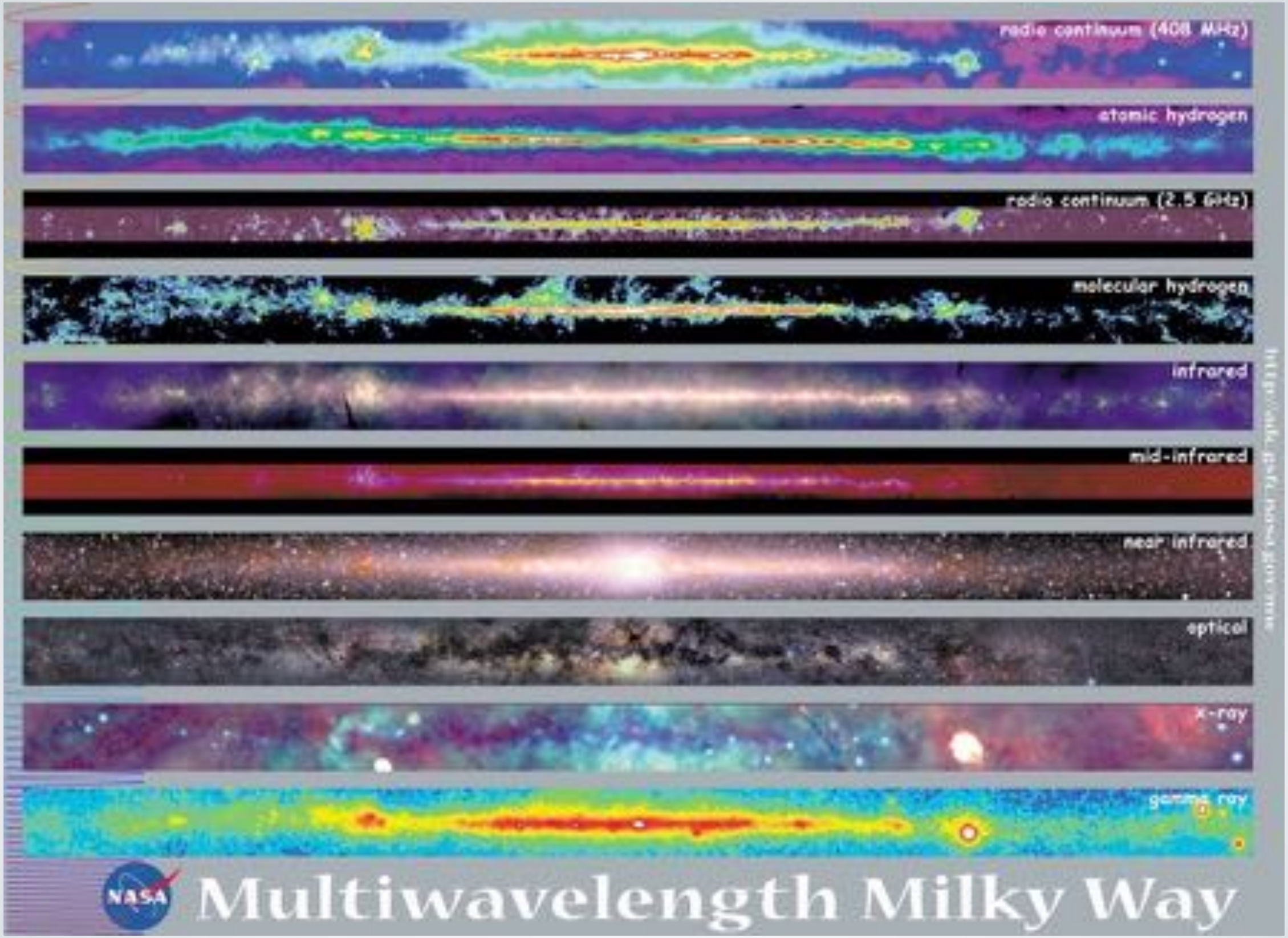
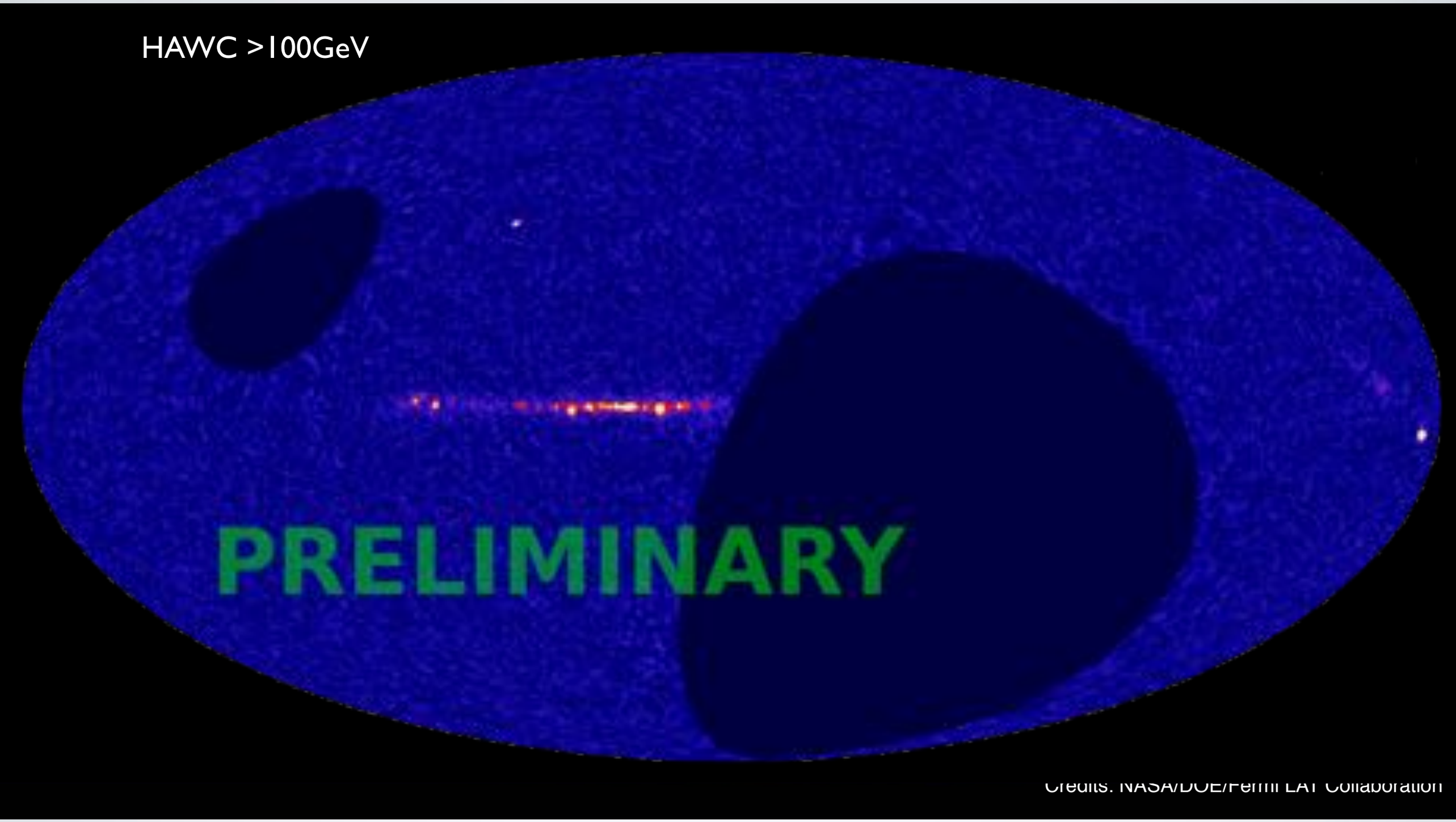
Gamma-ray Survey of our Universe

C. Michelle Hui
NASA/MSFC
Oct 12, 2016

Multi-Wavelength View of our Galaxy



Gamma-ray View of our Galaxy



Credits: NASA/DOE/Fermi LAT Collaboration

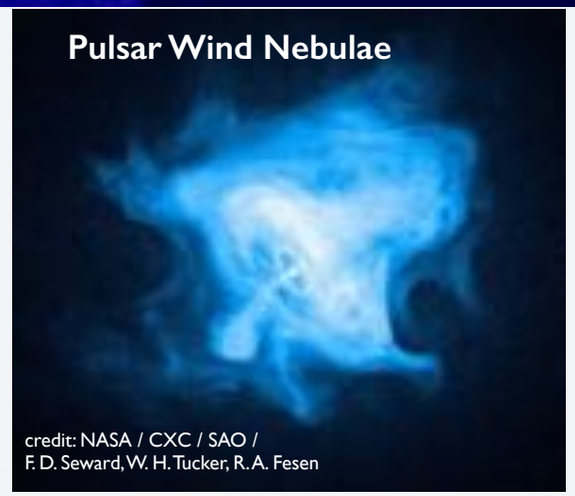
High Energy View of our Galaxy

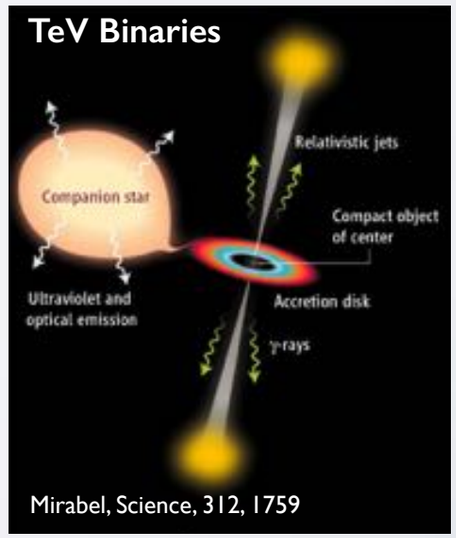
Fermi LAT 0.05 — 2 TeV, >6 years

Credits: NASA/DOE/Fermi LAT Collaboration

HESS >1TeV, 10 years

HAWC 0.1—100 TeV, 1 year





Gamma-Ray Detectors

Wide Field of View, C

Operations

nsitivity

MAGIC
VERITAS

HAWC collaboration

Georgia Institute of Technology
George Mason University
Los Alamos National Laboratory
Michigan State University
Michigan Technological University
NASA/Goddard Space Flight Center
NASA/Marshall Space Flight Center
Pennsylvania State University
Stanford University
University of California, Irvine
University of California, Santa Cruz
University of Maryland
University of New Hampshire
University of New Mexico
University of Rochester
University of Wisconsin-Madison
University of Utah

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Centro de Investigacion y de Estudios Avanzados del IPN
Benemérita Universidad Autónoma de Puebla
Universidad Nacional Autónoma de México:
  Instituto de Astronomía
  Instituto de Ciencias Nucleares
  Instituto de Física
  Instituto de Geofísica
Instituto Nacional de Astrofísica, Óptica y Electrónica
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Max-Planck Institute for Nuclear Physics
Instytut Fizyki Jadrowej im Henryka Niewodniczanskiego
Polskiej Akademii Nauk

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DGAPA-UNAM, México;
and the University of Wisconsin Alumni Research Foundation.

Mapping the Northern Sky in High-Energy Gamma Rays

HAWC Observatory

HAWC operates day and night, providing a large field of view for the observation of the highest energy gamma rays.

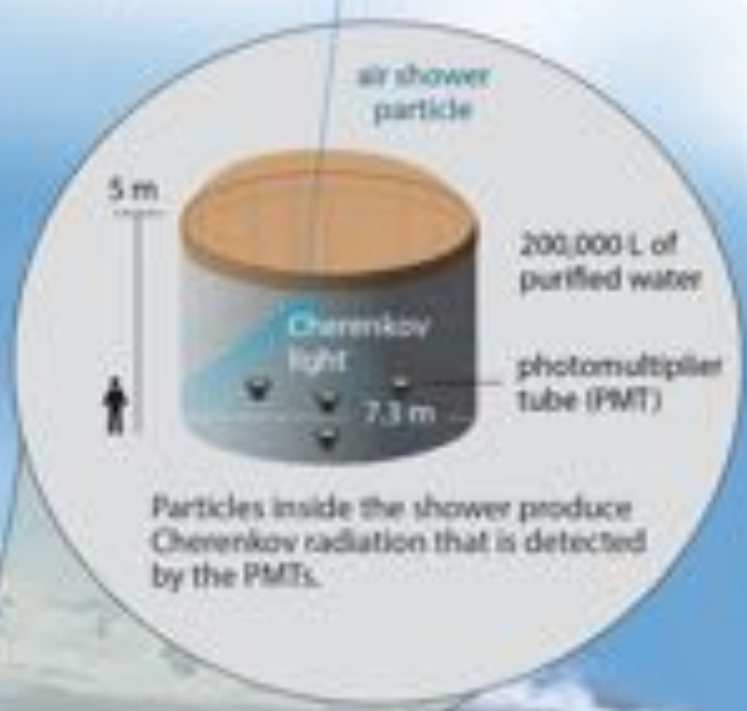
Pico de Orizaba
(5,626 m)

HAWC is located at 4,100 m above sea level, covering an area of 20,000 m².

150 m

Water Cherenkov tank

HAWC comprises an array of 300 tanks that record the particles created in gamma-ray and cosmic-ray showers.



Particles inside the shower produce Cherenkov radiation that is detected by the PMTs.

Gamma rays vs cosmic rays

HAWC selects gamma rays from among a much more abundant background of cosmic rays.

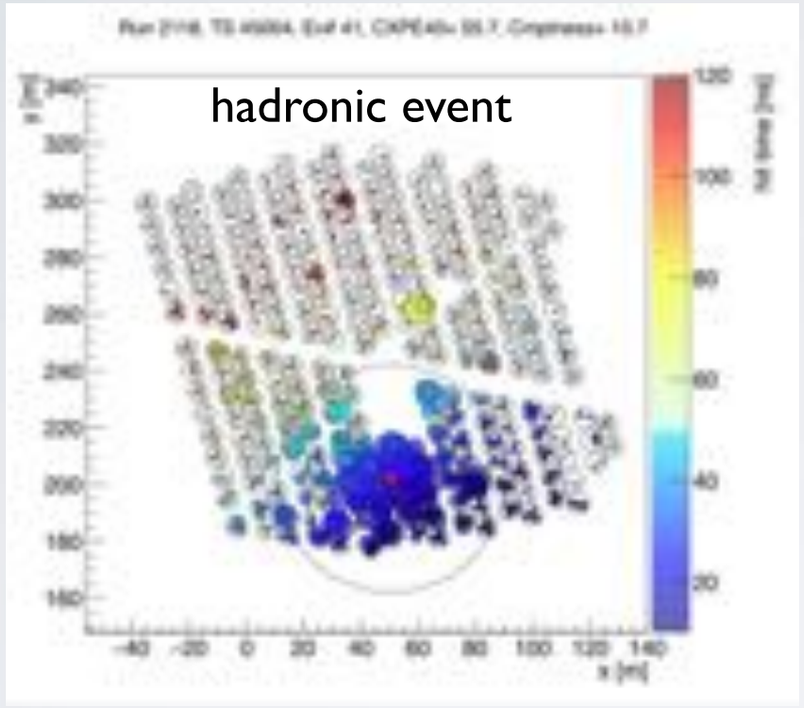
gamma-ray shower

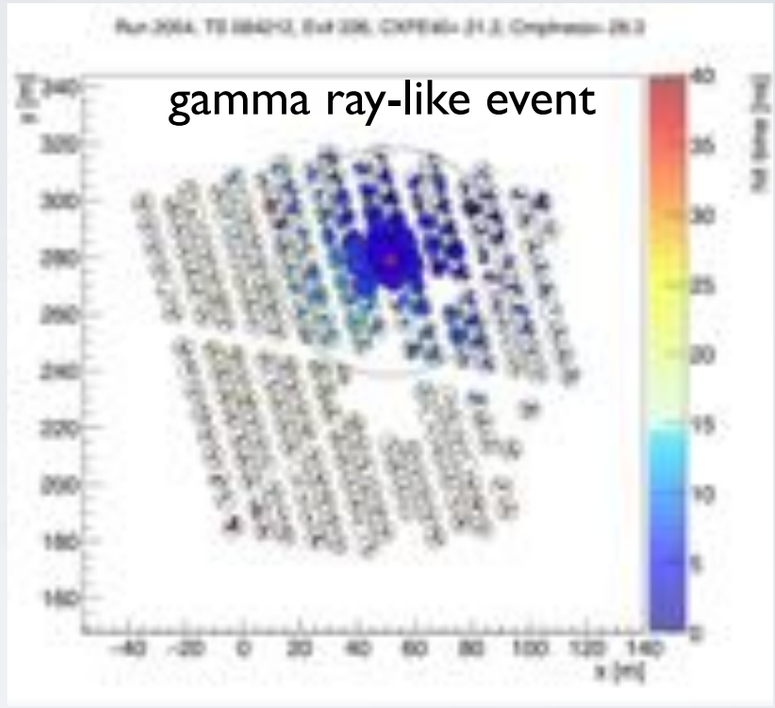
"hot" spots concentrate around the core

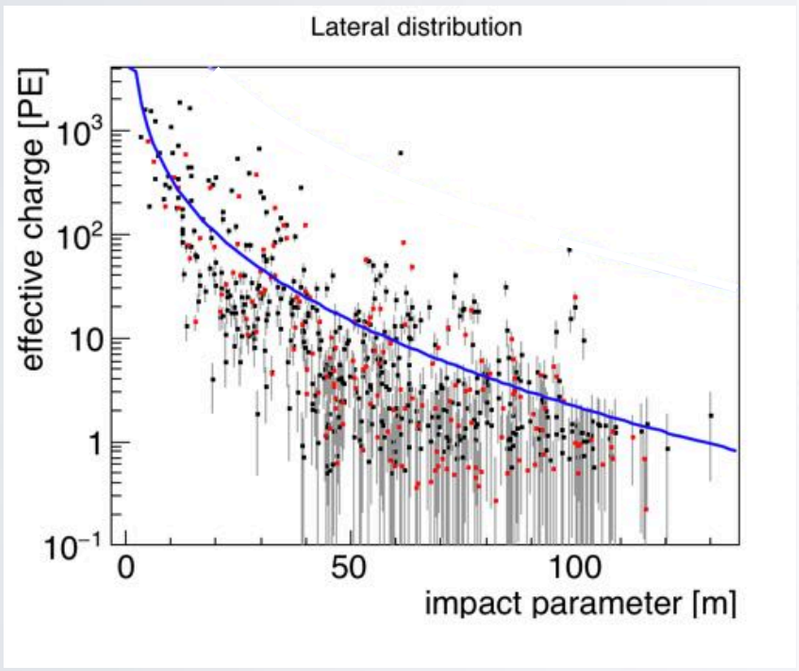
cosmic-ray shower

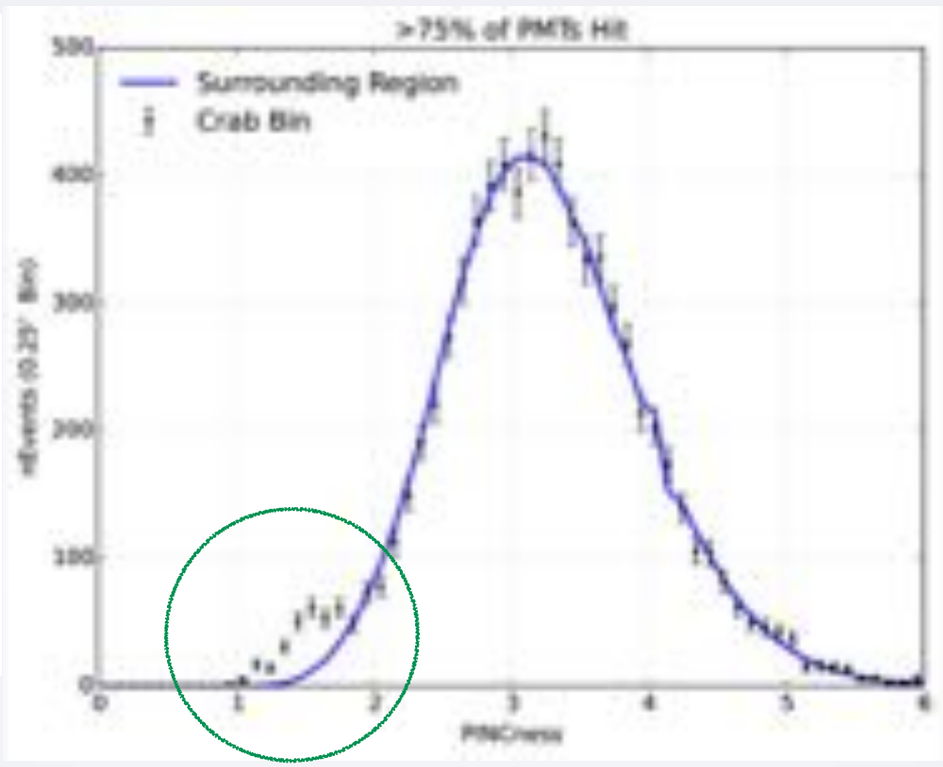
"hot" spots are more dispersed

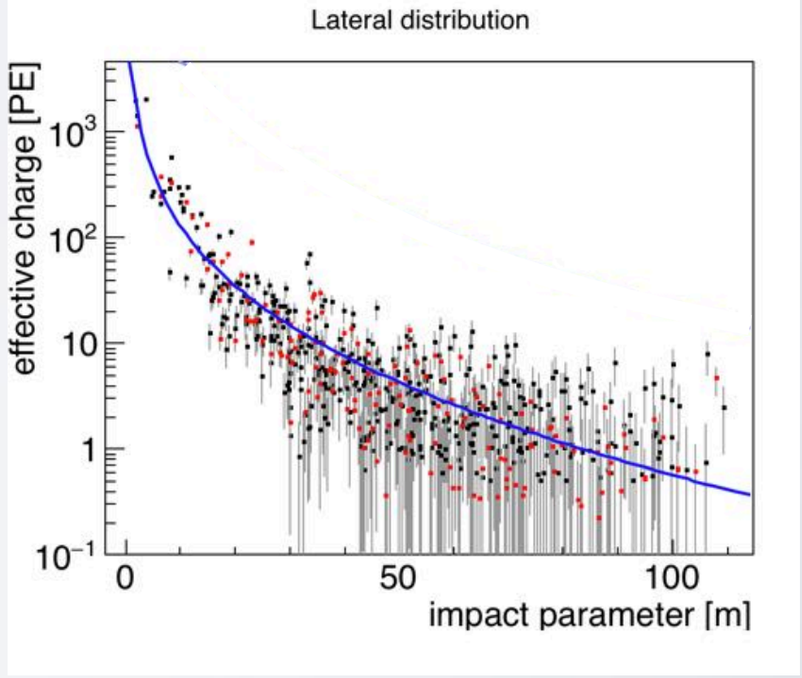
Gamma/Hadron Separation



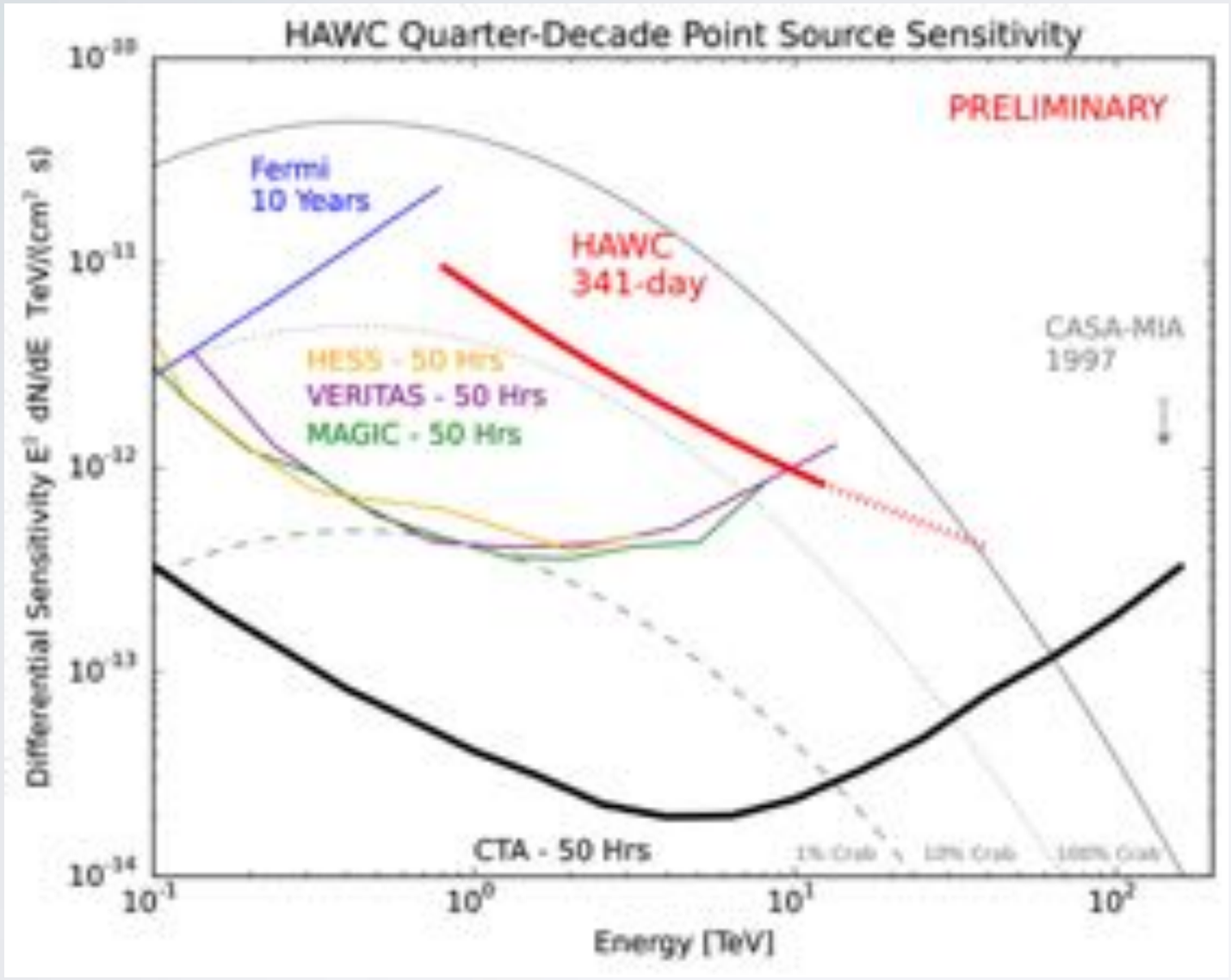


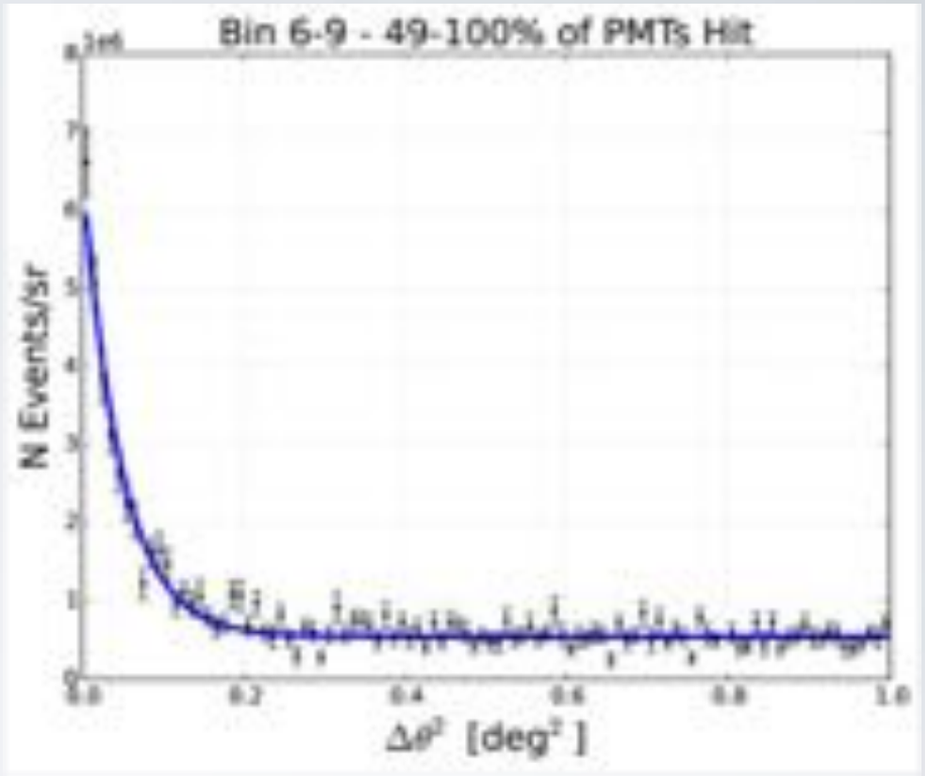


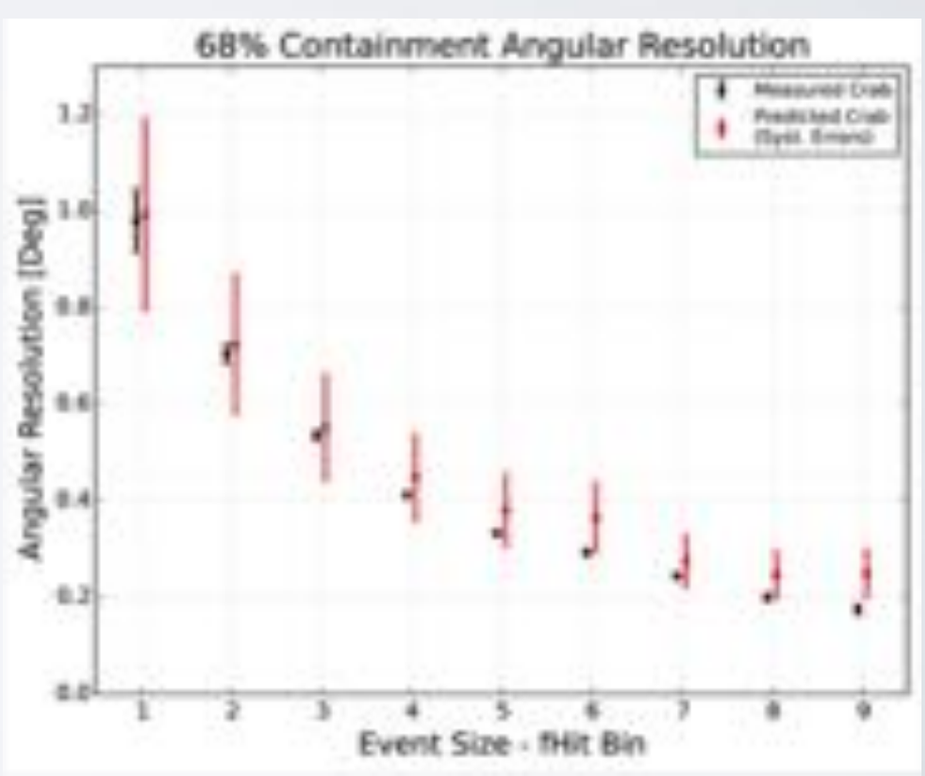




HAWC Sensitivity







- 0.2° $PSF_{68\%}$ at highest energy

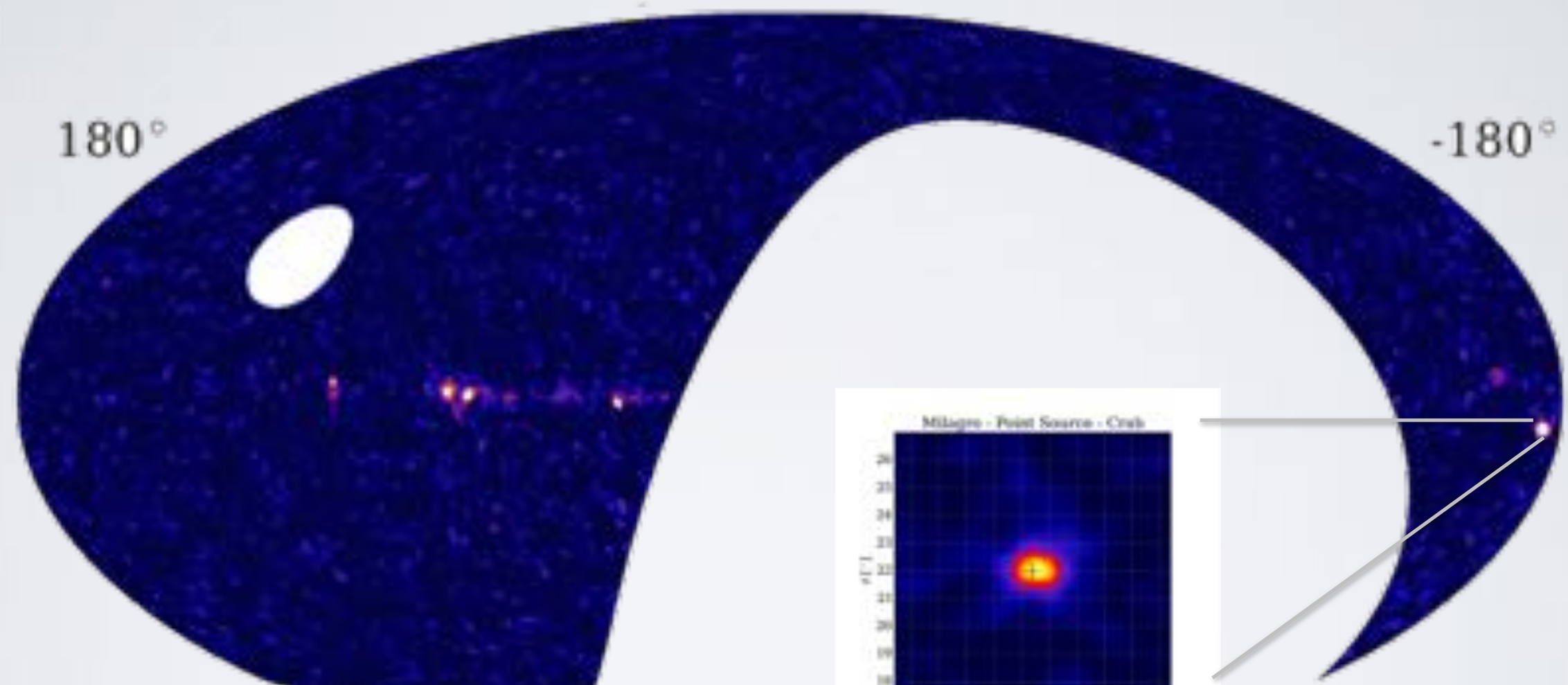
High Altitude Water Cherenkov Gamma-ray Observatory

- Sensitive from 100 GeV to 100 TeV.
- Angular resolution (68% containment) 0.2-1.0 degrees.
- 2sr instantaneous field of view, 2/3 of sky each day.
- >95% duty cycle.
- **Strengths:**
  Extreme high-energy reach.
  Wide field-of-view: ideal for transients and extended objects.
  High duty cycle.

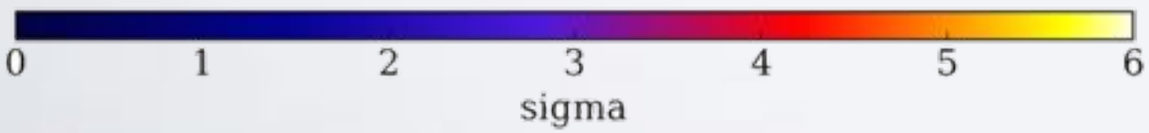
HAWC-30: began Aug 2012
HAWC-111: Jun 2013 (~280 days)
HAWC: Nov 2014 (341+ days)
Inauguration Mar 2015

Milagro 8-Year TeV Sky Survey

HAWC predecessor

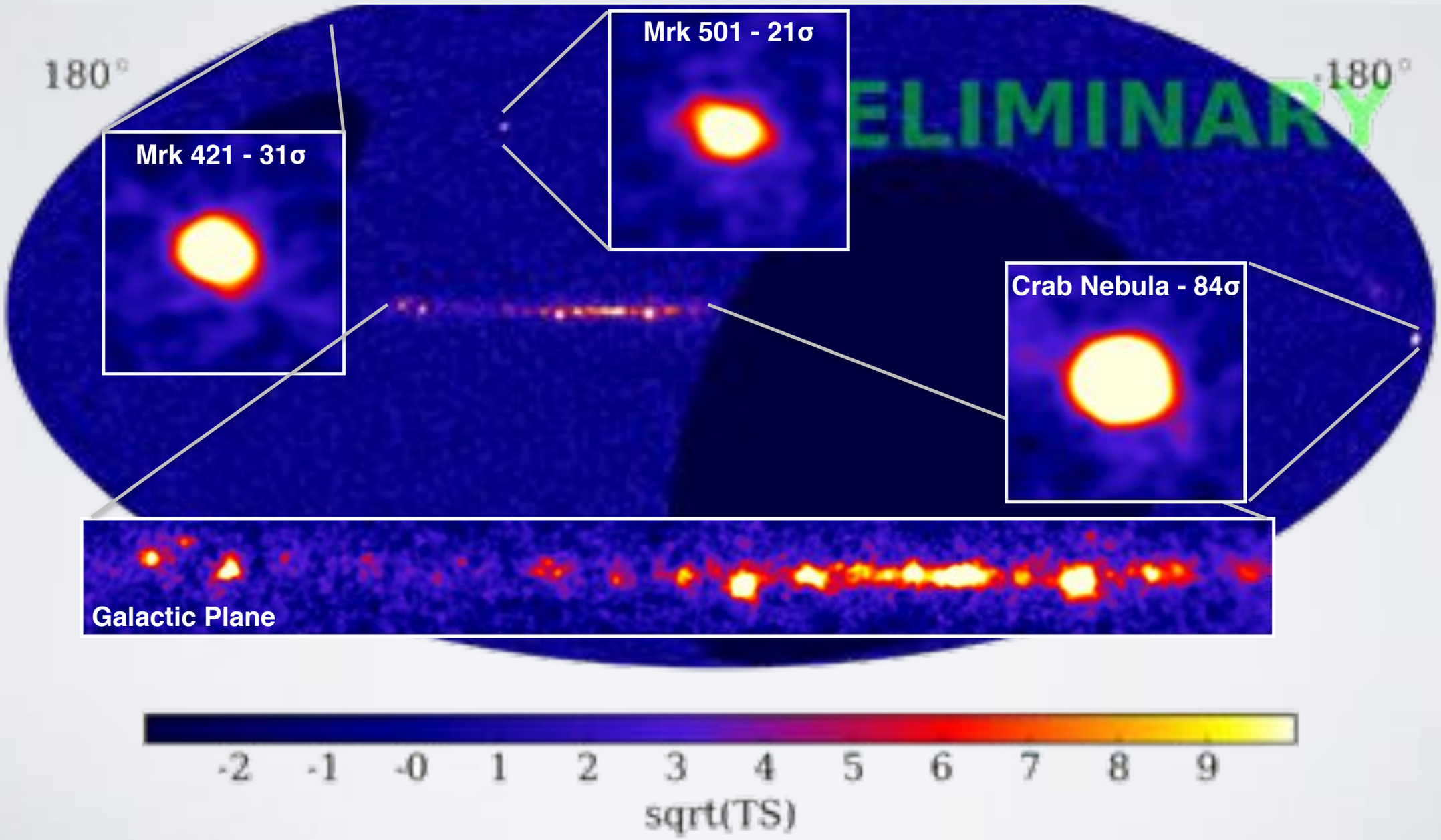


Crab at 17σ in 8 years.



HAWC TeV Sky Survey

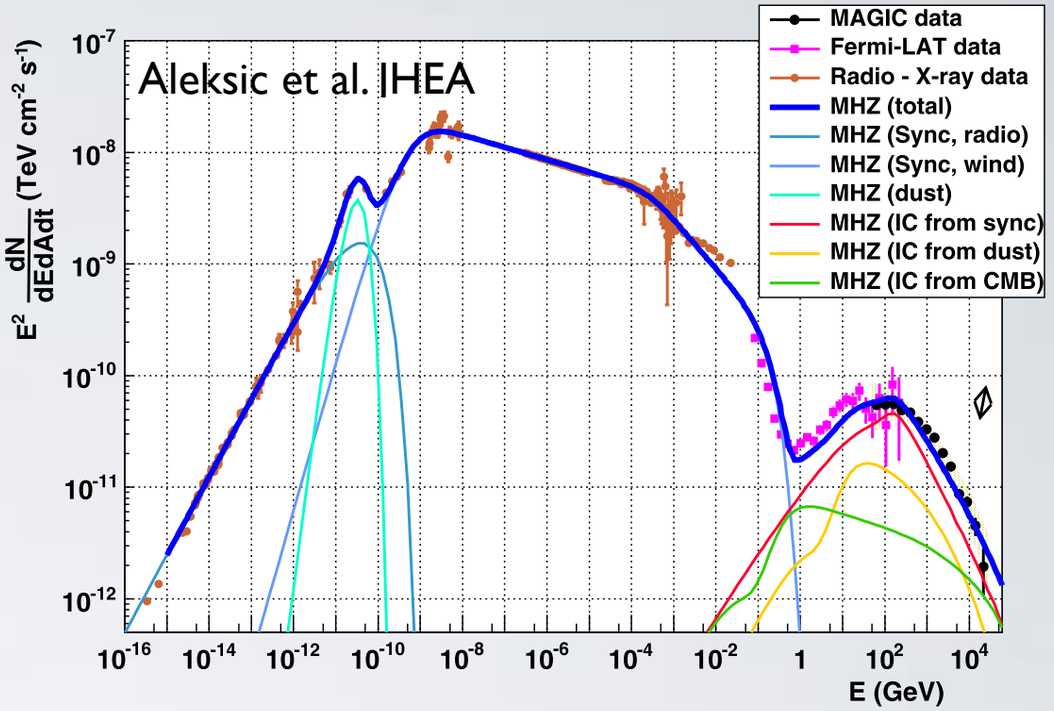
- HAWC is ~15x more sensitivity with lower energy threshold compared to Milagro, and more sensitive towards Galactic center.
- Skymap from 341 days of data taken with the finished HAWC array.
- Point source analysis assuming power-law index of 2.7.

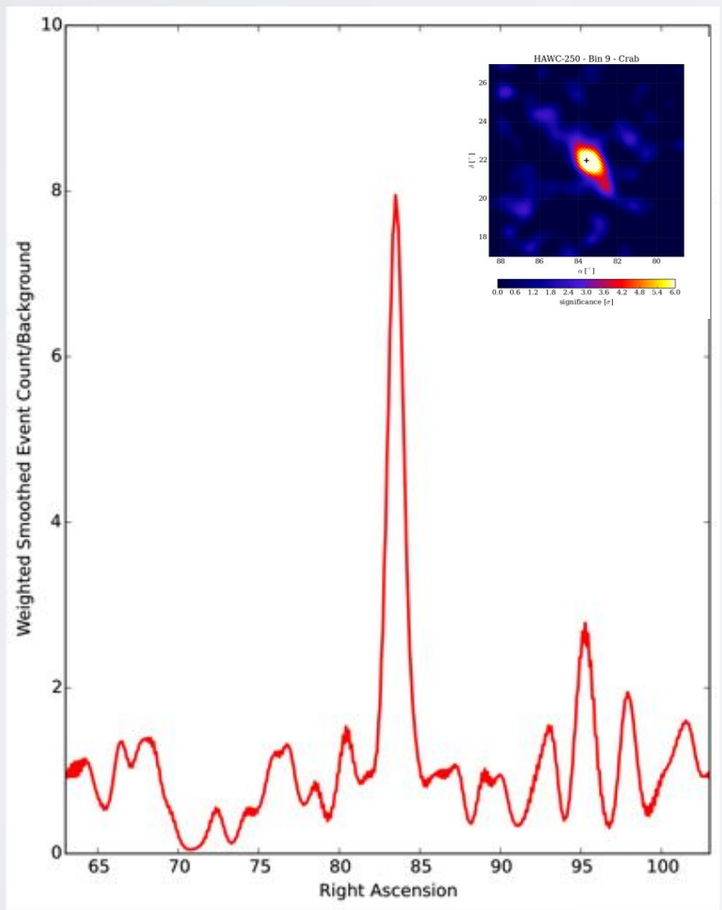


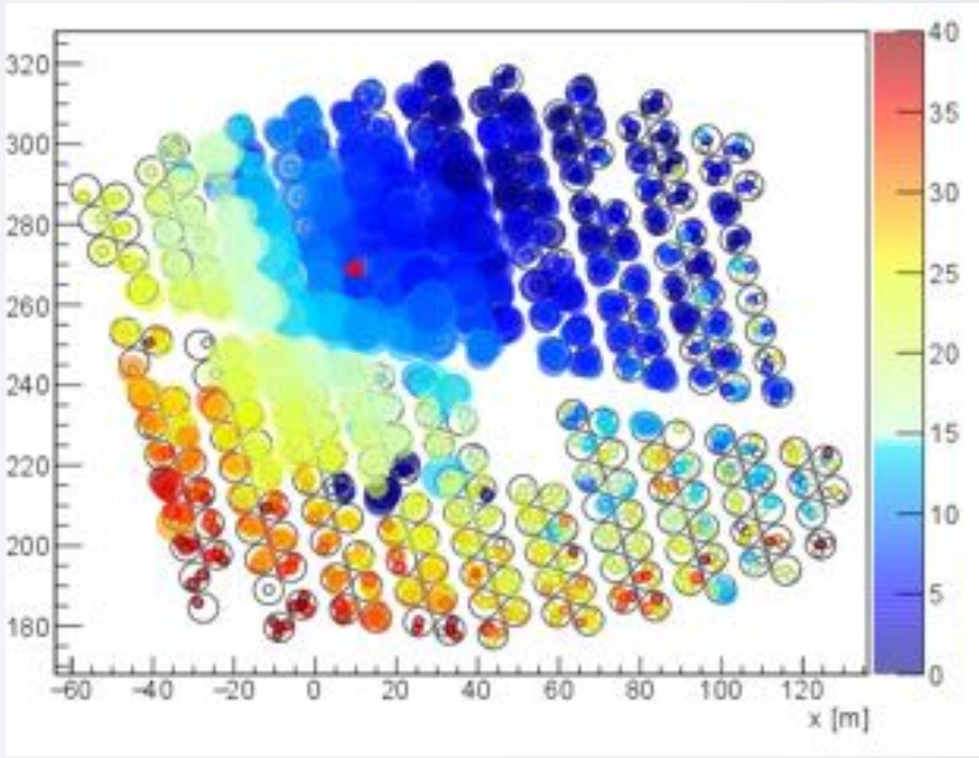
Pulsar Wind Nebulae

Crab Nebula at highest energies

- photons up to 80TeV reported by IACTs
- insight into magnetic field environment and efficiency of particle acceleration





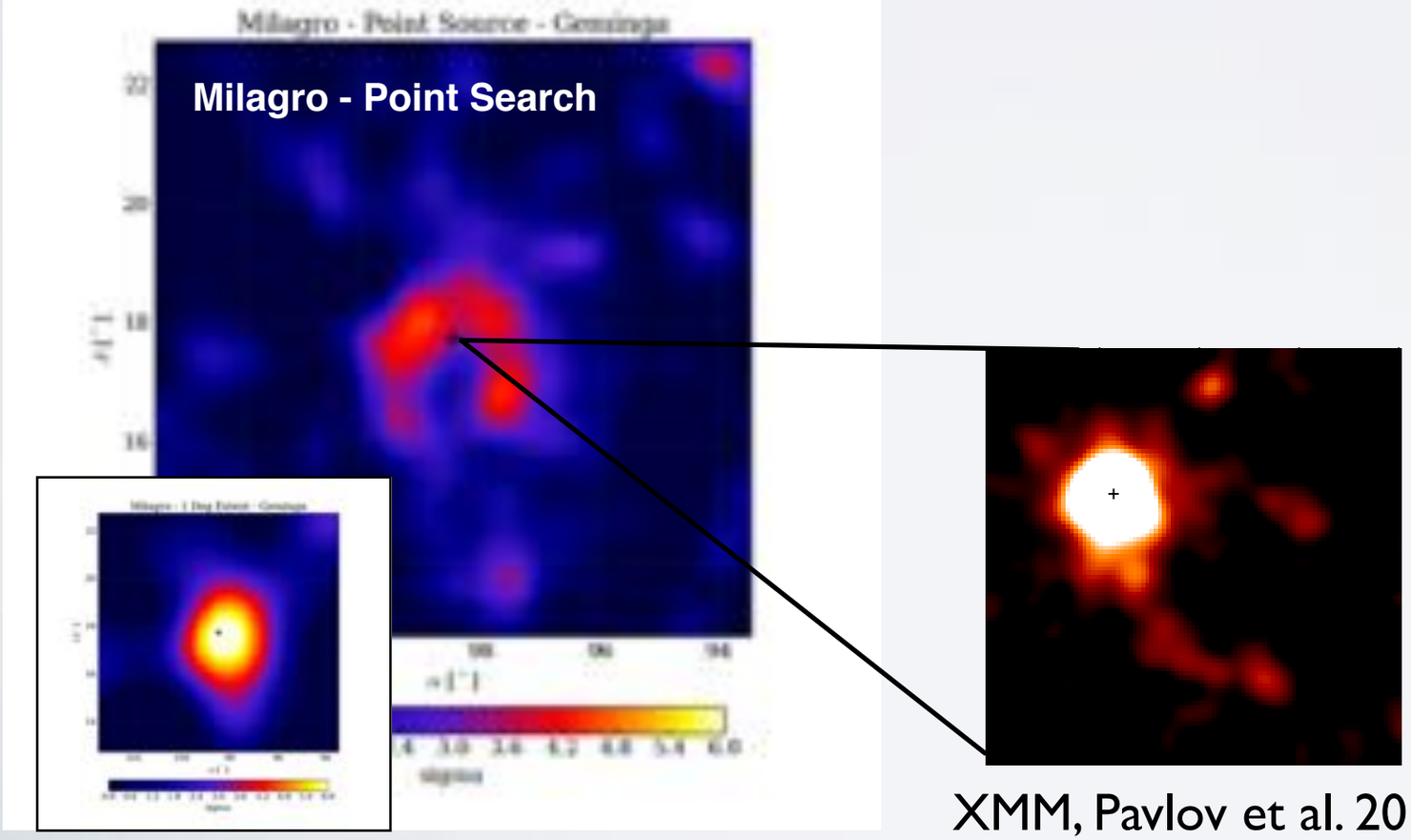


60TeV photon from the Crab Nebula seen by HAWC.

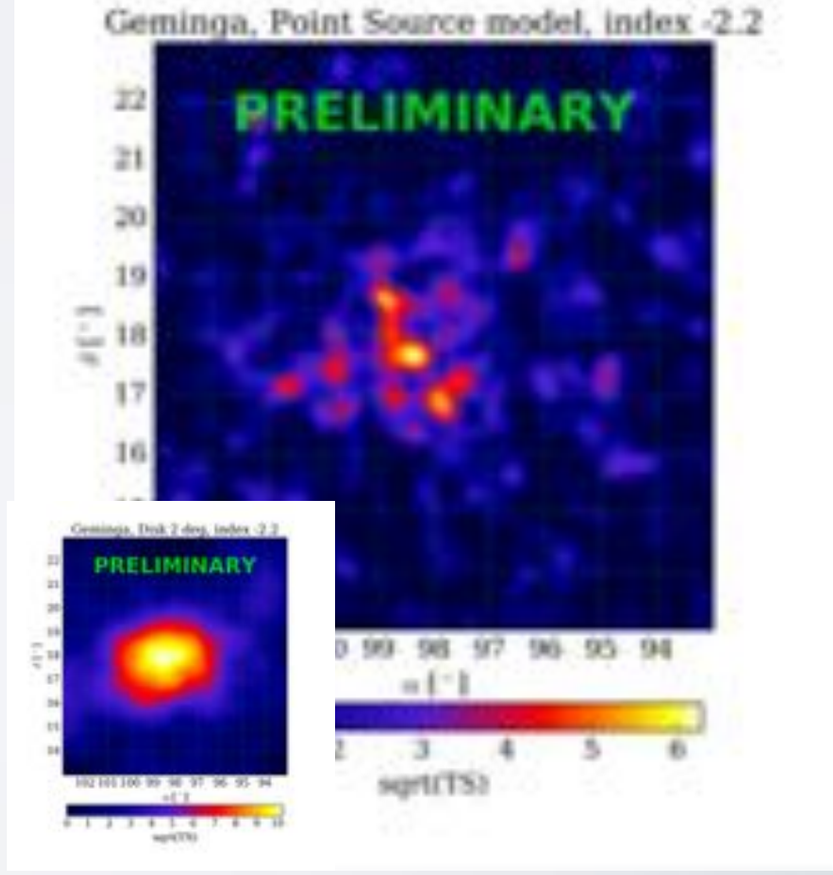
Pulsar Wind Nebulae

Geminga

- Closest known middle aged pulsar
- Possible nearby cosmic ray acceleration site
  — explanation for positron excess (Yuksel et al. 2009)
- Not seen by IACTs, extent maybe larger than IACT FOV.
- Ongoing morphological and spectral studies



XMM, Pavlov et al. 2010



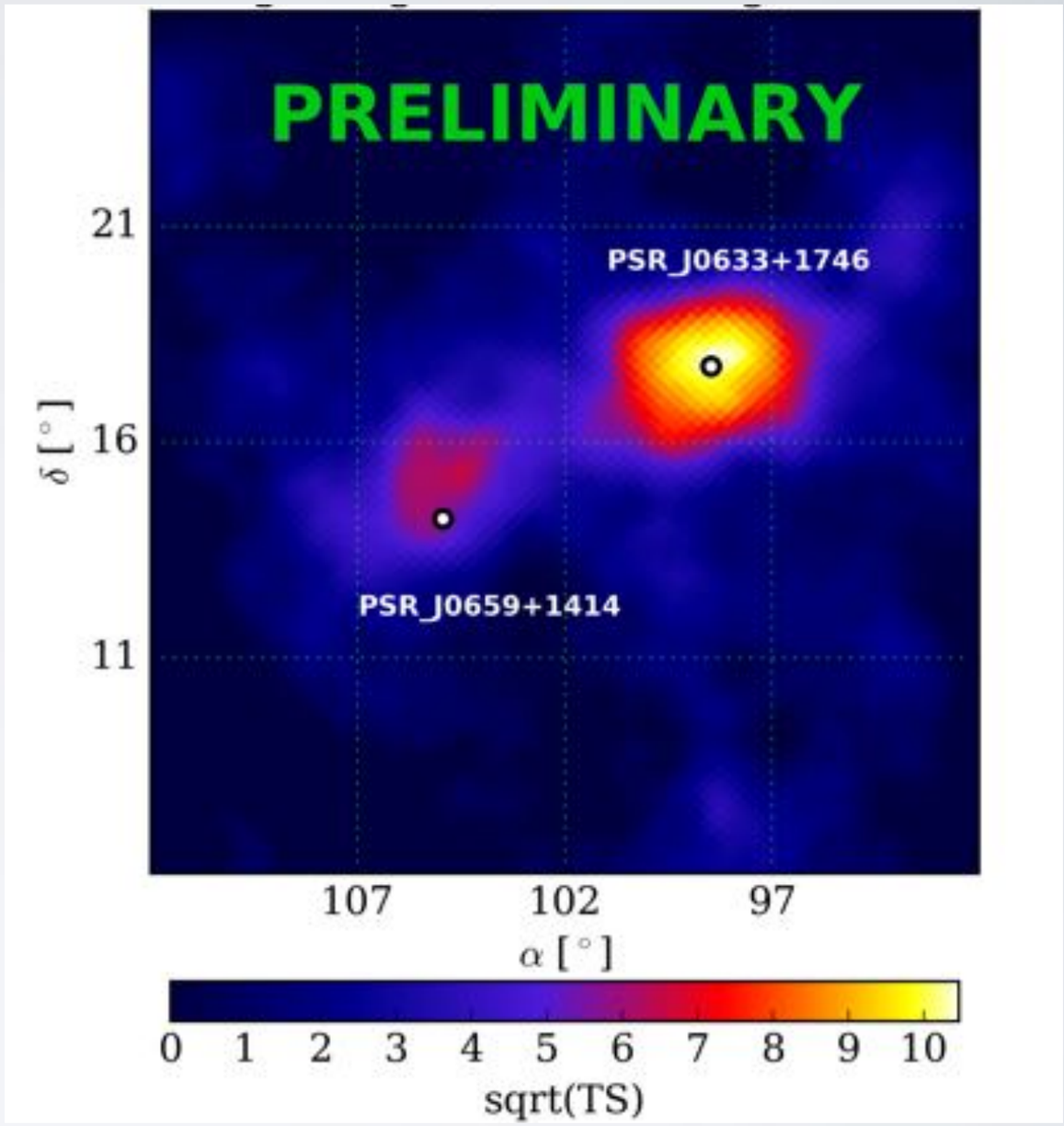
Pulsar Wind Nebulae

PSR J0659+14

- New PWN seen near Geminga!
- Similar large extension seen in data.
- This pulsar is very similar to Geminga pulsar:

	Geminga	PSR J0659+14
age [yr]	3E+05	1E+05
distance [pc]	250	288
spin-down power [erg/s]	3E+34	4E+34

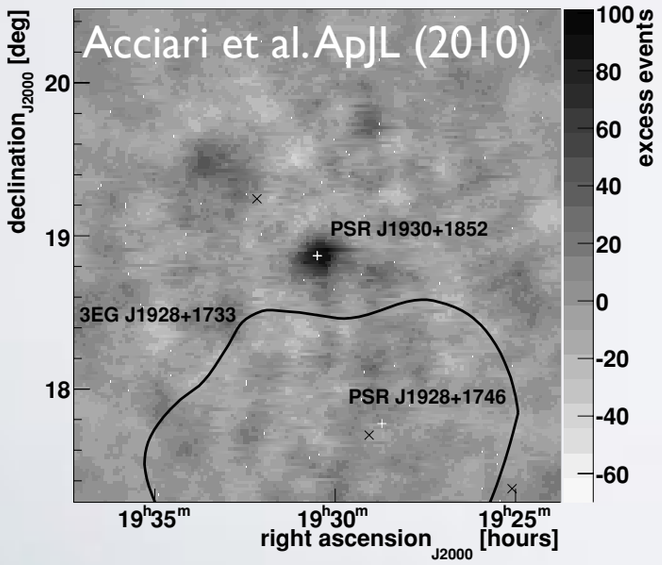
- Geometry and diffusion studies on propagation of electron/positron to Earth.

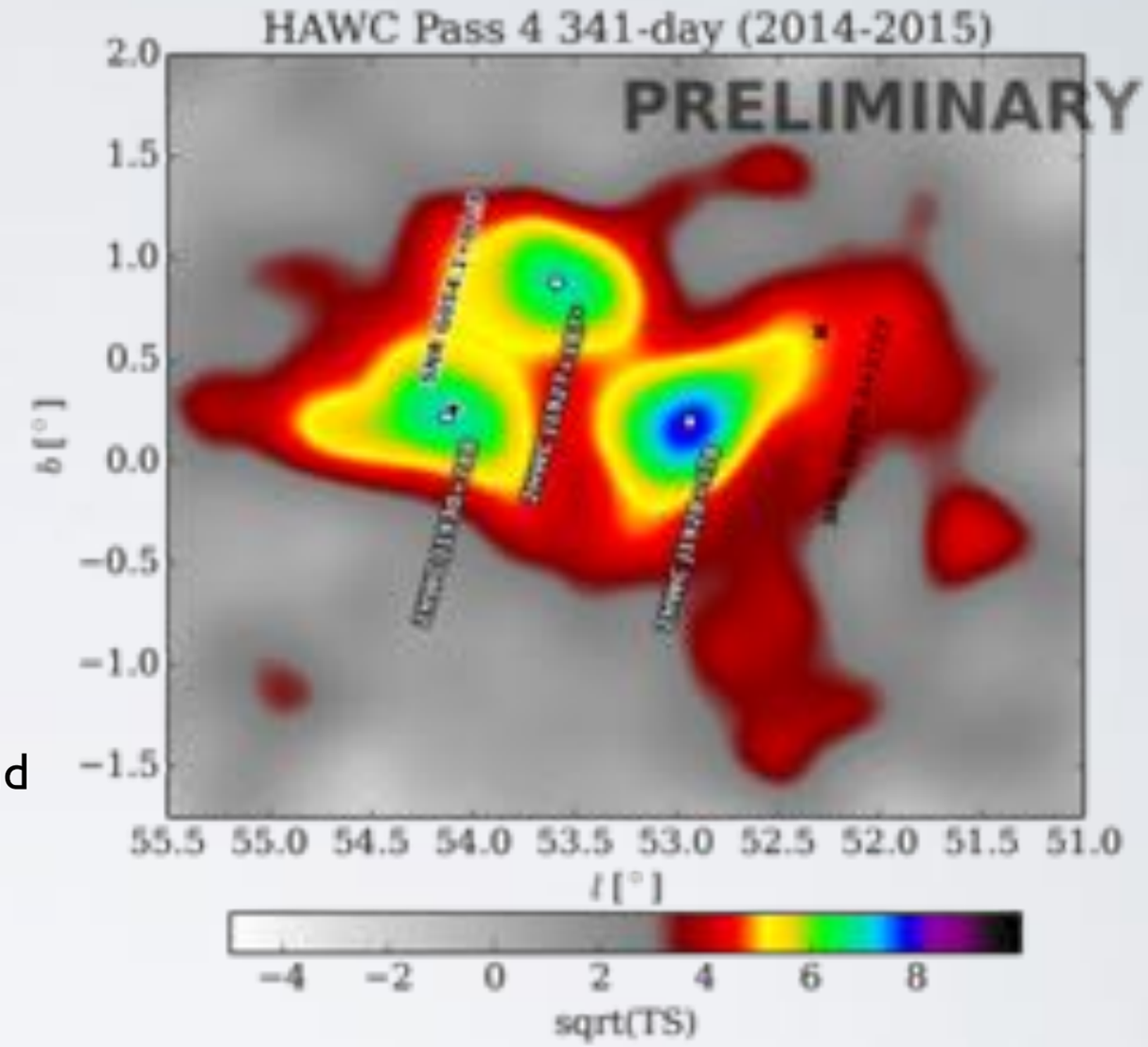


New TeV Sources!

New TeV emission region
2HWC J1927+187*
- ~7σ pre-trials
- current blind search algorithm identify this region associated with 2HWC J1930+188, ongoing analysis on spatial morphology

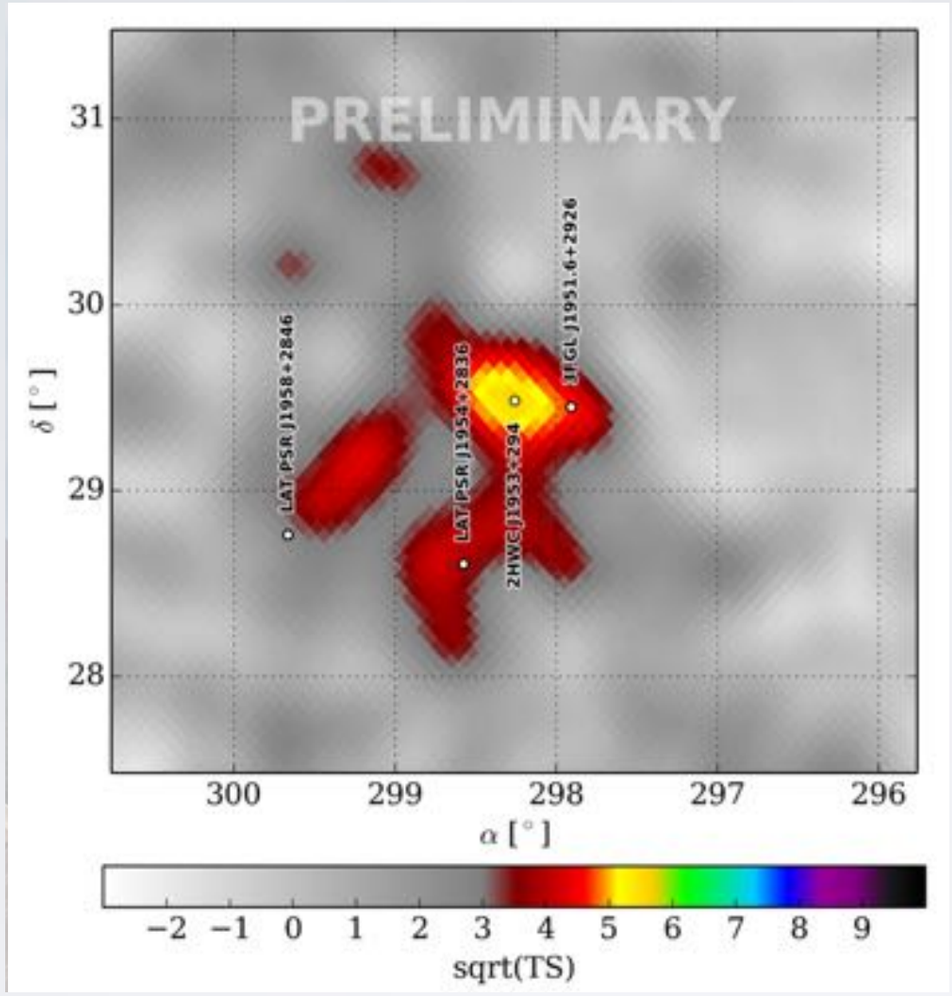
2HWC J1930+188
- coincident with VER J1930+188 (SNR G54.1+00.3 / PSR J1930+1852)
- TeV emission was reported to be point-like and likely from PWN
- nearby molecular CO cloud





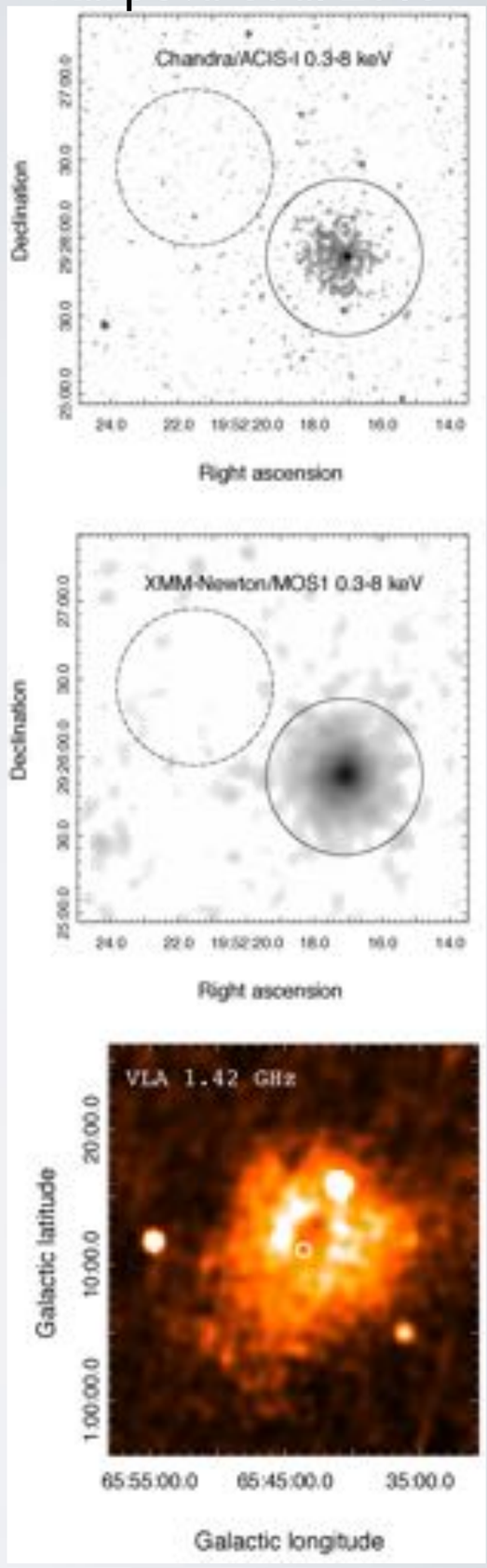
New TeV source
2HWC J1928+178
- ~8σ pre-trials
- coincident with PSR J1928+1746
- tail towards unidentified source 3FGL J1925.4+1727
- VERITAS point source upper limit ~1.4% of Crab

New TeV Sources!

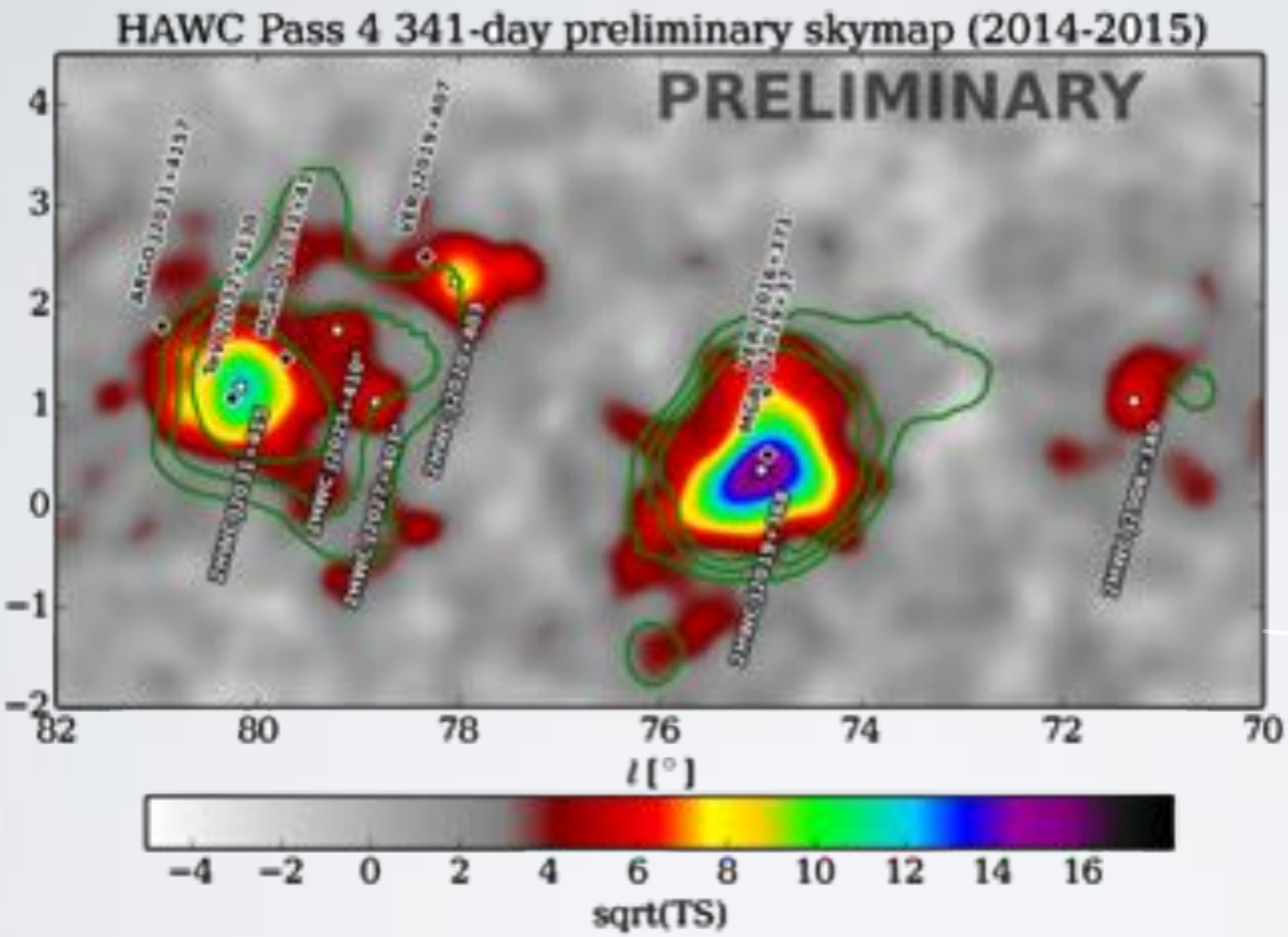


New TeV source
2HWC J1953+294
- confirmed by VERITAS
- potential association:
  - PWN DA 495 seen in X-rays
  - 3FGL J1951.6+2926

Karpova et al 2015

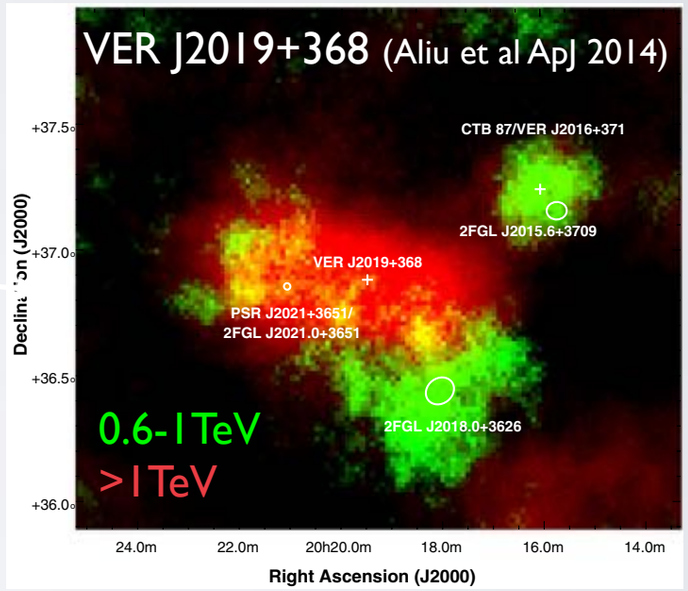


Cygnus Region



New TeV source
2HWCJ2006+340:

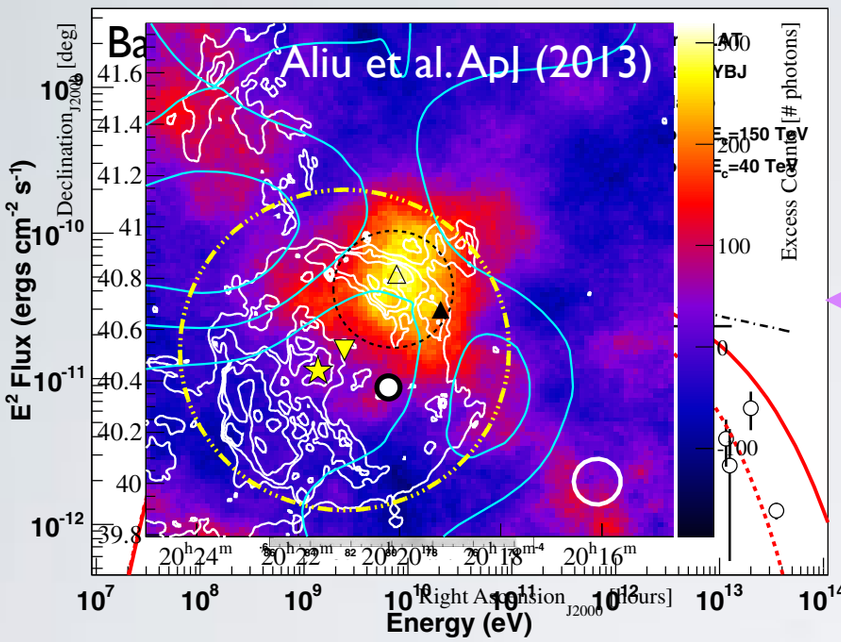
- >6σ pre-trials
- 0.6° from unidentified source 3FGL J2004.4+3338

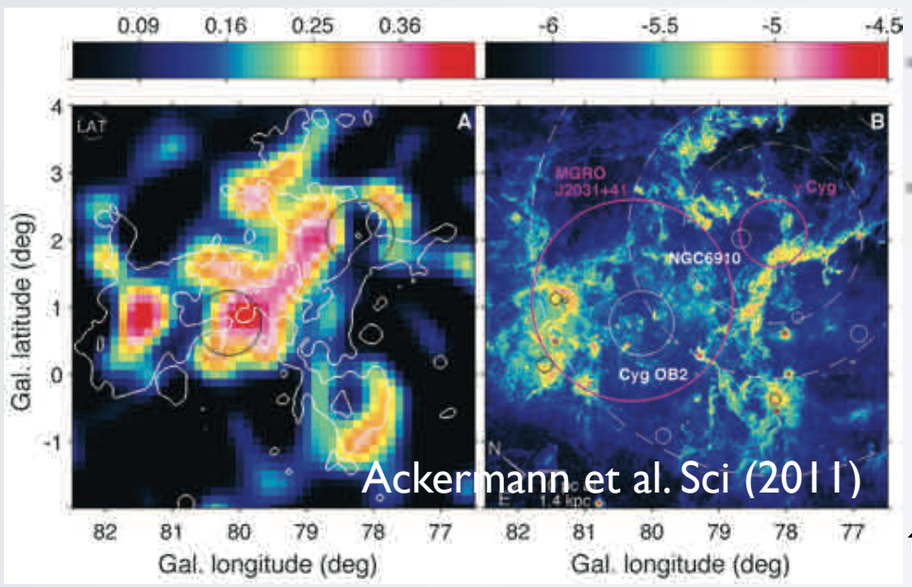


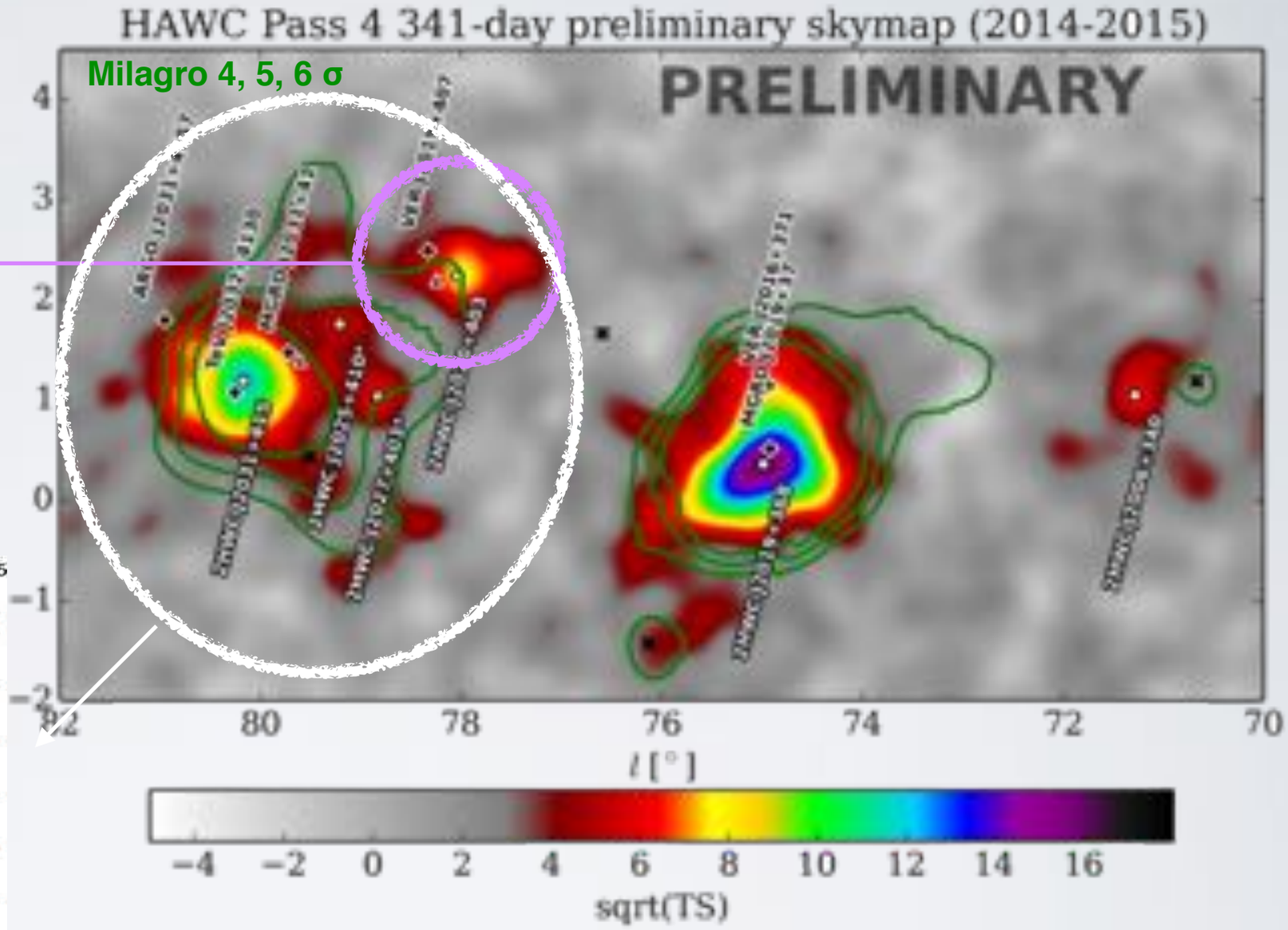
2HWC J2019+368 is coincident with MGRO J2019+37 and VER J2019+368

- extended emission including PSR J2021+3651 and HII region Sh 2-104

Cygnus Region







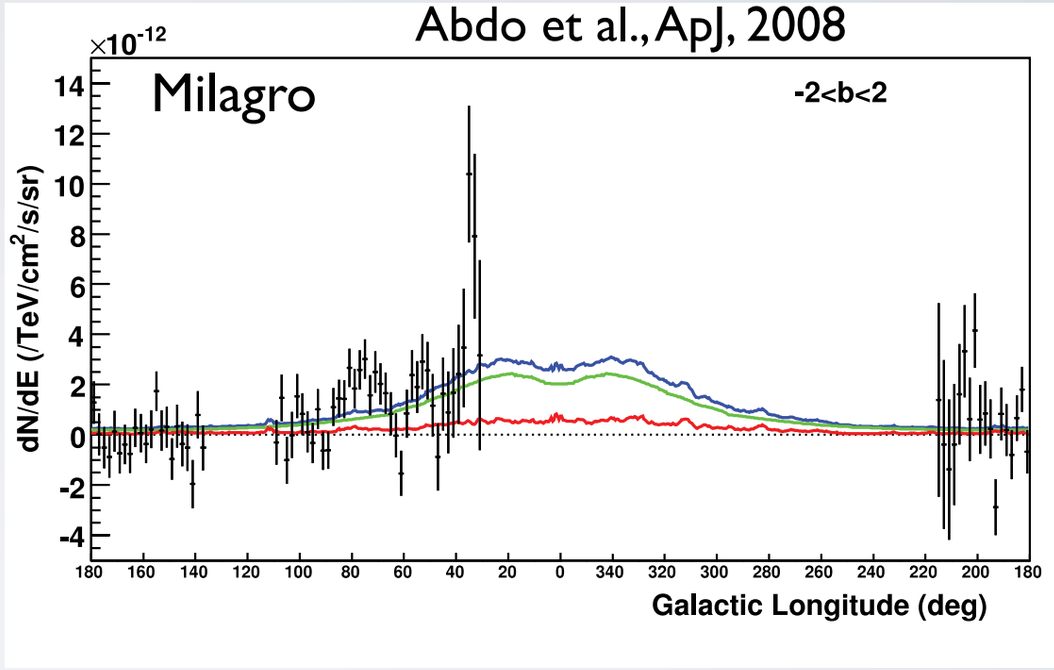
two distinct TeV sources:

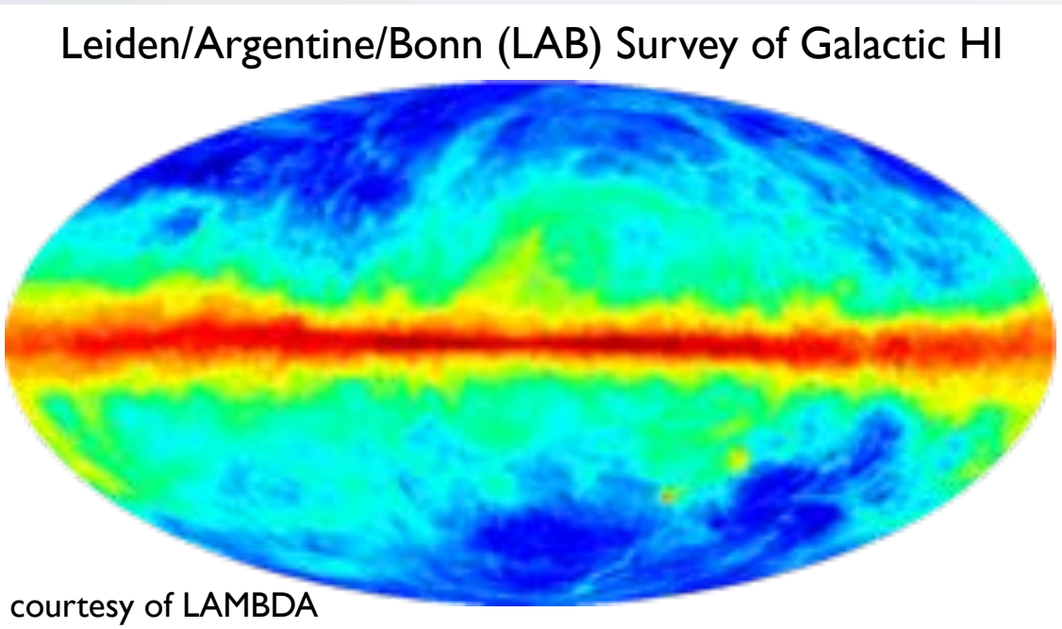
- 2HWC J2031+415 — TeV J2032+4130, a PWN
- 2HWC J2020+403 — VER J2019+407, UID encompassing SNR G78.2+2.1 and PSR J2021+4026
- extended emission region 2HWC J2025+410* and 2HWC J2027+403* at Fermi cocoon / ARGO superbubble region

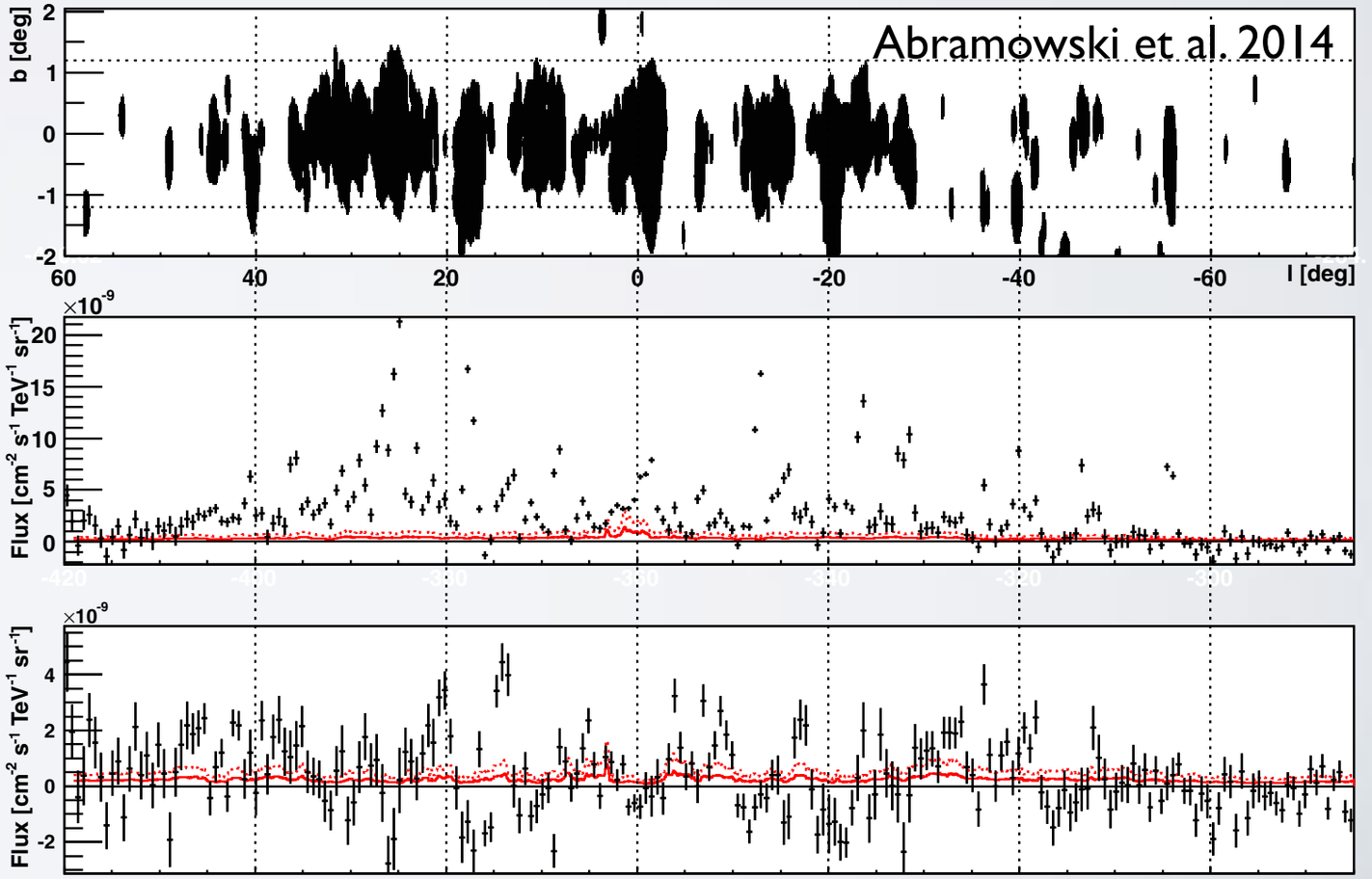
Galactic Diffuse Emission

Diffuse contributions:

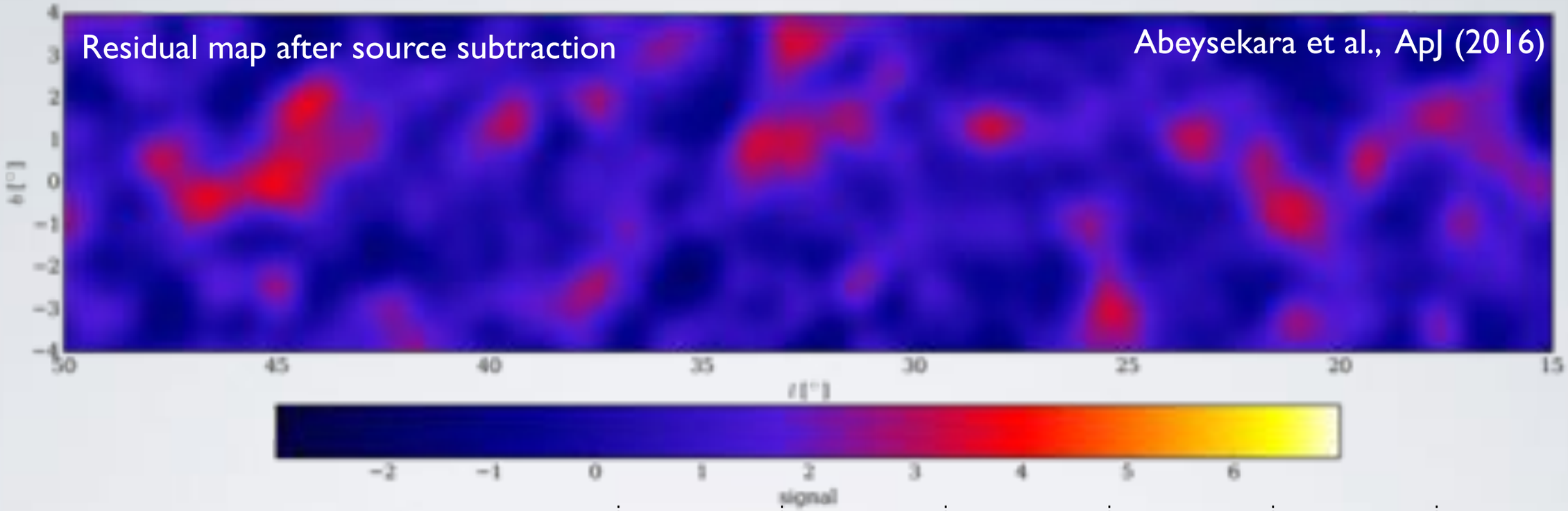
- Cosmic-ray interactions
  - molecular clouds
  - interstellar gas
- Inverse Compton
- Unresolved sources.

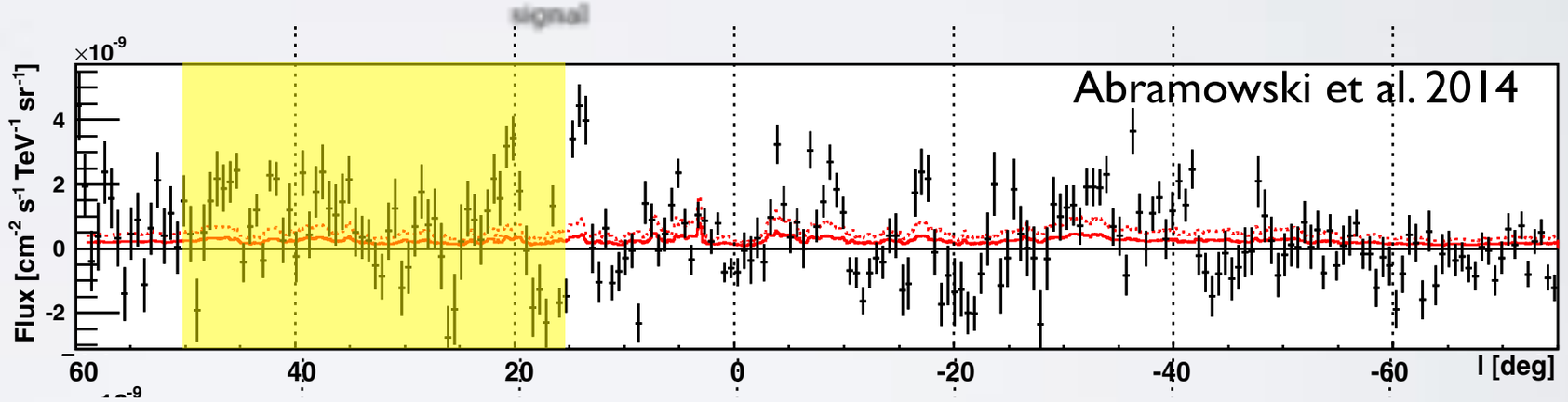






Galactic Diffuse — Limit from Pass 1

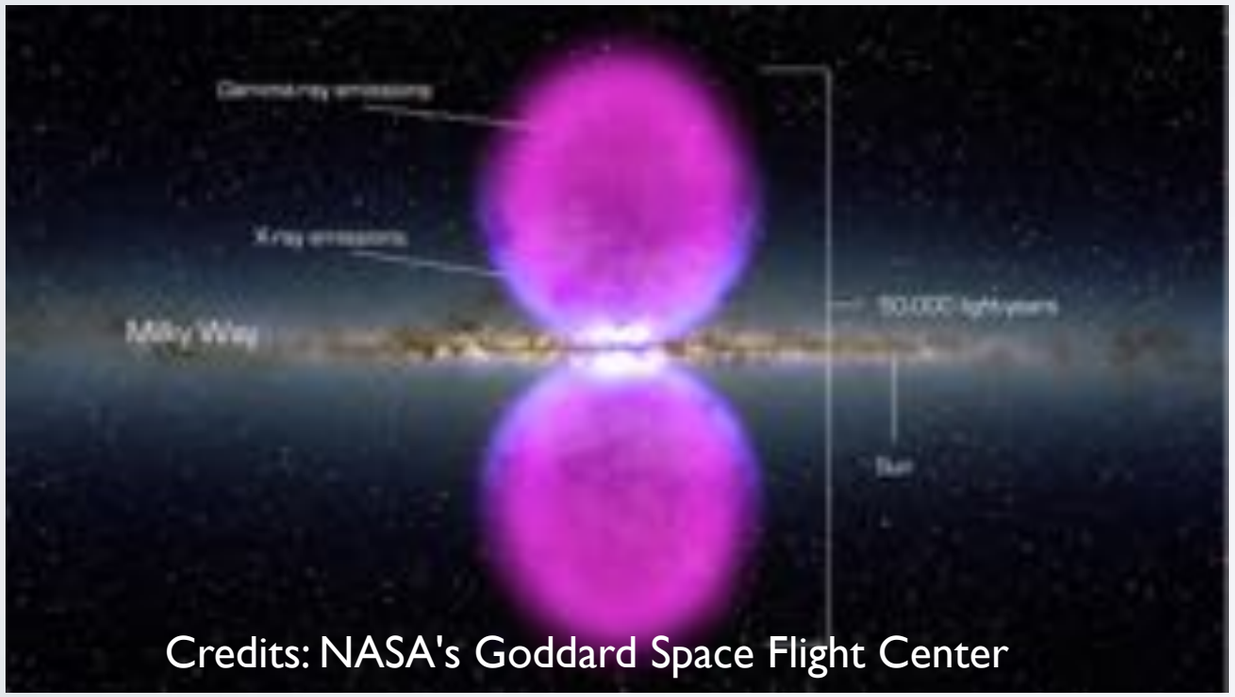


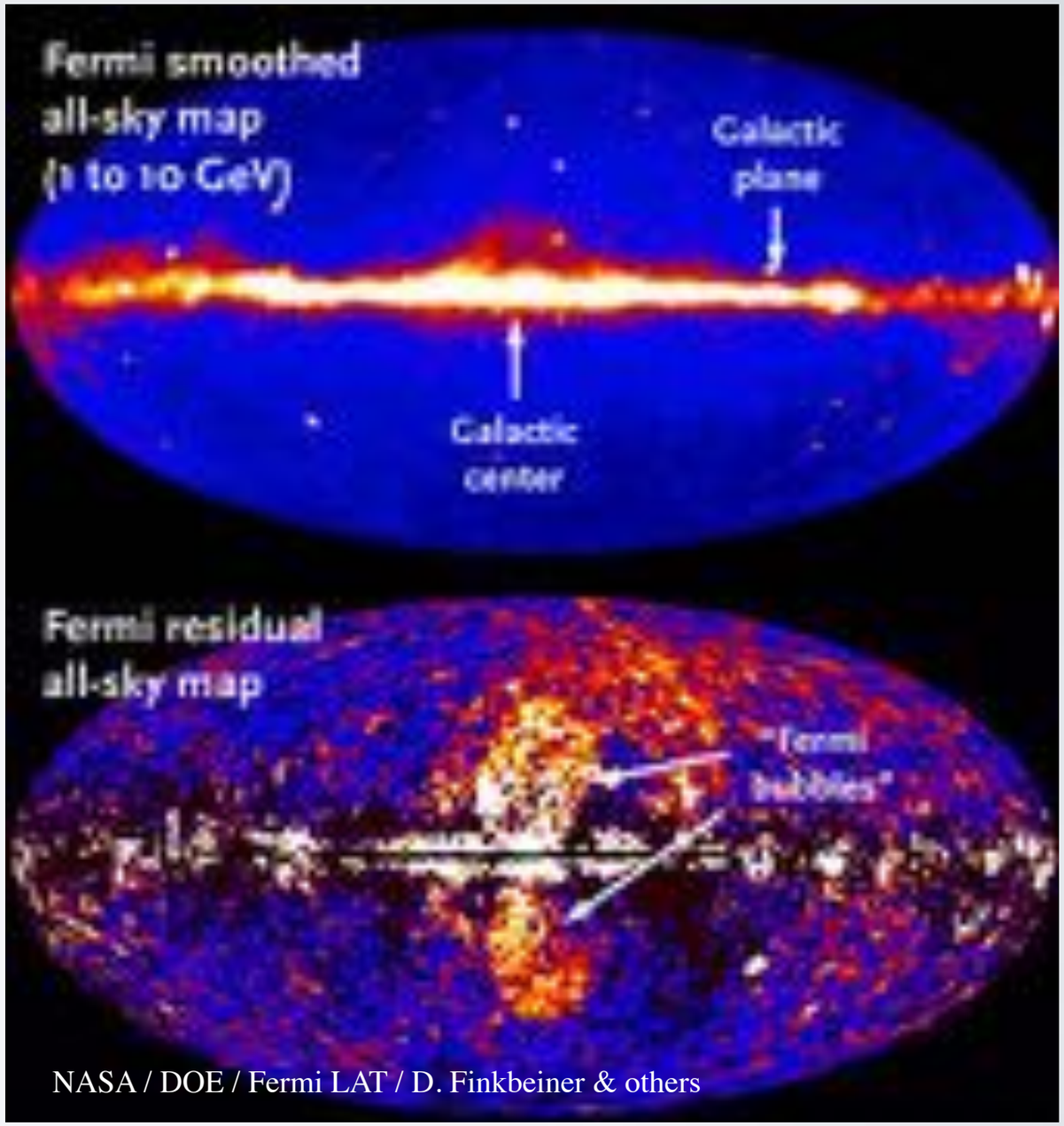


- A uniform surface brightness fit in addition to source model is preferred at **5.7σ**.
- The fitted surface brightness at 5 TeV is 1.6±0.4e-11 TeV^{-1} cm^{-2} s^{-1} sr^{-1}.
- HESS average diffuse extrapolated to 5 TeV is 1.0±0.2e-11 TeV^{-1} cm^{-2} s^{-1} sr^{-1}.
- Current limit from HAWC-111 dataset includes unresolved sources.

Large-scale structures e.g. Fermi Bubbles

- Large scale, non-uniform structures extending above and below the Galactic center.
  - Edges line up with X-ray features.
  - Correlate with microwave excess (WMAP haze)
  - Both hadronic and leptonic model fit Fermi LAT data. Leptonic model can explain both gamma ray and microwave excess.





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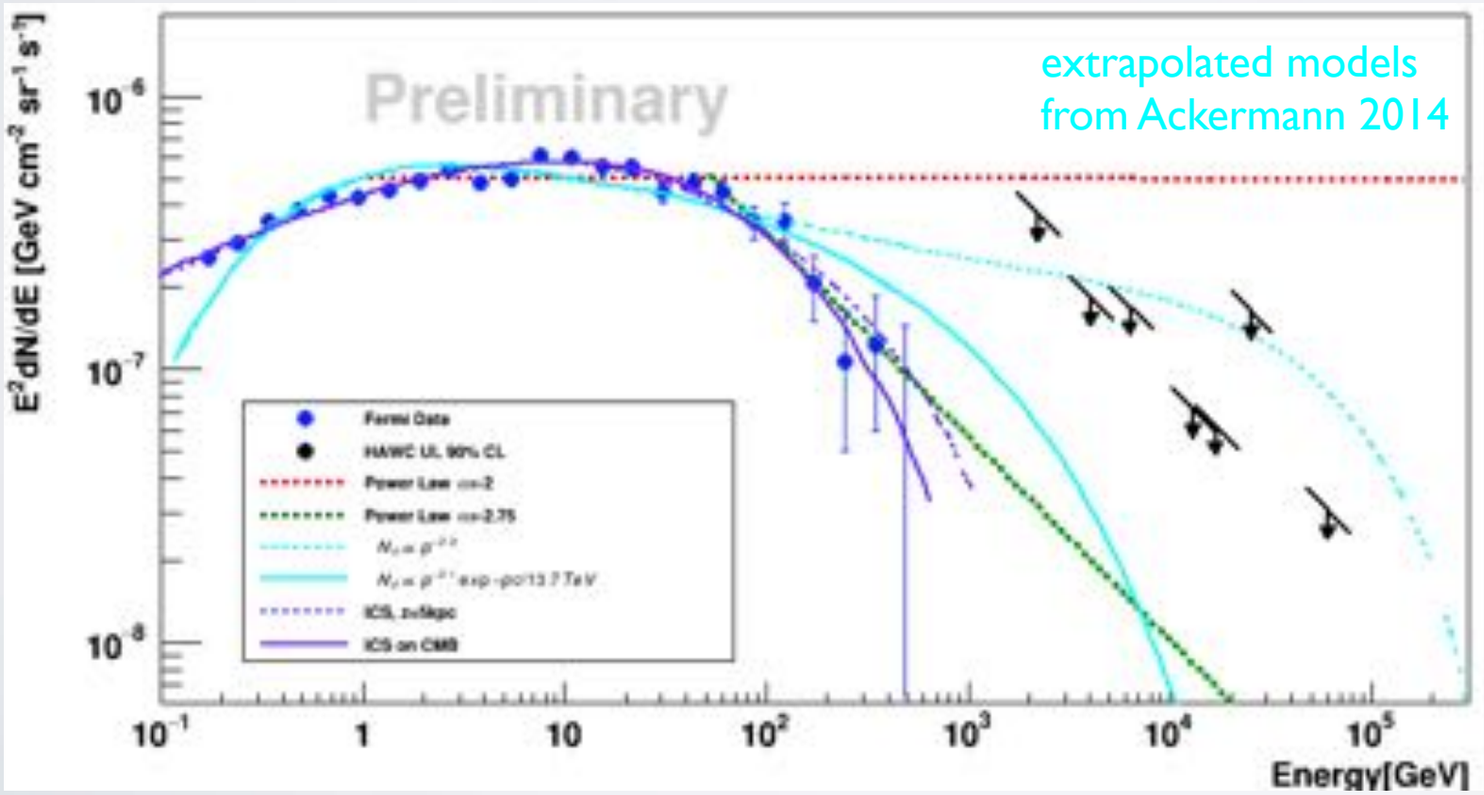
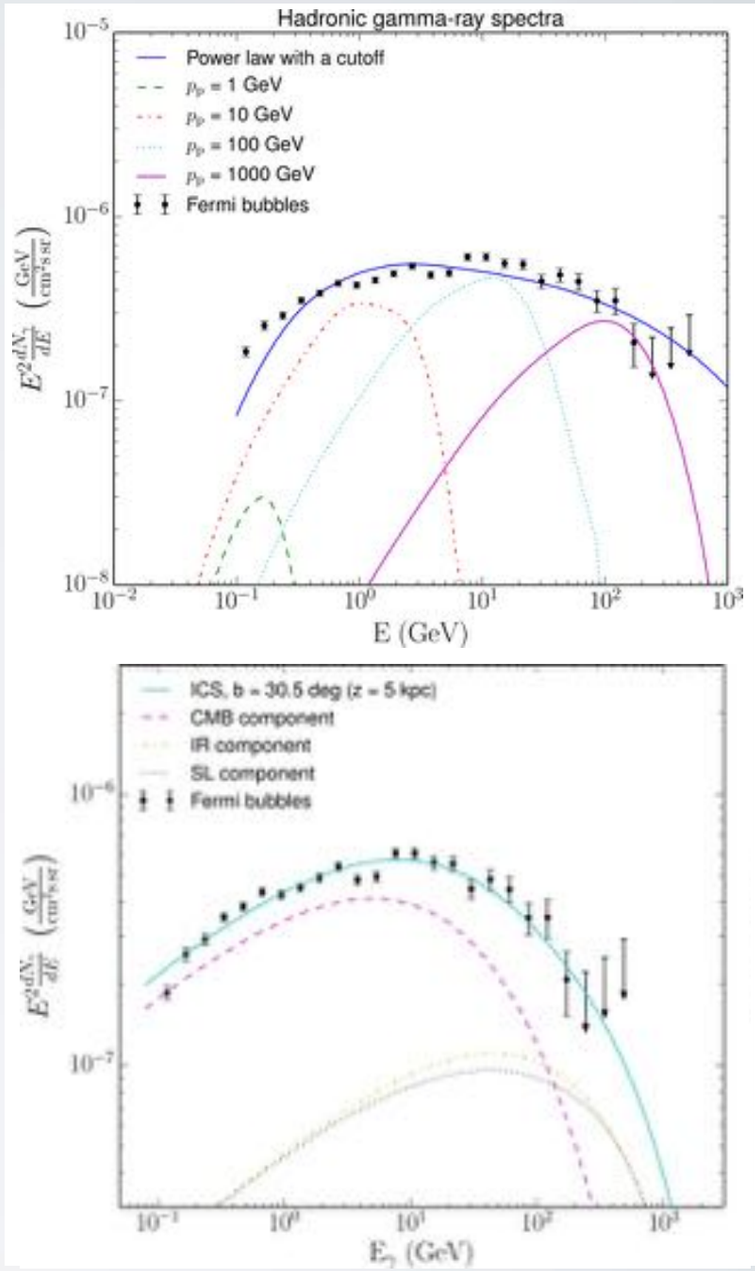
- Large scale, non-uniform structures extending above and below the Galactic center.
  - Edges line up with X-ray features.
  - Correlate with microwave excess (WMAP haze)
  - Both hadronic and leptonic model fit Fermi LAT data. Leptonic model can explain both gamma ray and microwave excess.
- First limits in TeV, **hard spectrum is highly unlikely.**





Ackermann et al. ApJ (2014)

Transient Search

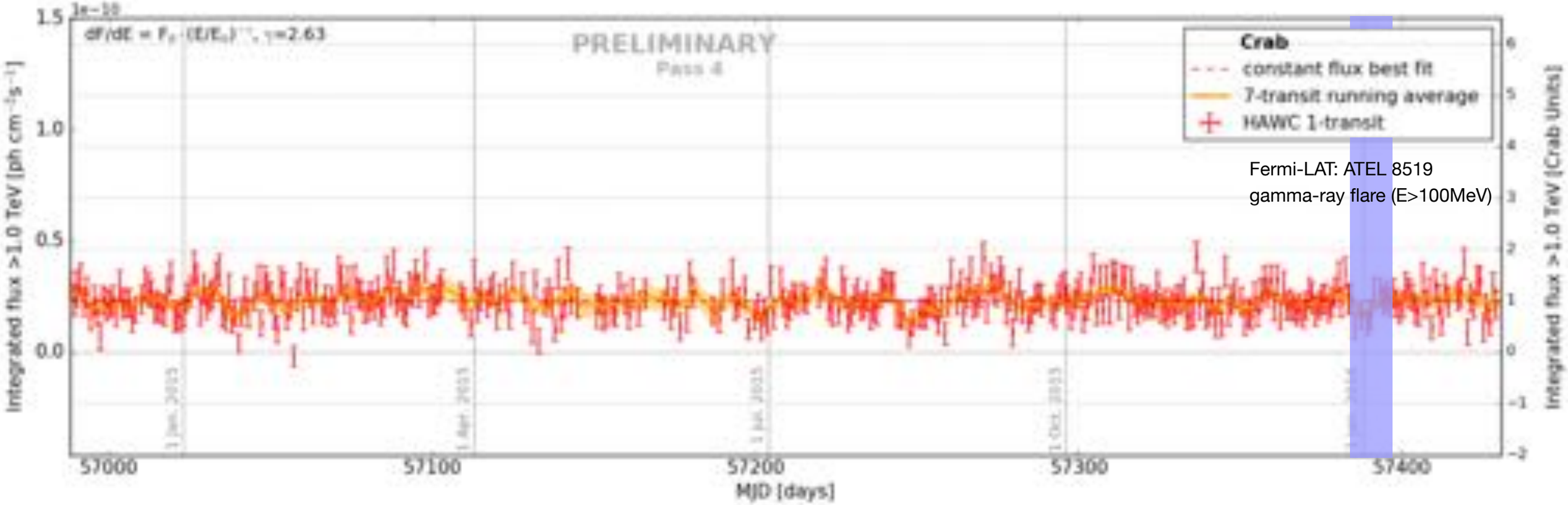
Crab Nebula

- Crab flares, continue up to TeV?
- No activity in radio, IR, and X-rays.

HAWC observation:

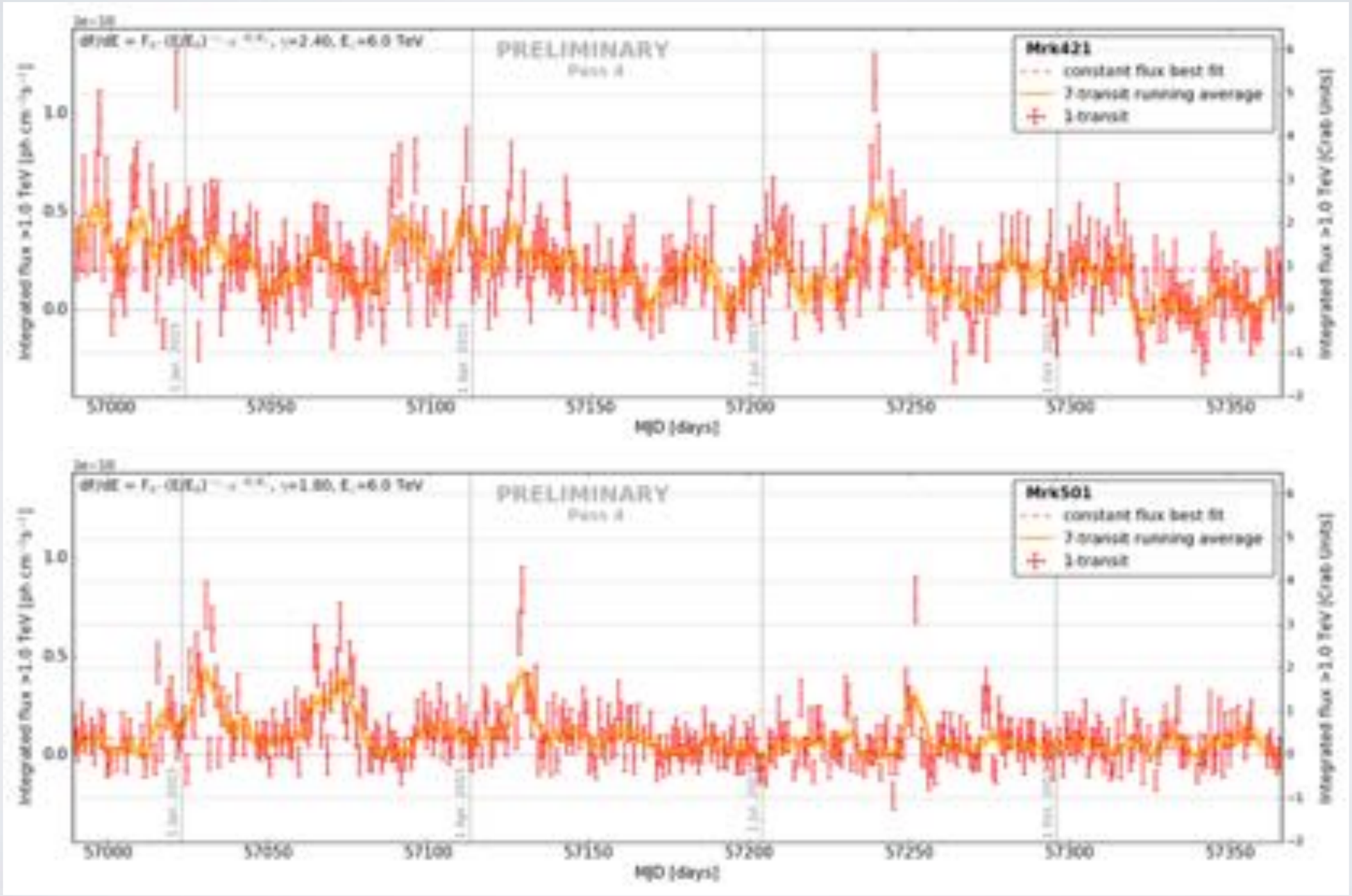
- Data is consistent with a constant flux.
- Coincident observation with Fermi-LAT reported Crab flare starting Jan 7 2016.
- 95% C.L. upper limit on 13-day average flux above 1TeV is 1.01x average Crab flux.

MeV-GeV gamma ray



Transient Search

AGN flares Mrk 421 / Mrk 501



Multi-wavelength / Multi-messenger

Have follow-up agreement with:
- Swift
- Fermi-LAT
- IACTs
  - FACT
  - HESS
  - MAGIC
  - VERITAS
- AMON
- IceCube
- ANTARES
- LIGO/VIRGO

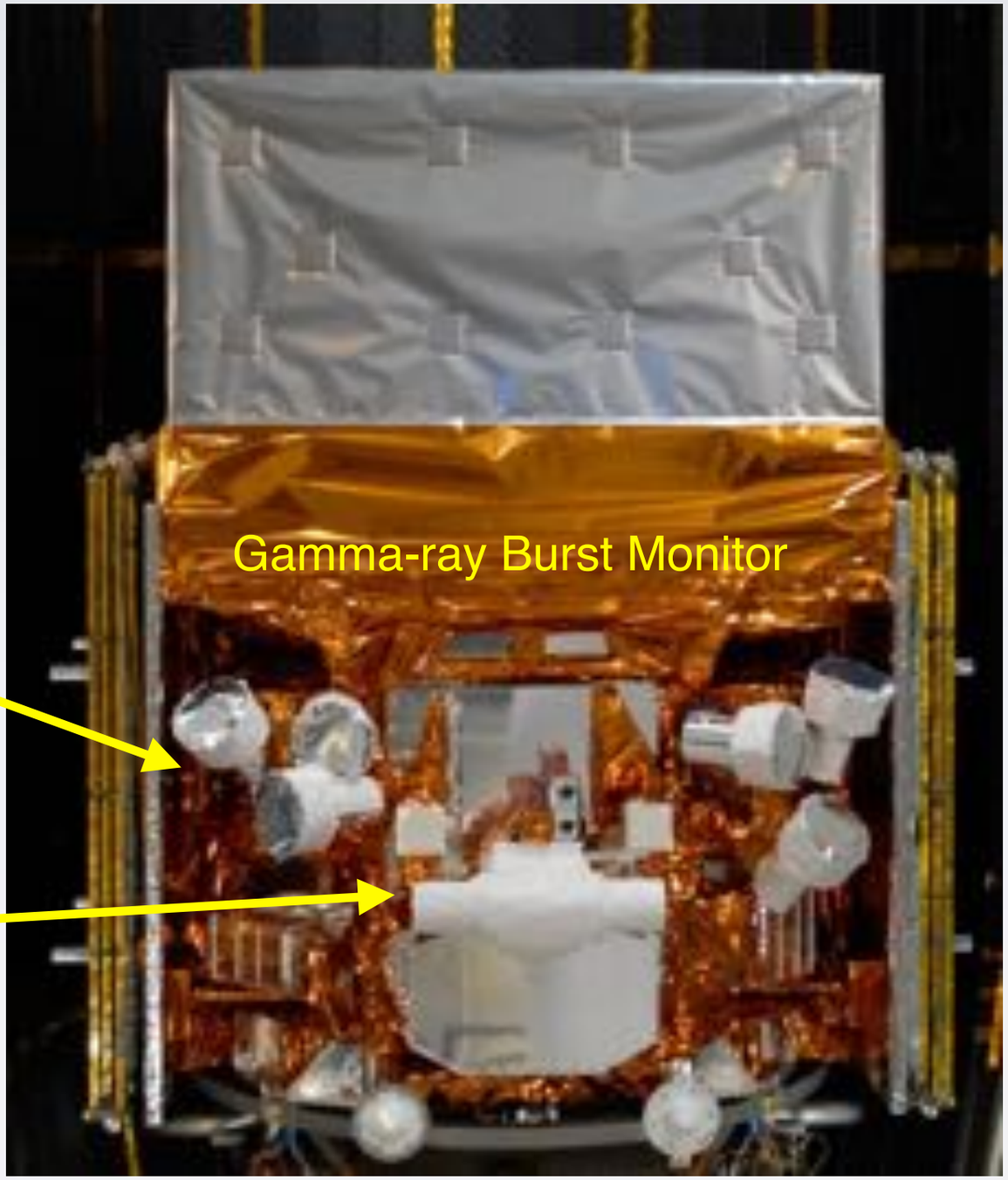
HAWC-triggered:
- New source candidates lists.
  - follow-up observations by IACTs such as VERITAS and MAGIC from Pass 1 release.
- Flares from known gamma-ray sources.

HAWC ATel #8922 on Mrk 501 flare

Externally triggered:
- IceCube alert on high confidence neutrino event (highest energy pointed astrophysical track-like).
- Fermi alerts on flaring activities.
- LIGO/VIRGO gravitational wave event follow-up

IceCube ATel: #7856
HAWC Follow-up ATel: #7868

Fermi Gamma-ray Space Telescope



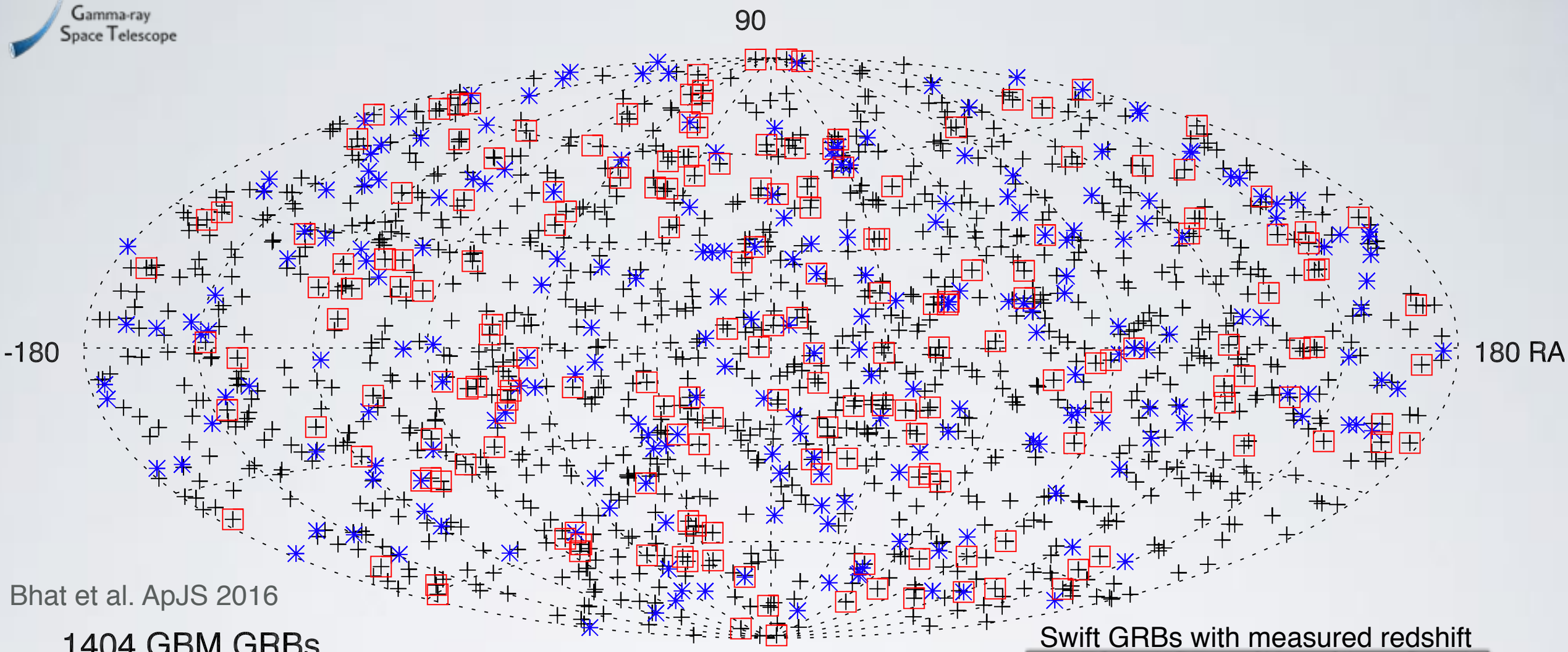
12 NaI detectors
(8keV—1MeV)

2 BGO detectors
(200keV—40MeV)

GBM:

- FOV >8sr
- Whole sky every ~90min

Fermi GBM GRBs in first six years of operation



Bhat et al. ApJS 2016

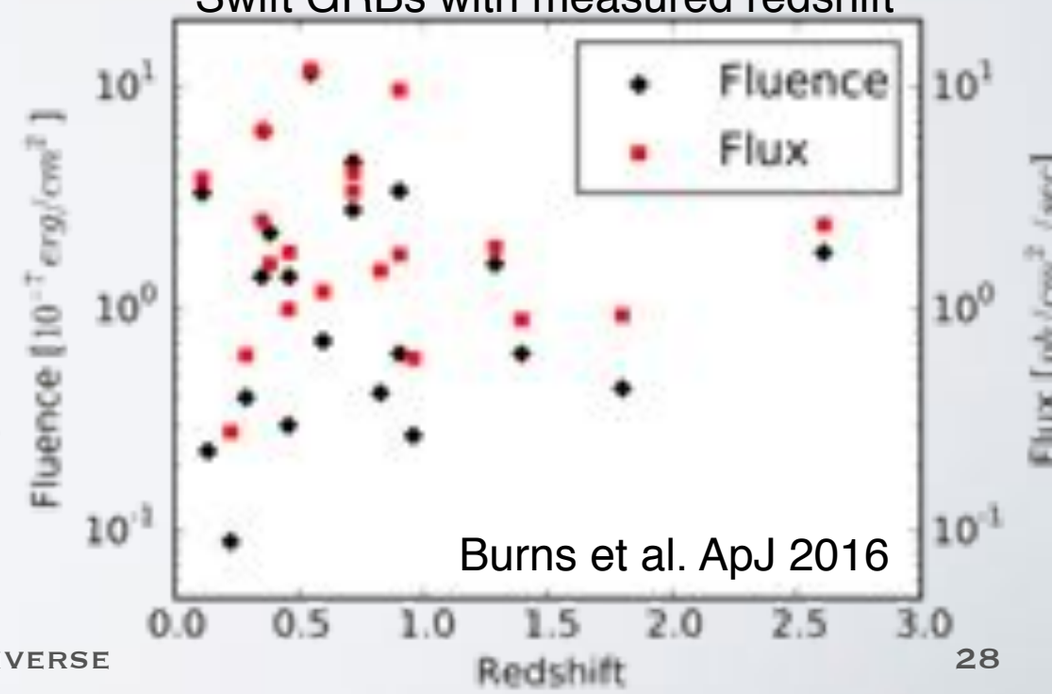
1404 GBM GRBs

+ 1175 Long

✳ 229 Short

□ 191 also triggered Swift-BAT

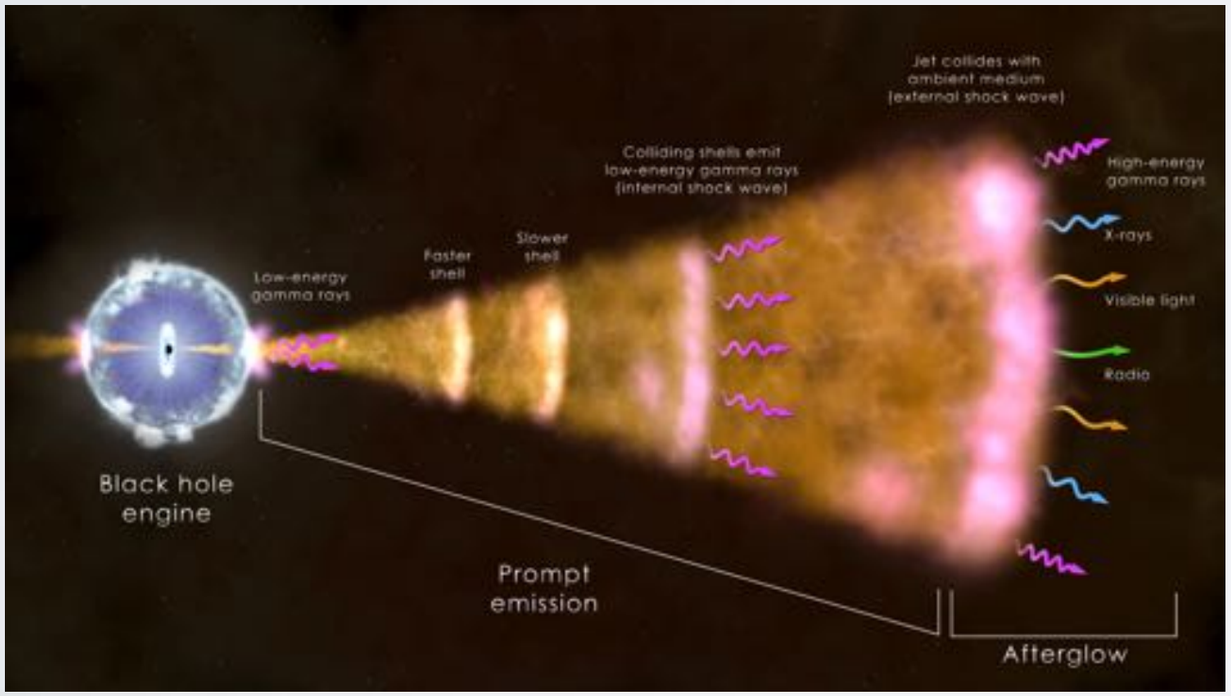
Swift GRBs with measured redshift

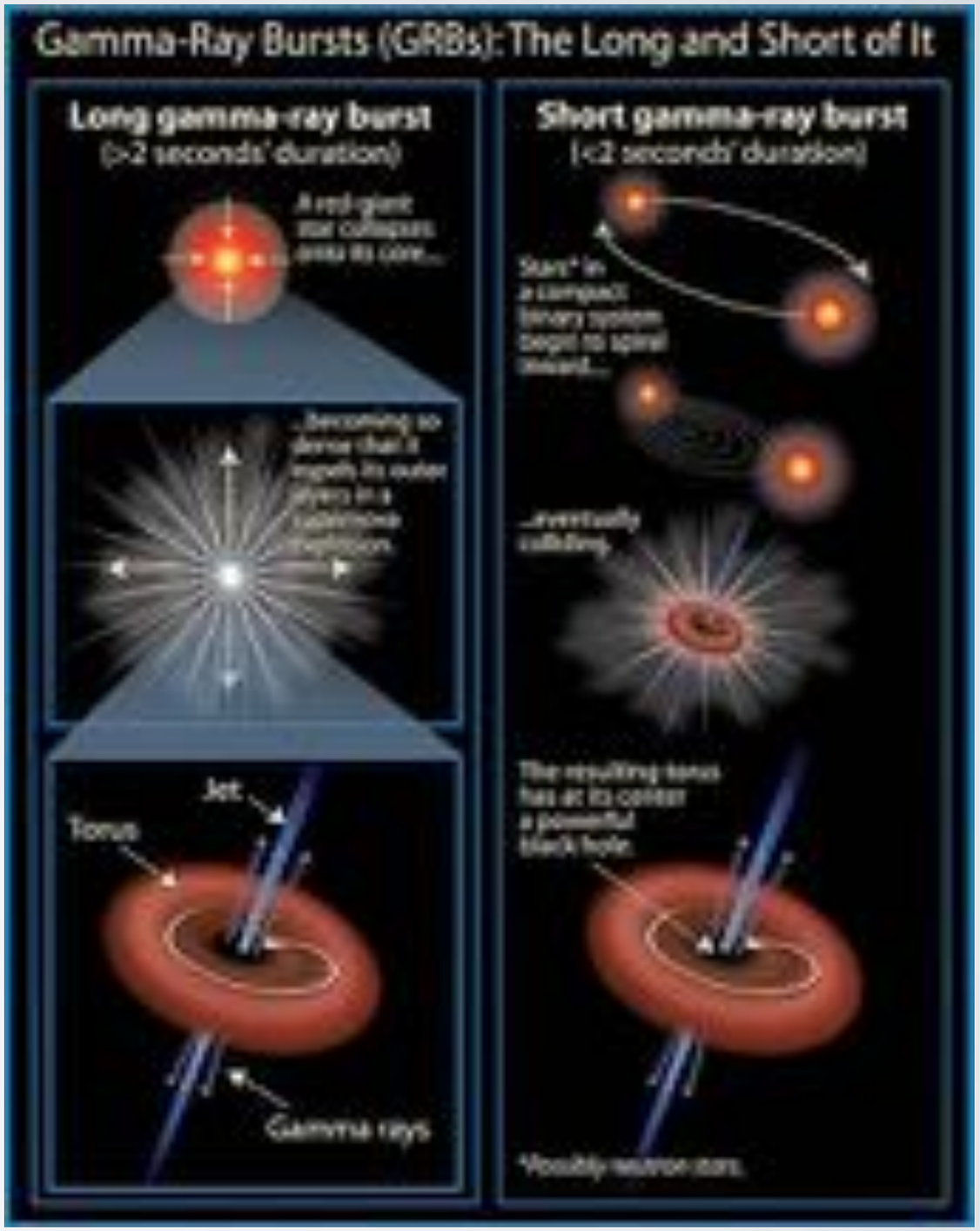


- Brightness of weak short GRBs does not appear to be redshift dependent
  - i.e. weak ≠ far away

Gamma-ray Bursts

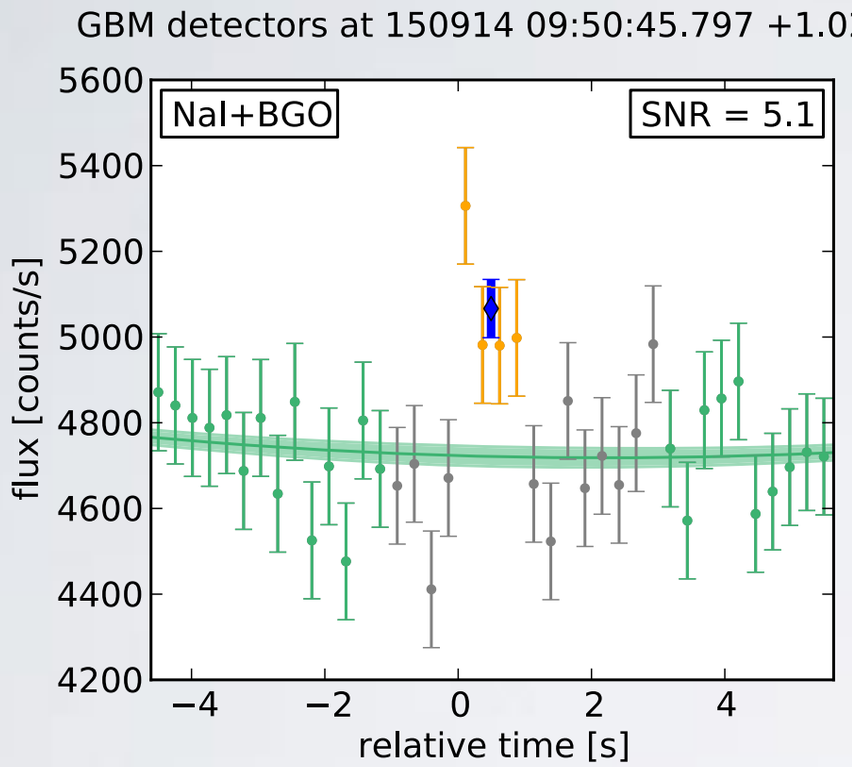
- Collapse of a massive star or merger of two compact objects.
- Collimated relativistic outflow.
- Prompt keV-MeV emission, afterglow in other wavelengths.
- Detected ~ once per day, distributed all over the sky.

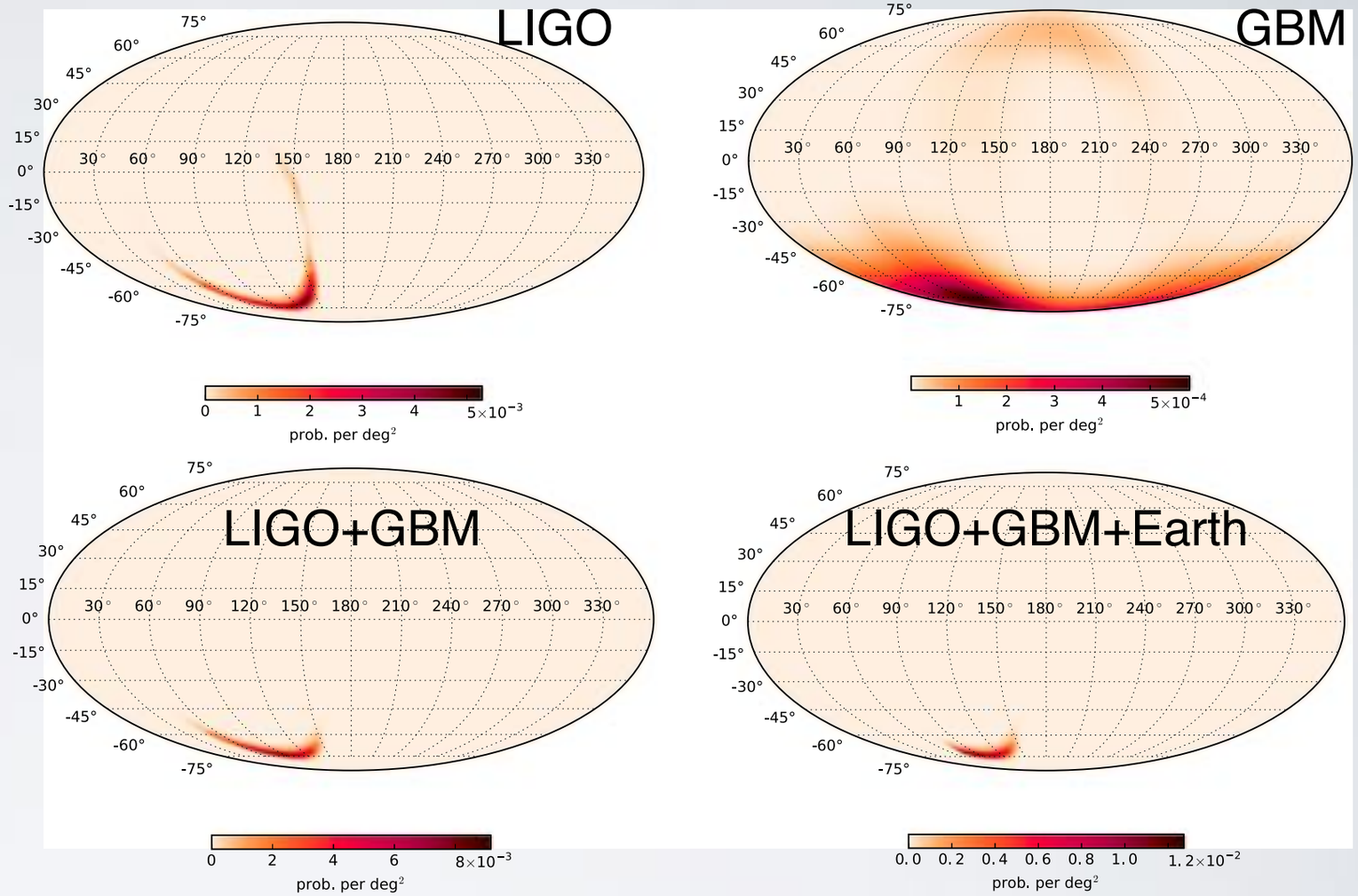




Follow-up to Gravitational Wave Event GW150914

Connaughton et al. ApJL 2016





601 sq deg ➡ 199 sq deg

- Untriggered sub-threshold signal 0.4s after LIGO trigger.
- Consistent with a low-fluence short GRB coming from behind Fermi.
- Poorly localized but consistent with LIGO localization.
- 0.2% post-trials probability in statistical fluctuation.

Untriggered GBM GRB search

- In additional to the directed search with LIGO events, untriggered search in the Continuous Time Tagged Events (CTTE) data is ongoing.
  - 2 μs time resolution with 128 energy channels
  - 10+ timescales: 64ms to 2.8+ s
  - multiple energy ranges
- Working towards creating automated GCNs, will be distinct from triggered events type.

http://gammaray.nsstc.nasa.gov/gbm/science/sgrb_search.html

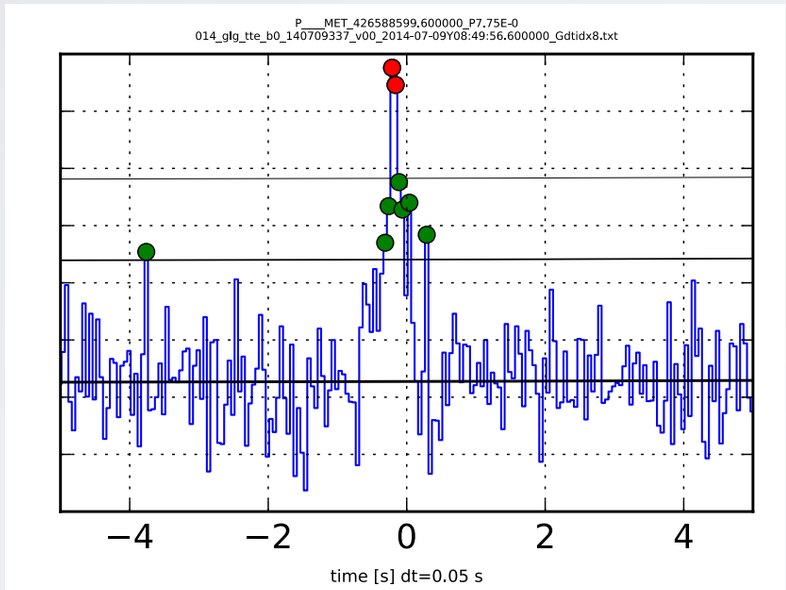
Short GRB Candidates

MET	RANK	DATE (UT)	TIME (UT)	RA (DEG)	DEC (DEG)	ERROR (DEG)	COMMENT
423745086.625	1.91E-0016	2014-06-06	10:58:13.625	232.07	+37.47	16.86	
424708158.025	2.36E-0007	2014-06-17	14:29:15.025	359.06	-32.47	5.59	
424757010.500	1.92E-0016	2014-06-18	04:03:27.500	278.84	+64.38	4.67	
424968038.500	2.80E-0007	2014-06-20	14:40:35.500	319.45	-17.40	17.05	
426319641.550	2.00E-0010	2014-07-06	06:07:18.550	64.10	+25.04	6.41	
426568599.500	7.75E-0014	2014-07-09	08:49:56.600	12.77	-49.36	8.53	
426850830.700	4.21E-0007	2014-07-13	13:27:7.700	264.57	-87.36	13.49	
427440602.000	2.65E-0007	2014-07-19	05:28:19.000	34.37	+45.94	15.21	
431283951.000	3.82E-0008	2014-09-01	17:05:48.000	80.94	+69.19	16.02	
431291510.000	3.03E-0007	2014-09-01	19:11:47.000	81.08	-17.32	15.88	
432797599.000	3.30E-0007	2014-09-19	05:33:18.000	177.15	-37.38	20.86	
433786586.000	1.95E-0007	2014-09-30	17:06:23.000	283.03	-9.27	11.33	

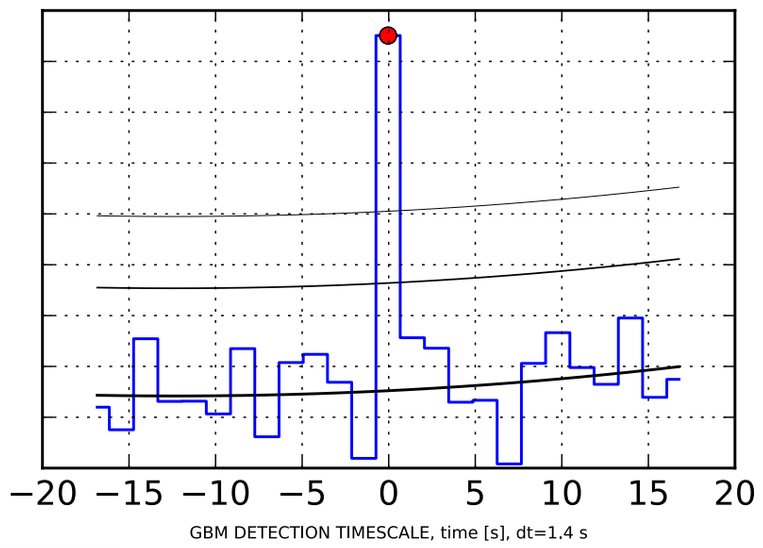
GBM Candidate Event

- 2014-07-09 08:49:56.600
- Found in 1.40s time binning
- 25 - 494 keV energy range
- P=7.75e-14

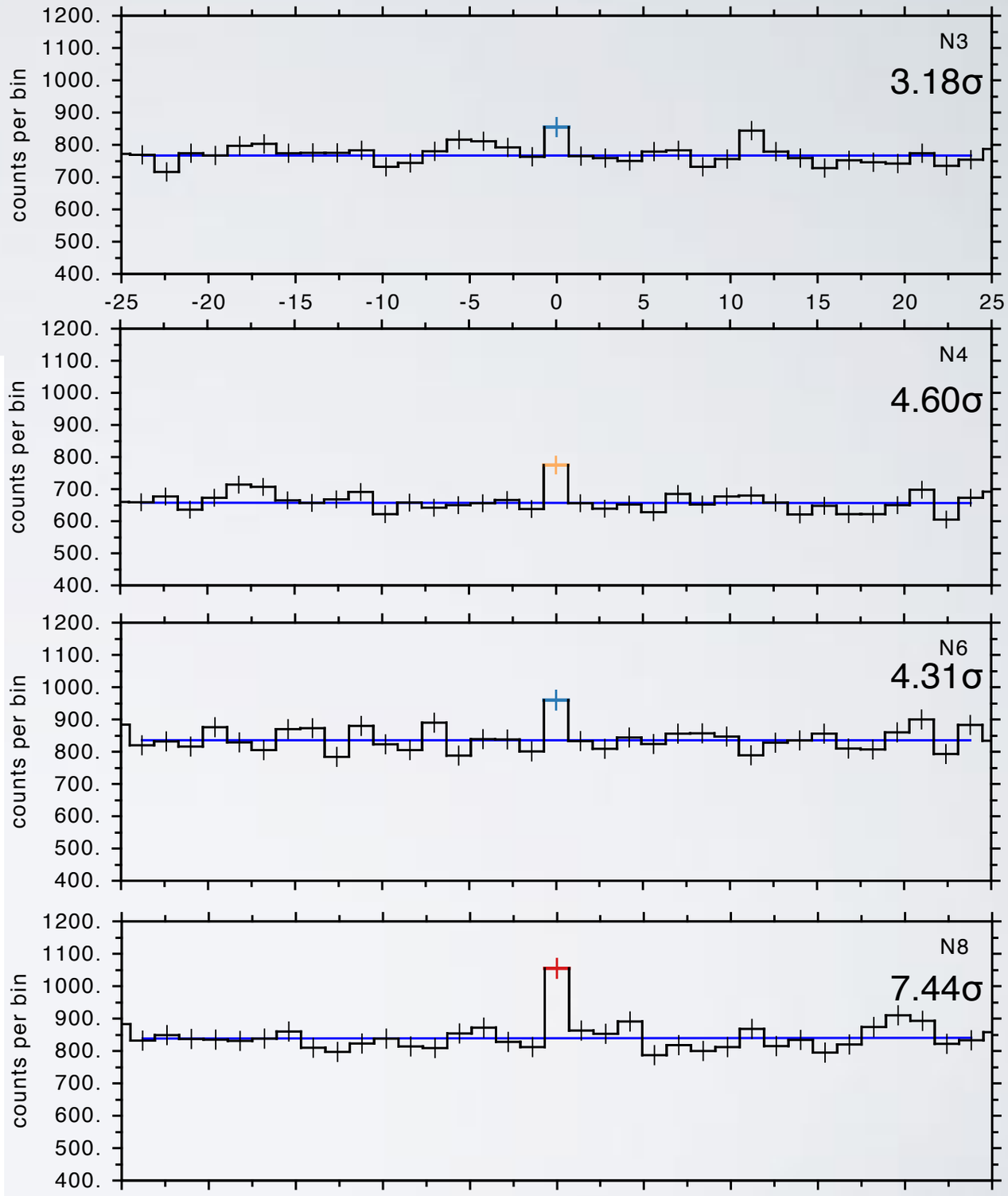
INTEGRAL Anti-Coincidence Shield(ACS) lightcurve



ACS native time bin



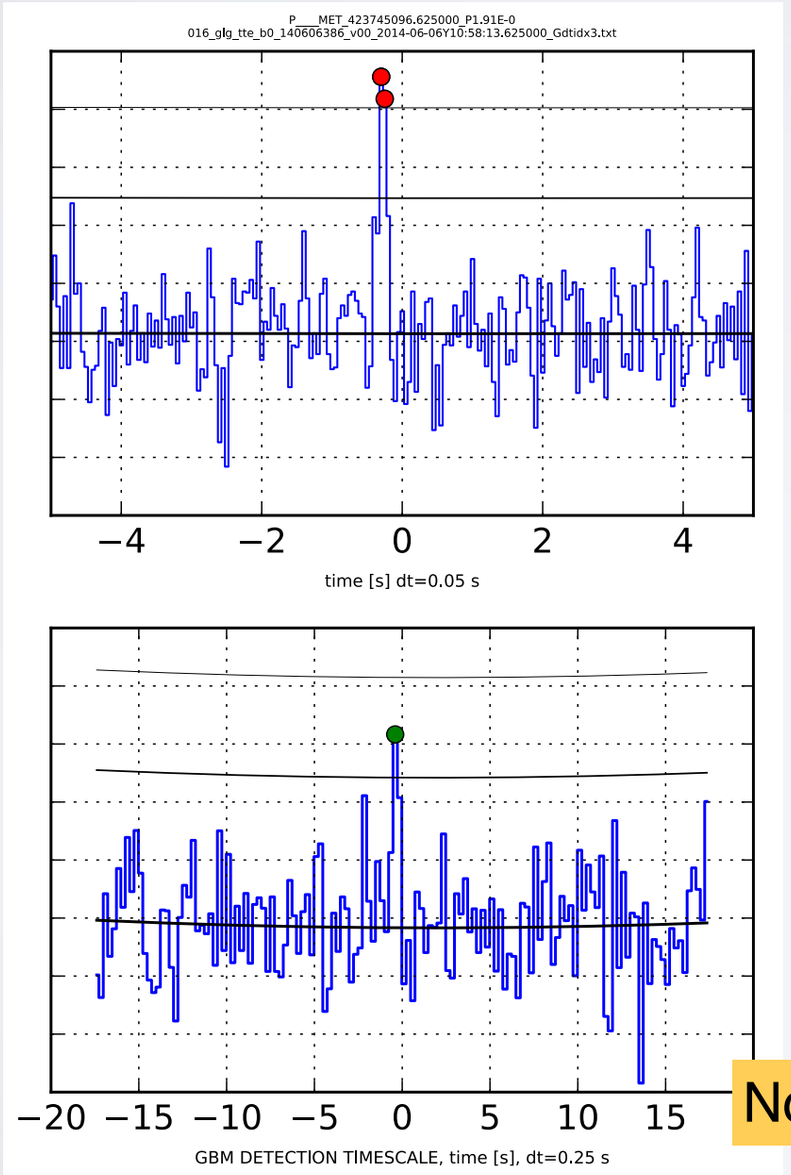
GBM timescale



GBM Candidate Event

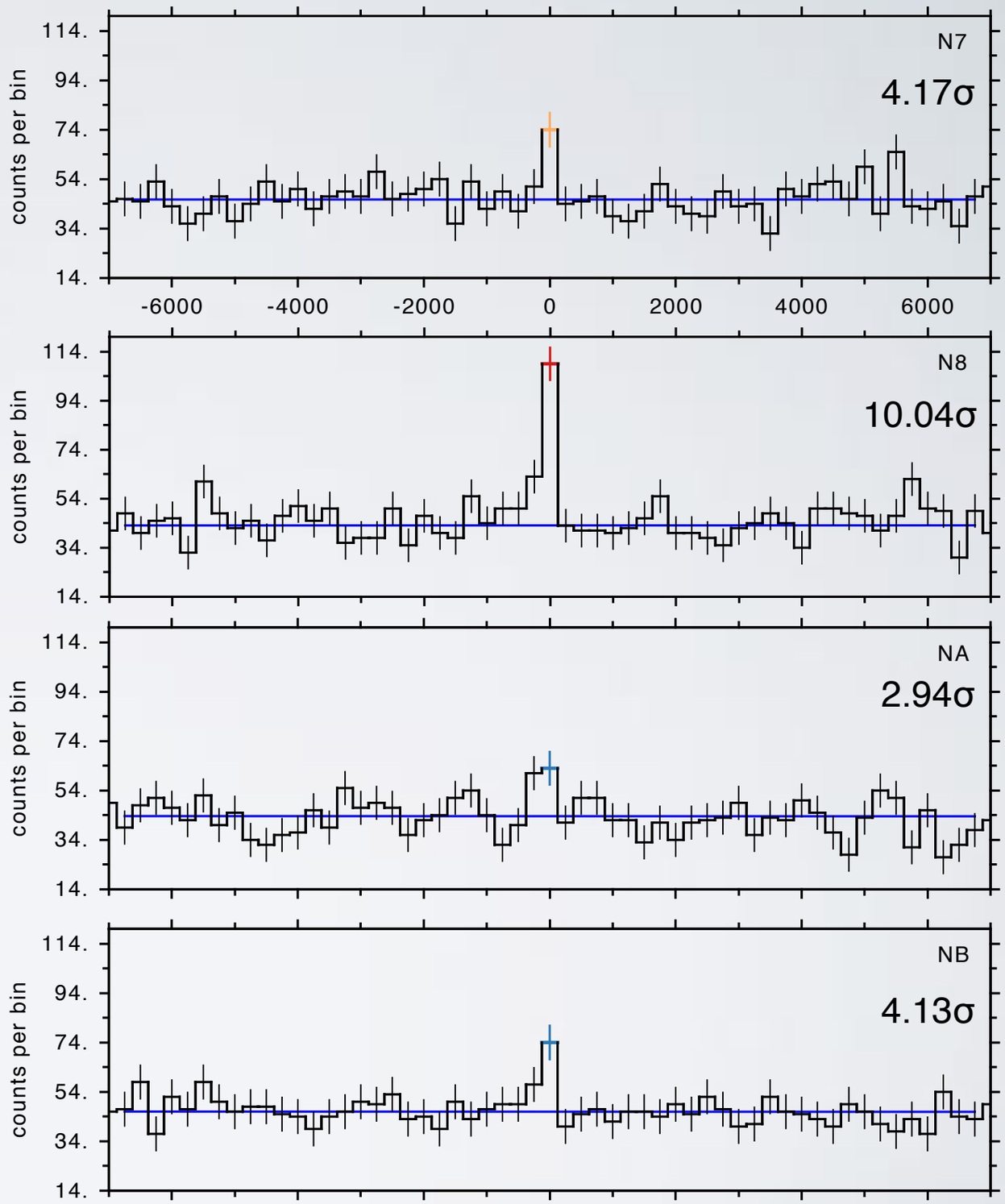
- 2014-06-06 10:58:13.625
- **Swift GRB 140606A**
- Found in 0.25s time binning
- 93 - 494 keV energy range
- P=1.91e-16

INTEGRAL ACS lightcurve



ACS native time bin

GBM timescale



Not all GBM triggered short GRB are detected by ACS.

Outlook

- Both Fermi and HAWC surveying and monitoring the gamma-ray sky in different energies, with ground-based telescopes such as VERITAS ready for follow-up.
- Many instruments from different waveband/messenger (X-rays, neutrinos, gravitational waves) available for simultaneous observation.

- HAWC observatory catalog of first year full operation is in prep (2HWC), with new TeV sources!
- Diverse science results, stay tuned!
- Upgrade to expand the array to enhance effective area >10 TeV by 3-4x is currently under installation.