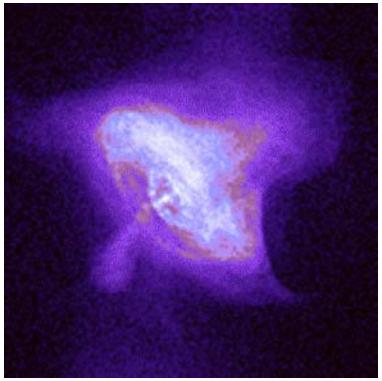
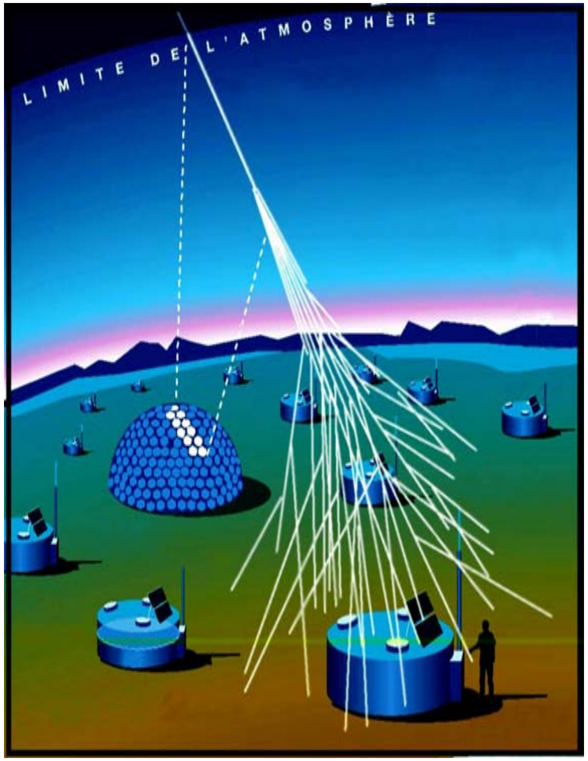
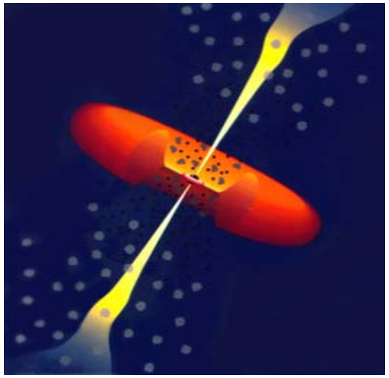
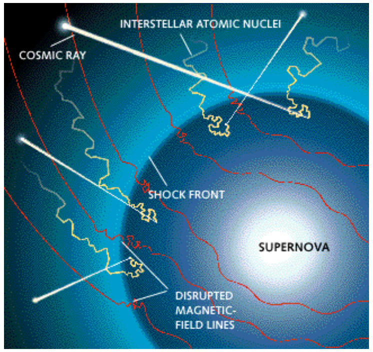
The Extreme Universe

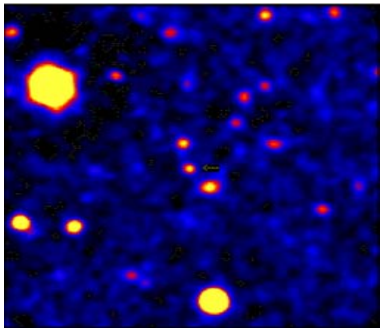
(The Limits of Particle Physics and Astronomy)











Rene A. Ong
University of California, Los Angeles

Brown University Colloquium
1 March 2004

OUTLINE

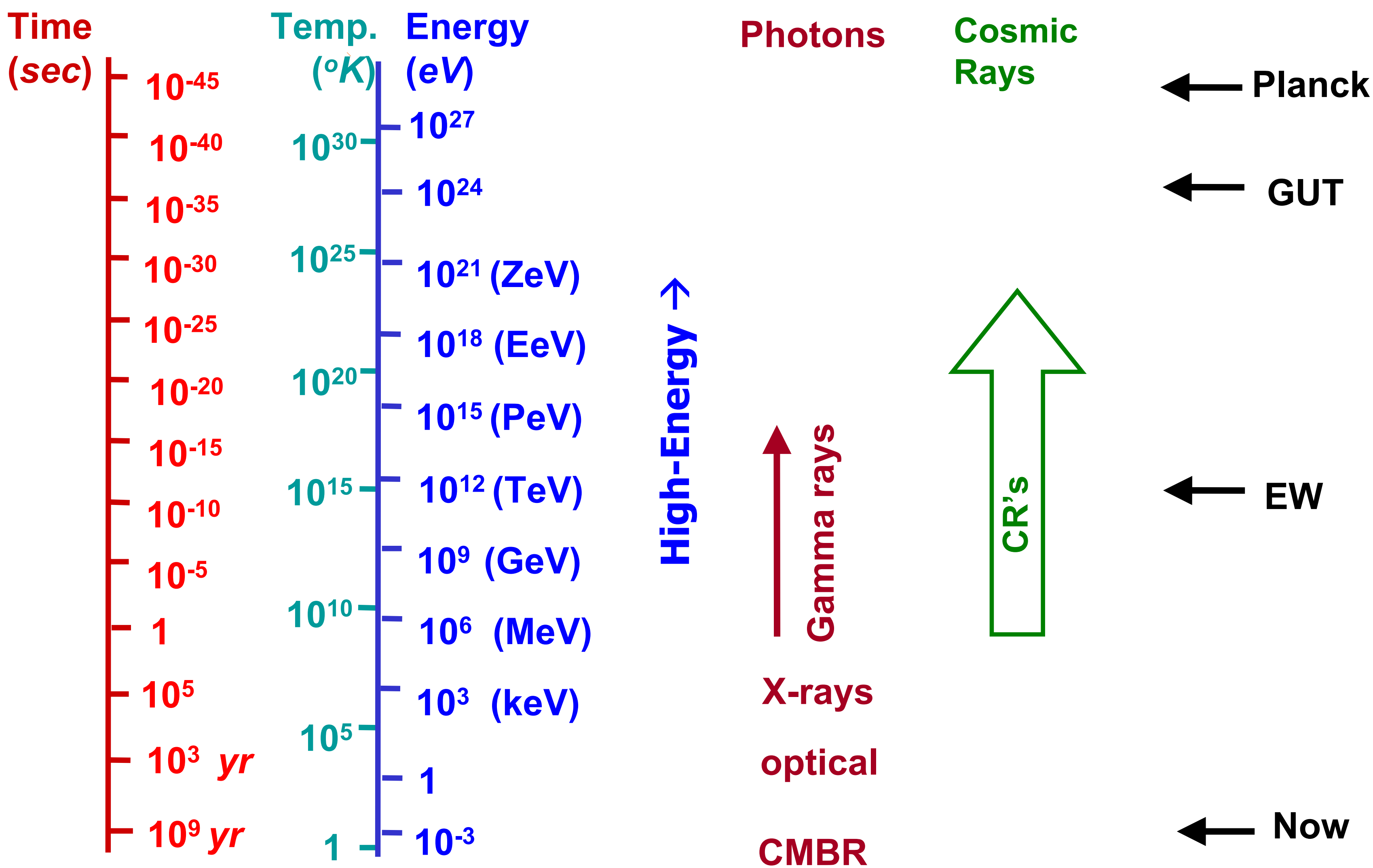
- Introduction
  - **Messengers, energy scales, & questions.**
- Detecting Very High Energy (VHE) particles
- Physics: Origin of VHE particles
  - **Power sources & particle acceleration.**
  - **Probing particle physics and cosmology**
- Astrophysics: Sources and what not
  - **γ-ray and ν skies at TeV energies.**
  - **Active galaxies and dark matter.**
- Future

Cosmic Messengers

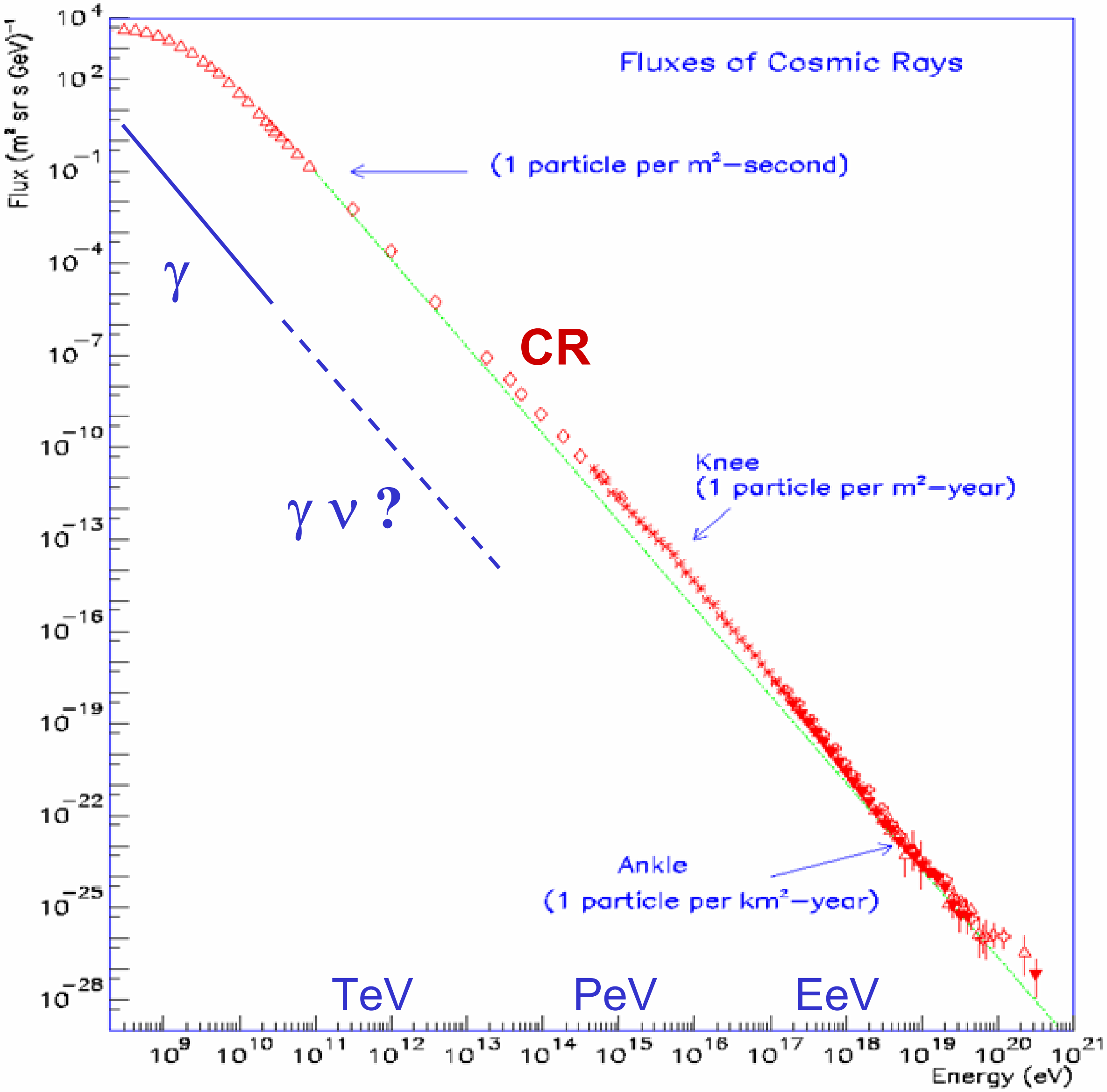
We know about the Universe primarily from:

	Particles	charge	status
1.	**Photons**	neutral	crucial
2.	**Cosmic Rays**	charged	v. important
3.	**Neutrinos**	neutral	developing
4.	**Grav. Waves**	neutral	infancy
5.	**(New stable particle)**		

Energy Scales

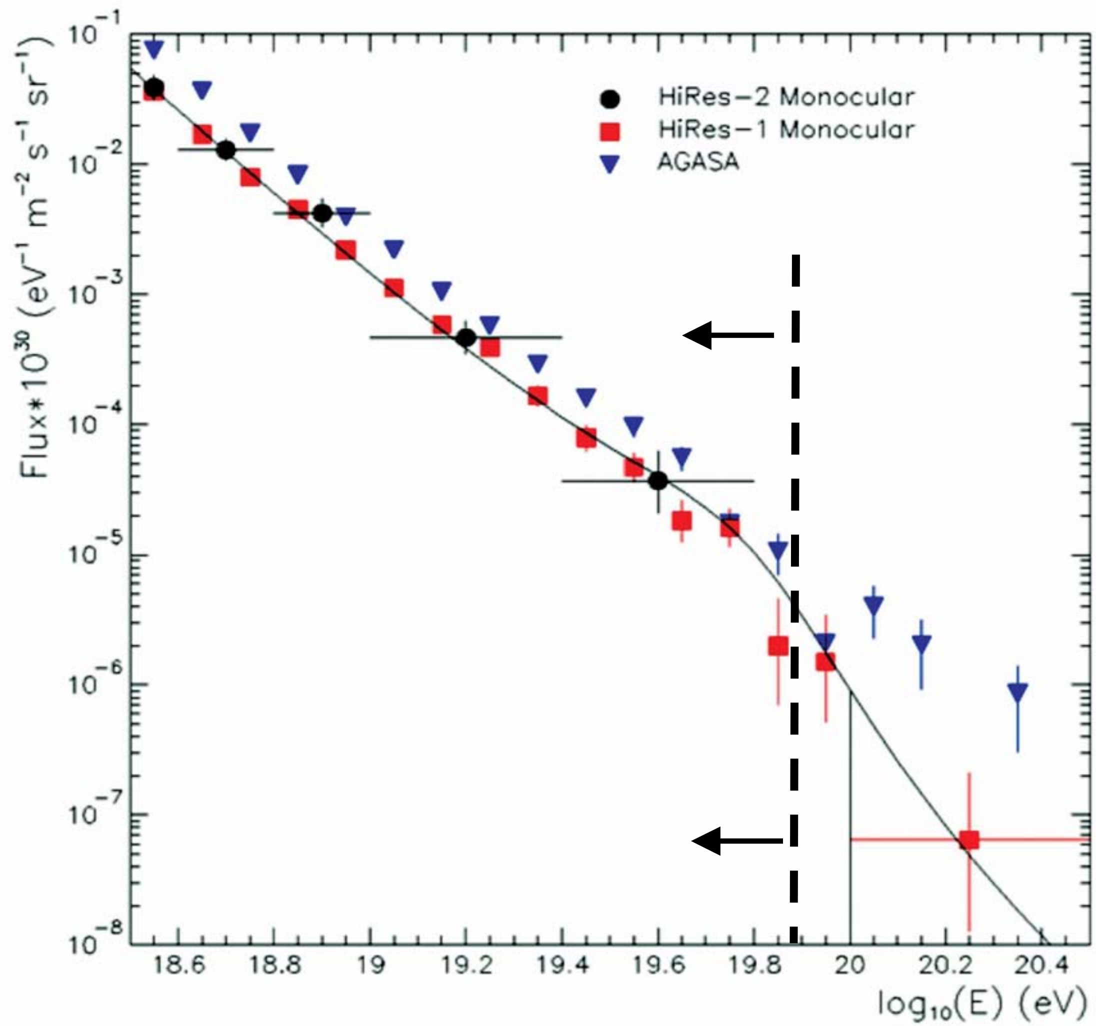


Cosmic Ray Spectrum



- Total,diffuse spectrum individual species not resolved.
- Power-law spectrum E^{-3} differential.
- $E > 10^{20}$ eV.
- Energy density ~ 1 eV / cm^3.
- What about gammas and neutrinos ?

At the Highest Energies



Particles E > 10^{20} eV are not expected:

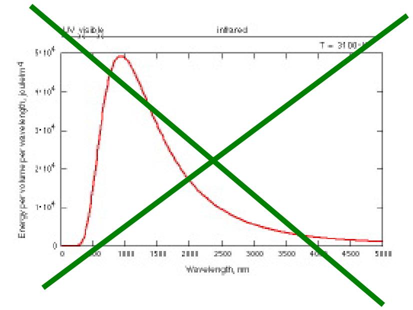
1. Very hard to accelerate to these energies.

2. Nuclei cannot travel beyond 100 Mpc

   $p\,\gamma_{cmbr} \rightarrow \Delta^+ \rightarrow \pi$'s

What are these particles and where do they come from ??

HE Implications



Phenomenological

Energy scale is reached by either:

1. Non-thermal & radiative processes (**Astrophysics**).

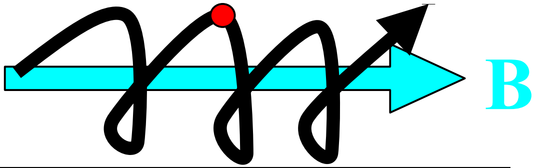
2. Decays, interactions from higher mass scale (**Particle Physics**).

Experimental

1. Particles are detected by total absorption.

2. We are required to measure tiny fluxes. (< 1 /km^2/century at highest energies).

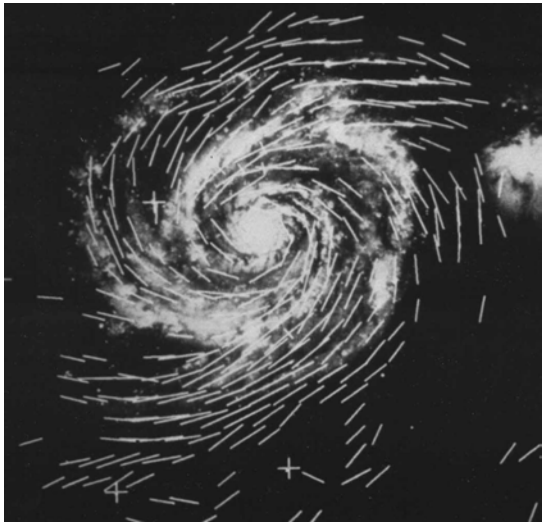
Magnetic Fields



1. Galaxies have magnetic fields.
   - Protons and nuclei will be deflected by the B ~ 3 μG galactic field.

   Larmor radius r = R/cB

R	r	
10^{15} eV	0.3 pc	
10^{20} eV	30 kpc	← size of galaxy



M51

2. Intergalactic fields may also be significant
   - Clusters (e.g. Coma) have field strengths B ~ 0.1 – 2 μG, perhaps extending out along sheets and filaments.

Charged CR directions will be scrambled by B fields.

We need neutral particles to do astronomy → γ, ν

Questions

1. **What is the origin of this diffuse flux of cosmic-ray particles?**
   - Abundant, extremely energetic particles. Sources must be both powerful and renewable.
   - At highest energies – we have no understanding of how they can be produced.

2. **Do these particles provide clues about the early Universe or about the physics at higher mass scales?**

3. **What can we learn from Astronomy at very high energies?**
   - Gamma-rays, ν's point directly back to sites of extreme particle acceleration or unexpected phenomena.
   - VHE particles can be used to probe radiation fields and the fabric of space-time.

DETECTION OF VHE/UHE PARTICLES

Experimental Techniques

Satellite

Balloon

Cherenkov Telescopes

Air shower array

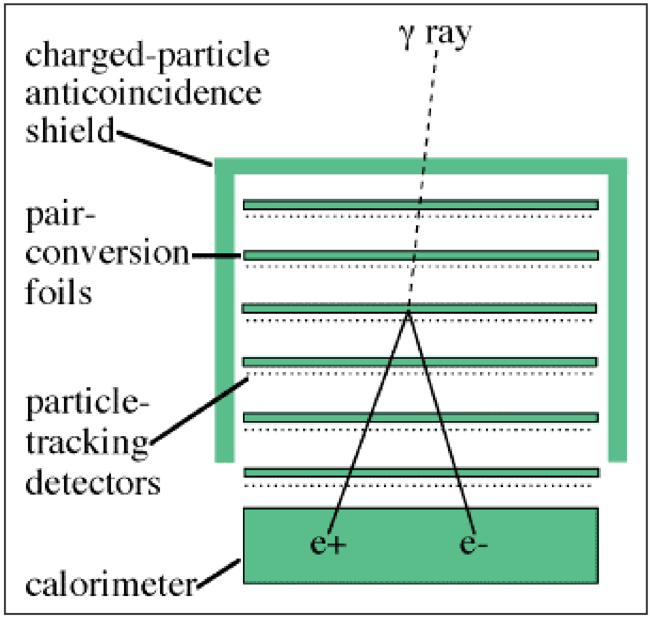
Ice/Water Cherenkov

EGRET (CGRO)

CGRO

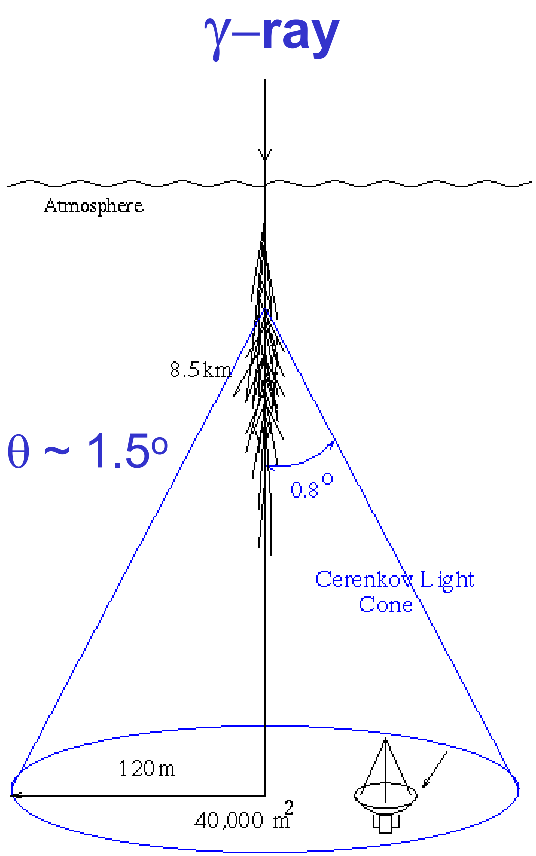
- Flew 1991-2000.
- Very successful mission.

EGRET



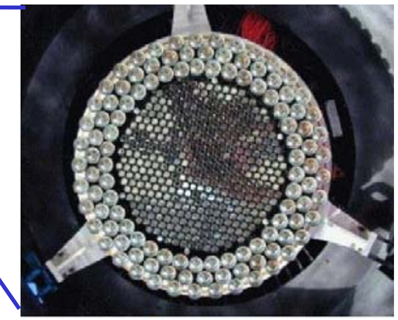
- Energy range 30 MeV – 20 GeV.
- Small collection area.
- Detected ~ 300 sources..

Cherenkov Telescopes

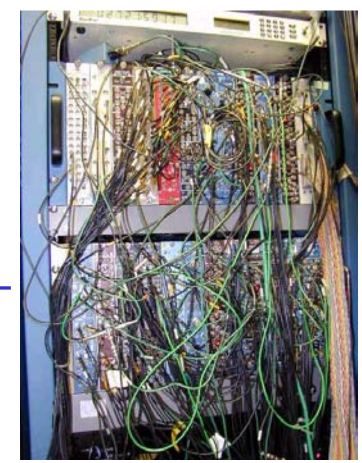


Area = $10^4 - 10^5$ m^2
~60 optical photons/m^2/TeV

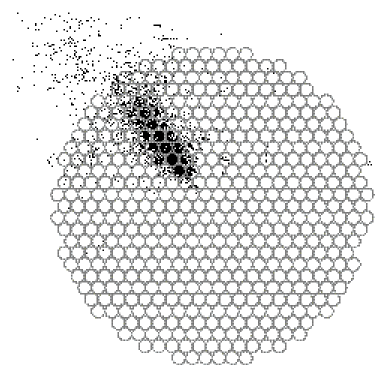
Whipple 10m (Arizona)



PMT camera

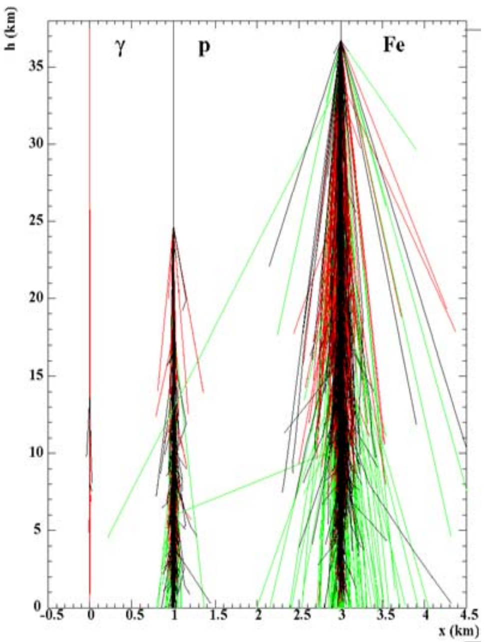


ns electronics

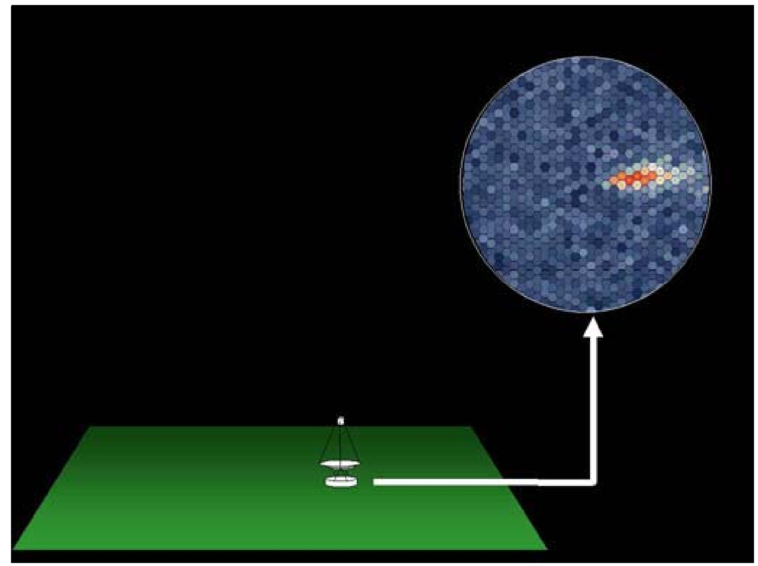


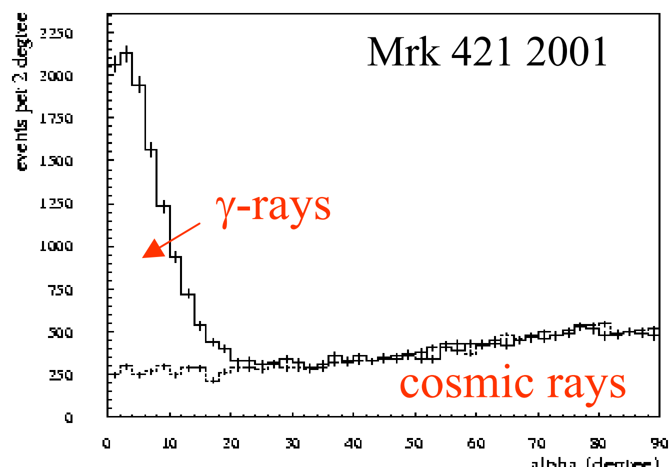
Cherenkov image

Isolating γ-rays



Shower profile
in atmosphere





Orientation angle (α)

Rejection Factor ~ 300 (single tel)

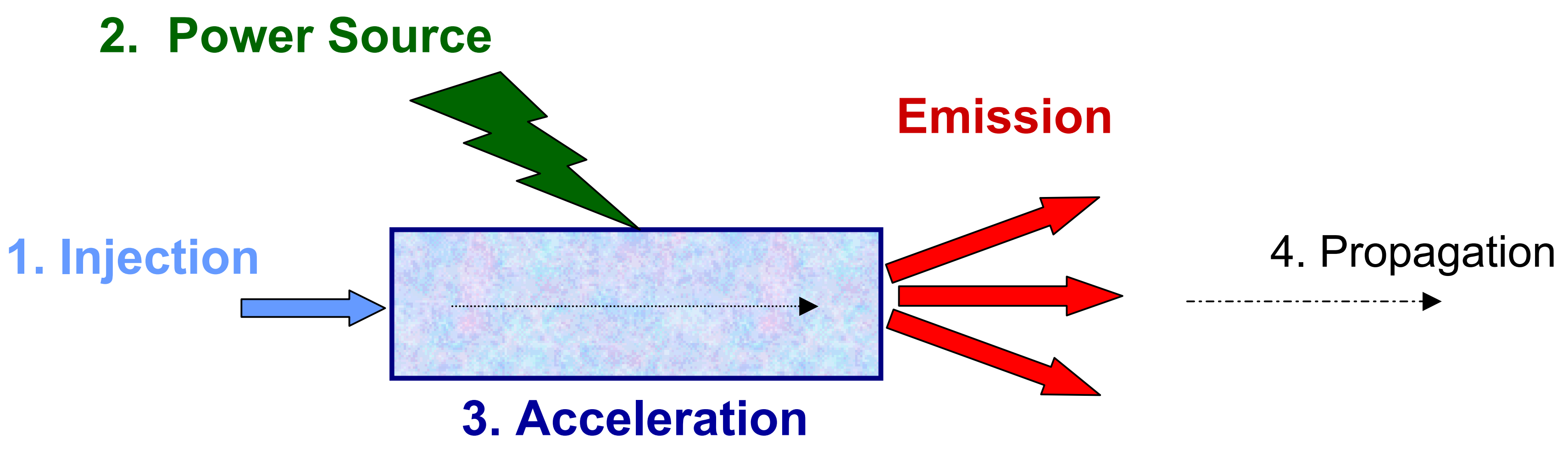
P Proton shower movie

γ γ-ray shower movie

ORIGIN OF
HE PARTICLES

Astrophysical Origins

To build a HE cosmic accelerator, we need the following parts:



Power Sources

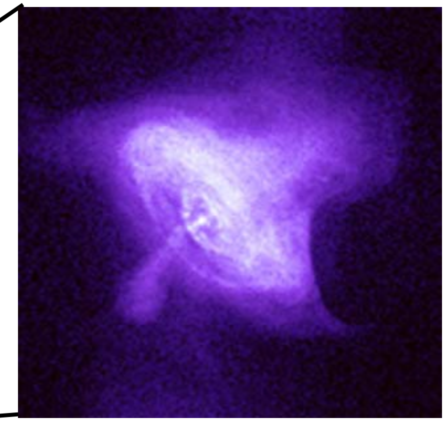
Broadly speaking, there are two types of sources:

1. Electromagnetic
   - Rotating highly magnetized object (Pulsar)

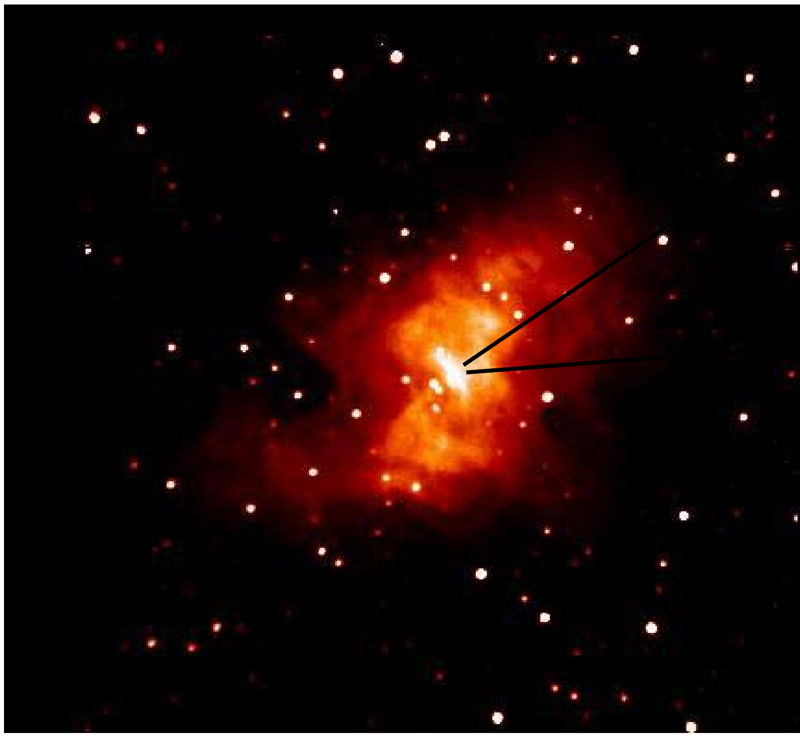
2. Gravitational
   - Core collapse of a massive star – SN and its remnant
     – Gamma-ray Bursts
   - Accretion onto a compact object (BH, NS, etc.)
   - other…

Somewhat intertwined – eventually acceleration is done electromagnetically, and often both are involved.

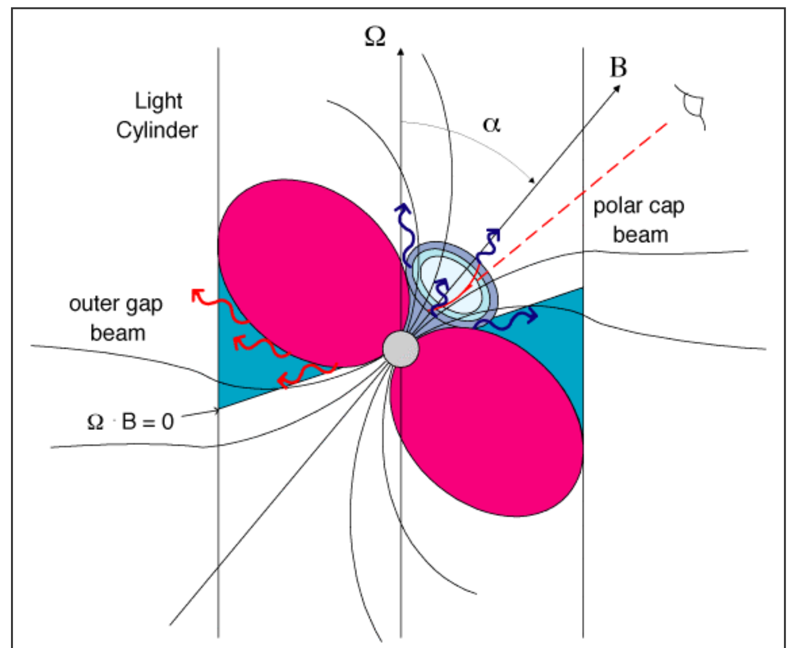
Power Source: Pulsar



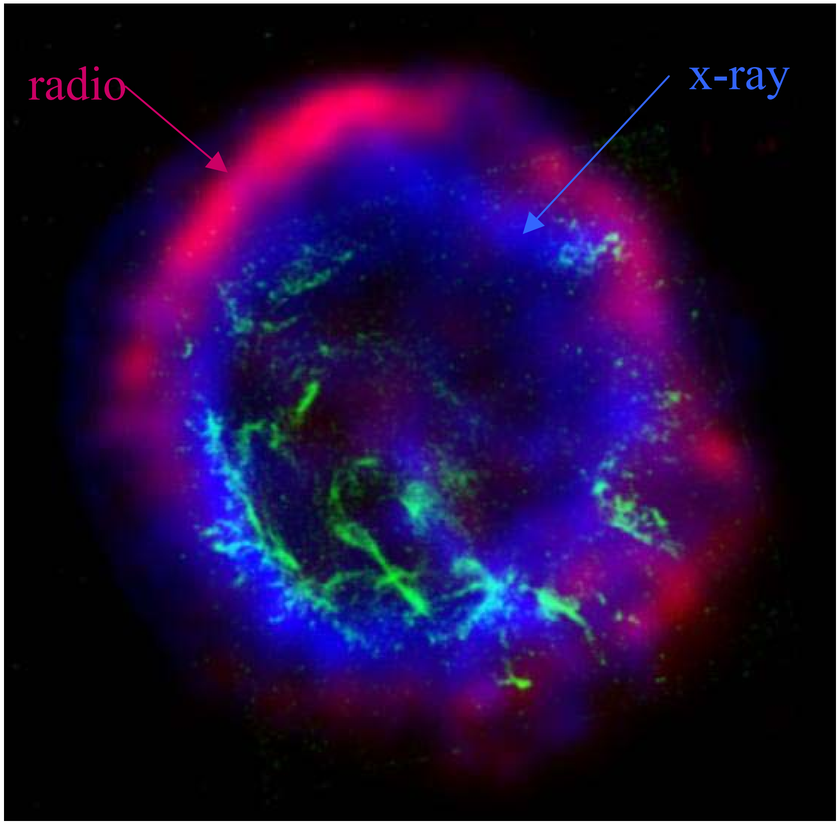
Pulsar



Crab Nebula



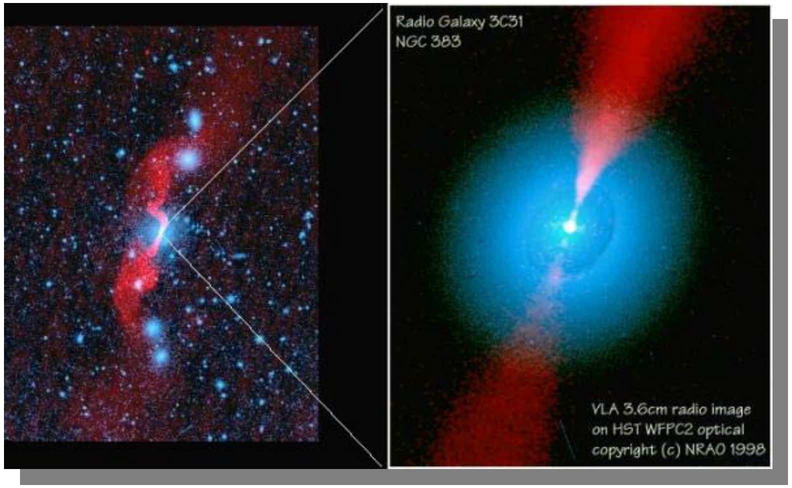
Supernova Remnant

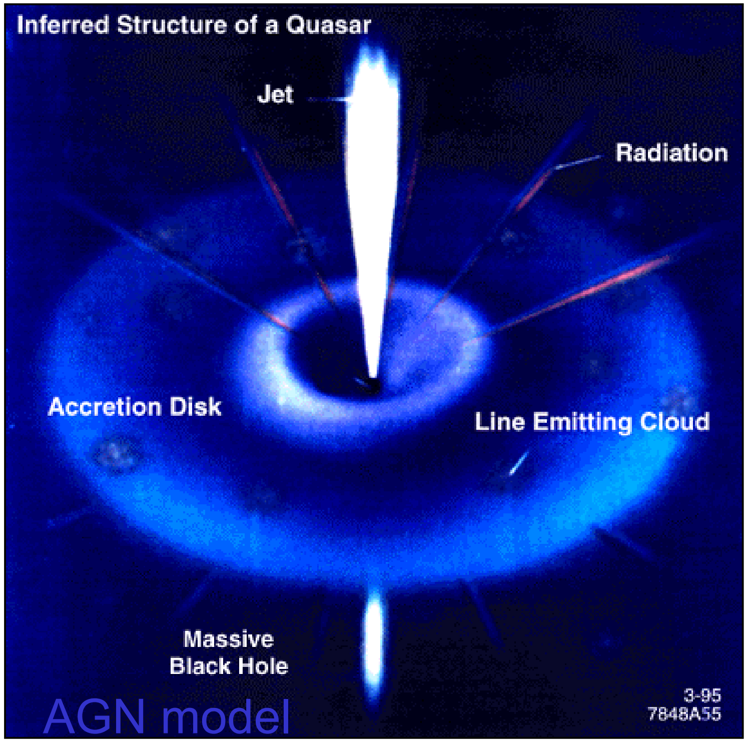


SNR E102

- Collapse of massive star.
- Outer layers ejected with $v \sim 1\text{-}2 \times 10^4$ km/s.
- Shell expands and shock front forms as it sweeps up material from ISM.
- In $\sim 10^4$ yrs, blast wave begins to deccelerate (Sedov phase) and slowly dissipate.

Active Galactic Nuclei (AGN)





- AGN are likely powered by accretion onto BH's of 10^6 – 10^9 solar masses.
- Matter falling in piles up in rotating accretion disk. Released energy powers jets of relativistic outflow.
- Leading candidate as a source of UHE cosmic rays and neutrinos.

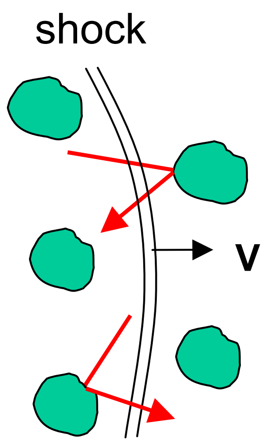
AGN Movie

Movie

Fermi Acceleration

A variety of mechanisms have been proposed to explain how HE particles are accelerated in astrophysical environments.

Leading contender: Fermi acceleration.



- Shock moves rapidly through ISM.
- HE particles move back and forth across shock, gaining energy.
  First-order Fermi acceleration ~(V/c).
- Naturally get power-law spectrum.

Applied to SN remnants, acceleration time ~ 10^4 yrs, we reach a limiting energy:

$$E_{max} < Z \times 10^{14} \text{ eV}$$

Very hard to go higher !

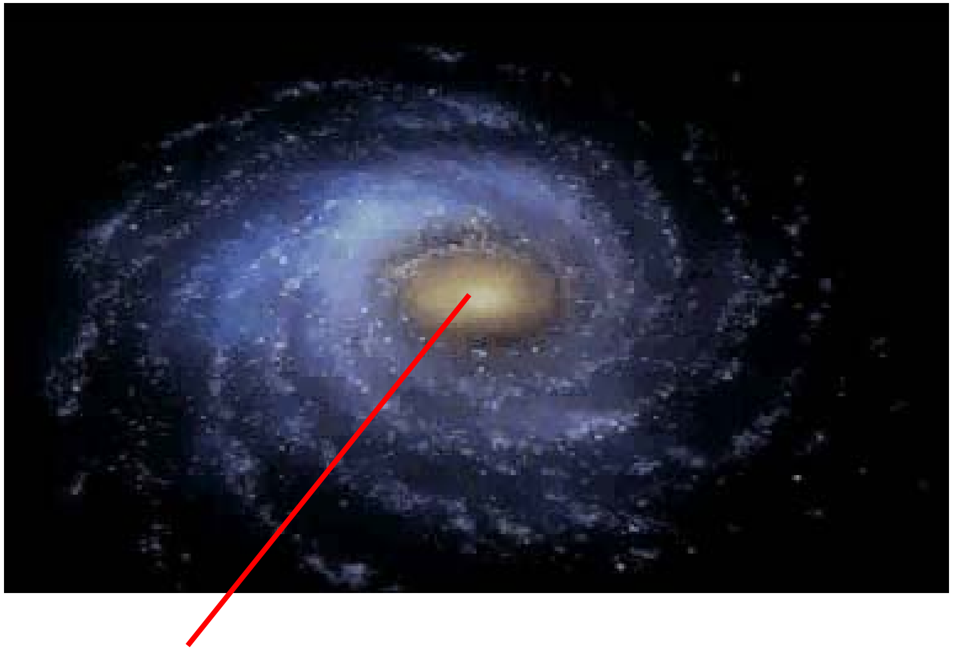
Beyond the Standard Models

Selected topics:

- SUSY & Dark Matter.
- Probing space-time at high energies.

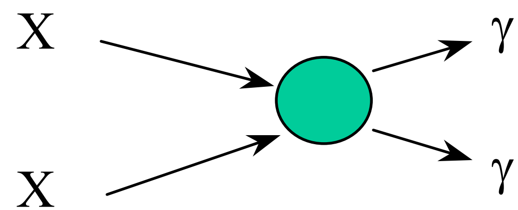
- ("GZK Neutrinos".)
- ("Top-down" sources of $E > 10^{20}$ eV particles.)
- (Primordial black holes).
- (Cosmic IR radiation).

Dark Matter & SUSY



Galactic Center

Neutralino Annihilation



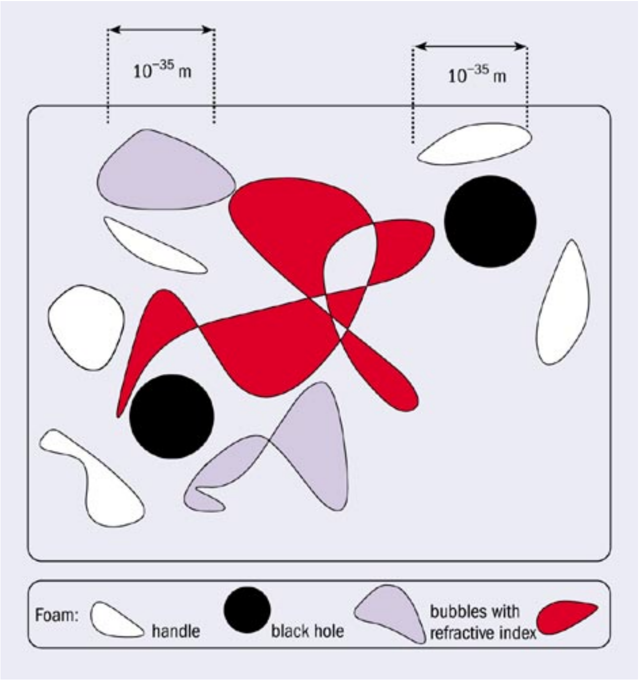
Flux ~ $(\rho / M_x)^2 \sigma v$

- Neutralinos can have enhanced density in GC.
- Annihilate to give γ-rays at GeV and TeV energies.
- Prospects depend strongly on the actual density.

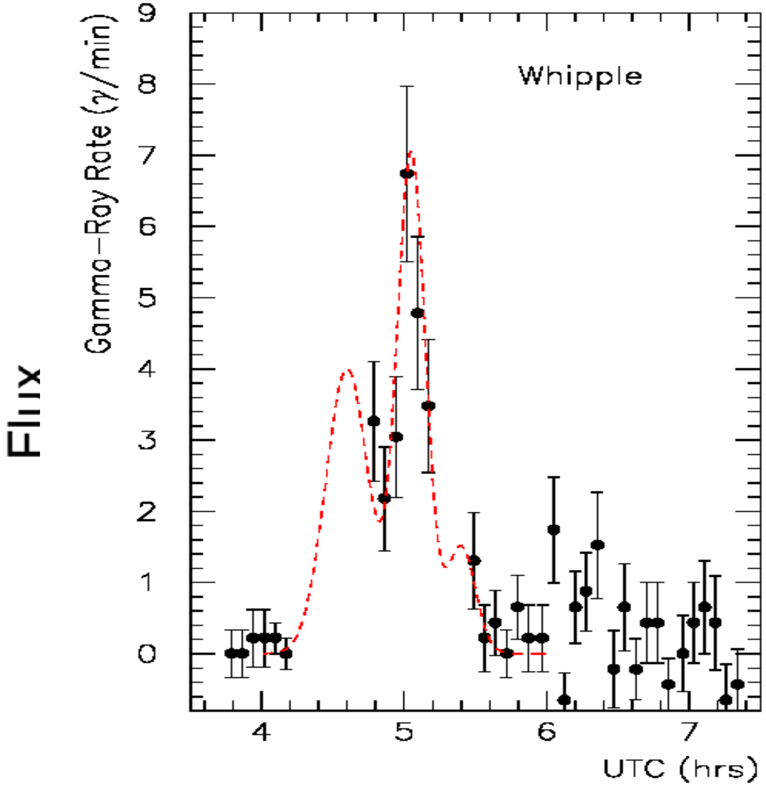
Probing Intergalactic Space-Time

Quantum gravity:

- Discrete space-time "foam"
- Effects propagation of light



AGN Flare
Whipple 1996

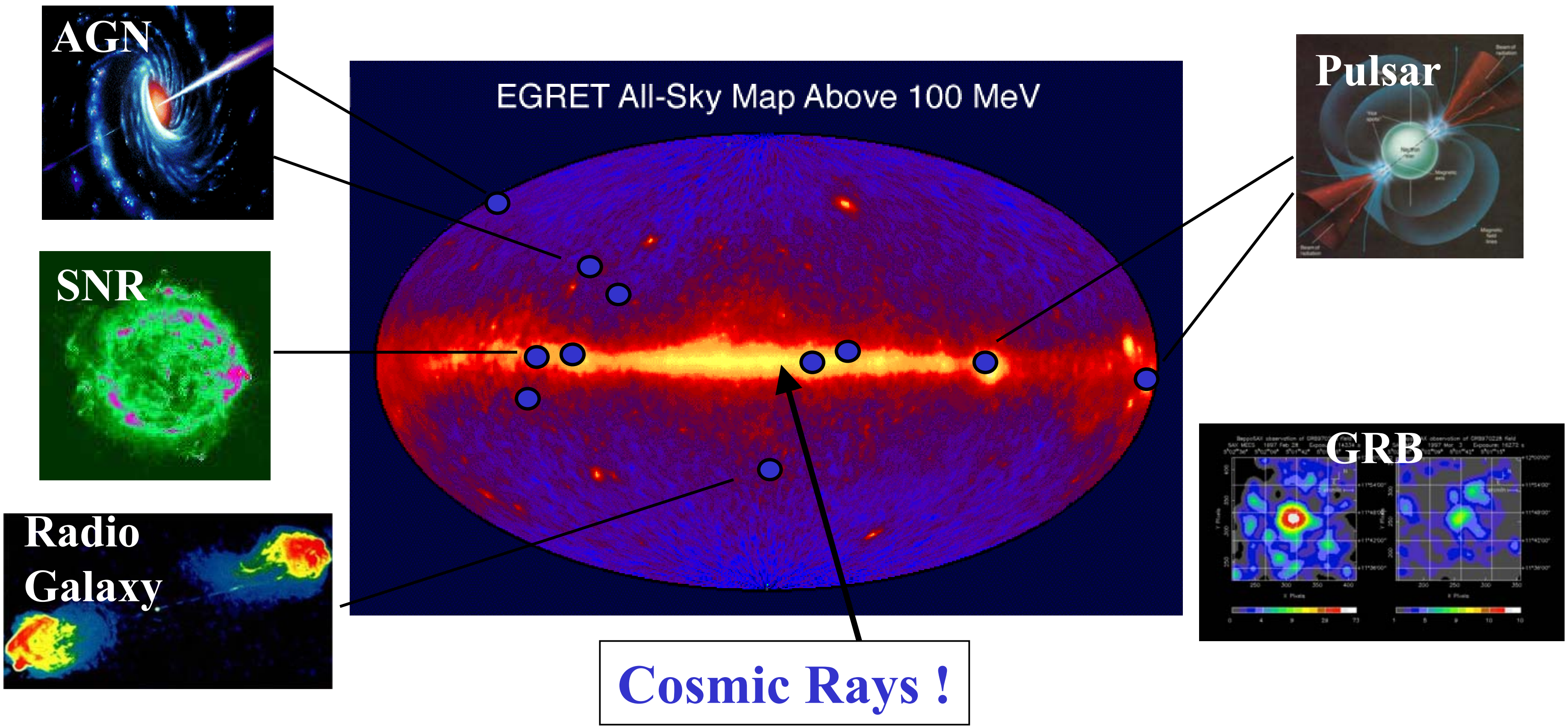


- Probe to M_{plank} / 100.

VHE γ-ray ASTRONOMY

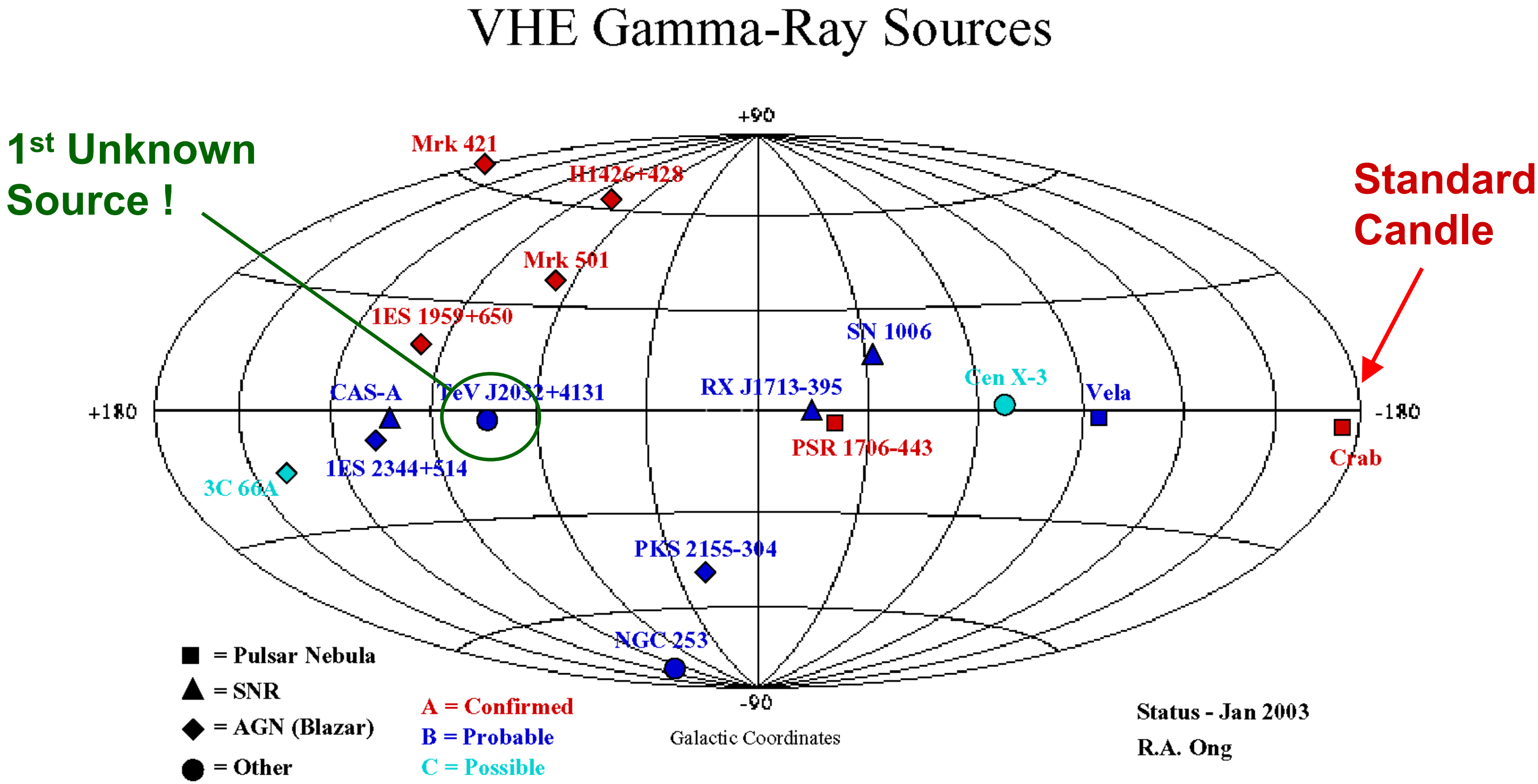
(A new window)

GeV γ-ray Sky



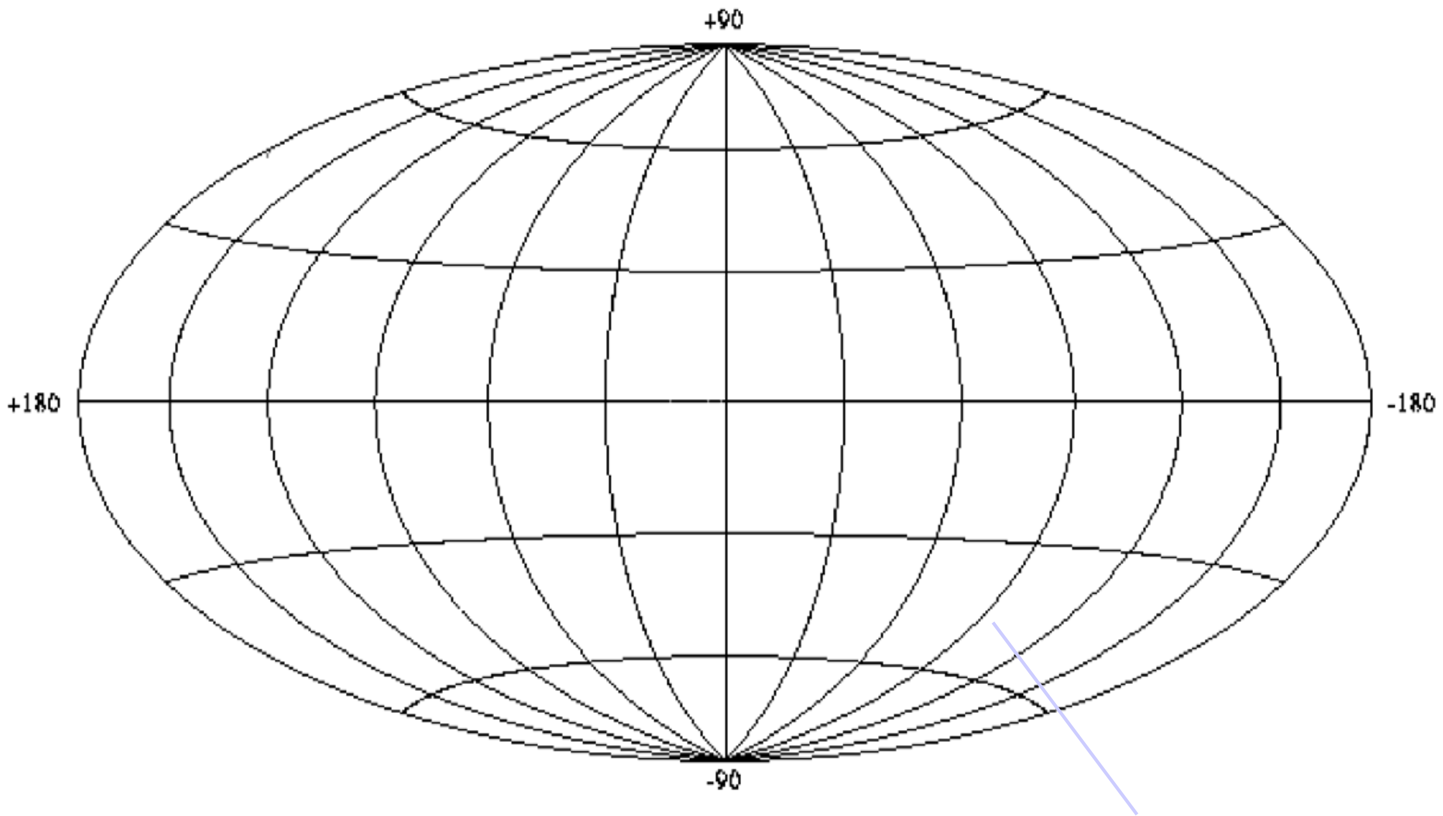
- ~ 250 HE point sources, most unidentified.

TeV γ-ray Sky



- Pulsars, SNR's, AGN, Starburst galaxy …
- All detected by Cherenkov telescopes.

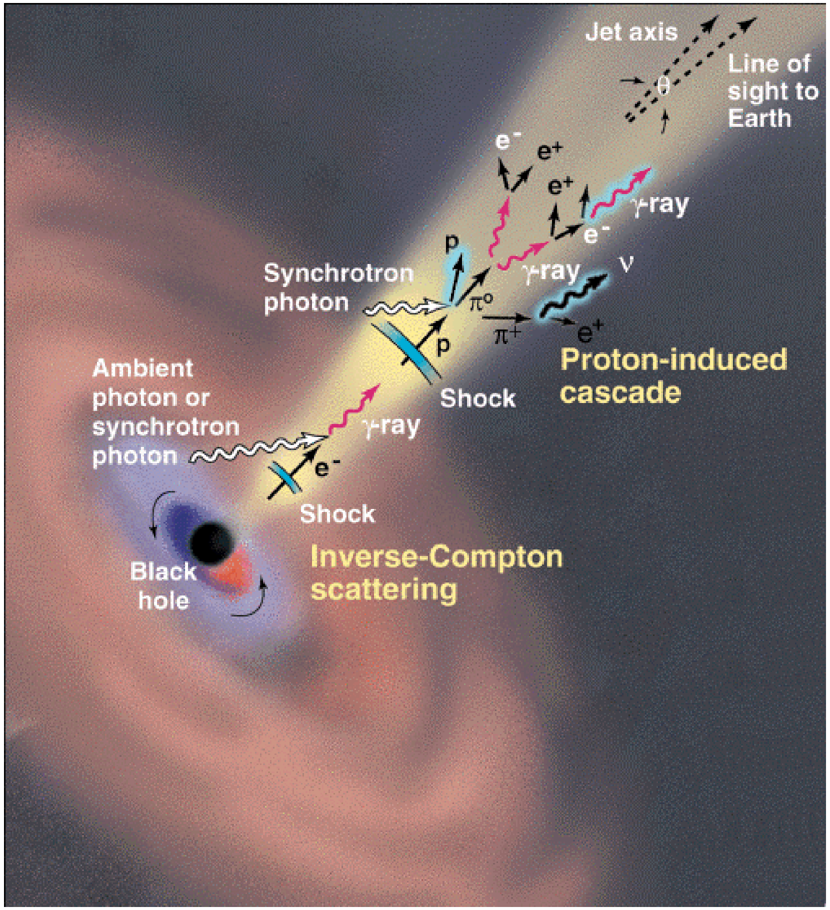
HE ν Sky



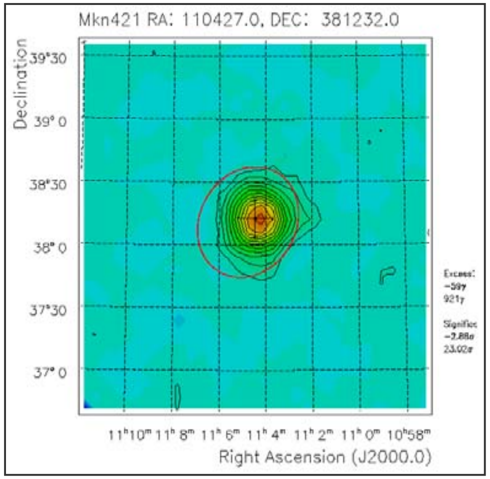
Galactic Coordinates

- No sources yet !

GeV and TeV AGN: Blazars



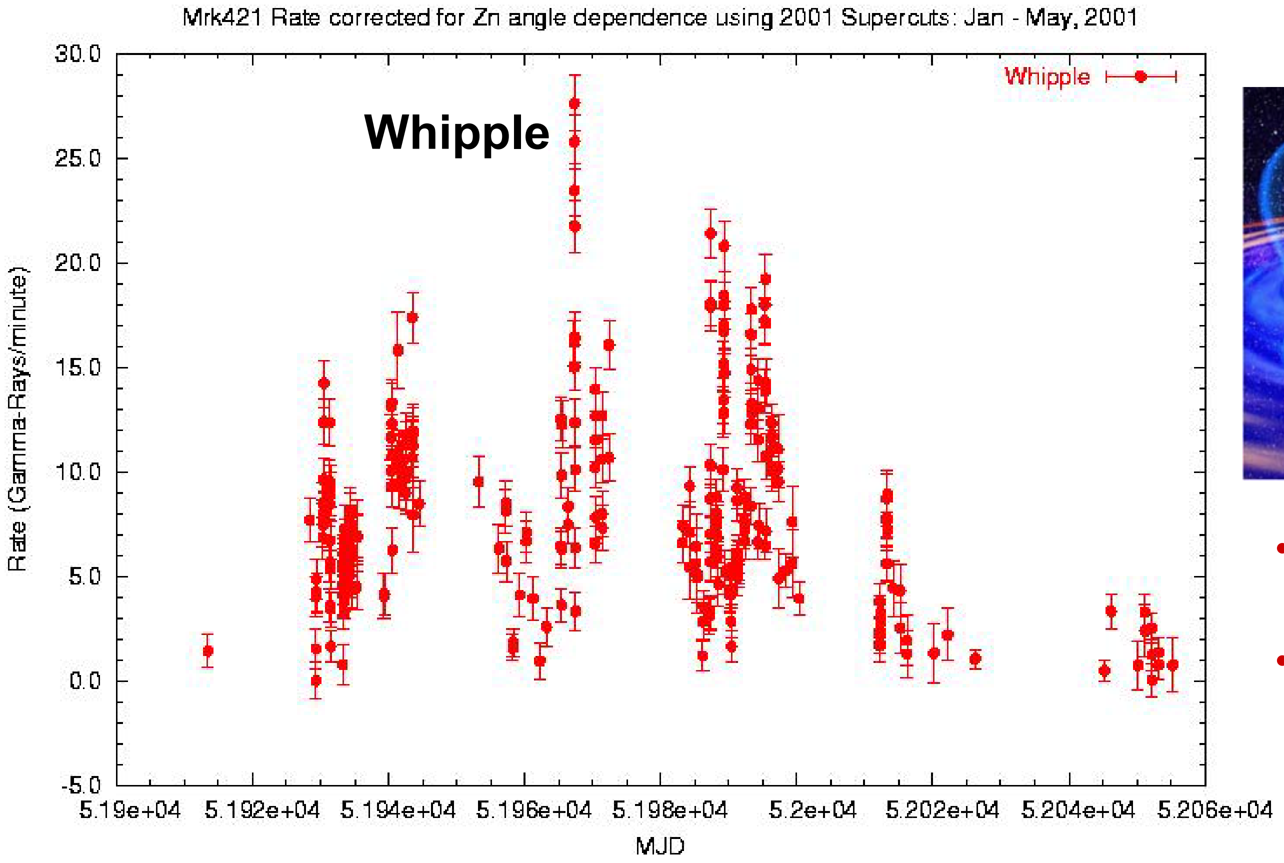
Mrk 421 Whipple

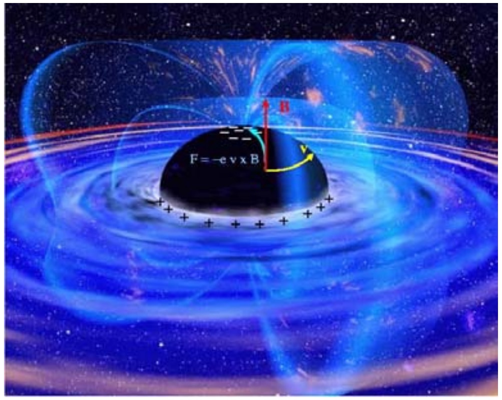


Blazars:

- Powerful, radio-loud objects.
- Highly variable at all wavelengths.
- Jets – superluminal motion.
- Produce GeV/TeV beams.

AGN Variability

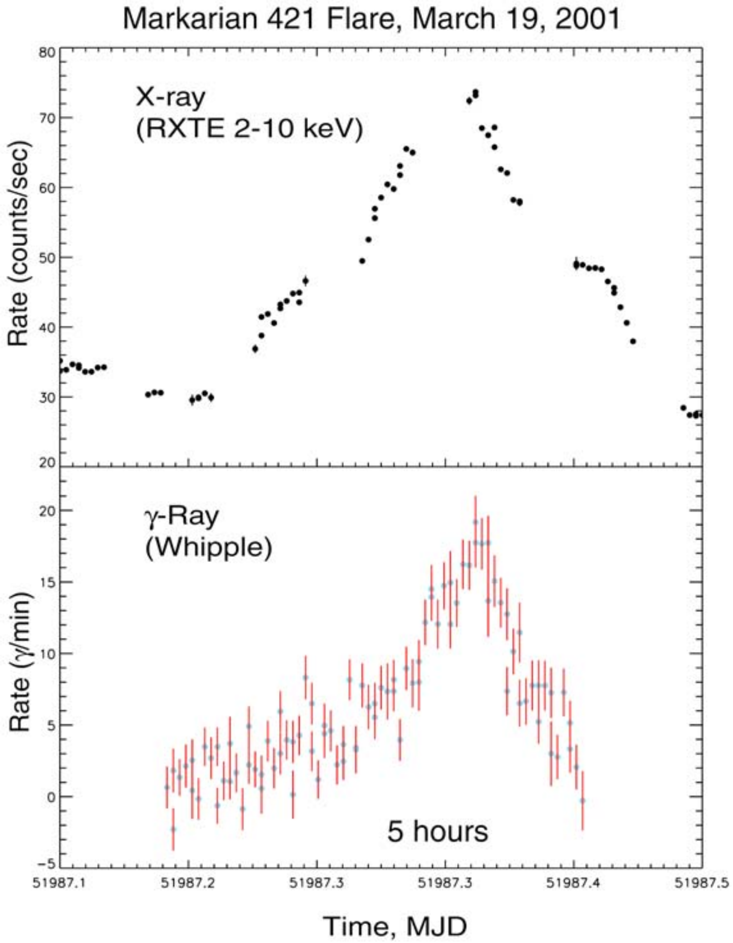


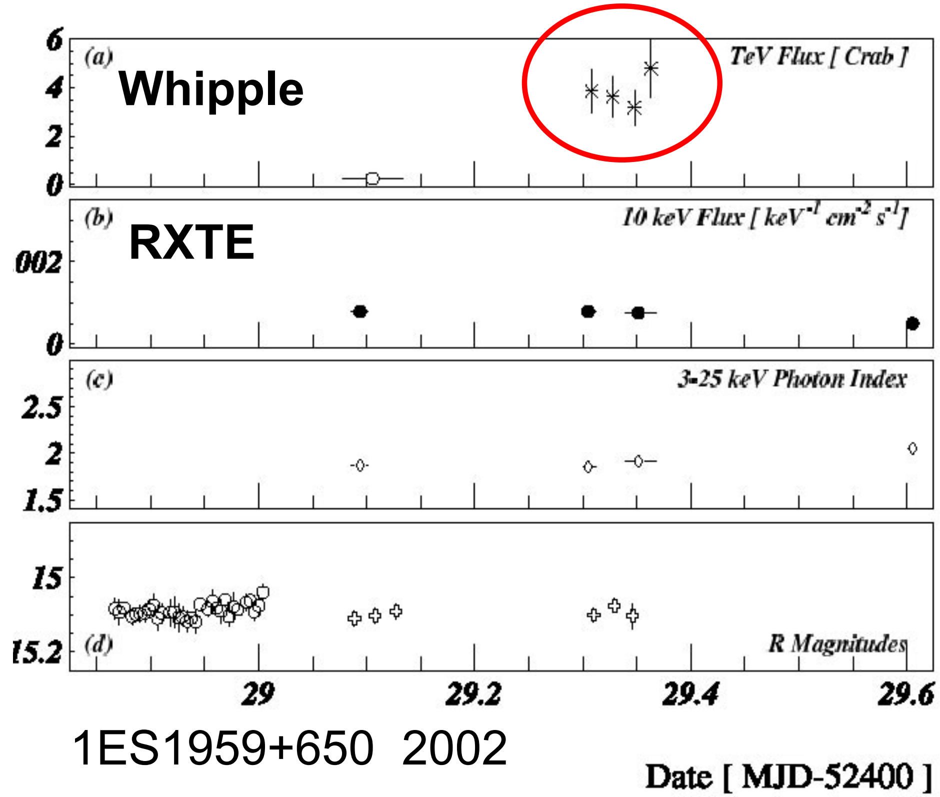


- $R < cT\delta / (1+z) \sim 10^{-4}$ pc
- For $M = 10^8 M_{sun}$, $R_s \sim 10^{-5}$ pc.

- Shortest variations probe to within factor of 10 of the Schwarzchild radius !

Correlation with X-rays

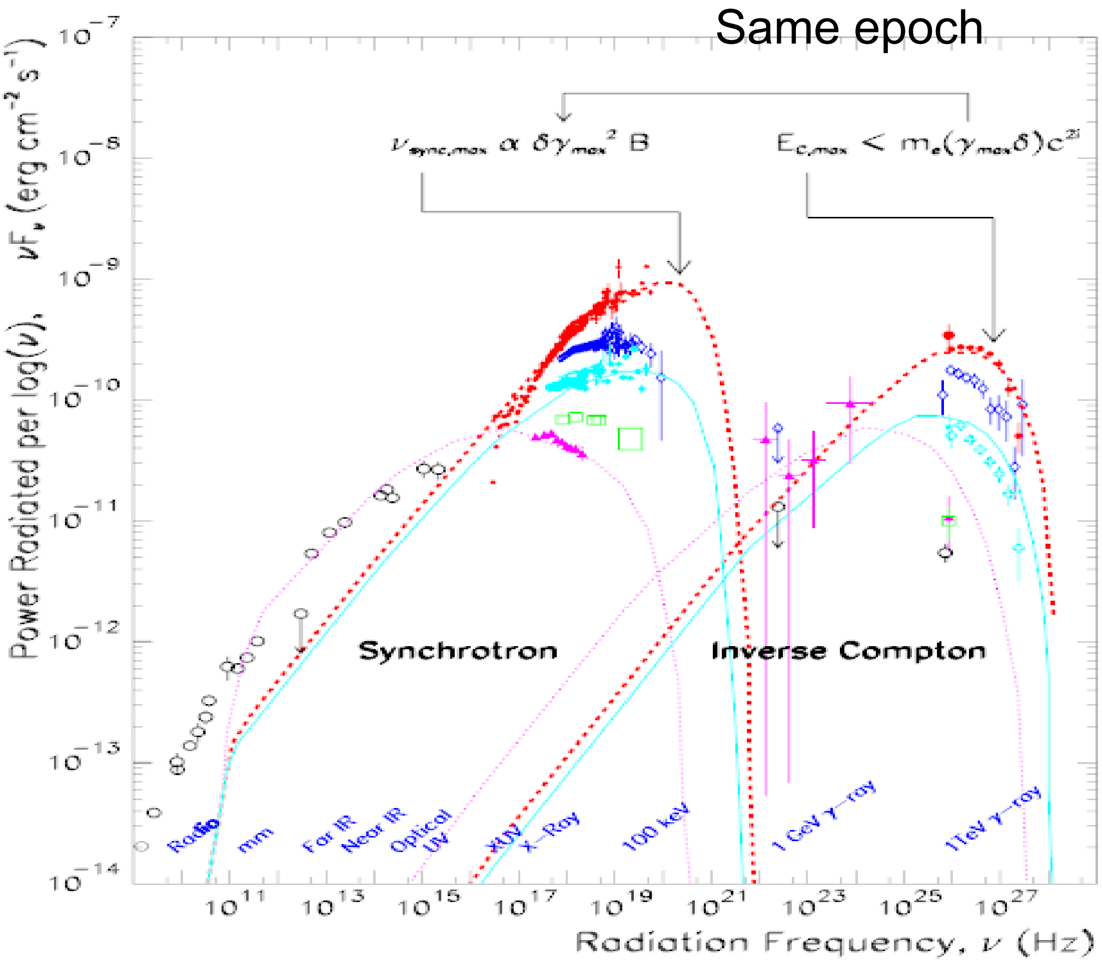




- VHE Flares are generally well correlated with X-ray flares.
- But not in this case !

Broadband Spectrum

Mrk 501



Correlation in γ-ray and X-ray variability is most easily explained in IC scenarios.

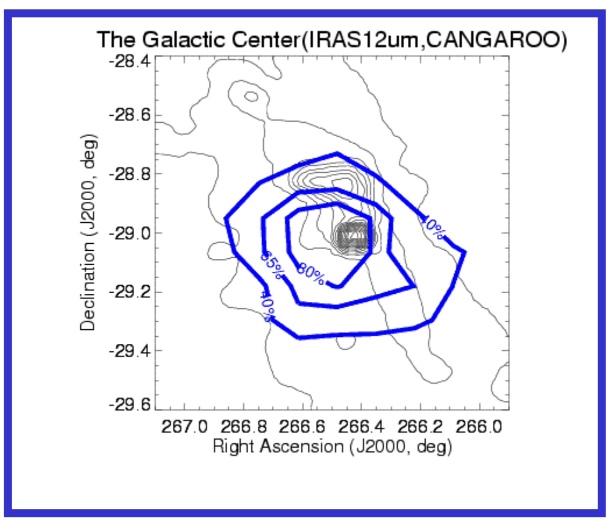
→ Same e^- population.

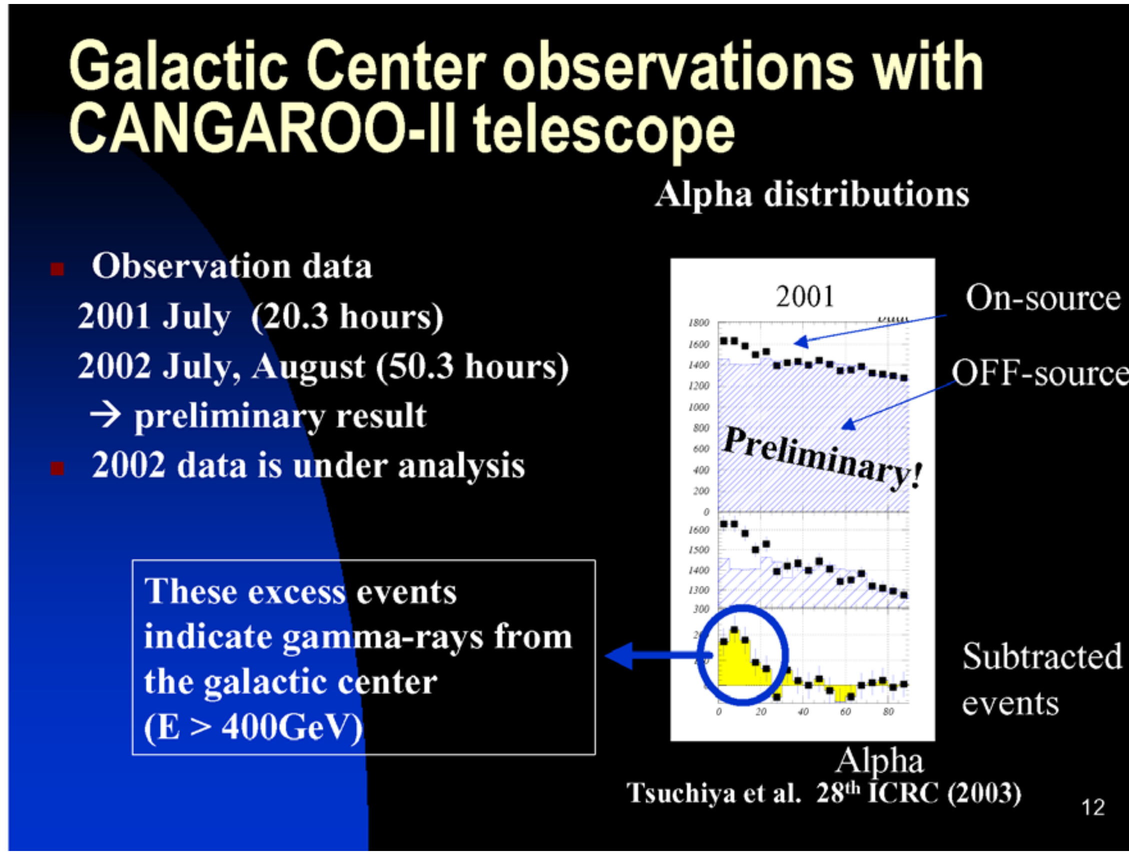
Additional constraints on electron energies, time scales, etc.

Starting to get a <u>detailed</u> understanding of these sources.

Has DM Already Been Detected?

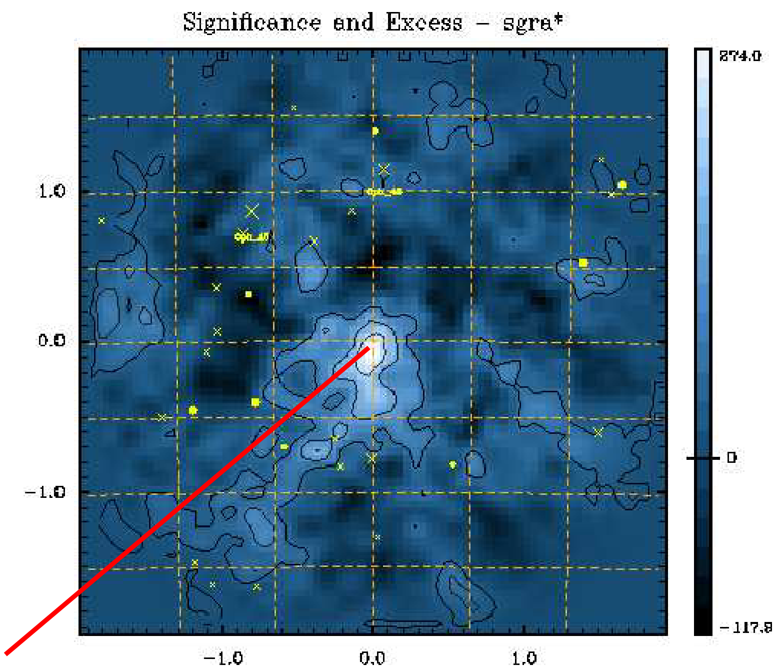
CANGAROO-II
(S. Australia)





Probably not !

More on Dark Matter

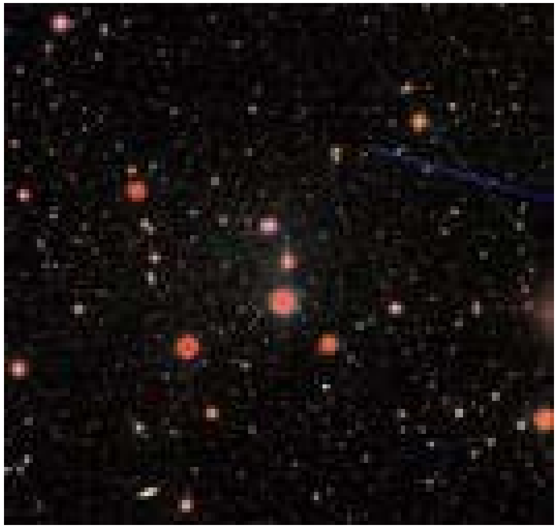


SGR A*

- Whipple result on GC
- Excess γ-ray map from 2000-2003 data (16 hrs).

STAY TUNED !

Core of Draco Dwarf



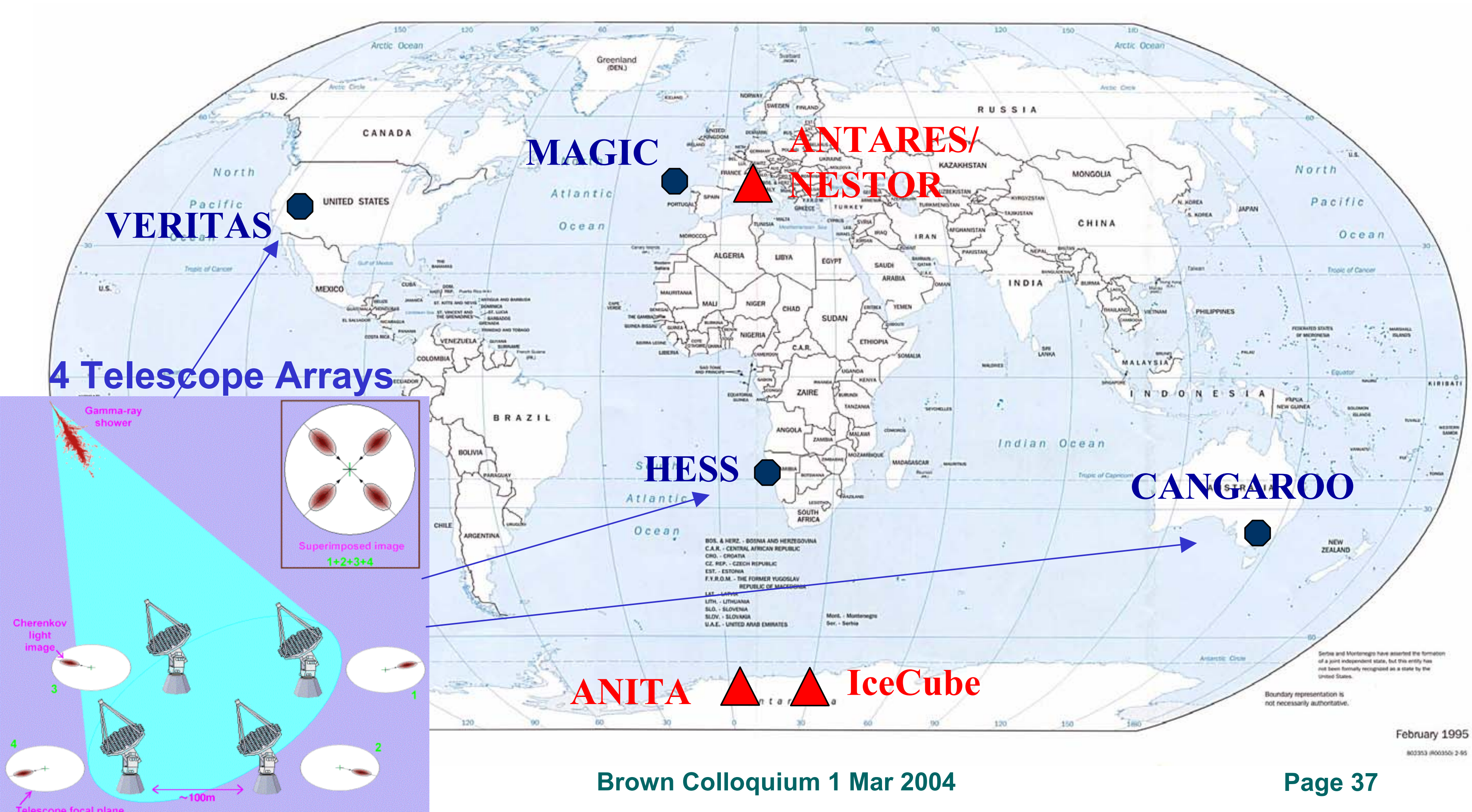
- Other good candidates include nearby galaxies with high mass/light: Draco, Ursa Minor, M32, M33.
- These are being pursued.

FUTURE

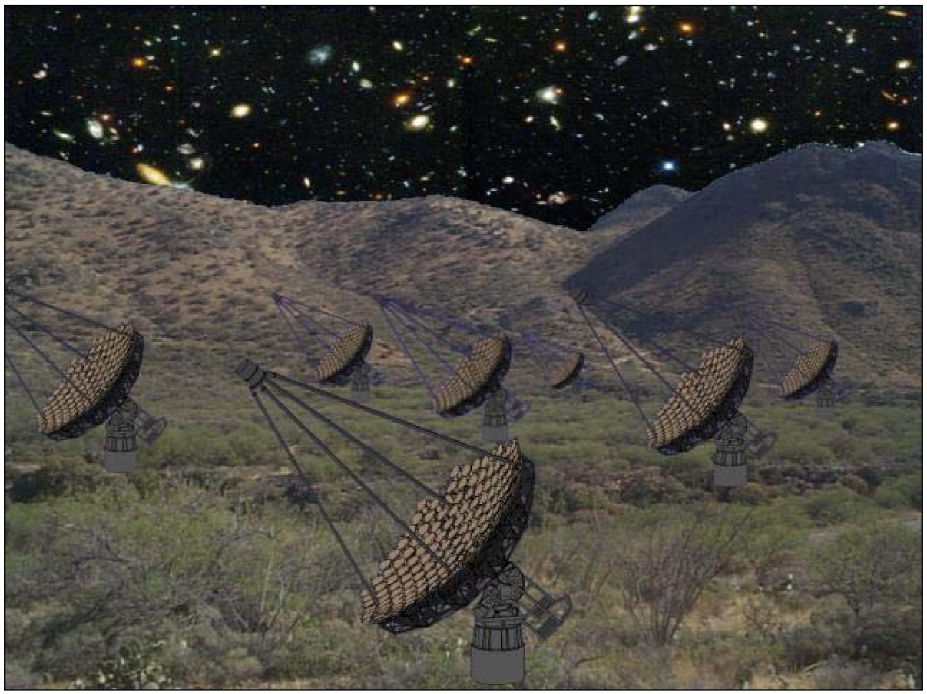
Future HE Telescopes

In space: GLAST, SWIFT

- γ-ray telescopes
- Neutrino telescopes



VERITAS



VERITAS CONCEPT

Collaboration: 50 scientists

U.S, Canada, U.K., Ireland

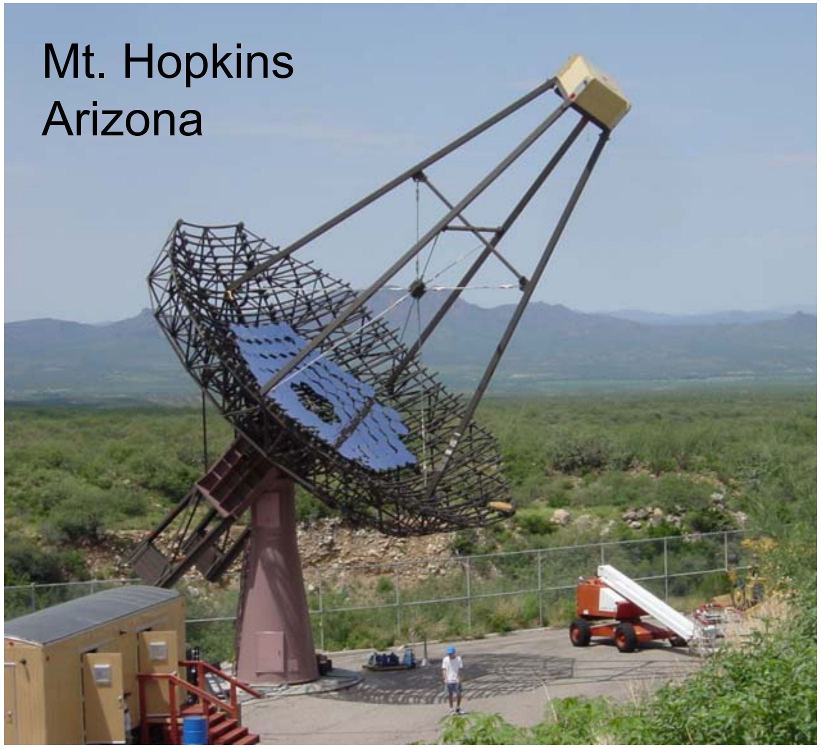
Detector Design:

- Seven 12m telescopes
- 500 pixel cameras (3.5^o)
- Site in southern Az (1700m)
- Phase 1 operational in 2006.

Some characteristics:

- Energy threshold ~ 100 GeV
- Ang. Resolution ~ 4 arc-min
- Crab rate ~ 35 γ/min (45s detection!)

VERITAS – Well Underway



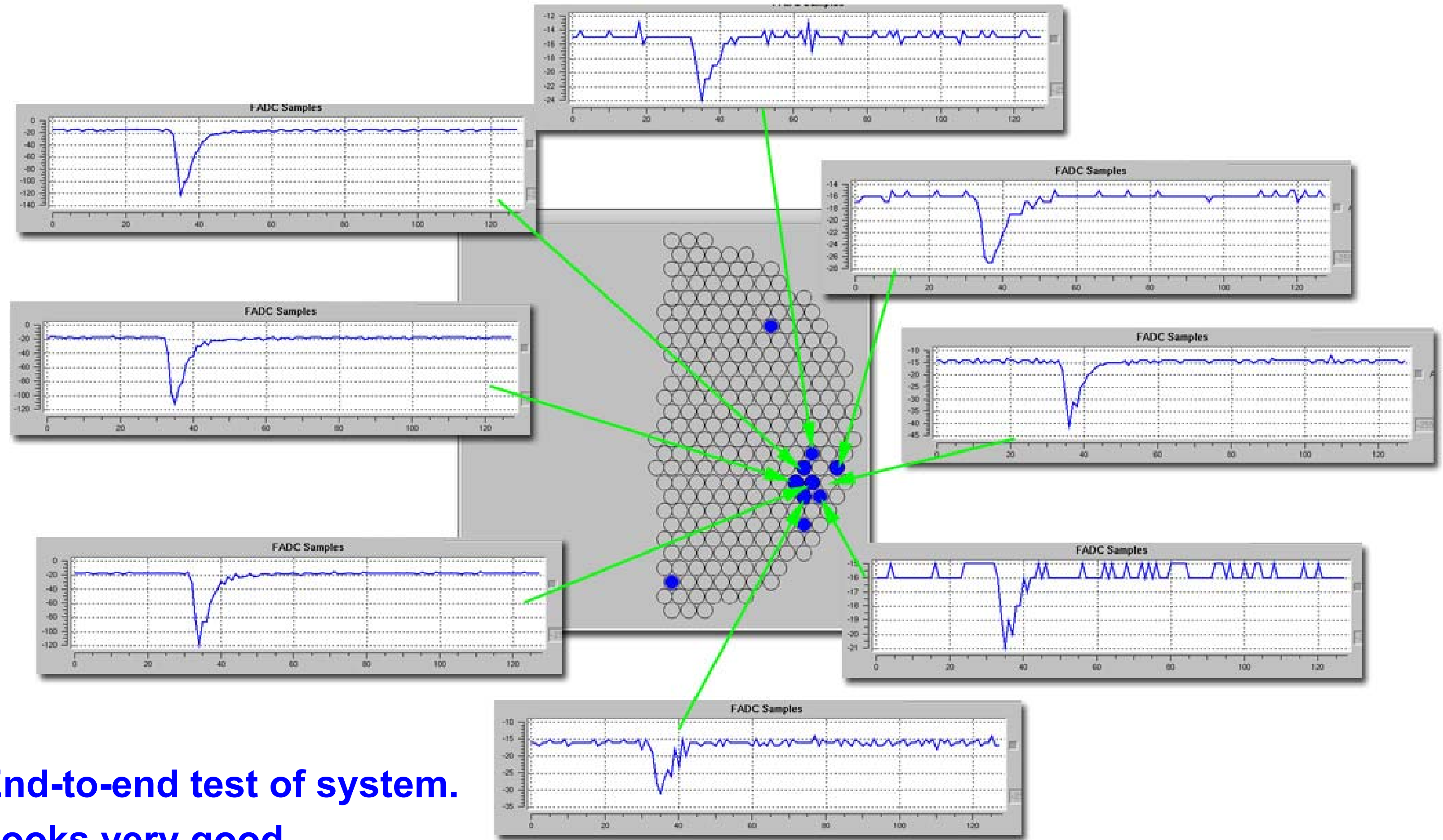
Electronics trailer

500 MHz FADC

Telescope 1:

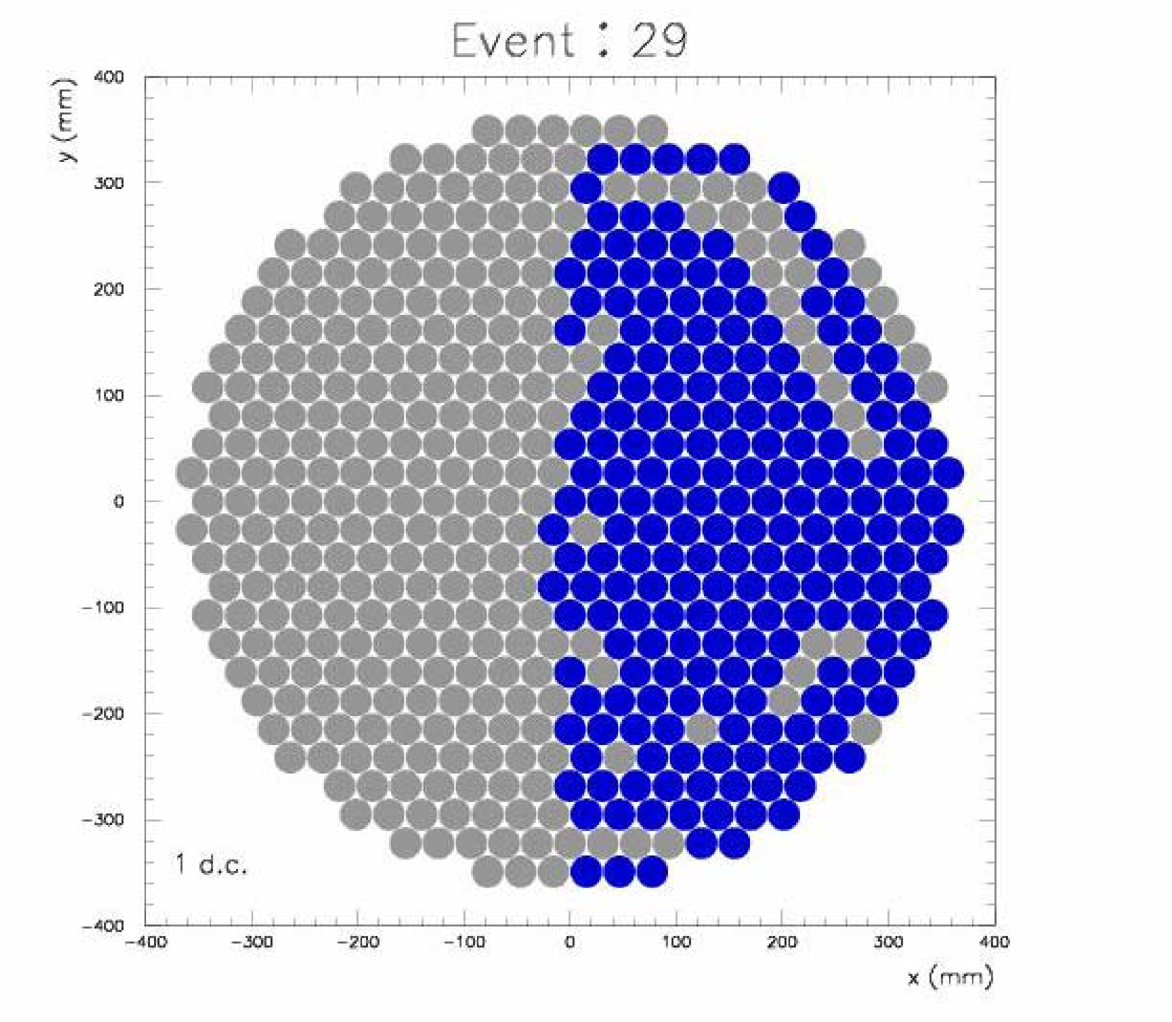
- All major systems tested.
- Operational in fall 2004.

VERITAS –1st Cherenkov Images

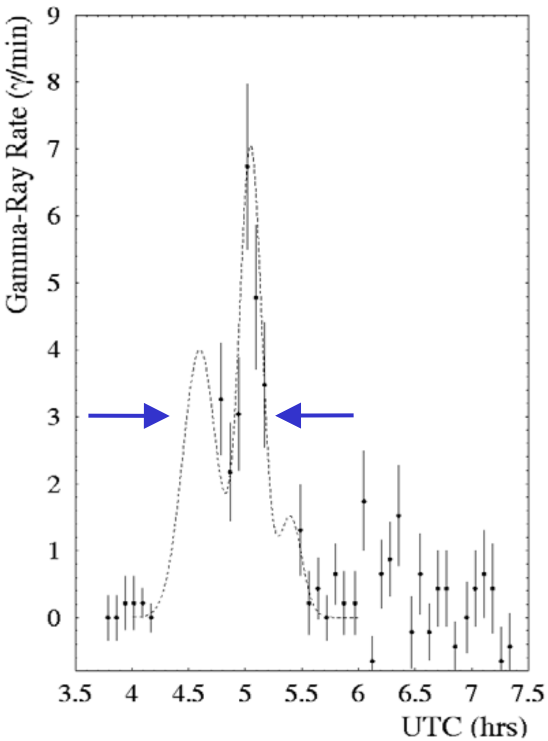


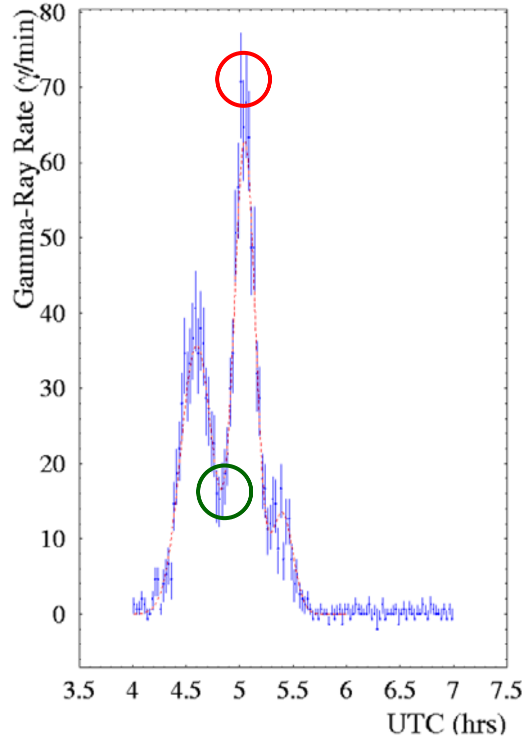
- End-to-end test of system.
- Looks very good.

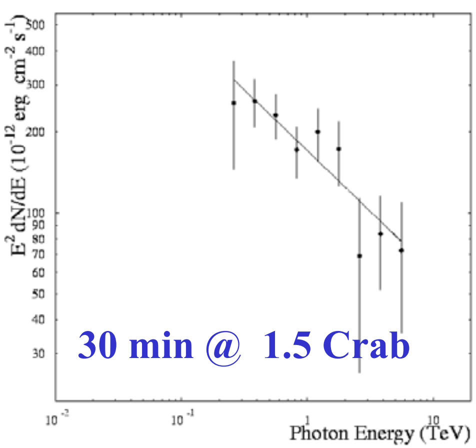
VERITAS Event Movie (Dec 03)

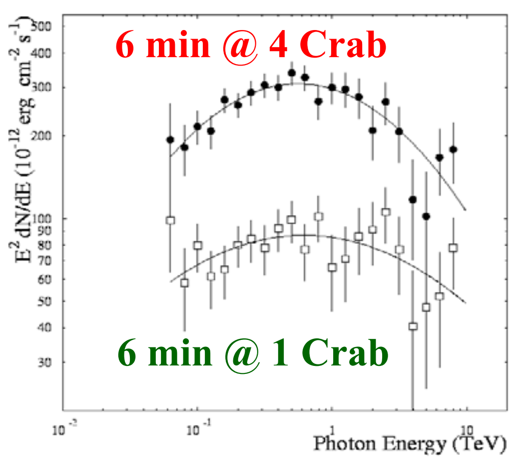


Variability Performance









VERITAS:

- has hour-scale sensitivity for time-resolved spectral measurements.
- can probe intrinsic variability timescales.

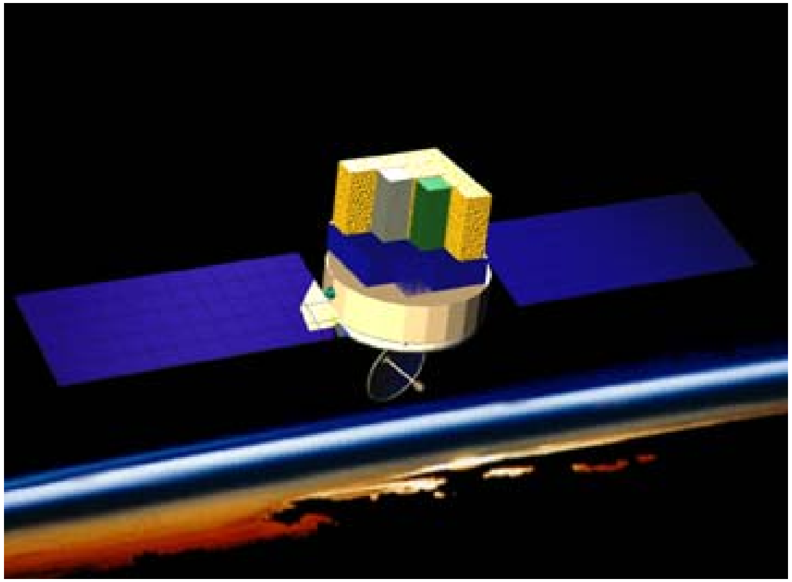
The Competition: HESS

- Jan 2004

H.E.S.S. Phase I
4 x 12m Telescopes

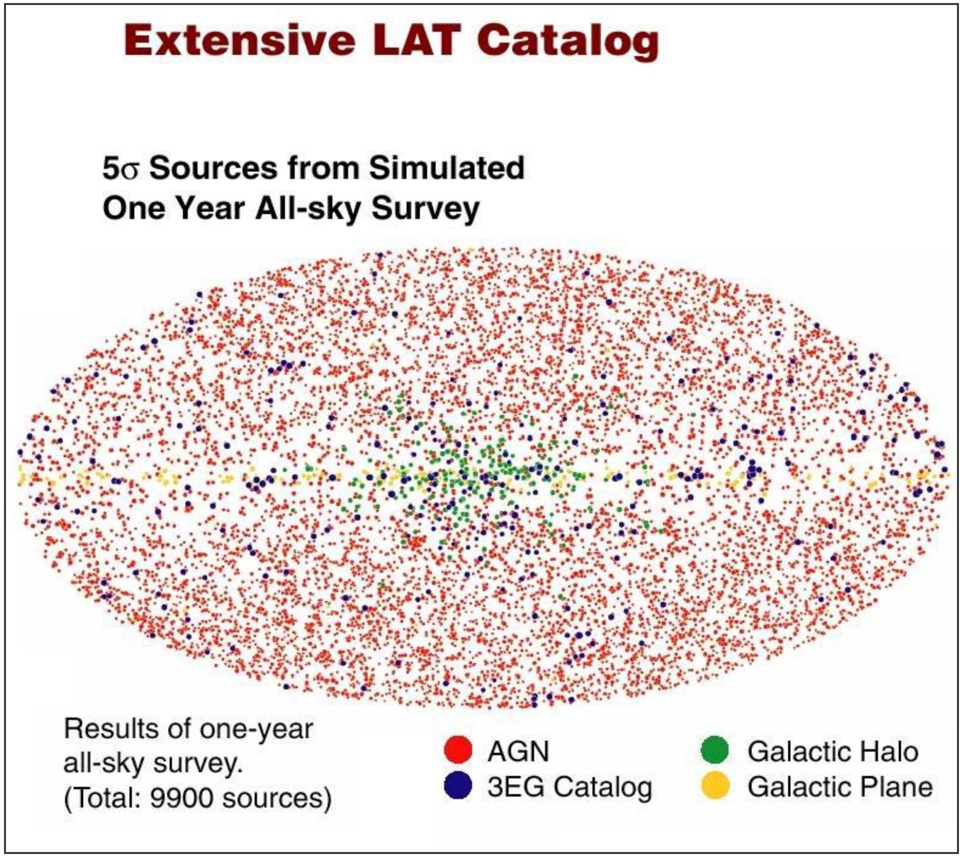
Namibia Site (1700 m)

GLAST – Satellite Telescope



GLAST LAT Instrument:

- Si tracker
- CsI calorimeter
- Anti-coincidence veto



Sky map from 1 year survey

Launch in 2007.

Summary

- Very HE particles provide unique tests of the limits of physical laws. Probe astrophysics in regimes not well understood.
- We have made a survey of the sky at GeV energies. At TeV energies, we have detected some remarkable phenomena, but most of the sky remains unexplored → New Instruments.
- Great potential for discovery of physics beyond our standard models. (But, this physics is <u>not</u> yet required).

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

Marcel Proust (1871-1922)