Gamma Ray Astronomy with Ground Based EAS Arrays for 30 Years

Zhen Cao

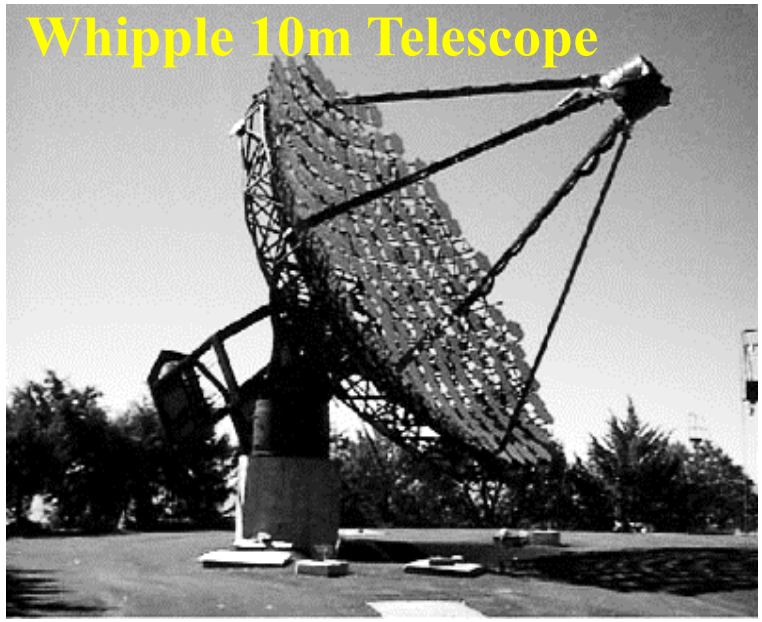
IHEP, China

Anniversary of MAGIC Operation for 15 years,
La Palma, June, 2018

Content

- EAS Arrays in 1989, when Crab Nebula was discovered
- 1st Generation Experiments and their Achievements
  - MILAGRO and ARGO-YBJ
- 2nd Generation Experiments
  - HAWC and ASγ +MDs
- 3rd Generation: LHAASO

TeV Gamma Ray Astronomy



- 1989, 1st TeV gamma ray source: Crab Nebula
- On the ground:

  All arrays were under construction

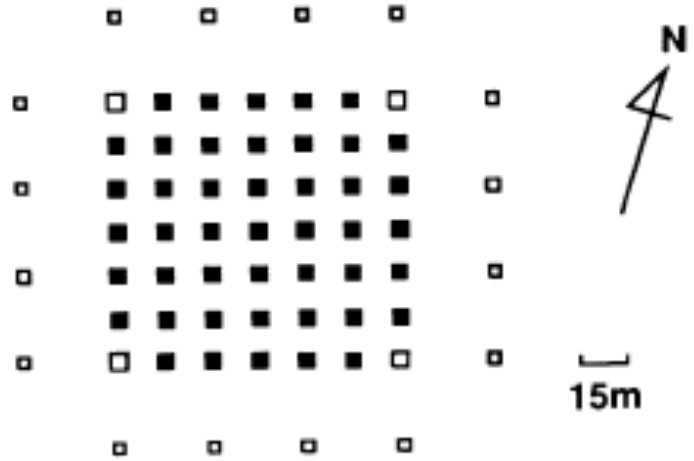
  – CASA-MIA ¼ km^2 @ 1500 m a.s.l. with muon-D's

  – Tibet ASγ 1% km^2 @ 4300 m a.s.l. without muon-D's

  – many similar scale experiments as ASγ

The Pioneers

- 3 years after the discovery, ASγ experiment



VOLUME 69, NUMBER 17 PHYSICAL REVIEW LETTERS 26 OCTOBER 1992

Search for Steady Emission of 10-TeV Gamma Rays from the Crab Nebula, Cygnus X-3, and Hercules X-1 Using the Tibet Air Shower Array

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(Tibet ASγ Collaboration)

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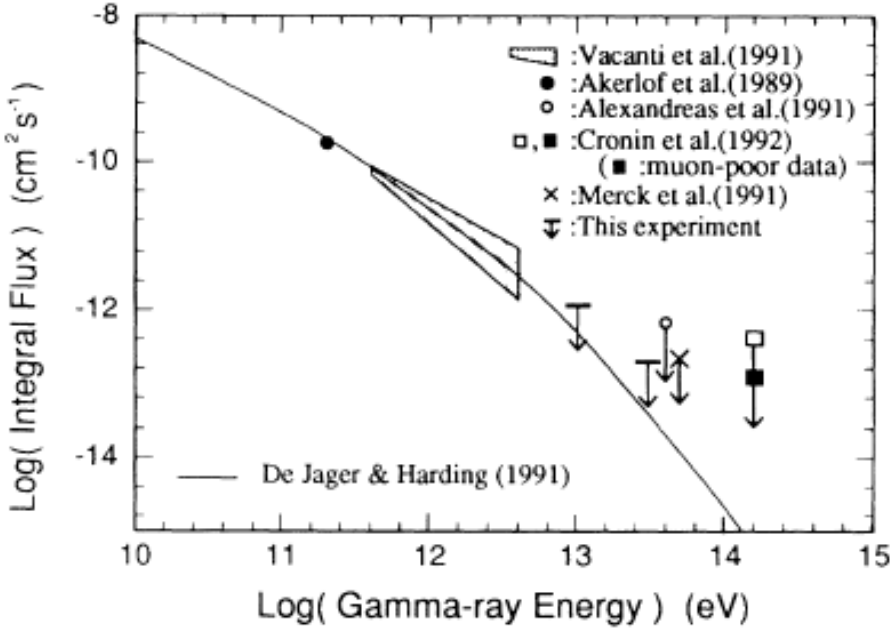


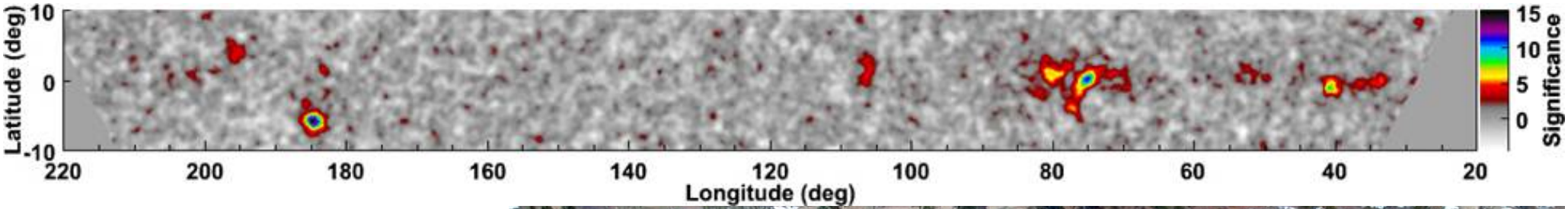
FIG. 4. A comparison of the experimental results for Crab fluxes and flux upper limits: Alexandreas *et al.* [13], Cronin *et*

- 1997, CASA-MIA terminated the operation

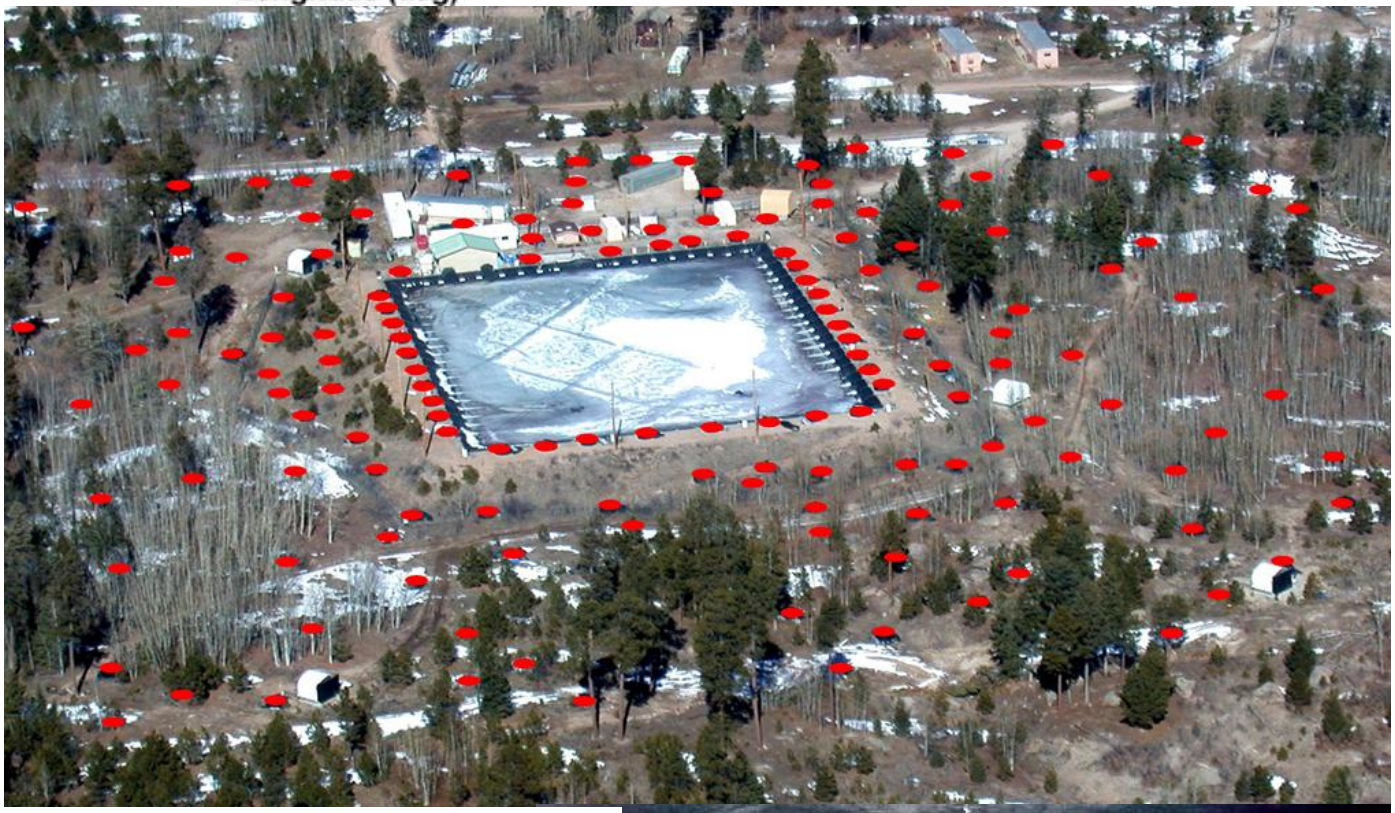
1st Generation

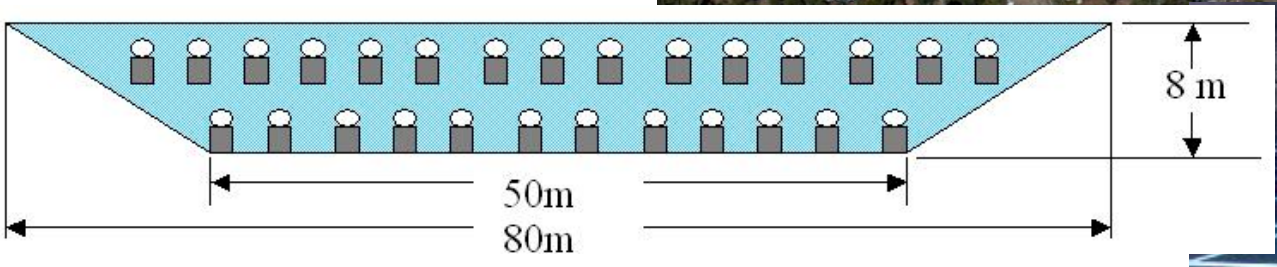
- 1999-2011, MILAGRO
- 2002, ASγ upgrading to Tibet-III
- 2006-2013, ARGO-YBJ

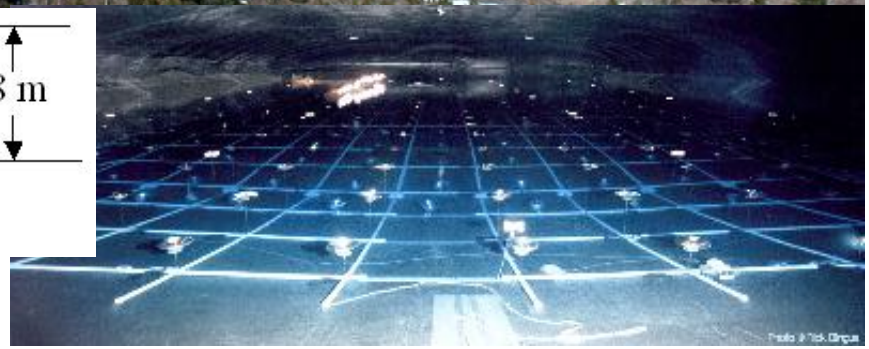
MILAGRO



2600 m a.s.l.
4800 m2
175 small tanks



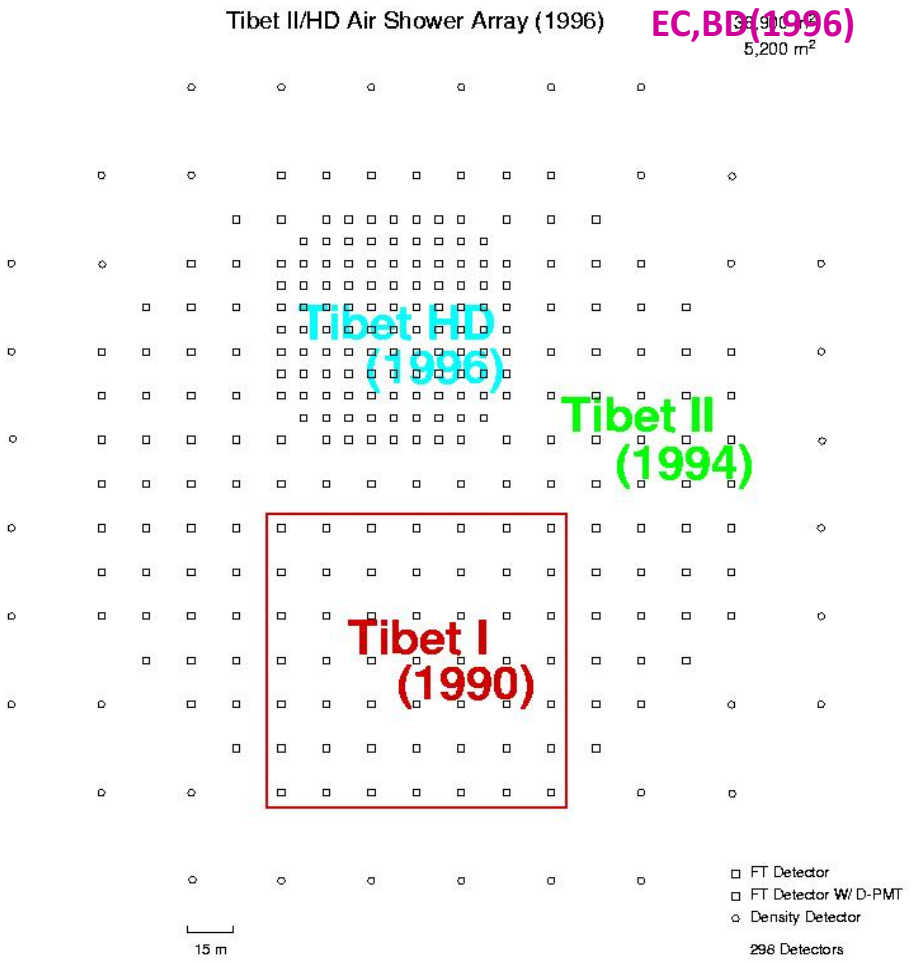




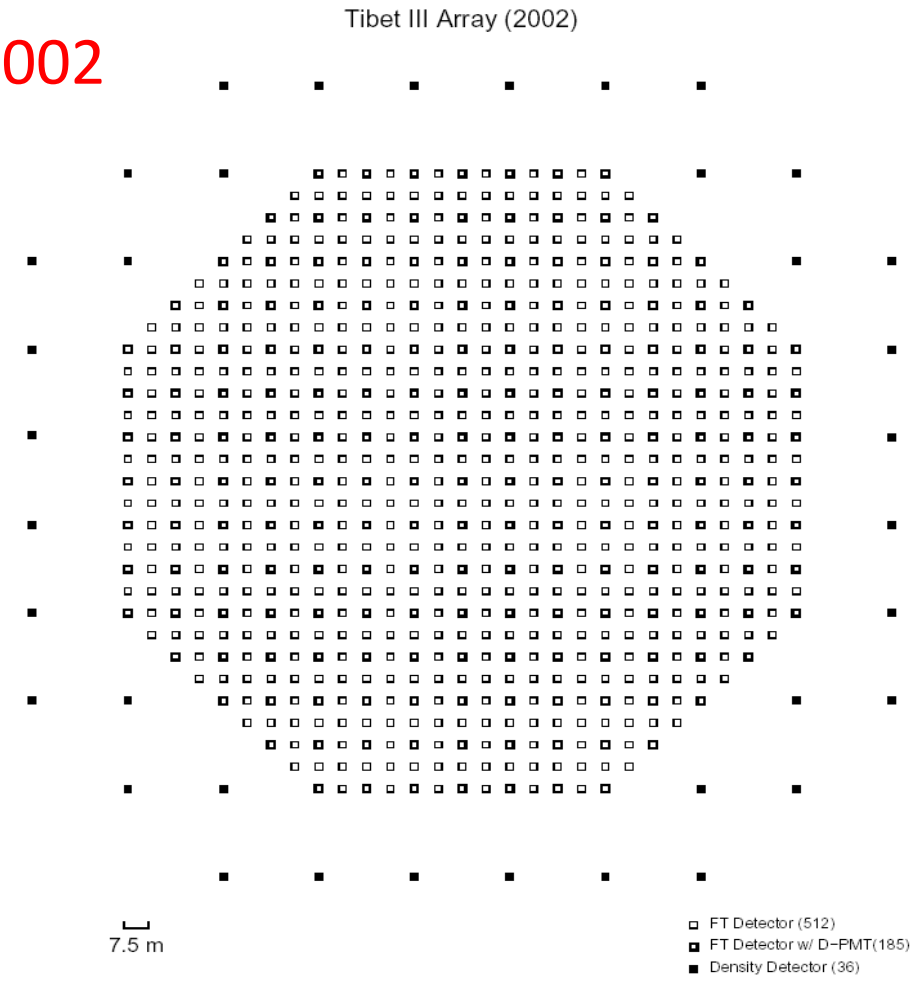
Brief history of the ASγexperiment

3TeV;115Hz;0.9 °

3TeV;1500Hz;0.9°



2002



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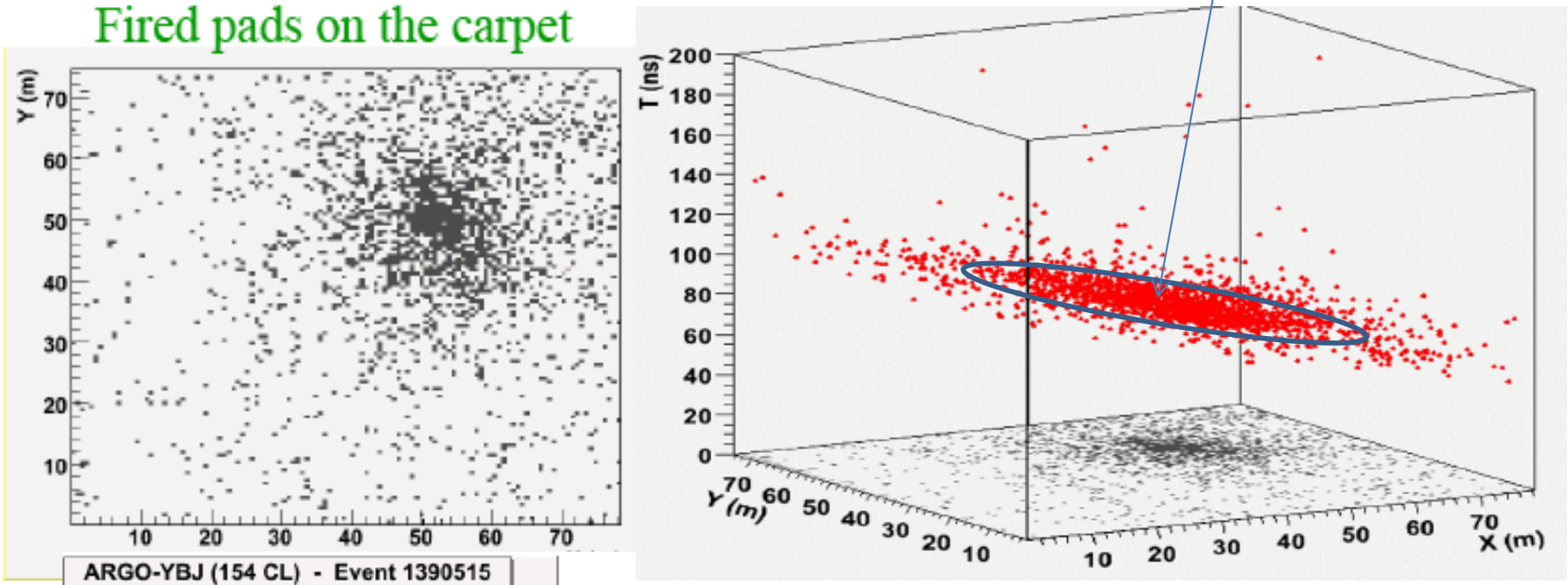
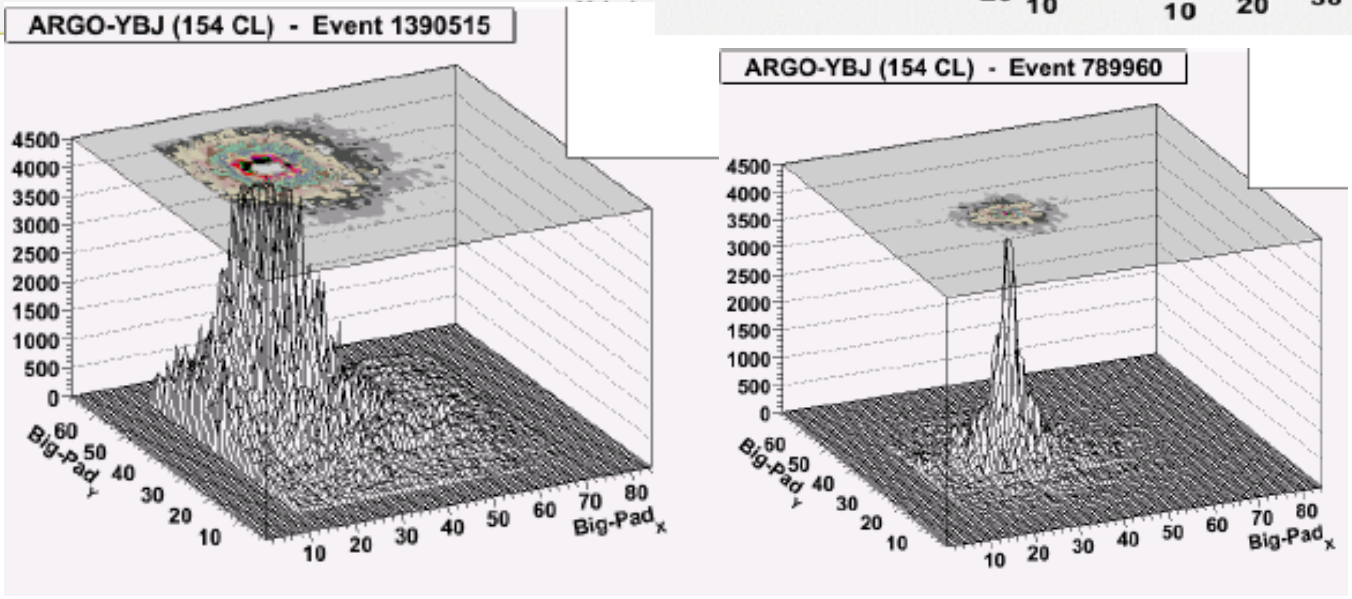
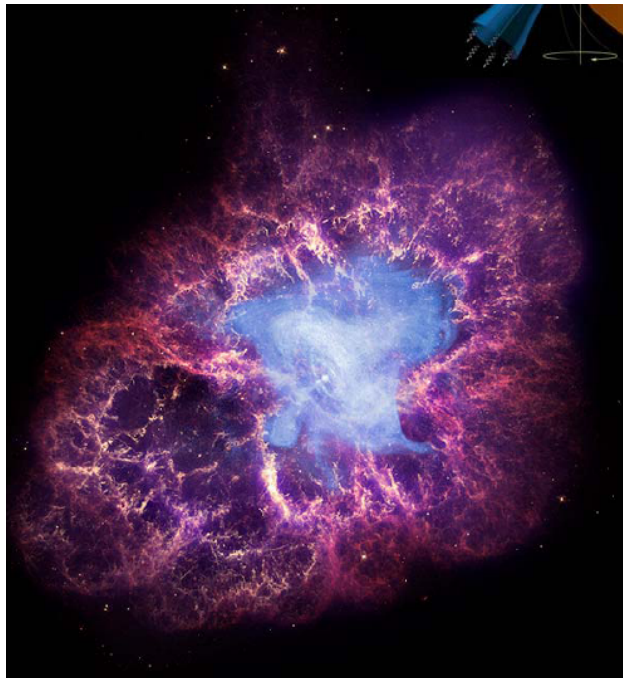
Shower Measurement and Reconstruction

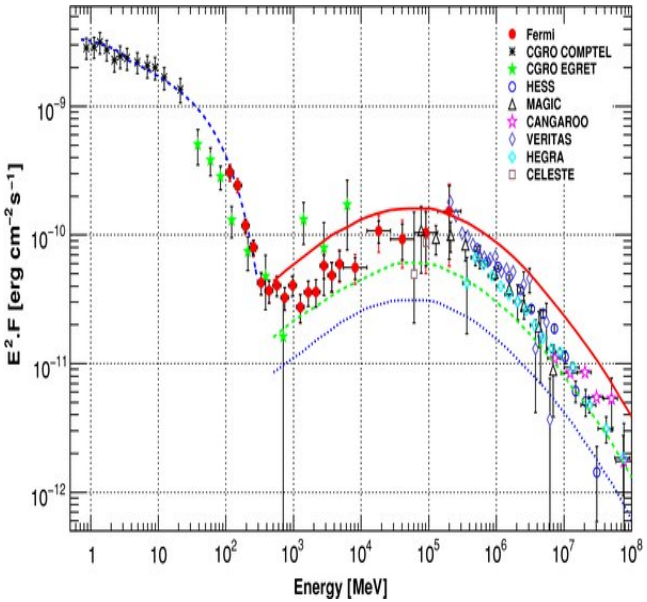


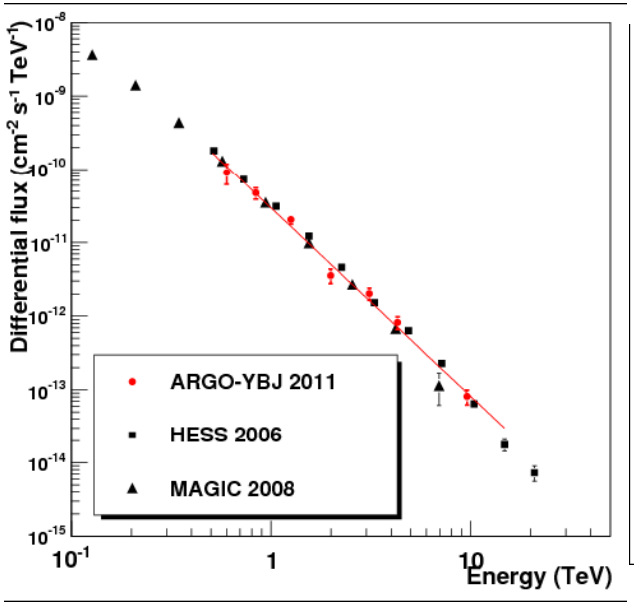


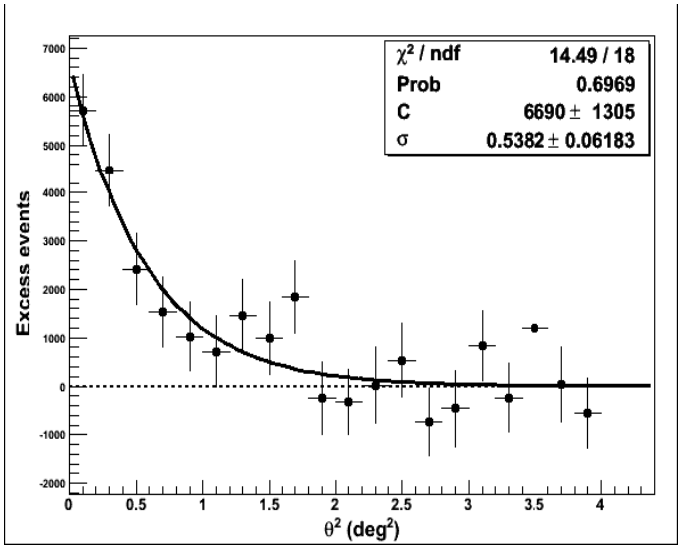
Spectroscopy: Crab Nebula



- **3.5 years of data taking of ARGO-YBJ**
- $\theta < 40^\circ$
- **5.8 hours per transit**
- **17 s.d. signal significance**
- **Energy spectrum consistent with IACT experiments**
- **Integrated sensitivity 0.3 Crab units**

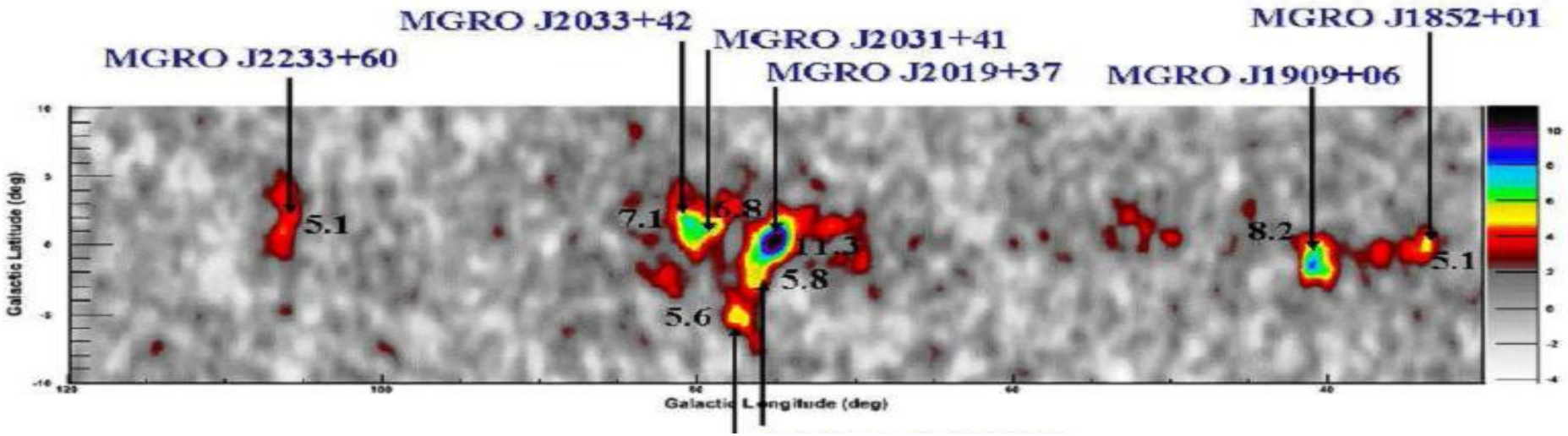






MILAGRO: Source Surveying

Very big object: Geminga



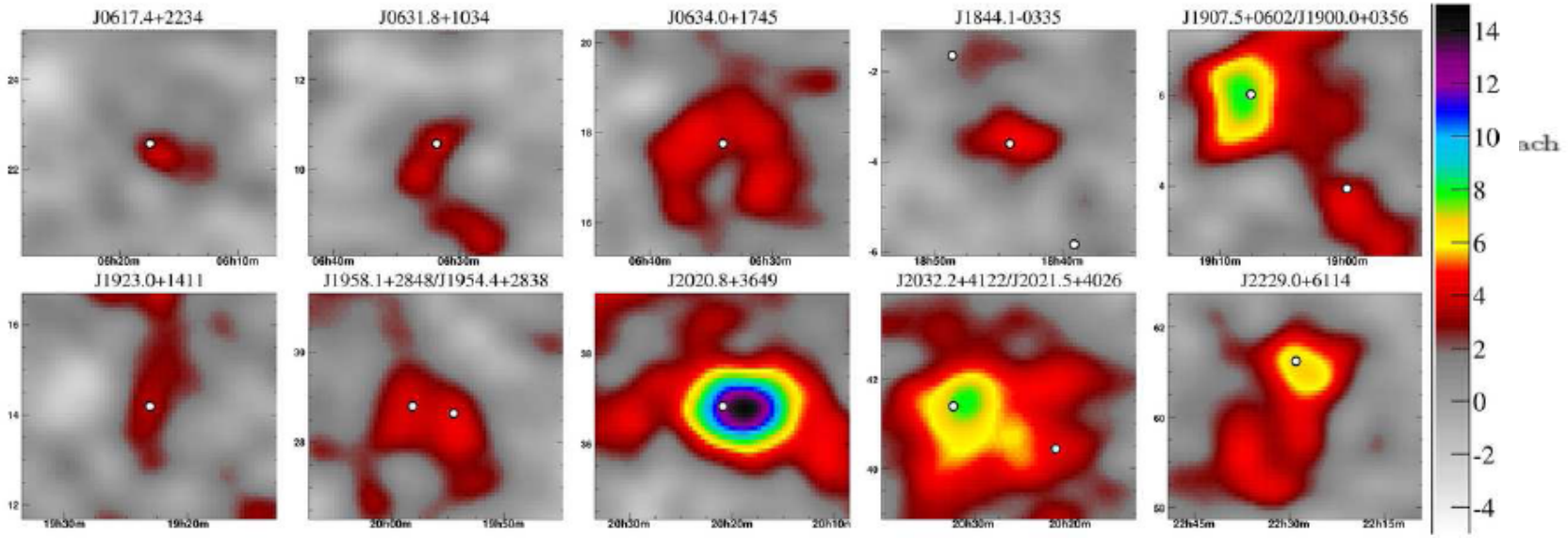
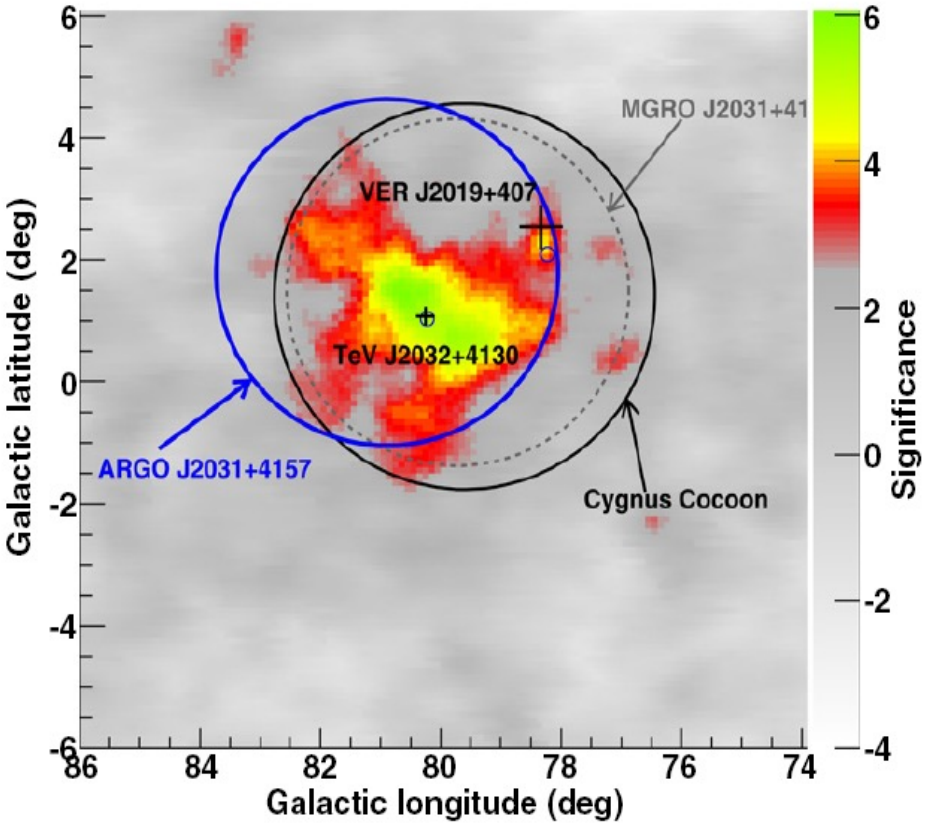
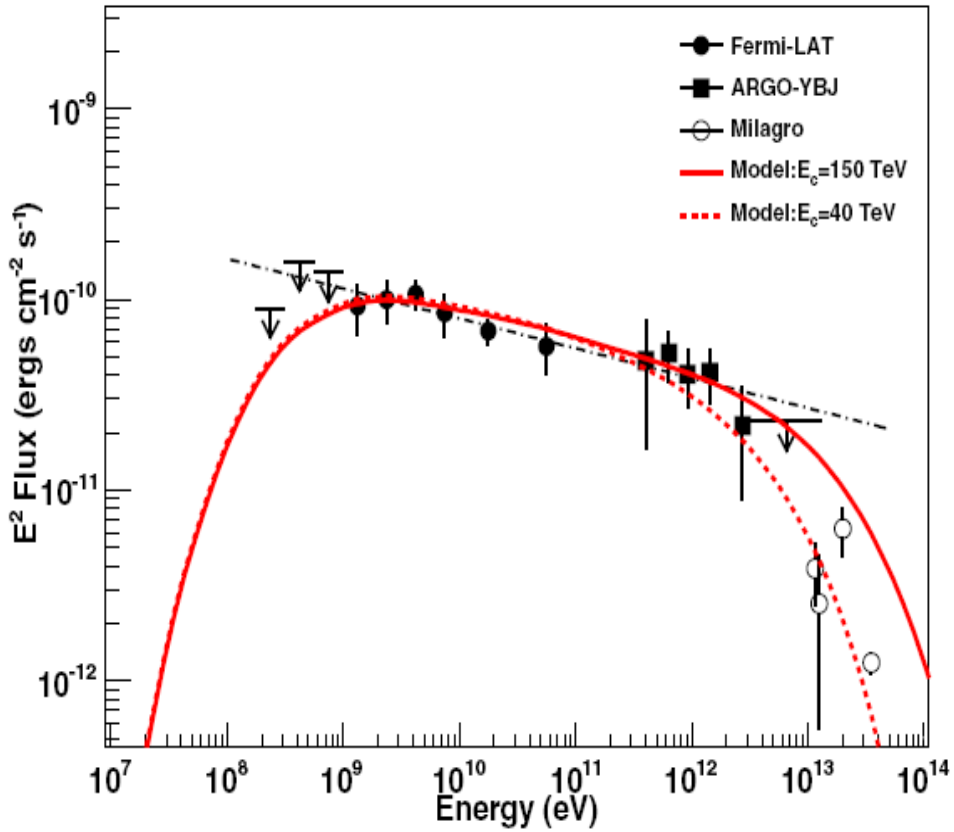


Figure 8. source.

ARGO-YBJ: ARGO J2031+4157

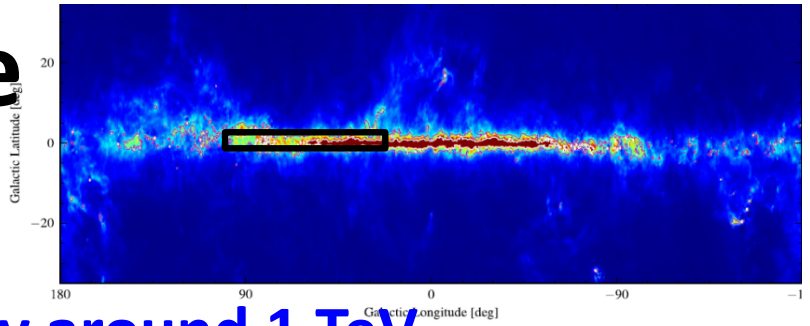
Identify the extended source (σ=1.8°$\pm$0.5°) to be the Cygnus Cocoon detected at GeV. The 1st TeV super-bubble





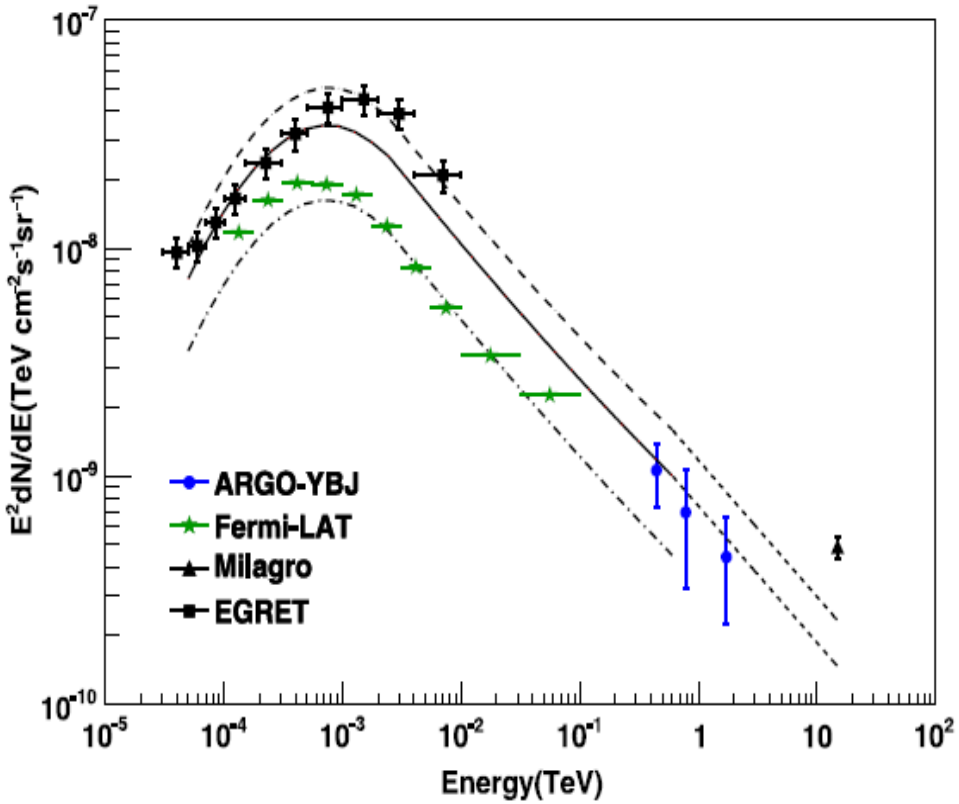
ARGO-YBJ coll., ApJ, 790:152, (2014)

ARGO-YBJ: Galactic plane Diffuse gamma-ray

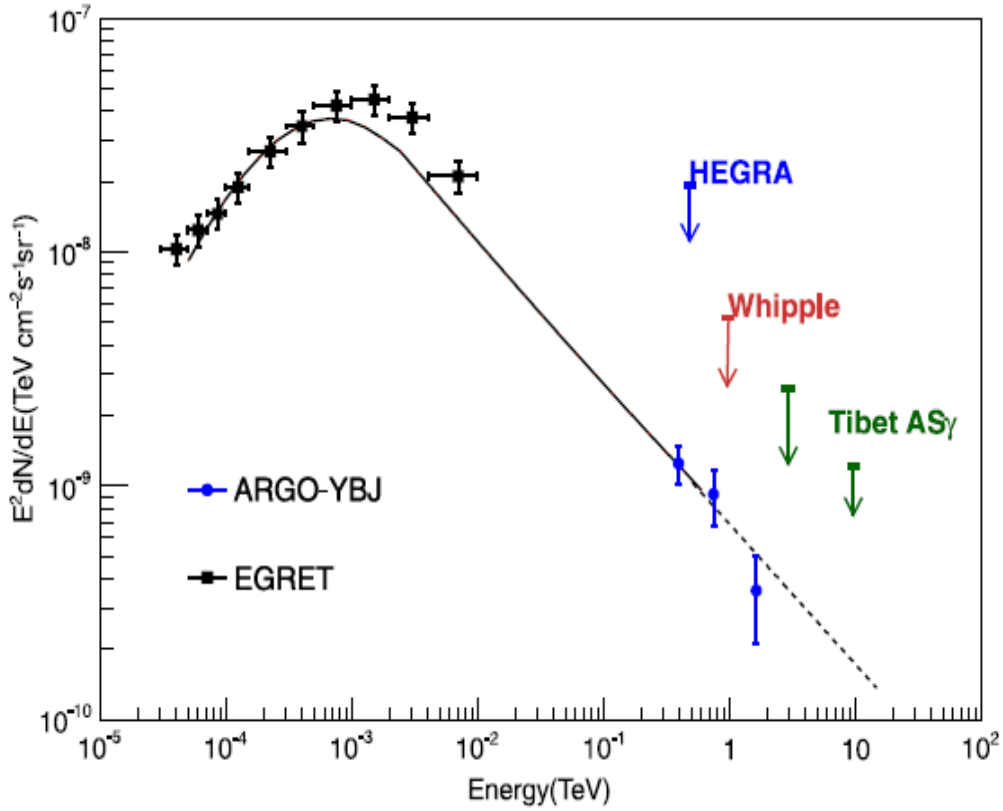


Measuring the GP diffuse gamma-ray around 1 TeV, which is consistent with the extrapolation of Fermi result.

$65° < l < 85°, |b| < 5°$



$25° < l < 100°, |b| < 5°$



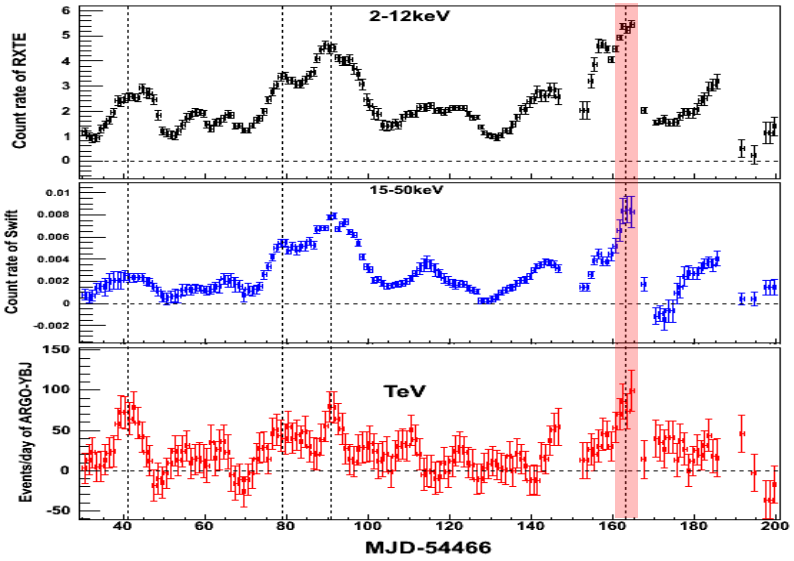
ARGO-YBJ coll., ApJ, 806:20, (2015)

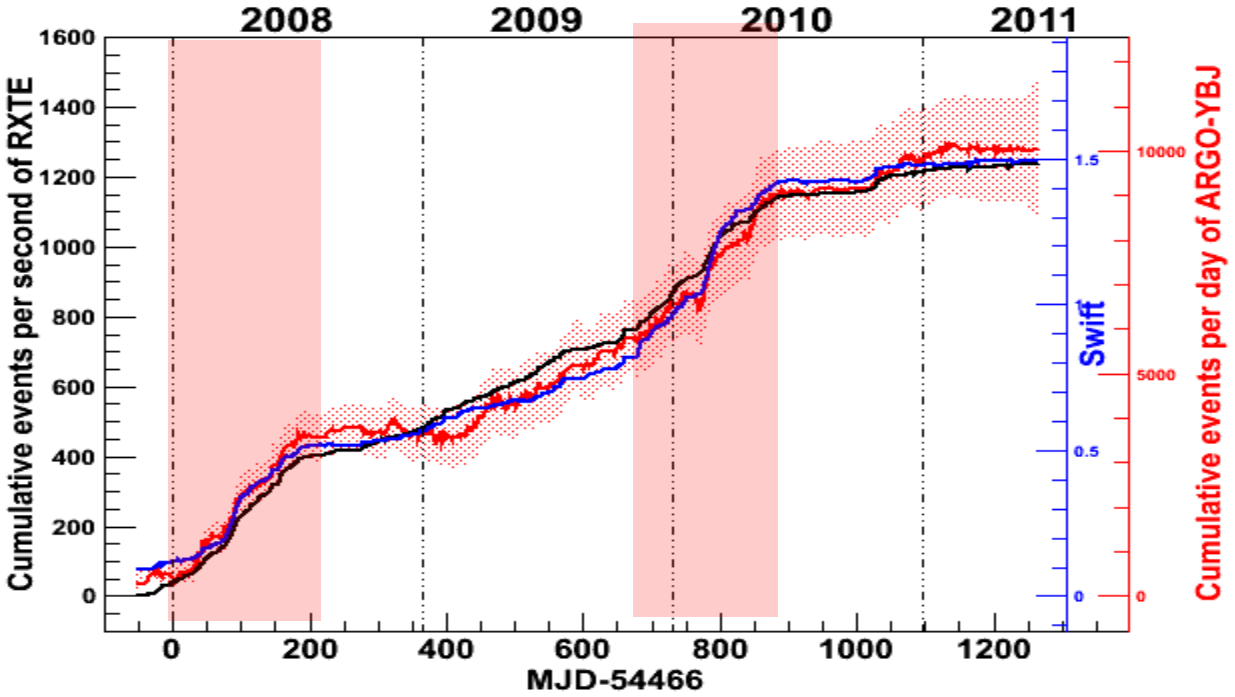
G. Aielli et al. –ApJL 714 (2010) L208

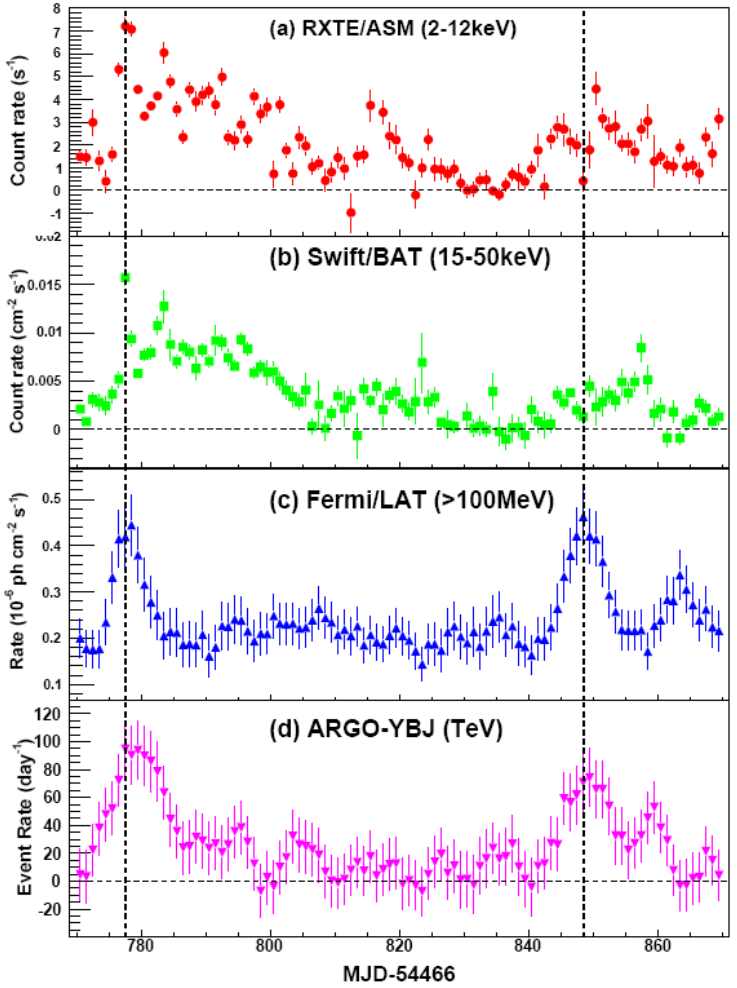
Astrophys.J.Suppl. 222 (2016) no.1, 6

Transient: AGNs

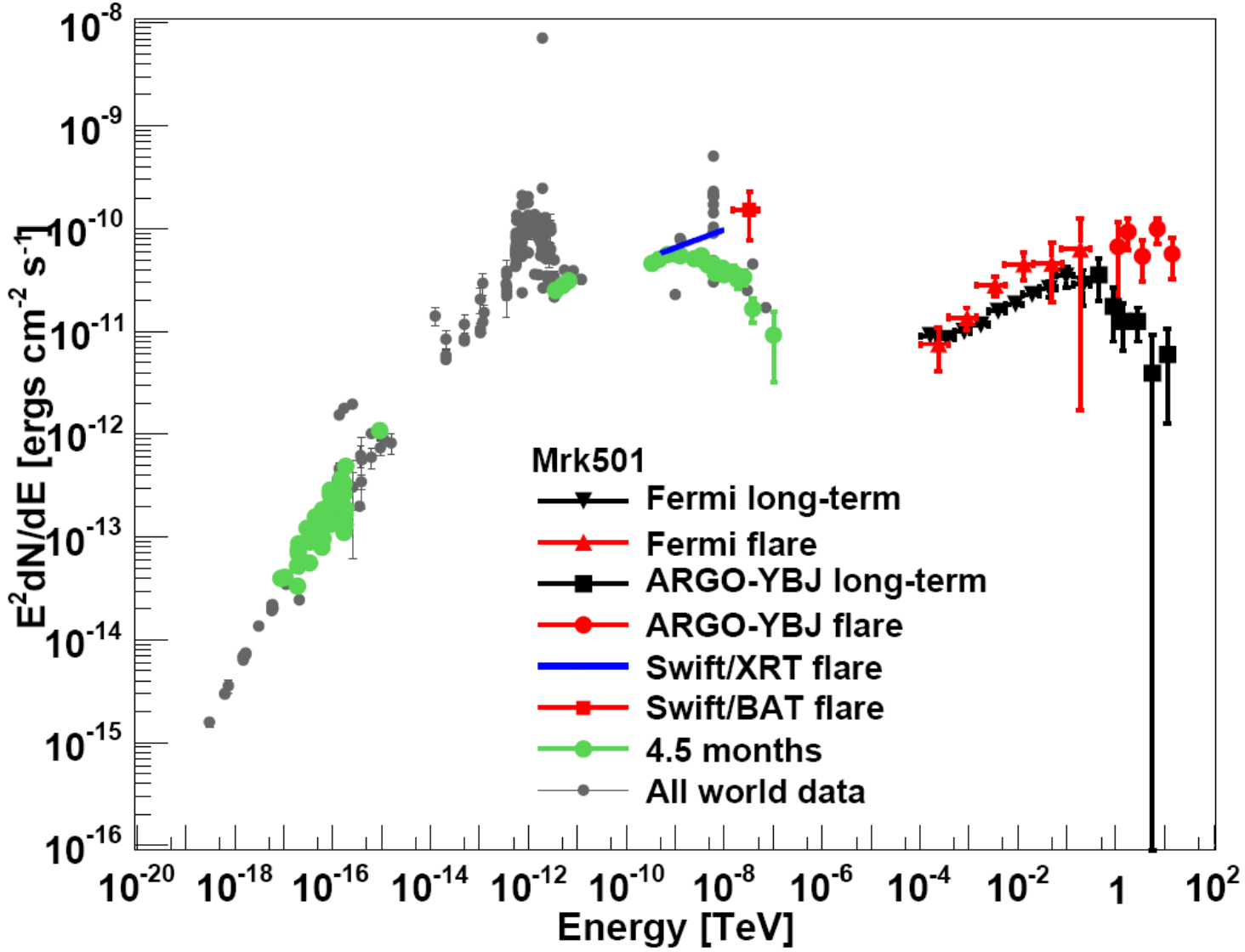
- Correlation between X and Gamma and other bands







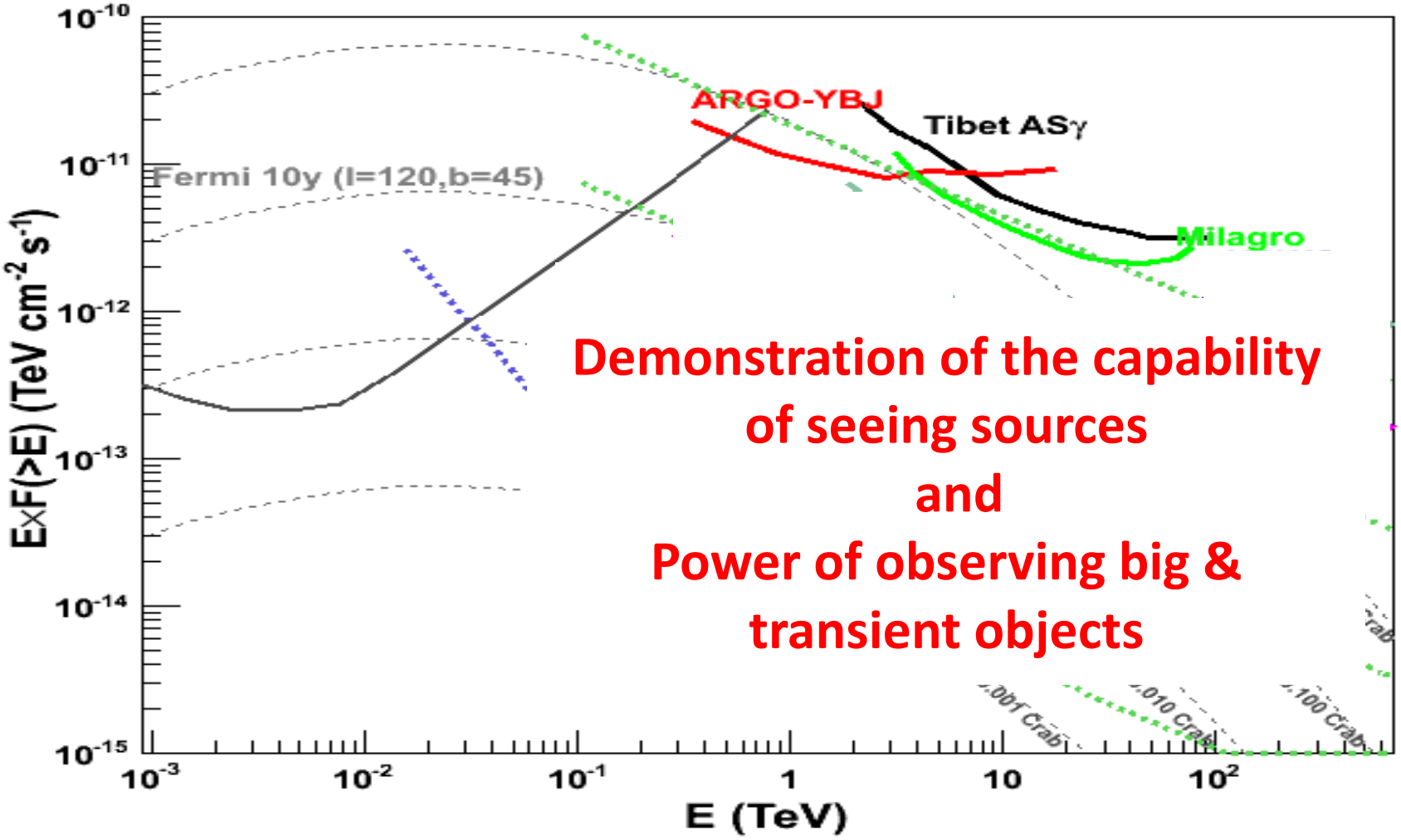
Mrk501 Flare: the largest since 1997



ApJ, 727:129 (2011) about the observation for 4.5 months

NASA/IPAC Extragalactic Database(NED) (http://ned.ipac.caltech.edu/) for world wide combined

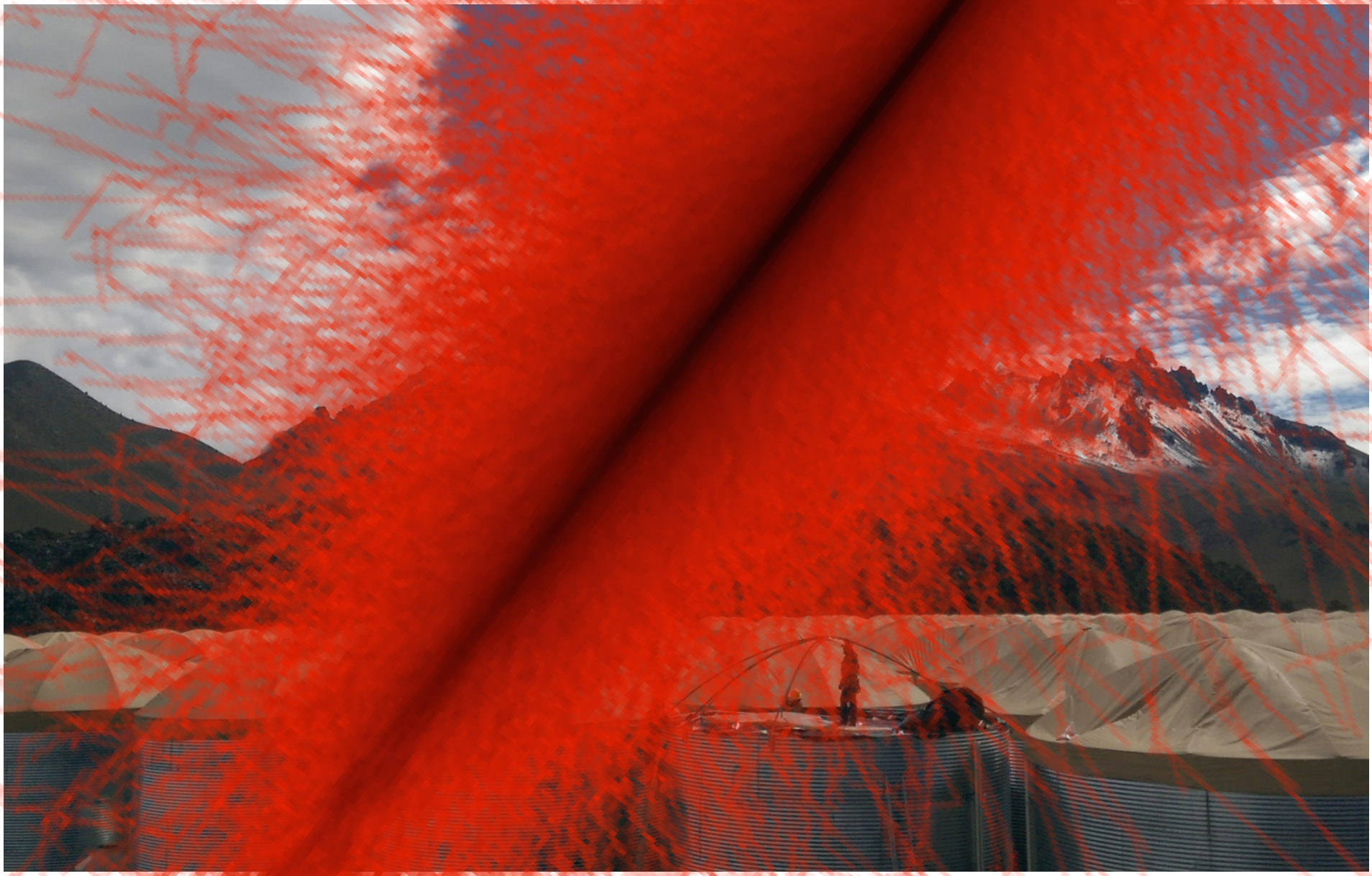
Sensitivity to gamma ray sources for ground arrays by 2013



2nd Generation

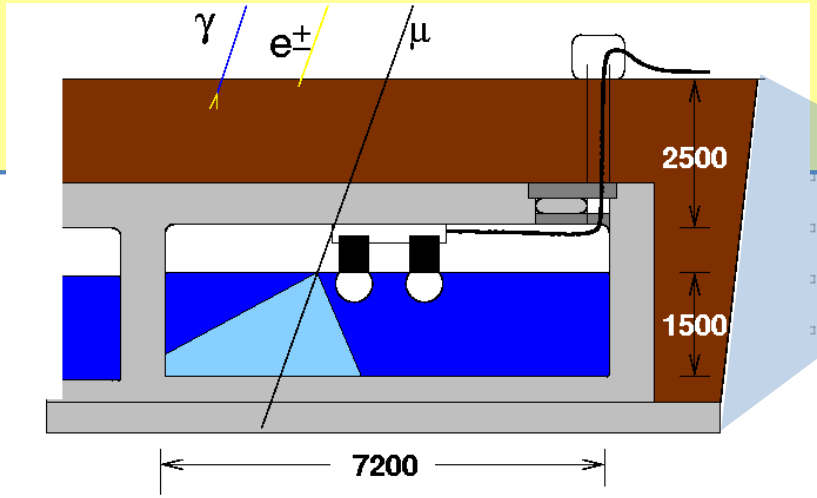
- 2013-, HAWC
- 2013, Major Upgrading ASγ with a plan of building a large muon-detector array inside the scintillation detector array

HAWC Observatory

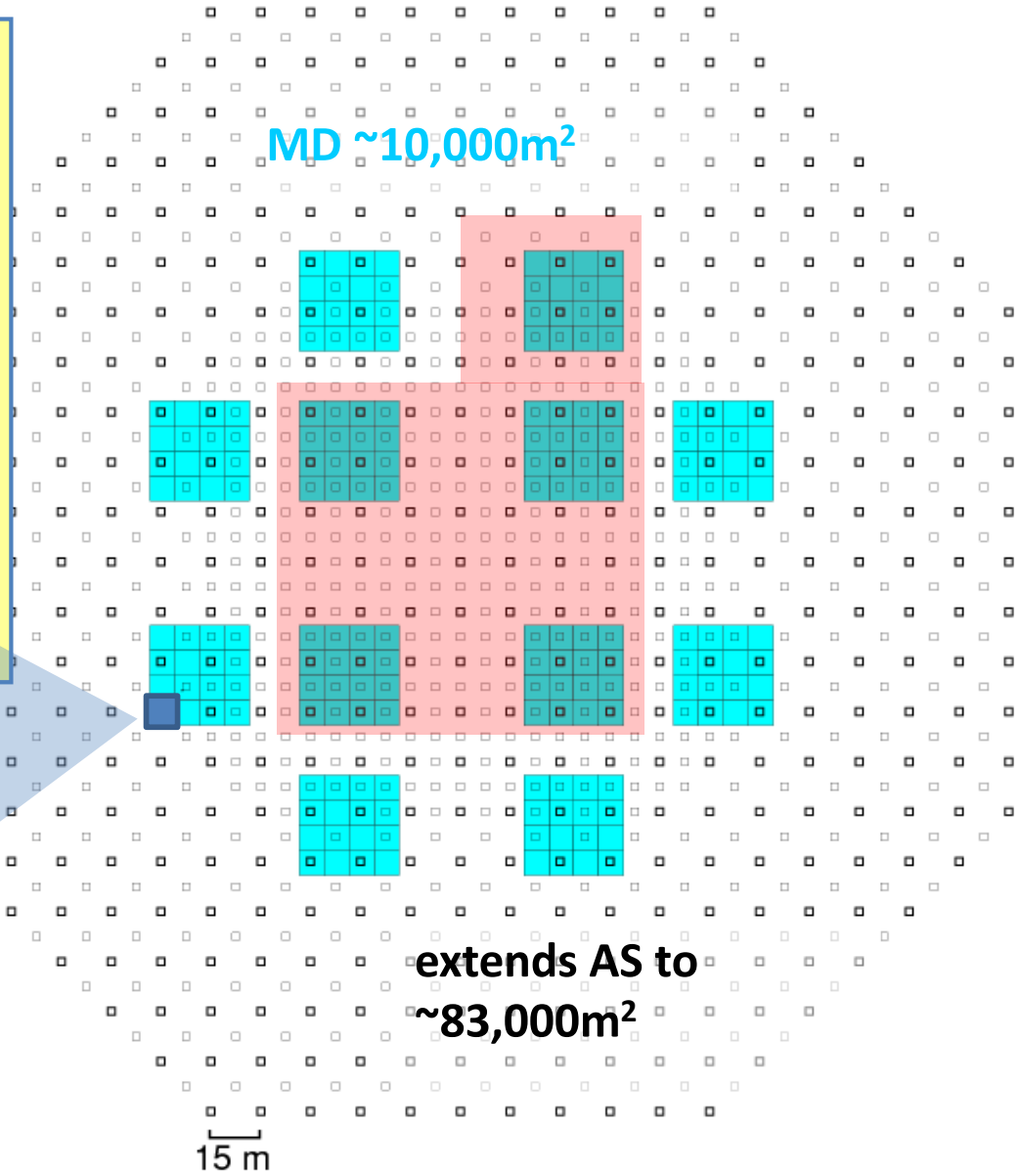


Tibet MD Array Plan at 2013

- Water Cherenkov type detector
- 12 concrete pools (10,000 m^2 in Total)
- A concrete pool = 16 water cells
- Underground 2.5m (515 g/cm^2 = 19X_0)
- A water cell = 7.2m x 7.2m x 1.5m depth
- With two 20"ϕ PMTs
  (HAMAMATSU R3600)



Muon data is passively recorded
as an air shower trigger generated



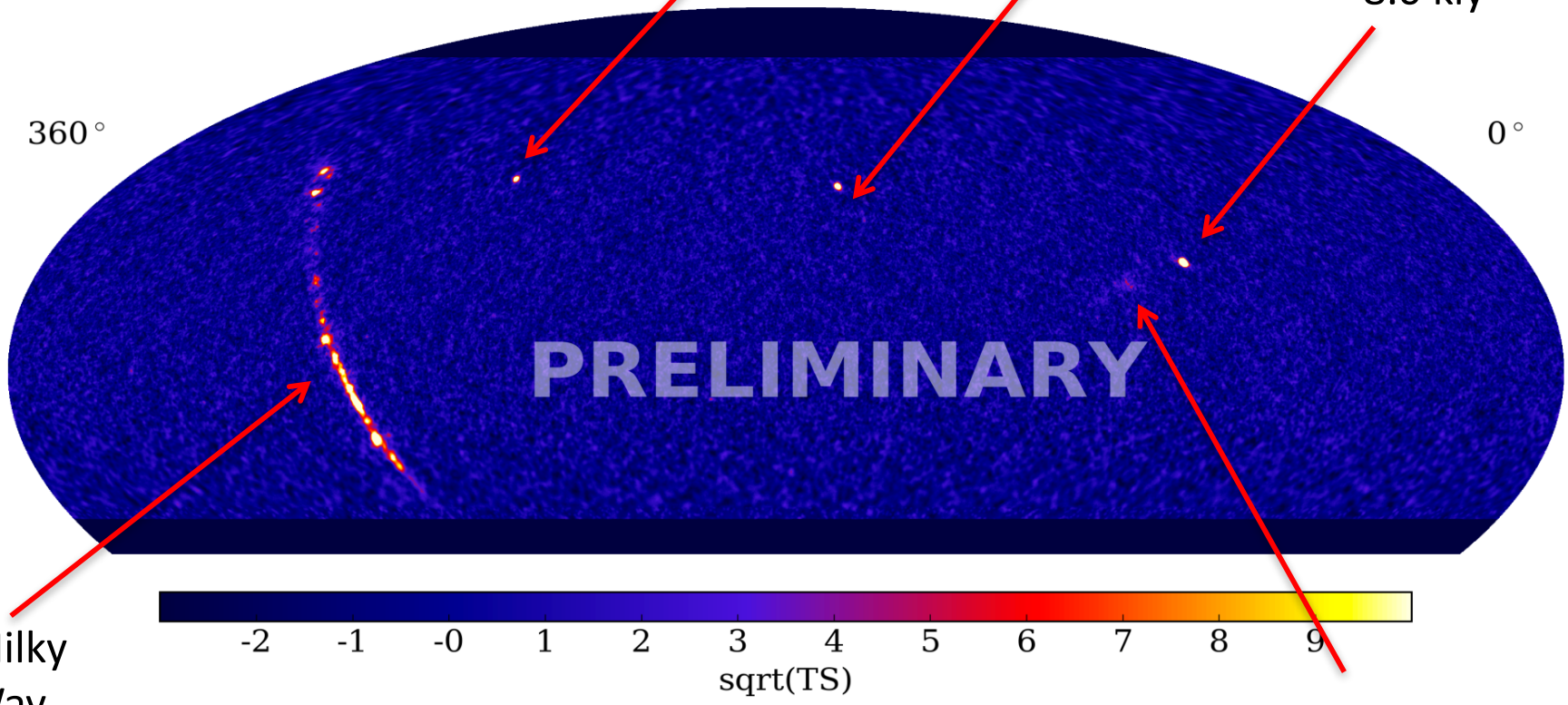
TeV Sky Results- HAWC point source TeV Sky Map 2HWC Catalog

2HWC catalog
http://iopscience.iop.org/article/10.3847/1538-4357/aa7556/meta

Mrk501
23 σ
140 Mpc
456 Mly

Mrk 421
33 σ
130 Mpc
430 Mly

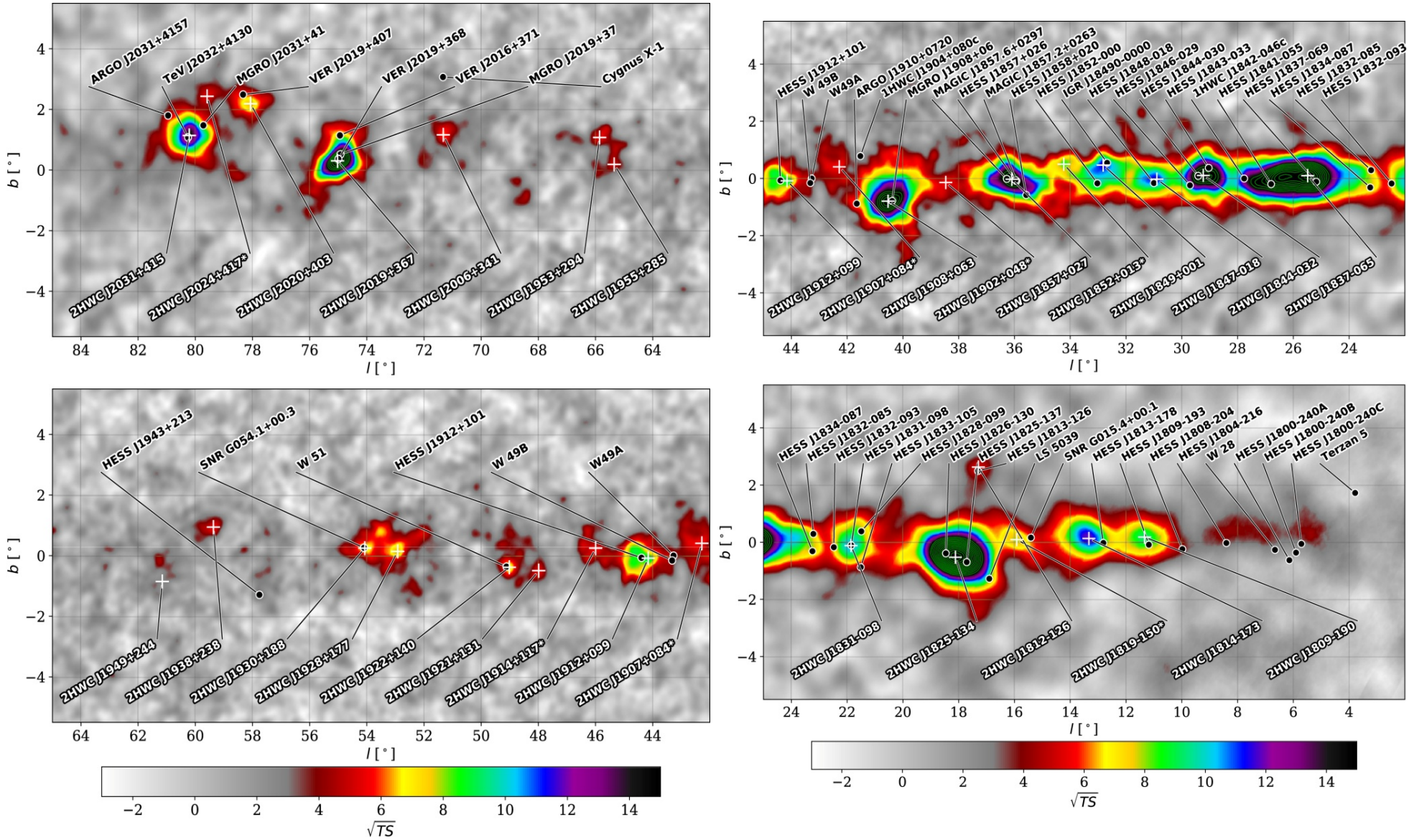
Crab Nebula
105 σ
2.2 kpc
8.0 kly



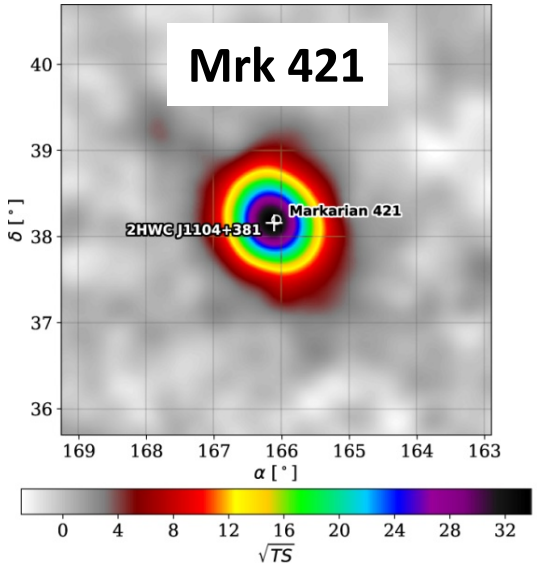
Milky Way Galactic Plane

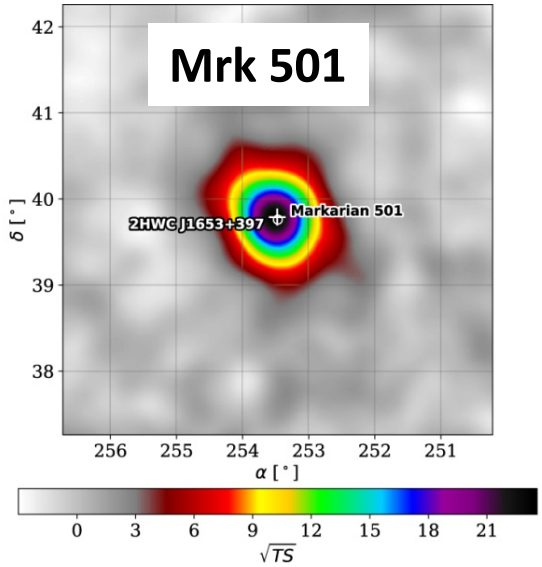
Geminga
0.8 kly

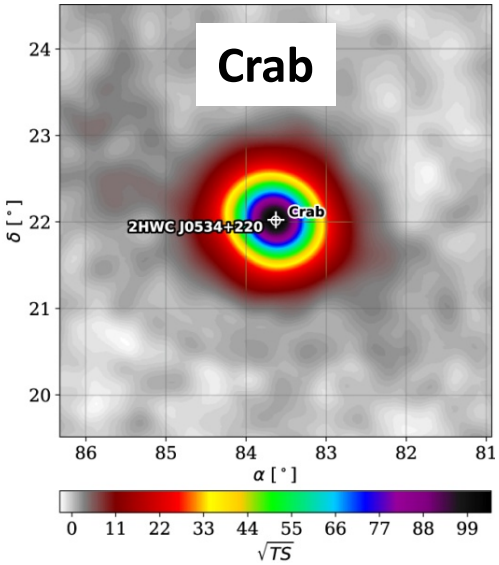
TeV Sky Results – Galactic Plane

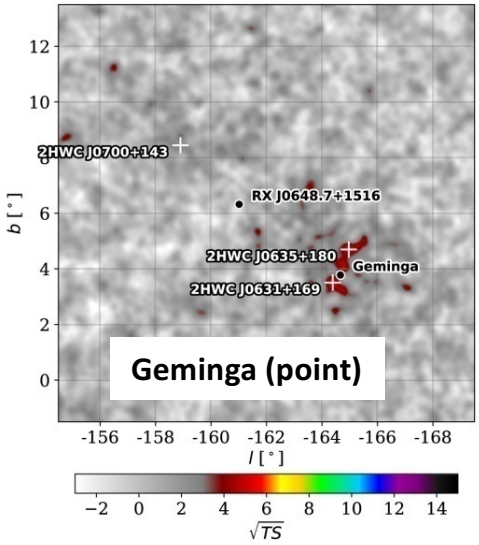


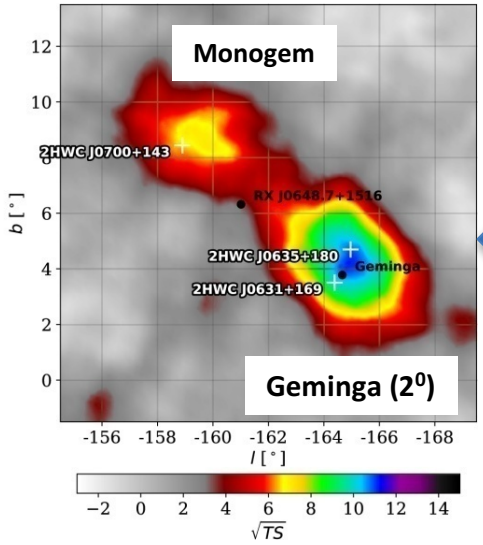
TeV Sky Results- Mrk 421, Mrk 501,







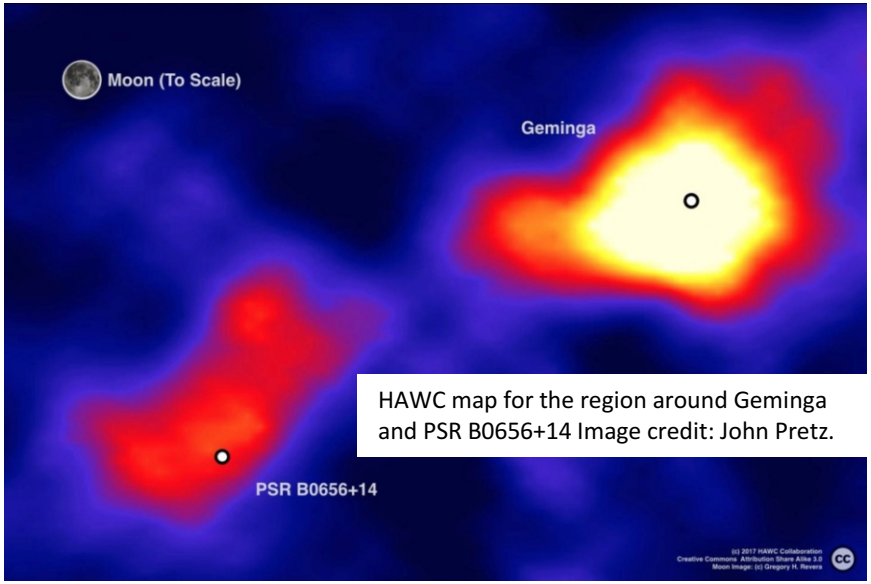




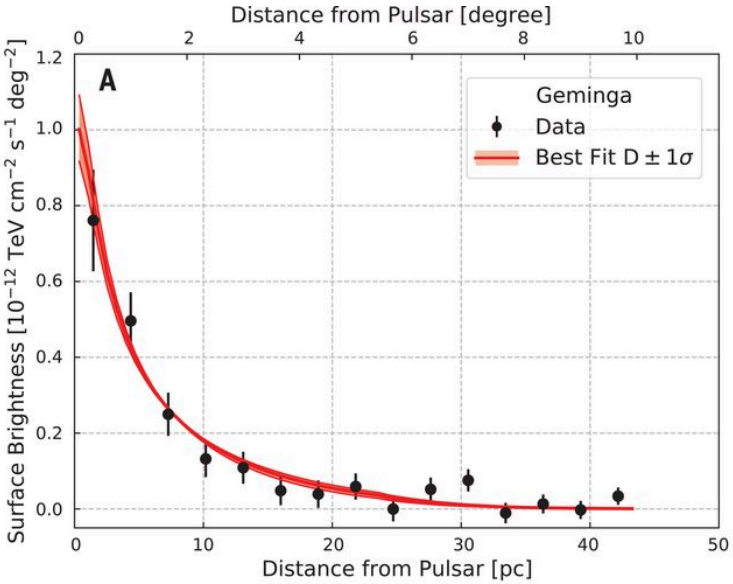
Extended Sources Observed as well !!!!

Geminga and Friend

Galactic Results - HAWC Extended Sources Geminga Pulsar Wind Nebula (+Friend)

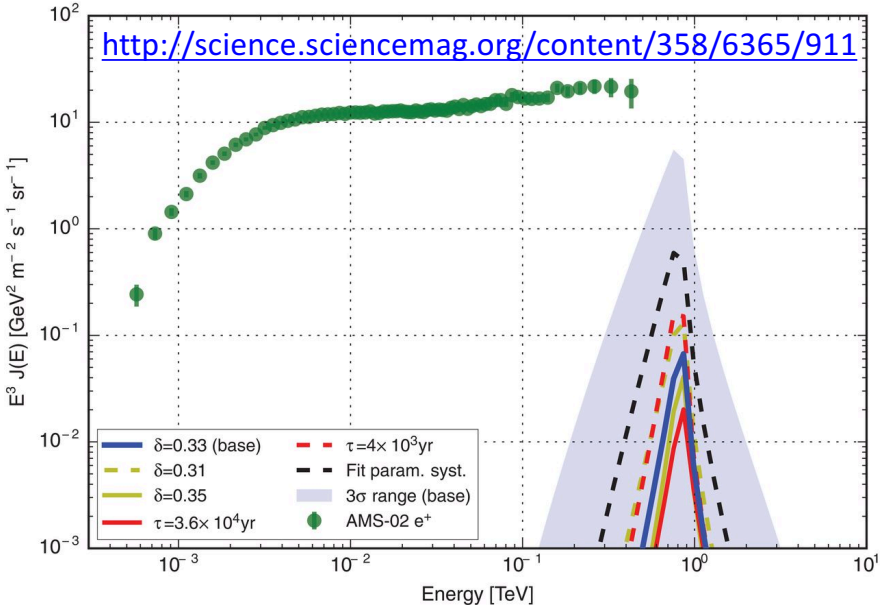


HAWC map for the region around Geminga and PSR B0656+14 Image credit: John Pretz.

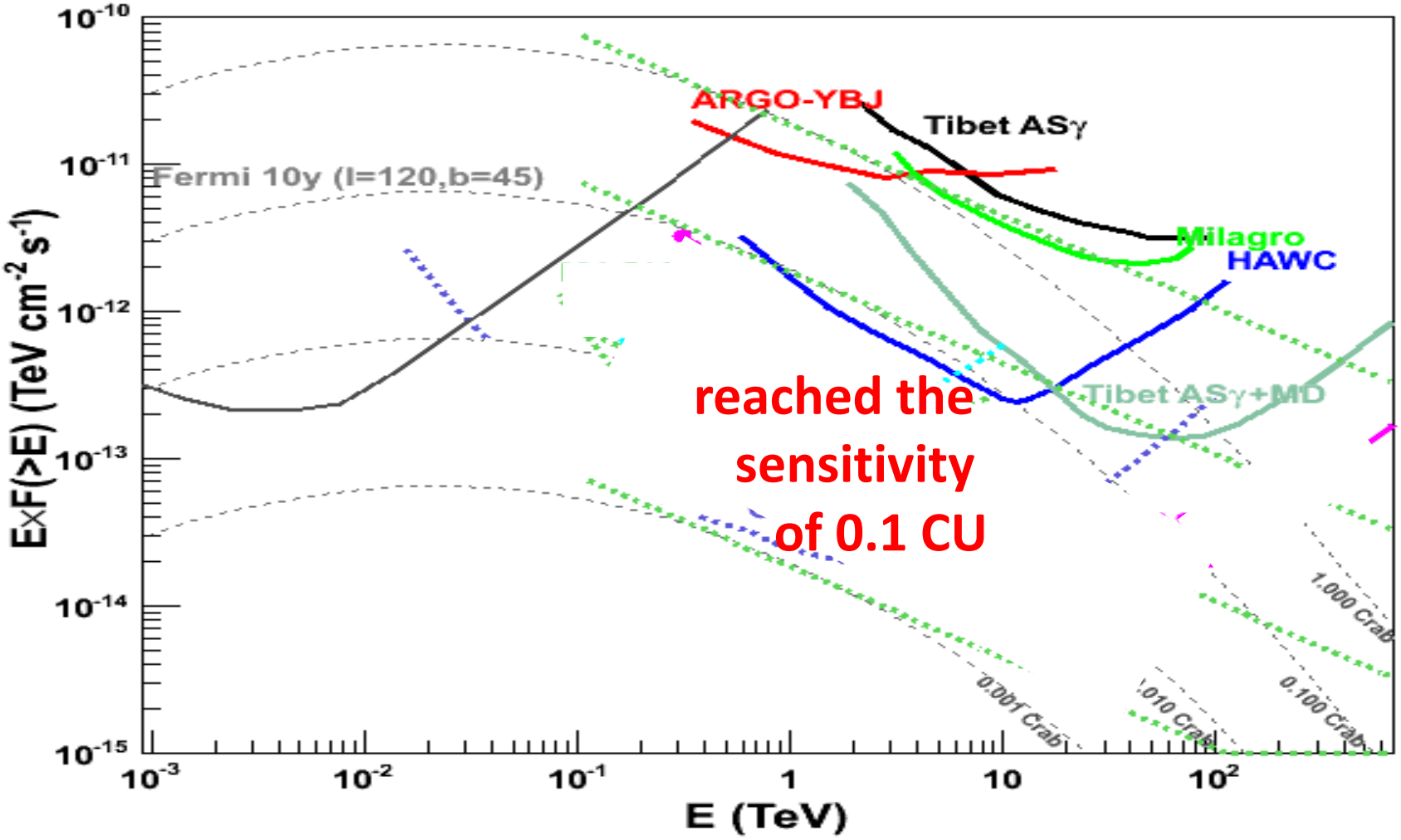


http://www.sci-news.com/astronomy/nearby-pulsars-origin-excess-antimatter-05443.html

- Geminga TeV gamma ray emission extended over 5^0 x 5^0 patch of sky
- Surface brightness measured as function of distance from pulsar
- Model predicts associated positron spectrum at Earth.
- **Nearby Pulsar Wind Nebulae do not explain AMS positron observations**



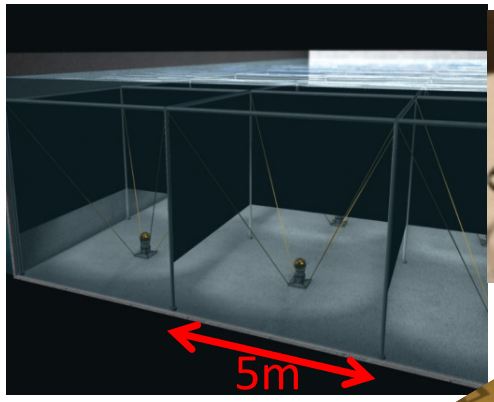
LARGE Objects need EAS array also for Spectroscopy



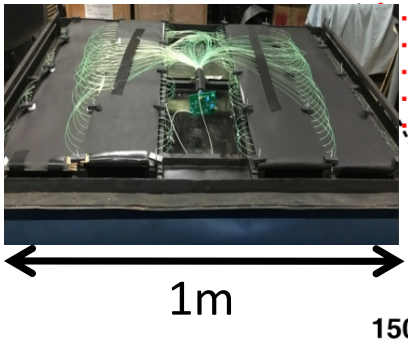
Two workshops were held in 2009,2011 and TeVPA2009

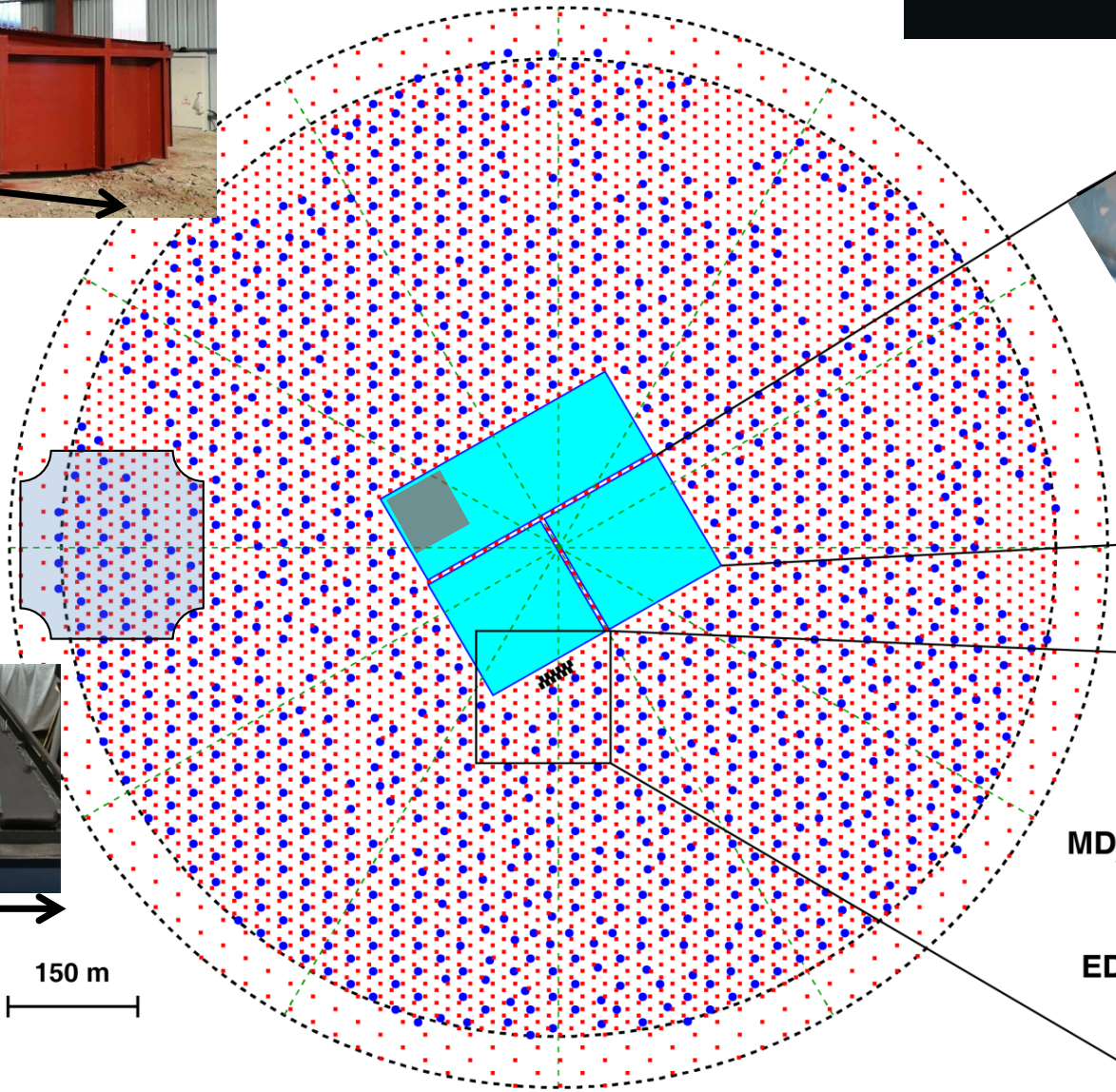
- Open discussions among representatives from major experiments helped to fix the CDR of LHAASO

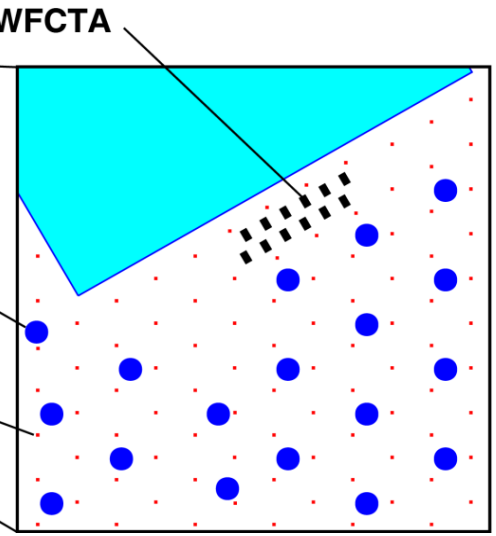
3rd Generation: **LHAASO**



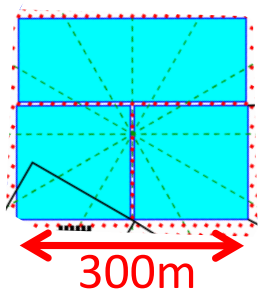
Size of AS
& ARGO-YBJ



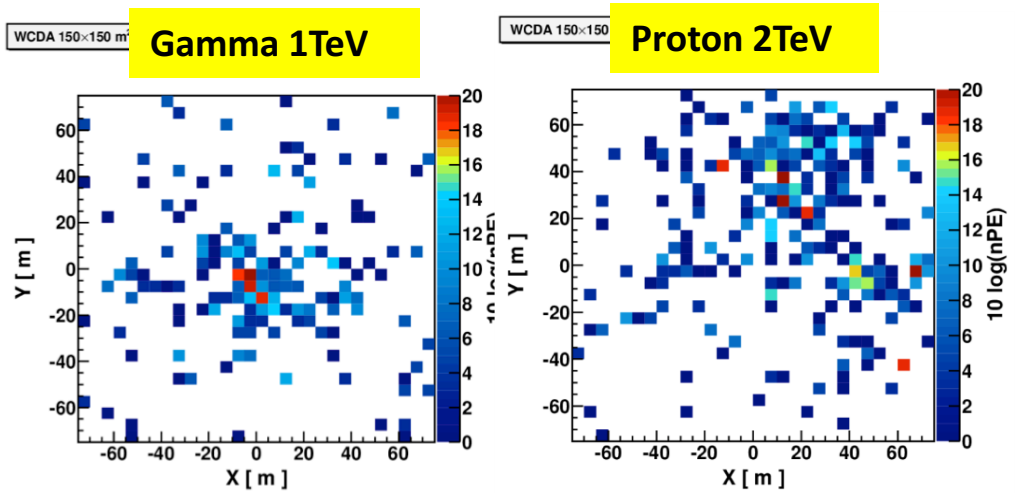


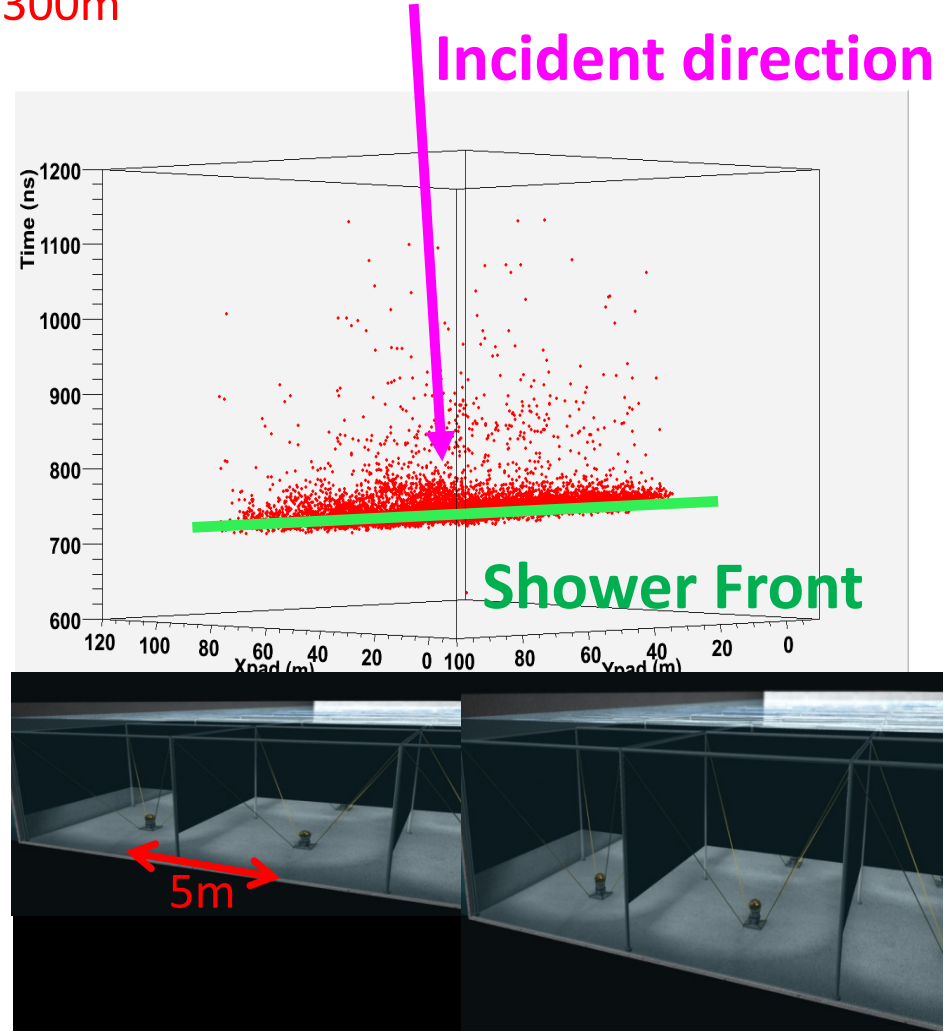


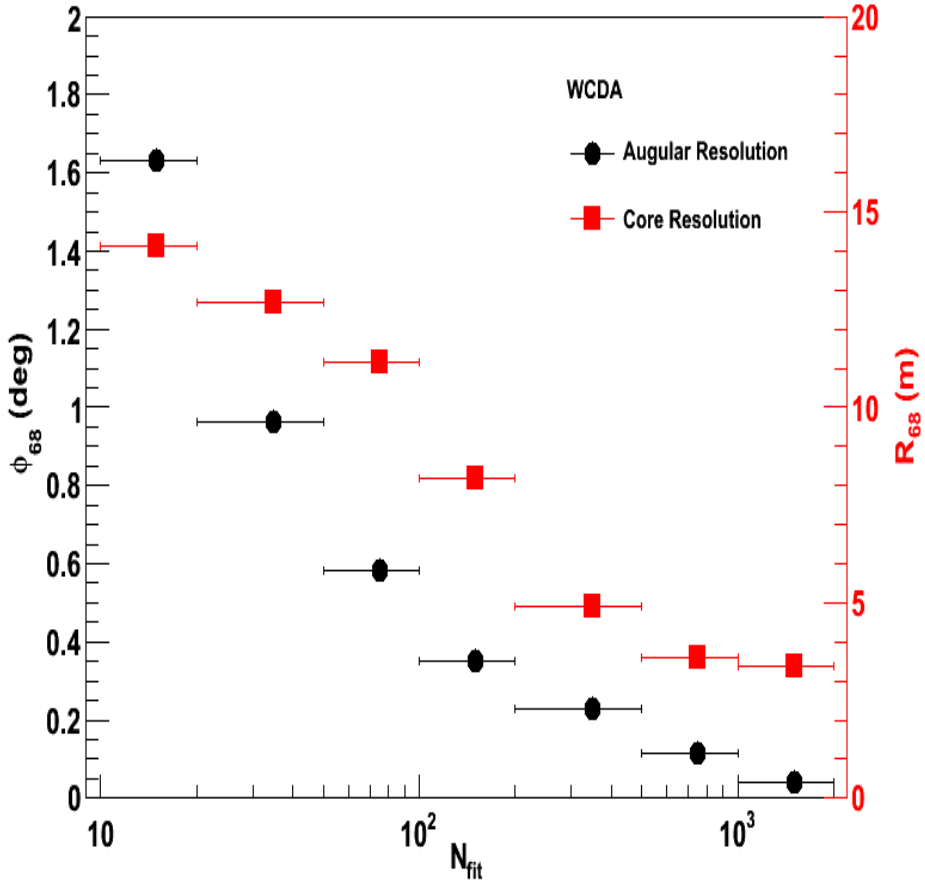
3 Pools

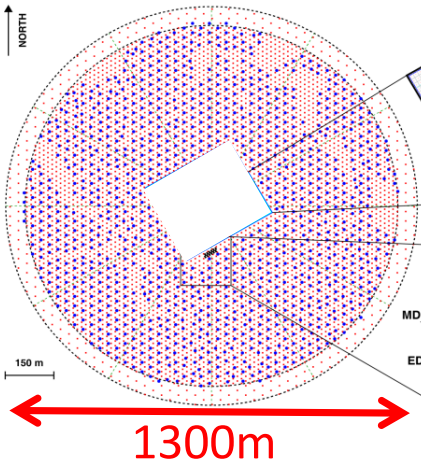


- Measuring shower direction and location
- Catching far muon signals in showers for γ/p



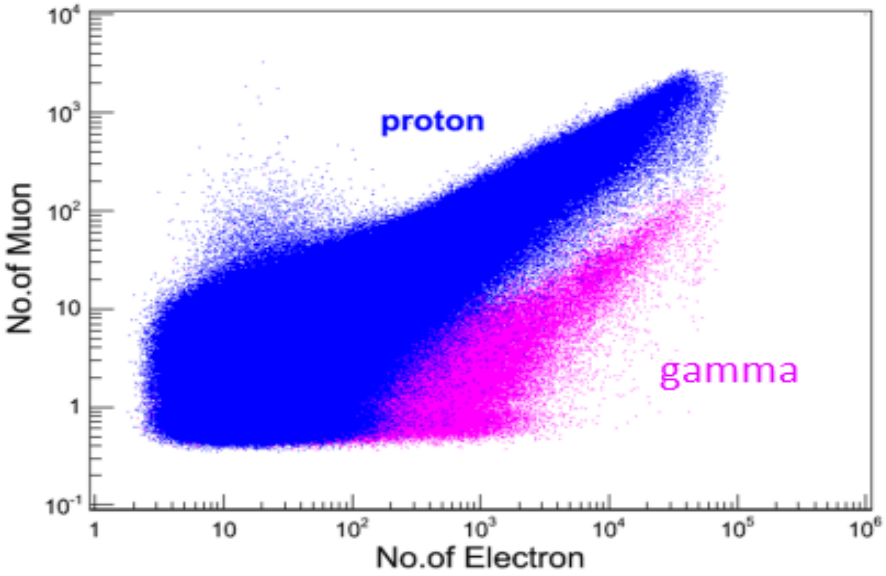


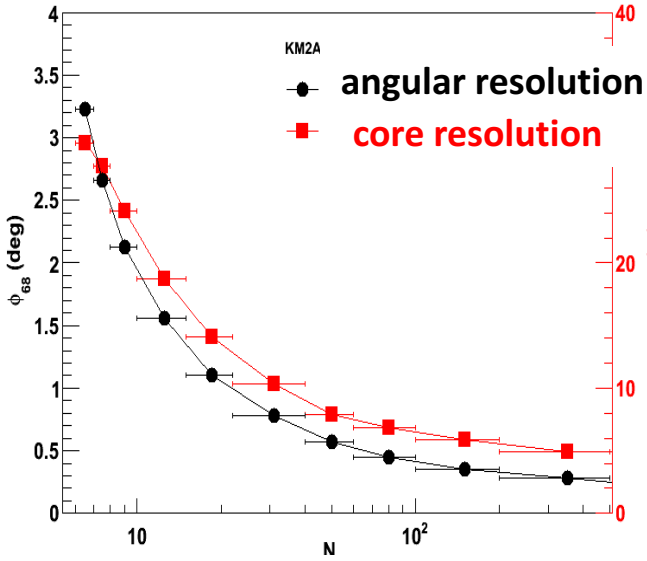


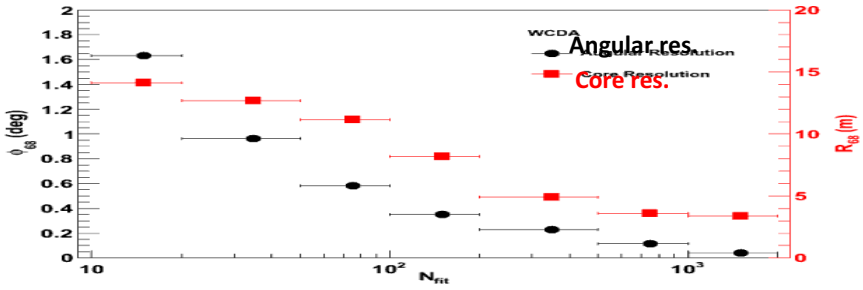


An Array of Scin. +MDs

- Measuring shower direction and location
- Measuring μ–content with the largest MD array ever
- Clean γ selection

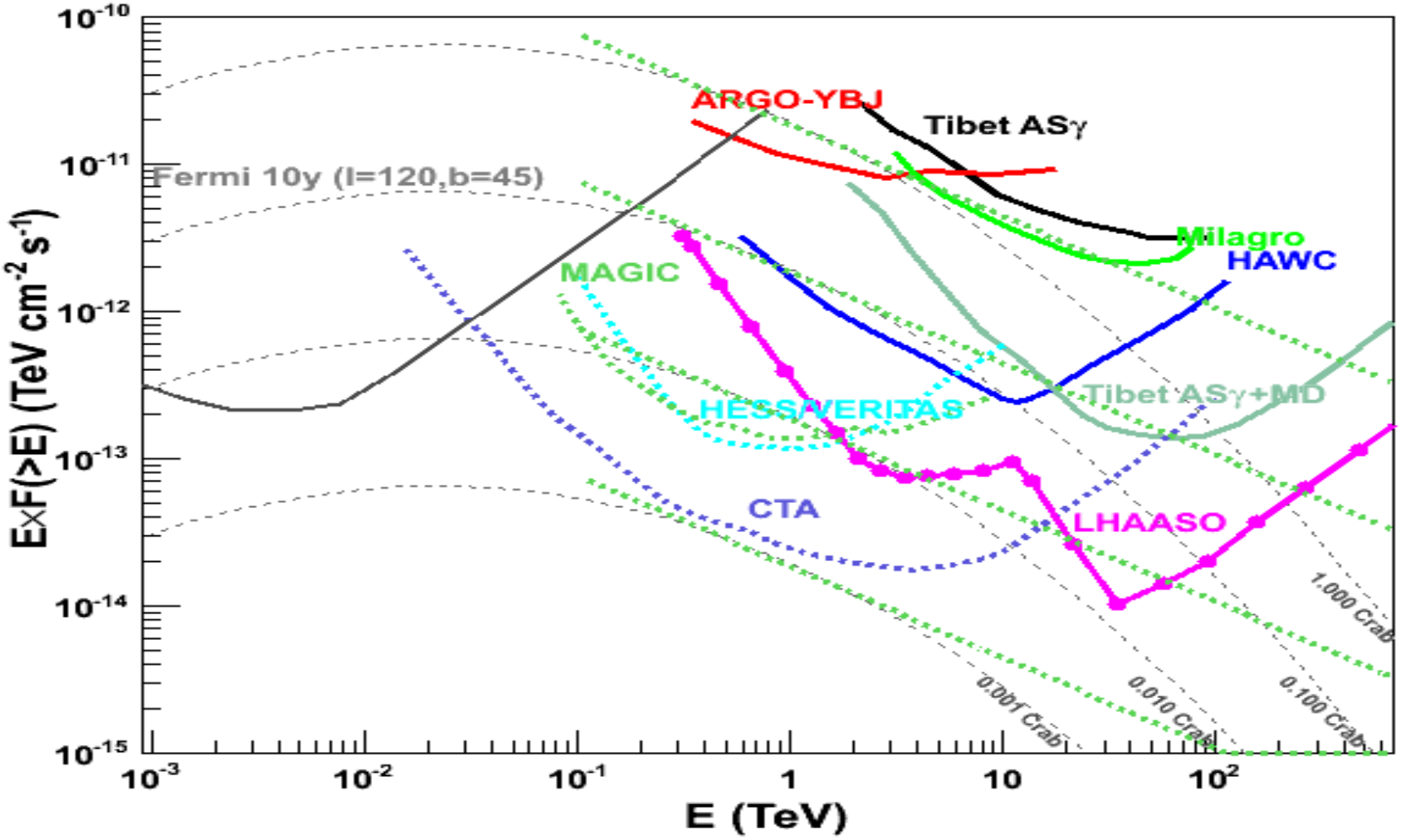






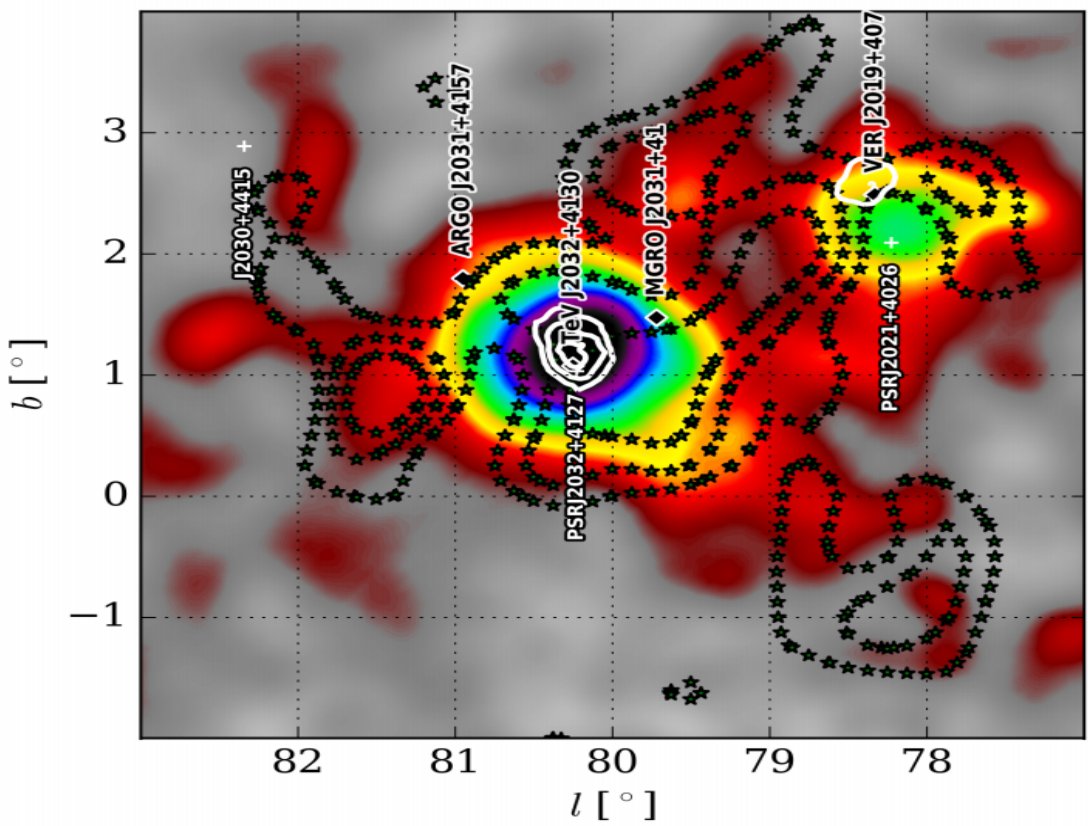
Sensitivity to gamma ray sources

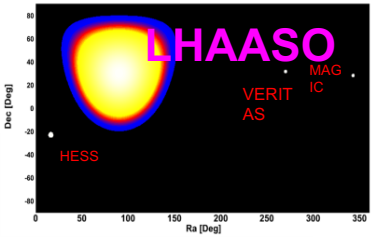
- **Integral: 1% Crab unit @3TeV & 50TeV**

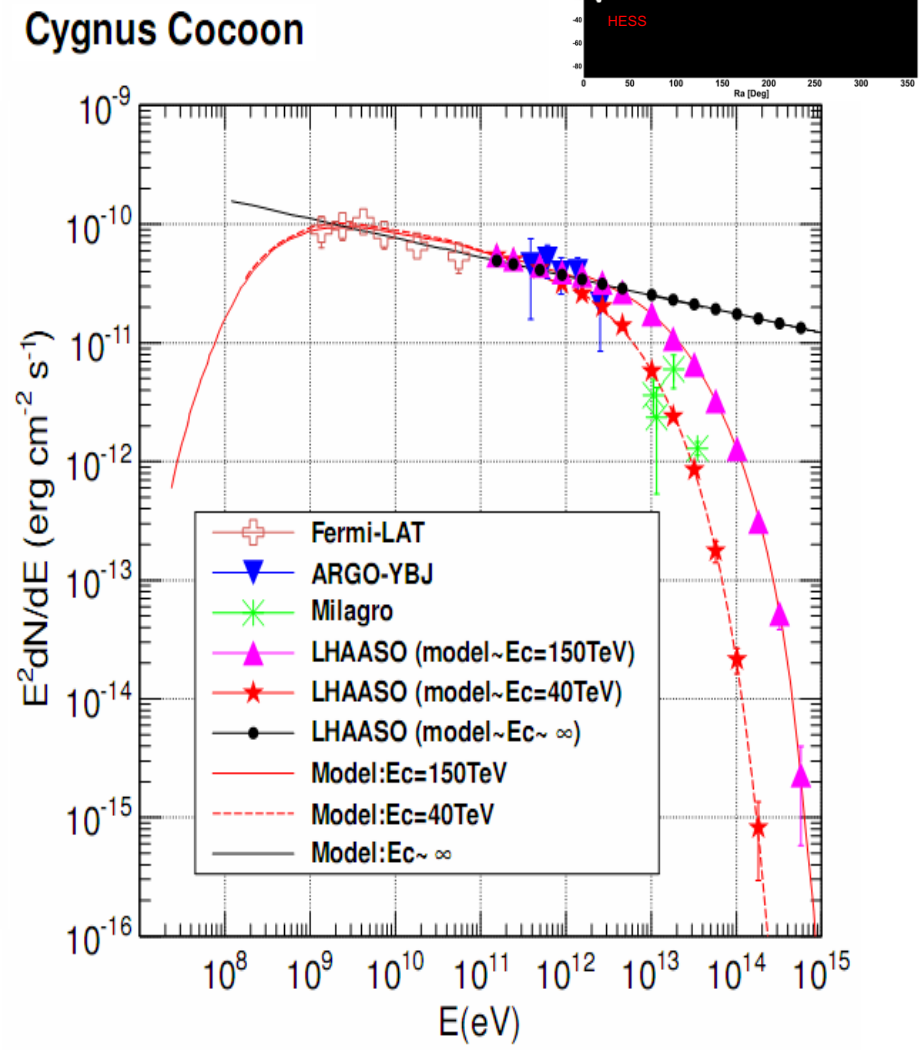


Broad Objects: Cygnus region

The 1st VHE supper-bubble by ARGO-YBJ







Overlapping sources？ Morphological study？ Multi-wavelength？

LHAASO on AGN flares

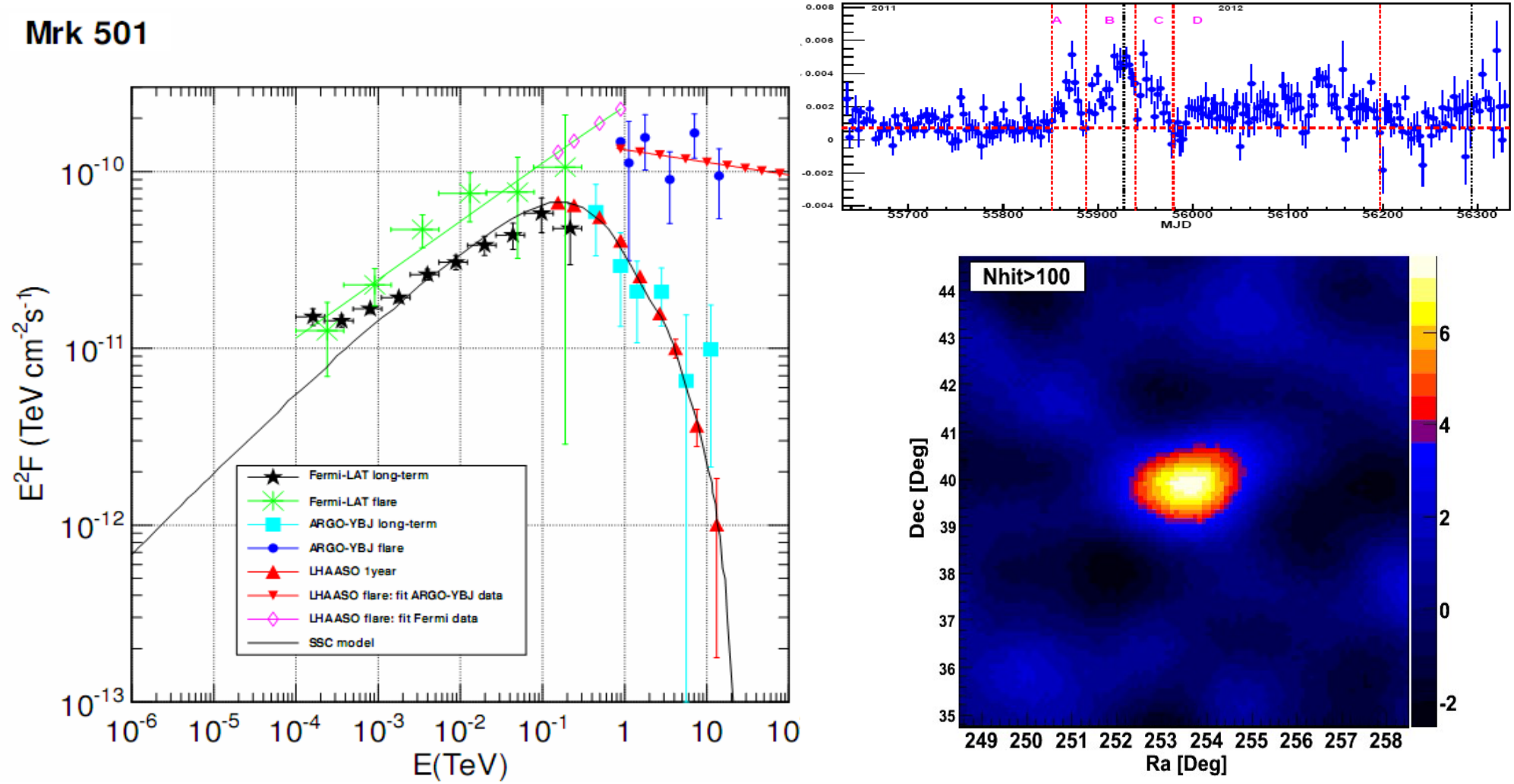
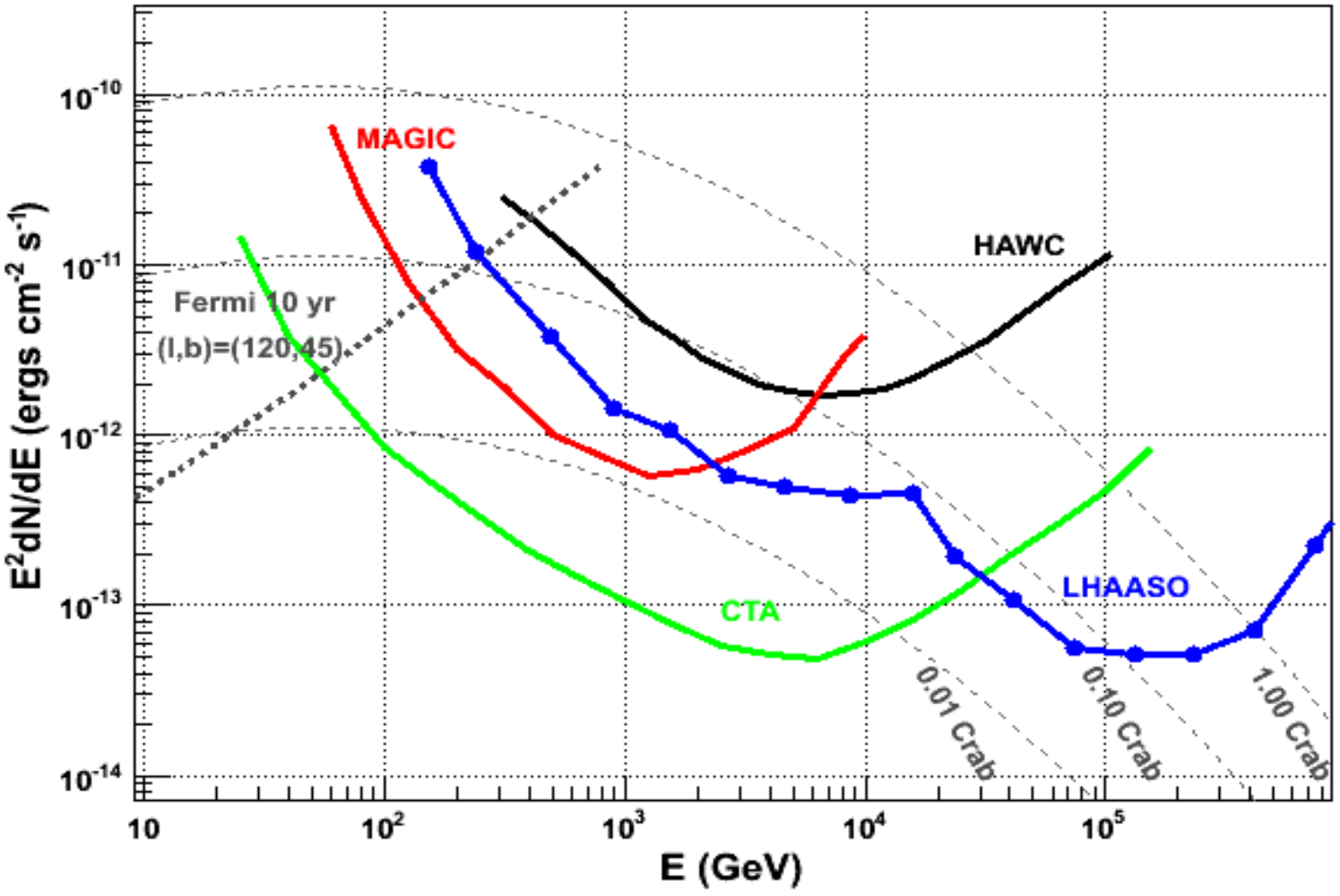


Figure 16: Expectation of the LHAASO project on Mrk501 [57], compared with the measurement of Fermi-LAT, ARGO-YBJ[27].

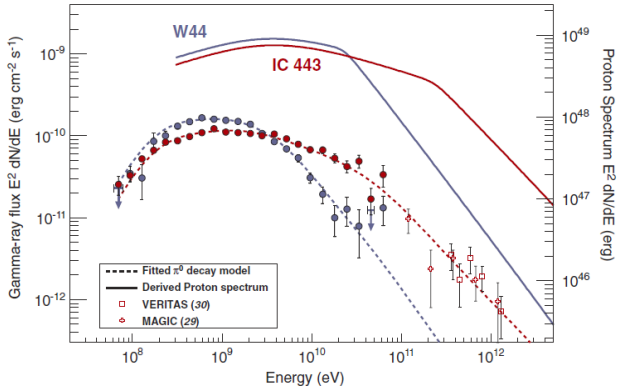
Differential Sensitivity to γ-ray sources

2% crab in TeV range & 1 crab at 500TeV



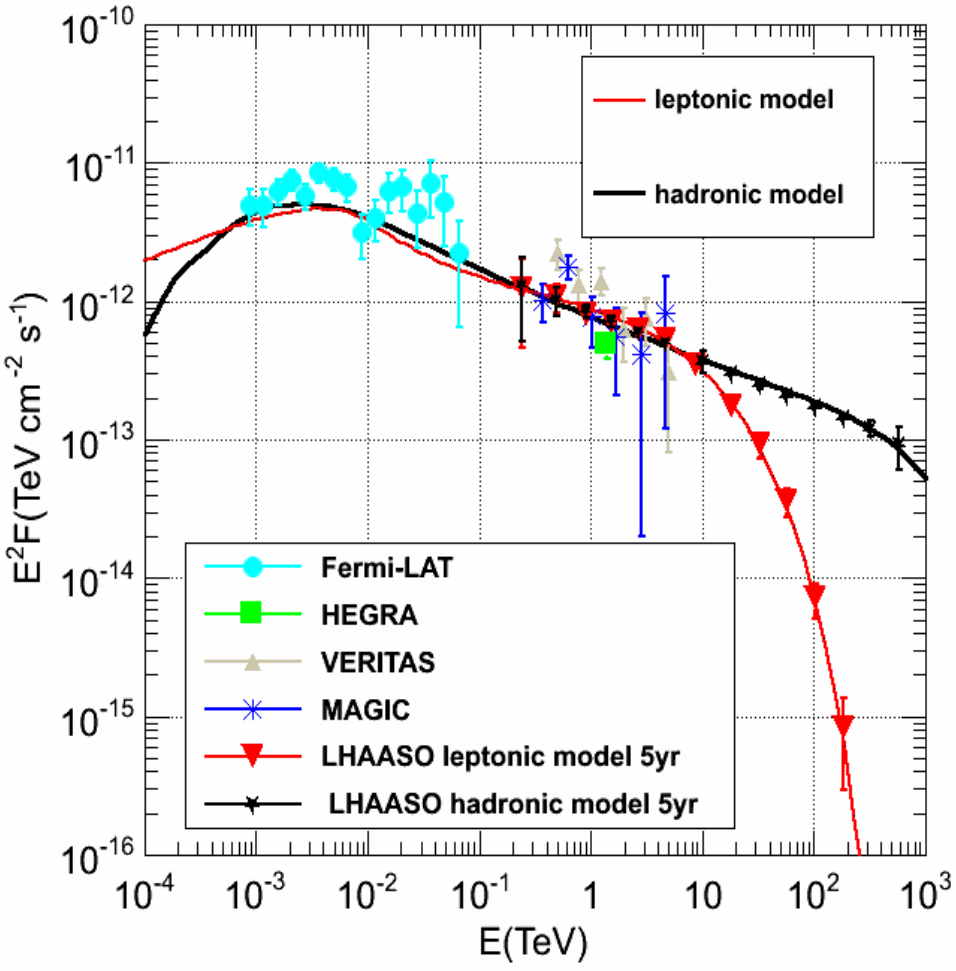
Hadronic vs. Leptonic

Characteristic signatures of π^0 decay: at highest energy by LHAASO

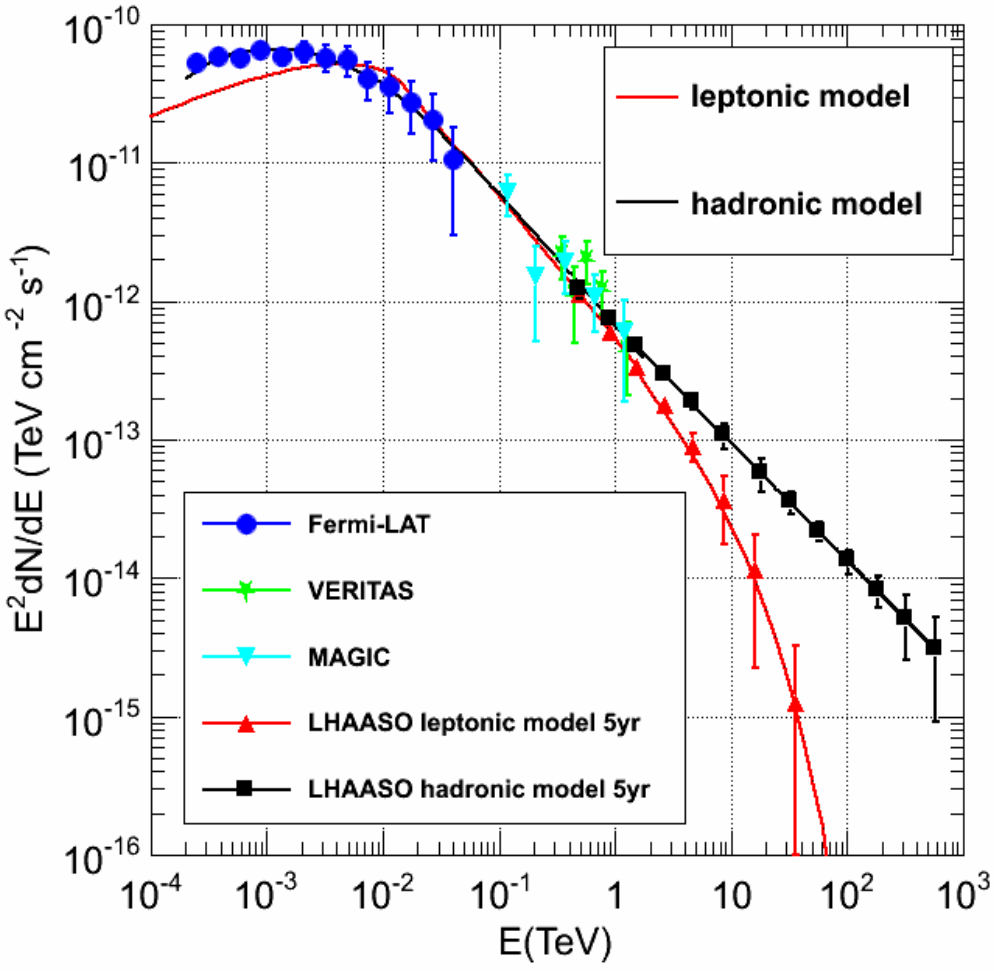


10.1126/science.1231160

Cassiopeia A Historical SNRs

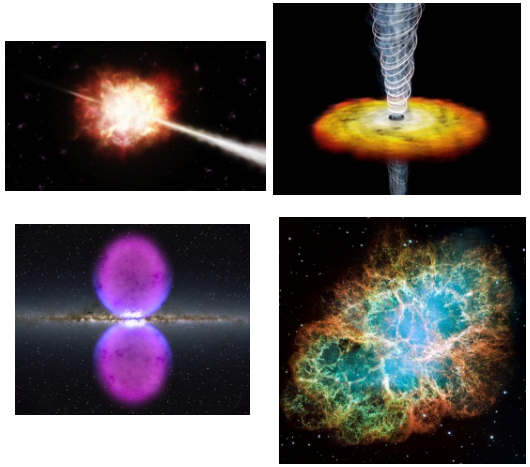


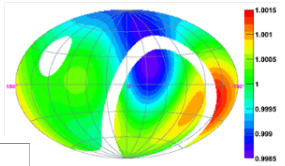
IC443 interacting with molecular clouds

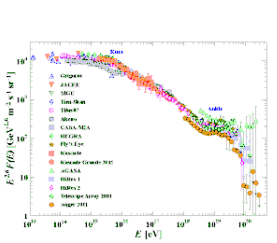


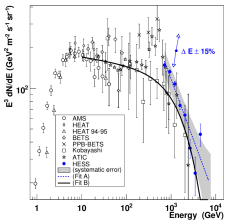
Physics of LHAASO

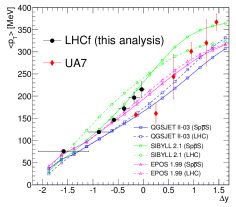
- VHE gamma sky survey (100 GeV-1 PeV):
  - Galactic sources;
  - Extragalactic sources & flares;
  - VHE emission from Gamma Ray Bursts;
  - Diffused Gamma rays.
- Spectrum measurement at the high end:
  - Nature of the acceleration: leptonic or hadronic;
  - Origin of cosmic rays – 100 years' mystery.
- Cosmic rays
  - Spectra of CR Species;
  - Anisotropy of VHE cosmic rays;
  - Cosmic electrons / positrons;
- Miscellaneous:
  - Gamma rays from dark matter;
  - Sun storm & IMF.

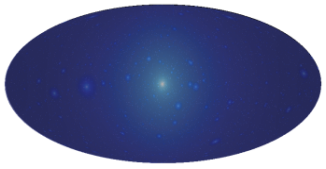


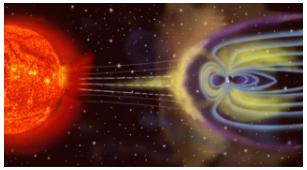












Summary

- EAS ground array has been proved to be a successful technique for VHE gamma ray astronomy with tremendous efforts in 30 years
- There are obvious advantages in observations on big and transient objects
- Even more promising potential is the precise measurement of the spectra at ultra high energy region which is more relevant to H/e origin of the gamma rays
- The next generation detector is around the corner ……

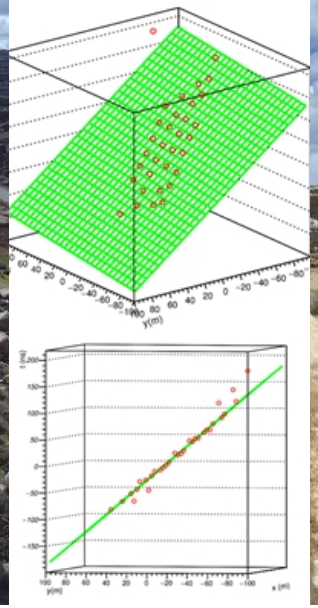
Construction of LHAASO-1/4

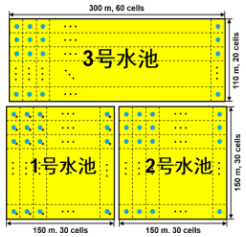
- Liner

1st muon detector

- 2018/02/04, first 33 scintillator detectors deployed.

The 1st LHAASO event

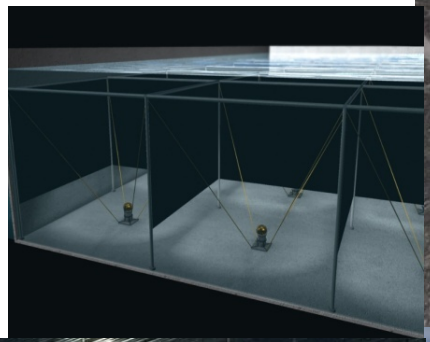




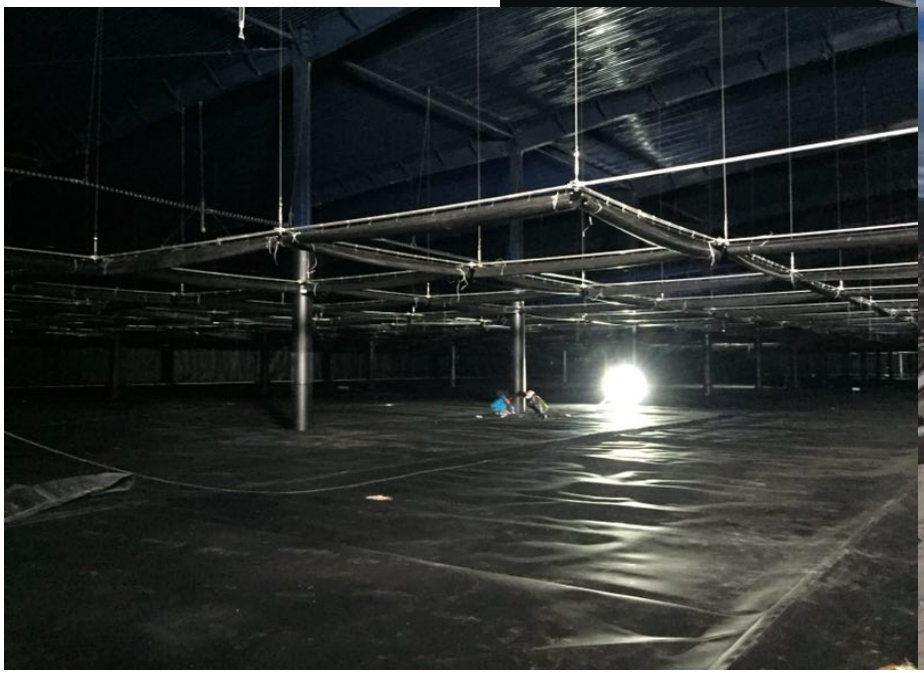
Construction

- #1 pool（150X150 m^2）is build
- 2018/04, #2 & #3 pools are started simultaneously

Installation Inside the pond



1st water pool



Differential sensitivity to point gamma ray sources

De Angelis, Mallamaci, arXiv:0805.05642