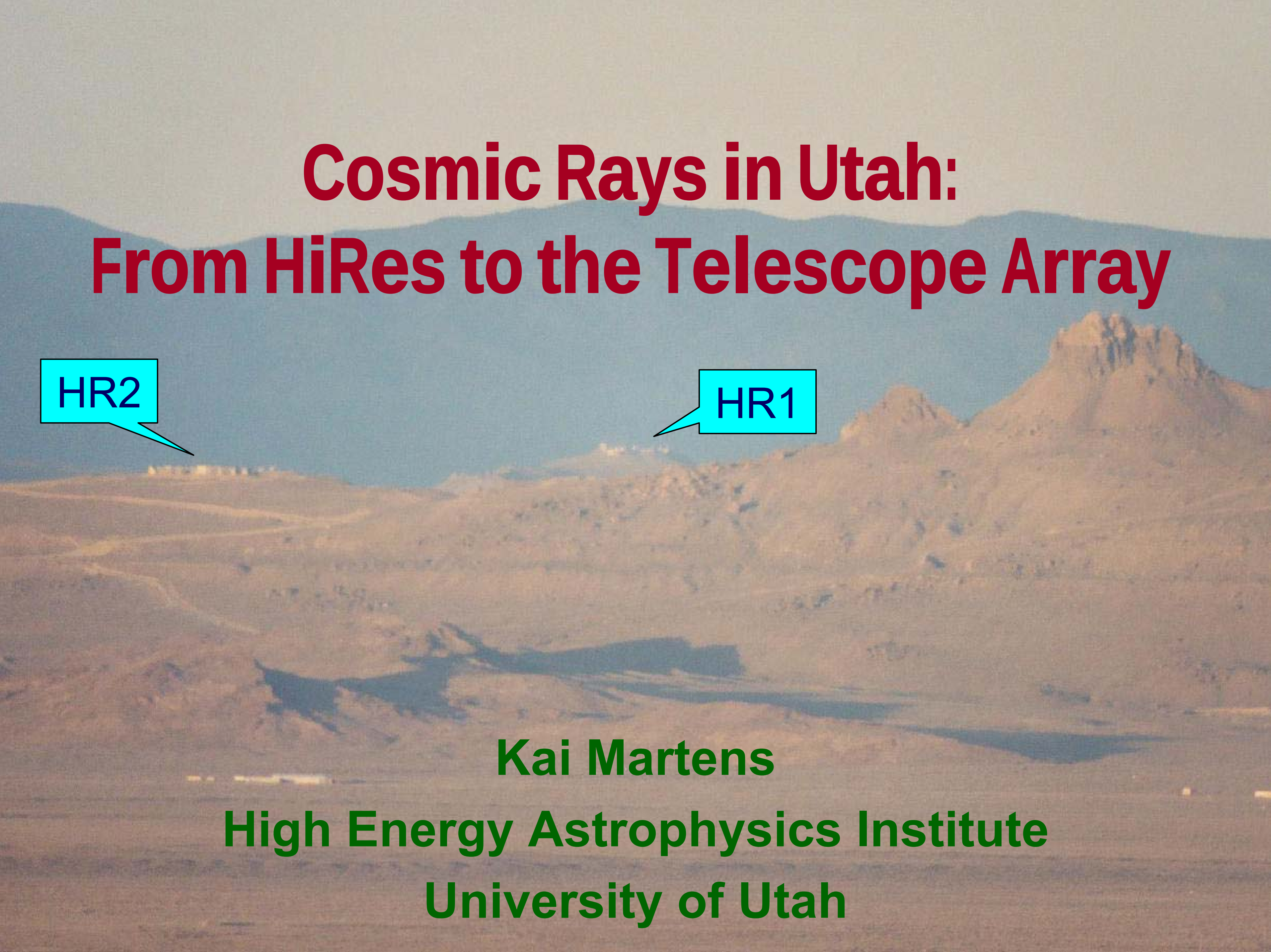
Cosmic Rays in Utah:
From HiRes to the Telescope Array



Kai Martens
High Energy Astrophysics Institute
University of Utah

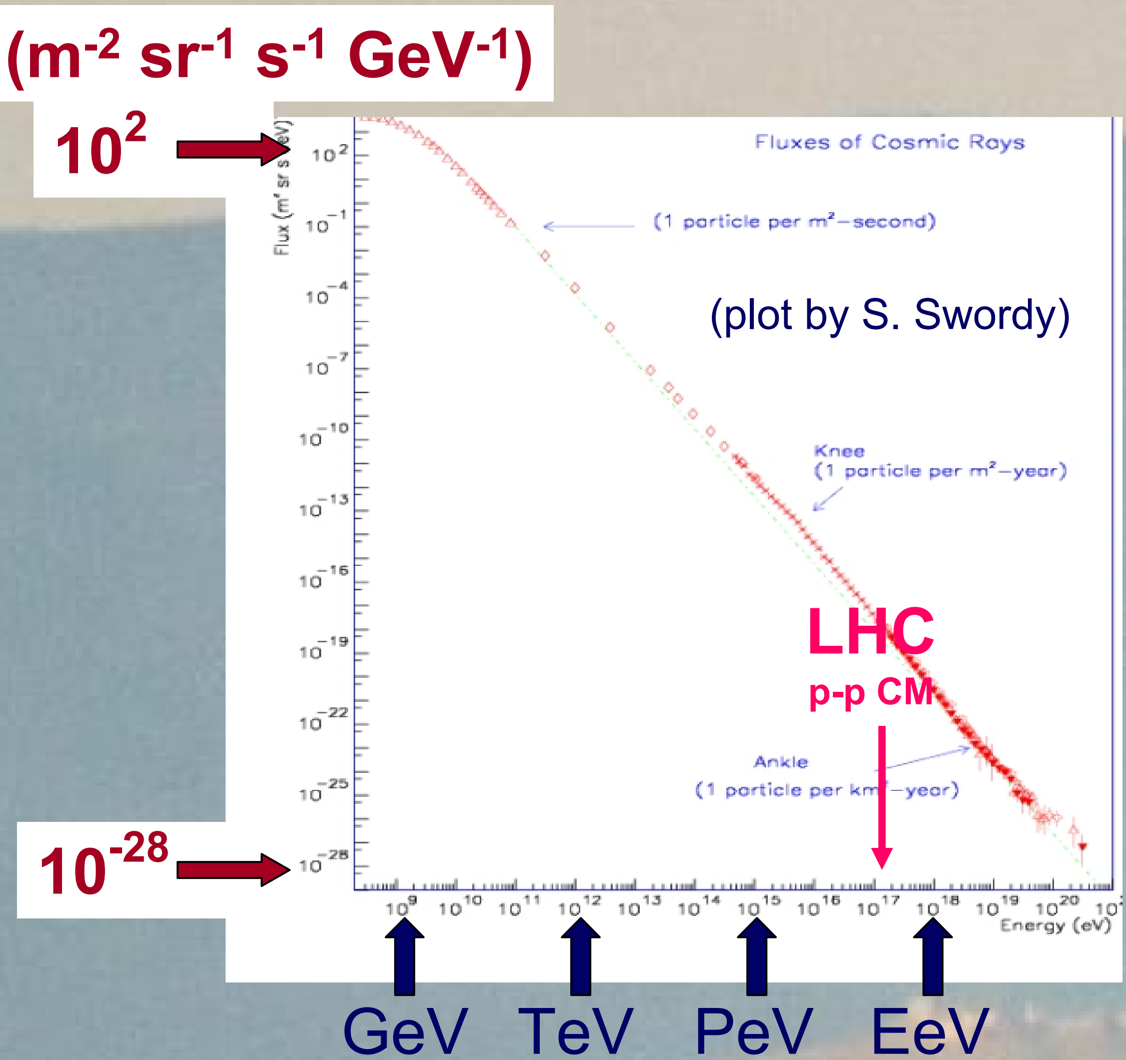
Overview

- Ultra High Energy Cosmic Rays
- Extensive Air Showers
- High Resolution Fly's Eye:
  - Spectra, Composition, & (non-) Correlations
  - Expectations for Neutrino Fluxes
  - Flux Limits from HiRes
- Telescope Array:
  - Full Operation since March 20, 2008
- Conclusions

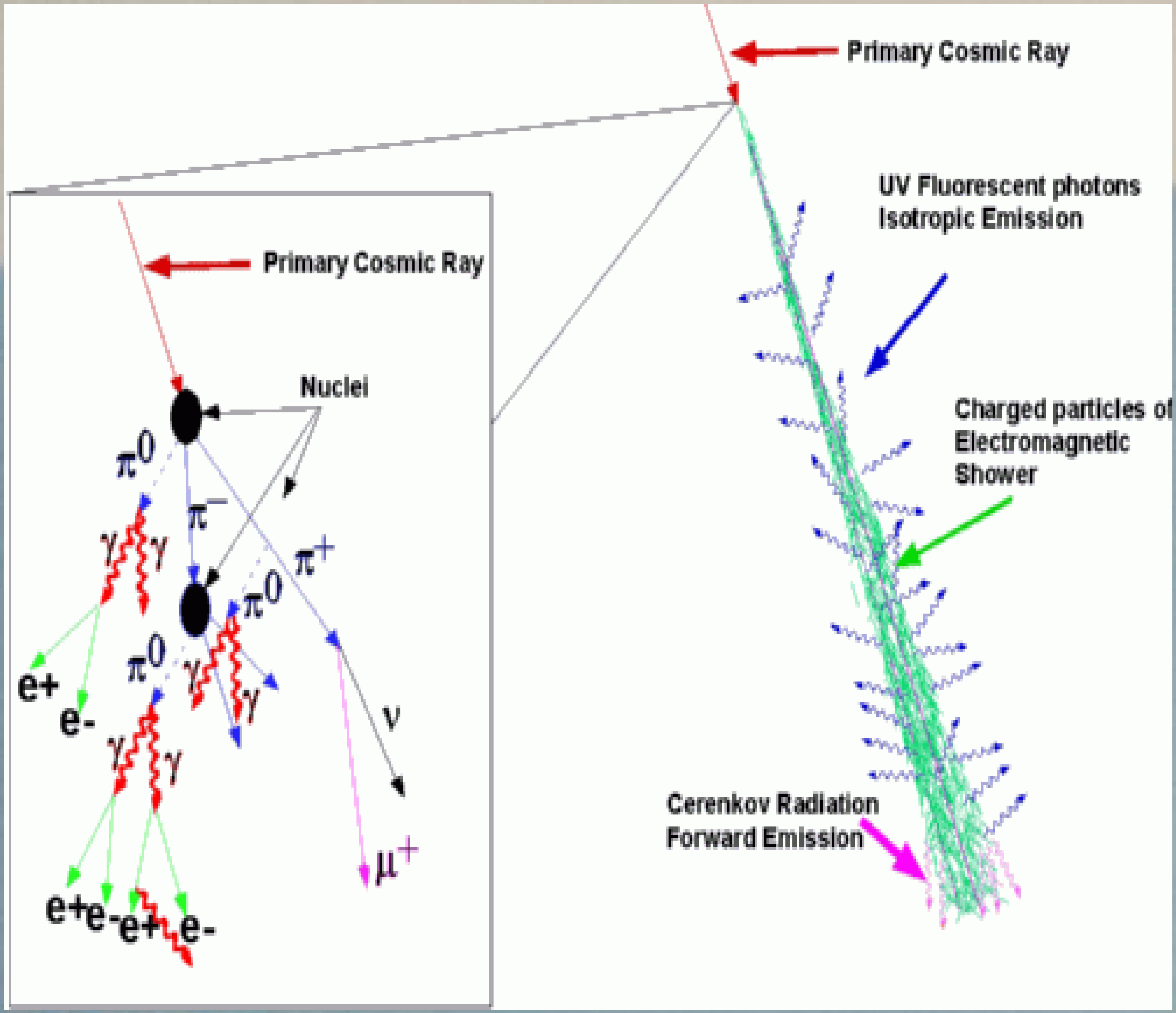
Flux Challenge: 10^{19}eV → 1/km²/ *century*...

power laws: $J \sim E^{\gamma}$

- < 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



Extensive Air Showers:



primary <u>interaction</u>:
- top of atmosphere

<u>evolution</u>:
- "pancake" propagating @ speed of light

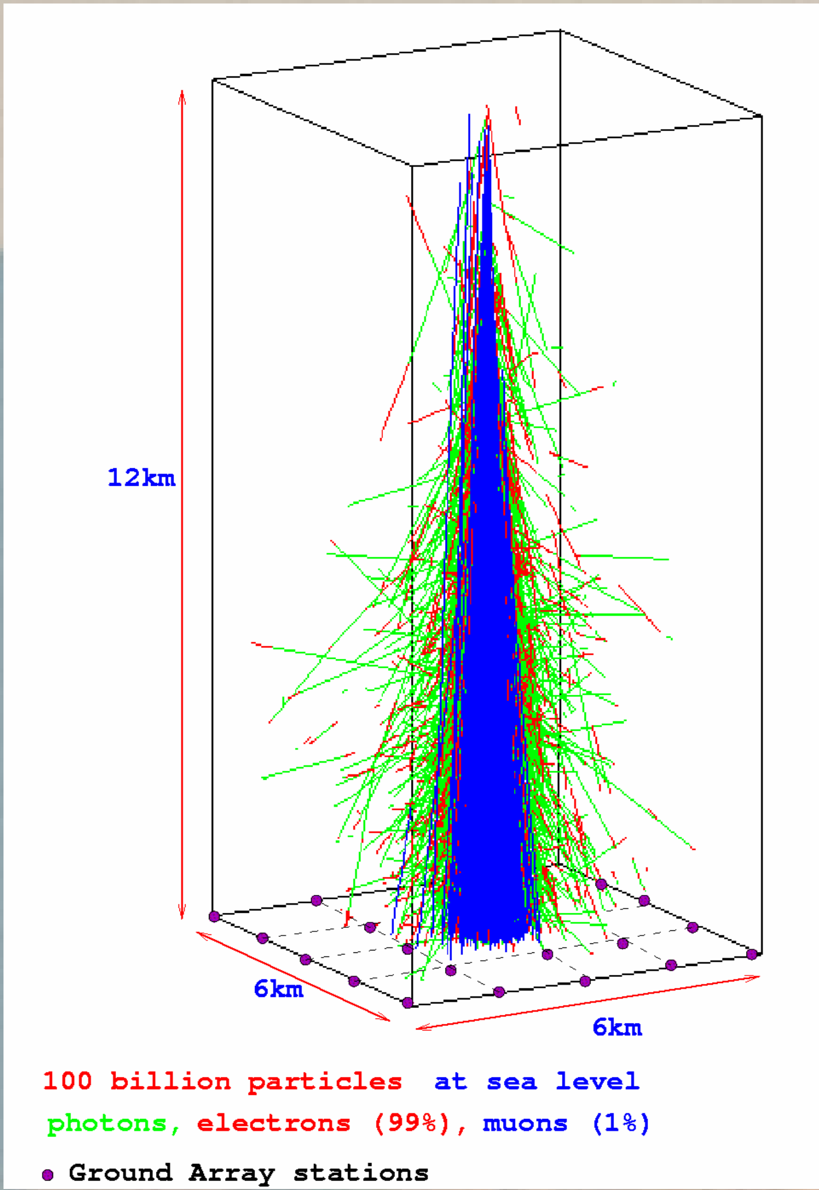
<u>description</u>:
- lateral profile
- longitudinal profile

Air Shower Dimensions

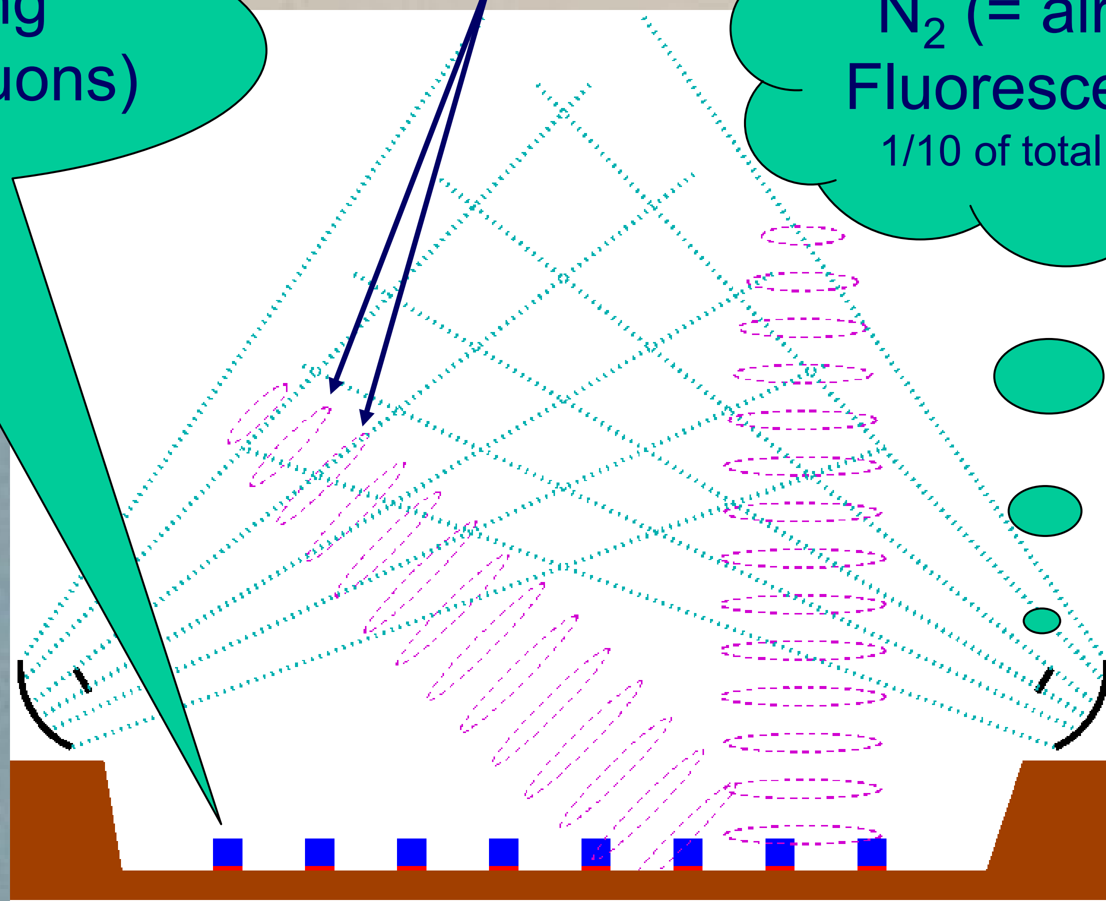
Cosmic Ray induced air showers:
- start at ~ 12 km above ground
- span up to 5 km across
- hundreds of billions of particles

Fluorescence Detector:
longitudinal profile
through atmosphere

Ground Array:
transversal profile
at ground level



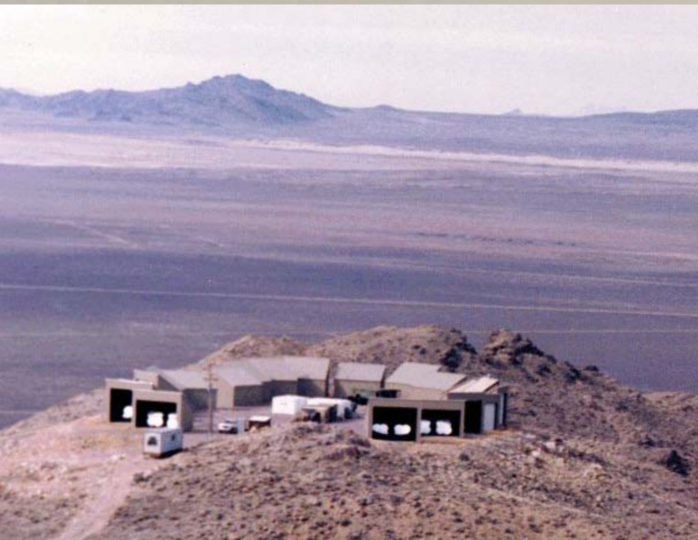
Air Shower Detection



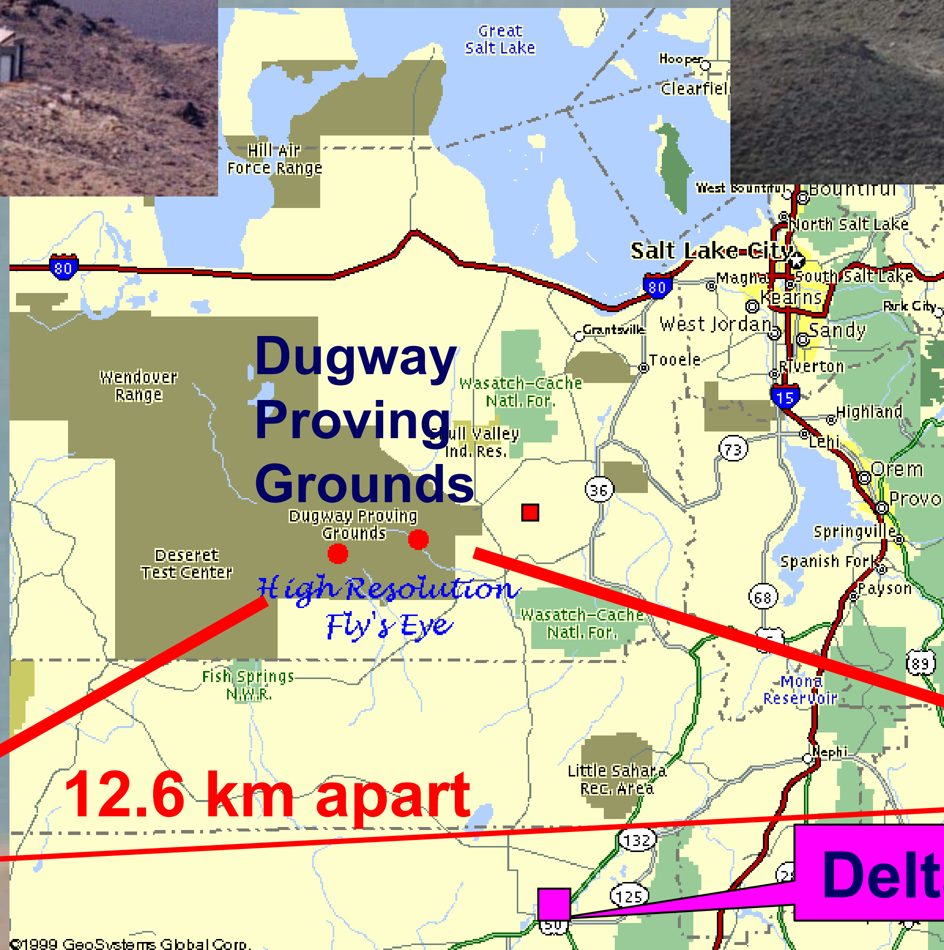
(underground: muon detection…)

Find:
- energy
- arrival direction
- chemical composition (of primary CR particle)

The HiRes Experiment:



HiRes on DPG:



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

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

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

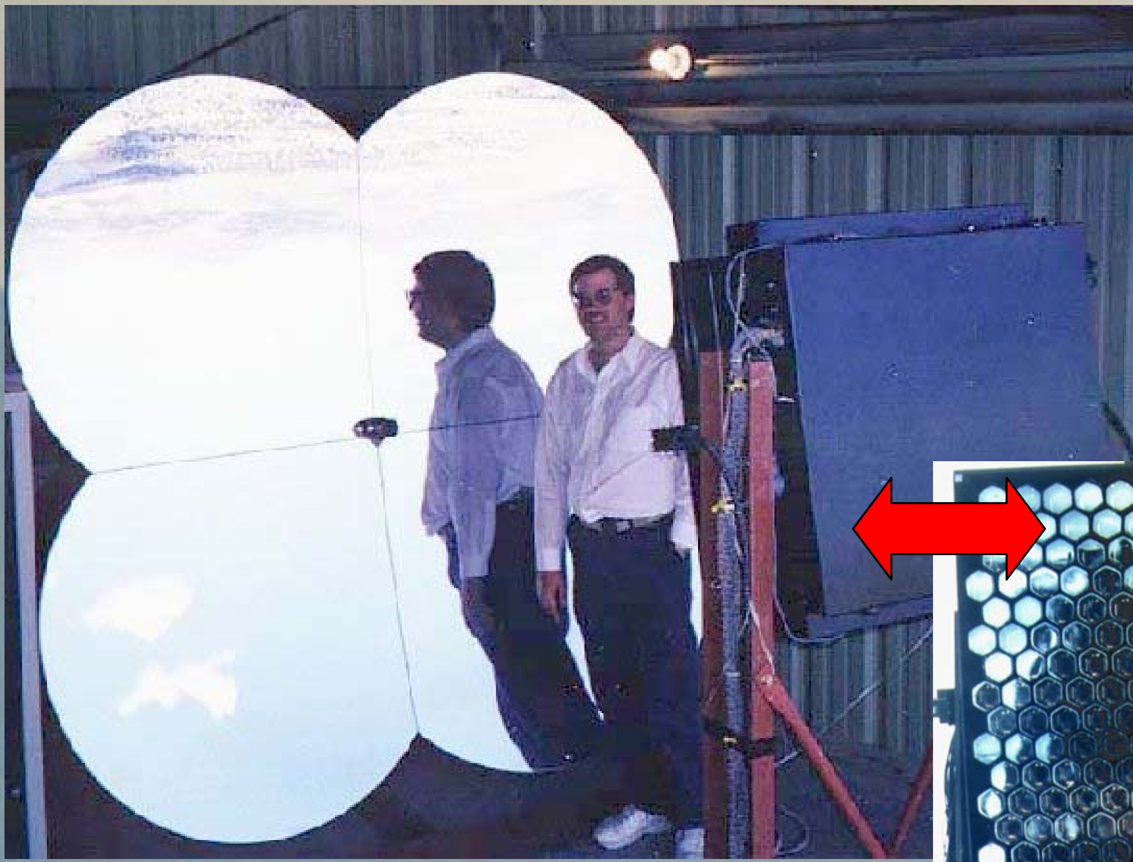
N. Manago, M. Sasaki
University of Tokyo

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

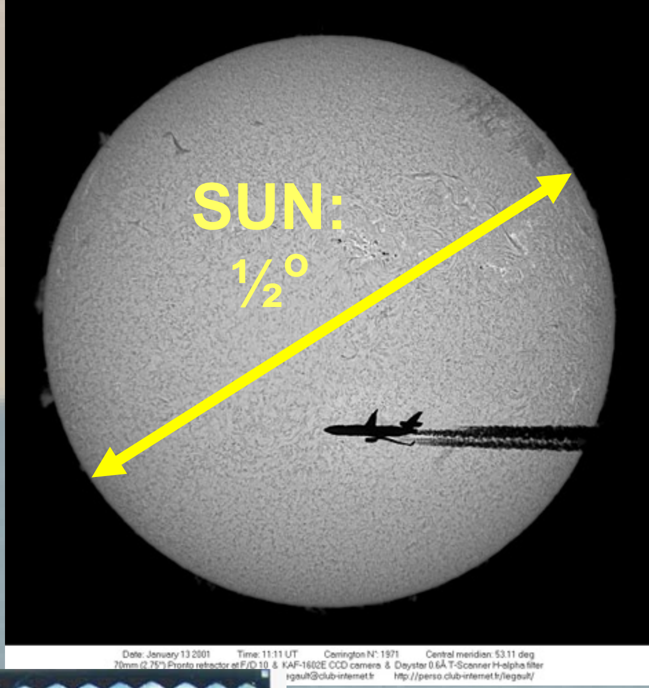
Z. Cao, B. Zhang, Y. Zhang, Y. Yang
IHEP Bejing

HiRes Optics:

low resolution
high speed



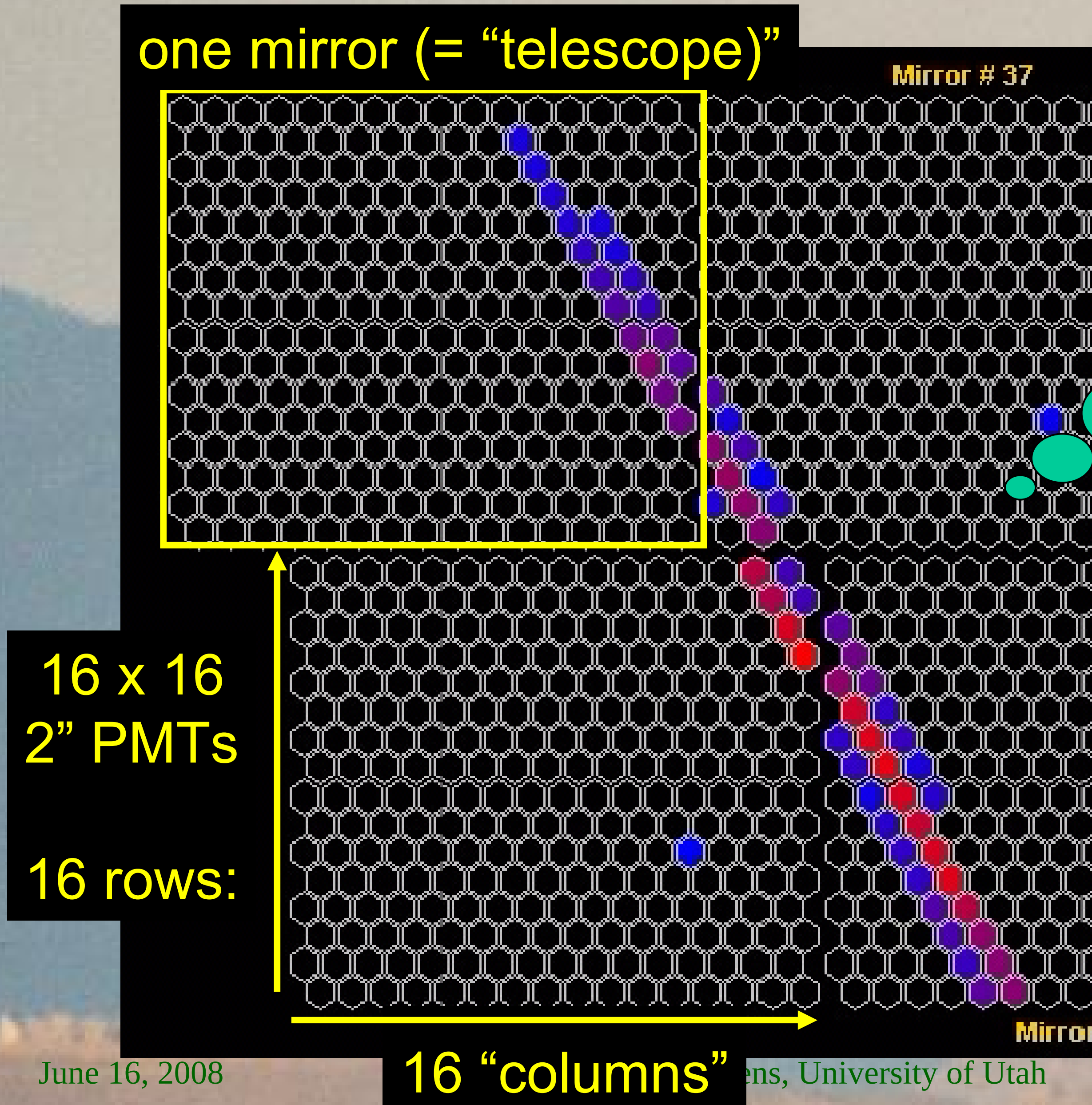
Mirror surface 5.1 m^2
Field of view: 16° x 14°

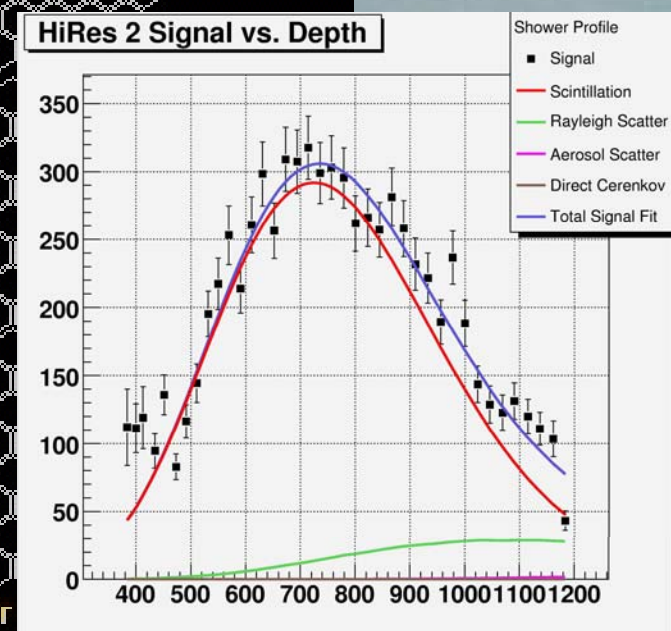


Camera:
16 x 16
PMT
each sees
1° x 1°
in sky

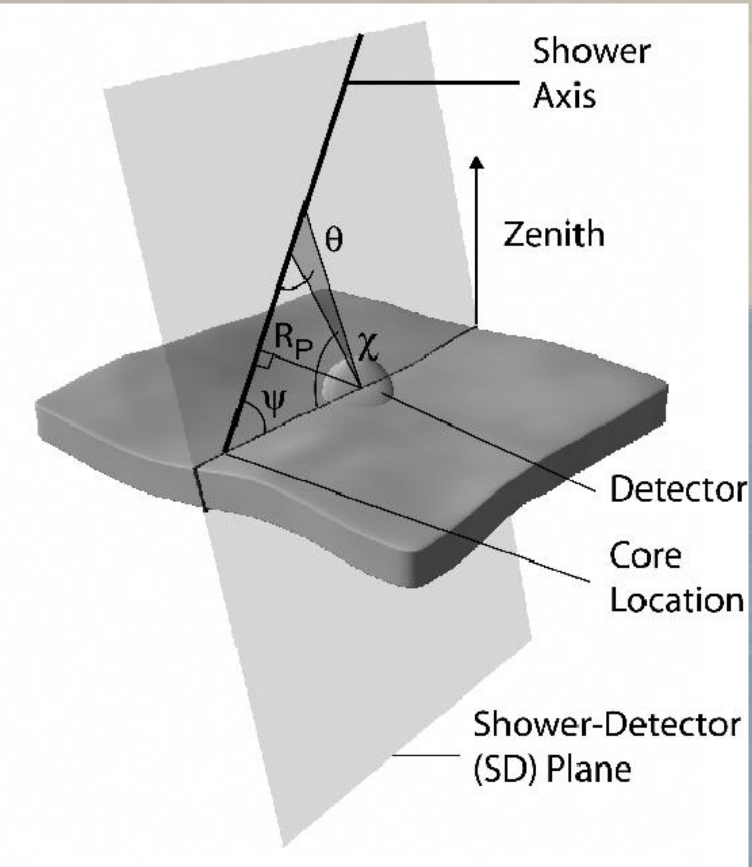
UV filter !!!
(protecting PMTs)

Fluorescence Light Curve: Energy!

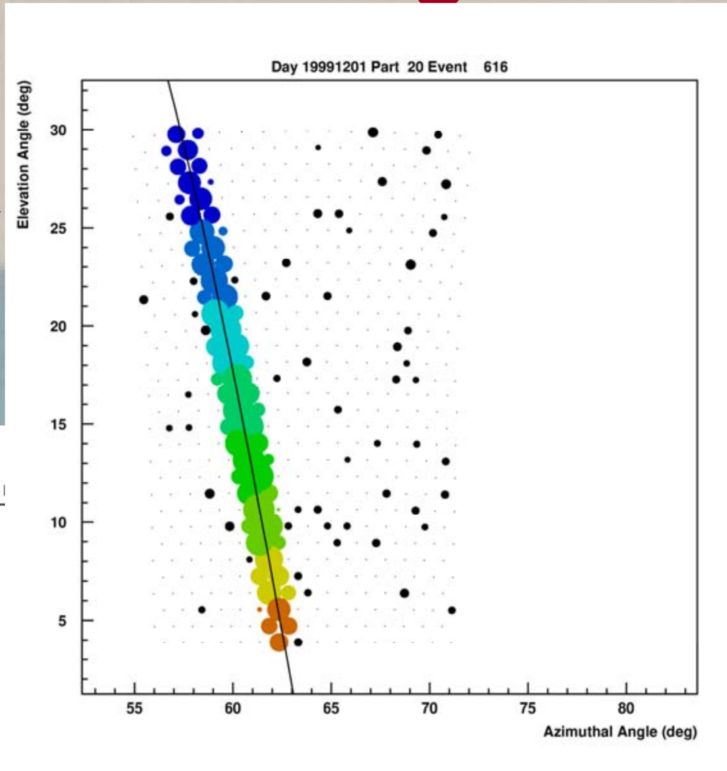




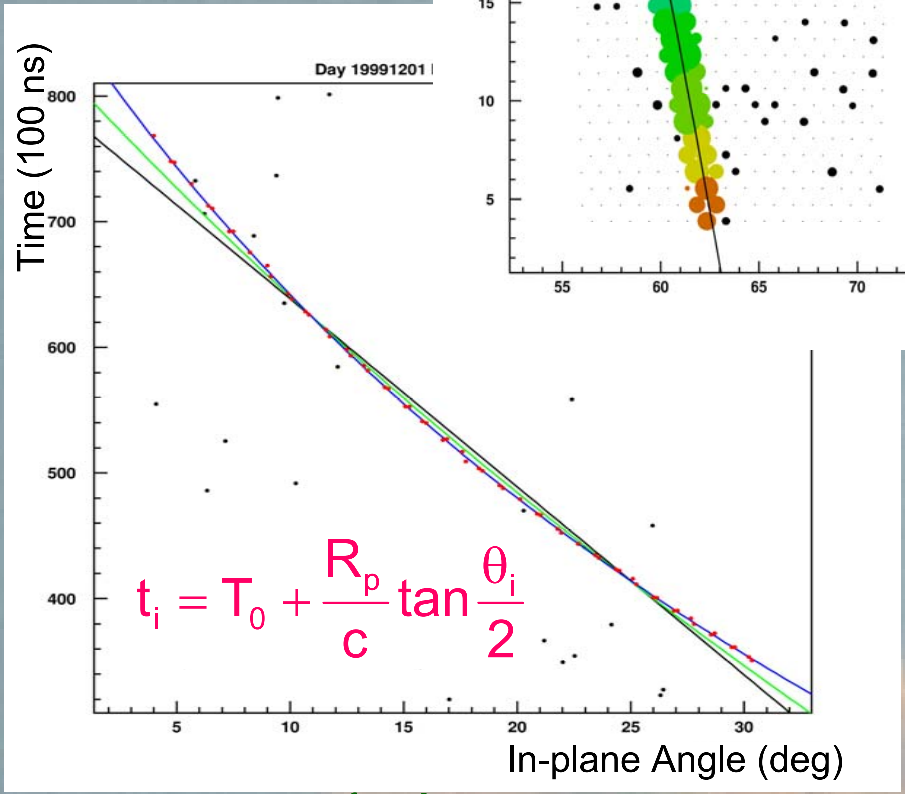
Mono Reconstruction Challenge:



Shower
Detector
Plane fit →

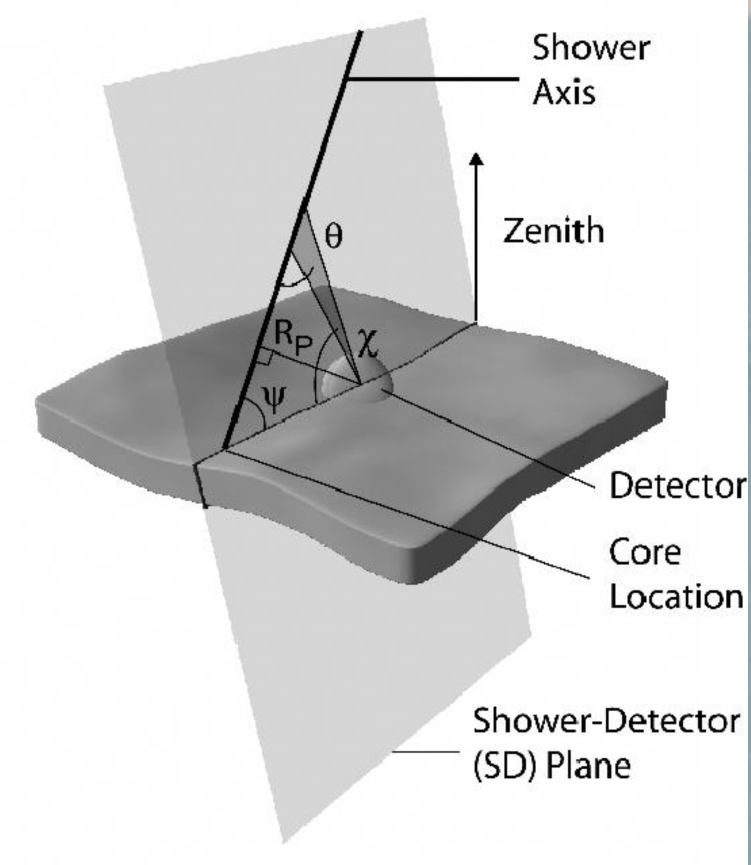


Timing fit <u>in SDP</u> →

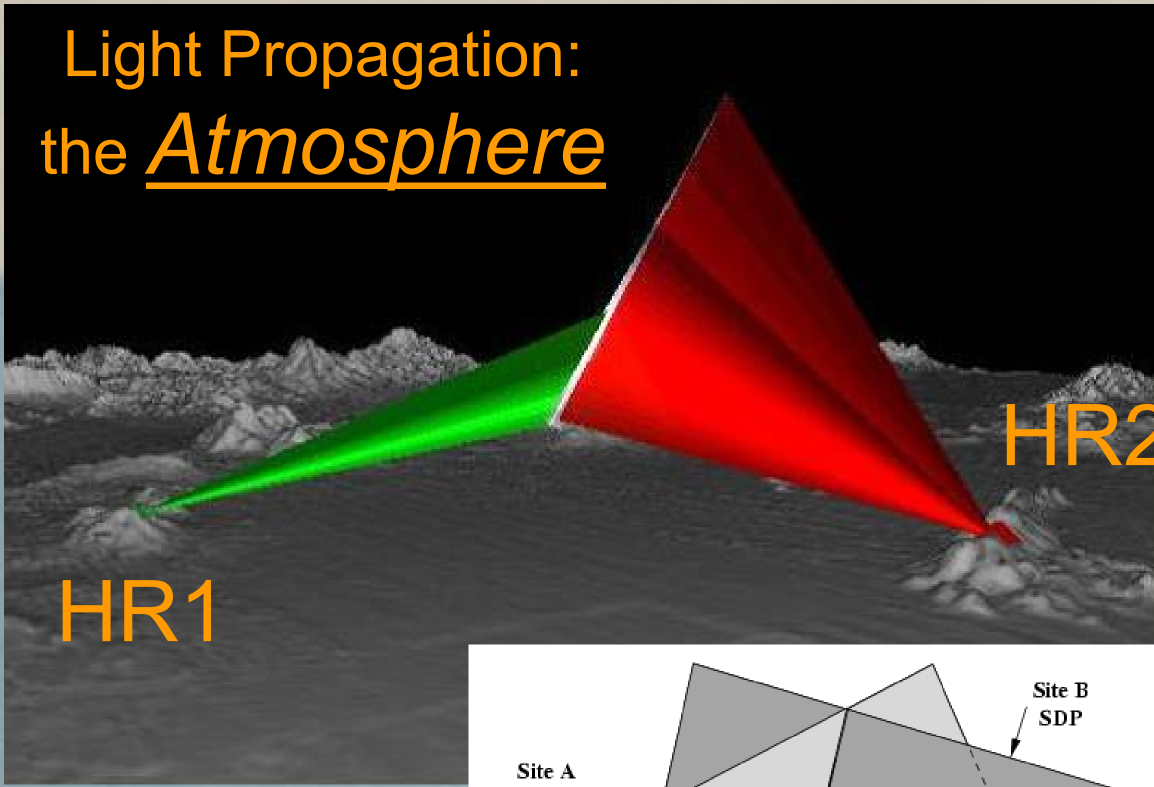


HiRes: Stereo!!!

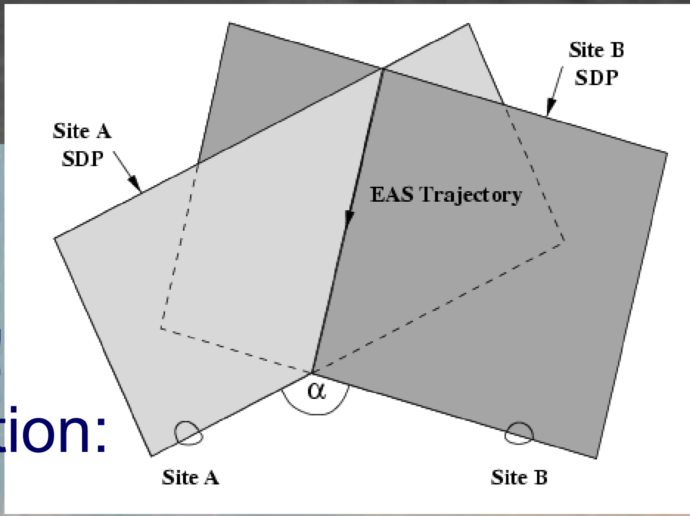
HR1: 6/1997 ← **MONO**
also: close by → **MONO**:
HR2: 12/1999 ← low E



Light Propagation:
the ***Atmosphere***



STEREO:
- cross checks!!!
- angular resolution:



The Atmosphere:

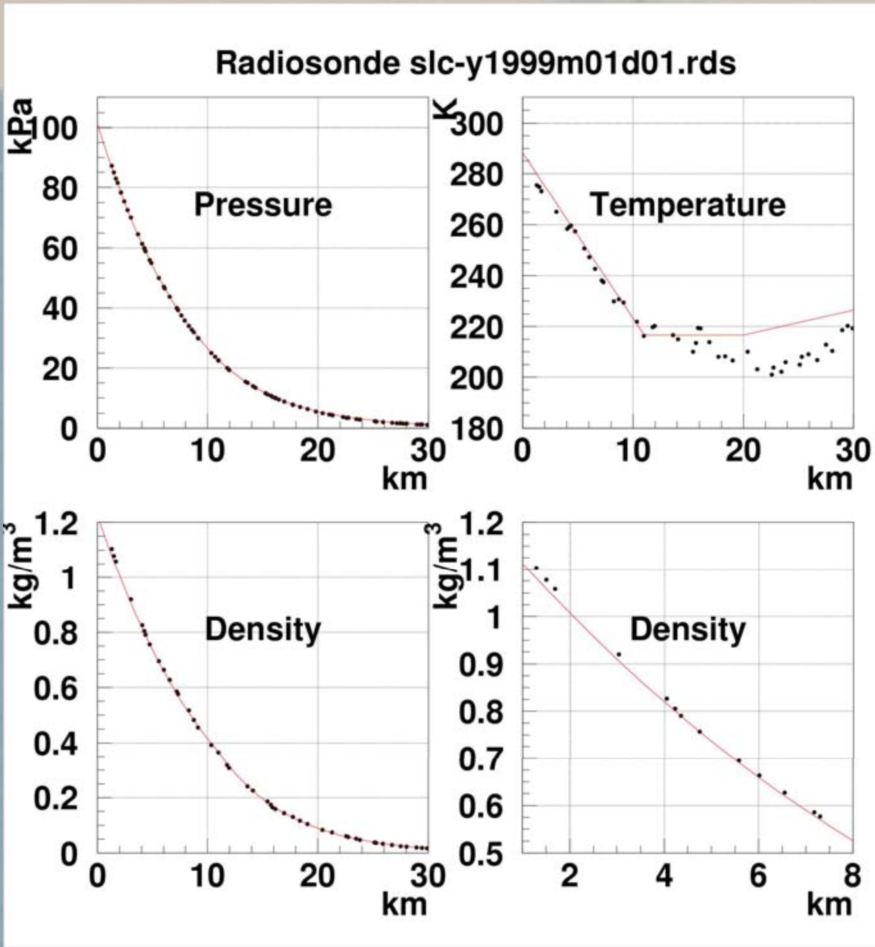
Affecting propagation:

two components:

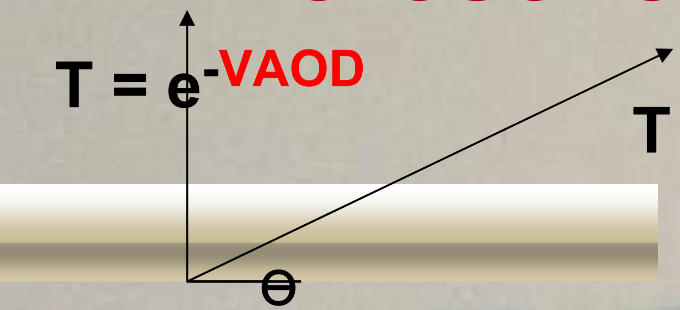
	molecular (N_2)	aerosols
scale height	~9 km	lower few km
horizontal scattering length	17.5km @350 nm	10m (fog) to infinite (molecular)
f(λ)	$\sim\lambda^{-4}$	$\sim\lambda^{-1}$
size	few x 10 nm	0.1 µm and up
scattering	Rayleigh	Mie

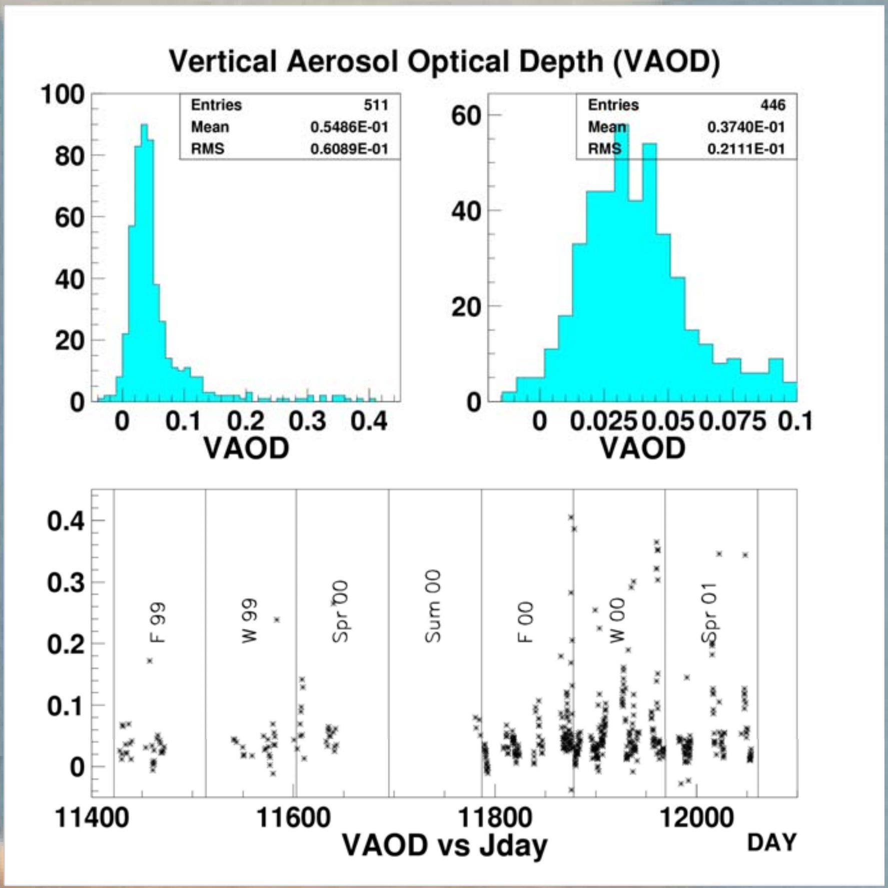
N2 fluorescence: 300nm – 400nm

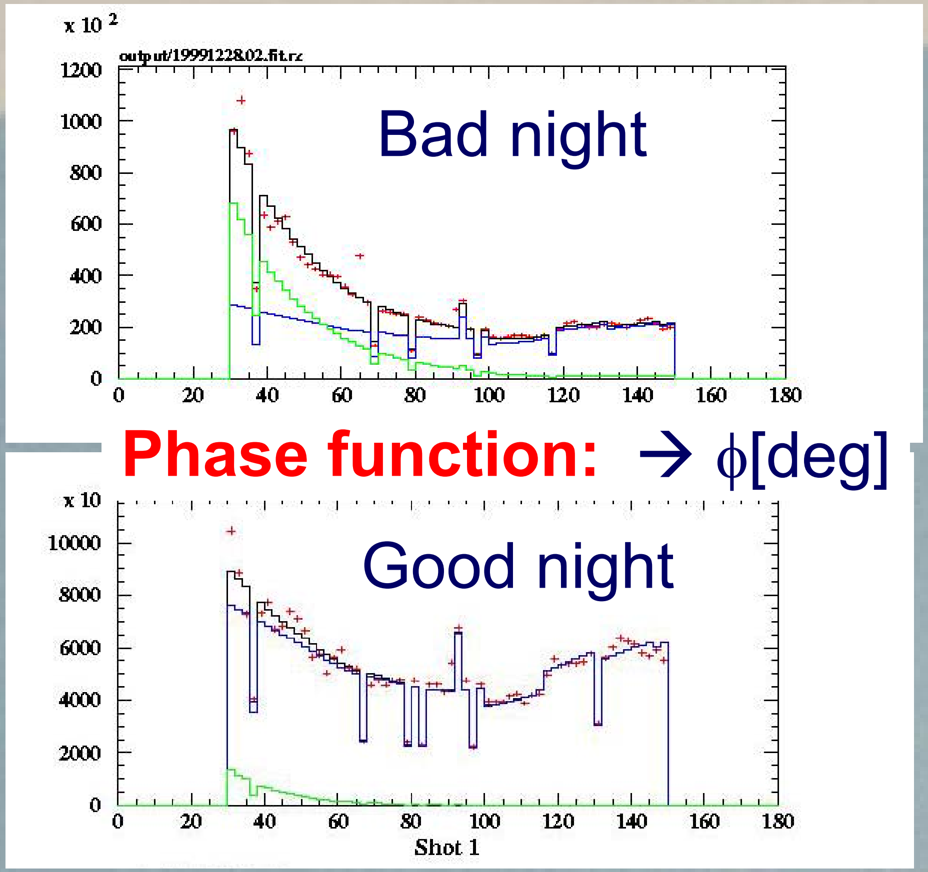
molecular component:



Aerosol Component: Variable...







Hourly Laser patterns from HR1 and HR2 @ 355 nm:

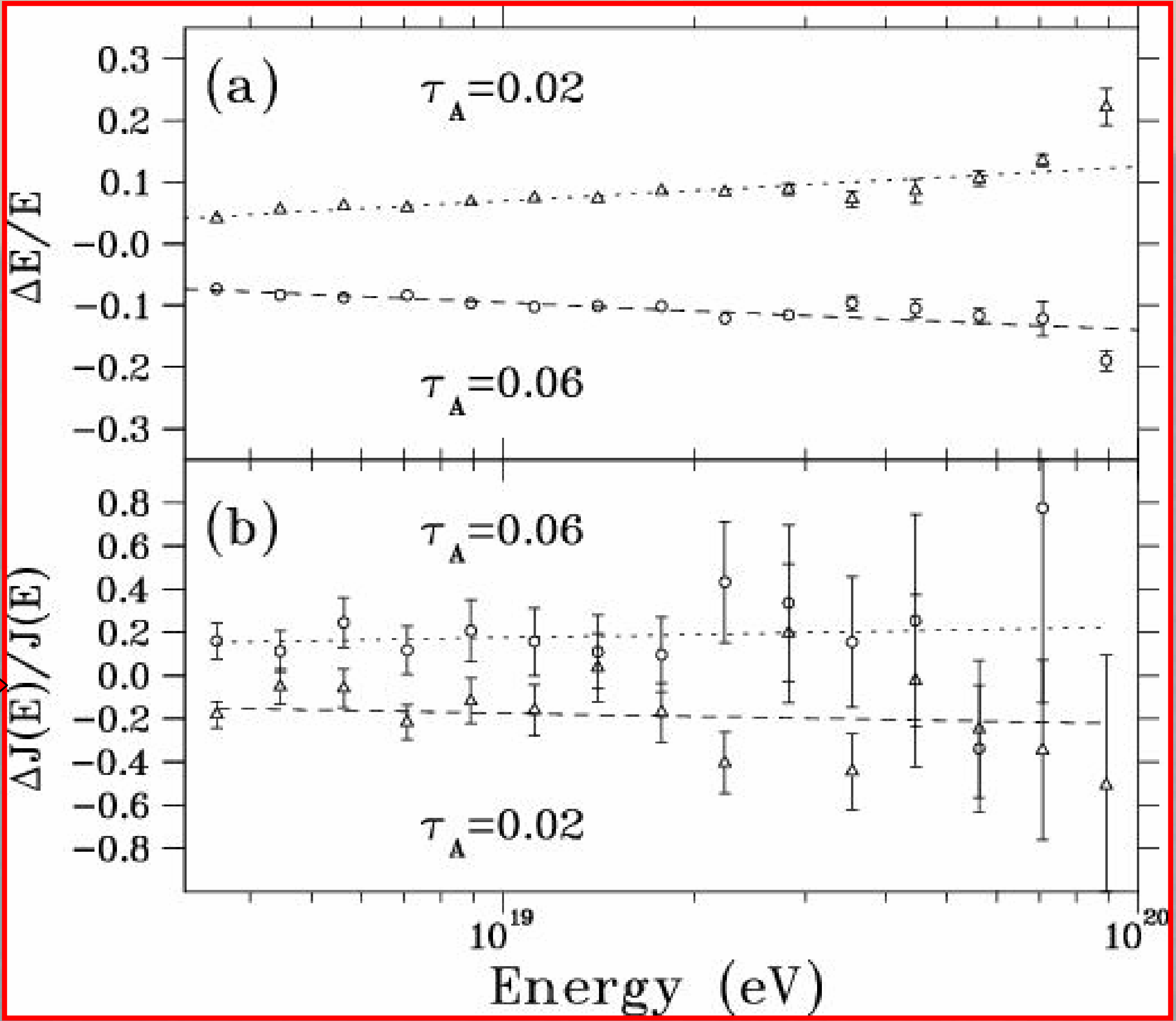
HR1 Mono → Average VAOD:

Average VAOD:
0.04 ± 0.02 (RMS)

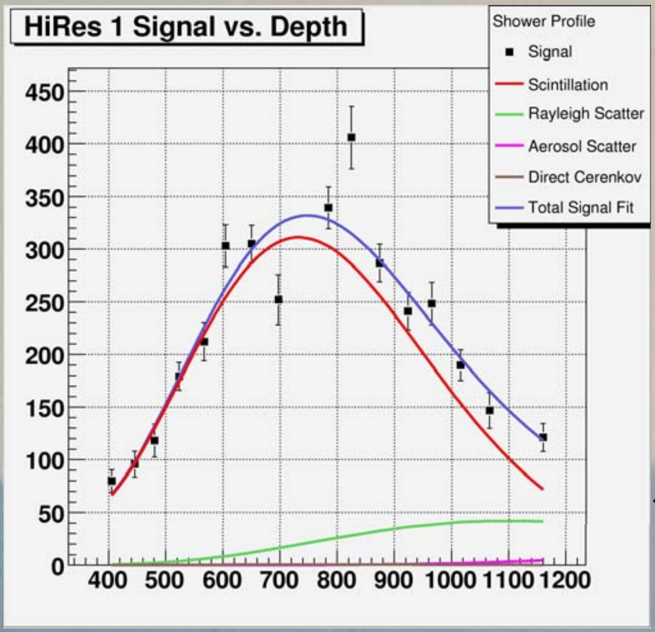
Systematics
also estimated:
± 0.02

reconstruct data:
VAOD = 0.02
VAOD = 0.06

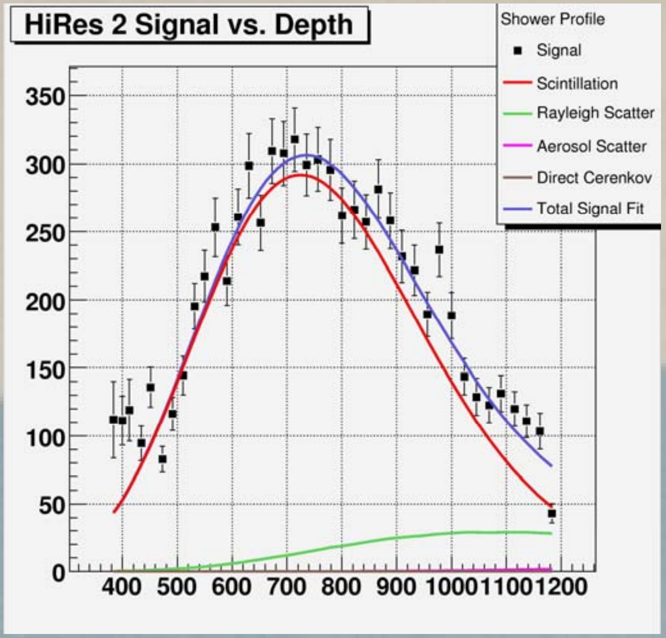
Relative to "clearest"
also okay…

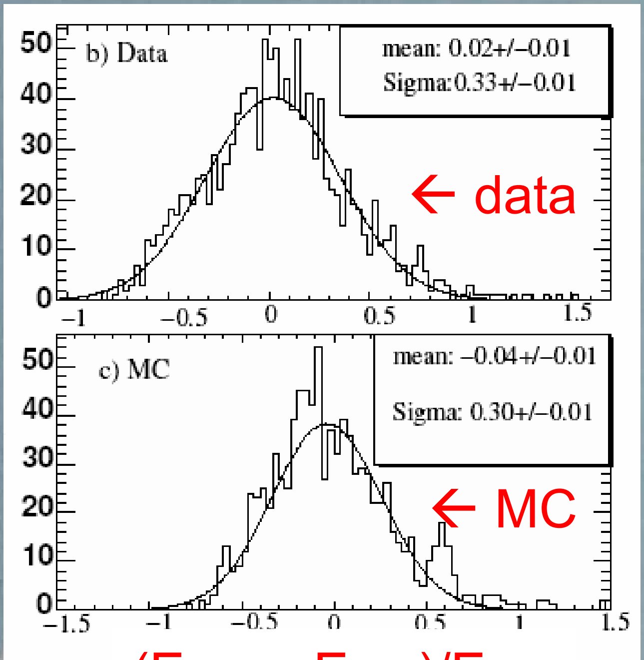


Stereo: One Shower Two Views



← **HR1** **HR2** →



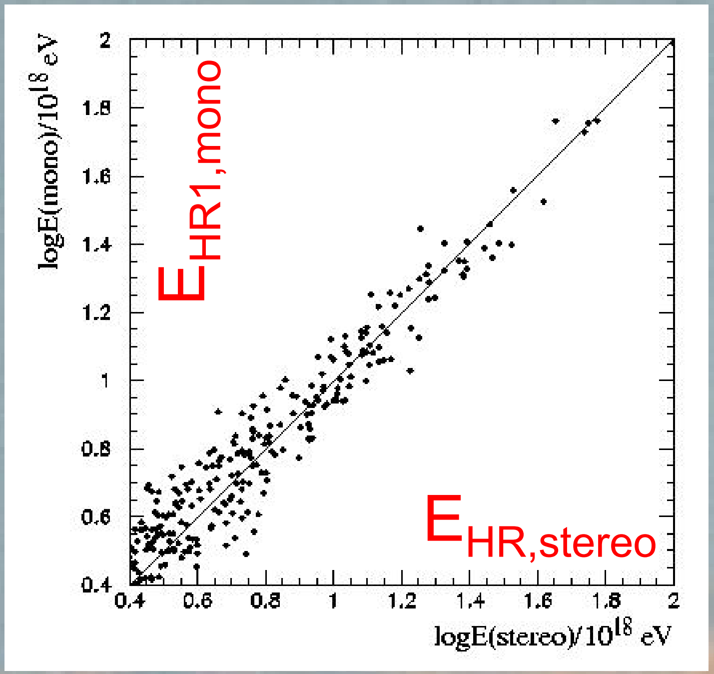


$(E_{HR1} - E_{HR2})/E_{HR2}$

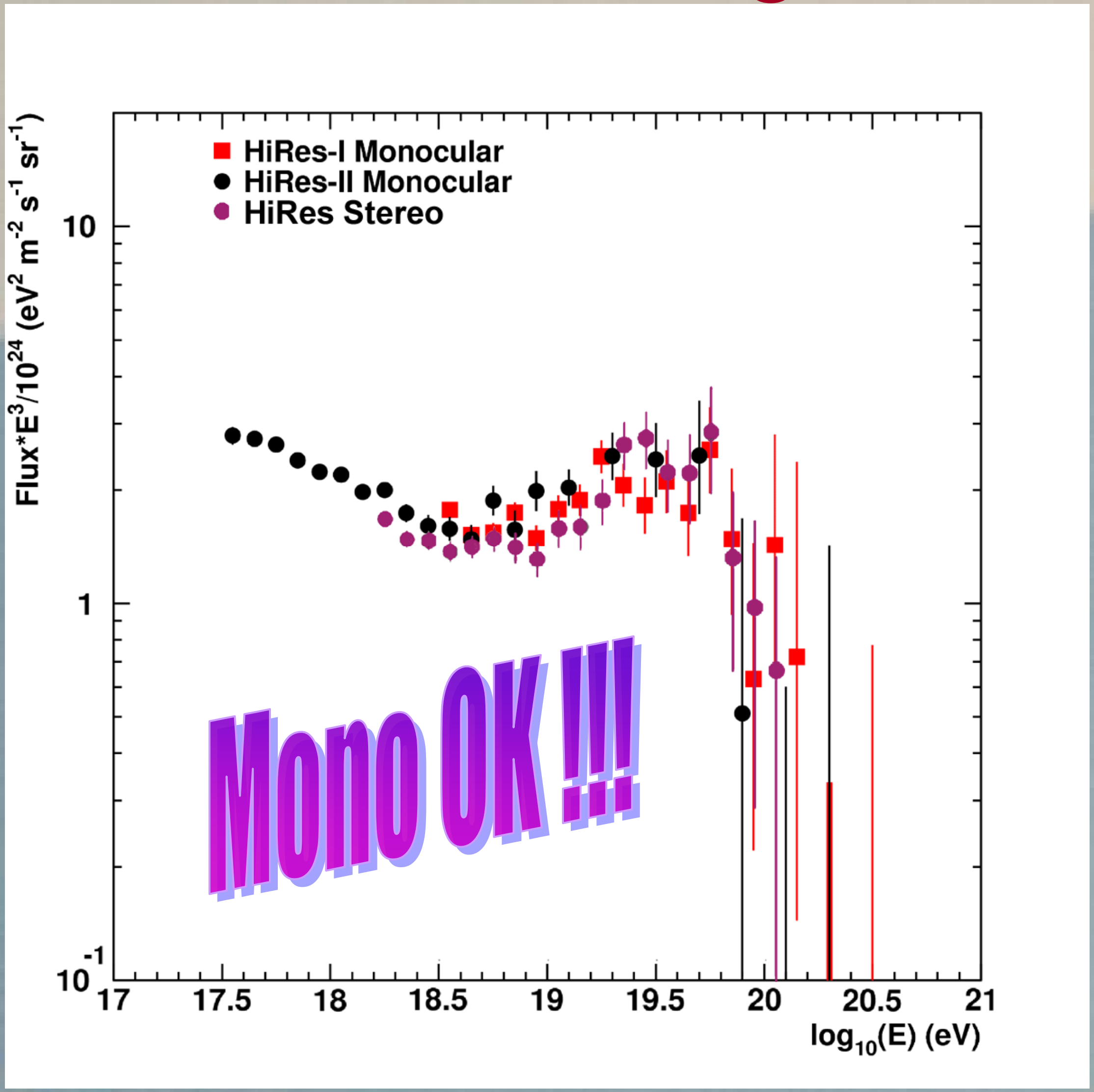
verification →
(not: calibration)

← resolution:
(understood!)

also: X_{max}



Message One:



"stereo paper": before end 2008…

HiRes: First Observation of GZK Cutoff

small (~10%) overlap between
HR1/HR2 exposures/events:
→ remove from HR1

results:

one BP to two BP:

reduction in χ^2: 27.9 (4.9σ)

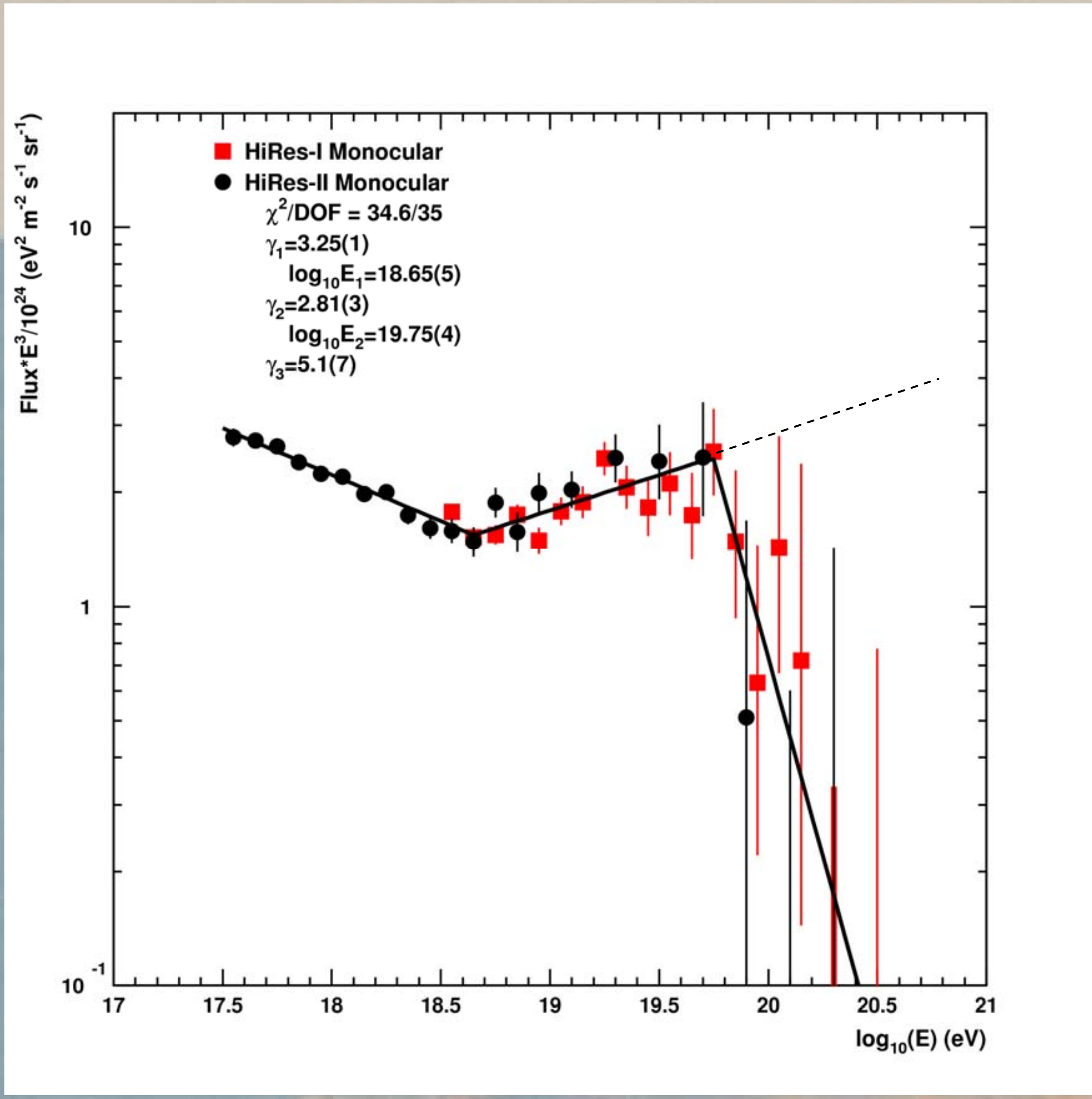
observe 13 events,

expect 43.2:

P=7.2×10^{-8} (→ **5.3 σ**)

extrapolate the integral spectrum
(from first BP): drop to ½:

$E_{½}$ @ $10^{19.73\pm0.07}$ eV
Berezinsky *et al*: → $10^{19.72}$eV



What We Don't Know:

What are they?

- GZK cutoff → protons?!
- composition measurement: statistical but supportive… (Auger… ?)

Where do they come from?

- Auger in Science: 27 events above 6×10^{19}eV:
  out to 75 Mpc, 3.1 degree circles
  → correlated with "AGN" ← marker for mass?

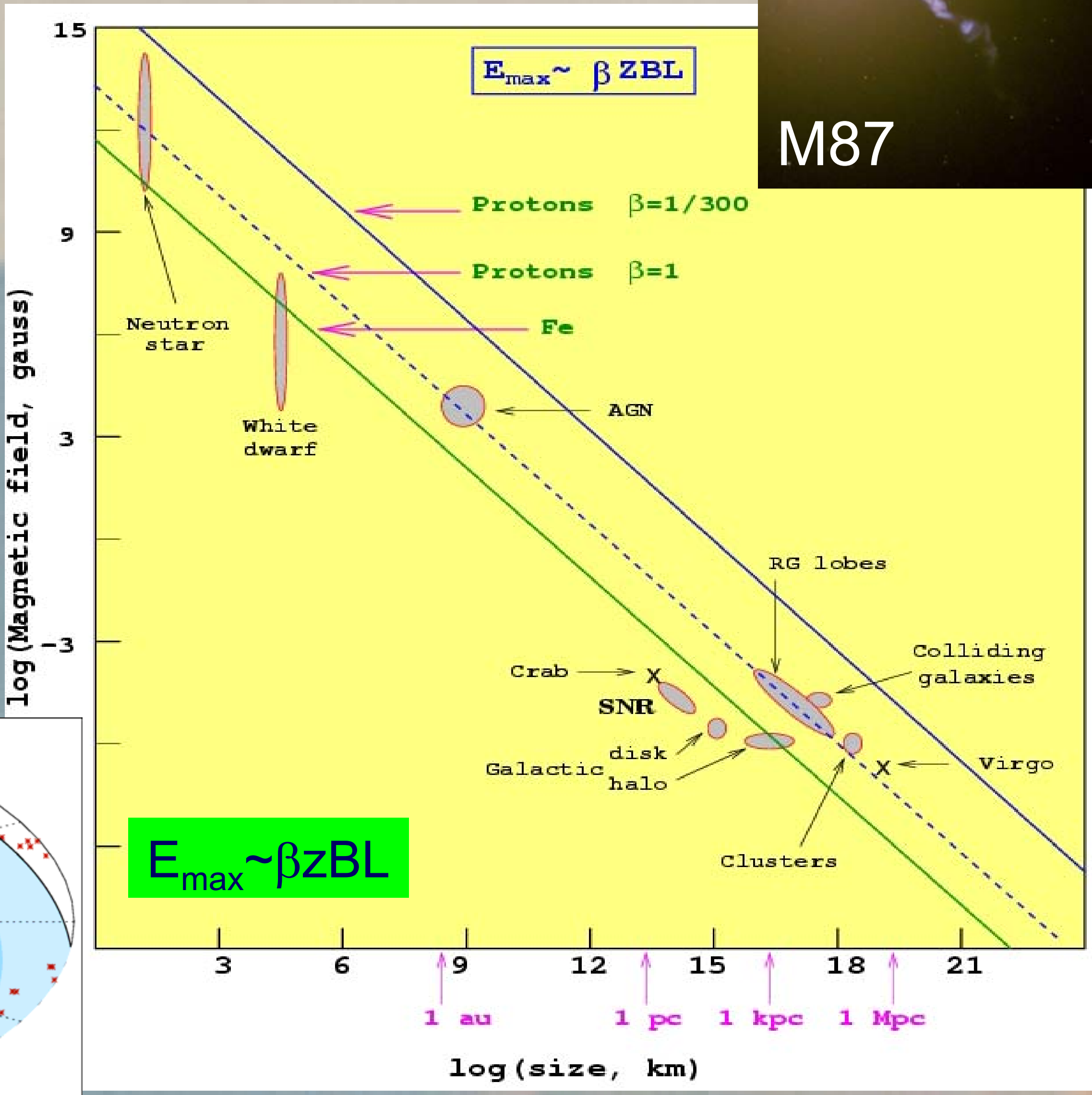
- HiRes **stereo**: 13 events above 6×10^{19}eV: isotropic…

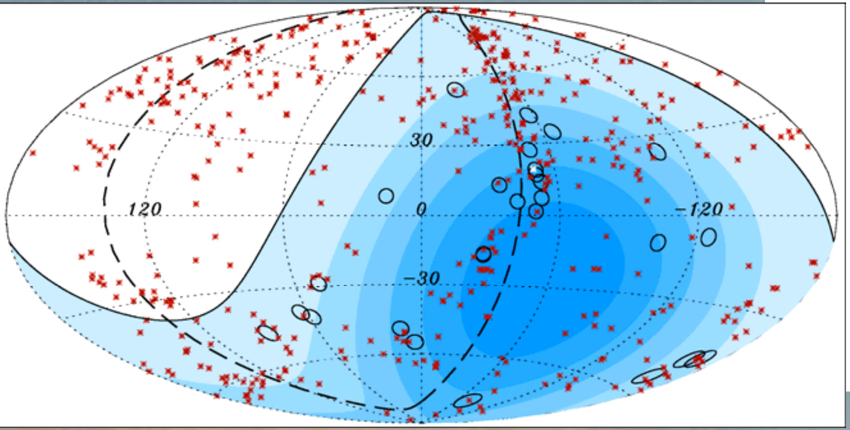
~ 10^{20}eV → intergalactic B-fields little influence on p-trajectory

Acceleration??!

GZK: top–down models
no longer "en vogue"

everybody's prejudice:
AGN → Auger:





Northern Hemisphere: HiRes Stereo

1.) apply PAO cuts ($E = E_{HR,stereo} - 10\%$)

→ (56.0EeV,3.1deg,0.018) 2/13 events, no significance

2.) apply PAO method: optimize on 1st half; apply to 2nd half

→ (15.8EeV,1.7deg,0.020): 14/101 events, no significance

3.) Finley/Westerhoff: all HR stereo → optimum:

E > 15.8 EeV,

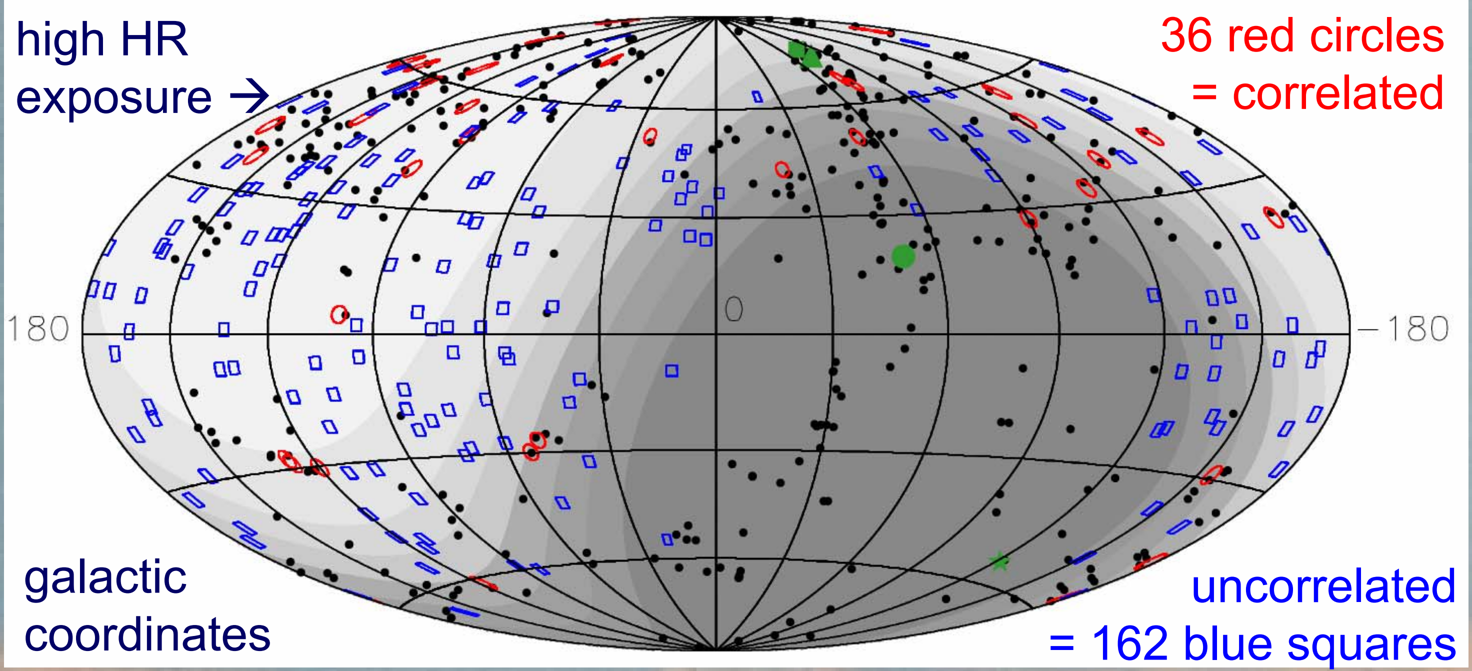
2.0 degree

z < 0.016,

→ 36/198

→ P=0.24…

HR & AGN: no significant correlation…



Northern Hemisphere: BL Lac History

Magnitude	Redshift	6cm Radio Flux	# Obj.	CR Sample	# CRs	Bin Size	# Pairs	Prob.
Catalog: Veron (9th Ed.) BL Lacs			22	AGASA >48 EeV Yakutsk >24 EeV	65	2.5°	8	$< 10^{-4}$
m < 18	z > 0.1 or unknown	S_{6cm} > 0.17 Jy		HiRes > 24 EeV	66	2.5°	0	1.00
Catalog: Veron (10th Ed.) BL Lacs correlated with EGRET sources			14	AGASA >48 EeV Yakutsk >24 EeV	65	2.9°	8	10^{-4}
no cut	no cut	no cut		HiRes > 24 EeV	66	2.9°	1	.70
Catalog: Veron (10th Ed.) BL Lacs			156	AGASA > 40 EeV	57	2.5°	12	.02
m < 18	no cut	no cut		HiRes > 40 EeV	27	2.5°	2	.78

Tinyakov & Tkachev, JETP 74 (2001) 445.
Tinyakov and Tkachev, Astropart. Phys. 18 (2002) 165.
Gorbunov et al., ApJ 577 (2002) L93.

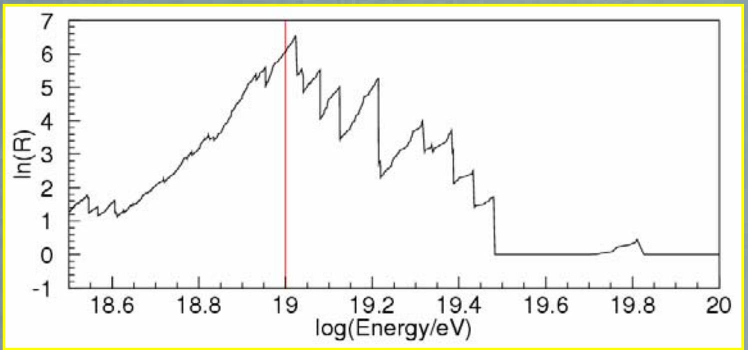
unknown: trial factors ???

Northern Hemisphere → BL Lac ???

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

Magnitude	Redshift	6cm Radio Flux	# Obj.	CR Sample	# CRs	Bin Size	# Pairs	Prob.
Catalog: Veron (10th Ed.) BL Lacs			156	HiRes > 10 EeV	271	0.8°	10	10^{-3}
m < 18	no cut	no cut		Need to test with new data				

10 EeV optimal for BL:



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

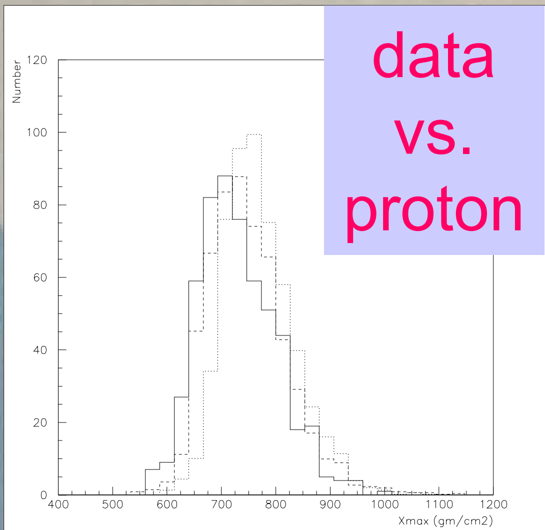
Confirmed BL Lacs		HiRes Events			
		< 10 EeV		> 10 EeV	
Mag.	Class	n_s	*F*	n_s	*F*
m<18	"BL" (157)	22	6×10^{-3}	8	2×10^{-4}
	"HP" (47)	0	0.7	3	6×10^{-3}
m≥18	"BL" (193)	0	0.7	0	0.4
	"HP" (21)	0	0.7	0	0.8

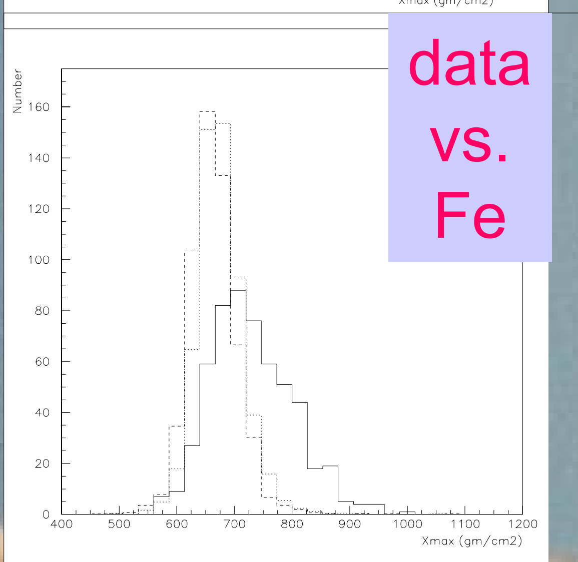
significant (or not) ???

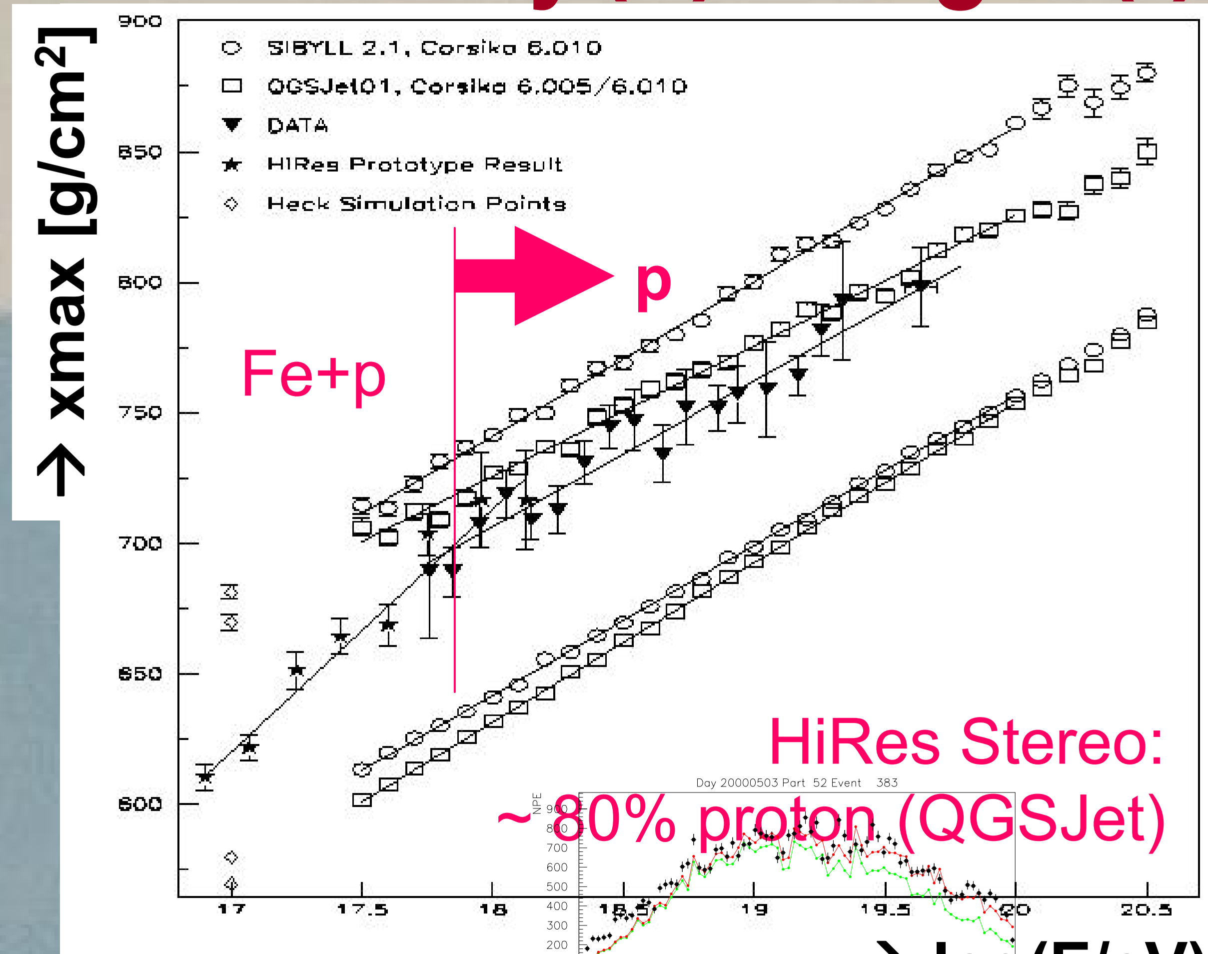
F: fraction of MC sets with larger correlation
n_s: number of events from source

HiRes Composition: Heavy (Fe) to Light (H)

X_{max} distributions:

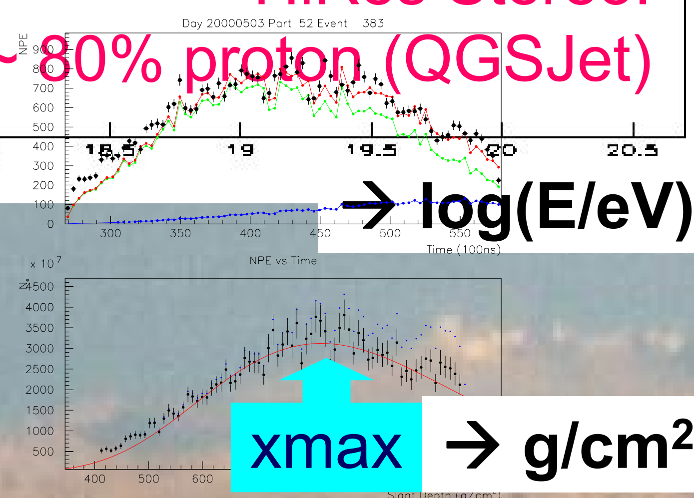




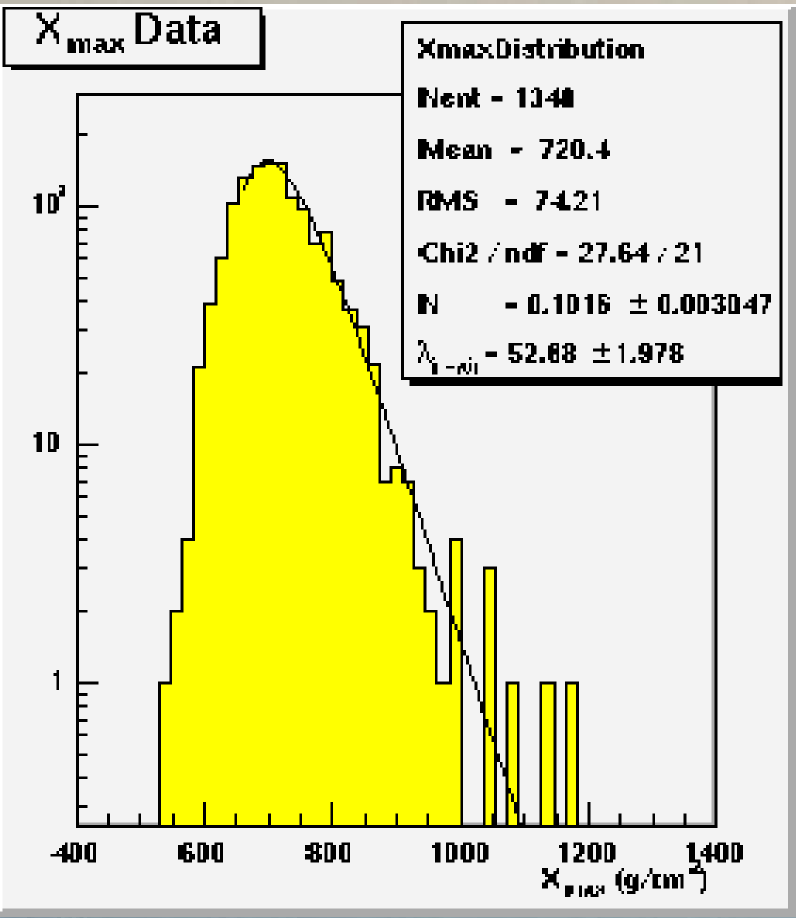


fluorescence profile:

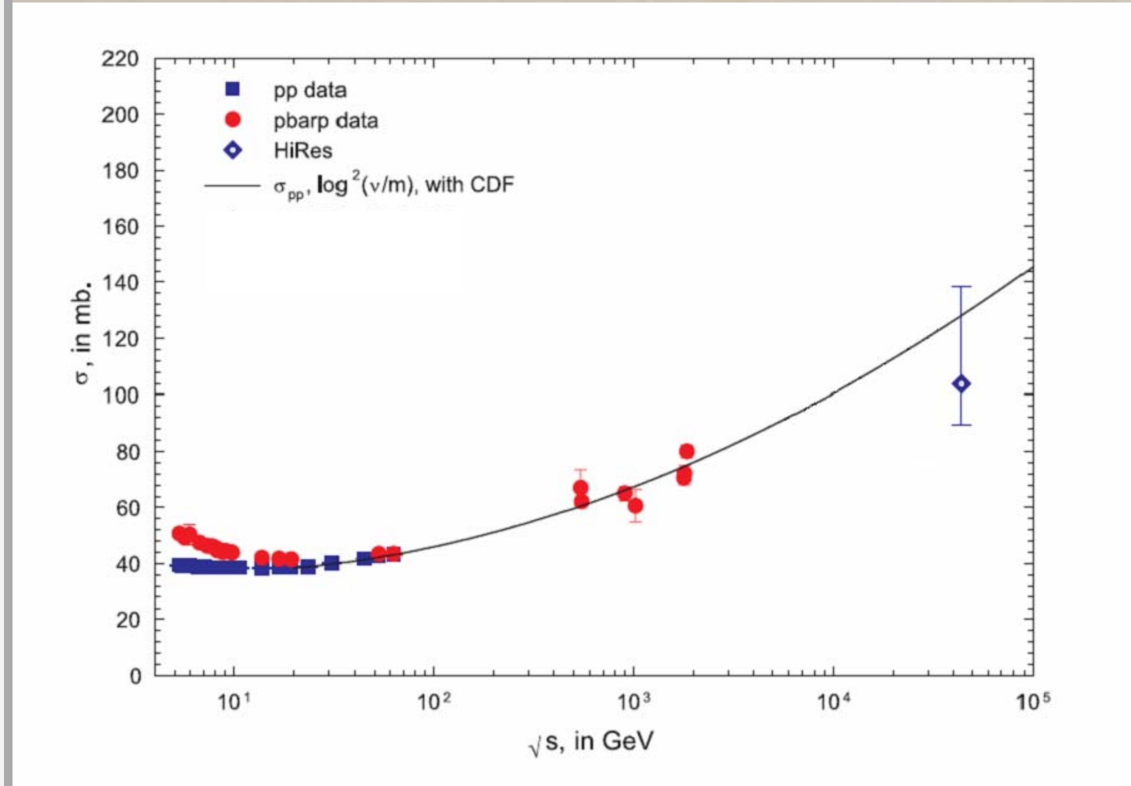
depth of shower maximum



HR: Fixed Target Experiment @ 3×10^{18}eV

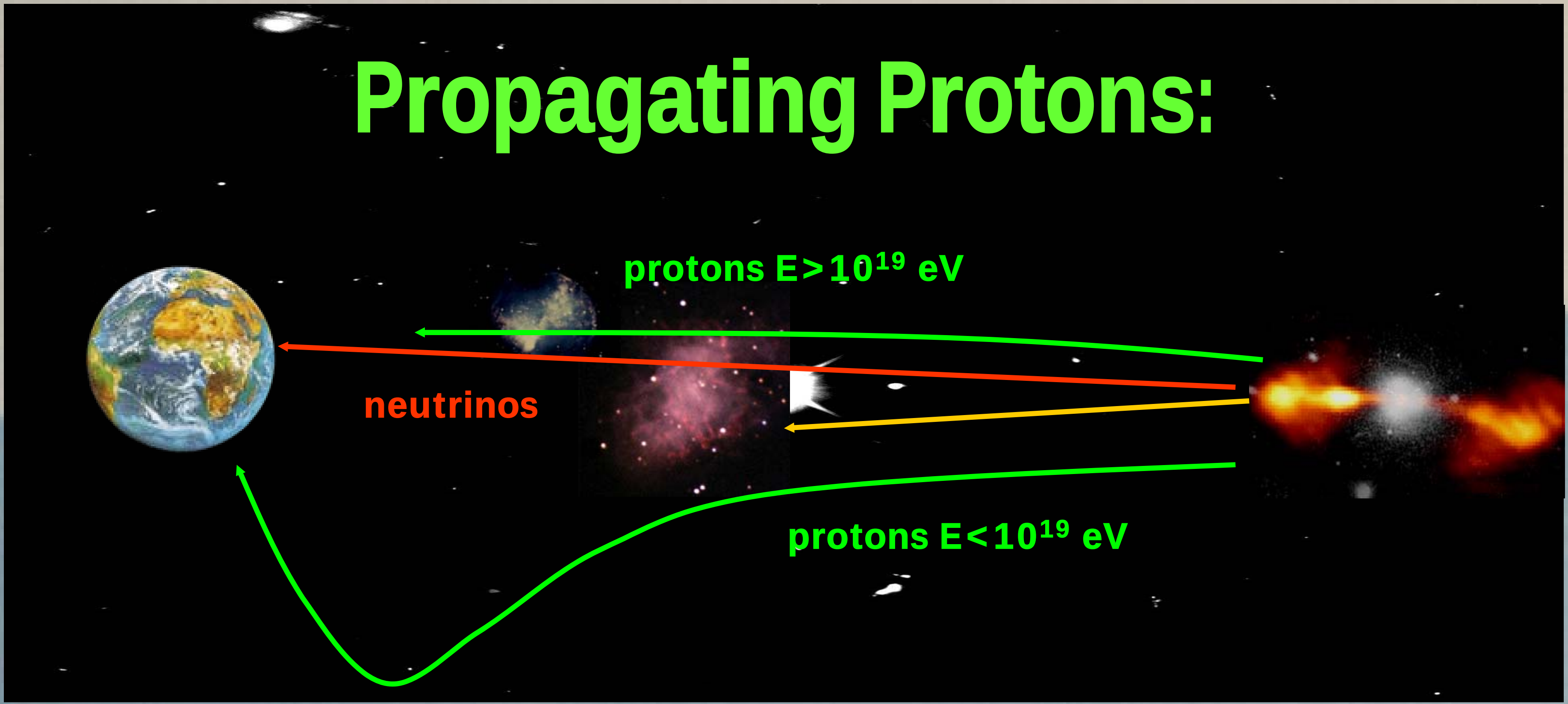


(using proton enriched sample!)



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

Propagating Protons:



<u>propagation:</u>

Hubble expansion

CMB:

- $p+\gamma \rightarrow p+e^{+}+e^{-}$
- $p+\gamma \rightarrow \Delta^{+} \rightarrow N+\pi$ ← ν_μ,ν_e,γ

↑ (ν_e)

<u>source model:</u>

injection spectrum: E^{γ}

source distribution:

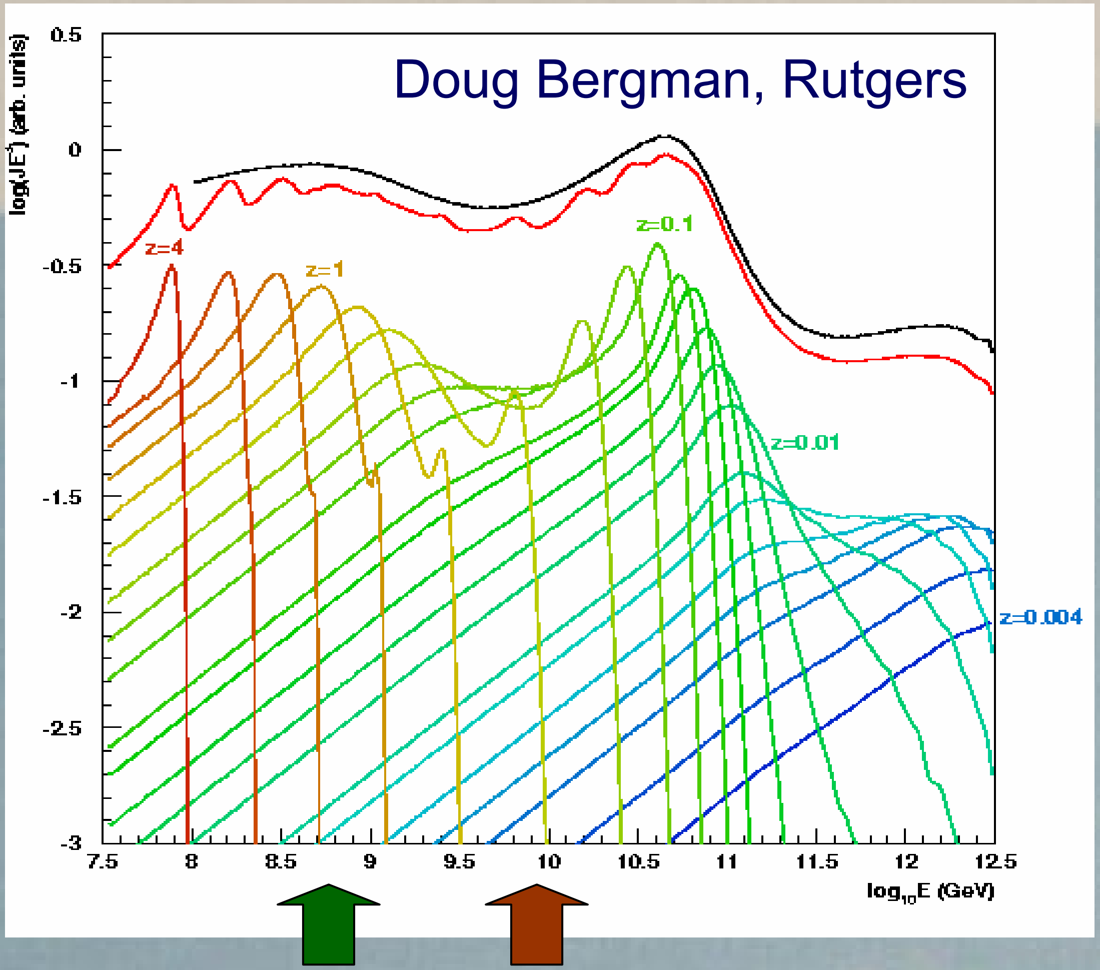
range: $0 < z < 4$

evolution: $\sim (1+z)^{m}$

Berezinsky: New Interpretation of Ankle

Fit interprets spectrum in terms of **extragalactic protons** that traveled from **cosmological sources**

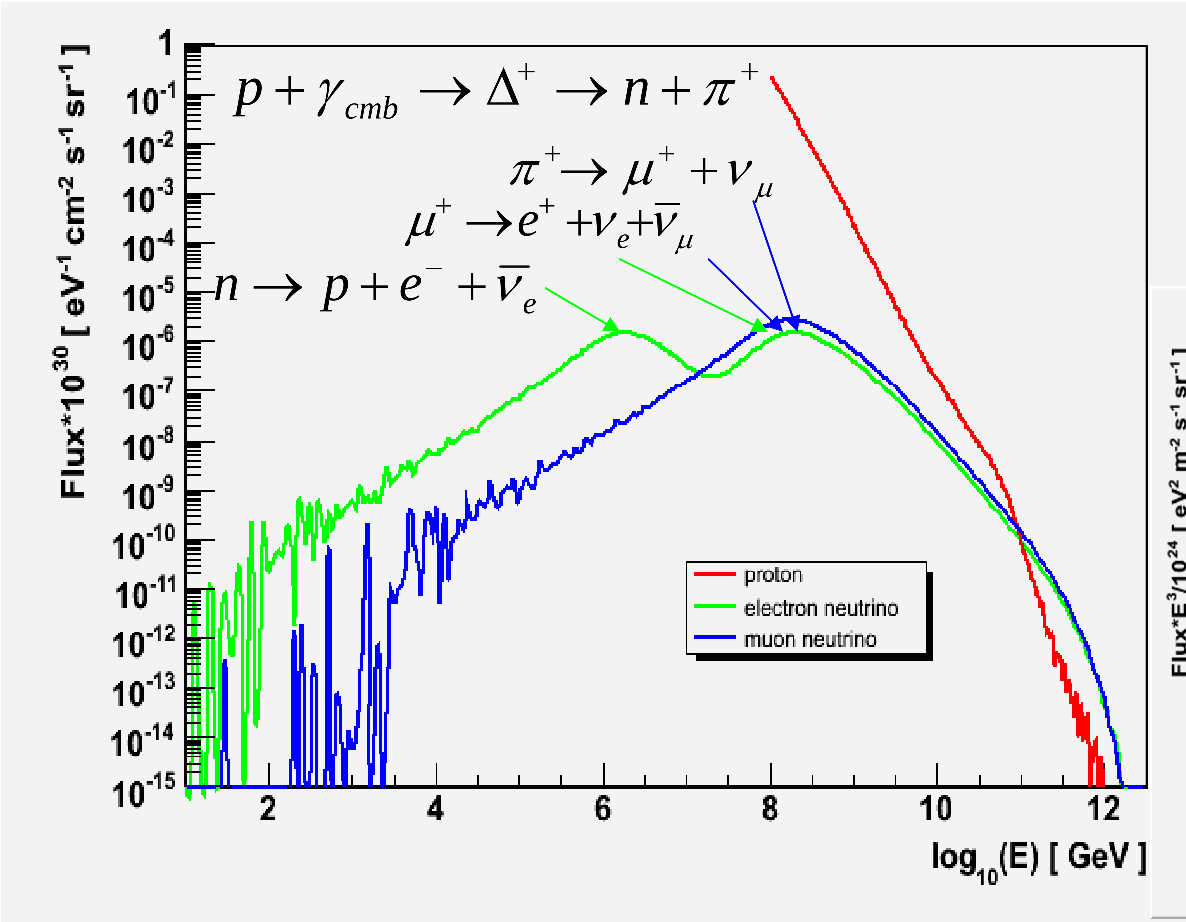
changed interpretation of ankle:

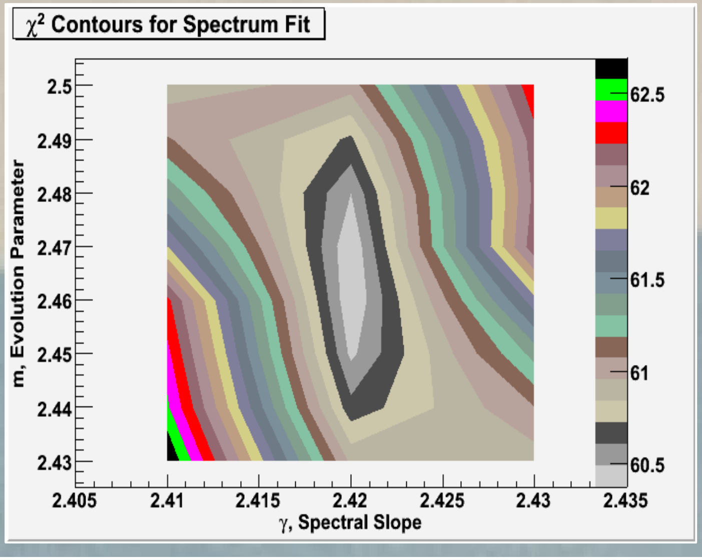


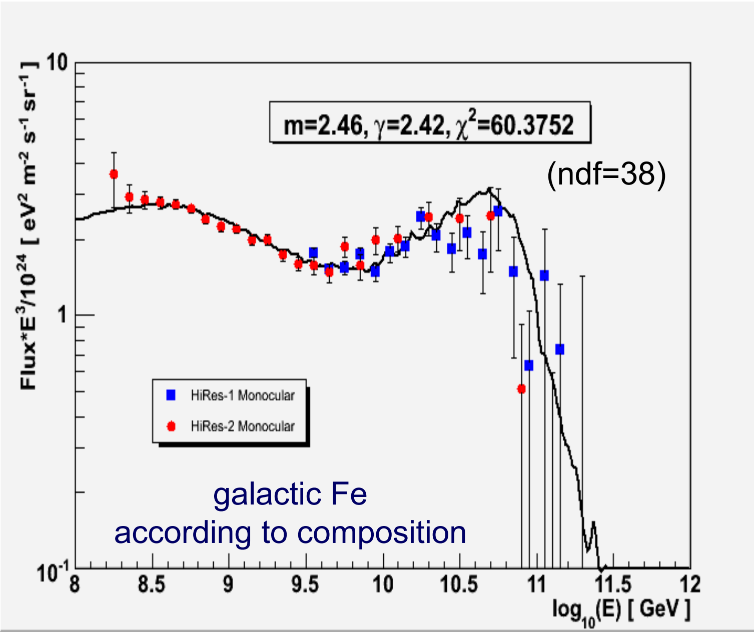
galactic/extragalactic transition: composition change vs. slope change

Cosmogenic Neutrino Fluxes from HiRes Mono Spectra:

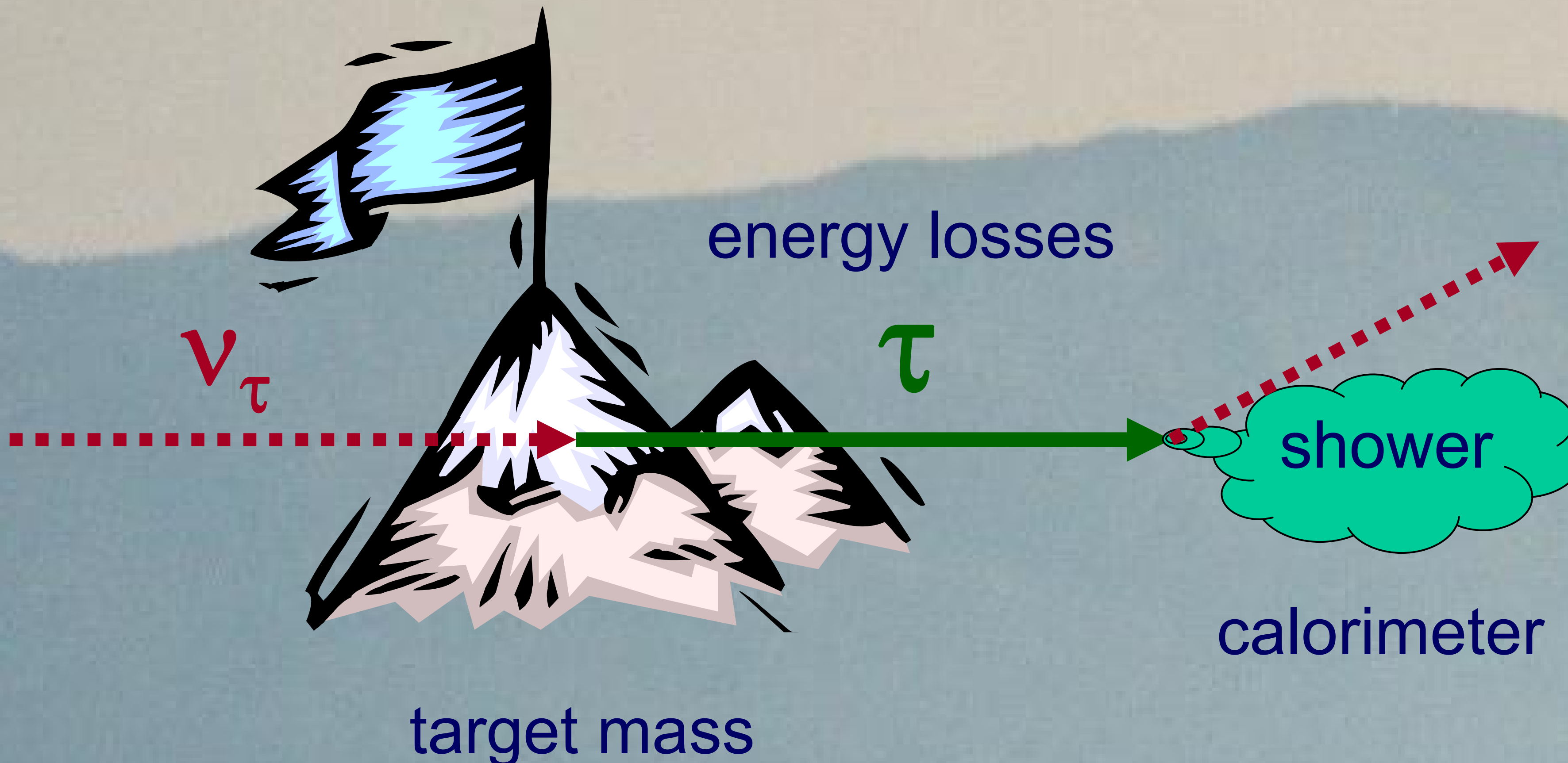
my student: Olga Brusova





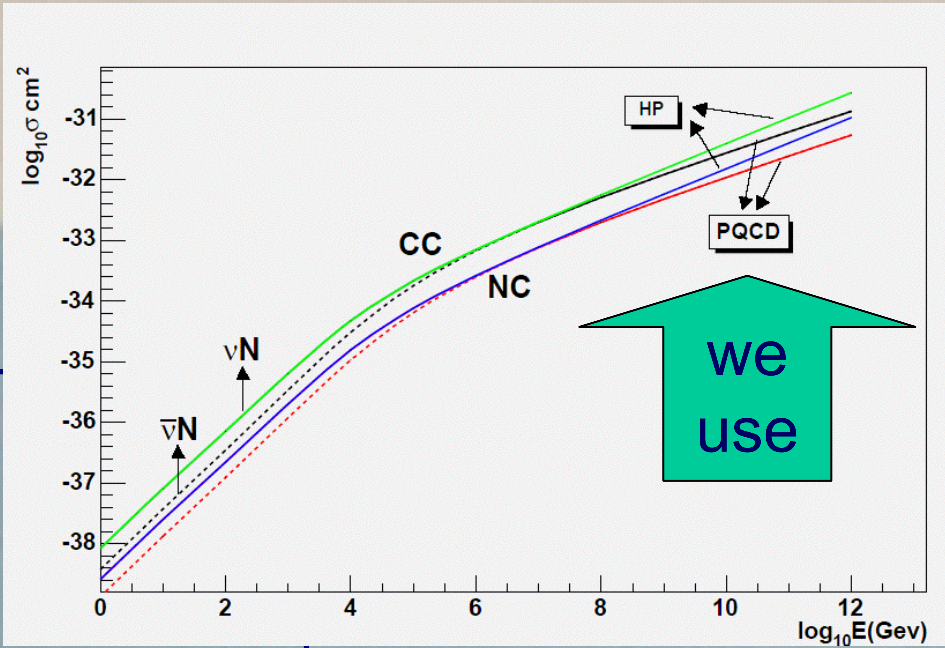


τ-Neutrino Detection:



ANIS (by Gazizov & Kowalski, AMANDA)

All Neutrino Interaction Simulation

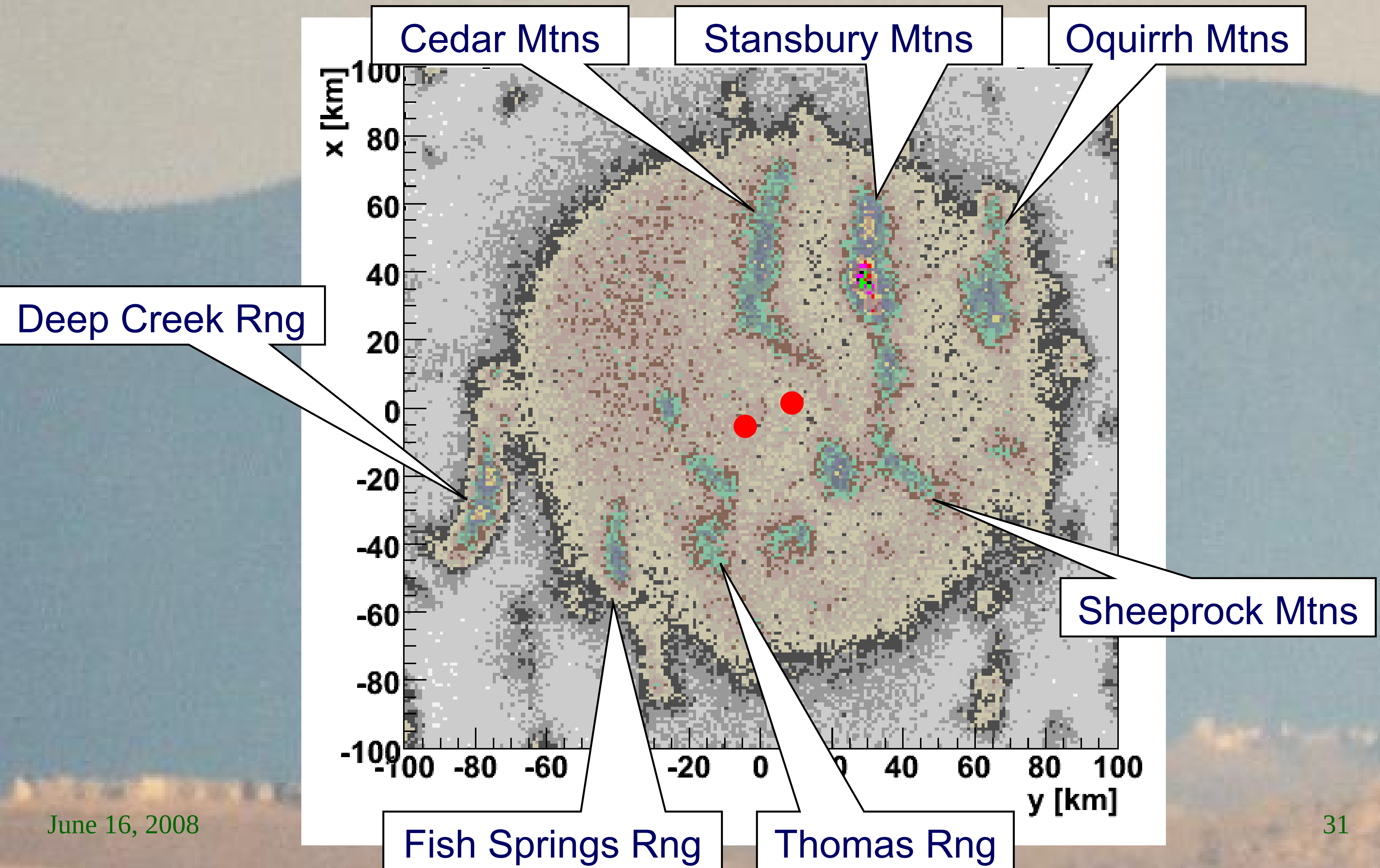


Incorporates:
- cross sections:
  CC, NC, ν_e–e^- (resonant)
- $\tau(\mu)$ energy loss (parameterization)
- decay tables
- TAUOLA for τ-decay

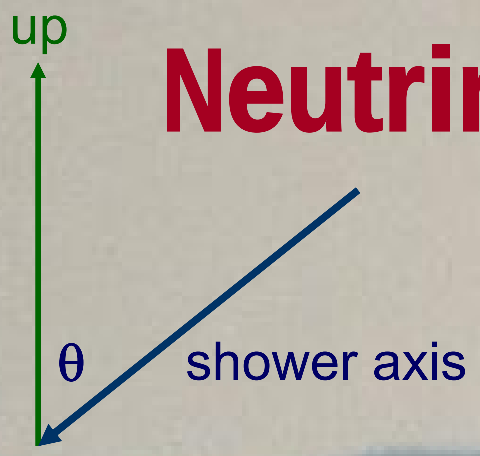
But: made for detectors inside a spherical earth…
(i.e. underground)

ν_τ-MC: Topography at Work

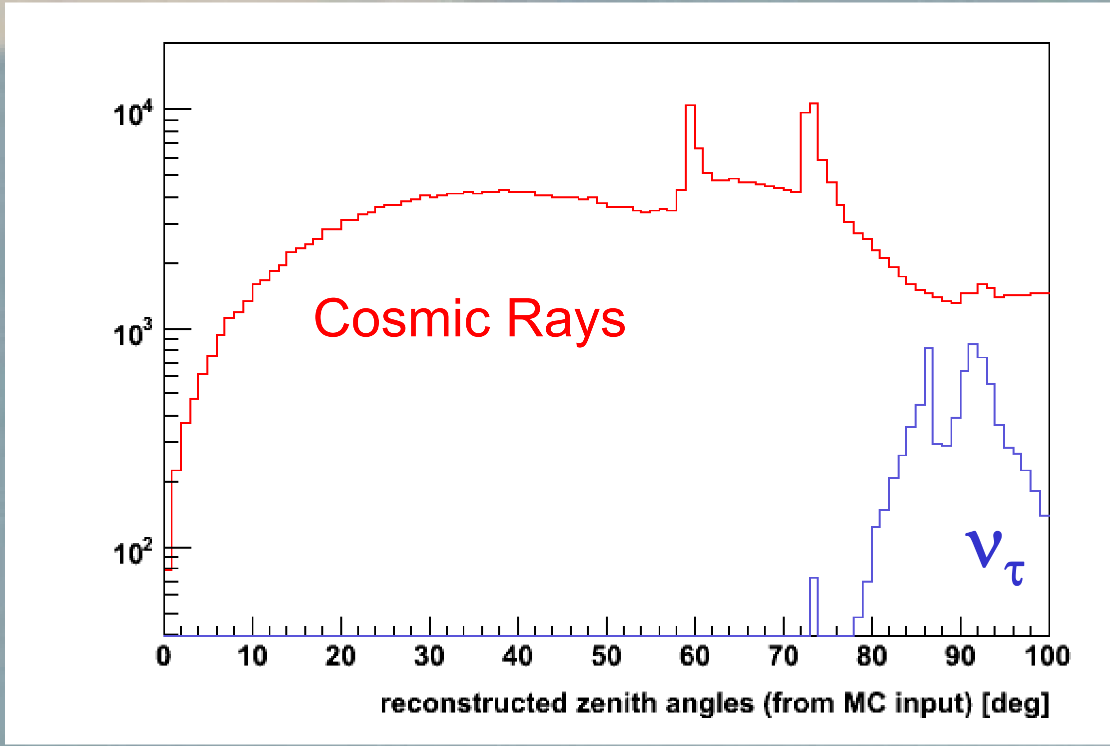
Neutrino interaction points (tau decay above ground):



Neutrinos: Zenith Angle $\theta > 90°$



MC statistics: ν_τ 11847
CR 341516



MC input:

- triggered events
- both detectors
- MC generated geometries

Zenith is the discriminator!

→ reconstruct geometry:

IF we do NOT find an event:

$$\frac{dN}{dt} = \varepsilon_{trigger}\varepsilon_{reconstruct}\int J(E)dE\int A(\Omega)d\Omega$$

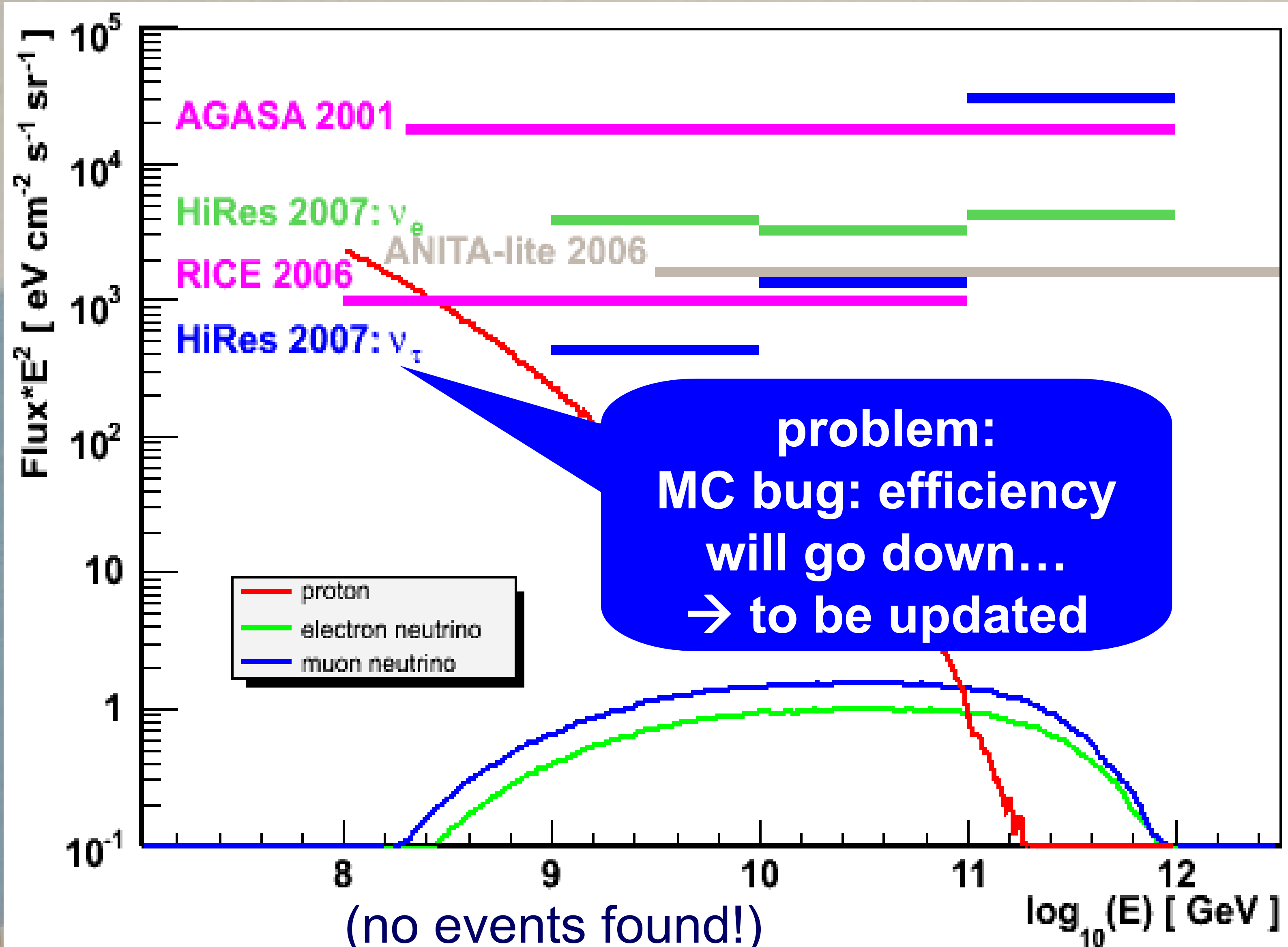
MC	??	$N(E) \sim E^{-1}$	MC

A Rough Estimate for an Isotropic ν Flux:

- total lifetime (Hr1 + Hr2) → 1y
- $\varepsilon_{reconstruct}$ ~ 1%
- flux E^{-1} between 10^{18}-10^{21}eV

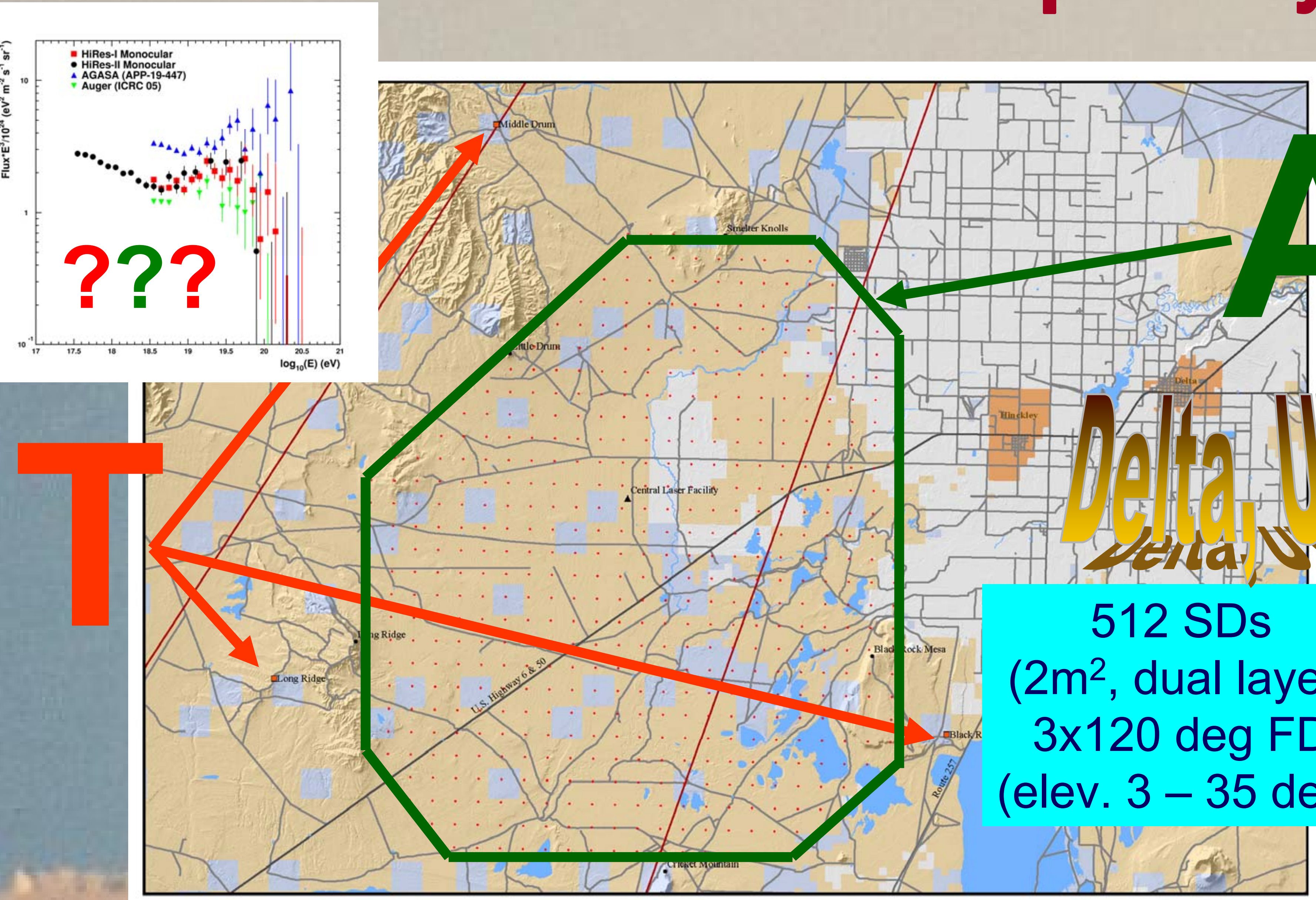
→ 2.3 events need dN/dt ~$10^{-17} s^{-1} cm^{-2} sr^{-1}$

HiRes: Cosmogenic Neutrino Limits



(no events found!)

AGASA &/vs. HiRes: Telescope Array



T

A

Delta, UT

512 SDs
($2m^2$, dual layer)
3x120 deg FD
(elev. 3 – 35 deg)

< 120 collaborators

< 30 institutes

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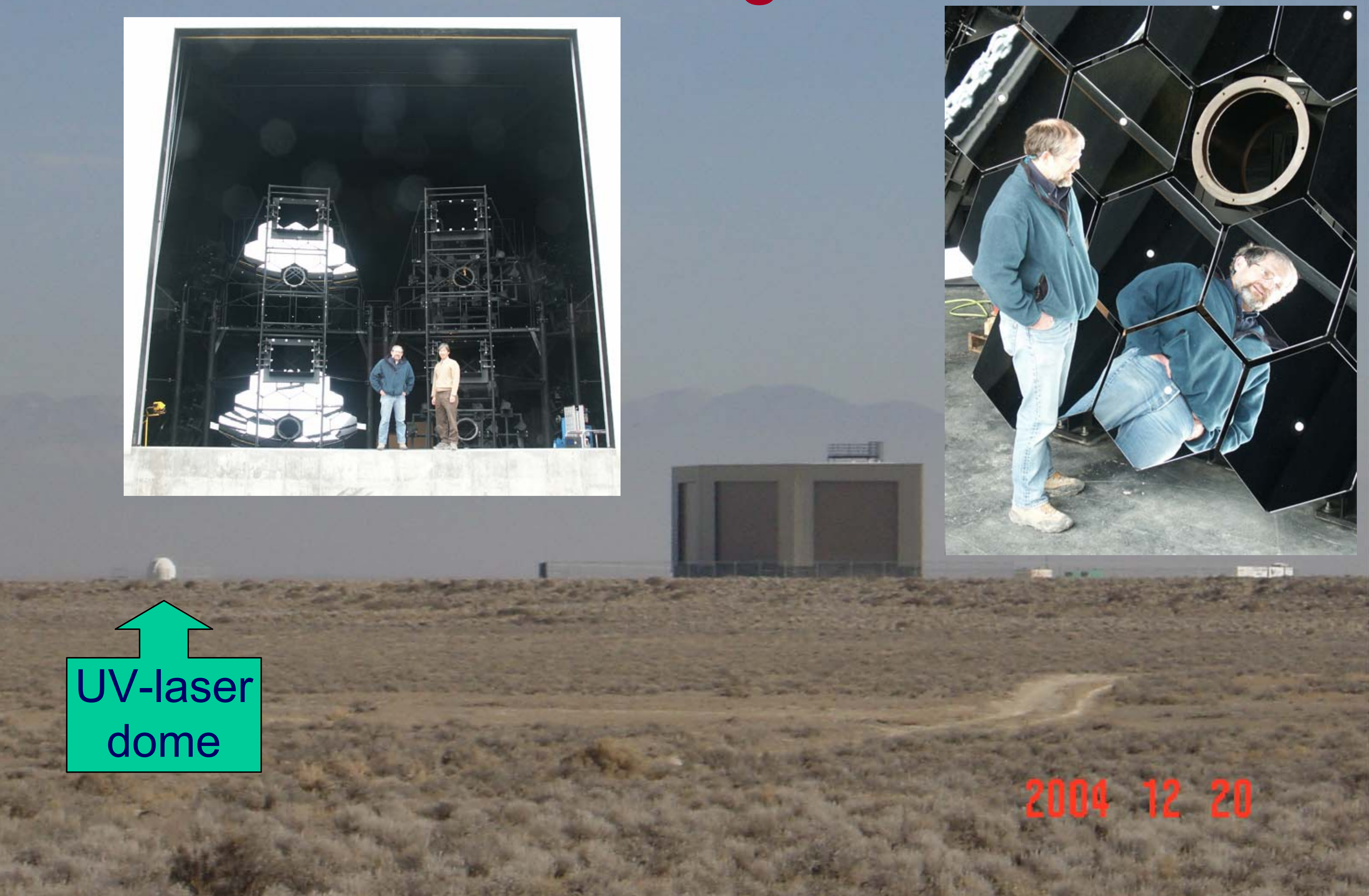
TA FD building on BRM:



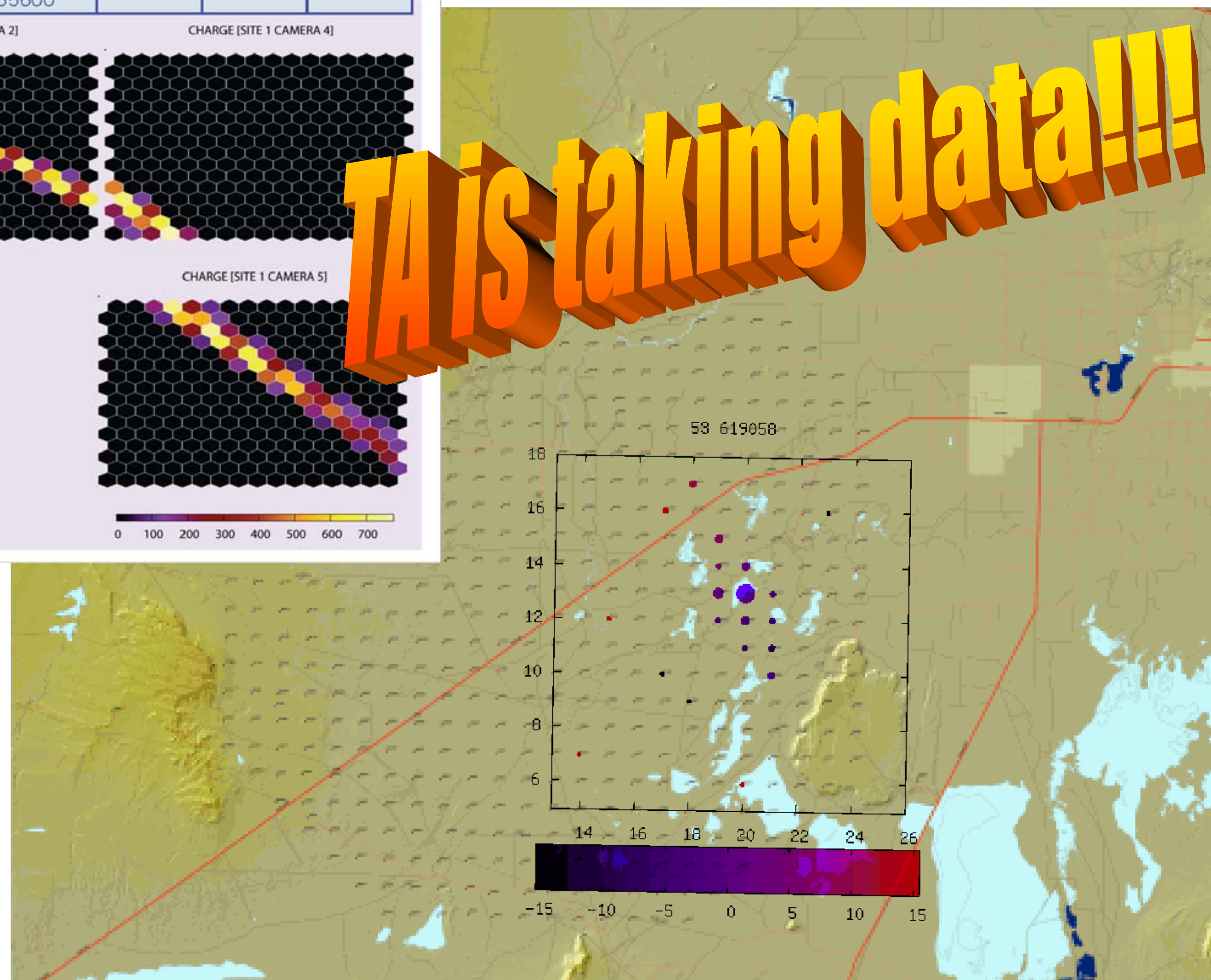
Ground Array: Heli Deployment

Message Two: Since March 20, 2008

	Time(UTC)	RUN-ID	TRIG-ID	CAM-ID
BRM	07/11/19 09:03:09.753991850	111905	107	5
LR	07/11/19 09:03:09.753955600	111907	4641	2, 4, 5

← 3 fluorescence detectors

TA is taking data!!!

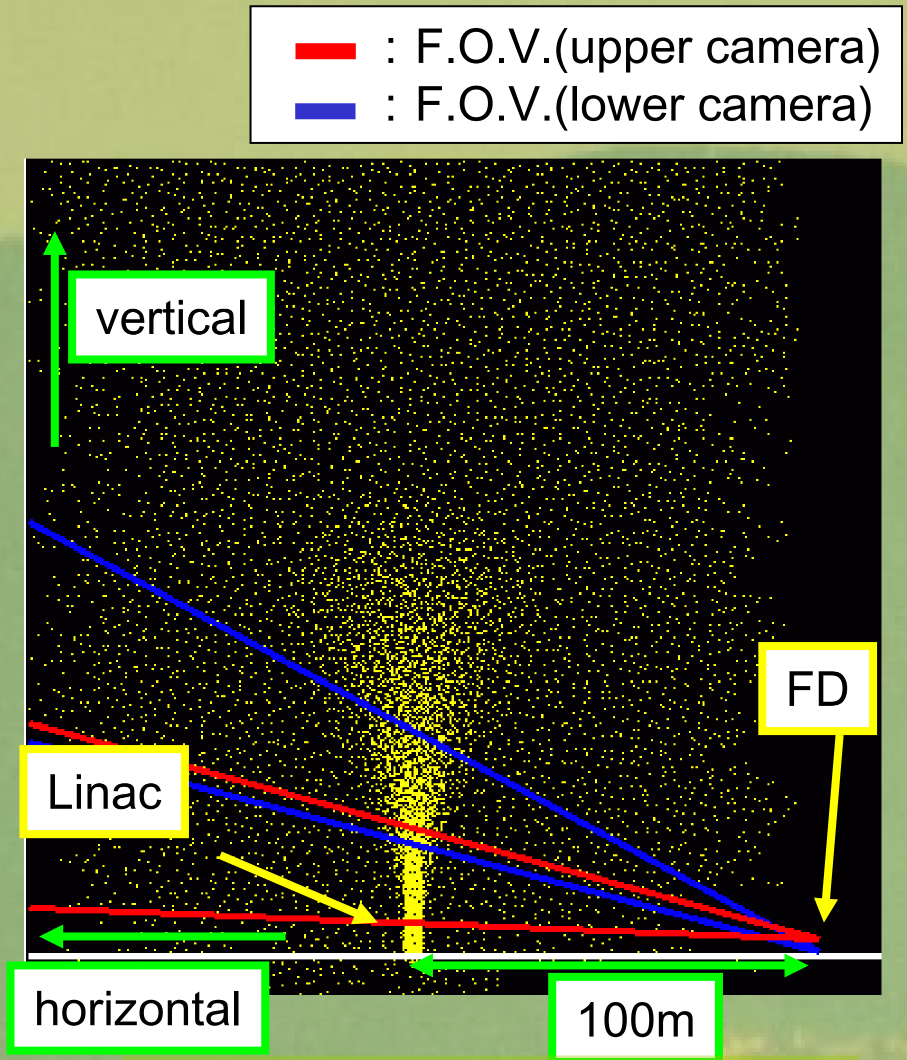


503 sintillators →

The TA-LINAC Idea:

Specs of TA-Linac
- Particle : e-
- Energy : 10, 20, 30, 40 MeV (variable)
- Pulse width : 1μsec
- Peak current : 0.16mA (10^9e-(=160pC)/pulse)
- Frequency : 1Hz
- Distance from FD : 100m

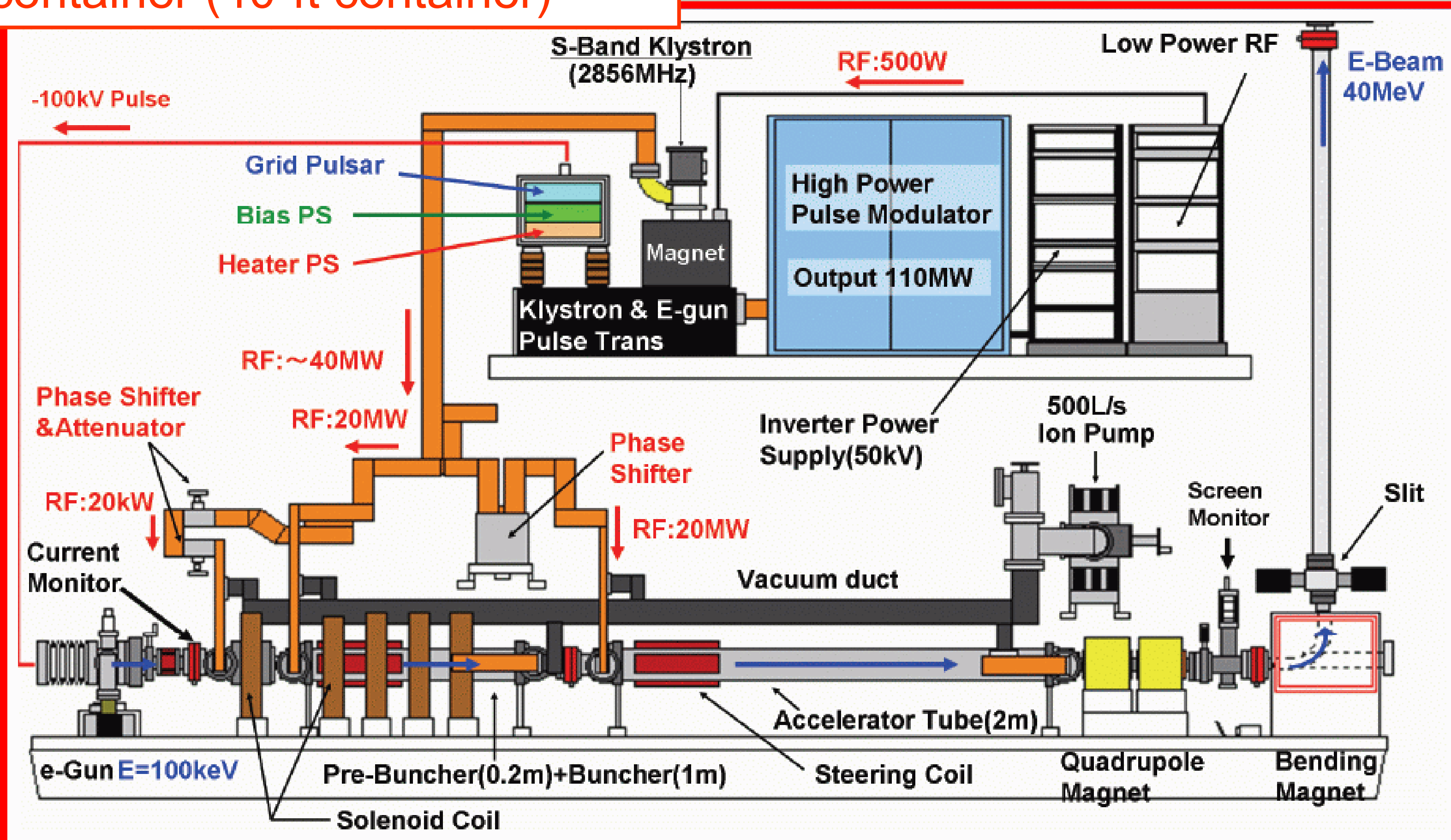
40MeV×10^9 e^-
@100m → ~10^{16}eV
⇔10^{20} eV @10km



Simulated with Geant4 (40MeV)

TA Linac Layout:

Main container (40-ft container)

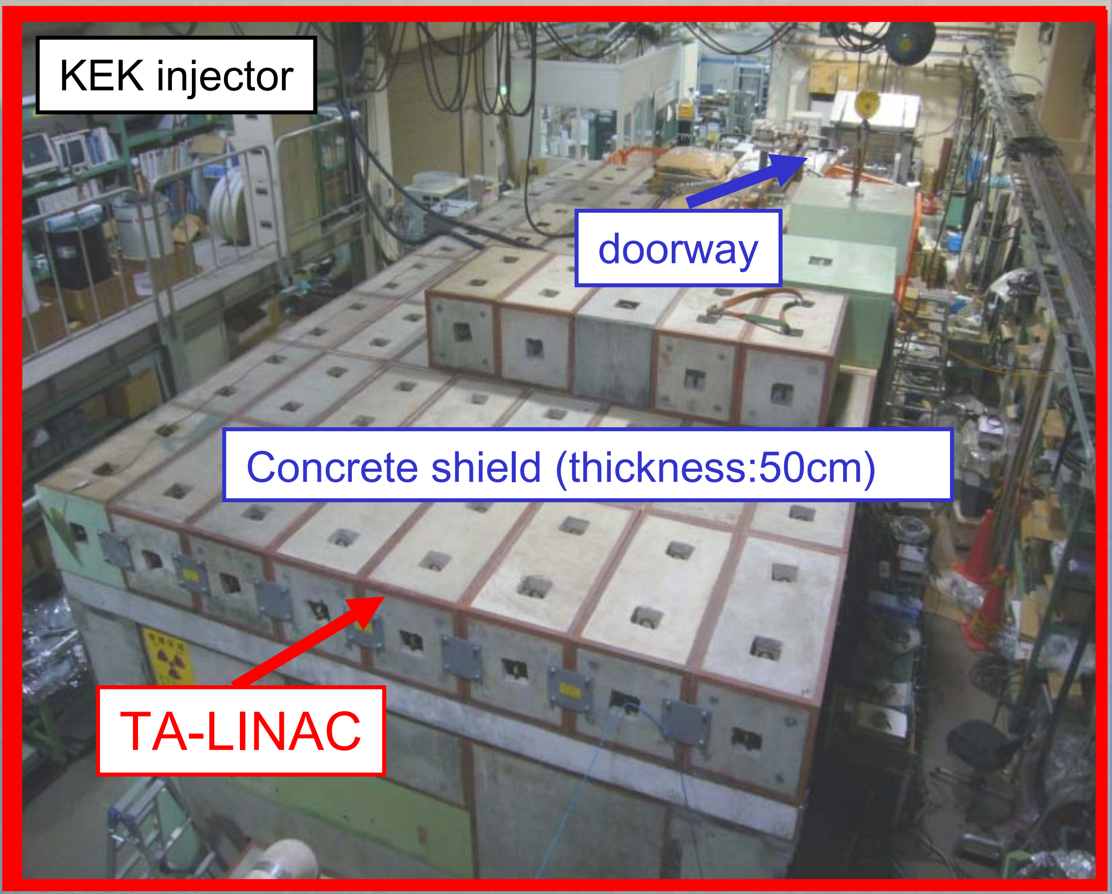


Sub container (20-ft container)

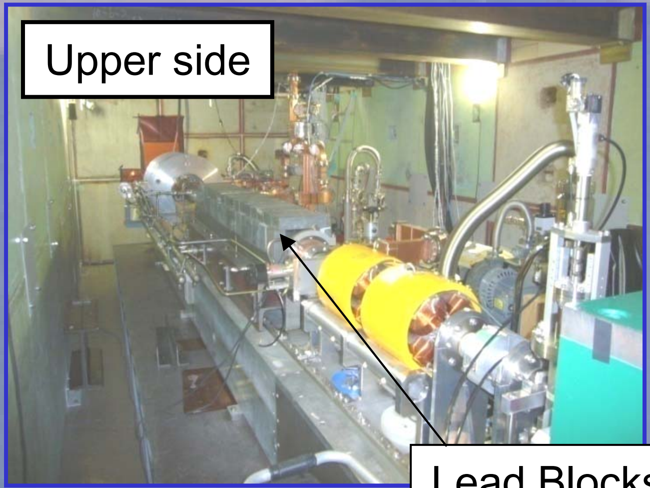
- Operating room
- cooling water system (600L,20kW)

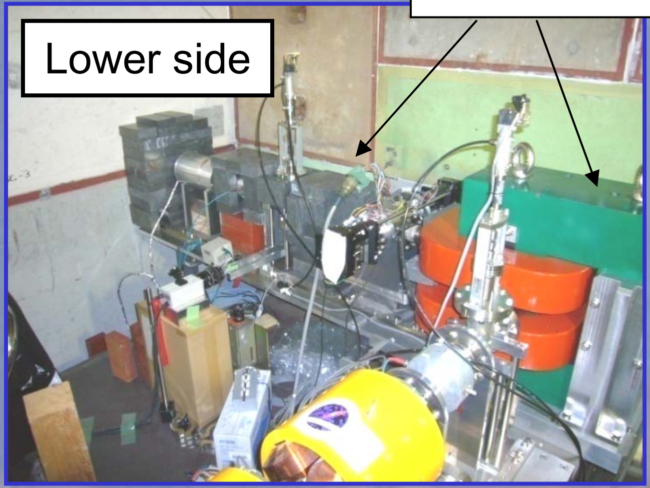
Power generator(~100kW)

TA-Linac @ KEK: Being Commissioned



In shield

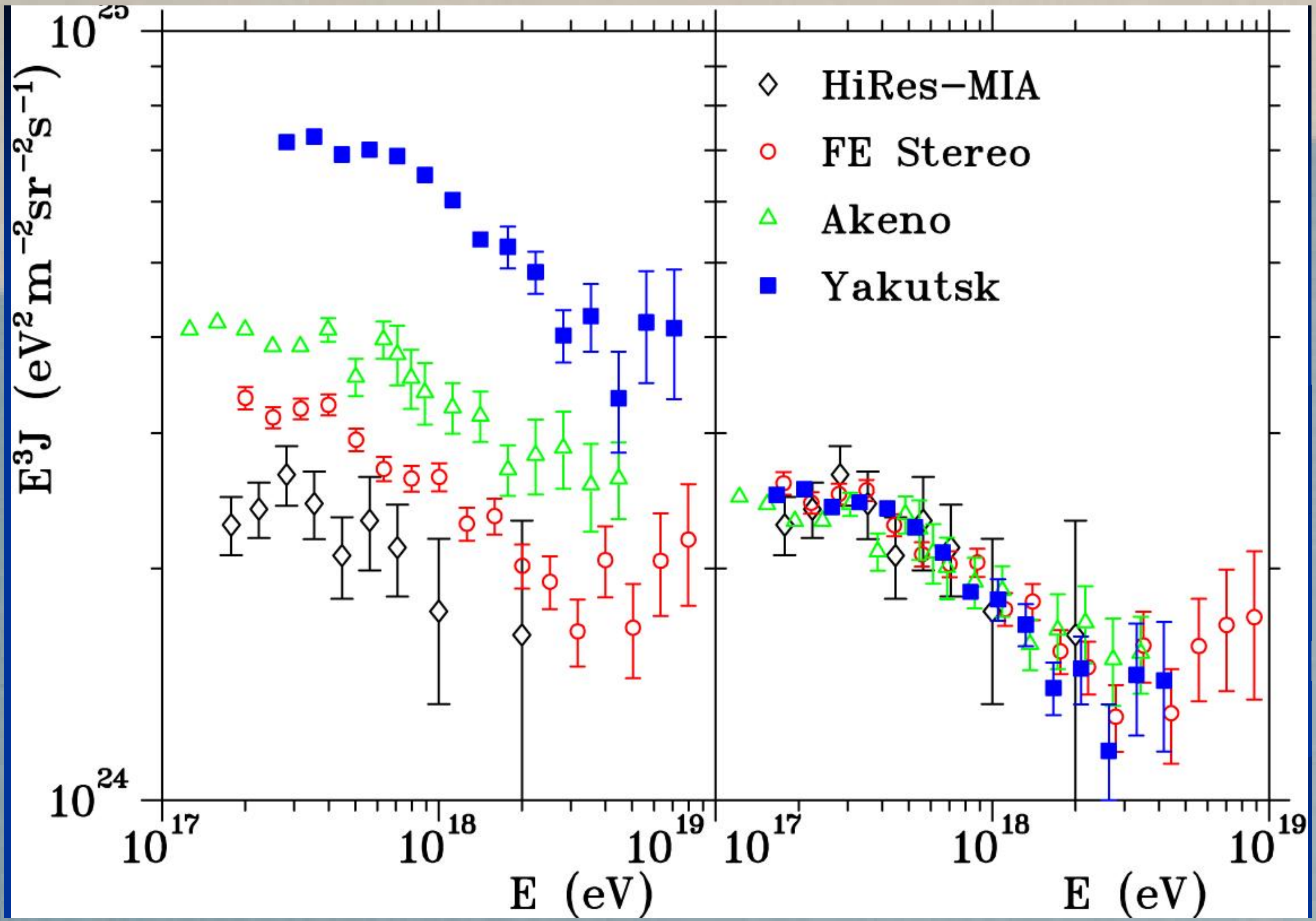




→Full-system beam test was started

What next (in Utah)?

2nd knee???



Enter: TA Low Energy Extension (TALE)

(details of layout still under revision; μ-counters?)

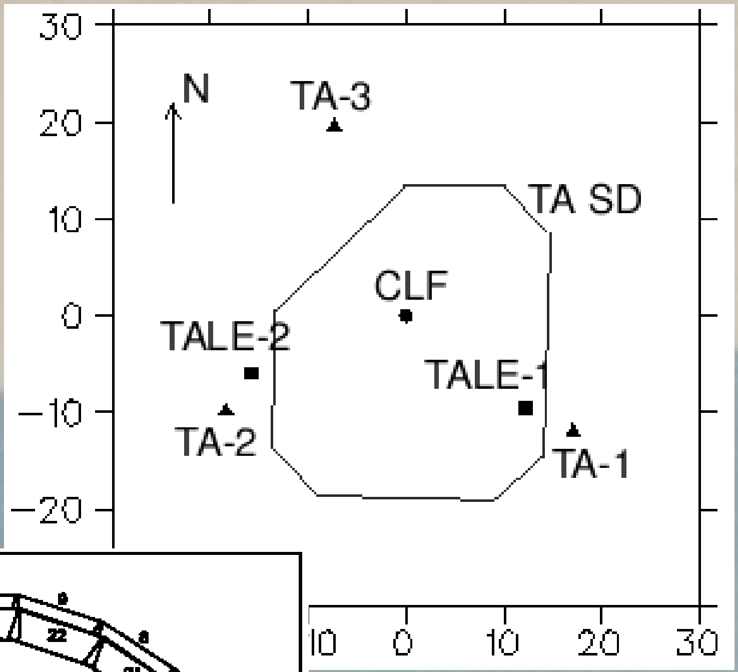
TA:	E>10^{19} eV	→ ε = 100%
	E>10^{18} eV	→ hybrid
HiRes (12,6km)	E>$10^{18.3}$ eV	→ stereo

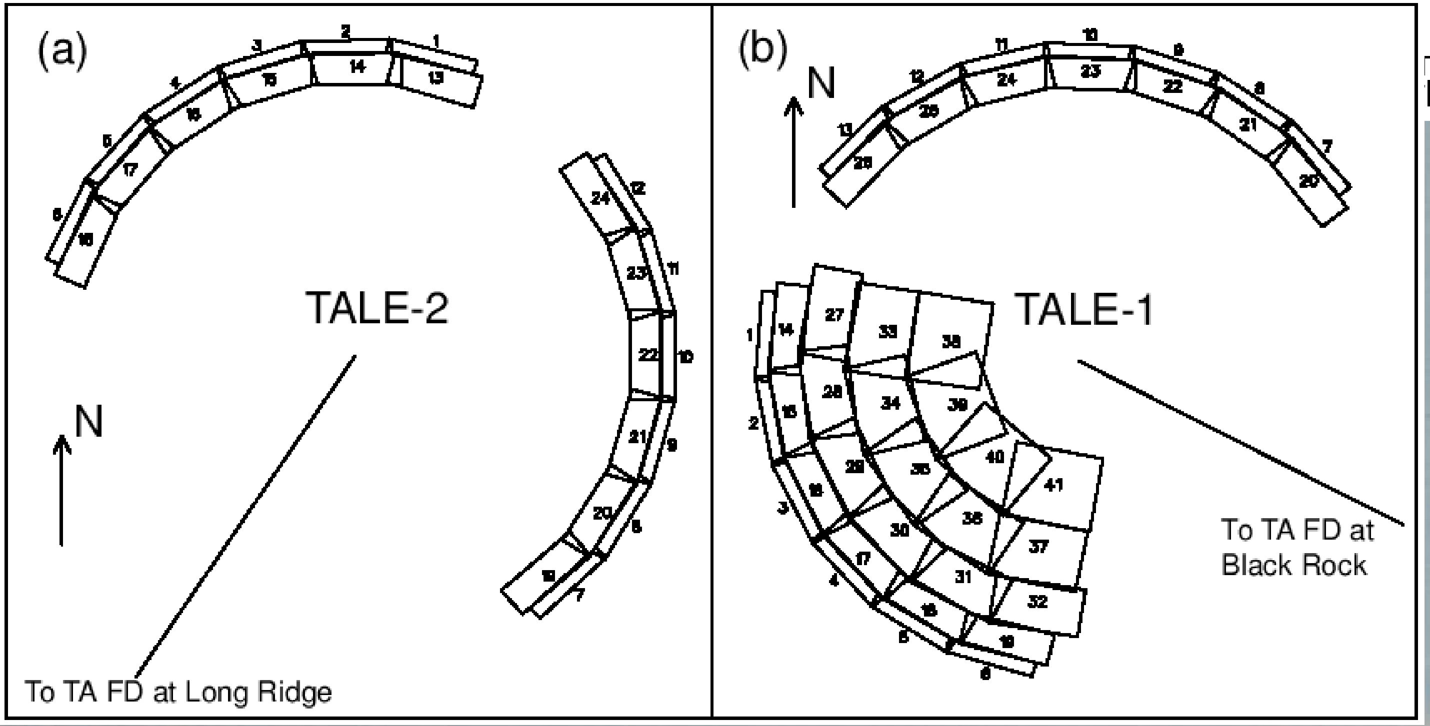
TALE:
- 6km stereo pairs (two of them) → best @10^{18} eV
- 72 deg elevation tower + infill (hybrid) → E>$10^{16.5}$ eV

All elements overlap (in energy and geometry) → cross calibration + control of systematics

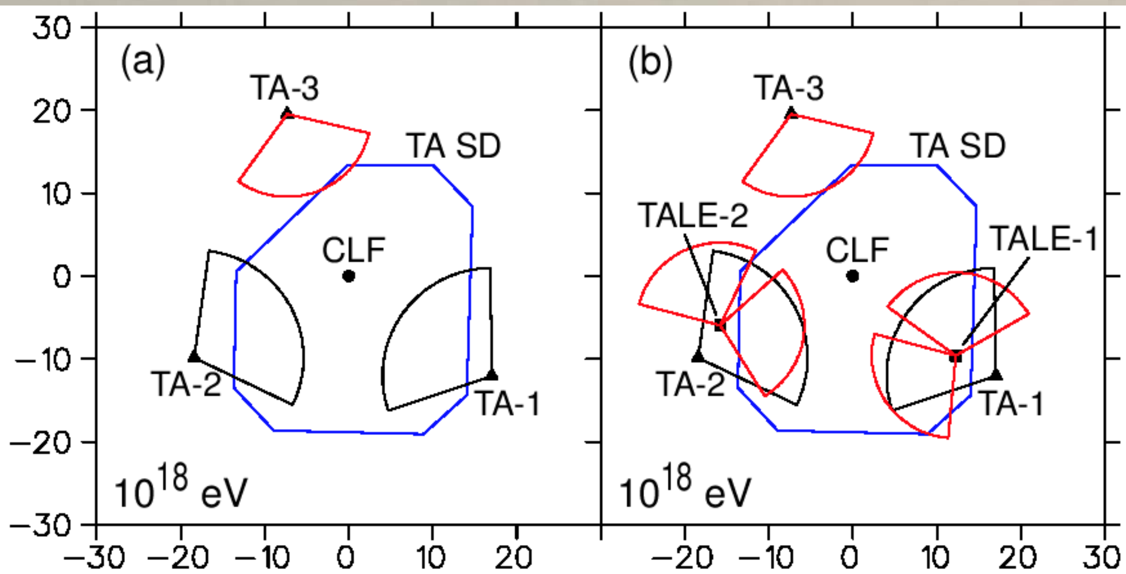
TALE Layout:

Design considerations:
- stereo angle
- CLF view
- # of HiRes mirrors:
  64 = 14 + 26 + 24



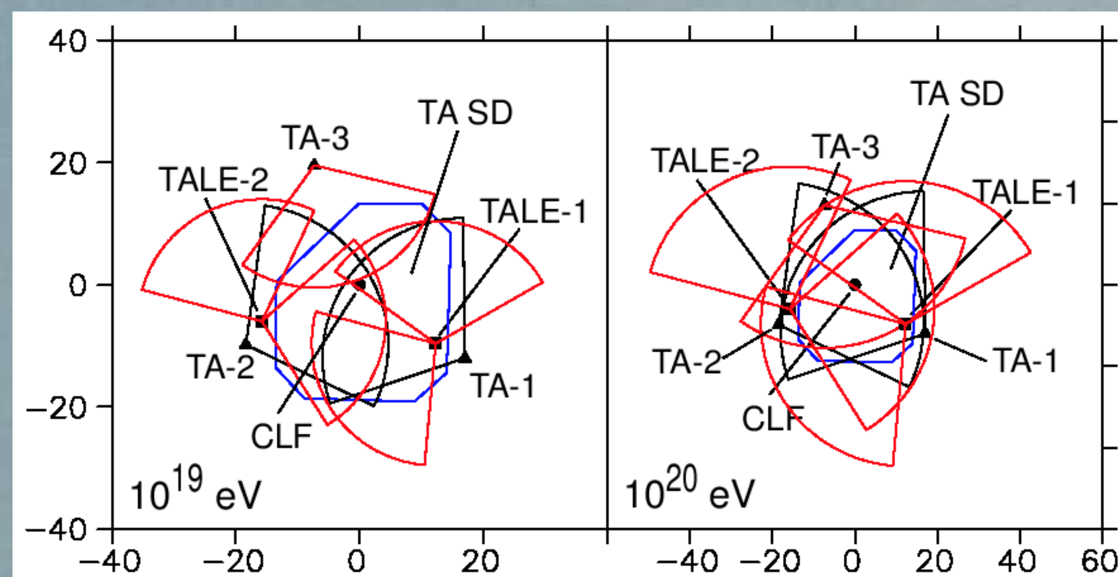


Fields of View:



FD aperture grows with energy:

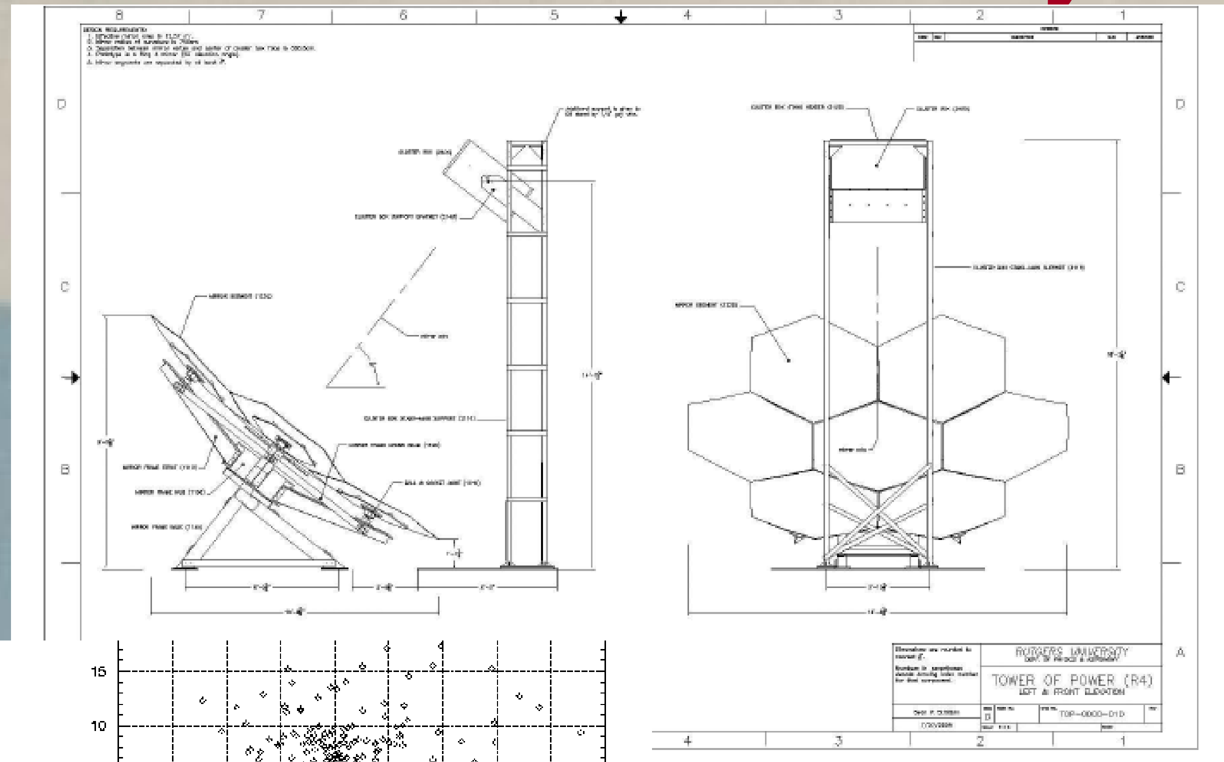
mirror area:
TA = HR + 20%



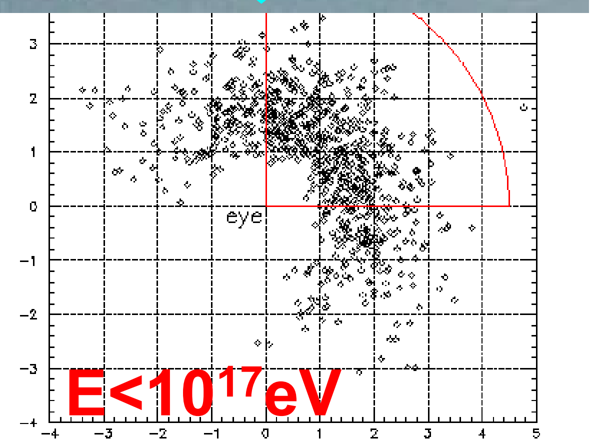
Tower Detector and Infill Array:

Infill: 110 x $2m^2$
400 m grid

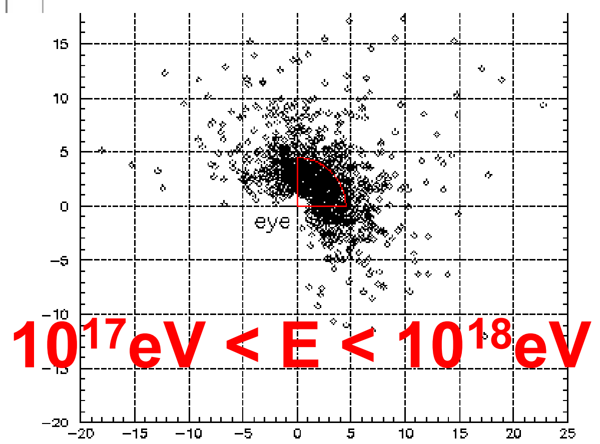
shower core locations



mirror area:
Tower = HR x 3



E<10^{17}eV



10^{17}eV < E < 10^{18}eV

0 5 km 0 25 km

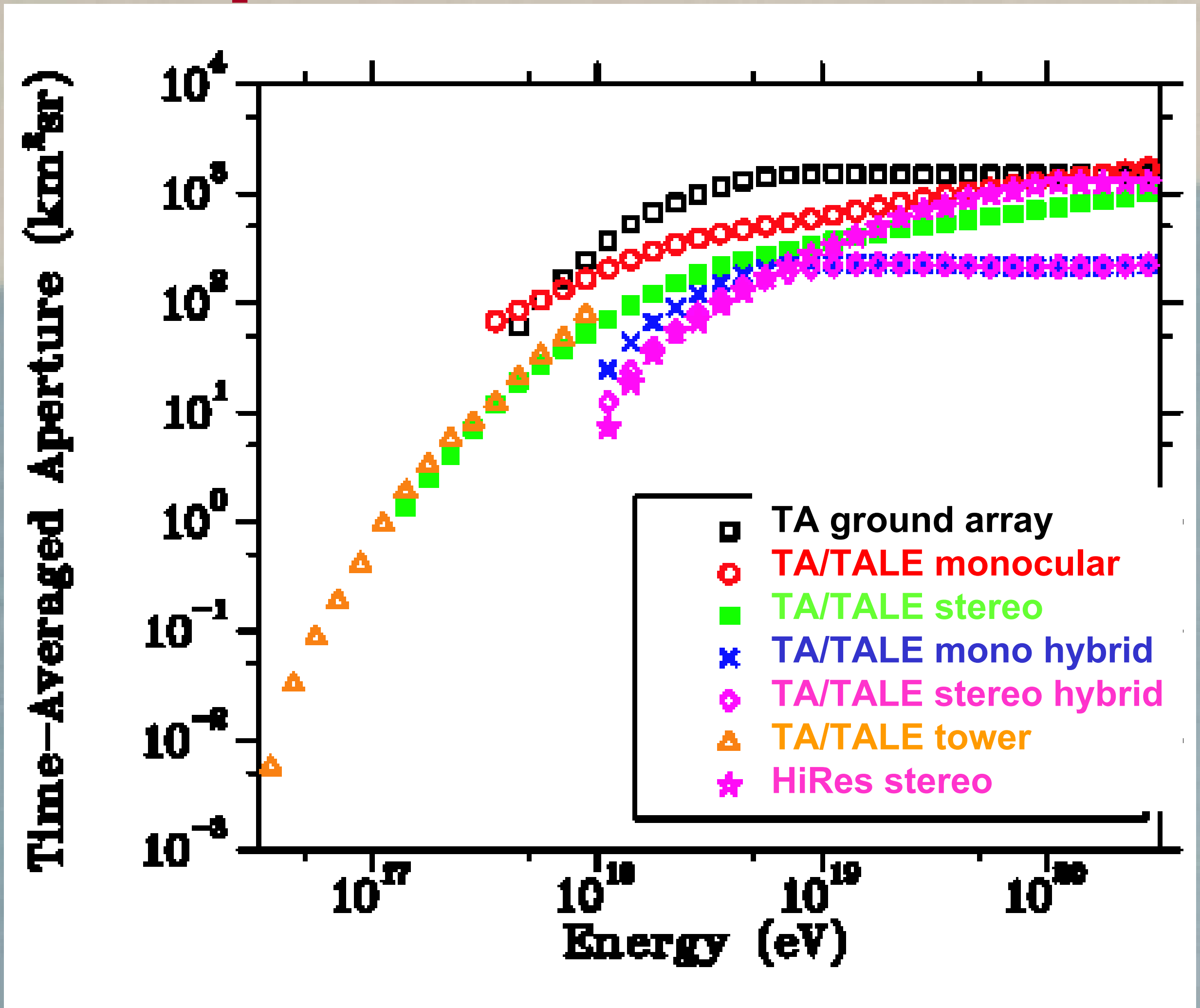
TALE Apertures:

Stereo:
- measure (!) resolution

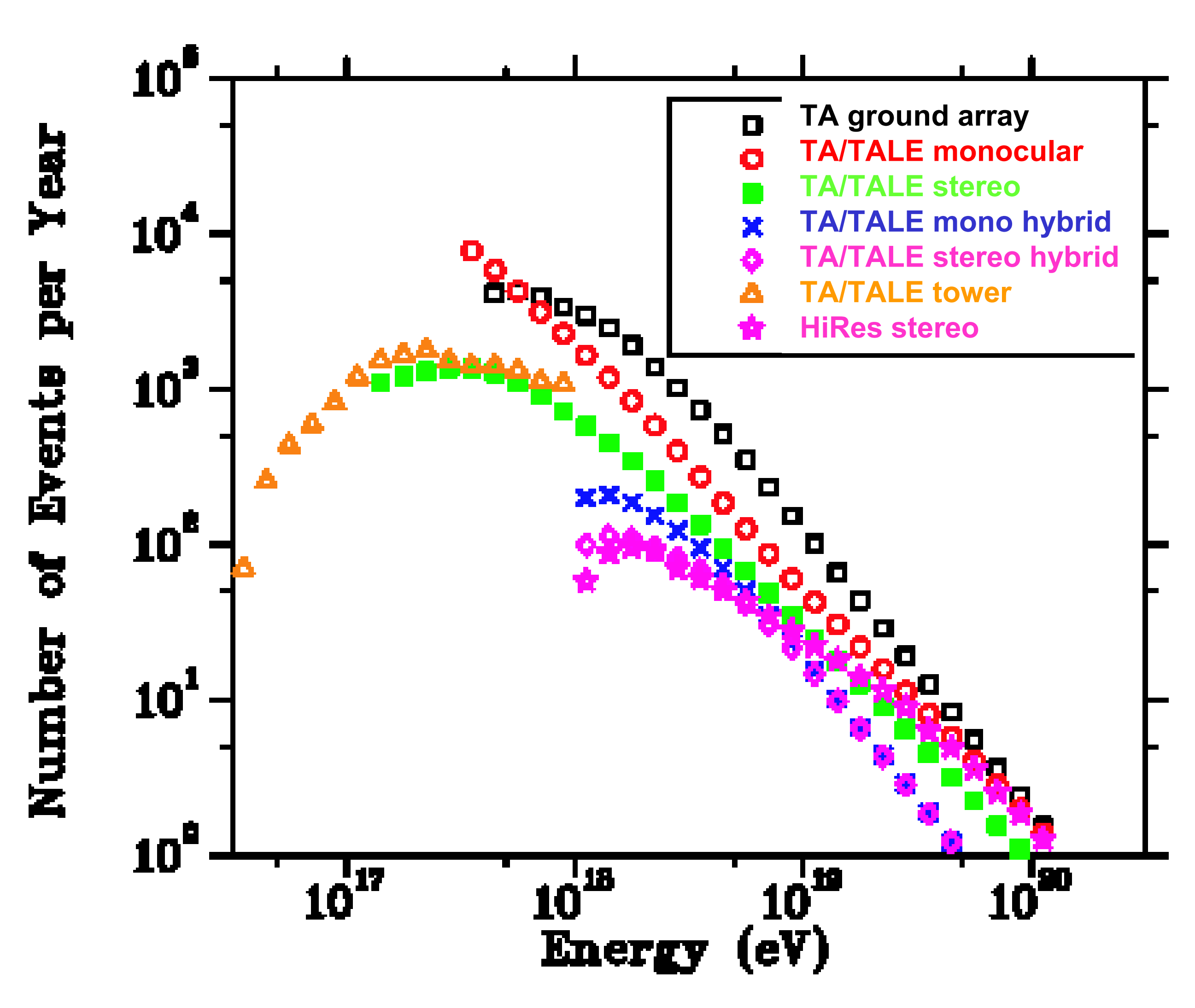
Overlap:
- calibration

Scintillator:
- e/m component

High energy aperture:
TA+TALE ≈ 2 x TA
≈ 3000 km²ster
≈ ½ S. Auger
≈ 3 x HiRes



TA/TALE: Events per Year



Conclusions:

- HiRes "found" GZK cutoff → find GZK neutrinos!?
- Auger found "AGN" correlation → charged particle astronomy?!
- surface vs. fluorescence → understanding particle physics
- spectrum & composition → down to 2nd knee

Telescope Array is taking data → ICRC 09 ?!?