Particle Astrophysics

Cosmic rays

Gamma-ray astronomy

Neutrino astronomy

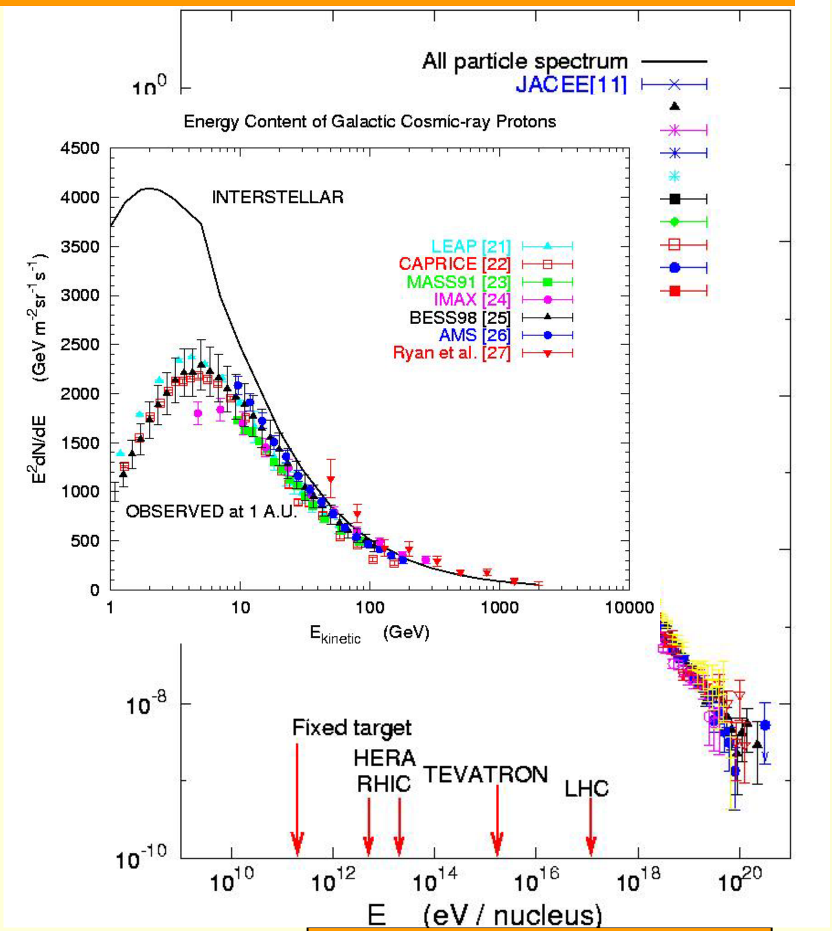
Multi-messenger astronomy

- Protons, γ-rays, ν, [gravitational waves] as probes of the high-energy universe
  - **Protons**: directions scrambled by magnetic fields
  - **Photons**: straight-line propagation but
    - reprocessed in the sources
    - extragalactic backgrounds absorb E_γ > TeV
  - **Neutrinos**: straight-line propagation, unabsorbed, but difficult to detect

Energetics of cosmic rays

Spectral Energy Distribution
(linear inset → most E < 100 GeV)

- Energy density: ρ_E
  $\sim 10^{-12}$ erg/cm^3 $\sim B^2 / 8\pi$
- Power needed: ρ_E / τ_{esc}
  galactic $\tau_{esc} \sim 3 \times 10^6$ 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

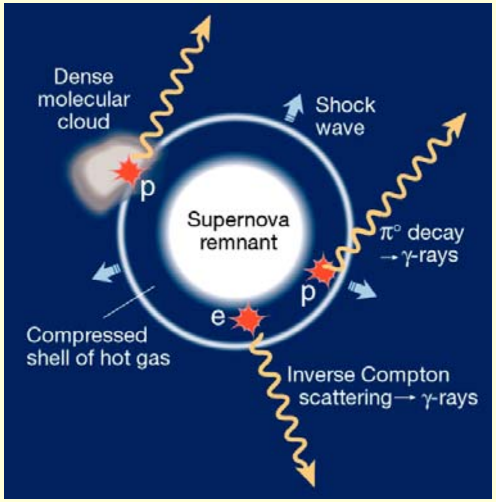


Kinetic energy per nucleus

Problems of simplest SNR shock model

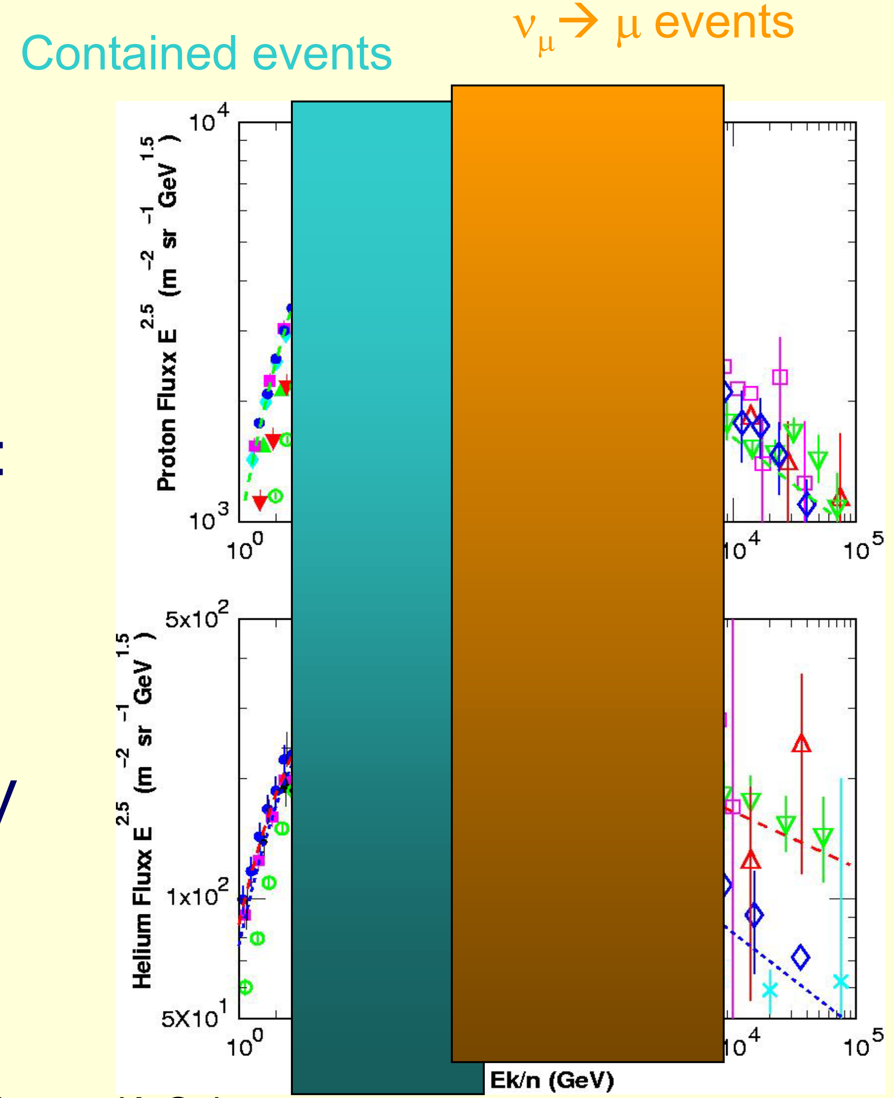
- Expected shape of spectrum:
  - Differential index $\alpha \sim 2.1$ for diffusive shock acceleration
    - $\alpha_{observed} \sim 2.7$; $\alpha_{source} \sim 2.1$; $\Delta\alpha \sim 0.6 \rightarrow \tau_{esc}(E) \sim E^{-0.6}$
    - $c\,\tau_{esc} \rightarrow T_{disk} \sim 100$ TeV
    - → Isotropy 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)
  - Interpretation uncertain; see
    - **Enomoto et al., Aharonian (Nature); Reimer et al.,** astro-ph/0205256
  - → Problem of elusive π^0 γ-rays



Spectrum normalizes atmospheric ν

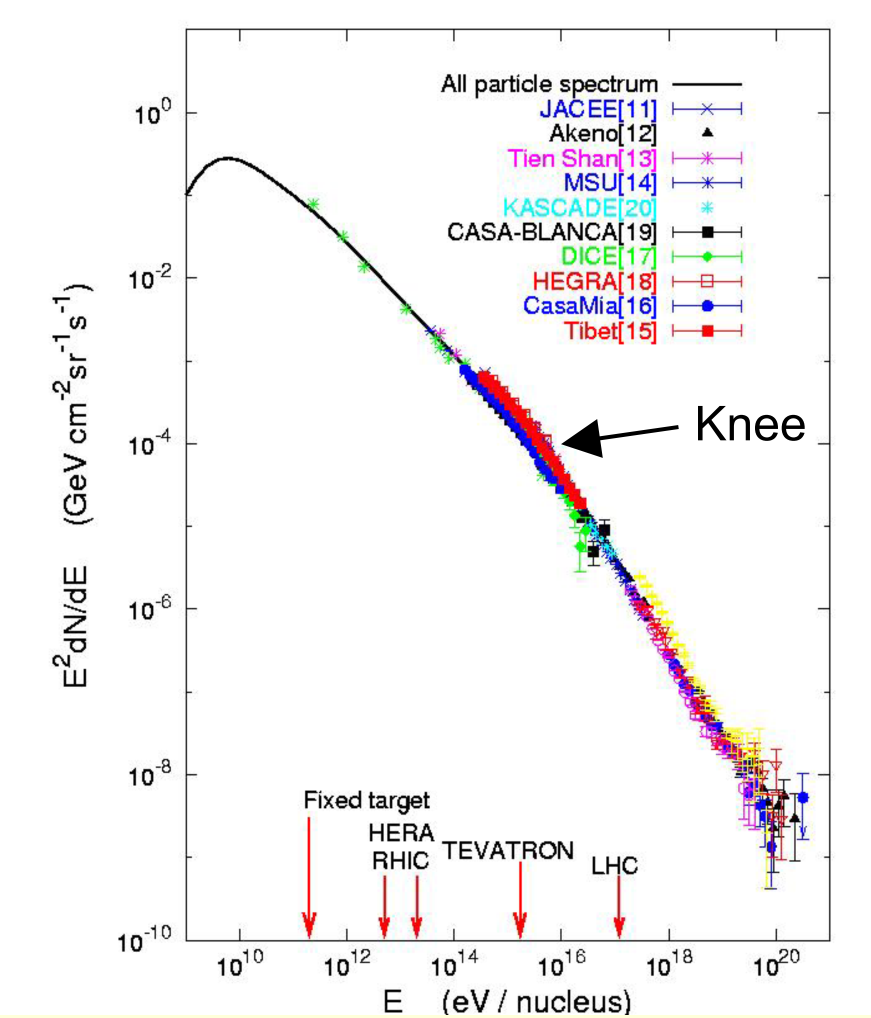
- GeV to TeV important for atmospheric ν
- Good agreement < 100 GeV
  - AMS, BESS
- Lack of TeV data; new expts:
  - Magnetic spectrometers:
    - PAMELA (2003)
    - AMS on Space Station (2005)
- Meanwhile, new μ-flux measurements E_μ > 100 GeV
  - Timmermans' talk on L3+C
  - Somewhat below previous measurements



TKG & Honda, hep-ph/0203272

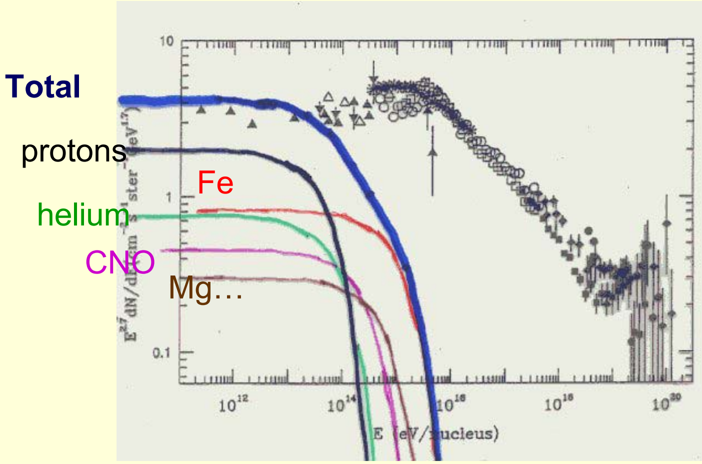
Knee of spectrum

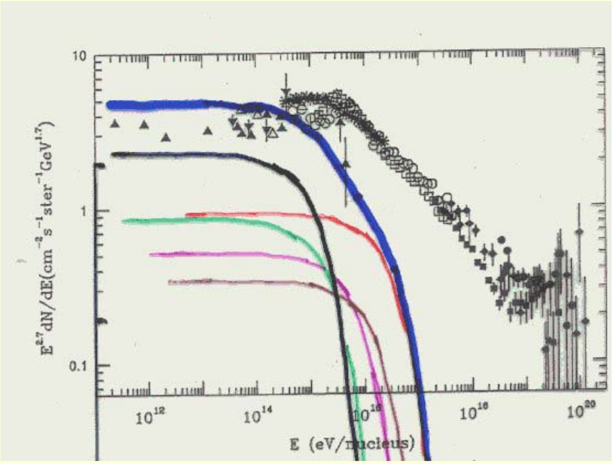
- Differential spectral index changes at ~ 3 x 10^{15}eV
  - $\alpha = 2.7 \rightarrow \alpha = 3.0$
  - Continues to 3 x 10^{18} eV
  - Expect $\exp\{-E / Z E_{max}\}$ cutoff for each Z
- Fine-tuning problem:
  - to match smoothly a new source with a steeper spectrum (Axford)
  - How serious is this?



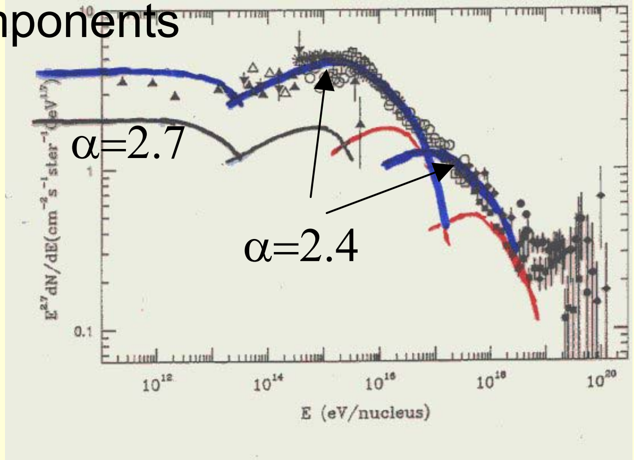
Speculation on the knee

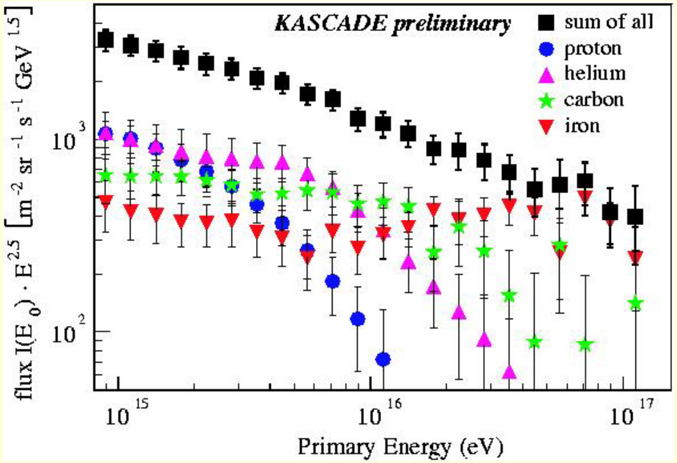
1 component: α = 2.7, E_{max} = Z x 30 TeV; or Emax = Z x 1 PeV





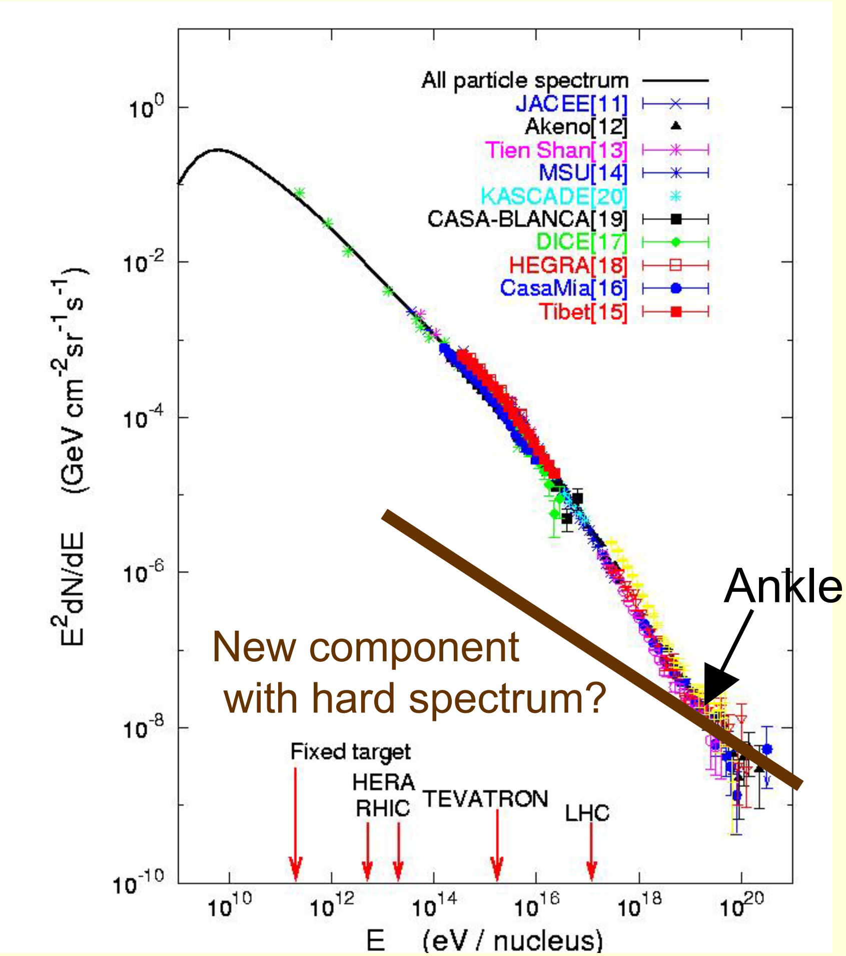
3 components





K-H Kampert et al., astro-ph/0204205

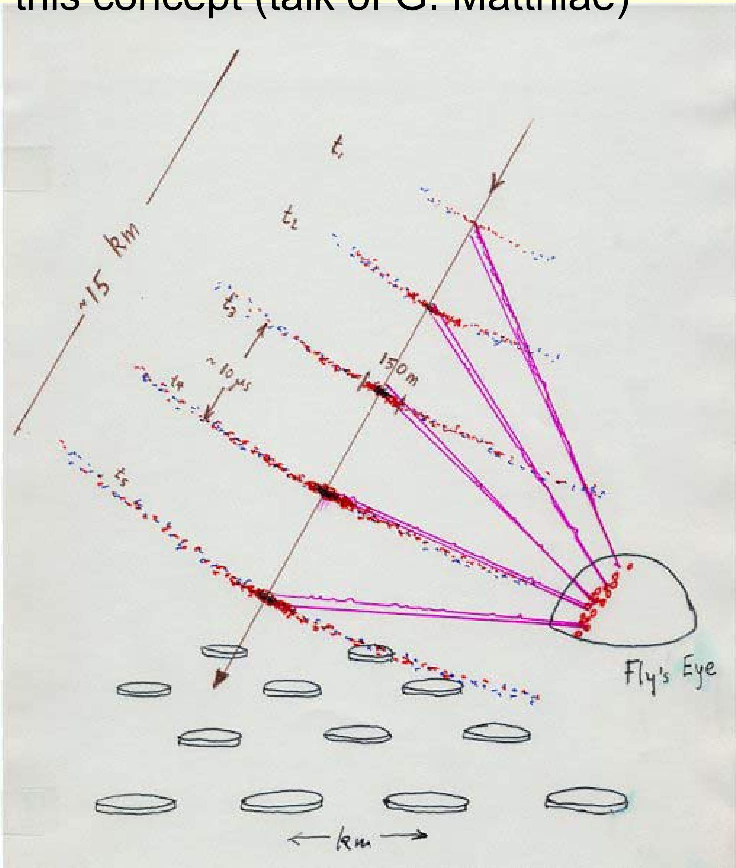
Transition to extragalactic origin?

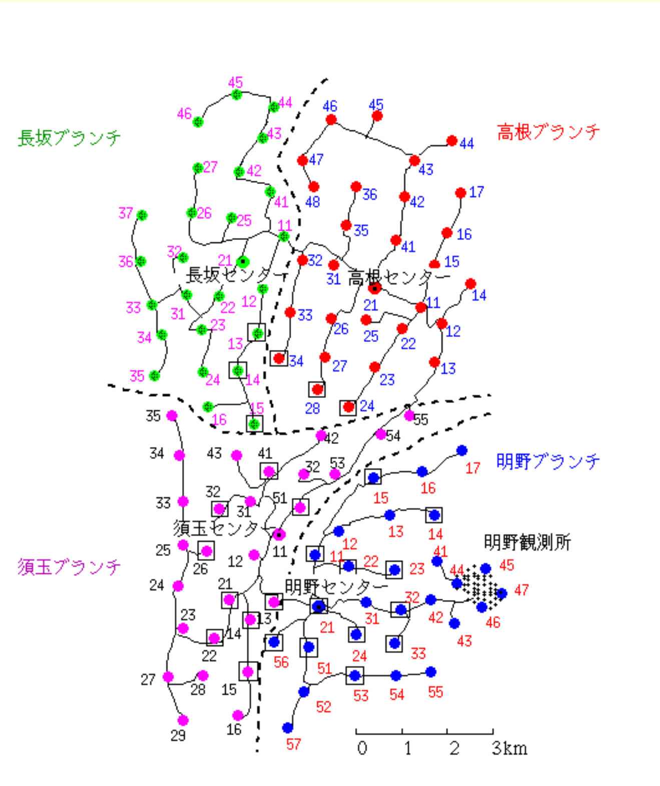


- Ankle
  new population of particles?
- Suggestive evidence:
  - hardening of spectrum
  - change of composition
- Measurements:
  - Energy
  - Depth of maximum (X_{max})
  - N_μ / N_e

Air shower detectors

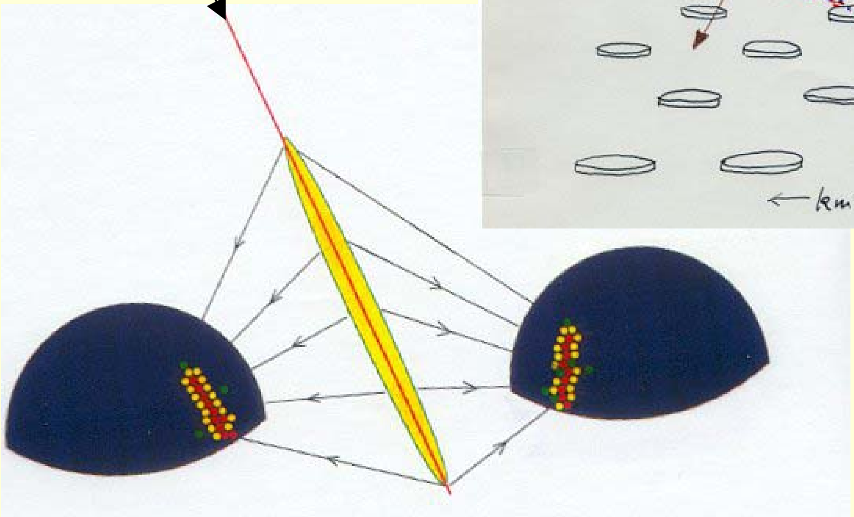
Sketch of ground array with fluorescence detector – Auger realizes this concept (talk of G. Matthiae)





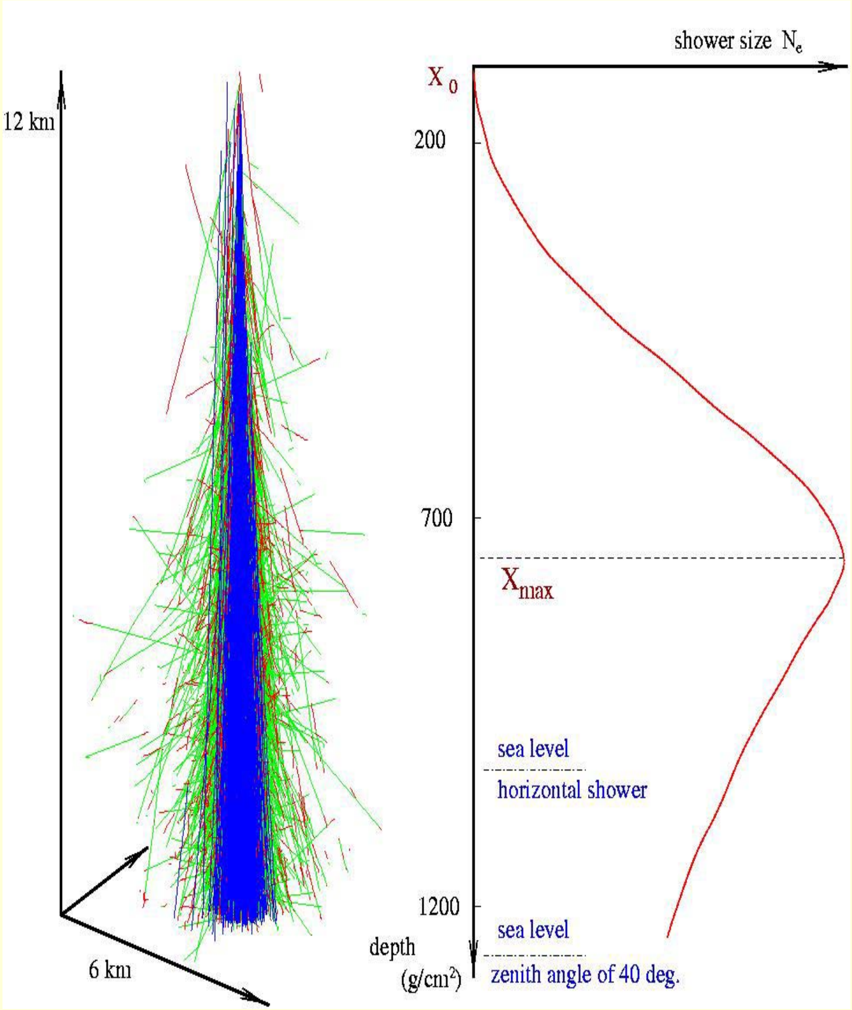
AGASA (Akeno, Japan)
100 km^2 ground array

Hi-Res stereo fluorescence detector (D. Bergman's talk)



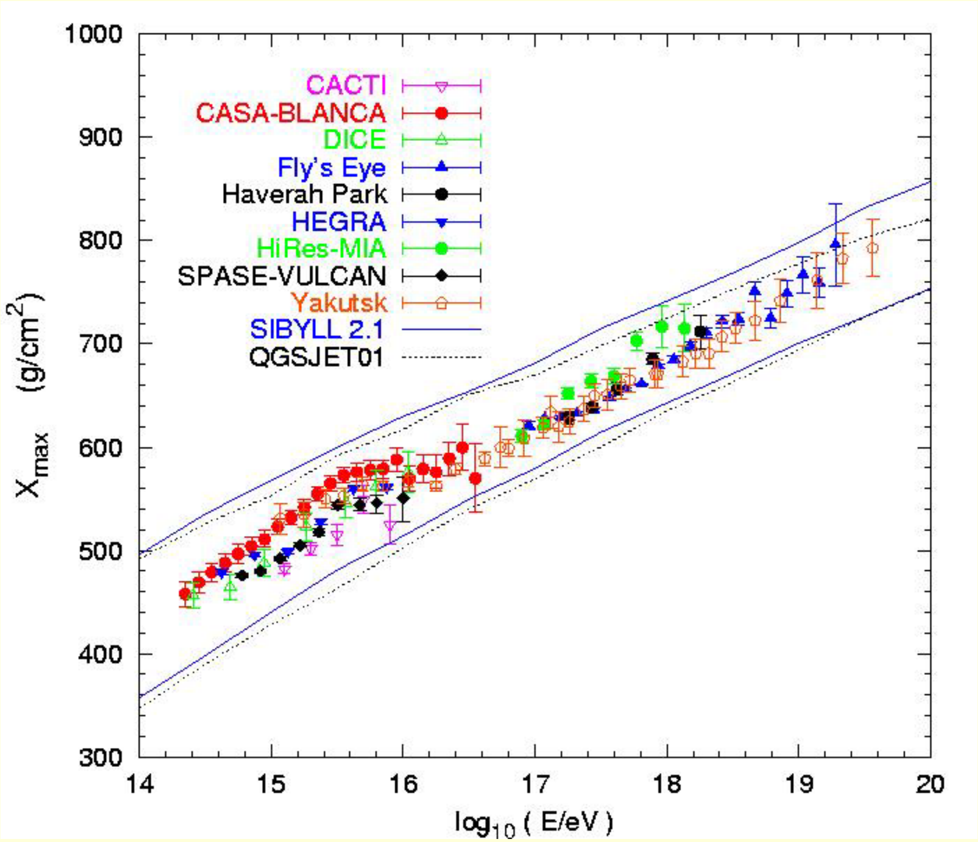
Measuring the energy of UHECR

- Ground array samples shower front
  - Well-defined acceptance
  - Simulation relates observed ground parameter to energy
- Fluorescence technique tracks shower profile
  - Track-length integral gives calorimetric measure of energy
  - X_{max} sensitive to primary mass: $X_{max} \sim \Lambda\, \mathit{ln}(E_0/A)$



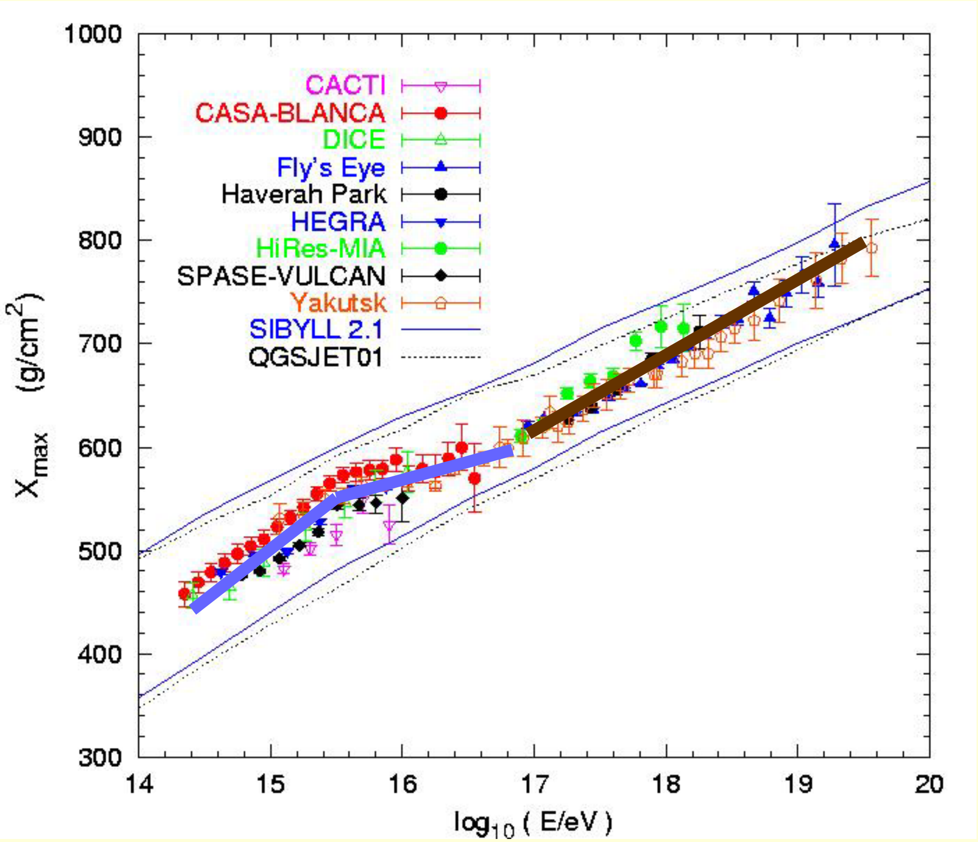
Xmax vs Energy

- Protons penetrate deeper into atmosphere
- Heavy nuclei develop higher up
- Plot shows a summary of data over 5 decades
- Several techniques
- Some dependence on models of hadronic interactions (R. Engel's talk)



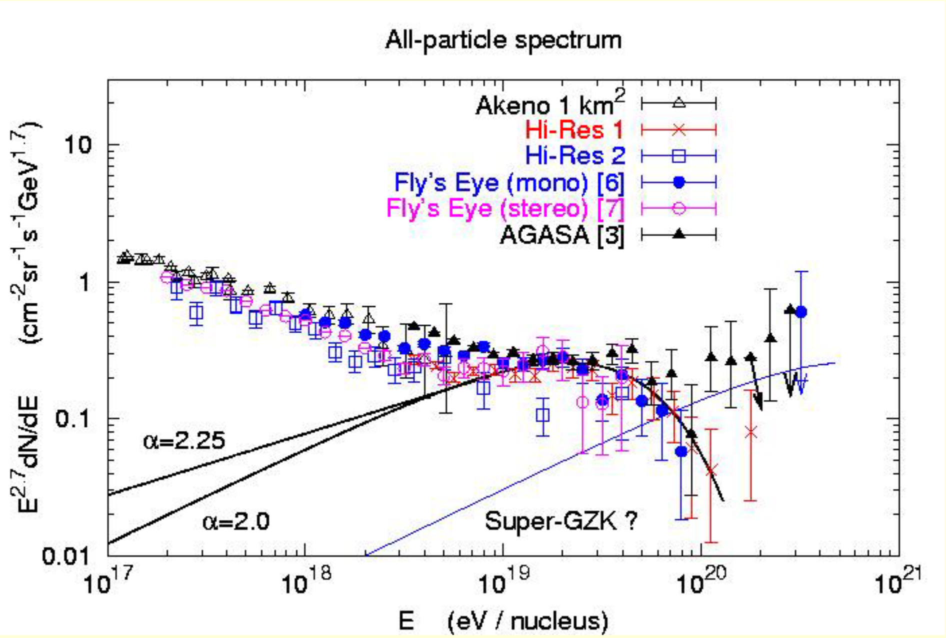
Xmax vs Energy

- Lines indicate trend of data:
- Light to heavy above the "knee" (~$10^{16} \rightarrow 10^{17}$ eV)
- Heavy to light at the "ankle" (~$10^{18} \rightarrow 10^{19}$ eV)
- AGASA looks at μ/e ratio in shower front and sees no evidence for change of composition at the ankle



Energy of extragalactic component

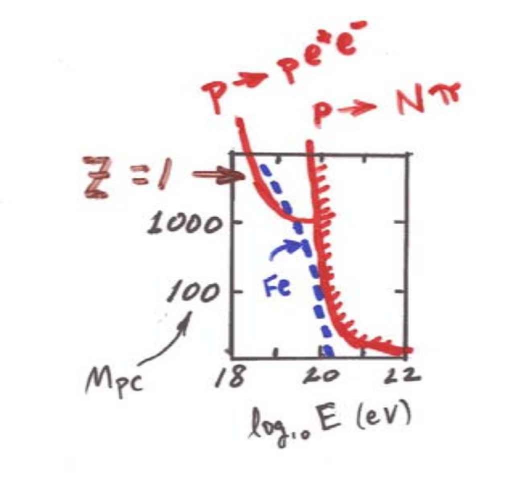
- Energy density:
  - $\rho_{CR} > \sim 2 \times 10^{-19}$ erg/cm^3
  - Estimate requires extrapolation of UHECR to low energy
- Power required
  - $> \rho_{CR}/10^{10}$ yr ~
  - 1.3 x 10^{37} erg/Mpc^3/s
  - 10^{-7} AGN/Mpc^3
    - Need $> 10^{44}$ erg/s/AGN
  - 1000 GRB/yr
    - Need $> 3 \times 10^{52}$ erg/GRB



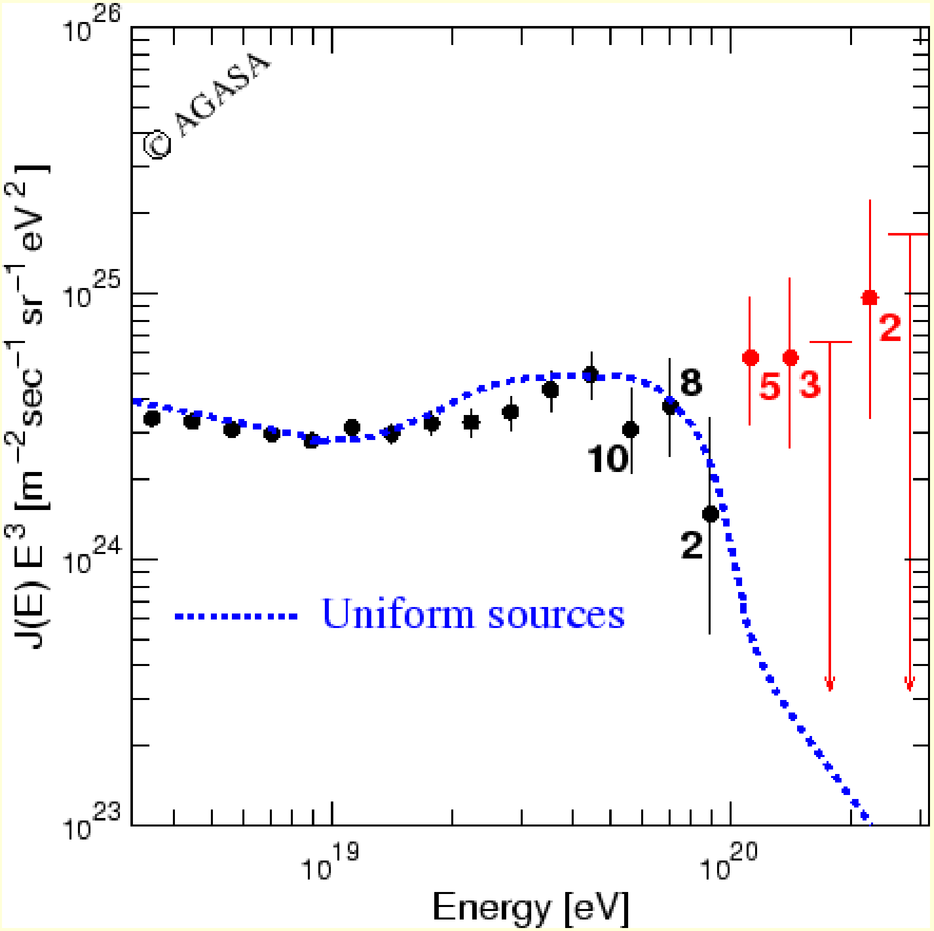
Assume extragalactic component with hard spectrum and GZK cutoff ~5 x 10^{19} eV.
$\alpha = 2.0$: ideal shock acceleration
$\alpha = 2.25$: expected for relativistic shocks
Integrate to estimate observed energy density

Highest energy cosmic rays

- GZK cutoff?
  - Expected from energy loss in 2.7° background for cosmological sources



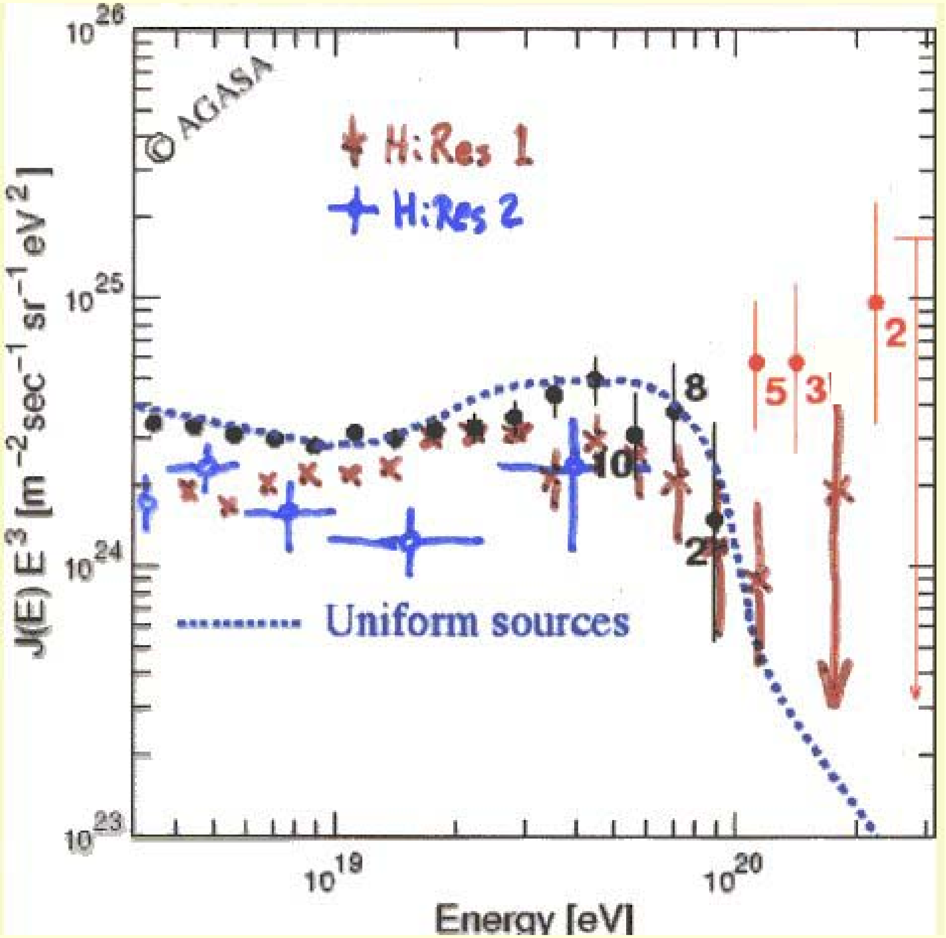
Attenuation length in microwave background



Compare AGASA & HiRes

Ground array   Fluorescence detector

- Exposure (10^3 km^2 yr sr):
  - AGASA: 1.3
  - HiRes (mono): 2.2
- Number events $>10^{20}$
  - AGASA: 10 (+2?)
  - HiRes (mono): 2?
  - Both detectors have energy-dependent acceptance (different)
  - Need more statistics and stereo results



Models of UHECR

(Incomplete list--
Refs. in written version)

- Bottom up (acceleration)
  - Jets of AGN
    - External
    - Internal (PIC models)
  - GRB fireballs
  - Accretion shocks in galaxy clusters
  - Galaxy mergers
  - Young SNR
  - Magnetars
- Observed showers either protons (or nuclei)

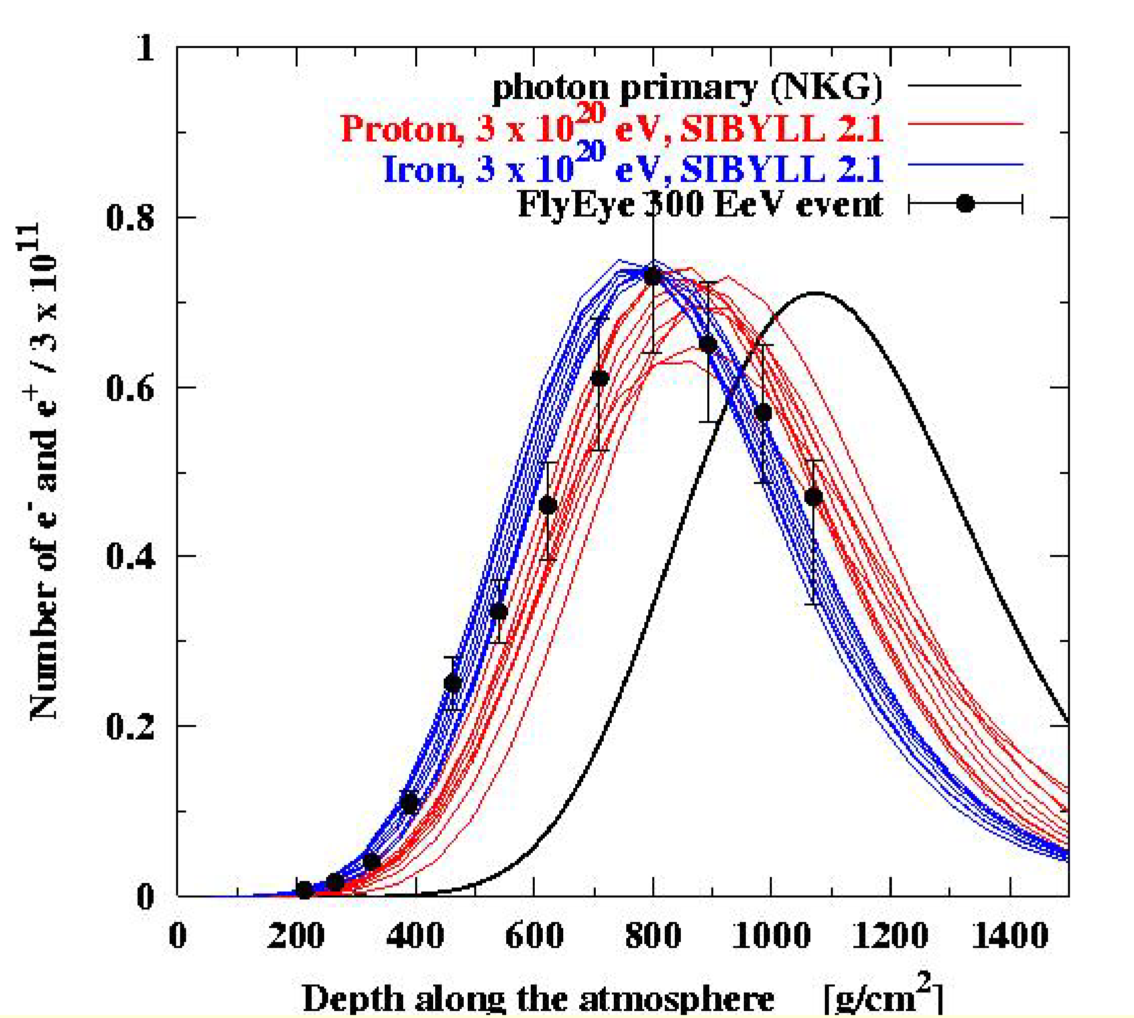
- Top-down (exotic)
  - Radiation from topological defects
  - *Decays of massive relic particles in Galactic halo
  - Resonant neutrino interactions on relic ν's (Z-burst)
- Large fraction of γ–showers (especially if local* origin)

If no cutoff, require a significant contribution from nearby sources. Local overdensity of galaxies is insufficient if UHECR source distribution follows distribution of galaxies.

Biggest event

Fly's Eye, Ap. J. 441 (1995) 295

- Comparison to
  - Proton showers
  - Iron showers
  - γ showers



Horizontal air showers

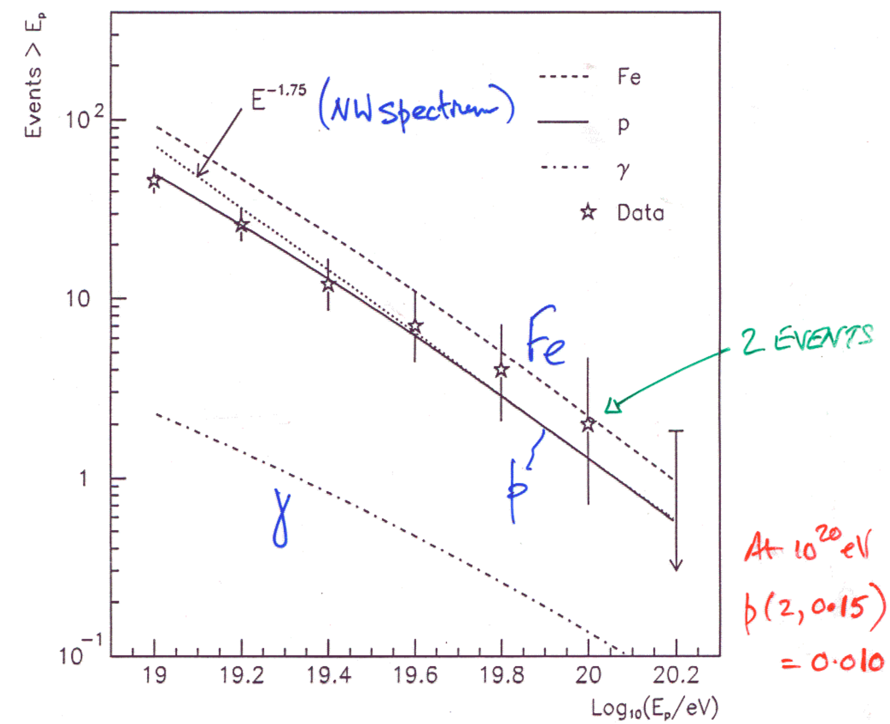
- Most of shower absorbed, mostly muons survive to the ground
- Heavy primaries produce more μ
- Incident photons produce few μ
- Analysis of vintage (aged ~25 yrs) data from Haverah Park array possible with modern simulation tools
- Results place interesting limits limits on Top-Down models:
- UHE events from decaying, massive relics accumulated in the Galactic halo would be mostly photon-induced showers. Such models are therefore disfavored
- Similar limit on γ/p from AGASA

$> 10^{19}$ eV (49 events)

figure 2

$\gamma/p \leq 40\%$

$Fe/p \leq 54\%$ at 95% CONFIDENCE LEVEL.



$60° < \theta < 80°$

AVE, HINTON, VAZQUEZ, WATSON & ZAS

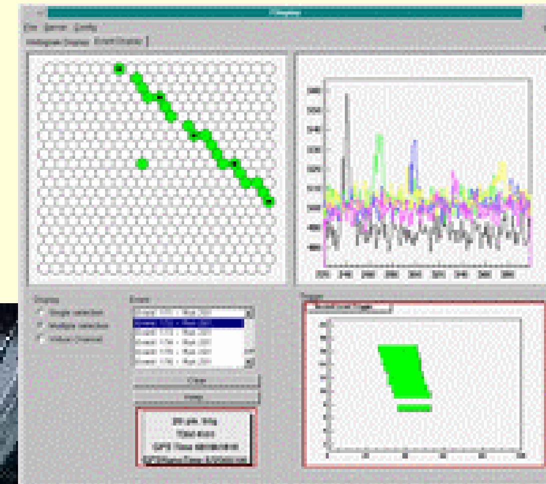
PRL 85, 2244, 2000

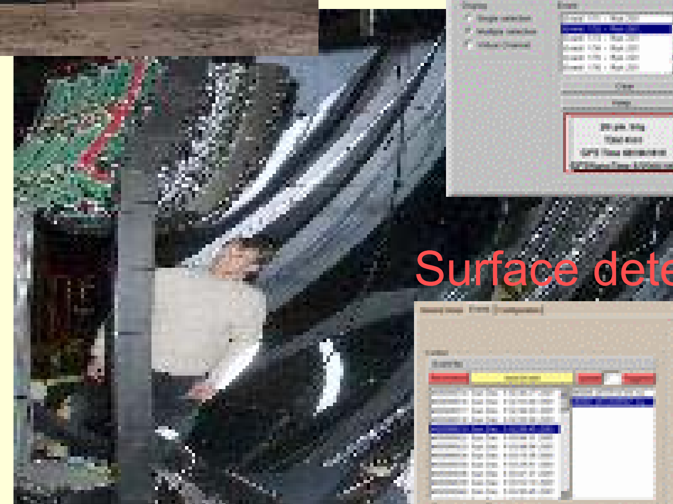
ICHEP 2002, Amsterdam, July 31, 2002

Auger hybrid event

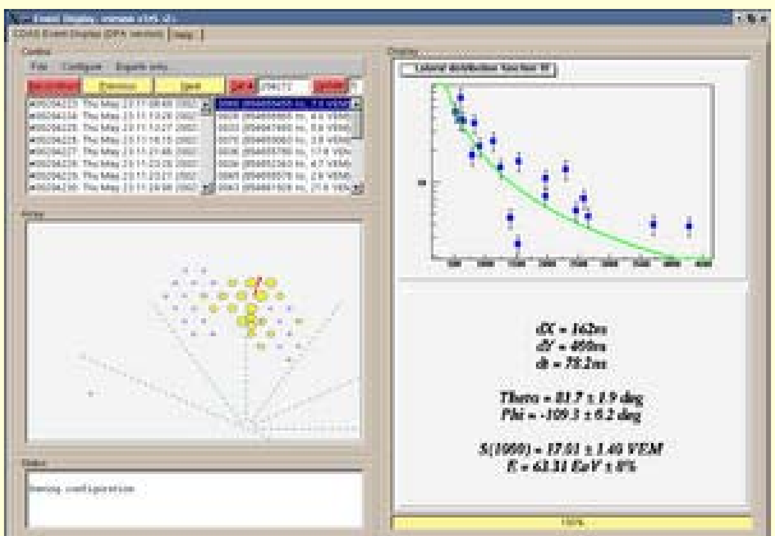
“Engineering Array”**:** SD with 40 modules ~ 100 km^2
viewed by fluorescence detector.
Now operating in Argentina.
100 more tanks running in 2003.

Fluorescence detector view

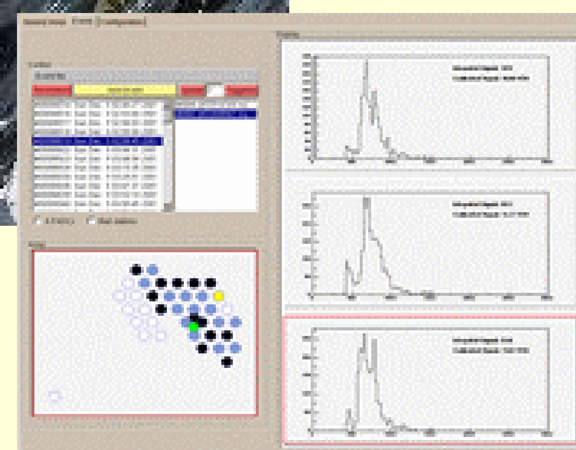




Nearly horizontal event of
40-station engineering array

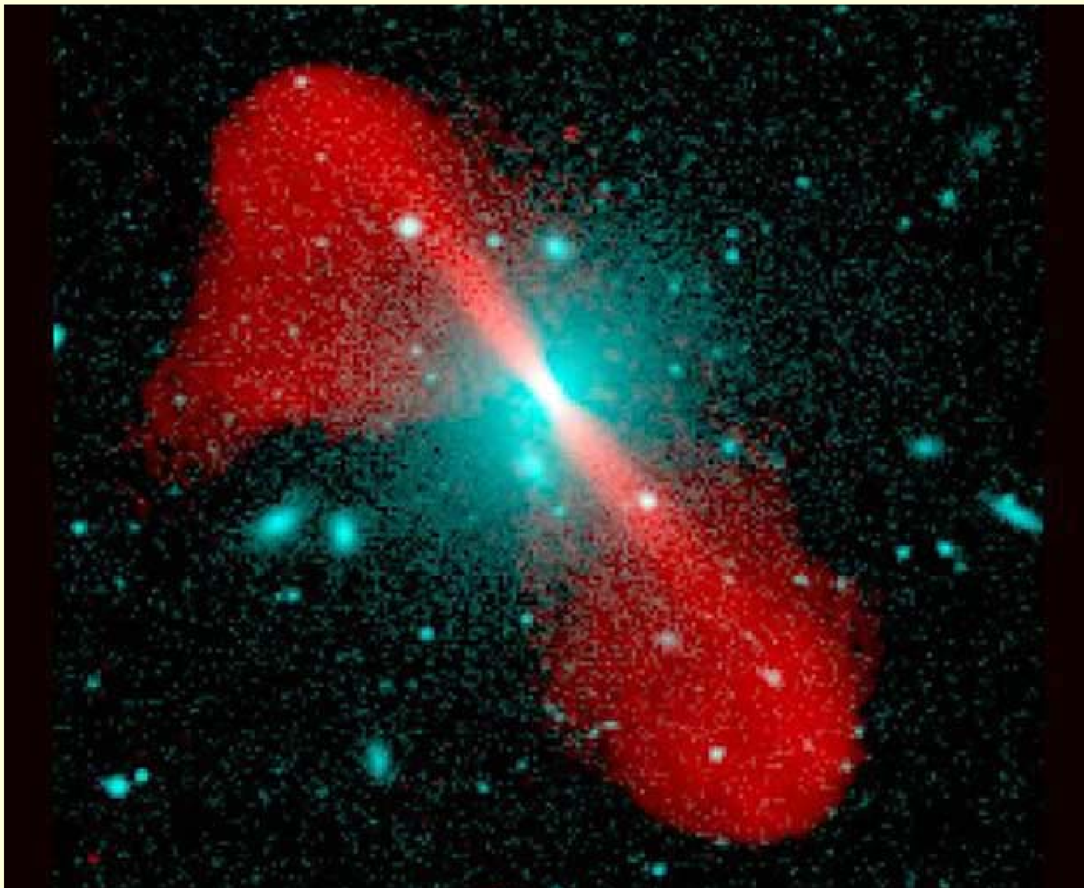


Surface detector view

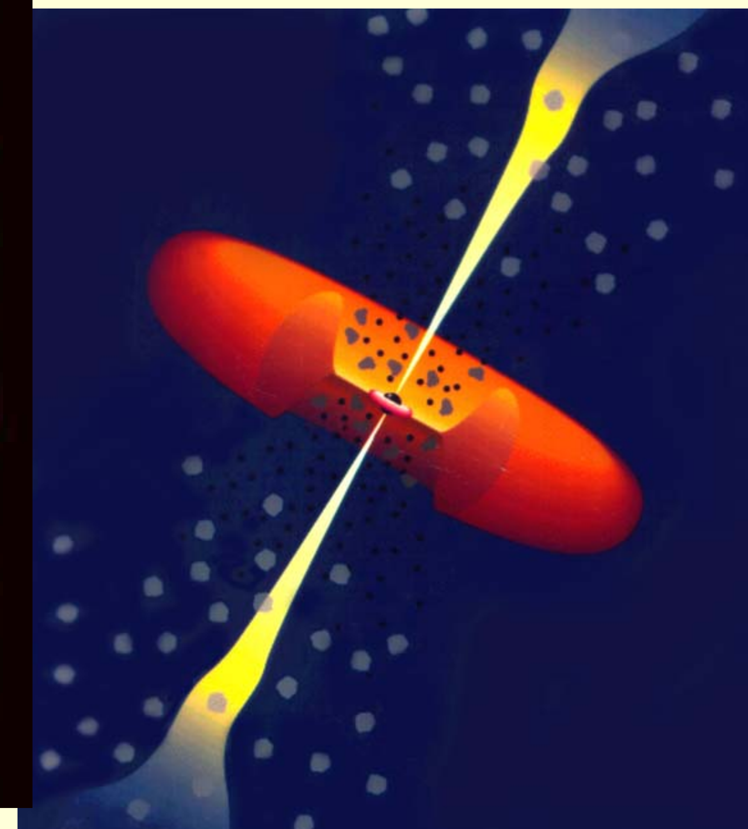


Active Galaxies: Jets

Radio Galaxy 3C296 (AUI, NRAO).
--Jets extend beyond host galaxy.



Drawing of AGN core

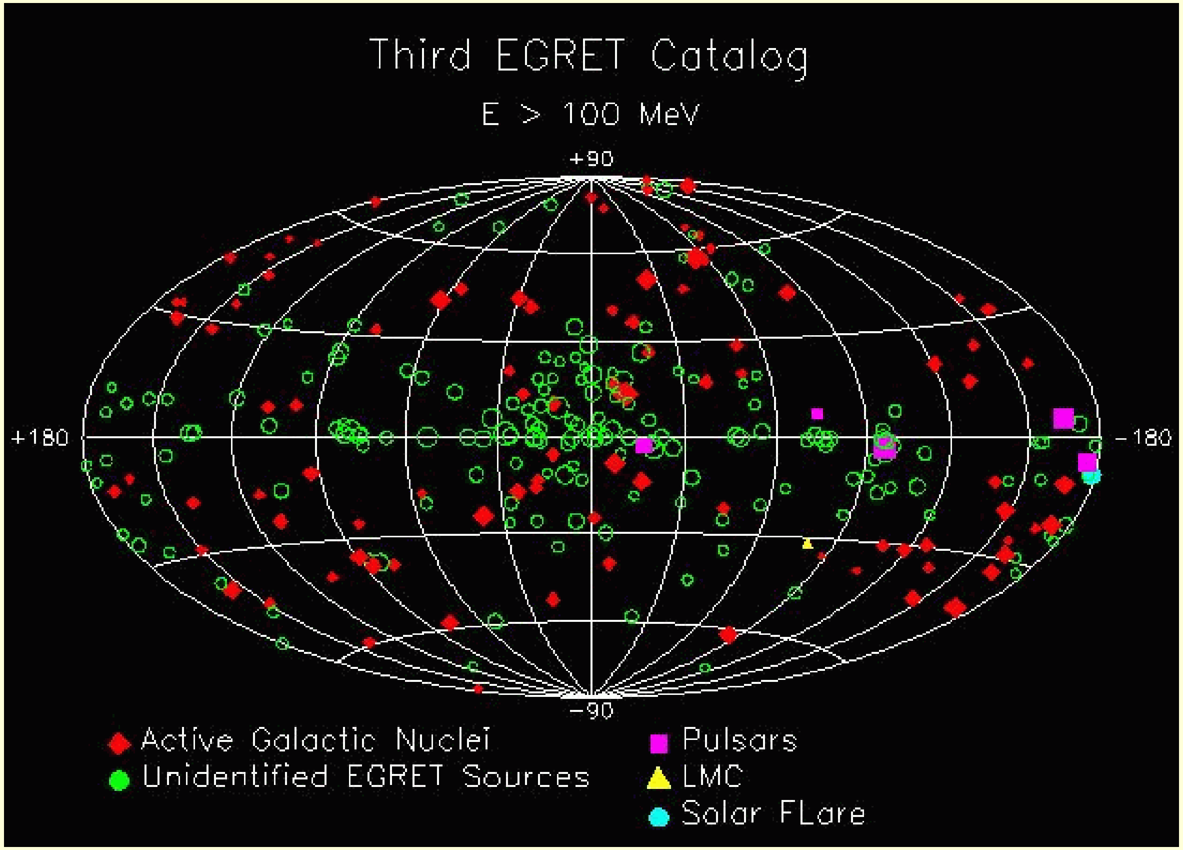


Egret blazars

•Blazars are AGN with jet illuminating observer.

•Two-component spectra interpreted as synchrotron radiation (low energy) plus inverse Compton generated by high-energy electrons accelerated to high energy in relativistic jets (Γ ~ 10).

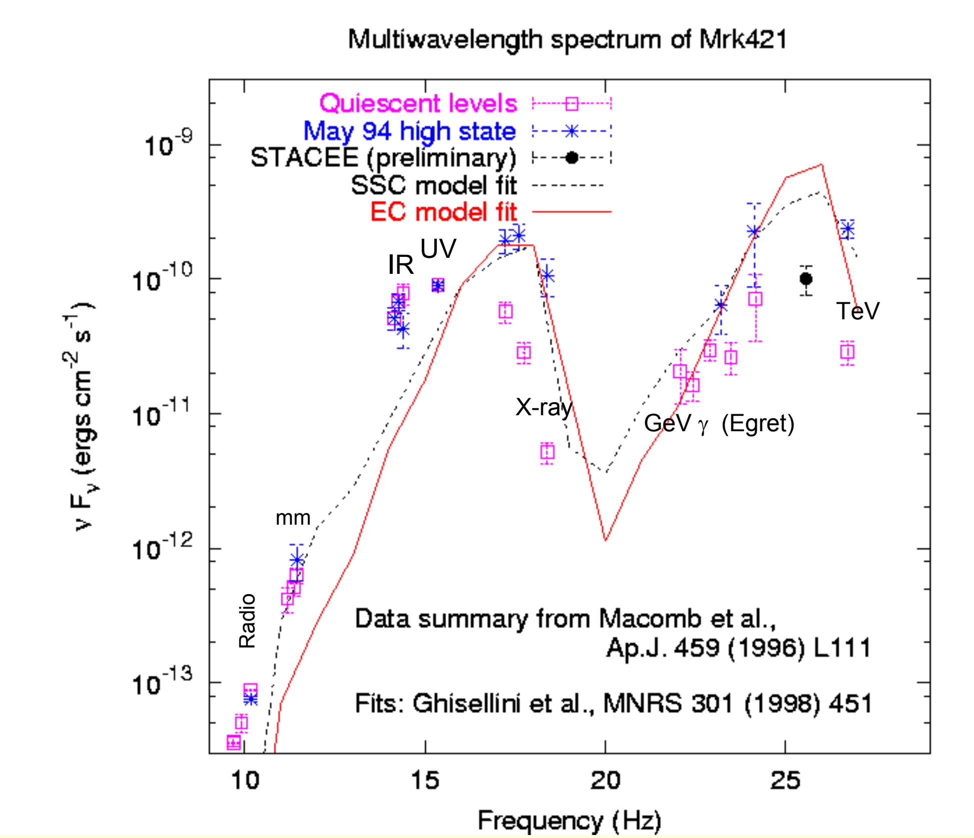
•A few nearby blazars have spectra extending to > TeV observed by ground-based Imaging Atmospheric Cherenkov Telescopes (IACT).



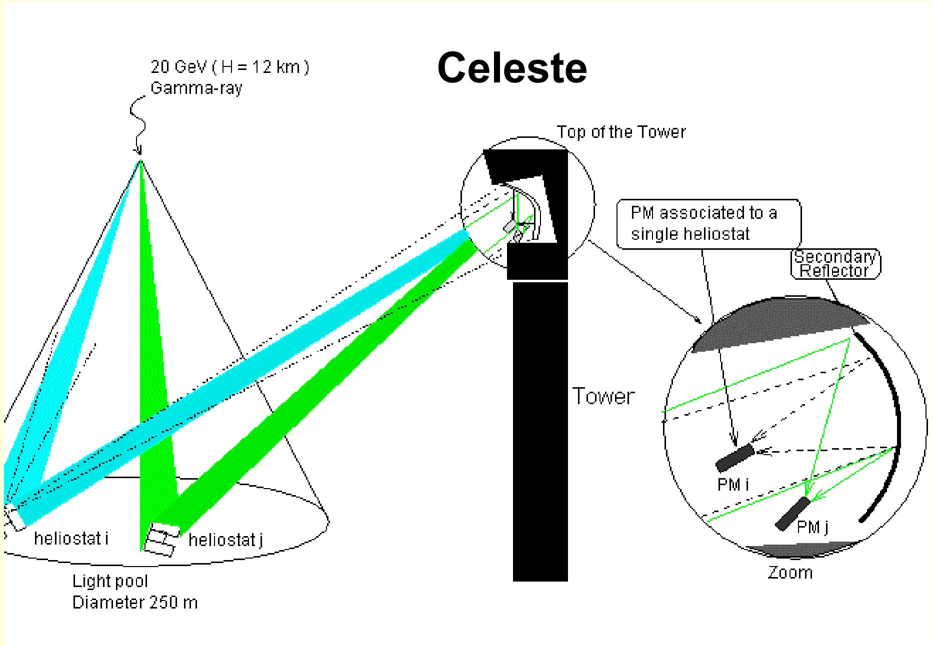
AGN Mulitwavelength observations

- SSC, EC, PIC models
  - 1^{st} peak from electron synchrotron radiation
  - 2^{nd} peak model-dependent; predict ν flux if PIC
  - Interpretation complex:
    - Sources variable
    - Locations of peaks depend on source-- factor of >100 range of peak energy
    - New detectors (GLAST, HESS, MAGIC, VERITAS) will greatly expand number, variety of sources

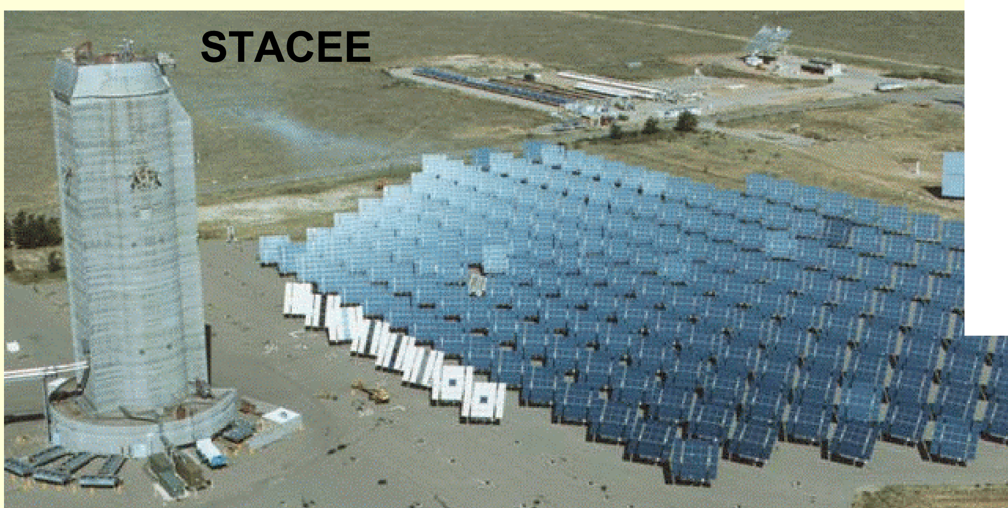
Example of Mrk421 with new (preliminary) result from STACEE ~100 GeV

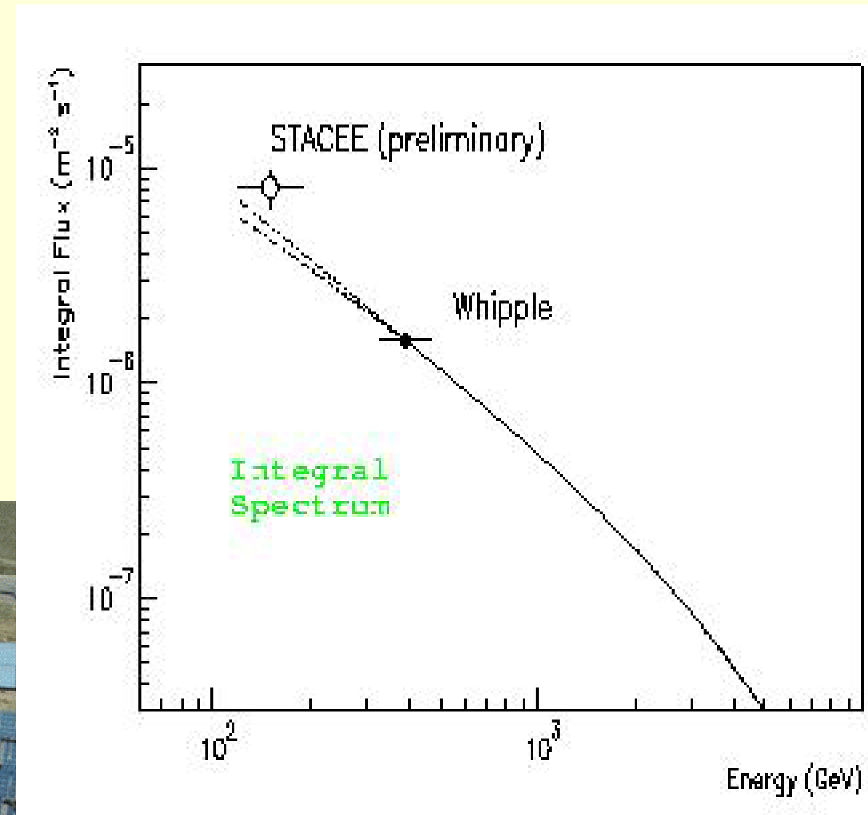


Solar arrays for γ-ray astronomy explore down to ~100 GeV:



CELESTE, STACEE in operation

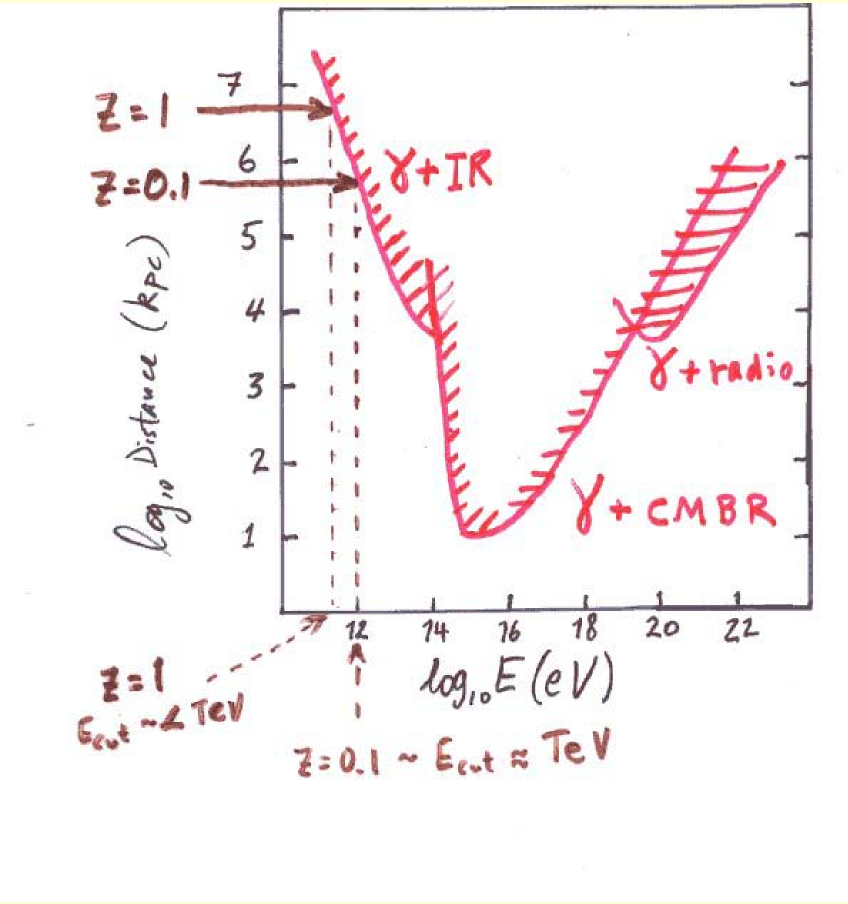




Gaisser

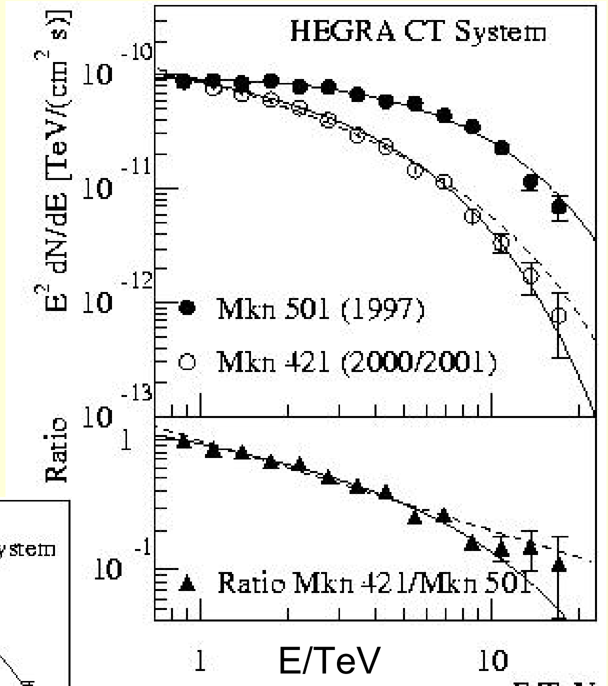
TeV γ Blazars

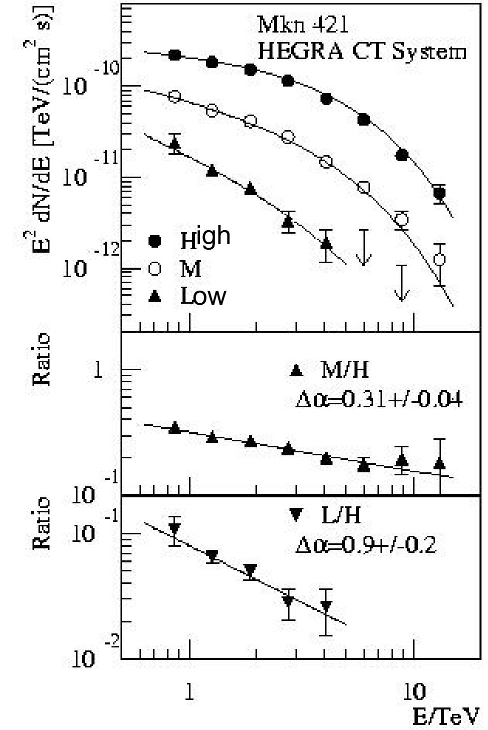
- Five detected
  - Mrk 421 (Z = 0.031)
  - Mrk 501 (Z = 0.034)
  - 1ES2344+514 (Z = 0.044)
  - 1H1426+428 (Z = 0.129)
  - 1ES1959+650 (Z = 0.048)*
    - * Whipple, IAU Circular 17 May 2002
- E_{max} vs Z probes era of galaxy-formation through IR background



Blazar spectra at high energy

- Mrk 421 & Mrk 501, both at z ~ .03
  - Cutoffs
    - Intrinsic?
    - Effect of propagation?
  - Variable sources
    - Low intensity – softer spectrum
    - Interpretation under debate
  - Need more observations of more sources at various redshifts



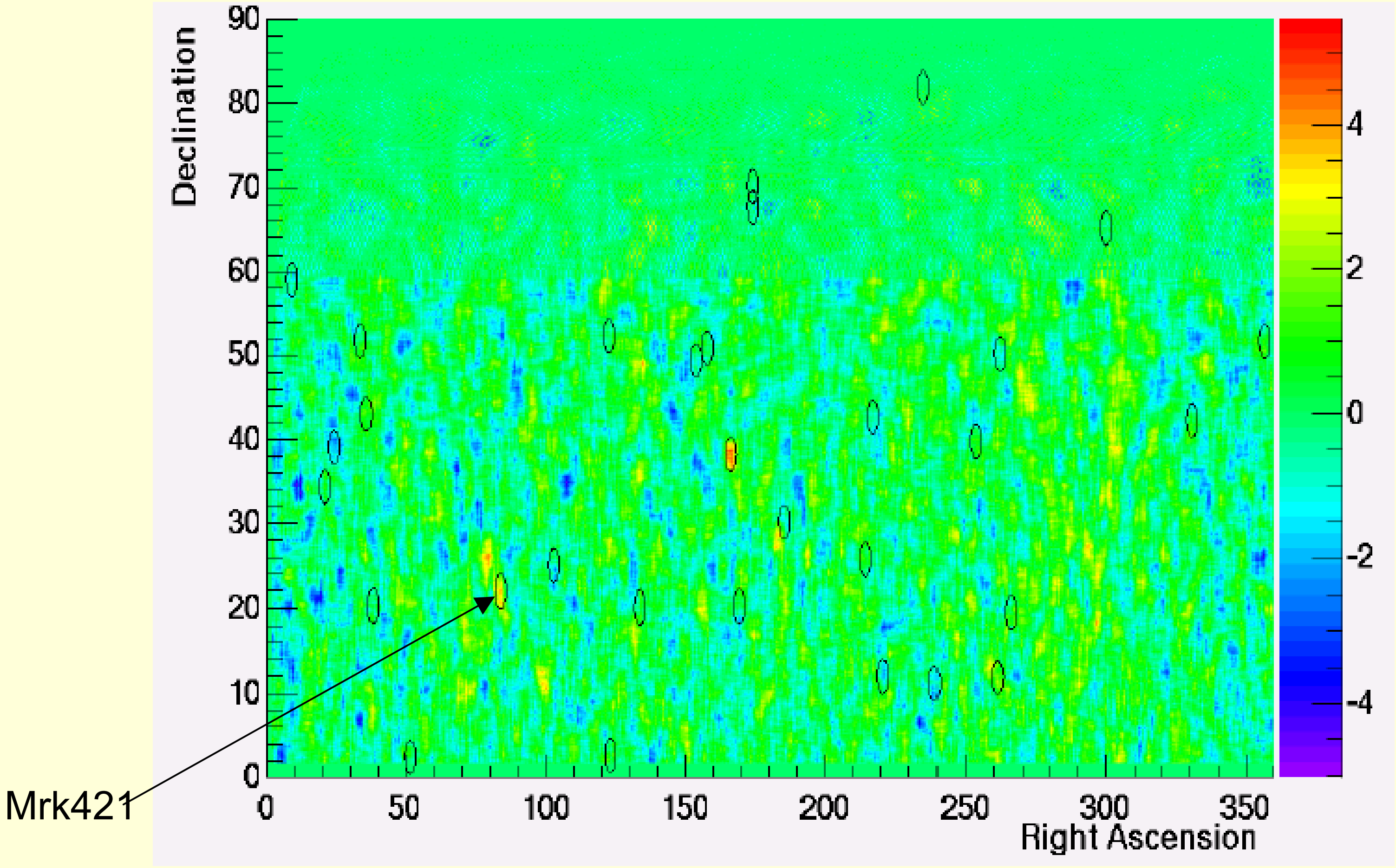


HEGRA plots from Aharonian et al. **astro-ph/0205499.** Different E_{cut} of 421 and 501 suggest cutoffs are intrinsic.

Comparable analysis of Whipple extends to lower energy. Seeing comparable cutoffs, they suggest effect is due to propagation. Krennrich et al., **Ap.J. 560 (2002) L45**

Sky map from the Milagro detector

Milagro is a compact air shower detector that uses a 60 x 80 m water Cherenkov pool covered and surrounded by air shower detectors.



Detectors for gamma-ray astronomy

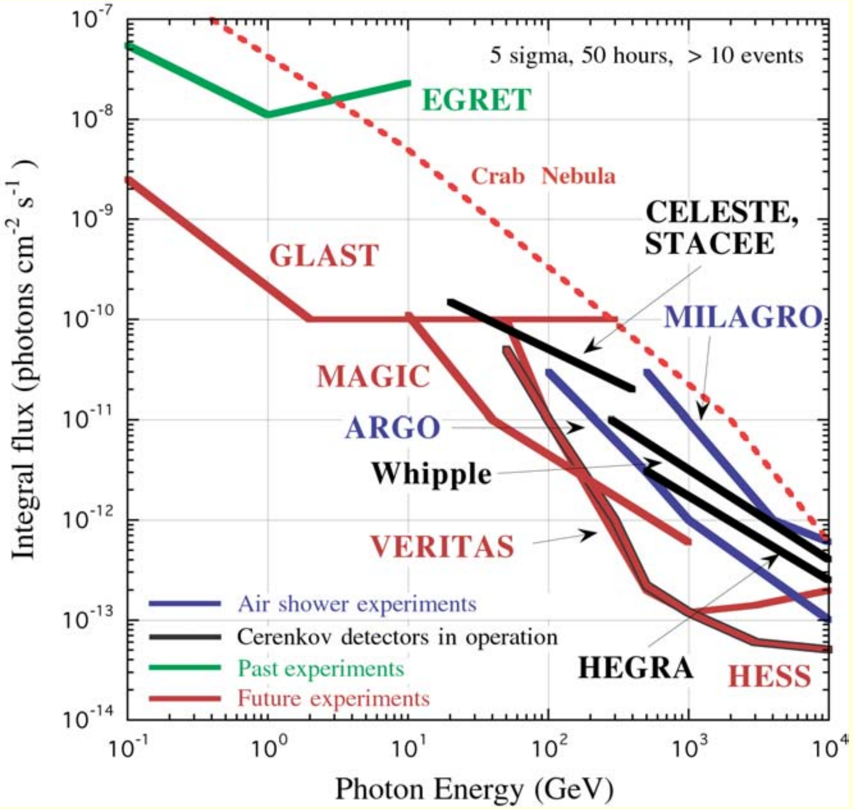
Egret 1991-2000

	IACT	Solar arrays	All-sky dets.	Space dets.
Presently running	Whipple	STACEE	Tibet ASγ	
	CAT	Celeste	ARGO-YBJ	
	Cangaroo II		MILAGRO	
	Hegra*			
Future	HESS* (2002)			SWIFT (2003)
	MAGIC (2003)			AGILE (03/04)
	Cangaroo III *		Glast papers by E. Bloom, L. Latronico	GLAST (2005)
	VERITAS*(2005)			

Gamma-ray astronomy present and future

Whipple
10 m
(Arizona)

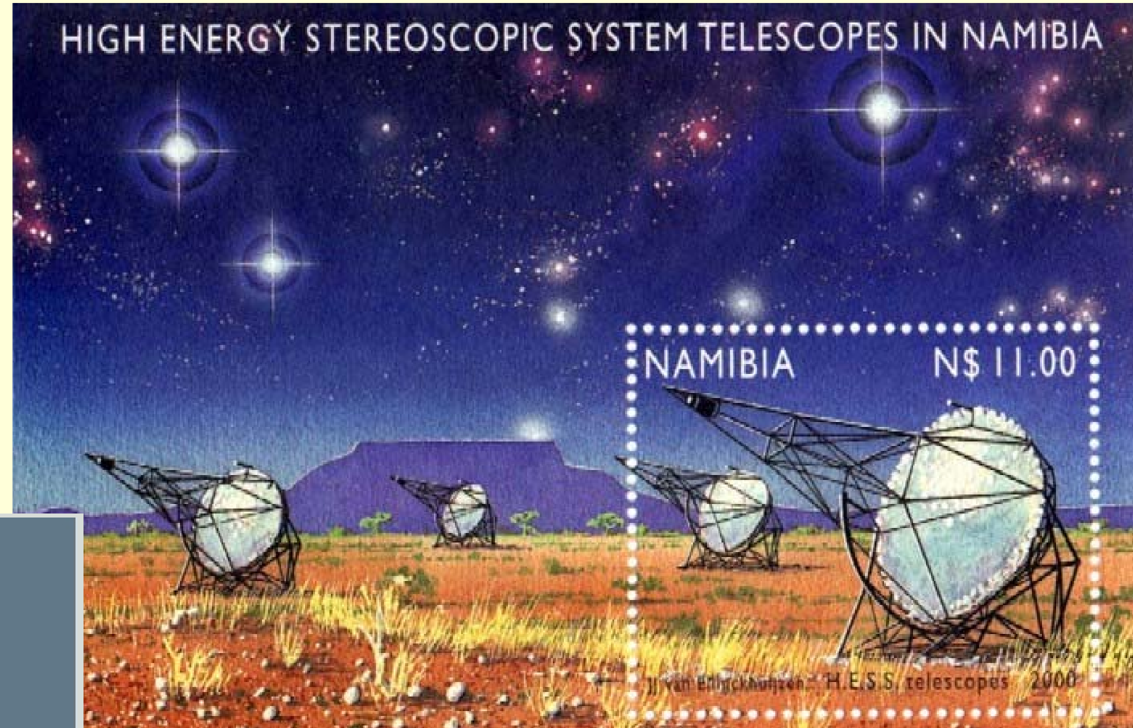
Magic
17 m
La Palma

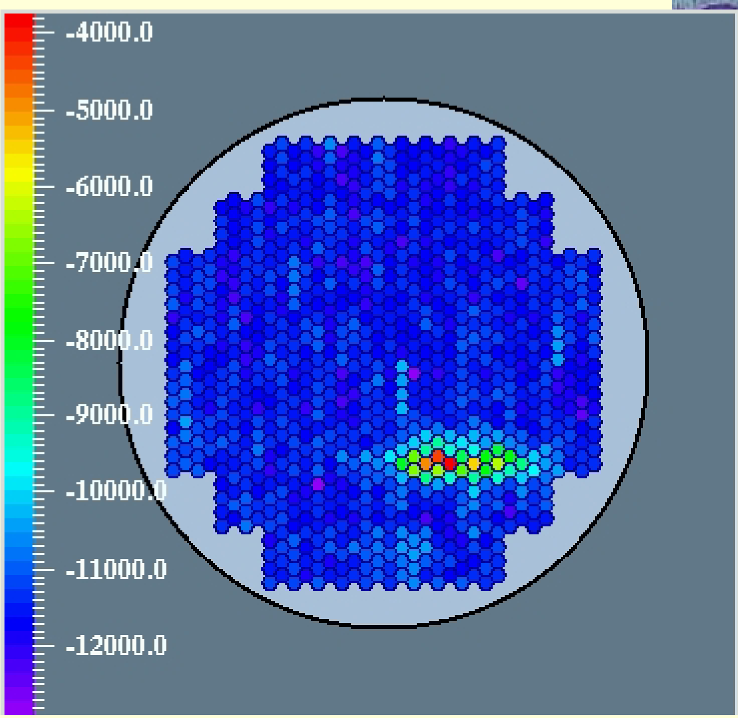


A. Morselli, S. Ritz

H.E.S.S.

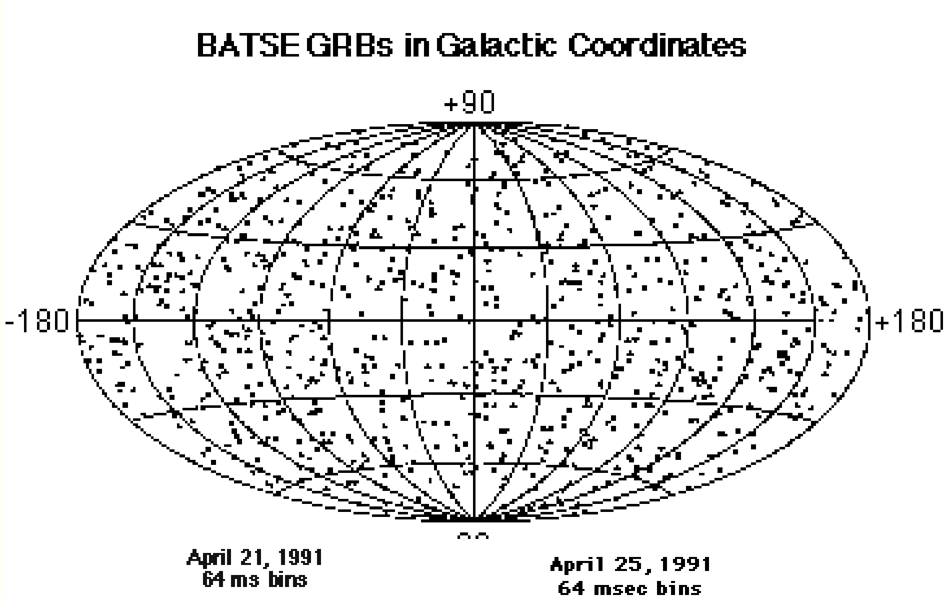
- First events
  - June, 2002

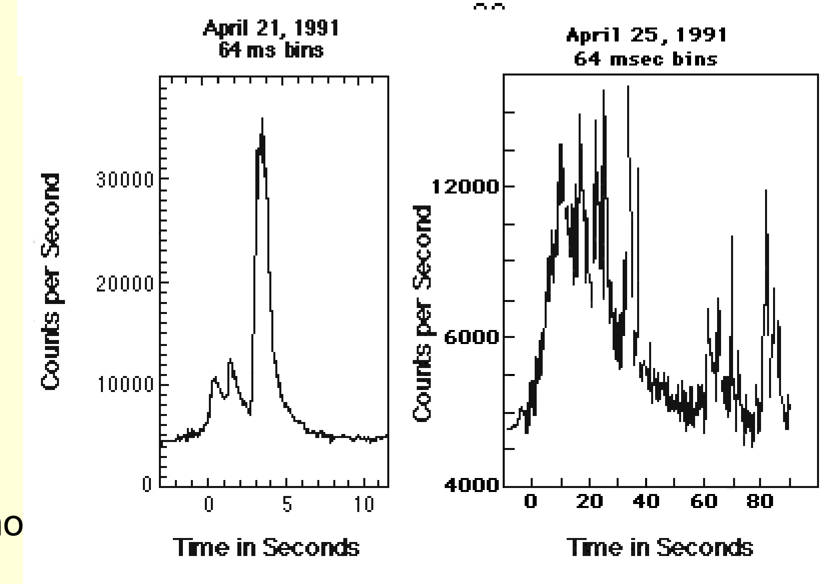




Gamma-ray bursts

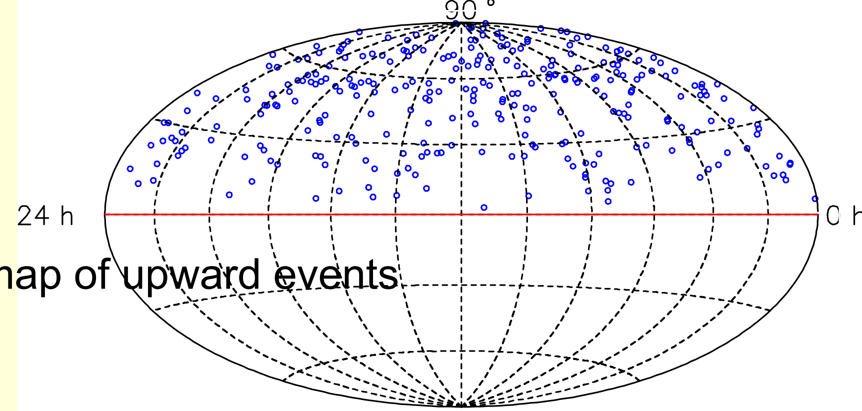
- Cosmological bursts
  - Studies of afterglows (ROTSE, Beppo-Sax ID) determine Z ~ 1
- Hypernova or coalescing compact objects
  - Relativistic jets (Γ ~ 100)
  - Acceleration at internal shocks
  - Possible acceleration when jets interact with environment
- Are GRBs sufficiently powerful and numerous to supply the UHECRs?
  - This question currently under debate
- Soft Gamma Repeaters
  - Galactic magnetars, B ~ 10^{15} G
  - Satisfy eβcBR > 10^{20} eV
- SWIFT to be launched in 2003



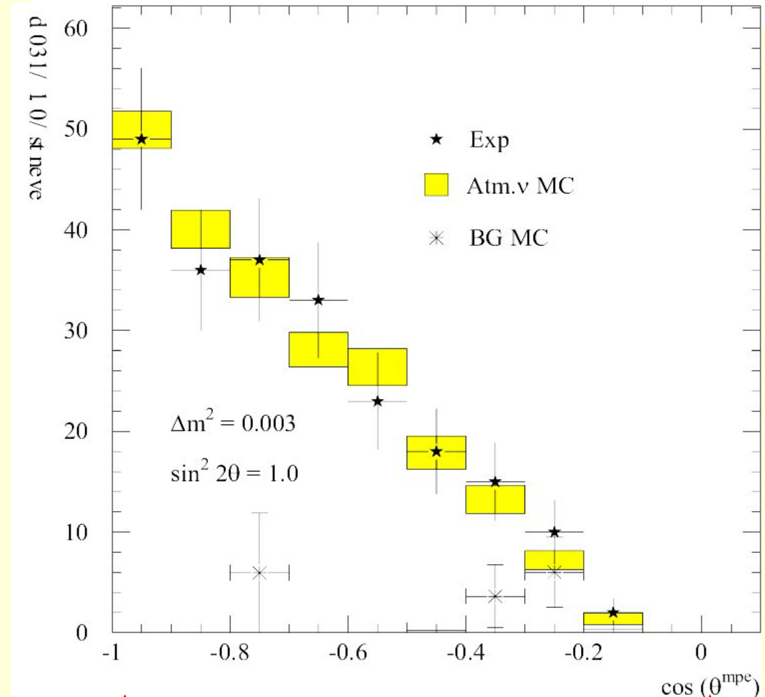


Neutrino Astronomy

- SN1987A, Solar ν
- High-energy ν astronomy
  - [DUMAND]
  - Baikal, AMANDA
    - Currently running
    - Atmospheric ν's detected
    - Limits on point sources, diffuse high-energy ν's, WIMPs, monopoles
  - Km3-scale projects getting underway



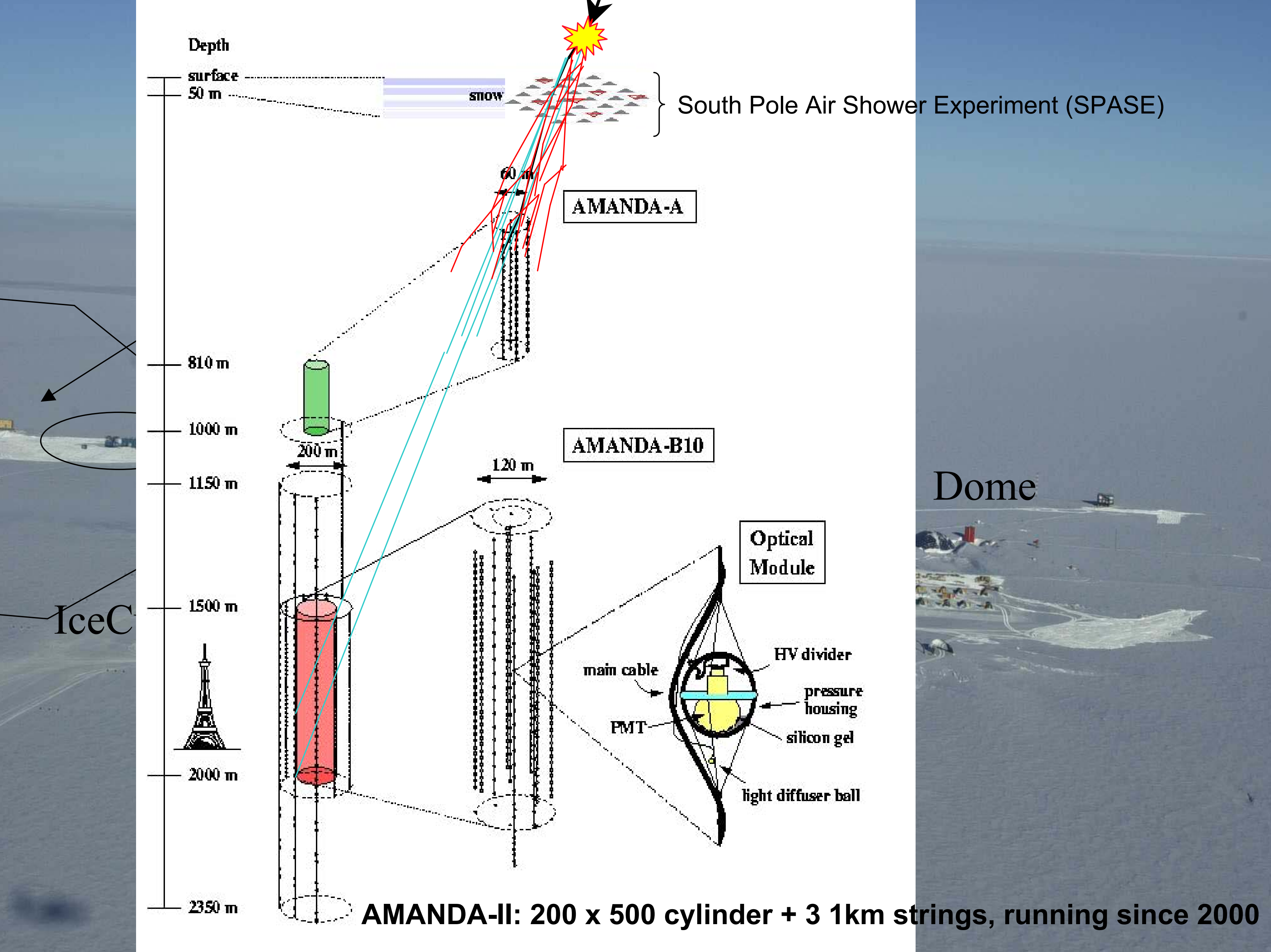
Skymap of upward events

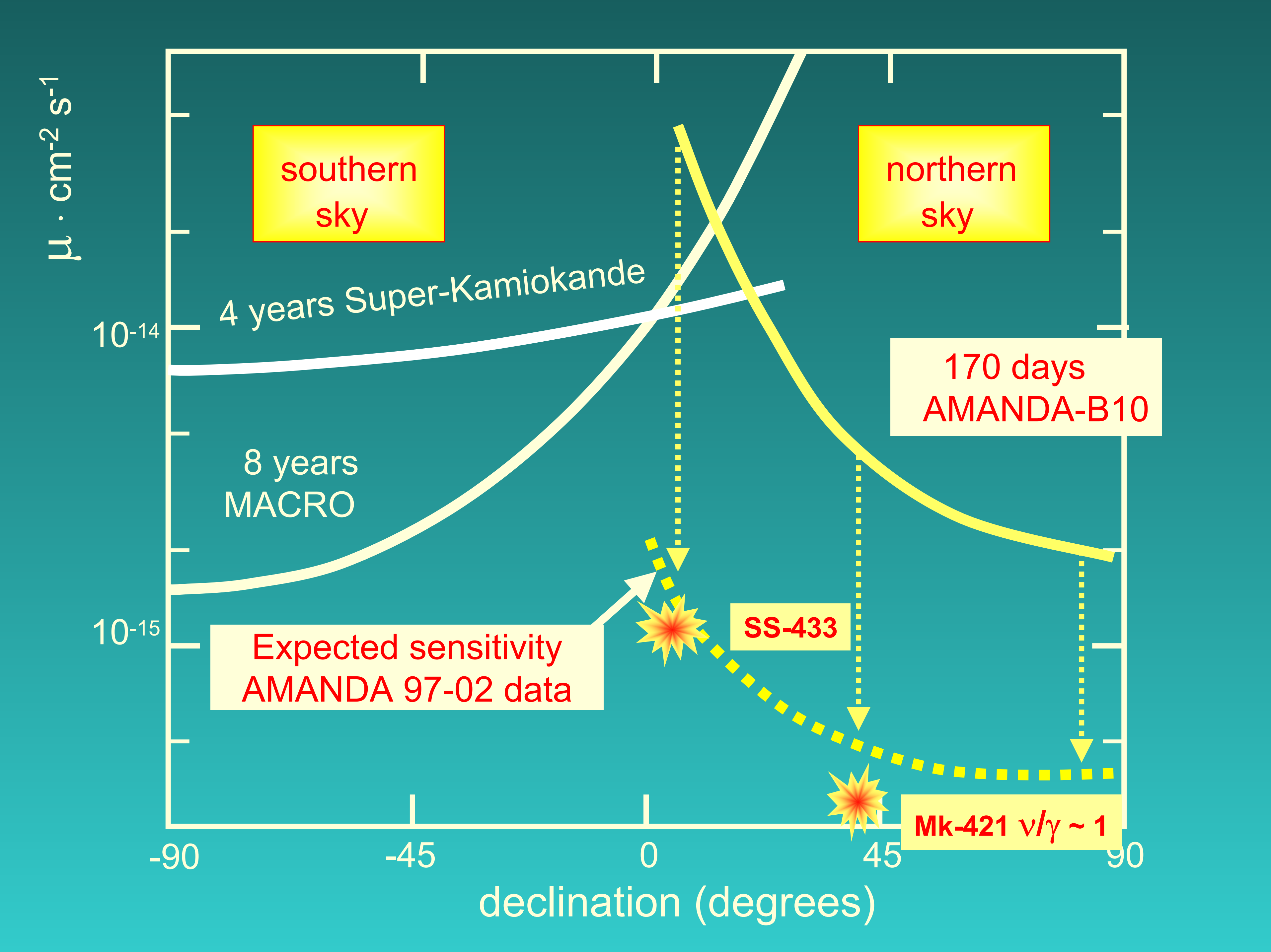


AMANDA: astro-ph/0205019

vertically up

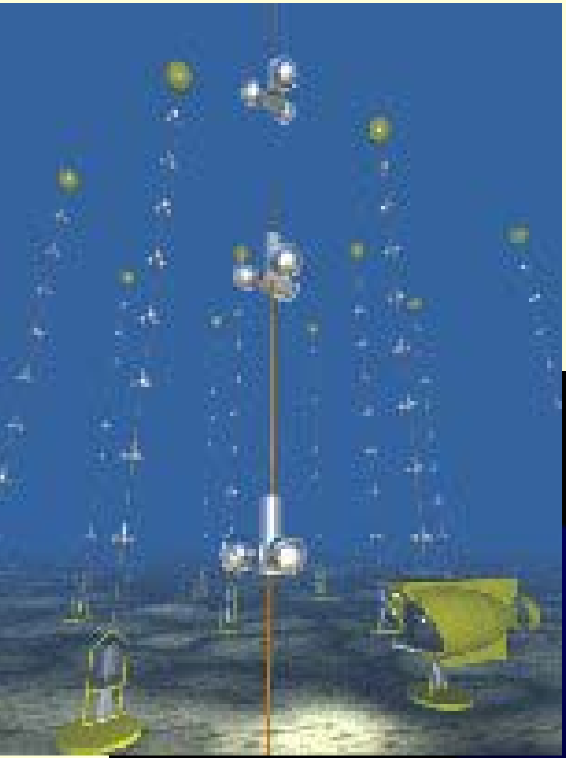
horizontally


Depth
surface
50 m
snow
South Pole Air Shower Experiment (SPASE)
60 m
AMANDA-A
810 m
1000 m
200 m
AMANDA-B10
1150 m
120 m
Dome
Optical Module
1500 m
IceC
HV divider
main cable
pressure housing
PMT
silicon gel
2000 m
light diffuser ball
2350 m
AMANDA-II: 200 x 500 cylinder + 3 1km strings, running since 2000



$\mu \cdot cm^{-2} s^{-1}$
southern sky
northern sky
4 years Super-Kamiokande
10^{-14}
170 days AMANDA-B10
8 years MACRO
10^{-15}
SS-433
Expected sensitivity AMANDA 97-02 data
Mk-421 $\nu/\gamma \sim 1$
-90
-45
0
45
90
declination (degrees)

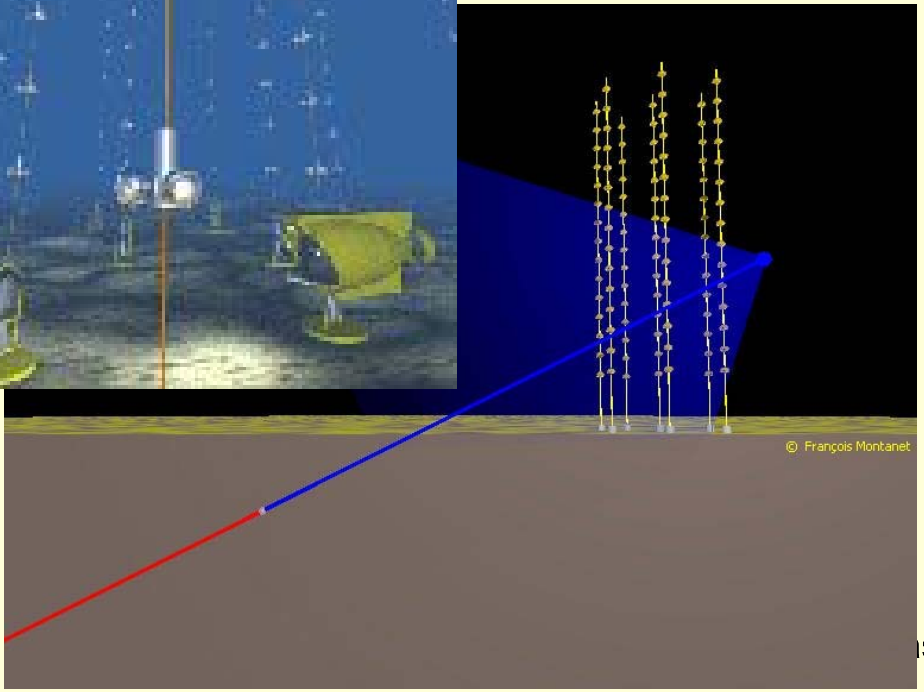
Development of kilometer-scale ν telescopes ... complementary sky-views and techniques



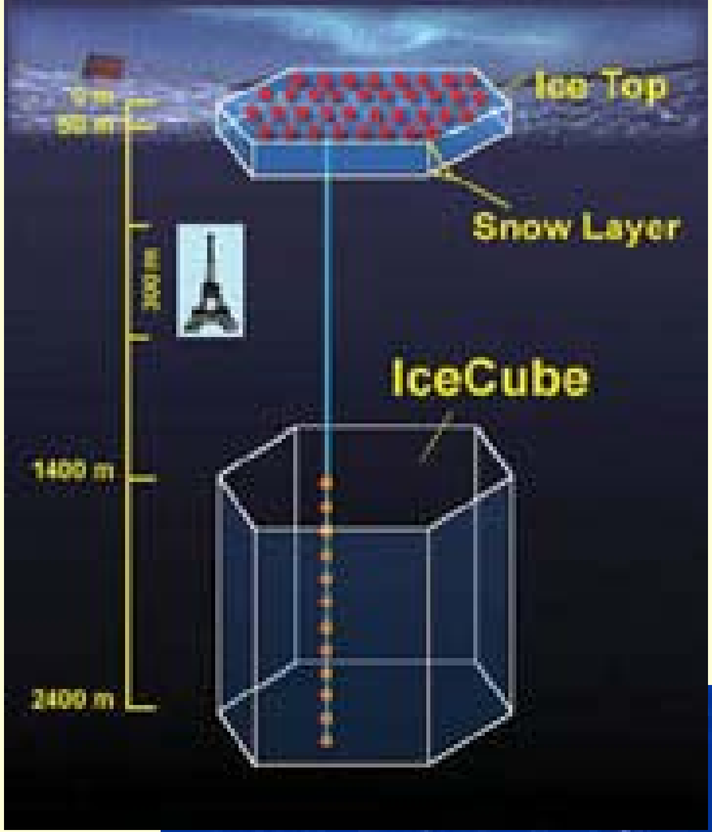
Antares
+ Nemo, Nestor

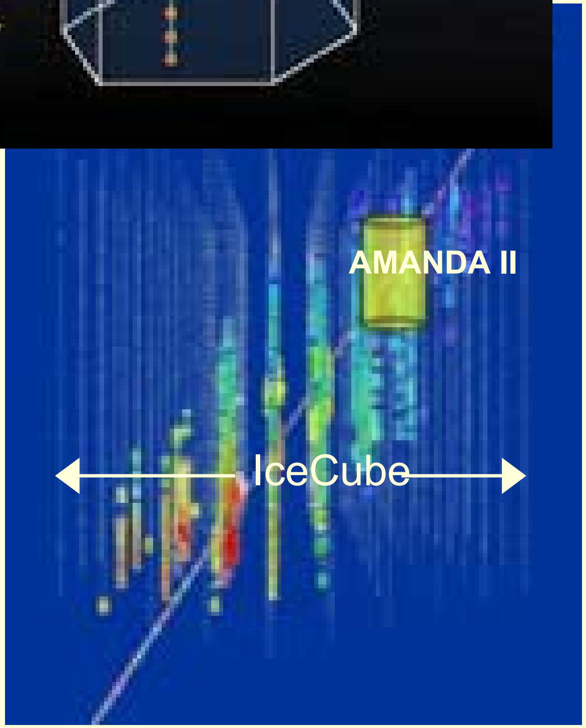
↓

Km^3 in the Mediterranean Sea



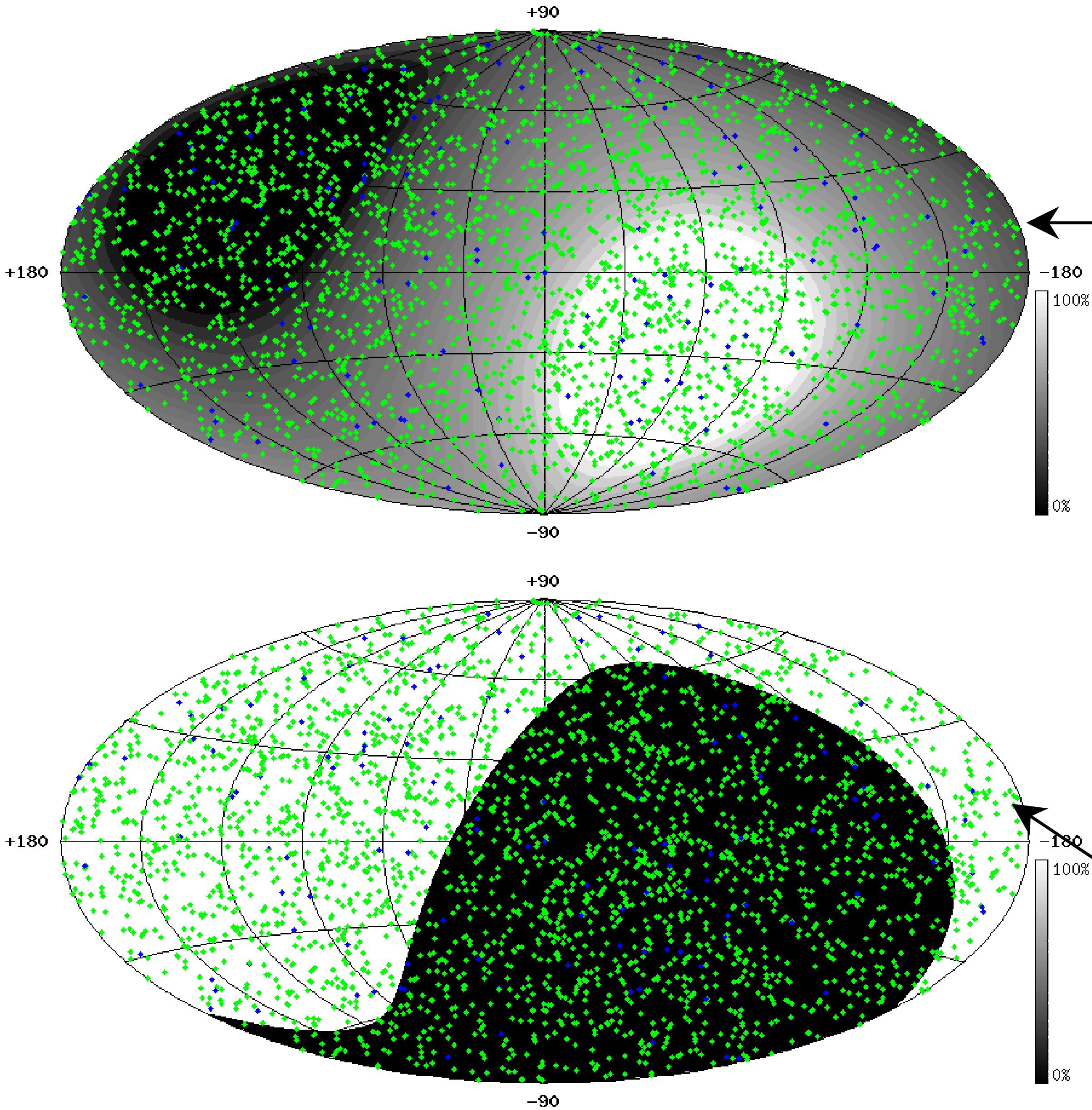
IceCube in Antarctic ice





s K. Gaisser

Skymaps and exposure to gamma-ray bursters



BATSE 2706 GRBs

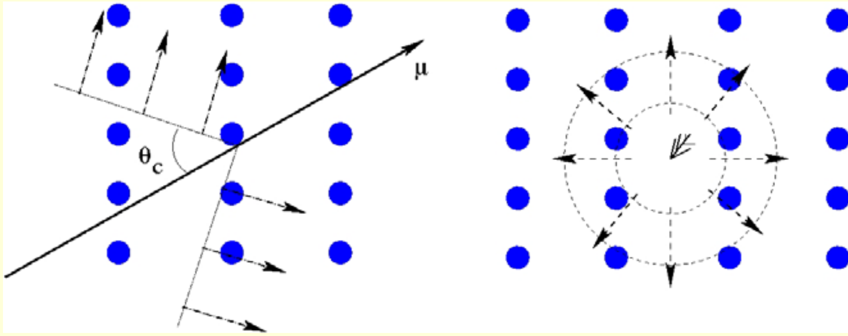
B*eppo*-SAX 126 GRBs

ANTARES location: Sources rise and set; partial overlap with South Pole F.O.V.

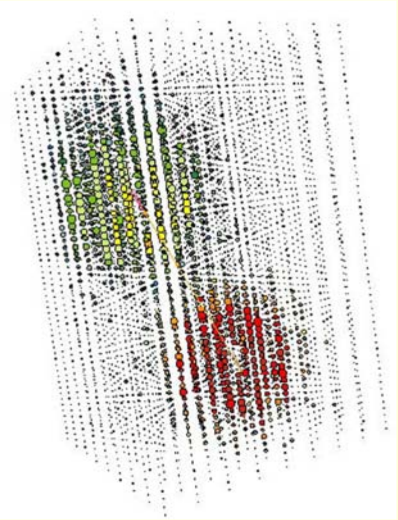
Plot by Teresa Montaruli is grey-scale image of sky coverage for upward events (black = no coverage, white = full coverage). Applies to E_ν< PeV when Earth needed to shield against downward events.

AMANDA location: Sources always at same elevation, a possible advantage for variable sources

Neutrino flavor ID

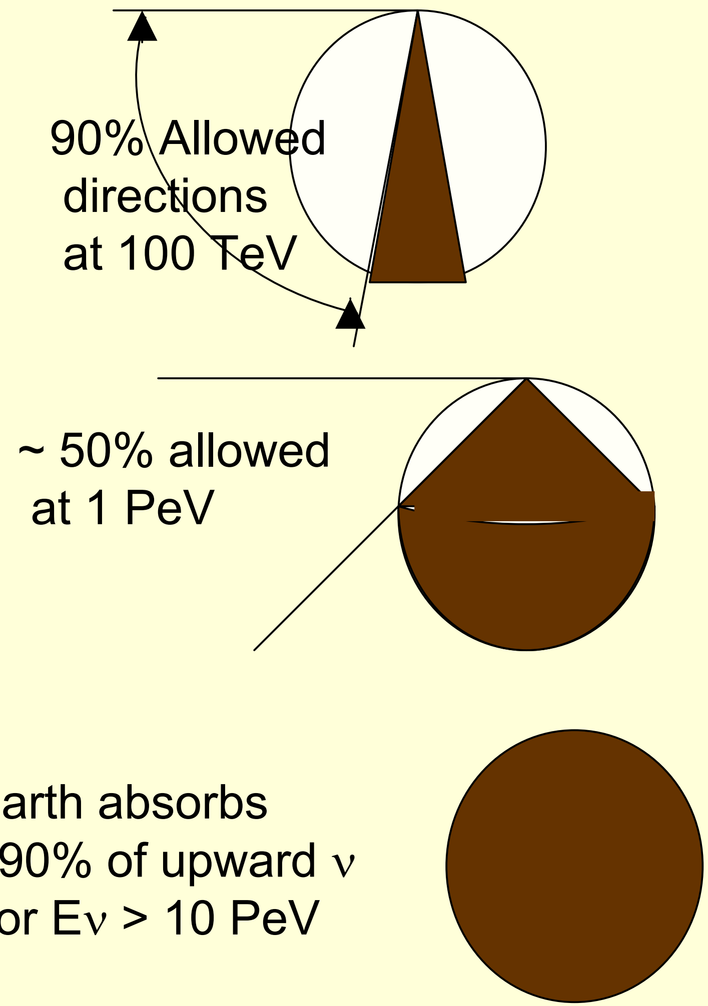


- $P \rightarrow \pi \rightarrow \nu_\mu + \mu \rightarrow e + \nu_e + \nu_\mu$
  - $\nu_\mu : \nu_e : \nu_\tau \sim 2 : 1 : 0$ at production
  - oscillations give 1 : 1 : 1 at Earth
- $E\nu$ < PeV
  - ν_μ: upward μ track
  - ν_e, ν_τ: cascades
- $E\nu$ > PeV
  - $R_\tau \sim 50$ m / E_τ (PeV)
  - ν_τ gives double bang or "lollipop" signature (large cascade preceded or followed by a long, "cool" track)



ν Propagation in the Earth

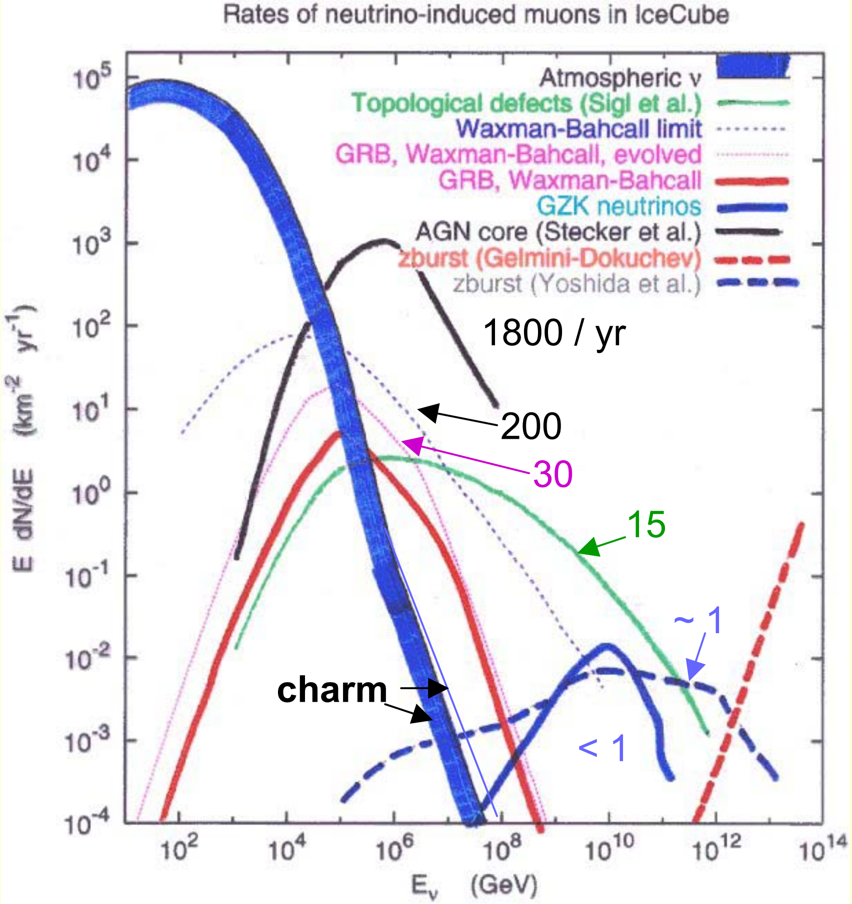
- Lower hemisphere 50% opaque for E_ν ~ PeV
- Regeneration of ν_τ
  - $\nu_\tau \rightarrow \tau \rightarrow \nu \rightarrow$ cascade:
  - Look for excess of upward cascades between 0.1 and 10 PeV
- For $E_\nu >$ PeV can use downward neutrinos as well as upward



Expected signals in km^3

- Possible point sources:
  - Galactic
    - SNR 0 - 10 events / yr
    - μ-quasars 0.1 - 5 / burst
    - ~ 100 / yr, steady source
  - Extra-galactic
    - AGN jets 0-100 / yr
    - GRB precursor (~100 s)
      - ~ 1000 bursts / yr
      - ~ 0.2 events / burst
    - GRB jet after breakout
      - smaller mean signal / burst
    - Nearby bursts give larger signal in both cases

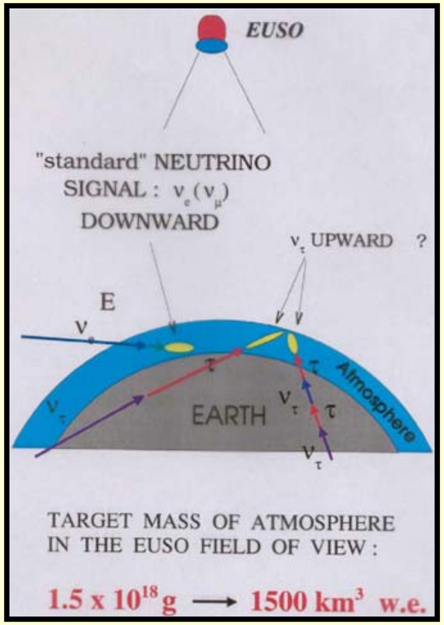
Diffuse (unresolved) sources--signature:
- **hard spectrum**
- **charm background uncertain**

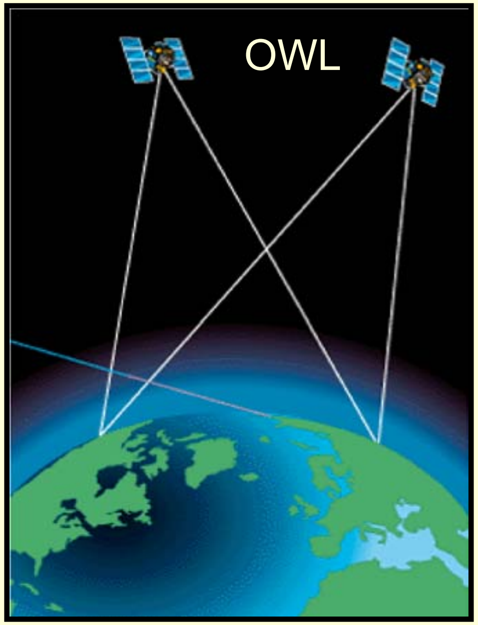


Proposed detectors for E_ν ~ EeV

- Air shower arrays
  - Signature: Horizontal EAS
  - V_{eff} ~ 10 m.w.e. x area
    - e.g. 30 Gt for Auger
    - (Acceptance ~30 x larger for ν_τ in Auger)
    - >1000 Gt for EUSO, OWL
- Radio detectors
  - RICE (antennas in S.P. ice)
  - ANITA (antennas on long-duration Antarctic balloon)
  - SALSA (…in salt domes)
  - GLUE (Goldstone antenna search for ν interact in moon)

- *Note: despite larger V_{eff}, rates may be comparable or smaller than in Km^3 detectors with lower $E_{threshold}$ by an amount depending on source spectrum*





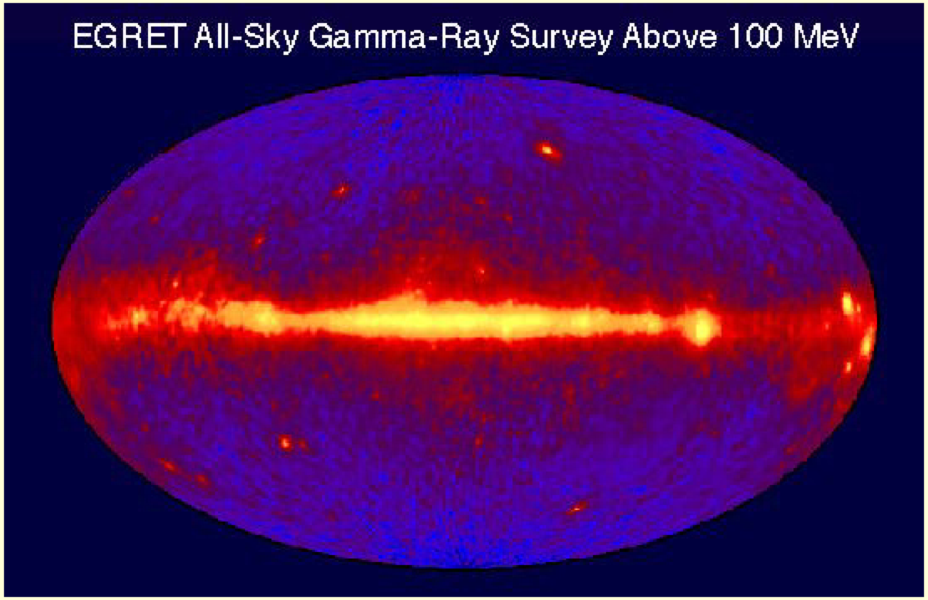
Summary

- Need more statistics and cross-calibration for ultra-high energy cosmic rays
- Expect another leap in g-astronomy with GLAST and new ground telescope arrays
- Kilometer-scale neutrino telescopes to open new window on energetic Universe
- *Many active and new experiments in this rapidly developing field -- stay tuned!*

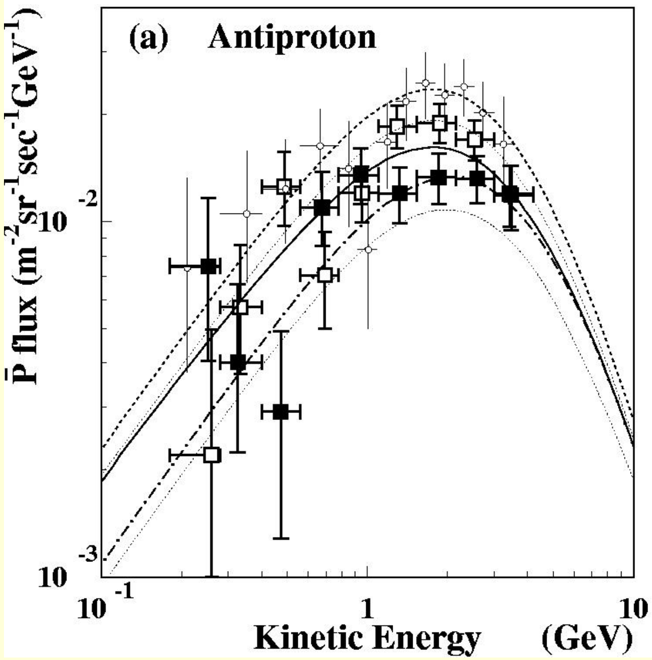
Diffuse galactic secondaries

p + gas → π^0, $\pi^{+/-}$, antiprotons

- $\pi^0 \rightarrow \gamma\,\gamma$ [$\pi^{+/-} \rightarrow \nu$]
- Hard γ-spectrum suggests some contribution from collisions at sources



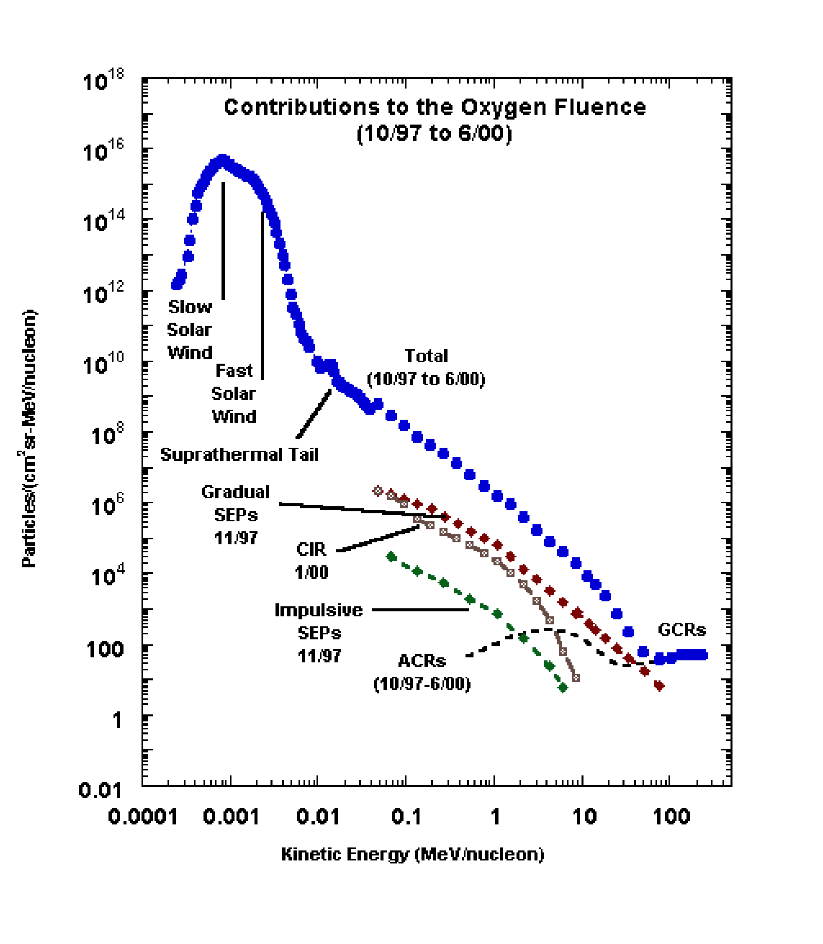
Phys.Rev.Lett. 88 (2002) 051101



BESS antiprotons, 1997, '99, '00.
- Fully consistent with secondary production by collisions in ISM followed by solar modulation varying with solar cycle

Lessons from the heliosphere

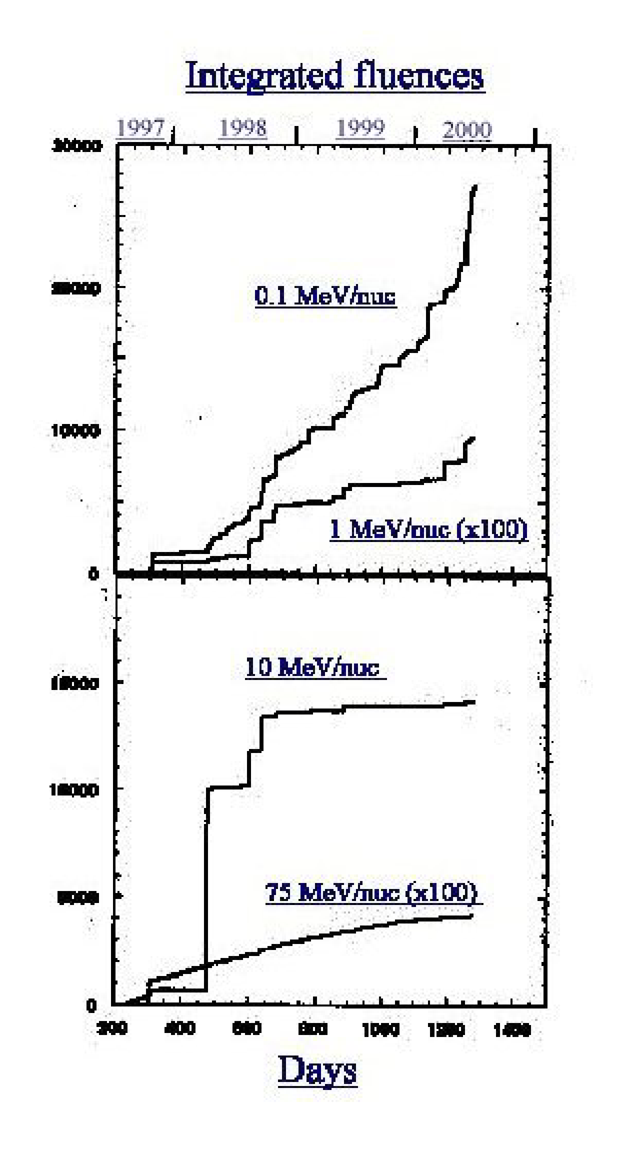
- ACE energetic particle fluences:
- Smooth spectrum
  - composed of several distinct components:
    - Most shock accelerated
    - Many events with different shapes contribute at low energy (< 1 MeV)
    - Few events produce ~10 MeV
  - Knee ~ Emax of a few events
  - Ankle at transition from heliospheric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



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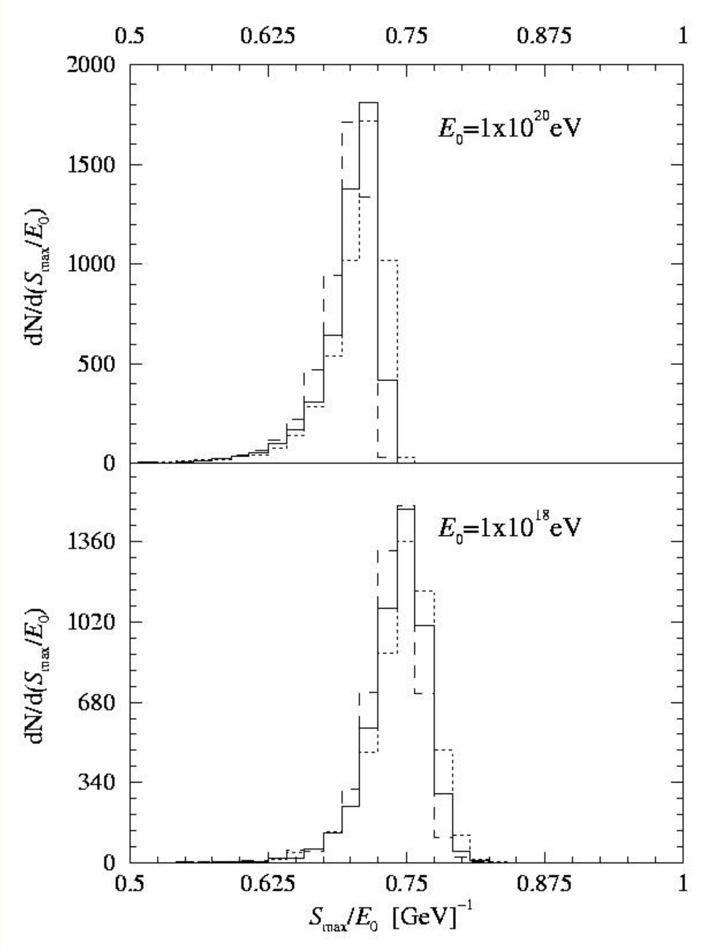
Reconstruction Handles for neutrino astronomy

	up/down	energy	source direction	time
Atmospheric ν_μ (calibration beam)	x			
Diffuse ν, EHE events	x	x		
Point Sources: AGN,WIMPs	x	x	x	
GRBs	x	x	x	x

Energy resolution

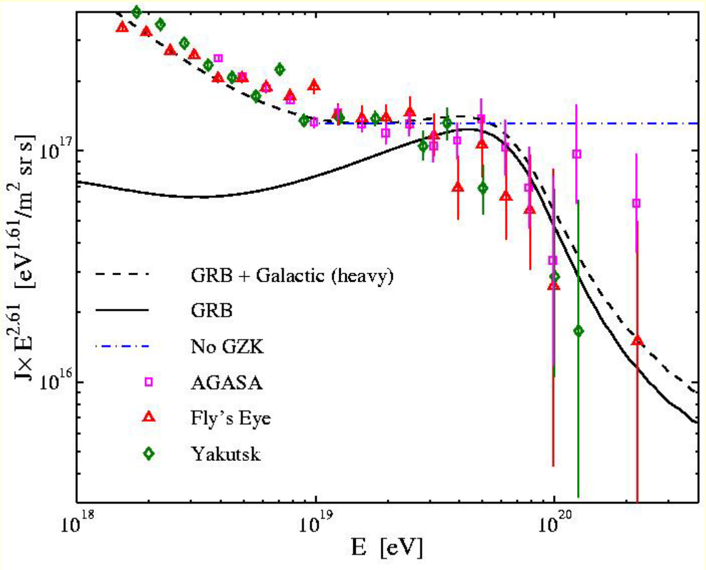
- Systematics
  - $\Delta E / E$ ~20% for ~10^{18} eV
    - By cross-calibrating different detectors
    - By using different models
    - By comparing spectra of different experiments and techniques
- Fluctuations in S_{max}
    - underestimate E if measured at max,
    - overestimate if past max

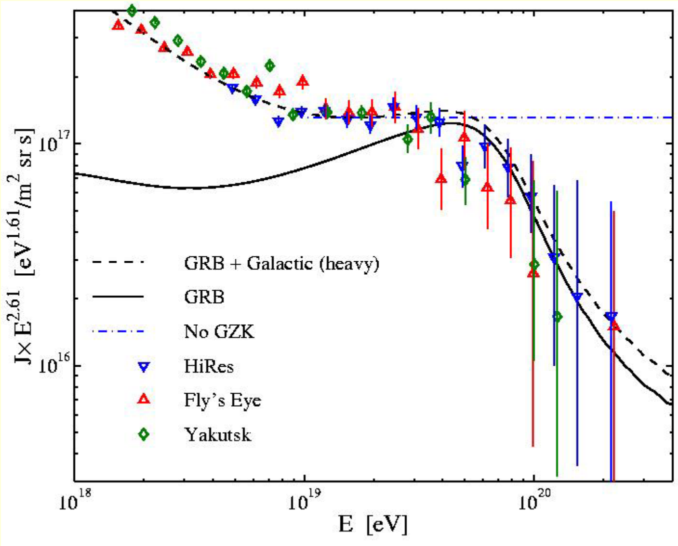


GRB model

Bahcall & Waxman, hep-ph/0206217

- Assumes E^{-2} spectrum at source
- 2.5 x 10^{53} erg/GRB
- 0.4 x 10^{37} erg/Mpc^3/s
- Evolution like star-formation rate
- GZK losses included
- Galactic→ extragalactic transition ~ 10^{19} eV



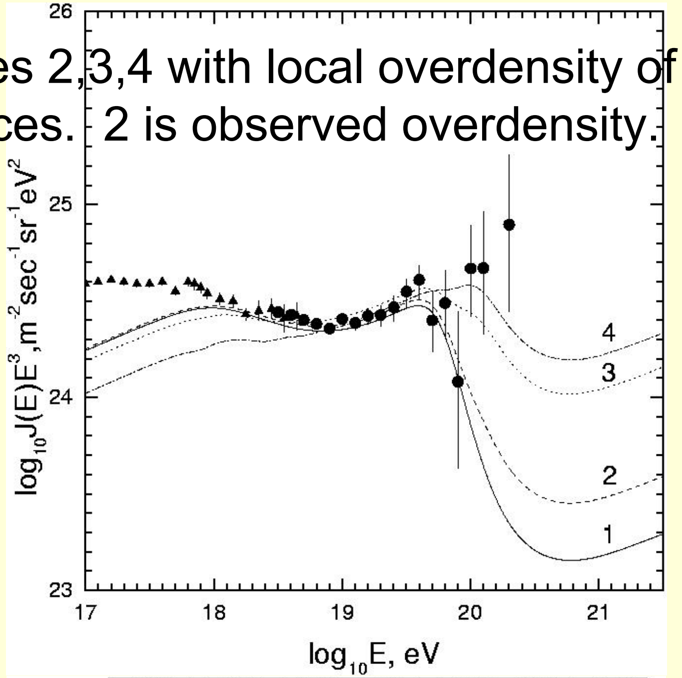


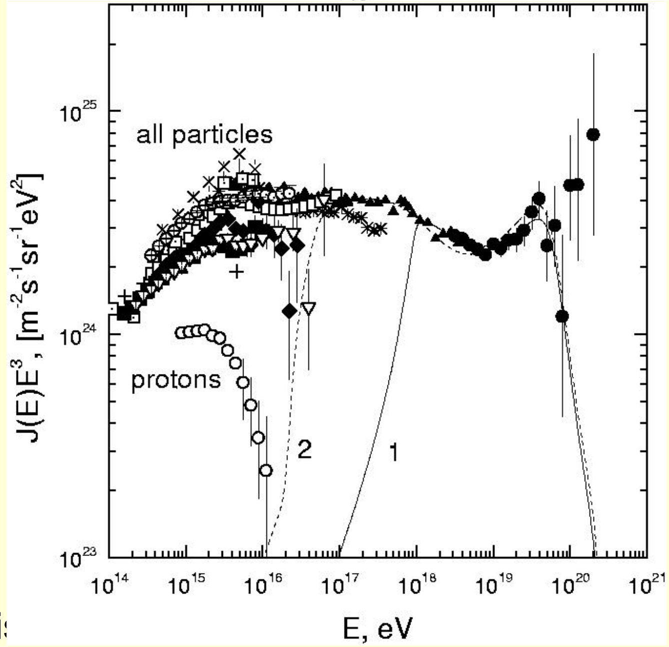
AGN model

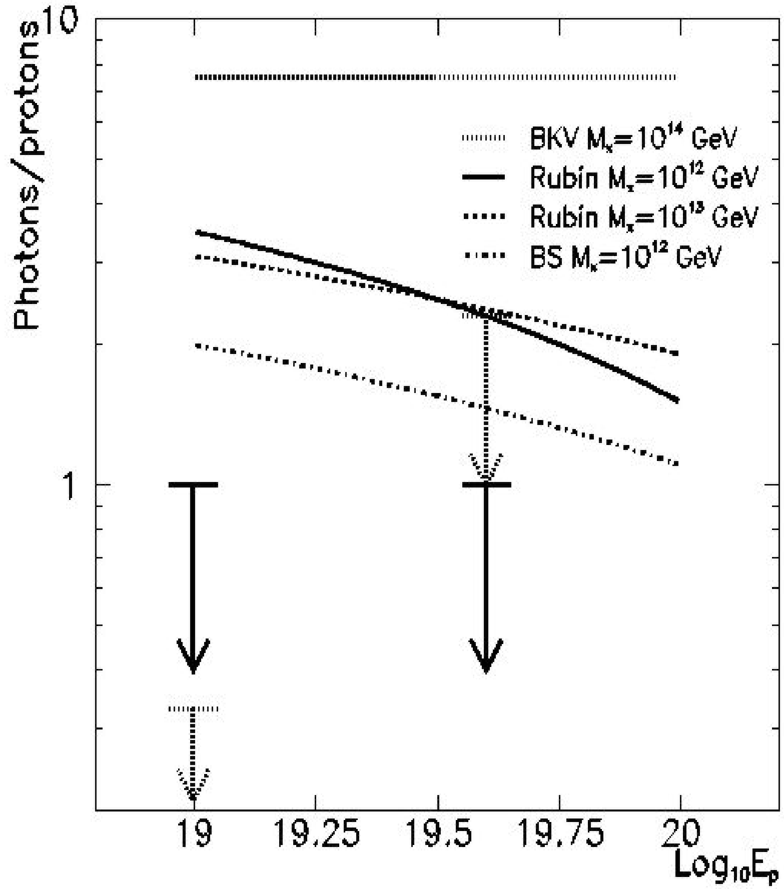
Berezinsky *et al.*, hep-ph/0204357

- Assumes two-component spectra
  - steep at high energy
- 10^{39} erg/Mpc^3/s
  - note high value
- Evolution, GZK losses
- Compares to AGASA data, cannot explain ~5 events
- Transition to extragalactic at low energy

Curves 2,3,4 with local overdensity of sources. 2 is observed overdensity.







Comparison of Haverah Park photon limit with theory