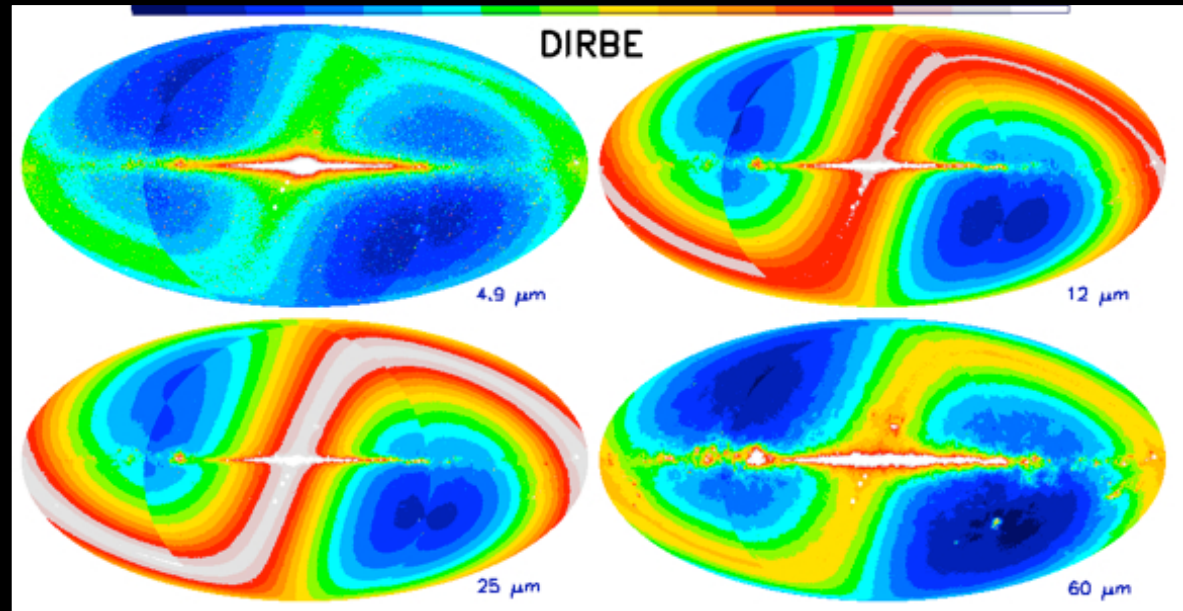
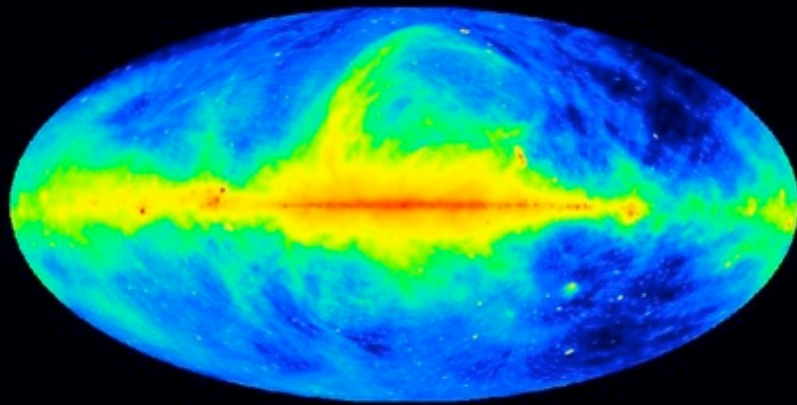


El Observatorio de rayos γ HAWC

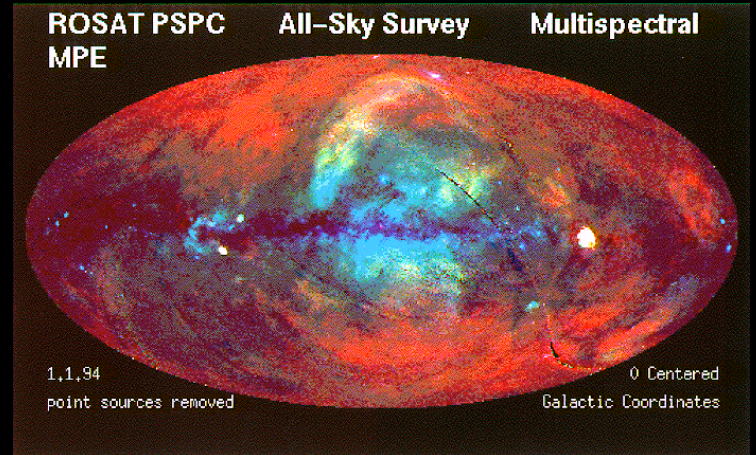
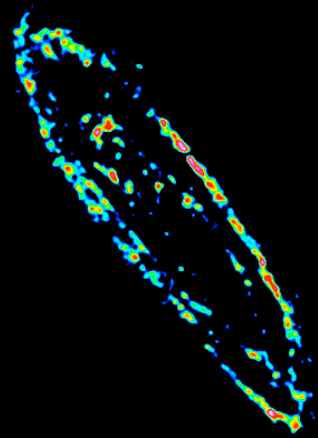
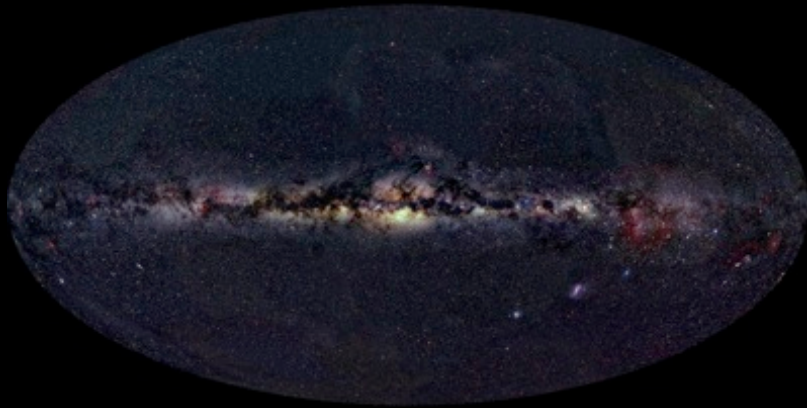
Alberto Carramiñana (INAOE)
por la Colaboración HAWC

Reunión de la DPyC-SMF
Puebla 12 de septiembre de 2012

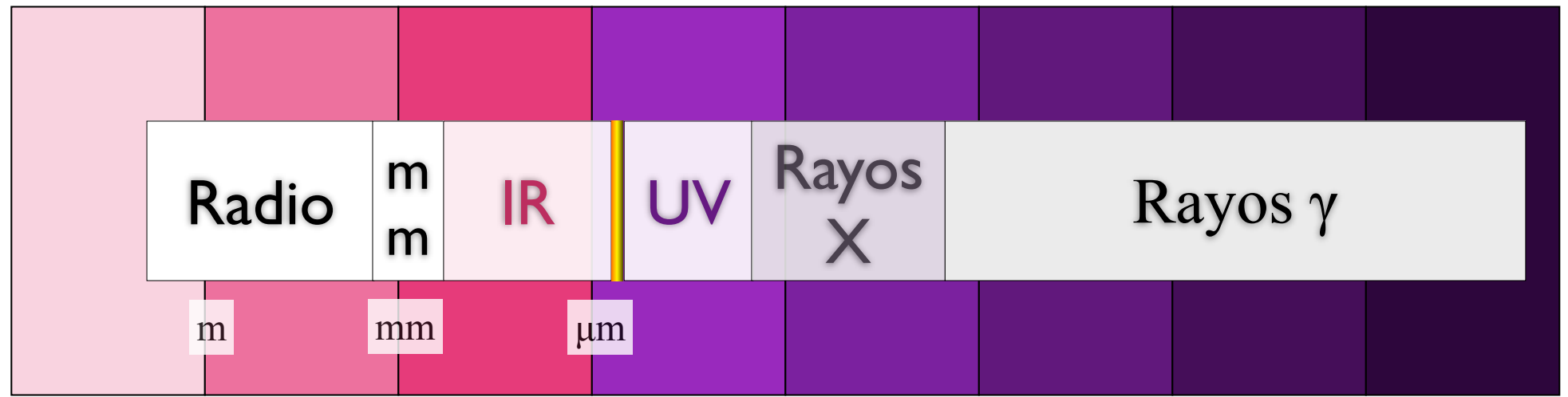




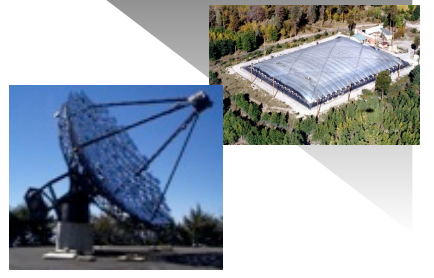
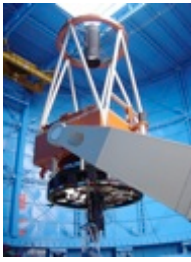
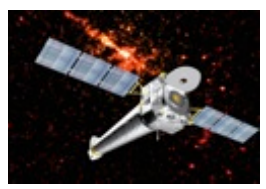
The Deep Sky



neV μ eV meV eV keV MeV GeV TeV PeV



MHz GHz THz



No térmico (e) → **Térmico** → No térmico (RCs)

Rayos γ

- Decaimiento radiactivo (keV -- MeV)
- Aniquilación de pares: $ee \rightarrow \gamma\gamma$
- Bremsstrahlung: $eZ \rightarrow eZ\gamma$
- Efecto Compton inverso: $e\gamma \rightarrow e\gamma$
- Decaimiento del π^0 ($\rightarrow \gamma\gamma$)

Requieren partículas de alta energía (relativistas)

Rayos cósmicos



Victor Hess 1912

- Radiación “cósmica”
- Partículas de alta energía

99% núcleos

{90% p + 9% α + 1% ($Z > 2$)}
+ 1% electrones

- Distribución isotrópica

El paradigma de Fermi

Fermi (1949, 1954):

- Los rayos cósmicos son producidos en explosiones de supernova.
- Aceleración en frentes de choque produce espectro de ley de potencias (E^{-k} con $k=2$)
- Propagación en la Galaxia modifica el espectro a $E^{-k-\delta}$ con $\delta=0.7$

$$u_{cr} \approx 0.03 \left(\frac{E_{sn}/t_{sn}}{V_{gal}} \right) t_{esc}$$

Supernovas

Baade & Zwicky (1934):

- Enunciaron la existencia de supernovas
- Predijeron la formación de estrellas de neutrones
- Predijeron remanente gaseoso en expansión
- Mencionaron que los rayos cósmicos podrían producirse en las SNe

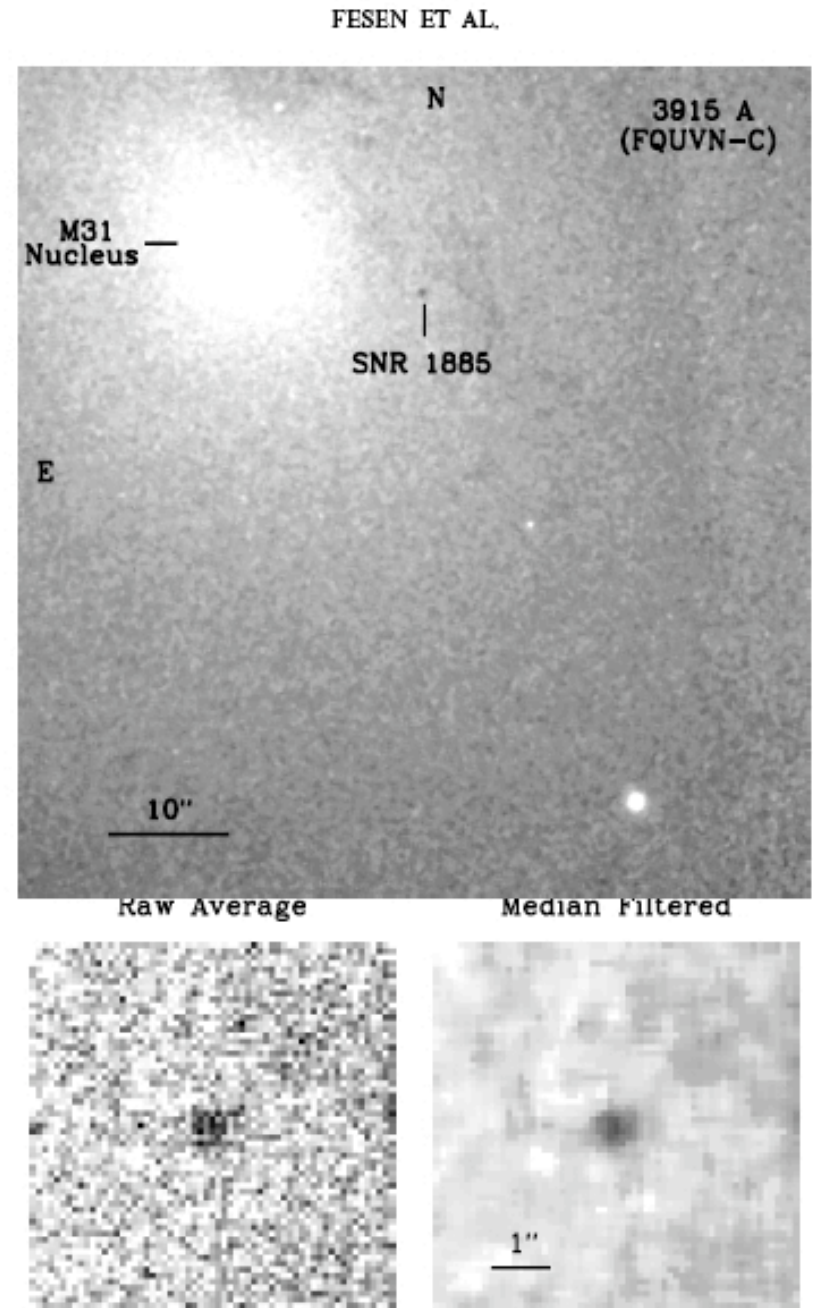


FIG. 1.—WFPC2 image of SNR 1885 in the bulge of M31

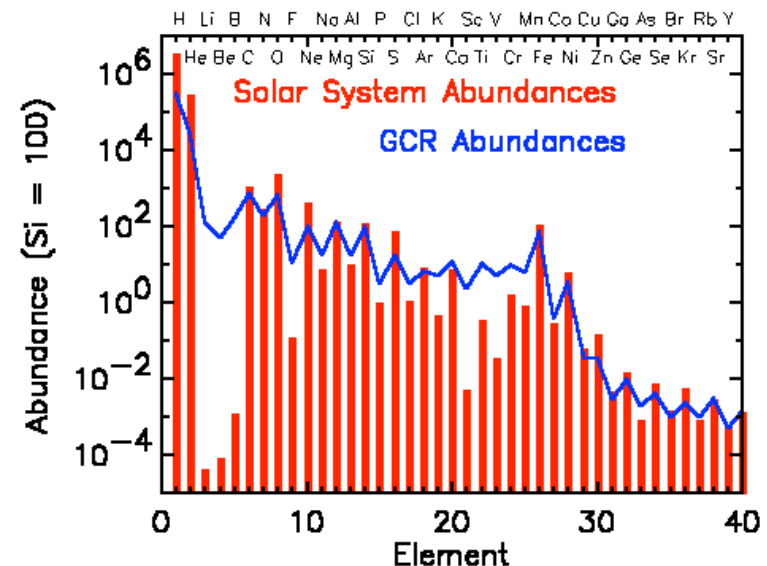
Aceleración de Fermi

- Partículas cargadas aceleradas por colisiones con espejos magnéticos ($\Delta E = \zeta E$).
- Para velocidad βc de la nube $\zeta \propto \beta$, $\zeta \propto \beta^2$ dependiendo de geometría (1st, 2nd order DSA).
- Produce espectro en ley de potencias dada una inyección de partículas relativistas ($E_0=pc$).
- Índice espectral modificado por propagación.
- Electrones afectados por pérdidas radiativas.

Propagación

- Propagación afectada por campo magnético interestelar
- Camino libre medio \ll distancia a fuentes \Rightarrow recorrido difusivo \Rightarrow isotropía
- Partículas con mayor energía escapan antes ($\delta < 0$)
- Interacciones con medio interestelar afectan abundancias
- Electrones afectados por pérdidas radiativas

$$r_\ell = 0.03 \text{ pc} \left(\frac{E/Z}{\text{TeV}} \right) \left(\frac{3 \mu\text{G}}{B} \right)$$



Manifestaciones de los RCs

- Radio
 - emisión sincrotrón de electrones relativistas
- Rayos gamma
 - sincrotrón, bremsstrahlung, Compton inverso
 - producción hadrónica

Colisiones nucleares

En la atmósfera o en el medio interestelar

$$p^* + \text{núcleo} \rightarrow p^* + \text{frag. núcleo} + \pi^\pm + \pi^0$$

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu \rightarrow e^\pm + \nu_e + \nu_\mu$$

$$\pi^0 \rightarrow \gamma\gamma$$

Los π^0 tienen masa de 135 MeV \rightarrow fotones de 67 MeV *en el marco en reposo* (\rightarrow 70 GeV para un protón de 1 TeV).

Proceso dominante en el MI Galáctico.

ICS

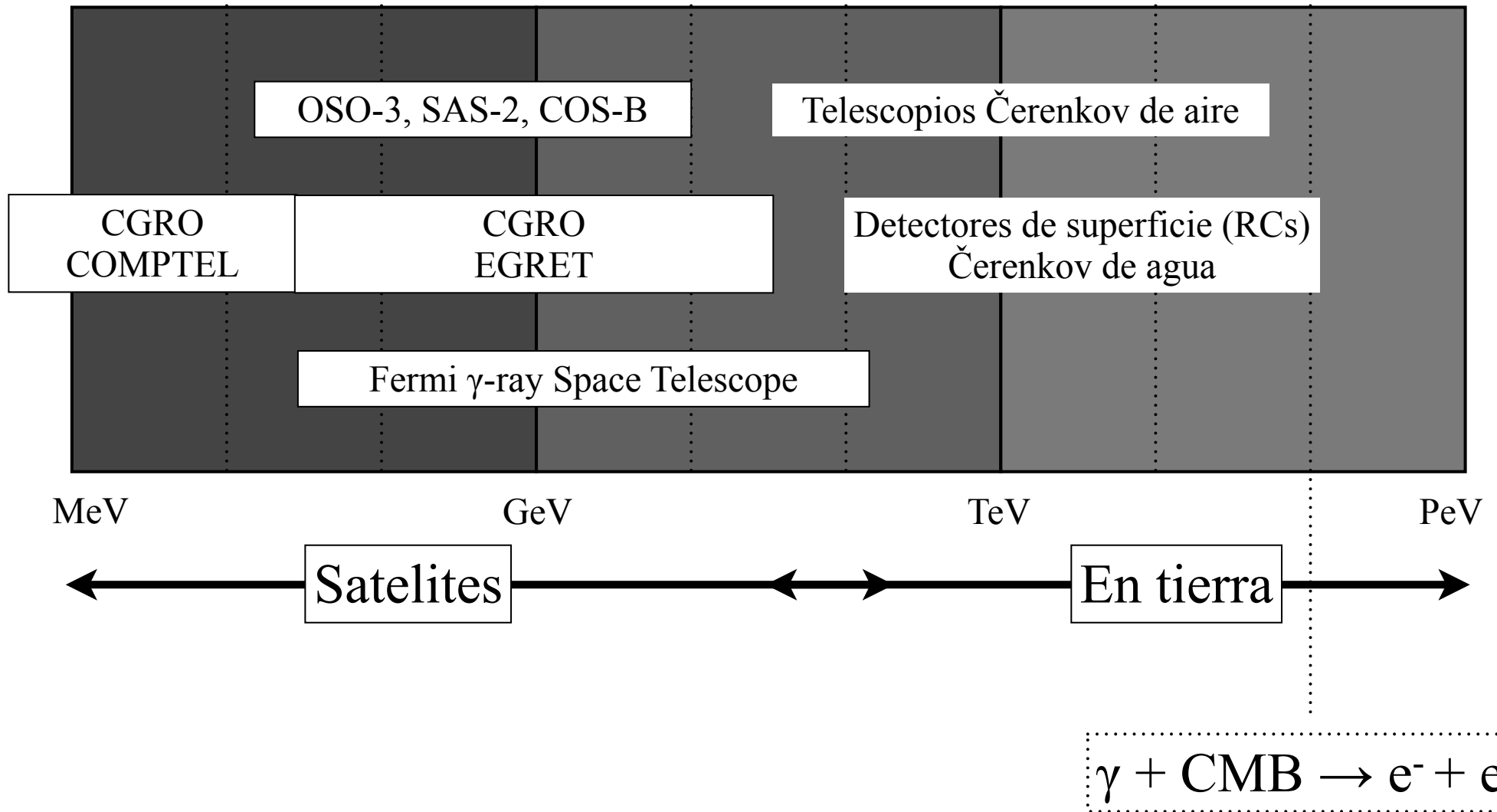
$$\omega \rightarrow \{ \gamma^2 \omega_0 ; \gamma \}$$

Un electrón de 1 TeV ($\gamma \approx 10^6$) puede producir

- un fotón de 1 TeV a partir de luz visible
- un fotón de 1 GeV a partir del CMB

Limitado por la sección eficaz KN para $\omega' \gg 1$

La banda gamma

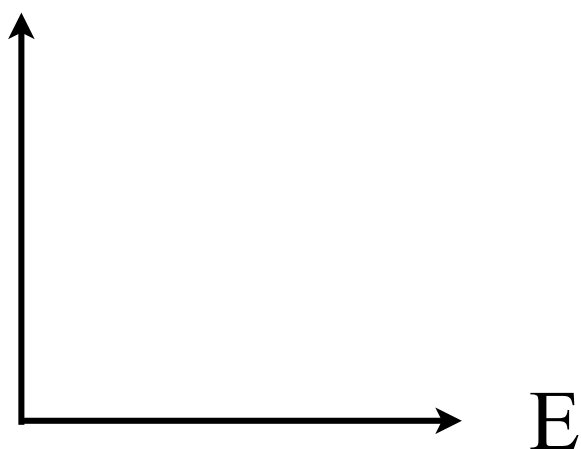


Sr



deg

FoV



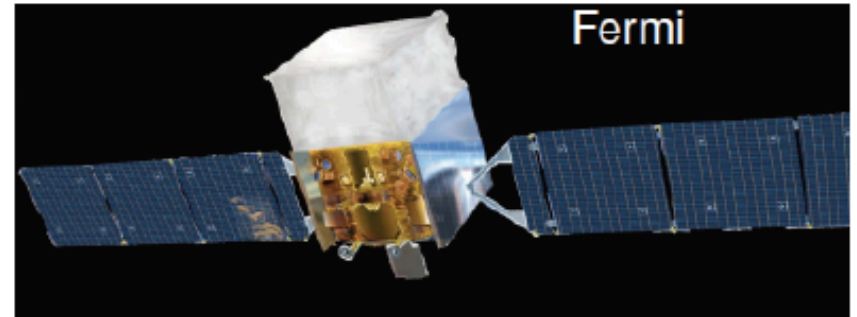
GeV



TeV

Satellite Experiments

- high **duty cycle** $\approx 100\%$
- large **sky coverage** LAT: $\approx 20\%$
- sensitive to **medium energies**
LAT: $\approx 30\text{ MeV} - 300\text{ GeV}$



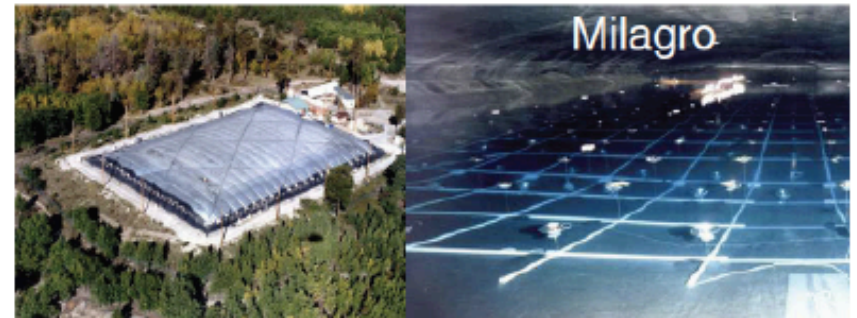
Air Cherenkov Telescopes

- very good **angular resolution** $\lesssim 0.2^\circ$
- large **effective area** $O(10^5\text{ m}^2)$
- sensitive to very **high energies**
 $\approx 100\text{ GeV} - 50\text{ TeV}$



Water Cherenkov Detectors

- high **duty cycle** $\approx 95\%$
- large **effective area** $O(10^4\text{ m}^2)$
- sensitive to very **high energies**
 $\approx 100\text{ GeV} - 100\text{ TeV}$



Telescopios espaciales

OSO III	1967 - 1968	621 fotones relevando la emisión del plano Galáctico (Kraushaar et al. 1972)
SAS II	1972 - 1973	Pulsares de Vela y Crab; γ 195+5 (Thompson et al. 1977)
COS B	1975 - 1982	Primer catálogo de fuentes celestes de rayos γ (Swanenburg et al. 1981); primera fuente extragaláctica 3C 273
CGRO-Comptel	1991 - 2000	Primer telescopio Compton en órbita; all-sky survey en la banda (0.7-30) MeV (Schönfelder et al. 2000)
CGRO-EGRET	1991 - 2000	Blazares; catálogos 3EG y GeV (Hartman et al. 1999; Lamb & Macomb 1997)
Fermi γ -ST	2008 -	Antes GLAST. Lanzado 11 junio 2008

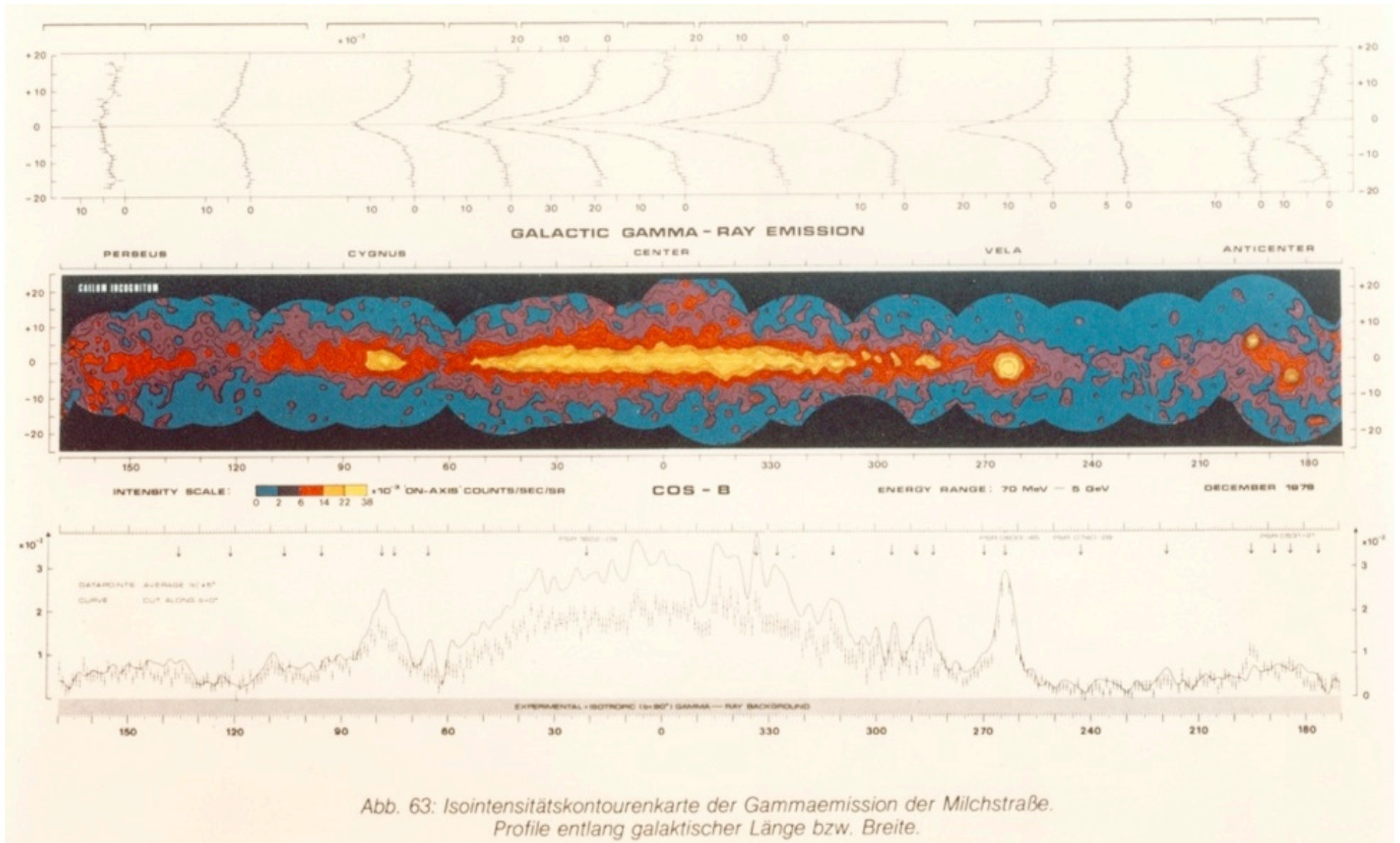


Abb. 63: Isointensitätskontourenkarte der Gammaemission der Milchstraße.
Profile entlang galaktischer Länge bzw. Breite.

Mayer-Hasselwander et al. (1982)

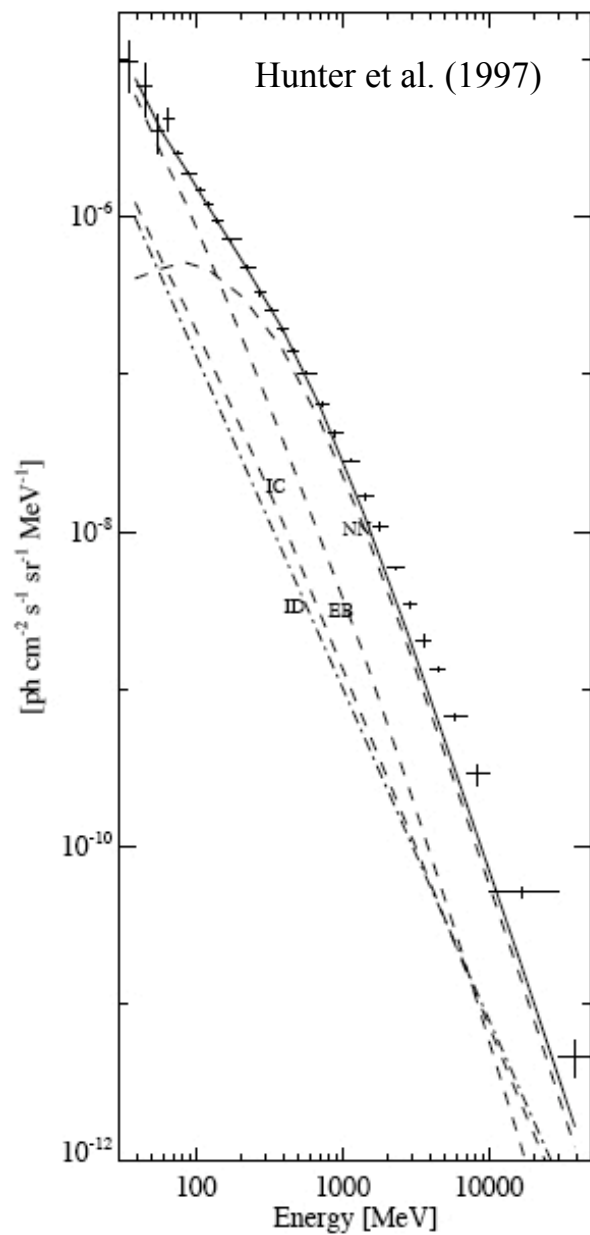
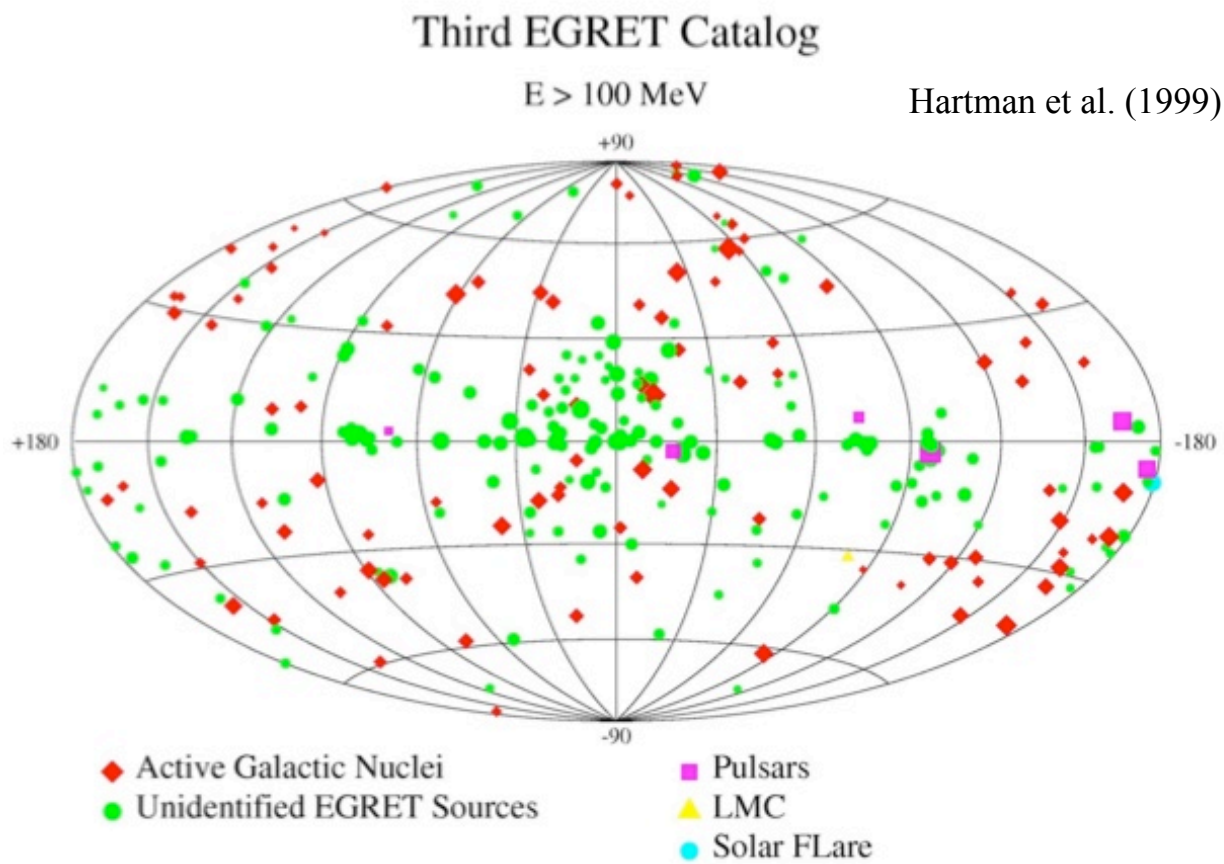
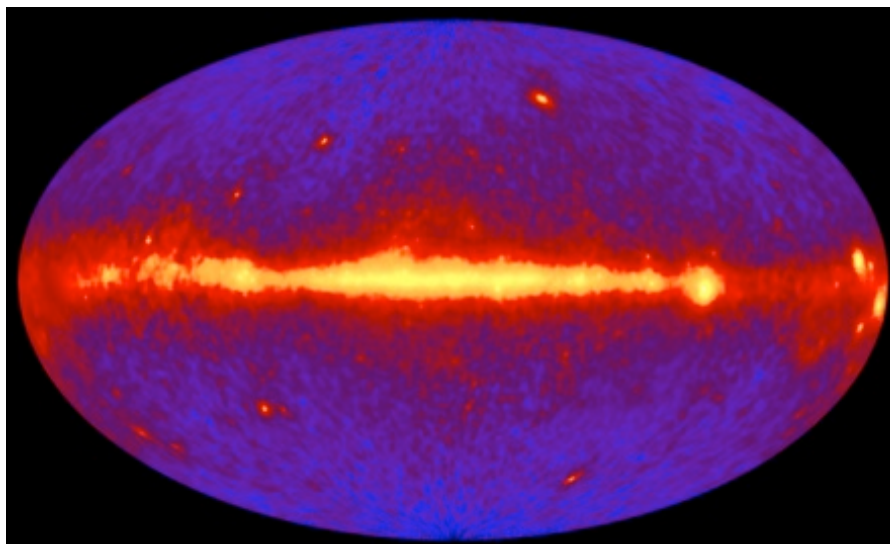
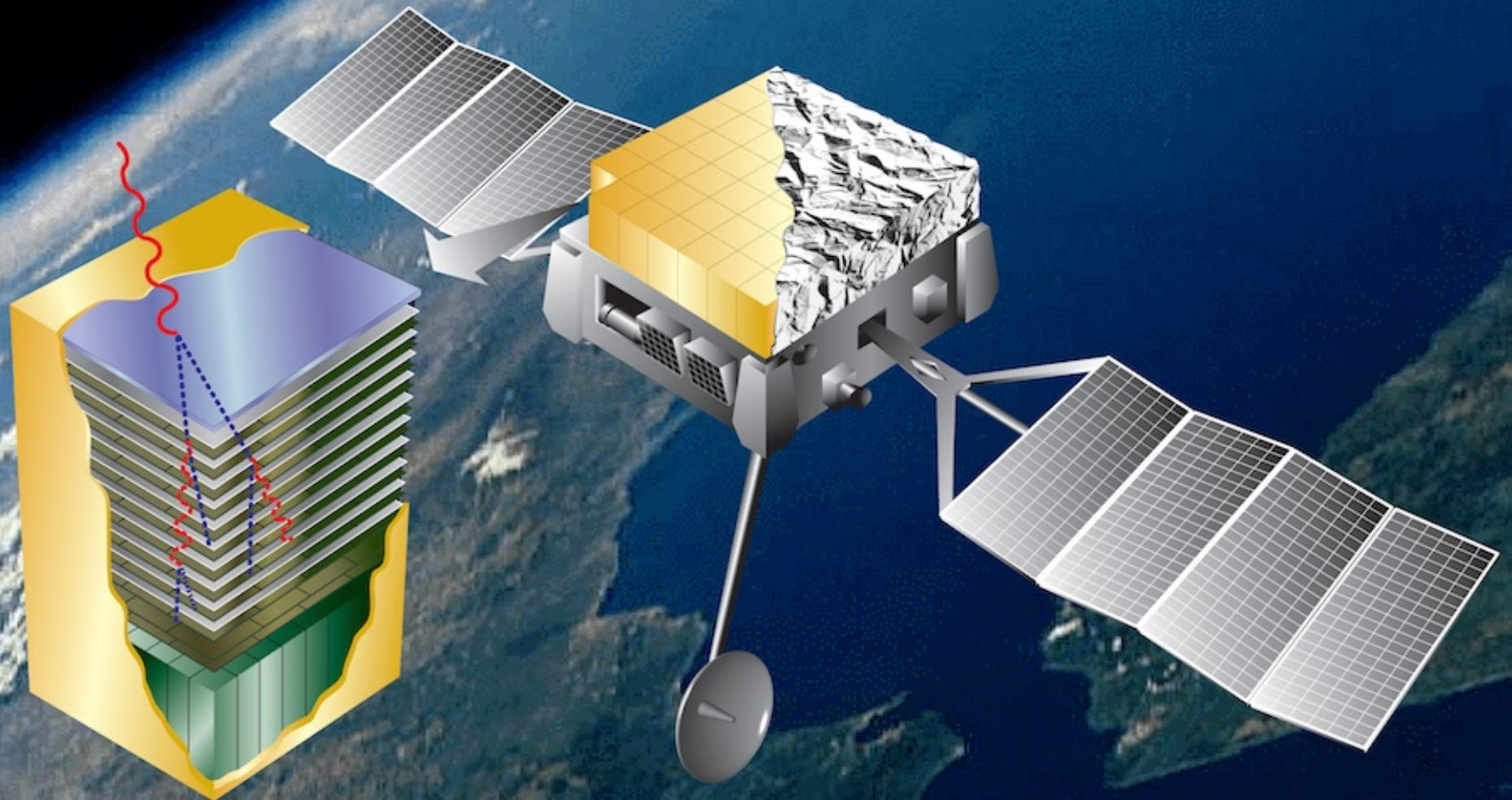


FIG. 4.—Average diffuse gamma-ray spectrum of the inner Galaxy region, $300^\circ < l < 60^\circ$, $|b| \leq 10^\circ$ (0.73 sr). The contributions from point sources detected with more than 5σ significance have been removed. The data are plotted as crosses where the horizontal line indicates the width of the energy interval and the vertical line the $\pm 1\sigma$ statistical error. The intensity and error for the four lowest energy intervals include corrections



GAMMA-RAY LARGE AREA SPACE TELESCOPE

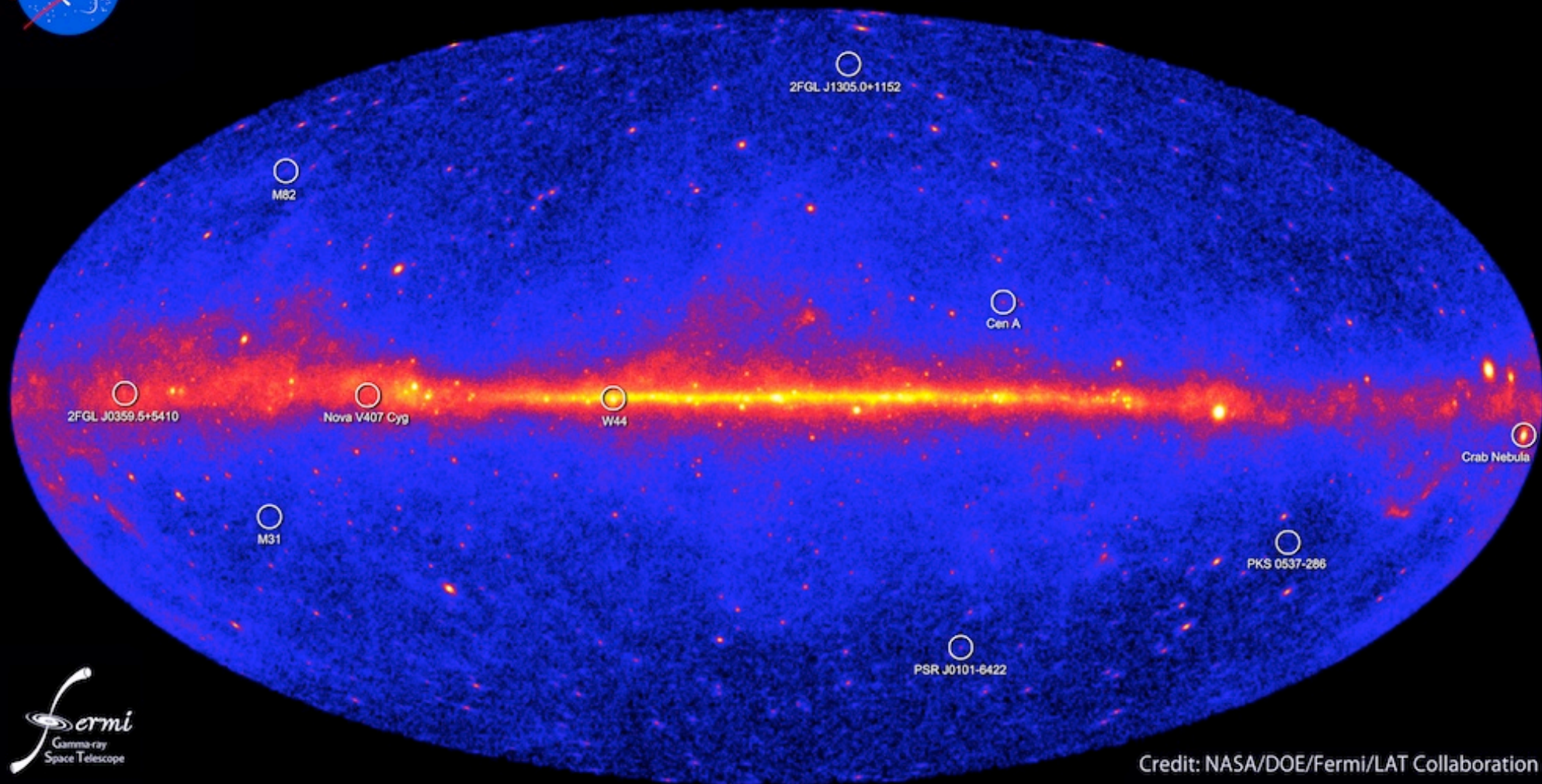


Exploded View:
One of Forty-nine Towers

- 10 Layers of 0.5 rad Length Converter (pb)
- 12 Layers of XY Silicon Strips
- Gamma Rays
- Positrons/Electrons



Fermi two-year all-sky map



Credit: NASA/DOE/Fermi/LAT Collaboration



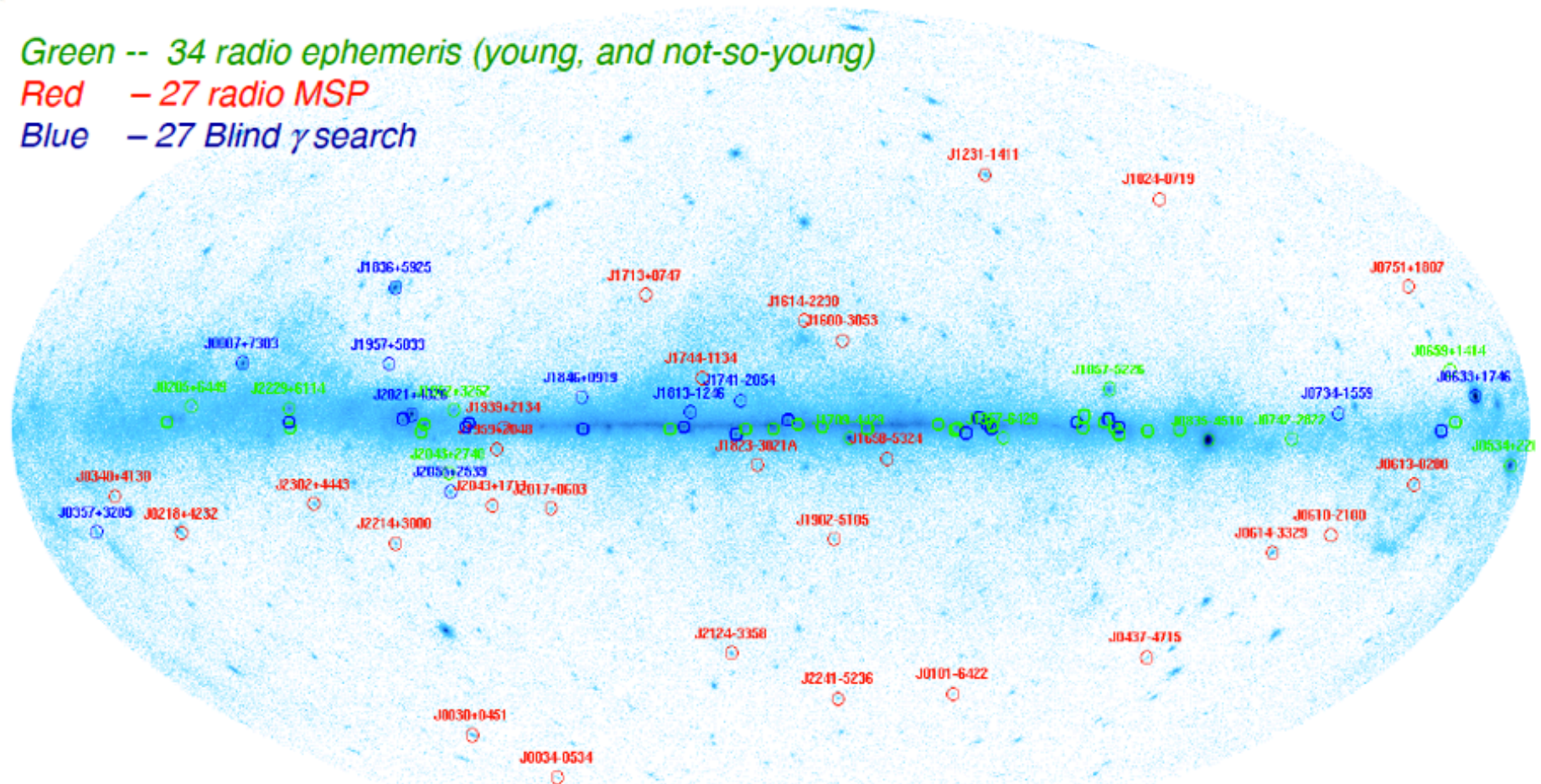
88 Gamma-ray pulsars

One for every musical note on a piano. One for every constellation.

Green -- 34 radio ephemeris (young, and not-so-young)

Red -- 27 radio MSP

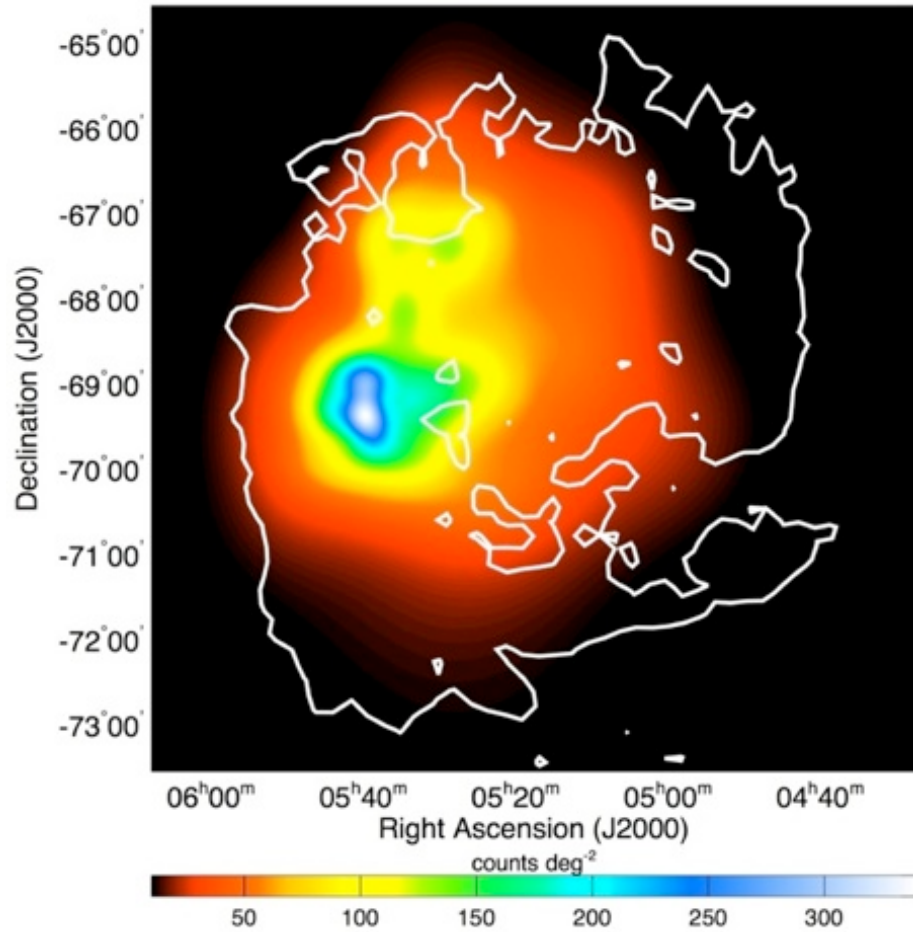
Blue -- 27 Blind γ search



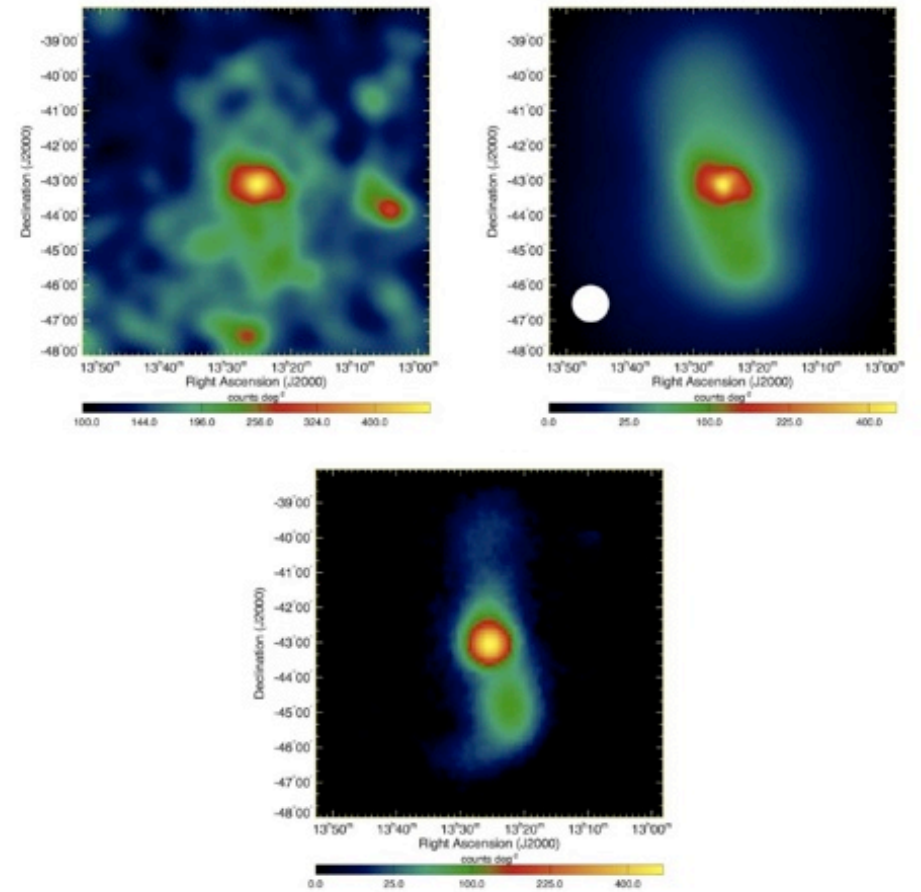
We require $>5\sigma$ pulsations using e.g. H-test, and ≥ 2 independent analyses.
~10 more with $>4\sigma$. Also awaiting ephemerides for ~20 MSPs found in Unid sources.

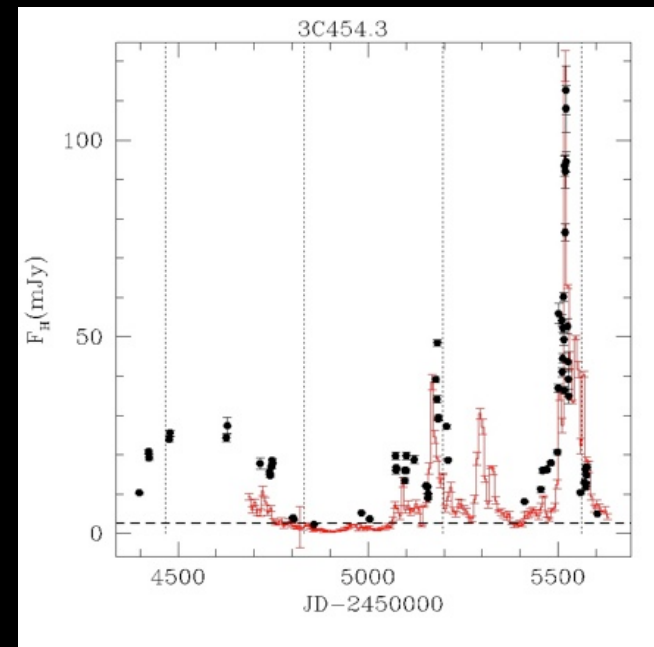
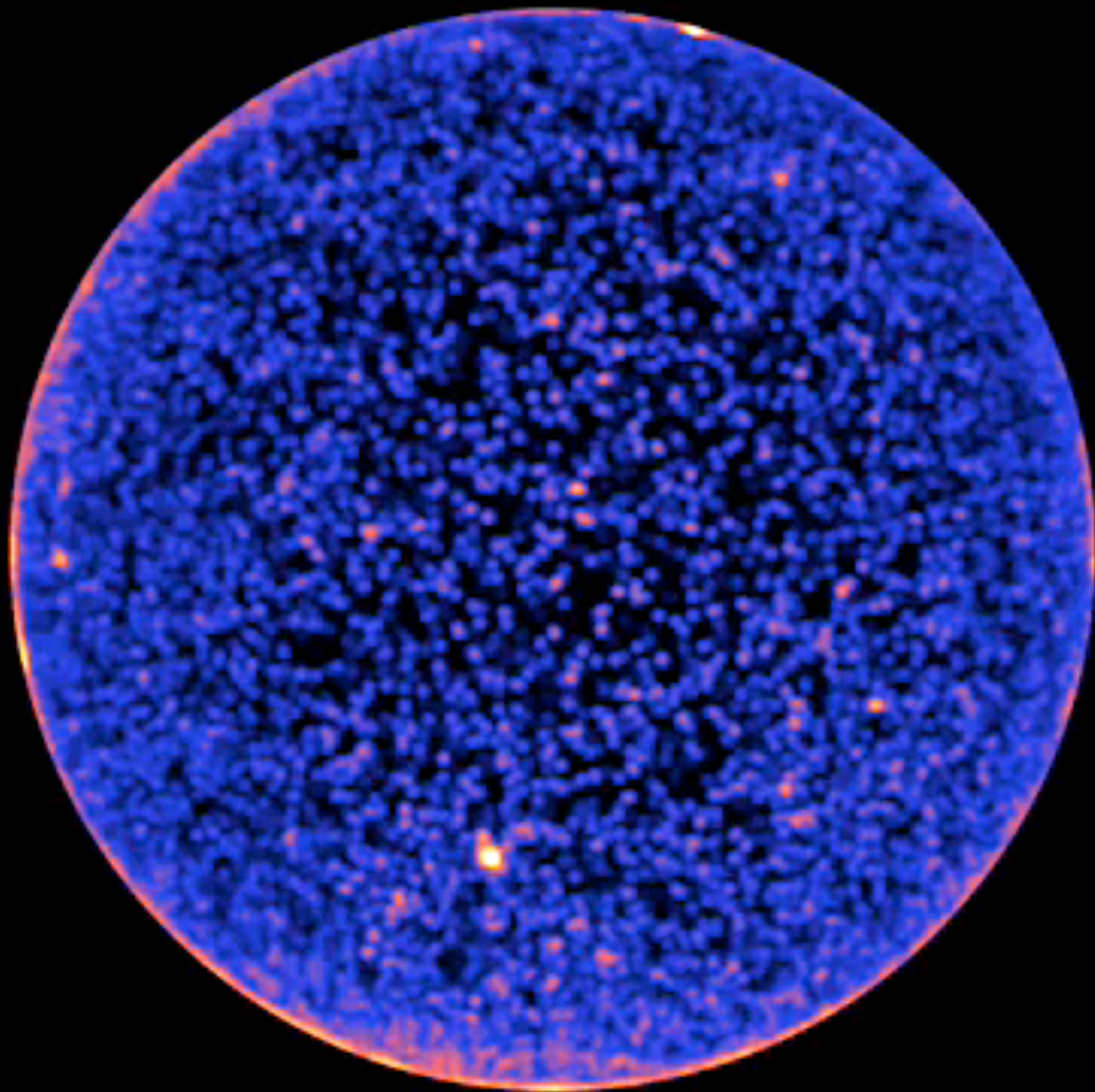
There were 46 in the "1st Fermi Pulsar Catalog", Abdo et al. ApJS 187, 460 (2010)

LMC



Cen A



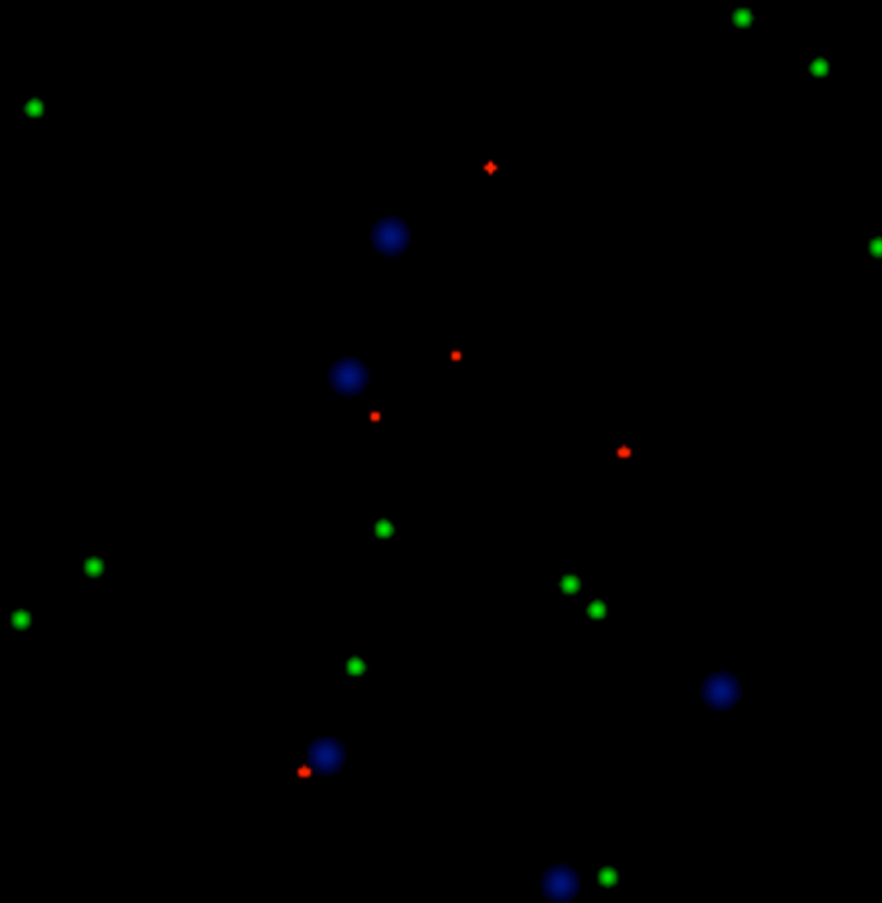


Fermi extragalactic sources

Normal galaxies	Starburst galaxies	Radio galaxies	Seyferts	FSRQ	Bl Lac
MW LMC SMC no M31!?	M82, NGC 253 NGC 4945 (Sb or Sy 2?)	M87, Cen A, NGC1275, NGC1218, NGC 6251	PMN J0948+0022, PKS 1502+036, PKS 2004-447, NGC 6951	Classical EGRETS, 3C 454.3	EGRETS and TeV sources
SF cosmic rays interacting with ISM matter	Larger SF than normal galaxies, no variability found. Weak AGN in M82?	Variable, particle acceleration in mild jet, misaligned AGN	Narrow line Sy1 Sy 2 LINER Maybe radio quiet Seyferts	Highly variable, acceleration in relativistic jet	Steeper γ spectrum, highly variable, acceleration in relativistic jet

Accelerator power: SFR / Jet / AGN →

GRB 080916C



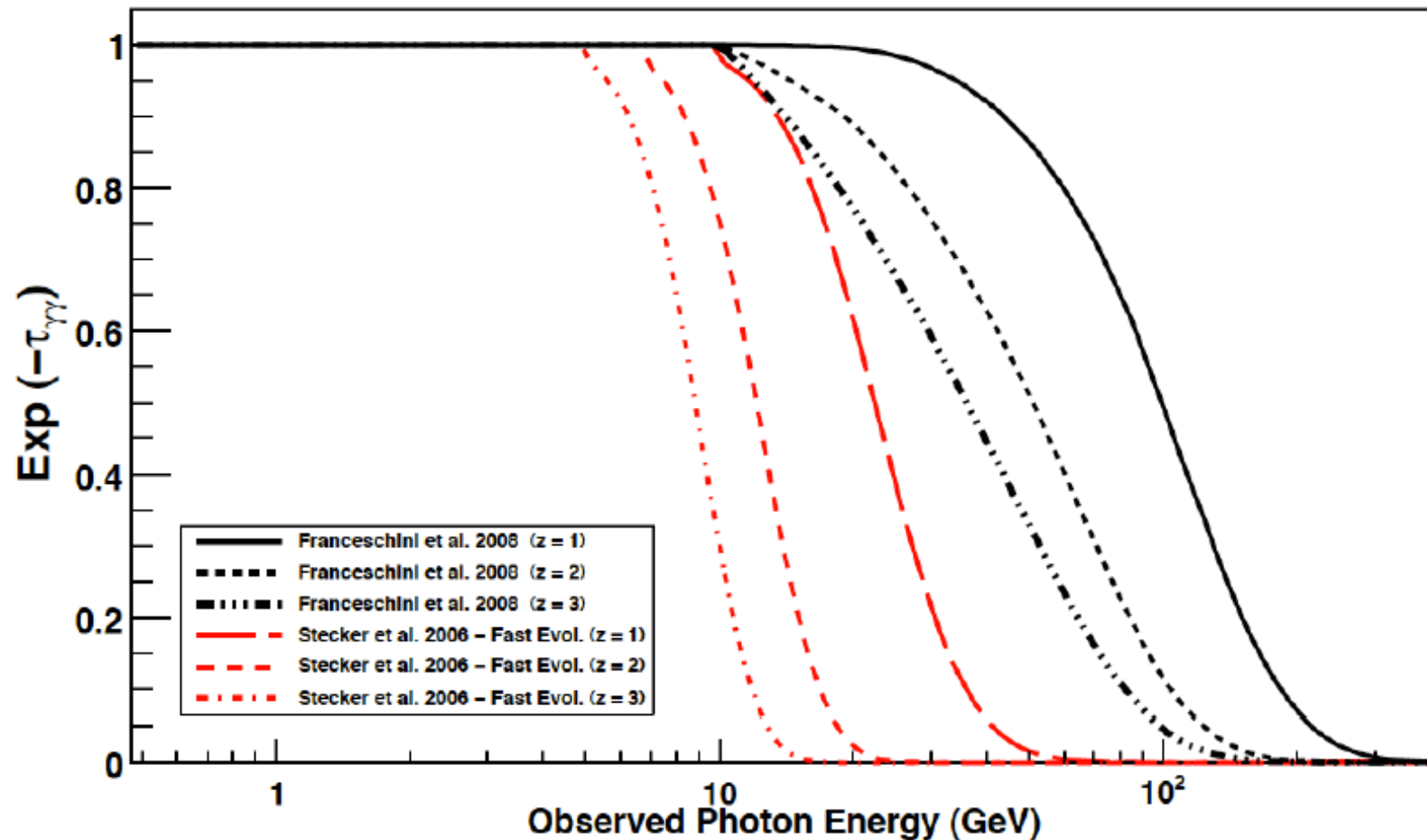
GRB	Sig.	Θ	ΔT (sec) [type]	Events > 100 MeV	Events > 1 GeV	E_{max} (GeV)	z	GCN cir- cu- lars
080825C	$\gtrsim 6\sigma$	60°	~ 35 [long]	~ 10	0	~ 0.6	-	[120]
080916C	$\gtrsim 35\sigma$	49°	~ 80 [long]	145	13	~ 14	4.3	[121]
081024B	$\gtrsim 10\sigma$	19°	~ 1 [short]	~ 10	2	~ 3	-	[122]
081215A	$\gtrsim 8\sigma^\dagger$	86°	** [long]	-	-	-	-	[123]
090217	$\gtrsim 8\sigma$	34°	~ 30 [long]	~ 10	1	~ 1	-	[124]
090323	$\gtrsim 5\sigma^{\dagger\dagger}$	57° *	** [long]	~ 20	$\gtrsim 1$	~ 7	3.6	[125]
090328	$\gtrsim 8\sigma^{\dagger\dagger}$	65° *	** [long]	~ 20	$\gtrsim 1$	~ 24	0.7	[126] [127]
090510	$\gtrsim 45\sigma$	14° *	~ 2 [short]	~ 150	~ 20	~ 31	0.9	[128] [129]
090626	$\gtrsim 8\sigma$	18° *	** [long]	~ 20	1	~ 2	-	[130]
090902B	$\gtrsim 40\sigma$	51° *	~ 20 [long]	~ 200	~ 30	~ 33	1.8	[131] [132]
090926A	$\gtrsim 40\sigma$	48° *	~ 20 [long]	~ 150	~ 50	~ 20	2.1	[133] [134]
091003A	$\gtrsim 10\sigma$	12° *	~ 21 [long]	~ 20	2	~ 3	0.9	[135]
091031A	$\gtrsim 6\sigma$	22°	~ 35 [long]	~ 20	0	~ 0.7	-	[131]
100116A	$\gtrsim 6\sigma$	29°	~ 35 [long]	~ 10	3	~ 2	-	[137]

Table 7.1: List of GRBs detected by the LAT up to January 2010 along with some general information. The Test-Statistic (TS) is computed via a likelihood fit for a point source (\dagger : based on specific analysis requiring non-standard data

LAT-GRBs a enero 2010

Bouvier
PhD Thesis (2010)

Absorción por luz de fondo extragaláctica



Source	z	E_{max} (GeV)	$\tau(z, E_{max})$ (F08)	$\tau(z, E_{max})$ (St06, baseline)	Number of photons above 15 GeV
J1147-3812	1.05	73.7	0.40	7.1	1
J1504+1029	1.84	48.9	0.56	12.2	7
J0808-0751	1.84	46.8	0.52	11.7	6
J1016+0513	1.71	43.3	0.39	9.0	3
J0229-3643	2.11	31.9	0.38	10.2	1
GRB 090902B	1.82	33.4	0.28	7.7	1
GRB 080916C	4.24	13.2	0.08	5.0	1

Table 4: Gamma-ray optical depth to HEP calculated using the EBL model of Franceschini et al (2008; F08) in comparison to the “baseline” model of Stecker et al. (2006) (St06). Also listed are the number of photons associated to the source which have ≥ 15 GeV energy and which can potentially constrain EBL models.

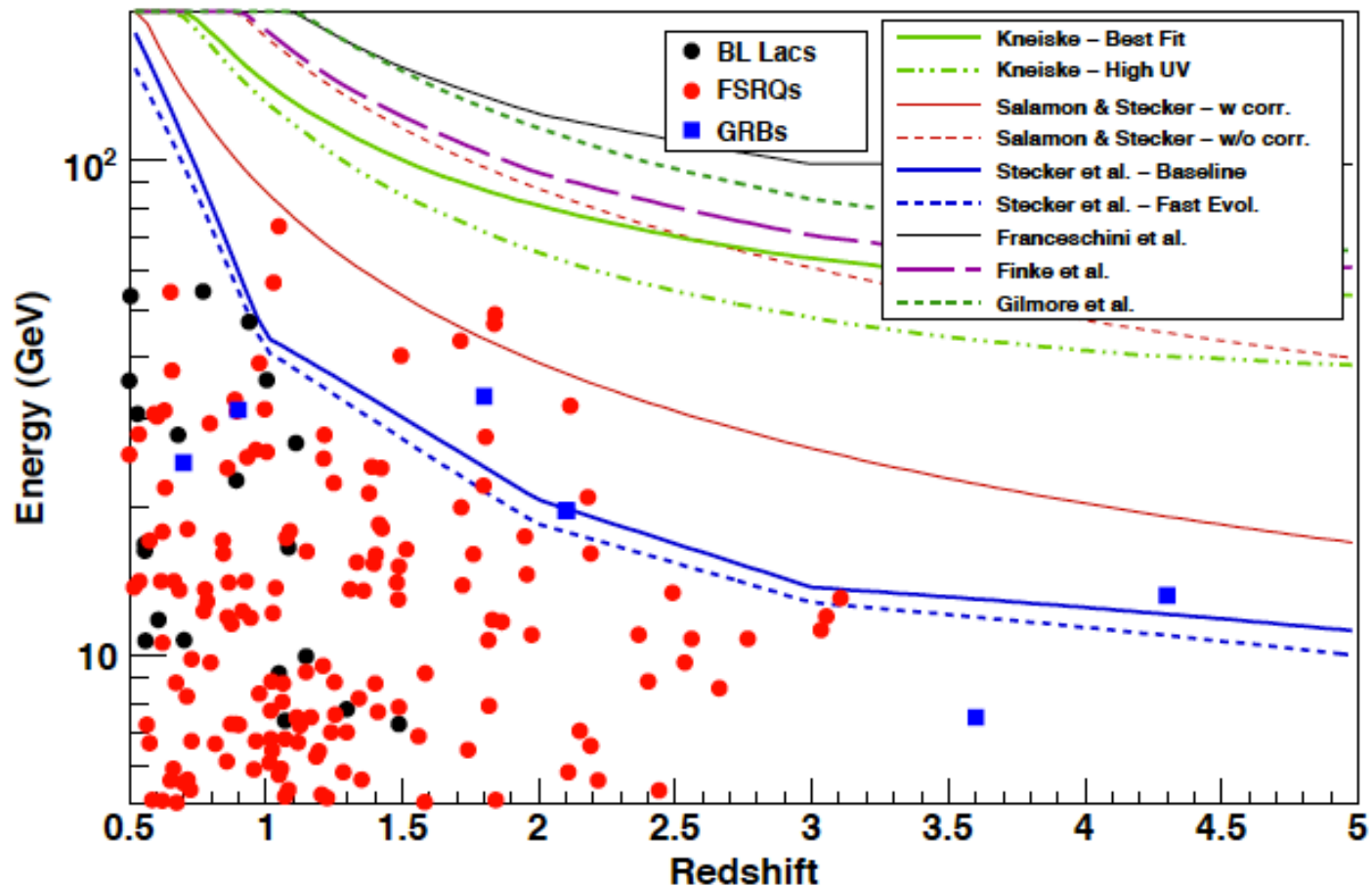
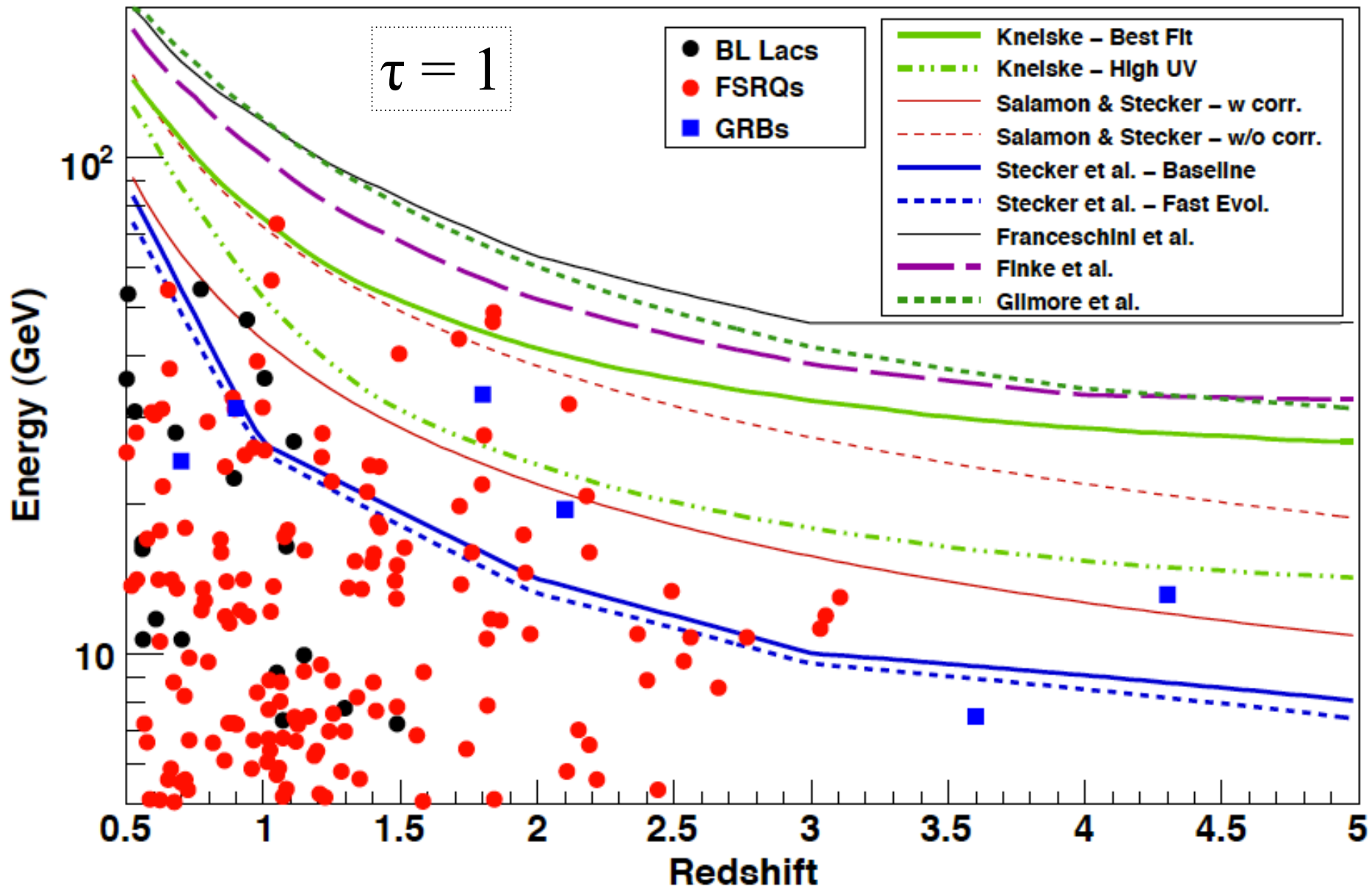


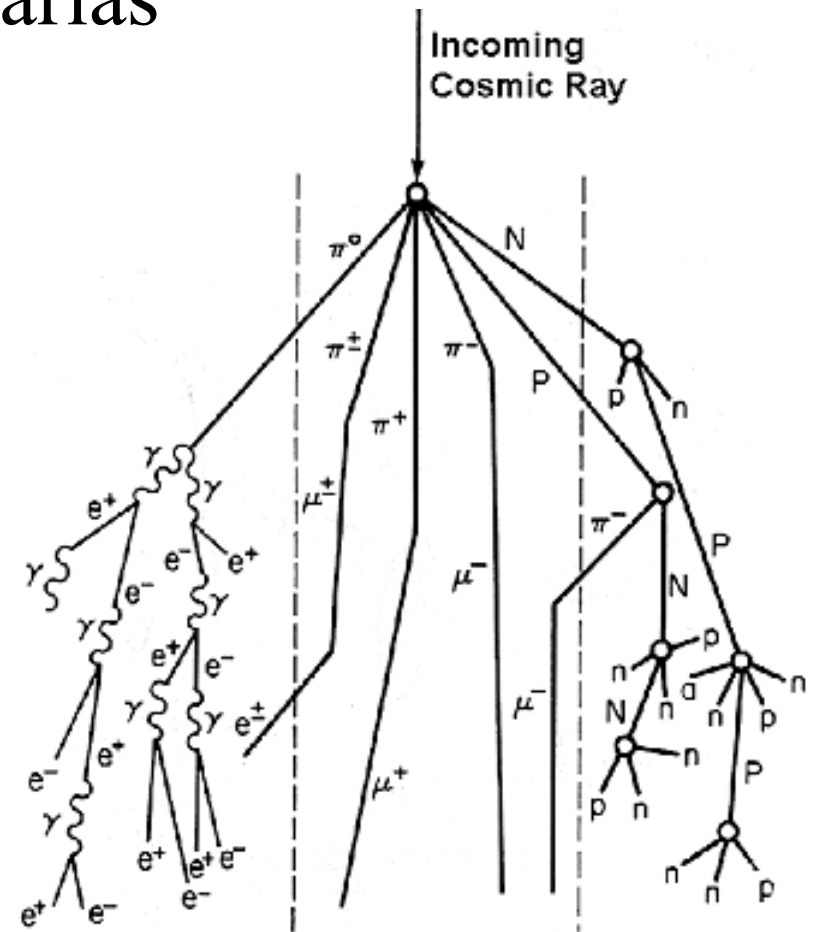
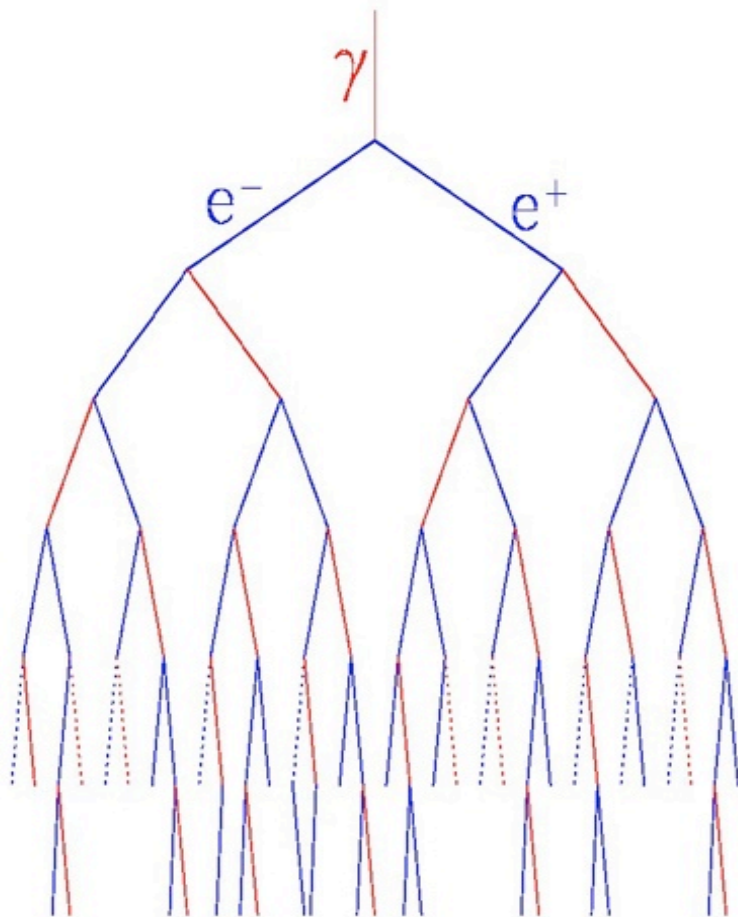
Fig. 3.— Highest-energy photons from blazars and GRBs from different models of $\gamma\gamma$ optical depth $\tau_{\gamma\gamma} = 1$ (top panel) and $\tau_{\gamma\gamma} = 3$ (bottom panel) are indicated by lines. Photons above model predictions are in EBL medium with a high γ -ray opacity. The likelihood of detecting the spectral characteristics of the source are considered in the method 3.2.1.



Abdo et al. 2010



Partículas de alta energía producen cascadas de partículas secundarias en la atmósfera



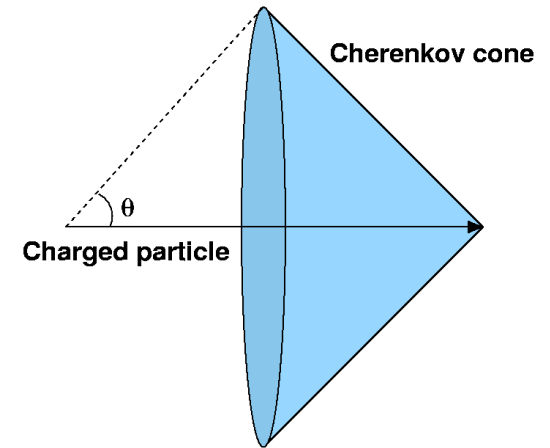
KEY

p	Proton	e	Electron
n	Neutron	μ	Muon
π	Pion	γ	Photon

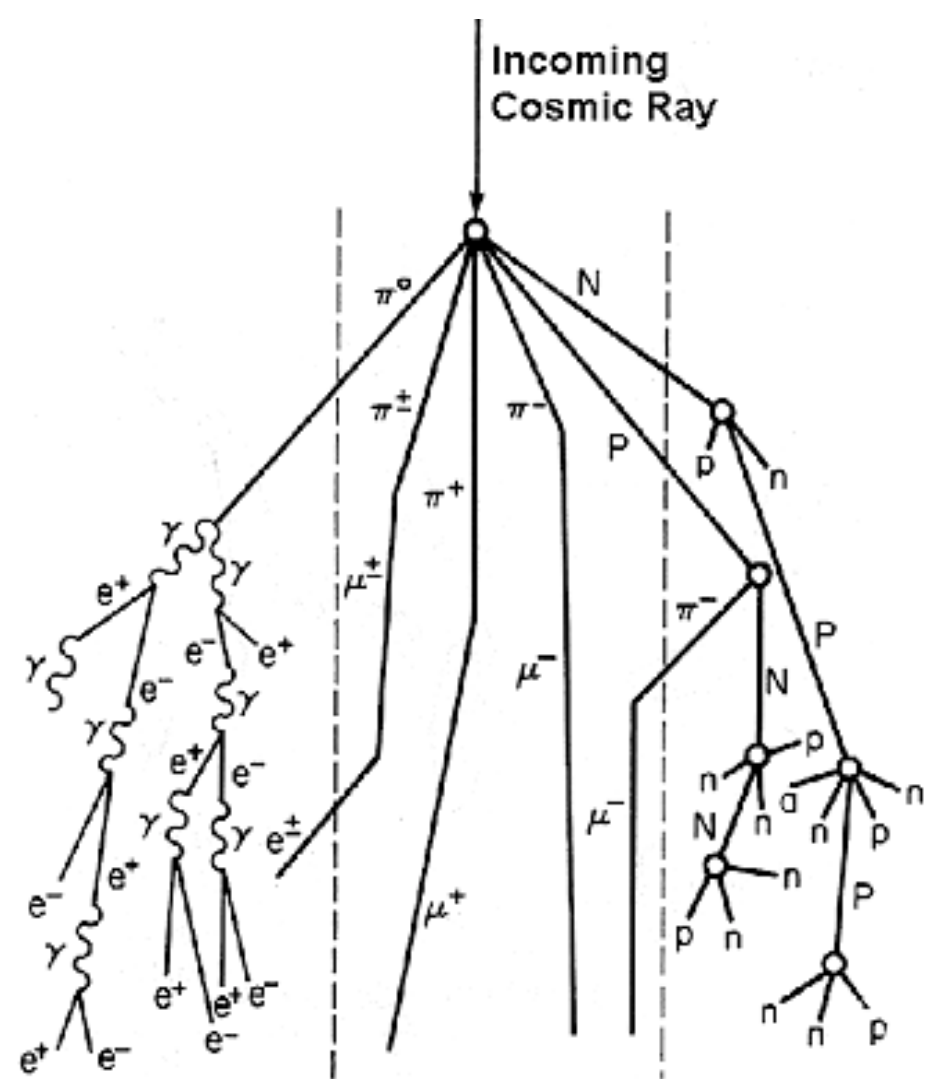
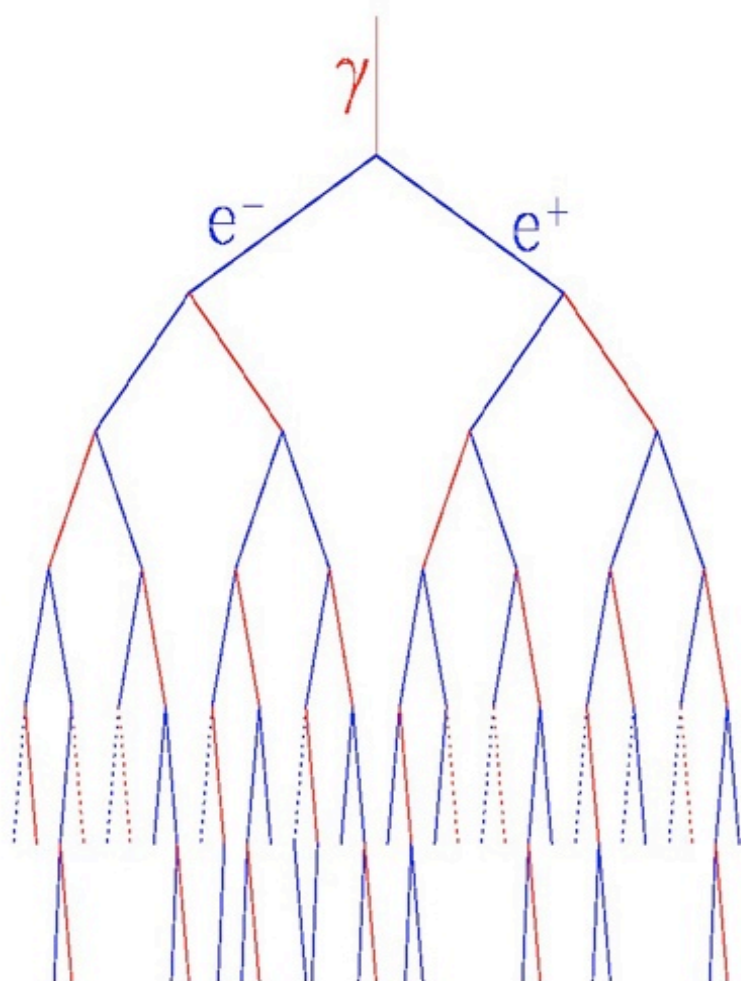
Radiación Čerenkov

Por una partícula cargada en un medio si $v > c/n$ con n el índice de refracción.

Va atrás de la partícula en un cono de apertura $\cos(\theta) = 1/n\beta$.



Medio	n	Umbral (γ)	θ_{\max} ($^{\circ}$)	dE/dx (eV/cm)
Aire	1.0003	40.8	1.4	0.34
Agua	1.335	1.5	41.2	3.27



KEY

P	Proton	e	Electron
n	Neutron	μ	Muon
π	Pion	γ	Photon

Telescopios Cherenkov atmosféricos

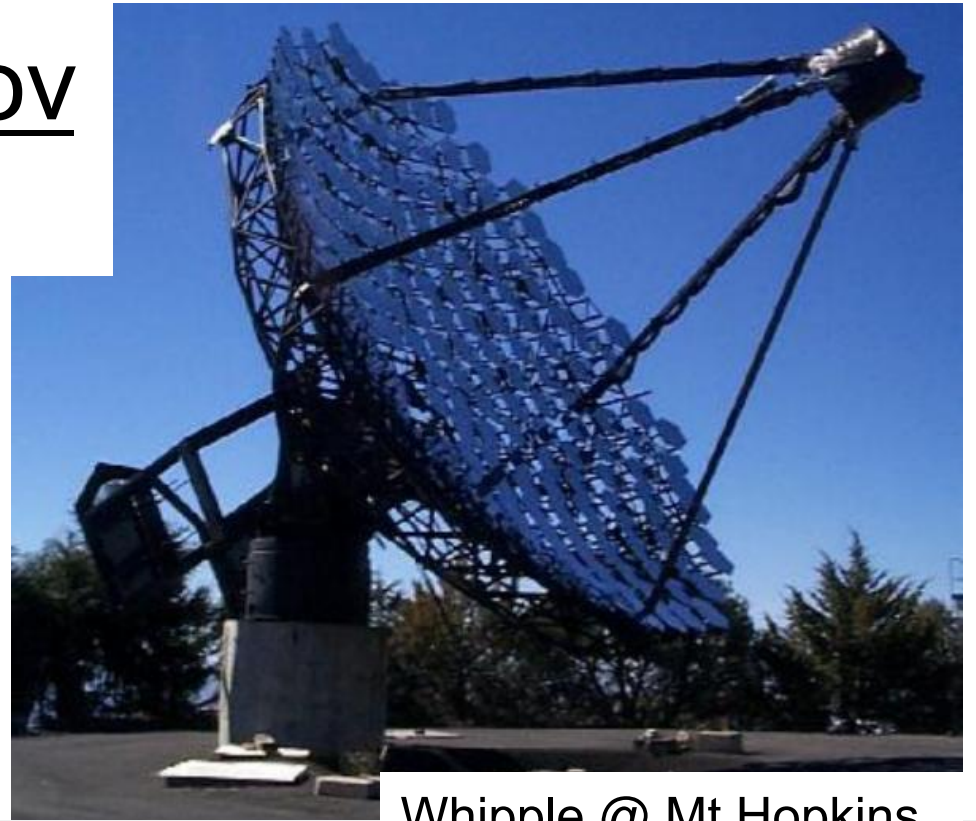
Experimentados desde los 1960s

Detectan la luz Cherenkov de las partículas de la cascada

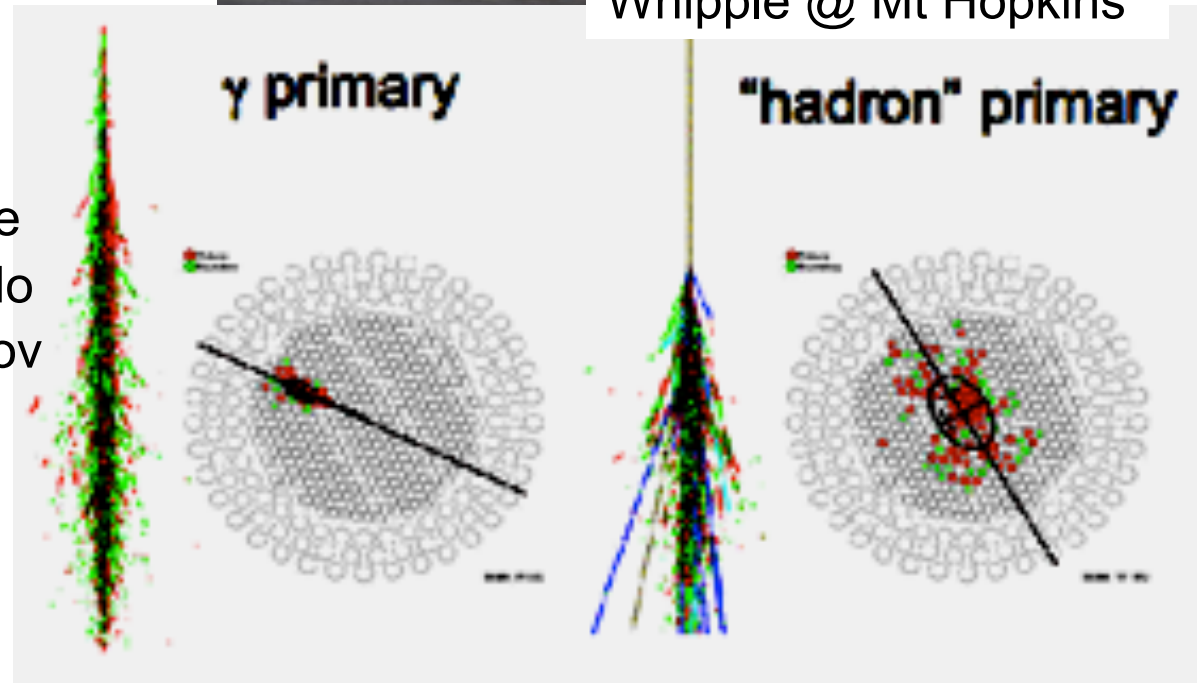
Se apuntan a una posición determinada del cielo

Requieren noches oscuras y despejadas

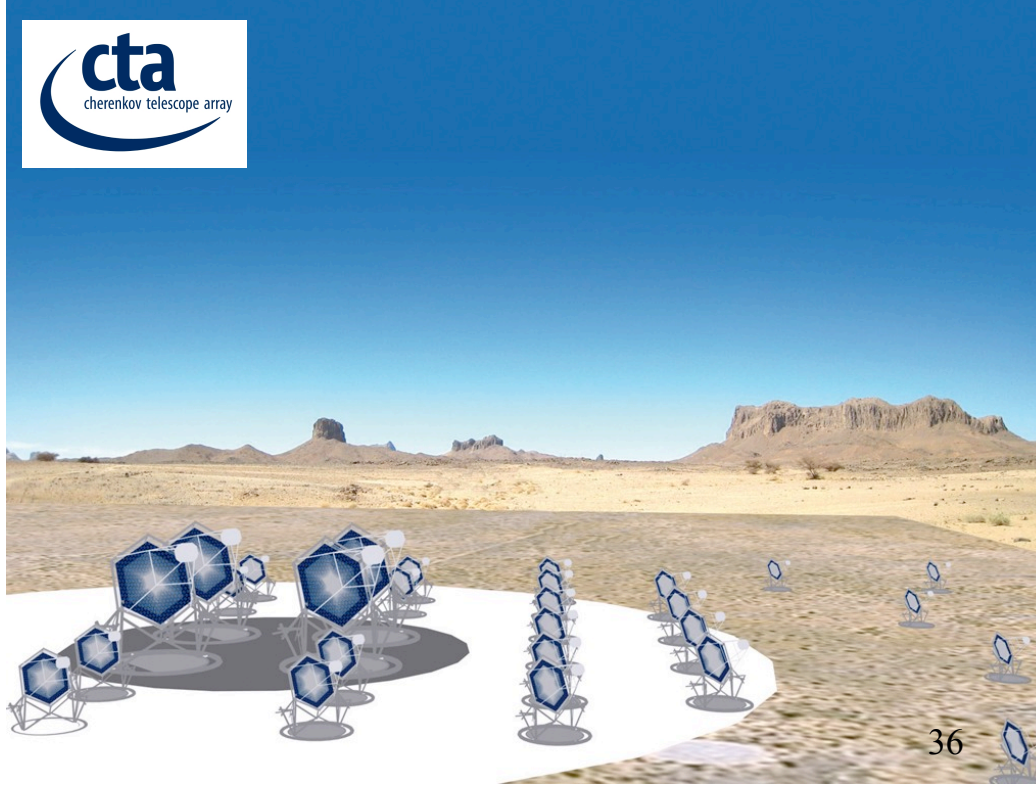
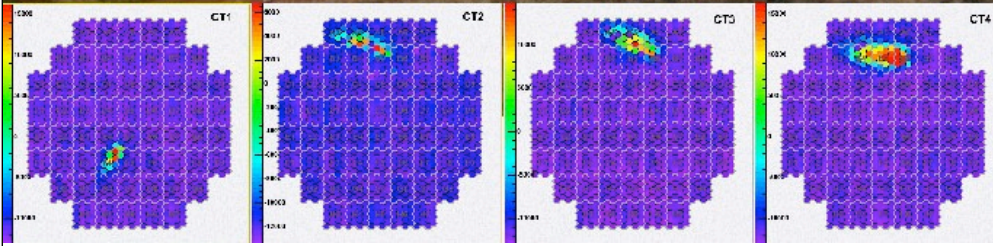
Distinguen cascadas de rayos γ de las de rayos cósmicos haciendo una imagen de la luz Cherenkov de la cascada



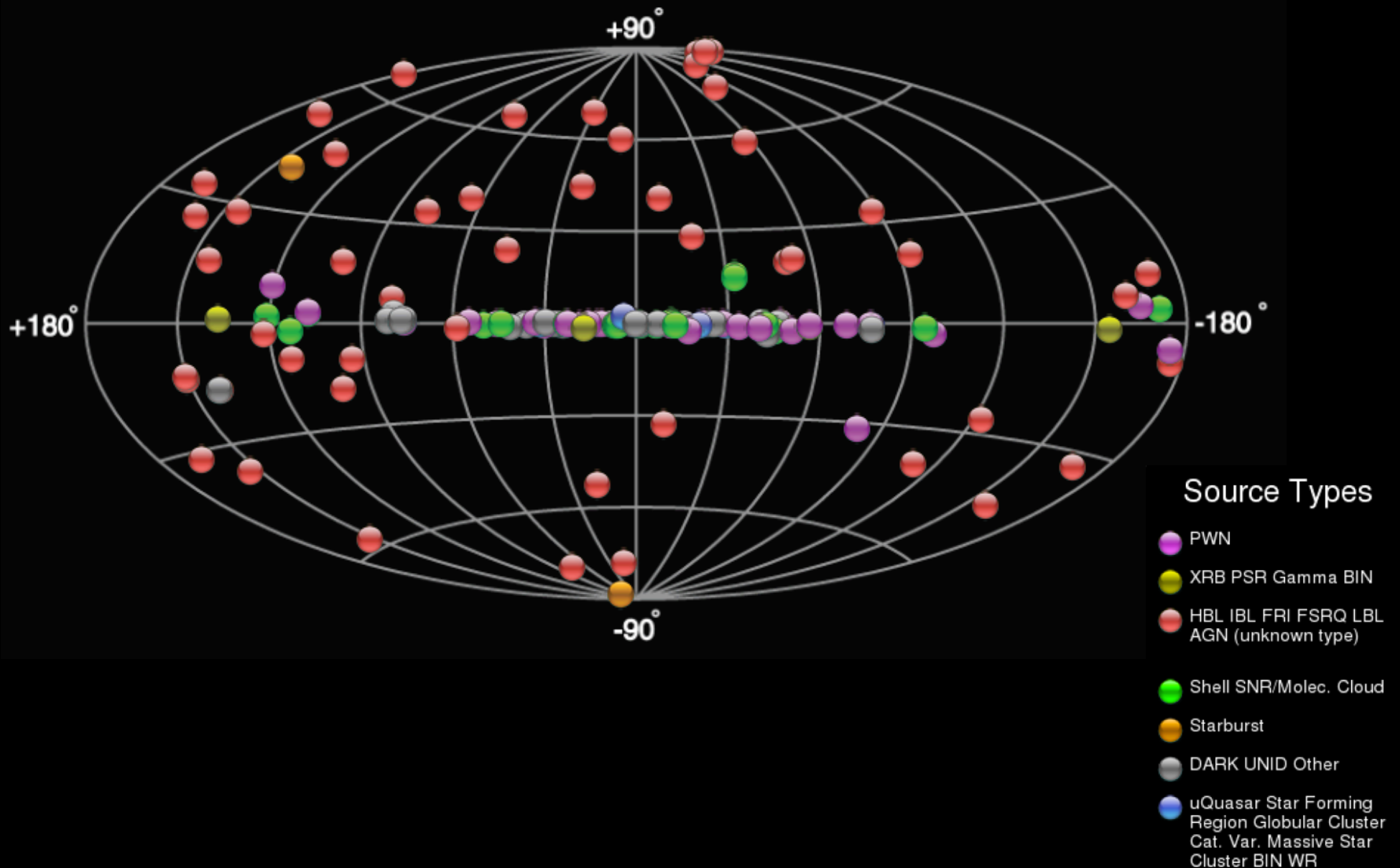
Whipple @ Mt Hopkins



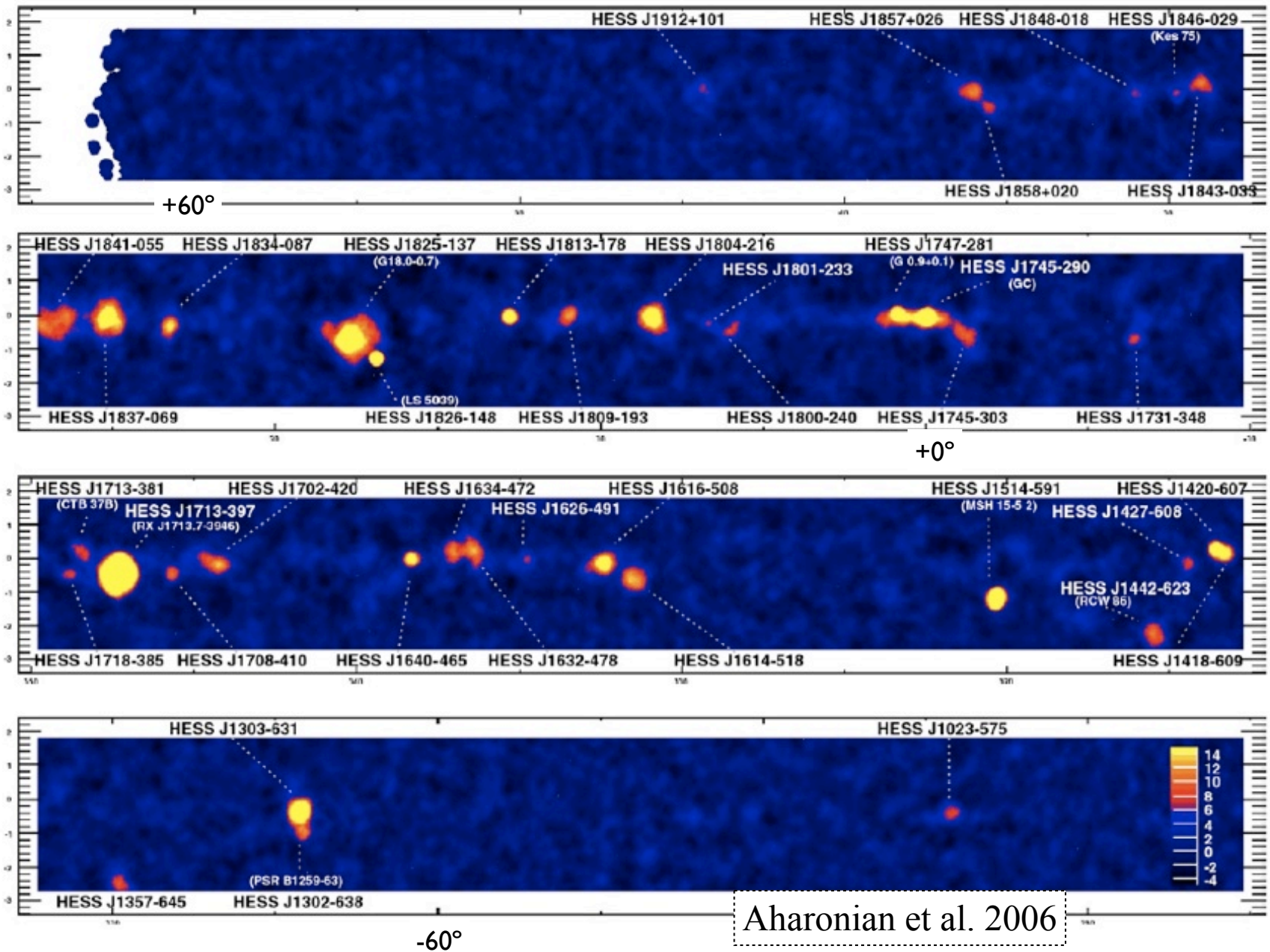
Dec. 10: All four H.E.S.S. telescopes operational !



tevcat.uchicago.edu



HESS Galactic Plane Survey



5°

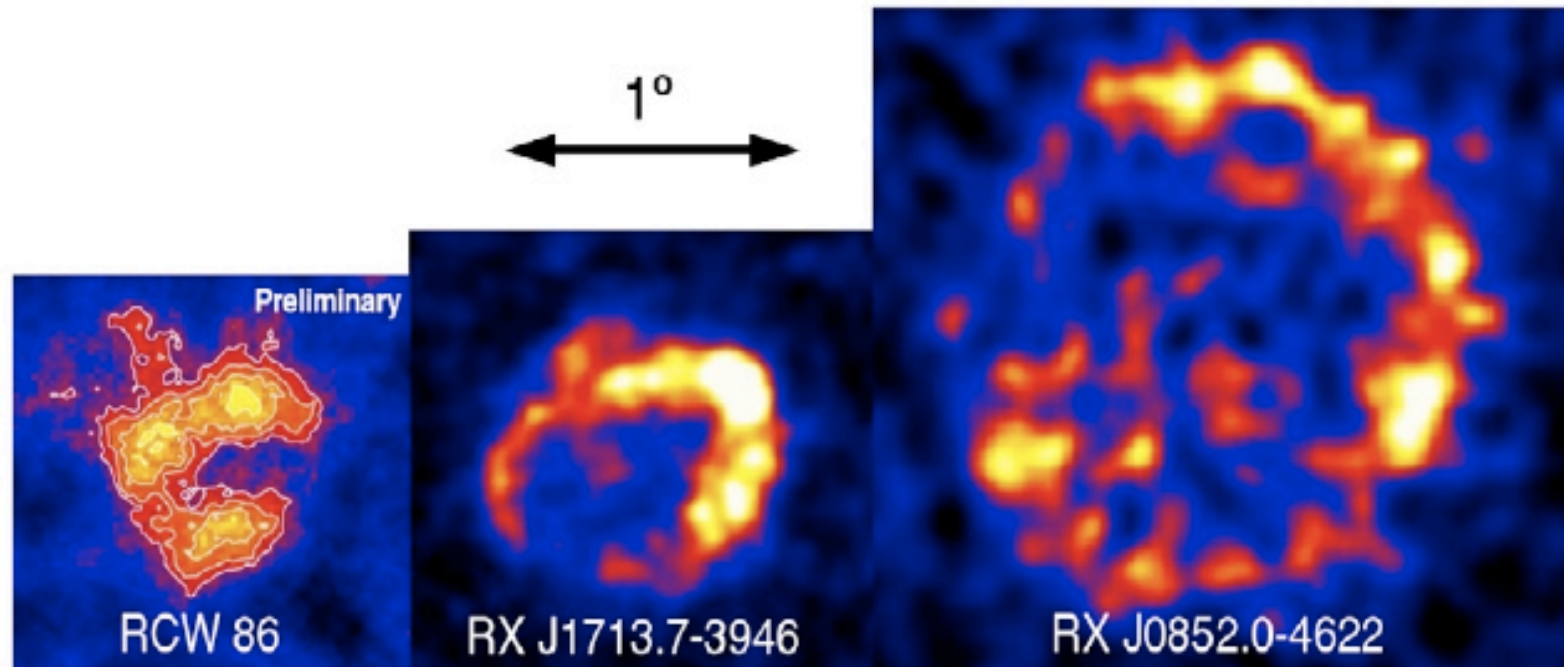
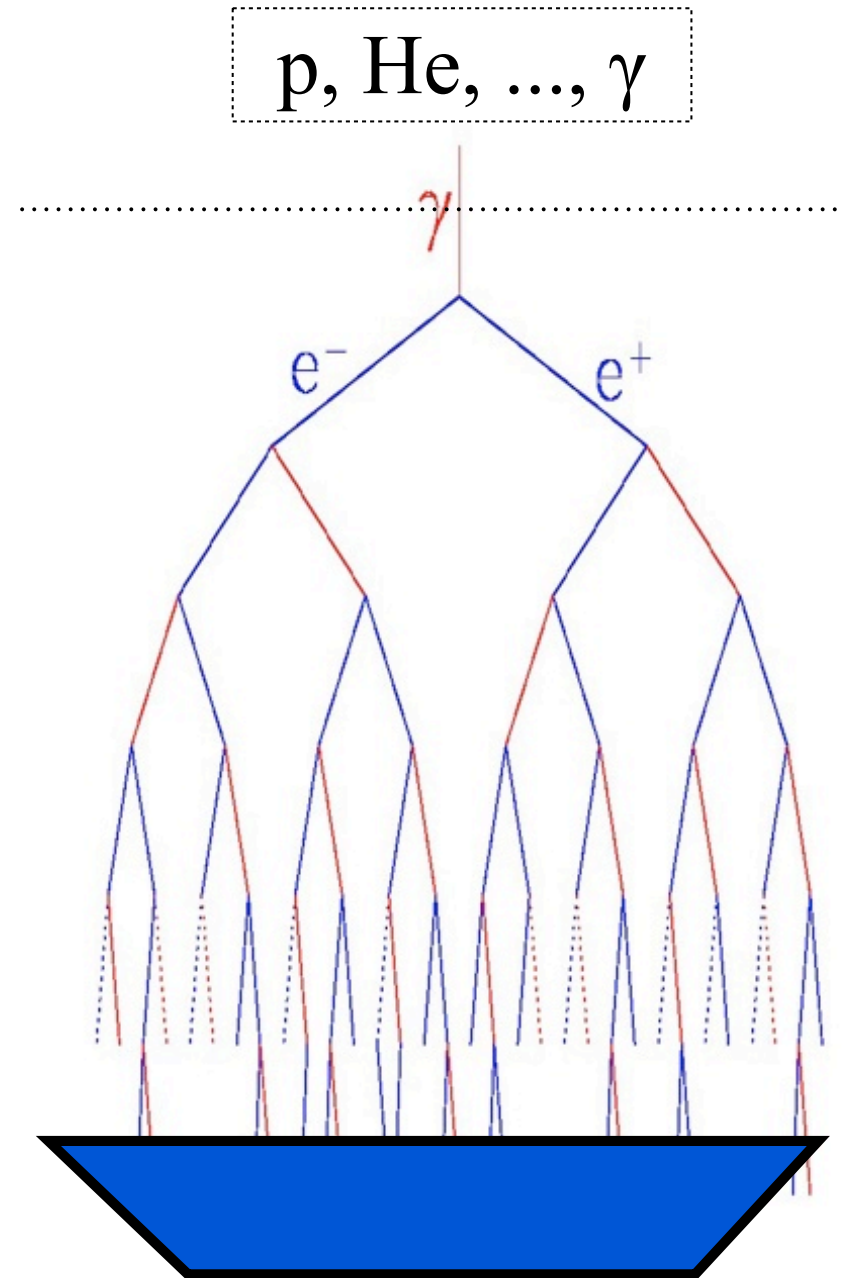


Figure 4. The shell-type TeV γ -ray supernova remnants: RCW 86 [54], RX J1713.7–3946 [63] and RX J0852.0–4622 (*Vela Junior*) [53]. All images are smoothed and were obtained using HESS.

Hinton (2009)

WČOs

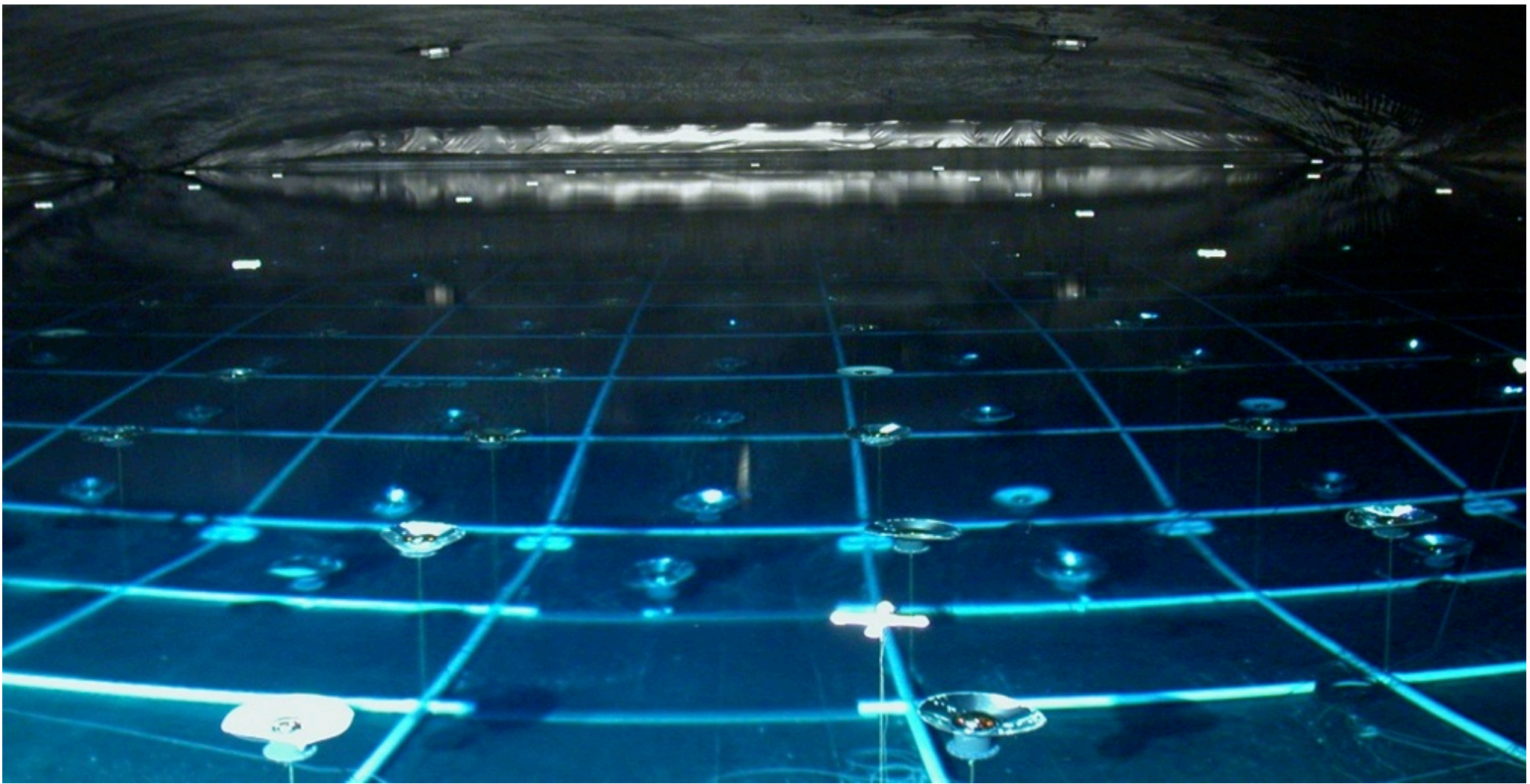
- Las partículas secundarias deben entrar al detector
 - a mayor altura mayor densidad de partículas
 - electrones (y muones) son detectados eficientemente por su radiación Čerenkov en el agua. Los rayos γ también.
 - Los tiempos de llegada relativos indican la dirección de propagación original.
- Instrumento de tránsito: observación permanente con amplio campo de visión (~ 2 sr)
- 10^4 eventos/s (>100 Mbps)



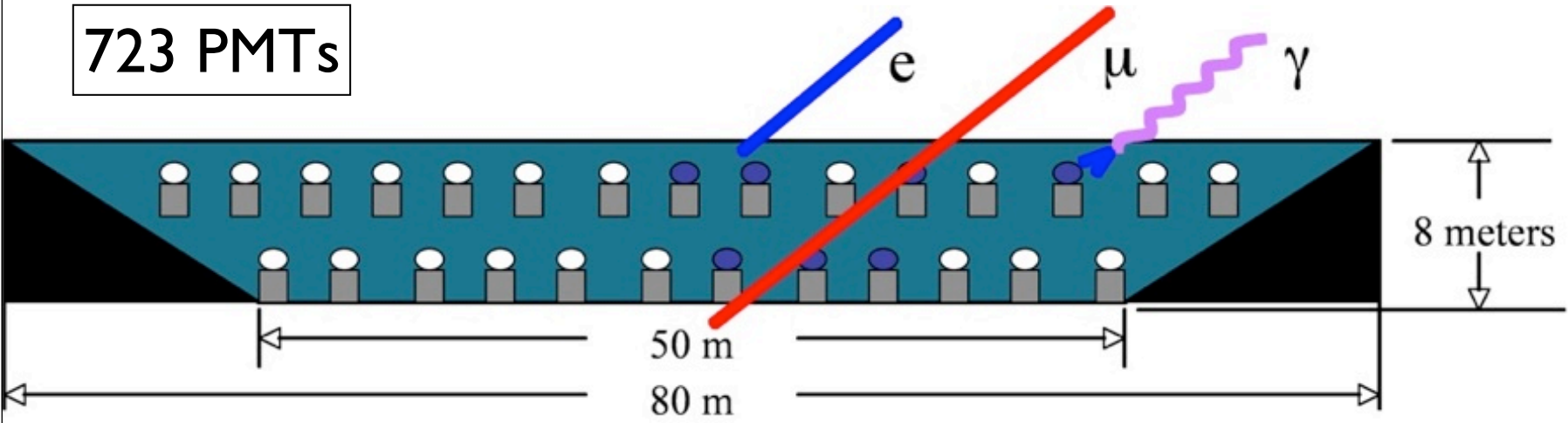
Milagro



- Primer observatorio gamma Cherenkov de agua
- Situado en Nuevo México a 2650m
- Operacional de 1999 a 2008

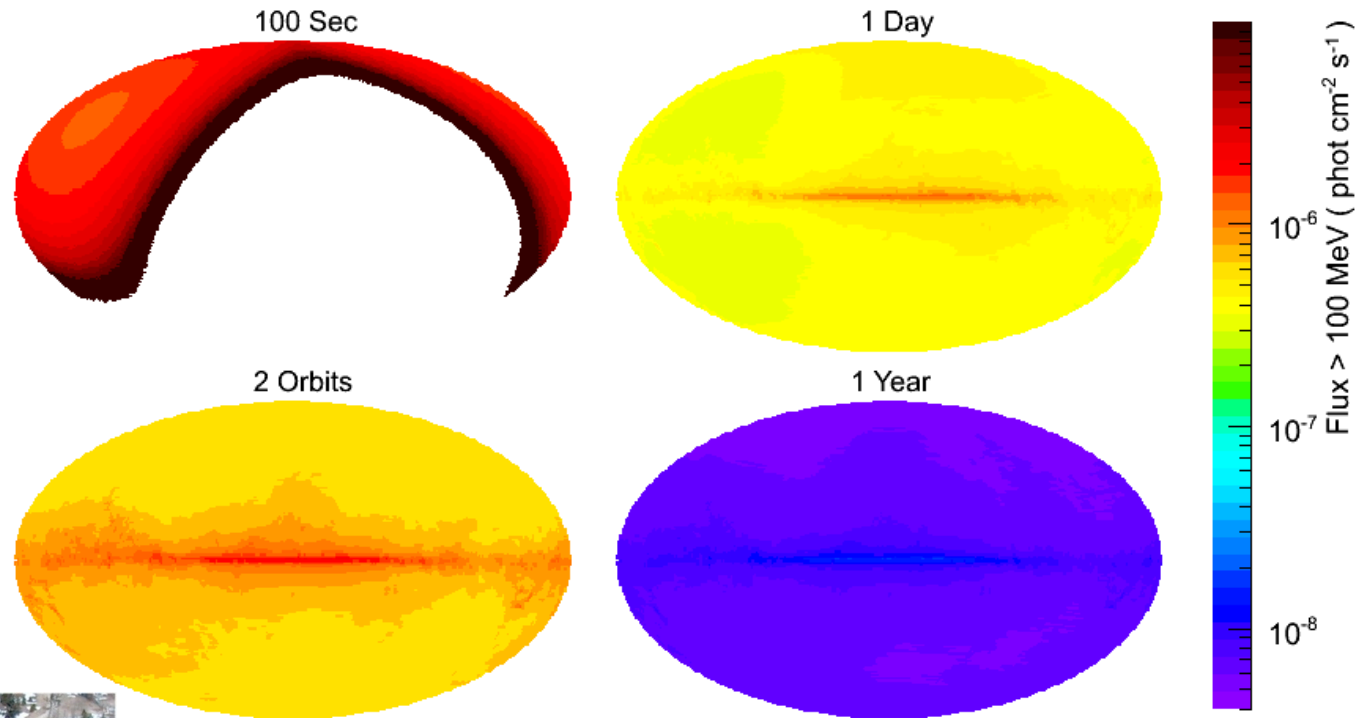


723 PMT_s



Operación de F γ RST

1 sky survey cada 3 horas

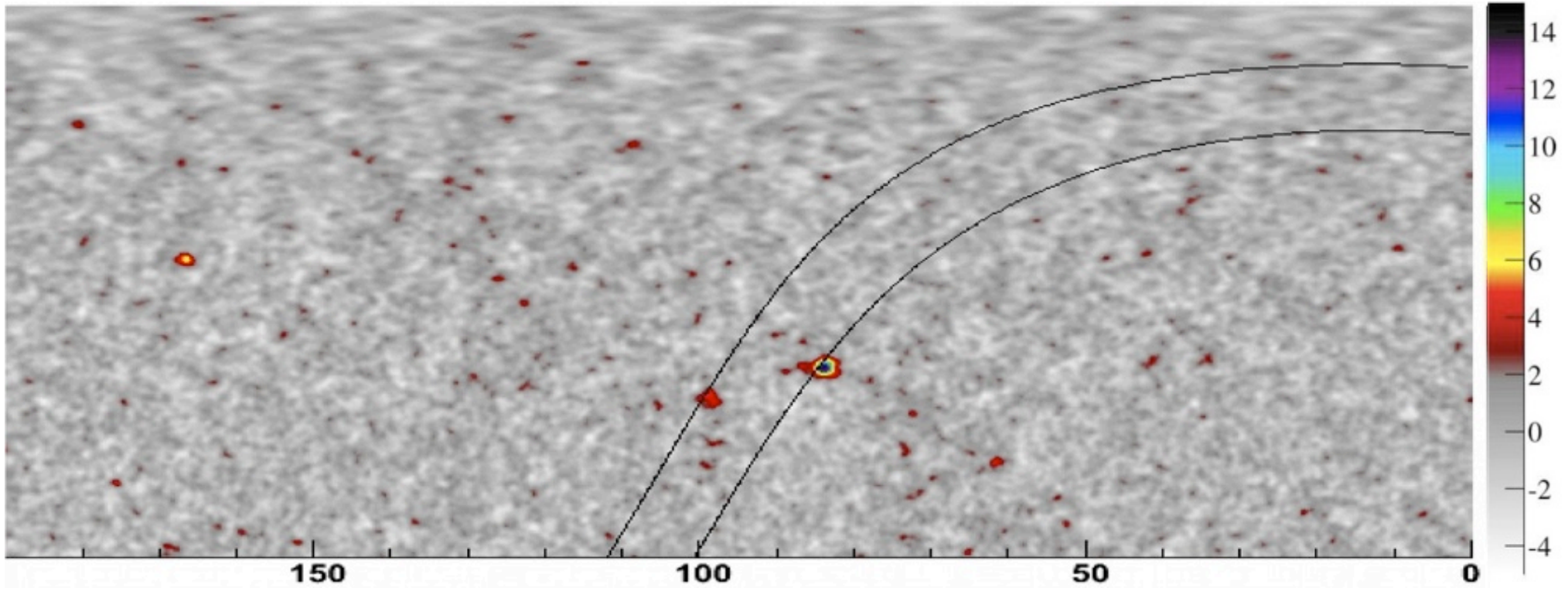
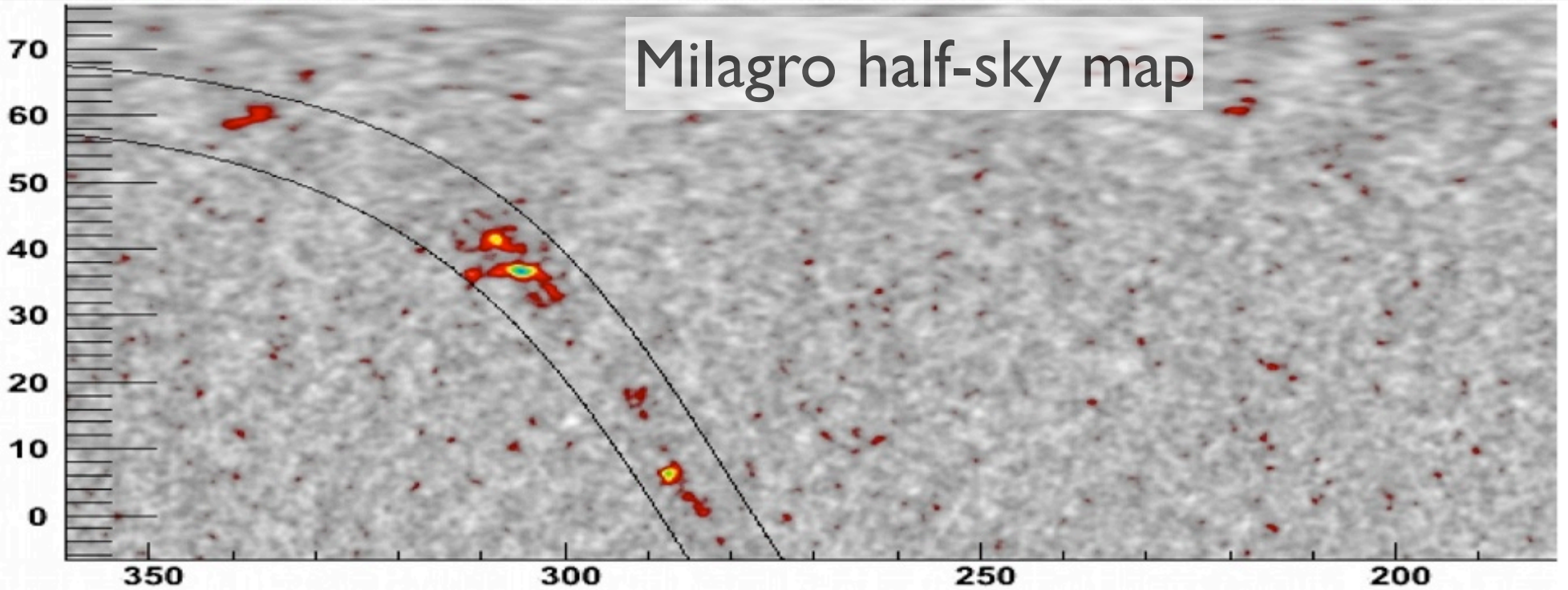


Operación de WČO

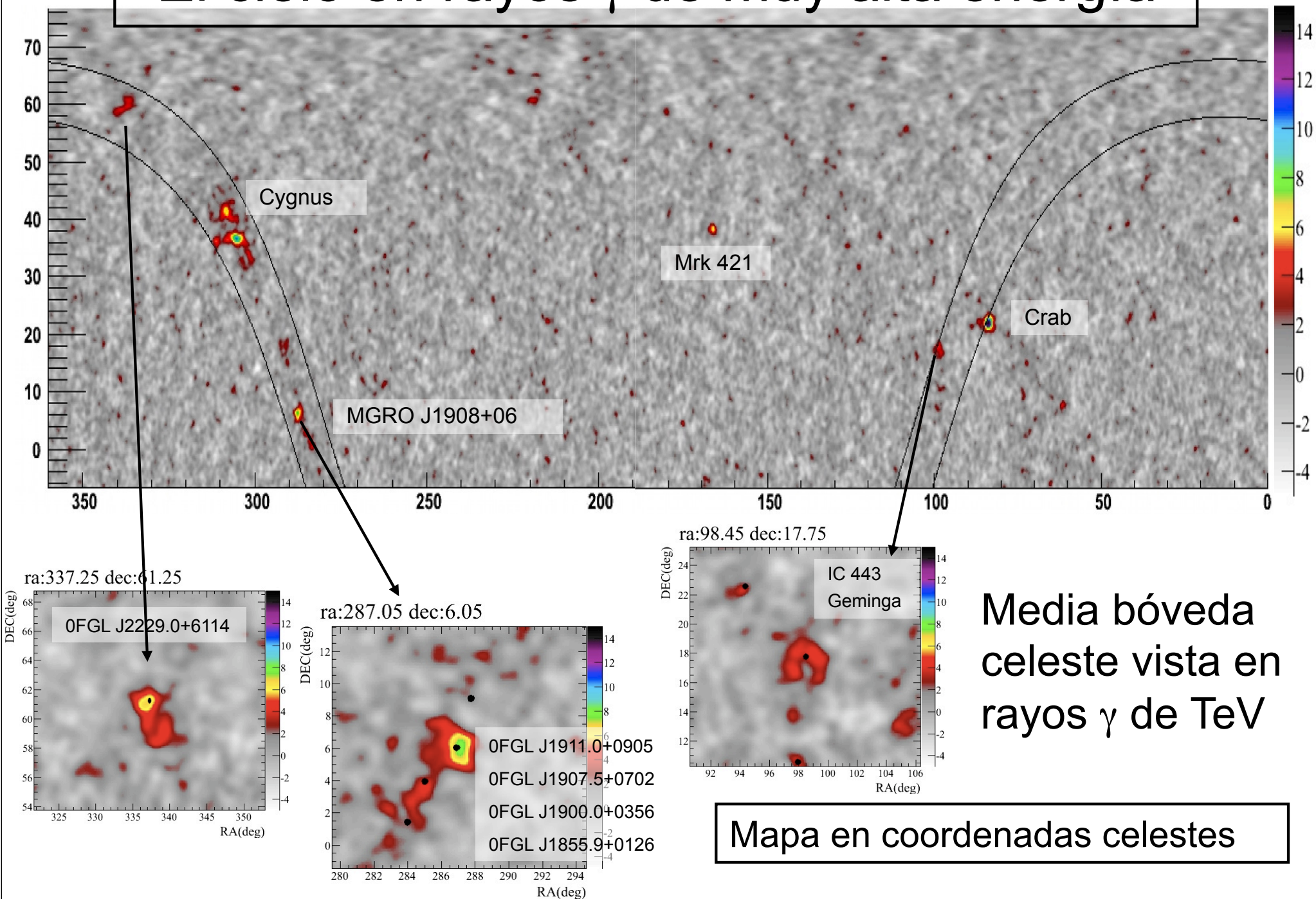
1 partial sky survey cada 24 horas

Milagro = 55%; HAWC = 66%

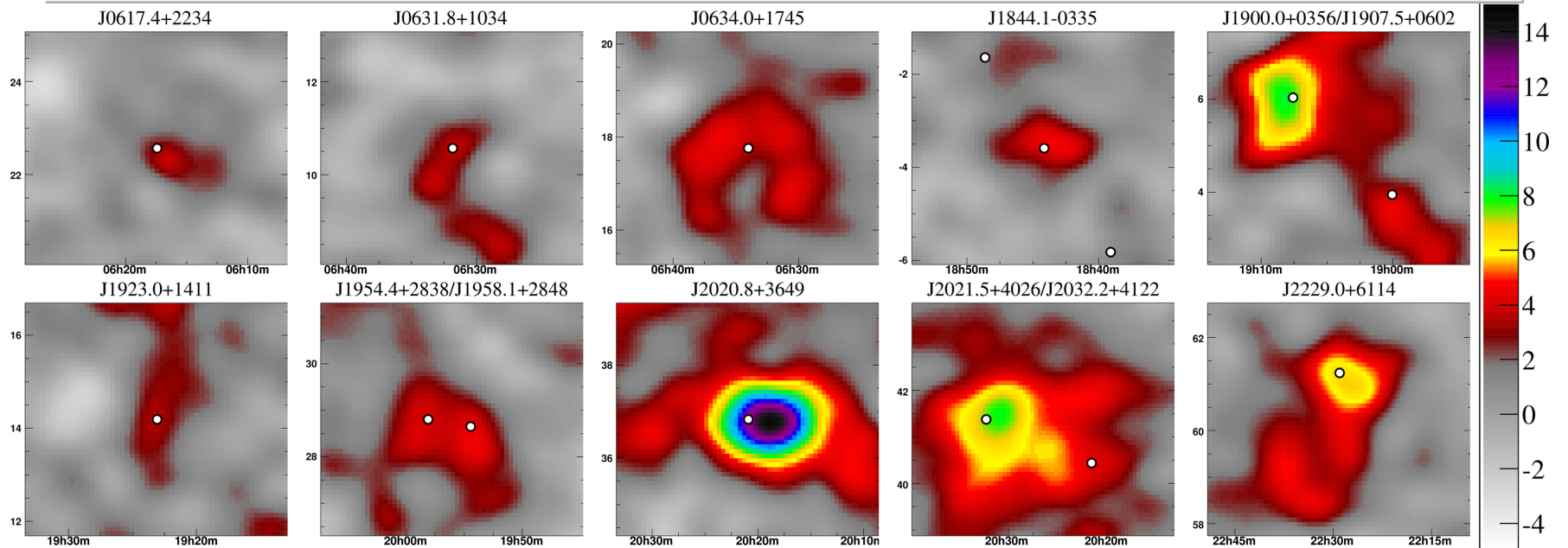
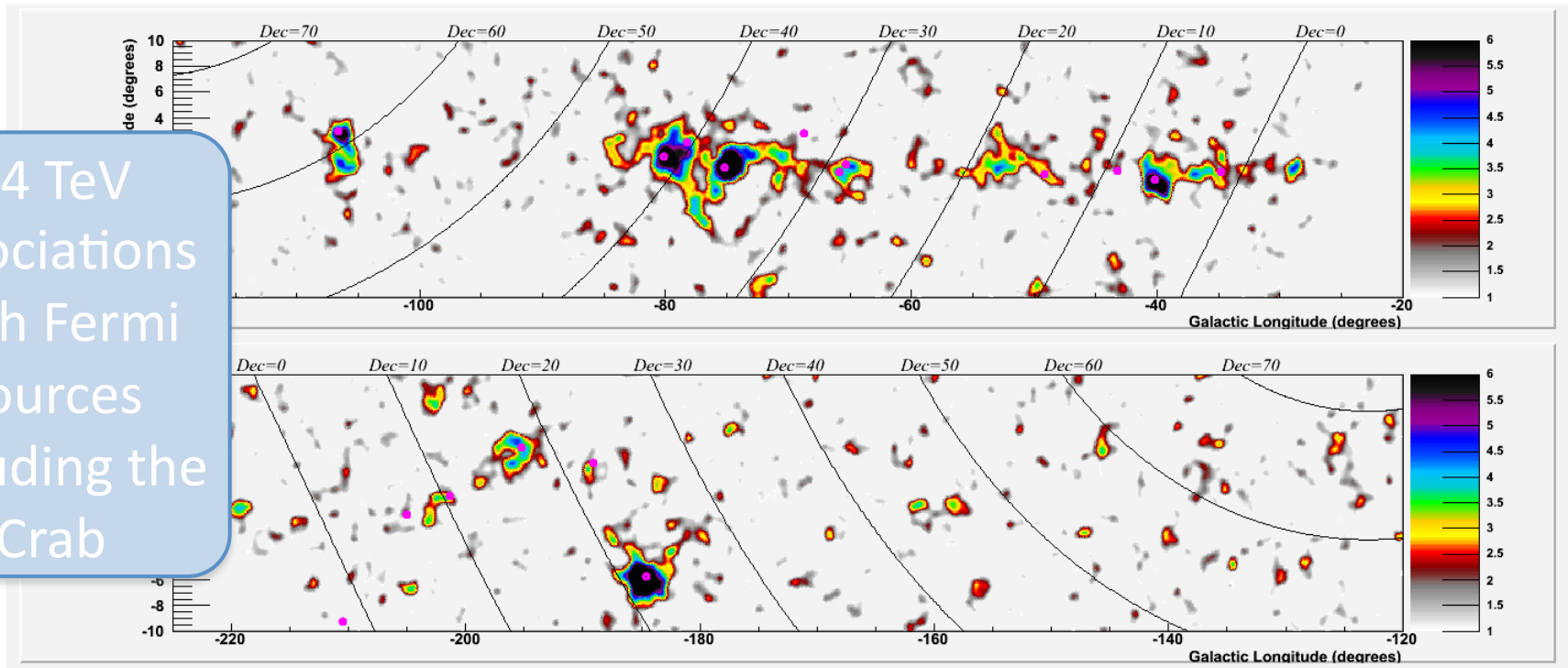
Milagro half-sky map



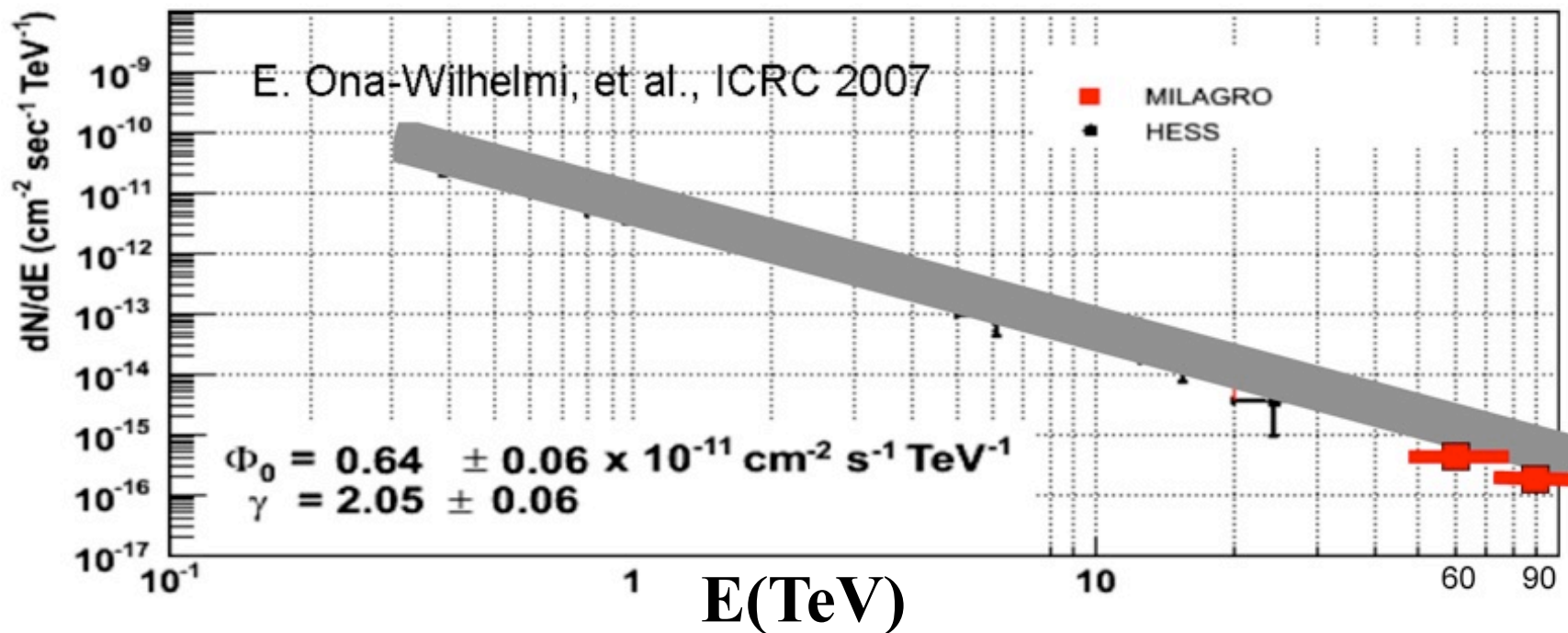
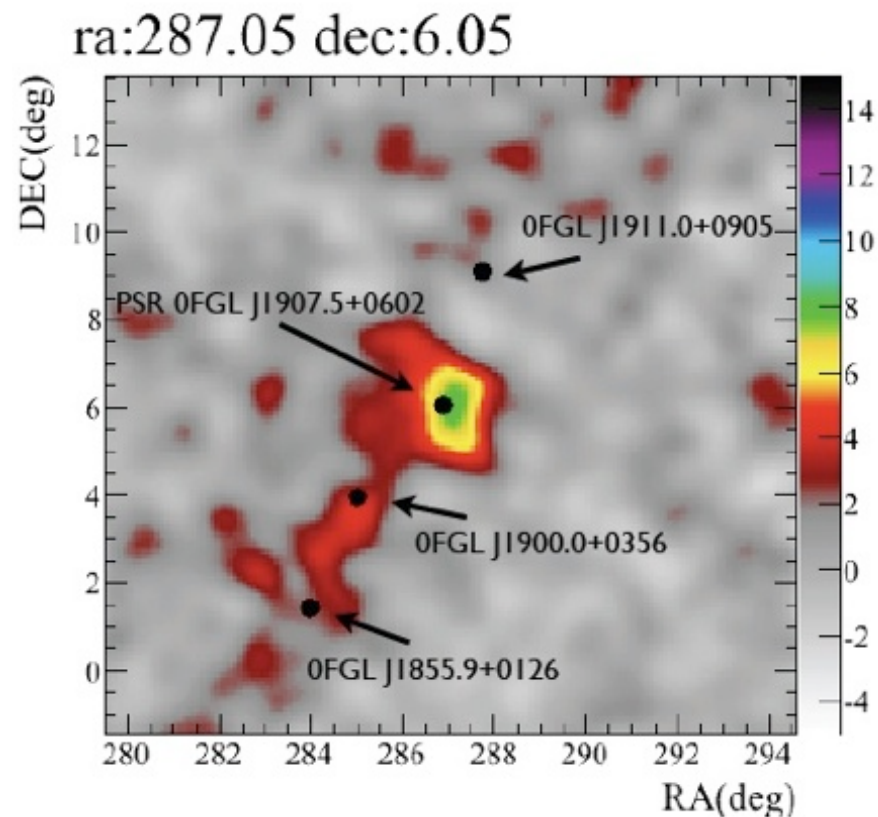
El cielo en rayos γ de muy alta energía



14 TeV associations with Fermi sources including the Crab



MGRO J1908-06



High Altitude Water Cherenkov

Citius, Altius, Fortius

- Mayor altura, mayores dimensiones, diseño óptimo \Rightarrow mejor detector
- Caso científico:
 - Mapa profundo del cielo
 - Mapear plano Galáctico
 - Restos de supernova; fuentes difusas Galácticas
 - Blazares (trazadores EBL)
 - Destellos de rayos γ
 - Ráfagas solares
 - Búsquedas / evidencias de materia oscura
 - Rayos cósmicos...

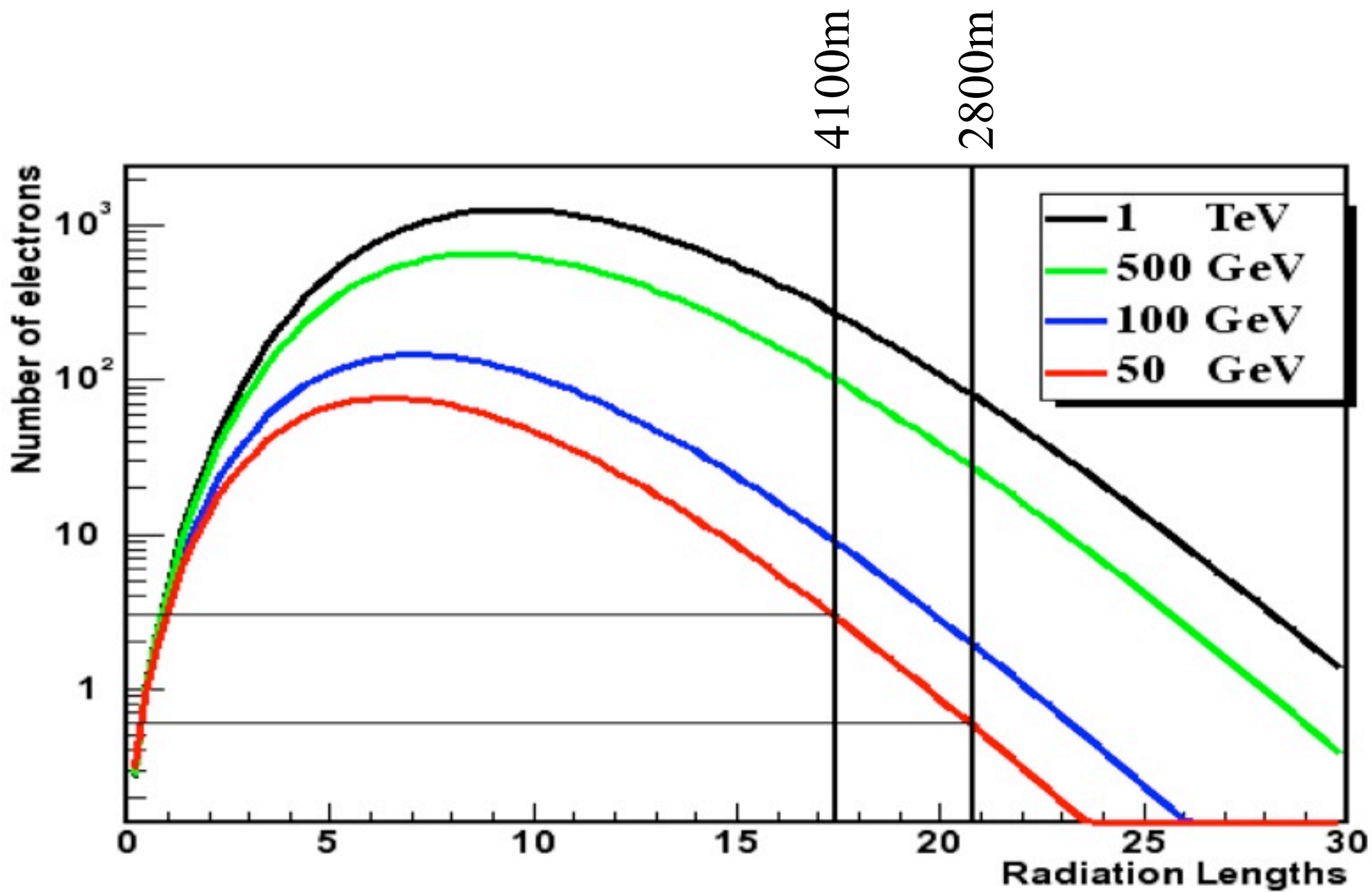
• Requerimientos

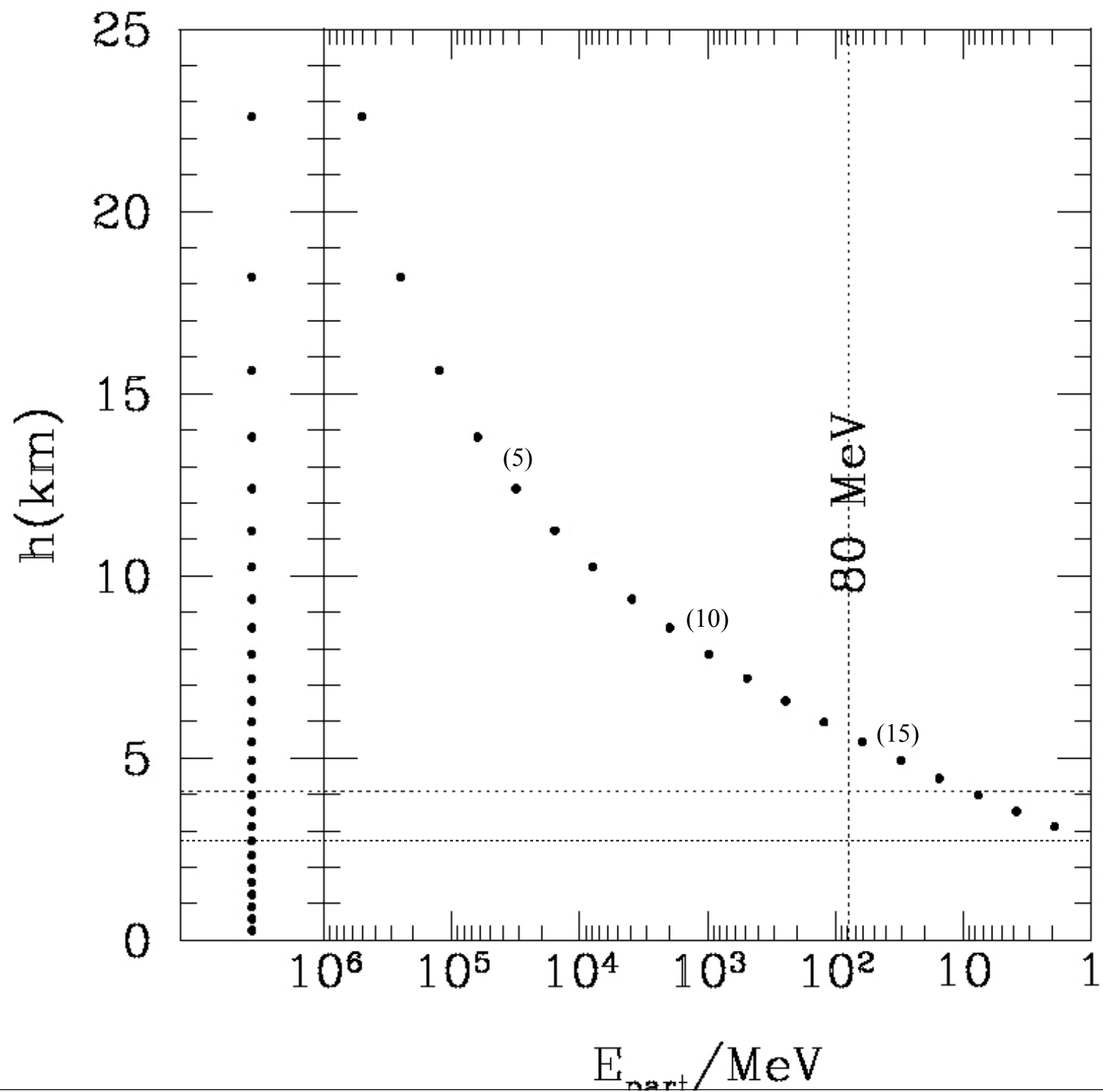
- Dimensiones: 150m
x150m x 4.8m
- Segmentado: celdas 5m
- Por encima de 4000m
(Bolivia, Tibet o México)
- 10 años de operación

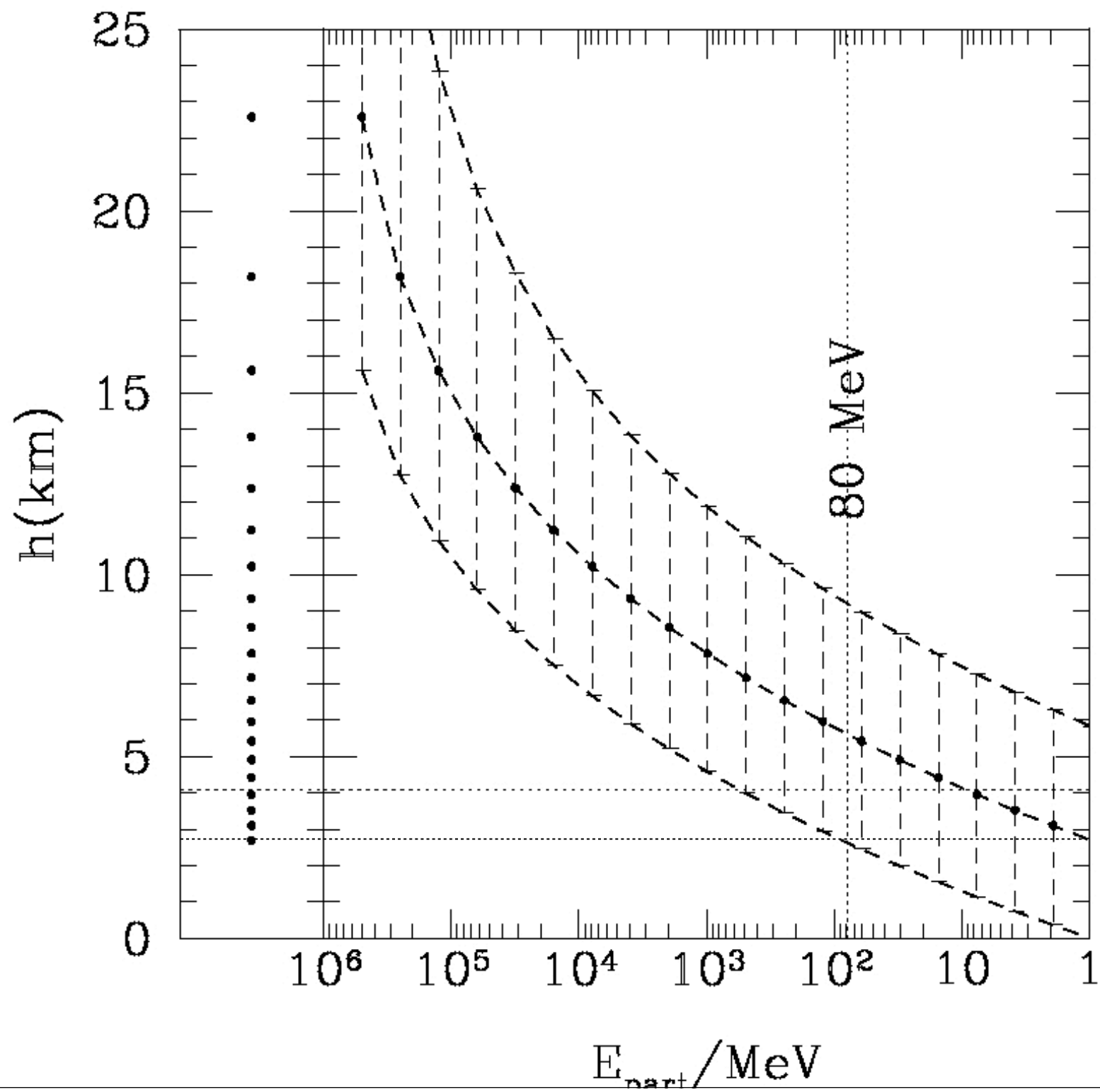
HAWC = 15 * Milagro

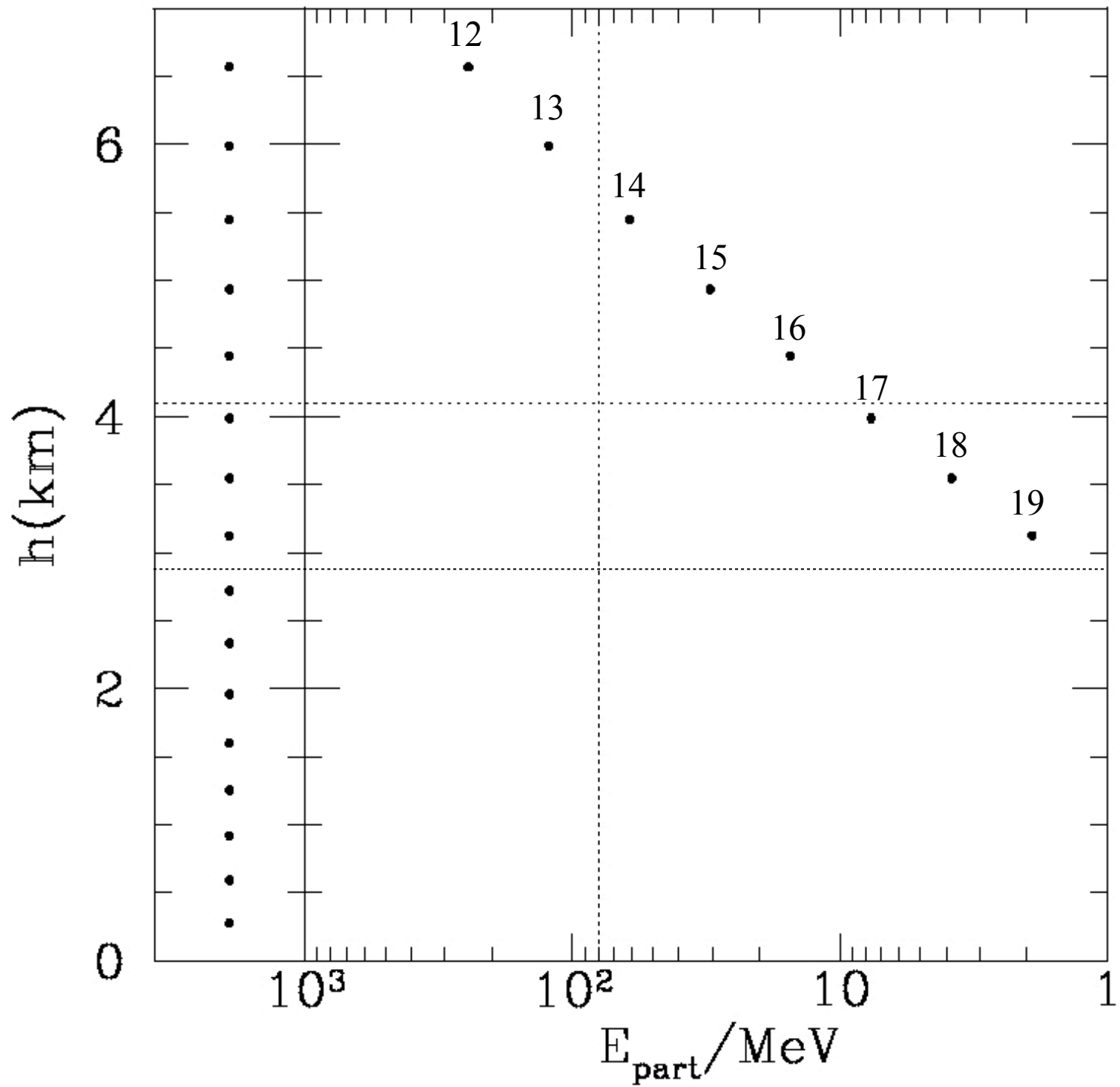
• HAWC @ México:

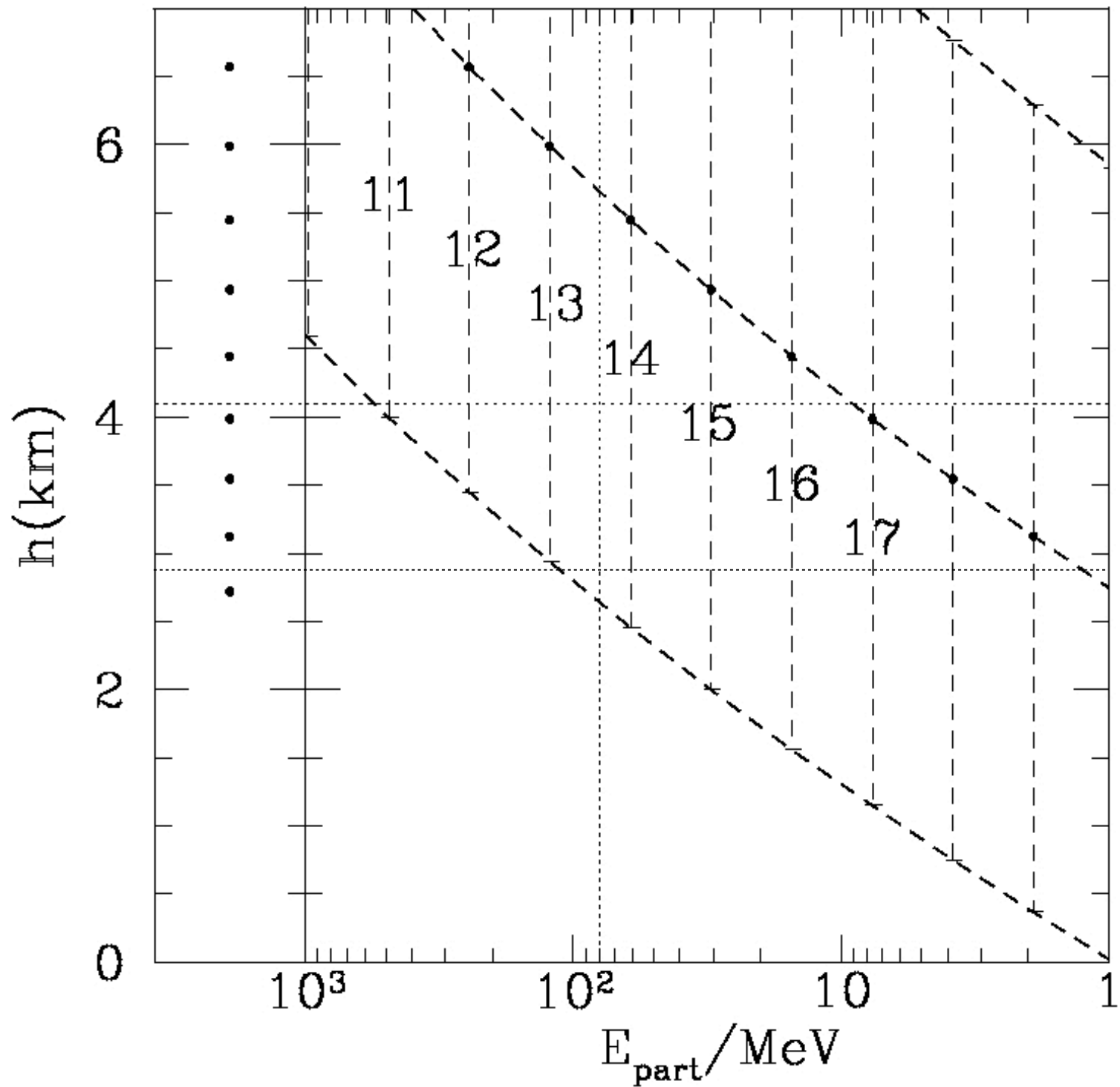
- Sierra Negra (4100m, 19°)
- infraestructura
- grupos científicos Mexicanos reconocidos

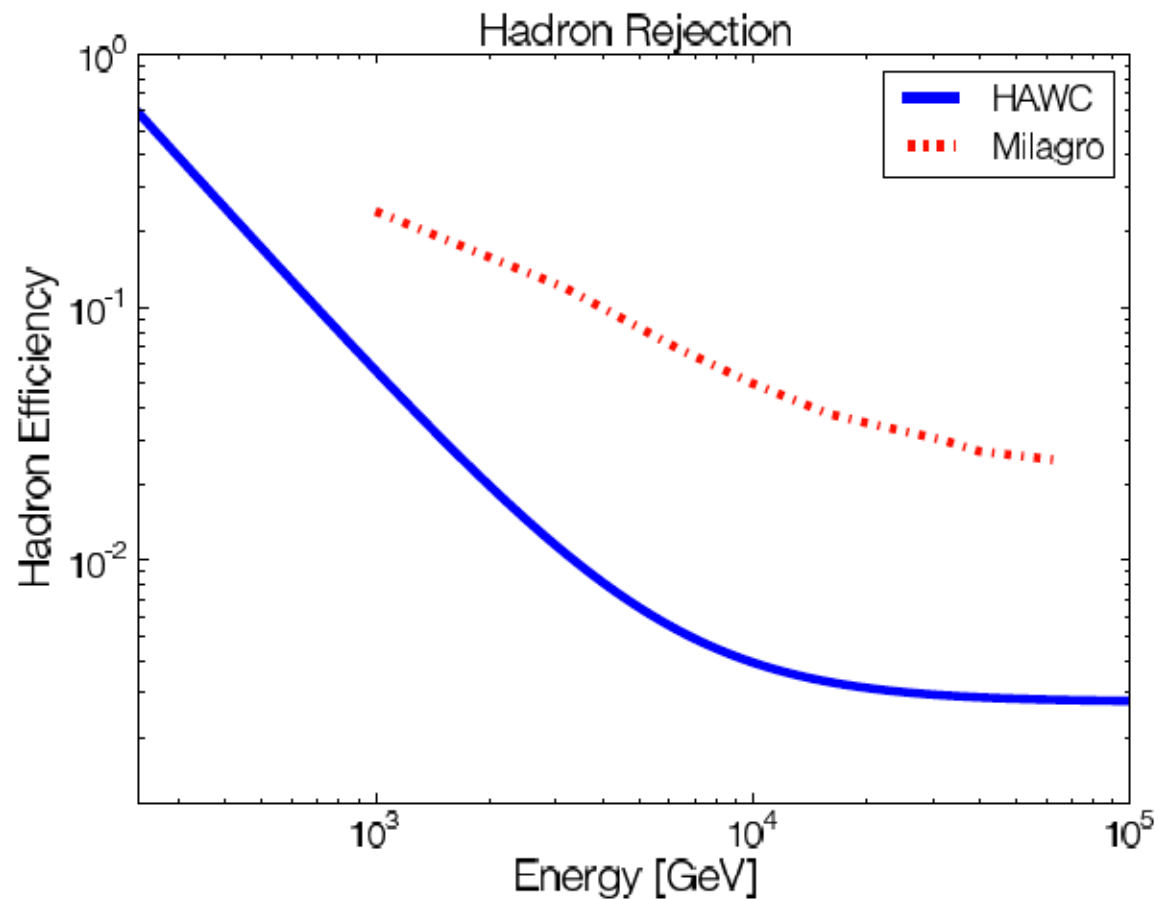
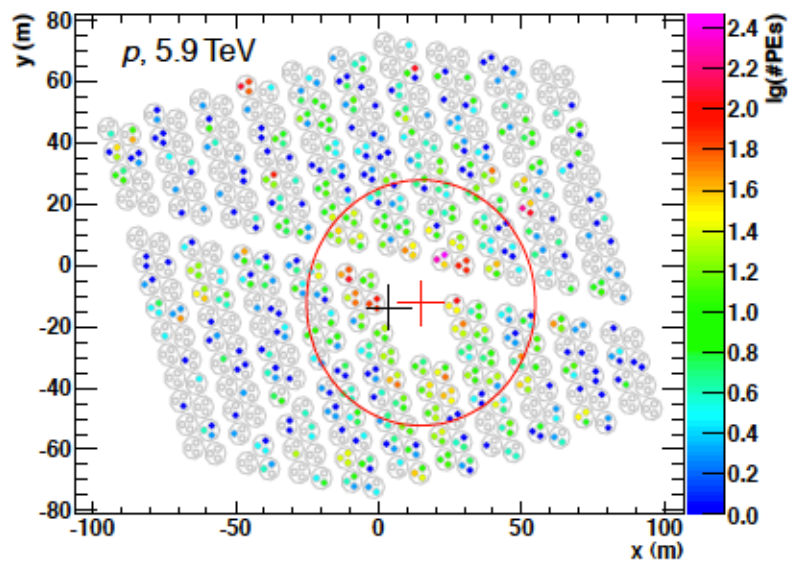
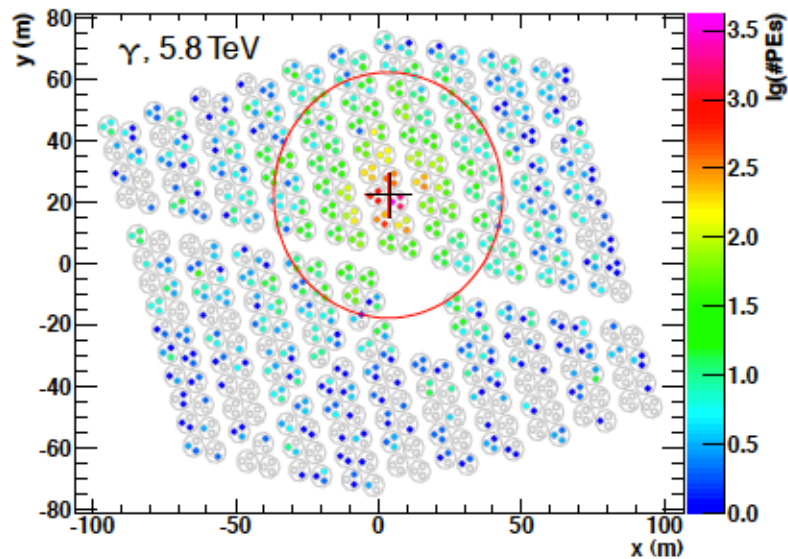






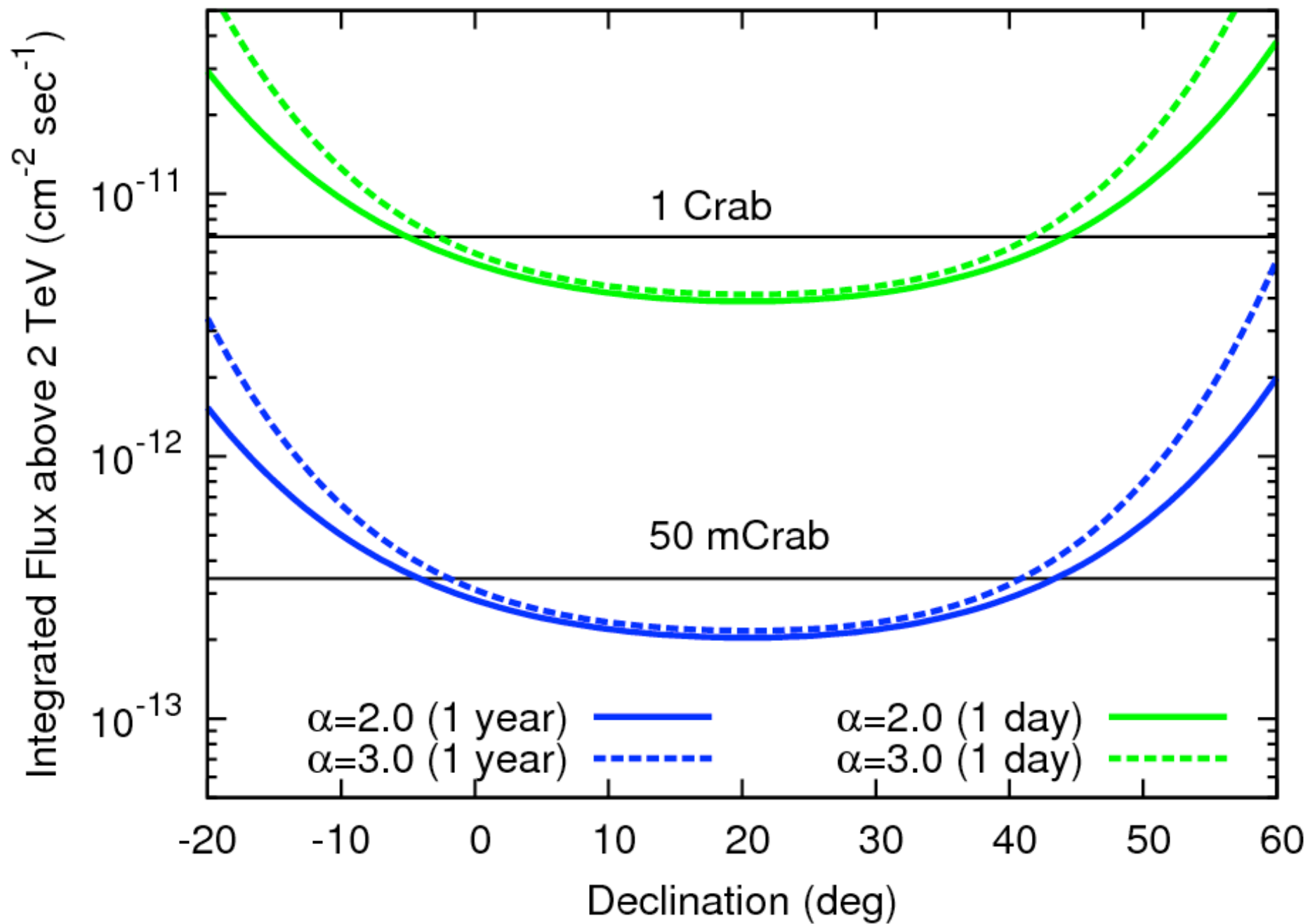


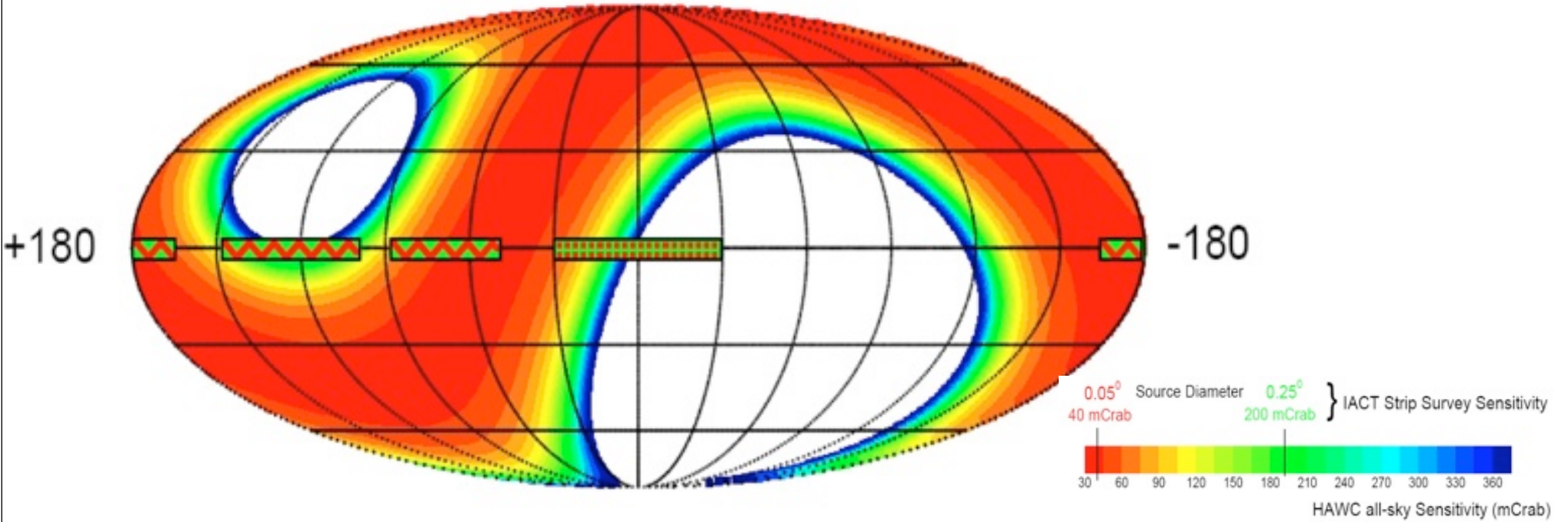




G/H separation is done by using the granularity of the shower foot print in the detector.







	Milagro	HAWC
Detector Area	3500 m ² /2100 m ²	20,000 m ²
Time to 5 σ on the Crab	120 days	5hrs
Median Energy	4 TeV	1 TeV
Angular Resolution	0.40 ^o – 0.75 ^o	0.25 ^o – 0.50 ^o
Energy Resolution at 5 TeV	140%	72%
Energy Resolution at 50 TeV	85%	35%
Hadron Rejection efficiency at 10 TeV	90%	>99.5%
Q for gamma/hadron rejection	1.6	5
Time to detect 5 Crab flare at 5 σ	5 days	10 minutes
Eff. Area at 100 GeV	5 m ²	100 m ²
Eff. Area at 1 TeV	10 ³ m ²	20x10 ³ m ²
Eff Area at 10 TeV	20x10 ³ m ²	50x10 ³ m ²
Eff Area at 50 TeV	70x10 ³ m ²	70x10 ³ m ²
Volume of Universe where 3x10 ⁻⁶ erg/cm ² GRB is detectable	7 Gpc ³	47 Gpc ³
Flux Sensitivity to a Crab-like source (1 year) (5 σ detection)	625 mCrab	45 mCrab

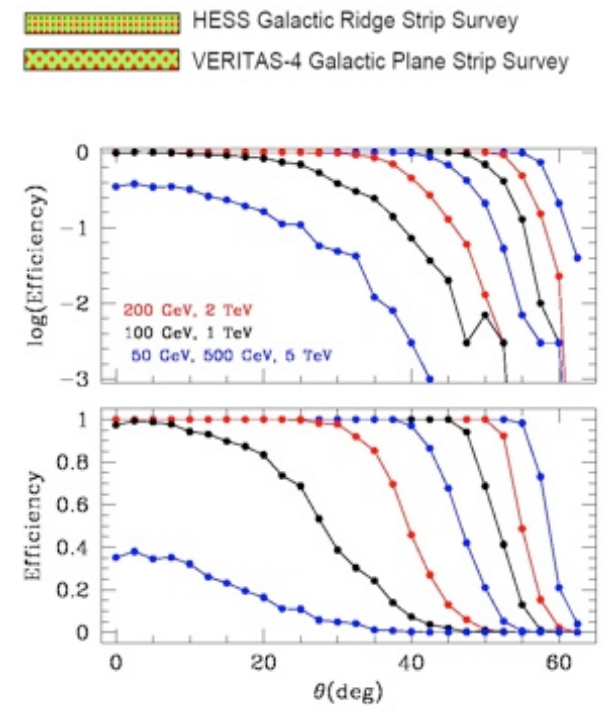
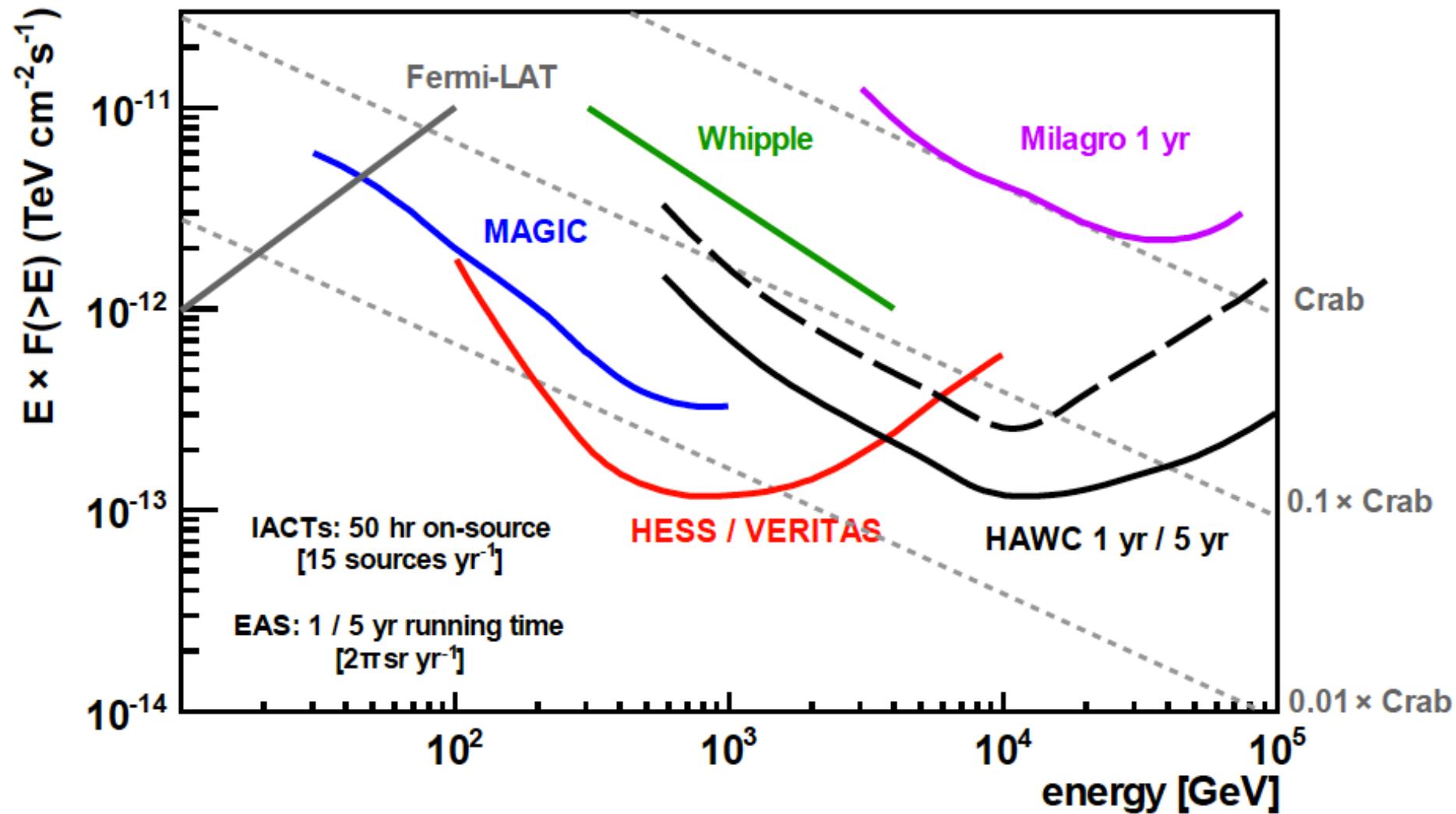
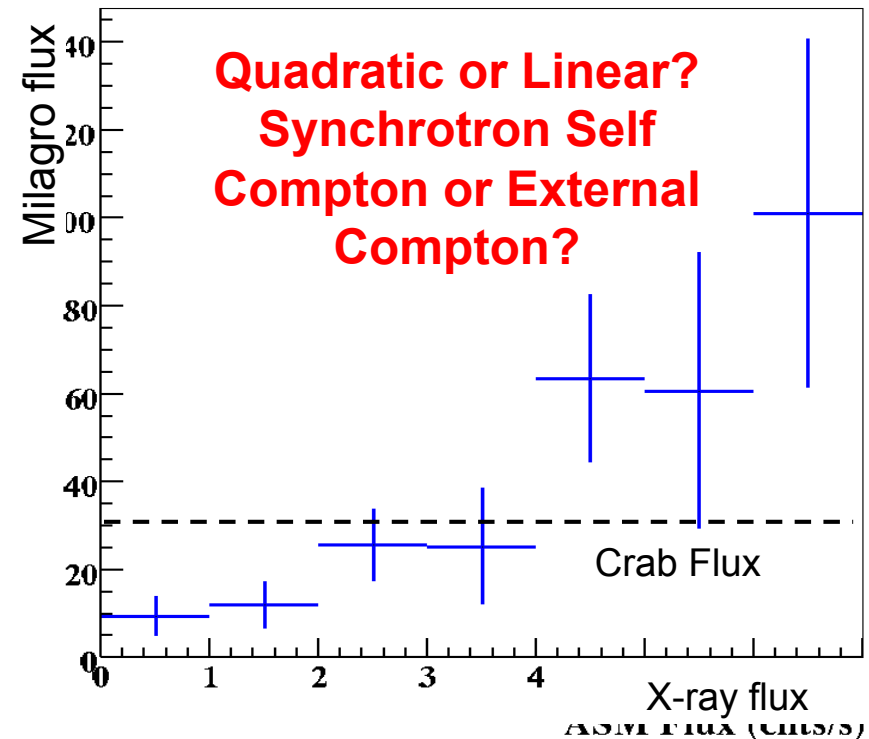
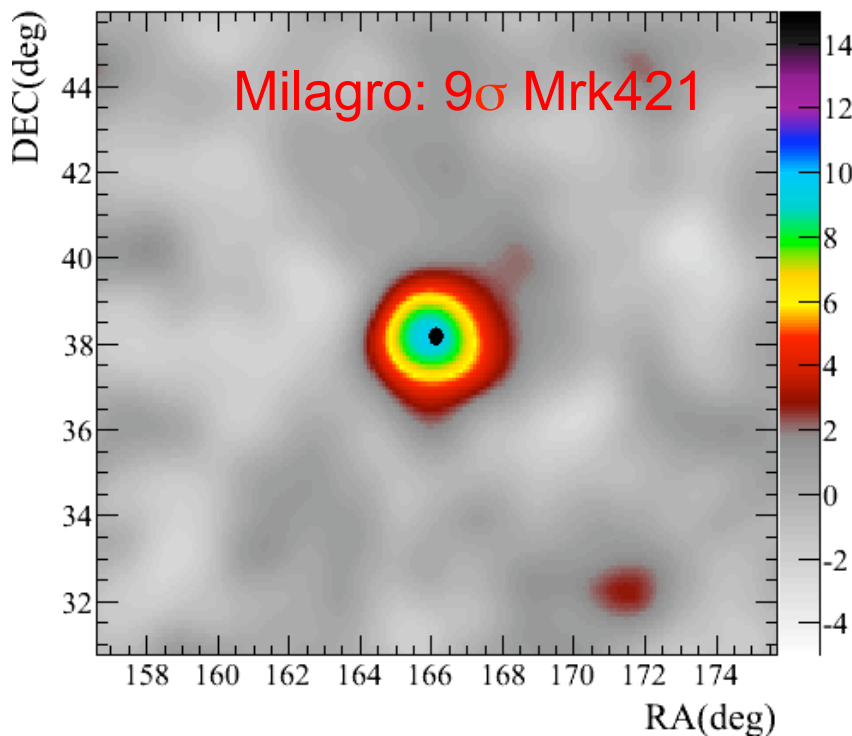


Table 1- A comparison of Milagro and HAWC. Note that comparisons are generally made for a Crab-like spectrum of differential photon spectral index -2.6. However, with a lower threshold some comparisons are between events at different energies. In some cases, the HAWC values will improve when we optimize our reconstruction for angular resolution and background rejection.

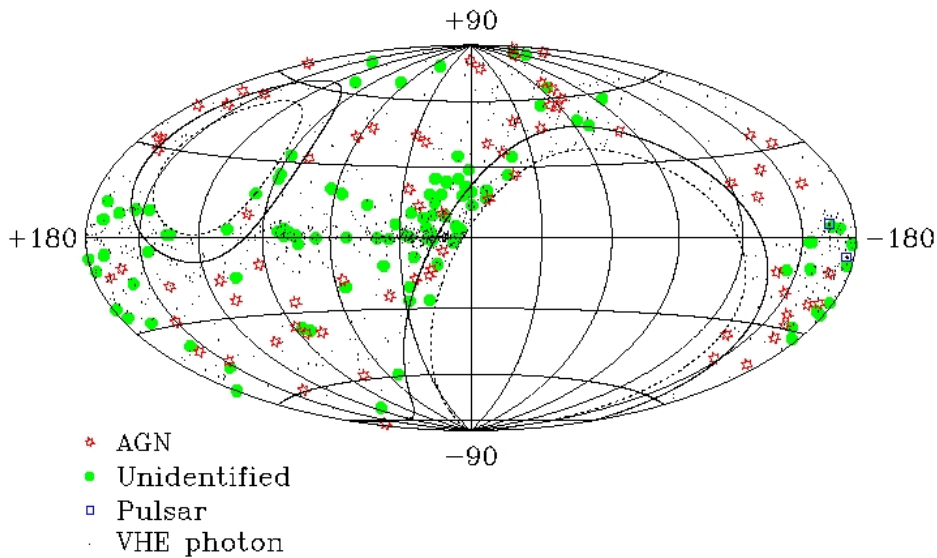


Ráfagas en AGNs

- HAWC hará observaciones diarias sin restricciones de clima, luna o Sol.
- Señal a ruido de 5σ para flujos de (10,1,0.1) Crab en (3 min, 5 hrs, 1/3 año)
- HAWC tendrá un sistema de alerta para seguimiento multi-frecuencia
- Correlaciones (como rayos X) permiten determinar en mecanismo de emisión
- Potencial de estudiar ráfagas TeV huérfanas y buscar emisión coincidente de neutrinos y RCUE



HAWC - GRBs



- Relevamiento diario de 2/3 de cielo $E > \text{TeV}$
- Expectativa de detección de GRBs en TeV

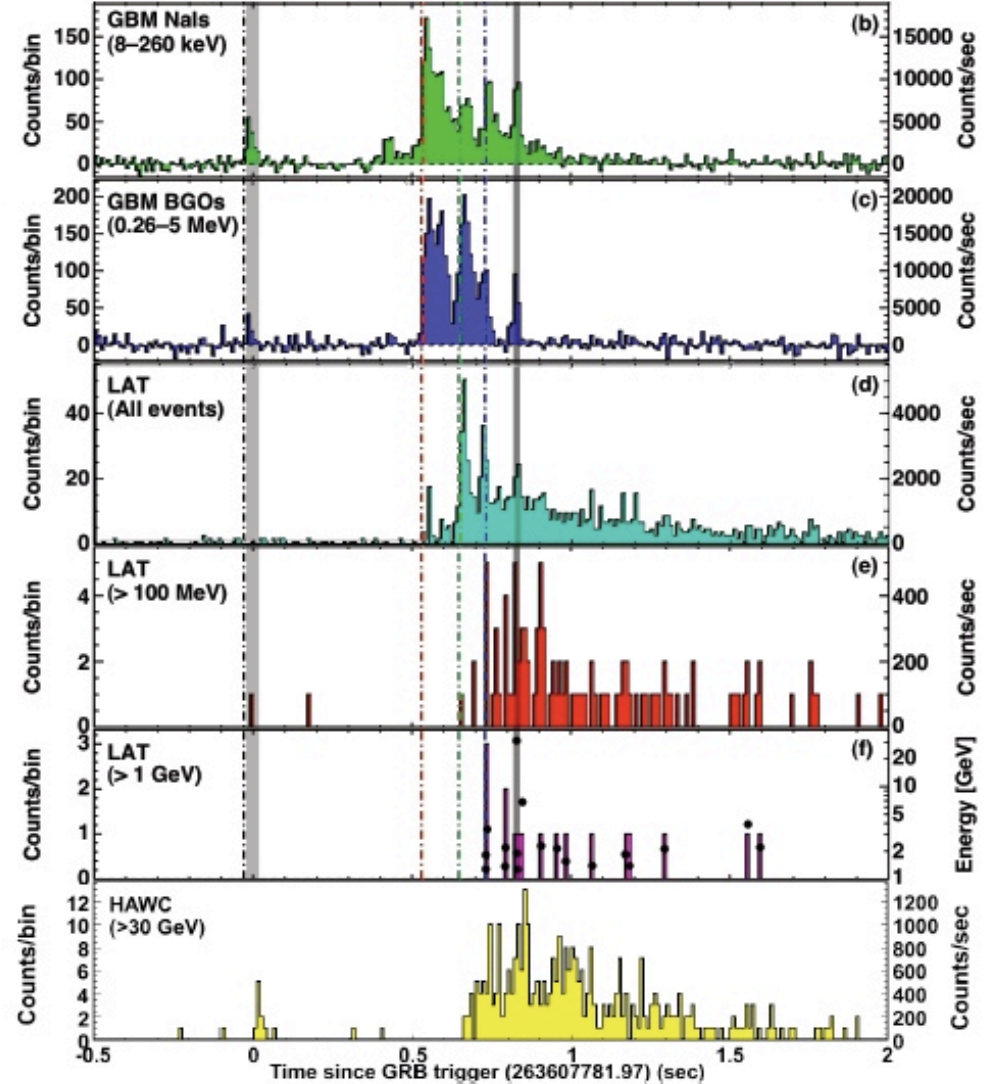


Figure 6 Fermi observation of GRB090510 at $z=0.9$ (top 5 panels) and HAWC's simulated lightcurve (including background). Approximately 200 events are simulated within the 0.5-1.0s interval which corresponds to a cutoff energy of about 125 GeV if the GRB were observed with $\cos\theta > 0.9$.

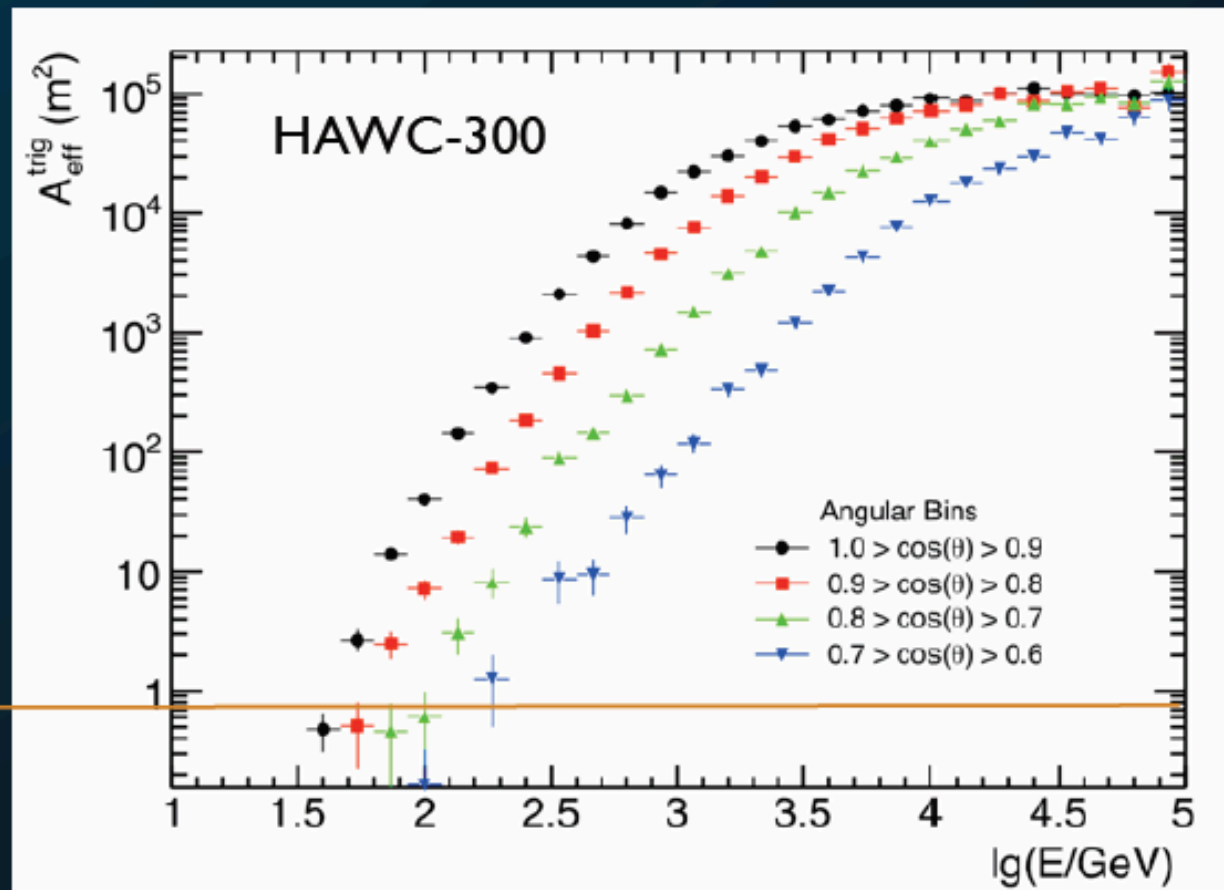
Energy threshold and effective area

$N_{hit} > 70$

Angular error < 1 deg

No hadron rejection
cut applied

Fermi LAT
(0.8 m^2)



- Geometric area $\sim 10^5 \text{ m}^2$ (6 x Milagro pond area)
- Energy threshold $\sim 30 \text{ GeV}$, fully efficient at $E > 3 \text{ TeV}$
- Still $\sim 100 \text{ m}^2$ at $E = 100 \text{ GeV}$

Alternative triggers
which would substantially
increase effective area at
low energies are under
investigation

CENTRO DE INFORMACION LUIS ENRIQUE ERRO



2006 4 28



Pico de Orizaba (Citlaltépetl)
5740 m; 18832 ft


LMT / Sierra Negra (Tliltépetl)
4600m; 15091 ft
97° 18' 53" W, +18° 59' 06"

Puebla 2200m - 120 km from INAOE/Puebla to LMT




Infraestructura
básica a 4600m




18.99, -97.31 

© 2012 Google
© 2012 INEGI
Image © 2012 GeoEye

Google earth

Fecha de las imágenes: 5/21/2011  2003

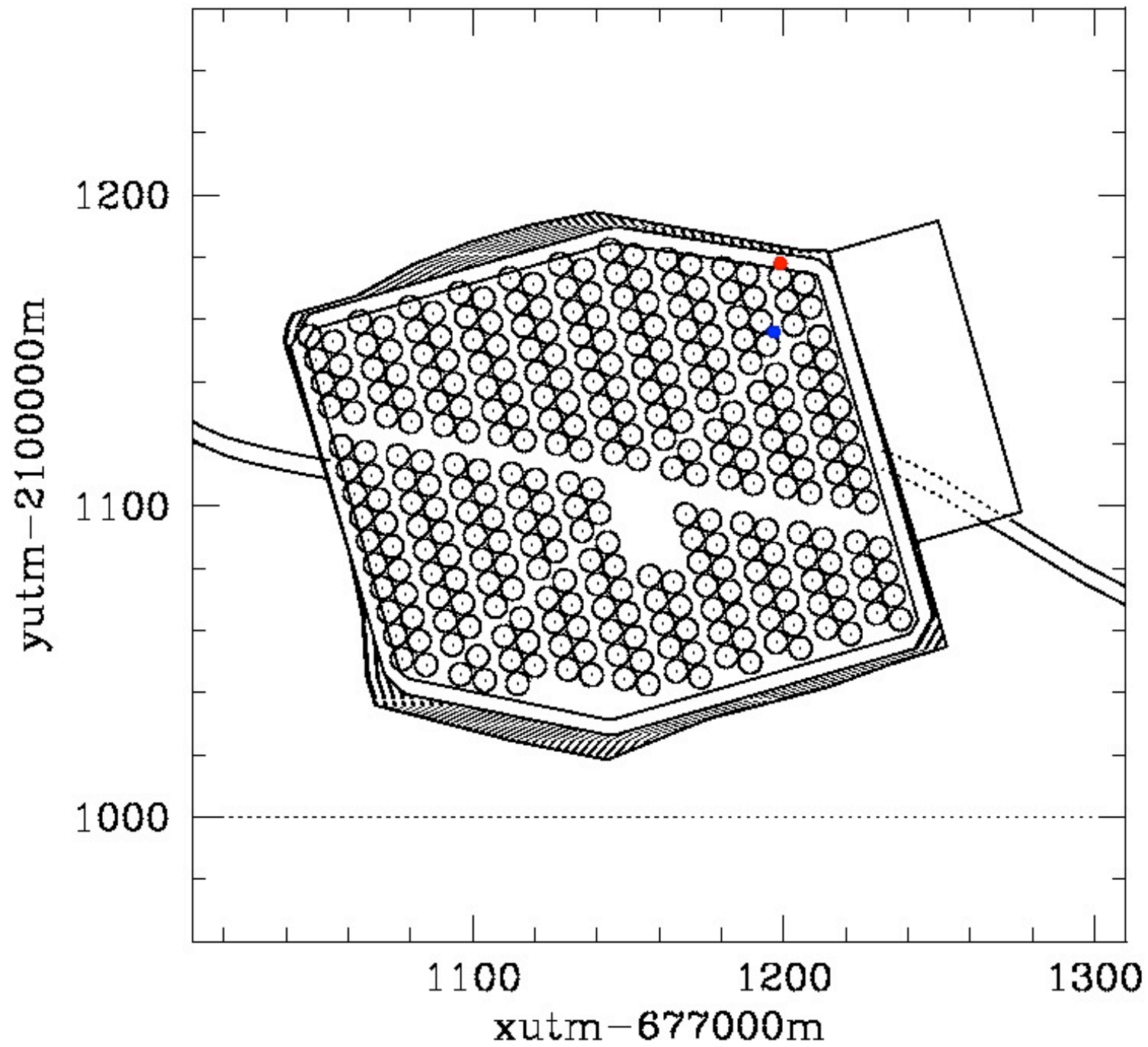
14 Q 677952.37 m'E 2100531.58 m N elev. 4286 m

Alt. ojo 6.07 km 



Julio 2009





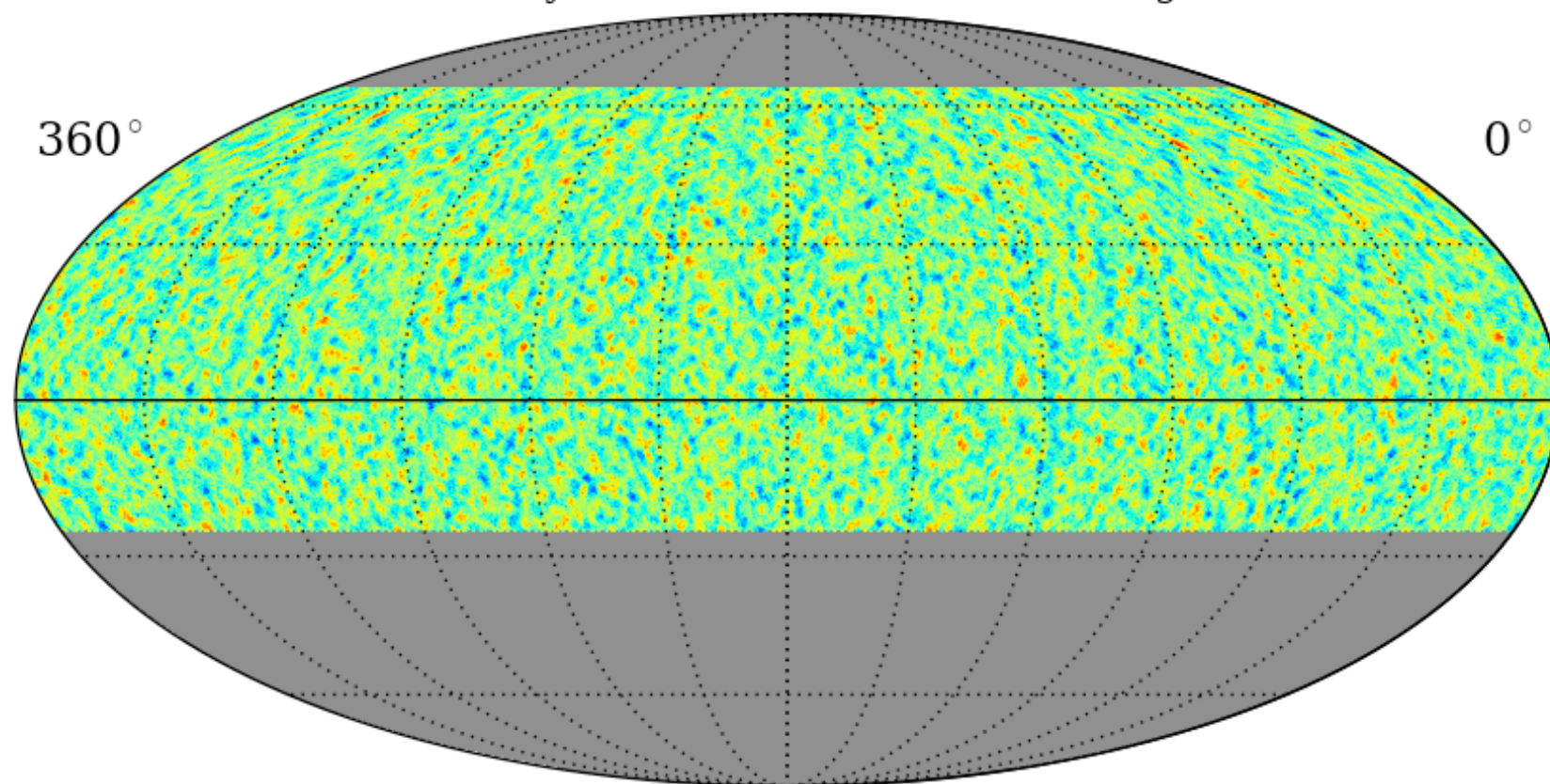


VAMOS

HAWC

25 Oct 2011

VAMOS Sky RUNs 190-1650: Smooth 1 degree

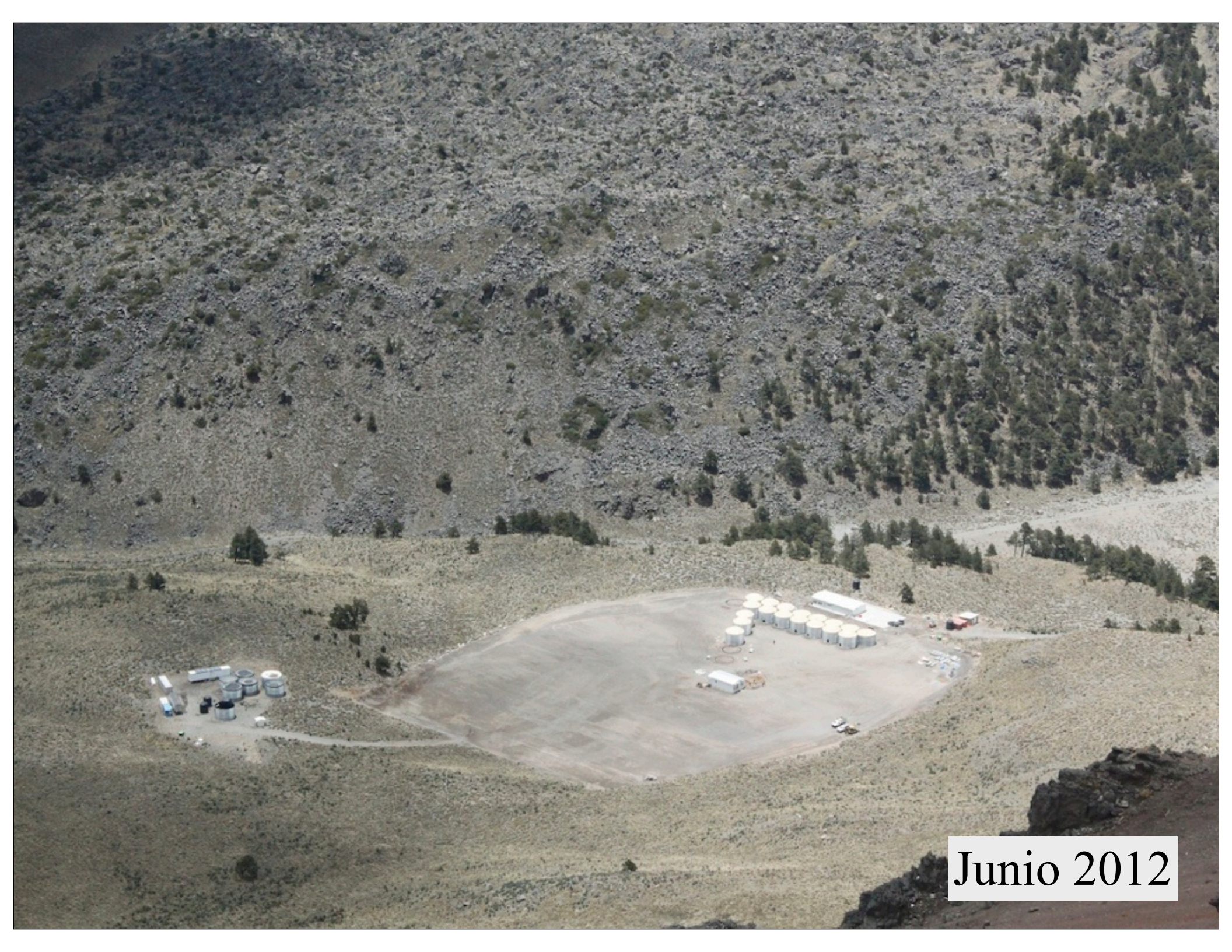




Enero 2012



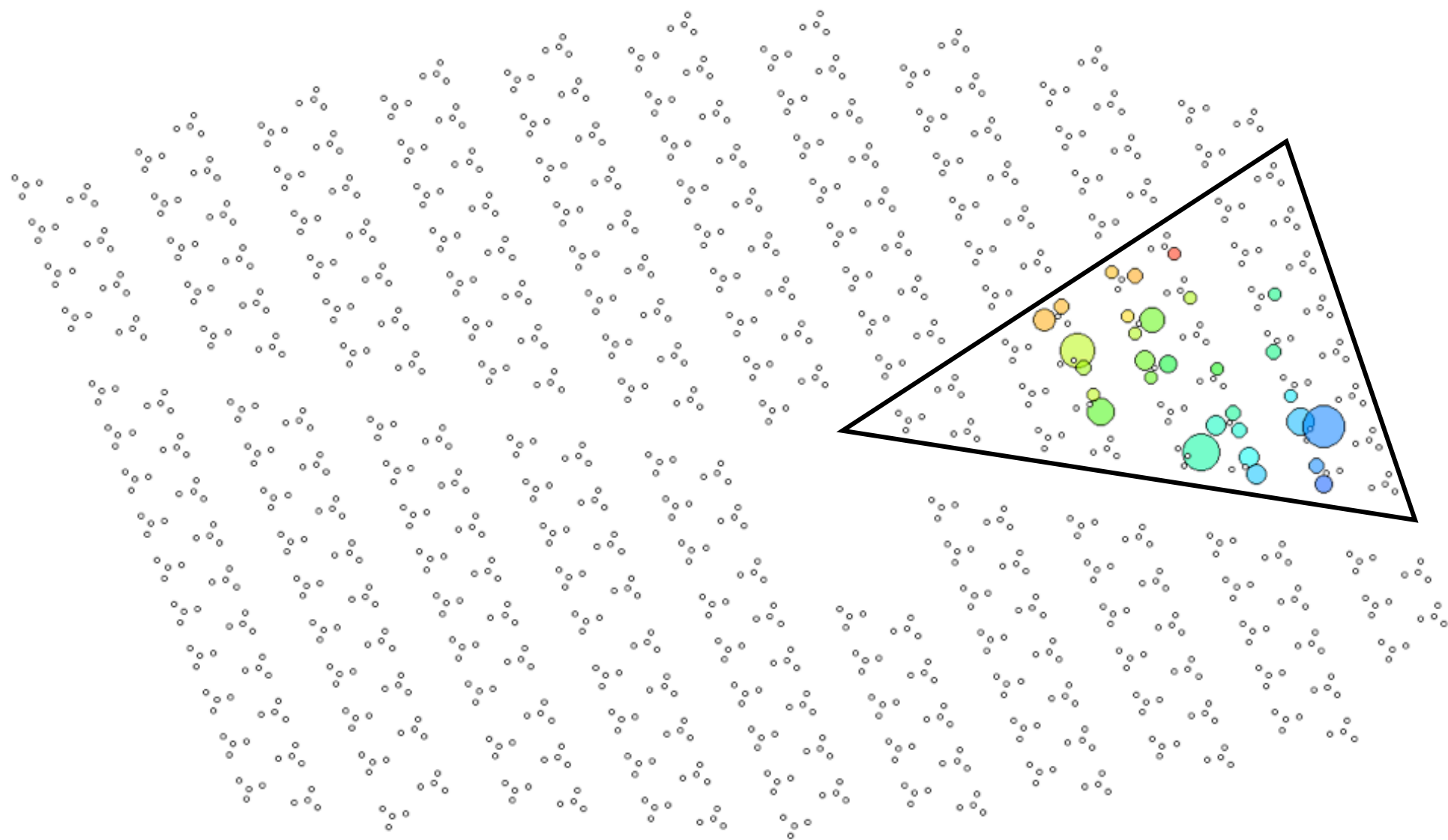
Abril 2012



Junio 2012



1 Sep 2012



-65

-25

15

55

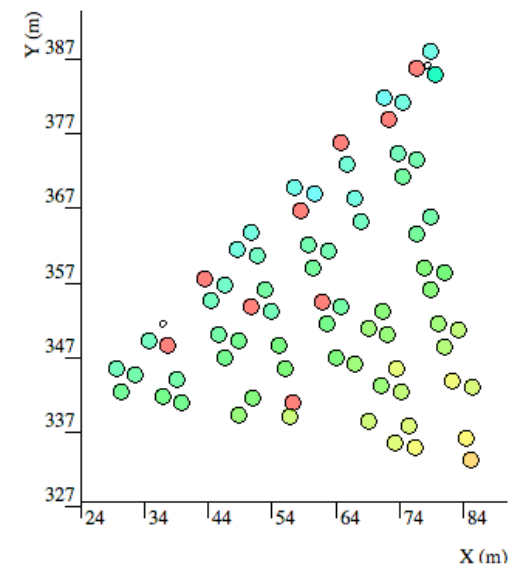
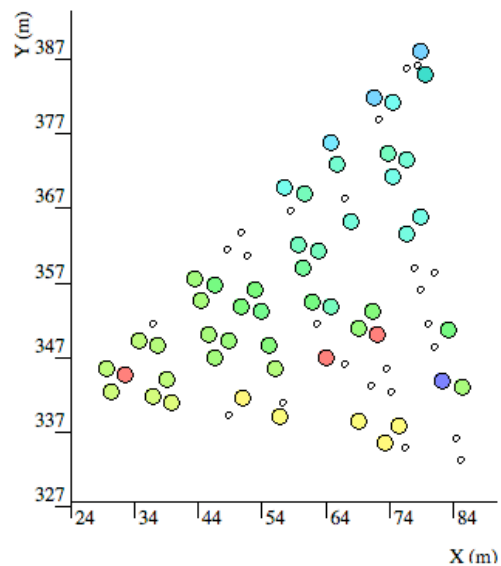
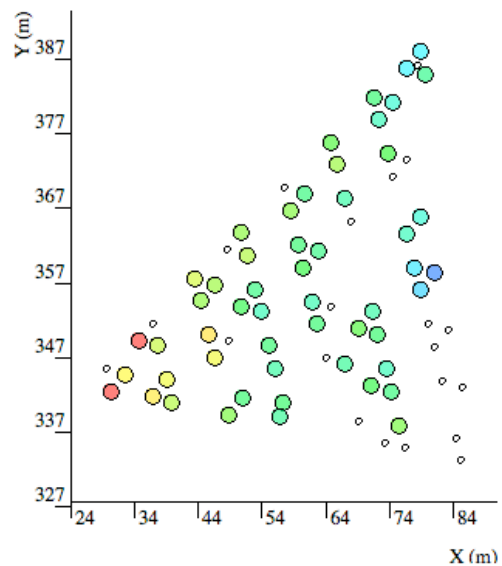
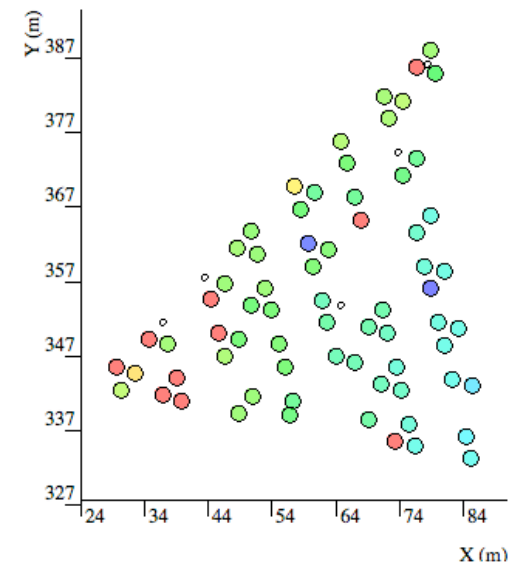
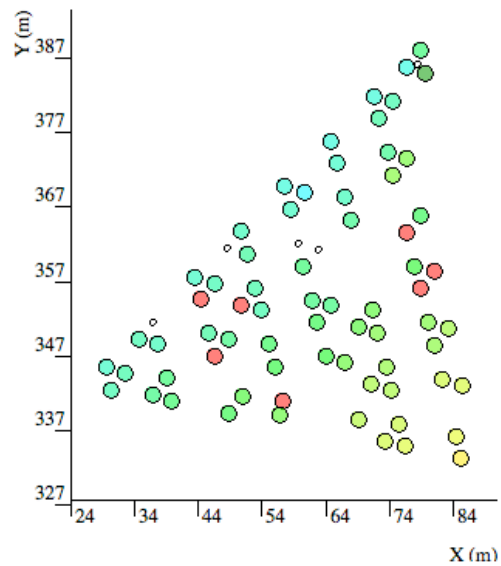
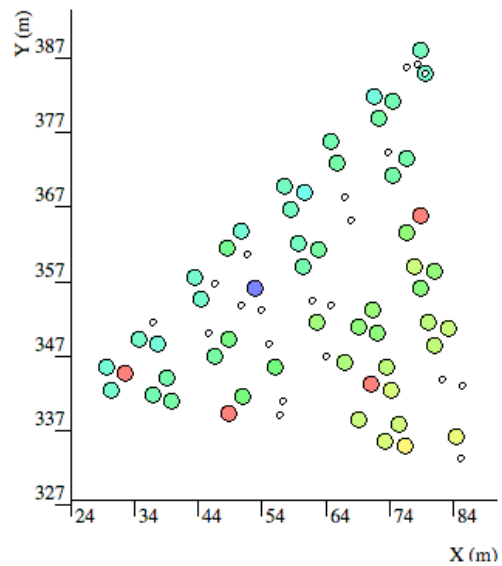
95

-14

26

66

Time (ns)



Milestone	Description	Months	Baseline Date
0	Start of Project Funding (DOE in R&D stage)	0	02/01/2011
1	VAMOS: Test array deployed and verified	7	9/01/2011
2	SITE: Electricity and Internet installed to site and ground prepared for full HAWC array	10	12/01/2011
3	HAWC 30: 30 WCDs deployed and verified	17	07/01/2012
4	HAWC 30: 30 WCDs integrated	19	09/01/2012
5	HAWC 100: 100 WCDs deployed and verified	27	05/01/2013
6	OPS: Integration complete for 100 WCDs, continuous operation begins	30	08/01/2013
7	Crab: Detect Crab at >10 sigma	36	02/01/2014
8	Full HAWC array (250 WCDs) deployed and verified	42	08/01/2014
9	Full Ops: 250 WCD array integrated & operational	42	08/01/2014

The HAWC Collaboration



USA

George Mason University
Georgia Institute of Technology
Harvey Mudd College
Los Alamos National Laboratory
Michigan State University
Michigan Technical University
NASA/Goddard Space Flight Center
Ohio State University at Lima
Pennsylvania State University
Univ. of California, Irvine
University of Maryland
University of New Hampshire
University of New Mexico
University of Utah
University of Wisconsin



México

Instituto Nacional de Astrofísica Óptica y Electrónica
Universidad Nacional Autónoma de México:
 Instituto de Astronomía
 Instituto de Física
 Instituto de Ciencias Nucleares
 Instituto de Geofísica
Benemérita Universidad Autónoma de Puebla
Universidad Autónoma de Chiapas
Universidad de Guadalajara
Universidad Michoacana de San Nicolás de Hidalgo
Centro de Investigación y de Estudios Avanzados
Universidad de Guanajuato

