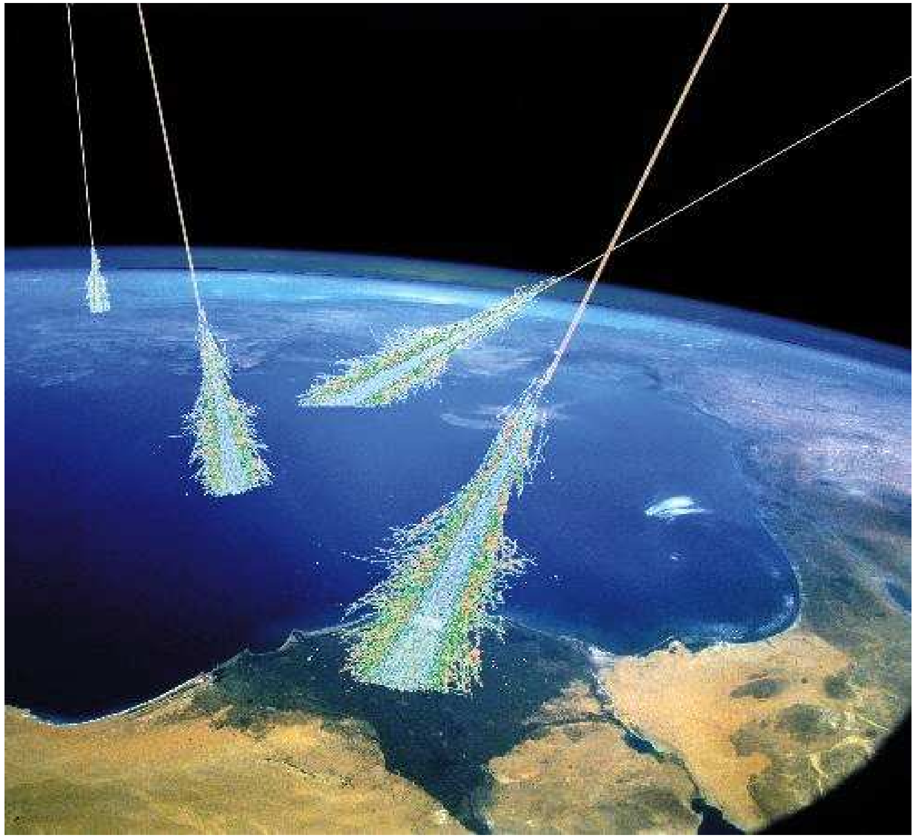
Ultra High Energy Cosmic Rays

Review on Theoretical Sides

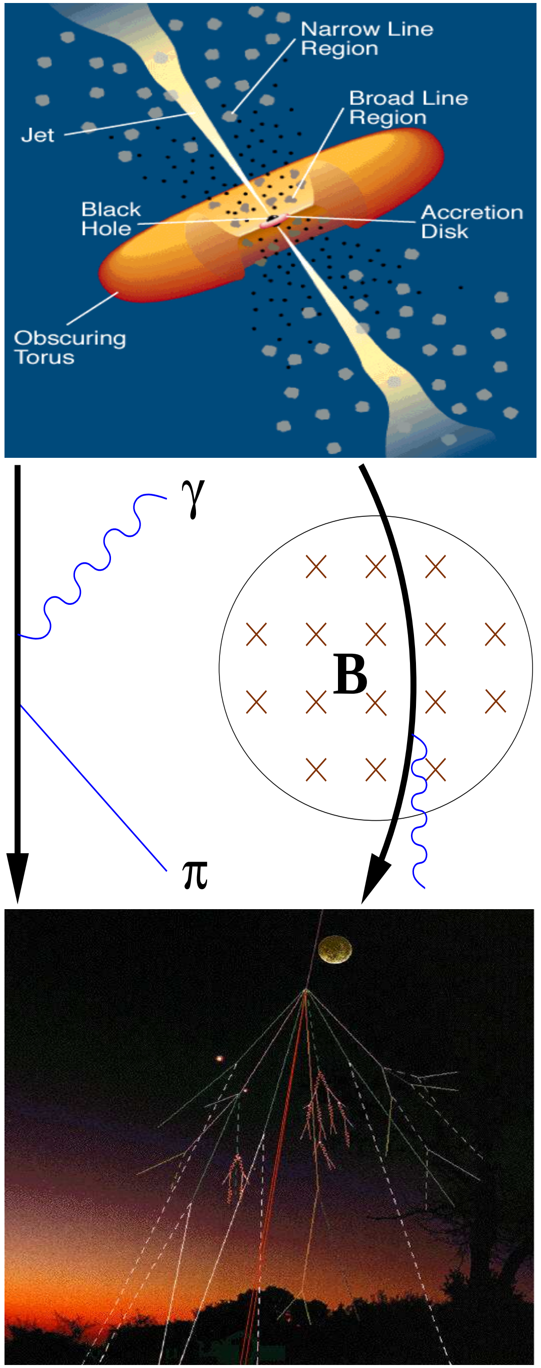


- Overview of Cosmic Rays
  - Observation
  - Propagation
  - Production
- Issues of UHECR
  - Experimental Status
  - Astrophysics Ideas
  - Particle Physics Ideas
- Challenges

Hang Bae Kim (Hanyang Univ.)

"The Dark Side of the Universe", KIAS, May 24, 2005

Ultra High Energy Cosmic Rays



Production

⇑ Acceleration of charged particles

⇓ Decay of superheavy particles

Propagation

Cosmic Background

– Microwave, Radiowave, Neutrino

– Cosmic Magnetic Field

- Energy Loss
- Secondary CR Production
- Deflection and Time Lag

Observation

Atmosphere as Calory meter/Scintillator

- Composition
- Energy Spectrum
- Arrival Directions

Observation

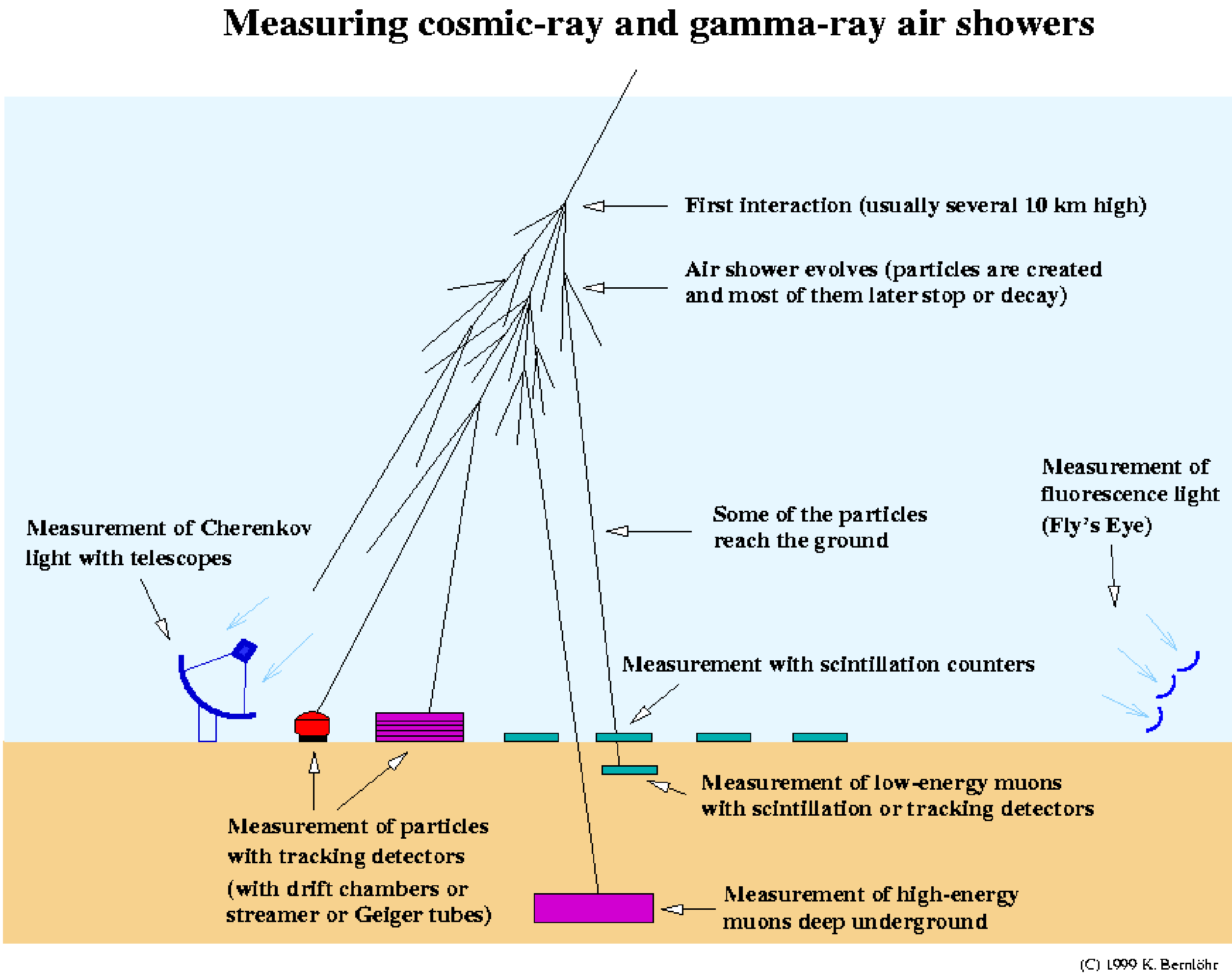
Detection of EAS

- Ground based detector array: AGASA, Auger, . . . , TA, COREA
- Fluorescence light detector: HiRes, Auger, . . . , EUSO, OWL

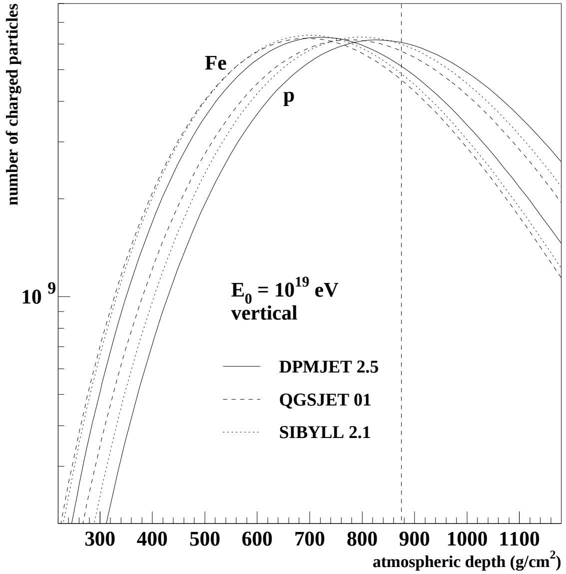
EAS Observables

- Longitudinal development
- Latteral distribution

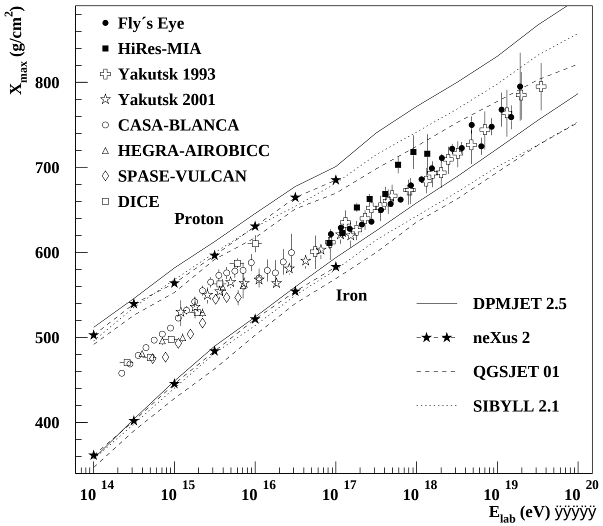
$\Longrightarrow$ Composition, Energy, Arrival Direction



Longitudinal development

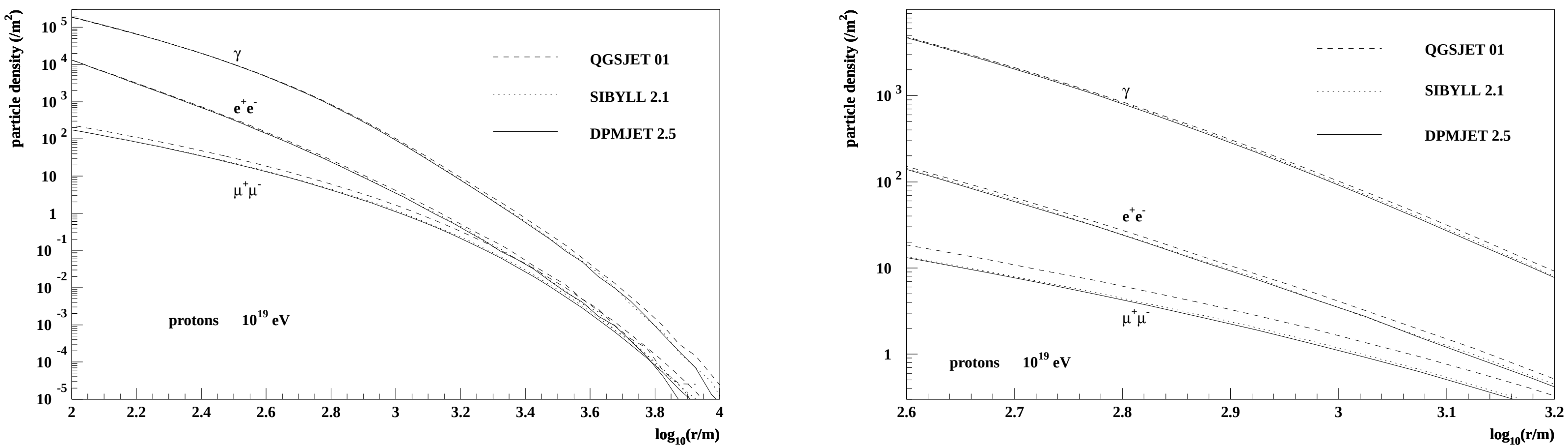


Average longitudinal shower development for vertical proton and iron showers of 10^{19} eV. The dashed vertical line indicates the atmospheric depth of the Auger site.



Shower maximum $\mathbf{X_{max}}$ as function of energy.

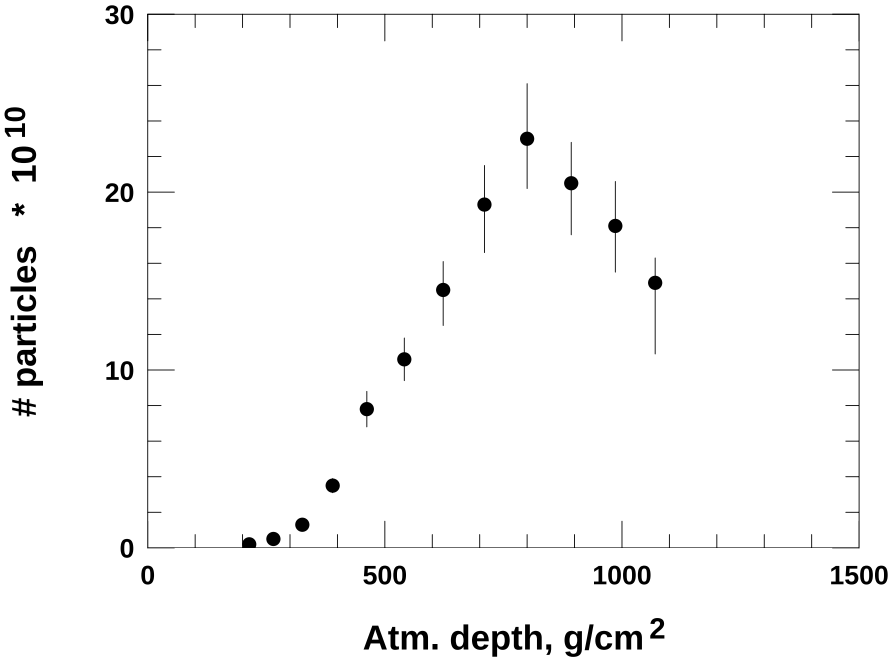
Latteral distribution

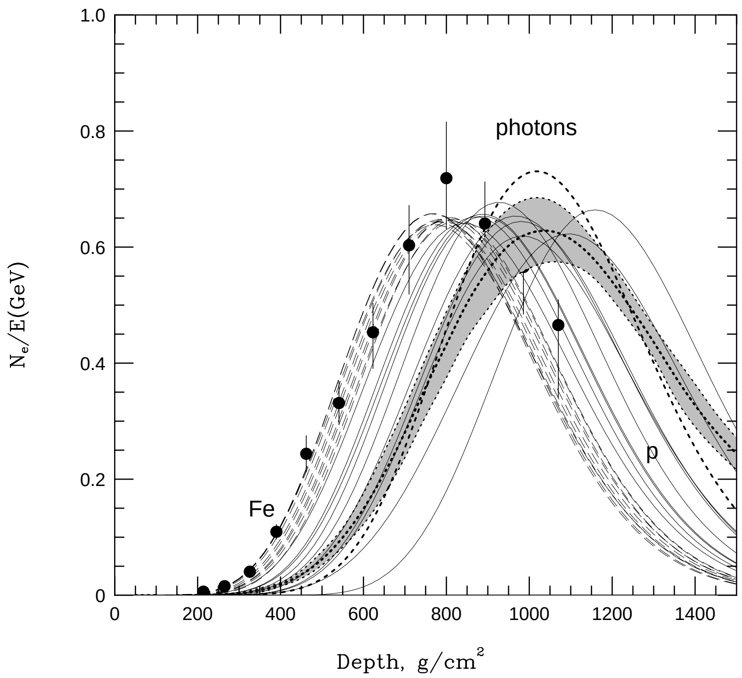


Average lateral distributions of photons, electrons and muons in vertical proton showers of $\mathbf{10^{19}}$ eV.

The Highest Energy Cosmic Ray Event

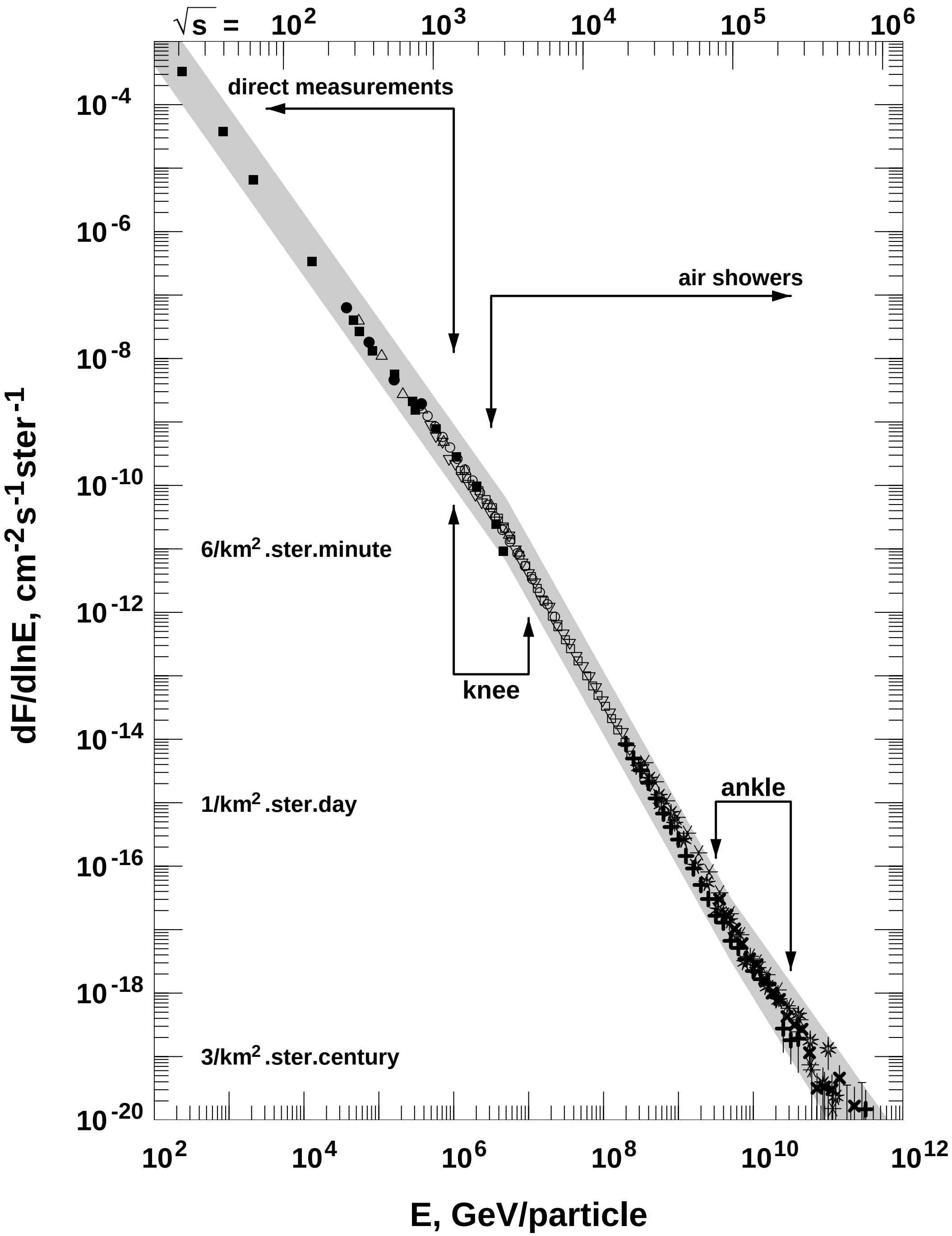
- Observed at Fly's Eye
- Energy $= 3 \times 10^{20}$ eV $\sim$ Kinetic Energy of 170 km/h tennis ball
- Longitudinal development

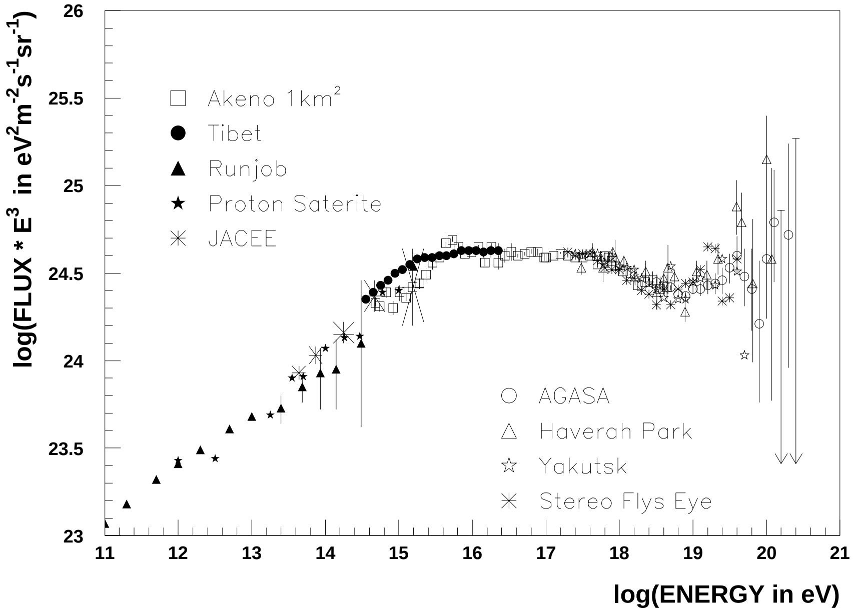


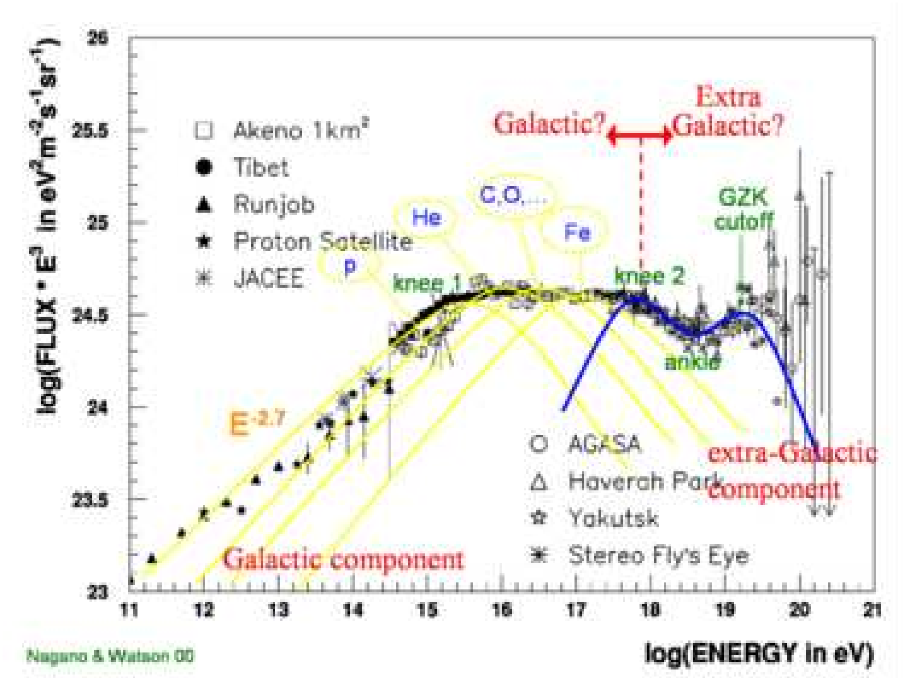


- The primary particles is not a γ-ray.

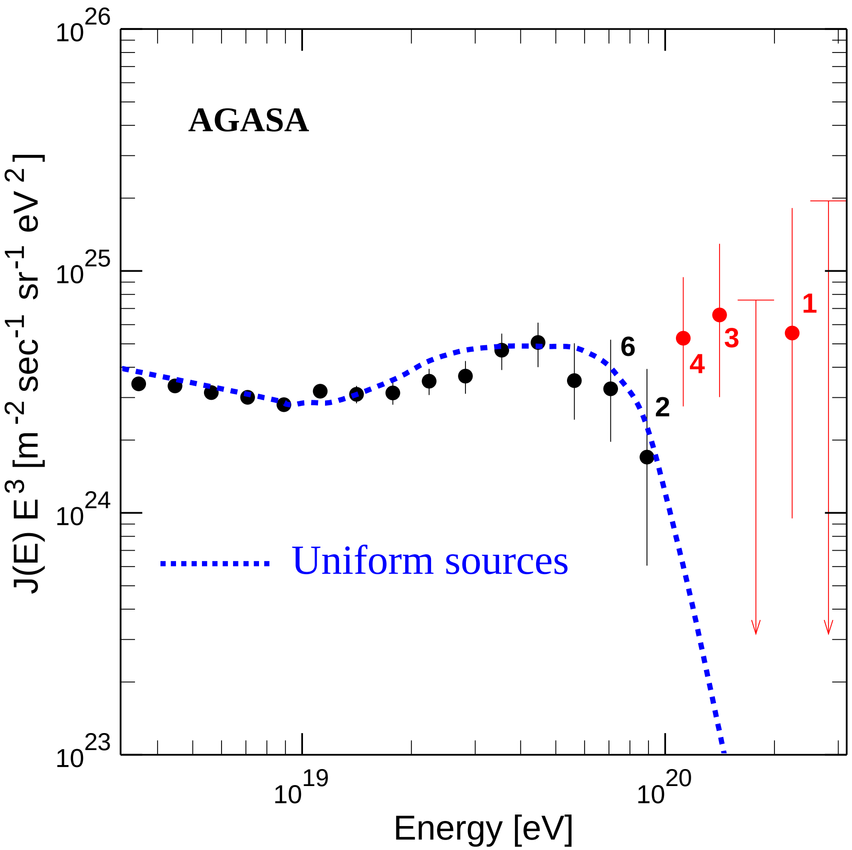
Energy spectrum of CR flux



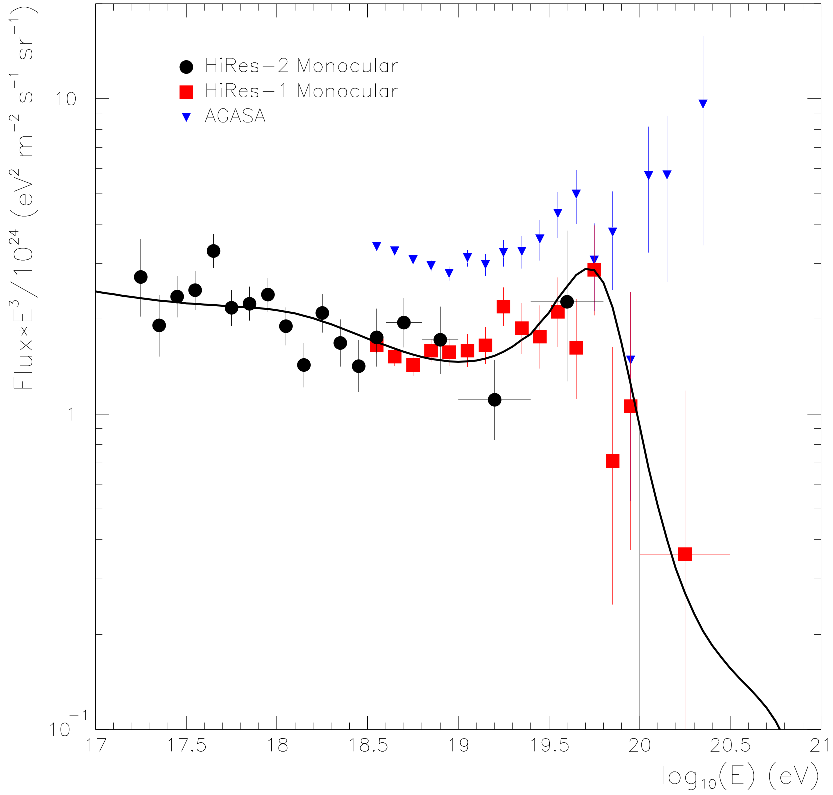




AGASA vs HiRes



Energy spectrum observed with AGASA. The vertical axis is multiplied by $\boldsymbol{E^3}$. Error bars represent the Poisson upper and lower limits at 68% and arrows are 90% C.L. upper limits. Numbers attached to points show the number of events in each energy bin. The dashed curve represents the spectrum expected for extragalactic sources distributed uniformly in the universe, taking account of the energy determination error.



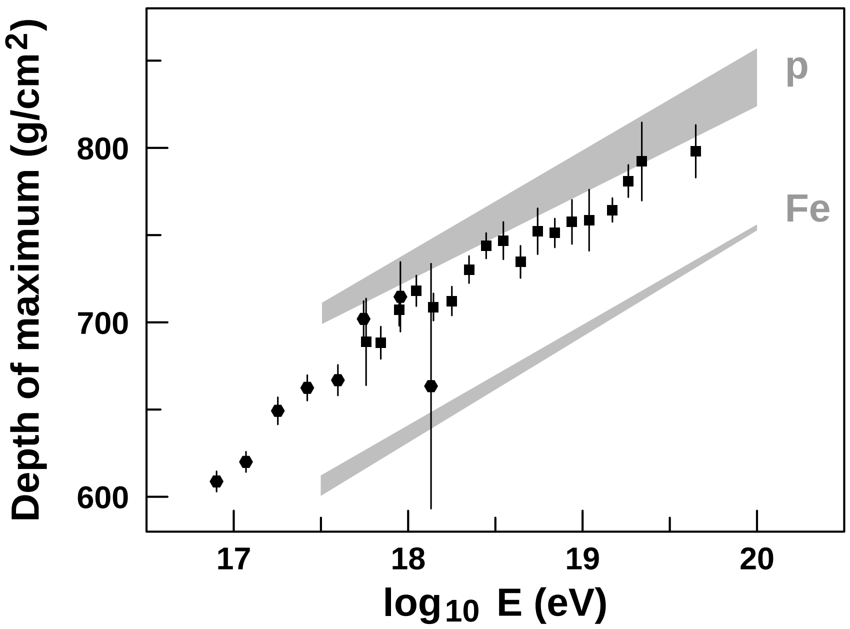
$\boldsymbol{E^3}$ times the UHE Cosmic Ray Flux. Results from the HiRes-I and HiRes-II detectors, and the AGASA experiment are shown. Also shown is a fit to the data assuming a model of galactic and extragalactic sources.

Composition

1GeV – Knee Mostly fully ionized atomic nuclei, H – Fe.
Similar to stellar composition

Above Knee Protons increase, but uncertain

UHECR p(n), γ, $\not\nu$, something else?



Shower Maximum

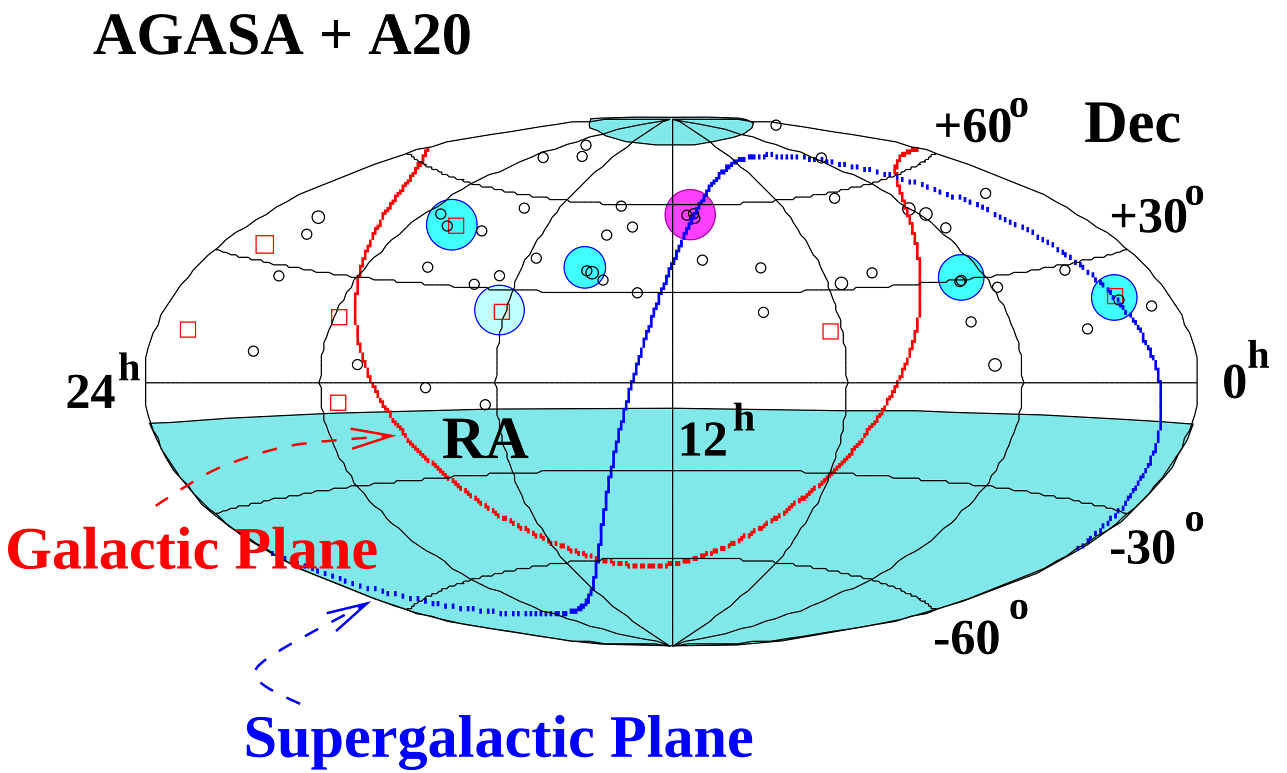
Muon Fraction

Arrival direction distribution

Large scale isotropy

Small (∼4%) anisotropy around $E = 10^{18}$eV
toward the galactic center (AGASA)

UHECR Small scale ($\sim 2.5^\circ$) clustering (AGASA,Yakutsk)



Propagation

Cosmic Background γ, ν

$\Longrightarrow$ **Energy loss, Secondary CR production**

p $N + \gamma \to N + \pi$ **(Photo-pion production)**

threshold energy $E_{\rm th} \approx 6.8 \times 10^{19} \left(\frac{E_{\gamma_B}}{10^{-3}{\rm eV}}\right)^{-1} {\rm eV}$

mean free path $\lambda = \frac{1}{n_{\gamma_B}\sigma} \sim {\rm Mpc}$

attenuation length $l \approx 50{\rm Mpc}$

$\Longrightarrow$ **GZK cutoff**

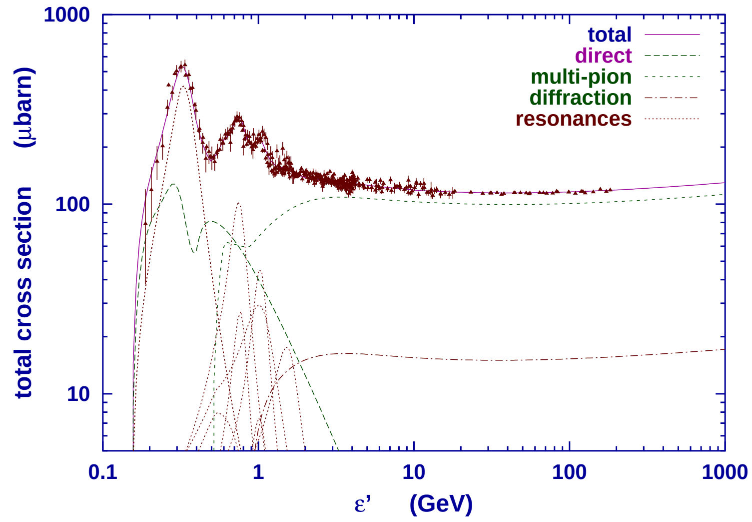
A $A + \gamma_B \to A_1 + A_2$ **(Photo-disintegration)**

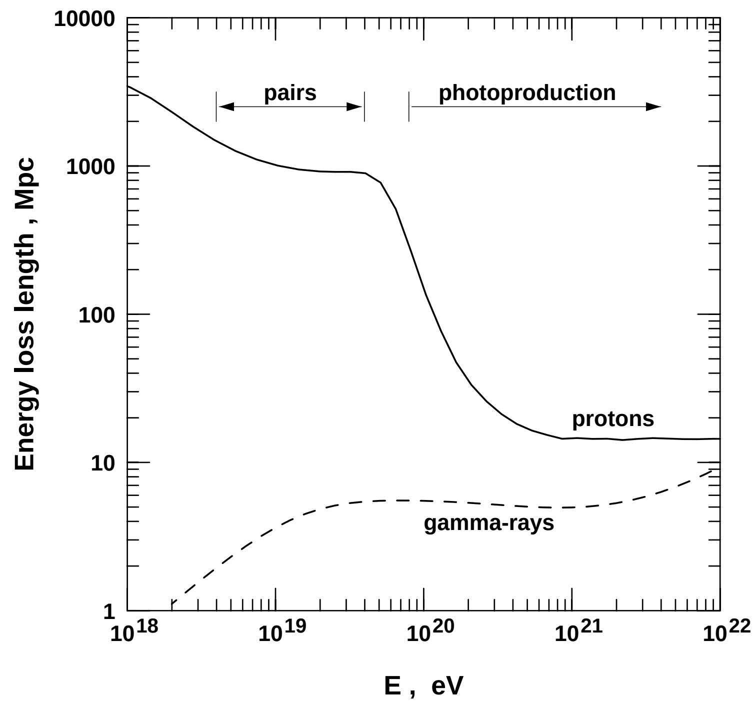
γ $\gamma + \gamma_B \to e^+ + e^-$ **(Pair production)**

$$E_{\rm th} = \frac{m_e^2}{E_{\gamma_B}} \approx 2.5 \times 10^{16} \left(\frac{E_{\gamma_B}}{10^{-3}{\rm eV}}\right)^{-1} {\rm eV}$$

ν $\nu + \nu_B \to Z^* \to f + \bar{f}, \cdots$

$\Longrightarrow$ **Z-burst**

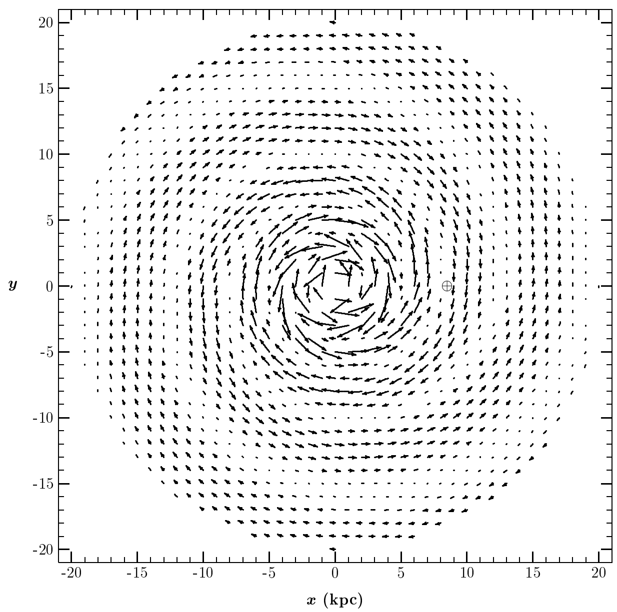




Cosmic Magnetic Field $\Longrightarrow$ Deflection and Time Lag

Gyration Radius $r_g = \frac{p}{qB} = Z^{-1}\left(\frac{E}{10^{18}\text{eV}}\right)\left(\frac{B}{1\mu\text{G}}\right)^{-1}$ kpc

Deflection Angle $\delta\theta = 0.52^\circ Z \left(\frac{E}{10^{20}\text{eV}}\right)^{-1}\left(\frac{d}{1\text{Mpc}}\right)\left(\frac{B}{10^{-9}\text{G}}\right)$



Galactic Magnetic Field (GMF)

Several models

$B_{\text{GMF}} \sim 1\mu\text{G}$, $R_{\text{GAL}} \sim 10\text{kpc}$

$\longrightarrow \delta\theta \sim$ a few $^\circ$ for UHECR

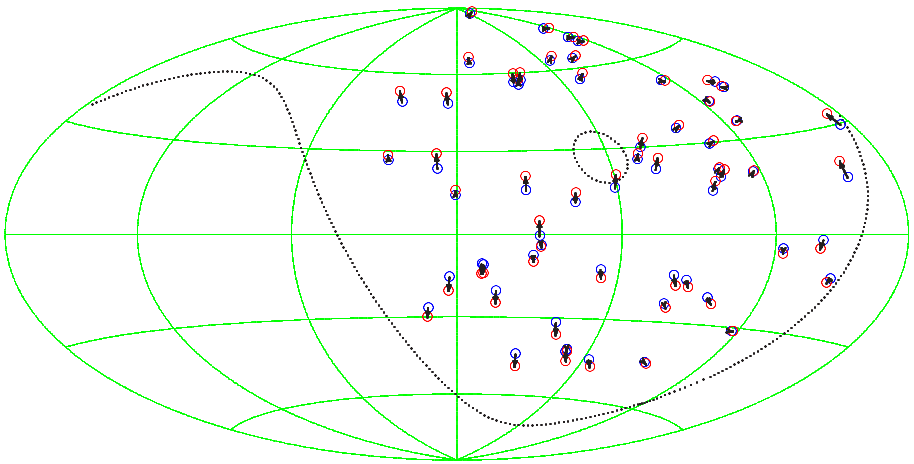
Extra-Galactic Magnetic Field (EGMF)

$$\delta\theta = 0.8^\circ Z \left(\frac{E}{10^{20}\text{eV}}\right)^{-1}\left(\frac{d}{10\text{Mpc}}\frac{l_c}{1\text{Mpc}}\right)\left(\frac{B}{10^{-9}\text{G}}\right)$$

$$\delta\tau = 1.5\times 10^3\text{yr}\, Z^2 \left(\frac{E}{10^{20}\text{eV}}\right)^{-2}\left(\frac{d}{10\text{Mpc}}\right)^2\left(\frac{l_c}{1\text{Mpc}}\right)\left(\frac{B}{10^{-9}\text{G}}\right)^2$$

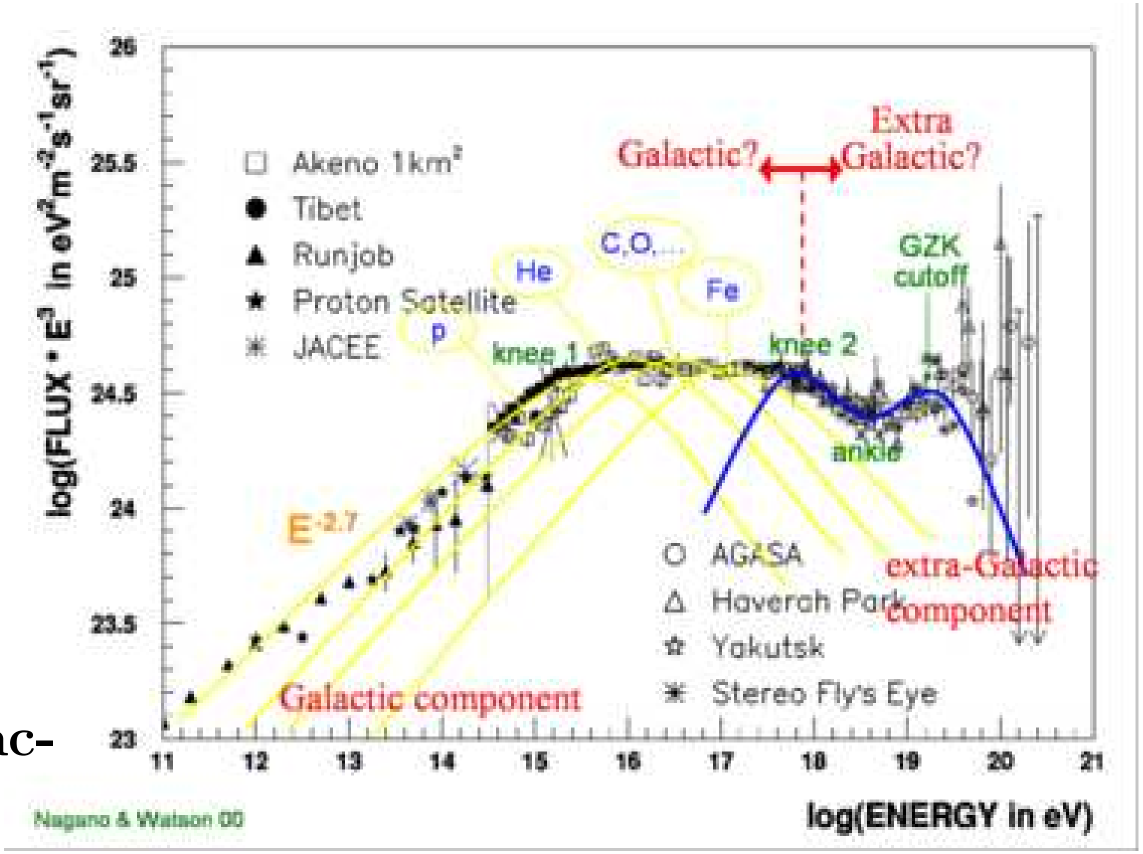
Faraday Rotation Measurements

$\Rightarrow B_{\text{EGMF}} \lesssim 10^{-9} - 10^{-6}\text{G}.$



Simulation of deflection of UHECR by GMF

Production



Below 1GeV

Solar origin

(temporal correlation)

1GeV–Knee

Galactic origin

(probably from SNRs)

Ankle

Possibly crossover from galactic to extragalactic origin

UHECR

Extragalactic origin (isotropy)

Production Mechanisms

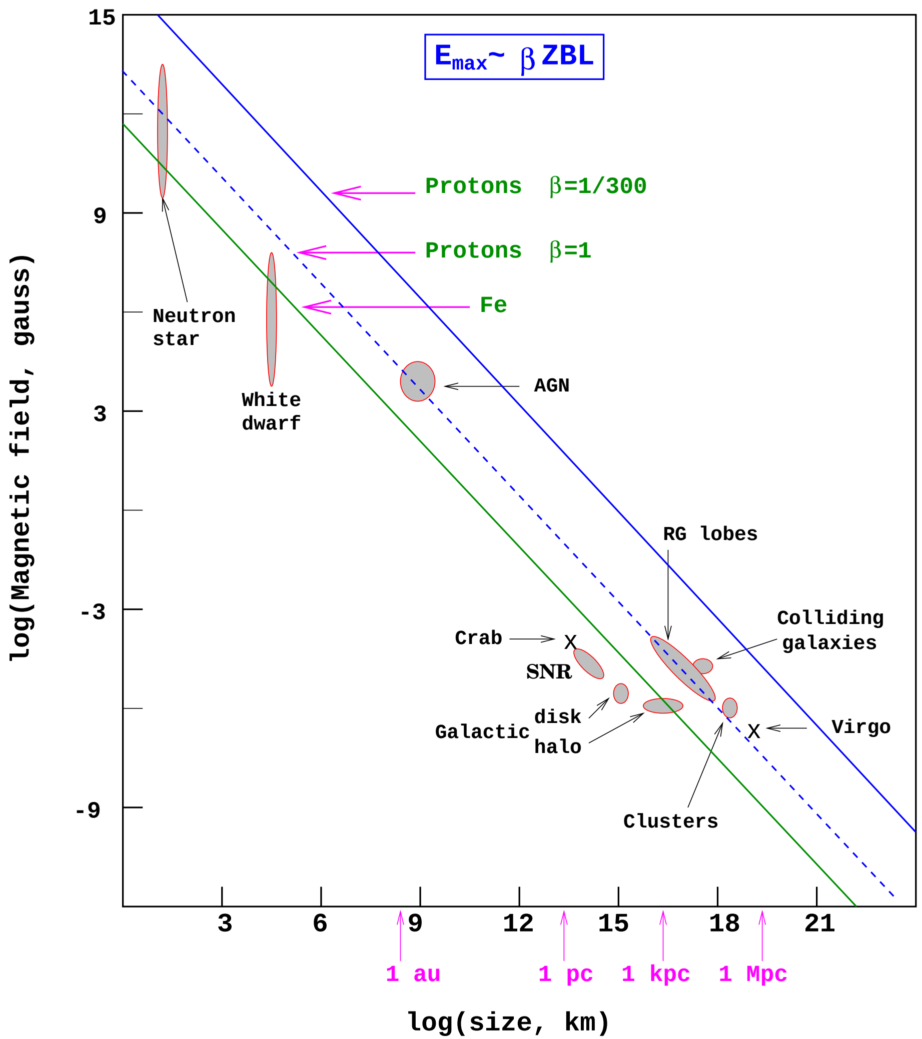
Bottom-Up - ACCELERATION

Diffusive Shock Wave Acceleration

- SNRs
- AGNs – QSOs, Blazars, BL lacertae
- ...

Top-Down - DECAY

- Super Heavy Particle
  with Long Lifetime
- Emission from Topological Defects
- Cosmic Origin – involves
  New (Cosmology + Particle Physics)



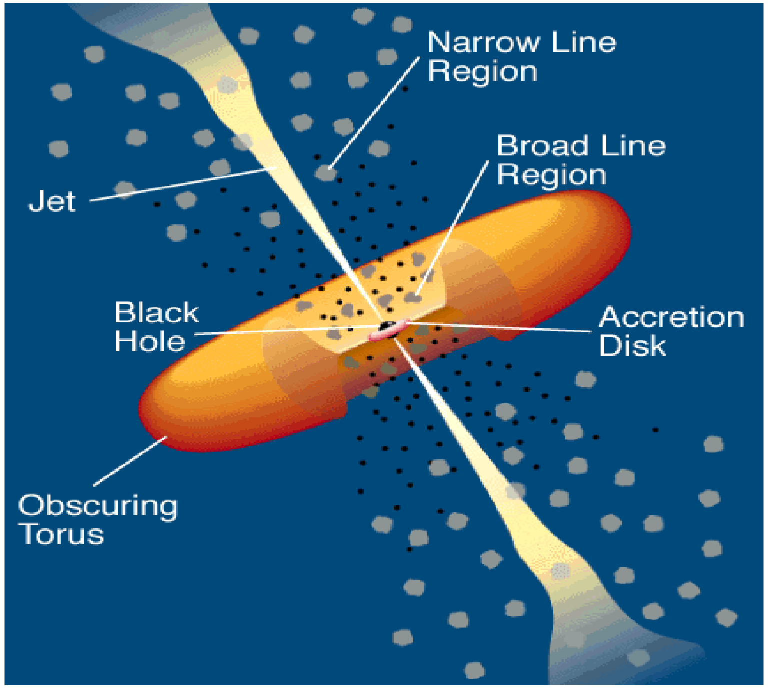
Known acceleration sites

Issues of UHECR

- The nature and origin of UHECRs – Puzzle of the Last Centry
  - (Location) What/Where are the sources?
  - (Mechanism) How can particles reach to extremely high energyies?
- Non(?)-observation of GZK cutoff and the absence of nearby sources
  - Why do the arrival directions of these particles not point back to recognizable sources in our local part of the universe?
  - Non-observation of GZK cutoff + Isotropy of arrival directions $\longrightarrow$ New Physics?
- What we should explain
  - Energy spectrum and propagation effects
    UHECRs come with γ's and ν's. – The observation of diffuse γ-ray background (e.g. EGRET) limits the injection of UHE particles.
  - Arrival directions and clustering, correlations with astrophysical objects

New Astrophysics or New Particle Physics?

- Astrophysics
  - New acceleration mechanisms
  - New astrophysical objects – AGN, GRB
  - Correlation with astrophysical objects
    - No strong evidence yet – BL lac
    - Autocorrelation - small scale clustering

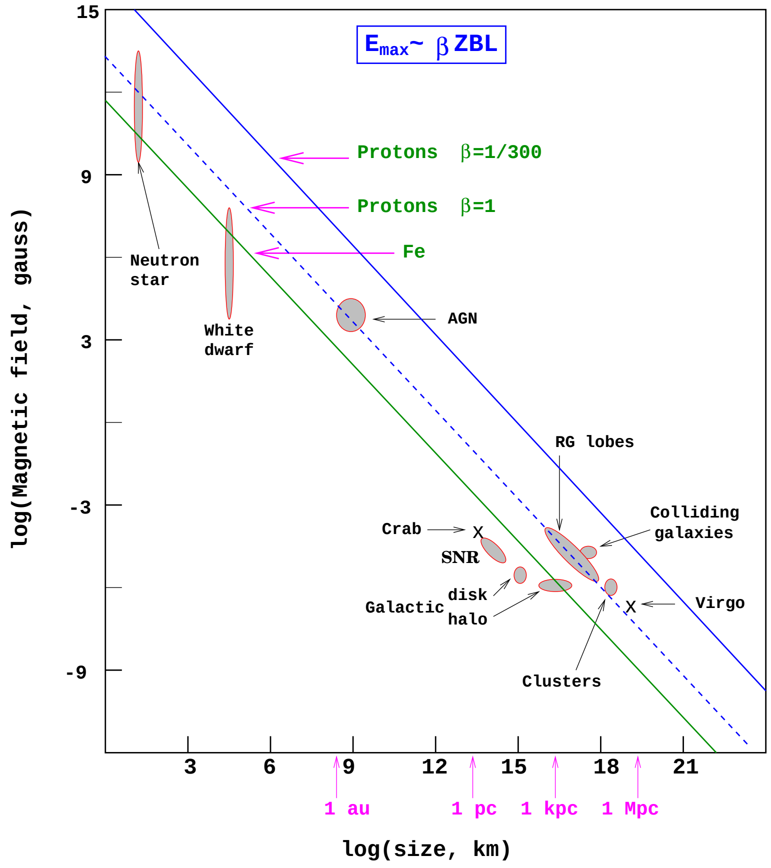


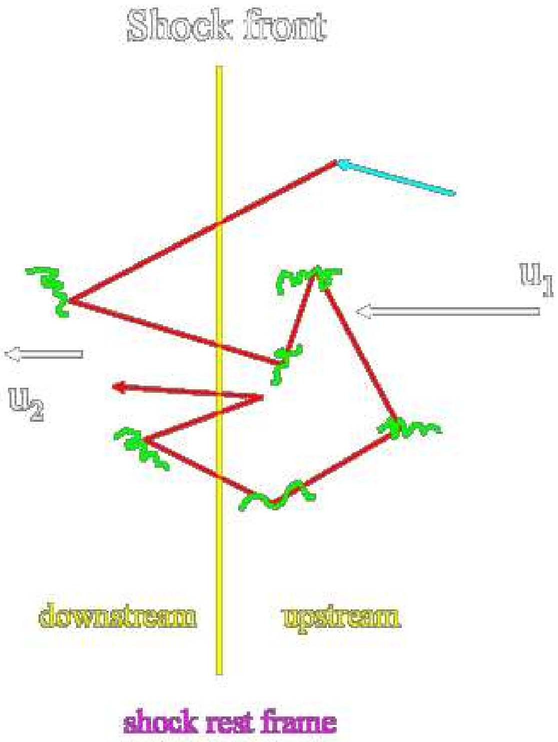
Conceptual picture of AGN

- Particle Physics
  - Topological defects - Strings, Monopolium, Cosmic necklaces
  - Superheavy dark matter (SHDM) - Cosmic origin, Wimpzilla, . . .
  - Signatures of Top-Down models
    - Spectral shape - No GZK cutoff, flat spectrum
    - Composition - Main components are Neutrinos and Photons
    - Arrival directions - Galactic Anisotropy

• Acceleration Mechanism

- Standard estimates for $E_{\rm max}$ of an accelerator
  Hillas : $E_{\rm max} = \beta Z B_{\rm gauss} R_{\rm pc}$ (ZeV)
- Collisionless shocks form in low density astrophysical plasmas via EM viscosities.
- Diffusive Shock Acceleration (DSA)

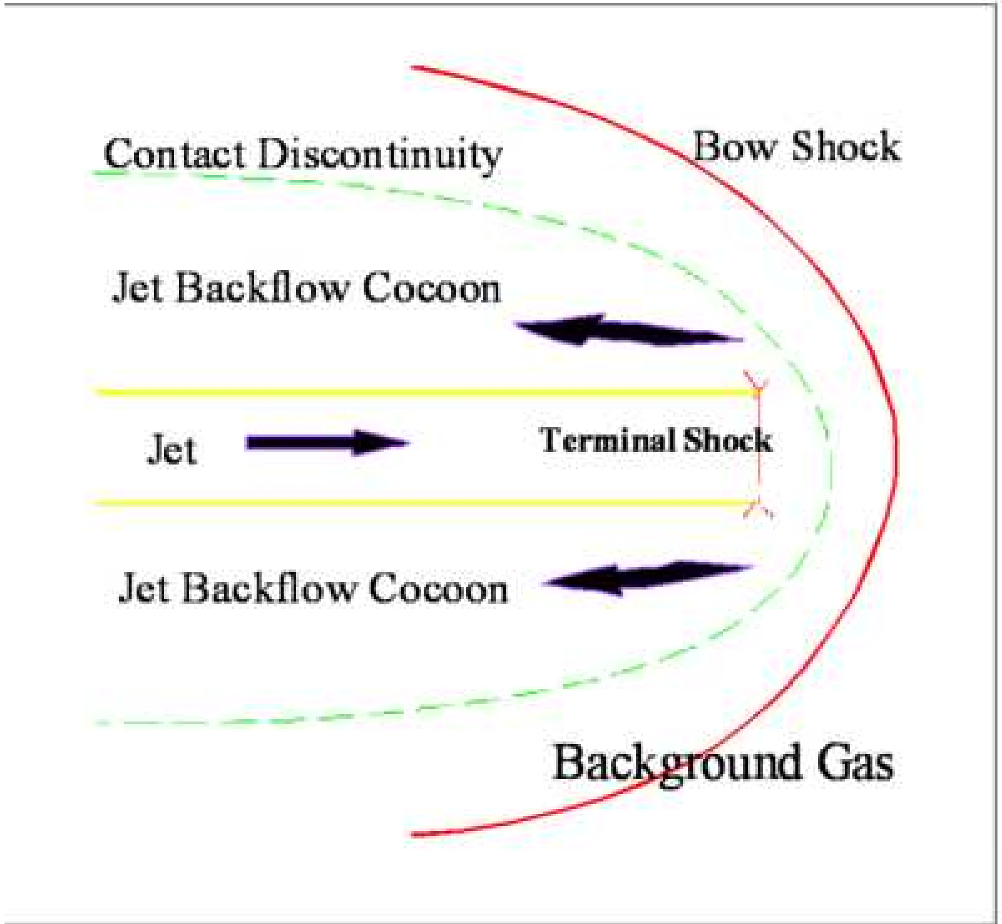




Alfven waves in a converging flow act as converging mirrors.

- Particles are scattered by waves
- Cross the shock many times
  "Fermi first order process"

Radio Jet Cartoon Model



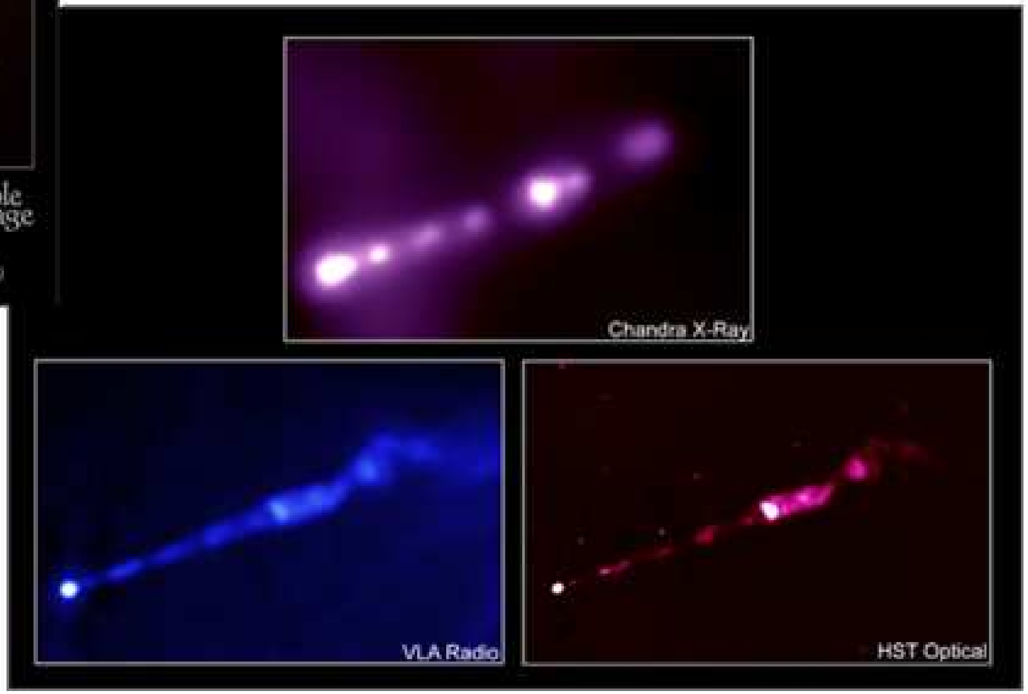
- Supersonic jet flow is dissipated in a strong terminal shock, $M_{ts} \sim M_j$
- Terminal shock accelerates Particles, creating a radio (&sometimes X-ray) "hotspot"

M87: Elliptical galaxy

in Virgo cluster (17Mpc)

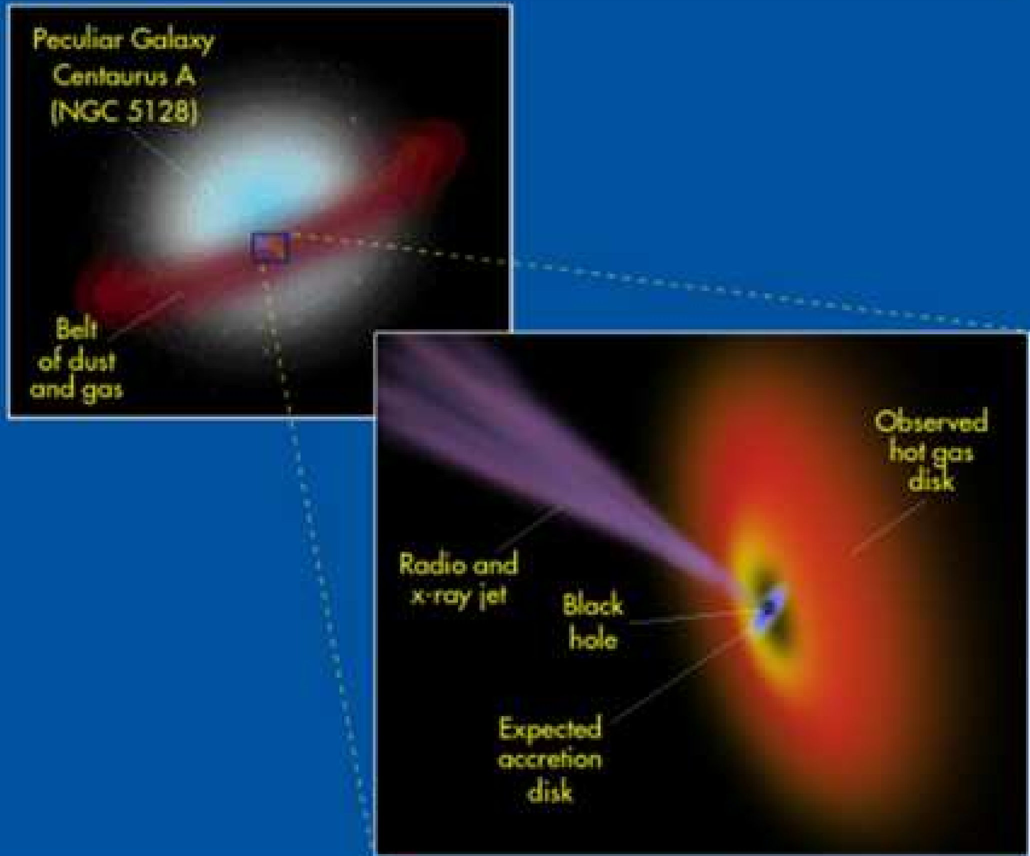
Relativistic jet: emanating from supermassive BH + accretion disk

$E_{max} \sim 10^{20}$ eV



Hubble Finds Twisted Gas Disk from Galaxy Collision Fueling Nearest Active Black Hole

Using the infrared vision of NASA's Hubble Space Telescope to penetrate a wall of dust girdling the nearest active galaxy to Earth, astronomers have gotten an unprecedented closeup look at a super-massive black hole caught in a feeding frenzy triggered by a titanic collision between two galaxies.

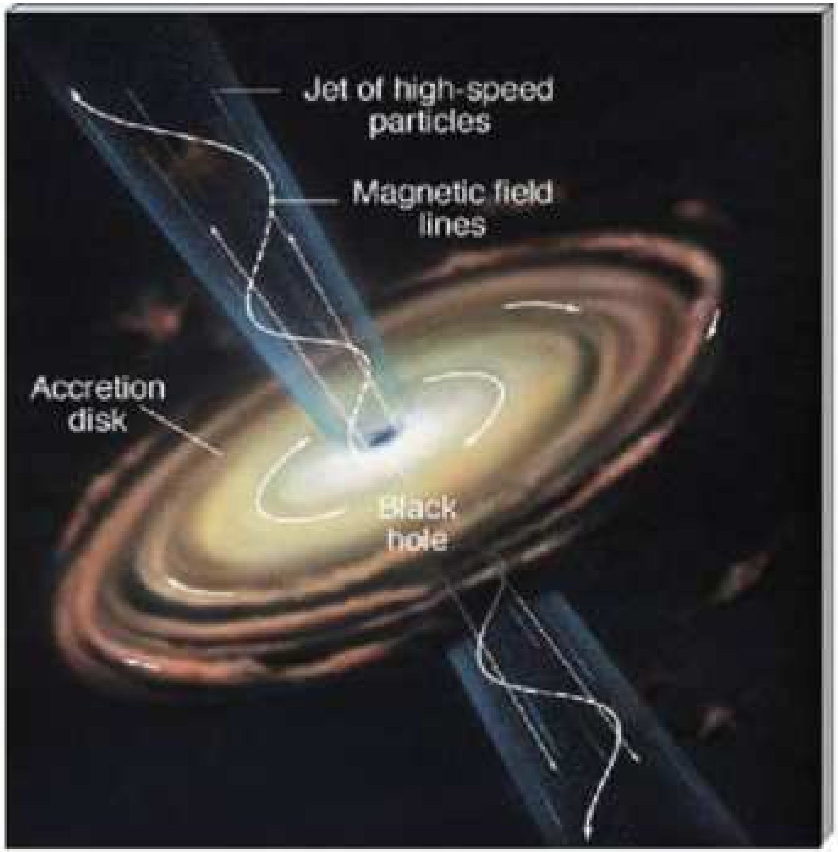


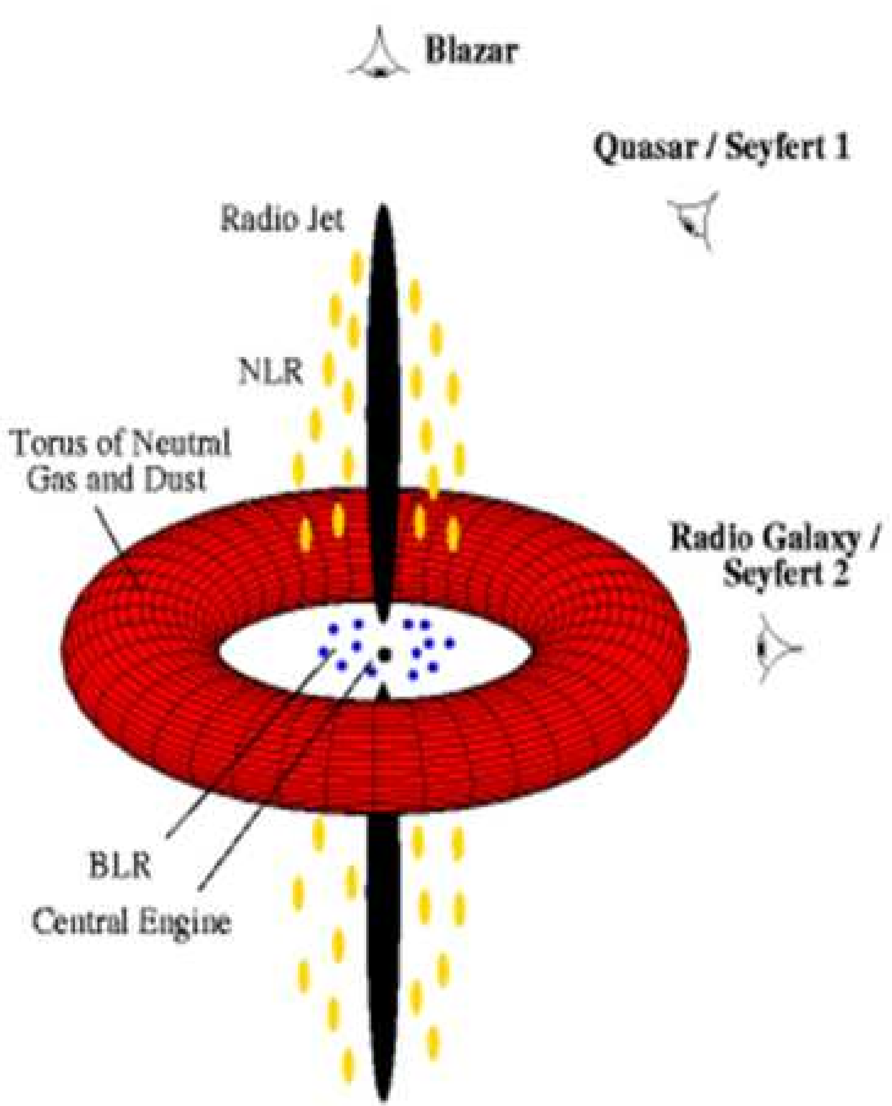
Cen A :FR I radio galaxy

NGC5128: Elliptical galaxy (+small spiral gal)

AGN= BH + disk + jet

3-4 Mpc, $E_{max} \sim 10^{19}$eV





Unified model of AGN

correlation btw arrival directions of UHECRs ($E<10^{20}$ eV) and **BL Lac obj.**

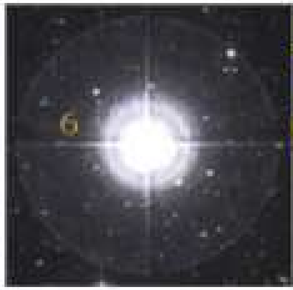
AGASA, Yakutsk, HiRes2

Gamma Ray Bursts

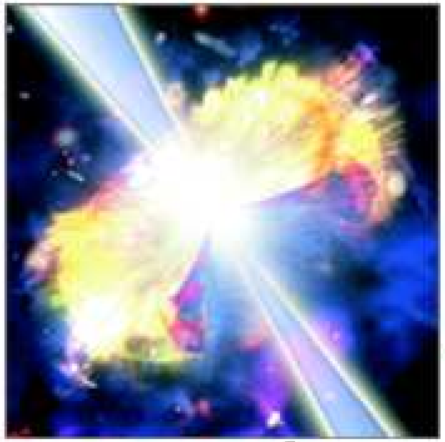
(long duration: ~30 seconds)

- a massive star: M> 25 Msun
- Wolf-Rayet Star: He envelope
- Core collapses into a BH
  - → Disk + jet : Hypernova
- E ~ 10^{53} erg = 100 x SN
- GRB030329 : at z=0.1685

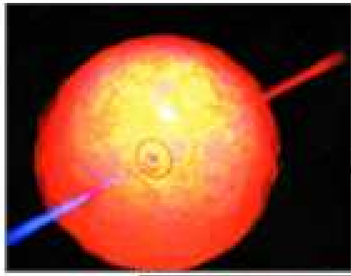
  SN spectrum, Vs~30,000km/s
- E_{max} ~ 10^{20} eV
- no correlation between GRBs and UHECRs in arrival directions
- one burst/100 years in 50 Mpc
  - → anisotropy, GZK cutoff



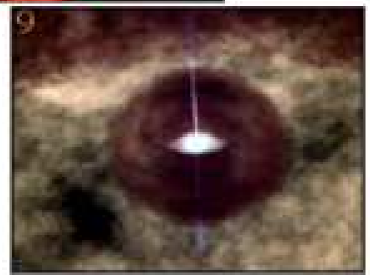
Typical massive star ("Wolf-Rayet" Star)



Hypernova



Gamma Ray Burst



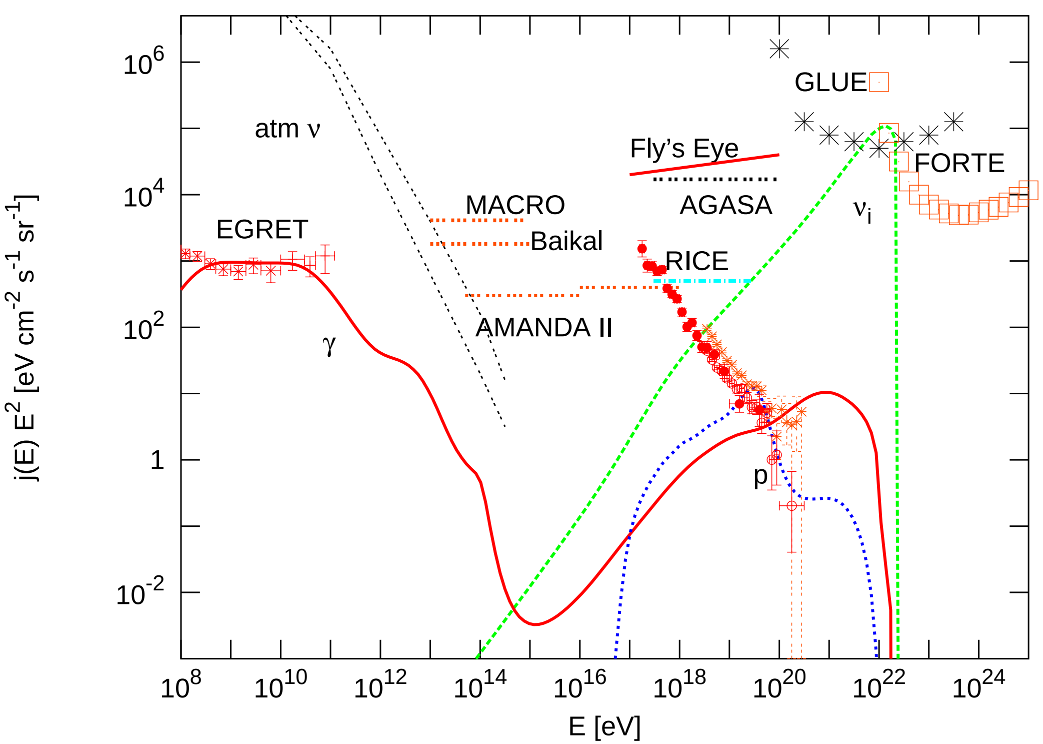
Black Hole (Chandra Image)

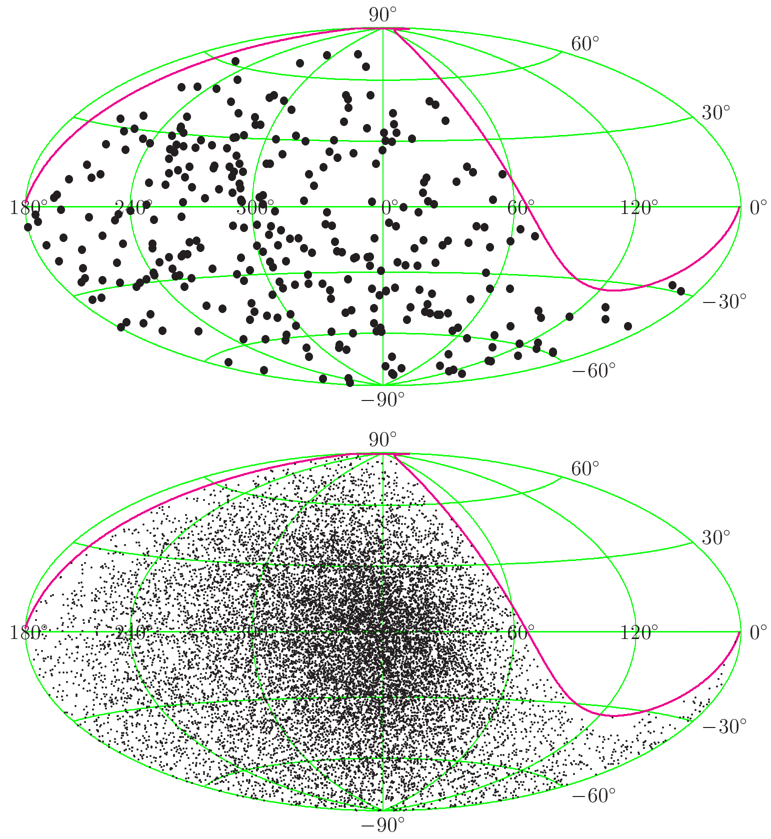
- **Review of Top-down Models**
  - **Basic Idea**
    - **UHECRs arise from the decay of long-lived superheavy relic particles.**
    - **CDM is supposed to contain a small admixture of long-lived superheavy particles.**
    - **Requirements: $m \gtrsim 10^{12}$ GeV, $\tau \gtrsim t_0$**
  - **Production Mechanism**
    - **Preheating**
    - **Phase transition**
  - **Observational Signals**
    - **Composition - Photons and Neutrinos dominant**

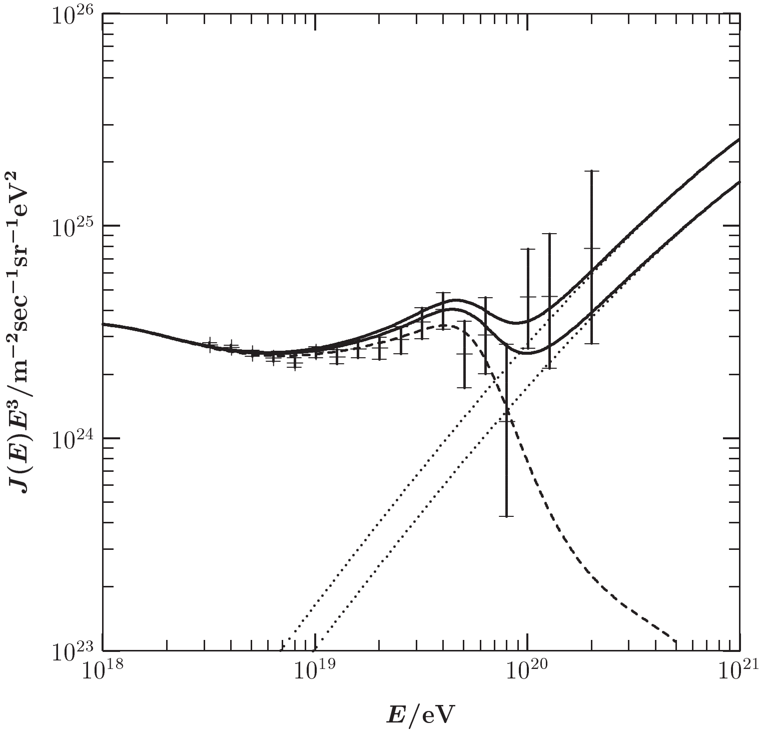
      It is assumed that hadronization of QCD is valid up to the energy $\sim 10^{24}$ eV.
    - **Energy spectrum - No GZK cutoff**
    - **Arrival directions - Anisotropy toward the galactic center direction**

      Local over-density $\delta \sim 10^5$

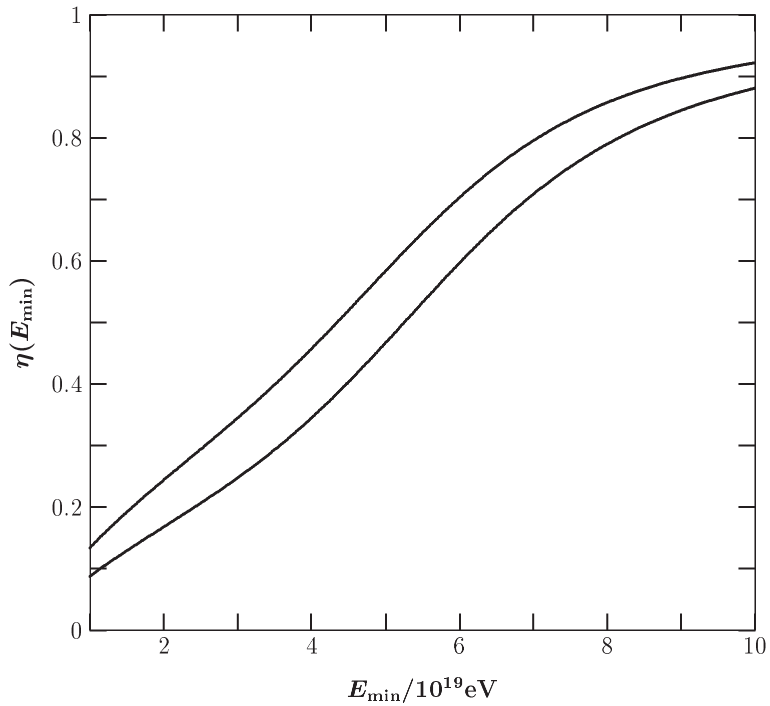
It is very important to cover both the galactic center and antigalactic center directions to search for significant contributions from relic particles.



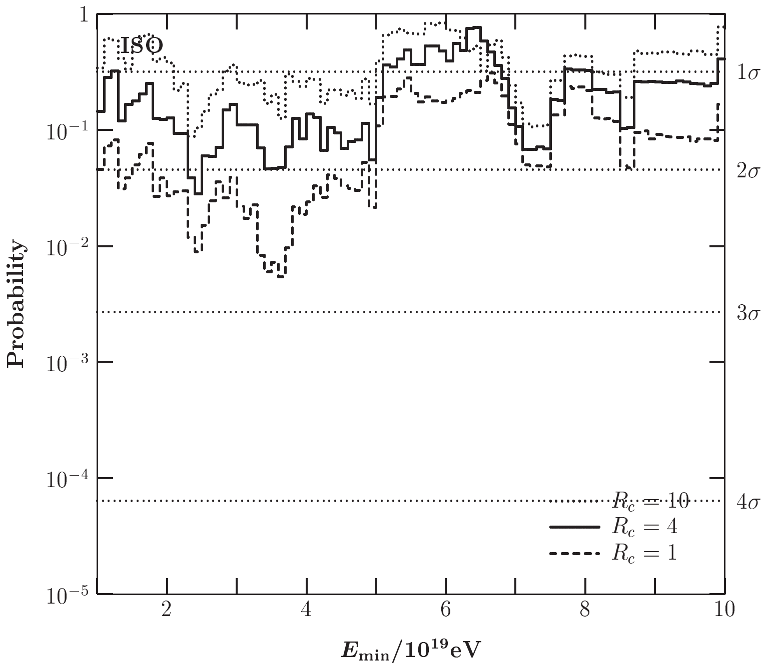




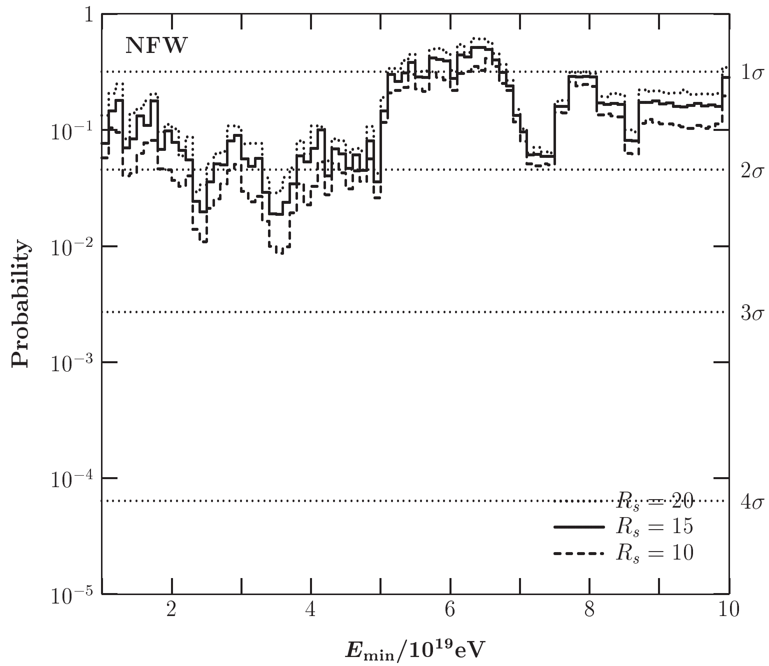
$J(E)E^3/\mathrm{m}^{-2}\mathrm{sec}^{-1}\mathrm{sr}^{-1}\mathrm{eV}^2$
E/eV



$\eta(E_{\min})$
$E_{\min}/10^{19}$eV



ISO
Probability
$E_{\min}/10^{19}$eV
1σ
2σ
3σ
4σ
$R_c = 10$
$R_c = 4$
$R_c = 1$



NFW
Probability
$E_{\min}/10^{19}$eV
1σ
2σ
3σ
4σ
$R_s = 20$
$R_s = 15$
$R_s = 10$

- **Neutrinos as primaries or messenger particles**
  - Motivation
    - ∗ Absence of GZK cutoff
    - ∗ Isotropic arrival directions
    - * Correlations with far-distant objects

      $\Rightarrow$ Particles that can traverse extragalactic space without attenuation even at energies $E \gtrsim E_{\rm GZK}$.
  - Neutrino

    weakly interacting with nuclei $\longrightarrow$ mainly horizontal shower

    Two options
    - ∗ Enhance the UHE neutrino-nucleon cross section by a factor $\sim 10^6$
    - ∗ Neutrinos are converted locally into hadrons or photons
  - Z burst model - Annihilations on relic neutrinos

$$\nu + \nu_B \longrightarrow Z^* \longrightarrow \gamma\text{'s, hadrons, } \ldots$$

Resonance Energy $E = m_Z^2/2m_\nu \approx 4 \times 10^{21}(m_\nu/\mathrm{eV})$ eV

Severe constraints - Source side

* Primary protons have to be accelerated to extremely high energies $E \gtrsim 10^{23}$ eV.
* Photons produced in the same reactions have to be hidden inside the source.
* The required neutrino luminosity of the source is very high. $L_\nu \sim \frac{\omega_\nu}{n_s t_0} \sim 10^{45}$ erg/s (normal galaxies), 10^{47} erg/s (Seyfert galaxies)

A possible way out: SHDM $\rightarrow \nu$ exclusively. - done at tree level, but loop contributions produce too much photons again.

Severe constraints - Local side

* Local over-density of neutrinos cannot be high if neutrinos are very light.
* Over-production of photons - EGRET Limit

– Strongly interacting neutrinos

Enhanced neutrino-nucleon cross section at high energies - Large extra-dimension KK modes

Black hole production can be important.

- Experimental and theoretical constraints make it very unlikely that neutrinos can explain the observed vertical EAS.
- Exciting possibilities: discovery of relic neutrino background, new neutrino-nucleon interaction in horizontal EAS

- **New primaries**
  - Strongly interacting particles with shifted GZK cutoff
  - Light gluino

- **Violation of Lorentz invariance**
  - Modification of the dispersion relation

$$E^2 - p^2 - m^2 \approx -2dE^2 - \xi \frac{E^3}{M_P} - \zeta \frac{E^4}{M_P^2}$$

  $\Rightarrow$ Modification of reaction kinematics

  $\Rightarrow$ Shift of GZK cutoff

- **Low Energy Quantum Gravity**

Challenges

- **After 90 years of research, the origin of cosmic rays is still an open question, with a degree of uncertainty increasing with energy.**
- **Statistically meaningful data have been accumulated, but not conclusive: composition, energy spectrum, arrival directions.**
- **Interconnection between physics and astrophysics of UHECRs and neutrino astronomy, γ-ray astronomy: All scenarios of UHECR origin are severely constrained by neutrino and γ-ray observations.**
- **What do we need?**
  - **Enough Statistics – Giant Array of Detectors, Satellite Detectors**
  - **Full Sky Coverage – Southern (Auger) & Northern hemisphere (?)**
  - **New Astrophysics**
    - **Acceleration mechanisms & Acceleration sites**
  - **New Particle Physics**