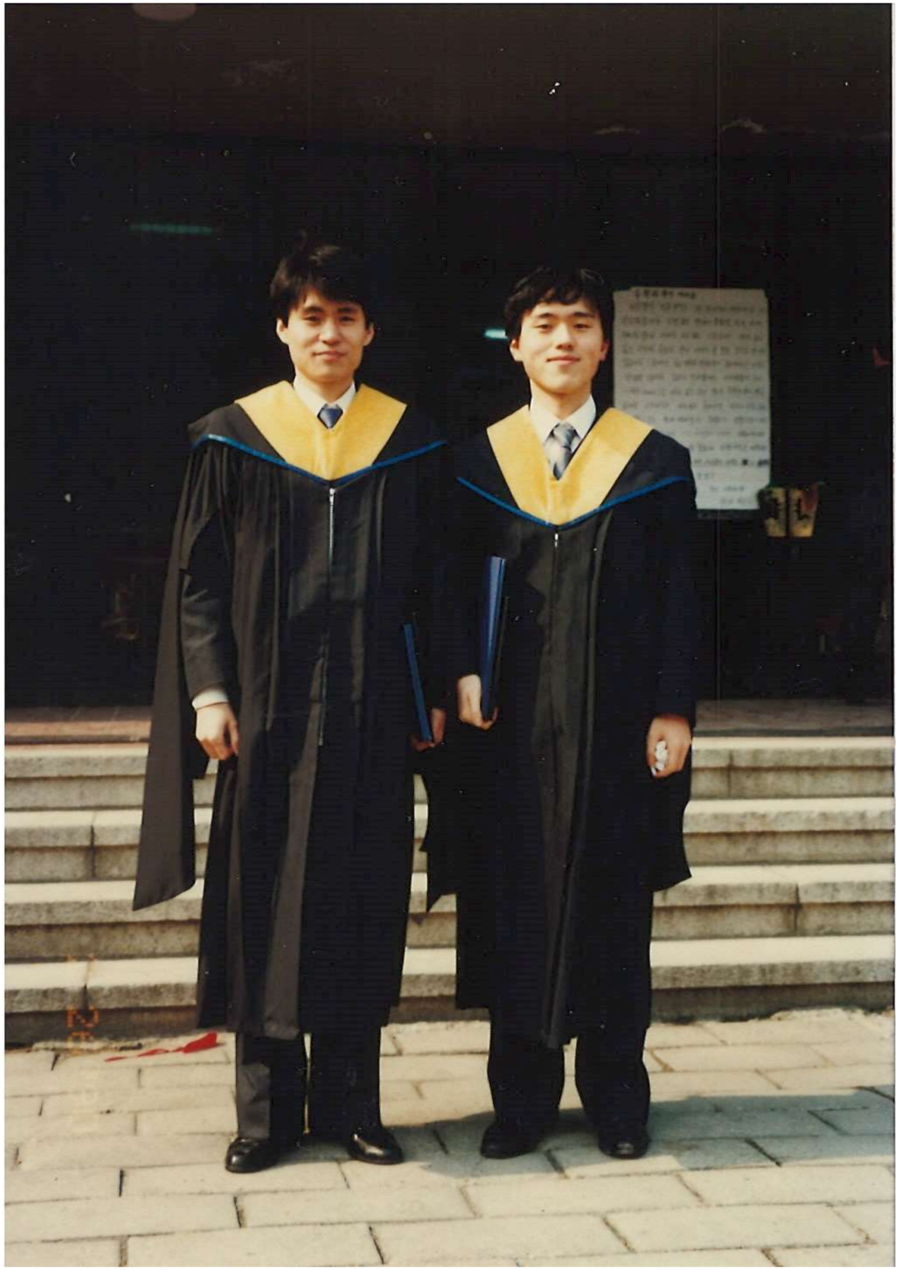
Amaterasu Particle & the Puzzle of Ultra-High Energy Cosmic Rays

Hang Bae Kim (Hanyang University)

IBS-CTPU, 2025.09.10

Reminiscence with Sanghyeon Chang



A Dark Matter Solution from the Supersymmetric Axion Model

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(Received 3 April 1996)

We study the effect of the late decaying saxino and find out that there is a possible dark matter solution from a class of supersymmetric extensions of the invisible axion model. In this class of models, the saxino acts as the late decaying particle which reconciles the cold dark matter model with high values of the Hubble constant $H_0 = 70-80$ km sec^{-1} Mpc^{-1}, which would be inconsistent with the standard mixed dark matter model. This class of models provides a plausible framework for the alternative cold dark matter plus late decaying particle model, with the interesting possibility that both cold dark matter and the extra radiation consist of an axion. [S0031-9007(96)00645-X]

PACS numbers: 95.35.+d, 14.80.Ly

Cosmological and astrophysical data accumulated in the past several years made it possible to test the theories of large scale structure formation in our Universe. The COBE-DMR discovery of cosmic microwave background (CMB) anisotropy provided the means for the accurate normalization of theories of structure formation. The study of galaxy correlations supplied complementary data on smaller scales. With the scale invariant initial spectrum, they manifested that the pure hot dark matter model cannot explain the small scale structure of the Universe and the pure cold dark matter (CDM) model shows best fit at the values $\Omega_0 h = 0.25$ [1] [Ω_0 = (the present energy density)/(the critical energy density) and h = (the present value of the Hubble constant)/(100 km sec^{-1} Mpc^{-1})], which is much smaller than the presently favored values. The mixed dark matter (MDM) model attracted broad attention because it gives good fit for $\Omega_\nu = 0.2$ and $\Omega_{\rm CDM} = 0.8$ at $h = 0.5$ [2].

For a better test of models, however, the accurate values of Ω_0 and h have been required. The observed value of Ω_0 is ranging from 0.2 to ~ 1, still plagued by a large systematic uncertainty. Several recent investigations of the Hubble constant tend to give higher values, in the range of $h = 0.7-0.8$ [3]. If we stick to the theoretical prejudice, $\Omega_0 = 1$, we have at least two serious problems. First, we cannot fit the power spectrum curve even in the MDM model. Second, it would be inconsistent with the estimated lower bound on the age of the Universe from the oldest globular clusters. An $\Omega_0 = 1$ universe has an age of only $t_0 = 6.5h^{-1}$ Gyr, giving $t_0 < 9.3$ Gyr for $h > 0.7$. On the other hand, the observed value of the age of the oldest globular cluster is around 15 Gyr [4]. Still there are a few possible ways to relax this bound, but it seems not to be less than 11 Gyr [5]. Assuming that the data from the globular cluster can be relaxed by some mechanism and considering error bars in Hubble constant observations, $h = 0.6$ would be marginally allowed. However, the standard MDM model is inconsistent with large scale structure data even for $h = 0.6$.

Introduction of the small cosmological constant corresponding to $\Omega_\Lambda = 0.7-0.8$ alleviates the Universe age crisis mildly and can revive good features of the CDM model with $\Omega_\Lambda + \Omega_{\rm CDM} = 1$ (the CDM + Λ model). However, such a small value of cosmological constant is still a theoretically knotty subject. One way to keep the cosmological constant to be zero and maintain good features of the CDM model is introducing the late decaying particle (LDP) (the CDM + LDP model) [6]. In the CDM + LDP model, the LDP decays into very light and weakly interacting particles in the late stage of the Universe. This new radiation dominates the radiation energy of the Universe and would delay the beginning of the matter dominated epoch, which is necessary for the CDM model to be consistent with structure formation data even at the high values of h. But there are severe restrictions on the mass, lifetime, and interactions of the LDP coming from structure formation data and preserving the successful predictions of nucleosynthesis and the CMB spectrum. We find that these can be met for the axion supermultiplet in supersymmetric extensions of the well-known axion model. It can provide cold dark matter with the late decaying particle consistently in a class of models.

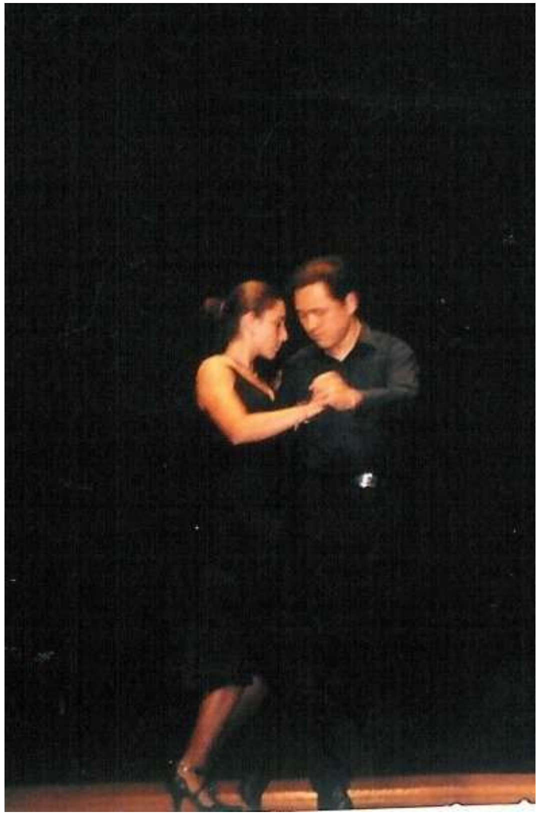
The axion is originally introduced to solve the strong *CP* problem. The axion model has an interesting cosmological effect. The axion produced from the initial vacuum misalignment has very small momentum and therefore is a good candidate of the cold dark matter.

In the supersymmetric extension of the axion model, the axion supermultiplet (Φ) consists of the axion (a), its real scalar superpartner saxino (s), and the fermionic superpartner axino ($\tilde{a}$). The cosmological impacts of these two additional weakly interacting particles were studied before [7,8]. In this Letter, we present unappreciated possibility of saxino cosmology, in which the saxino decays to two axions and acts as a LDP.

- **놀라운 손재주!**
  - 마이컬슨 간섭계를 손으로 조정…
  - 홀로그램 만들기를 유일하게 성공…
  - 컴퓨터 손보기와 리눅스 깔기…

- **장군이 일꾼이야!**
  - 다재다능하고 유능한 일꾼
  - 다양하고 끊임없는 썰…
  - 오지랖…

- **그러나, 몸치…**
  - 축구
  - 탁구
  - 그런데 놀랍게도…















12 Million
Views
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[다니엘]
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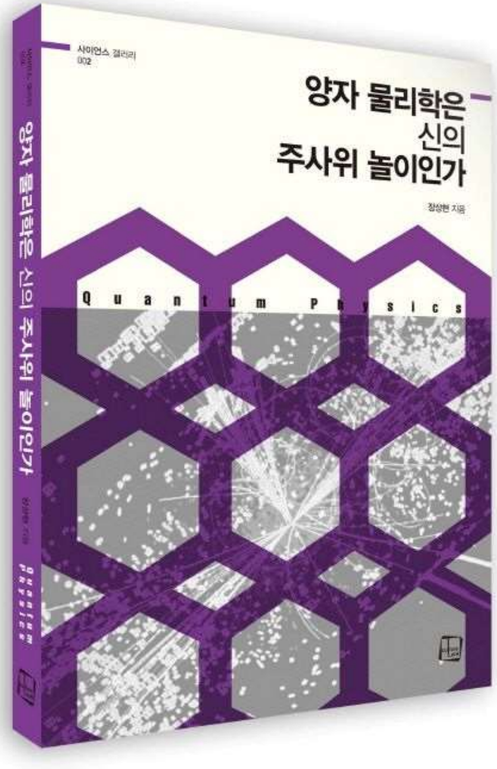
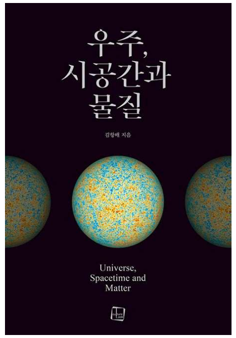
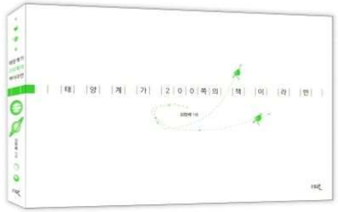
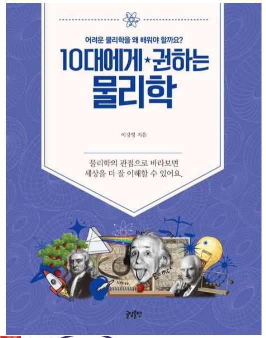
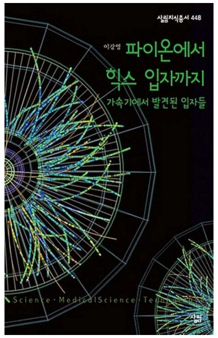
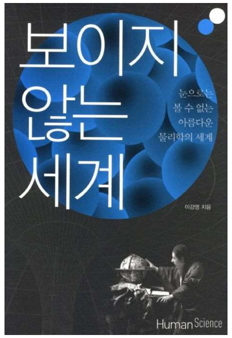

사이언스 갤러리
002
양자 물리학은 신의 주사위 놀이인가
정상현 지음
Quantum Physics


우주, 시공간과 물질
Universe, Spacetime and Matter




어려운 물리학을 왜 배워야 할까요?
10대에게 권하는 물리학
물리학의 관점으로 바라보면
세상을 더 잘 이해할 수 있어요.


살림지식총서 448
이강영 파이온에서 힉스 입자까지
가속기에서 발견된 입자들


보이지 않는 세계
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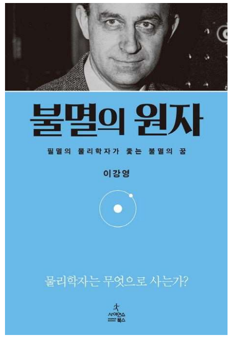
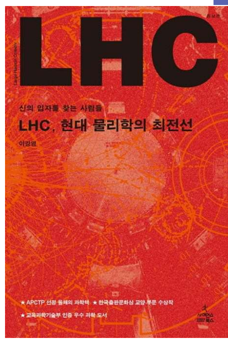
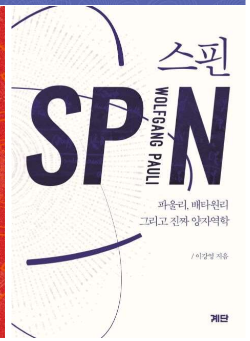
이강영 지음
Human Science

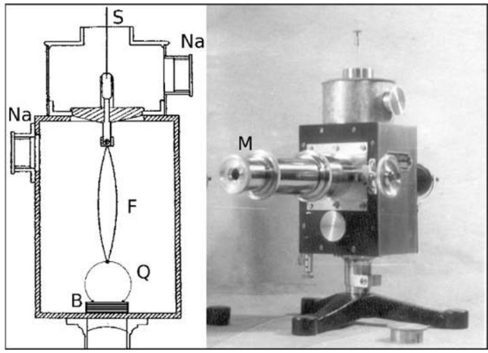

불멸의 원자
이강영
물리학자는 무엇으로 사는가?

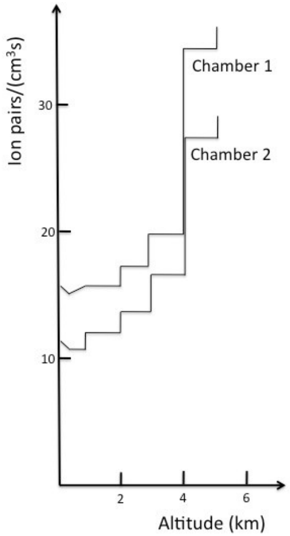

LHC
LHC, 현대 물리학의 최전선

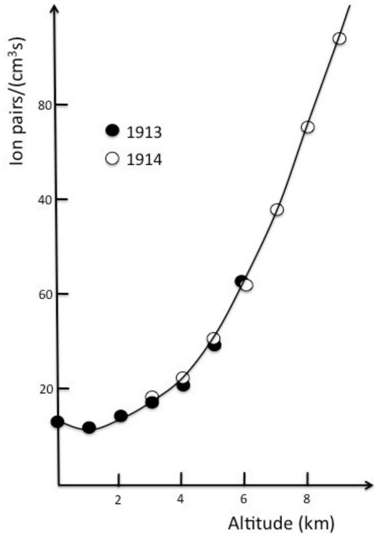

스핀
SPIN
WOLFGANG PAULI
파울리, 배타원리 그리고 진짜 양자역학
/ 이강영 지음
계단

Cosmic Rays - History

- Cause of atmospheric ionization
  - Radioactive elements in the ground or Radiations from the outer space?
  - Variation of ionization rate with the altitude
- Discovery of cosmic rays
  - In 1912, Victor Hess's experiment
  - The ionization rate increased at higher altitude – radiations from the outer space
  - Ruled out the sun as the source
  - Robert Millikan coined cosmic rays.

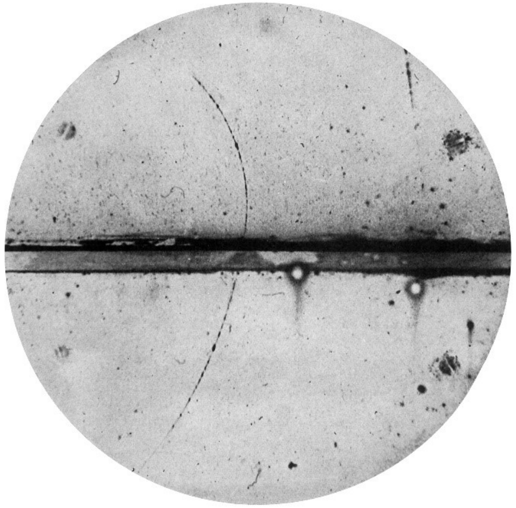


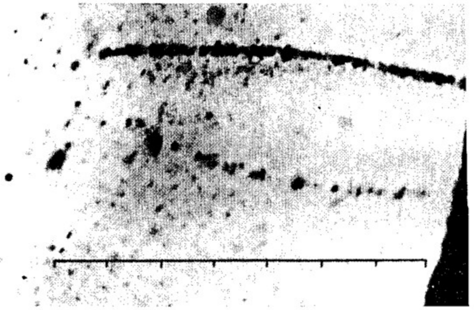




Cosmic Rays - History

- New types of detectors
  - Cloud chamber
  - Photographic emulsion
- New particles from the outer space
  - Discovery of the positron
  - Discovery of the muon
  - Discovery of the pion





"The other double trace of the same type (figure 5) shows closely together the thin trace of an electron of 37 MeV, and a much more strongly ionizing positive particle whith a much larger bending radius. The nature of this particle is unknown; for a proton it does not ionize enough and for a positive electron the ionization is too strong. The present double trace is probably a segment from a "shower" of particles as they have been observed by Blackett and Occhialini, i.e. the result of a nuclear explosion".

Kunze, P., Z. Phys. 83, (1933) 1

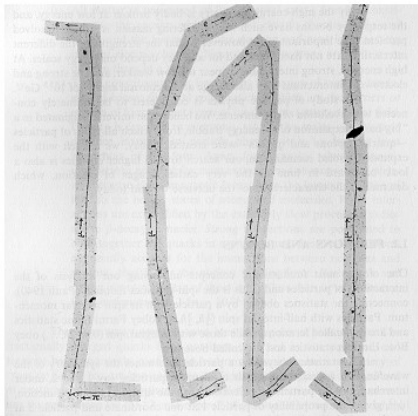
$$p + A \longrightarrow p + X + \pi^{\pm}, \pi^{0} + \cdots$$

p: primary cosmic ray

A: nucleus in atmosphere

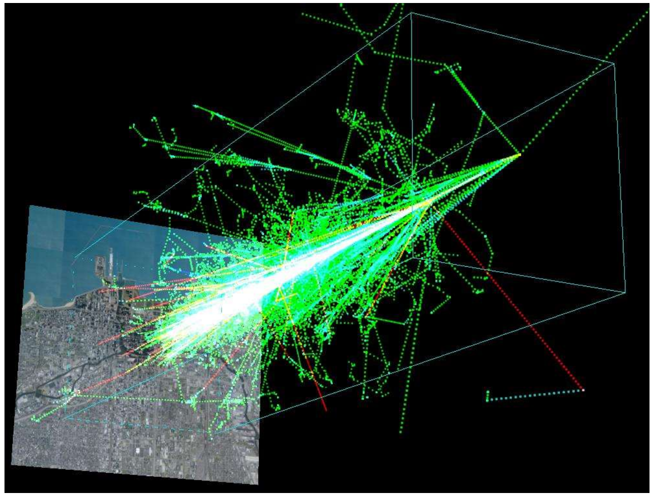
$$\pi^{\pm} \xrightarrow{3 \times 10^{-8}\,\mathrm{s}} \mu^{\pm} + \nu_{\mu}$$

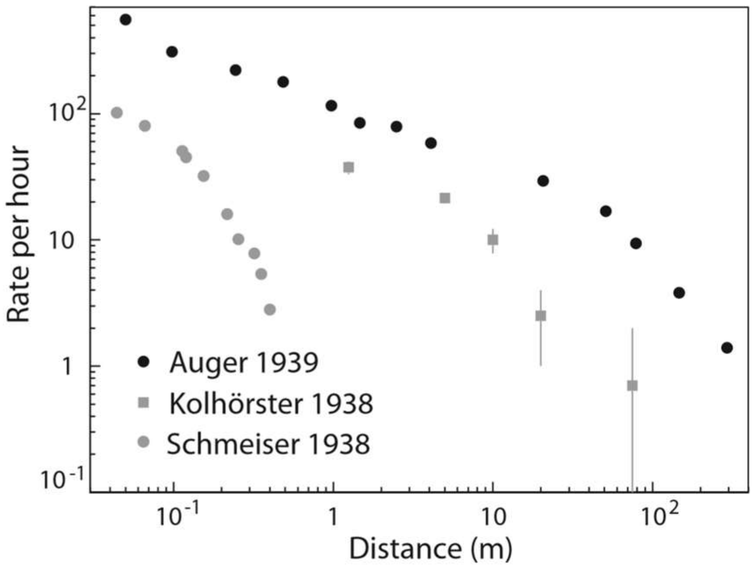
$$\mu^{\pm} \xrightarrow{2 \times 10^{-6}\,\mathrm{s}} e^{\pm} + \nu_{e} + \nu_{\mu}$$



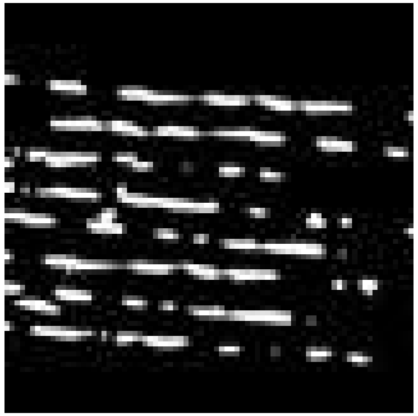
Cosmic Rays - History

- Discovery of the extensive air shower (EAS)
  - At the end of 1930s, Rossi, Schmeiser, Bothe, Kolhorster and Auger
  - Coincidence technique by Walther Bothe + Geiger-Muller counters
  - Simultaneous detection of secondary cosmic rays over large distances





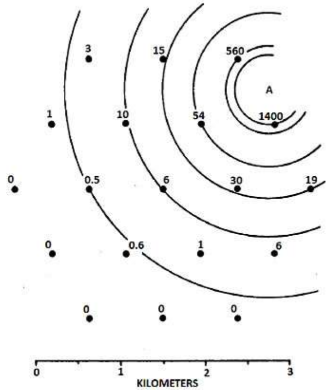
Geiger counter



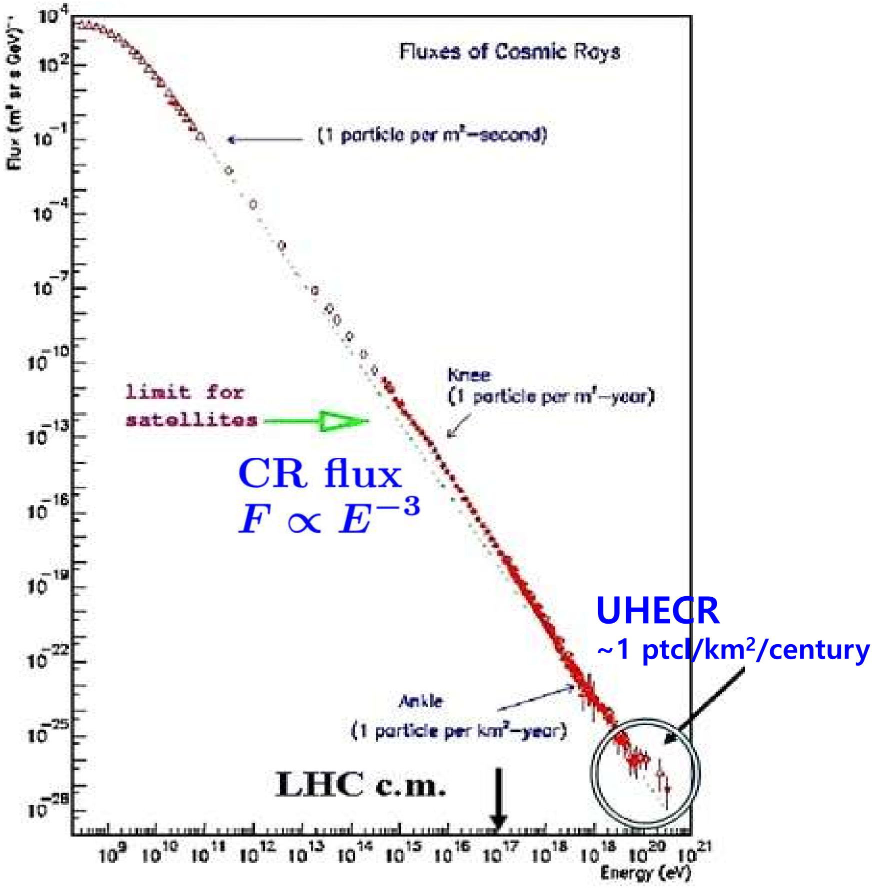
Air shower detected in a cloud chamber

Cosmic Rays - History

- Surface detector arrays covering more than 1km^2
  - Volcano Ranch
  - Haverah Park
  - The Yakutsk Array
  - The SUGAR Array
  - Akeno and AGASA
- Fluorescence detectors
  - Fly’s Eye and HiRes Fly’s Eye
- Hybrid detector arrays
  - Pierre Auger Observatory
  - Telescope Array



Ultra-High Energy Cosmic Rays (UHECR)



What are ultra-high energy cosmic rays?

- Cosmic rays with energy $E \gtrsim 10^{18}\,\mathrm{eV}$
  - 1962, CR with $E > 10^{20}$eV at Volcano Ranch
  - 1991, CR with $E = 3 \times 10^{20}$eV at Fly's eye
    OMG particle – A single particle (proton?) having the kinetic energy of a baseball (macroscopic object) with speed of 100 km/h
  - 2021, CR with $E = 2.4 \times 10^{20}$eV at TA SD
    Amaterasu particle
- UHECR are originated from extragalactic sources.
  - UHECR are so energetic, cannot be trapped by the galactic magnetic fields.

Where and How can elementary particles attain such extremely high energies?

Oh My God Particle in Wikipedia

Oh-My-God particle

22 languages

Article Talk Read Edit View history Tools

From Wikipedia, the free encyclopedia

Coordinates: 5^{h} 40^{m} 48^{s}, +48° 0′ 0″

Not to be confused with the "God Particle", or Higgs boson.

The **Oh-My-God particle** was an ultra-high-energy cosmic ray detected on 15 October 1991 by the Fly's Eye camera in Dugway Proving Ground, Utah, United States.[1][2][3] As of 2024, it is the highest-energy cosmic ray ever observed.[4] Its energy was estimated as $(3.2 \pm 0.9) \times 10^{20}$ eV (320 exa-eV). The particle's energy was unexpected and called into question prevailing theories about the origin and propagation of cosmic rays.

Amaterasu particle

11 languages

Article Talk Read Edit View history Tools

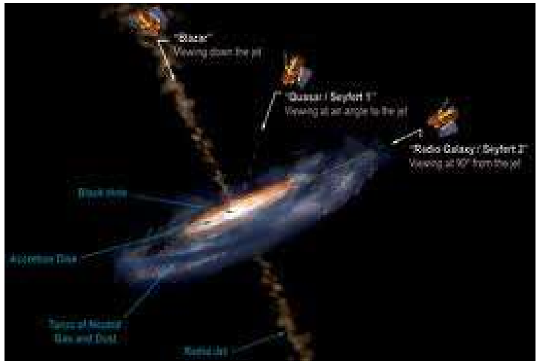
From Wikipedia, the free encyclopedia

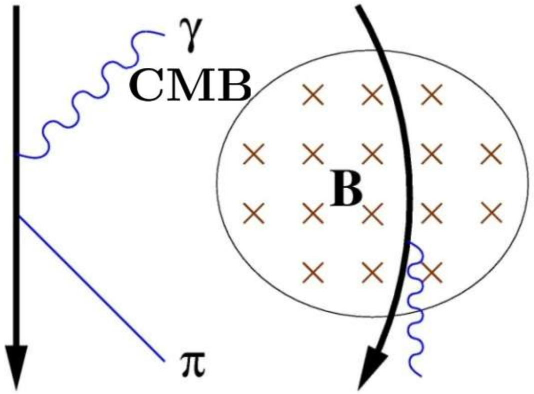
The **Amaterasu particle**, named after the sun goddess in Japanese mythology, was an unexpected ultra-high-energy cosmic ray detected in 2021 and later identified in 2023,[1] using the Telescope Array Project observatory in Utah, United States. It had an energy exceeding 240 exa-electronvolts (EeV) and was inferred through the two dozen particles it sent toward ground detectors. This single particle appears to have emerged, inexplicably, from the Local Void, an empty area of space bordering the Milky Way galaxy.[2] The single subatomic particle held energy roughly equivalent to a brick dropping to the ground from waist height.[3]

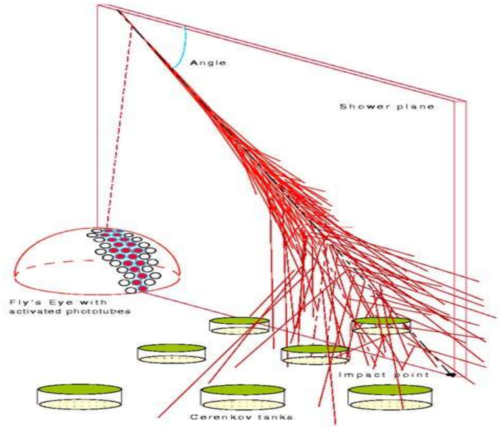
According to study leader, Associate Professor Toshihiro Fujii from Osaka Metropolitan University, "No promising astronomical object matching the direction from which the cosmic ray arrived has been identified, suggesting possibilities of unknown astronomical phenomena and novel physical origins beyond the Standard Model."[4]

Previously reported extremely high-energy cosmic ray events include a 320 EeV particle in 1991[5] (Oh-My-God particle), a 213 EeV particle in 1993[6][1] and a 280 EeV particle in 2001.[7] This makes the Amaterasu particle the third most powerful cosmic ray to have been detected.

UHECR – Production, Propagation, Observation







Production

Acceleration of charged particles
Decay of super-heavy particles

- Location (source distribution)
- Composition (particle species)
- Energy spectrum

Propagation

Interactions with cosmic backgrounds (Microwaves, Radio waves, Magnetic fields)

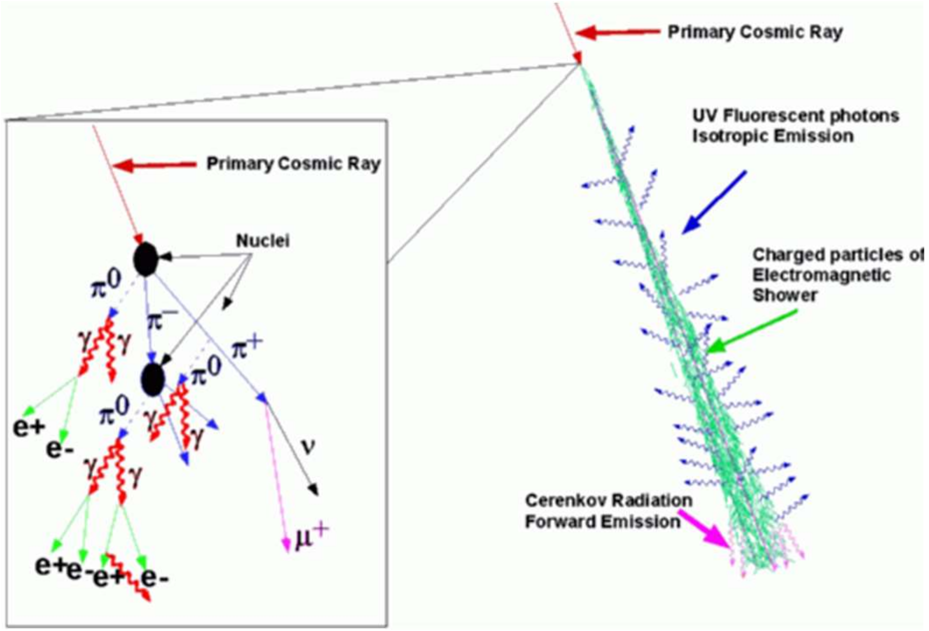
- Energy loss
- Deflection and Time lag
- Secondary CR production

Observation

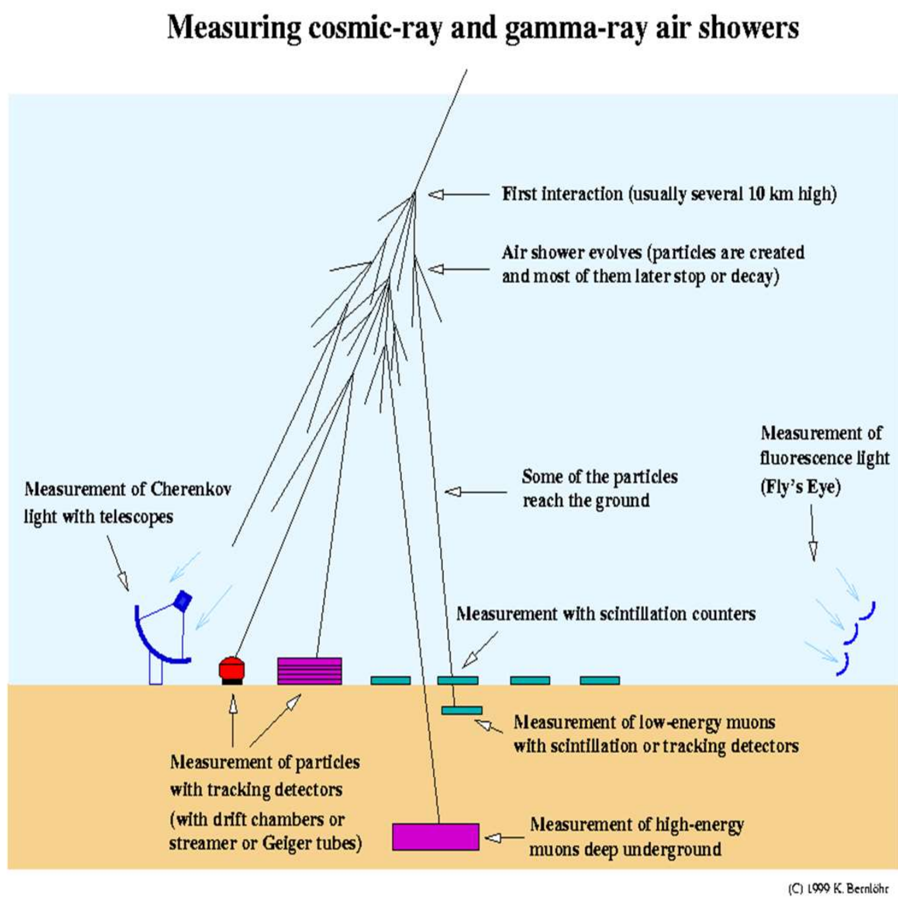
Atmosphere as calorimeter or scintillator

- Energy
- Arrival Direction
- Composition

Observation

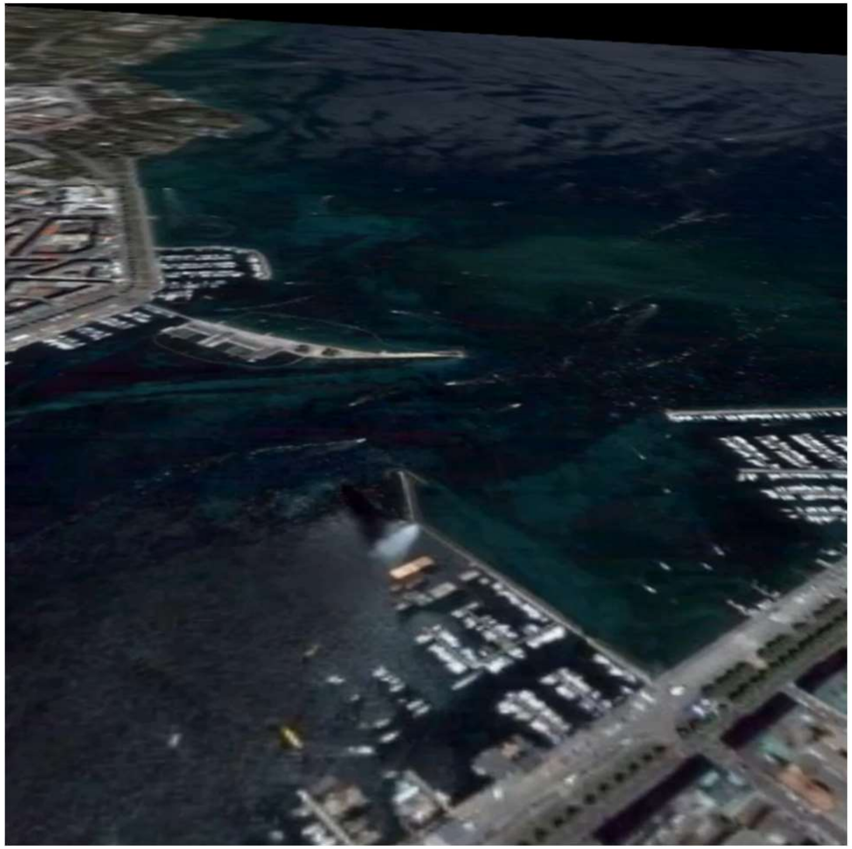


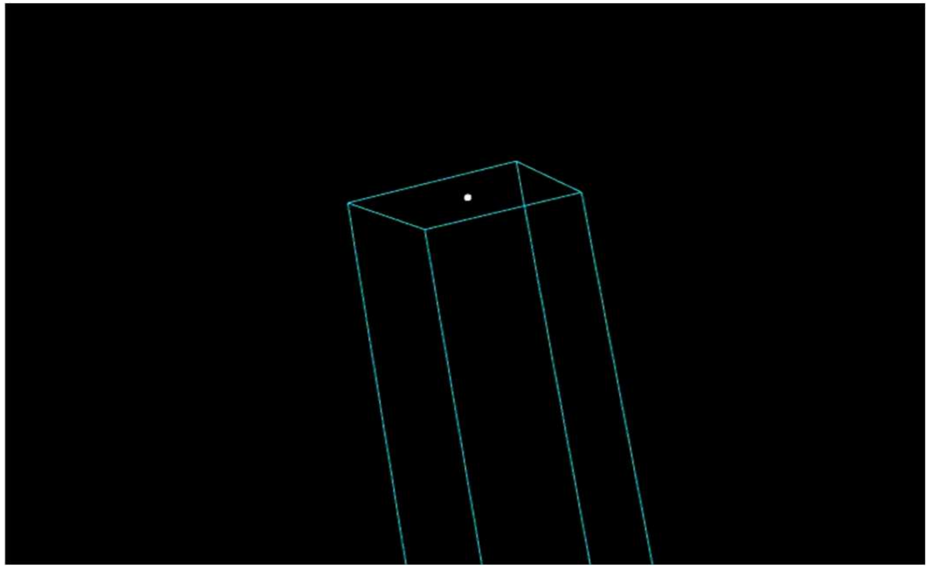
- **Detection of extensive air shower (EAS)**
  - Surface Detector (SD) – e, μ
  - Fluorescence Detector (FD) – UV
  - Cherenkov radiations, Radio waves



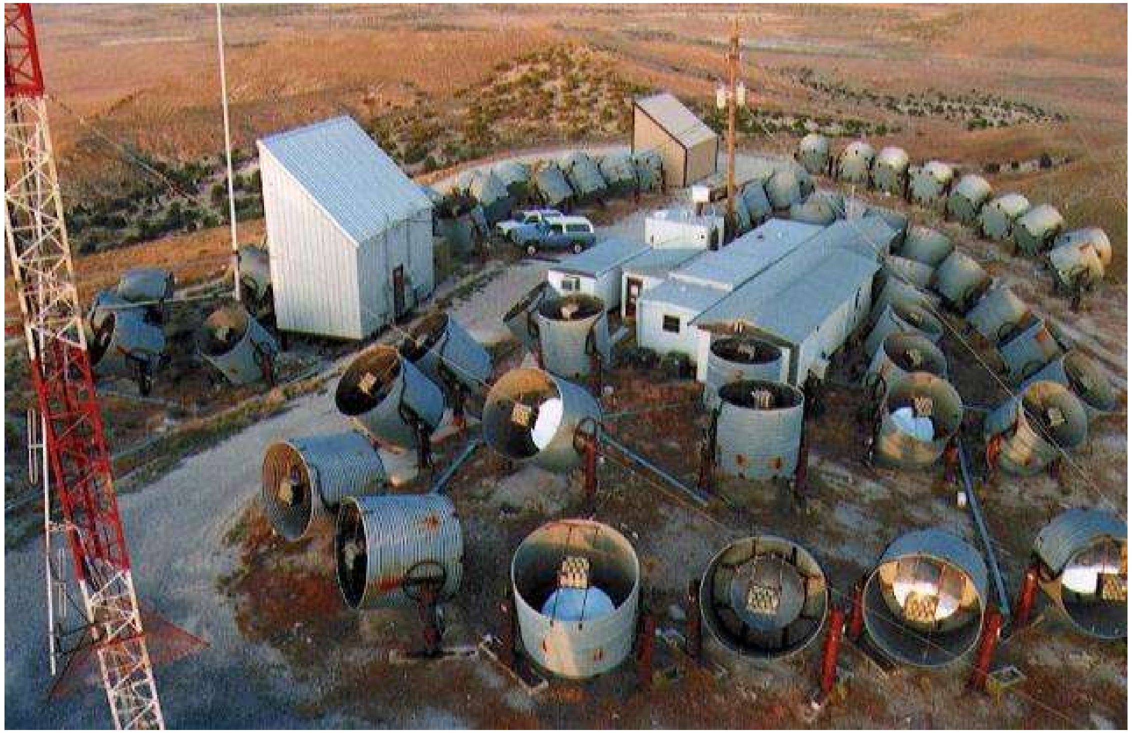
- Longitudinal development
- Lateral distribution

Simulation of the extensive air shower


A 1EeV proton cosmic ray air shower over Geneva



High Resolution Fly's Eye Observatory



- Location : Utah, USA
- Operation : 1981 - 2006
- FD : Rings of telescopes

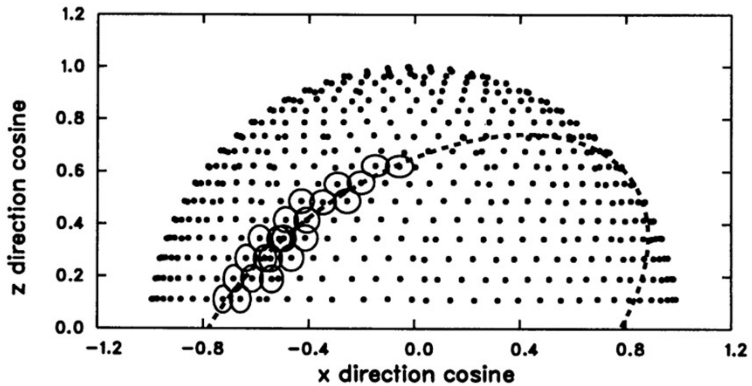
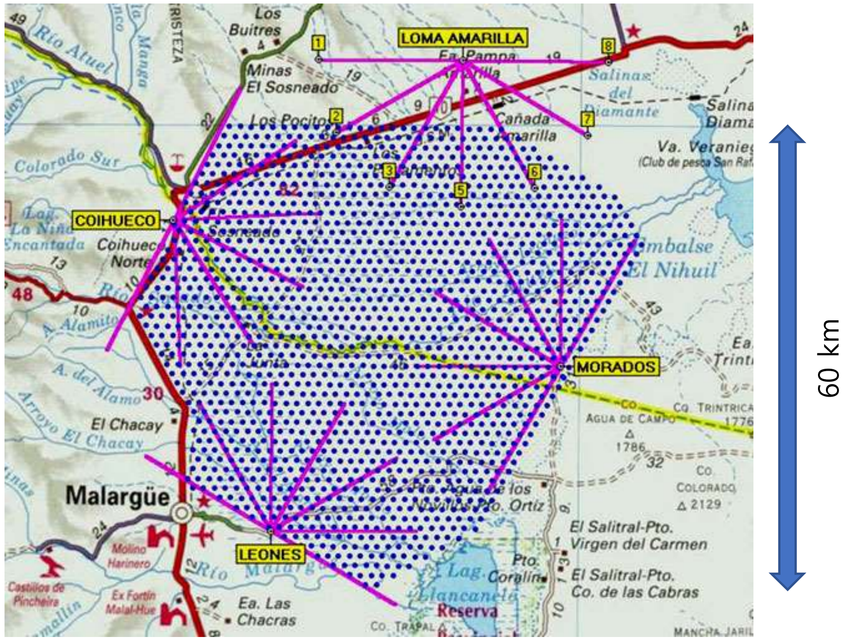


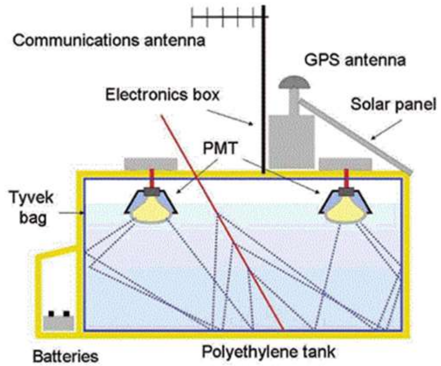
FIG. 1.—The pointing directions of the 22 phototubes which triggered in connection with this event are shown projected into the x-z plane. The x-axis points east, the y-axis north, and the z-axis upward. The triggered phototubes have positive y-components.

Pierre Auger Observatory (Auger)

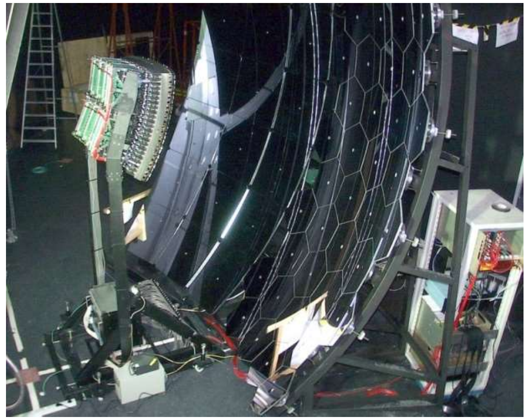
- Location : Mendoza, Argentina (35°.20S)
- SD : 1600 water Cherenkov detectors,
  1.5 km square grid, 3000 km^2 area
- FD : 24 telescopes in 4 stations



Surface Detector
Water Cherenkov



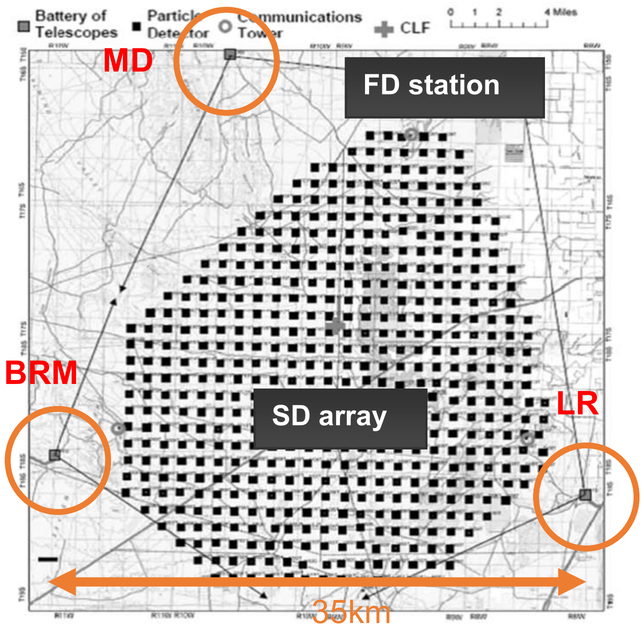
Fluorescence Detector
PMT pixel camera



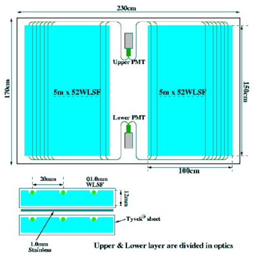
- Duty cycle
  - SD : ~100%
  - FD : ~10-15%

Telescope Array (TA)

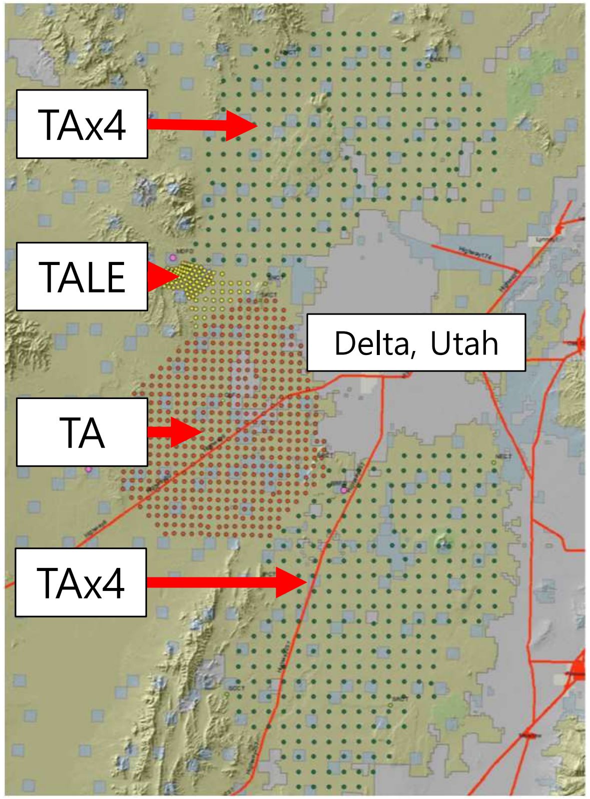
- Location : Utah, USA (39°.30N, 112.9°W)
- SD : 507 plastic scintillation detectors,
  1.2 km square grid, 678 km^2 area
- FD : 18 telescopes in 3 stations



Surface Detector
Plastic scintillator

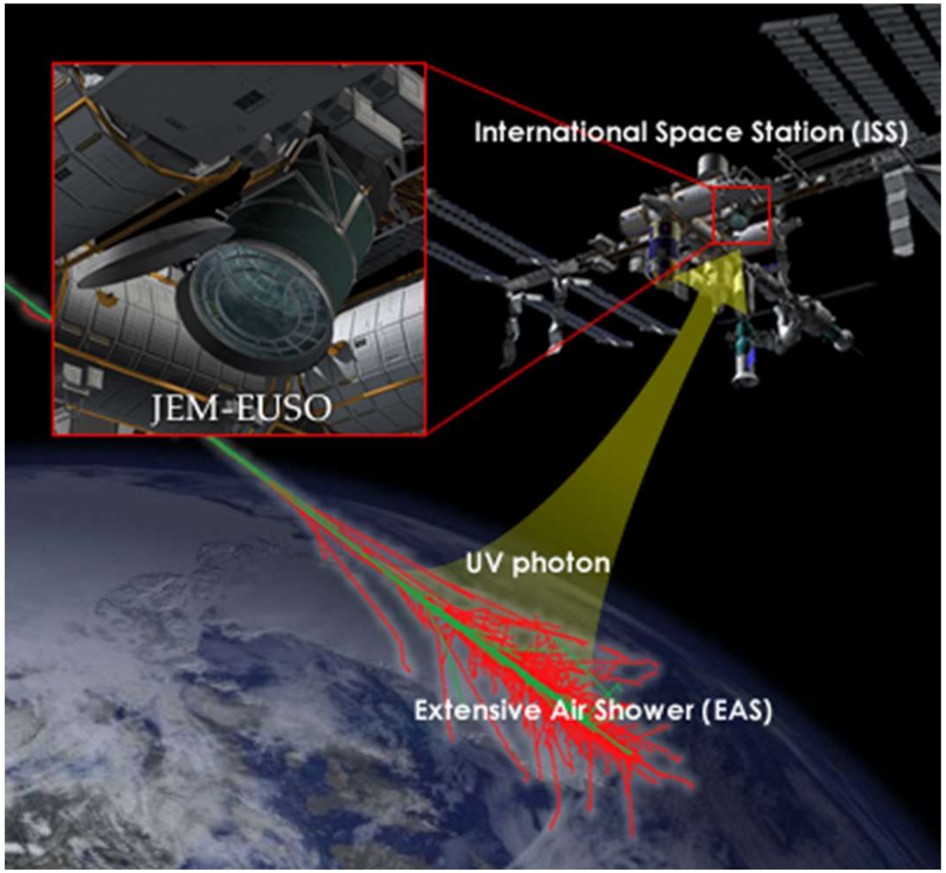


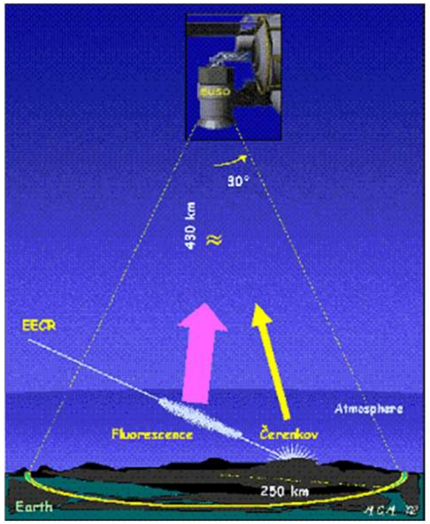
Fluorescence Detector
PMT pixel camera

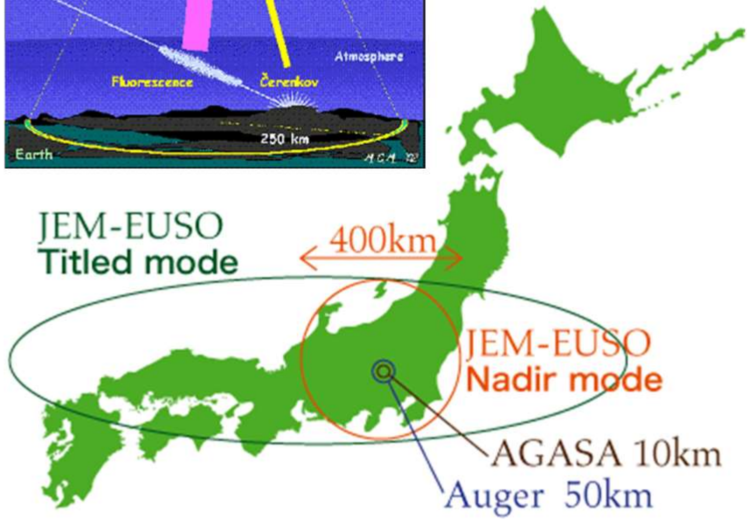


- TALE (TA Low Energy)
- TAx4 (under construction)

JEM-EUSO (proposal)

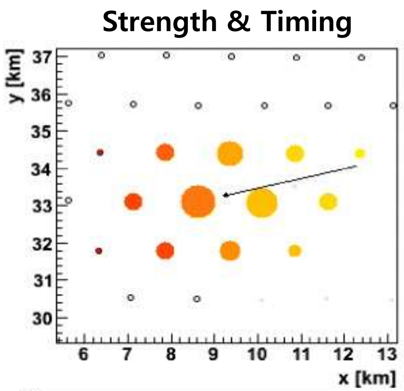


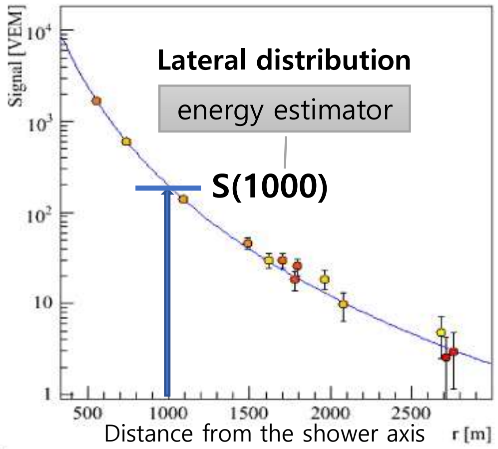




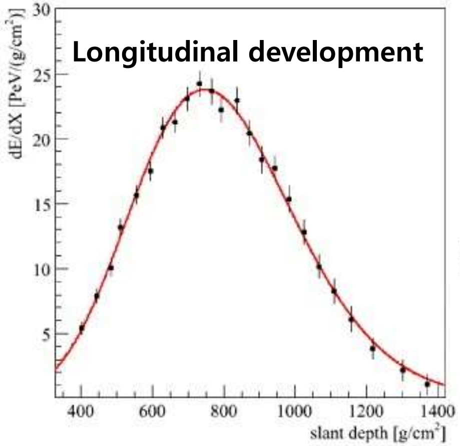
Arrival direction and Energy

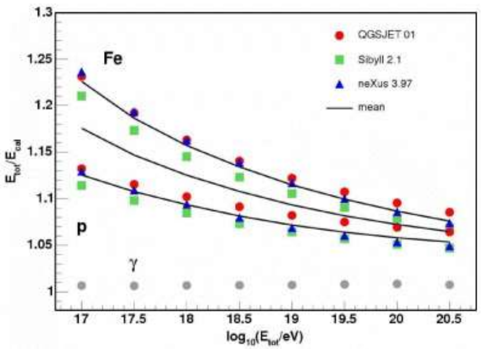
SD



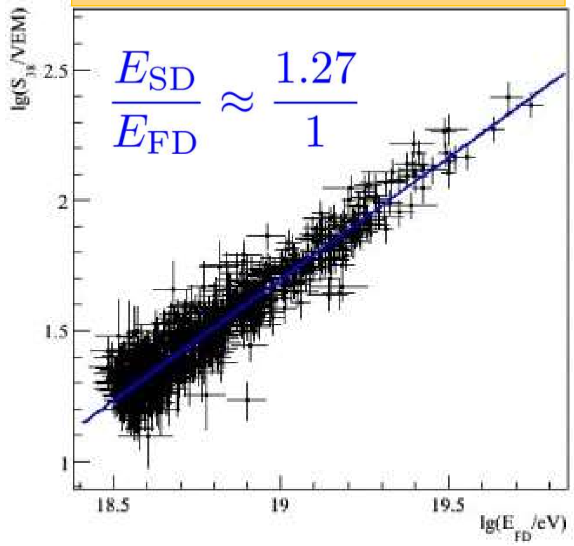


FD





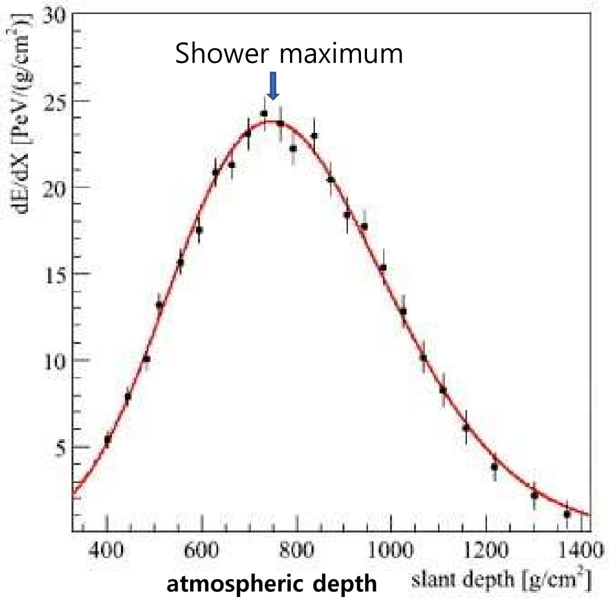
Energy Calibration
by FD-SD hybrid events



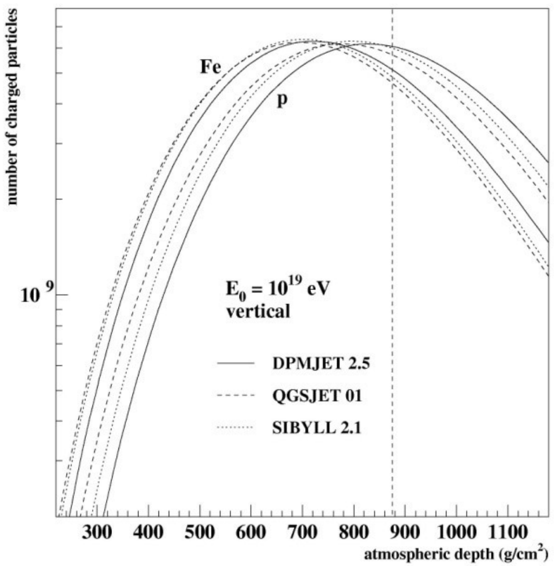
- FD-SD energy scale difference
  – Cause is unknown.
- Uncertainty
  – Energy 10~20%, Direction 1~2°

Composition

FD – Longitudinal development of shower



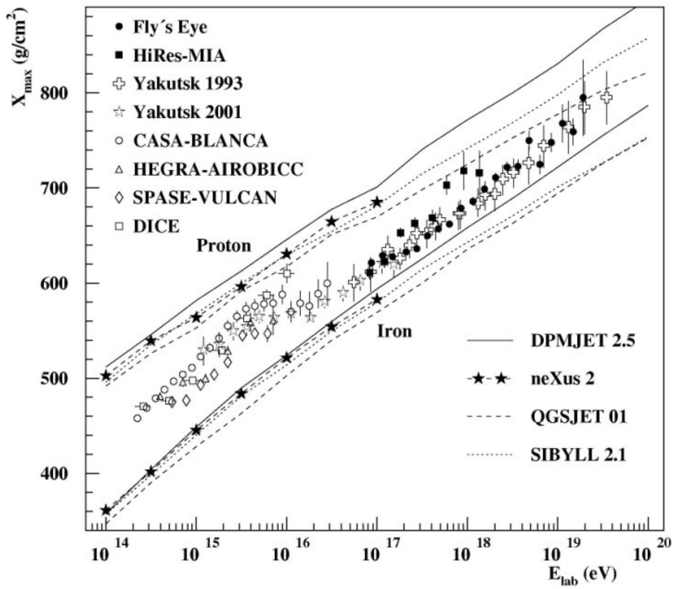
X_{max}, the depth of shower maximum depends on **energy** and **composition** of primary CR particle.



Average longitudinal development of proton and Fe nucleus obtained from simulation.
Proton has larger X_{max} than Fe.

$\langle X_{\mathbf{max}} \rangle$ and $\sigma(X_{\mathbf{max}})$

- Stochastic in nature – Composition identification cannot be done for each single event.

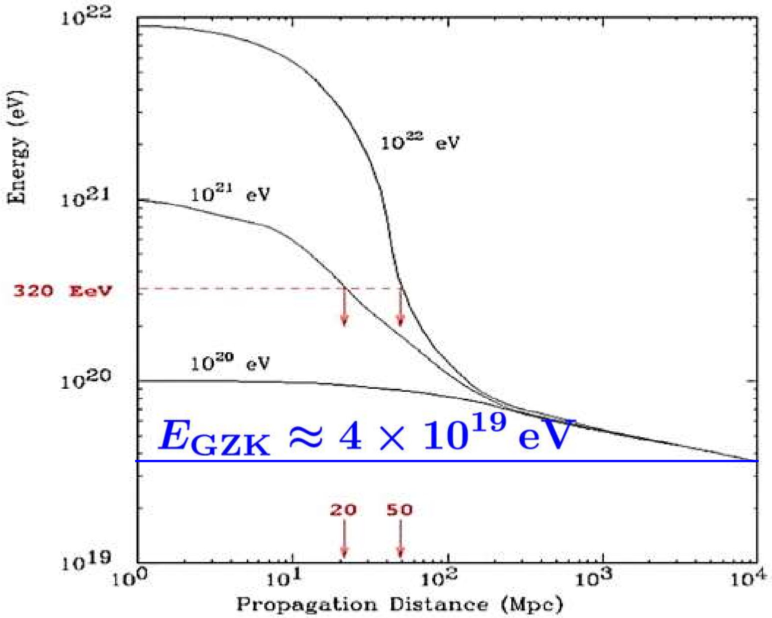


Observed variation of X_{max} as a function of energy.

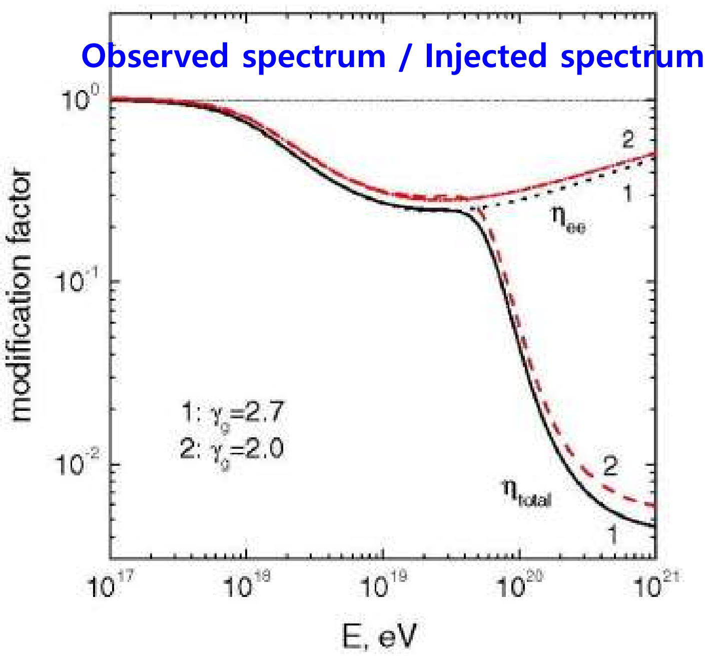
Propagation – Energy loss

- UHECR p, A, γ interact with CMB photons.

$$N + \gamma \rightarrow N + \pi \quad \text{(photo-pion production)}$$
$$E_{\rm th} \approx 6.8 \times 10^{19} \left(E_{\gamma_B}/10^{-3}\,\text{eV}\right)^{-1} \text{eV} \quad \text{(threshold energy)}$$



The energy of protons as a function of the propagation distance.



Change in the energy spectrum

- GZK suppression
  - If the sources are uniformly distributed …
  - Suppression of flux above the GZK energy $\sim 4 \times 10^{19}$ eV
  - GZK radius – attenuation length for super-GZK CR 100Mpc for proton
  - Excessive super-GZK CR may come from the sources within the GZK radius.

Propagation – Deflection and Time lag

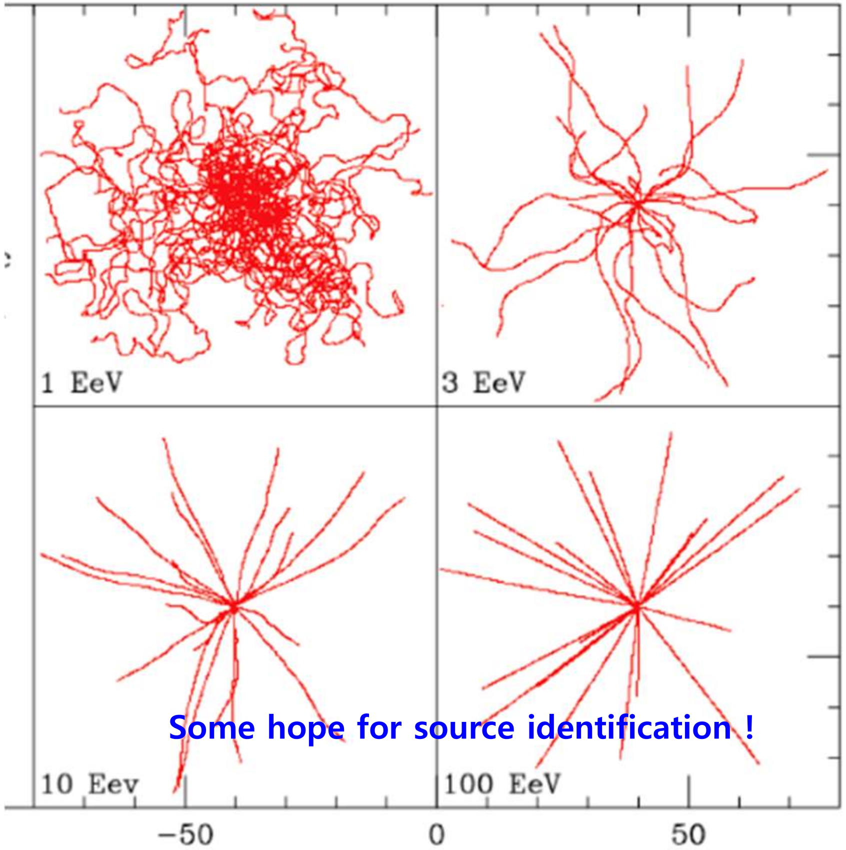
- Magnetic fields → Deflection and Time lag
- Deflection angle – Regular field

$$\delta\theta = 0.5^\circ Z \left(\frac{E}{10^{20}\,\mathrm{eV}}\right)^{-1} \left(\frac{d}{1\,\mathrm{Mpc}}\right) \left(\frac{B}{10^{-9}\,\mathrm{G}}\right)$$

- Deflection angle – Turbulent field

$$\delta\theta_{\mathrm{rms}} \approx 0.4^\circ Z \left(\frac{E}{10^{20}\,\mathrm{eV}}\right)^{-1} \left(\frac{(d \cdot L)^{1/2}}{\mathrm{Mpc}}\right) \left(\frac{B_{\mathrm{rms}}}{10^{-9}\,\mathrm{G}}\right)$$

- Galactic magnetic fields (GMF)
  - $B_G \sim 10^{-6}$ G
  - $R_G \sim 10$ kpc
- Extragalactic magnetic fields (EGMF)
  - $B_{EG} \sim 10^{-9} - 10^{-6}$ G (very uncertain)

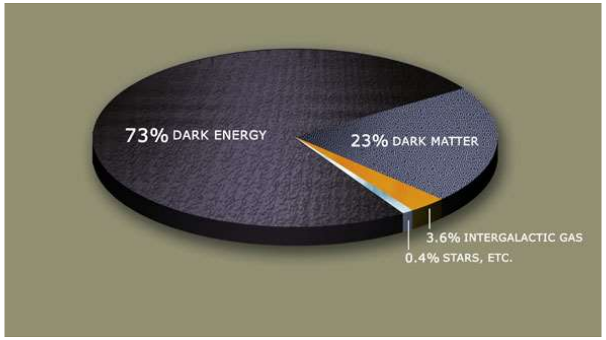


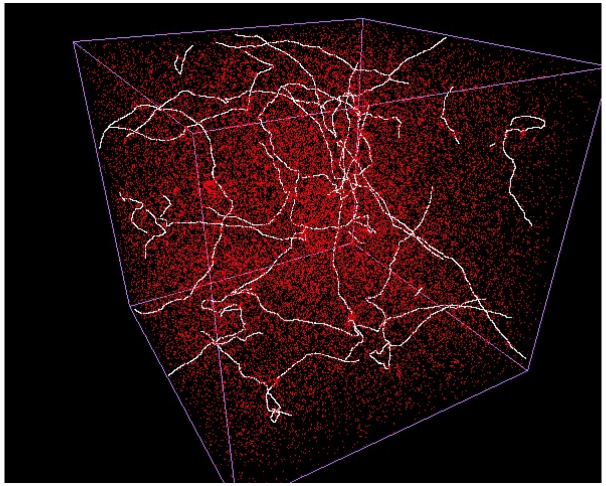
Proton propagation in a magnetic field of 10^{-9}G

Production – Top-down

- Cosmic origin involves new (cosmology + particle physics)
  - Decays of superheavy (dark matter) particle with long lifetime
  - Emissions from (cosmic remnant) topological defects

- Signatures of top-down models
  - Spectral shape – No GZK suppression, Characteristic spectrum
  - Composition – Neutrinos and photons are dominant
  - Arrival Directions
    - ➢ Superheavy DM → Strong anisotropy toward the galactic center

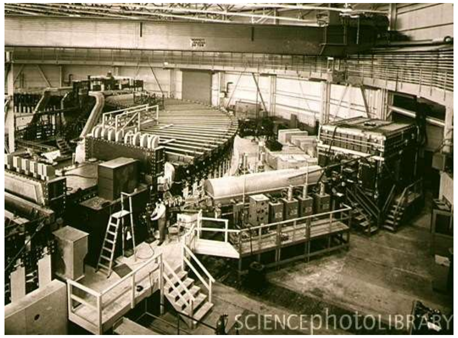




Production – Man-made Accelerators

- Accelerator – Device that accelerate charged particle using EM fields

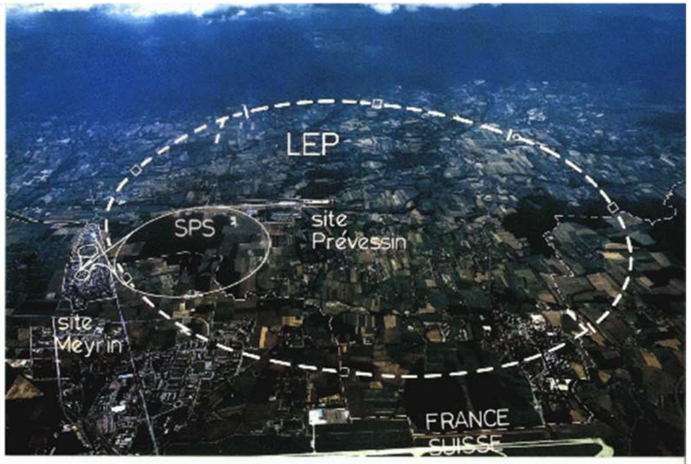
Cyclotron



- The higher energy to attain,
  the larger the accelerator needs to be.

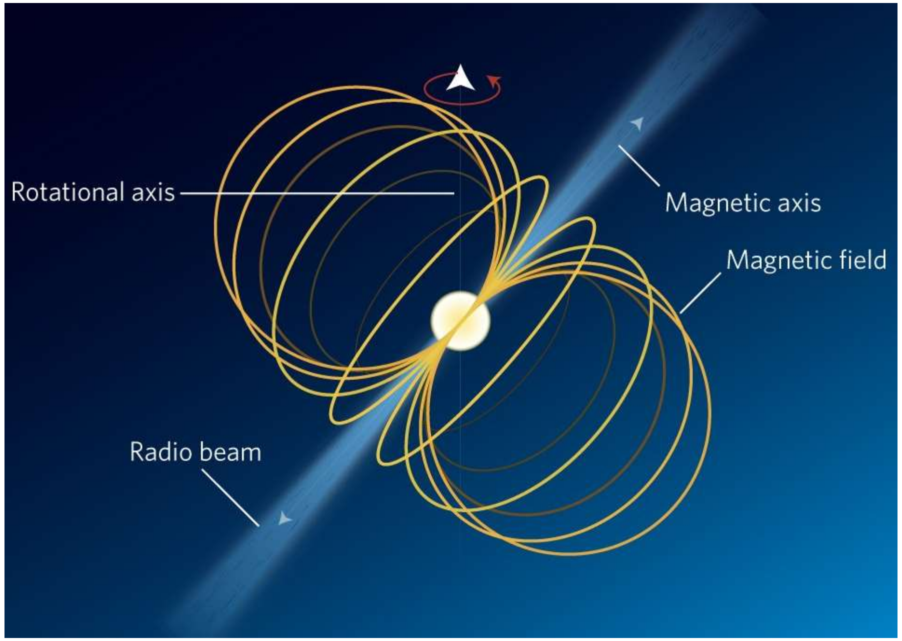
$$E_{\mathrm{max}} \propto B \times R$$

Synchrotron

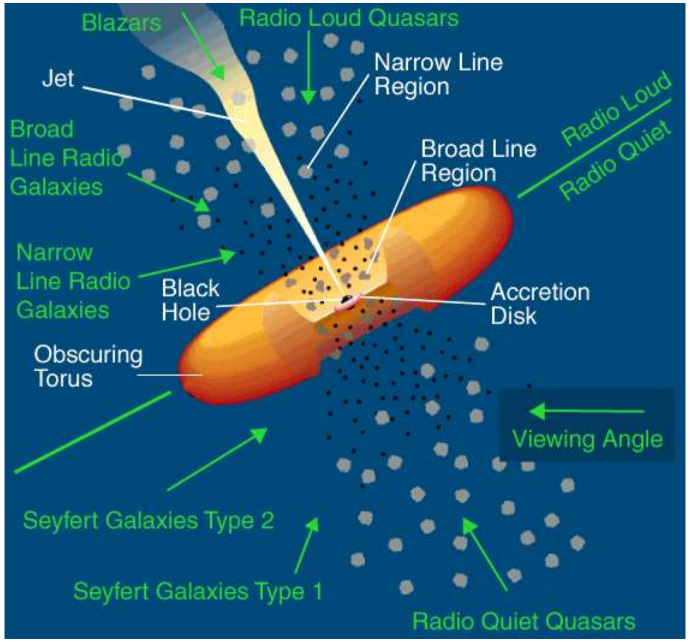


Production – Bottom-up – Cosmic Accelerators

- Neutron star

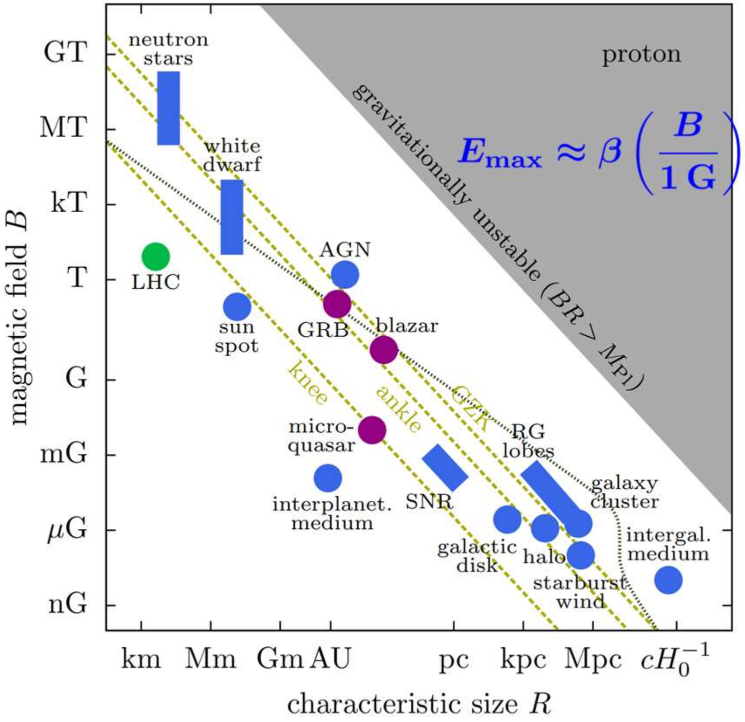


- AGN and supermassive BH



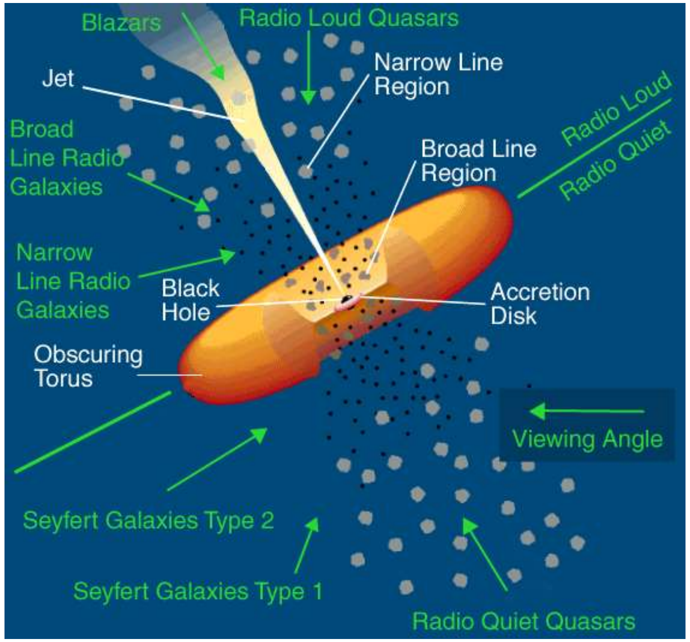
Production – Bottom-up – Cosmic Accelerators

- Acceleration mechanisms
  - Diffusive shock acceleration
  - Maximum energy attainable (Hillas plot)



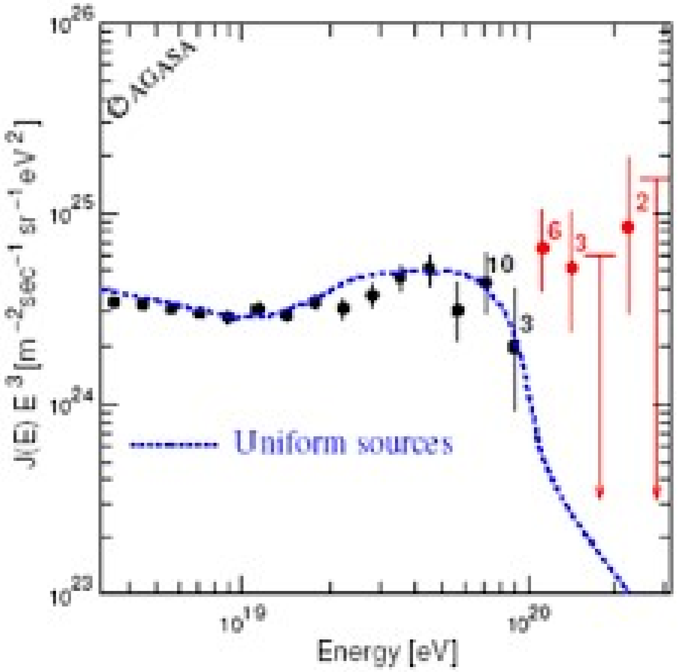
$$E_{\max} \approx \beta \left(\frac{B}{1\,\mathrm{G}}\right)\left(\frac{R}{1\,\mathrm{pc}}\right)\ \mathrm{ZeV}$$

- Acceleration sites
  - **AGN** – supermassive BH, jets and lobes
  - SBG – containing GRB, Magnestar
  - Galaxy clusters, filaments, …

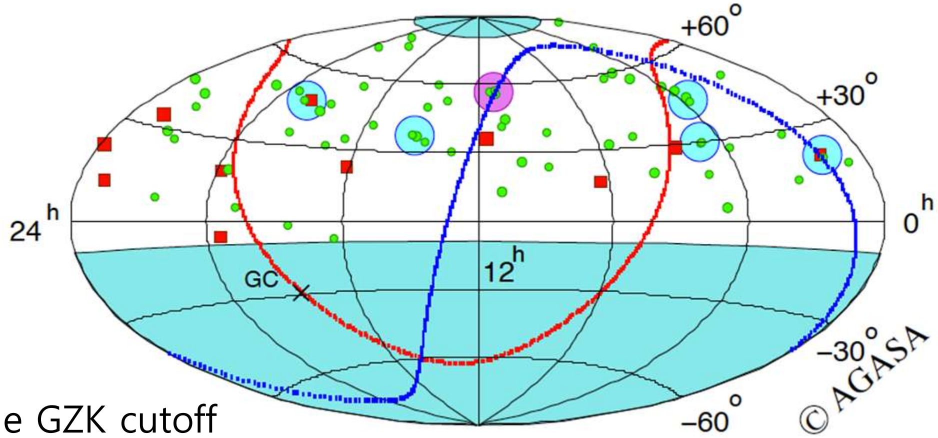


Issues – AGASA results

- AGASA (Hayashida et al. 2000)



Absence of the GZK cutoff



Isotropic with small clustering

- **Big puzzle**
  - Excessive super-GZK CR → Sources within GZK radius
  - Matter (~ galaxies) distribution within GZK radius
    – concentrated along a plane called super-galactic plane.
  - Isotropic distribution of CR → Violation of GZK?

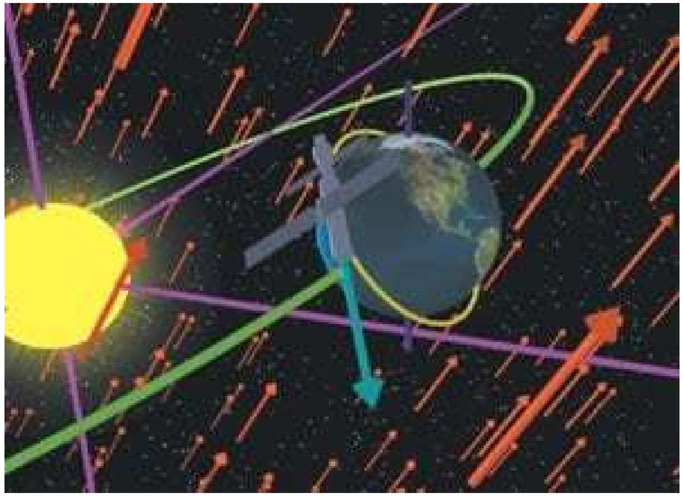
Crazy ideas

- Super-heavy dark matter

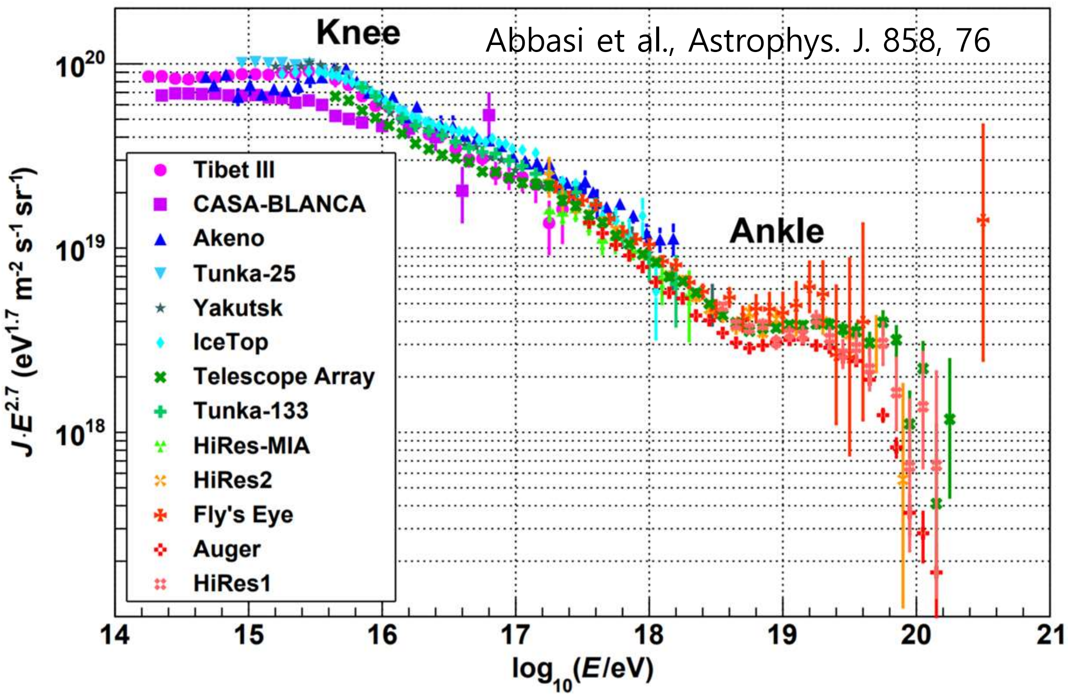
Figure 7. Dark matter may be much more massive than usually assumed, much more massive than wimpy WIMPS, perhaps in the WIMPZILLA class.

In perhaps the greatest image every to make it into a scientific paper, Figure 7 of Kolb, Chung, and Riotto's paper from 20 years ago highlights what a WIMPzilla might look like. The illustration is not to scale.
KOLB, CHUNG AND RIOTTO, 1998

- Lorentz symmetry violation



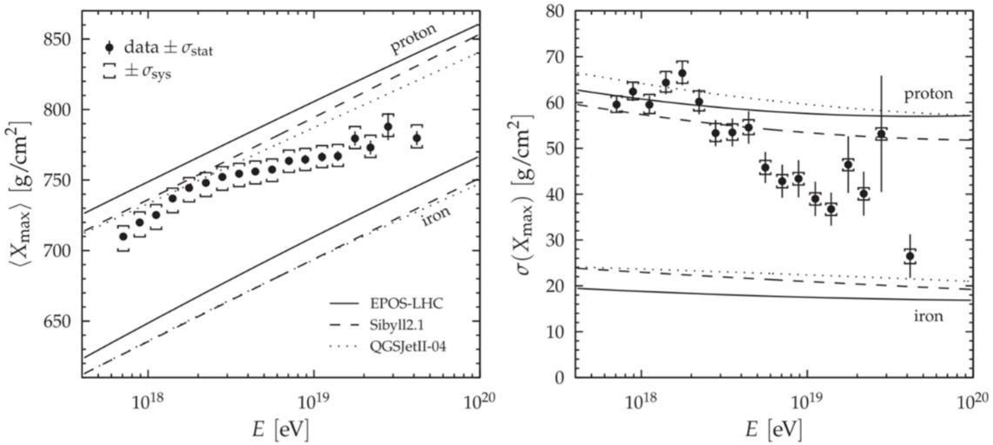
Issues – Energy spectrum

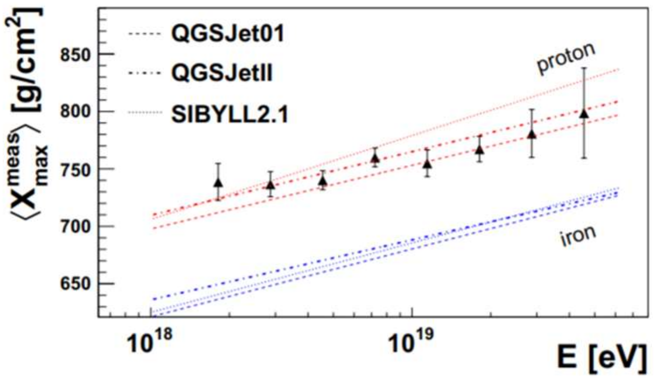


- Auger / TA – Energy scale difference
- Knee
  - Steep Fall → End of injection spectrum?
  - Astrophysical model – light to heavy nuclei
  - Leaky box model – Leakage of GCR
  - Interaction model – New physics in the interaction with the atmosphere
- Ankle
  - Rise → New component?
  - Ankle model – GCR → EGCR transition
  - Dip model – Pile up of GZK secondary
- GZK suppression
  - 1990s, AGASA – No GZK suppression
  - Confirmed by 2010s, HiRes, Auger, TA

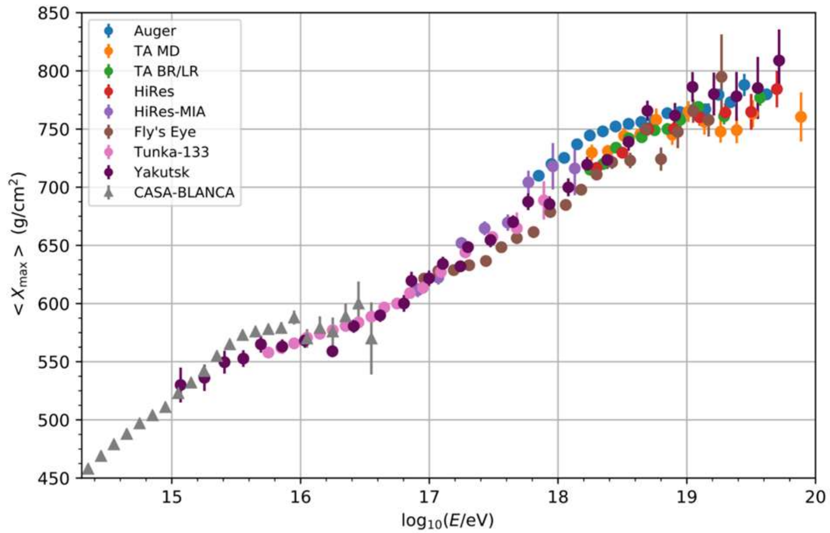
Issues – Composition

- $\boldsymbol{X}_{\mathbf{max}}$ – Auger vs TA



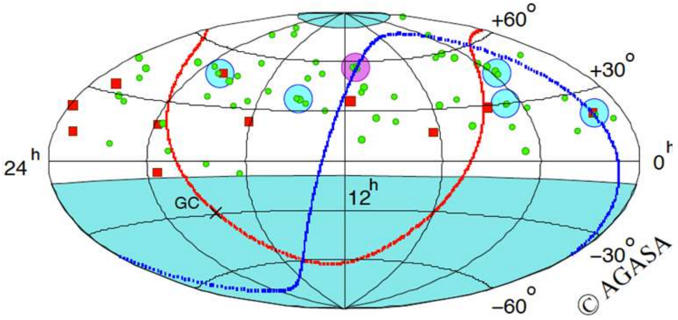


- Composition
  - Auger data favor heavy elements, while TA data stay at proton at high energies.
  - All $\boldsymbol{X}_{\mathbf{max}}$ results are compatible within statistical errors.



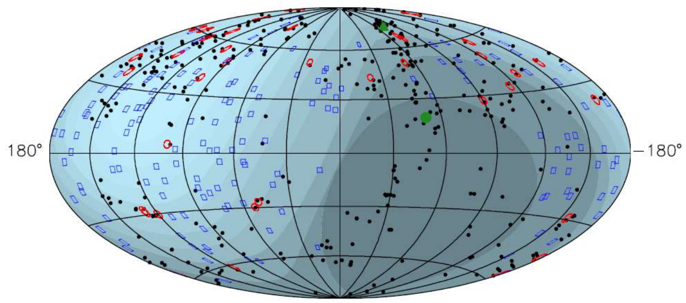
Issues – Arrival directions

- AGASA (Hayashida et al. 2000)



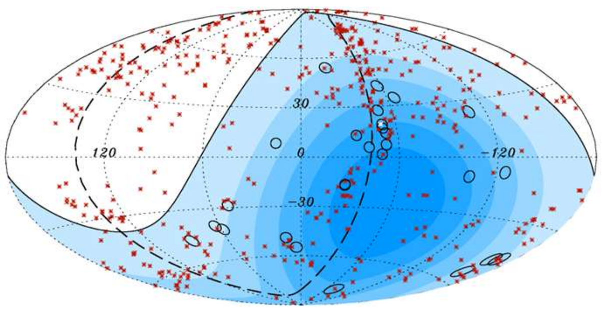
Isotropic, small clustering

- HiRes (Abbasi et al. 2008)



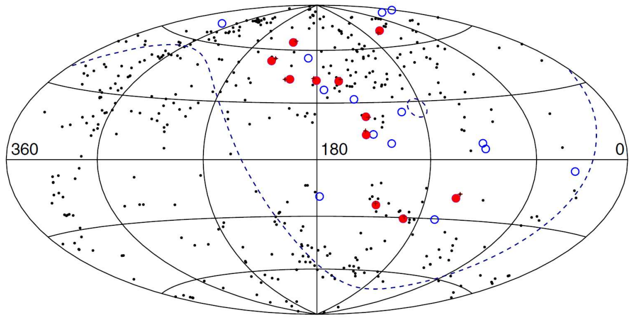
Anisotropic

- Auger (Abreu et al. 2010)



Anisotropic, Correlation with AGN

- TA (Abu-Zayyad et al. 2012)

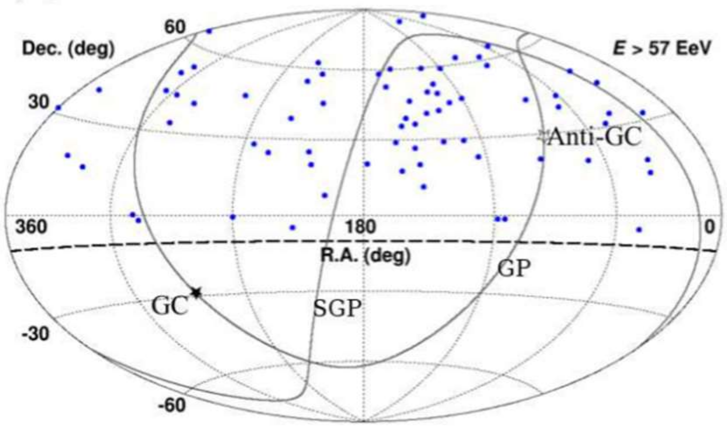


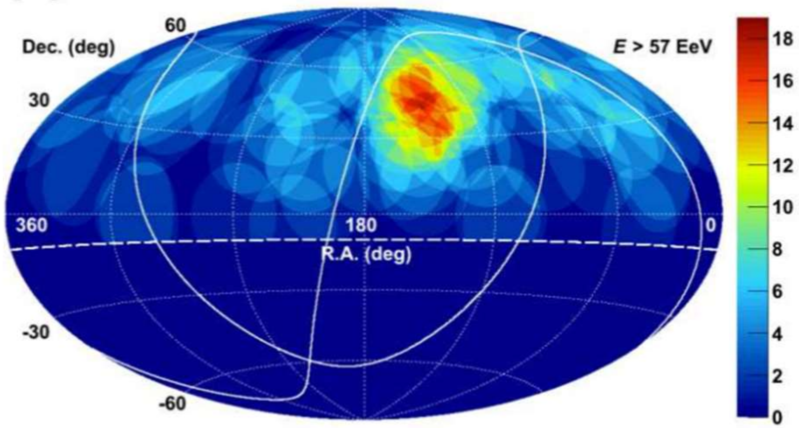
Anisotropic, Correlation with AGN

- Isotropy at low energies
  - Below Ankle – GCR
    – Strong GMF
  - Above Ankle – EGCR
    – Uniformly distributed sources
- Anisotropy above GZK energy
  - Sources within GZK radius
    – Not uniform → anisotropic
  - Influence of EGMF
    – Not strong (hopefully)
- Correlations of UHECR and Sources within GZK radius
  - UHECR – E > 57 EeV (Auger, TA)
  - Sources within 100 Mpc
  - Influence of EGMF, GMF
    – CR composition?

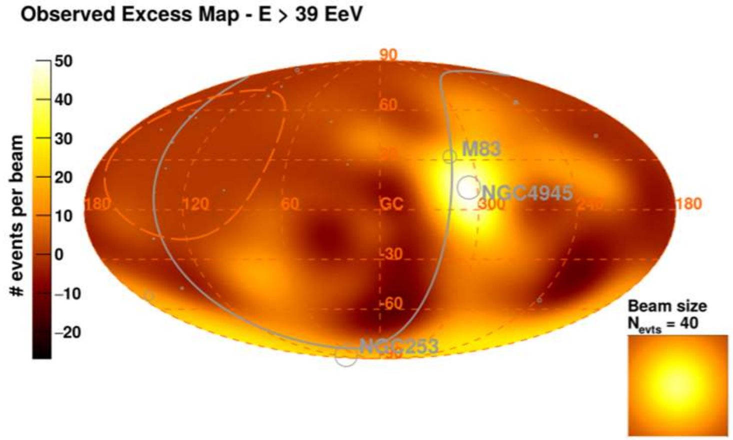
Issues – Arrival directions

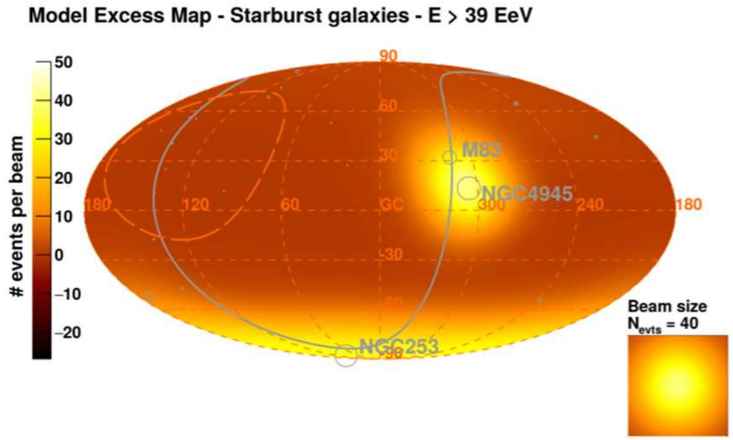
- TA – Hot Spot : $E \geq 57\,\mathrm{EeV}$





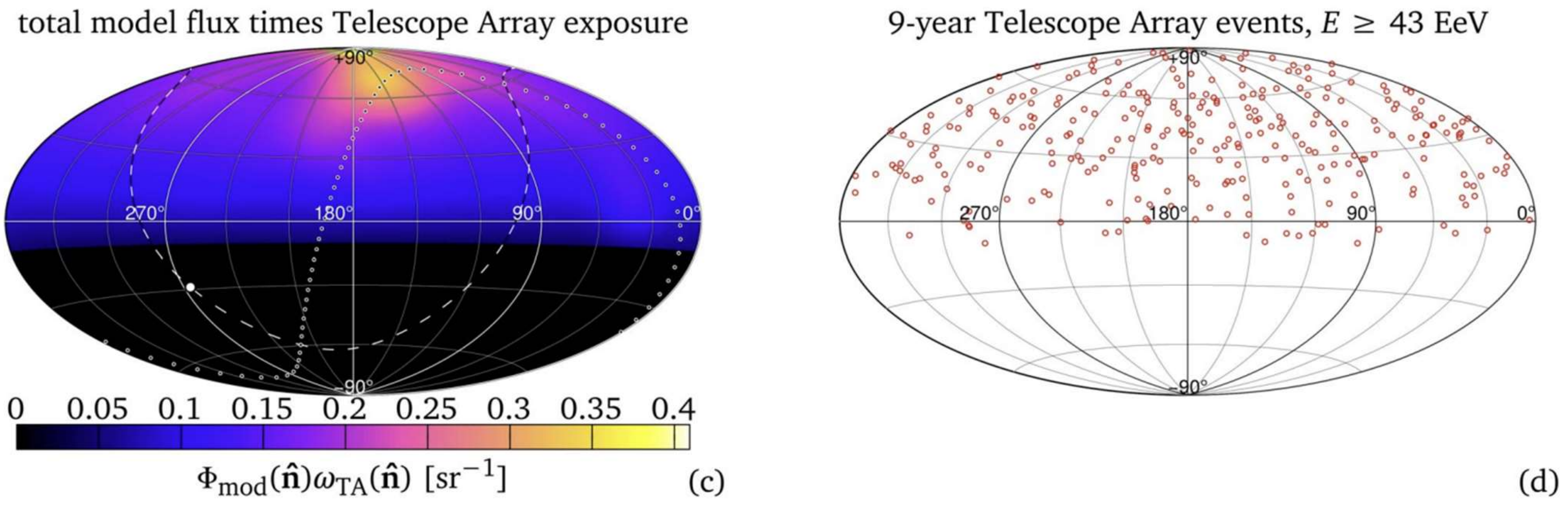
- Auger – Correlation with SBG : $E \geq 39\,\mathrm{EeV}$





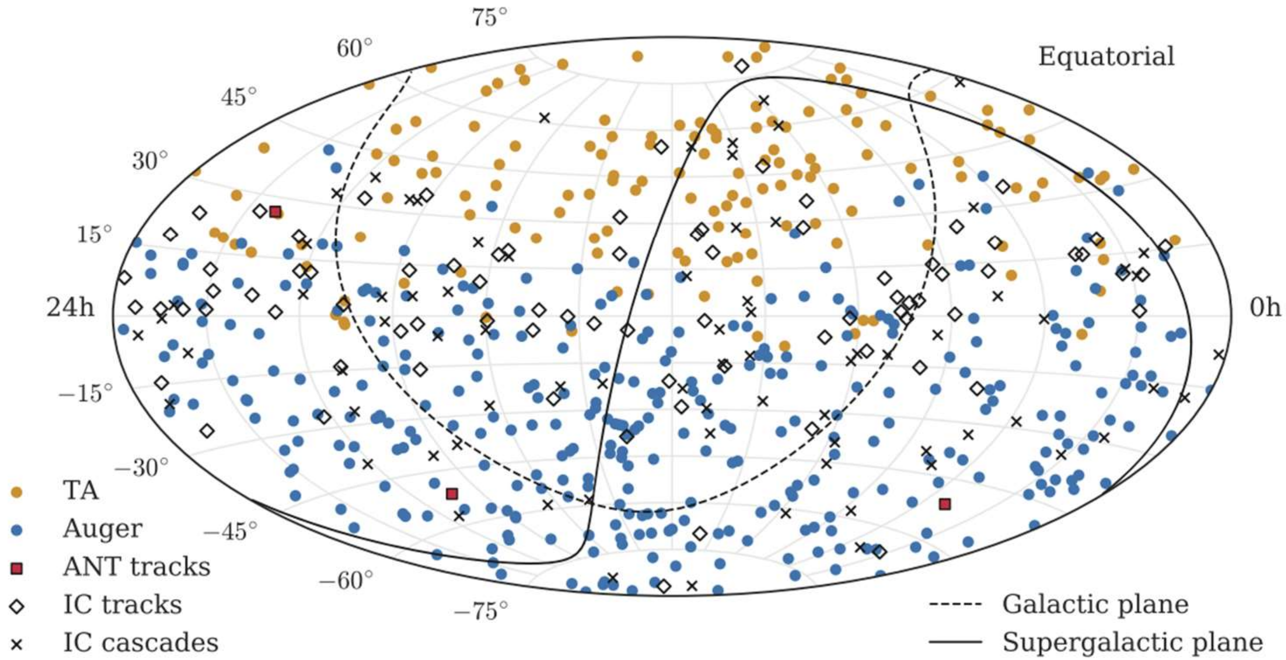
Correlation with SBG – TA

- TA UHECR and SBG correlation   Astrophys.J.Lett. 867 (2018) 2, L27
  - 23 nearby SBG
  - TA UHECR with $E \geq 43\ \mathrm{EeV}$ (Corresponding to $39\ \mathrm{EeV}$ of Auger energy)
  - Consistent with both isotropy and Auger claim (SBG fraction 9.7%, correlation angle 12.9°)

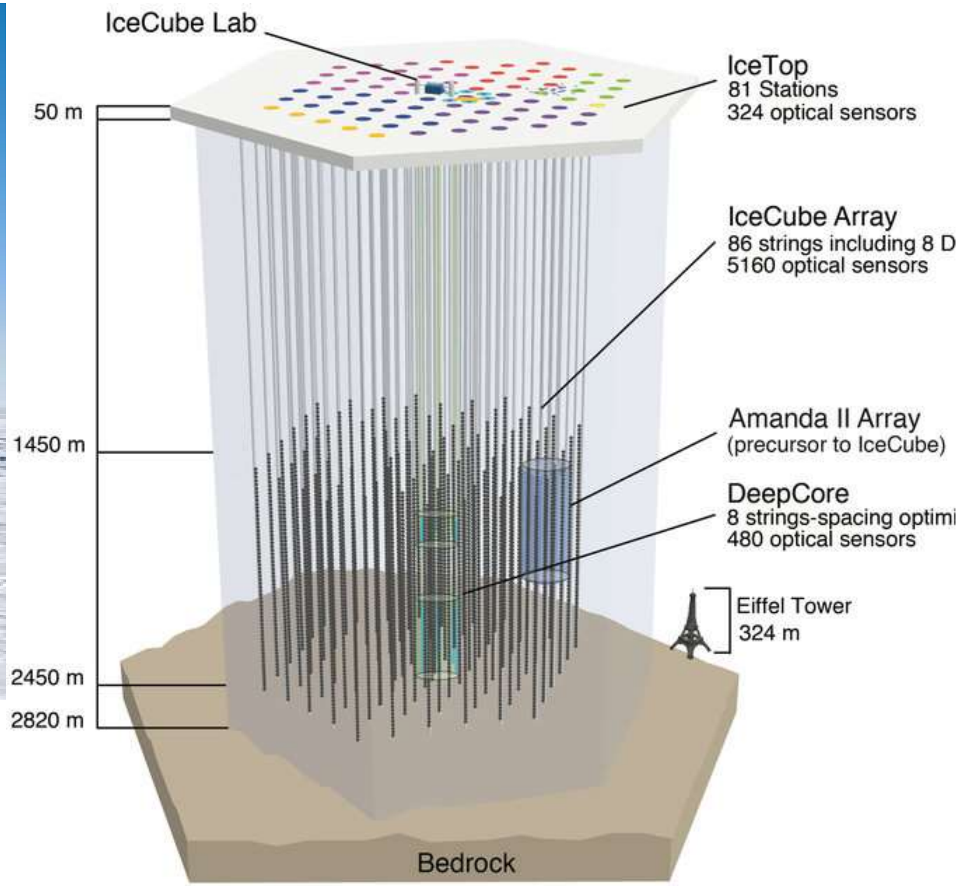


Multi Messengers – UHECR & Neutrinos

- Coincidence of high-energy neutrinos and UHECR
  - Observed data from (ANTARES+IceCube)+(Auger+TA)
  - JCAP 01 (2016) 037
    - ➢ Correlation – 3σ at 22°
  - ApJ 934, 164 (2022)
    - ➢ No significant correlation

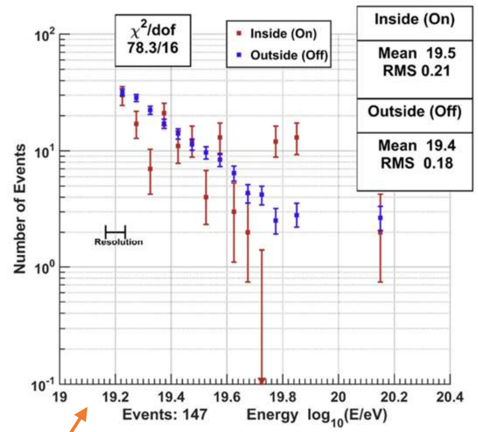


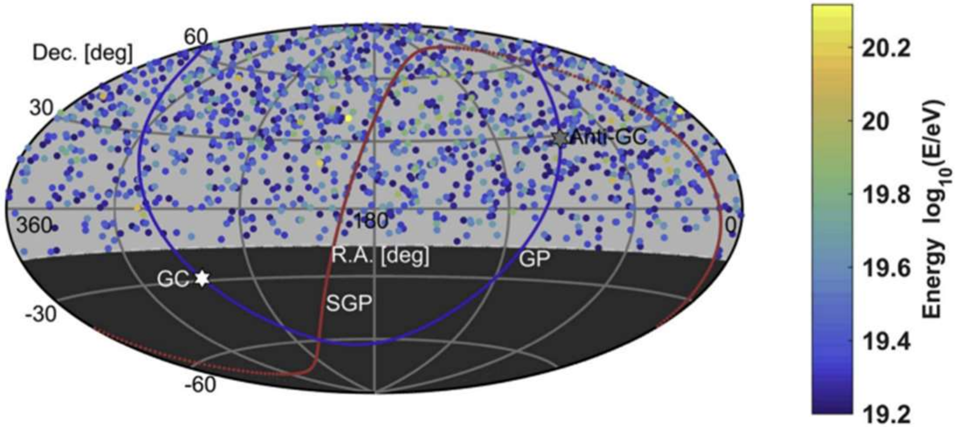
IceCube Neutrino Observatory

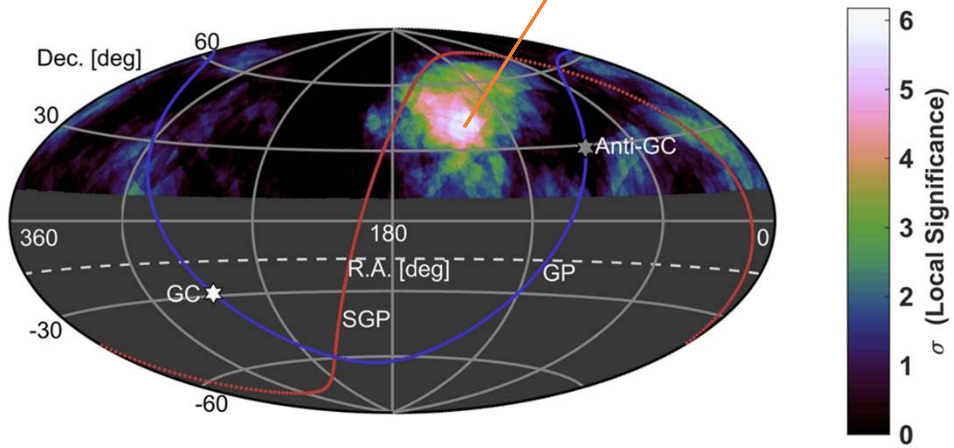


TA hot spot – Energy spectrum

- Energy spectrum anisotropies   Astrophys.J. 862 (2018) 91
  - TA 7-year data with $E \geq 10^{19.2}$ eV
  - Scan the sky with circular window of equal exposure (14% – adjusted)
  - Comparison method for energy spectrum
    - ➢ Binned Poisson likelihood ratio goodness of fit (GOF) test
  - Maximum significance at $(\alpha = 139°, \delta = 45°)$ with $p = 9 \times 10^{-5}$ (3.74σ)







Combined analysis – AD & E – TA

- Correlation between arrival directions and energy inverses
  - TA 7-year and 10-year data
  - Blind search for magnetic multiplets (point-like sources) –
    Scan the sky with wedge windows (shape adjusted) to examine
    the correlation between the angular distance
    from the source (position adjusted) and the energy inverse of CR
  - Comparison method for correlation – Kendal's τ ranked correlation
  - Supergalactic cosmic-ray multiplet
    Significant correlations along the supergalactic plane

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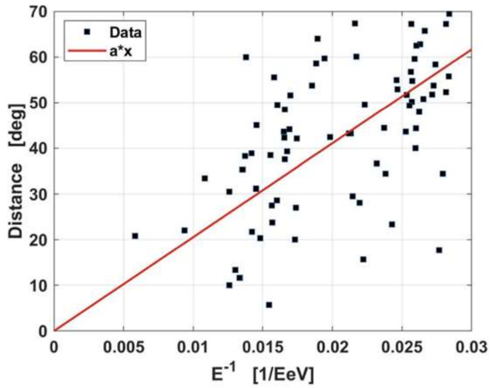
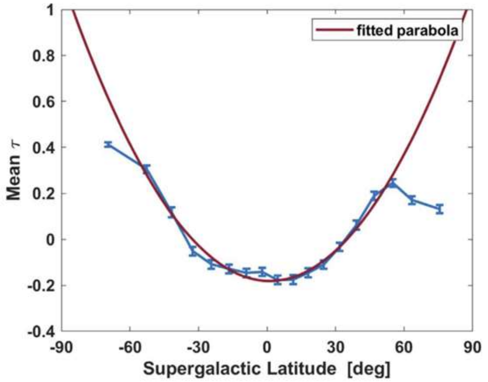
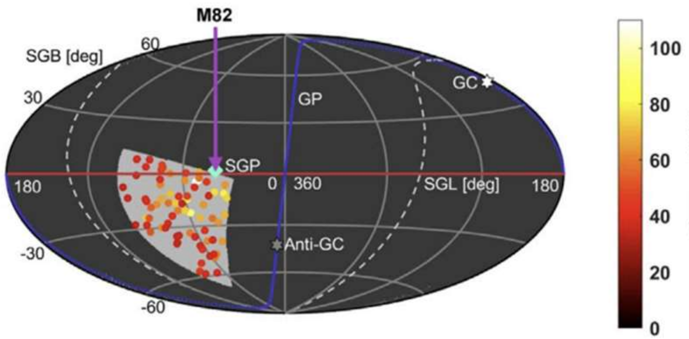
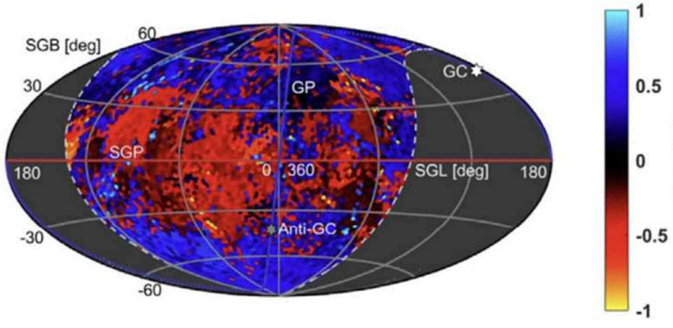






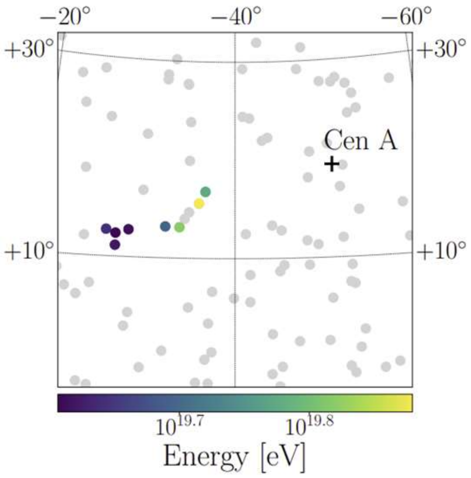


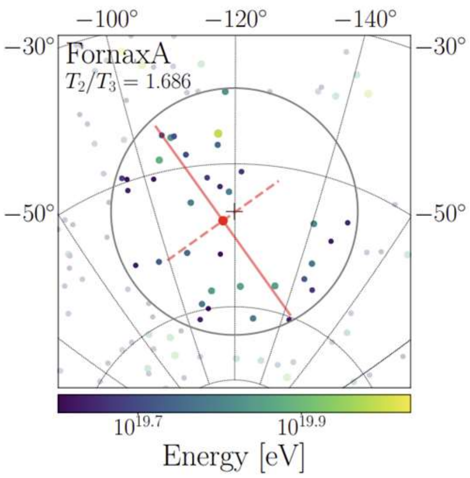
Combined analysis – AD & E – Auger

JCAP 06 (2020) 017
Eur.Phys.J.C 75 (2015) 269

- Correlation between arrival directions and energy inverses
  - Auger 14.5-year data
  - All-sky blind search and nearby-source-based search
    - ➢ Correlation between their arrival direction and the inverse of their energy → **Multiplet**
    - ➢ Principal axis analysis aimed to detect the elongated patterns → **Thrust**
  - No statistically significant features

Isotropic chance probabilities			
Target	Multiplets (40 EeV)	Thrust ratio (20 EeV)	Thrust ratio (40 EeV)
Cen A	1.2×10^{-2}	0.75	0.42
M 87	0.61	0.44	0.85
Fornax A	0.96	0.21	1.9×10^{-2}
NGC 253	0.54	0.98	0.88
NGC 4945	0.25	2.9×10^{-2}	3.7×10^{-2}
Circinus	0.99	0.82	0.58
M 83	0.20	0.14	0.54
NGC 4631	—	0.59	0.85
NGC 1808	0.61	0.63	0.77
NGC 1068	0.75	6.0×10^{-2}	0.29



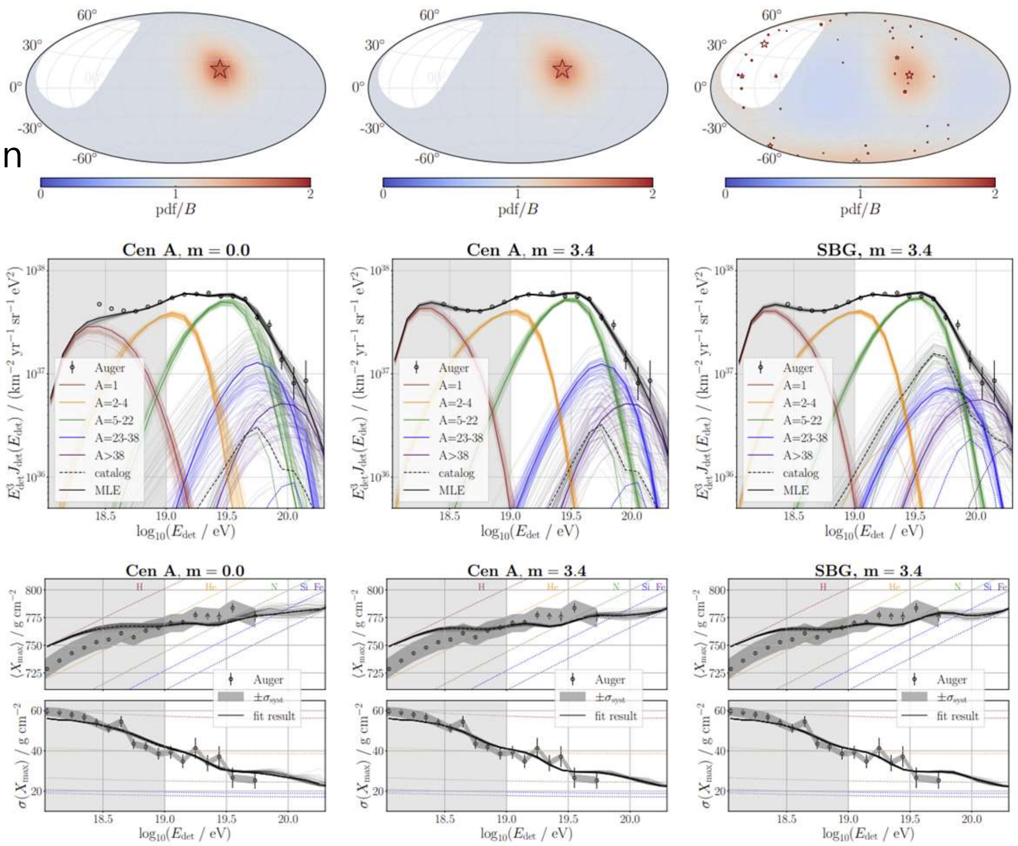


Combined analysis – Auger

JCAP 01 (2024) 022

- Source model – 9 parameters
  - Foreground (Cen. A, SBGs) + Background
- Auger data set
  - Arrival directions, Energy spectrum, Composition
- Best fit
  - SBG – 20% at 40 EeV, Blurring 20°

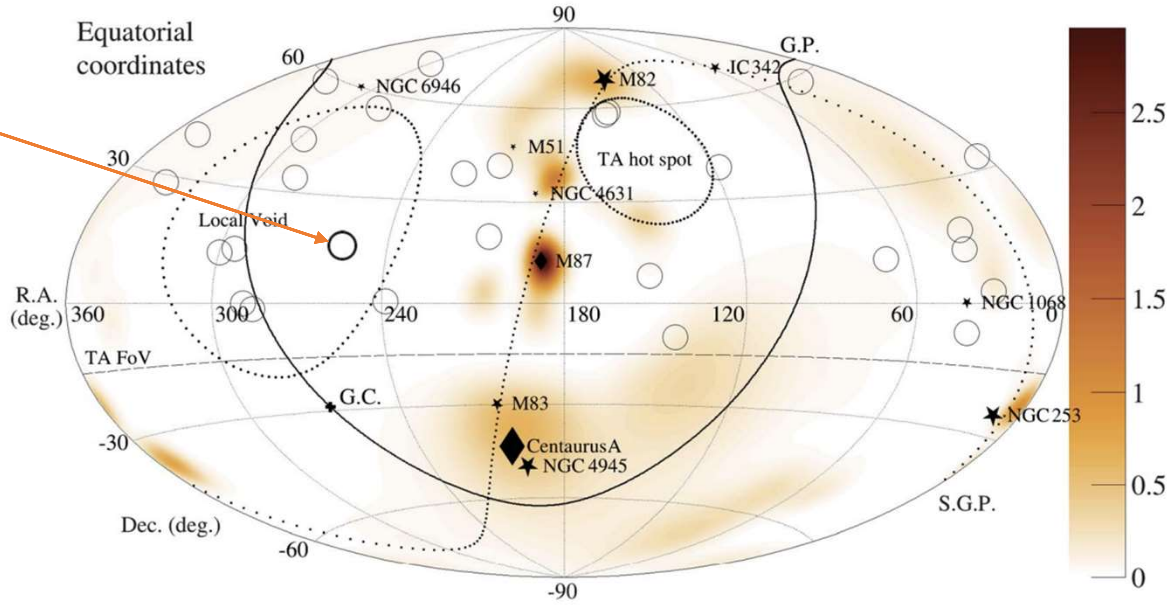
	Cen A, $m = 0$ (flat)		Cen A, $m = 3.4$ (SFR)		SBG, $m = 3.4$ (SFR)	
	posterior	MLE	posterior	MLE	posterior	MLE
γ	$-1.67^{+0.48}_{-0.47}$	-2.21	$-3.09^{+0.23}_{-0.24}$	-3.05	$-2.77^{+0.27}_{-0.29}$	-2.67
$\log_{10}(R_{\rm cut}/{\rm V})$	$18.23^{+0.04}_{-0.06}$	18.19	$18.10^{+0.02}_{-0.02}$	18.11	$18.13^{+0.02}_{-0.02}$	18.13
f_0	$0.16^{+0.06}_{-0.14}$	0.028	$0.05^{+0.01}_{-0.03}$	0.028	$0.17^{+0.06}_{-0.08}$	0.19
$\delta_0/°$	$56.5^{+29.4}_{-12.8}$	16.5	$27.6^{+2.7}_{-16.3}$	16.8	$22.2^{+5.3}_{-4.0}$	24.3
$I_{\rm H}$	$5.9^{+2.5}_{-1.7} \times 10^{-2}$	7.1×10^{-2}	$8.3^{+2.0}_{-8.3} \times 10^{-3}$	1.6×10^{-5}	$6.4^{+1.3}_{-6.4} \times 10^{-3}$	4.3×10^{-5}
$I_{\rm He}$	$2.3^{+0.3}_{-0.5} \times 10^{-1}$	1.9×10^{-1}	$1.3^{+0.2}_{-0.2} \times 10^{-1}$	1.4×10^{-1}	$1.7^{+0.3}_{-0.4} \times 10^{-1}$	1.8×10^{-1}
$I_{\rm N}$	$6.3^{+0.3}_{-0.3} \times 10^{-1}$	6.2×10^{-1}	$7.4^{+0.3}_{-0.3} \times 10^{-1}$	7.3×10^{-1}	$7.4^{+0.3}_{-0.3} \times 10^{-1}$	7.4×10^{-1}
$I_{\rm Si}$	$6.5^{+3.6}_{-3.3} \times 10^{-2}$	9.9×10^{-2}	$9.2^{+3.2}_{-2.3} \times 10^{-2}$	1.1×10^{-1}	$5.7^{+2.5}_{-3.1} \times 10^{-2}$	5.4×10^{-2}
$I_{\rm Fe}$	$1.6^{+0.7}_{-1.0} \times 10^{-2}$	2.0×10^{-2}	$2.5^{+0.8}_{-0.9} \times 10^{-2}$	2.3×10^{-2}	$2.5^{+0.8}_{-0.9} \times 10^{-2}$	2.3×10^{-2}
$\log b$	-264.0 ± 0.2		-272.6 ± 0.2		-266.9 ± 0.1	
D_E $(N_J = 14)$		22.3		28.5		33.3
$D_{X_{\max}}$ $(N_{X_{\max}} = 74)$		124.9		130.6		126.2
D		147.2		159.1		159.5
$\log \mathcal{L}_{\rm ADs}$		10.5		10.4		13.3
$\log \mathcal{L}$		-239.1		-245.1		-242.4



The highest energy event by TA SD

- The highest energy event detected by TA SD Science 382 (2023) 903
  - $E = 2.4 \times 10^{20}$eV
  - **Amaterasu** (天照) particle
  - **No plausible source behind**

TA UHECR with $E \geq 100$ EeV



Discussion and Outlook

- Directions of extended analysis
  - Composition from SD data
    - Multiple observables and Deep learning
  - Combined analysis
    - Multi-messenger –
      Neutrinos, Gamma rays
    - Combined observables –
      Arrival directions, Energy spectrum,
      and Composition
- How to pile up sufficient data
  - Northern hemisphere – TAx4 is running.
  - Space-based detector
  - Radio wave detector array
  - New technologies?
- Theoretical understanding
  - Hadronic physics at energies beyond LHC
  - Acceleration mechanisms
    - Supermassive black holes and jets
    - Detailed modeling
- Wishful thinking
  - **New physics at high energy**
  - **UHECR astronomy**
    - Source identification
    - Injected composition and spectrum
    - Probe of GMF and EGMF