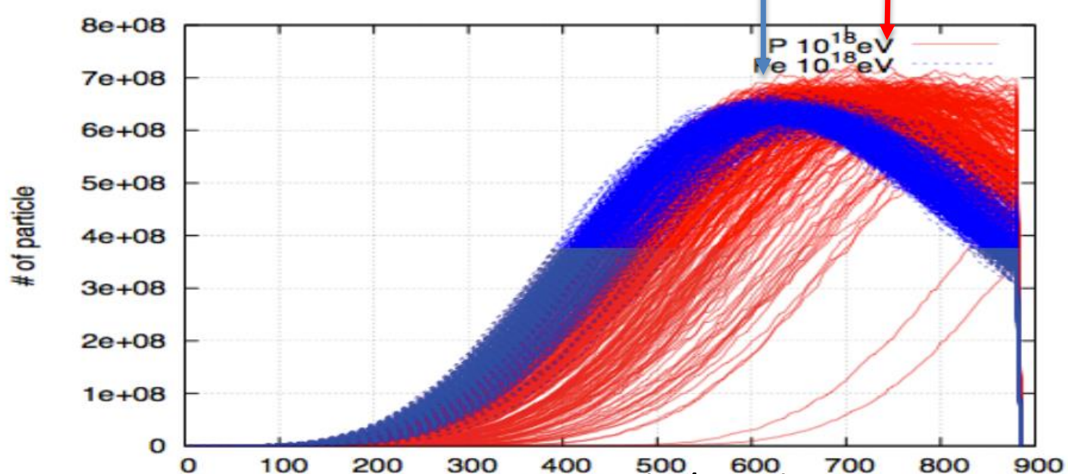


Mass composition

Shower maximum depth Xmax

iron proton



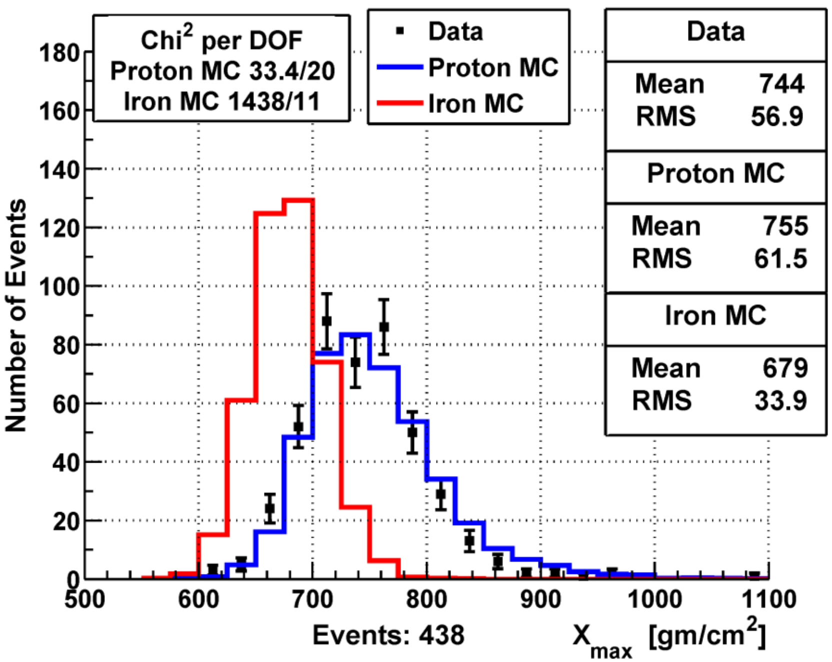


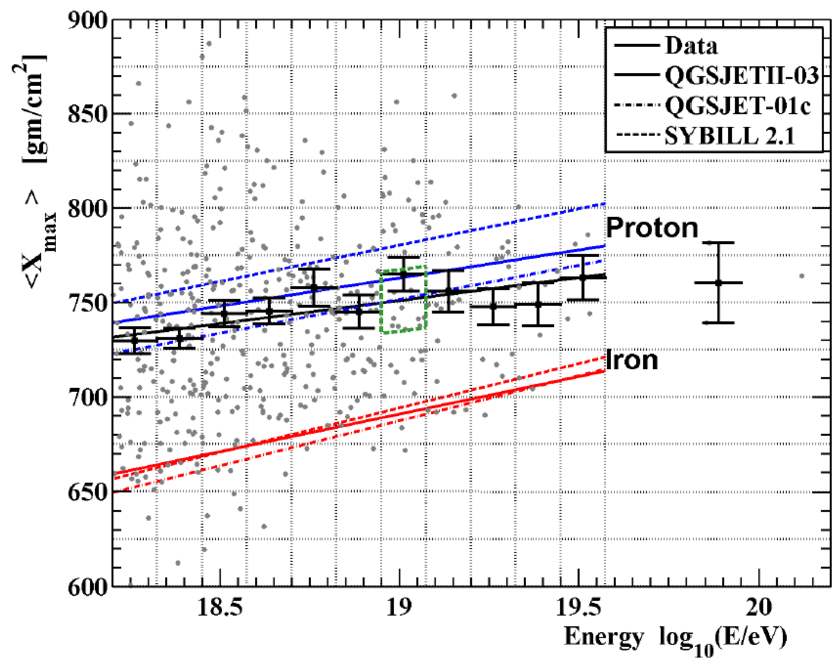
Shower depth (g/cm2)

Shower profile depends on mass composition

Mass composition using Xmax

Black points: TA data; MC: bule for proton, red for Fe





Consistent with light composition (predominantly proton)
Statistics is not enough at around the cutoff energy

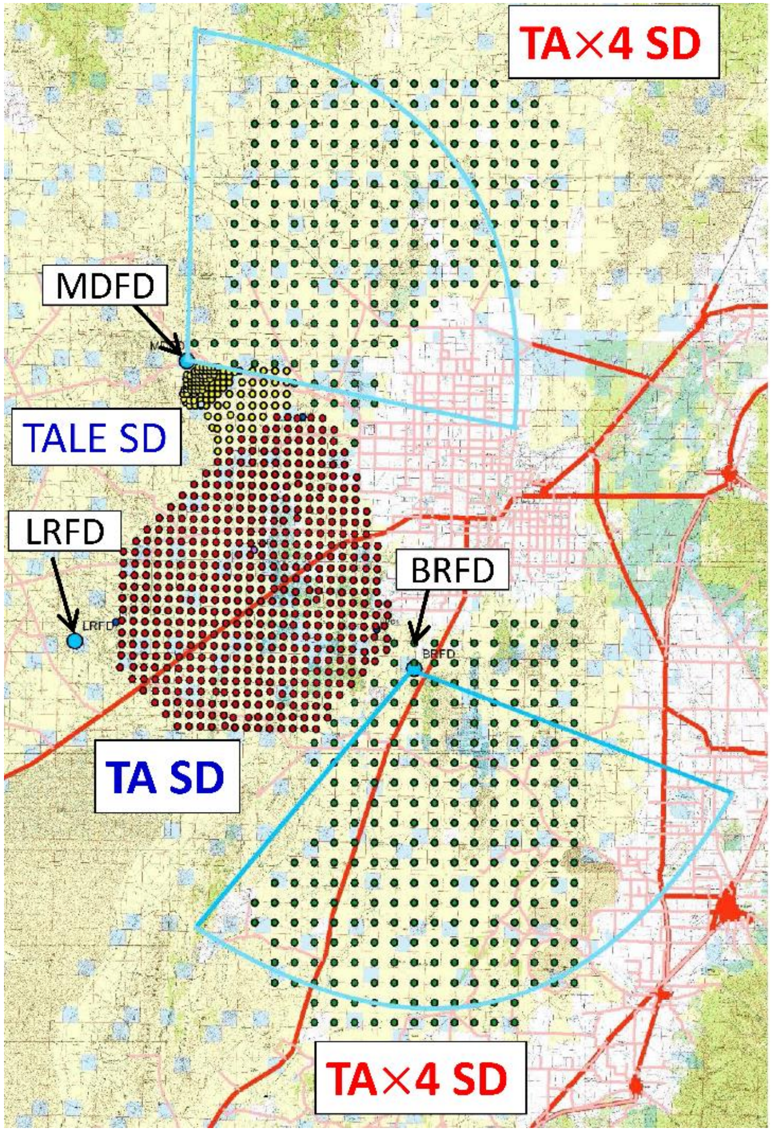
TA extension plans

- TAx4: quadruple aperture extension for highest energy cosmic rays
- TALE: TA low energy extension down to $10^{16.5}$eV

TA×4 proposal

- Quadrule TA SD (~3000 km^2)
  - **500** scintillator SDs
    2.1 km spacing (**Japan**)
- **2** FD stations each with 10 refurbished HiRes telescopes (US)

- Apply grants this fall (Japan, US)
- 2-year construction
- 3-year observation
  - **TA SD: 21 year** data
  - TA hybrid: **18** year data

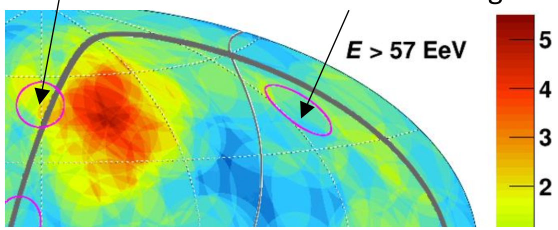


Subjects of anisotropy studies

1） Significance for TA 6-year data (2014)

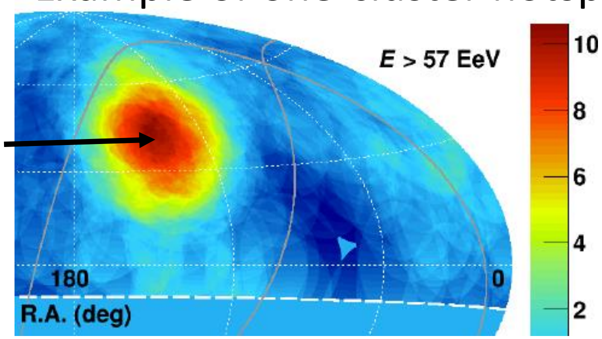
Ursa Major Cluster of galaxies

Perseus Cluster of galaxies



2） Example of one-cluster hotspot (2020)

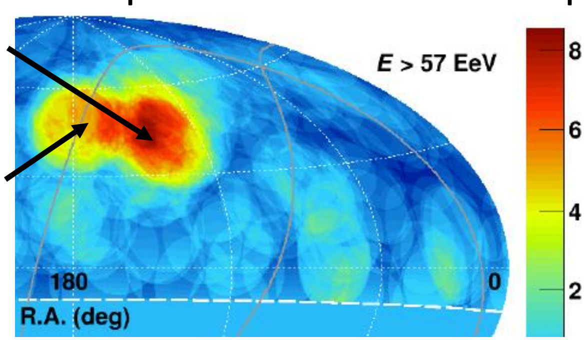
~10σ



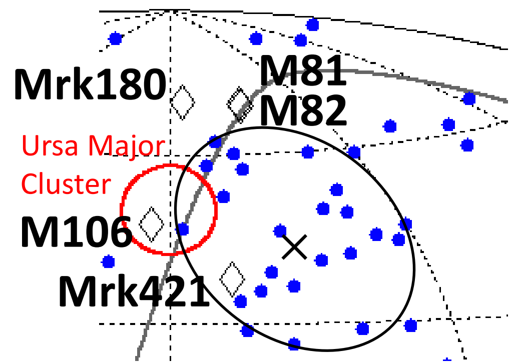
3） Example of two-cluster hotspot(2020)

~8σ

~5σ



- Hotspot source has not been found



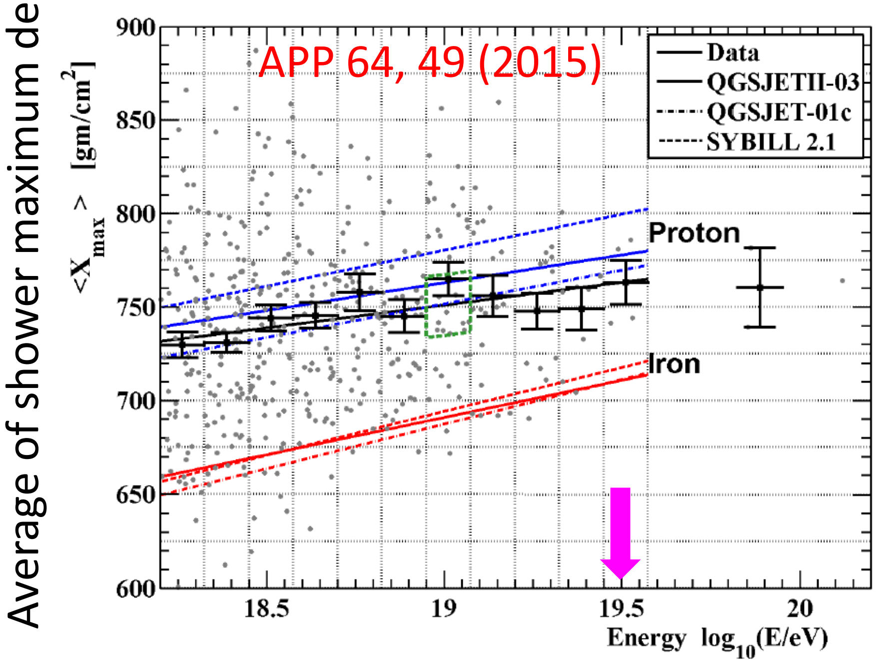
Prominent Active Galactic Nuclei near Hotspot

- Hotspot center is near supergalactic plane, but is shifted by 17 degrees
  - Expected to know the relation to magnetic field of the universe
- Analysis of correlations with gamma-ray sources and neutrinos: joint research with gamma-ray observatories and neutrino observatories
  - The joint research between TA, Auger, and IceCube started

Mass composition

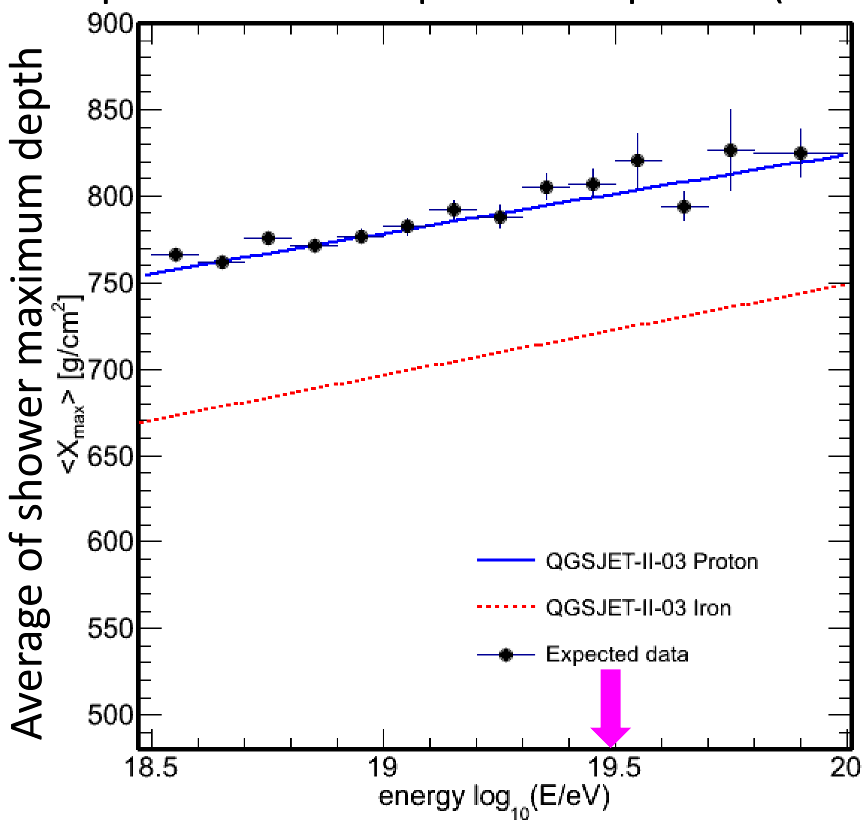
- Generation, acceleration, propagation of cosmic rays
  - The length of interaction with CMB photons depends on composition
  - Little charge for lighter composition → smaller effect on magnetic field of the universe → more difficult to be accelerated

black points: TA 5-year hybrid data
Simulation: blue (proton), red (iron)



Consistent with light composition (predominantly proton)
Number of events around the cutoff is not enough

Expectation if composition is proton (2020)



Analysis of mass composition near and above the cutoff

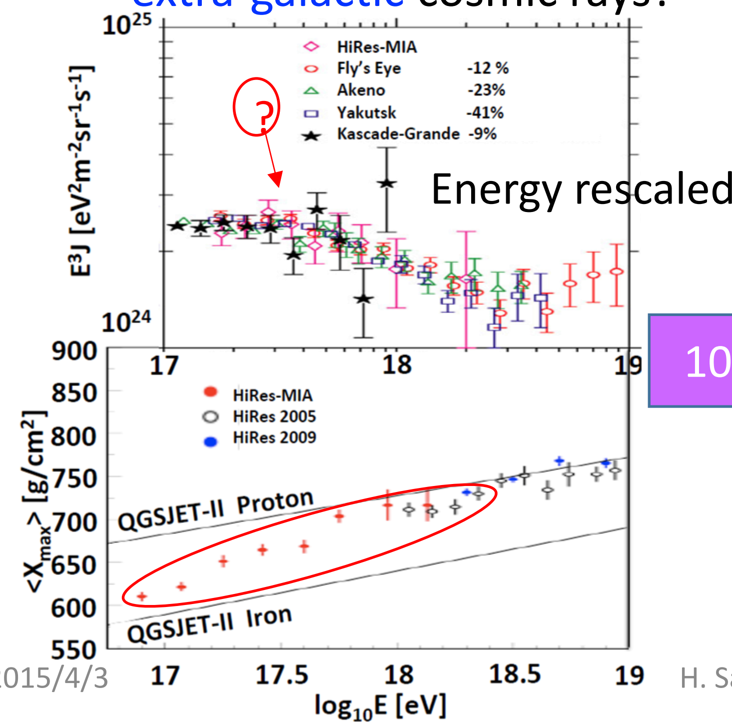
TALE (TA Low-energy Extension) down to $10^{16.5}$ eV

ICRC2013 Oral, 717

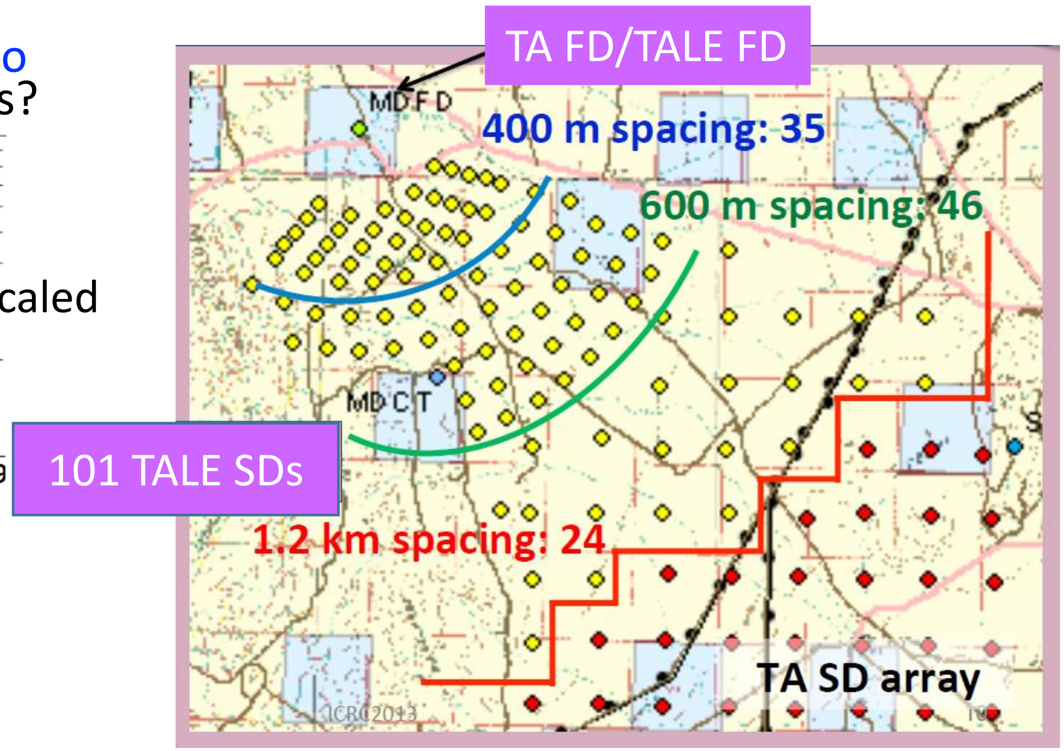
- E = $10^{16.5}$ – 10^{19} eV
  - Second knee at ~$10^{17.5}$ eV?
  - Drastic change of composition at 10^{17}~10^{18} eV?

    ↓
  - Transition from galactic to extra-galactic cosmic rays?

- ~10^{17} eV cosmic ray shower: compatible with LHC center-of-mass energy



TALE layout

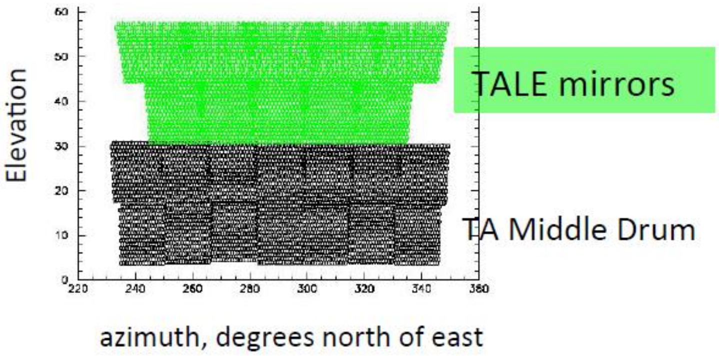


TALE (TA Low-energy Extension)

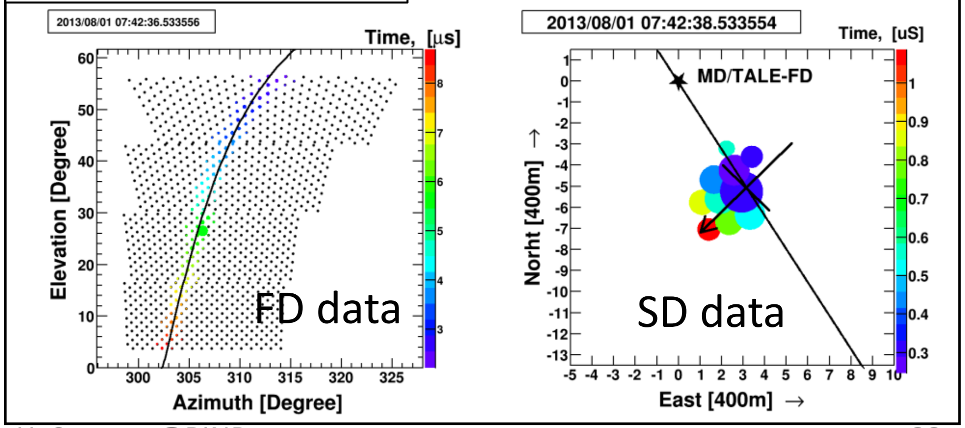
- 10 TALE FDs:
  - refurbished HiRes telescopes
  - all installed and running.

- TALE SDs (for good Xmax or composition measurement)
  - 35 TALE SDs were deployed among 101 SDs.
  - partially in operation

Remaining 70 SDs the stage of grant application

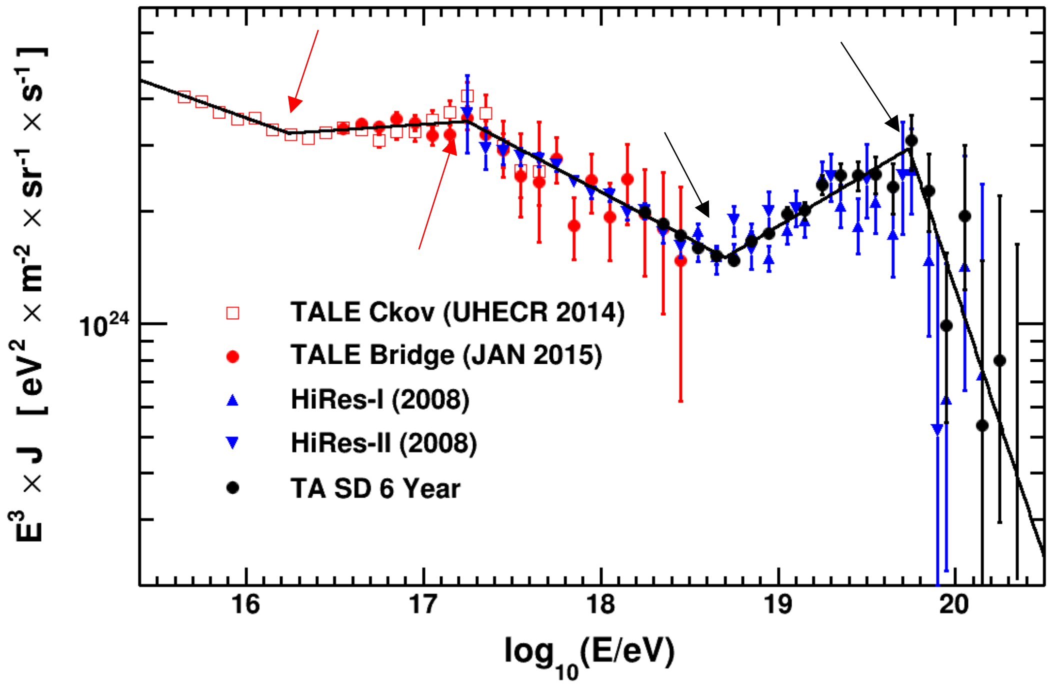


Observed hybrid events



TALE+TA spectrum ($E > 10^{15.6}$ eV)
(FD) (SD)

Energy region over 4 orders of magnitude



Good Xmax resolution is an urgent subject
→ Need hybrid analysis by constructing the full TALE SD array

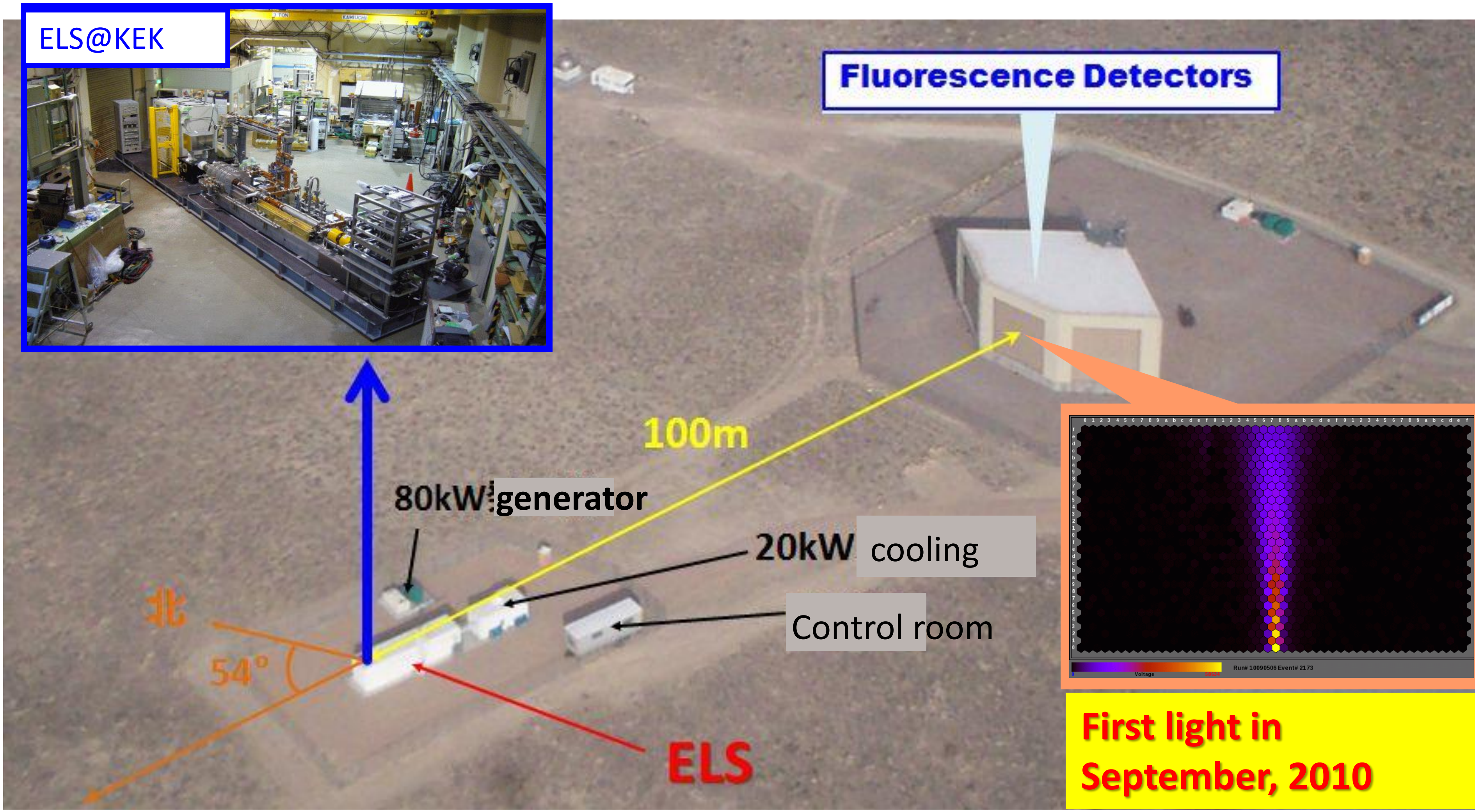
Other activities

- ELS (Electron Light Source, electron accelerator)
  - On-site FD calibration by pseudo air shower generated by known energy of electrons
    - 10^9 electrons of 40 MeV
- Associate experiments
  - Test of CR detection by radio
    - TARA (TA Radar): transmitter → shower → radio echo
    - Molecular Bremsstrahlung detection
  - Test of Fluorescence Detector
    - TA-EUSO: Test of prototype of JEM-EUSO at TA site
    - Mono-eye FD test
- TA SD burst events associated with lightning
- TA muon detector projects
  - Check Auger muon excess (1.8xMC)
    - Scintillator with absorber
    - Auger water tanks to the TA site
- etc.

Electron Light Source (ELS)

Electron beam source= End-to-end energy calibration

Observe pseudo air shower by electrons with known energy recorded by FD



Power=**40MeV** × **10^9e-**/pulse × 0.1-0.5 Hz, pulse widht: 1μsec

ELS event observed by the fluorescence detector

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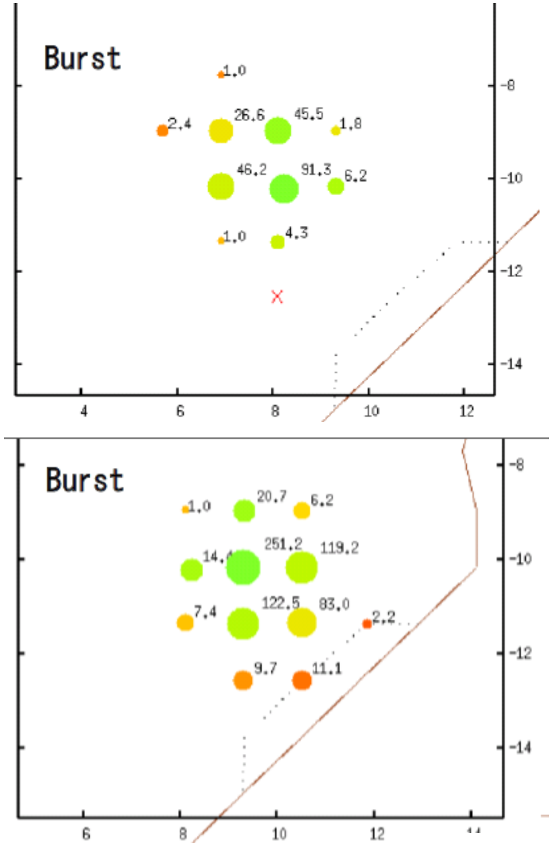
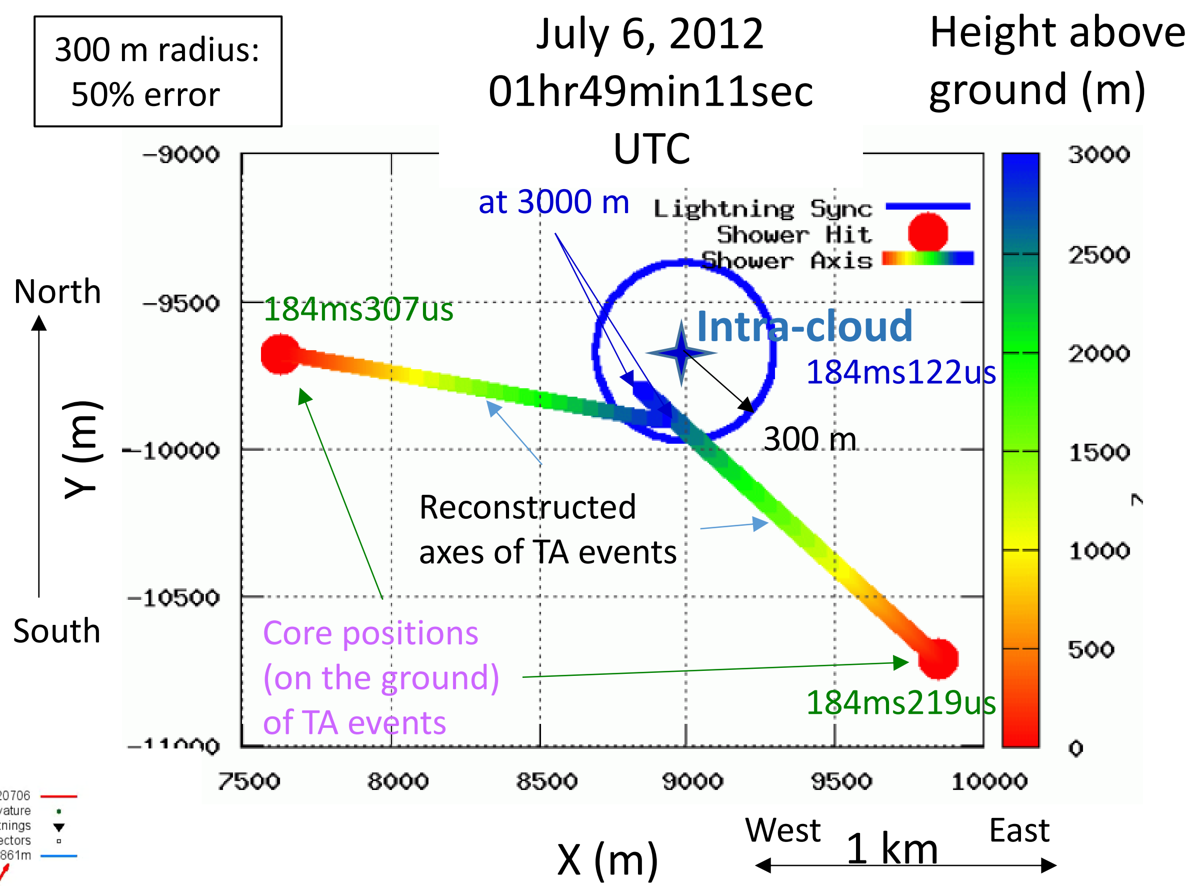
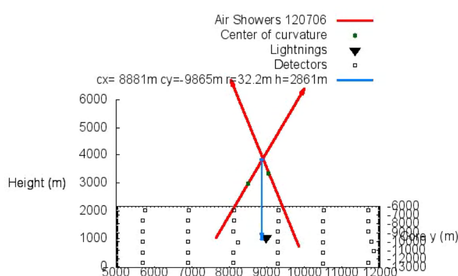
An example of TA reconstructed events with lightning

T.Okuda
COSPA2013
preliminary





(X, Y): distances are from CLF



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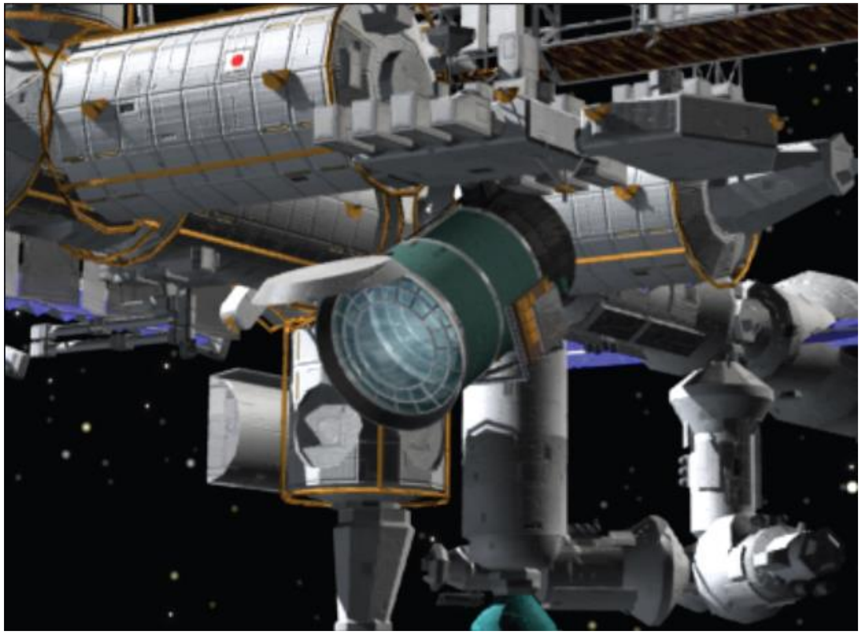
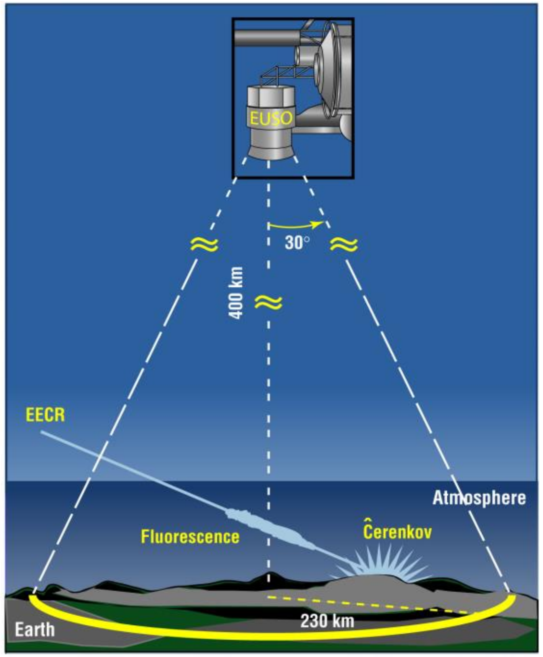
JEM-EUSO

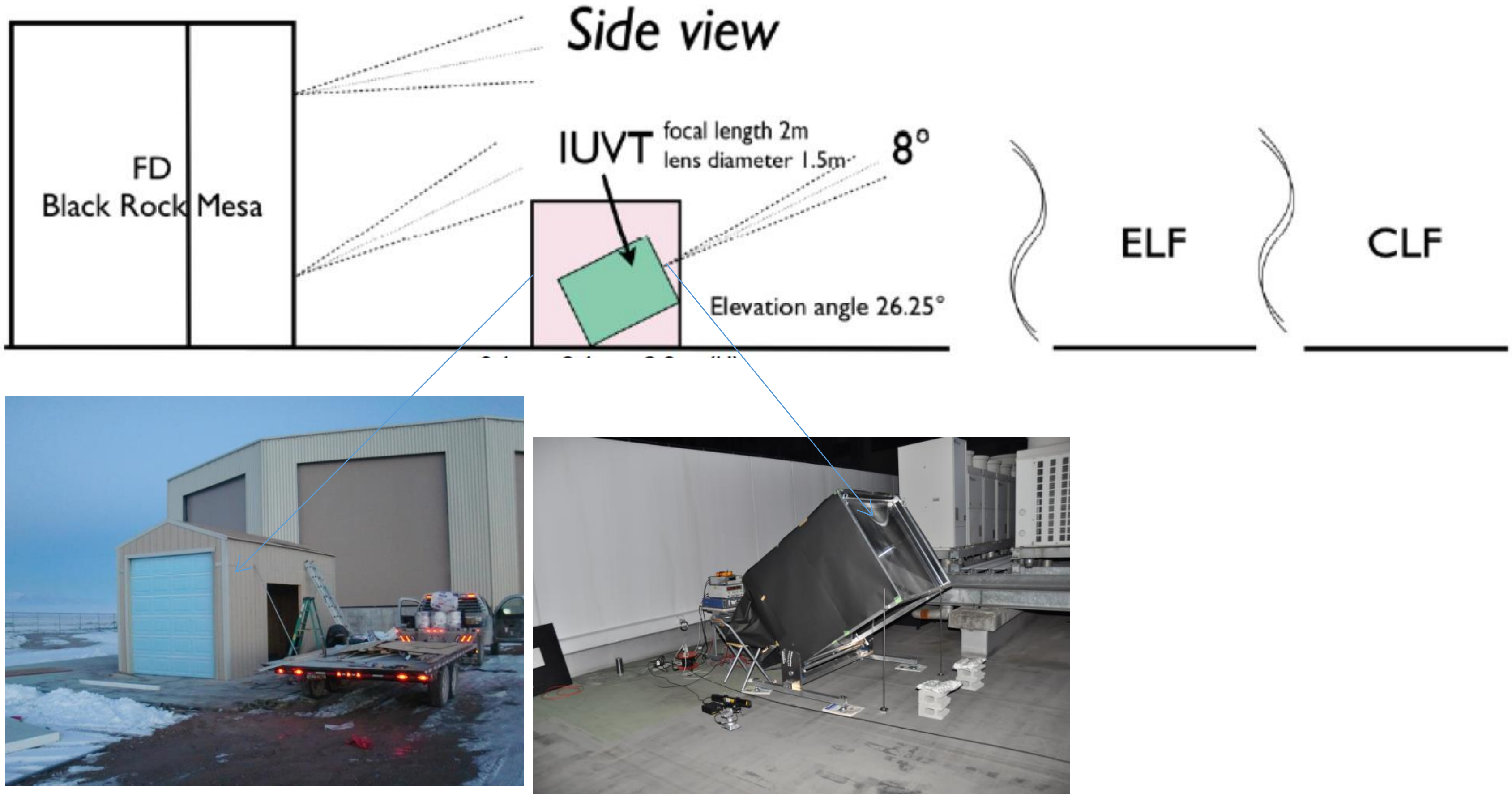
Extreme Universe Space Observatory onboard Japanese Experiment Module

- Observation of UHECRs from the universe
  - Wide FoV → Large statistics
  - Uniform exposure





Setup of JEM-EUSO prototype @ TA



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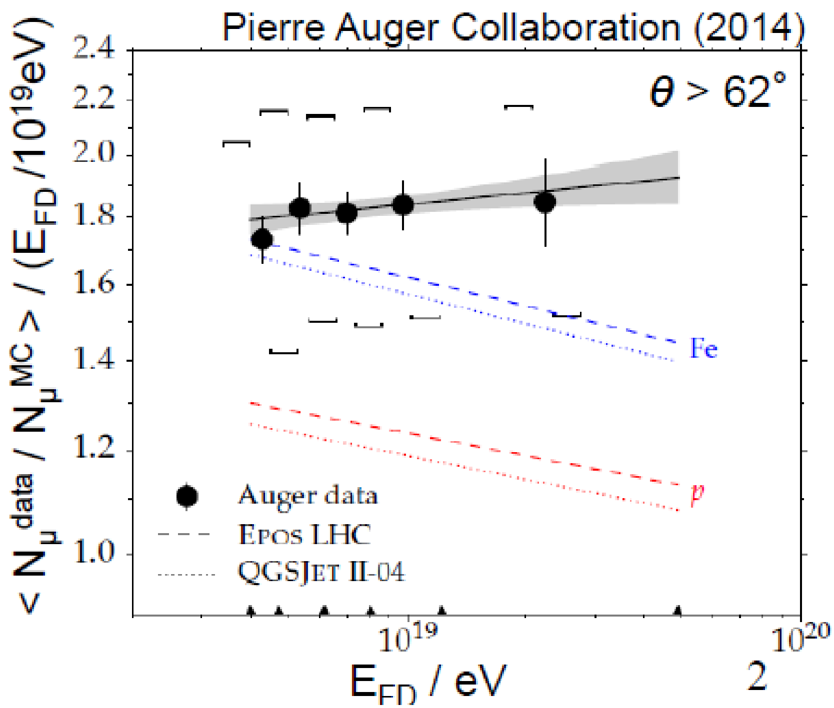
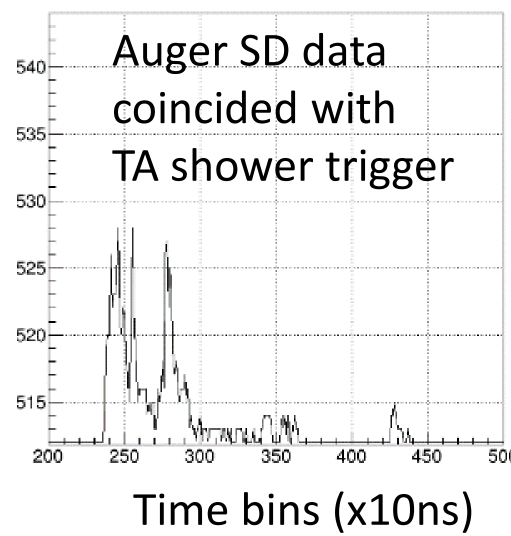
Auger water tank deployed at TA CLF

- μ excess issue

$N_{\mu}^{data} \sim 1.8\times N_{\mu}^{data}$ for Auger SD





Summary

- TA has been operating stably since 2008
- Results
  - Energy spectrum: cutoff at highest energy consistent with GZK cutoff
  - Anisotropy of arrival directions: hotspot with 400% anisotropy
  - Composition: consistent with light composition, predominantly proton
- Future plan
  - TAx4
    - 4 times TA to survey nearby super-galactic universe and unravel the relation with extreme phenomena in the universe
    - Frontier of astronomy by highest-energy cosmic rays
  - Low energy extension (TALE)
    - Understanding of transition from galactic cosmic rays to extragalactic cosmic rays

end