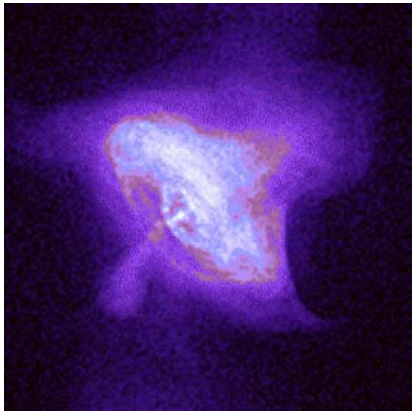
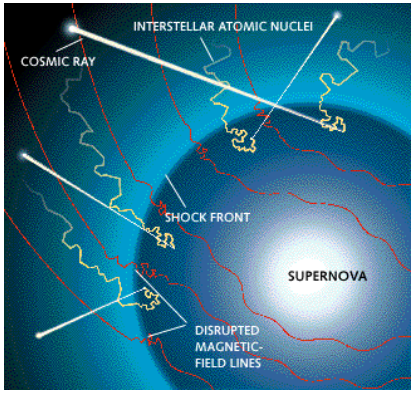
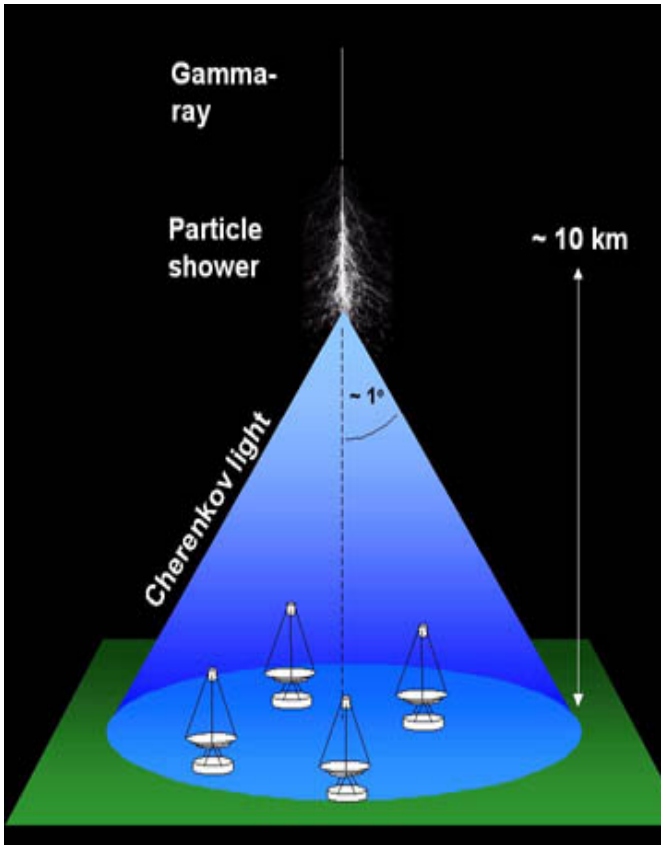
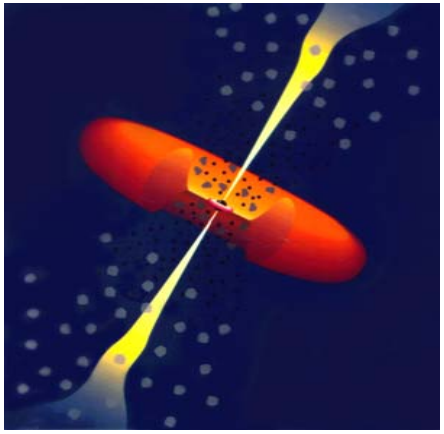
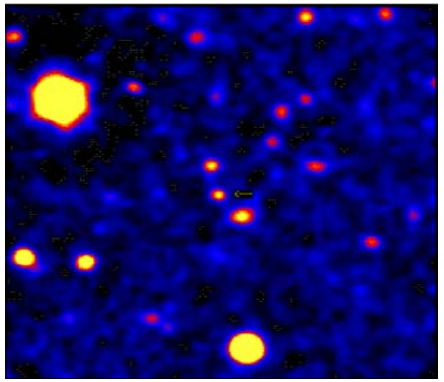
Very High-Energy Astrophysics











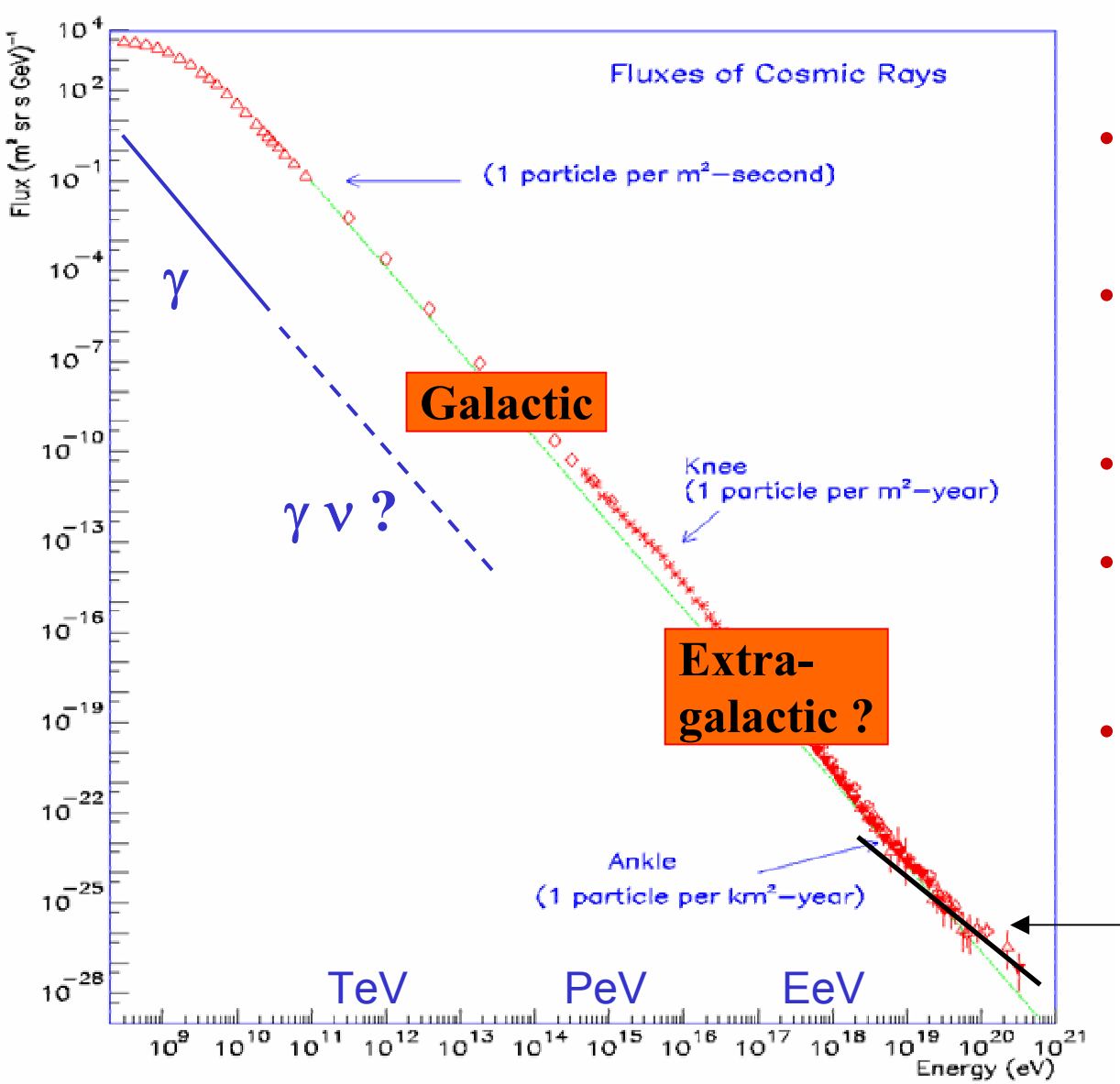
Rene A. Ong
University of California, Los Angeles

Columbia Univ. Colloquium
18 April 2005

OUTLINE

- Introduction
  - **Messengers, energy scales, & questions.**
- Detecting Very High Energy (VHE) particles
- GeV and TeV Astrophysics
  - **Power sources & particle acceleration.**
  - **Cosmic accelerators: pulsars, SN, active galaxies …**
- Physics beyond standard models (brief)
  - **Dark matter, GUT particles, etc.**
- Latest results – HESS telescope array
- Future – VERITAS & GLAST.

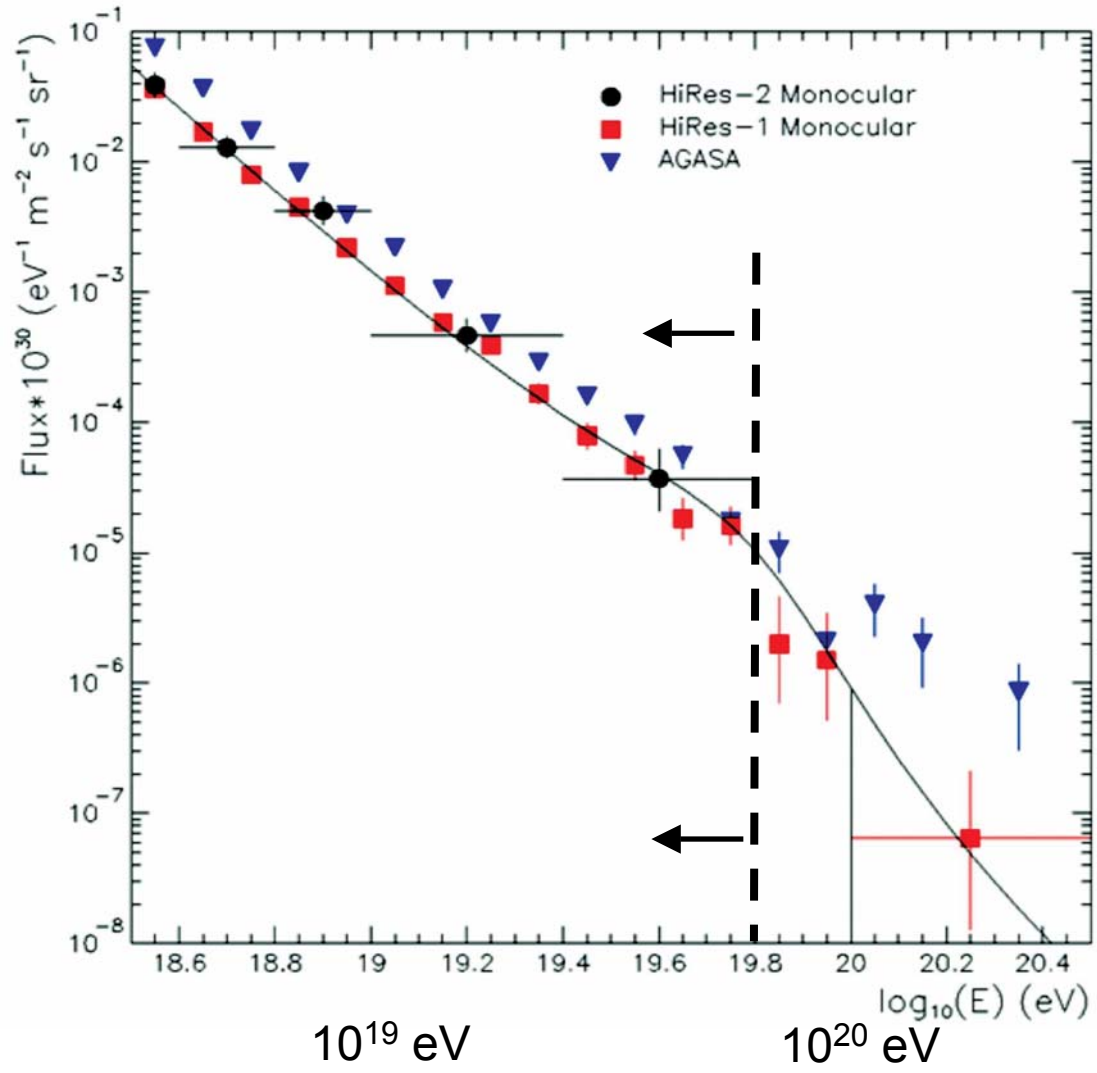
Cosmic Ray Spectrum



- Total, diffuse spectrum.
- Power-law E^{-3} differential.
- $E > 10^{20}$ eV.
- Energy density ~ 1 eV / cm^3.
- What about γ-rays and neutrinos ?

New component?

At the Highest Energies 10^{20} eV



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

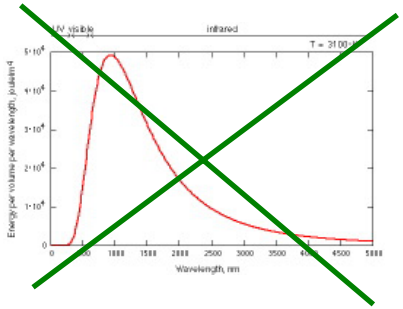
1. Very hard to accelerate to these energies.

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? … we don't know !

Impact of High Energies



Phenomenological

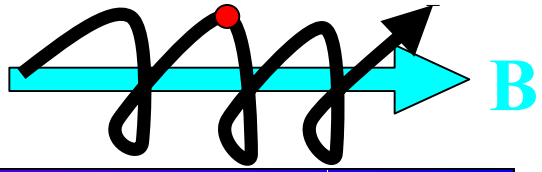
High energy is reached by either:

1. Non-thermal, radiative processes (**Astrophysics**).
2. Decays, interactions from higher 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).

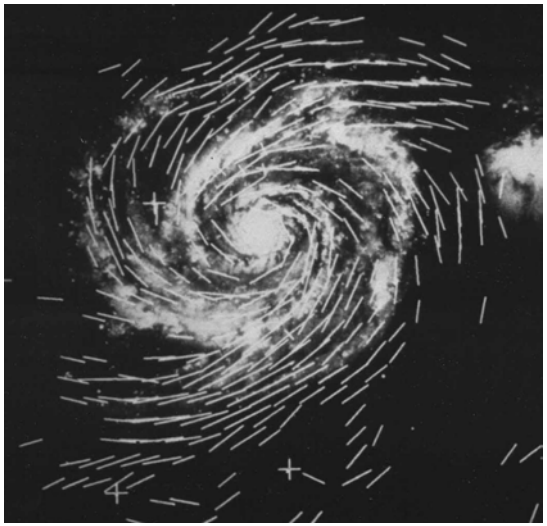
Magnetic Fields



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

We need neutral particles to do astronomy → γ, ν

Key Questions

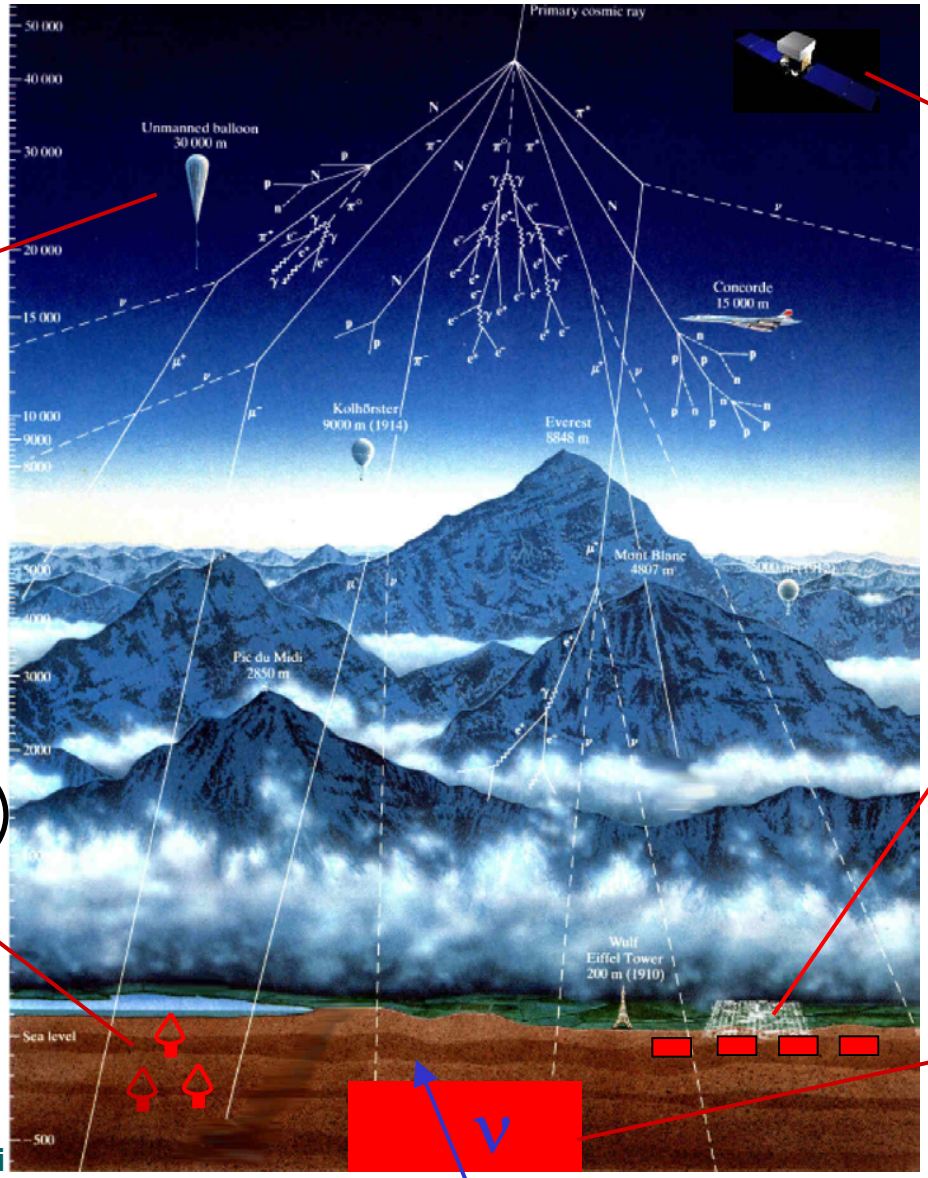
1. **What is the origin of the diffuse flux of cosmic-ray particles?**
   - We don't know, but the sources must be both powerful and renewable. We have no real understanding of physics mechanisms.

2. **Can VHE particles provide clues about the early Universe or about the physics at higher mass scales?**
   - Yes, via absorption features, new particles (e.g. dark matter) …

3. **What new astrophysics is revealed in VHE γ-rays?**
   - Gamma-rays point directly back to sites of extreme particle acceleration and unexpected phenomena.
   - Gamma-ray beams can be used to probe radiation fields and the fabric of space-time.

DETECTION OF VHE PARTICLES

Experimental Techniques



Balloon

Satellite

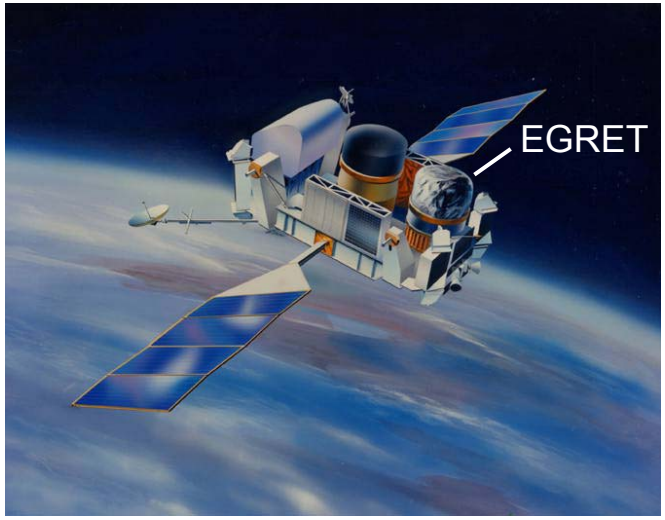
Cherenkov Telescopes

Air shower array

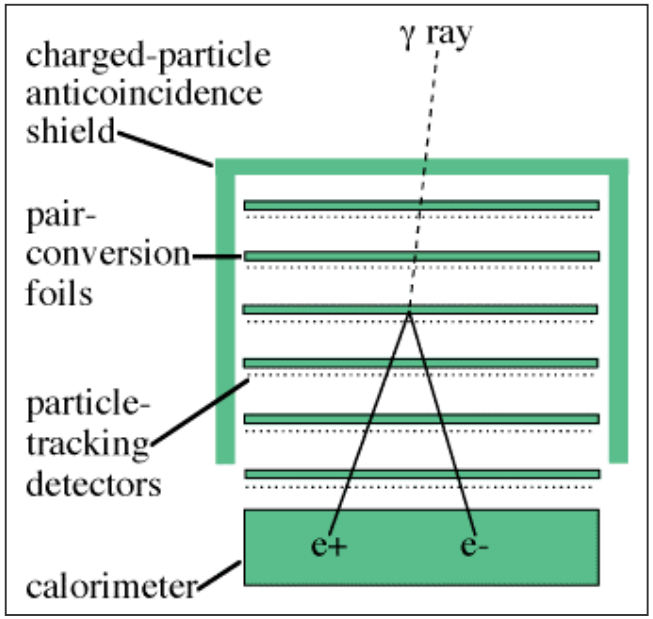
Ice/Water Cherenkov

EGRET (CGRO)

Compton Gamma-Ray Observatory



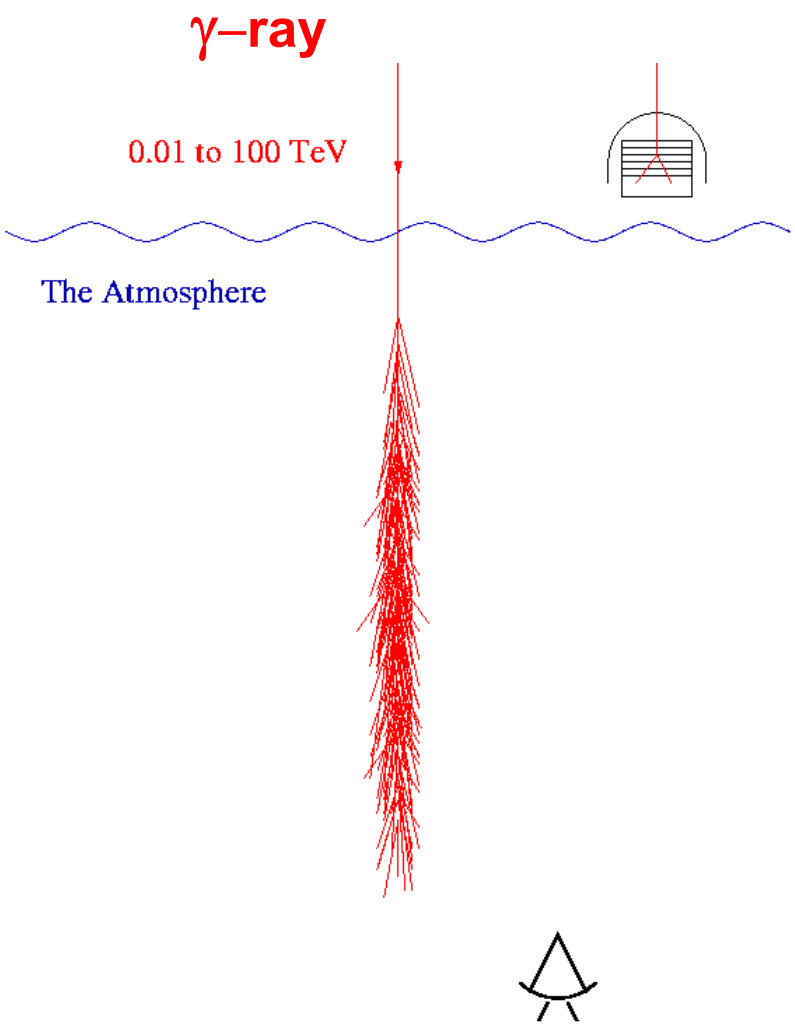
EGRET (30 MeV – 20 GeV)



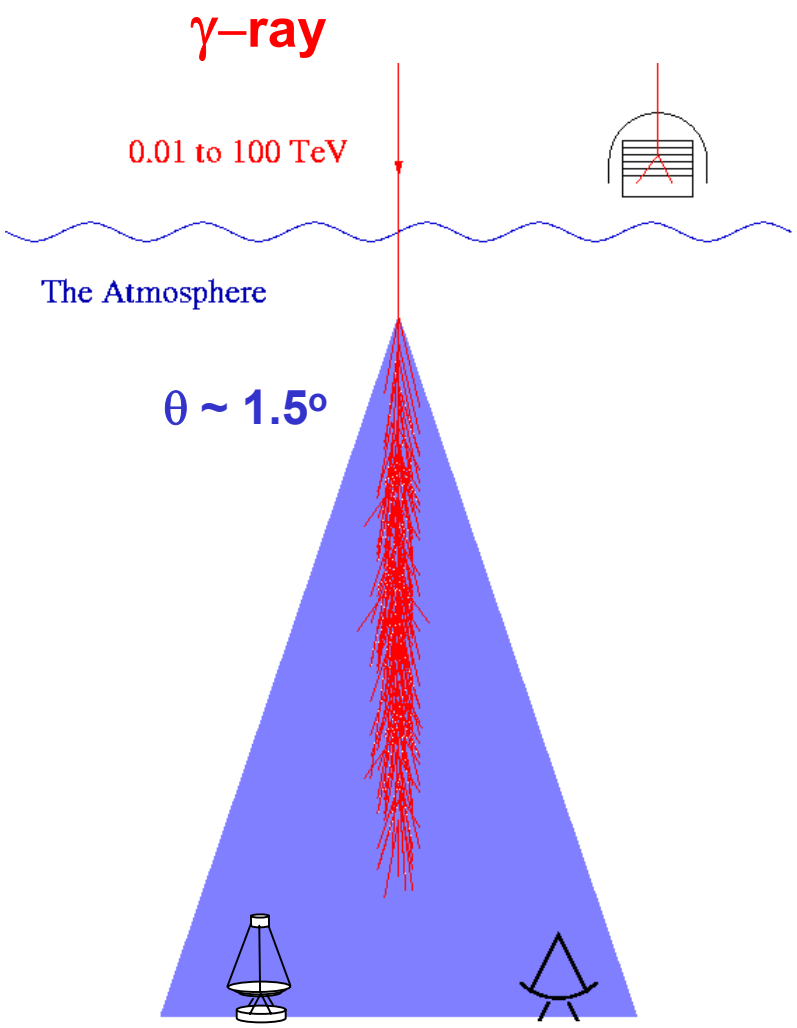
- **Flew 1991-2000.**
- **Very successful mission.**
- **EGRET detected ~ 300 points sources.**

Area < 1 m²

Air Showers



Cherenkov Telescopes



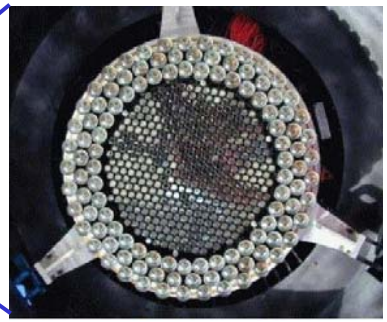
Area = 10^4 – 10^5 m^2

~60 optical photons/m^2/TeV

Whipple γ-ray Telescope

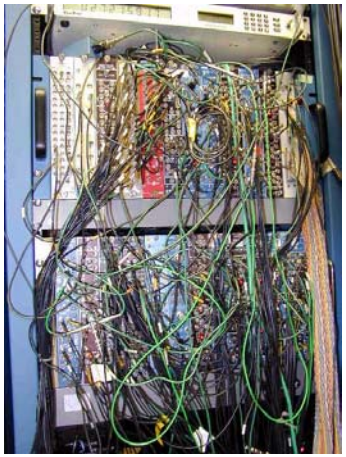
Whipple 10m (Arizona)

E_{th} ~ 300 GeV

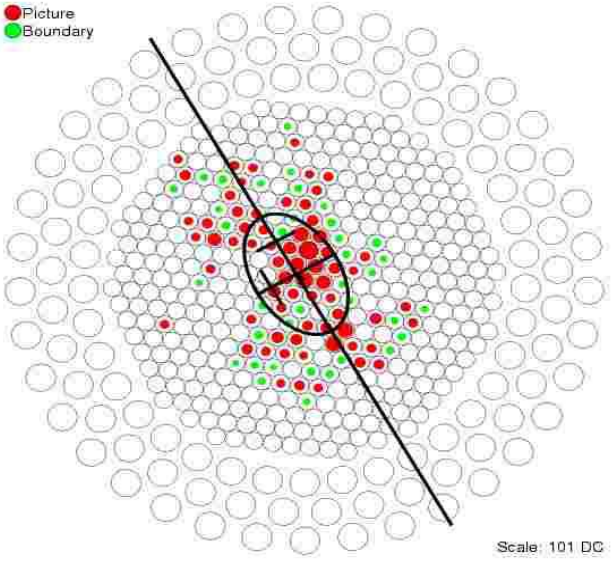


PMT camera

+



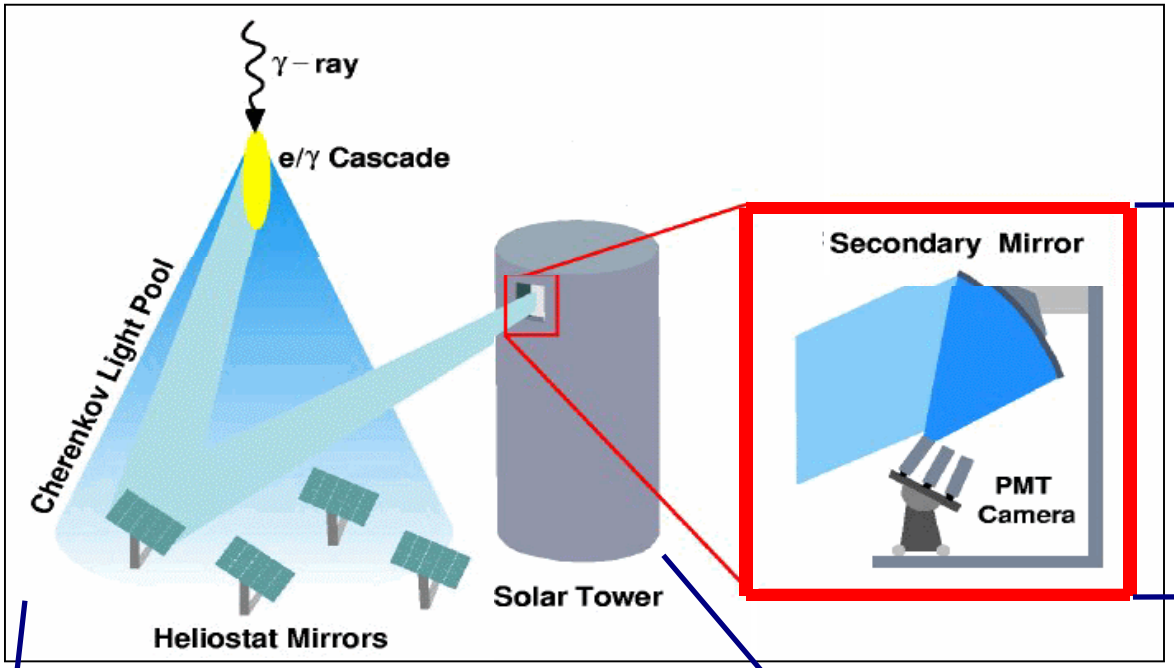
ns electronics



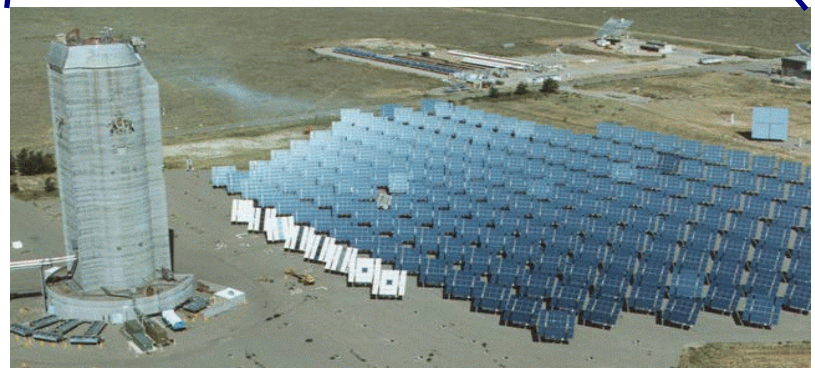
Cherenkov Image – Background rejection.

Cosmic Ray Rejection ~ 300

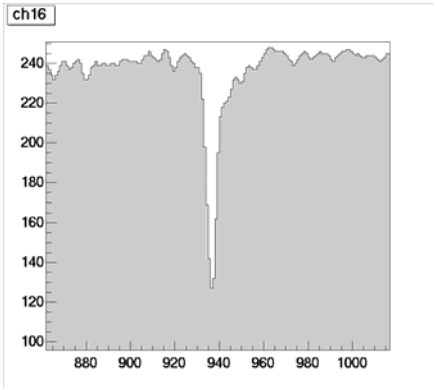
Solar Mirror Arrays I



Large Mirror Area
→ Low E Threshold
~ 100 GeV



STACEE (New Mexico)

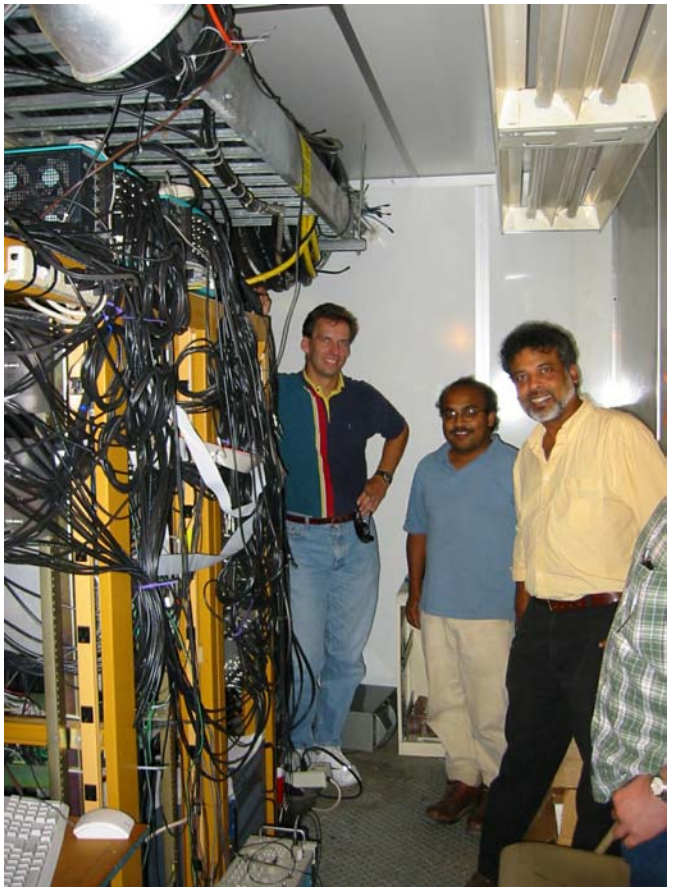


1 GHz Flash ADCs

Cosmic Ray Rejection ~ 100

Solar Mirror Arrays II

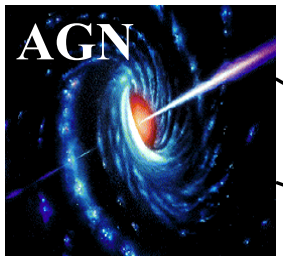
Keck Solar Two
(Barstow, CA)

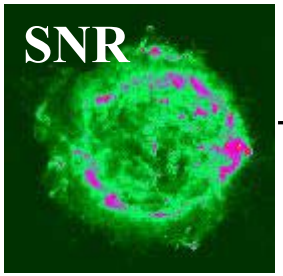


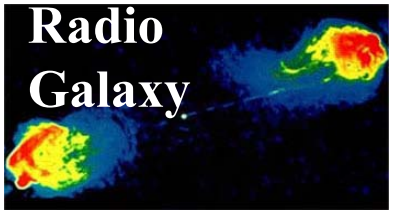
Heliostat Field: > 2,000 mirrors

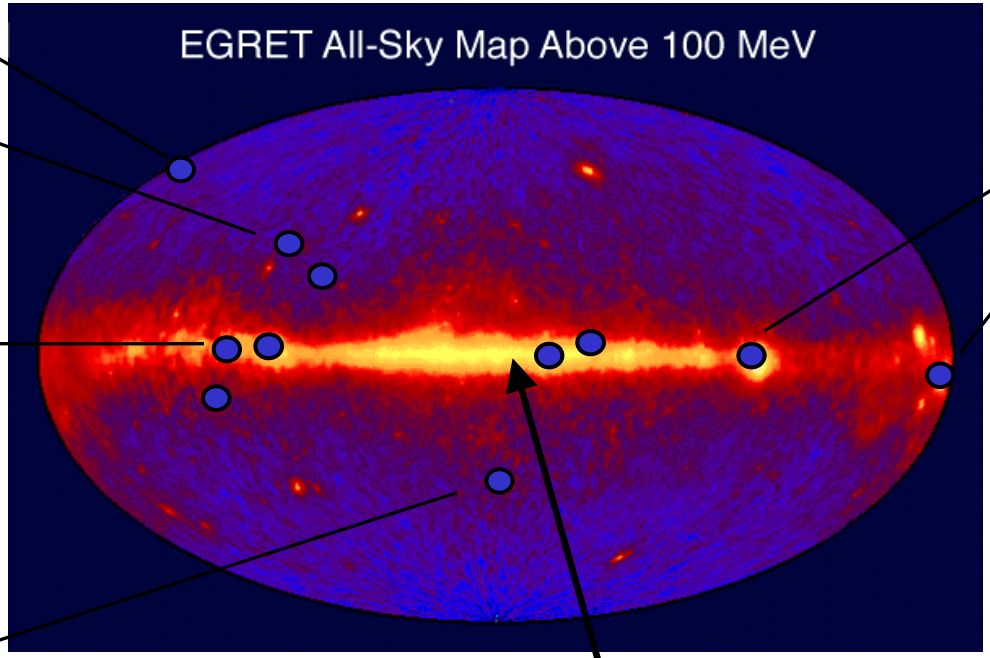
GeV and TeV Astrophysics

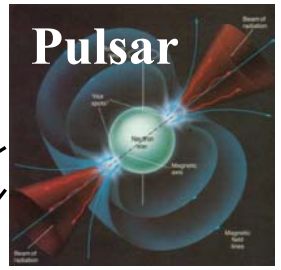
GeV γ-ray Sky

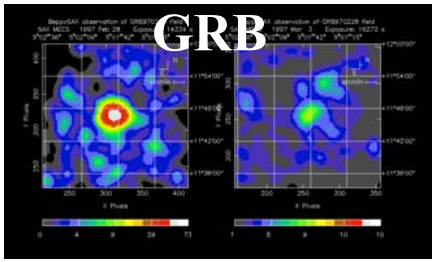








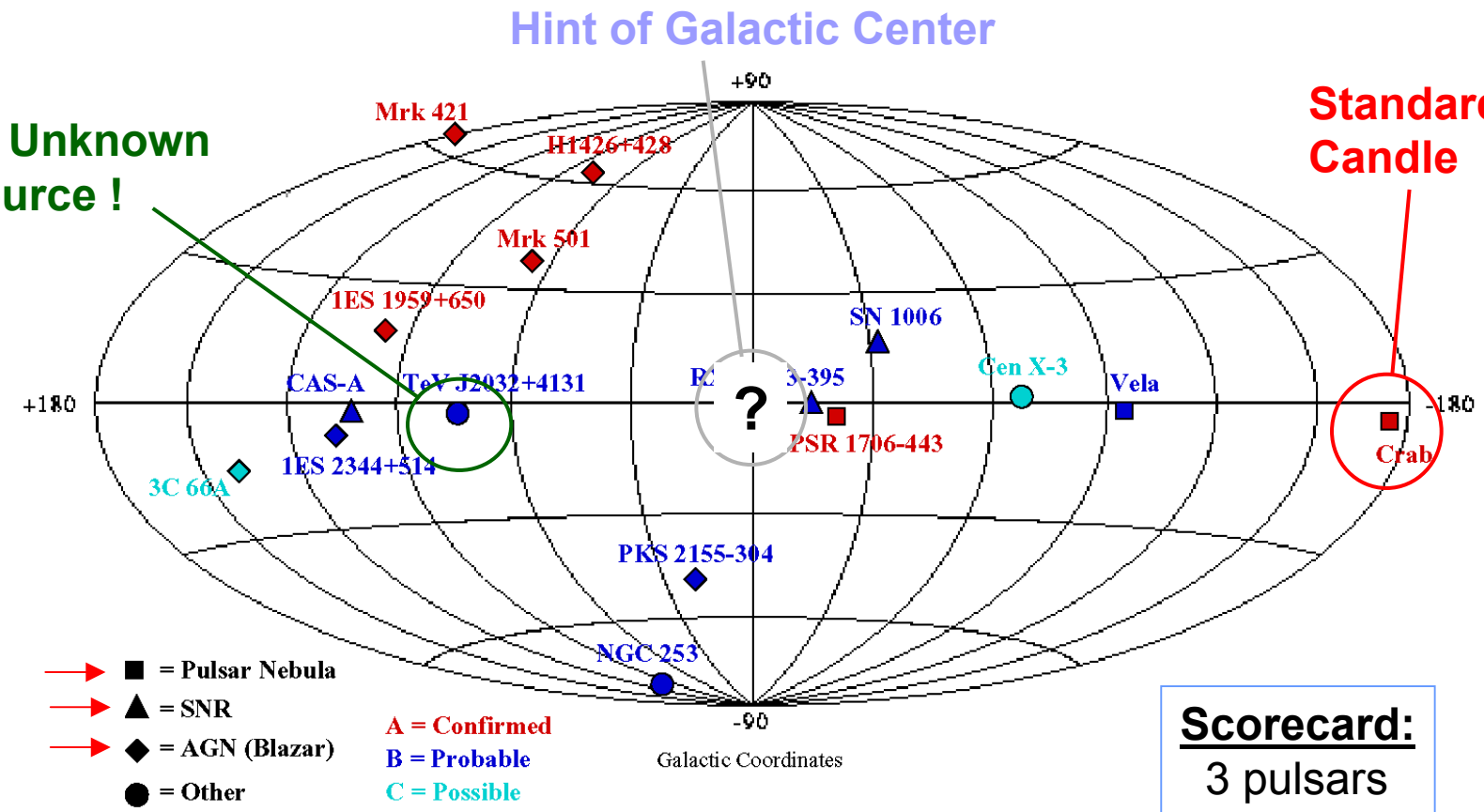




Cosmic Rays !

- ~ 300 HE point sources, most unidentified.
- Most identified sources are AGN – “Blazars”

TeV γ-ray Sky c2003

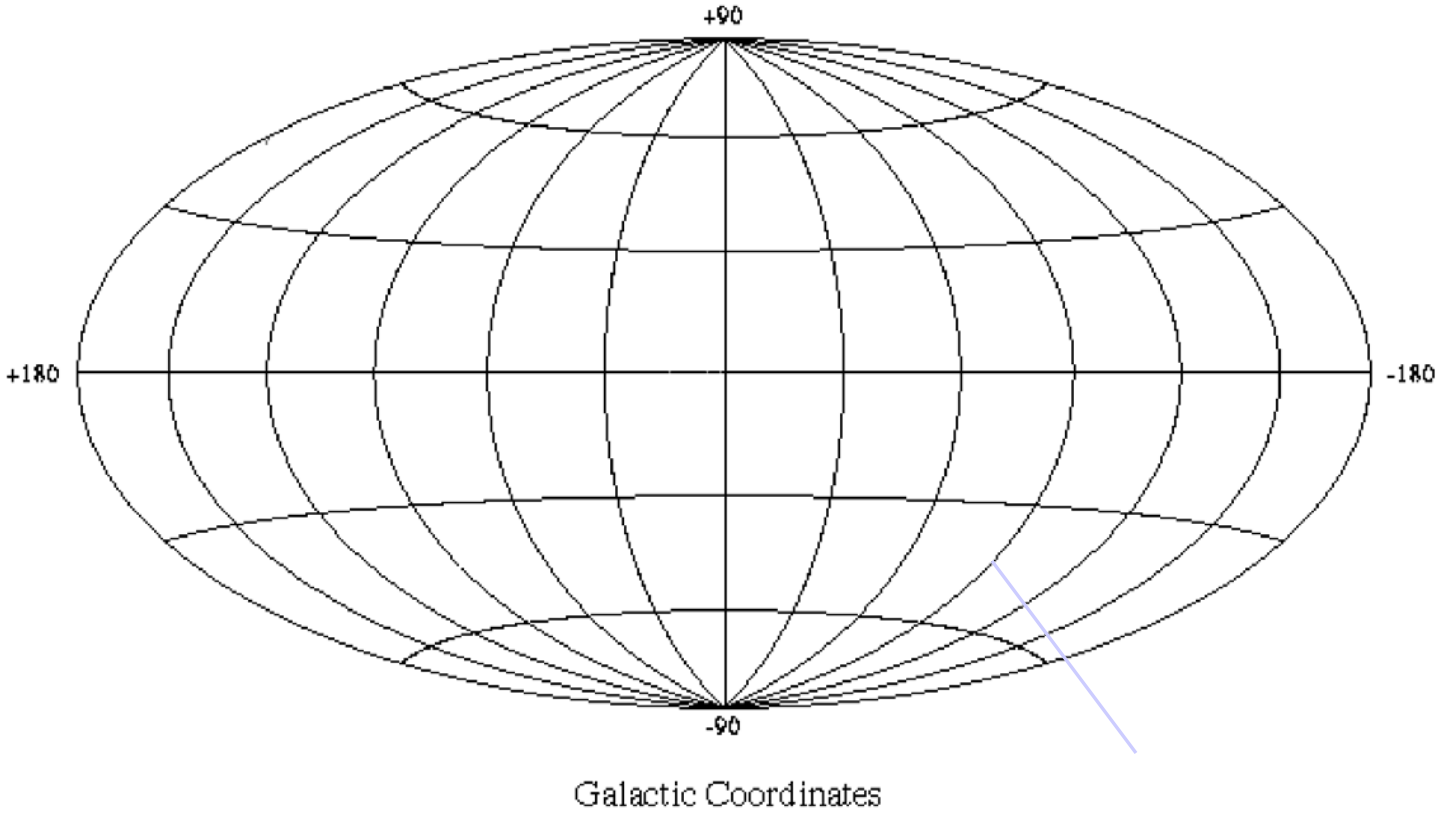


All discovered by Cherenkov telescopes.
(CANGAROO in S. Hemisphere)

Scorecard:

3 pulsars
3 SNR's
6 AGN
2 others
14 total

High-Energy Neutrino Sky



- No sources yet.

Power Sources

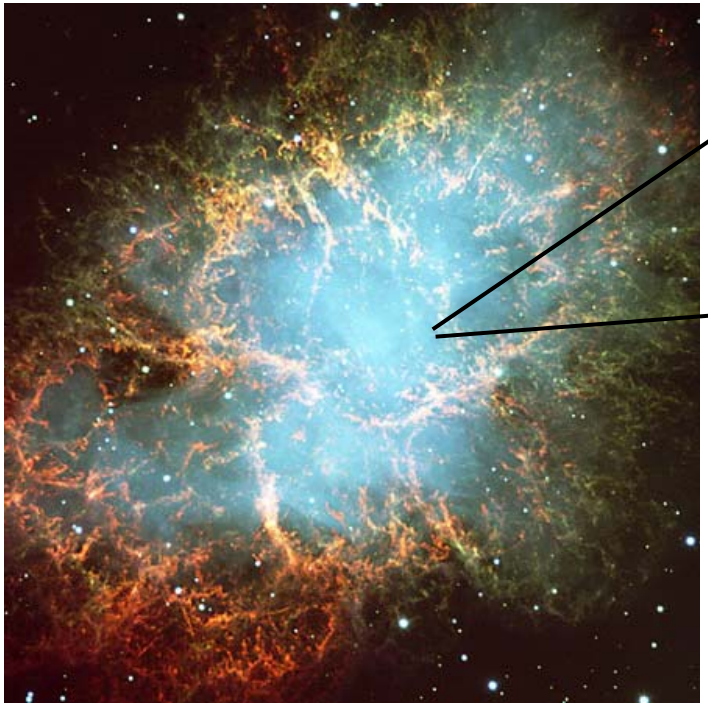
Broadly speaking, there are two types of sources:

1. Electromagnetic
   - e.g. rotating highly magnetized object – **Pulsar (1)**

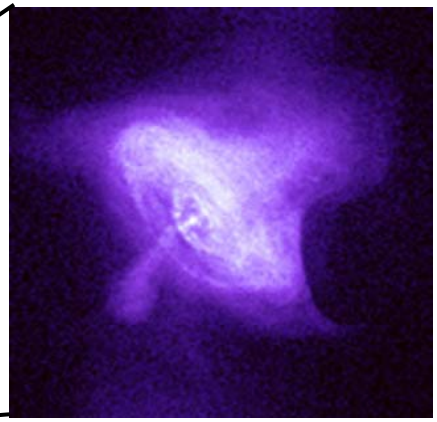
2. Gravitational
   - Core collapse of a massive star – **SN and its remnant (2)**
     – Gamma-ray Bursts … etc.
   - Accretion onto a compact object – **Active Galactic Nuclei (3)**
     – Microquasars … etc.

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

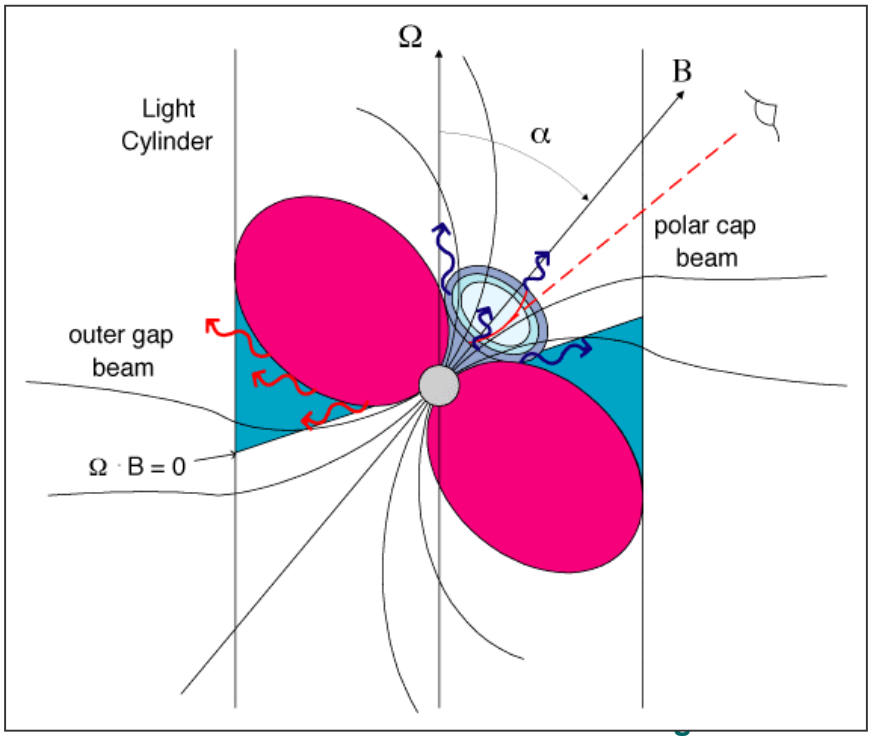
1. Pulsars



Crab Nebula

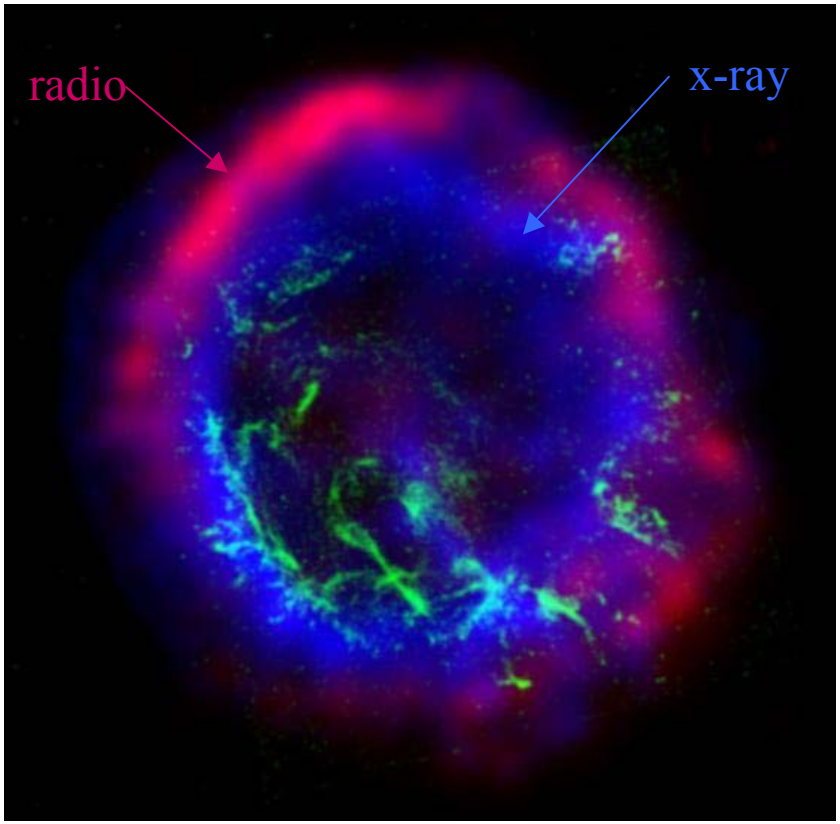


Pulsar



→ Particle acceleration by pulsar and by the nebula wind.

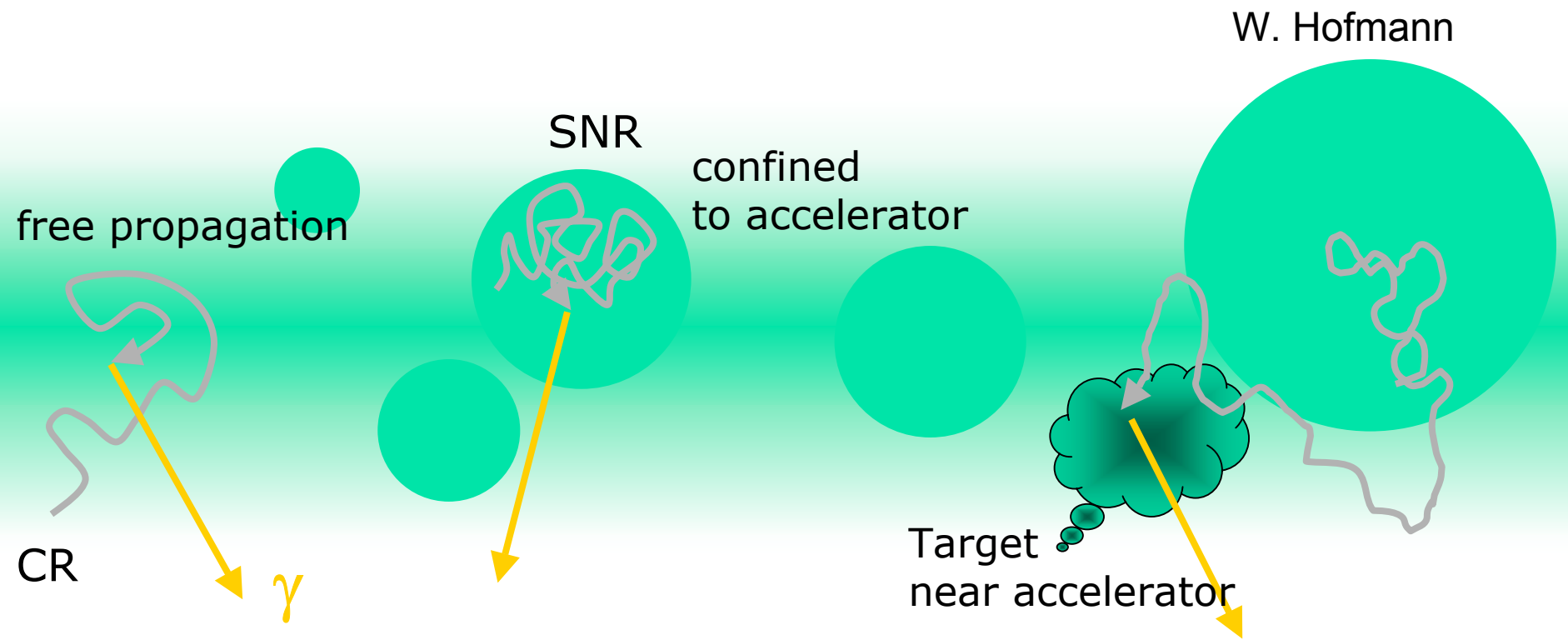
2. Supernova Remnants (SNR's)



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.
- Acceleration of particles via "canonical" Fermi process.
- In ~ 10^4 yrs, blast wave begins to deccelerate (Sedov phase) and slowly dissipate.

SNR's – Acceleration and Propagation



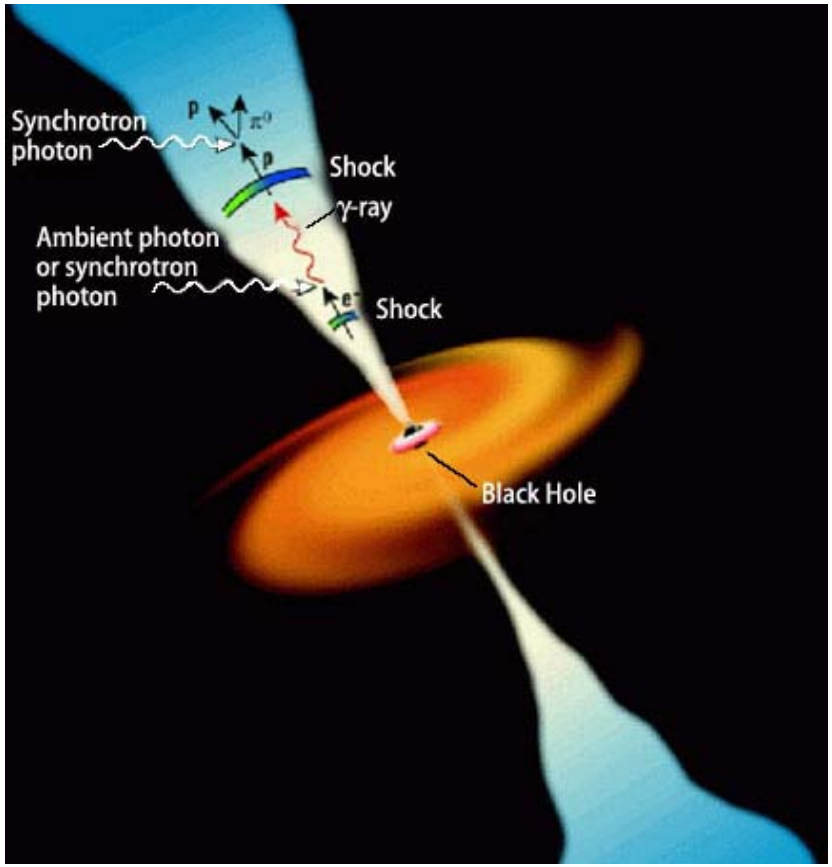
VHE gamma rays from secondary interactions:

p: π^o production and decay

e: Inverse Compton scattering and Bremsstrahlung

Trace beam density x target density

3. Active Galactic Nuclei (AGN)

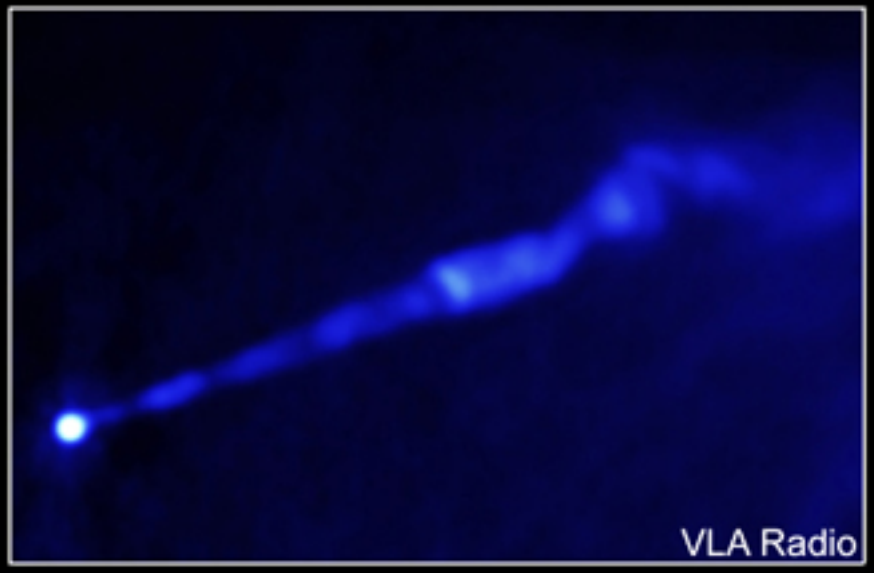


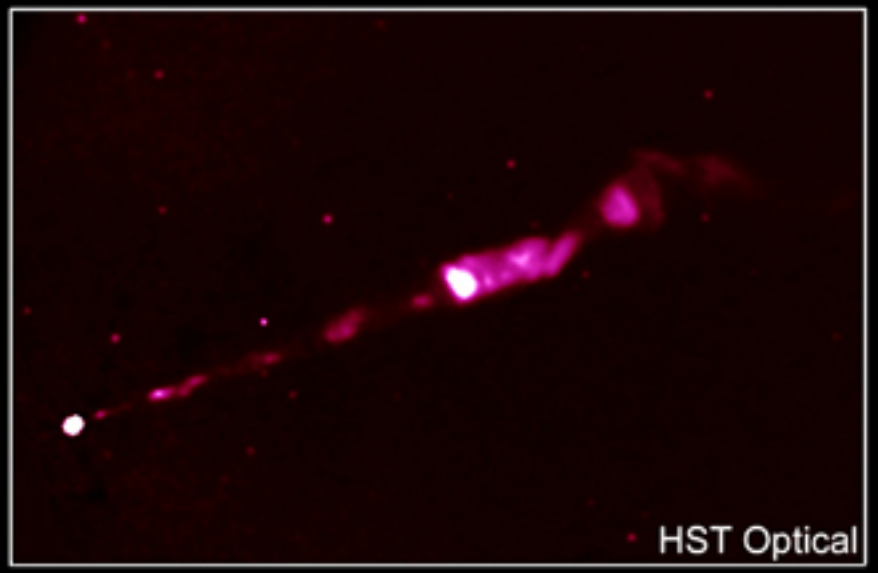
AGN model

AGN are very luminous galaxies with a bright central core.

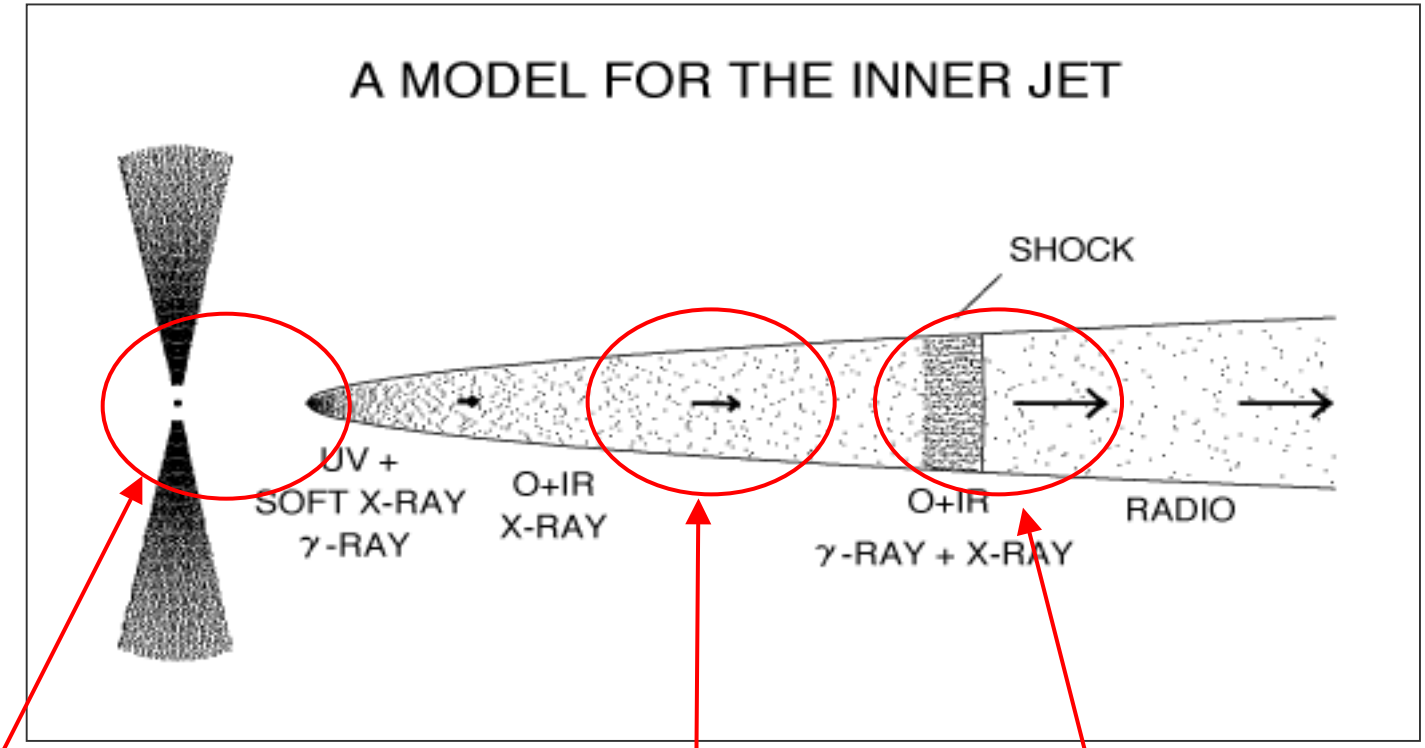
- Likely powered by accretion onto BH's of 10^6 – 10^9 solar masses.
- Released accretion energy powers jets of relativistic outflow.
- Particle acceleration (e,p) occurs in these jets → beams of γ's, ν's.

Jet in M87





Understanding AGN



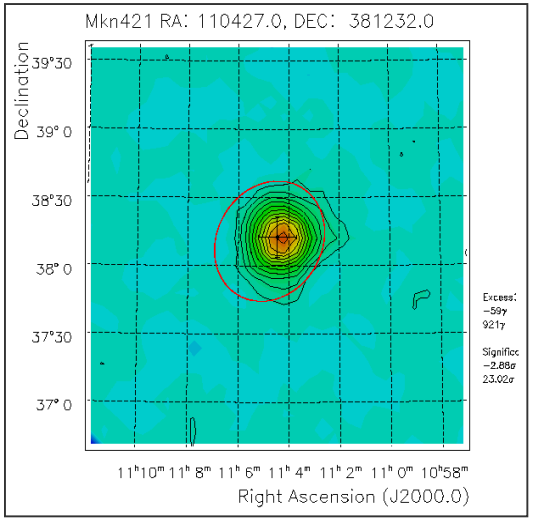
How do Jets form
& what powers them?

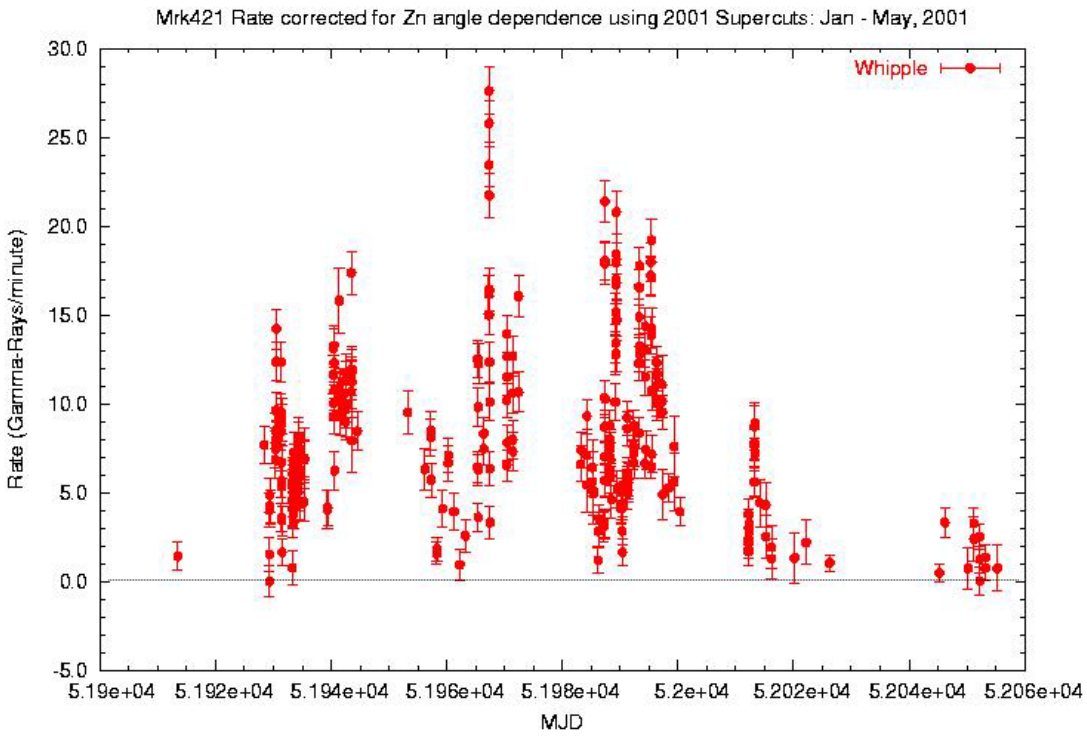
Nature of beam:
energetics Γ
particle type: e or p
field strengths B,γ

Geometry & External:
emission zones
source of soft photons

AGN Observations

Mrk 421 Whipple



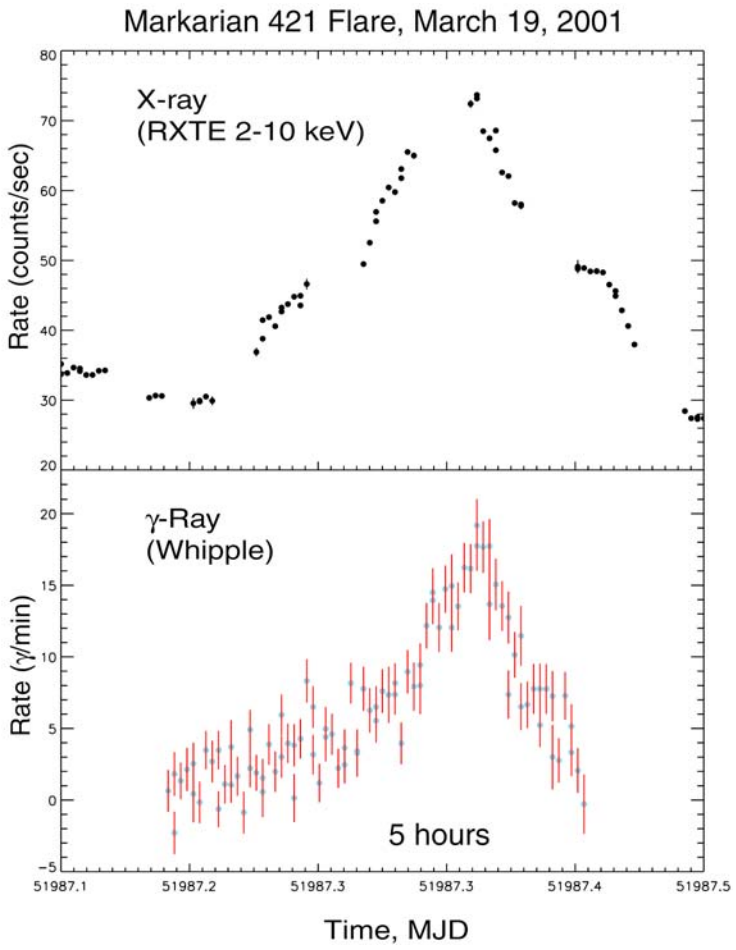


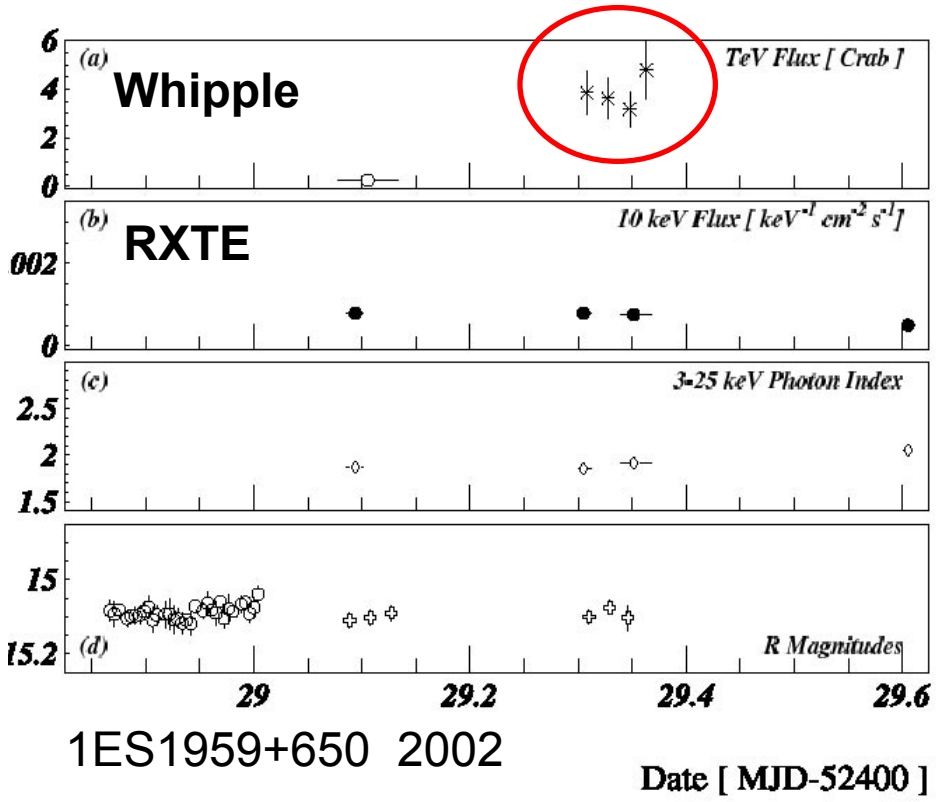
"BLAZARS":

- Powerful, radio-loud objects.
- Highly variable at all wavelengths.
- Jets – superluminal motion
  beamed emission to Earth.

- STACEE detected similar rapid variability.
- Shortest variations probe to ~ 10^{-4} pc, within a factor of ten of Schwarzchild Radius.

AGN: X-rays & TeV γ-rays

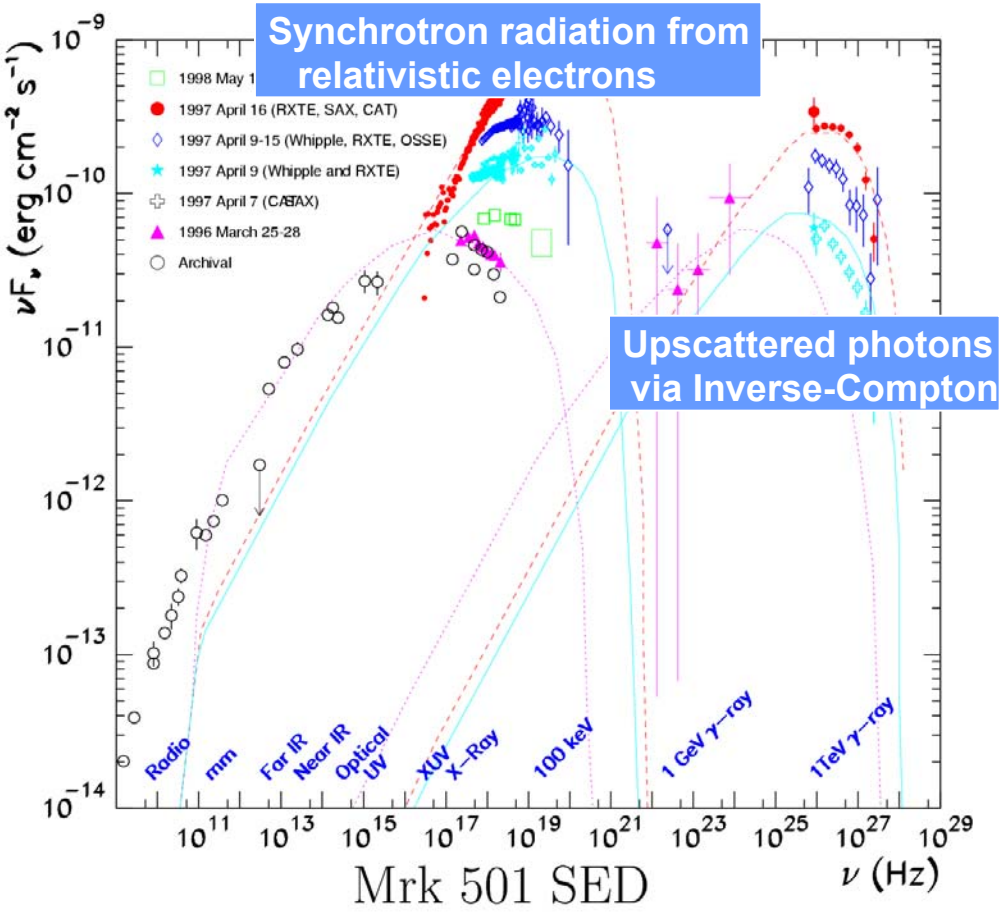




- VHE Flares are generally well correlated with X-ray flares.
- But not in this case !

AGN: Broadband Spectrum

Mrk 501



γ-ray and X-ray correlation is most easily explained in Synchrotron-IC scenarios.

→ Same e^- population.

Constraints on electron Γ, time scales, emission zones, soft photon density, etc.

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

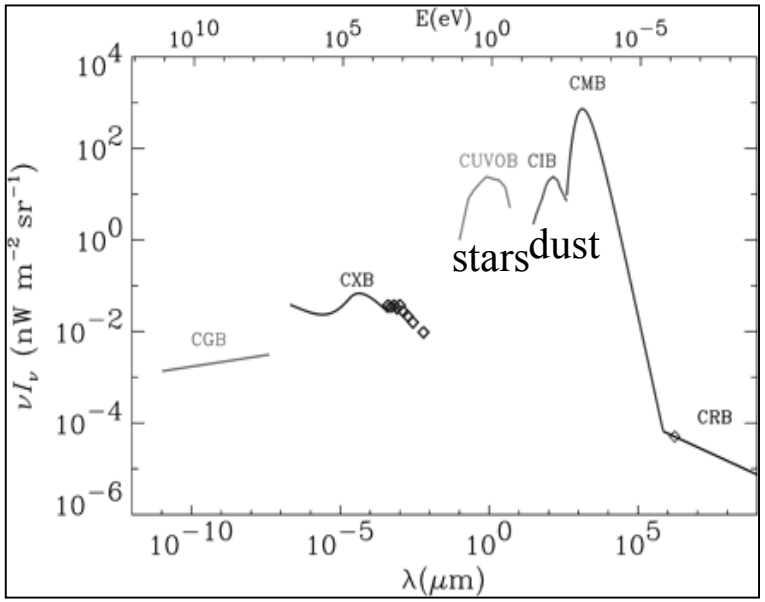
Cosmic Absorption

Gamma-rays will pair-produce off intergalactic radiation fields.

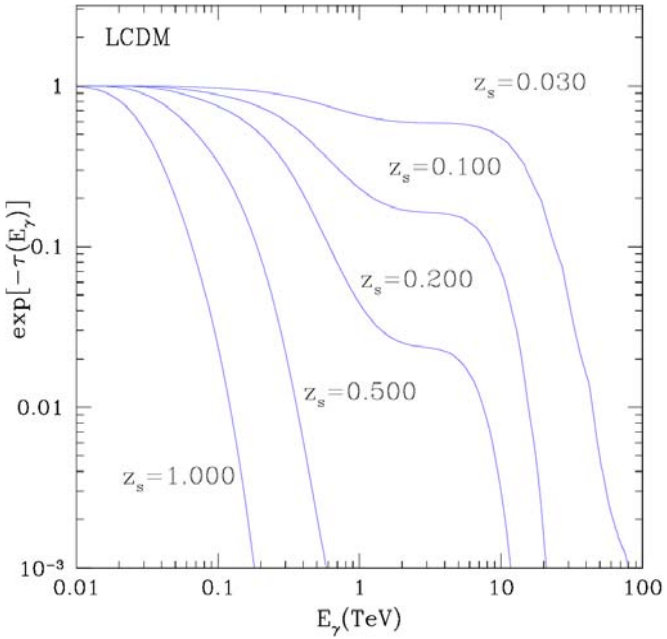
$\gamma\ \gamma \rightarrow e^+ e^-$

1 TeV 1 eV (1.2 μm)

Hauser & Dwek 2001



Diffuse radiation fields



(Primack et al. 1999)

Model γ-ray spectra

New Physics Origins

So far – only talked about astrophysical sources of VHE particles. Also exist **New Physics** possibilities.

1. **Particle Physics at higher mass scale, e.g.**
   - Supersymmetry (Dark Matter).
   - Top-down sources (GUT scale particles).
2. **Relics from early Universe, e.g.**
   - Primordial black holes.
   - Decaying heavy neutrinos.

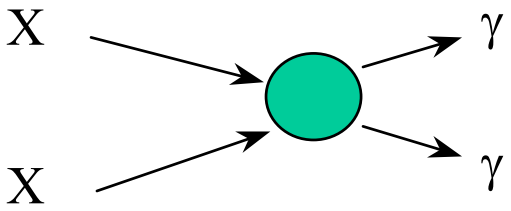
These are very intriguing, but speculative.

Also speculation on probing quantum gravity using distant sources of HE photons.

Dark Matter & SUSY

Galactic Center

Neutralino Annihilation

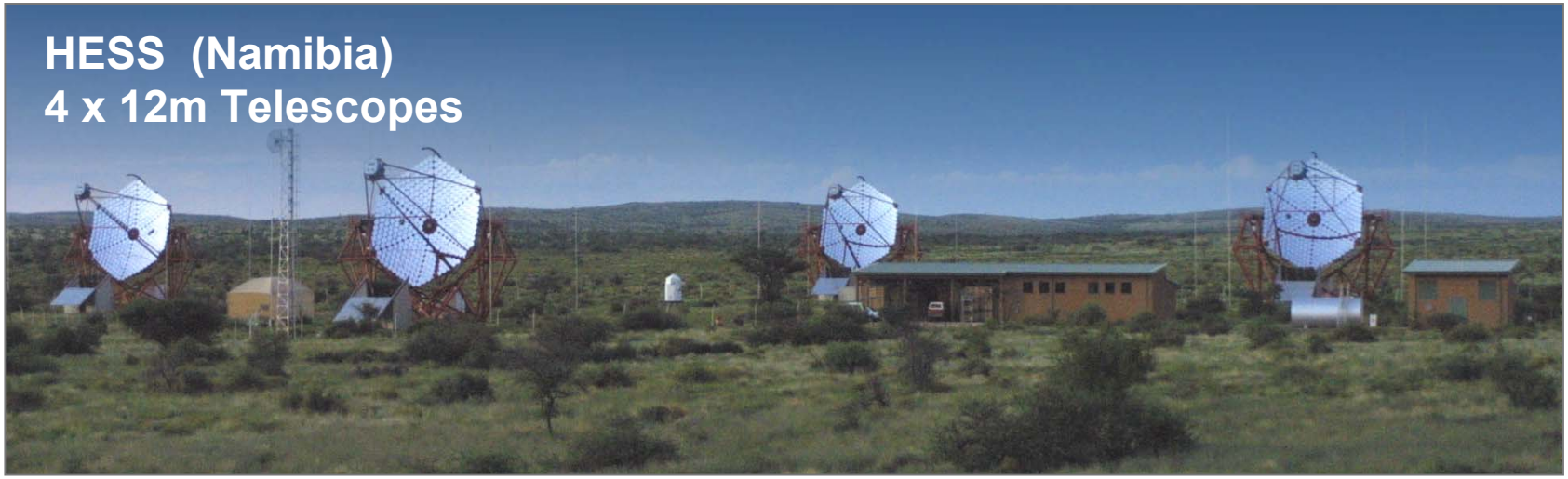


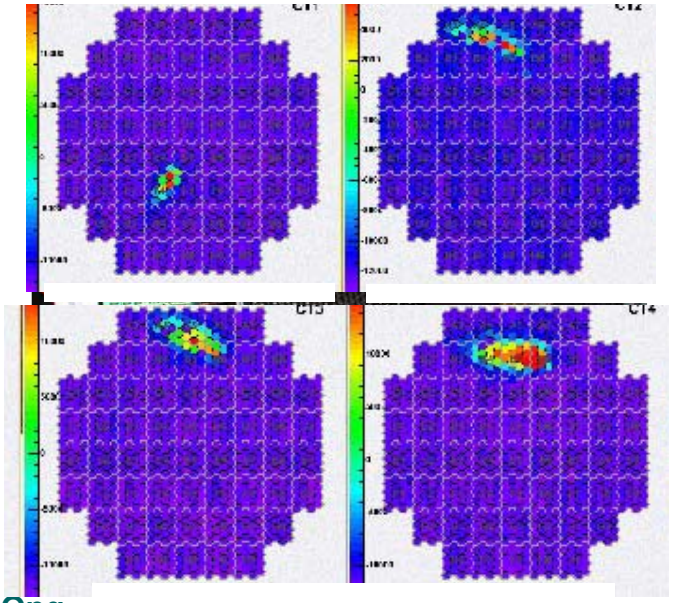
Flux ~ $(\rho_x / M_x)^2 \sigma v$

- Neutralinos can have enhanced density in GC.
- Annihilate to give γ-rays at GeV and TeV energies.
- Generally expect broad “bump” in γ-ray spectra.

Latest Results

NEW Telescope Arrays (2004)





4 Telescope Event

HESS:

E_{th} ~ 120 GeV

Ang. resolution ~ 4′

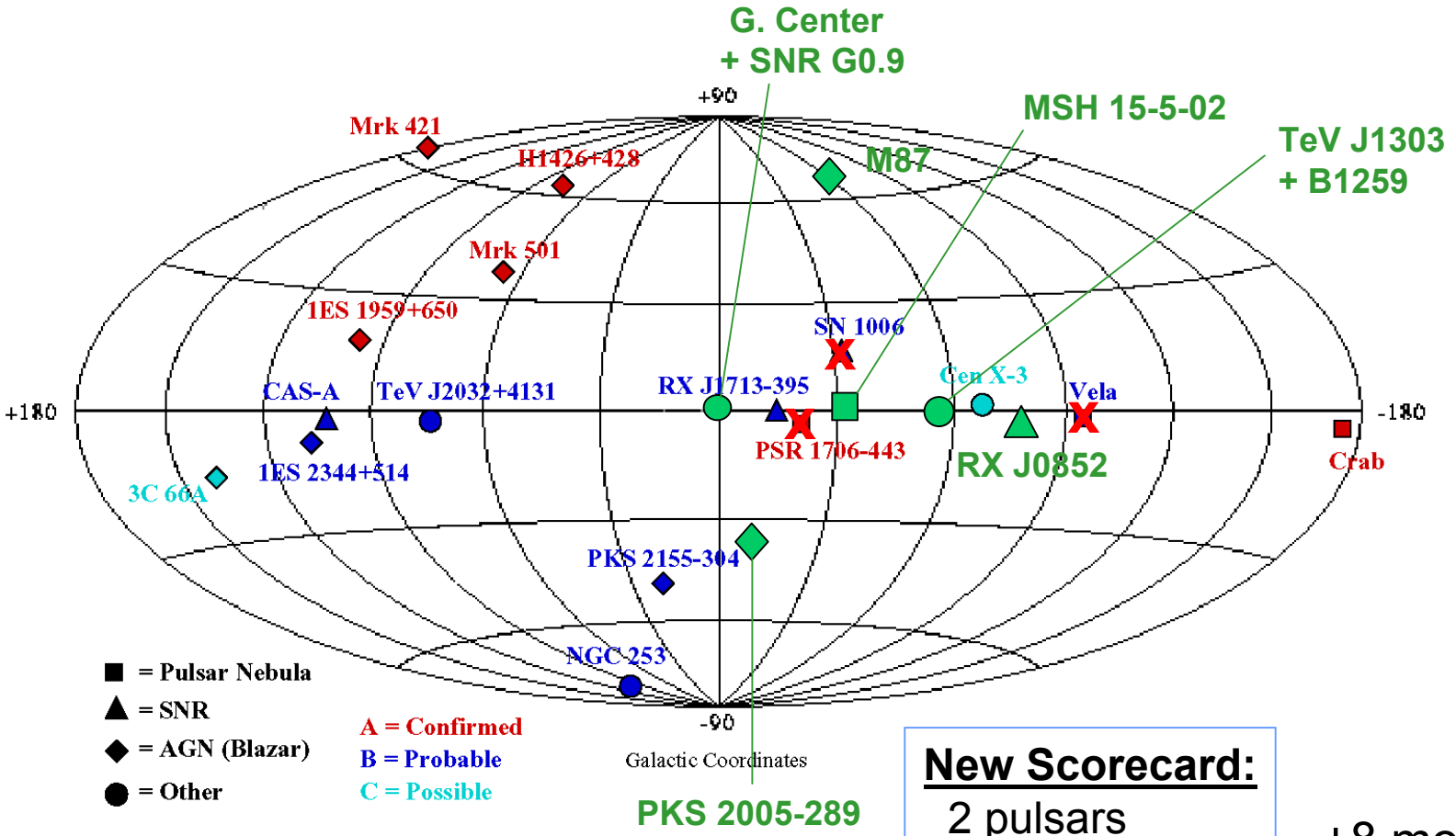
E resolution 10-15%

CR rejection > 5,000

Sensitivity:

10x better than Whipple.

TeV γ-ray Sky c2005



New HESS Sources (8)

X Excluded by HESS (3)

New Scorecard:

2 pulsars
4 SNR's
8 AGN
5 others
19 total

+8 more Sources ! (3/27/05)

1. SNR RX J1713 with HESS

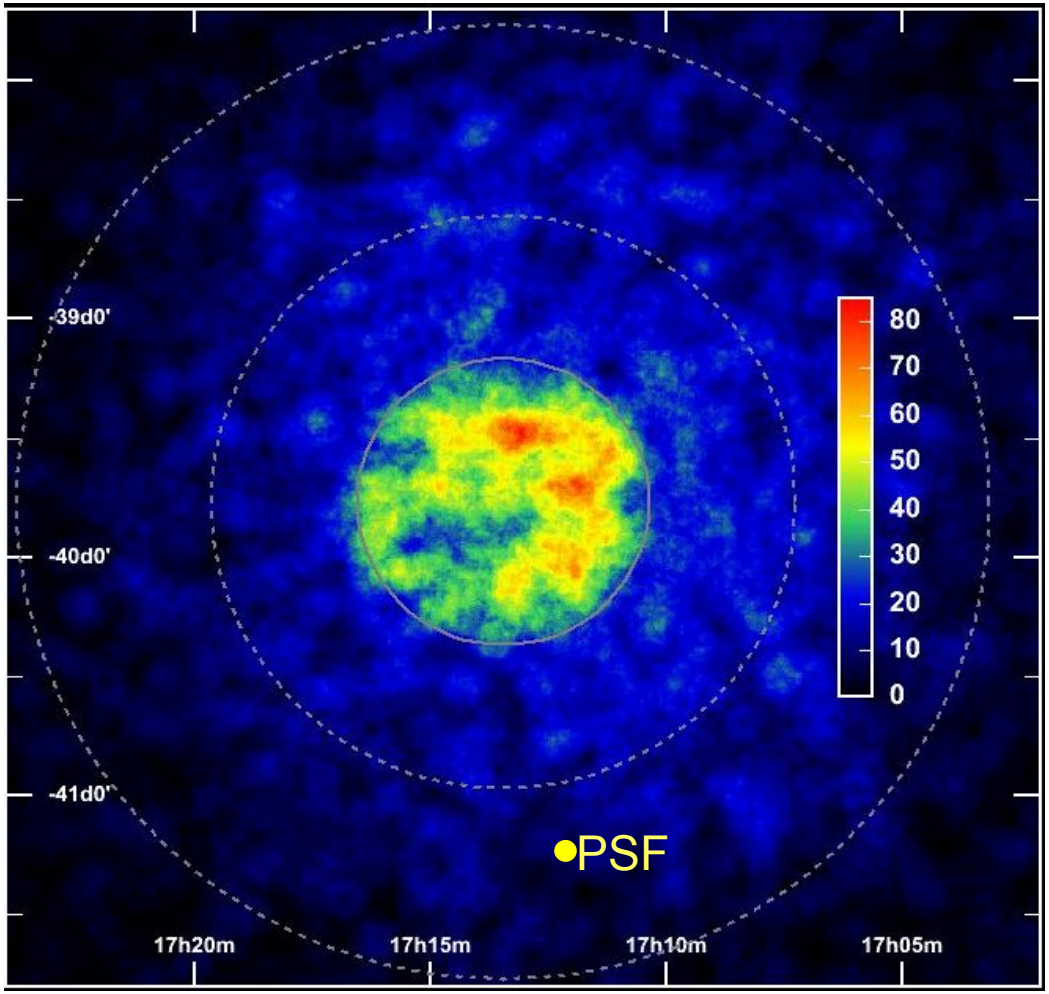
C. Masterson

Confirmed in 2004:

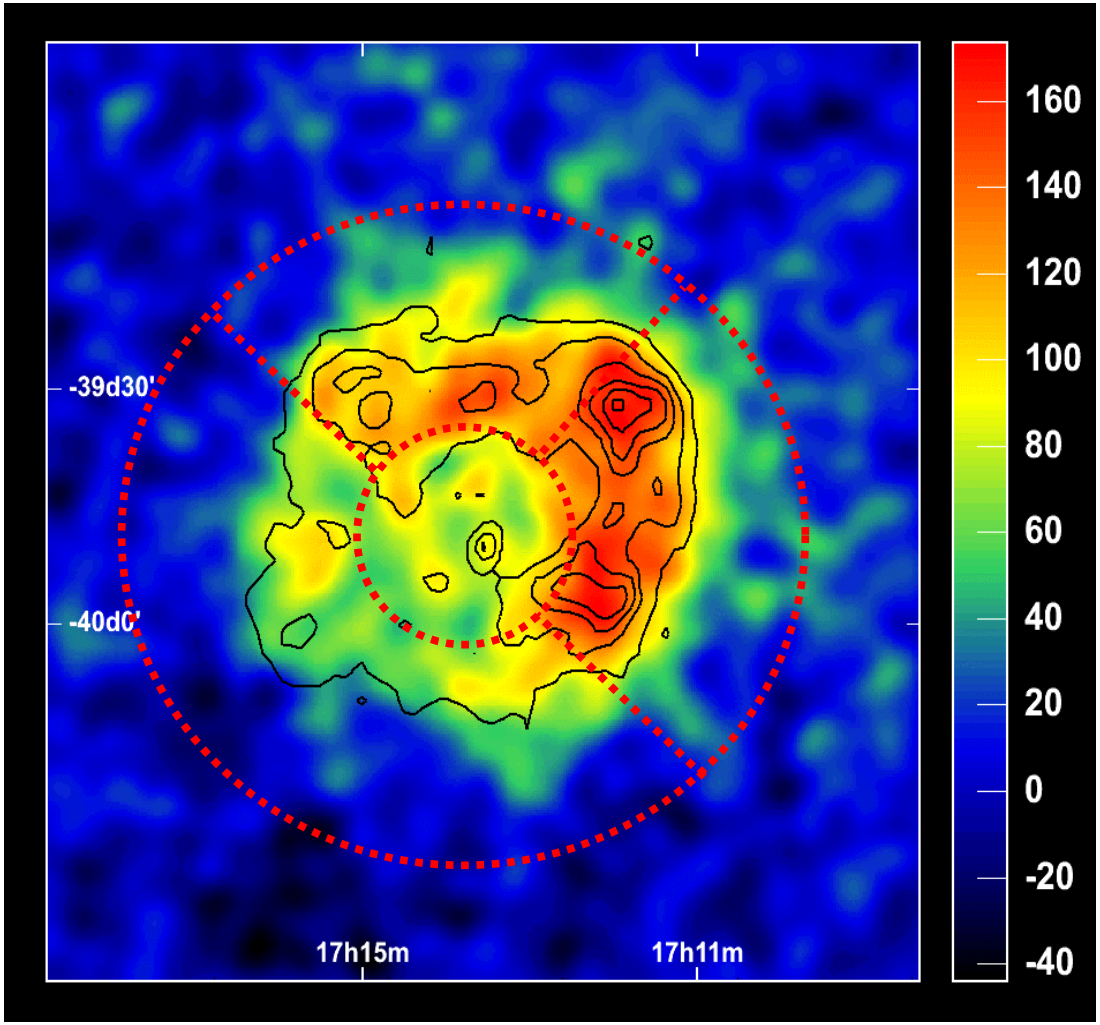
- **4 telescope data**
- **First extended γ-ray source**
- **Emission ~ 1° Ø**
- **Flux 65% Crab**
- **> 40 σ**
- **Confirmed flux**

Good correlation with X-ray image.

Real test of origin of CR's.



Precise Map of RX J1713



2. Galactic Center

C. Masterson

HESS Confirmed 2004

- **~ 50 hours 4 tel data**
- **> 40σ**

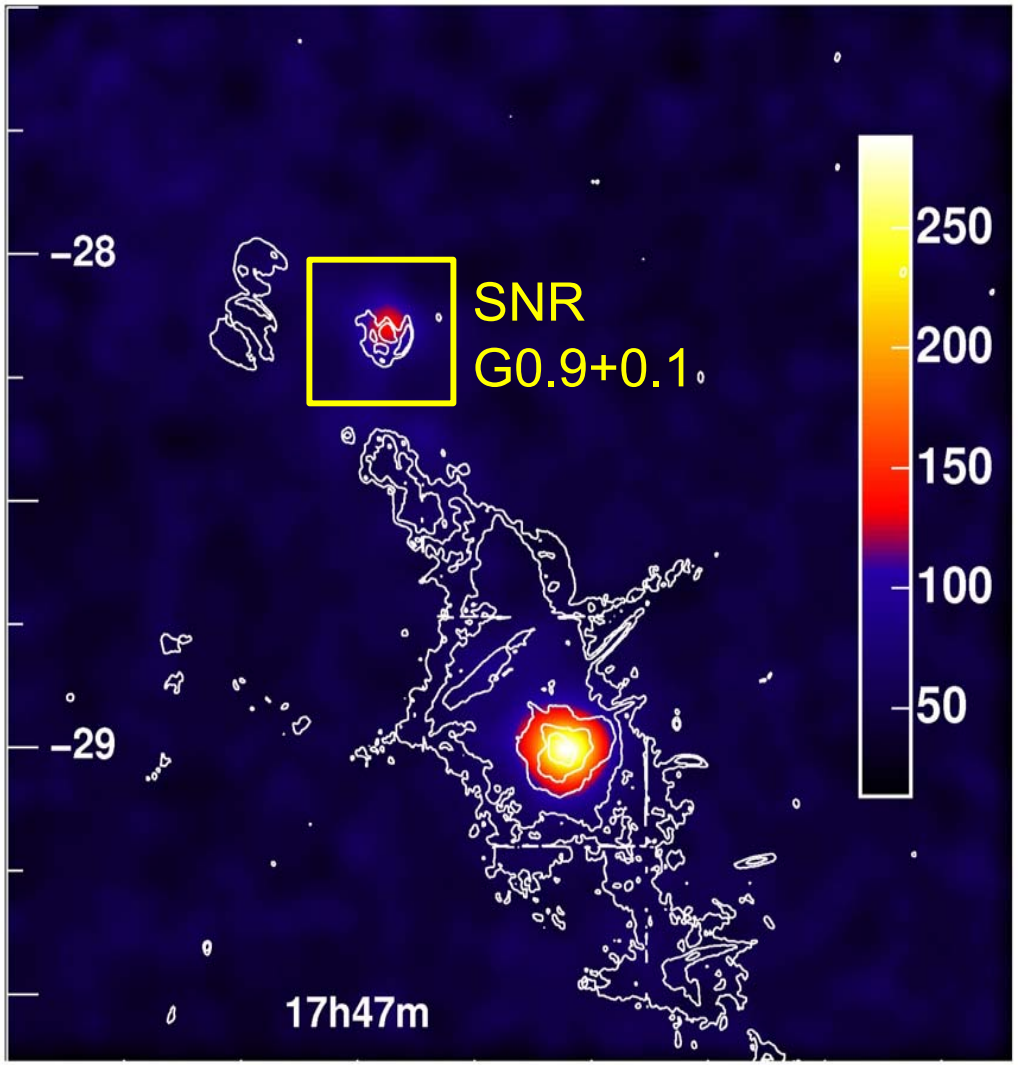
Point source

- **radius < 0.1°**
- **accurate position**

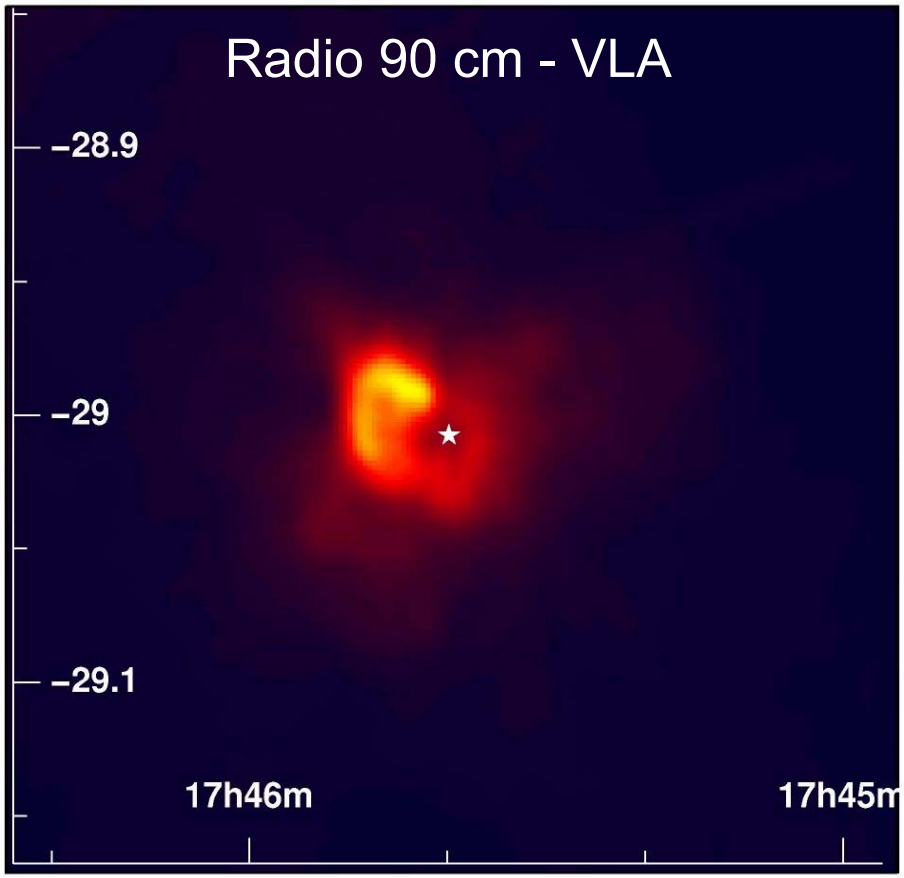
Hard, flat spectrum

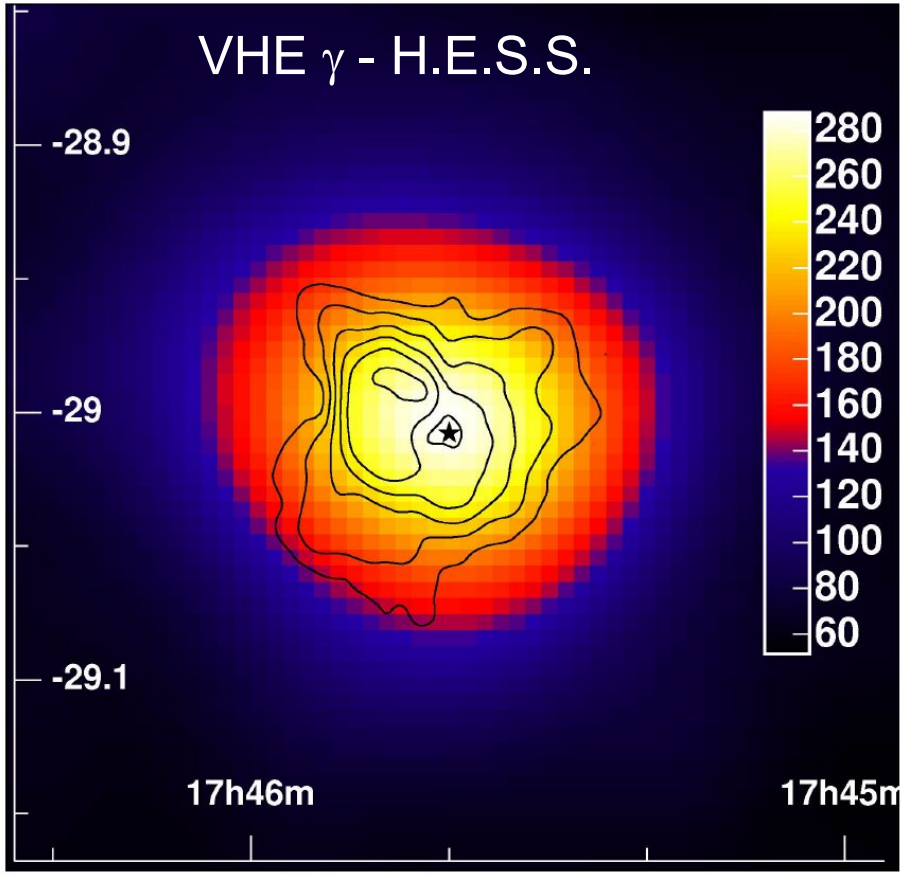
- **Γ = 2.21 ±0.09 ±0.1**

Dark Matter speculation…



Sgr-A* and Sgr-A East



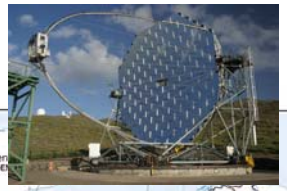


- Position compatible with Sgr A*

FUTURE

Major HE γ-ray Telescopes

GLAST (2007)



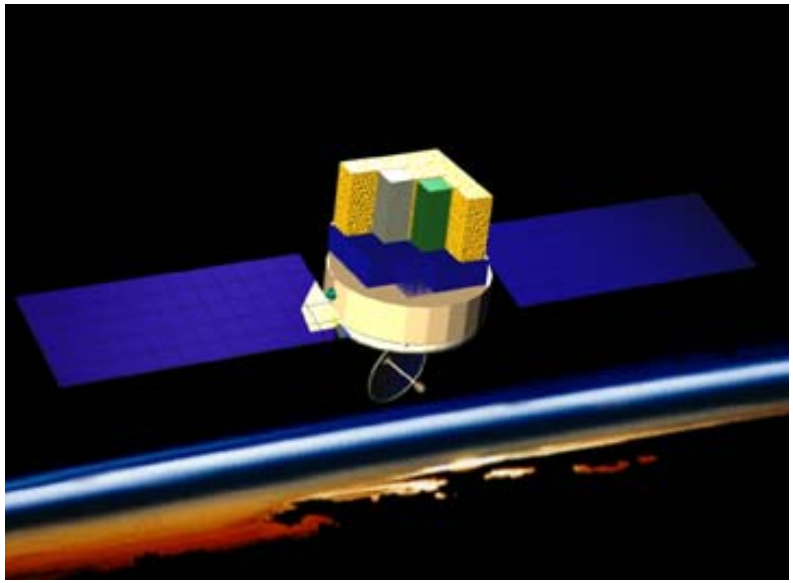
MAGIC

VERITAS

HESS

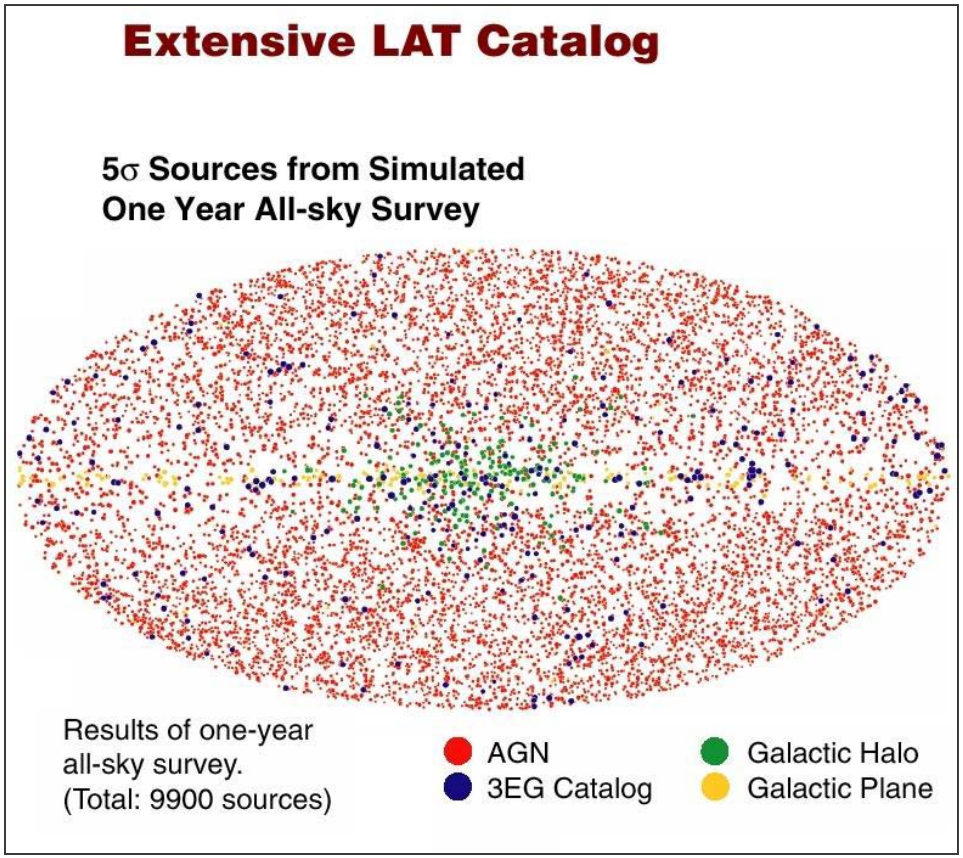
CANGAROO

GLAST – Satellite Telescope



GLAST LAT Instrument:

- **Si-strip tracker**
- **CsI calorimeter**
- **Anti-coincidence veto**



Simulated sky map from 1 year survey.

Launch in 2007.

VERITAS

VERITAS c2006.

Collaboration: 80 scientists
U.S, Canada, U.K., Ireland

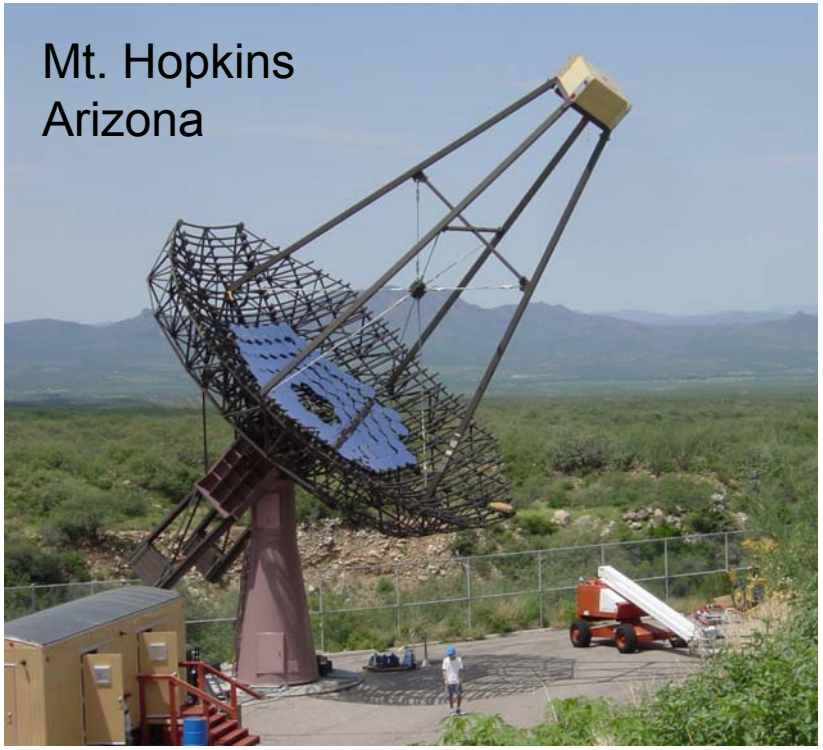
Detector Design:

- Four 12m telescopes.
- 500 pixel cameras (3.5^{o}).
- Site in southern Az (1700m),
- Fully operational in 2006.

Some characteristics:

- Energy threshold ~ 100 GeV.
- Ang. resolution ~ 4′.
- Crab rate ~ 50 γ/min. (detection in 20s).

VERITAS – Well Underway



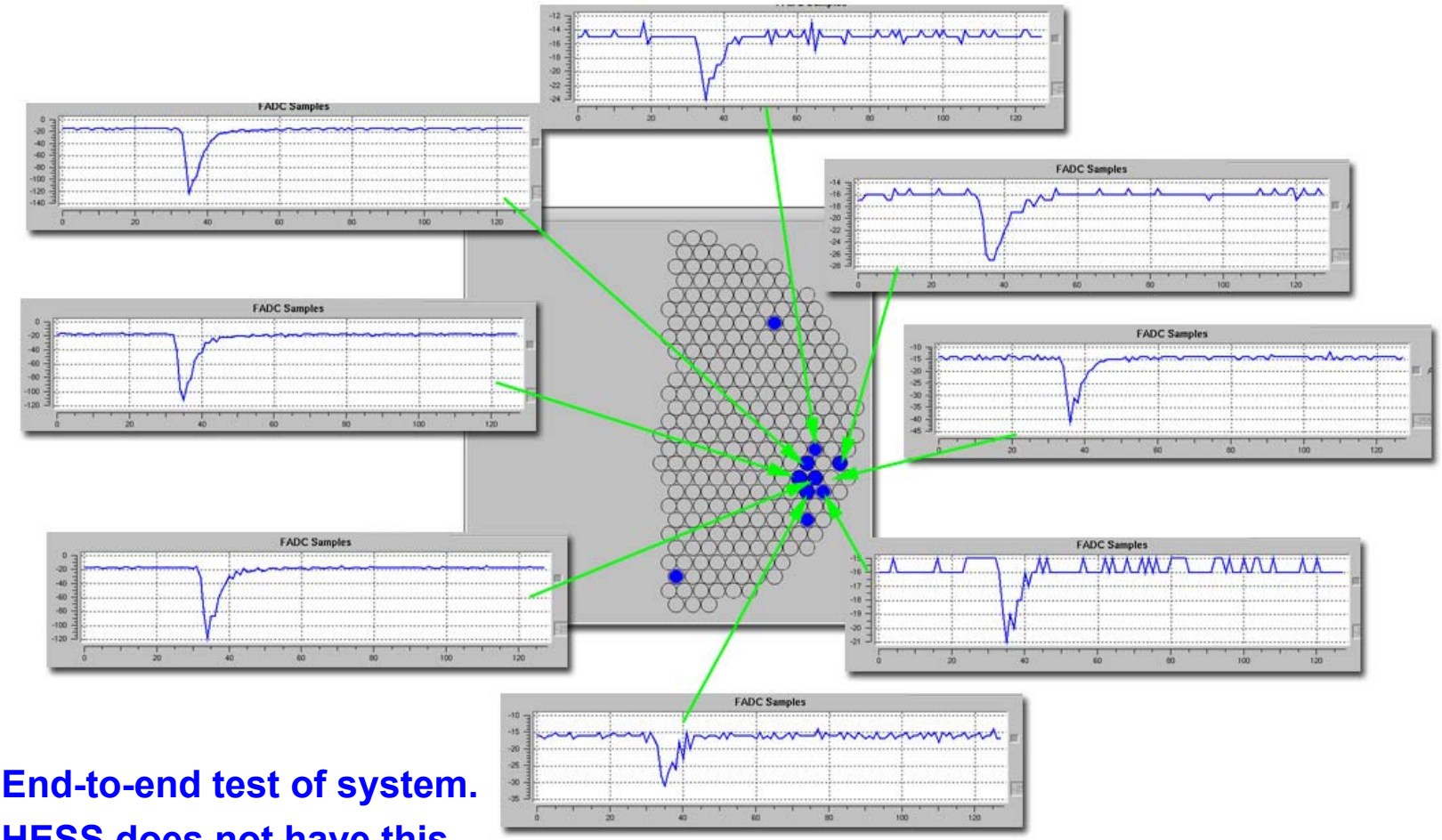
Prototype telescope (2004)

- All major systems tested.
- Several months of observations.

Electronics trailer

500 MHz FADC

1st Cherenkov Images



- End-to-end test of system.
- HESS does not have this capability.

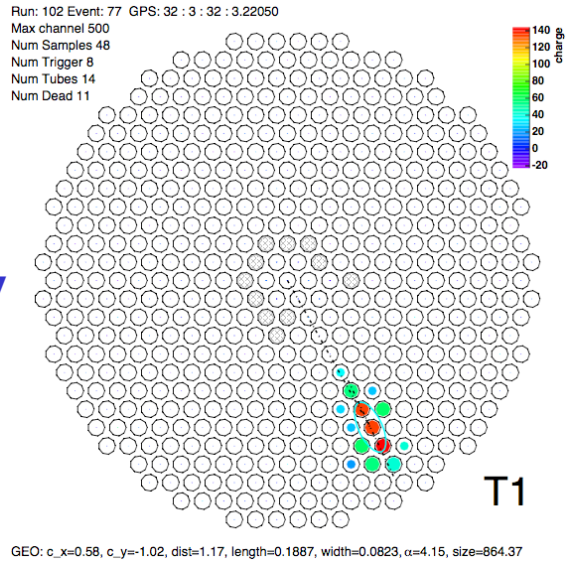
Telescope 1

Whipple Base Camp
Mt. Hopkins, AZ

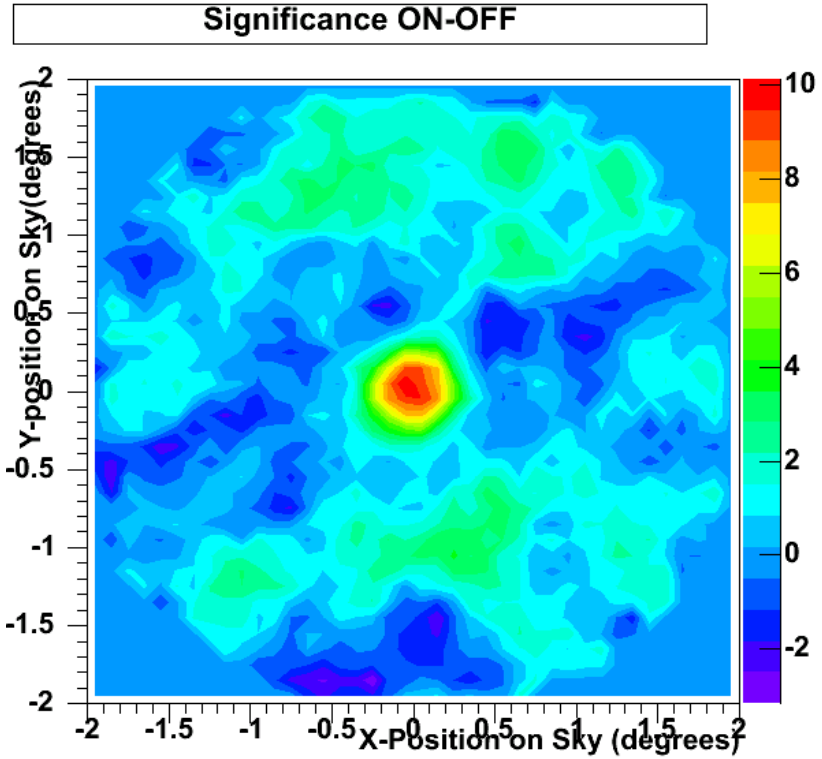
Telescope 1 (operational Feb 05)

Telescope 1

Camera



Cherenkov Image

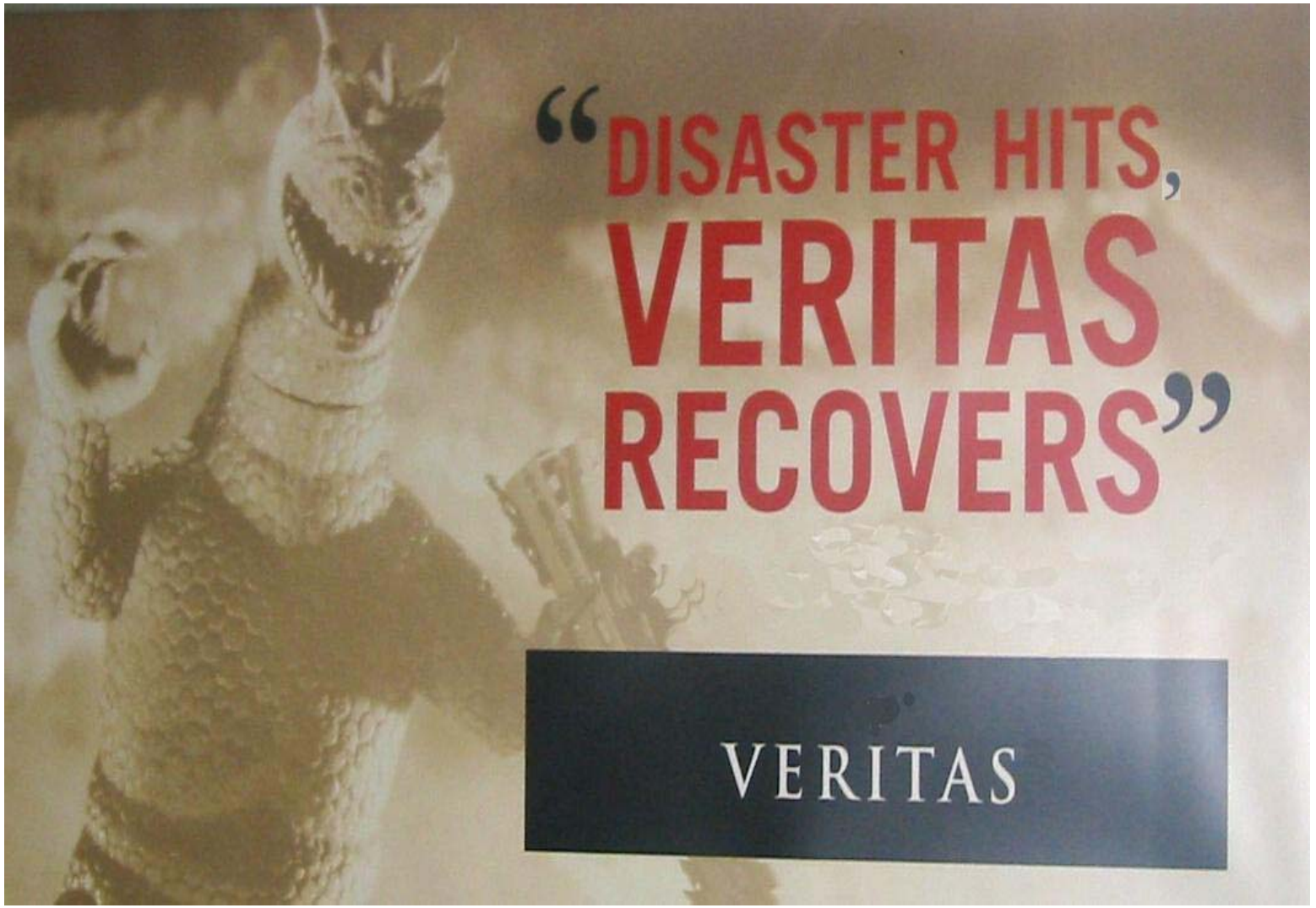


Crab Detection:
~ 10 σ /sqrt(hr)

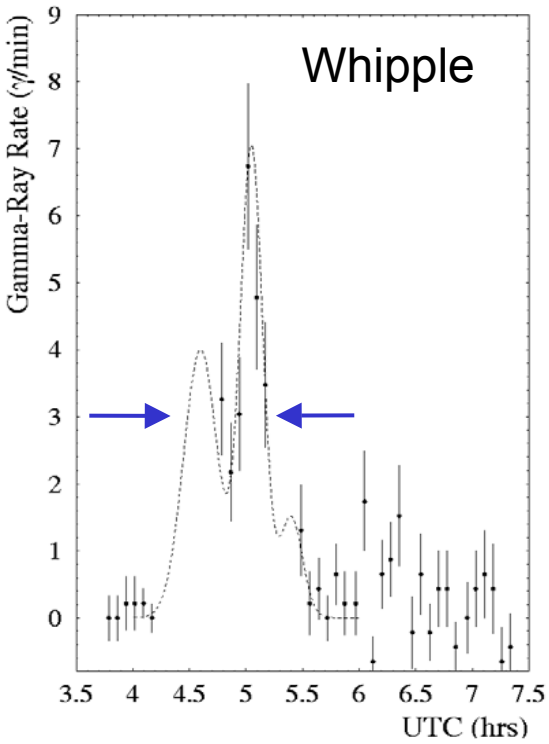
Kitt Peak Site (1700m)

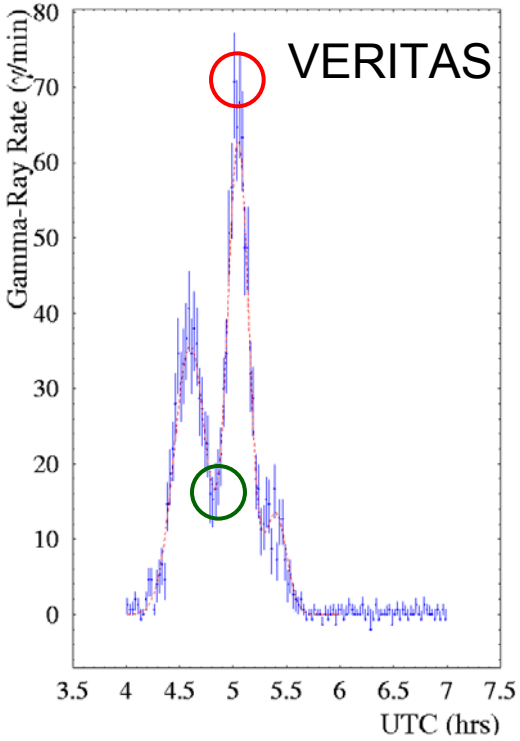
Kitt Peak Site (April 2005)

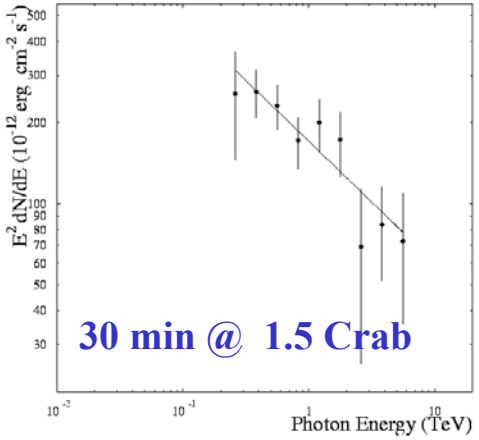
Bumps in the Road

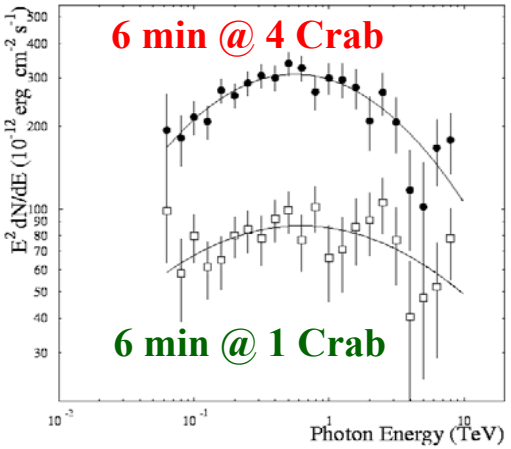


Expected Performance





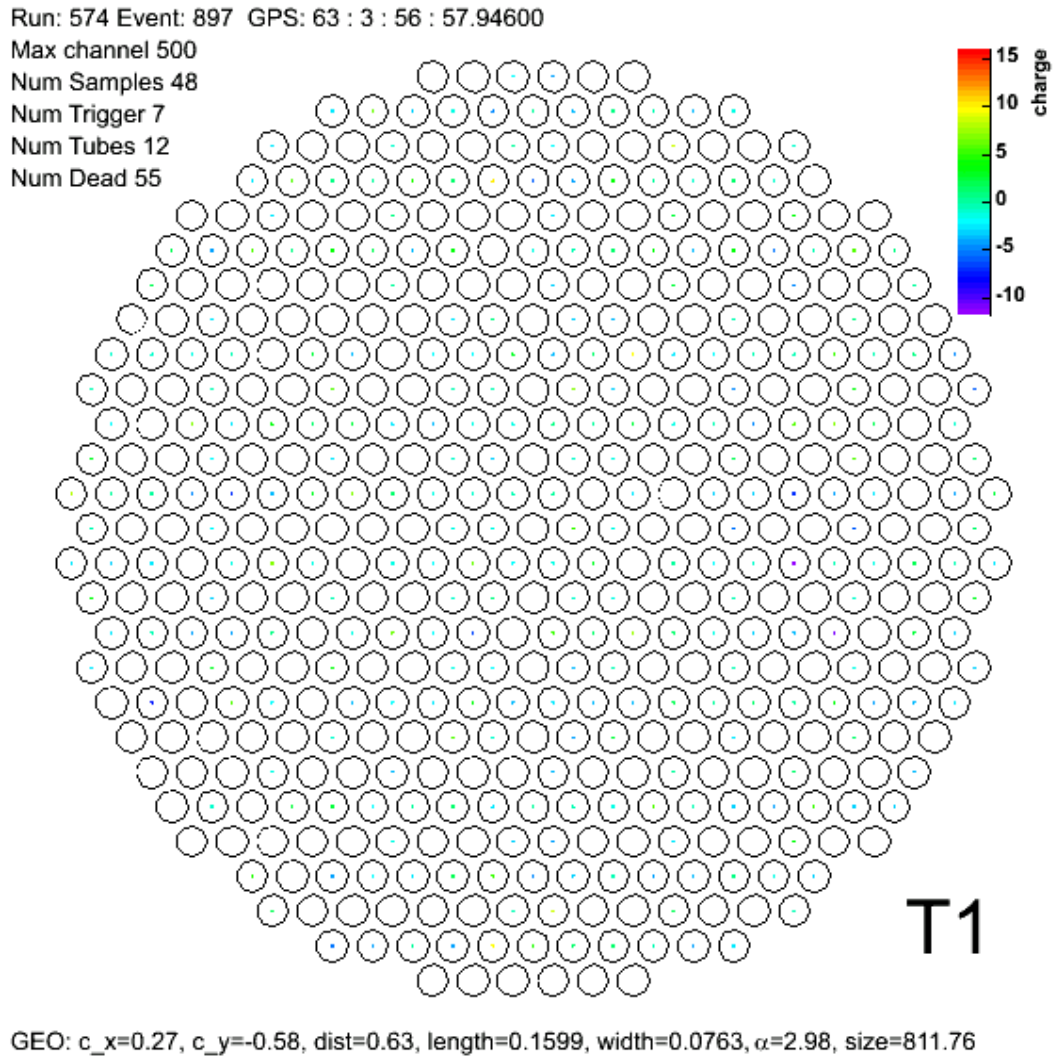




VERITAS …
will have sensitivity for time-resolved spectral measurements on hourly time scales.

Telescope 1 Movies

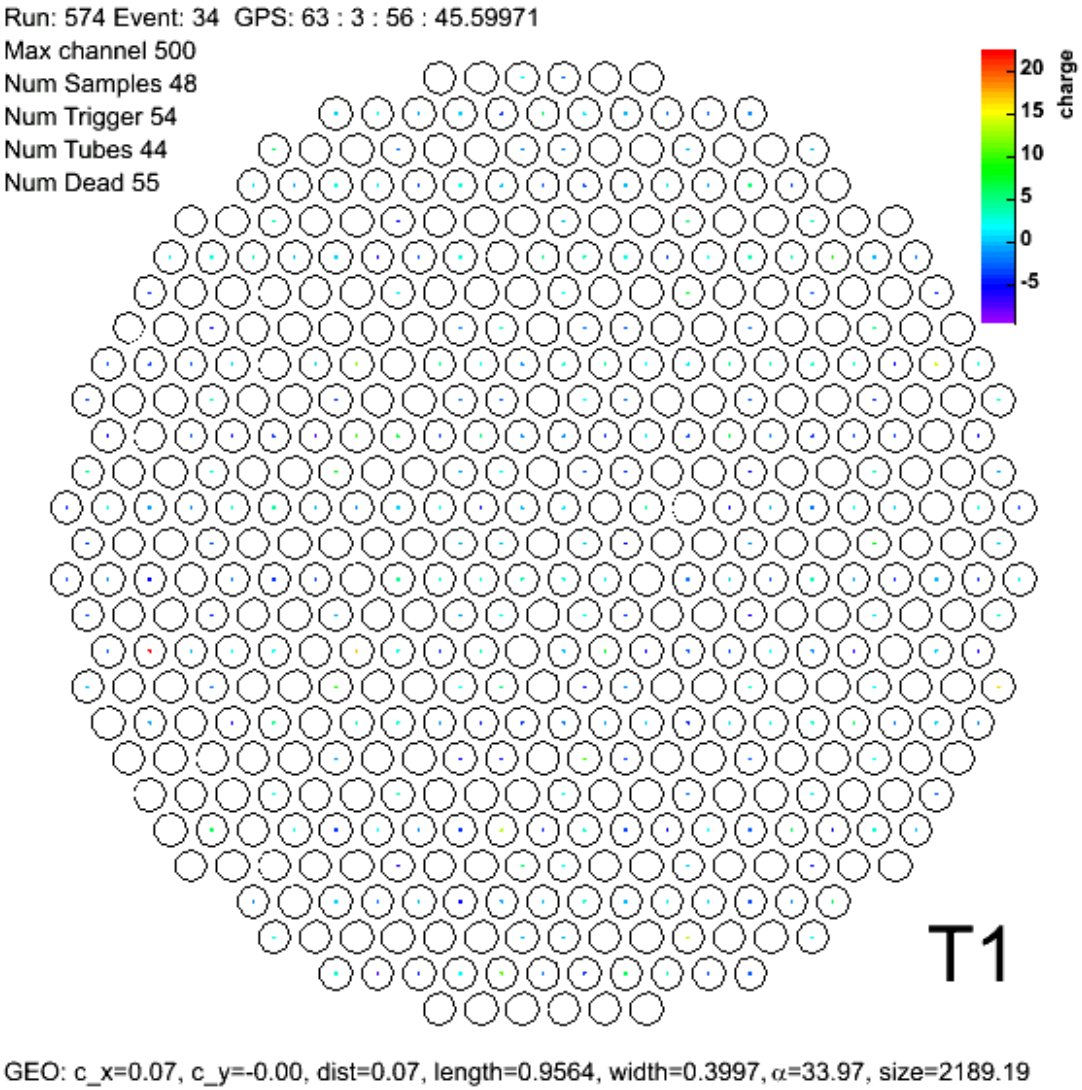
γ-ray



GEO: c_x=0.27, c_y=-0.58, dist=0.63, length=0.1599, width=0.0763, α=2.98, size=811.76

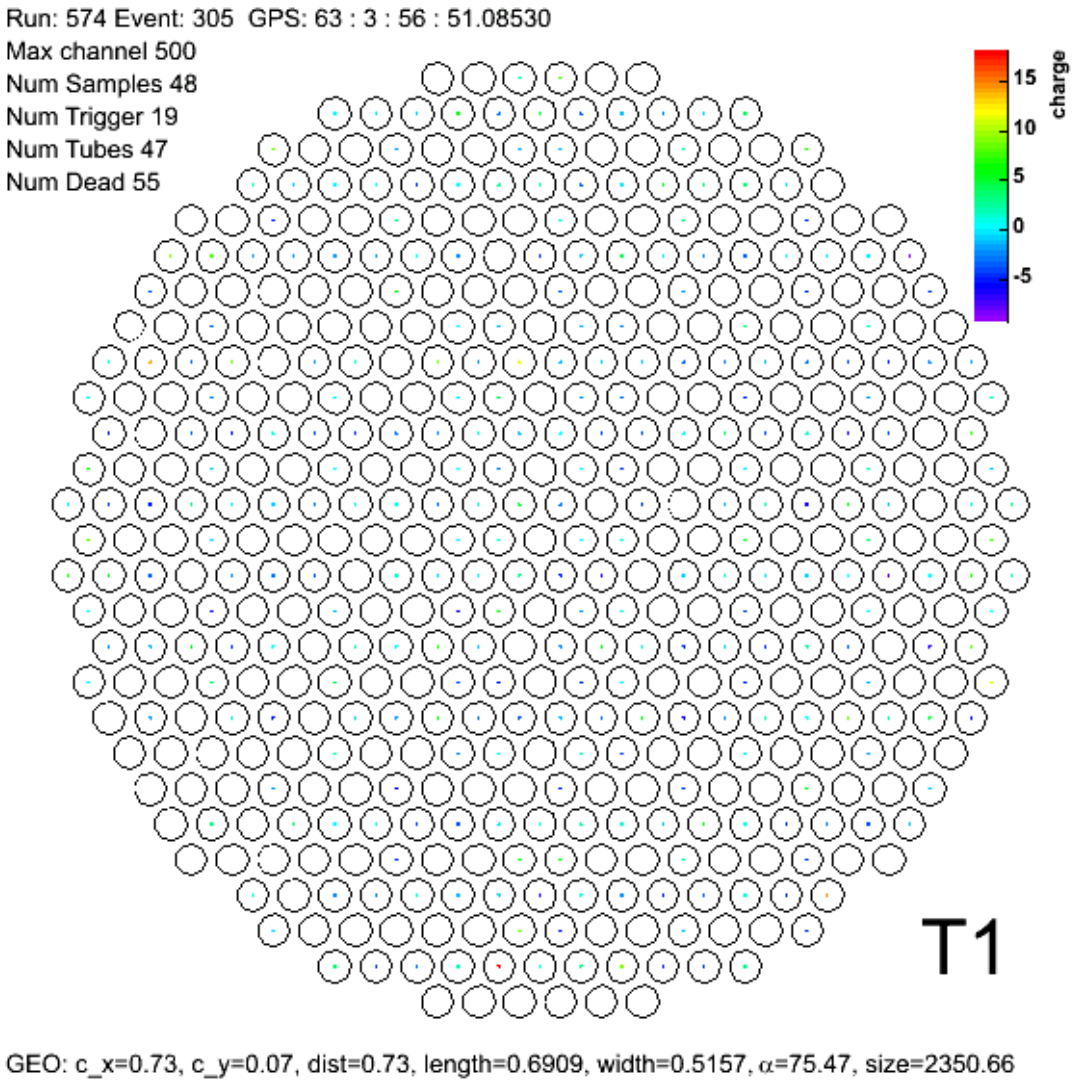
Telescope 1 Movies

Cosmic Ray



Telescope 1 Movies

Muon Ring



GEO: c_x=0.73, c_y=0.07, dist=0.73, length=0.6909, width=0.5157, α=75.47, size=2350.66

Summary

- VHE particles provide unique tests of the limits of physical laws. Probe astrophysics in regimes not yet explored.

- Full survey of the sky at GeV energies exists. At TeV energies, we have detected some remarkable phenomena – many sources now and beginning to answer some important questions … still, most of the sky remains unexplored

  → New Instruments: **HESS**, VERITAS, & GLAST.

- Great potential for discovery of physics beyond our standard models. (But, this physics is not yet required).

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

Marcel Proust (1871-1922)