Physics at the End of the
Galactic Cosmic Ray Spectrum

Some highlights of Aspen

Workshop on

Physics at the End of the Galactic Cosmic-ray Spectrum

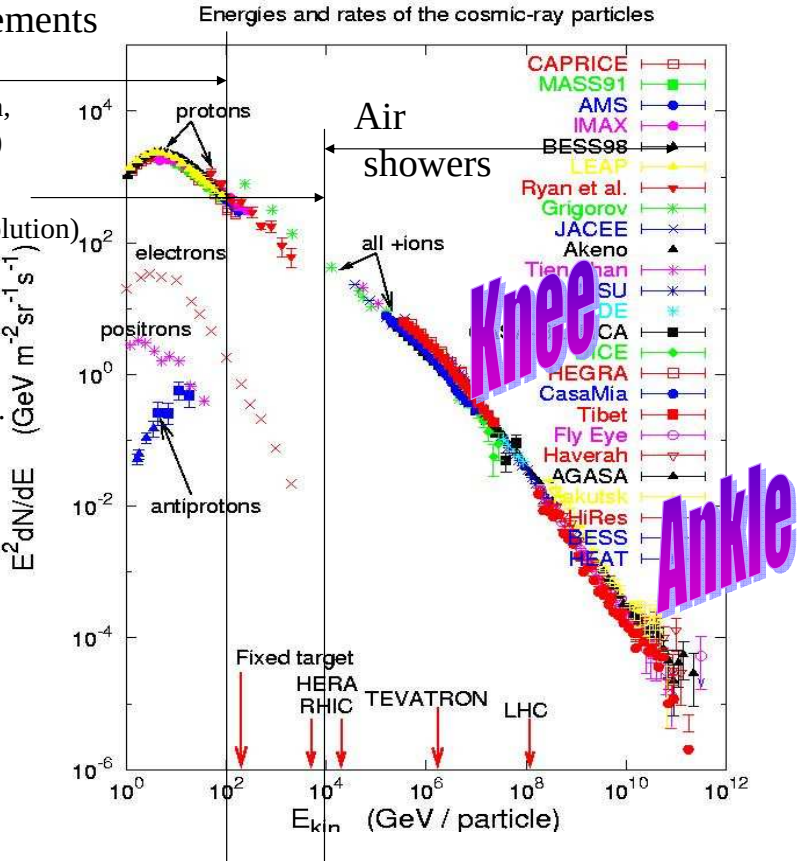
April 26-30, 2005

Direct measurements

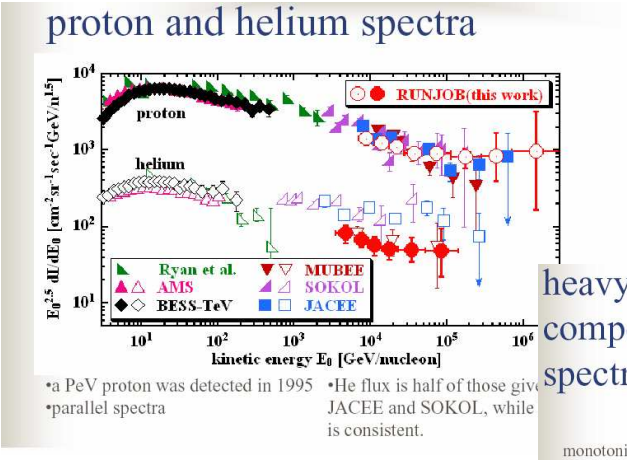
Spectrometers
(ΔA = 1 resolution, good E resolution)

Calorimeters
(less good resolution)

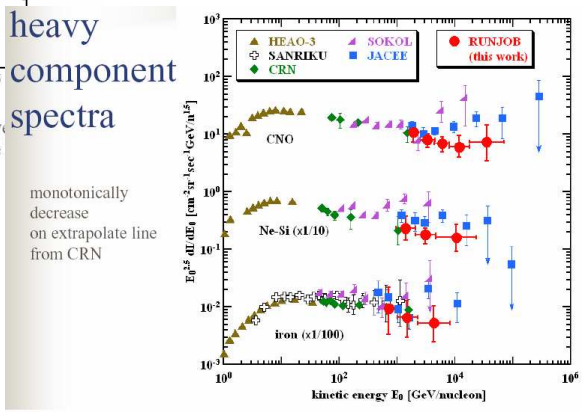
Air-shower arrays
on the ground to overcome low flux. Don't see primaries directly.



RUNJOB spectra (final)



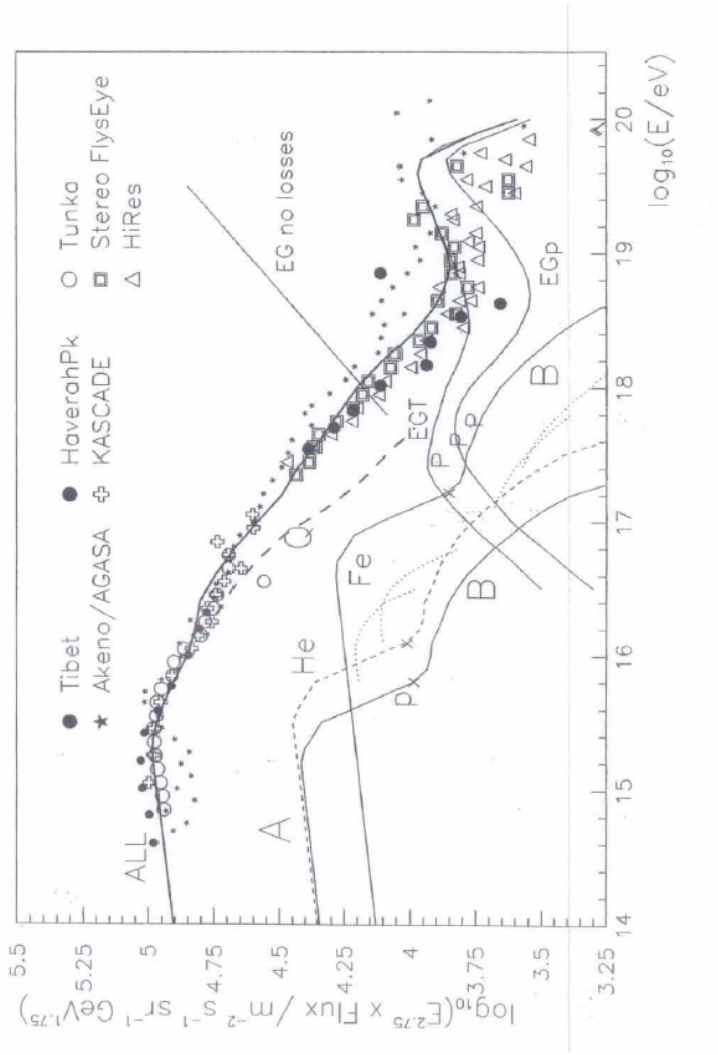
Observed spectrum ~ $E^{(-2.7)}$ to 100 TeV



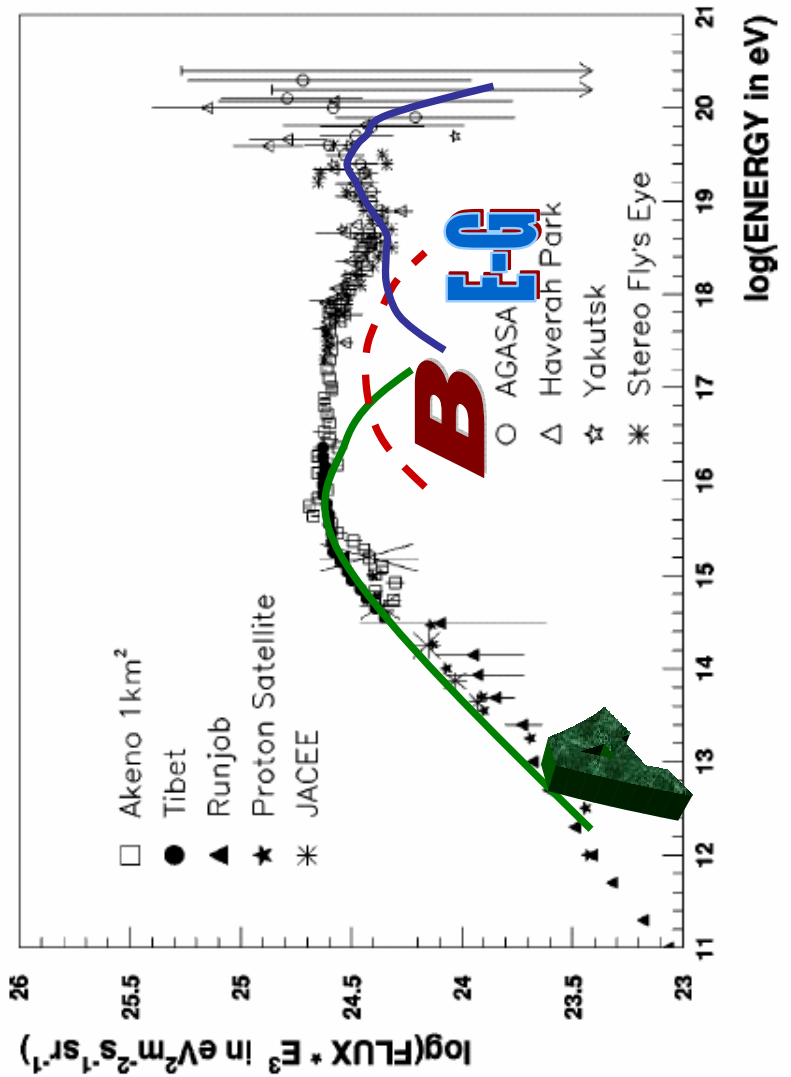
Standard model of cosmic-rays to ~100 TeV

- Diffusive shock acceleration in galactic SNR
  - 15 % of energy goes into accelerated p & nuclei
  - dN / dE ~ $E^{(-2.1)}$ (source spectrum)
  - secondary / primary nuclei → τ_{esc} ~ $E^{(-0.6)}$ to make dN / dE (observed) ~ $E^{(-2.7)}$
- Problems:
  - strong energy dependence of τ_{esc} violates observed isotropy when extrapolated to PeV
  - observed turbulence prefers τ_{esc} ~ $E^{(-0.3)}$
  - high efficiency → non-linear acceleration → event flatter source spectrum

➔ Best estimate of Galactic and Extragalactic flux components:

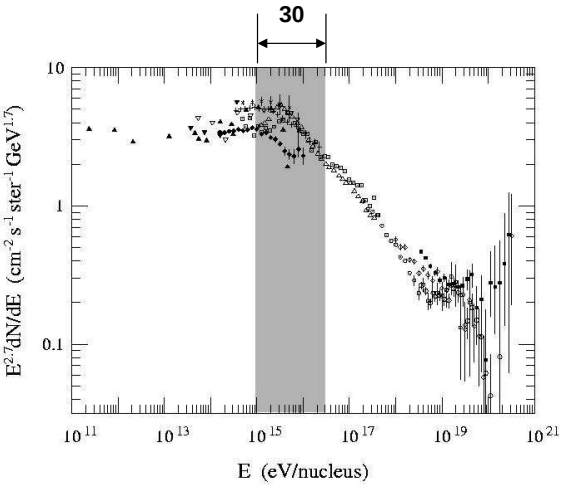


M. Nagano and A. A. Watson: Ultrahigh-energy cosmic rays



Rigidity-dependence

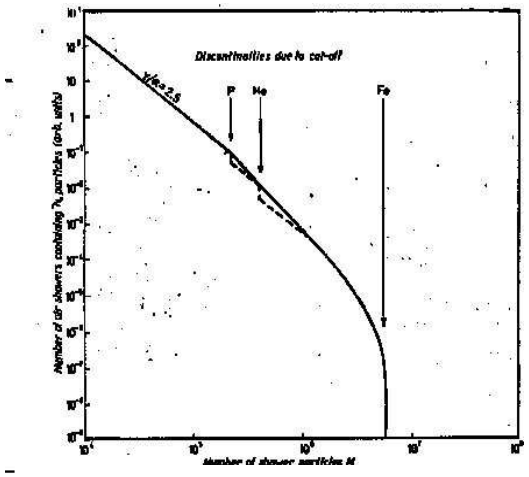
- Acceleration, propagation
  - depend on B: $r_{gyro} = R/B$
  - Rigidity, $R = E/Ze$
  - $E_c(Z) \sim Z R_c$
- $r_{SNR} \sim$ parsec
  - $\rightarrow E_{max} \sim Z * 10^{15}$ eV
  - $1 \leq Z \leq 30$ (p to Fe)
- Slope change should occur within factor of 30 in energy
- With characteristic pattern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

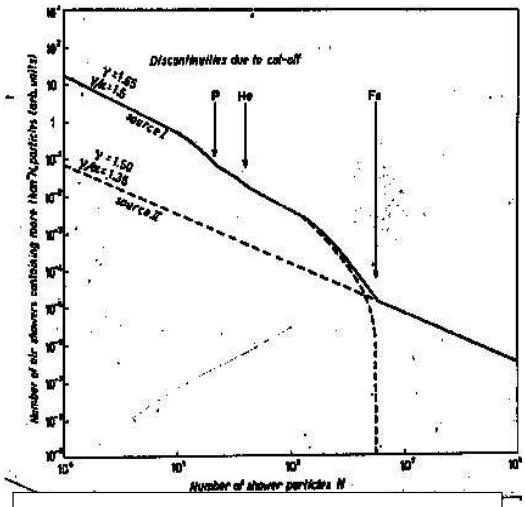


B. Peters on the *knee* and *ankle*

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

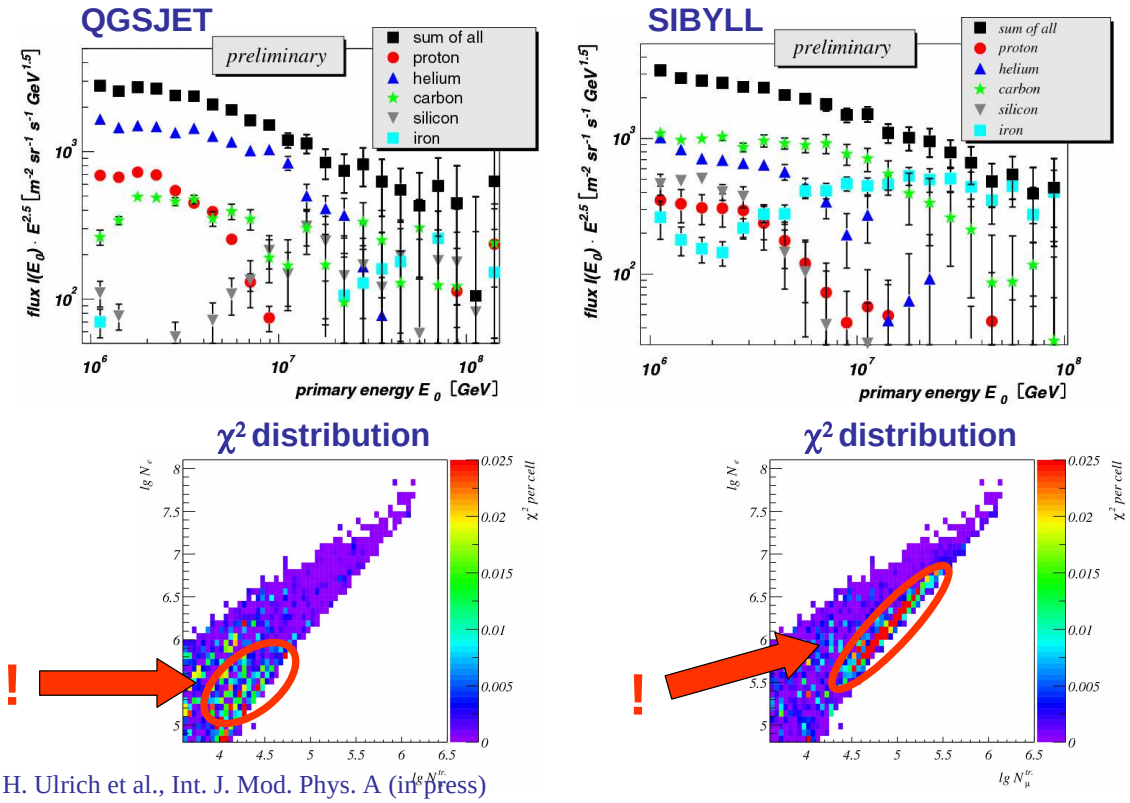
<A> should begin to decrease again for $E > 30 \times E_{knee}$





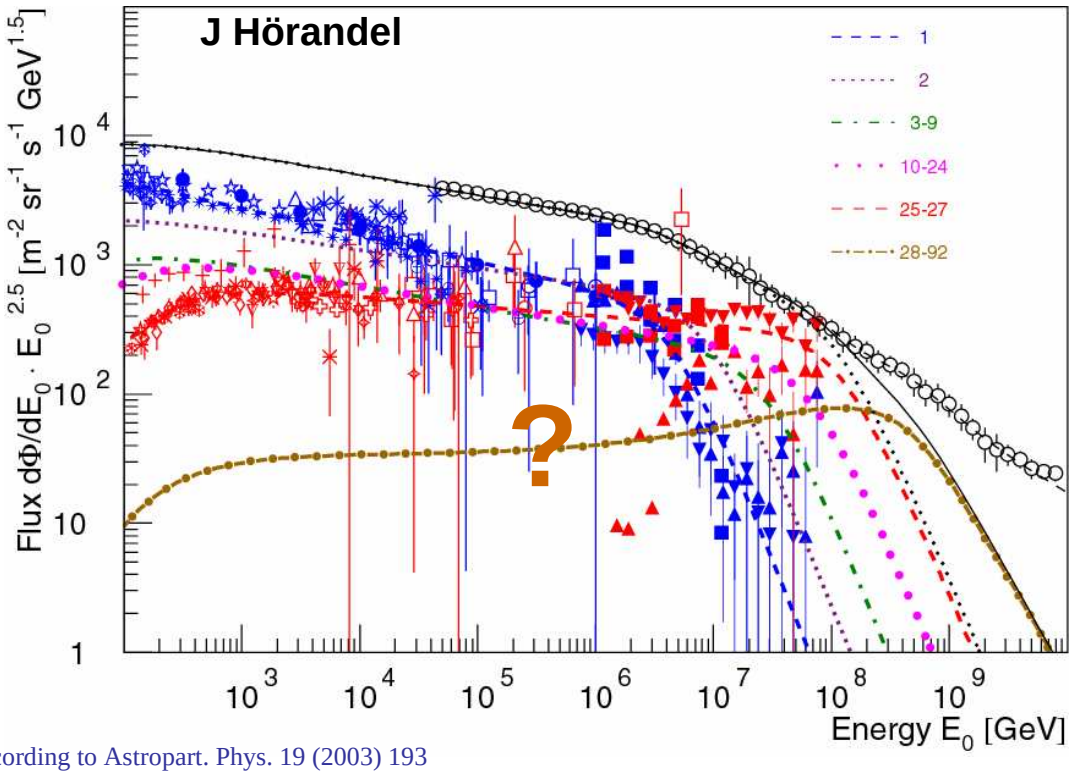
B. Peters, Nuovo Cimento 22 (1961) 800

KASCADE: Energy spectra for individual elemental groups

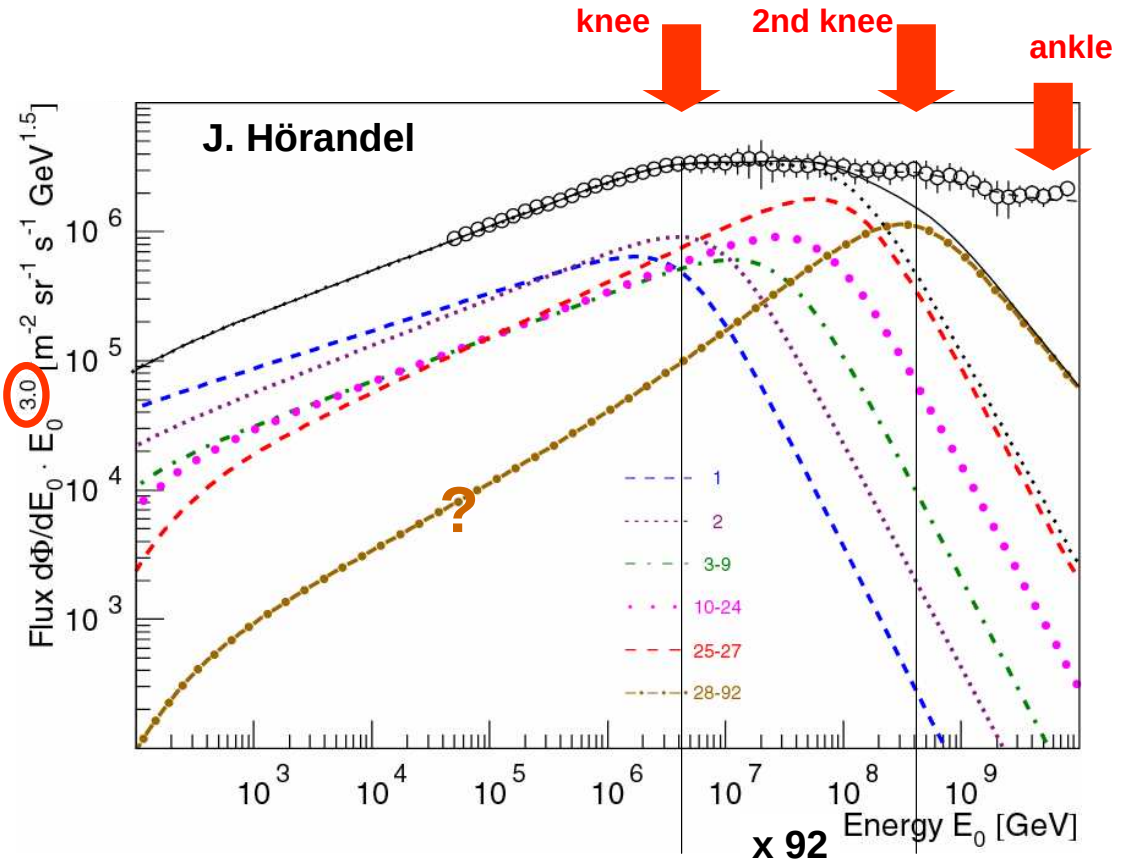


H. Ulrich et al., Int. J. Mod. Phys. A (in press)

Cosmic-ray energy spectrum



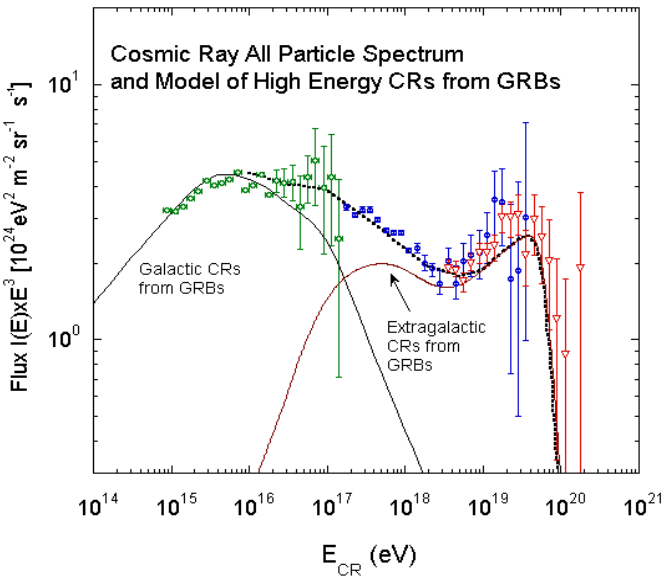
according to Astropart. Phys. 19 (2003) 193



Atoyan

Model: GRB origin of CRs *at* and *above* the knee

- Cosmic Rays below ≈ 10^{14} eV from SNe that collapse to neutron stars
- Cosmic Rays above ≈ 10^{14} eV from SNe that collapse to black holes
  - CRs between knee and ankle/second knee from GRBs in Galaxy
  - CRs at higher energy from extragalactic/ cosmological origin



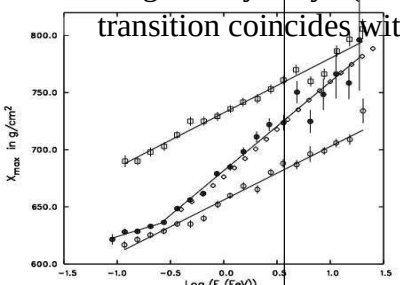
(Wick et al. 2004)

BEREZINSKY

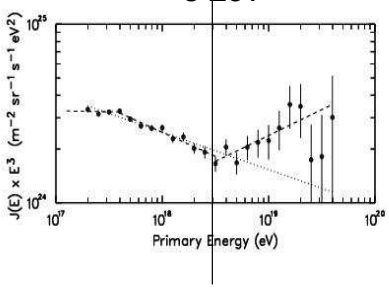
The galactic component at E □ 1×10^{17} eV is assumed to be iron nuclei. The spectrum is found as difference of the total (observed) spectrum and extragalactic proton spectrum (model).
E_c is considered as a free parameter in a range $(0.3 - 2)\times10^{18}$ eV

Where is transition to extragalactic CR?

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



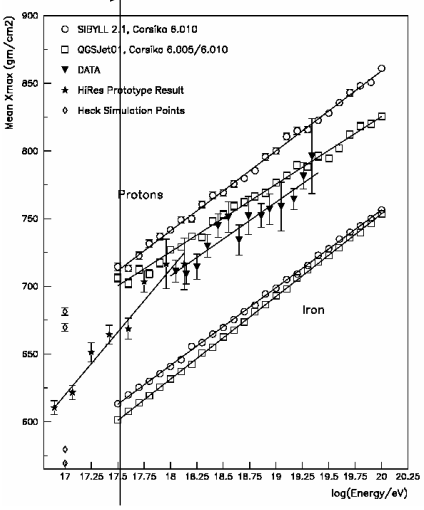
3 EeV



Stereo

HiRes new composition result: transition occurs before ankle

0.3 EeV

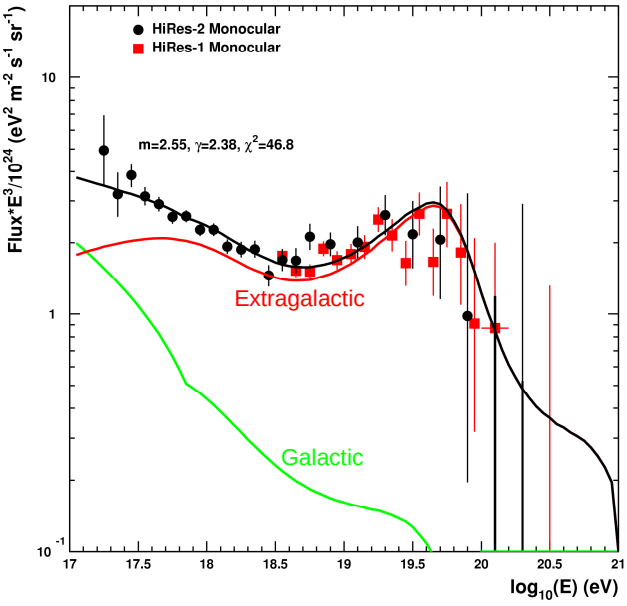


G. Archbold, P. Sokolsky, et al., Proc. 28th ICRC, Tsukuba, 2003

BERGMAN

Best USM Fit to HiRes

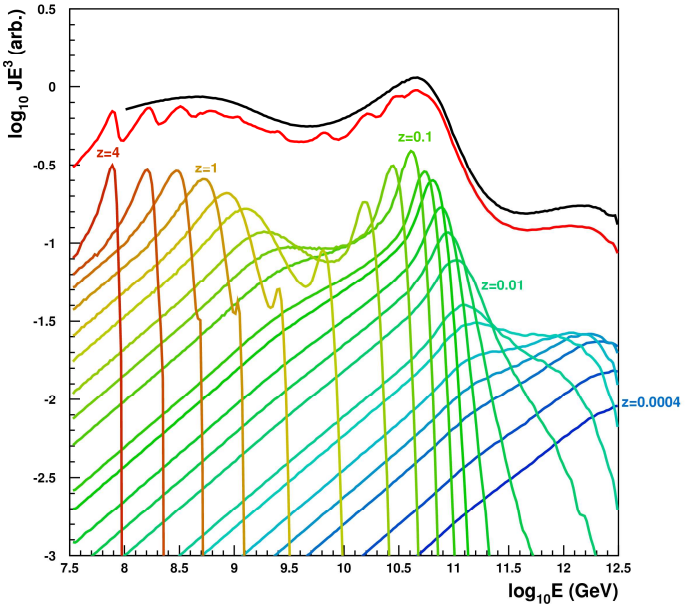
- Fit USM varying *m* and γ
  - $\gamma = 2.38$
  - $m = 2.55$
  - Galactic spectrum falls steeply above 100 PeV



BERGMAN

Uniform Source Model (XG)

- All the shells together
  - $\gamma = 2.4$
  - $m = 2.5$
- Each energy dominated by different range in *z*
  - Given energy is somewhat flat in *z* up to maximum
  - Allows one to do cosmology
- Sum of shells gives spectrum for fitting
- Actually need finer set of shells



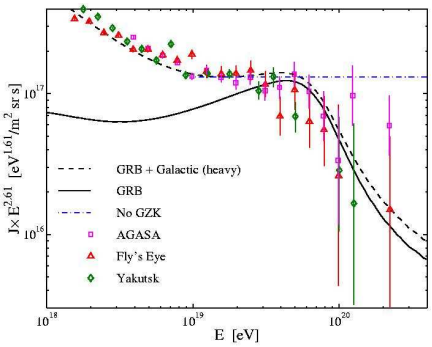
Three classes of sources

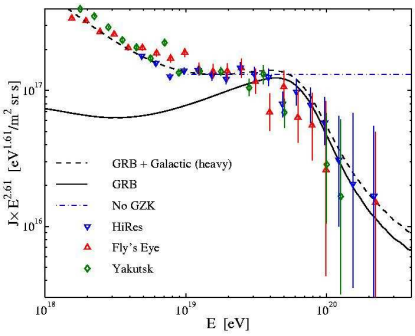
Presenter at this conference	A (R_c,PV)	B	Extra-	galactic	Power
			$\gamma + 1$	m	required
Atoyan		Galactic GRB	?	?	?
Berezinsky	2.5	None if E_c = 0.3 PeV	2.7	0	3.5 x 10^{46} erg/Mpc^3/yr, for E_c = 1 PeV
Bergman	-	-	2.4	2.5	?
Biermann	-	Wolf-Rayet SNR	?	?	?
Hillas	3	SNII into slow wind	2.3	3	?
Hörandel	4	UH nuclei	-	-	-

Bahcall & Waxman (GRB)

Physics Letters B556 (2003) 1

- Galactic→ extragalactic transition ~ 10^{19} eV
- Assume E^{-2} spectrum at source, normalize @ $10^{19.5}$
- 10^{45} erg/Mpc^3/yr
- ~ 10^{53} erg/GRB
- Evolution ~ star-formation
- GZK losses included





Bahcall & Waxman hep-ph/0206217

New experiments for

- Looking for compositional signatures of transition from galactic to extra-galactic particles
- New km^2 arrays
  - KASCADE-Grande (A. Haungs)
  - IceCube (includes IceTop) (Serap Tilav)
  - TUNKA-133 (planned air Cherenkov array)
- Low-energy extensions of giant arrays
  - TA + TALE (G. Thomson)
  - Low-energy extensions of Auger (M. Roth)

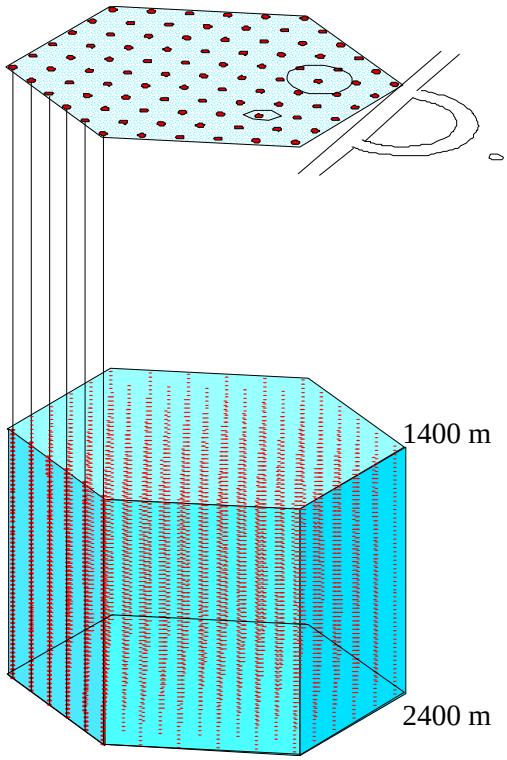
IceTop

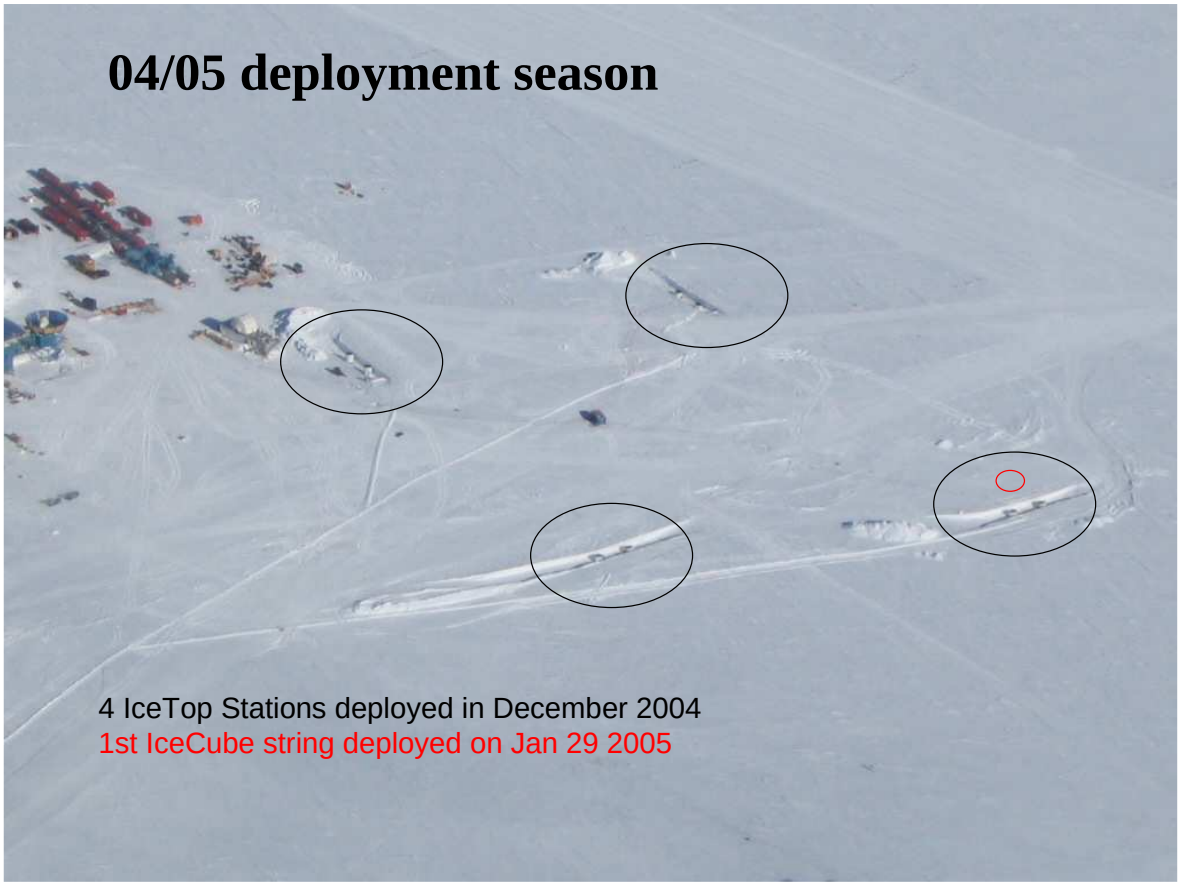
- **1 km^2 Air Shower Array**
- **1 station on top of each IceCube string**
- **2 ice tanks per station**
- **2 PMTs in each tank**

- **IceTop will detect Air Showers of energies 3x10^{14} eV to ~10^{18} eV**

IceCube

- **1 km^3 High Energy Neutrino Telescope**
- **4800 PMTs**
- **80 Strings**
- **IceCube is designed to detect neutrinos of all flavors at energies from 10^7 eV to 10^{20} eV**





Outstanding issues

- How many sources?
- How to accelerate protons to 100 PeV?
- Isotropy / propagation problem
- Non-linear acceleration → hard spectrum

See http://www.cosmic-ray.org/conf/ where presentations are posted

April 26

"Welcome and Introduction"	Pierre Sokolsky
"The Knee: Theory And Experiment"	Gaurang Yodh
"From the Knee to the Ankle, Theory & Experiment"	Tom Gaisser
"HESS Observations of Galactic TeV Sources"	Gavin Rowell
"Space Based Experiments"	Dietrich Mueller
"Approaching The Knee - Balloon-Borne Cosmic Ray Composition Measurement"	Mike Cherry
"A Review of Experimental Results at the Knee"	J. Hörandel
"Primary Cosmic-Ray Energy Spectrum Around The Knee Energy Region Measured By The Tibet Hybrid Experiment"	M. Takita
"Results from the Akeno Experiment"	N. Sakaki
"Results from the HiRes Experiment"	C. Jui

April 27

"Superbubbles, Wolf-Rayet Stars, and the Origin of Galactic Cosmic Rays"	R. Binns
"OB Associations, Supernova Generated Superbubbles and the Origin of Cosmic Rays"	V. Ptuskin
"The Origin of Galactic Cosmic Rays"	P. Biermann
“Wakefield Acceleration”	P. Chen
"Galactic Modulation of Extragalactic Cosmic Rays"	H. Muraishi & S. Yanagita
"UHE Cosmic Rays from Local GRBs"	A. Atoyan
"Magnetic Fields and Accelerated Shock Acceleration"	Tony Bell

April 28 (Morning)

"Final Results of RUNJOB and Related Topics"	M. Hareyama
"Cosmic Ray Transport in the Galaxy"	V. Ptuskin
"Galactic Magnetic Fields"	J. Han
"Galactic Transport of Cosmic Rays"	Todor Stanev
"The End Of The Galactic Cosmic Ray Energy Spectrum - A Phenomenological View"	J. Hörandel
"The Nature of the Knees and the Ankle"	V. Berezinsky
"Fitting the HiRes Data"	D. Bergman

April 28 (Afternoon)

"The Effects of Magnetic-Field Angle on the Acceleration of Energetic Charged Particles At Shocks" — J. Giacolone

"The Cosmic-Ray Knee Spectrum Seen as a Consequence of Bell's Self-Magnetised SNR Shock Acceleration Process" — Michael Hillas

"The Knee Caused by Change in Hadronic Interactions?" — Frank Jones

"Cosmic Ray Acceleration Beyond the Knee Up to the Ankle in Galactic Wind Halo" — V. Zirakashvili

"The Elusive p-air (Pierre?) Cross Section" — Martin Block

April 29

"The Structure of the Milky Way's Stellar Halo" — Heidi Newberg

"High-Energy Processes Within The Inner 5 Parsecs Of the Galaxy" — R. Crocker

"Hadronic Multiparticle Production and EAS Characteristics" — Ralph Engel

"Simulations of Cosmic Ray Interactions: Past, Present, and Future" — S. Ostapchenko

"Stereoscopic Cherenkov Imaging at Energies > 10 TeV" — Gavin rowell

"Veritas" — S. LeBohec

Supernova Origin of CR to the Knee & Gamma Ray Observations of SN — H. Völk

April 30

"Possible Future Experiments in Space" — Bob Streitmatter

"Investigating The Second Knee: Status Of The KASCADE-Grande" — A. Haungs

"ICECUBE/ICETOP" — Serap Tilav

"The TA and TALE Experiments" — Gordon Thomson

"Performance of the CRTNT Detector for sub-EeV Cosmic Ray Measurement" — Z. Cao

"Ideas for an Upgrade of the Southern Auger Observatory: Scientific Objectives and Plans for the Future" — M. Roth

Conference summary

Theory — Frank Jones and Randy Jokipii

Experiment — Pierre Sokolsky