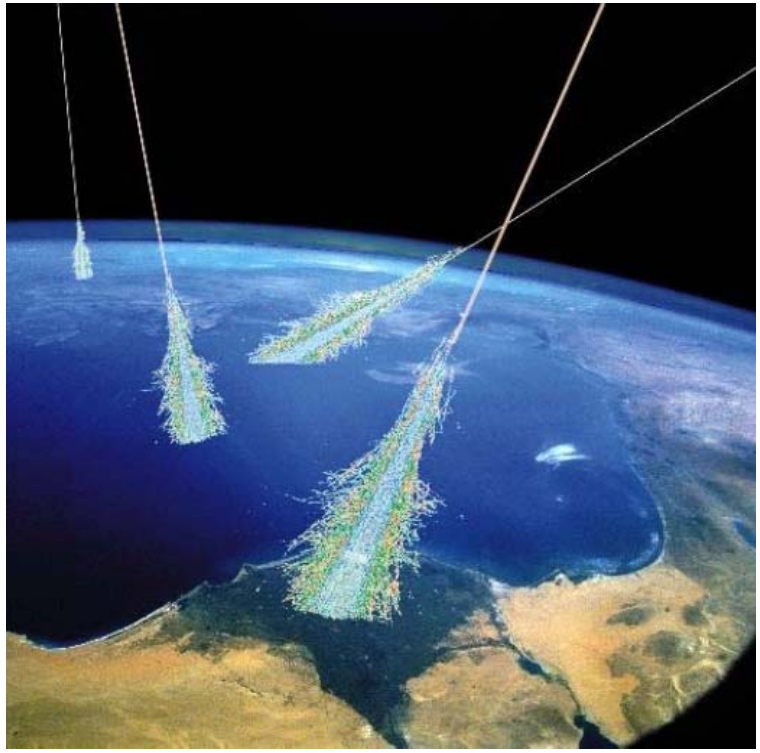
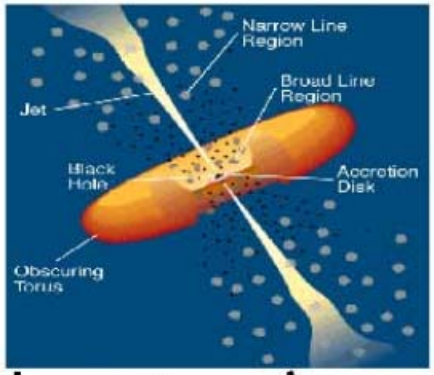
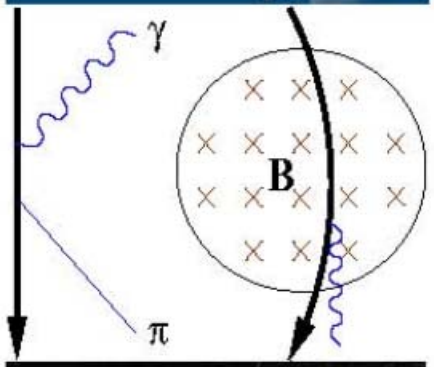
Top-Down Models for UHECRs



Hang Bae Kim
(Hanyang Univ., Seoul)

4th Korean Astrophysics Workshop
2006.5.17-19, KASI





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

Issues

- The nature and origin of UHECRs
  - How can particles reach these extremely high energies?
  - What / where are their sources?
- GZK cutoff and the absence of nearby sources
  - Why don't the arrival directions point back to recognizable sources in our local part of the universe?
  - No GZK cutoff + Isotropy of arrival directions → New Physics

The origin of UHECRs

- Bottom-Up : Acceleration

  Diffusive shockwave acceleration at

  - SNRs
  - AGNs - BL lacs, Blazers, QSOs, ...
  - ...

- Top-Down : Decay

  - Emission from Topological Defets (TD)
  - Superheavy particles with long lifetime
    * SHDM, Wimpzillar, Crypton, ...

What we want to explain

- Composition / Spectrum
  - Production/propagation of UHECRs comes with ν's and γ's.
    - * The observation of diffuse γ-ray background limit the injection of UHE particles.
    - * High energy neutrino astronomy will tell something in the future.
- Arrival directions
  - Isotropy
  - Clustering and Correlation with astrophysical objects

Top-Down Models

- Particle Physics Solutions + Astrophysics solutions
- Two components in UHECRs
  - UHECRs accelerated in far distant astrophysical objects (GZK cut off, Isotropic)
  - UHECRs originated from decays of SHP
    - SHDM — No GZK cutoff, Anisotropic
    - TD — GZK cutoff, Isotropic
- production — Cosmic origin
  - TD — Phase transition
  - SHDM — Preheating
- feaures
  - High γ, ν fractions, Anisotropy of arrival directions

• Topological Defects

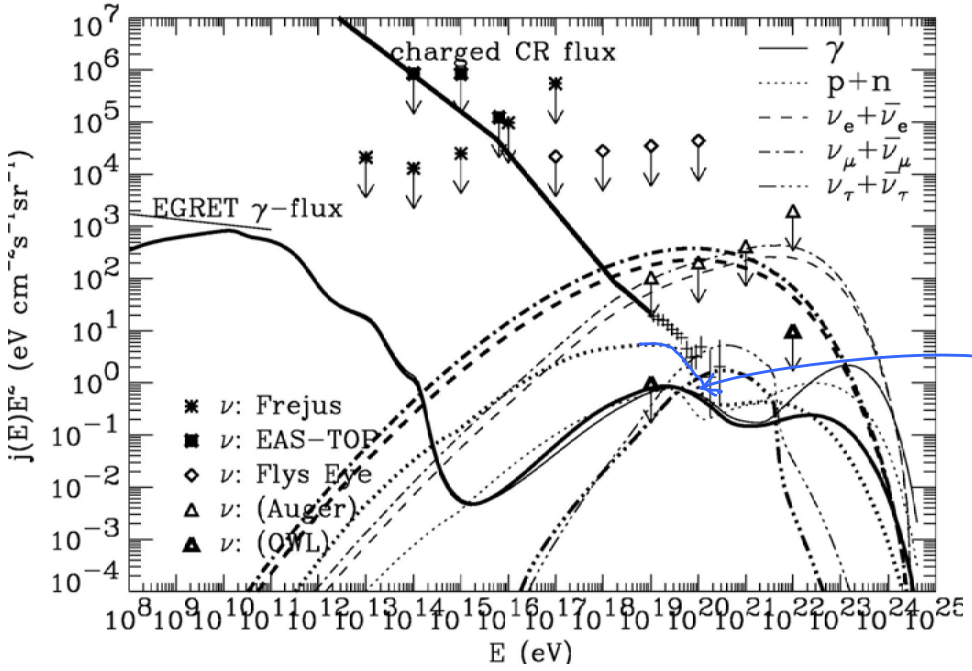
– Spontaneous breakdown of GUT → SM

GUT phase transition at $10^{16} - 10^{19}$ GeV

→ TD (magnetic monopoles, cosmic strings, vortons, ...)

topologically stable, but can emit X particles

→ X → (quarks —fragmentation→ hadrons (pions → ν_s, γ_s; nucleons) ; leptons → ν_e, γ_s) ← dominate over p



– Distribution of TDs

– uniform in the universe

→ Isotropic ADs with GZK cut-off

– γ and ν fluxes already reach the experimental bounds

◦ Superheavy Dark Matter (SHDM)

- metastable superheavy relic particles

  $m_X \gtrsim 10^{12}$ GeV , $\tau_X \gg t_0$, $\Omega_X \lesssim 0.2$

- Produced during preheating

  non-adiabatic expansion of the universe

  direct coupling between the inflaton and matter fields

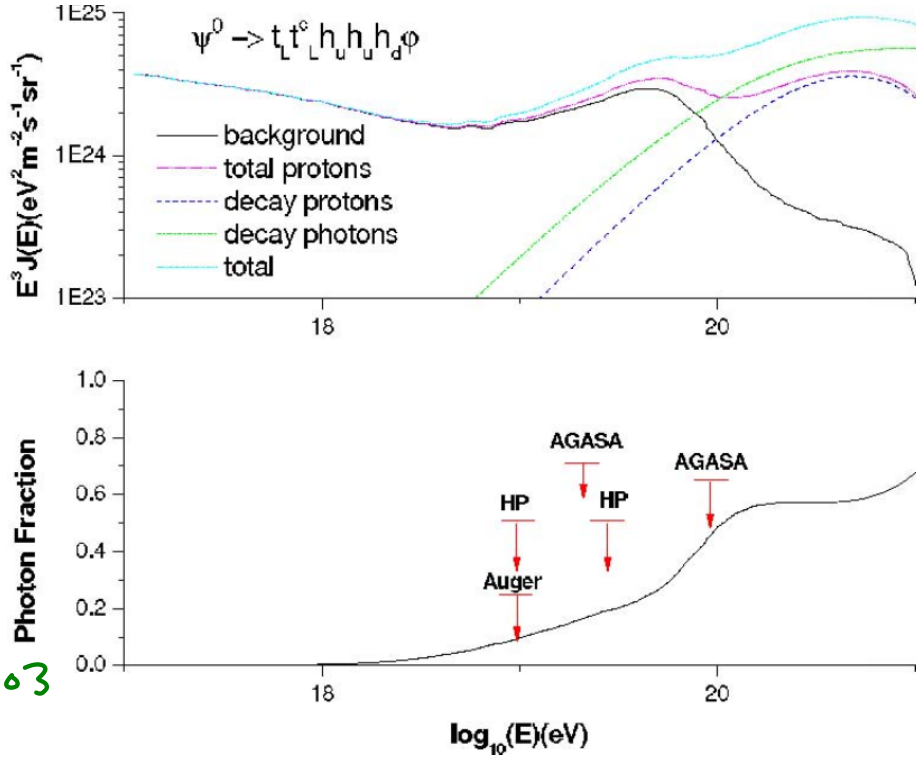
- Crypton

  Bound states of fractionally charged constituents in the hidden sector:

  ($m \sim 10^{12} - 10^{13}$ GeV

  ($\tau^0 \sim 10^{11} - 10^{17}$ yrs

- Anisotropy



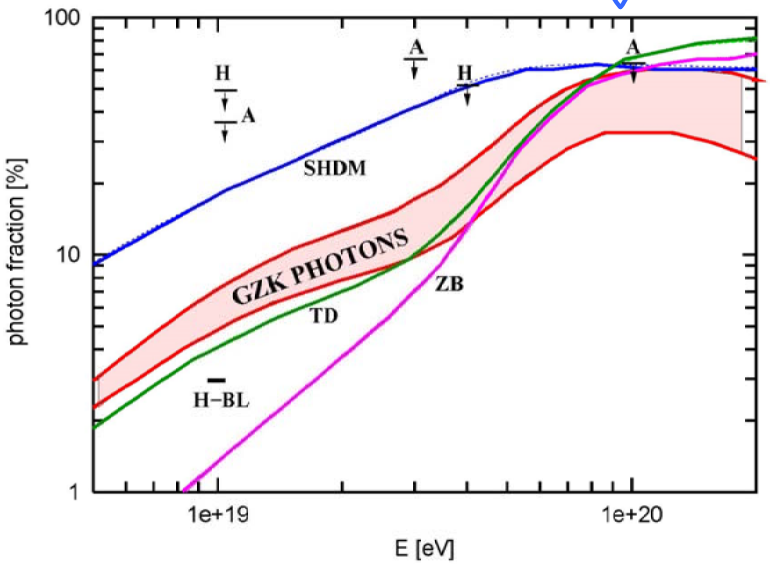
Ellis, Mayes, Nanopoulos, astroph/0512303

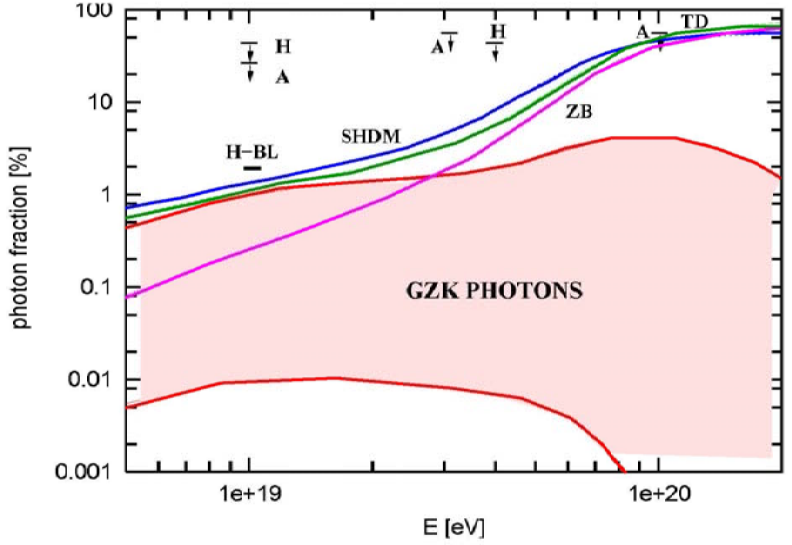
– Photon fraction

Gelmini, Kalashev, Semikoz, astro-ph/0506128

GZK photons – produced by extragalactic nucleons through the resonant photoproduction of pion

the initial protons have a hard spectrum ~1/E and be accelerated to energies as high as 10^{22} eV.





Arrival Directions

- SHDM model
  - The distribution of SHDM follows that of CDM.
  - Galactic halo models

$$\rho_{DM}(r) = \frac{\rho_0}{\left(\frac{r}{r_0}\right)^{\gamma}\left[1+\left(\frac{r}{r_0}\right)^{\alpha}\right]^{\frac{\beta-\gamma}{\alpha}}}$$

Normalization $\rho(r_\odot = 8.5\,\mathrm{kpc}) = 0.3\,\mathrm{GeV\cdot cm^{-3}}$

	α	β	γ	r_0 (kpc)	ρ_0 (GeV·cm^{-3})
ISO	2	2	0	4.0	1.655
NFW	1	3	1	16.7	0.347
M99	1.5	3	1.5	29.5	0.0536

  - Flux calculation

$$f(\theta) = \frac{1}{4\pi}\int_0^{r_m(\theta)} \mathcal{L}(\vec{R})\,dr$$

line-of-sight integration

Decay : $\propto n_{DM}(R)$

Annihilation, $\propto n_{DM}(R)^2$

  - Galactic/Extragalactic contributions

$$\frac{f_G(\theta)}{f_{EG}} = \frac{\int_0^{r_m}\rho_{GH}(R)dr}{\int_0^{R_{eff}}\rho_{CDM}dr} \sim \frac{\rho_0 r_0}{\rho_{CDM} R_{eff}} \sim \frac{5000\,\mathrm{Mpc}}{R_{eff}}$$

– Fraction of SHDM contribution

$$\eta(E_{cut}) = \frac{\int_{E_{cut}} f_{GH}(E)\,dE}{\int_{E_{cut}} \left(f_{GH}(E) + f_{ISO}(E)\right) dE}$$

– Comparison with Arrival Direction Data

- SUGRA data – SUGAR was an unique array operated in the southern hemisphere and covered the Galactic center direction directly, before P. Auger Obs.

– How to compare the arrival direction distributions?

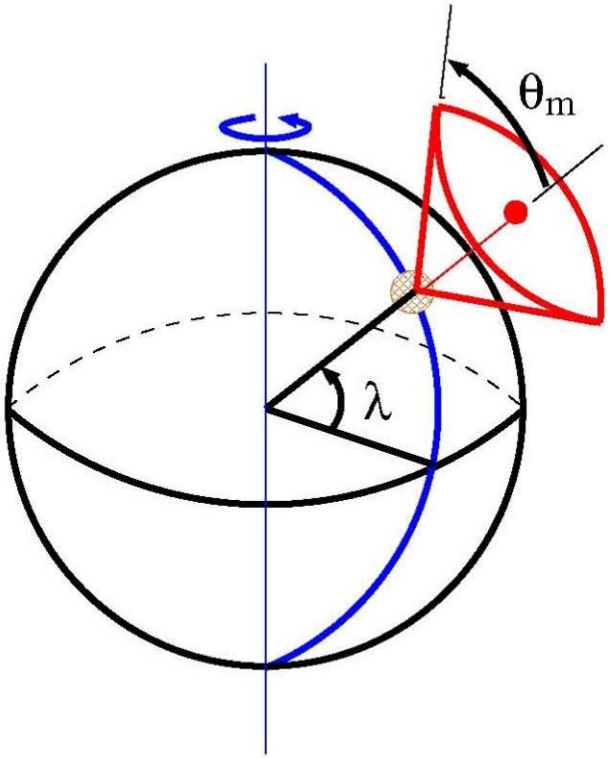
Kolmogorov-Smirnov Test uses the cumulative probability distribution function

$$S(x) = \int^{x} P(x')dx', \quad S_N(x) = \frac{1}{N}\sum_i \theta(x_i - x)$$

KS Statistic $D = \max |S_N(x) - S_M(x)|$

We use the distribution of the angles between the arrival directions and the Galactic center direction.

- **Exposure (Acceptance) Function**
  - The ground based detector arrays do not cover all directions of the sky equally.
  - Depends on the Geometry and Systematics of Detectors



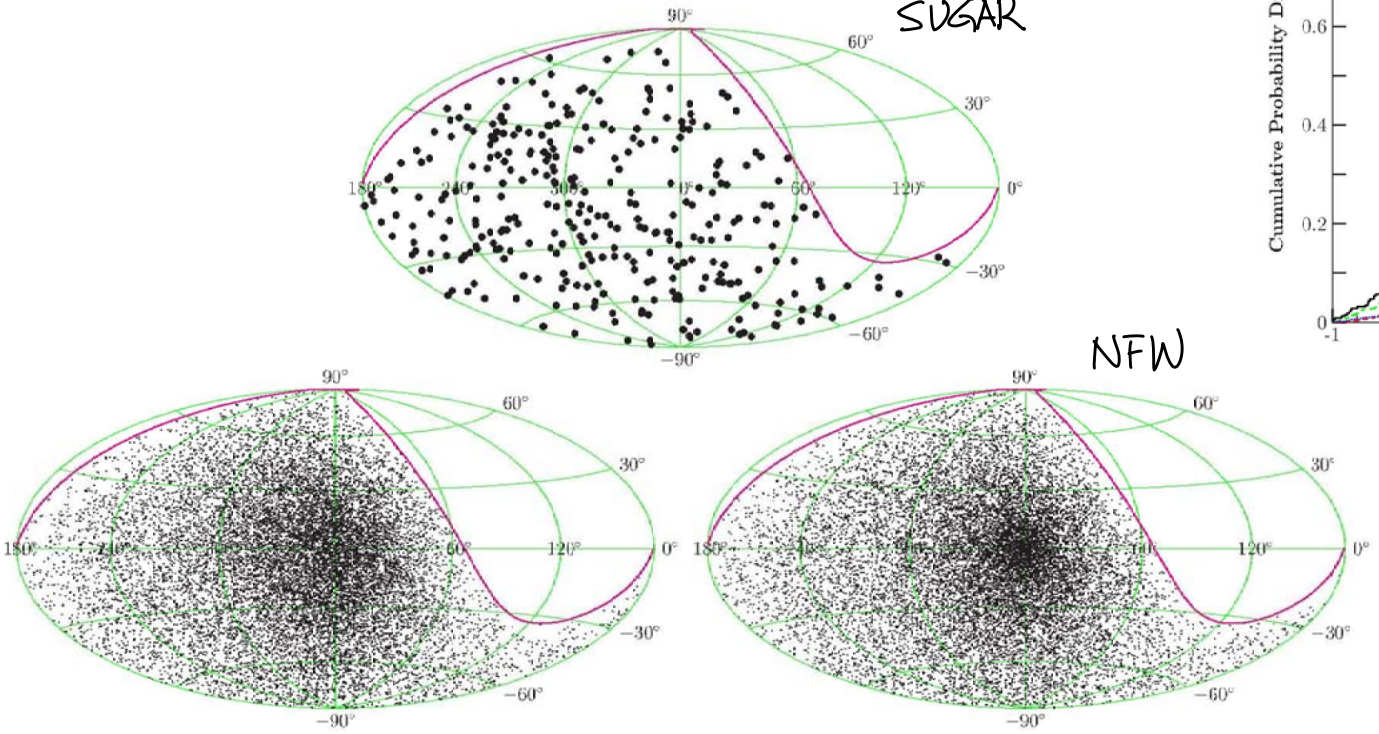
$$\lambda = \text{Latitude}, \quad \theta_m = \text{Zenith Angle}$$
$$\delta = \text{Declination}$$

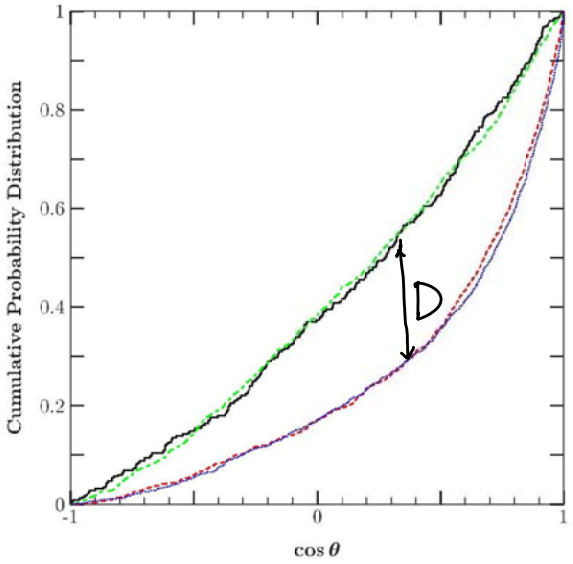
$$h(\delta) = \frac{1}{\pi}\left[\sin\alpha_m \cos\lambda \cos\delta + \alpha_m \sin\lambda \sin\delta\right]$$

$$\alpha_m = \begin{cases} 0, & \text{for } \xi > 1 \\ \pi, & \text{for } \xi < -1 \\ \cos^{-1}\xi, & \text{otherwise} \end{cases}$$

$$\xi \equiv \frac{\cos\theta_m - \sin\lambda \sin\delta}{\cos\lambda \cos\delta}$$

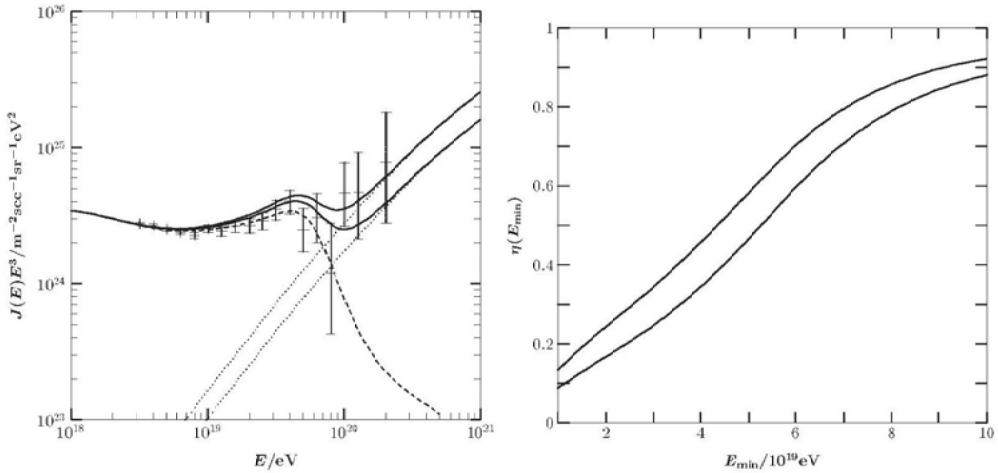
- **Simulation Results**





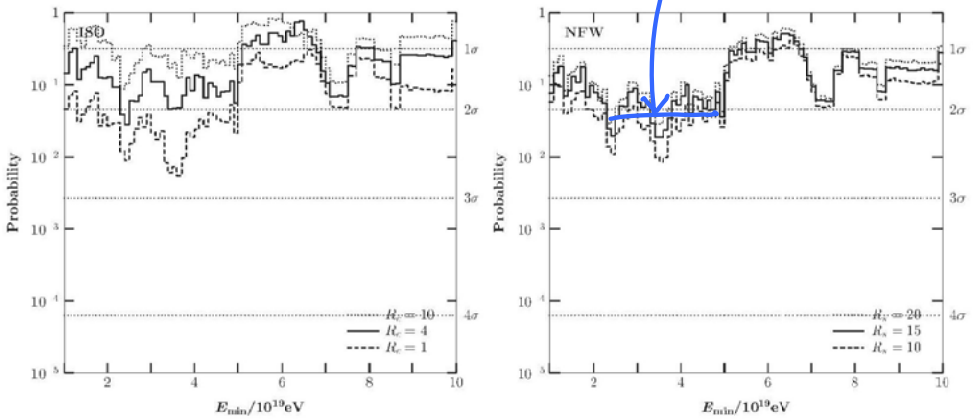
cumulative probability distribution

(a) The sky map of arrival directions of 316 SUGAR events with zenith angle $z \leq 60°$ and energy $E \geq 1.0 \times 10^{19}$ eV. (b) and (c) show 316×50 simulated events for the isothermal halo model with $R_c = 4$ kpc and the NFW halo model with $R_s = 15$ kpc, respectively. Galactic coordinates are used; the solid line is the boundary of the SUGAR acceptance with the zenith angle cut of 60°.



Left: Energy spectrum of the combined model fitted to AGASA data. Dashed line is for the isotropic component, dotted line for the SHDM component and solid line is the combined spectrum. Right: Energy cut dependence of the fraction of the SHDM component.

$E_{cut} = 2-5 \times 10^{19}$eV
2σ-level disfavor



Probability that SUGAR data come from the combined model for the isothermal model ($R_c = 4$ kpc) and the NFW model ($R_s = 15$ kpc).

Summary

- Top-Down Models for UHECRs
  - Particle Physics beyond the standard model
  - easier to identify the signals
    * High photon fraction at the highest energies
    * Hard spectrum above GZK cutoff
    * Anisotropy (toward the Galactic center)