Large-Field-of-View Ground-Based Detectors

A biased review of **unbiased** survey instruments

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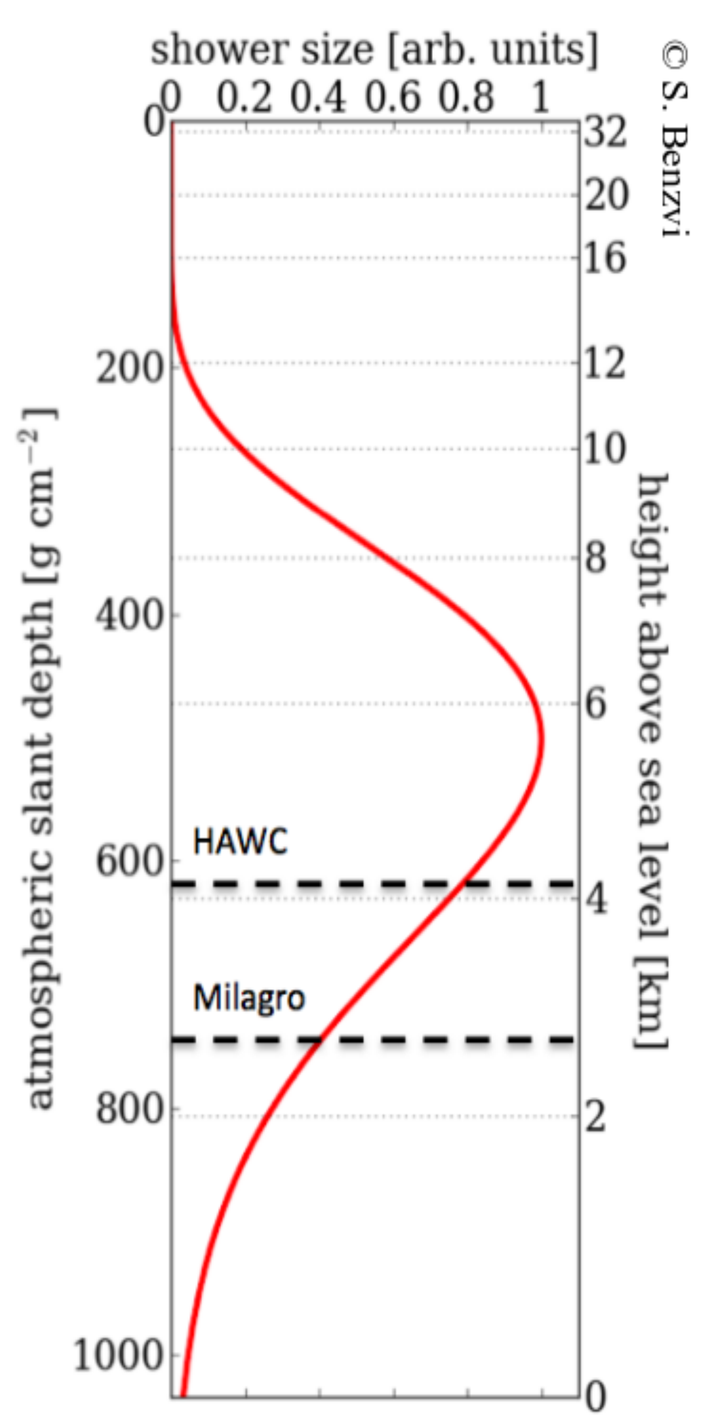
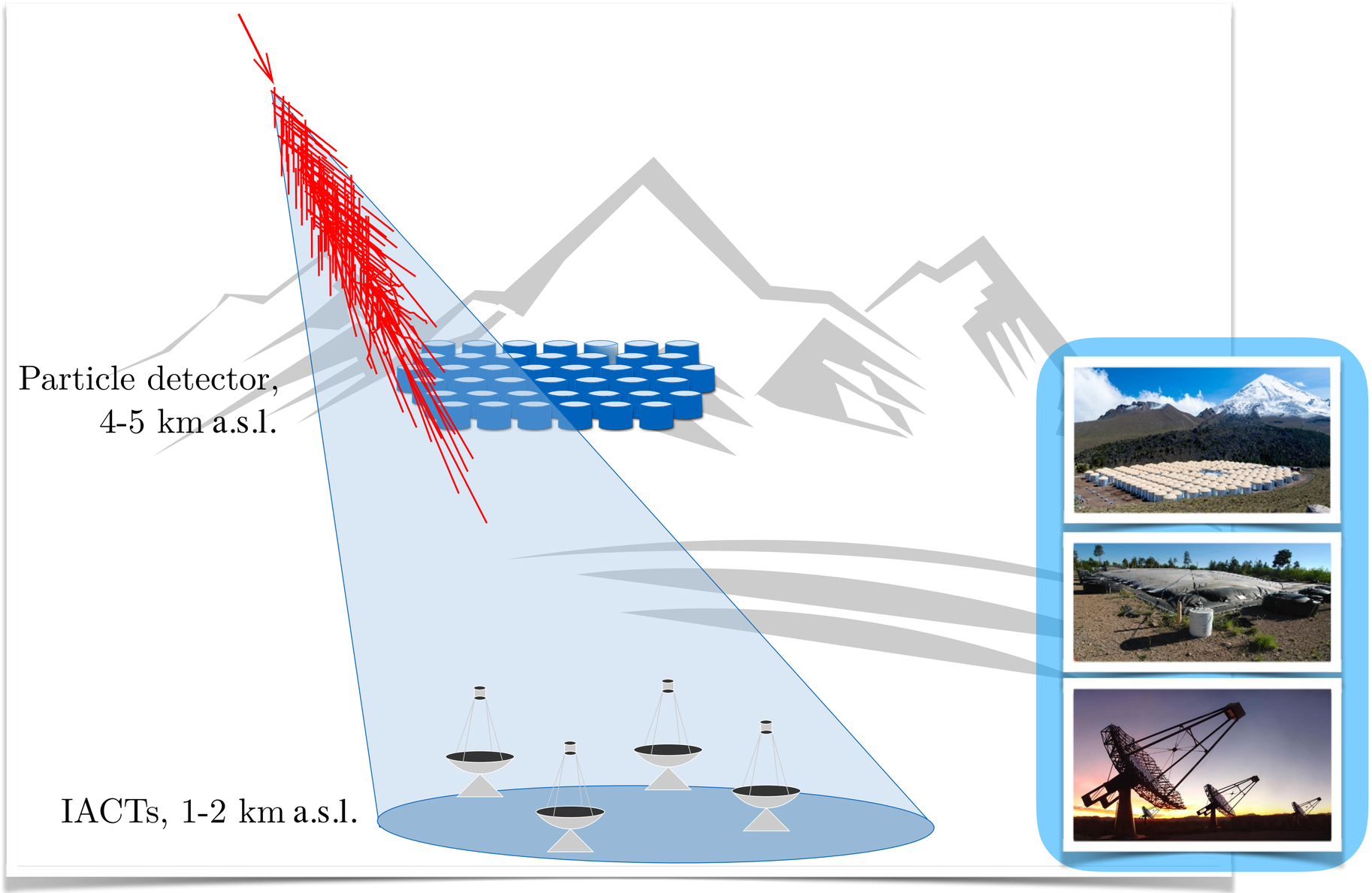
Michigan Technological University

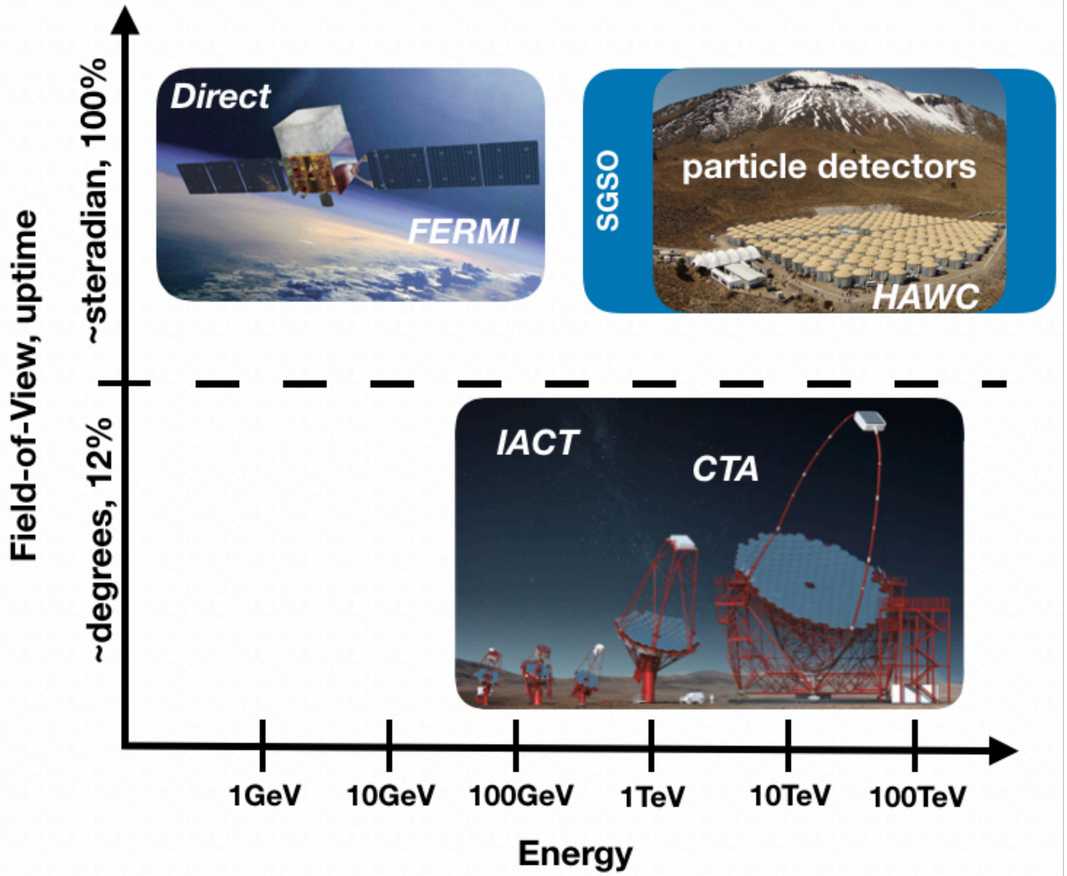
EAS Sampling Arrays & Altitude





Field of View & Energy

3 Main Features



Complementarity

- Hight Duty Cycle

☑ Transients

- Wide Field of View

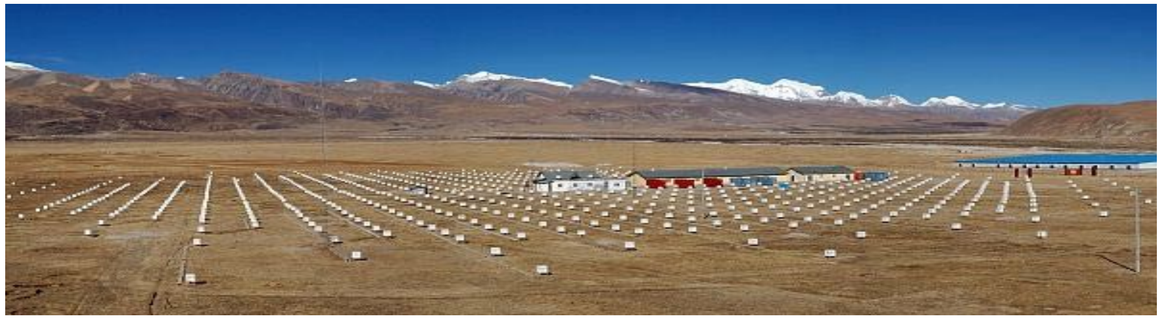
☑ Extended and Large Scale Emission

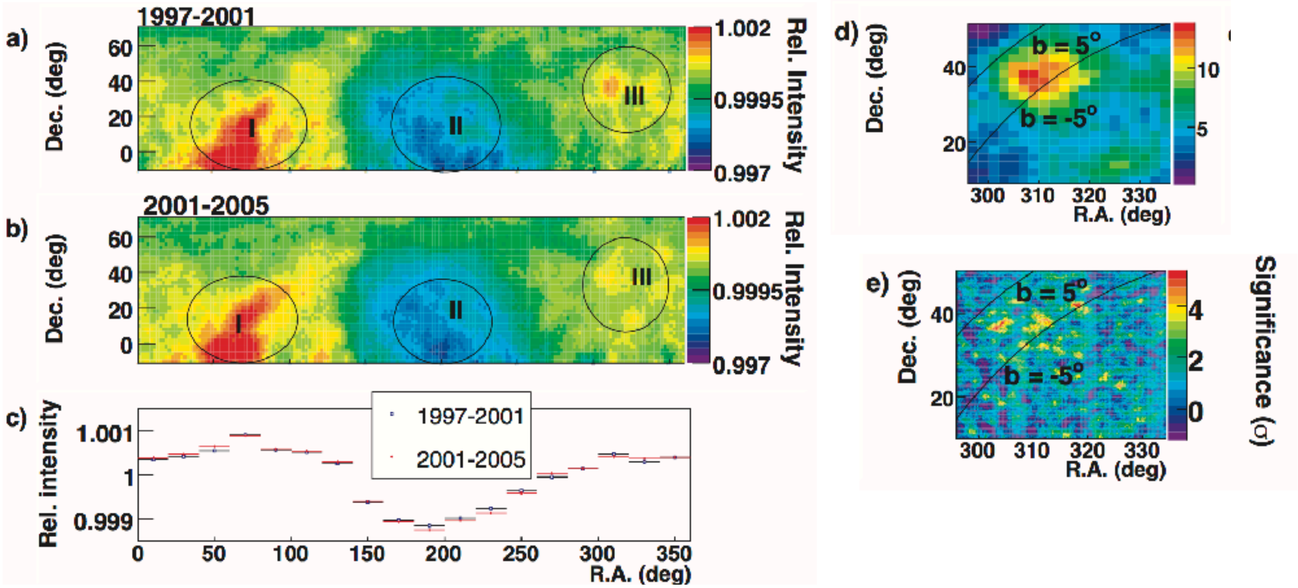
- Good Sensitivity, Angular & Energy Resolution above 10s of TeV

☑ Highest Energy Accelerators

Northern TeV Gamma & Cosmic-Ray Surveys

Tibet AS — Scintillators

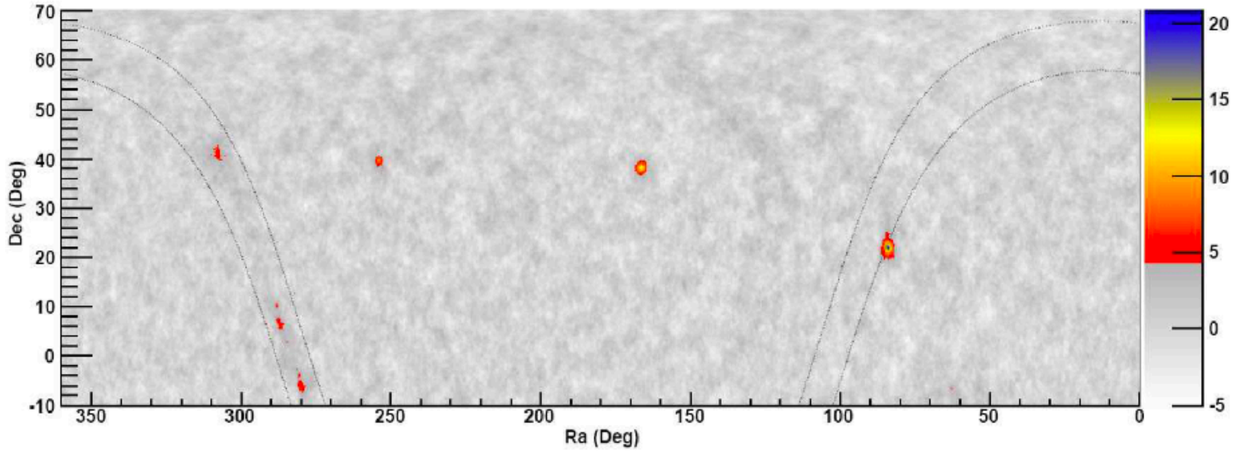




Science314:439-443,2006

ARGO-YBJ — RPCs

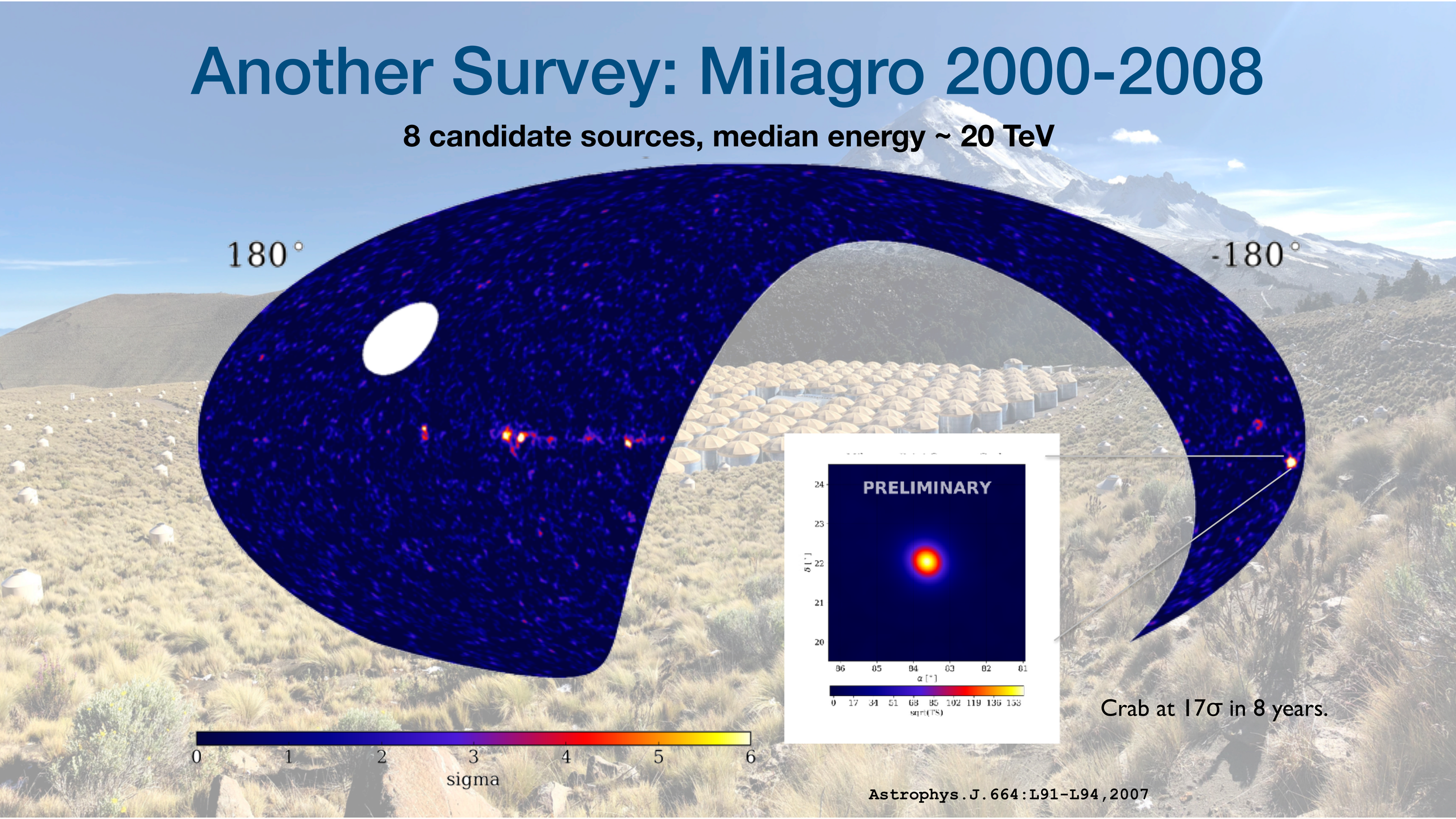
11 candidate sources, median energy ~ 1 TeV



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

Another Survey: Milagro 2000-2008

8 candidate sources, median energy ~ 20 TeV

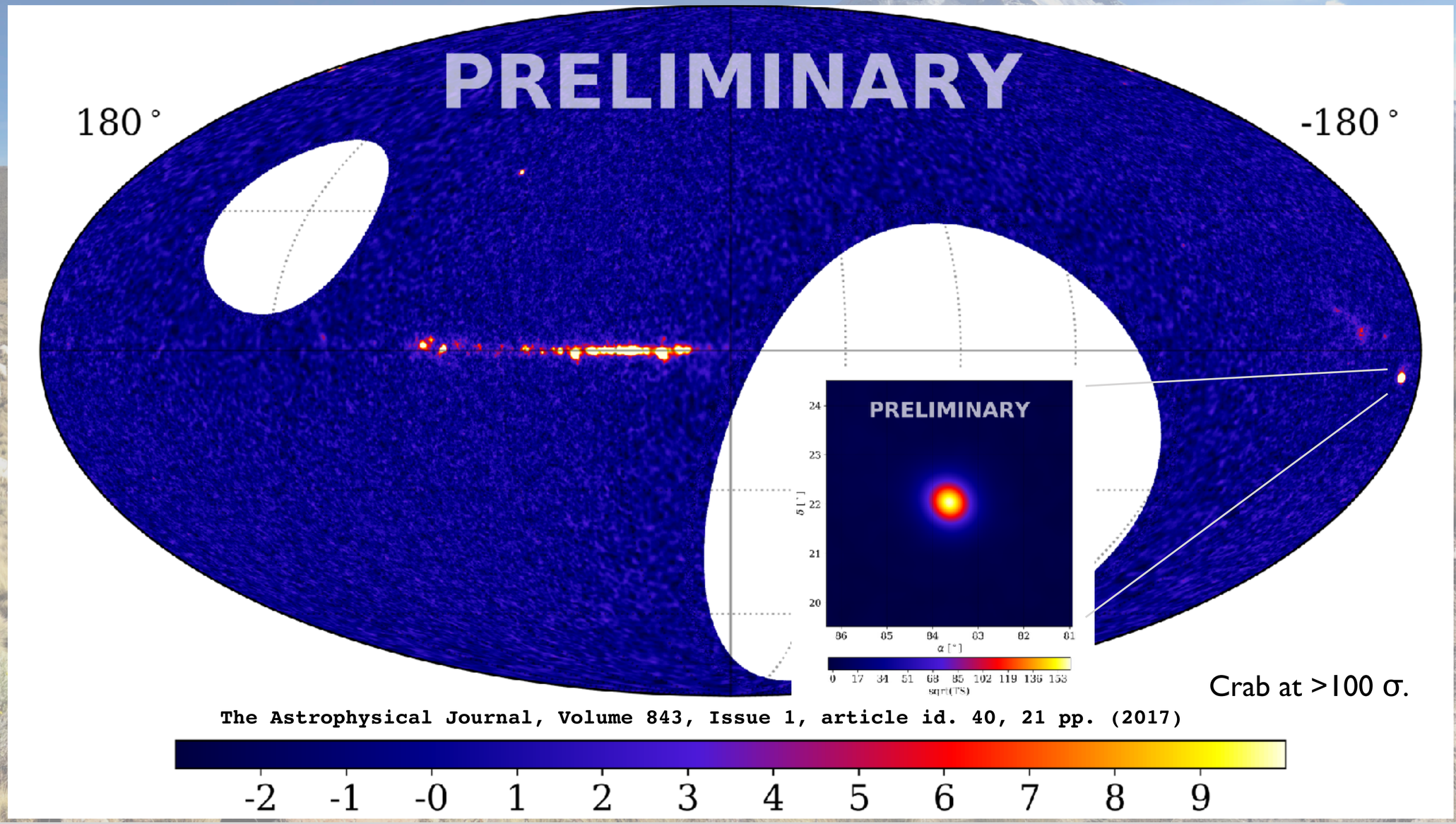


Crab at 17σ in 8 years.

Astrophys.J.664:L91-L94,2007

Latest Survey: HAWC 11/2014-04/2018

>39 candidate sources, pivot energy ~ 7 TeV

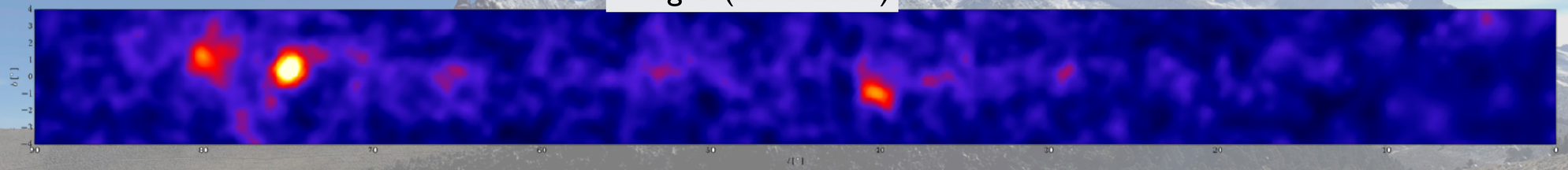


Crab at >100 σ.

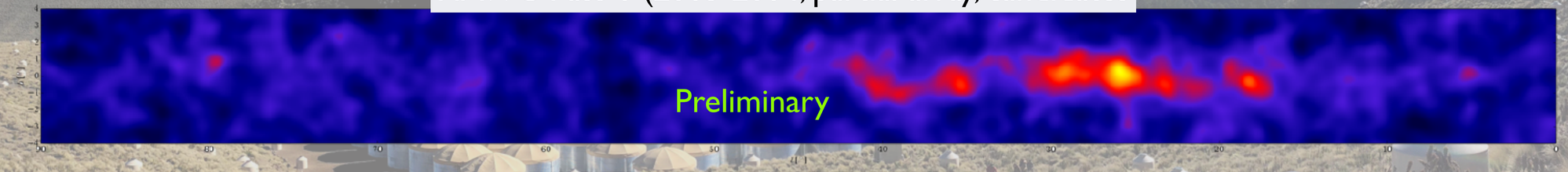
The Astrophysical Journal, Volume 843, Issue 1, article id. 40, 21 pp. (2017)

Galactic Plane Wide-Field of View Observations over the Years

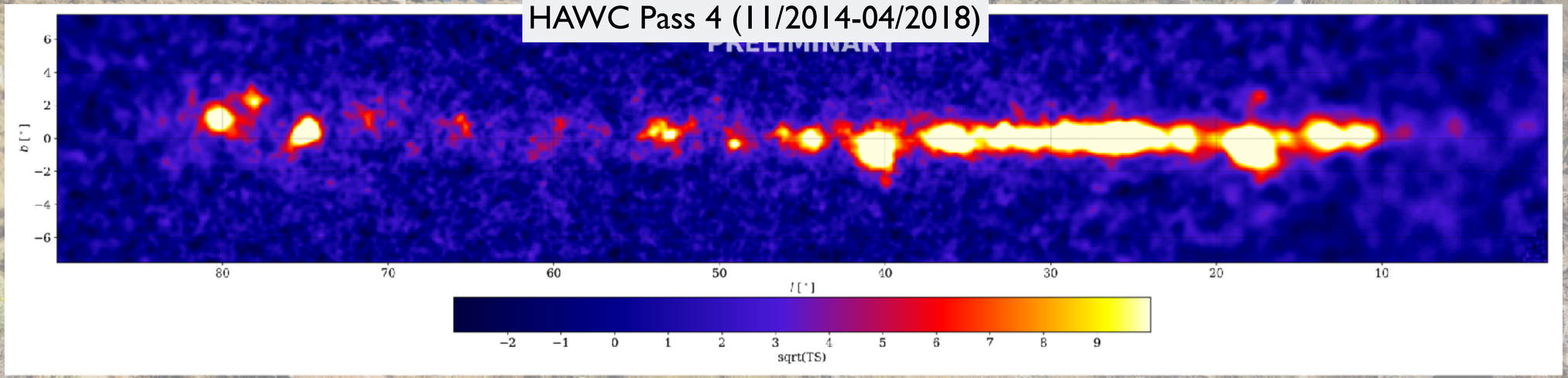
Milagro (2000-2008)



HAWC Pass 1 (2013-2014, partial array, candidates



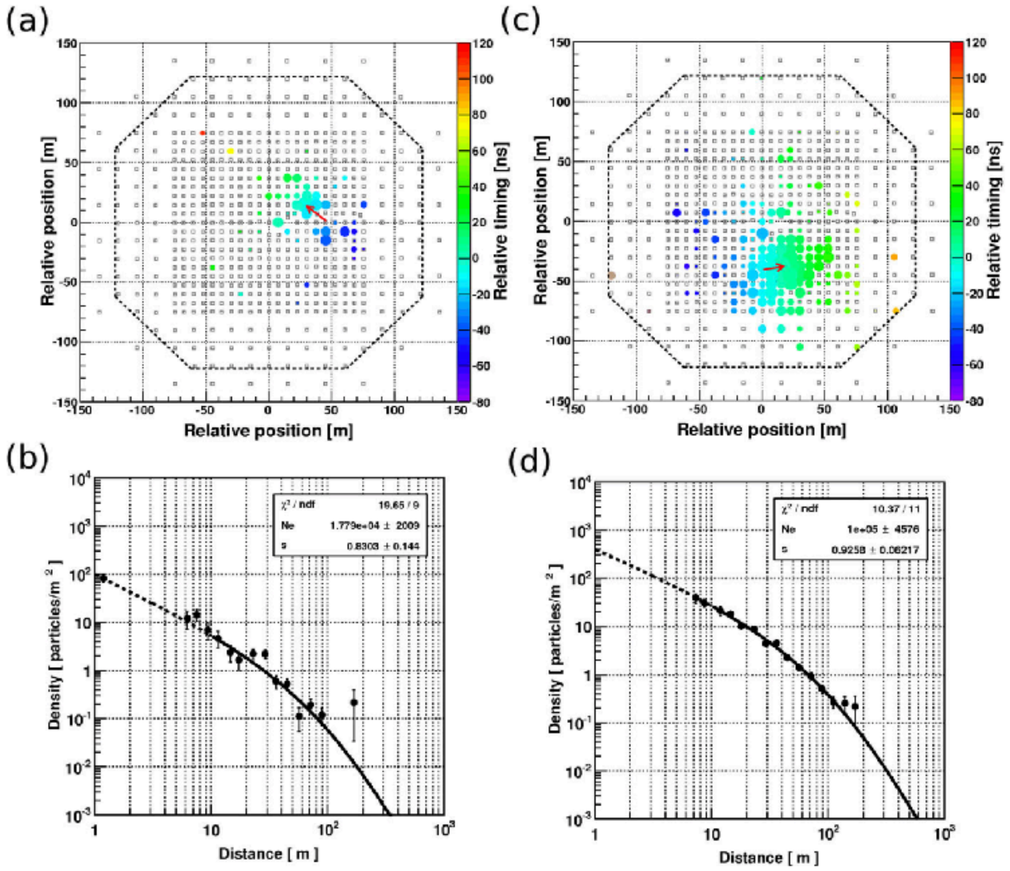
HAWC Pass 4 (11/2014-04/2018)



Milagro was located near Los Alamos, New Mexico — different sensitivity by declination along Galactic plane.

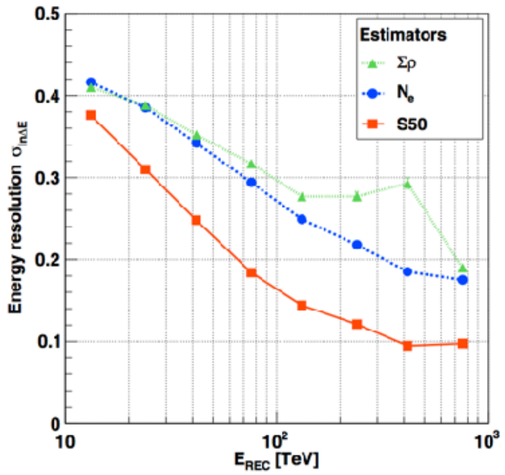
The Other Hillas Parameters: S(nn) or Rho (nnn)

Tibet AS: Particle Density S50

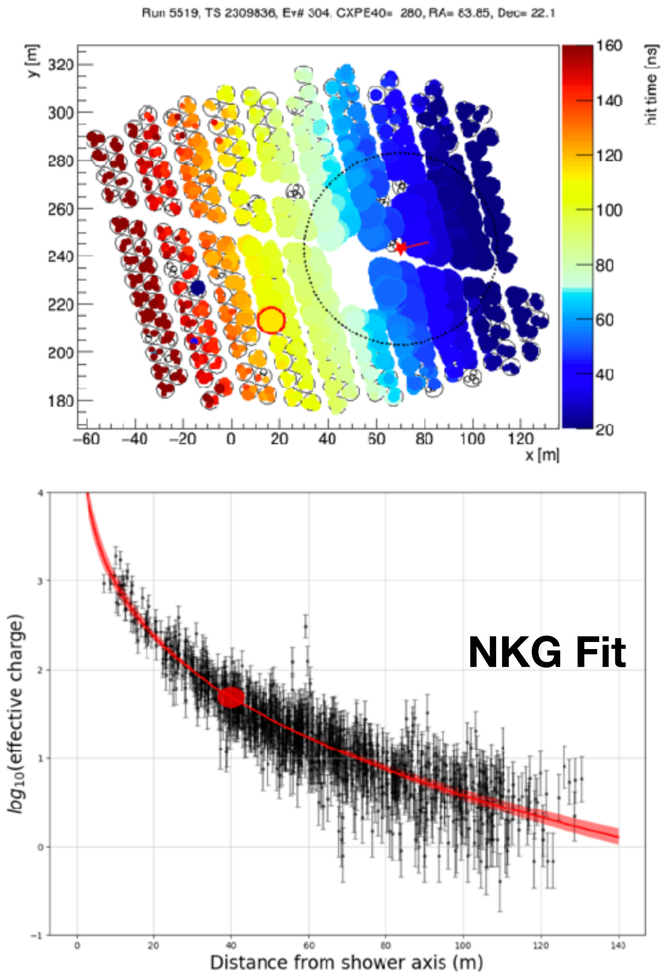


Experimental Astronomy, Volume 44, Issue 1, pp.1-9

Resolution



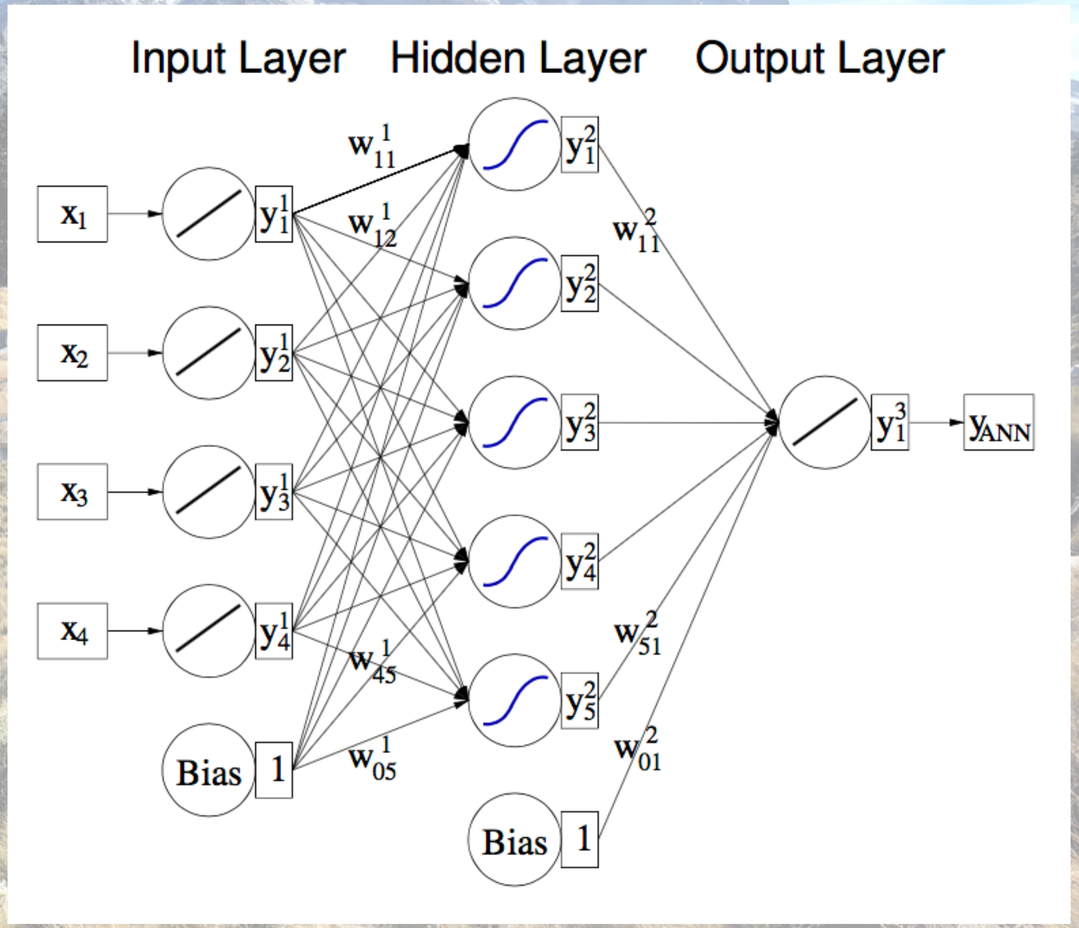
HAWC: Charge Density 'Q40'



K. Malone (LANL) - APS Spring Meeting 2019

Additional Development: Energy Estimation via ANN

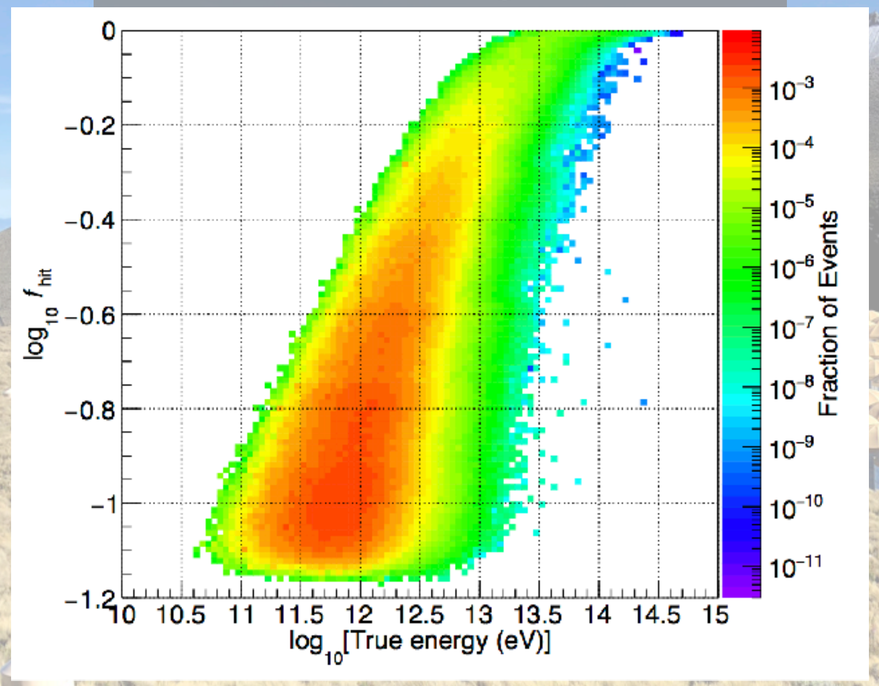
- **Toolkit for Multivariat Analysis (TMVA)[1]**
- **Input variable chosen to quantify:**
  - **Core position**
  - **Zenith angle**
  - **Signal at core**
  - **Radial distribution, annuli (show age)**
  - **Energy deposited in detector**
  - **Fraction of ground energy landing in the detector**
- **479 free parameters (weights) determined by training on Gamma-Ray Monte Carlo**



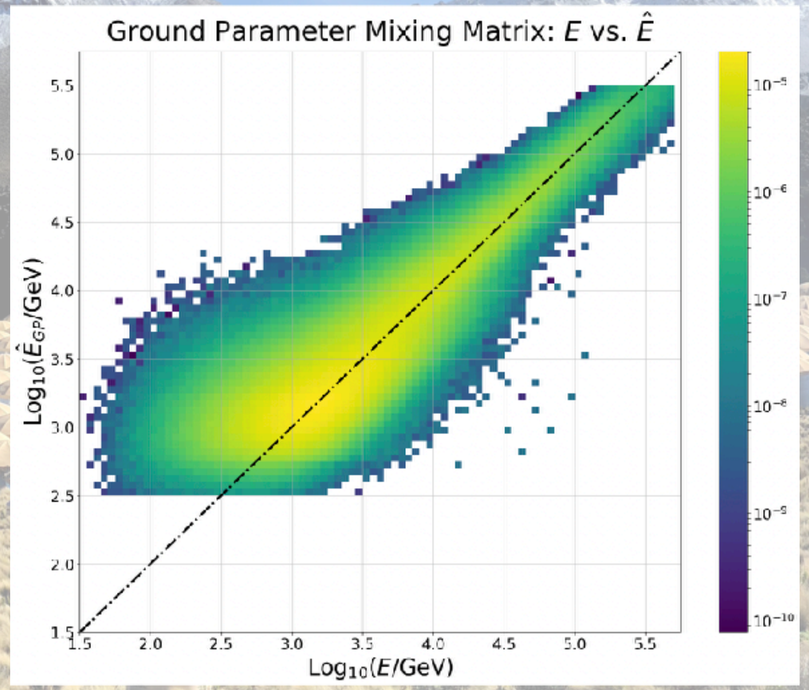
[1]http://tmva.sourceforge.net/

3 Methods of Energy Estimation

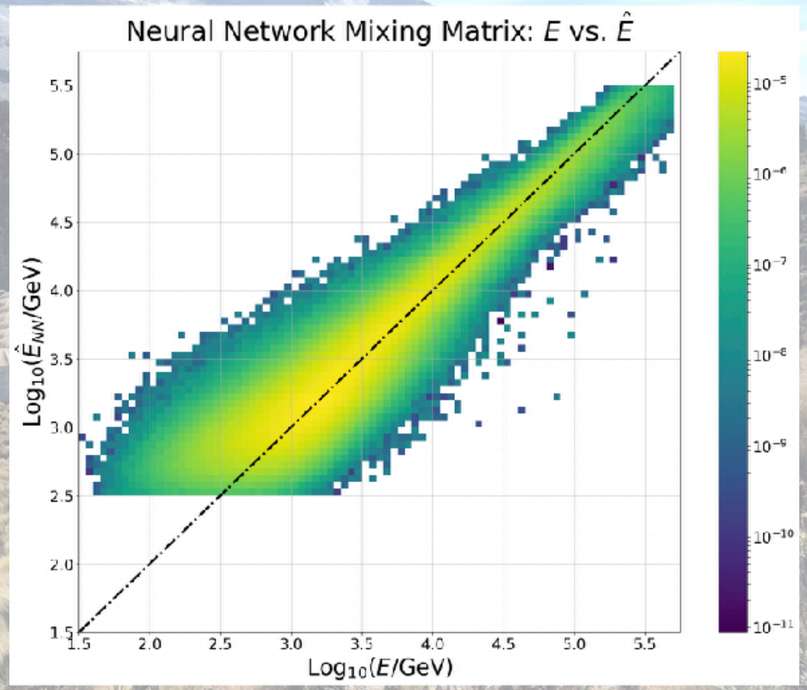
PMT Hit Occupancy
"f_{hit}"
2HWC Catalog Method



Q40

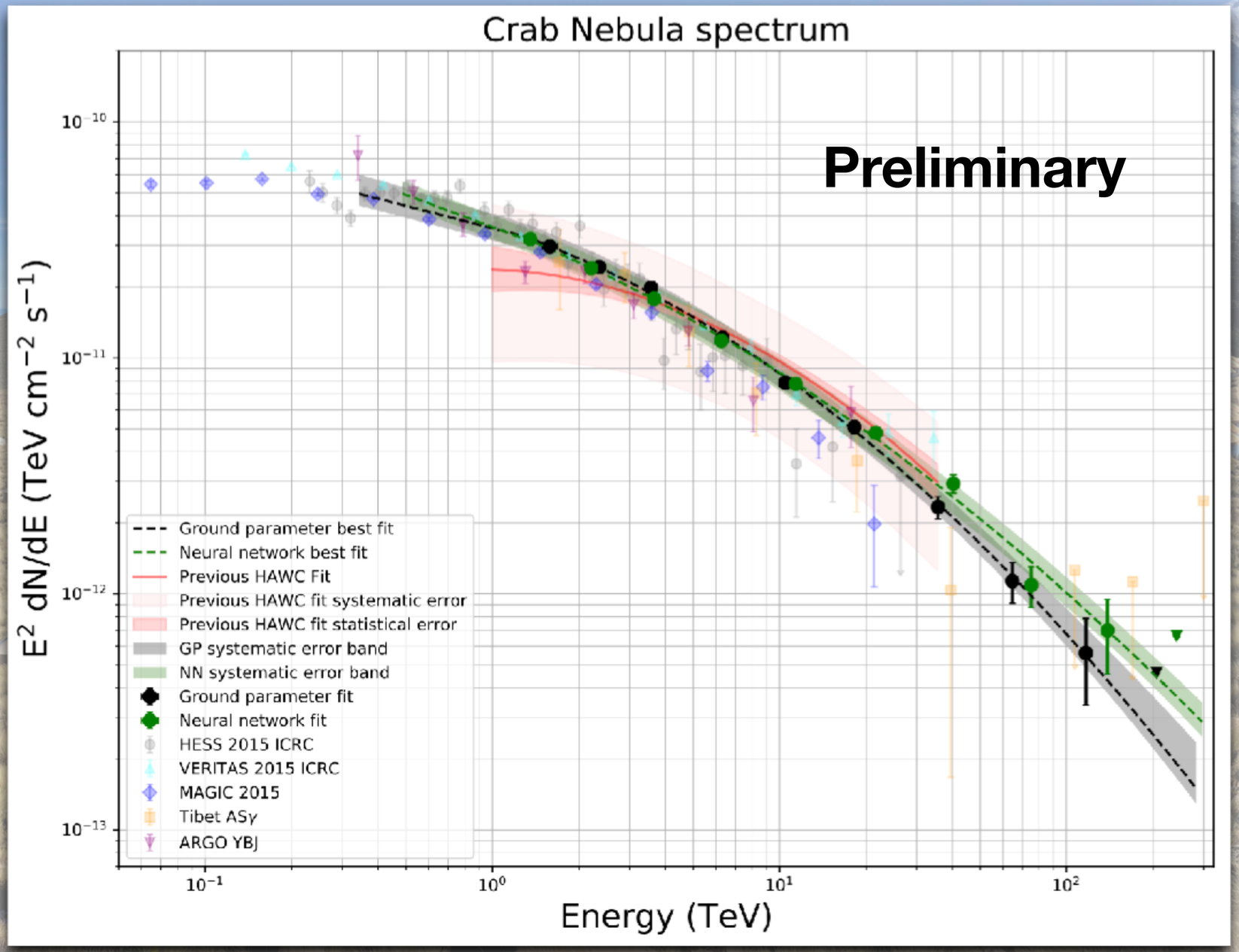


ANN



- **Q40/ANN better correlated with MC truth than previously used variable (fraction of PMT hits)**
- **Q40/ANN provide a way to determine energies beyond 10 TeV with considerably better precision (~20%, approaching 10% at highest energies)**

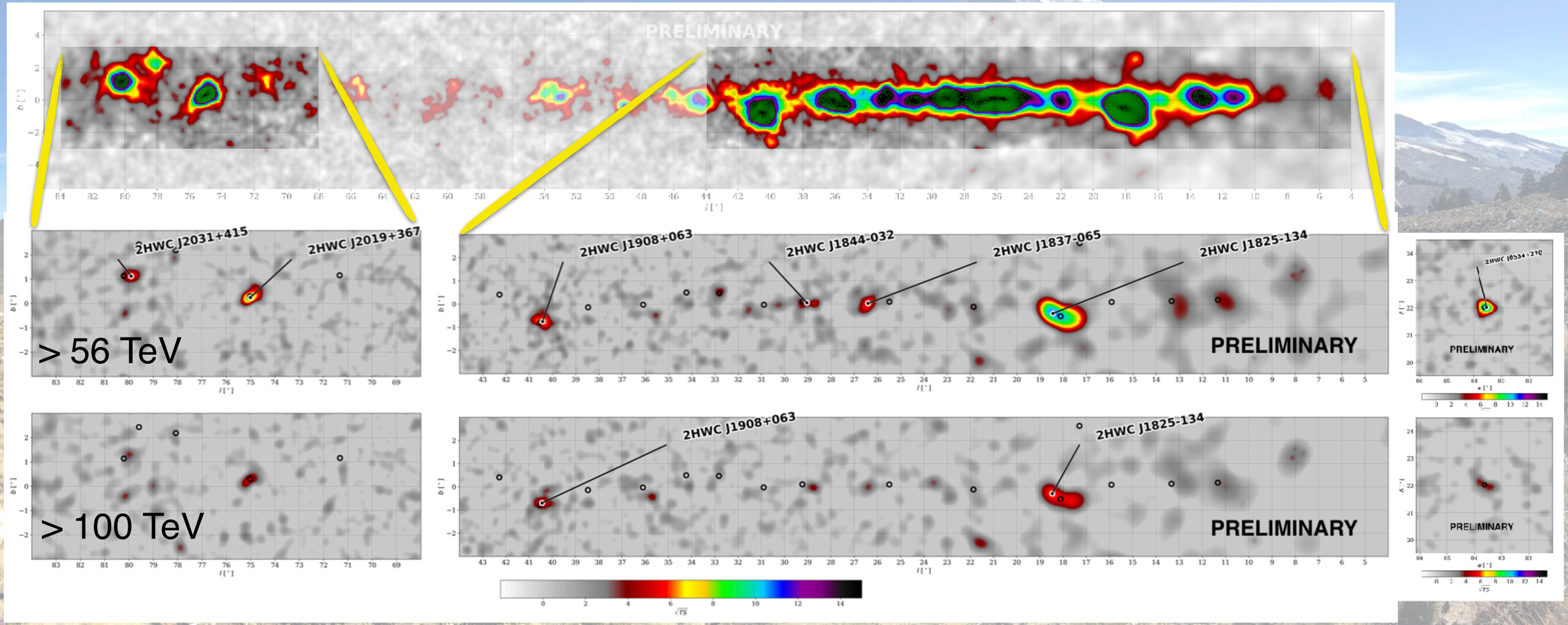
The Crab Nebula Spectrum



- 837 days
- Good agreement with other experiments in overlap region
- Approaching energy resolution of IACTs in overlap region

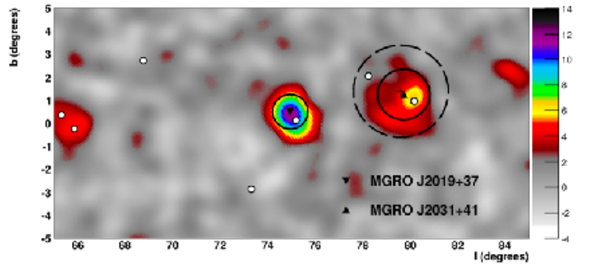
Highest Energy Gamma-Rays

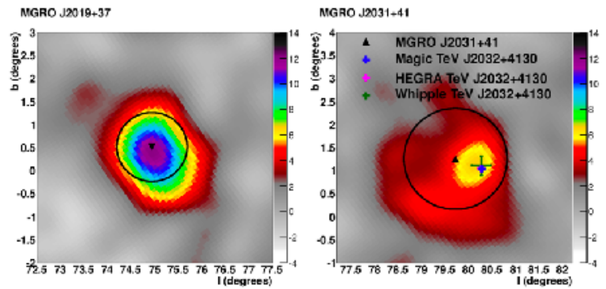
7 candidate sources, energy > 56 TeV

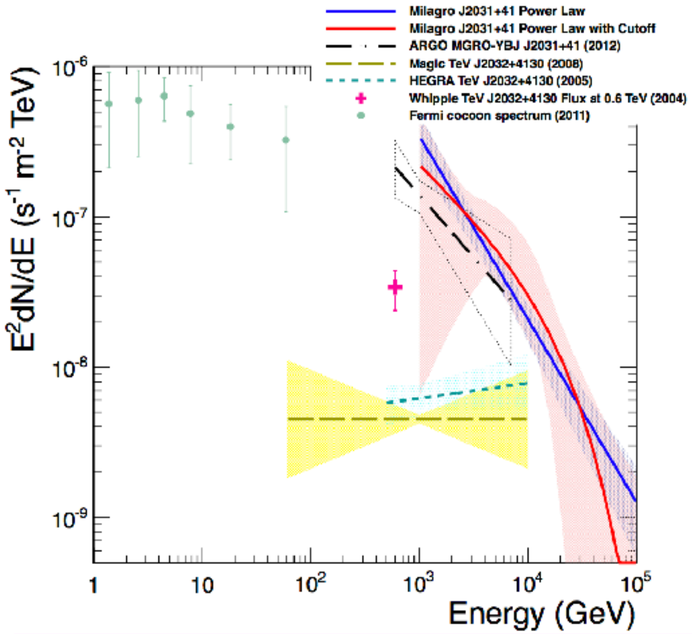


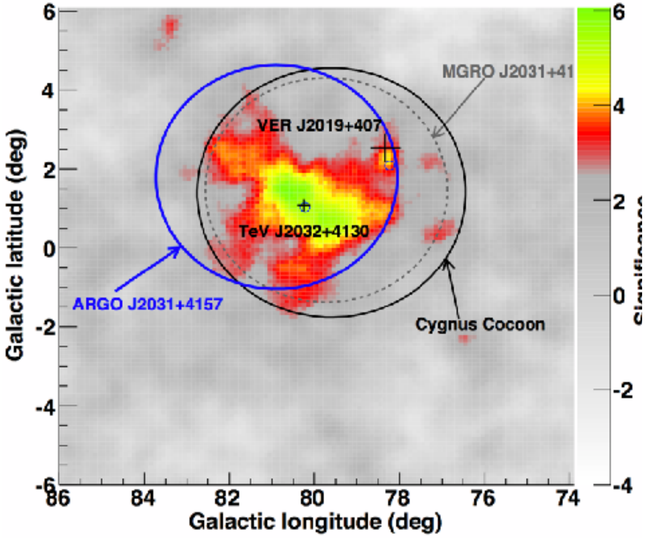
- **Acceleration mechanisms: hadronic or leptonic?**
- **Correlation with neutrinos?**
- **Prospects for testing Lorentz Invariance Violation.**

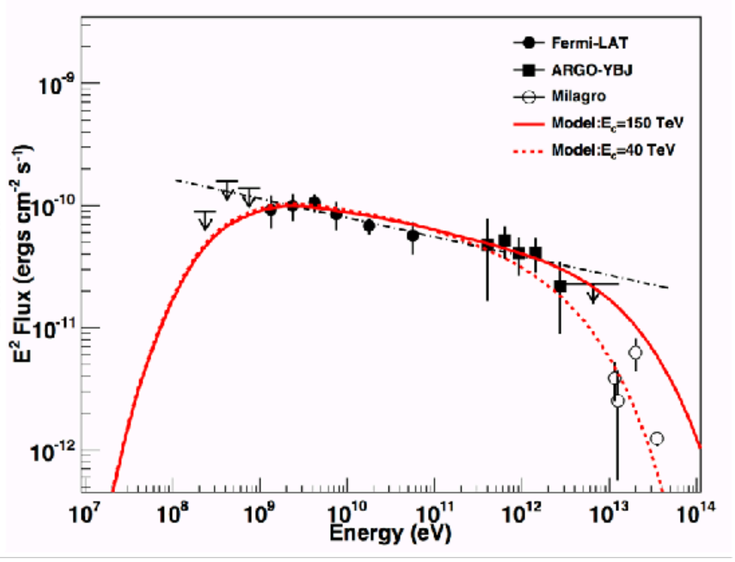
Multisource Fitting: Hunting for CR Acceleration in SFRs











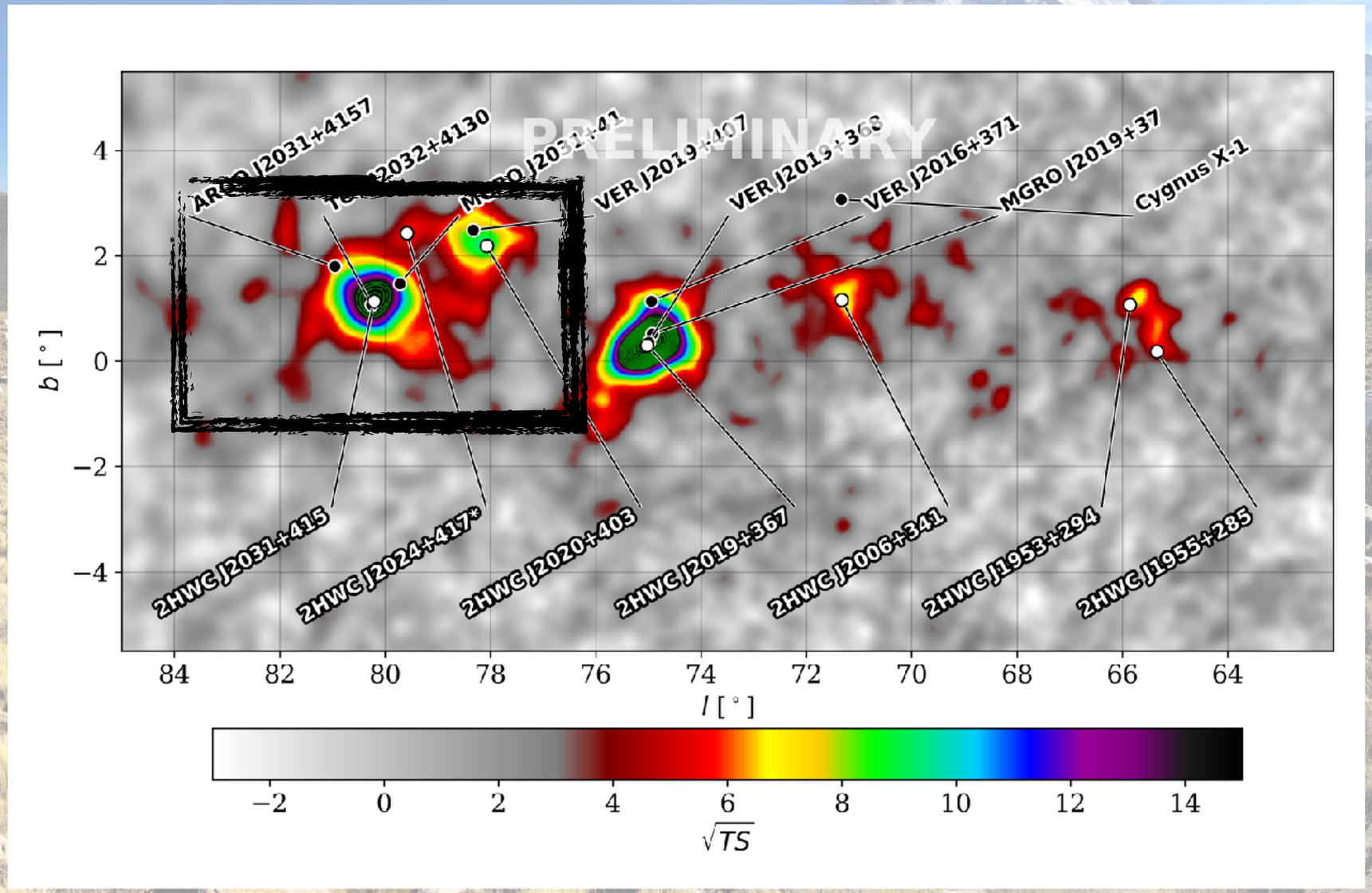
Milagro

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

Argo-YBJ

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

Multisource Fitting: Hunting for CR Acceleration in SFRs

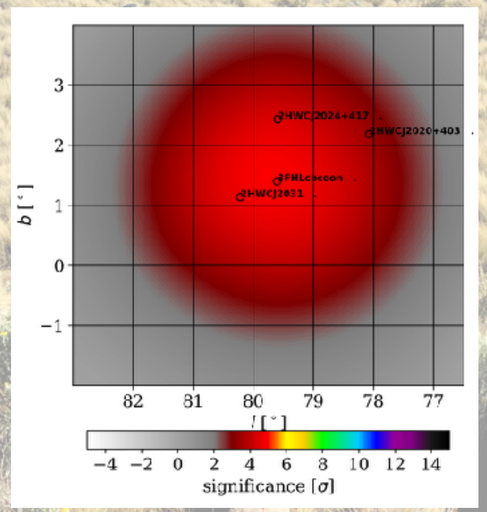


Model Building Blocks

- *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

- 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).

- 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.



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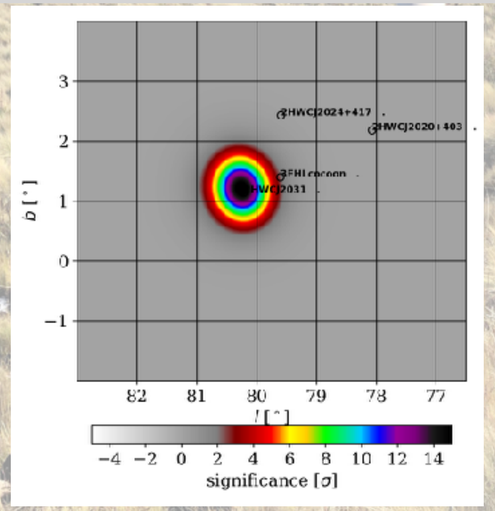

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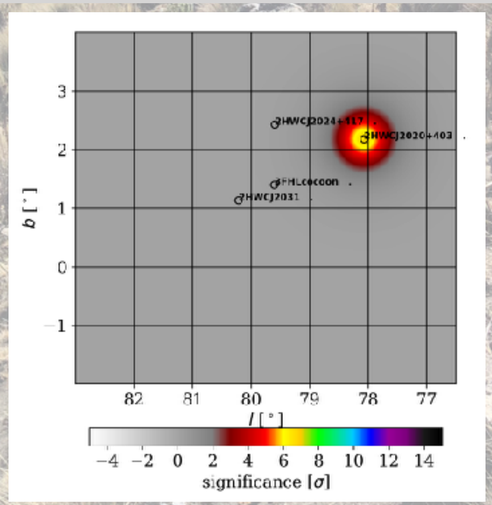
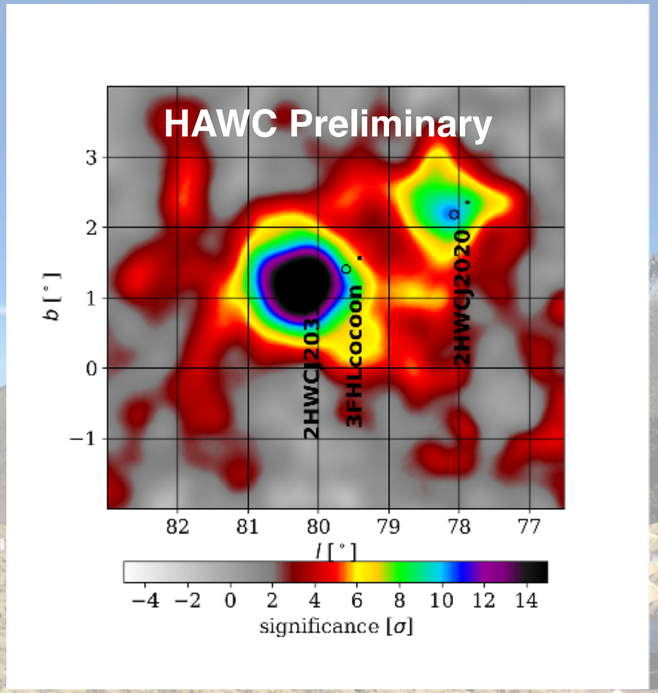
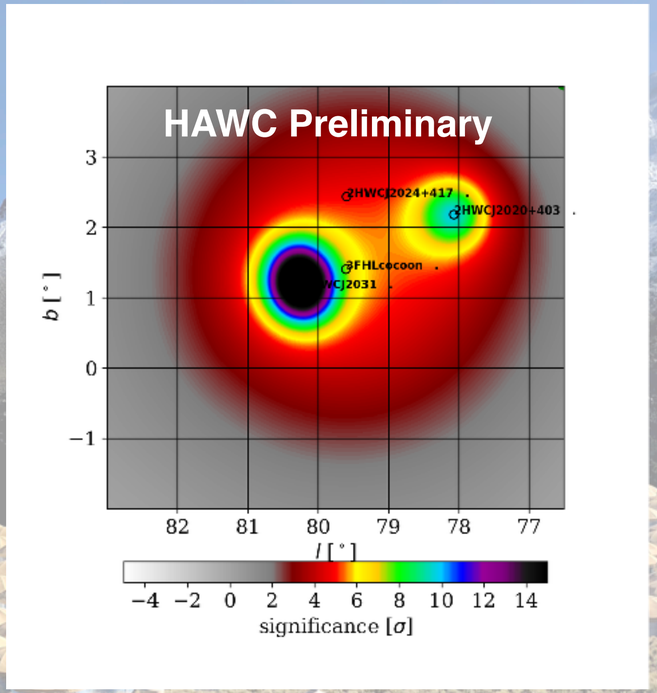
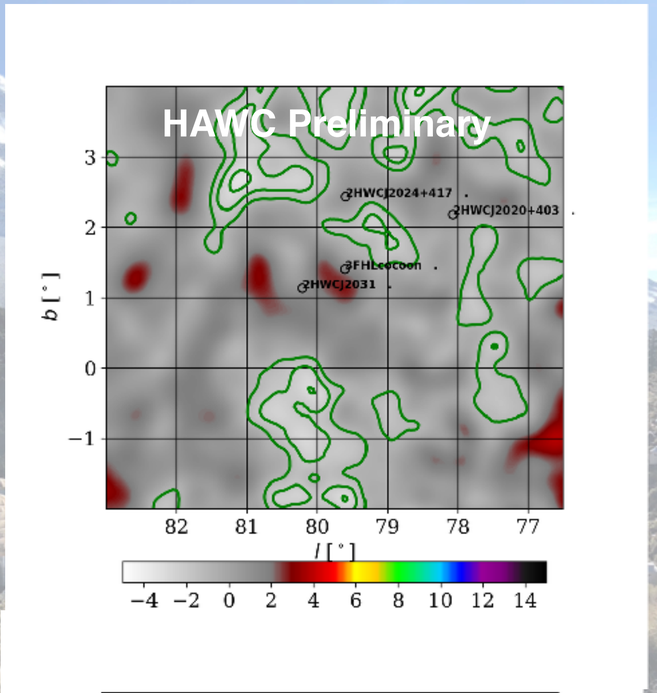


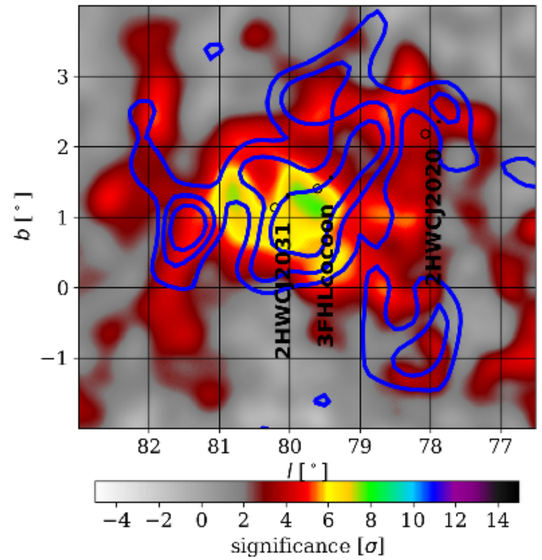
Combined Model & Residuals



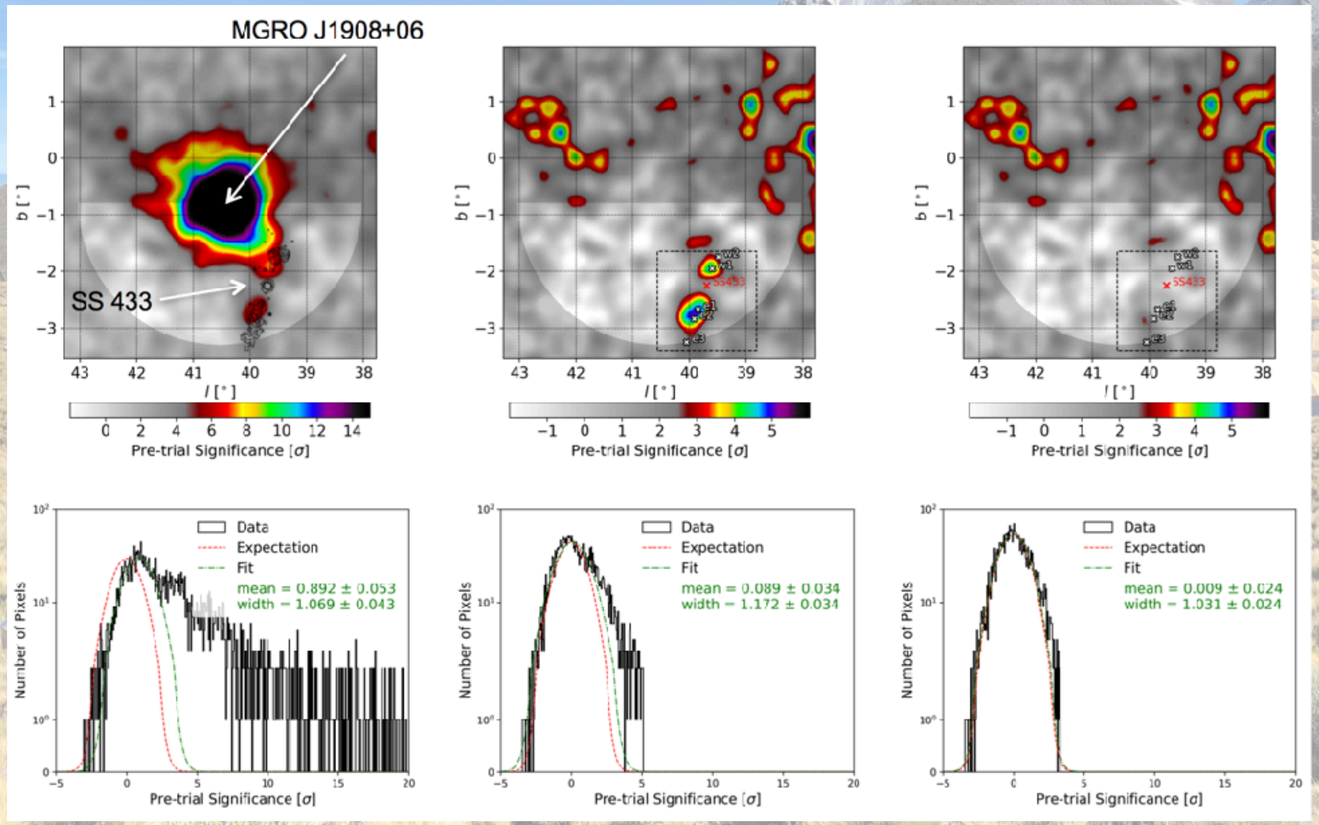


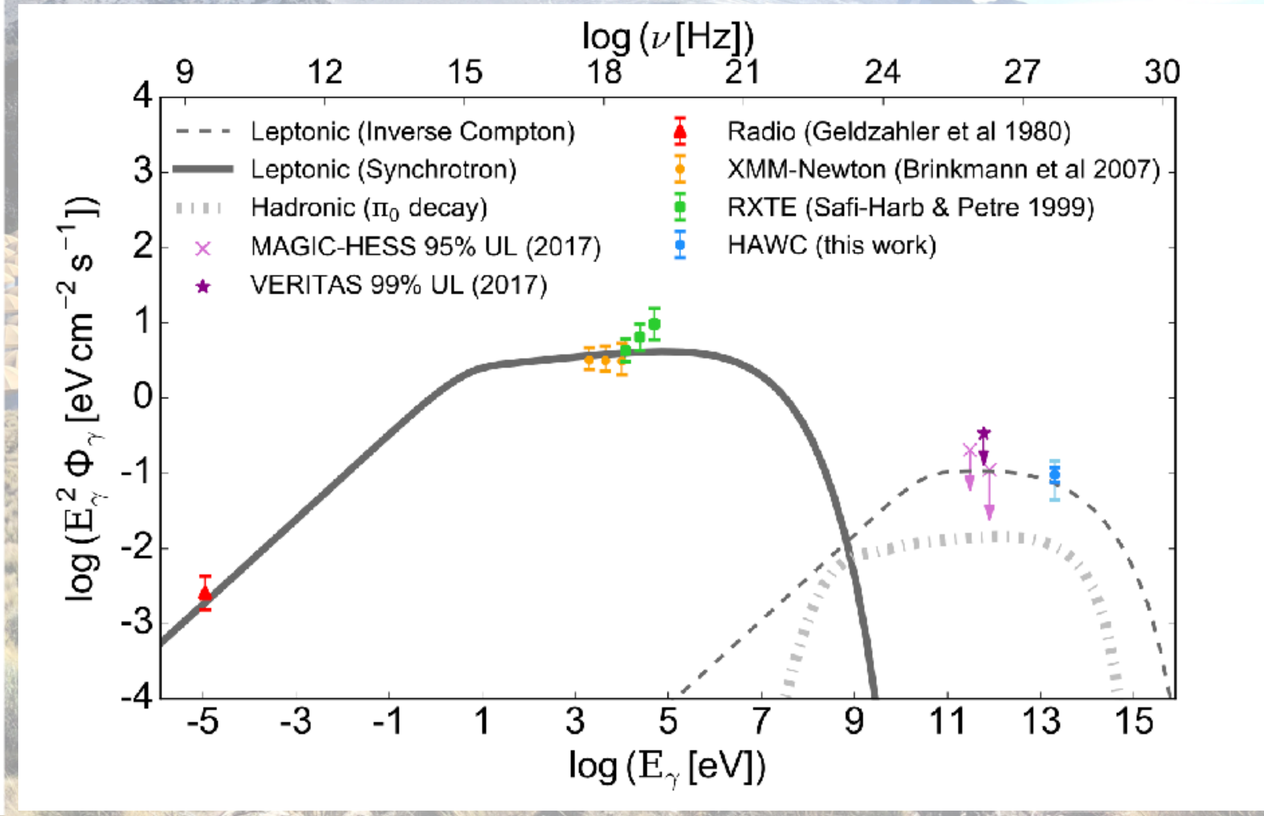


- PWN & Gamma-Cygni subtracted
- Blue Contours are Fermi-LAT
- Energy spectrum is forthcoming,
- Challenge: identification of the VHE energy emission, from PWN or from Cocoon

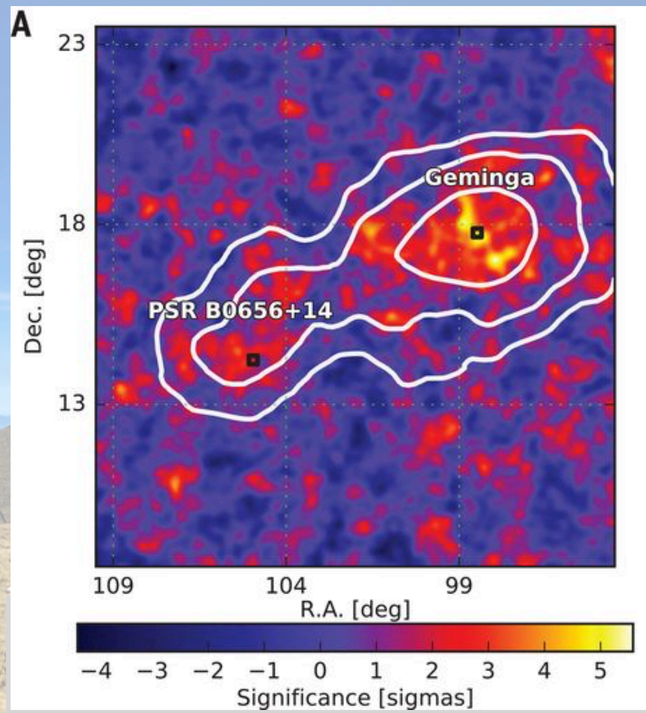


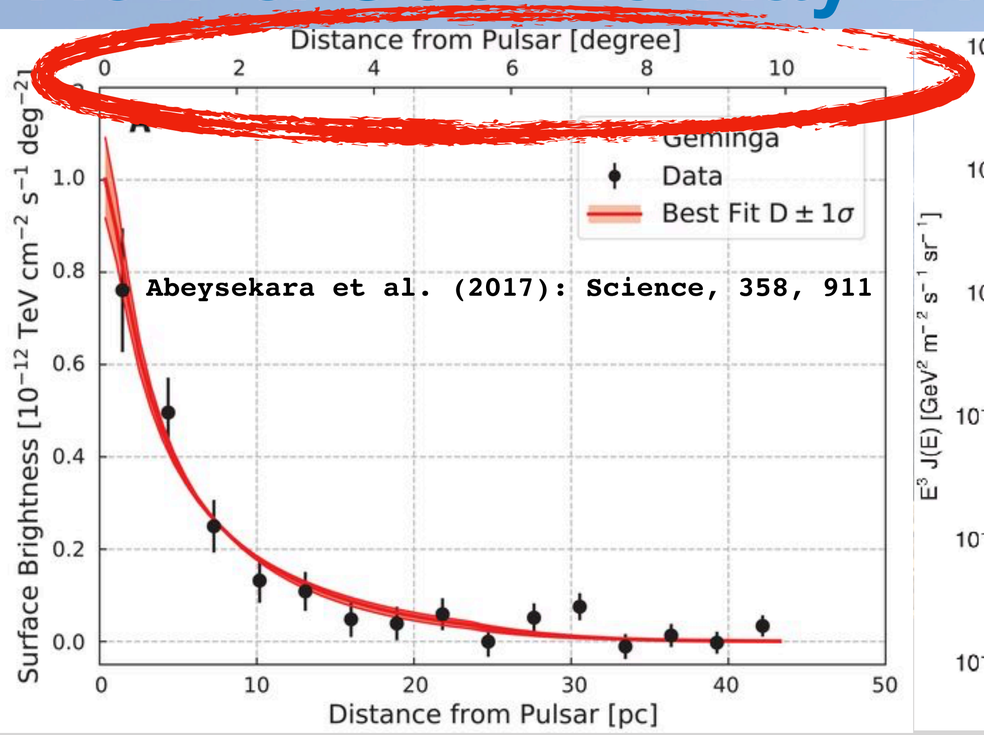
Multisource Fit Approach Also Used in Analysis of Micro Quasar SS43

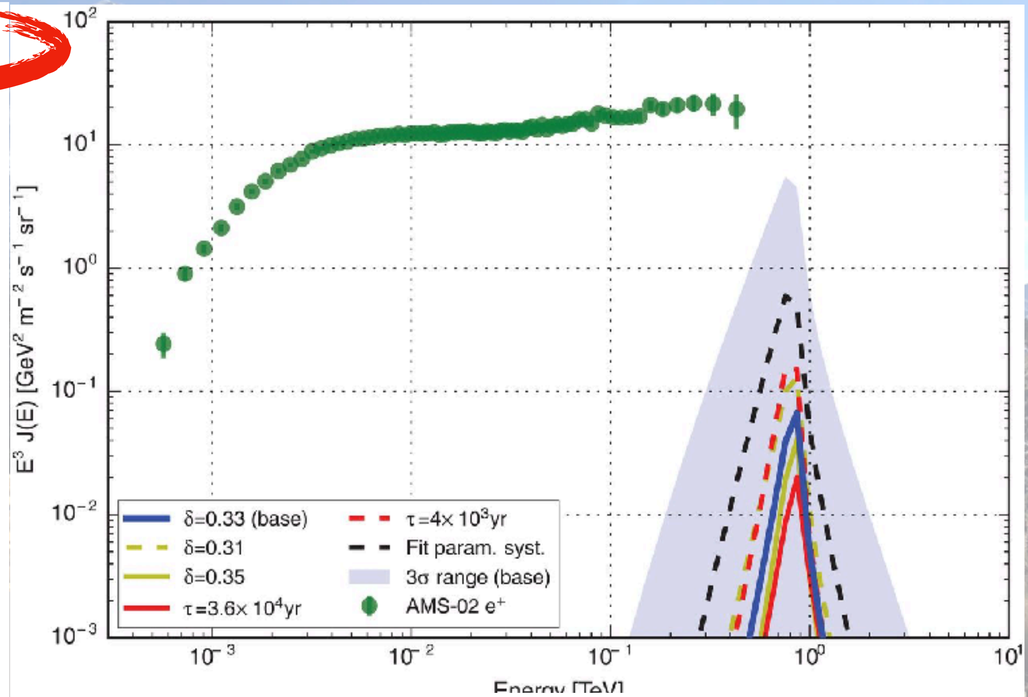




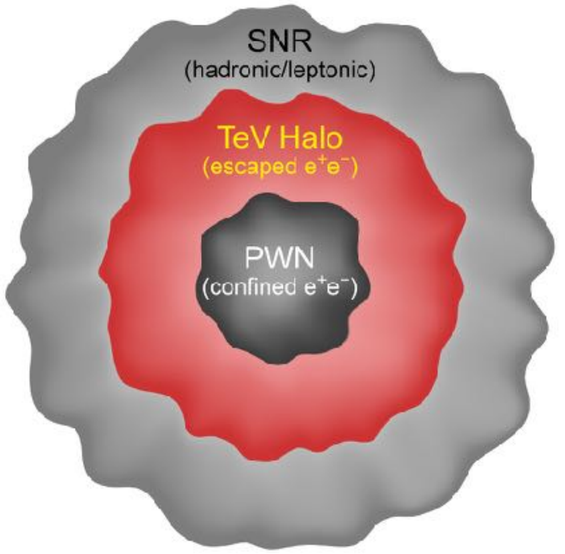
Large Field of View & Cosmic Ray Diffusion and Transport





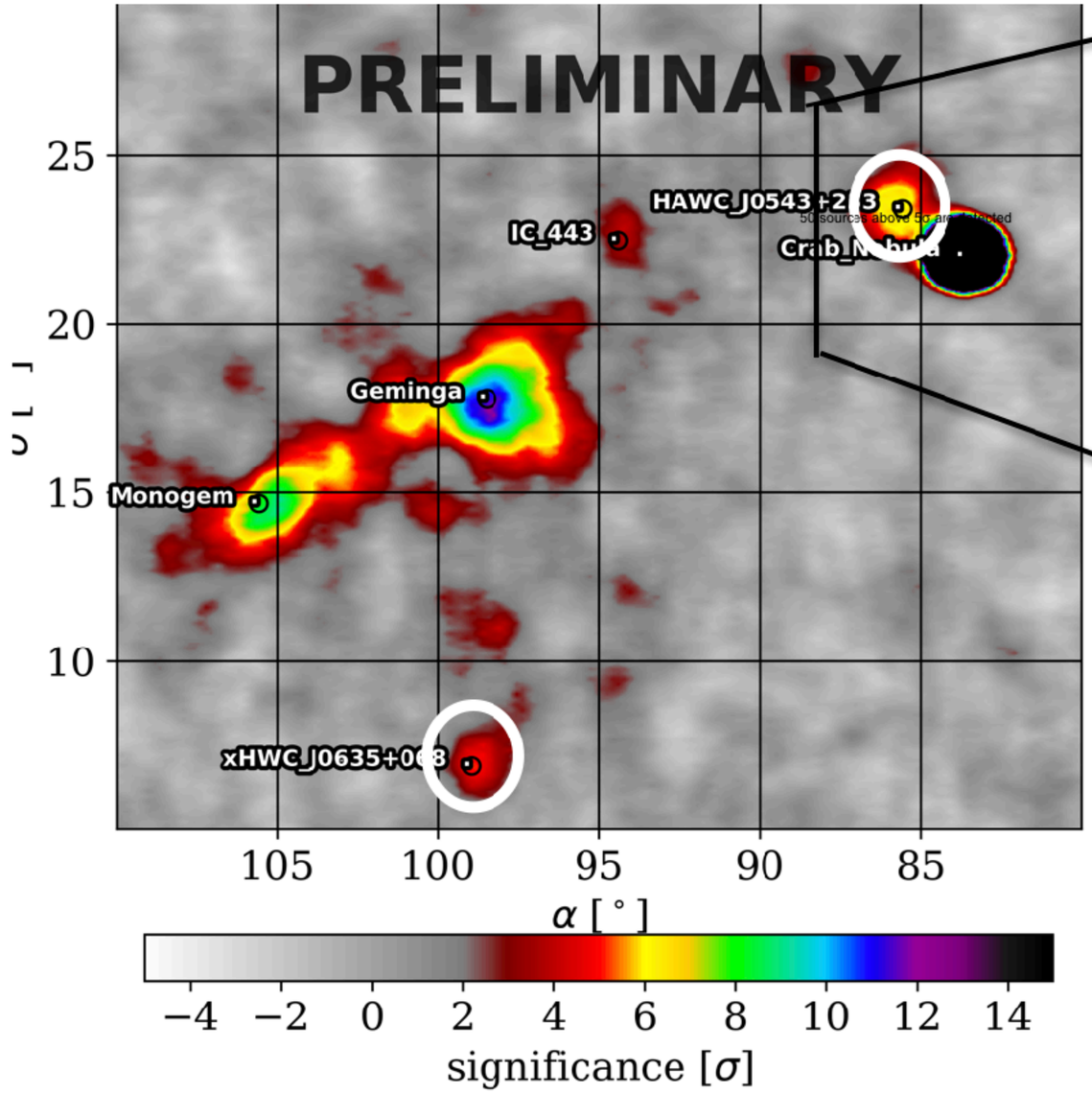


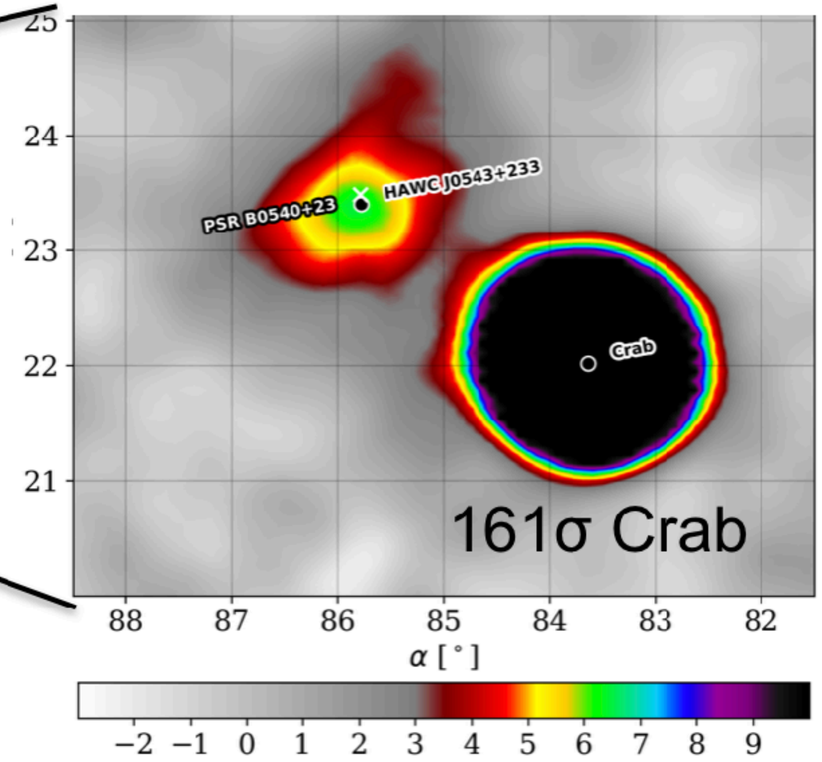
- Extended (tens of pc) gamma-ray emission regions.
- Also seen at GeV energies.
- TeV electrons escaping PWN, diffusing in surrounding medium.
- Electron diffusion suppressed.
- Unique objects or ‘Age of the TeV Halo’? (Linden et al. (2017): Phys. Rev. D



Discovery Potential: Hiding in Plane Sight

HAWC J0543+233: http://www.astronomerstelegram.org/?read=10941
HAWC J0635+070: http://www.astronomerstelegram.org/?read=12013

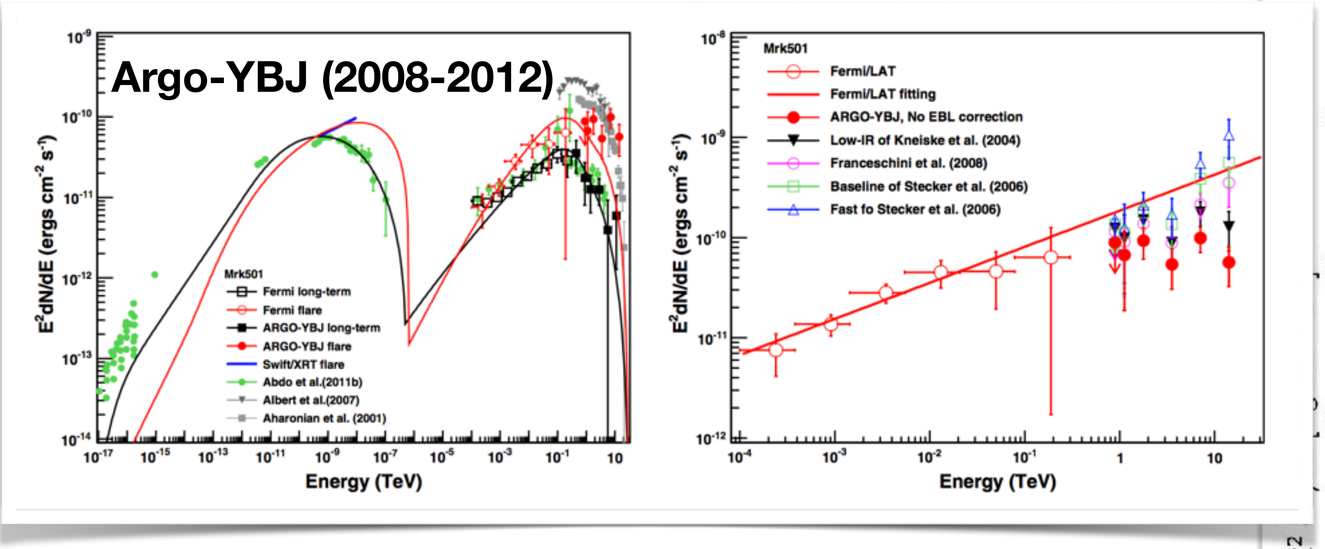


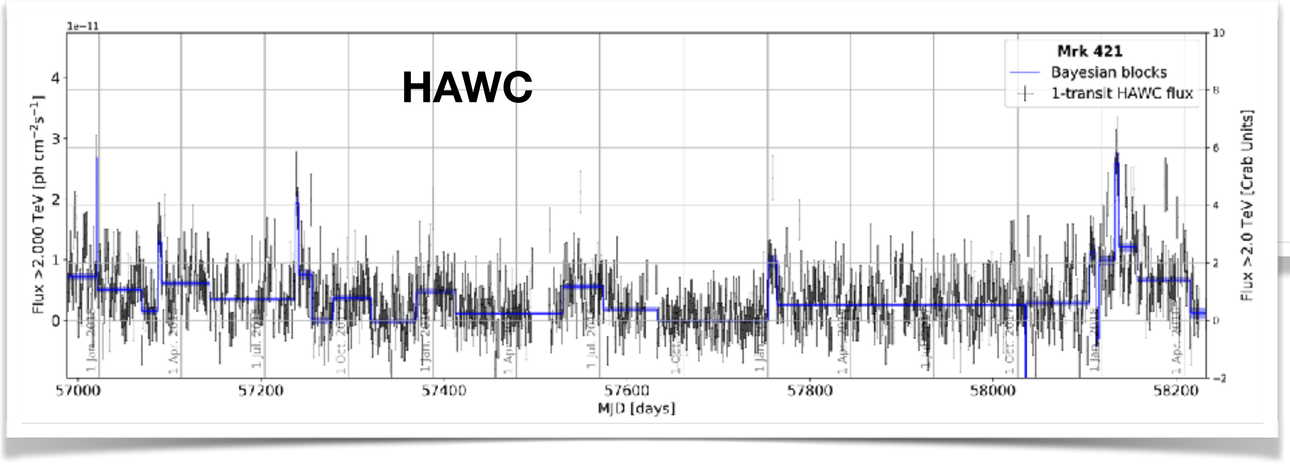


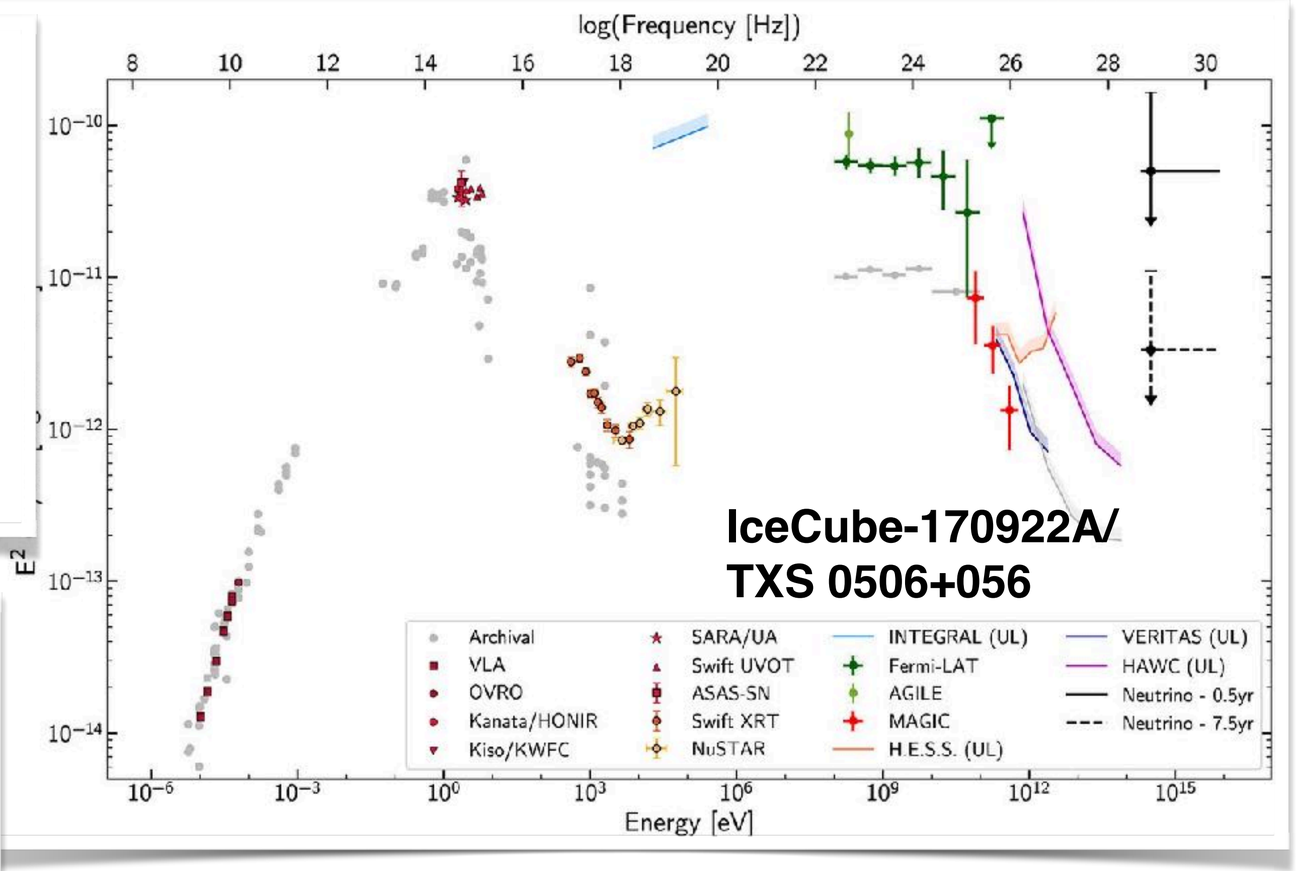
Another middle age PWN
similar to Geminga and B0656+14
$\dot{E} = 4.1 \times 10^{34}$ erg s−1,
d = 1.56 kpc, τ = 253 kyr

Can test if all are Geminga-like

Transient & Multimessenger Monitoring/Follow-Ups







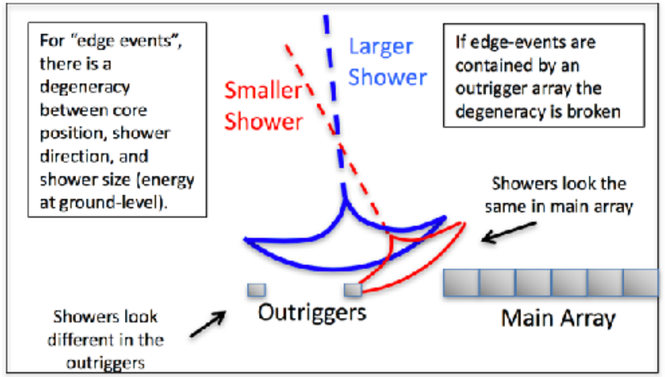
Alerts & Archival Searches

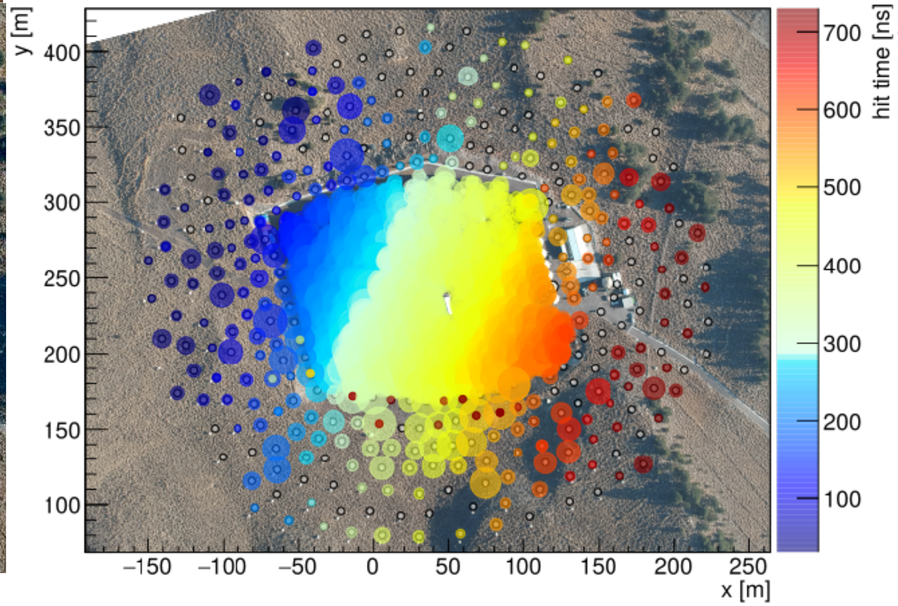
… And Many More Science Results, e.g. DM & LIV limits, CR Anisotropy & Spectrum etc.

Detector Upgrades & Further Analysis Improvements

4x sensitivity above 50 TeV:

- **Better shower core fit**
- **Shower containment (better energy resolution)**



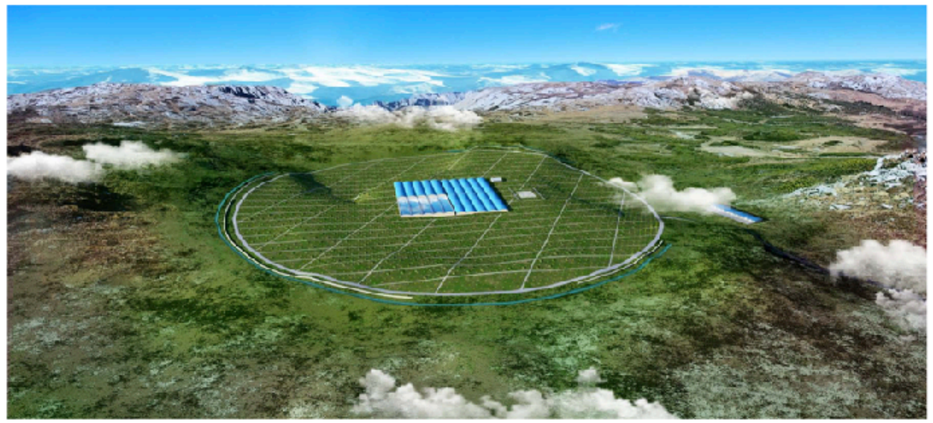


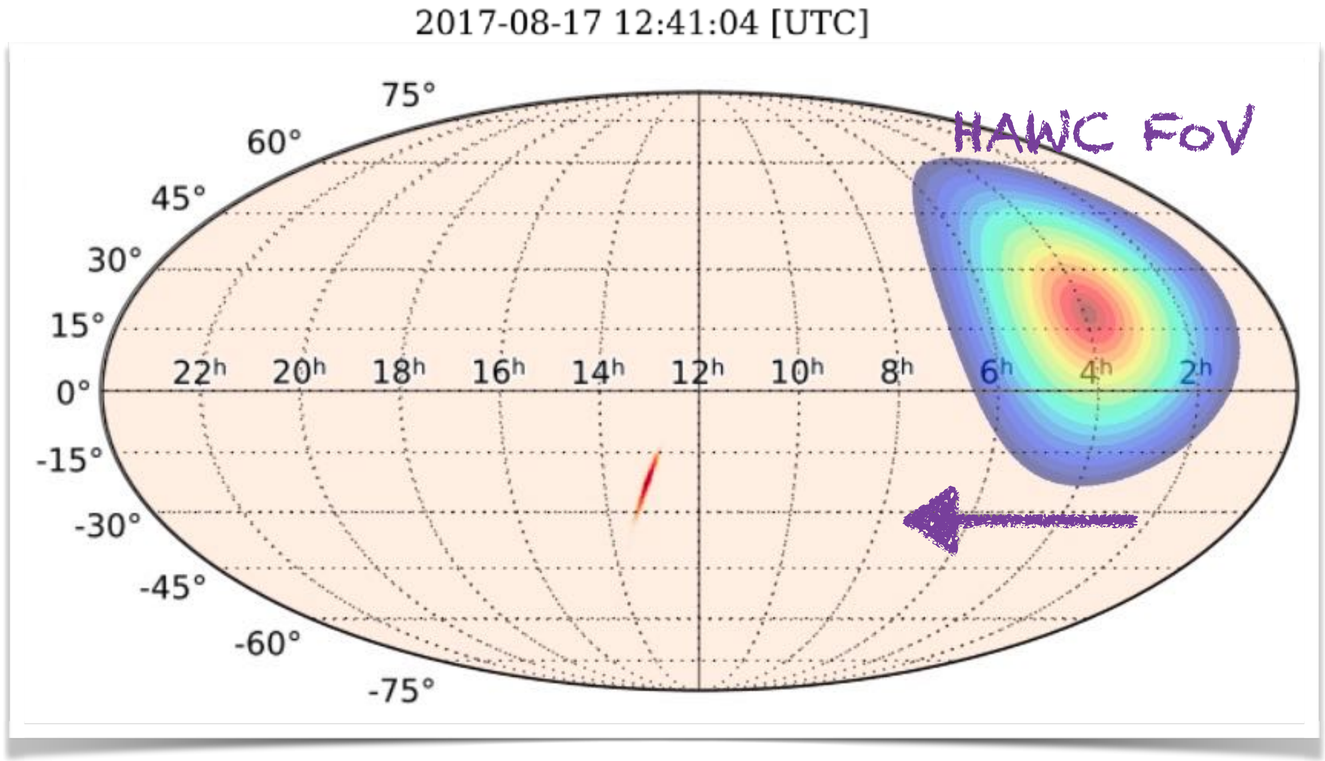
- **Current low-energy (small event) angle reconstruction is limited by noise.**
- **The "noise" in HAWC is almost entirely due to small non-triggering showers.**
- **New "Multi-Plane Fitter" identifies and isolates sub-showers within each event instead of assuming all hits are from a single shower.**

Begin of LHAASO Science Operation 04/2019

Complementarity of LHAASO & HAWC

Sichuan province
4400 m a.s.l.

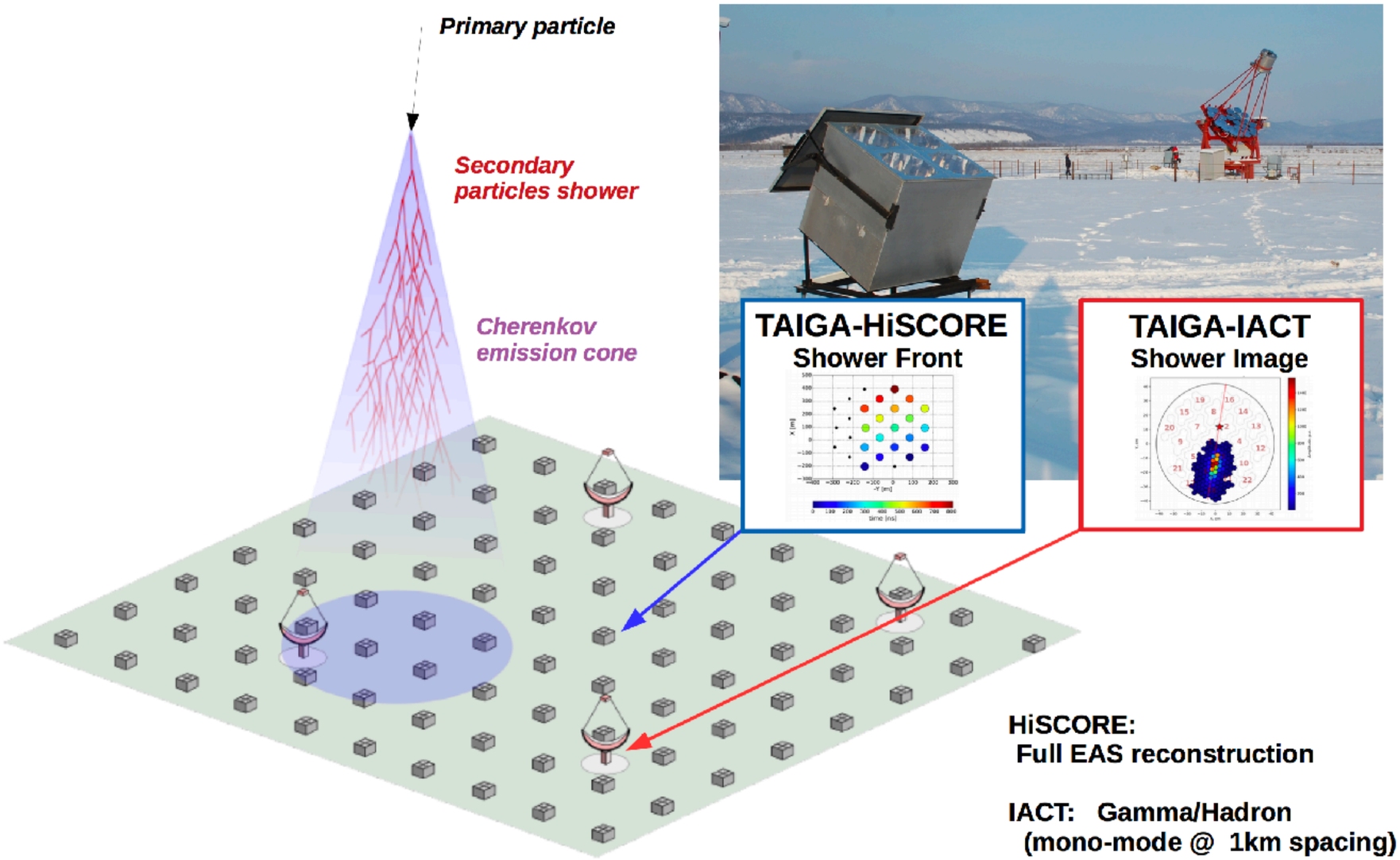




- **HAWC and LHAASO are at about the same latitude (28°N) but opposite sides of the globe. Together they minimize the survey gap of the Northern hemisphere!**
- **LHAASO is expected to reach HAWC sensitivity in about 5 years**

Other Ongoing Large-Field-of-View-Projects

The TAIGA Hybrid Detector: Imaging and Non-Imaging Techniques



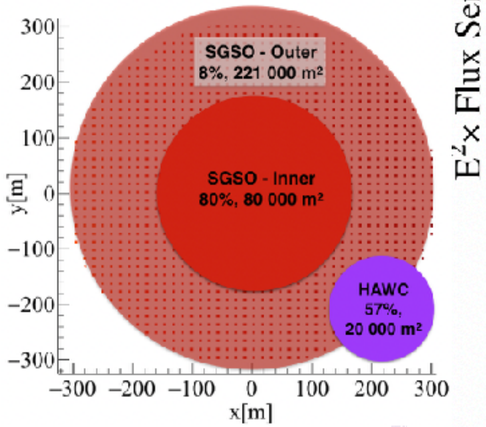
HiSCORE:
Full EAS reconstruction

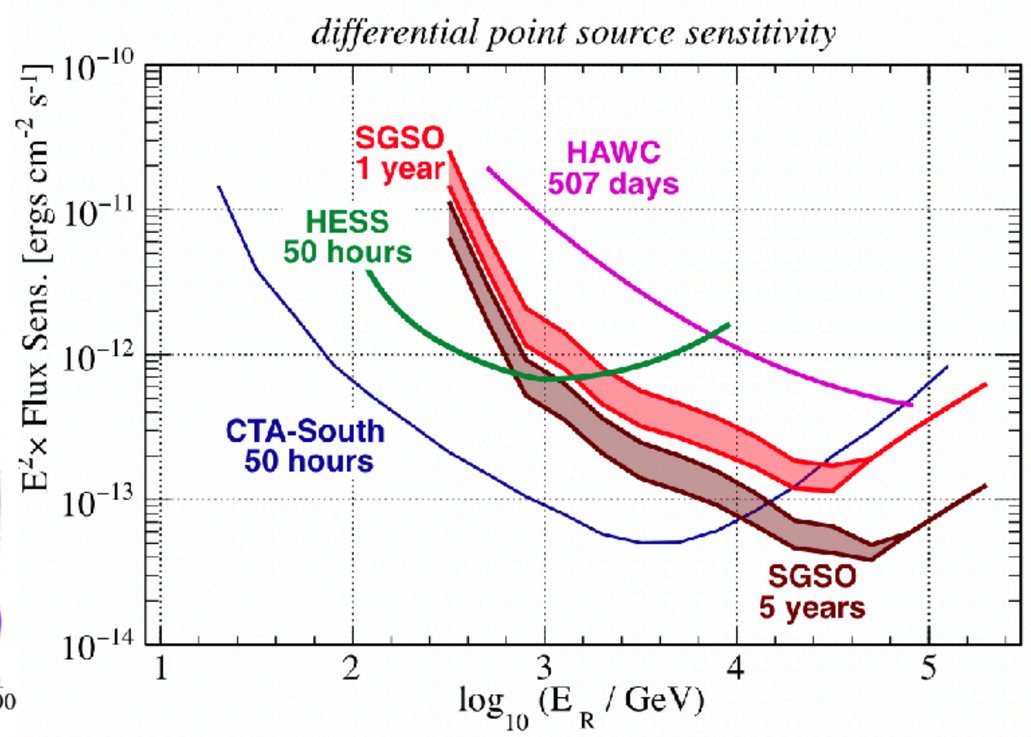
IACT: Gamma/Hadron
(mono-mode @ 1km spacing)

The Large-Field-of-View Future: SGSO

Design goals:

- Roughly on order of magnitude higher sensitivity than current generation
- Lower energy threshold





Synergy of TeV instruments with pointing (CTA) and survey (LHAASO, SGSO) capabilities; MW/MM follow-up and correlations.

The Large-Field-of-View Future: SGSO

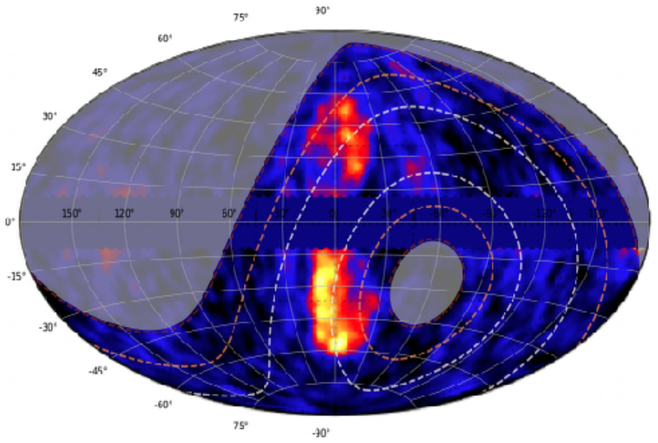
Physics goals:

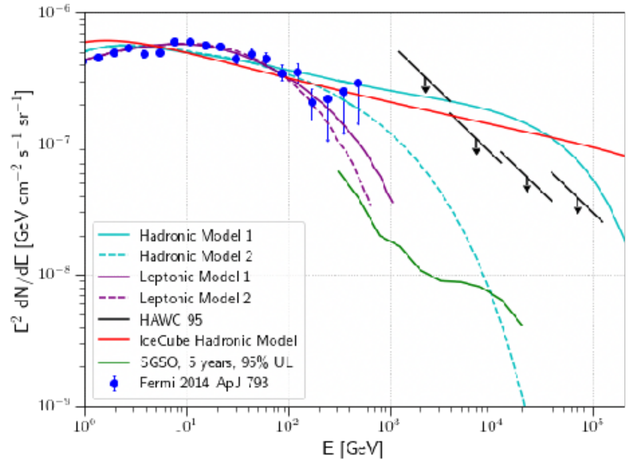
- Galactic accelerators (PeVatrons, TeV Halos)
- Transients (GRBs, blazars, …)
- Large-scale diffuse emission
- BSM searches

…

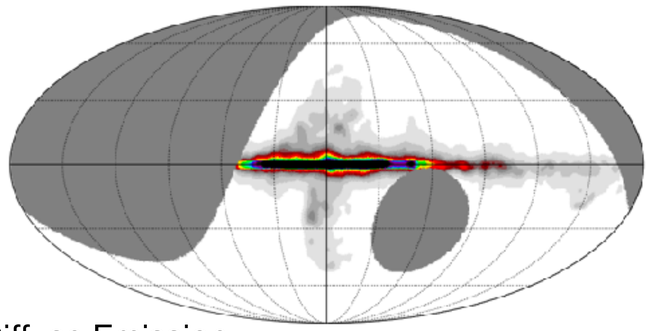
Synergy of TeV instruments with pointing (CTA) and survey (LHAASO, SGSO) capabilities:

eg. TeV source finder for CTA South, MW/MM follow-up and correlations.

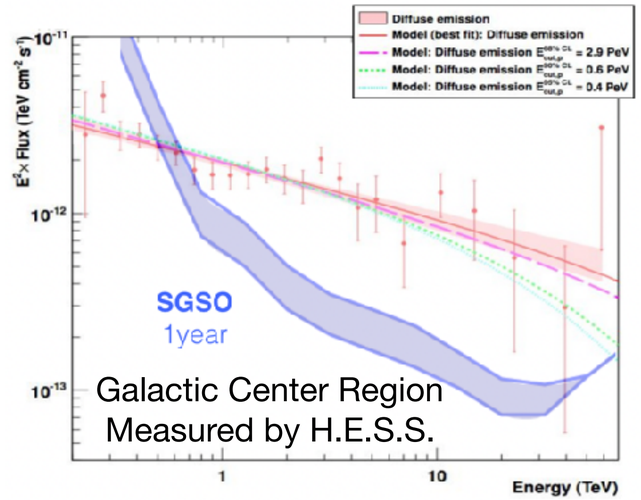




Fermi Bubbles



Diffuse Emission



Galactic Center Region
Measured by H.E.S.S.

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.

tradi- f these party. d with- hem a whose lately, t these f envi- ergetic … ls upon ions of gases,

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)*.

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-

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-

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