The HAWC γ-ray observatory

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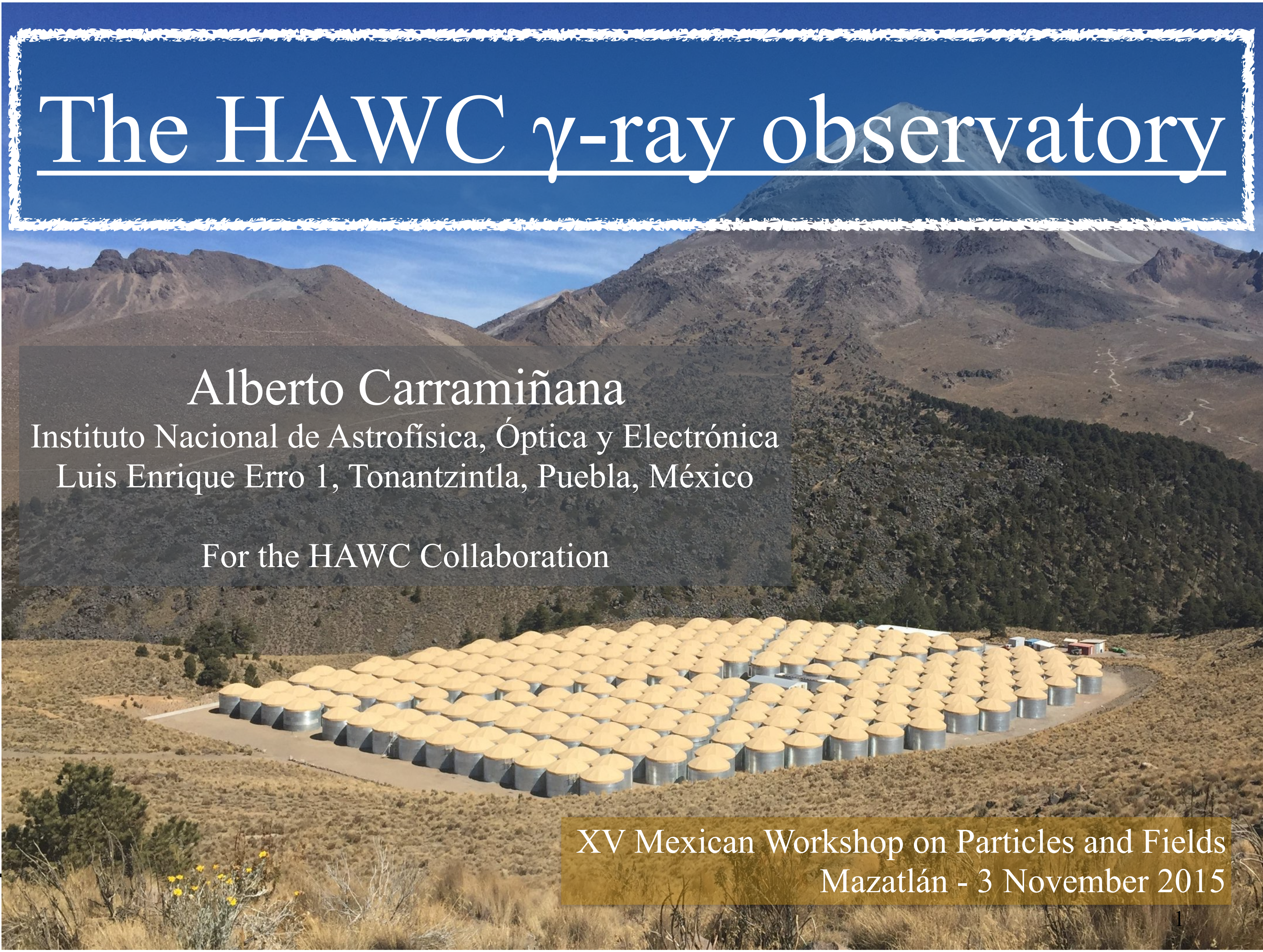
Luis Enrique Erro 1, Tonantzintla, Puebla, México

For the HAWC Collaboration

XV Mexican Workshop on Particles and Fields
Mazatlán - 3 November 2015



The HAWC γ-ray observatory

- Prelude: from Tonantzintla to Sierra Negra
- γ-ray astronomy from space and ground
- WCOs: from Milagro to HAWC
- The development of HAWC
- HAWC data and results
- Making more of HAWC

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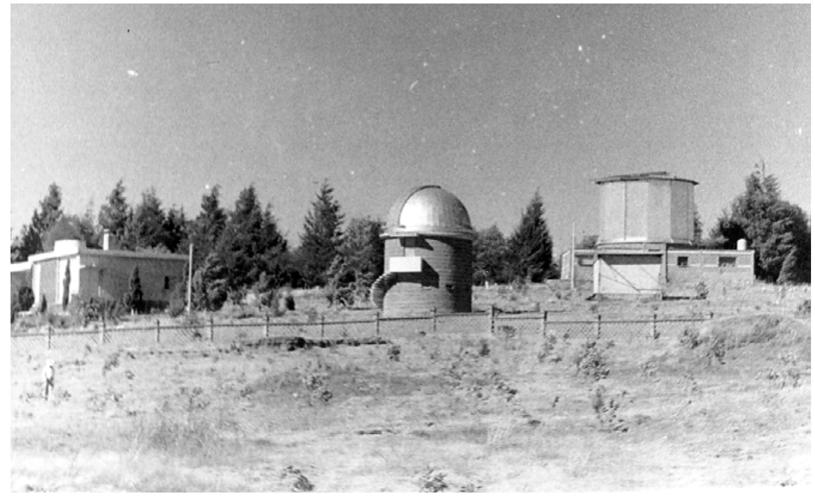
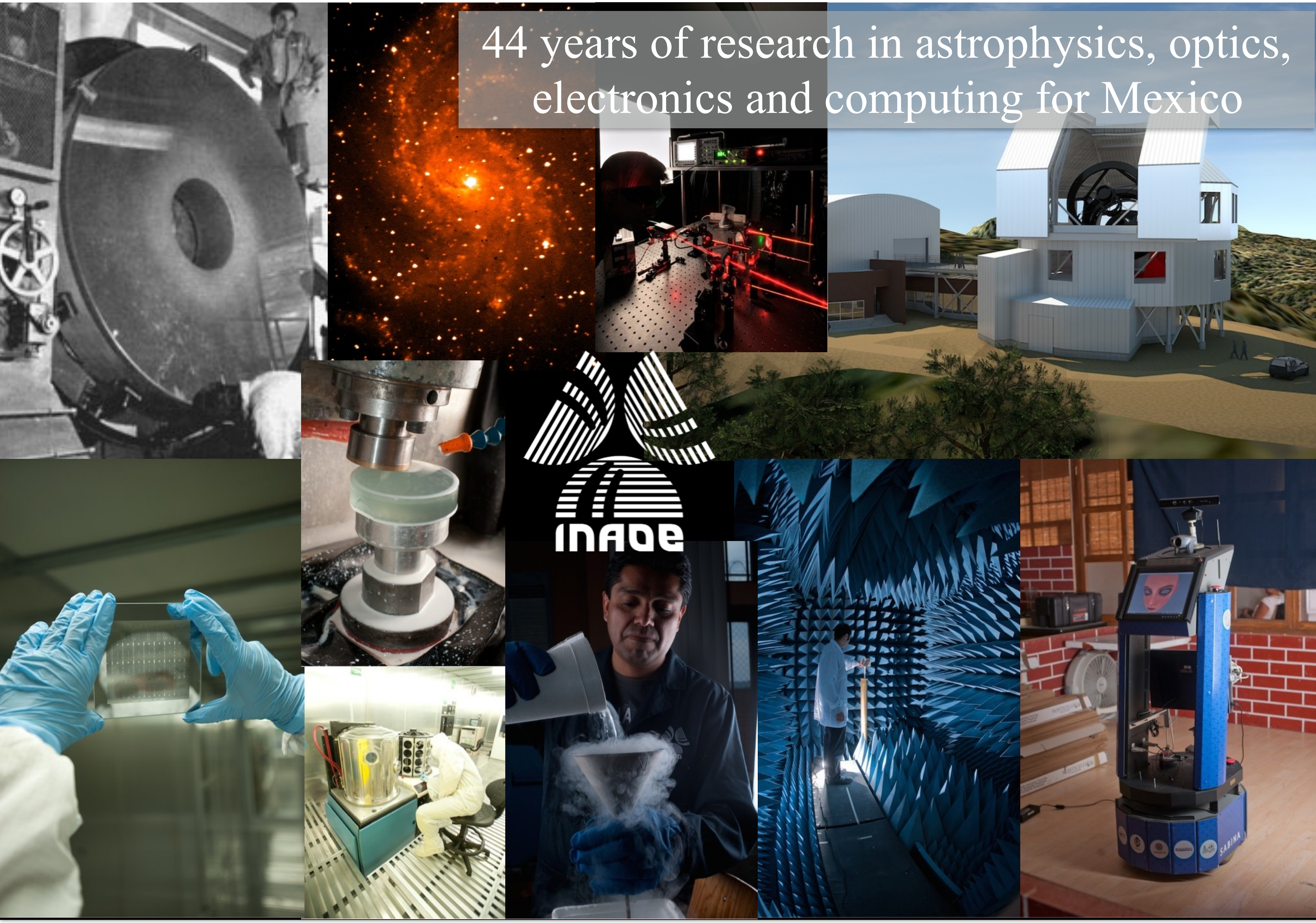
Instituto Nacional de Astrofísica, Óptica y Electrónica



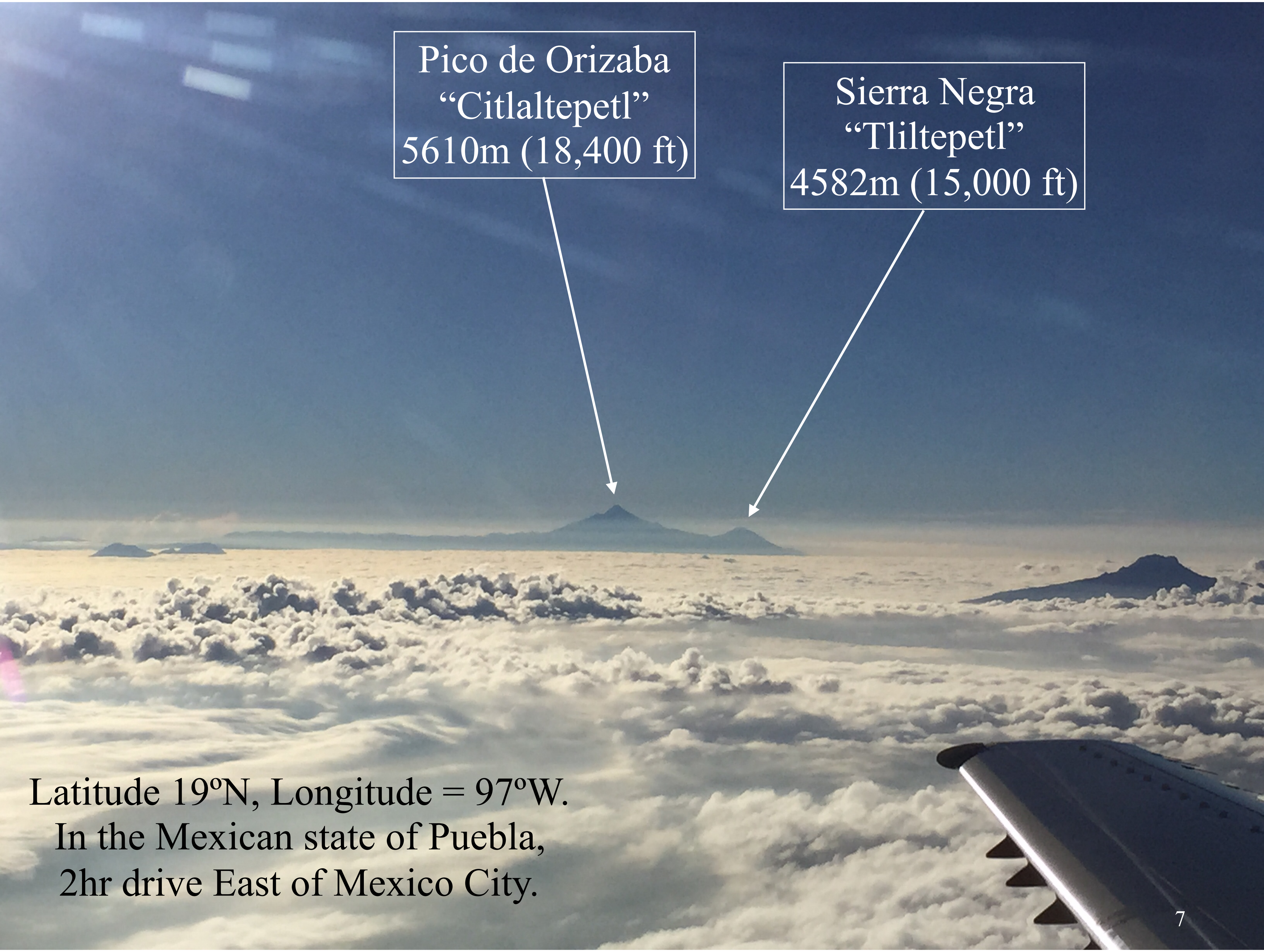
- The Observatorio Astrofísico Nacional de Tonantzintla (OAN-Ton), Puebla, was founded in 1942 by Luis Enrique Erro.
- Tonantzintla was the site of the discovery of HH objects (& Ton blue galaxies, flare stars…).
- In 1971 Guillermo Haro transformed the OAN-Ton into INAOE.
- INAOE was created with the project of establishing the Cananea observatory - today Observatorio Astrofísico Guillermo Haro, operational since 1988.

44 years of research in astrophysics, optics, electronics and computing for Mexico



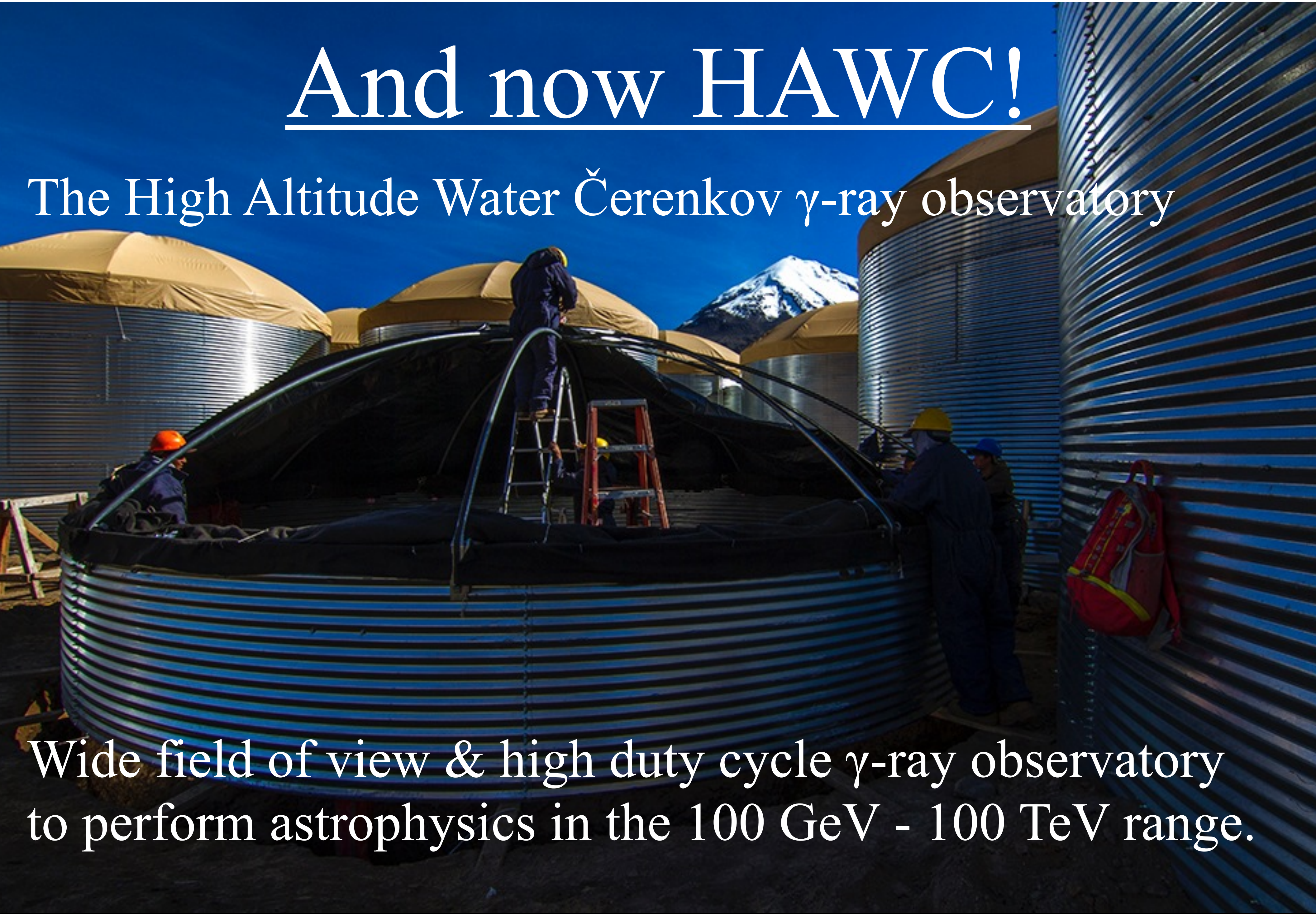
Gran Telescopio Milimétrico Alfonso Serrano

- The Large Millimeter Telescope Alfonso Serrano (LM/GTM).
- Twenty year collaboration between INAOE and UMASS, Amherst, to construct and operate the largest single dish mm telescope in the world: 50m antenna for observations in the 0.8 - 4.0 mm band.
- Installed at the top of Sierra Negra at 4593m.
- Operational since May 2013 with a functional aperture of 32m.
- On track for 50m operations in 2016.


Pico de Orizaba
“Citlaltepetl”
5610m (18,400 ft)
Sierra Negra
“Tliltepetl”
4582m (15,000 ft)
Latitude 19ºN, Longitude = 97ºW.
In the Mexican state of Puebla,
2hr drive East of Mexico City.

And now HAWC!

The High Altitude Water Čerenkov γ-ray observatory



Wide field of view & high duty cycle γ-ray observatory to perform astrophysics in the 100 GeV - 100 TeV range.

The HAWC Collaboration

Mexico		United States	
Instituto Nacional de Astrofísica, Óptica y Electrónica	INAOE	University of Maryland	UMD
Universidad Nacional Autónoma de México		Los Alamos National Laboratory	LANL
Instituto de Astronomía UNAM	IA-UNAM	Colorado State University	CSU
Instituto de Ciencias Nucleares UNAM	ICN-UNAM	George Mason University	GMU
Instituto de Física UNAM	IF-UNAM	Georgia Institute of Technology	GATECH
Instituto de Geofísica UNAM	IG-UNAM	Michigan State University	MSU
Benemérita Universidad Autónoma de Puebla	BUAP	Michigan Technological University	MTU
Instituto Politécnico Nacional		Pennsylvania State University	PSU
Centro de Investigación y Estudios Avanzados	CINVESTAV	NASA GSFC	
Centro de Investigación en Cómputo - IPN	CIC-IPN	University of California Santa Cruz	UCSC
Universidad Autónoma de Chiapas	UNACH	University of California Irvine	UCI
Universidad Autónoma del Estado de Hidalgo	UAEH	University of New Hampshire	UNH
Universidad de Guadalajara	UdG	University of New Mexico	UNM
Universidad Michoacana de San Nicolás de Hidalgo	UMSNH	University of Rochester	UR
Universidad Politécnica de Pachuca	UPP	University of Utah	UU
		University of Wisconsin	UW


HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory
HAWC Meeting
September 23–25, 2013
Michigan Technological University
Houghton, Michigan

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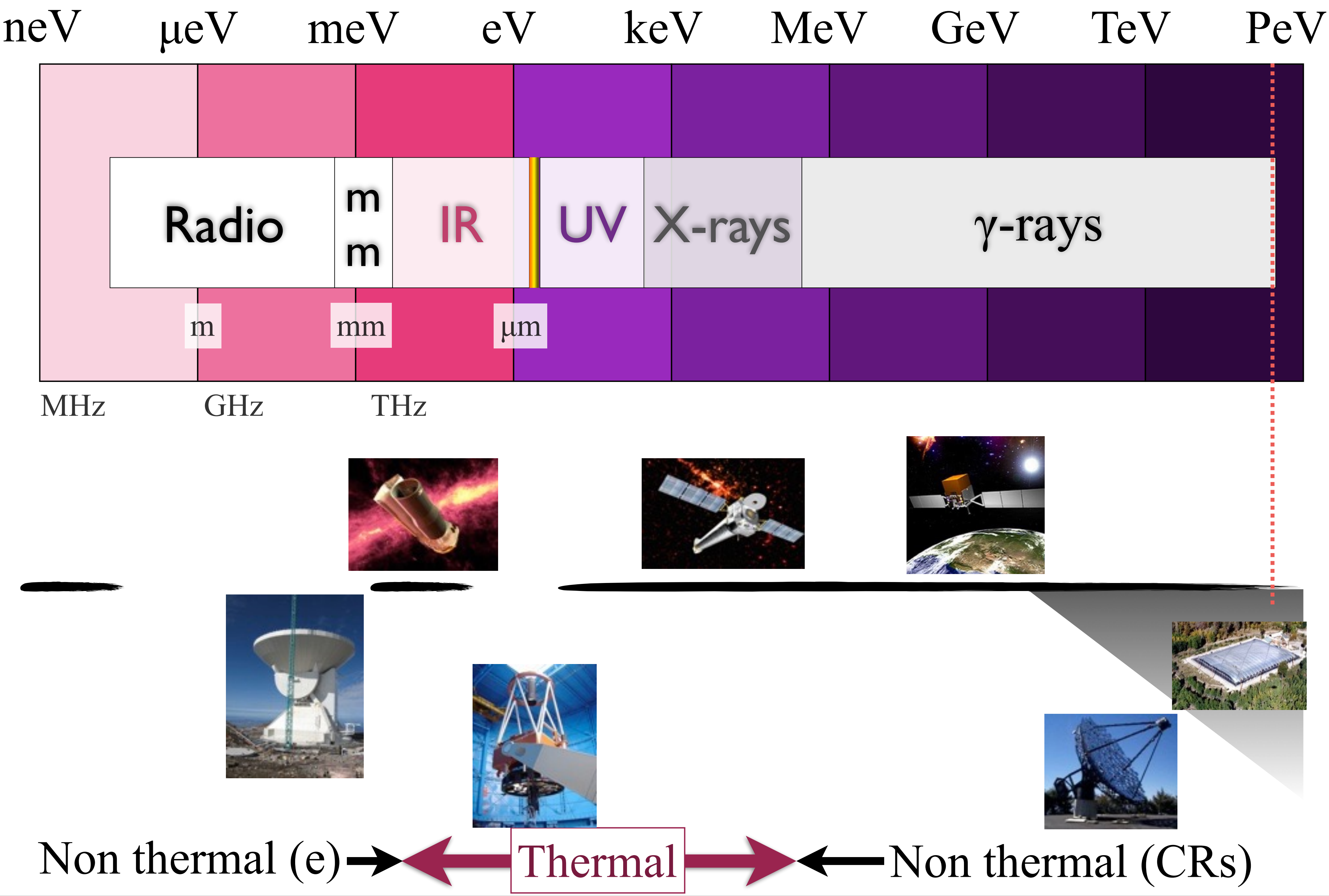
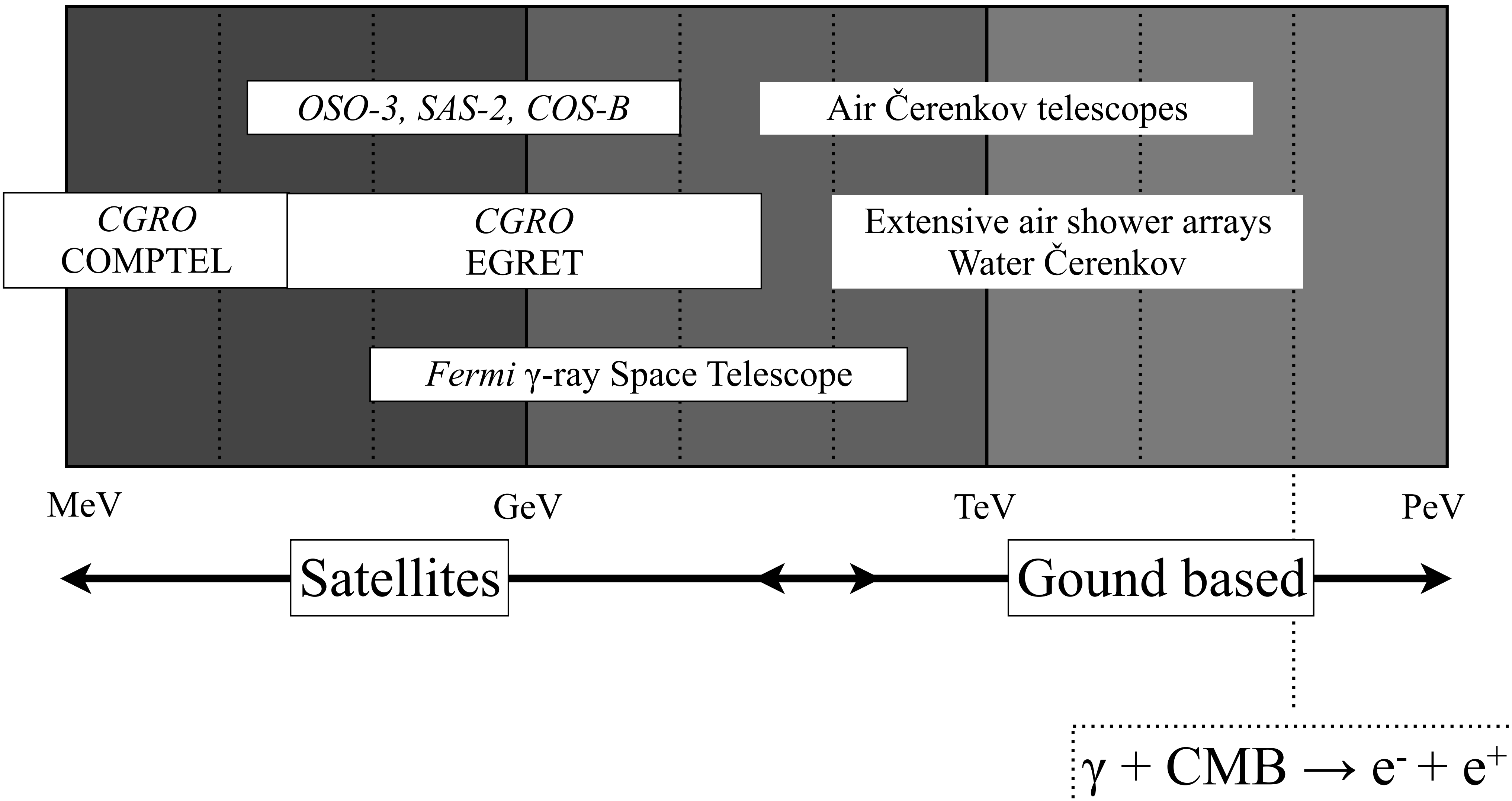
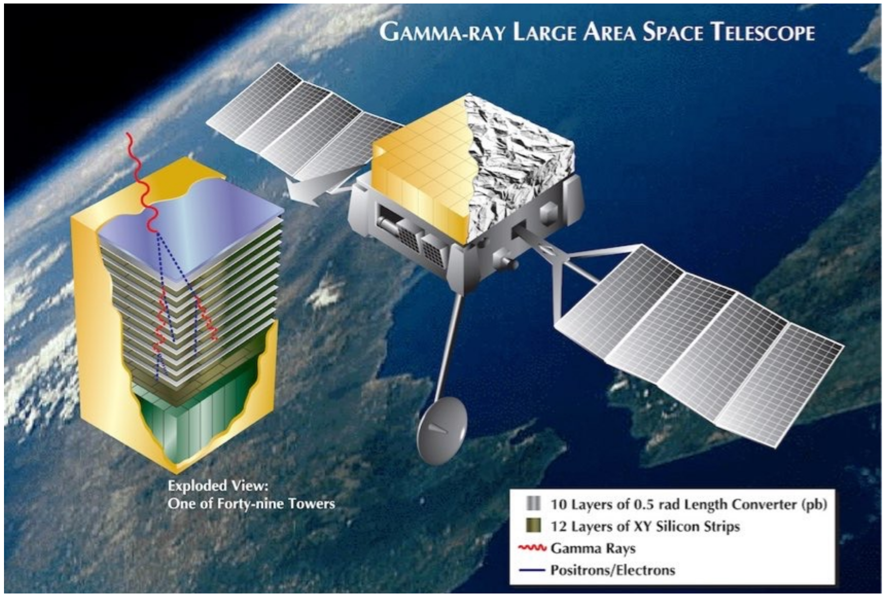


neV
μeV
meV
eV
keV
MeV
GeV
TeV
PeV
Radio
m m
IR
UV
X-rays
γ-rays
m
mm
μm
MHz
GHz
THz
Non thermal (e)
Thermal
Non thermal (CRs)

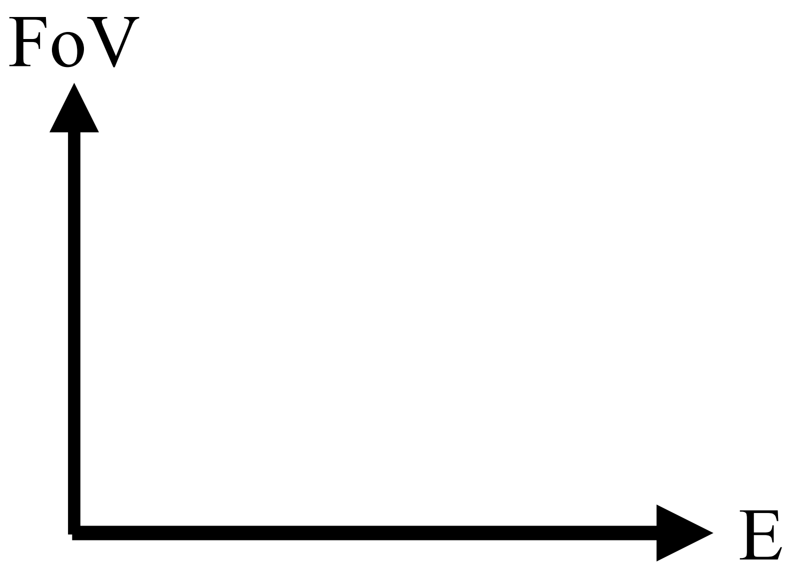
The γ-ray band

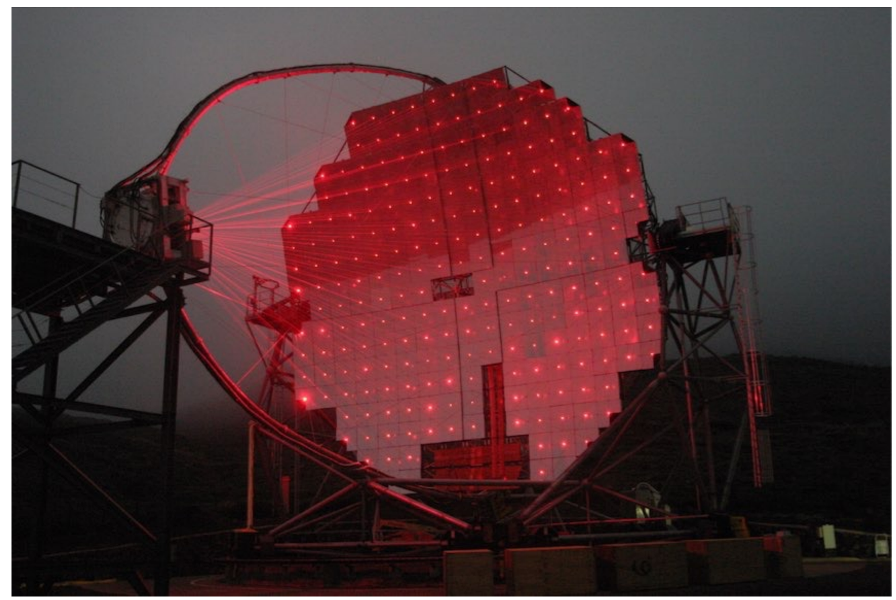


Sr



Deg





GeV

TeV

Sr

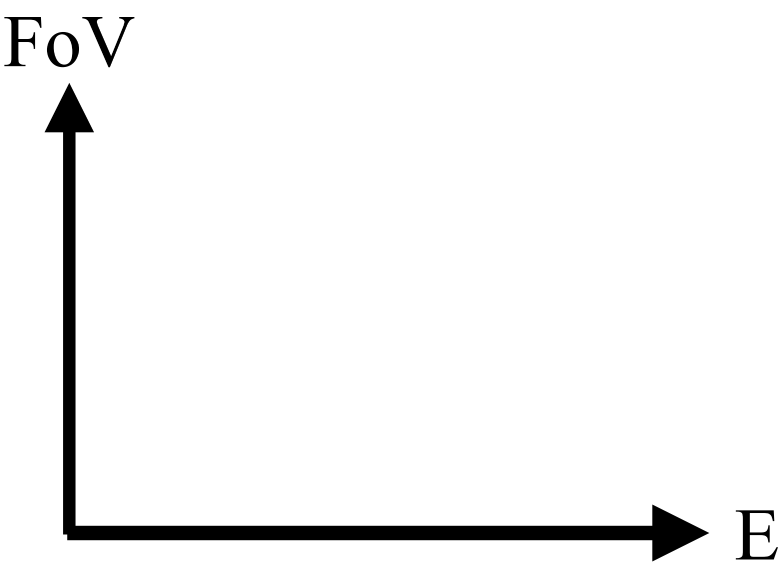
Pair production telescopes
0.1 - 100 GeV
Space based: small effective area
Background free
Large f.o.v. and high duty cycle

All sky survey & monitoring
Transients (AGN, GRB)
Extended diffuse emission

Extensive air-shower arrays
100 GeV - 100 TeV
Good background rejection
Large f.o.v. and high duty cycle

Partial sky survey & monitoring
Extended sources
Transients (AGN, GRB)
Highest energies

Deg

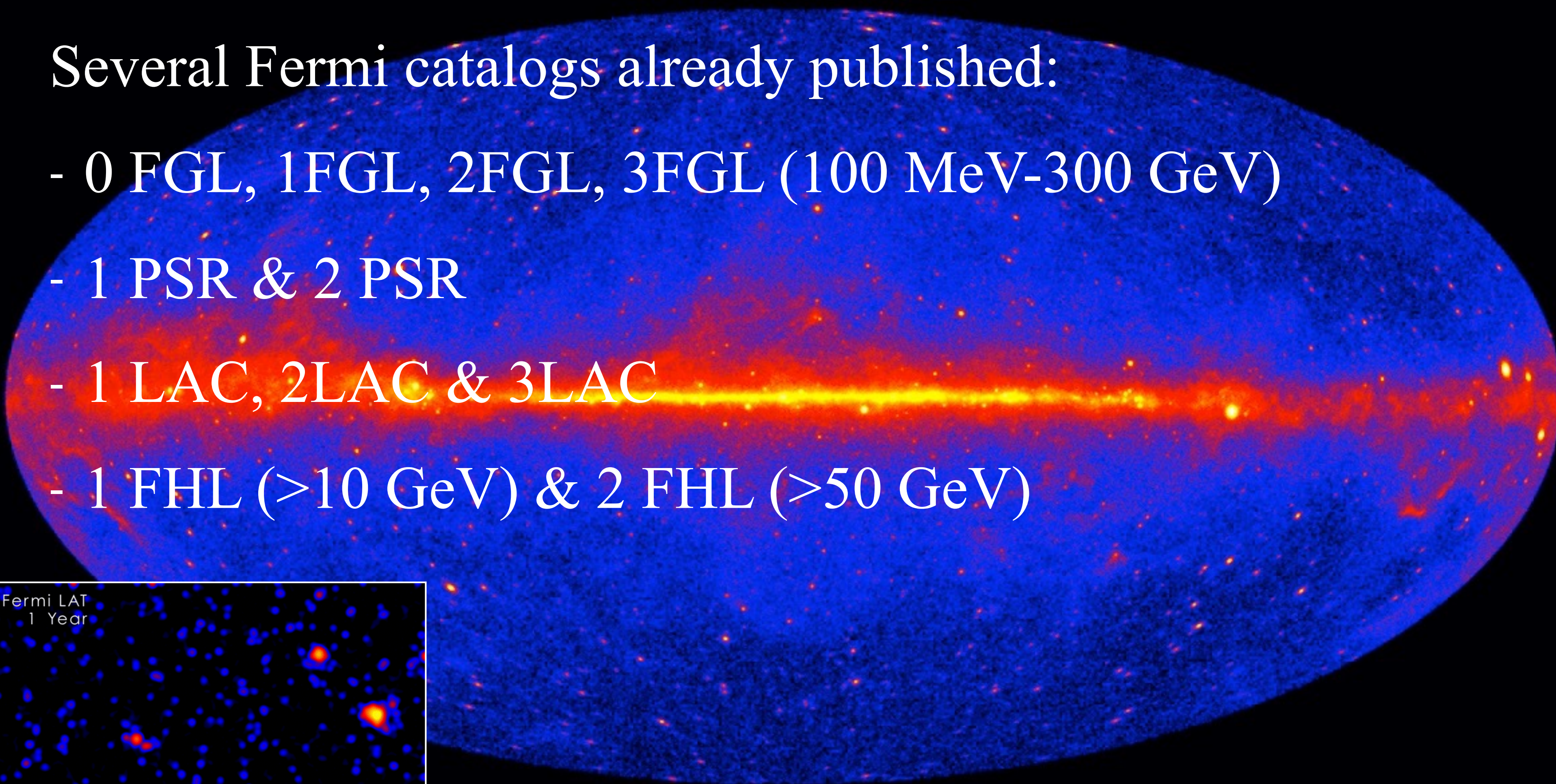


Atmospheric Cherenkov Telescopes
50 GeV - 100 TeV
Large effective area
Excellent background rejection
Small f.o.v. and low duty cycle

Detailed study of known sources
Deep surveys of limited regions
High resolution spectra

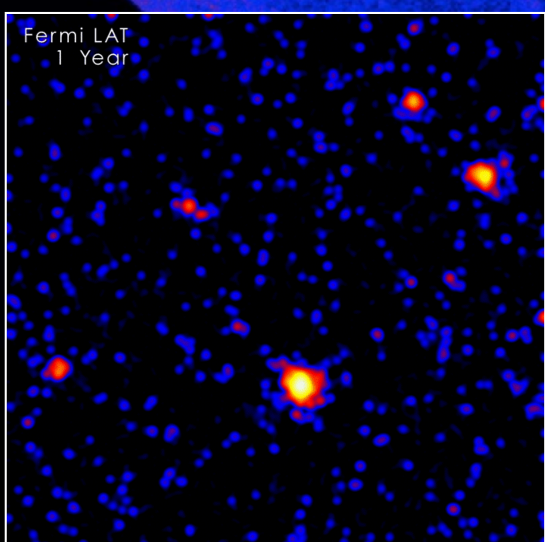
GeV TeV

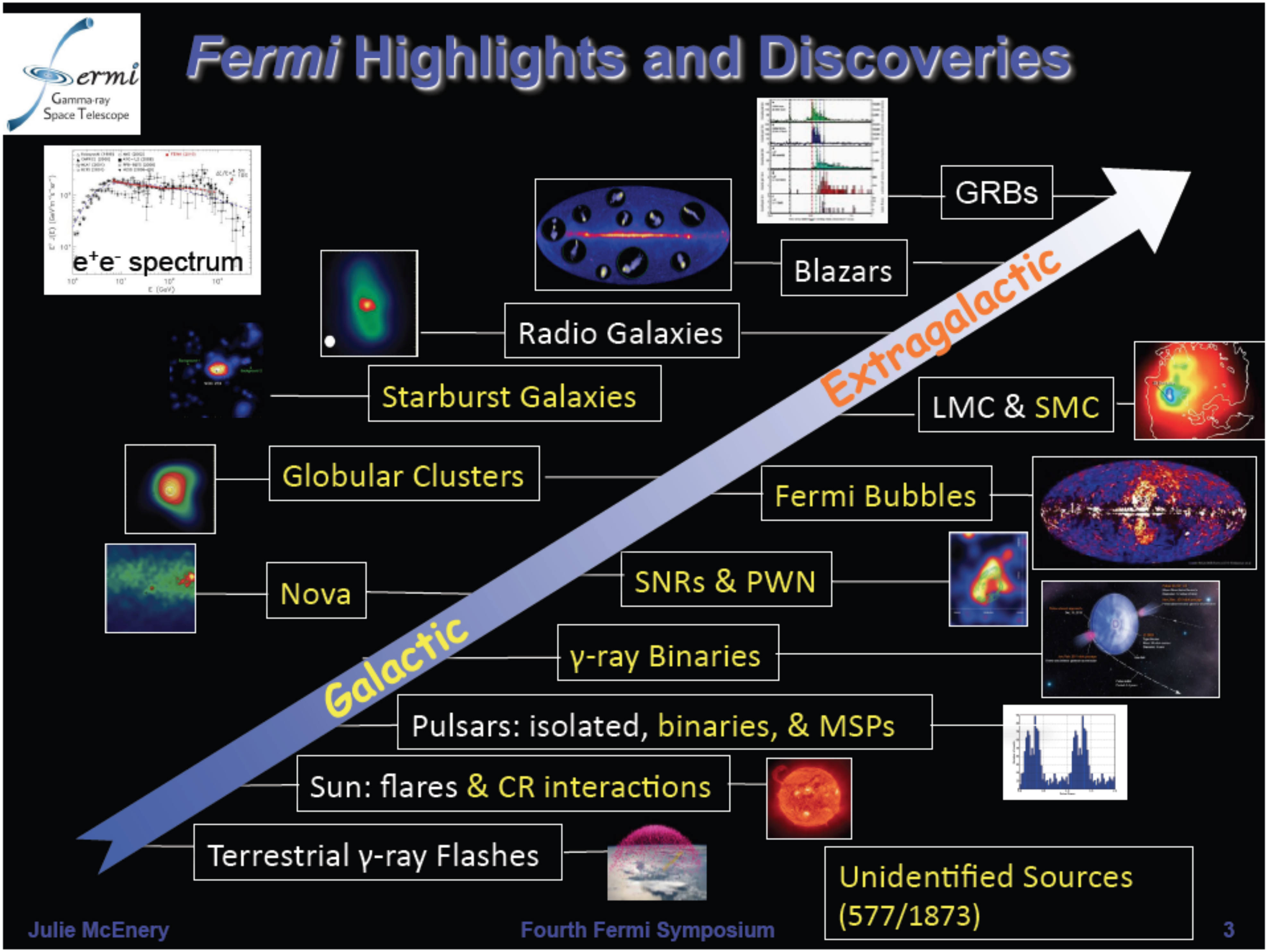
Fermi-LAT



Several Fermi catalogs already published:

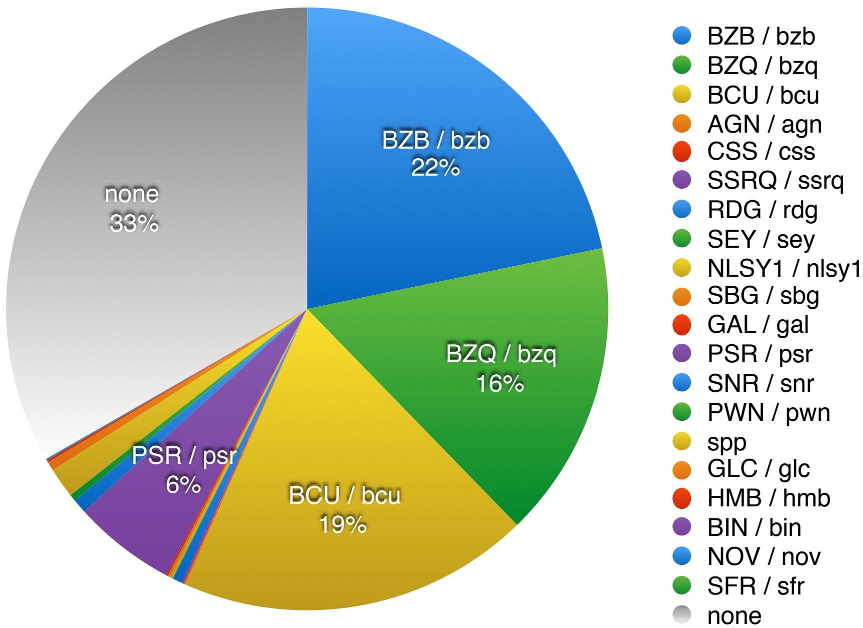
- 0 FGL, 1FGL, 2FGL, 3FGL (100 MeV-300 GeV)
- 1 PSR & 2 PSR
- 1 LAC, 2LAC & 3LAC
- 1 FHL (>10 GeV) & 2 FHL (>50 GeV)



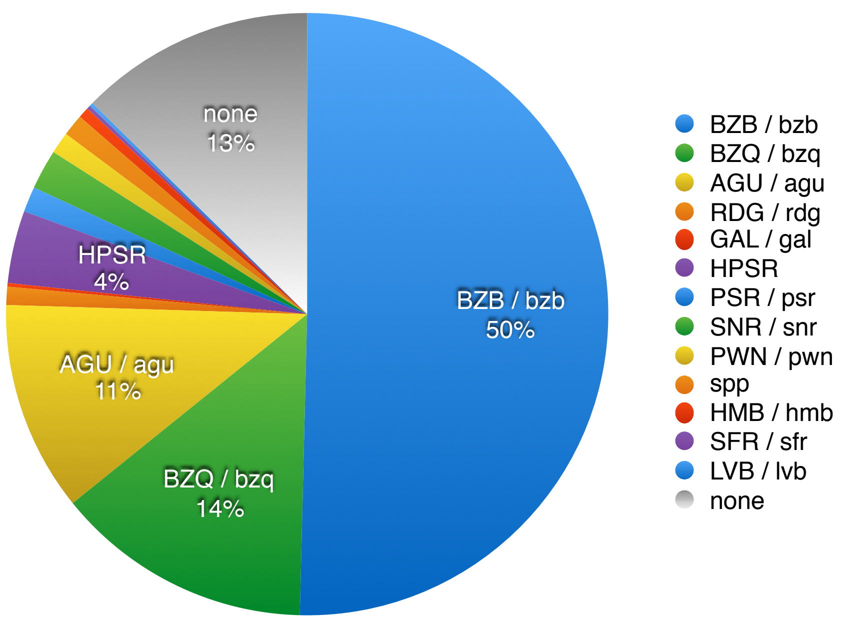

Fermi Gamma-ray Space Telescope
Fermi Highlights and Discoveries
e+e- spectrum
GRBs
Blazars
Radio Galaxies
Starburst Galaxies
Extragalactic
LMC & SMC
Globular Clusters
Fermi Bubbles
Nova
SNRs & PWN
Galactic
γ-ray Binaries
Pulsars: isolated, binaries, & MSPs
Sun: flares & CR interactions
Terrestrial γ-ray Flashes
Unidentified Sources
(577/1873)
Julie McEnery
Fourth Fermi Symposium
3

LAT catalogs: demographics

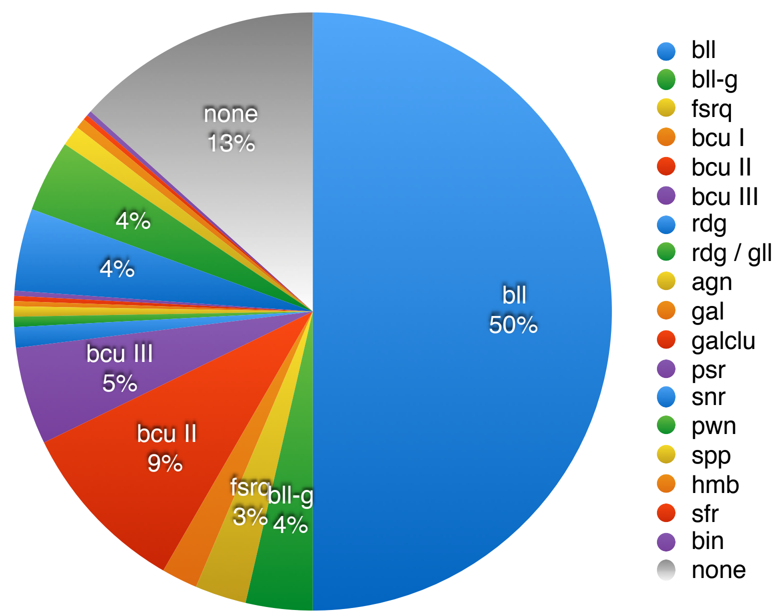
3FGL (0.1 - 300 GeV) :: 3033 sources



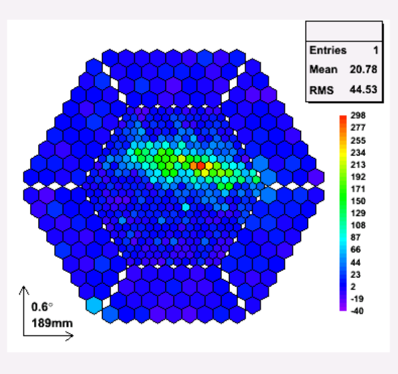
1FHL (E>10 GeV) : 514 sources

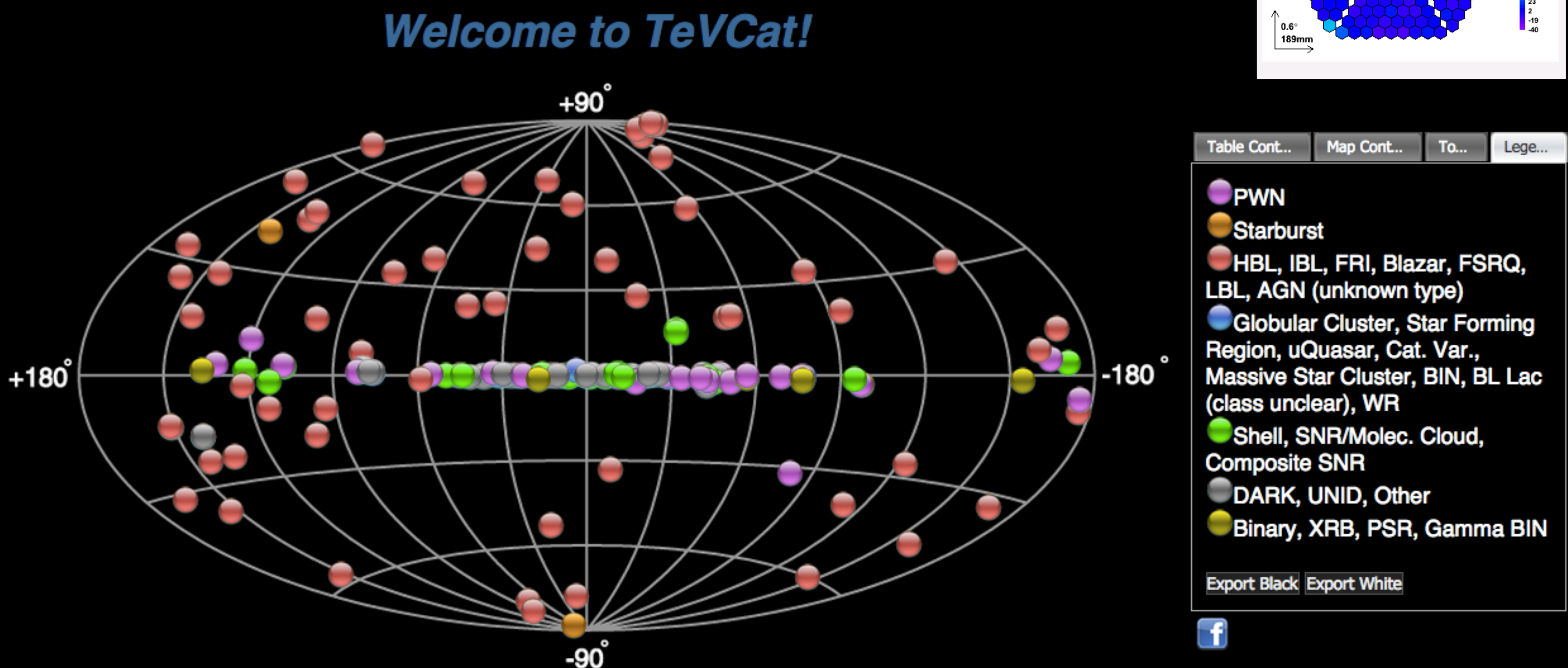


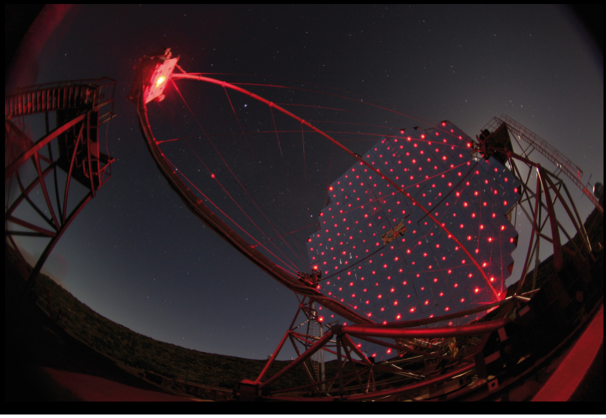
2FHL (50 GeV) :: 360 sources



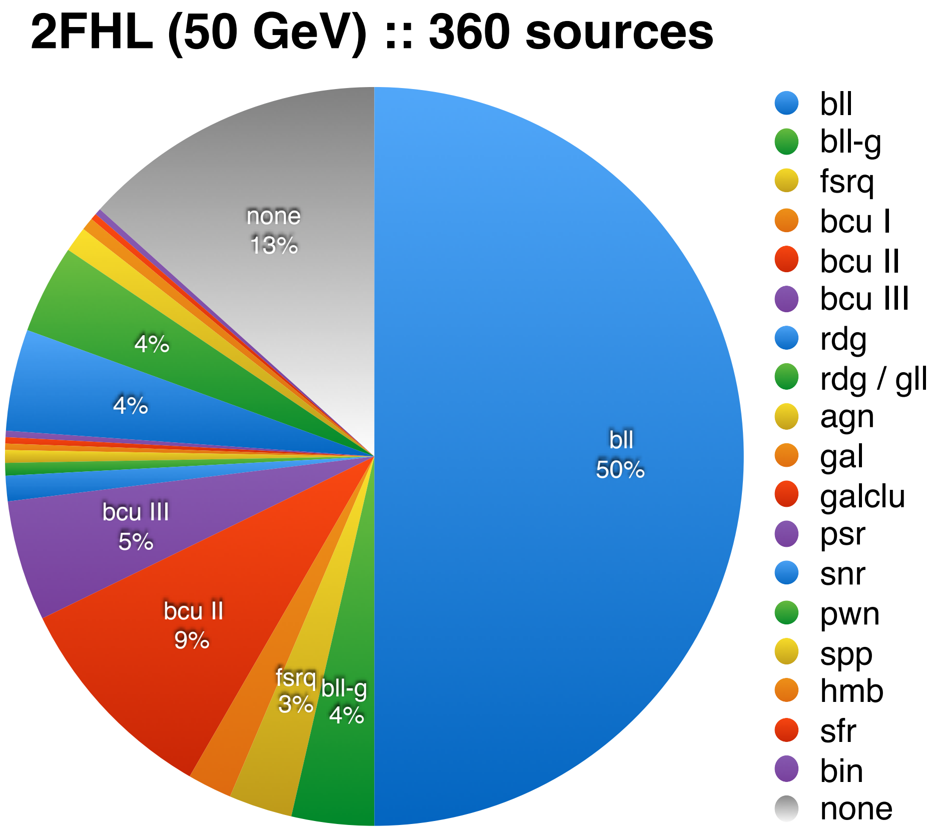
Atmospheric Cherenkov Telescopes

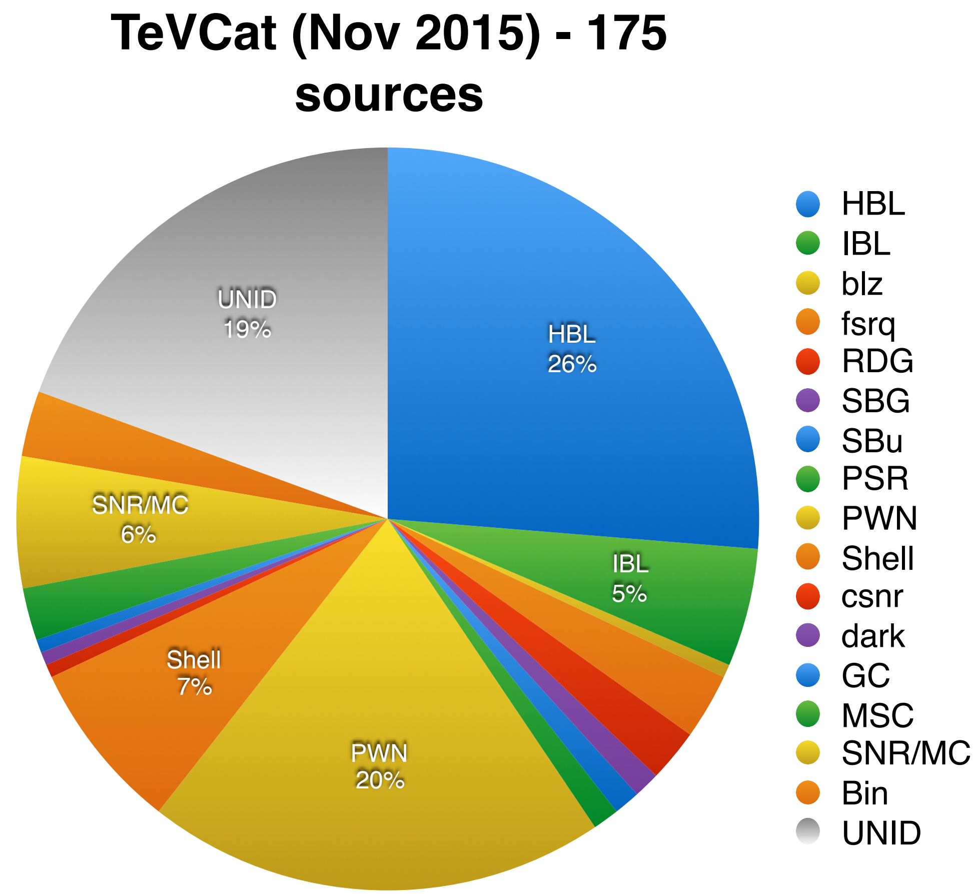




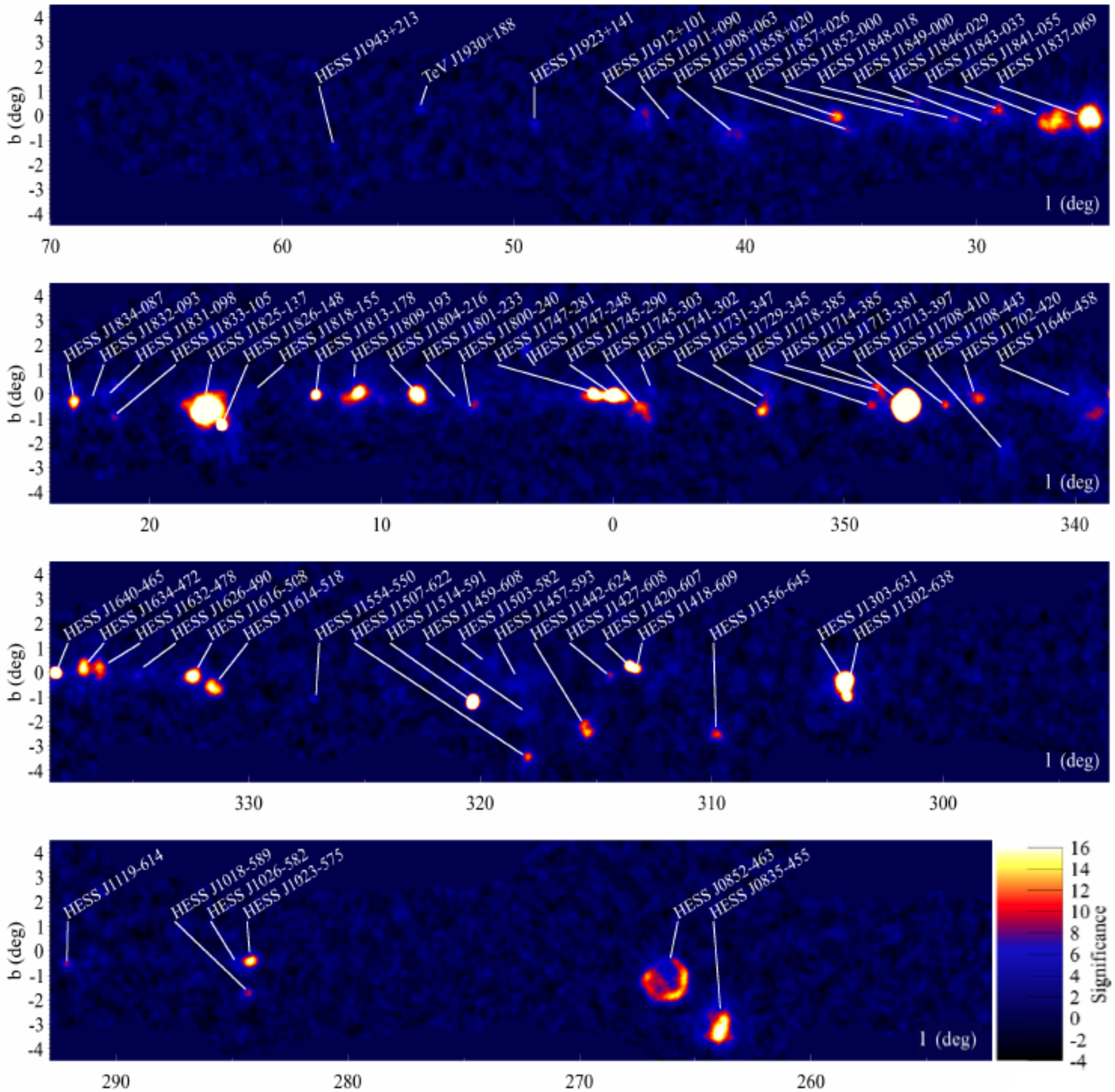


2FHL and TeVCat



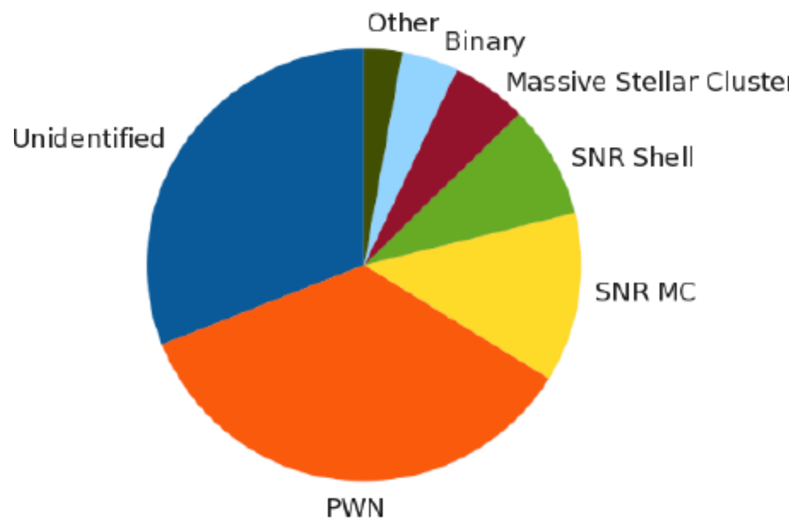


The HESS Galactic plane survey



Galactic latitudes |b|<4º and longitudes from 250º to 70º (i.e. $\Delta l = 180º$)

$\Longrightarrow \Delta\Omega = 0.45$ sr



ICRC 2013 - 1307.4690

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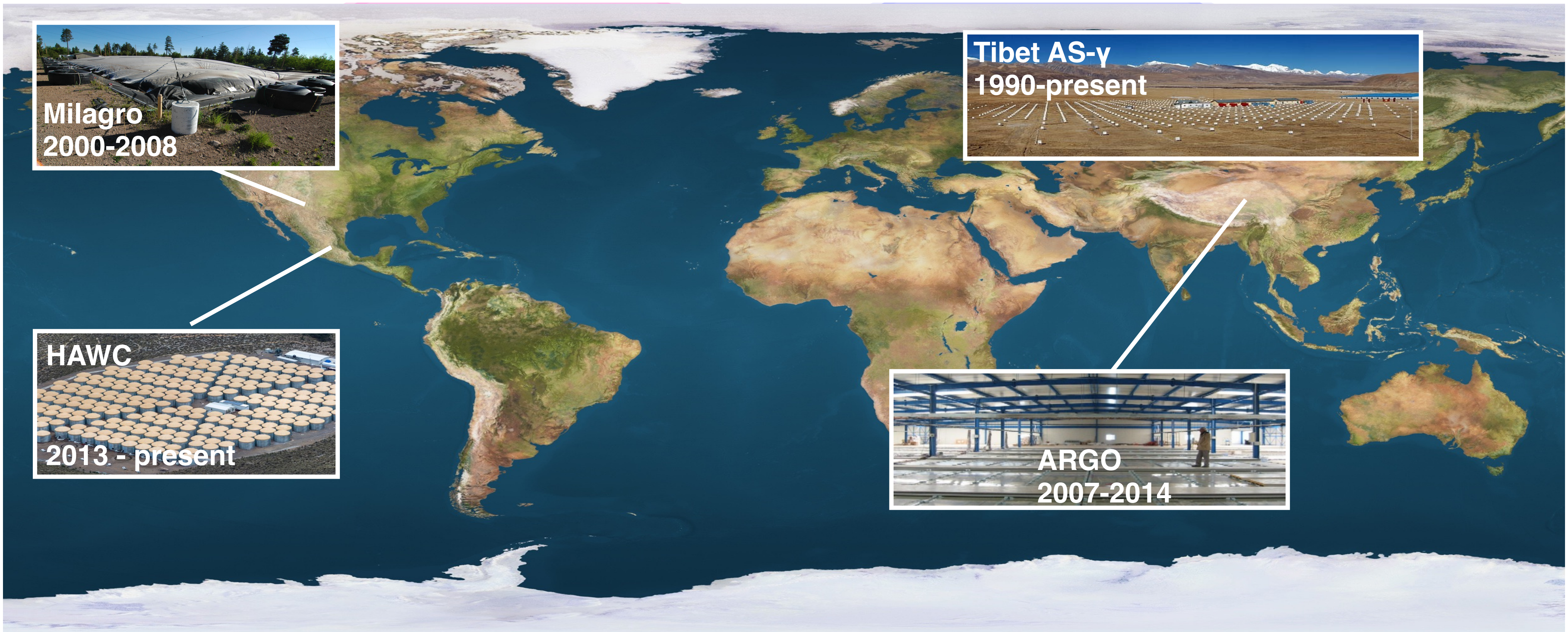
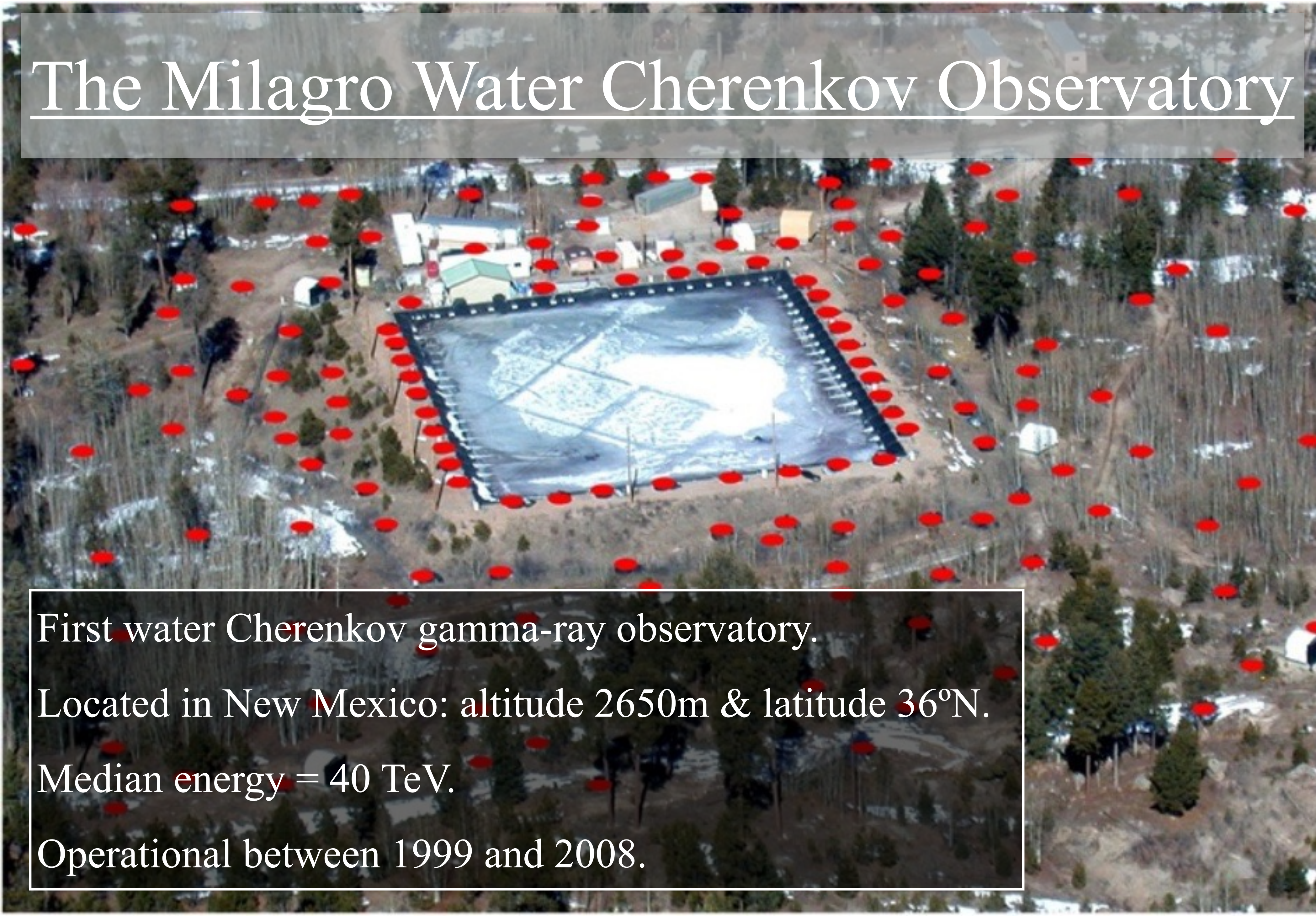
γ-ray observatories: air shower arrays



Ideal to monitor and map sizable portions of the sky.

They can perform unbiased partial sky surveys

The Milagro Water Cherenkov Observatory

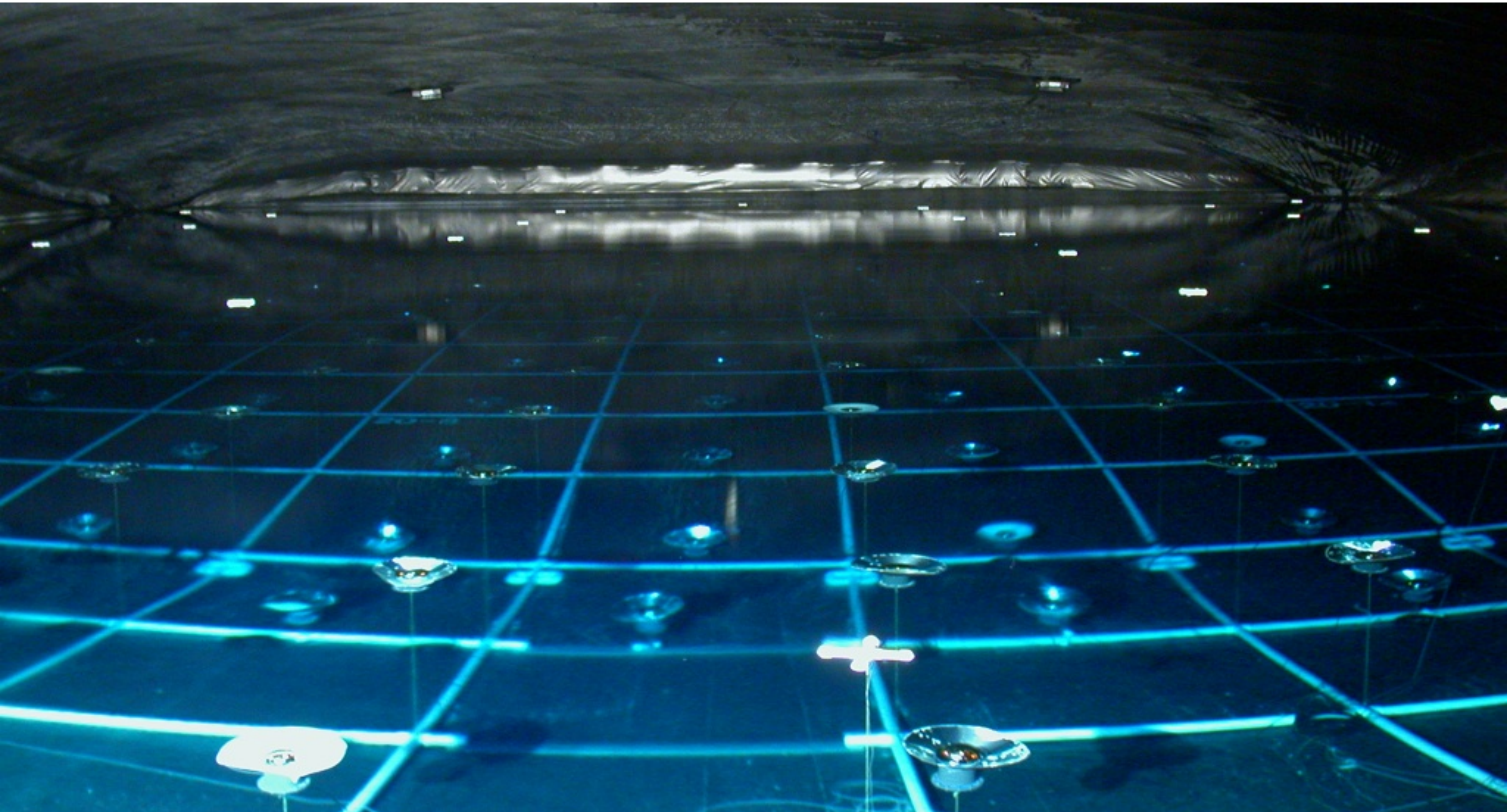


First water Cherenkov gamma-ray observatory.

Located in New Mexico: altitude 2650m & latitude 36ºN.

Median energy = 40 TeV.

Operational between 1999 and 2008.



Plane of 2GeV Photons at 20°

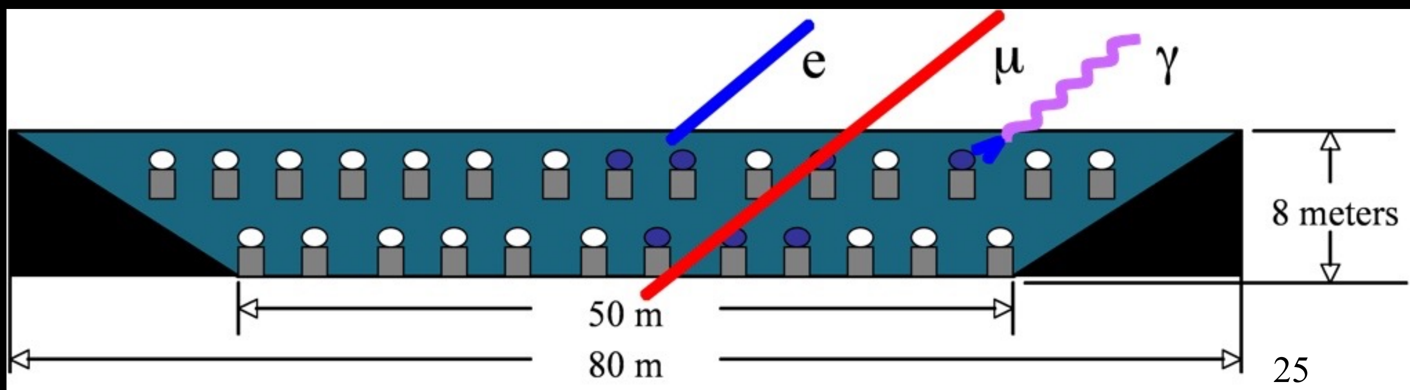
Side View

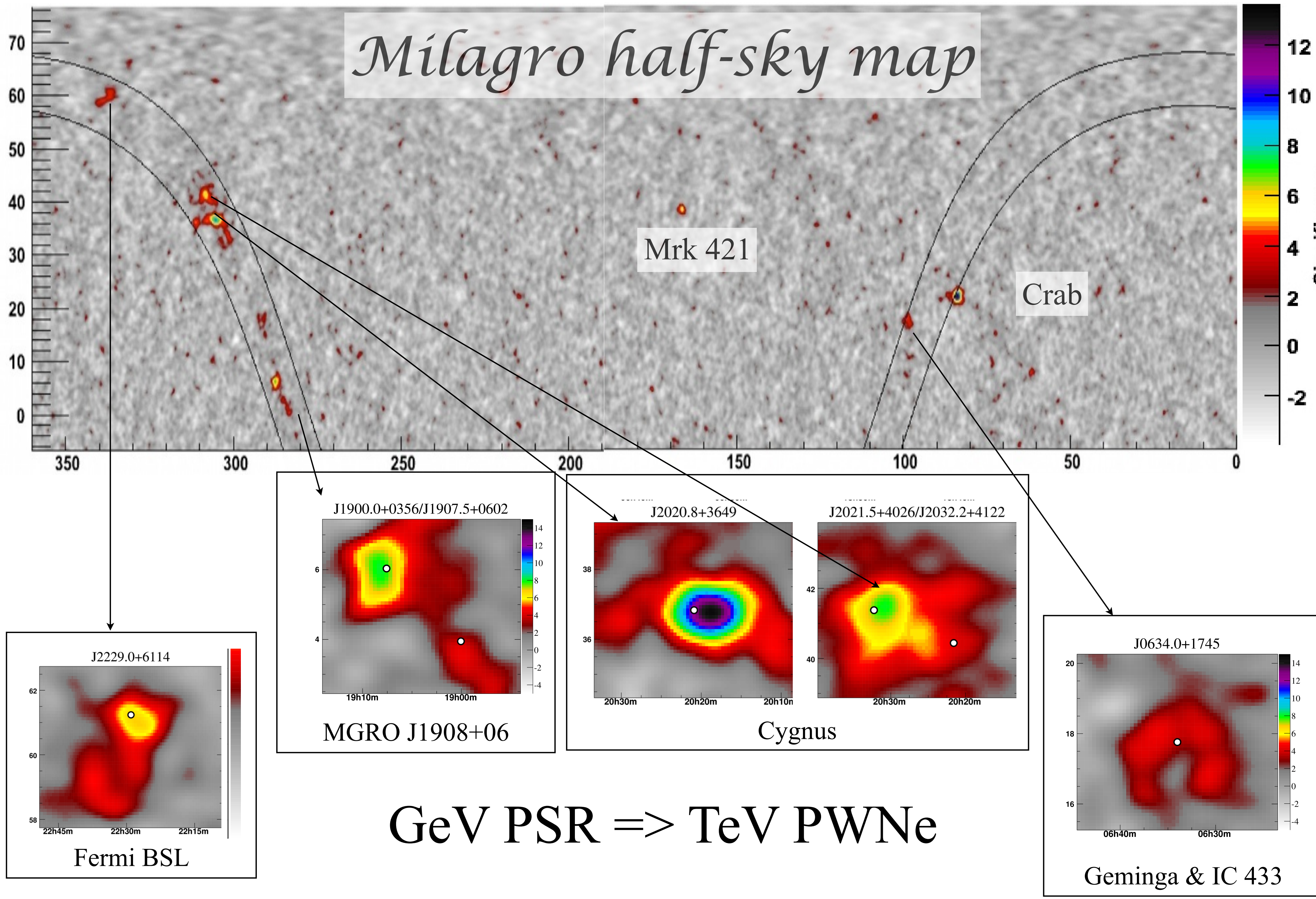
Again notice the detailed structure of the showerfront in the pond, and the very deep penetration. The refraction of this showerfront is delayed until very deep in the pond due to the penetration of the energetic gamma photons.

Red - electrons and positrons

Green - secondary gammas

Blue - Cherenkov Photons




Milagro half-sky map
Mrk 421
Crab
Significance
J2229.0+6114
Fermi BSL
J1900.0+0356/J1907.5+0602
MGRO J1908+06
J2020.8+3649
J2021.5+4026/J2032.2+4122
Cygnus
J0634.0+1745
Geminga & IC 433
GeV PSR => TeV PWNe

The High Altitude Water Cherenkov detector

Second generation WC γ-ray observatory - built from MILAGRO experience.

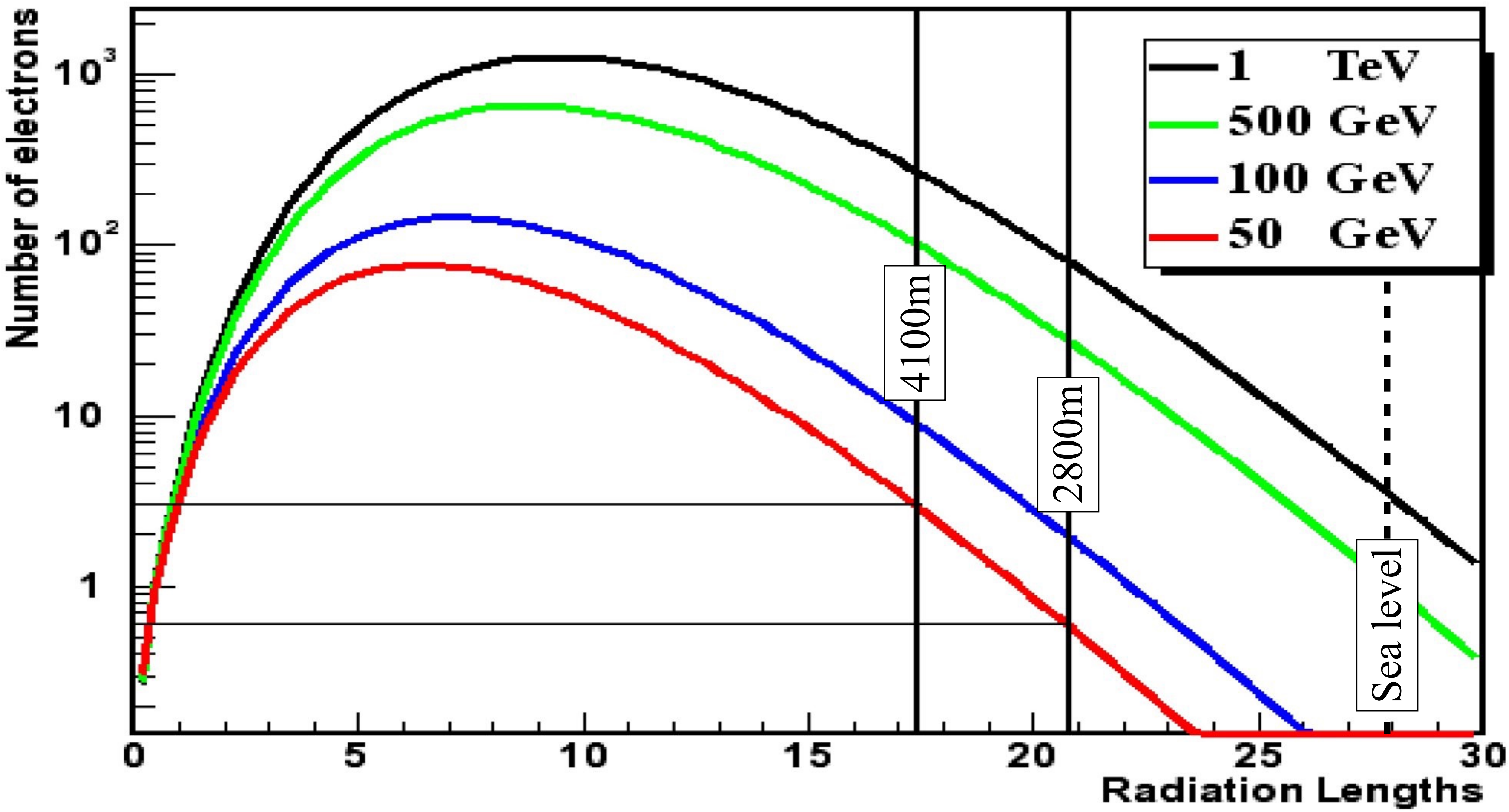
To be located above 4000m [Sierra Negra: 4100m and latitude 19ºN].

- 4 × larger dense sampling region (22,000m^2)
- 10 × larger muon detection area (22,000m^2)
- Optical isolation of detector elements
- 15 × more sensitive than Milagro

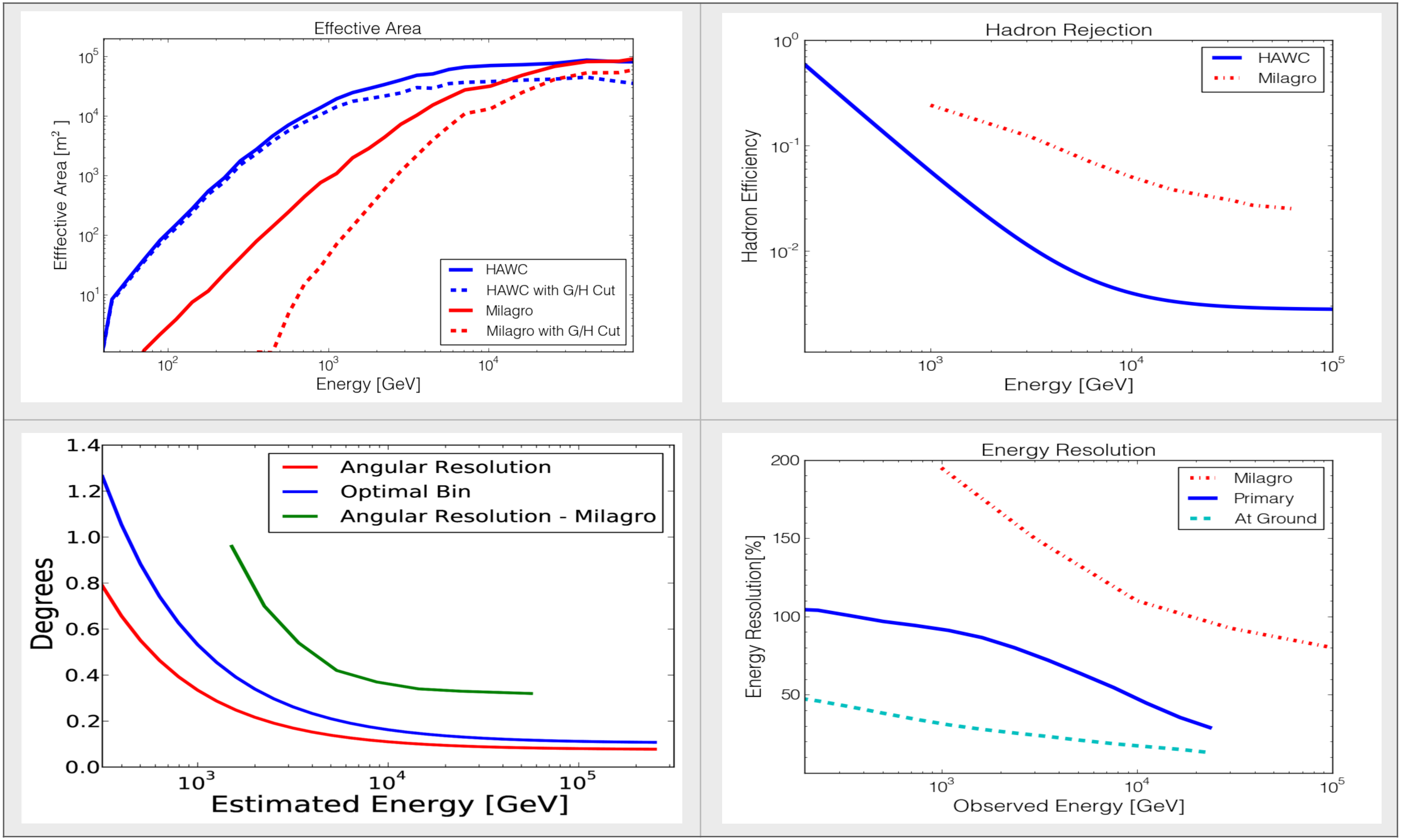
Energy range 100 GeV - 100 TeV :: also cosmic-ray detector.

FOV: 1/6 of the sky instantaneous => scans 2/3 of the sky each sidereal day.

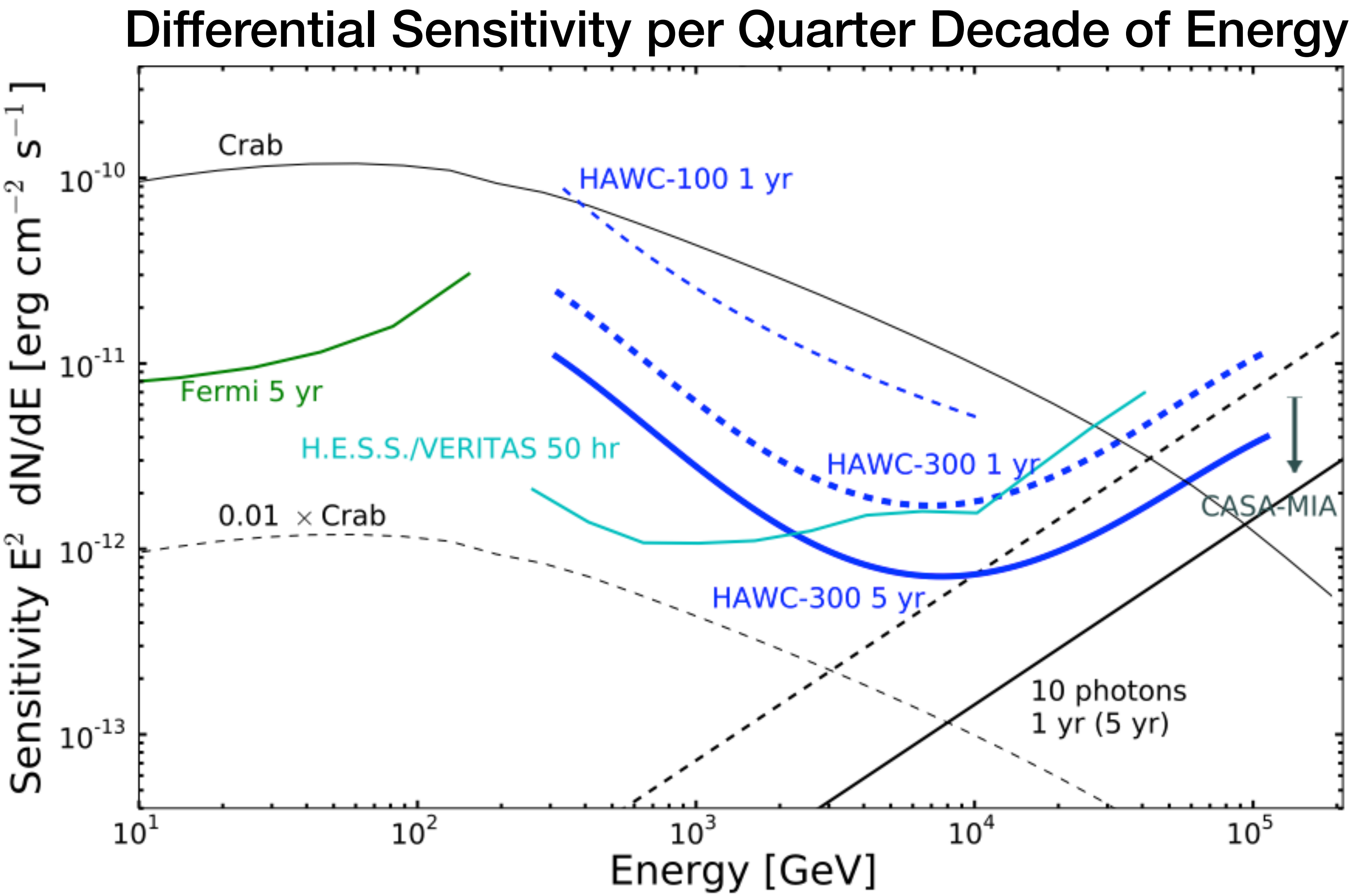
The atmosphere is part of the detector



Performance



Differential sensitivity



http://arxiv.org/abs/1306.5800 Astroparticle Physics 2013

Sensitivity & Field of View

Transit instrument

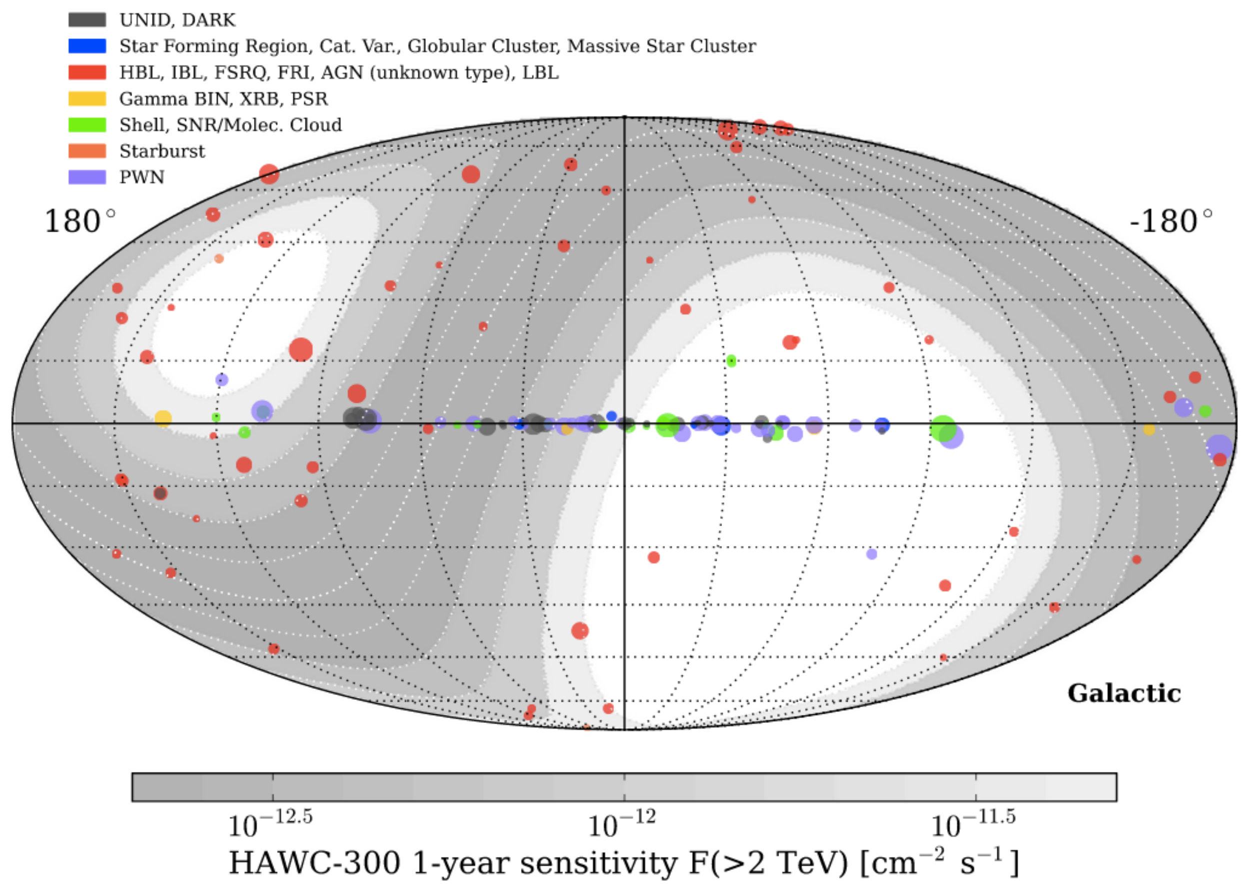
FOV = 1.8 Sr

HAWC to scan 2/3 of the celestial sphere every sidereal day to a depth of 1 Crab @ 5σ:

➡ transient events

➡ extended diffuse sources

➡ 60 mCrab / sqrt(year)



HAWC science

- Partial all-sky mapping:
  - deep mapping of 2/3 of the sky and of 2/3 Galactic plane.
  - Cosmic-ray anisotropies.
- γ-ray transient sources: AGNs, GRBs, PBHs, Galactic transients, Galactic Center.
- Mapping and characterizing extended γ-ray sources: SNR, PWN, diffuse.
- Solar events; dark matter searches.
- Multiwavelength & multimessenger synergies.

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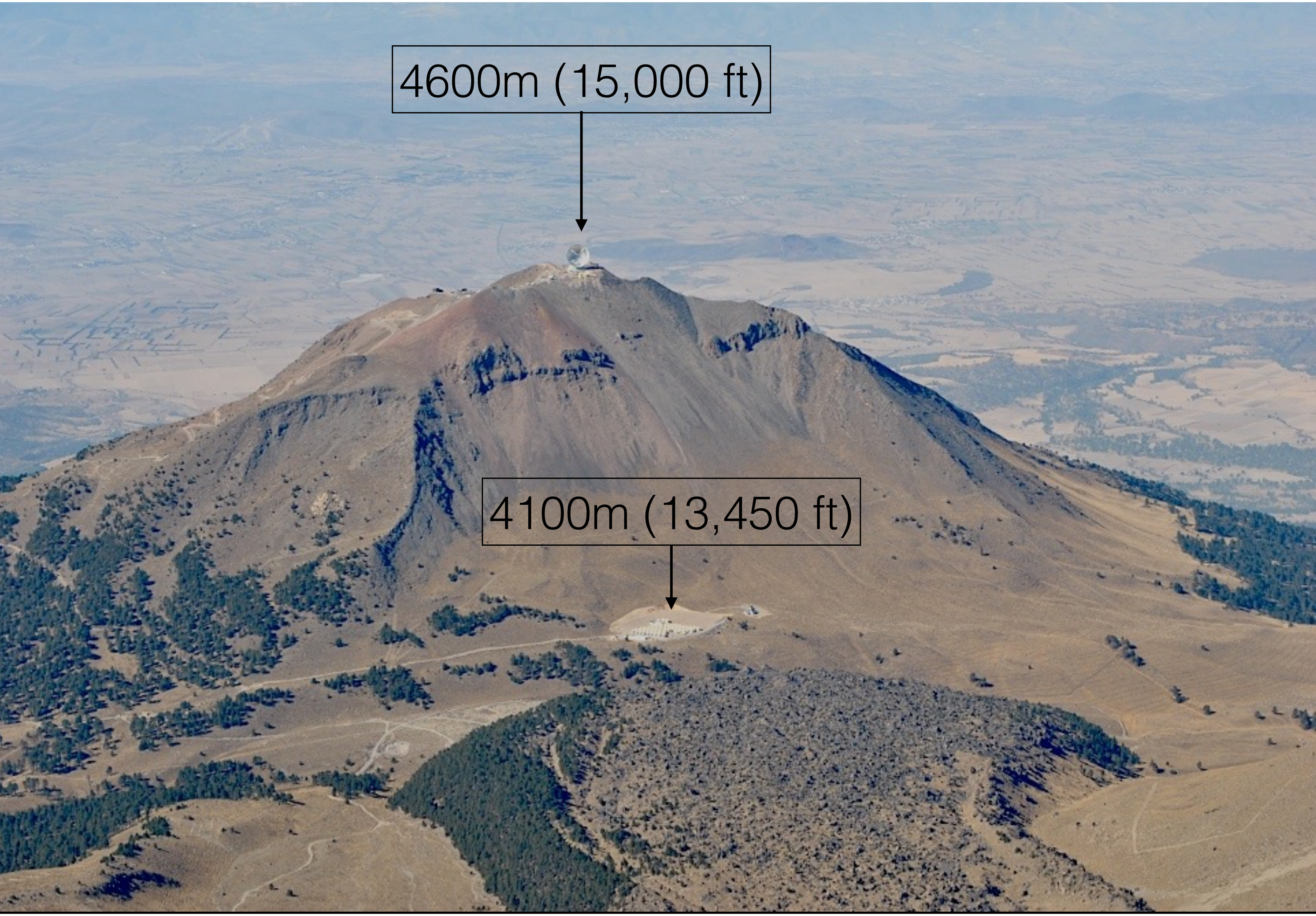

4600m (15,000 ft)
4100m (13,450 ft)

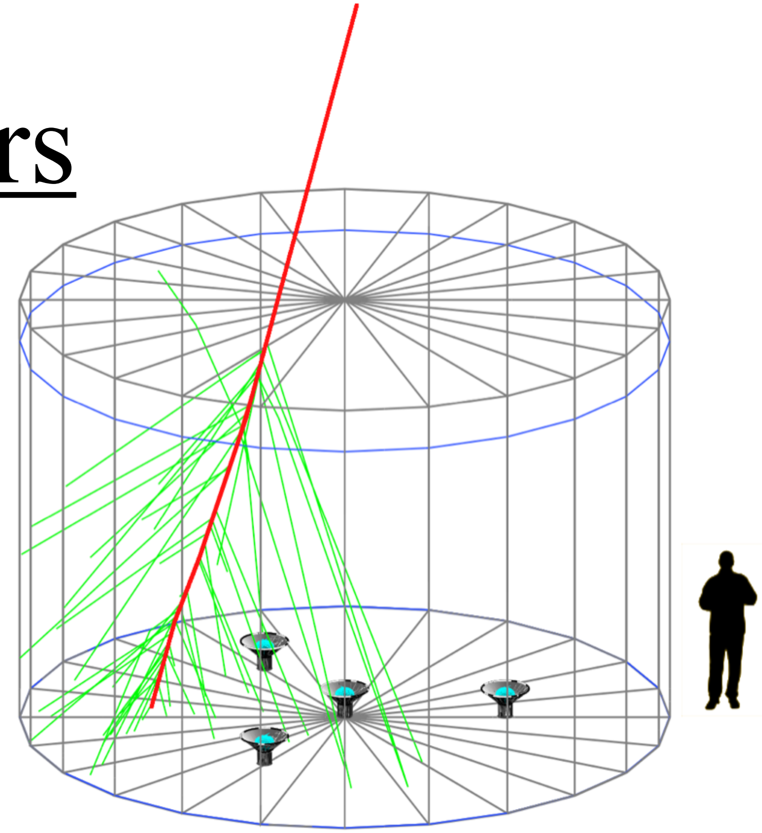
HAWC construction

February 2012 to December 2015


12/31/2014
Observatorio de Rayos Gama HAWC
Image © 2015 DigitalGlobe
Google earth
2003
Fecha de las imágenes: 12/31/2014 lat. 18.994865° long. -97.307674° elev. 4097 m alt. ojo 4.51 km


Mon Apr 22 00:02:58 GMT 2013

Water Cherenkov Detectors

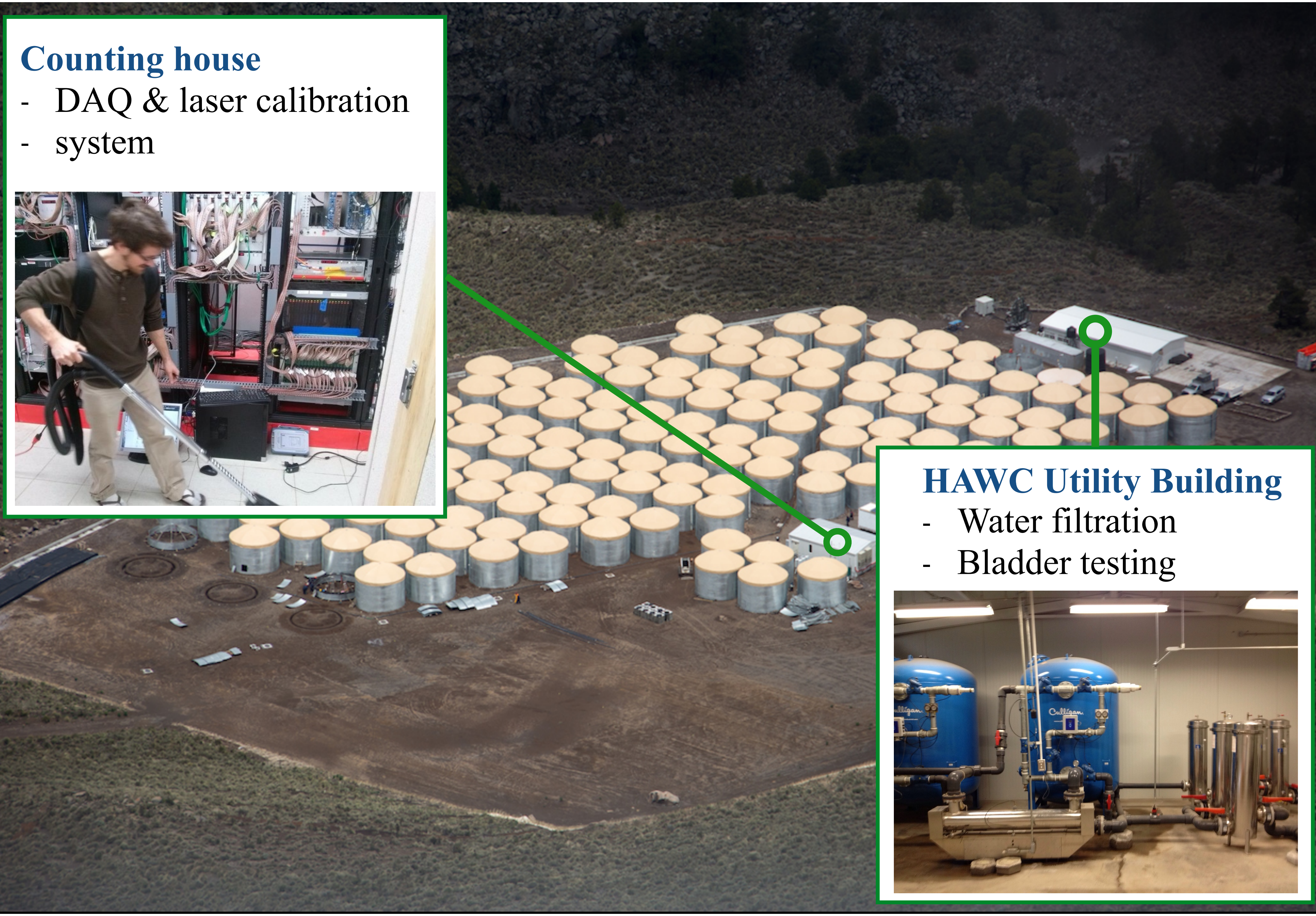


- Each WCD is filled with 180,000 liters of water.
- Water is treated to ensure maximum transparency.
- Each WCD has 3(8") + 1(10") PMT: fast response and good QE to Cherenkov light (blue to UV).
- Optical fiber for calibration.
- Every WCD is connected to the central counting house.


HAWC-100
Sept 2013

HAWC-100
Sept 2013

HAWC Utility Building
- Water filtration
- Bladder testing

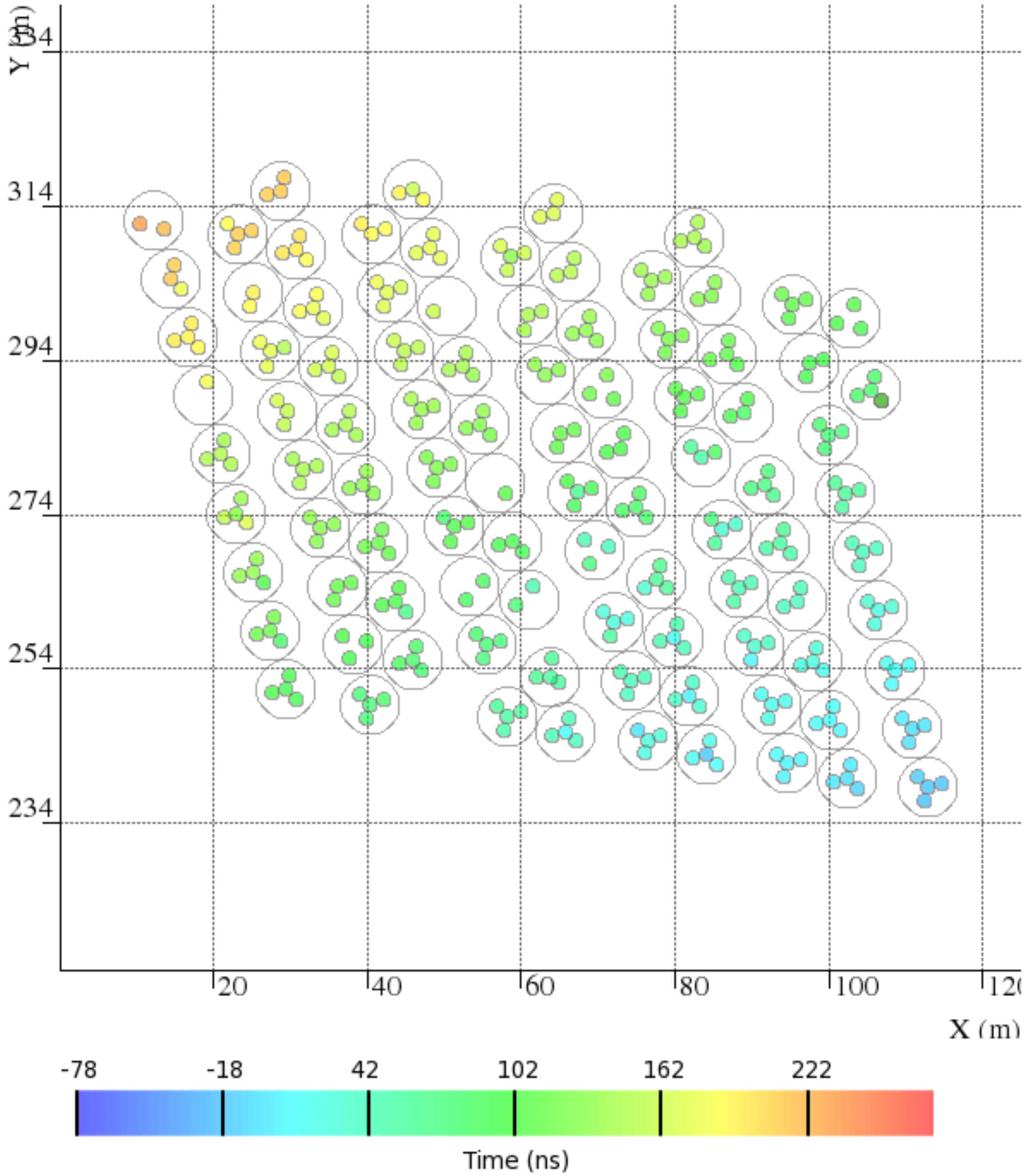


Counting house

- DAQ & laser calibration
- system

HAWC Utility Building

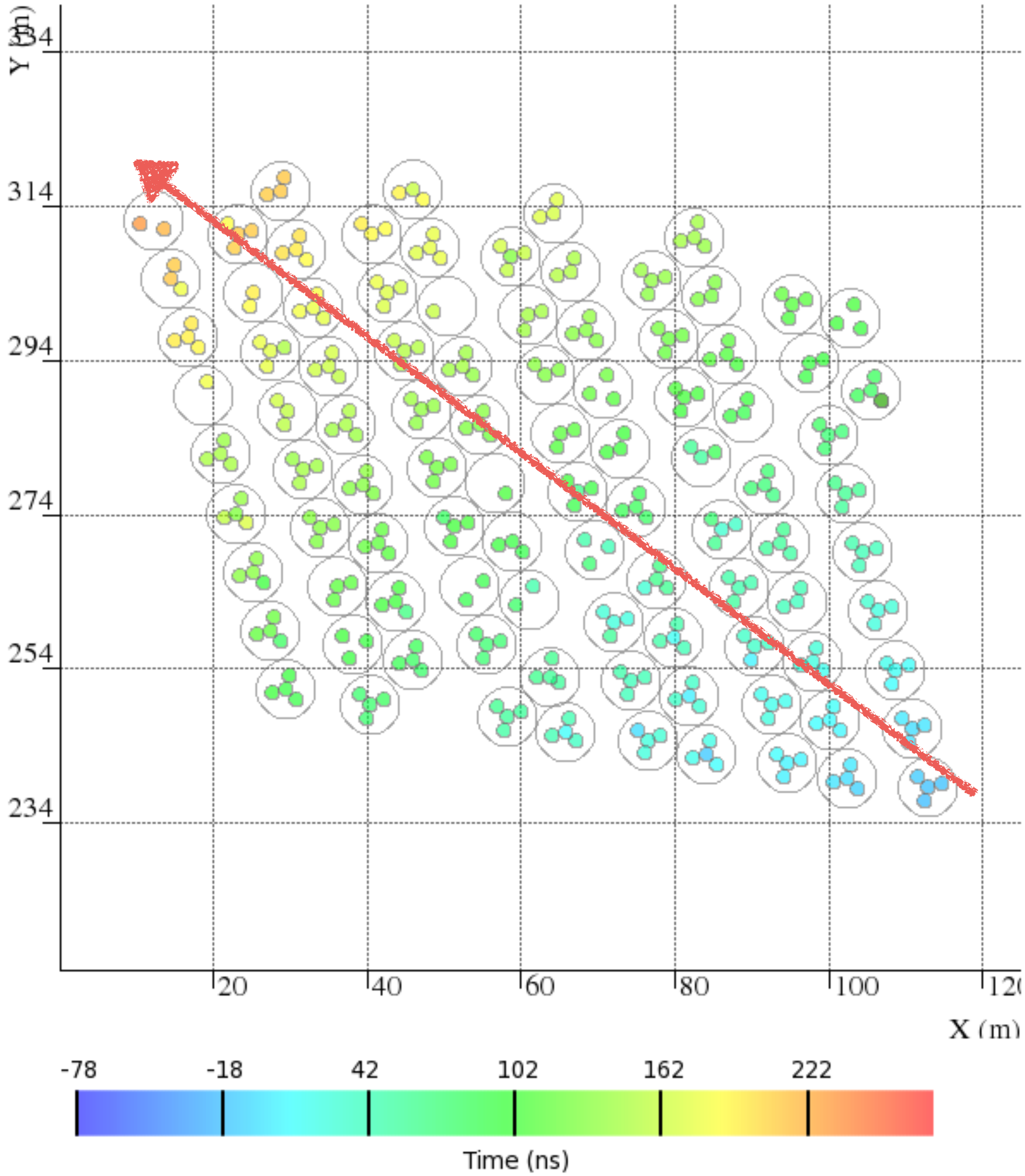
- Water filtration
- Bladder testing



Timing

The relative timing of signals allows to determine the arrival direction of primary particles in the sky.

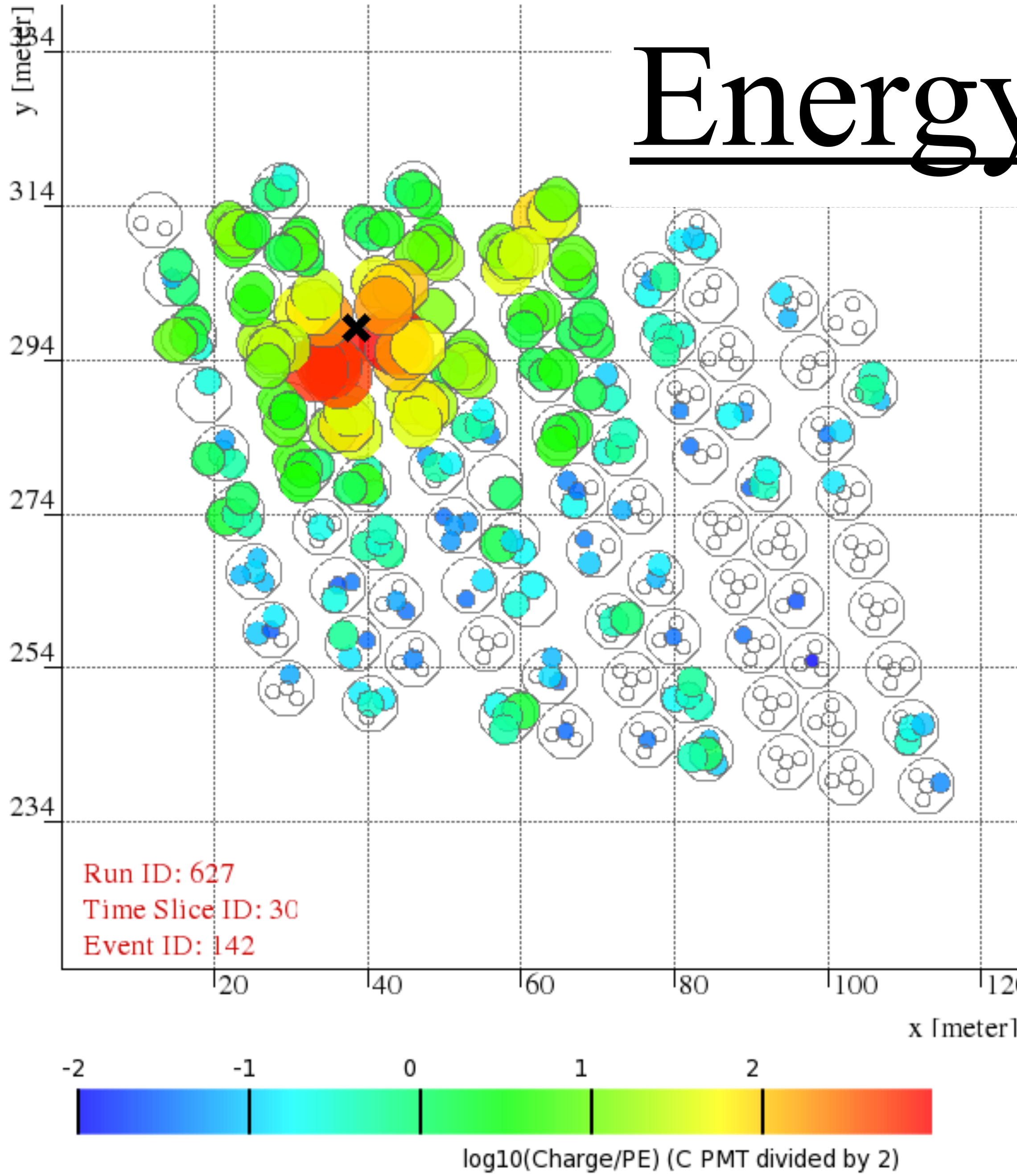
Timing



Tank spacing is 25 to 50 light-ns.

Arrival times are fitted to a curved shower front ⟹ timing residuals below 1ns.

Energy deposition

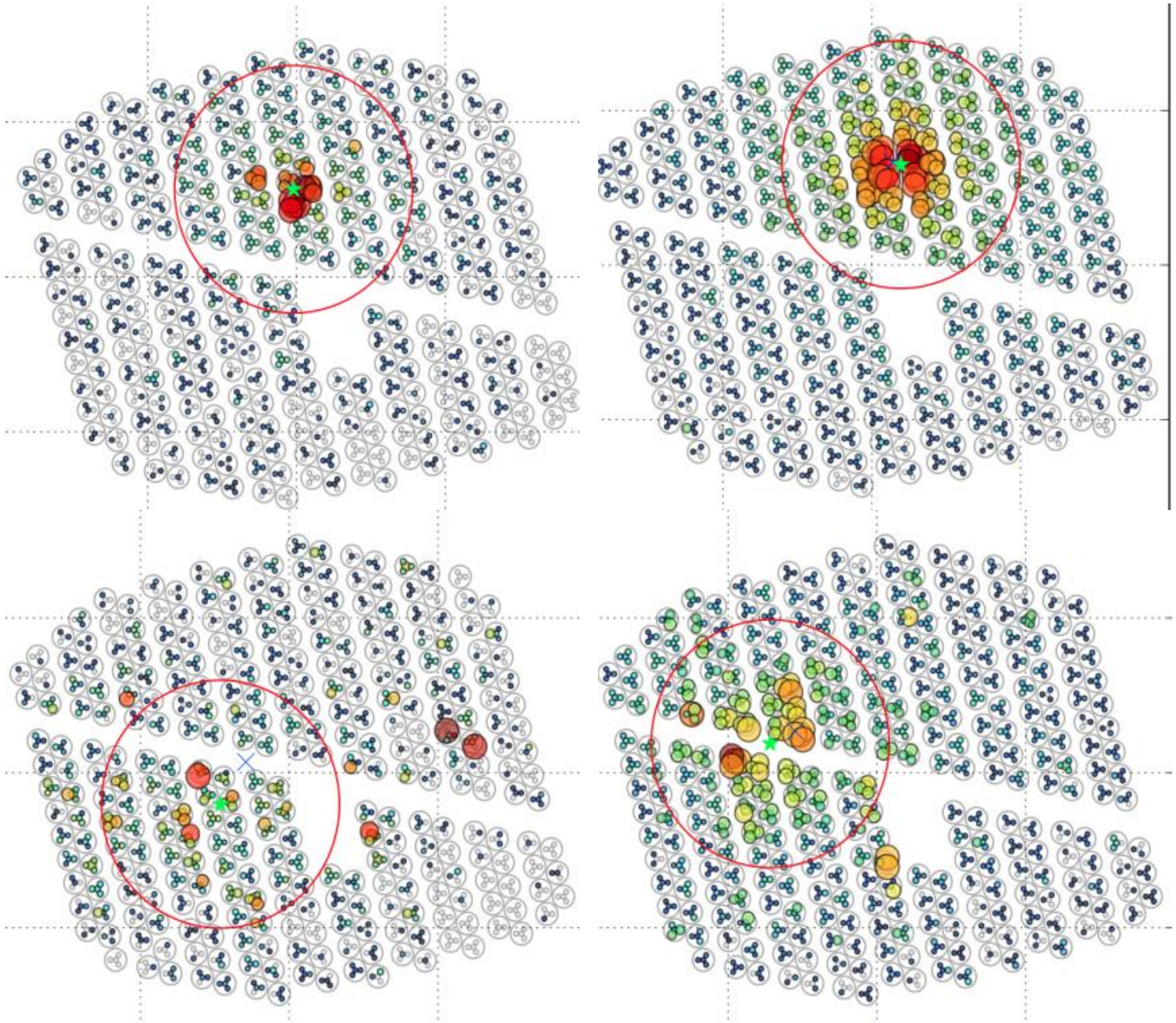


- Record of individual pulses of light for each PMT:
  - Energy estimation.
  - γ/hadron discrimination.
- Must locate shower core and model energy deposits according to standard shower models (NKG) and simulations of the response of HAWC.

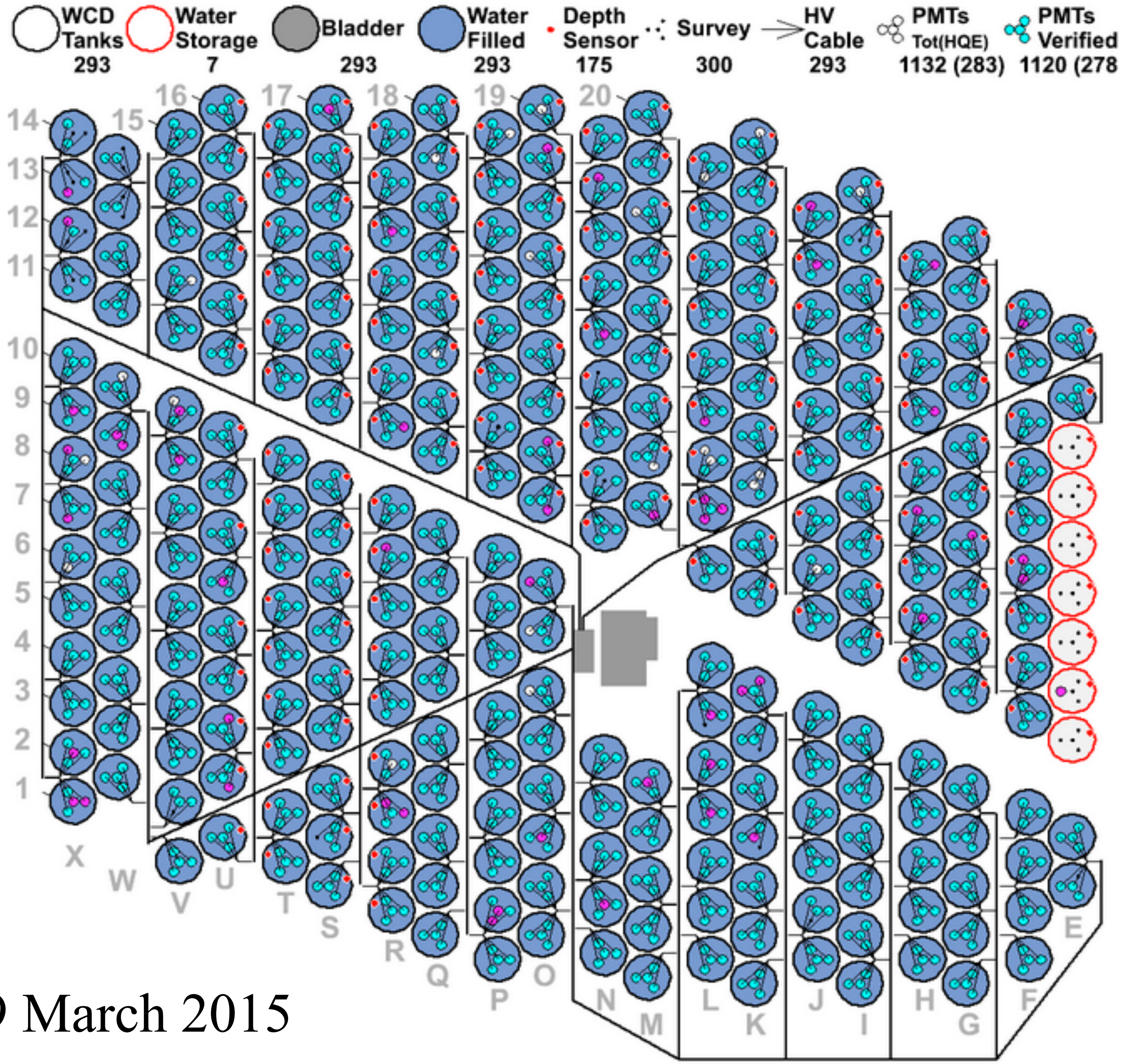
γ / hadron discrimination

γ-ray

Hadron



E



HAWC - 19 March 2015


HAWC
HAWC 300
Full operations
DATE: 03/20/2015
TIME: 12:26:30
SONY

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HAWC phases

VAMOS	October 2011	Scientific verification
HAWC 30	September 2012	Early science data
HAWC 111	August 2013	Beginning of formal science operations
HAWC 250	November 2014	Upgrade to quasi-full detector
HAWC 300	March 2015	Inauguration and beginning of full operations

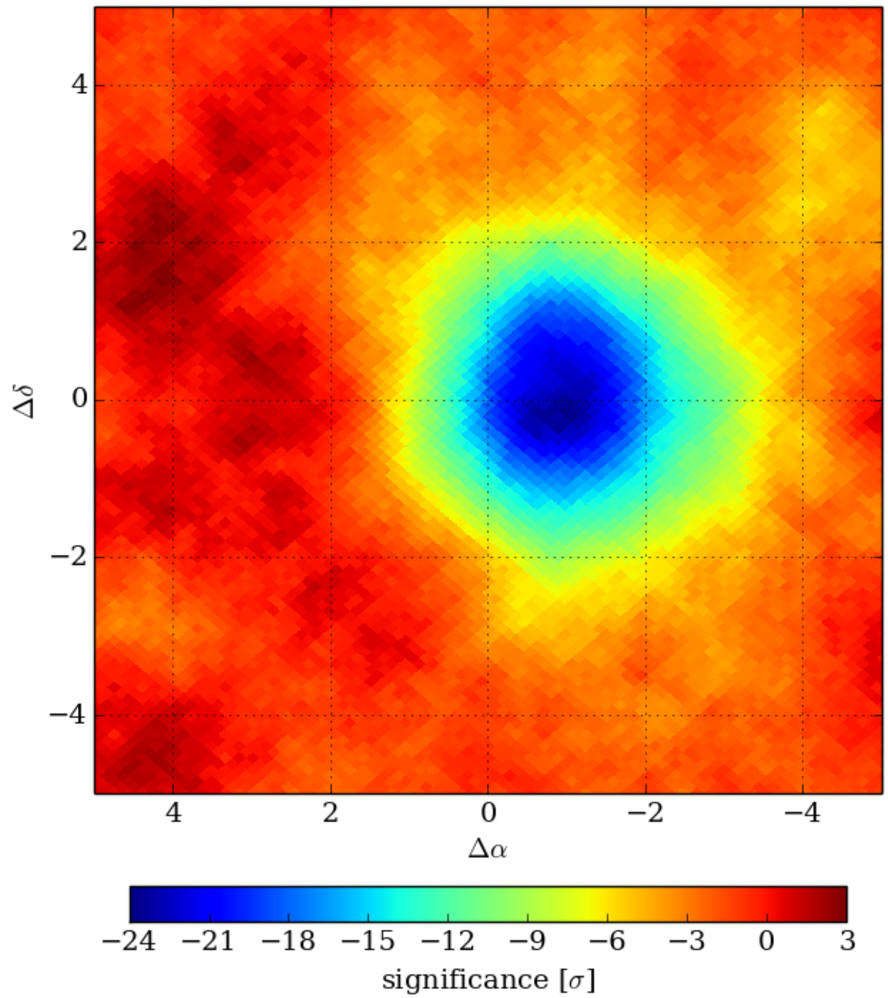
HAWC data

Data set	Span	Crab signal
HAWC 111	283 days	1.4σ / √day
HAWC Pass 3	200 days	3.1σ / √day
HAWC Pass 4	> 1 year	> 5σ / √day

- HAWC triggers at 20kHz on air showers, mainly cosmic-rays.
  - Data rate: 20MB/s = 1.7TB/day = 700 TB/year.
- HAWC data centers at ICN-UNAM and UMD.
- To reconstruct and analyze data in real time (seconds after trigger) requires 200 cores.
- As calibration and reconstruction improve, data are reprocessed with revised version of the analysis software [“Pass 4”].

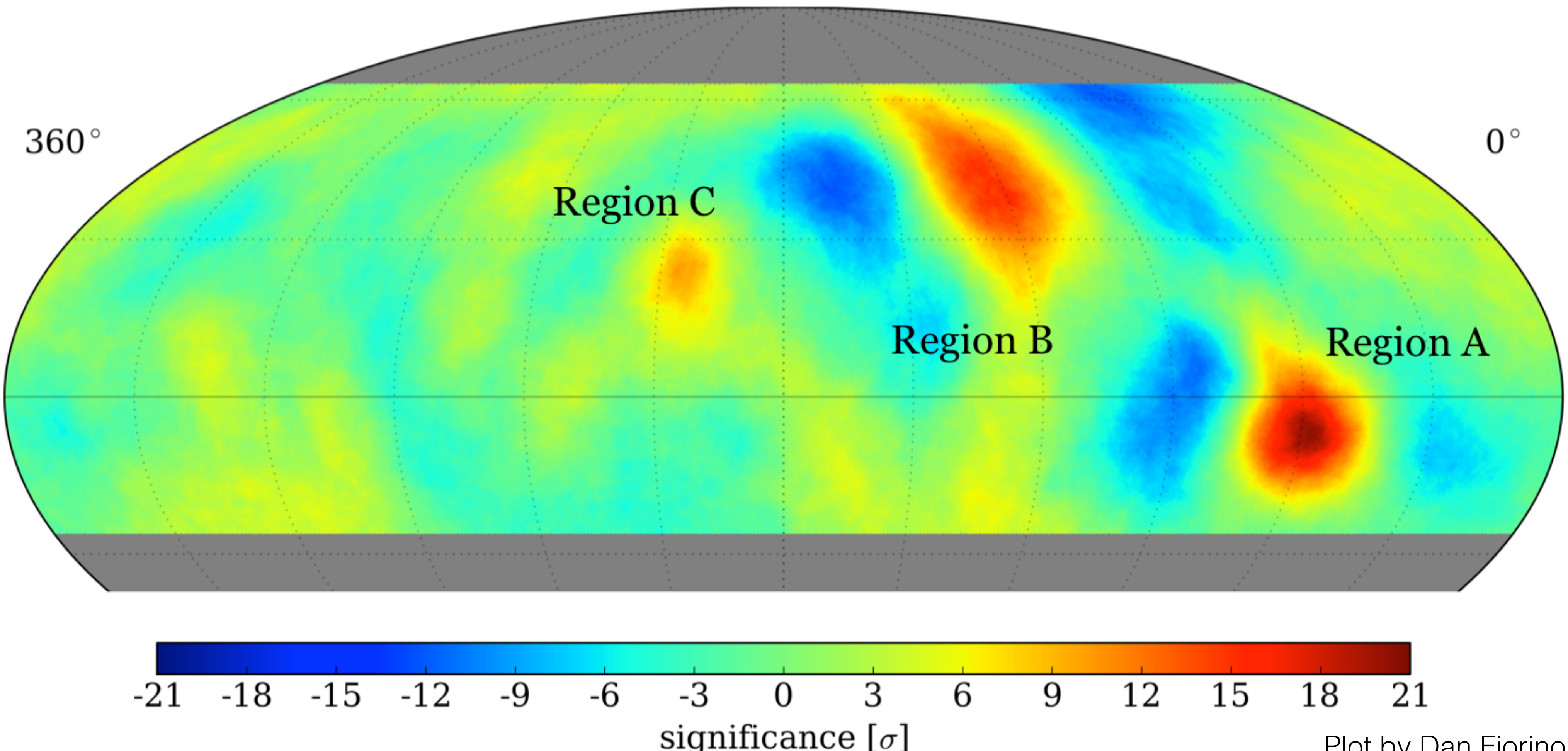
HAWC: cosmic rays - Moon shadow

- HAWC-95 and HAWC-111
- 12 June 2013 to 8 July 2014
- Full runs = contiguous 24hrs:
  - 181 days (4332 hours)
  - 85.6×10^9 events
- Median energy: 2 TeV
- Potential for $e^{\pm}$ flux measurements above 1 TeV.



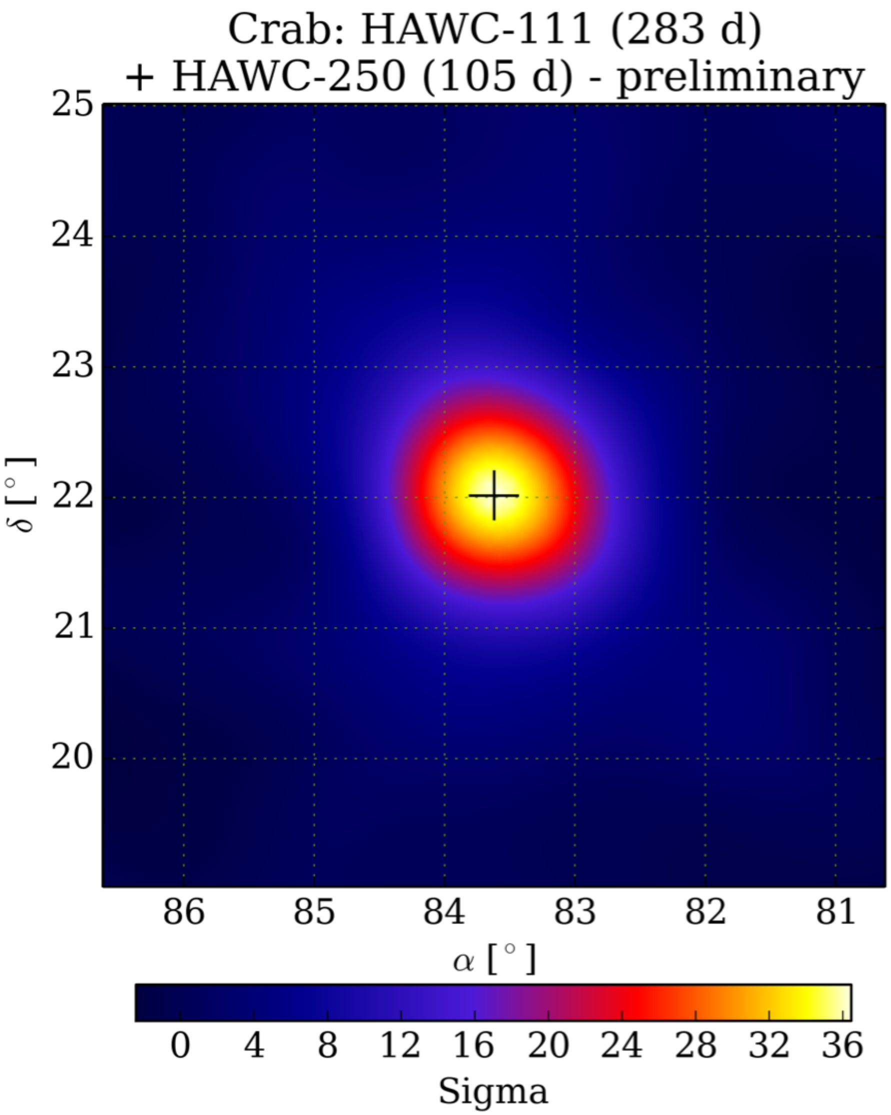
Abeysekara et al.
ApJ 796, 108 (2014)
astro-ph/1408.4085

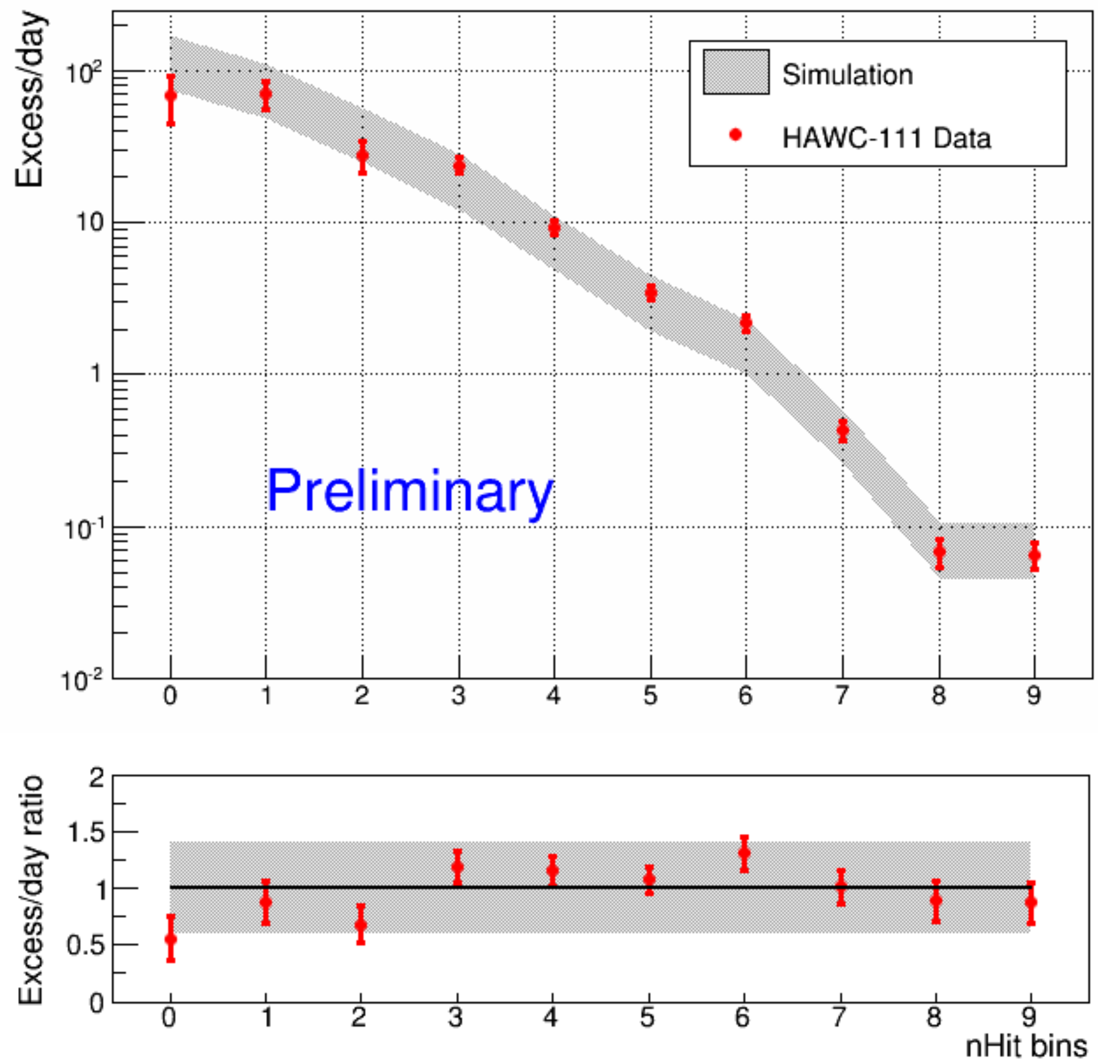
HAWC: cosmic rays - anisotropies



Plot by Dan Fiorino

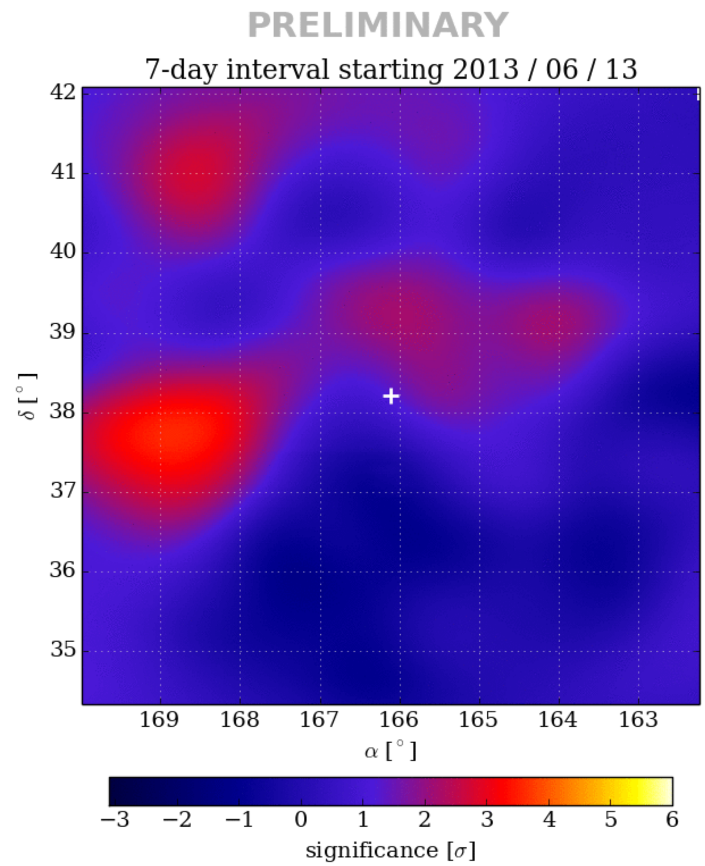
The Crab

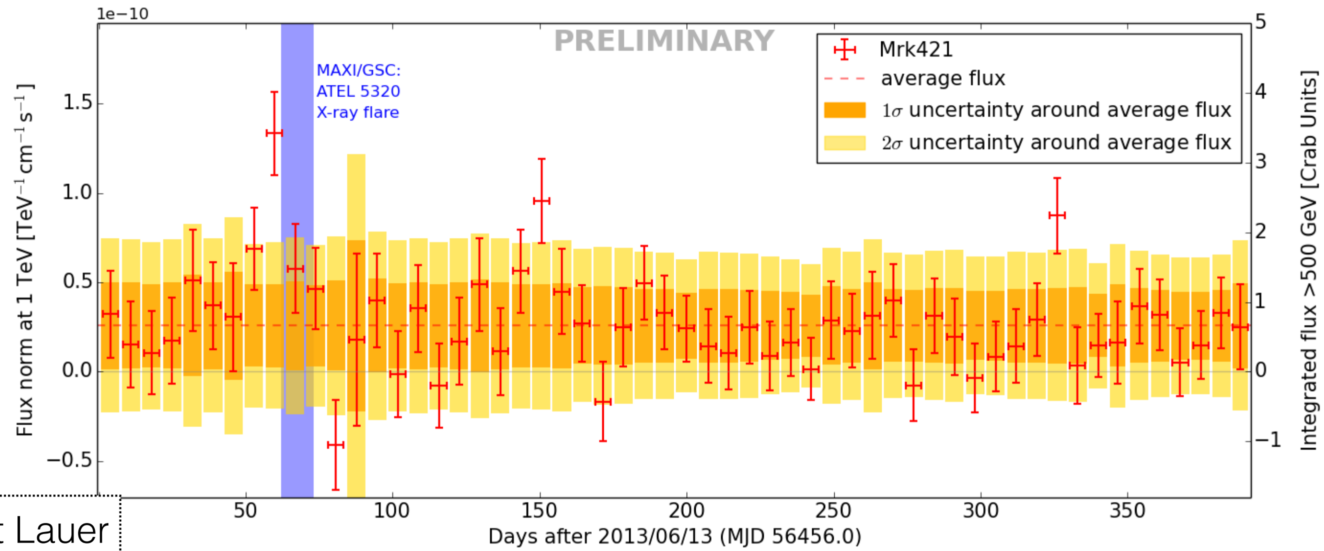

Crab: HAWC-111 (283 d)
+ HAWC-250 (105 d) - preliminary
25
24
23
22
21
20
δ [°]
86
85
84
83
82
81
α [°]
0
4
8
12
16
20
24
28
32
36
Sigma


Excess/day
Simulation
HAWC-111 Data
Preliminary
0 1 2 3 4 5 6 7 8 9
Excess/day ratio
nHit bins

Mrk 421

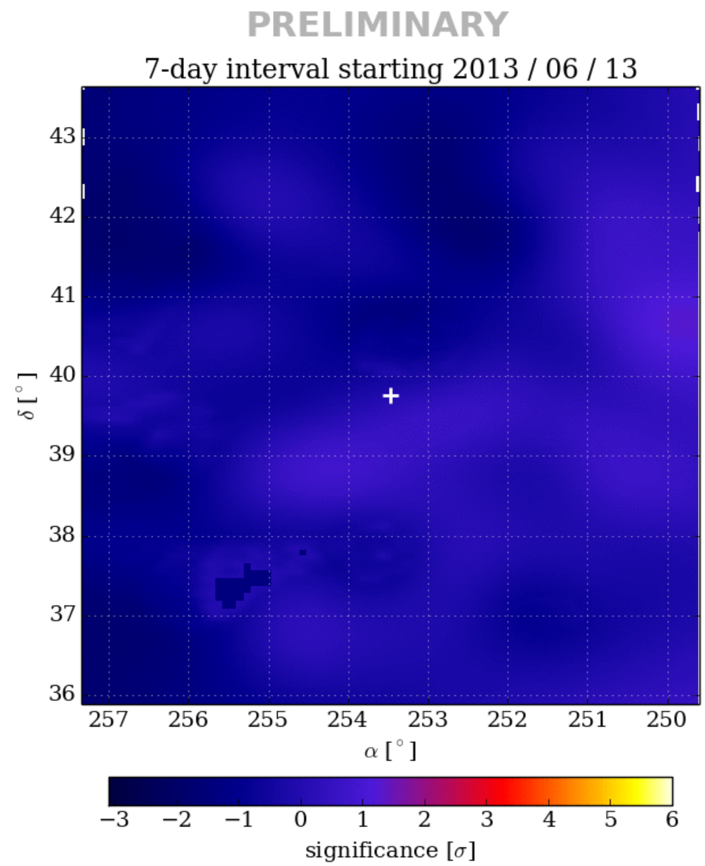
- Brightest quasar in the night sky.
- Nearby Bl Lac at z = 0.03.
- First extragalactic TeV source (Punch et al. 1992).
- Detected by Milagro.



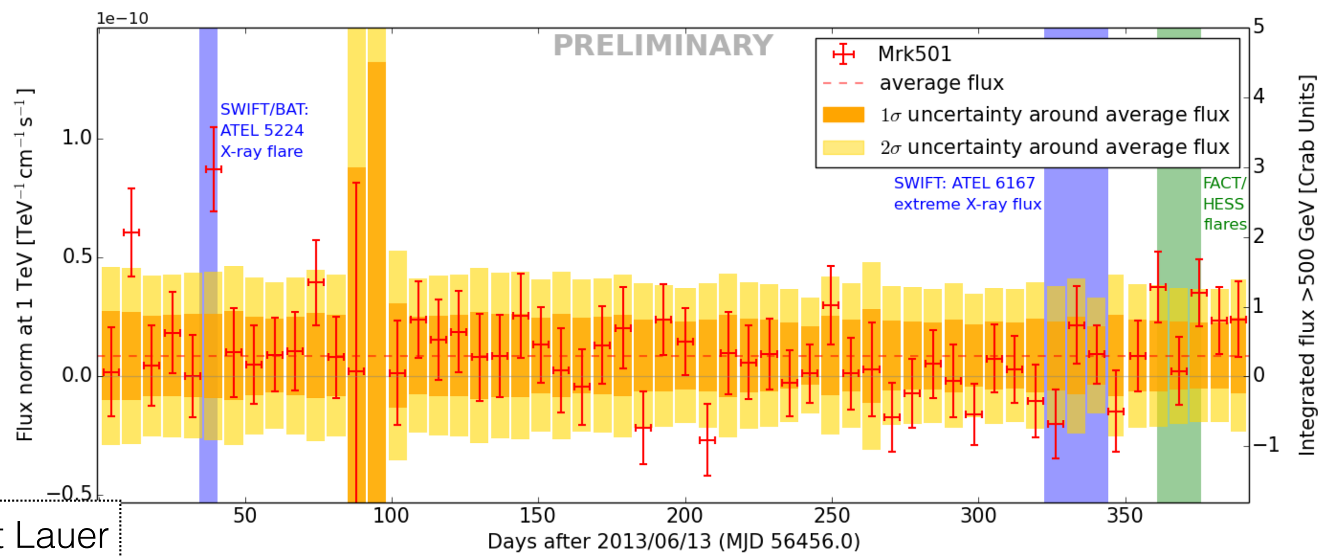


Animations and light curves by Robert Lauer

Mrk 501



- Nearby Bl Lac at z = 0.033.
- Highly variable TeV emission, with short timescales (Quinn et al. 1996).
- Marginal detection Milagro.



Animations and light curves by Robert Lauer

AGN & EBL

- HAWC to provide insight on AGN physics.
- HAWC limited to z≲0.3 horizon due to $\gamma\gamma\rightarrow ee$ interaction of γ-rays with the extragalactic background light.
- Axions can provide an explanation to TeV detections beyond EBL.

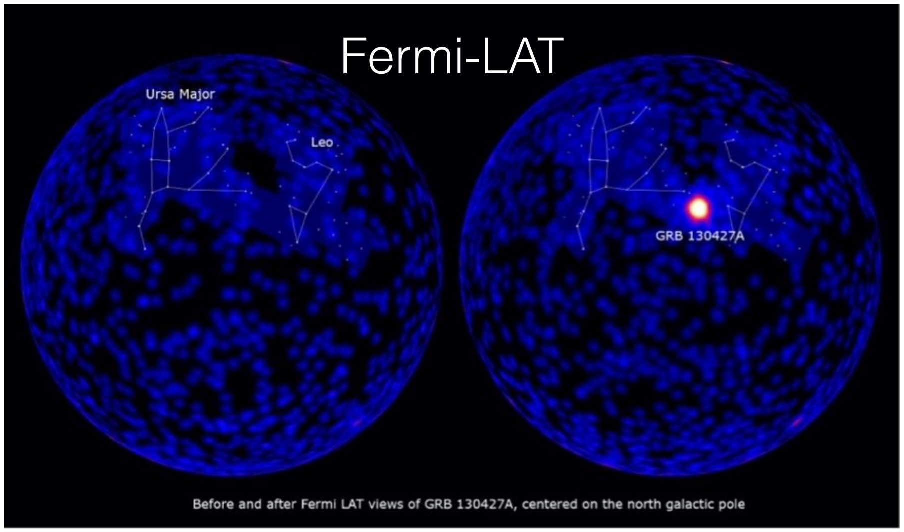
1FHL extragalactic sources potentially detectable with

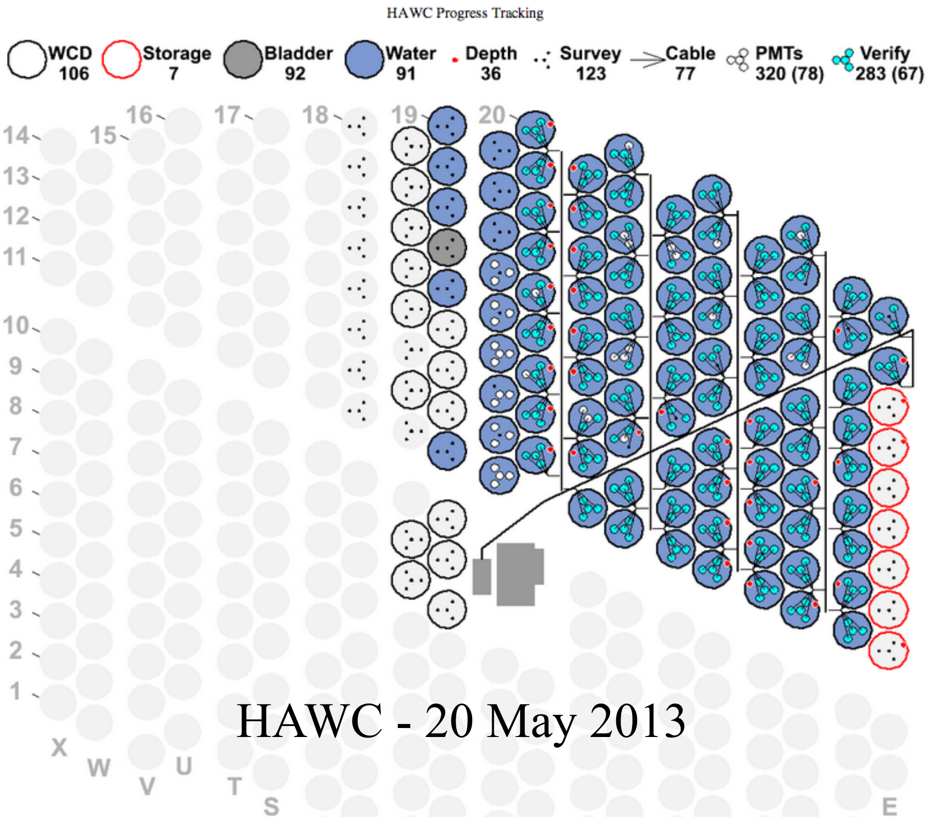
1FHL	Association	Type	z	Γ	σ / √yr
J0035.9+5950	1ES 0033+595	bzb	0.086	1.74 ± 0.18	6.02
J0152.6+0148	PMN J0152+0146	bzb	0.080	1.77 ± 0.34	4.85
J0316.6+4119	IC 310	rdg	0.019	1.31 ± 0.45	13.16
J0521.7+2113	VER J0521+211	bzb	0.108	1.97 ± 0.14	3.02
J0650.8+2504	1ES 0647+250	bzb	0.203	1.56 ± 0.18	10.25
J0816.3-1310	PMN J0816-1311	bzb	0.046	2.06 ± 0.27	3.19
J1104.4+3812	Mkn 421	bzb	0.031	1.91 ± 0.06	6.23
J1230.8+1224	M 87	rdg	0.004	1.25 ± 0.50	20
J1653.9+3945	Mkn 501	bzb	0.034	1.86 ± 0.10	5.30
J1728.3+5014	I Zw 187	bzb	0.055	1.67 ± 0.34	3.85
J2322.5+3436	TXS 2320+343	bzb	0.098	1.51 ± 0.32	9.68
J2347.0+5142	1ES 2344.514	bzb	0.044	1.48 ± 0.18	5.14

HAWC AGN/EBL sample by Sara Coutiño

Gamma-Ray Bursts

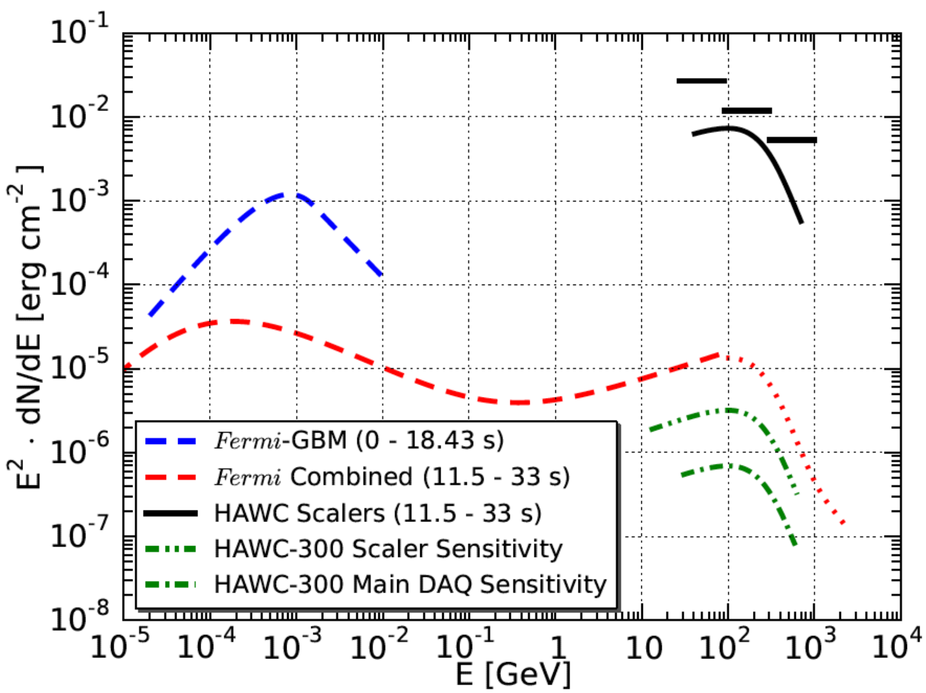
- GRB 130427A: one of the brightest and most energetic GRBs detected:
  - Bright optical counterpart: magnitude 7.4 and z=0.34.
  - Highest energy photon detected in any GRB: 95 GeV.
- Main HAWC DAQ not running at the time of burst.
- Zenith angle (57º) was too large for a HAWC detection.

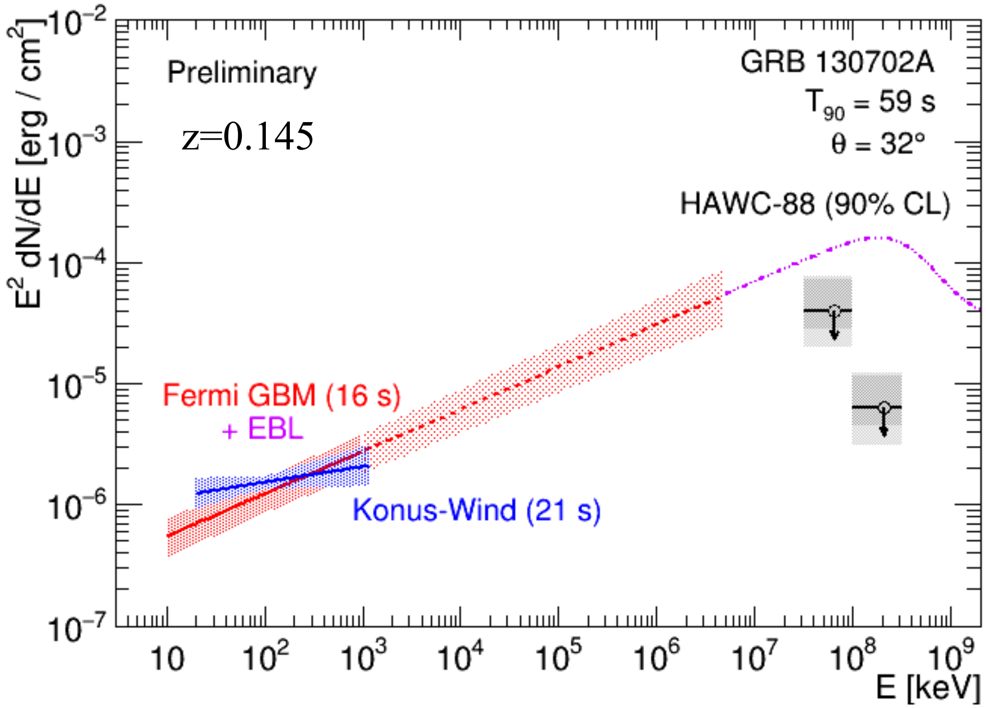




HAWC - 20 May 2013

Gamma-Ray Bursts

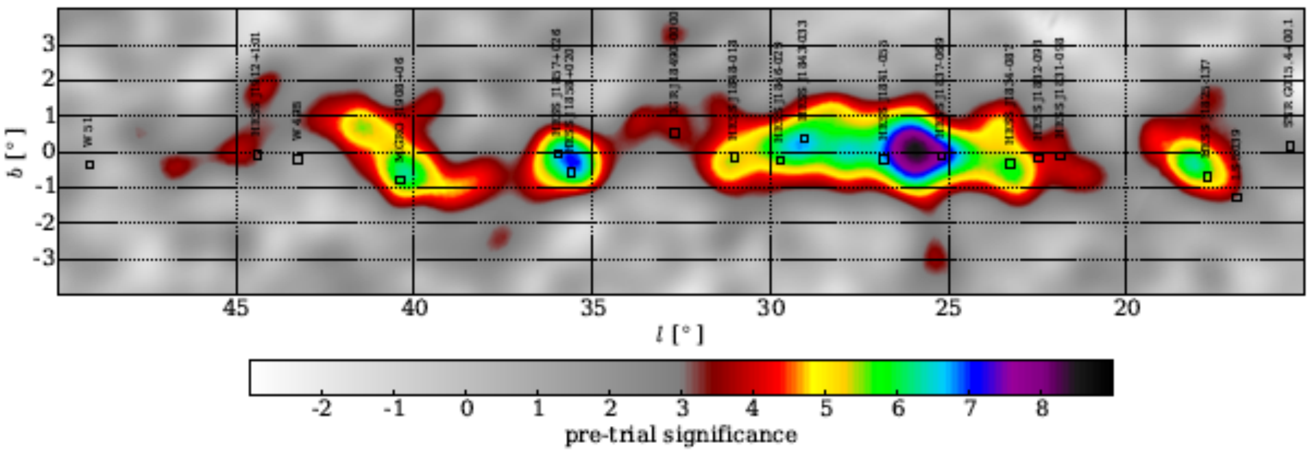




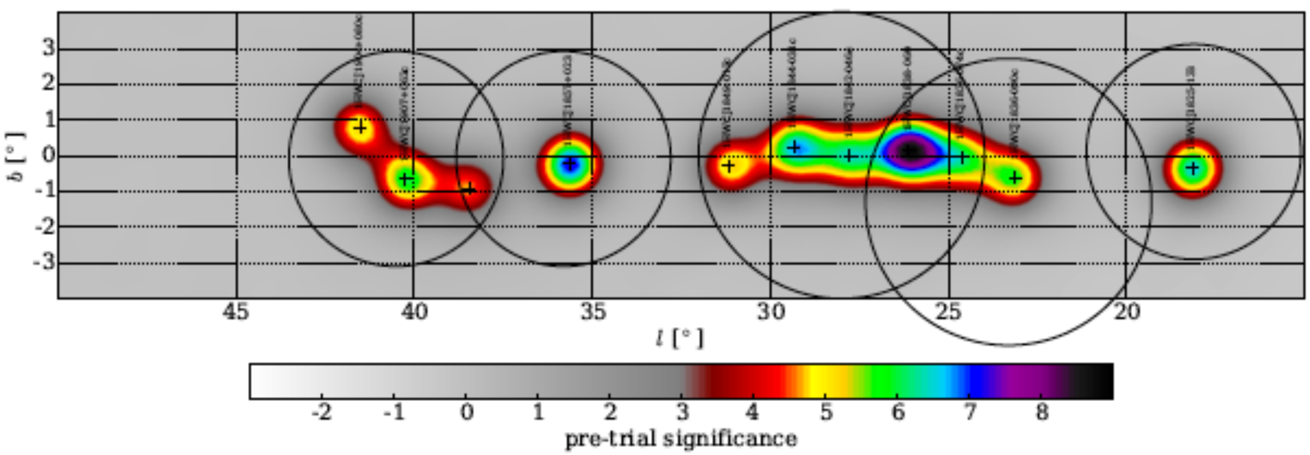
GRB 130427A
Abeysekara et al., ApJ 800, 78 (2015)

Kathryne Sparks Woodle
APS 2015 presentation

HAWC-111 on the Galactic Plane

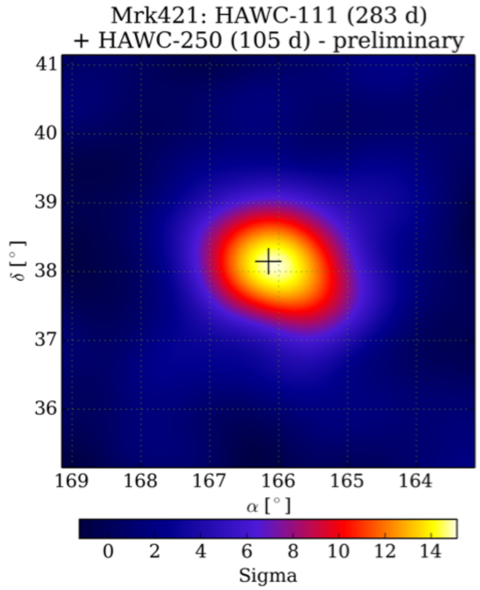


- Dedicated point source analysis on Galactic region: +15º < *l* < +50º and |*b*|< 4º.

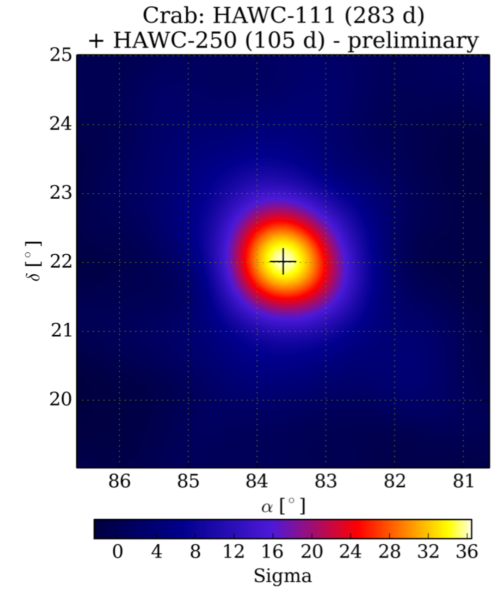


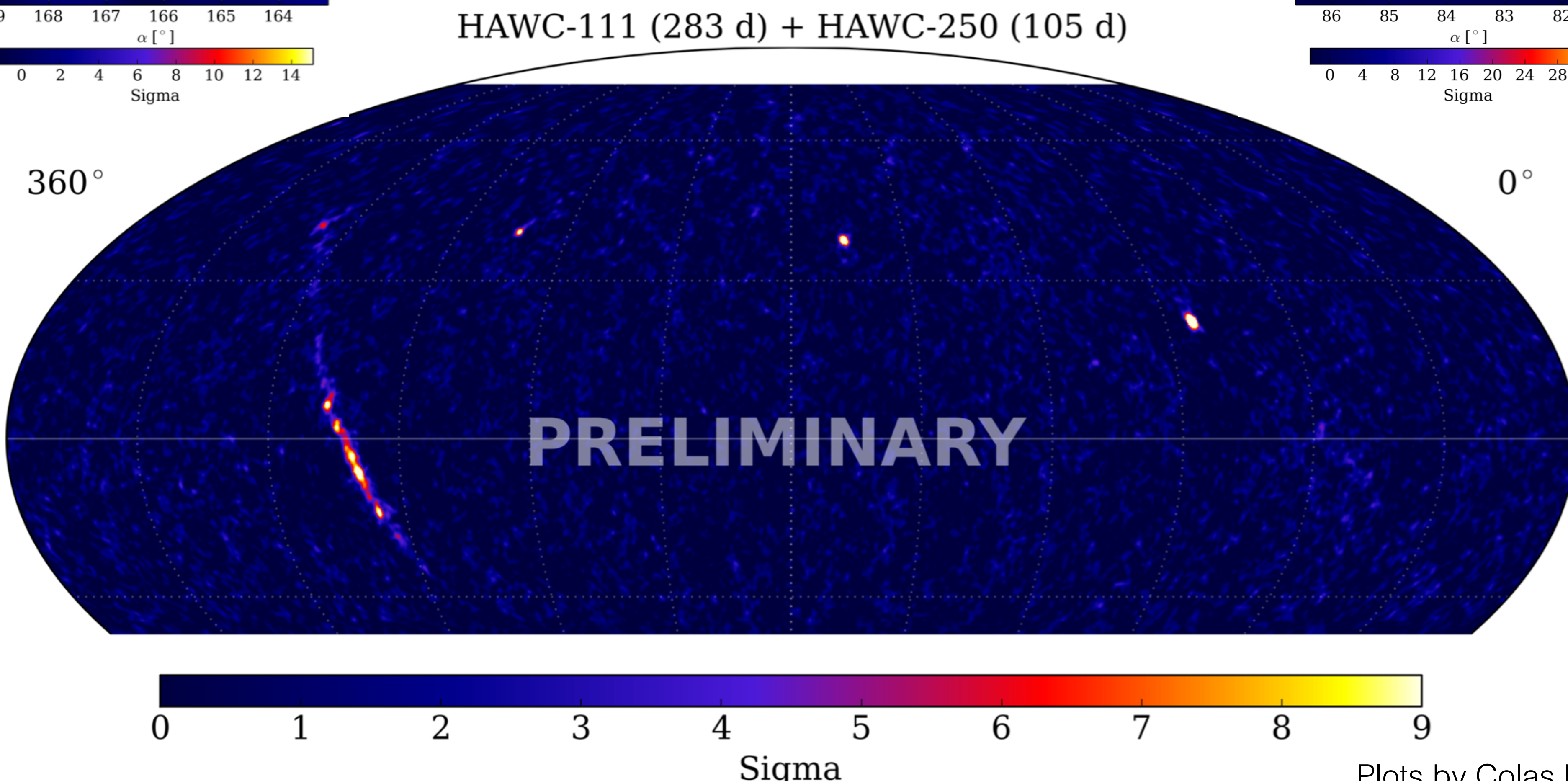
- Ten sources / candidate sources found; eight associations with known TeV sources.

Abeysekara et al. arxiv: 1509.05401 - submitted to ApJ



HAWC
γ-ray skymap



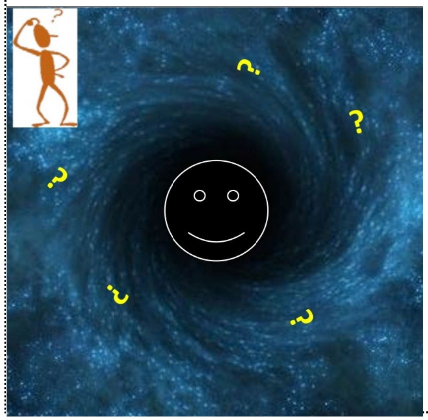


Plots by Colas Rivière

Primordial Black Holes

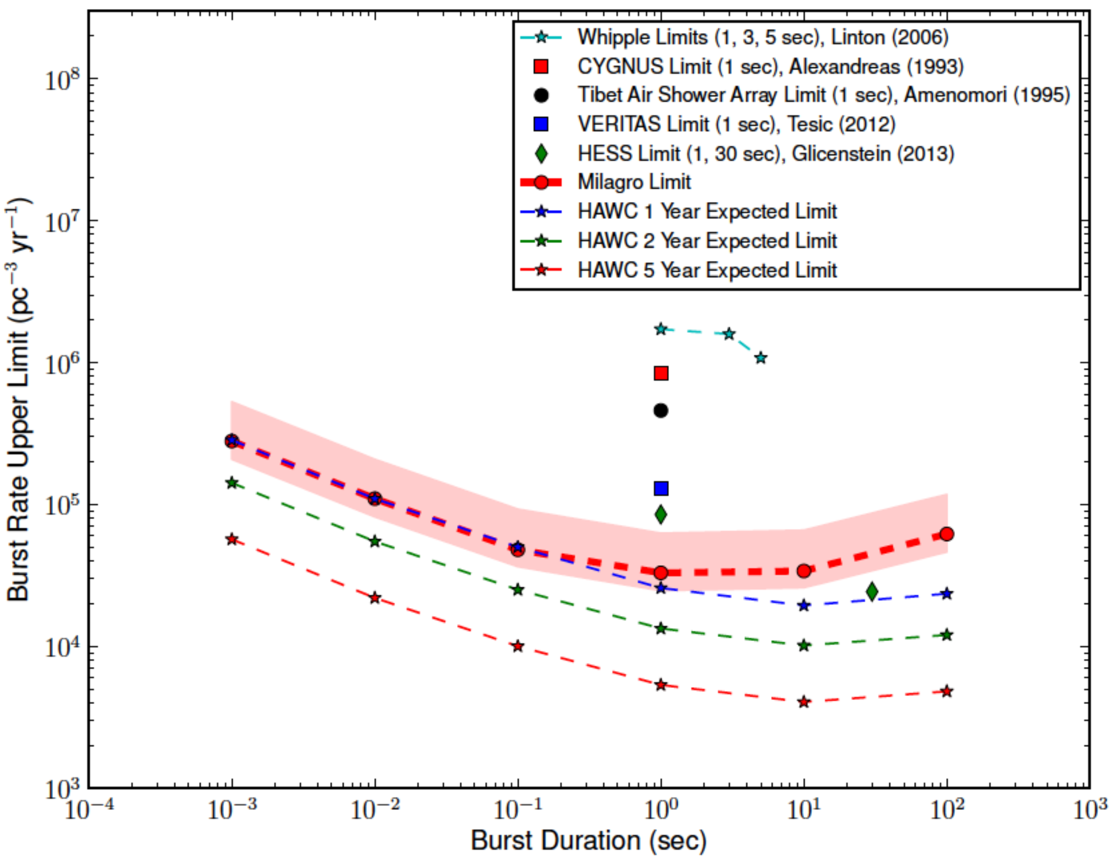
- Potential probes of:
  - PBHs affect early Universe processes.
  - viable dark matter candidates.
  - high energy physics: contributions to γ-ray background among other.
  - quantum gravity: evaporation process.

- Originated by density fluctuations in the very early Universe:
  - Collapse of cosmic loops.
  - Bubble collisions.
  - Collapse of domain walls.



Carr (2005)
Carr et al. (2010)

Primordial Black Holes



HAWC PBH expectations by Tilan Ukwatta
ICRC-0708 (2015)

- BH radiate thermally with a temperature (Hawking 1974):

$$T_{\rm BH} = \frac{\hbar\, c^3}{8\pi\, G\, M\, k_{\rm B}} \sim 10^{-7} \left(\frac{M}{M_\odot}\right)^{-1} {\rm K},$$

- Evaporation occurs in time scale:

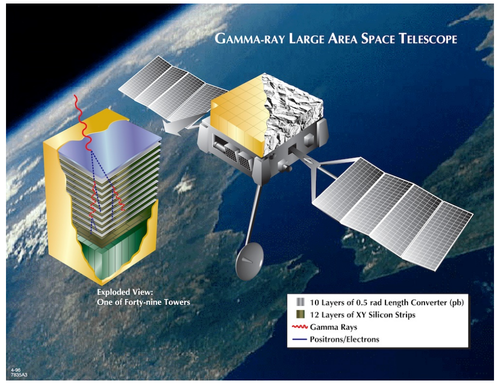
$$\tau(M) \sim \frac{G^2\, M^3}{\hbar\, c^4} \sim 10^{64} \left(\frac{M}{M_\odot}\right)^{3} {\rm yr}\,.$$

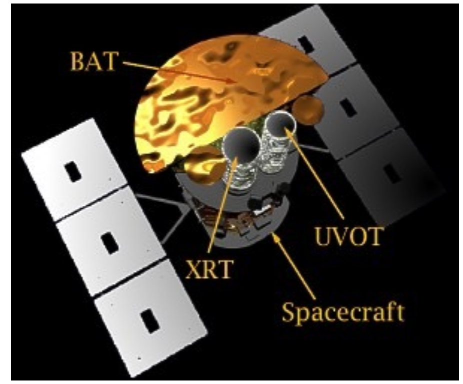
- PBHs smaller than 10^{15}g should have evaporated by now.
- PBH evaporation limits on multiple time scales set with Milagro (Abdo et al. 2015).
- HAWC will set the most stringent upper limits for burst lasting 1ms - 100s and emitting in the TeV range.

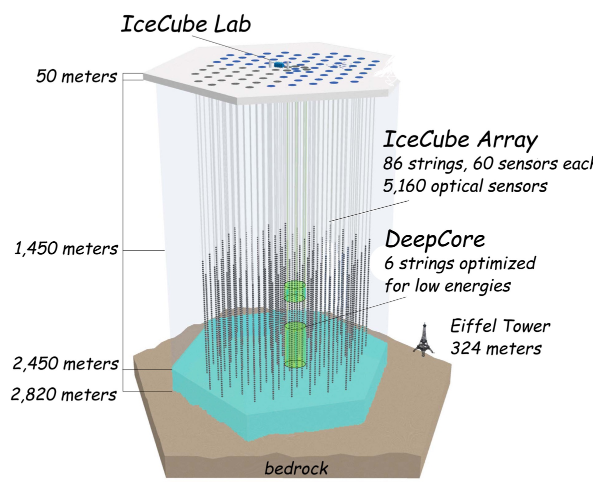
The HAWC γ-ray observatory

- Prelude: from Tonantzintla to Sierra Negra
- γ-ray astronomy from space and ground
- WCOs: from Milagro to HAWC
- The development of HAWC
- HAWC data and results
- Making more of HAWC

Multi-wavelength synergies

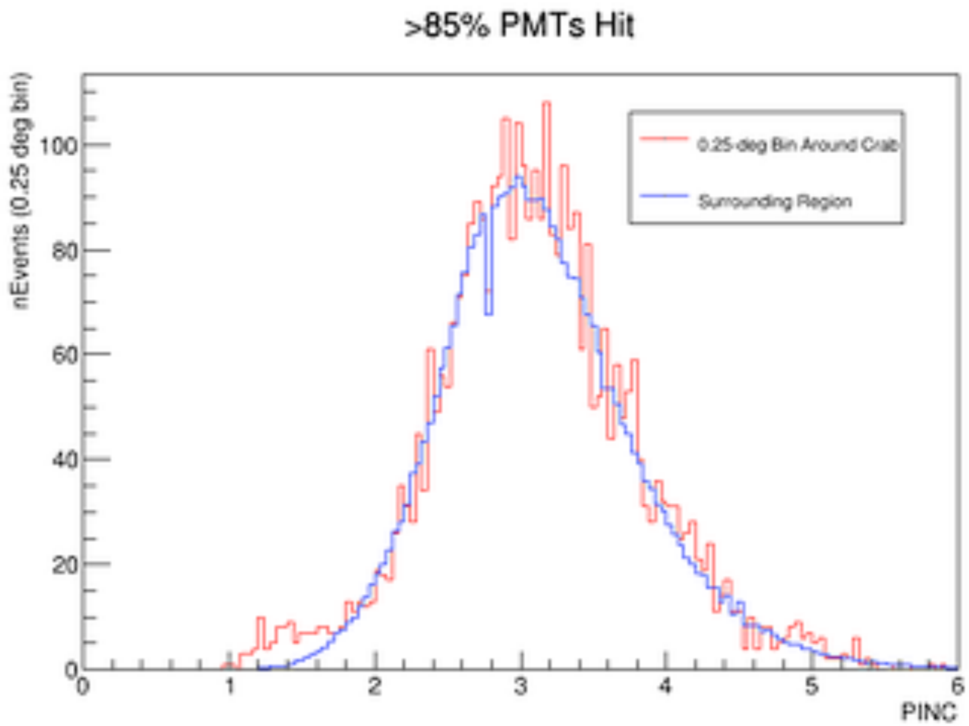




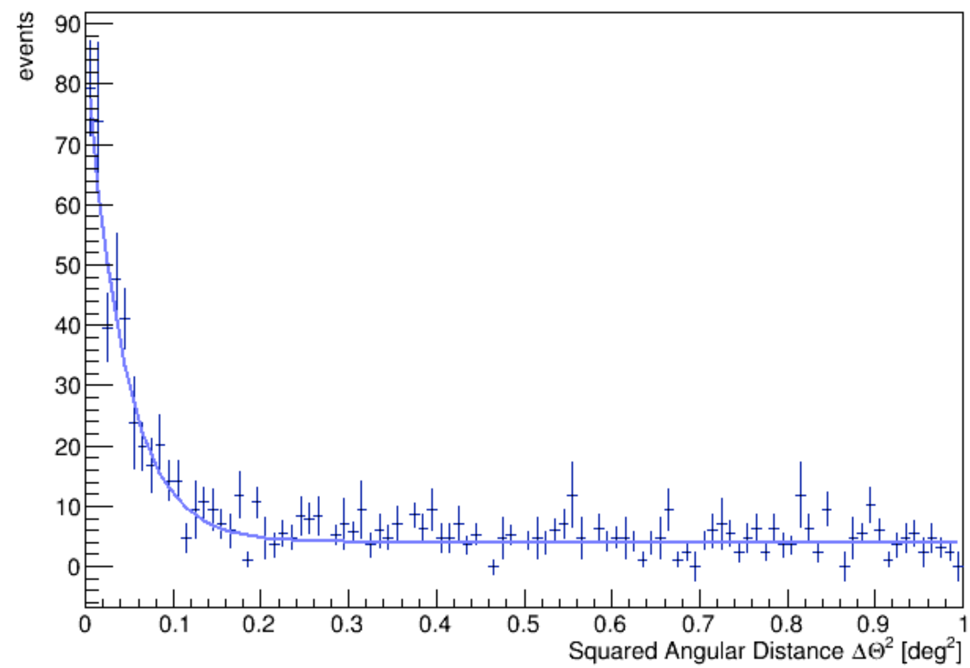


Multi-messenger synergies

“Pass 4” preview



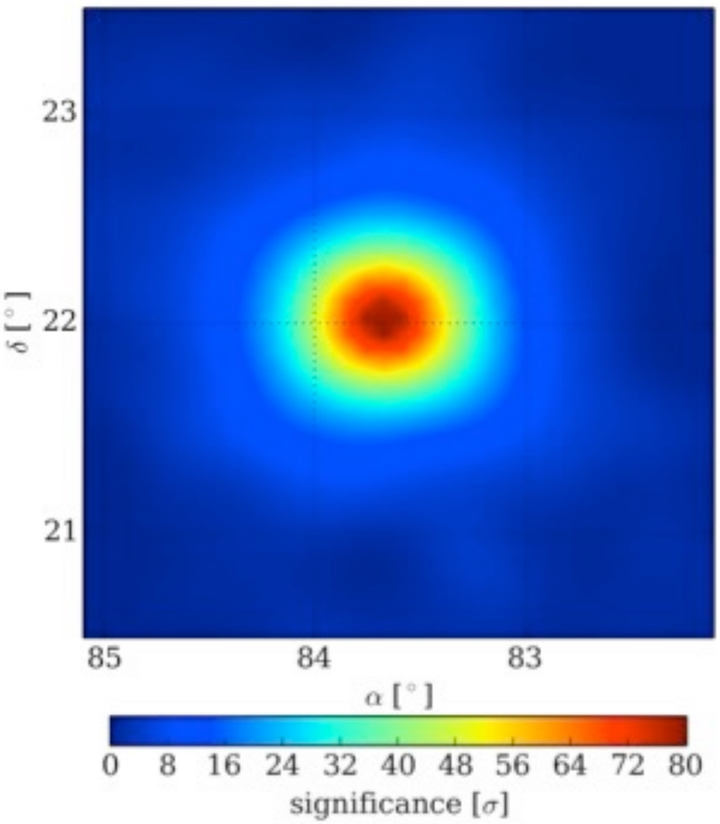
PING : Parameter for Identification of Nuclear Cosmic Rays
Reject > 99.9% hadronic background while retaining >50% of γ-rays



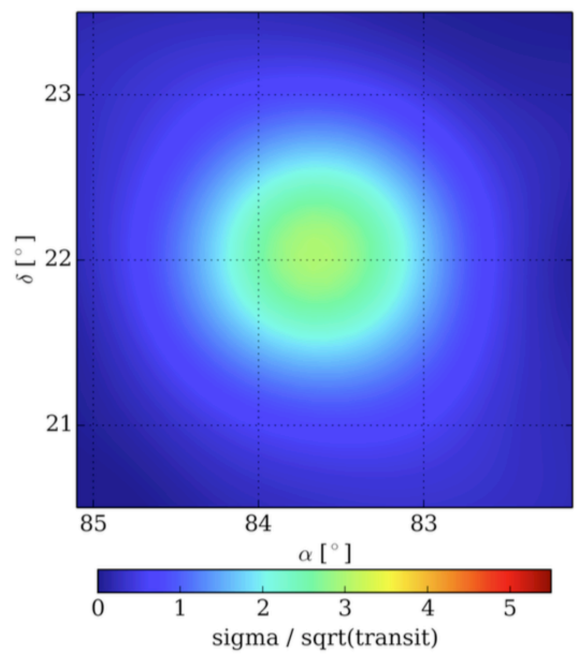
Angular resolution for large events ~0.15º
68% containment = 0.24º
Achieving proposed resolution

“Pass 4” preview

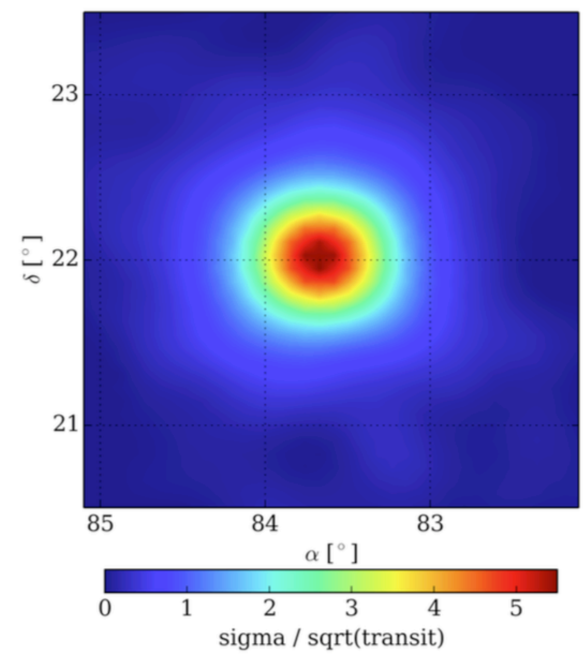
Pass4 -80σ on the Crab in 211 days



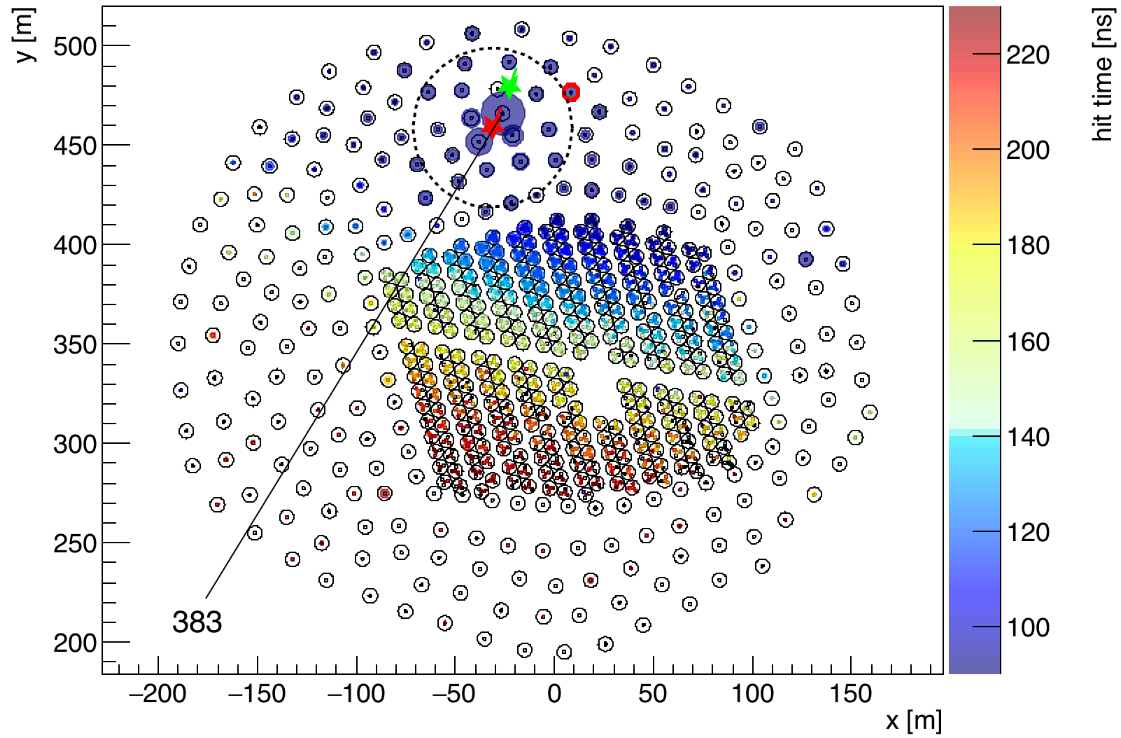
Pass 3
3.1σ/sqrt(day)



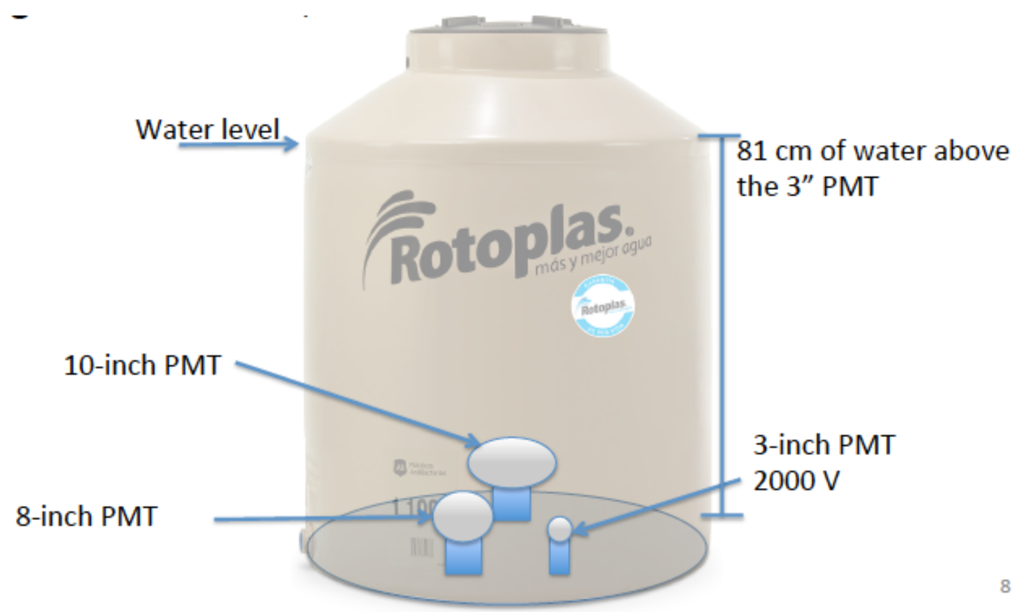
Pass 4
5.5σ/sqrt(day)



HAWC outriggers



- Proposal for a sparse outrigger array to improve the sensitivity beyond 10 TeV ⟹ up to a factor of 4 in effective area.
- About 300 WCDs of 2,500 liters.
- Accurate core determination for showers off the main array.
- Funding by LANL and Mexico.

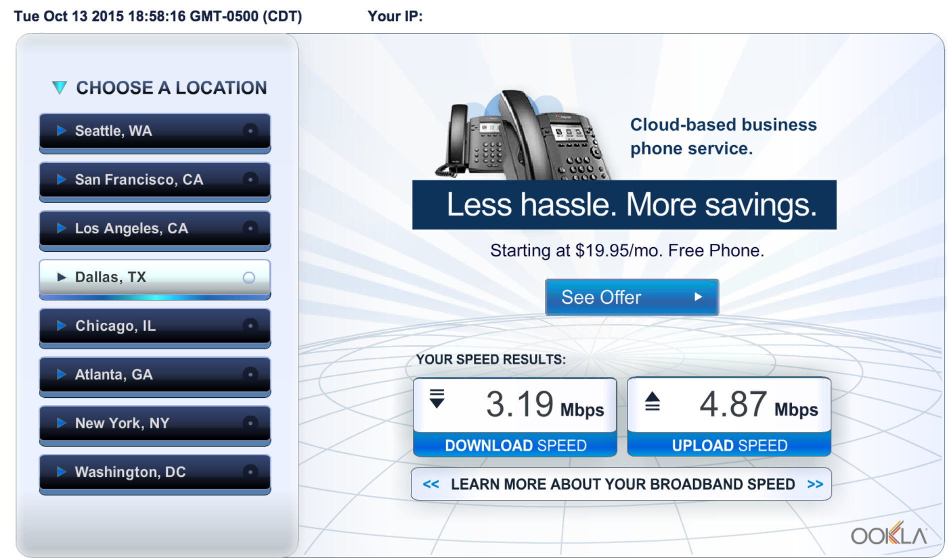


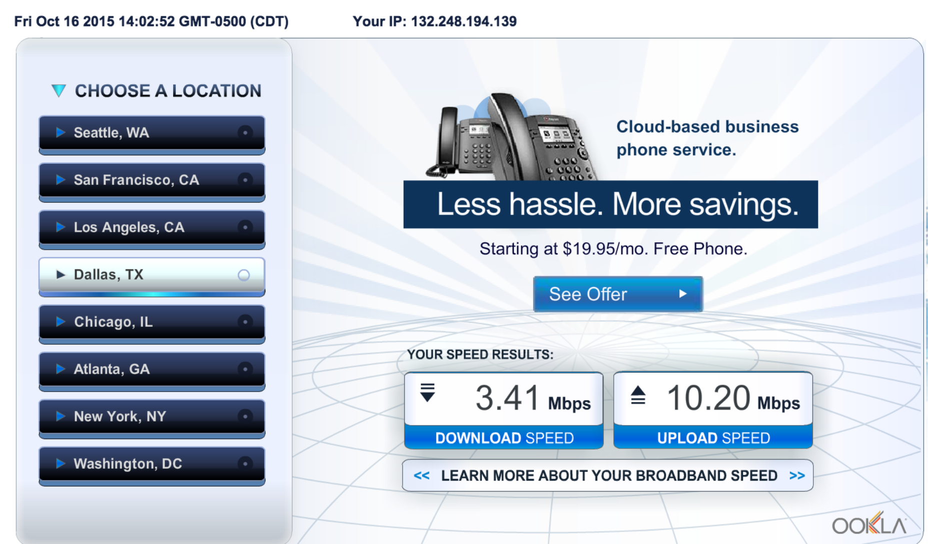
Connectivity

- A 13km optical fibre connects Sierra Negra with Atzitzintla and 25 km additional connect to Ciudad Serdán.

- Current connectivity reaches only 3Mbps / 10 Mbps, limiting current science operations.

- Since 2012, INAOE has sought a single fibre connection from Sierra Negra to Tonantzintla.





El anillo metropolitano de fibra óptica

- Following-up from the original INAOE fibre project, INAOE and BUAP have teamed to implement a more robust Internet connection, with the support of CUDI.

- The plan represents one of the first metropolitan fibre systems in Mexico.

- The agreement was signed by INAOE director and BUAP rector on 30th October.

Miércoles 14 de Octubre del 2015 | Webmail | Contacto | Regíst

cudi

Corporación Universitaria para el Desarrollo de Internet A.C.
Internet 2 - México

http://www.cudi.edu.mx/noticia/puebla-primeros-anillos-de-fibra-optica

Inicio | ¿Qué es CUDI? | Acervos | Proyectos | Miembros | Conexión a la Red | NOC CUDI | Comunida

Inicio

Puebla, instalará los primeros anillos de fibra óptica en México

Martes, 13 Octubre, 2015

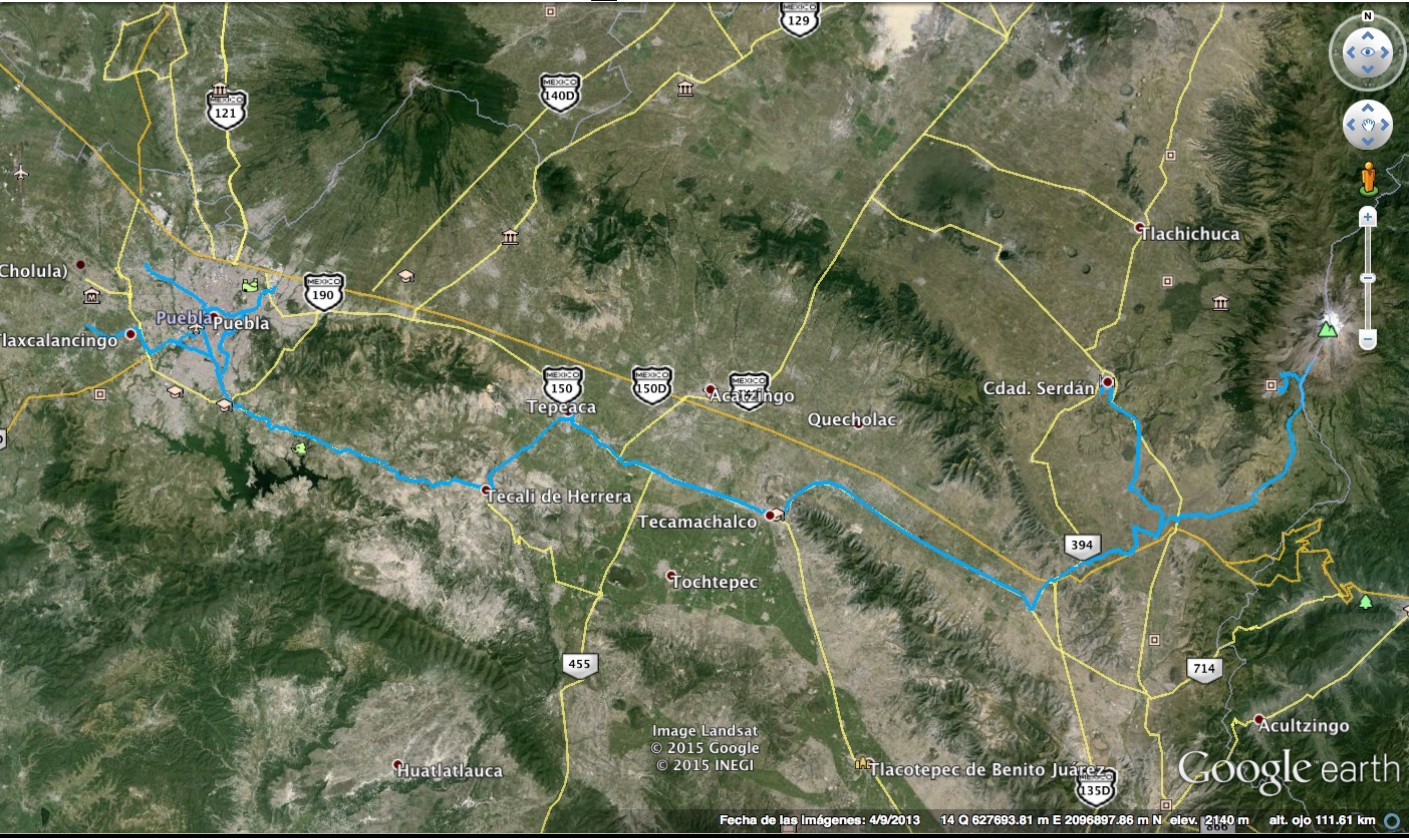
Con una inversión inicial de 1.5 millones de dólares, el proyecto ejecutado entre la BUAP y el INAOE se prevé que concluirá en cuatro meses. Su principal objetivo es abatir costos en servicios de conectividad, además de proporcionar el mismo a...

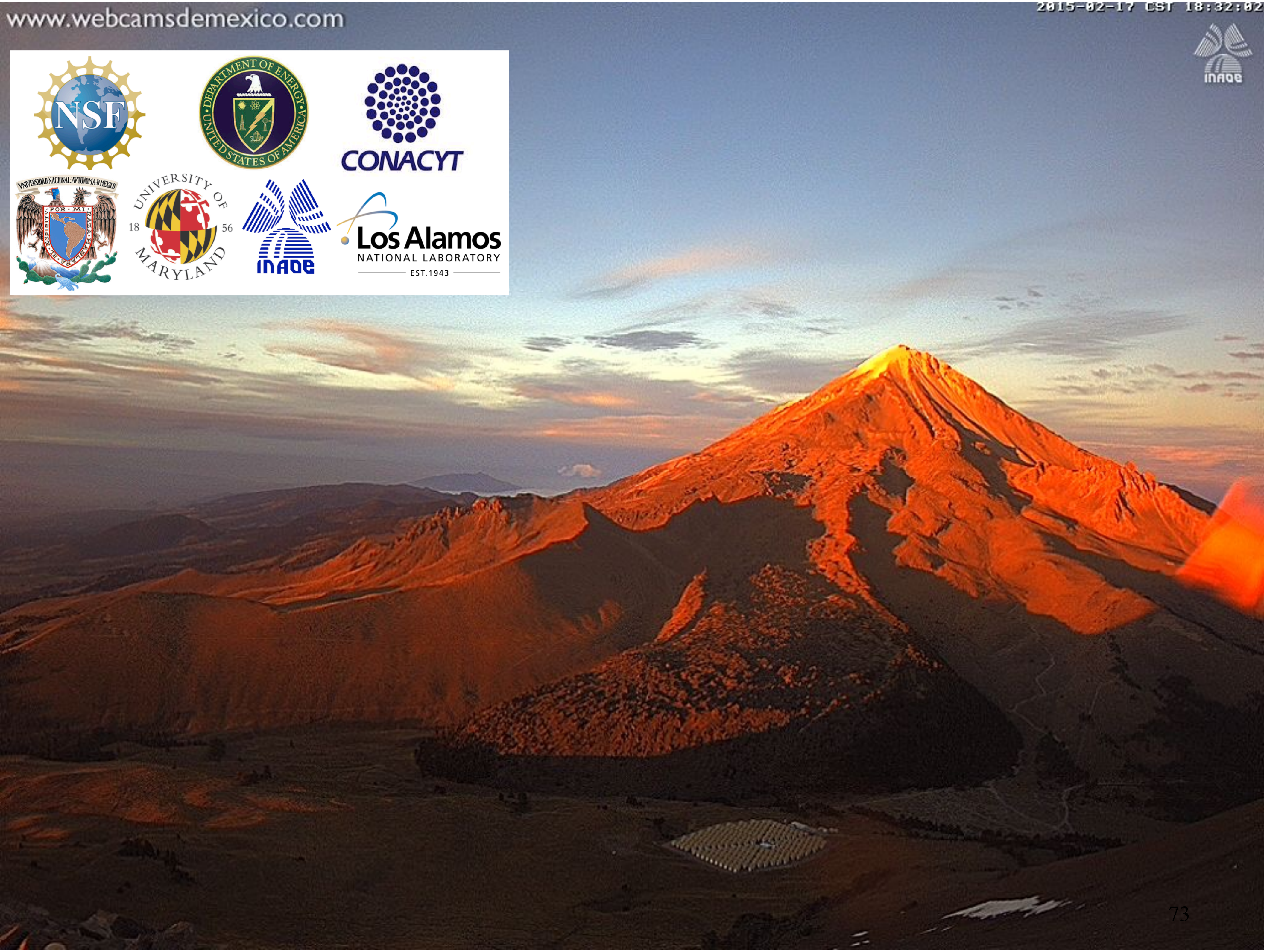
El Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE) y la Benemérita Universidad Autónoma de Puebla (BUAP), firmarán un convenio para tener 200 kilómetros de fibra óptica que conectará a distintas instituciones con el Laboratorio Nacional de Supercómputo.

Tras informar que la BUAP será sede de la trigésima Reunión Semestral de la Corporación Universitaria para el Desarrollo de Internet (CUDI), otoño 2015, Humberto Salazar Ibargüen, titular de la Dirección General de Cómputo y Tecnologías de la Información y la Comunicación de la universidad, informó que "140 kilómetros de fibra óptica comunicarán al INAOE y el Laboratorio Nacional de Supercómputo del Sureste de México (LNS), con el Observatorio de Rayos Gamma (HAWC) y el Gran Telescopio Milimétrico (GTM), 60 kilómetros más serán la red metropolitana que unirá todos los campus de la benemérita, y así interconectar en su totalidad a las instituciones de educación superior de Puebla".

Con el objetivo de abatir costos en servicios de conectividad y proporcionar el servicio a otras instituciones interesadas en los servicios del LNS, el proyecto ejecutado entre la BUAP y el INAOE estará terminado en

The optical fibre

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