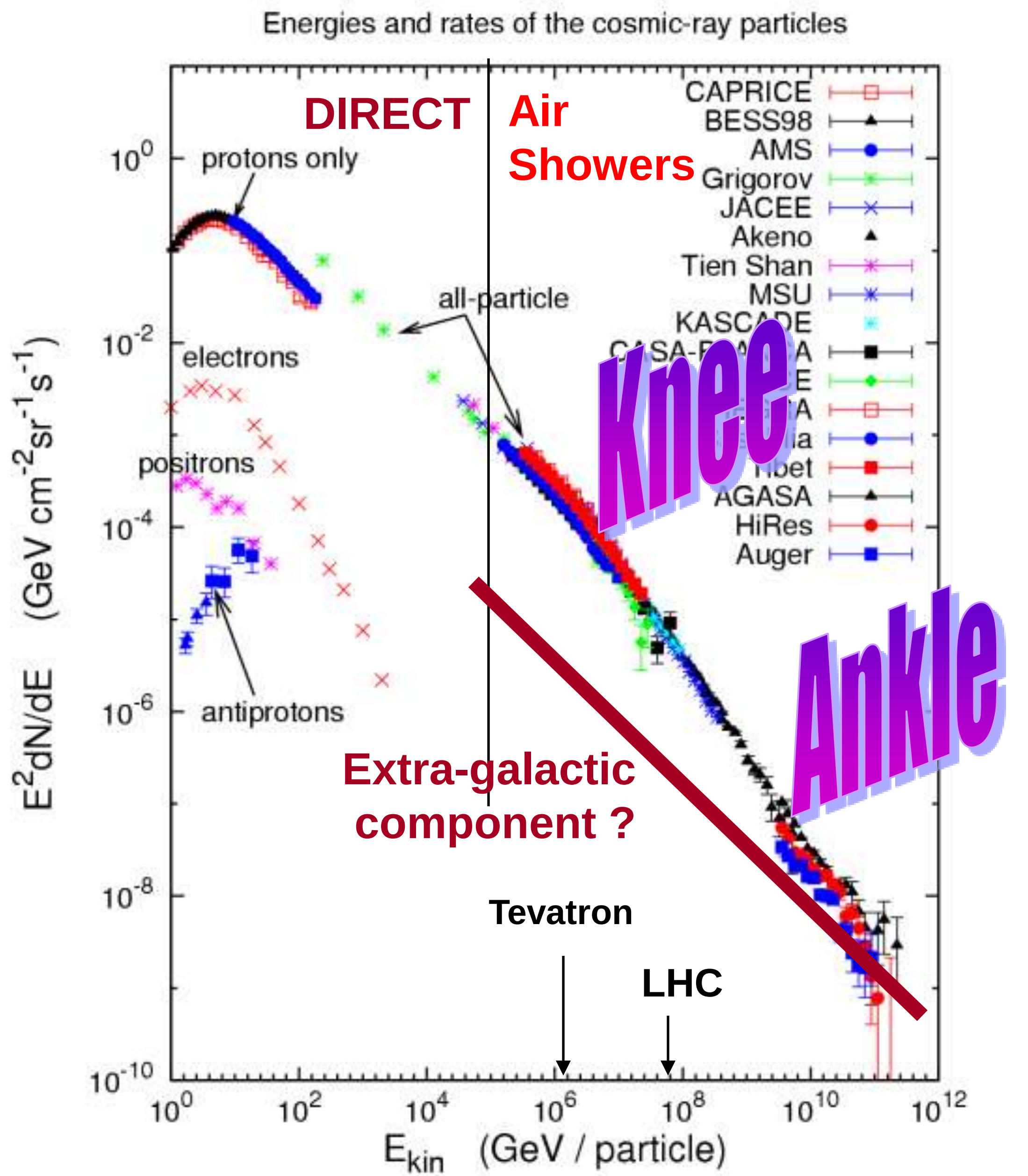
High-energy cosmic rays

And their acceleration

Outline

- Sources and acceleration mechanism
- End of the galactic cosmic-ray spectrum
- Transition to extra-galactic population
- Key questions

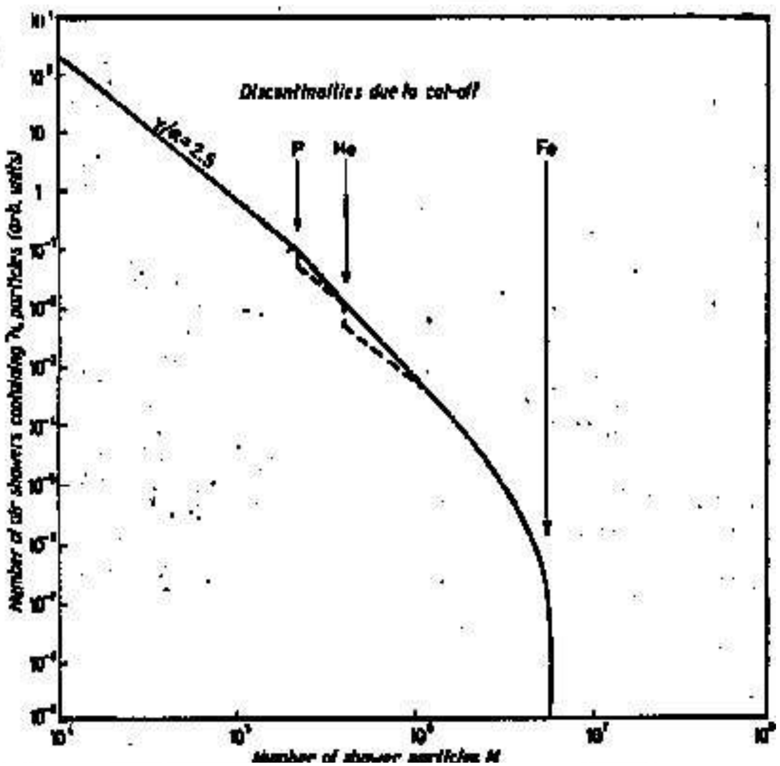
νF(ν) for cosmic rays



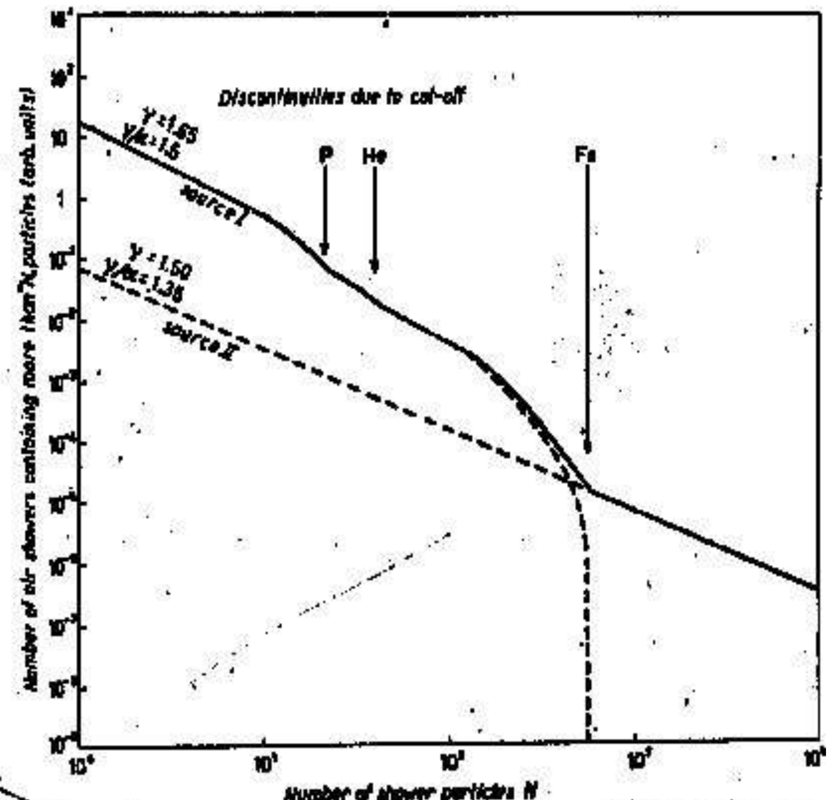
ICRR
28-08-2007

B. Peters on the *knee* and *ankle*

Peters cycle: systematic increase of < A > approaching E_{max}



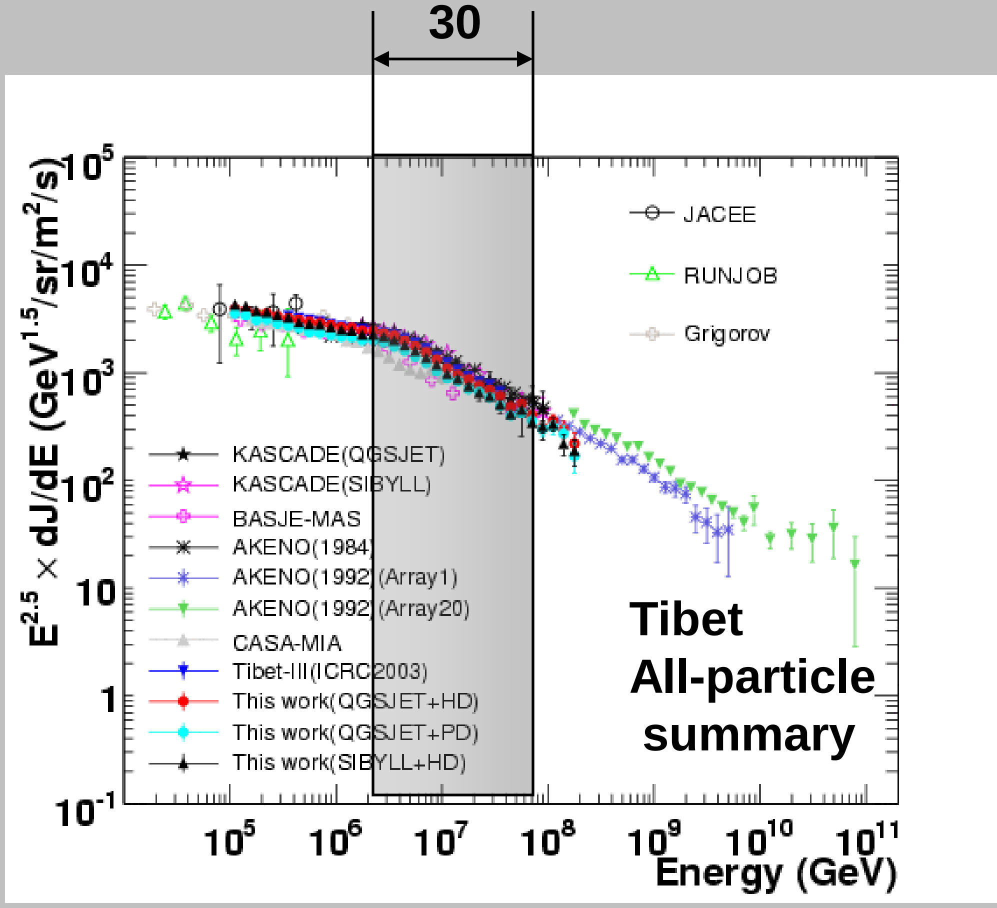
<A> should begin to decrease again for $E > 30 \times E_{knee}$



B. Peters, Nuovo Cimento 22 (1961) 800

Rigidity-dependence

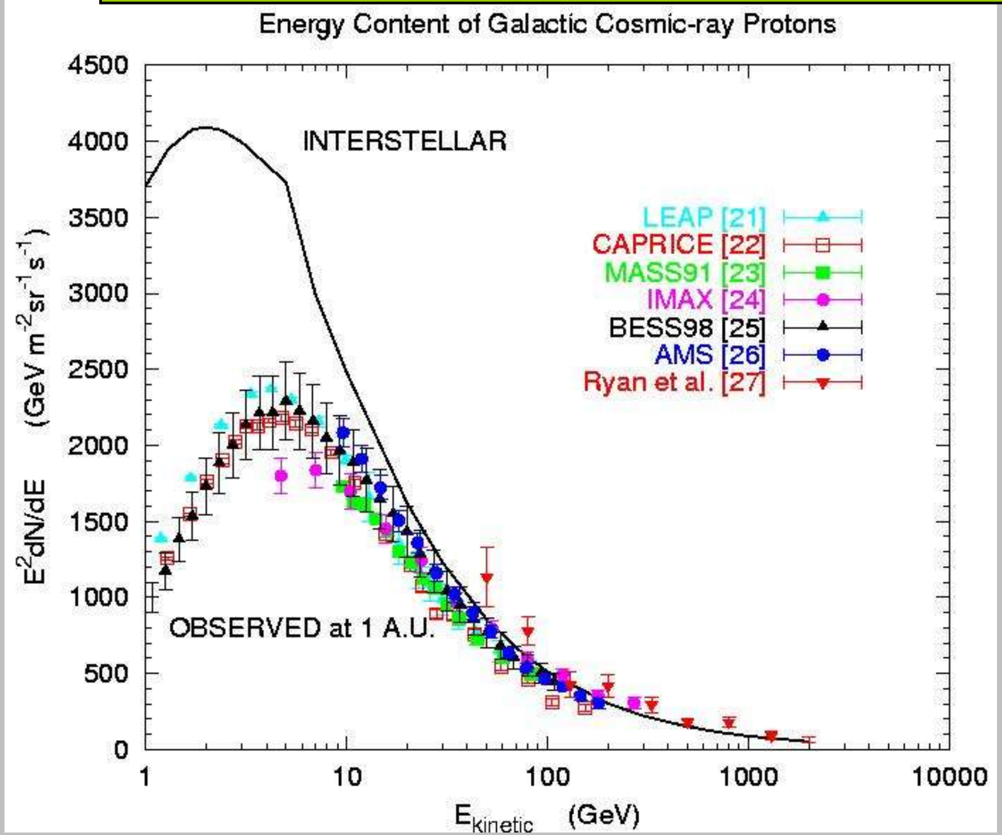
- Acceleration, propagation
  - depend on B: $r_{gyro} = R/B$
  - Rigidity, $R = E/Ze$
  - $E_c(Z) \sim Z\, R_c$
- $r_{SNR} \sim$ parsec
  - → $E_{max} \sim Z * 10^{15}$ eV
  - $1 \leq Z \leq 30$ (p to Fe)
- Slope change should occur within factor of 30 in energy
- With characteristic pattern of increasing A
- Problem: continuation of smooth spectrum to EeV



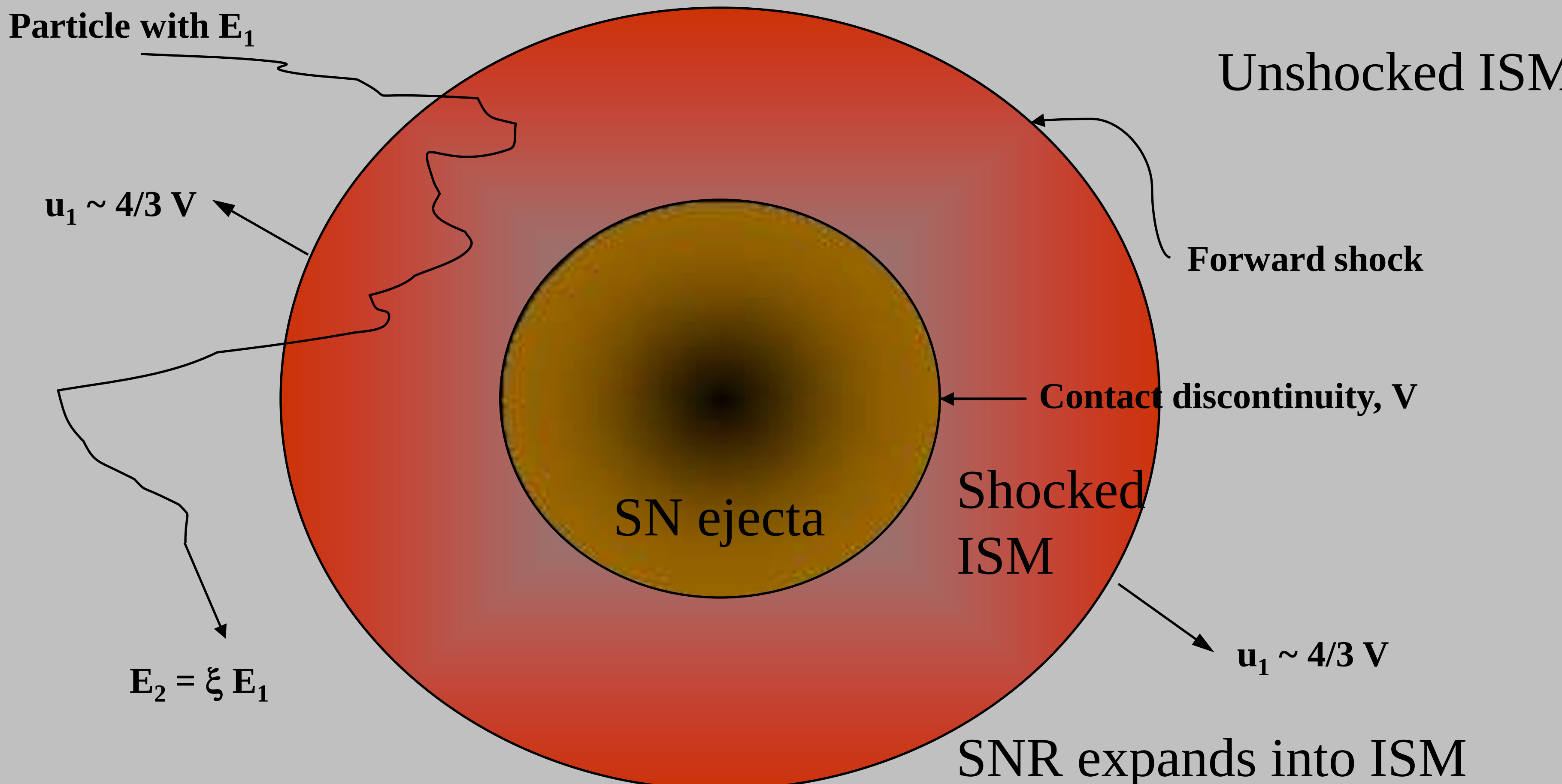
Energetics of cosmic rays

- Total local energy density:
  - $(4\pi/c) \int E\phi(E)\, dE$
    $\sim 10^{-12}$ erg/cm^3 $\sim B^2 / 8\pi$
- Power needed:
  $(4\pi/c) \int E\phi(E) / \tau_{esc}(E)\, dE$
  galactic $\tau_{esc} \sim 10^7\, E^{-0.6}$ yrs
  Power $\sim 10^{-26}$ erg/cm^{3}s
- Supernova power:
  10^{51} erg per SN
  ~3 SN per century in disk
  $\sim 10^{-25}$ erg/cm^{3}s
- SN model of galactic CR
  Power spectrum from shock acceleration, propagation

Spectral Energy Distribution
(linear plot shows most E < 100 GeV)
$(4\pi/c)\, E\phi(E)$ = local differential CR energy density



Supernova blast wave acceleration



SNR expands into ISM with velocity $V \sim 10^4$ km/s. Drives forward shock at 4/3 V

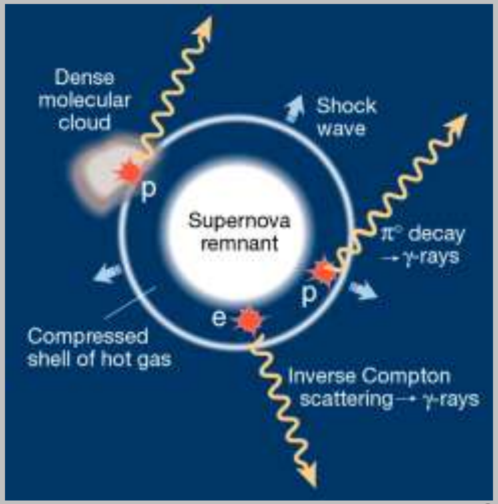
$T_{SN} \sim 1000$ yrs before slowdown

$E_{max} \sim Z \times 100$ TeV

Problems of simplest SNR shock model

- Expected shape of spectrum:
  - Differential index $\alpha \sim 2.1$ for diffusive shock acceleration
    - $\alpha_{observed} \sim 2.7$; $\alpha_{source} \sim 2.1$; $\Delta\alpha \sim 0.6 \rightarrow \tau_{esc}(E) \sim E^{-0.6}$
    - $c\,\tau_{esc} \rightarrow T_{disk} \sim 100$ TeV
    - → Isotropy problem
- $E_{max} \sim \beta_{shock}\, Ze \times B \times R_{shock}$
  - → $E_{max} \sim Z \times 100$ TeV with exponential cutoff of each component
  - But spectrum continues to higher energy:
    - → E_{max} problem

- Expect p + gas → γ (TeV) for certain SNR
  - Need nearby target as shown in picture from *Nature* (April 02)
  - Some likely candidates (e.g. HESS J1745-290) but still no certain example
  - → Problem of elusive π^0 γ-rays



Solutions to problems

- Isotropy problem
  - $\gamma_{source} \sim 2.3$ and $\tau_{esc} \sim E^{-0.33}$??
  - See talk of S. Torii
- Evidence for acceleration of protons at SNR
  - Look for TeV γ-rays mapping gas clouds at SNR
  - See talk of Trevor Weekes
- Acceleration to higher energy
  - Magnetic field amplification in non-linear shock acceleration

Diffusive shock acceleration

$$\frac{dE}{dt} = \xi \frac{E}{T_{cycle}} \qquad \xi \sim \frac{4}{3}\frac{V_{SN}}{c}$$

$$T_{cycle} \sim \frac{3D}{c\,V_{SN}}(1+r)$$

if $D \sim 3\cdot 10^{28}\,\frac{cm^2}{s}$ as in ISM

$$T_{cycle} > 1000\,yr$$

Too long!

Shock acceleration - 2

Solution is to recognize magneto-hydrodynamic turbulence generated by cosmic-rays upstream of the shock. Cosmic-rays scatter on MHD turbulence with wavelength matched to particle's gyro-radius $r_L = E / ZeB$

$D \sim r_L\, c / 3 \;\rightarrow\; T_{cycle} \sim 10^4$ s x E (GeV) ~ 1000 yrs to 10^{15} eV

Lagage & Cesarsky 1983: $D \sim \frac{1}{3} r_L c$

"Bohm diffusion"

$$r_L = \frac{E}{ZeB} \quad \text{and} \quad \frac{dE}{dt} \sim \frac{4}{15}\left(\frac{V_{SN}}{c}\right)^2 ZeB$$

$$E_{max} = \int_0^T \frac{dE}{dt}\,dt \sim Z \times 100\,\text{TeV}\left(\frac{B}{3\,\mu G}\right)$$

Shock acceleration - 3

- Cosmic-ray pressure in upstream region generates precursor
- Higher energy particles get further upstream
- Experience larger discontinuity $r = u_1(x) / u_2$

$$\frac{dN}{d\ln E} \sim E^{-\gamma}, \quad \gamma = \frac{3}{r-1} \quad \text{where } r = \frac{u_1}{u_2}$$

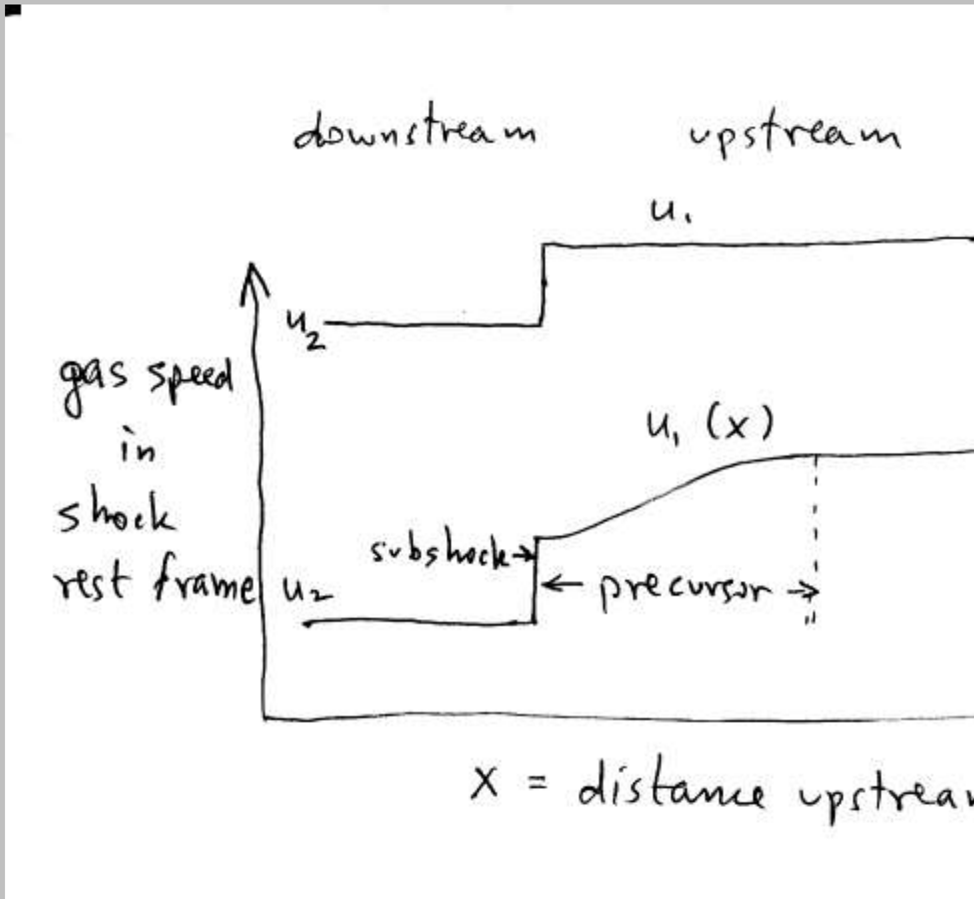
$$r = 4 - \frac{12}{(\mathrm{Mach})^2} \quad \text{at subshock}$$

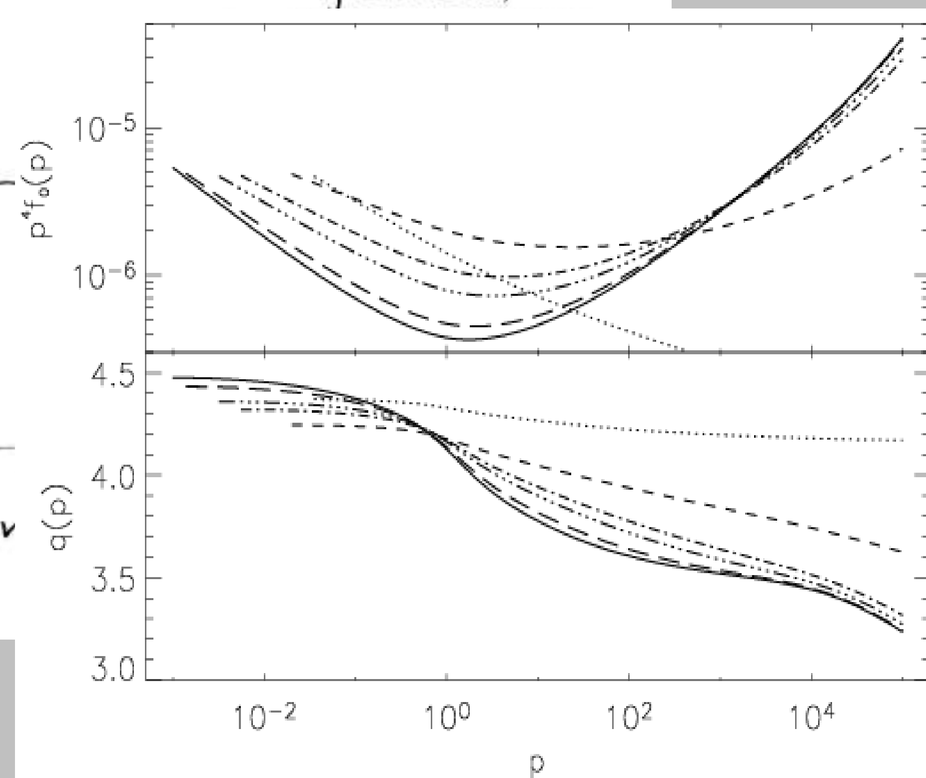
$$\Rightarrow \gamma = 1 + \epsilon \quad \text{at subshock}$$

$r > 4$ upstream of CRMS

Example: $r = 7 \Rightarrow \gamma = \frac{1}{2}$

Shock acceleration - 4





- Spectrum at shock concave,
- $\gamma < 1$ at high energy,
- energy concentrated at Emax

Shock acceleration - 5

- Cosmic-ray pressure also amplifies magnetic field (Bell, MNRAS 353, 550, 2004)
- E_{max} increases to 10^{16} or 10^{17} eV in early, free-expansion phase of SNR expansion
- applies to small fraction of accelerated particles

ALSO (Ptuskin & Zirakashvili, A&A 429, 755, 2005)

- In later phases of SNR expansion:
  - upstream scattering becomes inefficient as expansion slows down
  - $E_{max} \rightarrow E_{max}(t)$ decreases with time
  - Accelerated particles with $E > E_{max}(t)$ escape upstream
  - observed spectrum is integral of SNR history

Berezhko & Völk analysis (similar)

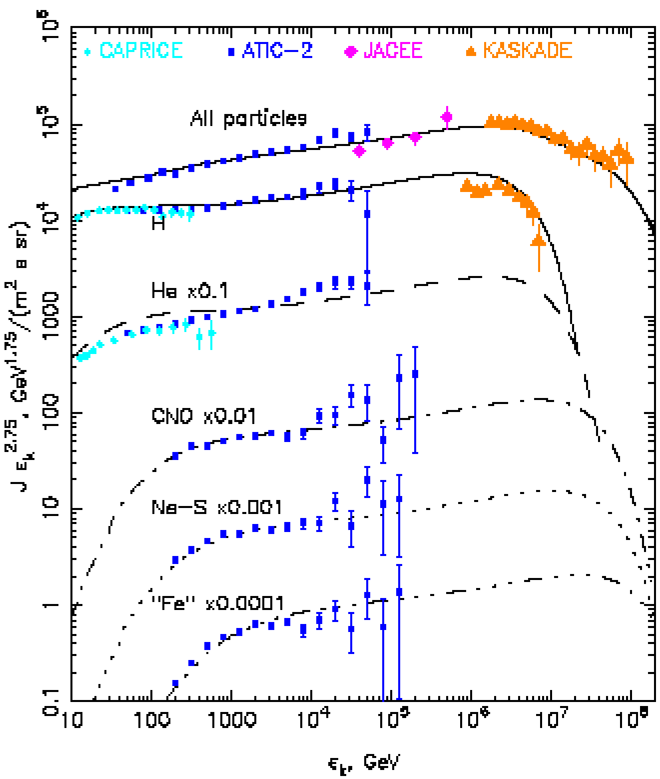


FIG. 1.— GCR intensities at the Solar system as a function of particle kinetic energy. Curves represent the CR spectra calculated for a proton injection rate $\eta = 10^{-4}$, ion-to-proton ratios which provide a fit for the data at $\epsilon_k = 1$ TeV, and for $\mu = 0.75$. Experimental data obtained in the CAPRICE (Boezio et al. 2003), ATIC-2 (Panov et al. 2006), JACEE (Asakimori et al. 2003) and KASKADE (Antoni et al. 2005) experiments are shown as well.

arXiv 0704.1715

$$\gamma_{observed} = 2.7$$
$$= \gamma_{source} + \delta$$

Problem is hard source spectrum:

- $\gamma_{source} < 2$ requires $\tau_{esc} \sim E^{-\delta}$ with $\delta \sim 0.75$ to compensate hard (concave) source spectrum
- Observed isotropy is a problem
- Also note He spectrum is harder than protons ??

Developments in the Theory of Diffusive Shock Acceleration (DSA)

- NON LINEAR THEORY OF DSA (Analytical: PB&Amato, OG341; Numerical: Berezhko&Volk, OG111; Edmon,Jones & Kang, OG789)

- MAGNETIC FIELD AMPLIFICATION BY STREAMING INSTABILITY (PB&Amato, OG342; Niemiec&Pohl, OG1047)

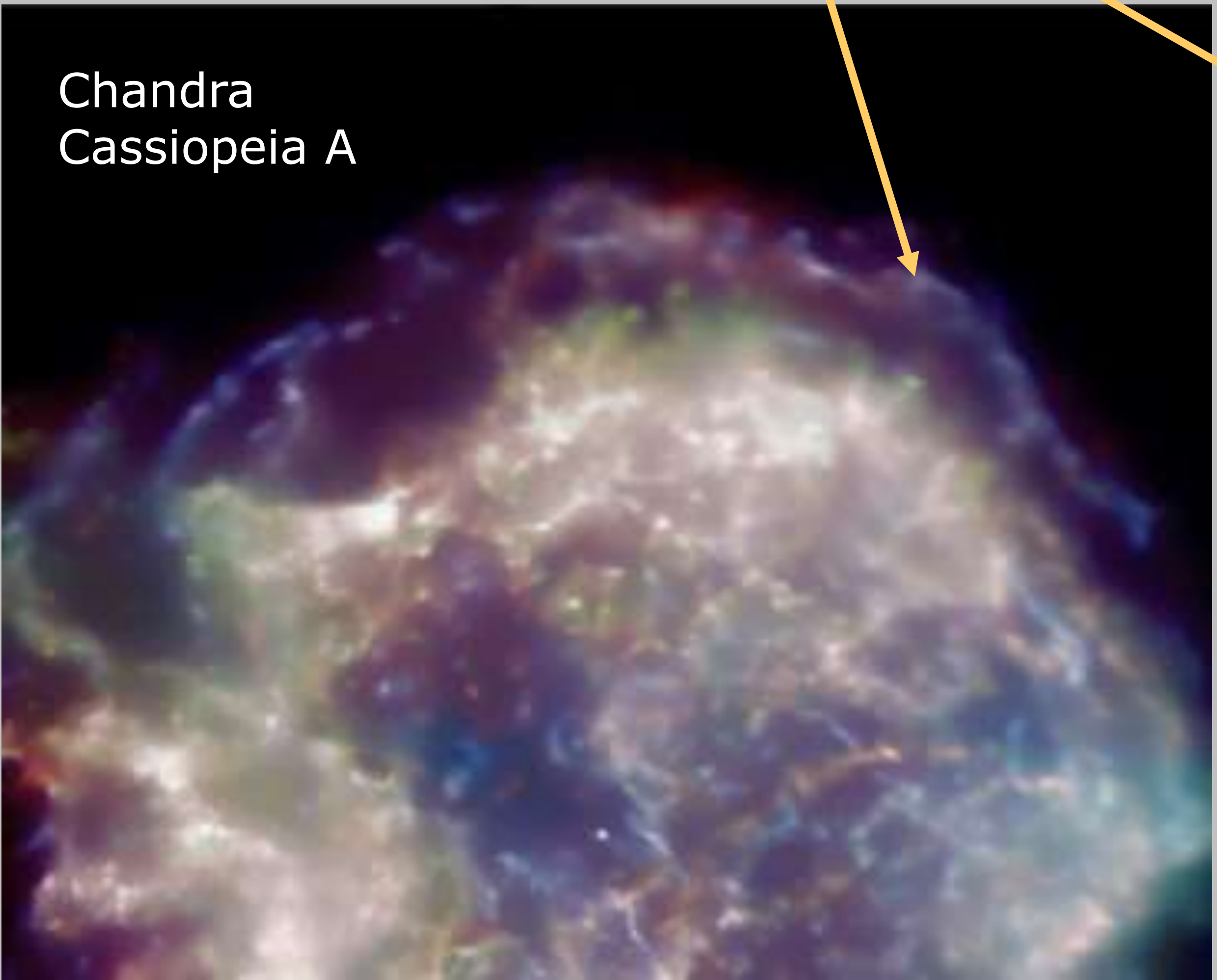
- PHENOMENOLOGY OF SNR's IN THE CONTEXT OF NON LINEAR DSA (Berezhko et al., OG597,OG614)

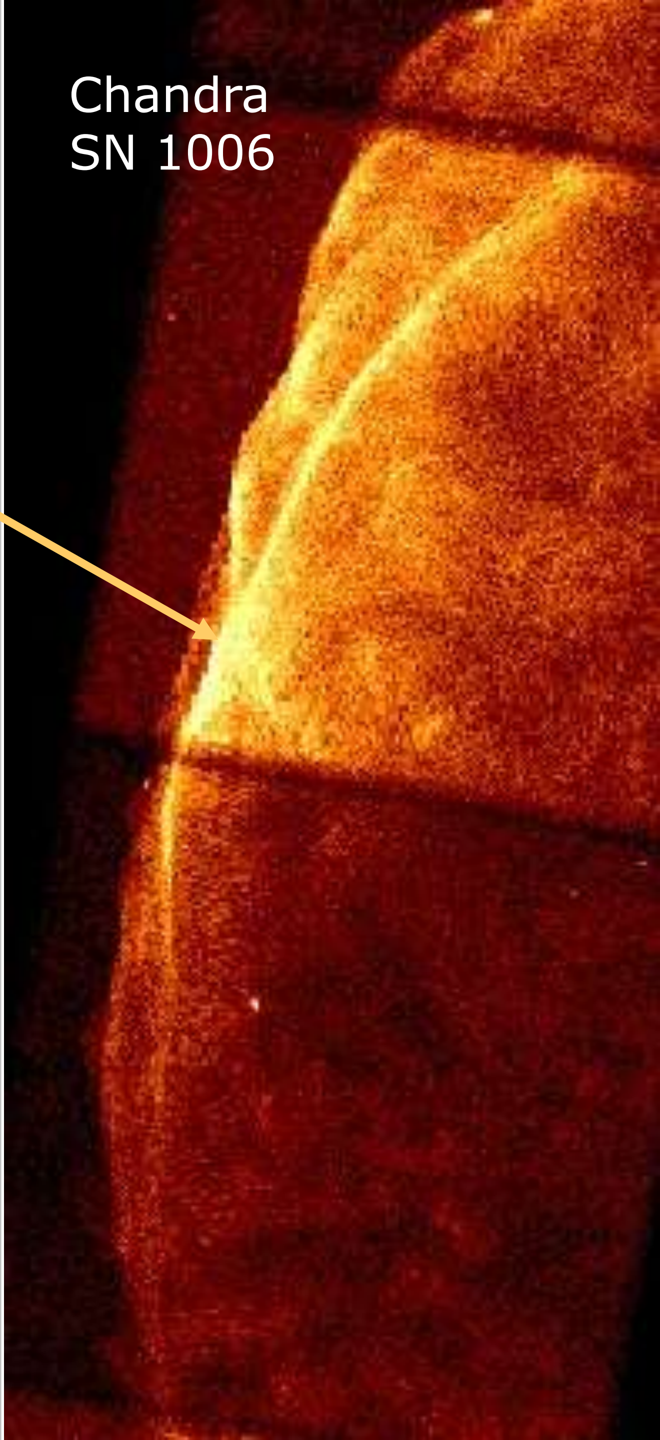
- MHD MAGNETIC FIELD AMPLIFICATION, UNRELATED TO ACCELERATED PARTICLES, AT PERPENDICULAR SHOCKS (Jokipii&Giacalone, OG078)

- TIME DEPENDENT ACCELERATION AT MODIFIED SHOCKS (also multiple shocks) (Ferrand et al., OG995; Edmon et al., OG789)

Filamentary structure of X-ray emission of young SNRs: Evidence for amplification, B ~ 100 μG

Berezhko&Volk, OG111

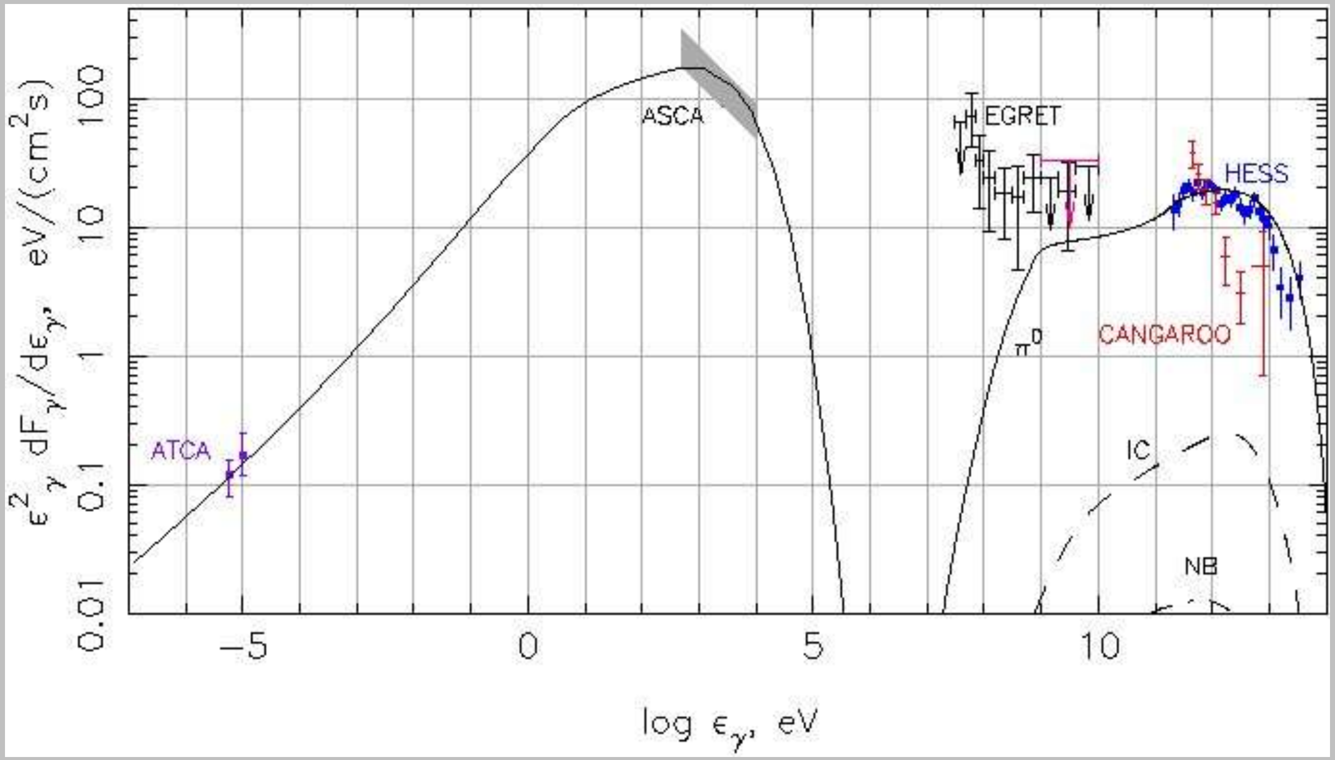




RX J1713.7-3946

Berezhko & Völk, arXiv:0707.4647

Contributions from electrons (IC, NB) suppressed by ~100 μG fields

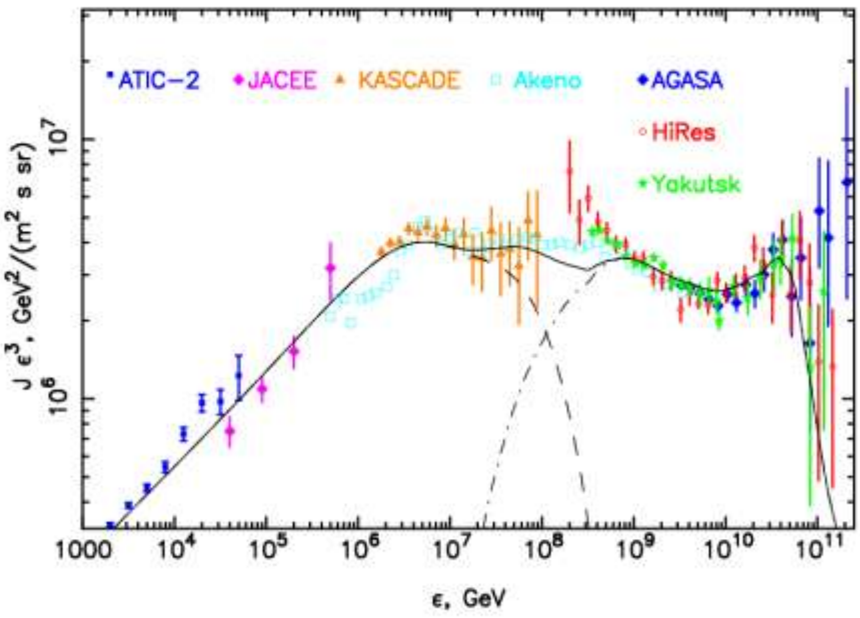


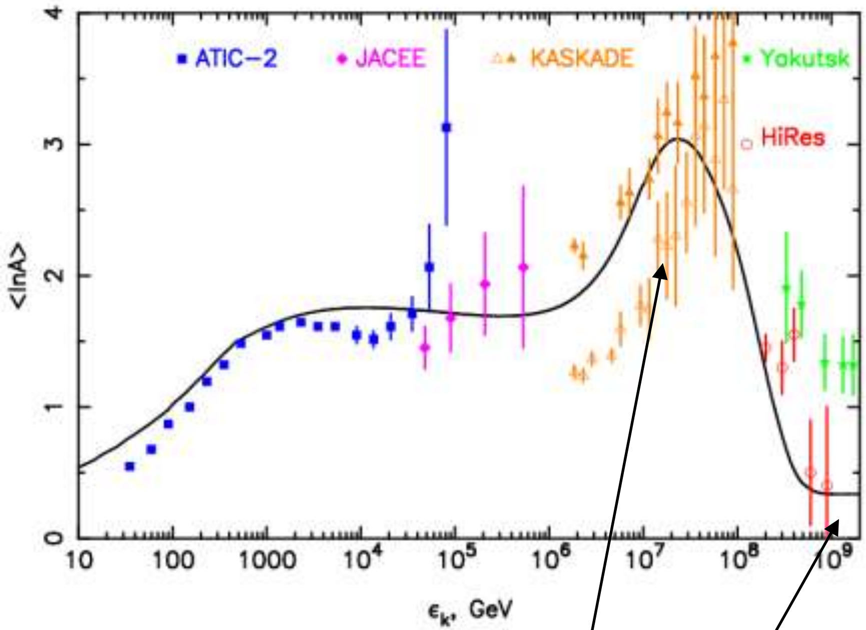
Berezhko & Völk

- Model galactic component
- Subtract from observed to get extragalactic

Transition predicted:

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





arXiv:0704.1715v1 [astro-ph]

Heavies at end of galactic

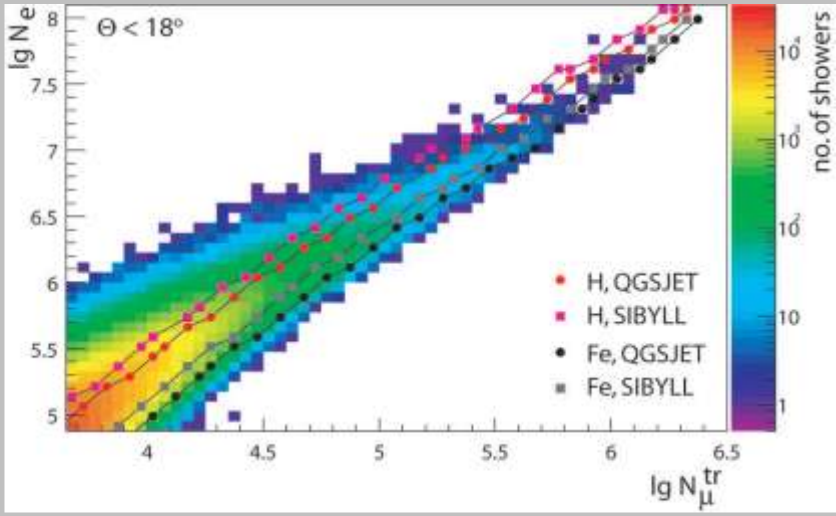
Extra-galactic protons

Tibet hybrid air shower array

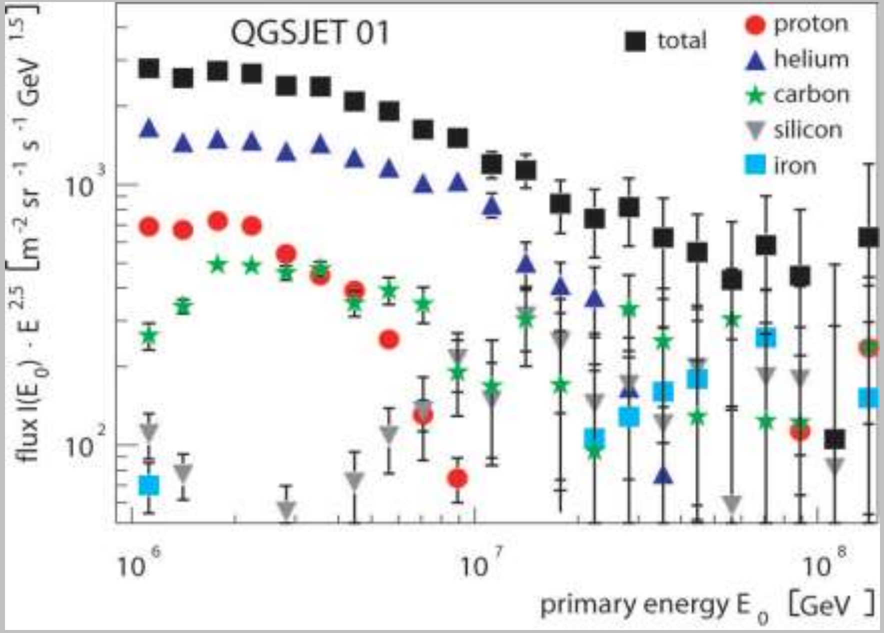
4300 m ~600 g/cm^2

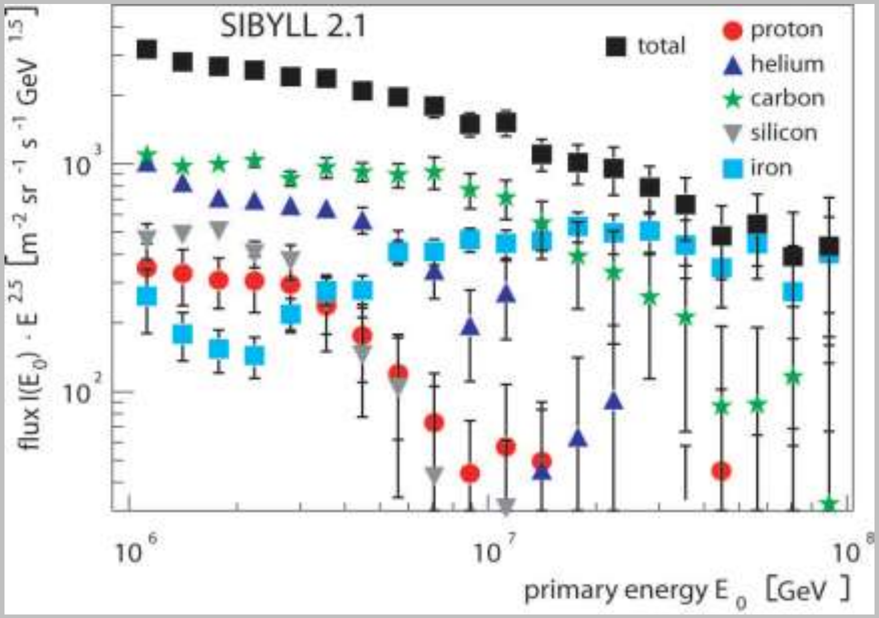
Extracts proton component from tagged γ-families in emulsion chamber coincident with EAS

KASCADE composition



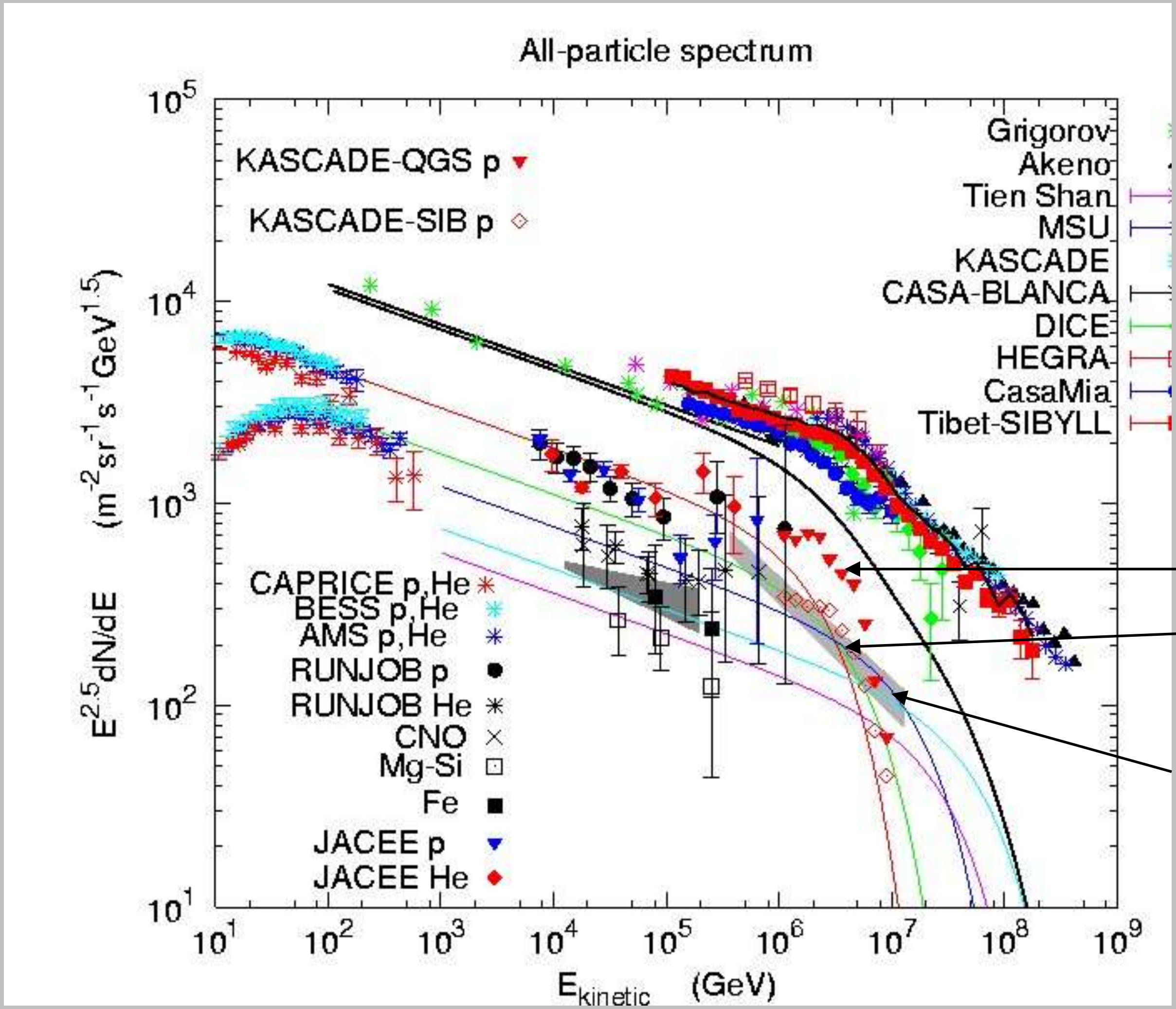
Unfolds components from measurement of muons / electrons
Result depends on hadronic interaction model
Detector at sea level, 1000 g/cm^2





Andreas Haungs, arXiv:0705.0202

Knee of cosmic-ray spectrum

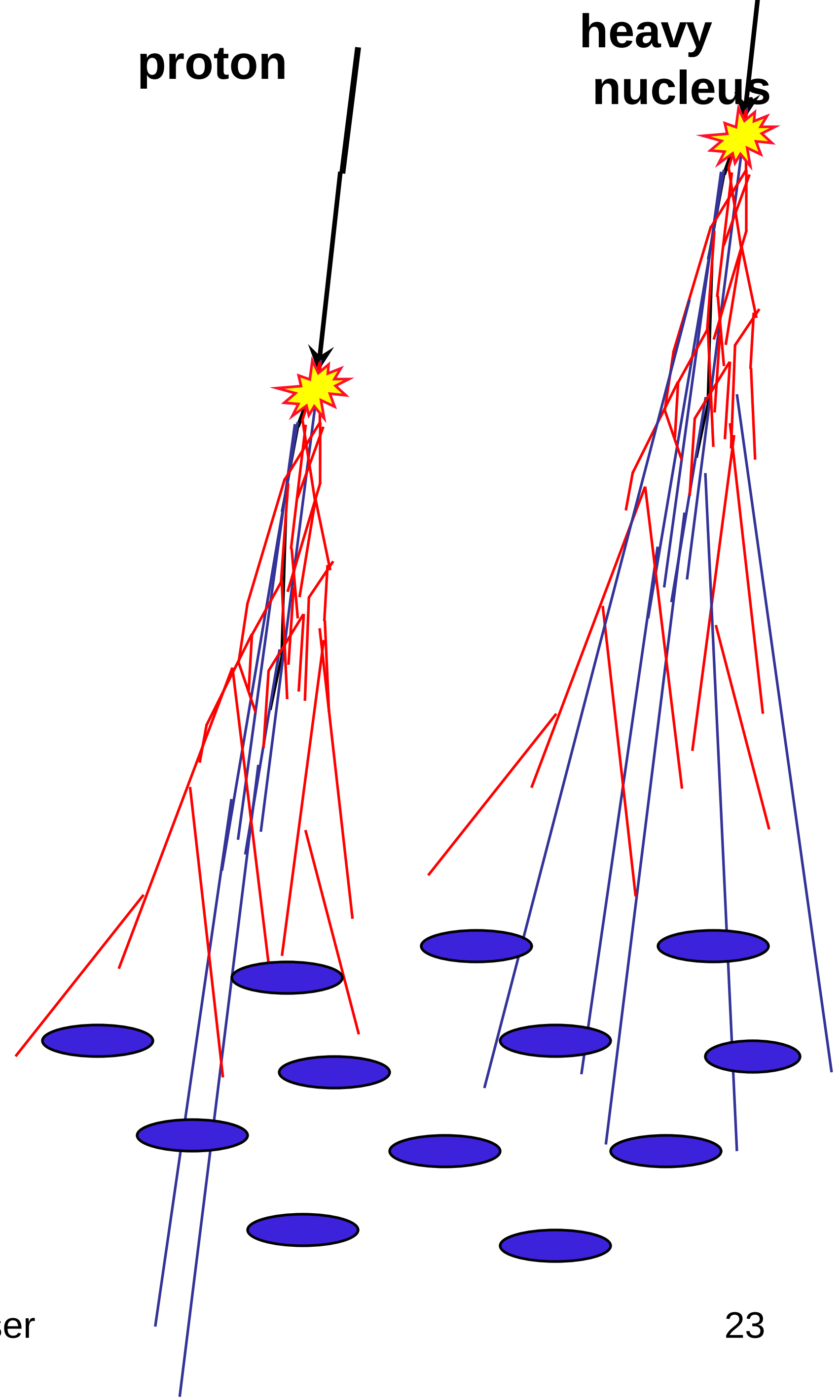


KASCADE protons
QGSjet
SIBYLL

Tibet hybrid protons (light gray band)

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

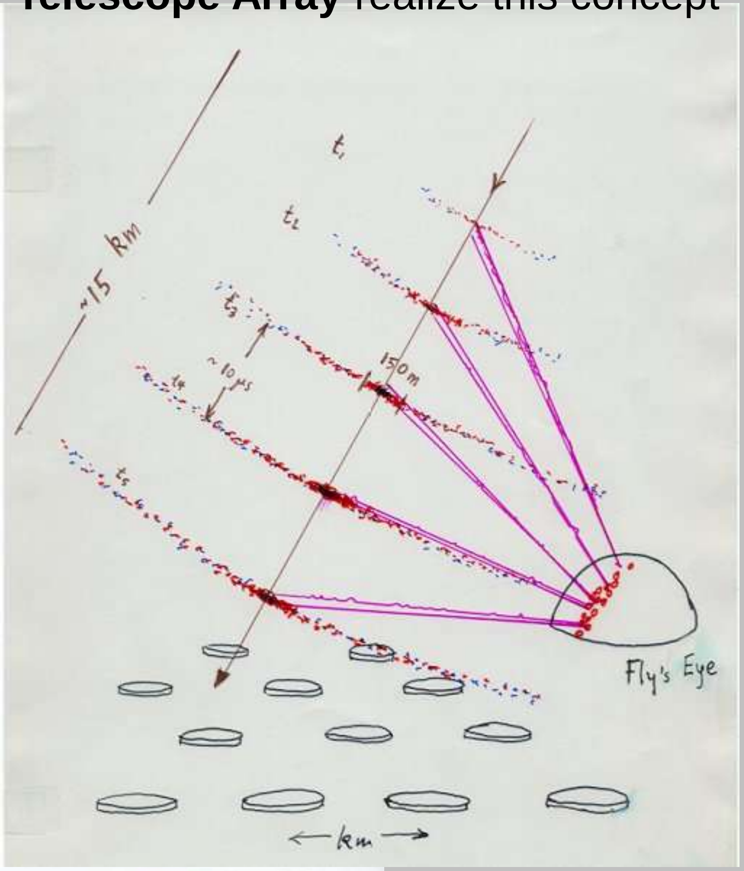


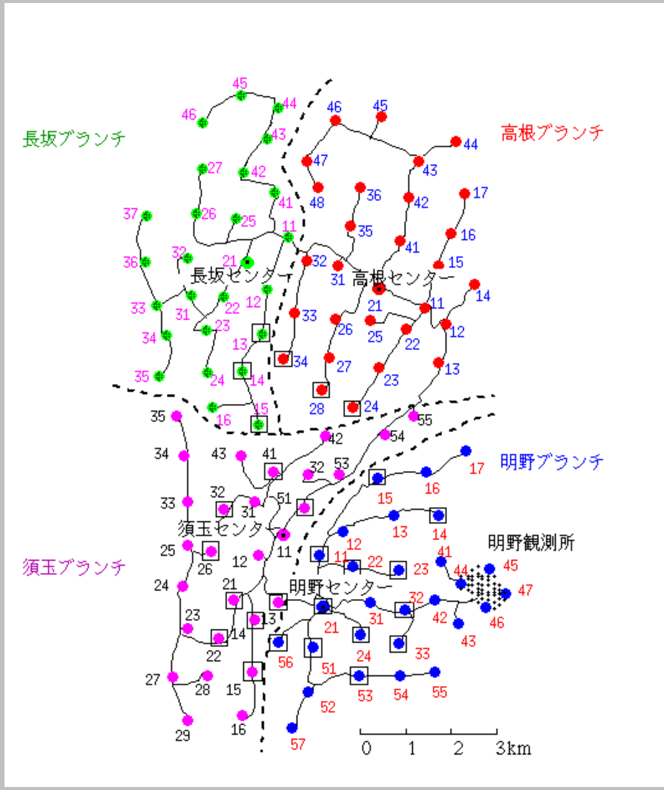
Use X_{max} for composition

- $\langle X_{max} \rangle$ = const + Λ 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
- Assume extra-galactic = primordial composition
  - (p + some He)
  - May not be correct

UHE shower detectors

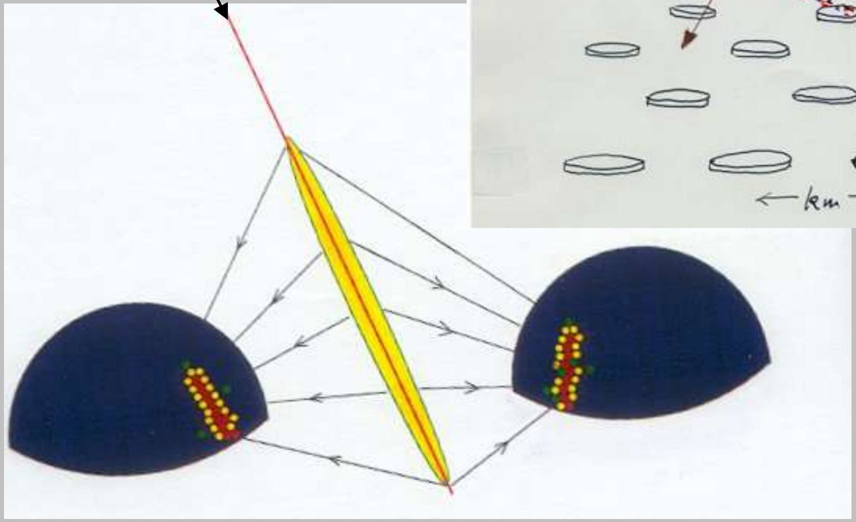
Sketch of ground array with fluorescence detector – **Auger** Project **Telescope Array** realize this concept





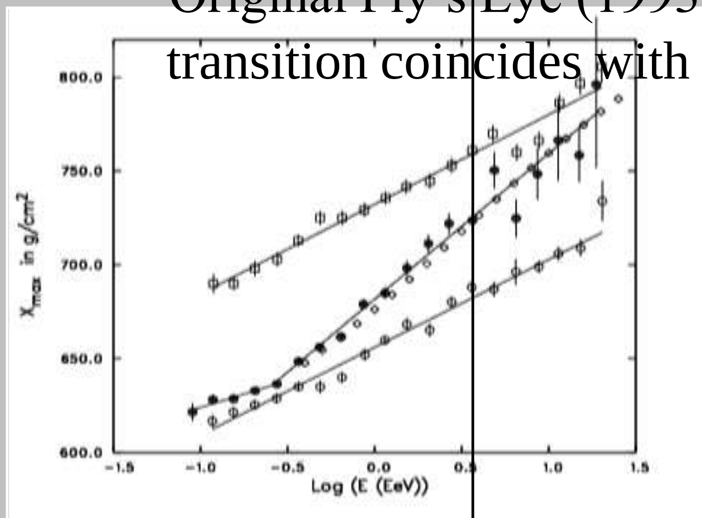
AGASA (Akeno, Japan)
100 km² ground array
1990 - 2003

Hi-Res stereo fluorescence detector in Utah
1997 - 2006

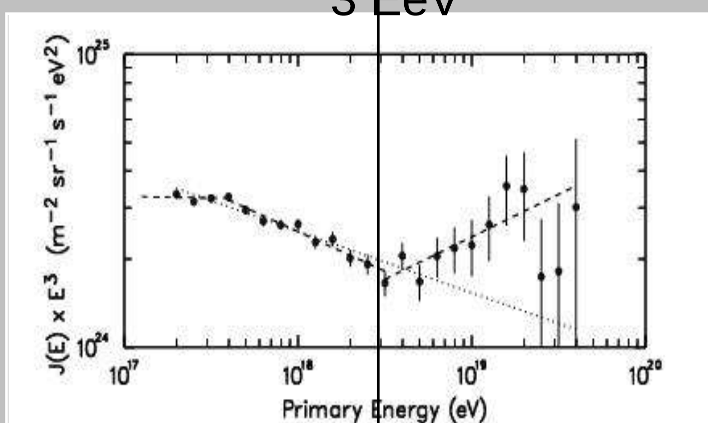


Where is transition to extragalactic CR?

Original Fly's Eye (1993):
transition coincides with ankle



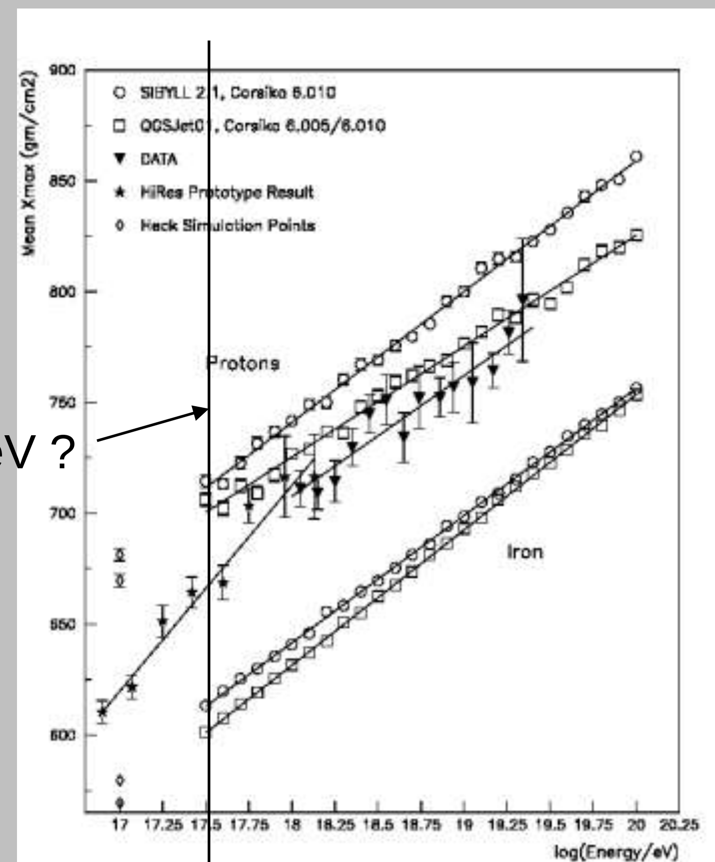
3 EeV



Stereo

HiRes new composition result:
transition occurs before ankle

or 0.3 EeV ?

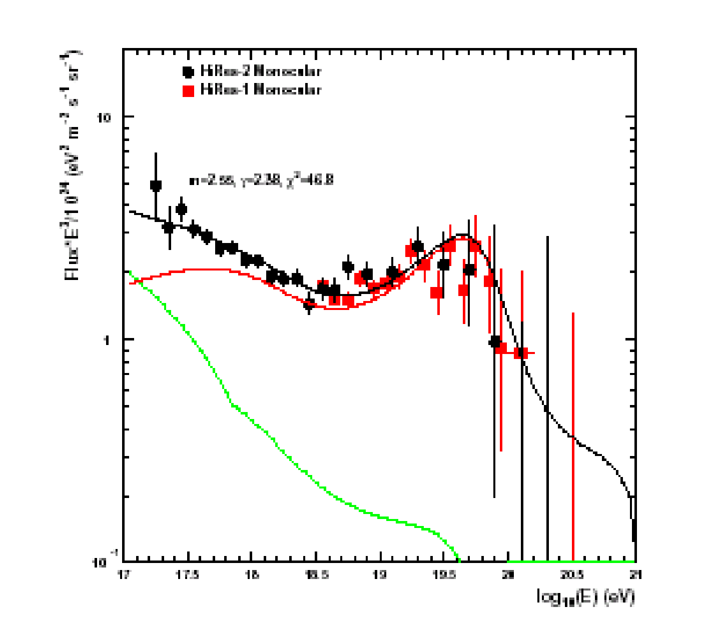


G. Archbold, P. Sokolsky, et al.
Proc. 28th ICRC, Tsukuba, 2003

HiRes analysis

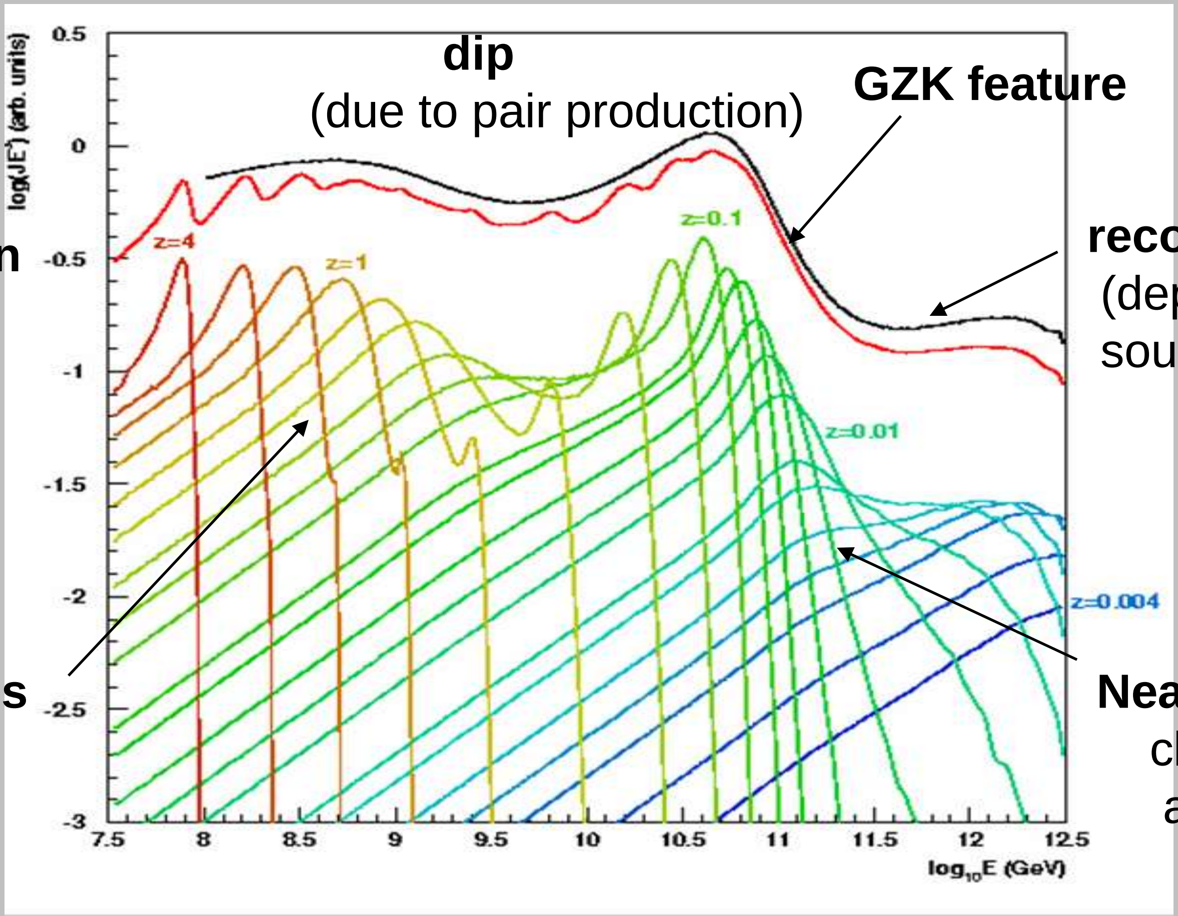
D. Bergman et al., astro-ph/0603797

- Estimate proton fraction
  - Use HiRes prototype + CASA/MIA $<X_{max}>$ measurement
  - Use QGSjet calculation
- Assume protons belong to extra-galactic population
  - 80% protons at 10^{18} ev
- Fit data as galactic (green) plus extra-galactic (red)
  - Parameters are evolution, m in $(1+z)^m$
  - And γ = source spectral index
- In principle, could determine cosmology of UHE sources



Problem is poor resolution and model dependence

(de) constructing the extra-galatic spectrum



dip
(due to pair production)

GZK feature

recovery
(depends on source density)

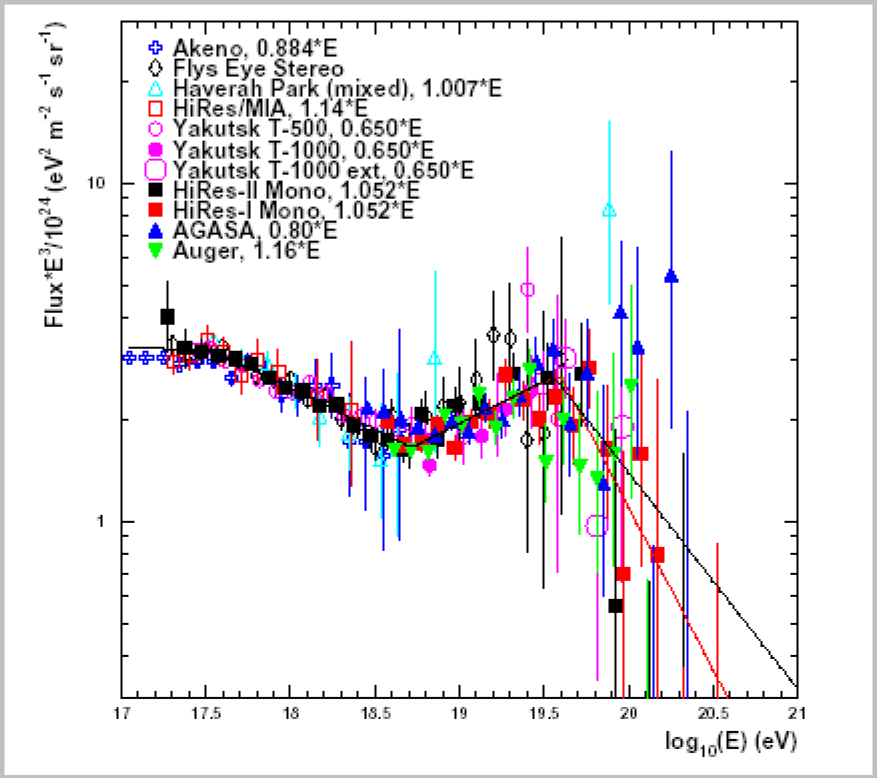
End of Galactic population
(not shown)

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

HiRes “Observation of GZK cutoff”



D. Bergman et al., astro-ph/0609431

- Energy loss via
  $\pi + \gamma \rightarrow \pi + N$
  and
- $p + \gamma \rightarrow e^+ e^- + p$
  this process gives a dip for E ~ 10^{19} eV if extra-galactic C.R. are protons (Berezinsky et al.)
- Spectrum for E< 10^{19} eV depends on
  - **cosmological evolution of sources**
  - **spectral index at source**
  - **inter-galactic magnetic fields**

X_{max} by Auger

30TH INTERNATIONAL COSMIC RAY CONFERENCE

M. Unger, Auger, arXiv: 0706.1495

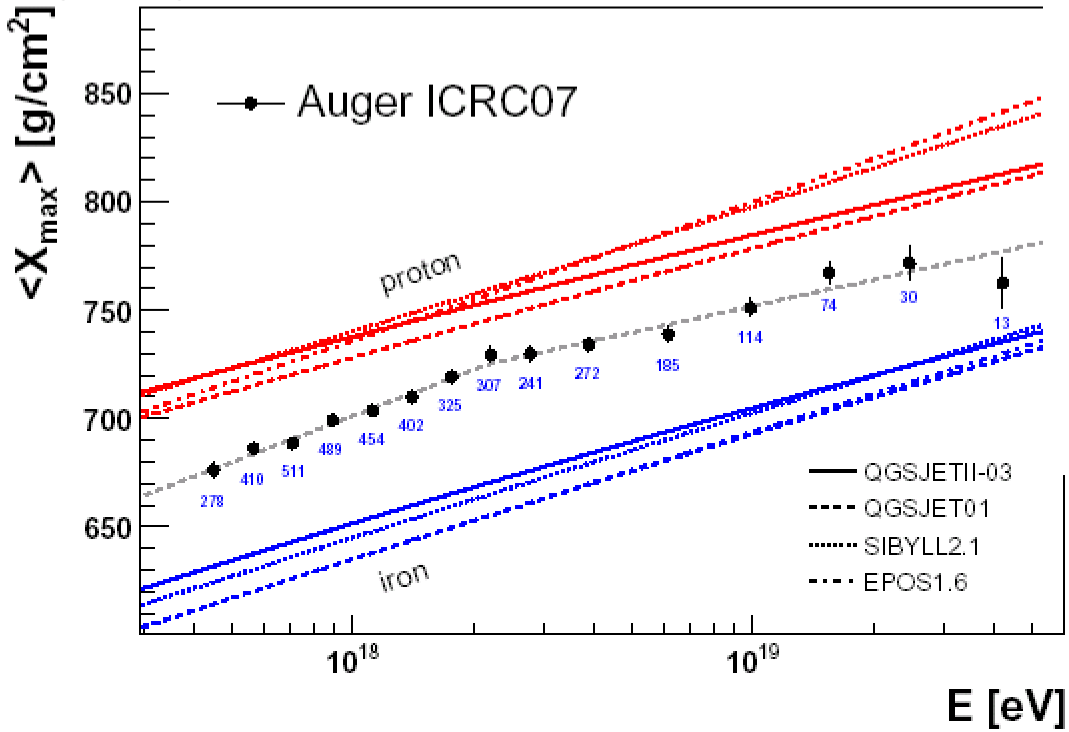


Figure 3: $\langle X_{\max} \rangle$ as a function of energy compared to predictions from hadronic interaction models. The dashed line denotes a fit with two constant elongation rates and a break-point. Event numbers are indicated below each data point.

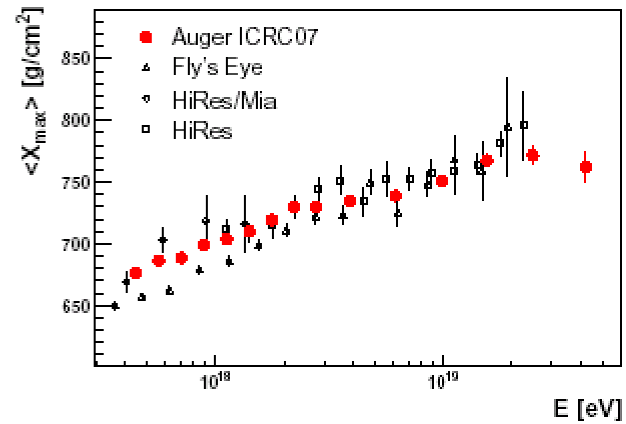
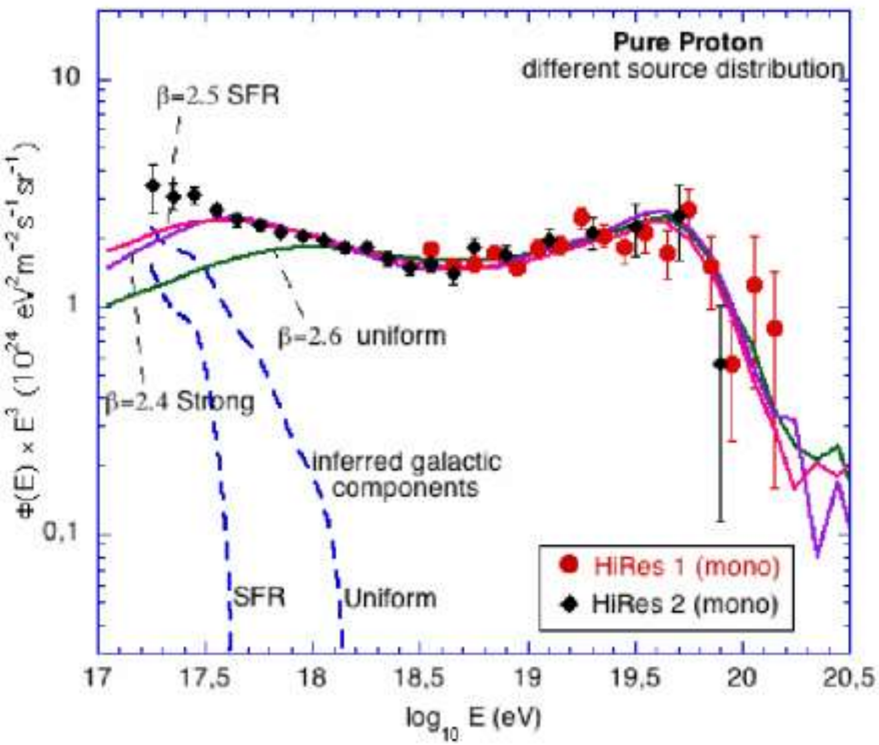
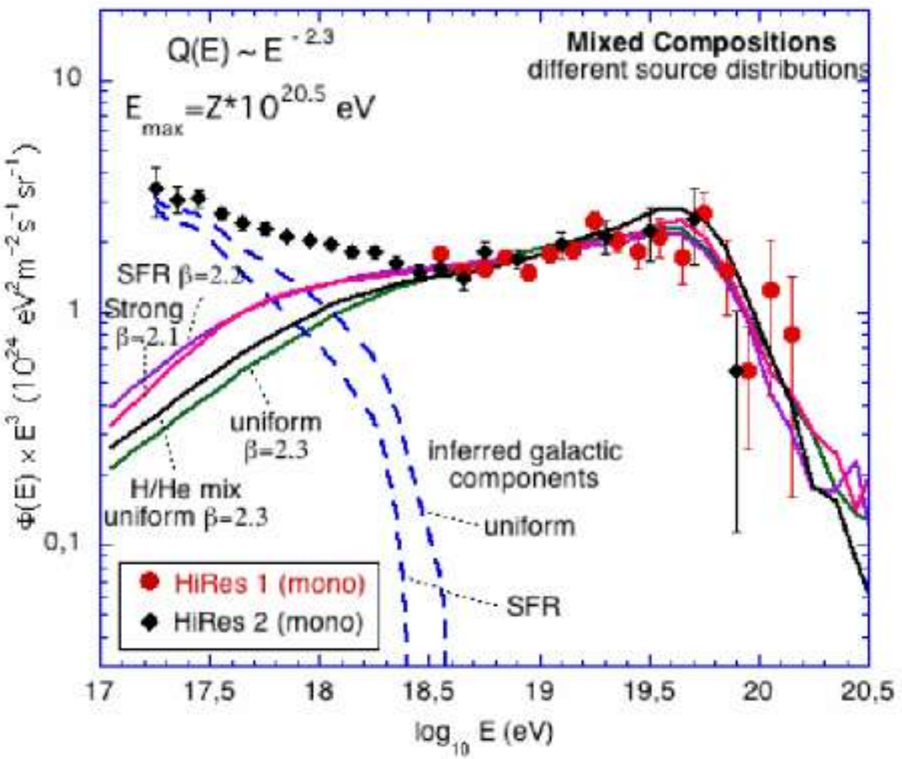


Figure 5: $\langle X_{\max} \rangle$ as a function of energy compared to previous experiments.

Alternatives for transition to E.G.

Allard, Olinto, Parizot, astro-ph/0703633



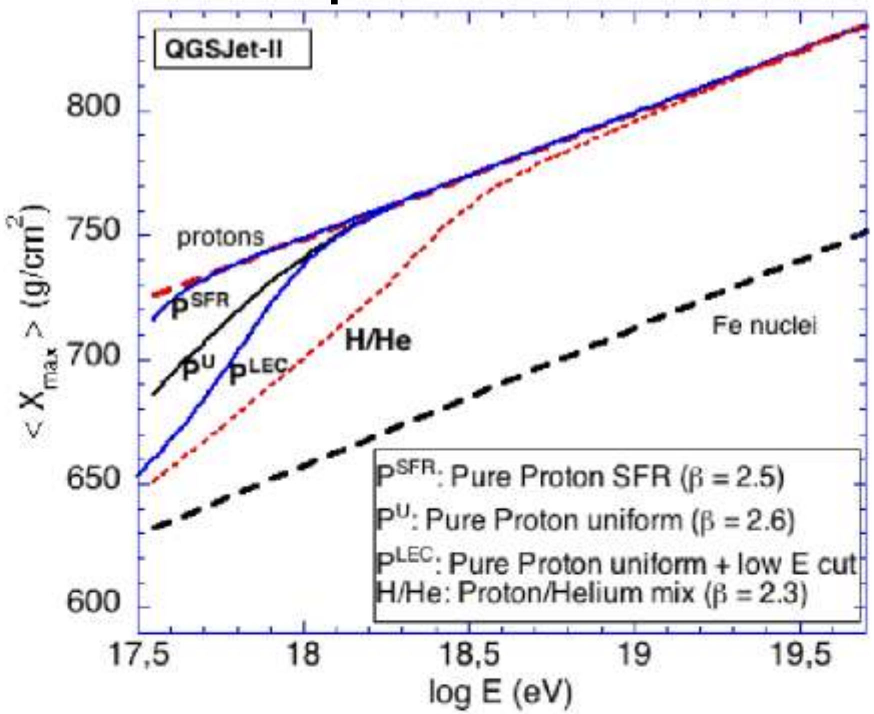


Model dependence of composition in galactic-extragalactic transition

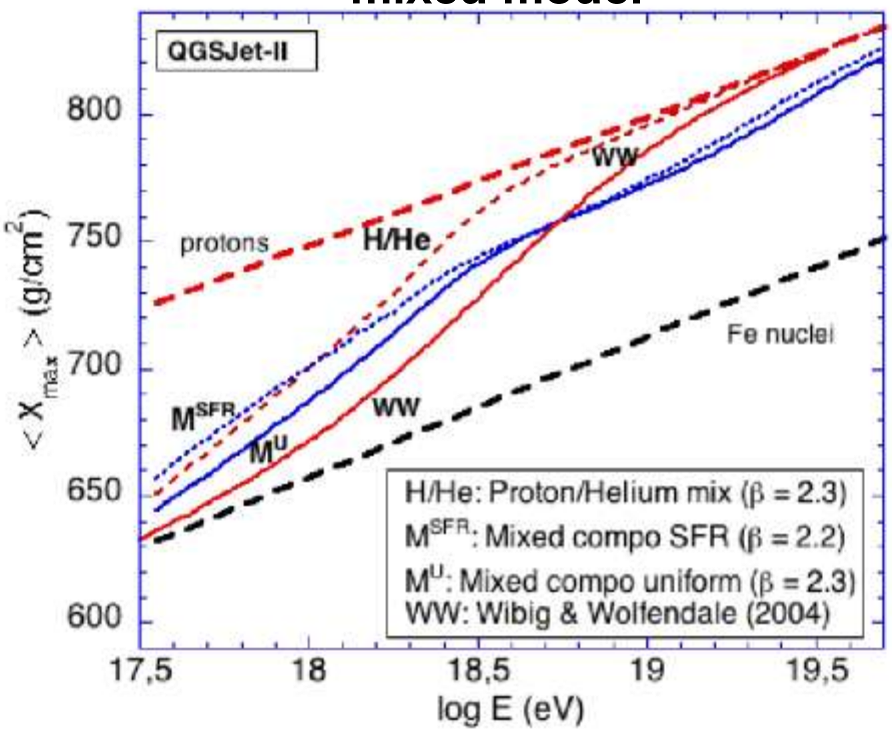
Allard, Olinto, Parizot, astro-ph/0703633

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

proton model

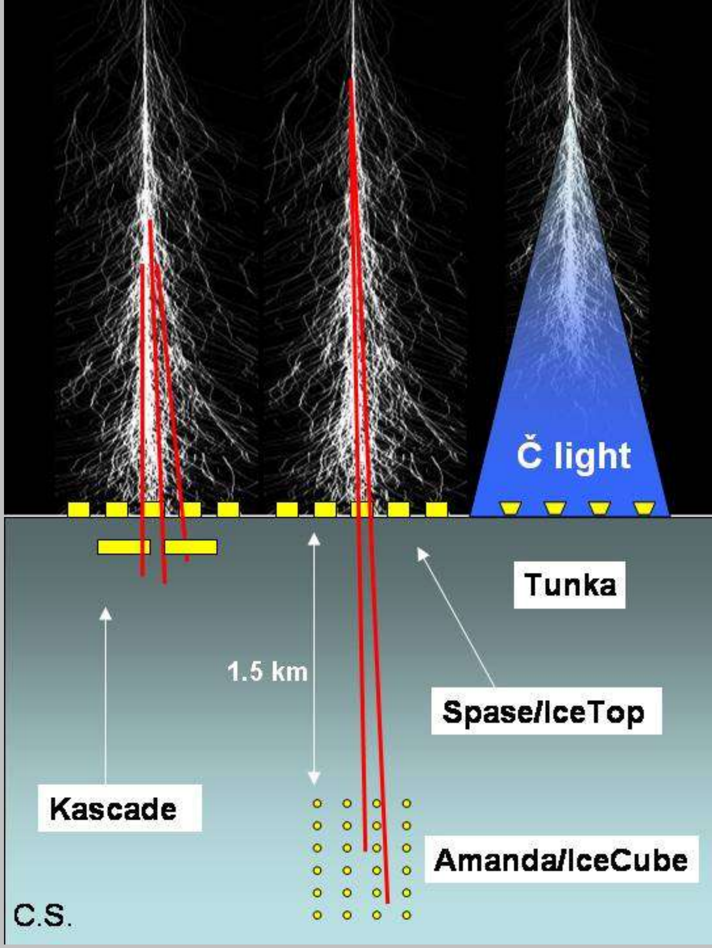


mixed model



Experiments for transition region

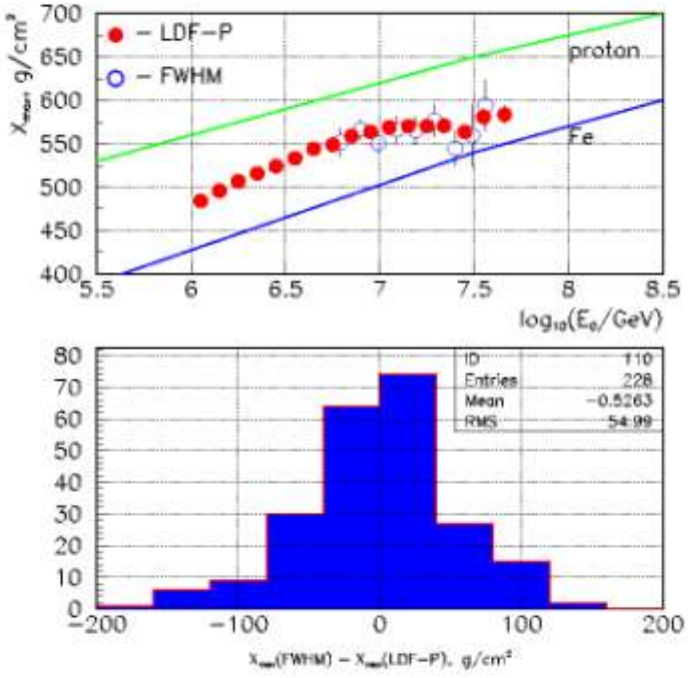
- Tibet at 4300 m is ideal for knee region
- KASCADE Grande, IceCube, Tunka-133
  - Cover from ~10^{15} (< knee) to 10^{18} eV
- Low energy extensions of Auger and Telescope Array (down to <= 10^{17} eV)

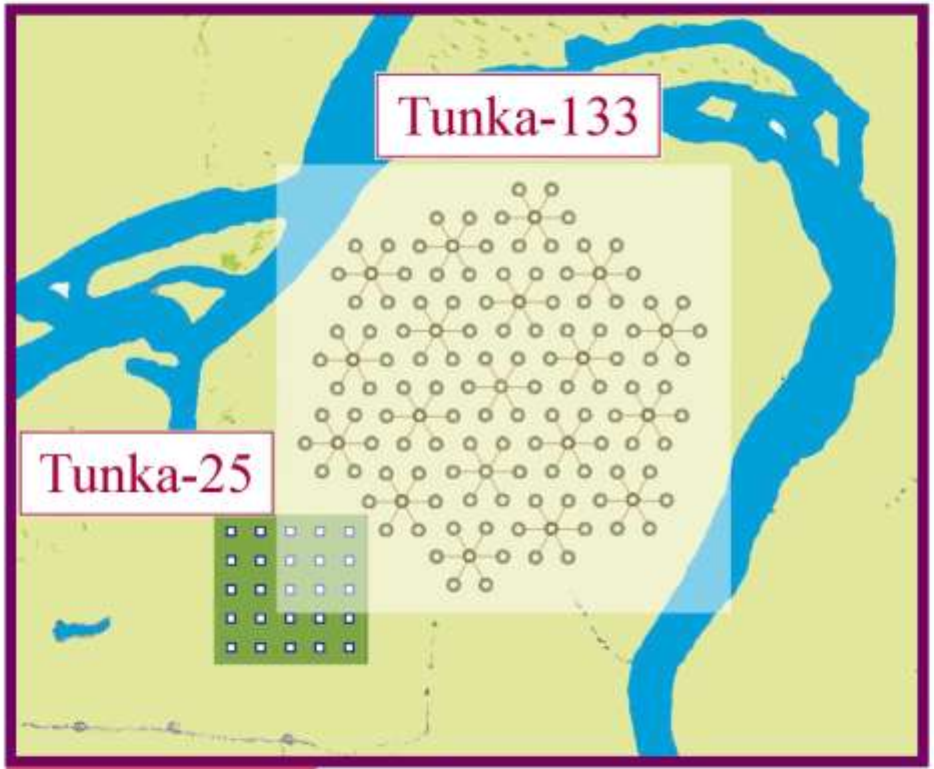


TUNKA-133

Under construction

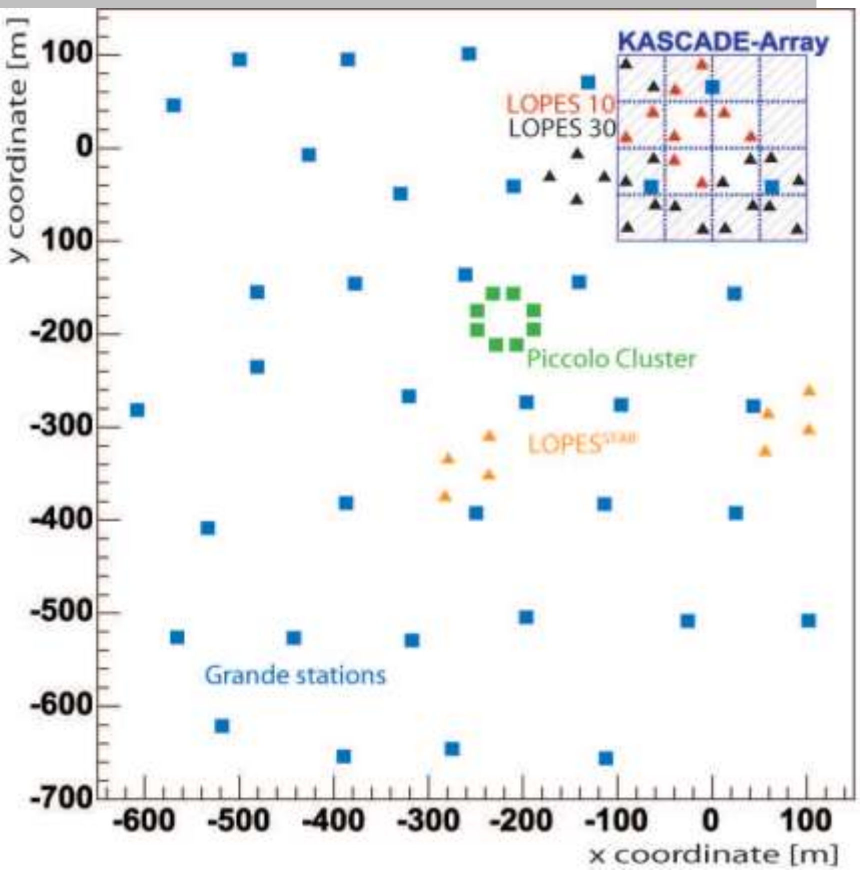
X_{max} from Tunka-25

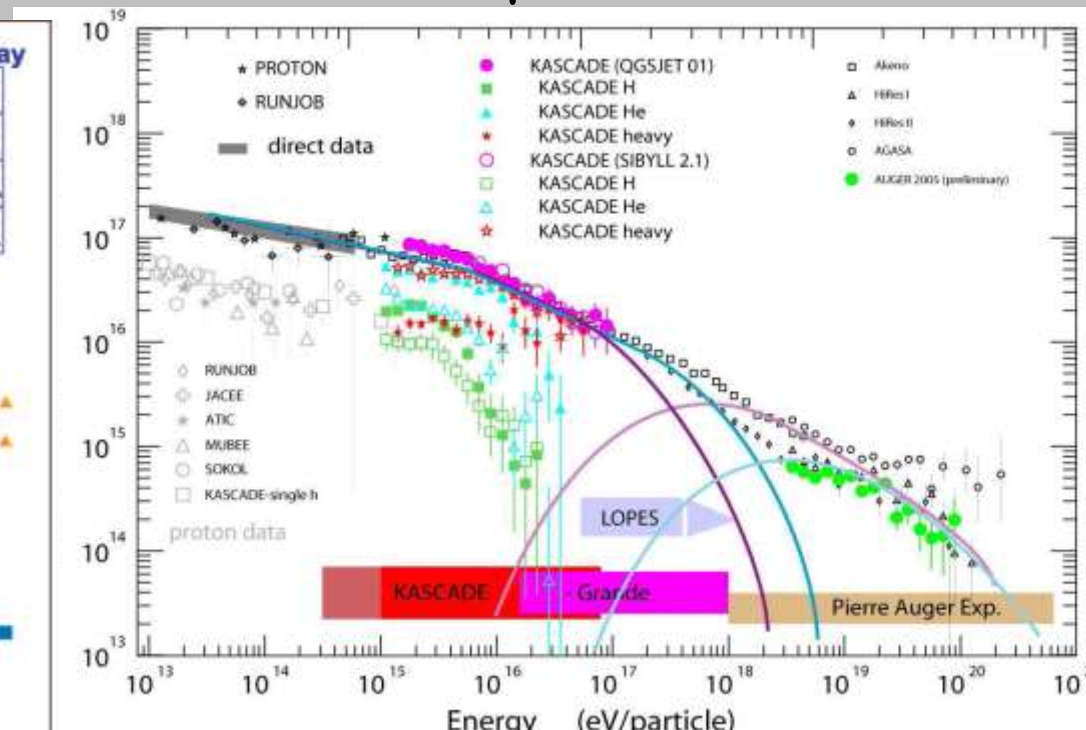




51° 48' 35" N
103° 04' 02" E
675 m a.s.l.

KASCADE-Grande + LOPES plans
Composition from N_μ / N_e



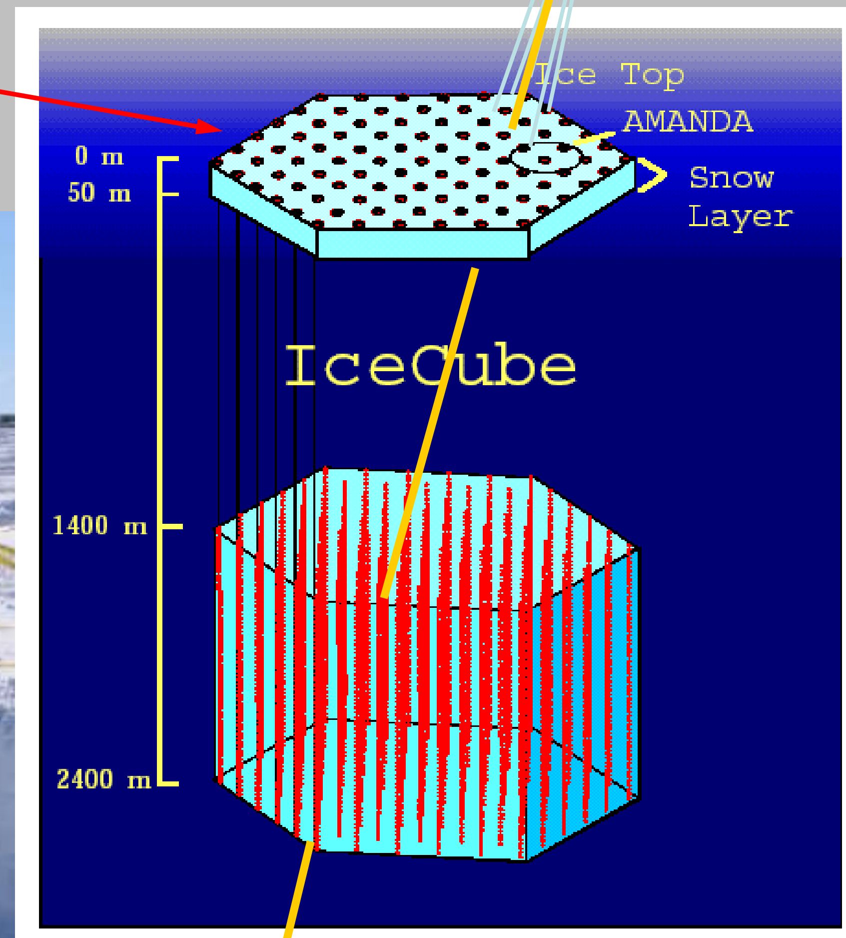


Note the potential for radio detection of air showers –
It is being explored also at Auger

Air Showers with IceCube: Calibration & cosmic-ray physics

Composition from N_μ(>500 GeV) / N_e

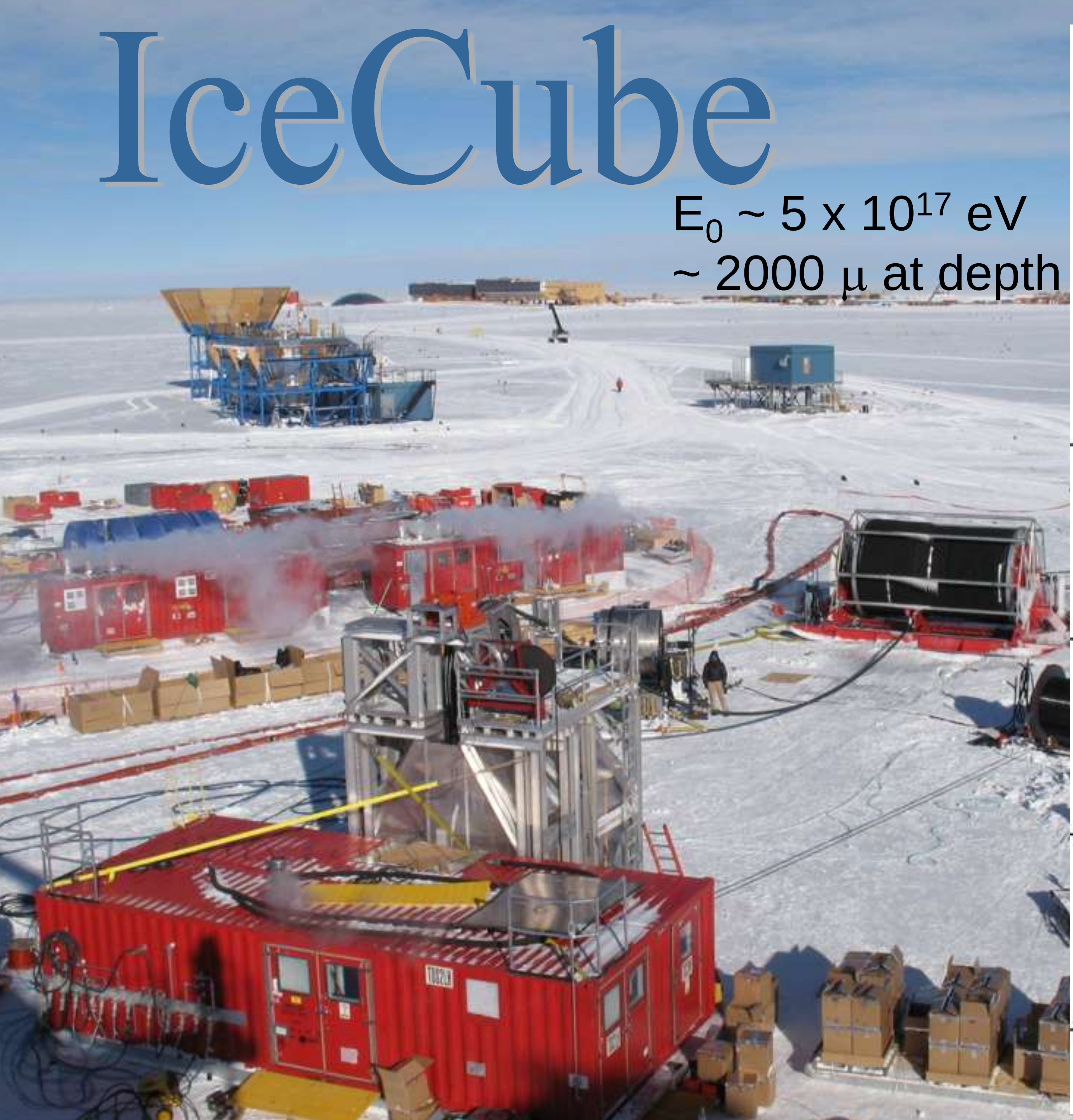
IceTop

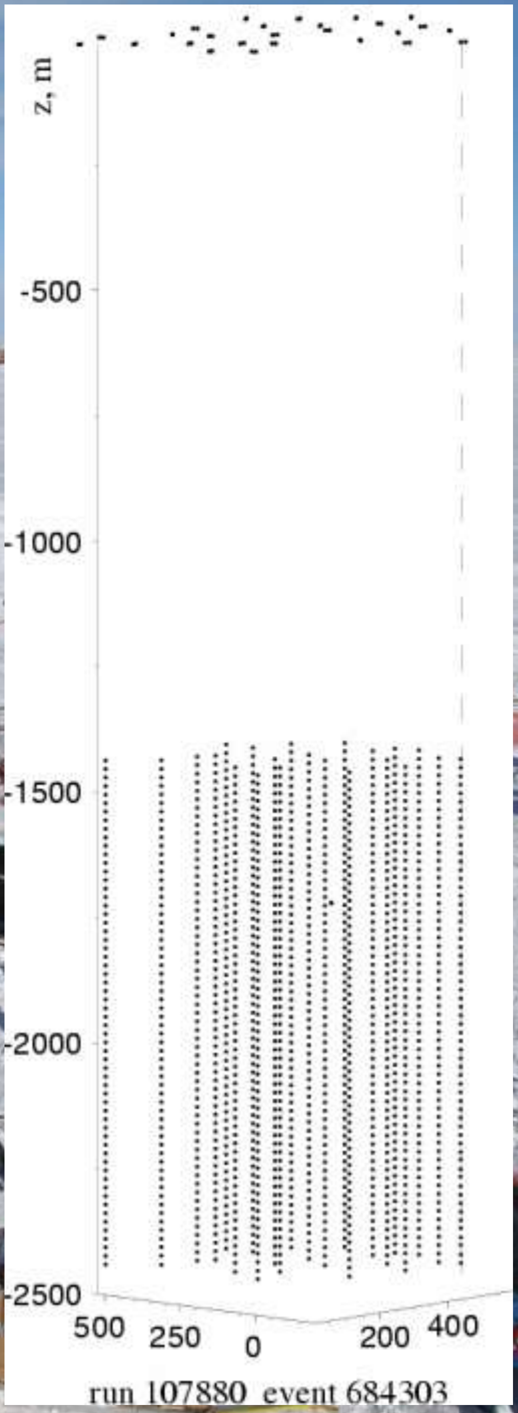


IceCube

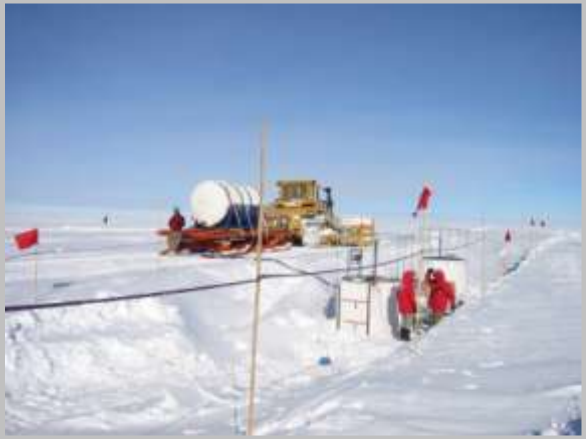
$E_0 \sim 5 \times 10^{17}$ eV

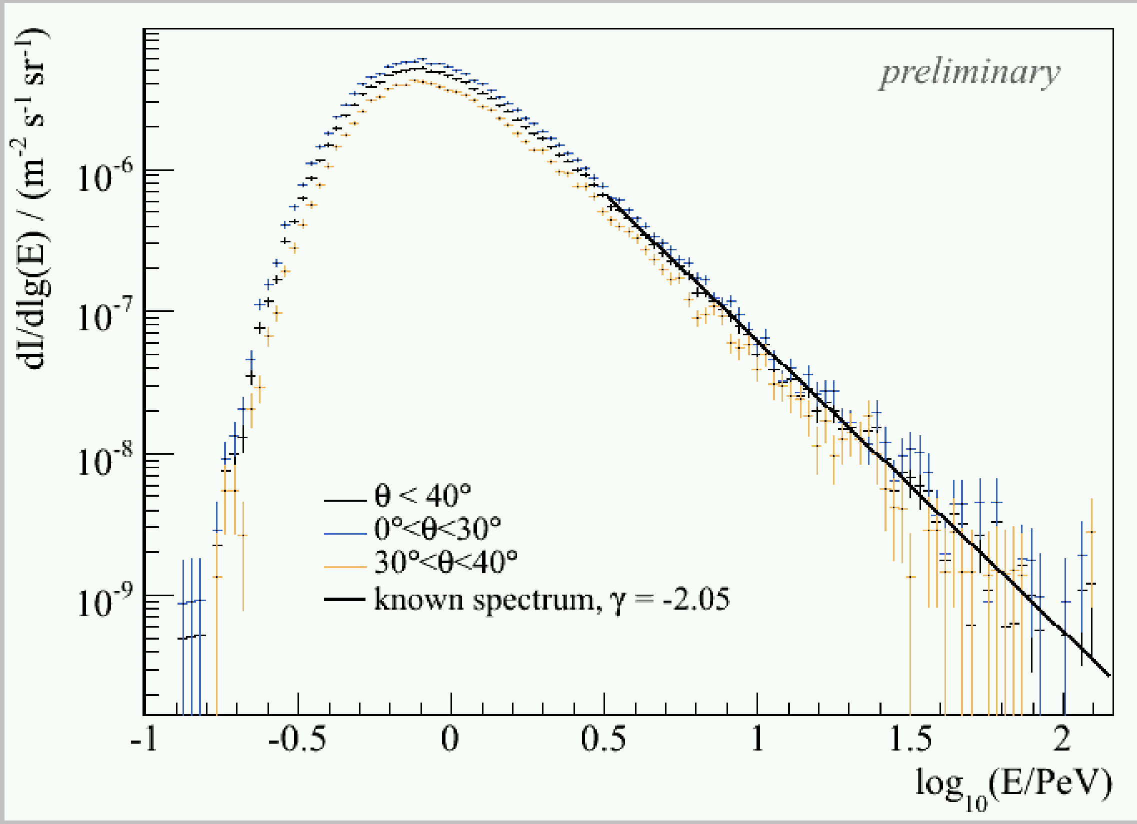
~ 2000 μ at depth





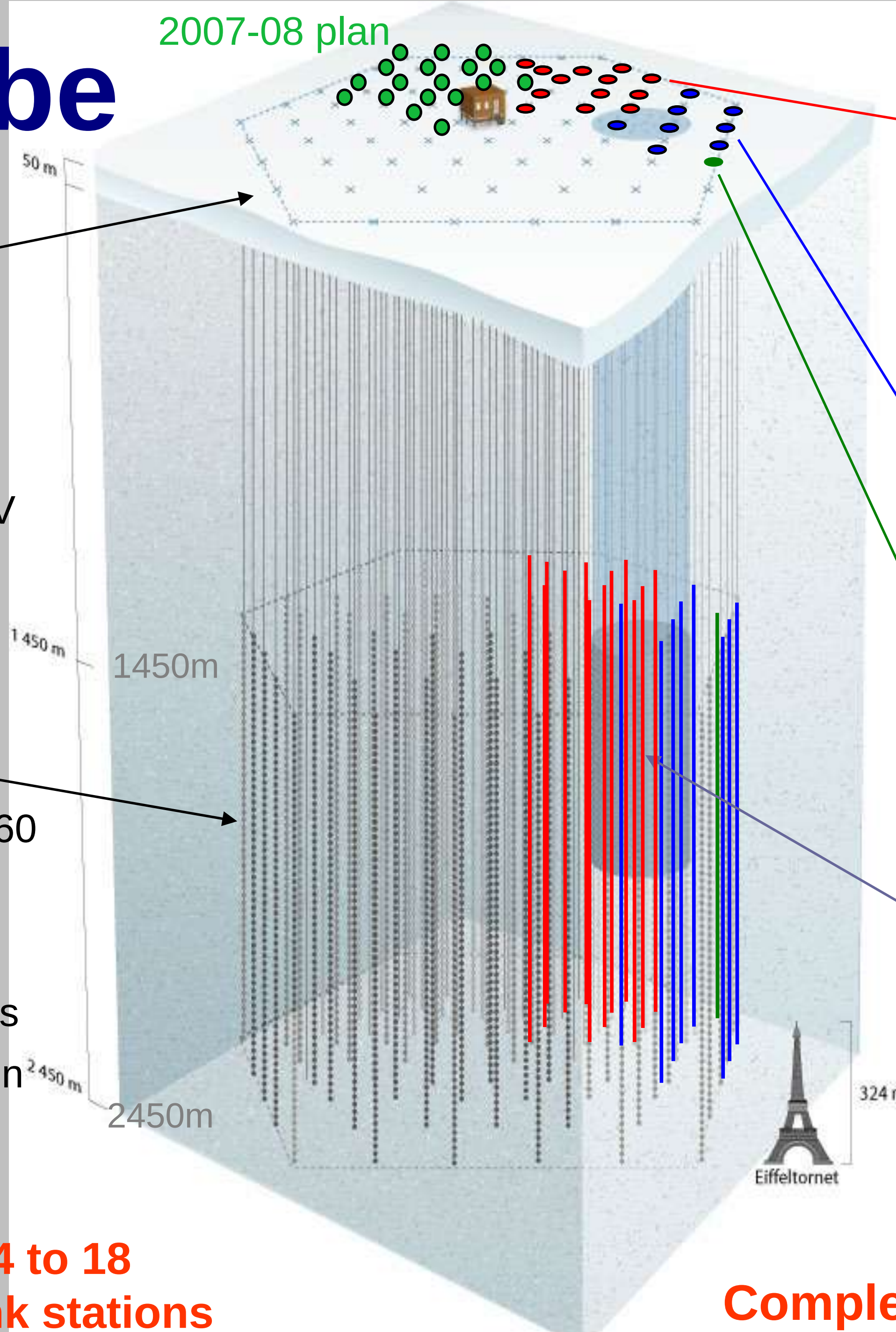
IceTop – 2 tanks per station





Preliminary energy spectrum with 2006 data

IceCube



IceTop

Air shower detector
80 pairs of ice
Cherenkov tanks
Threshold ~ 300 TeV

InIce

Planned 80 strings of 60 optical modules each

17 m between modules
125 m string separation

2006-2007:
13 strings deployed

Current configuration
- 22 strings
- 52 surface tanks

2005-2006: 8 strings

2004-2005 : 1 string

AMANDA-II
19 strings
677 modules

AMANDA now operating as part of IceCube

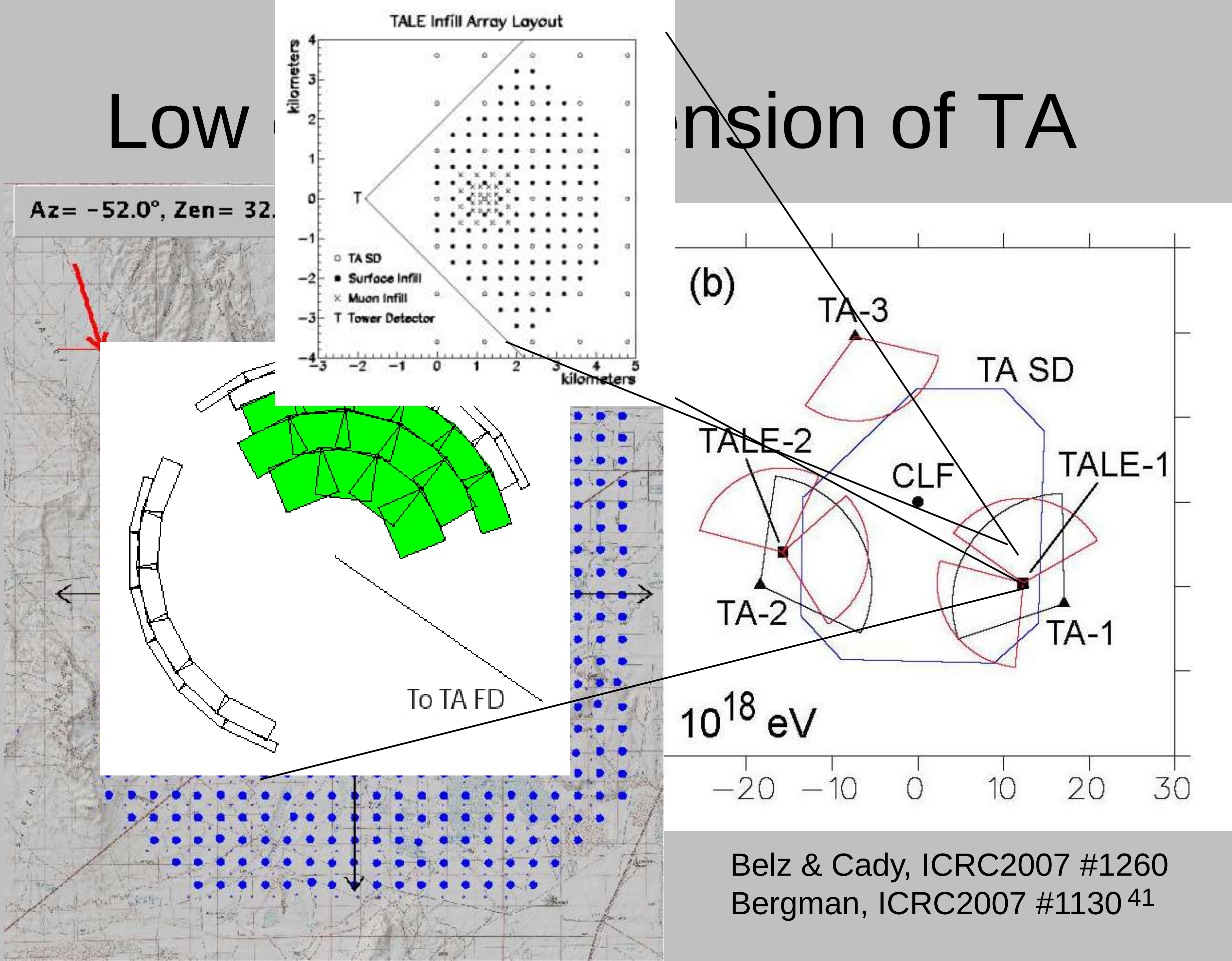
2007/08: add 14 to 18 strings and tank stations

Completion by 2011.

Plans to decrease the thresholds of Auger and TA

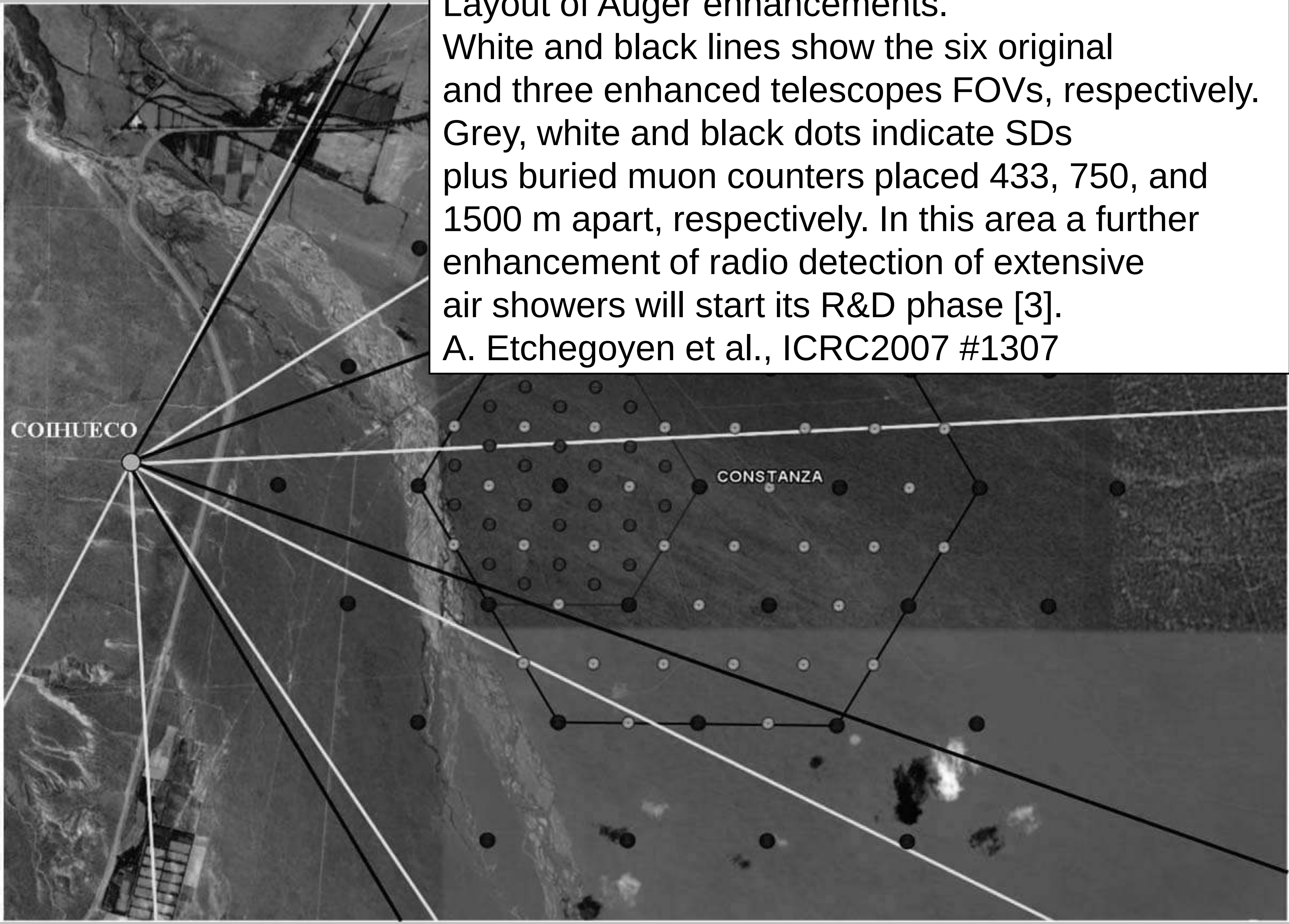
- Auger SD threshold 3 EeV, FD is 1 EeV
  - Goal: lower threshold to 0.1 EeV = 10^{17} eV
  - HEAT consists of 3 FTs viewing 30^o to 60^o
  - AMIGA is an in-filled surface array
- TA threshold 3 EeV
  - Goal: lower threshold to 3×10^{16} eV
  - TALE FD: 3 FDs including higher viewing angle
  - Overlooking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

Low … ension 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



Cross checks

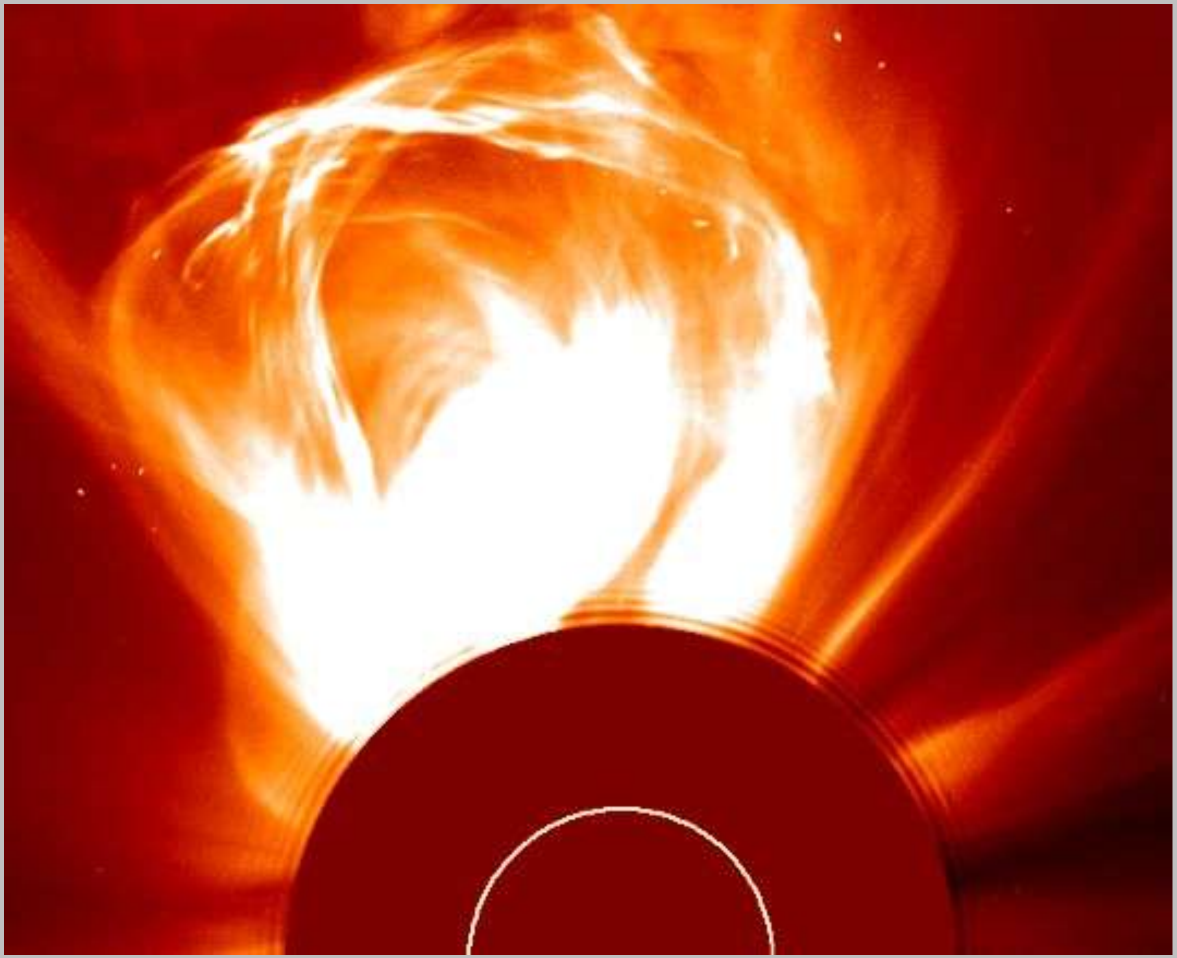
- Both TALE and Auger infill ground arrays
  - Include separate detectors for μ and e-m components
  - μ / e and X_{max} depend on composition in different ways
  - In principle allows breaking degeneracy between composition and hadronic interactions

High-energy cosmic rays: key questions

- What is the composition through the knee region?
  – Need 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?
  – Is there a component “B” ?
- What interaction model to use?
- Where is transition to extra-galactic population?

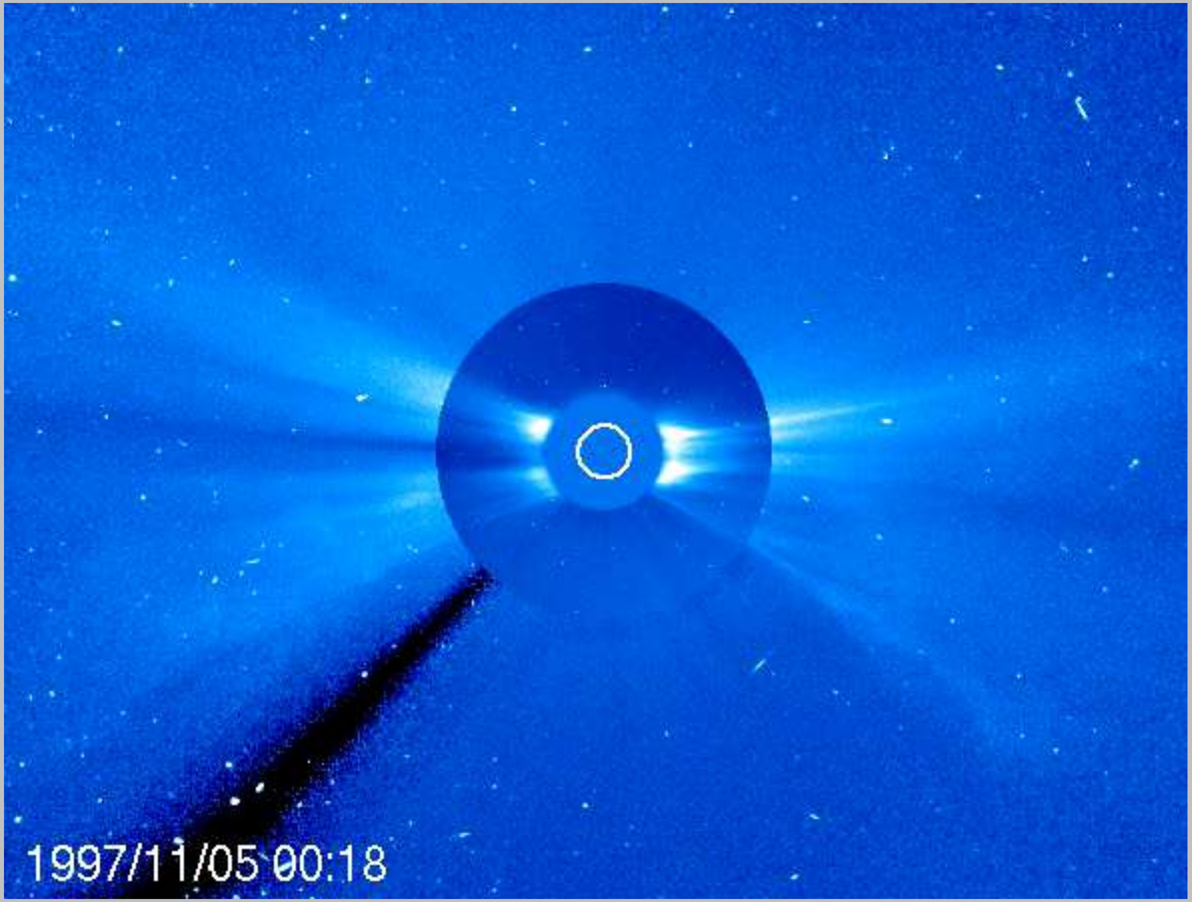
Solar flare shock acceleration

Coronal mass ejection
09 Mar 2000



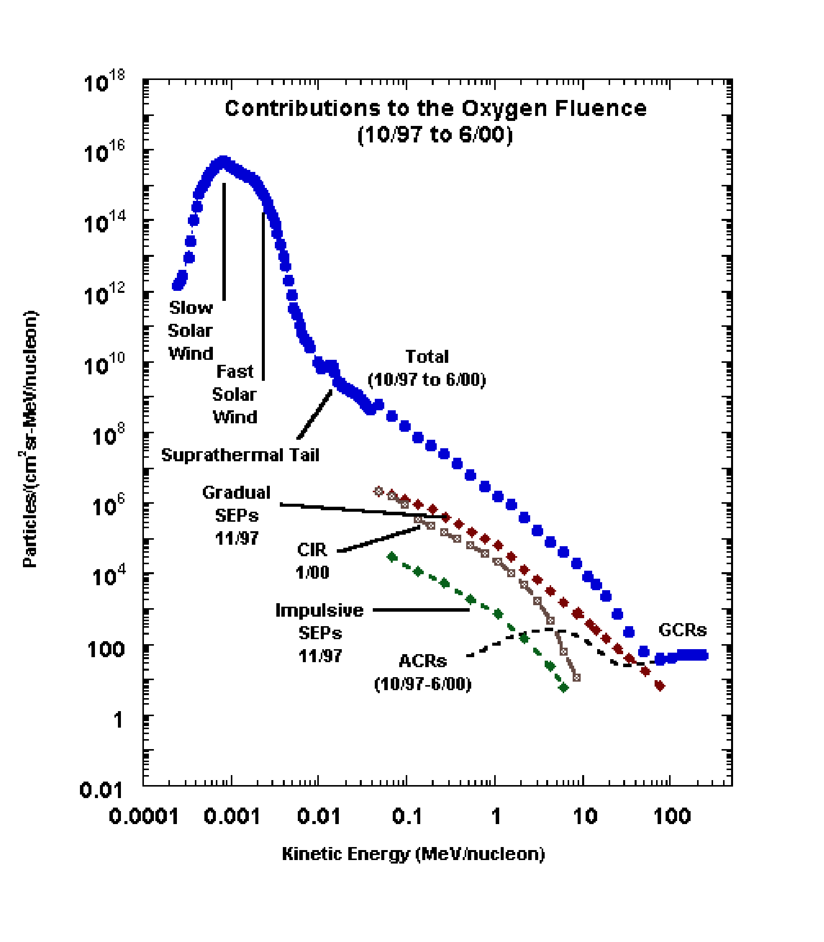
LASCO event of 23 Nov 97

http://lasco-www.nrl.navy.mil/best_of_lasco_apr98/index.htm



Lessons from the heliosphere

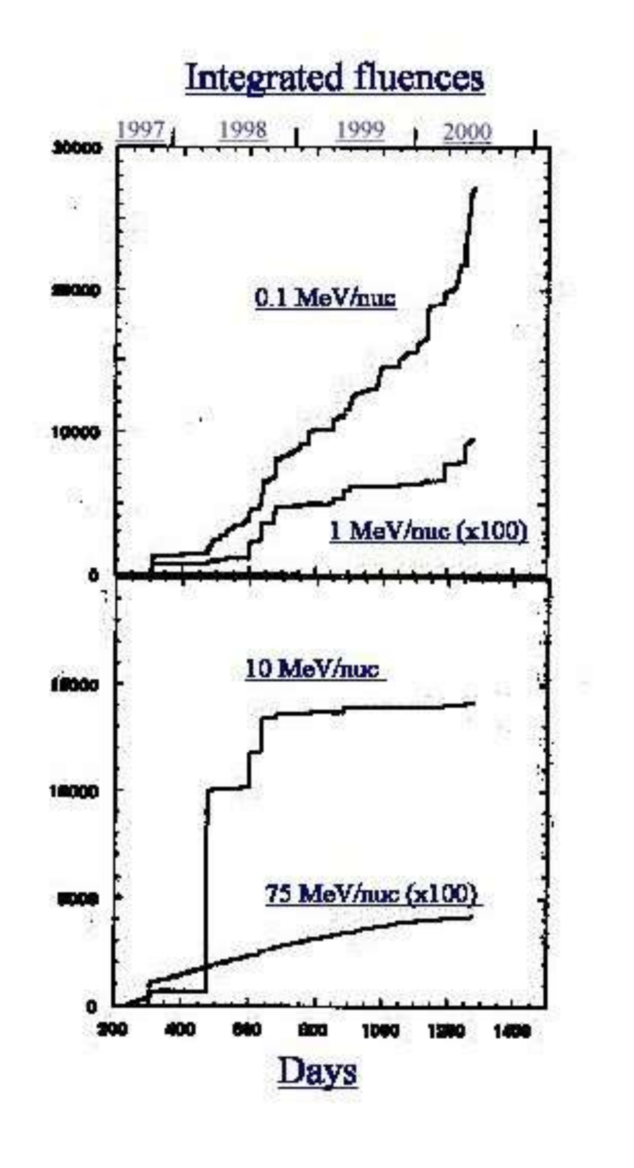
- ACE energetic particle fluences:
- Smooth spectrum
  - composed of several distinct components:
    - Most shock accelerated
    - Many events with different shapes contribute at low energy (< 1 MeV)
    - Few events produce ~10 MeV
  - Knee ~ Emax of a few events
  - Ankle at transition from heliospheric to galactic cosmic rays



R.A. Mewaldt *et al.*, A.I.P. Conf. Proc. 598 (2001) 165

Heliospheric cosmic rays

- ACE--Integrated fluences:
  - Many events contribute to low-energy heliospheric cosmic rays;
  - fewer as energy increases.
  - Highest energy (75 MeV/nuc) is dominated by low-energy *galactic* cosmic rays, and this component is again *smooth*
- Beginning of a pattern?



R.A. Mewaldt *et al.*, A.I.P. Conf. Proc. 598 (2001) 165