



VERITAS and HAWC Windows on Cosmic Particle Acceleration From 0.1-100 TeV



Andrew W Smith
University of Utah

TeV Astronomy Origins: Victor Hess

- Observed ionizing radiation increasing as function of altitude in balloon flights
- Discovery of Cosmic Rays! 1936 Nobel Prize



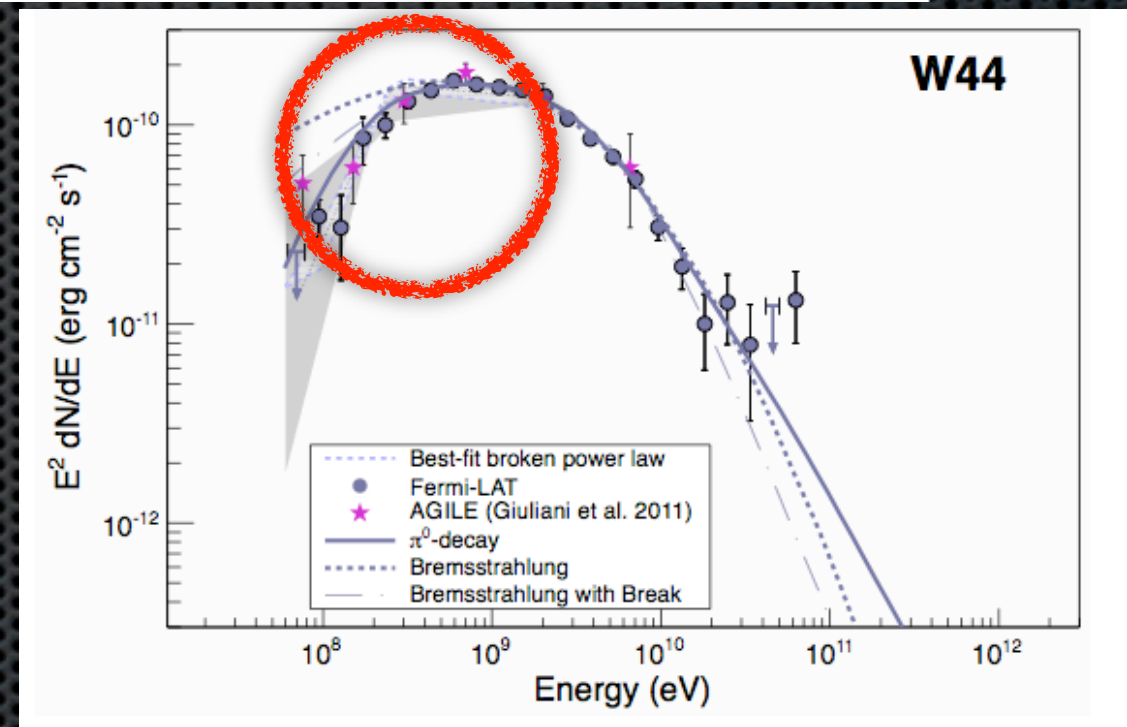
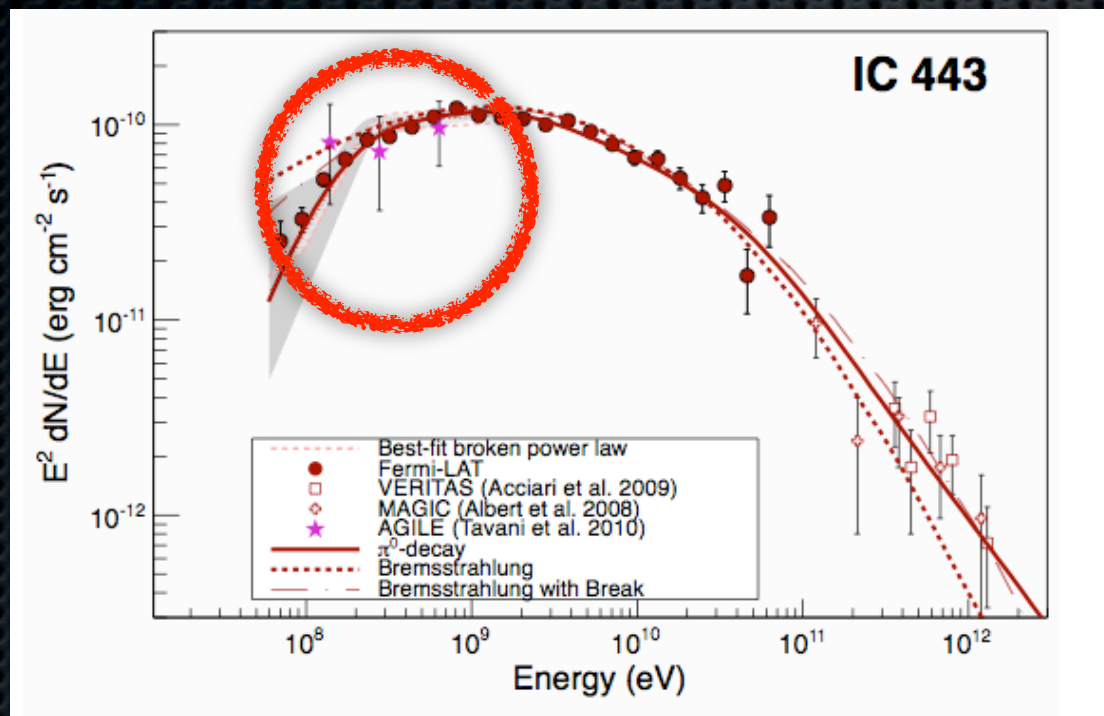
Fermi-LAT: 2013

Proof: Cosmic Rays Come from Exploding Stars

Particle Decay 'Smoking Gun' Settles Long Debate

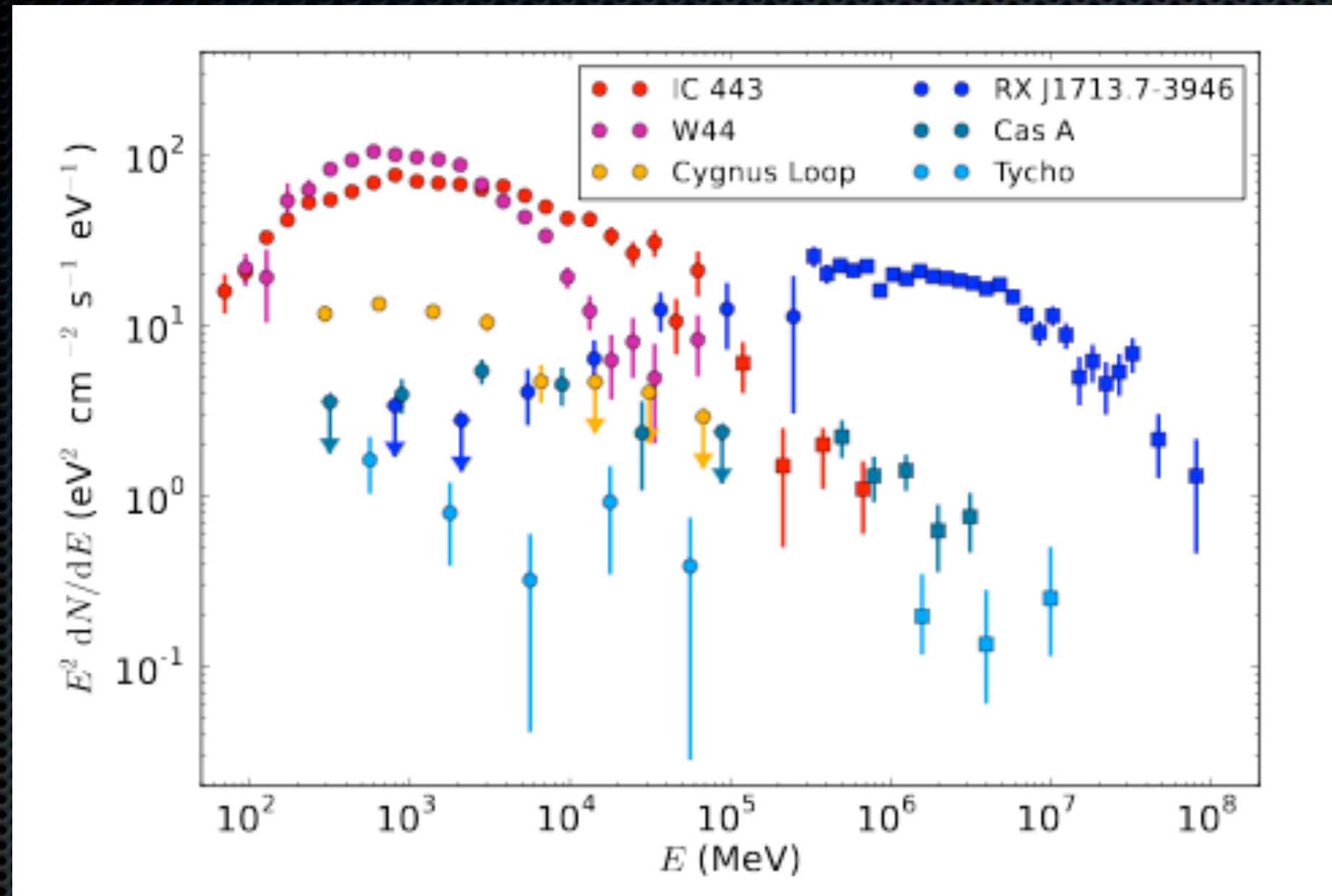
February 14, 2013

Menlo Park, Calif. — A new study confirms what scientists have long suspected: Cosmic rays — energetic particles that pelt Earth from all directions — are born in the violent aftermath of supernovas, exploding stars throughout the galaxy.



Cutoff around 200 MeV direct indication of pion bump: hadronic interactions

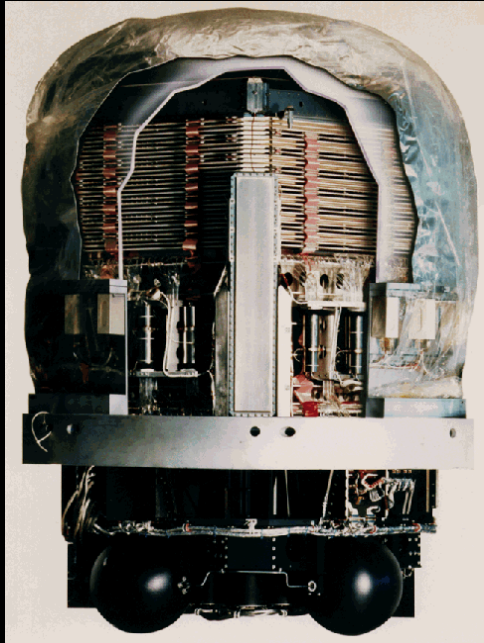
Fermi-LAT: 2013



- W44 and IC 443 are middle aged SNRs interacting with MCs and are special cases
- Clearly SNRs are contributors to CR population
- Is this it? What other sources are out there?

The Gamma-ray Sky

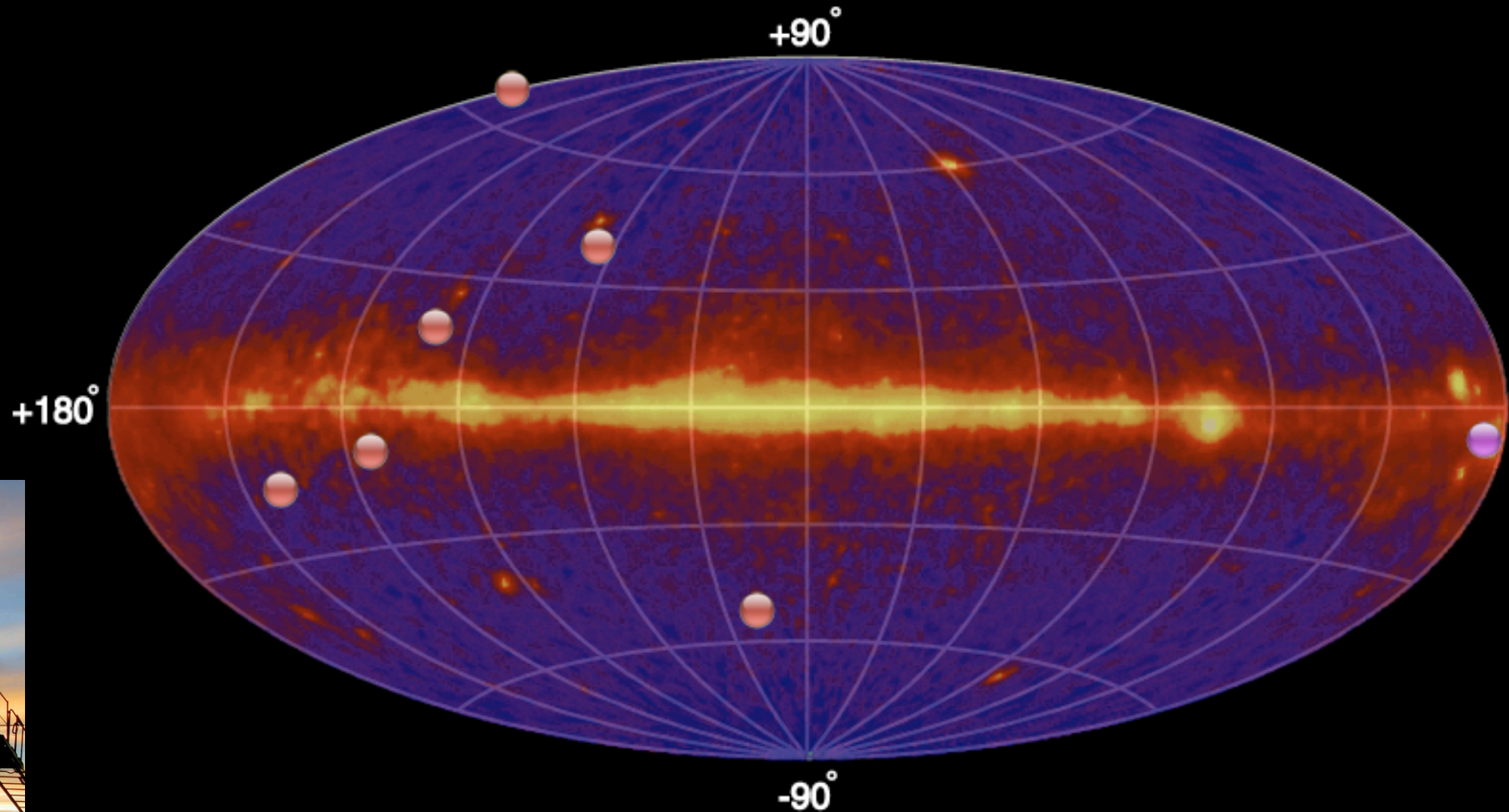
c. 2000



CGRO/EGRET
<1 GeV

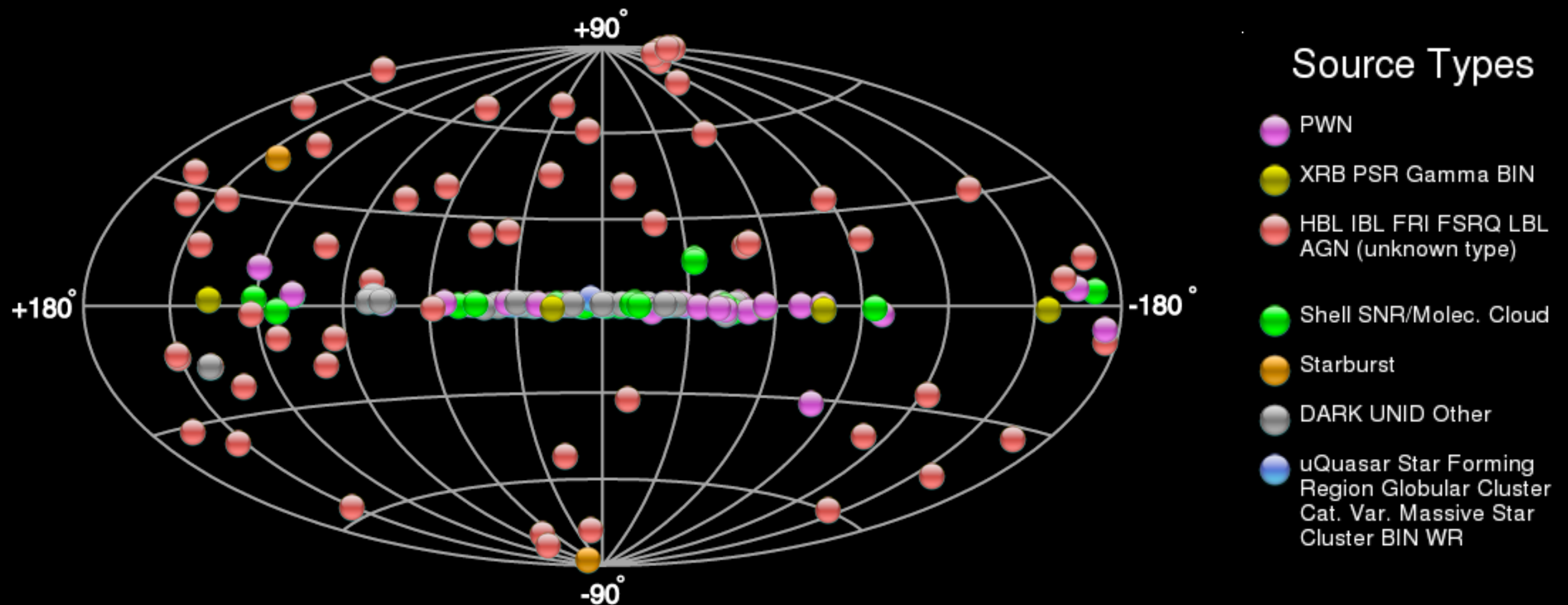


Whipple
>300 GeV

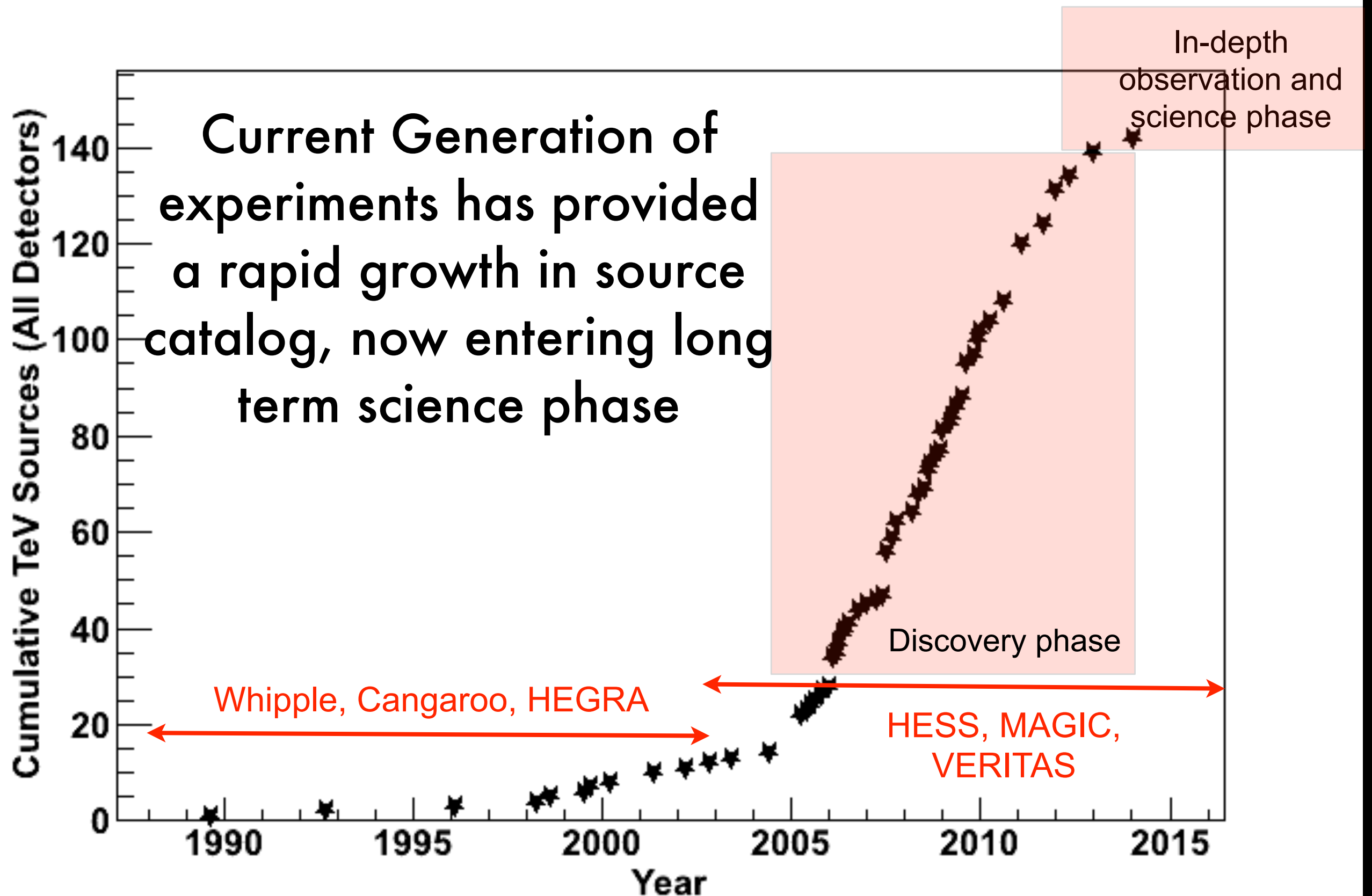


6 AGN + 1 Pulsar Wind Nebula (Crab)

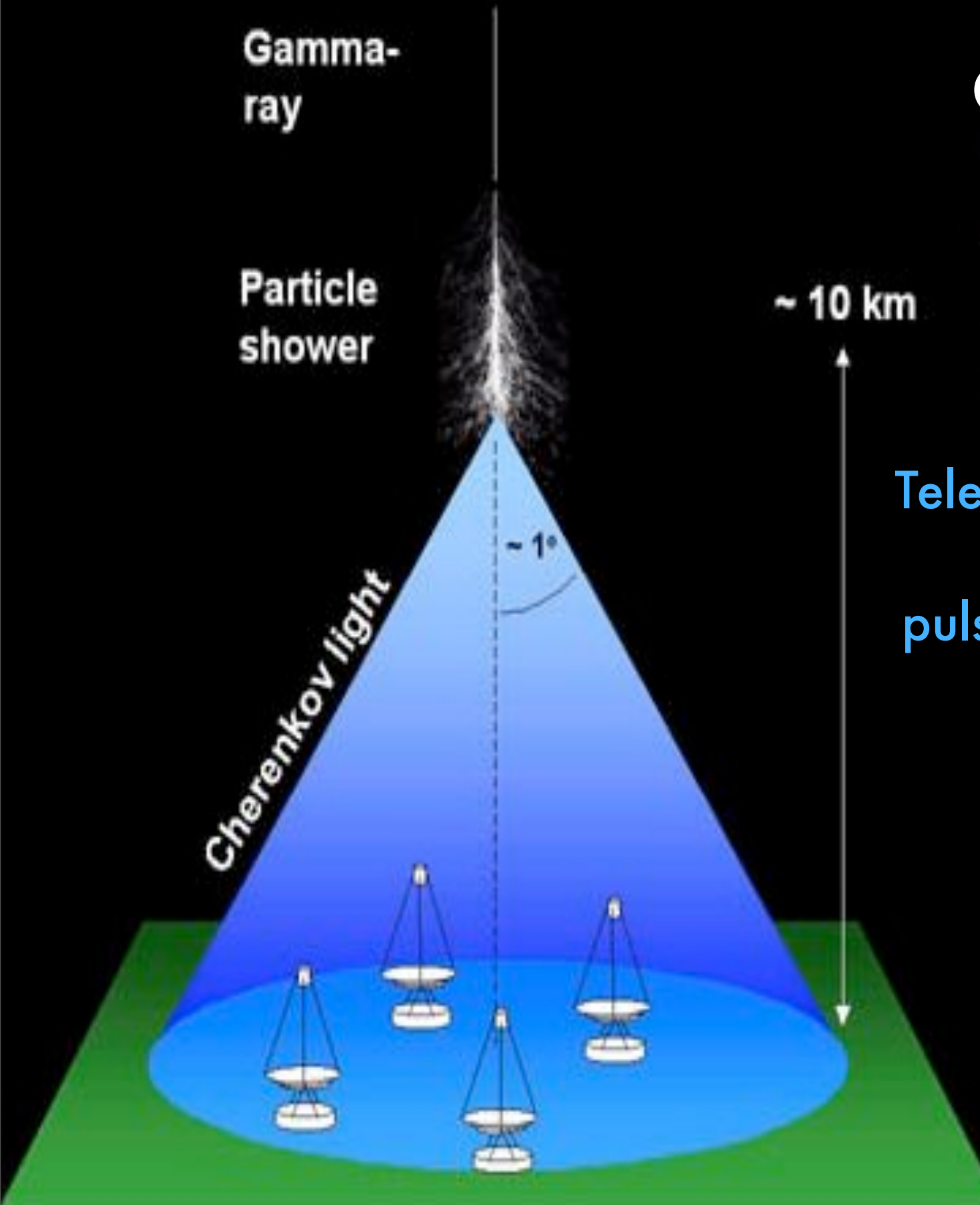
The TeV Gamma-ray Sky 2014



~ 150 TeV sources: radio galaxies, X-ray binaries, SNRs, starburst galaxies, UIDS.....

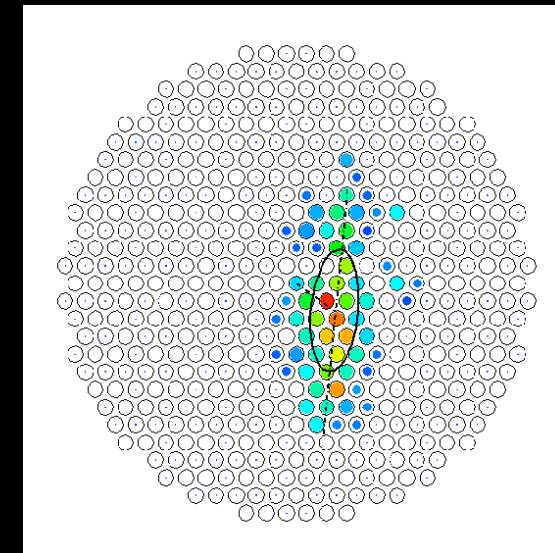
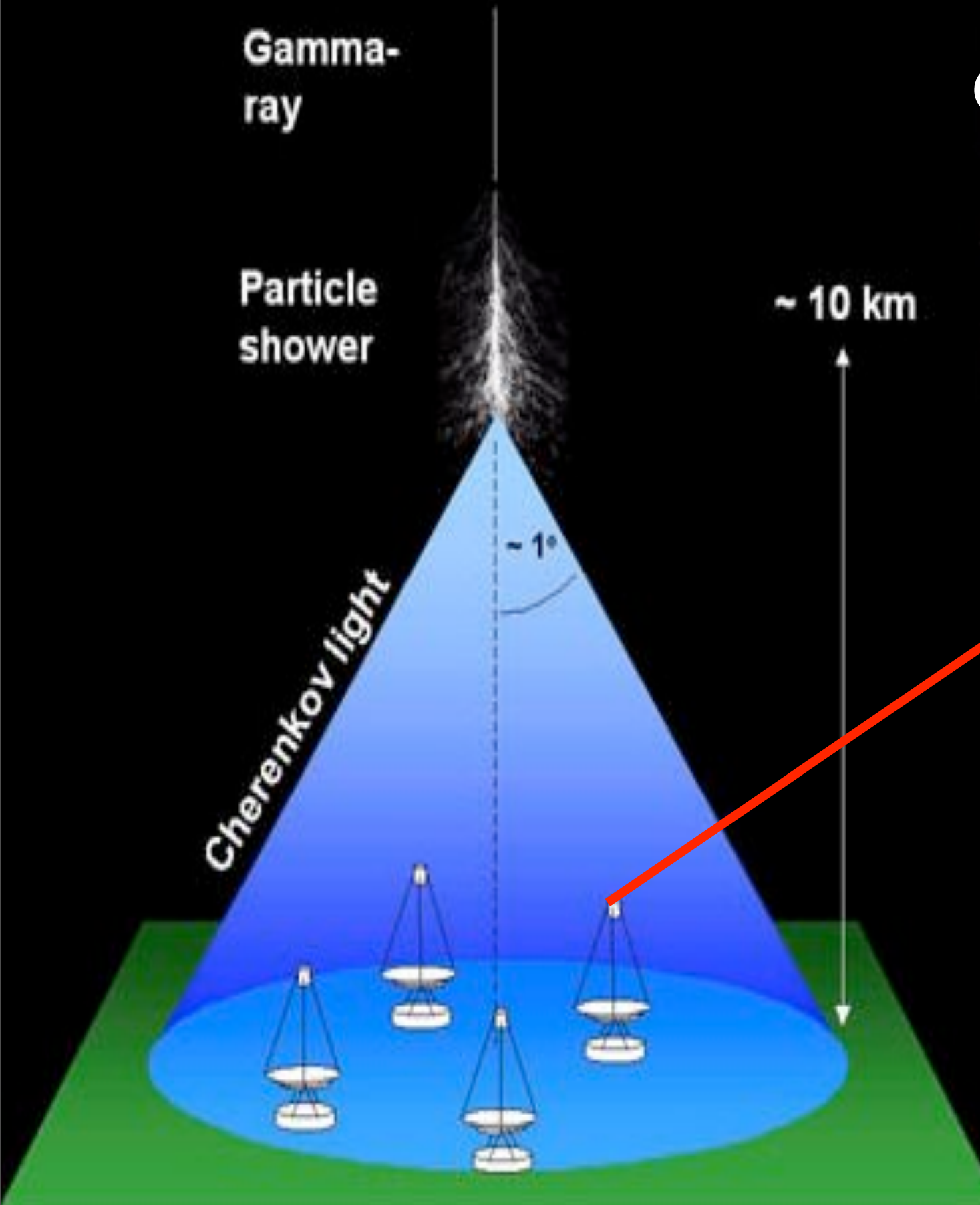


IMAGING ATMOSPHERIC CHERENKOV TELESCOPE (IACT) ARRAY



Telescopes on ground capture brief
($\sim 6\text{ns}$)
pulses of UV light from gamma-ray
induced
air showers.

IMAGING ATMOSPHERIC CHERENKOV TELESCOPE (IACT) ARRAY

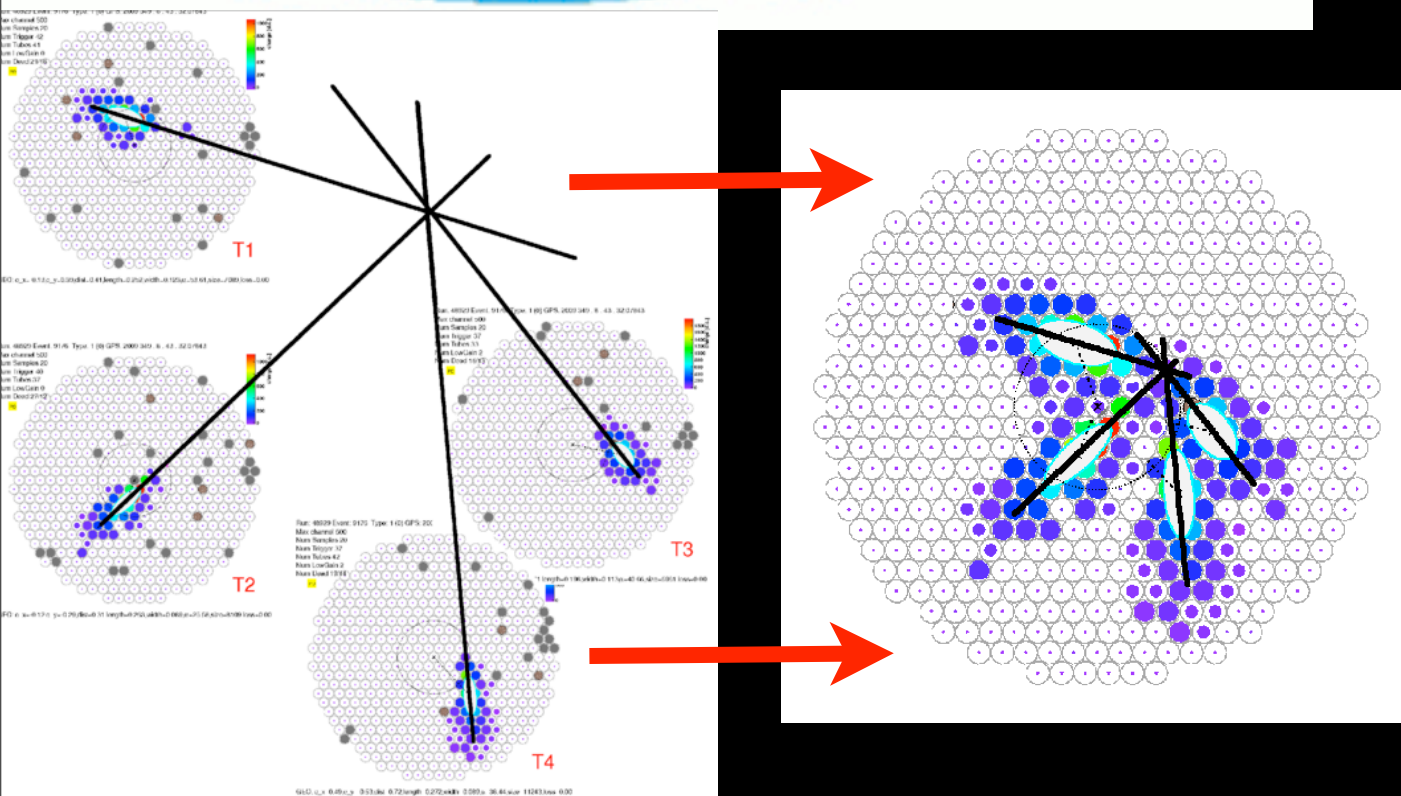
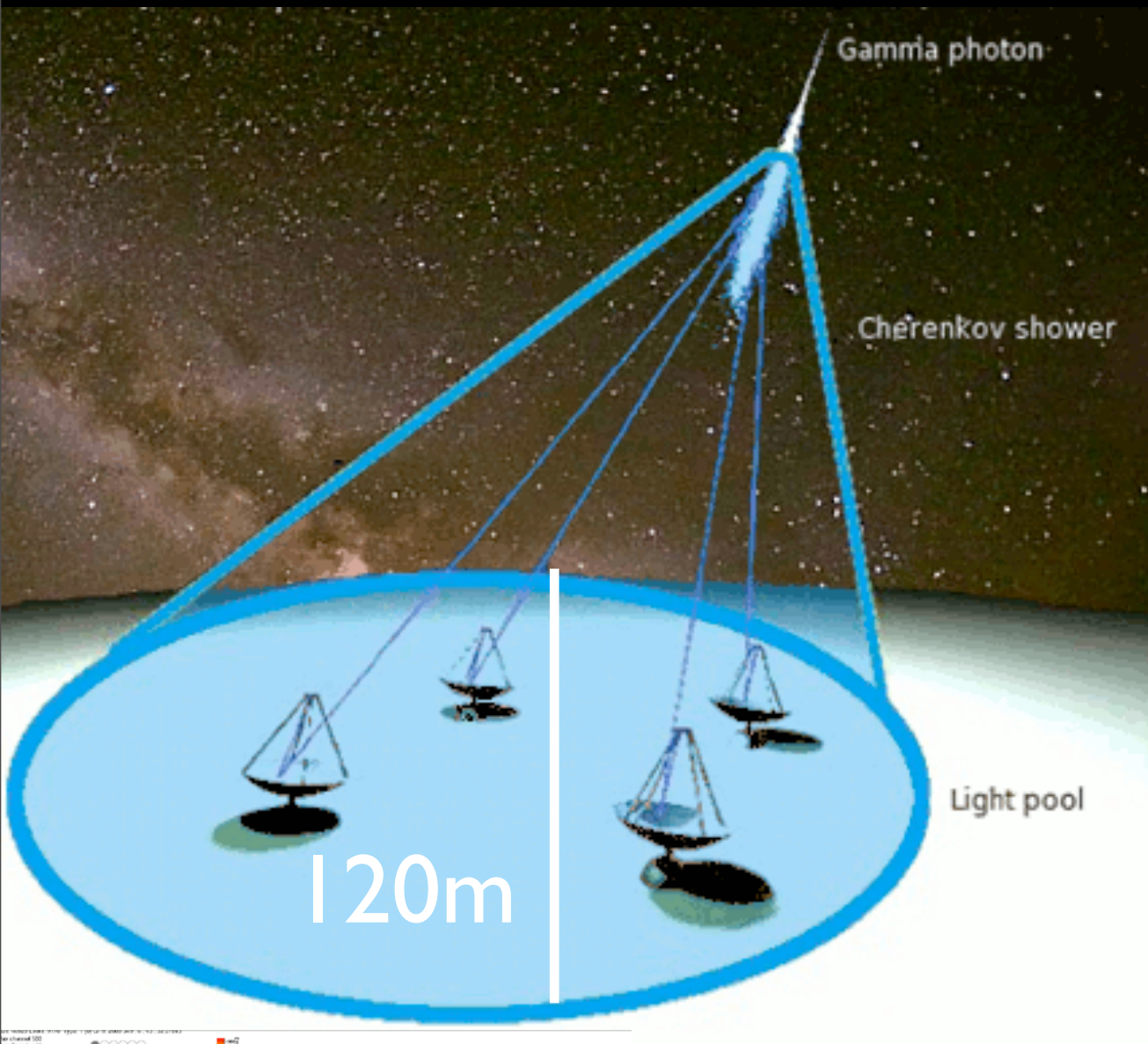


Pixelated cameras capture
entire
development of air shower

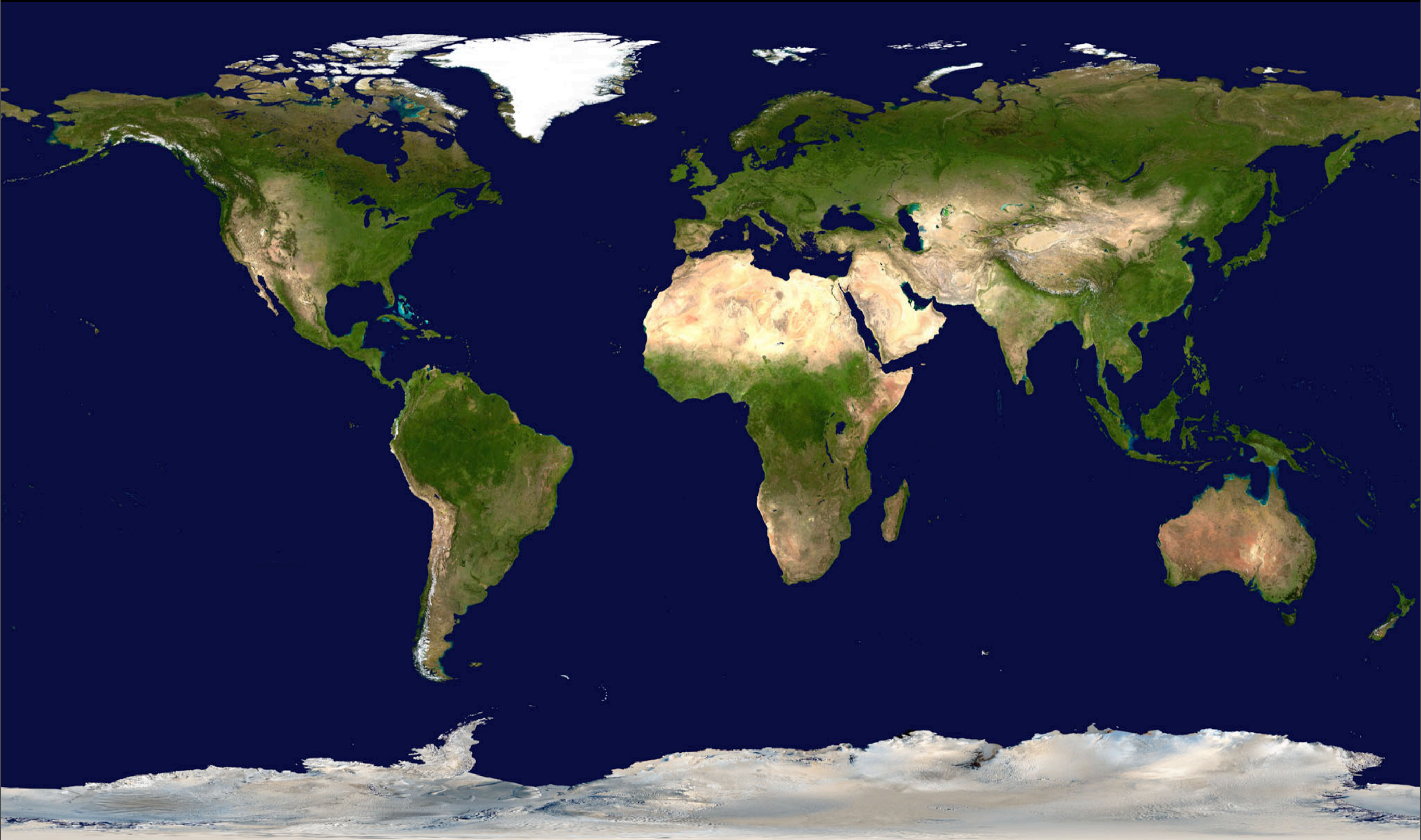
IMAGING ATMOSPHERIC CHERENKOV TELESCOPE (IACT) ARRAY

Multiple telescope imaging of the same air shower allows for very accurate reconstruction of original gamma ray's trajectory.

Typical showers result in Cherenkov light pool of diameter 120m. Since telescopes need only sample part of the pool, effective area of ground based TeV observatories $>10^5 \text{ m}^2$!



Current TeV Experiments (50-5000 GeV)



Current TeV Experiments (50-5000 GeV)



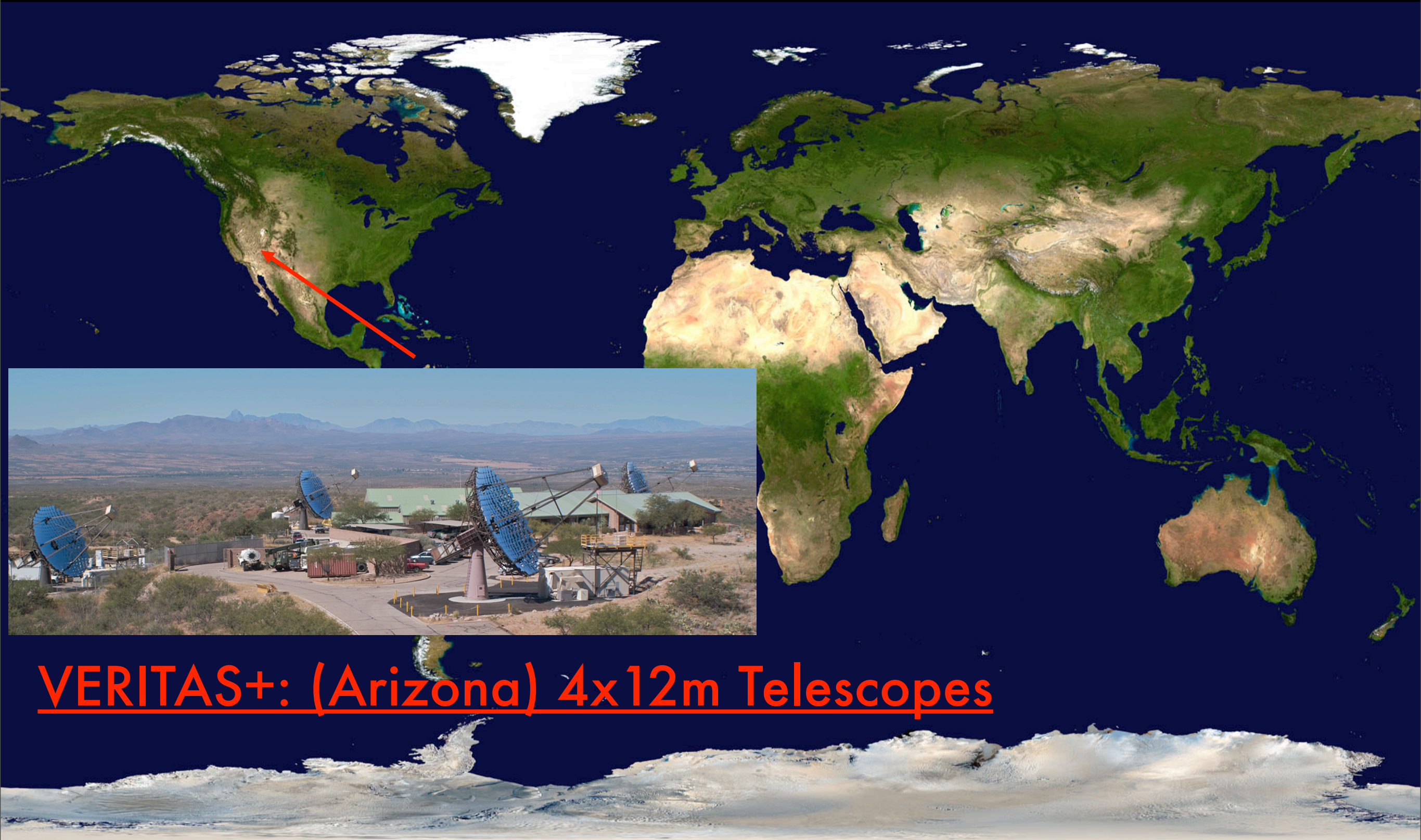
MAGIC 2 (Canary Islands)
2x 17m Telescope

Current TeV Experiments (50-5000 GeV)



H.E.S.S. 2 (Namibia)
4 12.5 m + 1 28m Telescope

Current TeV Experiments (50-5000 GeV)



VERITAS+: (Arizona) 4x12m Telescopes

VERITAS

The Very Energetic Radiation Imaging Telescope Array System

Support from:

Smithsonian Inst.
U.S. NSF
U.S. DOE
NSERC (Canada)
SFI (Ireland)



U.S.

Adler Planetarium
Argonne Nat. Lab
Barnard College
DePauw Univ.
Grinnell College
Iowa St. Univ.

Purdue
SAO
UCLA
UCSC
Univ. of Chicago
Univ. of Delaware
Univ. of Iowa
Univ. of Utah
Washington Univ.

Canada

McGill Univ.

Germany

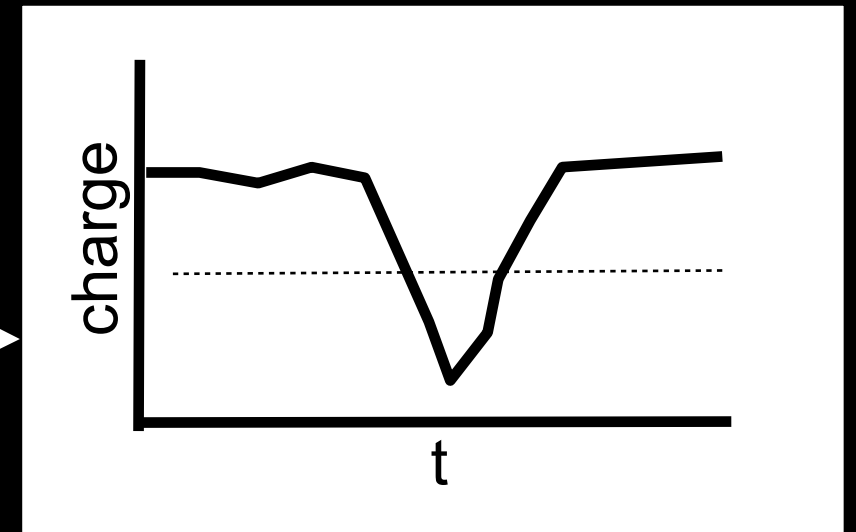
DESY- Zeuthen

Ireland

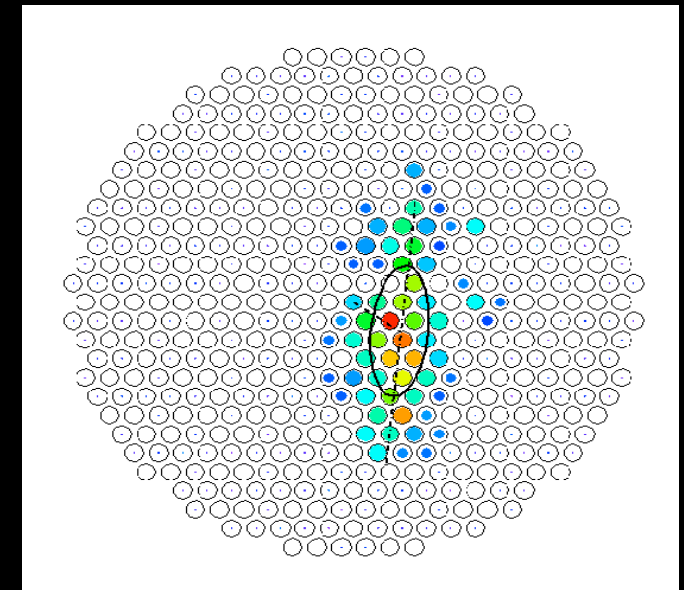
Cork Inst. Tech.
Galway-Mayo Inst.
N.U.I. Galway
UCD

3 Level Trigger:

L1: Pixel Level
(>threshold)



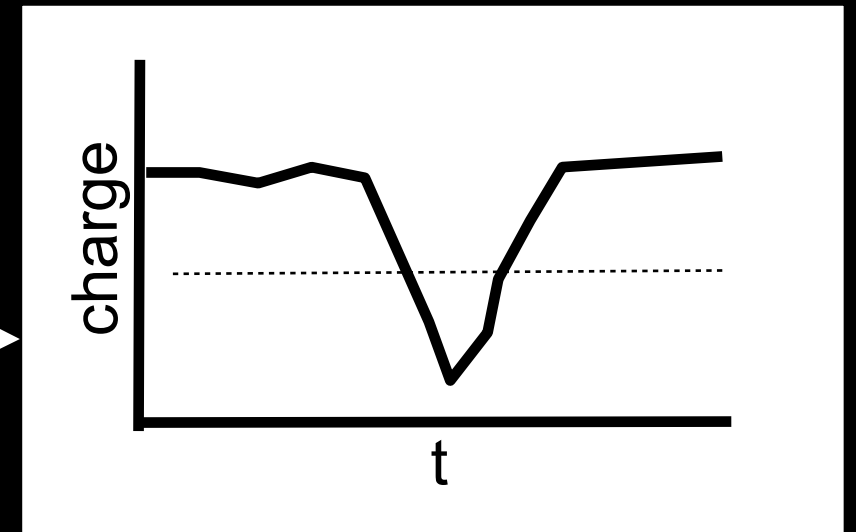
L2: Camera Level
(pattern based)



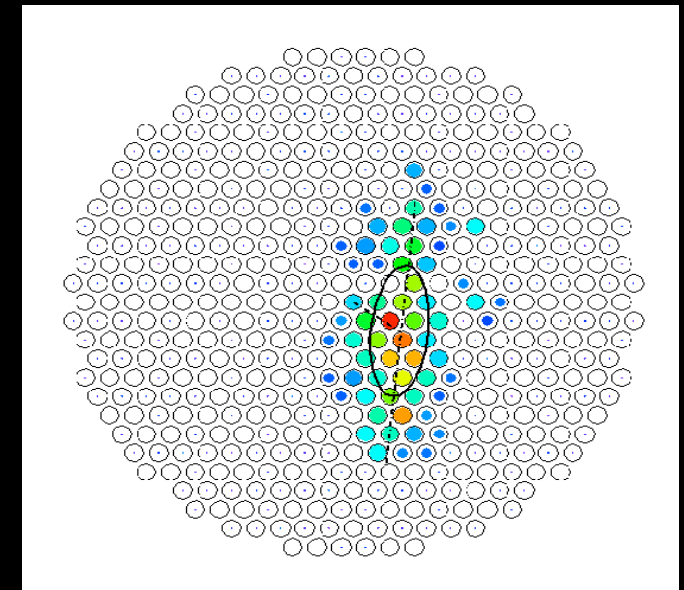
L3: Array Level: 2 or more L2 triggers w/in
100ns: images from 4 tels dumped from
buffer into data acquisition.

3 Level Trigger:

Upgraded
L1: Pixel Level
(>threshold)

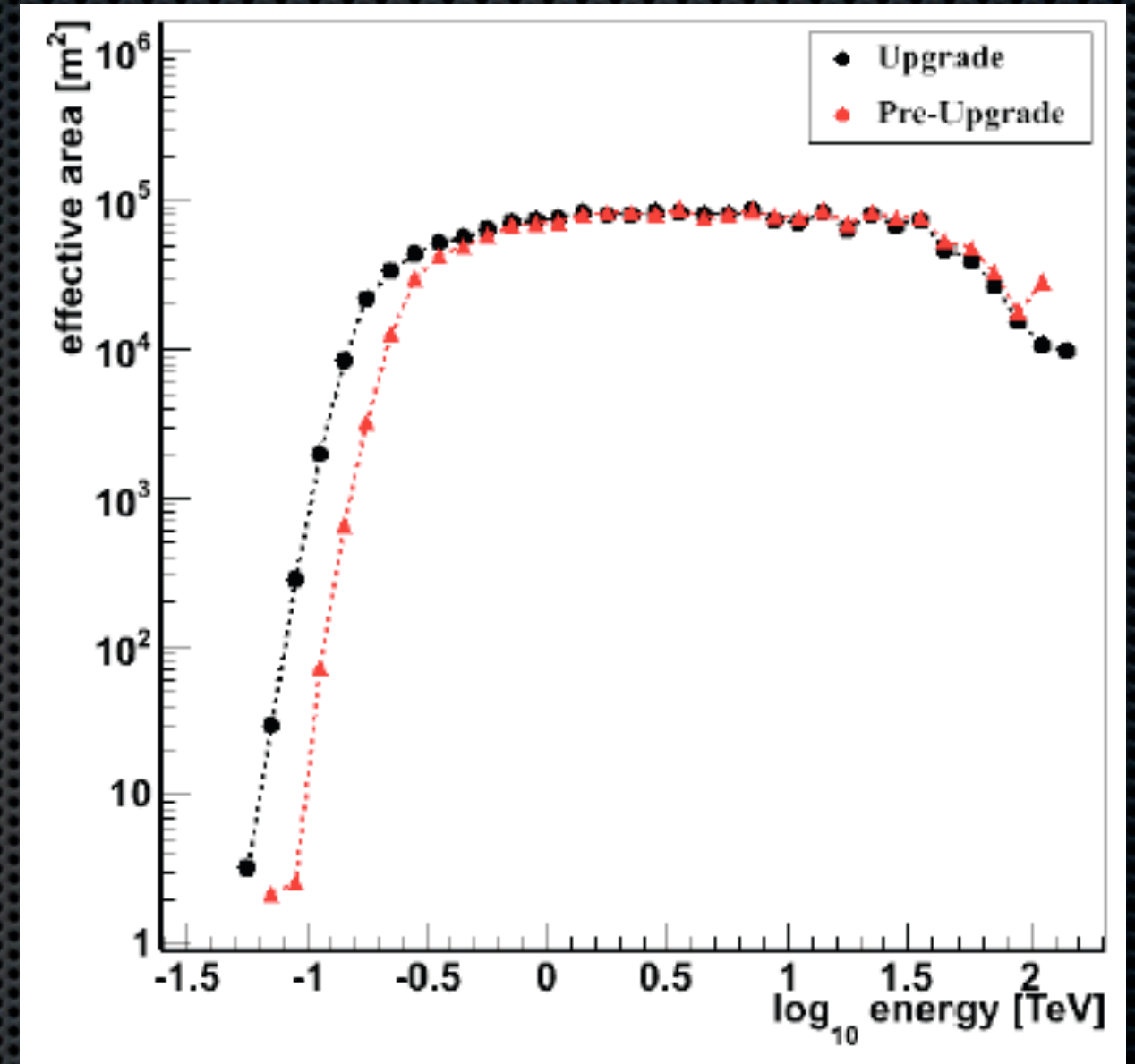
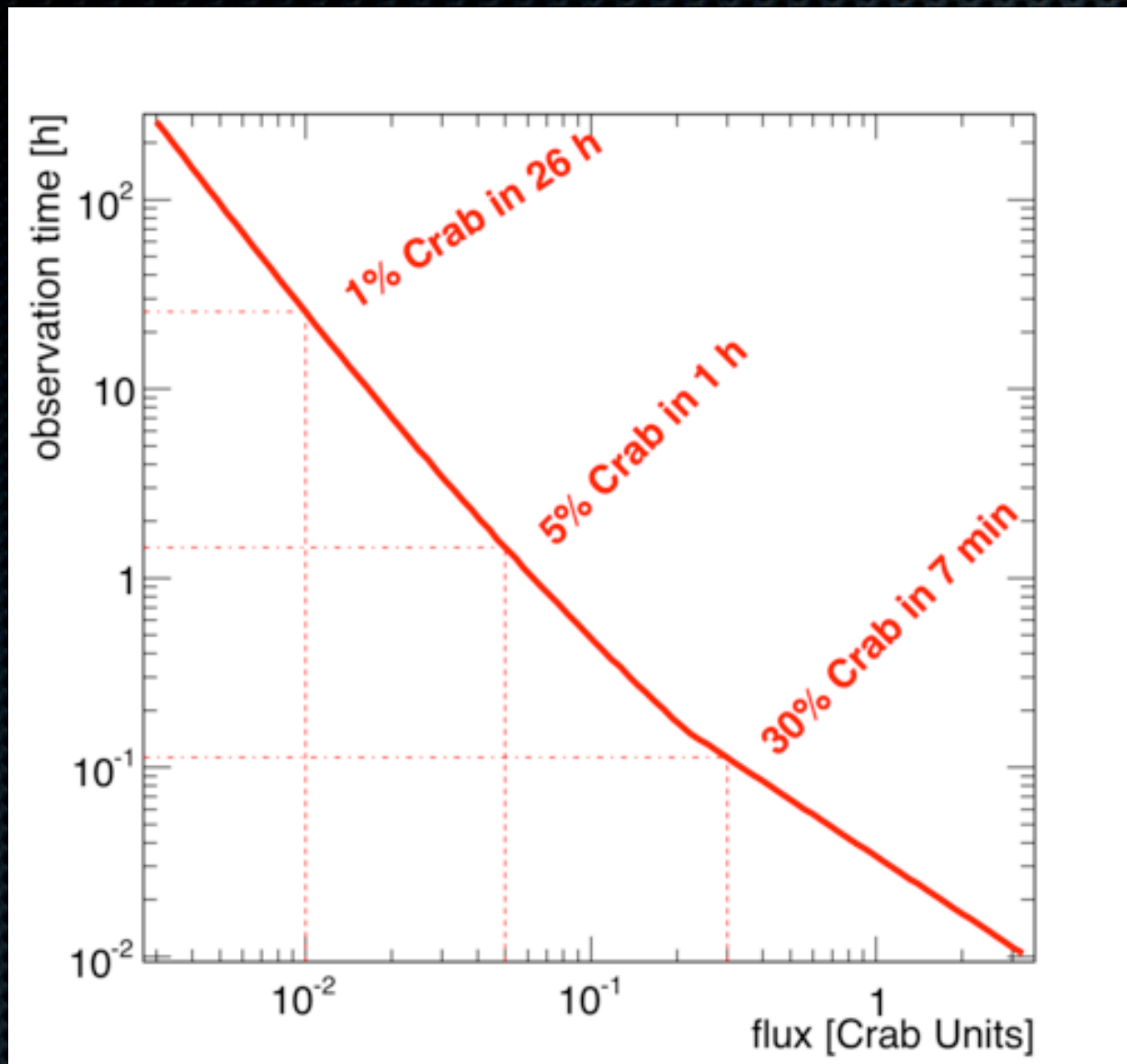


Upgraded
L2: Camera Level
(pattern based)



L3: Array Level: 2 or more L2 triggers w/in
100ns: images from 4 tels dumped from
buffer into data acquisition.

VERITAS Camera/TriggerUpgrade



Energy range: 85 GeV - 30 TeV

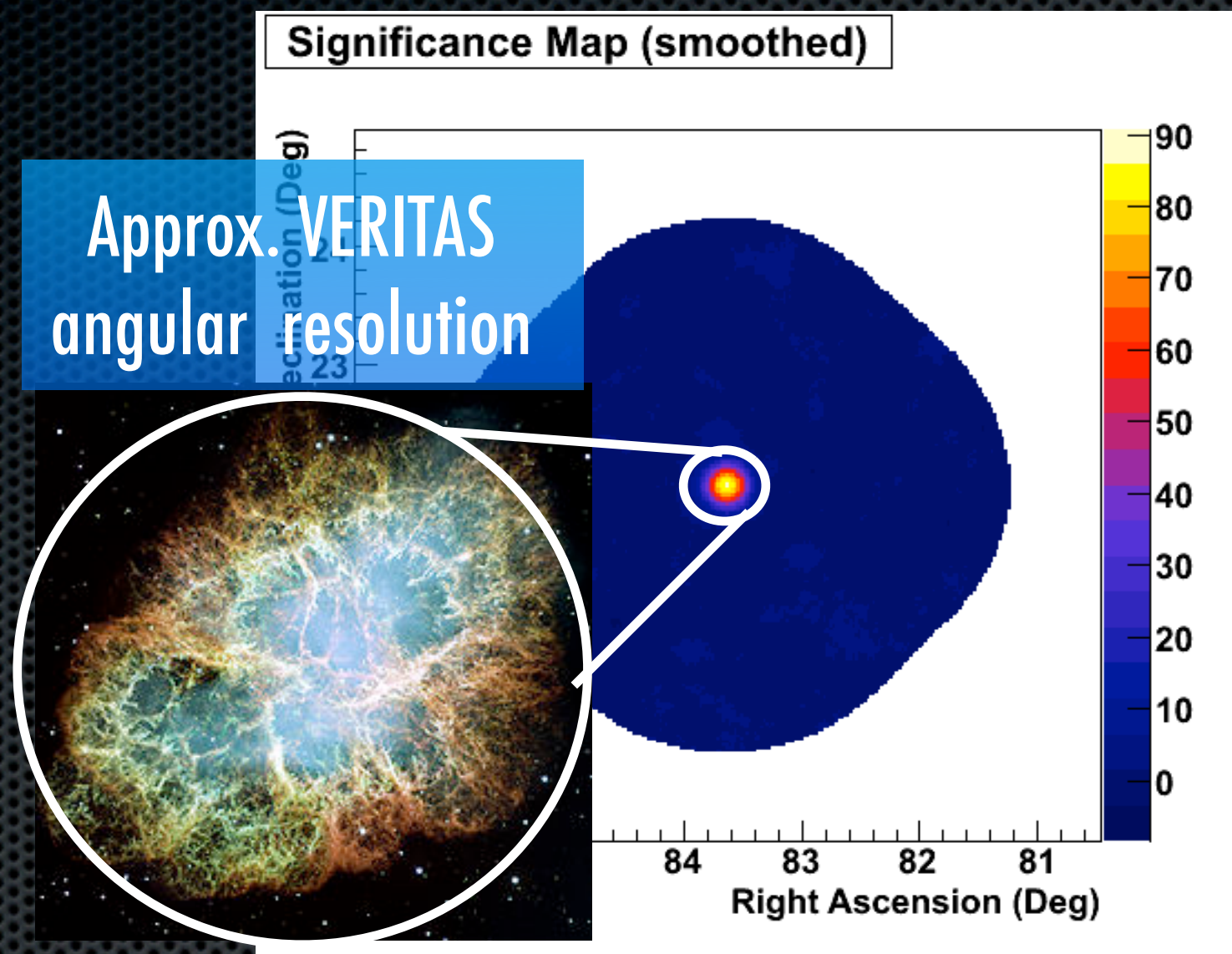
Energy resolution: 15% at 1 TeV

Angular resolution: <0.1 deg at 1 TeV, 0.14 deg at 200 GeV

Point source sensitivity: 1% Crab in $\sim 25\text{h}$, 10% in <30 min

Higher QE PMTs/faster event trigger has resulted in larger collecting area, greater CR rejection

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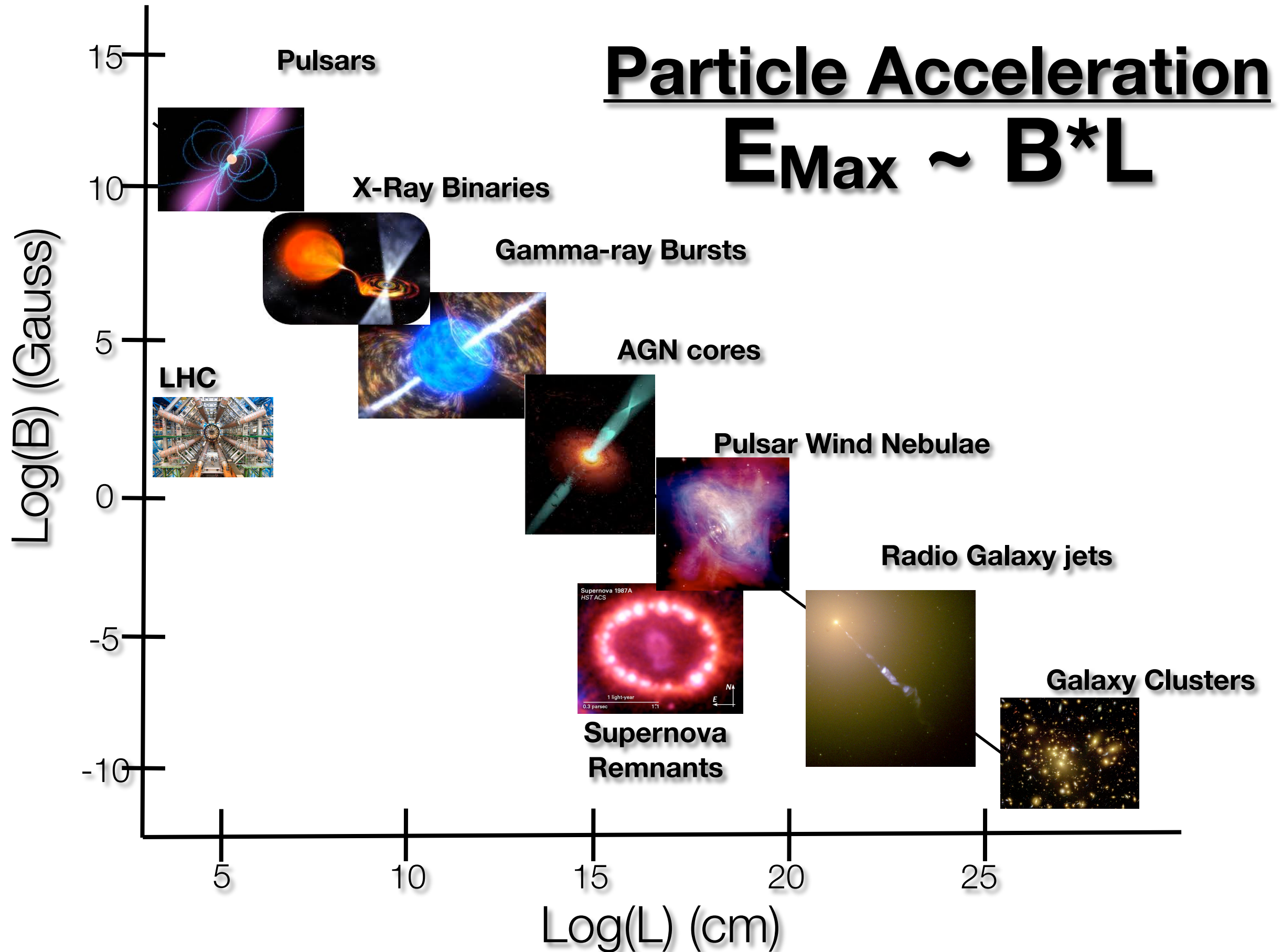
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VHE Particle Accelerators

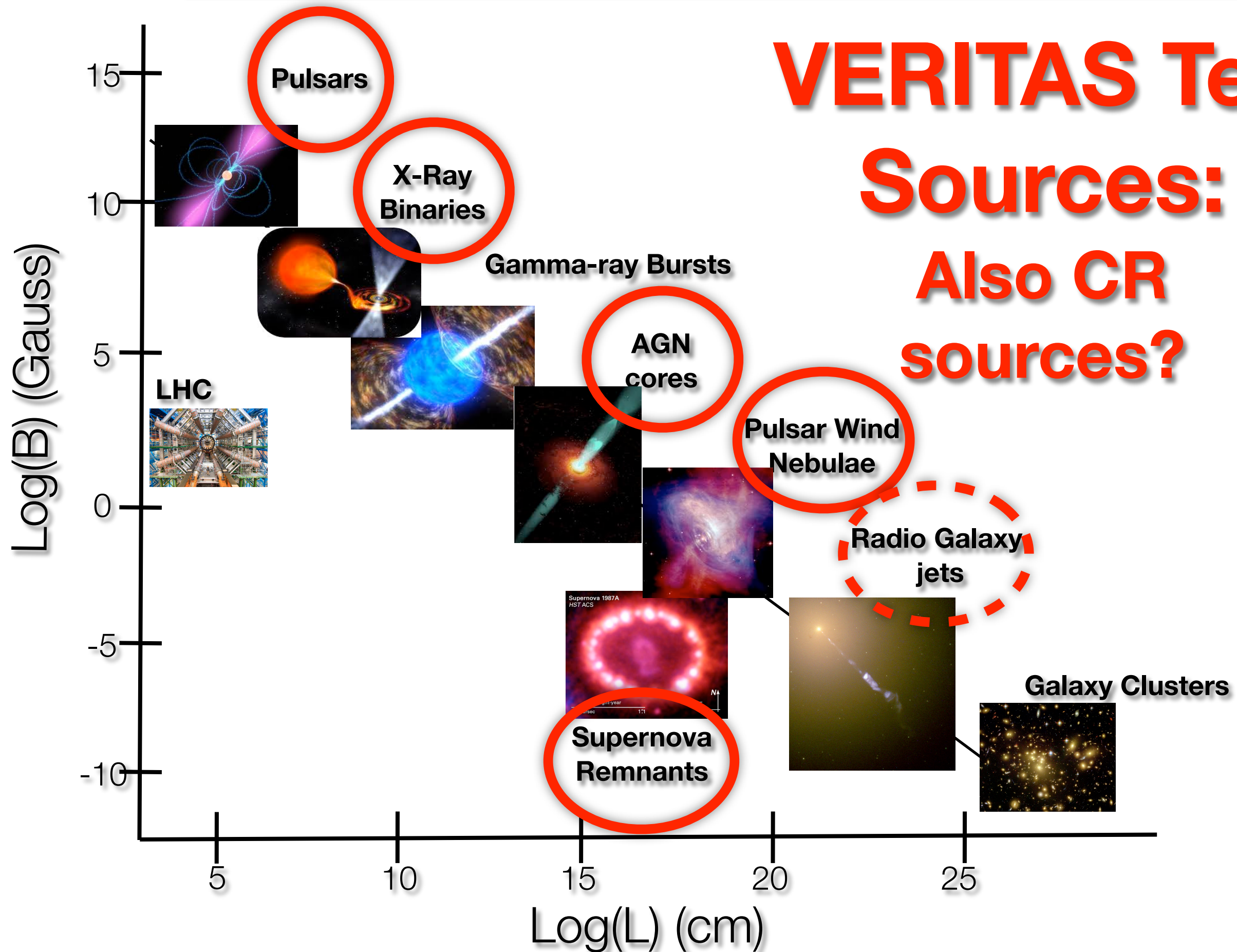


VHE Particle Accelerators

VERITAS TeV

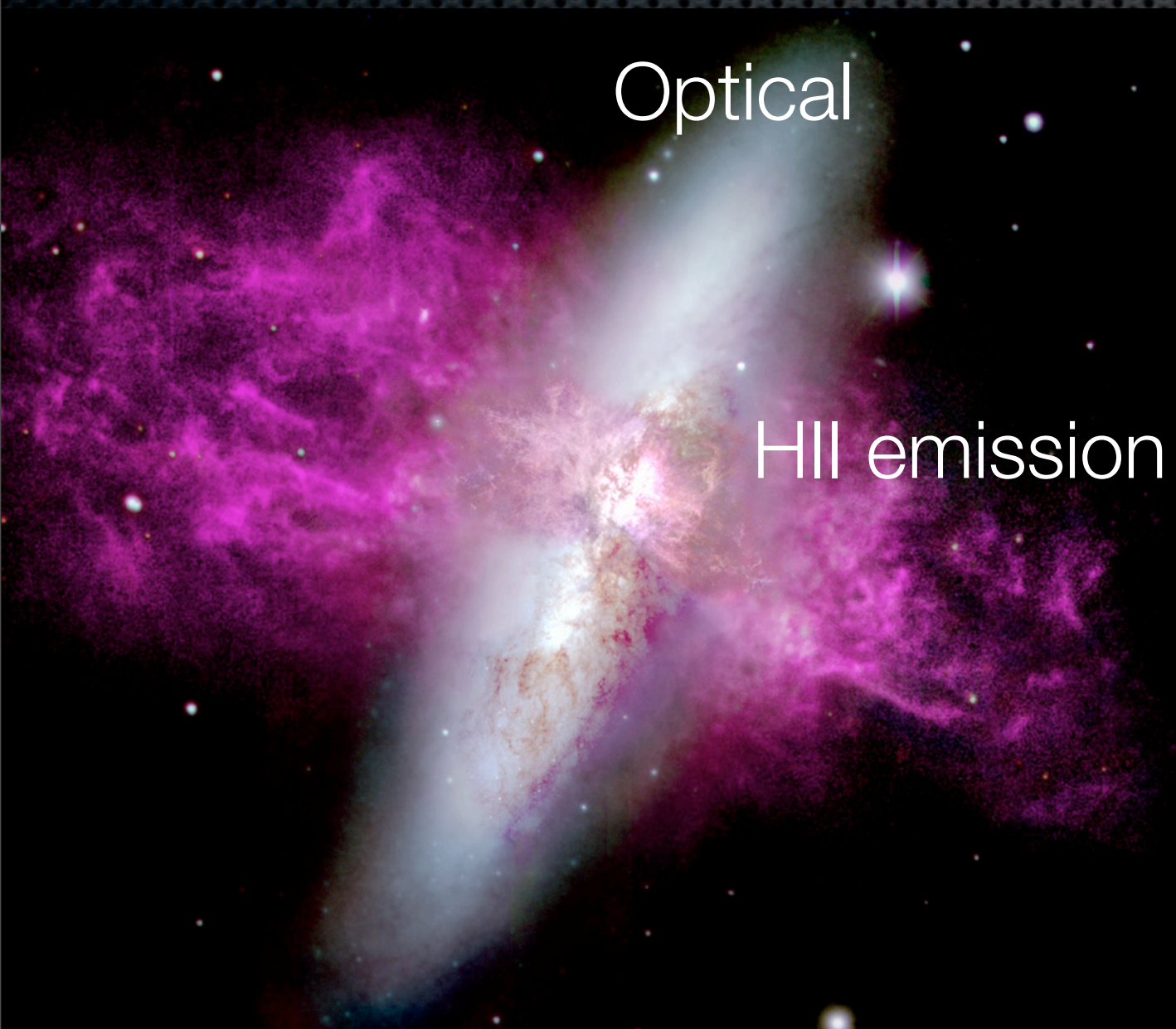
Sources:

**Also CR
sources?**



Evidence for CR Acceleration in VERITAS TeV Sources

Starburst Galaxy M82



Optical

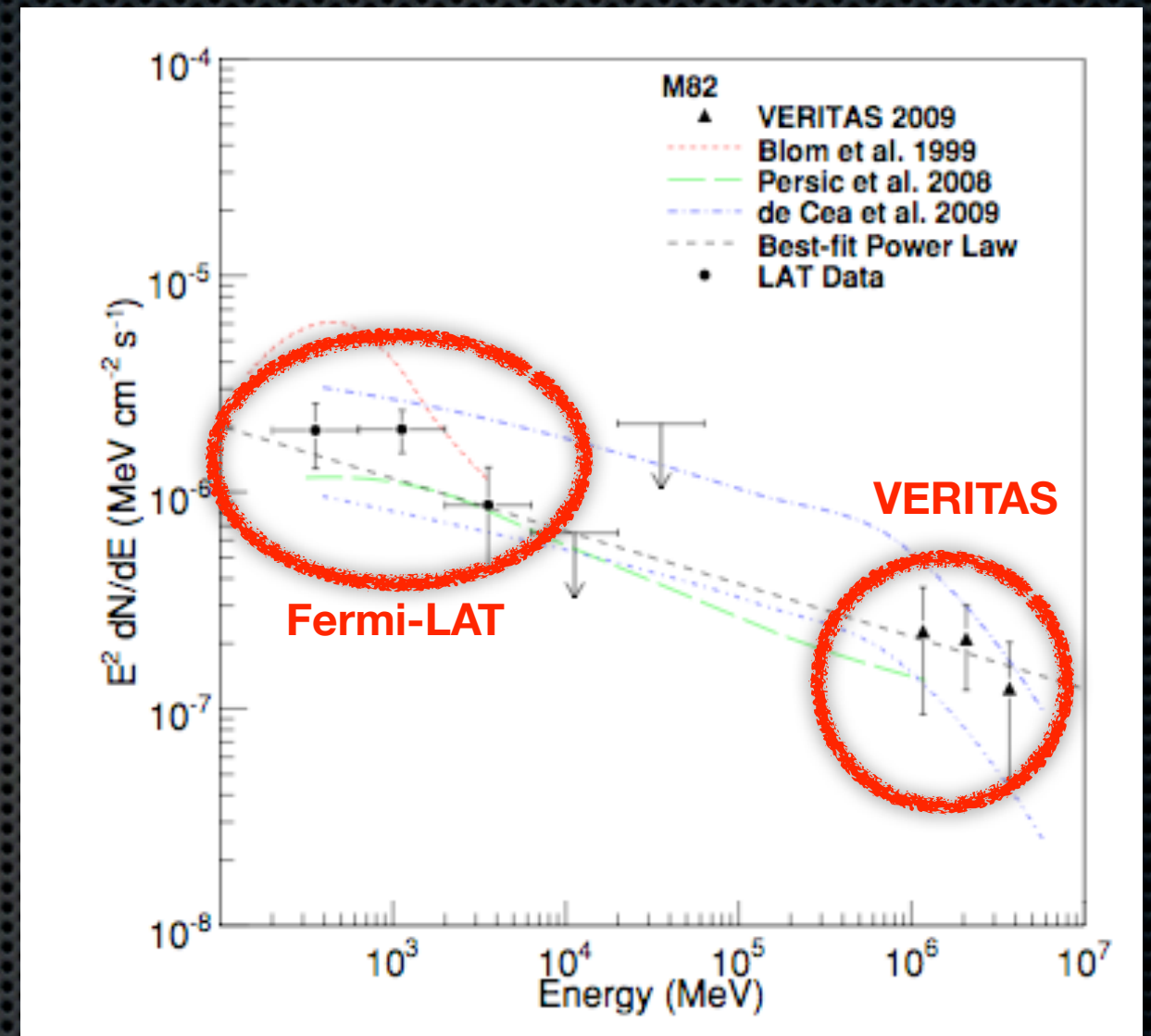
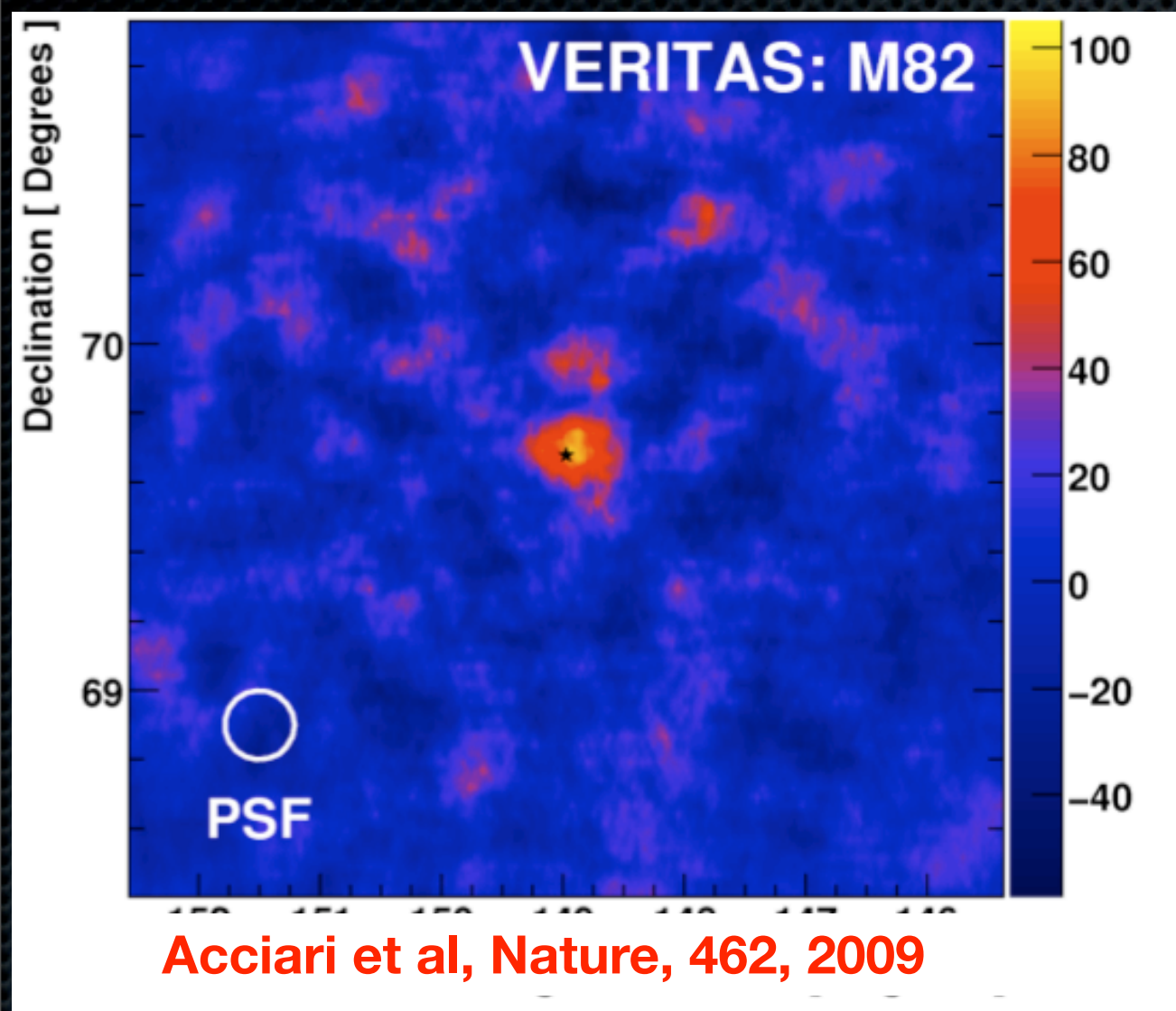
HII emission

-High Star Formation -> High SNR Rate

-High Gas Density $>150 \text{ cm}^3$

-No strong AGN or jet evidence

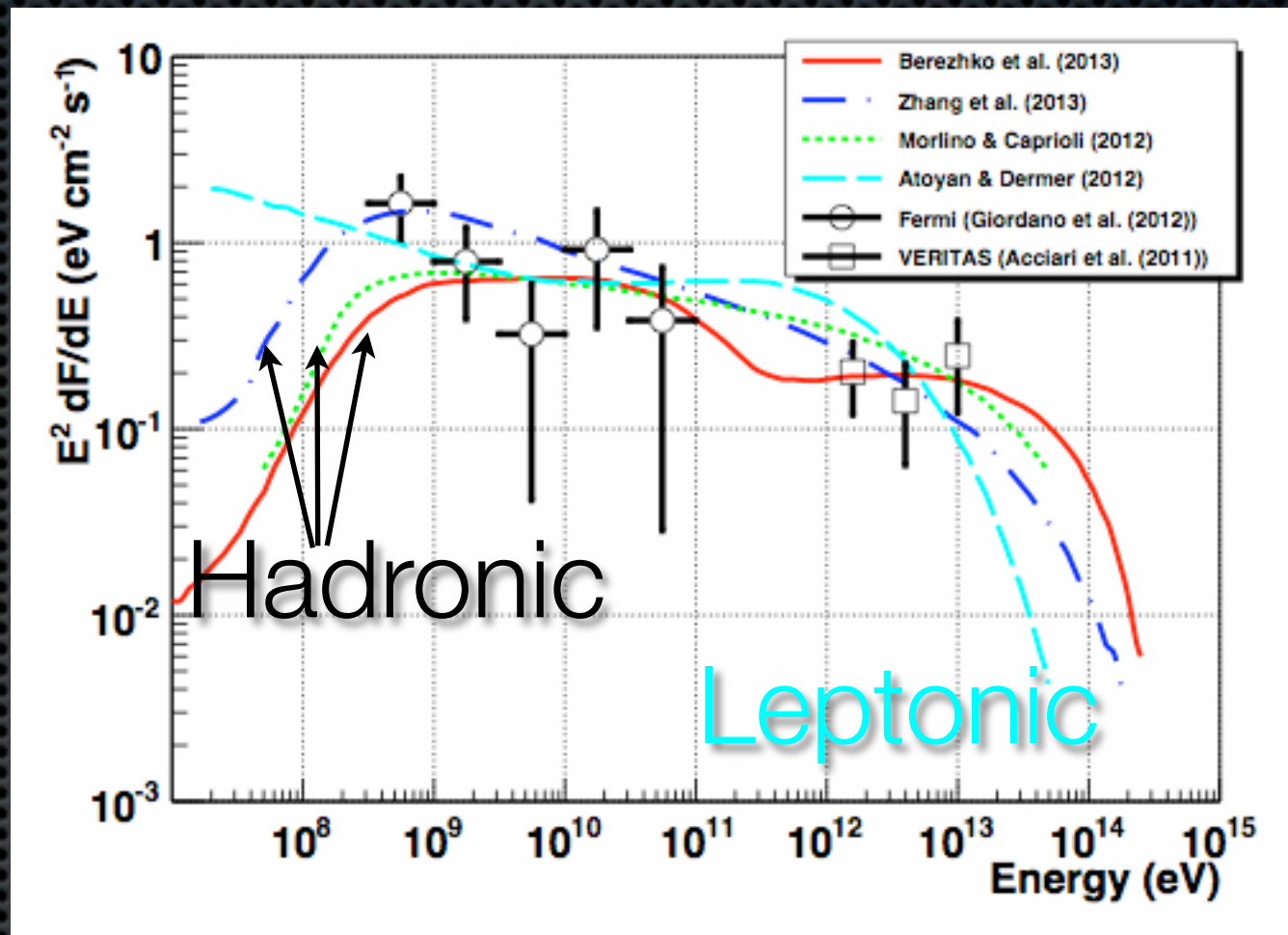
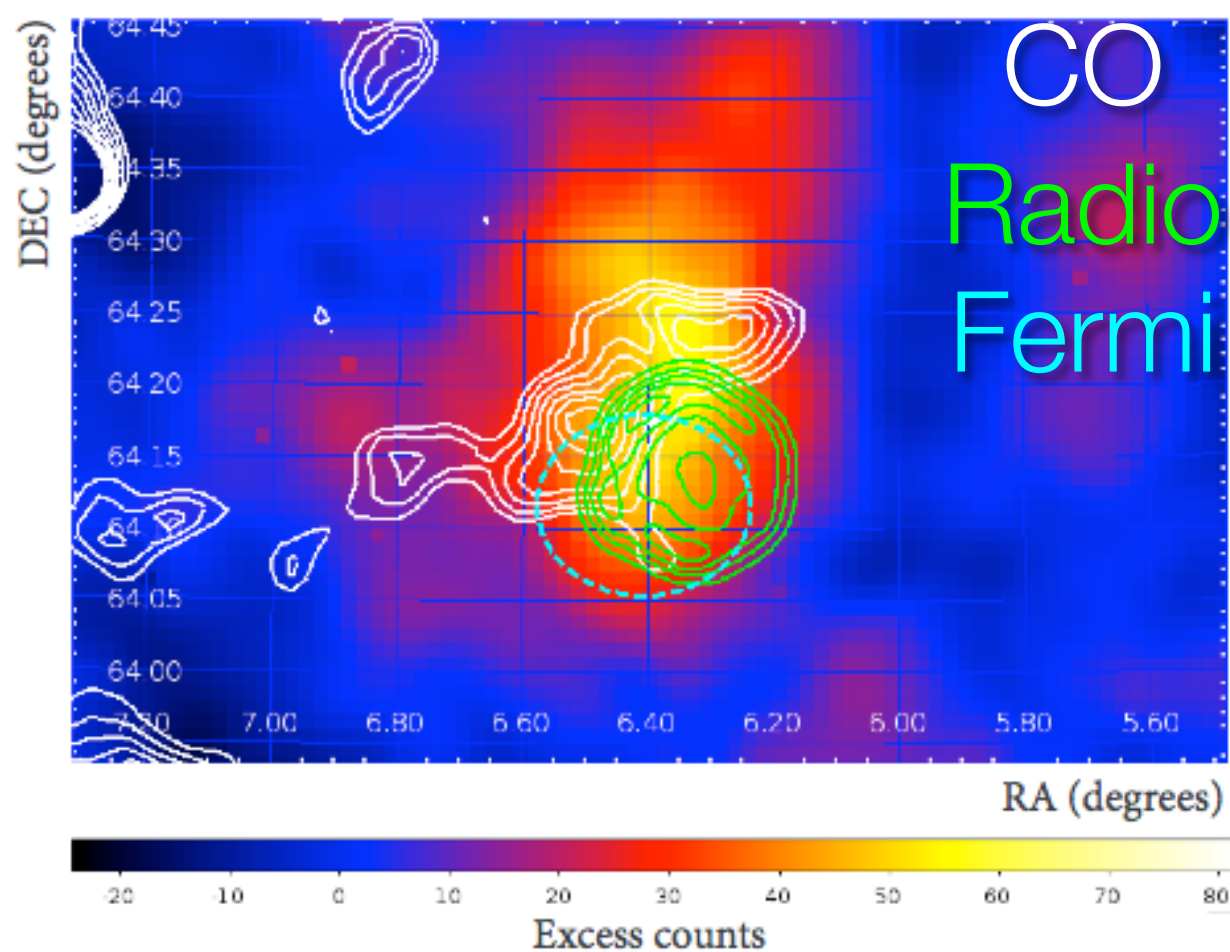
Starburst Galaxy M82



**(Highly) Plausible explanation for TeV:
SNe shocks accelerate CRs, $\text{CRs} + \text{Gas} \rightarrow \pi^0 \rightarrow \gamma$**

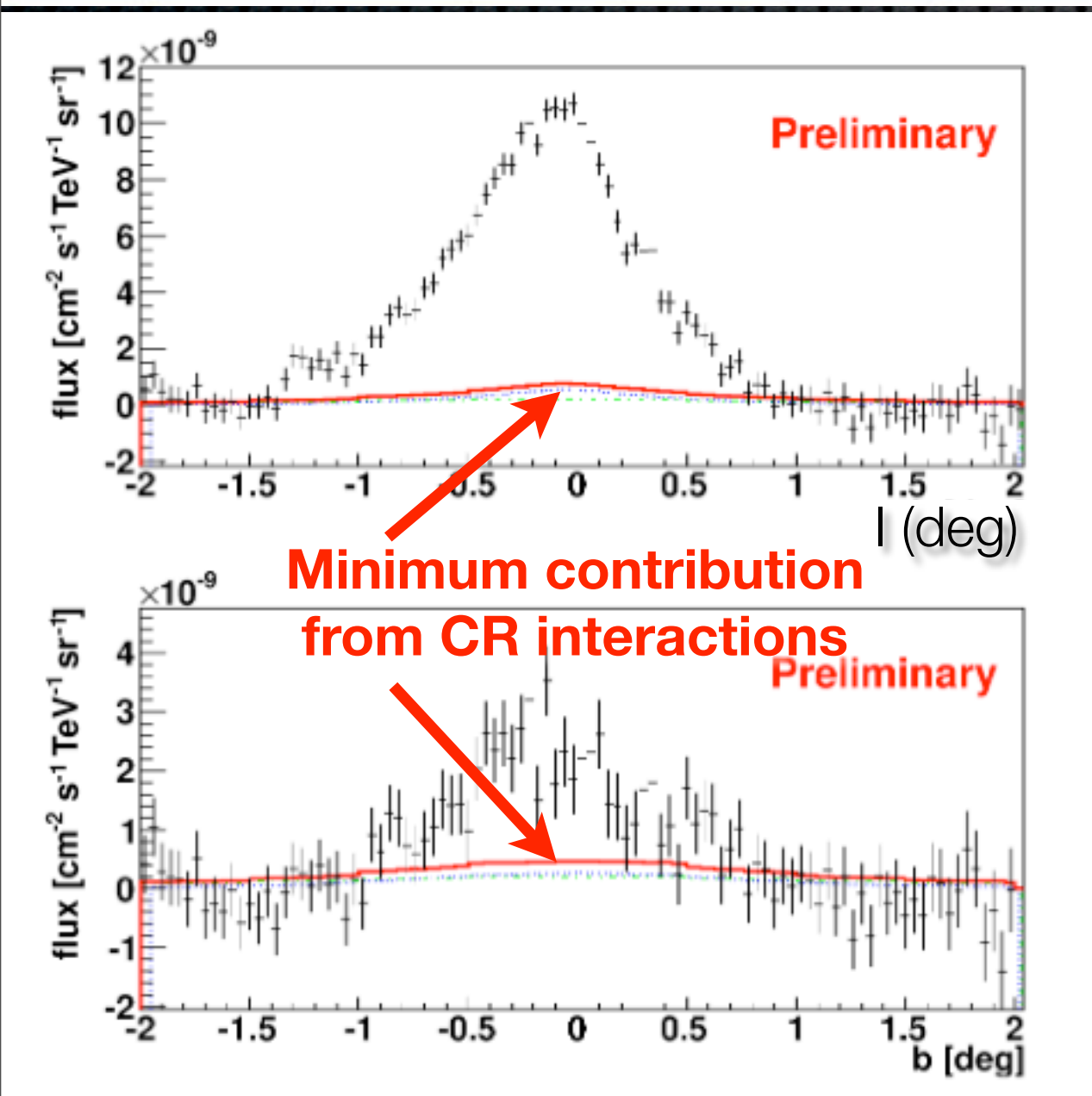
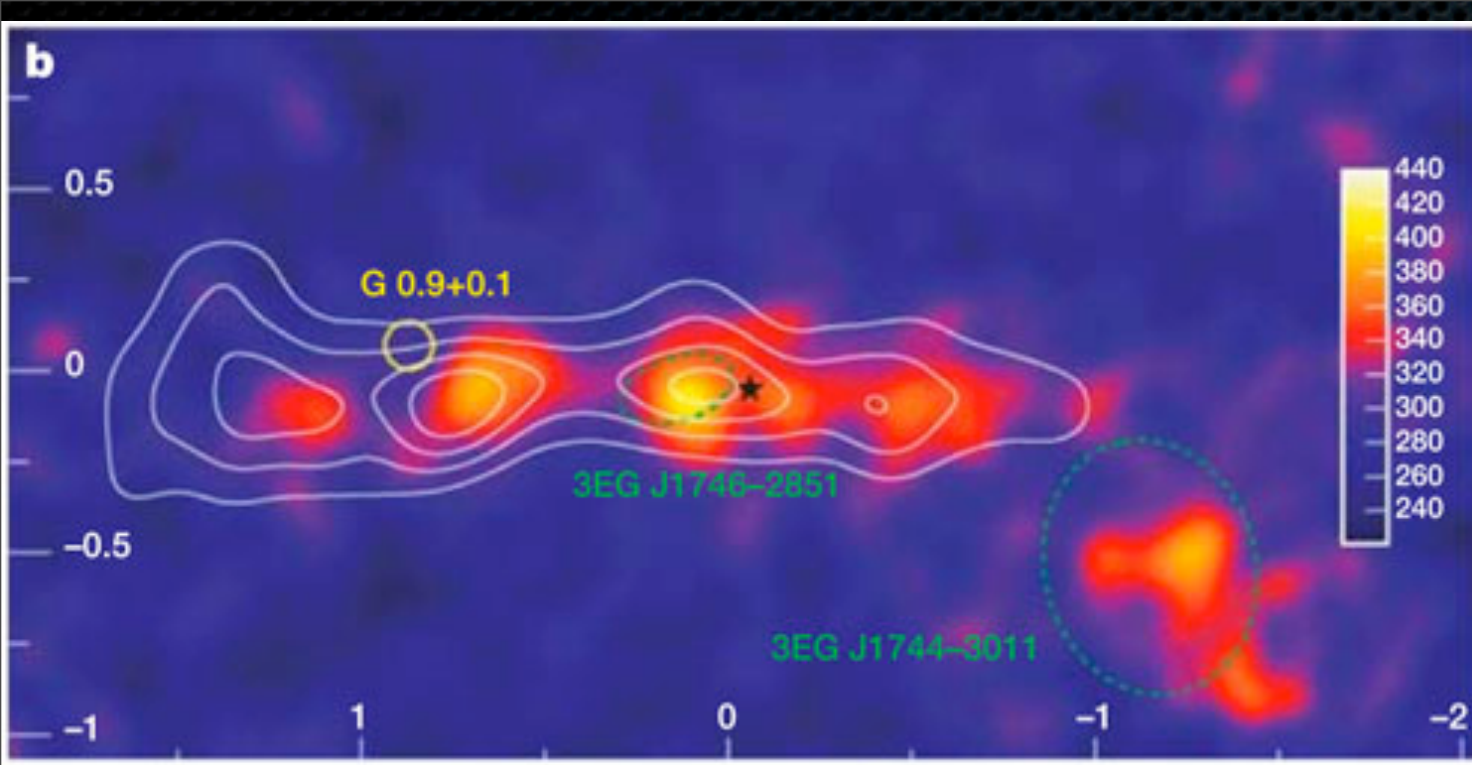
**Detection by TeV telescopes seems to reinforce hypothesis
that CRs are created in SNe**

Tycho Supernova Remnant



- VERITAS detection of Tycho SNR: Young, Type-Ia SNR**
- Possible interaction with Molecular Cloud**
- Spectrum favors hadronic models**

HESS Galactic Diffuse (>300 GeV)

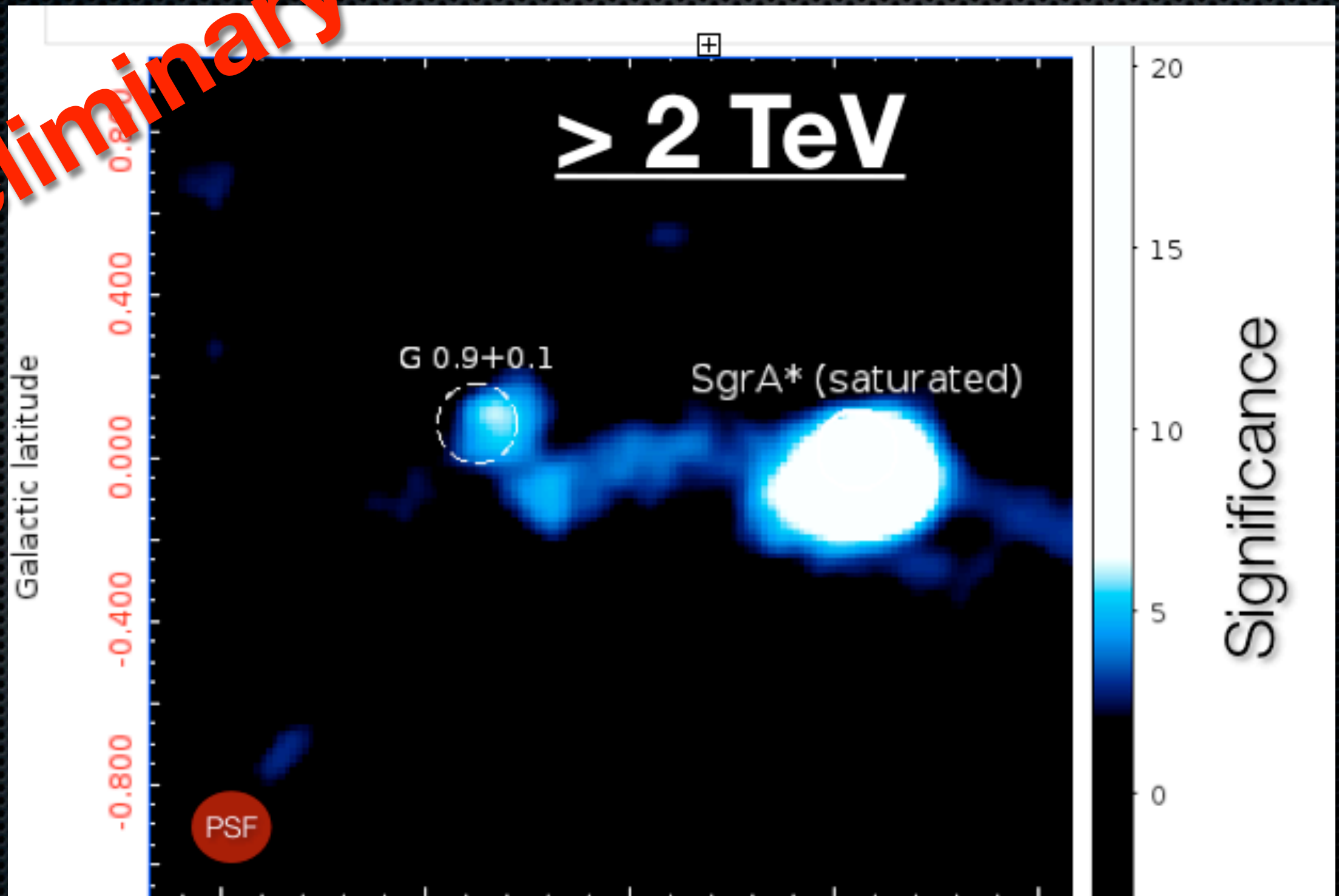


Observations probe
“cosmic ray sea”
produced at center of
Milky Way

VERITAS Observations 2010-2013

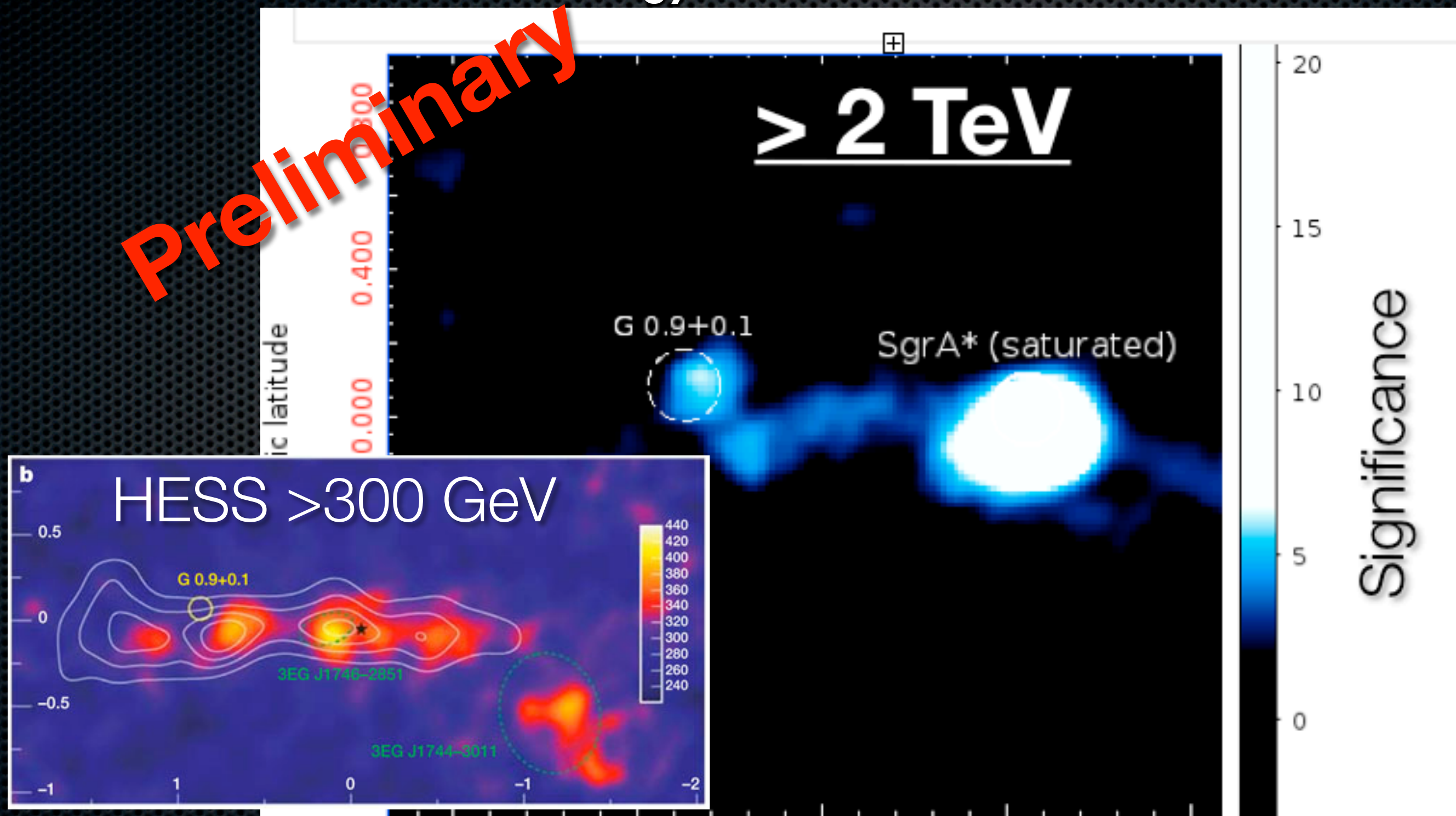
Large Zenith angle for VERITAS gives superior exposure at higher energies, probing higher energy end of CR sea

Preliminary



VERITAS Observations 2010-2013

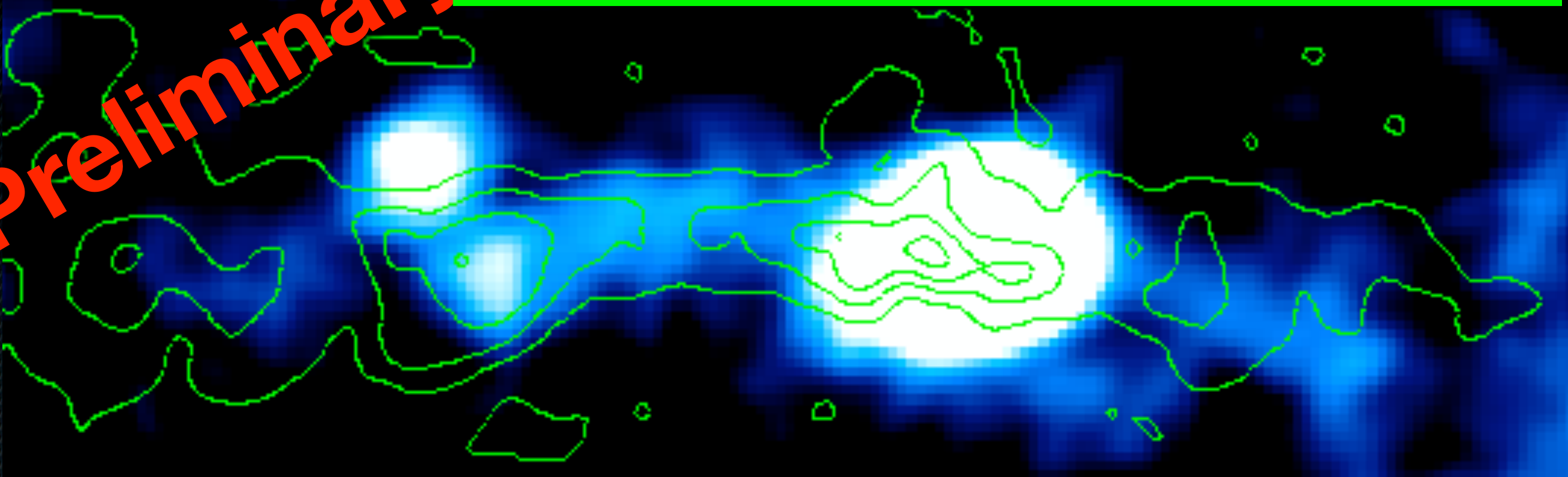
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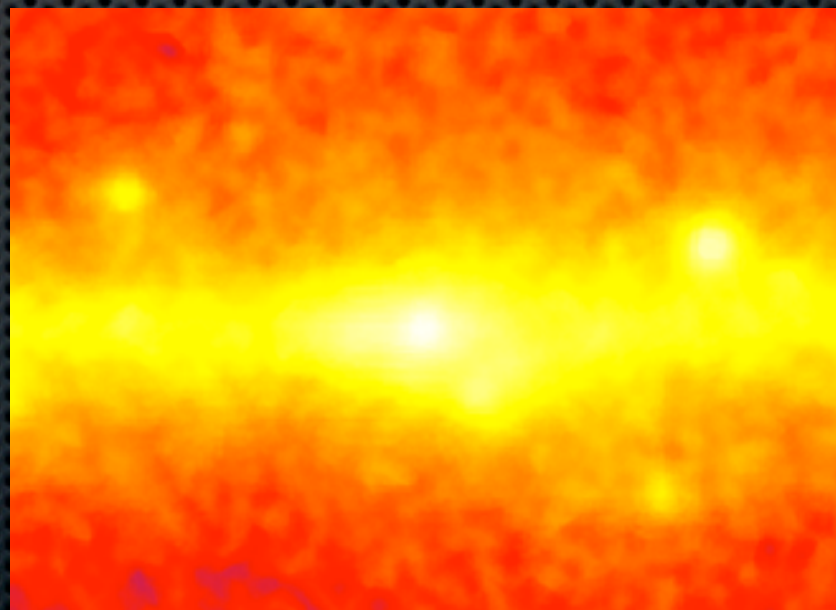
Blue/White: VERITAS significance

Green: NANTEN CO Line Contours

Preliminary

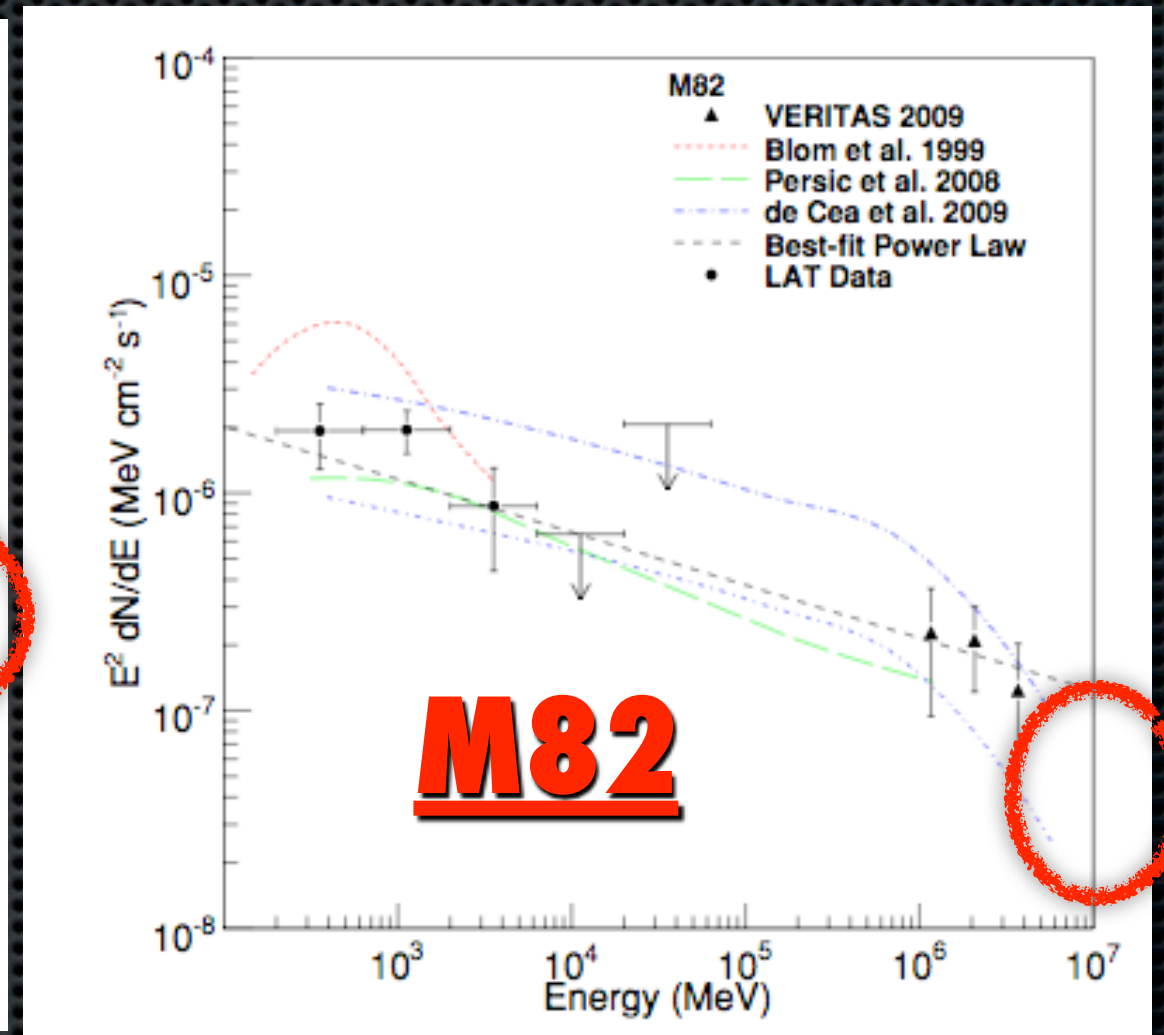
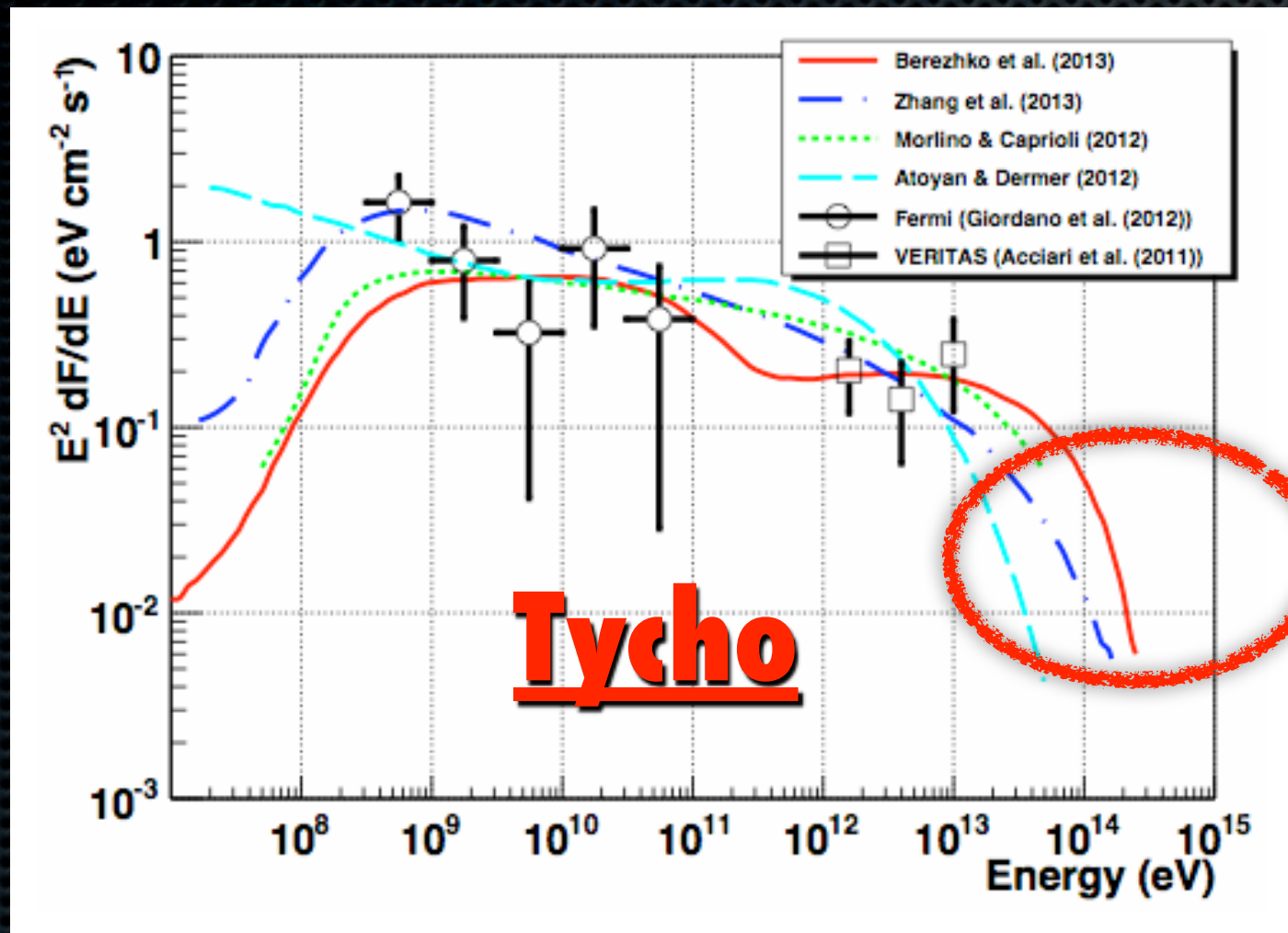


VERITAS >2 TeV traces CO emission reasonably well
Work in progress to extract true diffuse component



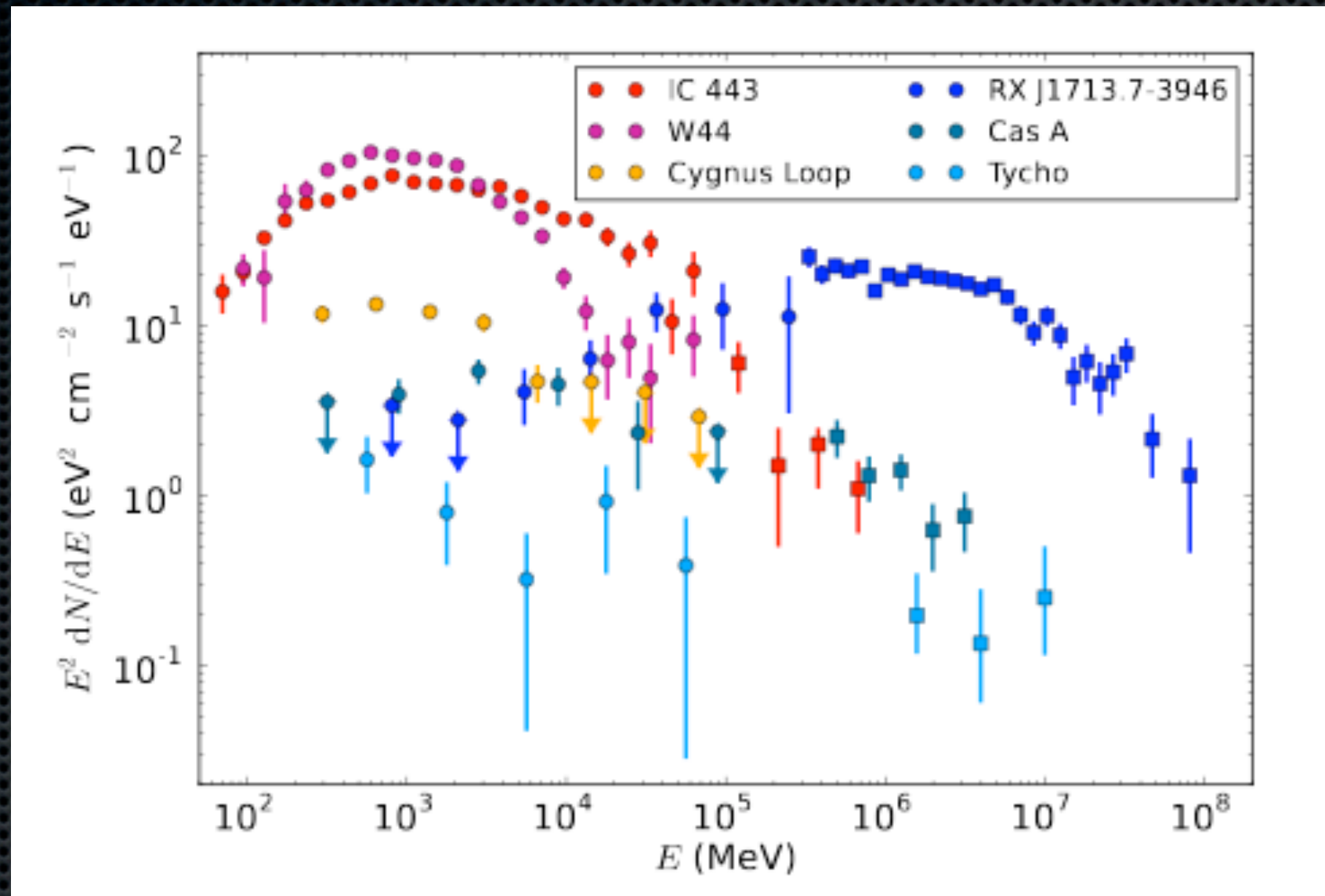
Fermi-LAT

Can IACTs (alone) say much more about CRs?



Problem 1: Hadronic vs Leptonic source models
highly dependent upon 10-100 TeV spectral behavior

Can IACTs (alone) say much more about CRs?



Problem 2: Limitations of small source populations of potential CR sources

Water Cherenkov Detectors:

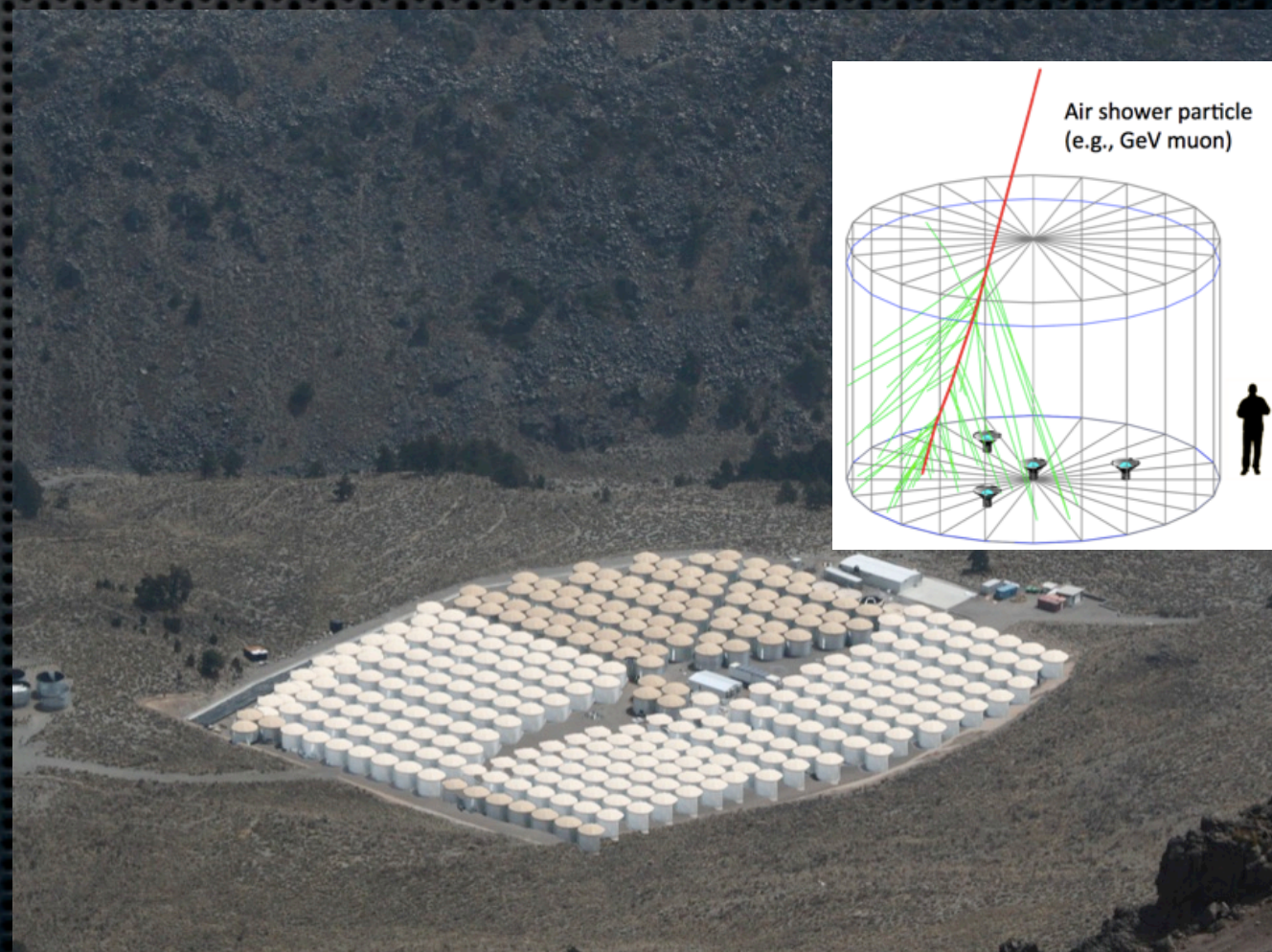
- Detect Cherenkov Emission from air shower secondaries in H₂O
- Loss of quality angular resolution (vs IACTs) compensated for by enhanced sensitivity at higher energy, $\sim 100\%$ duty cycle

WCDs serve as crucial pathfinders for sources for follow up with IACTs- also extend energy spectrum of known sources

1st Generation: Milagro

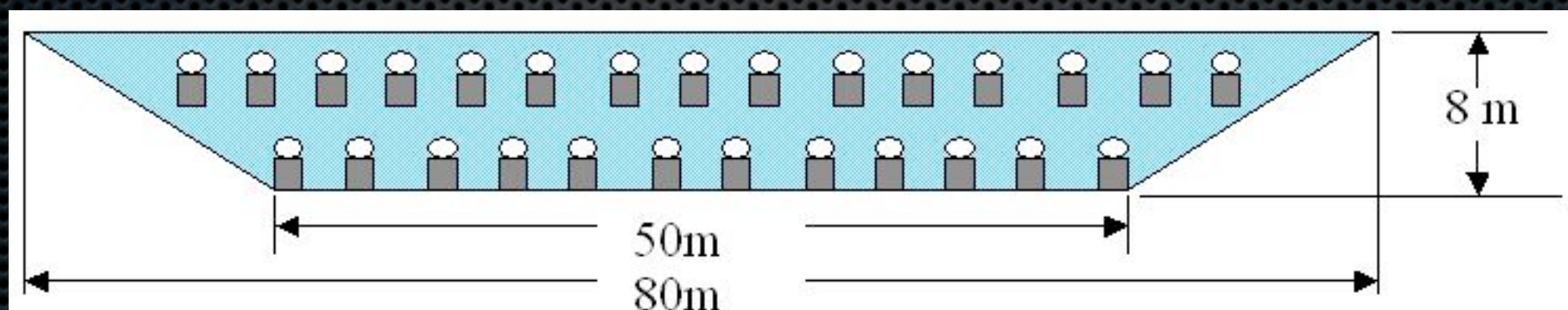
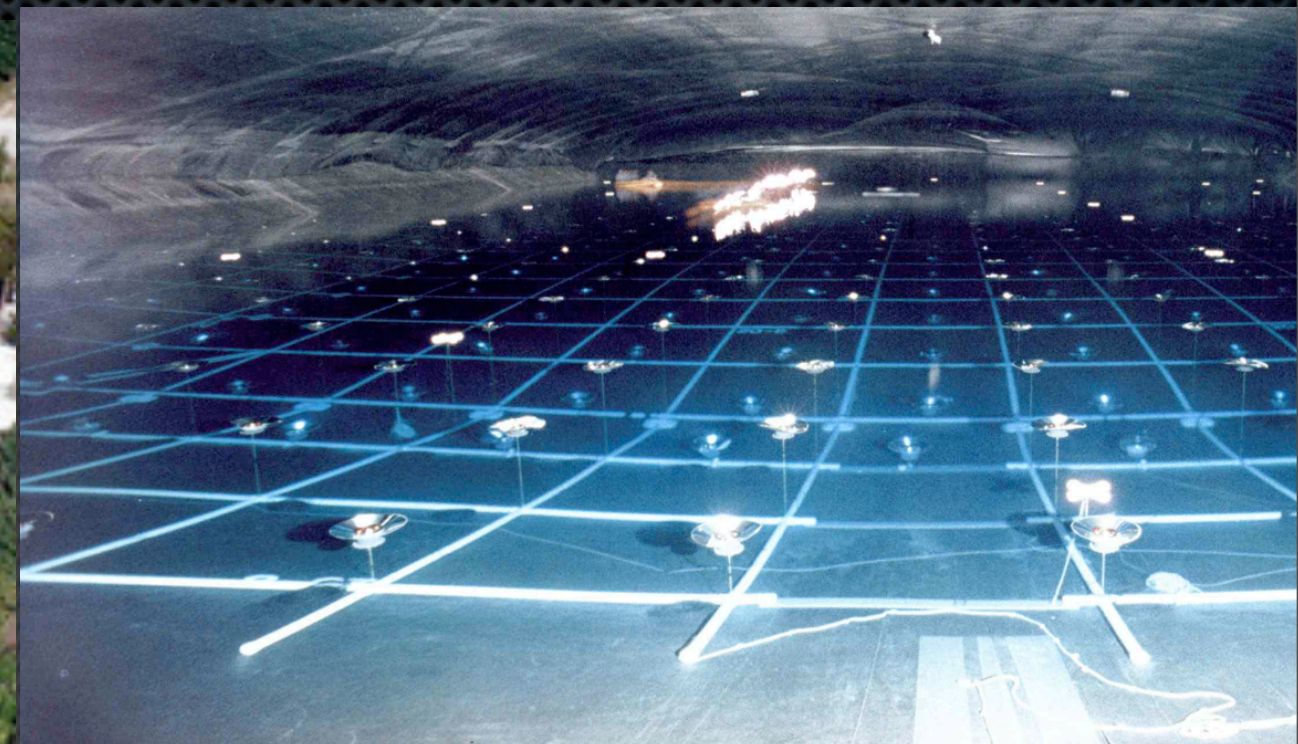


2nd Generation: HAWC



MILAGRO

(Los Alamos, New Mexico, USA)



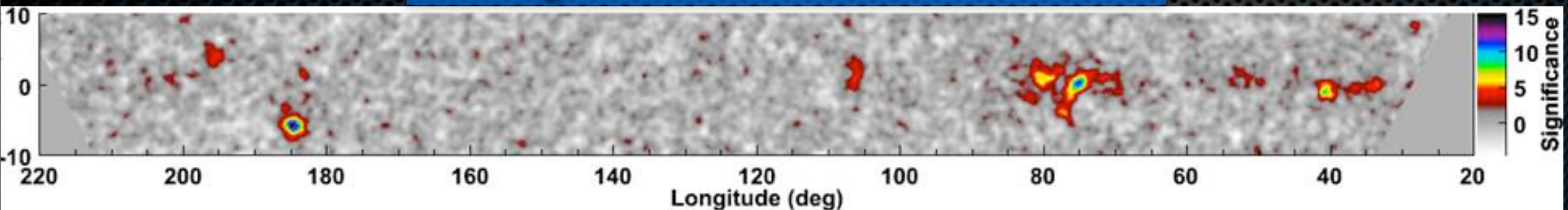
$\sim 5000 \text{ m}^2$, 20cm PMTs in 2 layers
Operated full time from 2001-2008 with sensitivity
from $\sim 1\text{-}100 \text{ TeV}$



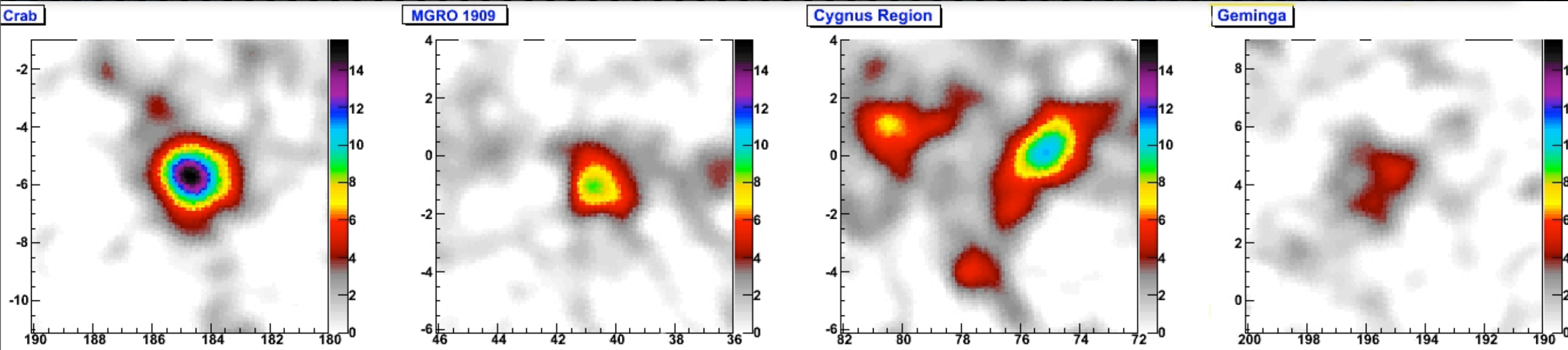
MILAGRO

(Los Alamos, New Mexico, USA)

Milagro Galactic Plane at 20 TeV

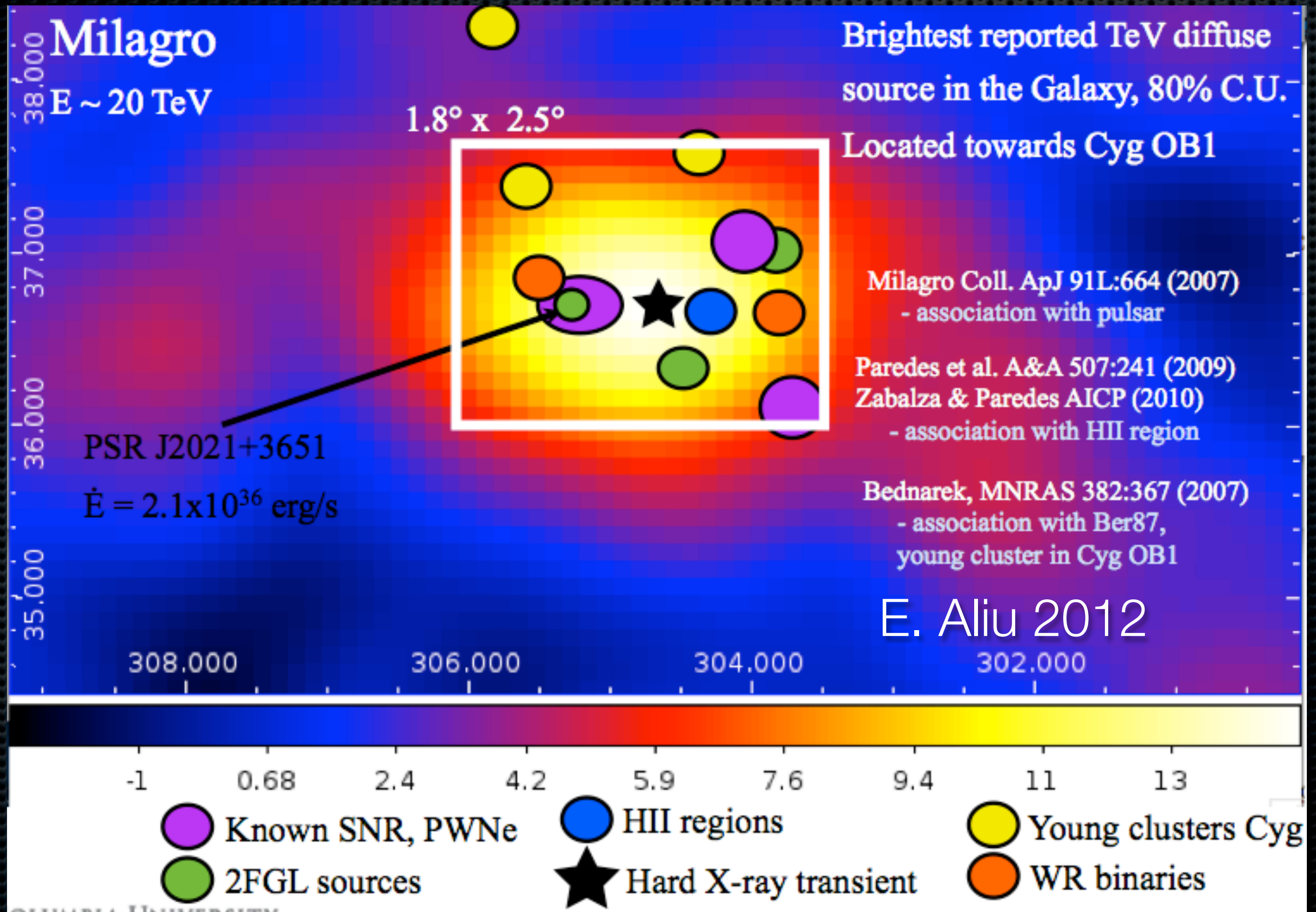


Milagro revealed many regions of multi-TeV emission: many extended sources not previously seen by IACTs, followed by a landslide of successful followup observations with VERITAS



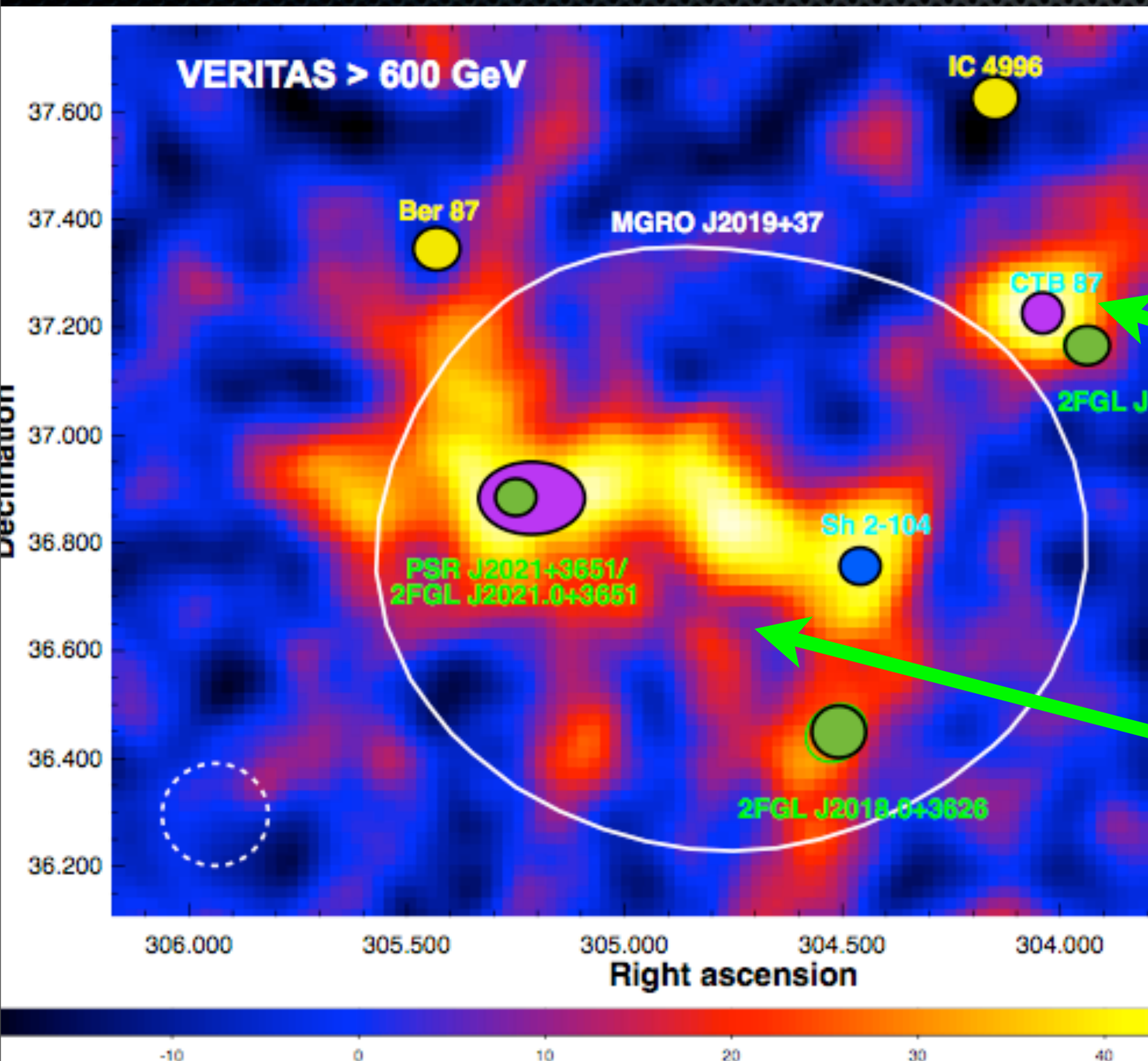
MILAGRO/VERITAS Sources

MGRO J2019+307



MILAGRO/VERITAS Sources

MGRO J2019+307



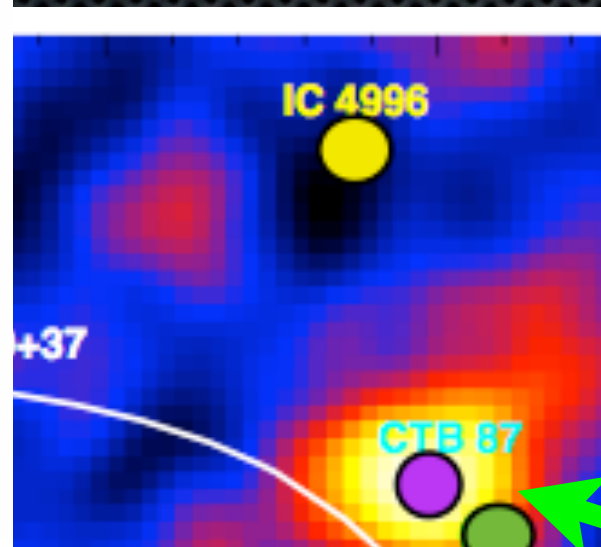
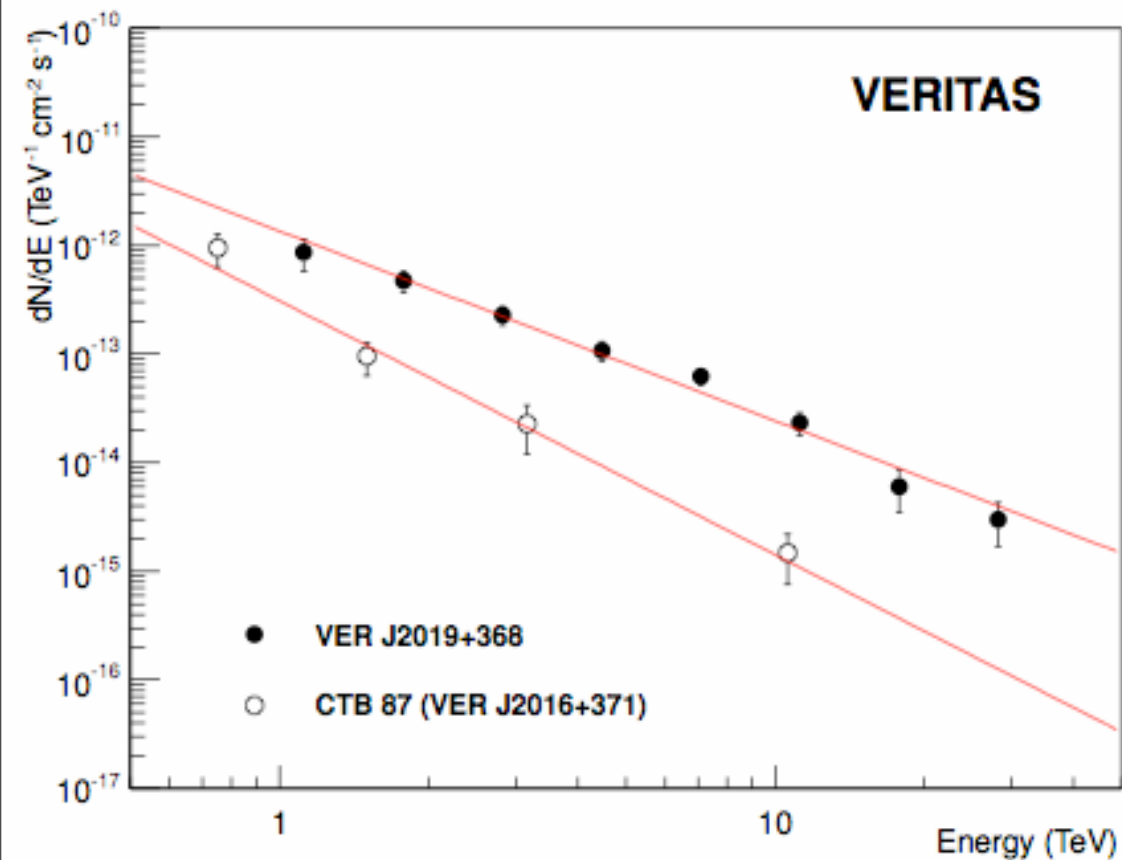
High Angular Resolution VERITAS observations reveal complicated network of TeV emission

VER J2016+371: point source, consistent with CTB 87 (PWN)

VER J2019+368: extended emission, possibly multiple sources covering ~1 deg

VERITAS Sources

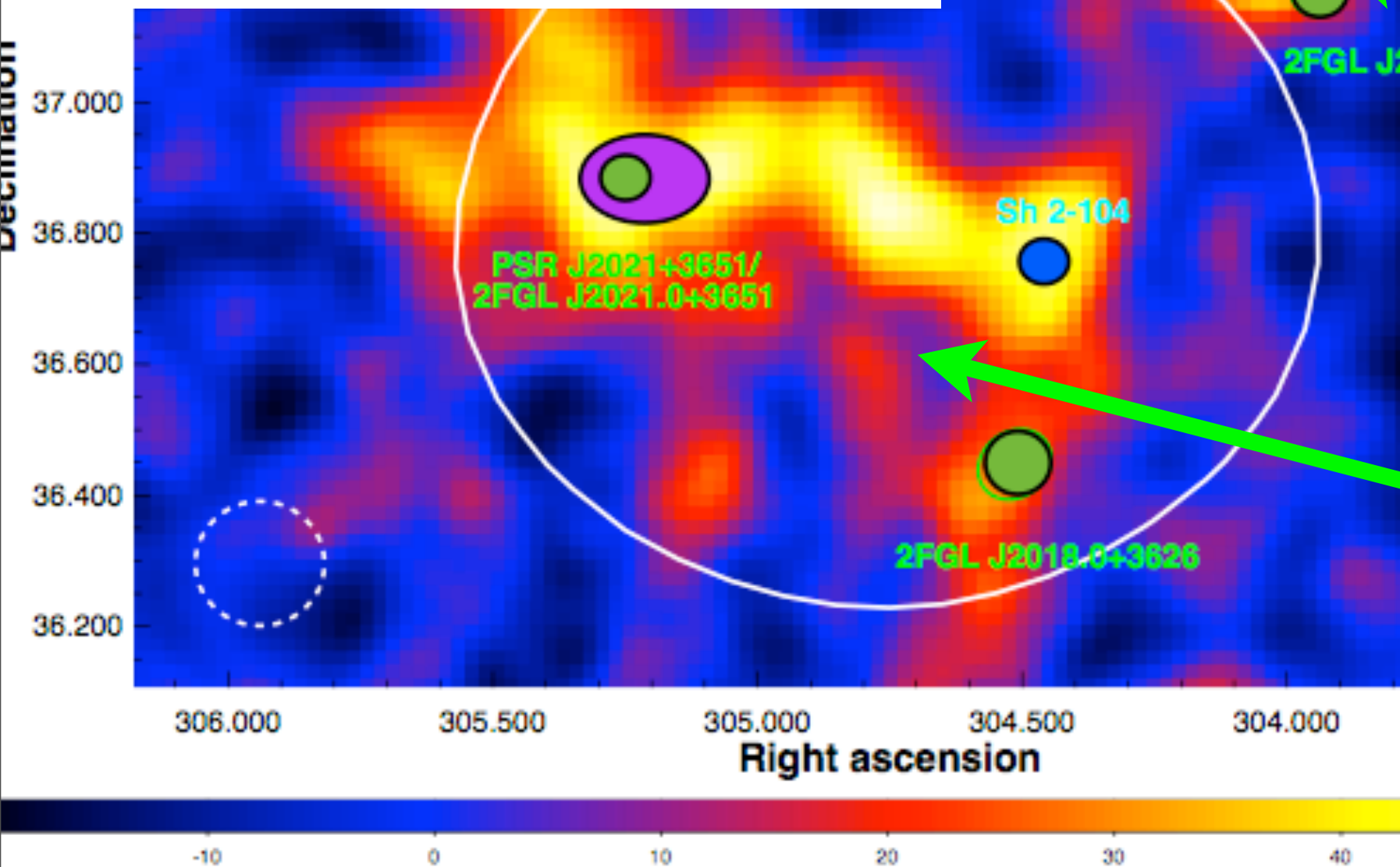
J2019+307



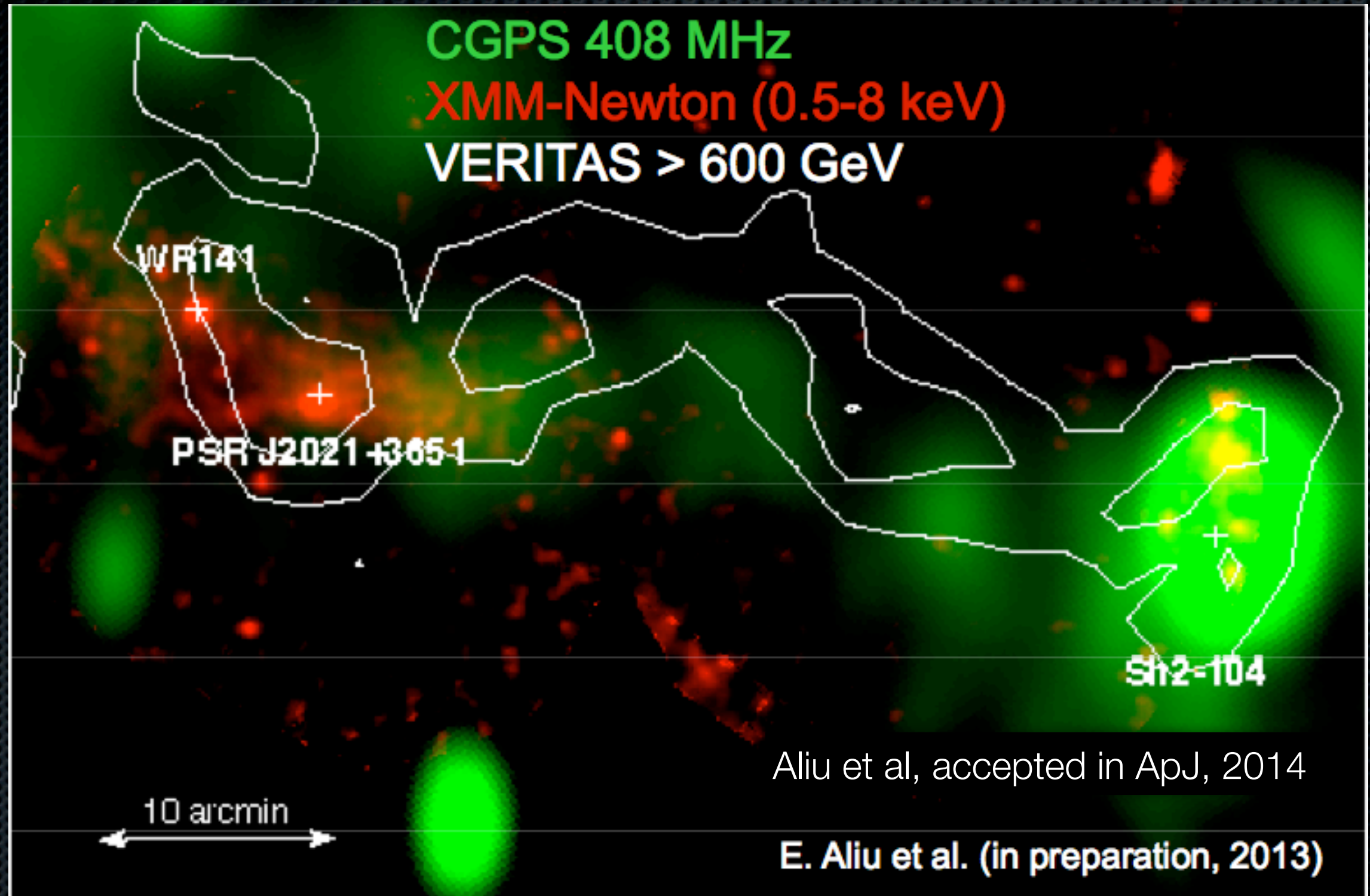
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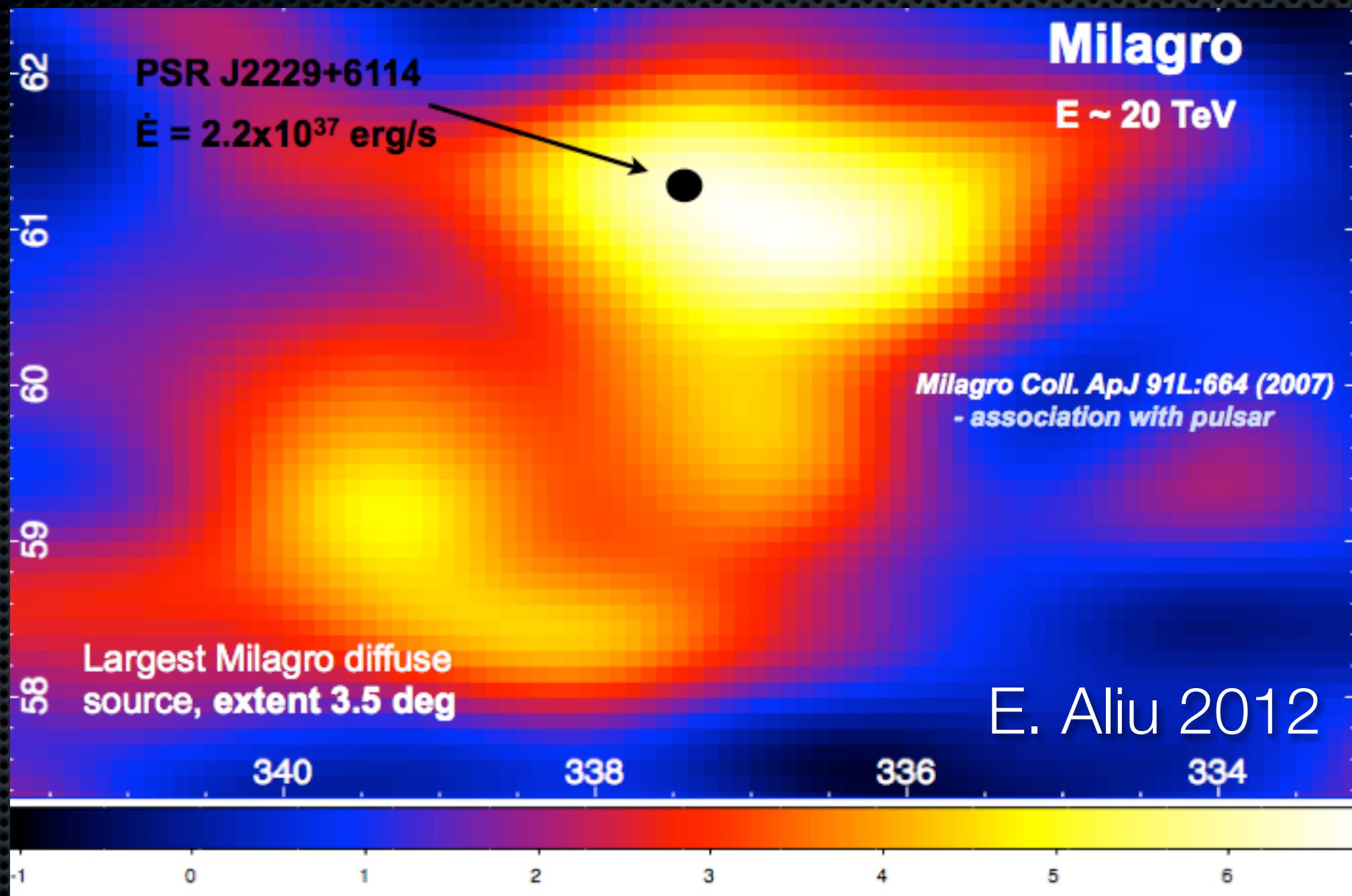
MGRO J2019+307



VERITAS >600 GeV emission appears to trace radio emission relatively well. Interactions with HII region possibly significant. 50% of emission possibly powered by PSR/WR141 in NW corner.

MILAGRO/VERITAS Sources

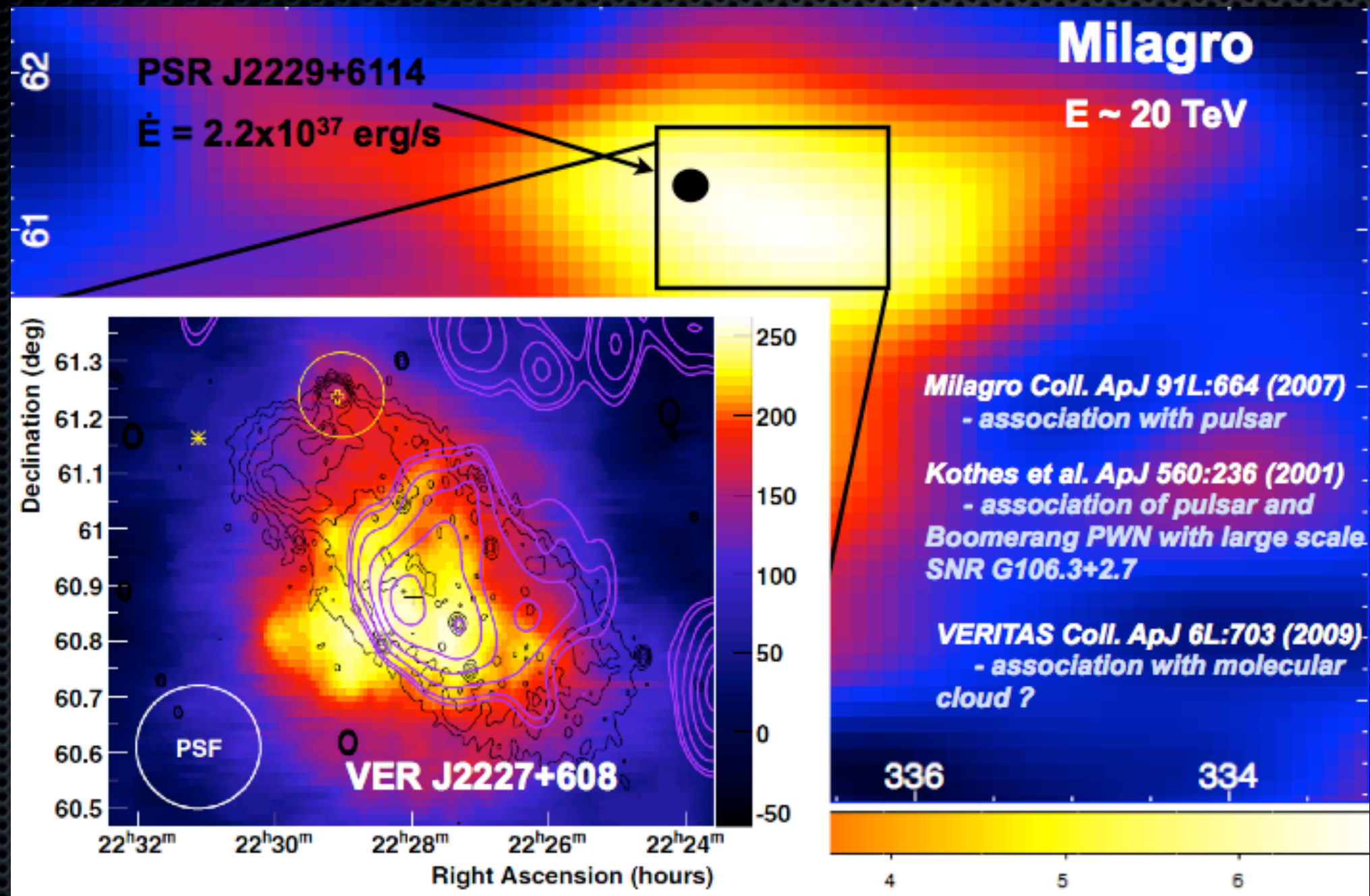
MGRO J2228+61



MGRO data indicates possible relation to either PWN shock or MC interaction

MILAGRO/VERITAS Sources

MGRO J2228+61



High-Res VERITAS observations reveal emission highly correlated with MC (CO contours). Possible hadronic CR acceleration site.

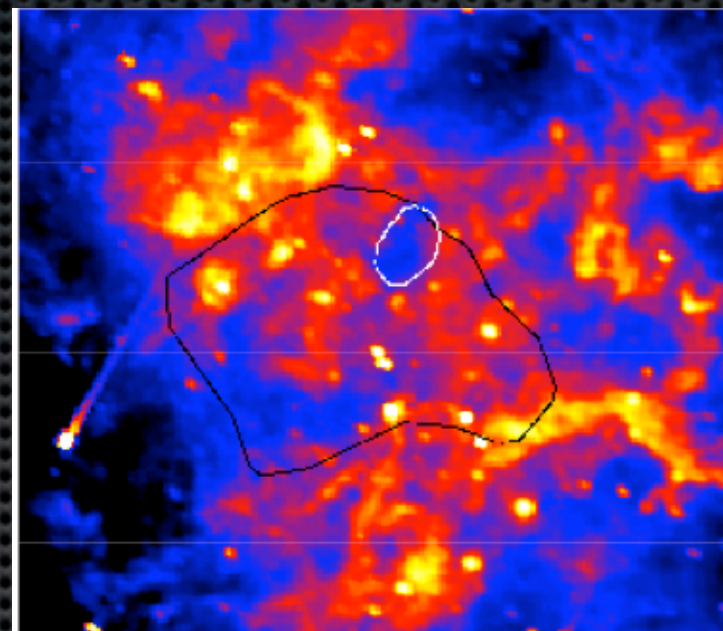
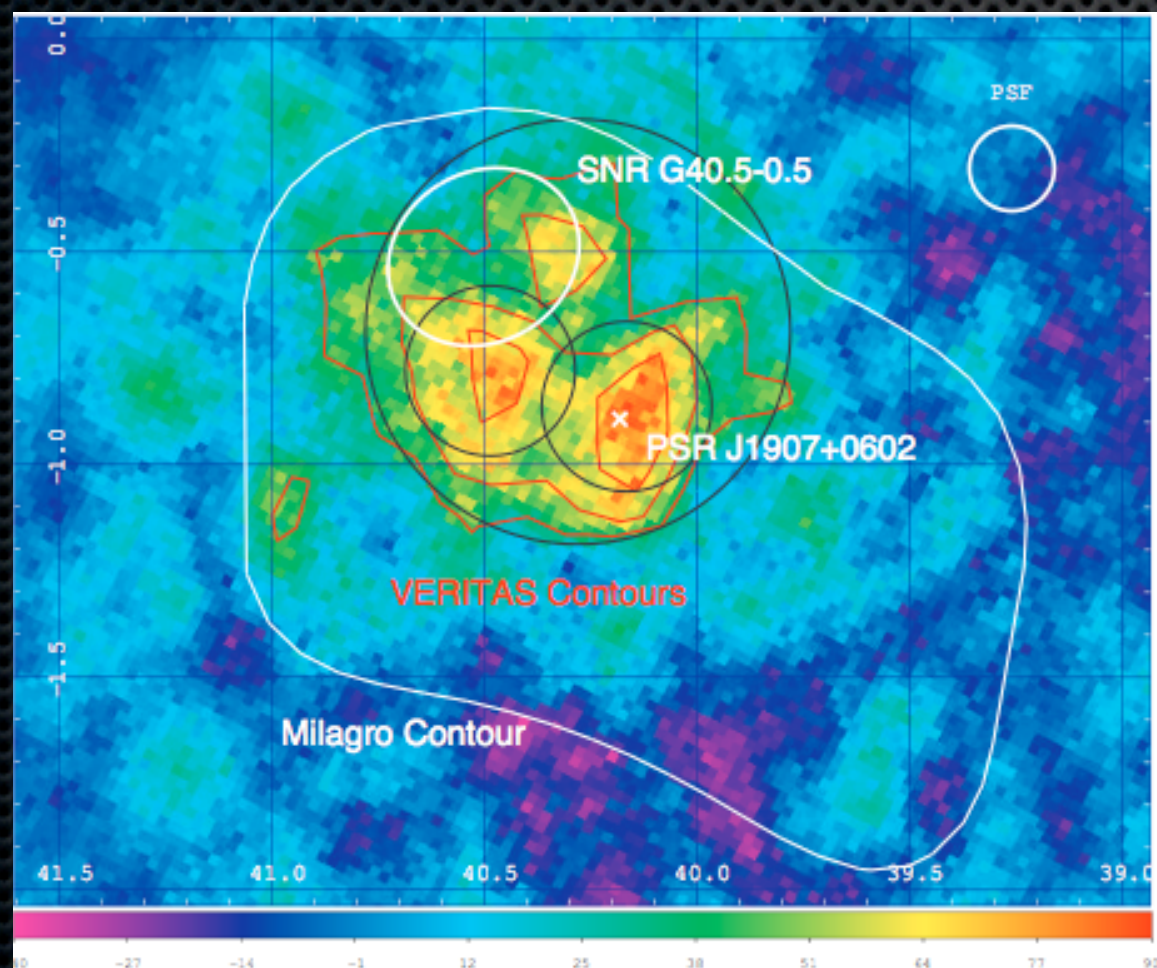
MILAGRO/VERITAS Sources

Other Examples: PWN powered sources

MGRO J1908/VER

J1907+06:

No strong radio or CO line emission coincident with TeV. Probable PWN powered system

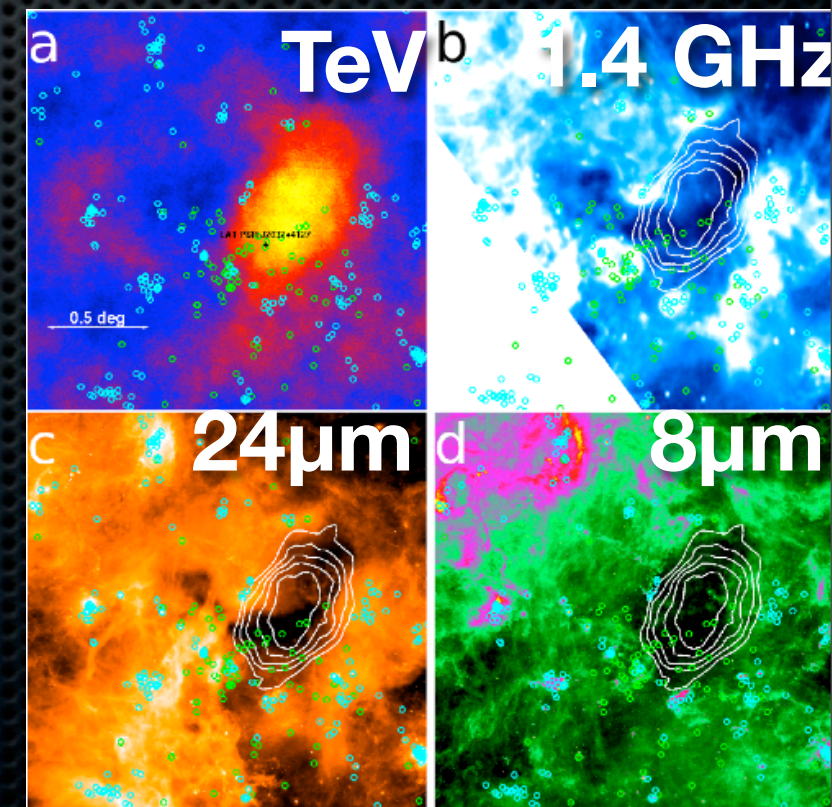


MSX 8 μ m survey
VERITAS = white line
Milagro = Black line

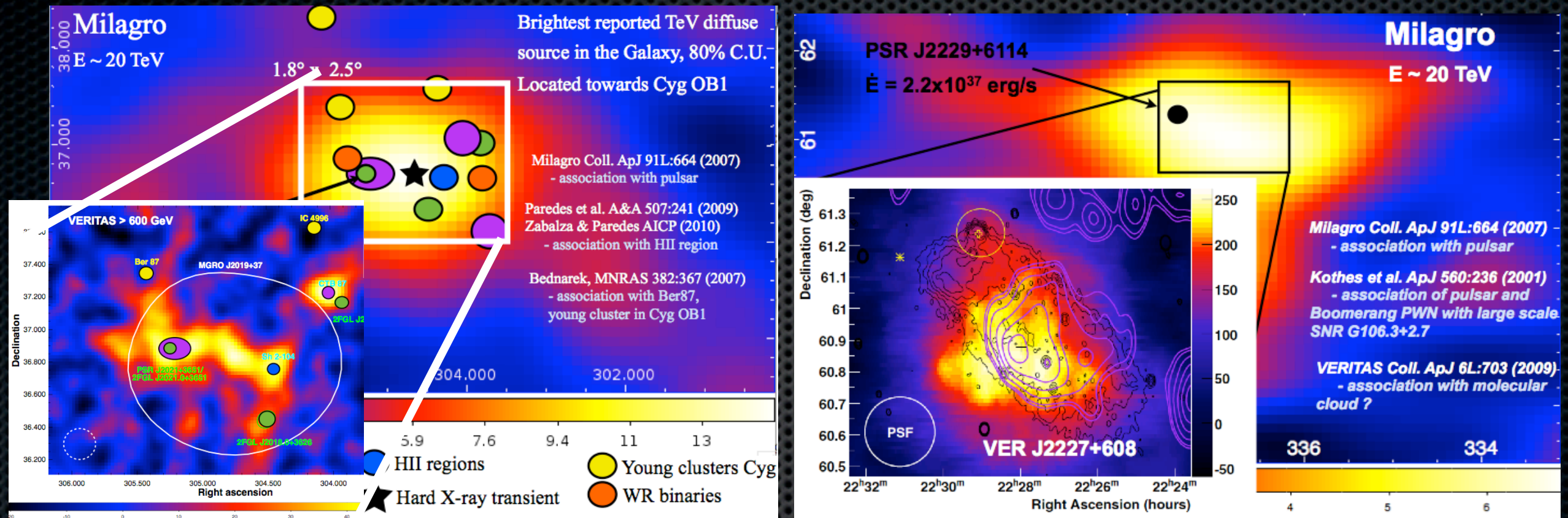
TeV J2032

Large Milagro region narrowed down by VERITAS

TeV emission uncorrelated with longer wavelengths. Probable PWN association



MILAGRO and VERITAS



Milagro wide field of view, combined with large duty cycle served as excellent pathfinder for large extended sources for VERITAS to resolve.

Next step: Upgraded VERITAS and The High Altitude Water Cherenkov Observatory



The High Altitude Water Cherenkov Observatory

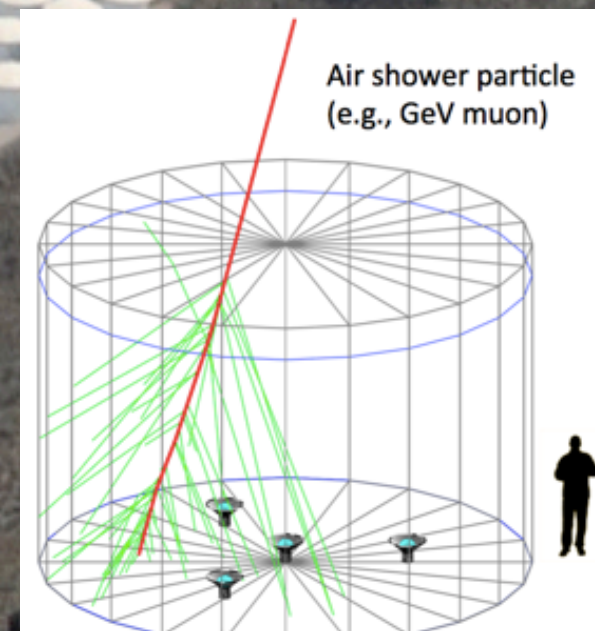
- 300 large water tanks
- 4100m asl
- 22,000 m² area
- 4 PMTs per tank
- 4m water above PMTs
- 15 x more sensitive than Milagro

>5x # of detectable shower particles relative to Milagro
Hadron rejection area and shower sampling

- 10x Larger muon detection area
- 4x Larger dense sampling region

Improved Angular & Energy Resolution

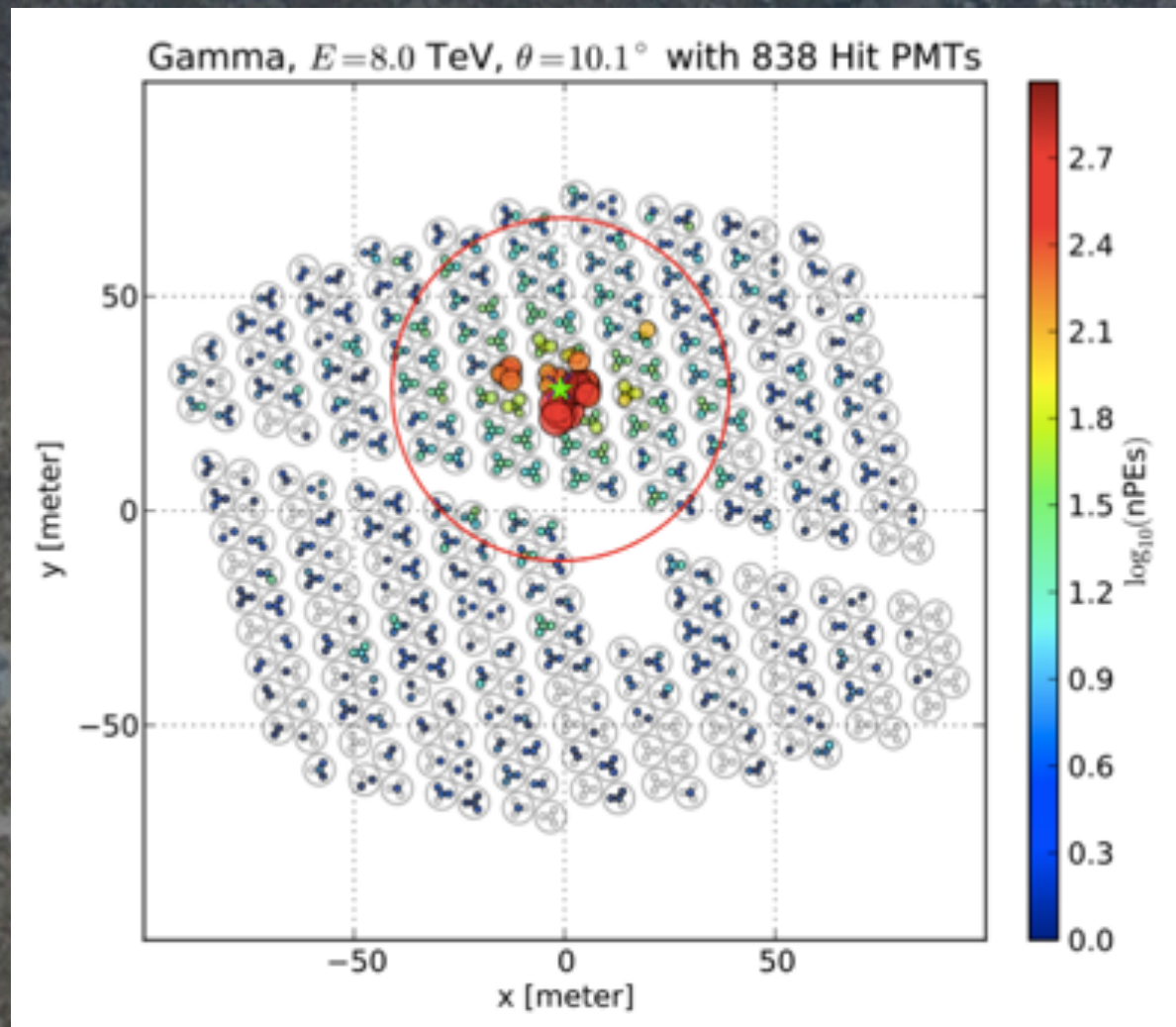
~Milagro
footprint



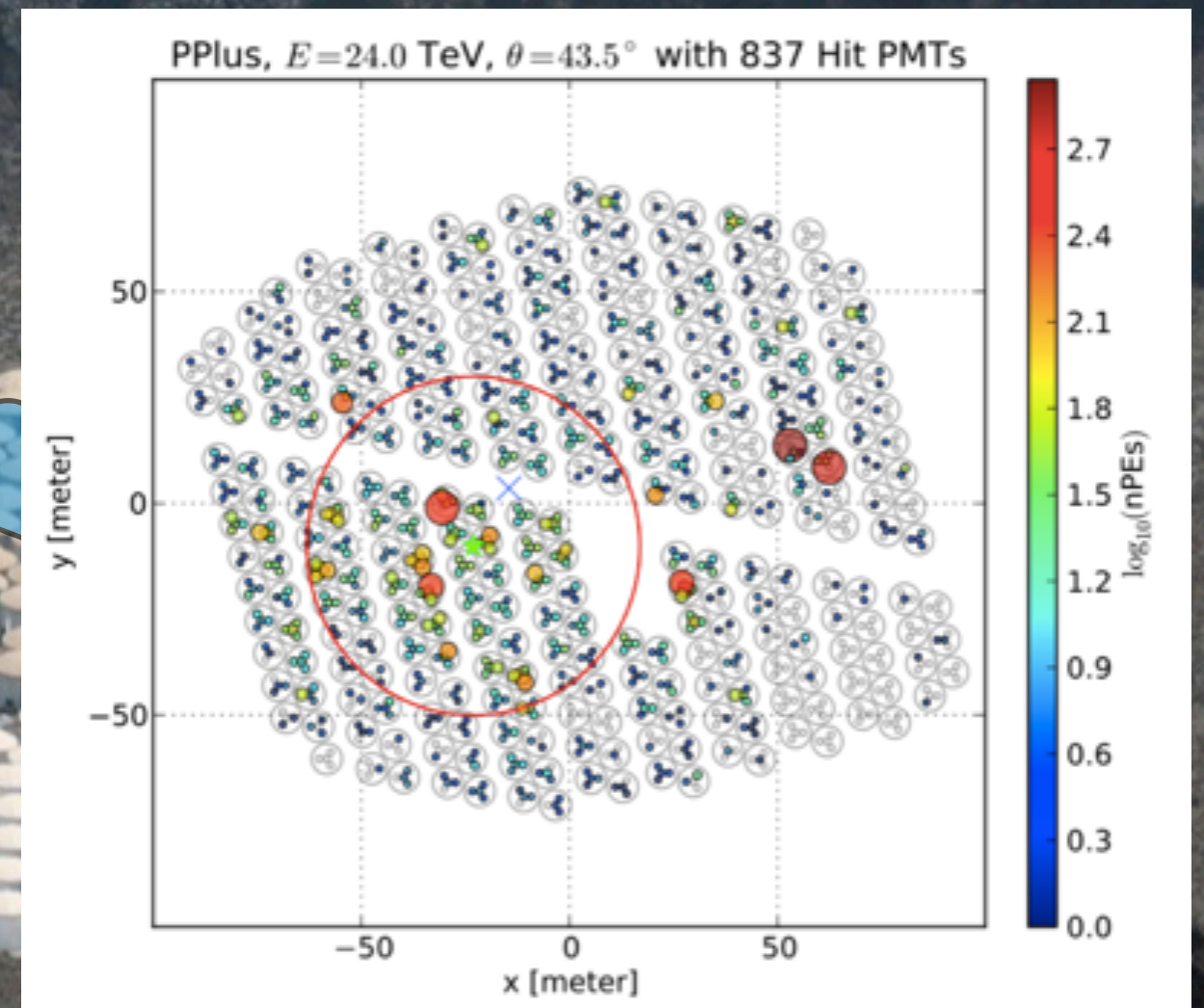


The High Altitude Water Cherenkov Observatory

Gamma Ray



Cosmic Ray





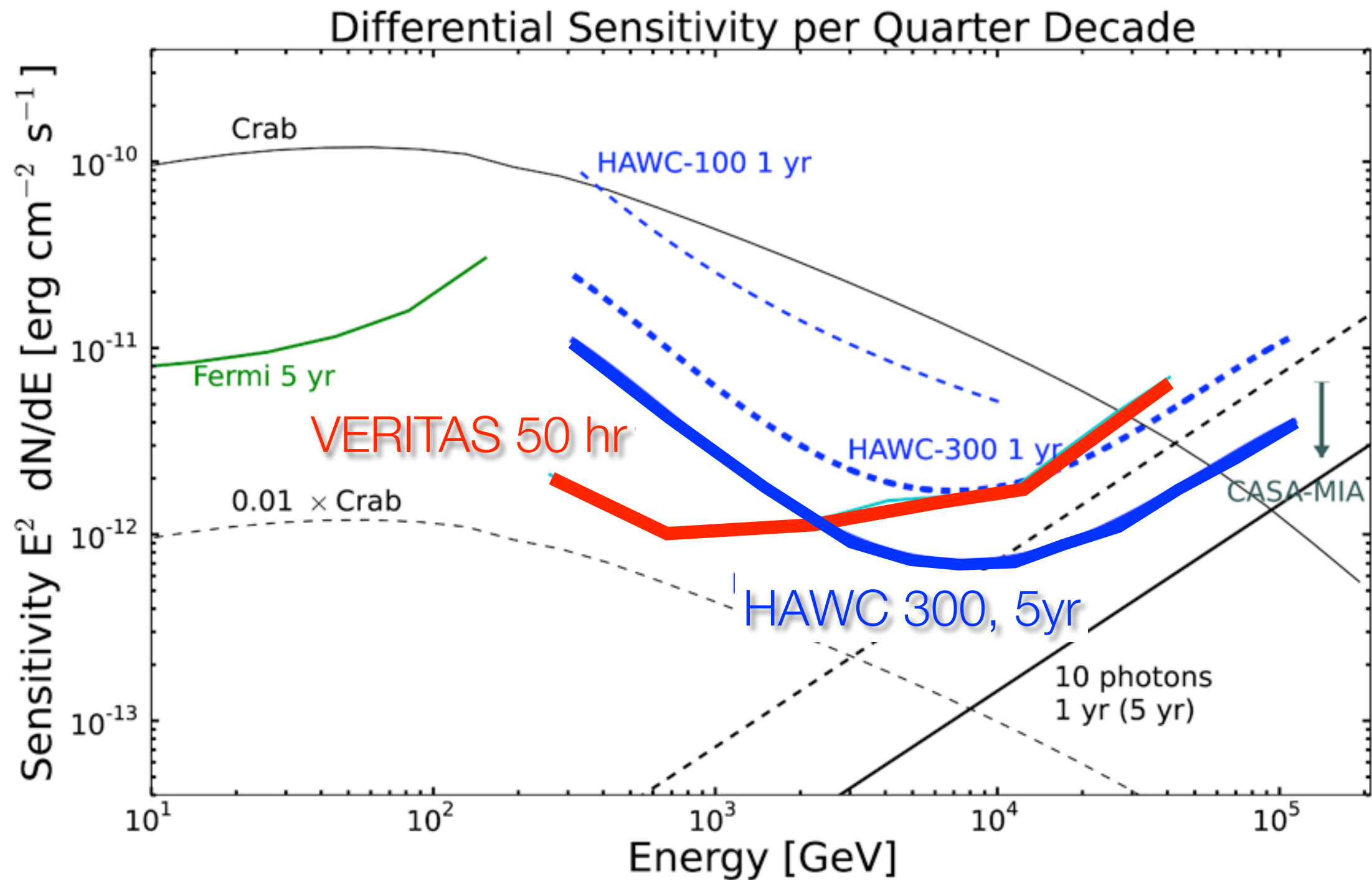
Pico de Orizaba

5636m

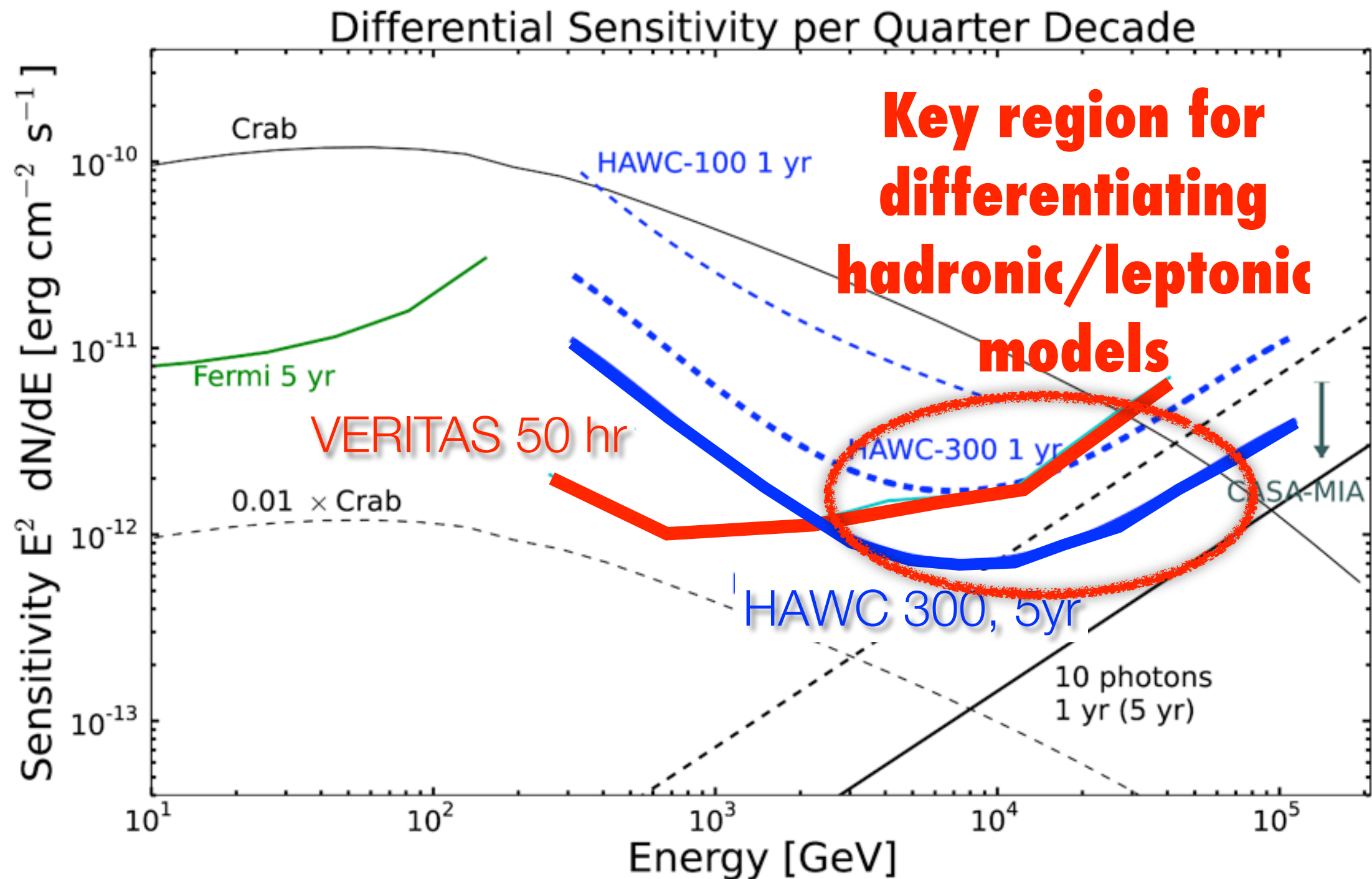
HAWC
4100m



HAWC and VERITAS

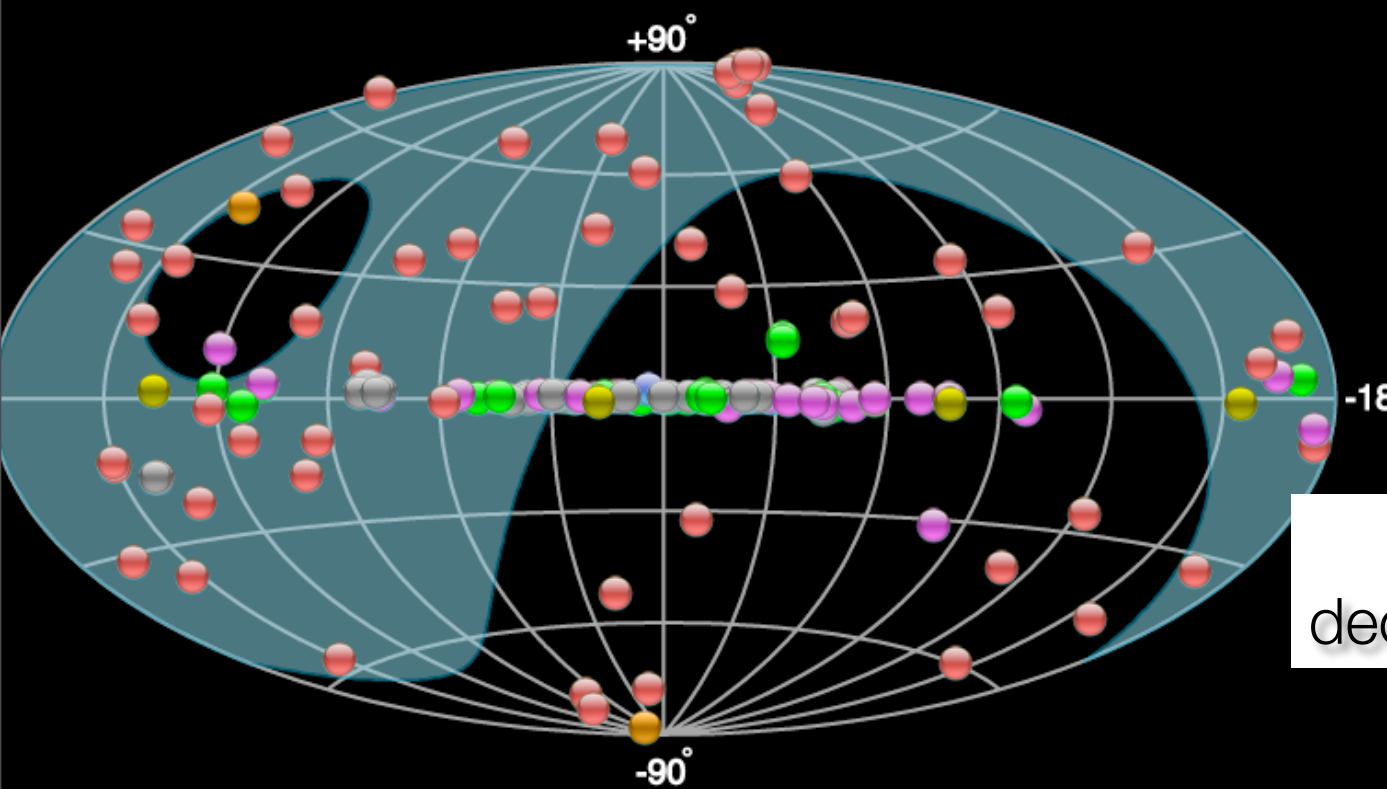


HAWC and VERITAS

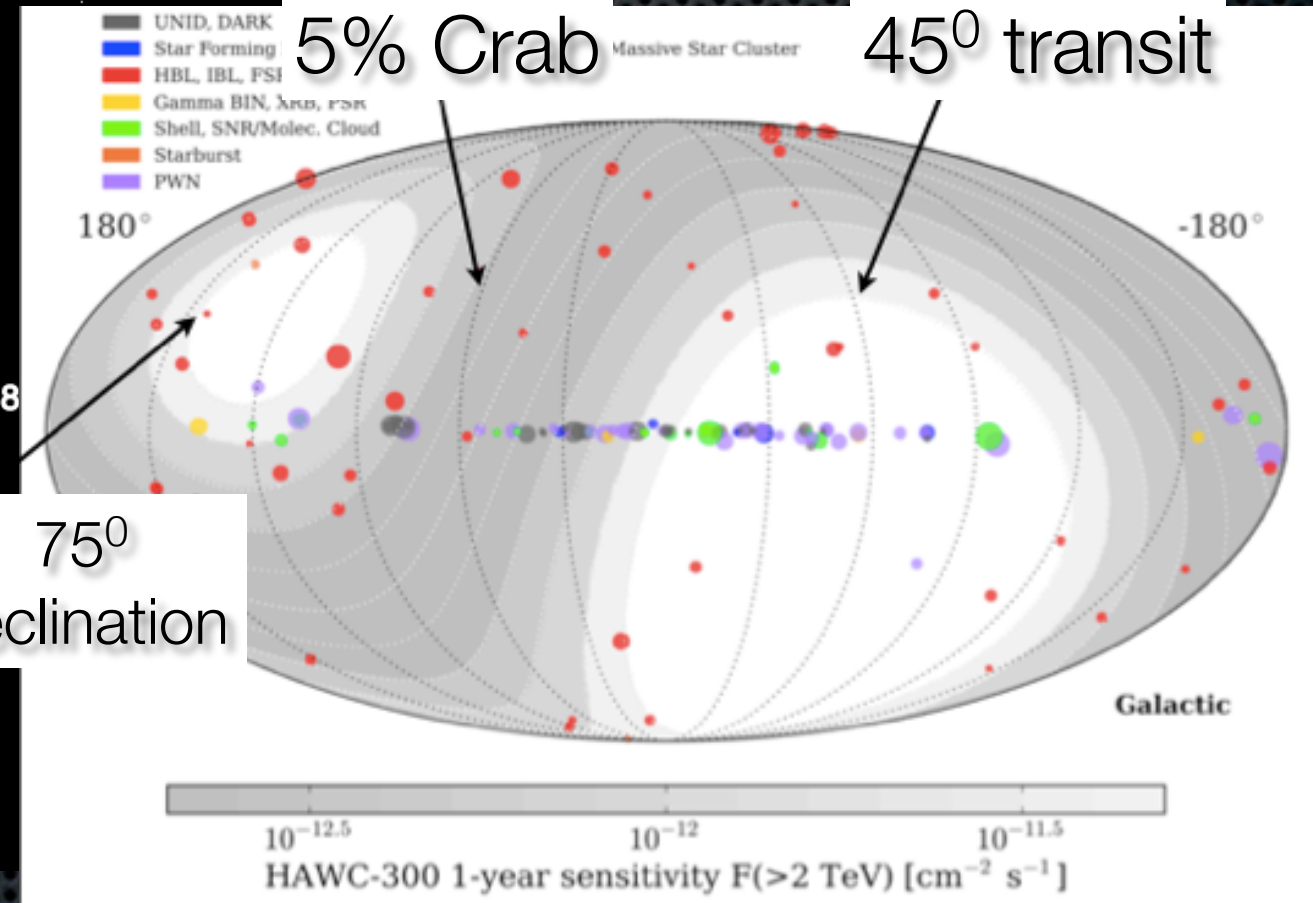


HAWC and VERITAS Will View Nearly Identical Regions of Sky

VERITAS



HAWC



MOU already in place for communication of ToOs

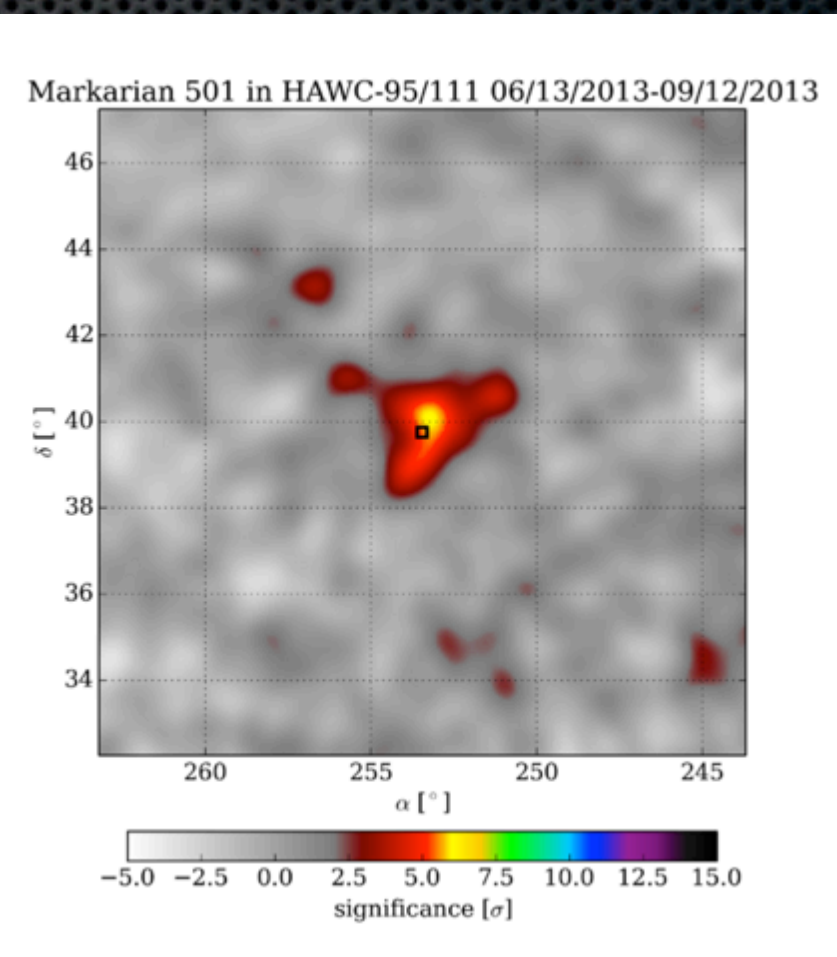
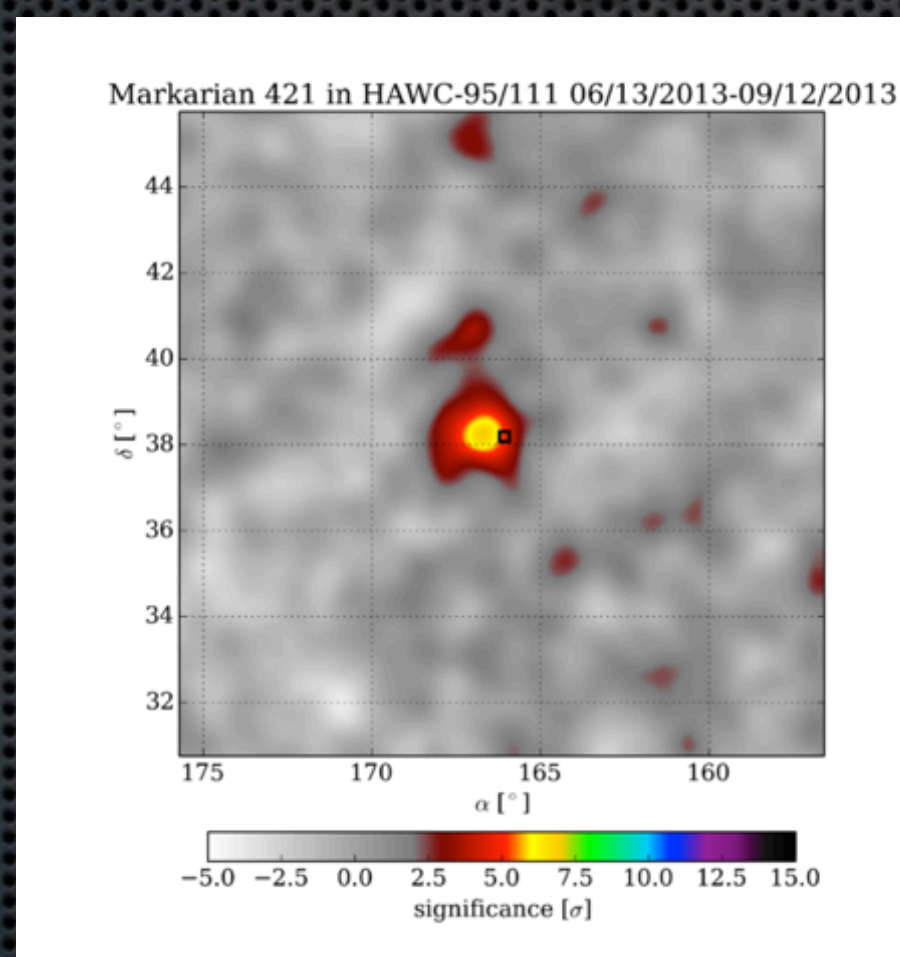
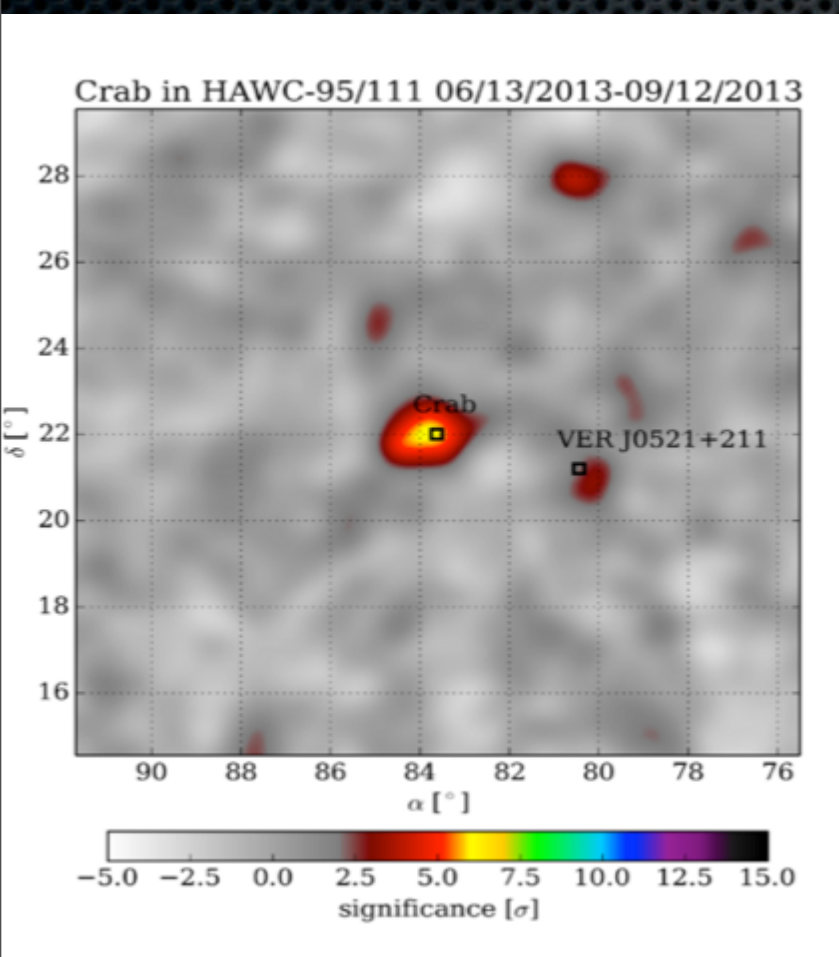
HAWC Still In Commissioning Phase

-Subarray already producing detections
(95/111 tanks)

Crab

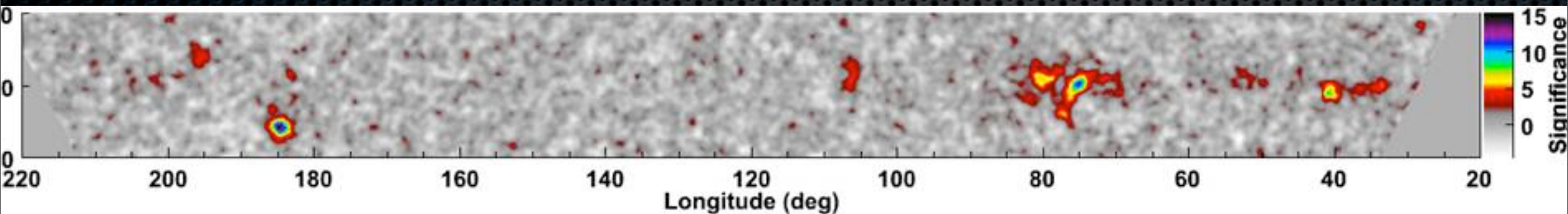
Mrk 421

Mrk 501



-Full 300 tank operations by Fall 2014

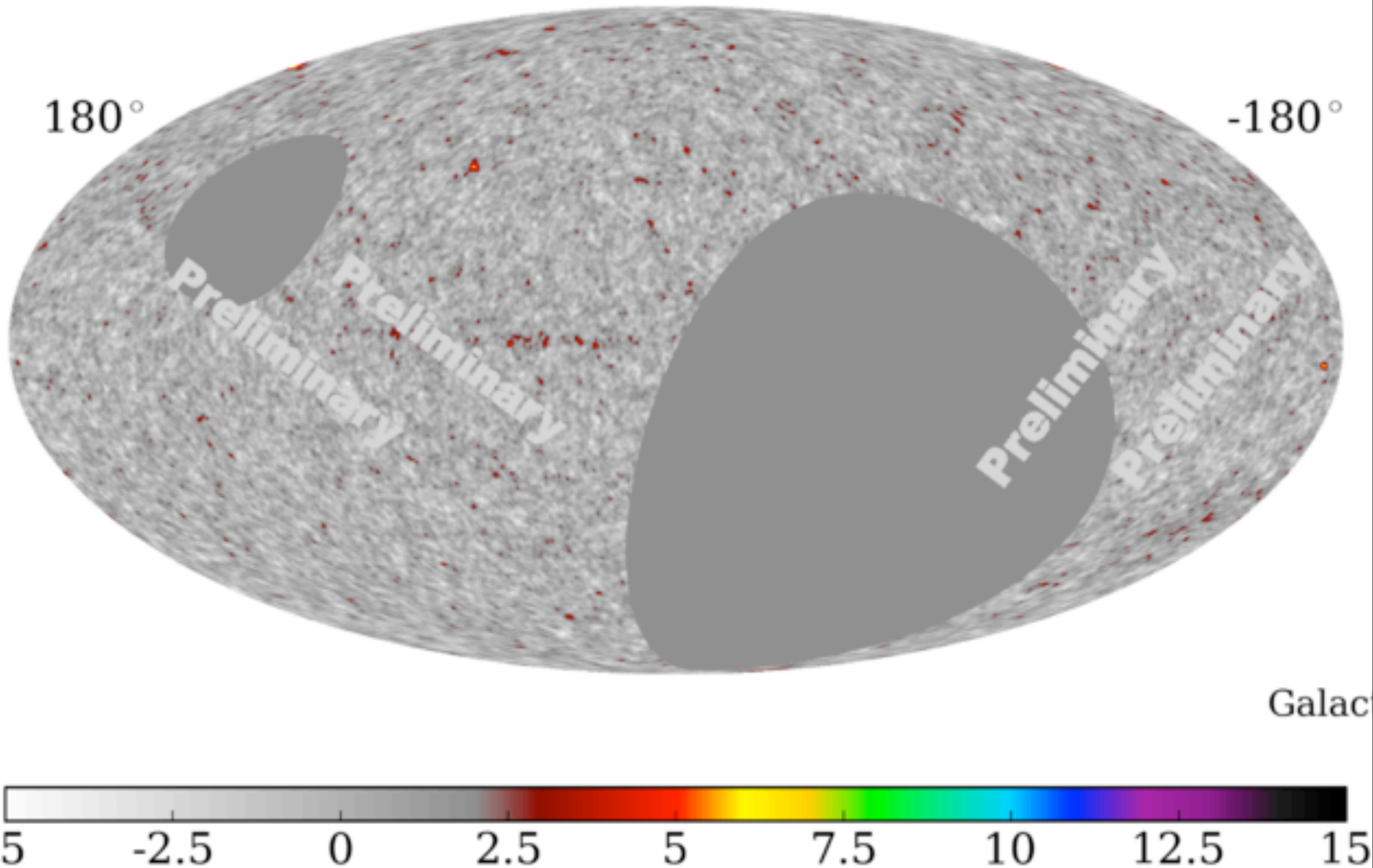
Milagro Galactic Plane



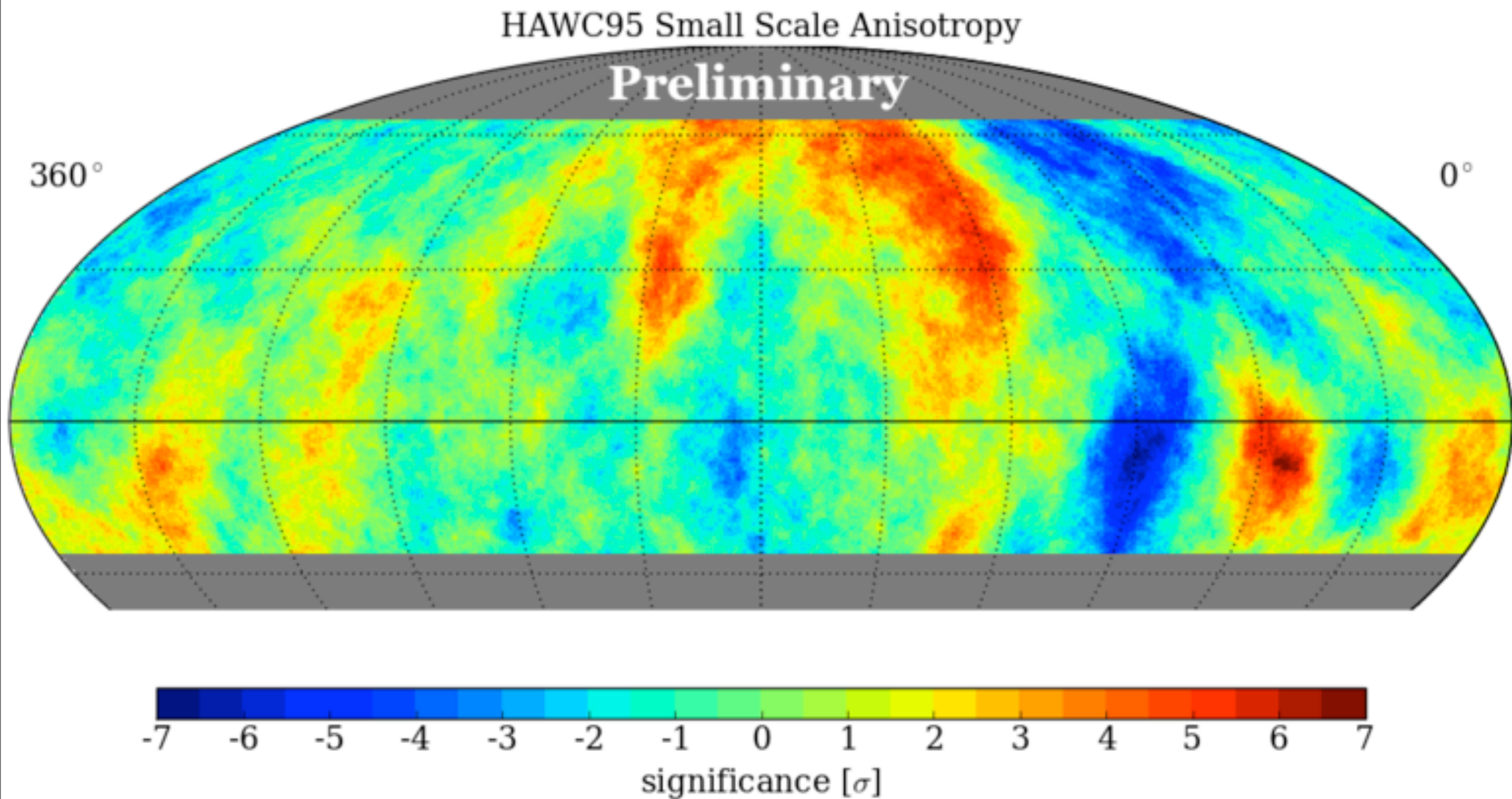
~ 1 month of full (300 Tank)
HAWC Array projected to
reproduce all of Milagro data

HAWC 95/111 Preliminary 3 Month SkyMap

HAWC-95/111 SKY 06/13/2013-09/12/2013



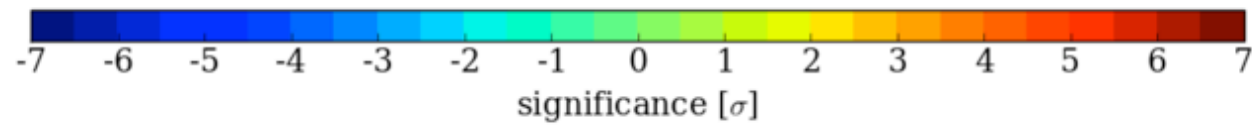
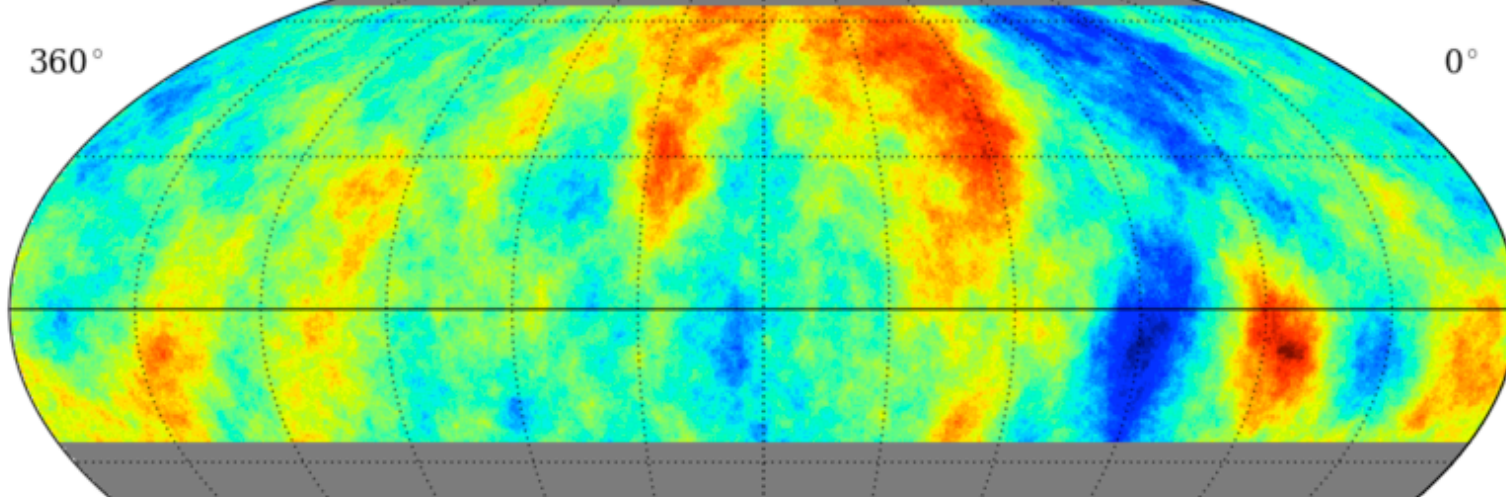
HAWC 95 CR Anisotropy



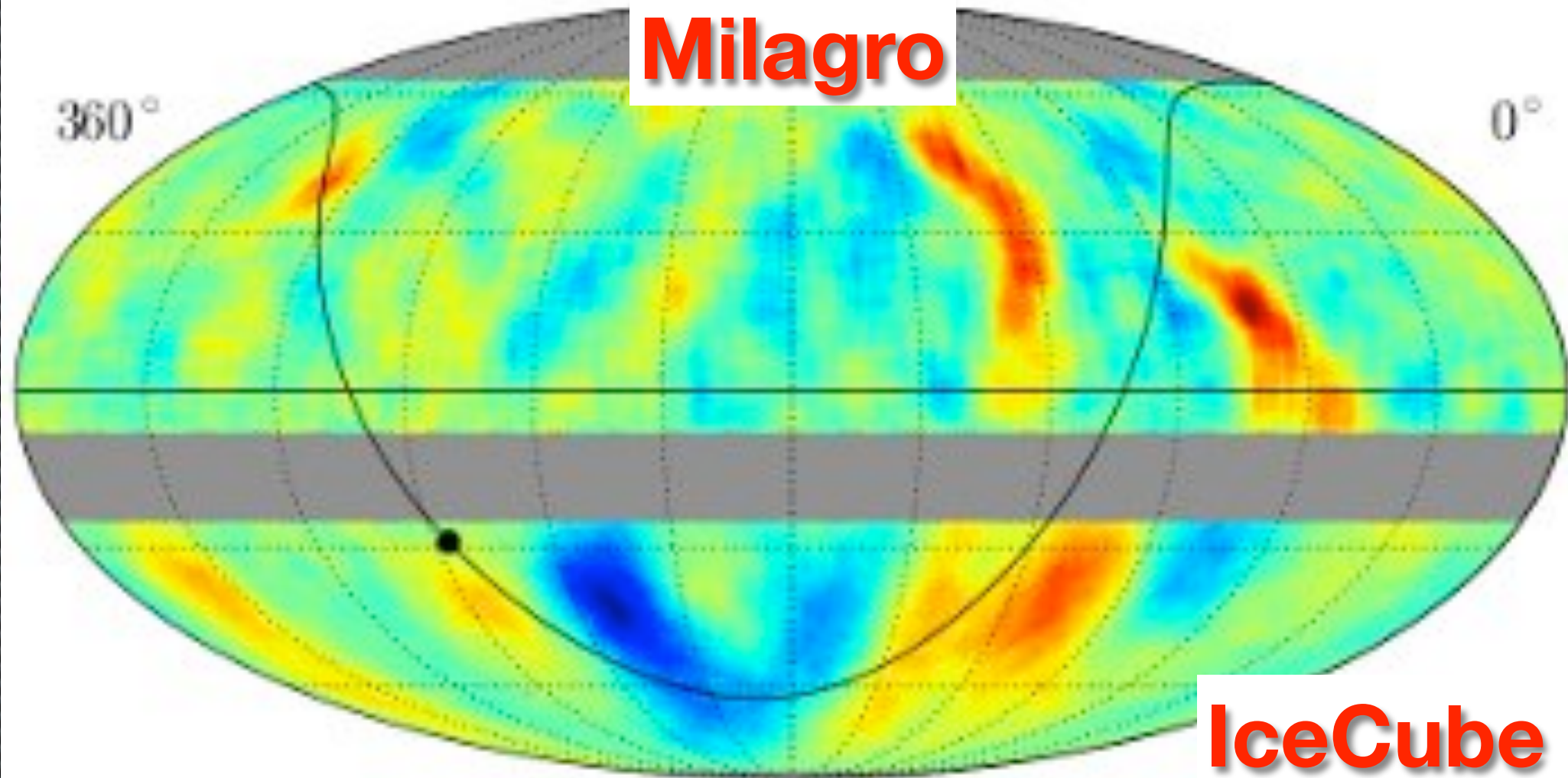
HAWC 95 CR Anisotropy

HAWC95 Small Scale Anisotropy

Preliminary

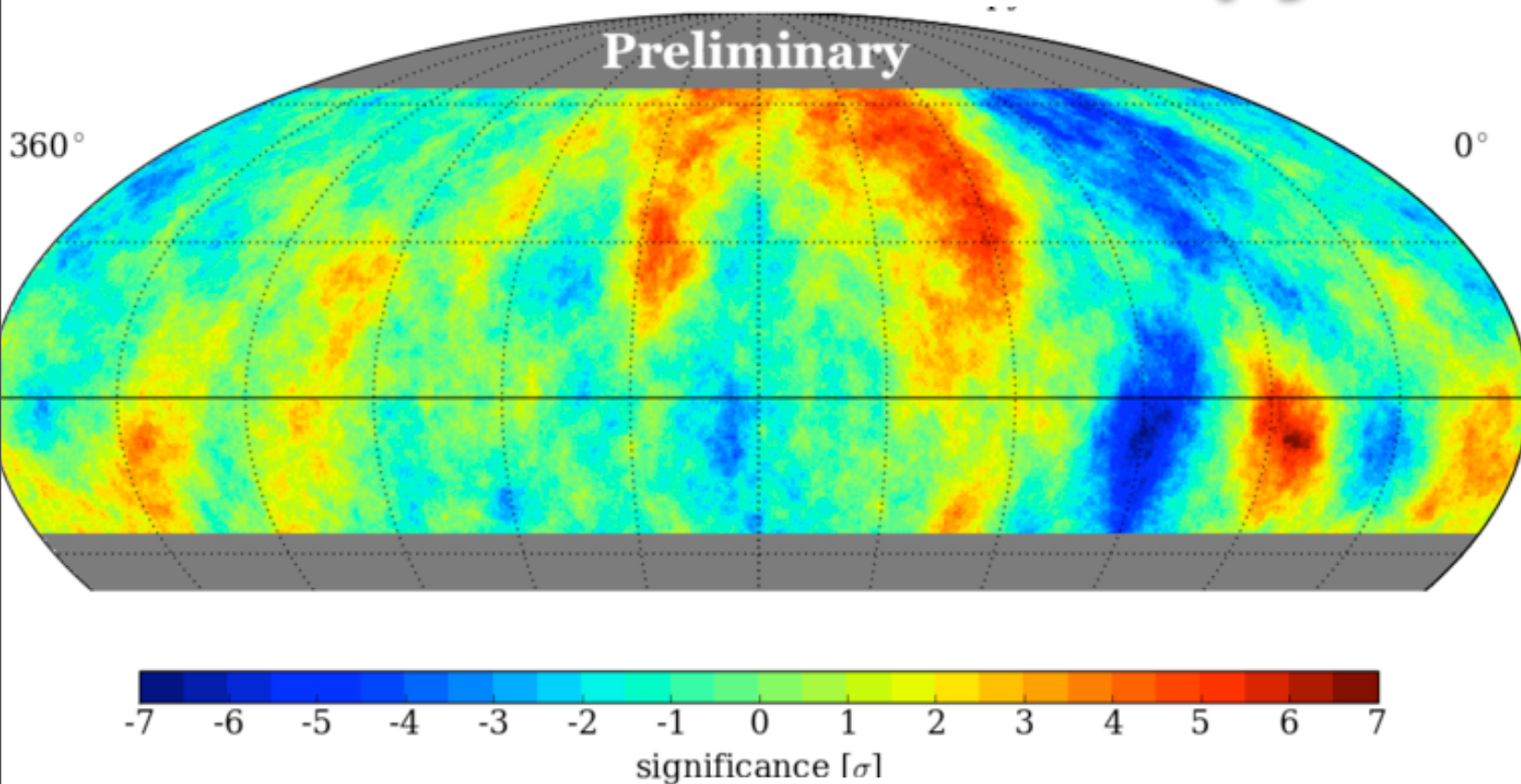


Milagro

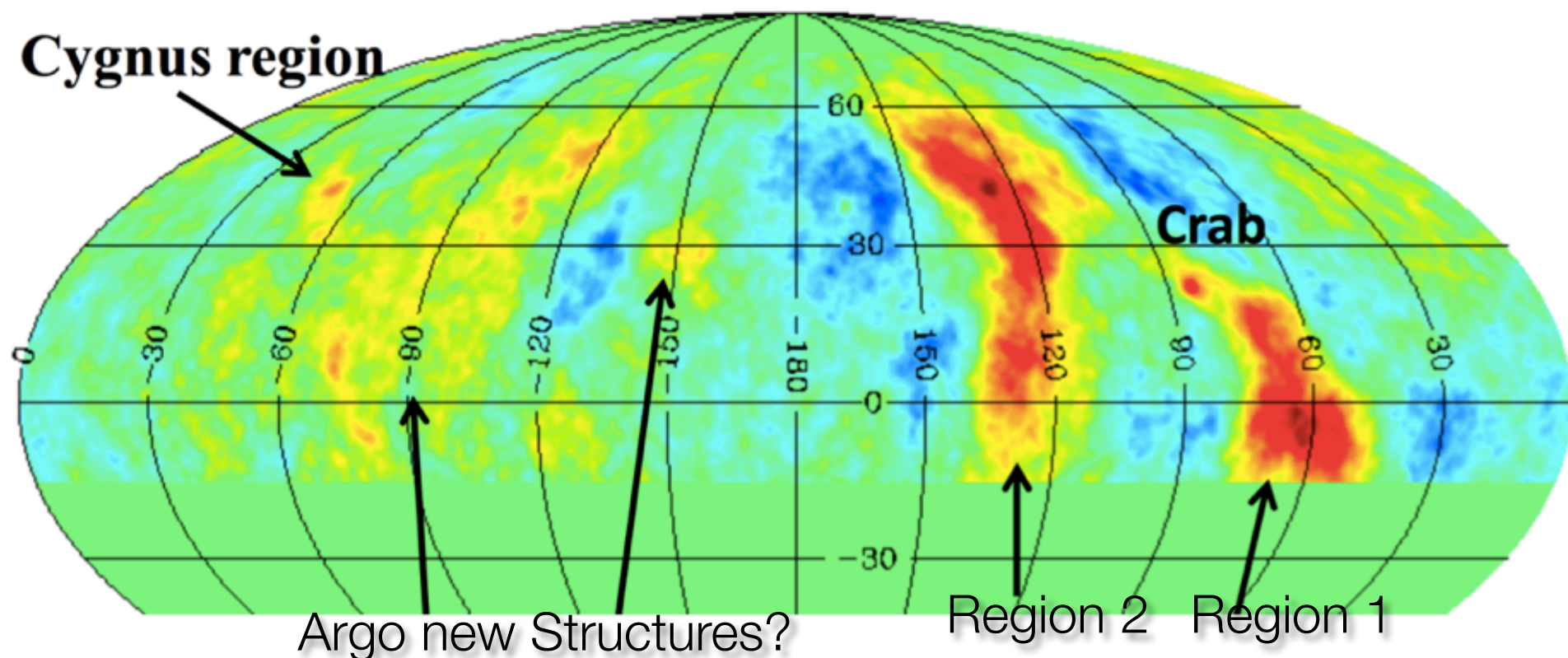


IceCube

HAWC 95 CR Anisotropy



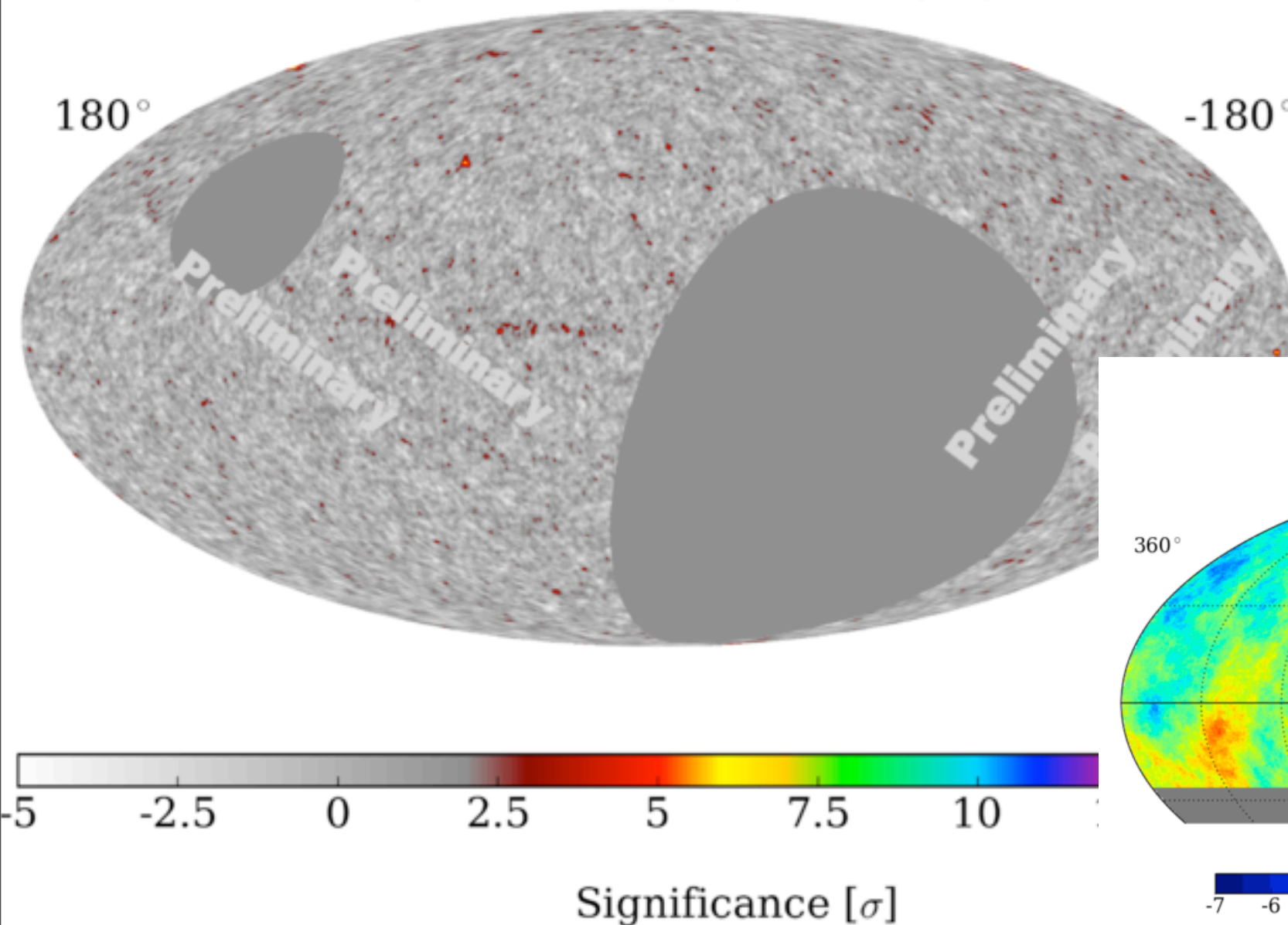
ARGO Anisotropy (Di Sciascio, 2012)



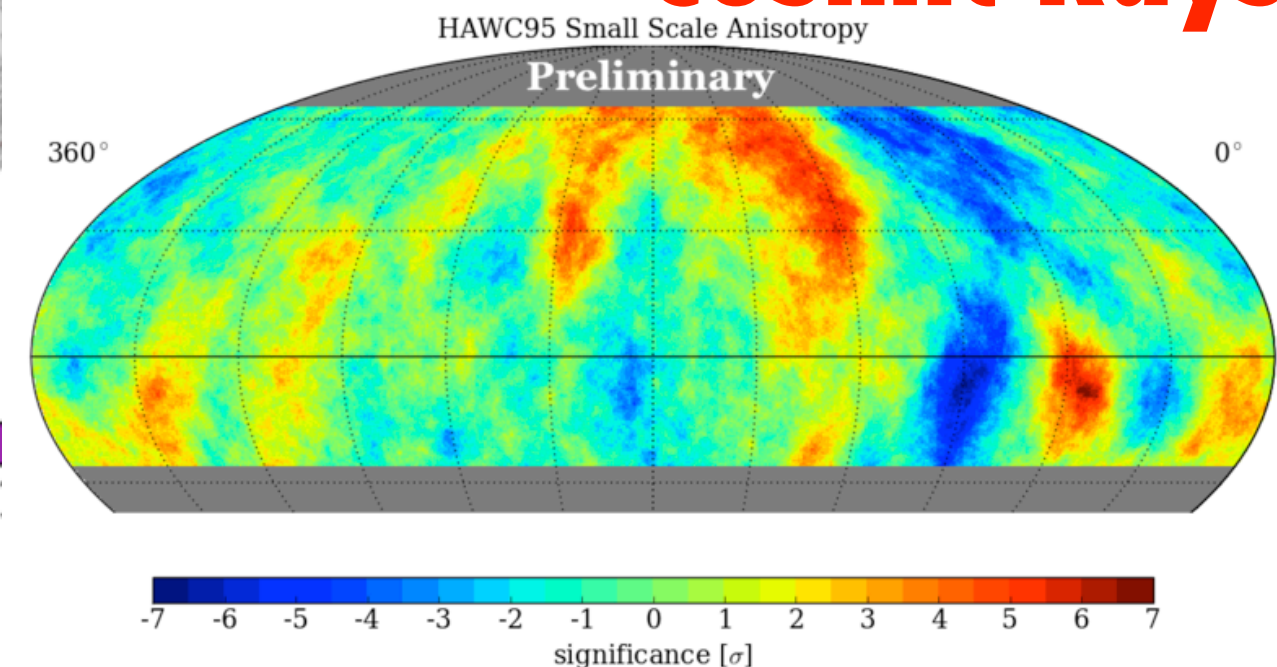
Summary

-HAWC will provide $\sim 15x$ more sensitive observations of the multi-TeV sky, with nearly 100% duty cycle. Array to be fully commissioned Fall 2014, initial results already indicate excellent performance ahead

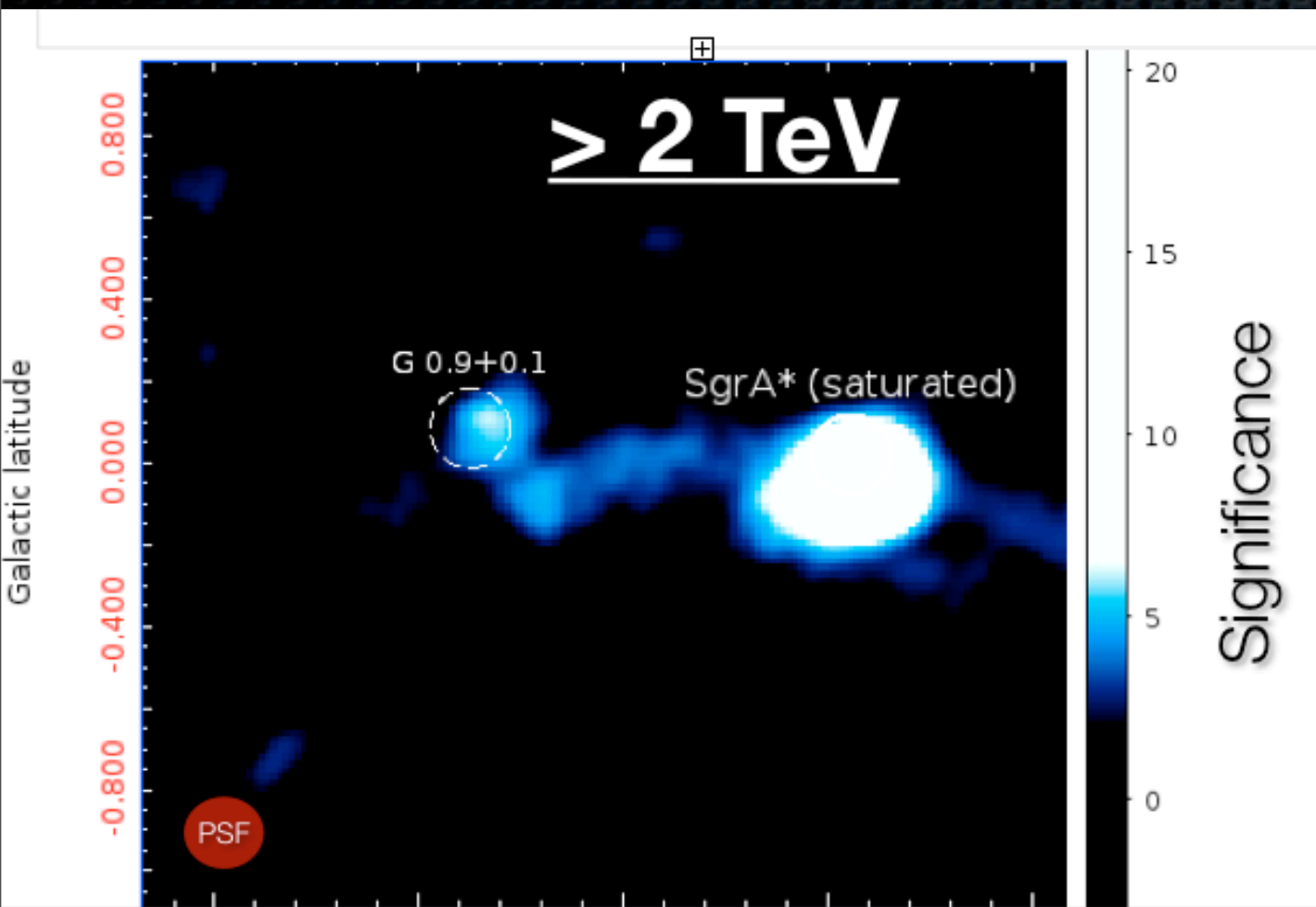
HAWC-95/111 SKY 06/13/2013-09/12/2013 **Gammas**



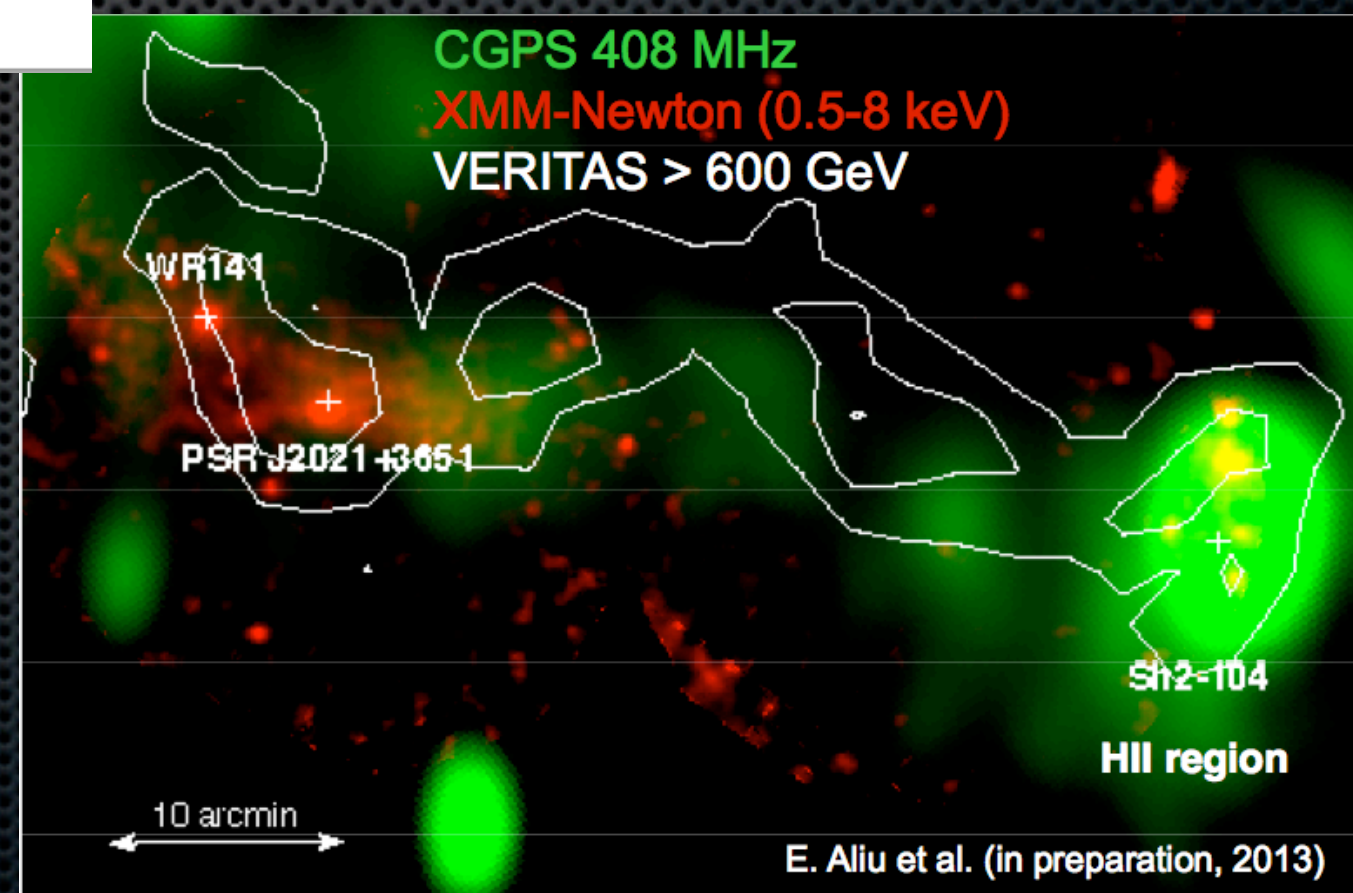
Cosmic Rays



Summary

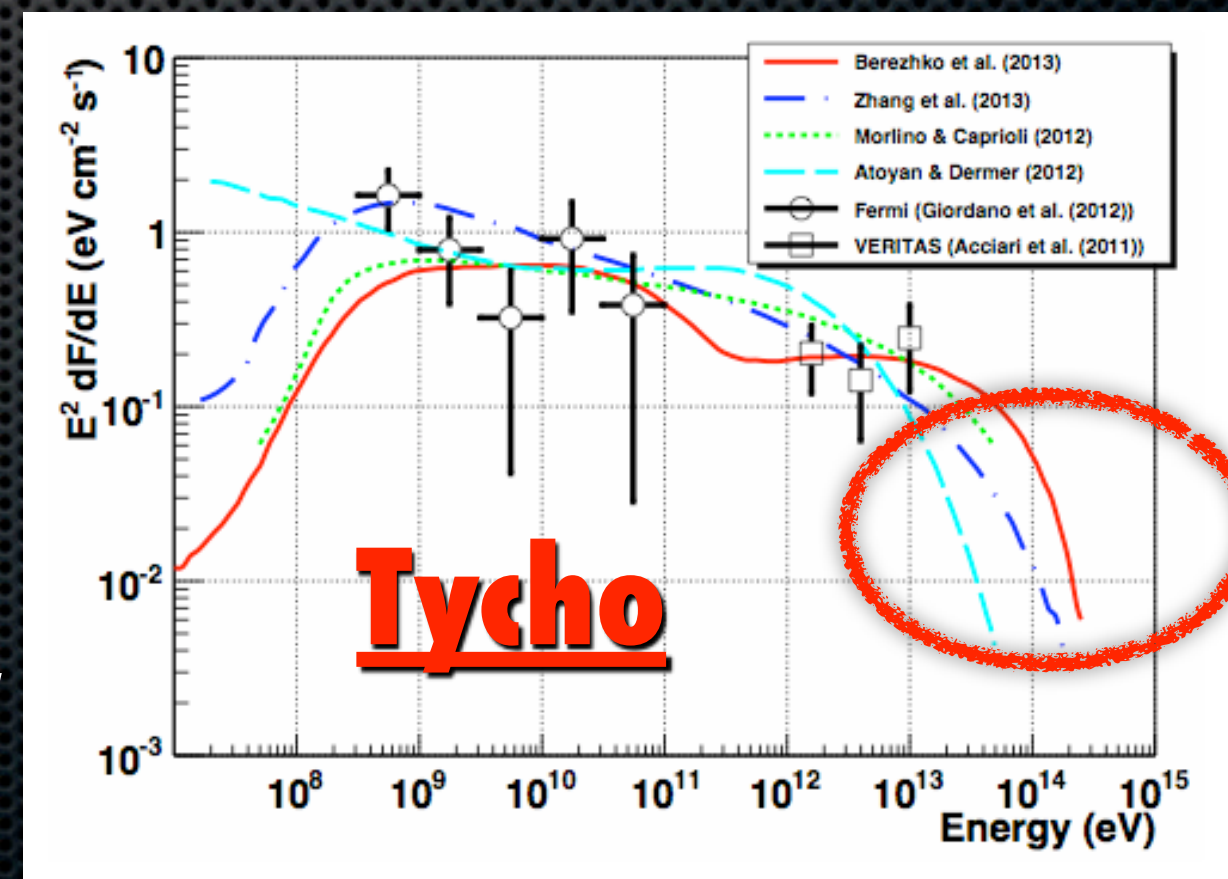
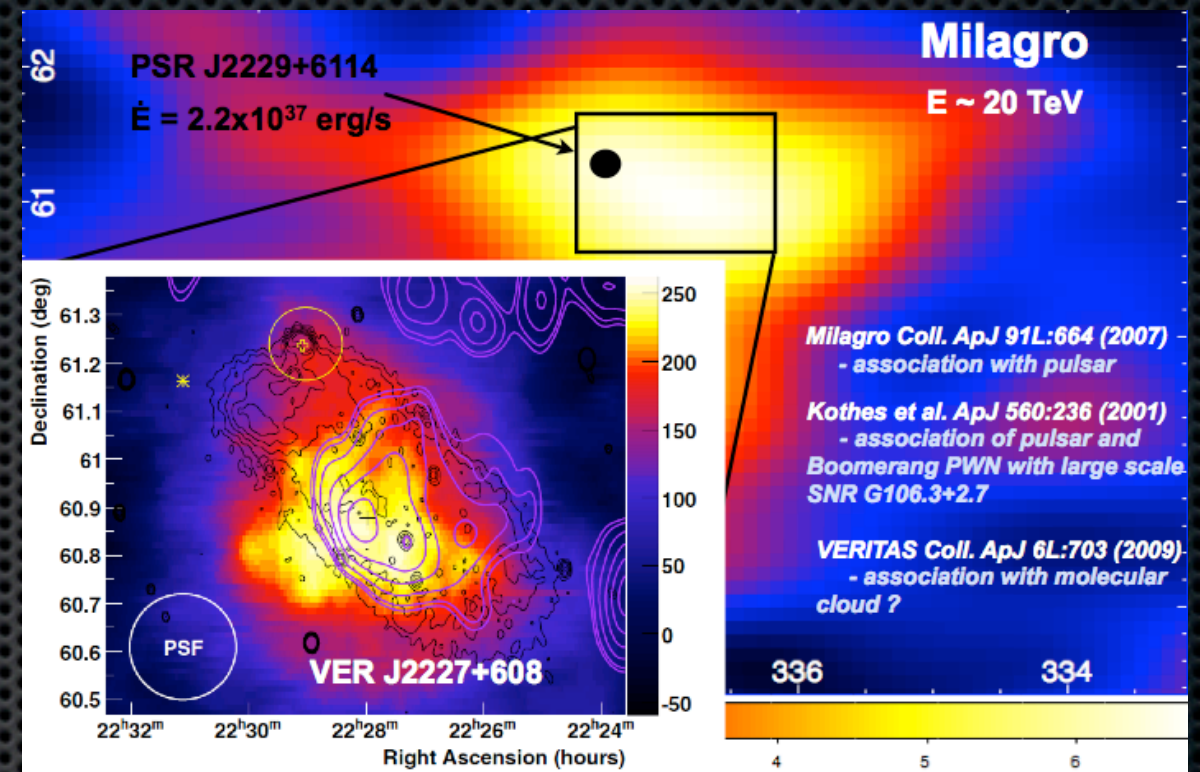
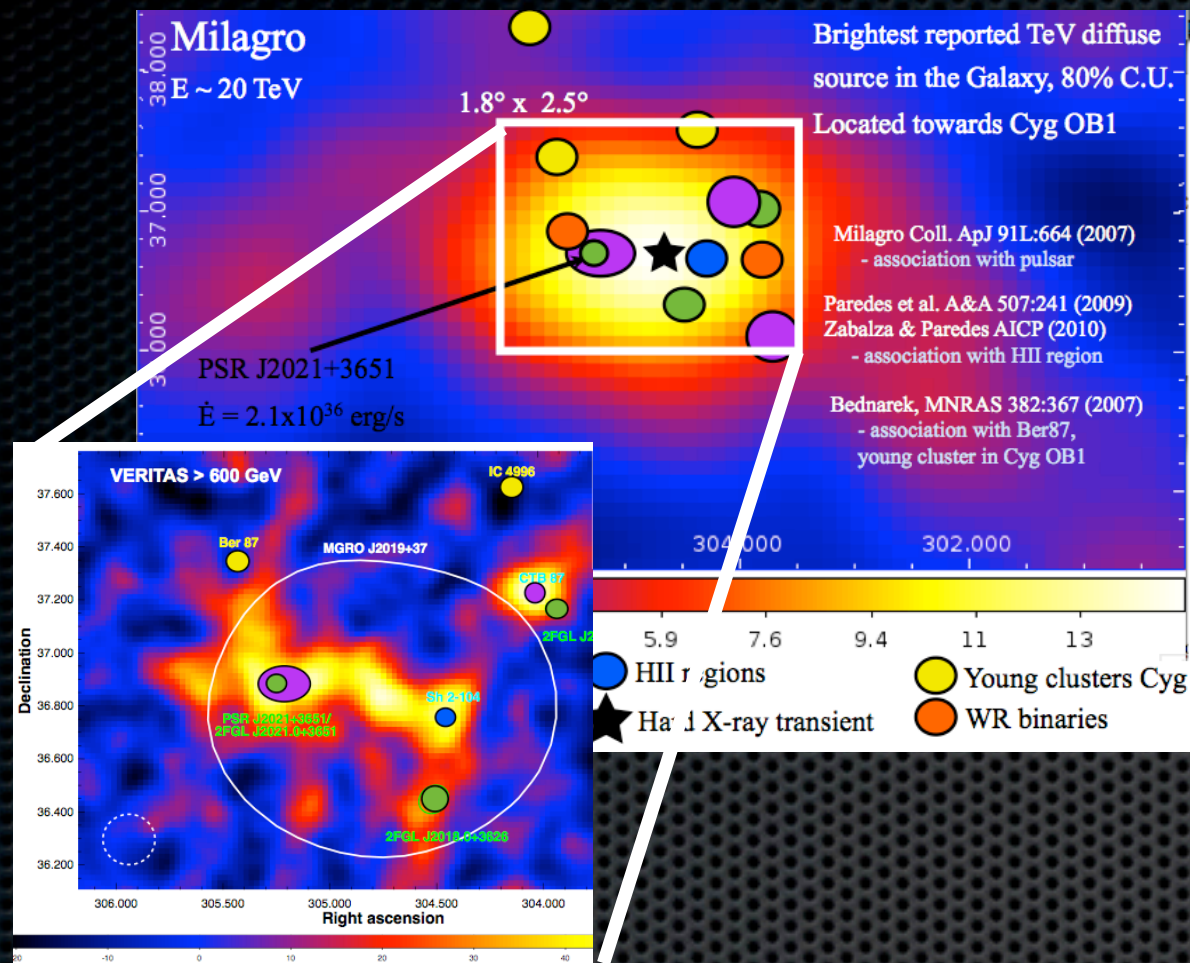


Upgraded VERITAS will continue to provide valuable insights into both potential point sources of CRs as well as the "sea" diffuse components in the most active parts of the galaxy.



E. Aliu et al. (in preparation, 2013)

Summary



Success of combining Milagro and VERITAS data already demonstrated: multiple overlapping sources revealing complicated networks of emission. With HAWC, this will only improve as well as allowing for combined spectra will allow for distinction between emission models

Thank you very much to the
organizers for the kind
invitation!

