HIGH ENERGY COSMIC RAYS

Graciela Gelmini - UCLA

DISCRETE 08- Valencia- December, 2008

A multi-messenger approach is necessary to study the most energetic sources in nature.

It requires multiple techniques.

- **HE Cosmic Rays:** ground arrays, atmospheric fluorescence telescopes, balloons, satellites, space station
- **HE Gamma-Rays:** ACT's, satellites, ground arrays, atmospheric fluorescence telescopes.
- **HE Neutrinos:** under ice and water detectors, balloons, radio telescopes (talk of Francis Halzen)

(This afternoon Auger talk by Jaime Alvarez-Muniz will discuss neutrino bounds)

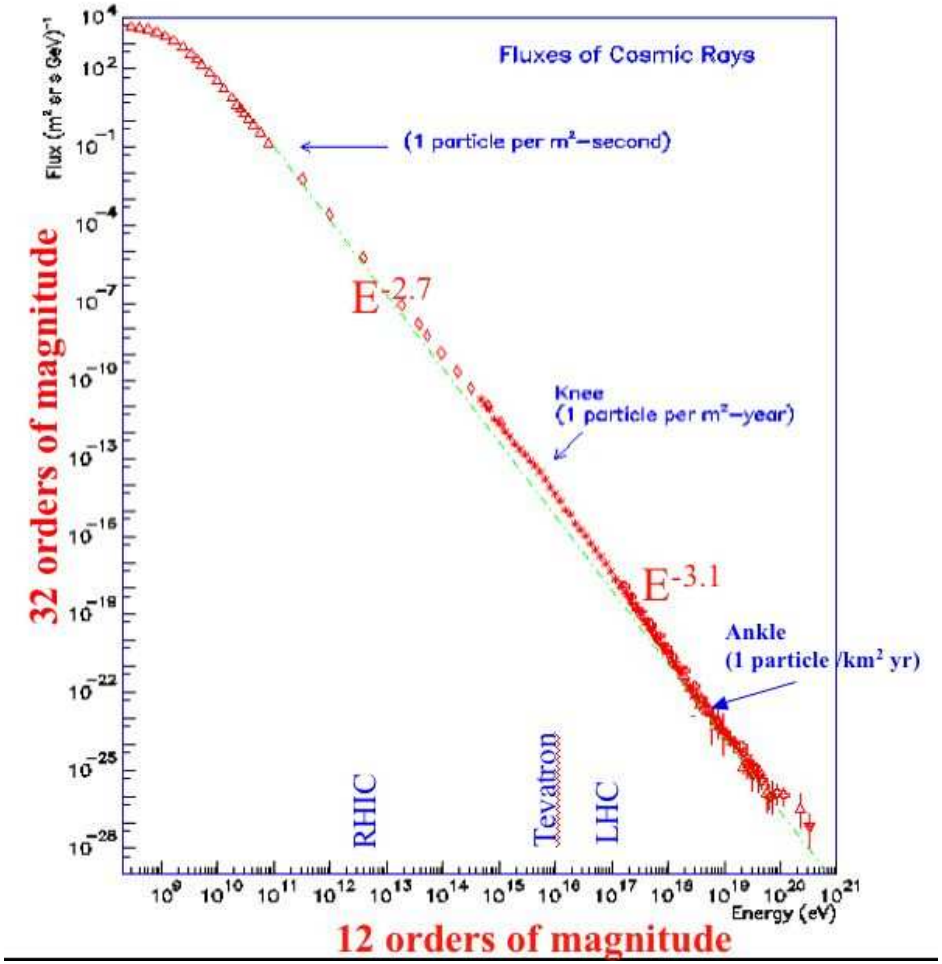
Cosmic Ray Spectrum

Non-thermal spectrum $\sim E^{-3}$

1 particle/ (m^2 sec) at 100GeV

1 particle/ (m^2yr) at 10^7GeV

1 particle/(km^2yr) at 10^{10}GeV



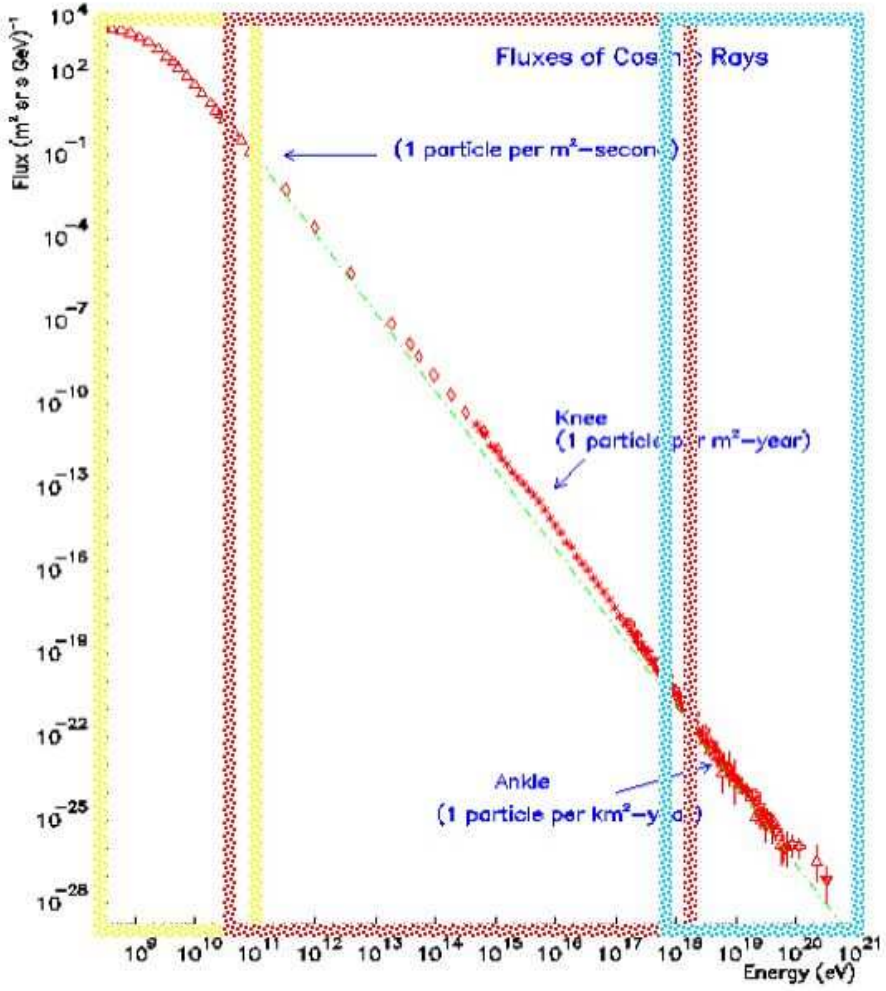
Cosmic Ray Spectrum

Each energy range addresses different physics:

Solar modulation:
$10^8 < E < 10^{11}$ eV

Galactic sources and Propagation:
$10^{11} < E < 10^{17-18?}$ eV

Extragalactic Sources:
$10^{17-18?} < E < 10^{20-2?}$ eV



PAMELA: (Payload for Antimatter Exploration and Light-nuclei Astrophysics)

(See talk of Mirko Boezio)

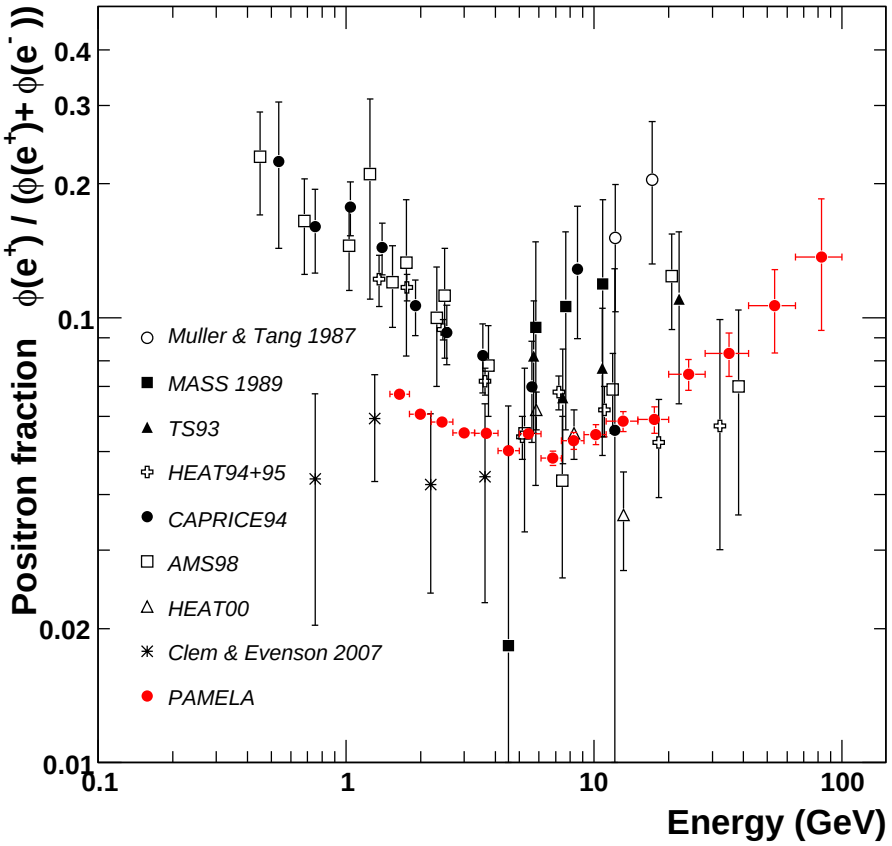
Magnetic spectrometer in orbit.

Launched in June 2006.

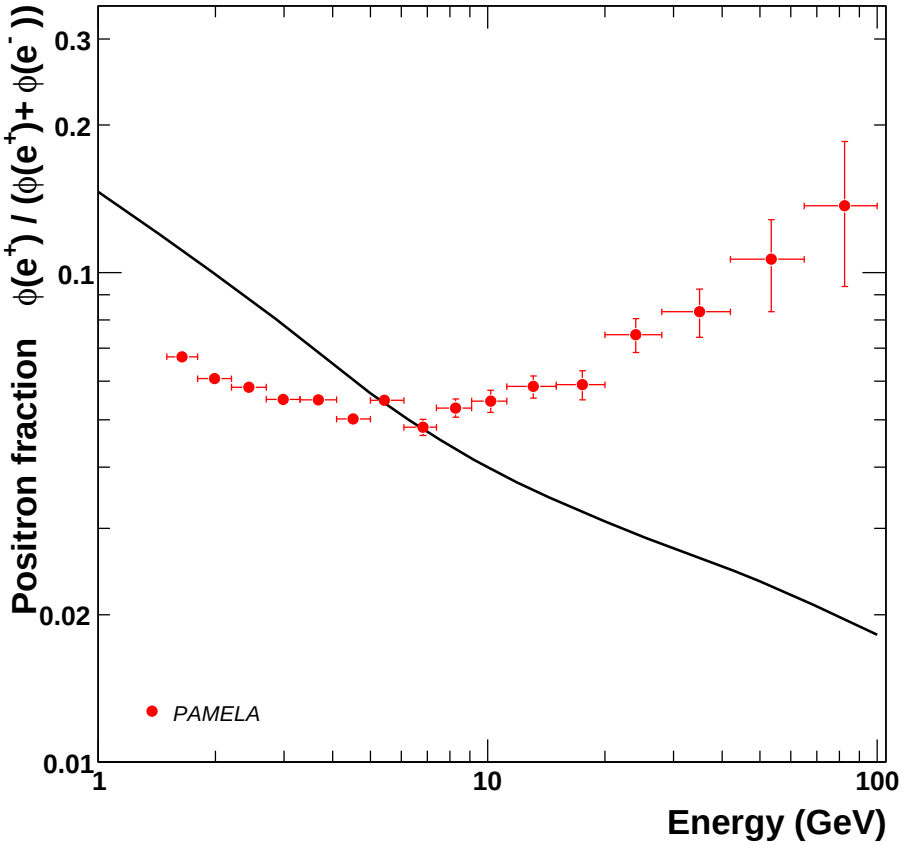
First data released this year.

Solar modulation effects important at $E < 10$ GeV

e^+-fraction excess at 10-100 GeV (Aug/08)!



PAMELA: Positron fraction excess 10-100 GeV



Also seen by ATIC: (Advanced Thin Ionization Calorimeter instrument)

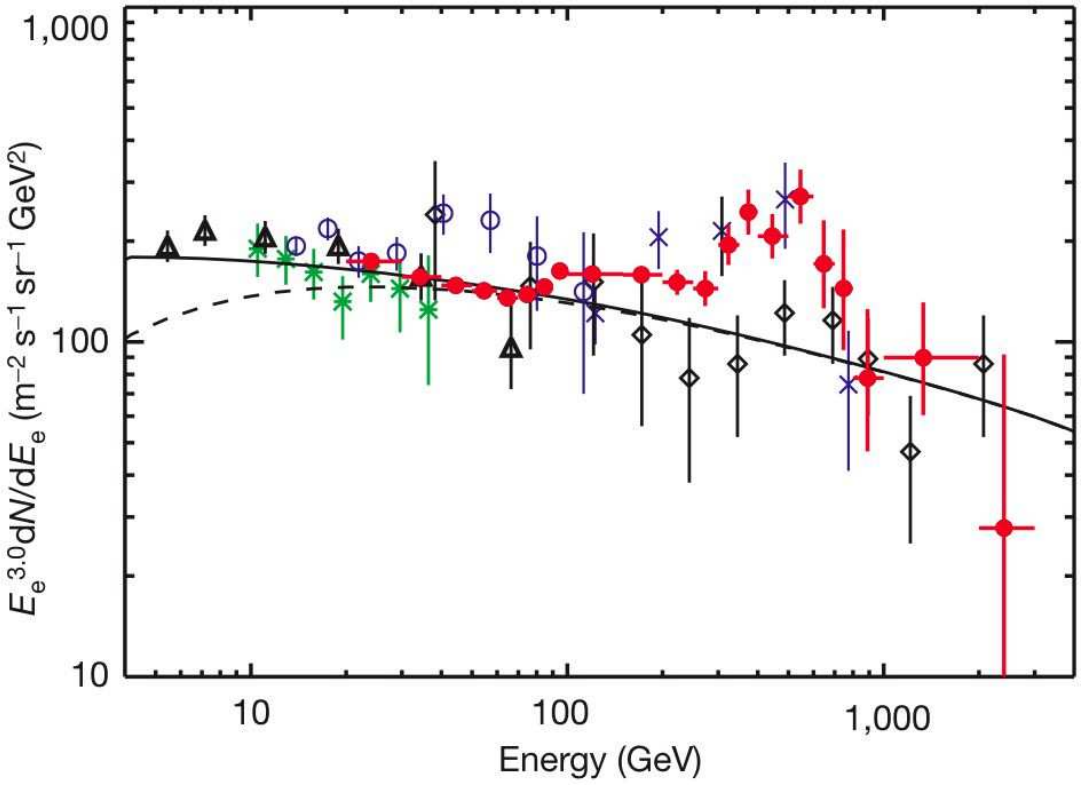
Balloon-born calorimeter launched

from McMurdo, Antarctica.

ATIC-1 in 2000-01

ATIC-2 in 2002-03.

$(e^+ + e^-)$ 6σ excess in the 300-800 GeV range (Nov/08)!



Source: astrophysical? Dark matter? More than 50 papers already!

- **e^+ e^- come from $<$ 1 kpc, so must be produced locally** e^+ e^- rapidly loose energy through synchrotron and inverse Compton processes

- **what produces e^+ could produce $\bar{p}$ (PAMELA) and γ (FST-ACT's)!**

  $\bar{p}$ come from a fraction of the galaxy

  γ of E$<$ TeV come from cosmological distances (point to sources)

Fits to ATIC: Hall, Hooper 11/08

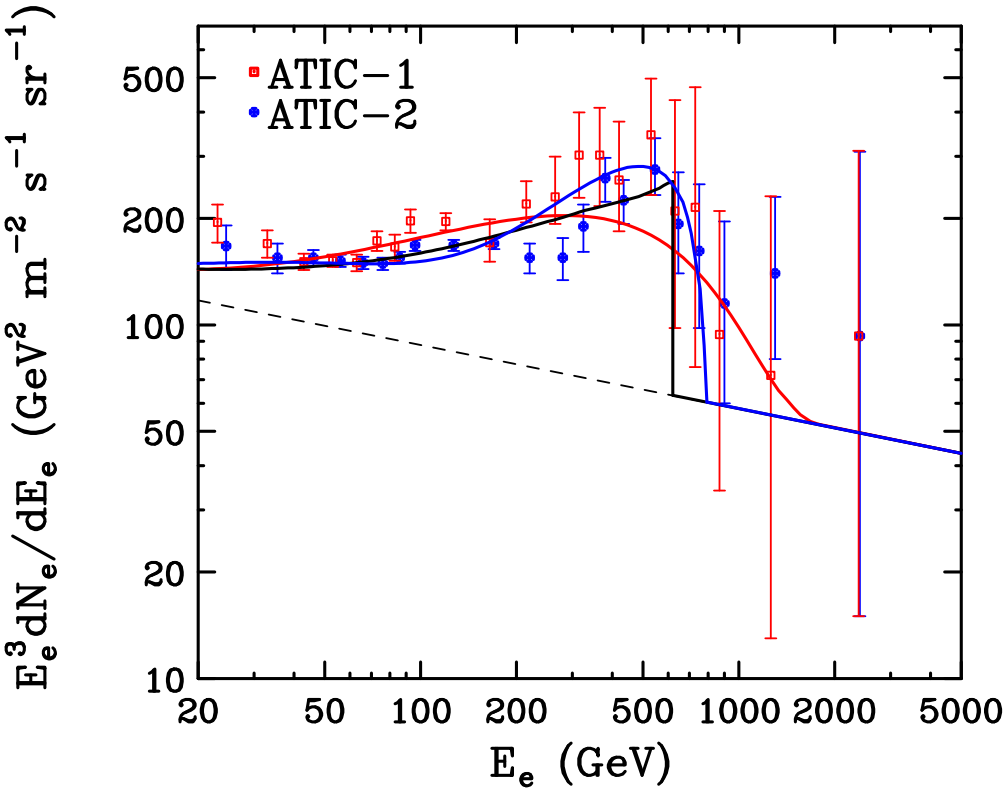
e^+ e^- from:

- a nearby pulsar (red)

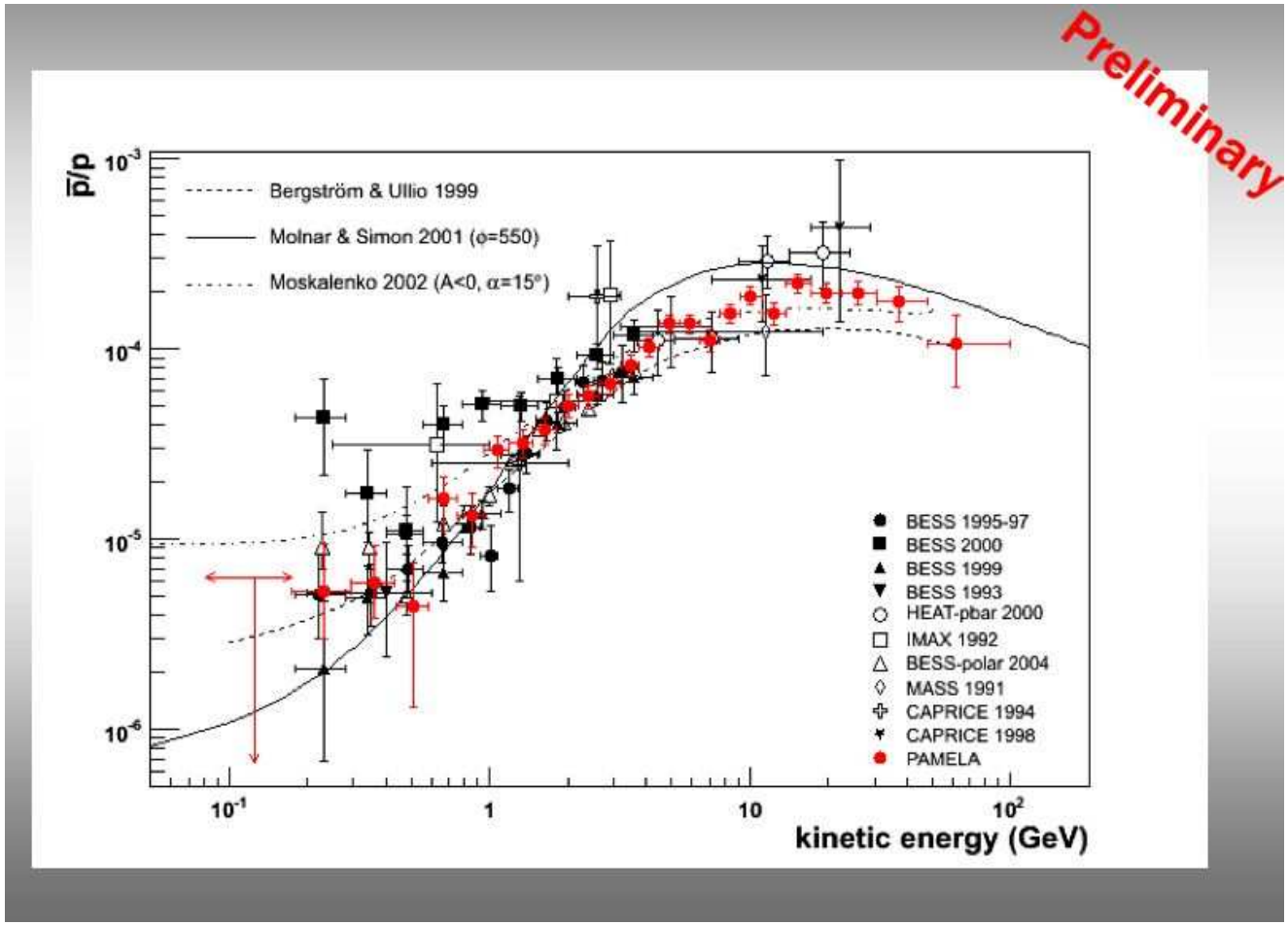
-annihilation of 800 GeV (blue)

-annihilation of 620 GeV KK DM (black)

DM require large Boost Factors!



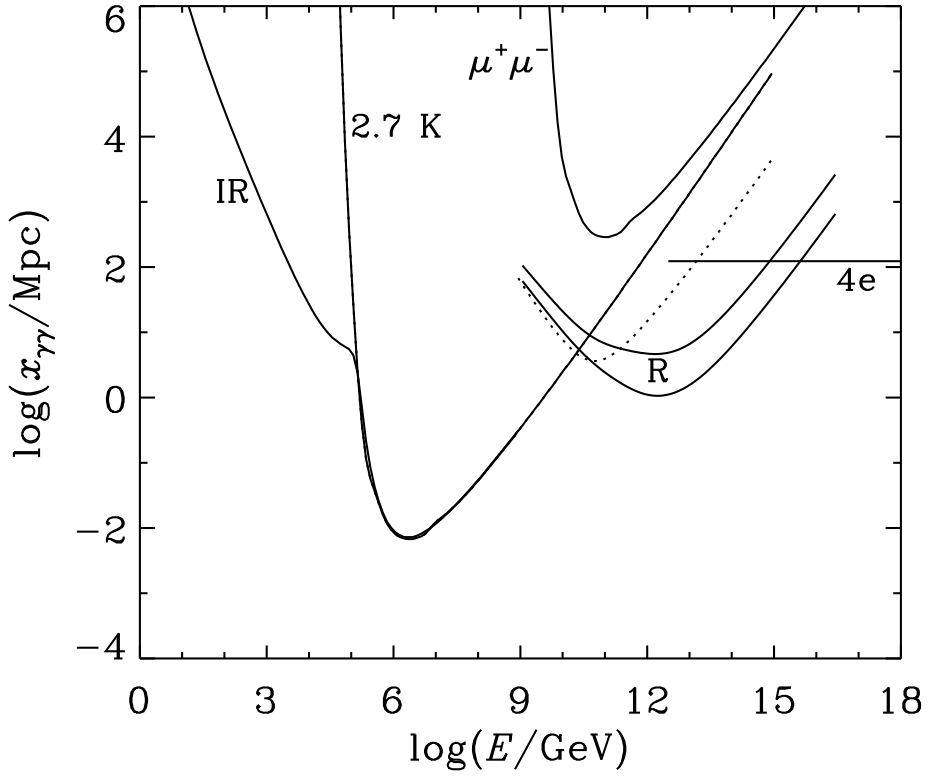
PAMELA: $\bar{p}/p$ new results (Feb/08) compatible with secondary cosmic rays



Interaction length of photons (Protheroe-Biermann 1996)

Pair production $\gamma\gamma_b \longrightarrow e^+e^-$ on IR, CMB and Radio

also $\longrightarrow \mu^+\mu^-$ and double e^+e^-

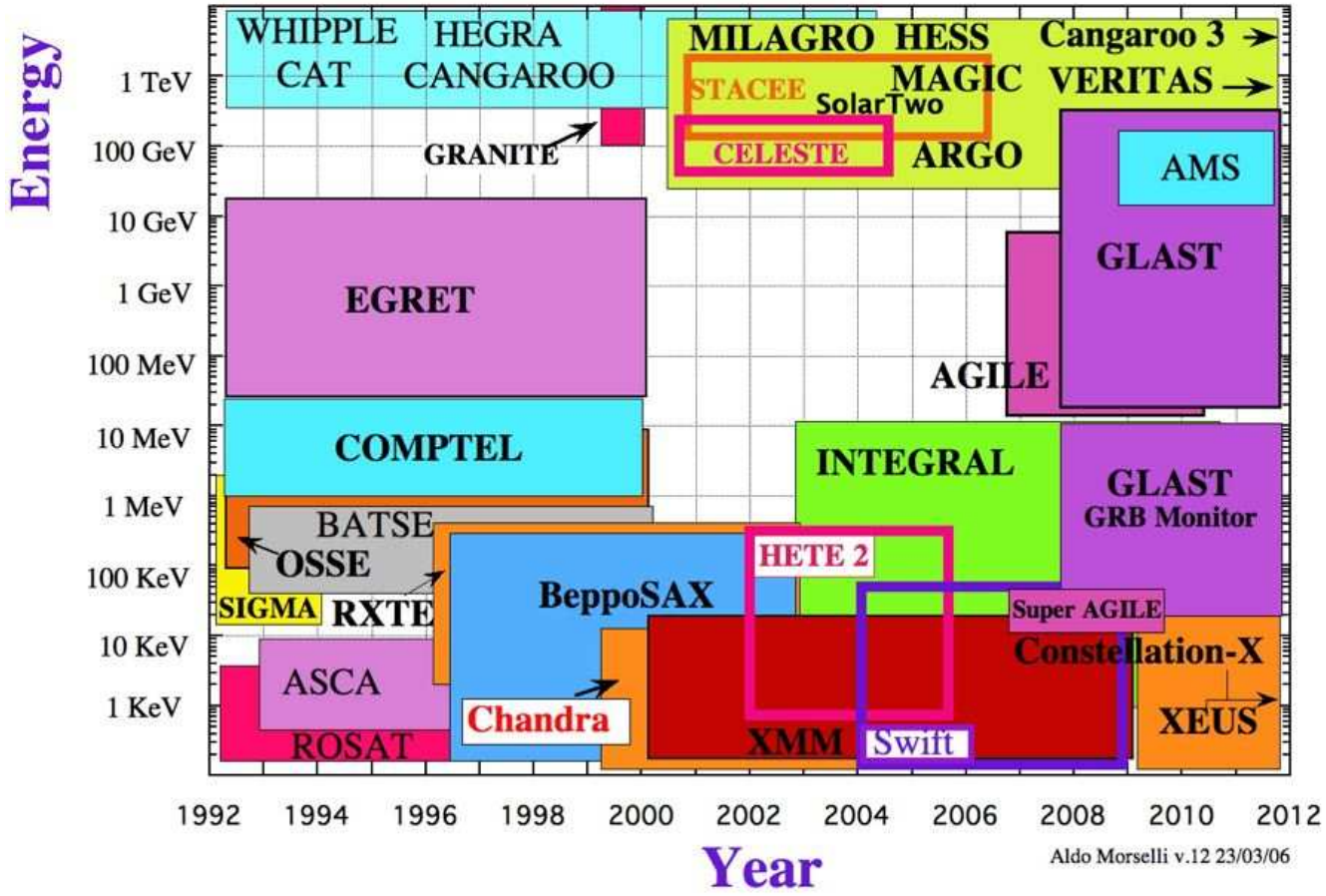


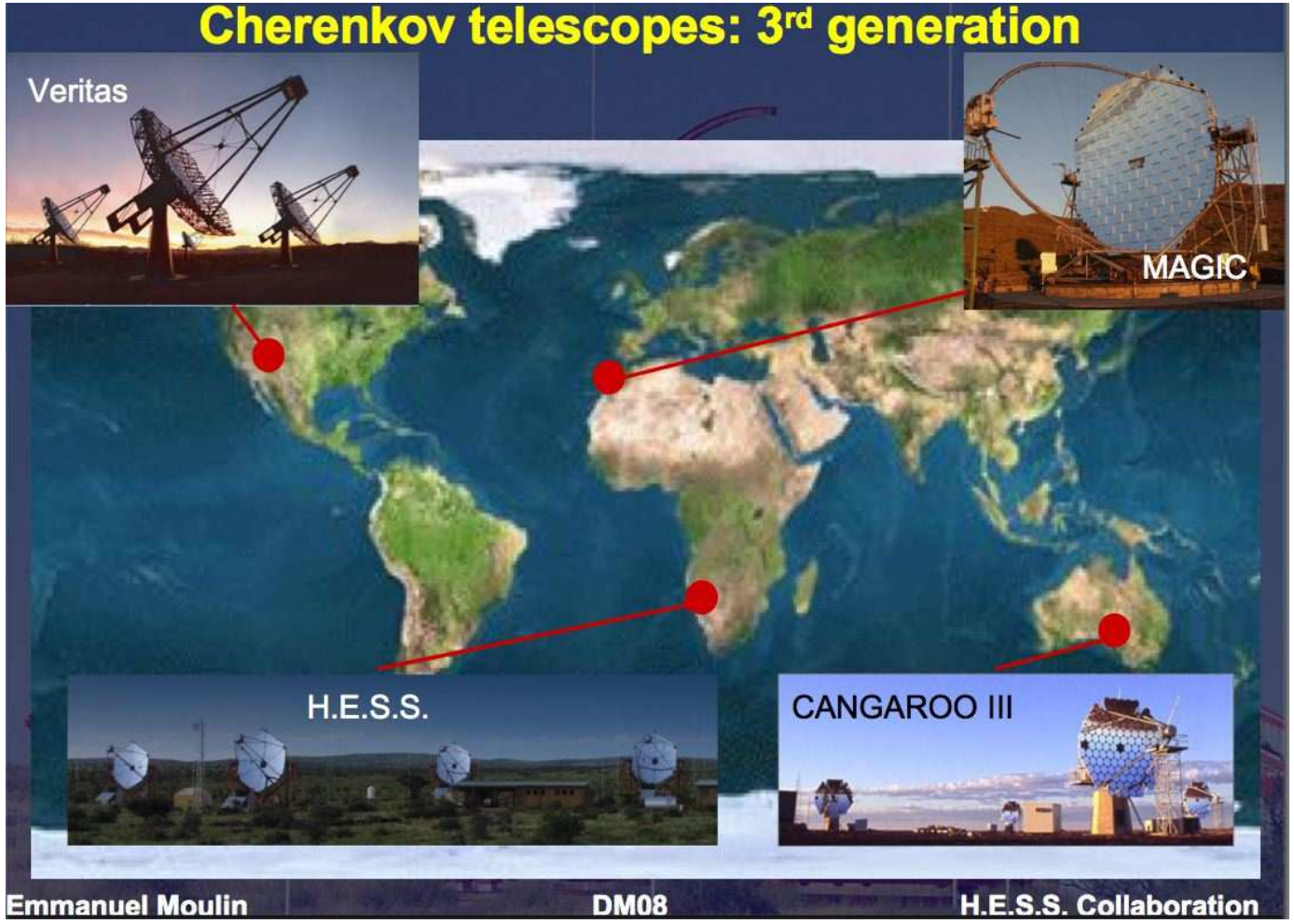
Universe is transparent to photons with

$E < 100$ TeV or

$E > 10^{10}$ GeV (UHECR)

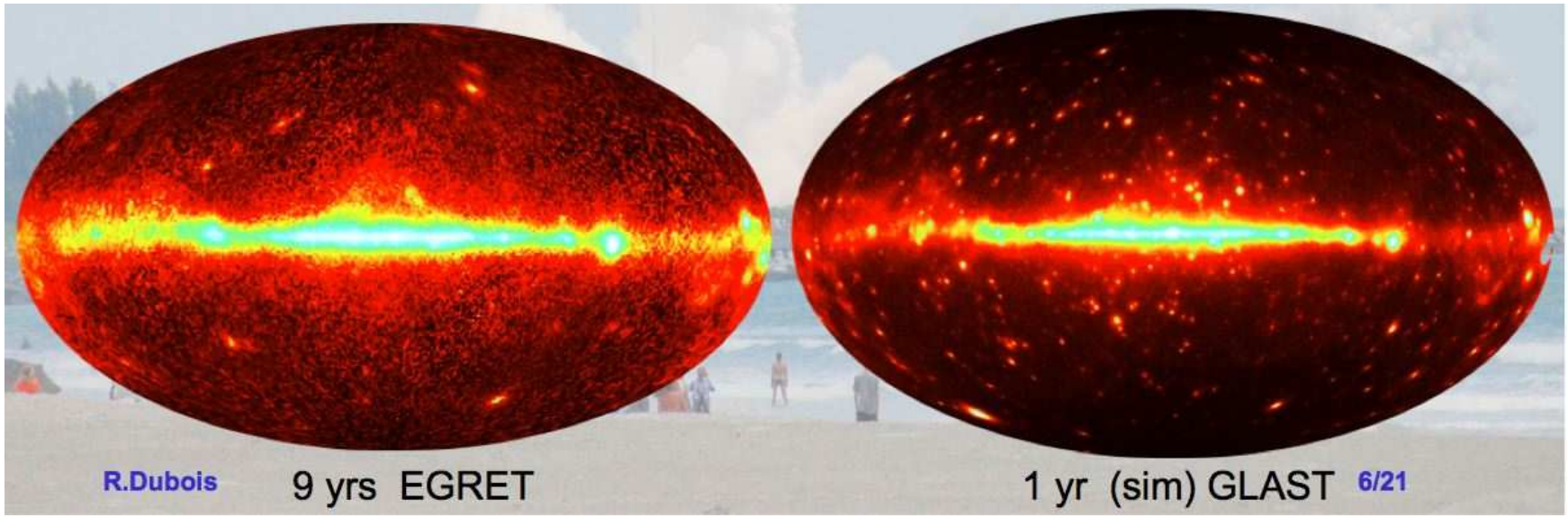
γ ray detectors (talk of Manel Martinez)




Cherenkov telescopes: 3rd generation
Veritas
MAGIC
H.E.S.S.
CANGAROO III
Emmanuel Moulin
DM08
H.E.S.S. Collaboration

Fermi Space Telescope (FST)
(ex GLAST, γ-ray Large Area Space Telescope):

launched Jun 11,08 is providing γ ray spectroscopic data of unprecedented quality (talk of Manel Martinez)



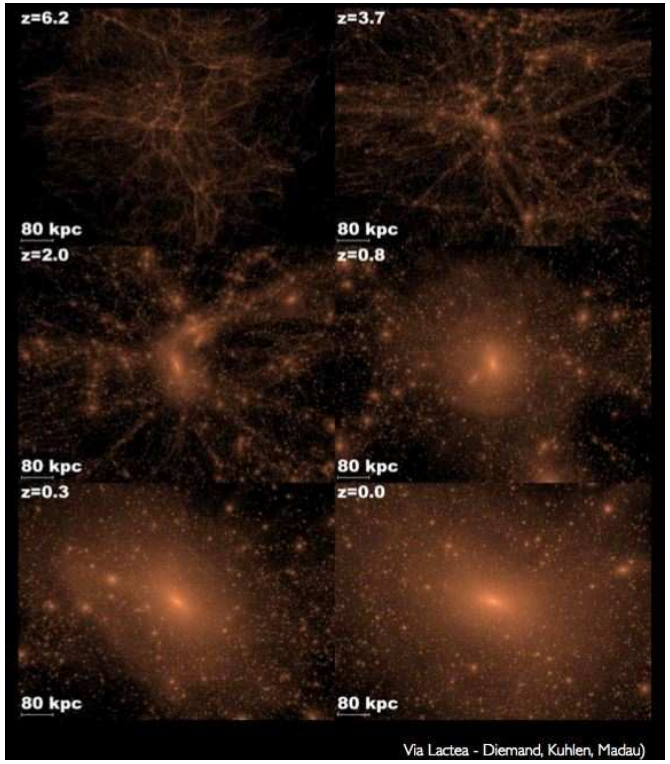
Boost factor given by dark halo substructure:

Annihilation rate $\sim \rho^2_{DM}$, thus lumps of higher ρ_{DM} boost annihilation signal.

(Hofman, Schwarz, Stocker 01; Green etal 04, 05; Berezinsky etal 03, 05, 06, 08; Diemand etal 05; Zhao etal 07; Loeb, Zaldarriaga 05; Bertschinger 06; Strigari etal 07)

Haloes grow hierarchically incorporating lumps and tidal streams from earlier phases of structure formation.

"Via- Lactea" simulations: FST may well discover from a few to 10's of subhaloes at 5σ significance



Kuhlen Diemand Madau arXiv:0805.4416

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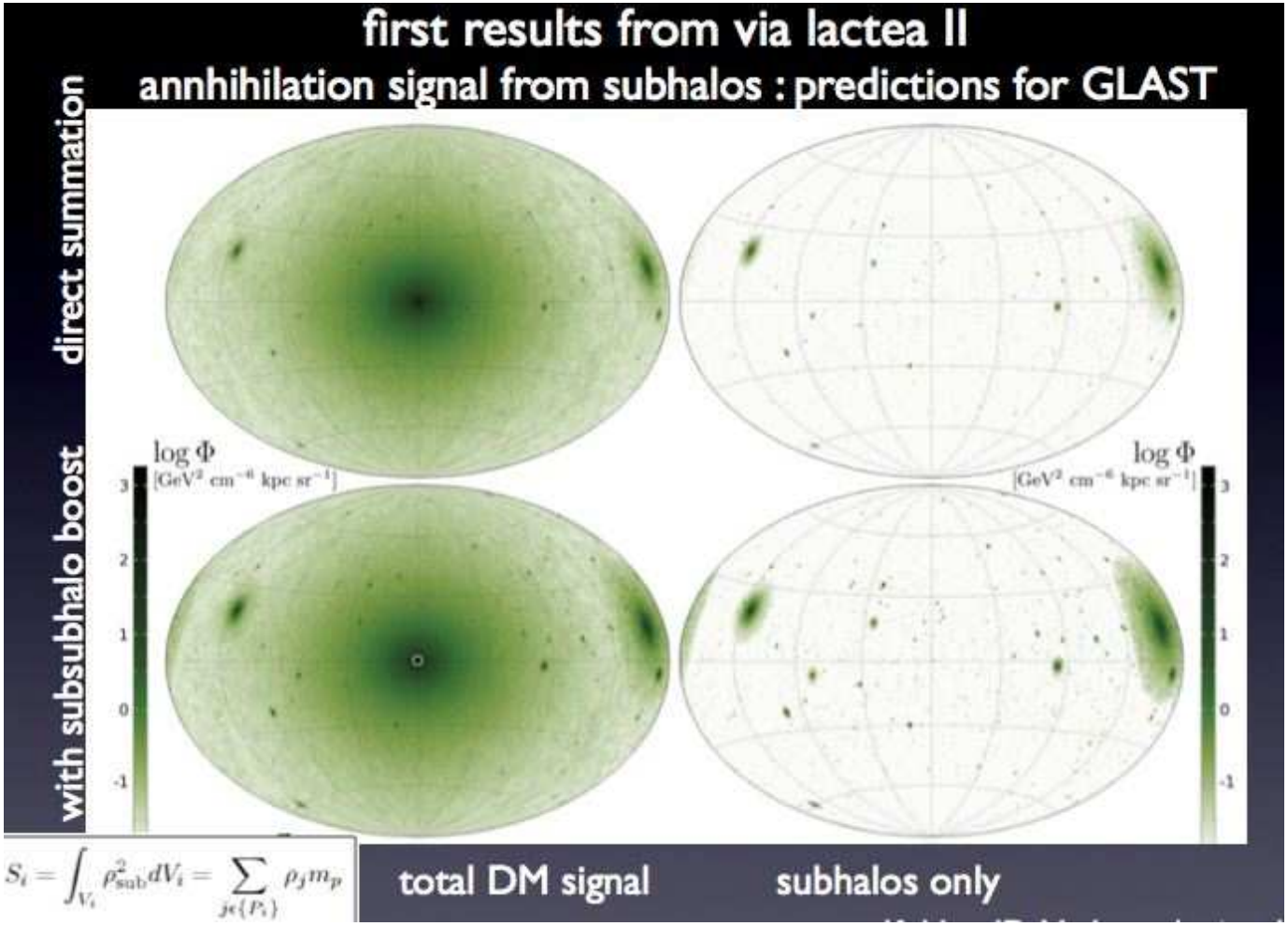

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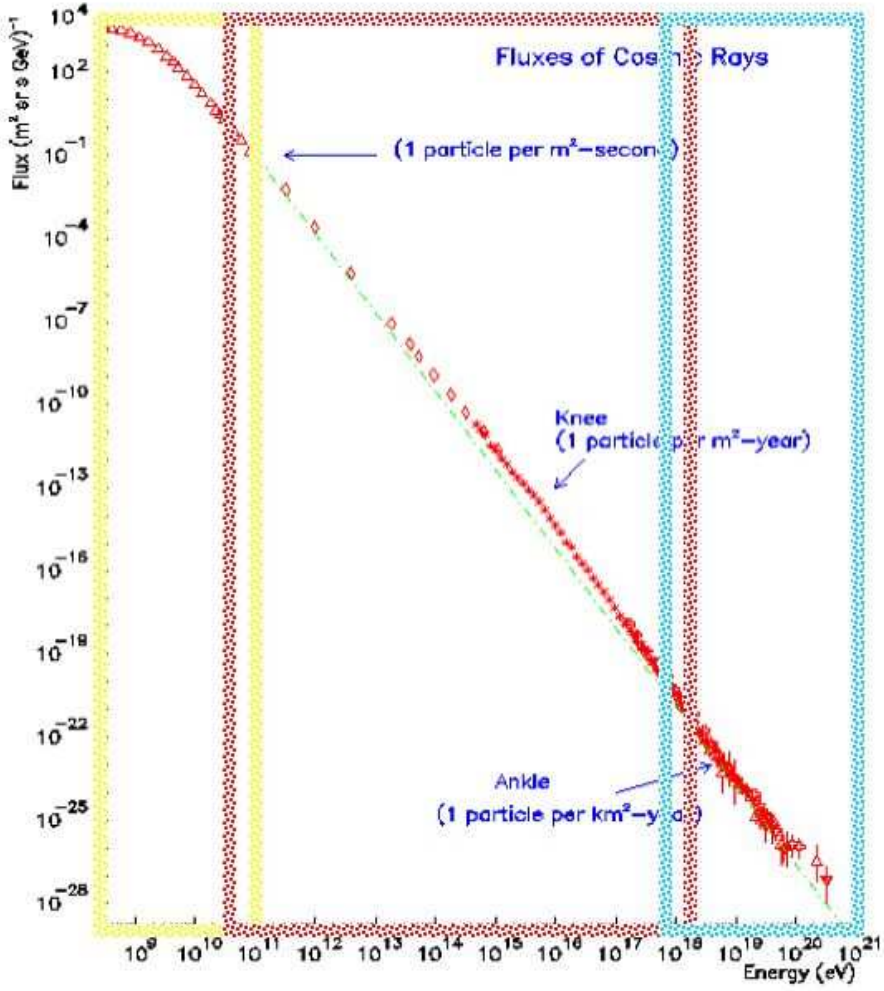
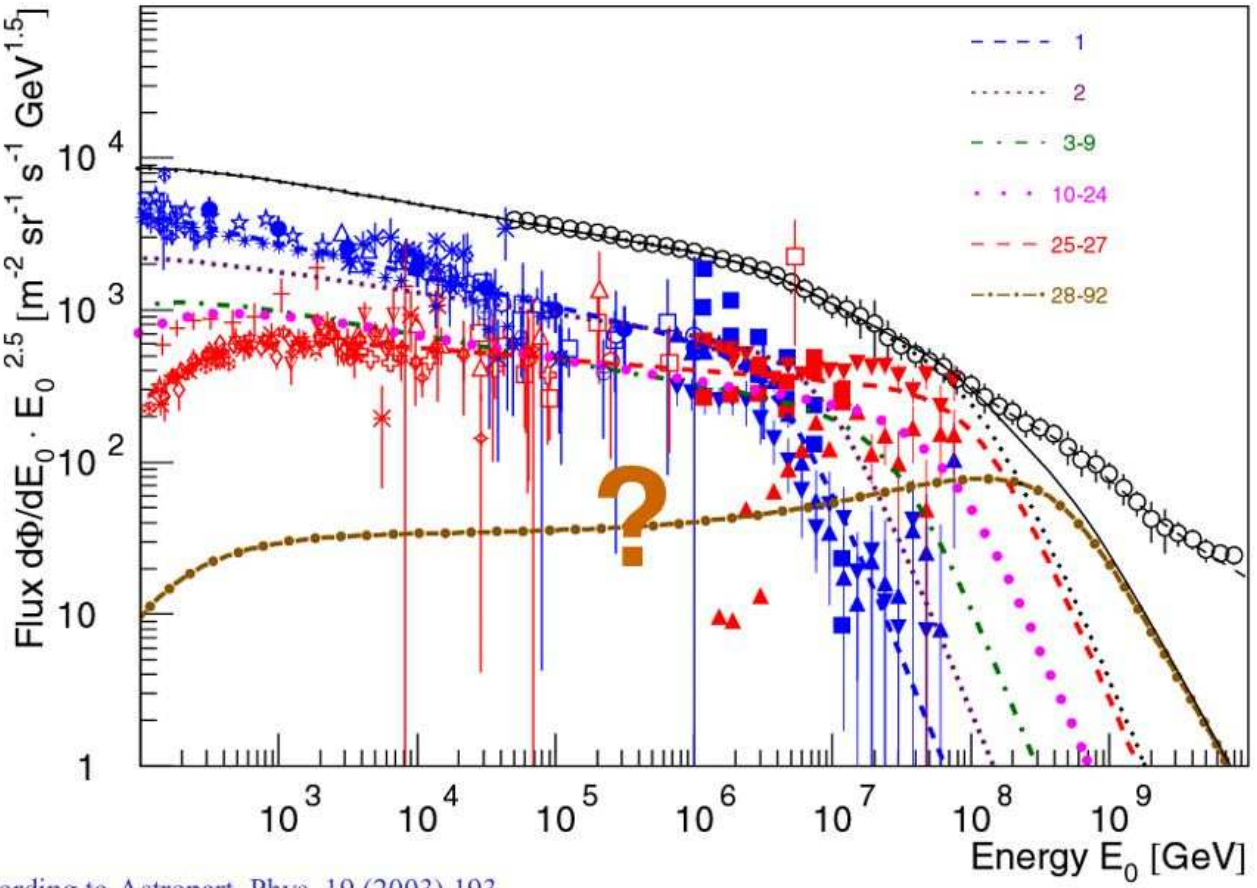


End of the Galactic CR spectrum

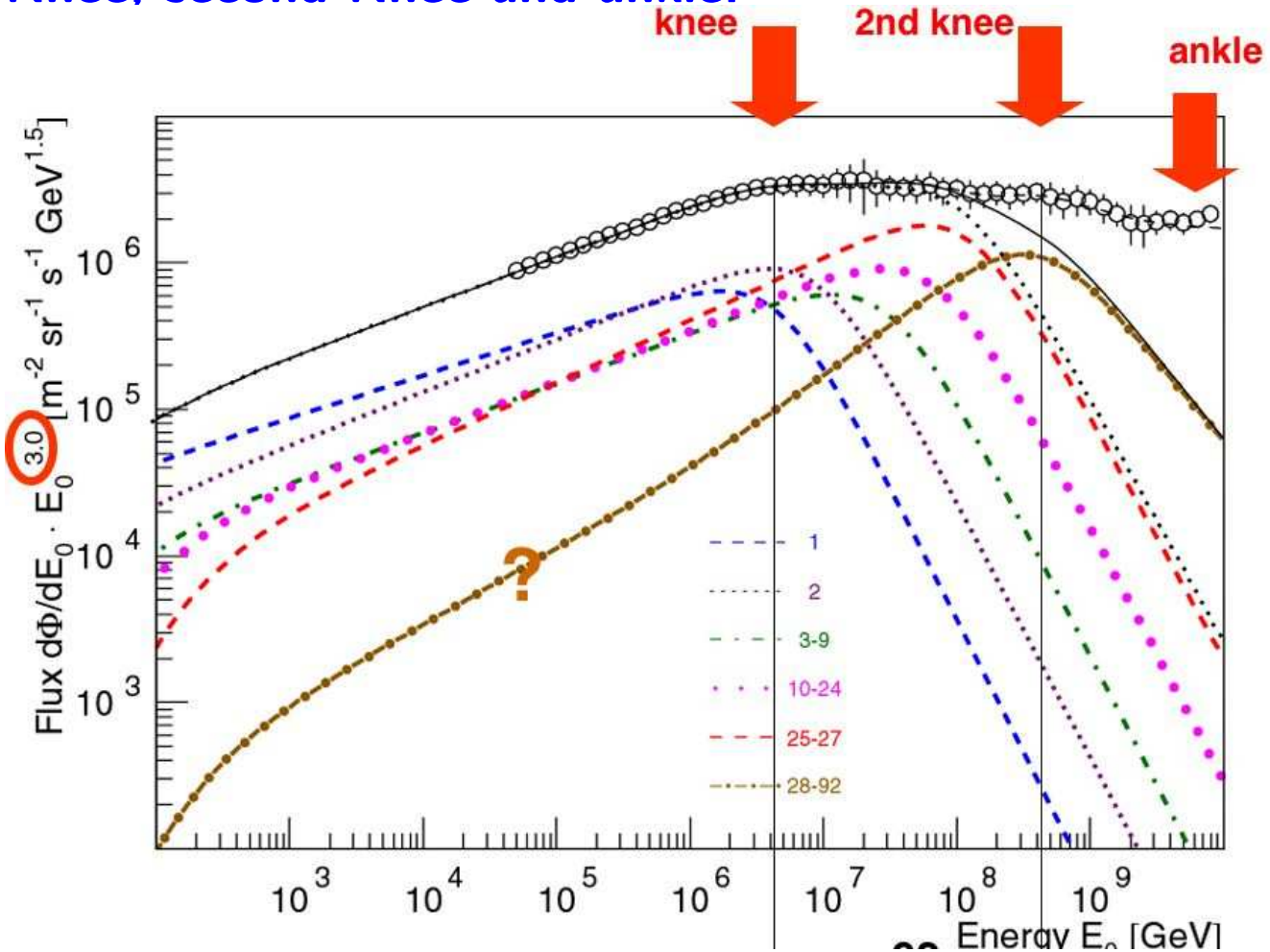
- **Knee:** caused by p cutoff due to leakage from galaxy.
- **cutoff of elements $\sim Z$:**
- **Second Knee:** caused by end of galactic component? Transition from Fe to p?
- **Ankle:** transition from galactic to extra-galactic or absorption feature (Berezinky et al. "DIP")?

Knee and second Knee:



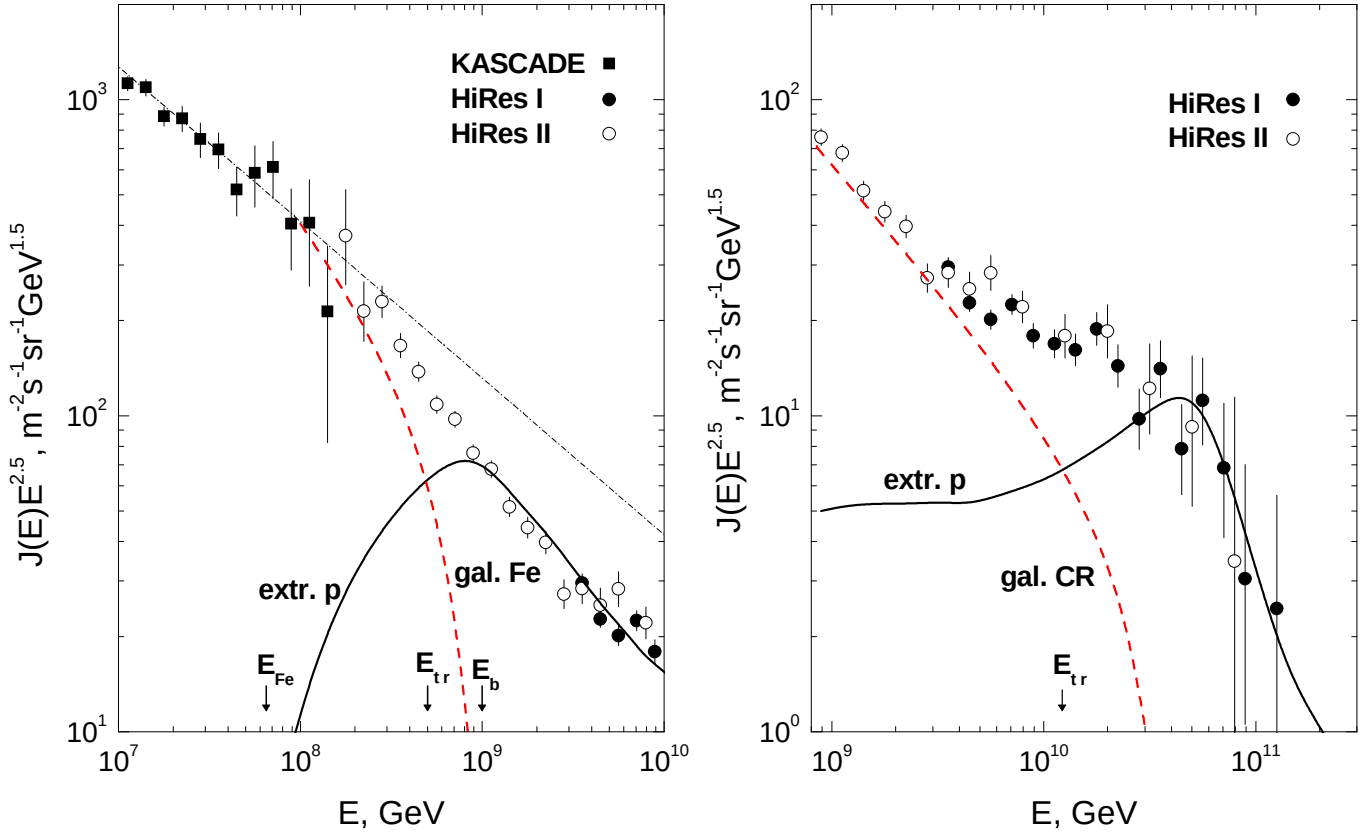
according to Astropart. Phys. 19 (2003) 193

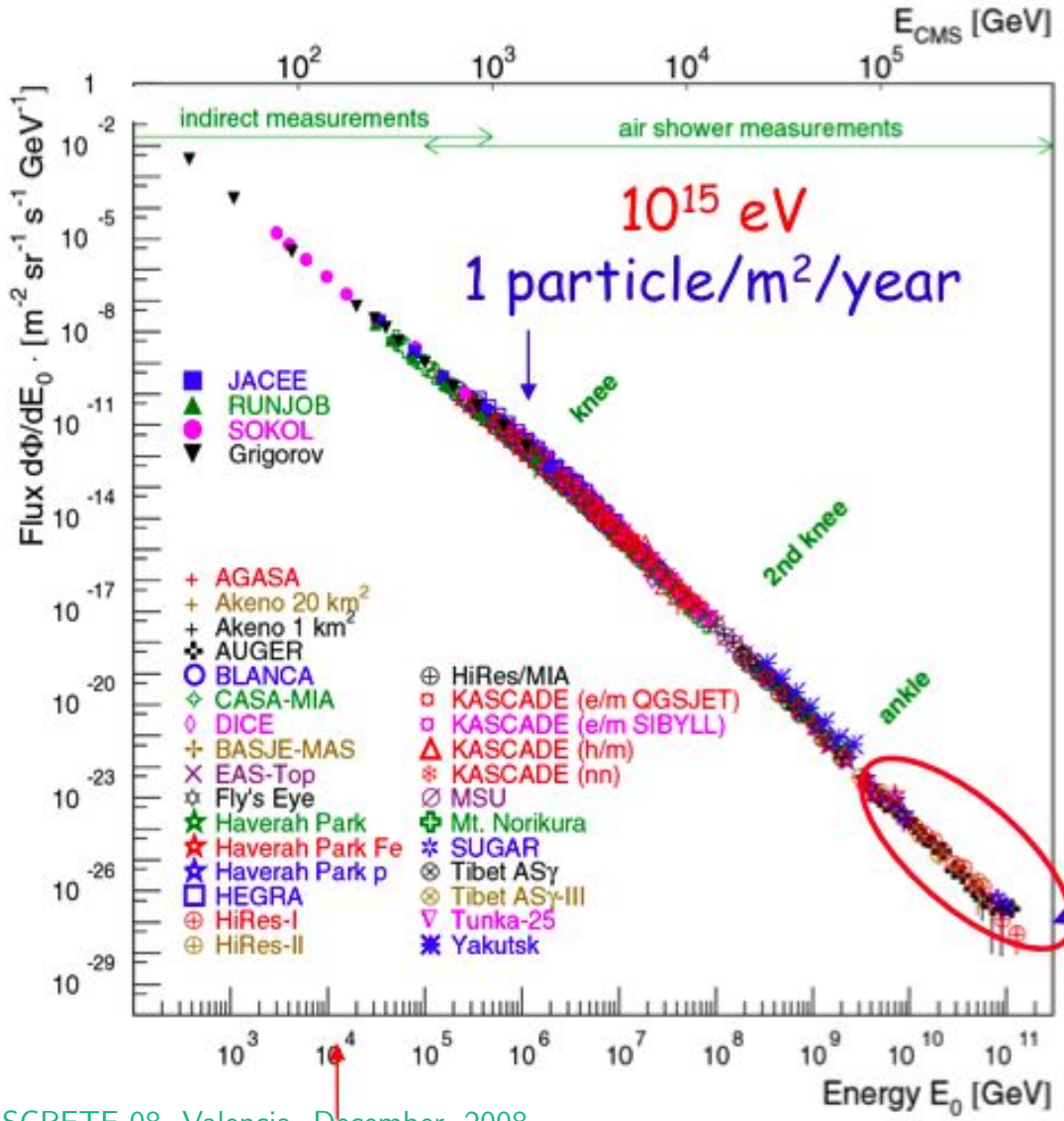
Knee, second Knee and ankle:



Ankle: feature in EG-p ("Dip") or transition from G to EG?

Aloisio, Berezinsky, Blasi, Ostapchenko PRD 77, 025007, 2008





~ E^{-3}

16 Joules!

10^{20} eV

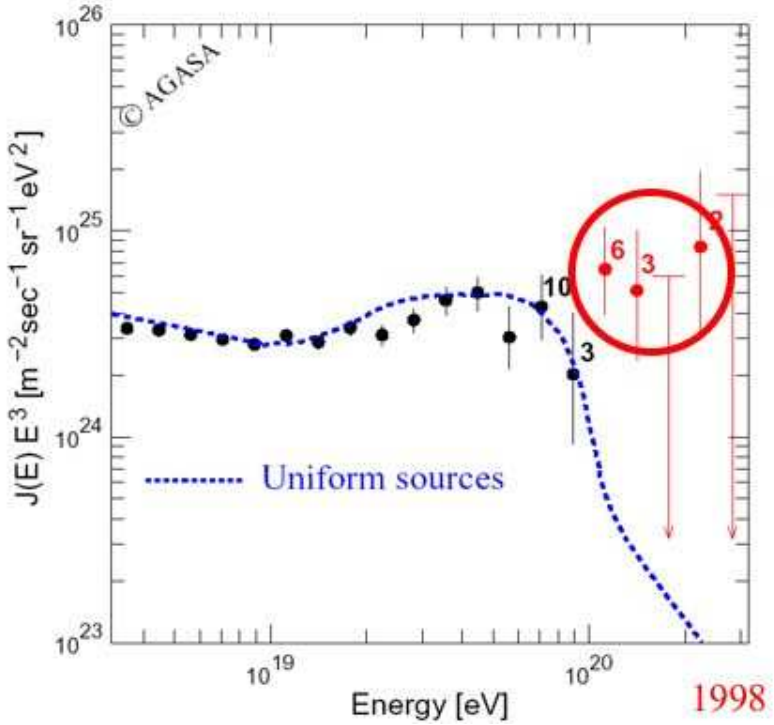
~ 1 particle /km^2/century

The Mystery of the UHECR

- 1930's: Pierre Auger observed CR with $E > 10^6$ GeV (10^{15} eV)
- 1956: Cocconi realizes extragalactic origin (galactic magnetic fields not large enough to contain them)
- 1963: John Linsley observes one 10^{20} eV shower
- 1965: Penzias and Wilson discover the CMBR
- 1966: Greisen and Zatsepin-Kuzmin point out that $E_{CR} < 4 \times 10^{19}$ eV if they are protons (GZK 'cutoff')!
- 1984- 2003: AGASA, 111 scintillators in 100 km^2-NO GZK...
- 1997-2006: High Res. Fly's Eye, 2 fluorescence telescopes- YES GZK...
- 2004: Pierre Auger Observatory: Hybrid observatory built to elucidate the issue

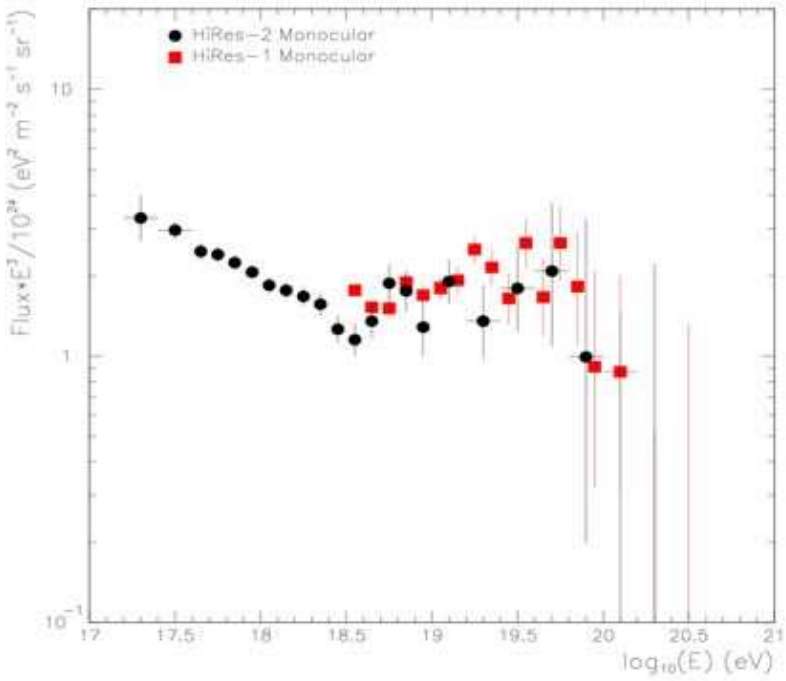
AGASA (1984-2003)

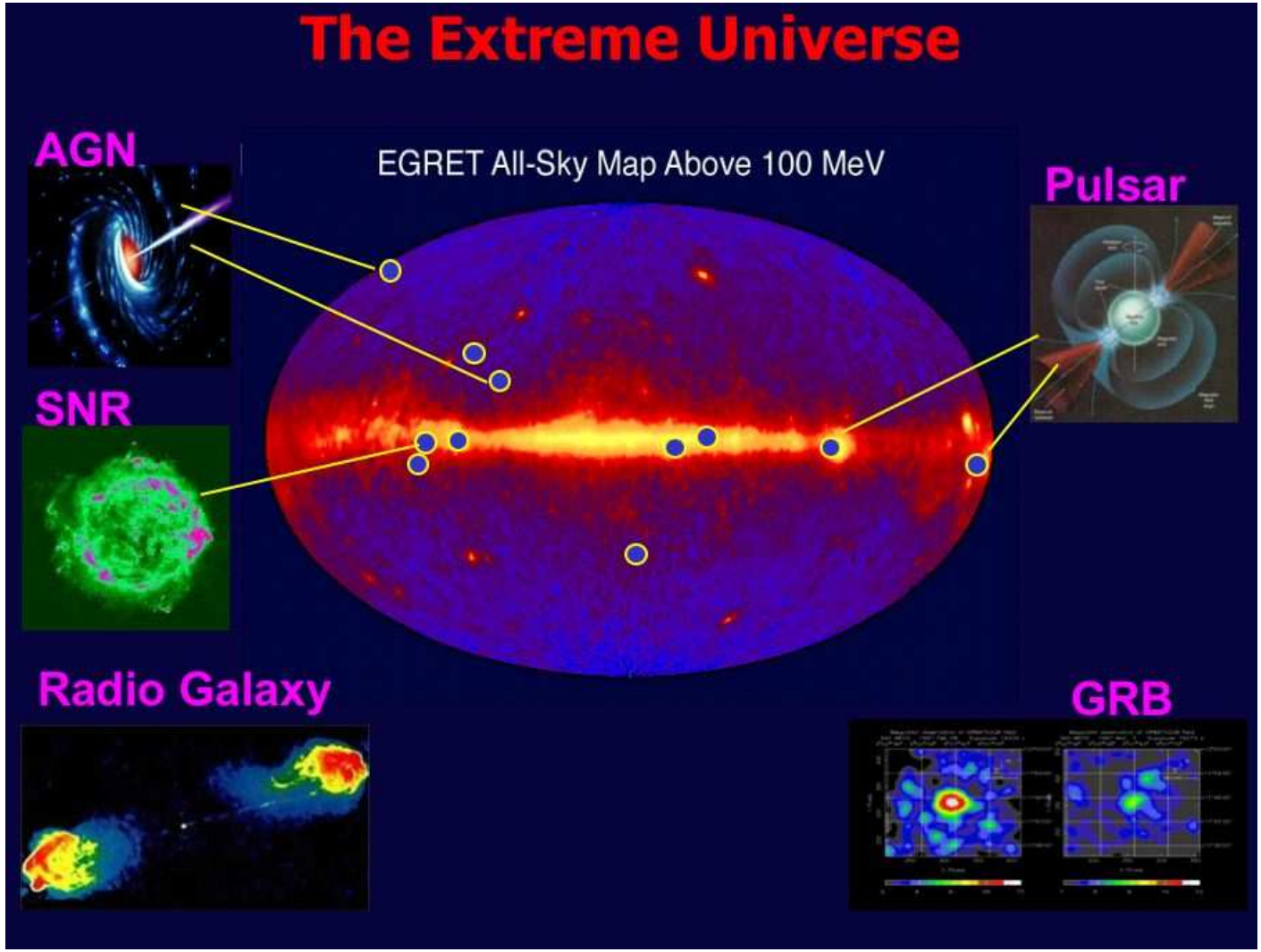
No GZK- cutoff



HiRes (1997-2006)

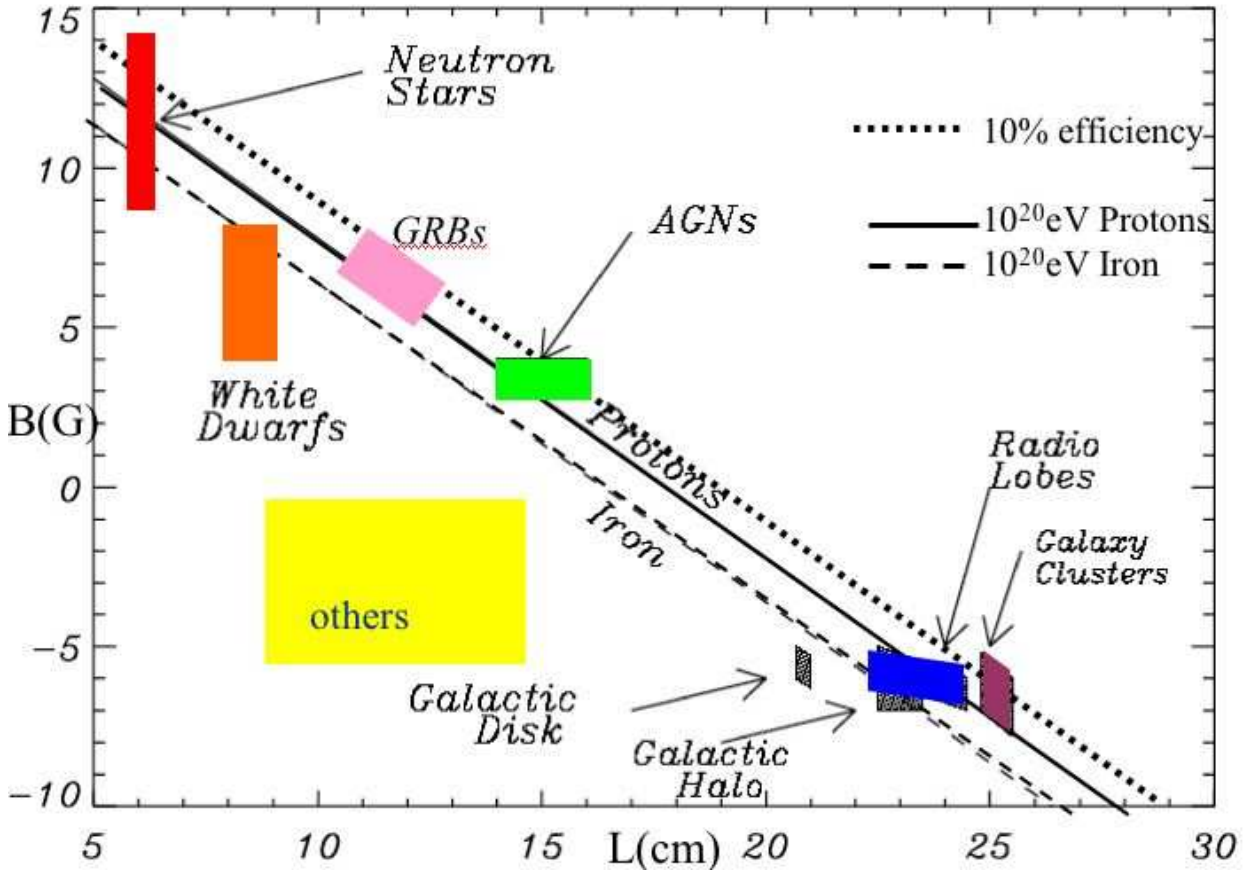
Compatible w/ GZK- cutoff




The Extreme Universe
AGN
EGRET All-Sky Map Above 100 MeV
Pulsar
SNR
Radio Galaxy
GRB

Sources: Extreme accelerators! E= Ze B L

To reach 10^{20} eV need LHC with radius 10^7 km (Sun-Mercury)!



Top-Down models: No GZK, no acceleration

- **TD: Topological Defects** (Hill, 1983;;Berezinky , Vilenkin ,1997)
  Such as cosmic strings, or 'necklaces'- closed string loops including monopoles- emit super heavy X particles $X \longrightarrow q, l \longrightarrow$ UHECR: $E_{max} \simeq m_X$
- **SHDM: Super Heavy Dark Matter** (Berezinsky etal 97; Kuzmin, Rubakov 97; Birkel, Sarkar 98)
  Metastable heavy X particles ('cryptons' , 'wimpzillas'...) $X \longrightarrow q, l \longrightarrow$ UHECR with $\tau >$ lifetime of the Universe. UHECR from within the dark halo of our galaxy (thus excess towards the galactic center). $E_{max} \simeq m_X$
- **Z-bursts** (Fargion, Mele, Salis-1999; Weiler -1999)
  UHE neutrinos from remote sources annihilate at the Z-resonance with background neutrinos, $Z \longrightarrow$ UHECR: $E_{max} \simeq E_{res} = M_Z^2/2\, m_\nu = 4 \times 10^{21} \mathrm{eV}(\mathrm{eV}/m_\nu)$

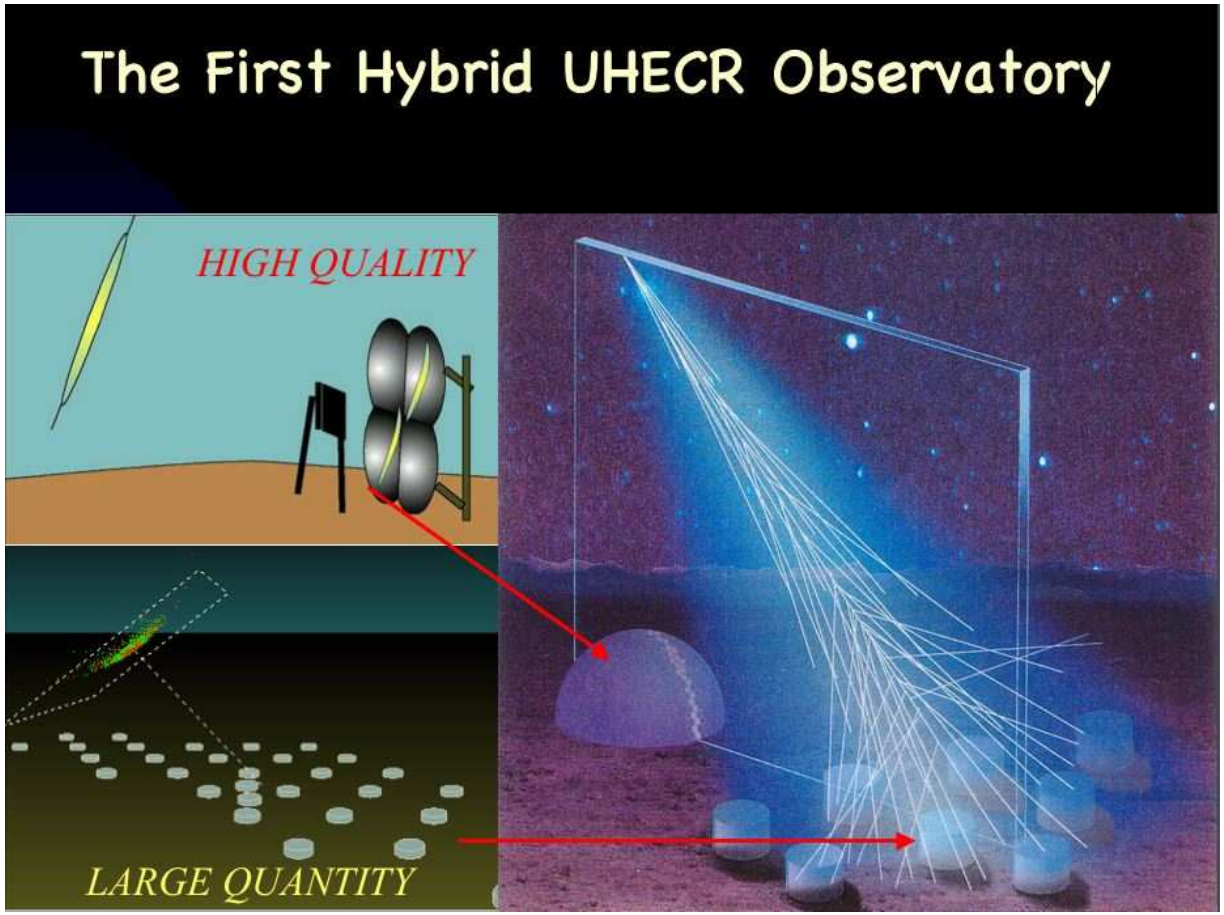
All produce mostly γ and ν.

Ultra High Energy Cosmic Rays, $E > 10^9$ GeV

Produce showers of secondary particles in areas up to many km^2 seen in

- Surface Detectors (SD): scintillator counters or water tanks (AGASA)
- Fluorescence Detectors (FD) telescopes of near-UV light which detect Nitrogen fluorescence emission induced by the shower (HiRes)

  Pierre Auger Observatory has both



FD:

-longitudinal shower dist.

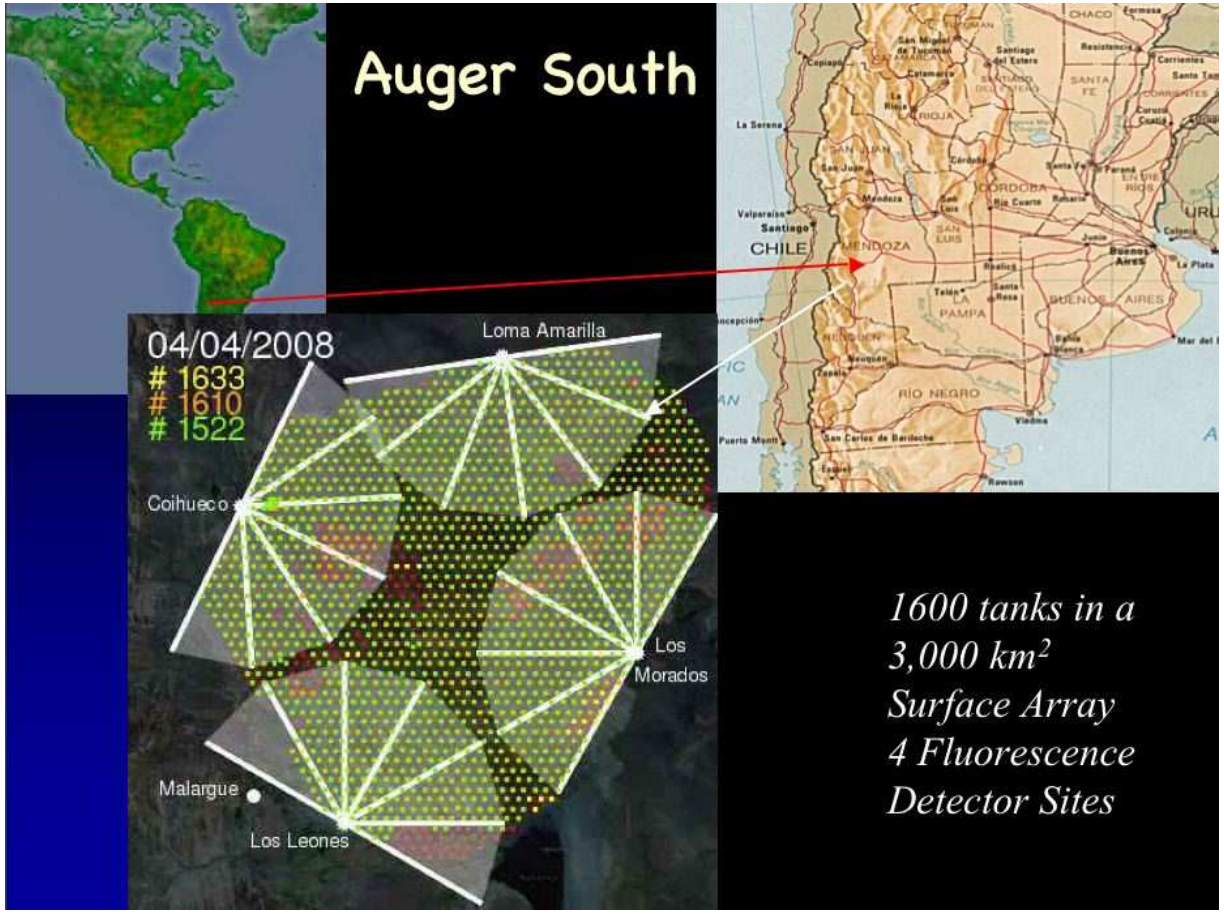
-calorimetric E measure

-10% duty cycle.

SD:

- transverse shower distrib.

-high statistics at largest E



Completed 6/08

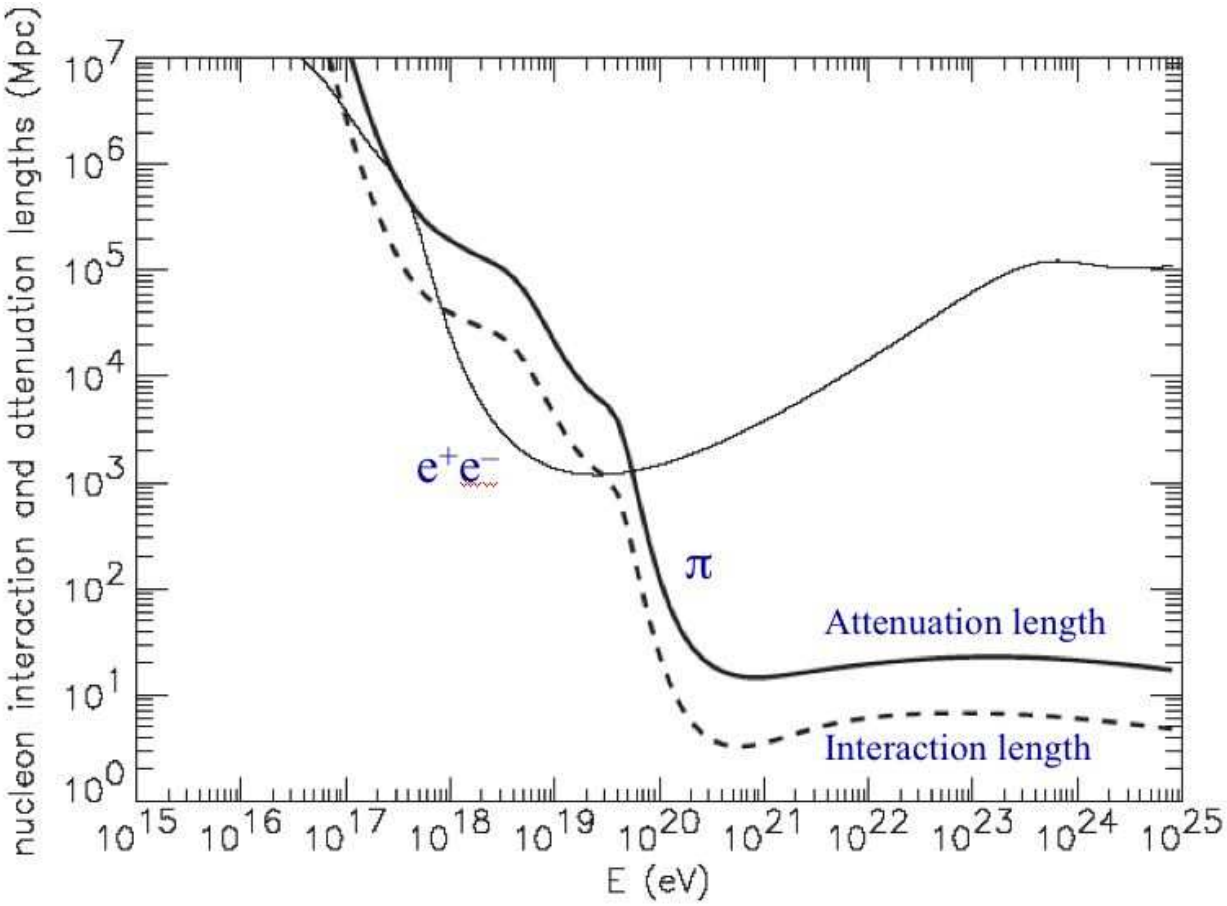
Exposure now:
$\sim 10^4$ km^2 sr yr

PAO made to study UHECR (E$> 10^{18}$ eV)

- **Energy spectrum:** GZK cutoff?
- **Composition:** protons, heavy nuclei, photons?
- **Arrival direction distribution:** large scale anisotropy, correlation with particular sources
- **Sources?**

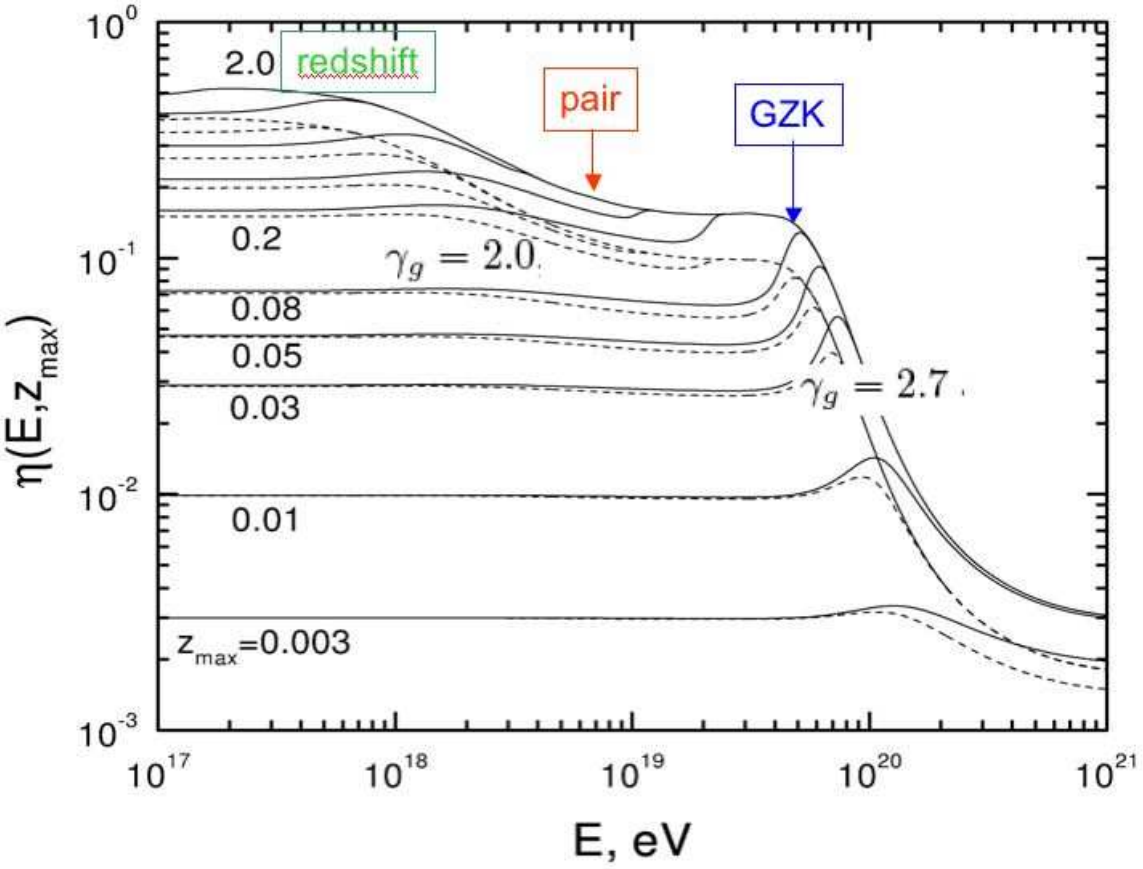
Attenuation of protons

$p\gamma \rightarrow pe^+e^-$, $p\gamma \rightarrow p\pi$

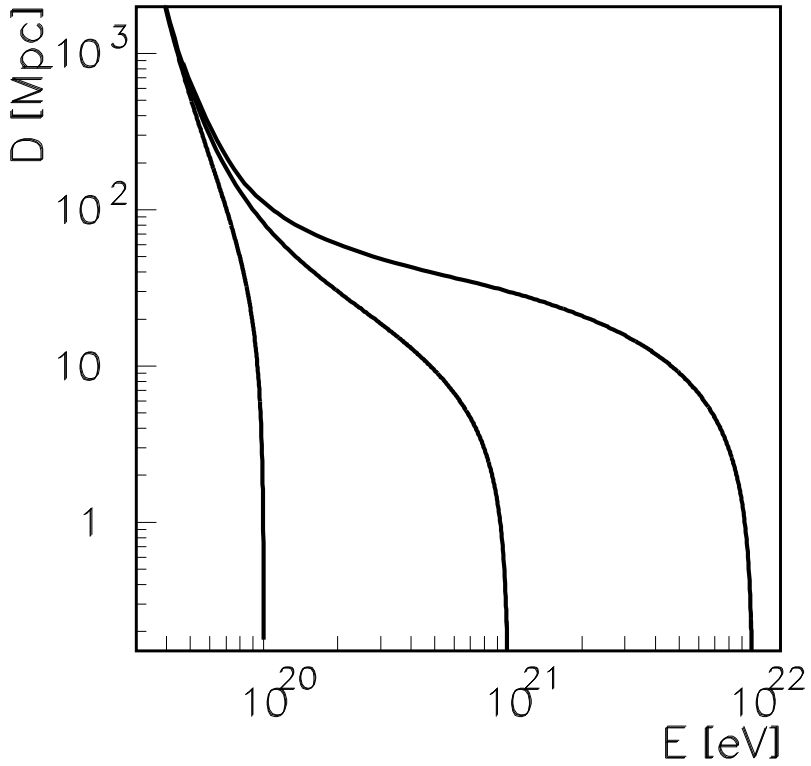


Energy loss features for protons

$\eta(E, z) = J_{\rm obs}/J_{\rm injected}$ (Berezinsky et al.)



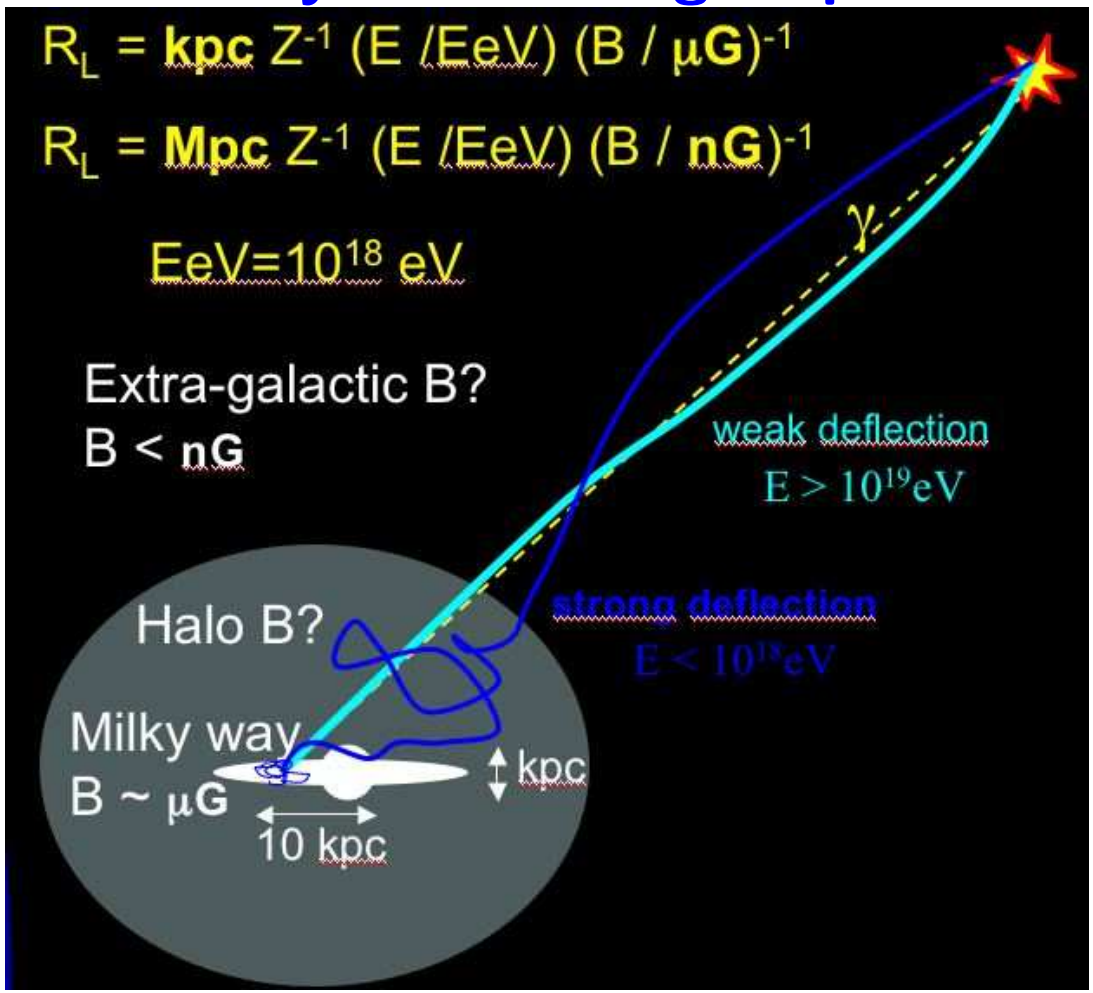
GZK effect on p and n:



(fig. from Anchordoqui et al., 2002)

p reaching Earth with $E > 10^{20}$ eV produced < 100Mpc

Astronomy with charged particles with $E > 10^{18}$ eV?



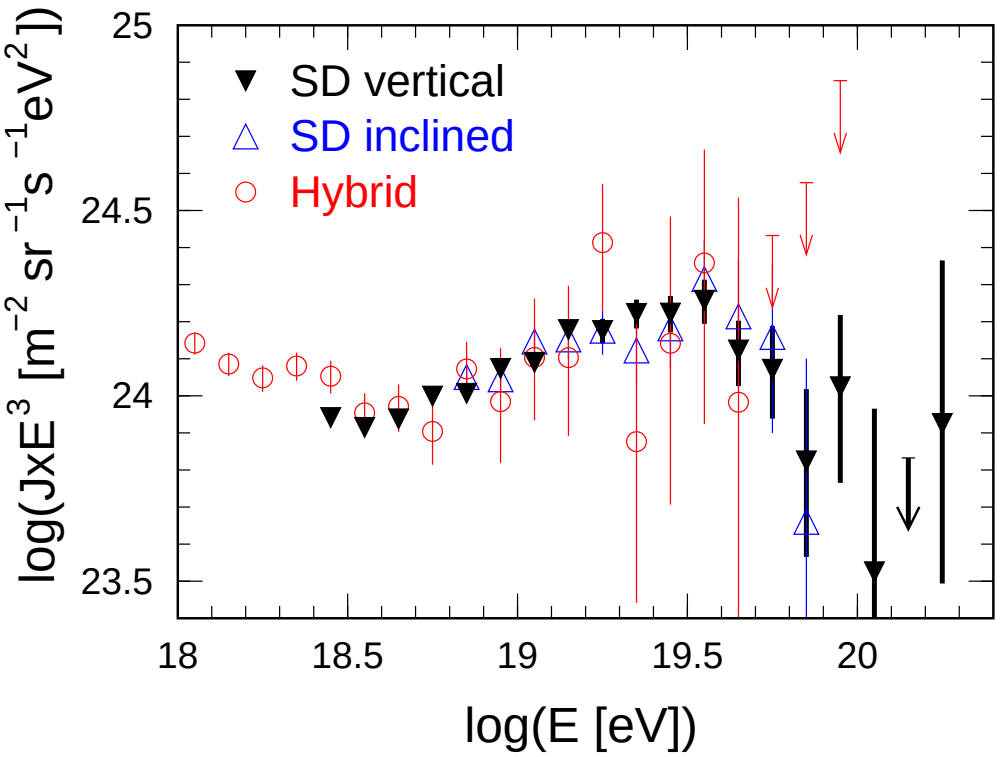
$E < 10^{18}$ eV: strong deflection

Window to $E < 10^{20?}$ eV?

PAO optimized for this range!

Combined Auger spectrum

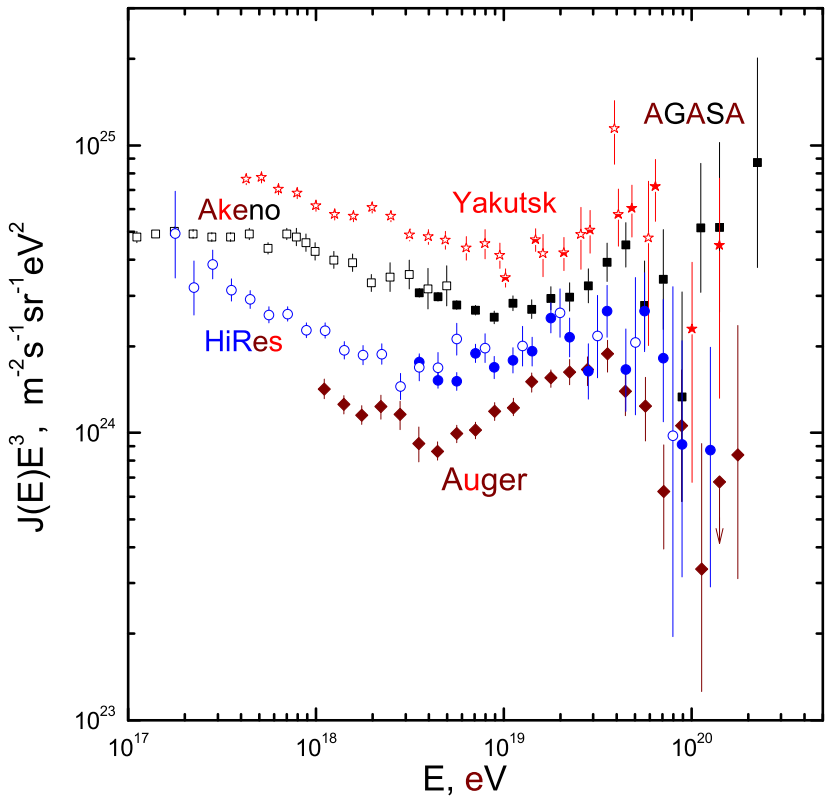
PAO Data 1/1/04 - 2/28/07



Ankle at $\sim 4.5 \times 10^{18}$ eV; GZK at 3.5×10^{19} eV

Auger HiRes and Agasa spectra

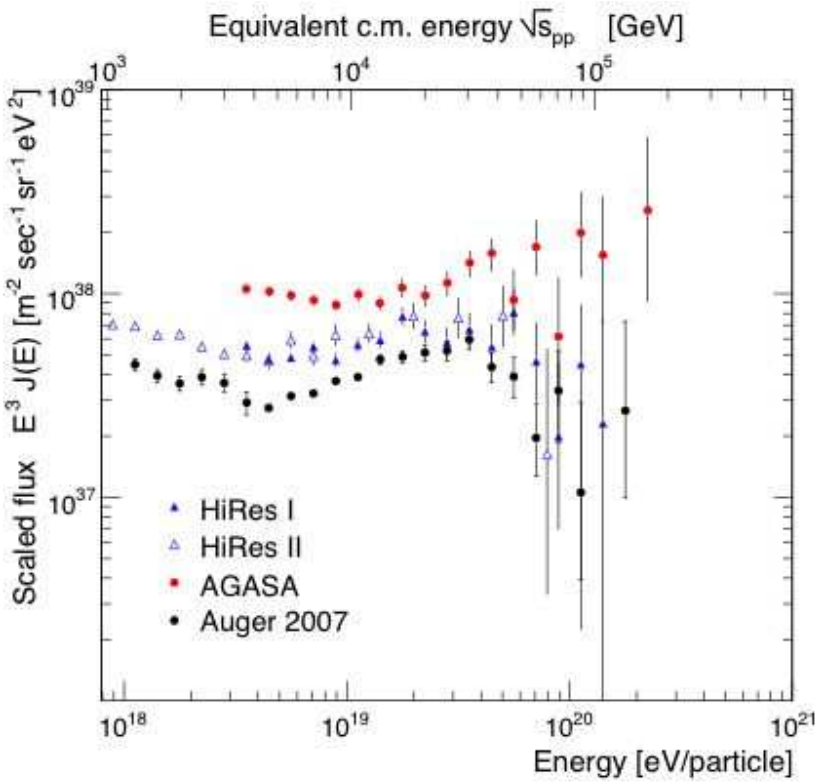
PAO Data 1/1/04 - 2/28/07

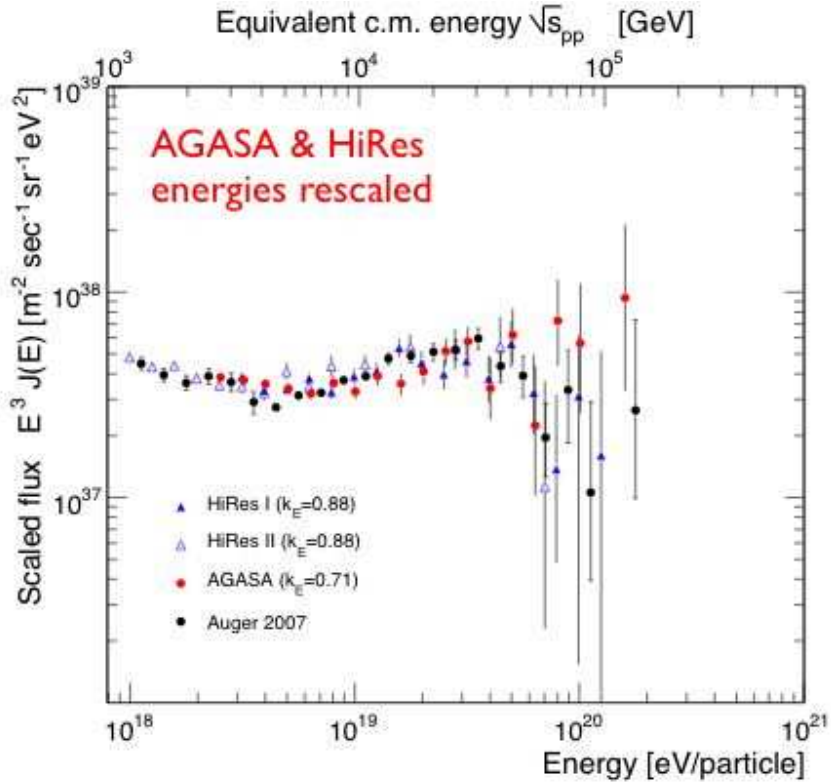


Ankle at $\sim 4.5 \times 10^{18}$ eV; GZK at 3.5×10^{19} eV

Auger finds GZK flux suppression at $\sim 6\sigma$

PAO Data 1/1/04 - 2/28/07 Use ankle to calibrate (Berezinsky)

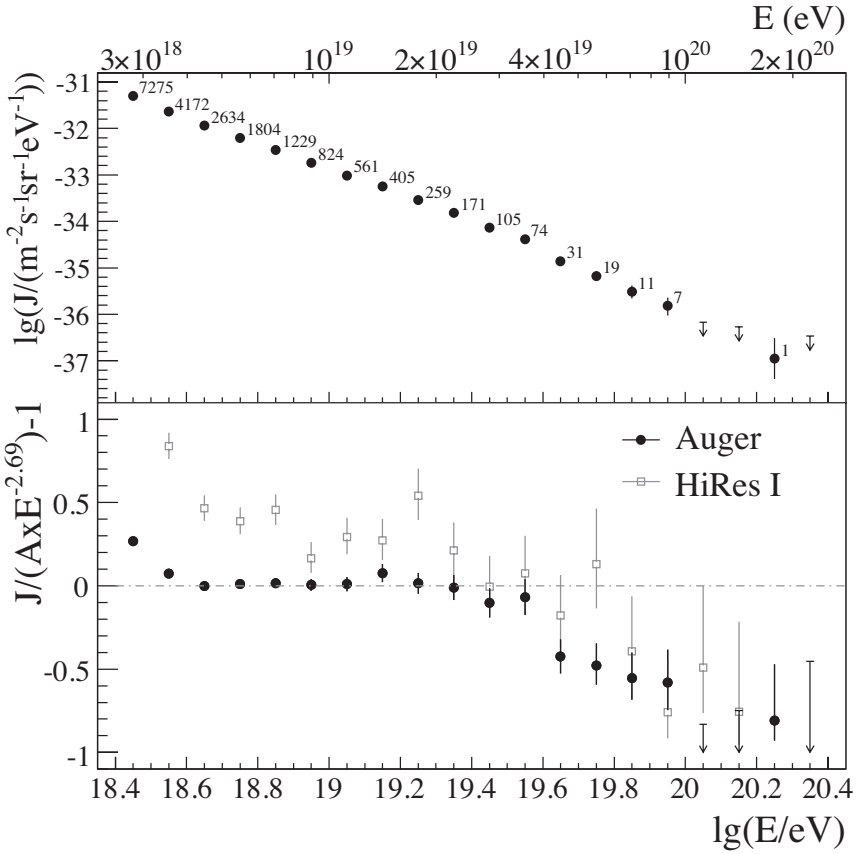




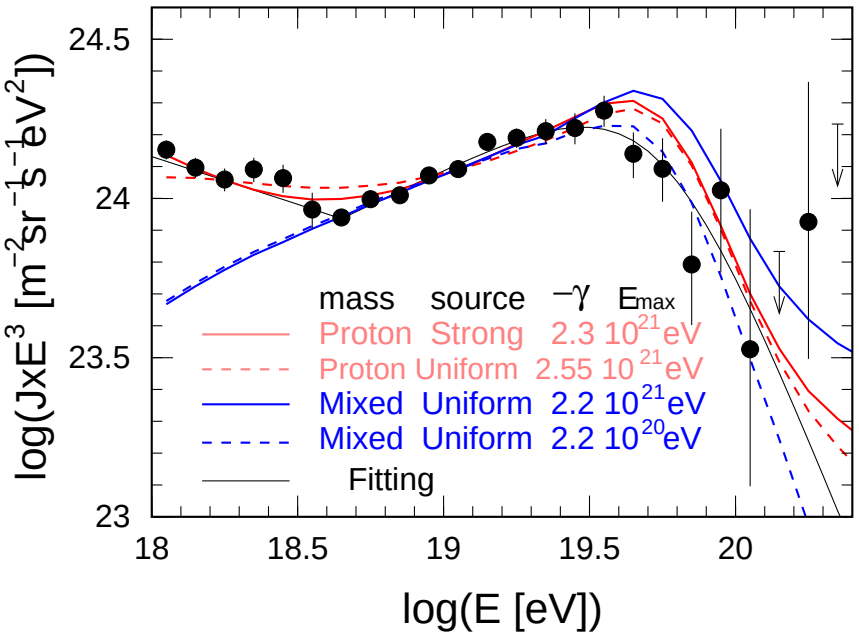
Systematic energy uncertainly: AGASA: 18%, HiRes 17%, Auger 22%

Auger-08, compared to HiRes and $\alpha = 2.69$ spectrum

PAO Data 1/1/04- 8/31/07 Flux Suppression $\sim 6\sigma$



Spectrum cannot determine composition

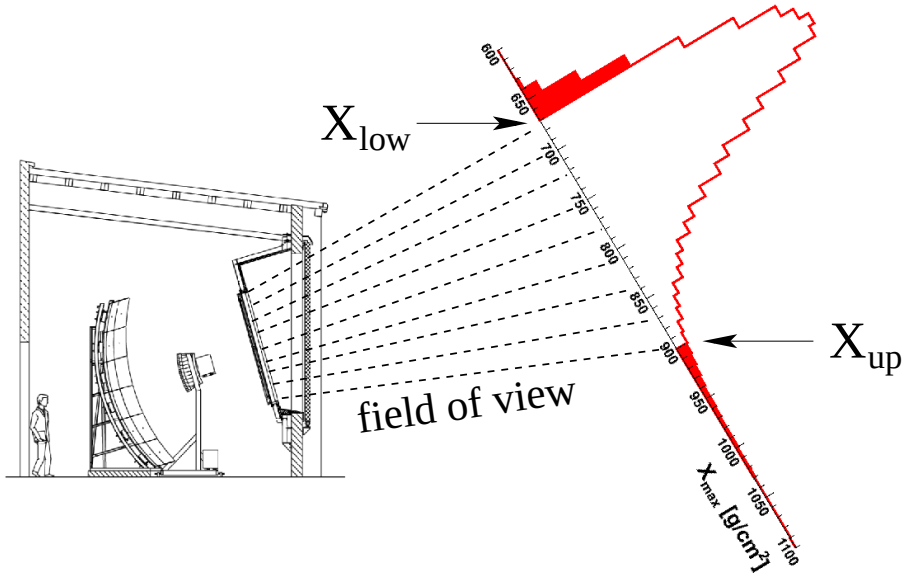


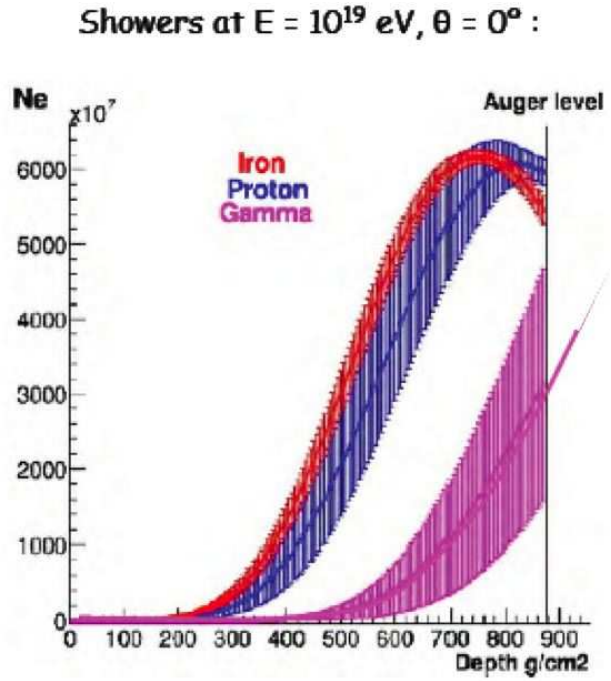
Ankle: galactic/ extra-galactic transition?

Suppression: GZK effect? or max energy of sources?

Knowledge of mass is crucial!

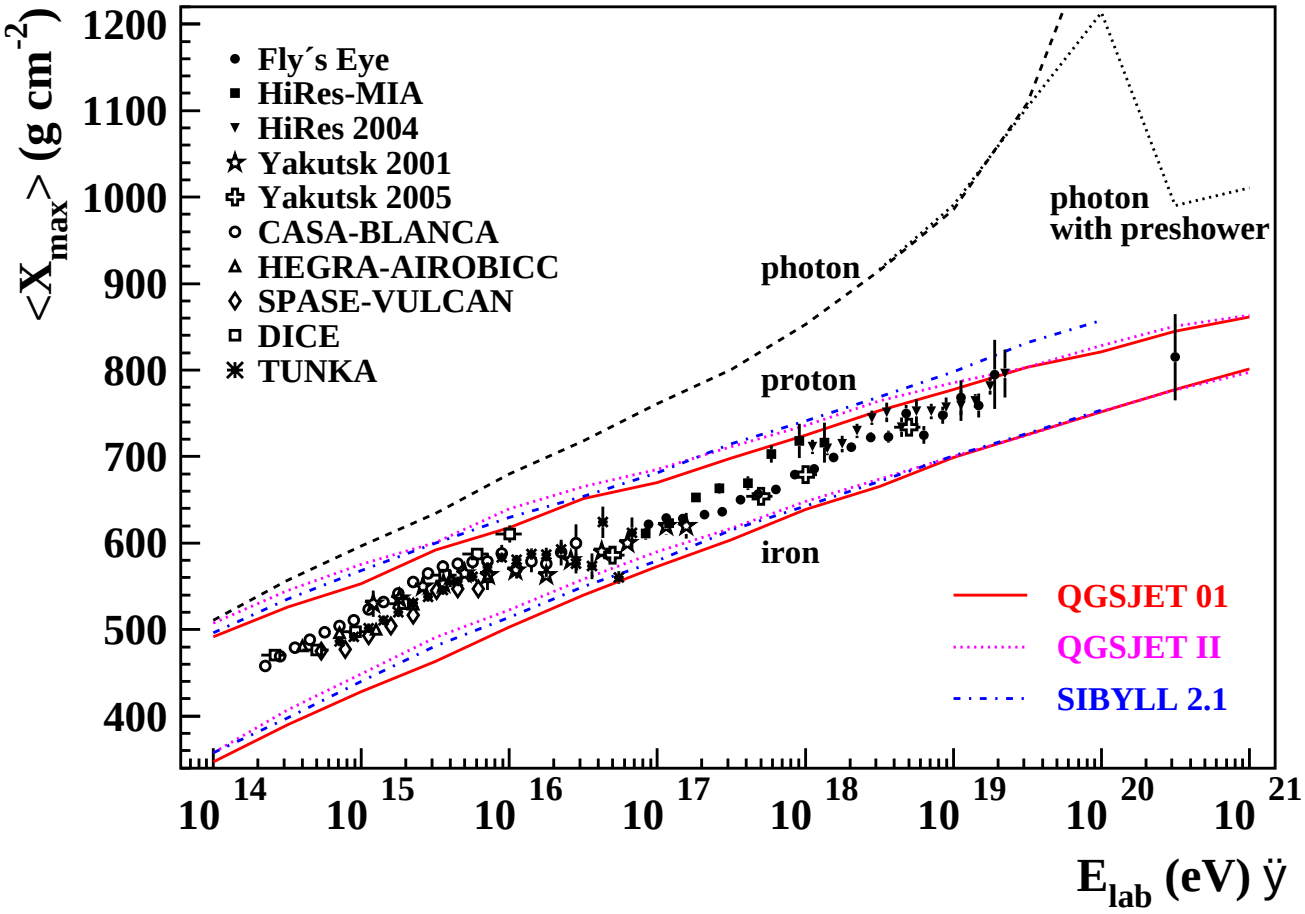
Composition: Longitudinal profile is main tool for particle identification



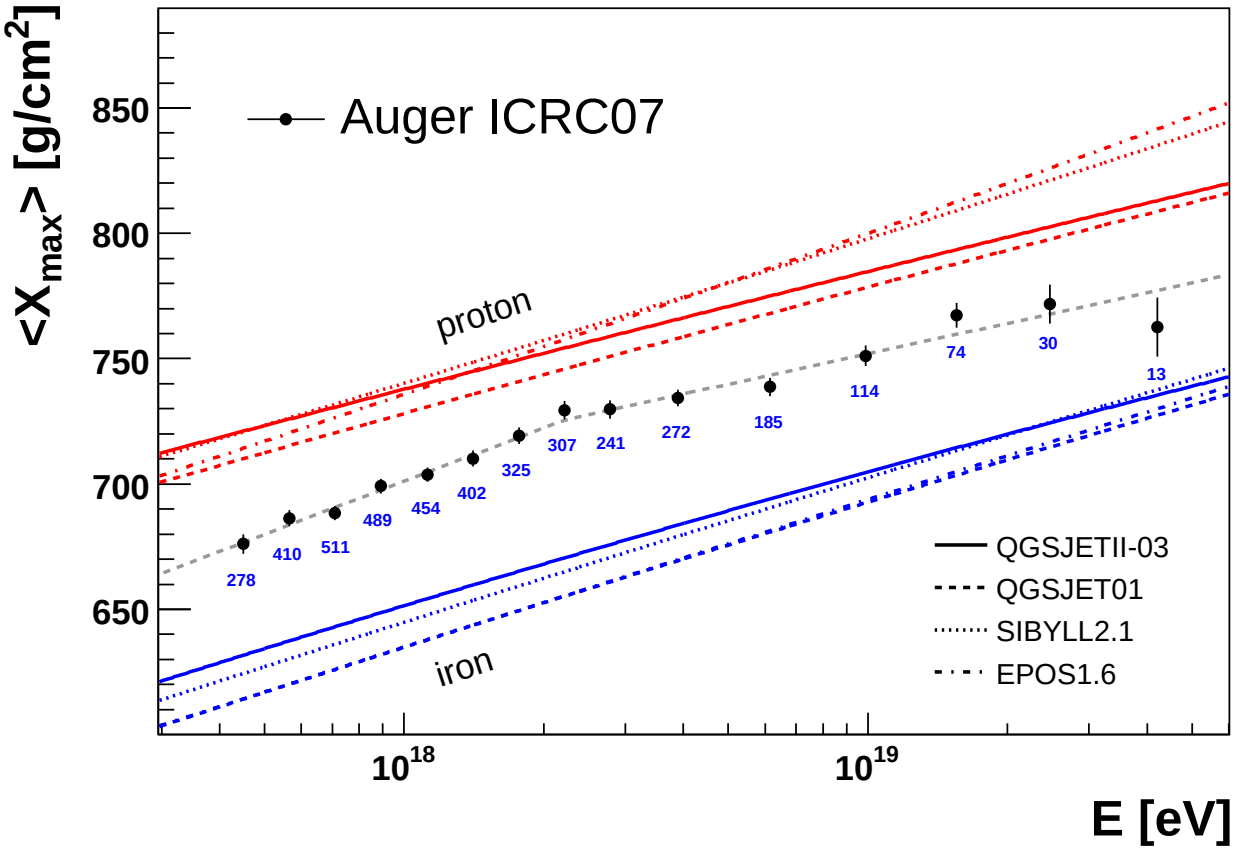


Xmax: Mean depth of shower maximum

Composition before Auger

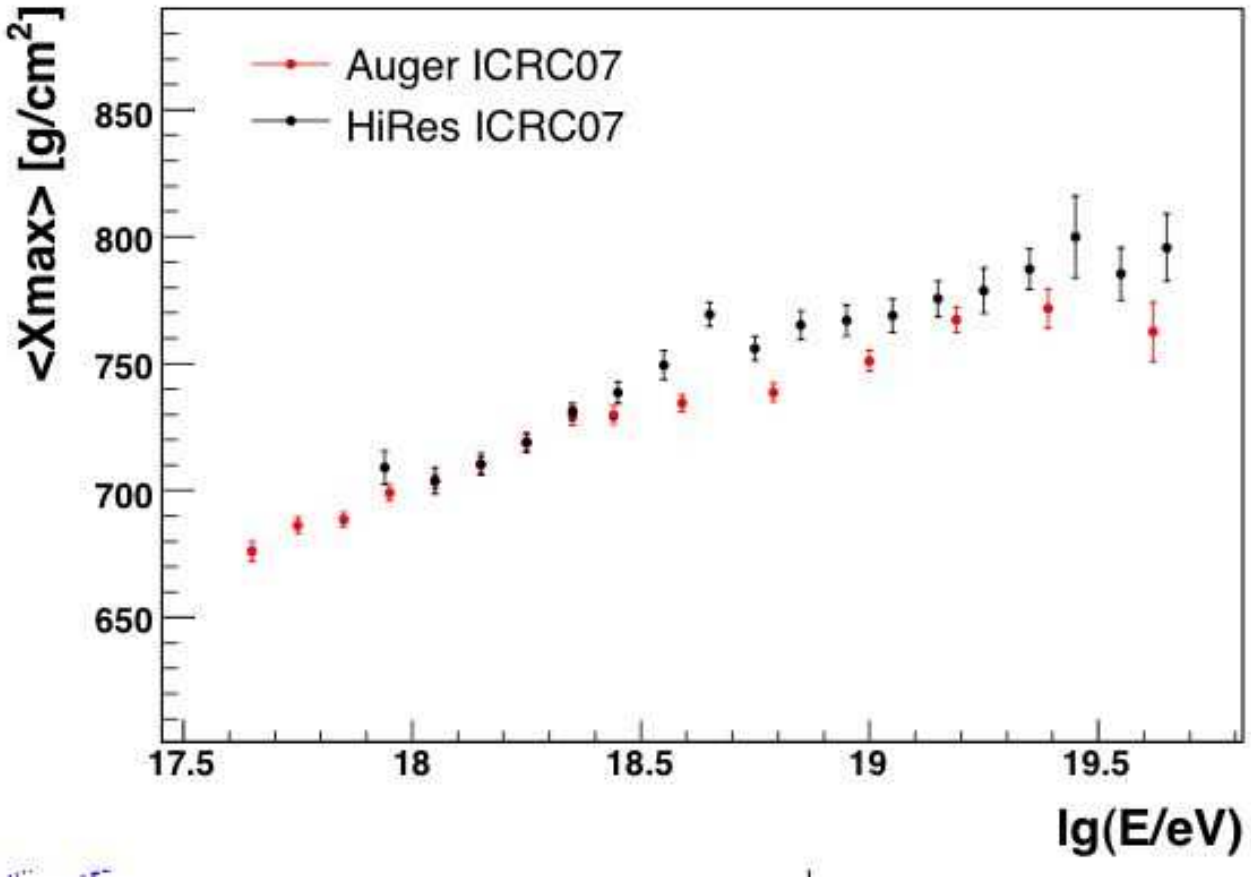


Auger composition: going to heavier at Highest E?

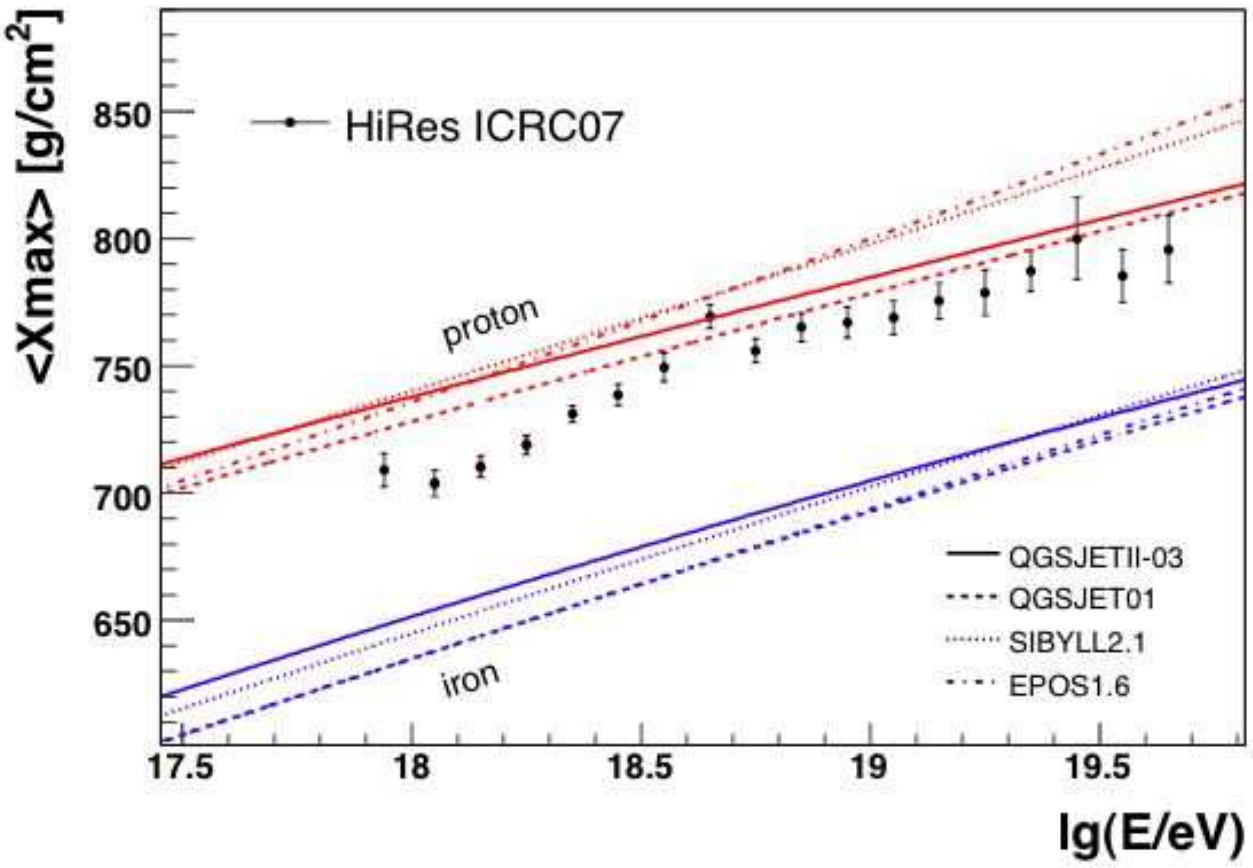


Mean depth of shower max-Sys. uncertainly ± 15 g/cm^2

Auger-HiRes composition?



HiRes composition: still p at highest energies



UHECR photons- Why photons?

- UHECR photons with $E > 10^{19}$ eV are one of the key observables to distinguish Top-Down from Bottom-Up production mechanisms

- GZK photons (decay products of the π^0 produced in the GZK process): always present at some level. May help understanding the primary particle spectrum and the intervening backgrounds (radio background and magnetic fields). Their flux is related to that of GZK (or cosmogenic) neutrinos.

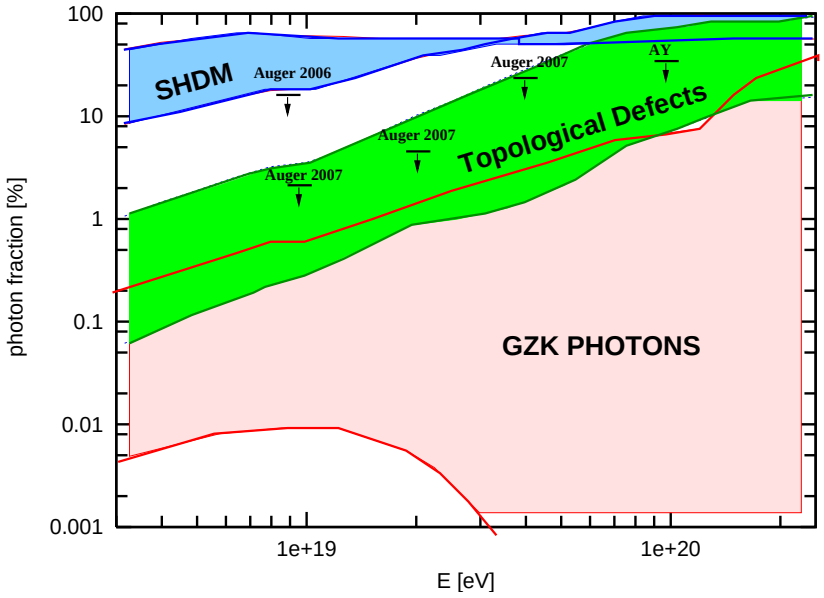
UHECR photons

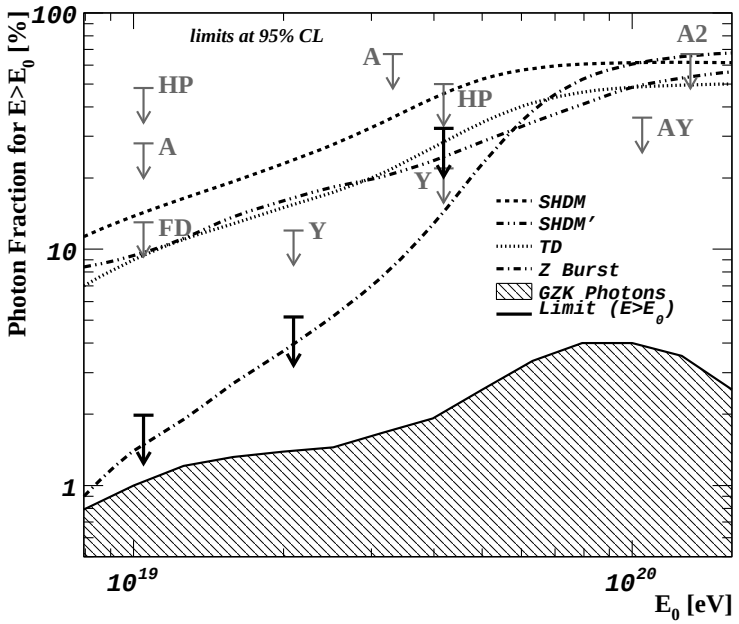
- Deeper shower (due to LPM effect), so smaller shower-front curvature radius.
- "Preshower" (magnetic conversion in terrestrial field) for $E > 5 \times 10^{19}$ eV.
- Poorer muon content, more low energy particles, thus longer signal-rise time.

No photons seen!

GZK and Top-Down photon fractions

Left: from Gelmini, Kalashev, Semikoz- Right: last Auger paper on photon limits





New Auger bounds and Agasa-Yakutzk (AY) make Top-Down models unlikely- result independent and complementary to the possible correlation with AGNs.

Anisotropy Searches

- Right ascension distribution at EeV energies (to test if still some galactic component): No anisotropy found

- Galactic Center at 0.1 to 1 and 1 to 10 EeV (Sag A Super black hole, H.E.S.S. source): Overdensities compatible with isotropic distribution

- Correlation with astrophysical sources at $E/Z > 10$ EeV (no considerable magnetic deflection):

  found correlation with AGN's in the Veron-Cetty Catalog


9 November 2007 | $10
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Correlation with AGN:

- Incomplete catalog: Restrict to D$<$ 100 Mpc since beyond catalog is very incomplete, and uniform sources would cover all sky.

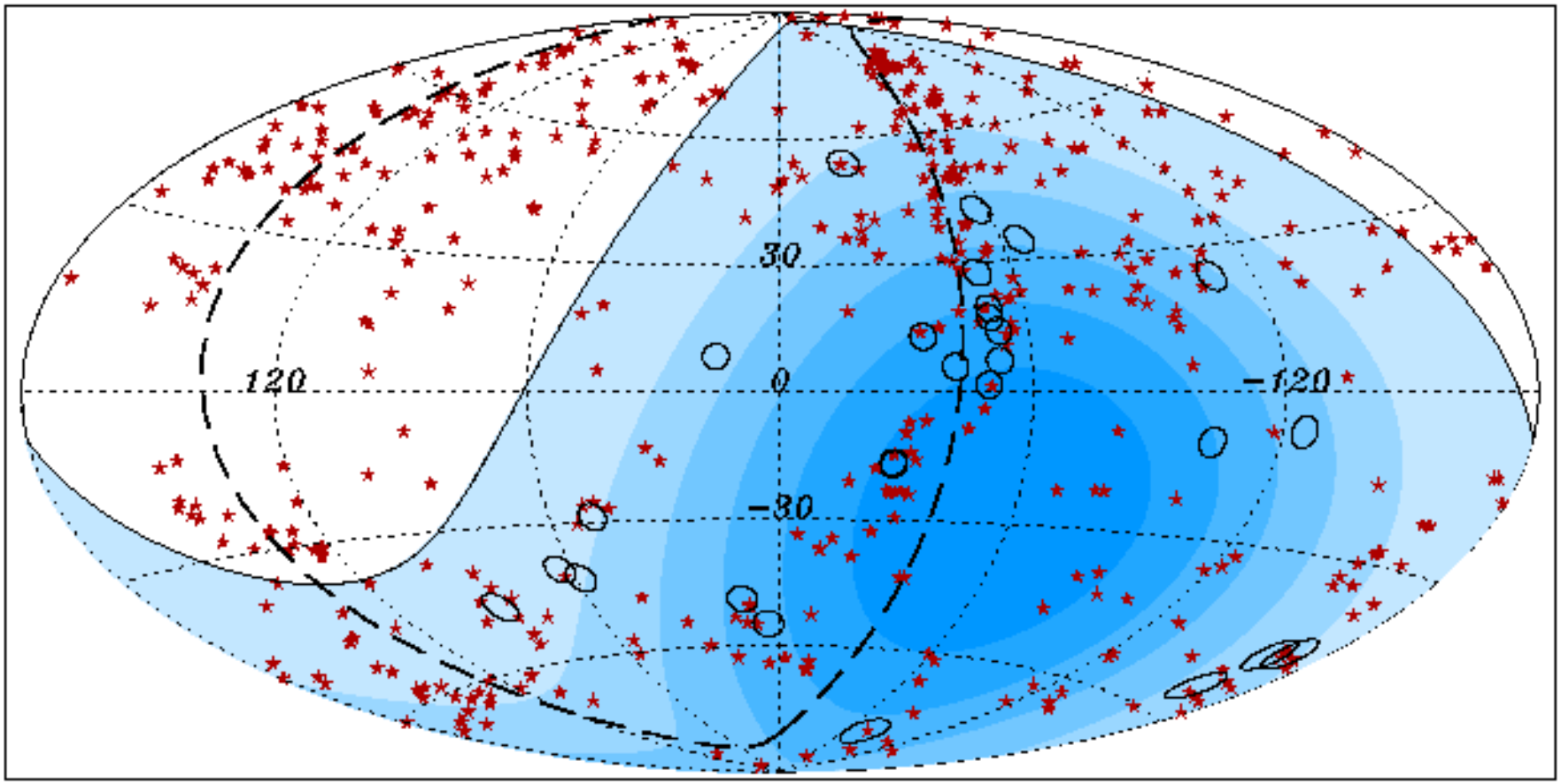
- Exploratory scan with data from 1/04 to 5/06: 12 out of 15events with $E \geq 56$ GeV D$<$ 75 Mpc, Δ(CR-AGN)$\leq 3.1^o$ (expected 3.1, P$_{iso} \sim 21\%$) $\rightarrow$ protocol

- Signal confirmation with dats 6/06 to 8/07: with same prescription 8 out of 13 correlate (2.7 expected, P$_{iso} = 1.710^{-2}$)

- With full data set: 20 out of 27 events with $E \geq 55$ GeV D$<$ 70 Mpc ($z \leq 0.018$), Δ(CR-AGN)$\leq 3.1^o$ correlated (5.6 expected, P$_{iso} \sim 10^{-5}$).

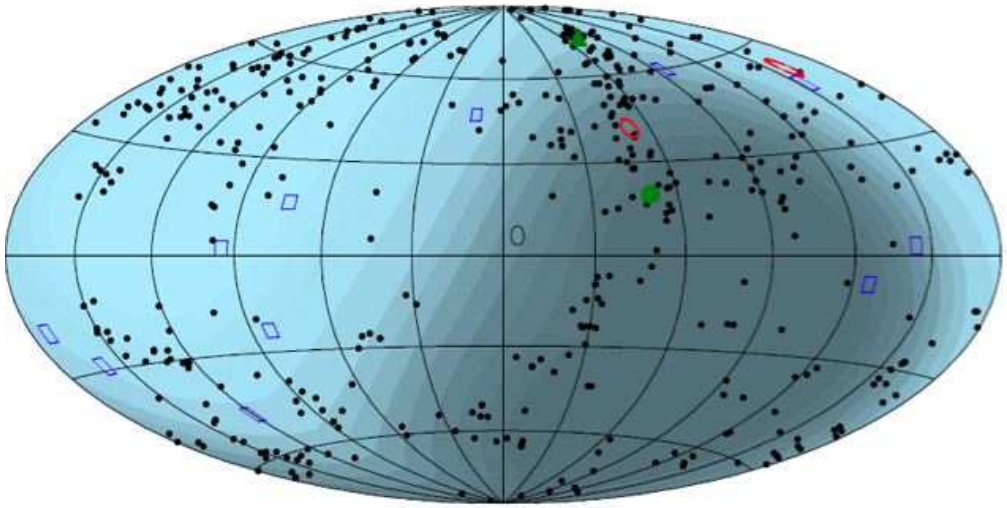
  Used 472 AGN (318 in field of view).

Correlation with AGN (galactic coordinates-3.2^o circles)



Clear correlation with the super-galactic plane!

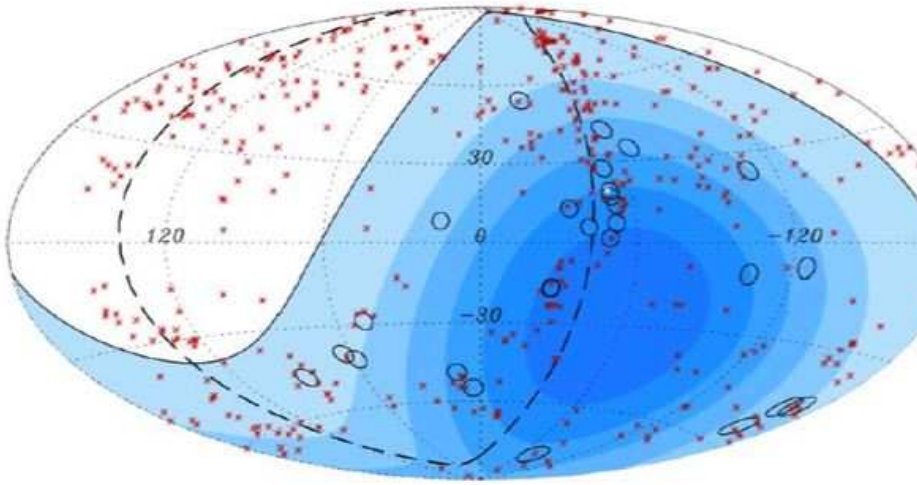
HiRes
ArXiv-0804.0382v1
3.1°, E > 56.0 EeV, z >0.018



Shading (1/exposure)

Claims no correlations

Auger
Astroparticle Physics 29 (2008) 188-20
3.2°, E > 57 EeV, z >0:017



Shading (~exposure)

Claim correlation with VCV AGNs

Correlation with AGN:

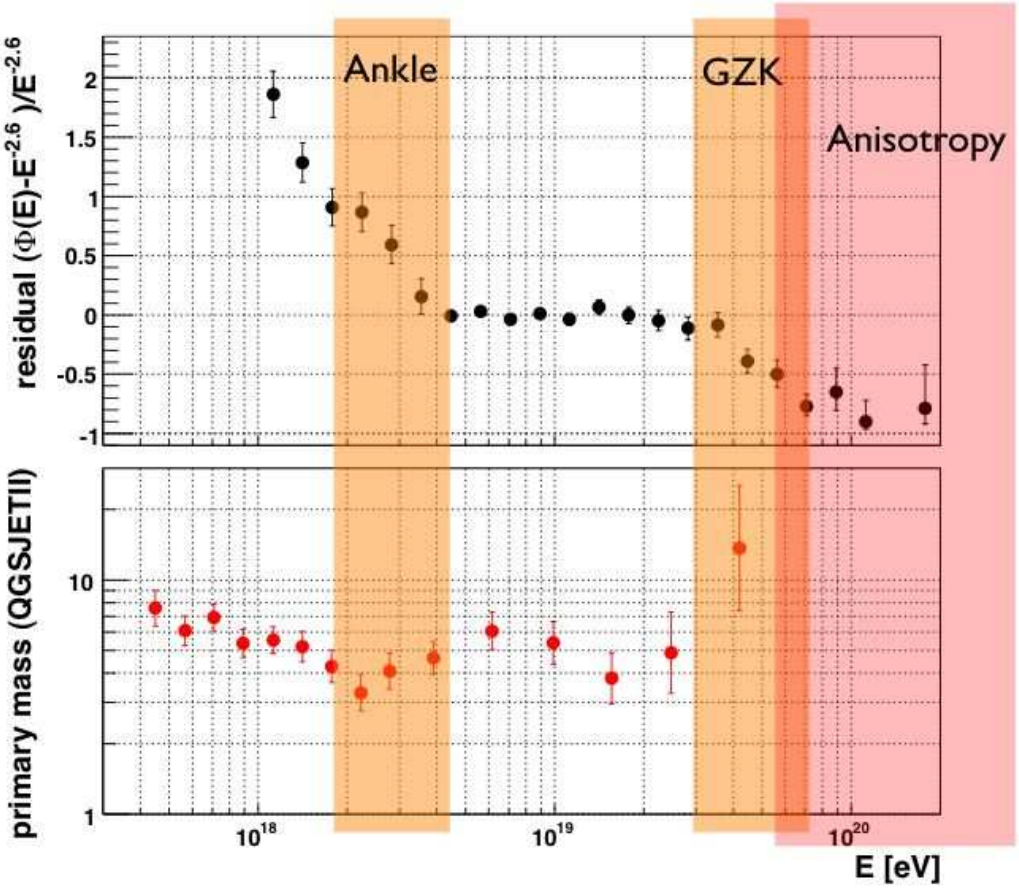
- HiRes: 2400 km^2 sr yr saw 13 events (2 correlated, 3.2 expected by chance), Auger correlation data: 9000 km^2 sr yr, saw 27 events. HiRes saw nearly TWICE the number of events of Auger for same aperture?
- Are Southern and Northern skies significantly different?
- Are AGN the sources (or some AGN) or tracers of real sources?
- No events from Virgo (closest cluster)... Is deficit real? may it be large magnetic field in that direction?
- 3^o deflection expected for p due to galactic magnetic field $\sim \mu$G (no heavy elements) but composition at high energy tends to heavier component? Which is correct? LHCf data needed to improve Montecarlos...

More data needed....

Comparison of Features: data at different energies

Deviation from $E^{-2.6}$ flux

Mean mass number



Conclusions: Many open questions to answer

GeV- TeV: Solar wind, PAMELA/ATIC excess: DM or pulsar/SNR nearby? Combination with data from MILAGRO, ICE-CUBE, ACT's, FST.....

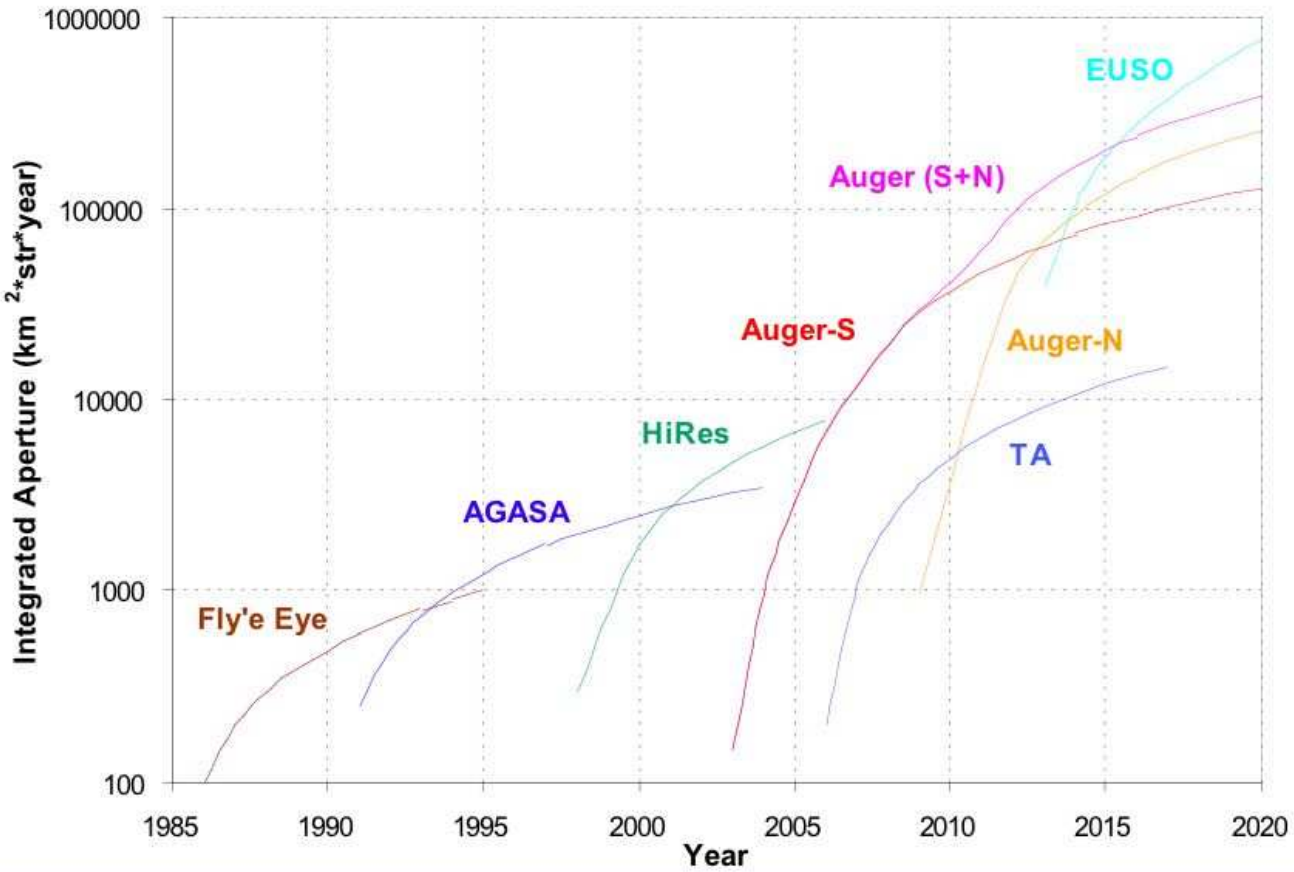
10^4 - 10^8GeV: CR composition, galactic sources and galactic propagation, galactic to extra-galactic (at second knee or ankle?)

$10^9 - 10^{11?}$GeV: Charged particle extragalactic astronomy!

NO Top-Down! Flux suppression due to GZK, to max. acceleration E, to both ? Extragalactic sources? + CR composition? will allow to elucidate the acceleration mechanisms? More data coming...

Future: Auger-S infield with μ counters, Telescope Array (with Low E extension, TALE) in Utah (will study the ankle), proposal for Auger-N in Colorado (4 10^3 detectors, 2 10^4 km^2)...

Comparison of Integrated Aperture



12/05/2007 *Katsushi Arisaka, UCLA*