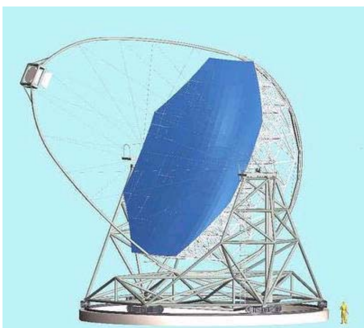
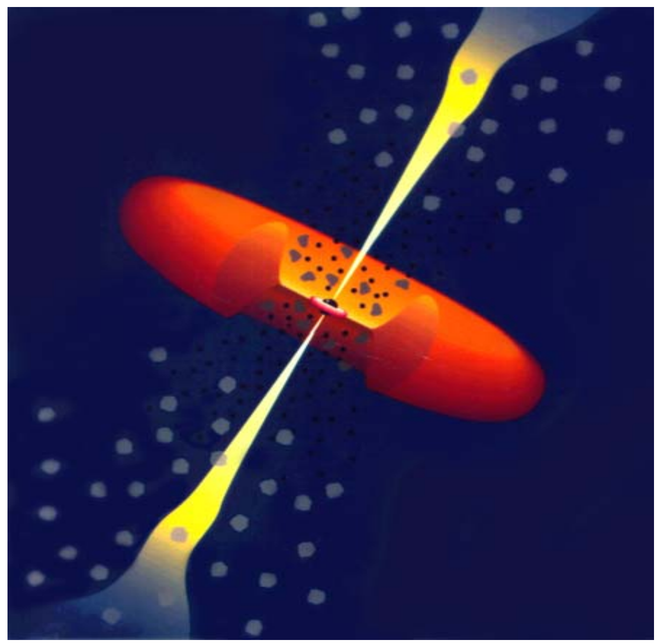
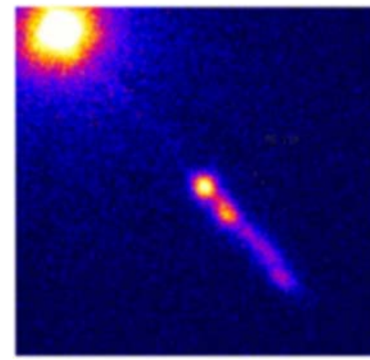
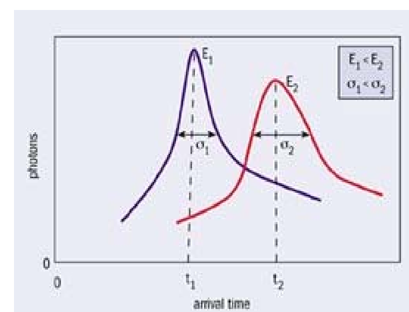
Observations of AGN at Very High Energies









Rene A. Ong
UCLA

UCSD Seminar
04 November 2003

OUTLINE

- Introduction – broad science goals
- Technique & history
- Current source catalog
- AGN highlights and interpretations
- Future – new telescopes (VERITAS)

Definitions

γ-rays

HE = E > 30 MeV (satellite)

VHE = E > 100 GeV (ground-based)

Distinctions becoming more and more arbitrary.

Broad Science Goals

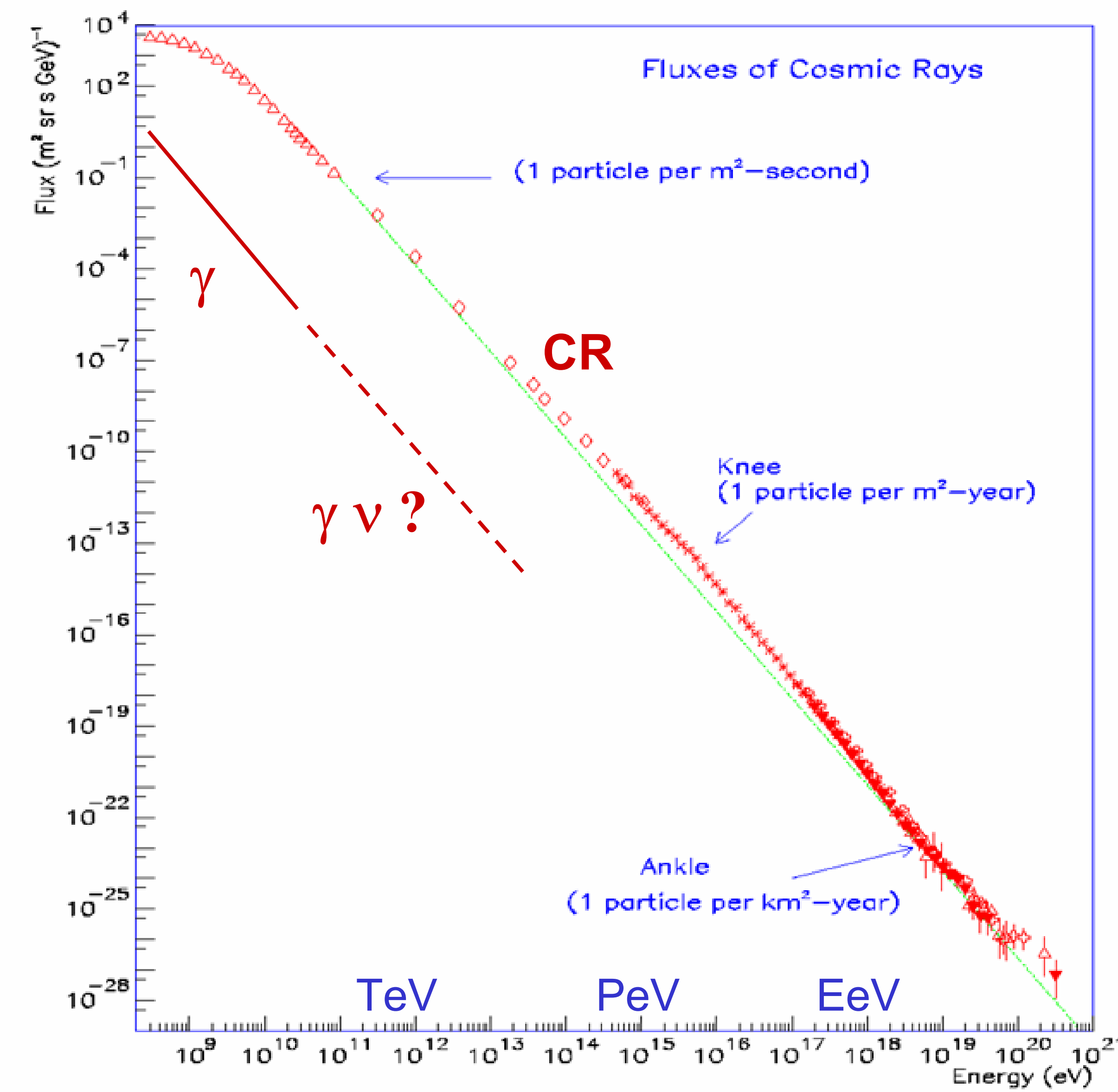
What are the origins of cosmic and γ-radiation?

- Studying particle acceleration in extreme astrophysical environments.
- Looking beyond standard models: relics from early universe, particles from high mass scales, etc.

Using γ-rays to probe intergalactic space.

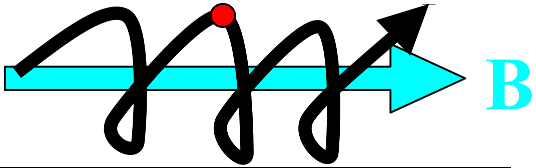
- Diffuse radiation fields.
- Fabric of space-time.

Cosmic Ray Energy Spectrum



- Total,diffuse spectrum individual species not resolved.
- Power-law spectrum E^{-3} differential.
- $E > 10^{20}$ eV.
- Energy density ~ 1 eV / cm^3.
- Diffuse ν not (yet) seen.

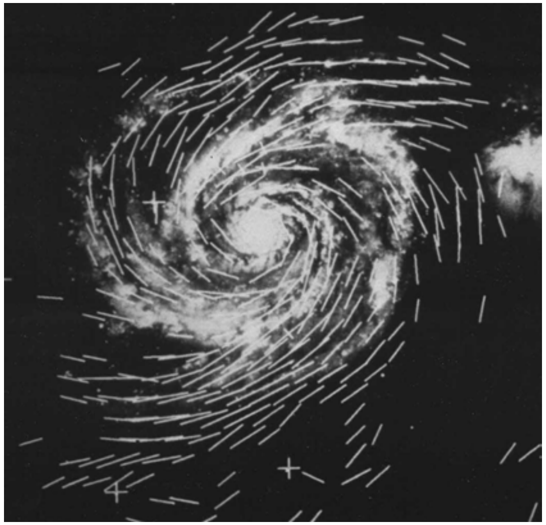
Magnetic Fields



1. Galaxies have magnetic fields.
   - Protons and nuclei will be deflected by the B ~ 5 μG galactic field.

   Larmor radius r = R/cB

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

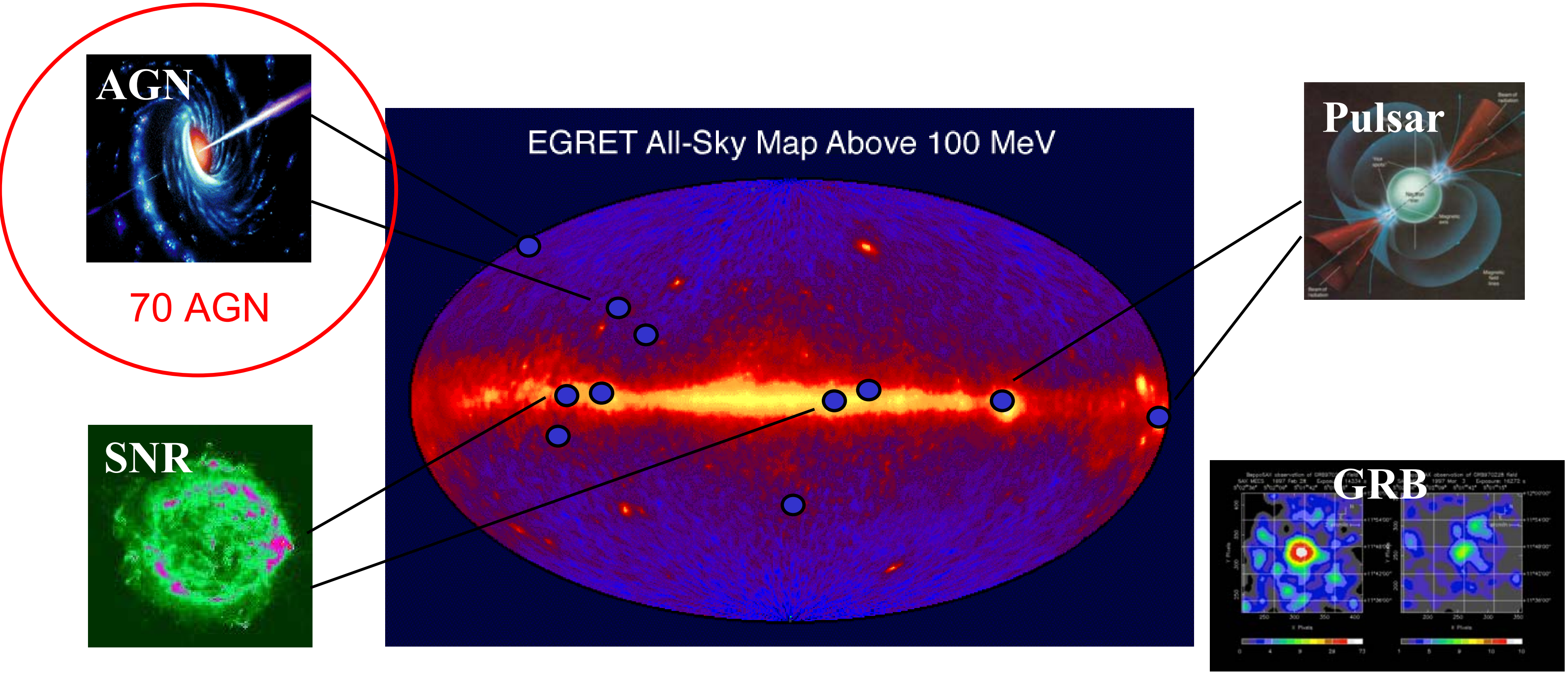


M51

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.
Gamma-rays and neutrinos will be undeflected.

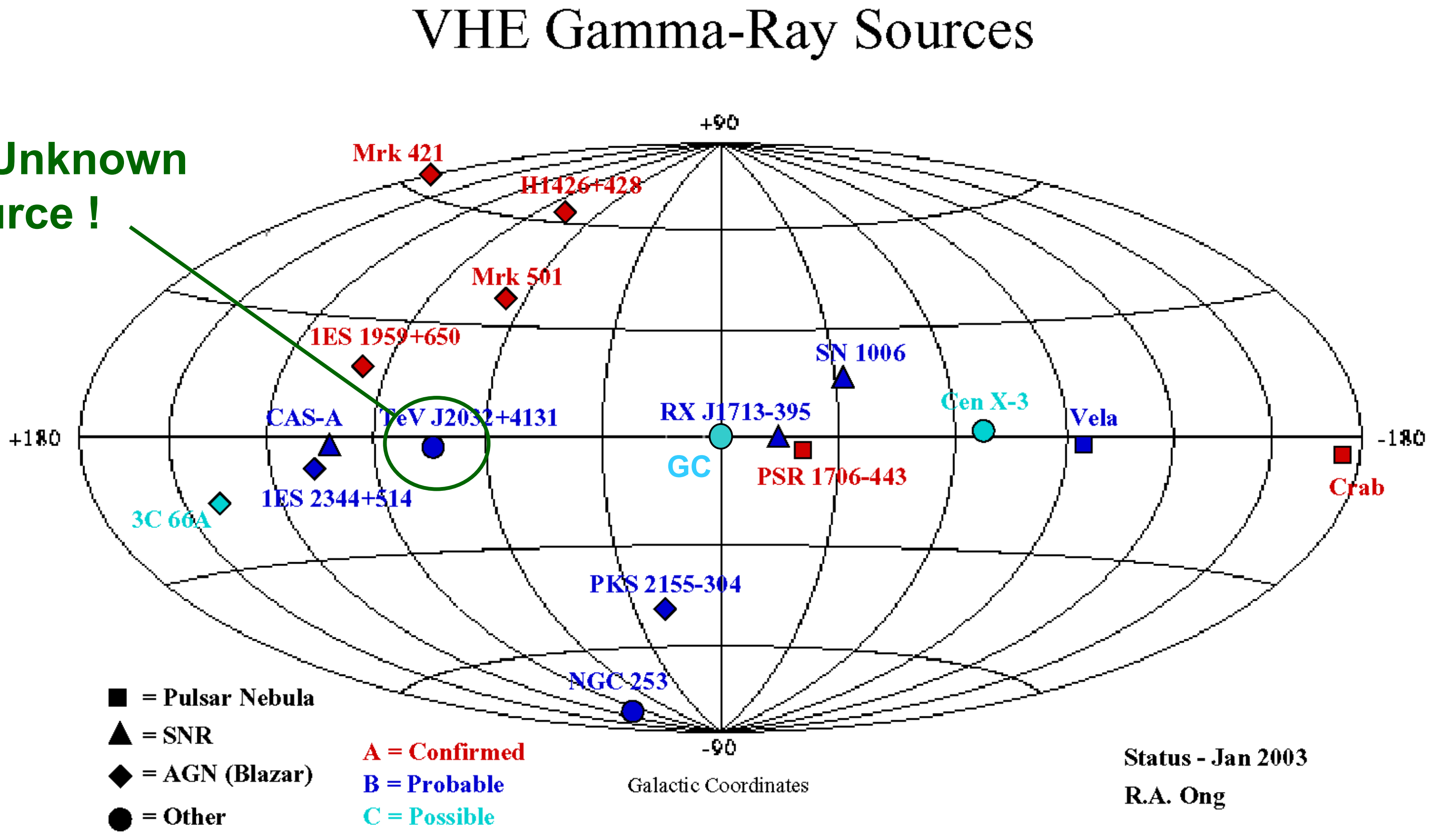
HE γ-ray Sky



- ~ 250 HE point sources, the majority unidentified.

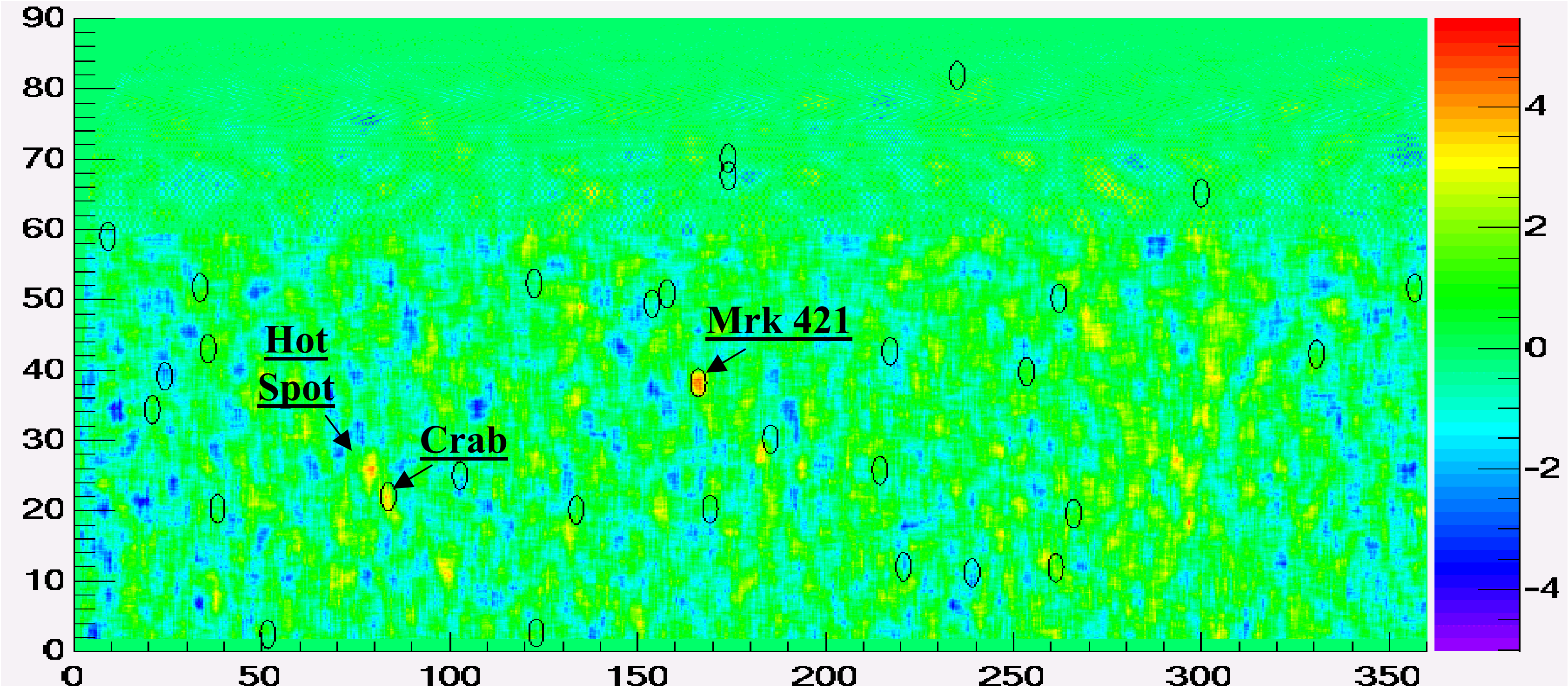
VHE γ-ray Sky

1st Unknown Source !



- **16 putative sources, 6 of which are AGN.**
- **All discovered by Cherenkov telescopes – few % sky.**

TeV Sky Survey



- Milagro: Very few sources comparable to Crab @ 1 TeV.

Technique
&
History

Experimental Techniques

Satellite (GLAST)

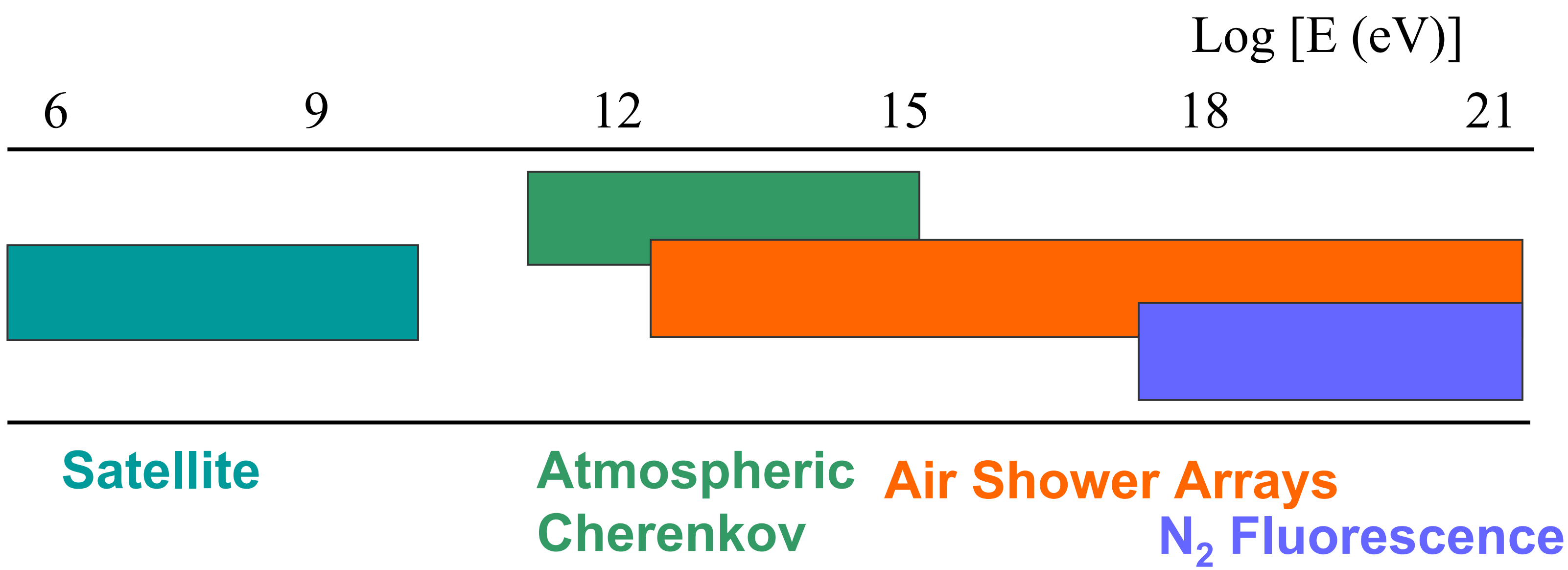
Balloon

Cherenkov Telescopes (VERITAS)

Air shower array (Milagro)

Experimental Techniques

Wide γ-ray energy range requires multiple techniques.



EGRET STACEE / WHIPPLE

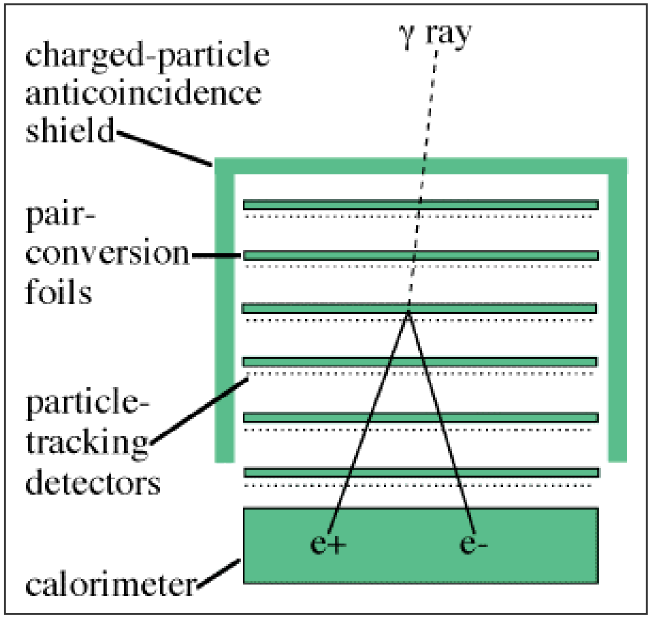
GLAST → ←VERITAS

EGRET (CGRO)

CGRO

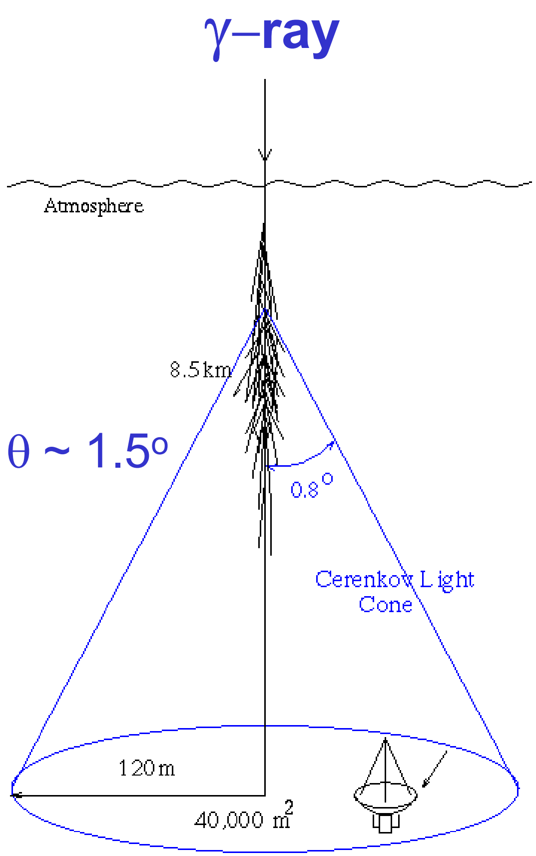
- Flew 1991-2000.
- Very successful mission.

EGRET

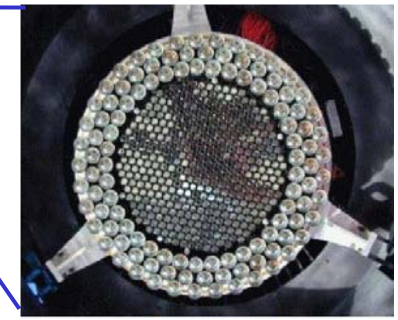


- Energy range 30 MeV – 20 GeV.
- Moderate FOV, collection area.
- Detected ~ 70 AGN.

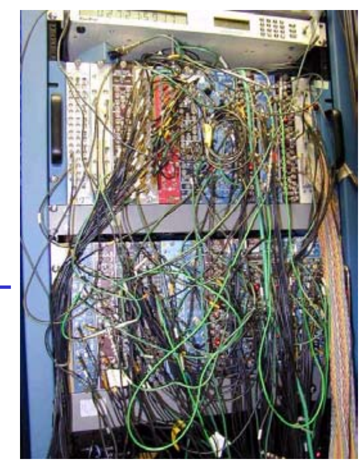
Cherenkov Telescopes (Imaging)



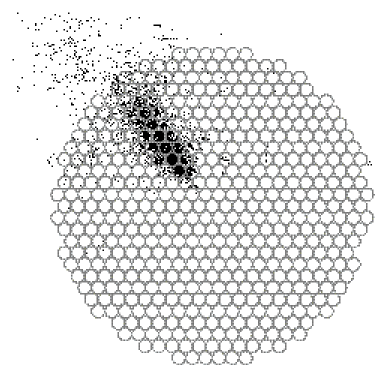
Whipple 10m (Arizona)



PMT camera



ns electronics

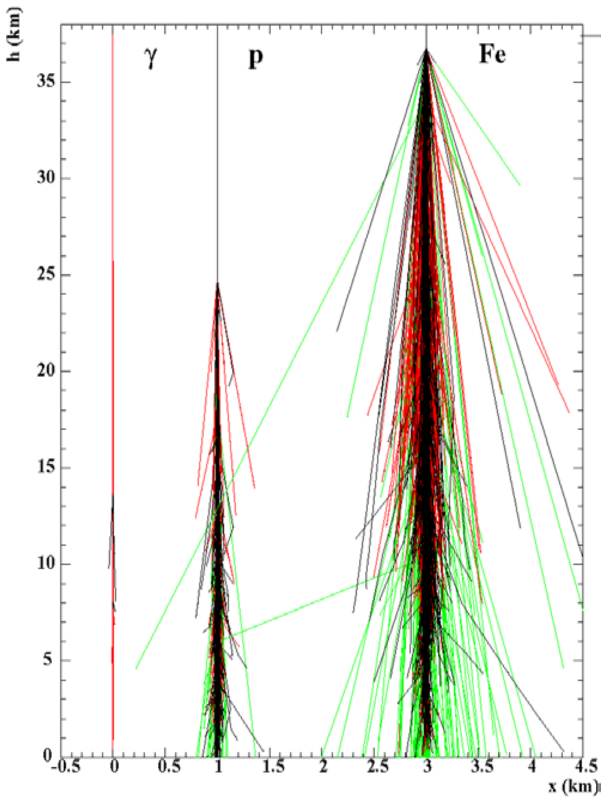


Cherenkov image

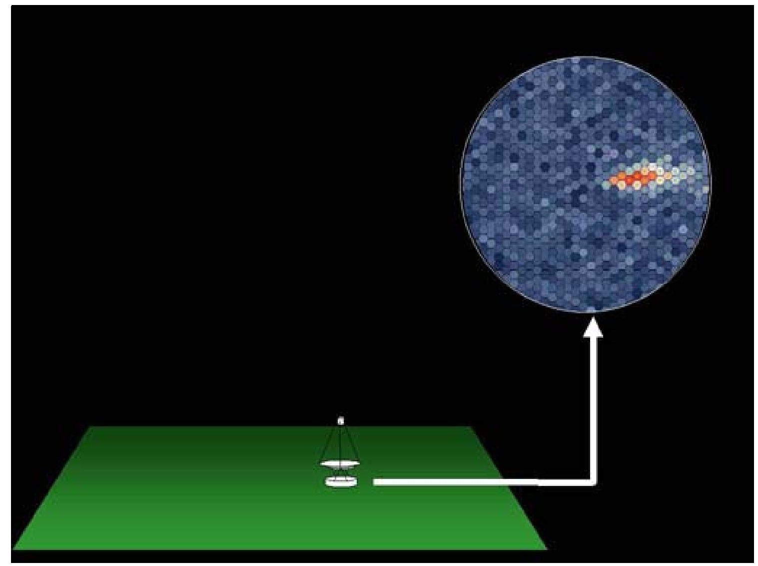
Area = $10^4 - 10^5$ m^2

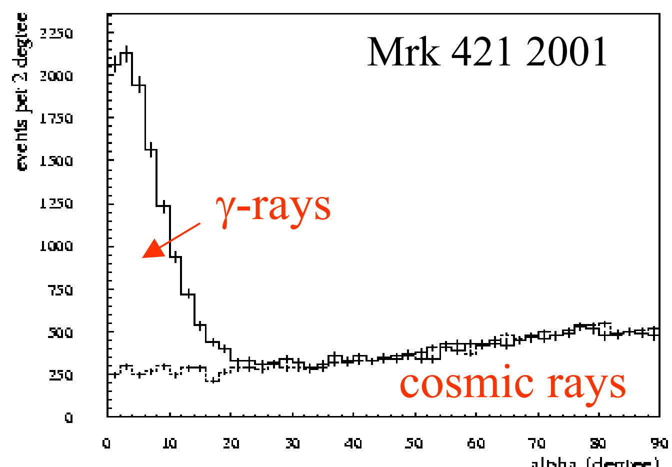
~60 optical photons/m^2/TeV

Isolating γ-rays



Shower profile
in atmosphere

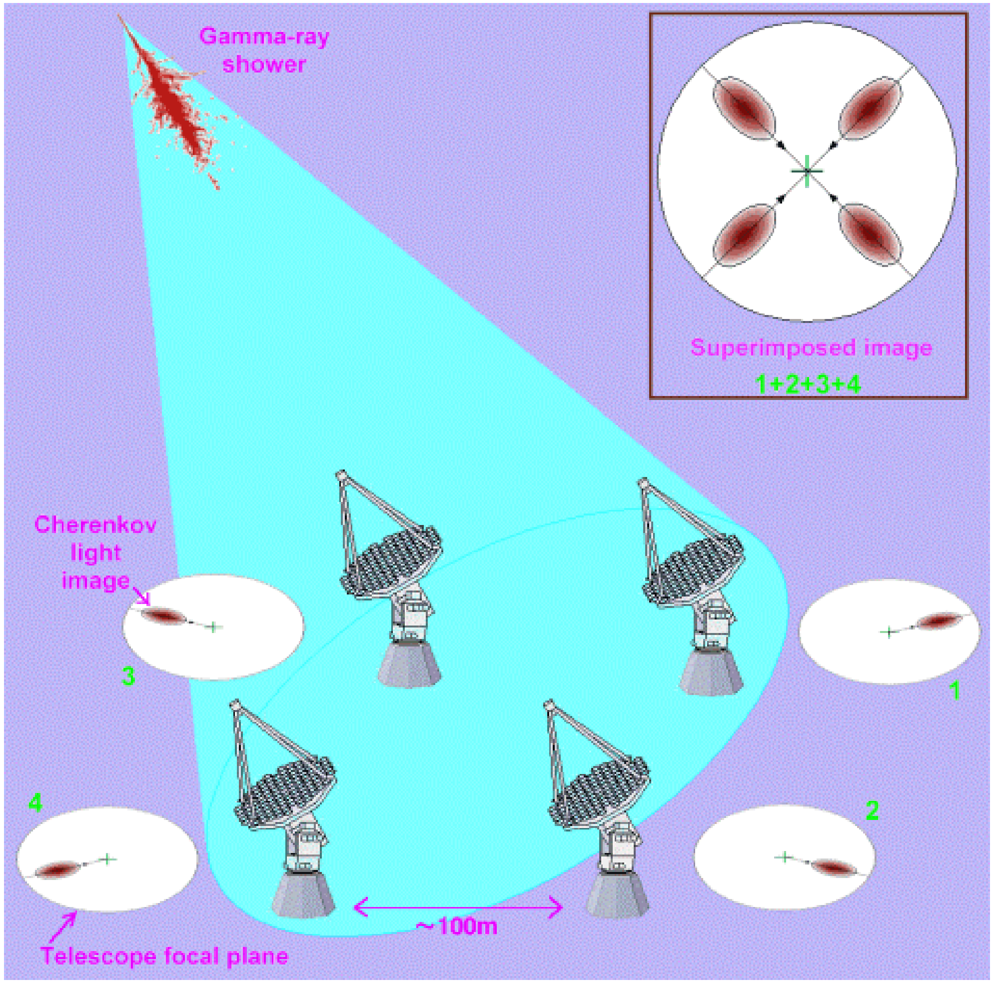




Orientation angle (α)

Rejection
Factor ~ 300
(single tel)

Array of Cherenkov Telescopes



HEGRA
(La Palma, decomissioned)

Rejection Factor ~ 5,000

HISTORY

- 1970's: First Experiments
- 1980's: X-ray binary period

1989:   Detection of Crab Nebula (Whipple)
1992:   Detection of Markarian 421 (Whipple)
1997:   Flares from Markarian 501
1998:   Detection of SN1006 (CANGAROO)
2002:   Detection of Unid TeV (HEGRA)

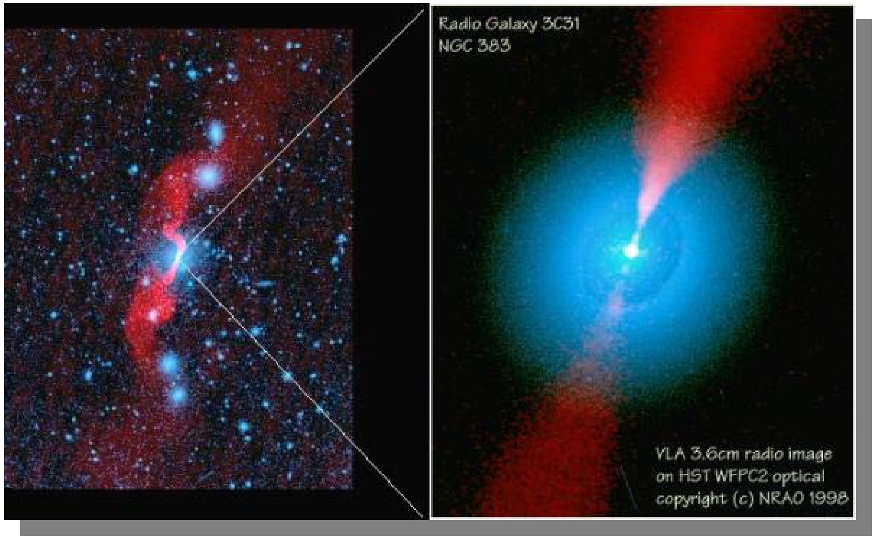
- 2004+: New generation of Telescopes

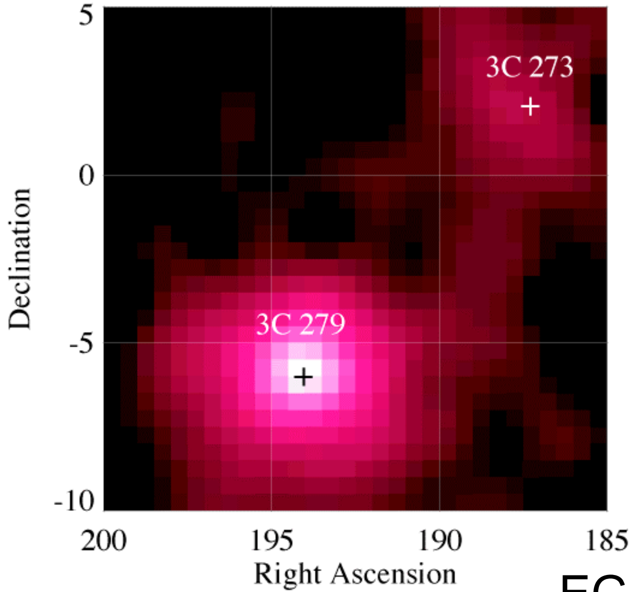
AGN Science

- Source list (6).
- (Sample) light curves.
- Spectra: SED's and correlations with X-ray & interpretation.
- Absorption on EBL → Cosmology.
- Violation of Lorentz invariance.

Blazars

- Giant elliptical galaxies.
- SM black hole, accretion power.
- Relativistic jets.



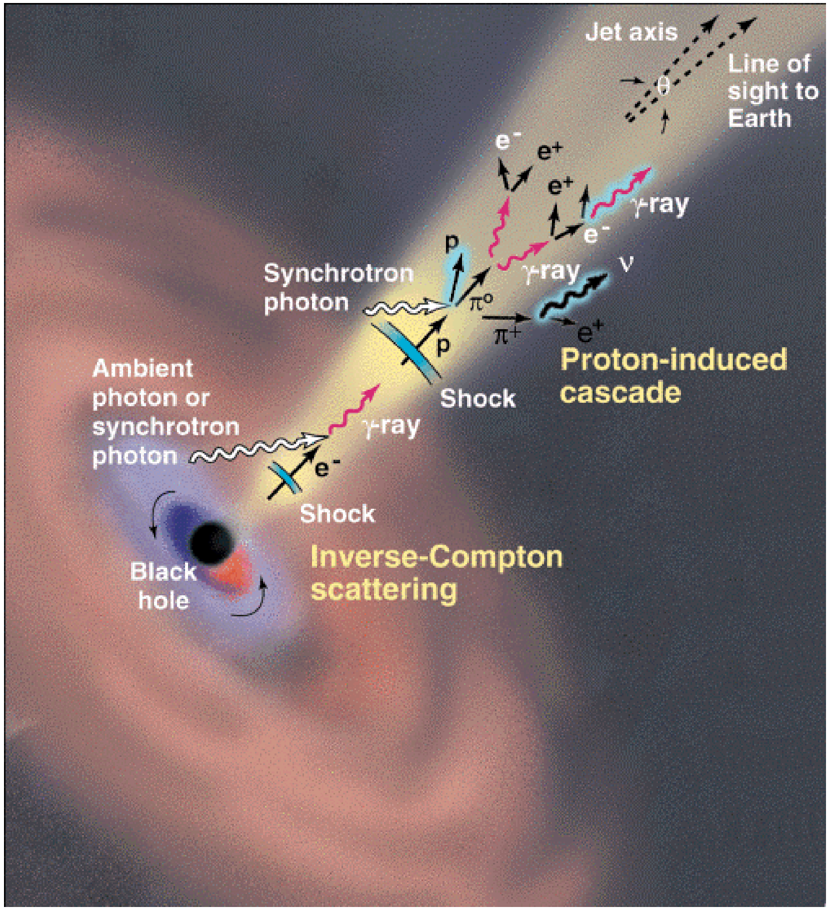


EGRET

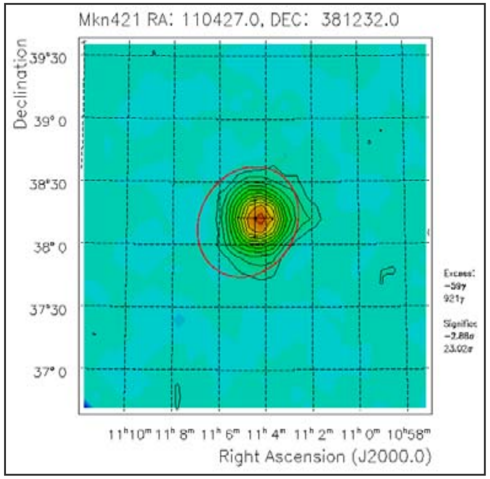
Blazars:

- Powerful, radio-loud objects.
- Highly variable at all wavelengths.
- Jets – superluminal motion.
- Two broad types:
  Quasars, BL Lac's.

Blazar Jets



Mrk 421 Whipple

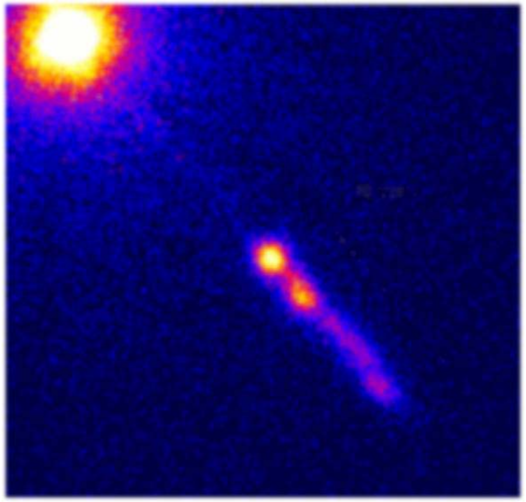


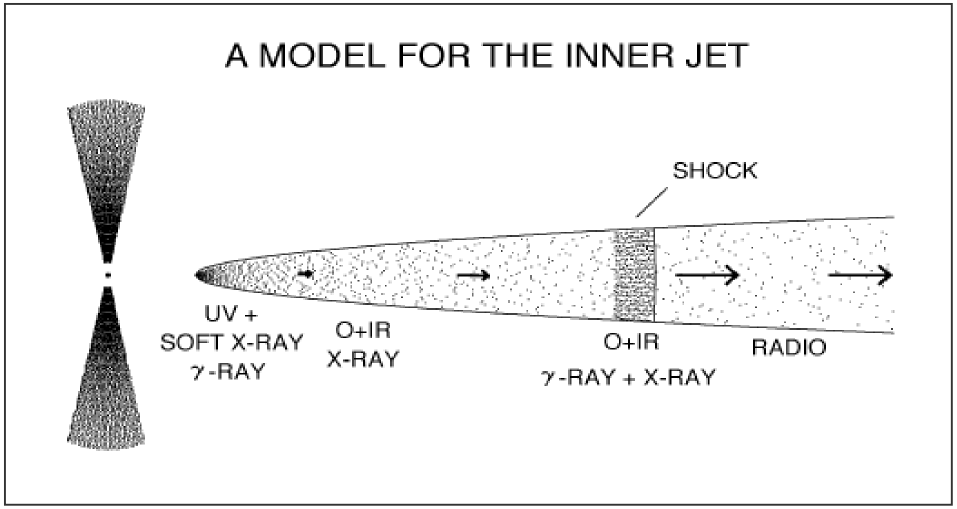
Current paradigm:

- Synchrotron self Compton
- External Compton
- Proton induced cascades
- Proton synchrotron

But many details not understood !

Blazar Dynamics



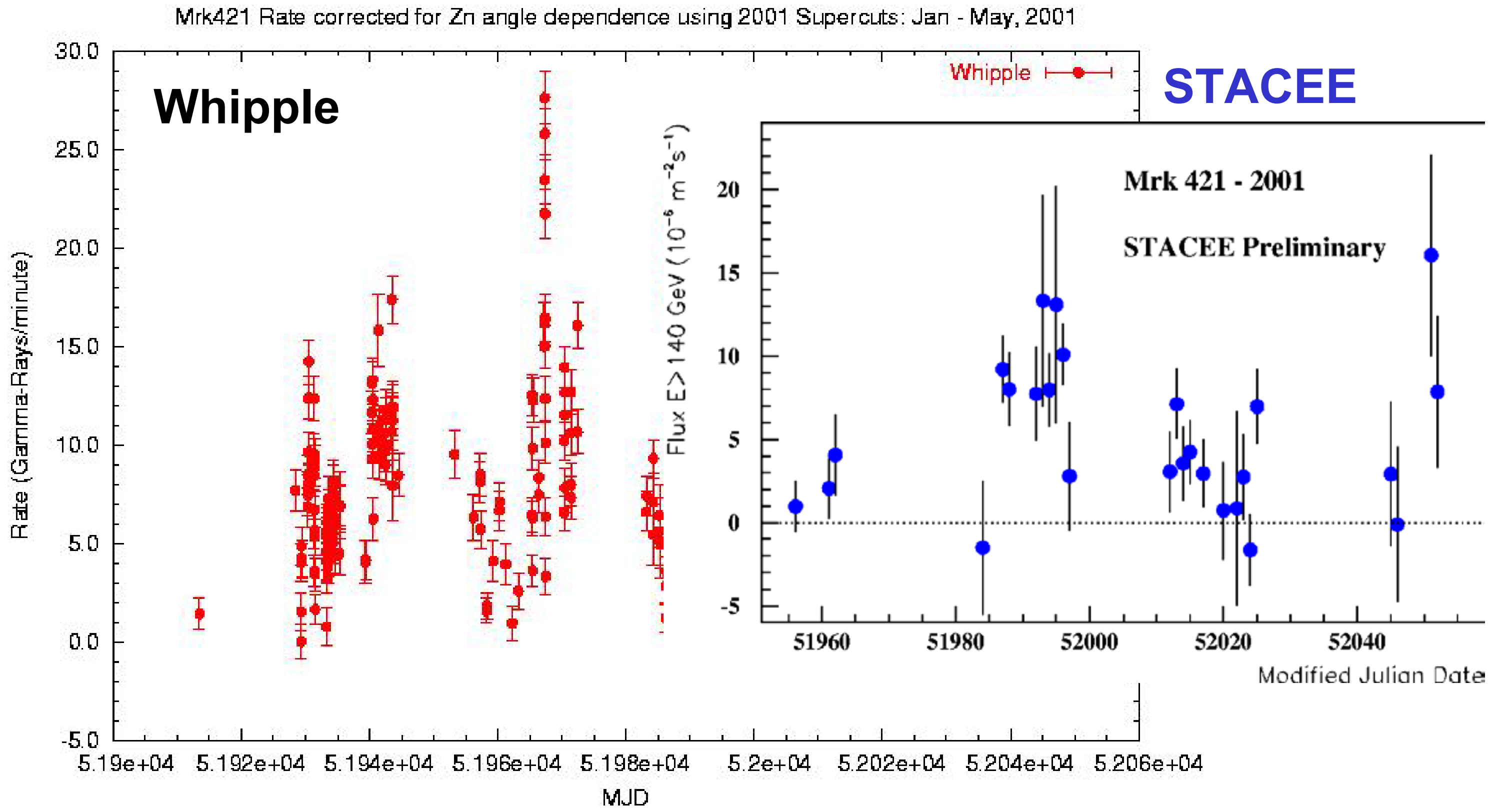


- Formation, collimation, and properties of Jet
- Doppler factors, geometry, zones
- Nature of beam: e or p
- Acceleration mechanisms
- Source of IC photons
- Magnetic and radiation fields
- . . .

Detected AGN

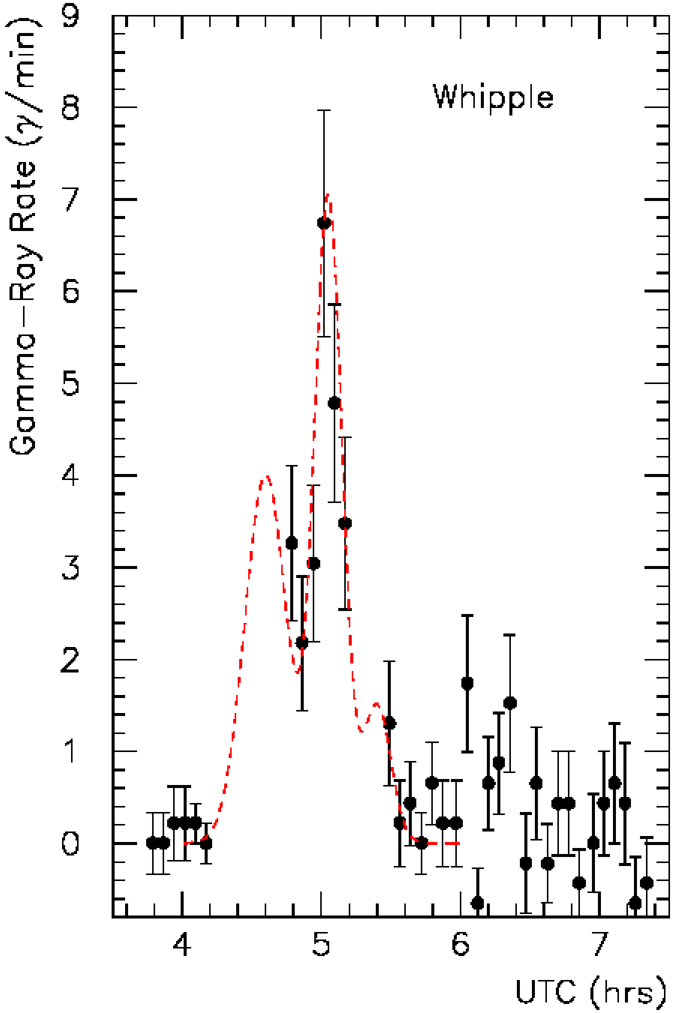
Source	Type	Z	Confirmed?	Comments
Mrk 421	BL Lac	0.031	Yes	flaring, X-ray, IR abs.? spectral variability
Mrk 501	BL Lac	0.034	Yes	flaring, X-ray, IR abs.?
1ES 2344+514	BL Lac	0.044	No	
1ES 1959+650	BL Lac	0.048	Yes	flaring, IR abs.?
PKS 2155-304	BL Lac	0.116	Yes	
1ES 1426+428	BL Lac	0.129	Yes	weak source

Light Curves



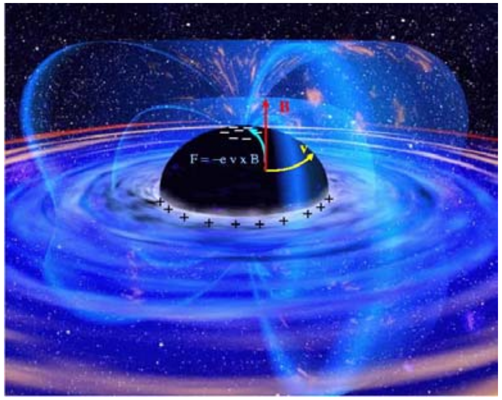
- Mrk 421, 2001 – "best case".
- Highly statistically significant.

Probing Central Engine: Very short time scales

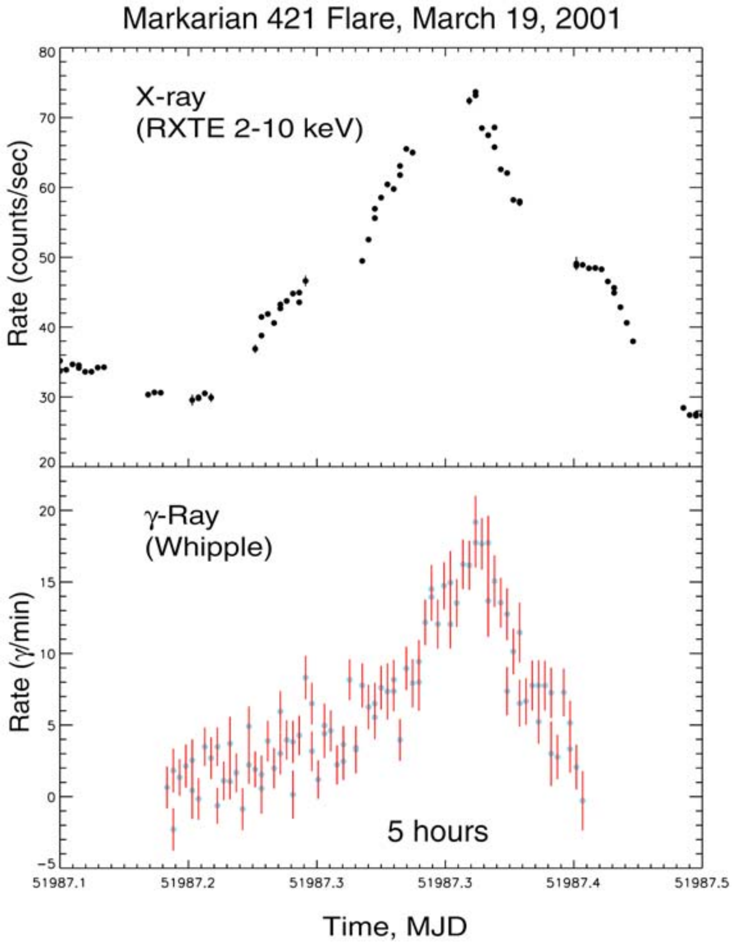


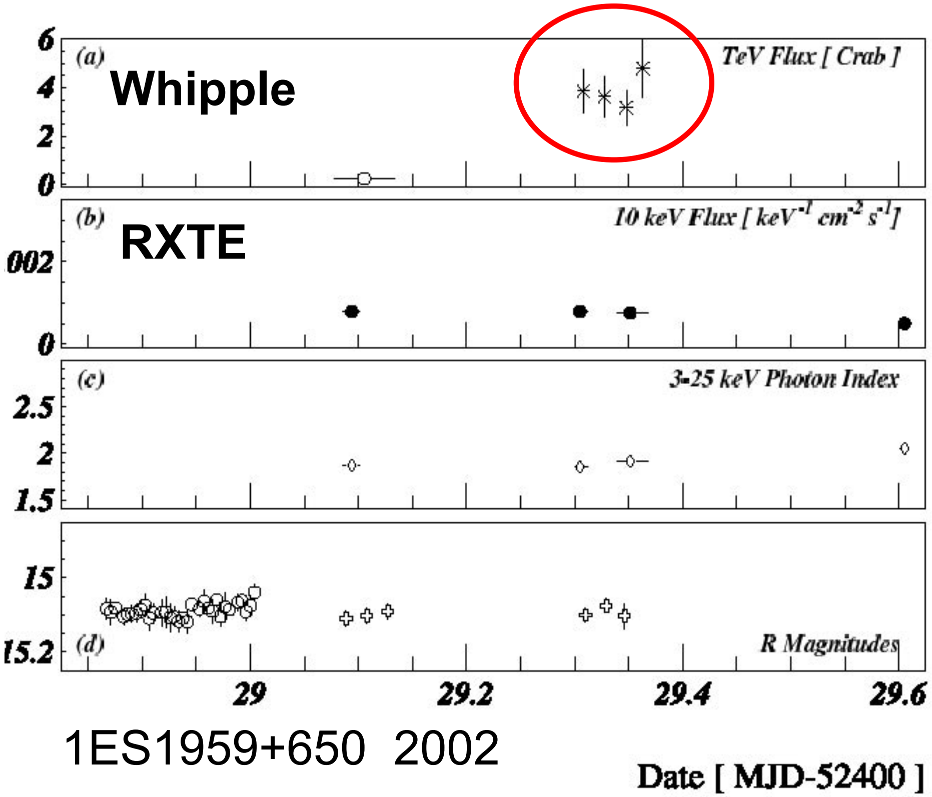
Mrk 421, May 1996

- T_{rise} ~ T_{fall} ~ 15 min !
- $R < cT\delta / (1+z)$ ~ 10^{-4} pc
- For $M = 10^8\ M_{sun}$, R_s ~ 10^{-5} pc.



Correlation with X-rays

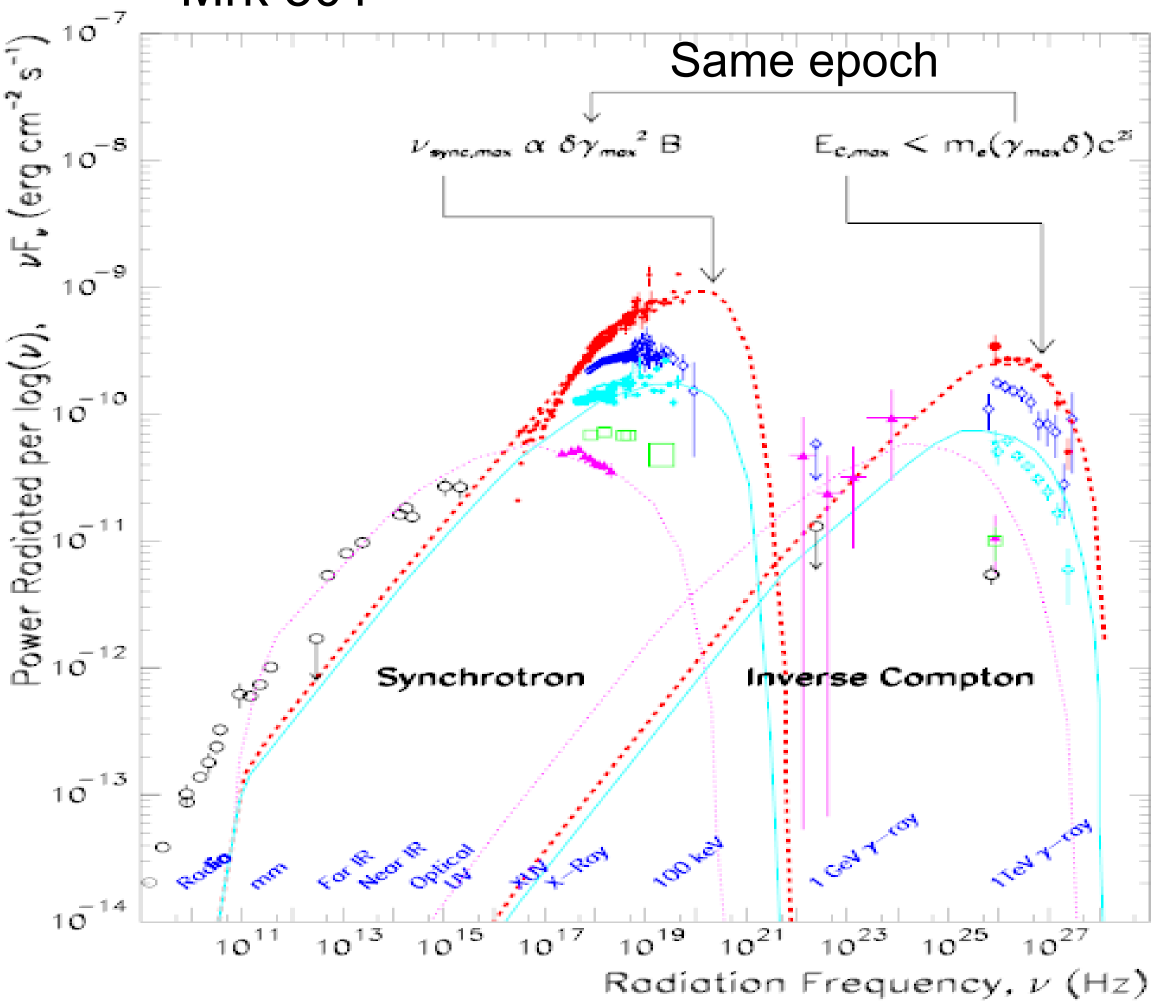




- VHE Flares are generally well correlated with X-ray flares.
- But not in this case !

Typical SED

Mrk 501

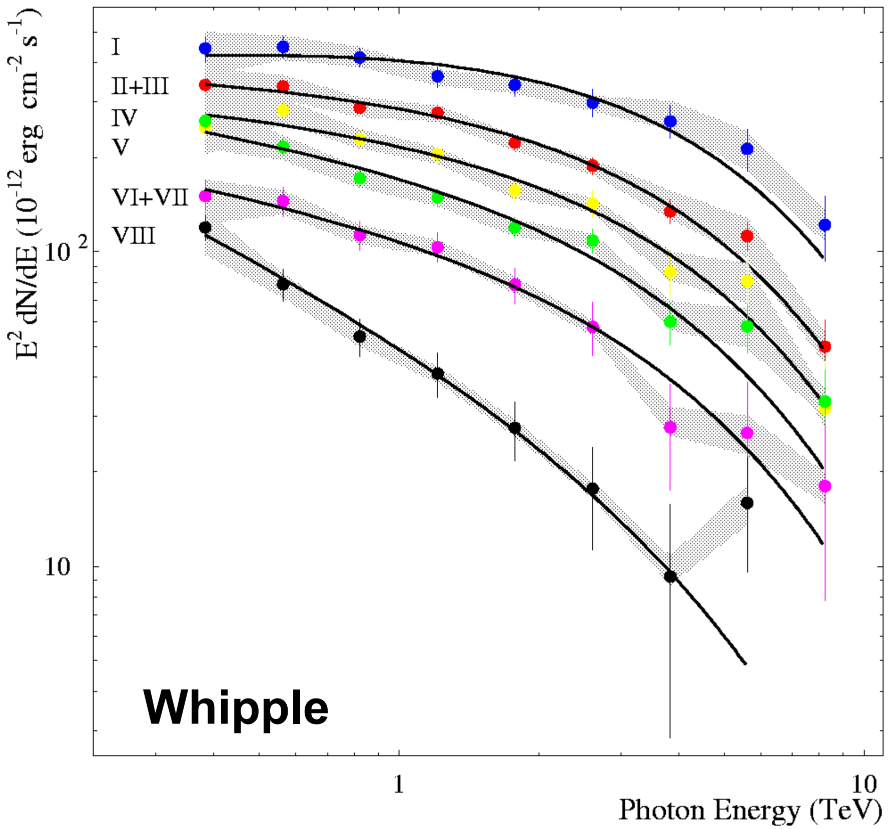


Correlation in γ-ray and X-ray variability is most easily explained in IC scenarios.

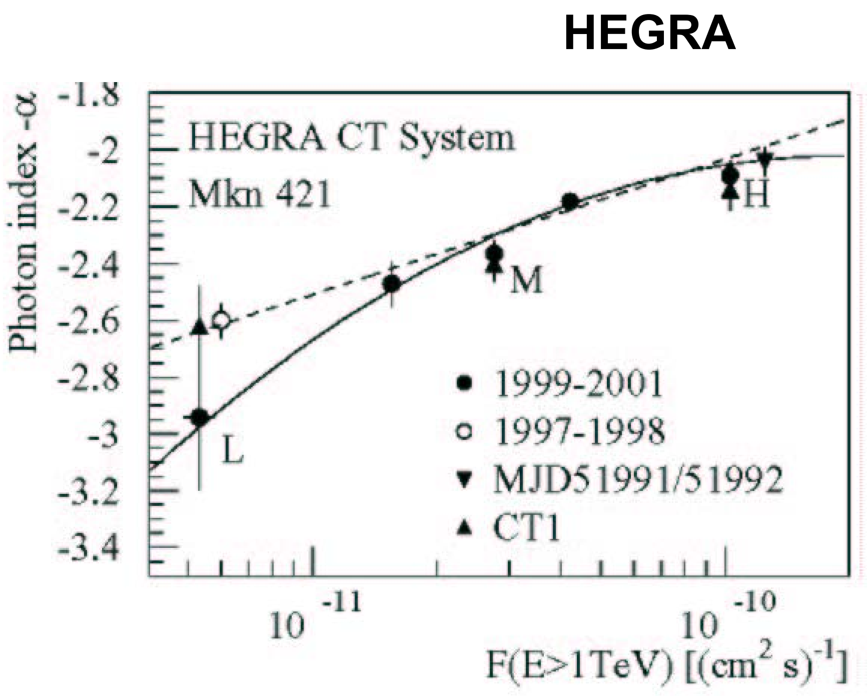
→ Same e^- population.

Additional constraints on electron energies, time scales, etc.

Spectral Variability



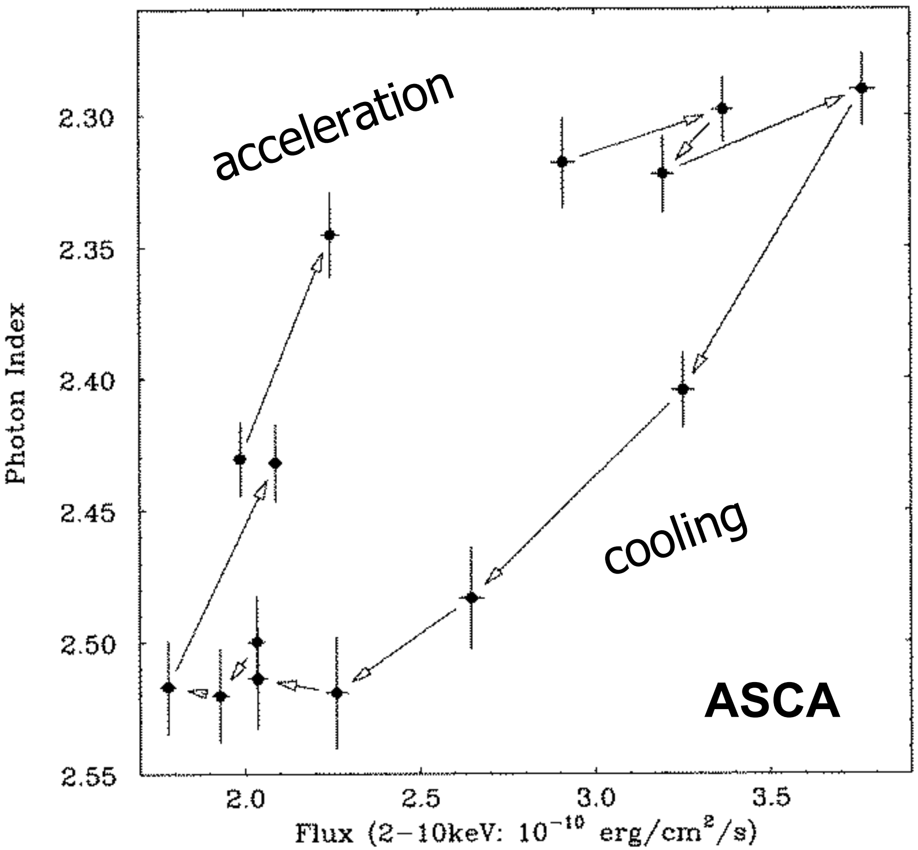
Mrk 421 2001-2



- **Spectral variability now clearly detected!**

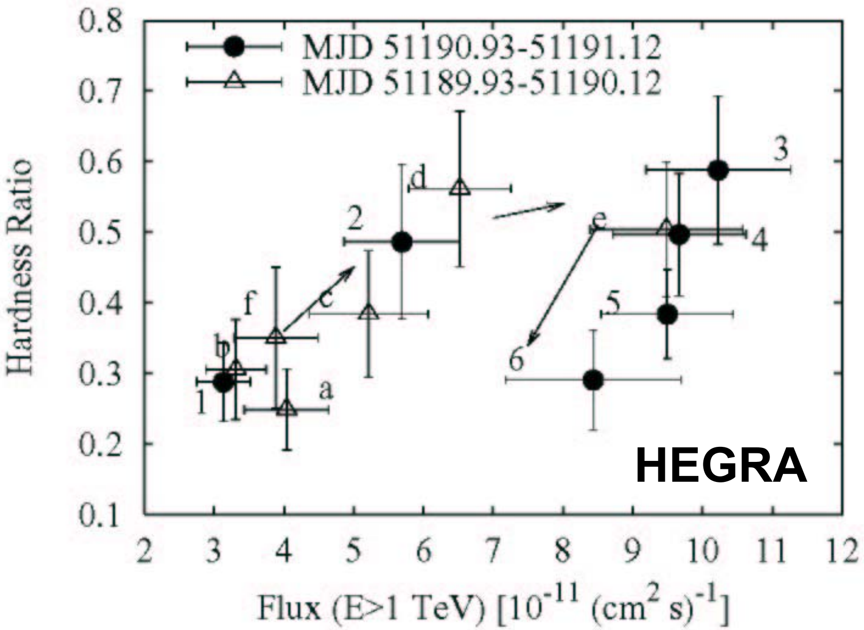
Spectral Evolution

X-ray Mrk 421



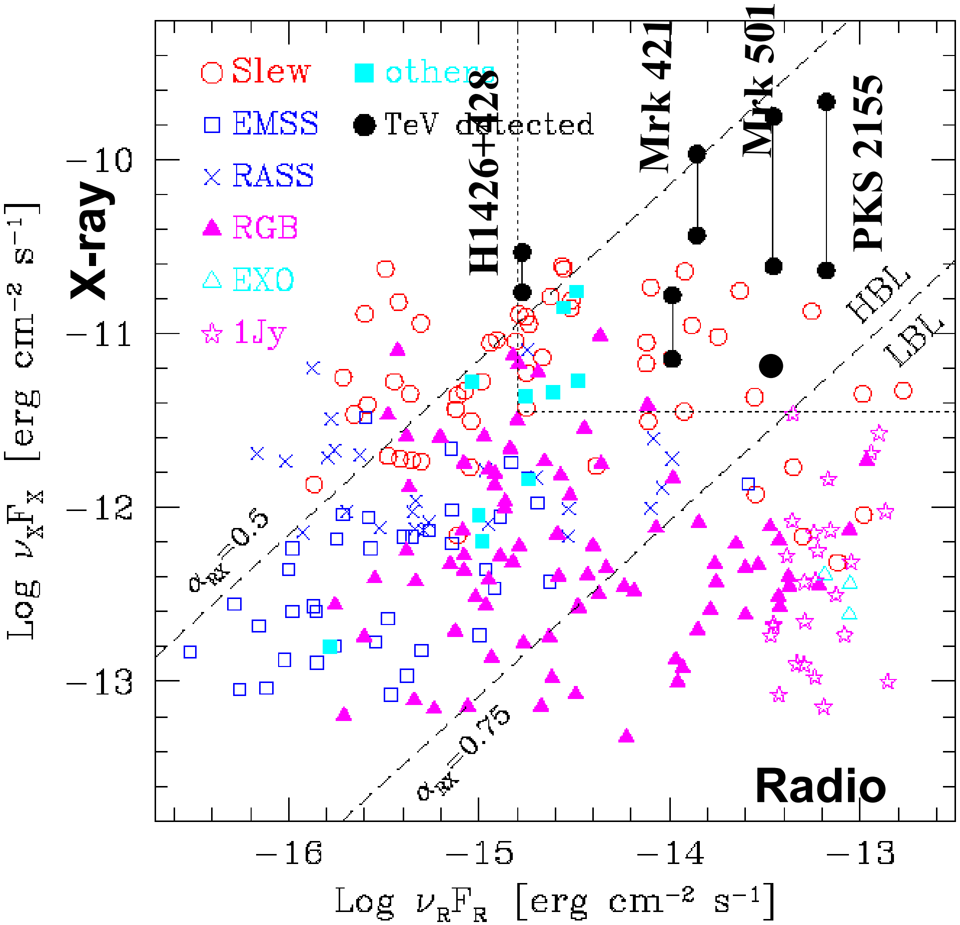
(Takahashi et al. 1996, ApJ 470 L89)

VHE γ-ray Mrk 421

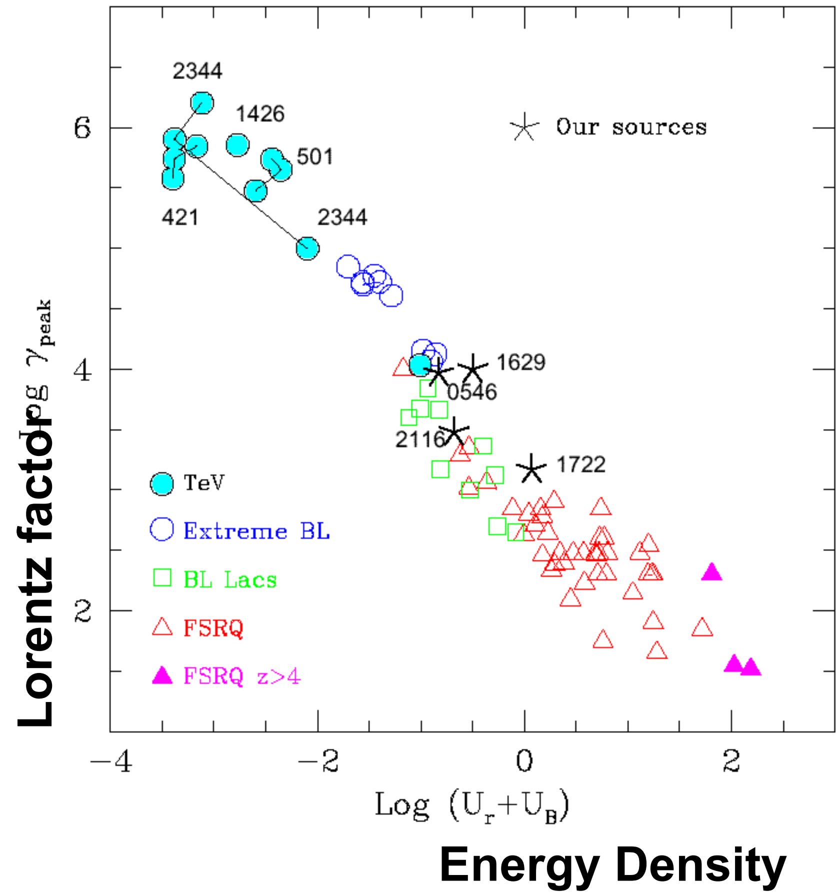


Rise and fall of flares help determine timescales: acceleration, cooling, emission size.

Understanding VHE Blazars

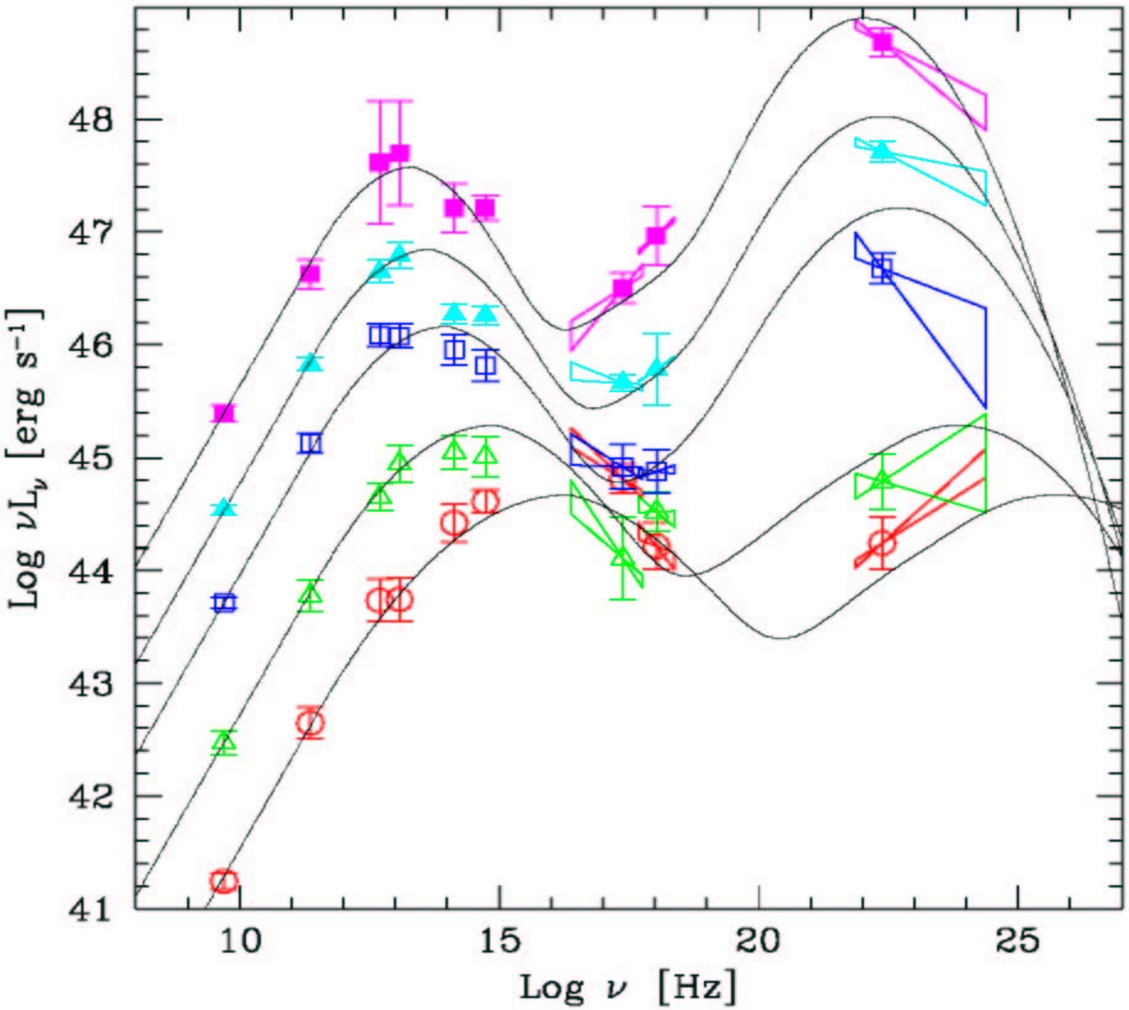


Costamante. & Ghisellini 2001, A&A, 384, 56



- Selection effects.
- Source continuum.

Understanding II – SED's



Fossati et al.:

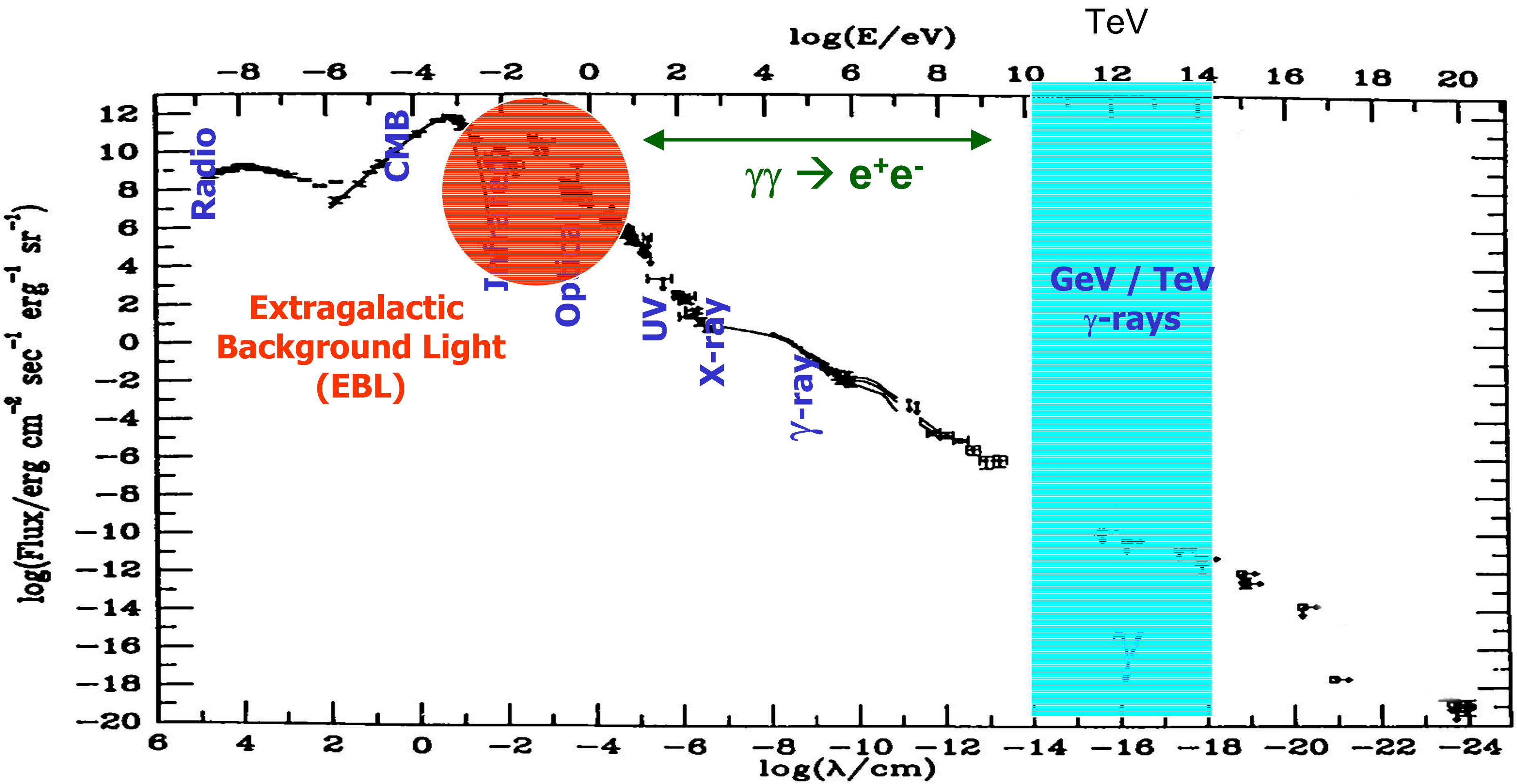
- Source families are characterized by bolometric luminosity.
- Relative components of Synch. and IC determine VHE emission or not.

General pattern – reasonable

But many questions remain !

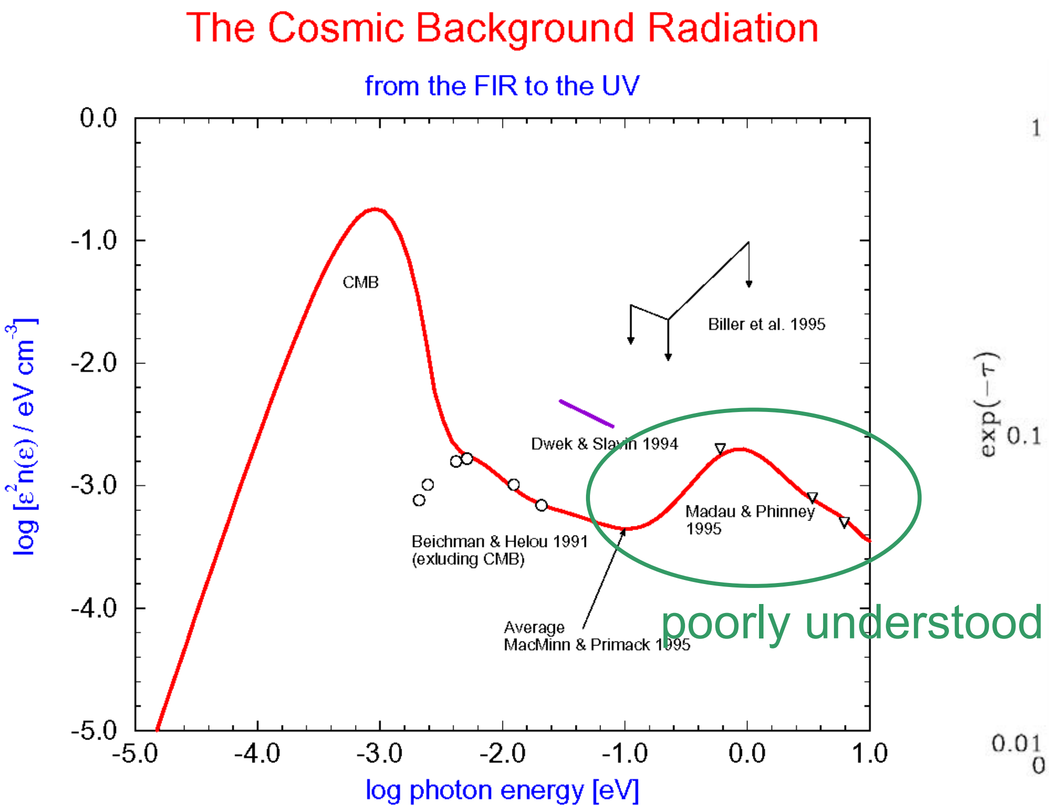
Using VHE γ-rays to Probe Intergalactic Space

VHE Cosmology

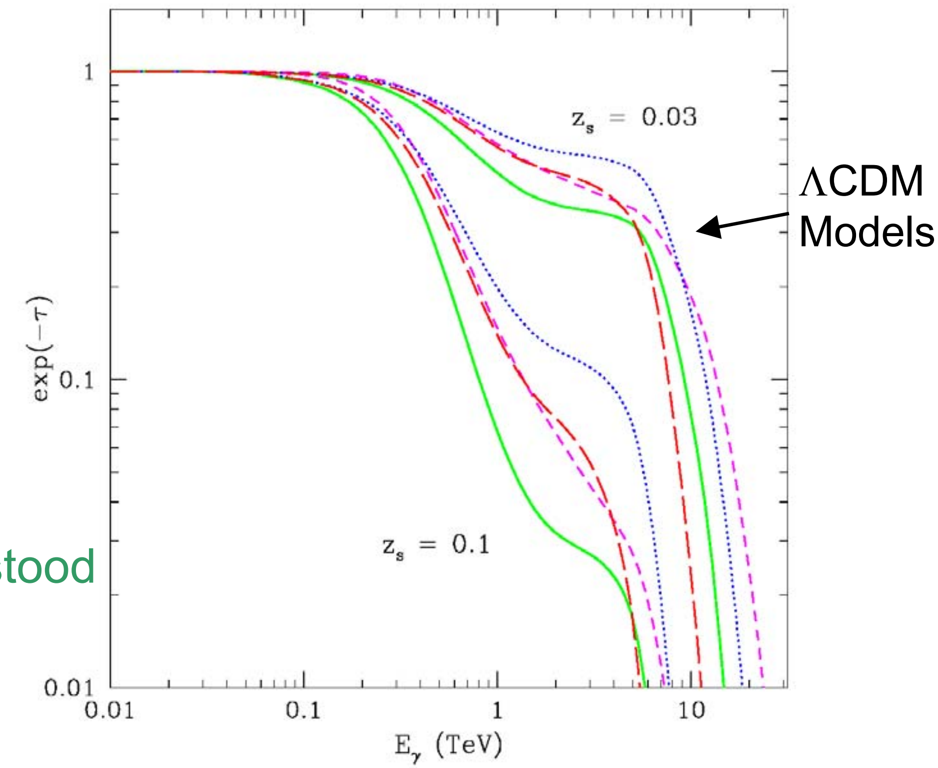


Nikishov, Gould & Schreder 1966
Stecker, de Jager, & Salamon 1994

γ-ray Absorption



Diffuse EBL



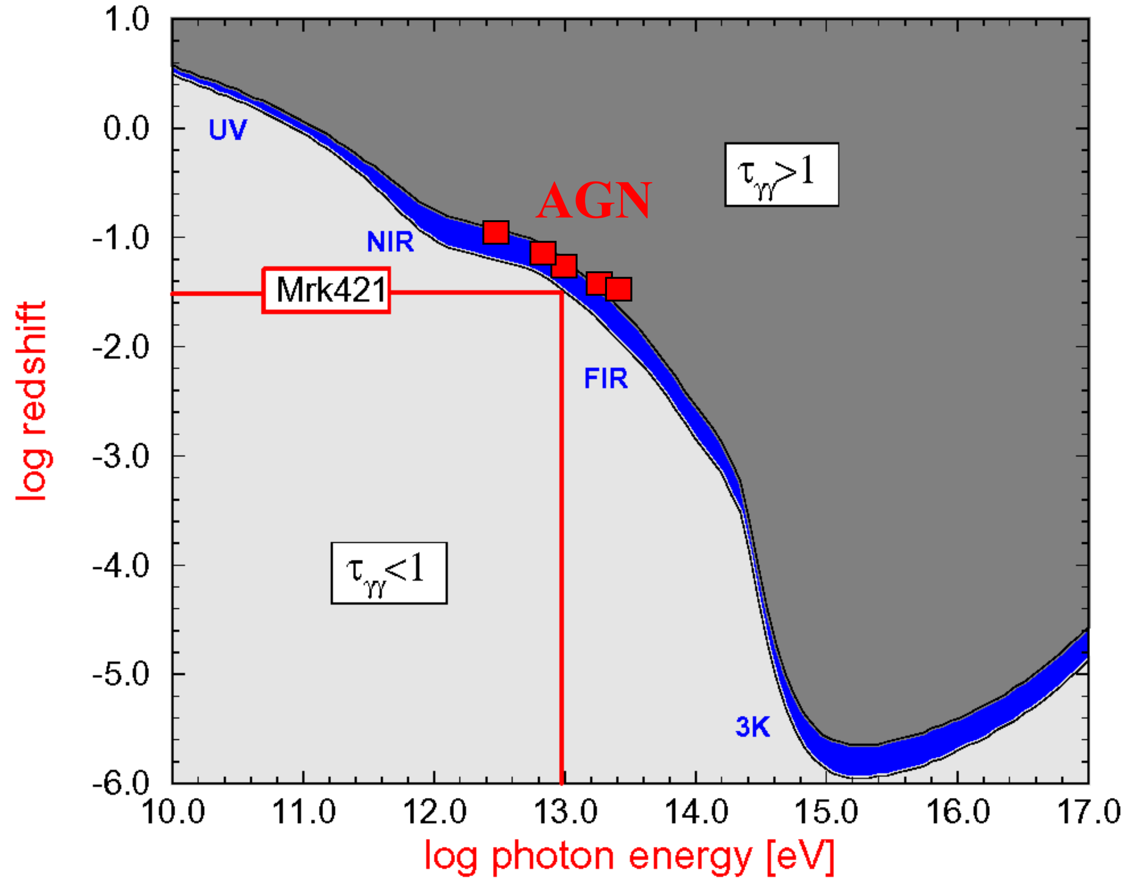
Absorption spectra
(Primack)

γ-ray Absorption

Pair-production

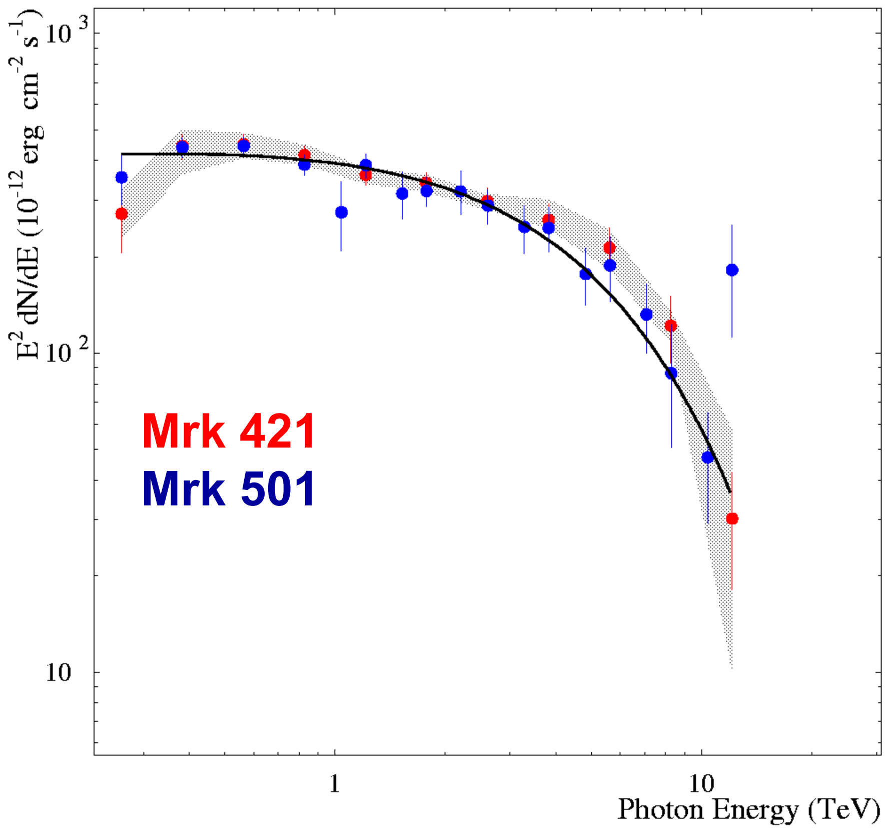
$\gamma\gamma \rightarrow e^+e^-$

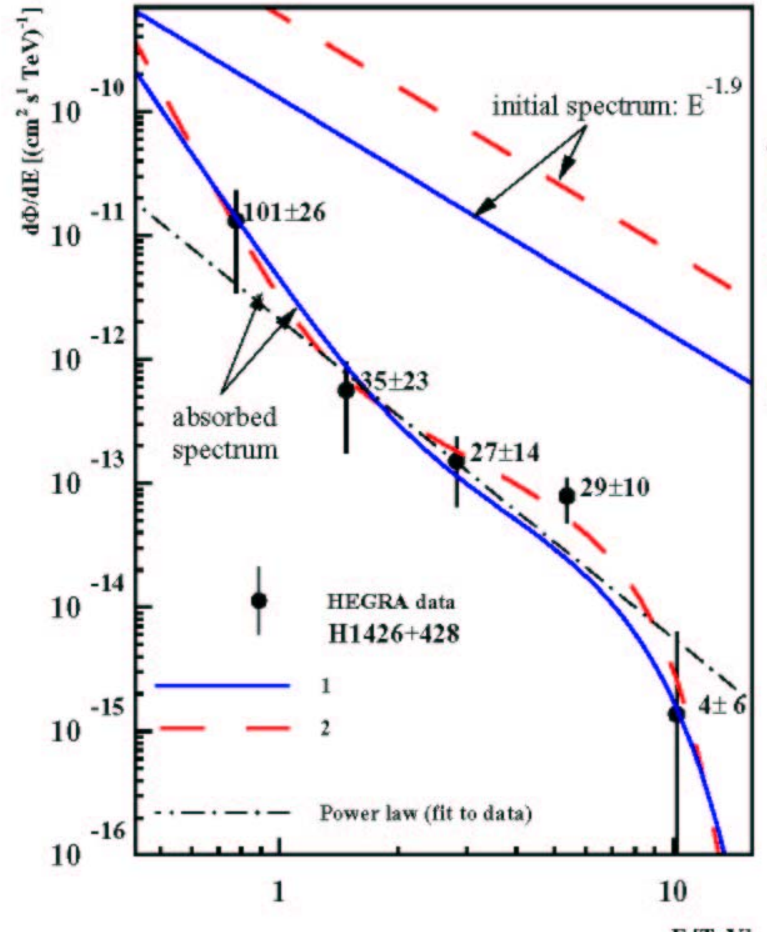
The Gamma Ray Horizon



← Satellite → ← Ground-based

Absorption Detected ?



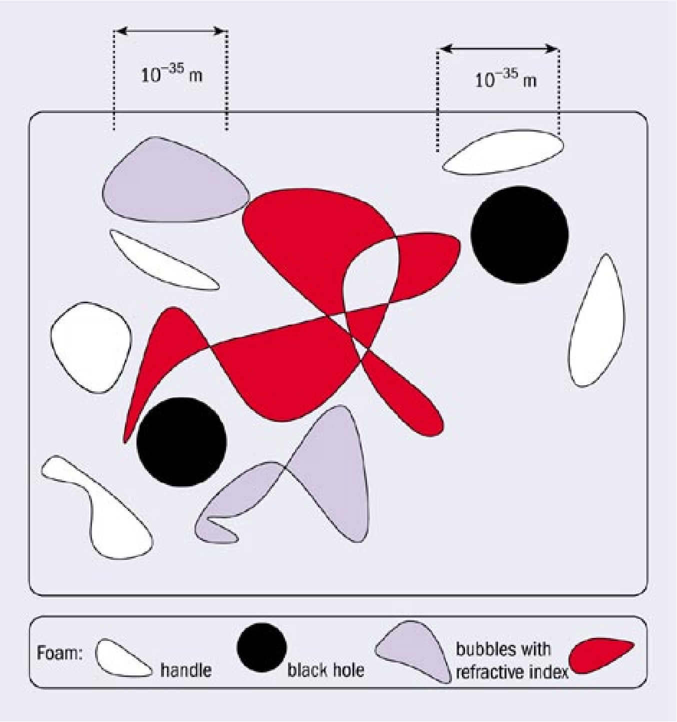


- Whipple data show similar cutoff values for two sources.
- HEGRA 1426 data. Very large uncertainties at present time.

Probing Quantum Gravity (speculative)

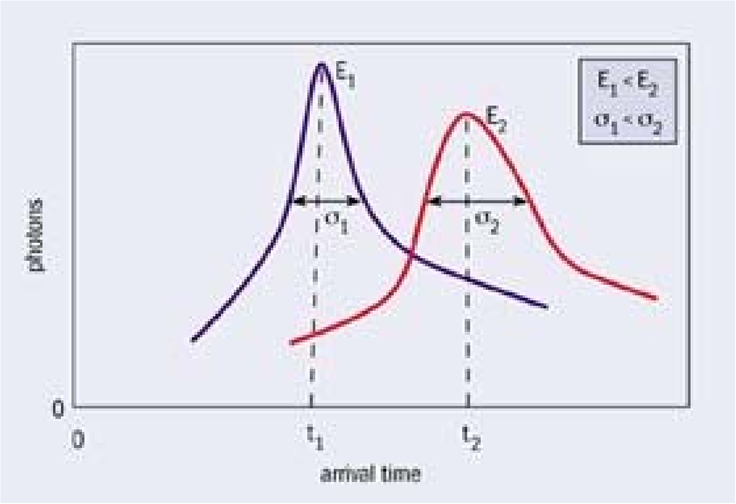
Quantum gravity:

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



γ-ray flares from AGN, GRB's:

- Time dispersion
- Very long distances
- Cumulative effect



Can probe to ~ $M_{\mathbf{Plank}}$ /10 ?

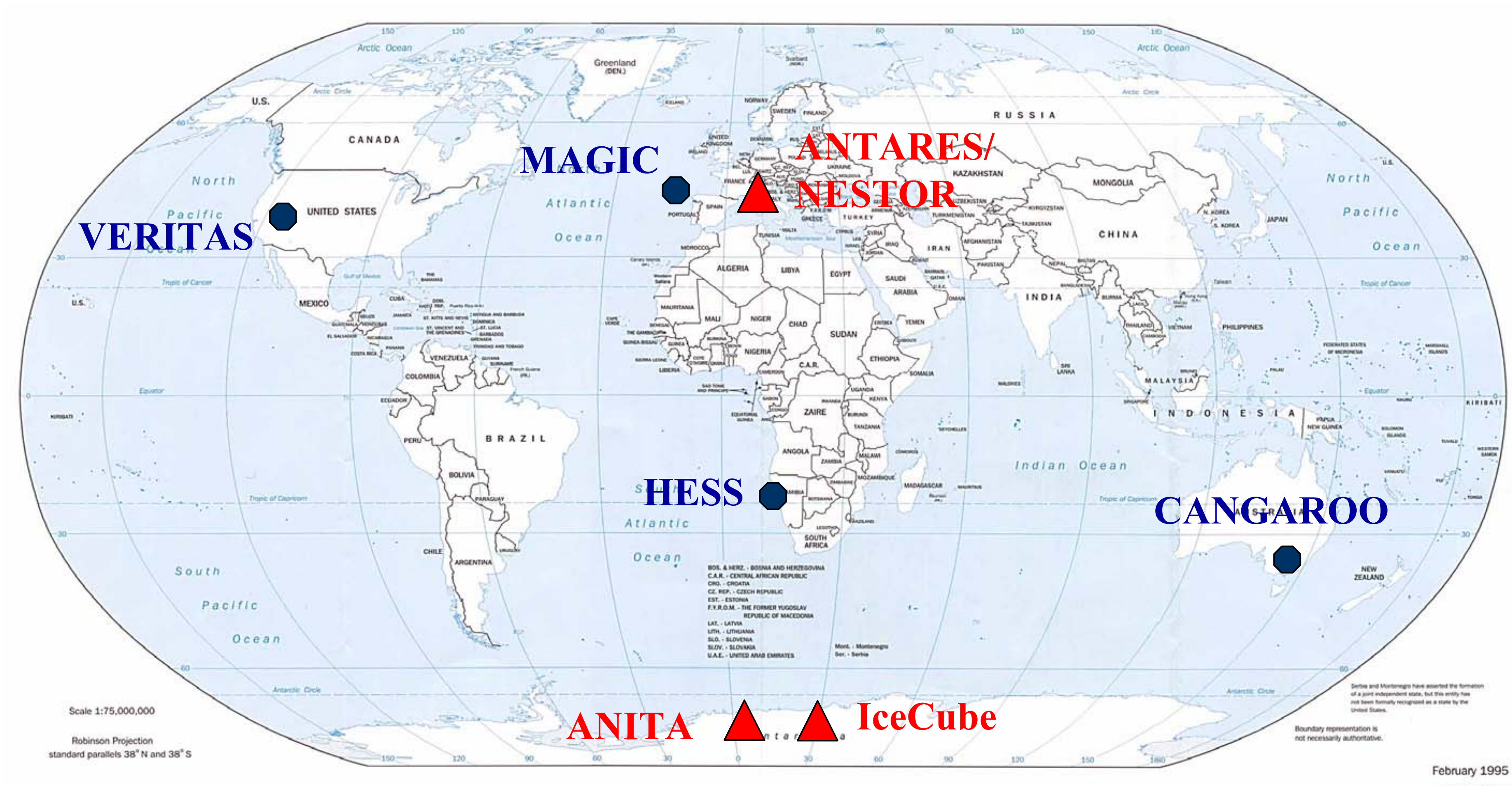
More important → testing Lorentz inv.

Future HE Telescopes

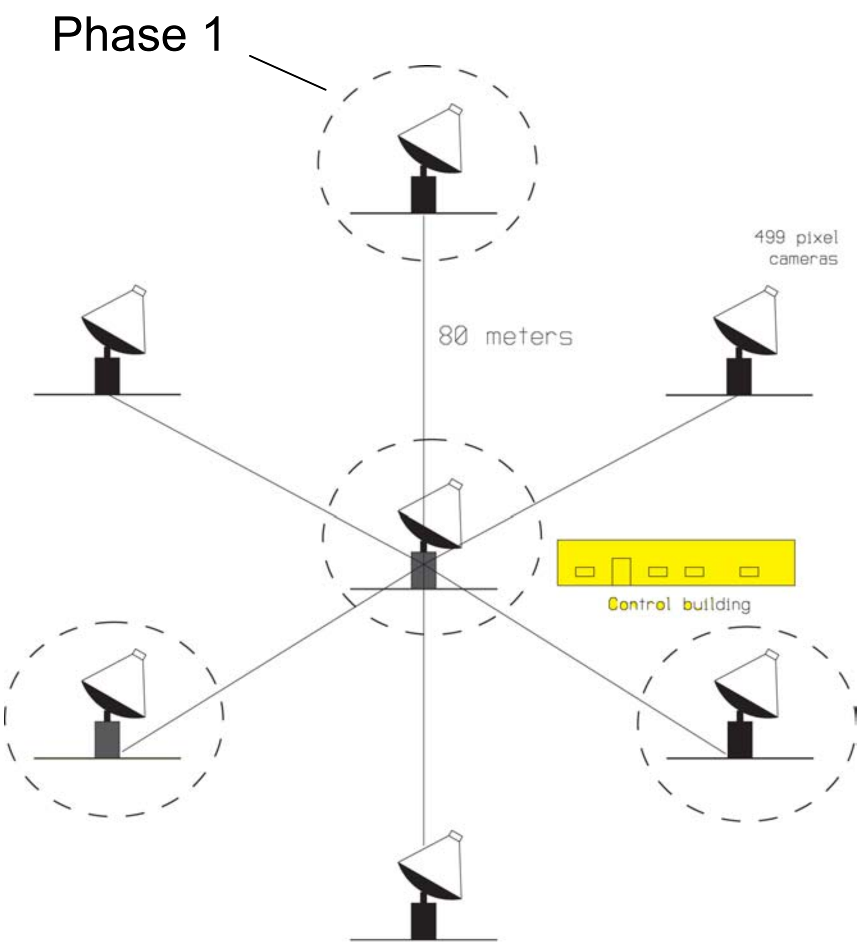
In space

● GLAST

● γ-ray telescopes
▲ Neutrino telescopes



VERITAS



Collaboration: 50 scientists from 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 History

1995: Concept study

1998: SAO/DOE proposal, SAGENAP review

2000: Decadal Survey (VERITAS in 10 mid-sized)

2001: Ritz Review – ready to go.

2002: SI & site difficulties. De-scope to Phase 1.
Blandford Review.

2003: Site issue settled (Horseshoe Canyon, Kitt Peak)
Construction funds start.

(2006:) Phase 1 operations begins (4 Telescopes).

VERITAS – Well Underway

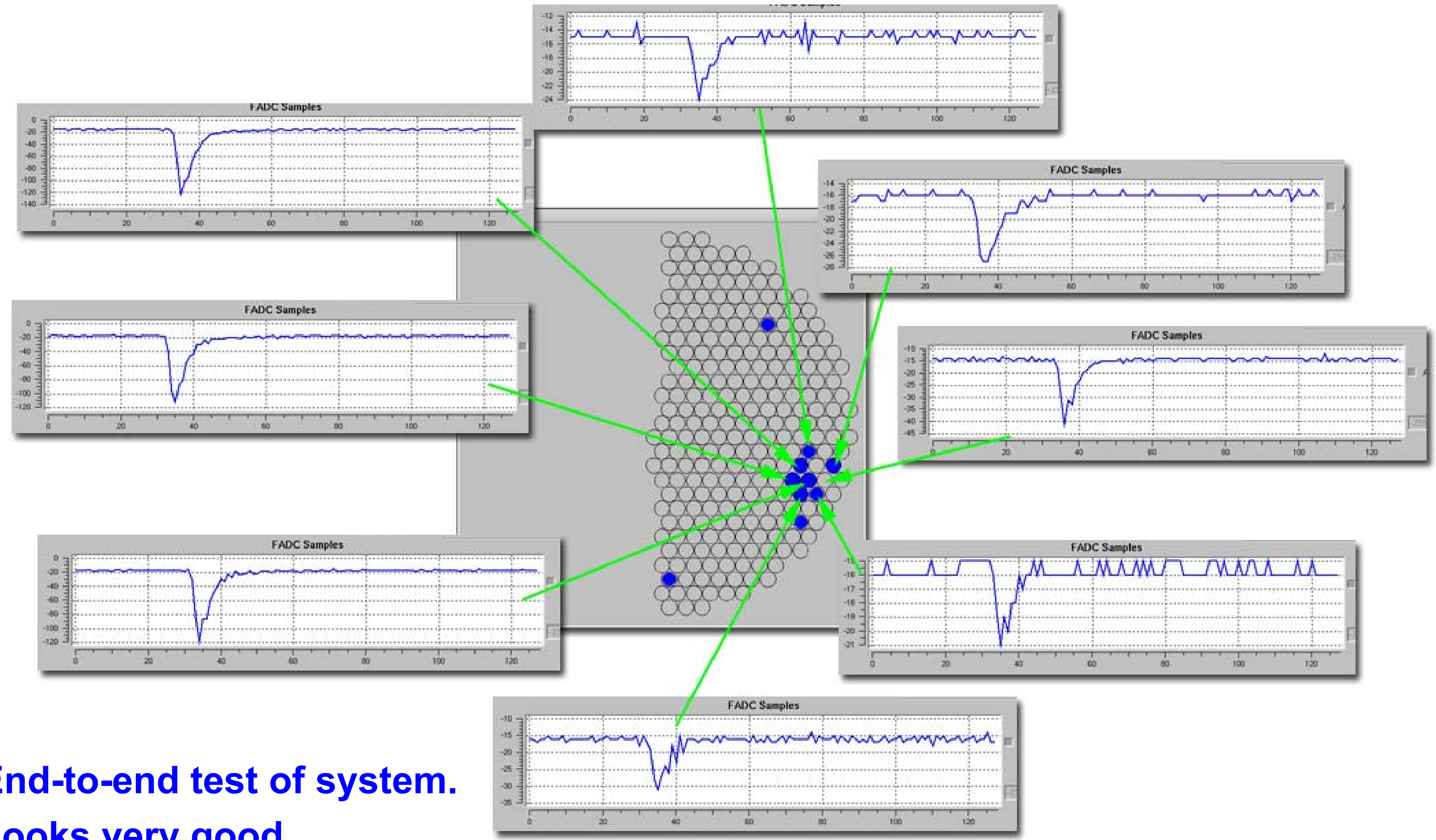
Electronics trailer

500 MHz FADC

Telescope 1:

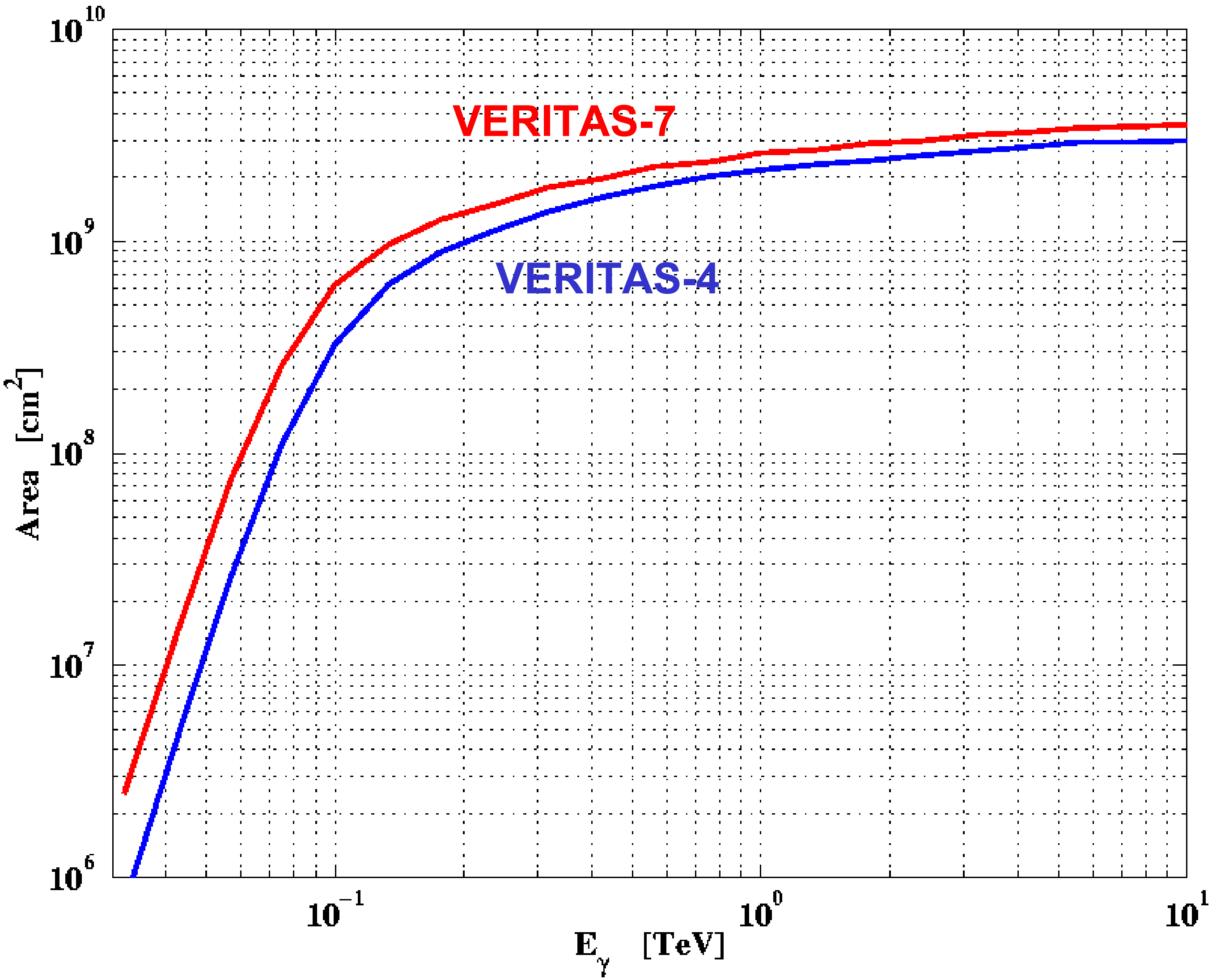
- All systems tested.
- Operational in spring 2004.

VERITAS – 1st Cherenkov Images



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

VERITAS Effective Area



VERITAS-4:

100 GeV - 3.3×10^8 cm^2
1 TeV - 2.2×10^9 cm^2
10 TeV - 3.0×10^9 cm^2

Trigger:
3 out of 4 telescopes
Pixel threshold– 5.6 pe

Main impact of seven telescopes is in flexibility.

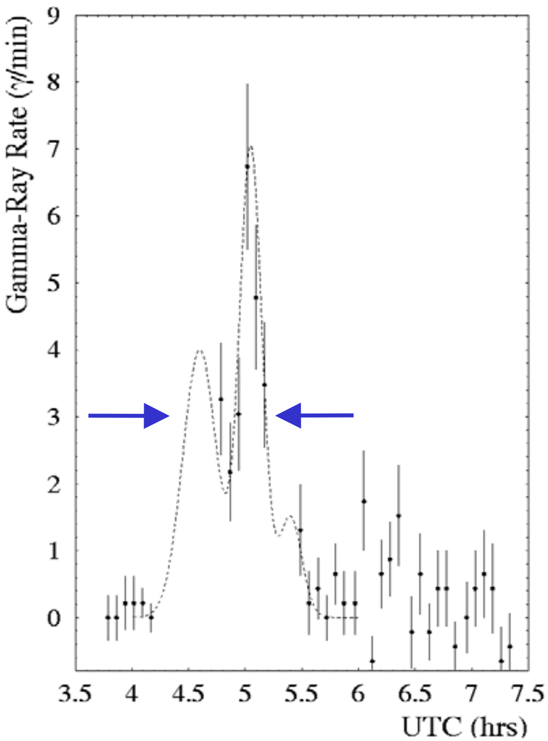
Telescope Characteristics

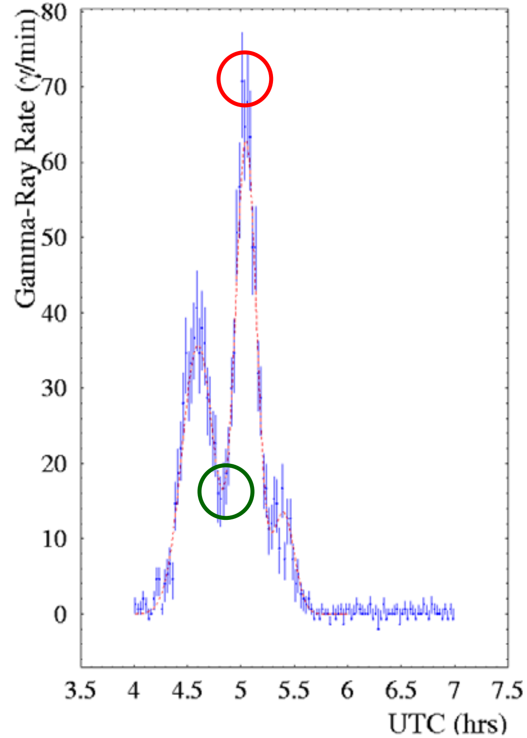
	Existing Instruments		c2006
Parameter	**Wavefront (STACEE)**	**Sing. Imager (Whipple)**	**Array Imager (VERITAS-4)**
Mirror Area	64 x 37m^2	1 x 80 m^2	4 x 110 m^2
E (peak)	75 GeV	350 GeV	110 GeV
FOV	0.75^o	3.5^o	3.5^o
P rejection	~ 50	~ 300	~ 5,000
Energy Res.	~ 40%	~ 25%	~10%
Ang. Res.	0.25^o	0.20^o	2′ – 5′
Crab rate (γ/min)	~ 5	~ 2	~ 35

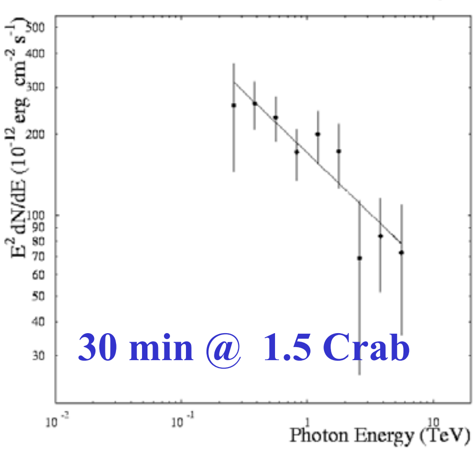
VERITAS Performance

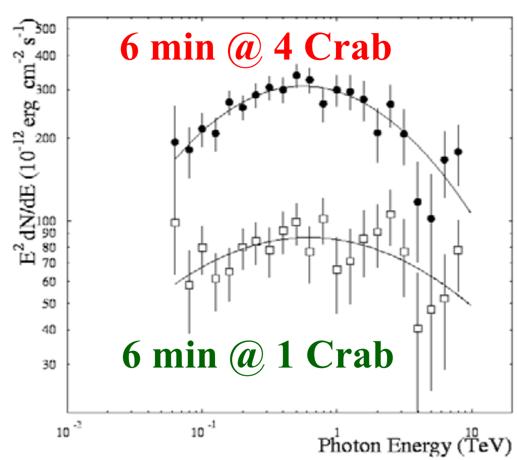
	VERITAS-4 Performance		
Operating Conditions	4 x 112 m^2 mirrors Trigger (tel): 3 pixels > 5.6 pe Trigger (array): 3 of 4 telescopes		
Peak Energy	110 GeV		
Crab Nebula Rate	35 gamma rays per minute		
Energy	Collecting area	Angular Res	Energy Res
100 GeV	3.3×10^4 m^2	8.6 arc-min	< 25%
1 TeV	2.2×10^5 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}		

Variability Performance





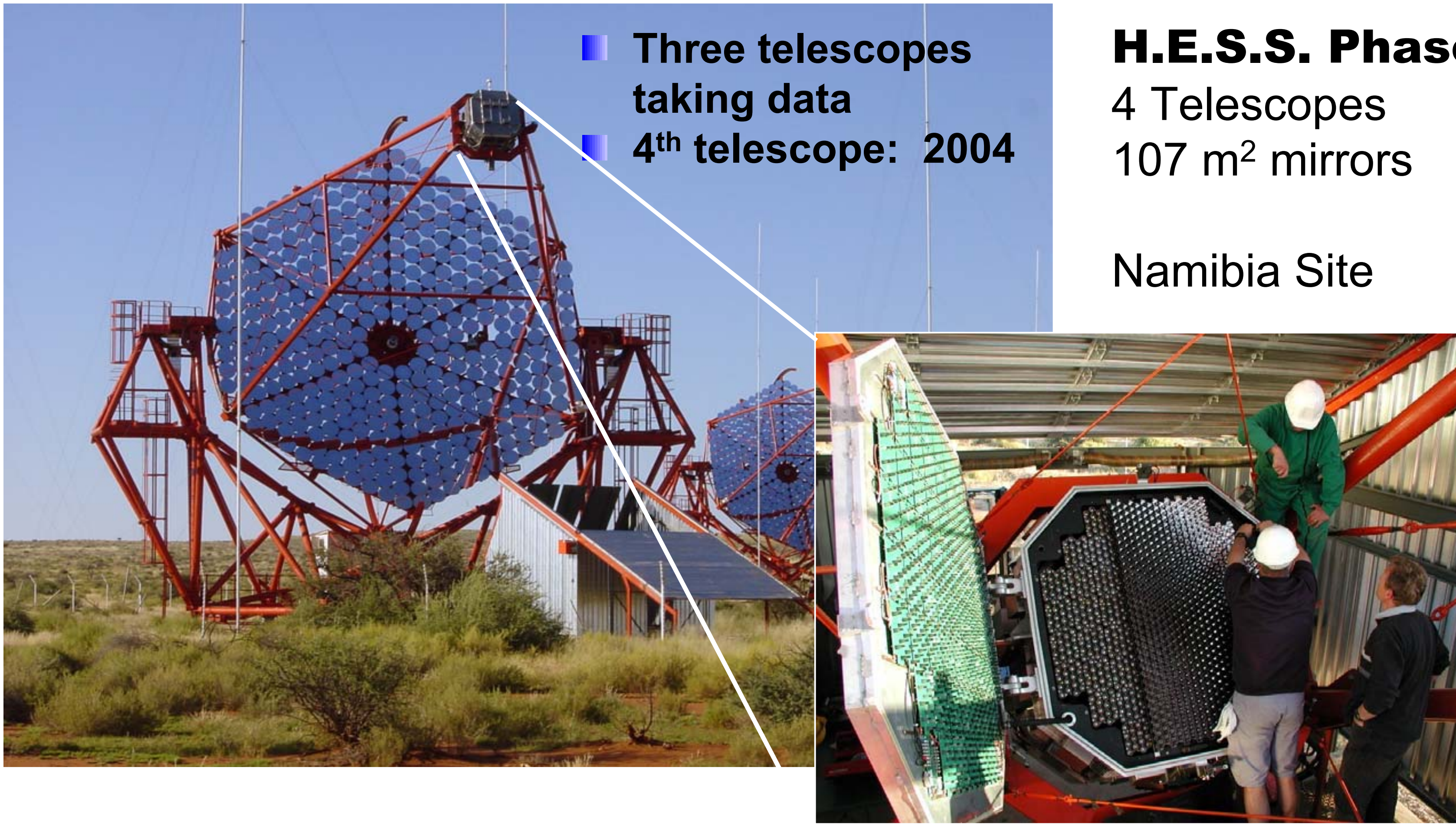




VERITAS:

- has hour-scale sensitivity for time-resolved spectral measurements.
- can probe intrinsic variability timescales; distinguish between
  - external absorption
  - intrinsic curvature
    - (variable)

HESS Telescope

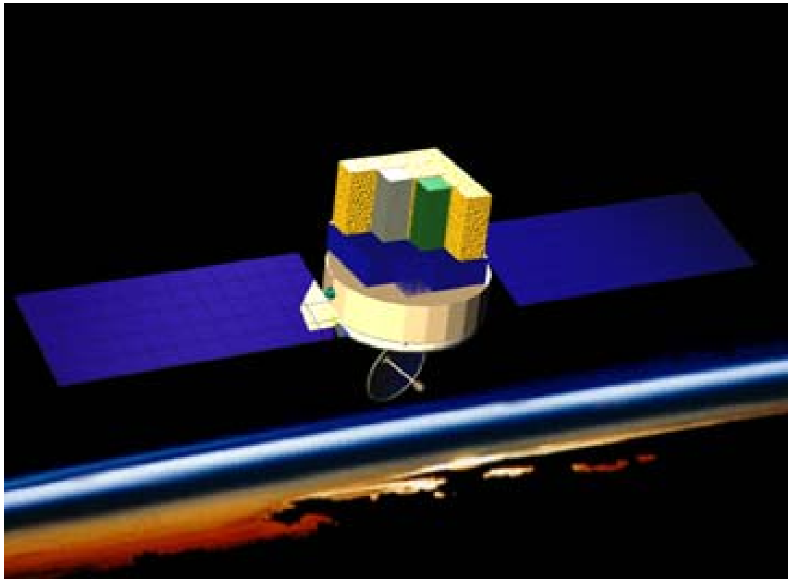


- **Three telescopes taking data**
- **4^{th} telescope: 2004**

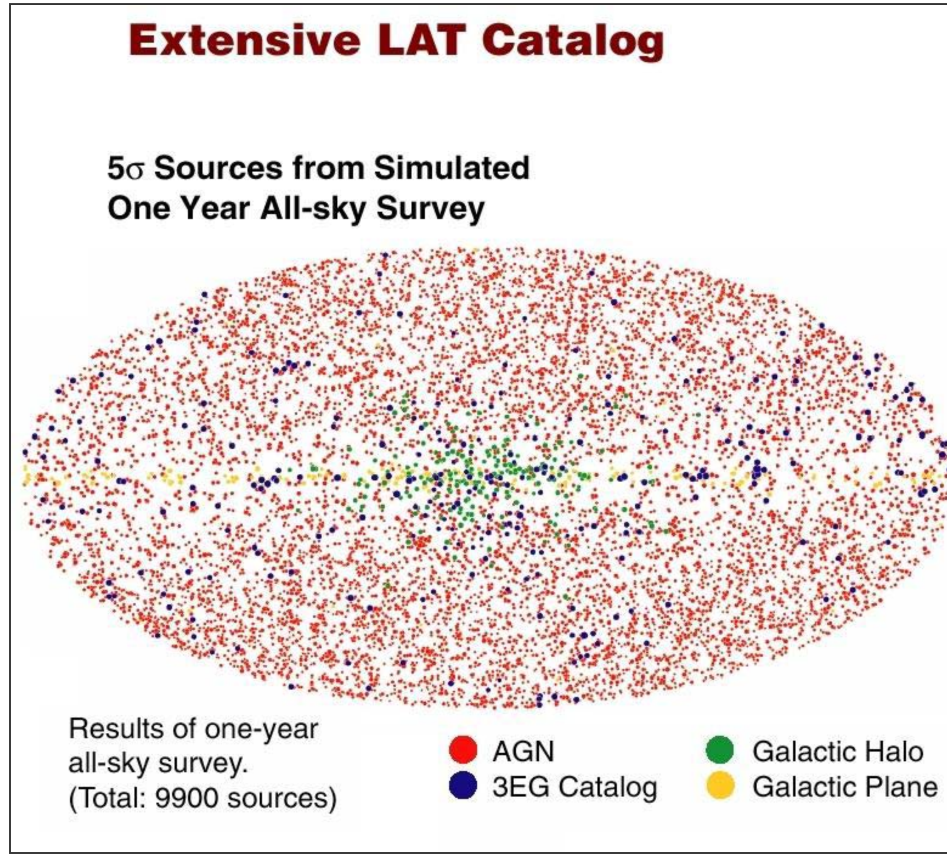
H.E.S.S. Phase I
4 Telescopes
107 m^2 mirrors

Namibia Site

GLAST – Satellite Telescope



GLAST LAT Instrument:
- Si tracker
- CsI calorimeter
- Anti-coincidence veto



Sky map from 1 year survey

Launch in 2006.

SUMMARY

- VHE γ-ray astronomy is developing rapidly.
- We have made detailed studies on half-dozen blazars – data are getting quite good – seriously testing our understanding of jet processes.
- Important topic not discussed here is GRB's – great potential for new discovery.
- Next generation telescopes will be much more sensitive and versatile. More sources (40-50 new AGN/hemisphere), superb sensitivity for short transients and weak sources.

Becoming a bona-fide field of astronomy.