Recent Results and Observational Status of TeV Gamma-ray Astronomy

Antje Kohnle, Max-Planck-Institut für Kernphysik
Heidelberg, Germany

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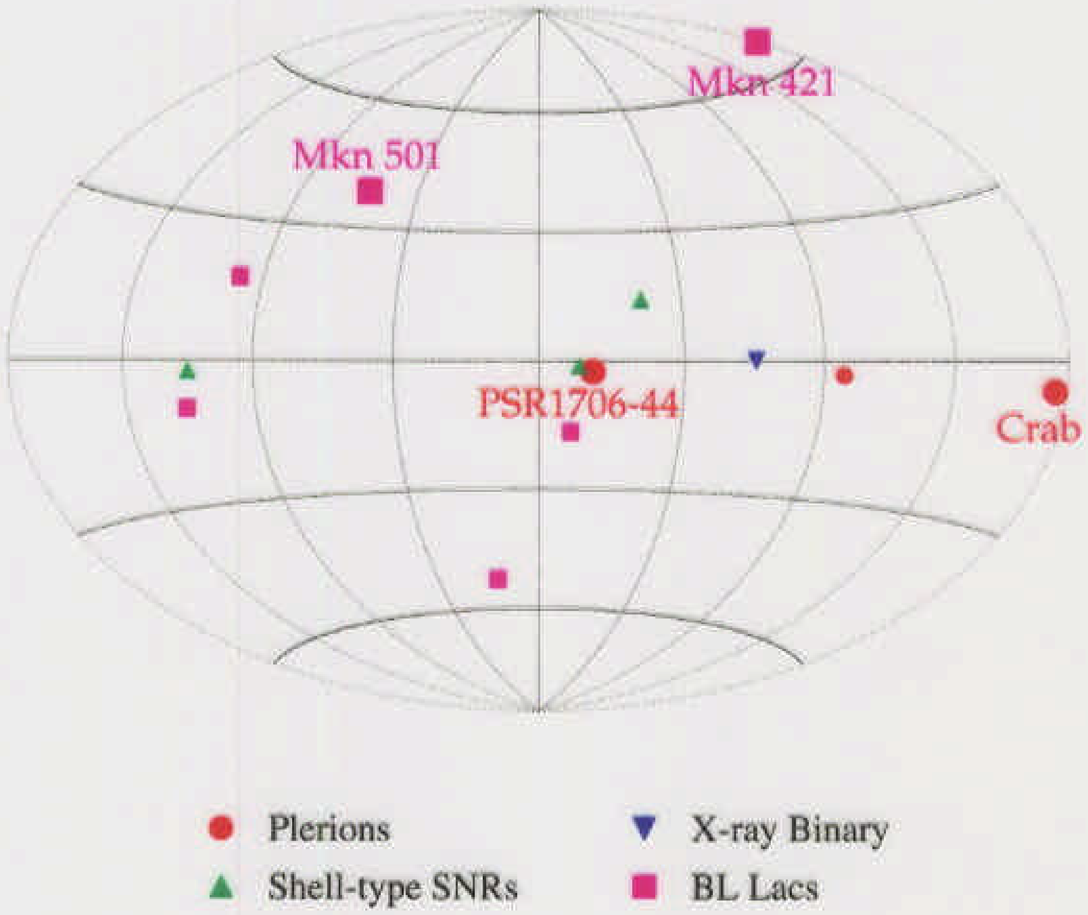
The Sky in the Light of >300 GeV Photons



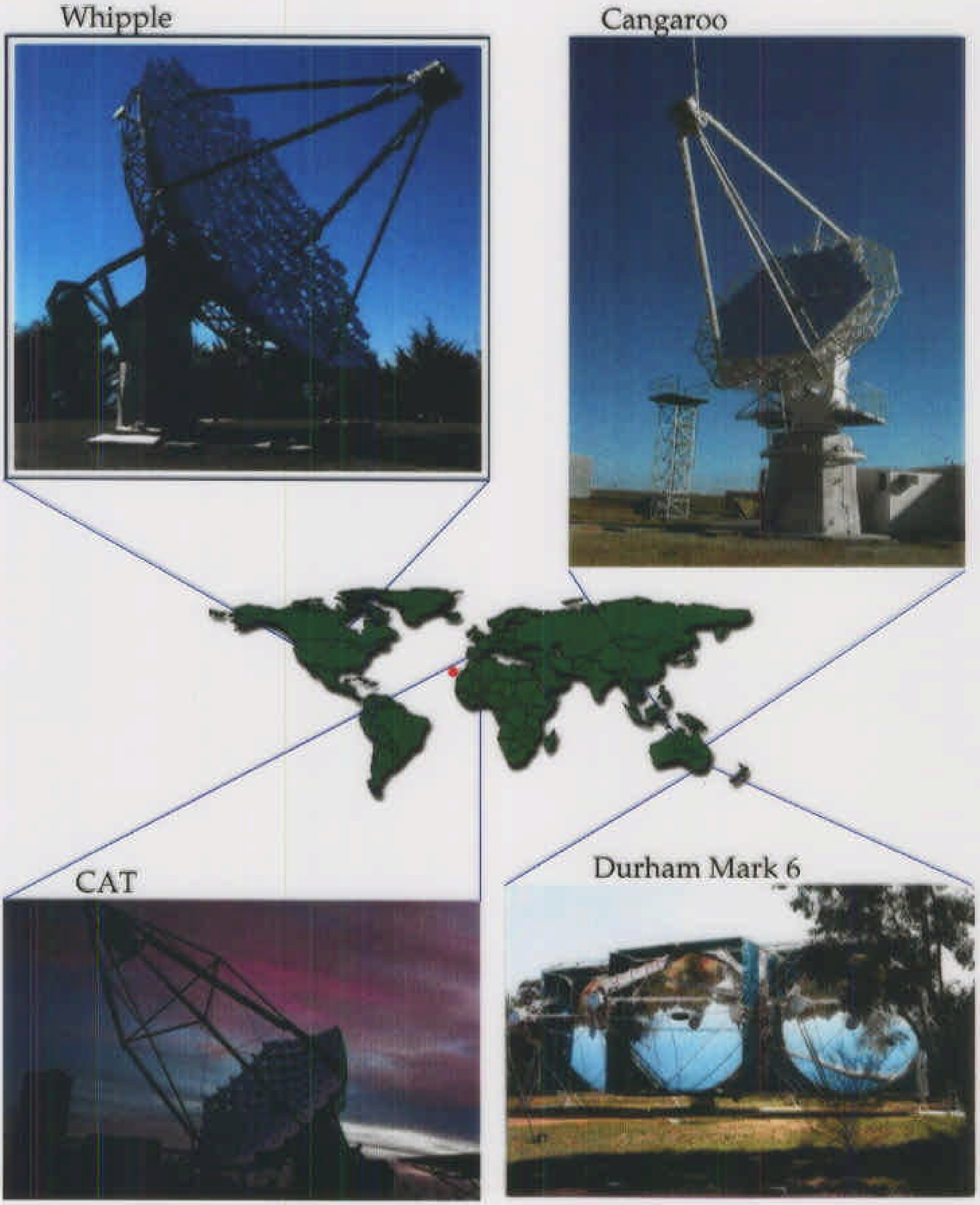
13 sources (+1 GRB?), 4 confirmed sources

Galactic Sources	Plerions
	Shell-type Supernova Remnants
	X-ray Binary
Extragalactic Sources	Blazars
Non-Detections	Galactic Plane
	Pulsars
	Non-blazar type AGNs

Existing Imaging Atmospheric Cherenkov Telescope (IACT) Facilities

Group	Countries	Locations	Telescopes Number x Aperture	Camera Pixels	Thresh. [TeV]	Epoch Beginning
Whipple	USA-UK-Ireland	Arizona, USA	10 m	331	0.25	1984
Crimea	Ukraine	Crimea	6 x 2.4 m	6 x 37	1.0	1985
SHALON	Russia	Tien Shen, Russia	4 m	244	1.0	1994
CANGAROO	Japan-Australia	Woomera, Austr.	3.8 m (now 10 m)	256	0.5	1994
HEGRA	Germany-Sp.-Arm..	La Palma, Spain	5 x 3 m	5 x 271	0.5	1994
CAT	France	Pyrenees, France	3 m	600	0.25	1996
(Durham)	UK	Narrabri, Austr.	3 x 7 m	1 x 109	0.25	1996
TACTIC	India	Mt. Abu, India	10 m	349	0.3	1997
(Seven TA)	Japan	Utah, USA	7 x 2 m	7 x 256	0.5	1998

[M.Catanese and T.Weekes, astro-ph/9906501]


Whipple
Cangaroo
CAT
Durham Mark 6

The HEGRA System of Imaging Atmospheric Cherenkov Telescopes

Canary Islands, La Palma, 2200 m asl

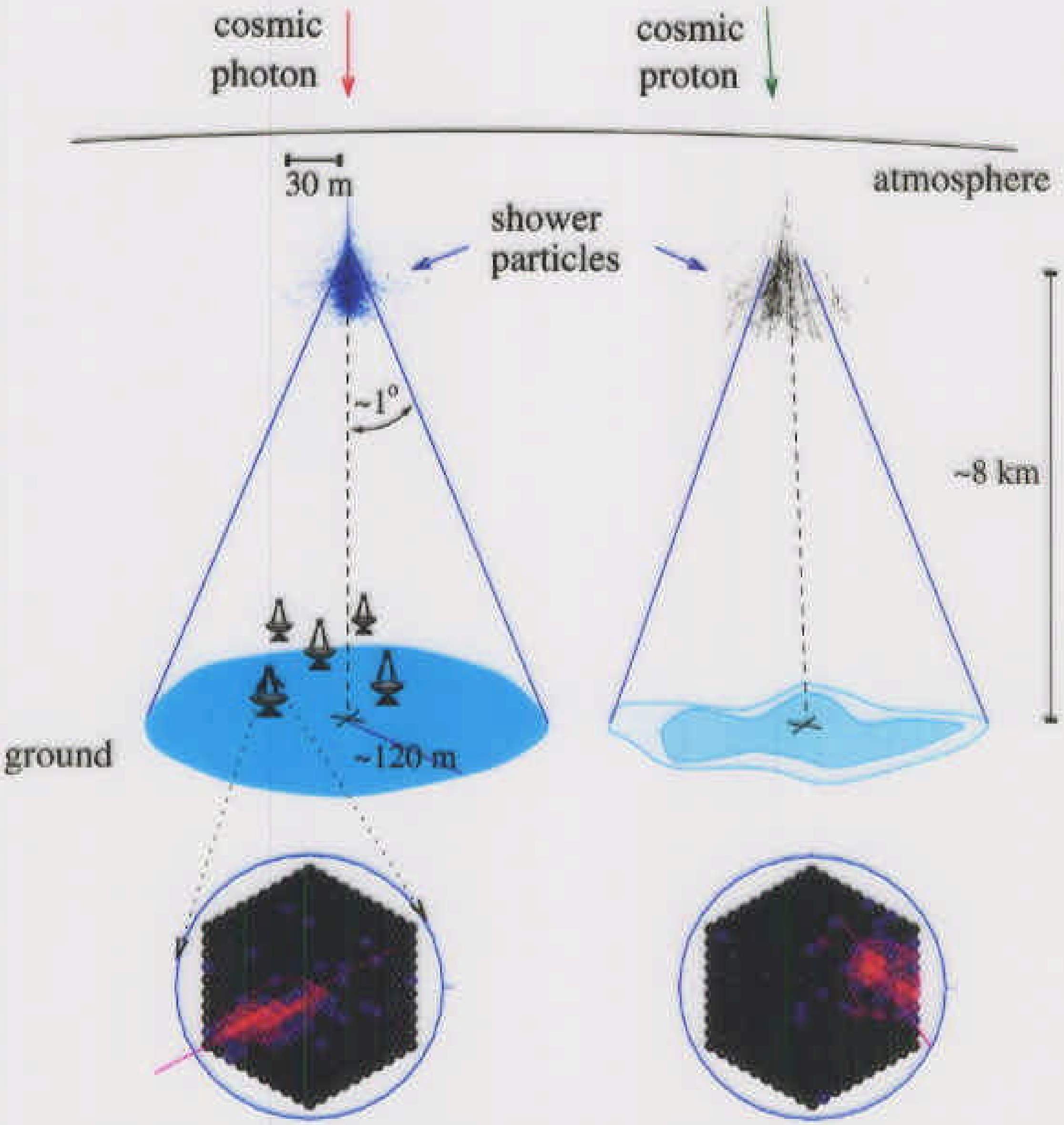
Stereoscopic System of 5 Telescopes

Reflector:	$A = 8.5\ m^2$
	$f = 5$ m
Camera:	271 Photomultipliers
	Pixel Size: 0.25°
	Field-of-view: 4.3°

System Performance

Energy Threshold	$E = 500$ GeV	
Angular Resolution	$0.05^{\circ} - 0.1^{\circ}$	} per event
Energy Resolution	$\Delta E/E < 20\,\%$	
Cosmic ray Rejection	$\kappa_{CR} = 1/100 \quad \kappa_{\gamma} = 40\,\%$	
Energy Flux Sensitivity	10^{-11} erg/cm^{2}s (1 h obs.)	

Stereoscopic Observations of Air Showers



HEGRA camera images:271 photomultiplier pixels

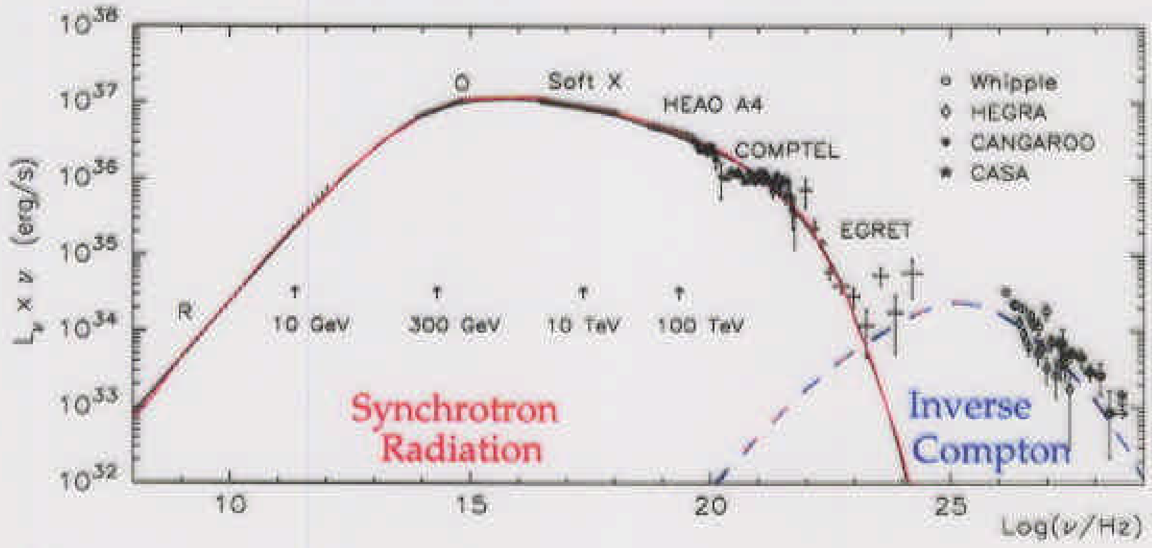
Shower core and primary particle direction	Superposition of the camera images
Particle identification	Image shapes
Energy reconstruction	Image amplitudes

TeV Plerions: The Crab Nebula (I)

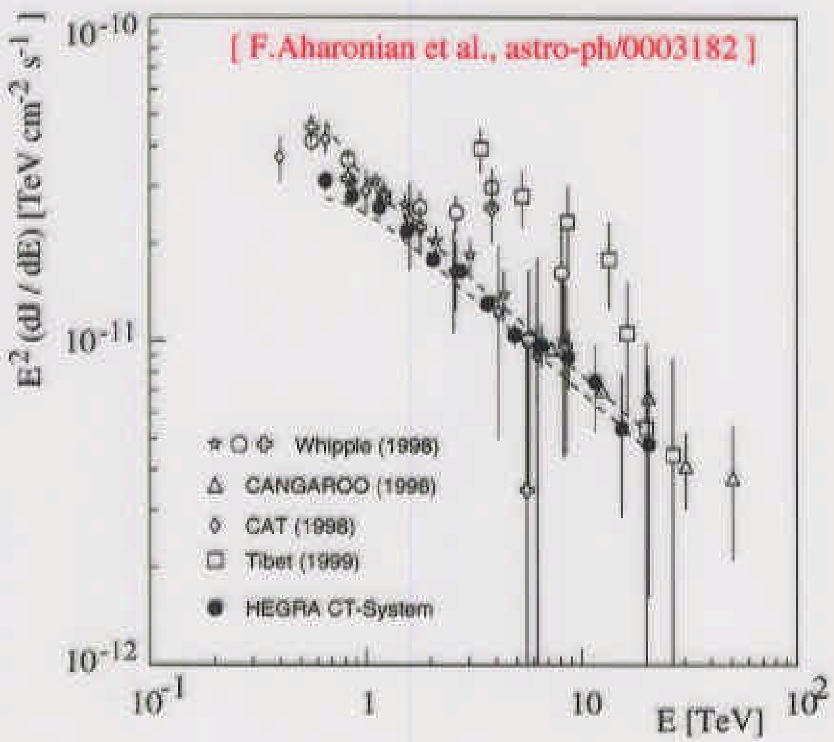
The "Standard Candle" of TeV astronomy

Radio - TeV flux well understood in the framework of

Synchrotron-Inverse-Compton models



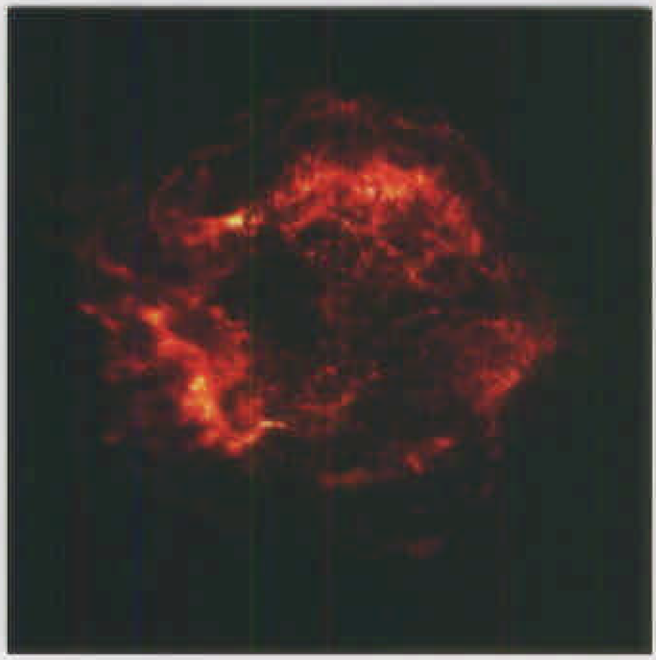
Good agreement of the TeV spectrum by different groups



$dN/dE = 2.79 \pm 0.02 \pm 0.5 \times 10^{-11} (E/TeV)^{-2.59 \pm 0.03 \pm 0.05} ph/cm^2\, s\, TeV$

Diffusive Shock Acceleration in Supernova Remnants

Supernova Remnants are
the best candidate sources
for cosmic rays < 10^{14} eV :



Energy balance: $L_{CR} \sim O(10^{-1})\ E_{mech}$

Fermi mechanism to naturally produce extended power laws

Heliospheric observations appear to confirm mechanism

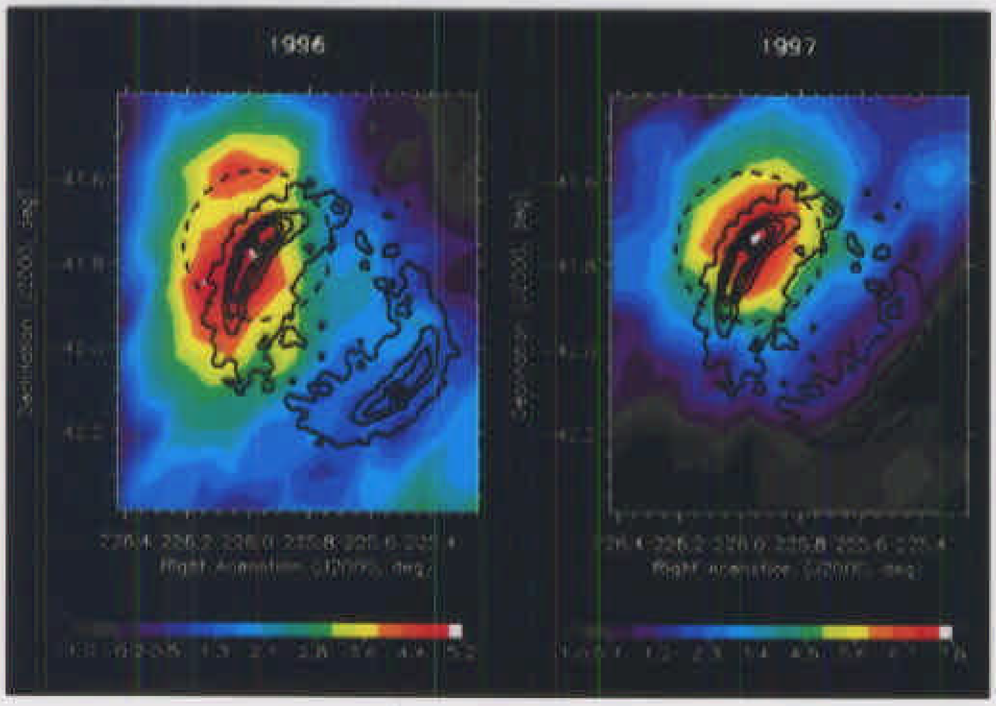
Detailed models: 10 % efficiency possible
predictions of time-dependent TeV flux

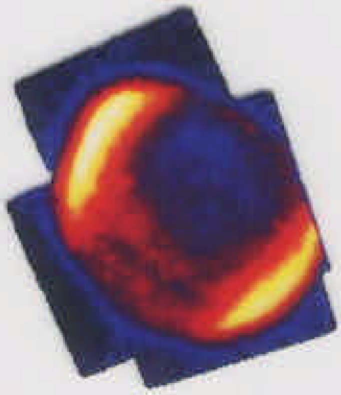
Detection of TeV emission from 3 shell-type SNRs:

Results not inconsistent with hadronic models, but also consistent with electron acceleration

Shell -Type Supernova Remnants: SN1006

Cangaroo: emission from the NE rim

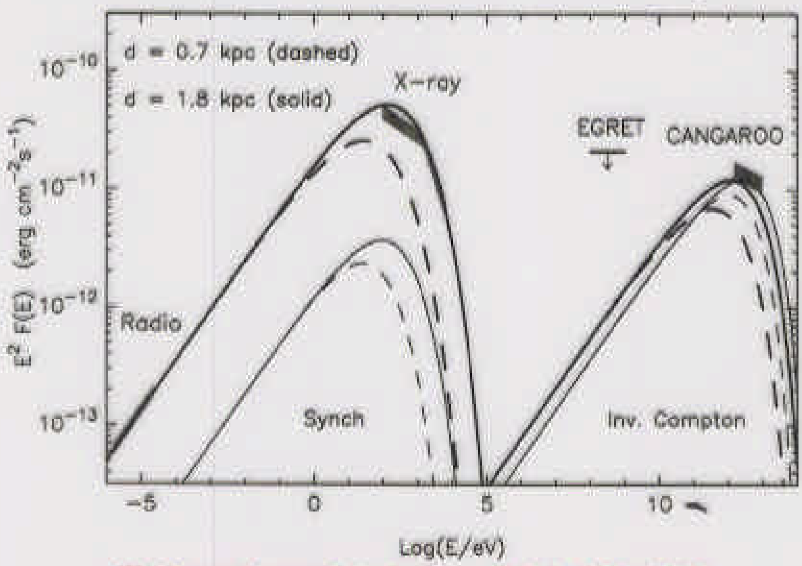




ASCA image

[T.Tanimori et al, ApJ, 497, L25, 1998]

Model: TeV flux arises from Inverse Compton emission of the non-thermal X-ray photons with the 2.7 K background field



[F.Aharonian and A.Atoyan, A&A, 351, 330]

Similar to SN1006: RXJ1713.7-3946 [H. Muraishi et al., astro-ph/0001047]

Shell-type Supernova Remnants: Cassiopeia A

HEGRA:

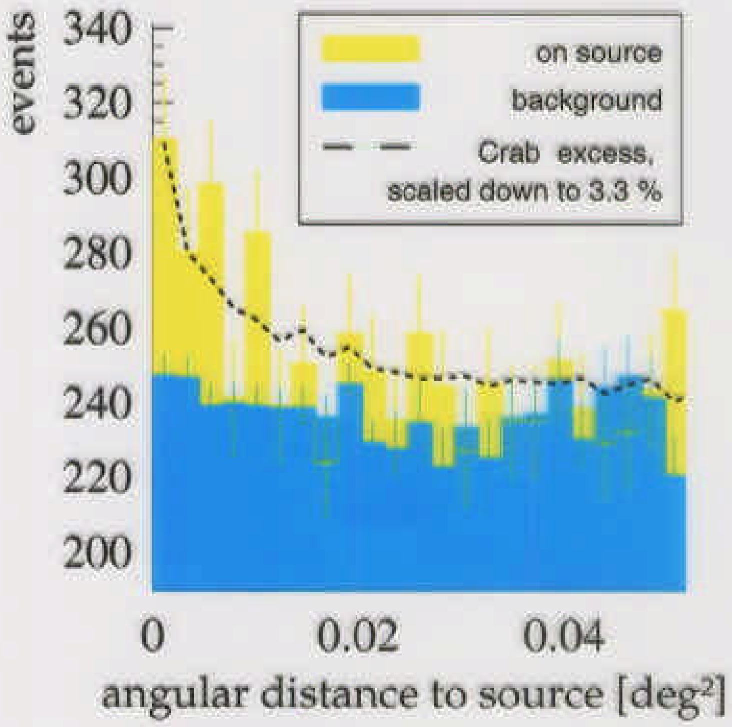
232 h, 4.9σ

Flux F(E > 1TeV) =

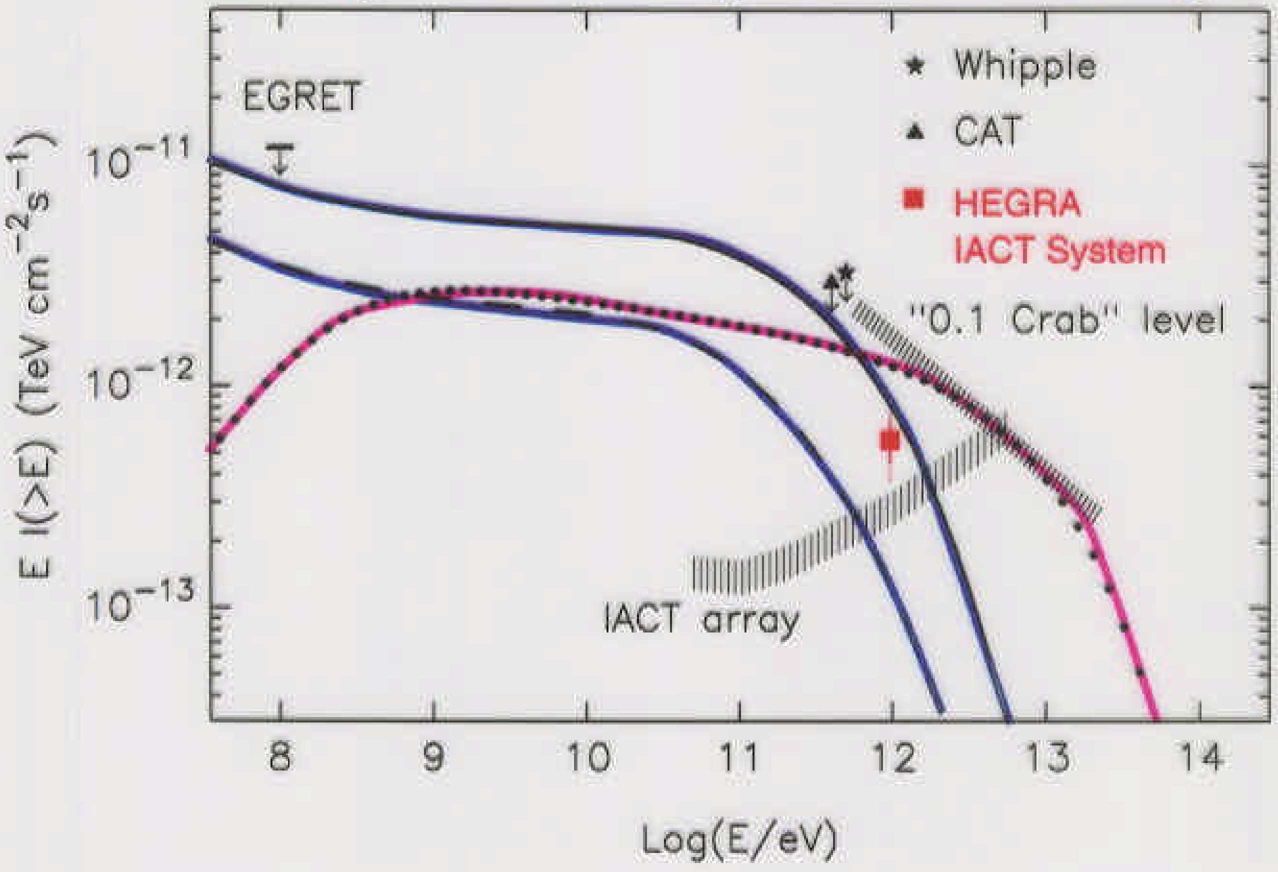
$(5.8+1.2+2.0) \times 10^{-13}$ ph /cm^2 s

(33 milli-Crab)

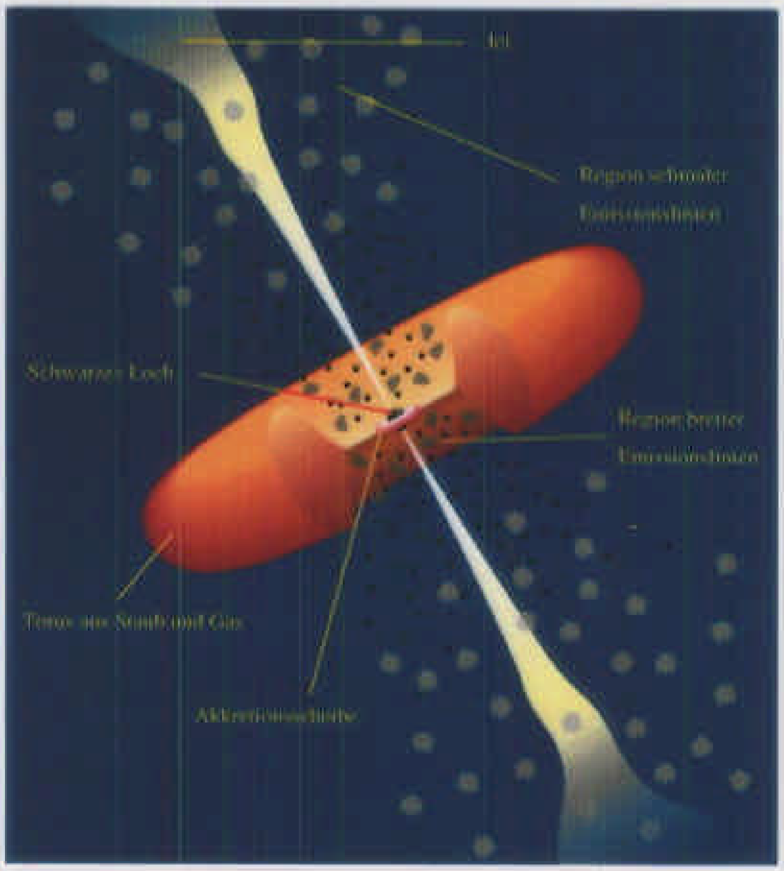
[Pühlhofer et al., 2000]



π^0-decay vs. inverse Compton and Bremsstrahlung



The Blazar Class of Active Galactic Nuclei (AGNs)



[C.Urry and P.Padovani, PASP, 107, 803, 1995]

Blazars are radio-loud AGNs characterized by polarized , luminous, rapidly variable, non-thermal continuum emission from radio to gamma-rays

Interpretation: Jets are closely aligned with the viewing angle

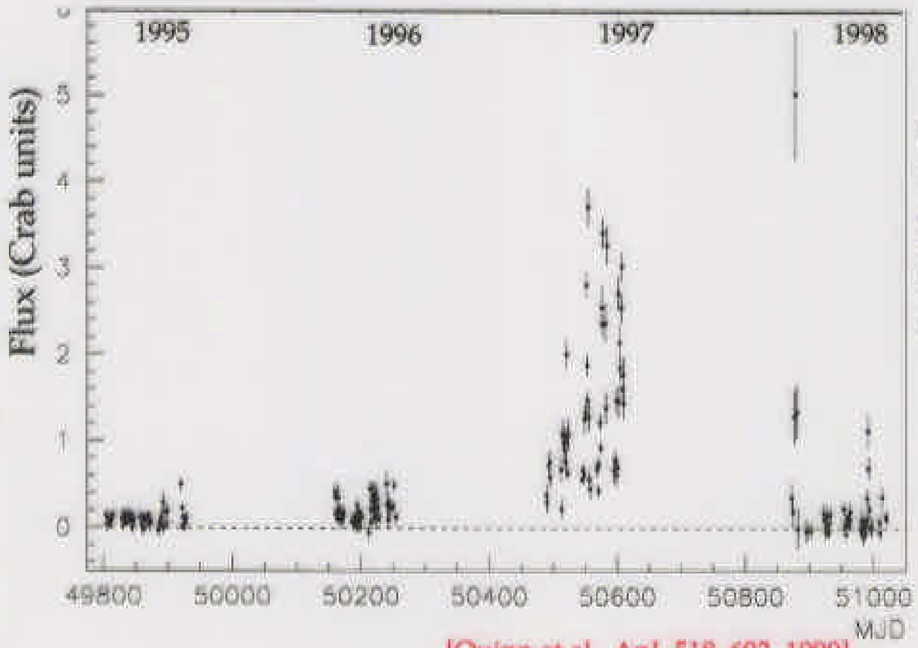
TeV emission: leptonic or hadronic origin?

Observational Status:
6 sources, 2 confirmed
Mkn 421, Mkn 501
1ES2344+514, PKS2155-304, 3C66A, 1ES1959+650

Time Variability in TeV Blazars

Mkn 501

Variability on timescales down to hours (minutes?)
Evidence for a 23-day periodicity in 1997

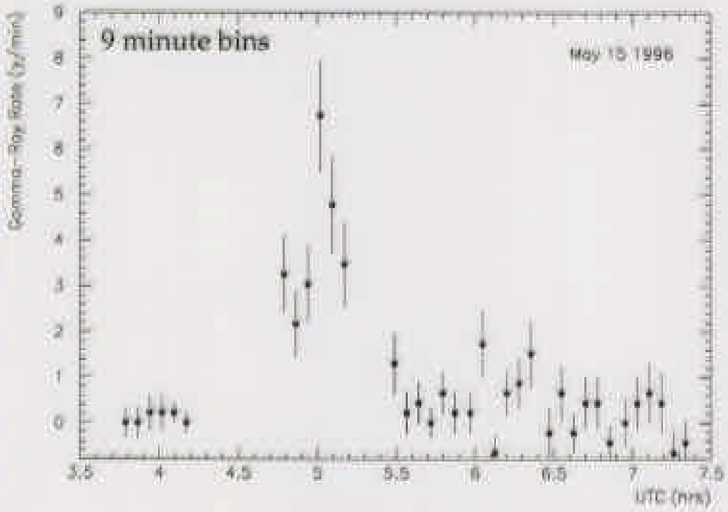


mean flux:
1995: 0.1 Crab
1996: 0.2 Crab
1997: 1.4 Crab
1998: 0.2 Crab

[Quinn et al., ApJ, 518, 693, 1999]

Mkn 421

Shortest doubling time 15-30 minutes



[Gaidos et al., Nature,383, 319, 1996]

Severe constraints on the size of the emitting volume:

$$R < \delta c \Delta t = 10^{15} \ (\delta / 10) \ (\Delta t / 1h) \ \text{cm}$$

region optically thin to TeV gamma-rays -> lower limit on δ

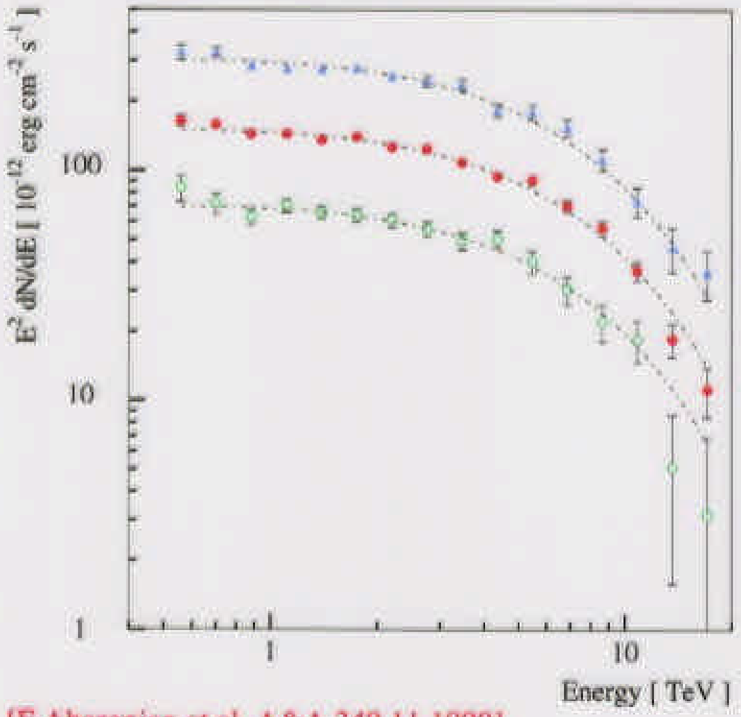
Limit on quantum gravity effects

$\Delta t = \xi E / E_{QG} \cdot L/c$ $\qquad$ $E_{QG} / \xi > 4 \cdot 10^{16}$ GeV 95% CL

[Biller et al., ApJ, 508, L21, 1999]

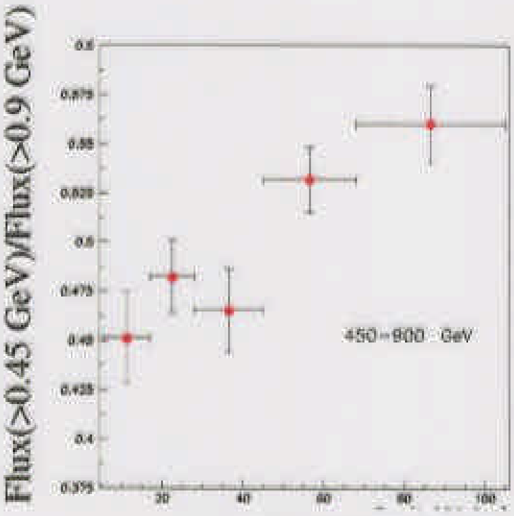
Spectra of TeV Blazars

HEGRA Mkn 501 flux-selected mean energy spectra for 1997: no evidence for correlation of absolute flux and spectral shape



[F.Aharonian et al, A&A,349,11,1999]

CAT: correlation between hardness ratio and source intensity

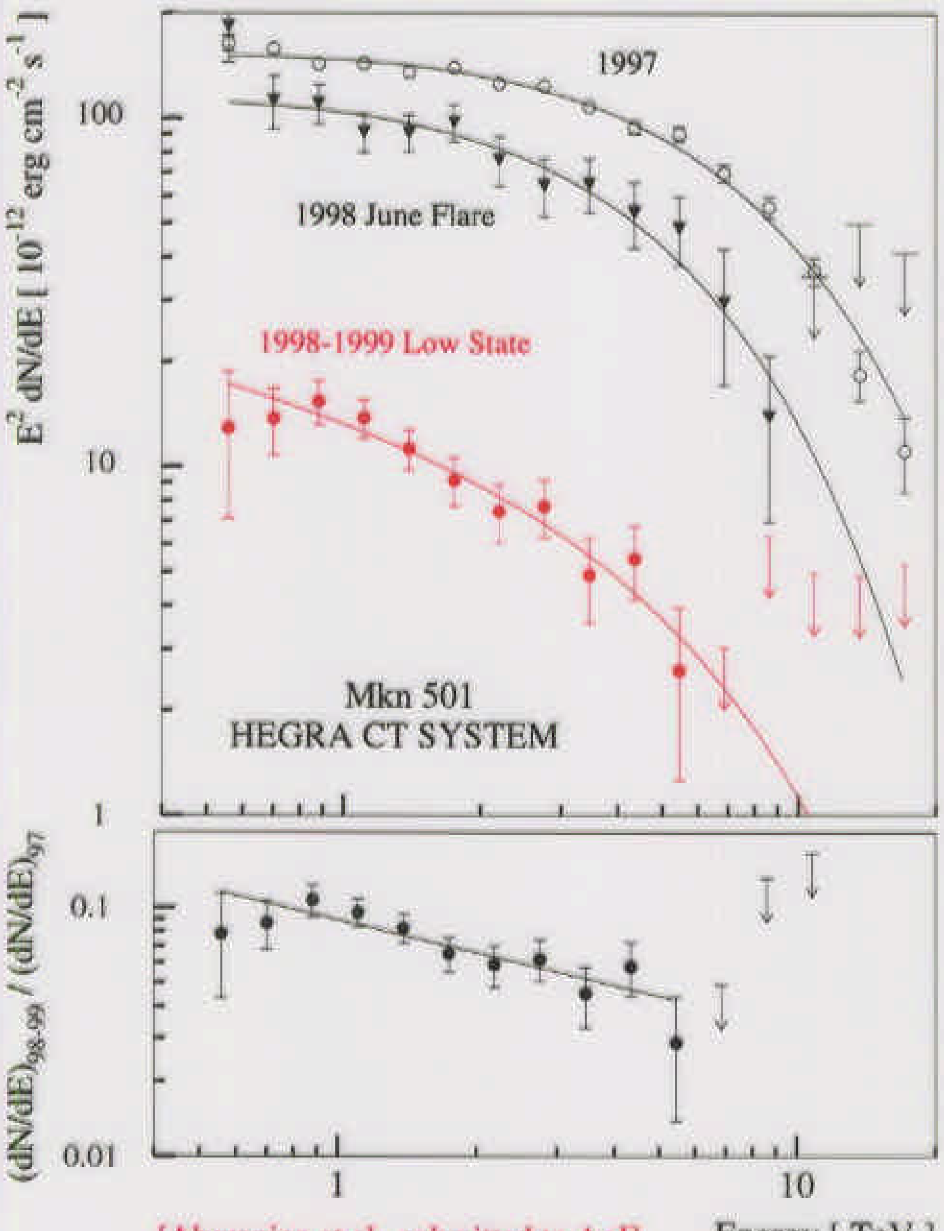


[A.Djannati-Atai et al, A&A,350,17,1999]

Results not necessarily in conflict (energy range, data sets)

Spectra of TeV Blazars (II)

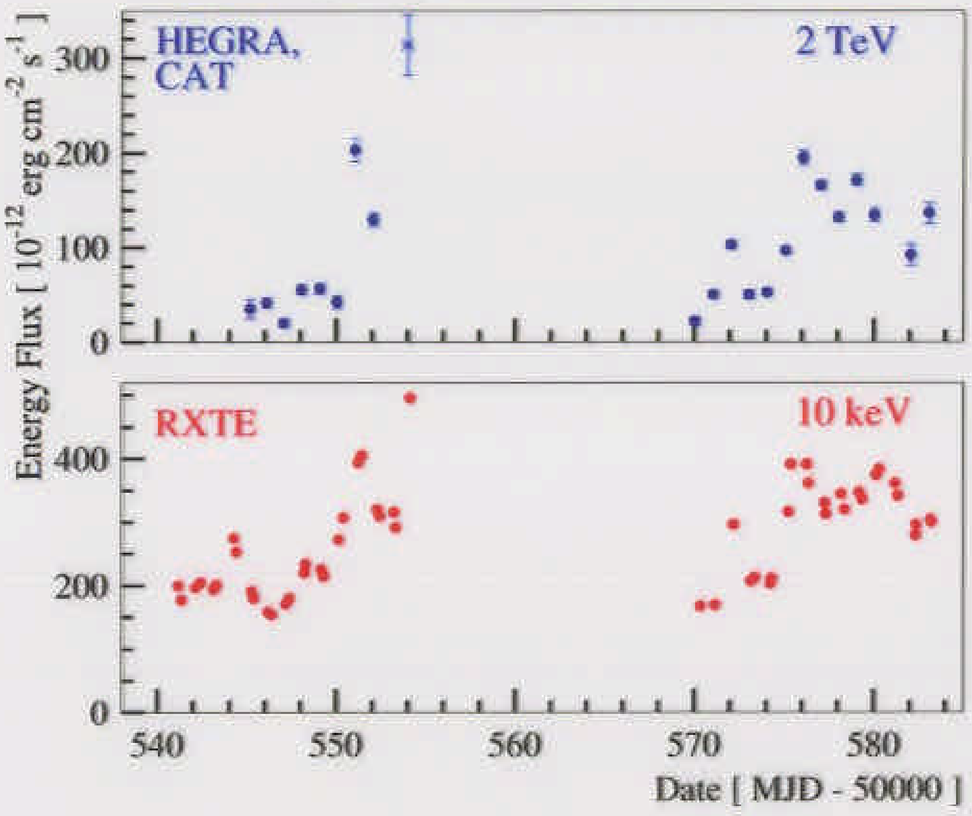
1998 - 1999 low state TeV energy spectrum of Mkn501:
Spectrum steepened by 0.44 +-0.1 compared with 1997



[Aharonian et al., submitted to ApJ]

Multiwavelength Observations of the Blazar Mkn 501 in 1997

TeV/X-ray integral flux vs. time:

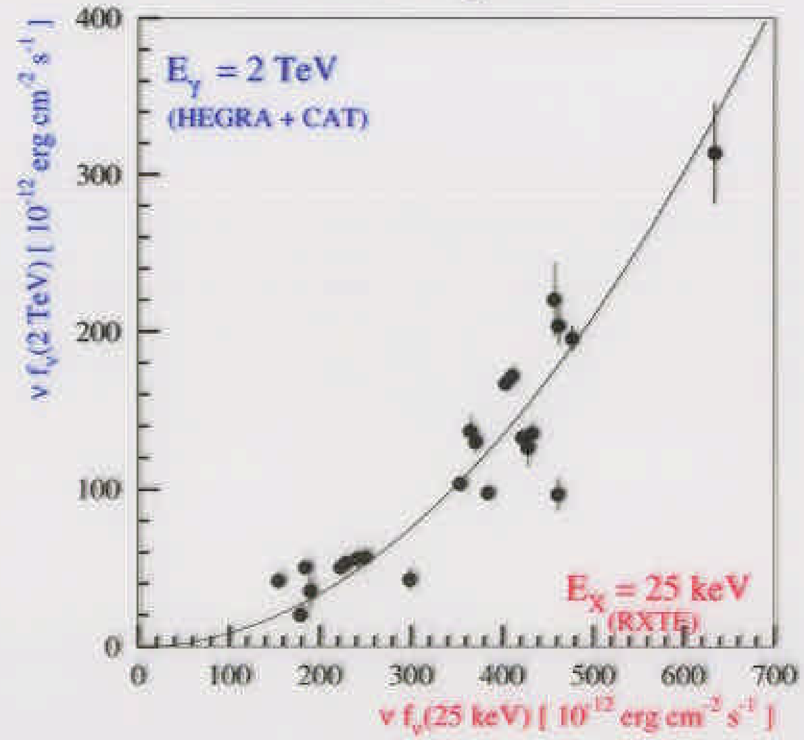


X-ray variations simultaneous with TeV variations (time lag < 15 h)

[H.Krawczynski, P.S.Coppi, T.Maccarone, F.A.Aharonian, 2000]

Tight correlation of the X-ray flux with the TeV flux

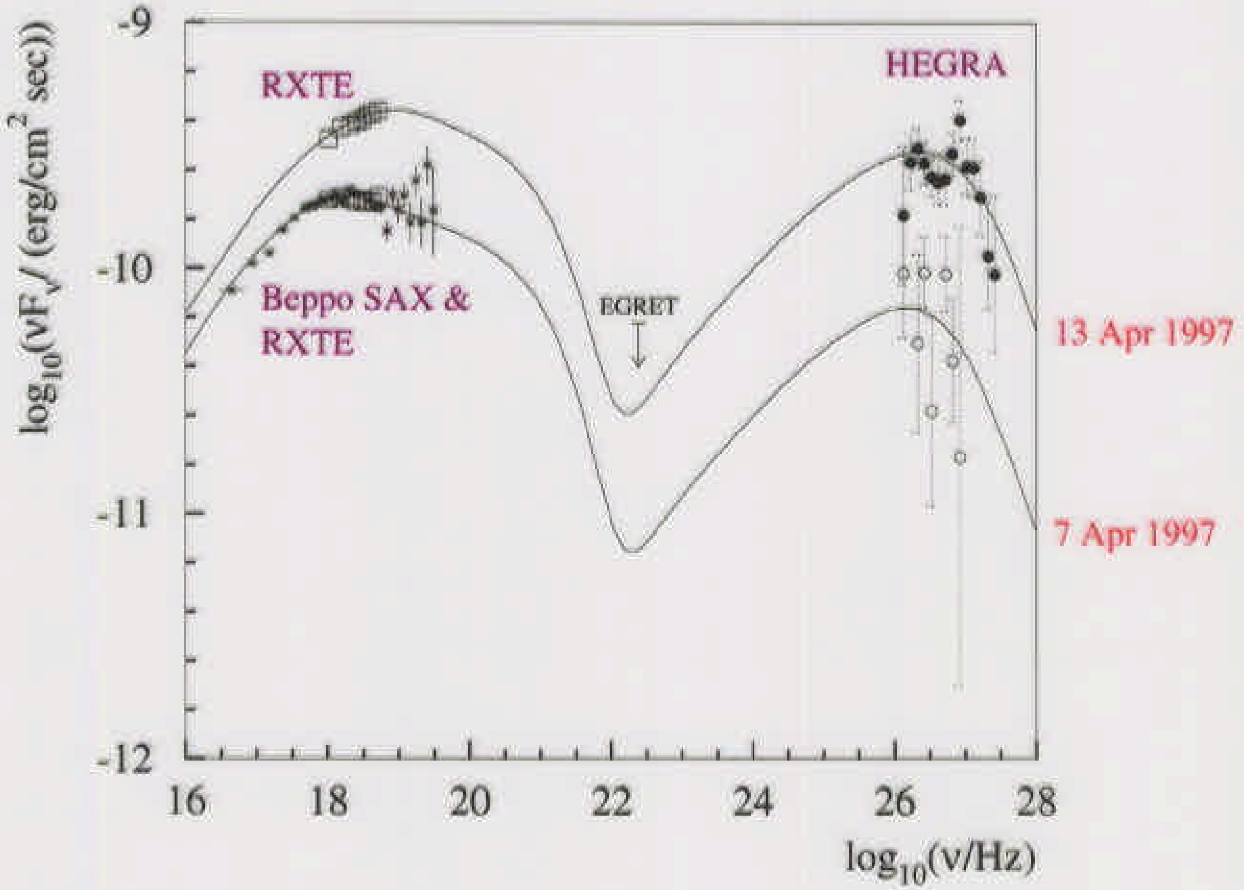
TeV flux varies quadratically with the X-ray flux



Modelling the 1997 Mkn501 Data

Interpretation in the context of shock acceleration

and synchtron-self Compton emission



$dN / dE \propto E^{-2.2}$

$\delta > 15$

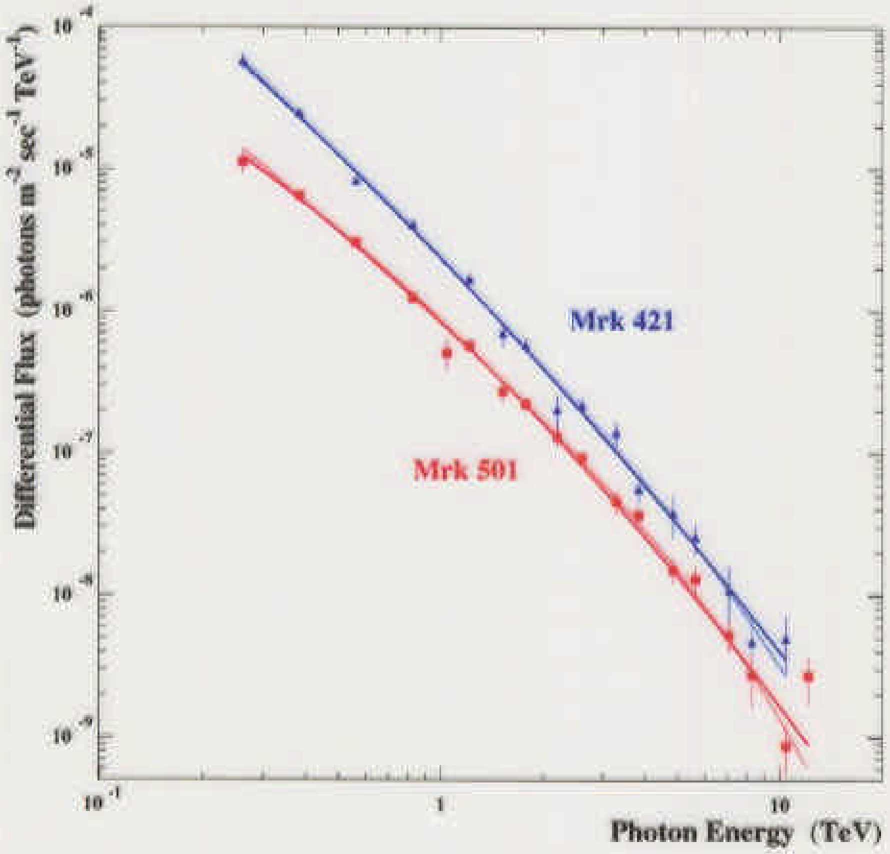
$0.012\ G < B < 0.12\ G$

SSC accounts for rapid variability (injection, change in high/low energy cutoff of electron spectrum), and tight and quadratic X/TeV correlation

BUT: where are the hadrons?

Probing the Extragalactic Background Light

Intriguing (but different) curvature in the Mkn 421 / Mkn 501 spectra: common curvature due to attenuation by extragalactic background light?



[F.Krennrich et al., ApJ, 511, 149, 1999]
[V.Vassiliev, Astropart.Phys.,12,217,2000]

Energy-dependent gamma-ray attenuation via

$\gamma_{EBL} + \gamma_{TeV} \longrightarrow e^{+} + e^{-}$

maximal cross-section for $\quad 0.28\, E_{TeV} \times E_{EBL} = (mc^2)^2$

(1.3 μm / 0.9 eV for 1 TeV)

Large uncertainty in direct EBL measurements

Determination of the infrared EBL probes the history of star formation in our Universe

Dark Matter Search with TeV Astronomy

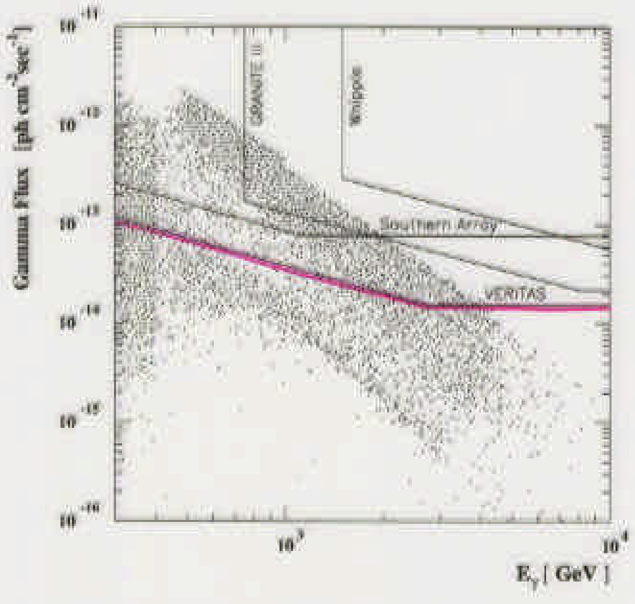
Radiation from wimp annihilation or relic particle decay from the Galactic halo or other close galaxies (M87, local dwarf galaxies) could lead to a detectable TeV signal for next-generation IACTs

Sensitivity to some regions parameter space

$\chi\chi$ --> $\gamma\gamma$ --> annihilation line
γZ^o

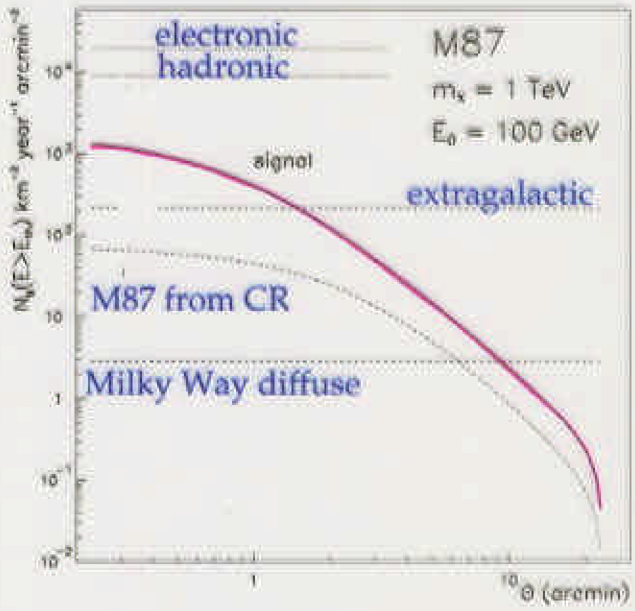
$\chi\chi$ --> W^+W^- --> hadrons --> gamma-ray continuum
or $Z^o Z^o$
χ $q\bar{q}$
⋮

Summed line flux from the Galactic center for heavy χ



[Bergström, Ullio and Buckley, 1997]

Radial profile of the χ-induced signal for M87

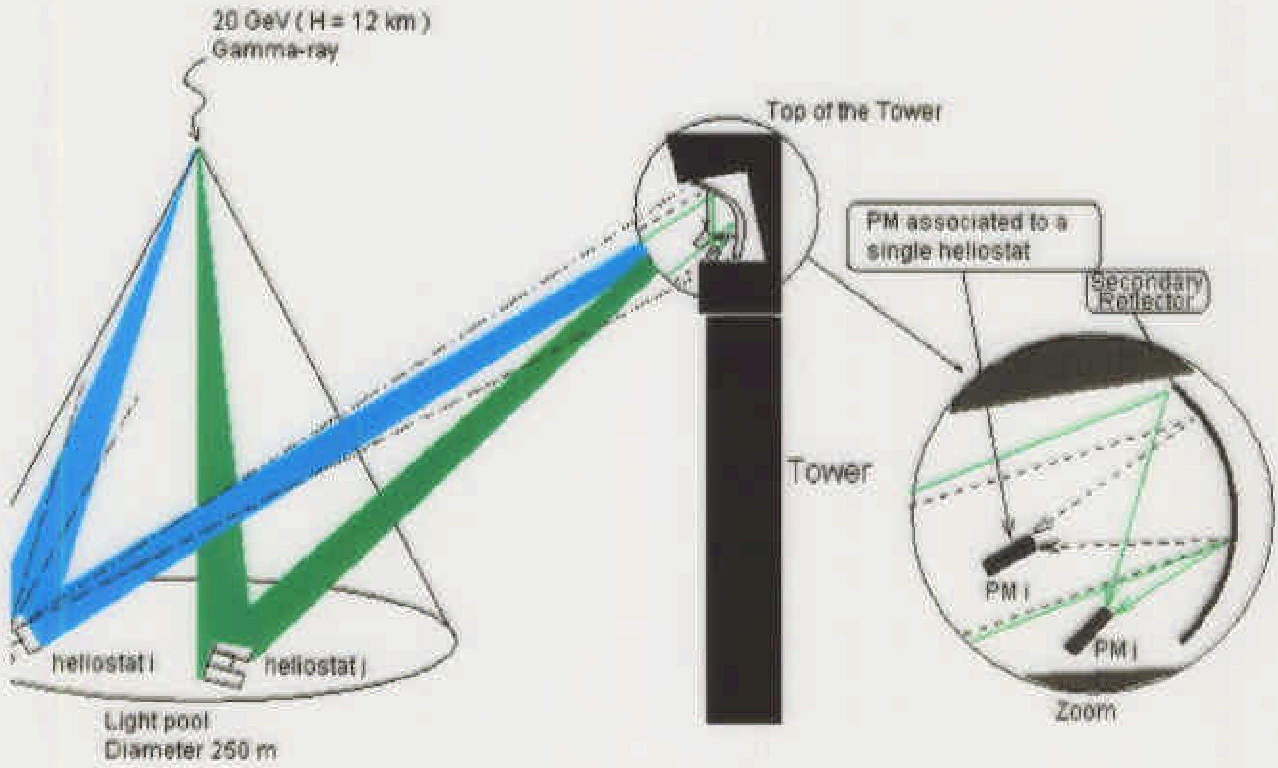


[Baltz et al., 1999]

Solar Farm Atmospheric Cherenkov Facilities (I)

Exploit the large mirror area of solar farm facilities to achieve a low energy threshold

Secondary optics in the tower : One Photomultiplier per heliostat



Solar Farm Cherenkov Telescope Facilities

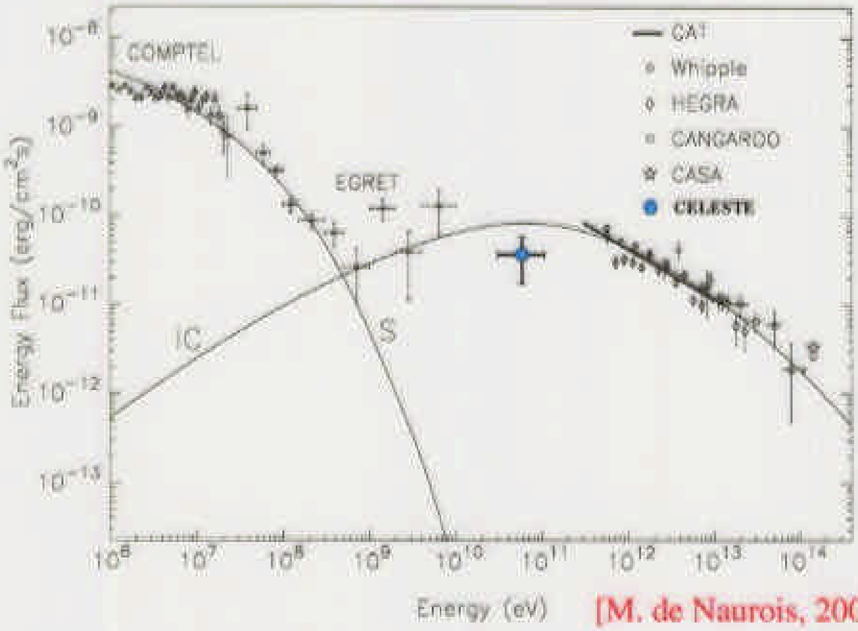
Group	Countries	Locations	Number of Heliostats	Mirror Area [m^2]	Thresh. [GeV]	Epoch Beginning
Stacee	USA-Canada	New Mexico, USA	32 (64)	1200 (2400)	190 (50)	1998
Celeste	France	Pyrenees, France	40 (54)	2200 (2900)	50 (30)	1998
Graal	Germany-Spain	Almeria, Spain	27 (63), 4 PMTs	1100 (2500)	(200)	1999
Solar Two	USA	California, USA	32 (64)	1300 (2600)		2000

CELESTE

STACEE

Results from Solar Farm Cherenkov Experiments

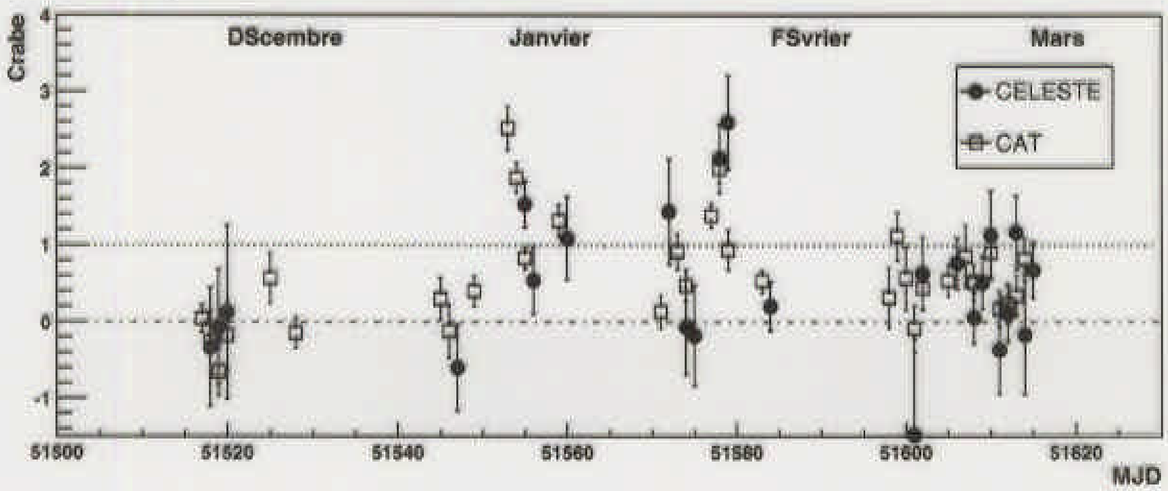
CELESTE: 7.6 σ from the Crab in 17 h of observation 99/00



[M. de Naurois, 2000]

Energy threshold: 50 GeV

8 σ from Mkn421 in 5 h of observation 01-02/00
variability correlated with CAT



STACEE-32: 7 σ from the Crab in 43 h 11/98-2/99
energy threshold: 190 GeV
just starting with 48 heliostats

lots of interesting physics to come:
turnover of pulsar emission, cutoffs of blazar spectra due to IR absorption, EGRET unidentified sources, SNR spectra, ...

Large field-of-view detectors for TeV astronomy

Group	Alt. [m asl]	Technique	Area [m^2]	Thresh. [TeV]	Start
Tibet HD array	4300	scintillator array	4800	3 TeV	1996
Milagro	4300	water Cherenkov	5000	<1 TeV	1999
Argo	4300	Res. Plate Counters	6500	<1 TeV	2001

Tibet III air shower array

Large field-of-view, high duty cycle at the cost of sensitivity

Ideal for All-sky monitoring of transients
Gamma-ray Bursts

Tibet HD array: 5.5 σ from the Crab (1996-1999)
4.7 σ from Mkn 501 in 1997

Milagrito (prototype Milagro detector):

3.7 σ from Mkn 501 in 1997
possible detection of the GRB 970417a
(2×10^{-3} chance probability)

The Future of TeV Gamma-ray Astronomy

. . . IS BRIGHT!

4 next-generation IACT experiments starting 2000-2004
One order of magnitude improvement in sensitivity
Lower energy threshold 30-100 GeV ($z \sim 1$)

Huge astrophysics and particle physics potential

Sources of cosmic rays, diffuse IR background, pair halos around UHE source, AGNs, Radio Galaxies, Quasars, Rich Galaxy clusters, nearby starburst galaxies, Supernova Remnants, Pulsars, Pulsar Nebulae, Accreting Neutron-Stars, Stellar Black Holes, Micro-Quasars, Giant Molecular Clouds, Charged Cosmic Rays, Diffuse Emission from the Galactic Disc, Gamma-ray Bursts, Dark Matter Search Lorentz symmetry violation, Observational Cosmology, . . .