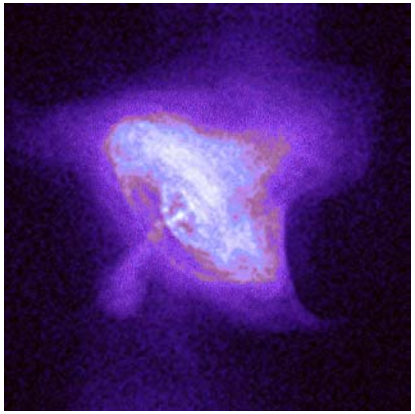
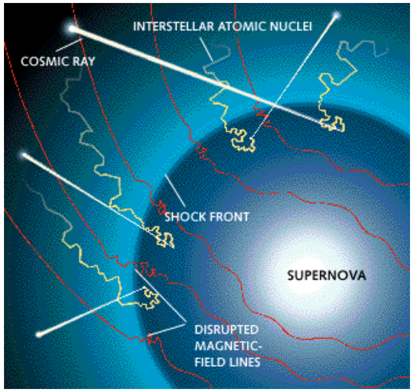
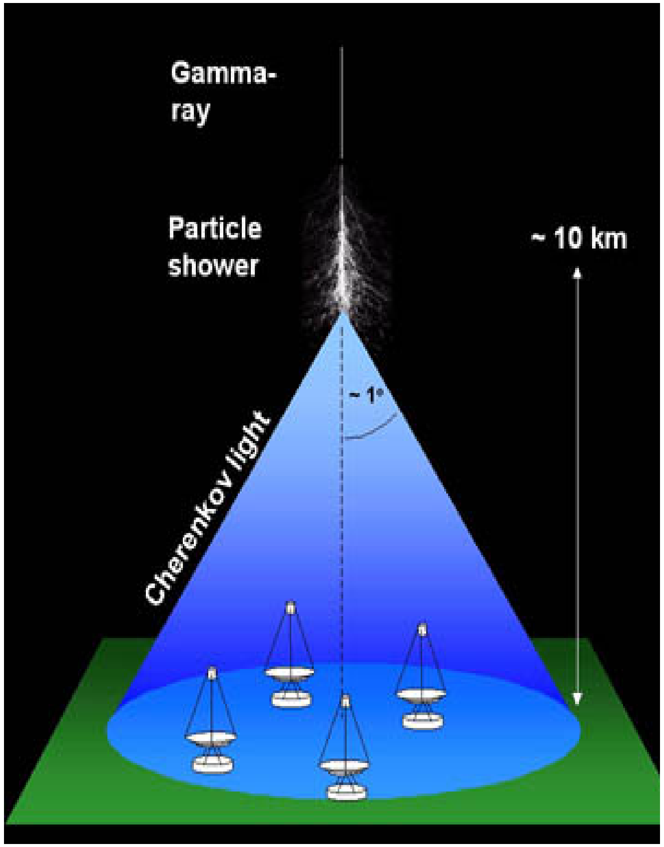
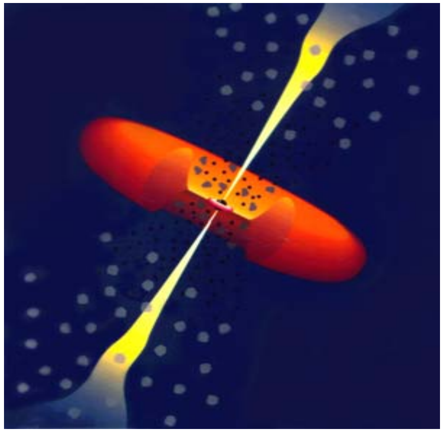
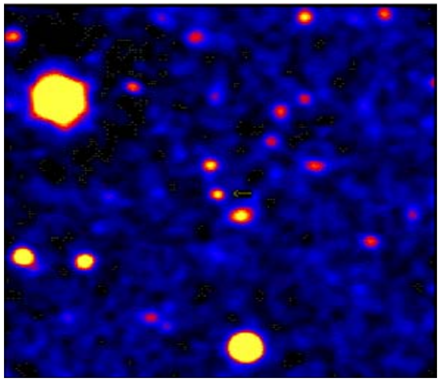
The Extreme Universe











Rene A. Ong
University of California, Los Angeles

Univ. of Michigan Colloquium
23 March 2005

OUTLINE

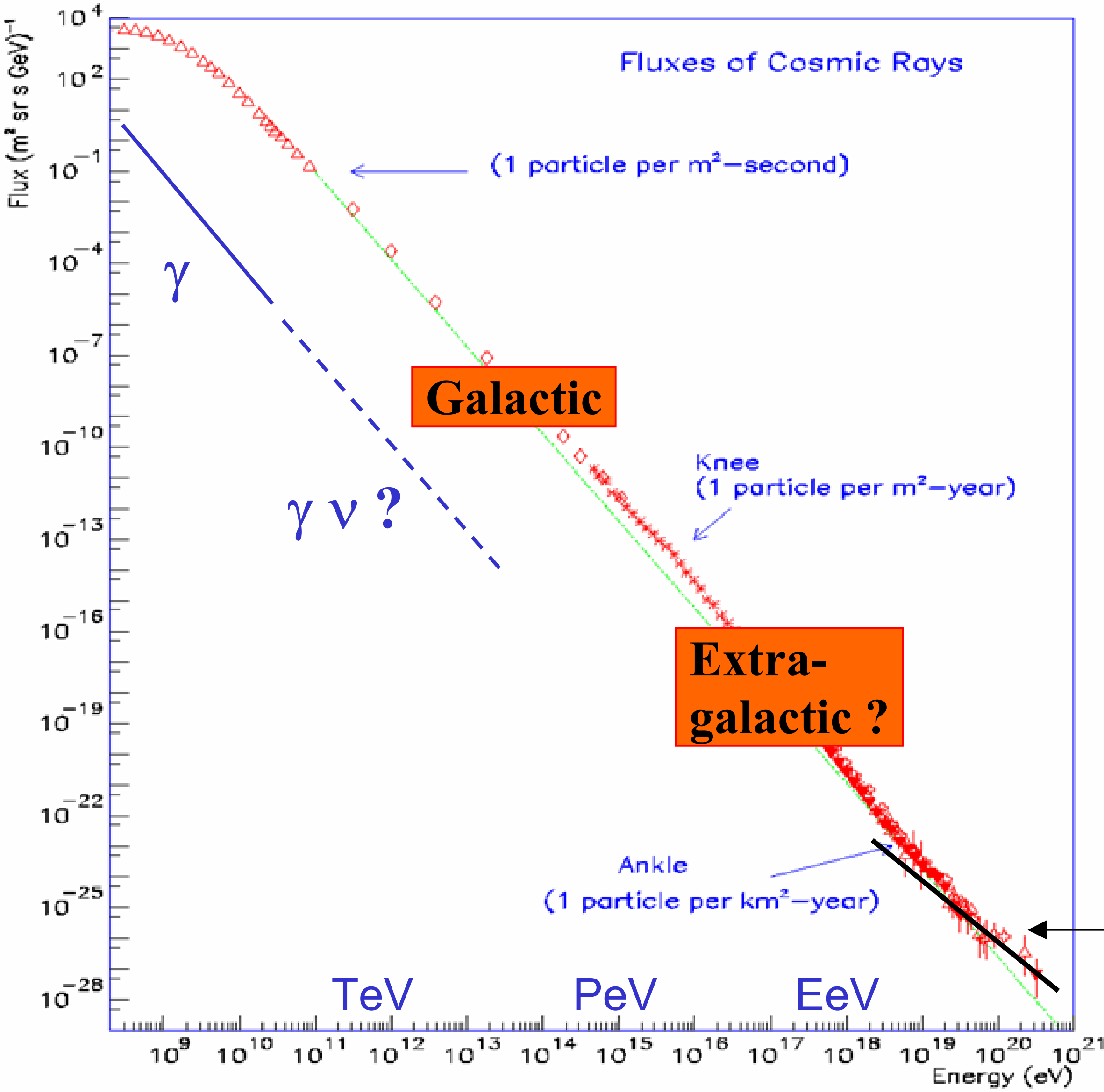
- Introduction
  - **Messengers, energy scales, & questions.**
- Detecting Very High Energy (VHE) particles
- Physics: Origin of VHE particles
  - **Power sources & particle acceleration.**
  - **Probing particle physics and cosmology.**
- Astrophysics: GeV and TeV sky
  - **c2003: Active galaxies, supernovae, pulsars, etc.**
  - **New results – HESS Telescope array.**
- Future – VERITAS & GLAST.

Cosmic Messengers

We know about the Universe from:

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

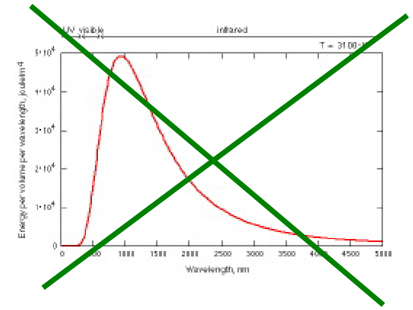
Cosmic Ray Spectrum



- 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?

Impact of High Energies



Phenomenological

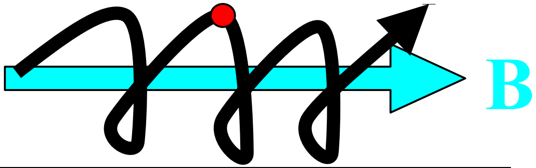
Energy scale is reached by either:

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

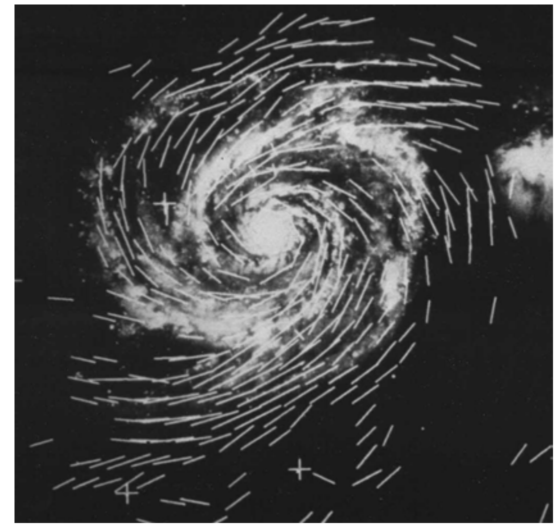
Magnetic Fields



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

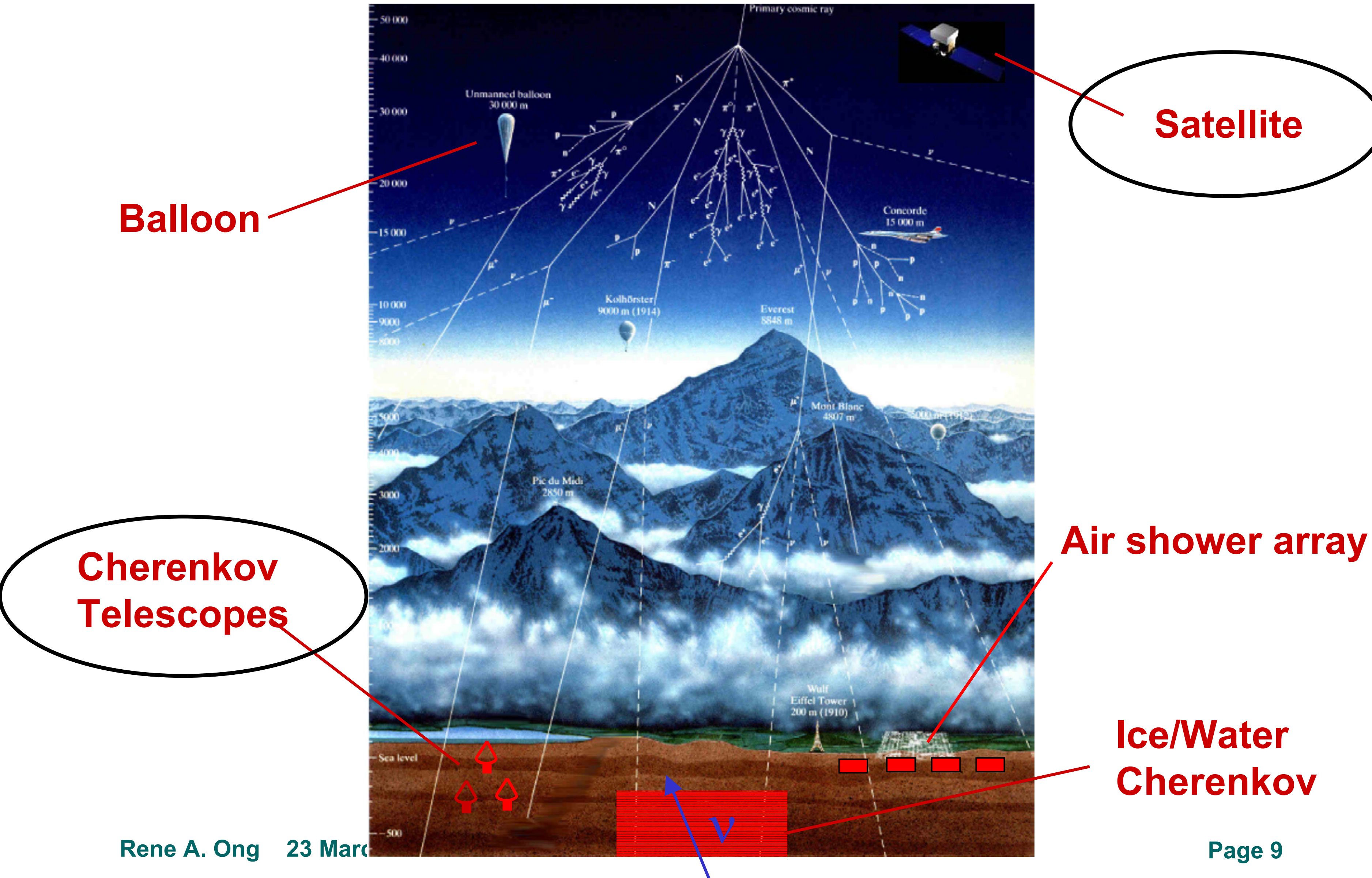
1. **What is the origin of this diffuse flux of cosmic-ray particles?**
   - We don't know, but the sources must be both powerful and renewable. We have no real understanding of physics mechanisms.

2. **Can VHE particles provide clues about the early Universe or about the physics at higher mass scales?**
   - Yes, in probing dark matter, relics from Big Bang, GUT scale particles.

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.

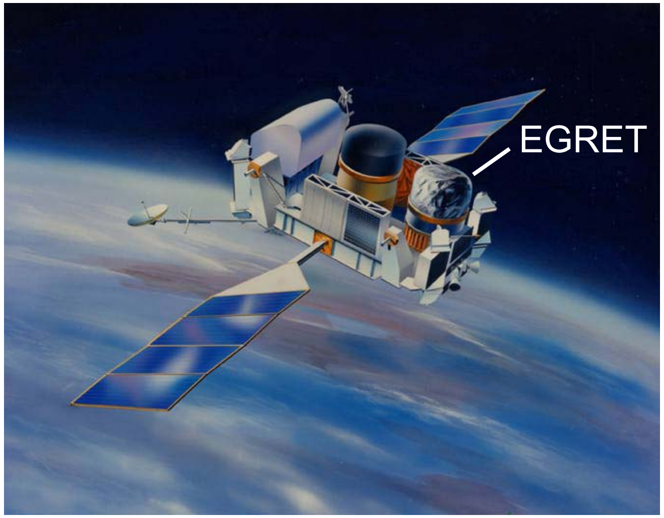
DETECTION OF VHE PARTICLES

Experimental Techniques

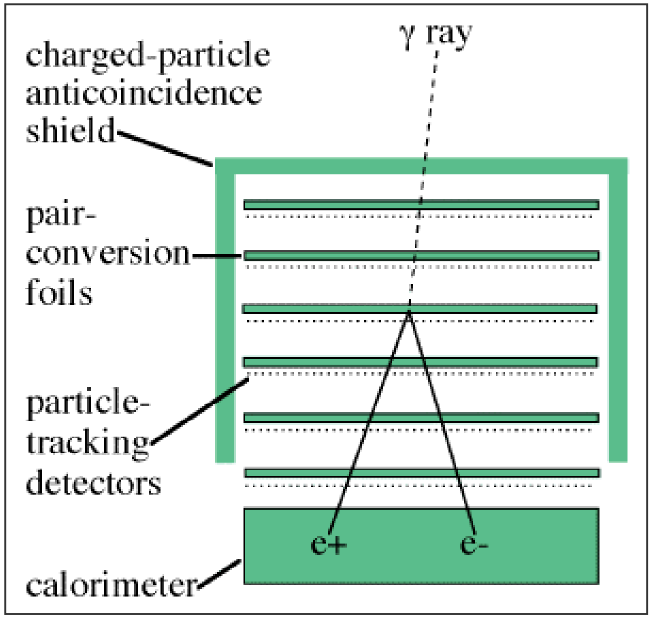


EGRET (CGRO)

Compton Gamma-Ray Observatory



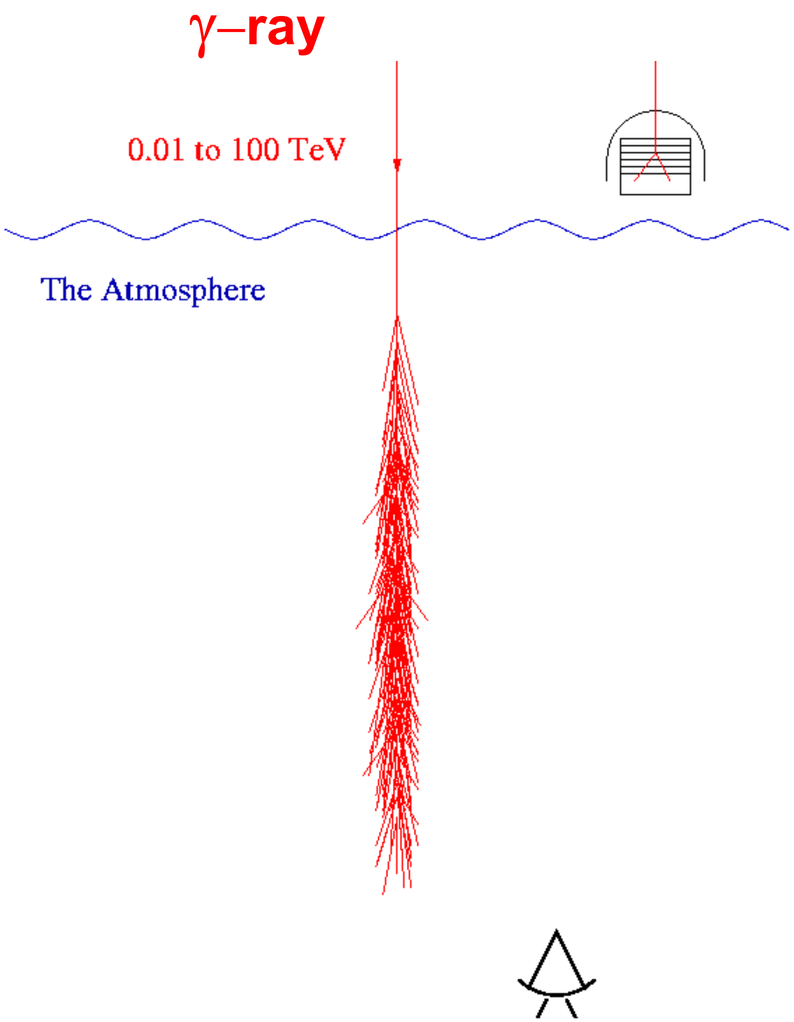
EGRET (30 MeV – 20 GeV)



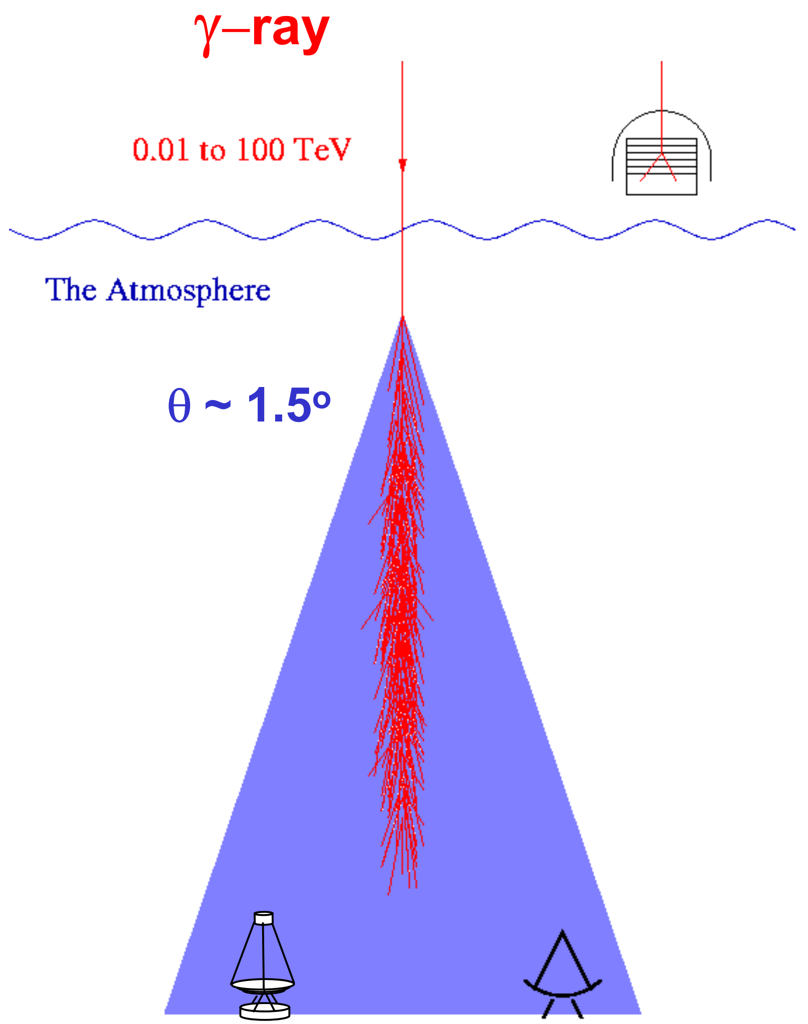
Area < 1 m^2

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

Air Showers



Cherenkov Telescopes



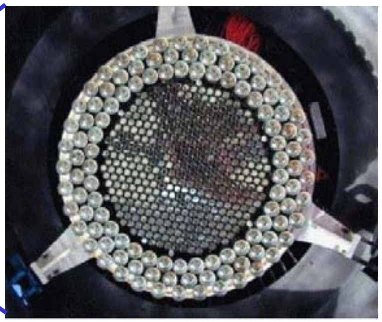
Area = $10^4 – 10^5$ m^2

~60 optical photons/m^2/TeV

Whipple γ-ray Telescope

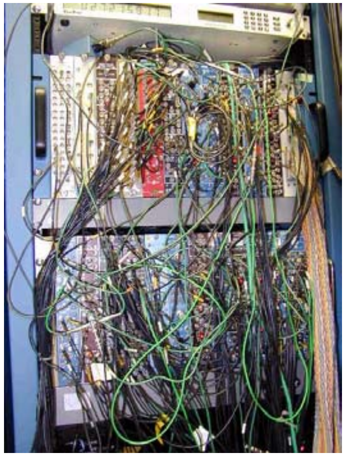
Whipple 10m (Arizona)

E_{th} ~ 300 GeV

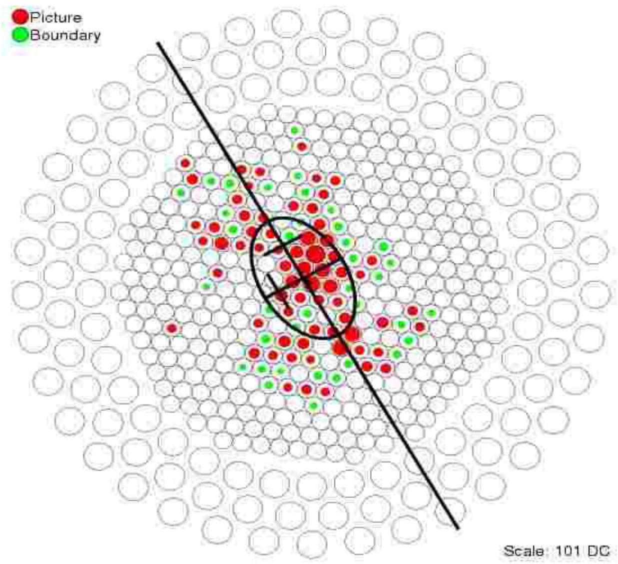


PMT camera

+



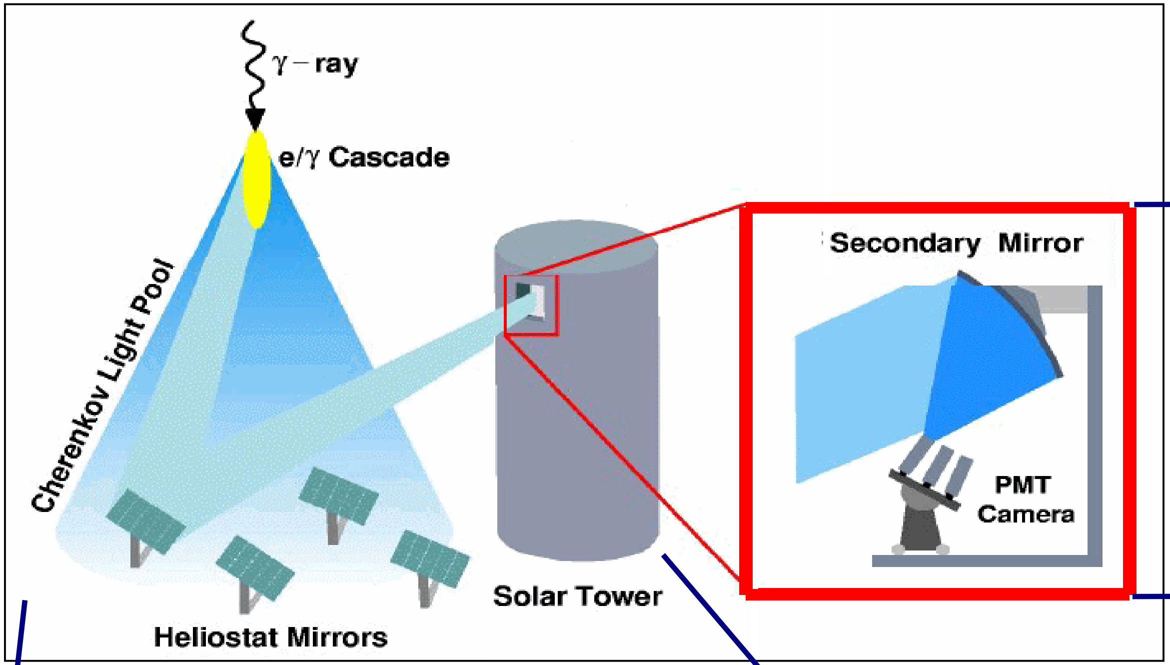
ns electronics



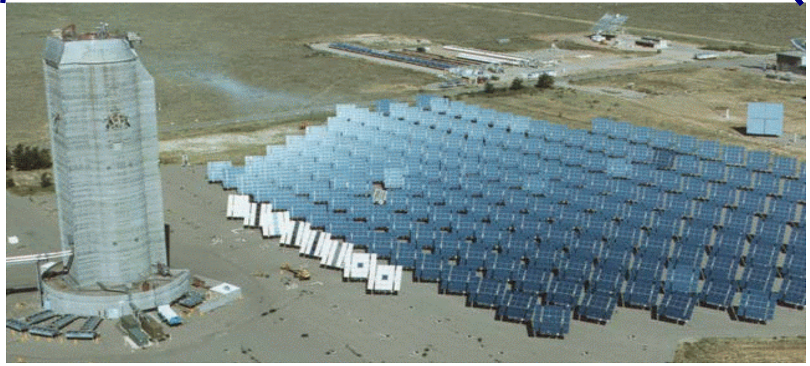
Cherenkov Image –
Background rejection.

Cosmic Ray
Rejection ~ 300

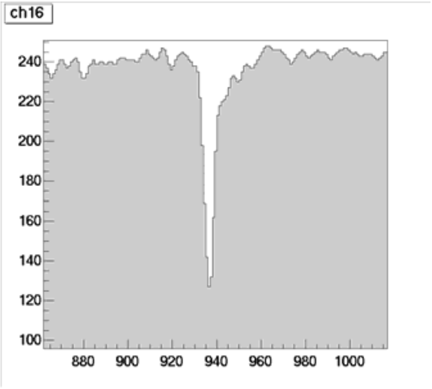
Solar Mirror Arrays



Large Mirror Area
→ Low E Threshold
~ 100 GeV



STACEE (New Mexico)



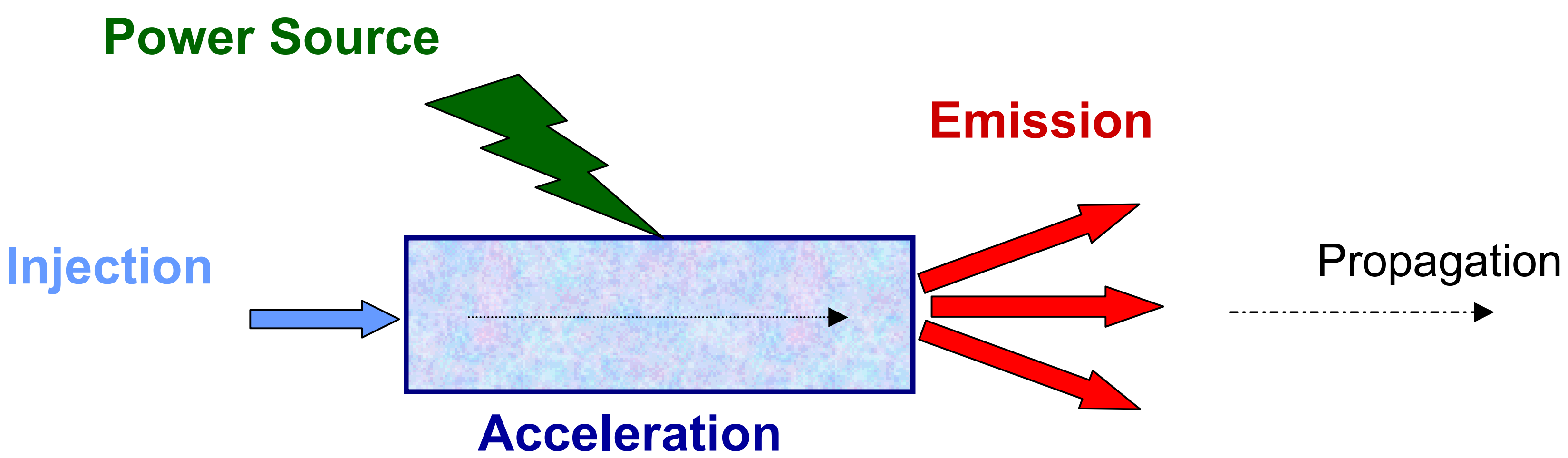
1 GHz Flash ADCs

Cosmic Ray
Rejection ~ 100

ORIGIN OF
HE PARTICLES

Astrophysical Origins

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



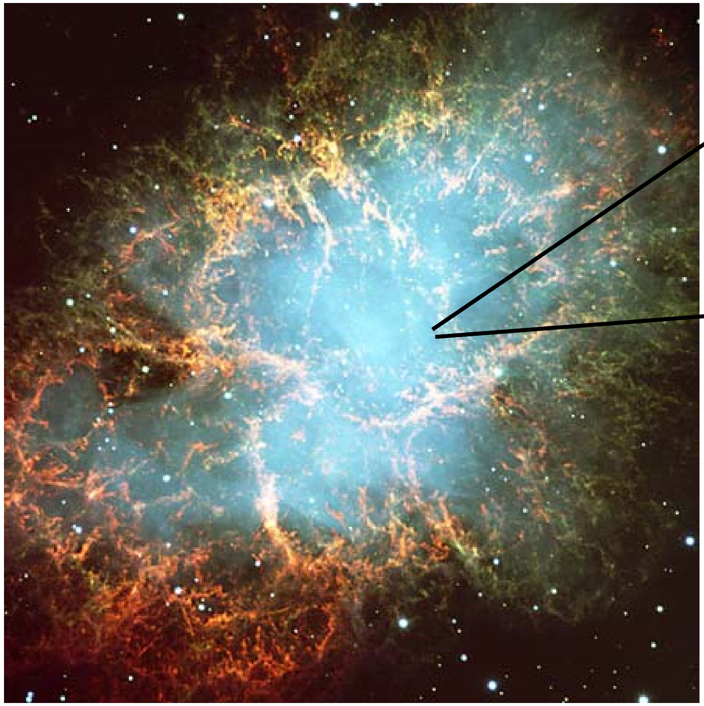
Power Sources

Broadly speaking, there are two types of sources:

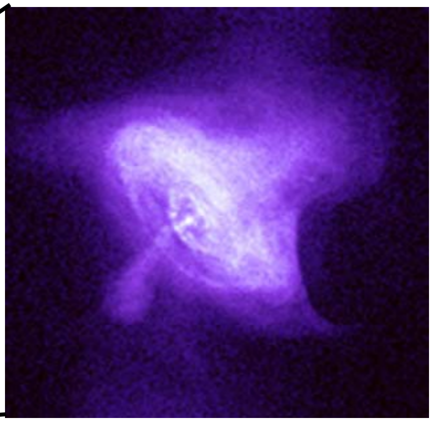
1. Electromagnetic
   - e.g. rotating highly magnetized object – **Pulsar (1)**
2. Gravitational
   - Core collapse of a massive star – **SN and its remnant (2)**
     – Gamma-ray Bursts … etc.
   - Accretion onto a compact object – **Active Galactic Nuclei (3)**
     – Microquasars … etc.

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

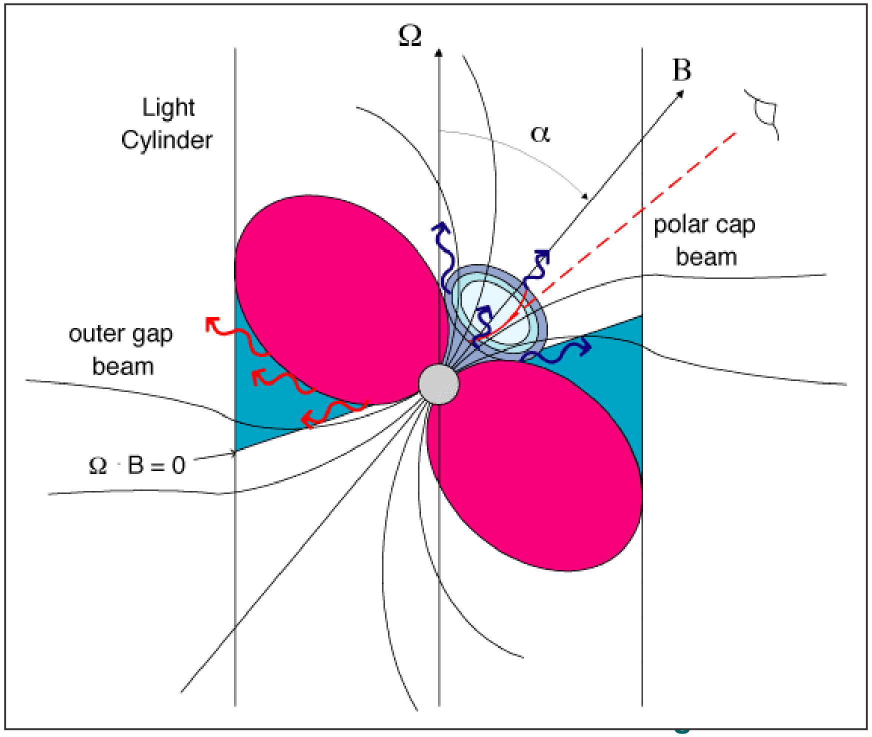
1. Pulsars



Crab Nebula

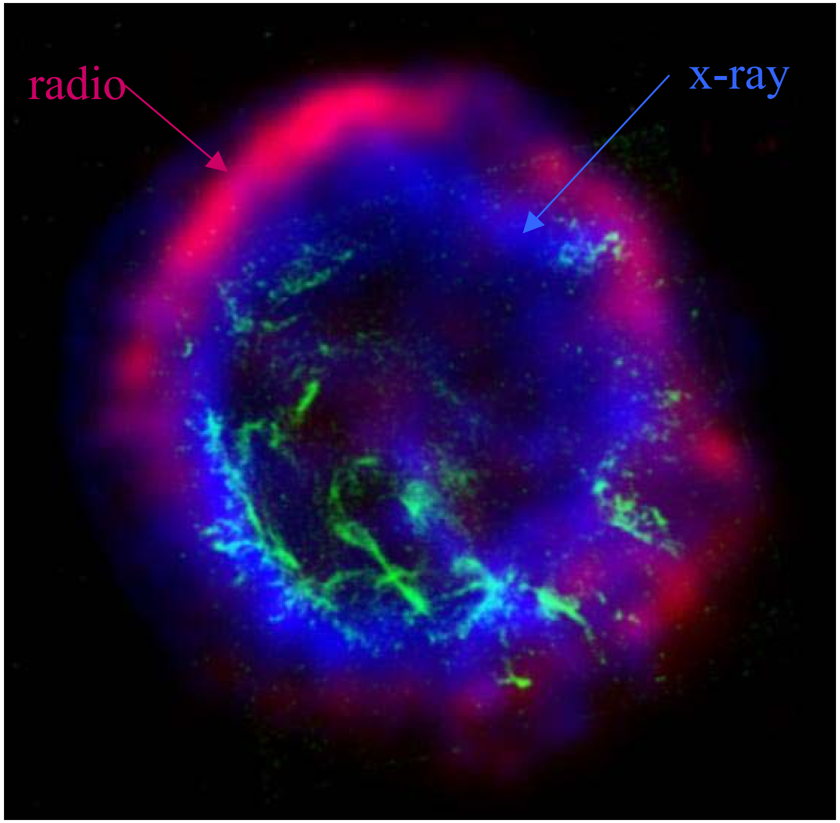


Pulsar



→ 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 ~ 1-2 x 10^4 km/s.
- Shell expands and shock front forms as it sweeps up material from ISM.
- In ~ 10^4 yrs, blast wave begins to deccelerate (Sedov phase) and slowly dissipate.

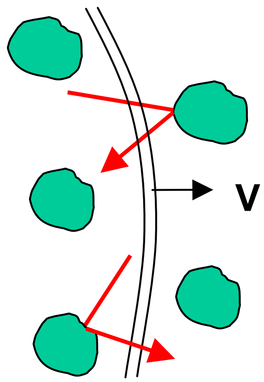
Shock Acceleration

Q: How do particles get accelerated in a shock environment?

Shock Acceleration

Q: How do particles get accelerated in a shock environment?

Variety of mechanisms proposed;
leading contender: Fermi acceleration.



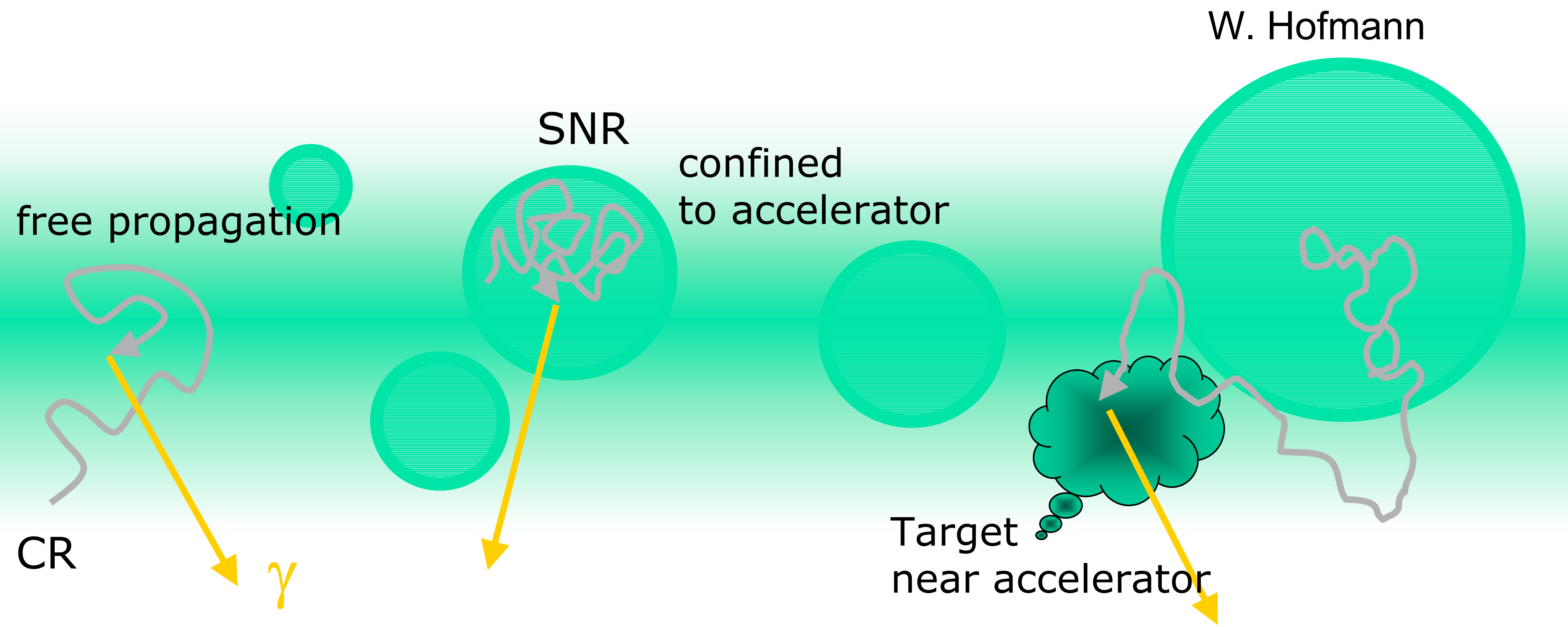
- Shock moves rapidly through ISM.
- HE particles move back and forth across shock, gaining energy.
  First-order Fermi acceleration ~(V/c).
- Naturally get power-law spectrum.

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 !

SNR's – Acceleration and Propagation



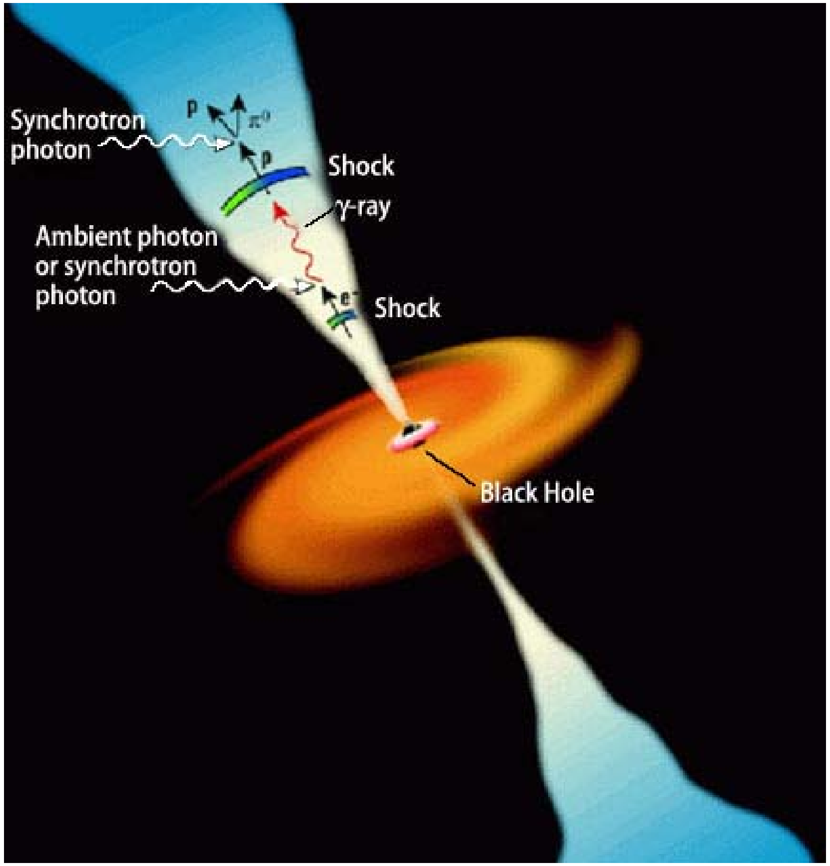
VHE gamma rays from secondary interactions:

p: π^o production and decay

e: Inverse Compton scattering and Bremsstrahlung

Trace beam density x target density

3. Active Galactic Nuclei (AGN)

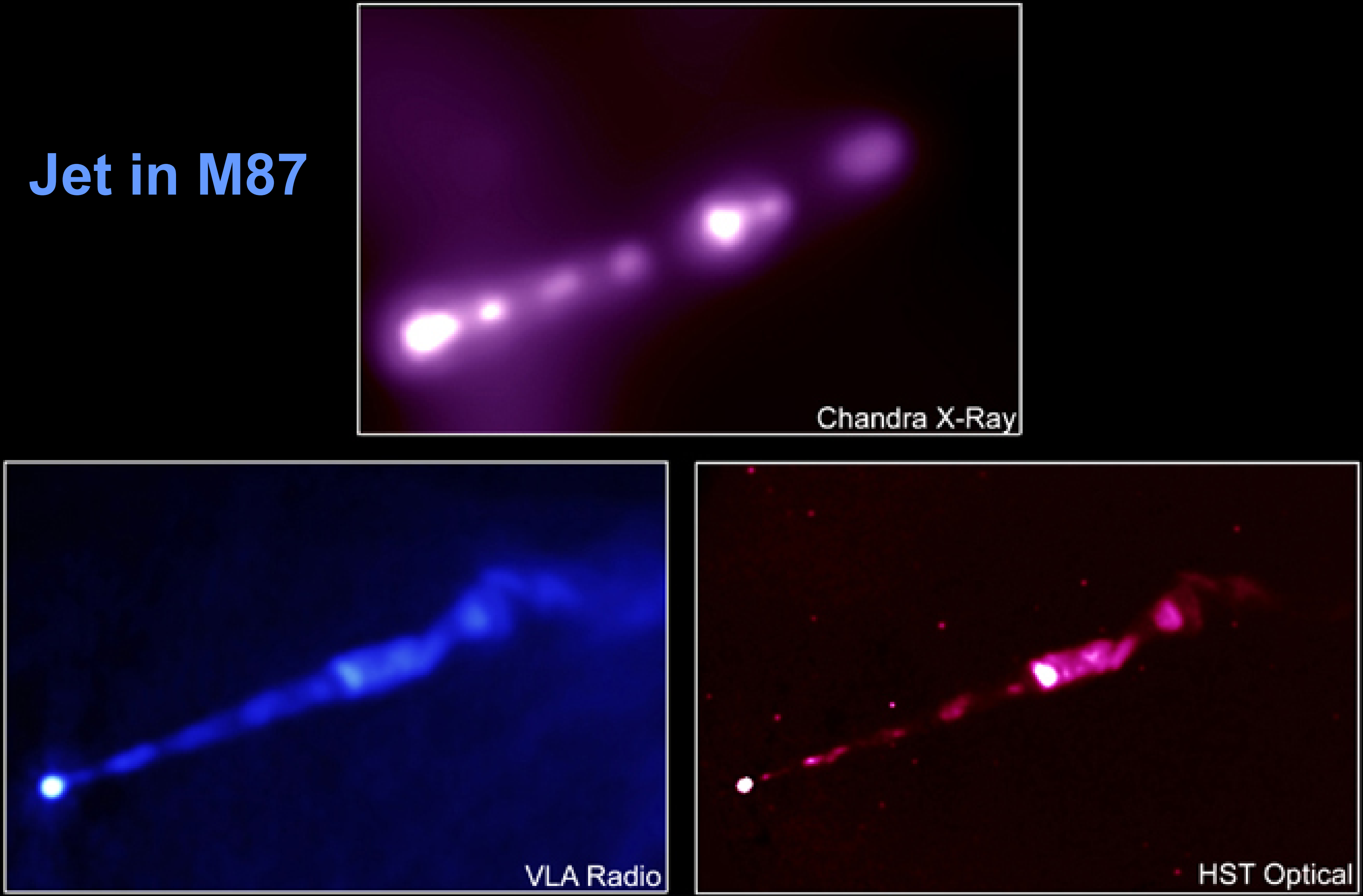


AGN model

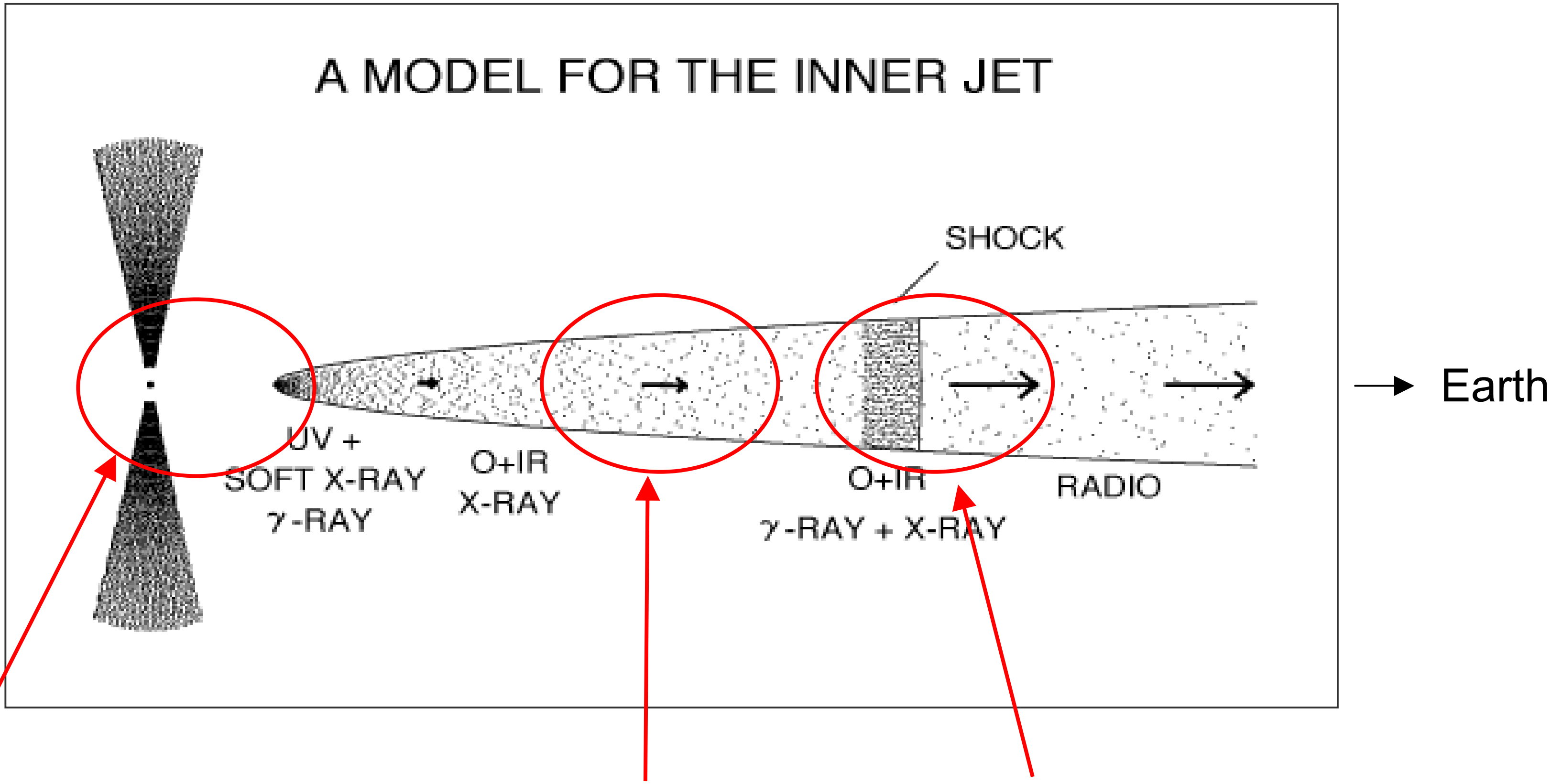
AGN are very luminous galaxies with a bright central core.

- 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

New Physics Origins

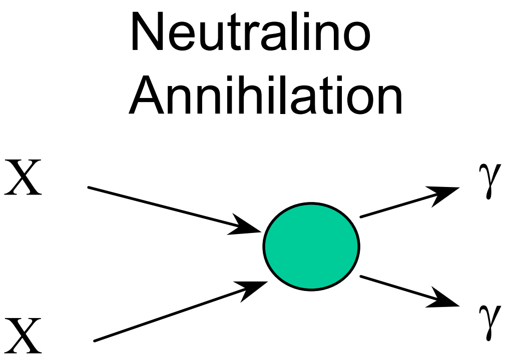
So far – only talked about astrophysical sources of VHE particles. Also exist **New Physics** possibilities.

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 <u>speculative</u>.

Also speculation on probing <u>quantum gravity</u> using distant sources of HE photons.

Dark Matter & SUSY



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

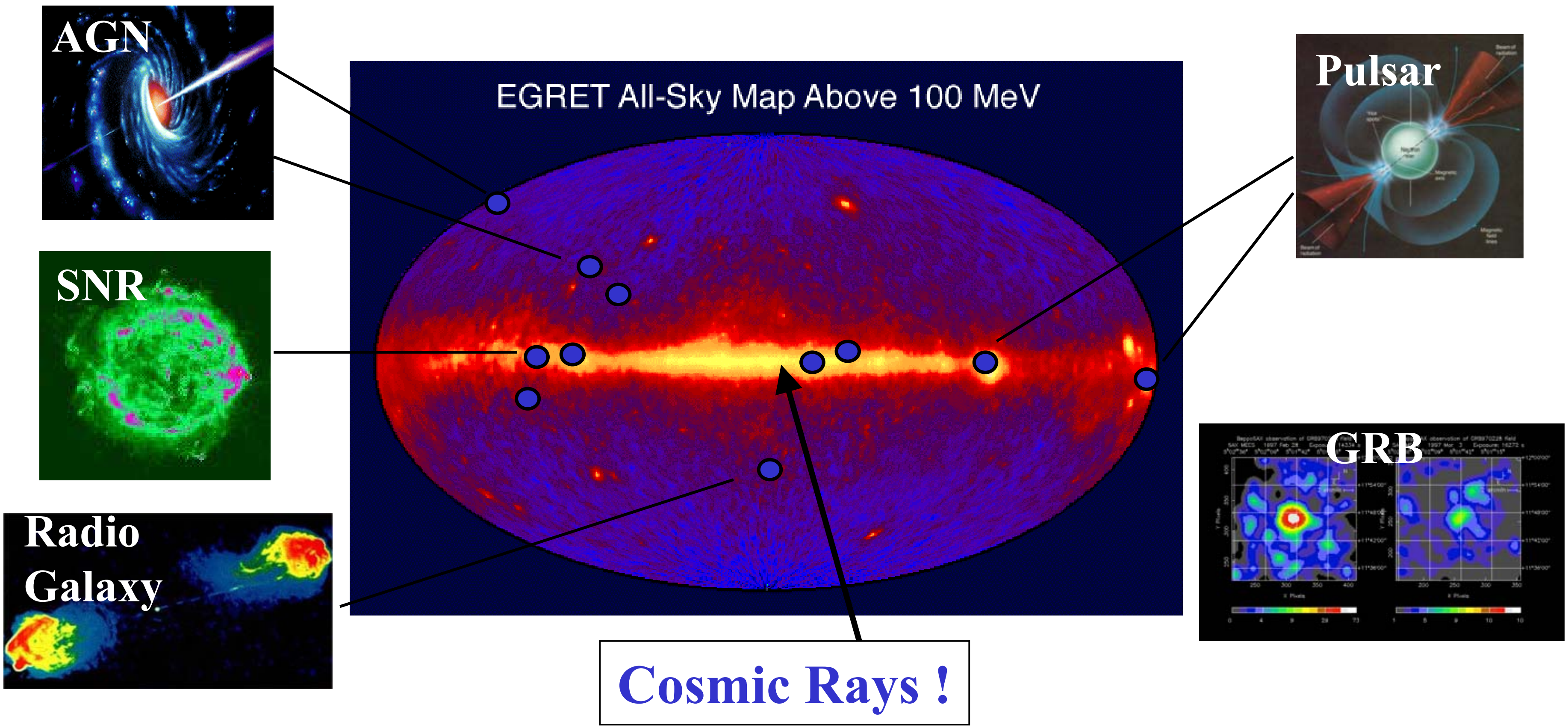
Galactic Center – see talk by A. Ghez next week !

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

ASTROPHYSICS:

GeV and TeV Sky

GeV γ-ray Sky



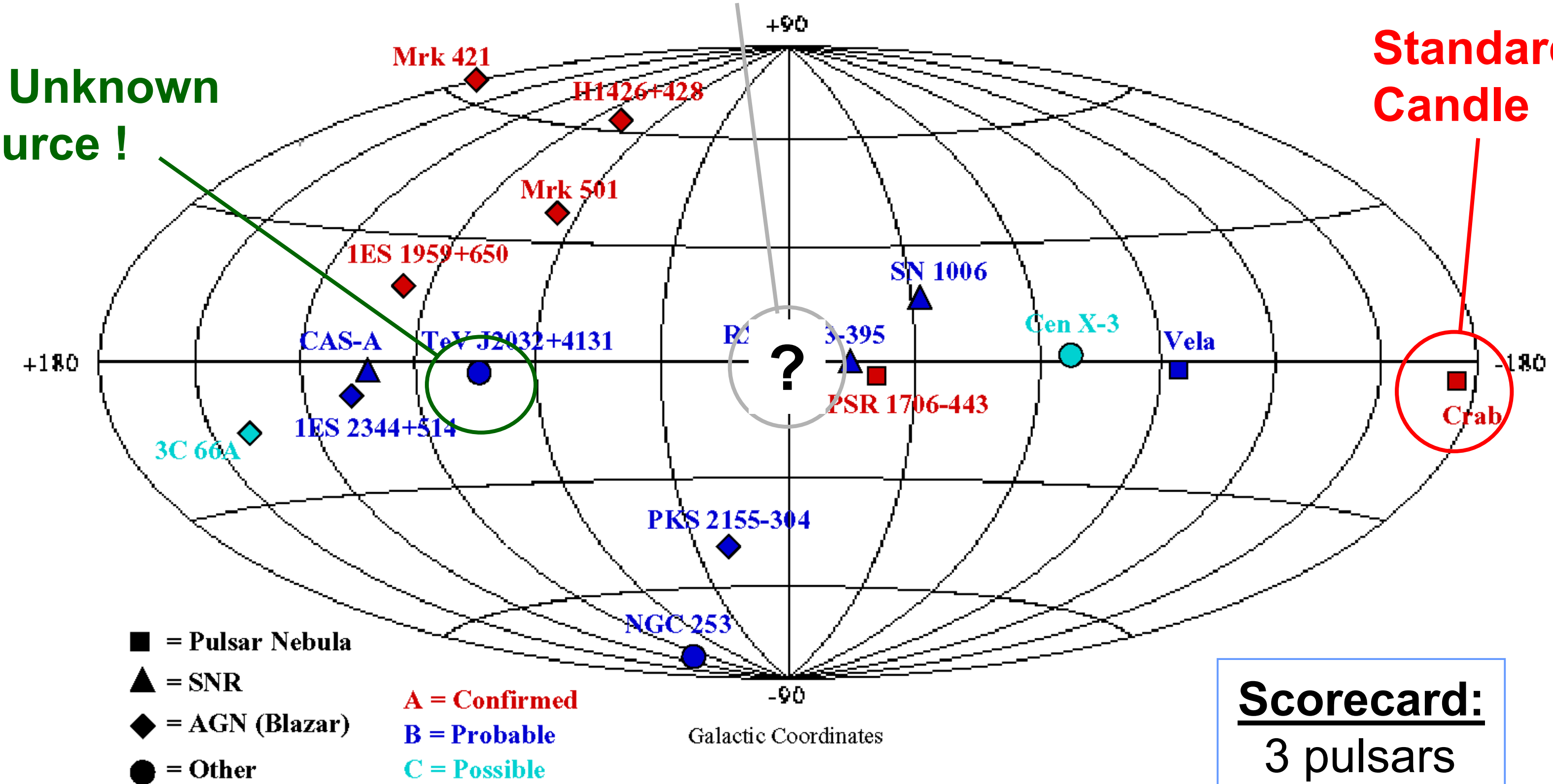
- ~ 300 HE point sources, most unidentified.
- Most identified sources are AGN – "Blazars"

TeV γ-ray Sky c2003

Hint of Galactic Center

1st Unknown Source !

Standard Candle



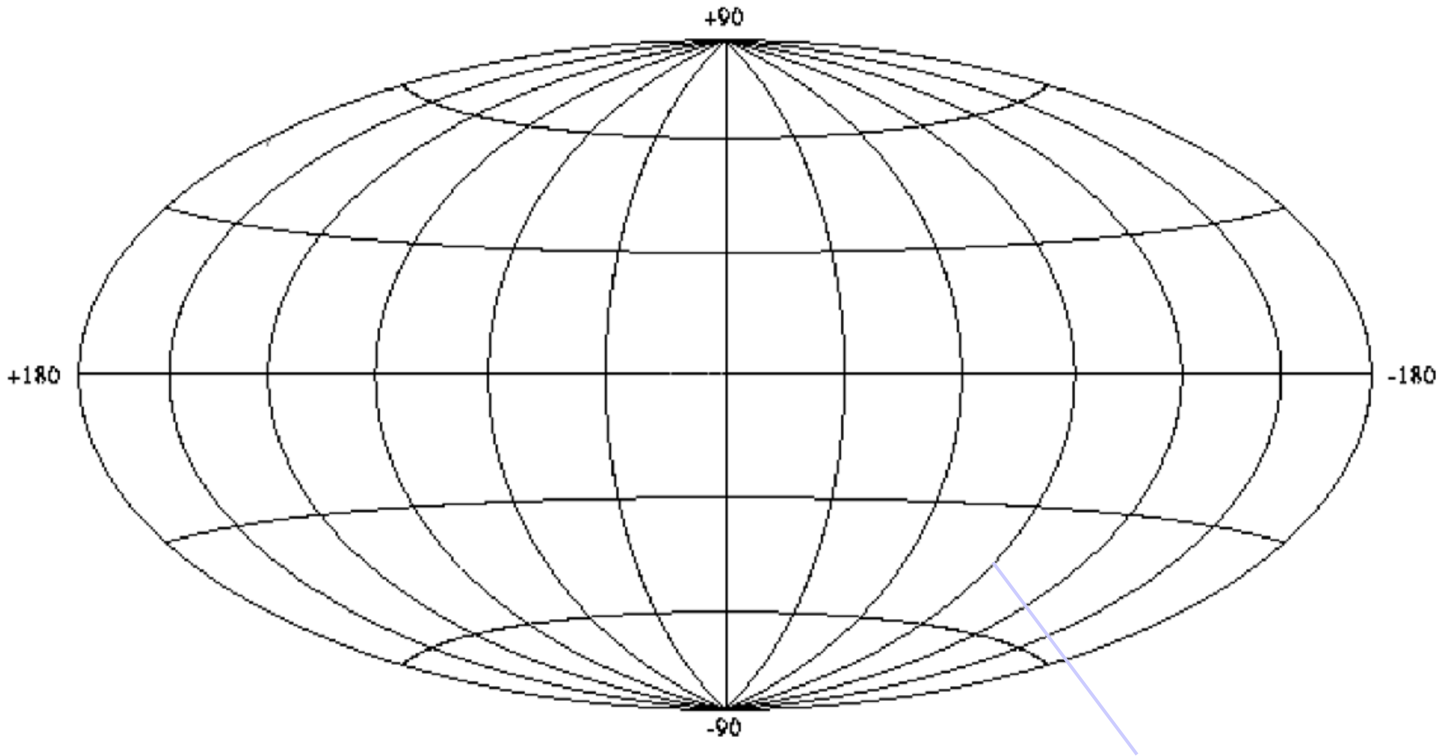
All discovered by Cherenkov telescopes.
(CANGAROO in S. Hemisphere)

Scorecard:

3 pulsars
3 SNR's
6 AGN
2 others

14 total

High-Energy Neutrino Sky

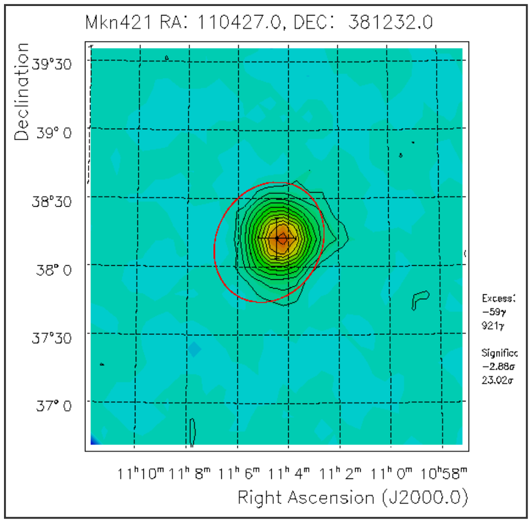


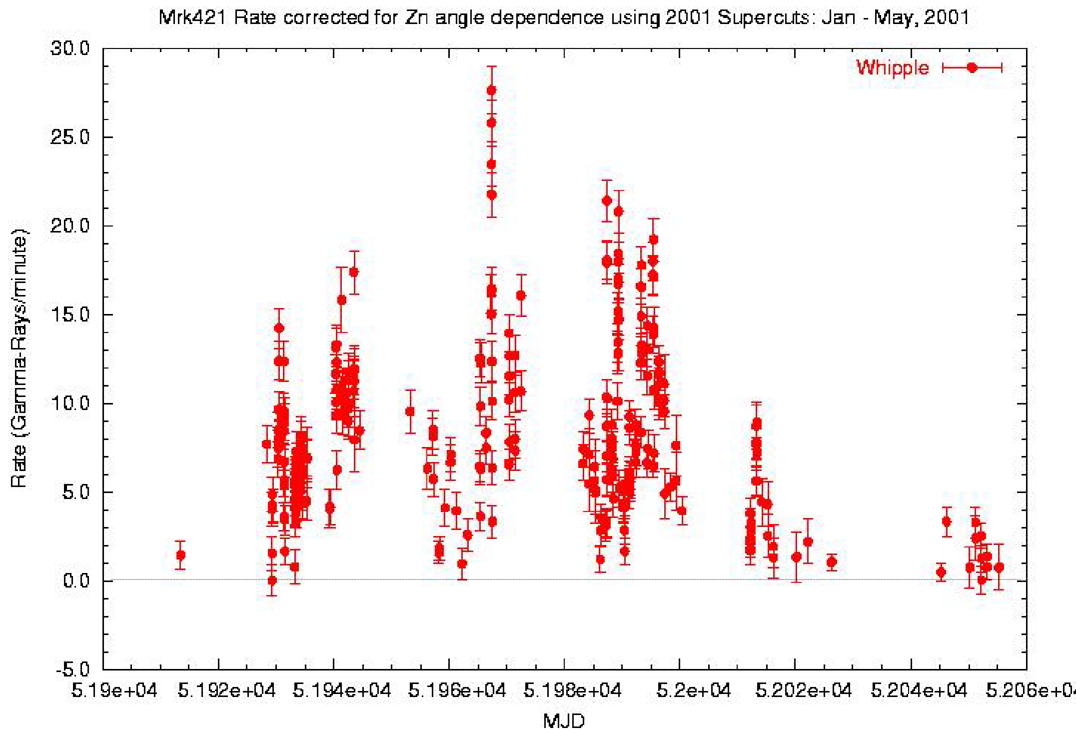
Galactic Coordinates

- No sources yet.

AGN at TeV Energies

Mrk 421 Whipple



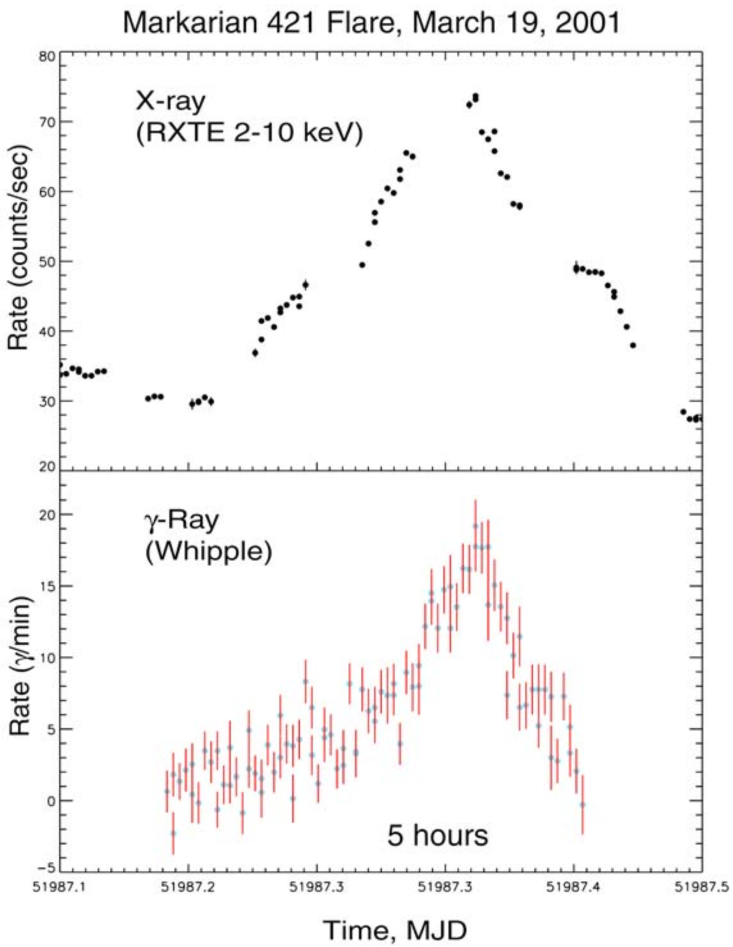


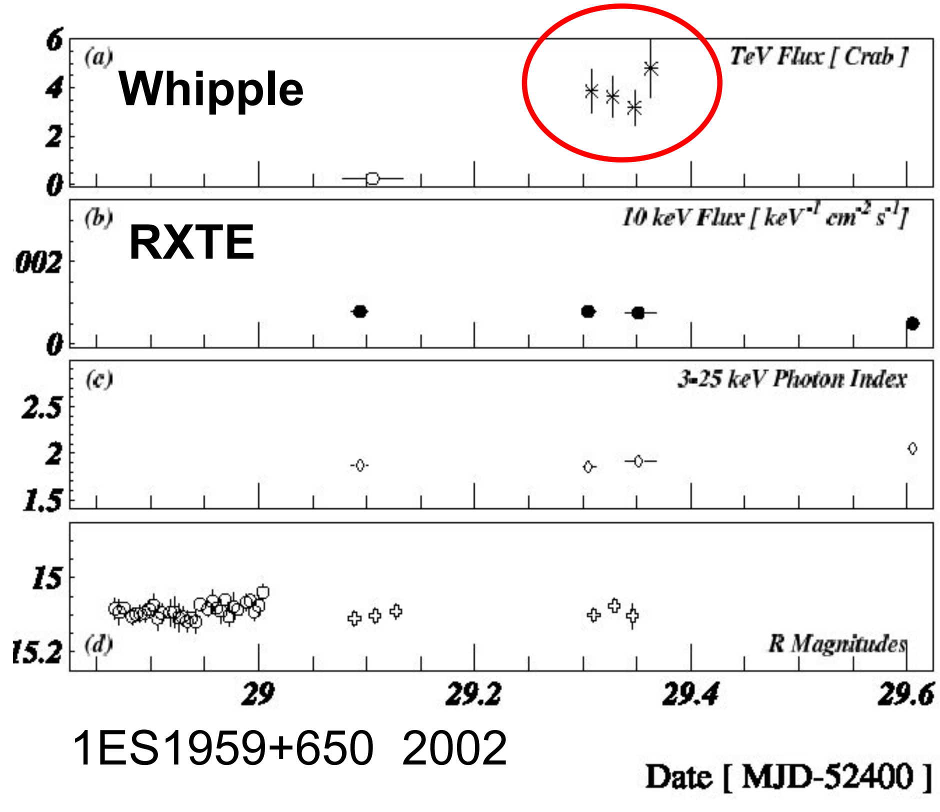
"BLAZARS":

- **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

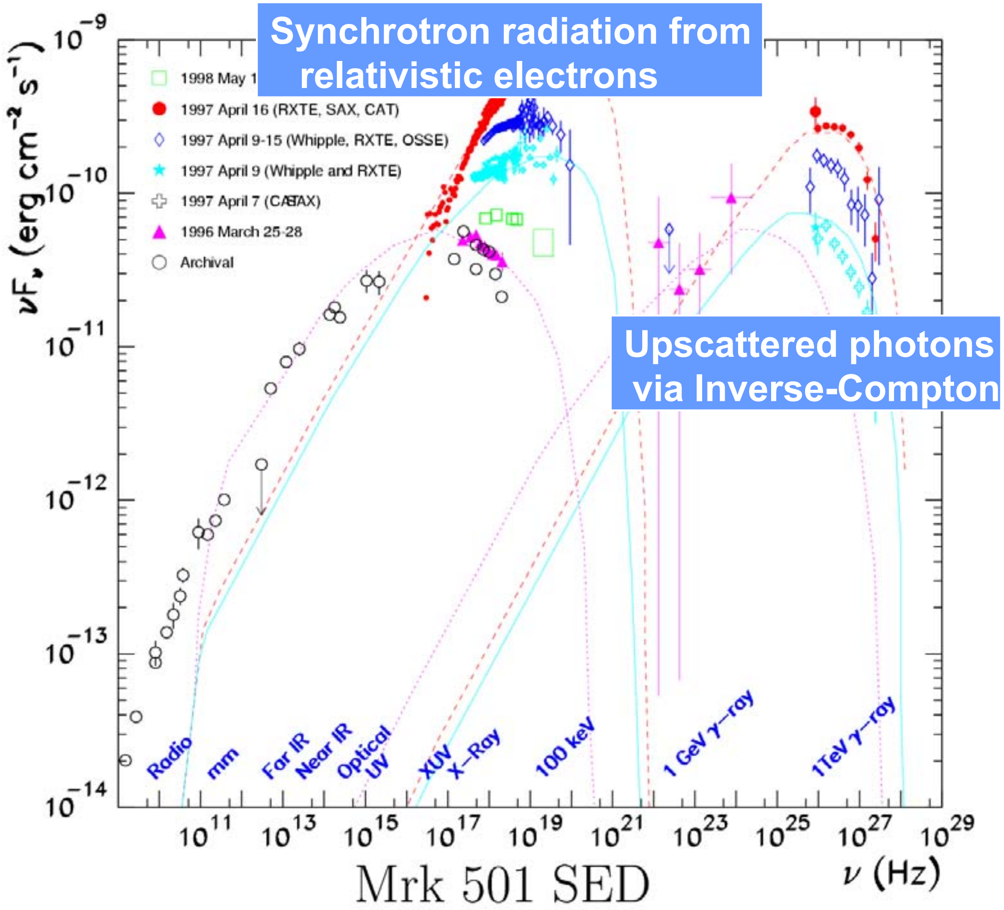




- VHE Flares are generally well correlated with X-ray flares.
- But not in this case !

AGN: Broadband Spectrum

Mrk 501



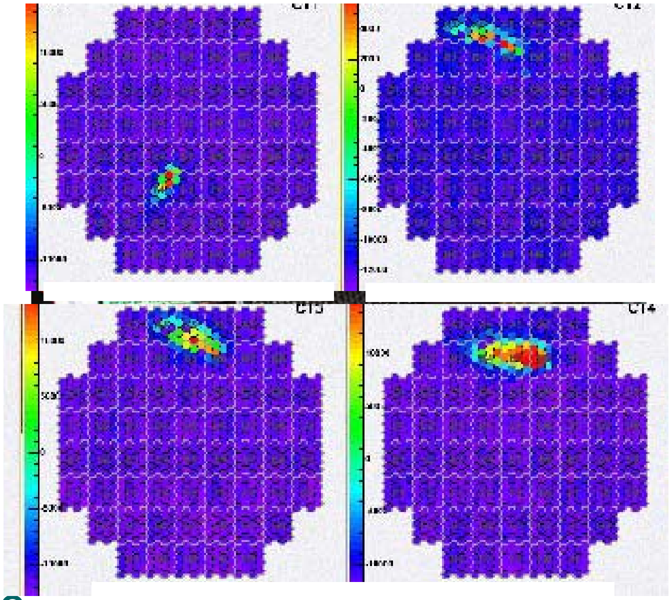
γ-ray and X-ray correlation is most easily explained in Synchrotron-IC scenarios.

→ 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.

NEW Telescope Arrays (2004)

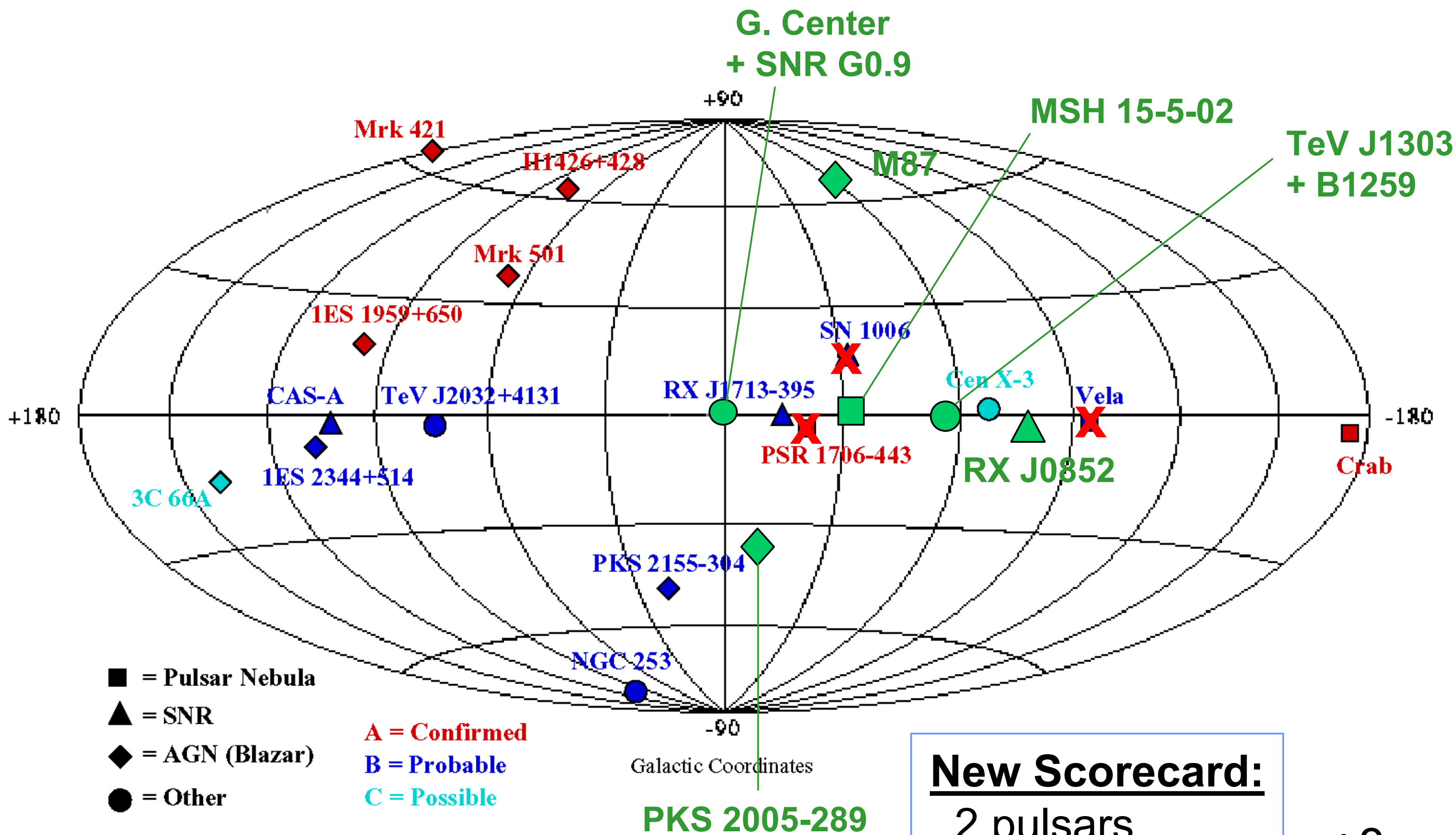


4 Telescope Event

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)

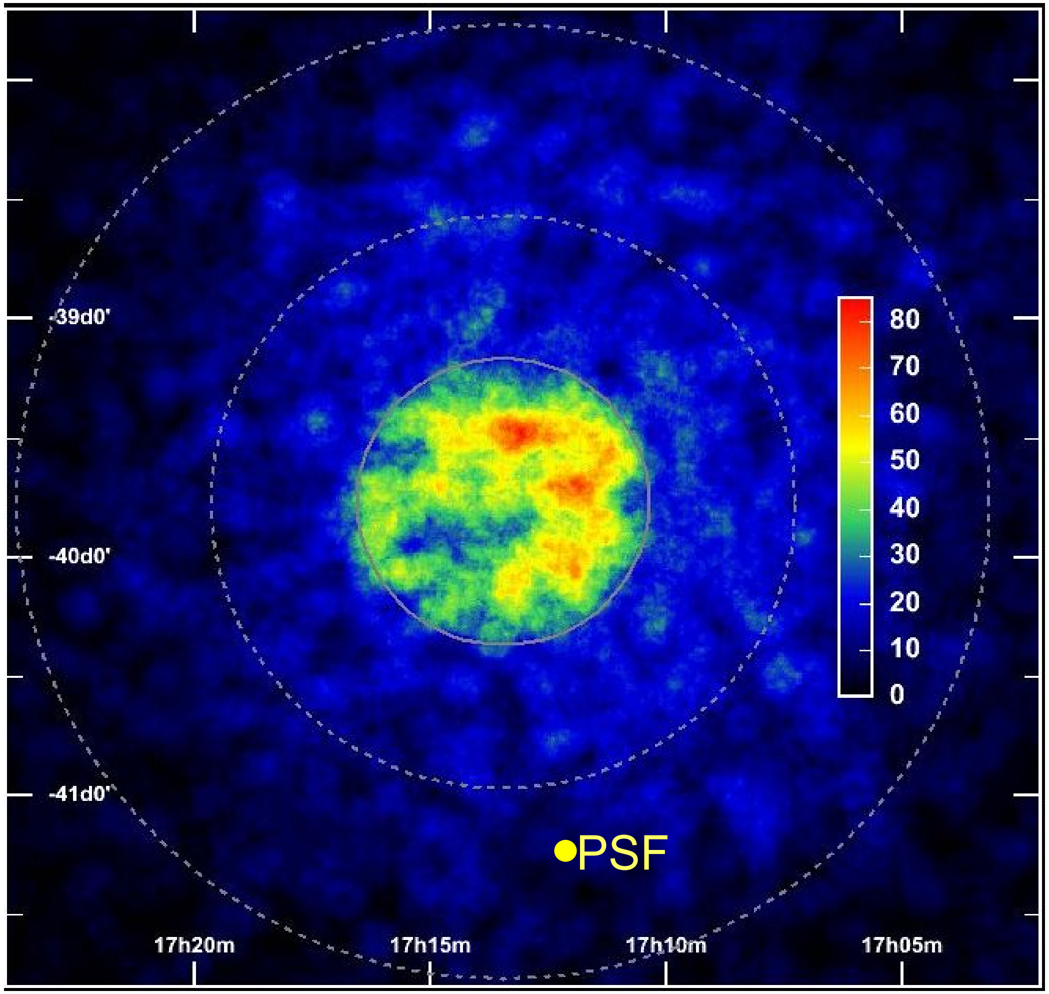
New Scorecard:

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

+8 more Sources ! (3/17/05)

1. SNR RX J1713 with HESS

C. Masterson



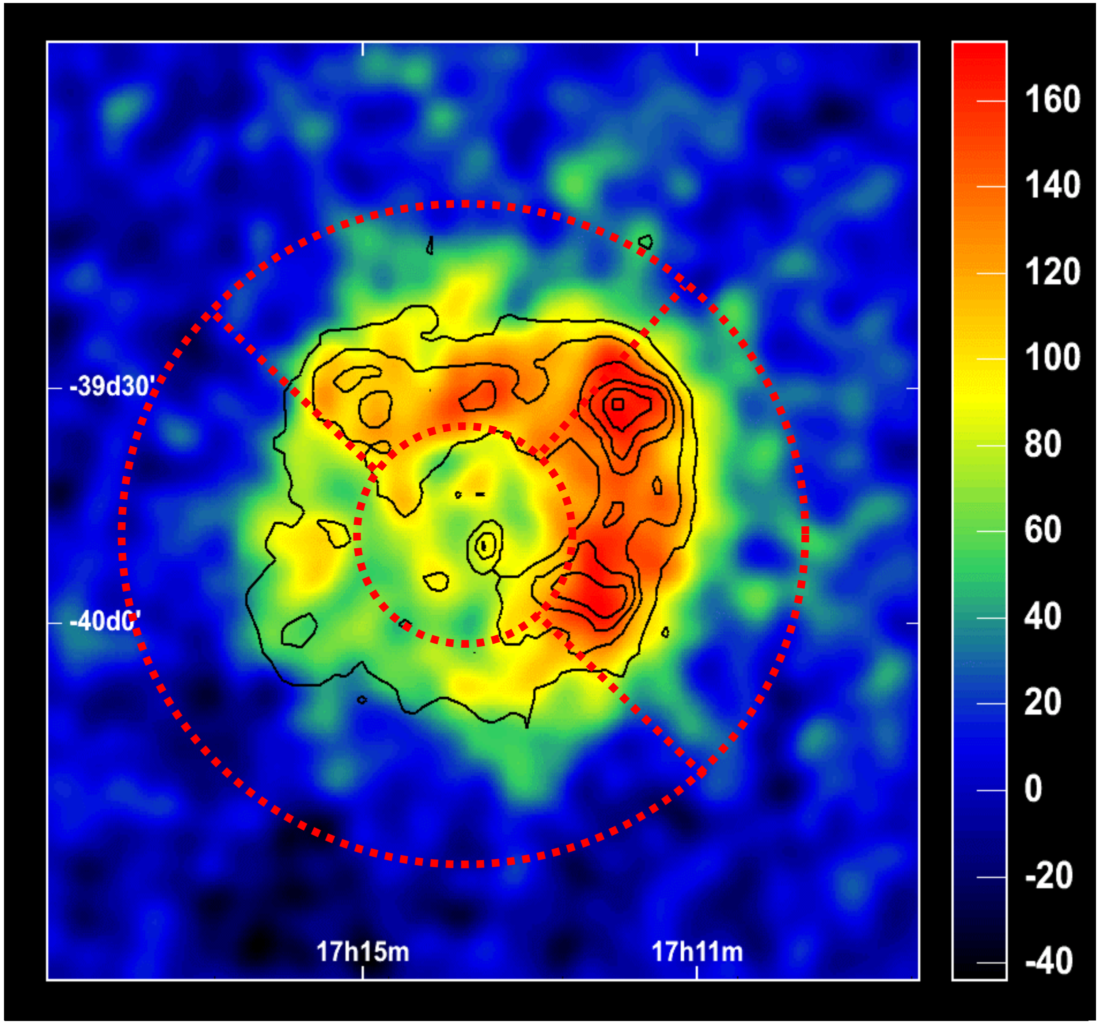
Confirmed in 2004:

- **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

HESS Confirmed 2004

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

Point source

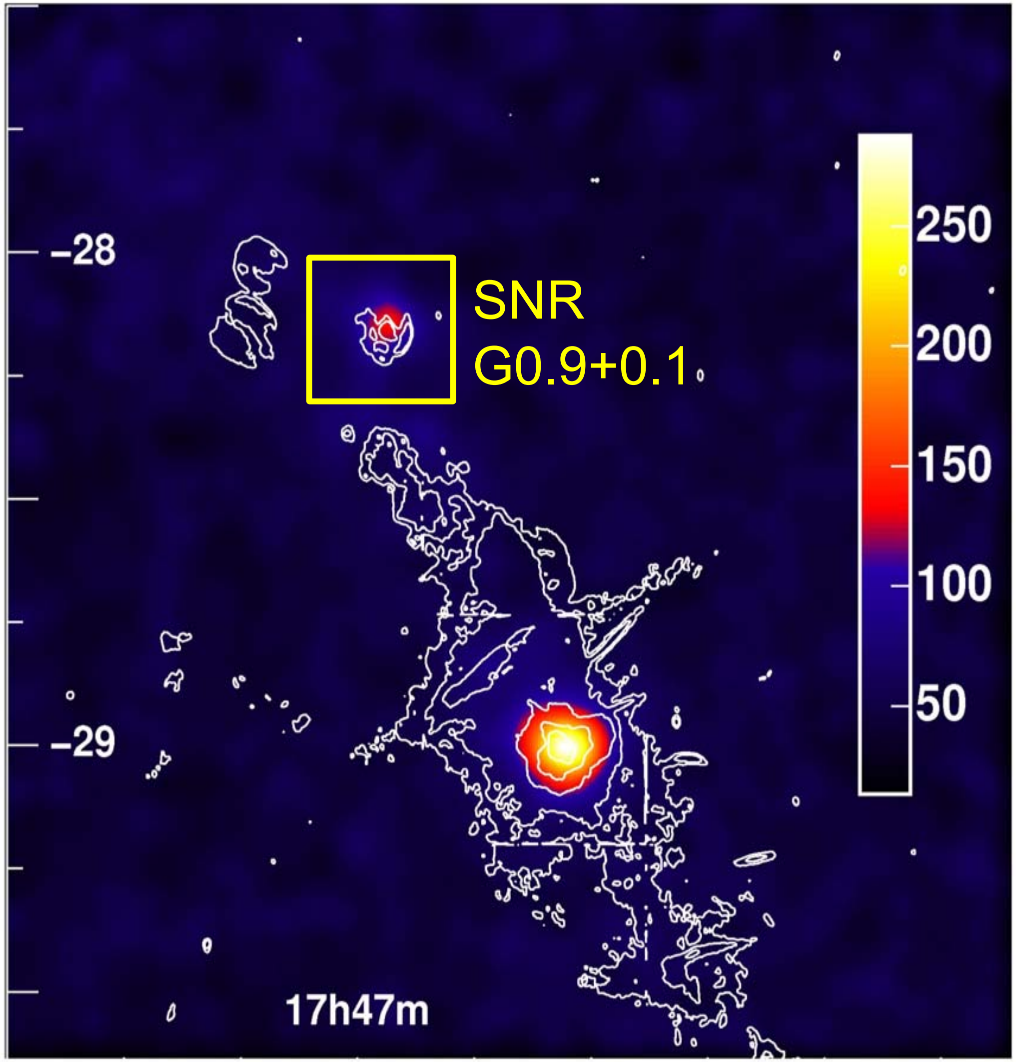
- **radius < 0.1°**
- **accurate position**

Hard, flat spectrum

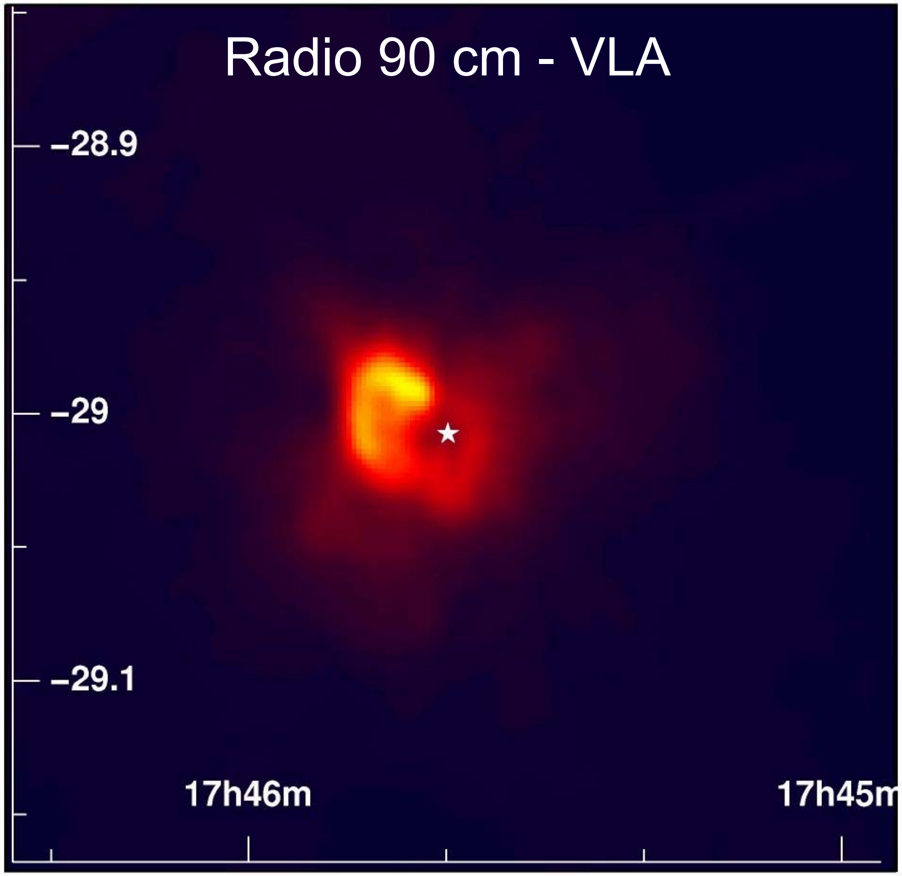
- **Γ = 2.21 ±0.09 ±0.1**

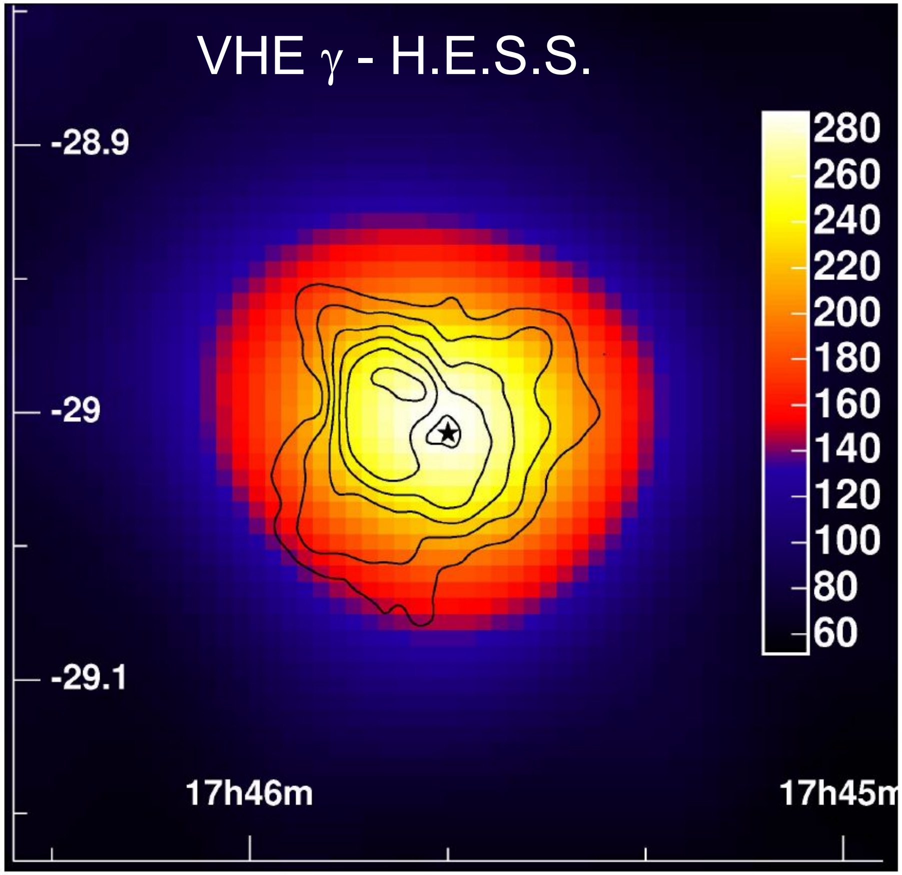
Dark Matter speculation…

C. Masterson



Sgr-A* and Sgr-A East

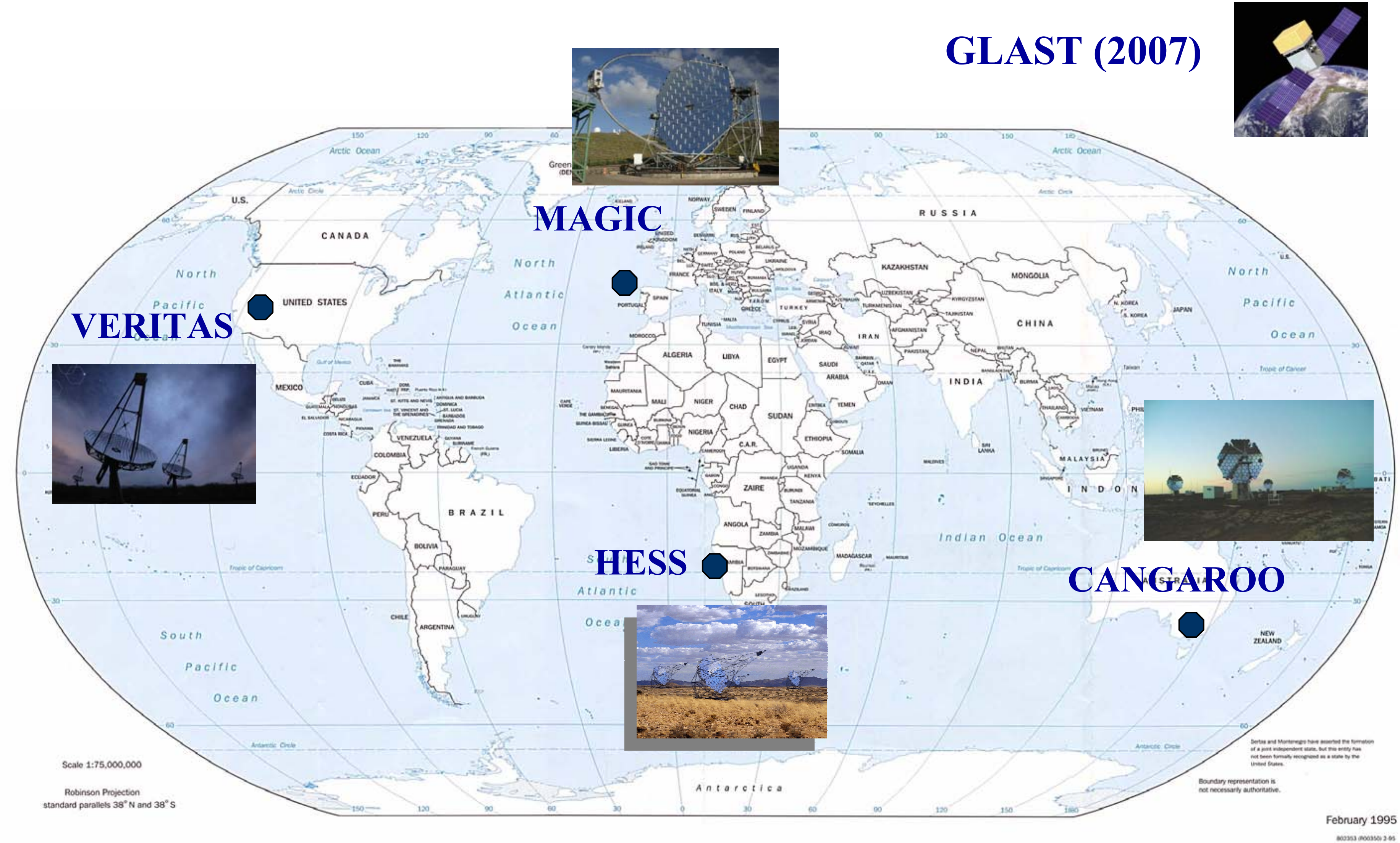




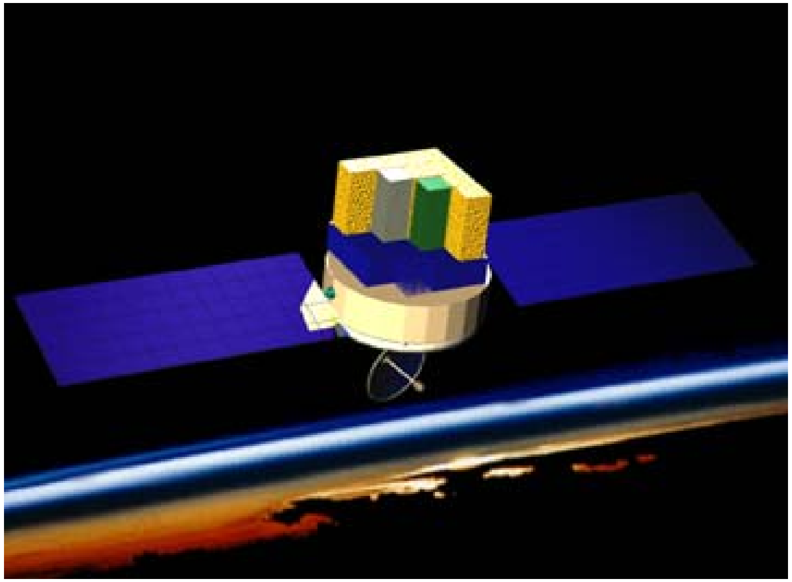
- Position compatible with Sgr A*

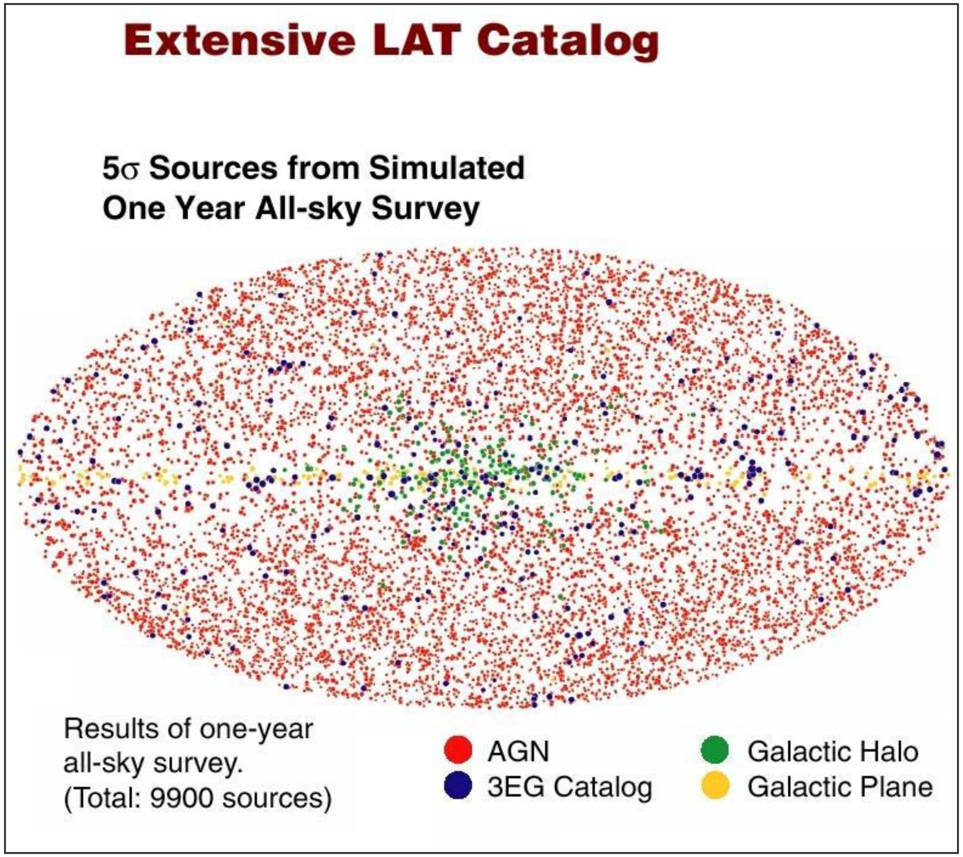
FUTURE

Major HE γ-ray Telescopes



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

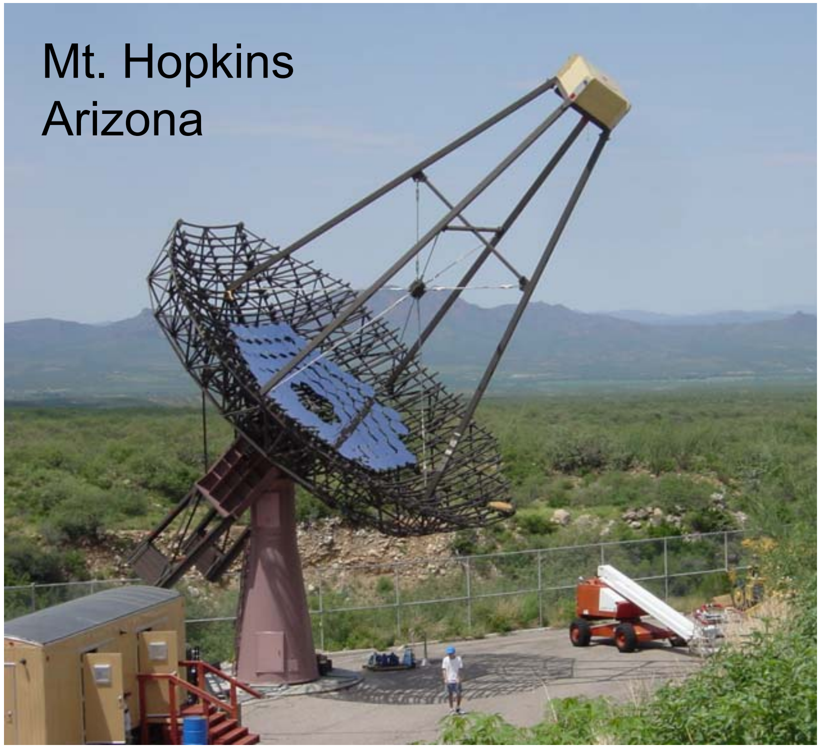
Detector Design:

- 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



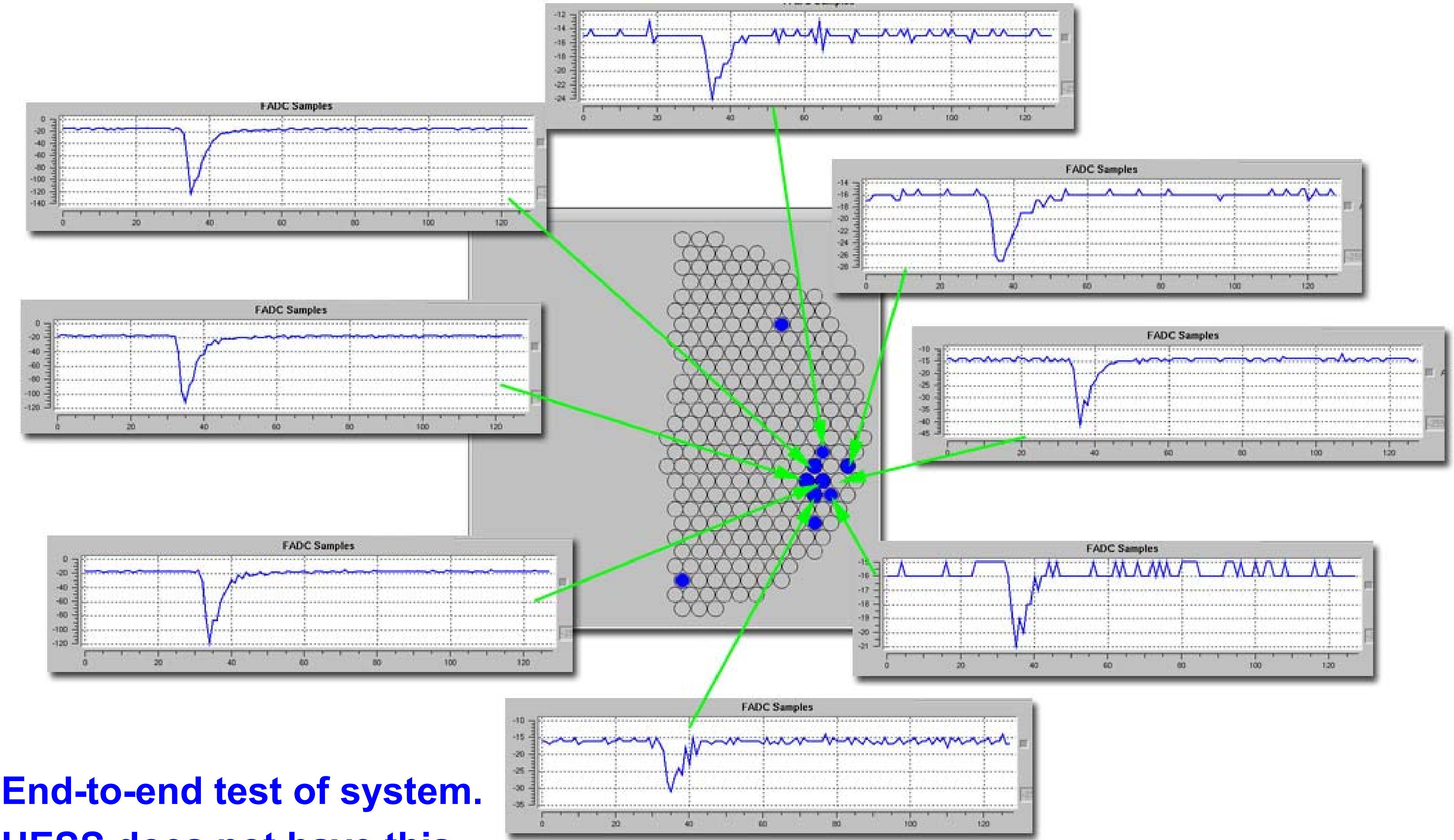
Prototype telescope (2004)

- 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.

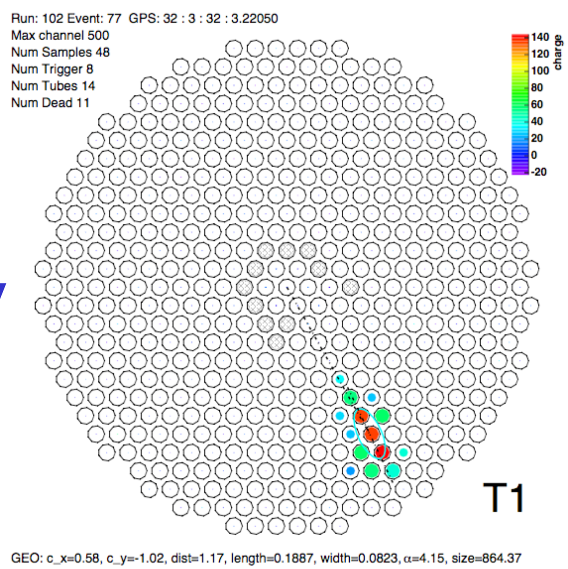
Telescope 1

Whipple Base Camp
Mt. Hopkins, AZ

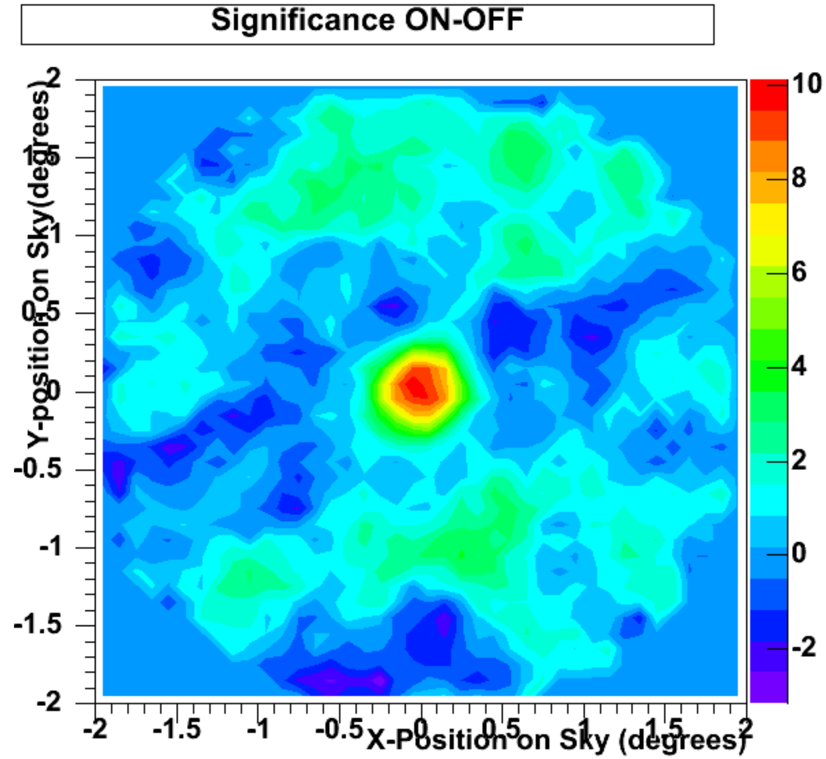
Telescope 1 (operational Feb 05)

Telescope 1

Camera



Cherenkov Image

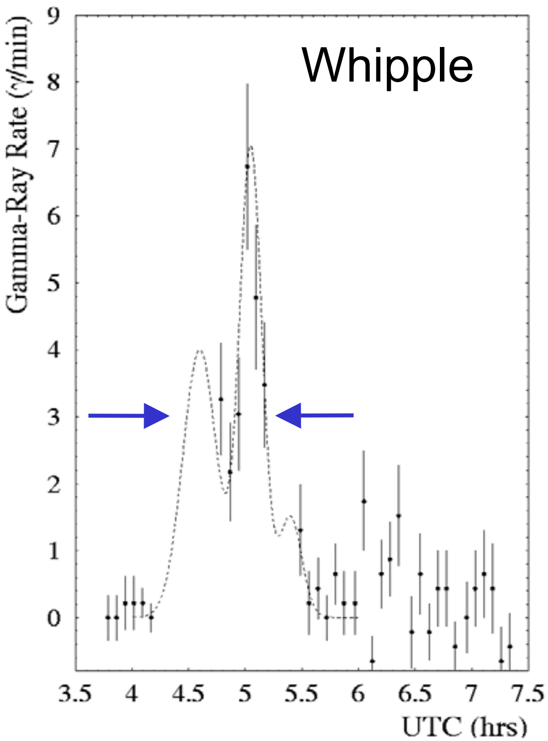


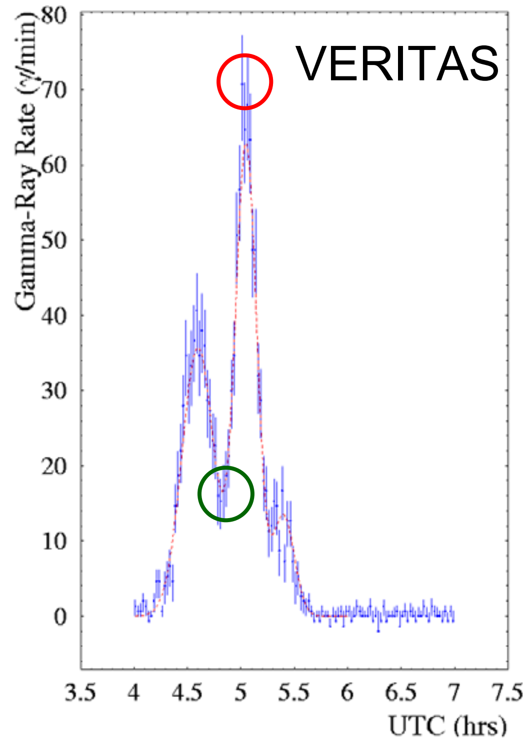
Crab Detection:
~ 10 σ /sqrt(hr)

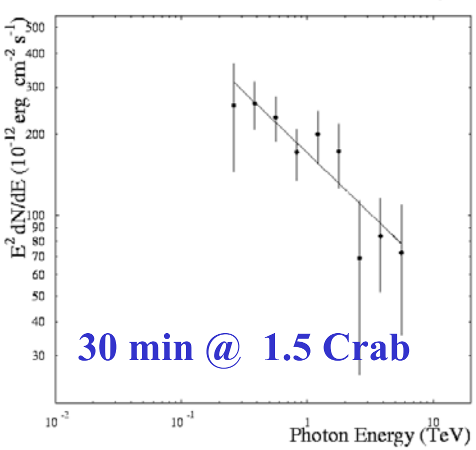
Kitt Peak Site (1700m)

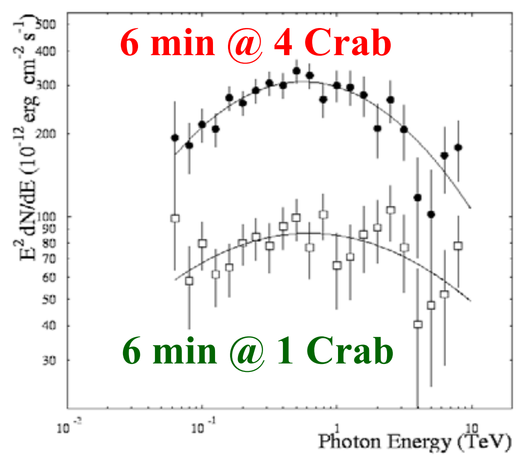
Kitt Peak Site (March 2005)

Expected Performance







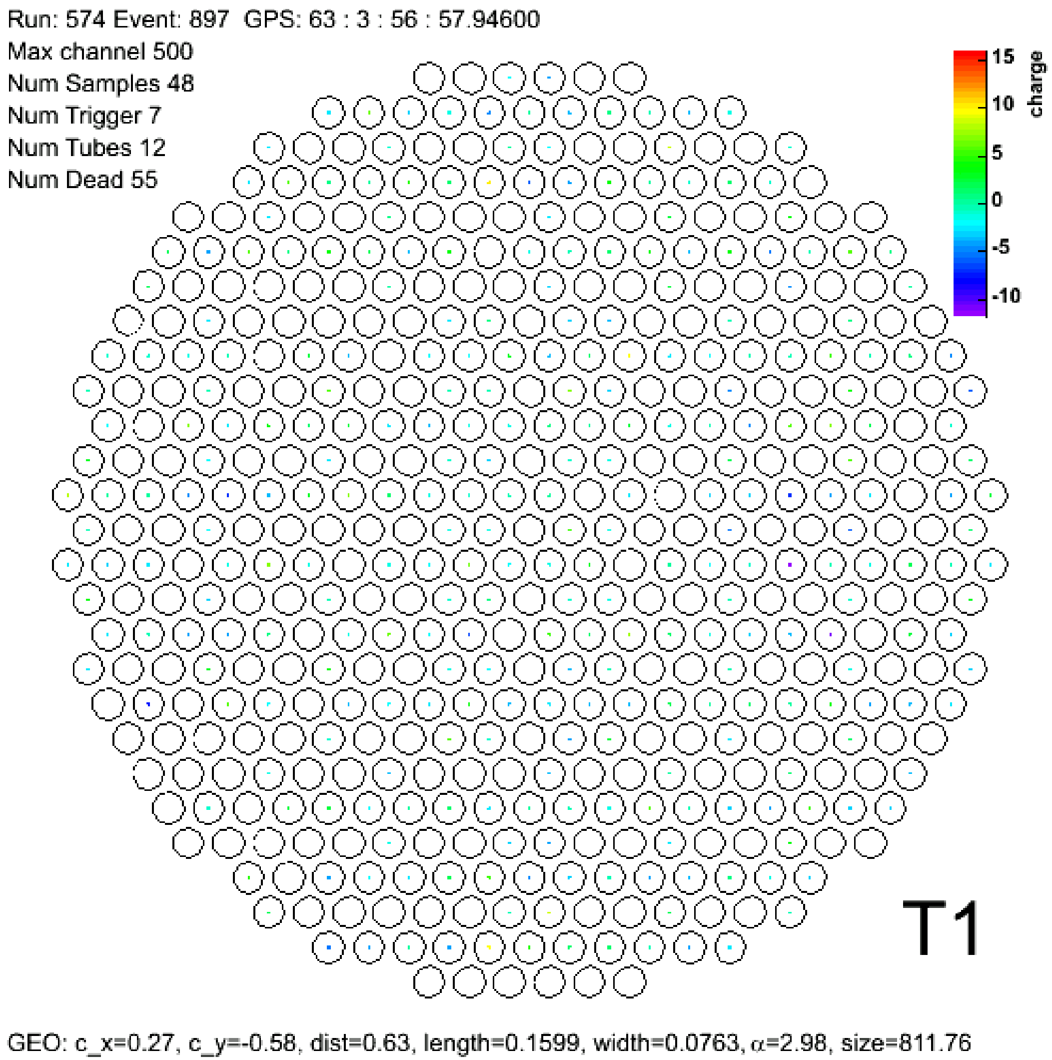


VERITAS …

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

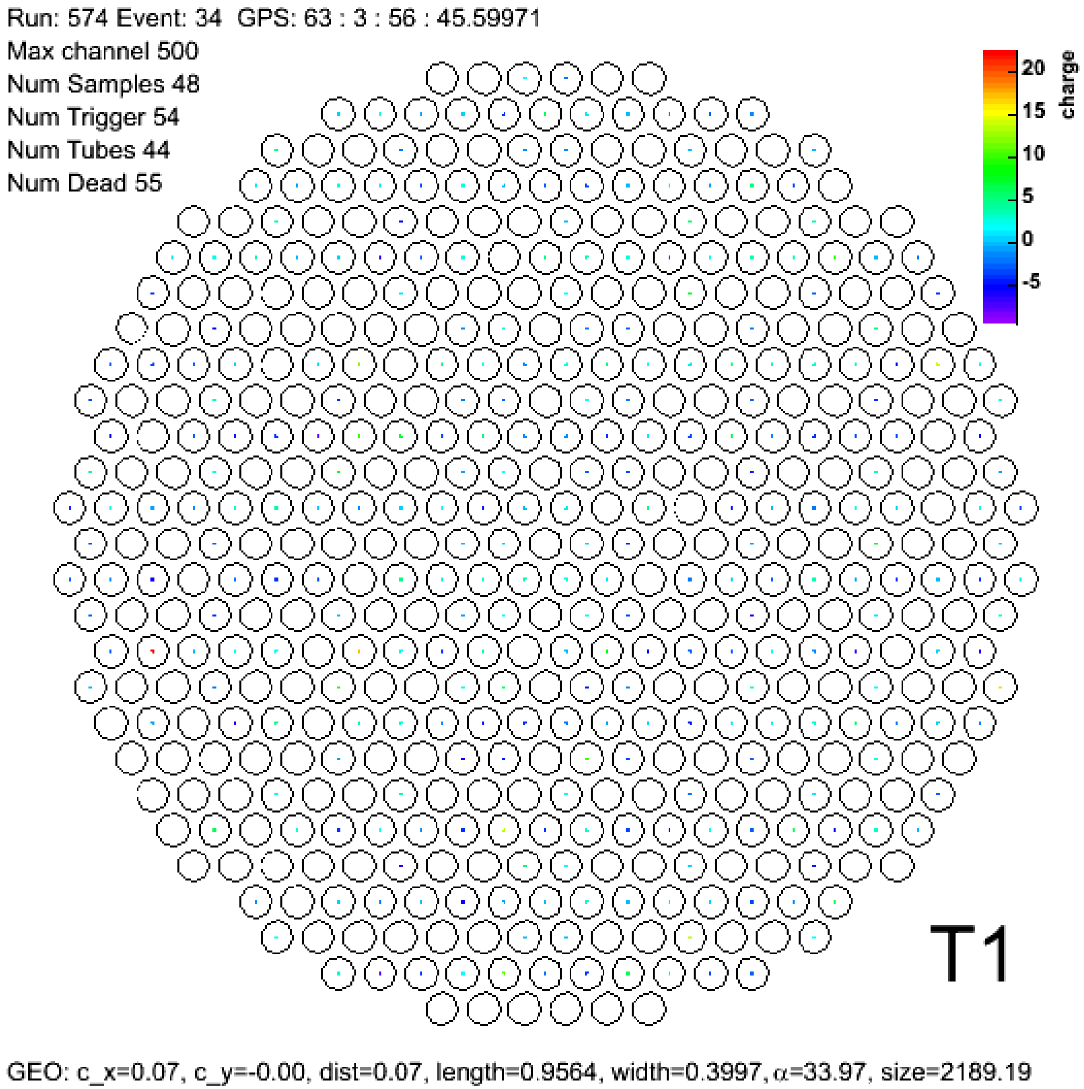
Telescope 1 Movies

γ-ray



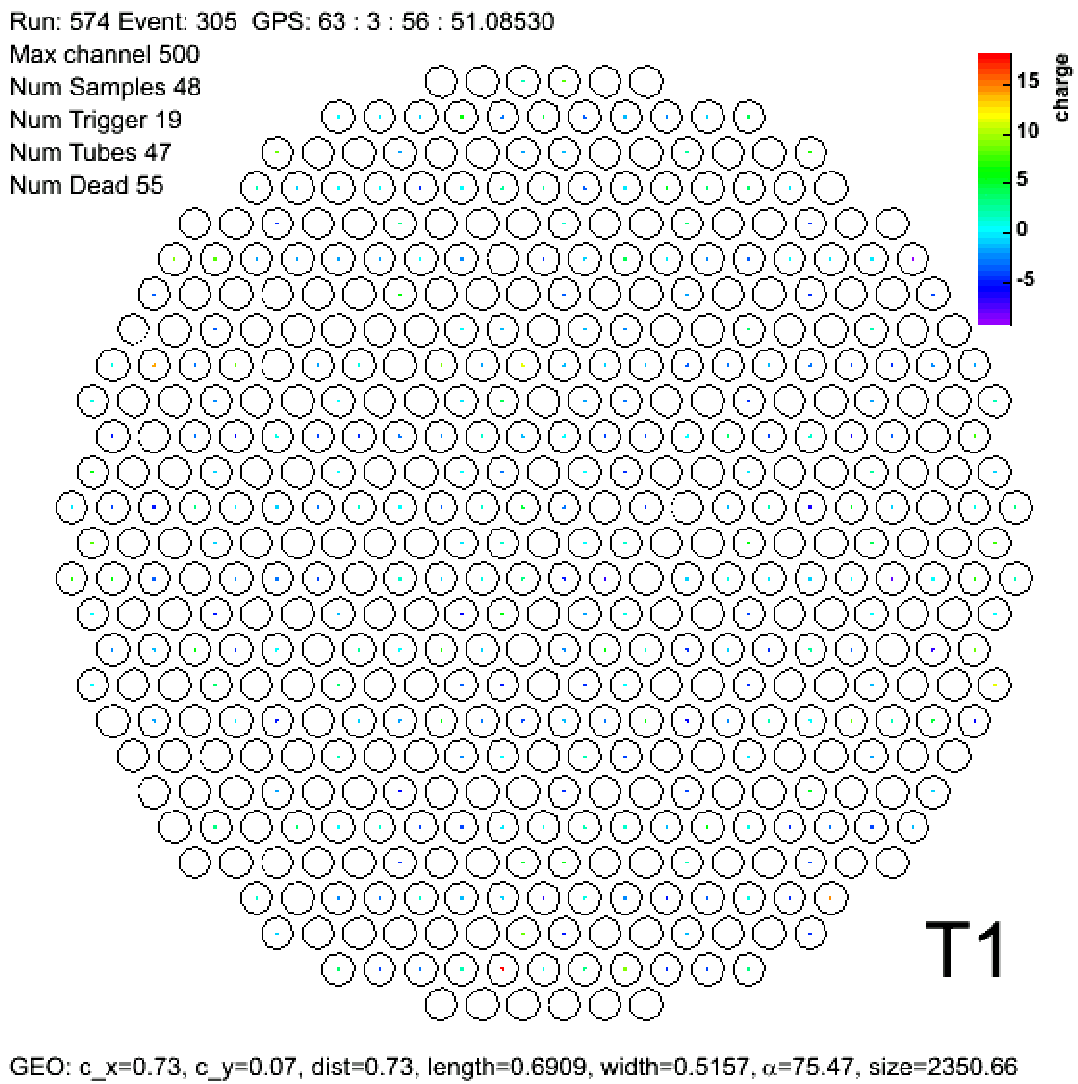
Telescope 1 Movies

Cosmic Ray



Telescope 1 Movies

Muon Ring



Summary

- Very HE particles provide unique tests of the limits of physical laws. Probe astrophysics in regimes not well understood.
- 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 <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)