

Experimental Particle Astrophysics
High Energy Particles from the Universe

Bernard DEGRANGE

LPNHE Ecole Polytechnique

and IN2P3/CNRS, France

THE UNIVERSE AS A LABORATORY

FOR ASTROPHYSICS

Violent, non thermal phenomena

Relativistic objects

Cosmic accelerators

Antimatter

FOR PARTICLE PHYSICS

Cosmological relics

(topological defects,

SUSY dark matter)

NEW LARGE EXPERIMENTS

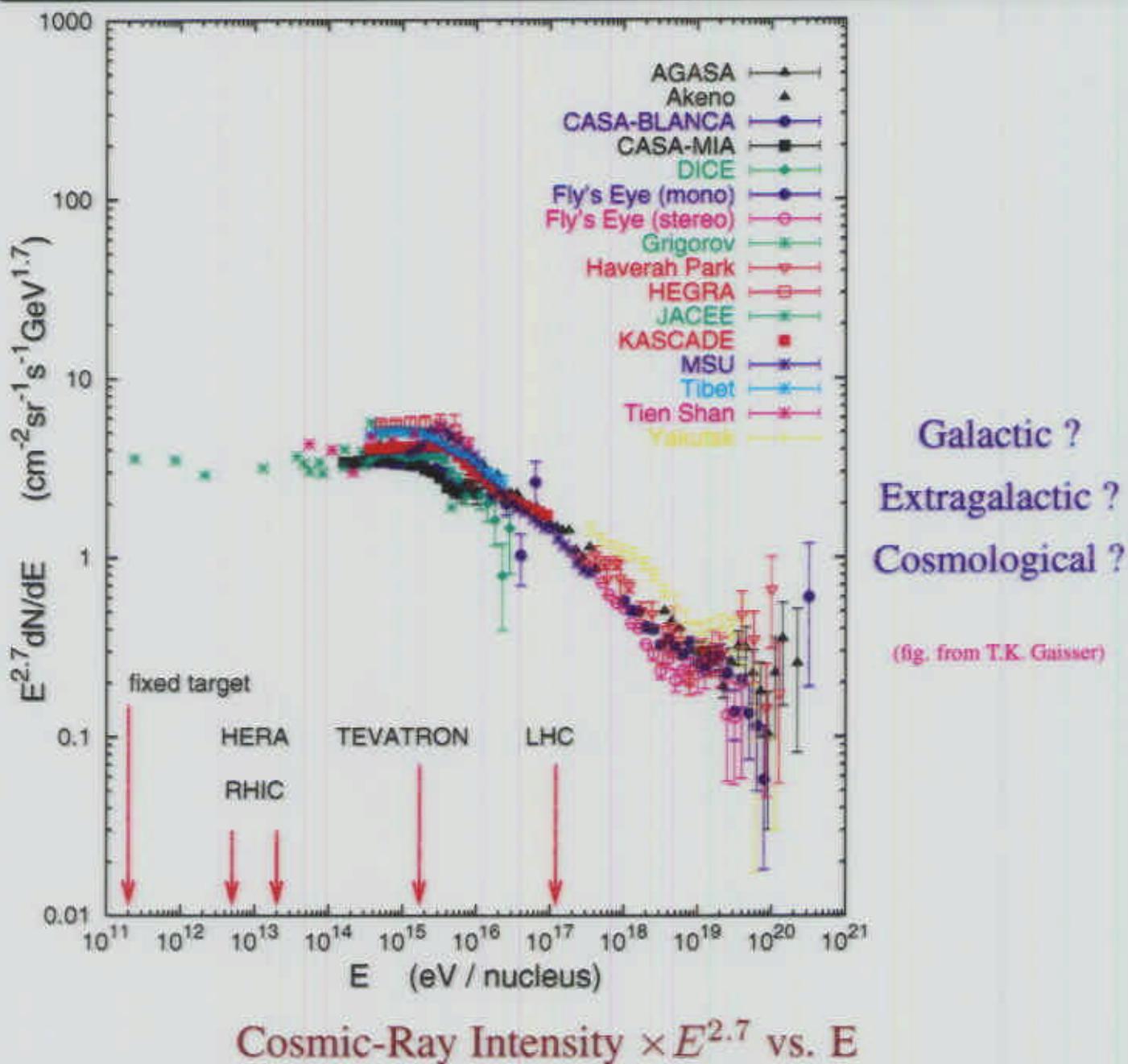
in space

ground-based

USING THE TECHNIQUES

OF PARTICLE PHYSICS

AN OLD ENIGMA : The origin of Cosmic Rays



- No **directional** information for charged cosmic rays:
(irregular $\sim \mu\text{G}$ galactic magnetic fields)
- Structures in the spectrum (**Knee**, **Ankle**) not understood
- Direct measurements from satellites up to $\sim 100 \text{ TeV}$
- Extensive air shower arrays above $\sim 100 \text{ TeV}$

Experimental Particle Astrophysics

High Energy Particles from the Universe

No directional information for charged cosmic rays
(irregular $\sim \mu\text{G}$ galactic magnetic fields)

DETECT MINORITY but MEANINGFUL PARTICLES

- Neutral and stable particles :
 γ -rays and neutrinos ($\nu, \bar{\nu}$)
- Protons and nuclei for $E > 10^{19}$ eV (UHE Cosmic Rays)
(Larmor radius > 10 kpc \sim dimensions of Galaxy)
- Antiprotons, anti-nuclei

PLAN OF THE TALK

1. Charged cosmic rays and antimatter
2. Cosmic-ray sources revealed by γ -ray astronomy
3. Gamma-ray astronomy : present & future
4. The birth of neutrino astronomy
5. Exploring the UHE energy domain

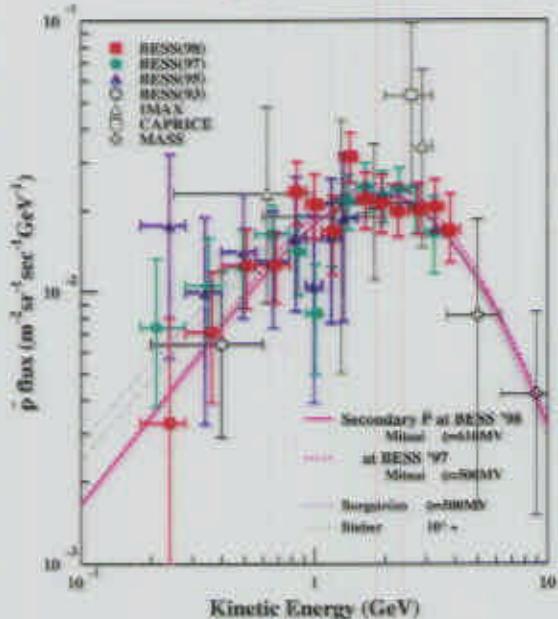
ANTIMATTER IN COSMIC RAYS

Magnetic spectrometer → Rigidity $\frac{pc}{Ze}$

dE/dx and time of flight → velocity and electric charge

Cherenkov counter → additional discrimination

- Are all \bar{p} 's due to interactions in the interstellar medium ?



Most recent results (BESS 98)
~ 400 \bar{p} 's (0.2 GeV - 3 GeV)
compatible with secondary origin
but significant amount of "exotic" \bar{p} 's
(e.g. from WIMP's annihilation)
not excluded

- Are there anti-nuclei ? Possible primordial antimatter ?

Most recent results on anti-helium

BESS 1993-1998	AMS-01 1998 flight
Altit. 37 km	Altit. 400 km
Balloon	Space shuttle
$0.085 \text{ m}^2 \times \text{sr}$	$0.30 \text{ m}^2 \times \text{sr}$
$\bar{He}/He < 0.74 \times 10^{-6}$	$\bar{He}/He < 1.1 \times 10^{-6}$

V. Choutko PA-09

FUTURE C.R. EXPERIMENTS IN SPACE

Larger areas. Rigidity measurements up to TV.

Better particle identification (TRD, RICH)

- **PAMELA** : launch in 2002 ; polar orbit

In 3 years : \bar{p} spectrum 100 MeV - 150 GeV

\bar{He}/He at the 10^{-7} level

- **AMS-02** on International Space Station in 2003

In 3 years : $10^6 \bar{p}$ with $E > 5$ GeV

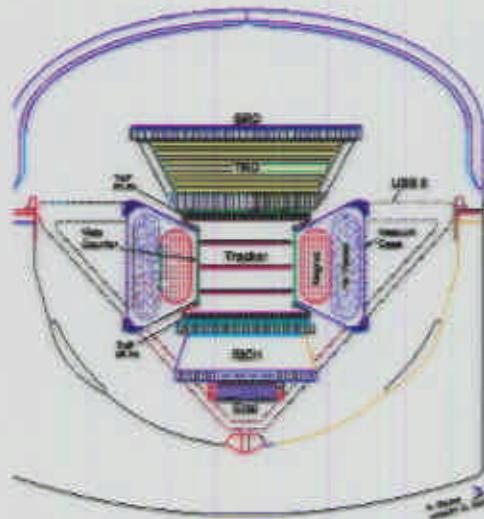
\bar{He}/He at the 10^{-9} level

High accuracy measurements of CR spectra for various nuclei up to TeV

(isotopic composition up to $A \sim 25$)

- **ACCESS** on International Space Station 2006 or 2007 ?

Ultra-heavy nuclei up to > 100 TeV (study stage)



A sketch ofAMS-02

High Energy Particles from the Universe

COSMIC RAYS SOURCES REVEALED BY γ -RAY ASTRONOMY

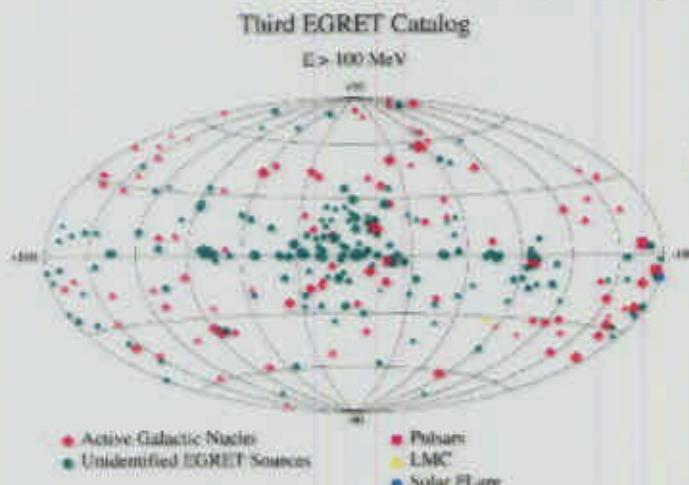
- 2.a The Compton GRO Mission
- 2.b Possible sources and processes

NON THERMAL PROCESSES	ACCELERATIONS			COSMOLOGICAL ORIGINS	
	"ONE SHOT", STOCHASTIC,	DIFFUSIVE	SHOCK ACC.		
ACCRETION ON COMPACT OBJECTS	RELATIVISTIC JETS	EXPLOSIVE PHENOMENA	MAGNETIC STARS	NEW PHYSICS	
				NEUTRINO Annihilation	
				PRIMORDIAL BLACK HOLES	
				TOPOLOGICAL DEFECTS	
				e ⁺ , e ⁻	
OB-JE-CTS					
X-ray Binaries μ -Quasars	ACTIVE Galactic NUCLEI	GRAN- RAY BURSTS	PULSARS & NEUTRINOS		
Emission	X, γ	X, γ	X, γ	X, γ	
ABSORPTION (Extragal. Sources)	$\gamma + \text{Proton} \rightarrow e^+e^-$	$\gamma + \text{Proton} \rightarrow \Delta^+ \rightarrow \pi^+ \pi^- \pi^0$	$\gamma + \text{Proton} \rightarrow \text{UHE}$	$\gamma, \nu\bar{\nu}, \bar{p}, p, e^+$	(?)

SOURCES AND PROCESSES

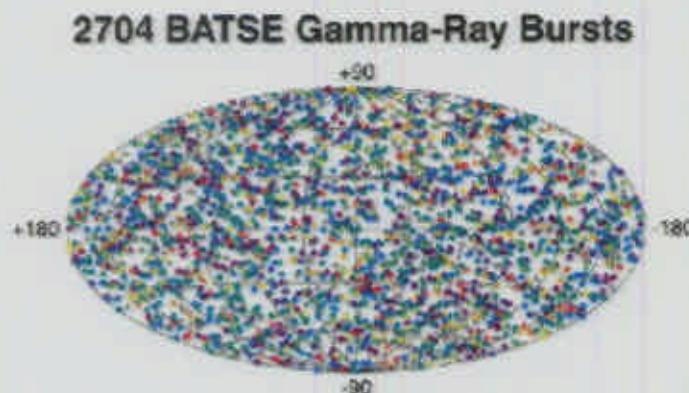
The Compton Gamma-Ray Observatory

(1991 - June 3rd 2000)



EGRET (Spark Chamber + Calor.)
100 MeV - 30 GeV
 ~ 300 sources

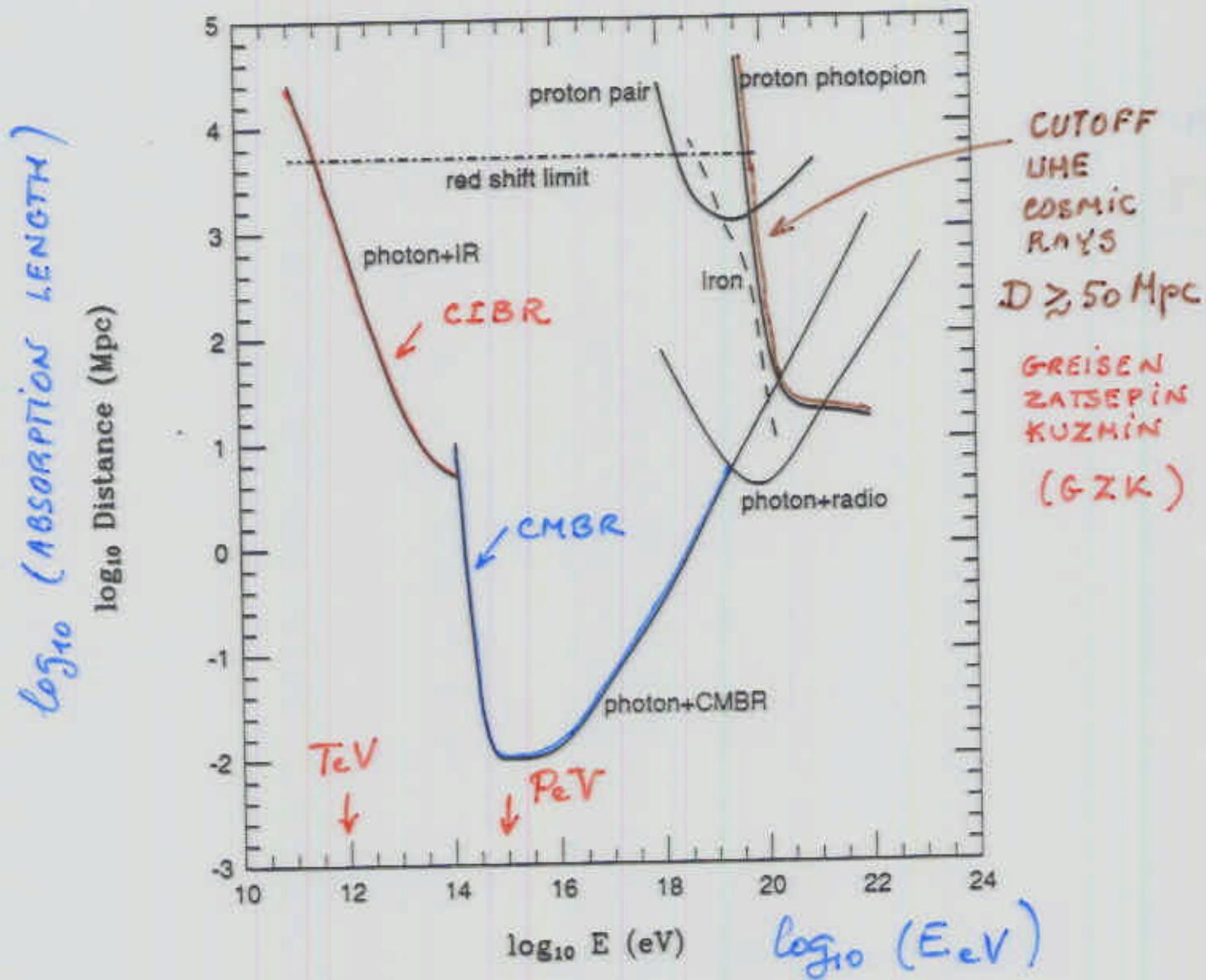
- Diffuse γ -ray flux : (CR + Interstellar Medium $\rightarrow \gamma$)
- Galactic sources : pulsars, supernova remnants, unidentified
- Extragalactic sources : blazar class of active galactic nuclei
Relativistic plasma jets with Γ (Lorentz) ~ 10
directed towards the observer



BATSE + X-ray satellites
(Beppo-SAX)
+ optical telescopes

- Isotropic distribution
- Up to 10^{53} erg in low-energy γ -rays in ~ 1 s
- Some gamma-ray bursts have large redshifts
Cosmological distances
- Relativistic motion (Jets ?) with Γ (Lorentz) ~ 100

ABSORPTION DUE TO THE
COSMIC BACKGROUND RADIATION FIELDS

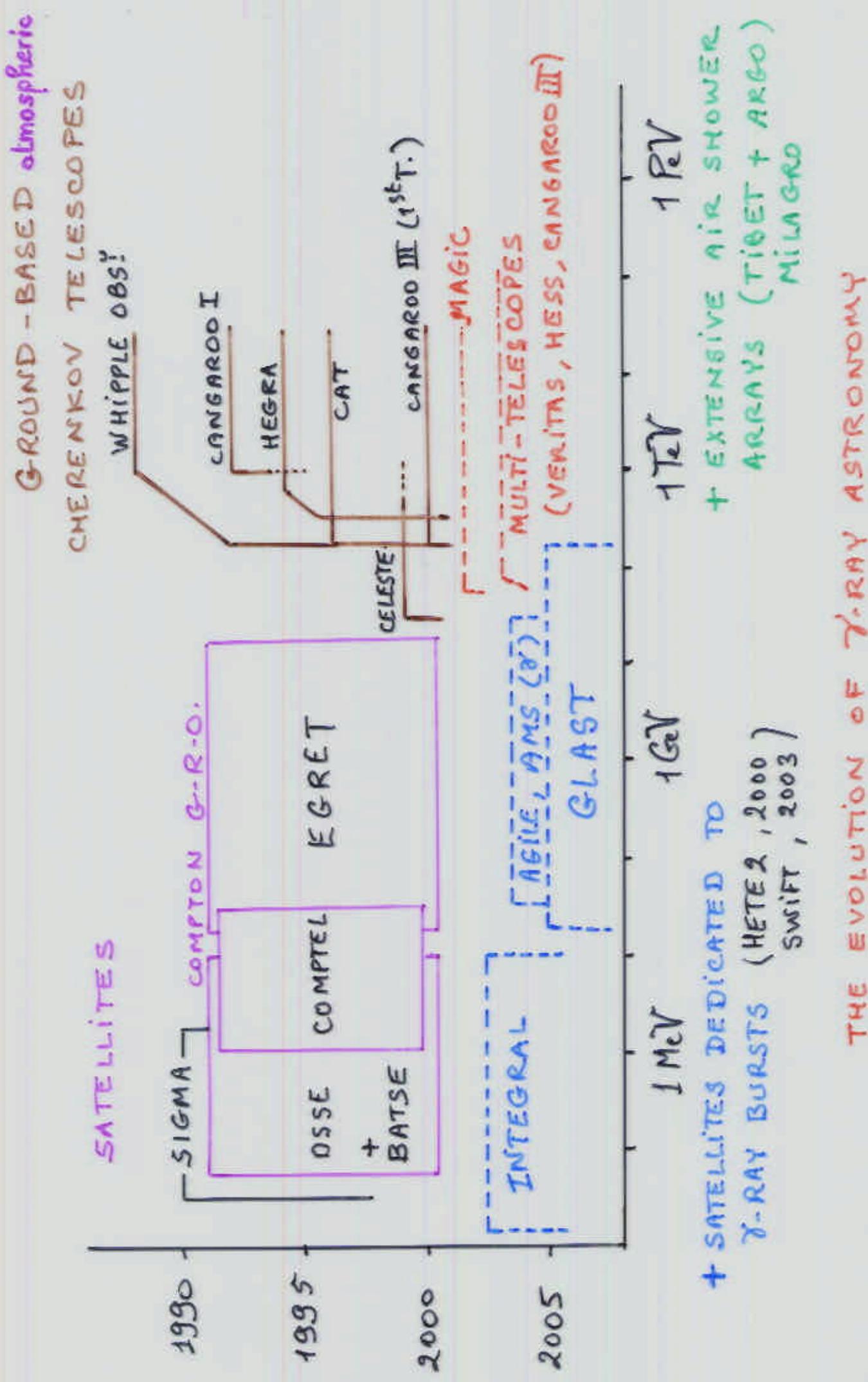


EXTRA-GALACTIC γ -RAY ASTRONOMY
FOR $E \lesssim$ some 100 TeV ONLY !

High Energy Particles from the Universe

GAMMA-RAY ASTRONOMY PRESENT AND FUTURE

- 3.a Beyond 30 GeV : the instruments
- 3.b Beyond 30 GeV : results
- 3.c Forthcoming experiments



Present ground-based experiments

Experimental challenges

- Typical flux sensitivity $\sim 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ at 1 TeV
(1/10 Crab nebula)
 \implies Large effective detection area ($\sim 3 \times 10^4 \text{ m}^2$)
- Select γ -ray showers among cosmic-ray showers
The needle in a hay-stack !
- Atmospheric Cherenkov techniques provide :
 - Efficient background rejection
 - Good angular resolution $\sim 0.2^\circ$ per γ
 - Improving energy thresholds
(500 GeV \rightarrow 250 GeV \rightarrow 50 GeV)

BUT

 - low duty cycle (moonless clear nights)
 - limited field of view (3° - 5°)

Typically $\sim 5\sigma \times \sqrt{t/\text{hour}}$ for the Crab nebula
- Extensive air shower arrays
 - High duty cycle, large field of view
 - Mostly above $\sim 1 \text{ TeV}$
 - Poor hadronic rejection

e.g. Tibet array 5σ in 502 days for the Crab nebula

MAIN CHERENKOV IMAGING TELESCOPES

- HADRONIC } • SHAPE OF SHOWER IMAGE + LIGHT PROFILE + DIRECTION (point-like sources)
 REJECTIONS } • STEREOSCOPY → ADDITIONAL REJECTION FACTOR ~ 100

EXPERIMENT Hemisph./Site	Collaboration	STEREO.		REFLECTOR AREA	# of pixels	CAMERA		APPROX. ENERGY THRESHOLD (GeV)
		# Telesc.	SPACING			Pixel spacing		
WHIPPLE Obs.	USA UK Ireland	1	-	75 m ²	91 (+18)	0.25° (0.5°)	250	↓
N CANGAROO II → III	USA	Japan Australia	1 (100m)	30 m ² 57 m ²	379 (+11)	0.12° (0.24°)	≥ 100 (1999)	↓
S HEGRA	Australia	Germany Spain	5 90 m	8.5 m ²	512 → 552	0.12°	300	↓
N NARRABRI	Australia	UK Australia	2 100 m	3 × 4.2 m ²	271	0.25°	500	
S γ-TELESCOPE ARRAY	USA	Japan USA	3 70 m	6 m ²	91 (central) 19 (lateral)	0.2° 0.5°	300	
N CAT	France Czech Rep.	France Czech Rep.	1 -	18 m ²	256 (multi-anode PMT's) 546 (+54)	0.25° 0.12°	600	
N	France						250	

ALSO : SHALON (Kazakhstan), CRIMEA obs! (Ukraine), TACNIC (India)

CHERENKOV SAMPLING TECHNIQUE

TOWARDS LOWER ENERGY THRESHOLDS

THRESHOLD IS DETERMINED BY NIGHT-SKY BACKGROUND

- VERY LARGE REFLECTOR AREA \Rightarrow SOLAR FARMS
- FAST TIMING (match Δt (Cherenkov) $\sim 2-3 \text{ ns}$)
- SAMPLE CHERENKOV WAVE-FRONT (Timing + intensity) ON DIFFERENT HELIOSTATS.

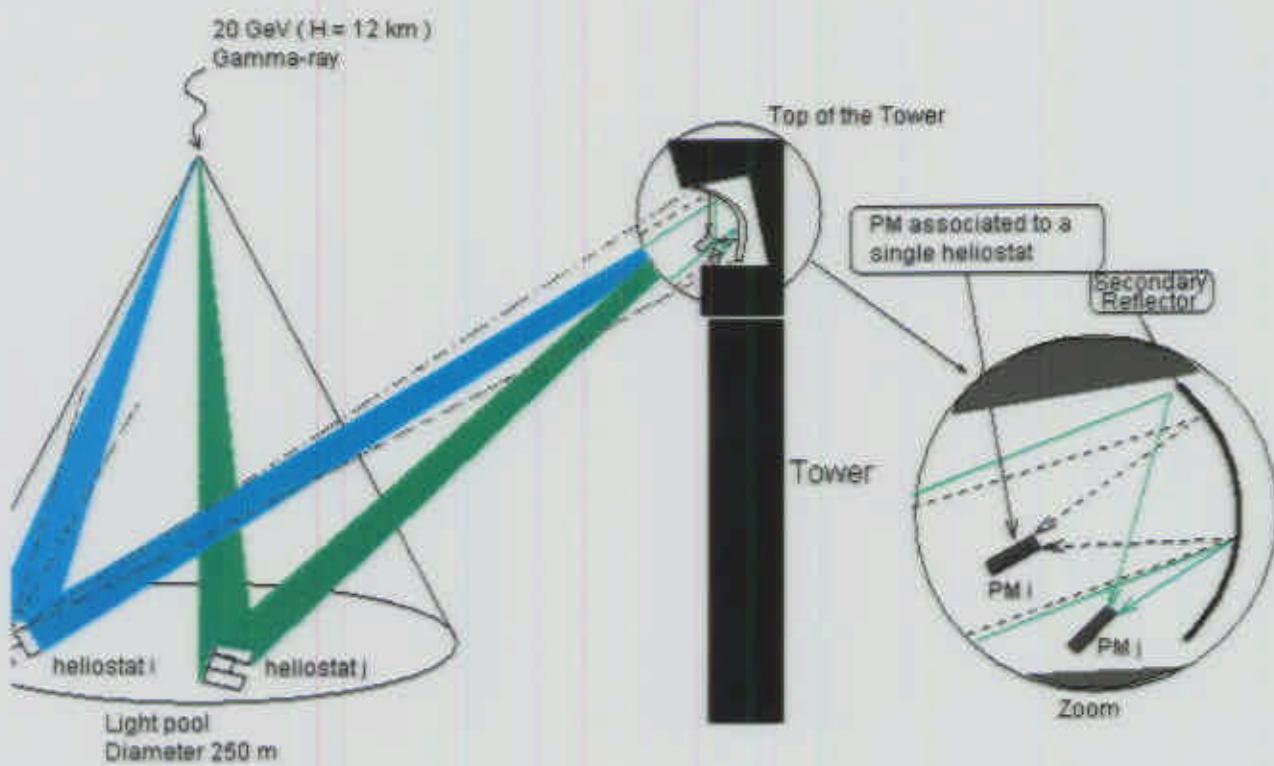
EXPERIMENT Hemisph./Site	COLLABORATION # OF HELIOSTATS	MIRROR AREA X APPROX. ENERGY THRESHOLD (GeV)	CRAB NEBULA
CELESTE N Thémis (*) France	40 Czech Rep. France	54 m^2 \downarrow (54)	30 (trigger) 50 (anal.) $\rightarrow 3.3 \sigma \sqrt{E/\text{hr}}$
STACEE N Sandia USA	32 Canada \downarrow 64	37 m^2 \downarrow	190 ± 60 ALSO GRAAL (Almeria, Spain)
SOLAR-TWO N Barstow USA	64	40 m^2	Under development.

(*) Same site as CAT imaging telescope

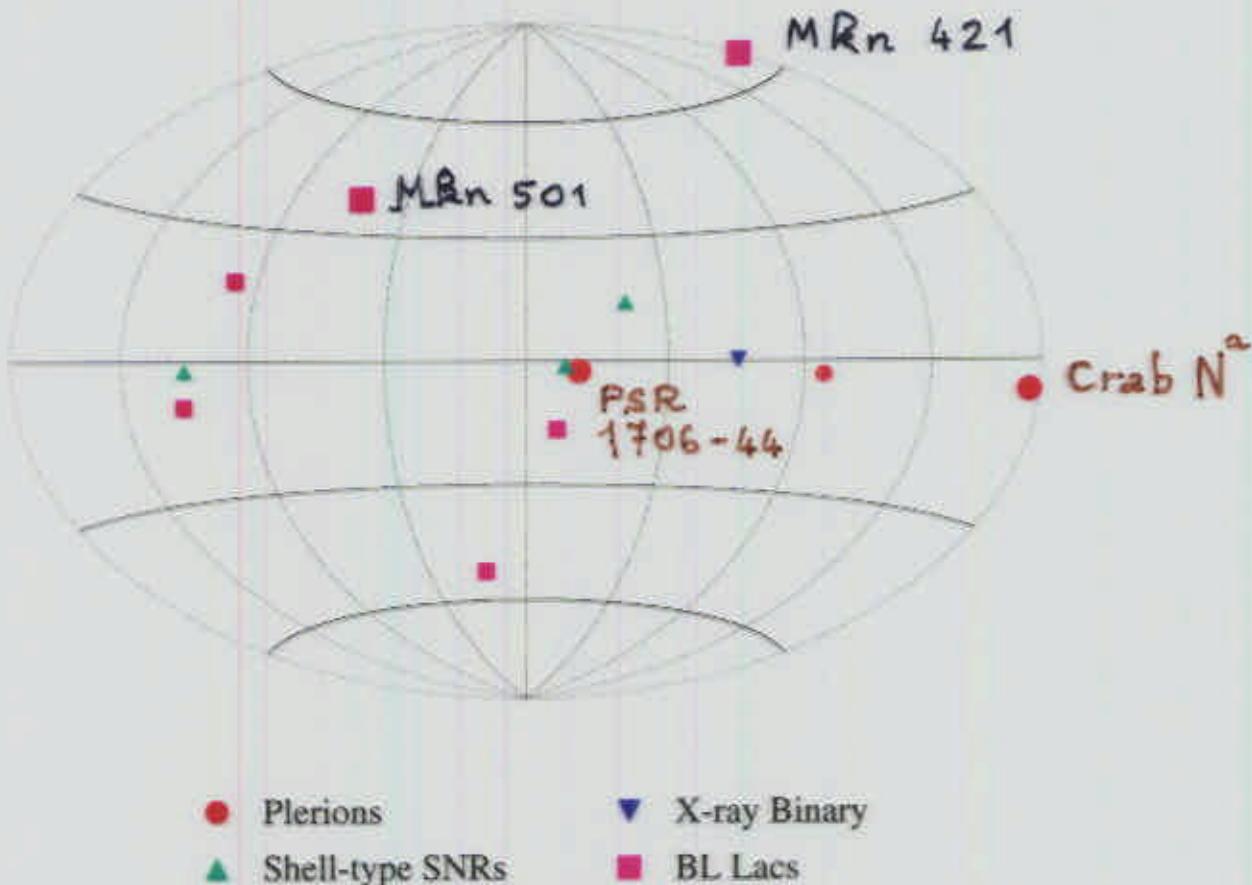
Solar Farm Atmospheric Cherenkov Facilities (I)

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

Secondary optics in the tower : One Photomultiplier per heliostat



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

γ -RAY ASTRONOMY : RESULTS SUPERNOVA REMNANTS

● "FILLED-TYPE" SNR's (OR "PLERIONS")

SHOCK WAVE INDUCED BY PULSAR WIND IN NEBULA

e.g. Crab nebula, PSR 1706-44

UNPULSED γ -RAY SIGNALS

2 BUMP MULTIWAVELENGTH SPECTRUM

SYNCHROTRON + INVERSE COMPTON
(below ~ 20 MeV) (\rightarrow high-energy γ 's)

due to e^\pm accelerated up to 10^{15} eV

- NEW! CRAB N^a {
- * CELESTE : 1st measurement at 50 GeV (preliminary)
 - * HEGRA : accurate spectrum $E > 500$ GeV
 - * TIBET : 1st γ -signal with EAS array

NO NEED OF π^0 's TO EXPLAIN THE γ -RAY SPECTRUM

● "SHELL-TYPE" SNR's

SHOCK WAVE = SUPERNOVA BLAST WAVE IN INTERSTELLAR MEDIUM

2 POSITIVE OBSERVATIONS (to be confirmed)

- {
- * SN 1006 (Cangaroo) connected to ASCA X-ray observations.
 - * Cassiopeia A (HEGRA) : 4.9 σ in 232 hrs.

BUT HADRONIC ORIGIN (π^0) OF γ -RAYS
NOT PROVED ! (e accel." could explain data)

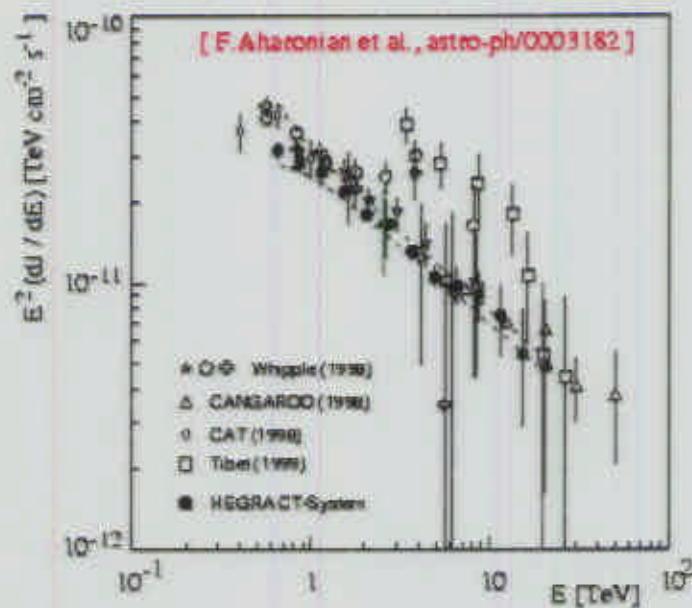
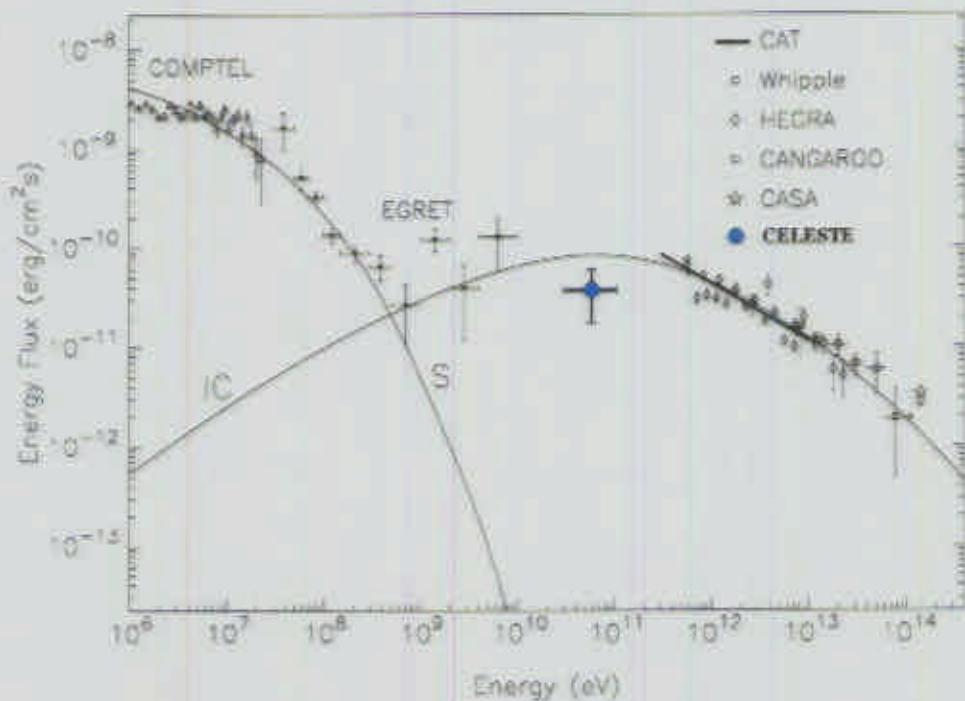
MORE SENSITIVE DETECTORS NEEDED

TO CHECK THAT SNR's DO ACCELERATE
PROTONS OR NUCLEI

Crab nebula spectrum

Spectral energy distribution $E^2 \frac{d\Phi}{dE}$

New measurement from CELESTE at 50 GeV



New precision measurement from HEGRA stereoscopic system (●)
Also results from Tibet Array $E > 3 \text{ TeV}$ (□)

BLAZARS

Radio-loud Active Galactic Nuclei

WITH PLASMA JETS POINTING TOWARDS US

● EGRET BLAZARS VS. TeV BLAZARS

Spectral Energy distribution $E^2 \frac{d\phi}{dE}$
exhibit a TWO-BUMP STRUCTURE

Synchrotron bump

γ -ray Bump

* A CONTINUOUS FAMILY OF BLAZARS

(Ghisellini et al 1998)

EGRET blazars \rightarrow TeV extreme Blazars

{ Synchr. peak = IR, optical { Synchr. peak = UV, X
 { γ -ray peak \sim GeV { γ -ray peak \sim 0.5 TeV

* TeV BLAZARS HAVE SMALL REDSHIFTS

Mkn 421 (0.031) Mkn 501 (0.034)

Absorption by IR background radiation
for $z \gtrsim 0.1$ in the TeV range.

● STRONG γ -RAY VARIABILITY (doubling time from 15 min to 1 day) CORRELATED TO X-RAY VARIABILITY in TeV Blazars.

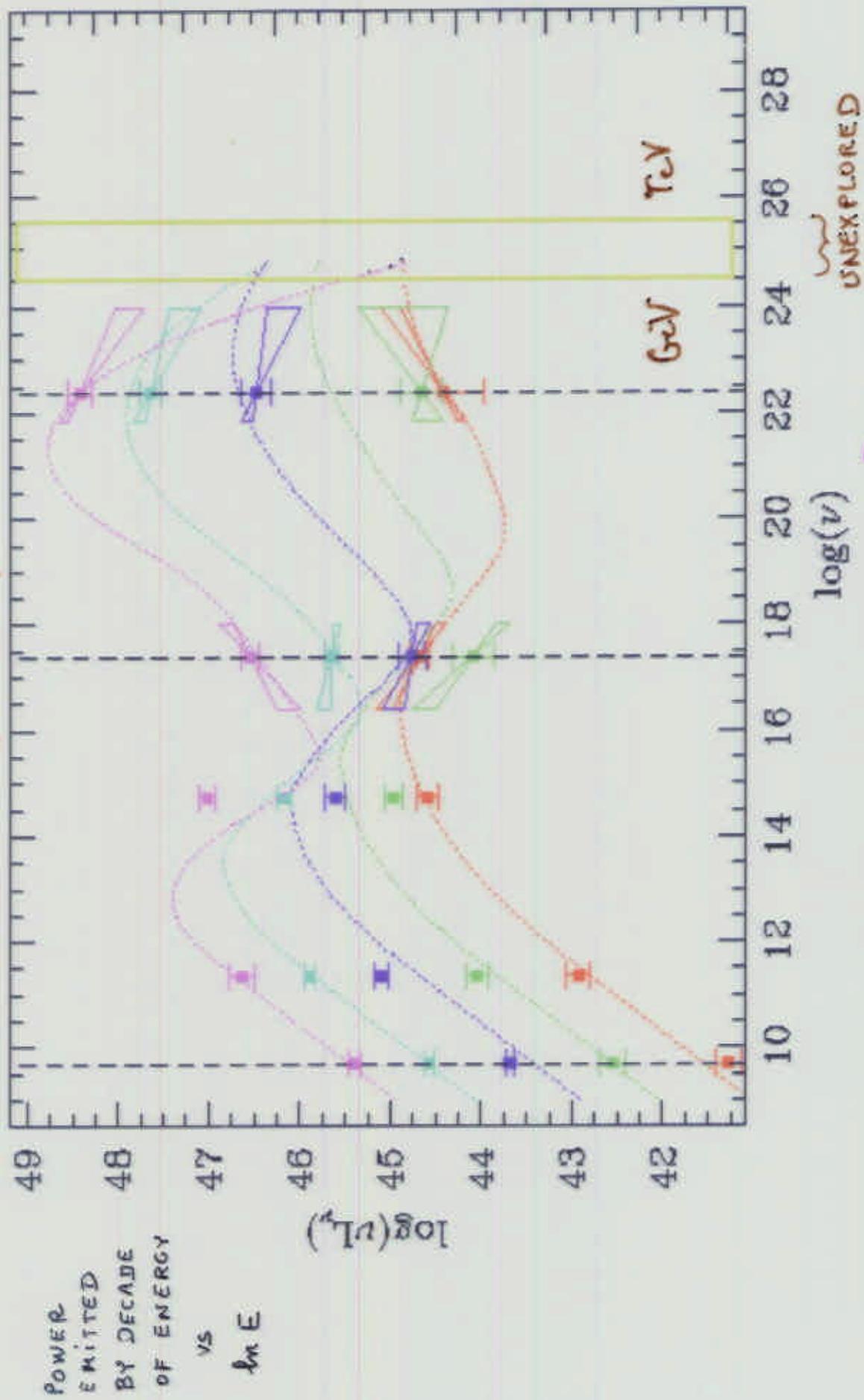
Natural explanation : γ (Inverse Compton)
and X-ray (synchrotron) from the same
population of electrons.

Alternative : γ -rays as synchrotron radiation
from UHE proton cascades

● SOME EVIDENCE FOR SPECTRAL VARIABILITY FOR Mkn 501

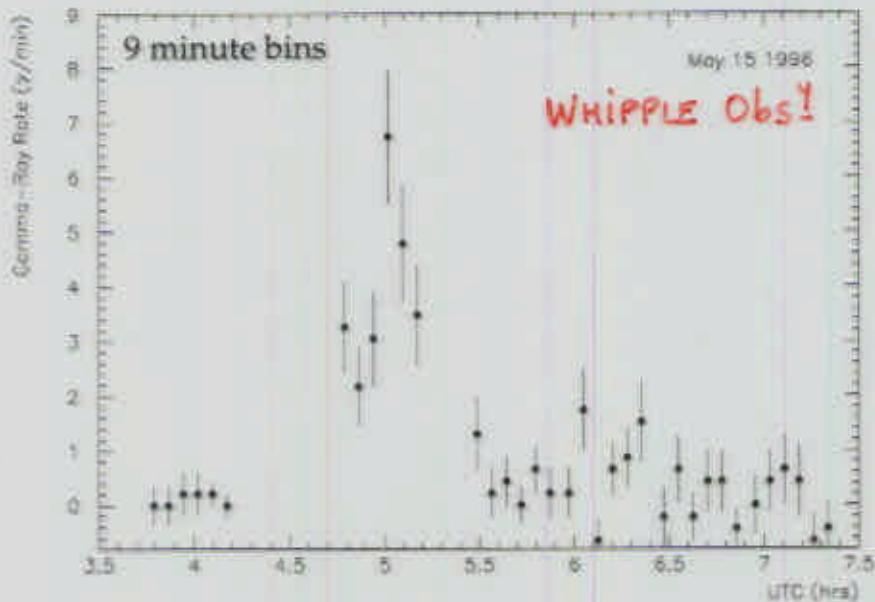
HARDER SPECTRA \leftrightarrow MORE INTENSE FLARES

BLAZAR SPECTRAL ENERGY DISTRIBUTIONS



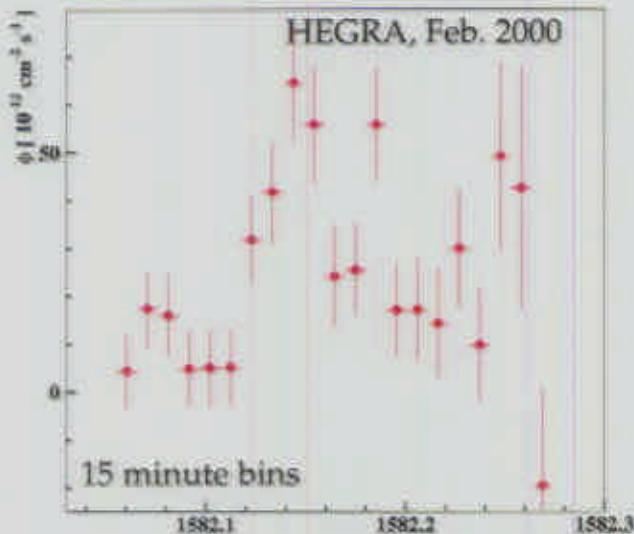
Time Variability of TeV Blazars (II)

Mkn 421: shortest doubling time 15-30 minutes



PROVIDING
A TEST OF
"IN VACUO" DISPERSION
(Quantum Gravity
effect)
Biller et al.,
Phys. Rev. Lett. 83
(1999) 2108
 $E_{Q.G.} > 6 \times 10^{16}$ GeV

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



places severe constraints on the size of the emitting volume:

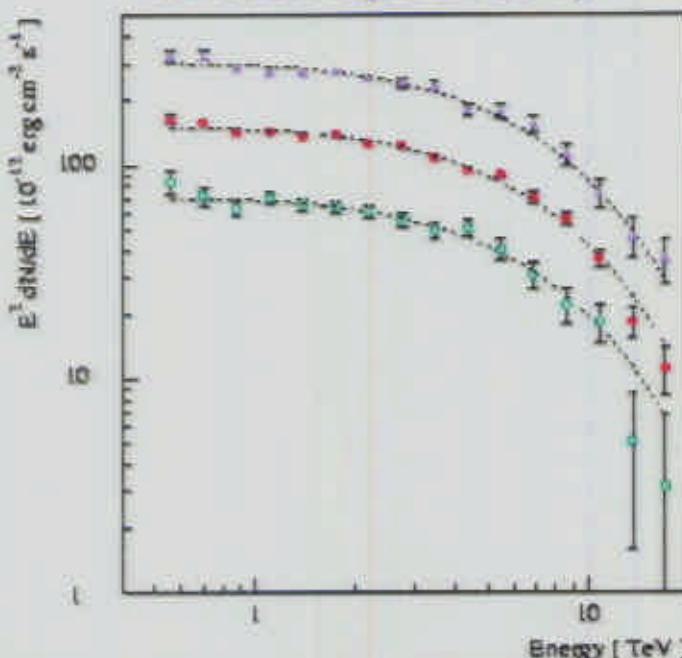
$$R < \delta c \Delta t = 10^{15} (\delta / 10) (\Delta t / 1h) \text{ cm}$$

region optically thin to TeV gamma-rays

TeV Blazars : Spectra

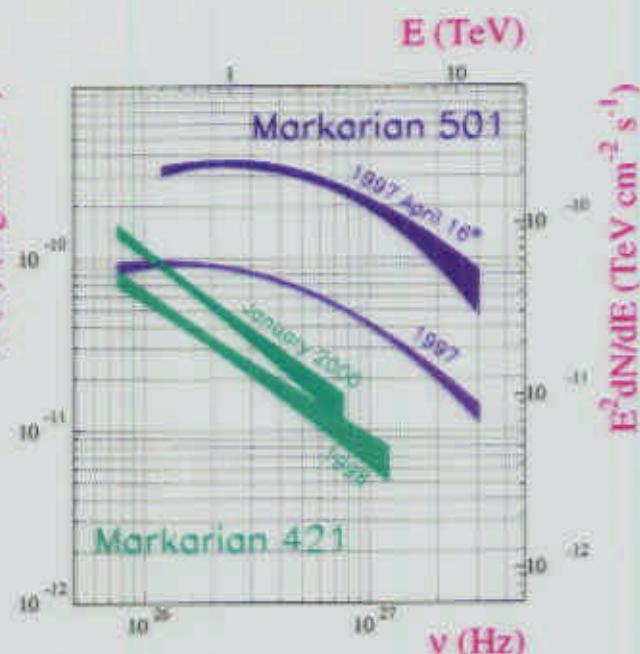
Spectral energy distribution $E^2 d\Phi/dE$

HEGRA (Mkn 501)



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

CAT (Mkn501 & Mkn 421)

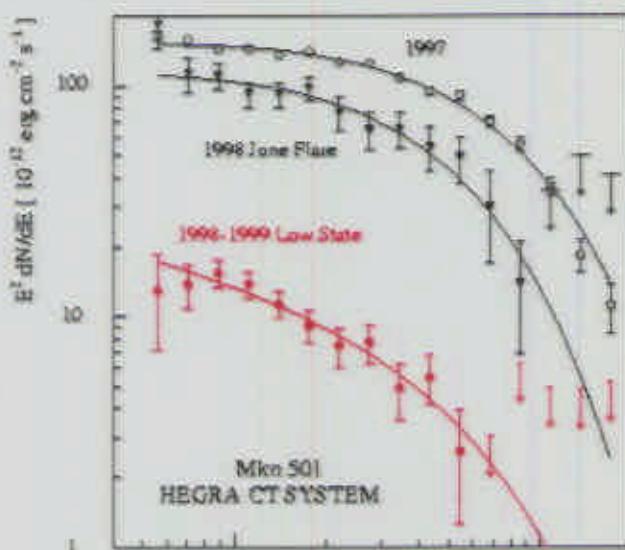


Evidence for spectral variability

HEGRA (Mkn 501)

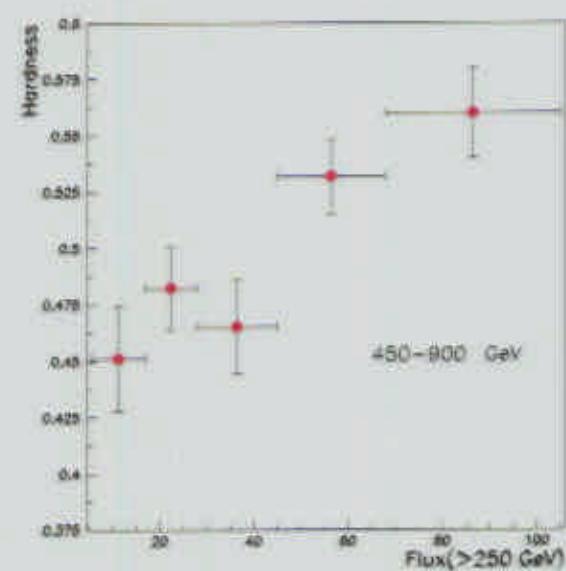
1998 - 1997

Spectrum steepened by 0.44 ± 0.1 compared with 1997



1997 vs. 1998-99

CAT (Mkn501)



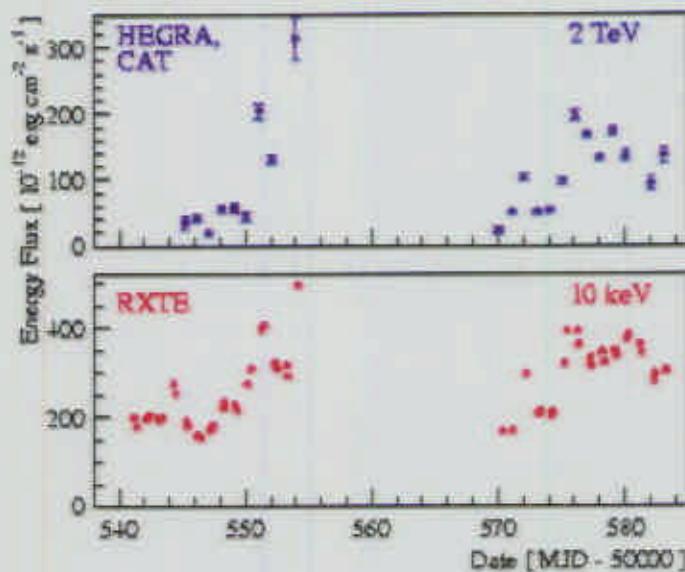
Hardness ratio 1997

TeV Blazars : γ -rays vs. X-rays

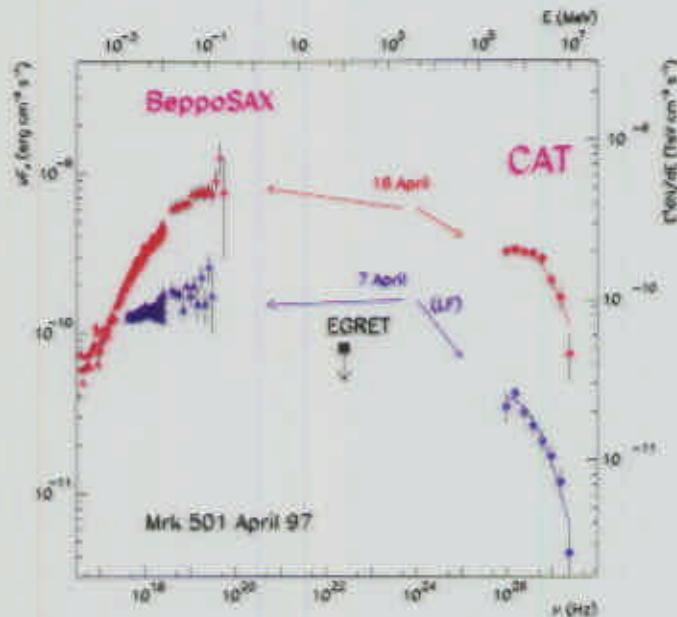
Mkn 501 : correlation between γ -rays (HEGRA, CAT) and X-rays (Rossi-XTE, Beppo-SAX)

TeV/X-ray integral flux vs. time:

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



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



Simultaneous data April 16th and April 7th 1997

Future Gamma-Ray Observatories in Space

Energies > 20 MeV

- **AGILE** (ASI) launch in 2002
 - Sensitivity comparable to EGRET
- **AMS-02** on International Space Station in 2003
 - with a light (e.g. $0.3 X_0$) converter
 - Sensitivity comparable to EGRET,
 - but non-pointable instrument
- **GLAST** (NASA) launch in 2005
 - Large gain in flux sensitivity : $\times 25$ better than EGRET
 - Large gain in angular resolution
 - Significant statistics up to ~ 300 GeV
 - Angular resolution per 10 GeV γ -ray : 0.15°



The GLAST detectors

NEW PROJECTS : ARRAY OF CHERENKOV

IMAGING TELESCOPES

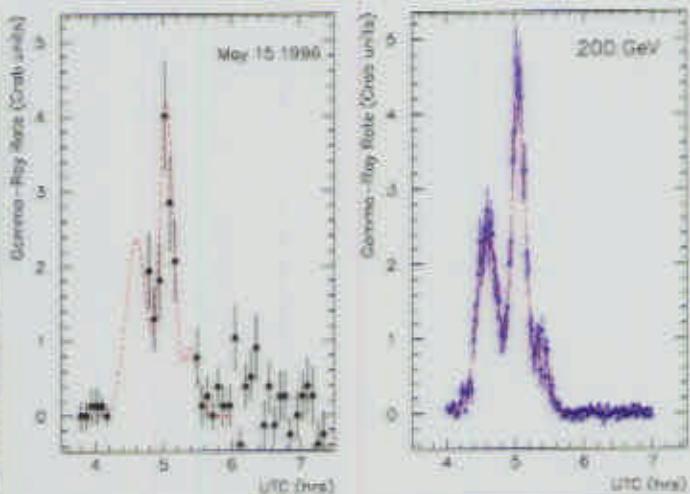
LOWER THRESHOLDS , HIGHER FLUX SENSITIVITY ($\times 10$)

PROJECT Hemisph./ Site	Collabor. ⁿ	# of telesc.	STEREO, REFLECTOR AREA	CAMERA		APPROX. ENERGY THRESH. (GeV)
				# of pixels	Field of view	
VERITAS	USA	7	80 m ²	78,6 m ²	499	0.15°
	UK					3.5°
	Ireland					50-100 GeV
HESS	Germany France UK, Czech R. Namibia South Afr. (16)	4	120 m ²	100 m ²	960	0.15°
						5°
						50-100 GeV
CANGAROO III	Japan Australia	4	100 m ²	57 m ²	552	0.12°
						3°
						100 GeV
MAGIC	Germany Spain	1	-	234 m ²	600	0.05°
						6°
						0.10°
N Canaries Isl.						

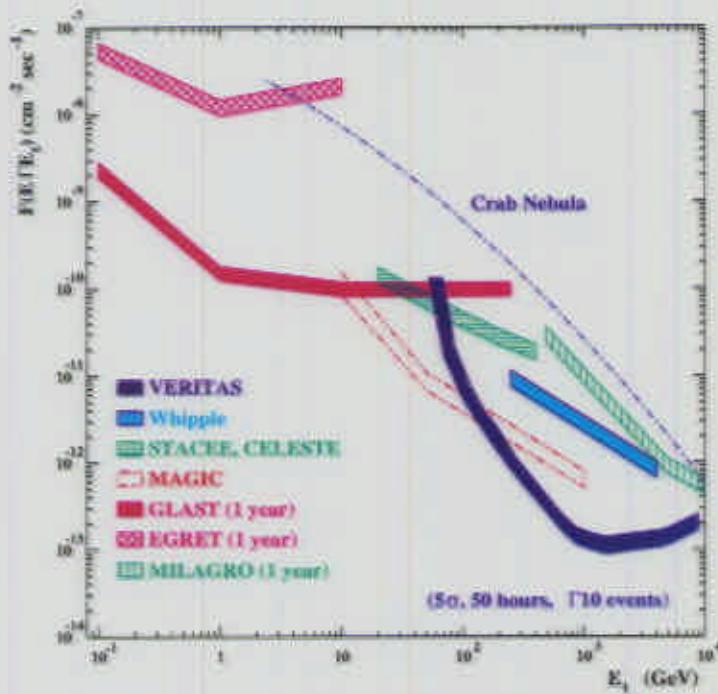
Future aim
20 GeV

The Future of TeV Gamma-ray Astronomy

... IS VERY BRIGHT!



HESS (2003)



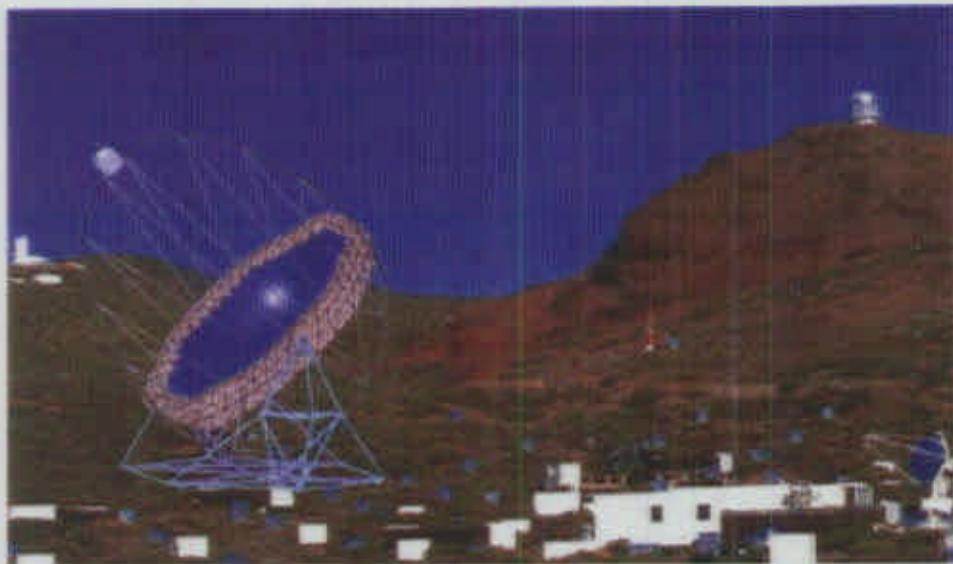
[Catanese and Weekes, astro-ph 9906501]



γ -RAY FLUXES FROM NEUTRALINO ANNIHILATIONS
(DARK MATTER AT GALACTIC CENTER OR M87)
MAY BE WITHIN REACH

New imaging telescopes

MAGIC : Towards lower energy thresholds



MAGIC on the HEGRA site (La Palma)

Extensive Air Shower Arrays for gamma-ray astronomy

- **TIBET (4300 m a.s.l.)**

185 scintill. detectors over 36900 m^2

High density array : 109 scintill. det. over 5175 m^2

Threshold : $\sim 3 \text{ TeV}$

- **MILAGRO (Los Alamos) (2650 m a.s.l.)**

$80 \text{ m} \times 60 \text{ m}$ water pool, 8 m deep

Water Cherenkov technique ; two layers of PMT's

450 PMT's (top layer) + 273 PMT's (bottom layer)

Threshold : $\sim 3 \text{ TeV}$

- **ARGO (Tibet, 4300 m a.s.l.)**

5800 m^2 of resistive plate chambers in 2001-2003

High Energy Particles from the Universe

THE BIRTH OF NEUTRINO ASTRONOMY

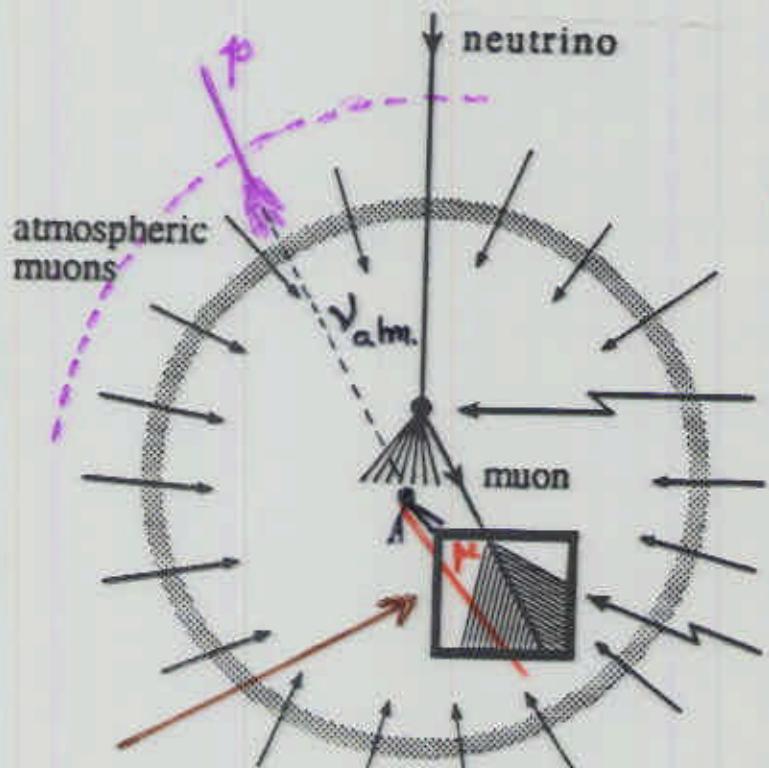
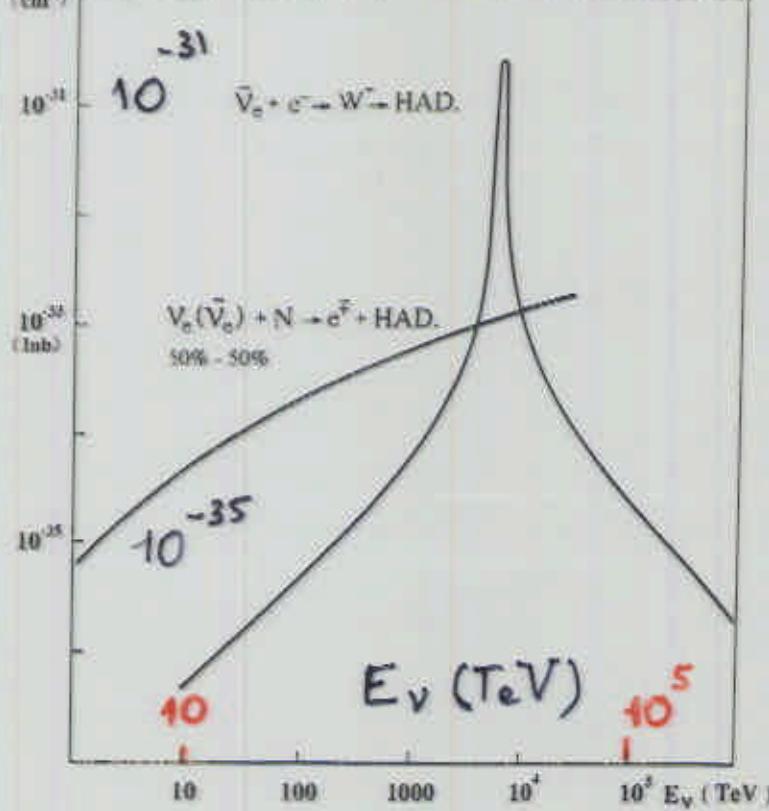
- 4.a Experimental challenges
- 4.b Present and forthcoming experiments
- 4.c The stakes of neutrino astronomy

NEUTRINO ASTRONOMY

σ (cm²)

CROSS SECTION

cm⁻²)



$\sim \text{km}^2$ EFFECTIVE
DETECTION AREA
NEEDED

DETECTING MEDIUM = SEA or POLAR ICE

EXPERIMENTAL CHALLENGES :

- WEAK FLUXES BUT ALSO CROSS SECTIONS $\sigma \sim 10^{-35} - 10^{-33} \text{ cm}^2$
- DETECT ν_μ THROUGH HIGH-ENERGY MUONS → EXTENDS EFFECTIVE TARGET VOLUME μ RANGE IN WATER \sim several km BUT WORSENS ANGULAR RESOLUTION below 10 TeV
- RESTRICT TO UPWARD-GOING MUONS (remove penetrating μ 's from atmospheric showers)
- UNESCAPABLE DIFFUSE BACKGROUND OF ATMOSPHERIC ν 's, A STRONG LIMITATION AT LOWER ENERGIES.

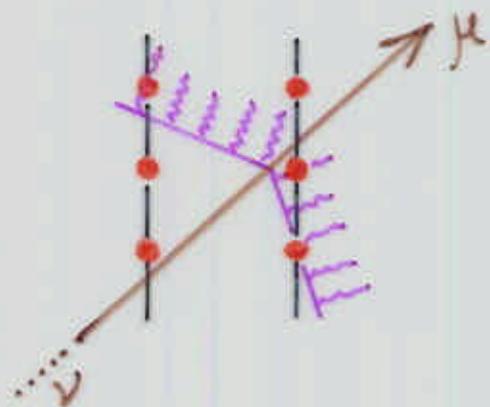
NEUTRINO ASTRONOMY

THE WATER/ICE CHERENKOV TECHNIQUE

OPTICAL MODULES (O.M.'s) = PHOTODETECTORS

RECORDING TIMING AND INTENSITY INFORMATION

FROM CHERENKOV
LIGHT



IN ORDER TO RECONSTRUCT UPWARD-GOING MUONS ($\uparrow\mu$), ONE HAS TO DISCRIMINATE AGAINST THE BACKGROUND OF DOWNWARD-GOING MUONS ($\downarrow\mu$)

$\sim 10^5$ MORE FREQUENT FOR
DEPTHES OF 1 - 2 Km

- FIRST DEMONSTRATION OF FEASIBILITY :
Baikal NT96 , 12 $\uparrow\mu$ in 70 days
- AMANDA present results :
170 $\uparrow\mu$ from 1997 data.

ICE VS. WATER

Background light	none	^{40}K , Bioluminesc.
Attenuation length	$\sim 100\text{ m}$	$\sim 60\text{ m}$
Scattering length	24 m broadens time signals $\sim 1^\circ$	$> 100\text{ m}$
Angular resol": μ		$\sim 0.4^\circ$

THE BIRTH OF NEUTRINO ASTRONOMY

Pioneers : Baksan, IMB, Kamiokande, Frejus

$$\text{EFFECTIVE AREA } A \lesssim 10^3 \text{ m}^2$$

Italy, USA

MACRO since 1989	LNGS Gran Sasso	Liq. Scint. + Streamer tubes	$E_{\mu} > 1 \text{ GeV}$ $1100 \uparrow \mu$
BAIKAL $\text{NT36} \rightarrow \text{NT200}$ 1993 1998	Lake Baikal 1.1 km	Water Cherenkov 192 O.M.'s in 8 strings	$E_{\mu} > 10 \text{ GeV}$

Russia, Germany

$$A \sim 10^4 \text{ m}^2$$

USA, Germany, Sweden D. Cowen PA-08-e

AMANDA $B4 \rightarrow B10$ 1996 - 1998	South Pole ICE 1.5 - 2 km	Cherenkov 418 O.M.'s in 13 strings	Upgraded \rightarrow AMANDA II
NESTOR	Mediterr. (Greece) 3.8 km	Cherenkov 168 O.M.'s in 1 tower	Under development

$$A \sim 10^5 \text{ m}^2 \quad \text{TOWARDS } 1 \text{ km}^2$$

USA, Germany, Sweden

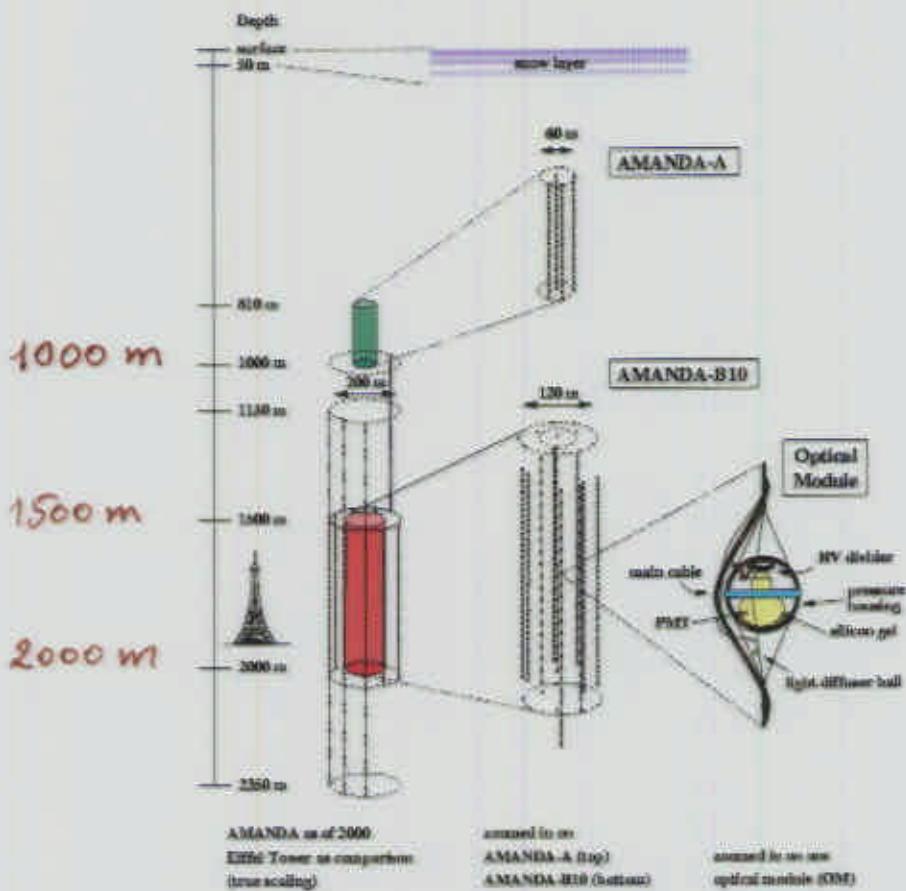
AMANDA II 2000 - ...	South Pole ICE 1.5 - 2 km	Cherenkov 681 O.M.'s	Taking data
ANTARES start 2003	Mediterr. (France) 2.4 km	Cherenkov 1000 O.M.'s in 13 strings	Building phase. 1 st string 2001 \rightarrow ANTARES II

France, UK, Spain, Italy, Netherlands, Russia

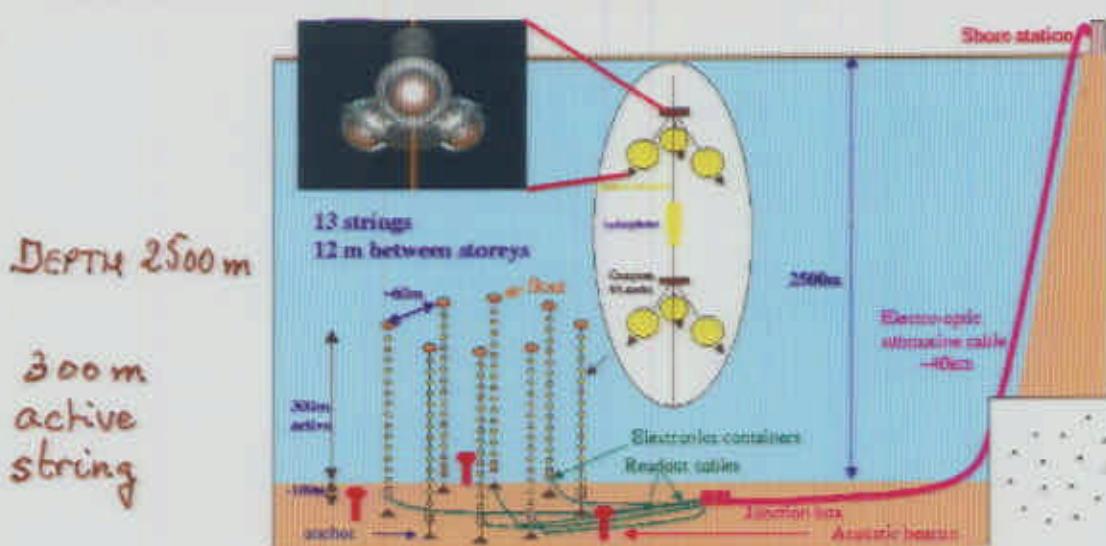
J.J. Hernandez PA-08-e

5000 to
10000
OM's

0.1 km² Neutrino Detectors



AMANDA II (South Pole Ice)
operational with 681 optical modules



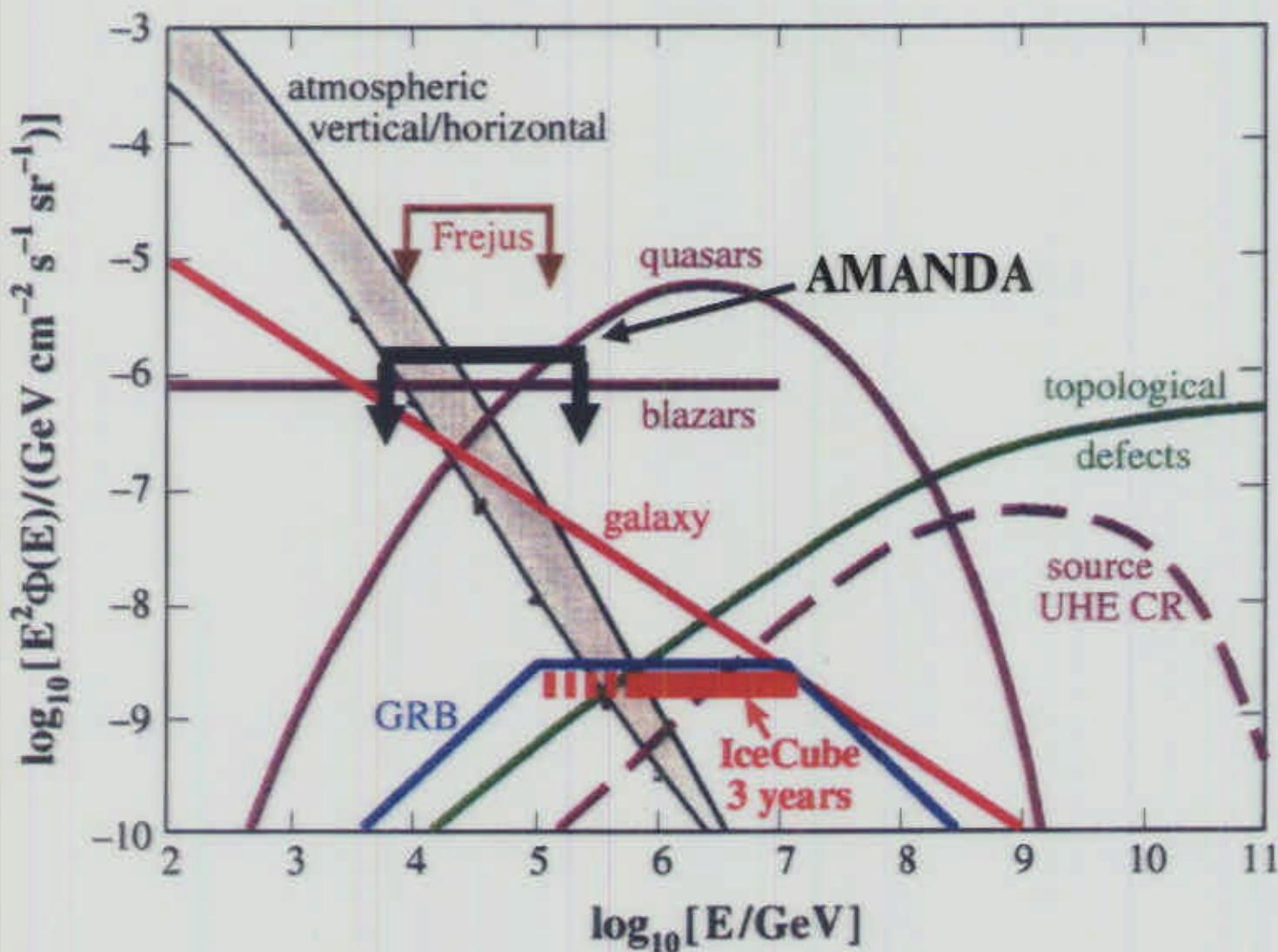
ANTARES (Mediterranean, Toulon)

First string deployed in 2001. Completion in 2003

MAIN STAKES OF γ ASTRONOMY

- GAMMA-RAY BURSTS : $\nu, \bar{\nu}$ EMISSION VERY LIKELY IF GRB's ARE THE SOURCE OF U.H.E. COSMIC RAYS (Halzen, Hooper 1999).
A few very bright bursts per year could be detected even with 0.1 km^2 detectors
(ANGULAR + TEMPORAL) SIGNATURES \rightarrow Small background.
* NO COINCIDENCES WITH BATSE BURSTS FOUND TO DATE (MACRO, AMANDA).
- DIFFUSE FLUX OF ALL ACTIVE GALACTIC NUCLEI
COMPLEMENTARY OF γ -RAY ASTRONOMY:
 - * SENSITIVE TO REGIONS OPAQUE TO γ -RAYS: "CENTRAL ENGINE" with high density of UV photons from accretion disk.
 - * EXPECTED TO DOMINATE THE ATMOSPHERIC BACKGROUND FOR $E > 100 \text{ TeV}$, where extragalactic γ -rays are absorbed by CMB photons.
- NON BARYONIC DARK MATTER (with $\sim 100 \text{ GeV}$ THRESHOLD)
Annihilation of neutralinos
 - $X + X \rightarrow \dots \rightarrow \nu, \bar{\nu}$
captured in Earth or Sun or from Galactic Center
 - * SOME BOUNDS FROM PRESENT DETECTORS:
Earth or Sun: $\uparrow \mu \text{ FLUX} < 10^4 \text{ fm}^{-2} \text{ yr}^{-1}$
(Baksan, MACRO, AMANDA)
 - Galactic Center: MACRO excludes "Central Spike"
(Gondolo & Silk)

Diffuse UHE ν Flux Limit



$$E^2 \Phi_\nu < 1.6 \times 10^{-6} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$$

Note that this flux is expected to be 10^3 larger than that for point sources. Also, atm. ν backgrounds are somewhat worse.

High Energy Particles from the Universe

EXPLORING THE ULTRA-HIGH-ENERGY DOMAIN

- 5.a The techniques
- 5.b Present results
- 5.c Forthcoming experiments

The detection of UHE Cosmic Rays

1 event per km^2 per year at 10^{19} eV

1 event per km^2 per century at 10^{20} eV

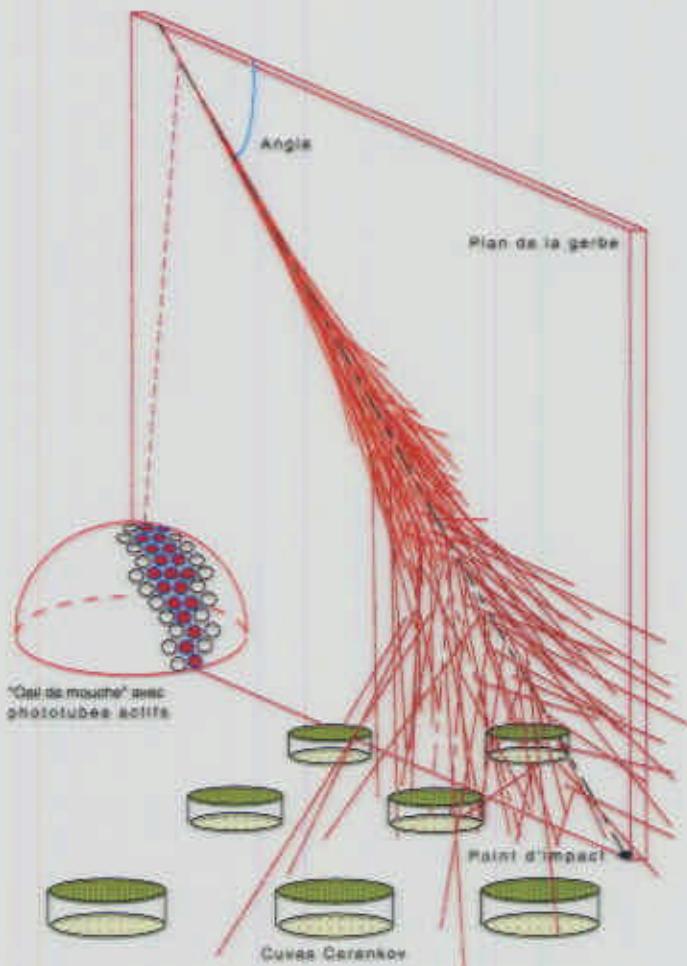
Detect charged particles
on the ground

(Scintillators, Water Cherenkov)

$3 \times 10^{10} \gamma, e^\pm, \mu^\pm, E > 200$ keV
at 10^{19} eV

Detect fluorescence light
produced by the shower
(isotropic light)

4 photons per e^\pm at 1 Atm.



Représentation schématique de la détection d'une gerbe atmosphérique par un détecteur hybride. Reproduit avec la permission de E. Zas, d'après un article dans la Revista Española de Física.

Recent data on UHE Cosmic Rays

Former results from : Volcano Ranch, Haverah Park, Yakutsk, Fly's Eye

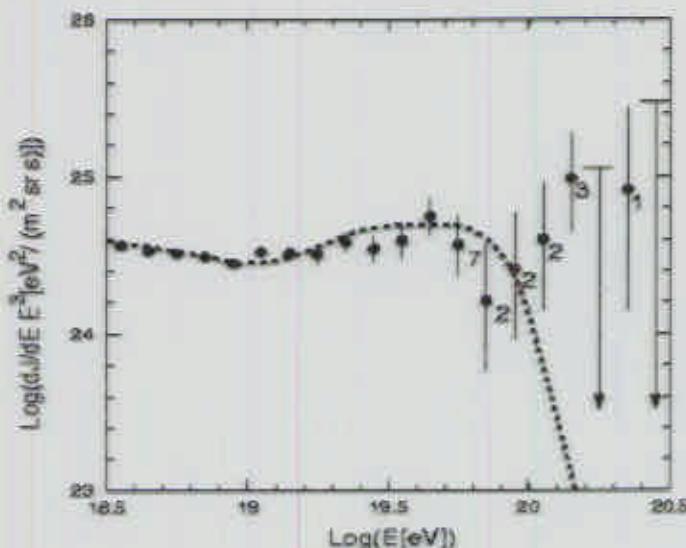
Experiment (site)	Technique	$\Delta E/E$	$\Delta\theta$
AGASA (Japan) since 1990	EAS array 111 scintillators (2.2 m^2) deployed over 100 km^2	30 %	3° (10^{19} eV)
HI - RES (Utah, USA) since 1997	Fluorescence detector (2^{nd} detector in 2000 binocular fly's eye)	10 %	0.4°

Both experiments have similar sensitivities above 10^{20} eV :

$$\sim 1000 \text{ km}^2 \times \text{sr} \times \text{yr.}$$

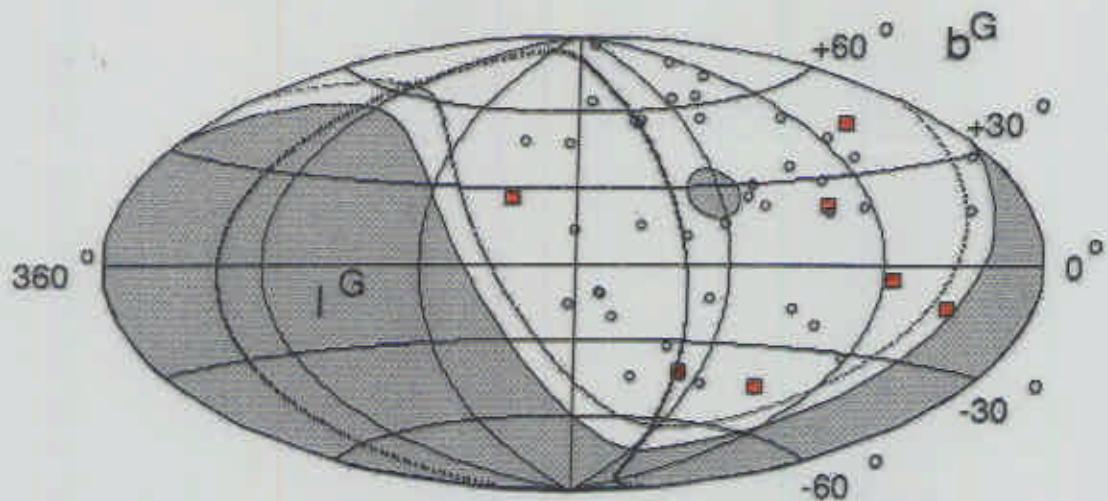
Both have 7 events with $E > 10^{20} \text{ eV}$

BEYOND THE GREISEN-ZATSEPIN-KUZMIN cutoff.



AGASA Spectrum $\times E^3$

1 triplet, 3 doublets $\Delta\theta < 2.5^\circ$



ANGULAR DISTRIBUTION OF AGASA events

IN GALACTIC COORDINATES ($E > 4 \times 10^{19} \text{ eV}$)

■ = ($E > 10^{20} \text{ eV}$)

Takeda et al
1999

NEW EXPERIMENTS ON U.H.E. COSMIC RAYS

- AUGER (EAS Array + Fluorescence det.)
3000 km^2 (Argentina)
- TELESCOPE ARRAY : New fluorescence detector
Prototype in Akeno (Japan)
Site in Utah (USA)
- FURTHER STUDIES FOR DETECTING
FLUORESCENCE LIGHT FROM SPACE
(OWL / AIR WATCH / EUSO)

The AUGER Observatory Project

M. Kleistges PA-09

- Provide much larger statistics :
~ 500 events/year with $E > 4 \times 10^{19}$ eV } with 2 sites
~ 60 events/year with $E > 10^{20}$ eV }
by deploying detectors over 3000 km²
- Use both techniques : EAS array and fluorescence detectors
Combine high duty cycle (array)
and angular resolution + energy resolution (fluorescence)
 $\Delta\theta \sim 0.20^\circ - 0.35^\circ$; $\Delta E/E \sim 10\% - 20\%$ in hybrid mode
- Array of 1600 water Cherenkov detectors over 3000 km²
Good separation of μ 's from e, γ 's
Good sensitivity to large zenith angle (UHE ν 's)
- Fluorescence detectors : 30 electronic telescopes with 13000 pixels
- Site in Southern Hemisphere : El Nihuil, Argentina
First test of “engineering array” (40 water Cherenkov detectors + one fluorescence telescope over 40 km² in summer 2001)
Building phase till 2004, but some data expected in 2002.
- Identical setup planned in Northern Hemisphere (Utah, USA)

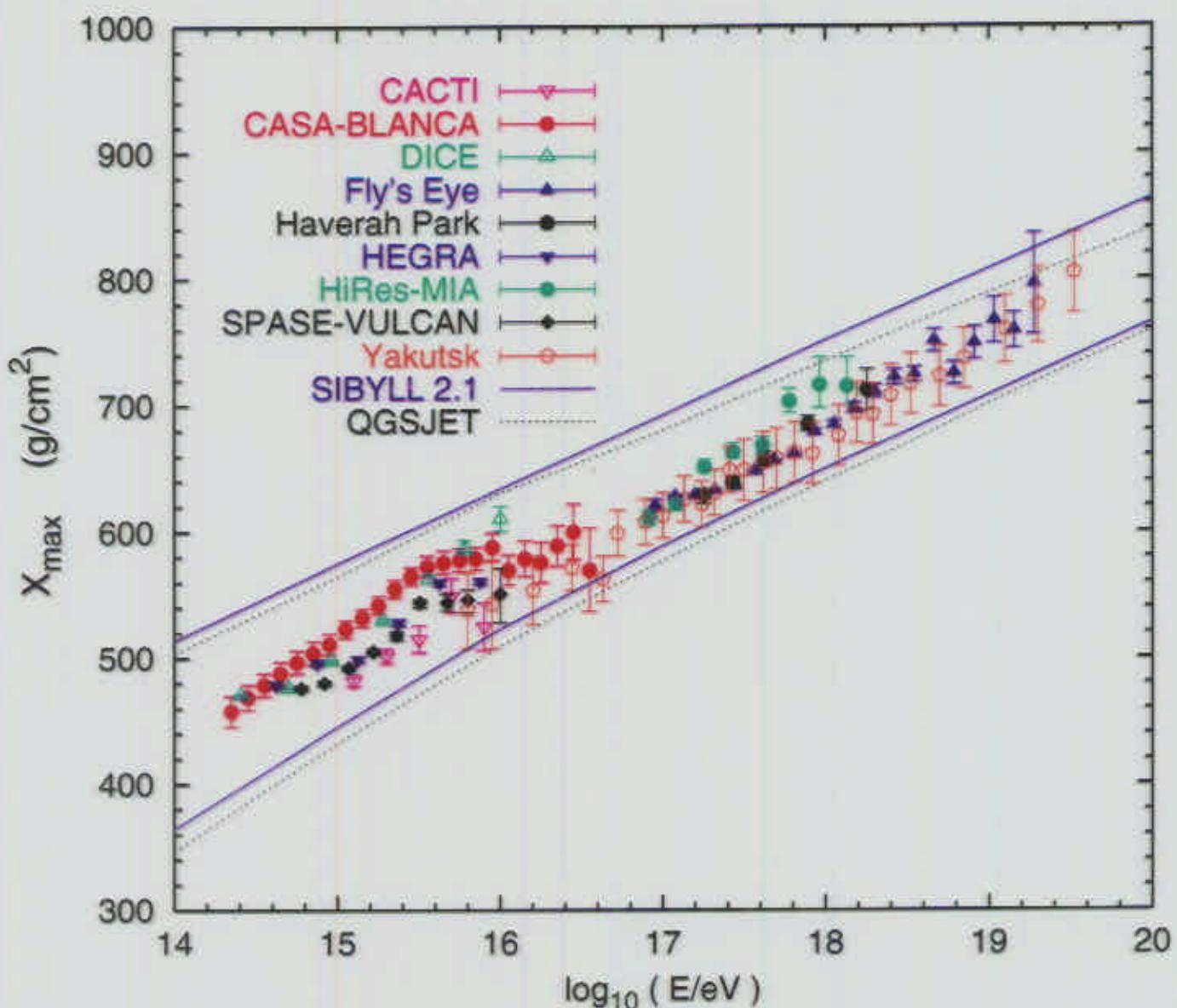
CONCLUSION

HIGH ENERGY ASTROPHYSICS : A FIELD IN RAPID DEVELOPMENT.

- NEW PRECISION MEASUREMENTS ON COSMIC RAYS
IN SPACE → Antimatter, CR propagation
(AMS, PAMELA).
- GAMMA-RAY ASTRONOMY: INCREASED FLUX SENSITIVITY
 - * IN SPACE ($\times 25$ GLAST + HETE2, SWIFT)
* ON THE GROUND ($\times 10$)
VERITAS, HESS, MAGIC, CANGAROO III
 - { Are supernova remnants the accelerators of galactic CR's ?
 - { Nature of unidentified EGRET sources ?
 - { Gamma-ray bursts at high energies ?
 - { New AGN sources ? More extreme blazars ?
- NEUTRINO ASTROPHYSICS WILL COMPLEMENT γ -RAY DATA.
AMANDA, ANTARES, ICE CUBE
 - { Hidden sources (not seen in γ -rays) ?
 - { ν signals from GRB's ? from AGN ?
 - { Hadronic contribution from γ -ray sources ?
- UHE COSMIC RAYS
 - { Hi-Res, Telescope ARRAY, AUGER
 - { Connection with GRB ?
 - { Exotic origin ?

ALL TOPICS ARE INTERCONNECTED AND CONNECTED TO MAINSTREAM ASTROPHYSICS.

AN OLD ENIGMA : The origin of Cosmic Rays



Depth of Shower Maximum vs. Energy (fig. from T.K. Gaisser)

- Chemical composition (p, He, heavier nuclei):
Only indirect and partial information above 100 TeV
- Air shower development:
Uncertainties in particle and nuclear physics
for energies **above those covered by accelerators**

RELATIVISTIC BULK MOTION

Micro-quasars
 Active Galactic Nuclei } jets
 Gamma-Ray Bursts

SHORT-TIME-SCALE
 VARIABILITY

vs.

HIGH γ -RAY
 LUMINOSITY

WOULD BE CONTRADICTORY IF THE SOURCE
 WERE AT REST WITH RESPECT TO
 THE OBSERVER
 (OPACITY TO $\gamma + \gamma \rightarrow e^+ e^-$) .

RELATIVISTIC BULK MOTION IS THUS
 REVEALED IN:

- Microquasar jets (galactic objects)
 $\Gamma(\text{Lorentz}) \sim 2$
- Blazar jets (extragalactic jets)
 $\Gamma(\text{Lorentz}) \sim 10 - 20$
- Gamma-ray bursts (beamed emiss^{n?})
 $\Gamma(\text{Lorentz}) \sim 300$

ACCELERATORS MOVING TOWARDS US WITH
 RELATIVISTIC VELOCITIES

→ Additional Lorentz boost for particles

TWO "ENERGETIC" COINCIDENCES

- ARE SUPERNOVA REMNANTS (SNR's) THE ACCELERATORS OF GALACTIC COSMIC RAYS ?
A power of $\sim 10^{34}$ W must be supplied in order to maintain the cosmic-ray flux in our Galaxy; (compensate for energy losses and escaping particles).
THIS IS $\sim 10\%$ OF THE MECHANICAL POWER PRODUCED BY SUPERNOVA EXPLOSIONS (1SN / 30 years / galaxy)

SNPL = favoured candidates for accelerating galactic C.R. $\rightarrow 100 \text{ TeV}$

- ARE GAMMA-RAY BURSTS SOURCES OF ULTRA-HIGH-ENERGY COSMIC RAYS ?
THE INJECTION POWER OF UHE COSMIC RAYS ($E > 4 \times 10^{19} \text{ eV}$) IS COMPARABLE TO THAT PROVIDED BY GAMMA-RAY BURSTS (GRB's) WITHIN THE GREISEN-ZATSEPIN-KUZMIN CUTOFF RADIUS.

If this (more controversial) assumption is true, GAMMA-RAY BURSTS SHOULD BE $\nu, \bar{\nu}$ SOURCES.

Whipple



Cangaroo



CAT



Durham Mark 6



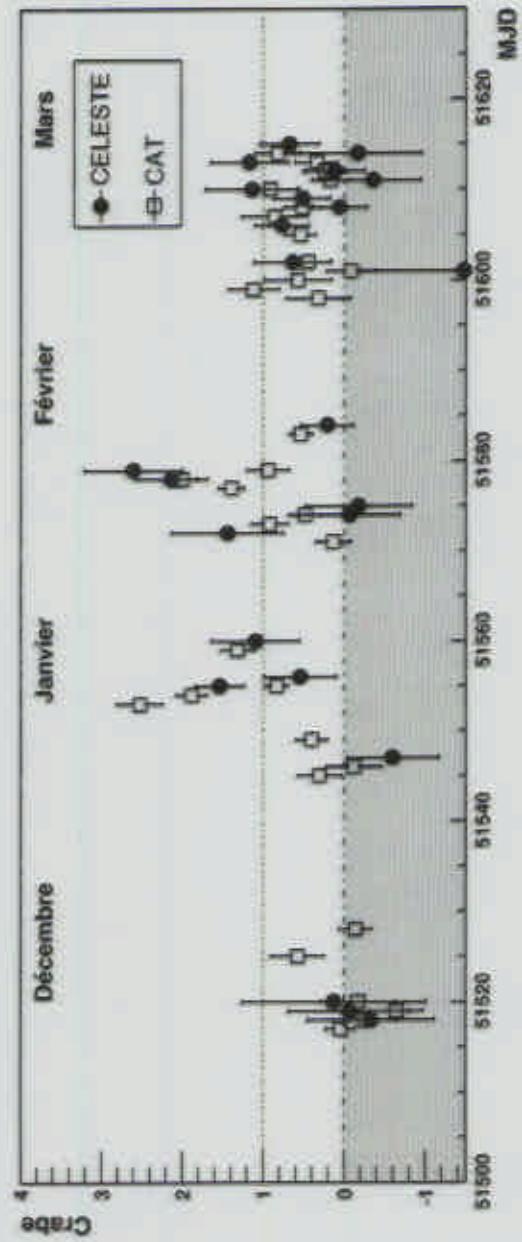
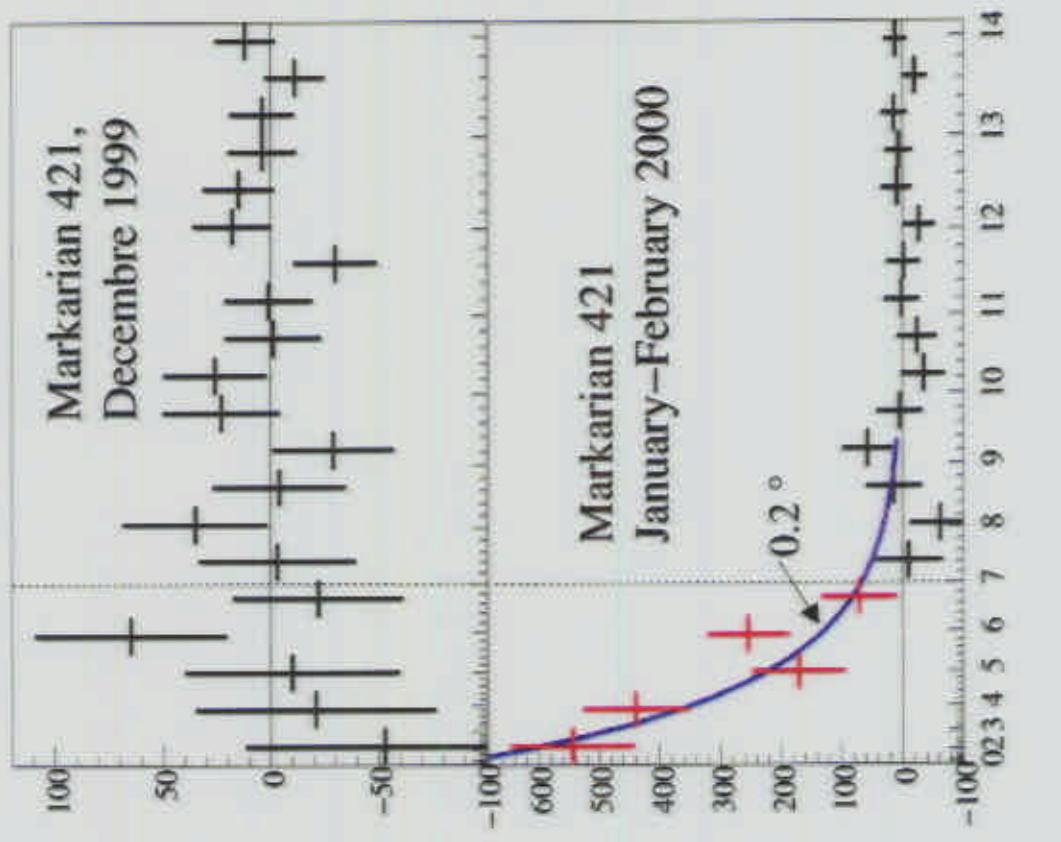
Markarian 421

- ❑ Quiet in December 99
- ❑ Active (according to CAT) in January/February 2000

8.2 σ in 5 hours (2 x Crab)

- ❑ Evidence for correlation between CAT & CELESTE:

Angular Distributions:



The Shell-type Supernova Remnant Cassiopeia A

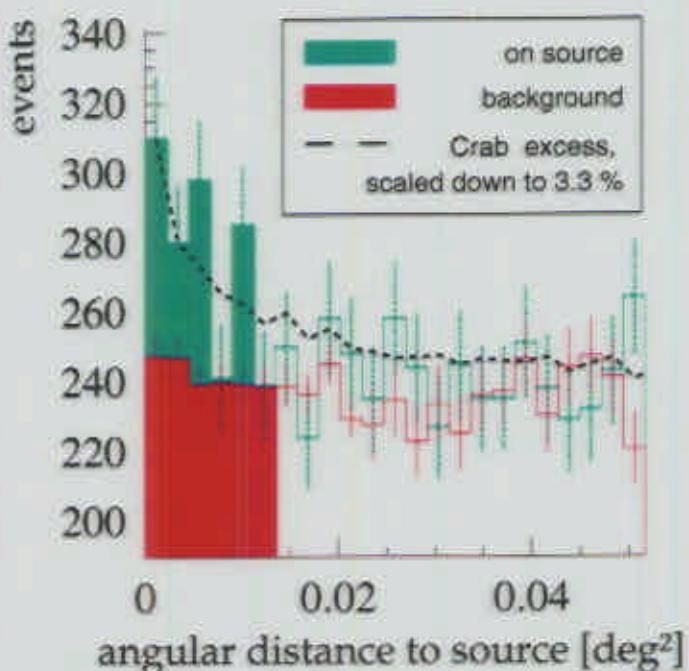
HEGRA:

232 h, 4.9σ

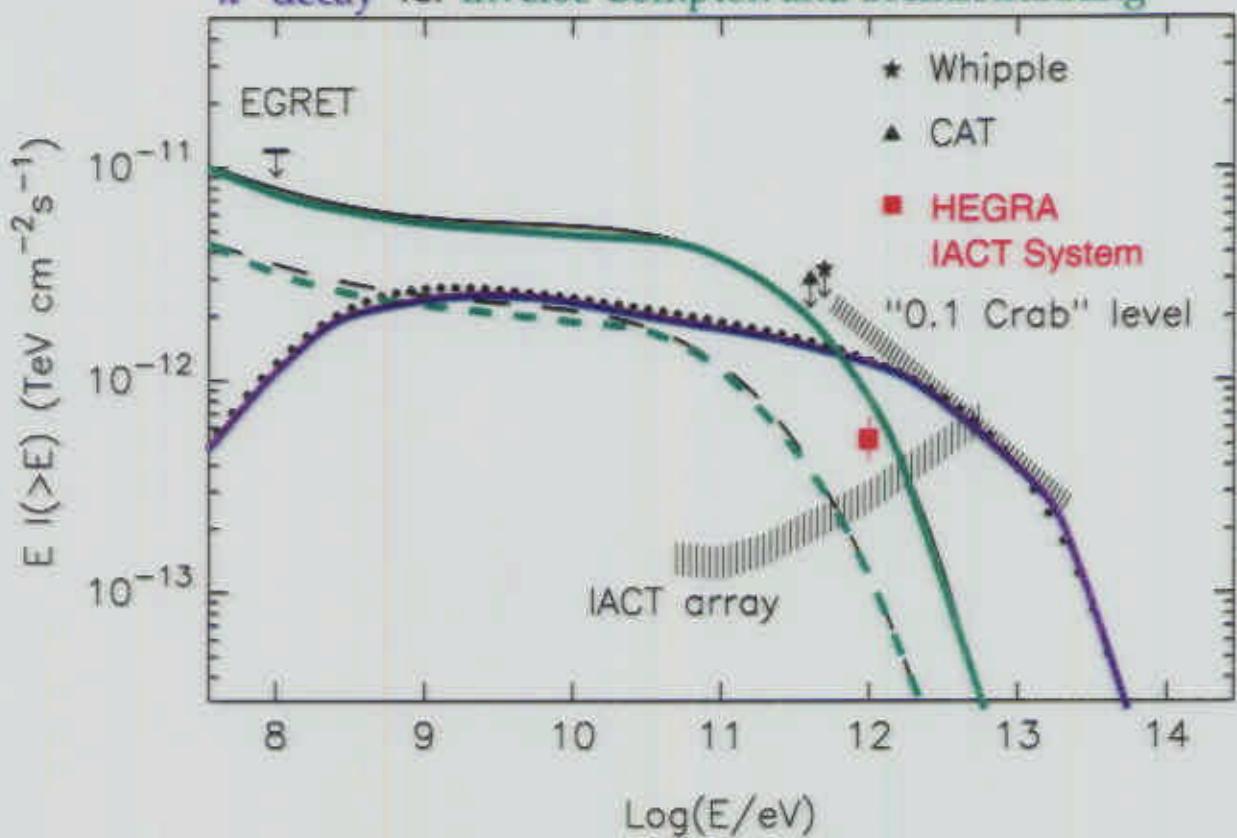
Flux F($E > 1\text{TeV}$) =

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

(33 milli-Crab)



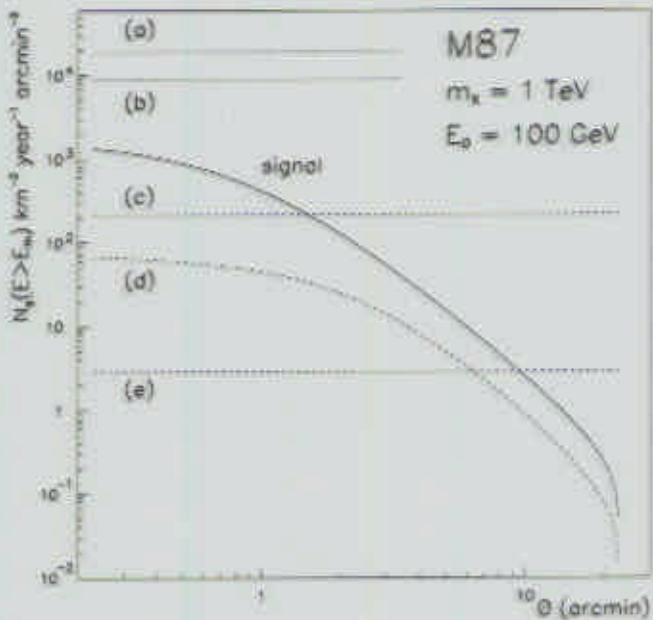
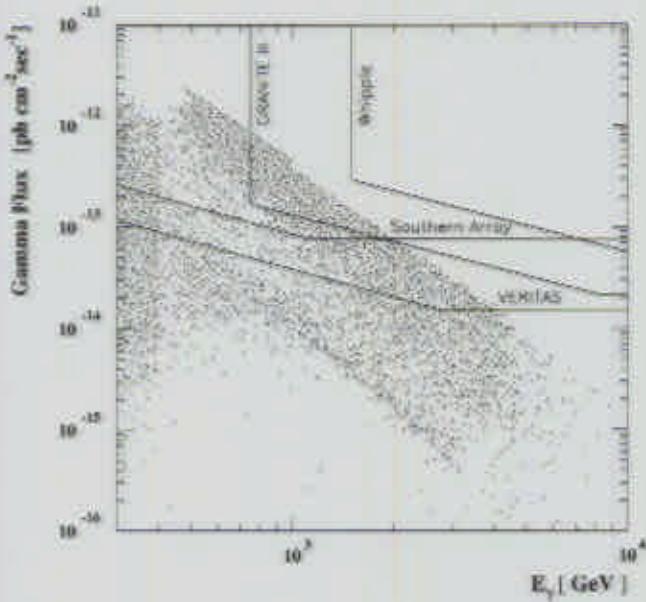
π^0 -decay vs. inverse Compton and Bremsstrahlung



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

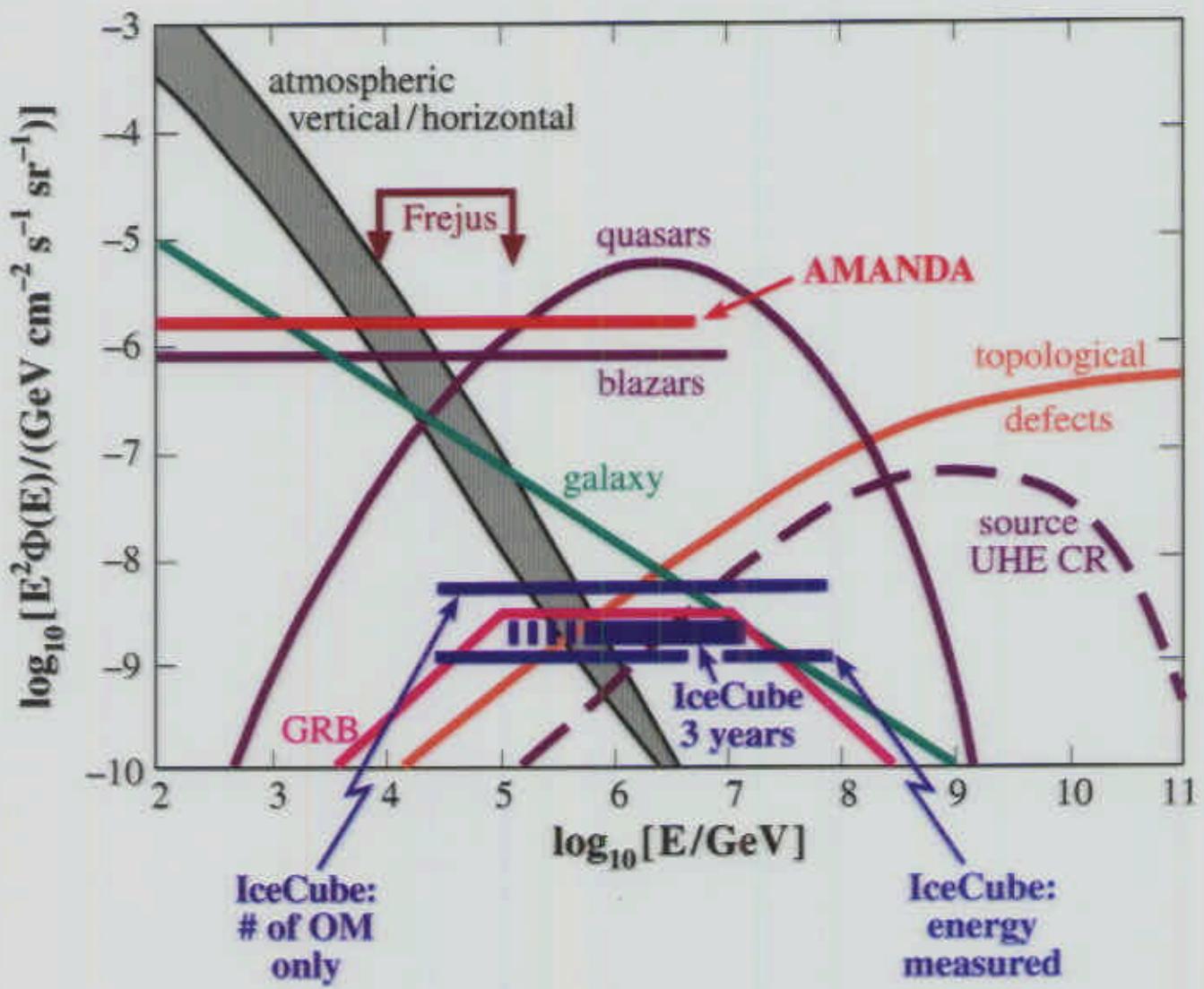
Sensitivity to some regions parameter space



High Energy Particles from the Universe

CHARGED COSMIC RAYS

- 1.a A brief outlook
- 1.b Antimatter in cosmic rays

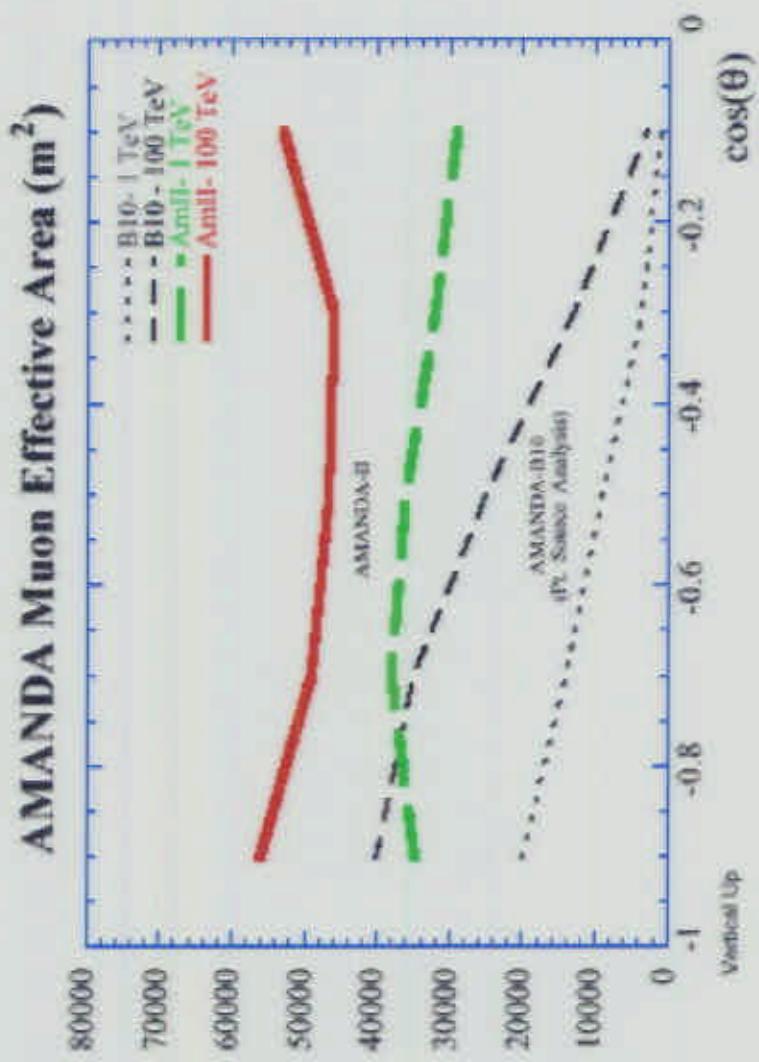


(from F. Halzen)

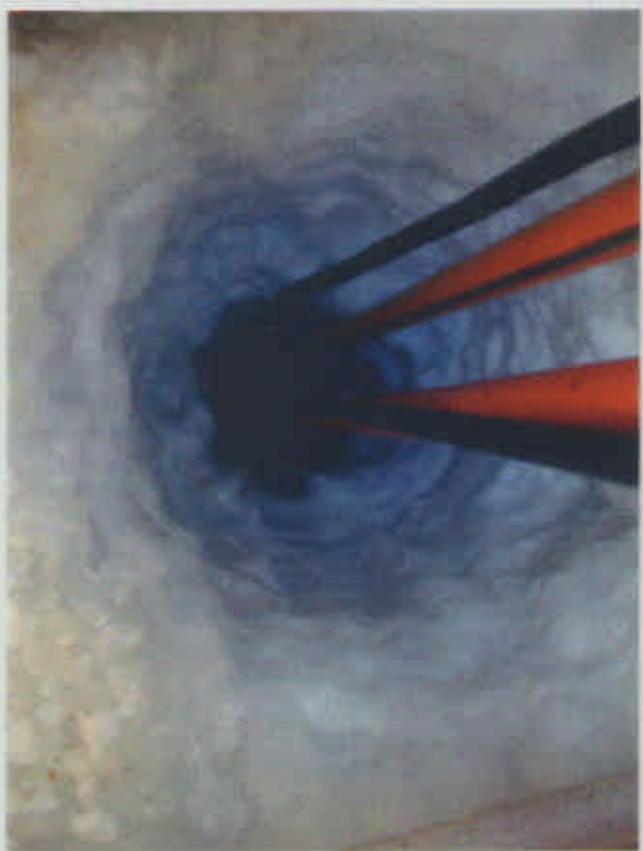


AMANDA Effective Area

- AMANDA-II
 $30,000\text{--}50,000 \text{ m}^2$
- AMANDA-II has
nearly uniform
response over all
zenith angles

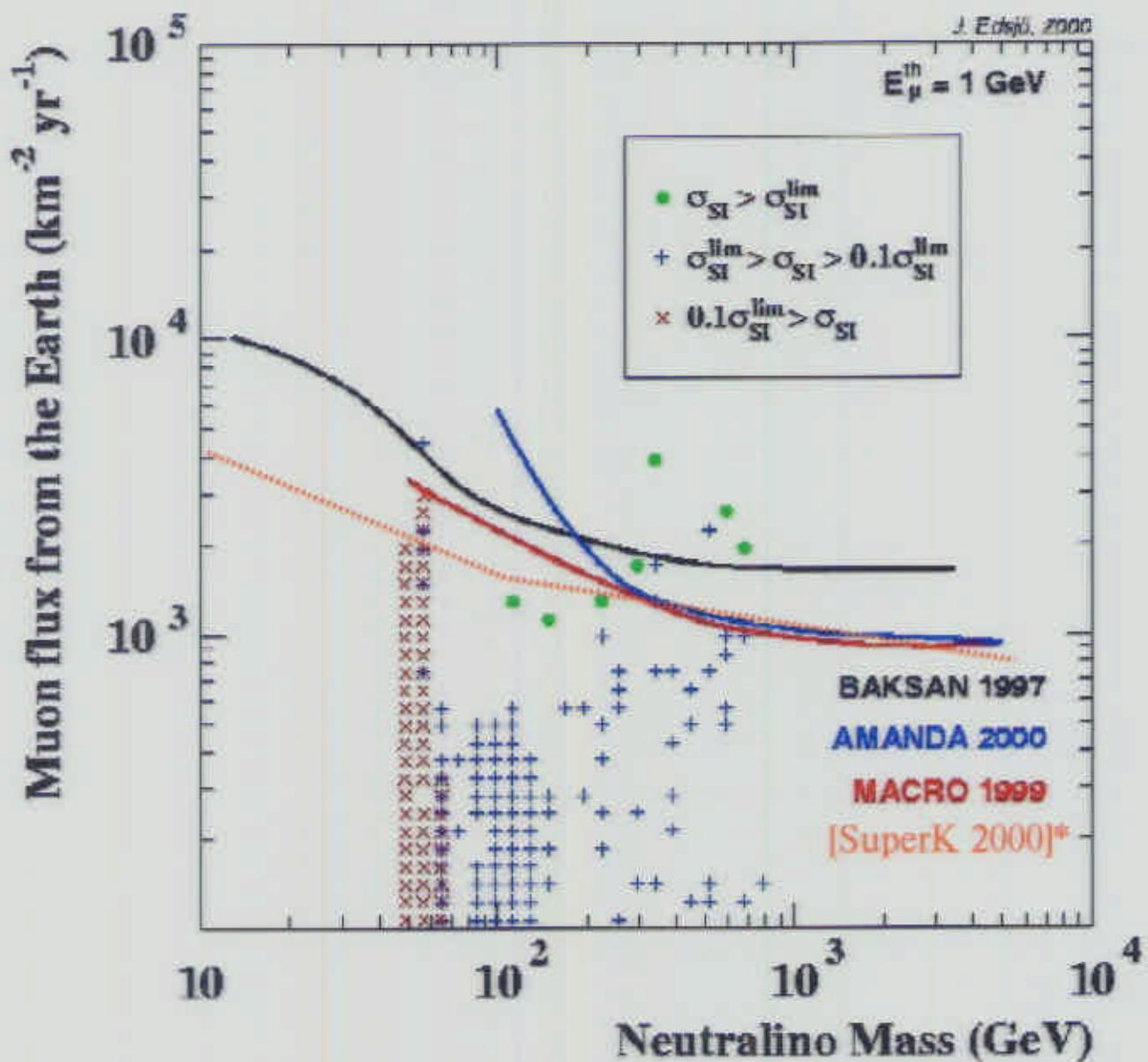


Deployment: Drilling



WIMPs from Earth

Optimize for vertical neutrinos.
AMANDA limits are competitive.



*Unofficial, added for completeness

Relativistic Monopole Search

Search
for signal
due to
high
ionization
signal of
monopole

