HIGH ENERGY GAMMA RAYS

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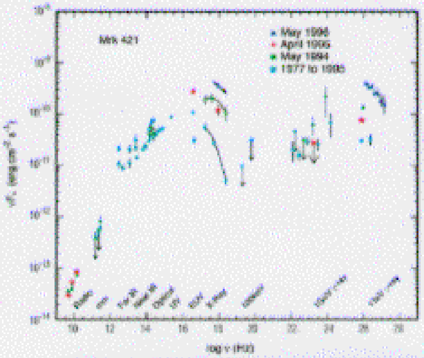
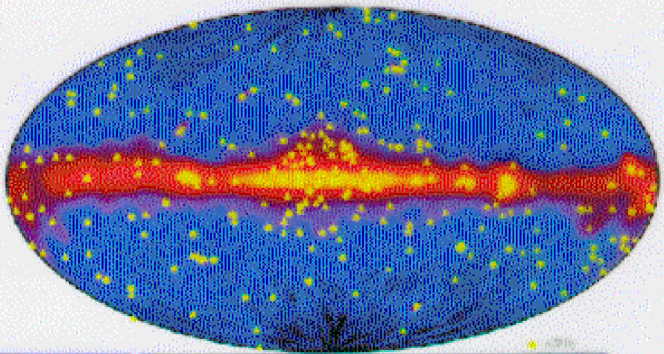
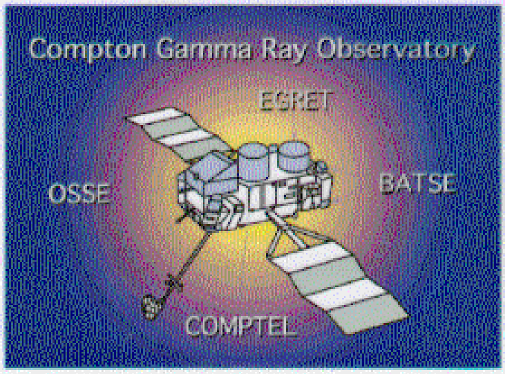
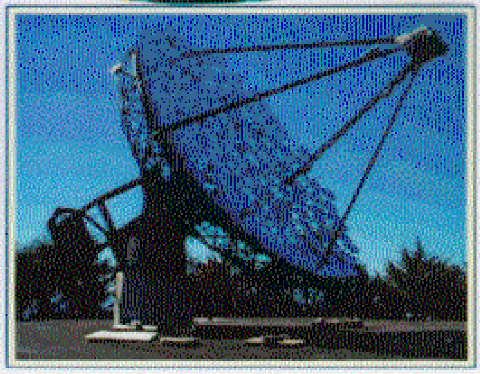








OUTLINE:

- Broad overview
- Scientific motivation
- Experimental techniques
- Results
- Future experiments

NEUTRINO 2000 , SUDBURY, 21 JUNE 200

OVERVIEW

Four "messengers" tell us about the Universe outside the Solar System:

- 1. Light
- 2. Cosmic Rays
- 3. Neutrinos
- 4. Gravity Waves

1. Cornerstone of Astronomy - Historical expansion of astronomy from optical light to new wavebands

2. High energy processes occurring in our Galaxy

3. & 4. Relatively difficult to detect –
But great astronomical potential

In the future: Multiple messengers providing complementary information

This talk will summarize what we know about the high energy Universe using light at energies 30 MeV - 20 TeV.

Why is high energy Astrophysics interesting?

- Exploratory, but rapidly developing phase.

- Astrophysical situations in which physics operates under extreme conditions - e.g. intense gravitational or magnetic fields.

- AGN studies: Extremely luminous, powered by gravitational potential contained in supermassive blackholes.

- Origin of $> 10^{17}$ eV cosmic rays is still a mystery. Are AGN sites of cosmic ray acceleration?

- γ-rays could be used as probes for interstellar radiation fields.

- Probe novel astrophysical phenomena which could arise as a result of new physics beyond the standard model of particle interactions.
  – Search for dark matter in the form of WIMPs through their characteristic annihilation radiation

- Progress in the last ~ 10 years has put the field of high energy γ-ray astronomy on a solid foundation.

Compton Gamma-Ray Observatory.

Ground-based VHE experiments

Particle Astrophysics

- Probe novel astrophysical phenomena which could arise as a result of new physics beyond the standard model of particle interactions.

- Eg: Widely believed that our galaxy is immersed in dark halo that outweighs the luminous components by ~ order of magnitude.

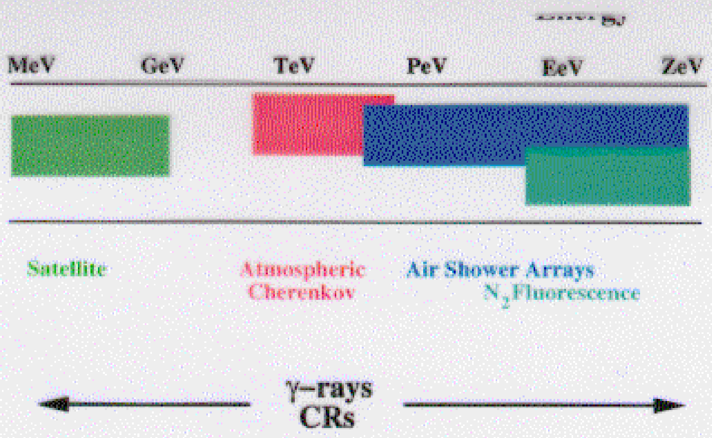
- Nature of dark matter is one of the greatest mysteries in particle astrophysics.

- One leading candidate for dark matter - WIMPs.

- For e.g. – in super symmetric extensions of the SM, the particle could be a neutralino – a linear combination of the SS partners of the photon, Z0 and Higgs bosons.

- Most plausible models of WIMP mass $\sim 10 - 300$ GeV.

- If WIMPs exist in the Galactic halo - could annihilate and produce photon of energies ~ WIMP mass.



- **High Energy Astrophysics:**

30 MeV – 10 GeV.

EGRET ≡ Energetic Gamma Ray Experiment Telescope.

What have we learnt?

- **Very High Energy observations with current TeV telescopes ($>$ 250 GeV):**

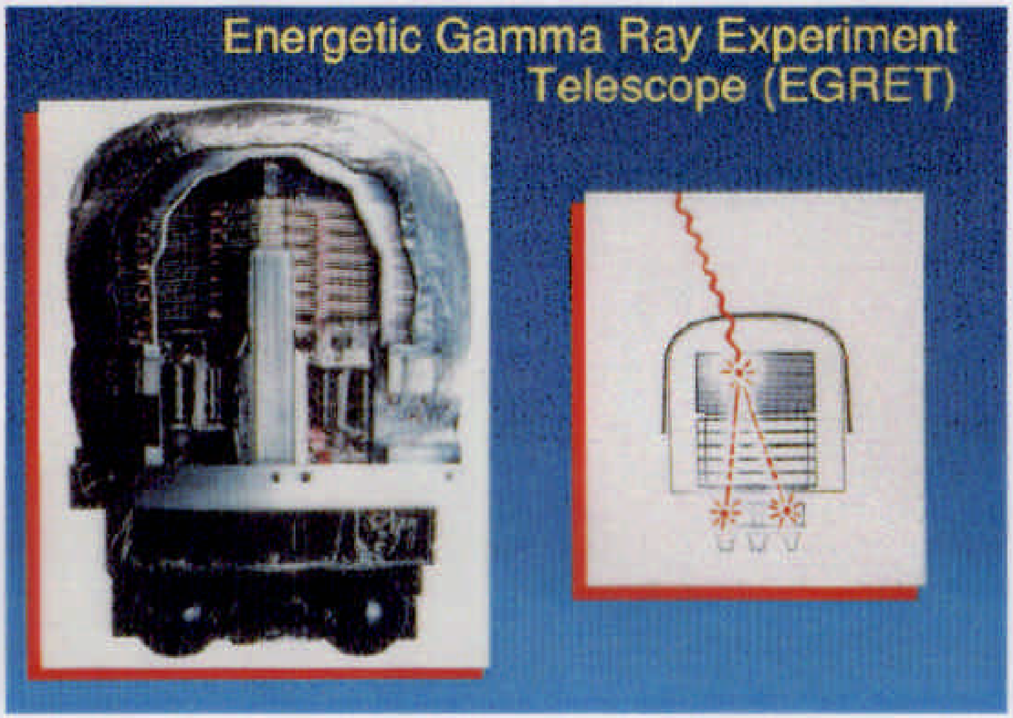
What is the connection with the EGRET results?

- **Future Observations: Ground based instruments in the 20-250 GeV range.**

What is the scientific motivation?

Current status in development.

EGRET PARAMETERS

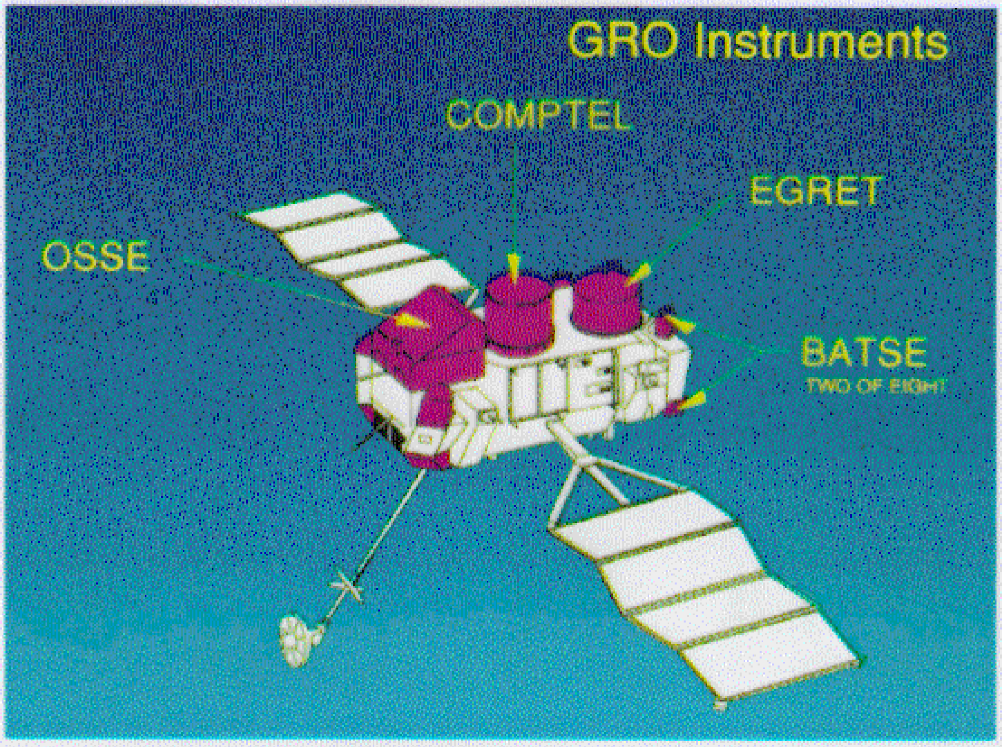


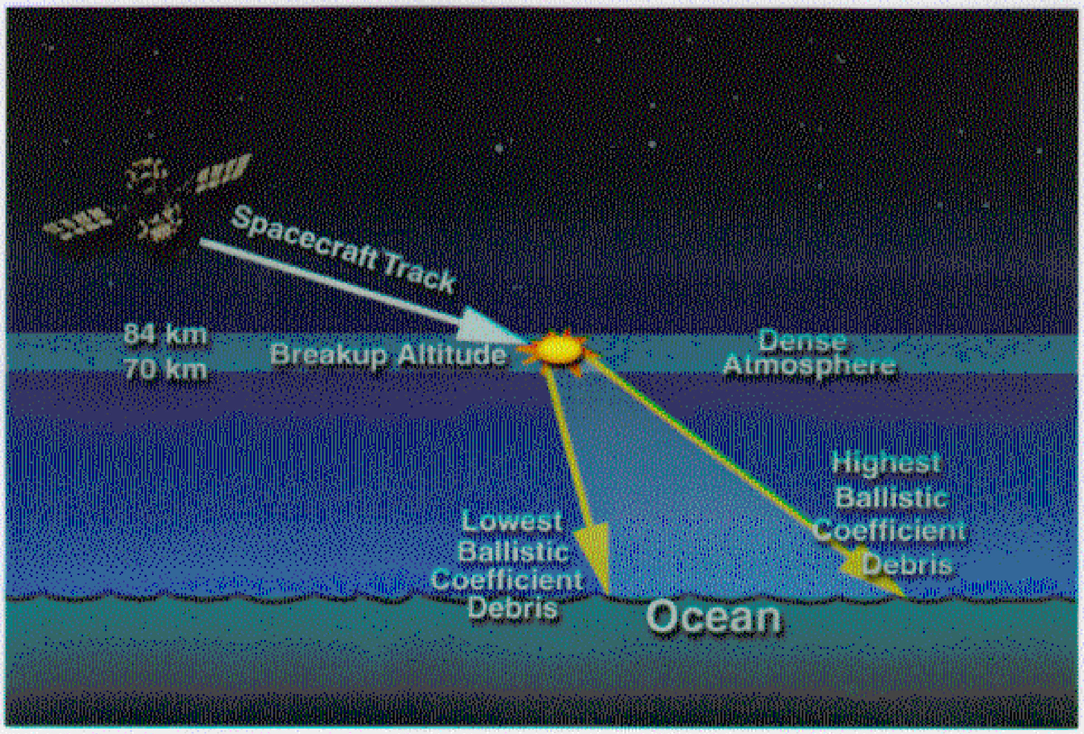
Energetic Gamma Ray Experiment Telescope (EGRET)

- Energy range 30 MeV – 30 GeV.
- At < 70 MeV: PSF deteriorates.
- At high energies better psf and energy res., but only a few photons detected > 5 GeV.
- Ang. resolution: 8° @ 60 MeV, 0.4° @ 3 GeV.
- Threshold sensitivity: $\sim 1 \times 10^{-7}$ ph cm^{-2} s^{-1}.
- Large FOV: $\sim 40^\circ$.

Compton Gamma-Ray Observatory

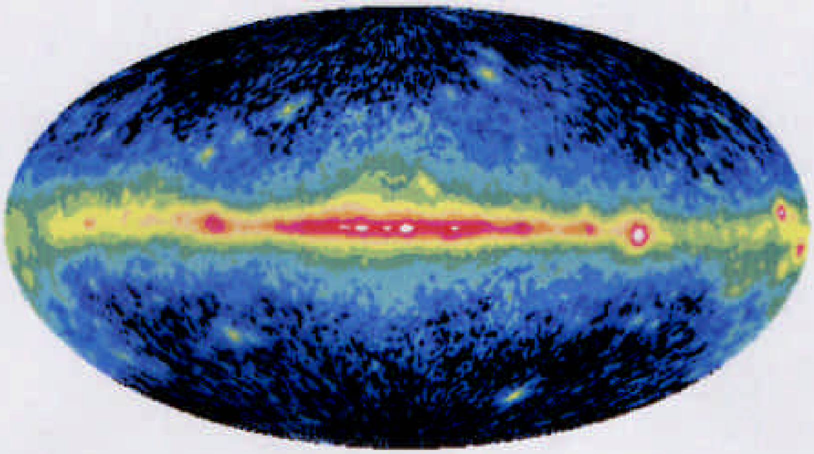
1991 – 2000

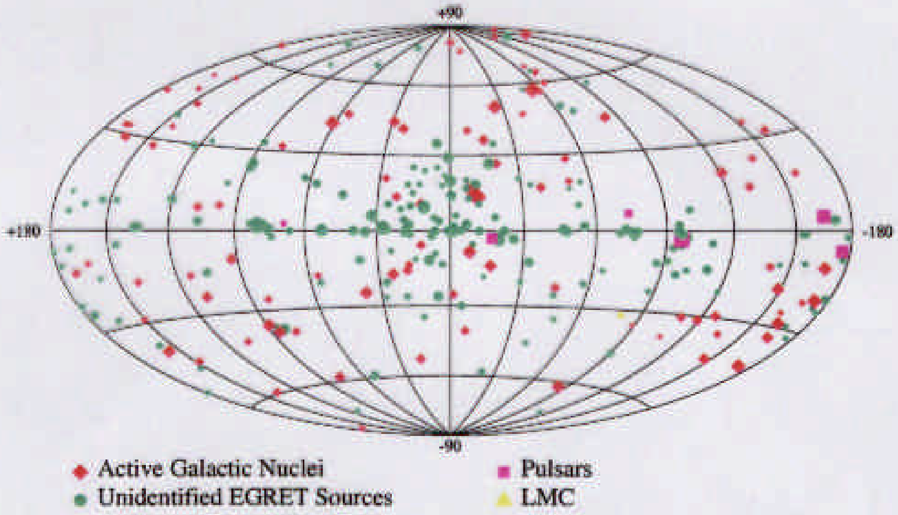




CGRO re-entry into Earth's atmosphere – 2:10 am EDT, June 4, 2000

EGRET SOURCES



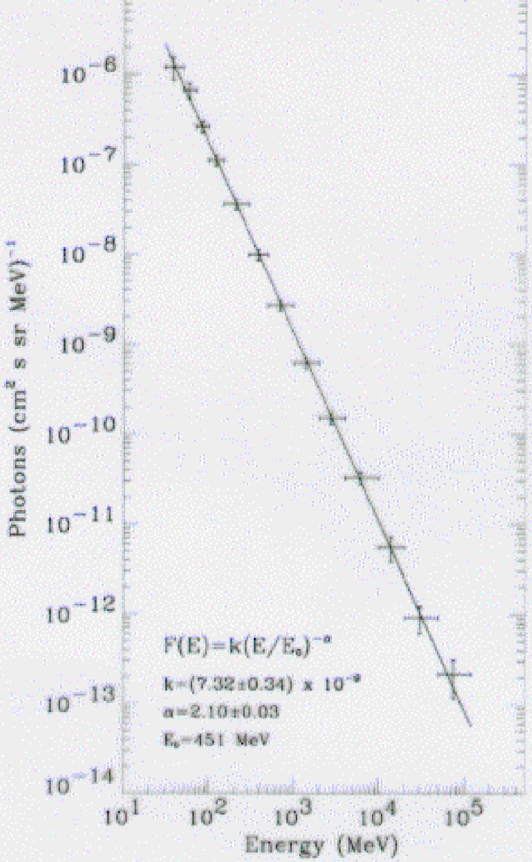


Source count (Hartman et al. July 1999, ApJS)

Source class	$\# > 5\sigma(> 4\sigma)$	other references
blazars	67 (94)[1] (35%)	Mukherjee et al. 1997
pulsars	6 (2%)	Thompson et al. 1997
unidentified	170 (62%)	Hartman et al. 1998

[1]: 27 blazars have “marginal” identifications.

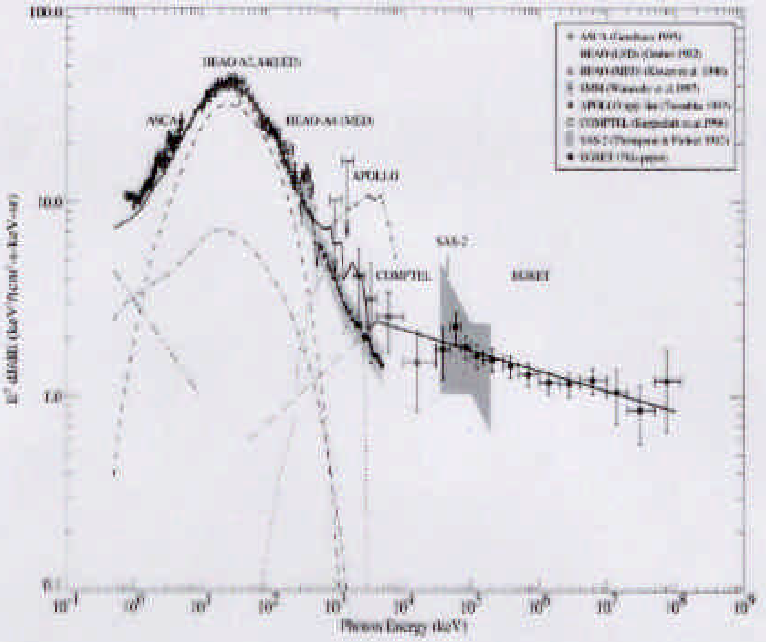
Extragalactic Gamma-Ray Background



Sreekumar et al. 1998

- **EGRET** observations show the presence of an extragalactic diffuse emission above 30 MeV
- A single power law spectrum (-2.1 ± 0.03) characterizes the emission from 30 MeV to 100 GeV
- Precise origin of the emission is not fully resolved

Origin of the Extragalactic γ-Ray Background



The extragalactic γ-ray background above 10 MeV is presumably made up of a combination of diffuse origin + unresolved sources

- **Various theories of diffuse origin (Sreekumar et al. 1998)**

- **Gravity-induced shock waves → highly relativistic electrons which scatter microwave background photons (Loeb & Waxman 2000 – astro-ph)**

Unresolved sources:

- **AGN (1-100 GeV) (Stecker & Salamon 1996 (100%); Chiang & Mukherjee 1998 (25%); Mücke & Pohl 1998)**

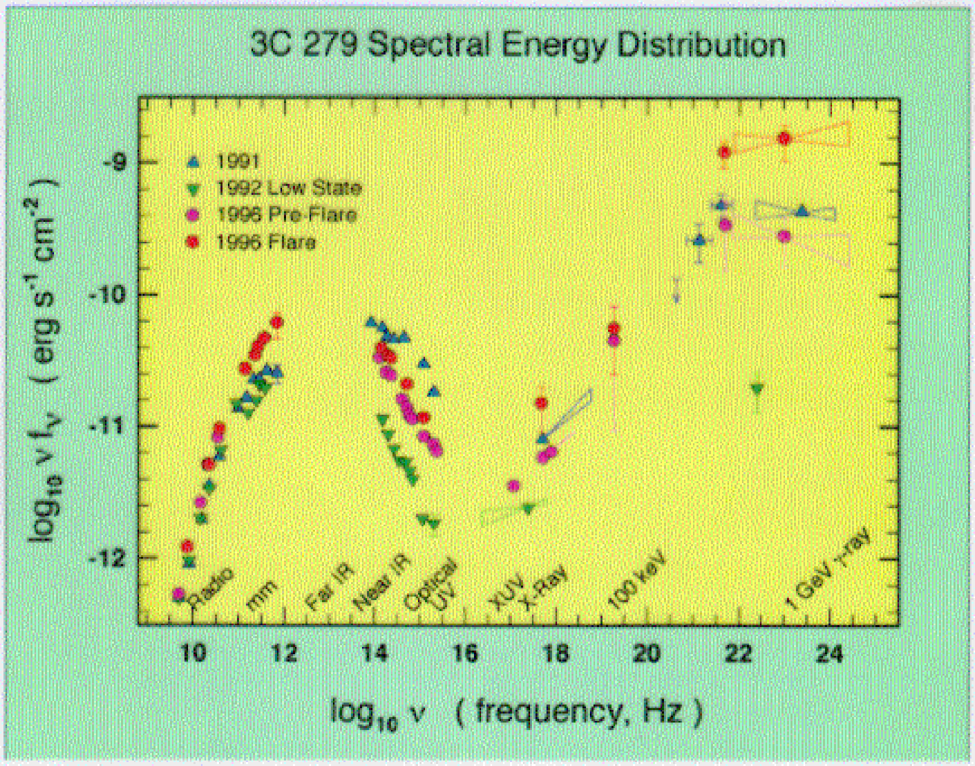
- **Normal Galaxies (Strong et al. 1976) (3 - 10%)**

- **Clusters of Galaxies (Dar & Shaviv 1995; Erlykin & Wolfendale 1995; Colafrancesco & Blasi 1998)**

- **FIR Galaxies**

General Characteristics of EGRET AGN

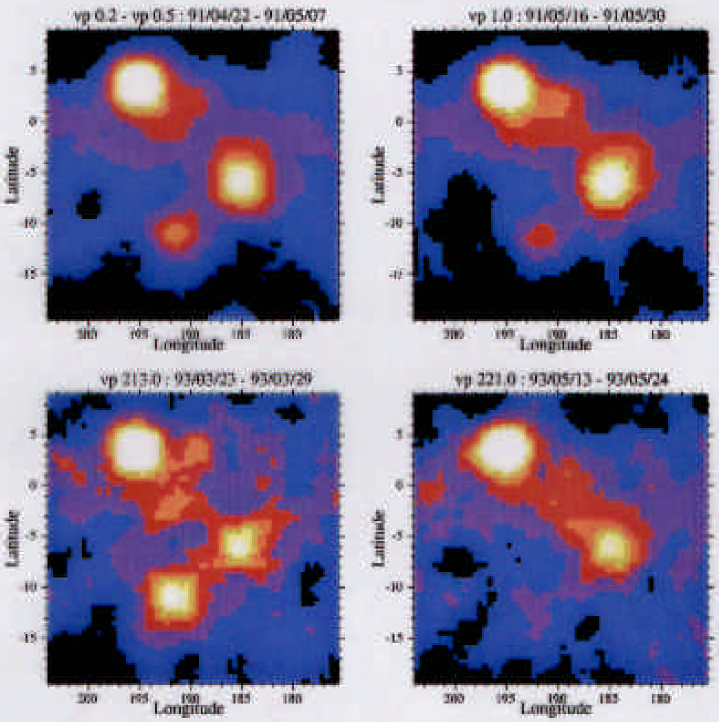
- **Radio-loud, flat-spectrum sources ($\alpha_r > -0.6$).**
- **"Blazar" class of AGN (BL Lac objects, highly polarized ($> 3\%$) quasars (HPQ), and optically violently variable (OVV) quasars.)**
- **High fraction are superluminal. (Evidence from VLBI).**
- **Non-thermal continuum spectrum, luminosity peaks in the IR.**
- **Dramatic peak at γ-ray energies indicates the importance of nonthermal processes in these objects. "Apparent" luminosity $\sim 10^{48}$ ergs s^{-1}.**

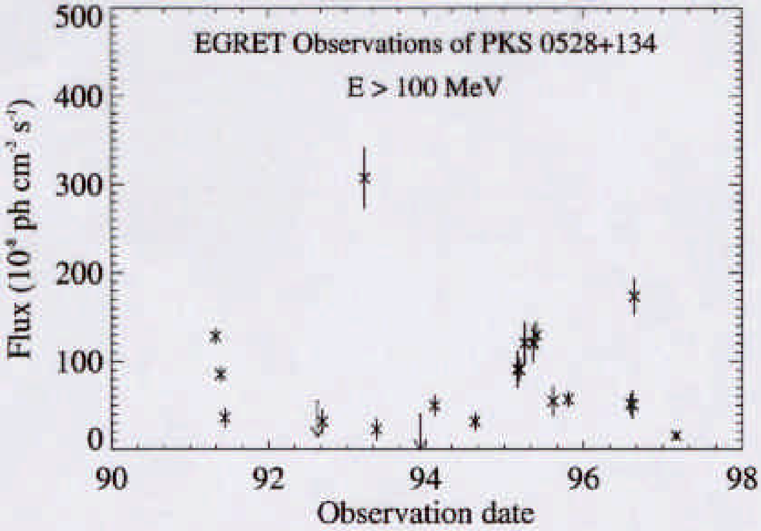

3C 279 Spectral Energy Distribution

General Characteristics of EGRET AGN

- **Strong variability ~ days to months. $R < c\Delta t$, where $\Delta t = \Delta t_{obs}/(1+z)$, is the corrected intrinsic variability in the cosmological time frame.**

GALACTIC ANTICENTER MAPS: Crab & Geminga pulars with variable blazar PKS0528+134





Blazar PKS 0528+134 in the Galactic anticenter region

AGN Model Constraints from Observations

- Rapid variability, high compactness, and superluminal motion $\Rightarrow$ γ-ray emission originates in strongly beamed sources.

- Powered by accretion of matter onto a supermassive black hole.

- γ-rays are beamed radiation from a collimated relativistic jet.

- Two Arguments for beaming:

Absence of intrinsic $\gamma\gamma$ pair absorption

- Optical depth for $\gamma\gamma \rightarrow e^+e^-$ $\propto$ source compactness $\sim \sigma_T L/4\pi c < \epsilon > R$.

- For isotropic emission from a uniform spherical source at rest, and intrinsic $L > 10^{48}$ ergs/s $\Rightarrow$ optical depth is $\gg 1$.

- Incompatible with the observed γ-ray spectra of the source.

Violation of the Elliot-Shapiro relation:

- For a spherically symmetric source in a steady state, $L \leq L_{Edd} < 1.3 \times 10^{38}(M/M_\odot)$ ergs/s.

- Min. intrinsic time scale of variation : $\Delta t \geq R_s/c = 10^{-5}(M/M_\odot)$

- $\log \Delta t_{obs}/(1+z) \geq \log L_{48}$. This condition is violated for several EGRET blazars.

Blazar Models

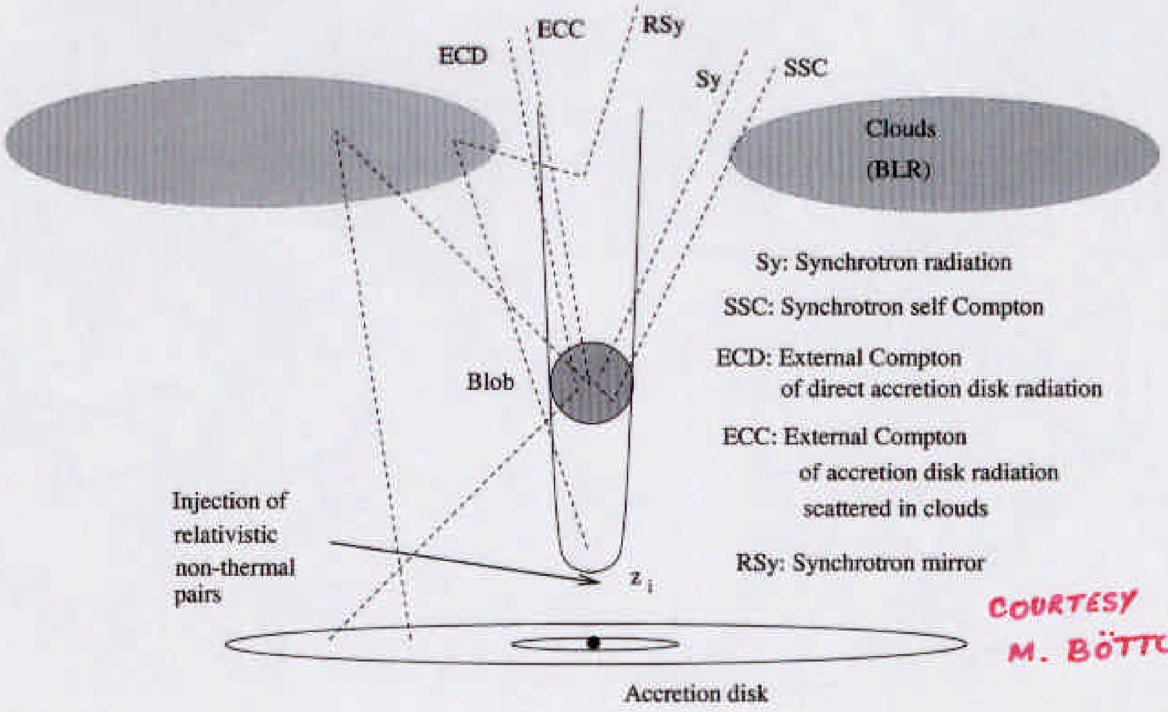
General Assumptions:

- A central supermassive black hole $\sim 10^{10}\ \mathrm{M}_{\odot}$ surrounded by an accretion disk and possibly a gas and dust torus.

- Accretion energy powers a beamed jet of material with a high bulk Lorentz factor γ.

- Emitting region $\sim$ sphere (blob) of constant radius R, with a homogeneous magnetic field B, ejected at a small angle θ with the jet axis.

- Relativistic e^{+}, e^{-}, p (?) are continuously injected at a certain rate. Injected particles are distributed in energy as power law, $\mathrm{n}(\gamma) \propto \gamma^{-\mathrm{s}}$ and have a certain Lorentz factor γ in the rest frame of the blob.



Sy: Synchrotron radiation

SSC: Synchrotron self Compton

ECD: External Compton of direct accretion disk radiation

ECC: External Compton of accretion disk radiation scattered in clouds

RSy: Synchrotron mirror

COURTESY
M. BÖTTCHER

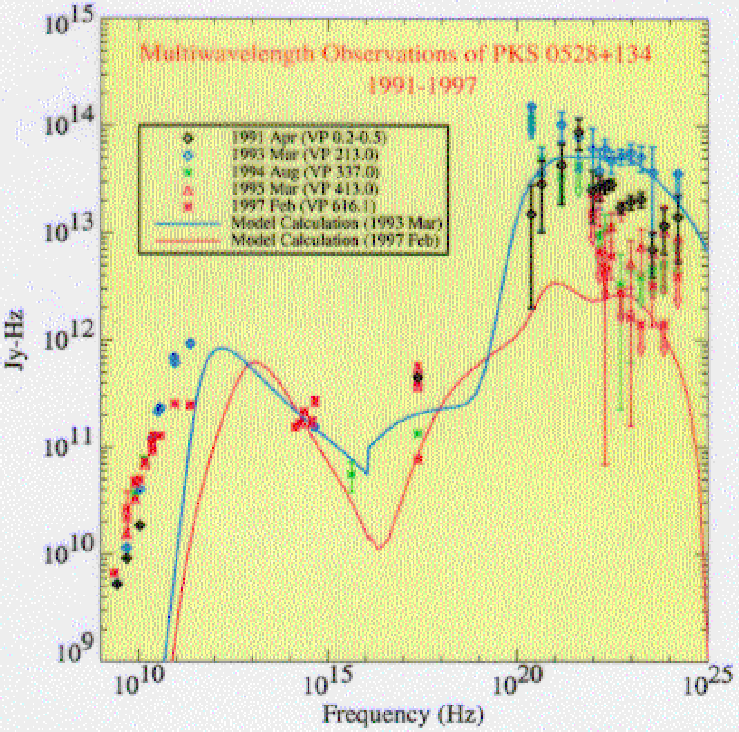
Spectral Energy Distribution of Blazars
Leptonic Models

- Radio through optical/UV emission is due to synchrotron emission from the plasma in relativistic motion.

- High energy emission: Inverse Compton scattering.

Synchrotron-Self Compton (SSC): Soft photons are from within the jet.

External Radiation Compton (ERC): Soft photons are external to the jet (either accretion disk photons, photons reflected by the emission line clouds)



Mukherjee et al. 1999

Many Questions:
Nature of beam particles, Acceleration processes, Magnetic fields Seed photons, Emission zone(s) .... ??

Proton Blazar Models

- **SED explained in terms of acceleration of protons and subsequent cascading (PIC)**

- **Models of synchrotron radiation produced by $\mu^{\pm}$ from $\pi^{\pm}$ decay and by protons has been applied to the case of blazars Mrk 421 & Mrk 501 (Aharonian 2000)**

- **High energy neutrinos produced as a result of photoproduction? e.g. $\pi^+ \rightarrow \mu^+\mu_\mu$ followed by $\mu^+ \rightarrow \mathrm{e}^+\nu_\mathrm{e} + \bar{\nu}_\mu$**
or Production and decay of charged kaons

- **Some earlier models (Mannheim 1993, 1995) predict equal photon and neutrino energy fluxes.**

- **Mücke & Protheroe (2000) predict lower neutrino flux**

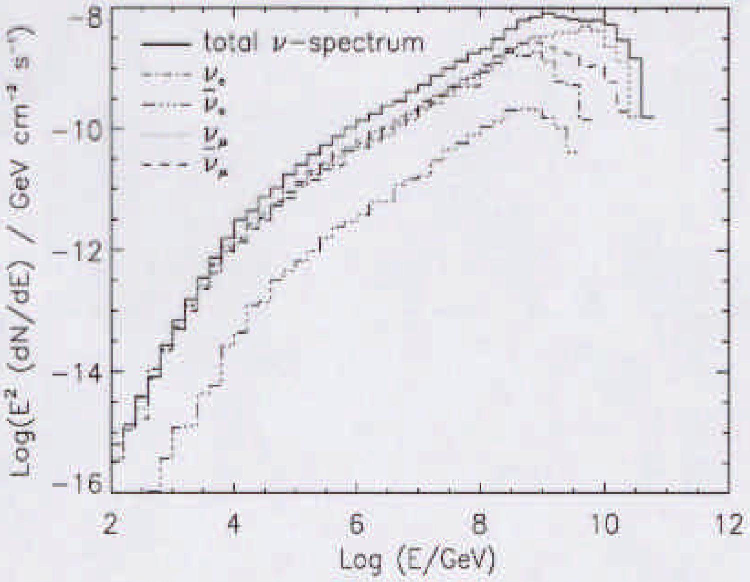


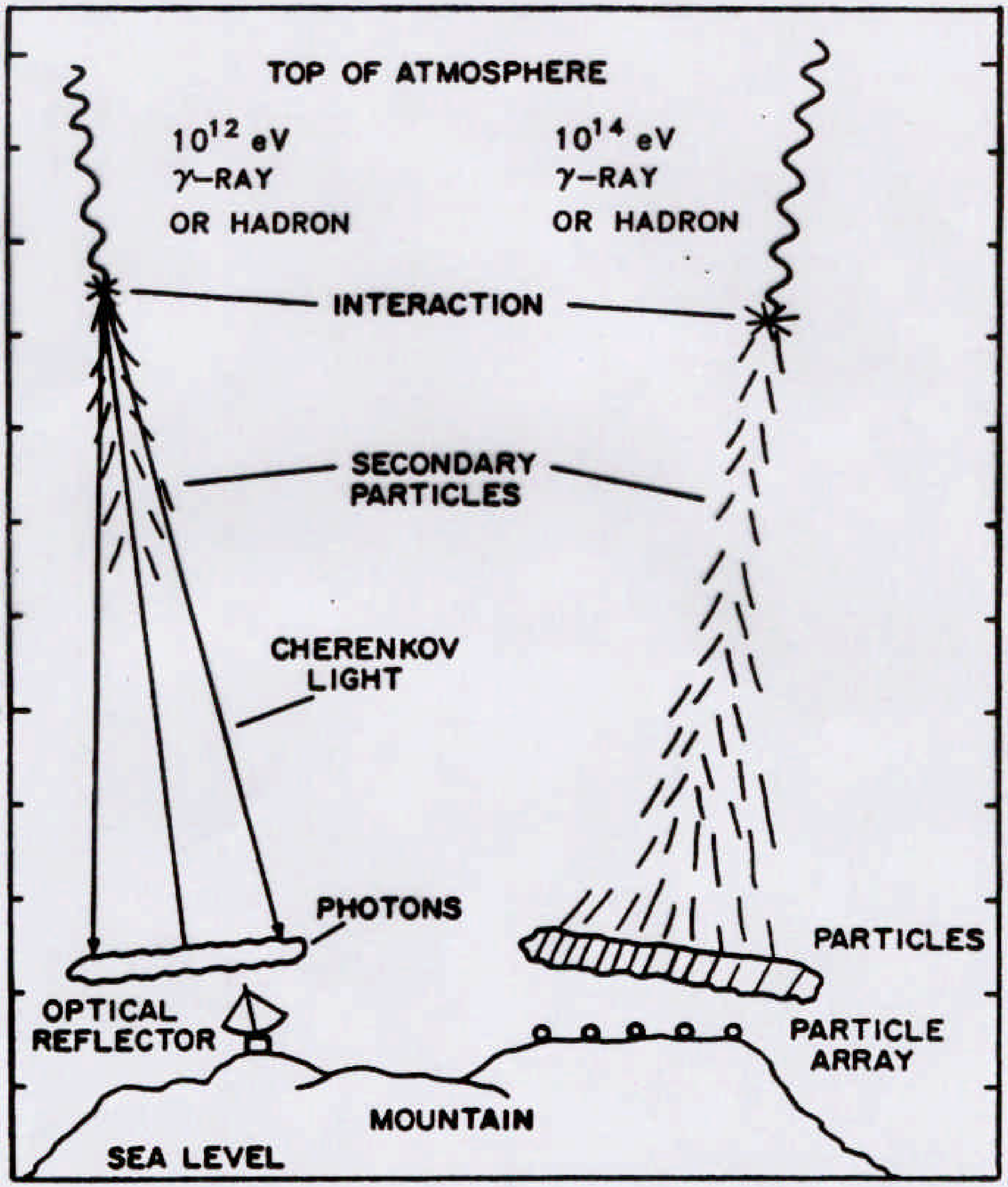
Figure 8: Predicted spectra of ν_e, $\bar{\nu}_e$, ν_μ and $\bar{\nu}_\mu$ from Mkn 501. The contribution of νs due to pion production of the emerging cosmic rays while propagating through the cosmic background is not considered here.

Mücke et al. 2000

Atmospheric Cherenkov Telescopes

- **At TeV energies, photon flux is severely limited (E^{-2} spectrum).**
- **At VHE indirect γ-ray detection is possible.**
- **VHE γ-rays initiate cascades, or extensive air showers (EAS) of particles.**
- **A high energy ($\sim$ 100 GeV) cosmic ray or γ-ray interacts with the atmosphere (10 - 15 km), creates cascade showers.**
- **Relativistic charged particles in EAS emit Cherenkov radiation.**
- **Cherenkov photons are strongly beamed in the forward direction.**
- **Radiation is Calorimetric.**
- **Light pool on ground is relatively uniform in density.**
- **Cherenkov light arrives with very tight time structure ($\sim$ 5 ns).**

γ–ray and CR techniques:



Cherenkov telescopes

Air shower experiments

R. ONG (1998)

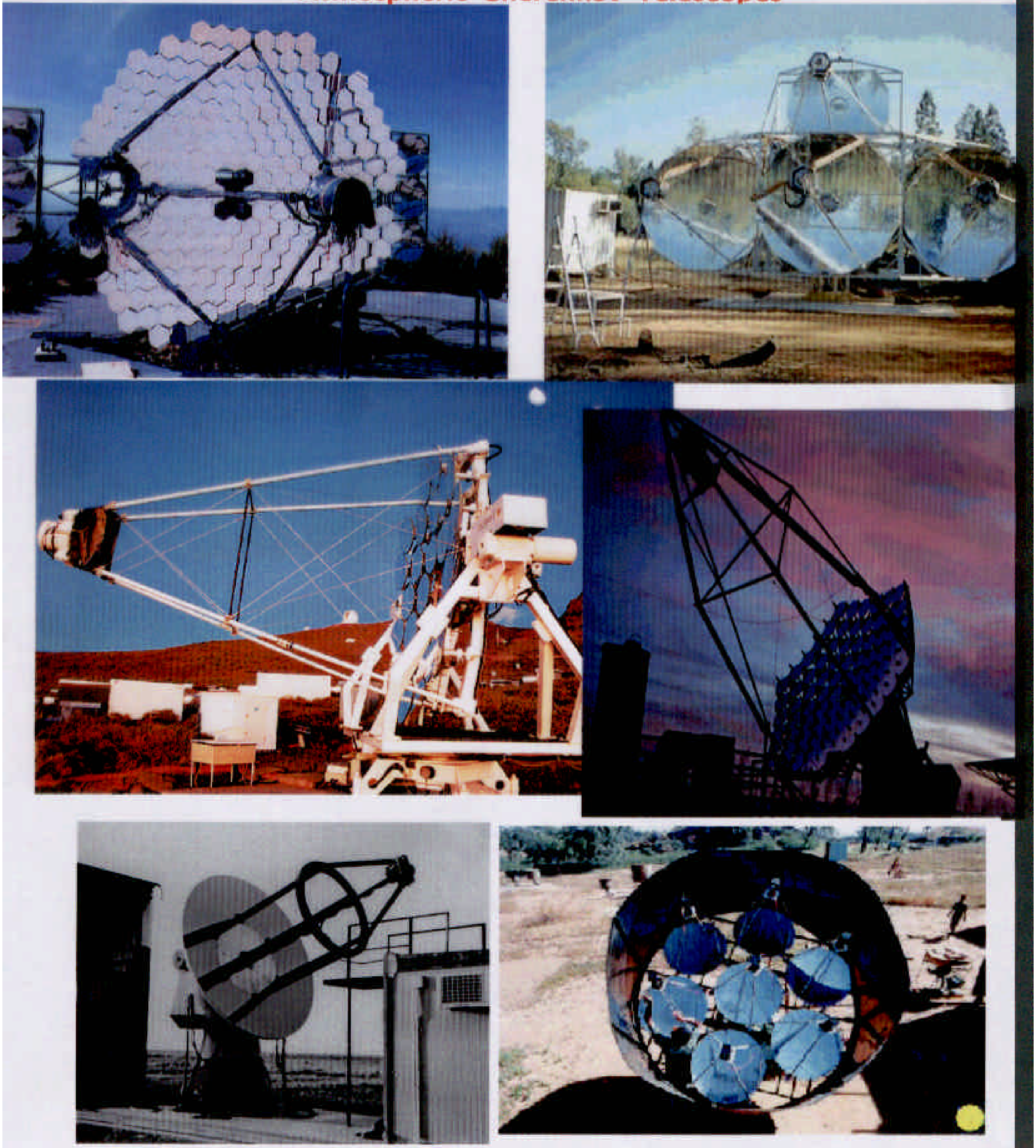
PROPERTIES

ATMOSPHERIC CHERENKOV TELESCOPES

Experiment (Location)	Mirrors	A (m^2)	PMTs	FOV (°)	$E_{\rm th}$ (GeV)
Cangaroo (Cangaroo)	2	11	256	3.0	1000
CAT (France)	1	18	600	4.8	250
Durham (Australia)	3	42	109	3.4	250
GT-48 (Ukraine)	2	27	37	2.7	900
HEGRA-CT (Spain)	6	9	271	4.6	500
Nooitgedacht (S. Africa)	4	7	4	1.7	700
Pachmari (India)	25	4	1	3.0	
SHALON (Russia)	1	10	144	7.2	1000
TACTIC (India)	4	10	349	2.8	
Tel. Array (USA)	3	6	256	4.5	500
Whipple (USA)	1	75	151	3.5	250

Compiled from Ong (1998).

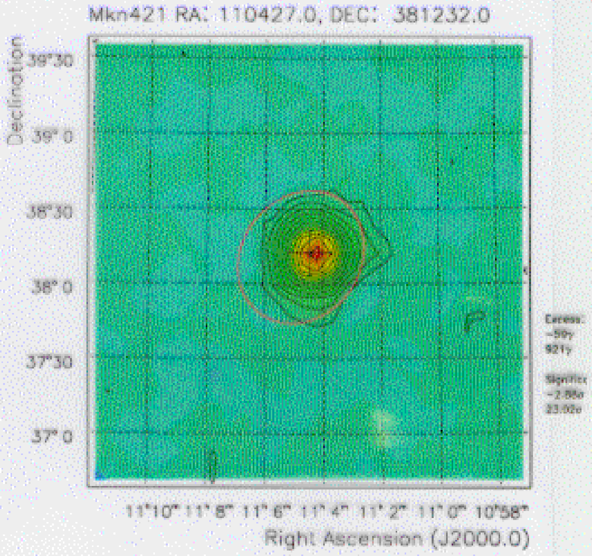
Atmospheric Cherenkov Telescopes



Results from Ground-based Instruments: Extragalactic Sources

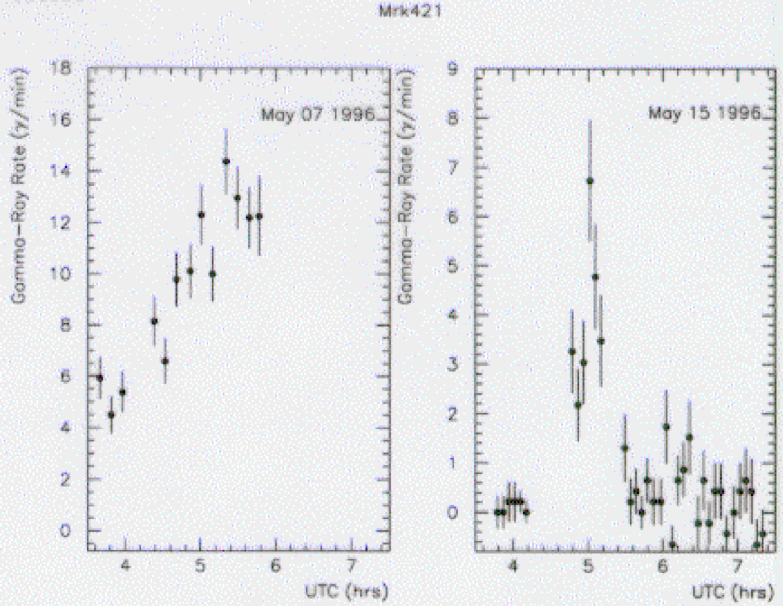
Markarian 421

- **First TeV detection of AGN: Mrk 421 by Whipple (1992)**
- $z = 0.031$ **(closest BL Lac)**
- **TeV flux:**
  -Flare: 10 Crab
  -Quiescent: ~ 0.3 **Crab**



Mrk 421: Flux Variability

- **Rapid:** < 15 **min**
- **Entire flare lasted** ~ 30 **min**
- **Fastest time-scale variability seen from any blazar at any** γ**-ray energy.**

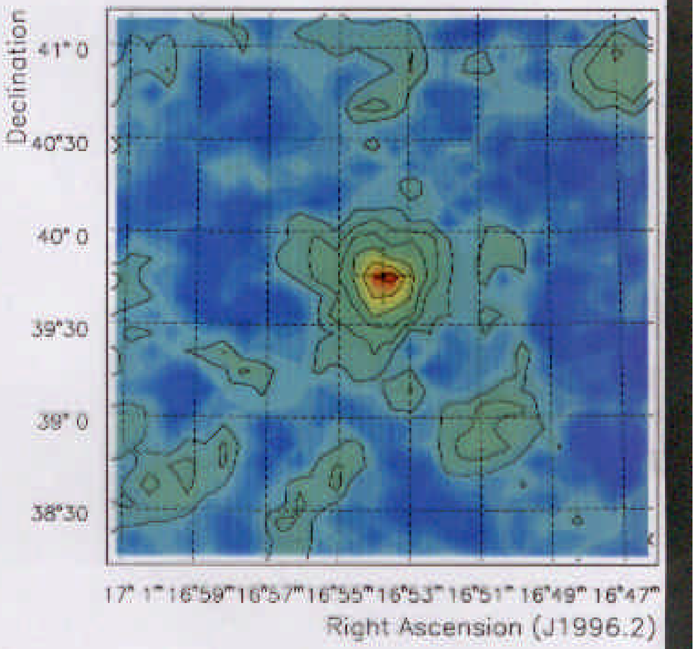


Catanese & Weekes 1999

Results from Ground-based Instruments: Extragalactic Sources

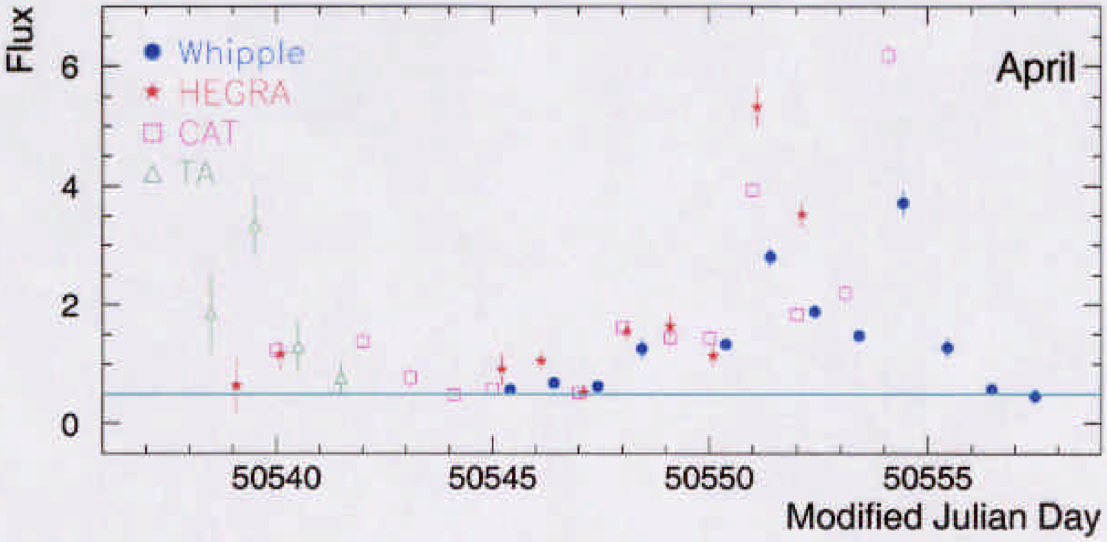
Markarian 501

- $z = 0.034$
  (2nd closest BL Lac)
- TeV flux:
  -Flare: 6 Crab
  -Quiescent: $\sim 0.1 - 1.4$ Crab



Mrk 501: Flux Variability

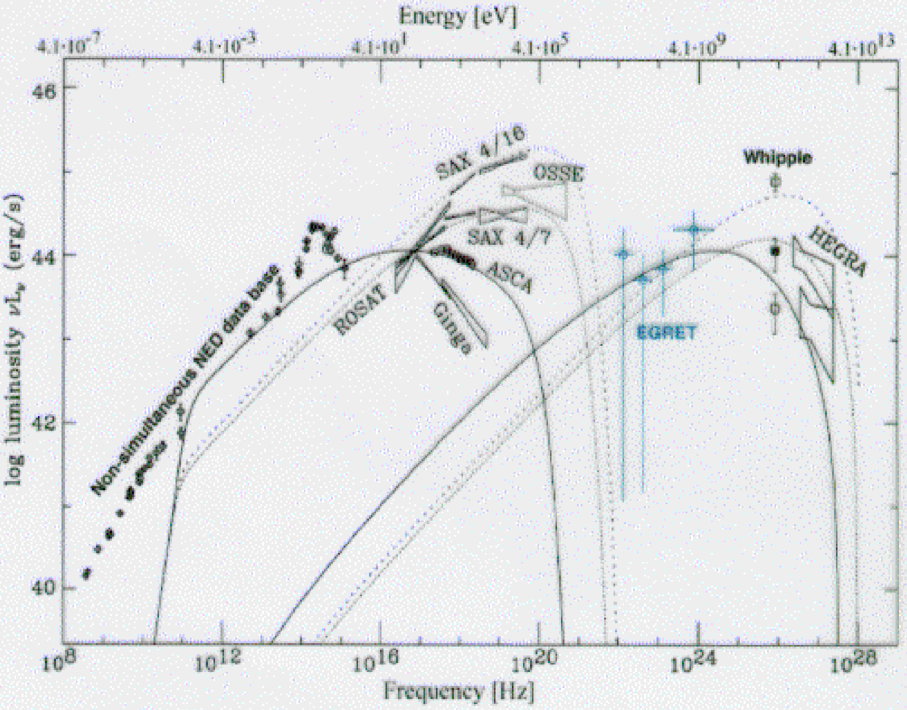
- Rapid: < 2 hours
- Large-amplitude: Average flux $>>$ Crab flux
- Baseline level present, but variable: 0.1 - 1.5 Crab



Catanese & Weekes 1999

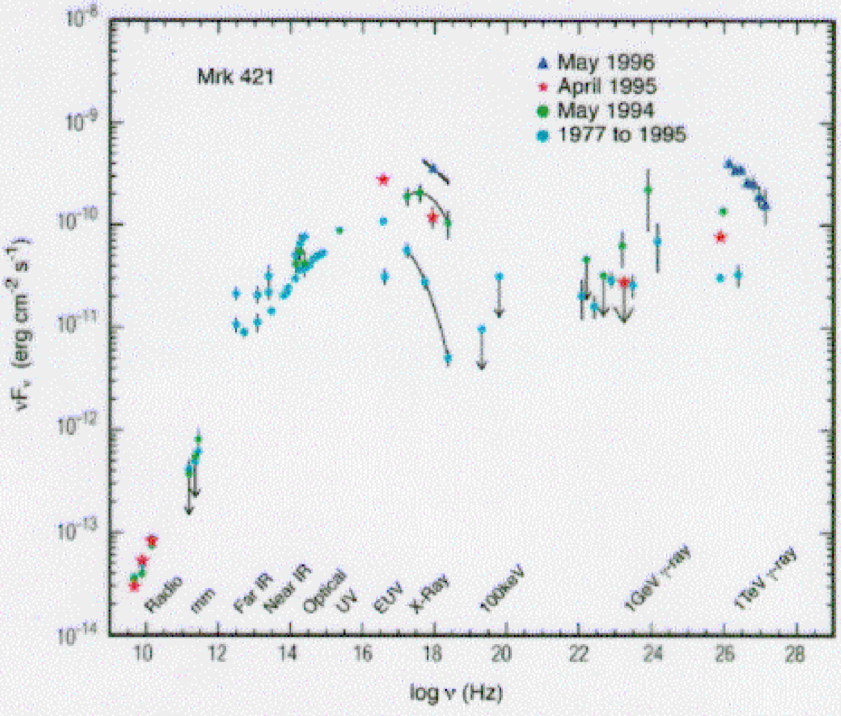
Spectral Energy Distributions

Mrk 501



Kataoka et al. 1999

Mrk 421



Catanese & Weekes 1999

Spectral Energy Distributions

Mrk 421 & Mrk 501

Similarities:

- Both have a peak in the synchrotron emission at X-ray energies – typical of X-ray selected BL Lacs.

- High energy peak of both lies in the 10-250 GeV range.

- Synchrotron and IC peaks are similar in power output (in contrast to EGRET FSRQs).

- During flare, X-ray spectrum of both tend to harden significantly. VHE spectrum is not observed to change.

Differences:

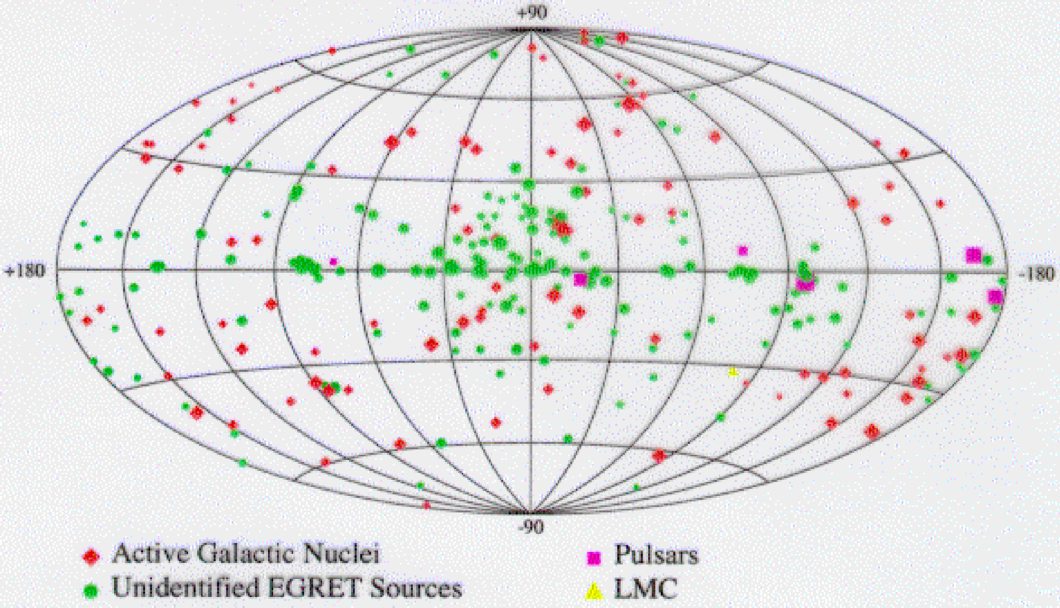
- Mrk 501: Significant (synch) peak shift to higher energies during a flare.
  – Synchrotron spectrum extends well beyond 1 keV - typical of X-ray selected BL Lac objects.
  – During 1997 flare, peak was at $\sim$ 100 keV.

- Mrk 421: Peak shift is not as significant. Peak was never observed beyond $\sim$ 1 keV. Not detected by OSSE.

- Power ouput of Mrk 501 in VHE range can be considerably less than in X-rays in low state.

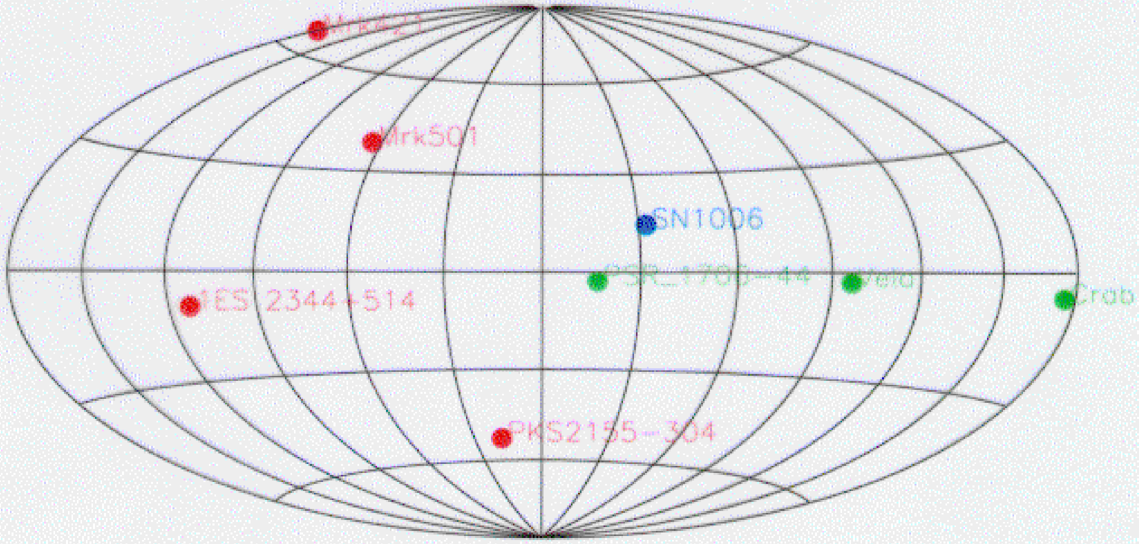
– Mrk 421: similar power output in X-rays and TeV

Comparison of the GeV & TeV Sky



Third EGRET Catalog

E > 100 MeV



TeV SOURCE CATALOG

Blazar Spectral Cutoffs

- **Most EGRET blazars are NOT detected at > 250 GeV.**

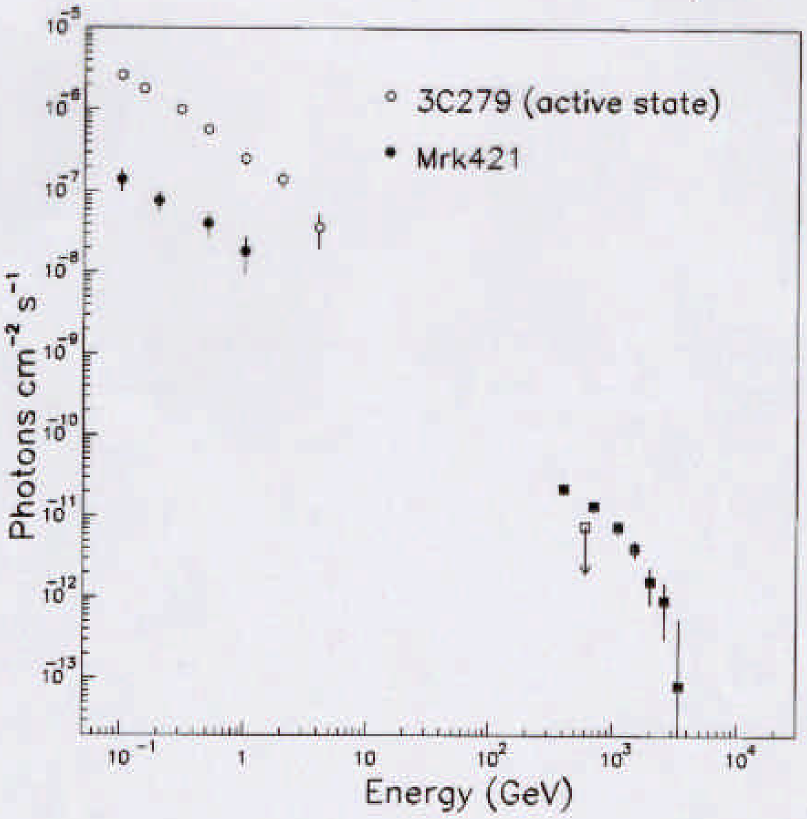
- **Cutoffs could be either due to intergalactic absorption or intrinsic absorption at the source.**

- **The opacity of intergalactic space to high energy γ-rays can be calculated as a function of redshift.**

- **The study of blazar spectra below 250 GeV is a physically interesting subject.**

- **Attenuation of γ-rays from source $\sim$ optical depth τ.**

$$\mathbf{I(E) = I_0(E)e^{-\tau}}$$
$$\tau \sim \mathbf{n_{IR} D} \sigma_{\gamma\gamma}$$



Opacity Calculation Models

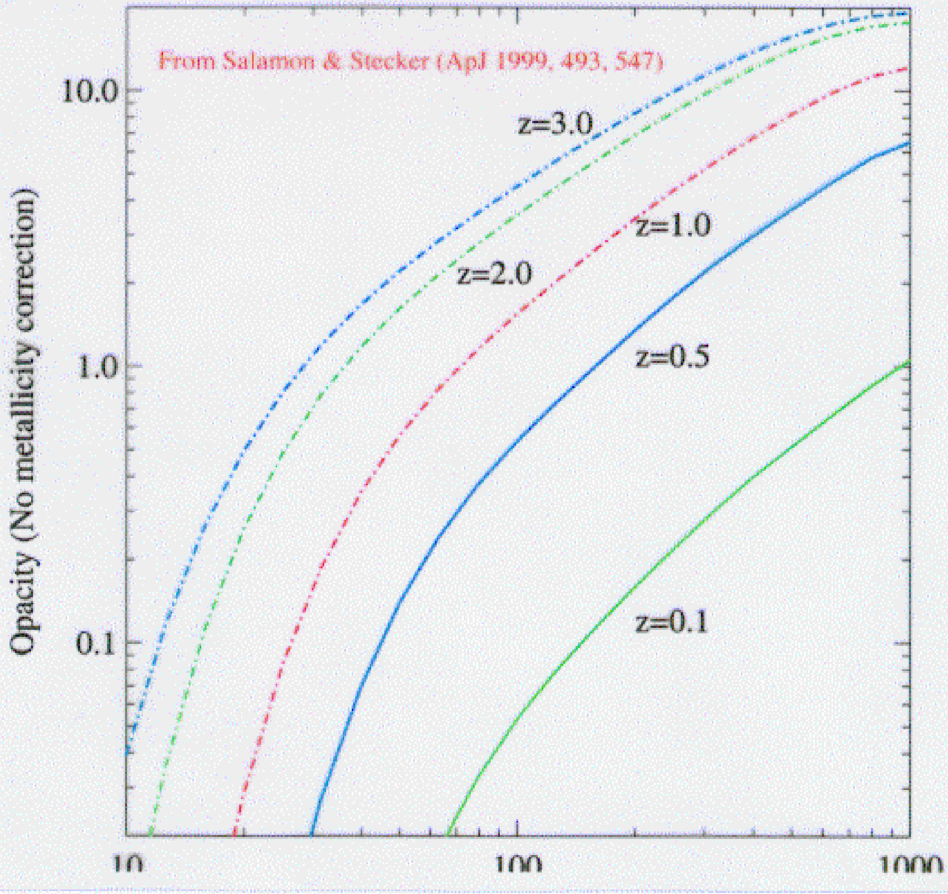
- Not much is known about CIR at present, nor how it developed over time

- Star formation is expected to be a major contributor to CIR (e.g. Madau et al. 1996; Primack et al. 1999)

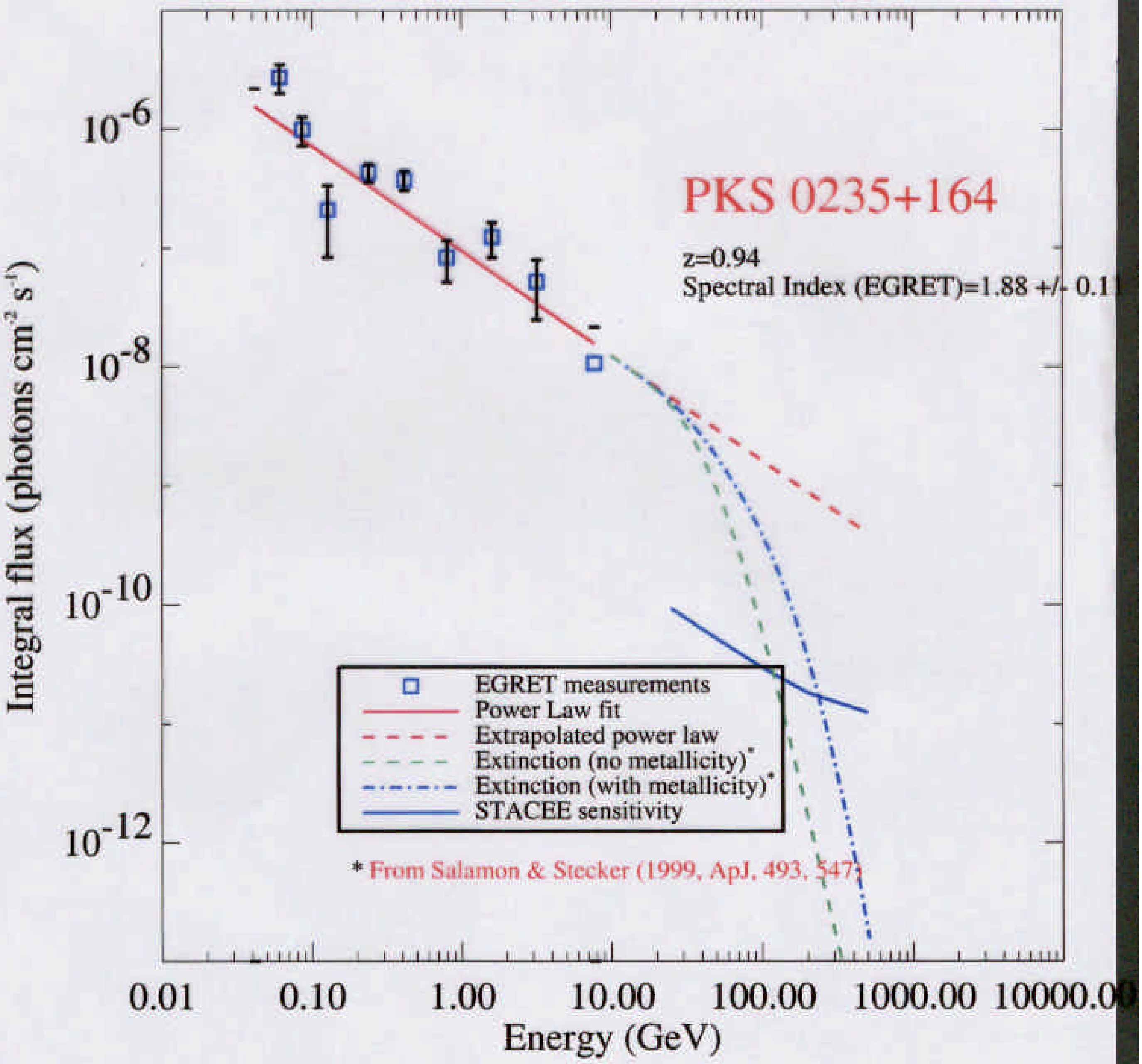
- Density of starlight at any given epoch depends on the - unknown - cosmological history of star formation, metal production, etc.

- Determining the CIR background in turn allows us to model the evolution of the galaxies which produce it.
– Need to know SED (z) and $n(\epsilon, z)$ of CIR background.

Example: Salamon & Stecker (1998) opacity model:



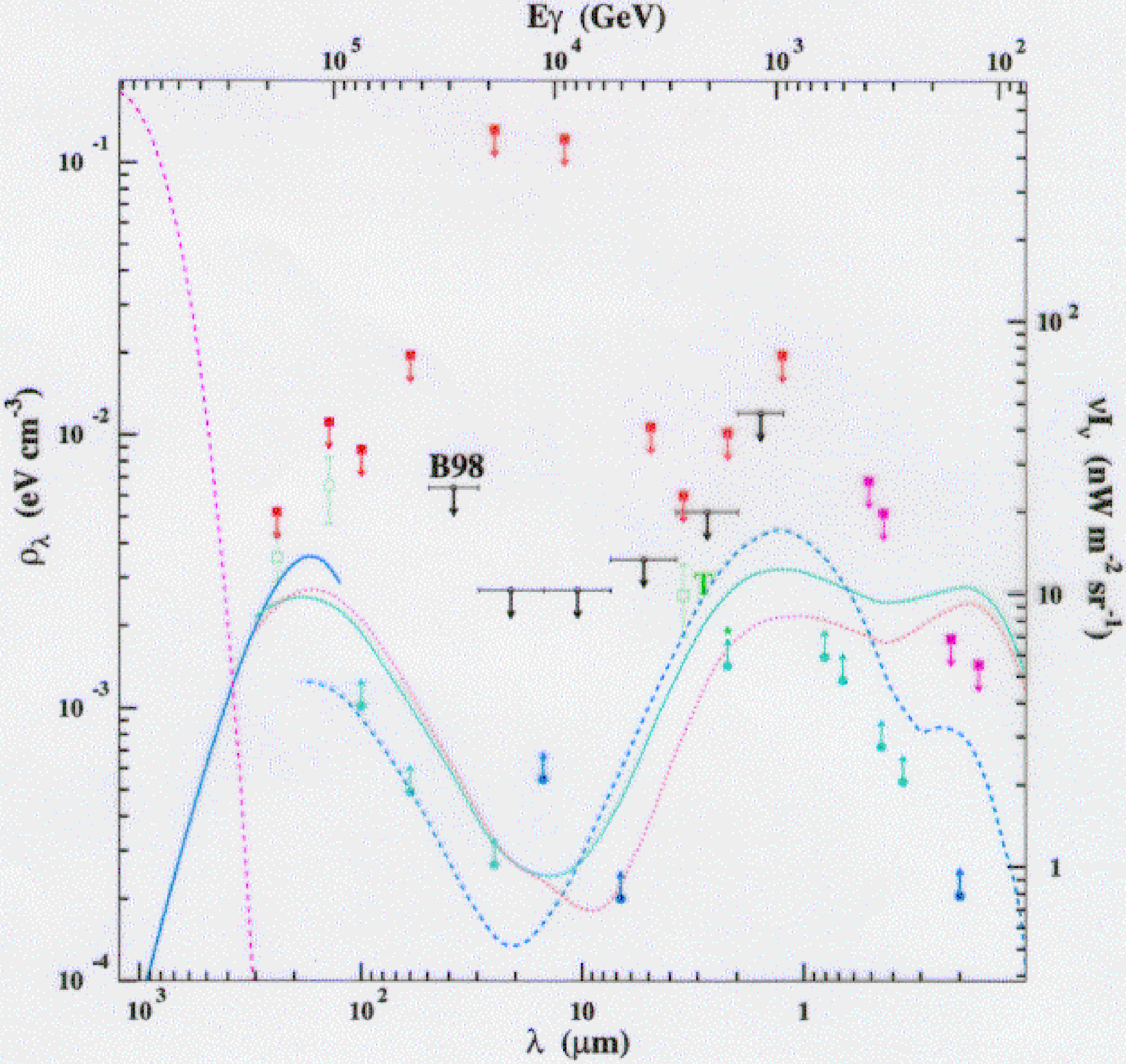
Effect of Absorption on Blazar Spectra



Mukherjee et al. 1999

- **Spectral cutoffs are expected in EGRET AGN spectra in the 10 – 250 GeV range.**

Extragalactic Background Light



Vassilev 2000

- TeV γ-rays pair produce with $\sim 0.03 - -1\ \mu$m photons in travelling intergalactic distances.
- Spectra of Mrk 421 and Mrk 501 limit the density of EBL.
- Need more sources to improve limits or be confident of unfolding the EBL density spectrum.

γ–ray Astrophysics

Selected topics:

* Pulsars:	TeV γ–rays detected from nebulae. No emission from pulsar?
* SNRs:	Detected SN1006: e acceleration Origin of cosmic rays?
* GRBs:	Some bursts are cosmological. What about other bursts? What about HE component?
* AGNs:	Remarkable emission from a few nearby blazars. How do they work? What about many other AGN?
* Dark matter:	Need to carry out astrophysical searches.

New instruments required to:

1. Explore region between 20 – 250 GeV
2. Achieve much greater sensitivity
3. Carry out all–sky surveys

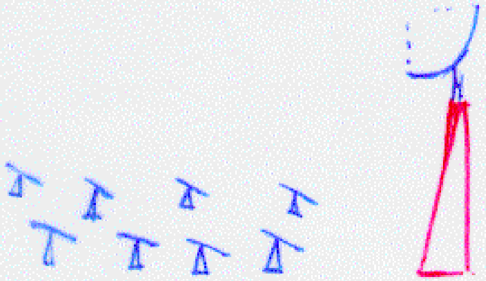
Atmospheric Cherenkov Technique

- Energy threshold :

$$E_{th} \propto \sqrt{\frac{B\Omega t}{A\epsilon}}$$

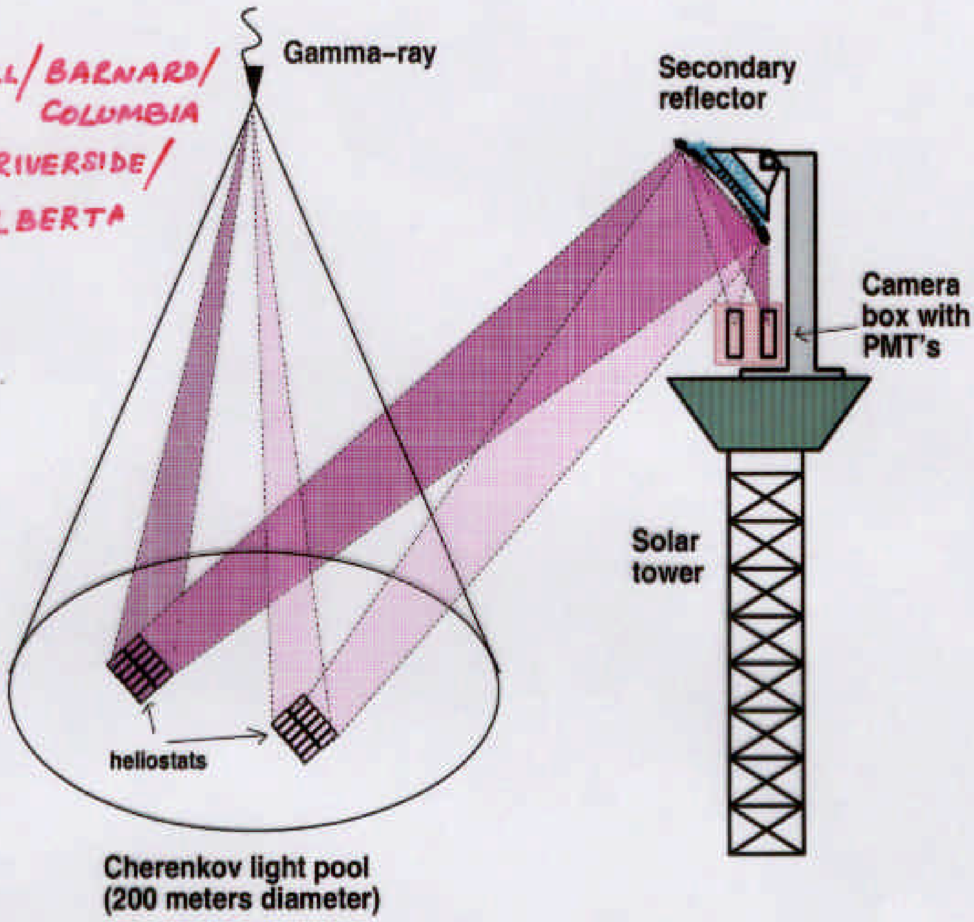
- ⇒ Larger collection area.
- For $E_{th} \sim 20$ GeV, $A \sim 10000\ m^2$.
- Single large steerable mirror is mechanically difficult.
- Either: Several small mirrors, each with a camera (eg. VERITAS).

- Direct many mirrors on an array of PMTs (eg. STACEE, CELESTE).



STACEE CONCEPT

CHICAGO / MCGILL / BARNARD / COLUMBIA
SANTA CRUZ / RIVERSIDE / ALBERTA



Using solar mirrors (heliostats) to detect Cherenkov light.
The radiation is reflected by heliostats to a central tower.
Secondary mirrors on tower focus light onto PMTs

STACEE: Solar Tower Atmospheric Effect Experiment (Sandia)

CELESTE: Cherenkov Low Energy Sampling and Timing Experiment (Pyrenees)

Solar Two (California)

NSTTF Heliostats & Solar Tower

- Site: National Solar Thermal Test Facility (NSTTF) at Sandia National Lab. (Albuquerque).
- 220 heliostats (37 m^2) of which 32 are used.

1998–99 OBSERVING

* STACEE–32 operational on Nov. 1

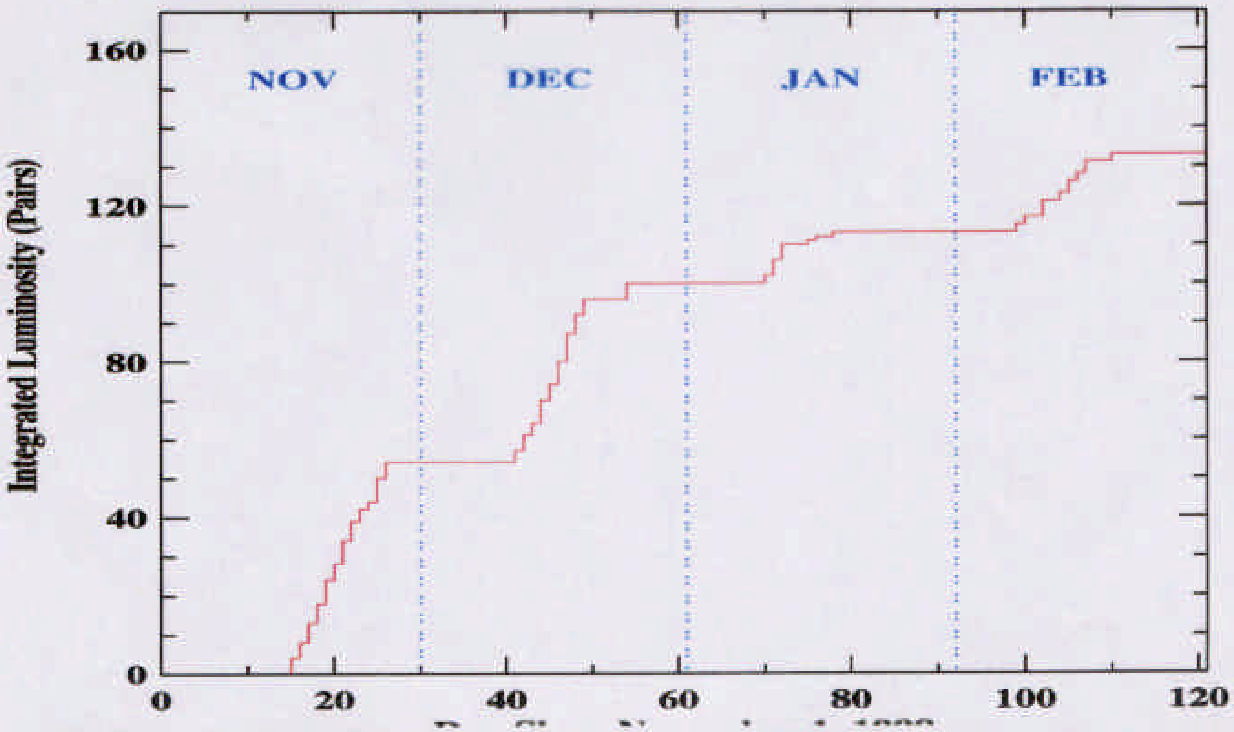
* Nov–Apr: took steady data, > 60 clear nights!
lots of development work

* Data

Source	Type	Pairs taken
Crab	Plerion	133
Mrk 421	z=0.03	14
Mrk 501	z=0.03	16
1219+285	z=0.51	24

* On/Off method: 30 minute pairs

Crab Luminosity



STACEE: Observations & Prospects

- Currently operating with 48 heliostats. Plans exist for 64 heliostats in the near future.

- Operated on most clear moonless nights since 1998 October. Data taken to verify performance and calibrations.

- Crab Nebula was observed from 1998 Nov. to 1999 Feb.

- STACEE detects the Crab at $\sim +7\sigma$ in $\sim$ 50 hrs of observations. Oser et al. (1999, 26th ICRC).

- Monte Carlo studies indicate a trigger threshold $\sim$ 150 GeV. Observed γ-ray rate: $\sim$ 2/min. (Covault et al. 1999, 26th ICRC)

STACEE Future Prospects

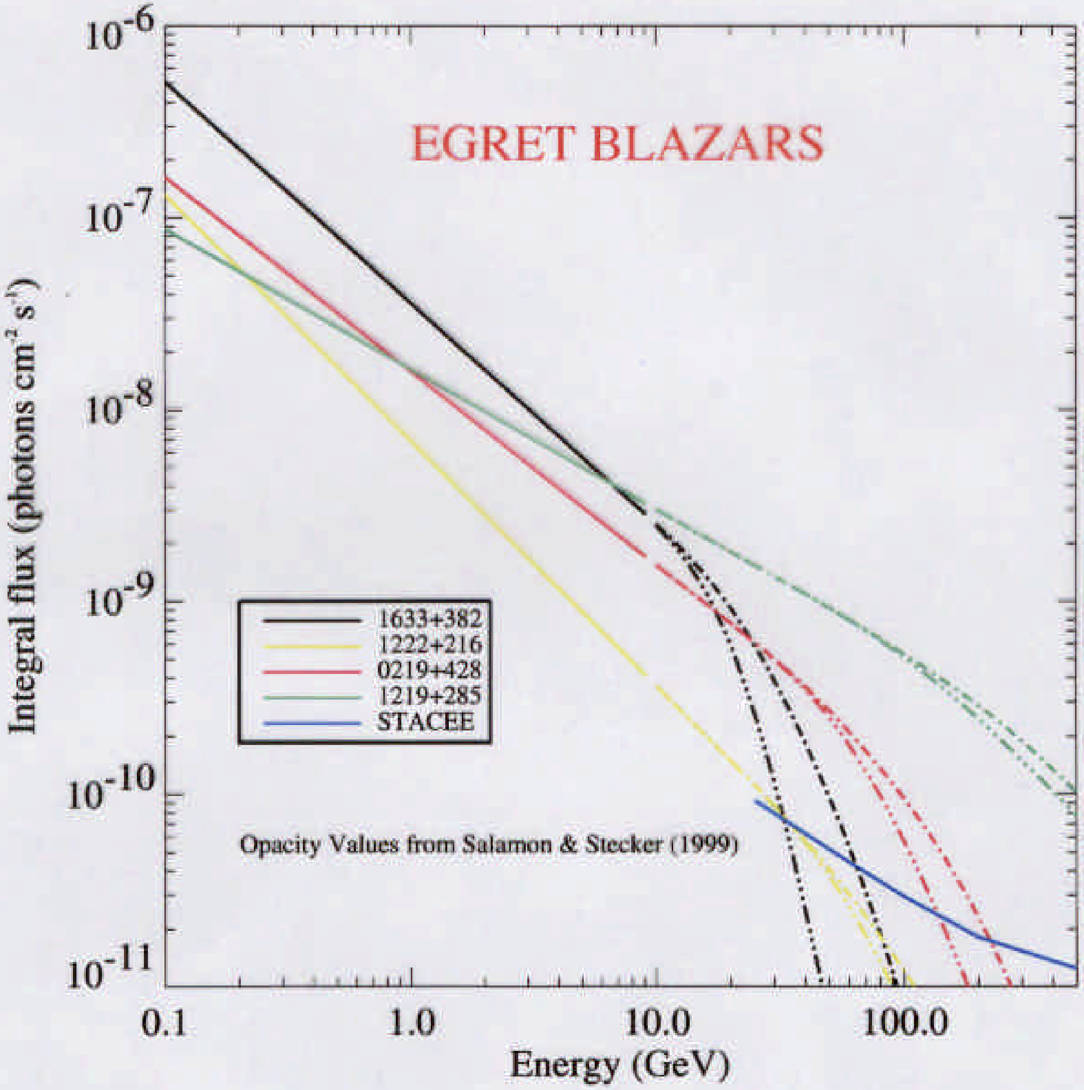
- Results from STACEE & CELESTE indicate "proof of principle": Clearly feasible to explore the 50-250 GeV regime using the solar mirror array experiments.

- STACEE should be able to detect sources at a fraction of the Crab intensity.

- Some of the key sources to study include AGN, pulsars, and SNRs.

Projected Sensitivity of STACEE

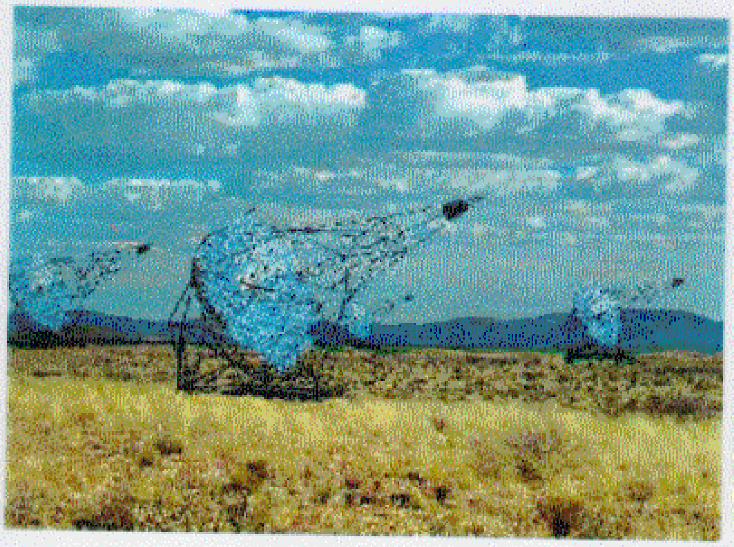
Effect of Absorption on EGRET BL LACs & FSRQ Spectra



Some EGRET Blazars

Source	Γ	z	Type
0219+428	2.01 ± 0.14	0.444	BLL
1219+285	1.73 ± 0.18	0.1	BLL
1222+216	2.28 ± 0.13	0.4	FSRQ
1633+382	2.15 ± 0.09	1.8	FSRQ

HIGH SENSITIVITY IMAGING CHERENKOV TELESCOPES



- Improve sensitivity by a factor of 10,
  Energy range 50 GeV – 10 TeV

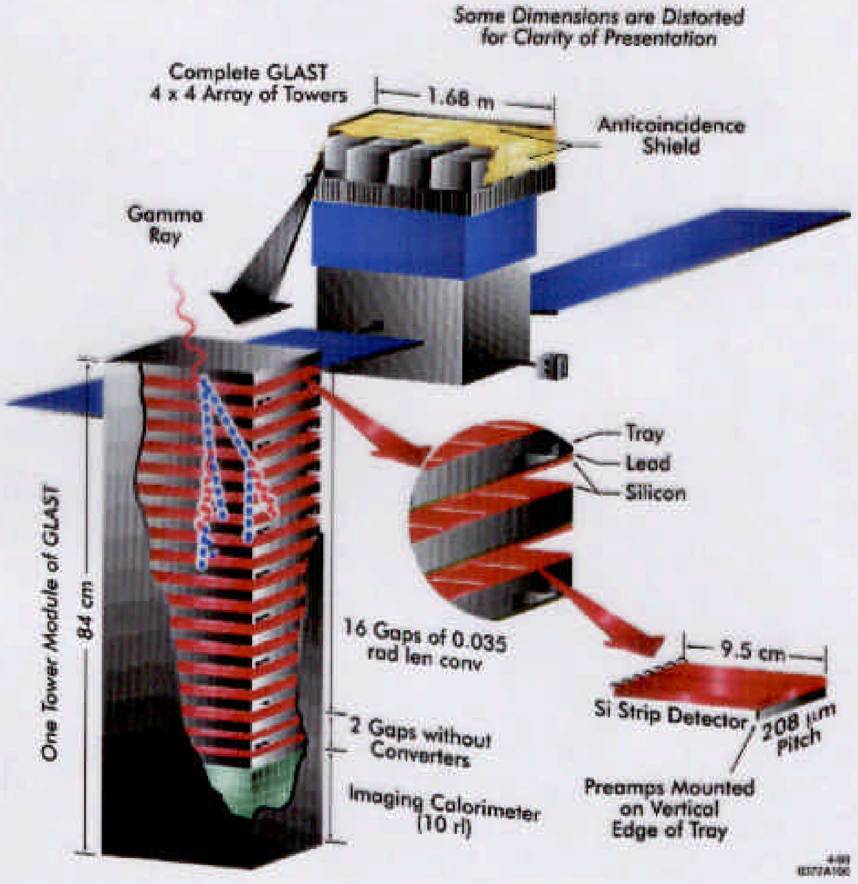
- MILAGRO (water Cherenkov detector) (See Atkins et al. 1999)

- Four new project starts:
  CANGAROO III (Australia)
  HESS (Namibia)
  MAGIC (La Palma)
  VERITAS (Arizona)

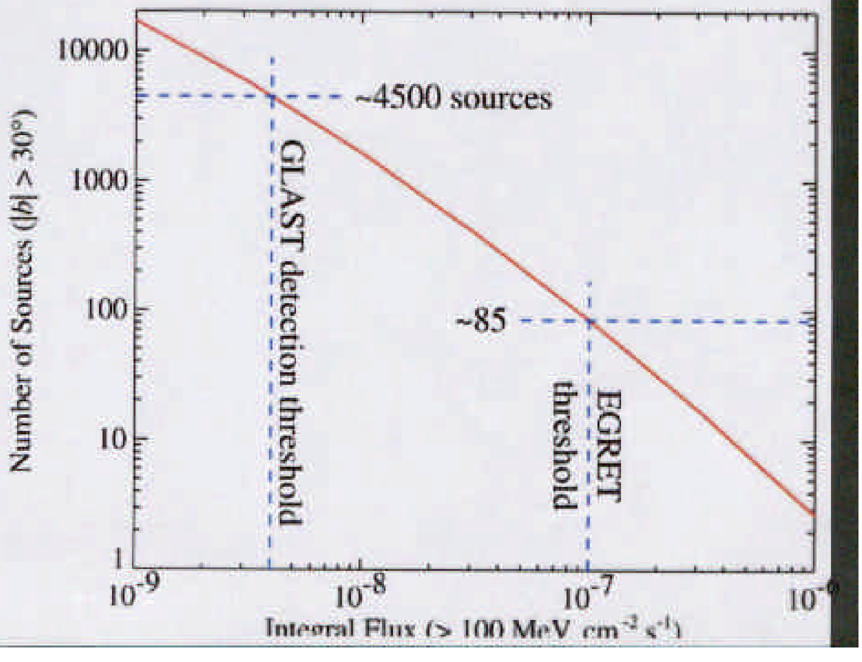
Gamma–ray Large Area Space Telescope (GLAST)

- ~~Two possible technologies: Silicon, SciFi~~

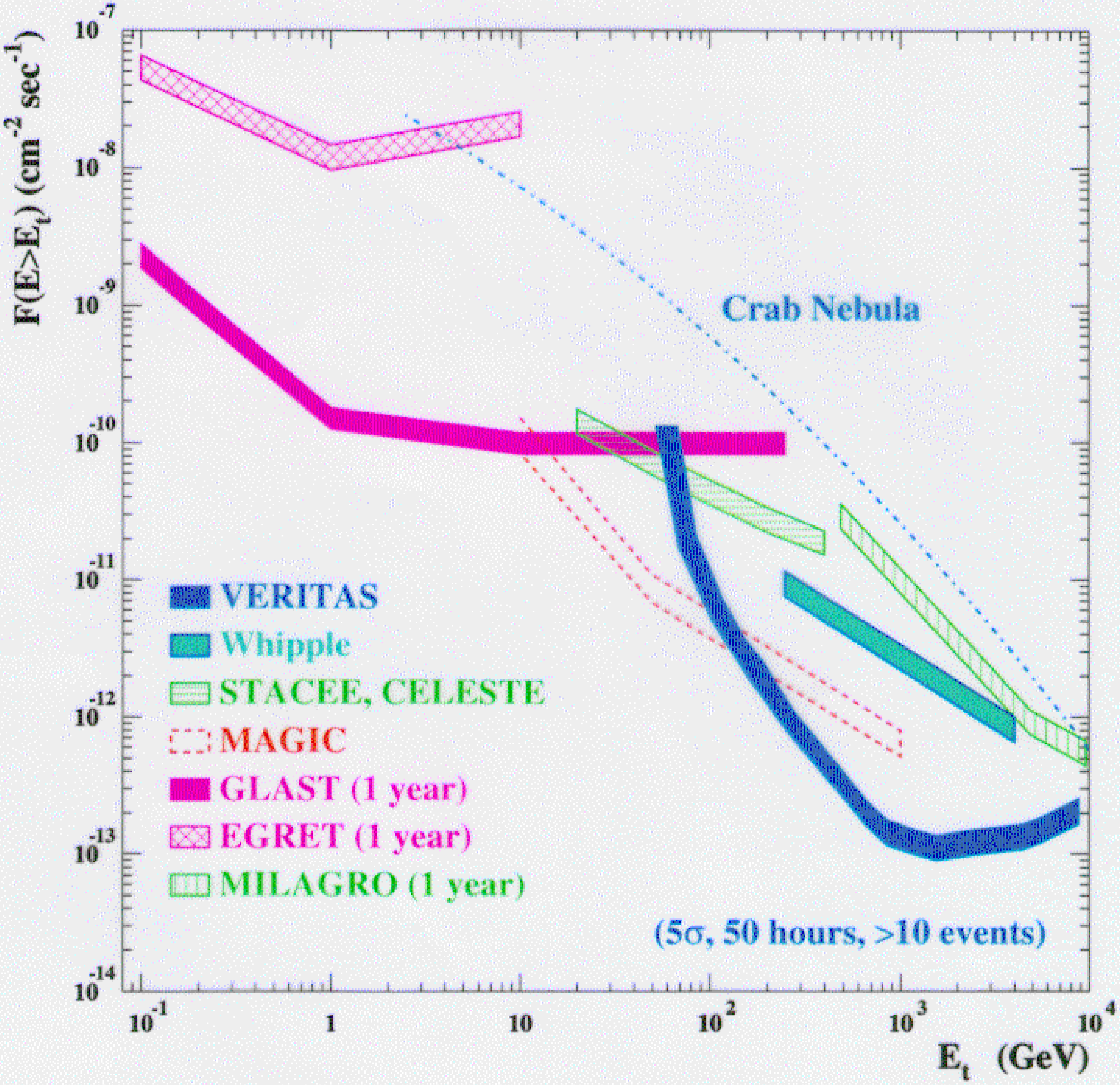
Si–GLAST Option:


Some Dimensions are Distorted for Clarity of Presentation

Greatly enlarge AGN sample:



Sensitivities of future γ−ray experiments:



R.ONG (1998)

What Went Unsaid

- Detector New and Future

-Future Imaging: VERITAS (Catanese & Weekes 1999)
-Water Cherenkov: Milagro (Atkins et al. 1999)

- Detections from telescopes other than the imaging ACTs

-Mrk 501 by Milagro (Atkins et al. 1999)
-Detection of Crab & Mrk 501 by Tibet Air Shower Array (Amenomori et al. 1999, 2000)
-Gamma-ray Burst by Milagro (Mcenry et al. 1999)

- Pulsars and Supernova Remnants

EGRET pulsars (Thompson et al. 1997) Plerionic SNR, Shell-type SNRs (Catanese & Weekes 1999)

- Unidentified sources

(Review Mukherjee et al. 1997)
Recent results: Grenier 2000, Gehrels et al. 2000

- Diffuse galactic radiation (Hunter et al. 1997)

- Gamma-ray bursts

SUMMARY

- Many reasons to be optimistic about the future of γ-ray astronomy

- Significant scientific progress made using space- and ground-based instruments
Growing catalog of sources

- Discoveries raise new questions

- Order-of-magnitude gap exists between space and ground-based data

- Central tower solar power stations can be exploited at very modest costs to fill the gap

- Ever expanding panoply of experiments
Cherenkov Telescopes, GLAST, AGILE