The Extreme Universe

Probing the Limits of Particle Physics and Astronomy

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Outline

- Big Picture
  - Cosmic messengers & observables
  - Scientific motivation
  - Experimental techniques
- Recent excitement
  1. (Gamma-ray bursts)
  2. Extragalactic TeV sources
  3. Ultrahigh energy cosmic rays
- Future

Cosmic Messengers

We learn about the universe from four messengers:

1.	Photons	neutral	basis for most of astronomy
2.	Cosmic rays	charged	important in our galaxy
3.	Neutrinos	weakly inter.	only detection – SN1987A
4.	Grav. waves	neutral	still in infancy

To fully understand astrophysical sources we need information from multiple messengers.

This talk concentrates on 1 & 2 at high energies.

Observables

- Particle type - γ, CR, ν, …
- Energy spectrum - physics
- Direction - astronomy
- Variability
- (Polarization)

High Energies

GeV $= 10^9$ eV

TeV $= 10^{12}$ eV

PeV $= 10^{15}$ eV

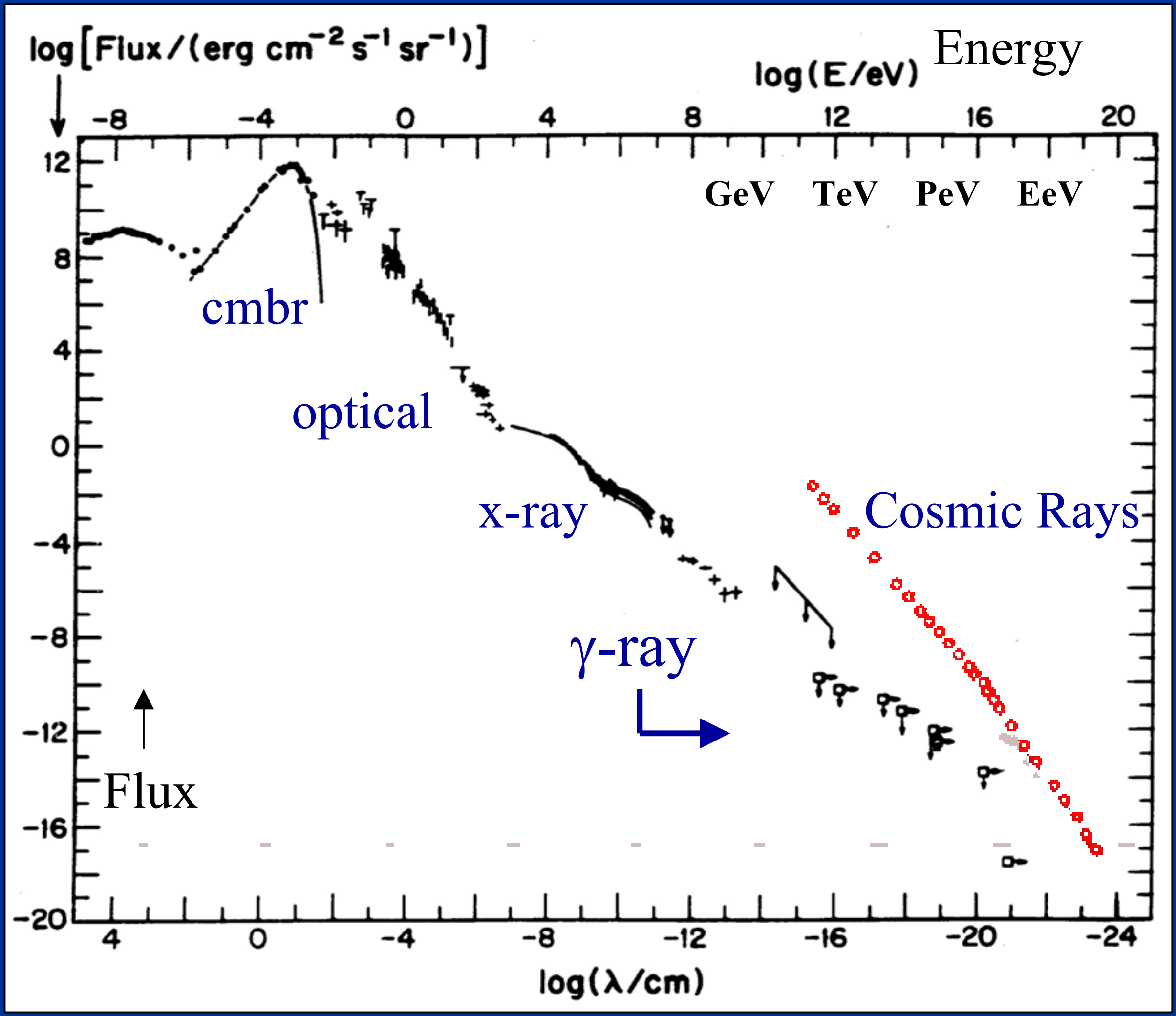
EeV $= 10^{18}$ eV

ZeV $= 10^{21}$ eV

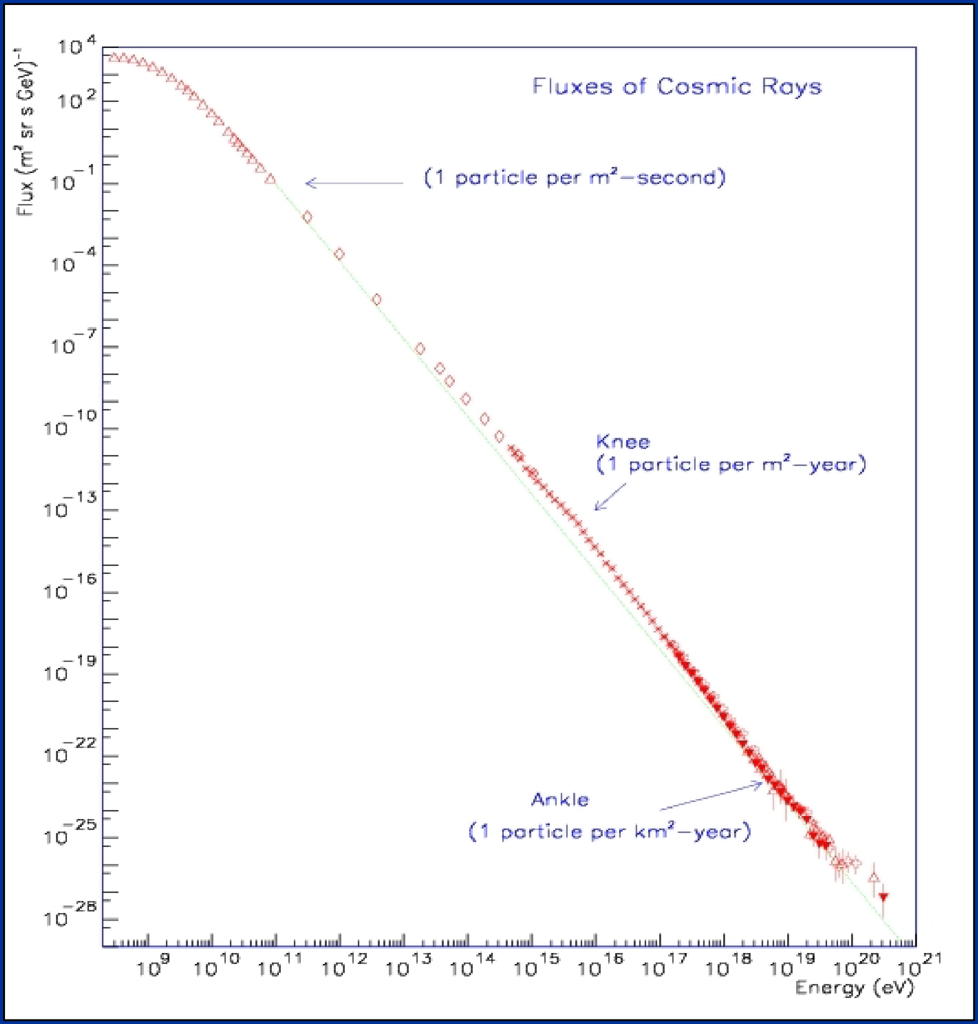
Space-based

Ground-based ↓

Diffuse Photon Spectrum



Cosmic Ray Spectrum

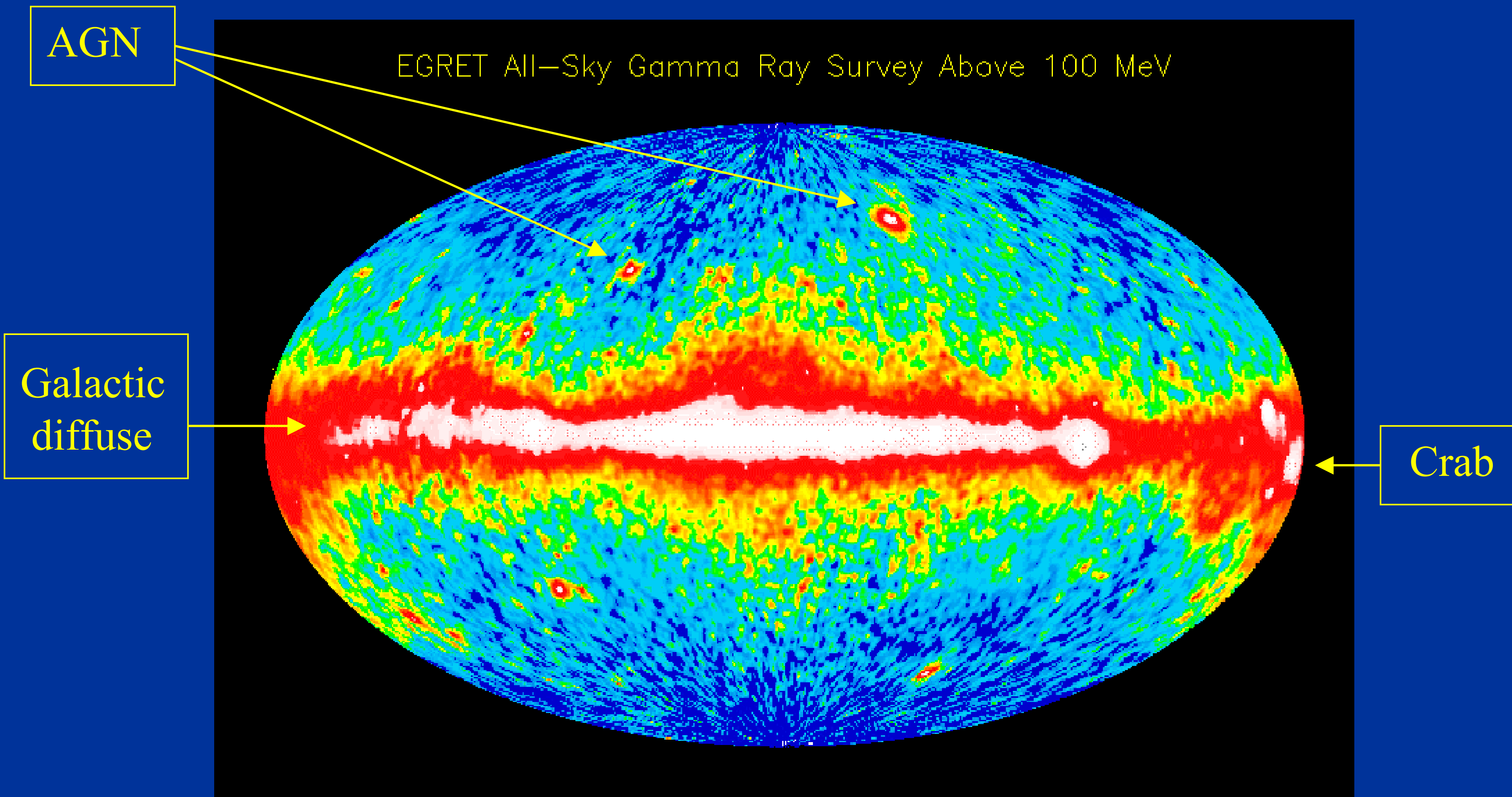


- Power law spectrum
- Abundant
  $\rho \sim 1$ eV / cm^3
- Luminous
  L > 10^{40} erg/s
- Larmor radius r = R/cB

R	r
10^{15} eV	0.3 pc
10^{20} eV	30 kpc

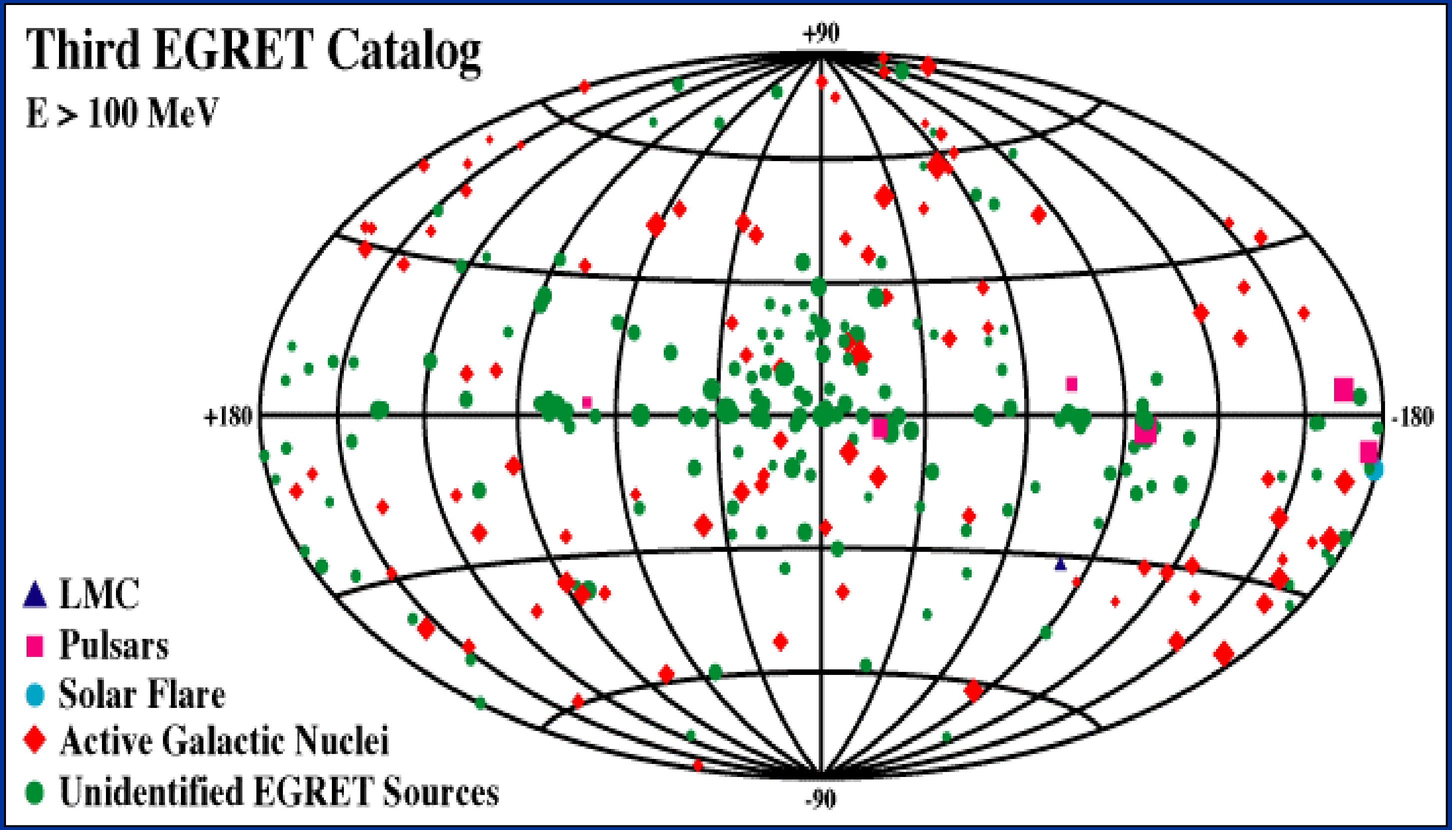
- <u>HE origin remains completely unknown.</u>

GeV γ-ray Sky Map



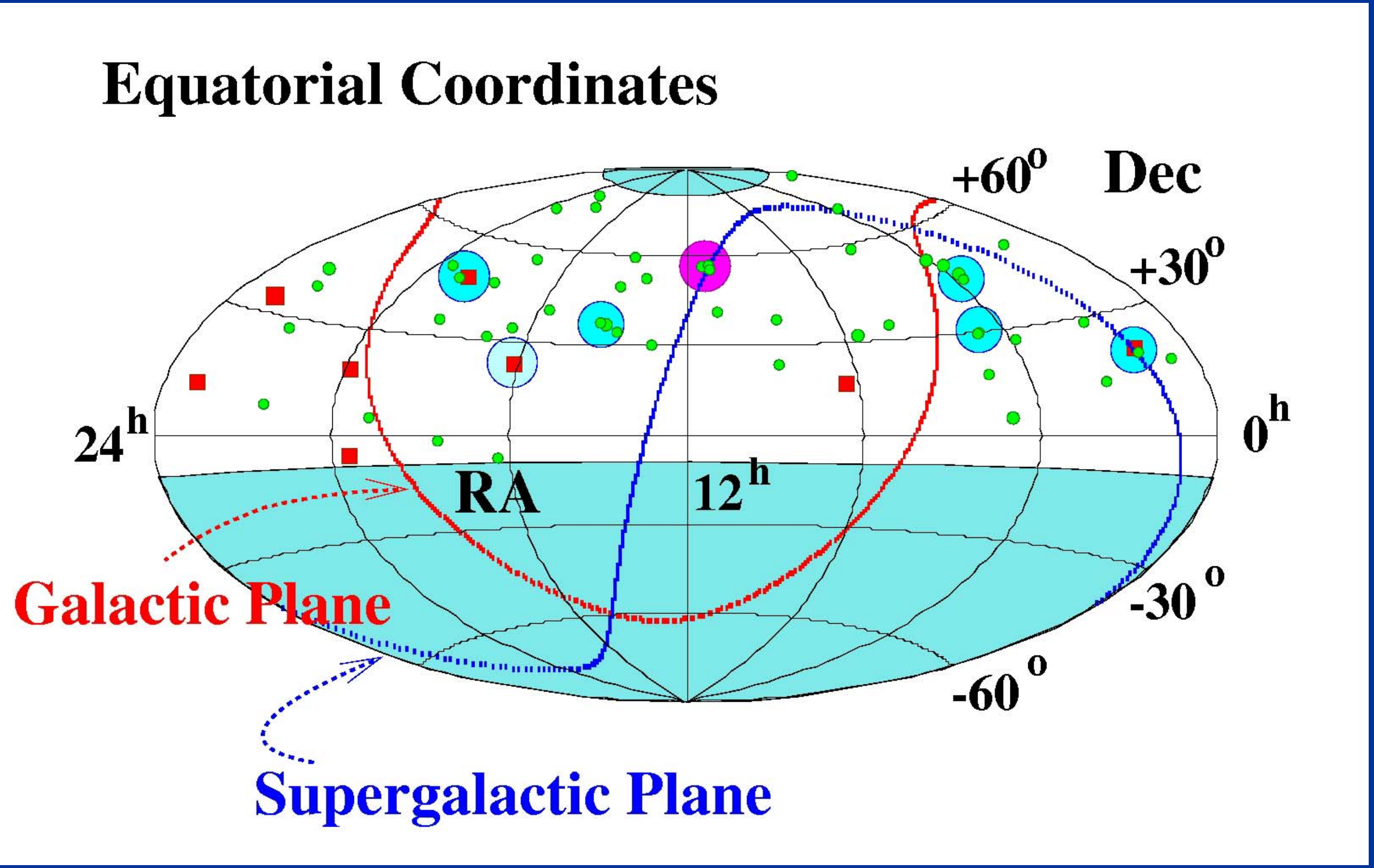
EGRET

GeV γ-ray Sky Map



+ GRBs

UHECR Sky Map



AGASA   59 evts > 4×10^{19} eV

ν Sky Map

Scientific Motivation

- Explore a new window of astronomy
- "Extreme Astrophysics":
  1. Test limits of physical law using most extreme environments.
  2. Probe high energy, non-thermal astrophysical mechanisms.
- Probe beyond standard models of particle physics and cosmology:
  1. Use "particle beams" across interstellar space.
  2. Search for new particles or new relics from the Big Bang.

Examples from these various topics . . .

Extreme Astrophysics

High energy astrophysical sources exist!

How do we make such sources?

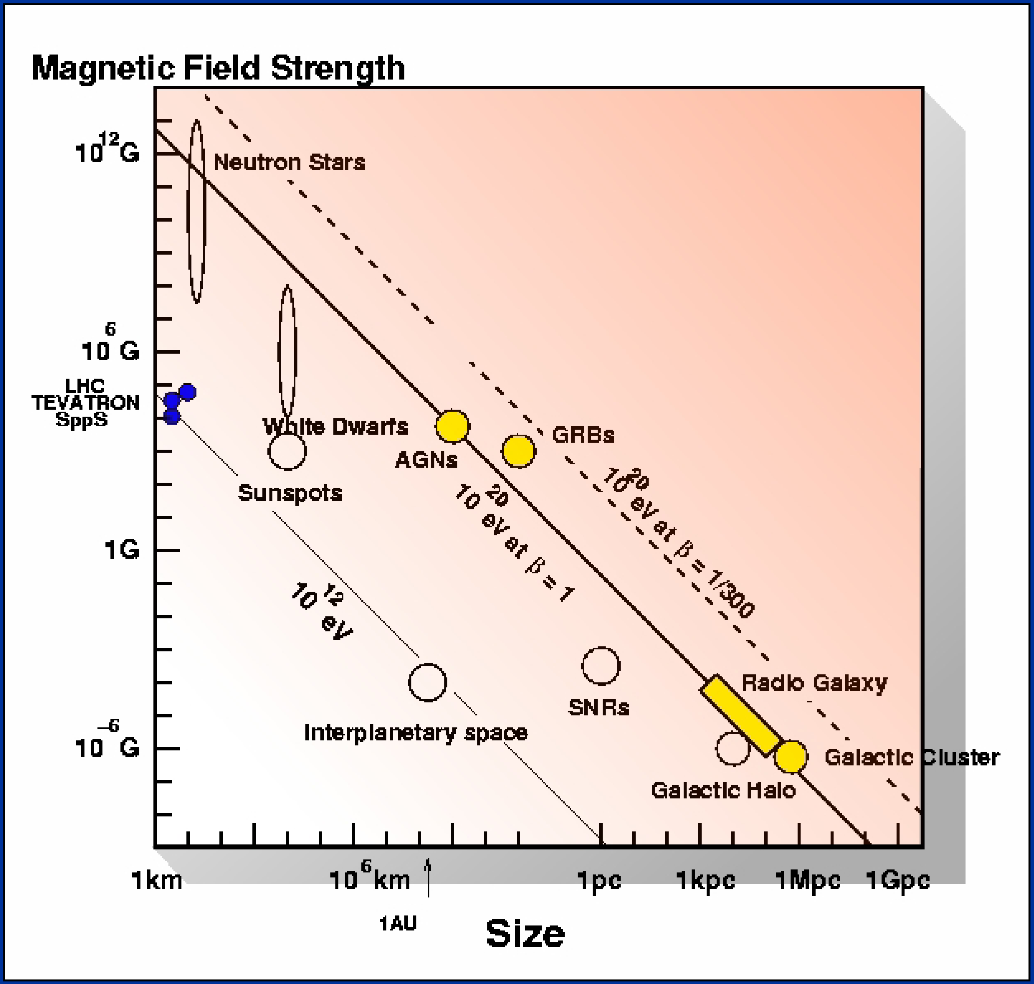
Three ingredients:

1. Power source - electromagnetic, gravitational
2. Acceleration - shock acceleration (Fermi)
3. Emission - particle interaction and decay

Reaching Very High Energies

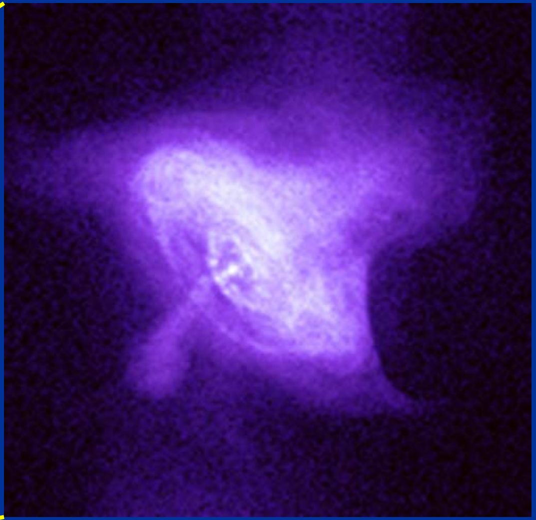
Hillas plot

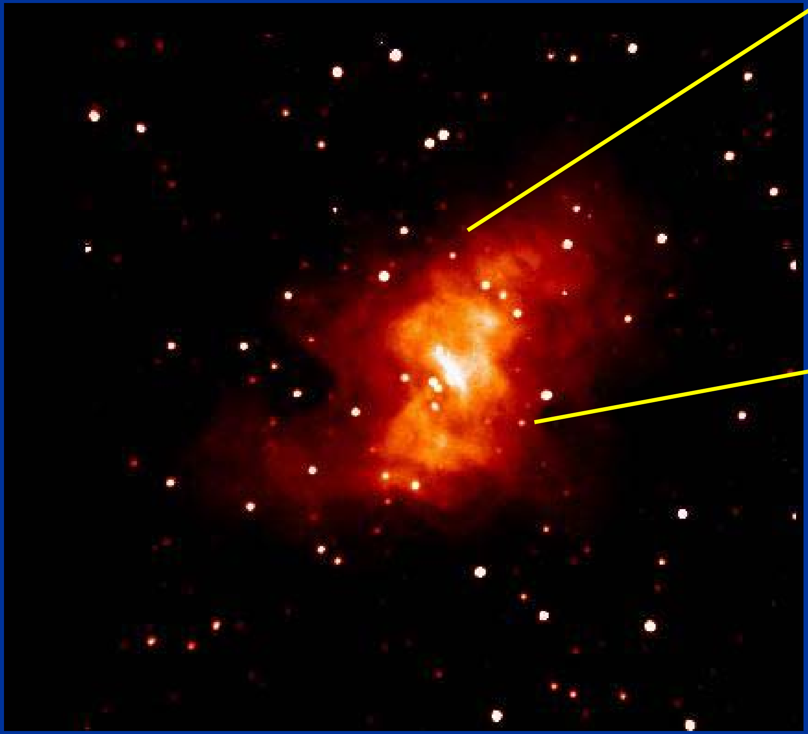
Require gyroradius to fit within acceleration region.



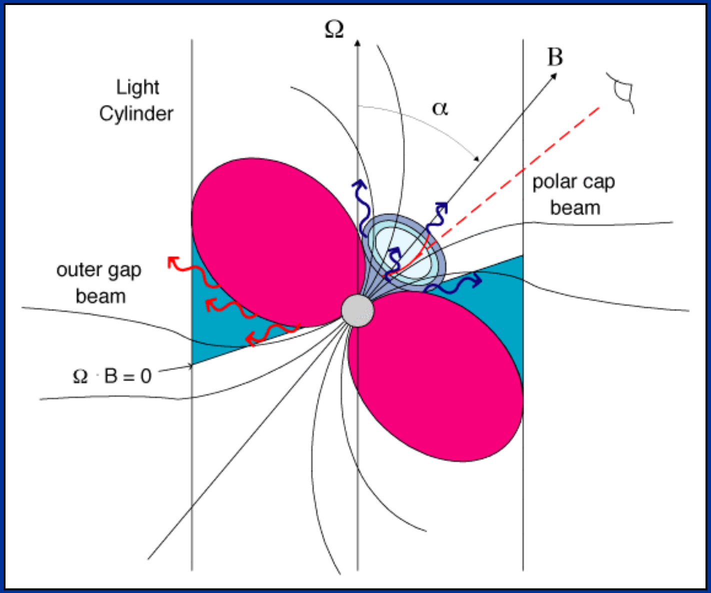
Power Sources: Pulsars

Pulsar- NS rotation





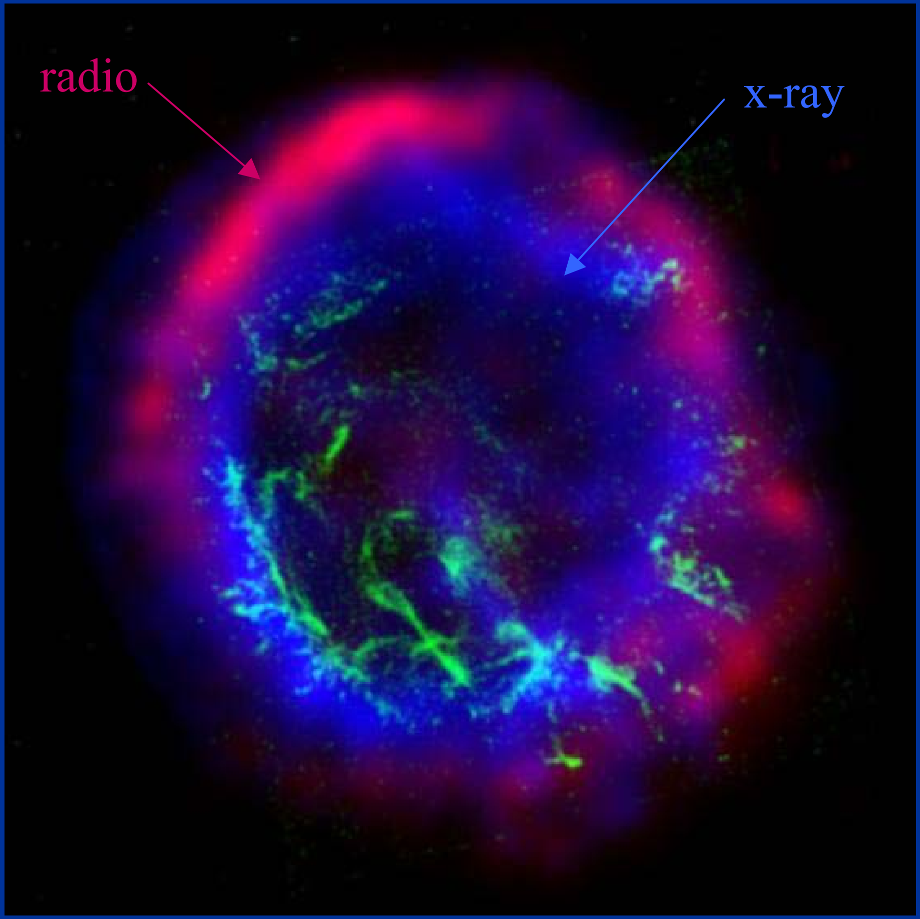
Crab Nebula



models

Produces γ-rays up to 10^{15} eV.

Supernova Remnants



E0102
AAT, HST, Chandra

- Collapse of massive star
- Remnant expansion powers shock wave
- Particle acceleration via Fermi mechanism

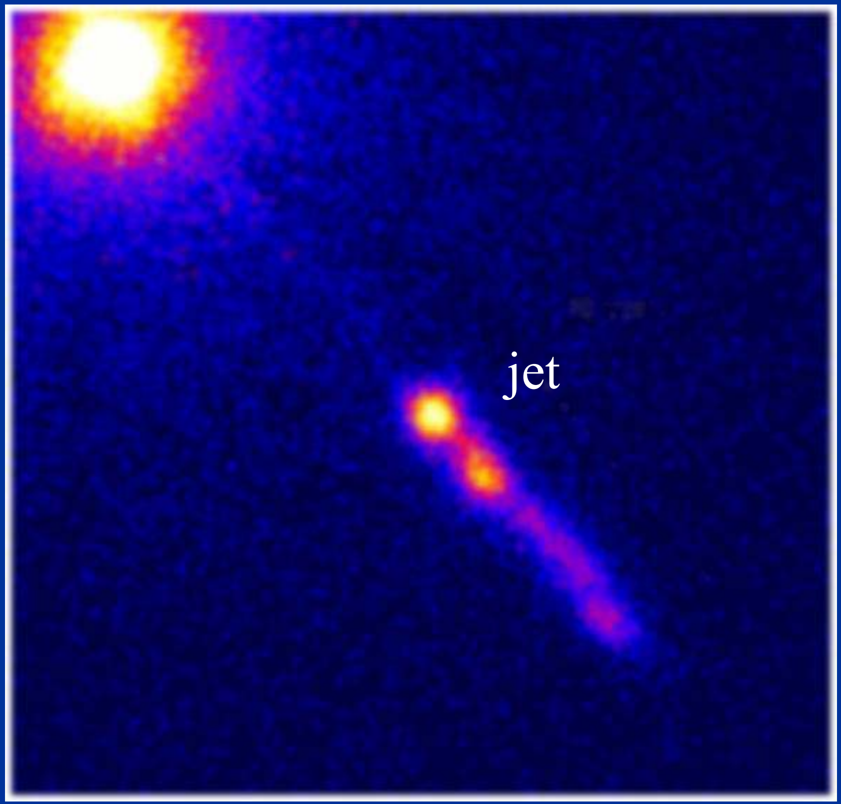
Energy $\sim 10^{51}$ erg
Rate $\sim$ 1 / 30 yr (galaxy)
L $\sim 10^{42}$ erg/s

$L_{cr} = \varepsilon L$
$= 10^{40} - 10^{41}$ erg/s

SNR could explain the origin of cosmic rays ($E < 10^{15}$ eV).

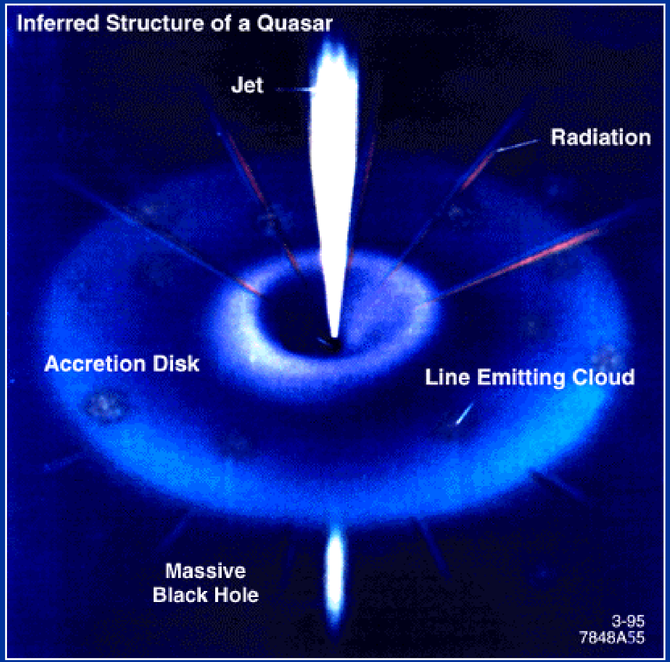
Active Galactic Nuclei (AGN)

3C273



Chandra

model



- BH accretion powers jets
- Shock acceleration in jets
- Relativistic electrons, protons

Emission mechanisms

Inv. Compton: $e\gamma \rightarrow e\gamma$

Decay: $\pi^o \rightarrow \gamma\gamma$

$\pi^+ \rightarrow \nu$

Beyond the Standard models

1. Using "particle beams" across interstellar space

- Absorption features in spectra of distant sources:
  - Absorption of HE γ-rays by pair-production.
    More on this later.
  - Cutoff of extragalactic cosmic rays by CMBR (GZK cutoff).

- Dispersion in time of flight of arrival particles:
  - Quantum gravity effects – energy dependent c -
    time dispersion of photons from distant source (AGN, GRB).
  - Dispersion in arrival time of neutrinos – ν mass limit.

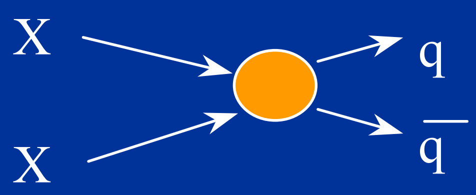
Beyond the Standard models

2. New Particles and Relics

- Supersymmtery:
  - Neutralinos at galactic center.
  - S^o – explain origin of UHECR.
- Primordial black holes $M \sim 10^{15}$ g
- Topological defects
  - Cosmic strings, domain walls $M_X \sim 10^{15}$ GeV.
- . . .

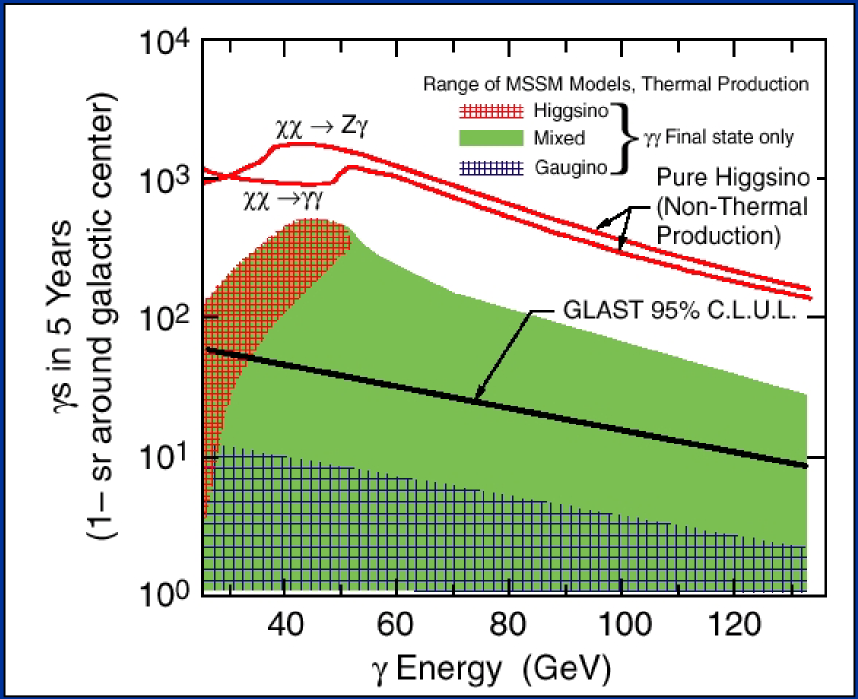
SUSY – Neutralino annihilation

Annihilation:



or $\gamma\gamma$, $Z\gamma$

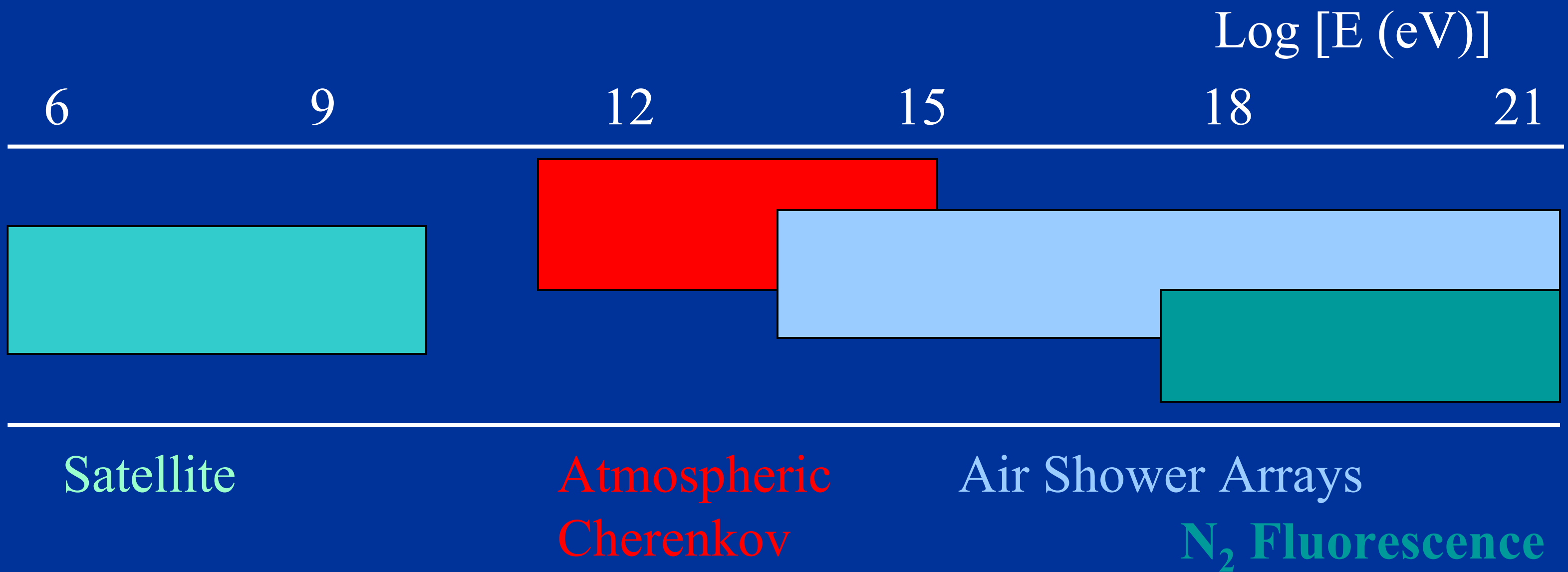
γ-ray detectors have sensitivity to neutralinos in the important energy range.



Annihilation at Galactic Center

Experimental Techniques

Wide energy range requires multiple techniques

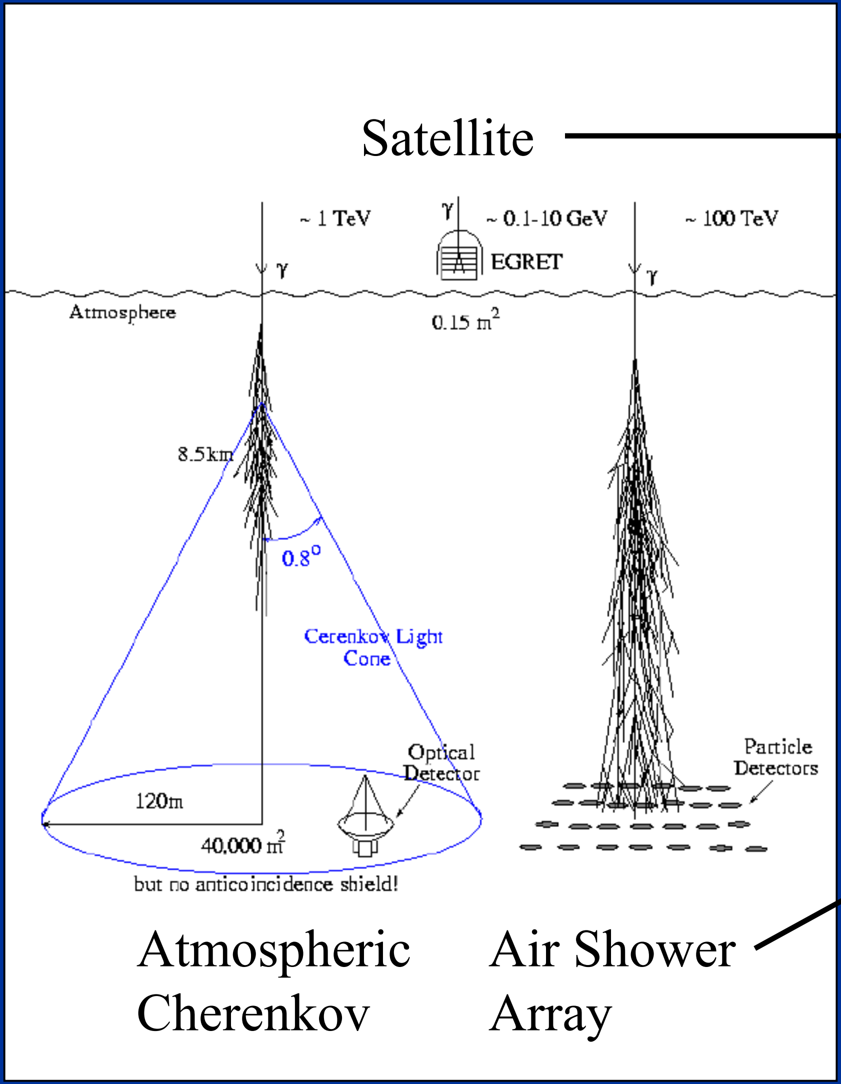


EGRET GLAST

STACEE WHIPPLE VERITAS

AGASA FLY'S EYE AUGER

Detecting HE Particles



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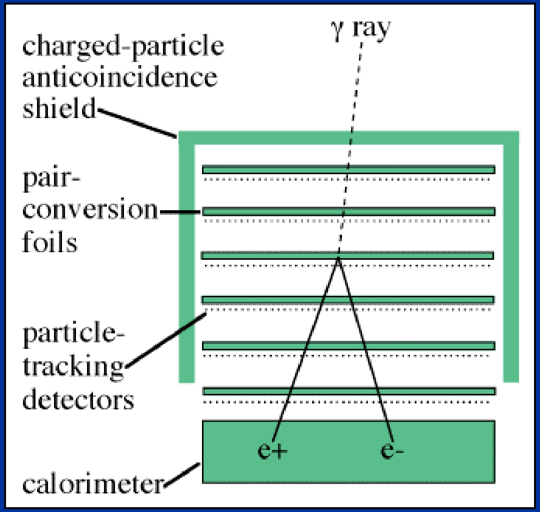
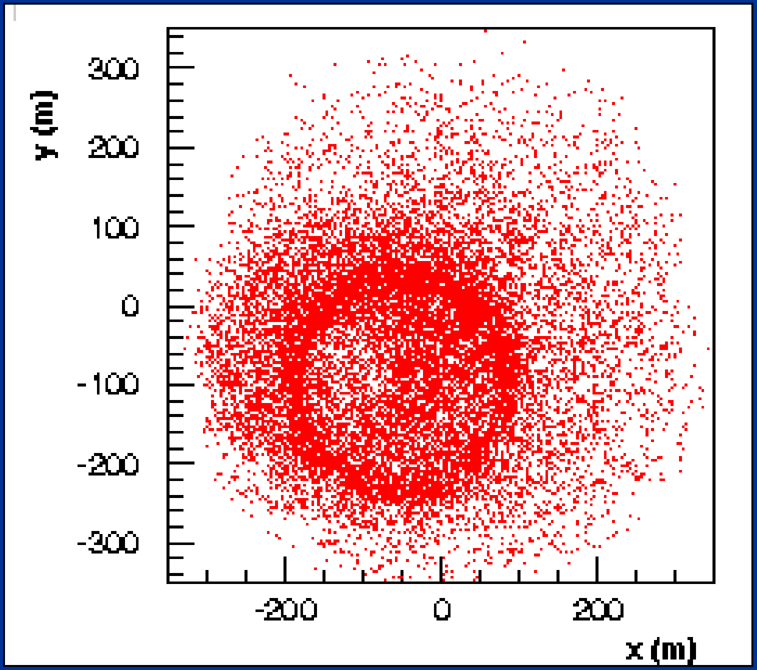


CASA-MIA (Dugway, UT)

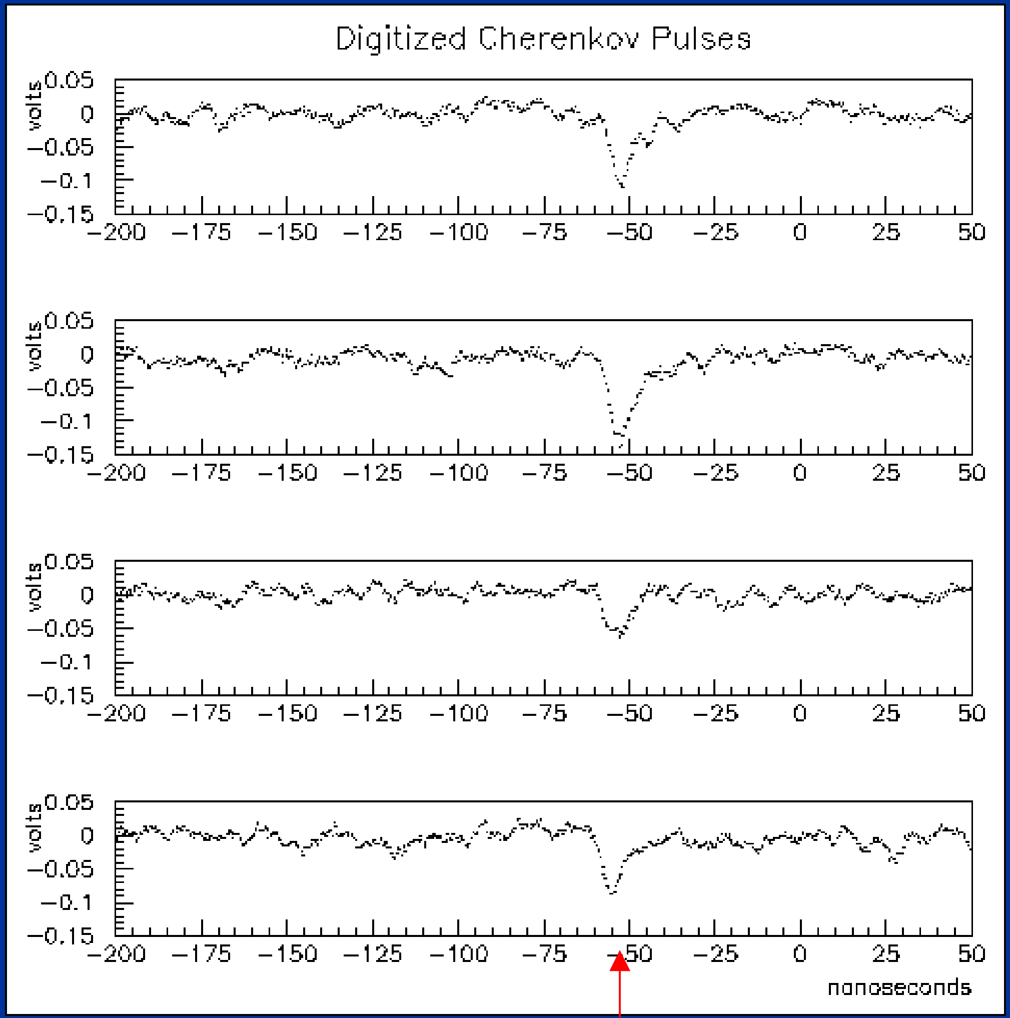
Atmospheric Cherenkov Technique



Cherenkov Light Pool

Whipple 10m Reflector
(Mt Hopkins, AZ)

Cherenkov Pulses



Pulse ~ 5 nsec

Recent Excitement

1. (Gamma-ray bursts)

2. Extragalactic sources of TeV photons
   - Detection of luminous "blazars"
   - 20-200 GeV "terra incognita"
   - Development of STACEE project

3. 10^{20} eV cosmic rays

Extragalactic TeV sources

1992 Detection of TeV photons from the active galaxy
Mrk 421 (z=0.031).
1994 First major variability detected by TeV telescopes.
1997 Dramatic flaring detected in second source
Mrk 501 (z=0.033).

1998 Additional sources detected.
to Multi-wavelength studies.
2001 Dramatic flaring of Mrk 421.

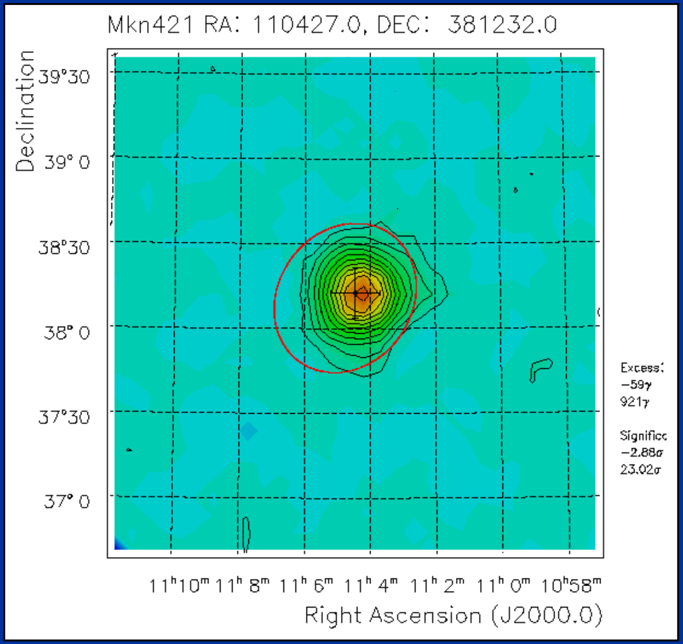
These powerful objects are fascinating and enigmatic !

“Blazars”

Blazars are a type of AGN with some key features:

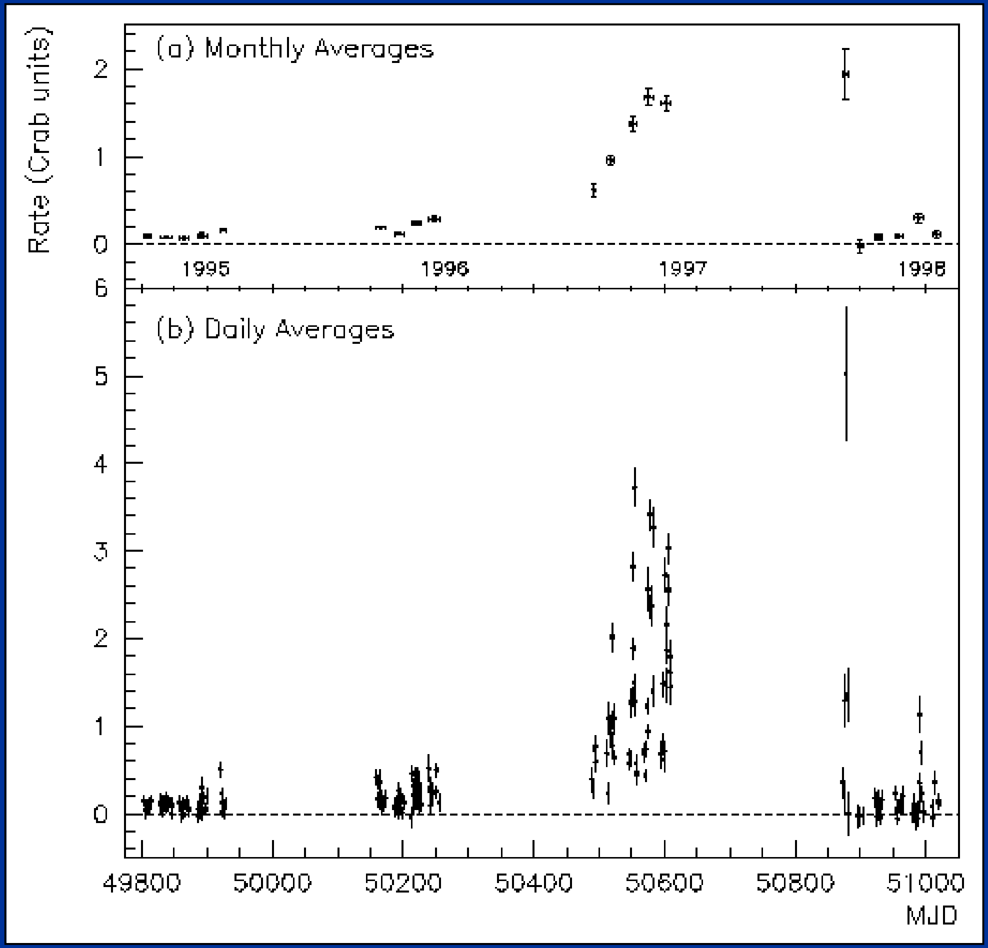
- Powerful, radio-loud
- Highly variable at all wavelengths
- Relativistic jets – superluminal
- Power peaks in X-rays, γ-rays

TeV image of Mrk 421



Whipple 23σ detection

Blazars – powerful, variable sources

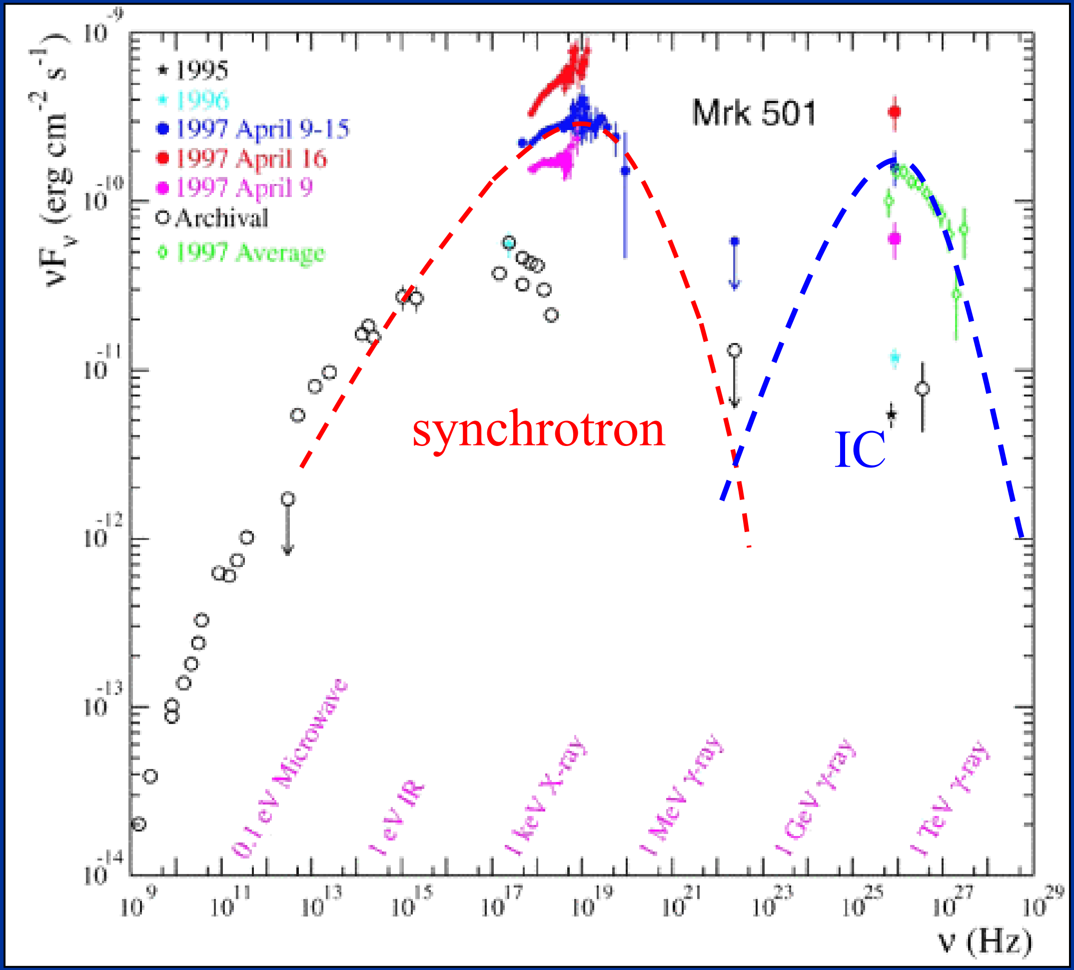


Whipple

Mrk 501

- Dramatic variability: time scales < 30 min.
- Large fluxes: 10^{11} TeV γ-rays / sec to earth.
- Energies > 10 TeV.

Blazar Energy Distribution

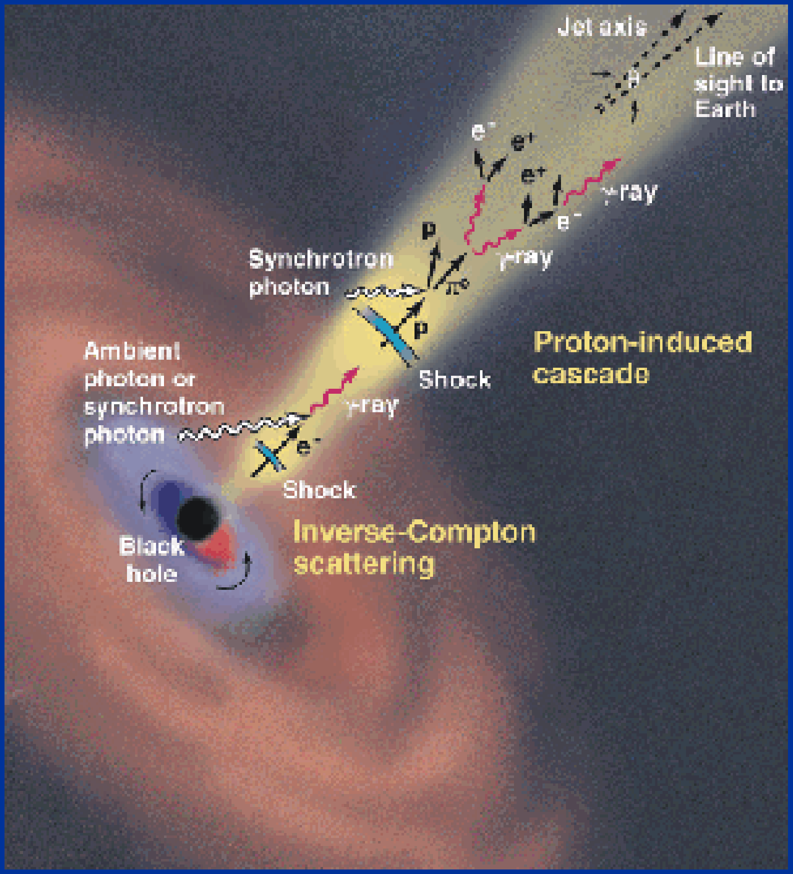


- Double peaked: power is at HE.
- X-rays & γ-rays highly correlated
- Model components:
  Synchrotron
  Inverse Compton

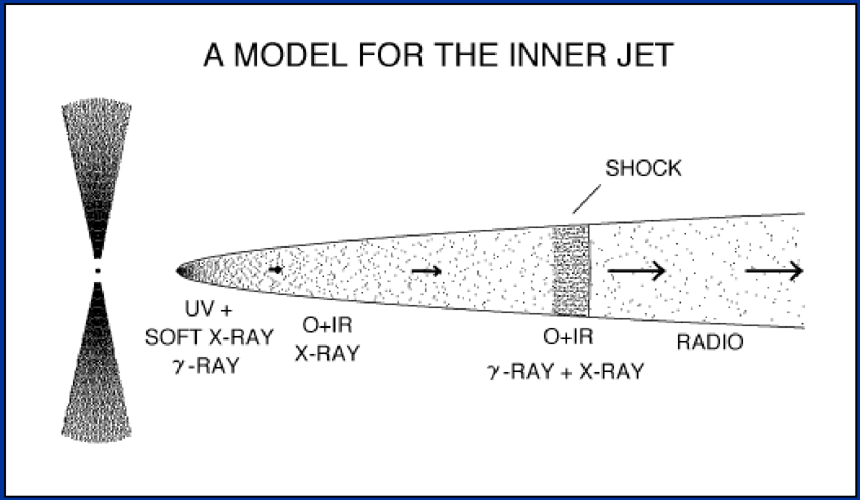
Key Questions about Blazars

- How do blazars really work?
  - must explain: fluxes, variability, correlations …
- Why don’t we see more of them at TeV energies?
  >70 sources at GeV, but only handful at TeV.
  Is absorption instrinsic or intergalactic ?
- Are blazars sources of UHECRs or ν ?

Blazar Dynamics



General picture



- Origin and properties of Jet
  - Doppler boost δ, geometry
- Nature of beam: e or p
- Source of IC photons
- Emission zones
- Magnetic and radiation fields
- . . .

The extragalactic background light

- Cosmic EBL produced by normal star formation and evolution

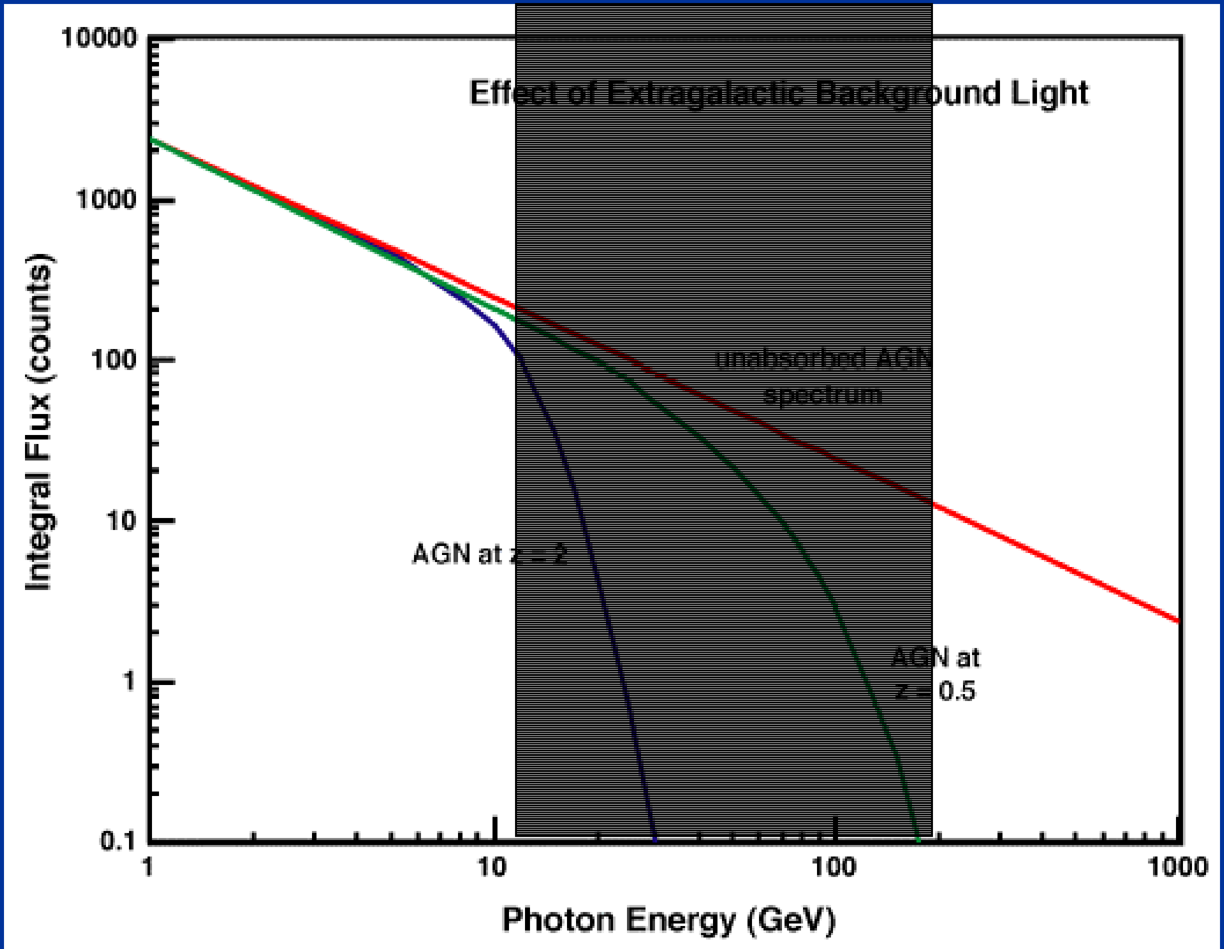
- HE γ-rays from AGN will interact with EBL via pair production: $\gamma\,\gamma \rightarrow e^+\, e^-$

- Can determine EBL density from optical depth:

$$\tau \sim n_{EBL}\, \sigma_{\gamma\gamma}\, D$$
$$\sim n_{EBL}\, \sigma_{\gamma\gamma} / H_o$$

n_{EBL} depends on early astrophysics and cosmology

EBL Absorption of γ-rays



20-200 GeV "Terra Incognita"

- Window 20-200 GeV not explored by any experiment:
  - Above range of satellite instruments.
  - Below range of Cherenkov telescopes.
- Energy threshold of Cherenkov telescopes is set S/N

  Can achieve a low threshold by using a <u>large mirror area.</u>

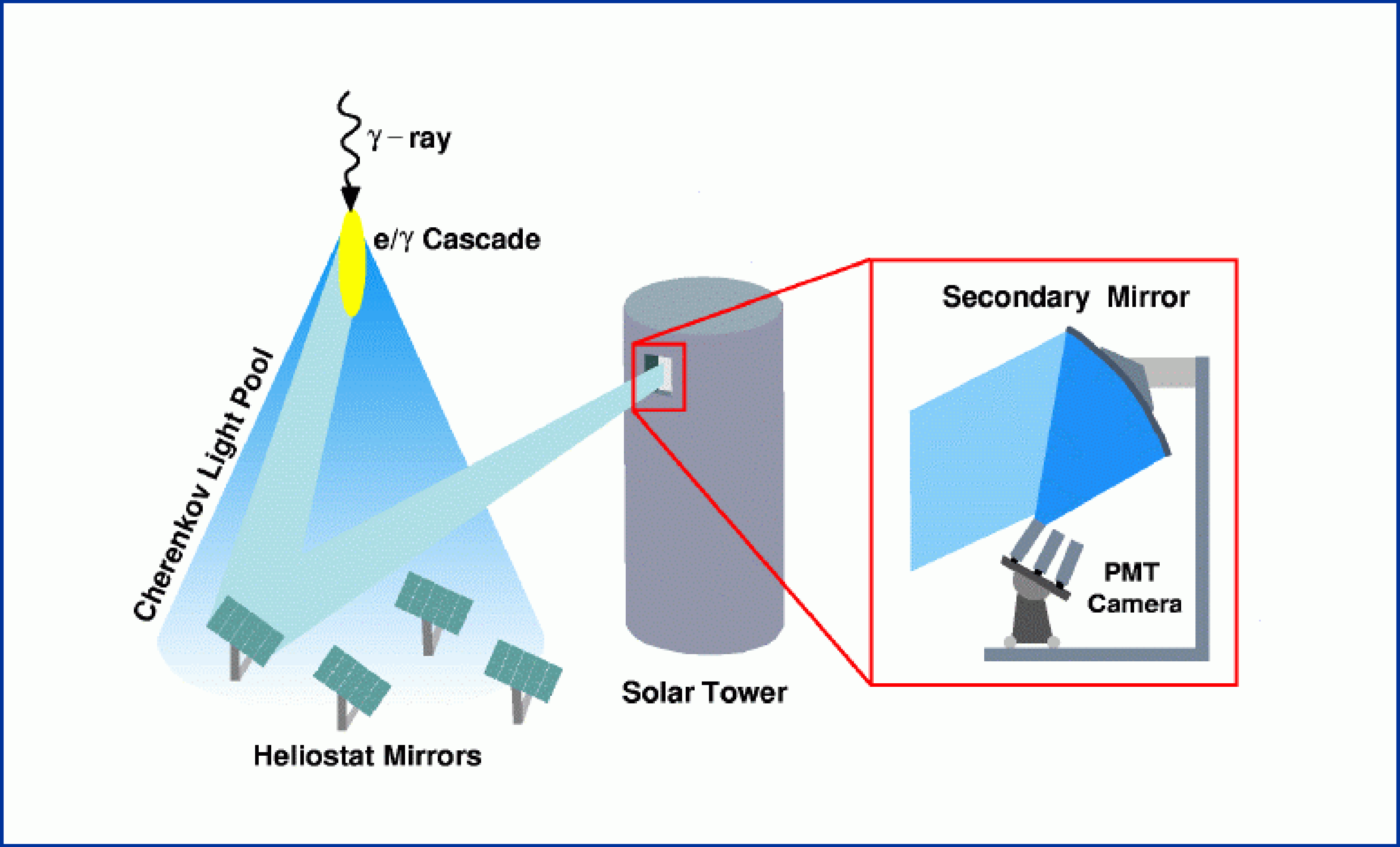
- Large mirrors exist at Solar research facilities (e.g. Sandia)

STACEE Project

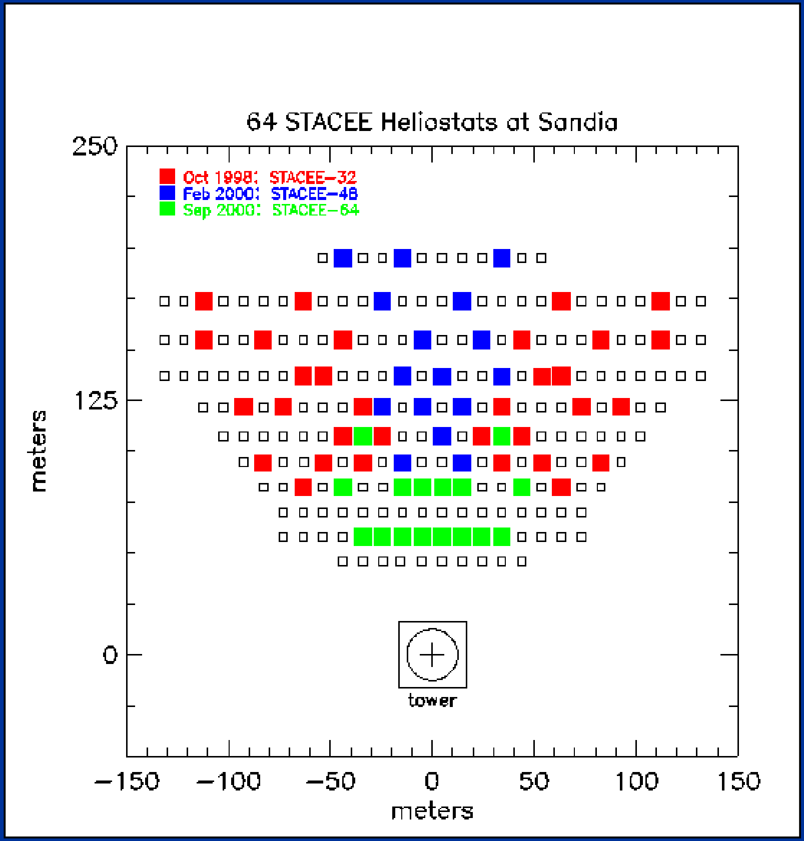
Solar Tower Atmospheric Cherenkov Effect Experiment

National Solar Thermal Test Facility
Sandia National Labs

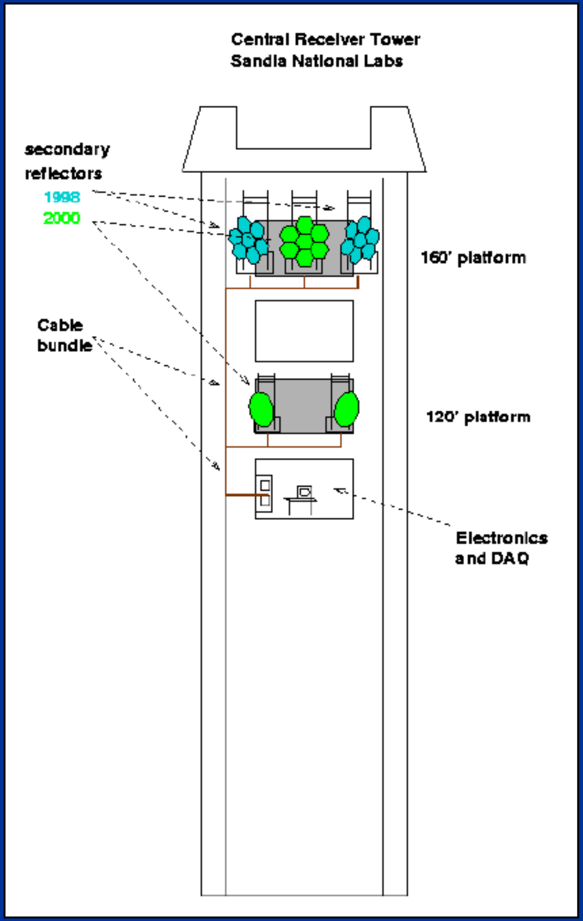
STACEE Concept



Primary and Secondary Mirrors



62 STACEE Heliostats
Total mirror area = 2,400 m^2

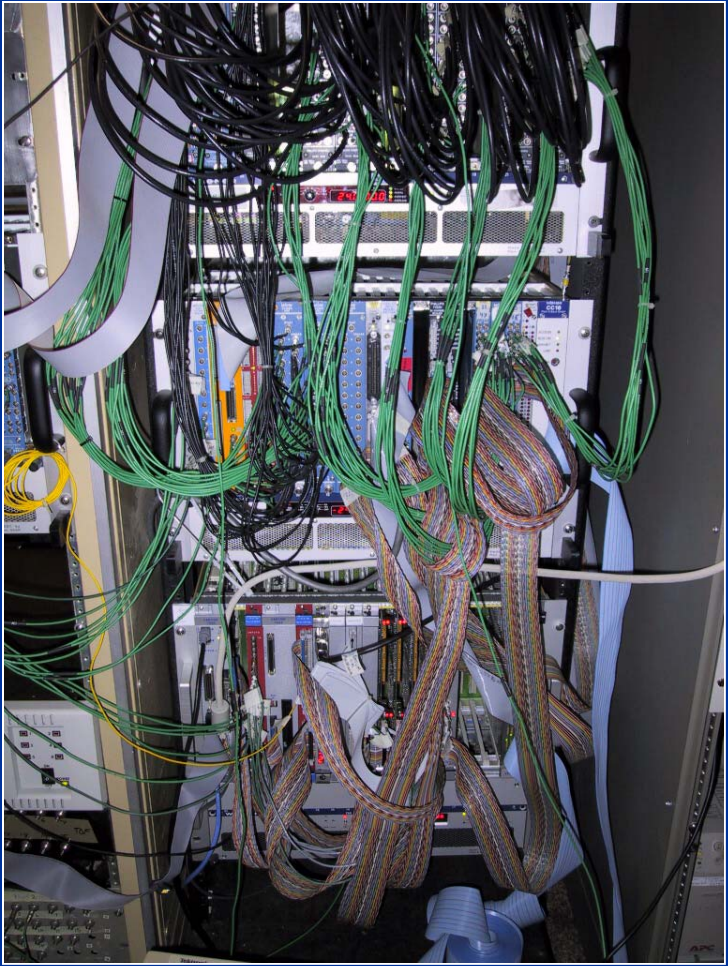


Secondary mirrors on Tower

Heliostat Field

Tower

Secondary mirror and camera



Electronics Trigger & FADCs

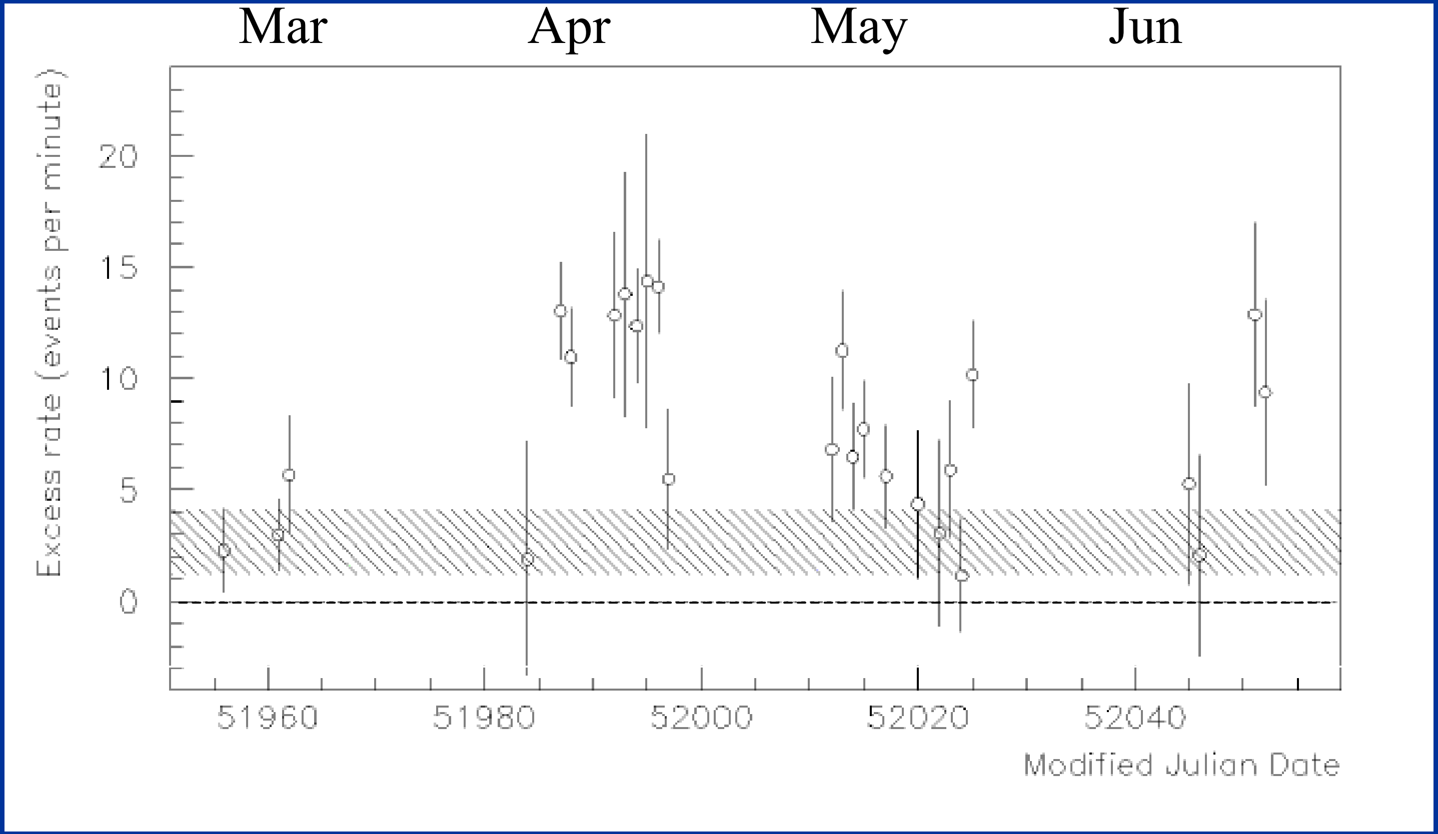
STACEE Timeline

1997	Start construction		
1999	32-heliostats	E= 190 GeV	Detect Crab Nebula 7σ
2001	48-heliostats	E= 110 GeV	Detect Mrk 421 flares ~ 15σ
	64-heliostats	E=80 GeV	Operational

Collaboration:

Alberta:	D. Gingrich
U. California:	L. Boone, J. Carson, R. Ong, D. Williams, J. Wong, J. Zweerink
Case Western:	C. Covault, J. Hinton, R. Scalzo
Columbia:	D. Bramel, R. Mukherjee
McGill U:	P. Fortin, D. Hanna, C. Mueller, K. Ragan

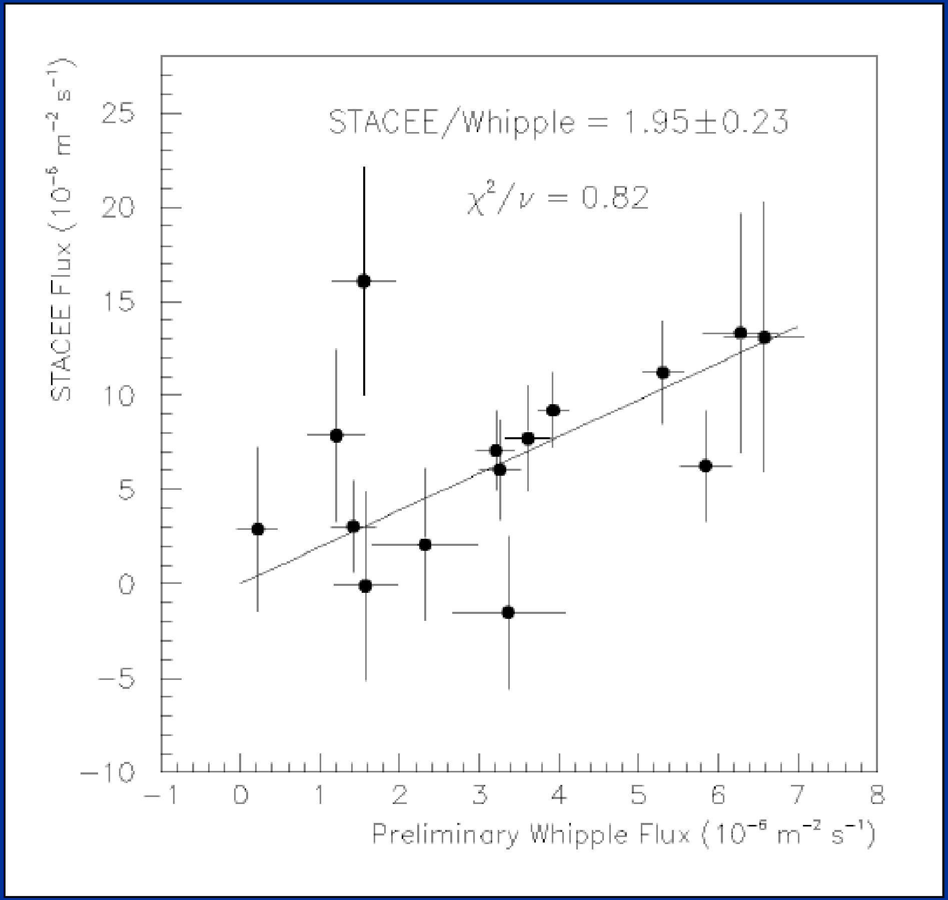
Mrk 421 Light Curve (2001)



STACEE-48 E=110 GeV

Comparison with Whipple

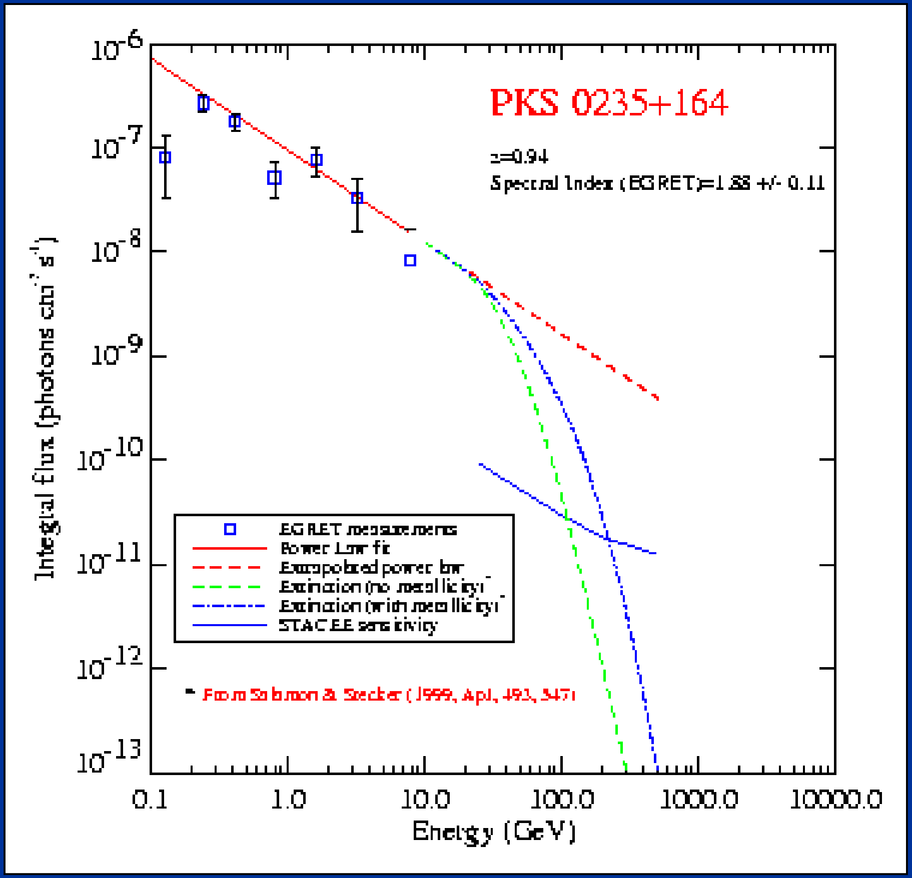
STACEE Flux



Whipple Flux

- Correlated fluxes
- STACEE ~ 2 times Whipple in flux

Projected Sensitivity



Spectra from distant AGN (z=0.94)

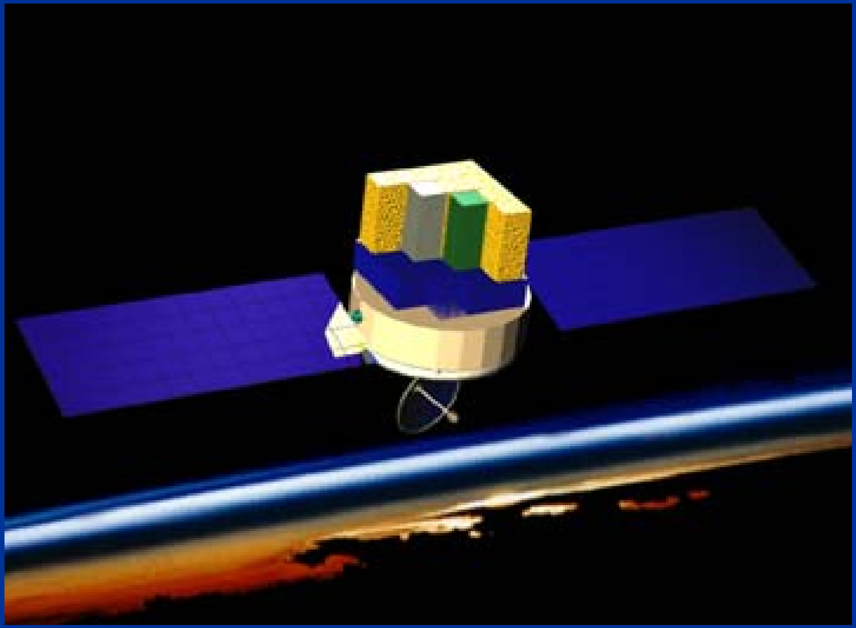
Future: γ-rays

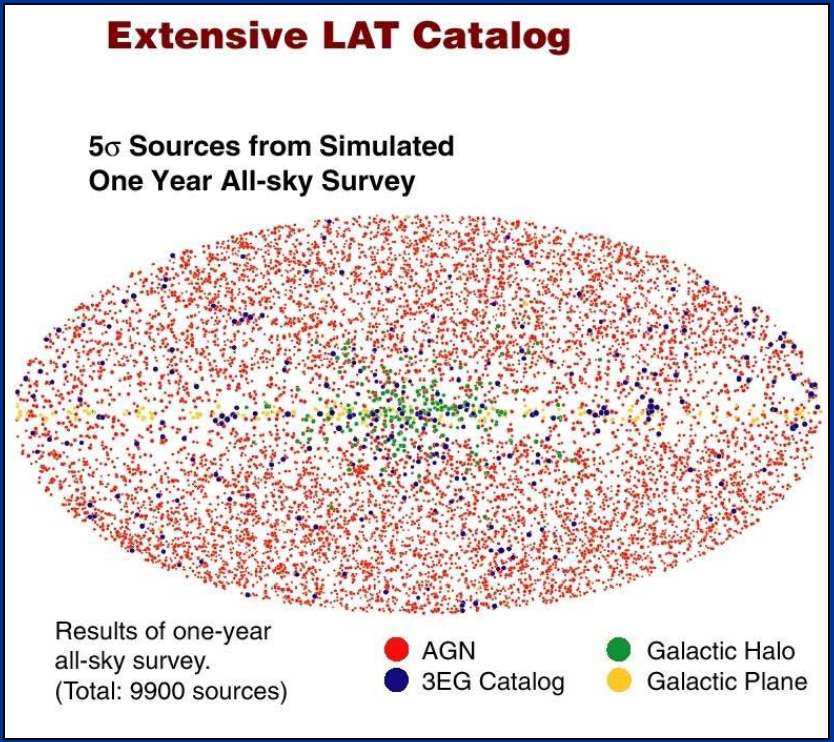
- New generation of telescopes
  space: SWIFT, GLAST
  ground: Cherenkov Tel. Arrays –VERITAS

- Big gains in:
  - Source sensitivity (10 mCrab)
  - Angular and energy resolution
  - Energy coverage

- Expect number of HE sources to increase substantially.

GLAST





GLAST Instrument:

- Si tracker
- CsI calorimeter
- Anti-coincidence veto

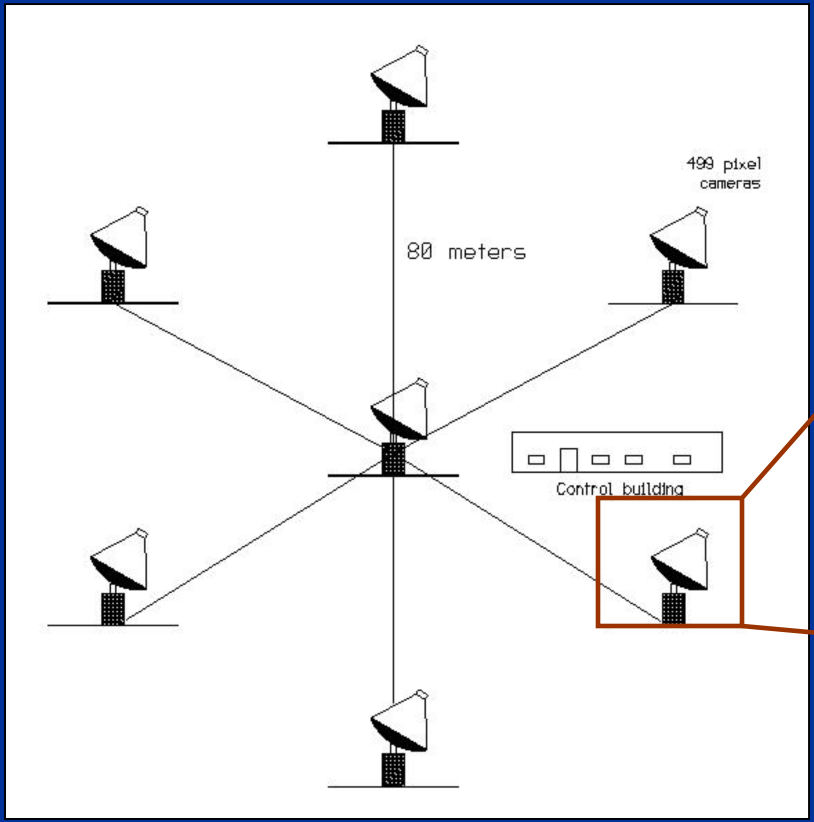
Sky map from 1 year survey

Launch in 2006.

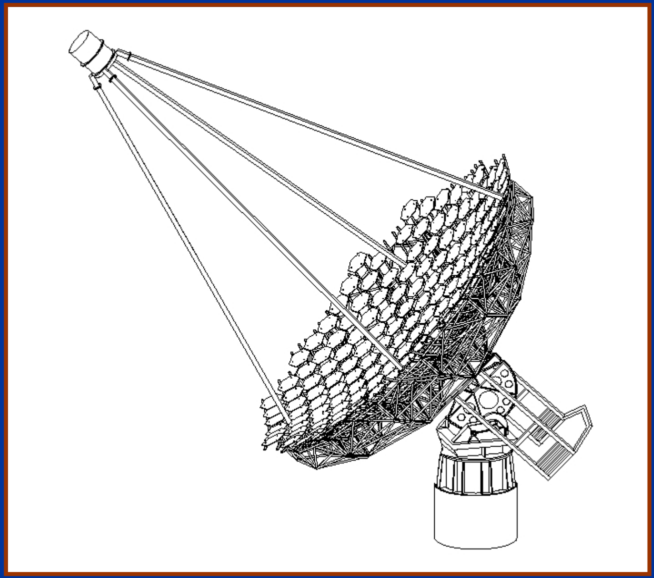
VERITAS

Mt. Hopkins, AZ

VERITAS - Design

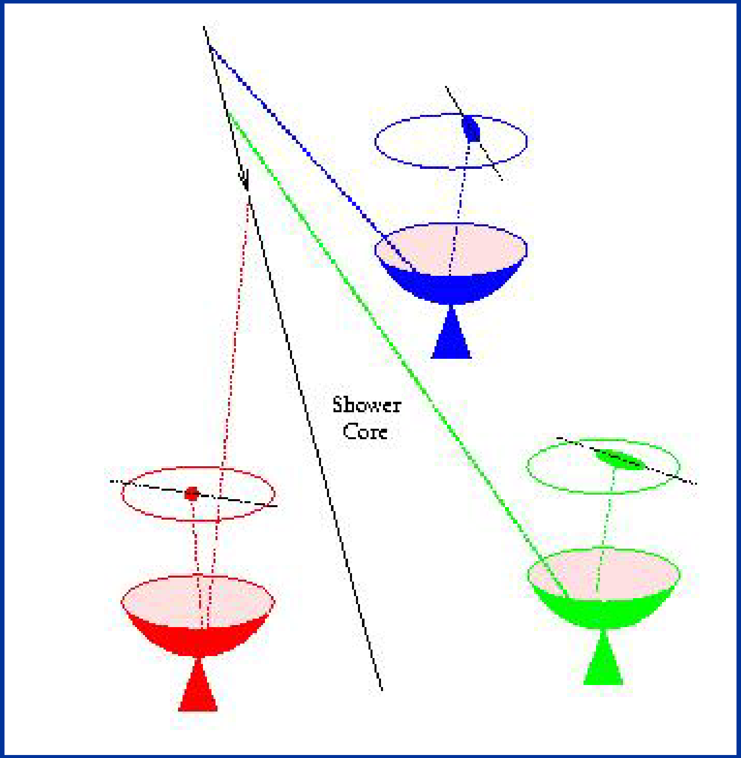


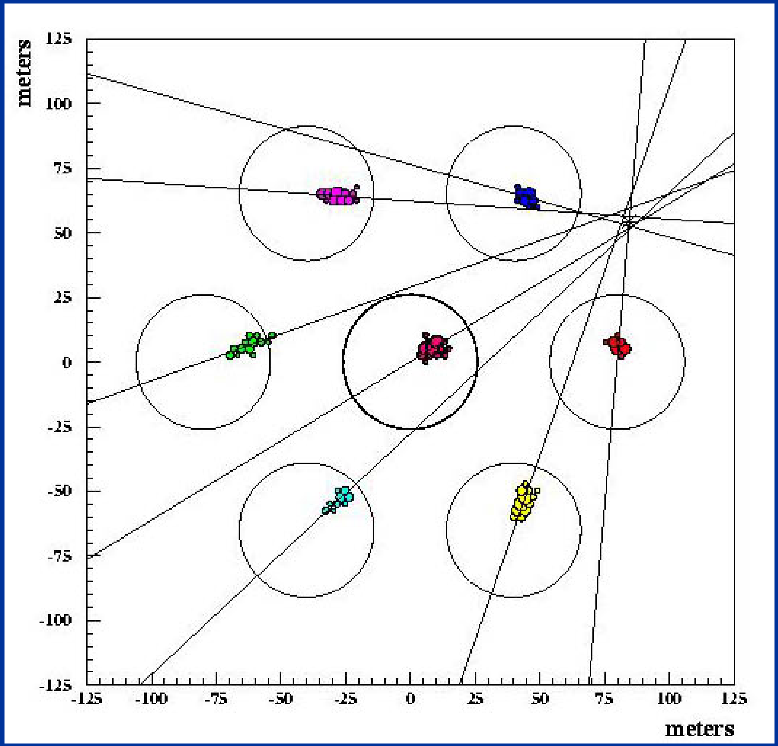
Telescope Array



Updated design f 1.2

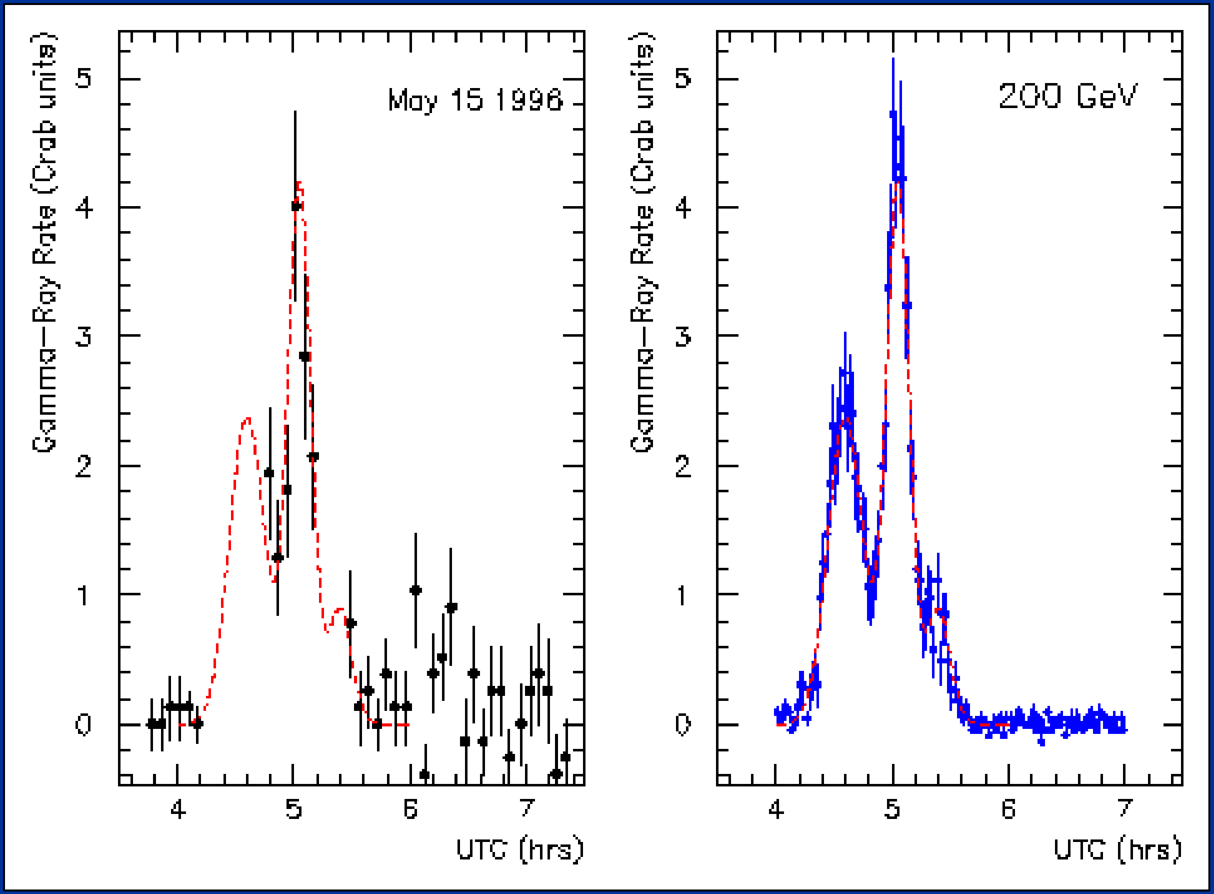
VERITAS - Reconstruction





- Stereo reconstruction
- Excellent angular and energy resolution

AGN Sensitivity



Whipple VERITAS (2004)

Summary

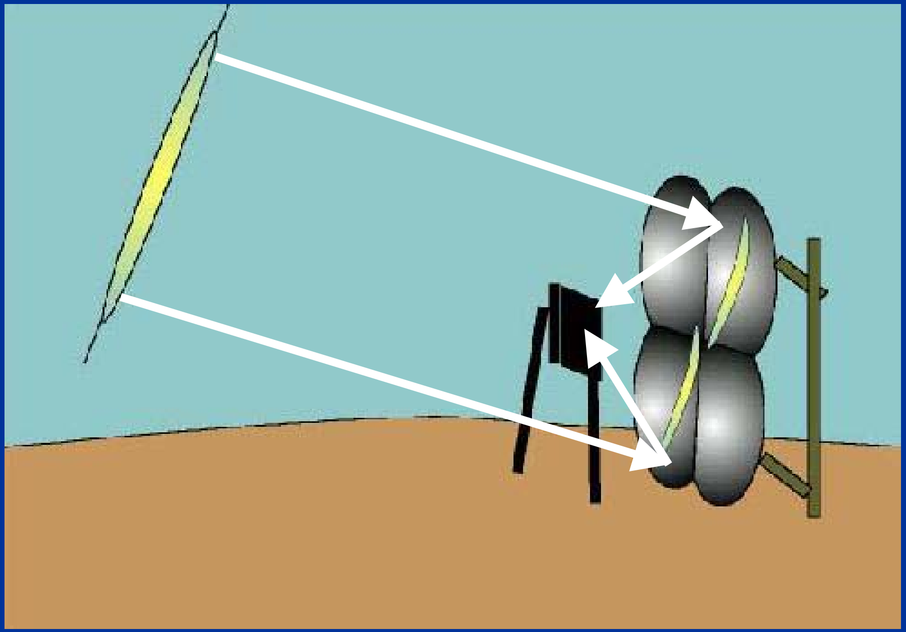
- High energy particle astrophysics is an emerging, exciting area.
- Research is experimentally driven – probing limits of known astrophysics and possibly beyond standard models.
- For γ-rays: GRBs and AGN are the most powerful astrophysical objects known.

  STACEE – project to explore region 20-200 GeV.
- For cosmic rays: future experiments will resolve a very compelling problem.

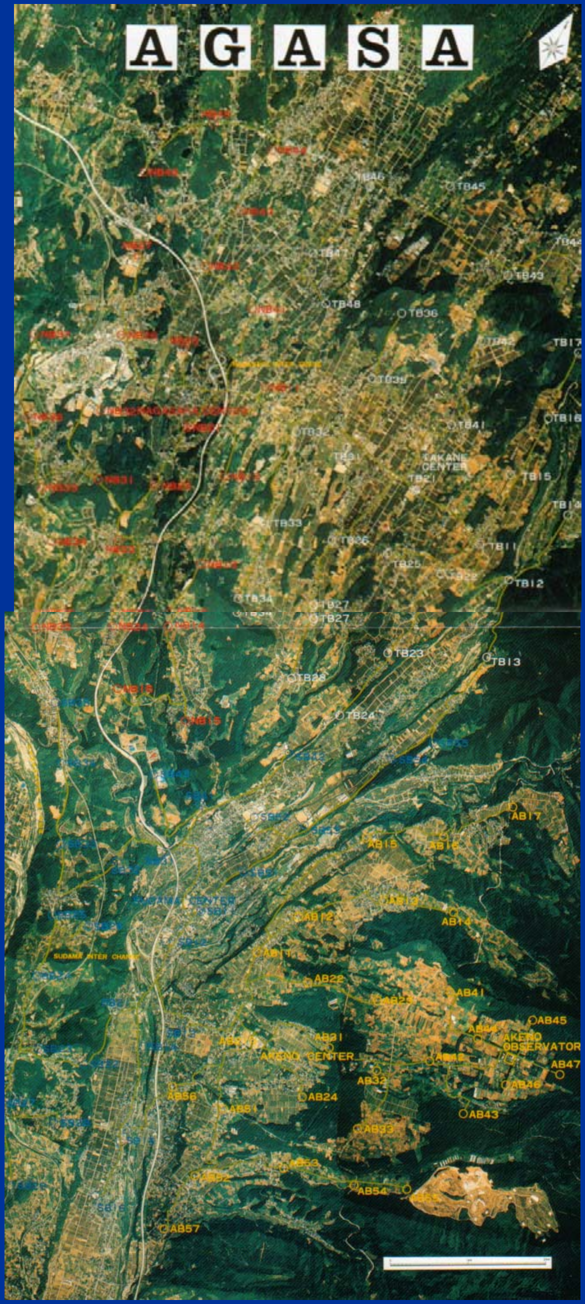
UHECRs

UHECR Detectors - Fly's Eye

HiRes mirror sheds
Dugway, UT



Nitrogen fluorescence technique

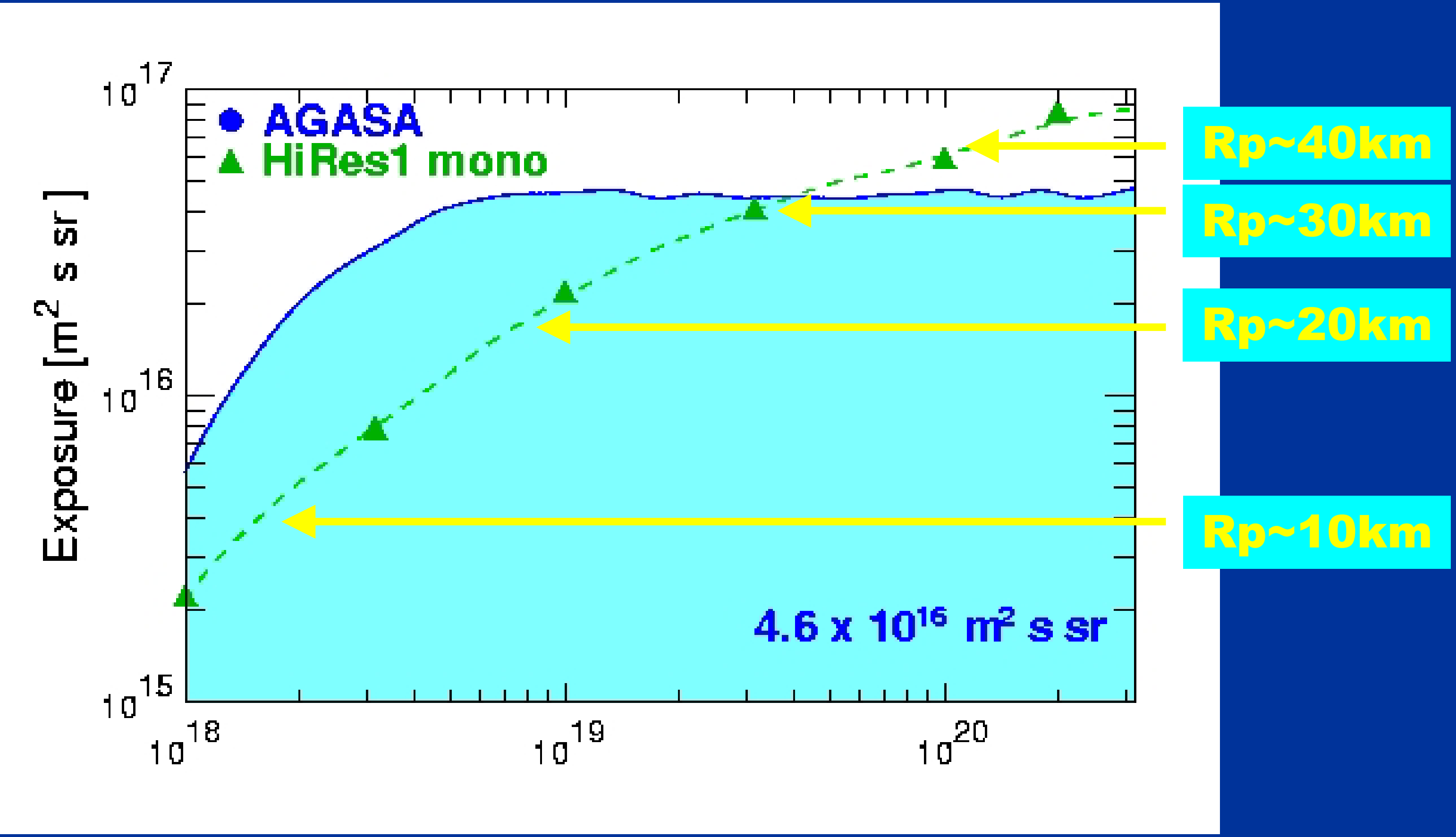


UHECR Detectors - AGASA

- 100 km^2 surface array
- Honshu, Japan

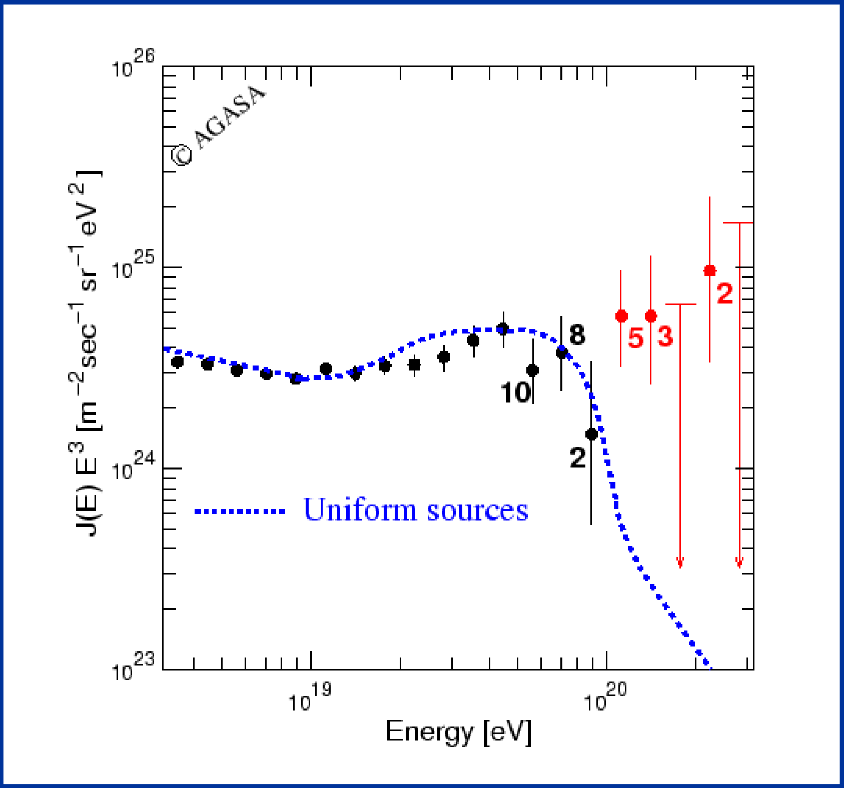
Charged particle detectors

Comparison of Aperture

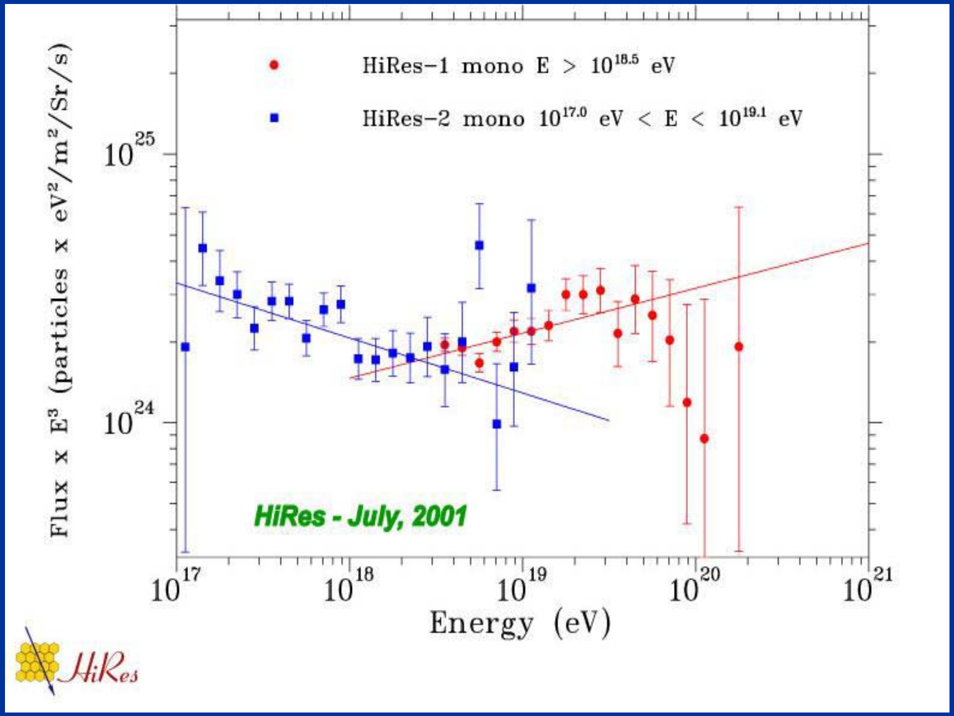


- Possible systematic errors ?

Ultrahigh Energy Spectrum



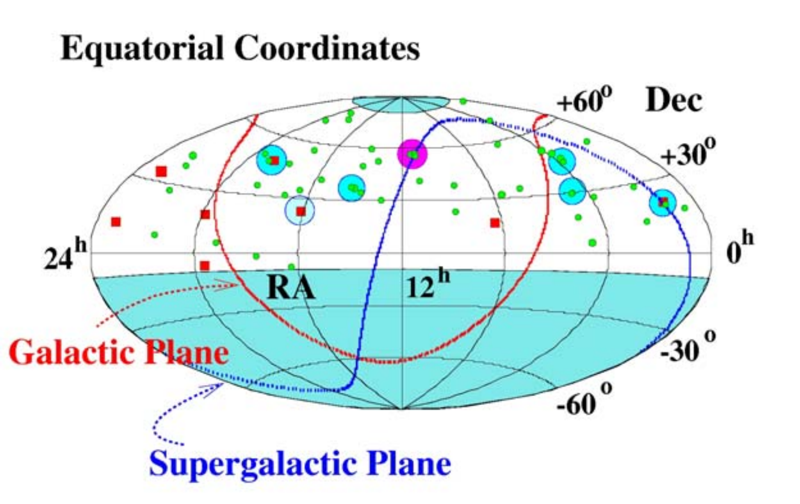
AGASA
9 yrs of data



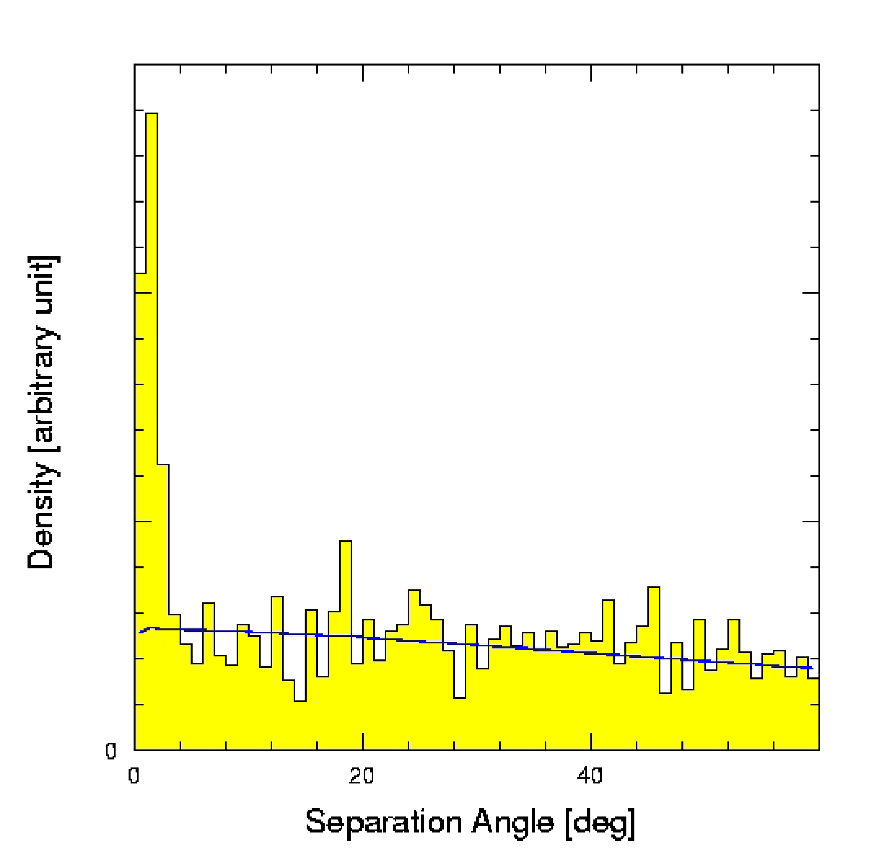
Fly's Eye HiRes
4 yrs of mono data

Similar exposure – much different flux above 6 x 10^{19} eV.

Directional correlations (AGASA)



Sky map



Angular correlation
~ 5σ effect

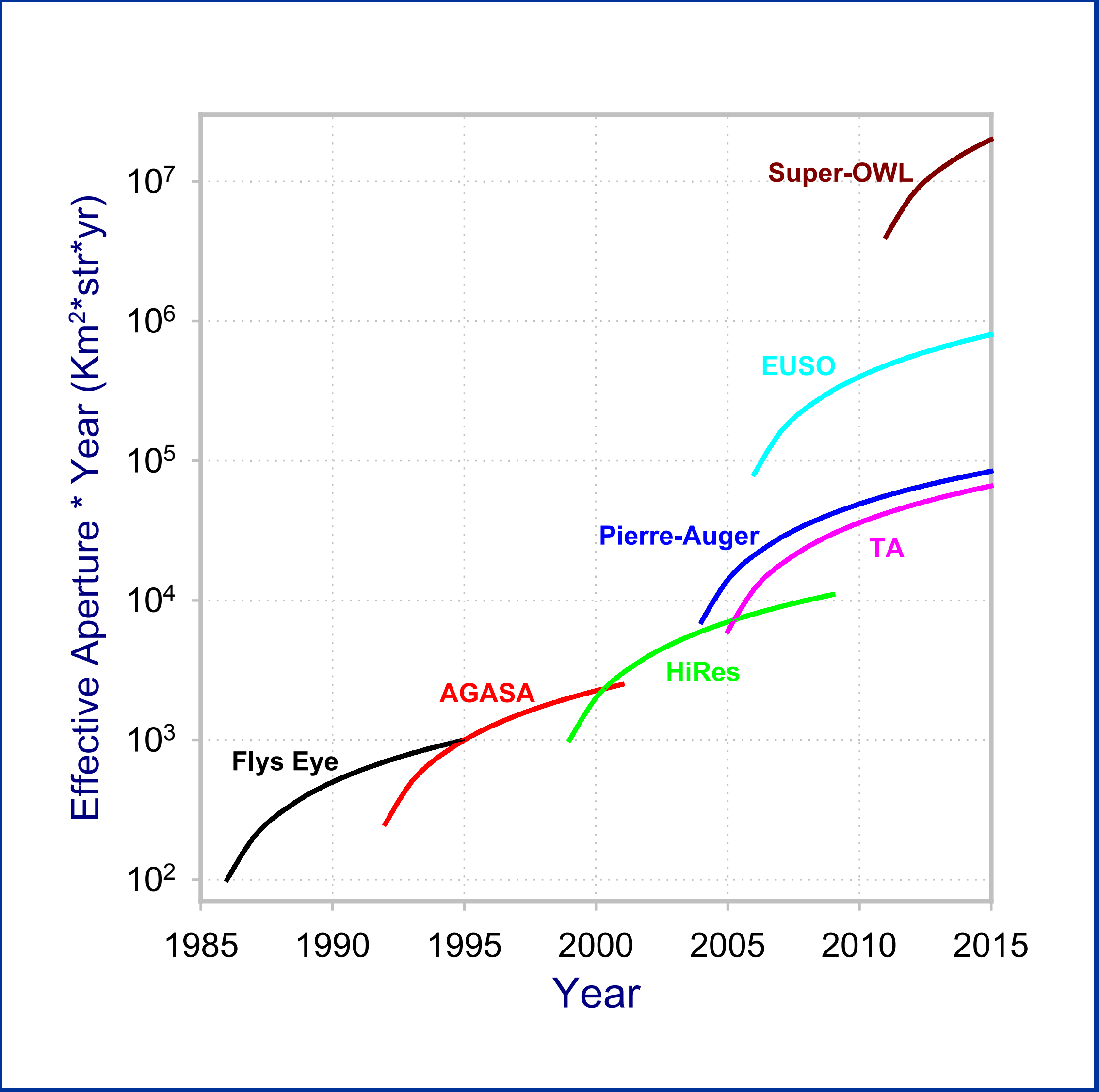
UHECR Questions

- Do Super-GZK events really exist?
  - discrepancy between AGASA and Fly's Eye.
- Do the events cluster on the sky?
  - evidence from AGASA suggests this.
  - astrophysical sources.
- What is the composition of the events?
  - contradictory information from the experiments.

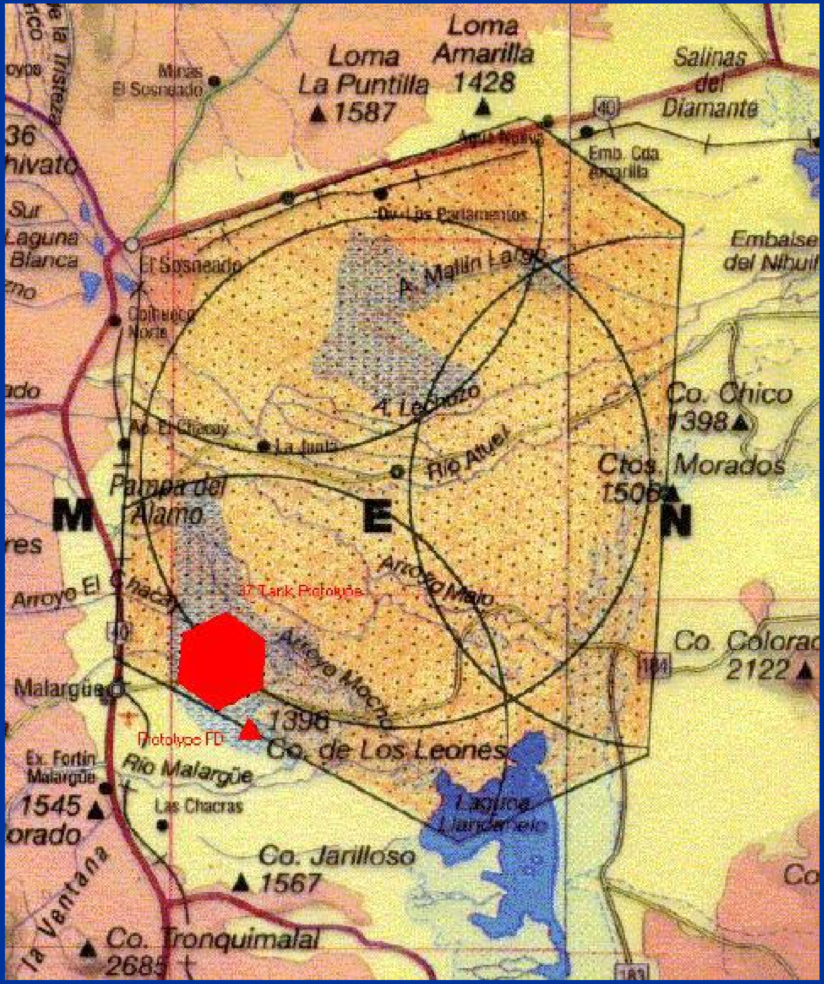
Clearly need a new generation of more powerful experiments!

Future: UHECRs

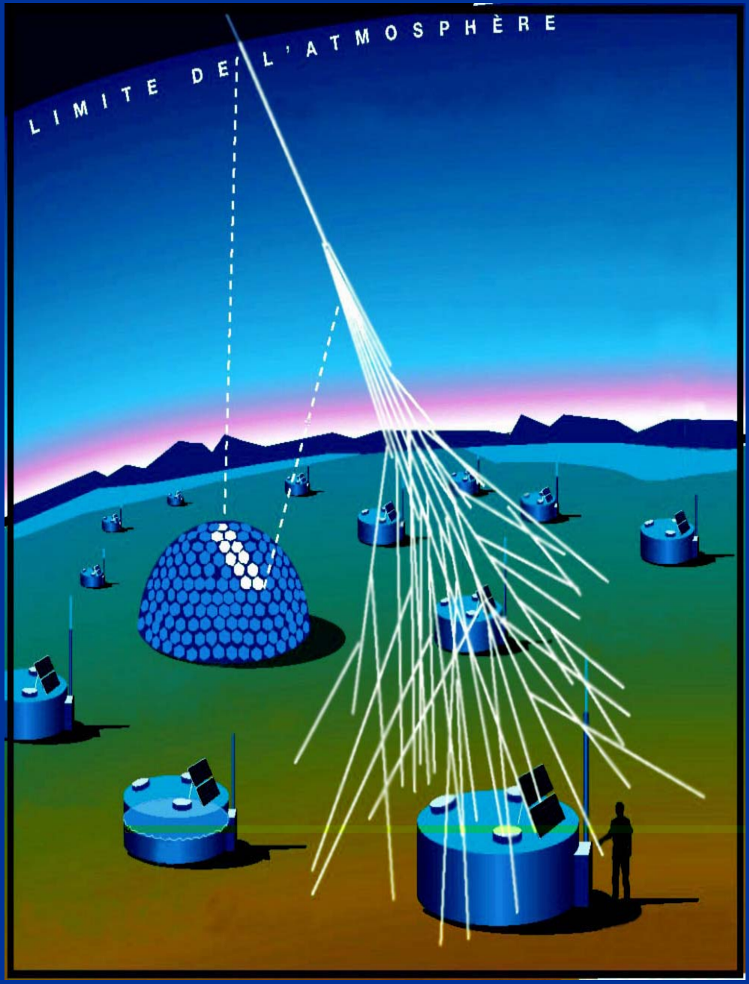
Aperture . . .



Pierre Auger Project

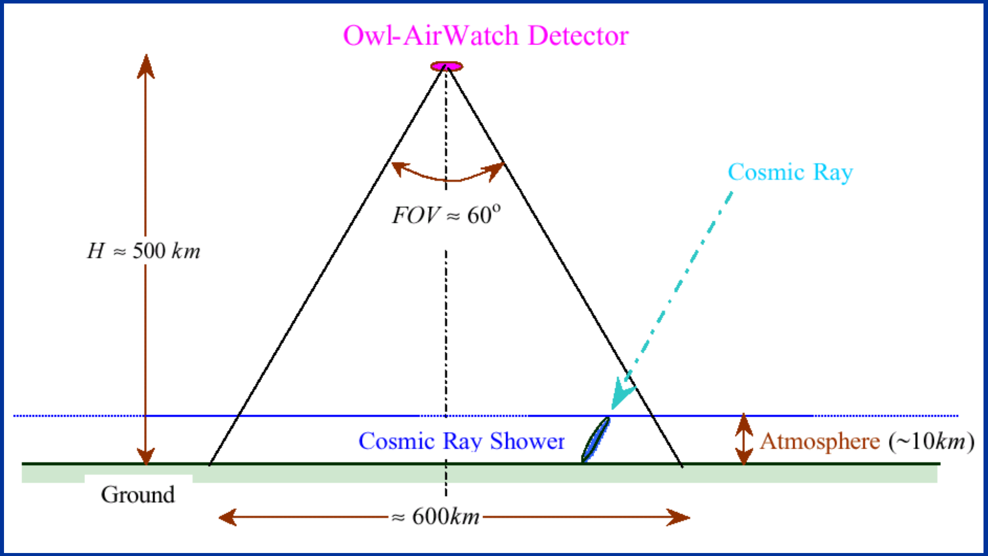


Mendoza, Argentina

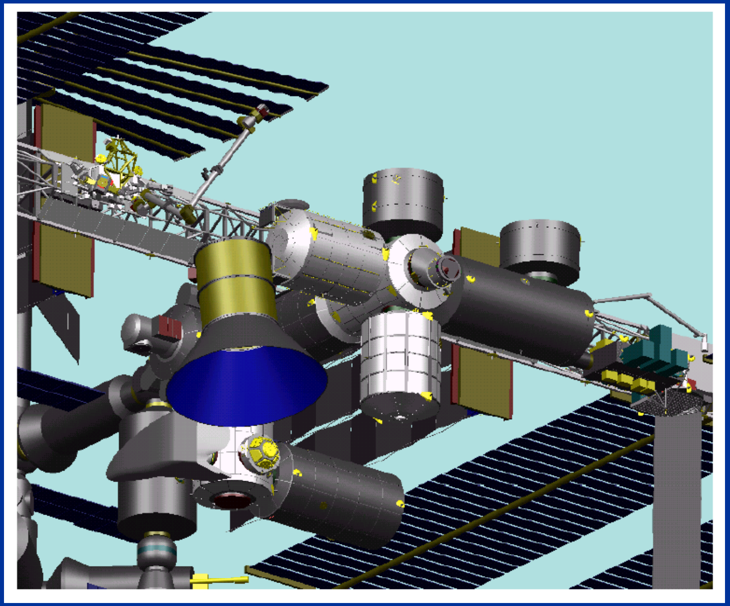


Hybrid Array

UHECRs from Space



General concept

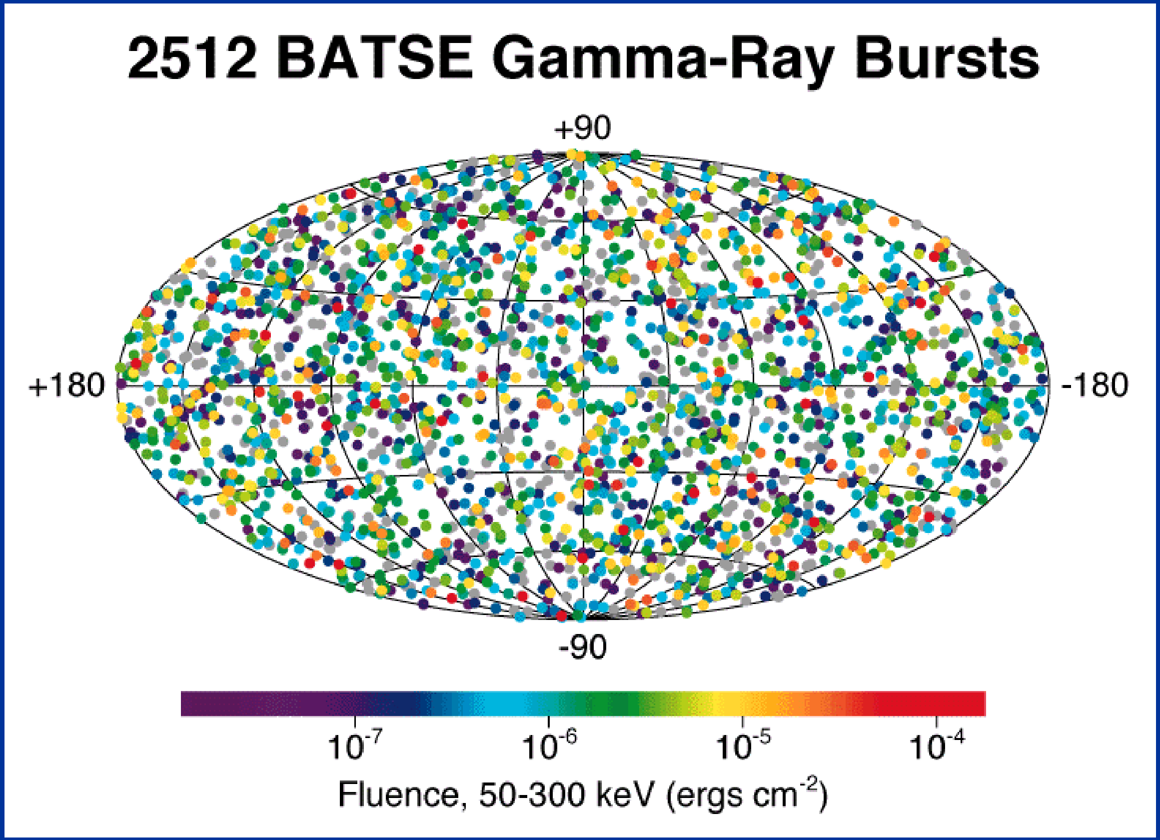


EUSO on ISS

Gamma Ray Bursts

Gamma Ray Bursts

30 Year Old Mystery !



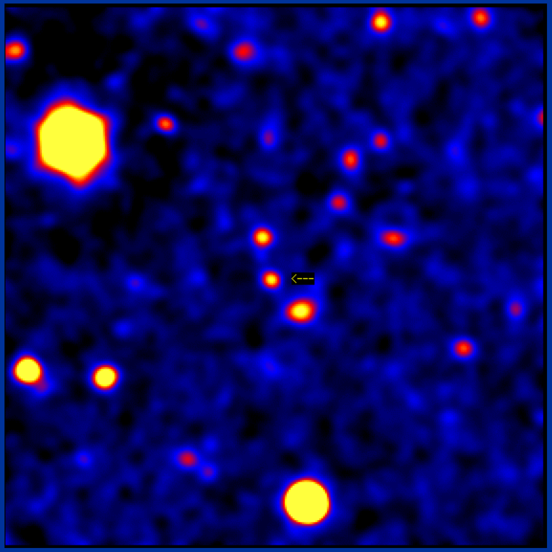
BATSE ~ 1 GRB/day

ISOTROPC

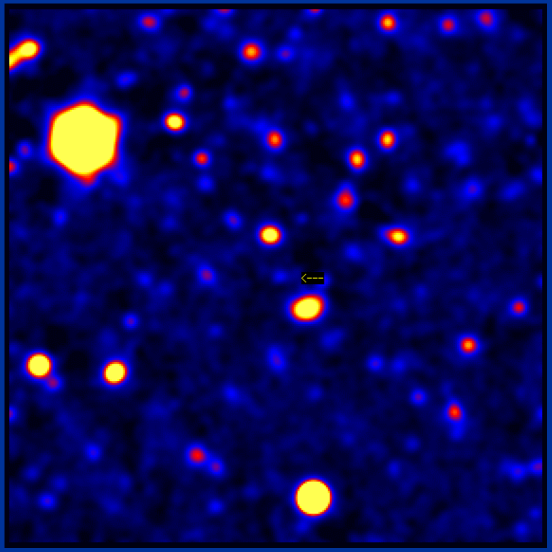
GRB Counterparts

1997 Major Breakthrough
BEPPO/SAX provides accurate positions
Redshifts for dozens of afterglows determined

Before



After

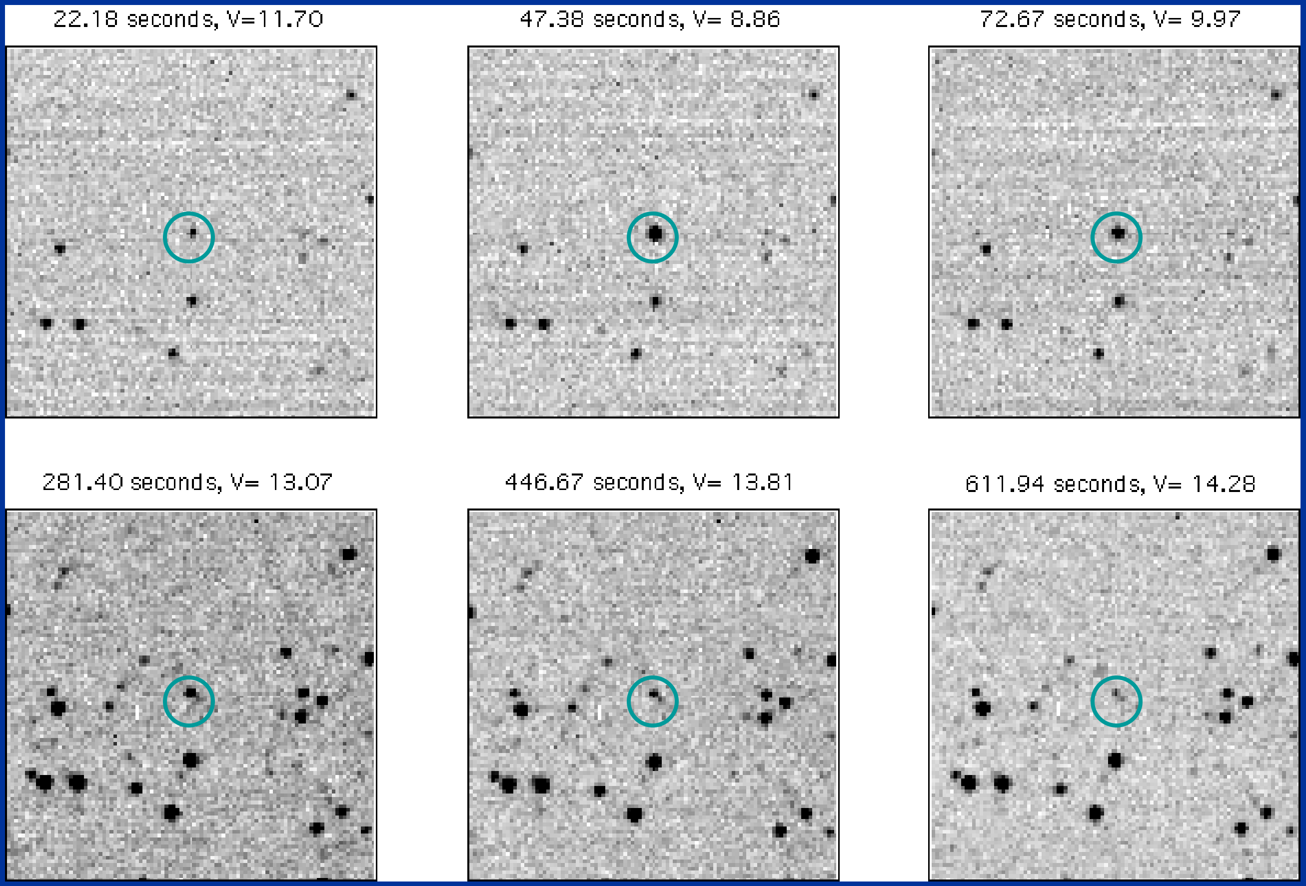


Keck
GRB 981214
Z= 3.412

"Afterglow"

GRB 990123

Detection of GRB in process !



ROTSE

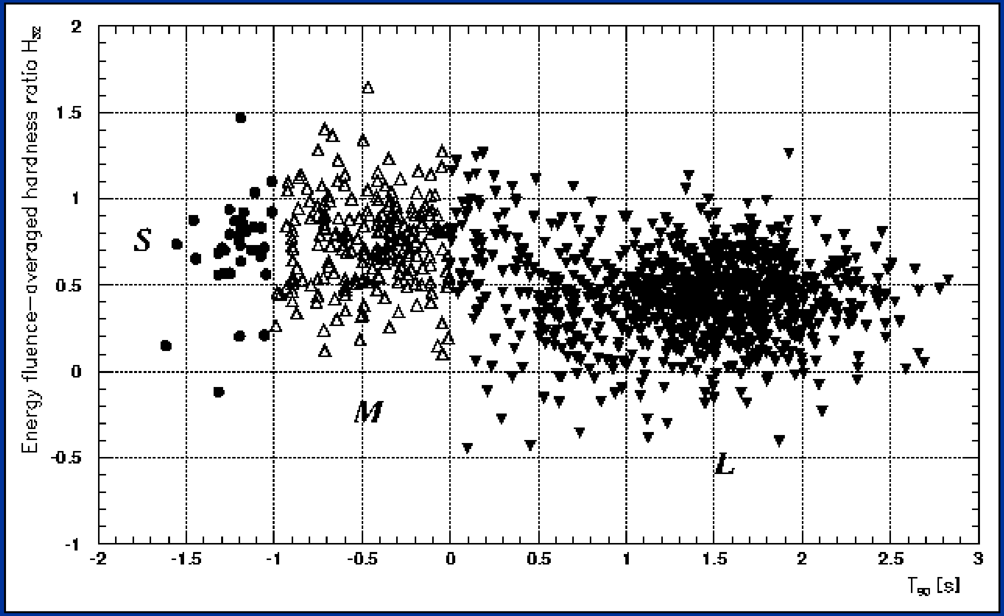
GRB 990123
Z= 1.600
Mag = 8.95

Energy released
$\sim 10^{54}$ ergs
(isotropy)

GRB Enigmas

- Mechanisms not fully understood – "fireball" models
  - Hypernova – "collapsars"
  - NS-NS collisions
- Types of GRB not understood

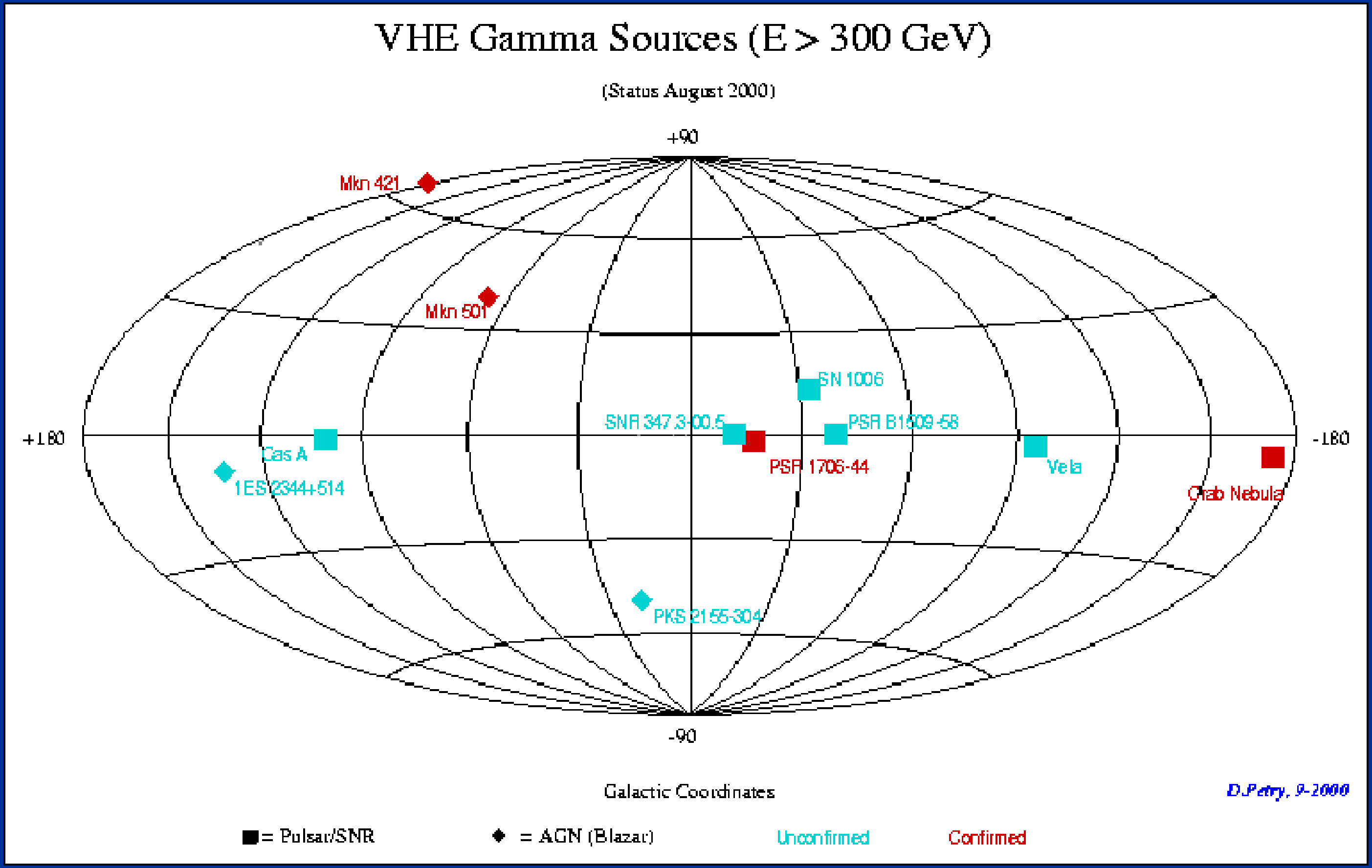
Counterparts detected for long, energetic bursts



Short bursts may have different origin!

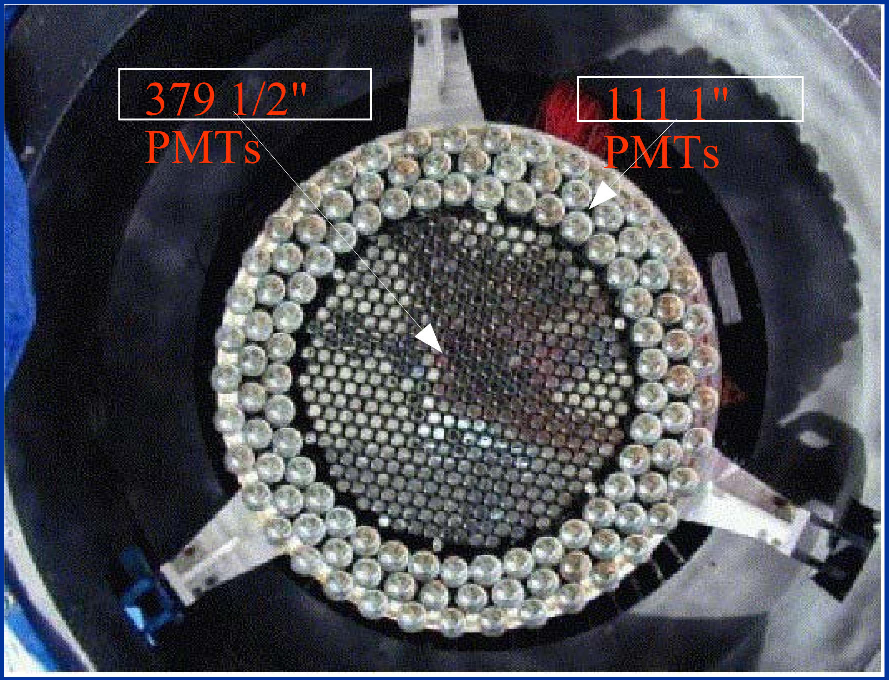
Other Slides

TeV Sky Map

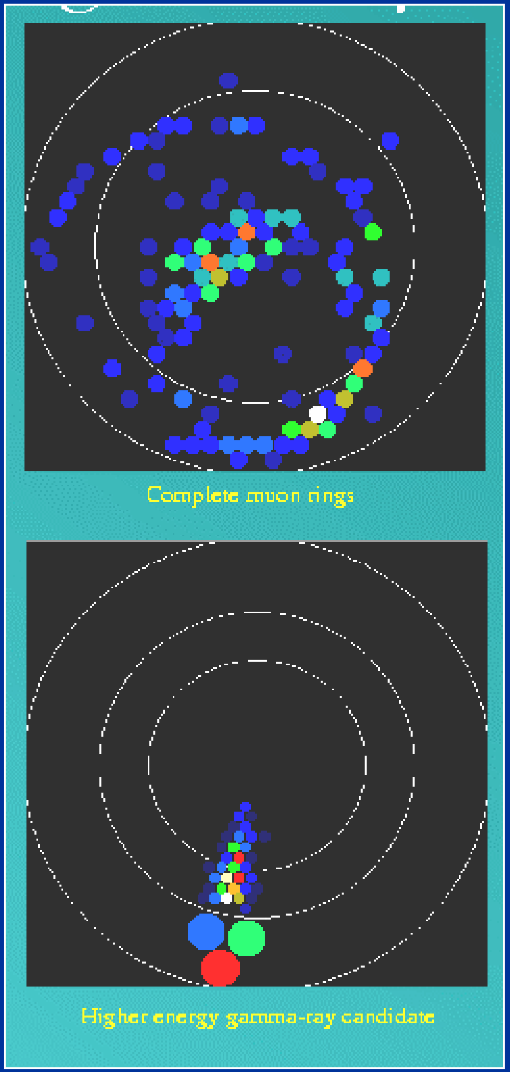


~ dozen sources

Cherenkov Camera



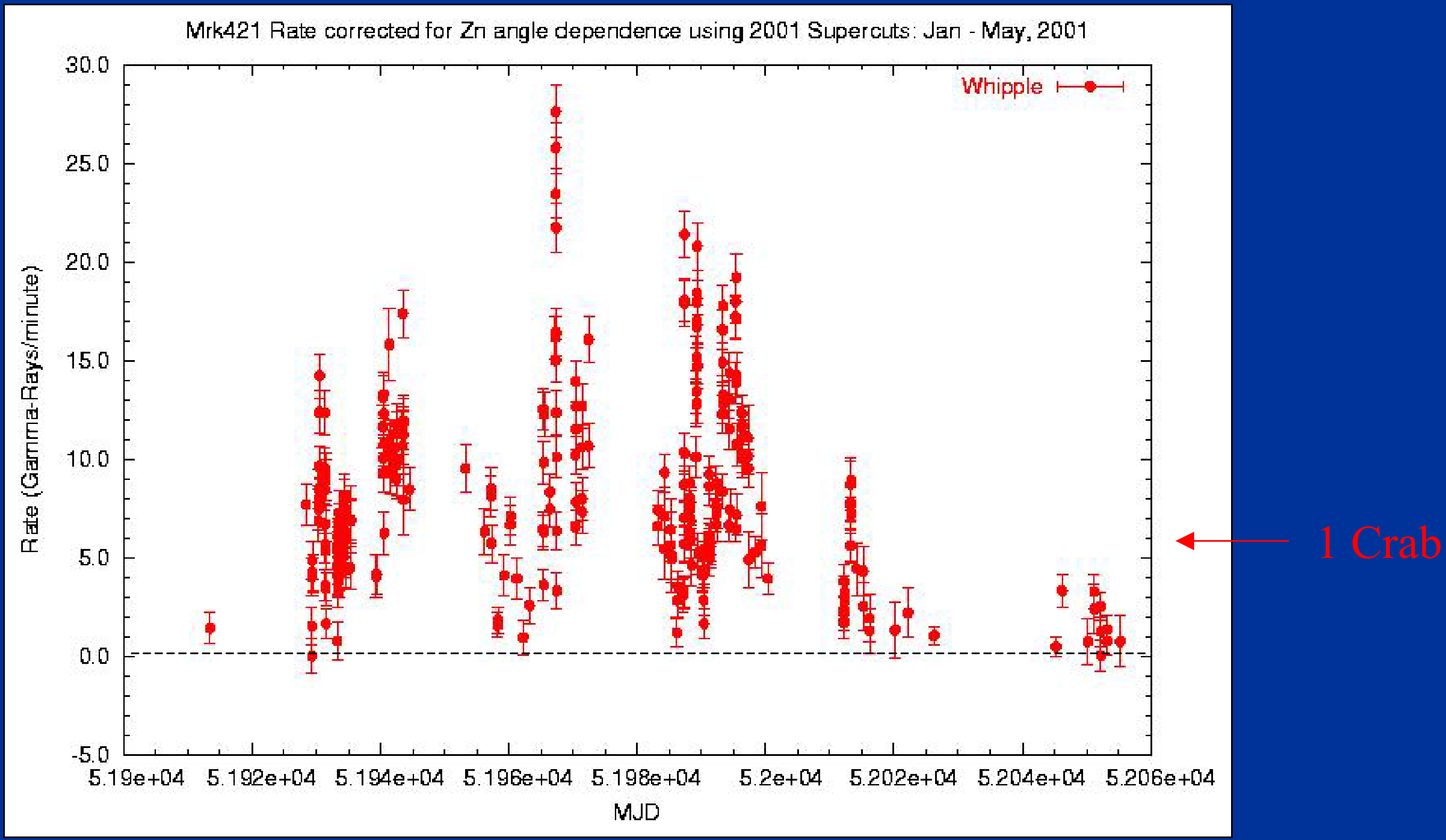
Imaging PMT Camera
500 Elements



Proton
Primary

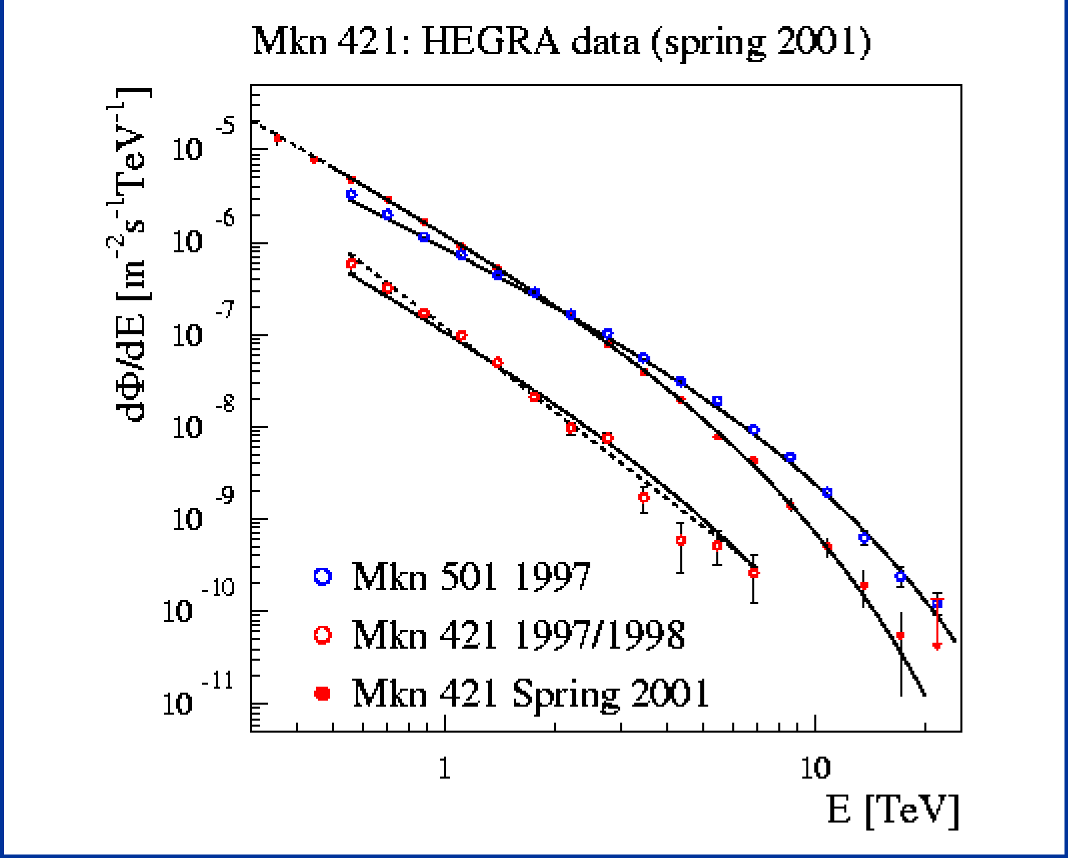
γ - ray

Flaring of Mrk 421 in 2001



Whipple

Mrk 421, 501 Spectra



HEGRA

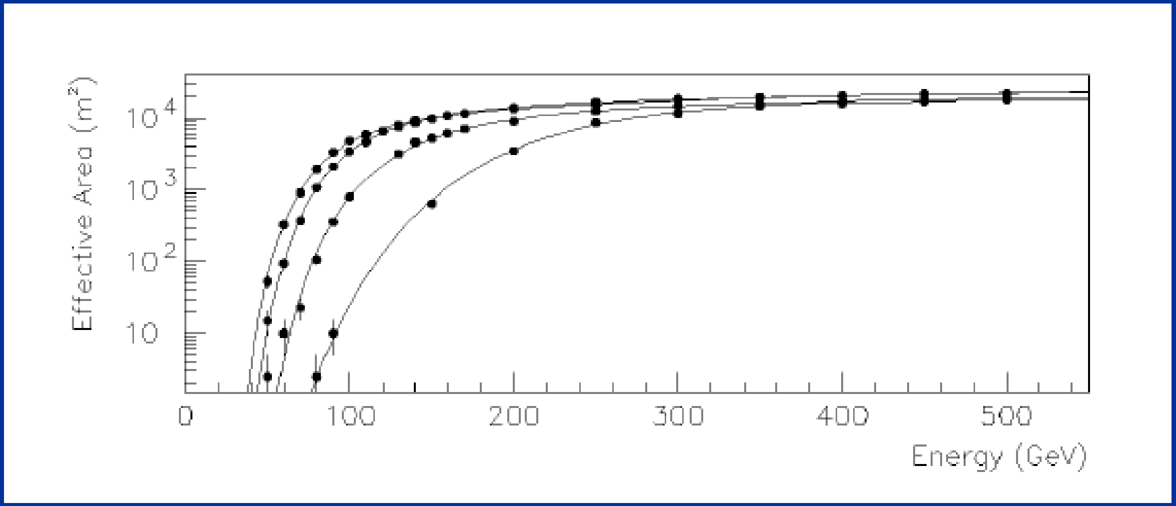
Difficult to measure absorption:

Wide dynamic range
Control of systematics

Still an open question.

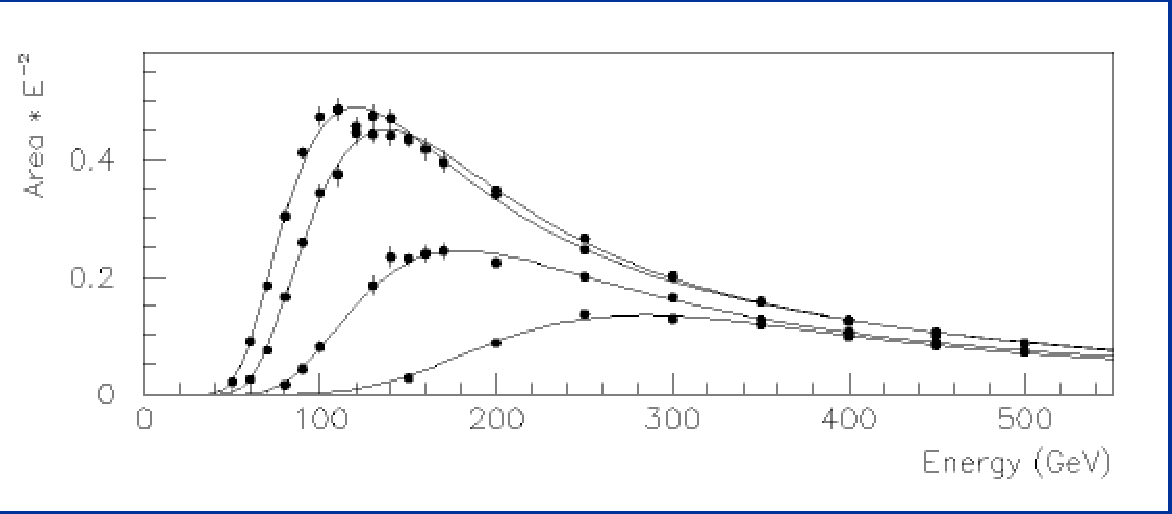
STACEE-48 Area & Threshold

Collection Area



Energy Threshold

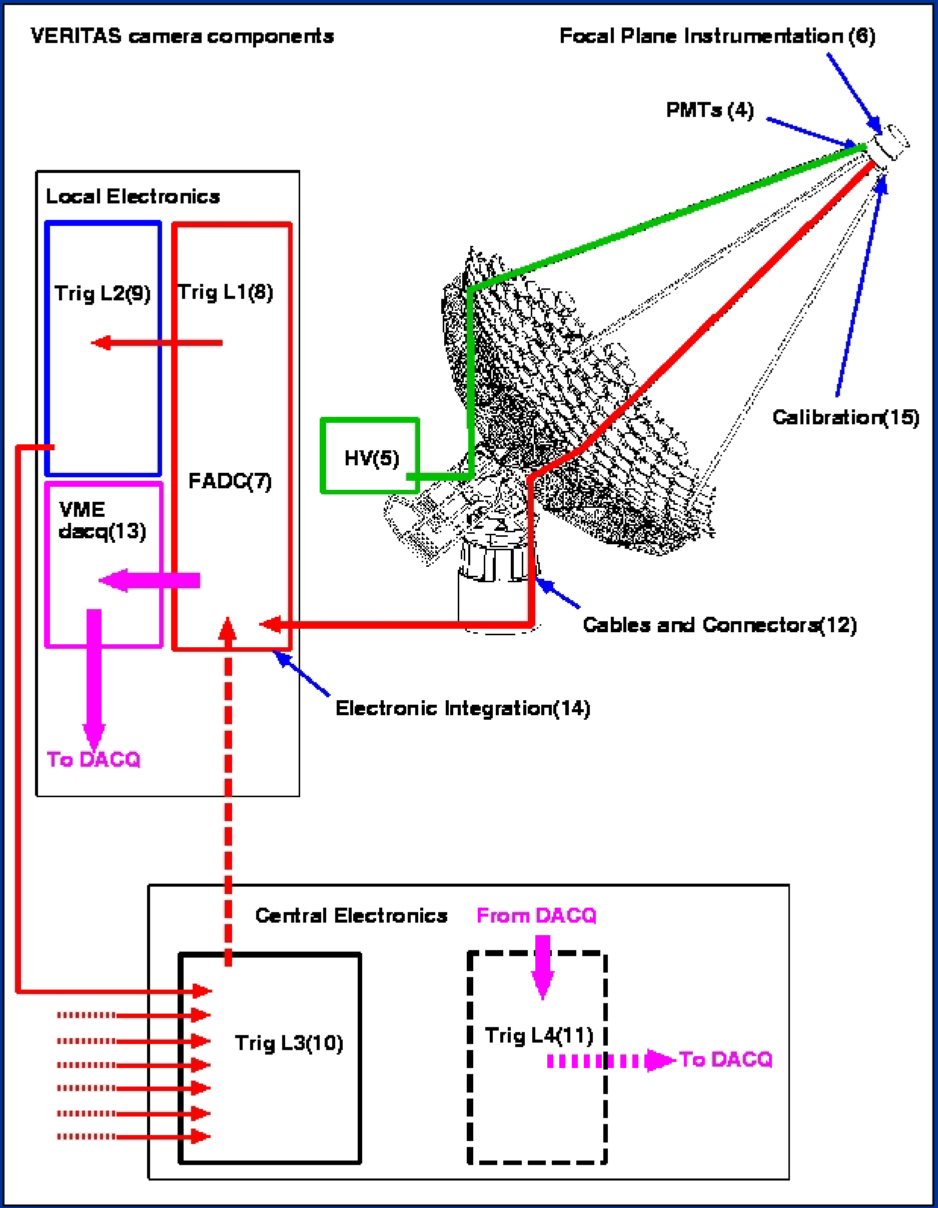
$E^{-2.3}$ spectrum



VERITAS

Advanced hardware

Multi-level trigger
500 MHz FADCs
High speed DAQ

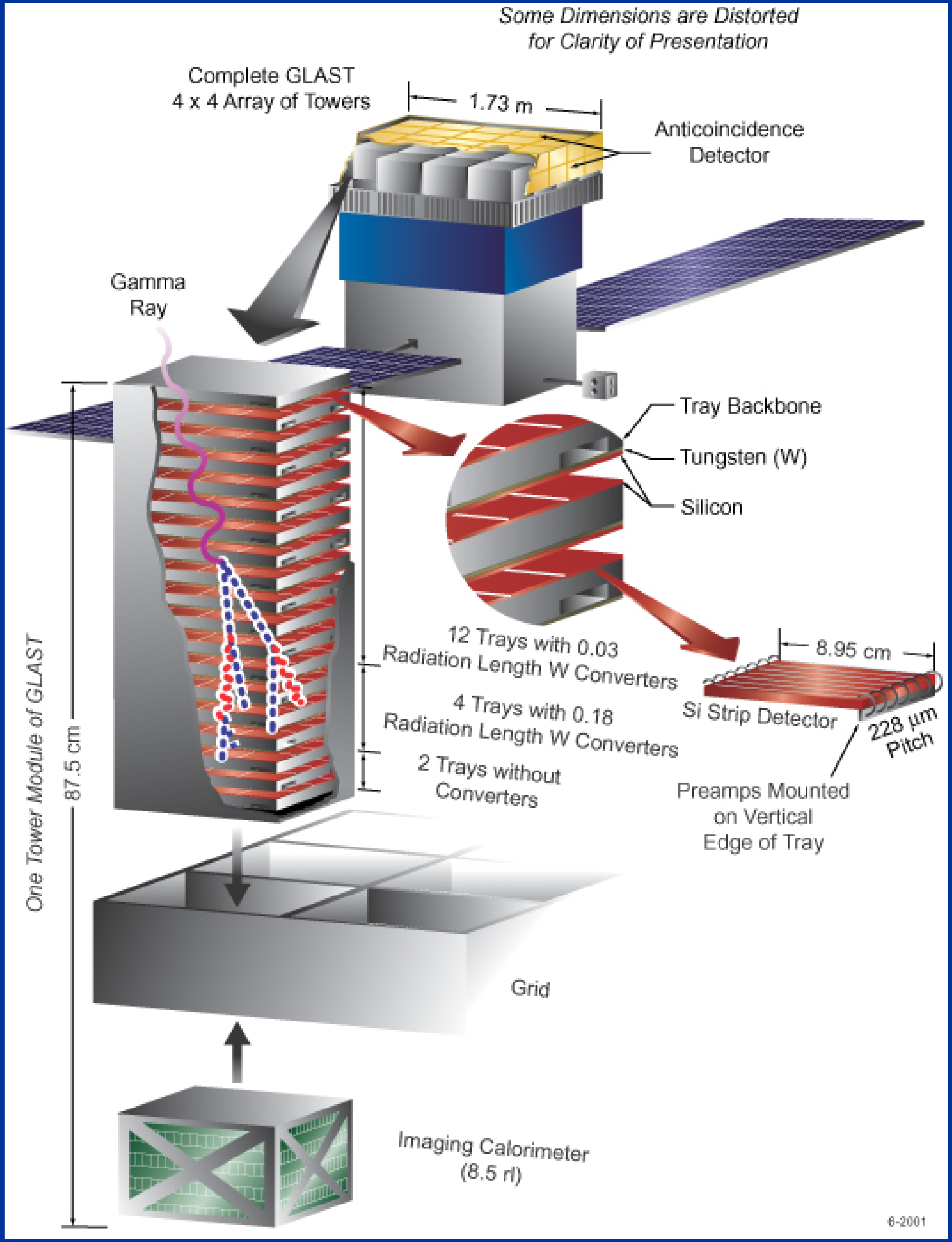


VERITAS Groups

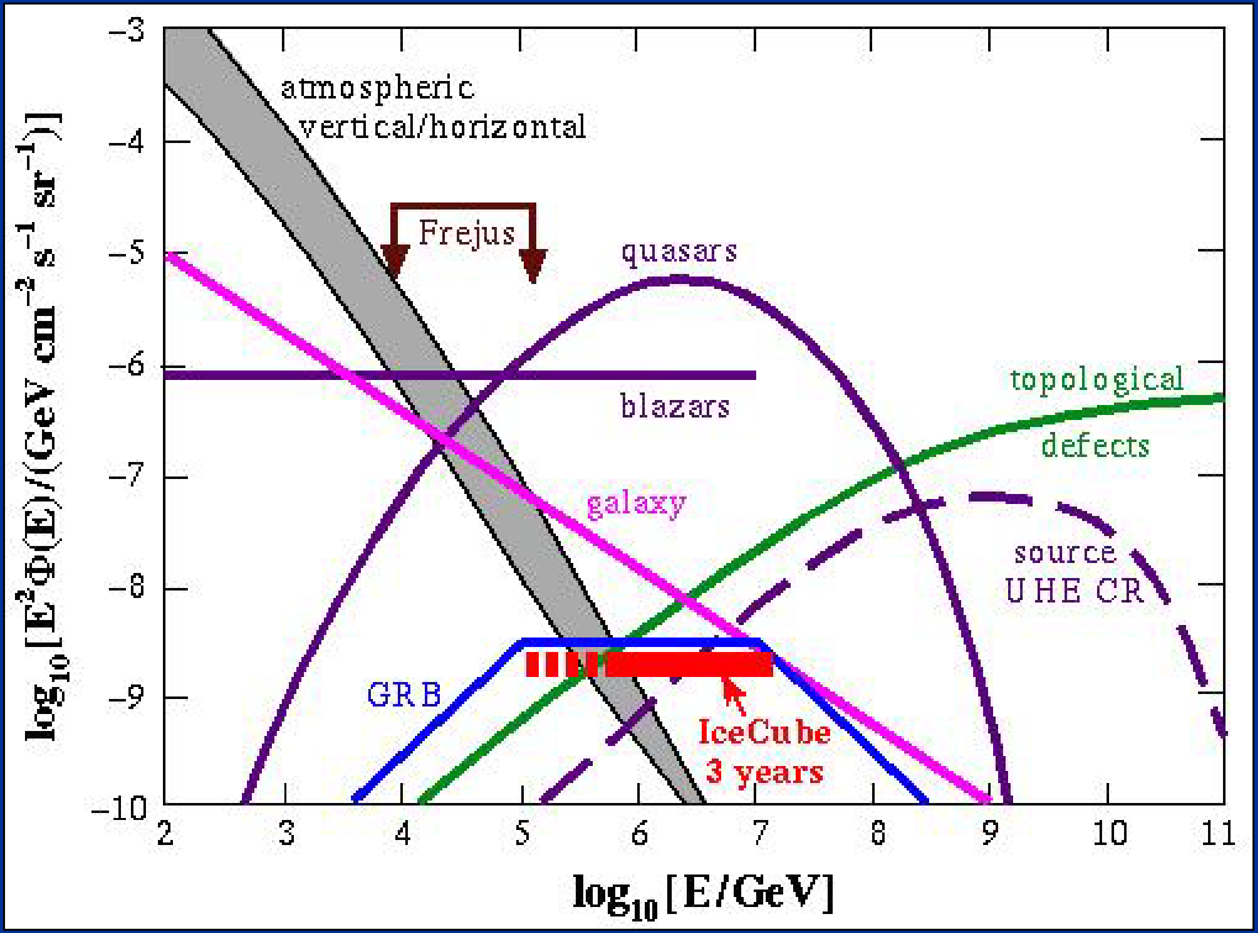
GLAST - LAT

Hardware from particle physics and space physics fields

Partnership:
- DOE
- NASA
- International



Neutrino Spectra



• Completely hypothetical !