The Extreme Universe

Extending the Limits of Particle Physics and Astronomy

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UC, Irvine Colloquium
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Cosmic Messengers

We learn about the Universe with 4 messengers:

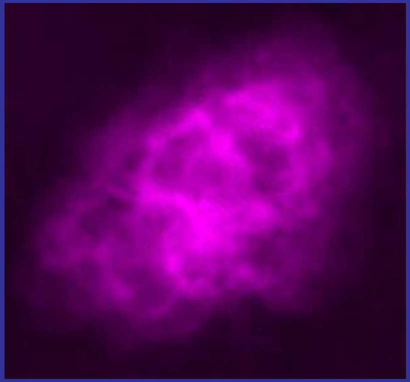
1.	Photons	neutral	most of astronomy
2.	Cosmic rays	charged	important
3.	Neutrinos	neutral	developing
4.	Grav. waves	neutral	infancy

Concentrate here on #1 and #2.

New Wavebands = New Physics

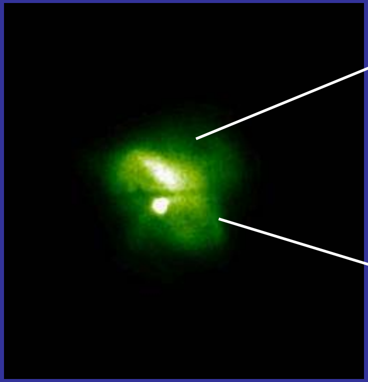
- Before 1940's – Astronomy used visible light.
- Since then – Other wavebands (radio, IR, X-ray, γ-ray …)
  Other particles (CR's, ν's …)

Observations of Crab Nebula and Pulsar

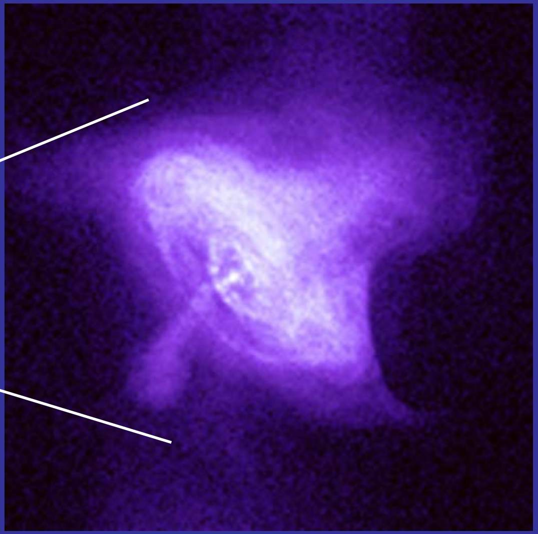


Radio

Visible



X-ray



Crab Pulsar

Outline

Introduction

- New messengers and new wavebands
- Producing and detecting extreme energies

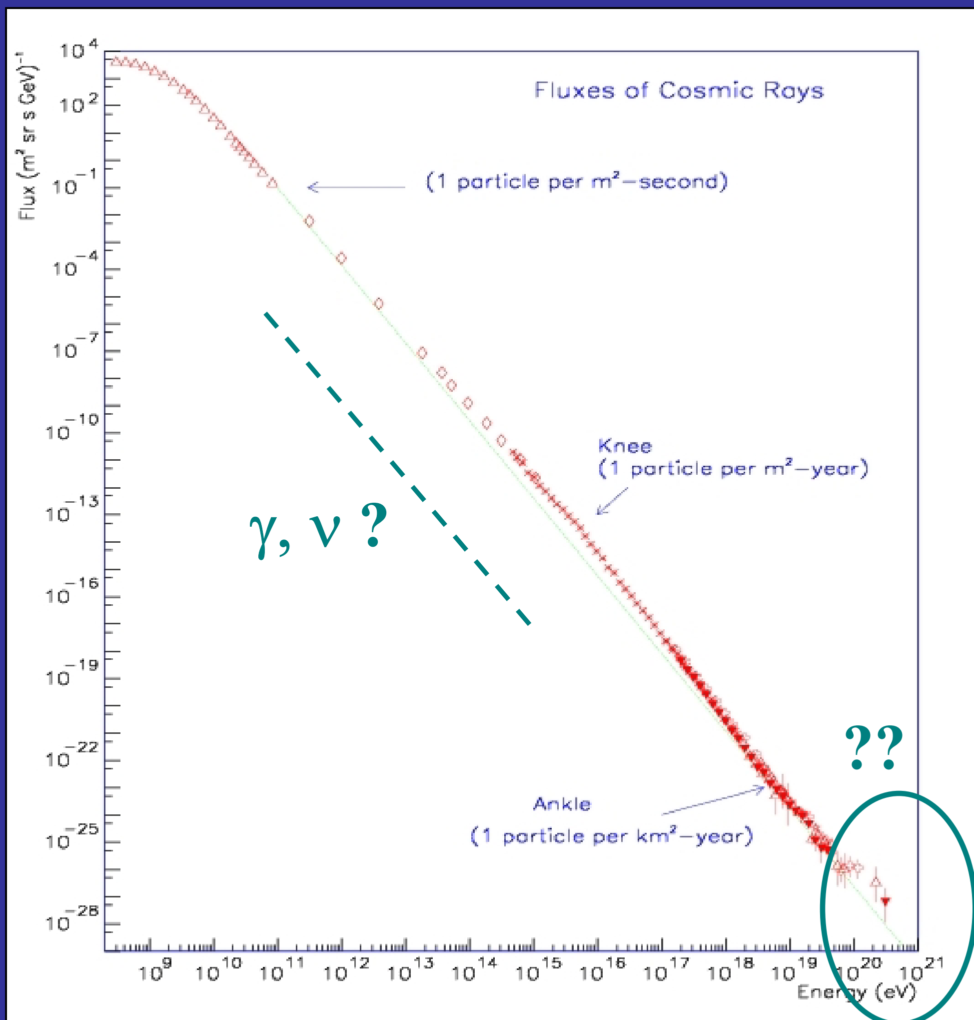
The Science

- Known γ-ray sky
- Cosmic Accelerators – examples
- (UHECR sky)

Experimental Techniques

- Atmospheric Cherenkov Telescopes
- STACEE Telescope
- Future Projects

Cosmic Ray Spectrum



- Power law – enormous range
- Abundant
- Luminous
- Larmor radius r = R/cB

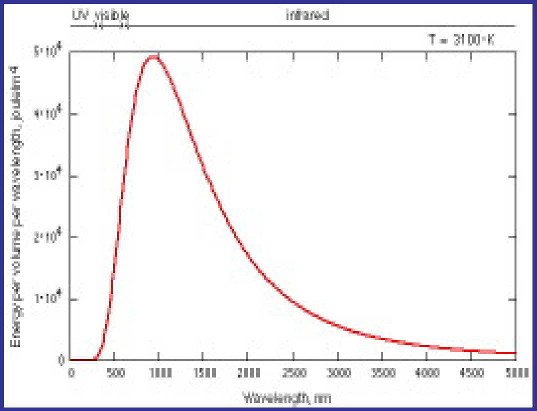
R	r
10^{15} eV	0.3 pc
10^{20} eV	30 kpc

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

Two Major Difficulties

1. **How do we even <u>produce</u> such extreme energies ?**

Thermal Universe E < 10 KeV



Blackbody

Non- thermal Universe E > 10 KeV

Accelerator

2. **How do we even <u>detect</u> such extreme energies ?**

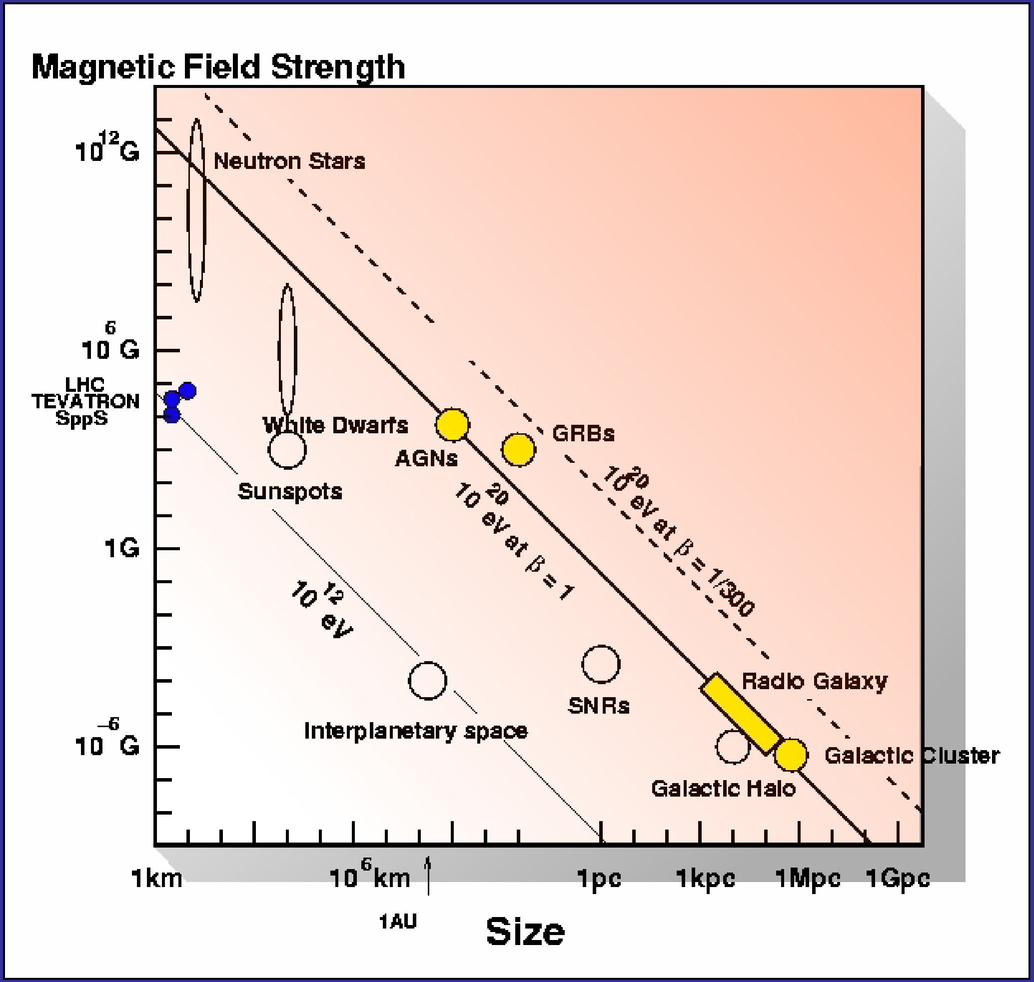
Can only detect by total absorption.

Reaching Extreme Energies

Hillas Plot

Require gyroradius to fit within acceleration region.

Totally hypothetical !

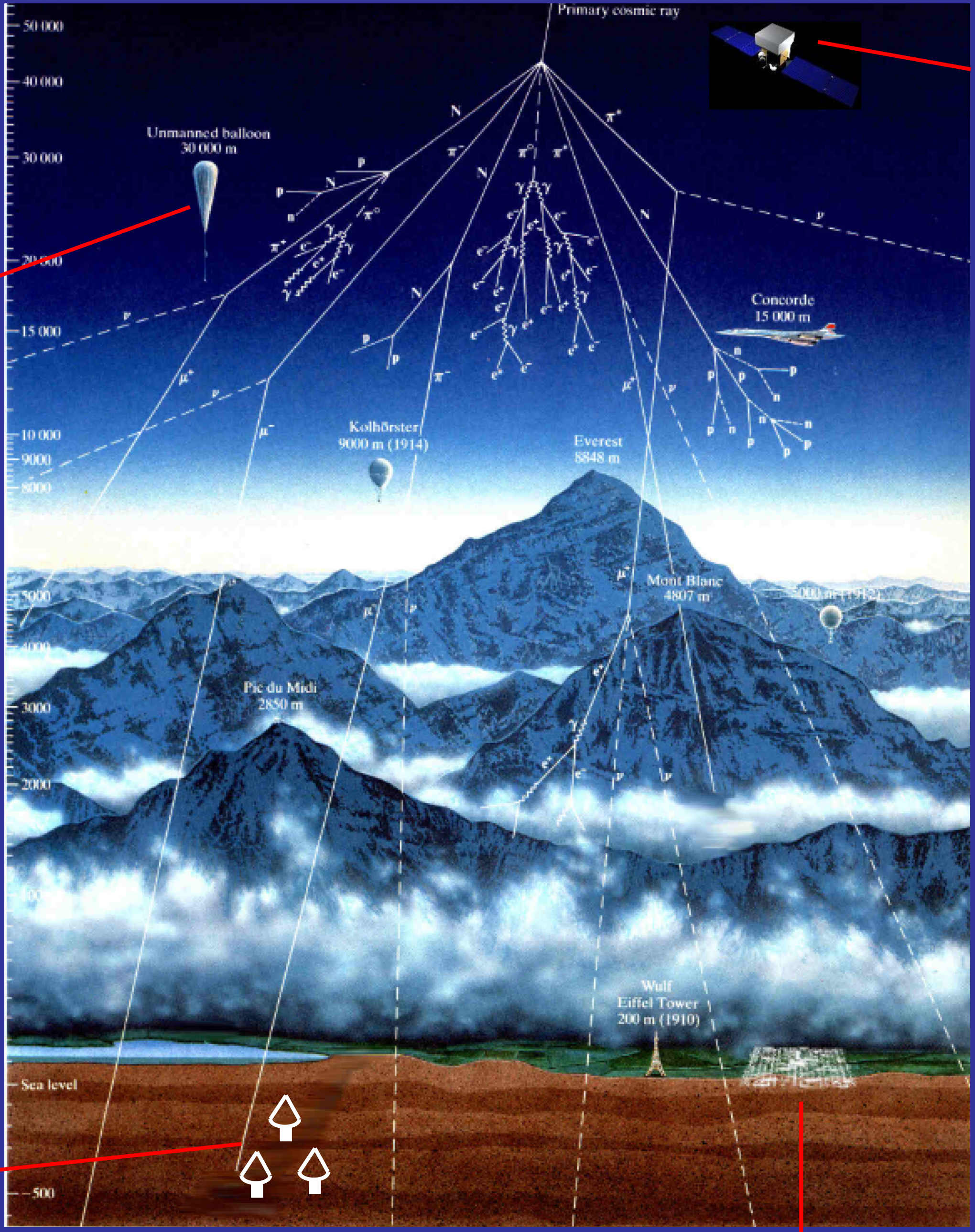


Broad Motivation

Explore a new window of astronomy

- “Extreme Astrophysics”: (“bottom up”)
    1. Test limits of physical law in the most extreme environments.
    2. Study non-thermal astrophysical mechanisms.
- Beyond Standard Models (“top down”)
    1. Search for new particles or new relics.
    2. Use particle beams to probe interstellar space.

Detecting γ-rays, CR's



The Science

Why γ-rays ?

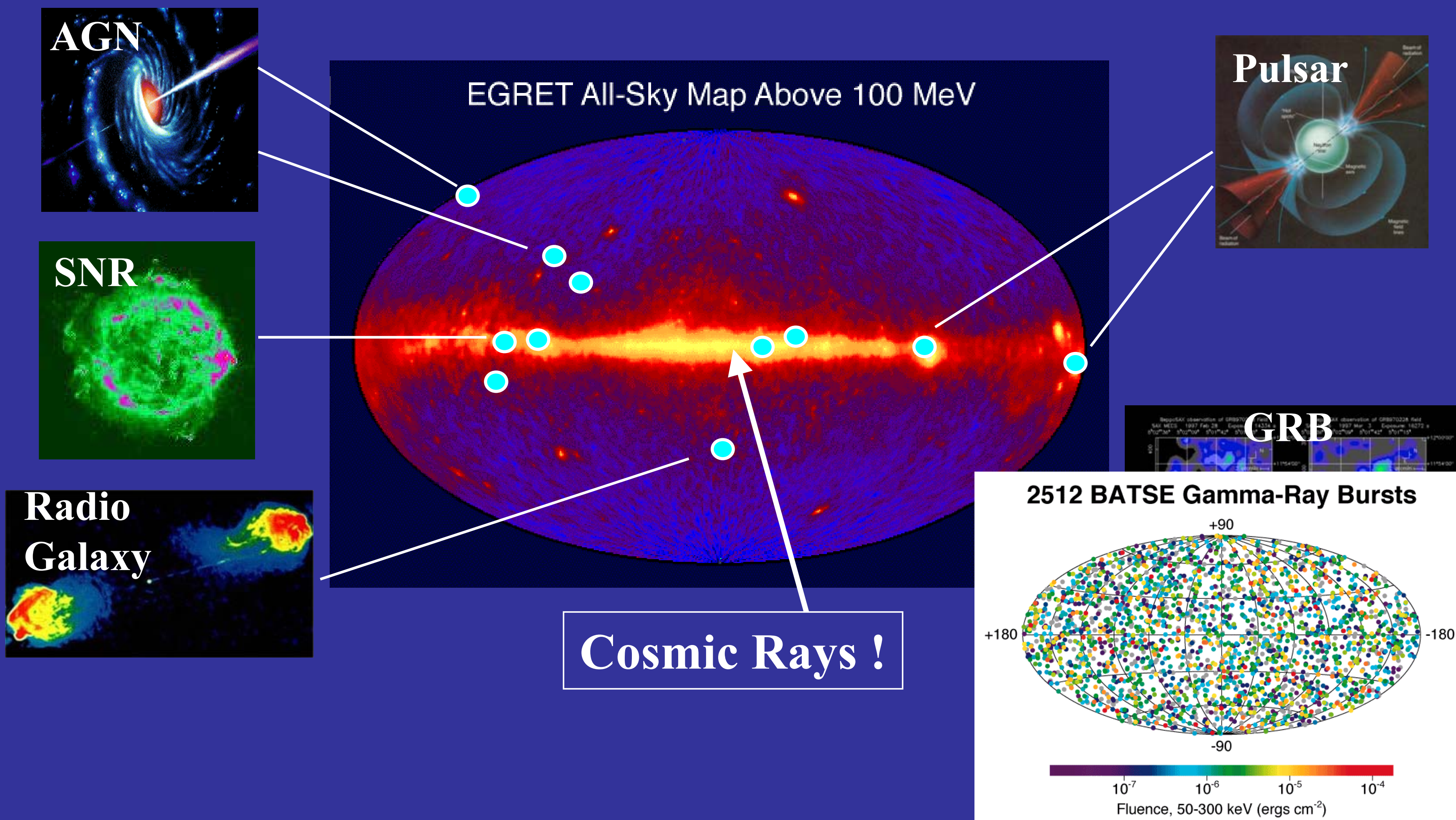
Pros:

- Unlike CR's γ-rays point directly back to their origin. Essential for astronomy.
- Unlike ν's, γ-rays have v. high interaction prob. (~1). Translates into ~ 10^6 increase in collection area.
- Photons are ubiquitous in astrophysical situations. γ-ray observations connect to rest of astronomy.

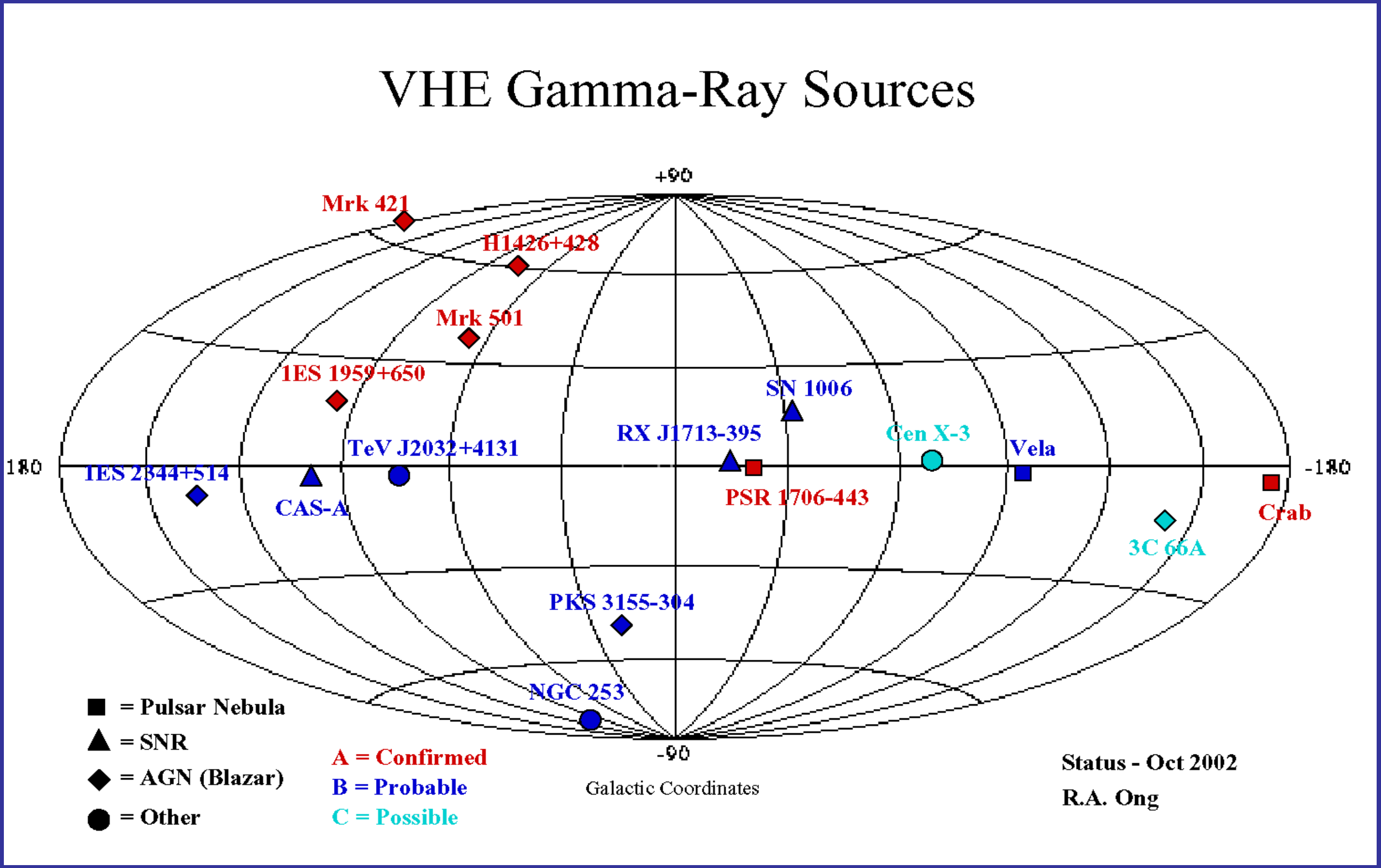
Cons:

- Photons can be absorbed by interstellar fields.

GeV γ-ray sky


AGN
SNR
Radio
Galaxy
EGRET All-Sky Map Above 100 MeV
Pulsar
GRB
2512 BATSE Gamma-Ray Bursts
+90
+180
-180
-90
10^{-7}
10^{-6}
10^{-5}
10^{-4}
Fluence, 50-300 keV (ergs cm^{-2})
Cosmic Rays !

TeV γ-ray sky

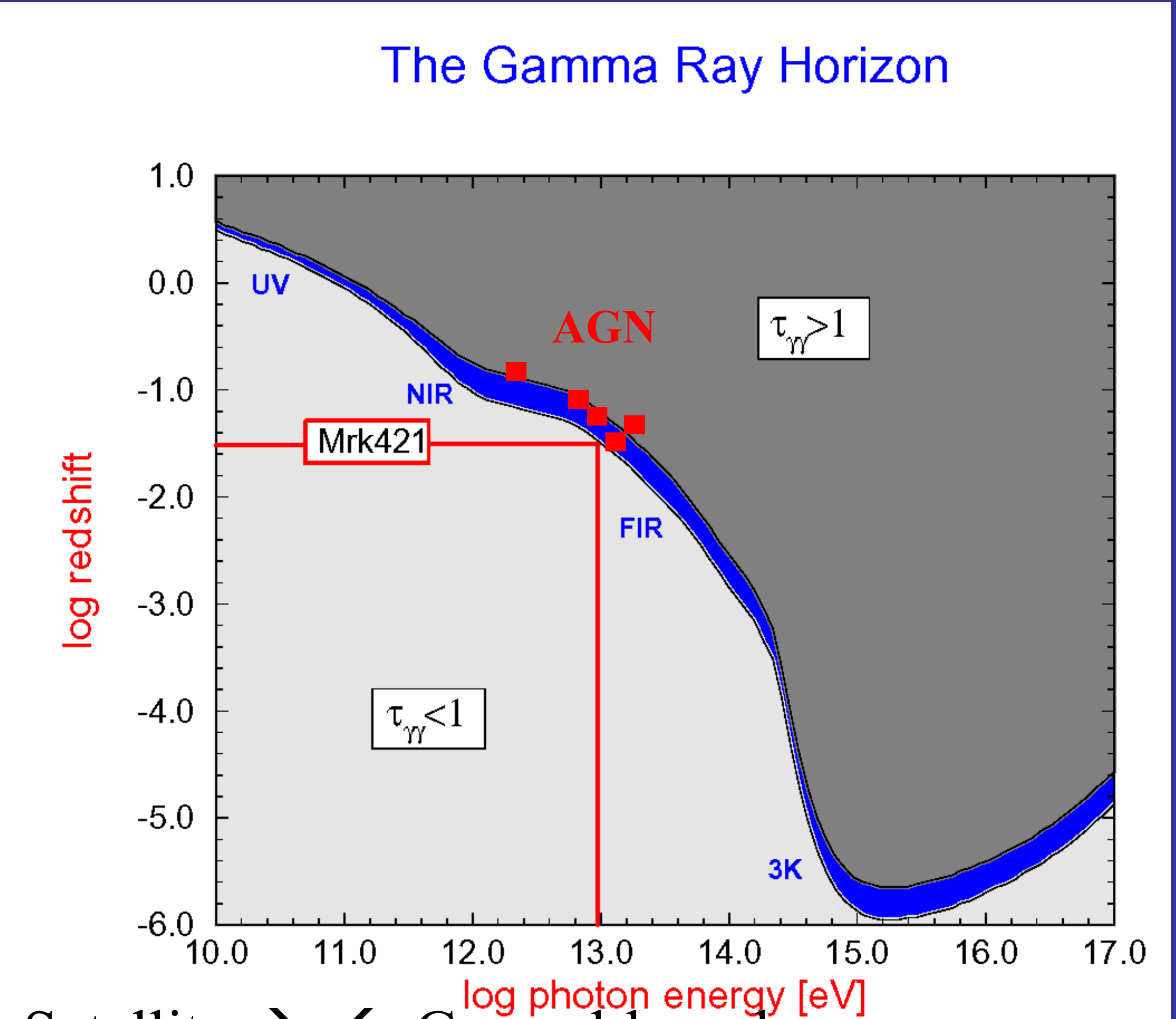


- Variety of source types
- All discovered by Cherenkov telescopes

γ-ray absorption

Pair-production
$\gamma\gamma \rightarrow e^+e^-$

"pessimistic"



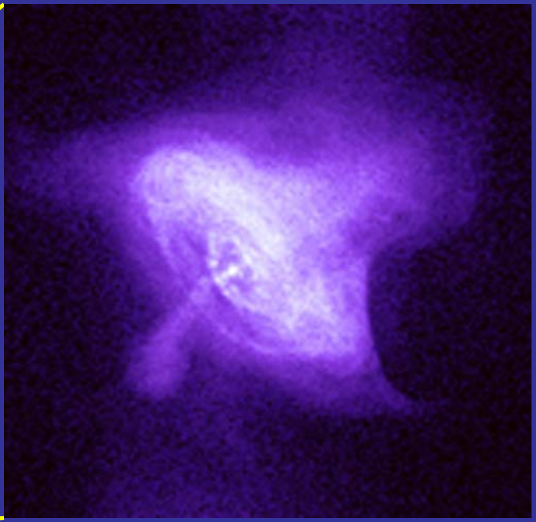
← Satellite → ← Ground-based

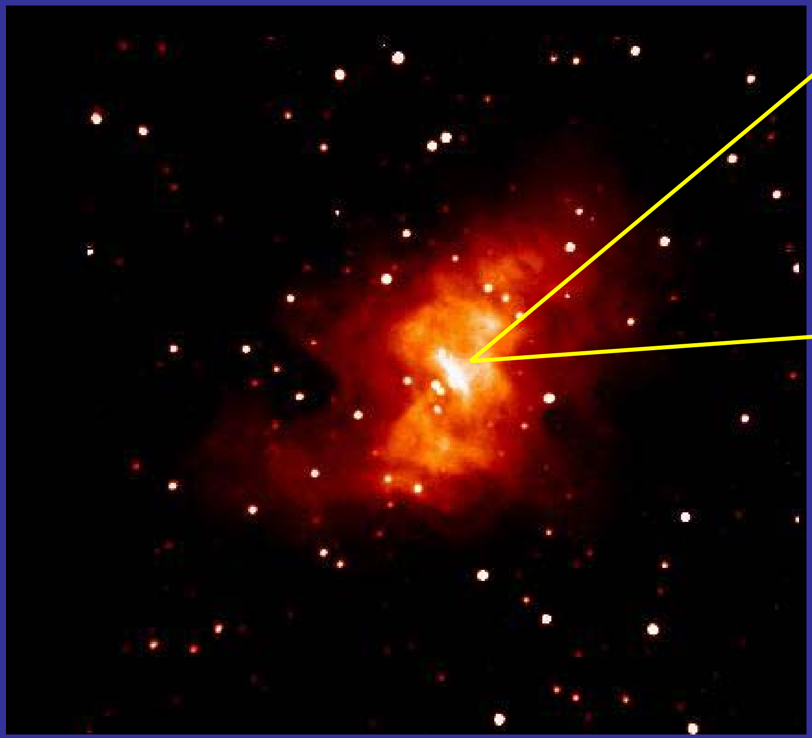
Making a Cosmic Accelerator

POWER SOURCE	+	ACCELERATION	+	EMISSION
Gravitational, EM Energy		Shocks, turbulence, etc.		Radiation Process

Power Sources: Pulsars

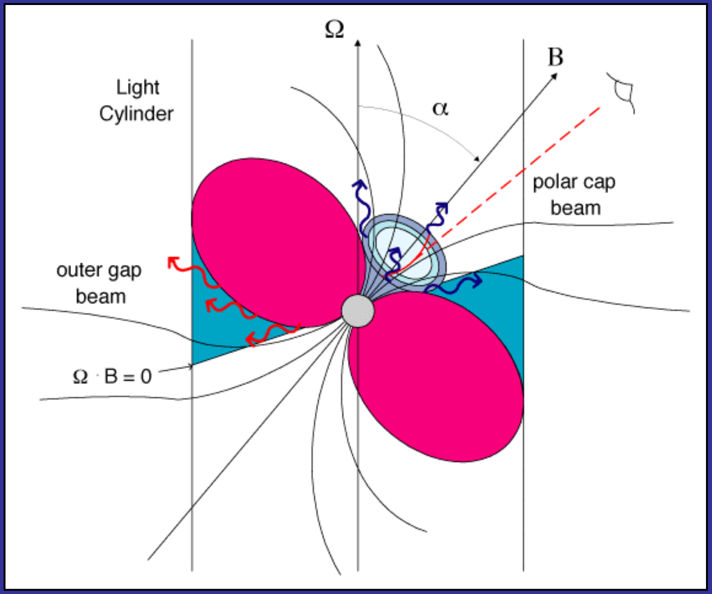
Pulsar- NS rotation





Crab Nebula

Produces γ-rays up to 10^{15} eV.

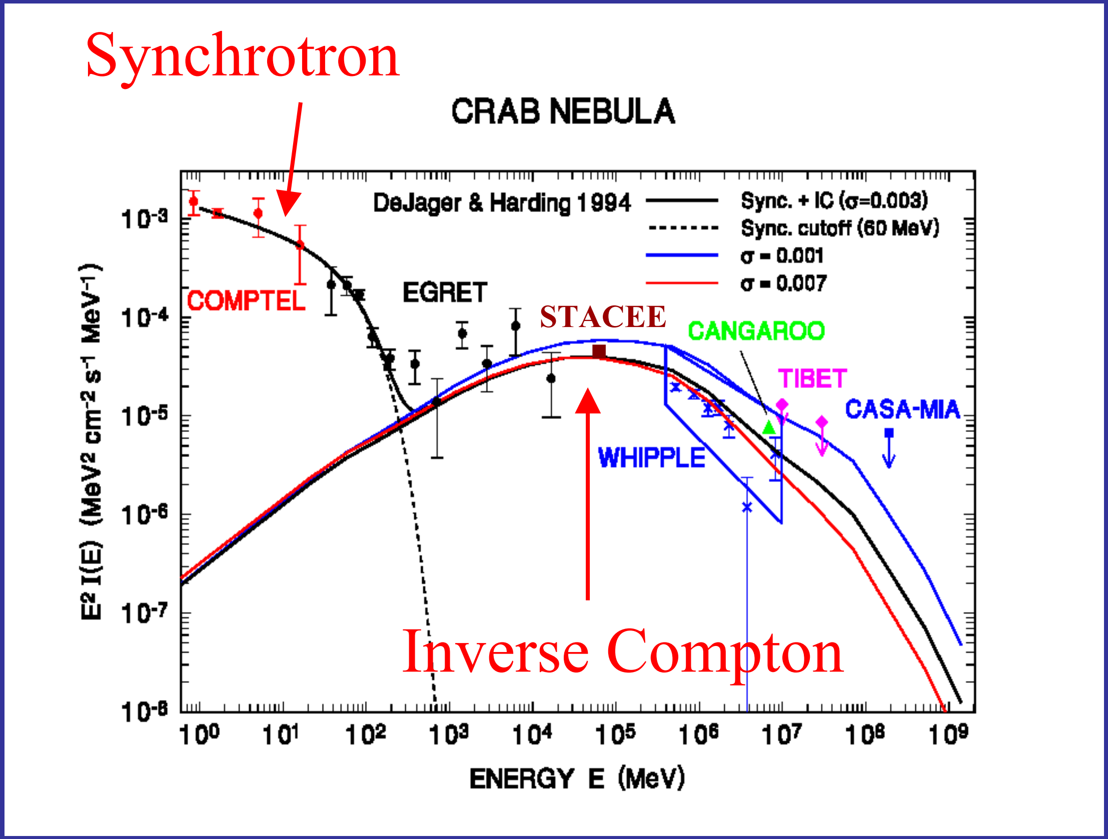


models

Crab Nebula Emission

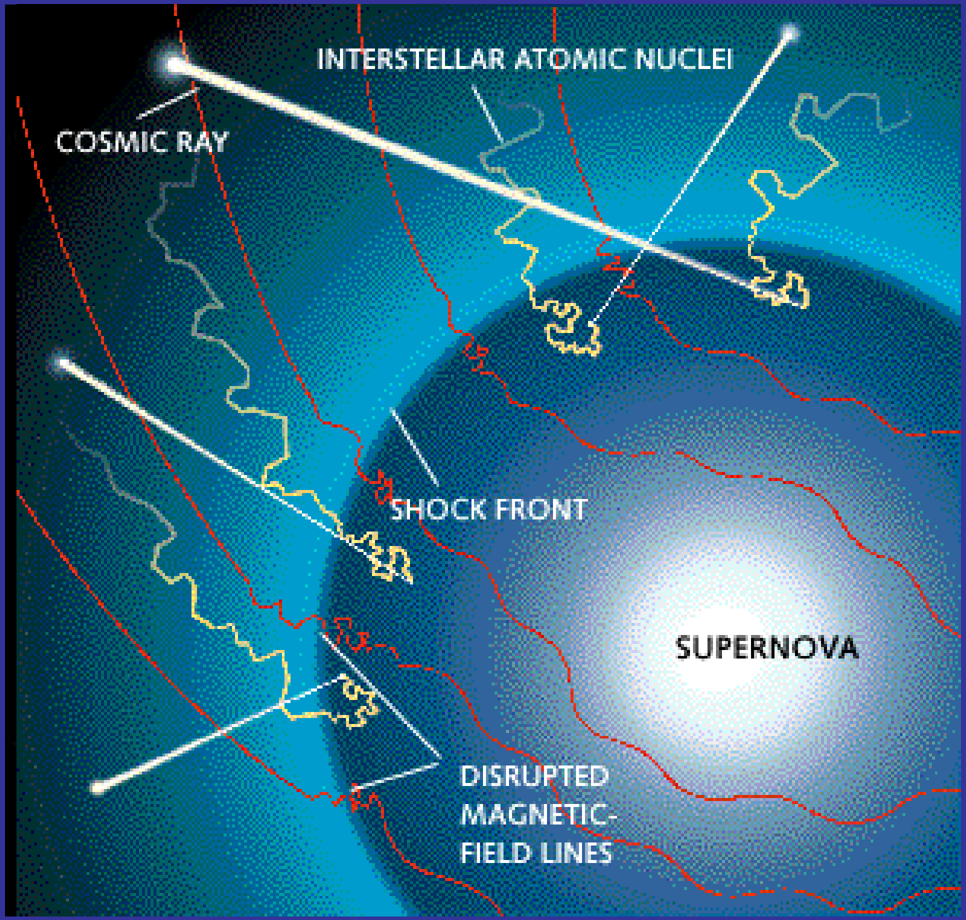
- Relativistic e$^-$ wind
- Synchrotron + Inverse-Compton
- Constrains B field

We understand the Crab !



Eight γ-ray pulsars known.

Supernova Remnants



E0102
AAT, HST, Chandra

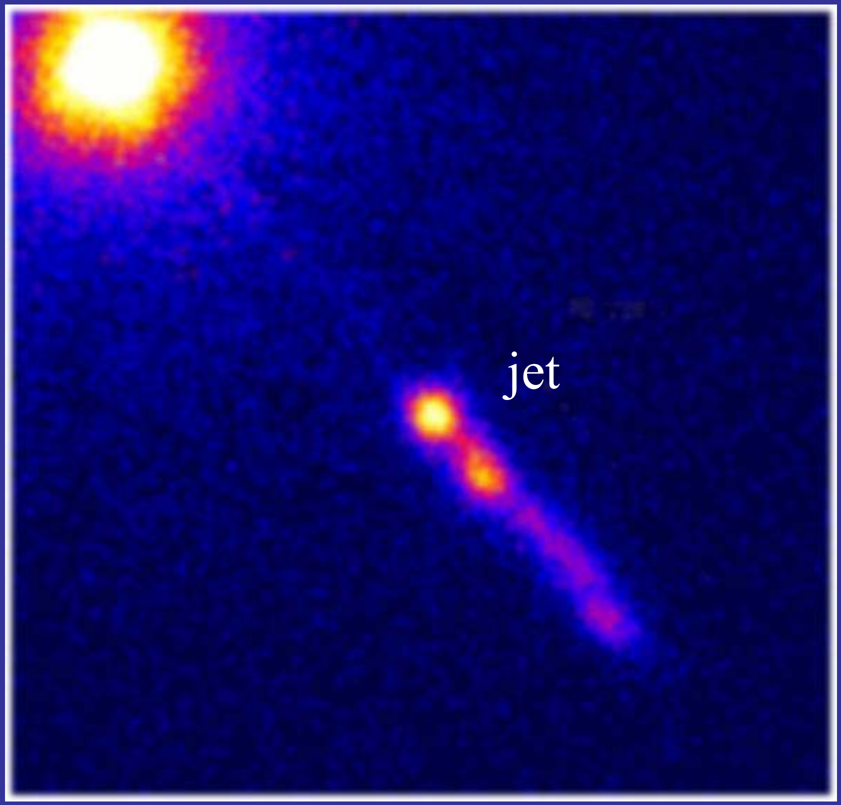
- Collapse of massive star
- Remnant expansion powers shock wave
- Particle acceleration via Fermi mechanism

Energy ~ 10^{51} erg
Rate ~ 1 / 40 yr (galaxy)
L ~ 10^{42} erg/s

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

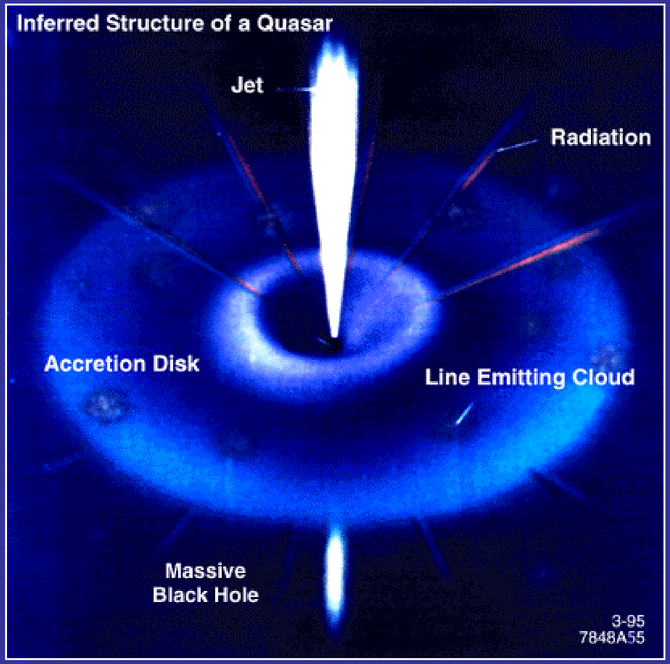
Active Galactic Nuclei (AGN)

3C273



Chandra

model

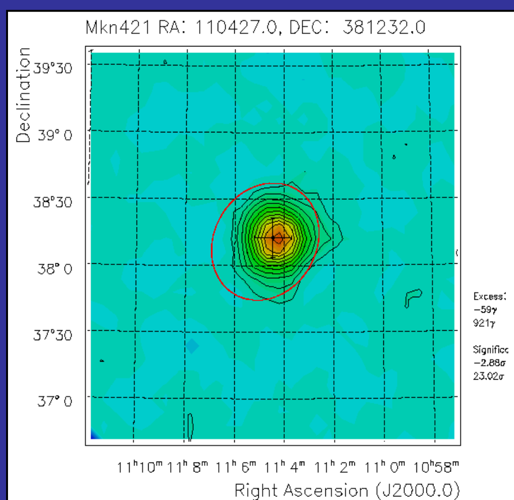


- BH accretion powers jets
- Shock acceleration in jets
- Relativistic electrons, protons

“Blazars”

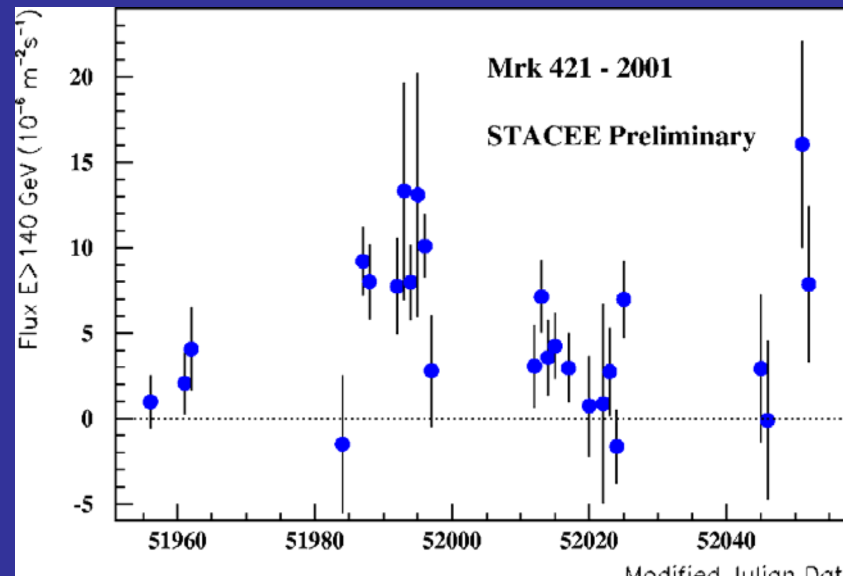
Blazars:
- Powerful, radio-loud objects
- Highly variable at all wavelengths
- Relativistic jets – superluminal

Image Mrk 421



Whipple >100σ detection

Light Curve STACEE

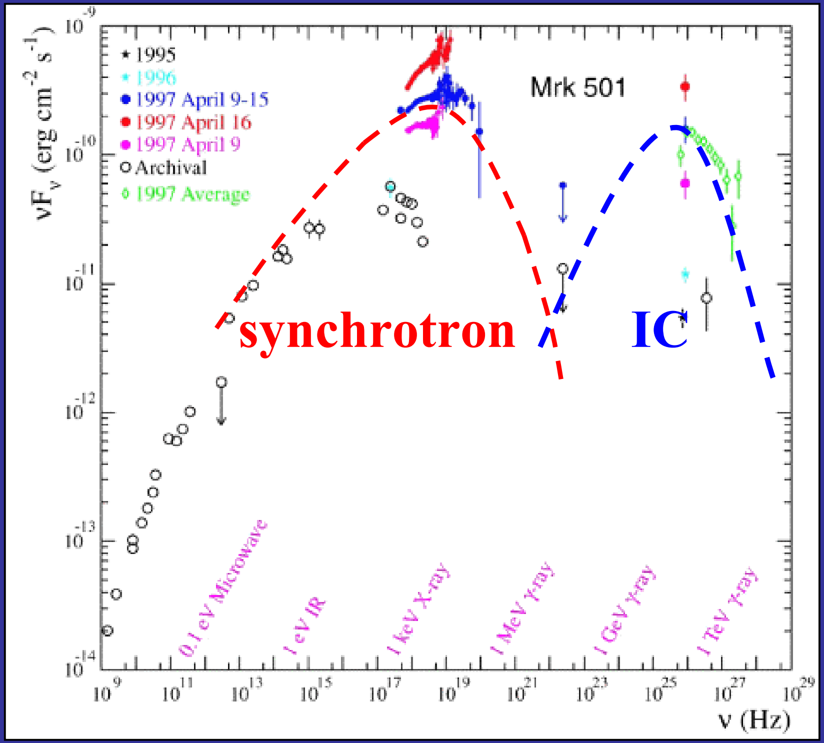


- Dramatic variability:
  time scales < 30 min.

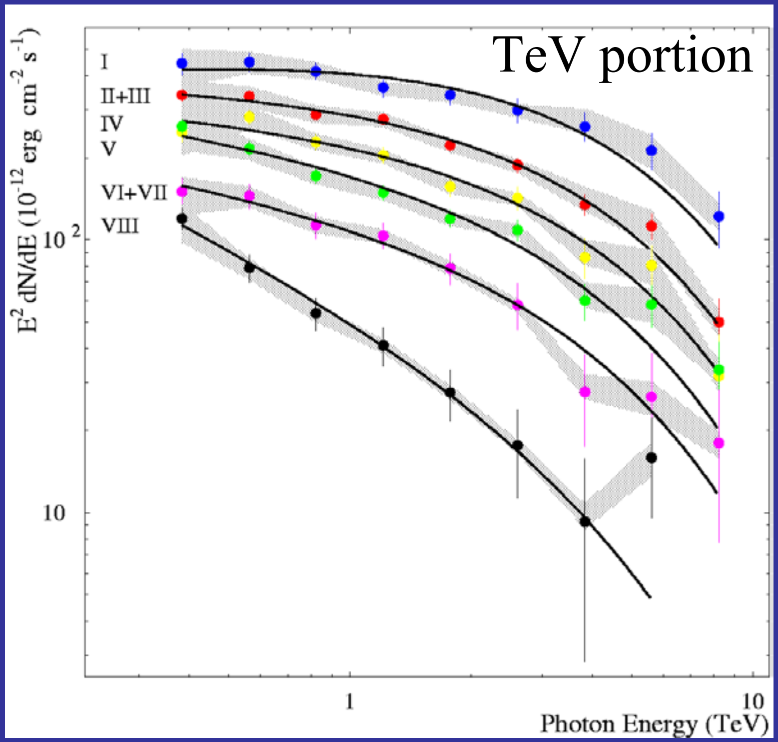
- Large fluxes:
  10^{11} TeV γ-rays/s hit Earth.

Blazar Spectra

Spectral Energy Distribution



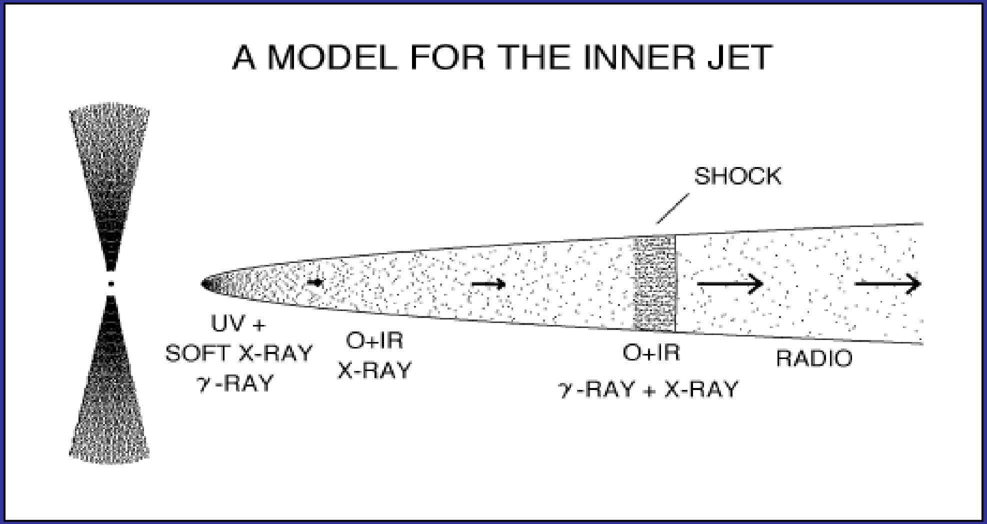
Spectral variation



- X-rays & γ-rays, highly correlated

- Clear spectral roll-over → absorption ?
- Spectrum varies with flux level !

Blazar Dynamics



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

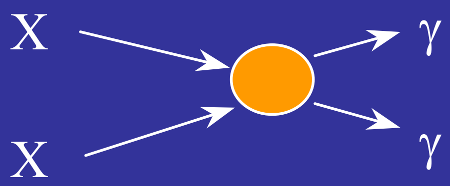
New Physics

DARK MATTER

Galactic center

Dark matter:

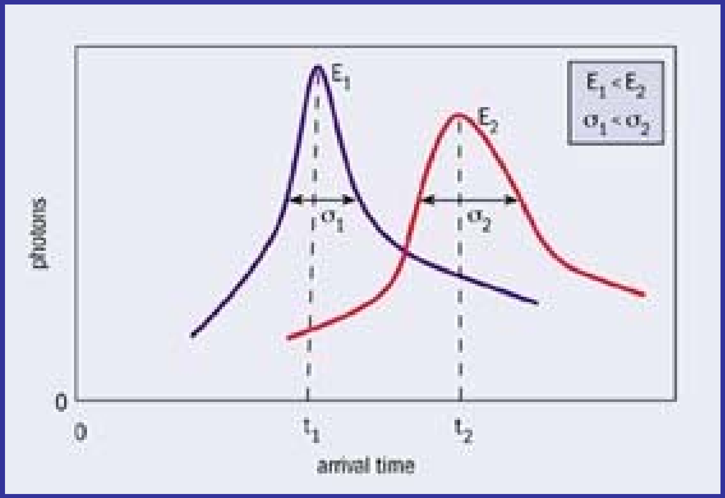
- New supersymmetric particle
- Decays to γ-rays



QUANTUM GRAVITY

Gravity "foam" in space-time:

- Variation in speed of light.
- Detectable at high energies over very long distances.



Sensitive to M_{Planck} / 10 ?

Summary of Sources

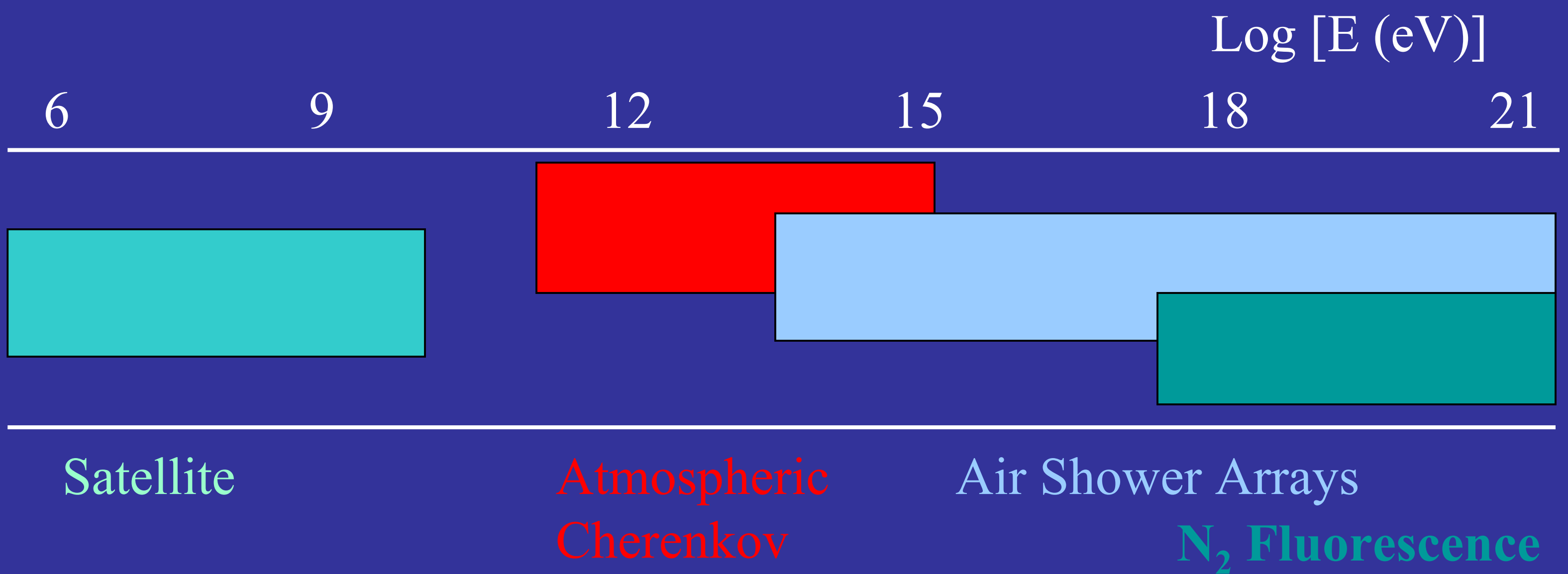
Sources (in order of our level of understanding):

- Pulsars, pulsar nebula
- SNR's
- Other galactic (e.g. starburst galaxies)
- AGN
- Gamma-ray bursts
- Unidentified sources (GeV – 150, TeV – 1)

- WIMPs & other relic particles
- Primordial black holes
- …

Experimental Techniques

Wide γ-ray energy range requires multiple techniques.



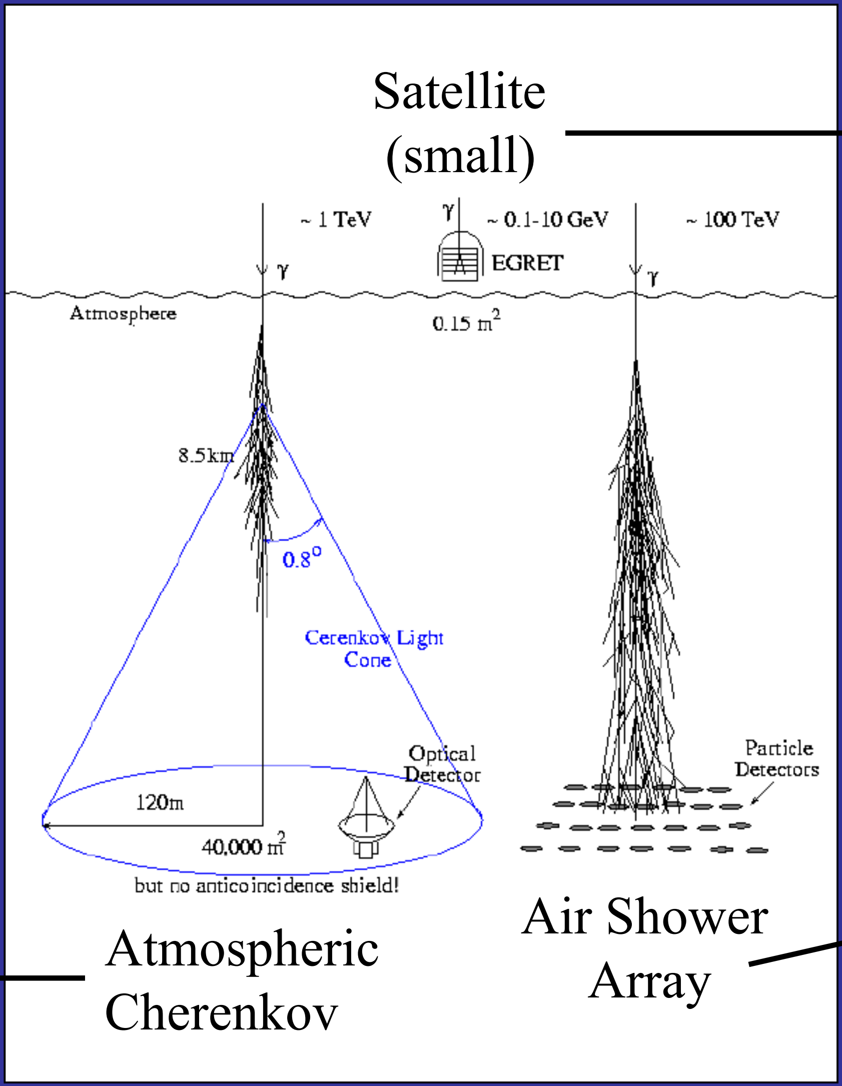
EGRET WHIPPLE AGASA

← STACEE HiRes

GLAST → **VERITAS** **AUGER**

Detecting HE Particles

EGRET (NASA)

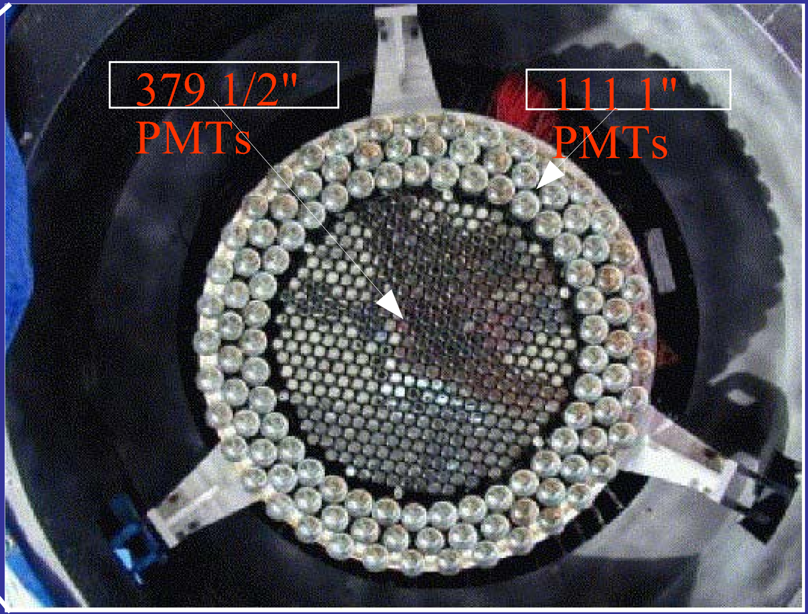


Next
page

Milagro (New Mexico)

"Standard" Cherenkov Telescope

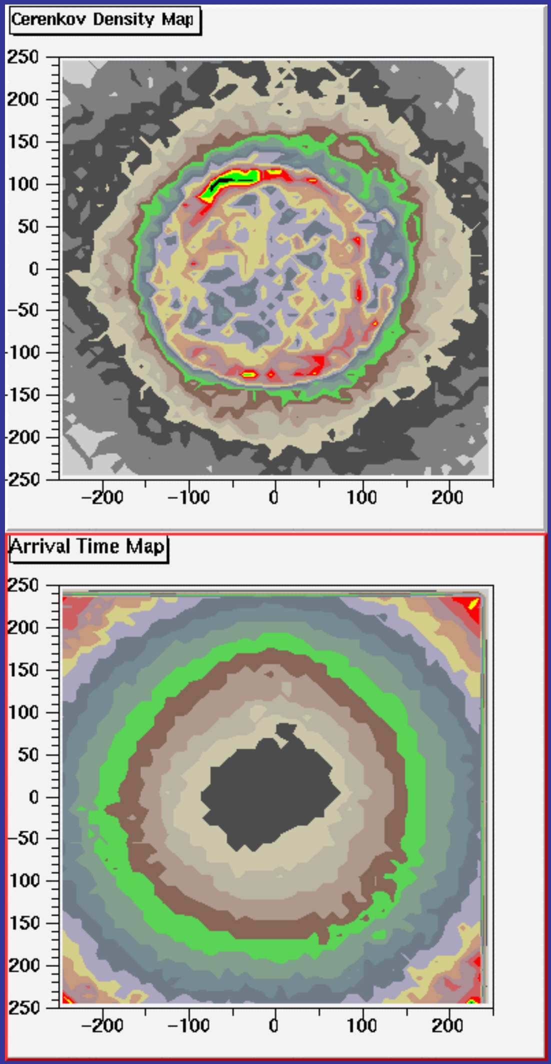
Whipple 10m Reflector
(Mt Hopkins, AZ)



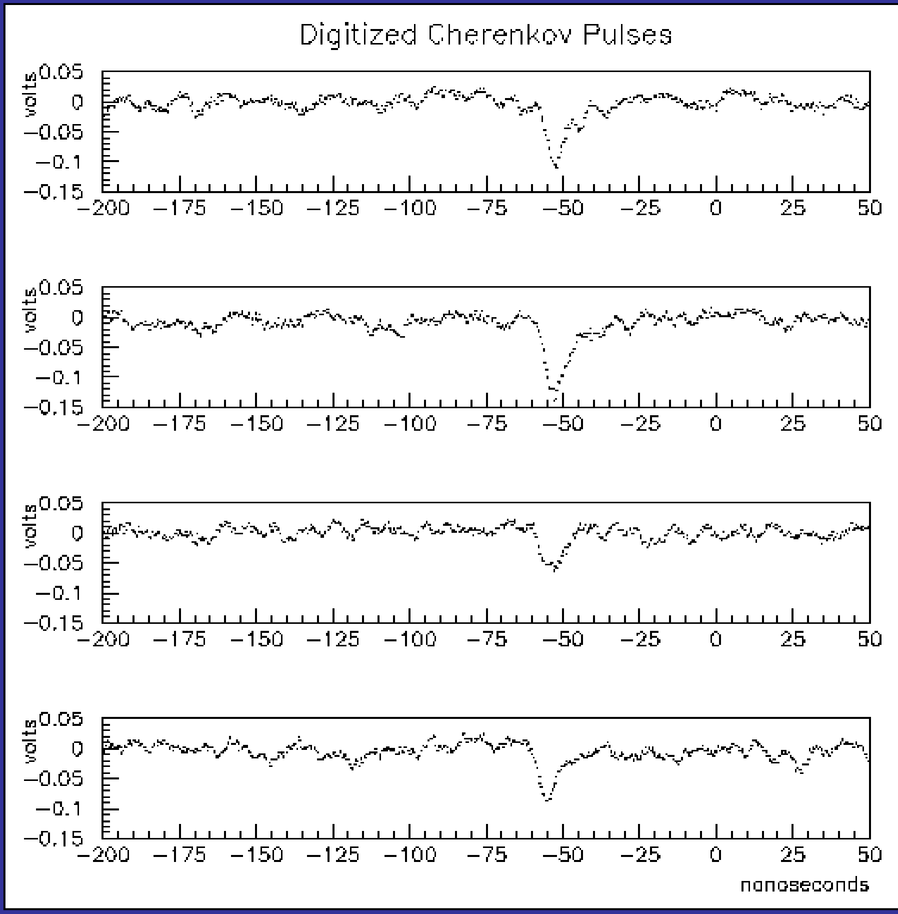
Imaging PMT Camera
500 Elements

Cherenkov Showers

Smooth density of light.

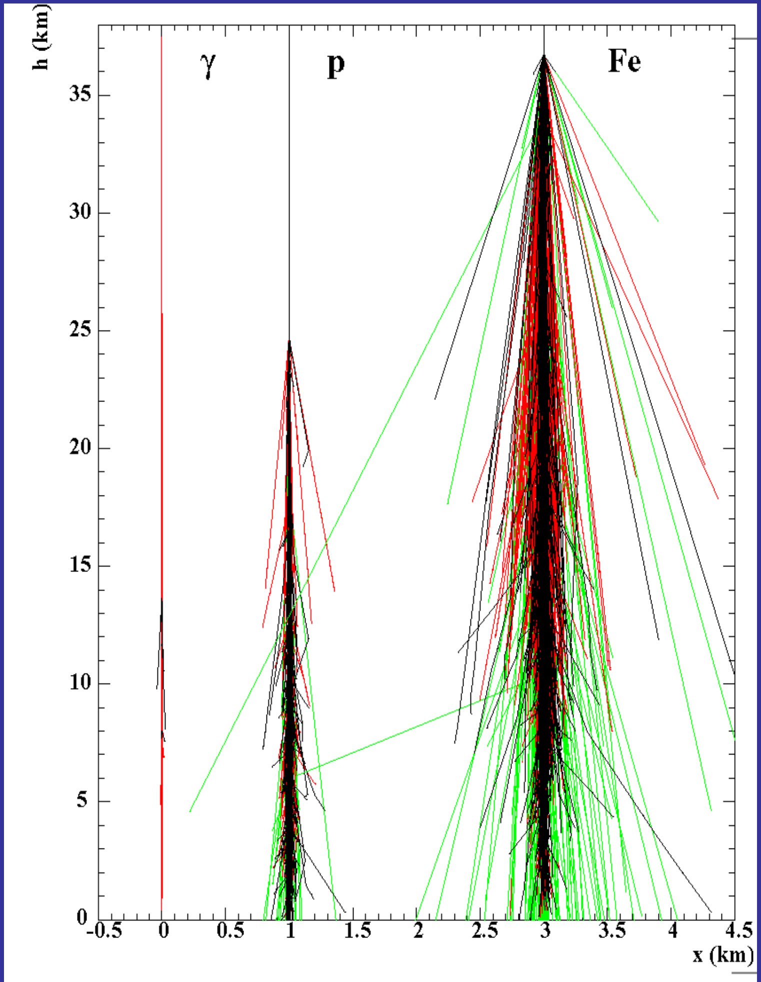


Sharp time of arrival.

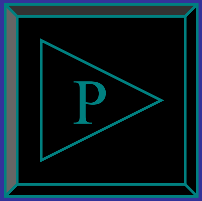


Pulse ~ 5 nsec

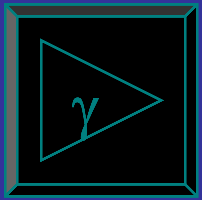
Isolating γ-rays



Differences between Primaries.

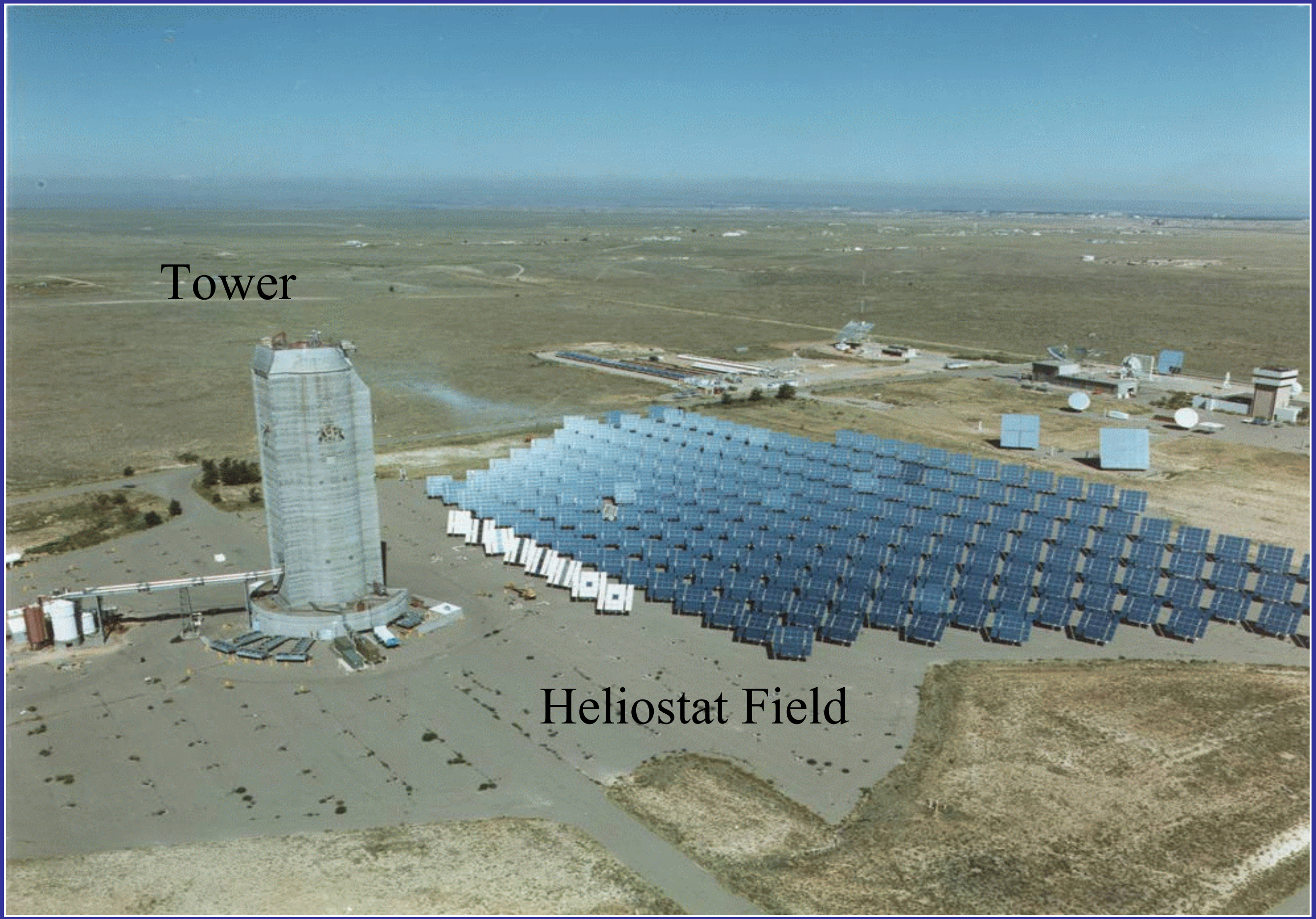


Proton shower movie



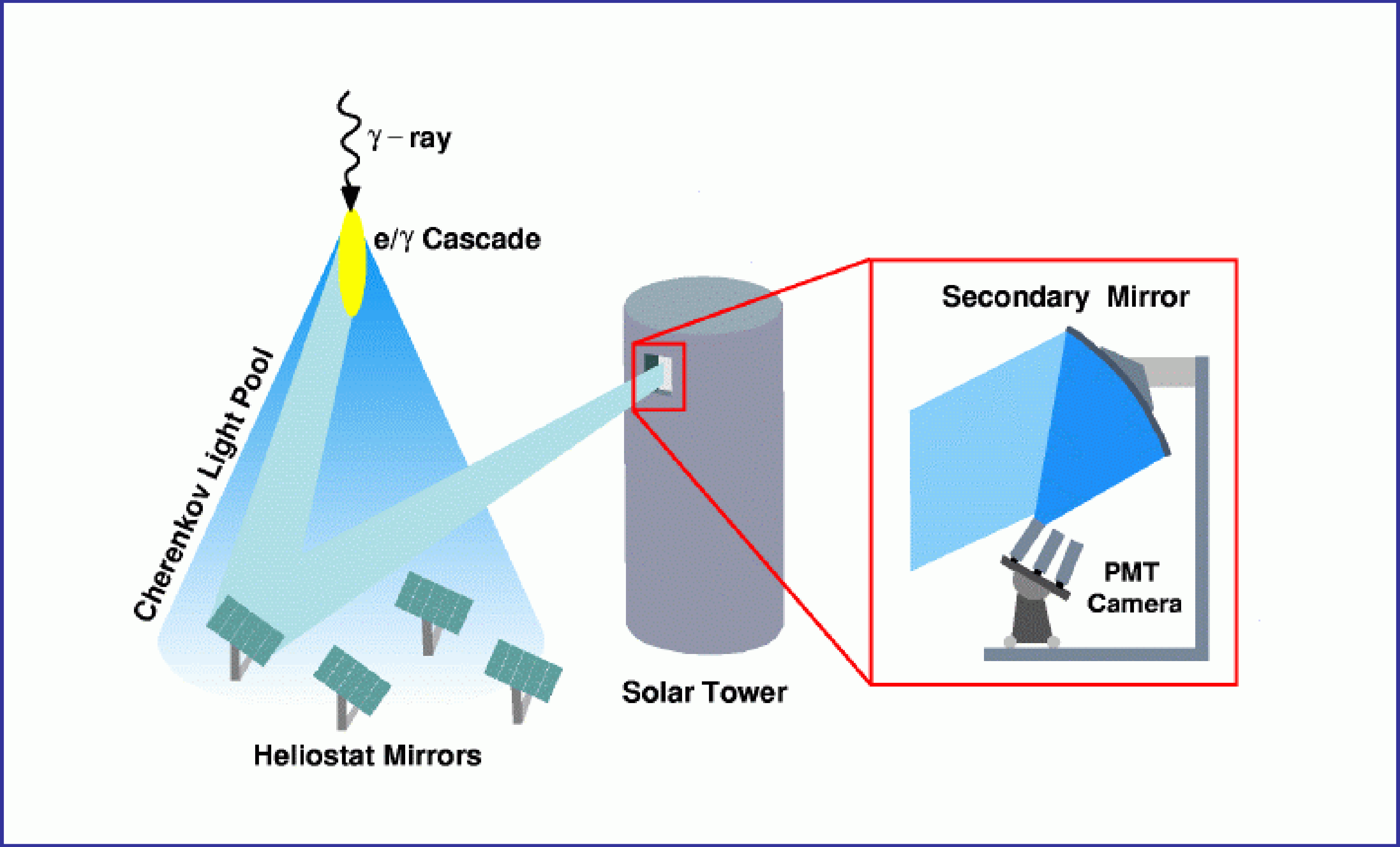
γ-ray shower movie

STACEE
Low-energy Cherenkov Telescope



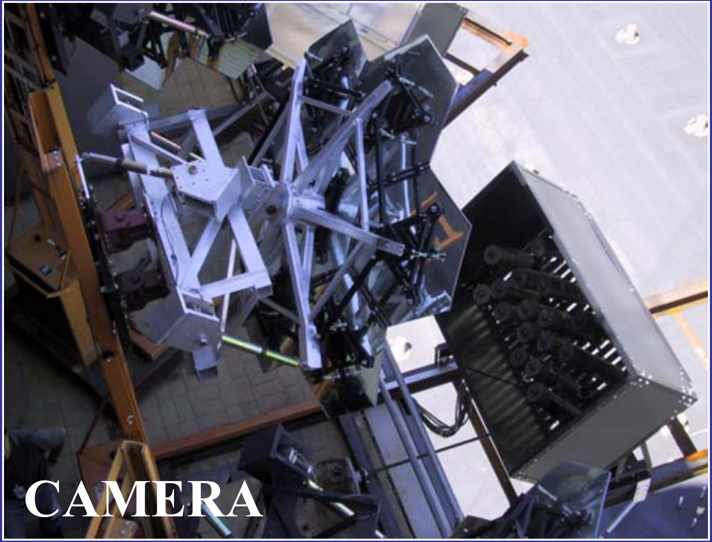
National Solar Thermal Test Facility
Sandia National Labs – Albuquerque, NM

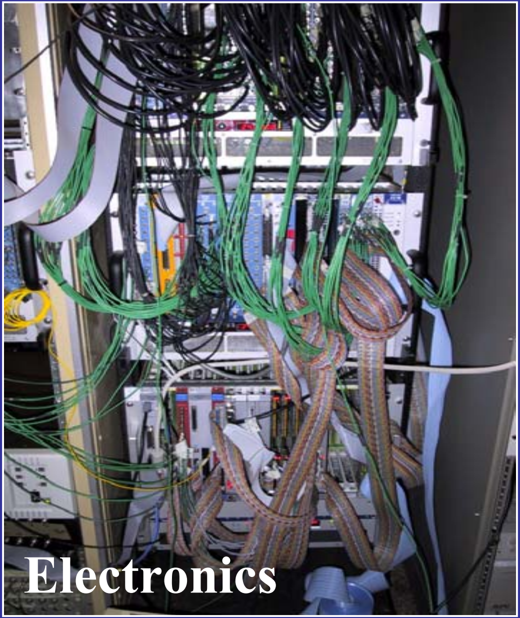
Solar Tower Atmospheric Cherenkov Effect Expt. (STACEE)



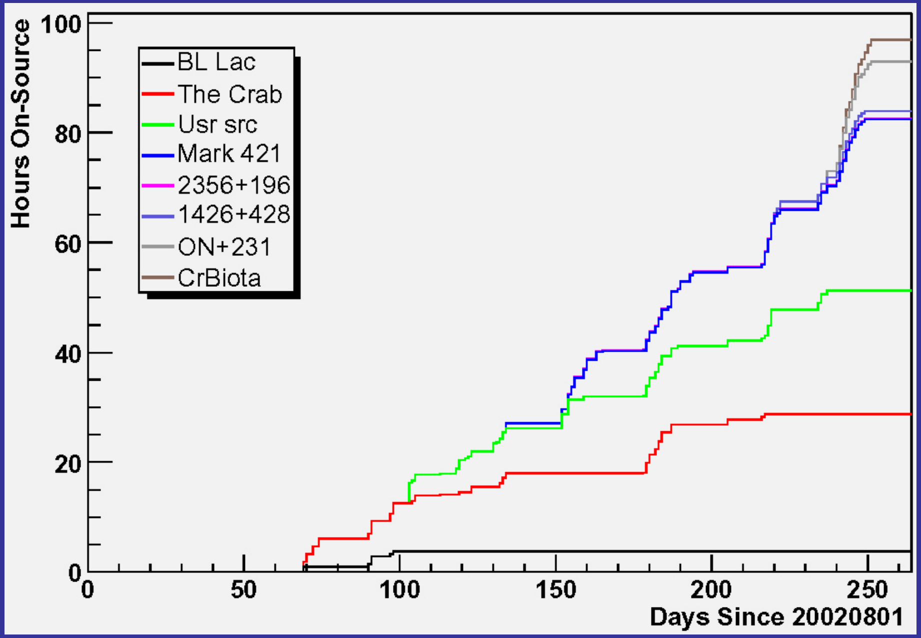
Each heliostat maps → single pixel in camera.

STACEE





STACEE
Observations & Performance



2002-3 Observations

Threshold:

4 p.e. (~ 50 GeV)

Crab Sensitivity (10s):

25 hrs – w/out hadron rejection

6 hrs – with rejection

100 GeV Performance:

0.16º Angular Resolution

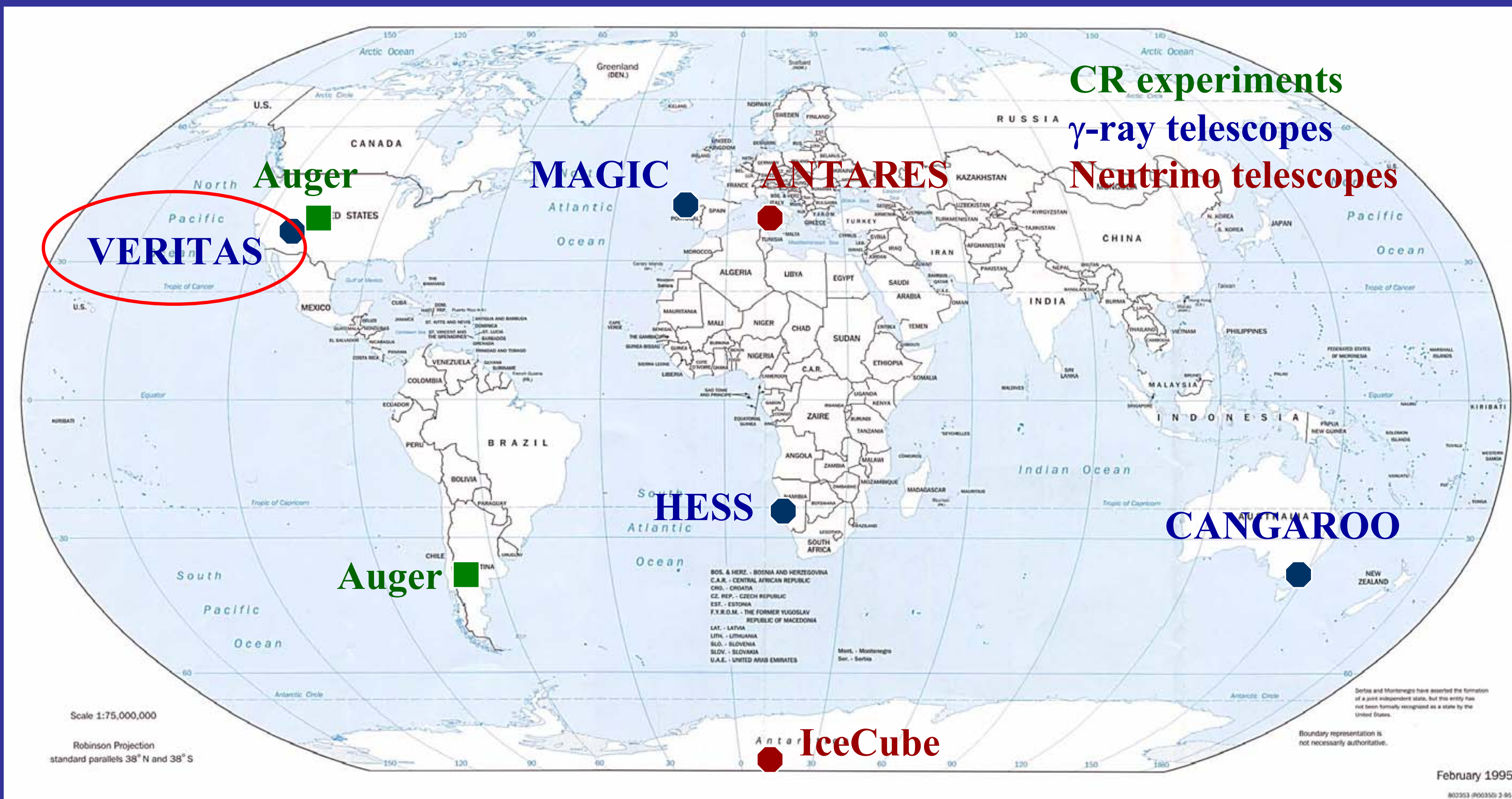
25% Energy Resolution

7,600 m^2 Effective Area

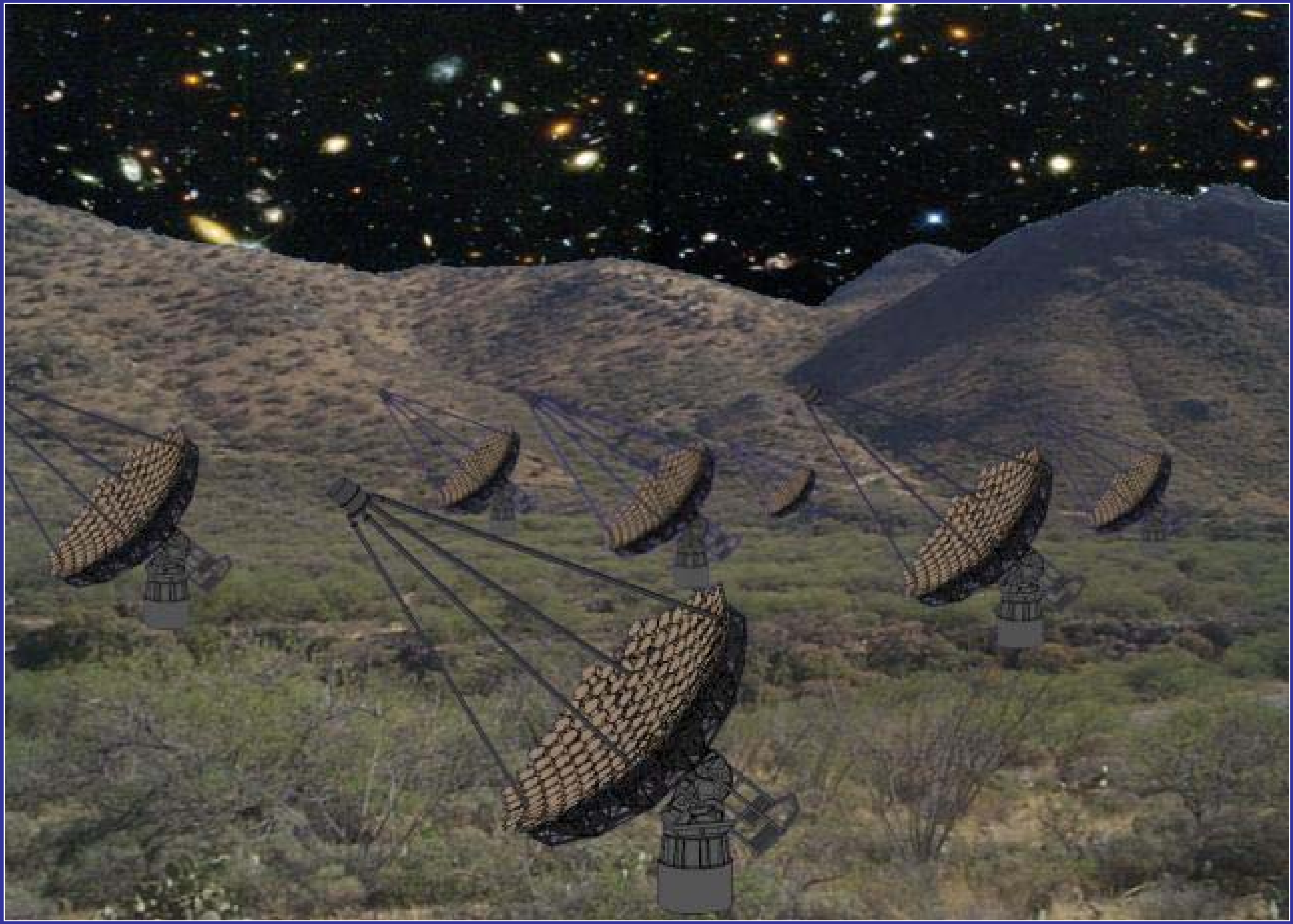
Future Experiments

In space

GLAST
EUSO

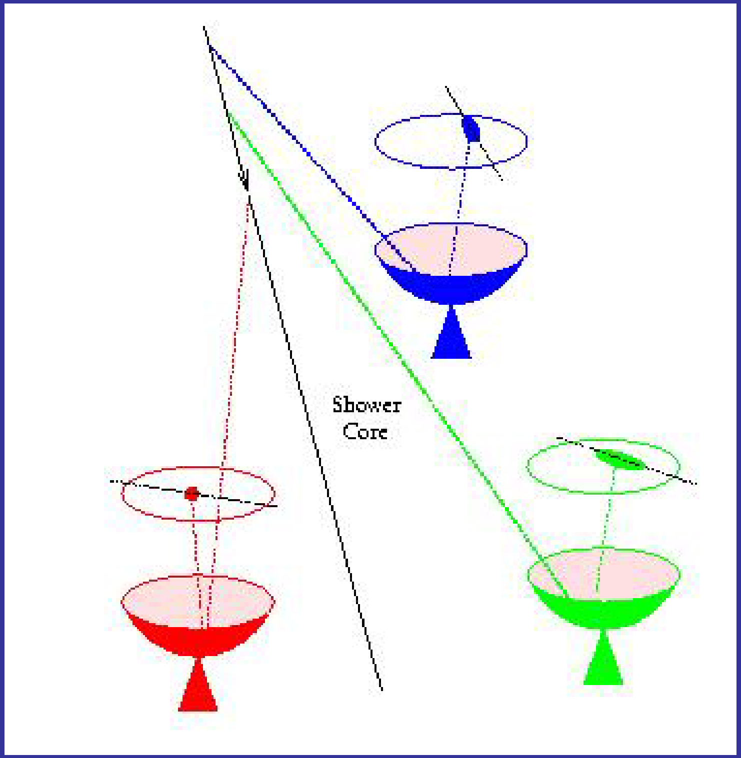


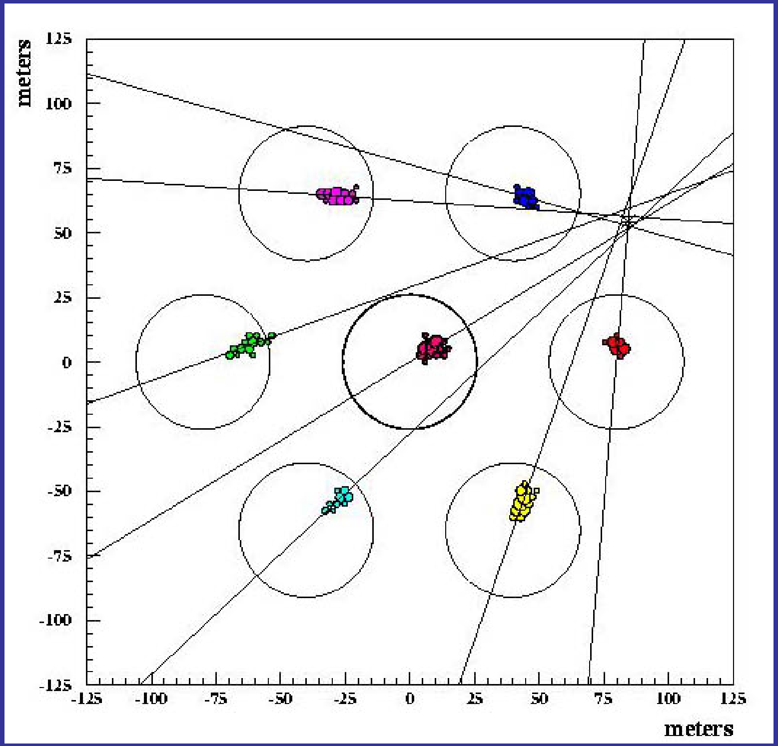
VERITAS Project



Arizona, USA

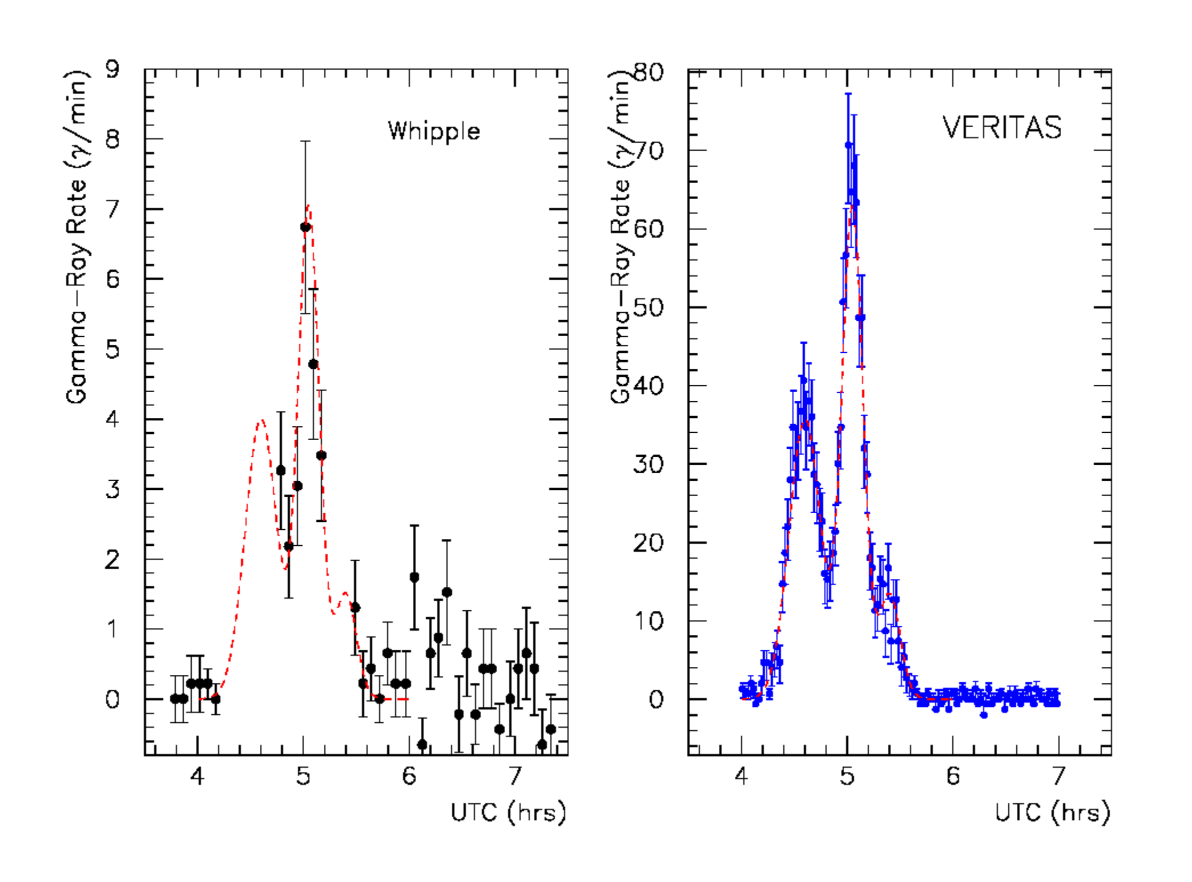
VERITAS Reconstruction





- Stereo reconstruction
- Excellent angular and energy resolution

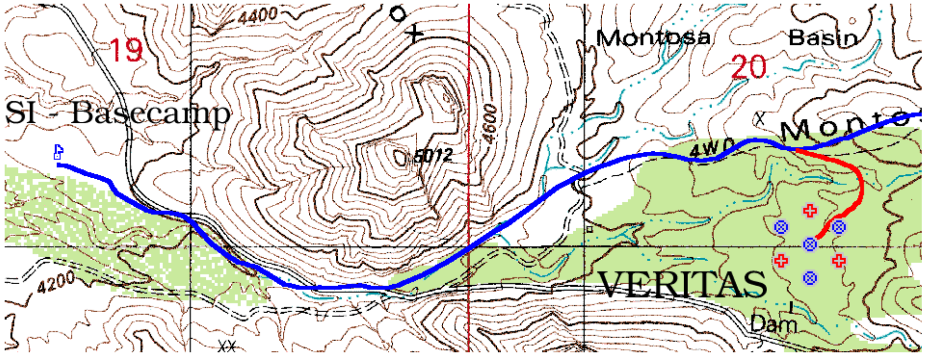
AGN Sensitivity



Whipple VERITAS (2005)

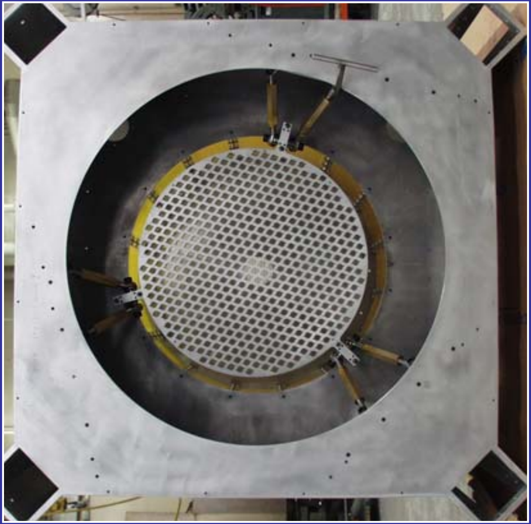
VERITAS Timeline

1997	First Proposal
1998-9	SAGENAP, Decadal Survey Presentations
	Strong endorsements
2001	OMB Announces Smithsonian re-organization.
2002	Forest Service turns down site request
	NSF & DOE learn to work together
2003	Prototype telescope progress



Proposed Site
Mt. Hopkins, AZ

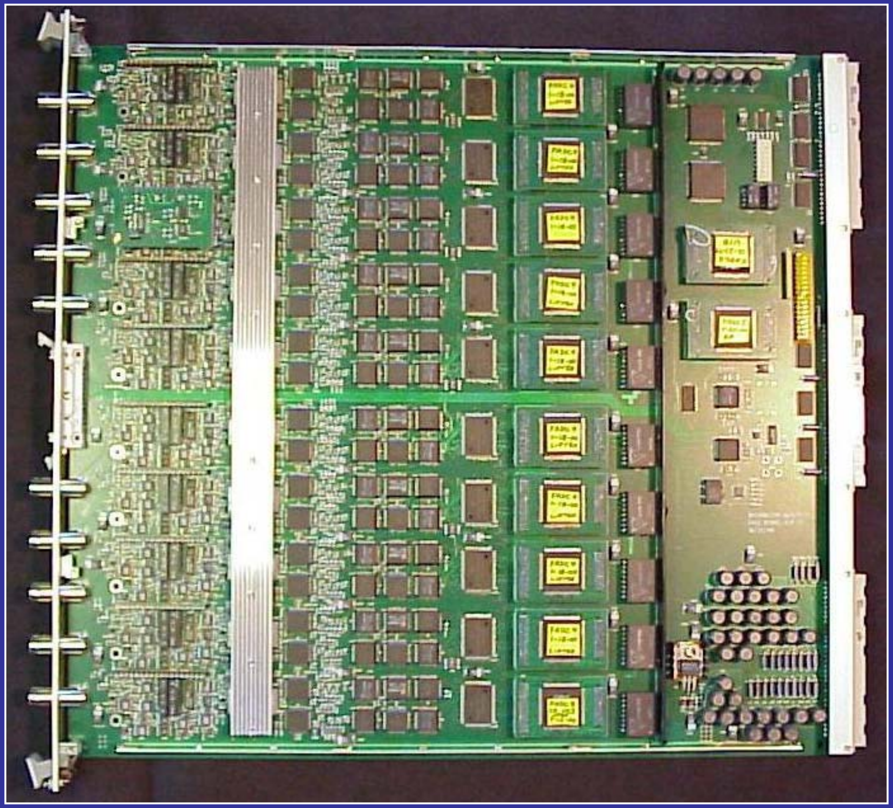
Camera & Electronics



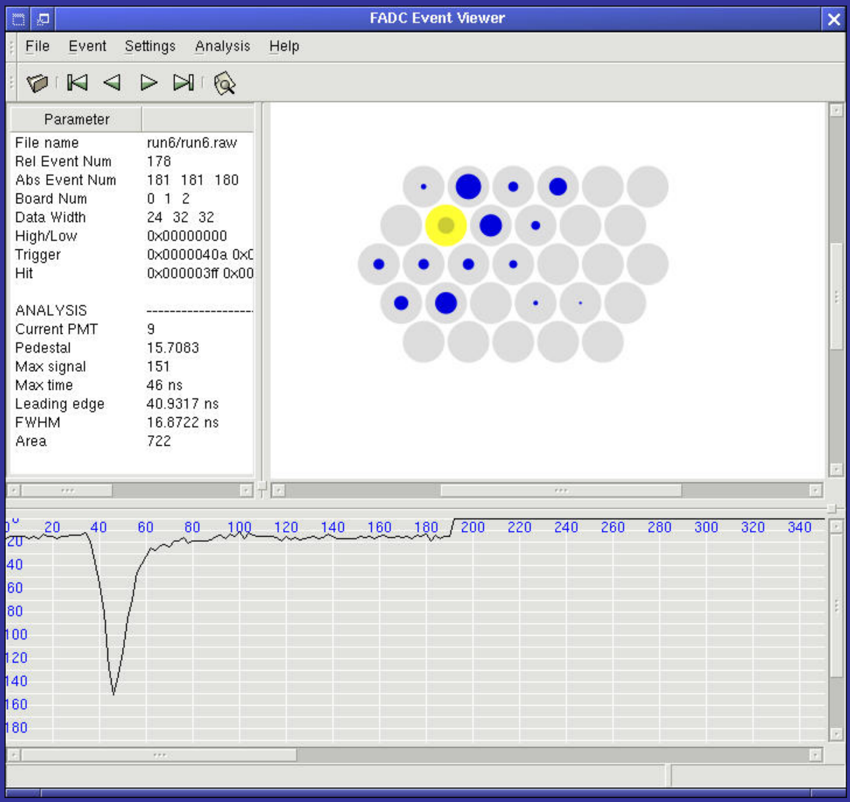
Camera Assembly

Electronics in Trailer

Flash-ADCs



Completed FADC Board
10 chans, 9U VME



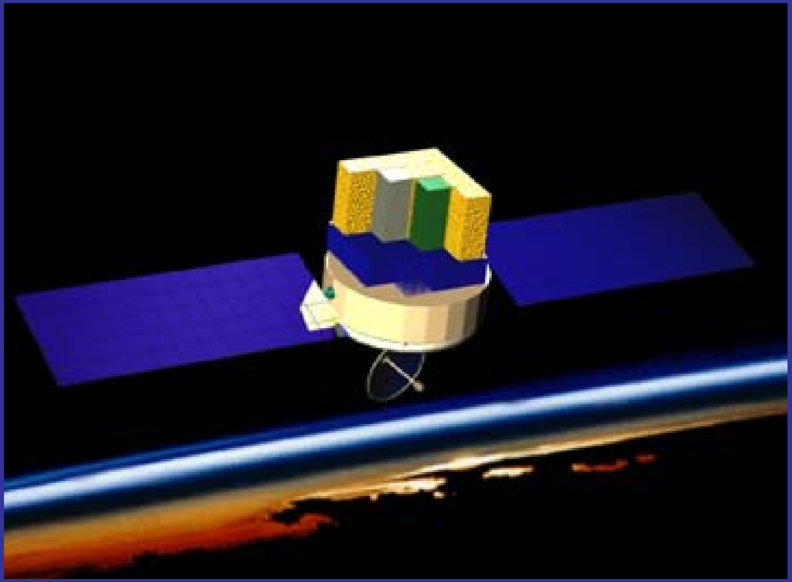
Cherenkov Waveform

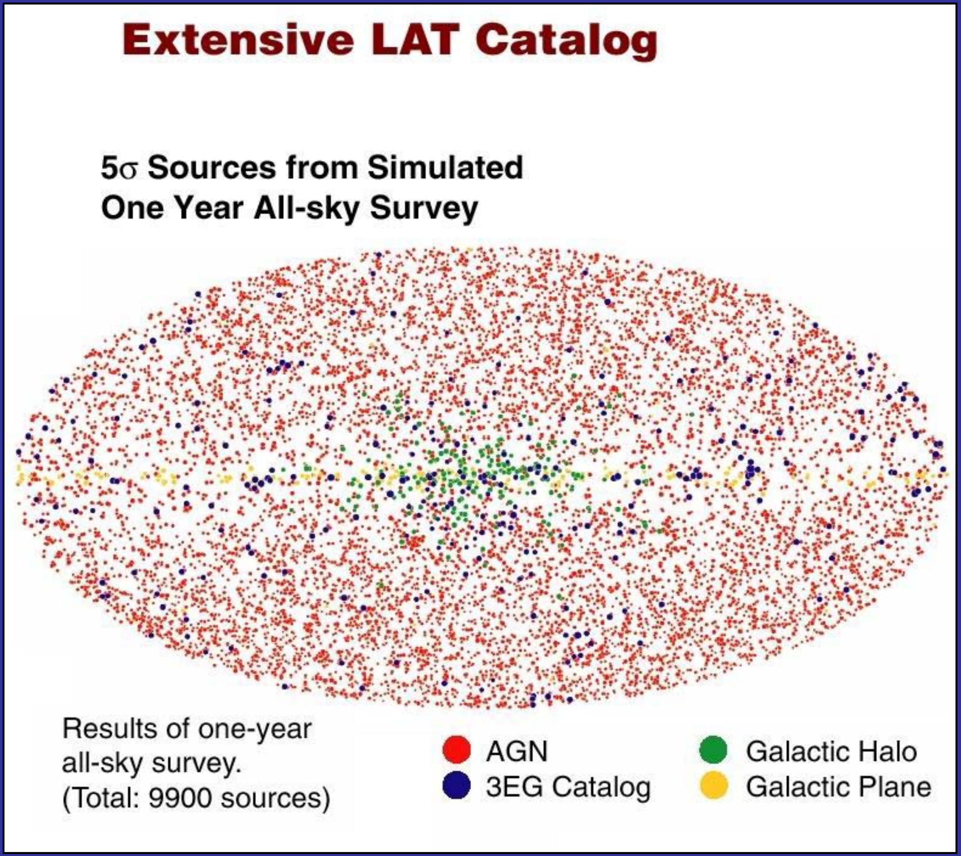
The Competition

HESS telescope (Namibia)

HESS camera

GLAST – Satellite Telescope





GLAST LAT Instrument:

- Si tracker
- CsI calorimeter
- Anti-coincidence veto

Sky map from 1 year survey

Launch in 2006.

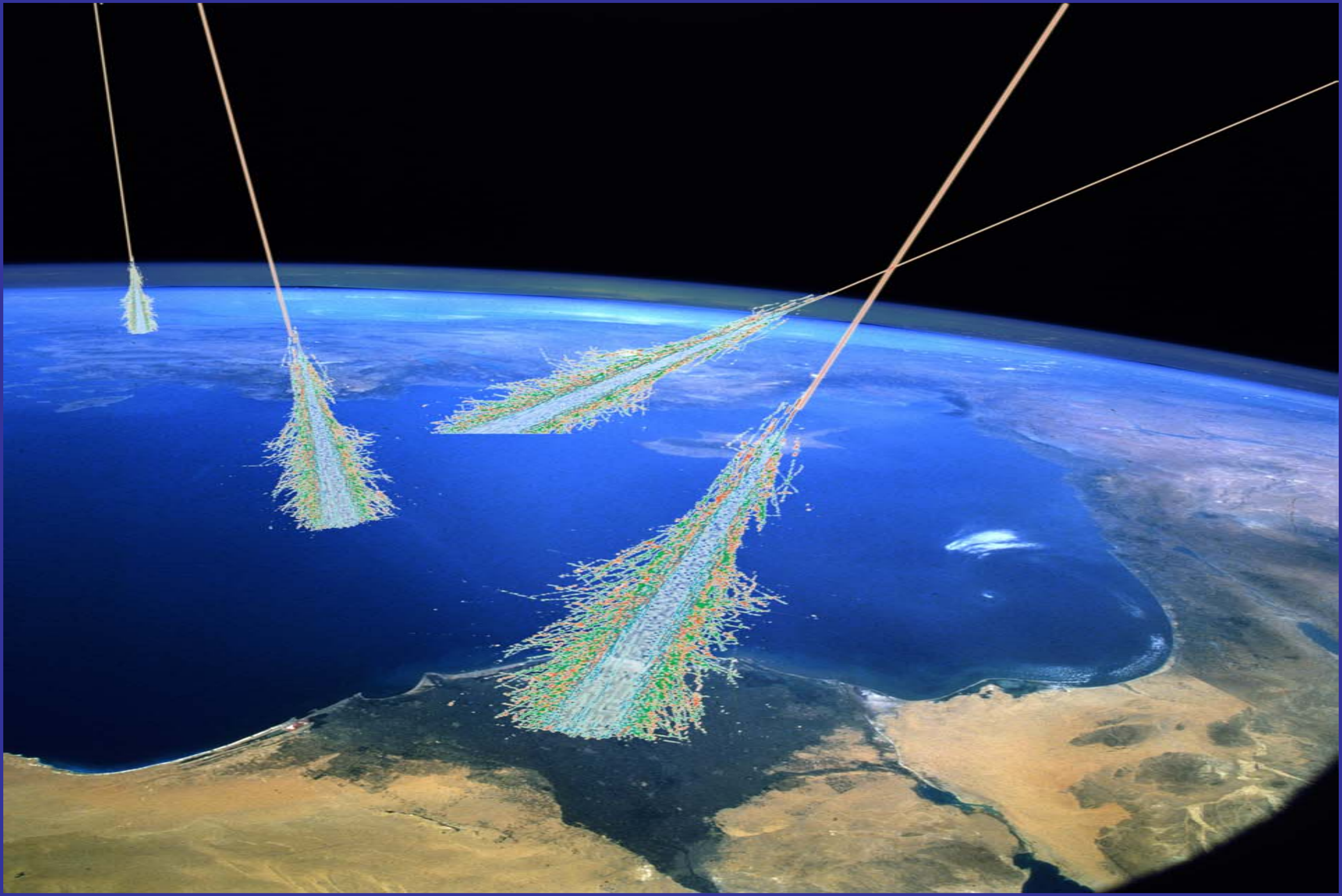
Summary

- High energy particle astrophysics: emerging, exciting area.
- Research is experimentally driven – probing limits of known astrophysics and possibly beyond standard models.
- For γ-rays: growing catalog of sources & phenomena
- (For cosmic rays: future experiments will resolve a very compelling problem.)

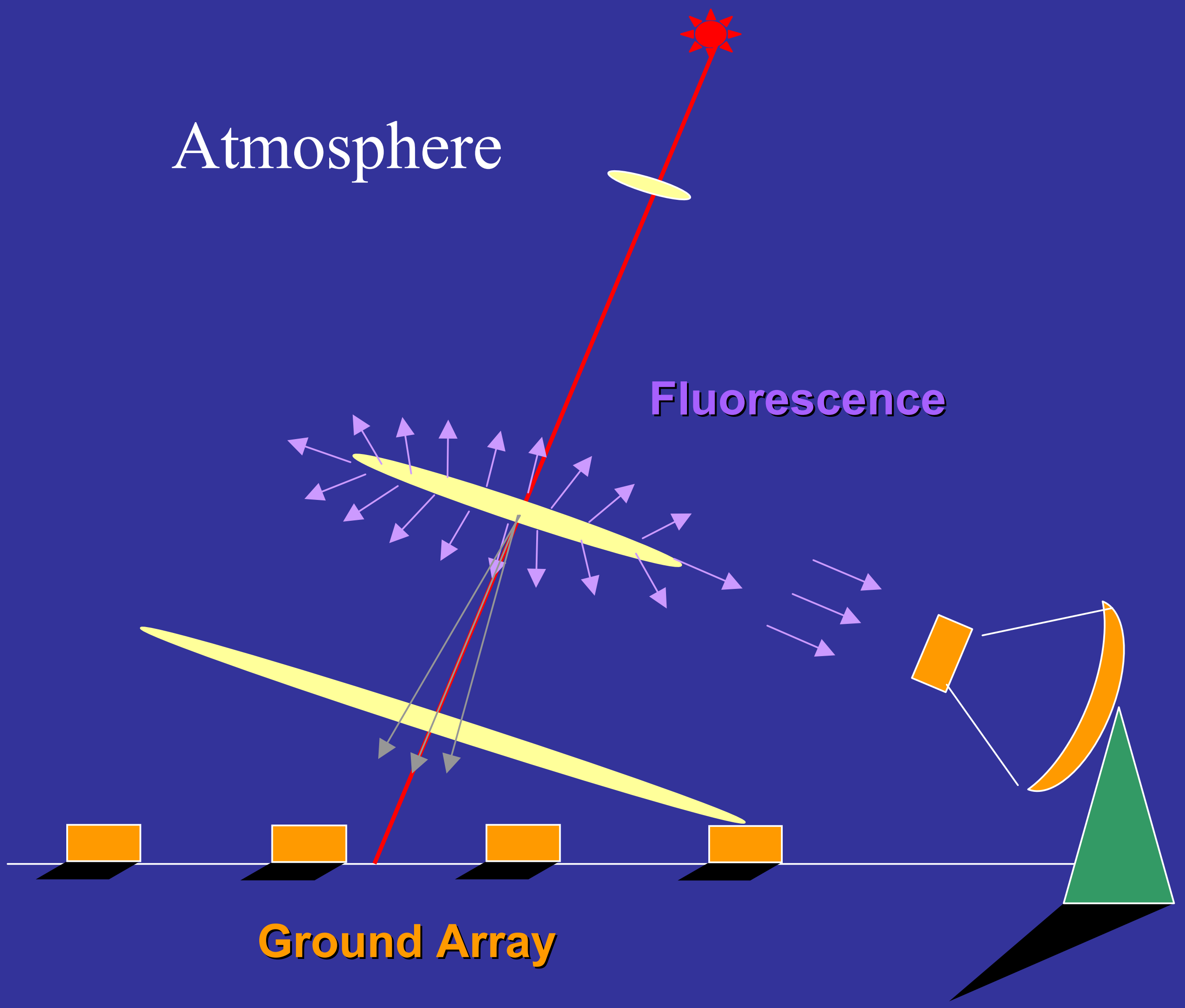
"The real voyage of discovery consists, not in seeking new landscapes, but in having new eyes."

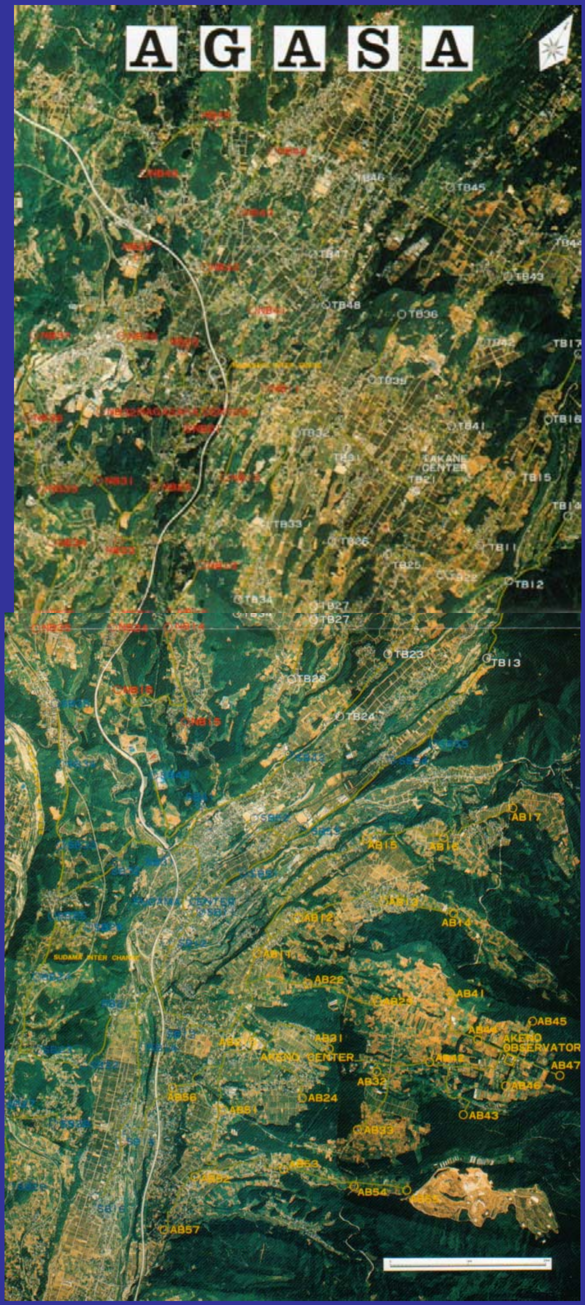
Marcel Proust (1871-1922)

Giant Air Showers (> 10^{20} eV)



UHECR Detection





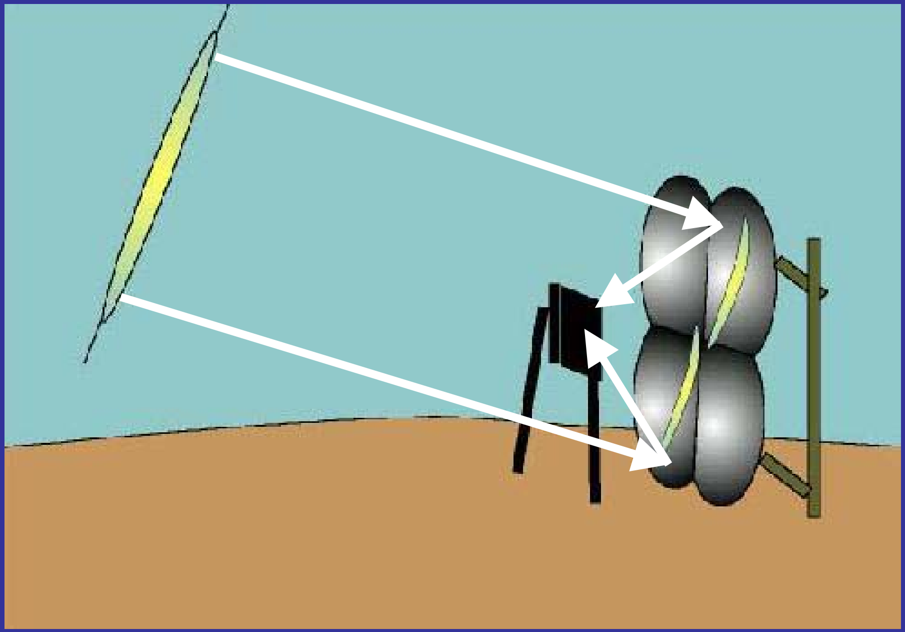
UHECR Detectors - AGASA

- 100 km^2 surface array
- Honshu, Japan

Charged particle detectors

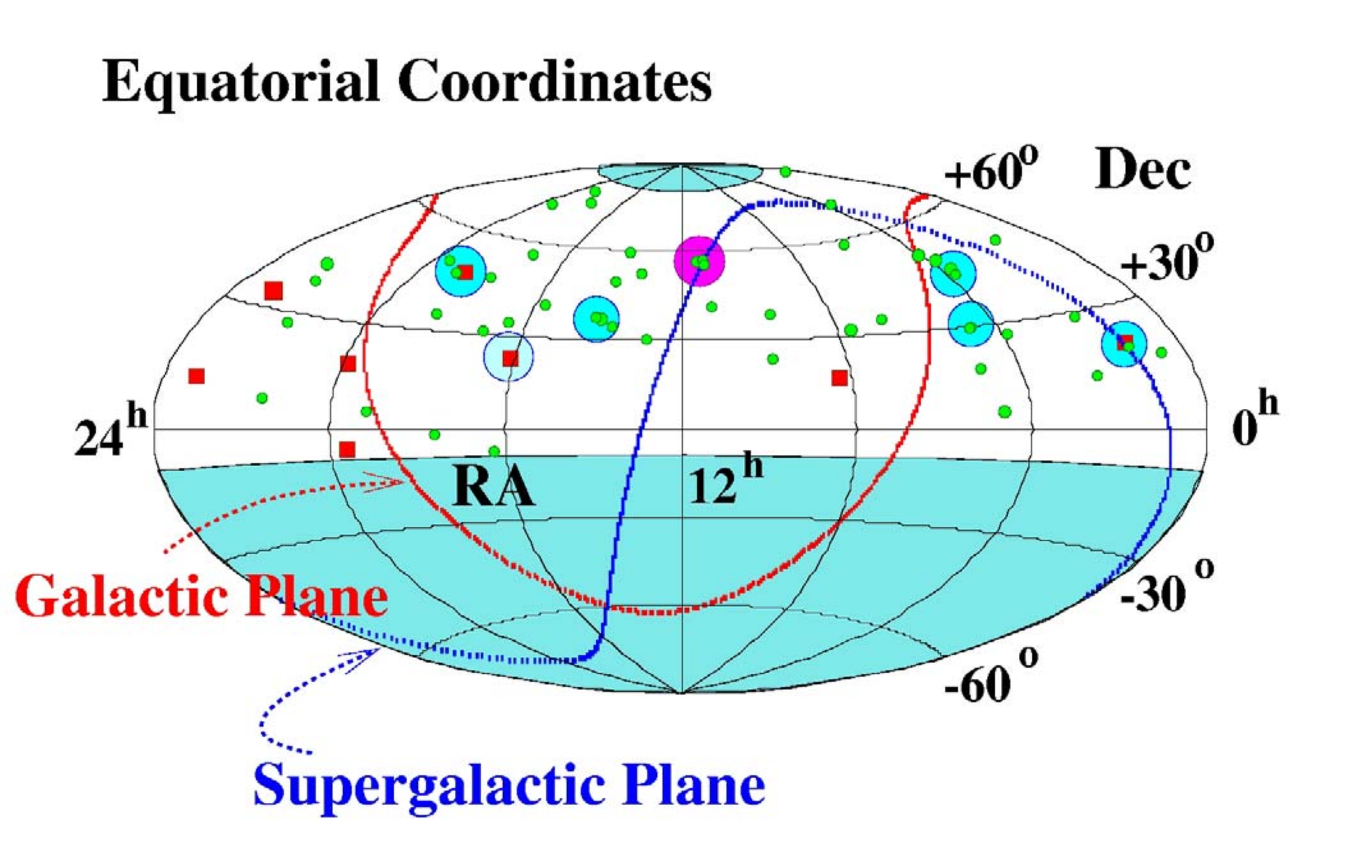
UHECR Detectors - Fly's Eye

HiRes mirror sheds
Dugway, UT



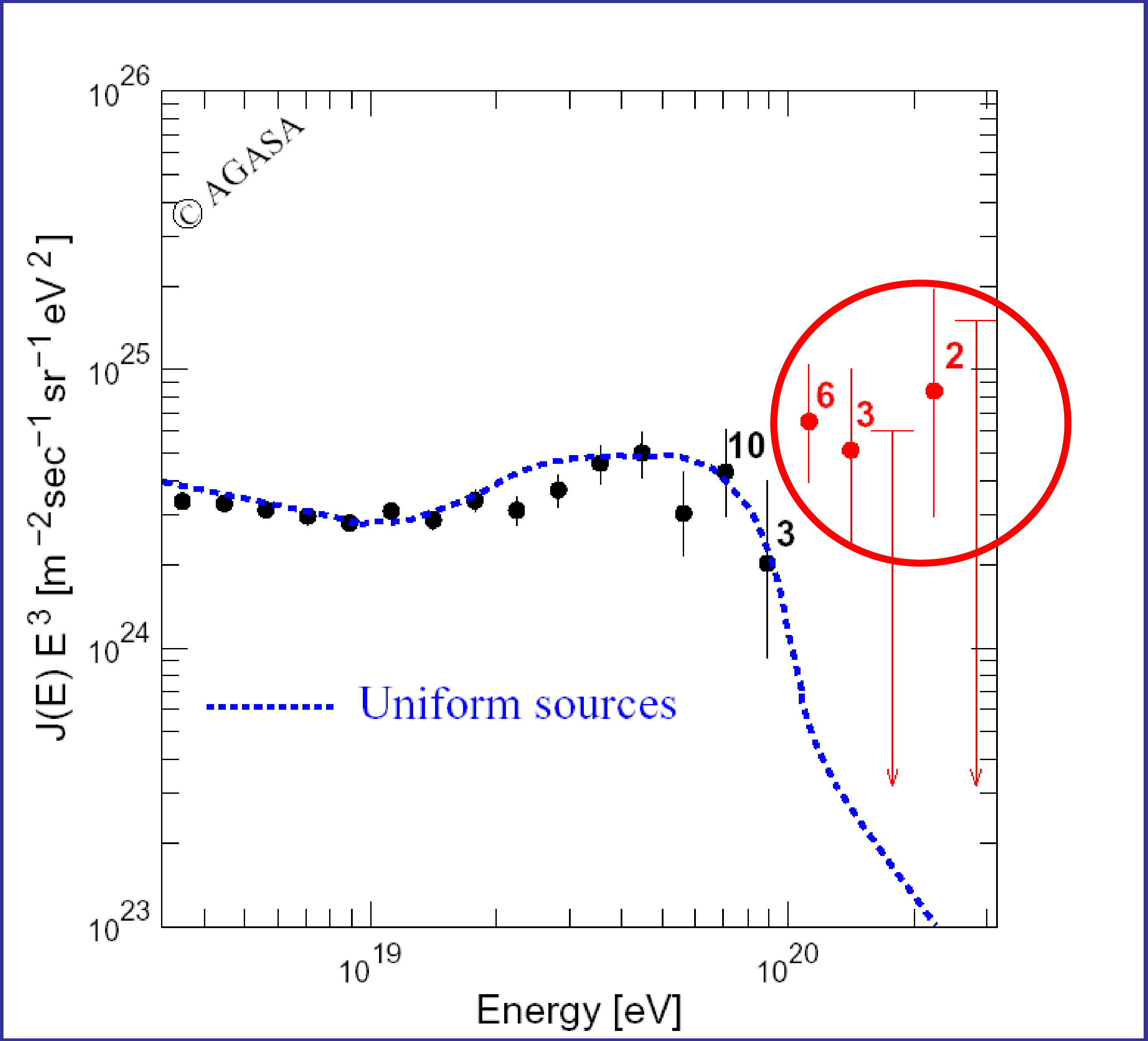
Nitrogen fluorescence technique

UHECR Sky Map



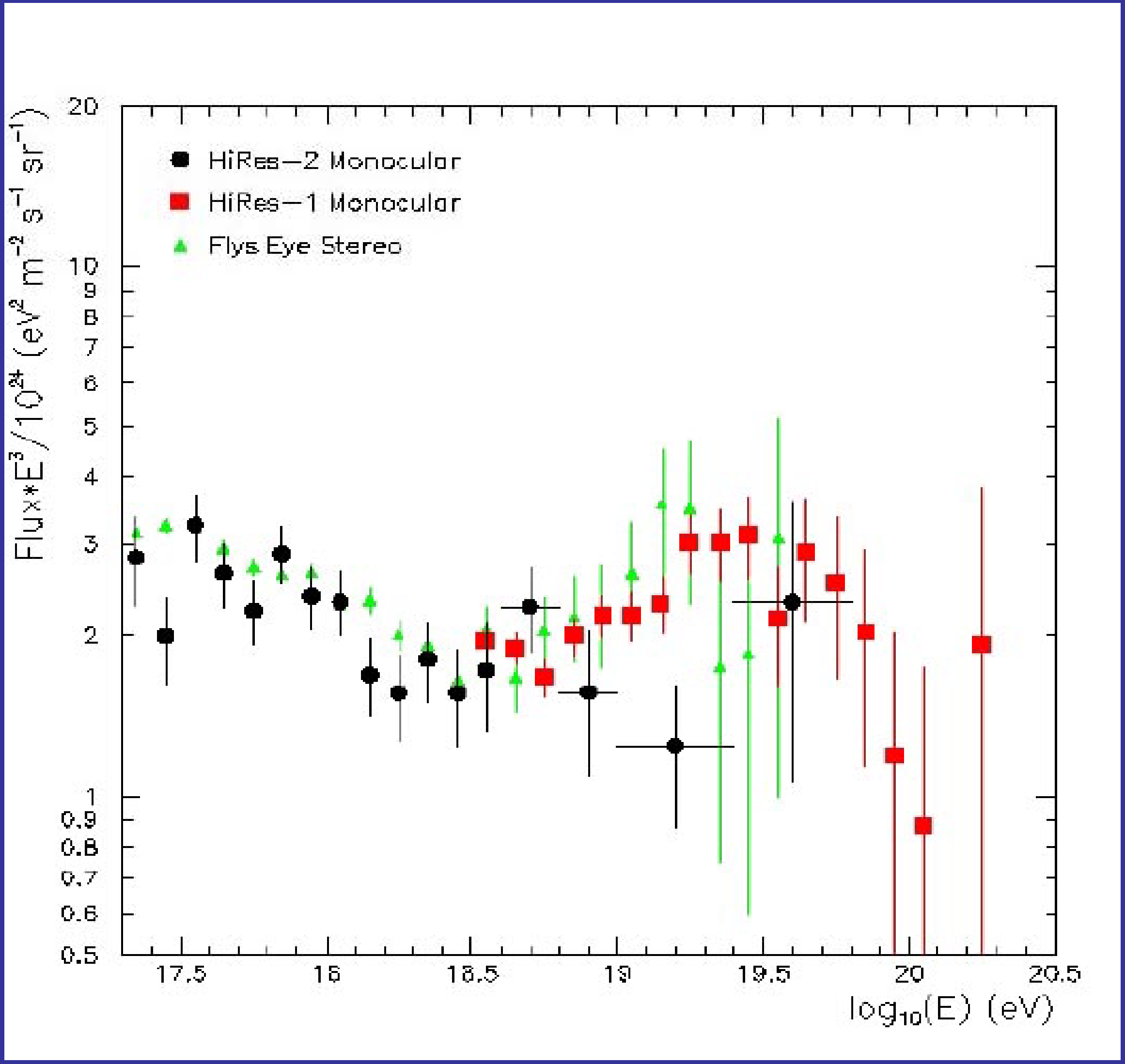
AGASA 59 evts > 4 x 10^{19} eV
Possible clustering – but not compelling.

UHECR Spectrum - AGASA

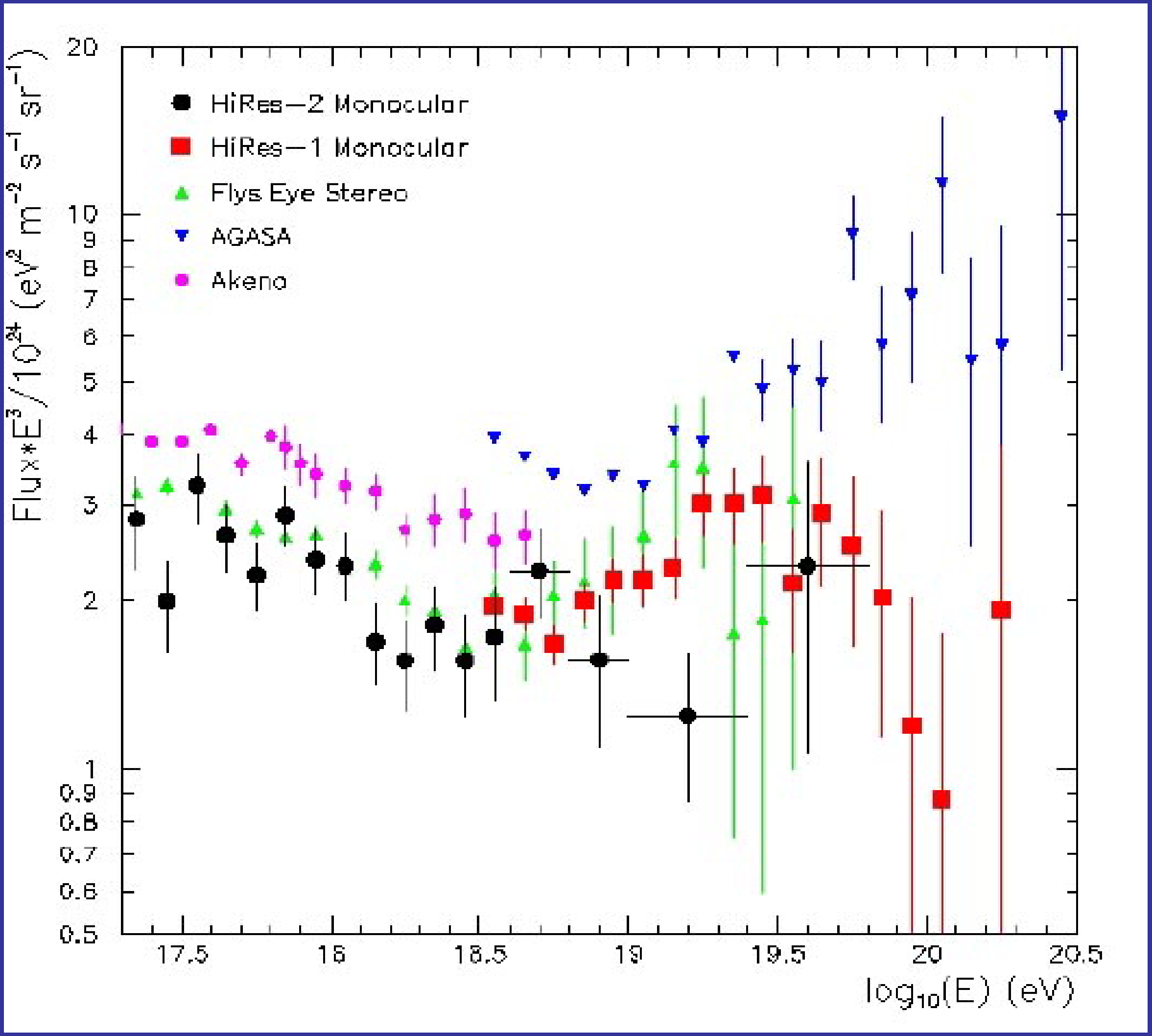


AGASA: ~ 11 events above 10^{20} eV!!!

UHECR Spectrum –Fly's Eye HiRes

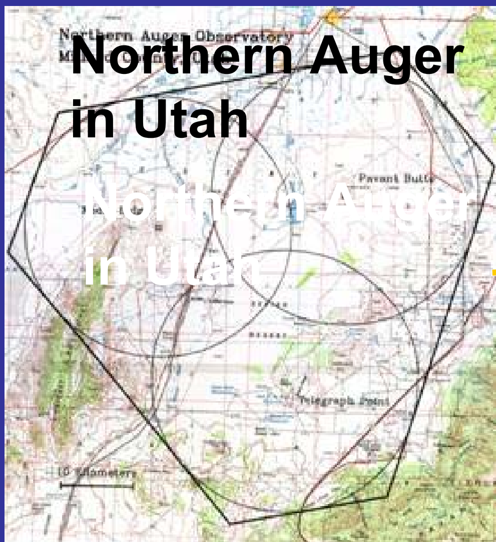


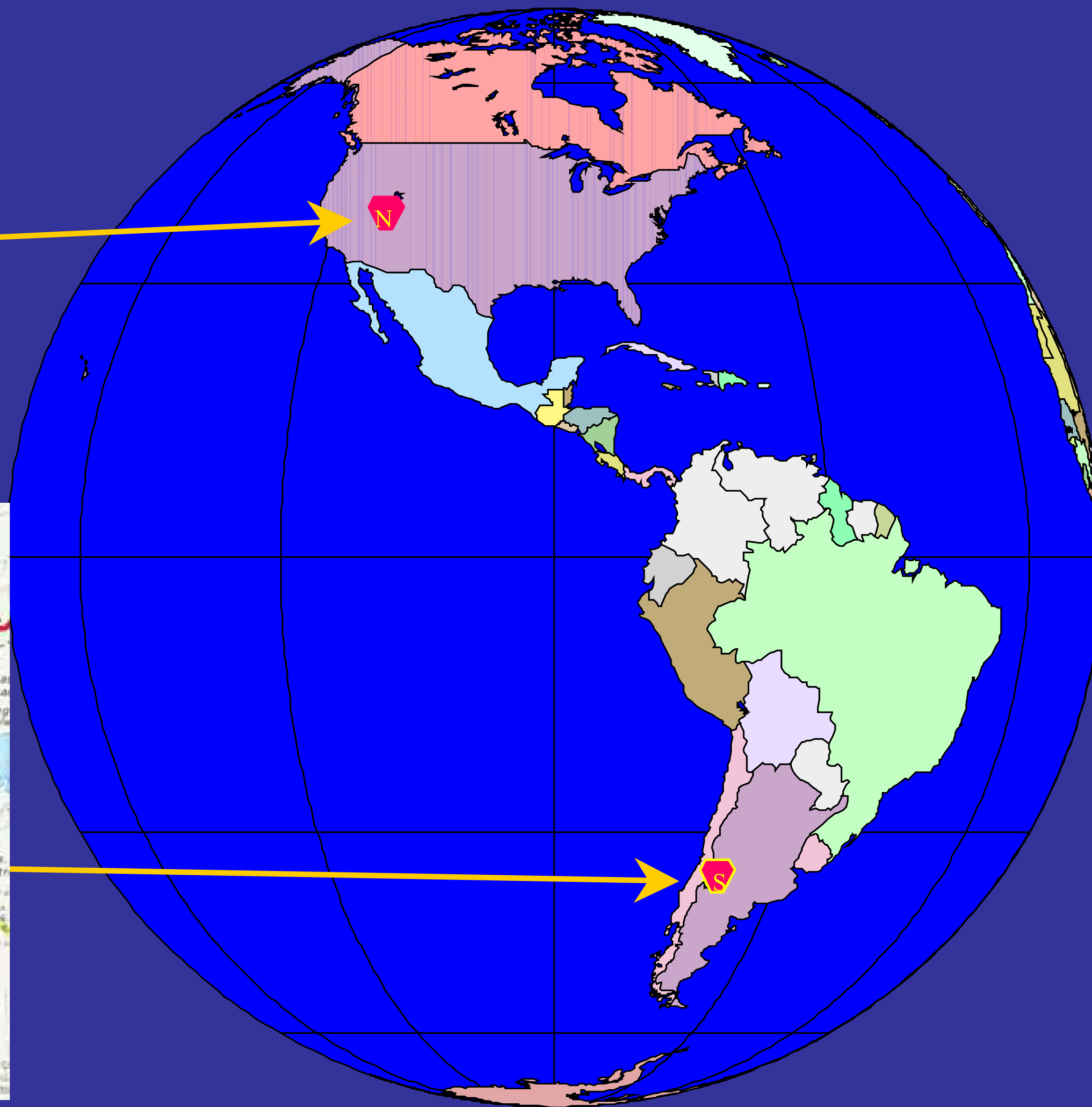
AGASA vs HiRes



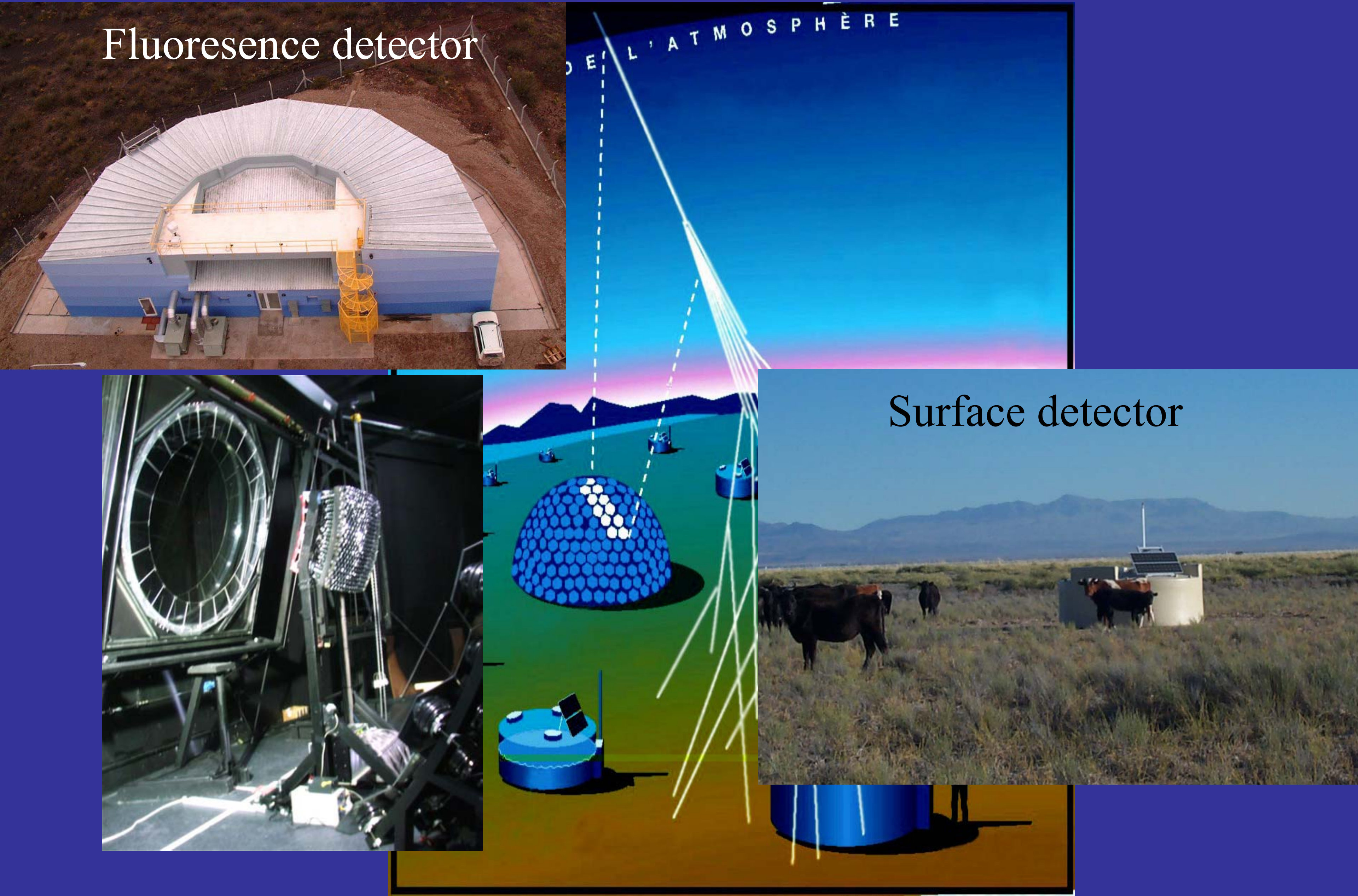
Clear inconsistency – Energy calibration problem?

Pierre Auger Project

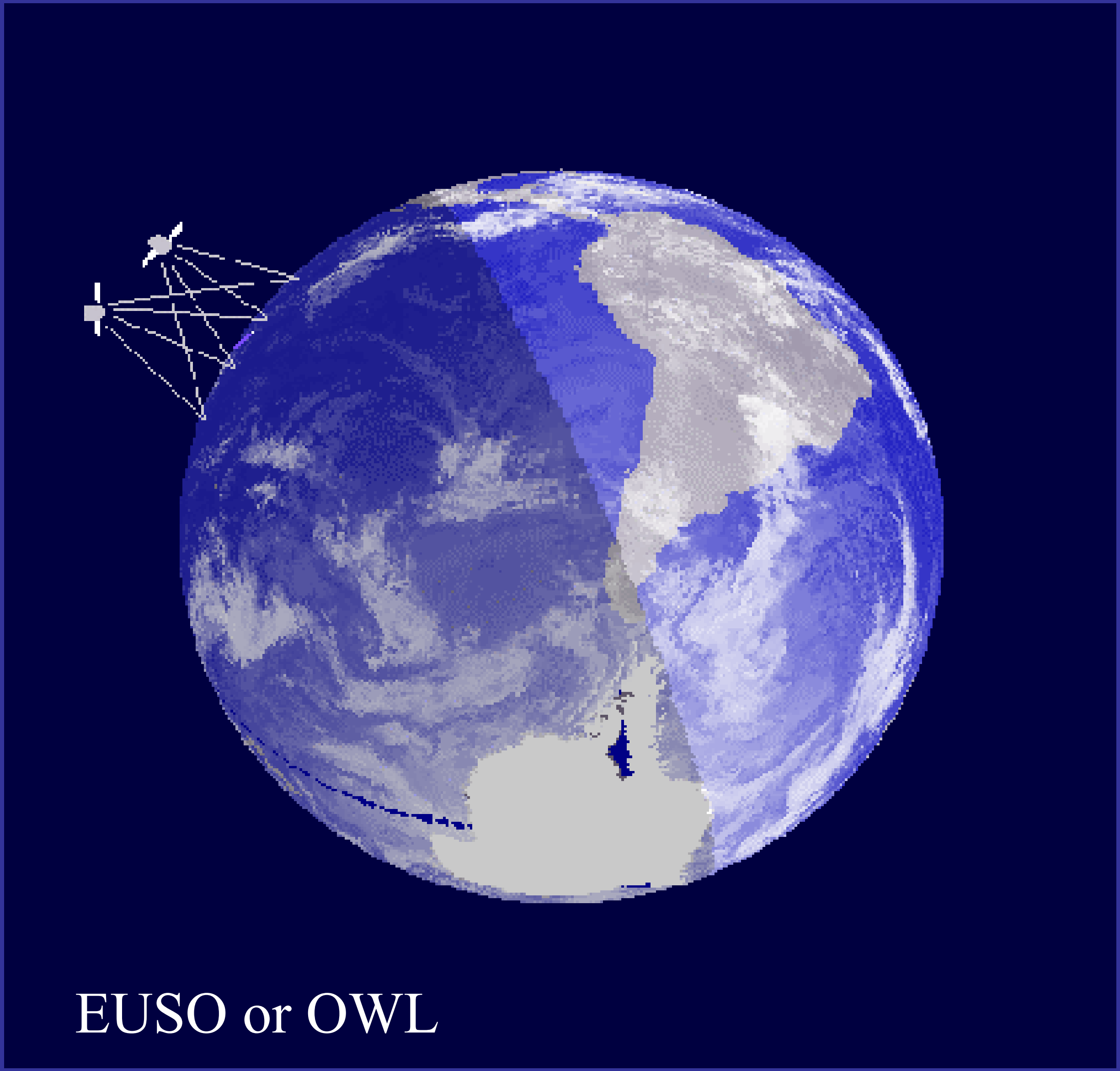




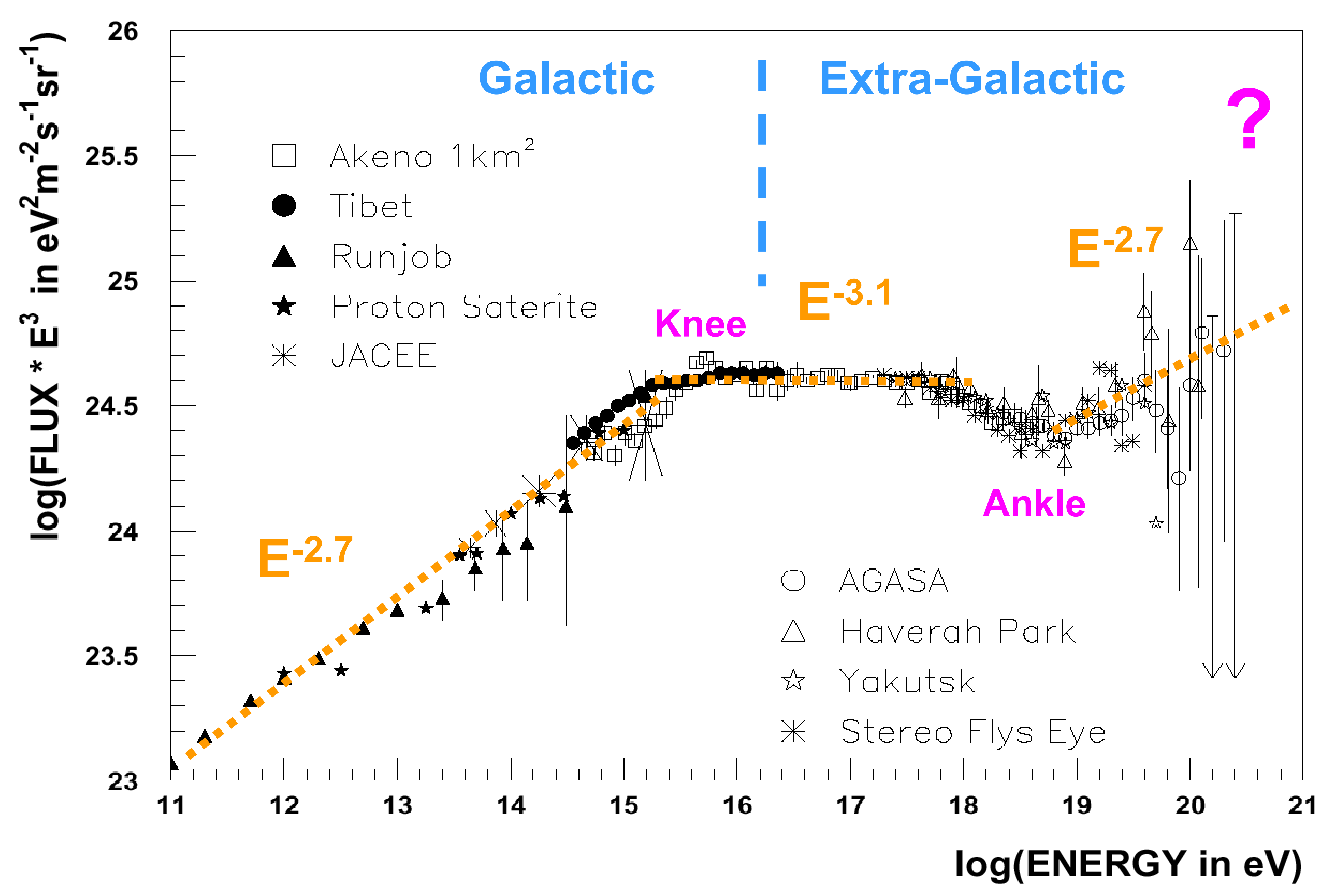
Pierre Auger Project



Air Showers From Space



Energy Spectrum - Flattened



Extra

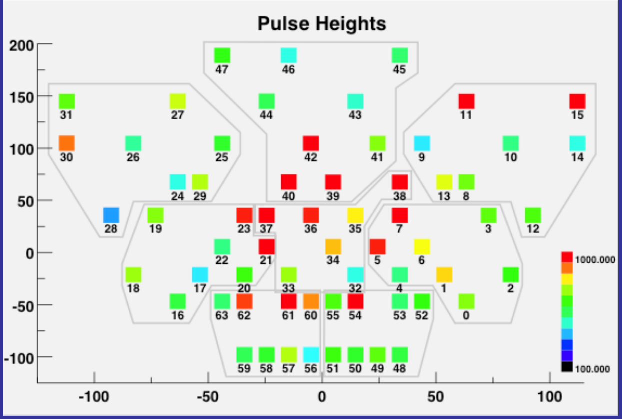
Capabilities of VERITAS

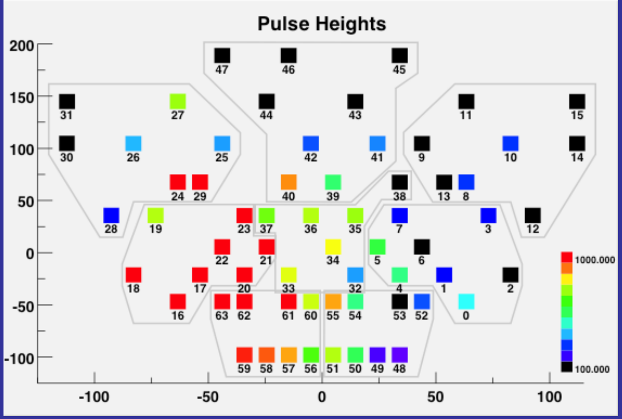
	VERITAS-4 Performance		
Operating Conditions	4 x 112 m^2 mirrors Trigger (tel): 3 pixels > 5.6 pe Trigger (array): 3 of 4 telescopes		
Peak Energy	110 GeV		
Crab Nebula Rate	35 gamma rays per minute		
<u>Energy</u>	<u>Collecting area</u>	<u>Angular Res</u>	<u>Energy Res</u>
100 GeV	3.3×10^4 m^2	8.6 arc-min	< 25%
1 TeV	2.2×10^5 m^2	4.3 arc-min	< 15 %
10 TeV	3.0×10^5 m^2	1.8 arc-min	< 15%
Flux sensitivity (50hr)			
10 TeV	1.4×10^{-11} erg cm^{-2} s^{-1}		
1 TeV	1.4×10^{-12} erg cm^{-2} s^{-1}		
100 GeV	3.7×10^{-12} erg cm^{-2} s^{-1}		

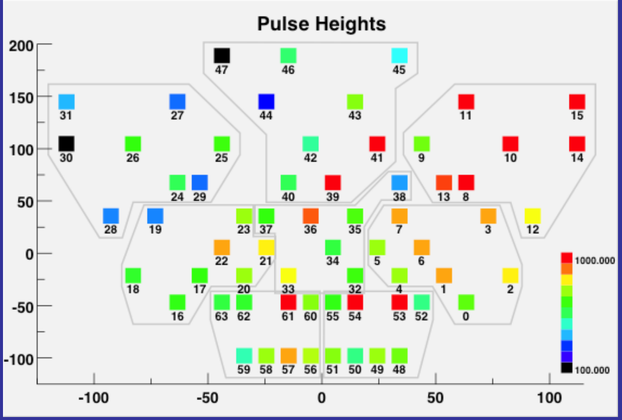
STACEE Showers

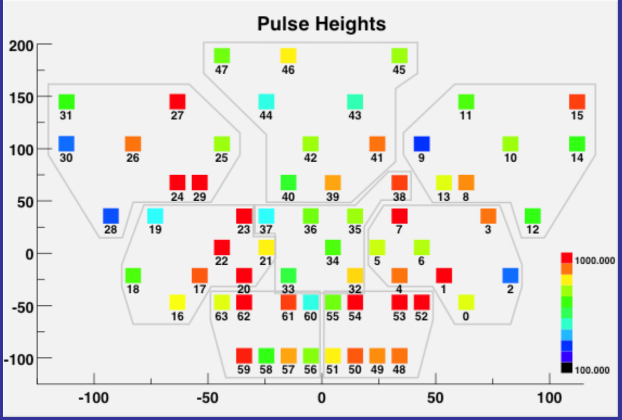
Monte Carlo 100 GeV gammas

Zenith data showers



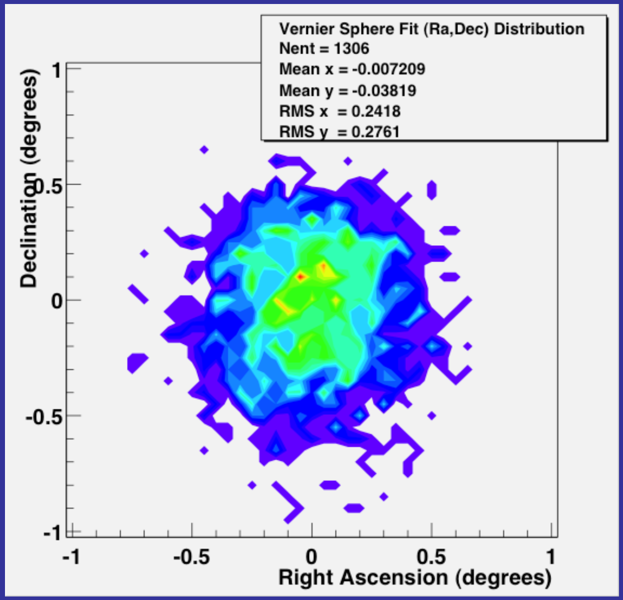


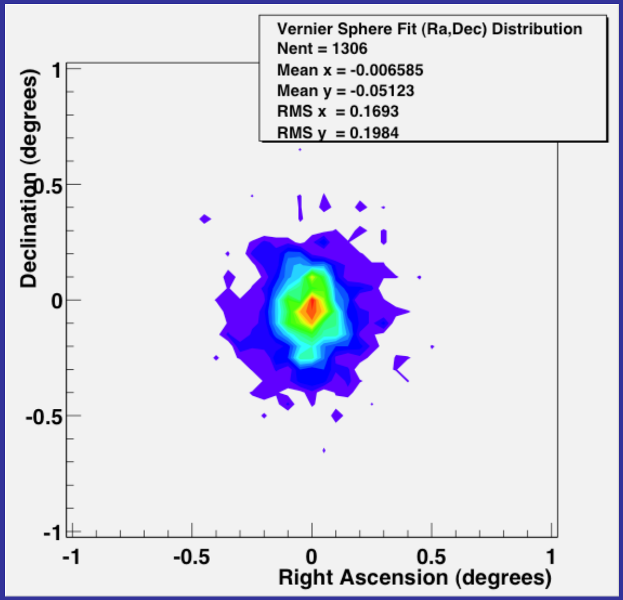




STACEE Shower Reconstruction

Simulated Vertical Gamma Rays

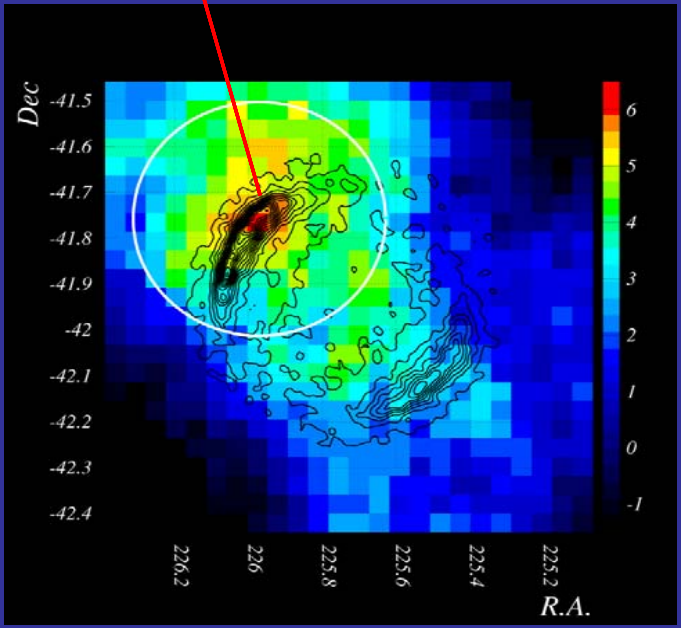


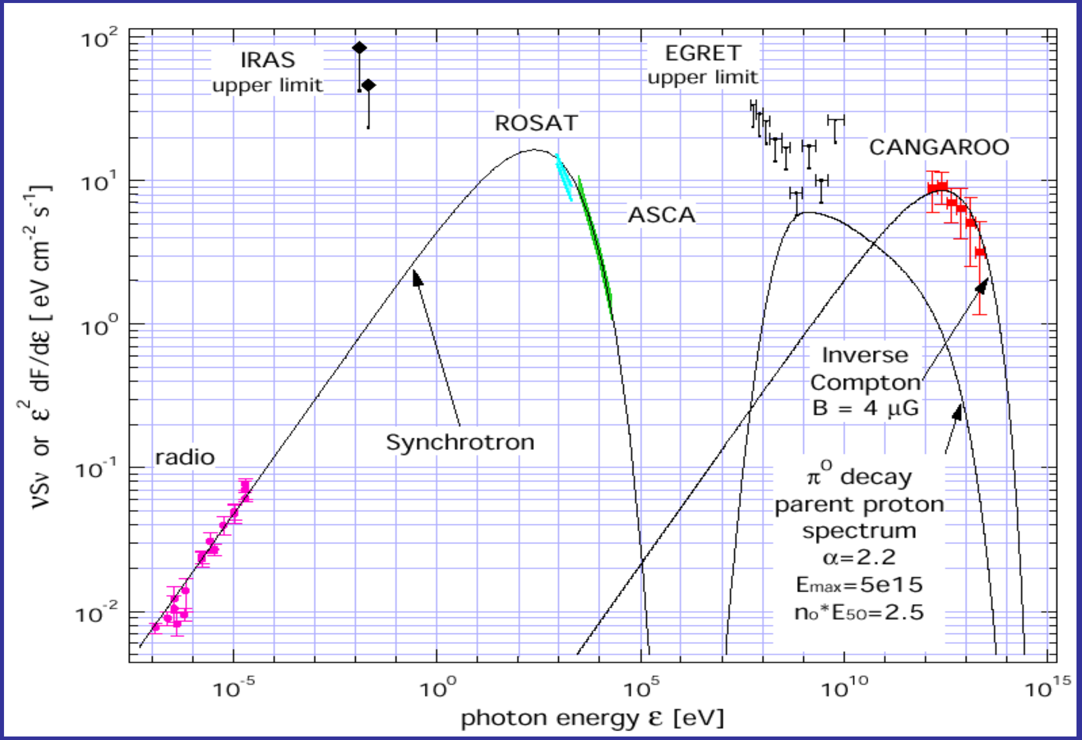


Core finding with pulse height info (right) improves energy and angular resolution

Background rejection quality factor of 2.5 to 3.5

Remnant SN1006





γ-ray data (CANGAROO)
X-ray data contours

Evidence for non-thermal acceleration of electrons. Very complicated!

Understand SNR's reasonably well – no direct evidence for CR's.

High-energy ν Sky