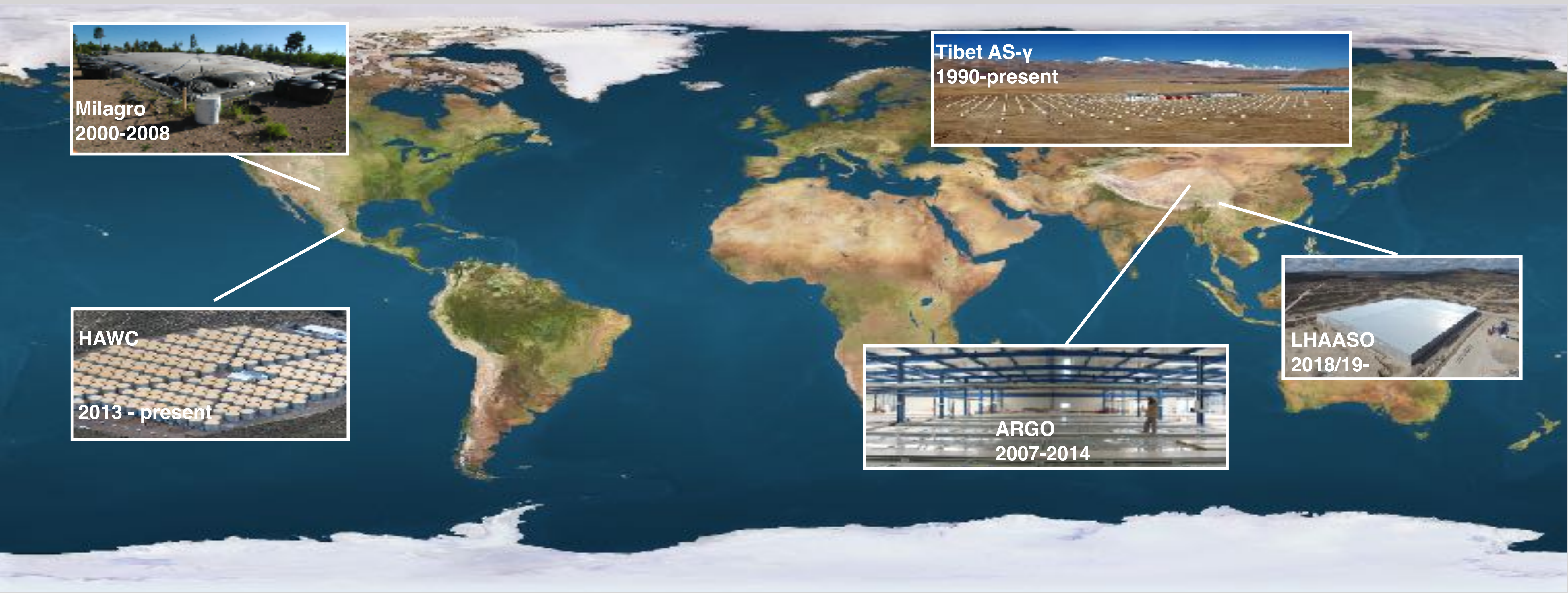
VHE Gamma-Ray Astronomy via Particle Detection at the Ground Level

Or
A biased review of VHE Gamm-Ray Survey Instruments

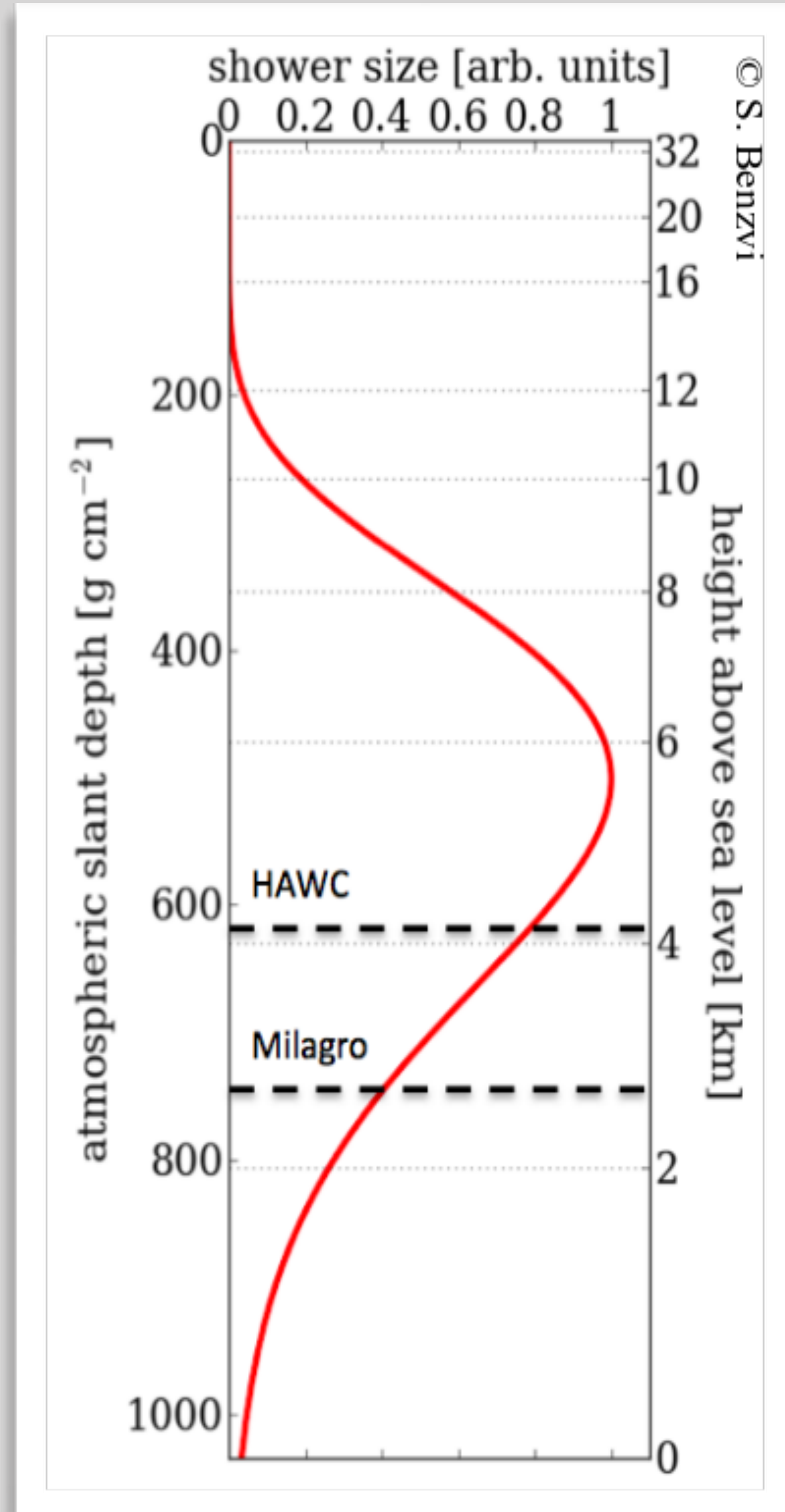
Petra Huentemeyer
petra@mtu.edu

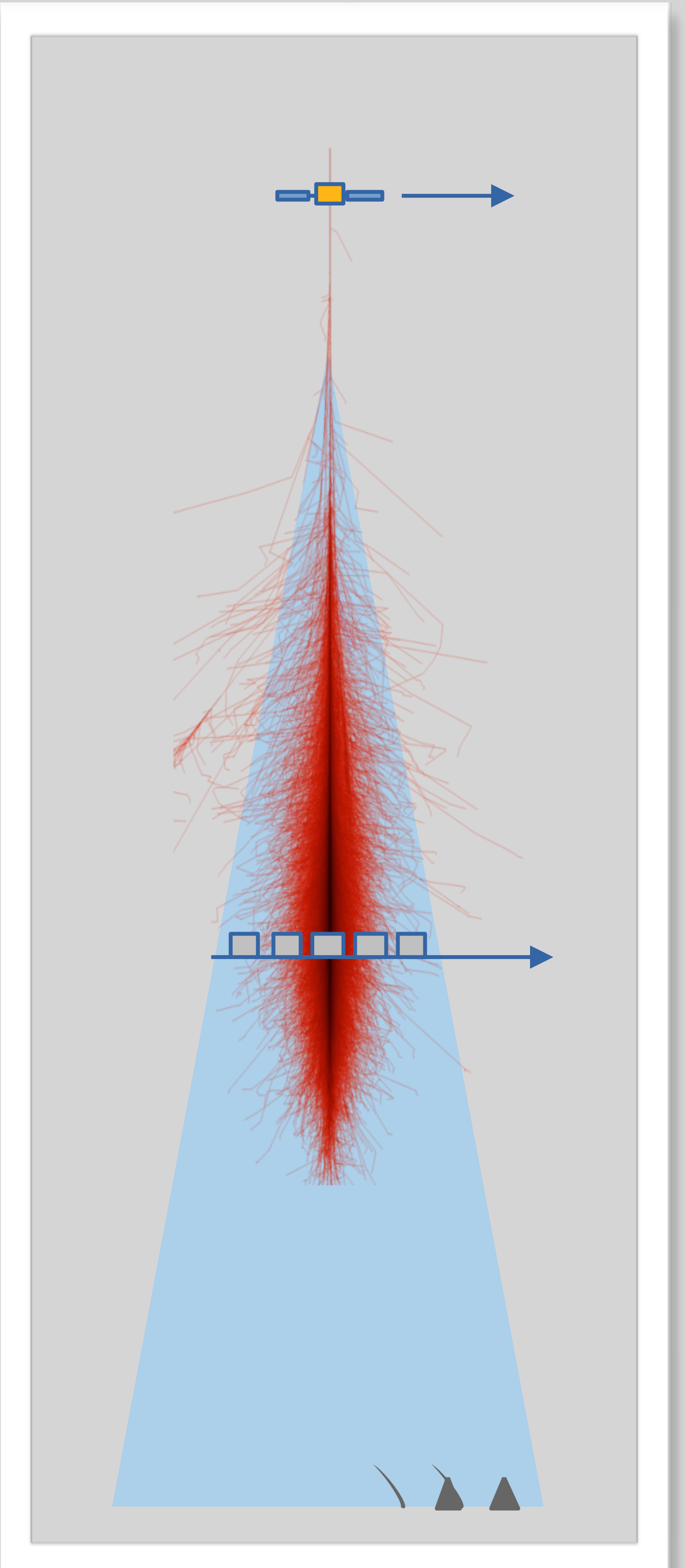
Michigan Technological University

The Players:
EAS Arrays
Particle Sampling Gamma Rays



Altitude Gamma-Ray Detectors





EAS Sampling Arrays
3 Main Features

- Hight Duty Cycle

  ☑ Transients

- Wide Field of View

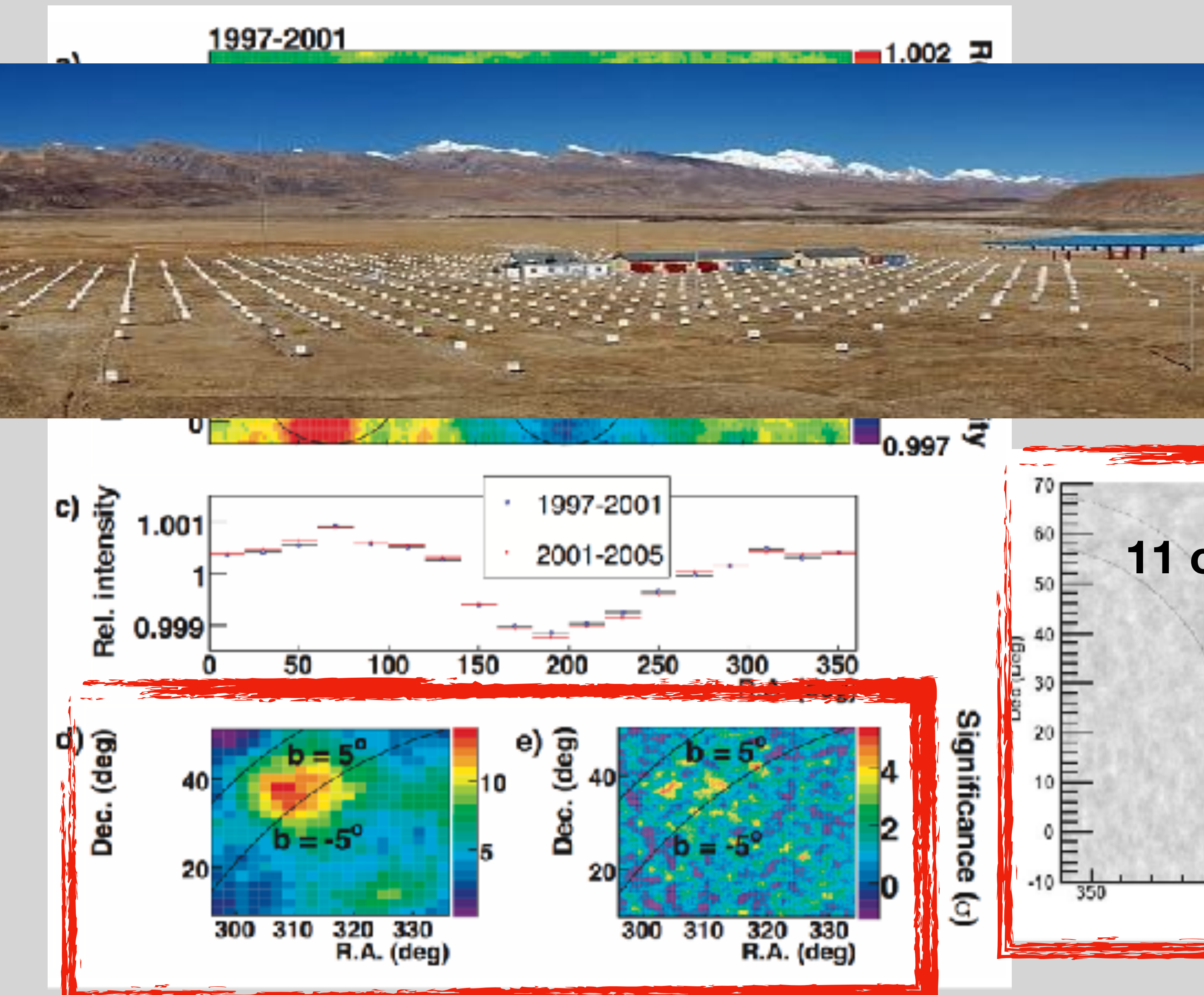
  ☑ Extended and Large Scale Emission

- Good Sensitivity, Angular & Energy Resolution above 10s of TeV

  ☑ Highest Energy Accelerators

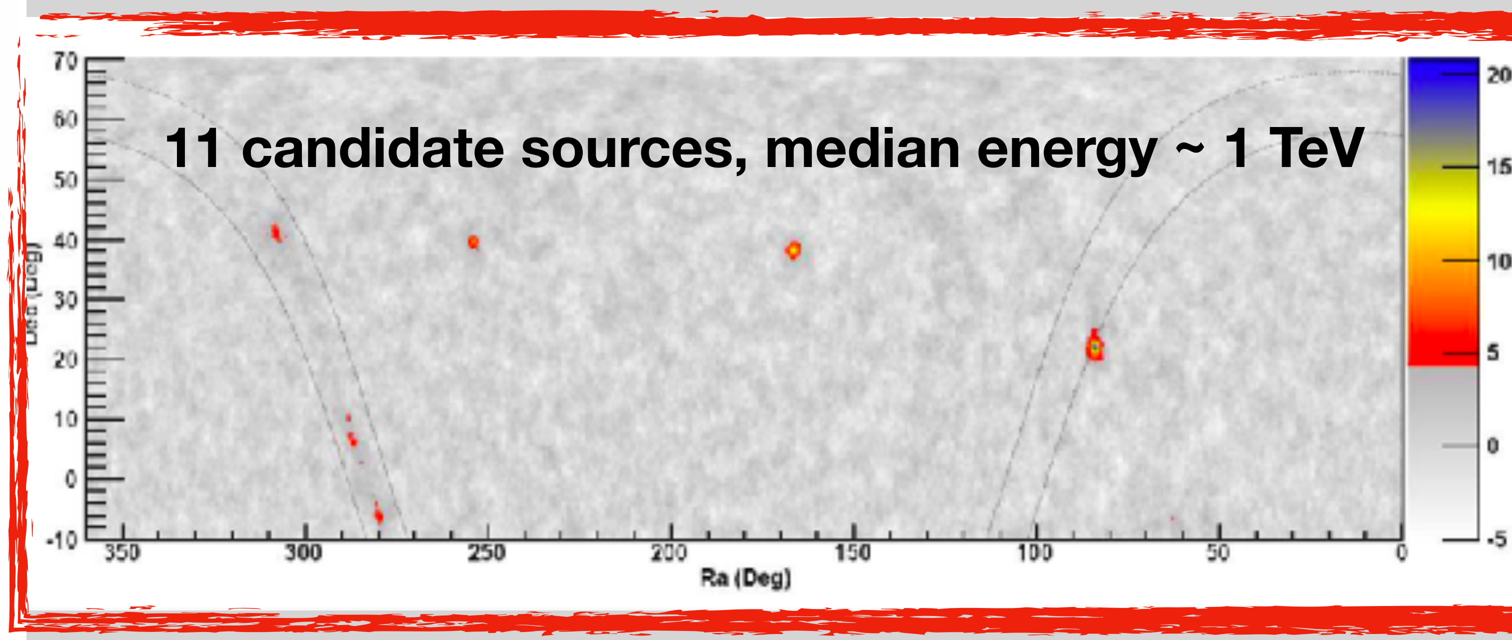
Northern TeV (Gamma-Ray) Surveys

Tibet AS-γ



Science314:439-443,2006

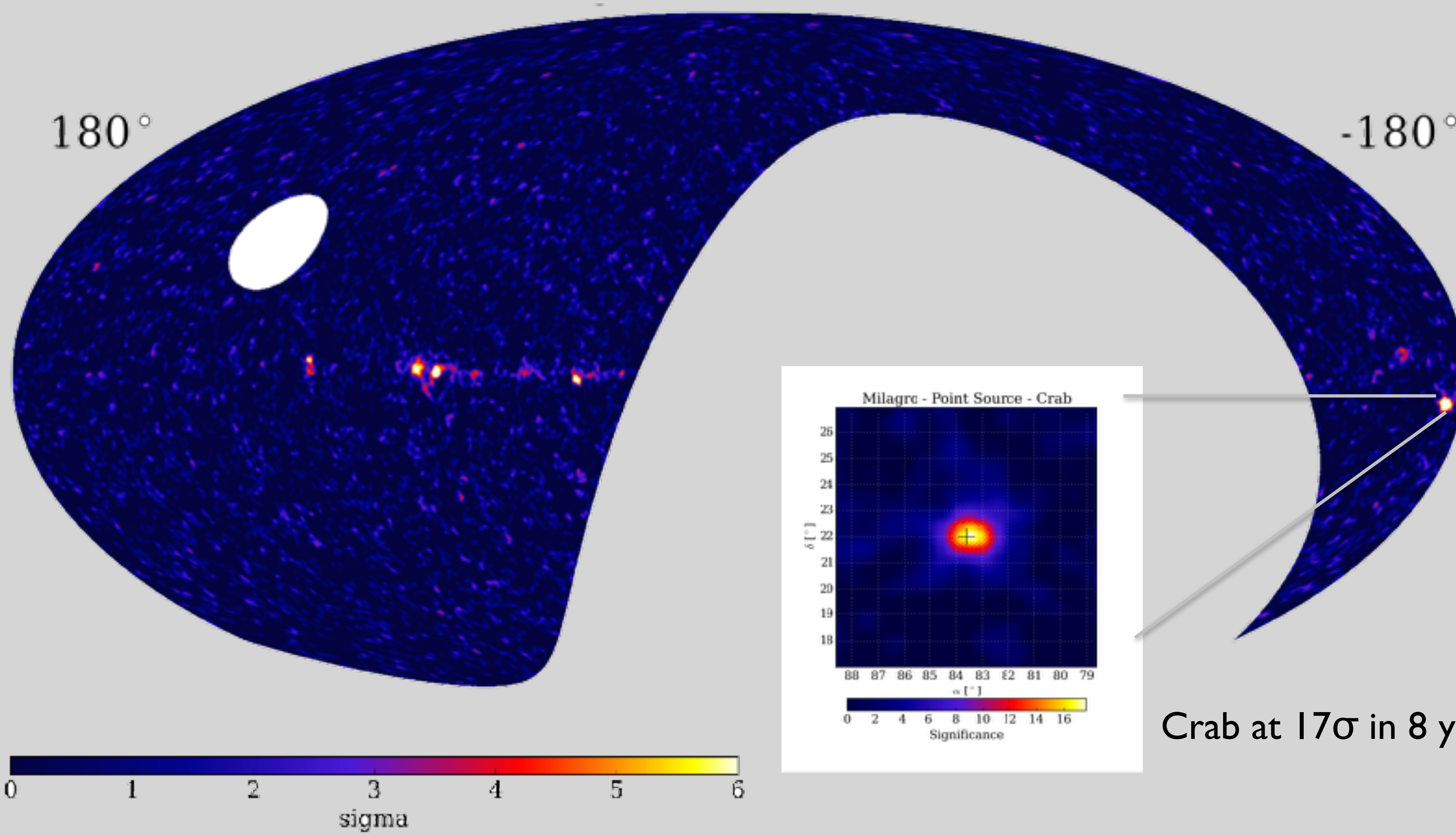
ARGO



B. Bartoli et al. [ARGO-YBJ Collaboration], ApJ **779**, 27 (2013)

Another Survey: Milagro 2000-2008

8 candidate sources, median energy ~ 20 TeV

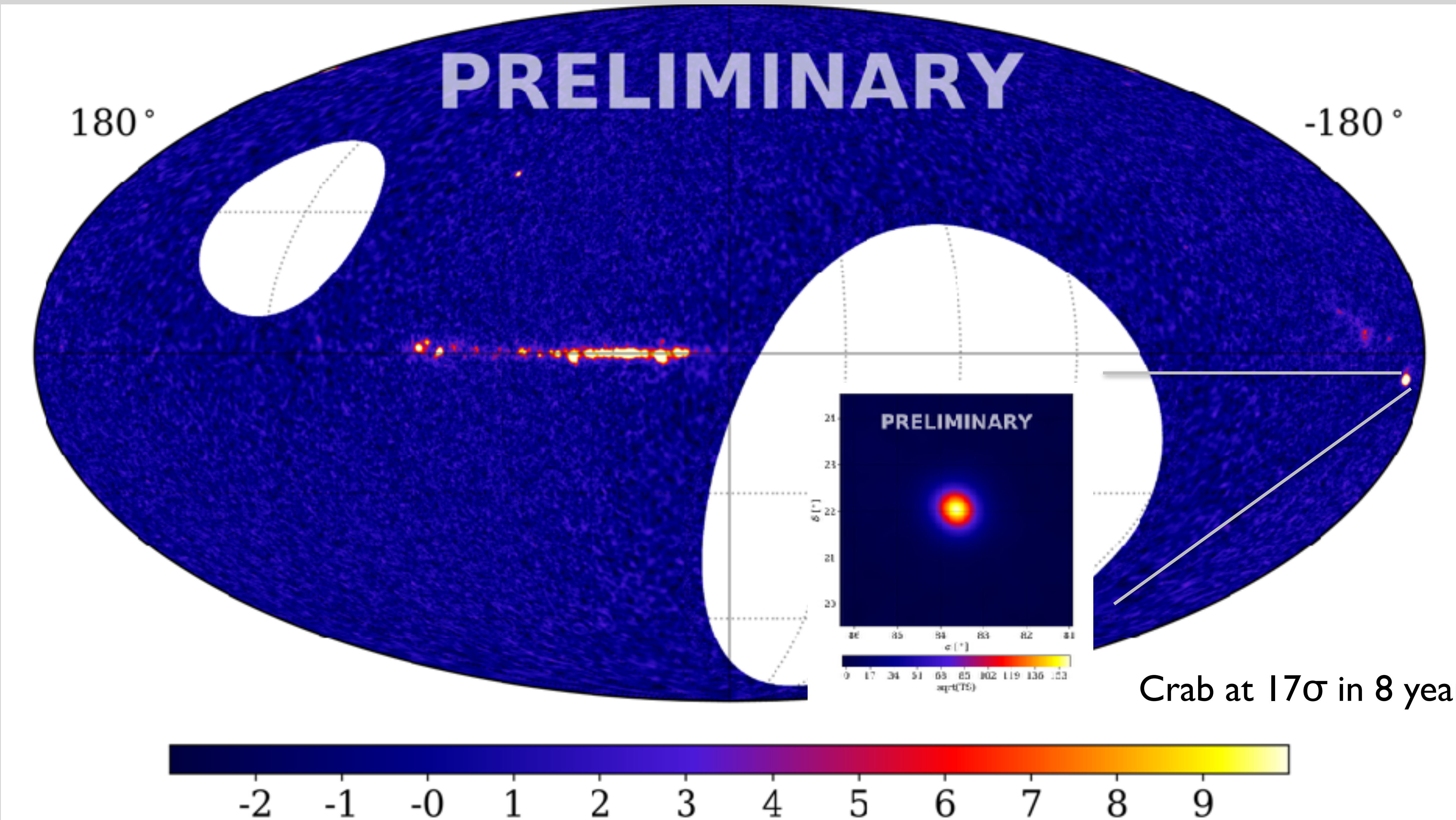


Crab at 17σ in 8 years.

Astrophys.J.664:L91-L94,2007

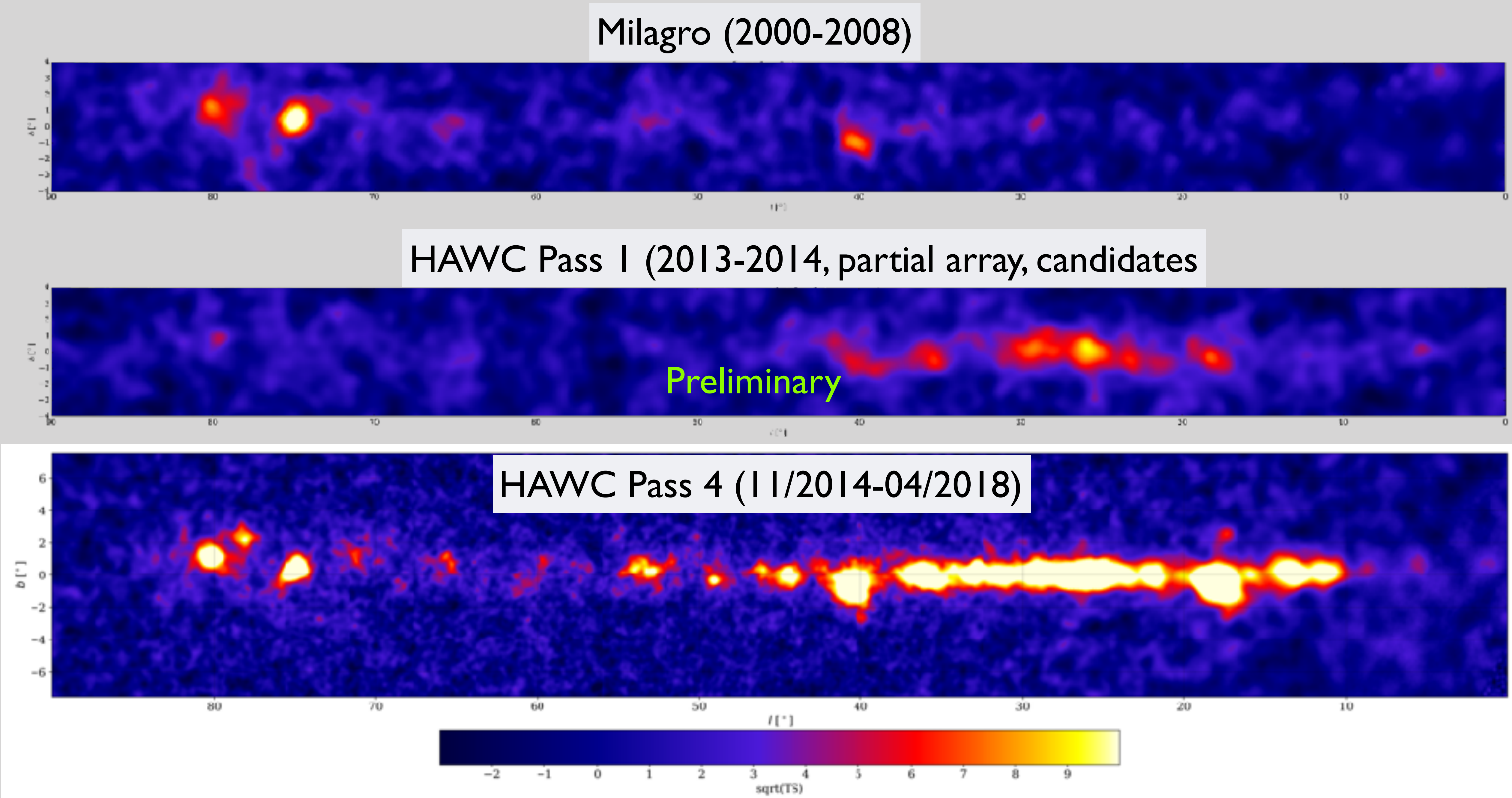
Latest Survey: HAWC 11/2014-04/2018

>39 candidate sources, pivot energy ~ 7 TeV



The Astrophysical Journal, Volume 843, Issue 1, article id. 40, 21 pp. (2017)

Galactic Plane Observations over the Years

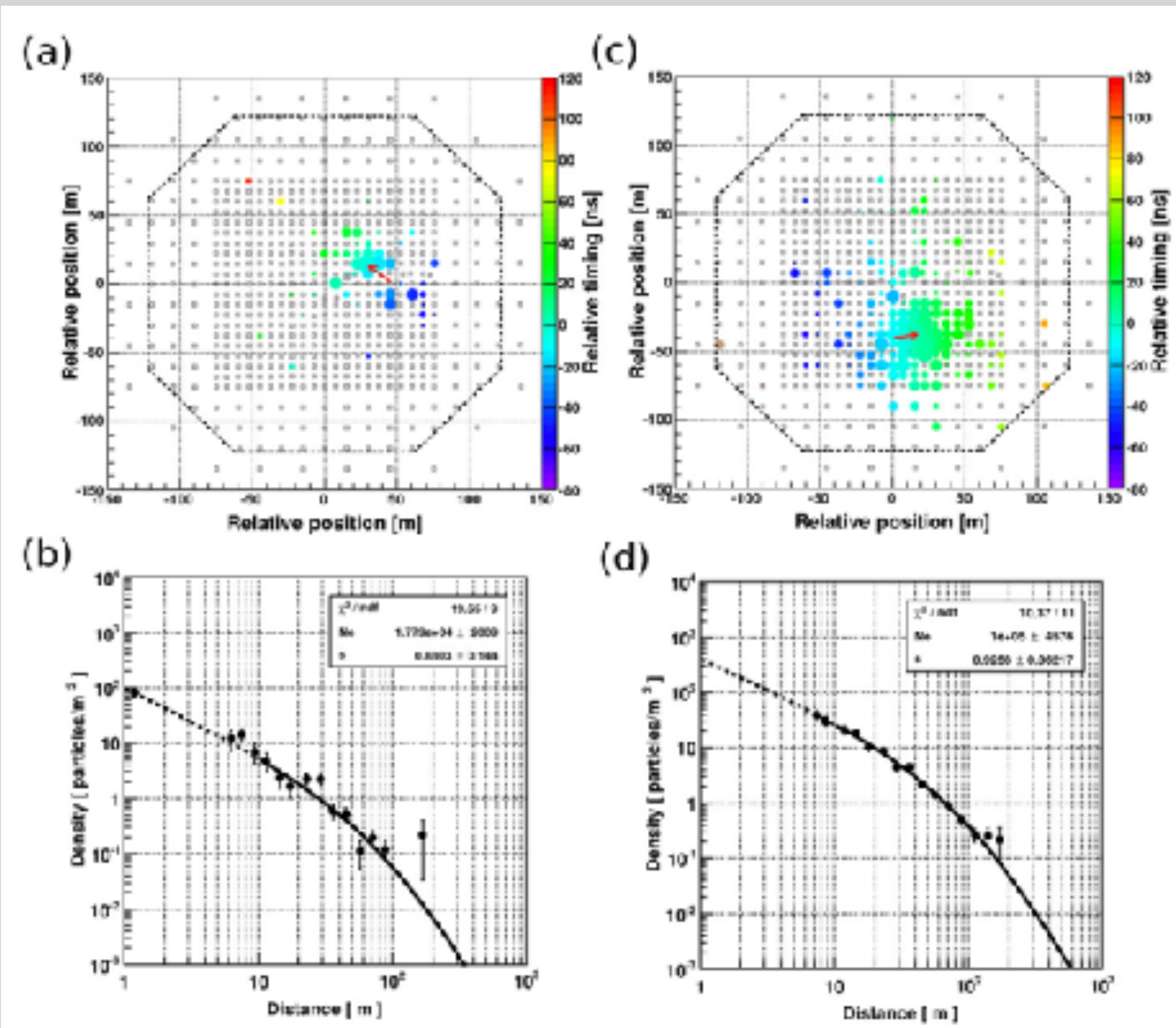


Milagro was located near Los Alamos, New Mexico

- different sensitivity by declination along Galactic plane.

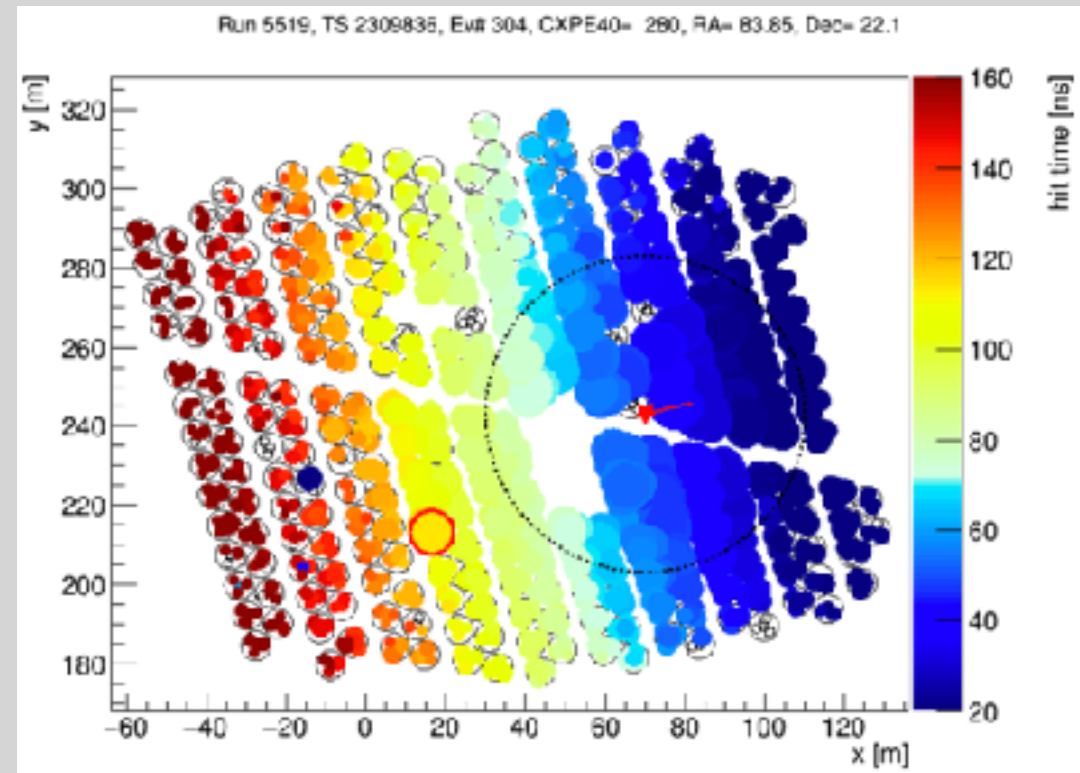
The Other Hillas Parameter: S(nn) or Rho (nnn)

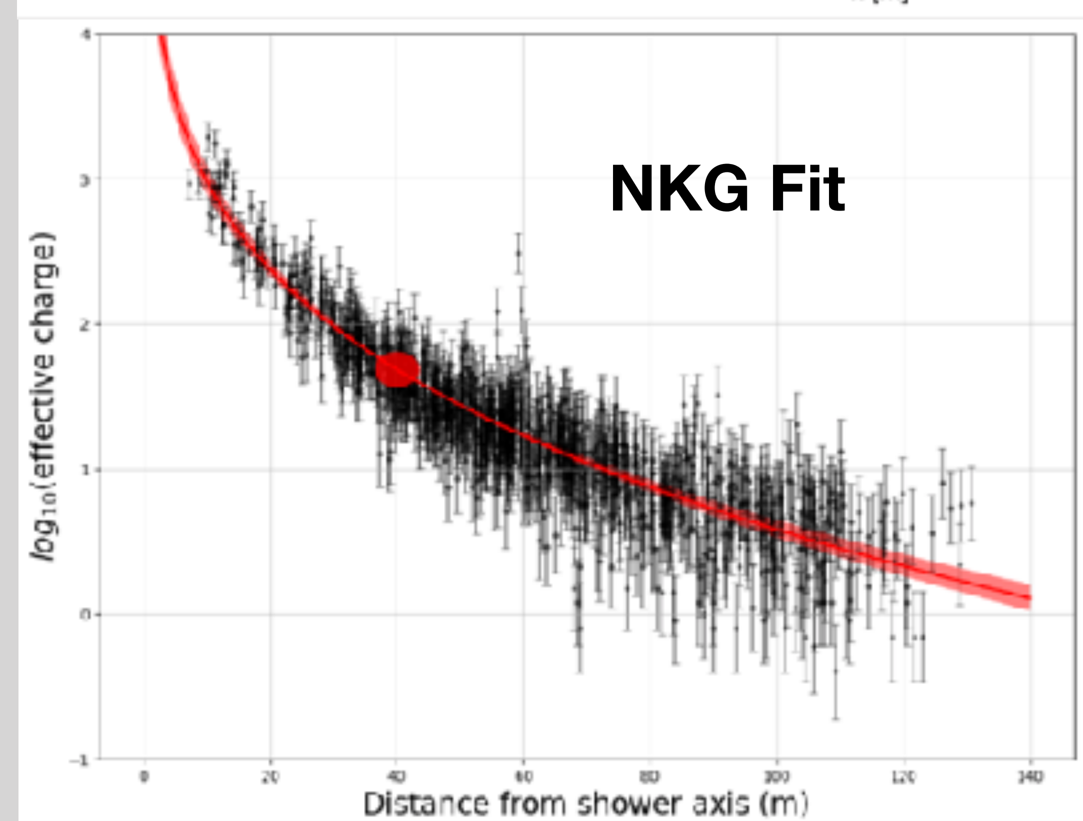
Tibet AS-γ: S50



Experimental Astronomy, Volume 44, Issue 1, pp.1-9

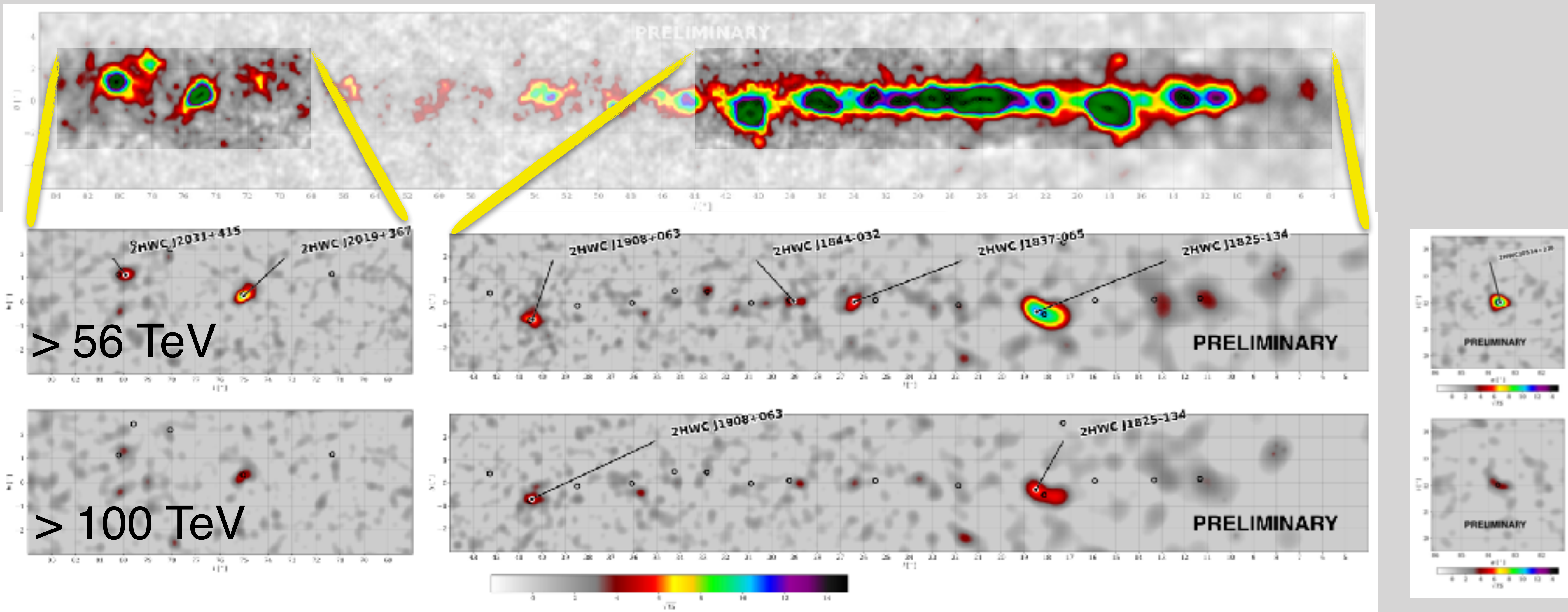
HAWC: S40





HAWC High Energy Catalog

7 candidate sources, energy > 56 TeV, energy spectra forth coming



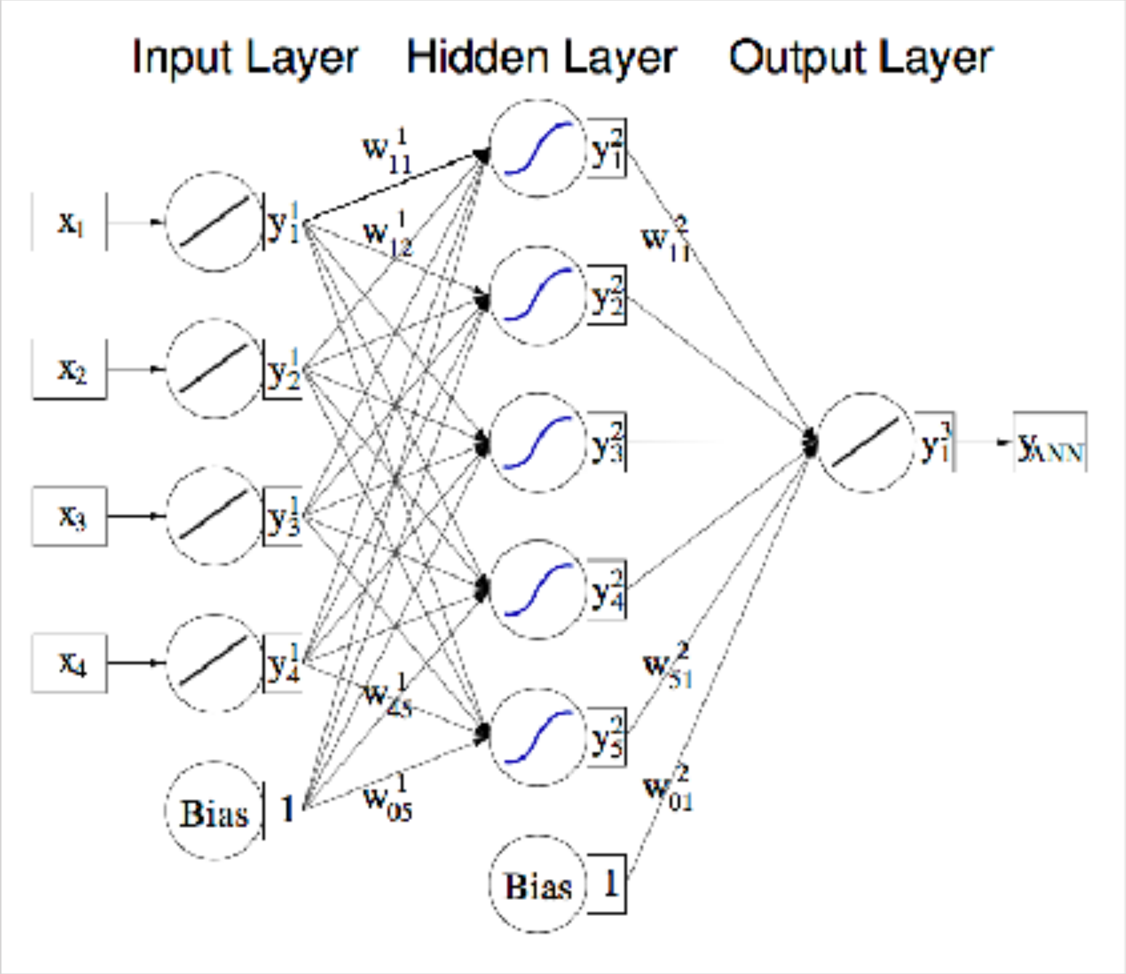
- Acceleration mechanisms: hadronic or leptonic?
- Correlation with neutrinos?
- Prospects for testing Lorentz Invariance Violation.

Addition Development: Energy Estimation via ANN

- Toolkit for Multivariat Analysis (TMVA)[1]

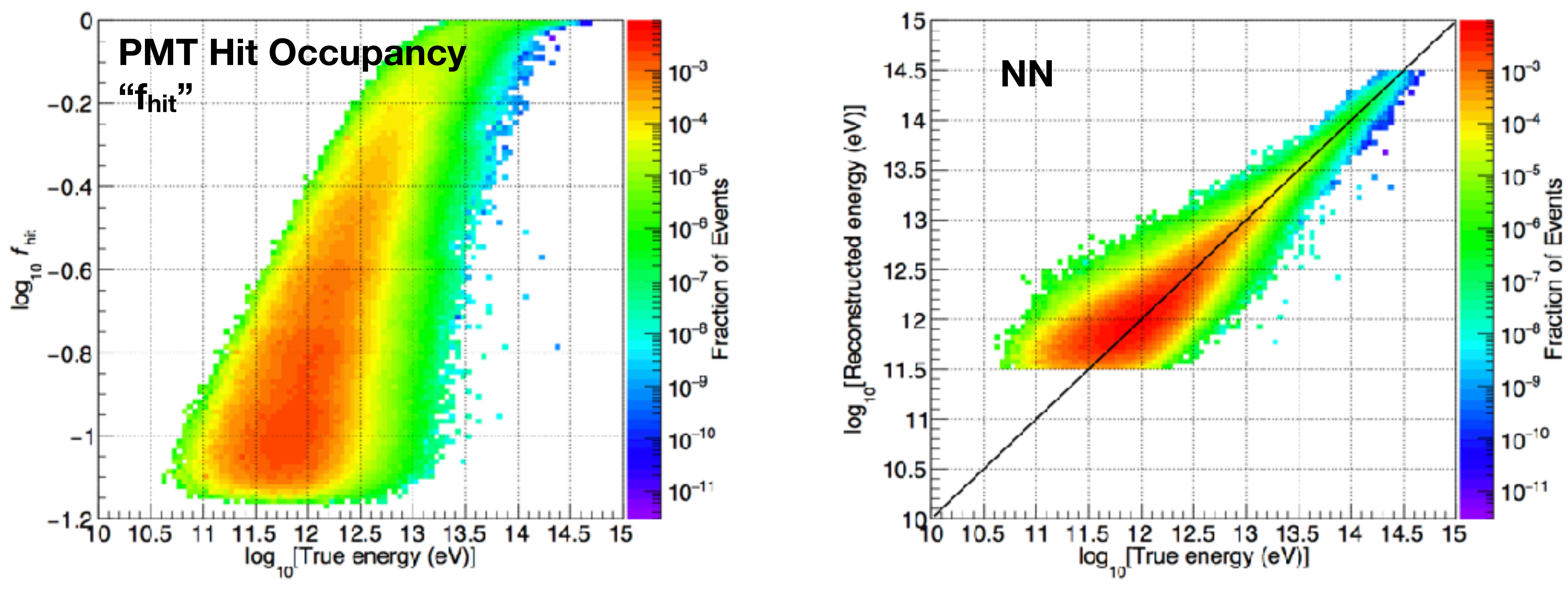
- Input variable chosen to quantify:
  - Core position
  - Zenith angle
  - Signal at core
  - Radial distribution, annuli (show age)
  - Energy deposited in detector
  - Fraction of ground energy landing in the detector

- 479 free parameters (weights) determined by training on Gamma-Ray Monte Carlo



[1]http://tmva.sourceforge.net/

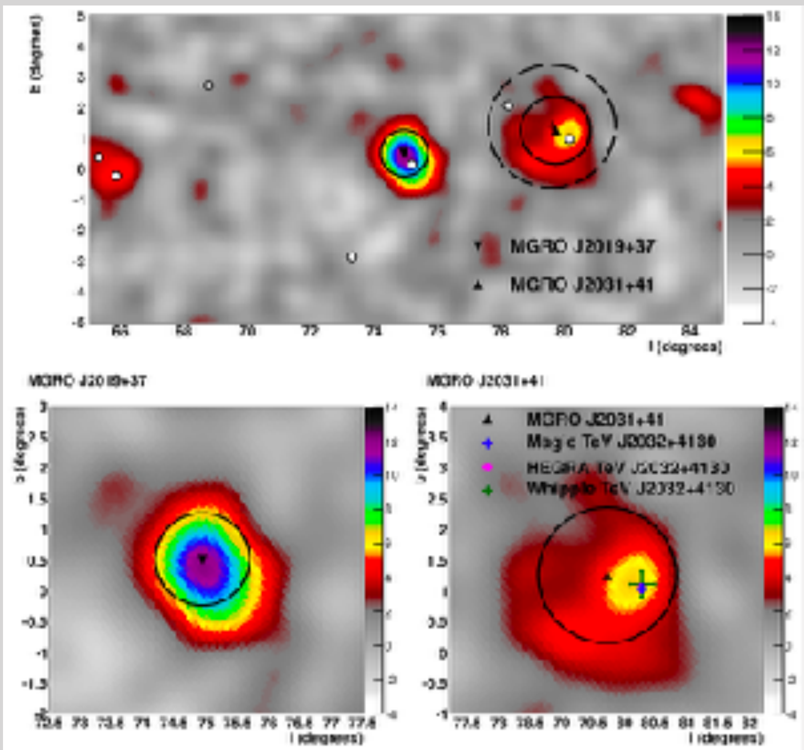
Energy Estimation via ANN

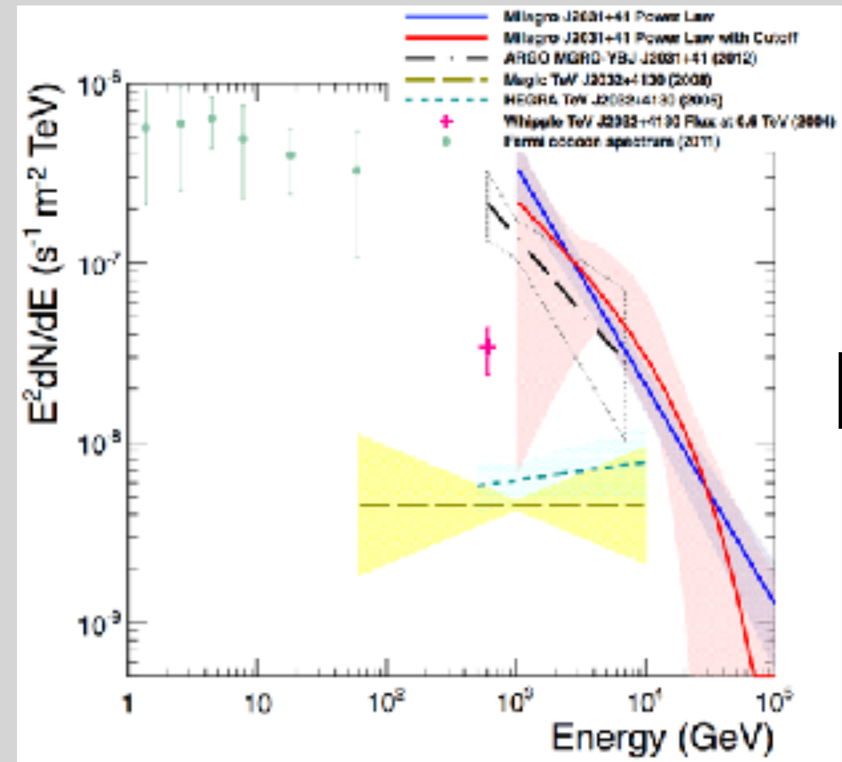


- NN Energy better correlated with MC truth than previously used variable (fraction of PMT hits)
- As for S40 provides a way to determine energies beyond 100 TeV with considerably better precision (~ 16 % at highest energies)
- Stay tuned for spectra (after systematics have been sorted out)

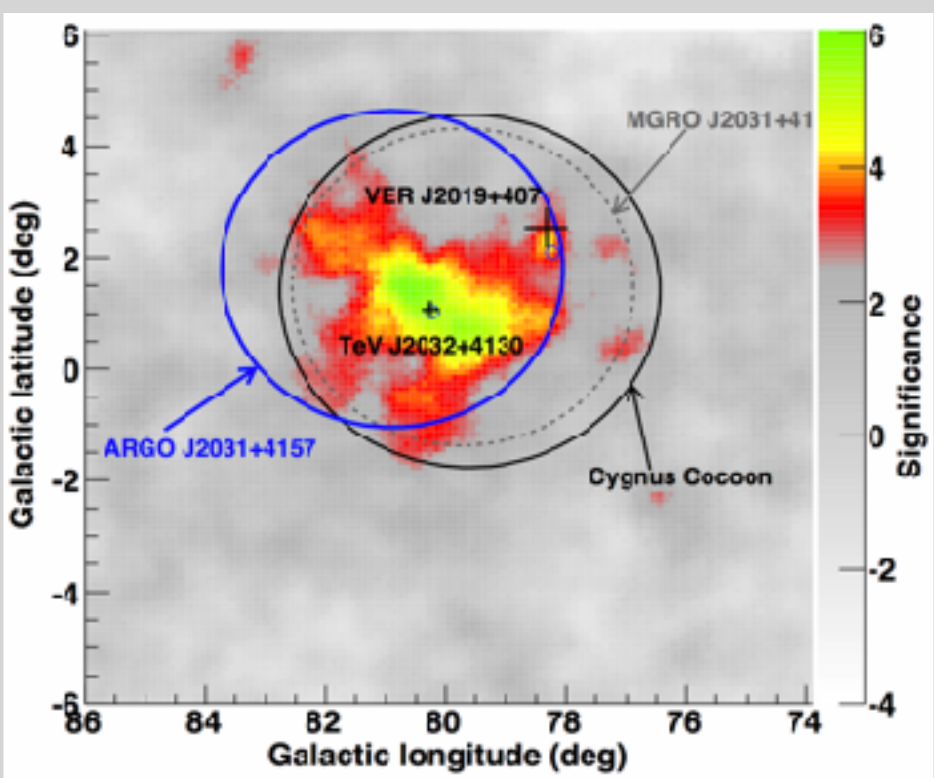
Multisource Fitting Example: Hunting for CR Acceleration in SFRs

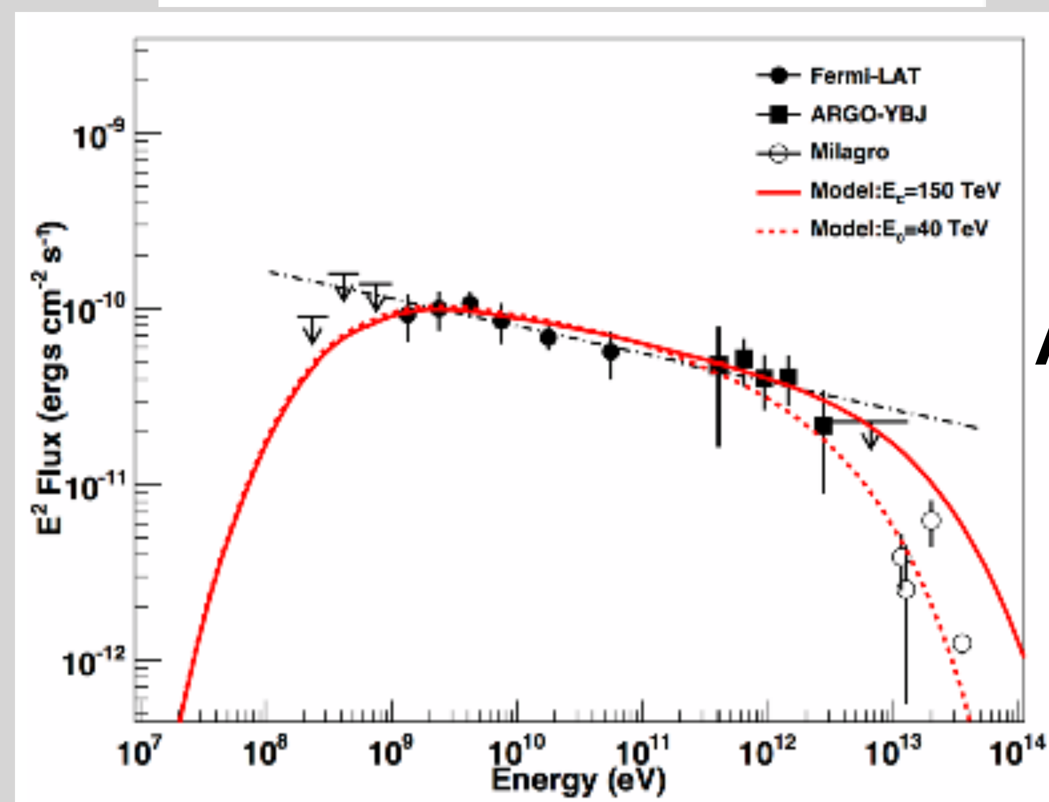
The Astrophysical Journal, Volume 753, Issue 2, article id. 159, 8 pp. (2012)





Milagro

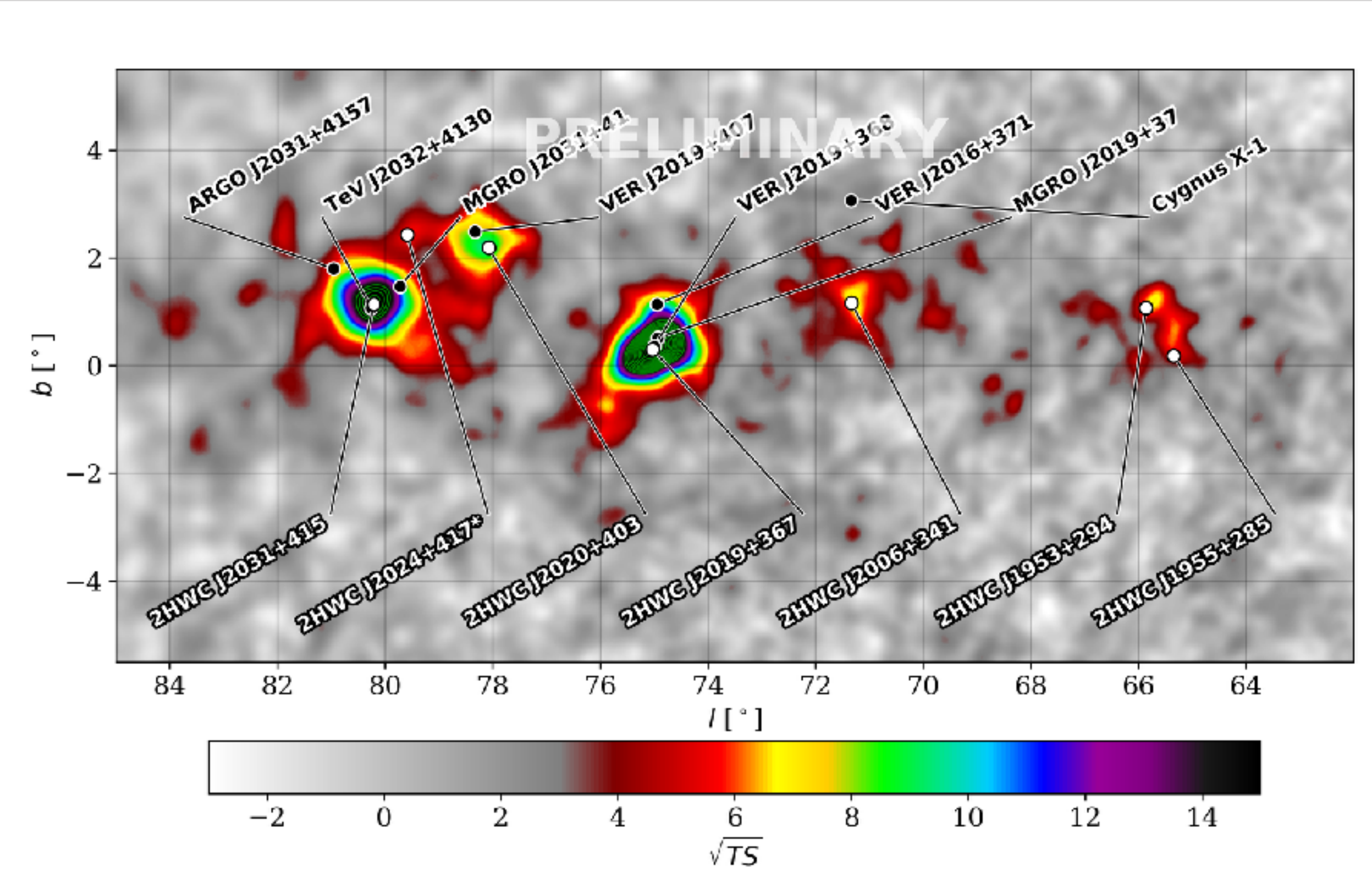




Argo

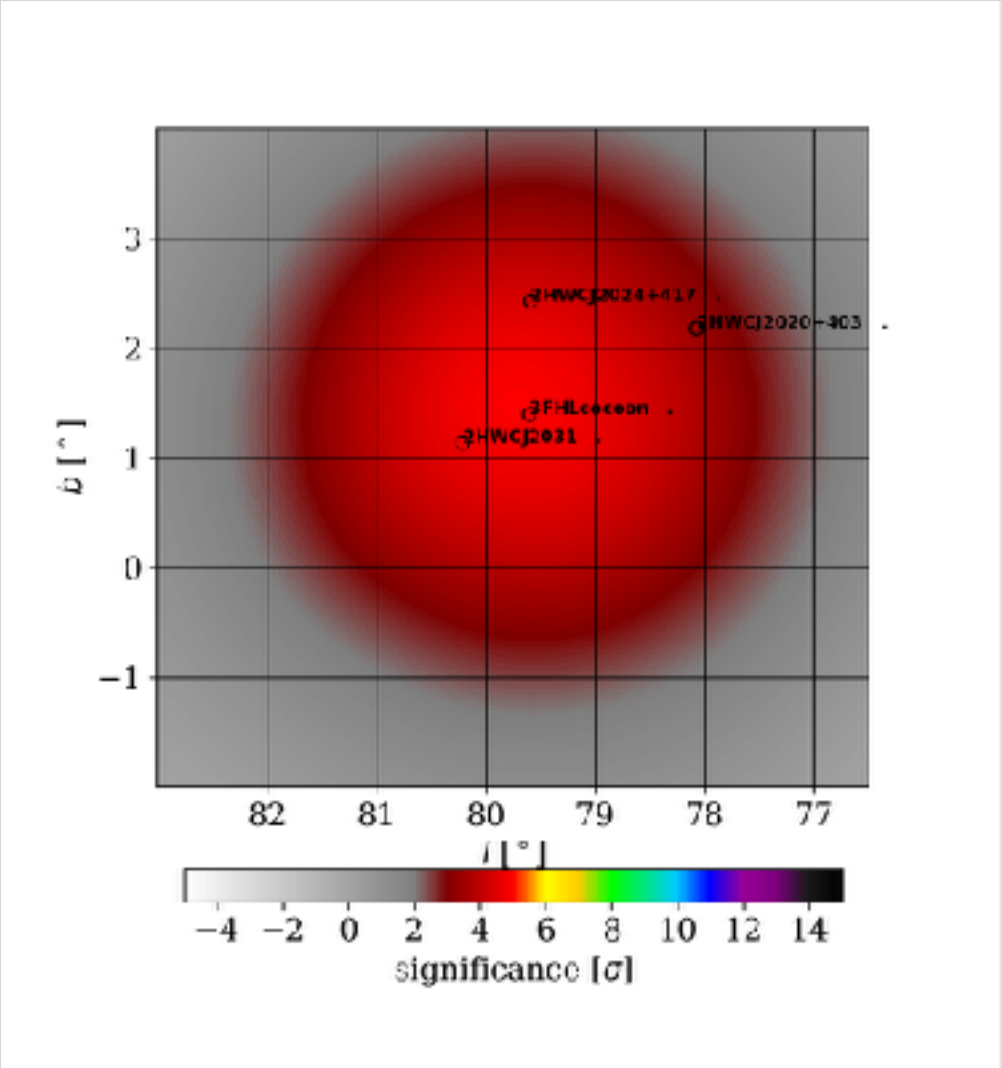
The Astrophysical Journal, Volume 790, Issue 2, article id. 152, 5 pp. (2014)

Multisource Fitting Example: Hunting for CR Acceleration in SFRs with HAWC



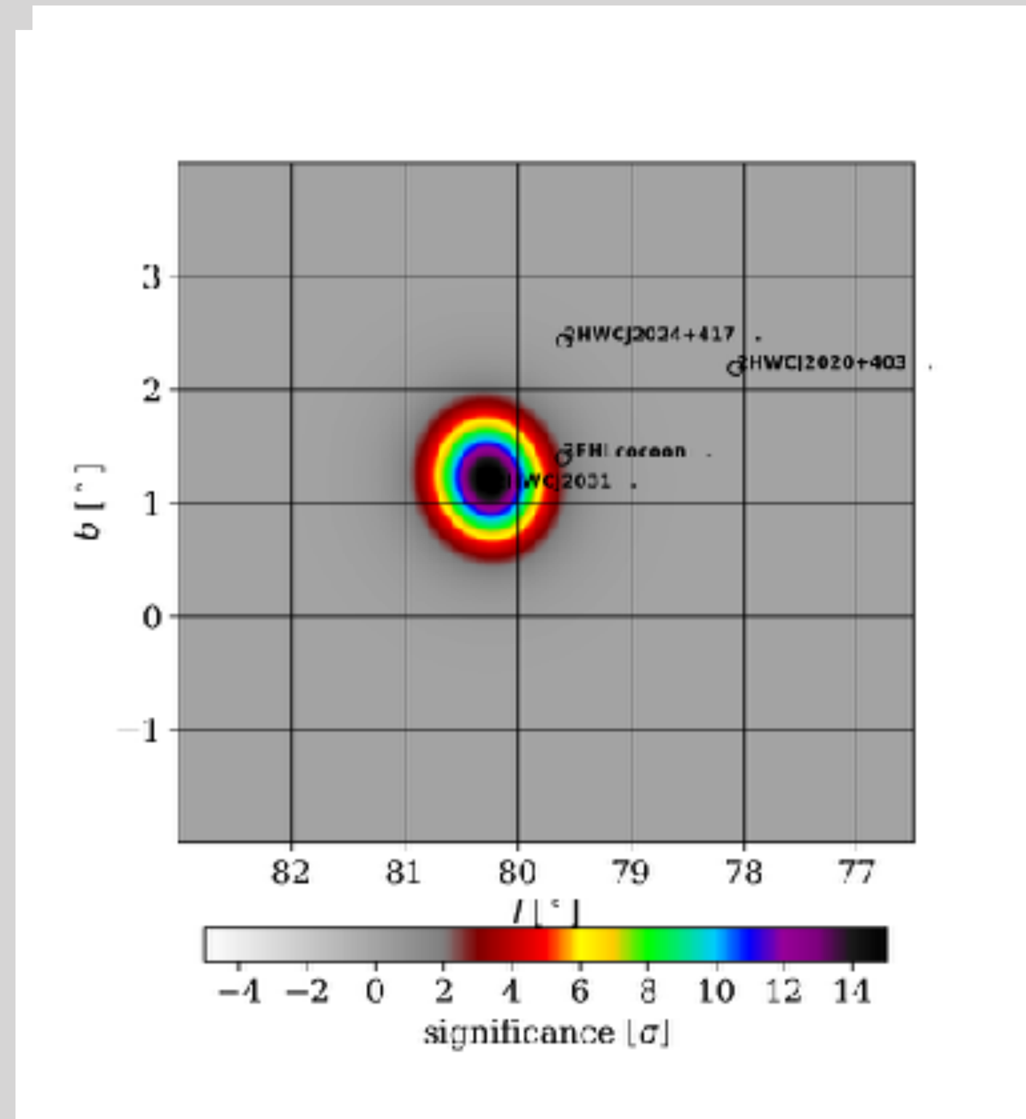
Model Building I

- *Fermi detection at GeV* (Ackermann et al., ***Science*** 334, 2011)
  - Extended (50 pc) diffuse HE gamma-ray source
  - 'Cocoon' of freshly accelerated CRs
  - Accelerator:
    - γ Cygni SNR?
    - OB2 association (star-forming region)?
  - Modeled as symmetric Gaussian



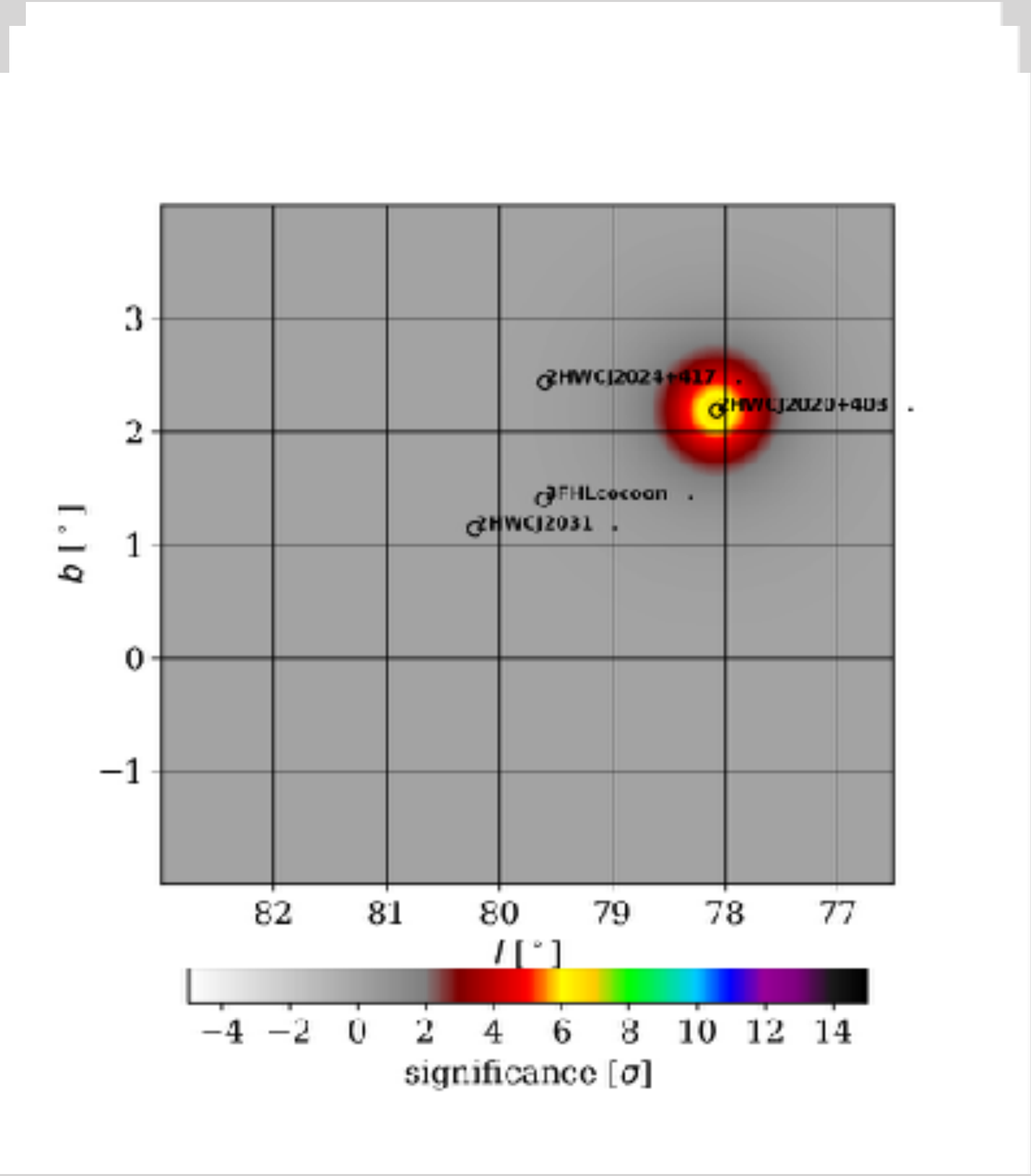
Model Building II

- Extended VHE gamma-ray source (E.Aliu et al. Apj 783, 2014)
- Associated with PWN of PSR J2032+413
- Long-period binary system:
  - Period of 50 years (Ng et al, 2017).
  - Periastron in November 2017.
- Modeled as asymmetric Gaussian, PL spectrum (R. Bird et at, ICRC 2017).

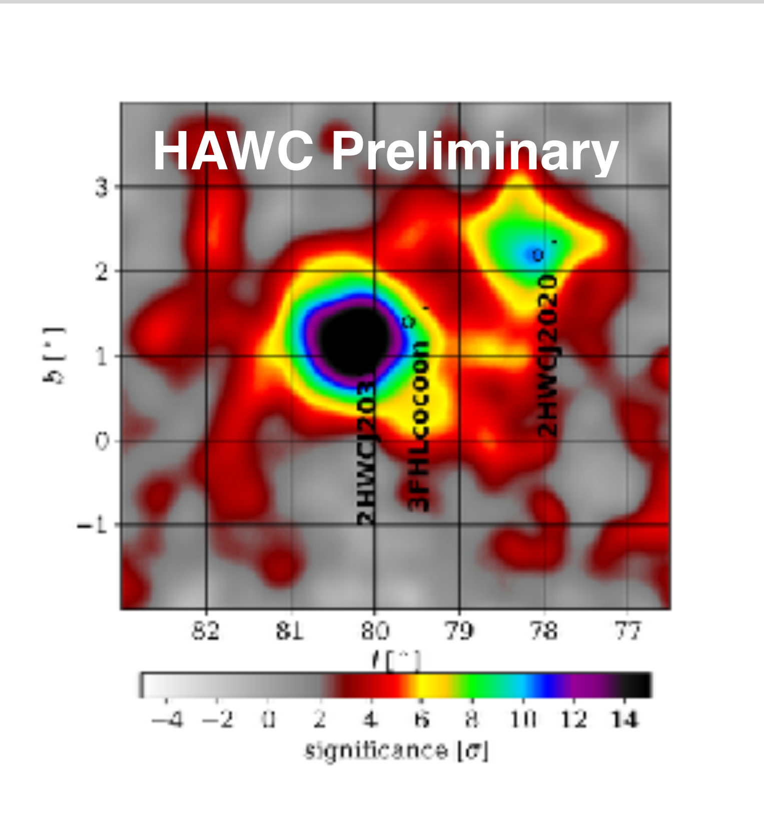


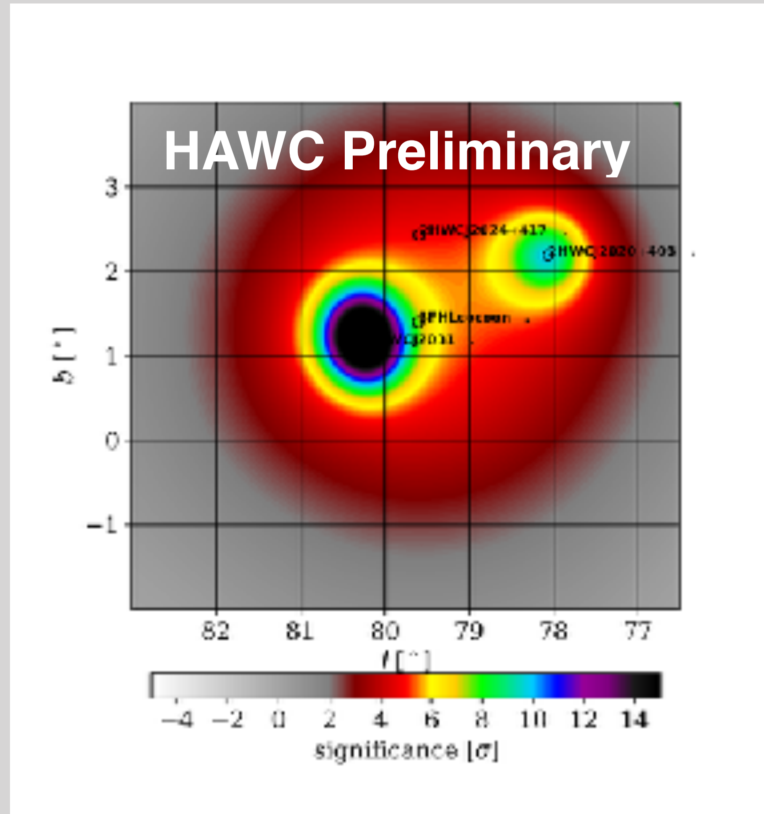
Model Building III

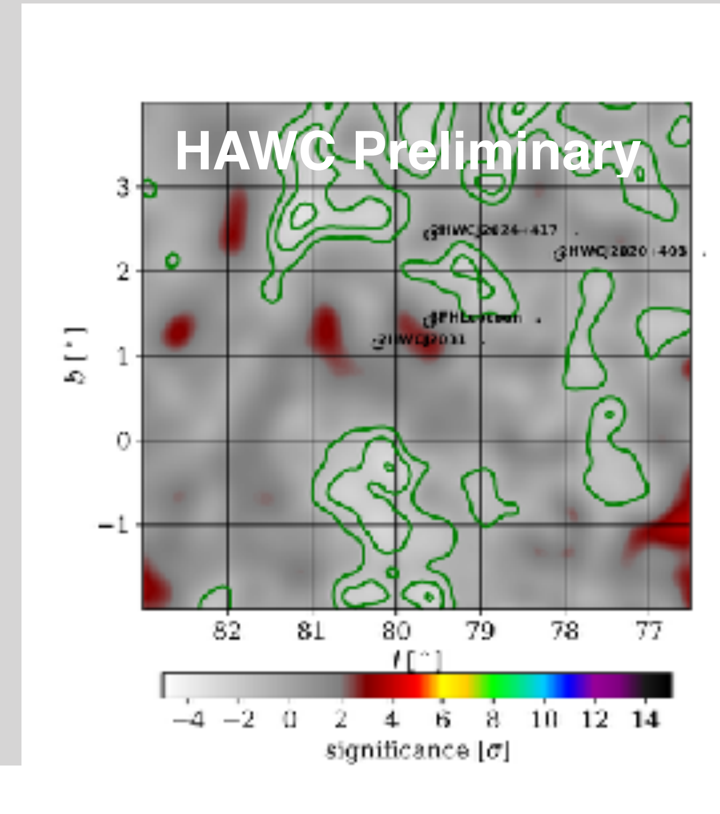
- Extended (0.1 deg) VHE gamma-ray source (E. Aliu et al., ApJ 770, 93, 2013)
- Additional extended disk component (Strysz et al., ICRC 2017).
- SNR G78.2+2.1 of PSR J2021+4026
- Offset between HAWC & VTS centroids.
- Modeled as PS (morphological studies ongoing), PL spectrum.



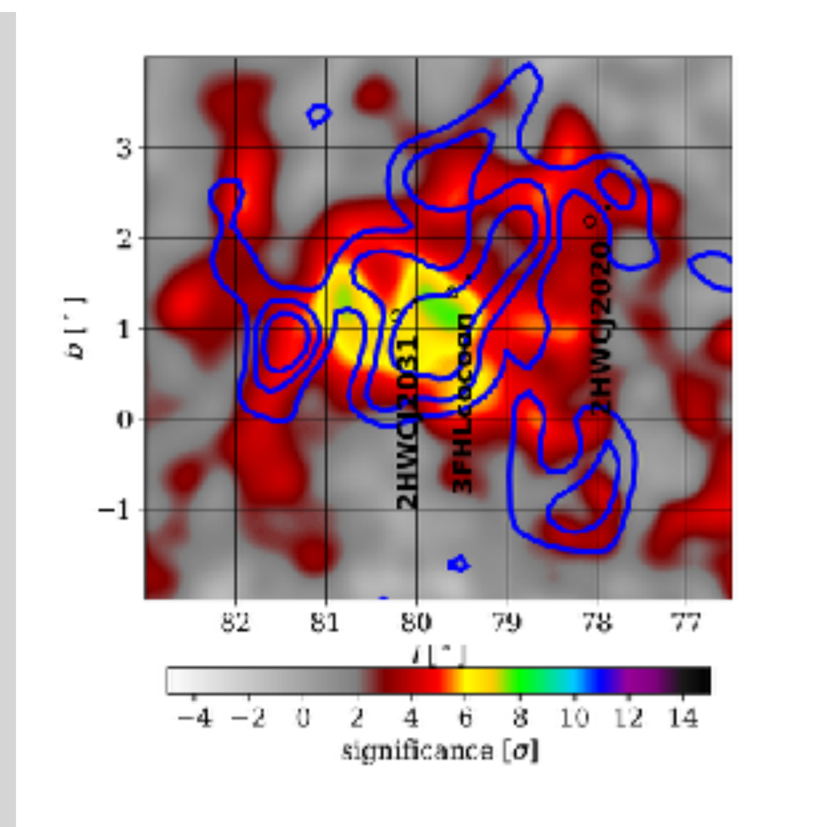
Combined Model



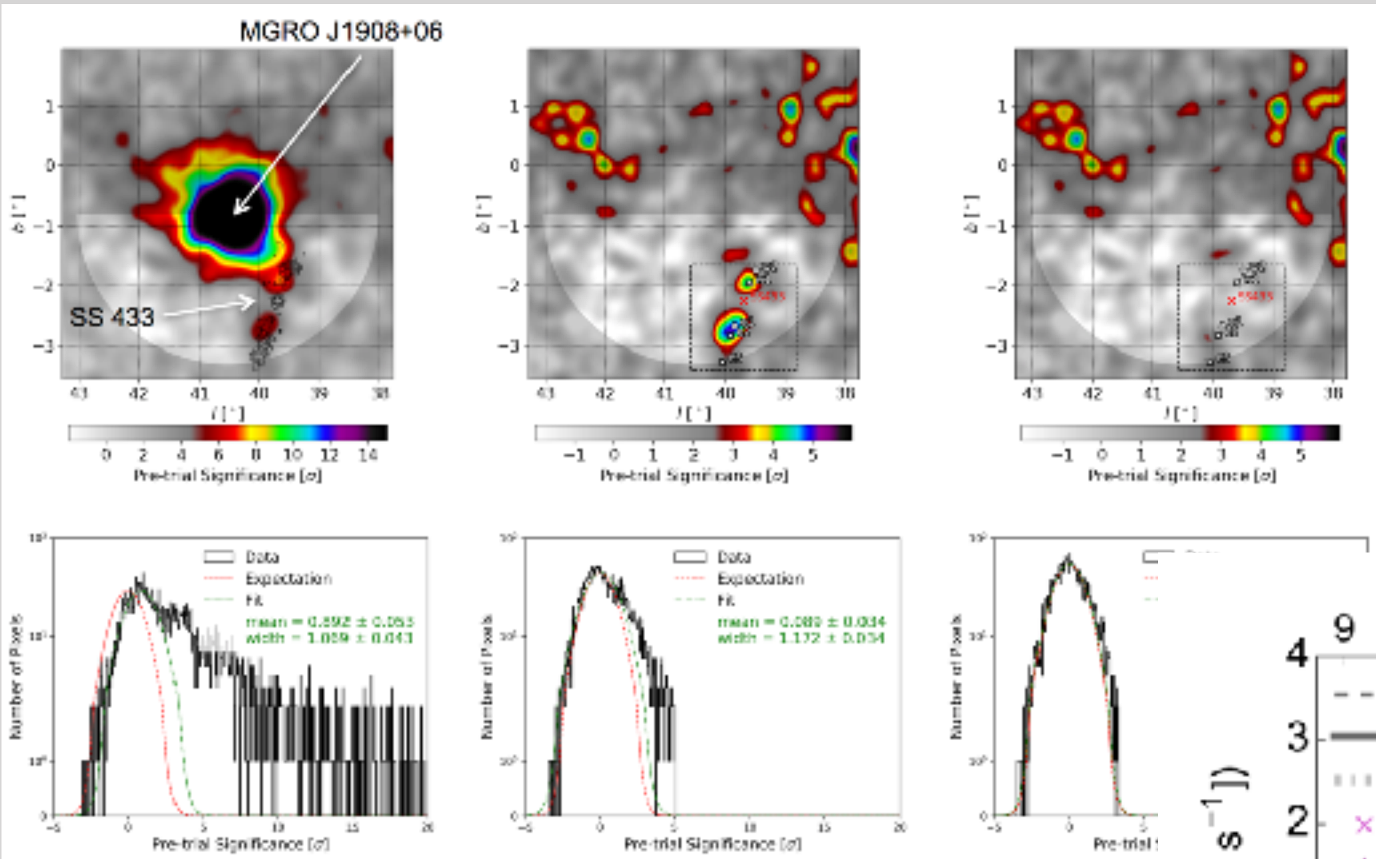


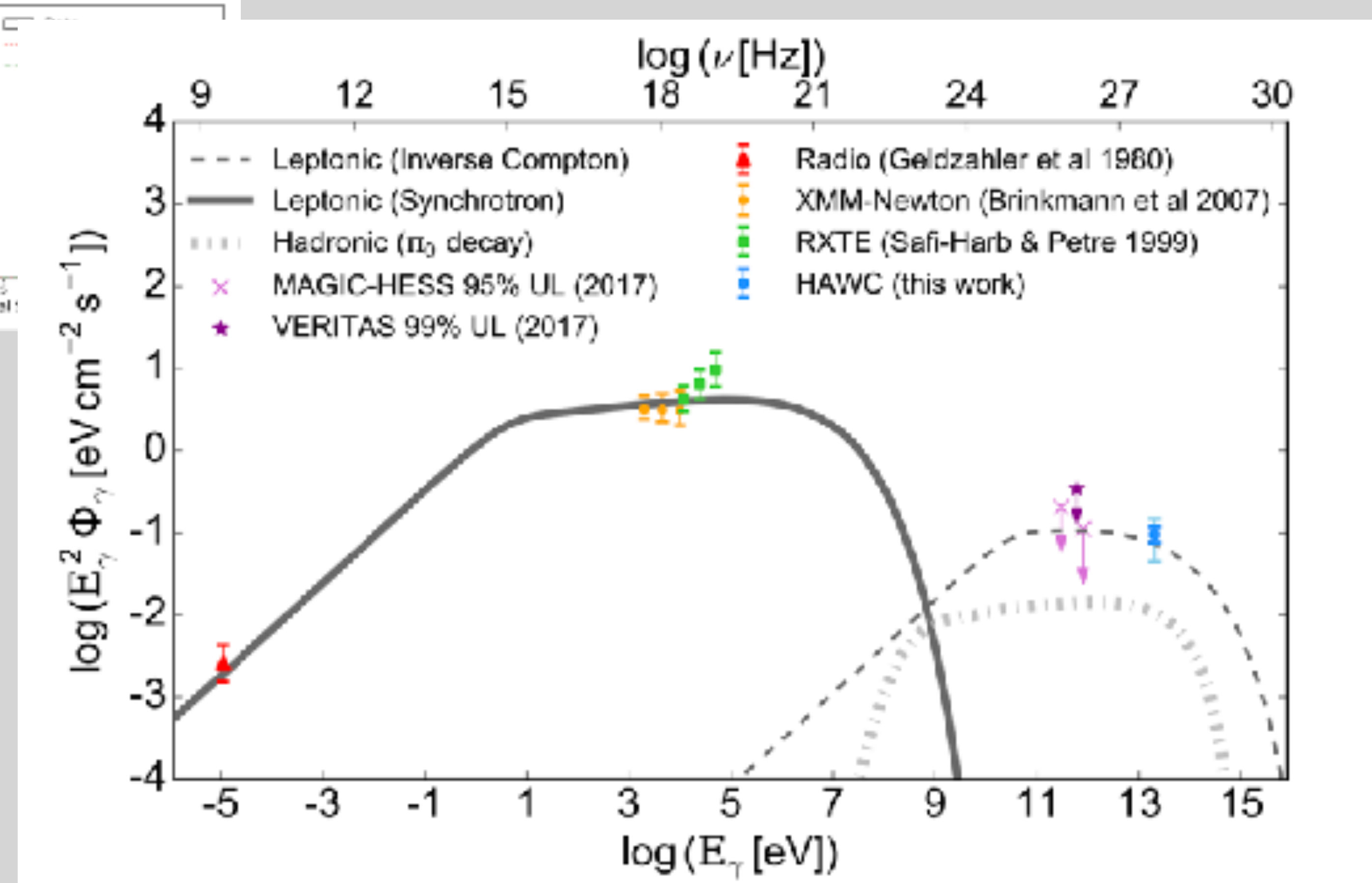


- **Map on the left has PWN & Gamma-Cygni subtracted**
- **Blue Contours are Fermi-LAT**
- **Energy spectrum is forthcoming, challenge:**
  ➡identification of the VHE energy emission, from PWN or from Cocoon

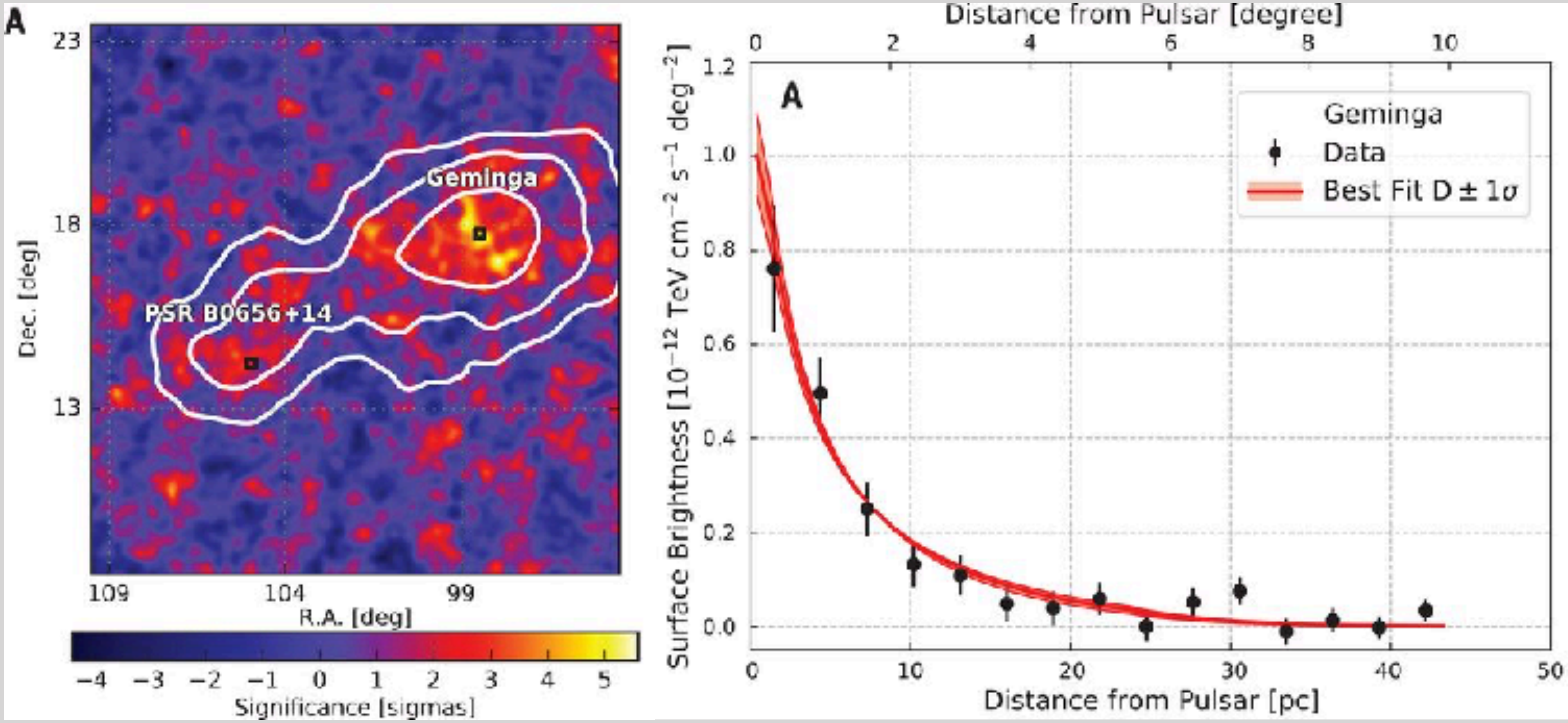


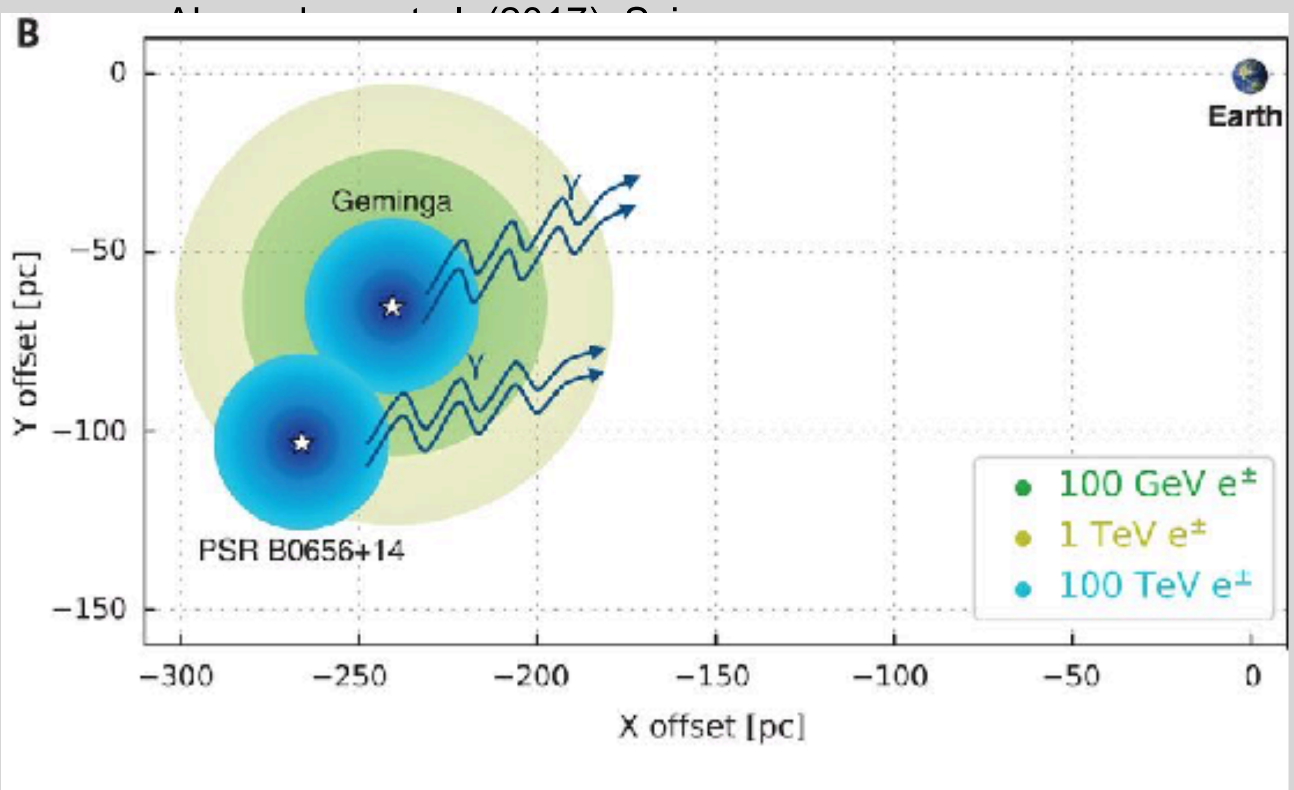
Multisource Fit Approach was used in HAWC Analysis of micro quasar SS43

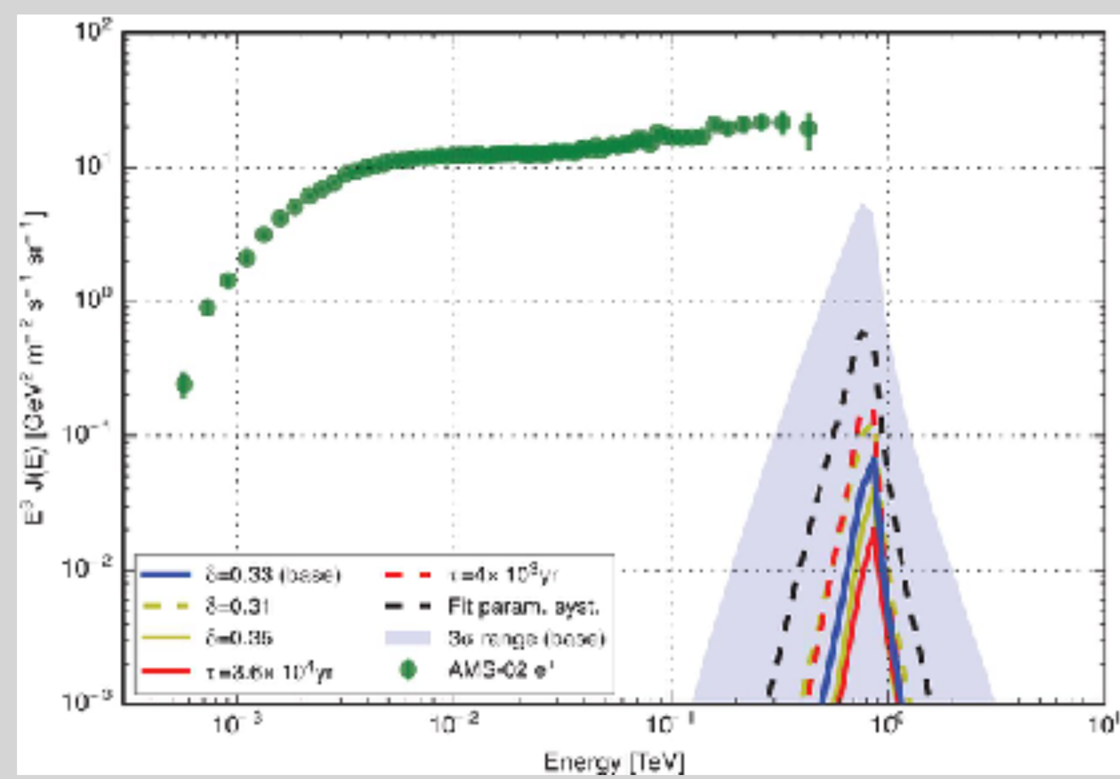




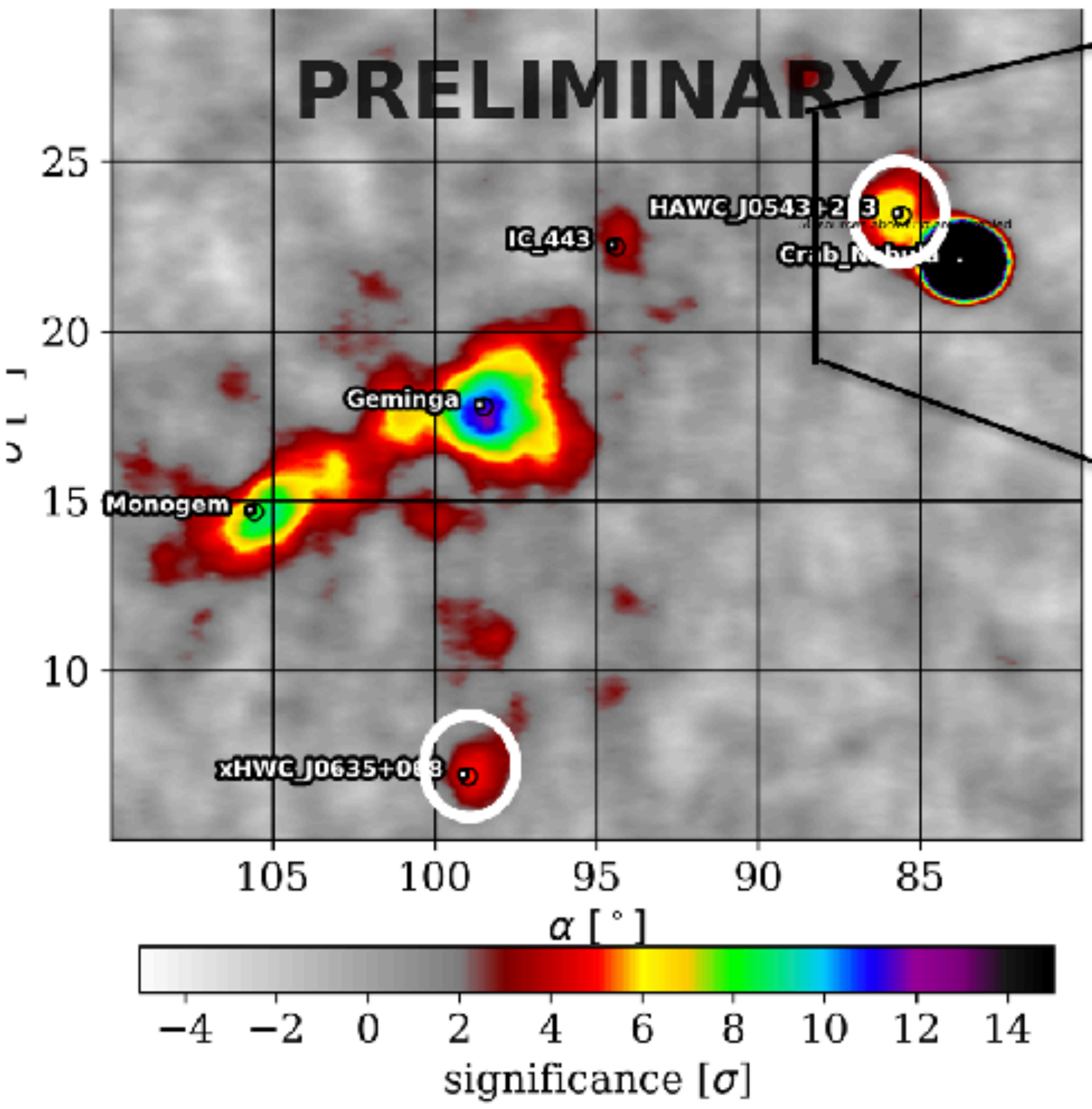
Physics Model & Templates: Example Geminga

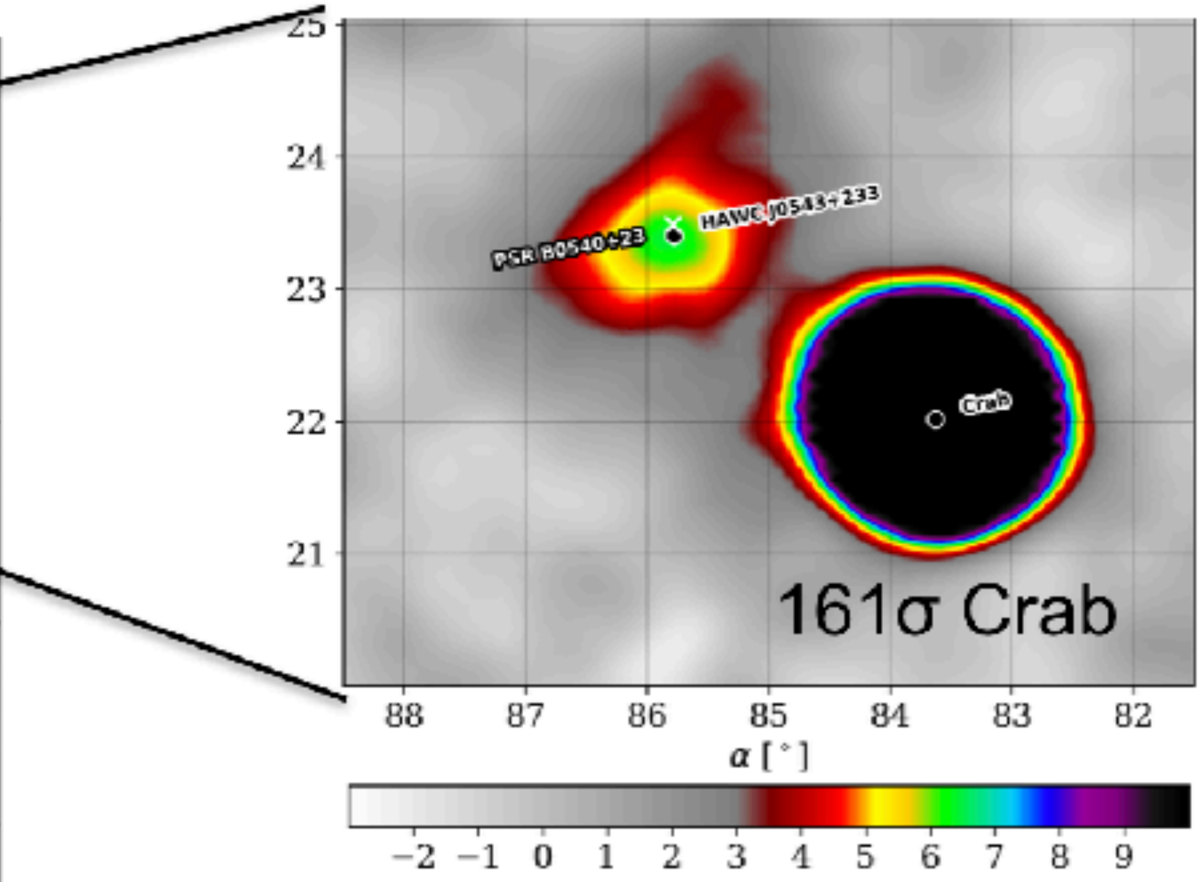






Discovery Potential: Hiding in Plane Sight





Another middle age PWN similar to Geminga and B0656+14
$\dot{E} = 4.1 \times 10^{34}$ erg s−1,
d = 1.56 kpc, τ = 253 kyr

Can test if all are Geminga-like

Discovery Potential: Hiding in Plane Sight

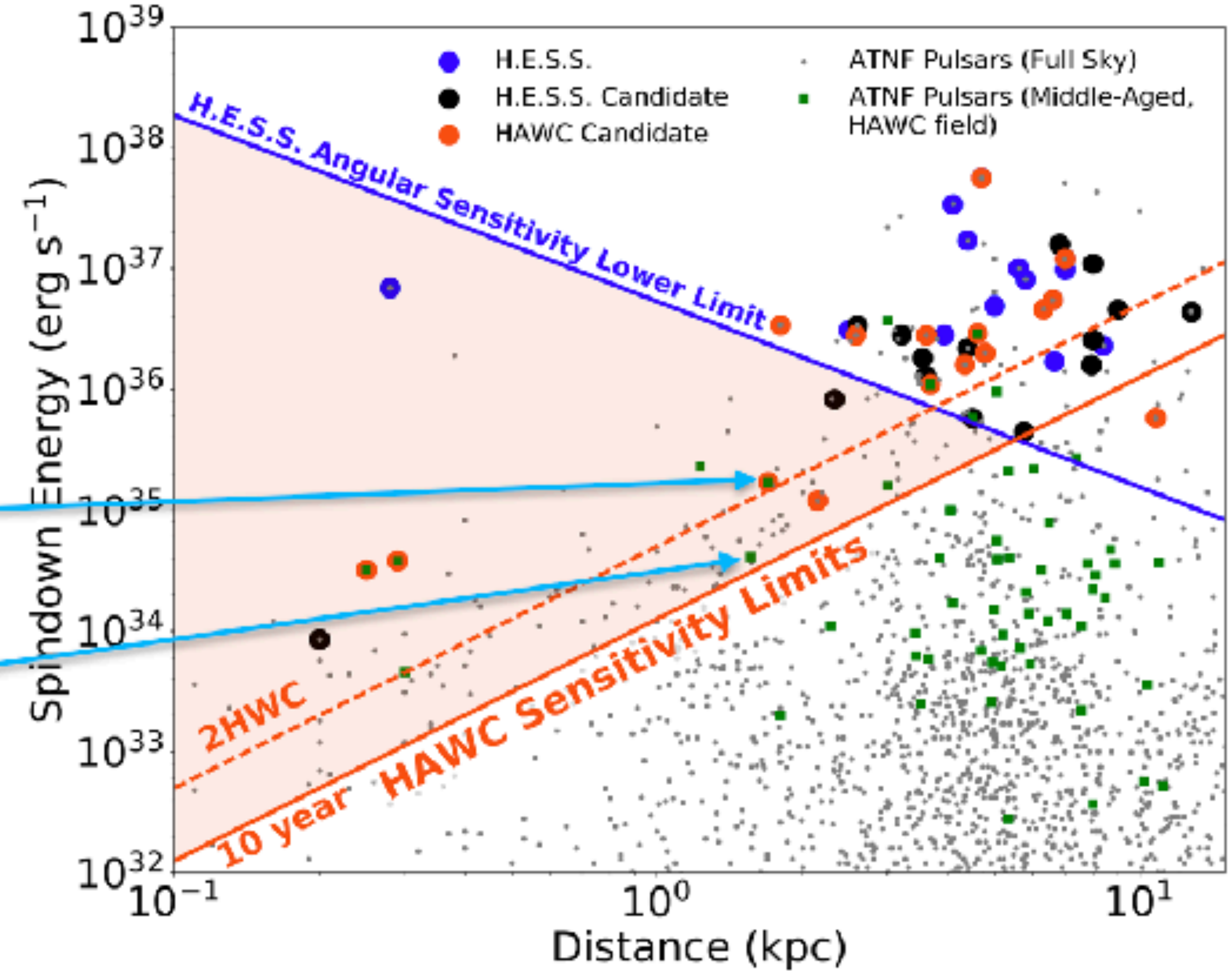
- Linden suggest that there are more nearby PWN to be found based on spin down power and distance
- HAWC has already seen several of these

HAWC detection of TeV source HAWC J0635+070

ATel #12013; *Chad Brisbois (Michigan Technological University), Colas Riviere (University of Maryland), Henrike Fleischhack (Michigan Technological University), Andrew Smith (University of Maryland) on behalf of the HAWC collaboration*
on 6 Sep 2018; 14:47 UT
Credential Certification: Colas Riviere (riviere@umd.edu)

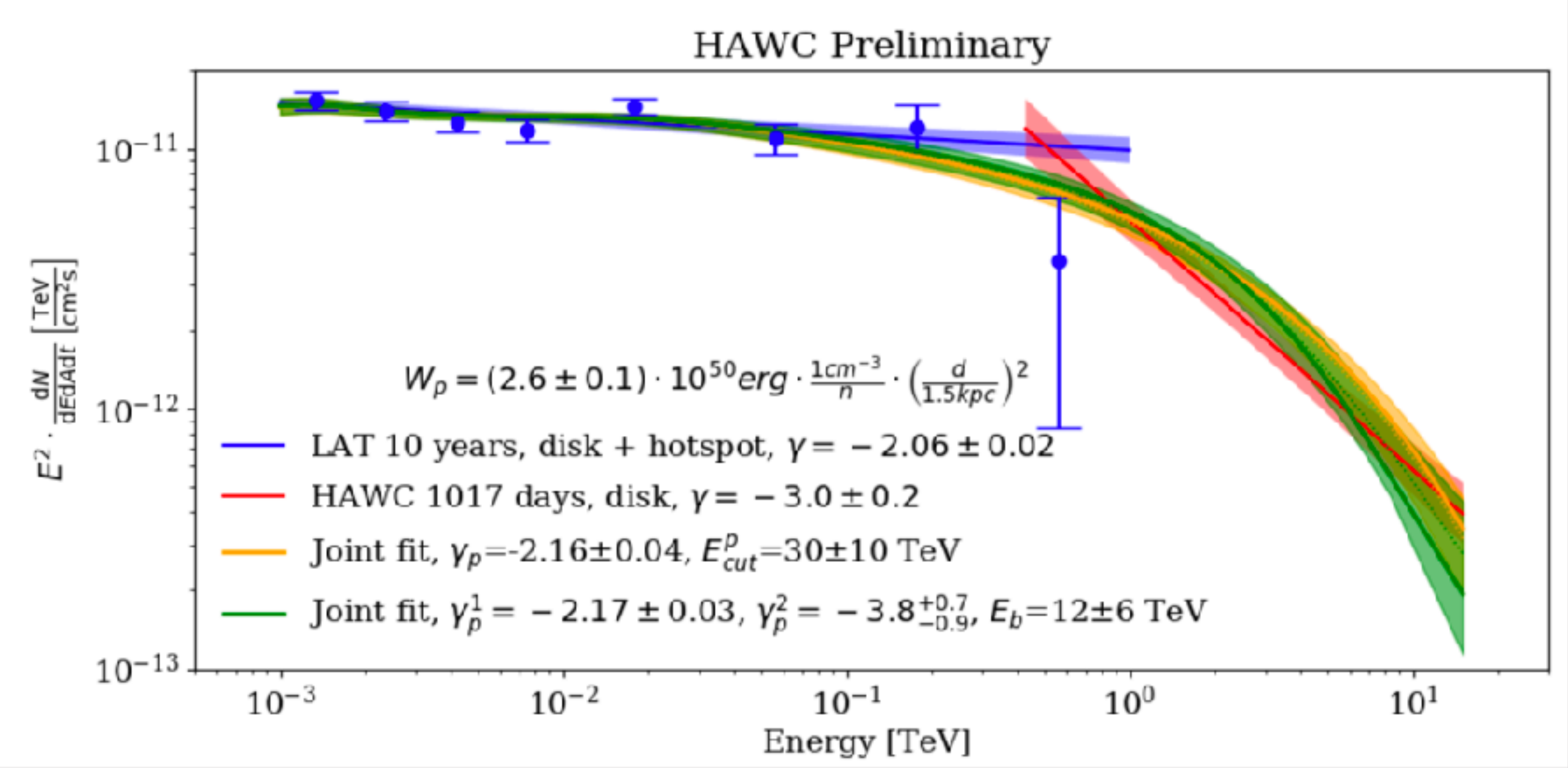
HAWC detection of TeV emission near PSR B0540+23

ATel #10941; *Colas Riviere (University of Maryland), Henrike Fleischhack (Michigan Technological University), Andres Sandoval (Universidad Nacional Autonoma de Mexico) on behalf of the HAWC collaboration*
on 9 Nov 2017; 23:11 UT
Credential Certification: Colas Riviere (riviere@umd.edu)



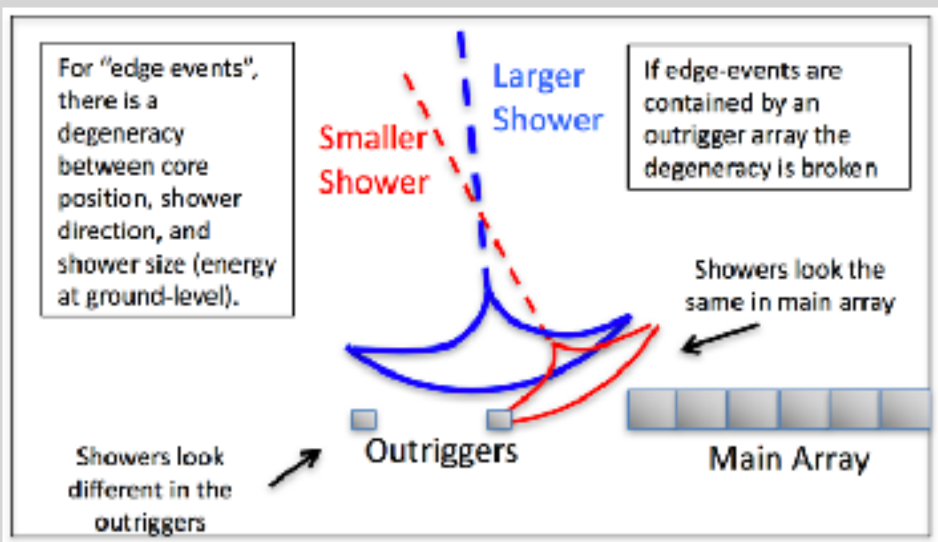
Linden et. al 2017 PhysRevD.96.103016

Multi-Instrument Fits: Example Gamma-Cygni

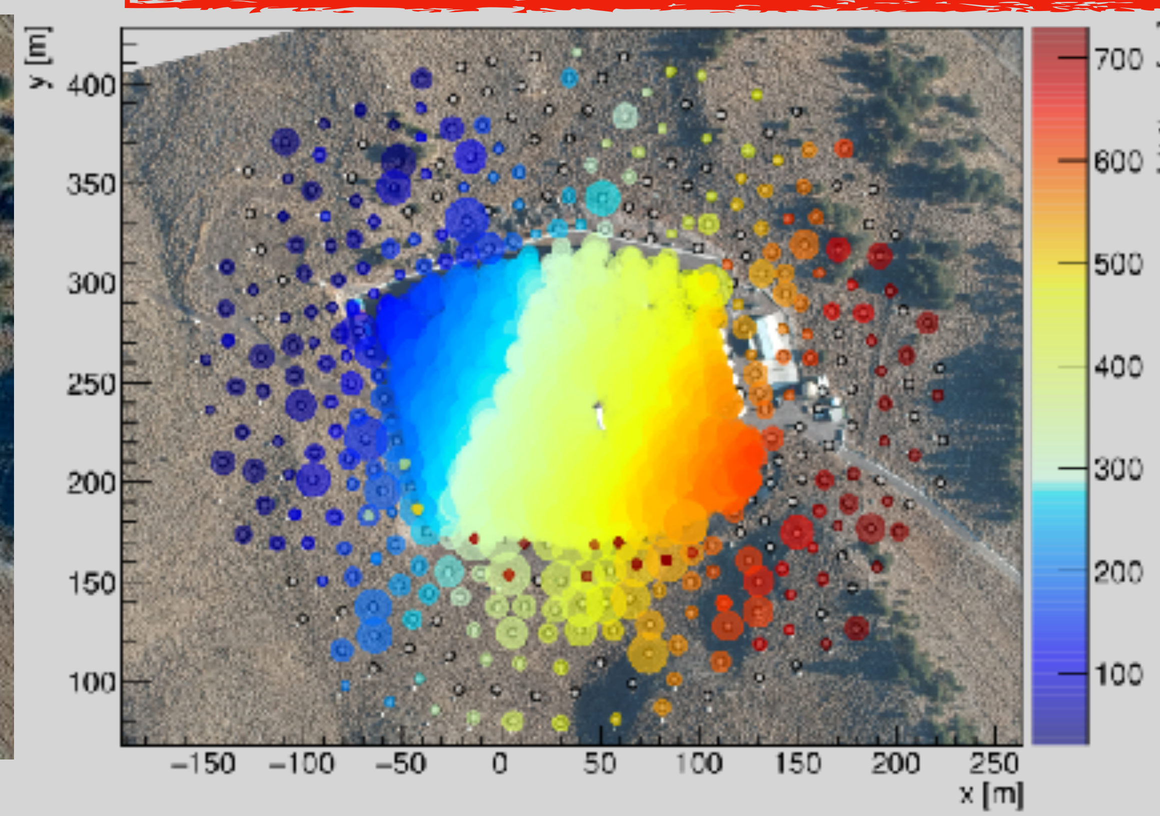


Outriggers & Further Analysis Improvements

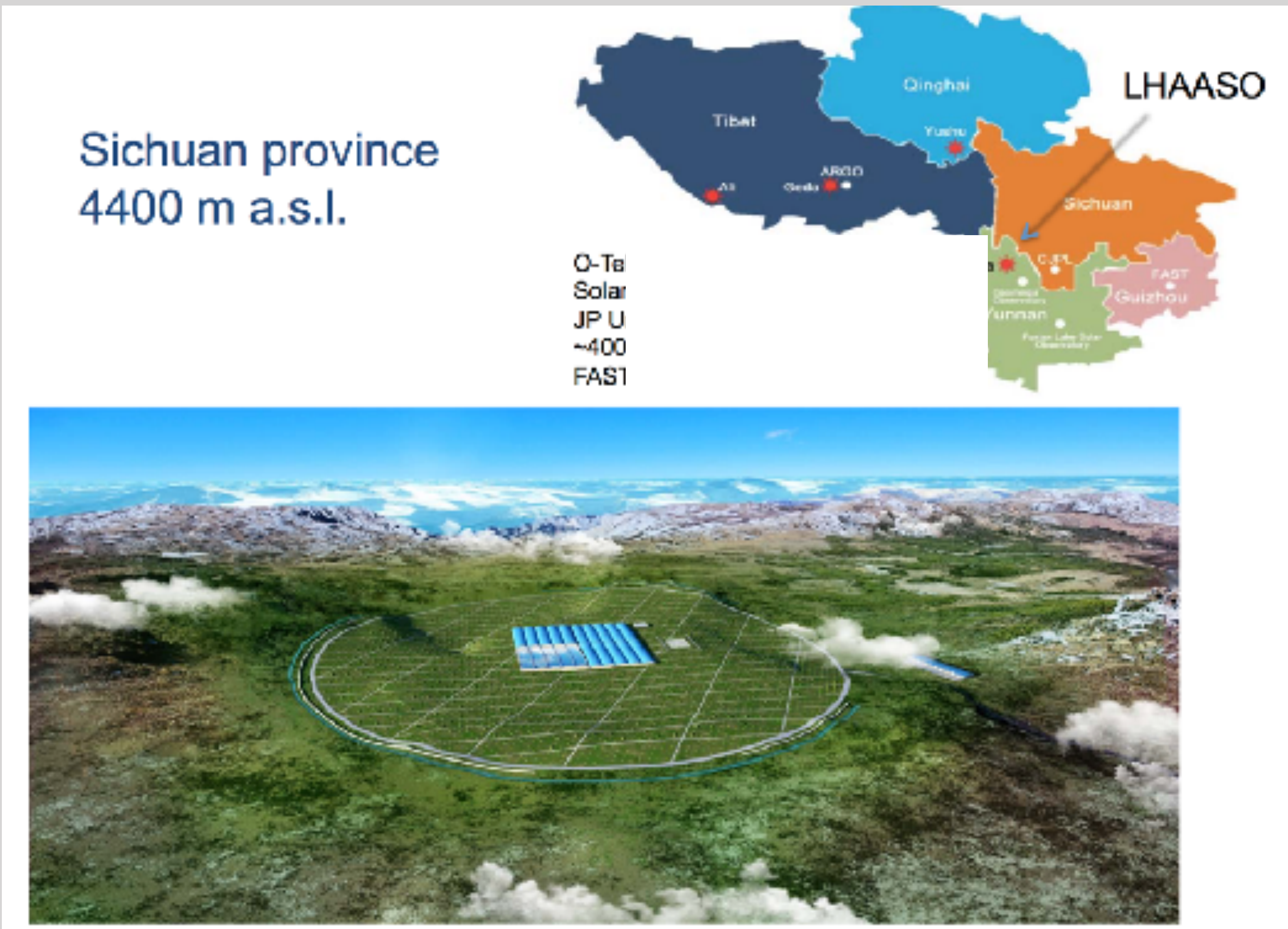
4x sensitivity above 50 TeV:
- **Better shower core fit**
- **Shower containment (better energy resolution)**

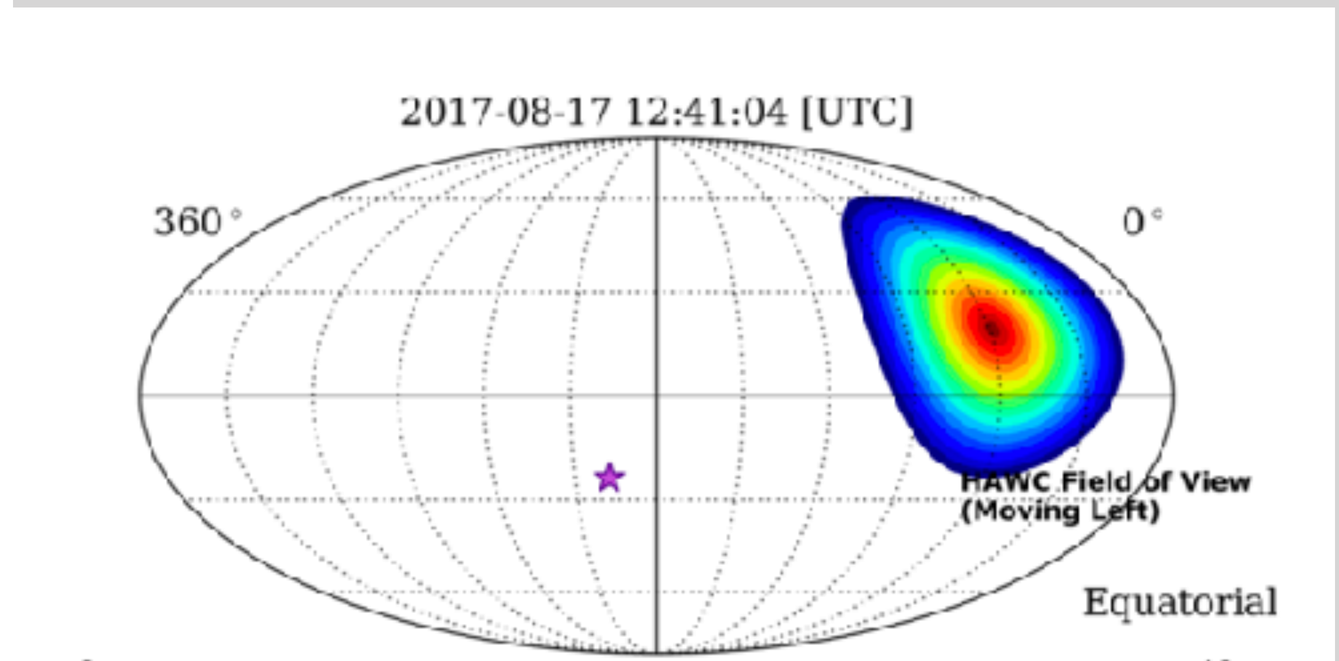


- **Current low-energy (small event) angle reconstruction is limited by noise.**
- **The "noise" in HAWC is almost entirely due to small non-triggering showers.**
- **New "Multi-Plane Fitter" identifies and isolates sub-showers within each event instead of assuming all hits are from a single shower.**



Complementarity
LHAASO & HAWC



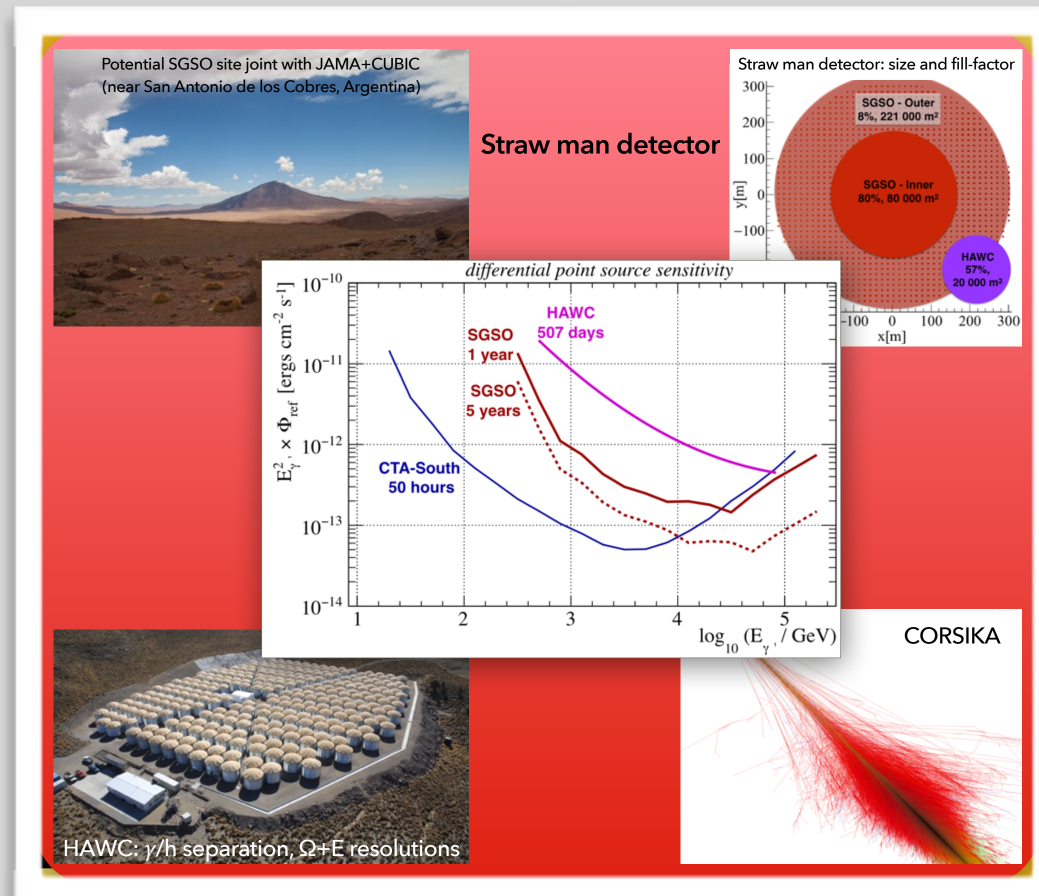


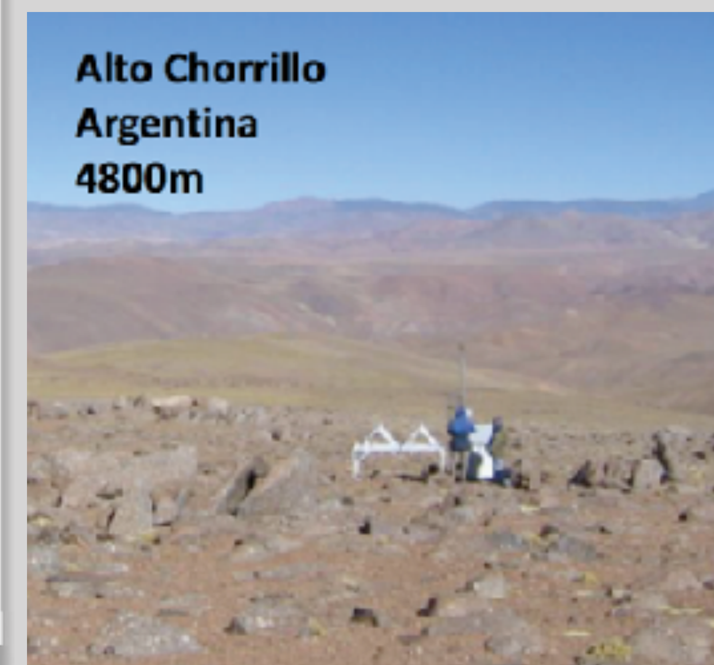
HAWC and LHAASO are at about the same latitude (28°N) but opposite sides of the globe. Together they minimize the survey gap of the Northern hemisphere!

Gravitational Waves

The EAS Sampling Future: SGSO

- Factor of 4 increase in sensitivity between ALMA (5000 m a.s.l.) and HAWC (4100 m a.s.l.) altitude
- Lower energy threshold
- Discovering rate transient events requires full sky coverage (e.g. GRBs & GW)
- TeV source finder for CTA South





ASTROPHYSICS

Astronomers Turn New Eyes On the Cosmic Ray Sky

To understand why physicists have traditionally shunned cosmic rays, think of these mysterious visitors as gate-crashers to a party. Not only do they appear uninvited and without pedigree, but they bring with them a menagerie of other unwanted creatures whose presence can only wreak havoc. But lately, physicists have started to wonder about these mysterious strangers. Just what kind of environment could spawn this uniquely energetic lot? Cosmic rays are now in vogue.

as ever. The verdict on Cygnus X-3 and Hercules X-1 is in, and it's disappointing: They aren't the cosmic ray beacons they seemed to be. But that hasn't discouraged anyone, just convinced the cosmic ray crowd to settle in for a longer haul of data gathering.

And these, in turn, insouciantly trespass through the pristine grounds of carefully tended physics experiments, confounding detectors and ruining many a research party. But lately particle physicists have become entranced by the observation that some cosmic rays carry energies of 10^{20} electron volts (eV)—10 million times higher than will be attained by the Superconducting Super Collider (SSC). That makes them the most energetic particles in the universe, and it raises a simple question that is driving the new subfield of cosmic ray astronomy. As Nobel Prize–winning physicist James Cronin of the University of Chicago puts it: "How does nature do that?"

He and other researchers are convinced that when the answer comes, it will lead to new insights about some of the most ener-

Keen observers. Casa-Mia's array of particle detectors *(top)*, photodetectors from the prototype Fly's Eye *(right)*, and Milagro's swimming pool, which will hold layers of particle and muon detectors *(above)*.

dustry lying at the interface of physics and

helium to lead. The galaxy's magnetic field warps these particles along curving paths so that, from Earth, they seem to emanate equally from all directions. Only neutral particles are likely to point back toward their origin, and of those, only gamma rays—high-energy photons—would survive the trip from source to Earth. (Neutrons, the most common neutral particles, would decay back into protons long before they reached Earth.) But gamma rays, says Cronin, constitute only one or two out of every 100,000 cosmic rays, which makes for a dismaying signal-to-background challenge.

Worse, at the highest energies even the "background" of charged cosmic rays dwindles to almost nothing. The flux of cosmic rays at "low" energies, explains Pierre Sokolsky of the University of Utah, is great enough that researchers can observe them directly by flying a detector in a high-altitude balloon or on a satellite. But at 10^{13} or 10^{14} eV, says Sokolsky, "you'd have to have a 10-