Cosmic Rays in large air-shower detectors

The cosmic-ray spectrum from Galactic to extra-galactic

Cascade equations

For hadronic cascades in the atmosphere

$$\frac{\mathrm{d}N_i(E,X)}{\mathrm{d}X} = -\left(\frac{1}{\lambda_i} + \frac{1}{d_i}\right) N_i(E,X) + \sum_j \int \frac{F_{ji}(E_i,E_j)}{E_i} \frac{N_j(E_j)}{\lambda_j} \mathrm{d}E_j,$$

X = depth into atmosphere

d = decay length

λ = Interaction length

$$F_{ac}(E_c,E_a) \equiv E_c \frac{\mathrm{d}n_c(E_c,E_a)}{\mathrm{d}E_c}$$

Boundary conditions at top of atmosphere:

Primary spectrum:

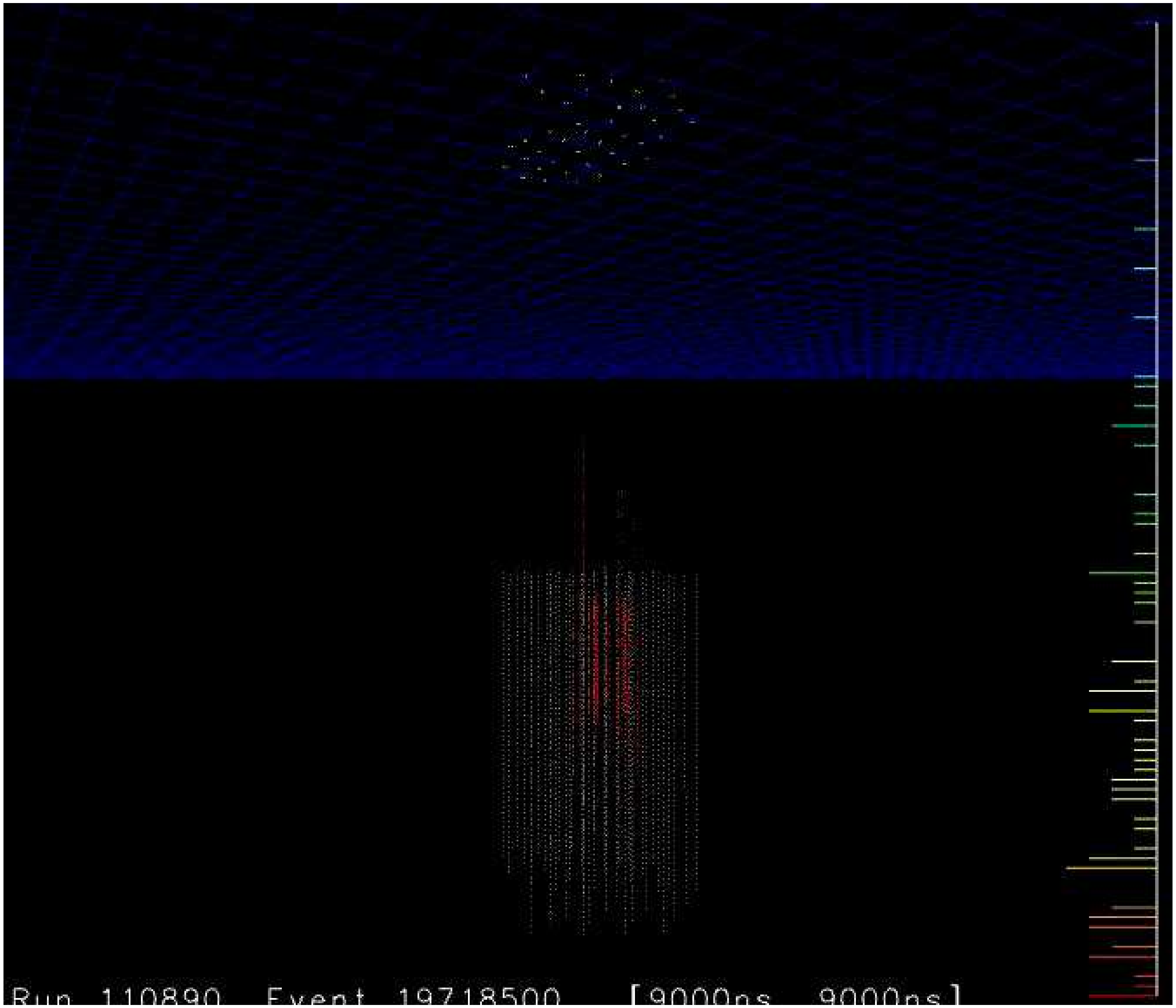
$$N(E,0) = N_0(E) = \frac{\mathrm{d}N}{dE} \approx 1.8\, E^{-2.7} \frac{\mathrm{nucleons}}{\mathrm{cm^2\, sr\, s\, GeV}/A}$$

Single nucleus

$$N(E,0) = A\,\delta(E - \frac{E_0}{A}),$$

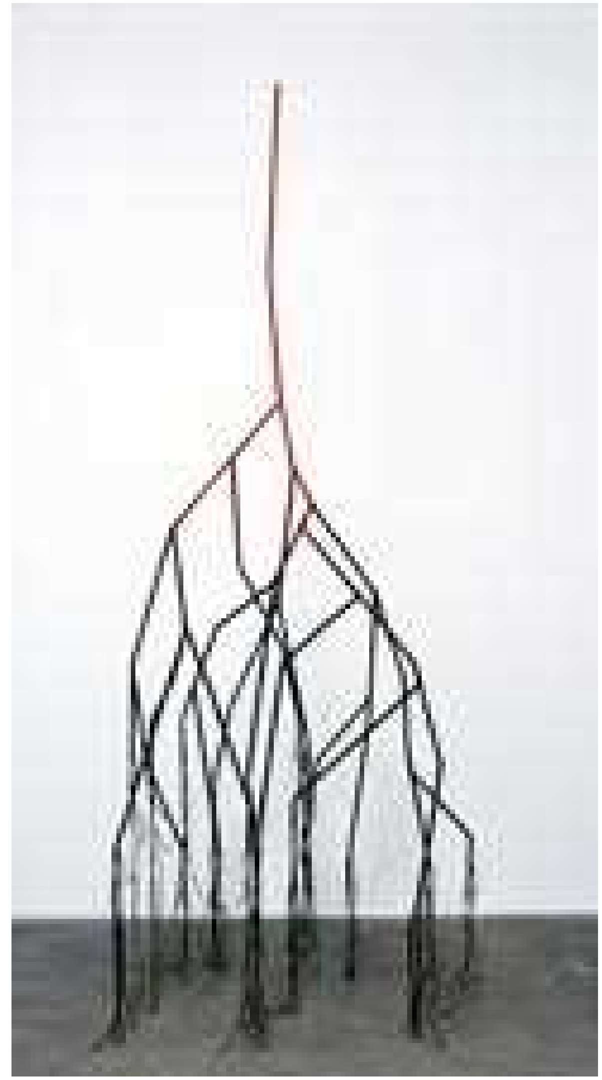
Solution for air showers

- Same set of equations subject to
  - $N(E,0) = A\,\delta(E - E_0/A)$
  - $\Pi(E,0) = K(E,0) = 0$
- Analytic approximate solutions possible
  - Compare Rossi & Greisen (1941) e-m cascades
- In practice need Monte-Carlo simulations
  - QGSjet-II S.S. Ostapchenko, Nucl. Phys. B (Proc. Suppl.)151 (2006)143.
  - SIBYLL 2.1 R. Engel et al., 26^{th} ICRC (199) & E-J Ahn et al. 0906.4113
  - EPOS K. Werner & T. Pierog, PRL 101 (2008) 171101


Run 110890 Event 19718500 [9000ns, 9000ns]

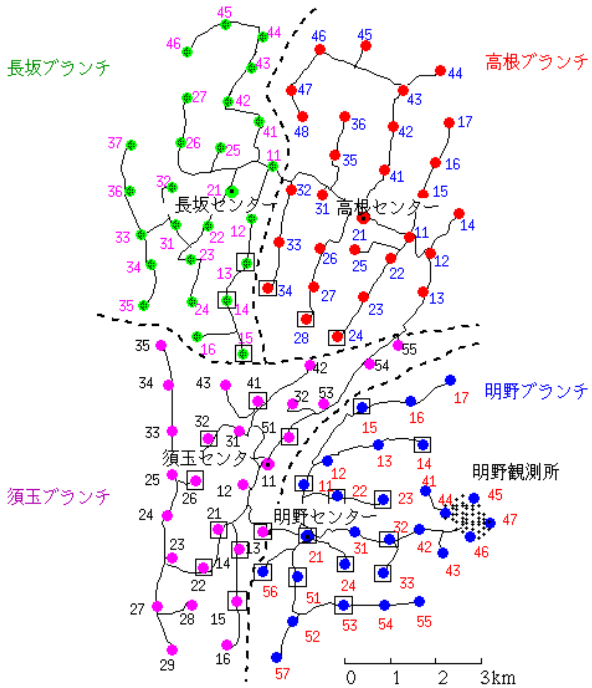
Structure of EAS

- Primary nucleus interacts
  - Core of energetic hadrons
    - $\pi^{\pm}$, K interact; feed core
    - π^0 decay at production, generate e-m subshowers
    - $\pi^{\pm}$, K with E < $\varepsilon_{critical}$ decay
      - → μ and ν
      - TeV μ and ν produced with lower probability ~ 1 / E
  - $e^{\pm}$ in e-m cascade dissipate most energy
  - ~ 2.2 MeV per g/cm^2 per charged particle ionizes the air
- Measure dE/dX via atmospheric fluorescence (Fly's Eye technique)
- Measure $e^{\pm}$ and μ at the ground
  - Relate to energy via simulations



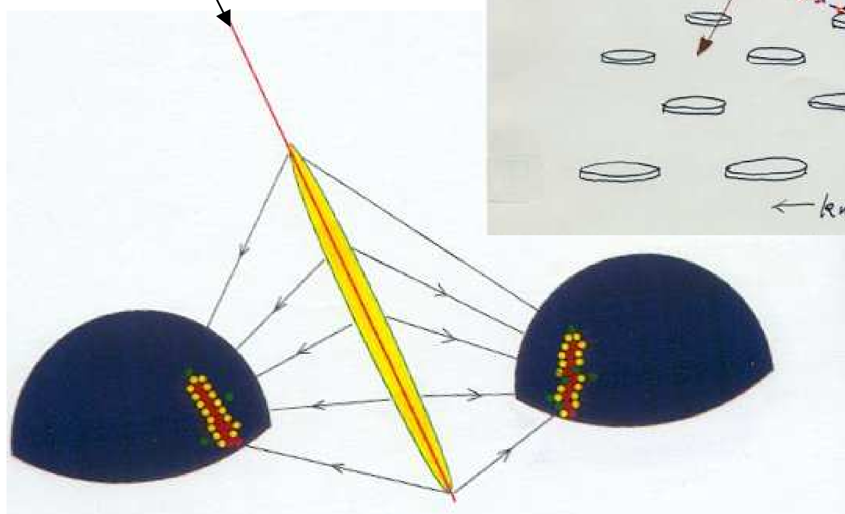
"Knock-Knock" a sculpture by Eva Rothschild, Tate Britain

UHE shower detectors

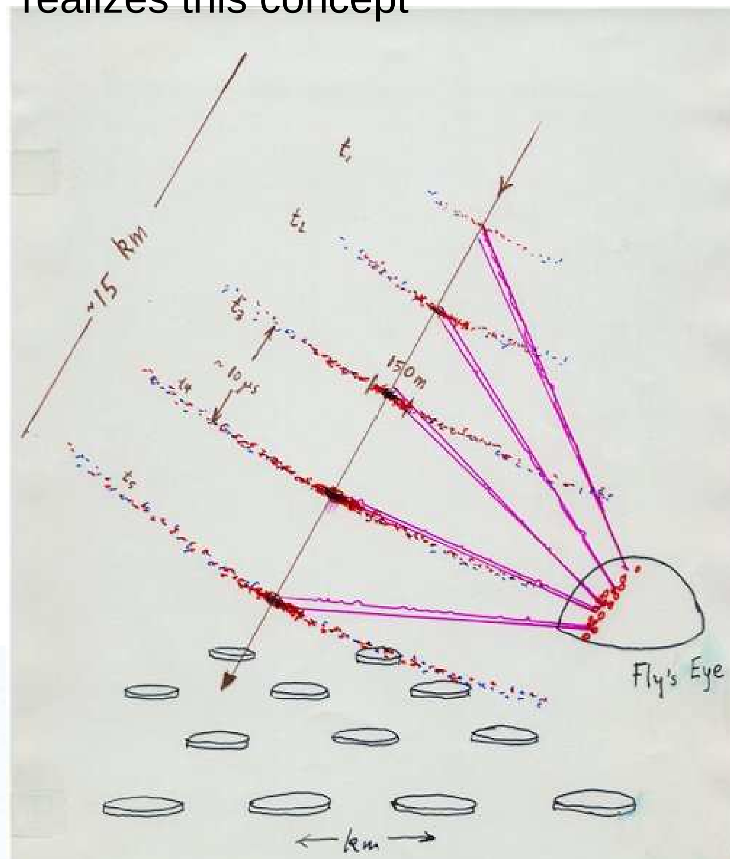


AGASA (Akeno, Japan)
100 km^2 ground array

Hi-Res stereo fluorescence detector in Utah

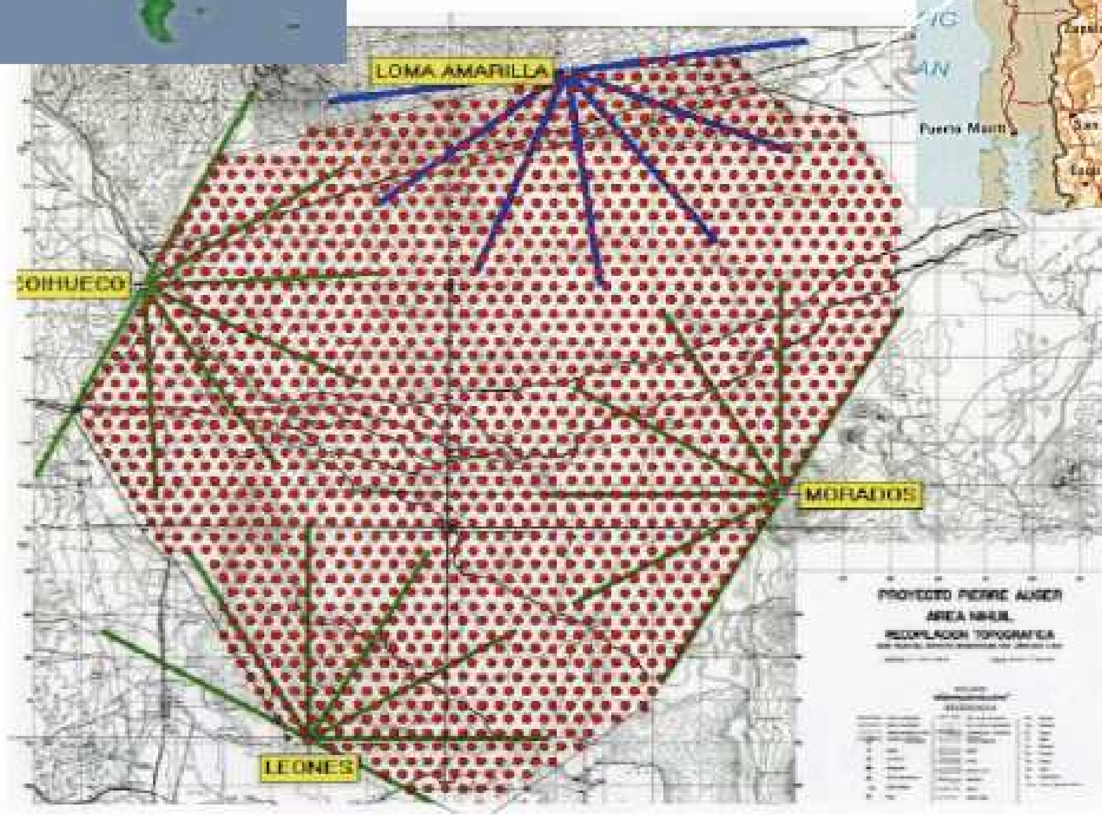


Sketch of ground array with fluorescence detector – Auger Project realizes this concept



Auger South

Completed in 2008

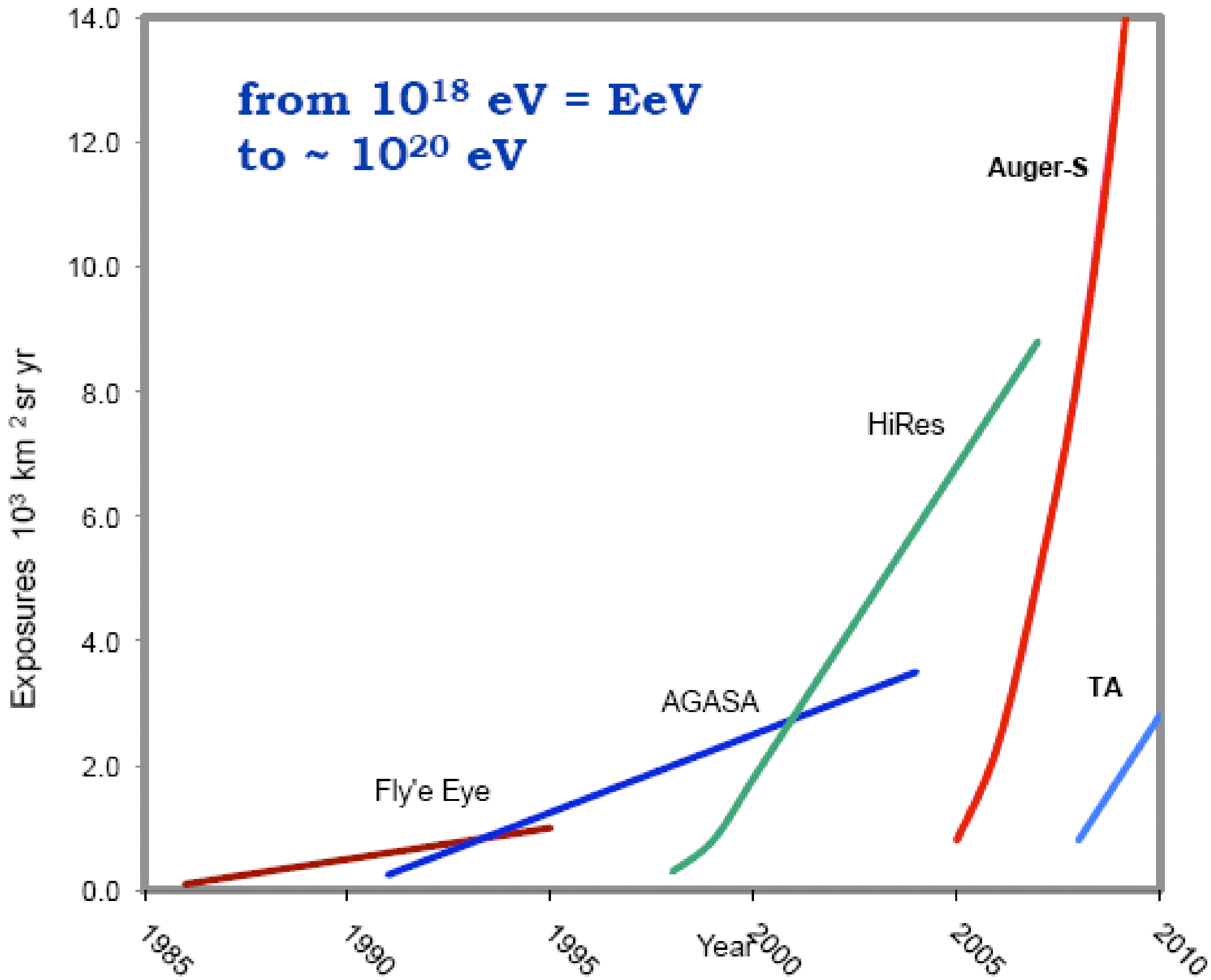


1660 tanks in a 3,000 km^2 Surface Array
4 Fluorescence Detector Sites

Angela Olinto
TeV PA 2009

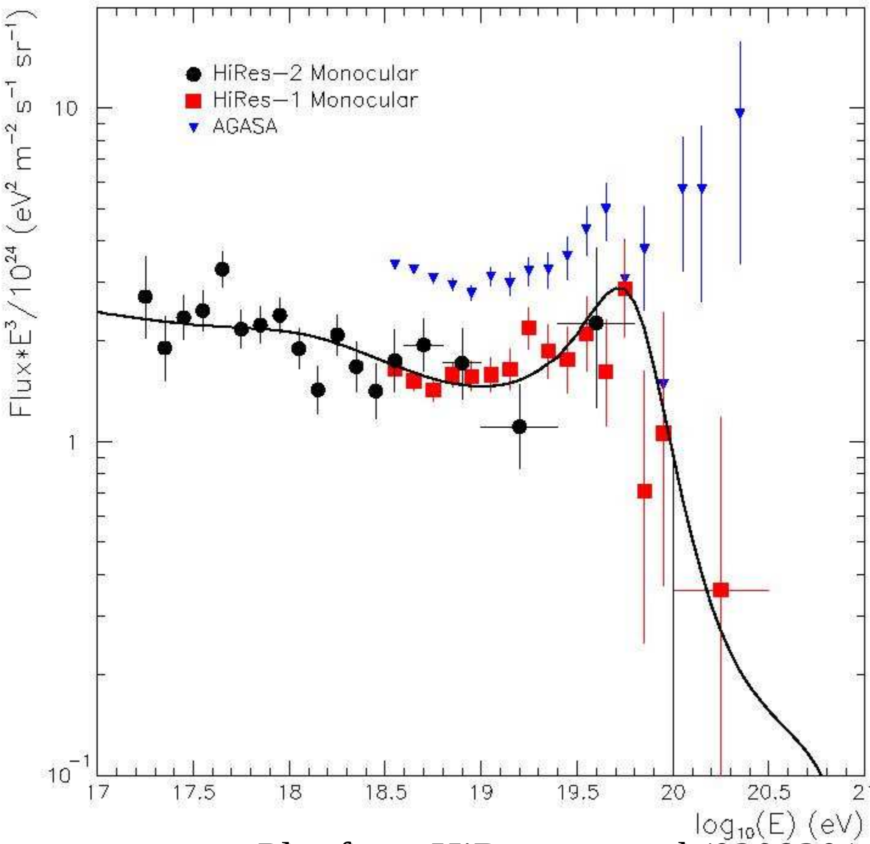
Growth curve for exposure

Angela Olinto
TeV PA 2009



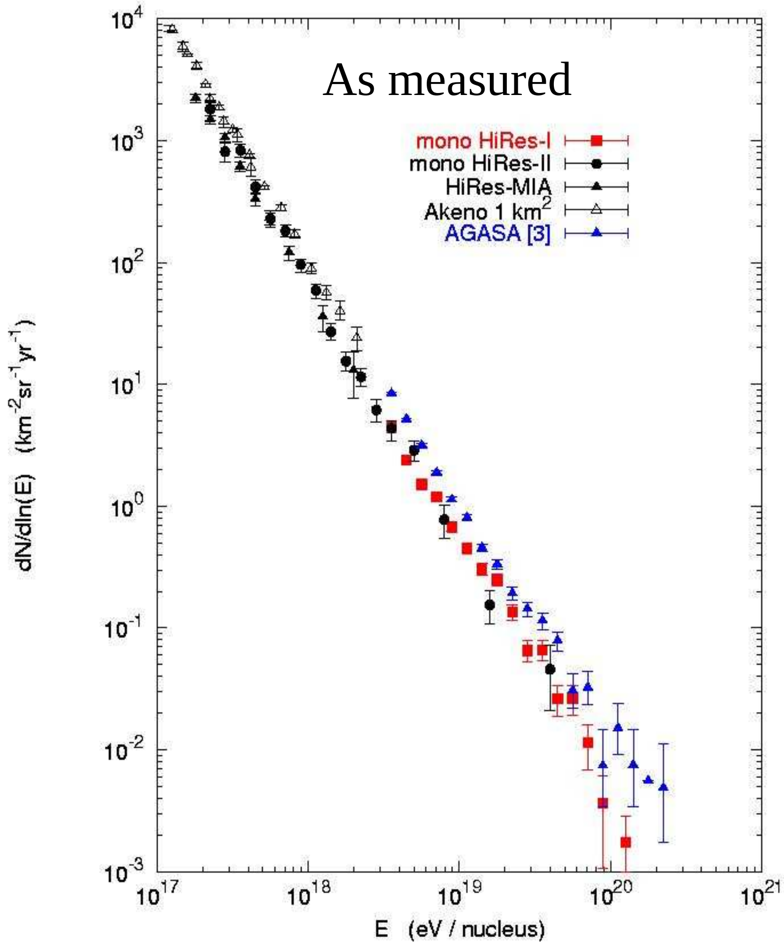
Hi-Res / AGASA circa 2003

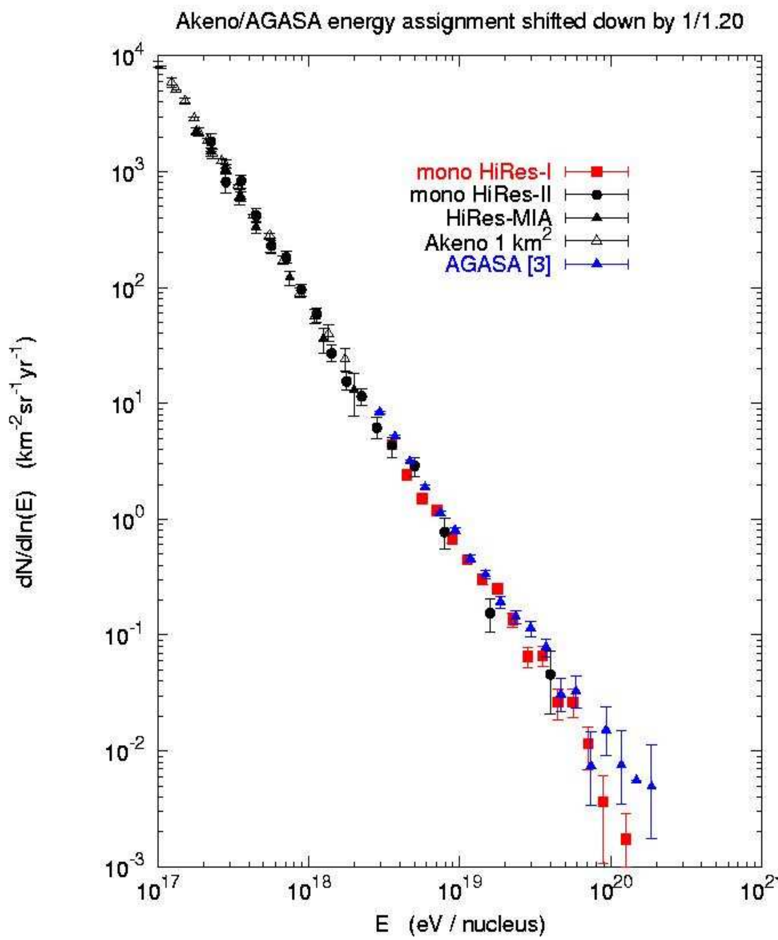
- Where is the “end” of the cosmic-ray spectrum?
- Expect suppression for E > 5 x 10^{19} eV from energy loss in the CMB
  - p $\gamma \rightarrow$ N π X and
  - A $\gamma \rightarrow$ A’ + nucleons



Plot from HiRes, astro-ph/0208301

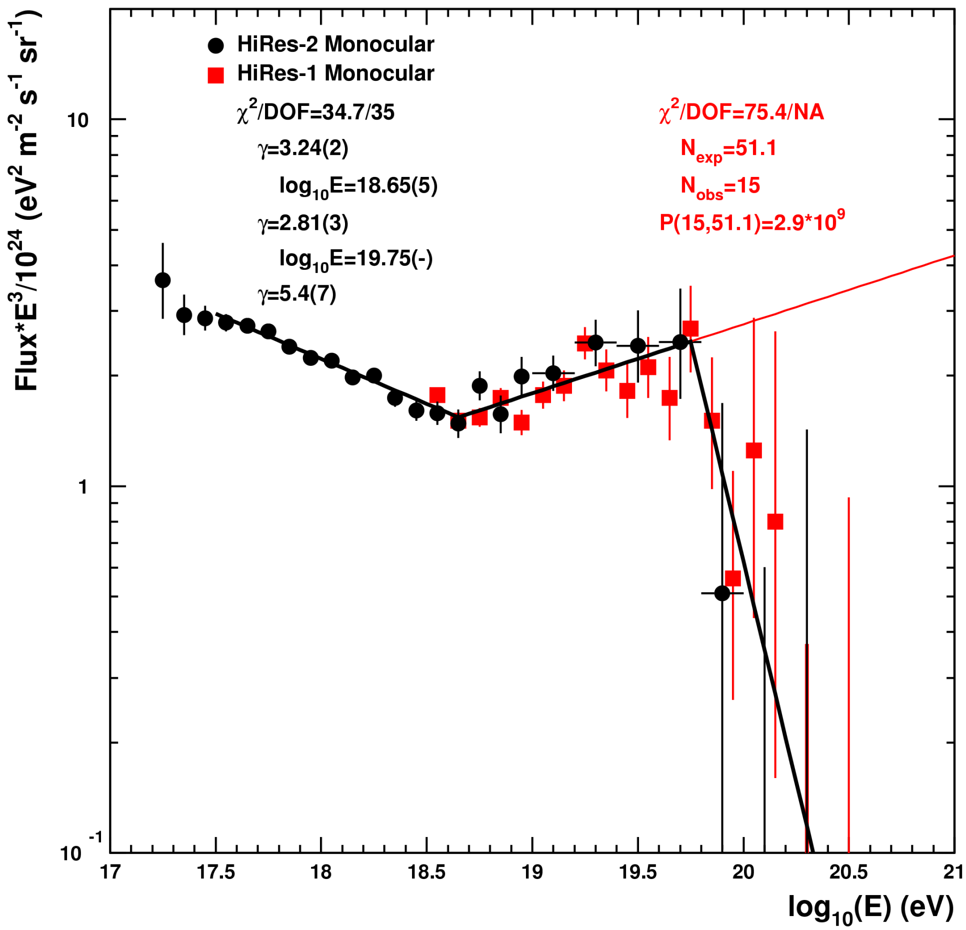
Akeno-AGASA / HiRes: comparison of what is measured





5σ Observation of the GZK Suppression (mono)

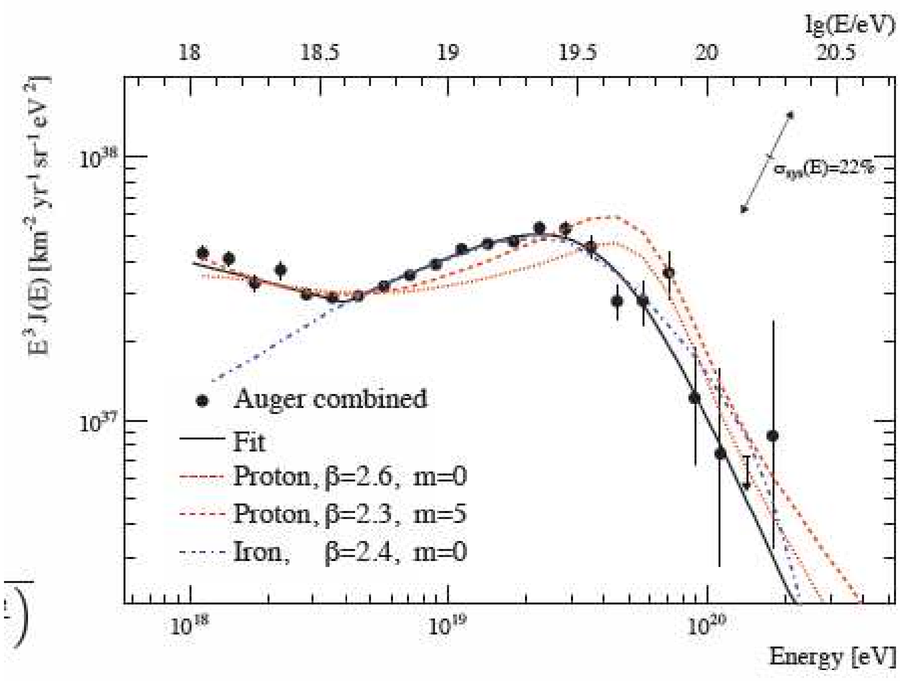
- **Broken Power Law Fits (independent data)**
  - No Break Point
    χ^2/DOF = 162/39
  - One BP
    - χ^2/DOF = 63.0/37
    - BP = 18.63
  - Two BP's
    - χ^2/DOF = 35.1/35
    - 1st BP = 18.65 +/- .05
    - 2nd BP = 19.75 +/- .04
  - BP with Extension
    - Expect 43.2 events
    - Observe 13 events
    - Poisson probability:P(15;51.1)= $7x10^{-8}$(5.3σ)



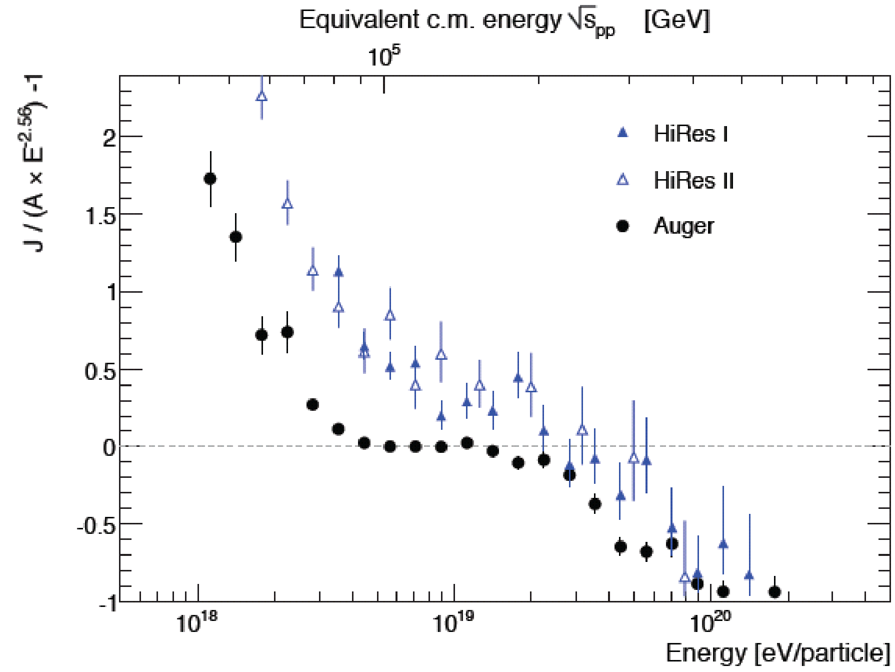
Pierre Sokolsky, Socor, June 2009

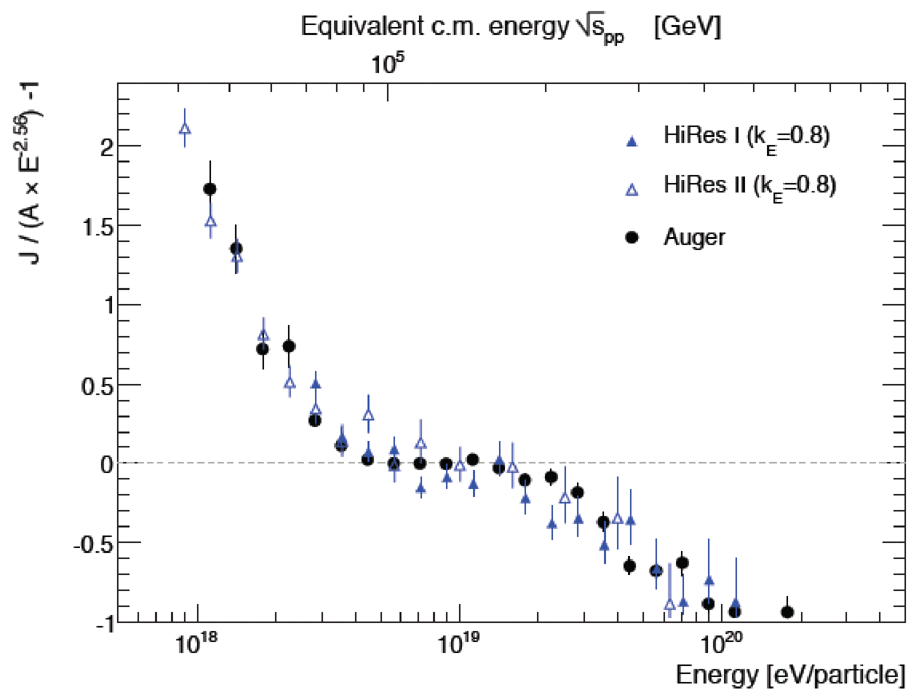
Auger spectrum compared to HiRes

M. Roth, Socor 2009



With a cosmological evolution of the source luminosity of $(z+1)^m$





UHECR propagation in CMB

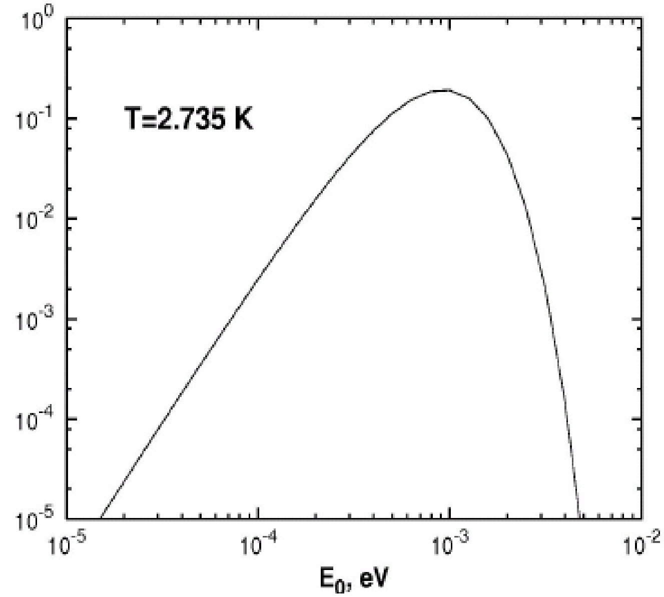
General reference:
High Energy cosmic Rays by Todor Stanev (Springer Verlag, 2004) with references to key papers by Berezinsky et al.

Basic idea was pointed out independently by Greisen and by Zatsepin & Kuz'min in 1965 right after discovery of the CMB

400 CMB photons/cm^3, $\varepsilon \sim 10^{-3}$ eV

$\sigma \sim 3 \times 10^{-28}$ cm^2 at Δ resonance

$d \sim 1 / \rho\, \sigma \sim 10^{25}$ cm = 3 Mpc



Cross section for photoproduction

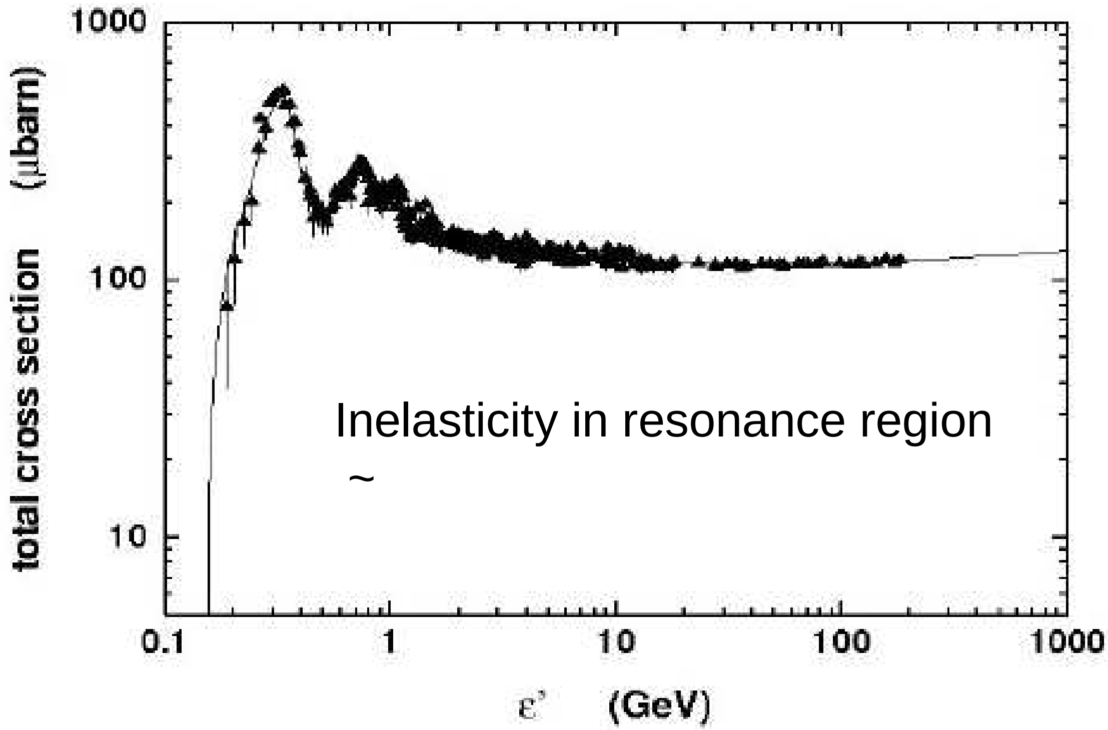
Photoproduction interactions

p + γ = p + π + ...

$$s = m_p^2 + 2E_p\epsilon(1-\beta_p\cos\theta)$$

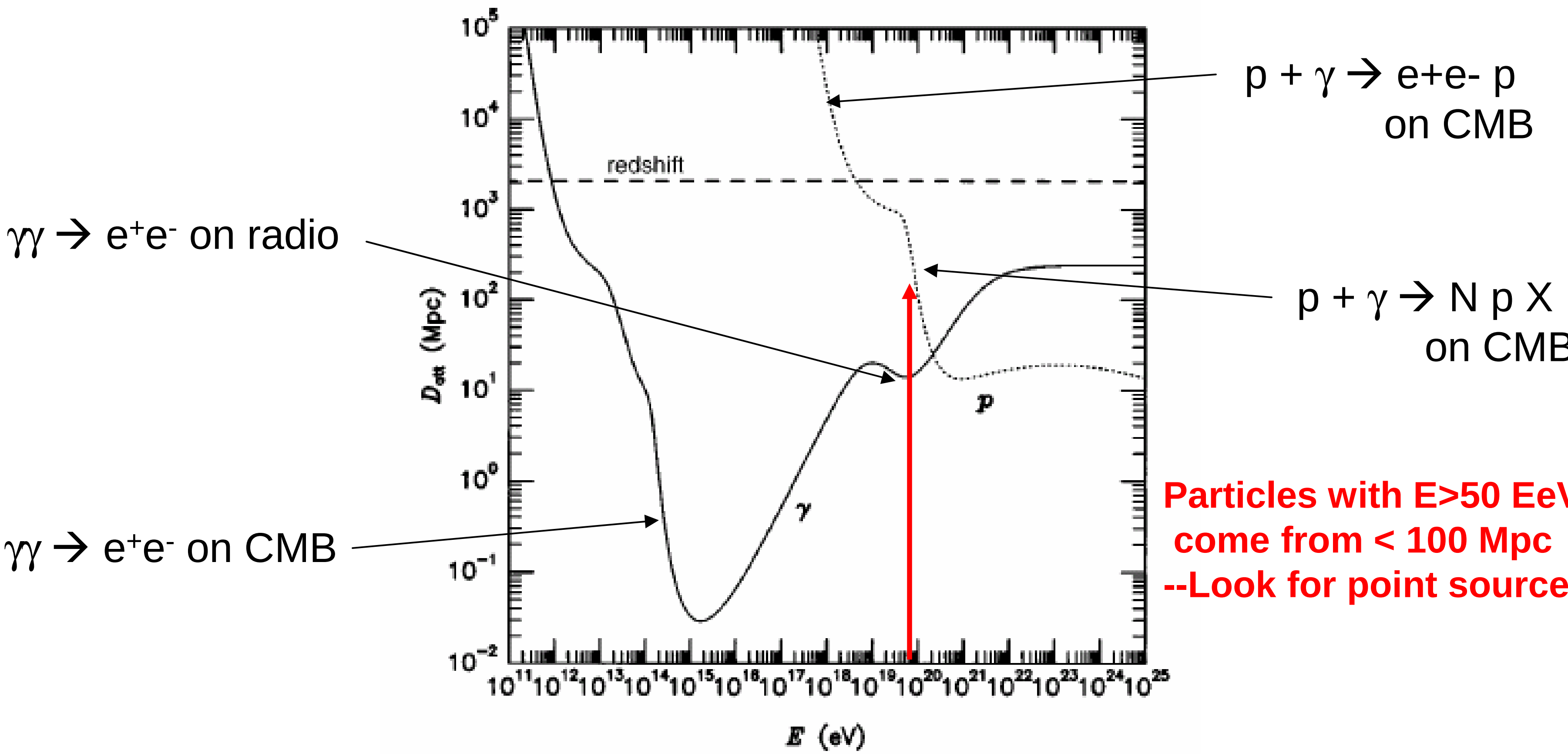
$$E_p = \frac{m_{\pi^0}}{4\epsilon}(2m_p + m_{\pi^0}) \simeq 10^{20}\,\mathrm{eV}\,.$$

ε' is the photon energy in the proton frame, where the energy threshold is 0.13 GeV



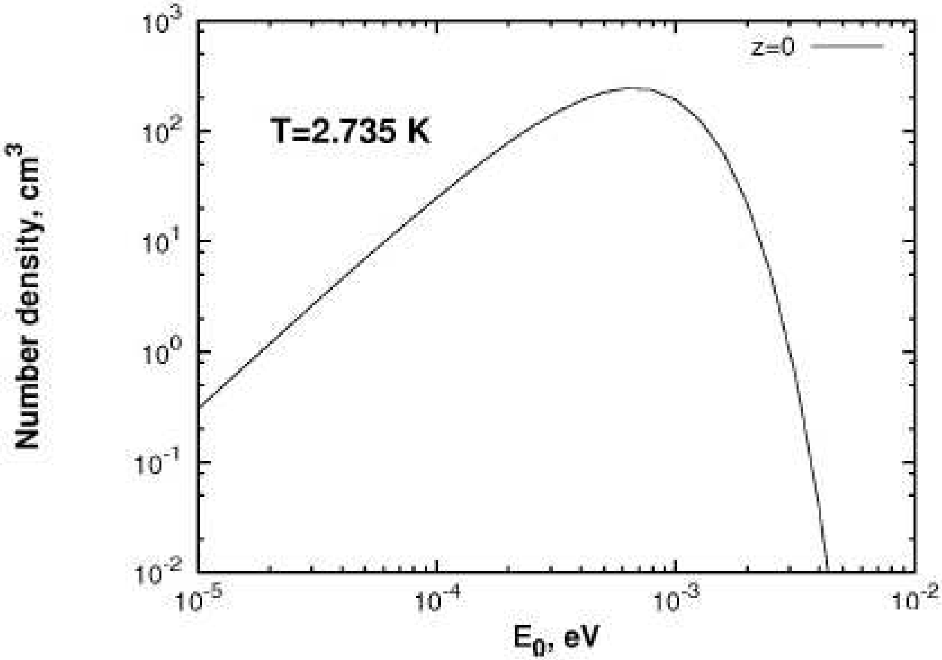
Energy loss in CMB + radio

SANGJIN LEE **PR D58 (1998) 043004**



Particles with E>50 EeV
come from < 100 Mpc
--Look for point sources

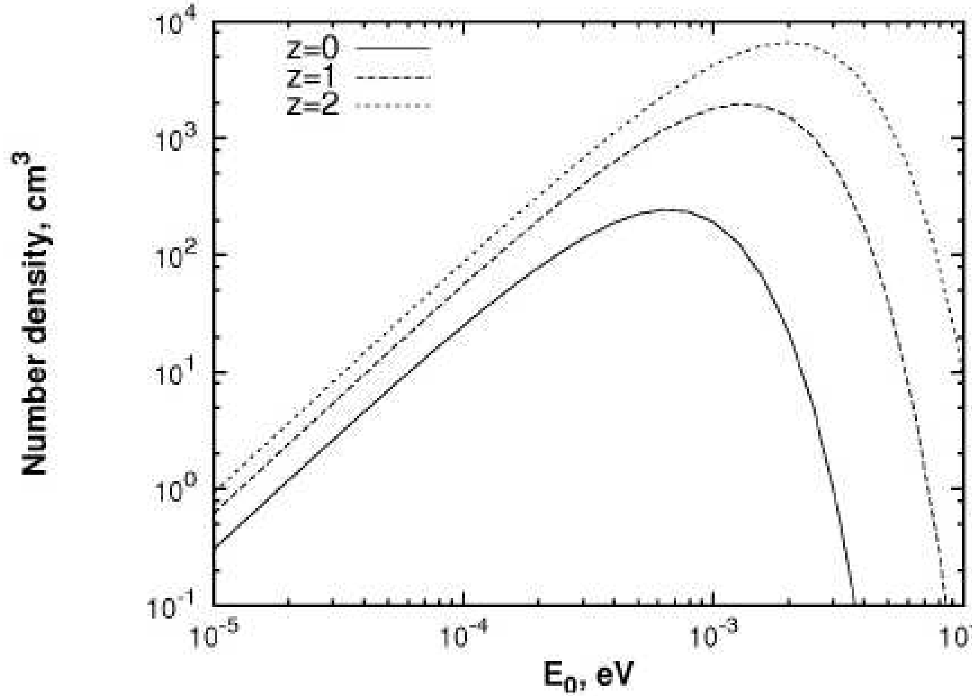
FIG. 10. The energy attenuation lengths for cascade photons and for protons as a function of energy assuming the radiation background photon spectrum shown in Fig. 2. These curves were obtained by running the code over small distances and ignoring the production of non-leading particles, which corresponds to the CEL approximation.



Current number density of MBR

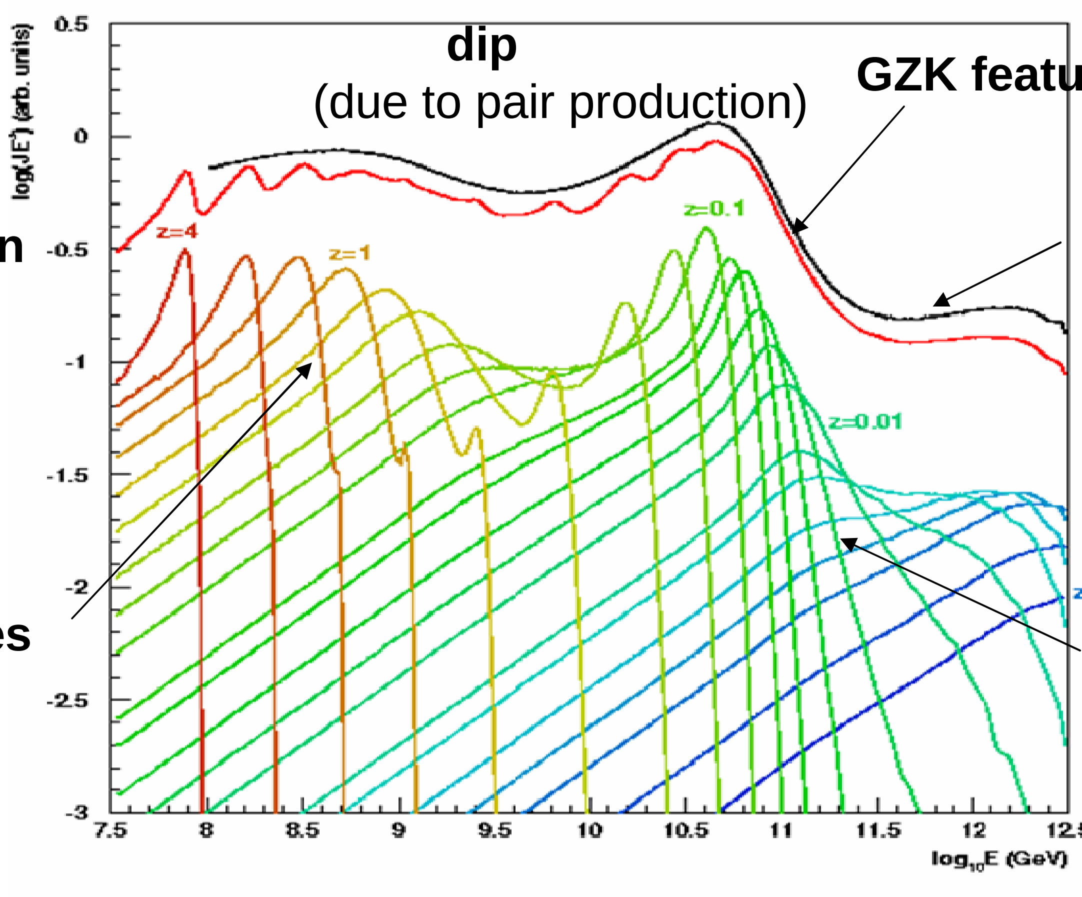
Cosmological evolution of CMB
(Todor Stanev)

Evolution of the mbr number density with redshift. The mbr number density increases as $(1 + z)^3$. Energy increases as $(1 + z)$, i.e. Total luminosity increases as $(1 + z)^4$.



(de) constructing the extra-galatic spectrum

End of Galactic population
(not shown)



recovery
(depends on source density)

Distant sources
Contribution depends on evolution and propagation in $B_{extra\text{-}galactic}$

Nearby sources
clustering, anisotropy?

Doug Bergman et al. (HiRes), Proc 29th ICRC, 7 (2005) 315

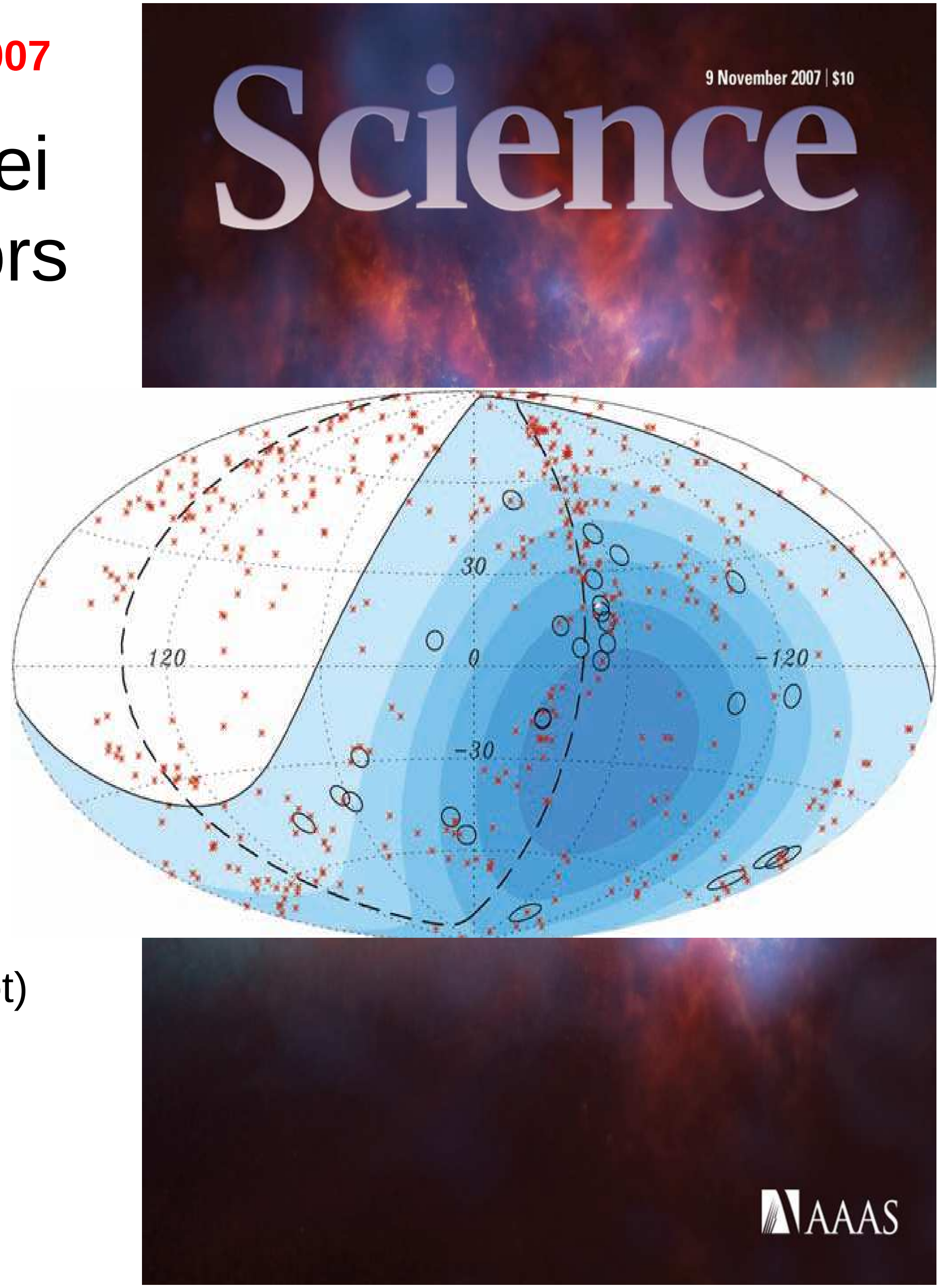
2007

Active Galactic Nuclei as cosmic accelerators

Auger Collaboration:

20 of 27 events with E > 57 EeV
are within 3.1 degrees of an AGN
less than 75 Mpc away.
Centaurus-A (4 Mpc, white dot) is
especially prominent.
(57 EeV = 0.01 Joule)
(1 Mpc = 3 million light years)

- AGN are cosmic accelerators
- Accelerated protons may (or may not) interact in or near the sources to produce neutrinos
- Neutrinos could discriminate



Auger AGN correlation – ICRC 2009

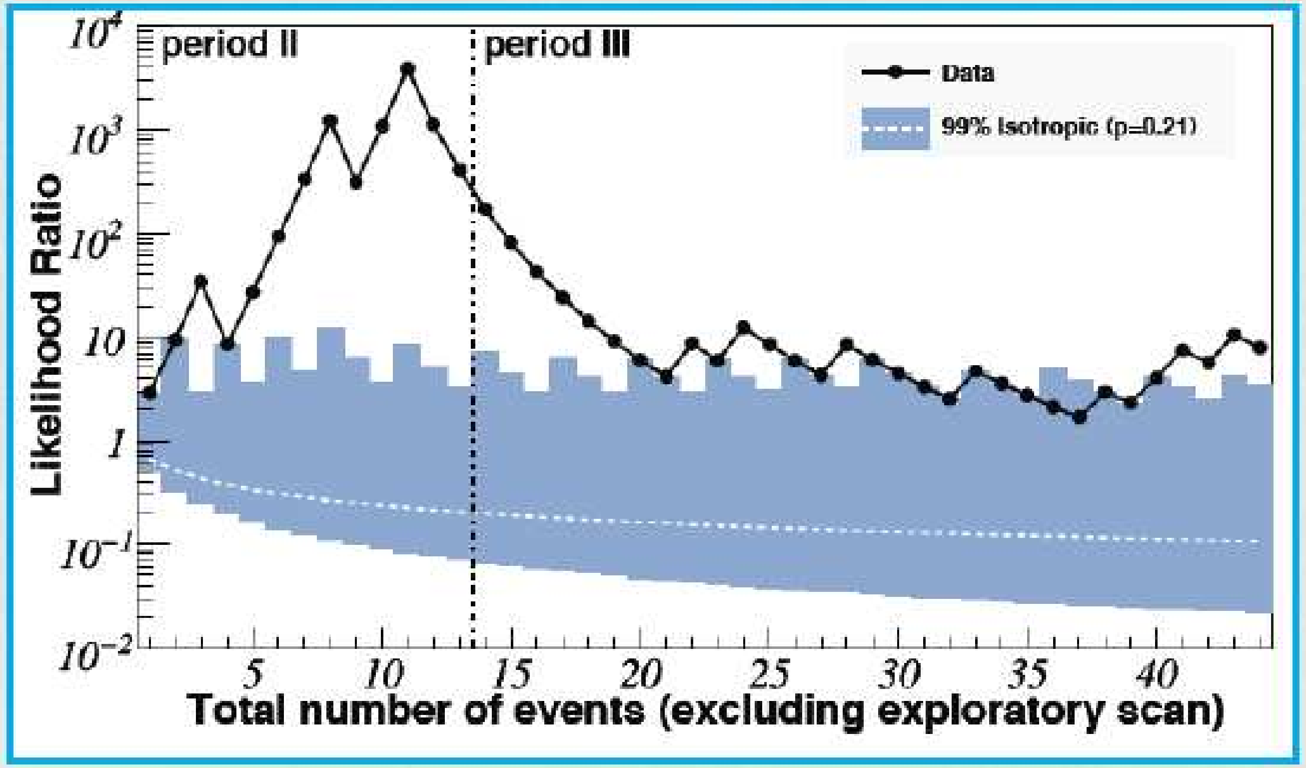
- Data to 31 August 2007 (*Science*, 9 November 2007)
  - Control sample: 14 events used to define cuts
  - After control sample, 9 of 13 with E > 55 EeV events fell within 3.1^o of a nearby (z < 0.018) AGN in the VCV catalog
- Data from 01 Sept 2007 – 31 March, 2009
  - 8 of 31 events satisfy criteria
- Total data after control sample
  - 17 of 44 events satisfy pre-determined criteria
  - Chance probability < 1% from an isotropic distribution
- Note prominence of area around Cen-A
  - Could see γ from first generation p + CMB $\rightarrow$ p + π^0
    - Taylor et al., arXiv:0904.3903

Piera Ghia, Auger Collaboration, TeV PA 2009

ADDING NEW DATA: 27/5/2006-31/3/2009

$$R = \frac{\int_{p_{iso}}^{1} p^k (1-p)^{N-k}\, dp}{{p_{iso}}^k (1-p_{iso})^{N-k+1}}$$

Likelihood ratio: binomial probability of correlation over binomial probability in isotropic case (p_{iso}=0.21)

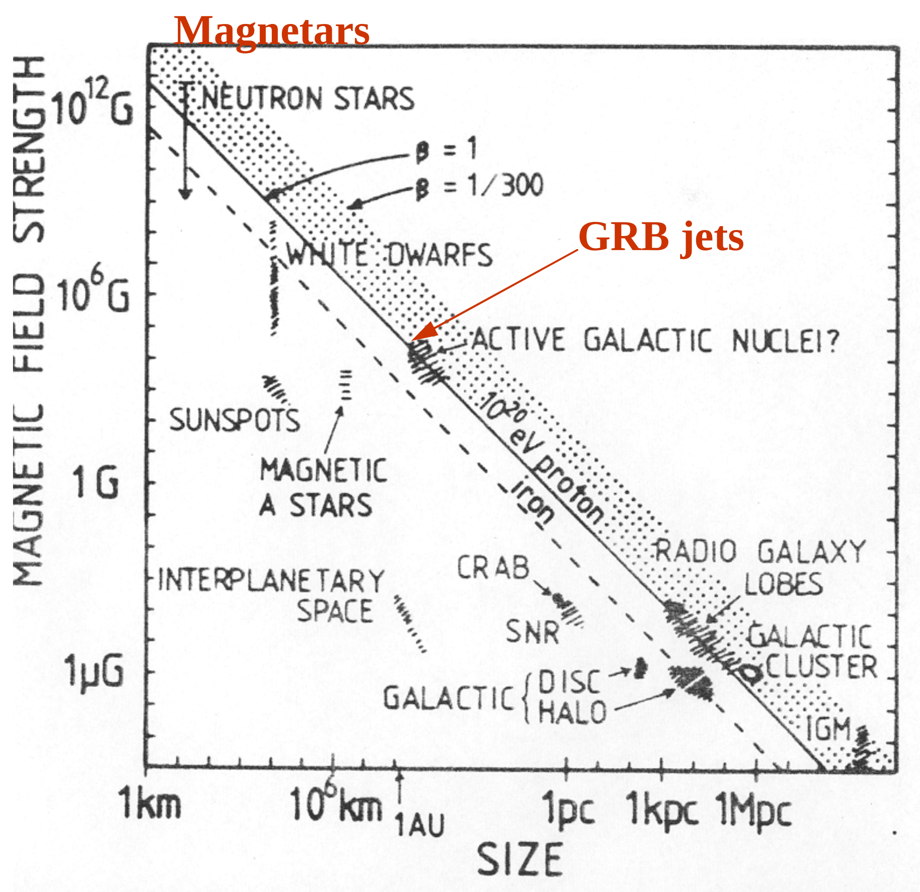


17/44 EVENTS IN CORRELATION (P=0.006)

ISOTROPY STILL REJECTED AT 99% C.L.

The "Hillas Plot" (1984)

- $E_{max} \sim \beta_{shock}$ (ZeB) R
- Plot shows B, R to reach 10^{20} eV
- Since 1984, two more candidates
- Active Galaxies, Gamma-ray Bursts are favored

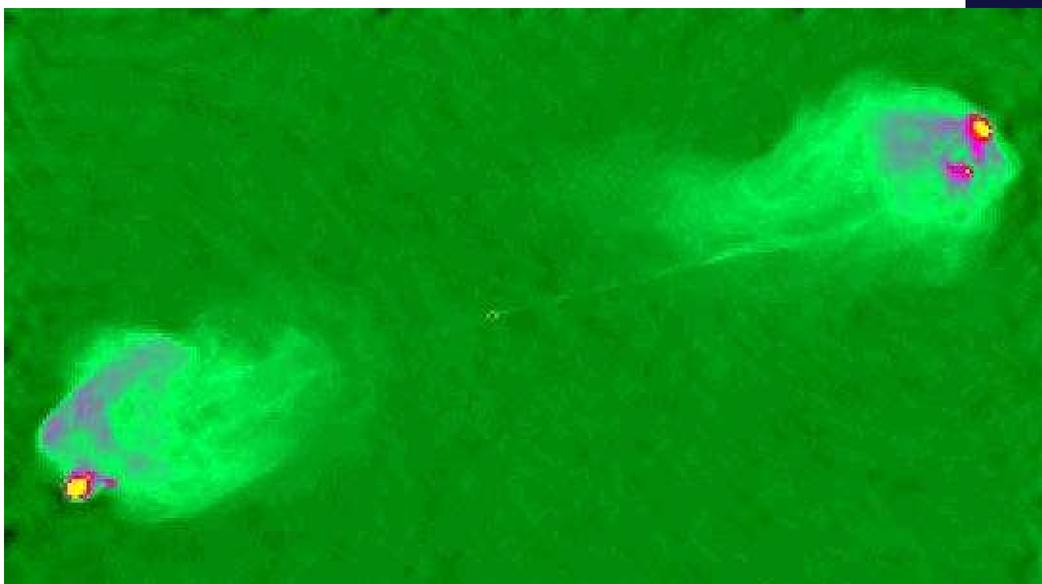


Accretion and astrophysical jets

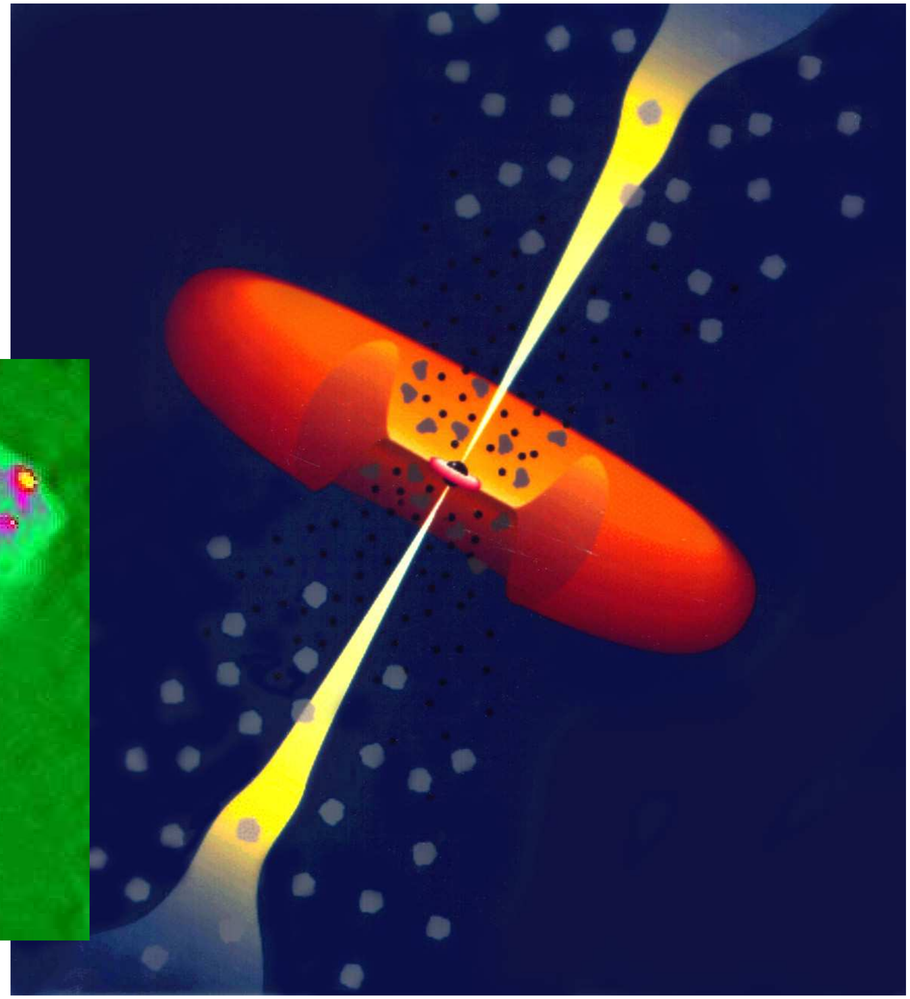
A common phenomenon on both stellar & galactic scales:

Matter falls onto black hole or neutron star driving collimated, relativistic jets perpendicular to the disk

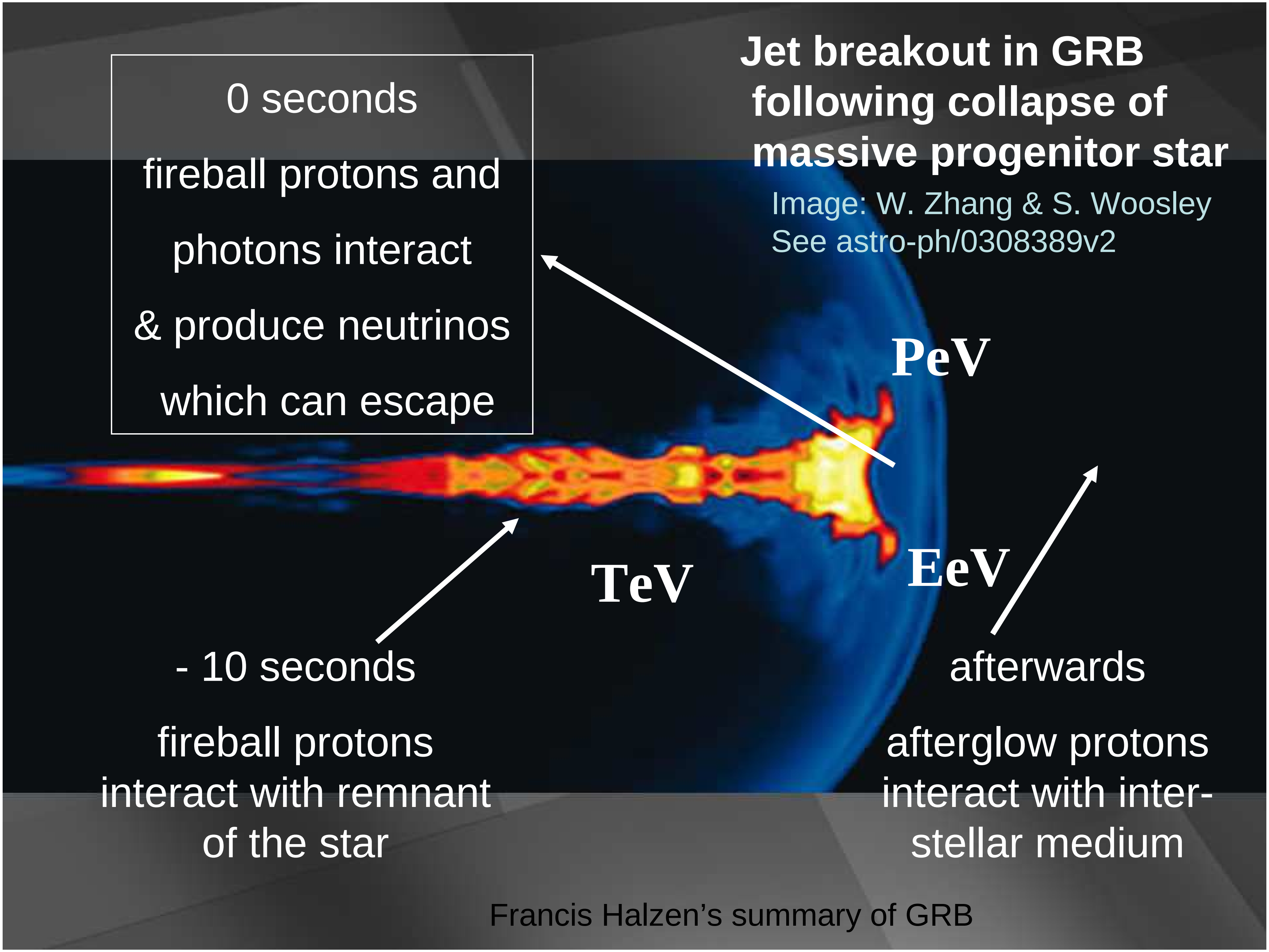
Acceleration can occur both at remote termination shocks and at internal shocks near the central engine



VLA image of Cygnus A
An active galaxy



M. Urry, astro-ph/0312545

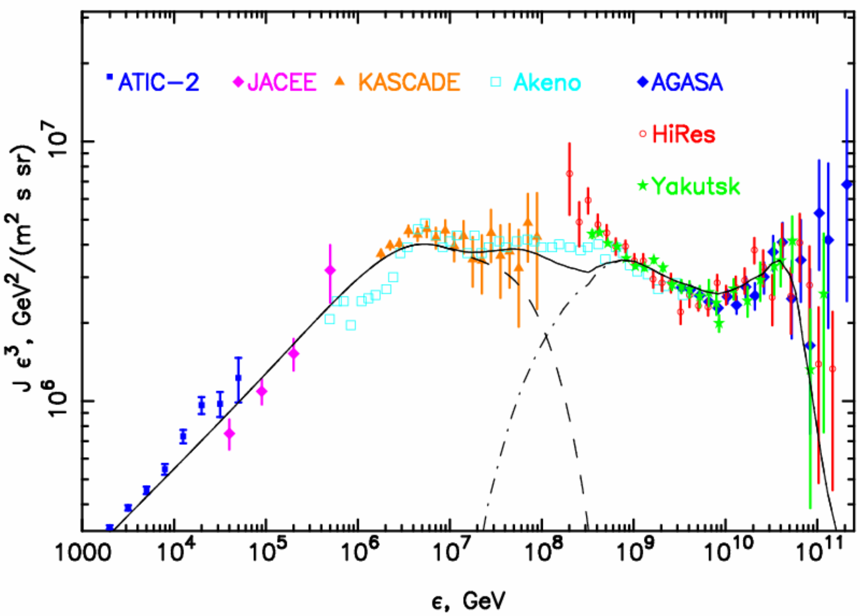

Jet breakout in GRB following collapse of massive progenitor star
Image: W. Zhang & S. Woosley
See astro-ph/0308389v2
0 seconds
fireball protons and photons interact & produce neutrinos which can escape
PeV
TeV
EeV
- 10 seconds
fireball protons interact with remnant of the star
afterwards
afterglow protons interact with inter-stellar medium
Francis Halzen’s summary of GRB

Where is the transition from galactic to extra-galactic CR?

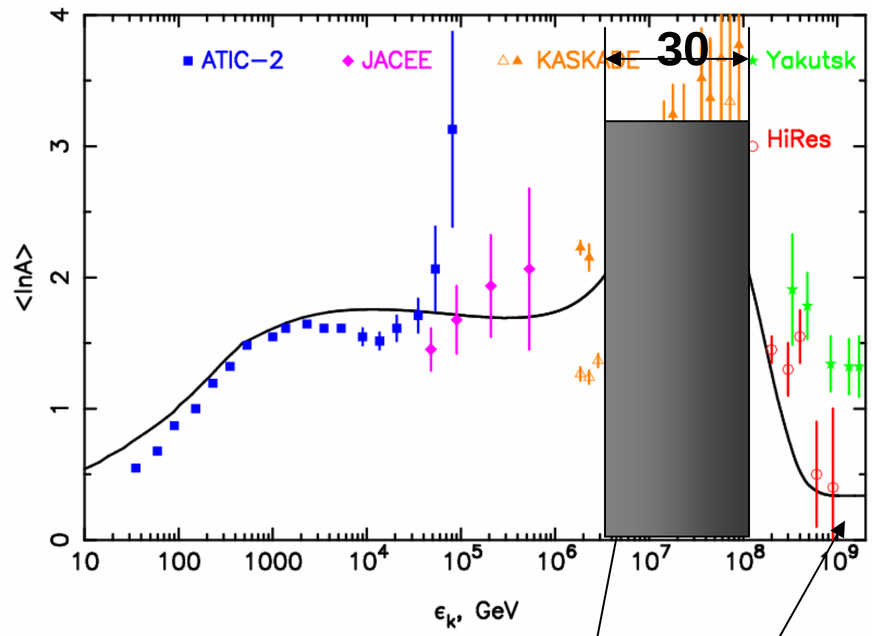
- Model galactic component
- Subtract from observed
  to get extragalactic

Transition predicted:

$10^{16.5}$ to $10^{17.5}$ eV



Berezhko & Völk
arXiv:0704.1715v1 [astro-ph]



Heavies at end of galactic

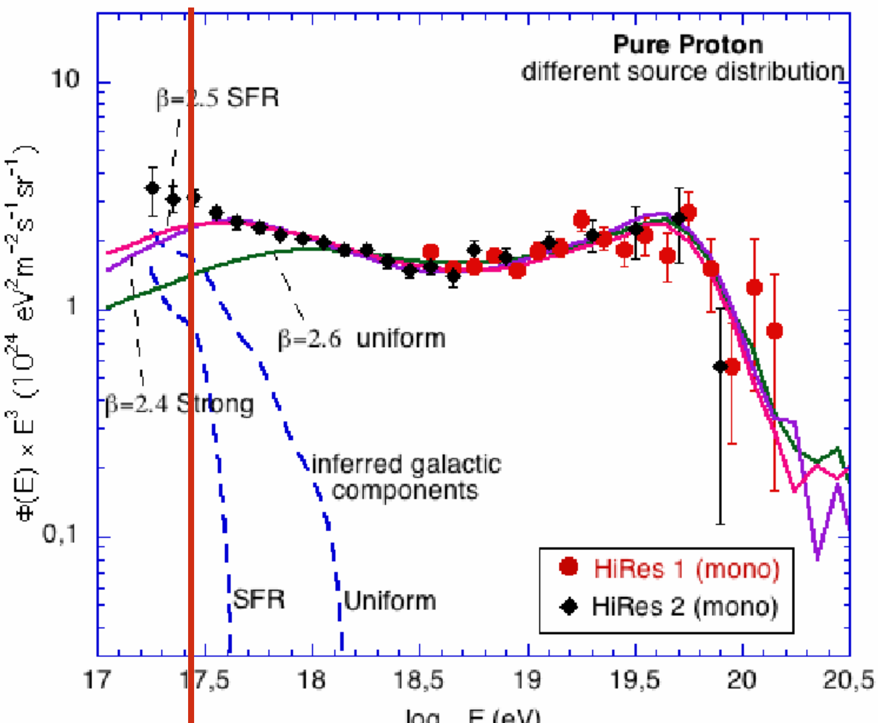
Extra-galactic protons

Or start with a model of the extra-galactic component

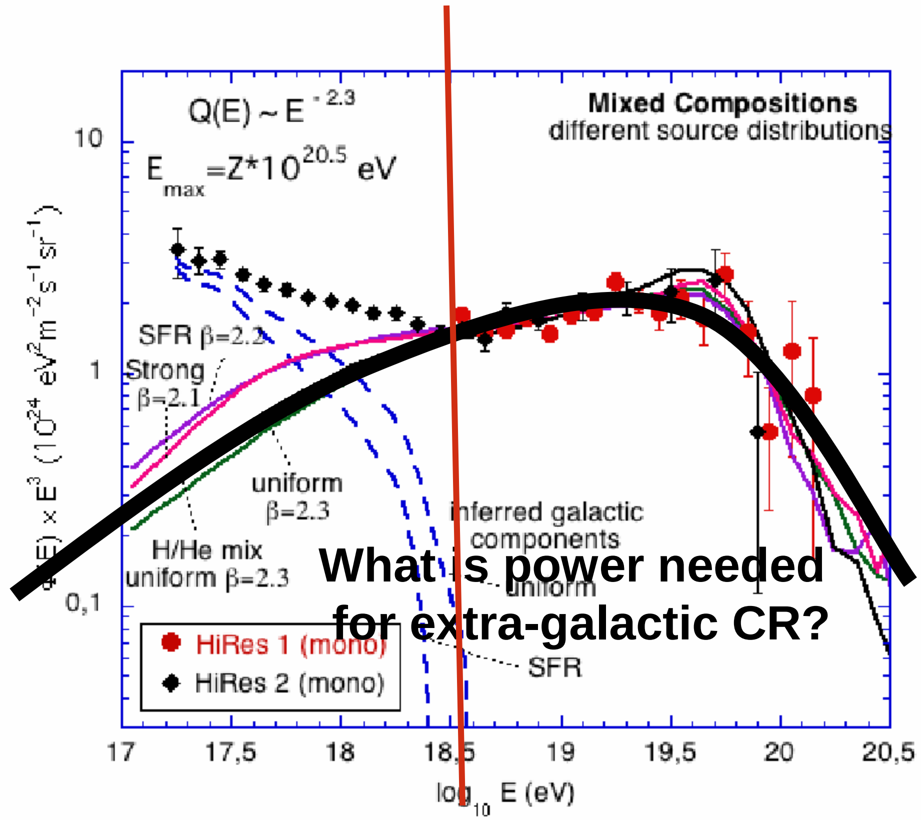
Subtract it from the observed spectrum to get the galactic component

Allard, Olinto, Parizot,
Astron. Astrophys. 473 (2007) 59

3 x 10^17eV



3 X 10^18 eV



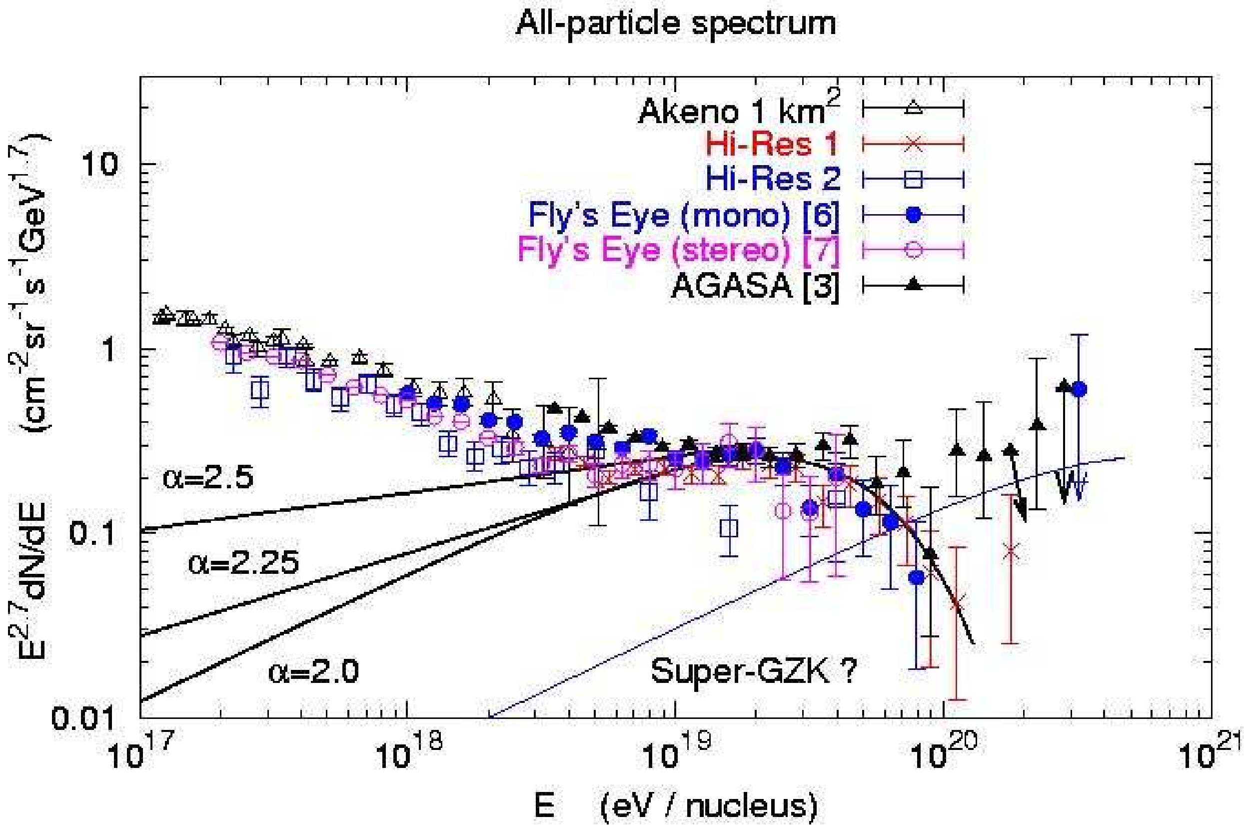
Energy content of extra-galactic component depends on location of transition

- Composition signature: transition back to protons

Uncertainties:

- Normalization point:
  - 10^{18} to $10^{19.5}$ used
  - Factor 10 / decade

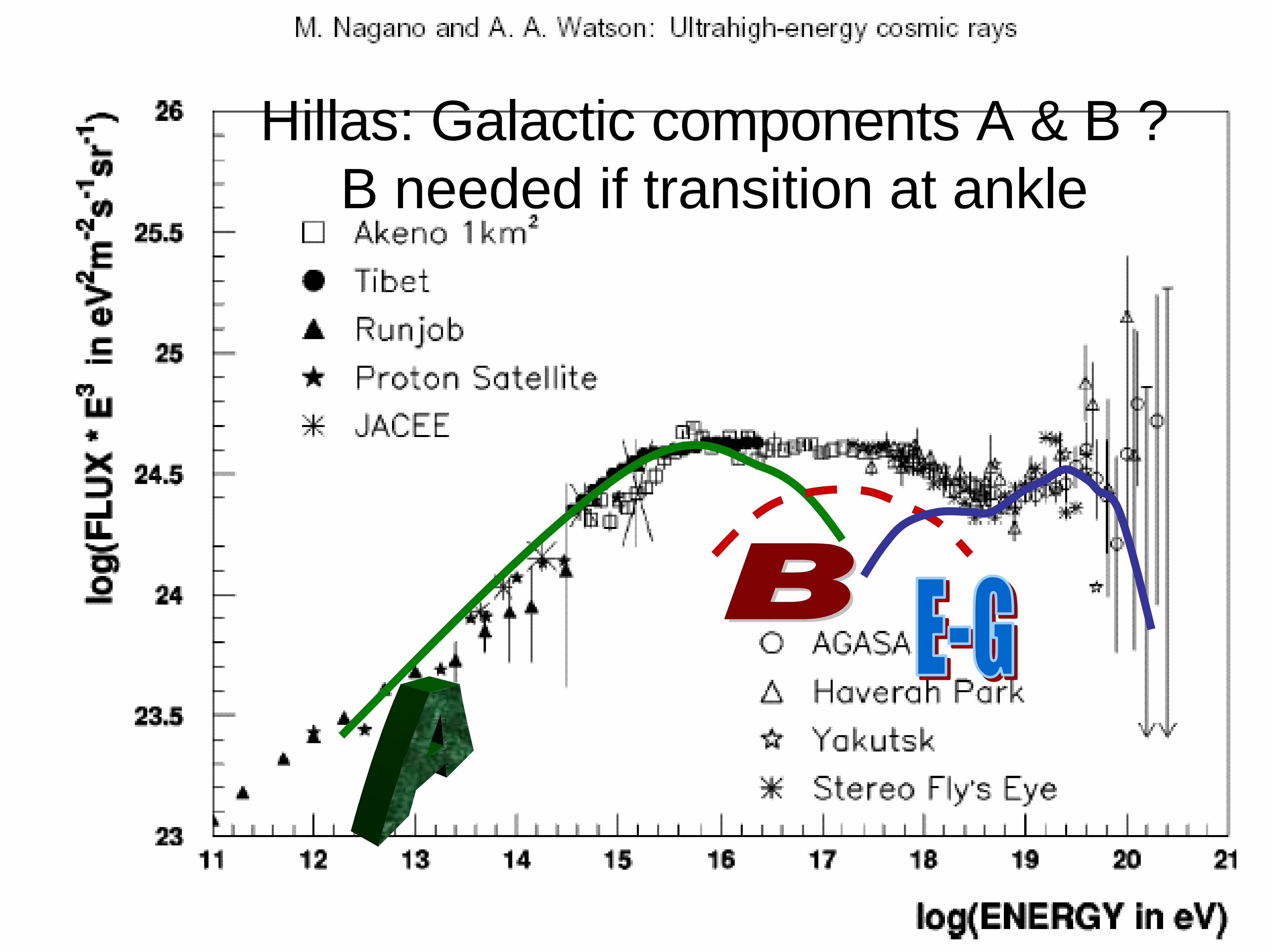
- Spectral slope
  - Steeper spectrum requires more power
  - (α=2.3 for rel. shock
  - But $E_{min} \sim m_p (\gamma_{shock})^2$)



Power needed for extragalactic cosmic rays assuming transition at 10^{19} eV

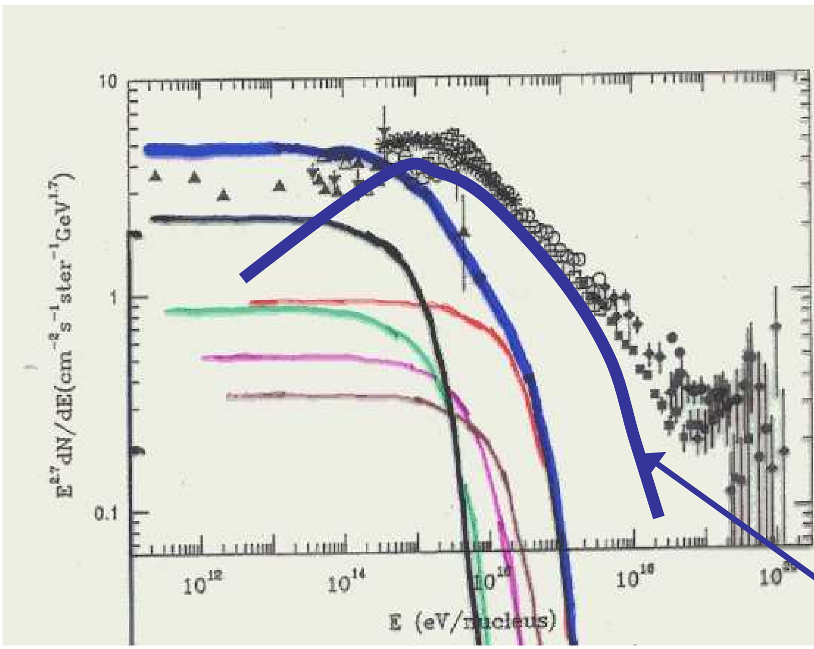
- Energy density in UHECR, $\rho_{CR} \sim 2 \times 10^{-19}$ erg/cm^3
  - Such an estimate requires extrapolation of UHECR to low energy
  - $\rho_{CR} = (4\pi/c) \int E\phi(E)\, dE = (4\pi/c)\{E^2\phi(E)\}|_{E=10^{19}eV} \times ln\{E_{max}/E_{min}\}$
  - This gives $\rho_{CR} \sim 2 \times 10^{-19}$ erg/cm^3 for differential index $\alpha = 2$, $\phi(E) \sim E^{-2}$
- Power required $\sim \rho_{CR}/10^{10}$ yr $\sim 1.3 \times 10^{37}$ erg/Mpc^3/s
  - Estimates depend on cosmology and assumed spectral index:
  - 3×10^{-3} galaxies/Mpc^3 — 5×10^{39} erg/s/Galaxy
  - 3×10^{-6} clusters/Mpc^3 — 4×10^{42} erg/s/Galaxy Cluster
  - 10^{-7} AGN/Mpc^3 — 10^{44} erg/s/AGN
  - ~1000 GRB/yr — 3×10^{52} erg/GRB

Hillas: Galactic components A & B ?
B needed if transition at ankle



Power for “B” component

Emax = Z x 1 PeV



Depends on

- diffusion model, $\tau(E)$
- γ of source acceleration
- onset of extra-galactic

Galactic “B” component

Power needed for knee B-component

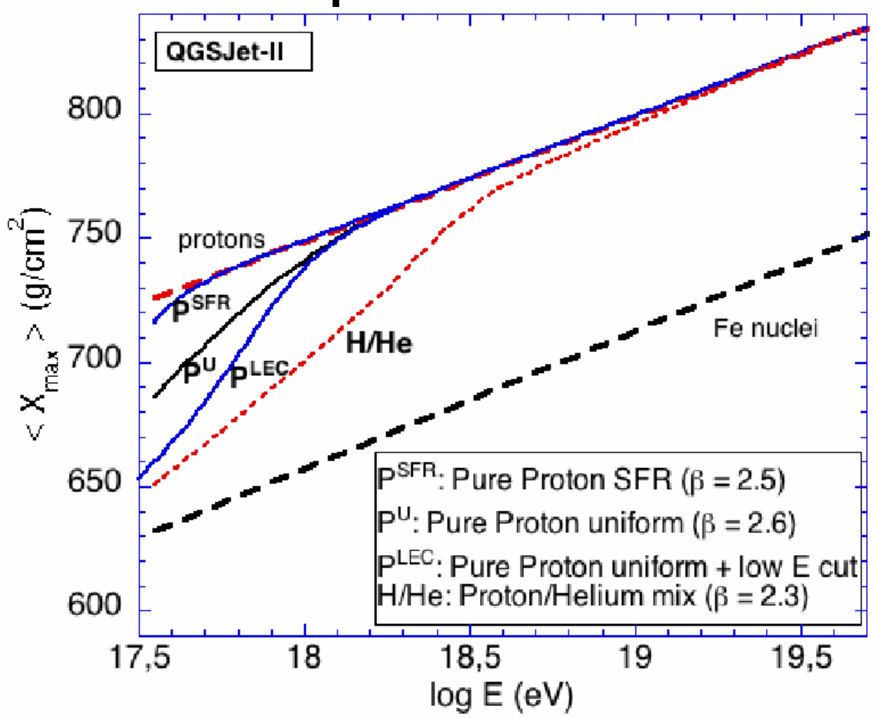
- Integrate to $E > 10^{18}$ eV assuming
  - $\tau_{esc} \sim 2 \times 10^7$ yrs x $E^{-1/3}$
  - source spectral index ~ 2.1
  - $V_{galaxy} \sim \pi\,(15\text{ kpc})^2 \times 200\text{ pc} \sim 3 \times 10^{66}\text{ cm}^3$
  - Total power for “B” component ~2×10^{39} erg/s
- Possible sources
  - Sources may be nearby
  - e.g. μ-quasar SS433 at 3 kpc has L_{jet} 10^{39} erg/s
  - Eddington limited accretion ~ 2×10^{38} erg/s
  - Neutron source at GC ~ 10^{38} erg/s
- Speculations call for more experiments

Model dependence of composition in galactic-extragalactic transition

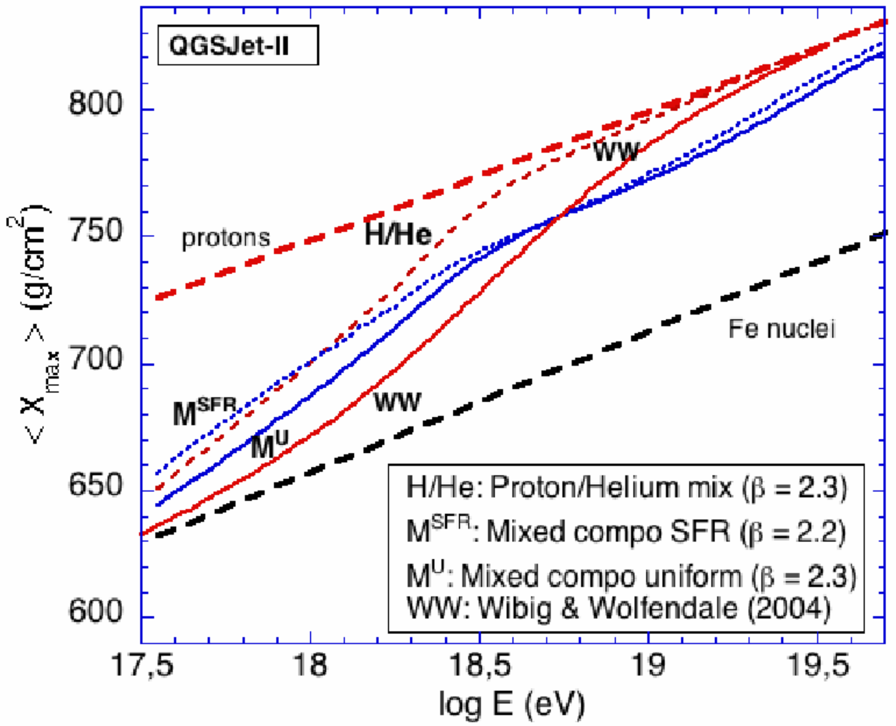
Allard, Olinto, Parizot, astro-ph/0703633
Astron. Astrophys. 473 (2007) 59

- Model extragalactic component
- Subtract from observed to get galactic component

proton model



mixed model



Primary composition with EAS? Use Xmax

Heitler's pedagogical toy model of multiplicative cascades

$N(x) \sim e^{x/\lambda}$ and $E(x) \sim E_0 / N(x)$

$N_{max}(X_{max}) = e^{X_{max}/\lambda} \equiv E_0 / E_{critical}$

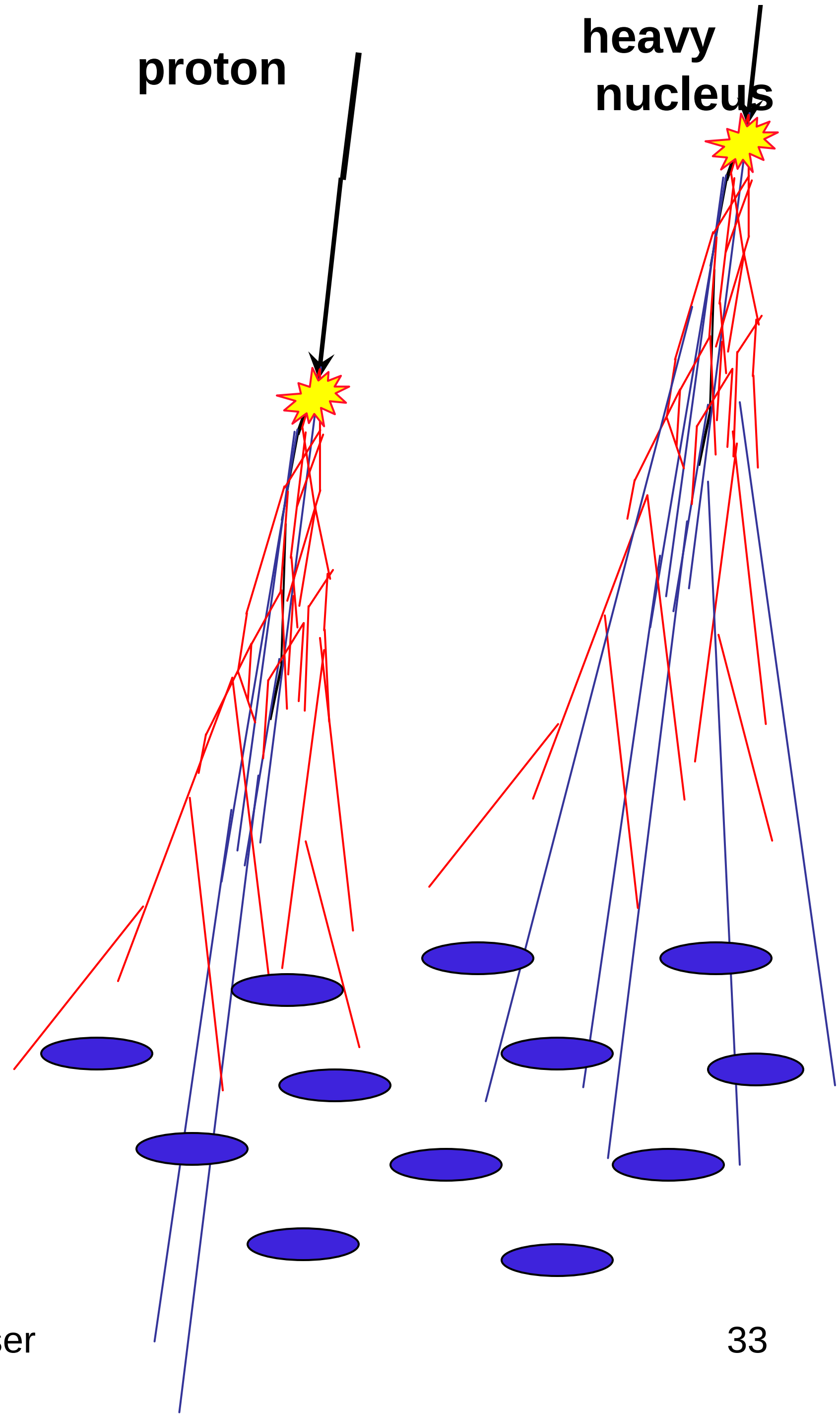
$X_{max} \sim \lambda \ln(E_0 / E_{critical})$

For a nucleus of mass A $X_{max} \sim \lambda \ln(E_0 / A \cdot E_{crit})$

and $N_{max} \sim E_0 / E_{critical}$

Composition with air showers

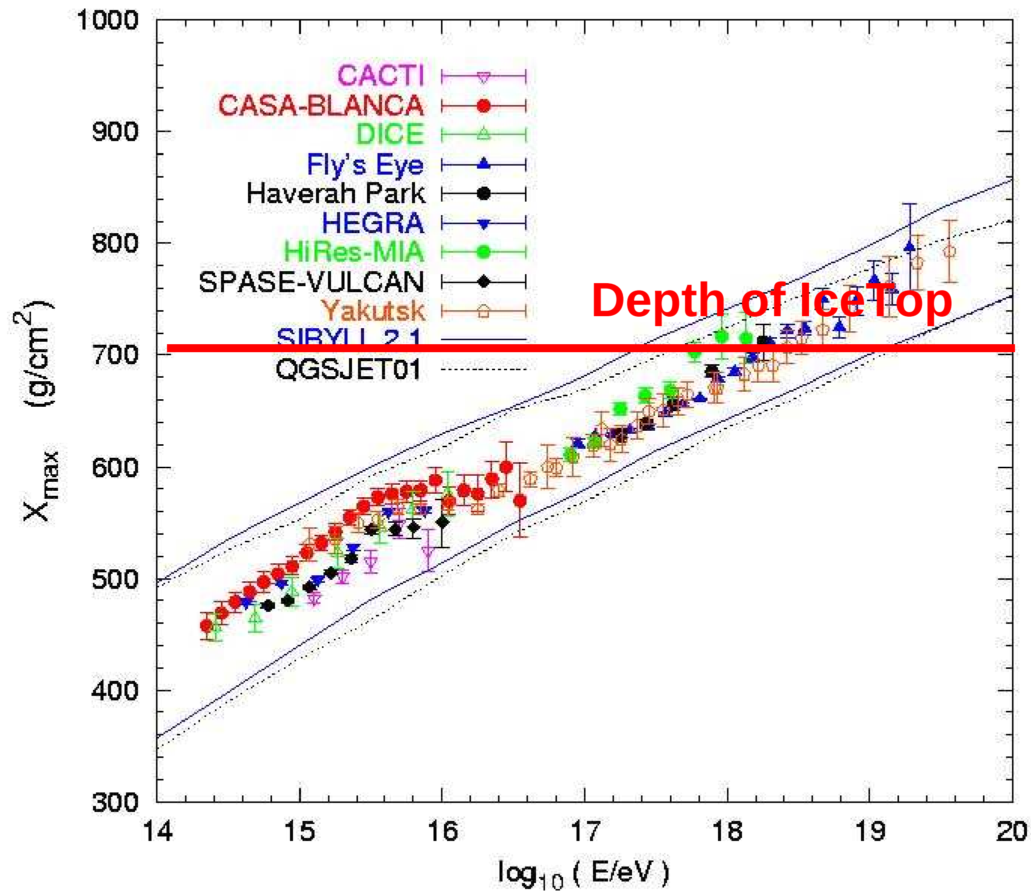
- Proton penetrates deep in atmosphere
  - Shower max deeper
  - (mu / e) smaller
  - muons start deeper
- Heavy nucleus cascade starts high
  - shower max higher up
  - (mu / e) larger
  - muons start higher

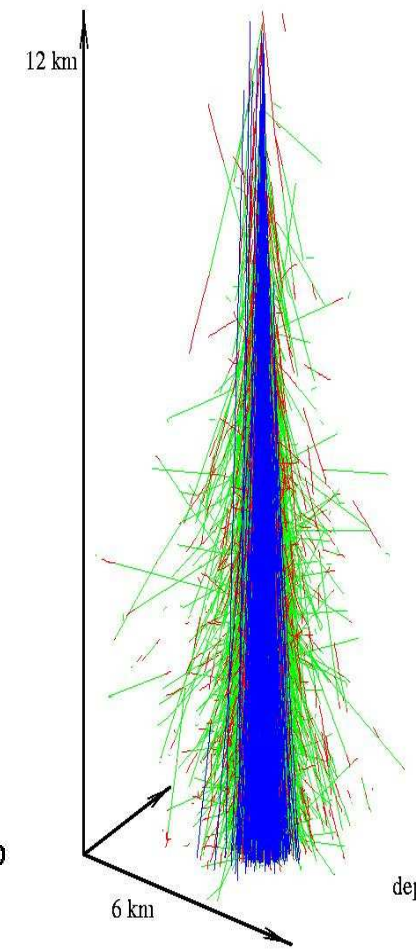


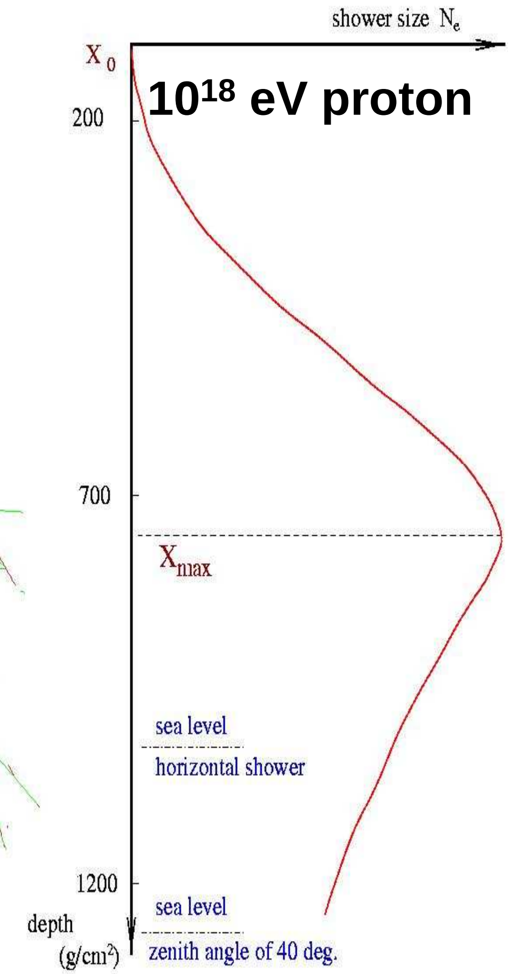
X_{max} for composition

- $\langle X_{max} \rangle = \text{const} + \Lambda \log(E / A)$
- Interpretation depends on comparison to simulations of cascade development
  - Different models give different results
  - Extrapolations to high-energy differ
    - Need minimum bias data outside central region
    - LHCf can help
- Distributions of X_{max} less model-dependent
- Also look at μ / e with ground arrays

Depth of maximum via air Cherenkov or fluorescence

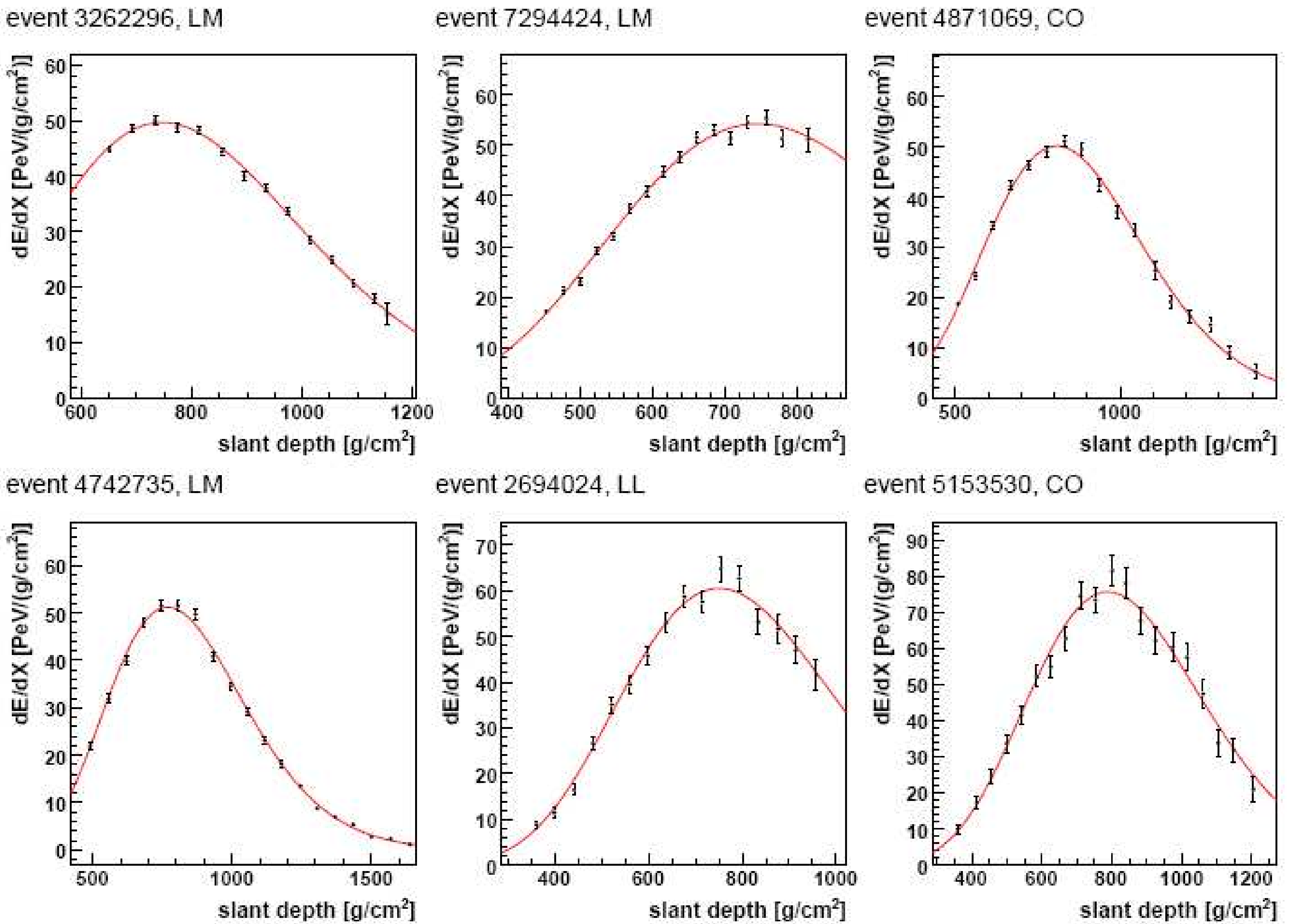






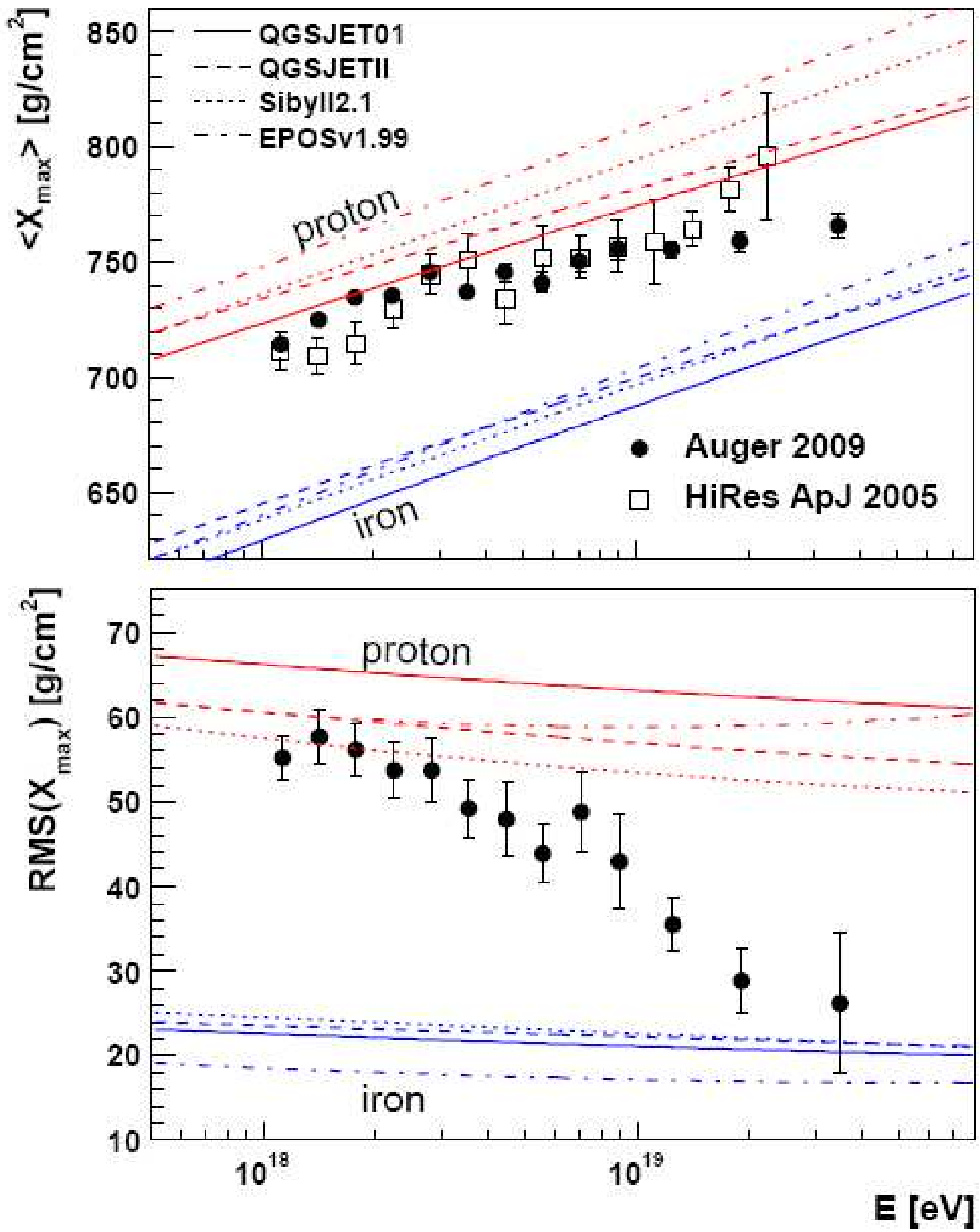
Fluorescence Detector: Longitudinal Shower Profiles

M. Unger, Socor 2009



Auger
Depth of Maximum

Auger, HiRes Comparison
M. Unger, Socor 2009



Fluctuations suggest transition to significant fraction of heavy nuclei

HiRes Xmax results consistent with protons > EeV

Pierre Sokolsky, Socor, June 2009

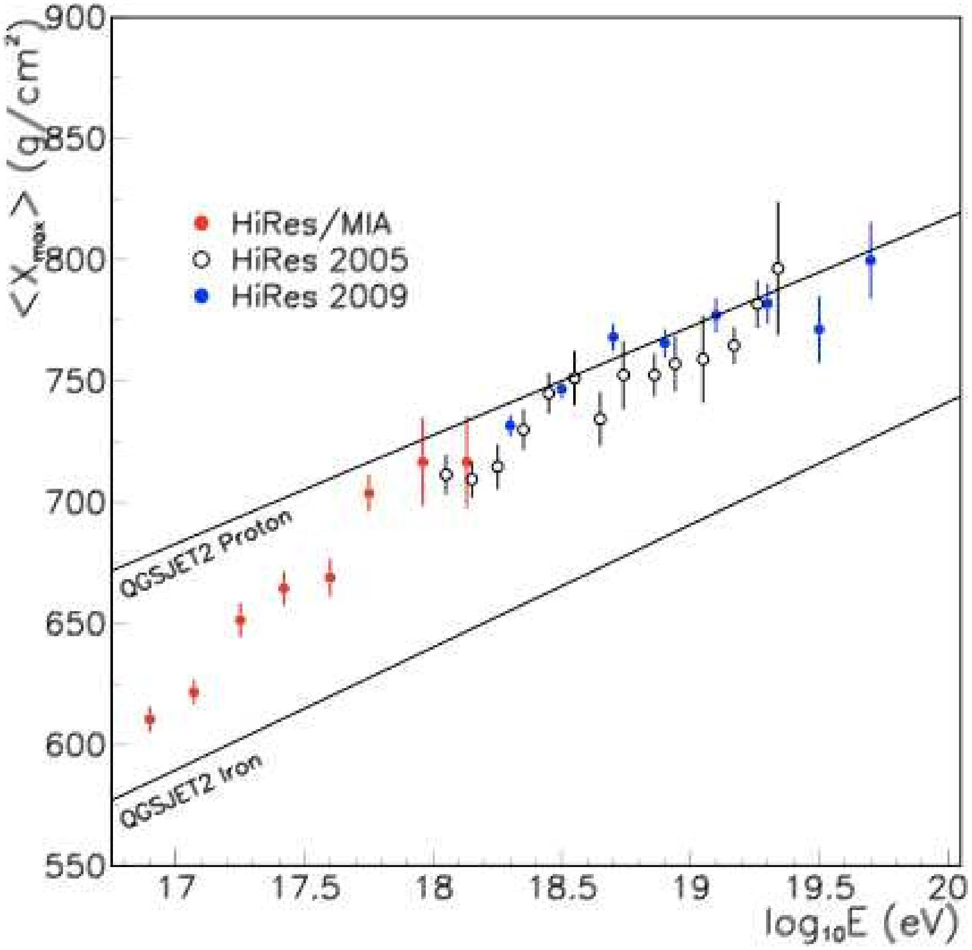


Fig. 25.— Comparison of current HiRes stereo <X_{max}> results with results from the HiRes-prototype/MIA hybrid (Abu-Zayyad et al. 2001) and previously published HiRes stereo results (Abbasi et al. 2005).

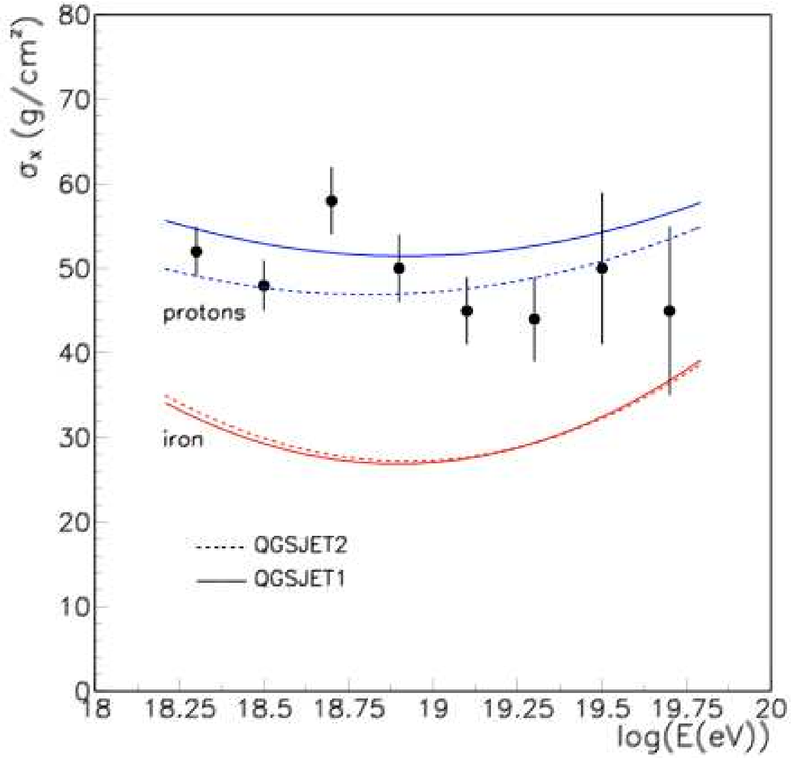
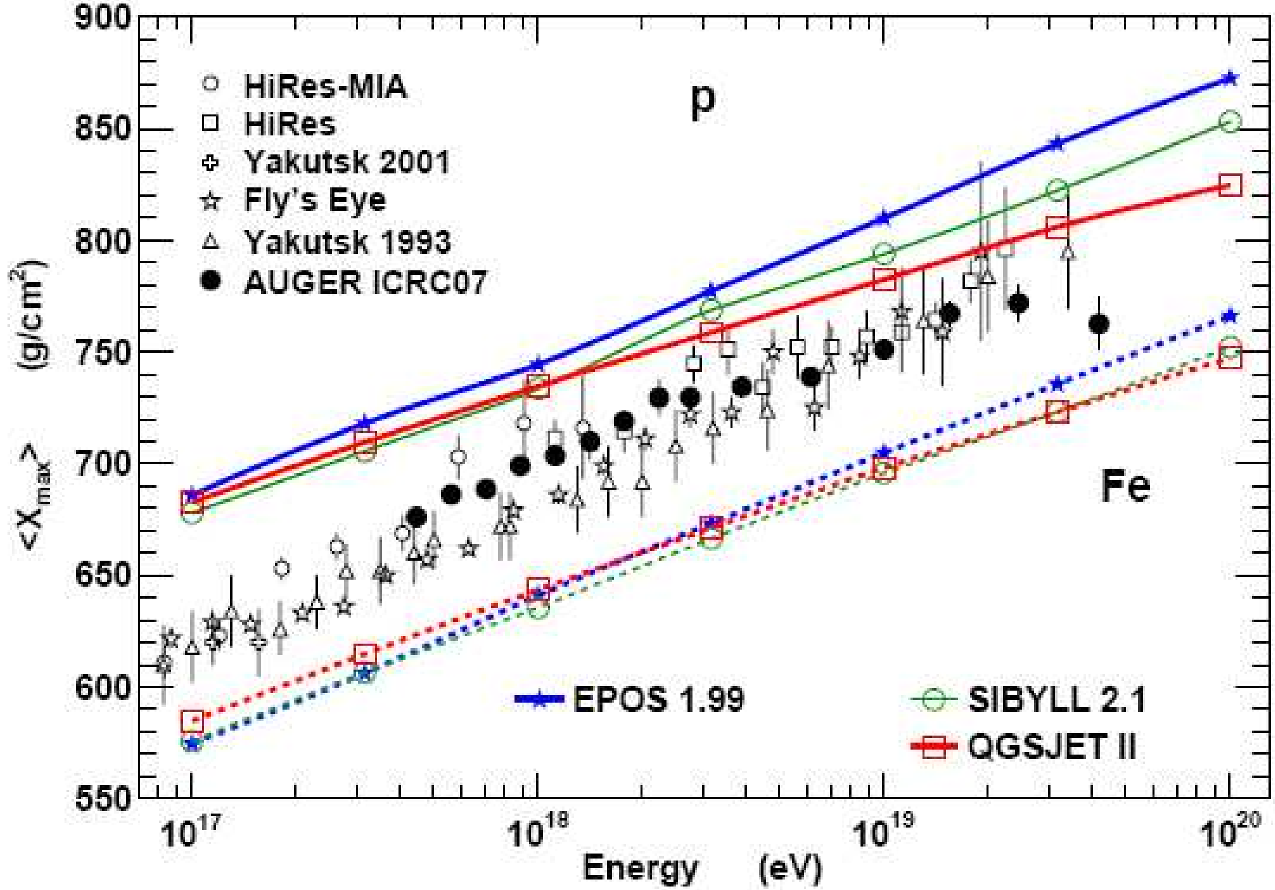


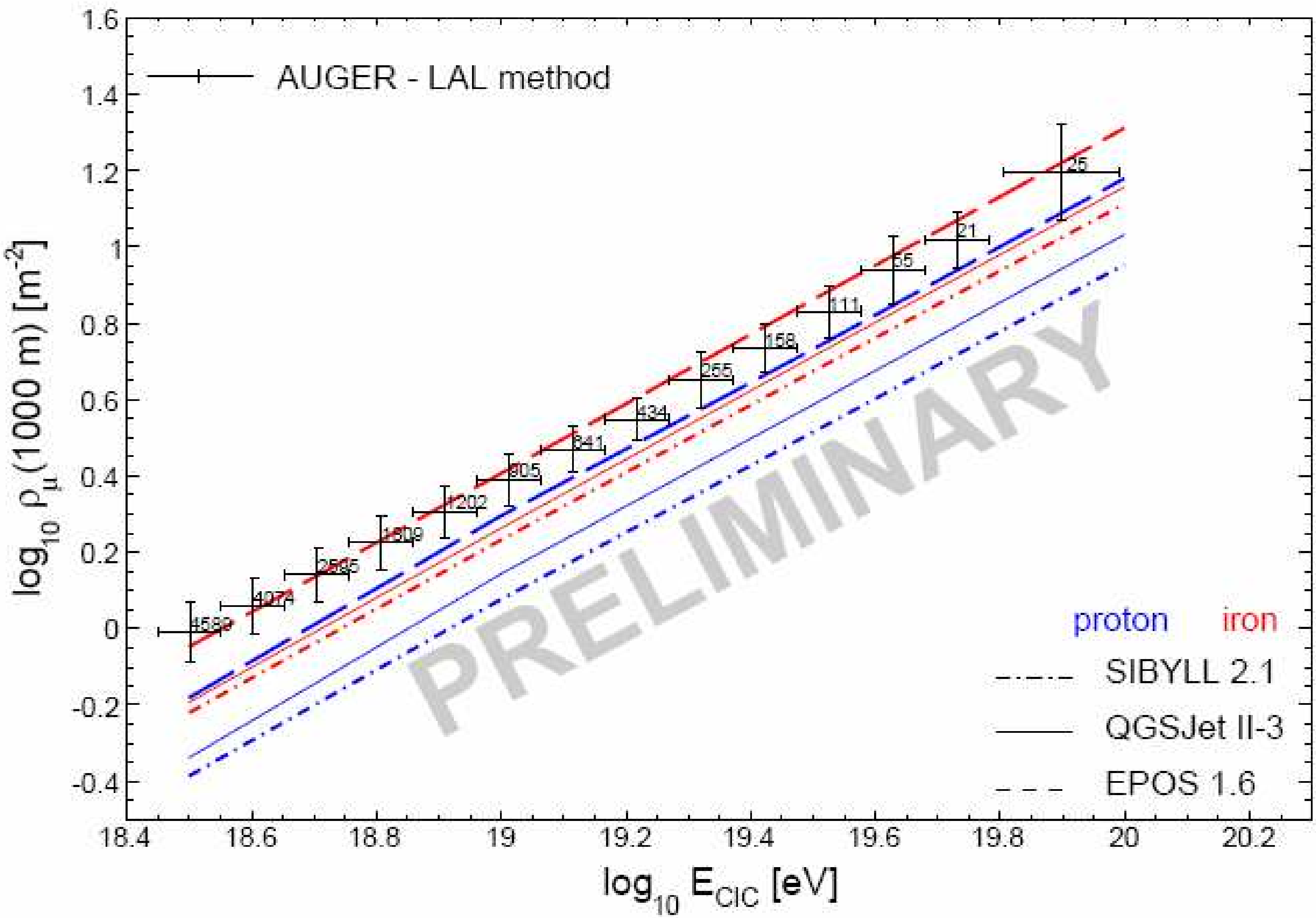
Fig. 28.— Results of fitting HiRes stereo data X_{max} distribution to Gaussian truncated at 2 × RMS (black points). Superimposed are curves representing expectations based on QGSJET1 and QGSJET2 proton and iron Monte Carlo. Gaussian-in-age parametrization used in reconstruction.

Xmax: comparison to simulations



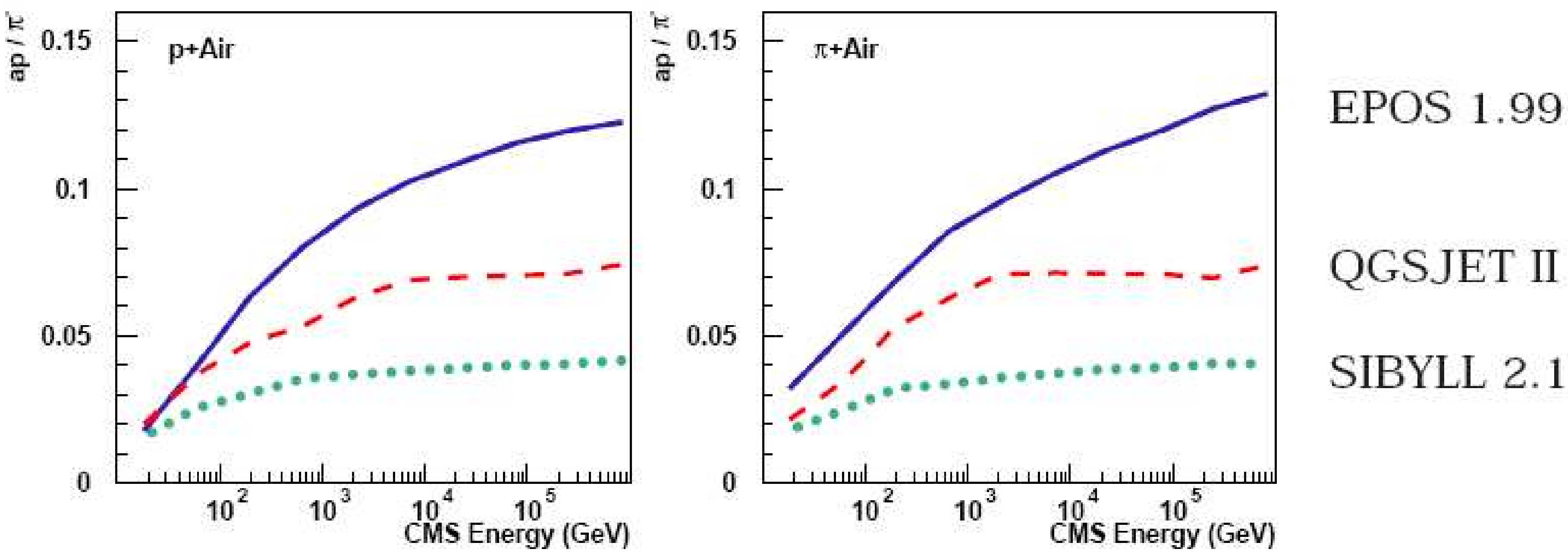
Summary of Xmax and comparison to simulations: Klaus Werner, Paris June 09

Muon density AUGER



Why more muons in EPOS ?

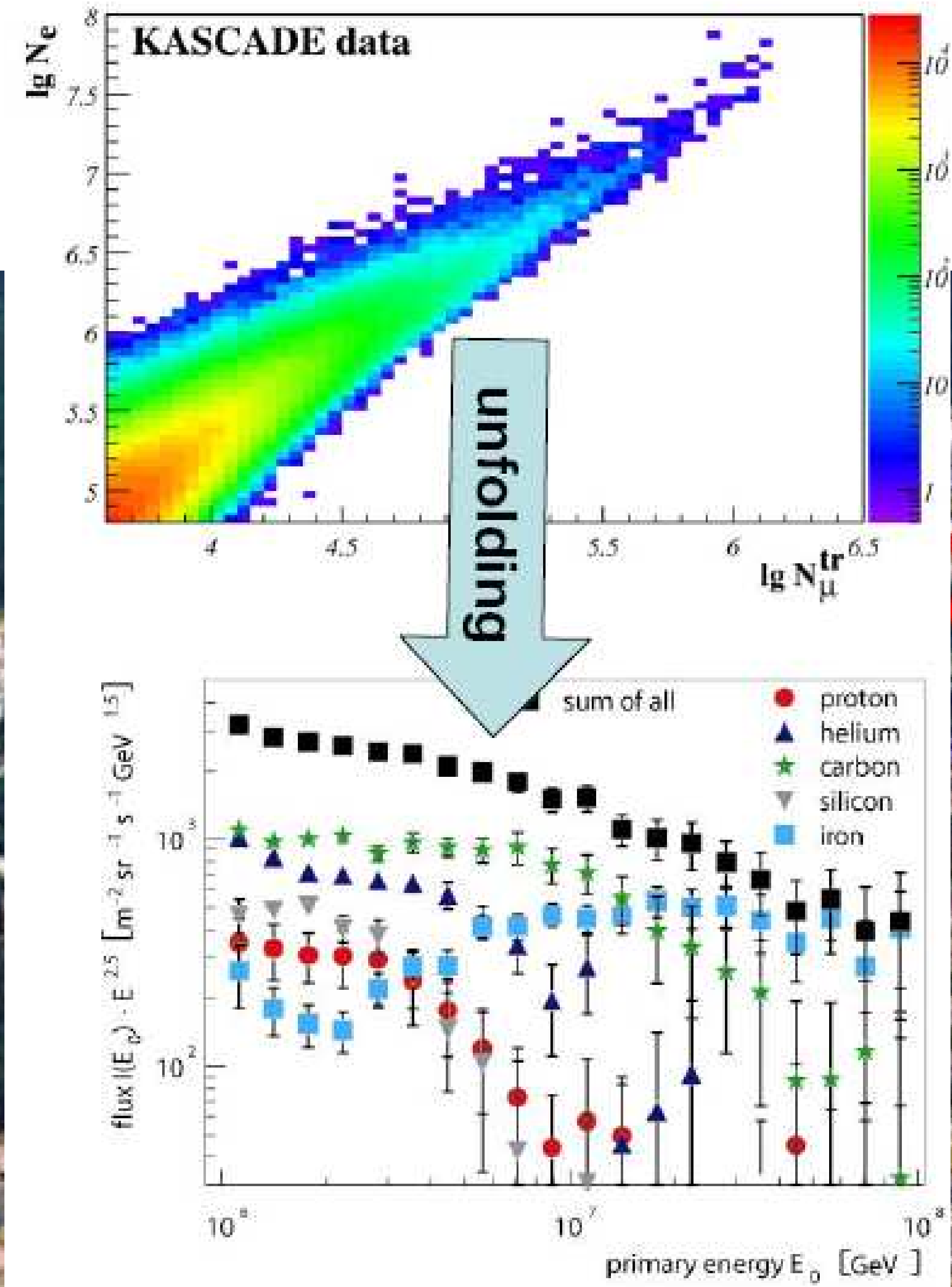
... because EPOS produces more baryons

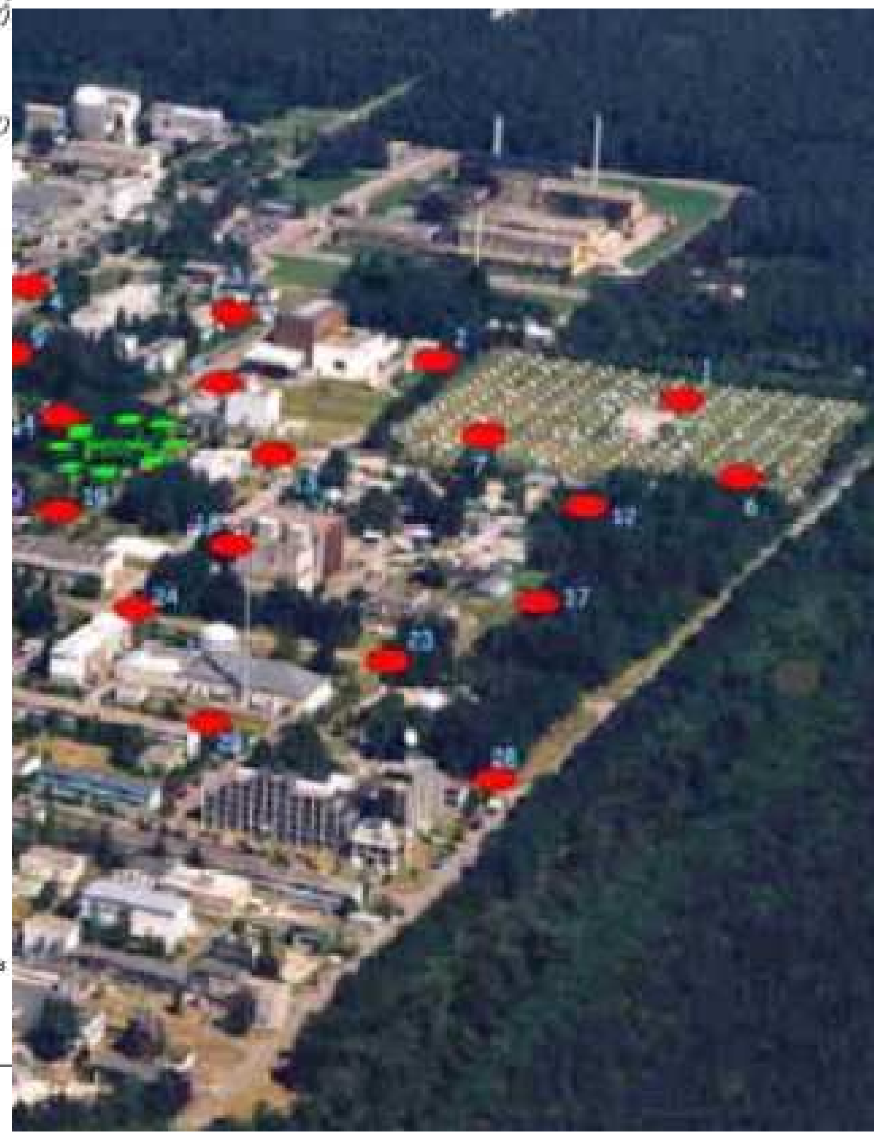


Baryon = no π^0 $\rightarrow$ no EM cascade

$\rightarrow$ chance to make muons

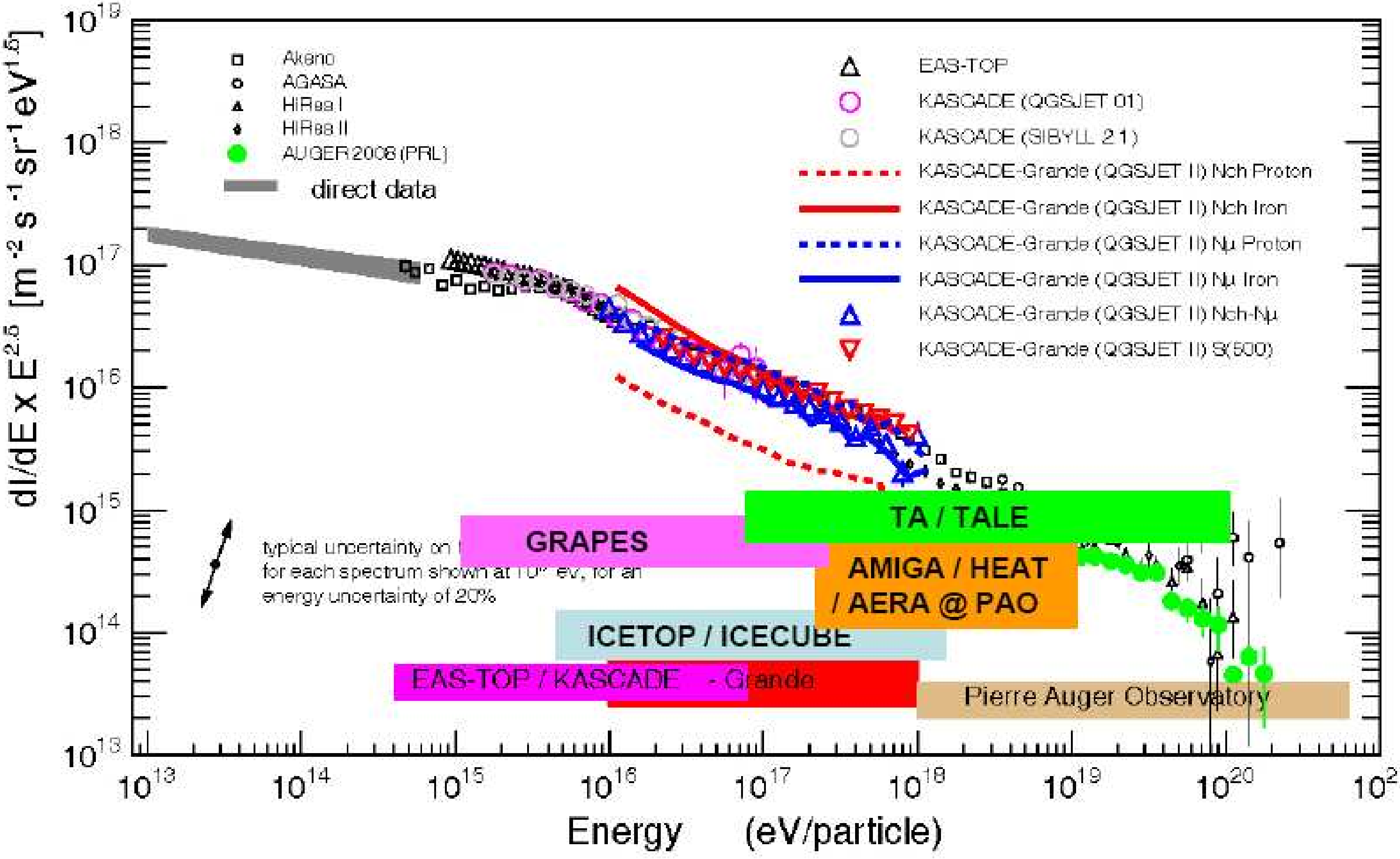
Kascade & Kascade-Grande





KASCADE-Grande

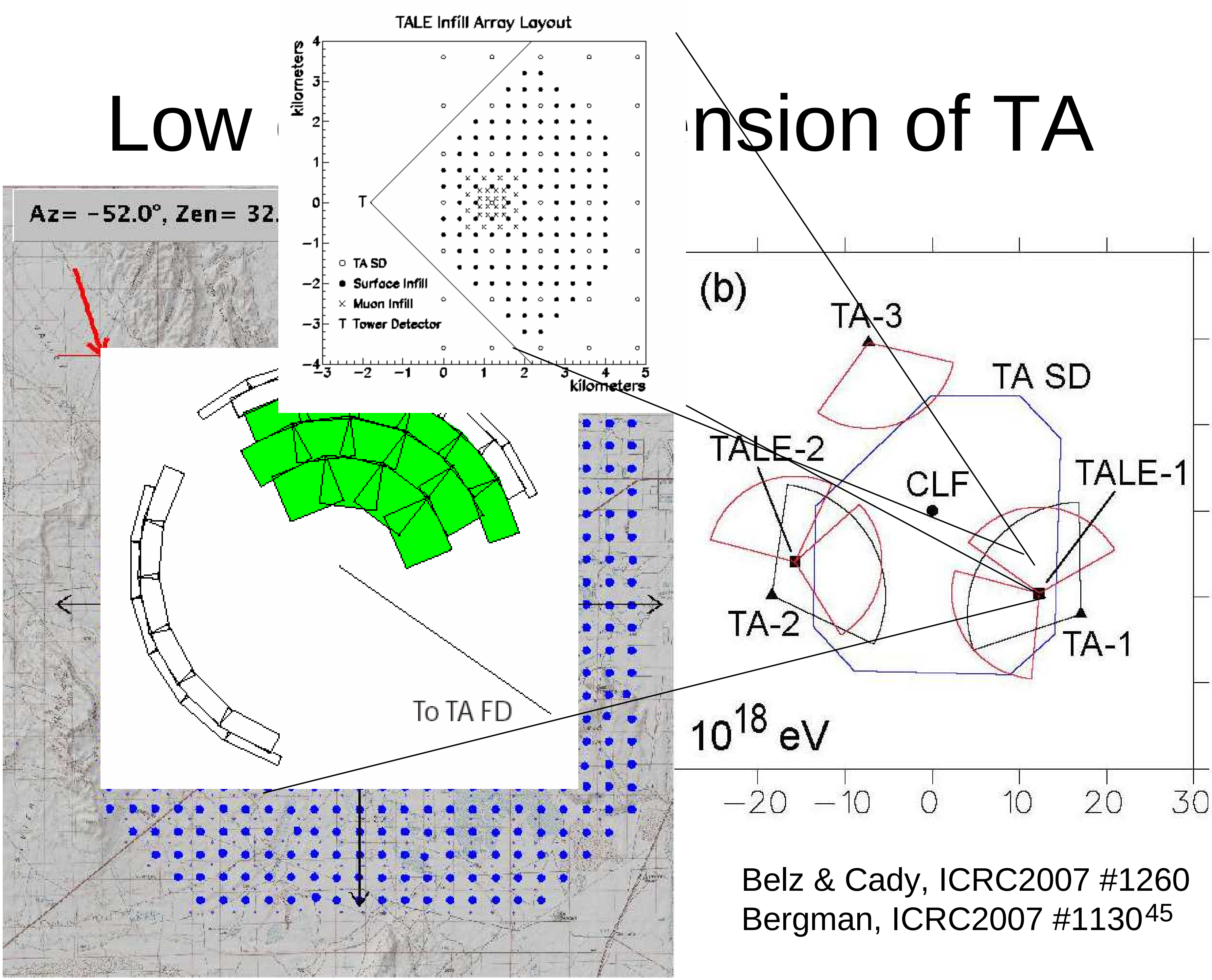
Andreas Haungs, Socor2009



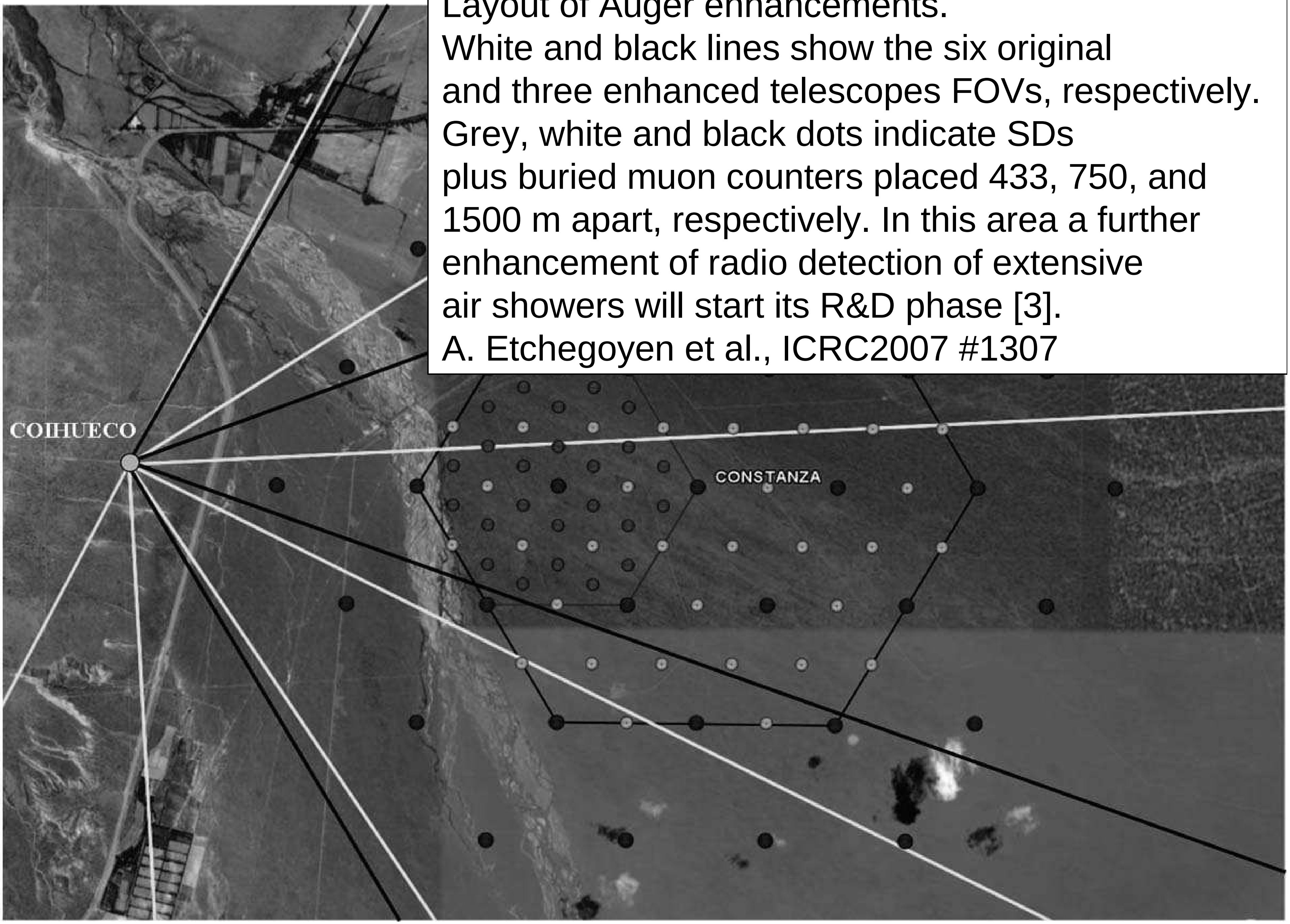
Plans to decrease the thresholds of Auger and TA

- Auger SD threshold 3 EeV, FD is 1 EeV
  - Goal: lower threshold to 0.1 EeV = 10^{17} eV
  - HEAT consists of 3 FTs viewing 30^o to 60^o
  - AMIGA is an in-filled surface array
- TA threshold 3 EeV
  - Goal: lower threshold to 3×10^{16} eV
  - TALE FD: 3 FDs including higher viewing angle
  - Overlooking a graded infill array

Low ... nsion of TA

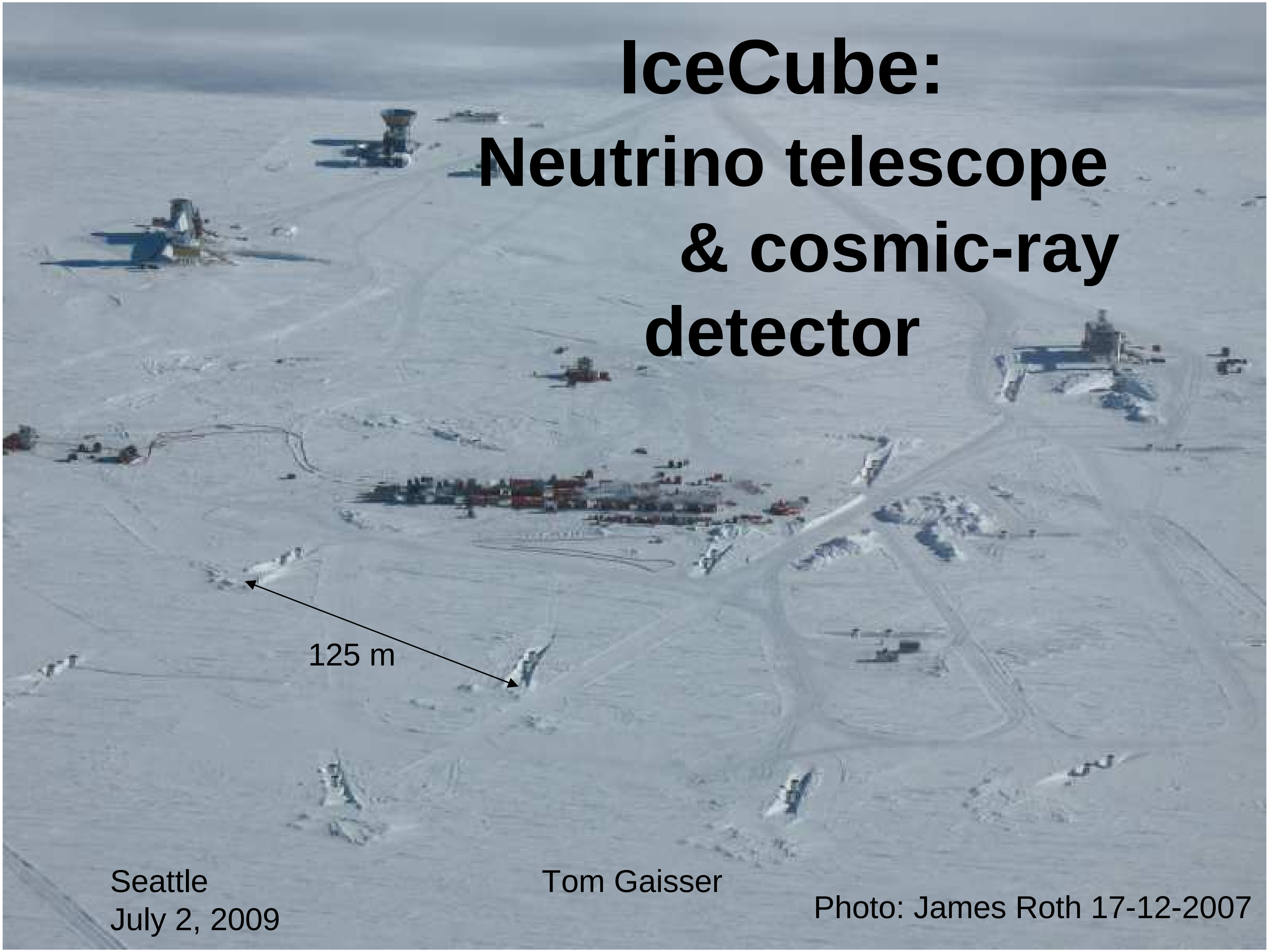


Belz & Cady, ICRC2007 #1260
Bergman, ICRC2007 #1130



Layout of Auger enhancements.
White and black lines show the six original
and three enhanced telescopes FOVs, respectively.
Grey, white and black dots indicate SDs
plus buried muon counters placed 433, 750, and
1500 m apart, respectively. In this area a further
enhancement of radio detection of extensive
air showers will start its R&D phase [3].
A. Etchegoyen et al., ICRC2007 #1307

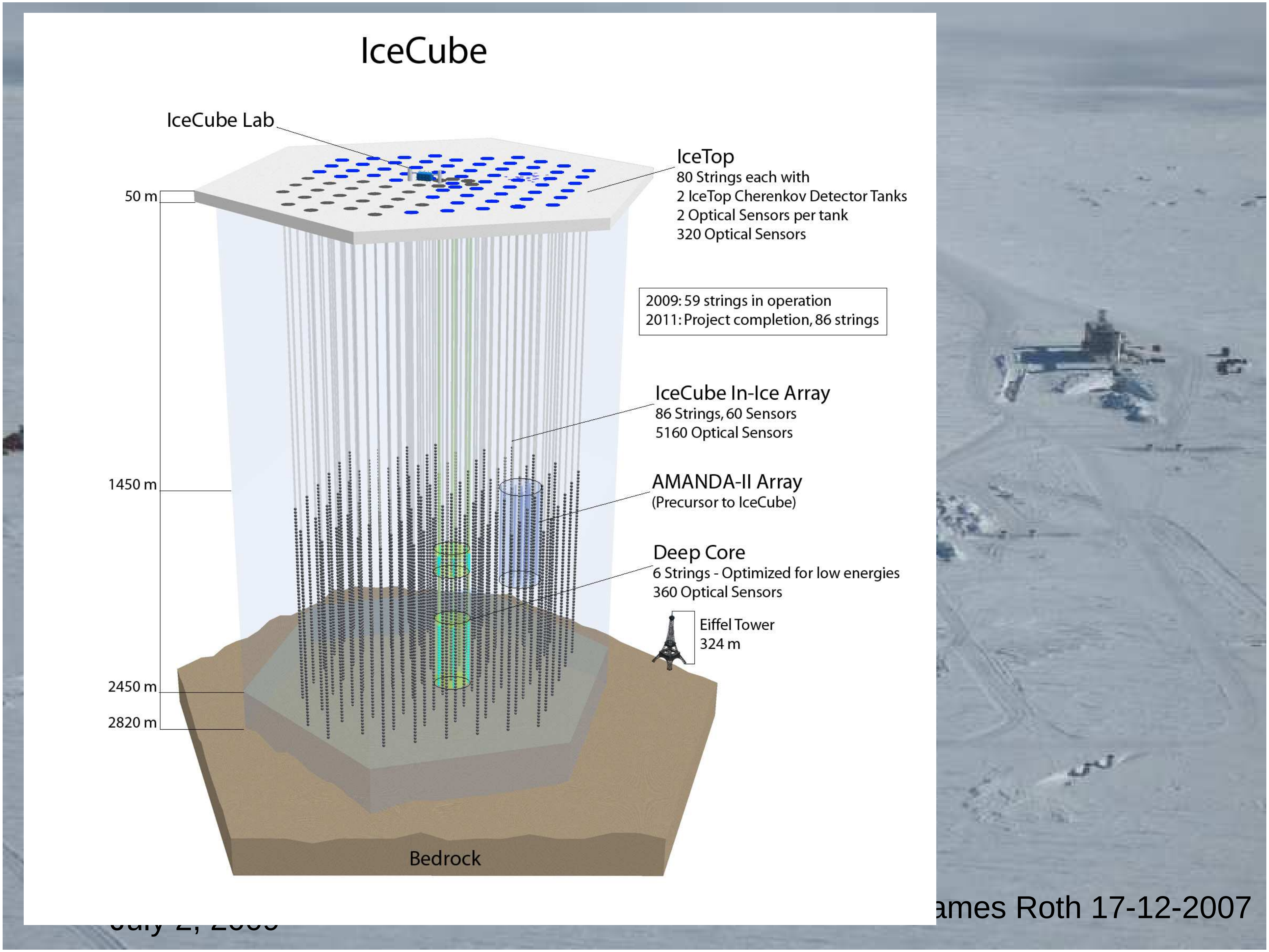
IceCube: Neutrino telescope & cosmic-ray detector



Seattle
July 2, 2009

Tom Gaisser

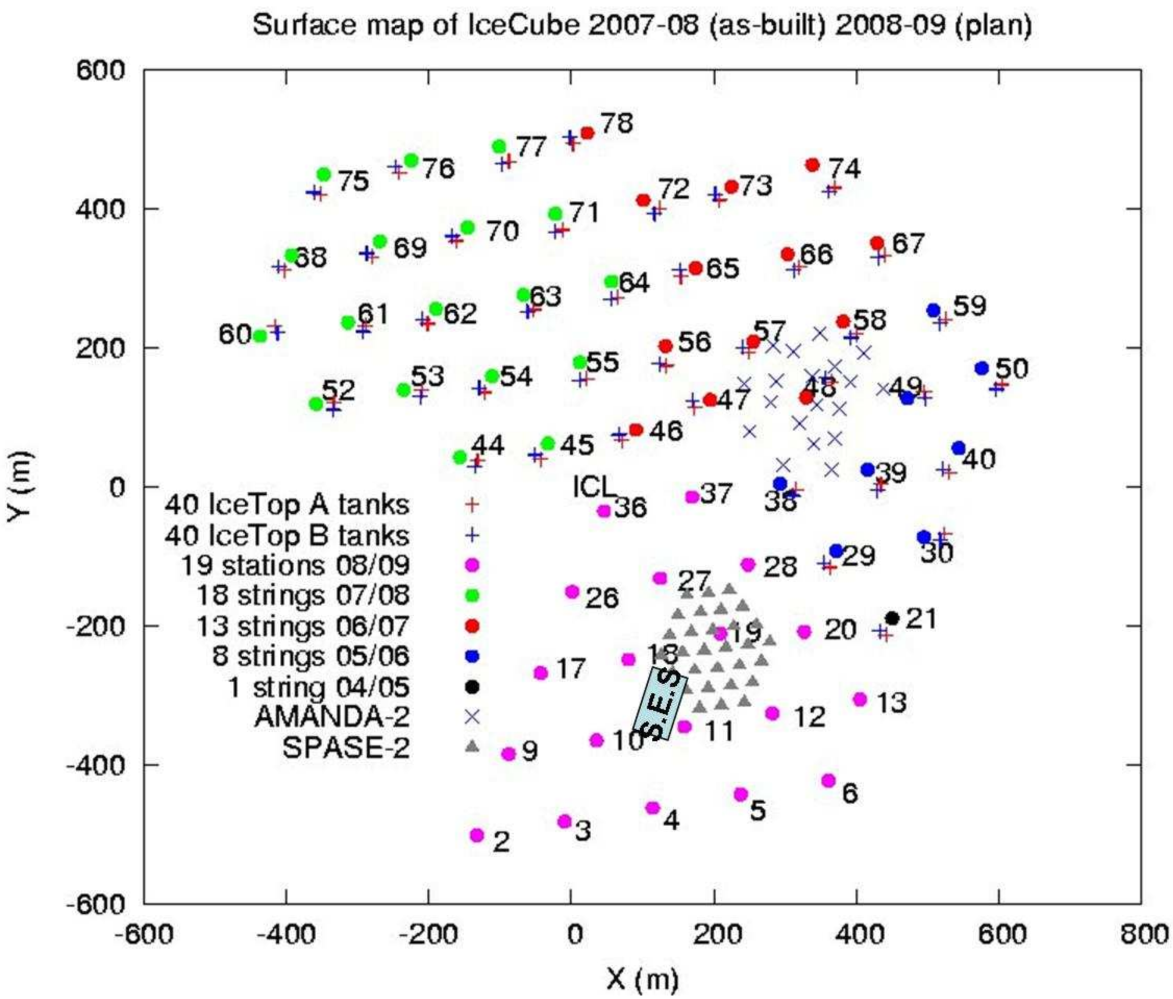
Photo: James Roth 17-12-2007



IceCube
IceCube Lab
IceTop
80 Strings each with
2 IceTop Cherenkov Detector Tanks
2 Optical Sensors per tank
320 Optical Sensors
2009: 59 strings in operation
2011: Project completion, 86 strings
IceCube In-Ice Array
86 Strings, 60 Sensors
5160 Optical Sensors
AMANDA-II Array
(Precursor to IceCube)
Deep Core
6 Strings - Optimized for low energies
360 Optical Sensors
Eiffel Tower
324 m
50 m
1450 m
2450 m
2820 m
Bedrock
ames Roth 17-12-2007

Cosmic-ray physics with IceCube

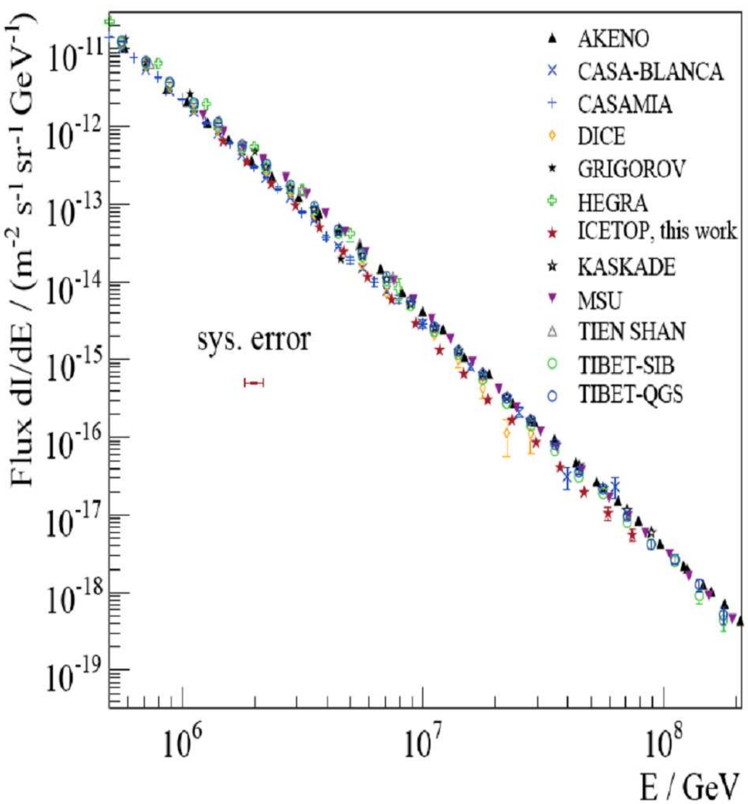
- Goal:
  - Composition, & spectrum
  - $10^{15} - 10^{18}$ eV
  - Use coincident events
  - Look for transition to extra-galactic cosmic rays

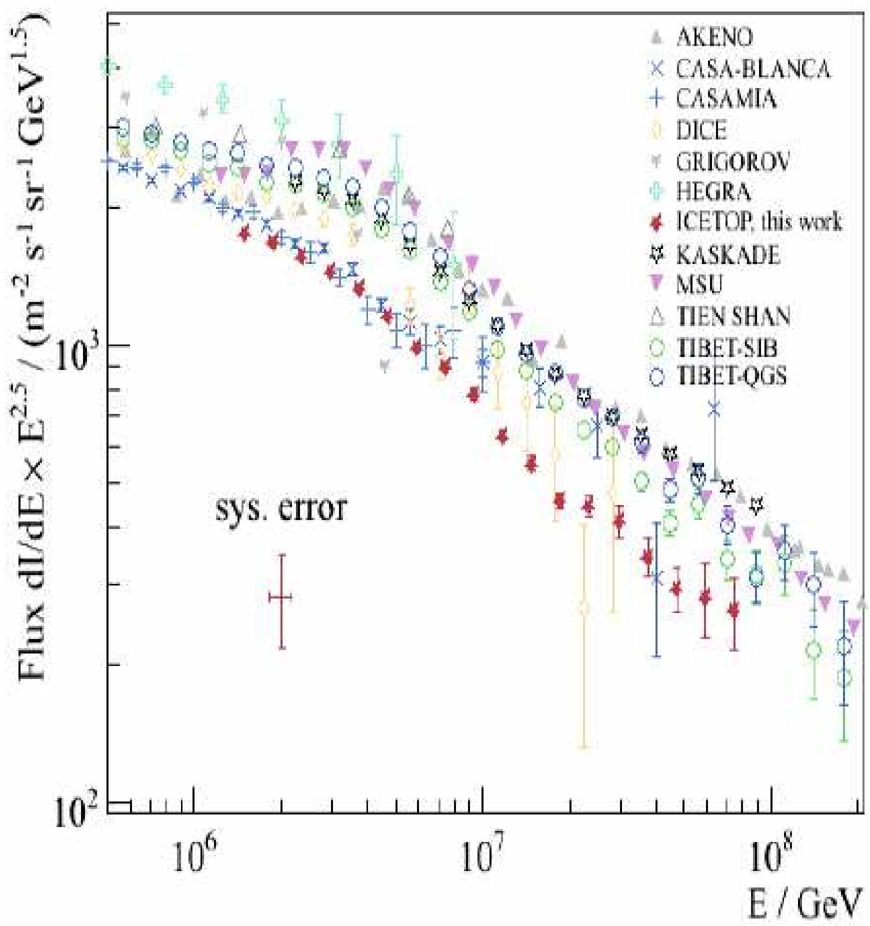


IceTop 40
(plus 19 stations planned for 08/09)

Preliminary IceTop Spectrum

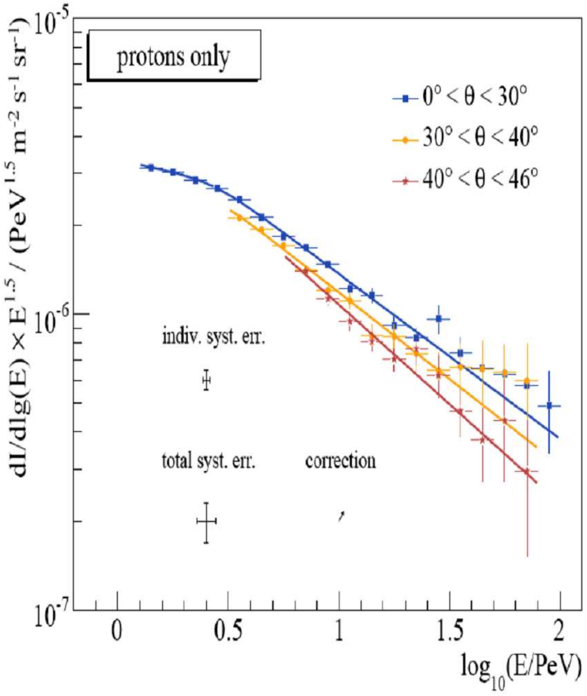
One month of data from IceTop-26 in 2007



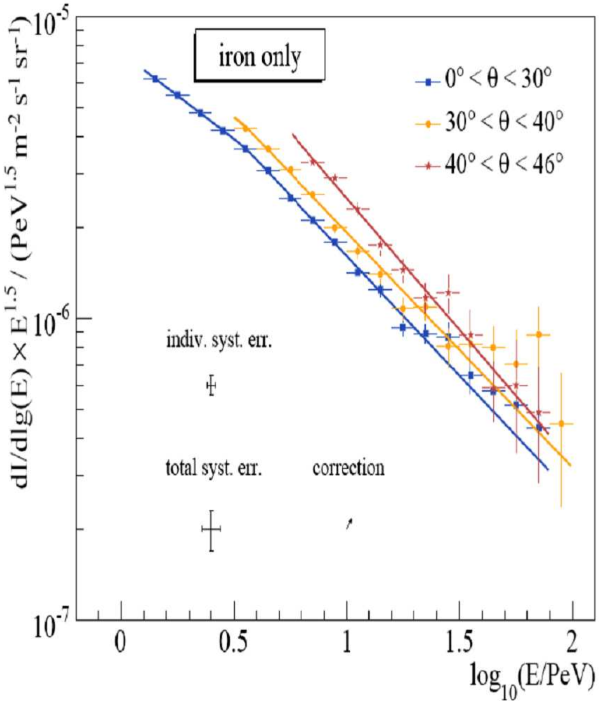


Composition from angular dependence of spectrum

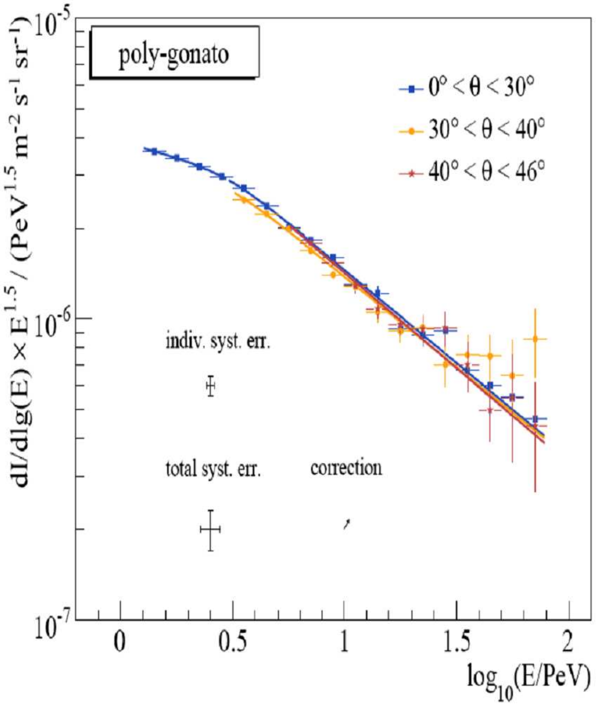
Protons only



Iron only

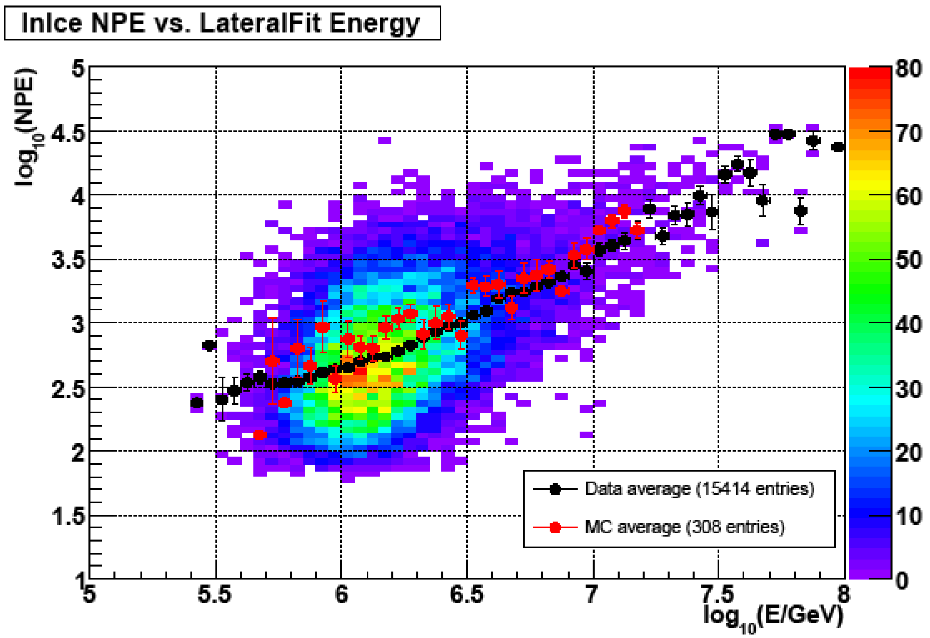


5-compnents



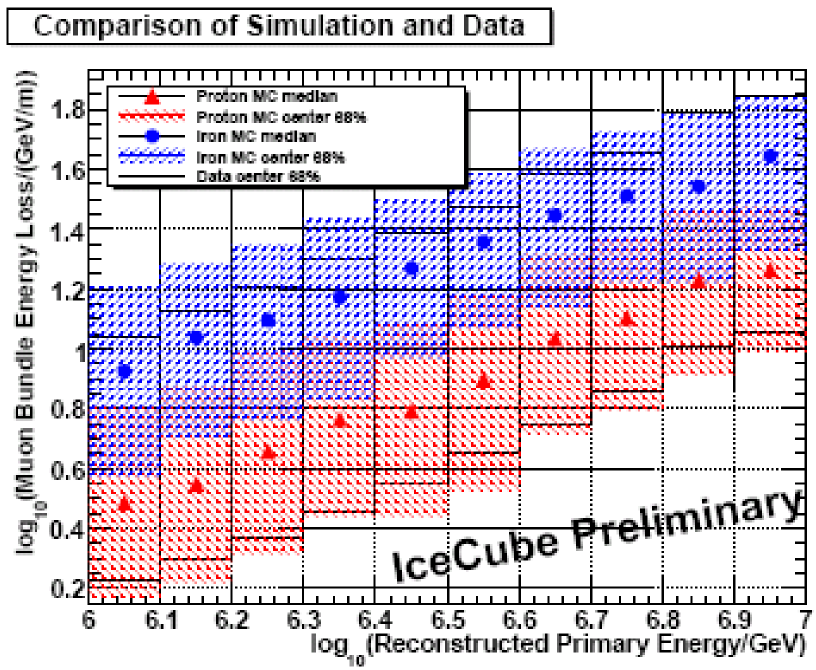
Composition from IceTop, In-ice coincident events

- Reconstruct muon bundle to get energy deposition by muons in deep IceCube
- Reconstruct surface shower to get $E_{primary}$
- Require consistency with angular distribution and μ/e measured on the surface



Number of photoelectrons in deep IceCube
Vs energy reconstructed by IceTop

Composition-dependence: factor 2 - 3 between p and Fe



T. Feusels, J. Eisch, C. Xu (IceCube, ICRC 2009, paper 0518

Cross checks

- Kascade-Grande, IceCube, TALE and Auger infill ground arrays
  - Include separate detectors for μ and e-m components
  - μ / e and X_{max} depend on composition in different ways
  - In principle allows breaking degeneracy between composition and hadronic interactions

High-energy cosmic rays: key questions

- What is the composition through the knee region?
  - Need more direct measurements for calibration
- How to make a complete picture of galactic cosmic rays?
  - Isotropy / propagation problem
  - Non-linear acceleration → hard source spectrum
  - How many sources?
- What interaction model to use?
- Where is transition to extra-galactic population?
  - Is there a Galactic component “B” ?
  - Are there nearby extra-galactic sources of UHECR?
- What are the sources of the highest energy particles?
  - Do they accelerate primarily protons or a mixture of nuclei?
  - Heavy component of >50EeV particles cannot point to sources because of bending locally in galactic magnetic field
- Look for cosmogenic neutrinos (a.k.a. GZK neutriinos)

Auger North

see talk by
Miguel Mostafa
TeV PA 2009

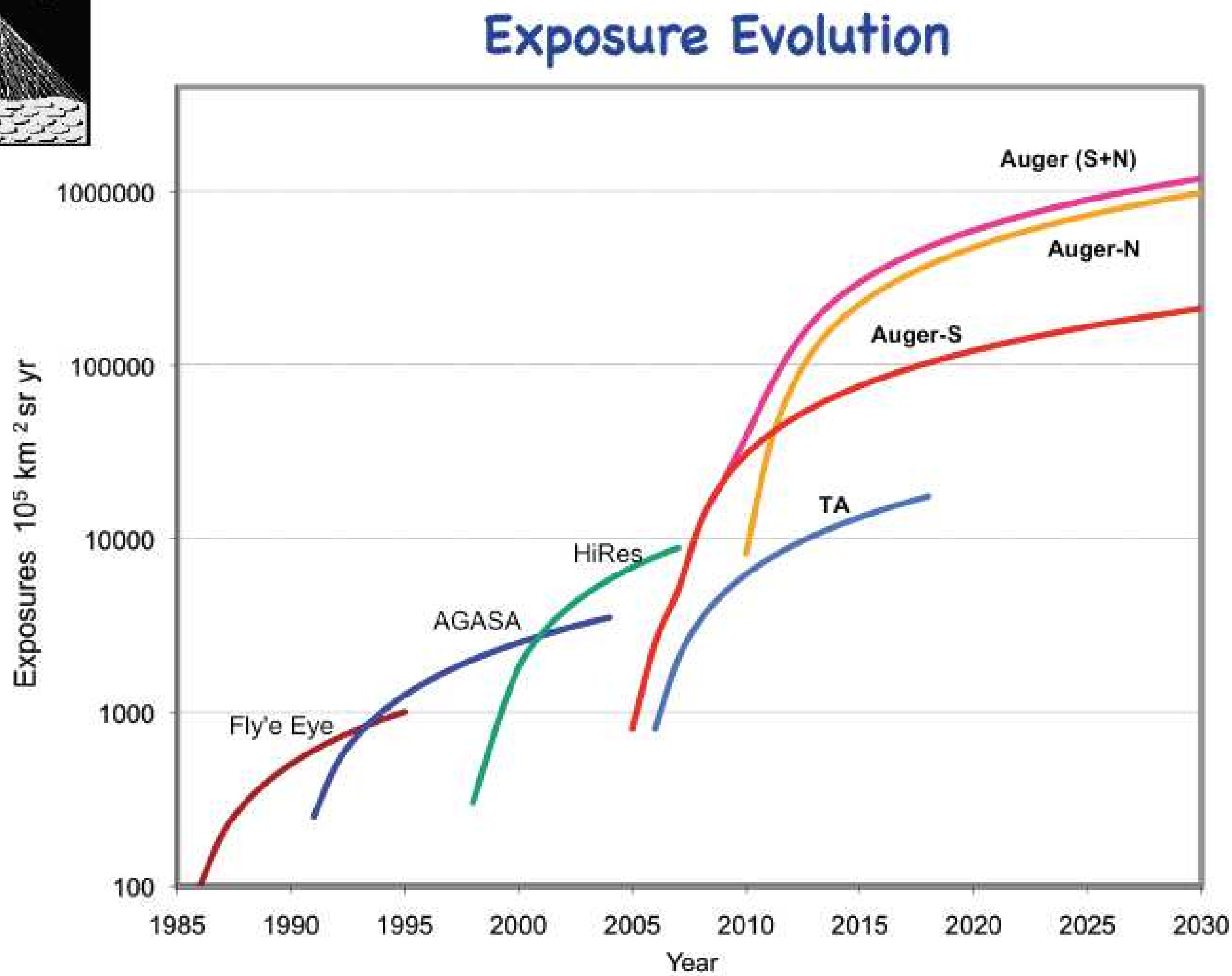
Auger
North

Auger North:
4400 detectors
1.42 mi Square Grid
21,000 km^2 (8000 mi^2)

Auger South:
1600 detectors
1.5 km Triangular Grid
3000 km^2 (1200 mi^2)

Auger South

to scale



see talk by Miguel Mostafa

neutrinos from GZK interactions

Slide by
Francis Halzen