Results from HiRes

Kai Martens
High Energy Astrophysics Institute
University of Utah

Overview

- Ultra High Energy Cosmic Rays → UHECR
- Extensive Air Showers → EAS
- High Resolution Fly's Eye → HiRes
  - Introductions
  - Calibration
  - Physics:
    - spectra
    - GZK
    - anisotropy
    - clustering
    - BL Lac
- Conclusions

The Cosmic Ray Fux:

(m^{-2} sr^{-1} s^{-1} GeV^{-1})

10^{2} →

Power laws for

Flux → $J \sim E^{\gamma}$

< 3 PeV: $\gamma = -2.7$

~ 3 PeV: knee

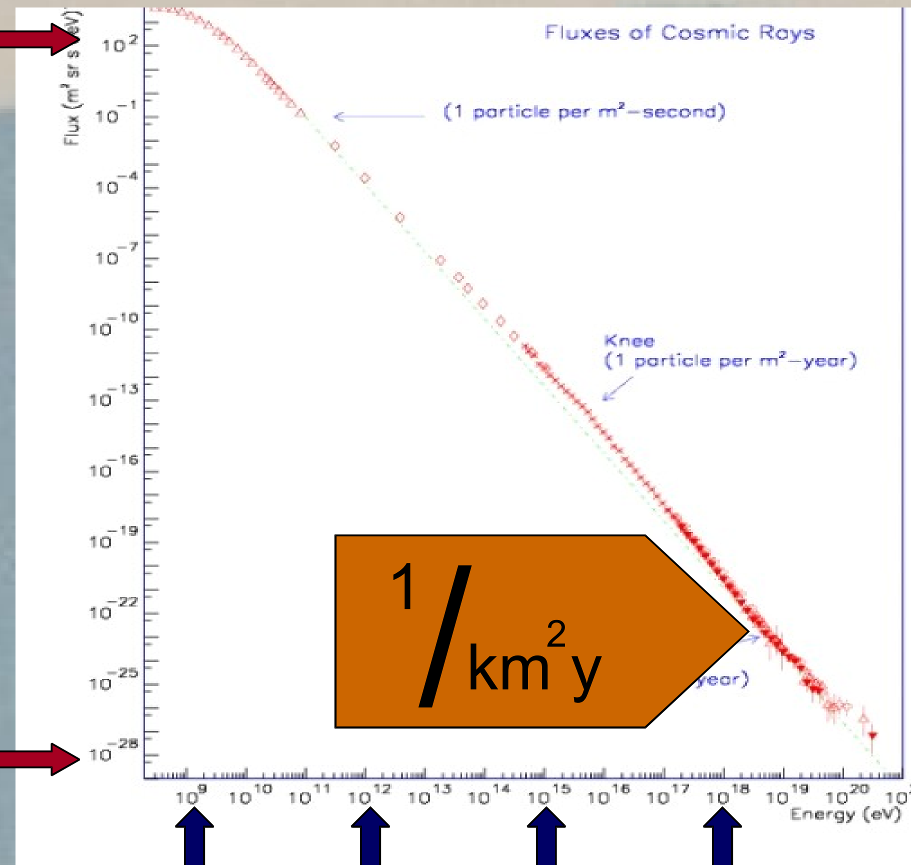
> 3 PeV: $\gamma = -3.0$

~0.4 EeV: 2nd knee

>0.4 EeV: $\gamma = -3.3$

~ 3 EeV: ankle

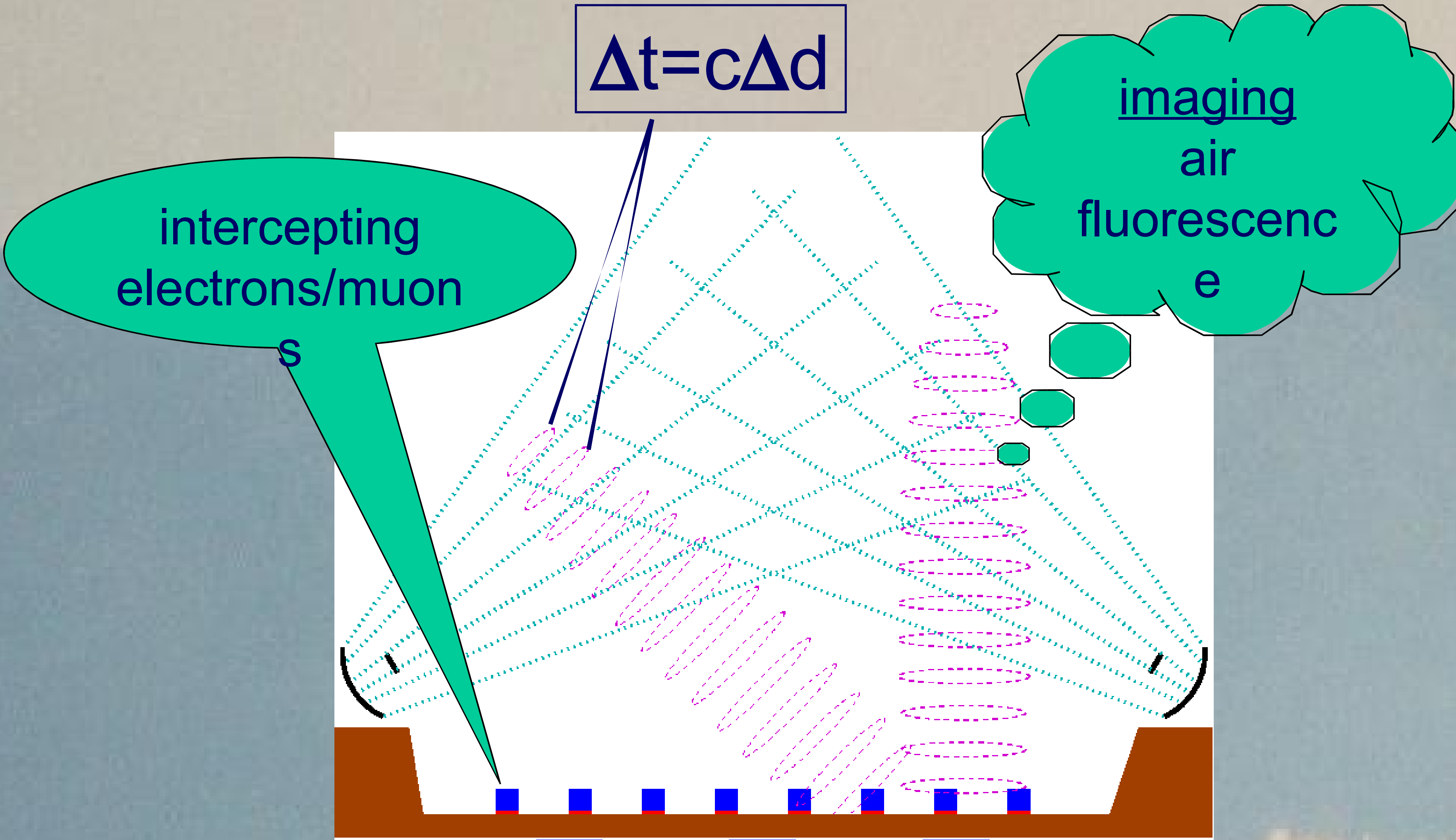
10^{-28} →



GeV TeV PeV EeV

(plot by S. Swordy)

Air Shower Detection

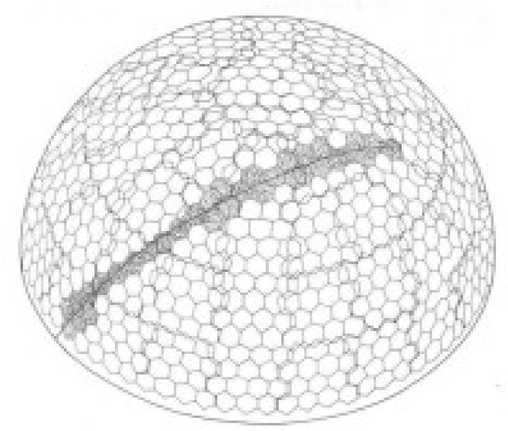


(underground: pure muon detection…)

Fluorescence in Utah: A Proud Tradition

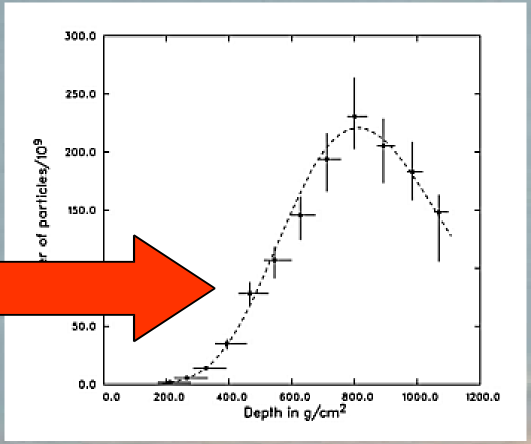
Fly's Eye: 1981-1993

Dugway Proving Grounds



- Site 1 (FE1): 67 mirrors
- Site 2 (FE2): 34 mirrors
- 12-14 pixels (PMT) per mirror
- Each pixel covers 5 deg x 5 deg

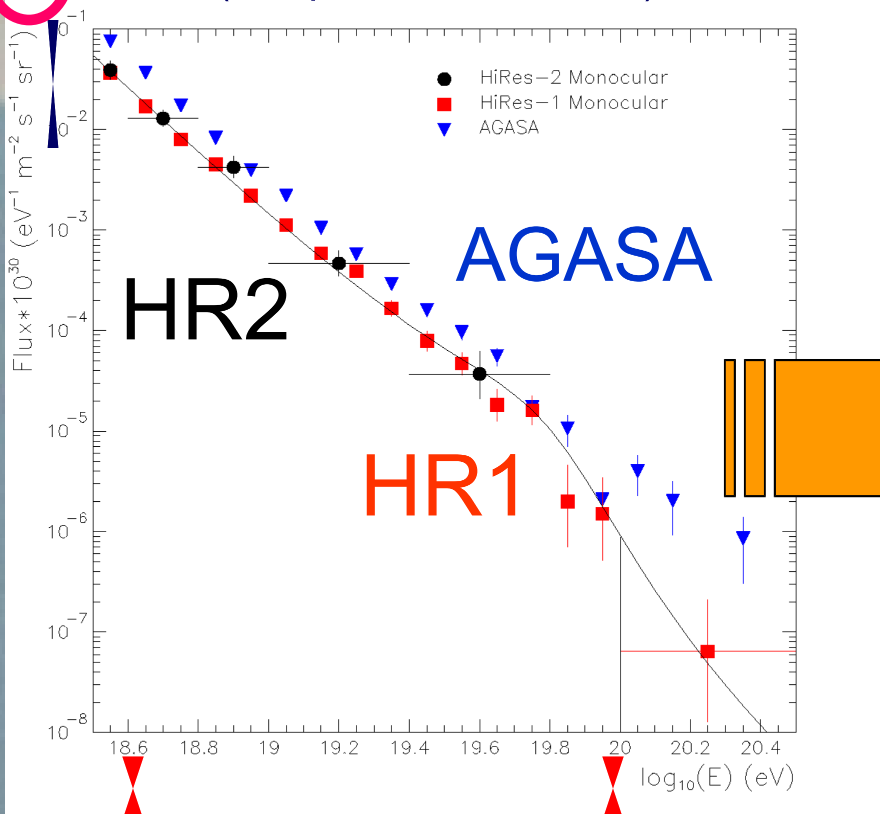
Nov. 1991:
The big event
320 EeV



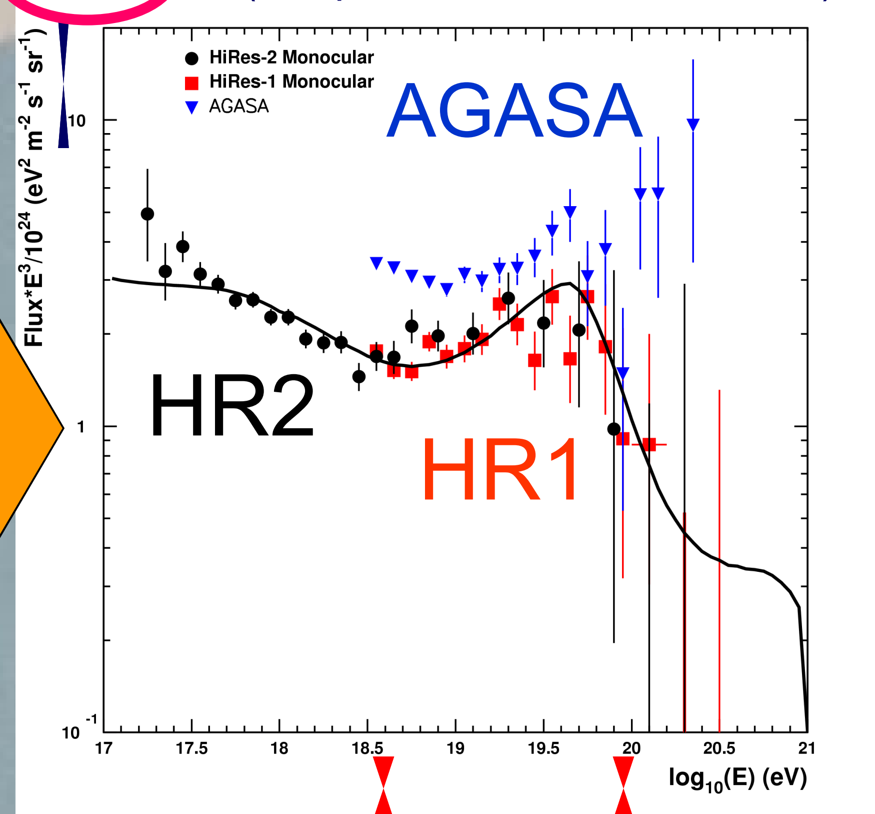
Highest Energy Cosmic Rays:

OLD data !!!
NEW → Coming up

J (this plot uses old data)



J×E³ (this plot uses *other* old data…)



$10^{18.6}$ 10^{20} **lg(E[eV])** $10^{18.6}$ 10^{20}

HiRes: The Collaboration:

S. BenZvi, J. Boyer, B. Connolly, C.B. Finley, B. Knapp, E.J. Mannel, A. O'Neill, M. Seman, S. Westerhoff
Columbia University

J.F. Amman, M.D. Cooper, C.M. Hoffman, M.H. Holzscheiter, C.A. Painter, J.S. Sarracino, G. Sinnis, T.N. Thompson, D. Tupa
Los Alamos National Laboratory

J. Belz, M. Kirn
University of Montana

J.A.J. Matthews, M. Roberts
University of New Mexico

D.R. Bergman, G. Hughes, D. Ivanov, L. Perera, S.R. Schnetzer, L. Scott, S. Stratton, G.B. Thomson, A. Zech
Rutgers University

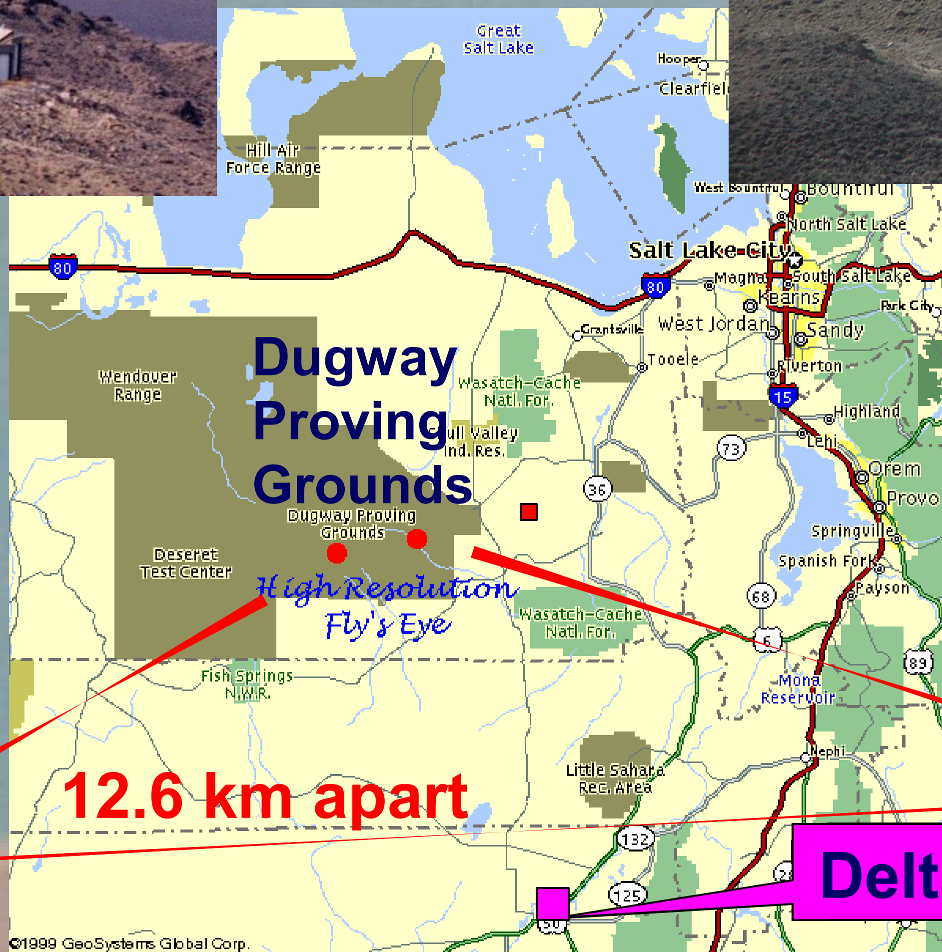
N. Manago, M. Sasaki
University of Tokyo

R.U. Abbasi, T. Abu-Zayyad, G. Archbold, K. Belov, Z. Cao, W. Deng, W. Hanlon, P. Huentemeyer, C.C.H. Jui, E.C. Loh, K. Martens,
J.N. Matthews, K. Reil, J. Smith, P. Sokolsky, R.W. Springer, B.T. Stokes, J.R. Thomas, S.B. Thomas, L. Wiencke
University of Utah

Z. Cao, B. Zhang, Y. Zhang, Y. Yang
IHEP Beijing

HiRes: The Experiment:

HiRes on DPG:

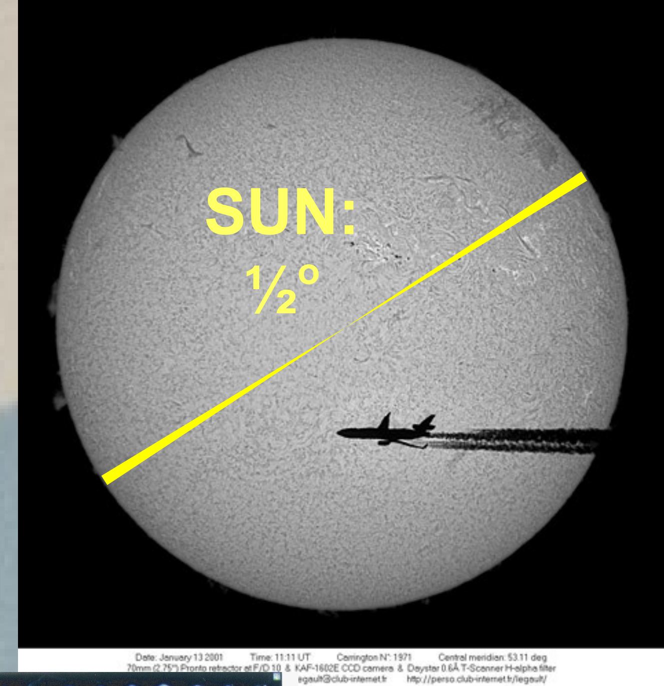


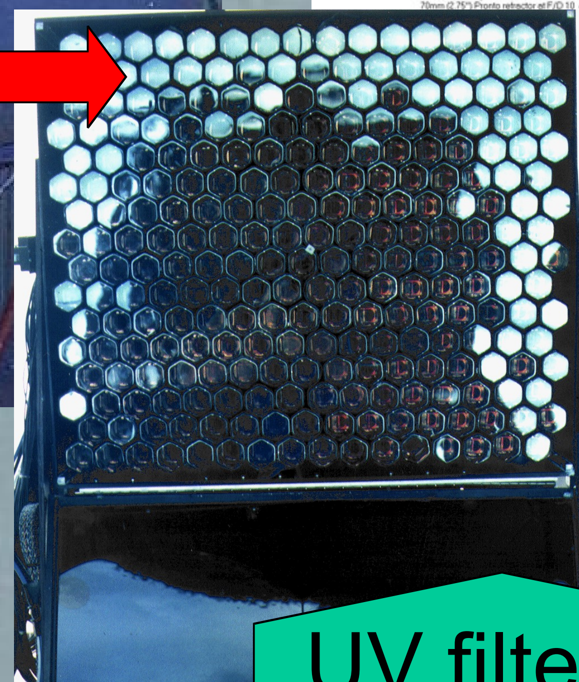
HR2: 12/1999
42 mirrors
3°-31° elevation

HR1: 6/1997
19 mirrors
3°-17°elevation

HiRes Optics:

low resolution
high speed





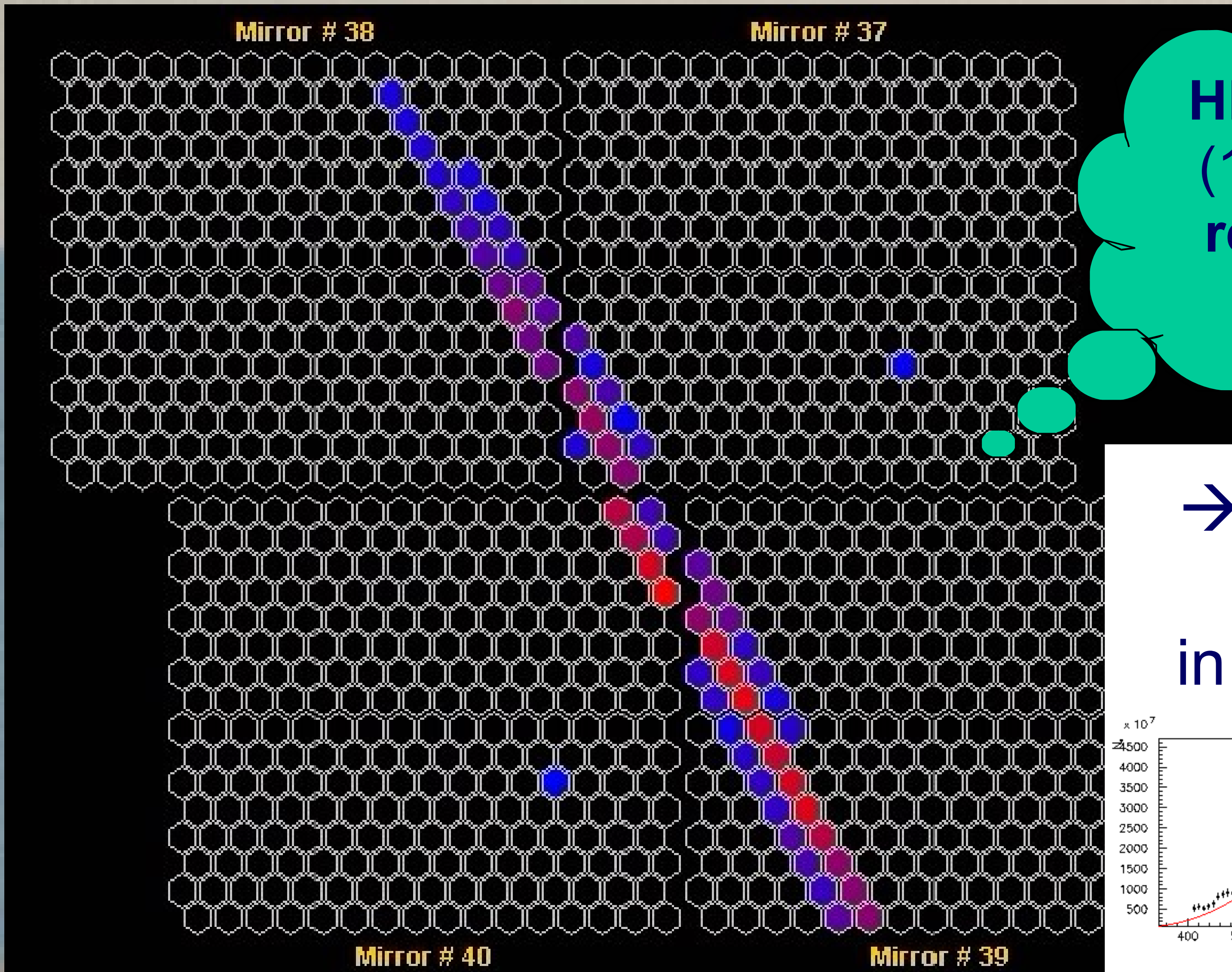
Mirror surface 5.1 m^2

Field of view: 16˚ x 14˚

Camera:
16 x 16
PMT
each sees
1° x 1°
in sky

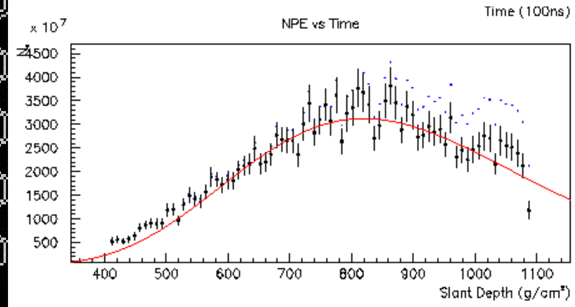
UV filter !!!
(protecting PMTs)

Fluorescence Event: Light Curve



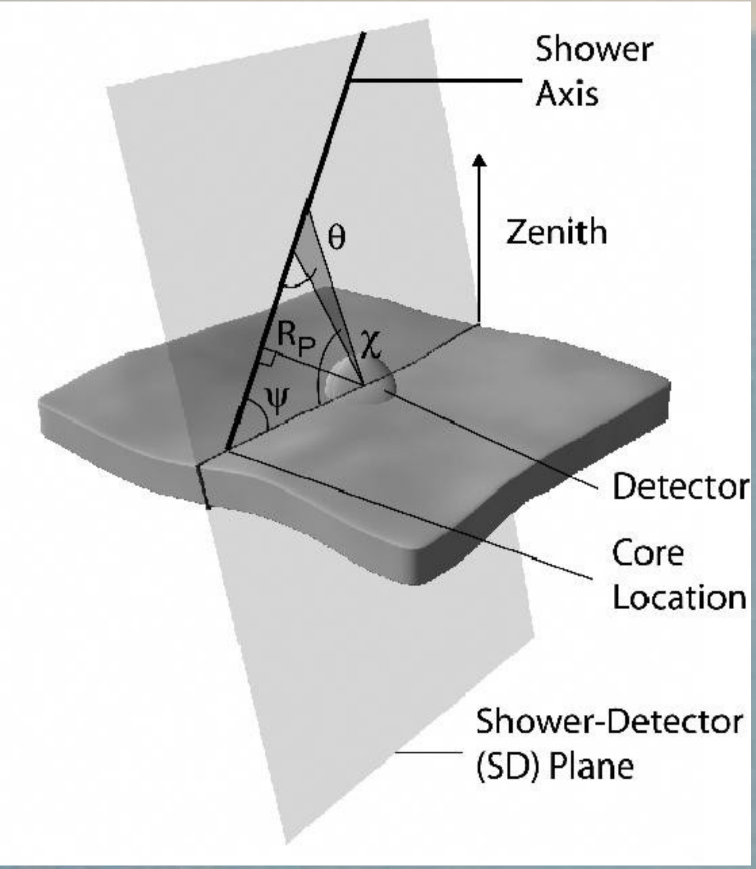
HR2 FADC
(100 MHz)
real time:
~ 25 µs
total

→longitudinal evolution in timing bins:

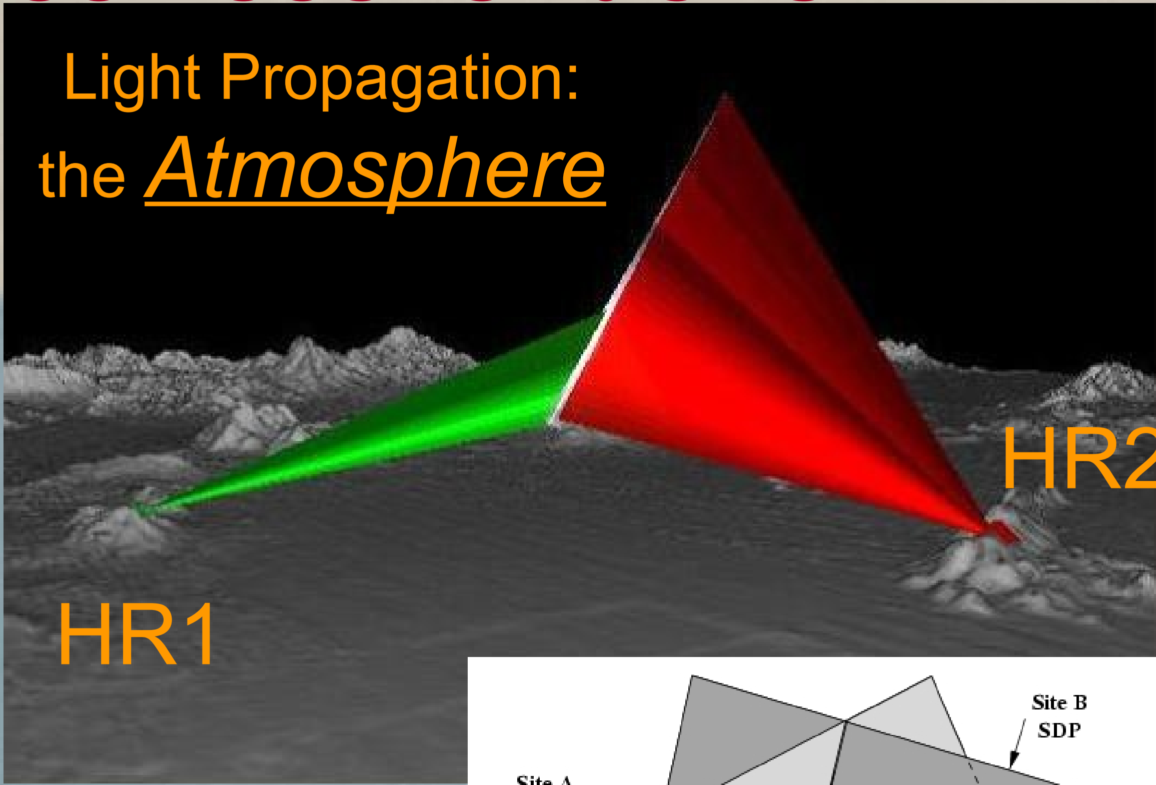


Fluorescence Reconstruction:

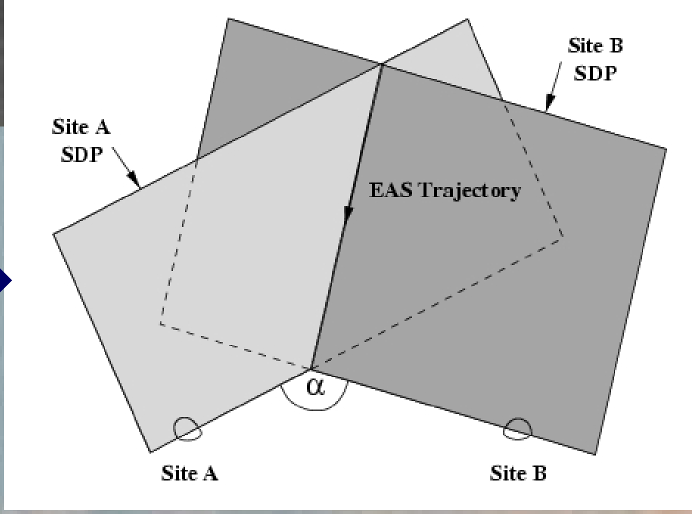
HR1: 6/1997 ← **MONO**
HR2: 12/1999 ← 30˚ LE



Light Propagation:
the *Atmosphere*

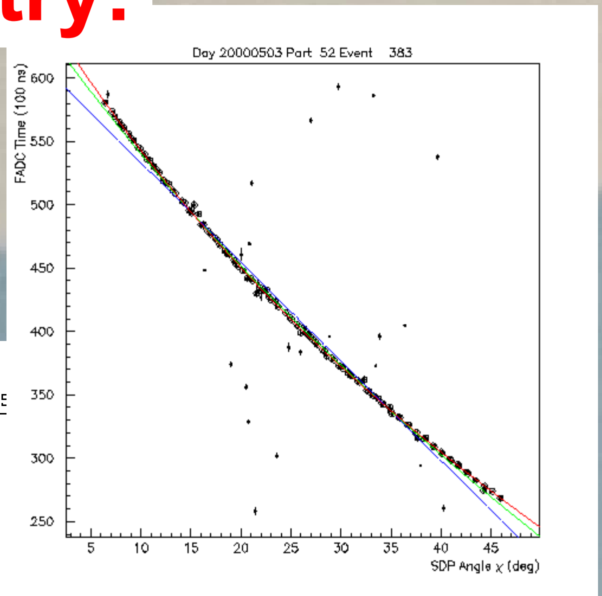


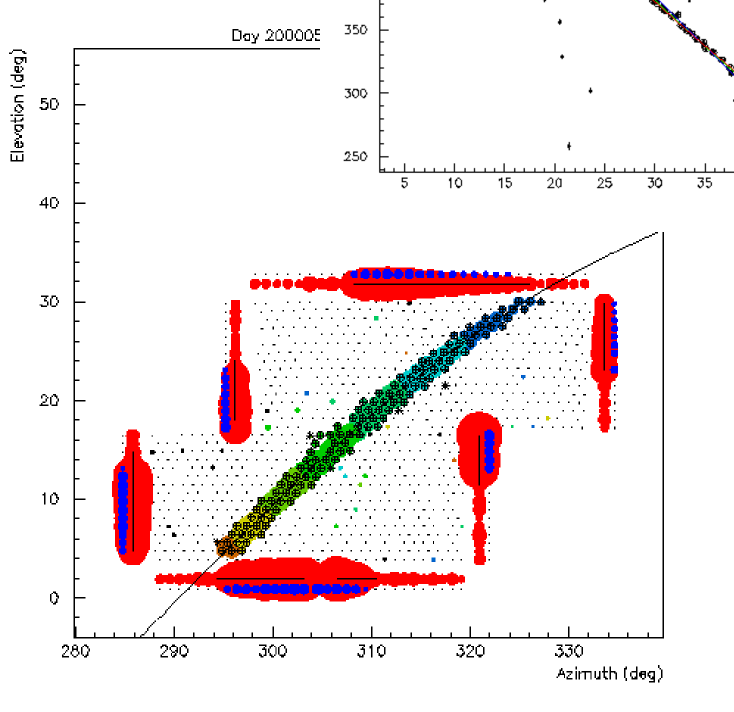
STEREO →

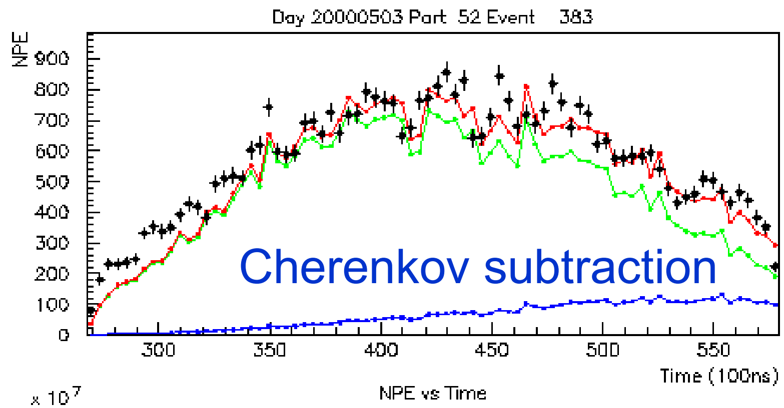


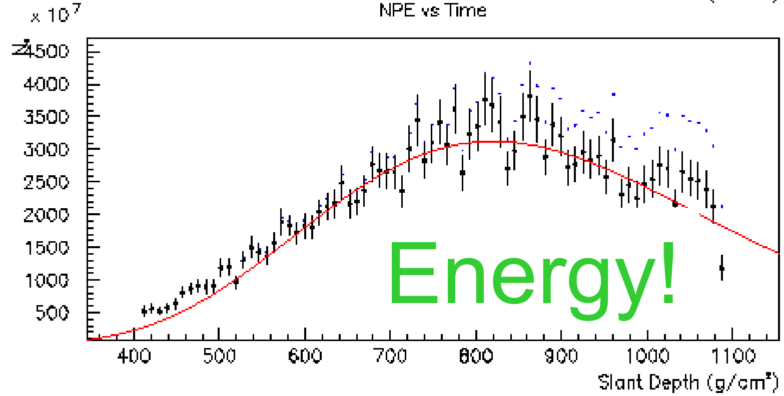
Event Reconstruction @ HR2:

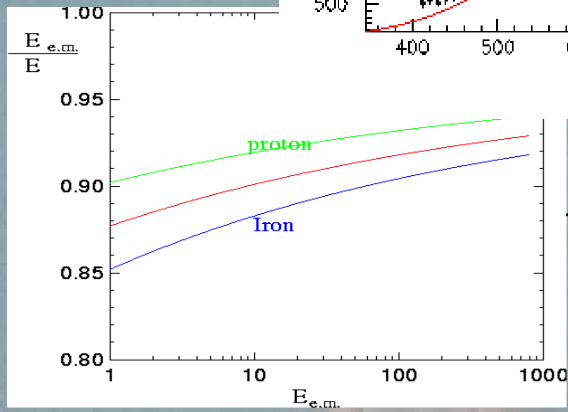
Geometry:











Invisible energy

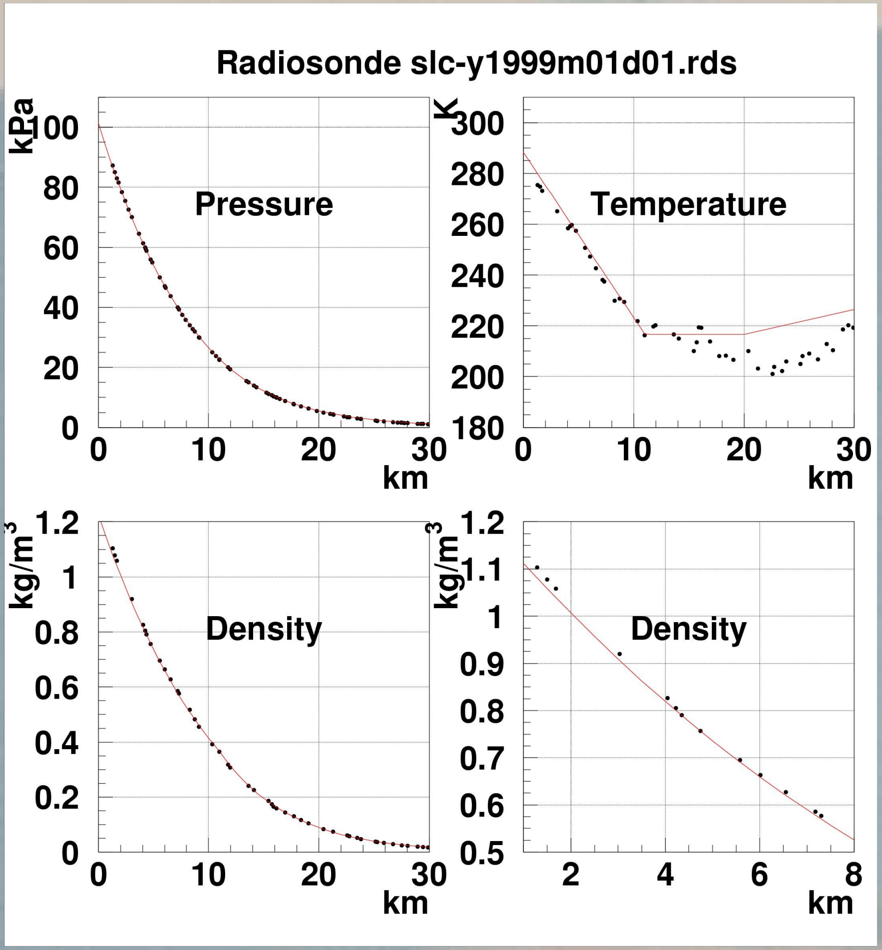
The Atmosphere:

Affecting propagation:
two components:

	molecular (N_2)	aerosols
scale height	~9 km	lower few km
horizontal scattering length	17.5km @350 nm	10m (fog) to infinite (molecular)
f(λ)	$\sim\lambda^{-4}$	$\sim\lambda^{-1}$
size	few x 10 nm	0.1μm and up
scattering	Rayleigh	Mie

N2 fluorescence: 300nm – 400nm

molecular component:



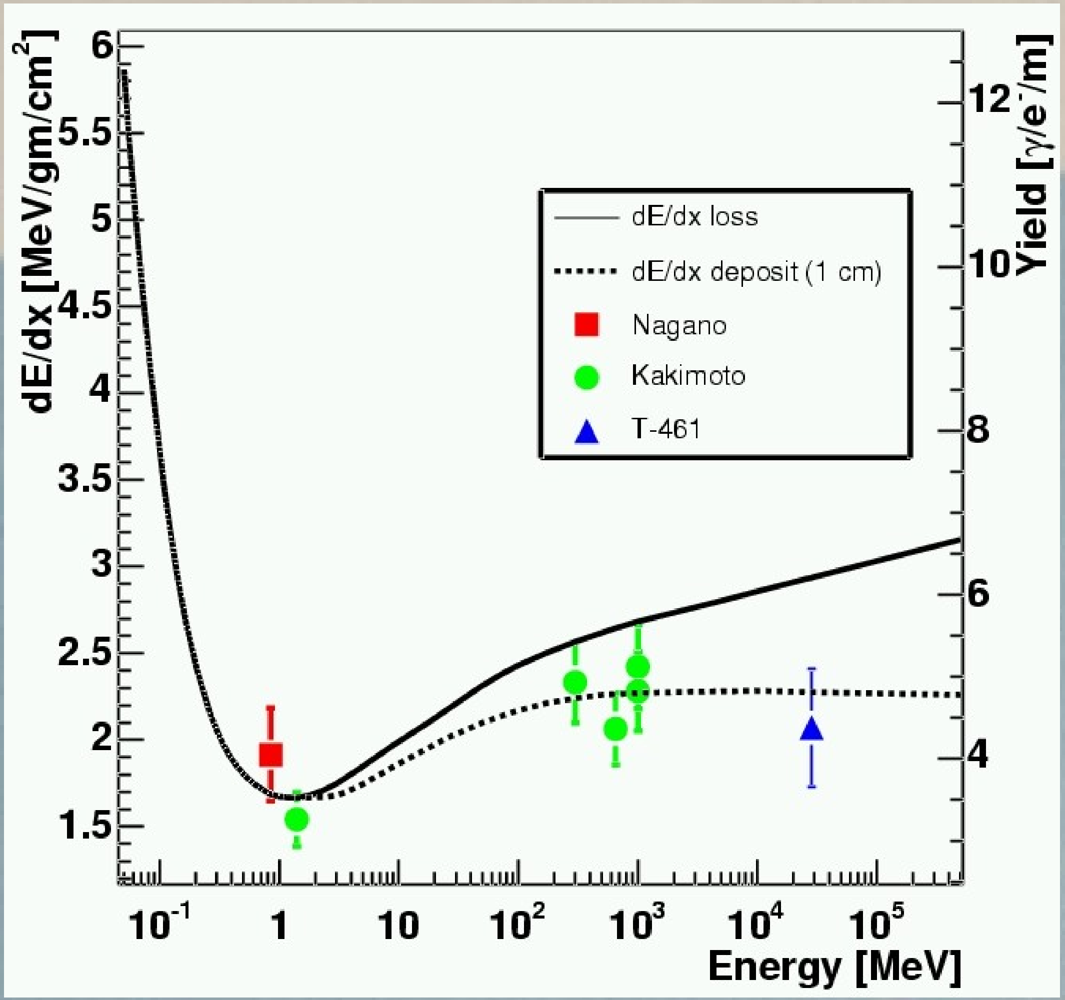
Fluorescence Yield:

T-461: FLASH @ SLAC
test run

Nagano: similar Kakimoto
better calib.

Ratio: (T+N)/K = 1.00±0.06

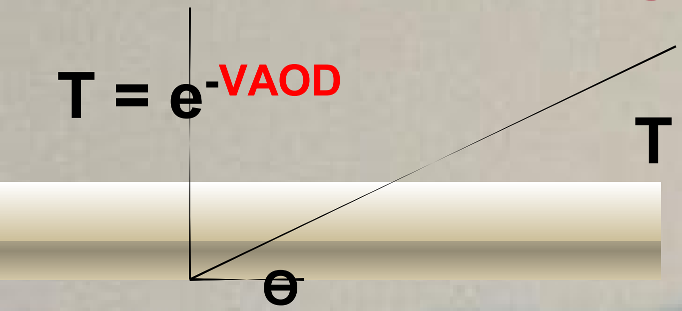
SUMMARY:
Yield understood ~10%

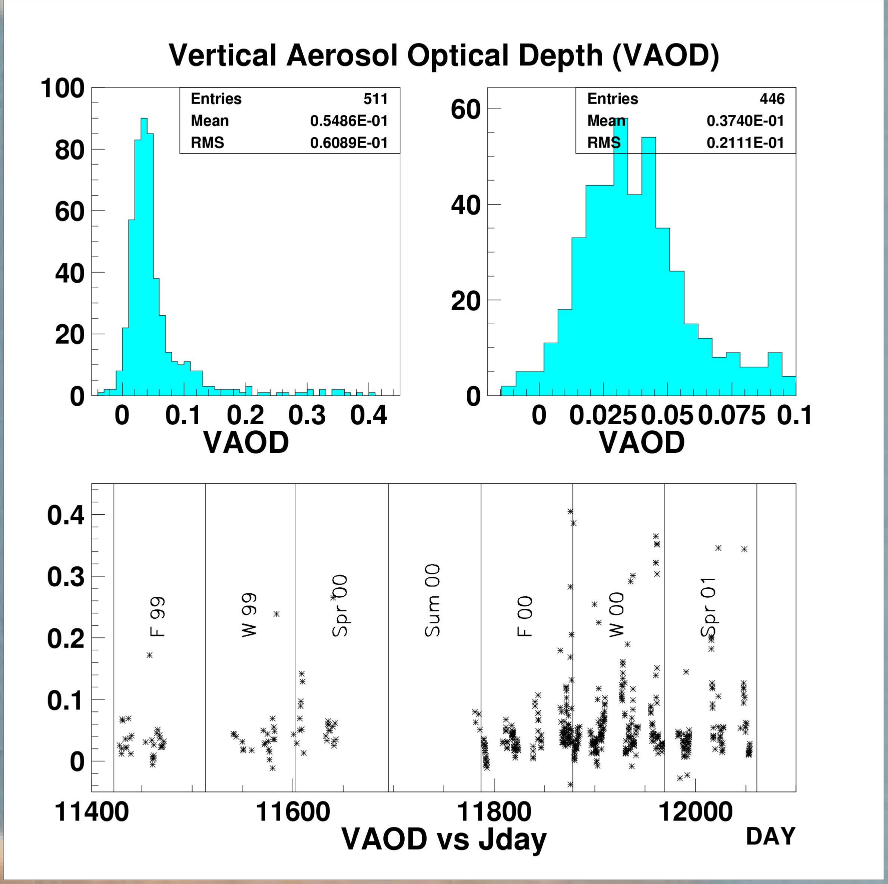


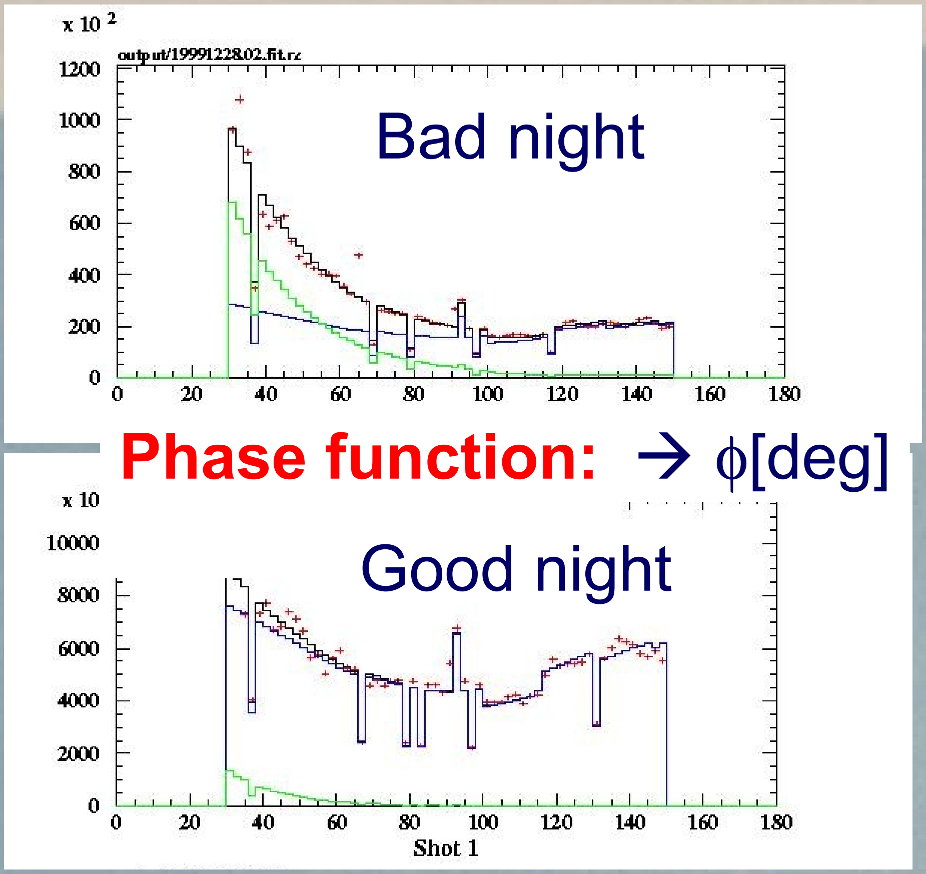
Aerosol Component: Variable…

$T = e^{-VAOD}$

$T = e^{-VAOD/\sin\theta}$







Hourly Laser patterns from HR1 and HR2 @ 355 nm:

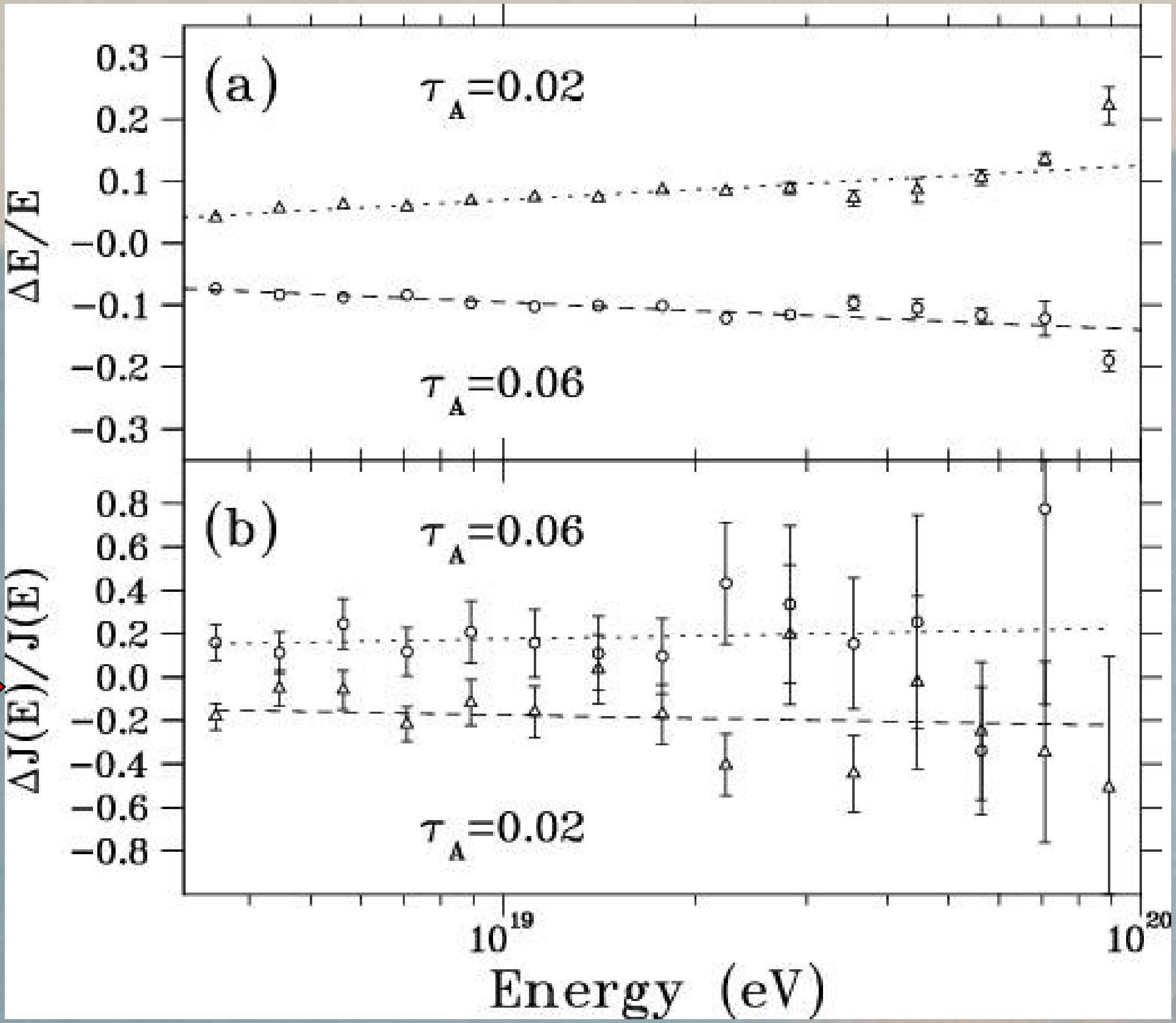
HR1 Mono → Average VAOD:

Average VAOD:
0.04 ± 0.02 (RMS)

Systematics
also estimated:
± 0.02

reconstruct data:
VAOD = 0.02
VAOD = 0.06

Relative to “clearest”
also okay…



Monocular Reconstruction @ HR1:

Event Selection (Pattern Recognition)

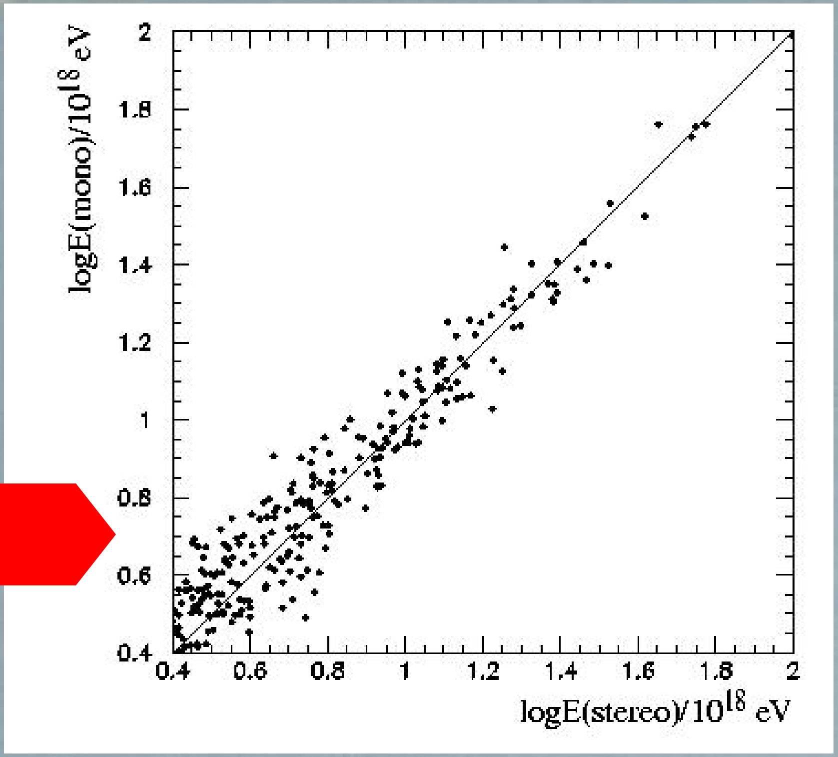
HR1:

- Gaisser-Hillas profile fit
- Profile Constraint Geometry fit (7 degree in plane)

Geometry

Light Path

Reconstructed Energy:
Verify on data: HR1 mono geom. vs. stereo geom.

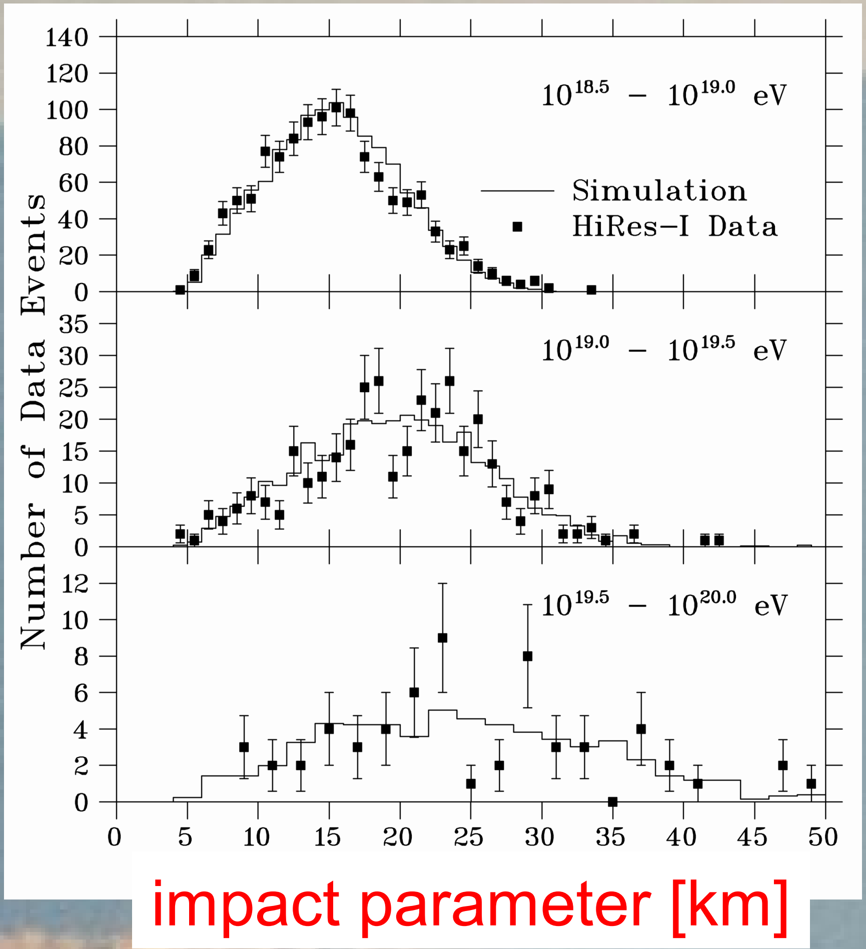


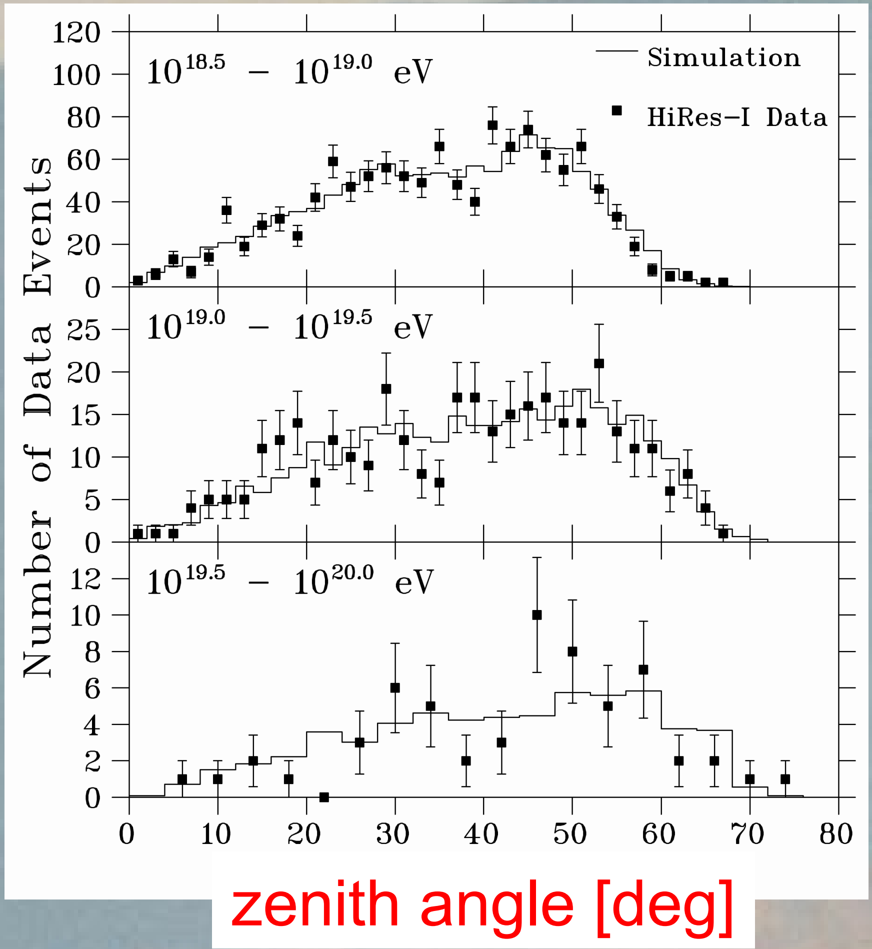
HR2:

- timing fit… ← 30% better resolution in SD plane (5 degree)…

Data/MC Comparisons → HR1:

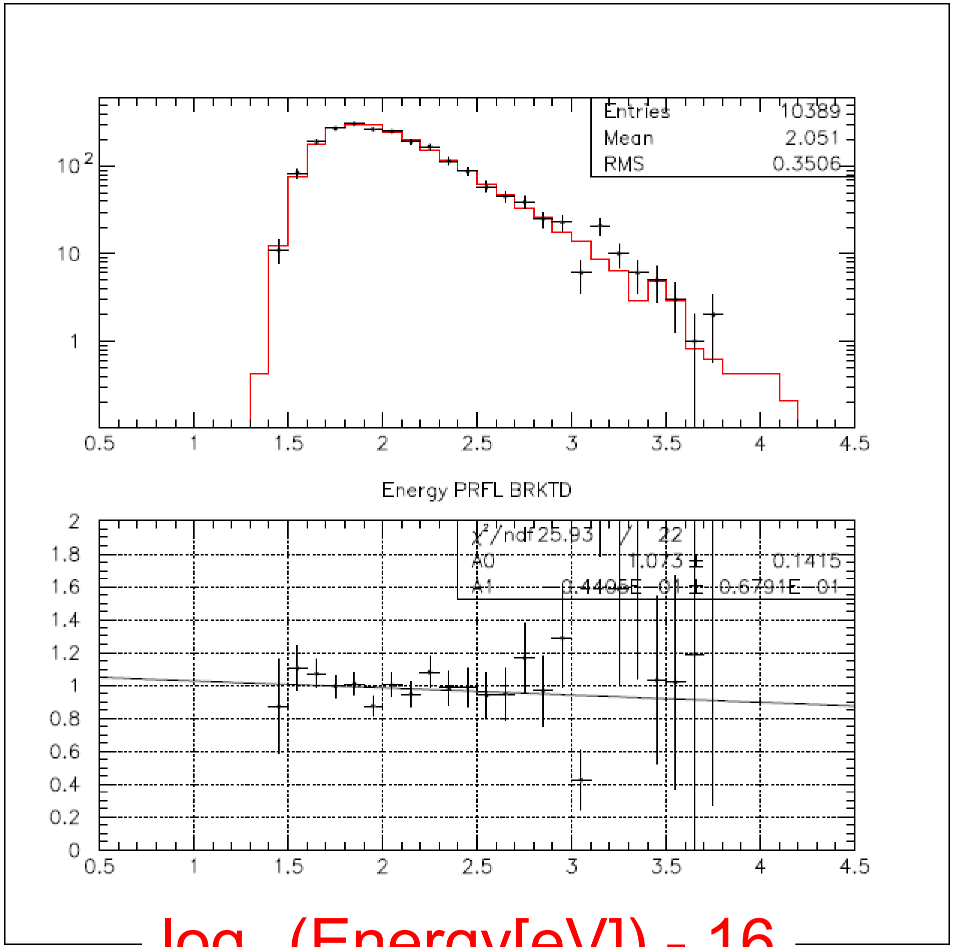
MC input: - Fly's Eye Stereo Spectrum
- HiRes Prototype/MIA & HiRes stereo composition



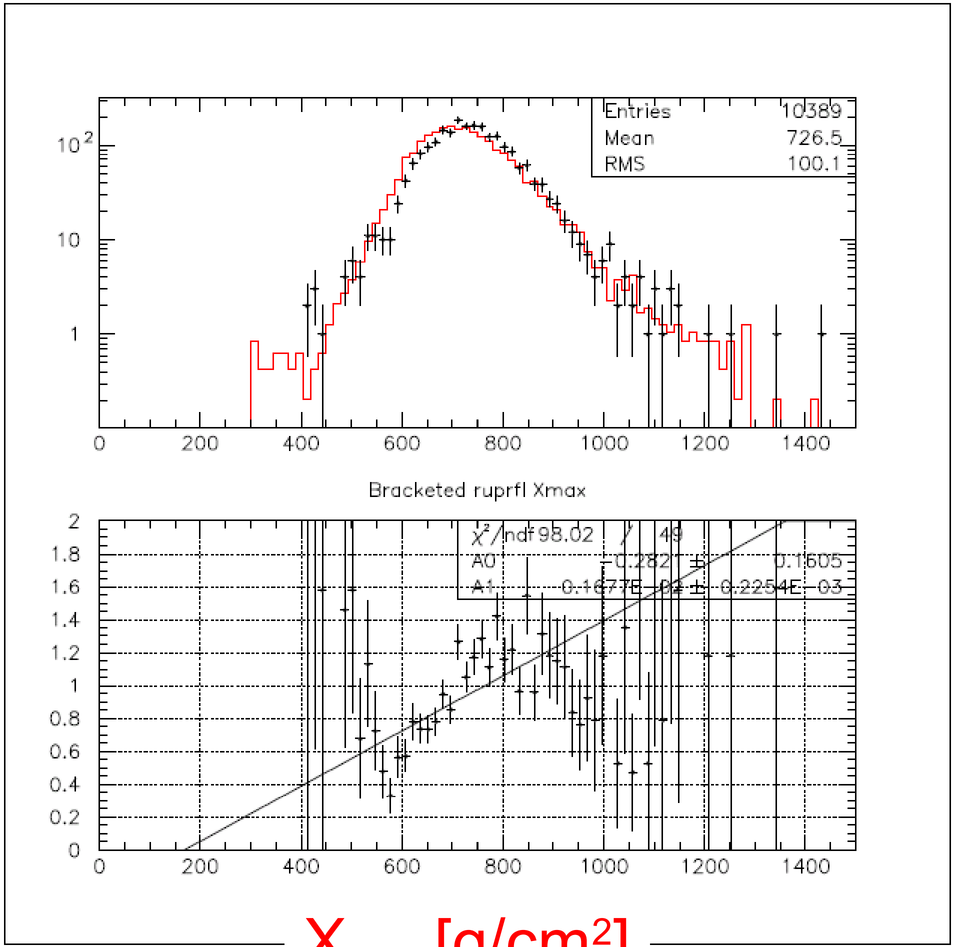


Data/MC Comparisons → HR2:

MC input: - Fly's Eye Stereo Spectrum
- HiRes Prototype/MIA & HiRes stereo composition



$\log_{10}$(Energy[eV]) - 16



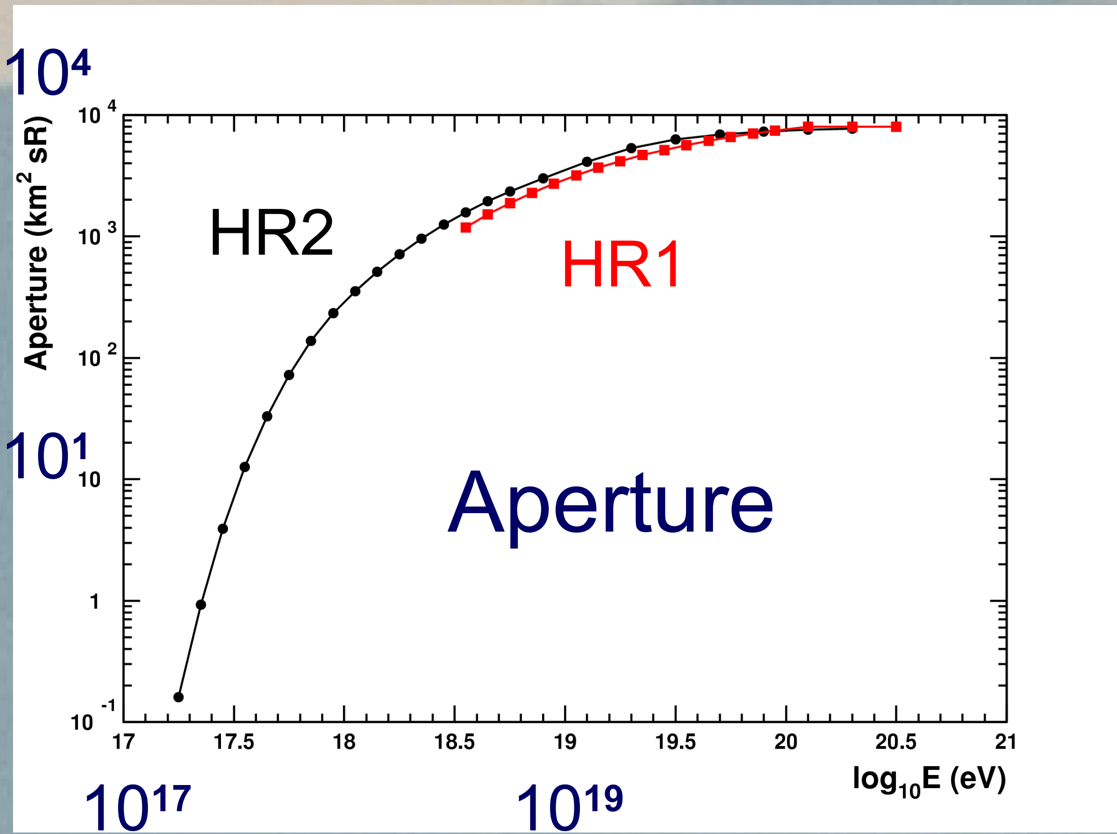
X_{max} [g/cm^2]

Statistics:

HR2: 12/99 – 08/04

310 good nights
~ 1500 hours good
~ 6600 events after cuts
(bracketing,
cherenkov,…)

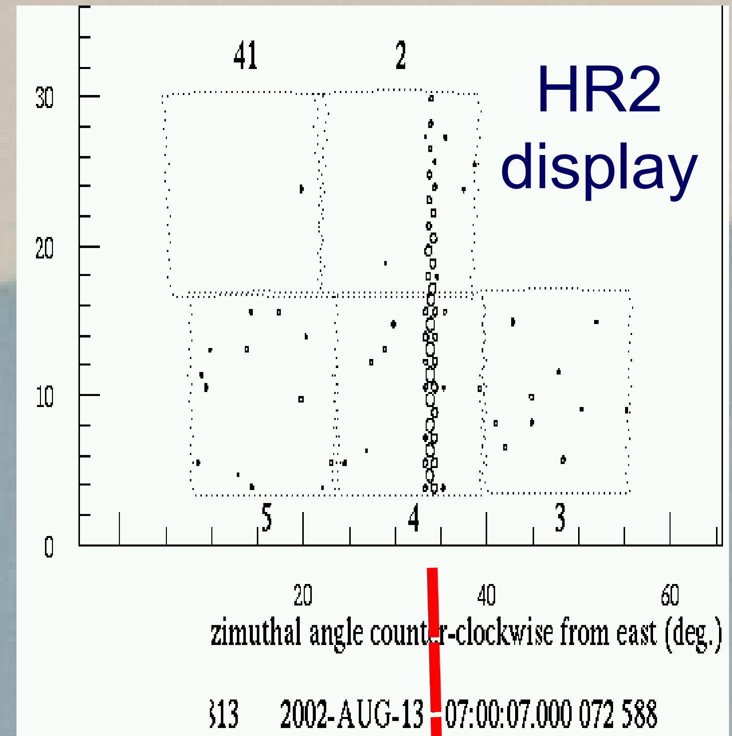
HR1: 05/97 – 06/05
~ 3x HR2 statistics



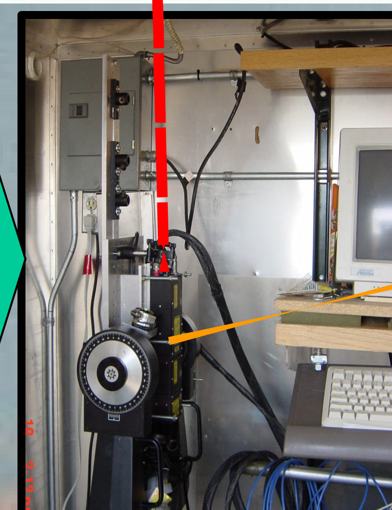
Aperture: Vertical Laser @ 35 km (HR2)

VAOD < 0.1:

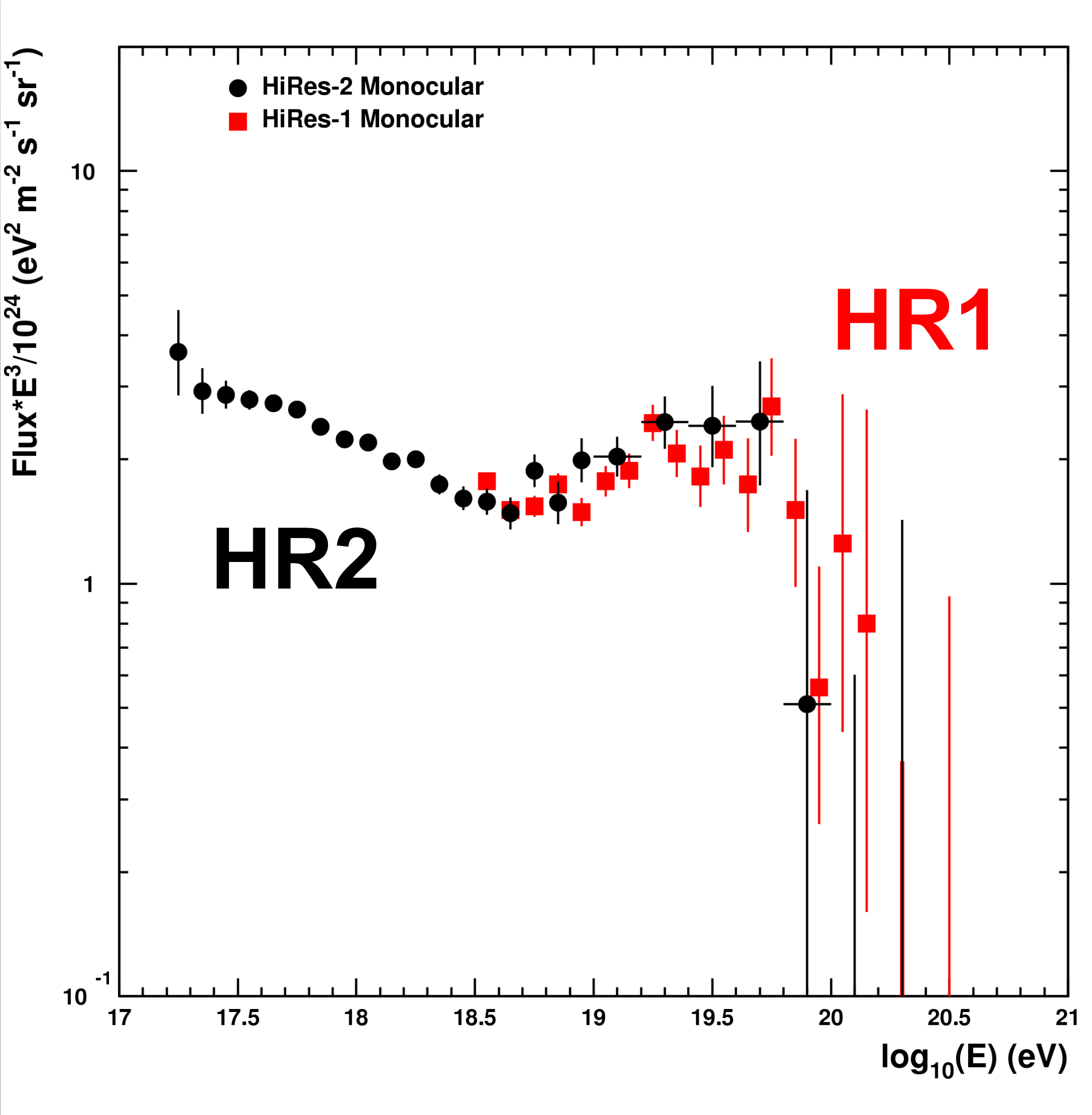
→100% of shots seen
@ ~ 3×10^{19} eV



Terra
site



HiRes Monocular Spectra:

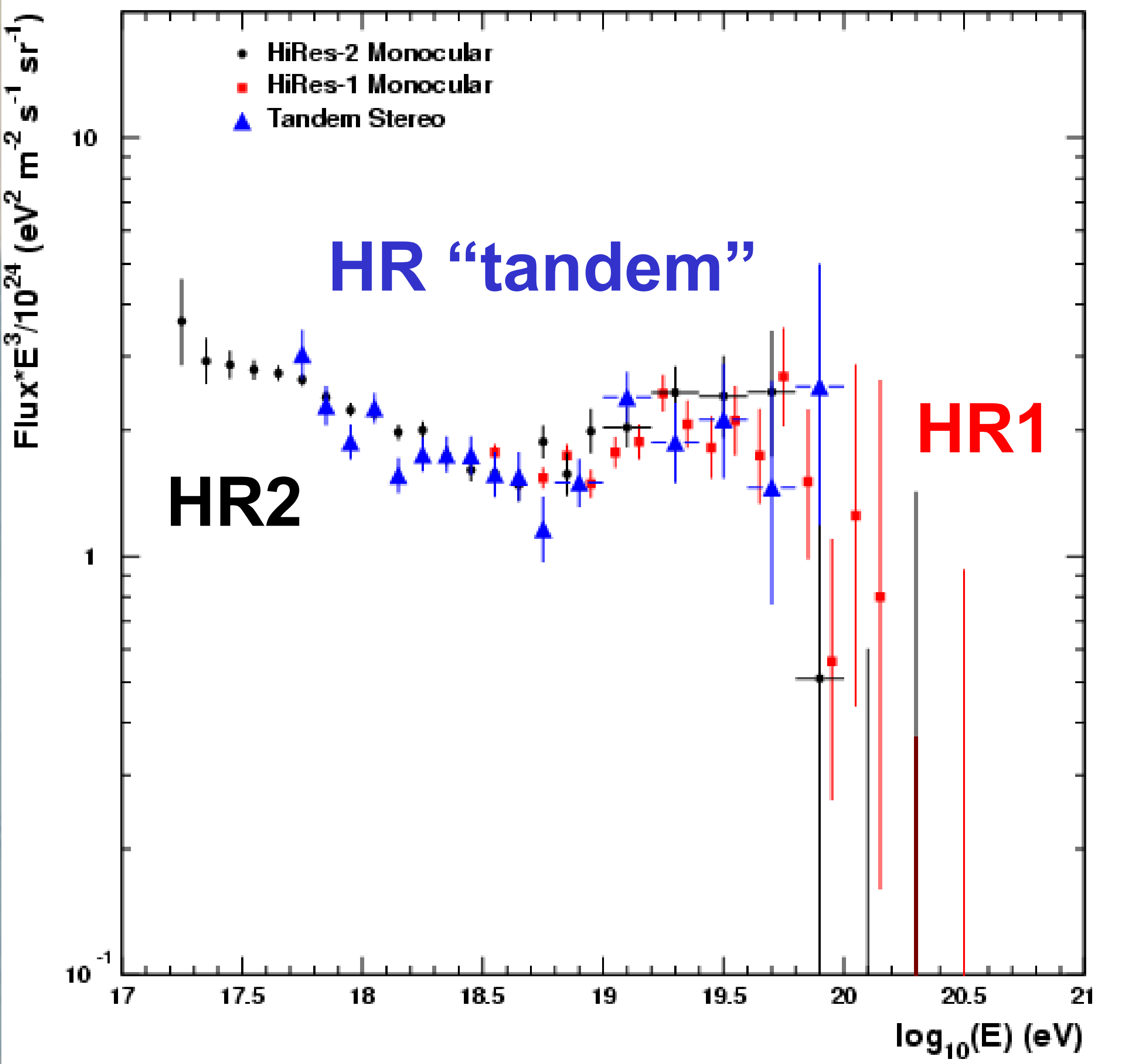


HiRes Spectra Combined:

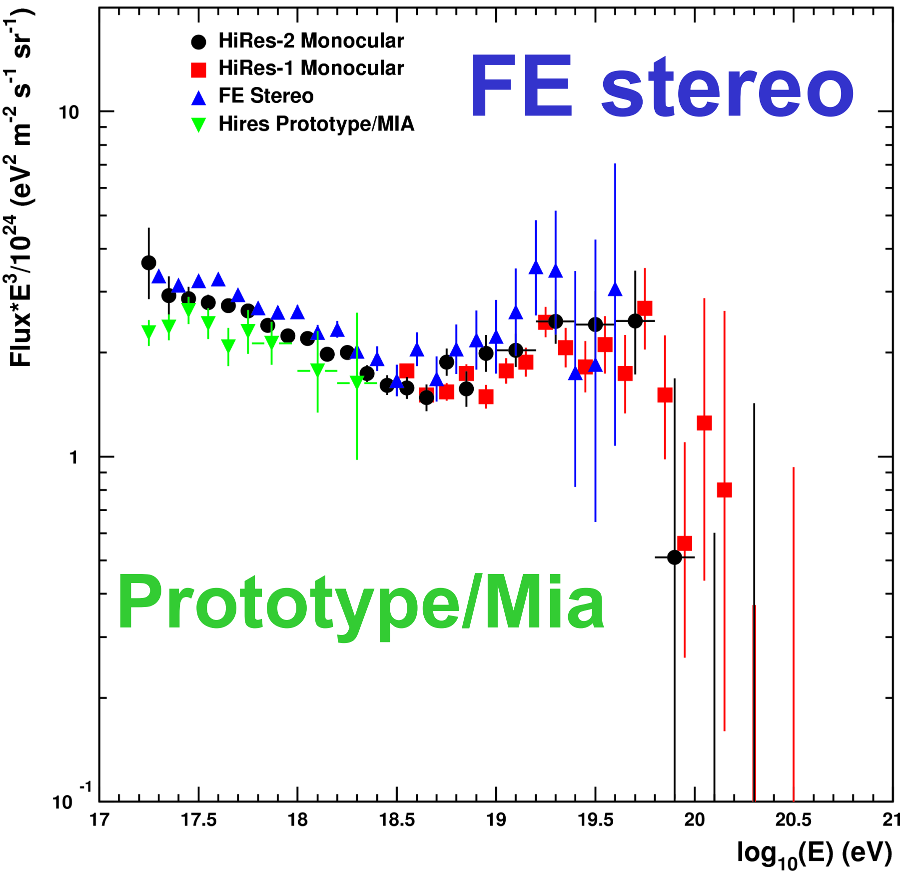
Tandem analysis:
HR1 with geometry by stereo plane intersects

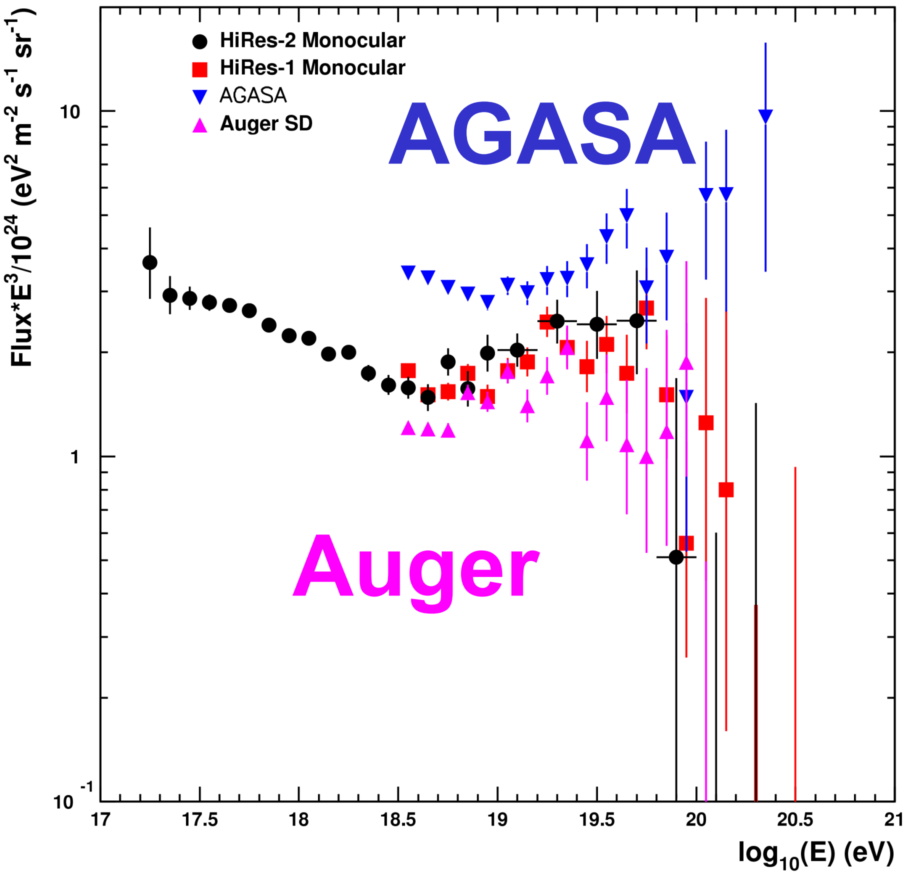
12/99 – 09/01
05/02 – 05/03
→ 811 hours
→ 898 events

Cuts:
planes > 5 deg
$600 < x_{max} < 1150$ g/cm^2
$x_{first} < 1000$ g/cm^2



Monocular Spectra in Comparison:



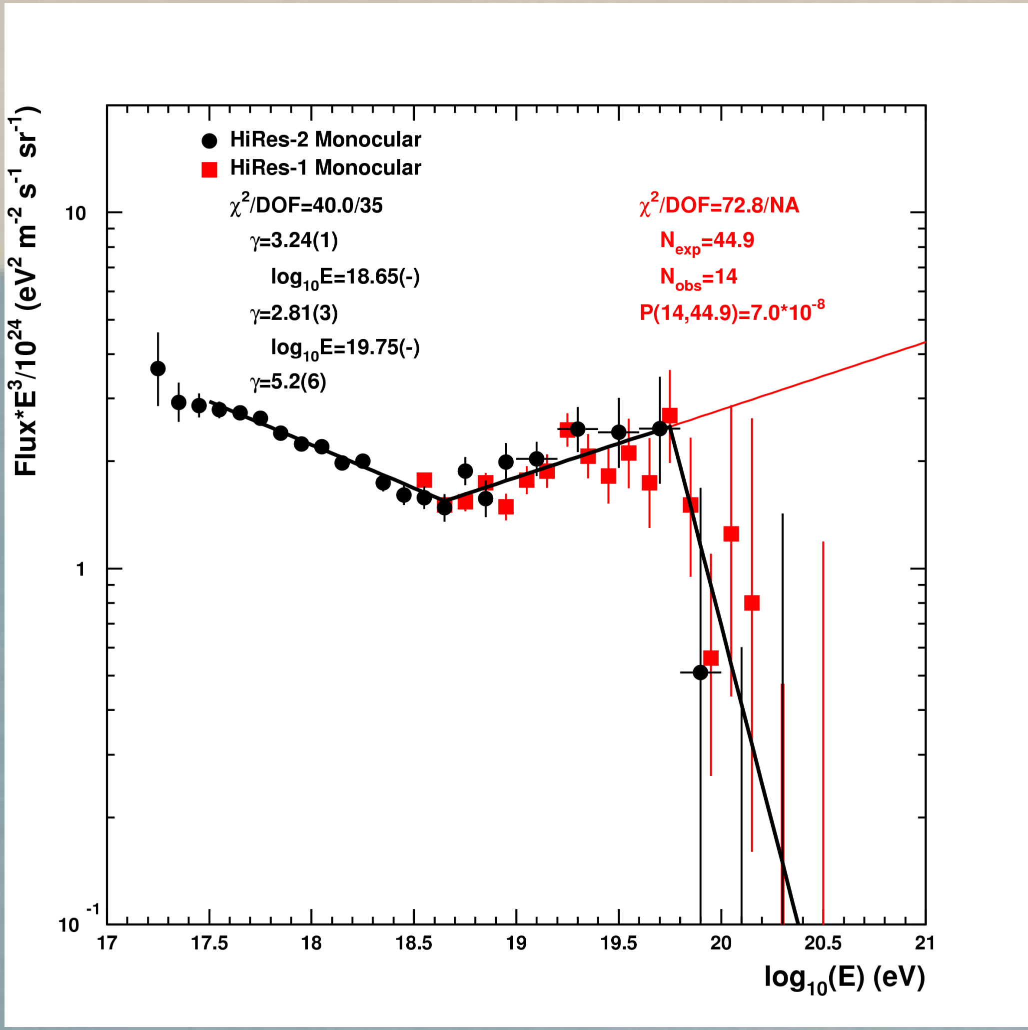


What about GZK?

Spectra and Power laws

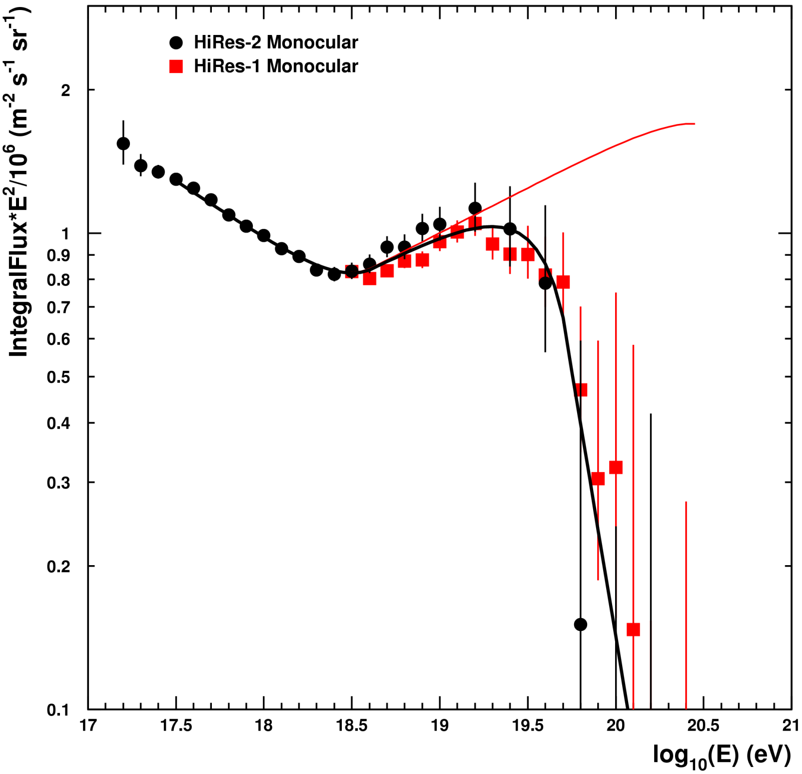
Break Points (BP) in fits are free:

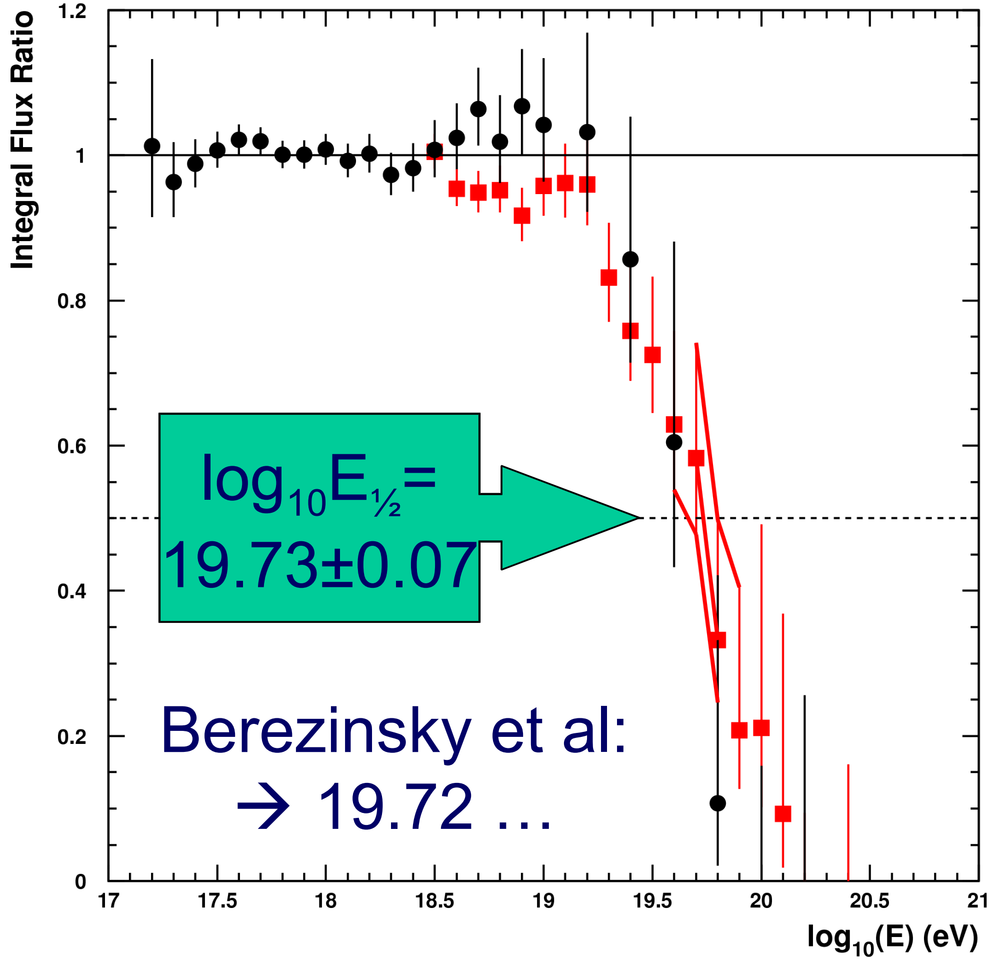
- **0 BPs**
  - Bad fit: c^2=154/39
- **1 BP**
  - Better fit: c^2=67.0/37 DOF
  - Find Ankle at 4 EeV
- **2 BPs (shown →)**
  - Good fit: c^2=40.0/35 DOF
  - Reduce c^2 by 27
  - HE break at 60 EeV



Berezinsky: Integral Spectrum:

$E_{½}$: look for energy where the integral flux is half of "expectation"

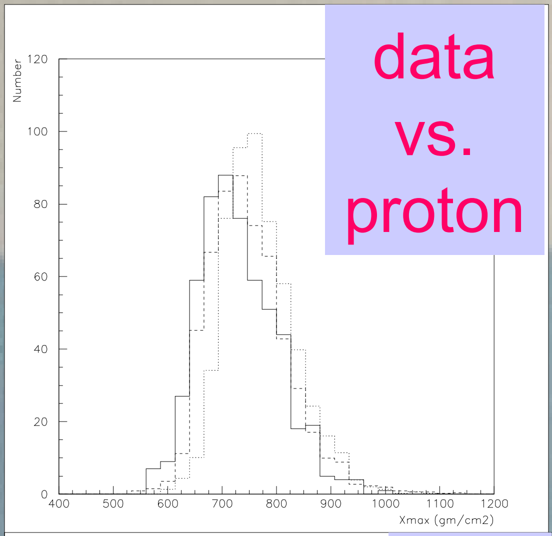


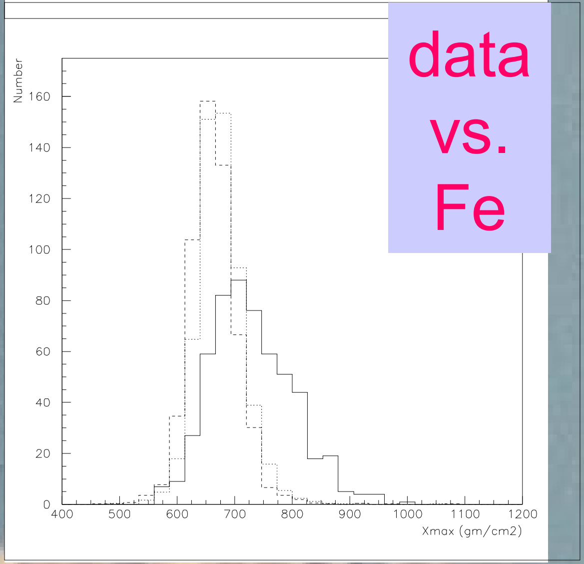


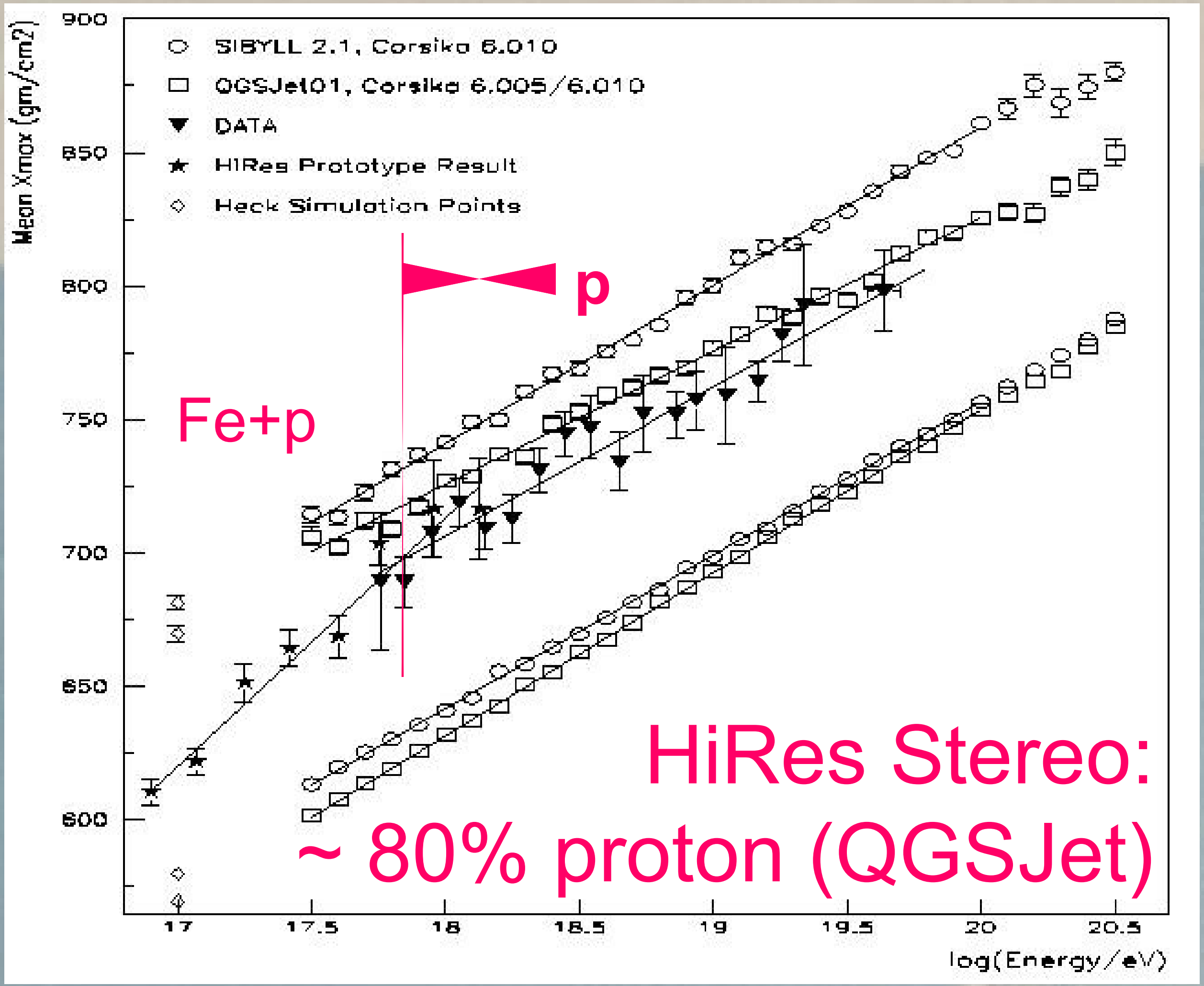
Berezinsky et al:
→ 19.72 …

Composition:

X_{max} distributions:







Traveling the Distance (protons):

Follow Berezinsky, Gazizov, & Grigorieva in hep-ph/0204357:

- universe expands
- pair production:

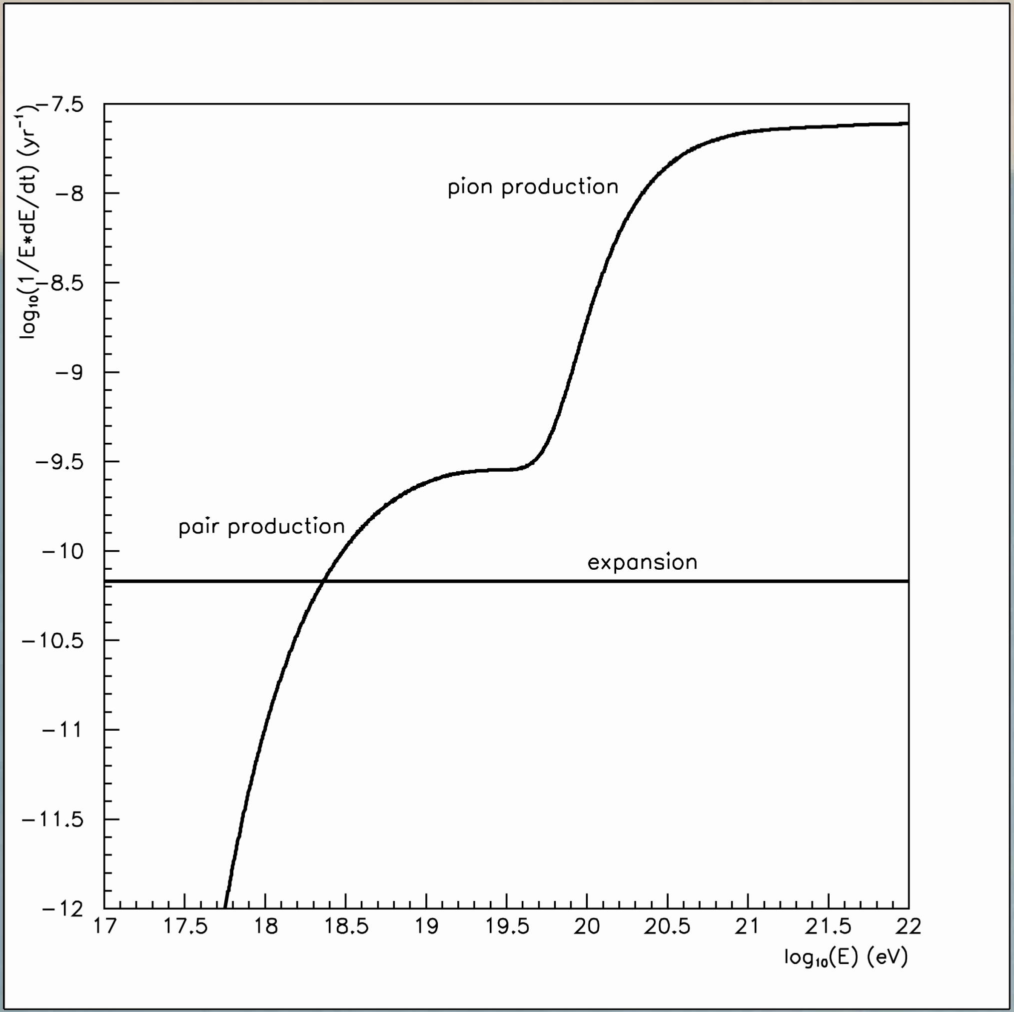
$$p + \gamma_{CMB} \rightarrow p + e^+e^-$$

Follow DeMarco, Blasi, & Olinto in Astropart. Phys. 20 (2003) 53:

- pion production:

$$p + \gamma_{CMB} \rightarrow N + \pi$$

λ_{int} ~ 50 Mpc → stochastic



Interpretation following Berezinsky:

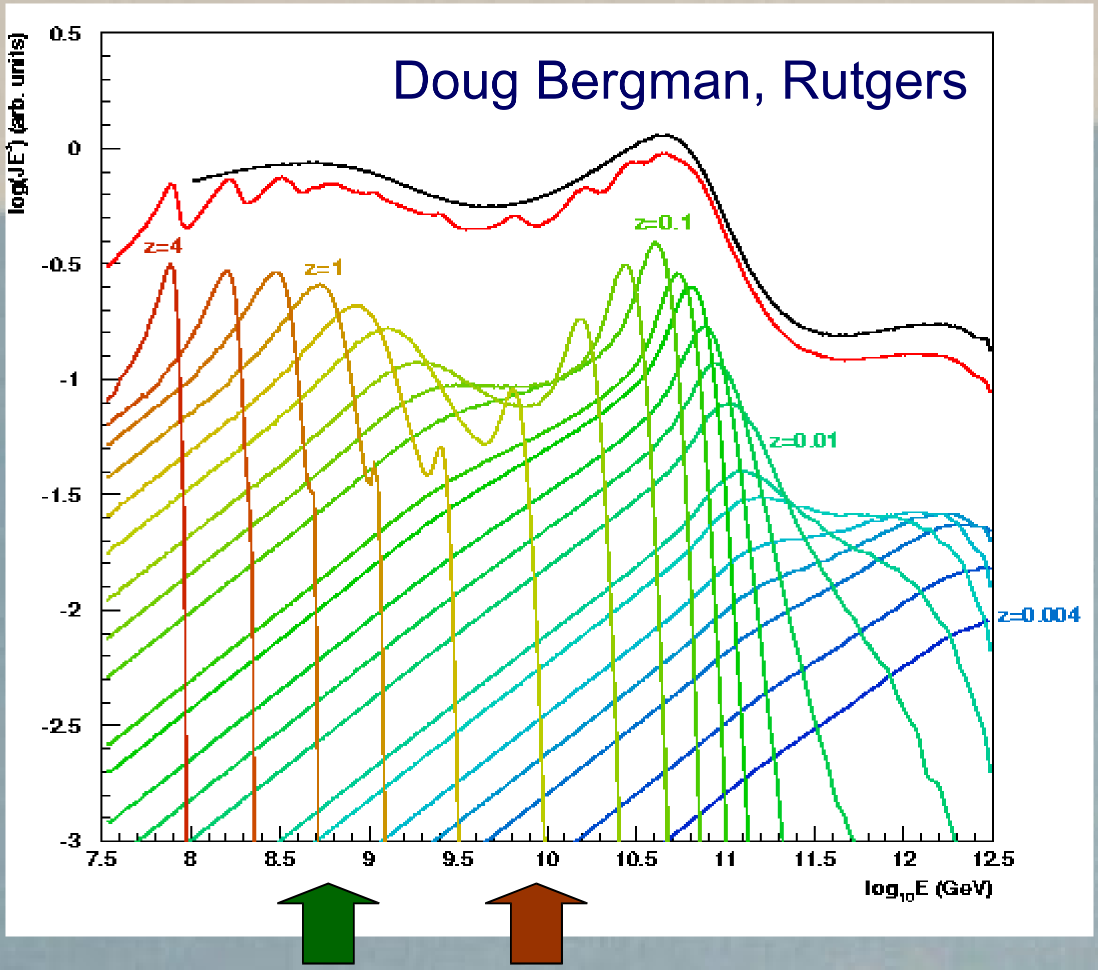
changed interpretation of ankle:

Fits interpret spectrum in terms of **extragalactic protons** that traveled from **cosmological sources**

$p + \gamma_{CMB} \rightarrow \Delta(1232) \rightarrow \pi + N$

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

$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e} + \nu_{\mu}$

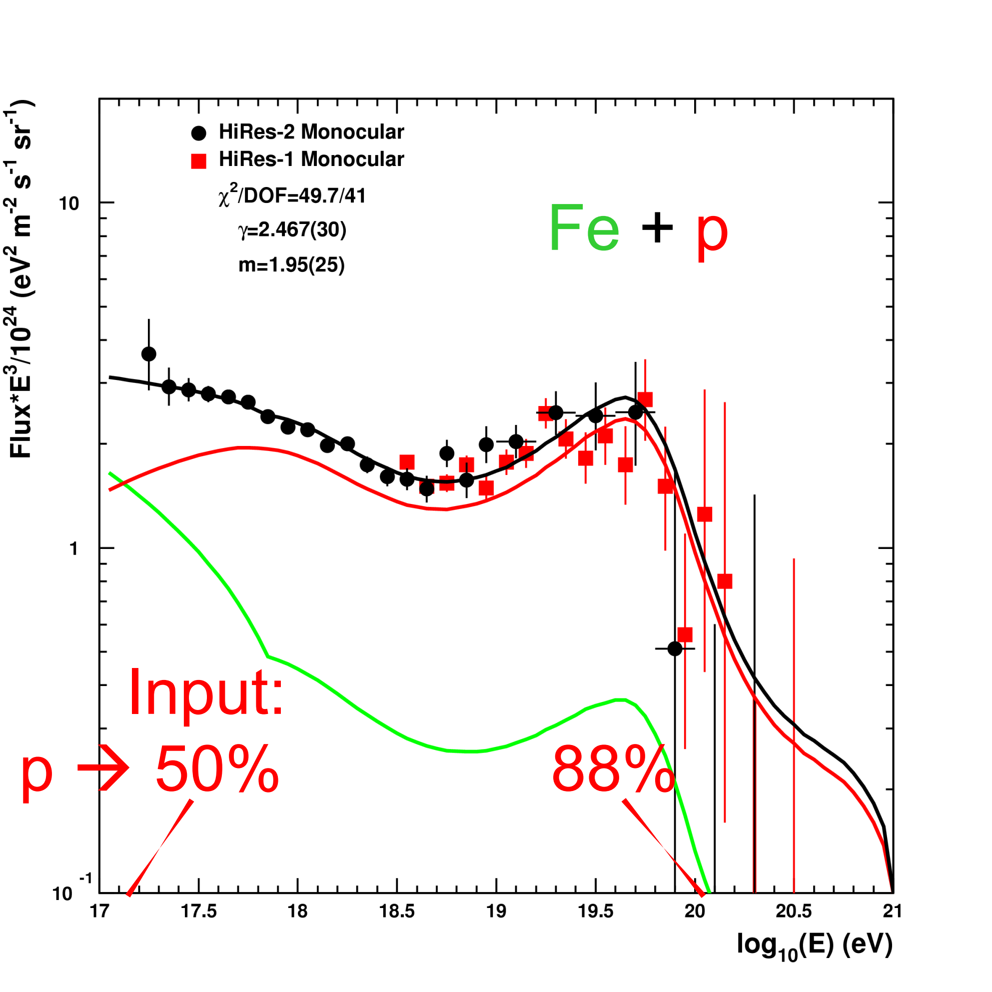


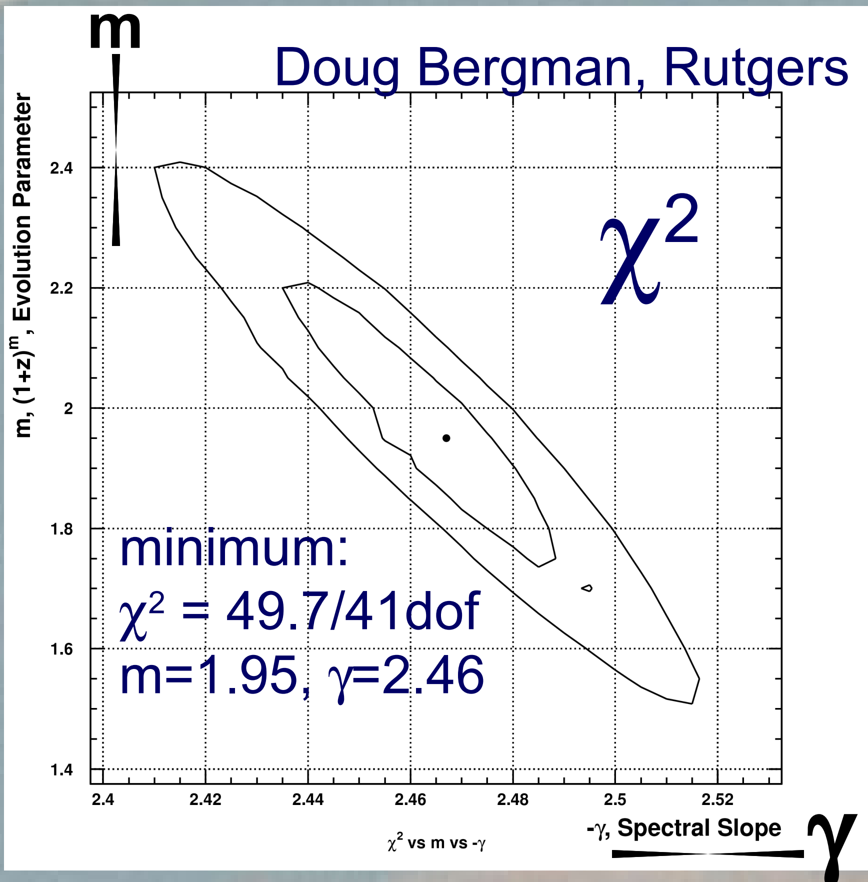
galactic/extragalactic transition: composition change vs. slope change

Fitting for Source Distributions...

Source distribution: $(1+z)^m$, emission spectrum: E^γ

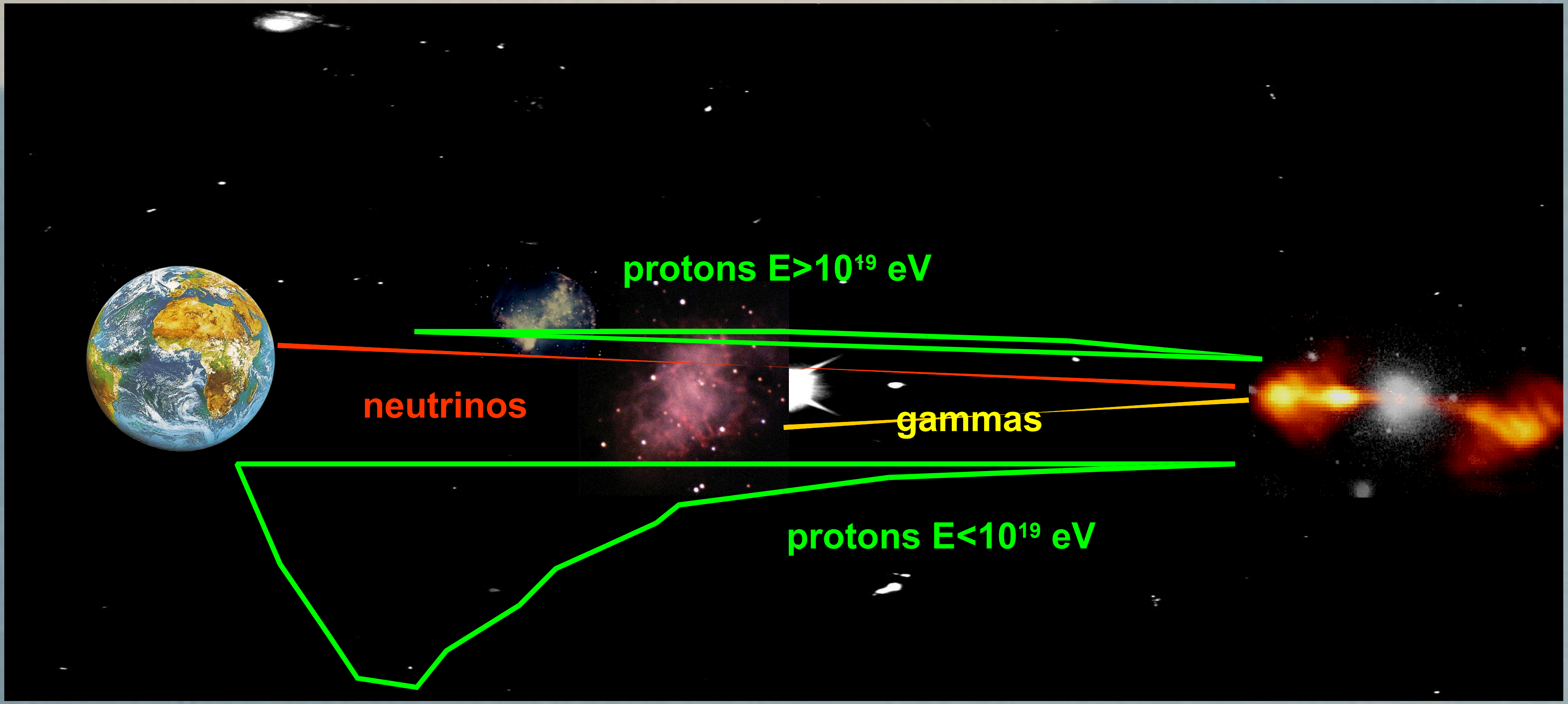
tag by composition: galactic ← Fe, extragalactic ← p



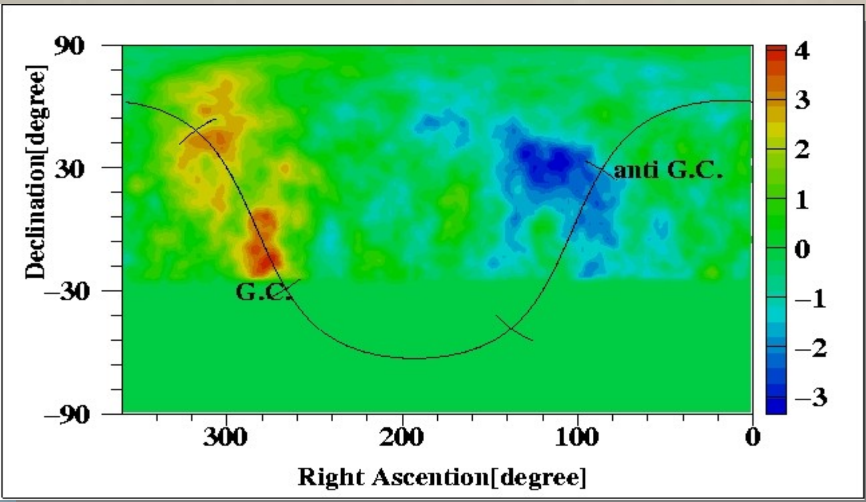


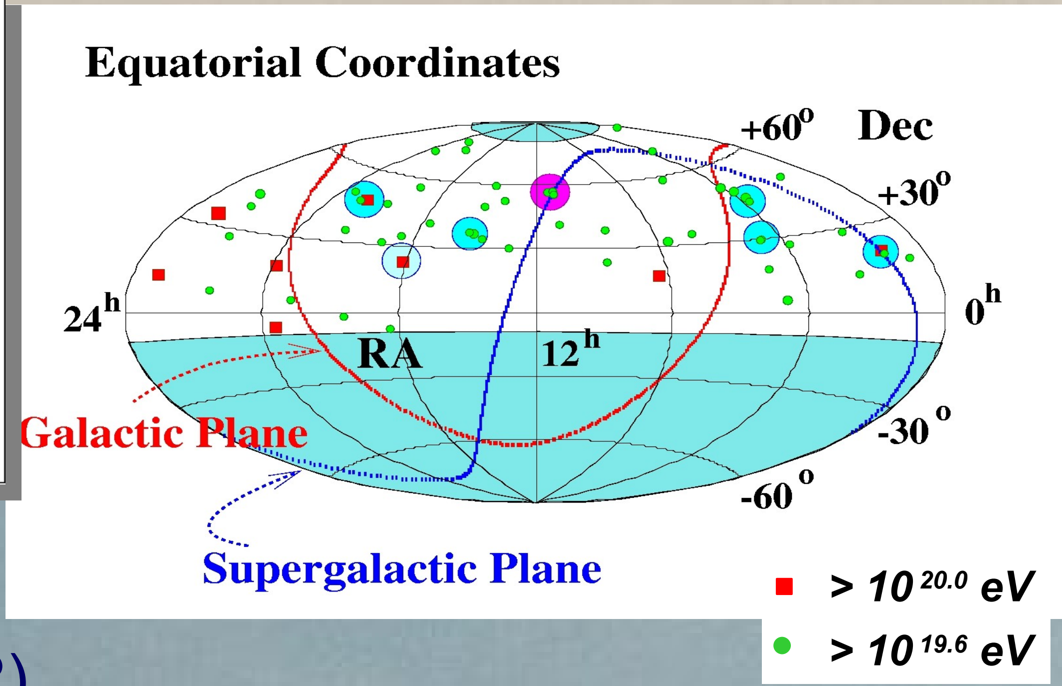
Protons and Sources:

(Graphic stolen from unremembered source…)

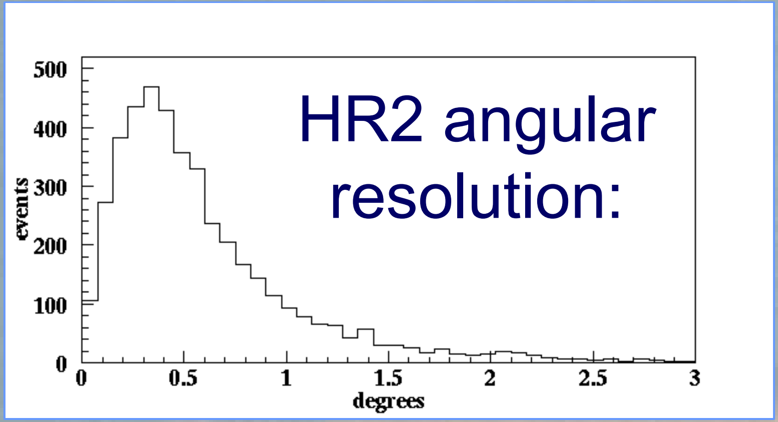


Anisotropy: AGASA Reminder





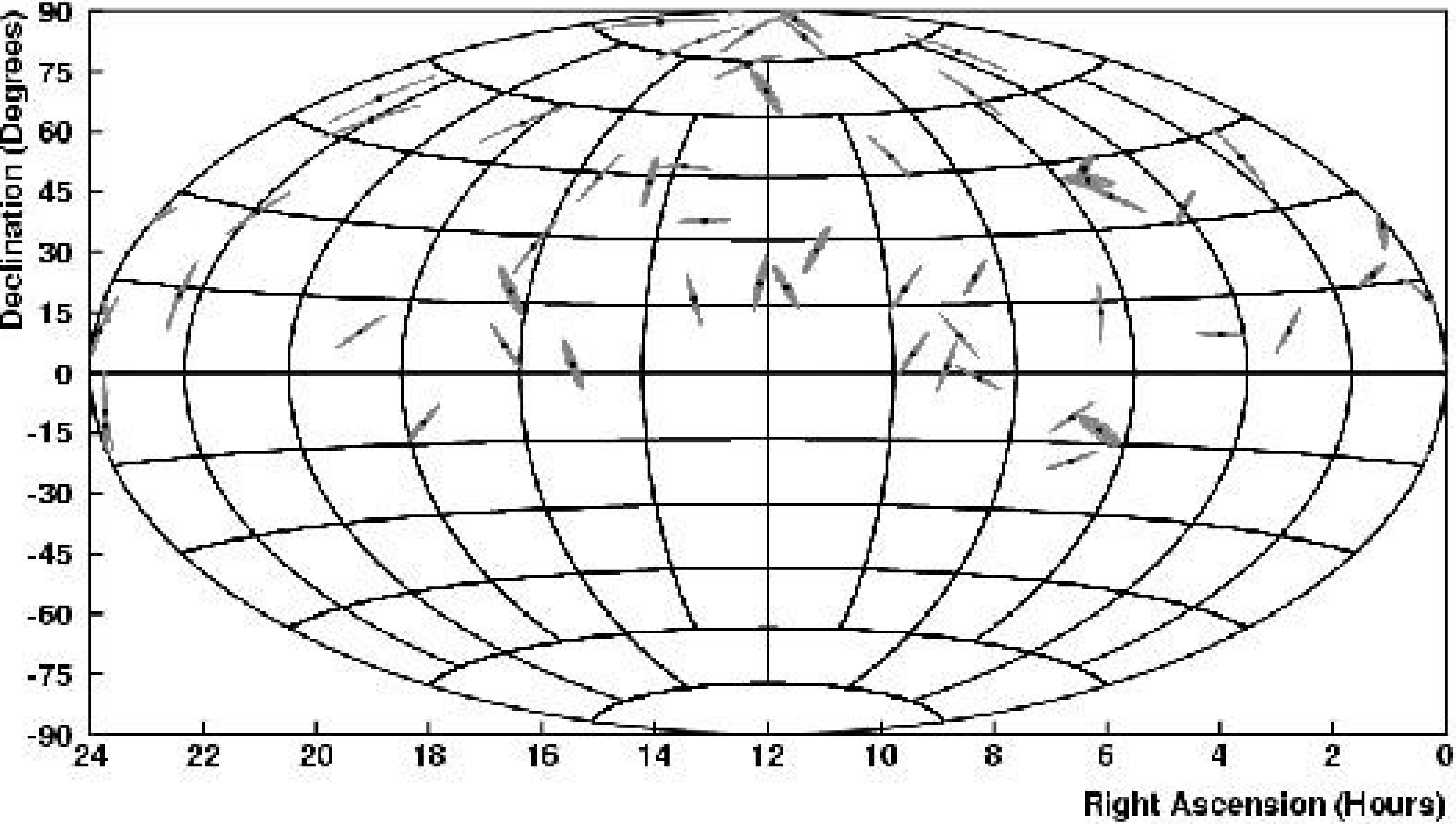
- **AGASA:** set agenda:
  - galactic center (SUGAR)
  - clustering
- **HiRes**: two data sets:
  - mono → large statistics
  - stereo → excellent pointing →



HR1 mono Arrival Directions (1σ ellipses)

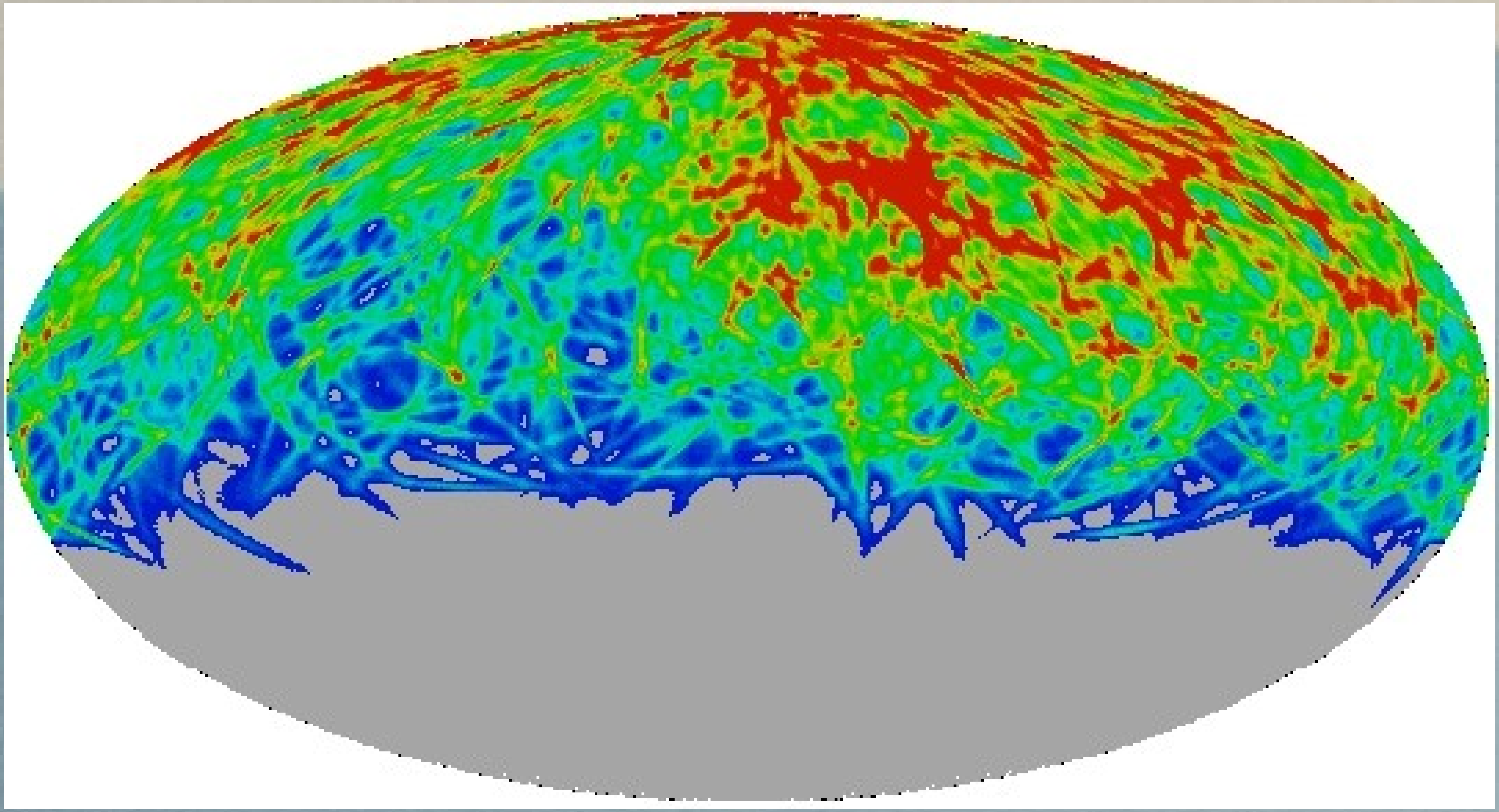
@ 3×10^{18} eV: 0.5 deg / 14 deg

E > 3×10^{19} eV



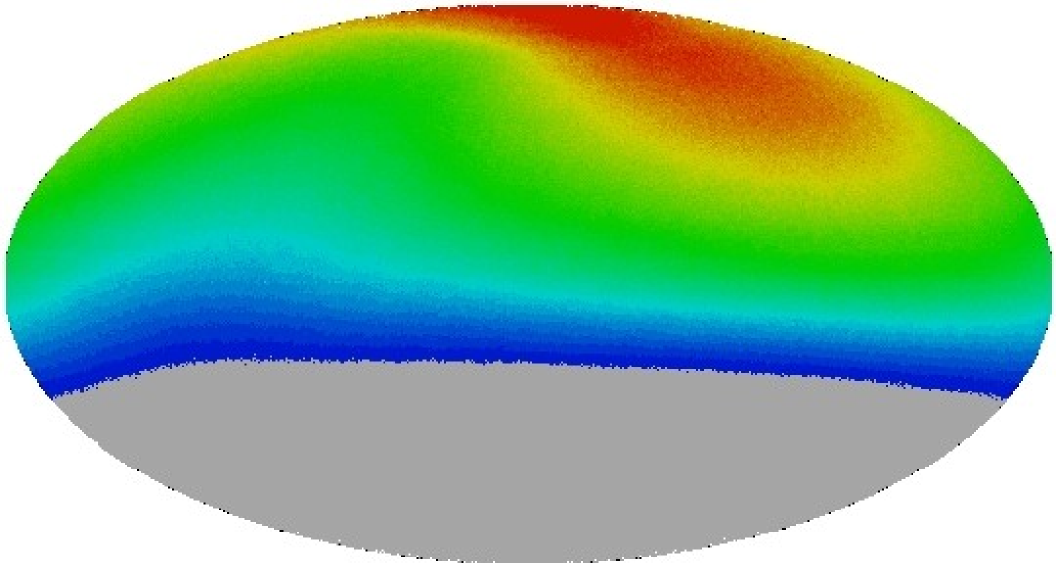
Inhomogeneous Coverage: Data

$E > 3 \times 10^{18}$ eV



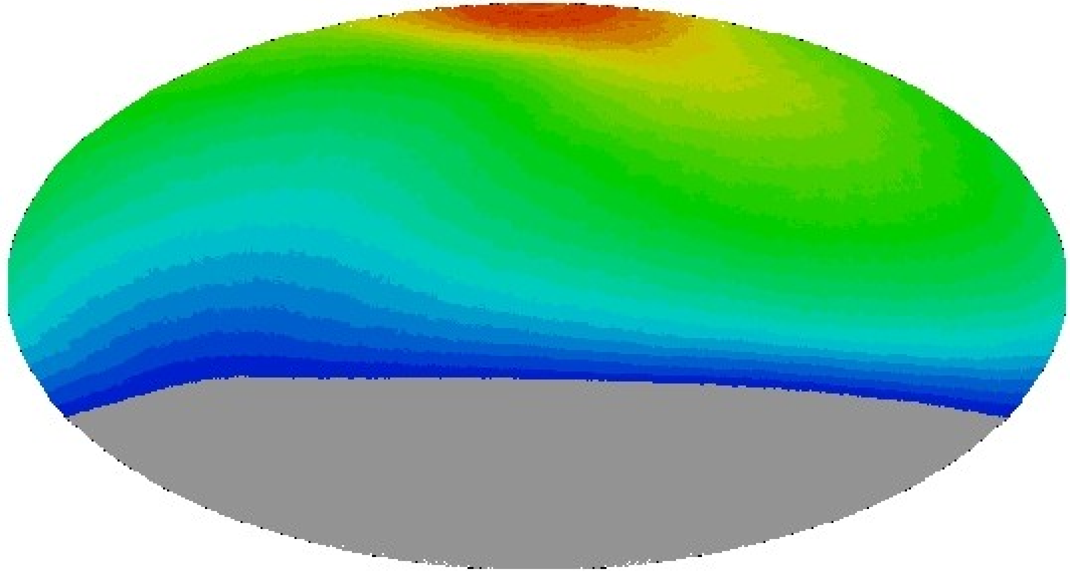
Estimate Exposure from MC !!! (← resolution…)

HR1 Relative Exposure Maps

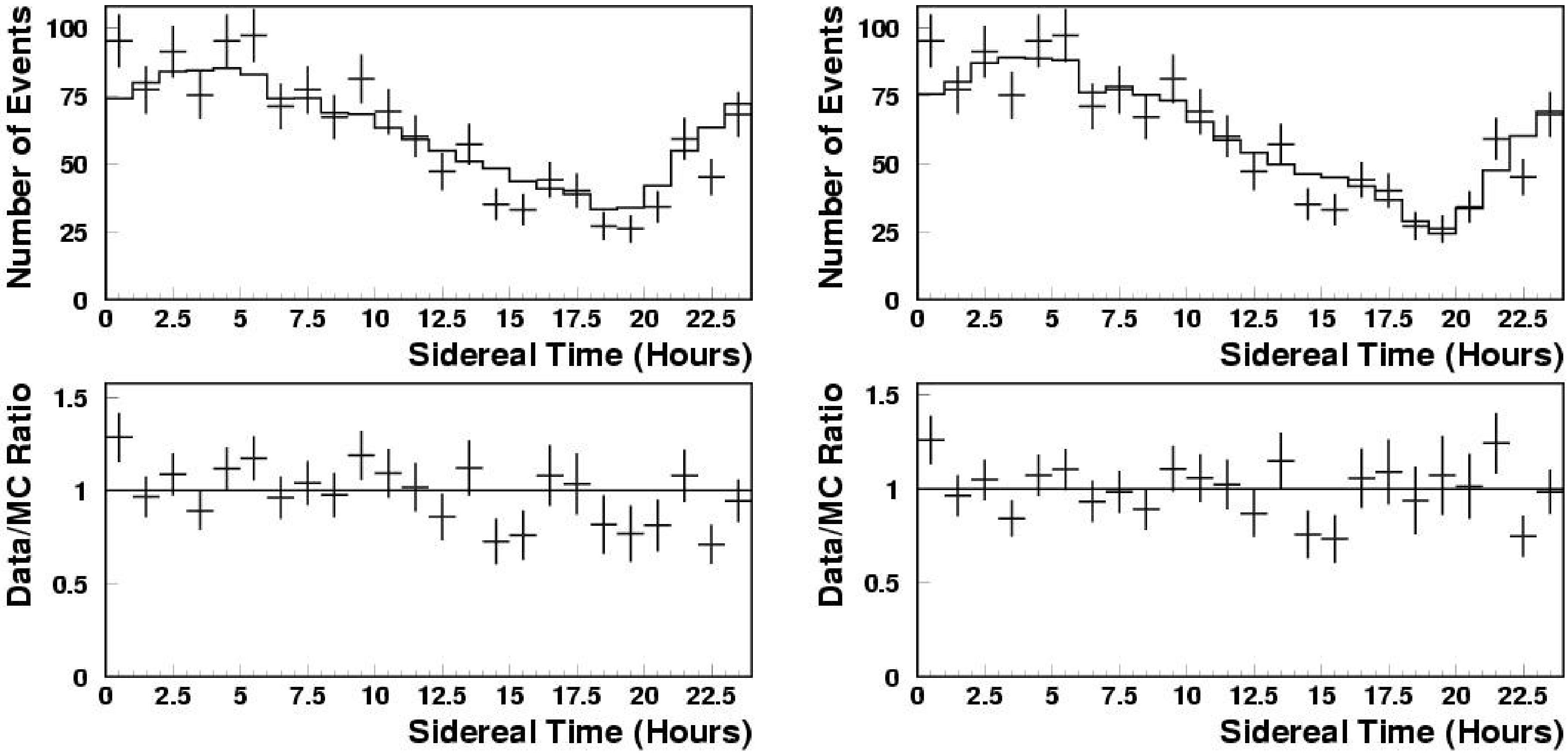


$> 3 \times 10^{18}$ eV

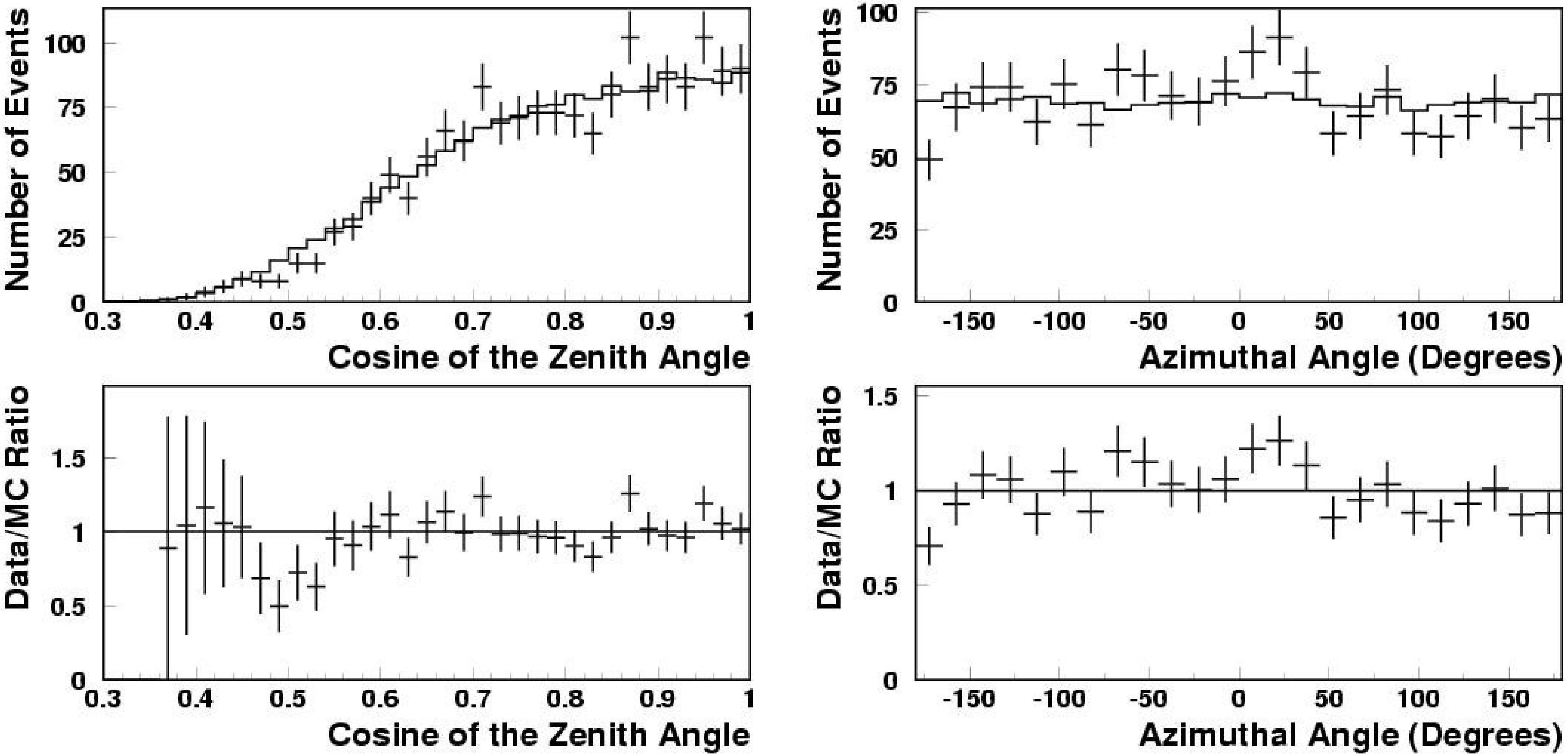
$> 3 \times 10^{19}$ eV



Exposure Estimation Verification



More MC Verification



Global Dipoles (Fixed Directions)

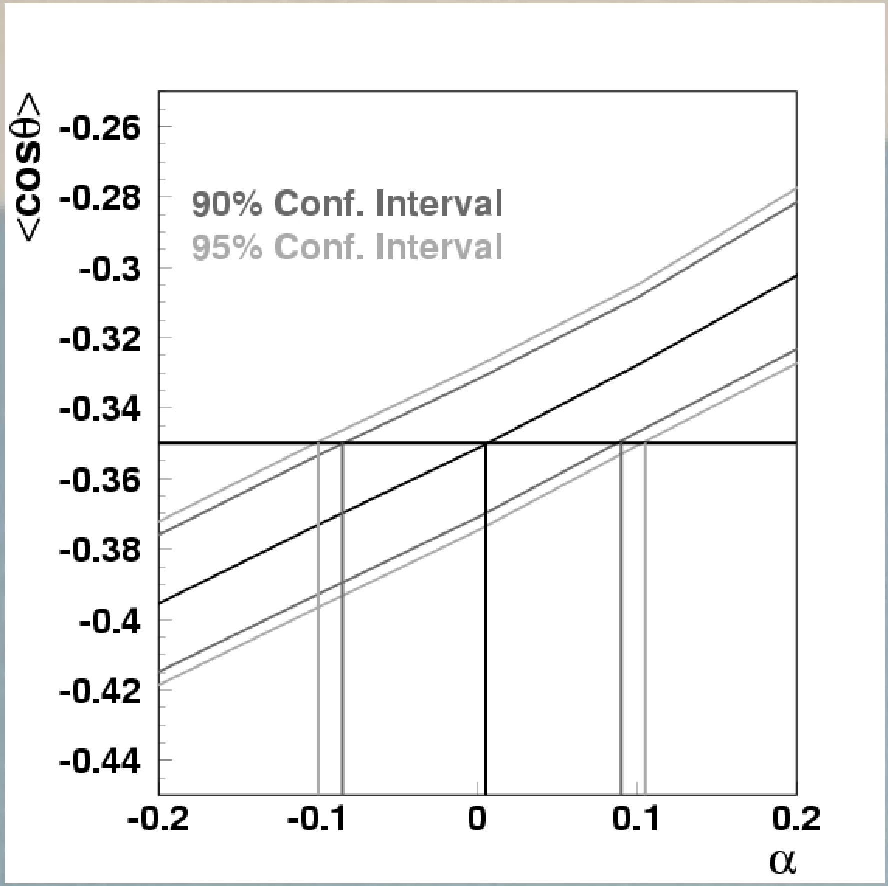
dipole: $n=(1 + \alpha \cos \theta)/2$

evaluate: $\langle\cos \theta\rangle$ for data

compare to MC distributions
for $-1 < \alpha < 2$:

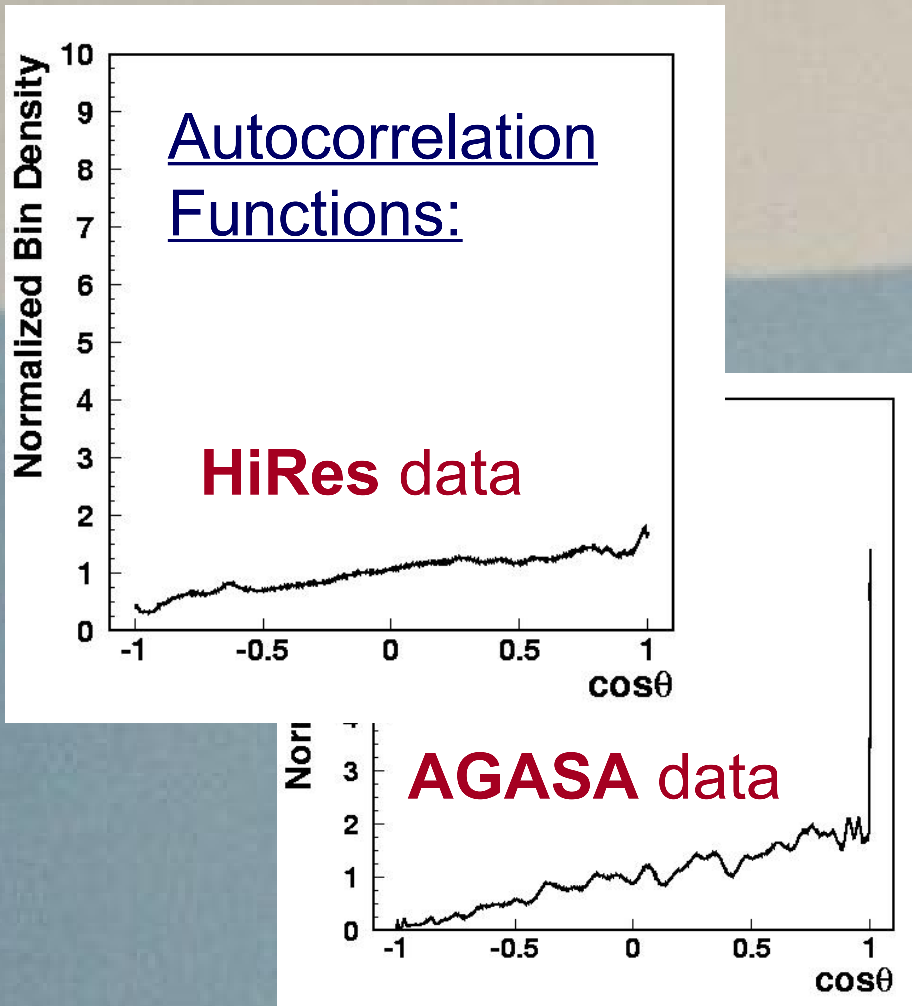
- SagA → $\alpha = 0.005 \pm 0.055$
- CenA → $\alpha = -0.005 \pm 0.065$
- M87 → $\alpha = 0.010 \pm 0.045$

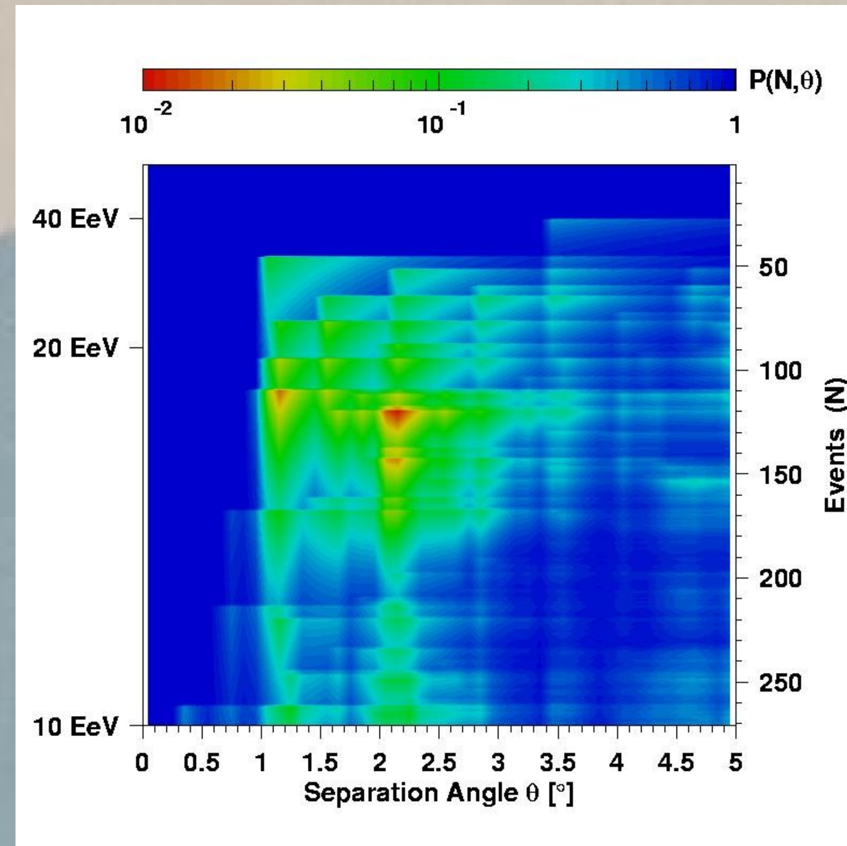
→ **Consistent with Isotropy**



$$\langle\cos\theta\rangle = \frac{1}{2}\int \cos\theta\left(1+\cos\theta\right) d\left(\cos\theta\right) = \frac{1}{3}\alpha$$

Stereo Data → Autocorrelations





Scan: data & MC
→ strongest signal:
P_{chance} = 51%

HiRes consistent with no correlation…

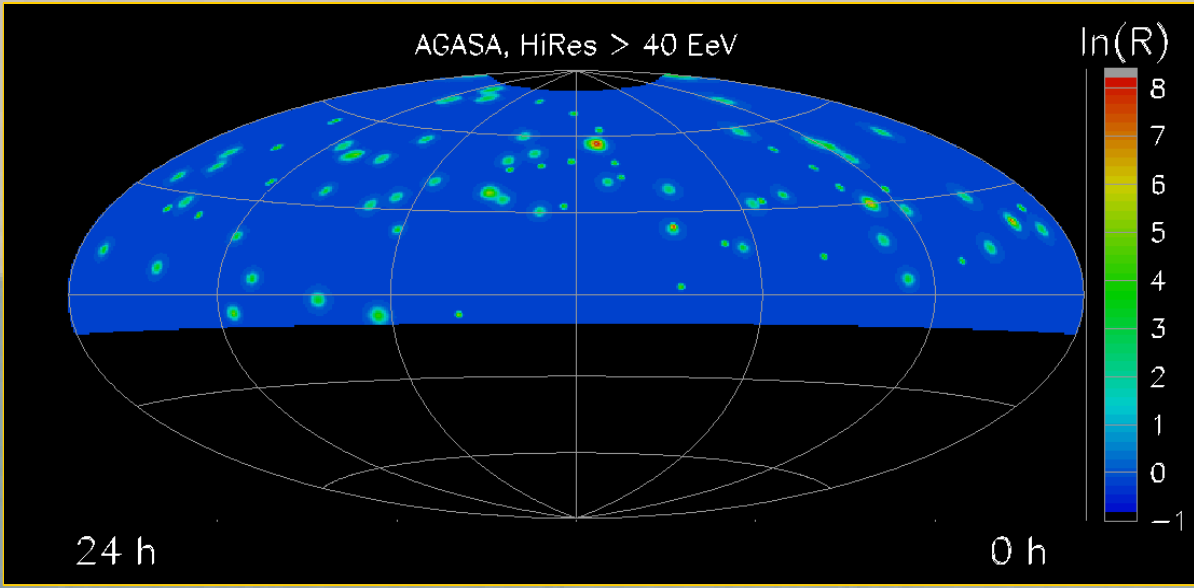
Stereo Data → Correlation with AGASA

Likelihood ratio test:
(E > 40 EeV)

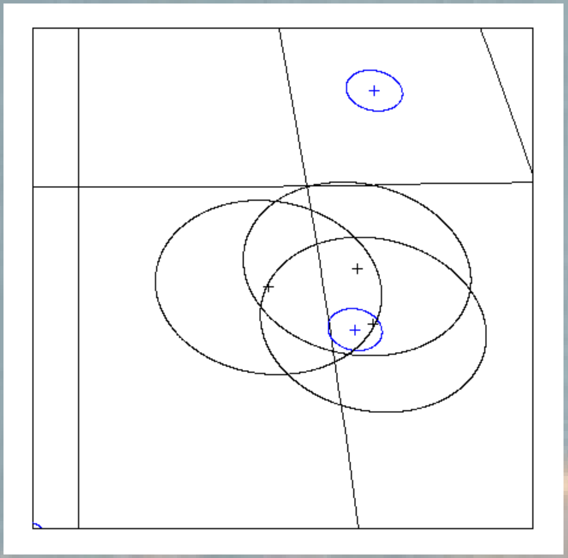
$$L(n_s, x_s) = \prod_{i=1}^{N} P_i(x_i, x_s, n_s)$$

$$\ln(R) = \ln \frac{L(n_s, x_s)}{L(0, x_s)}$$

28% of MC sets
> ln(Ratio) @ triplet
→ **not significant**



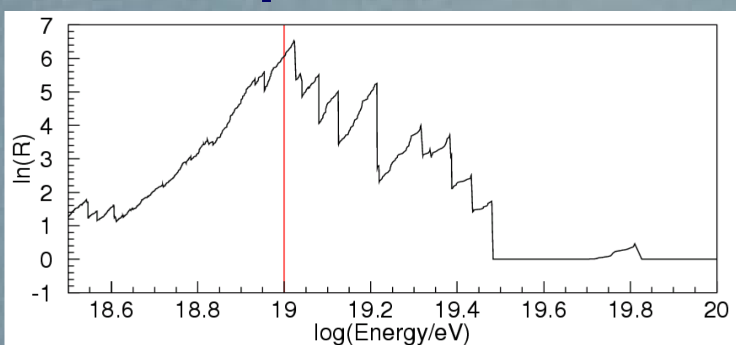
But: lower HiRes threshold:
40 EeV → 30 EeV
→HiRes event in triplet…
MC > ln(Ratio) = 0.5%
without penalties for tampering!!!



Stereo Data → BL Lac

Gorbunov et al., JETP Lett. 80 (2004) 14 → **HiRes analysis:**

10 EeV optimal for BL: Vernon 10th catalog: BL + HP (high pol.)
Gorbunov uses only BL



"new" data: since 01/04
to be seen…

"old" data: trial factors ???

F: fraction of MC sets with larger correlation

n_s: number of events from source

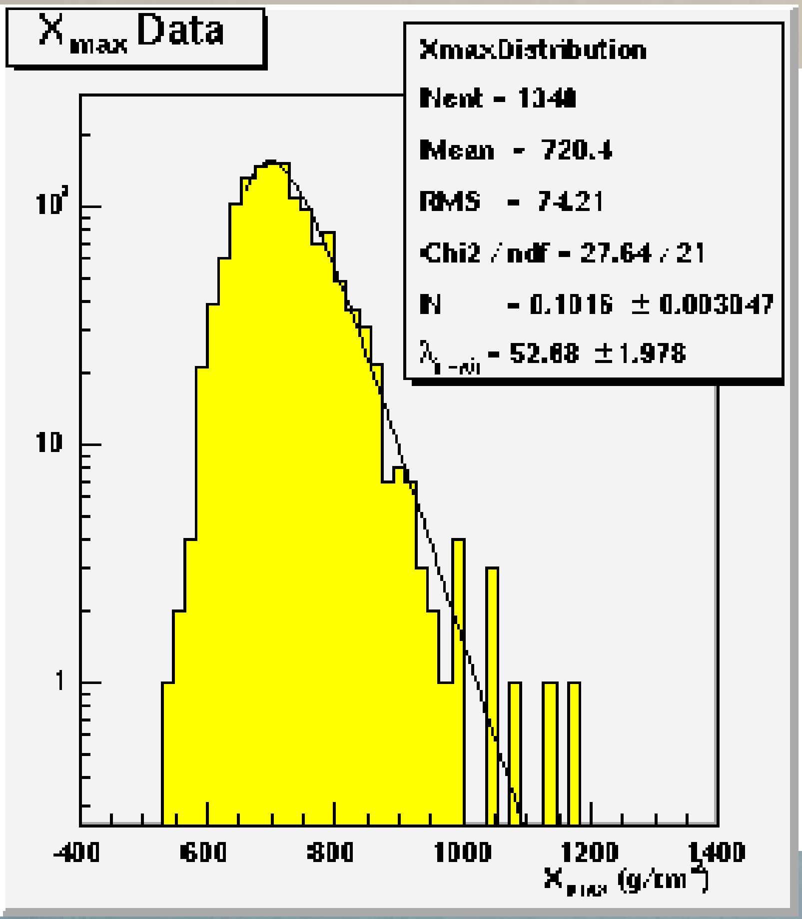
Conclusions

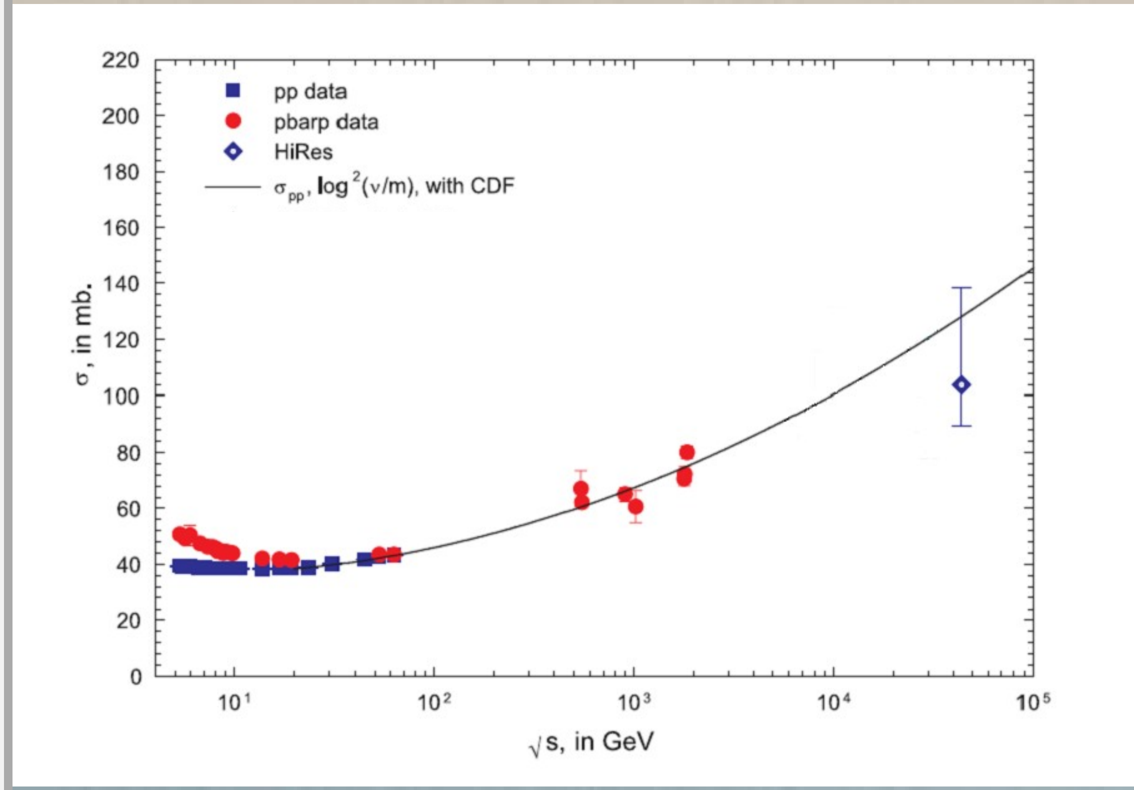
- HiRes has stopped taking data in 04/06
  → transition to Telescope Array

  - HiRes has seen the GZK cutoff
  - no dipole enhancment in HiRes
  - no small angular scale correlations in HiRes
  - one event added to AGASA triplet … → ???
  - please tell me what to think about the BL Lacs…

Cosmic Rays are not boring quite yet!

Fixed Target Experiment @ 3×10^{18}eV

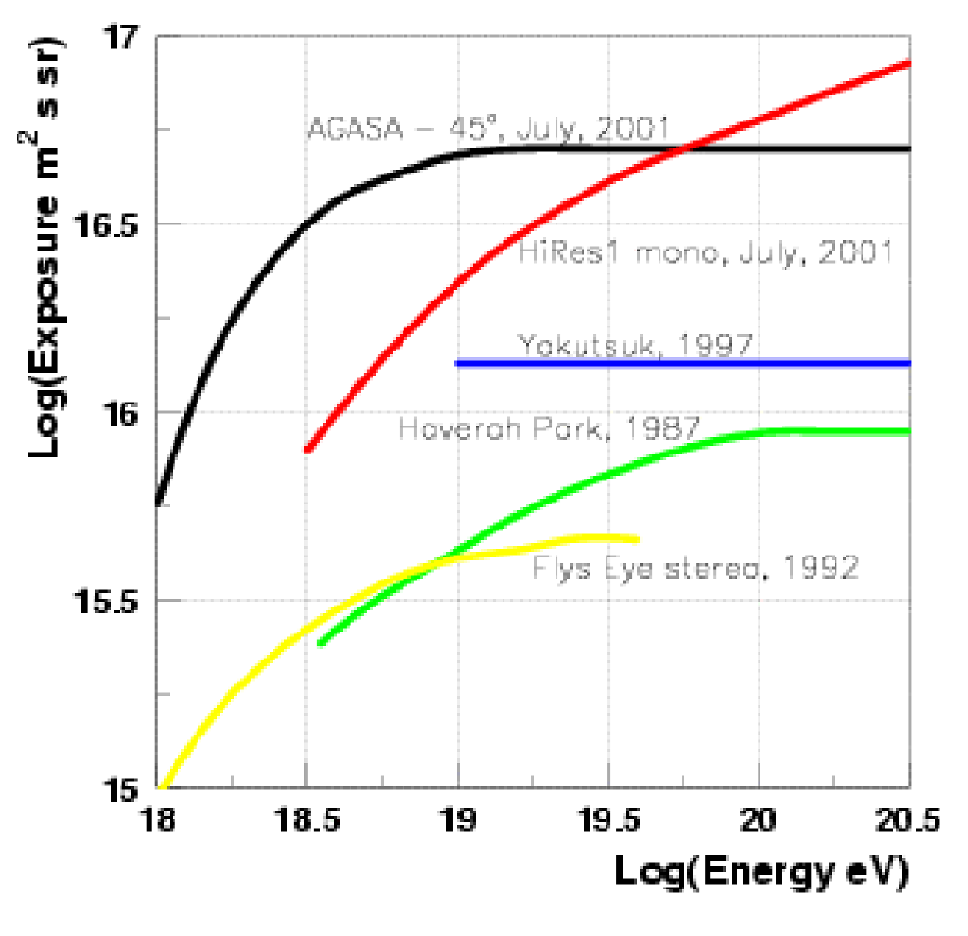




HiRes: $\sigma_{in}^{p\ \ Air} = 456 \pm 17\,(stat)\ \ 39\,(sys) + 11\,(sys)\ mb$

Exposures by ICRC 2001

plot by M.Teshima, ICRR (AGASA)



Air Fluorescence:

Aperture rises with shower energy

Duty cycle: 10%

Ground Array:

Aperture saturates as shower "width" over-reaches detector spacing

Duty cycle: 100%

(exposure = aperture x lifetime)