

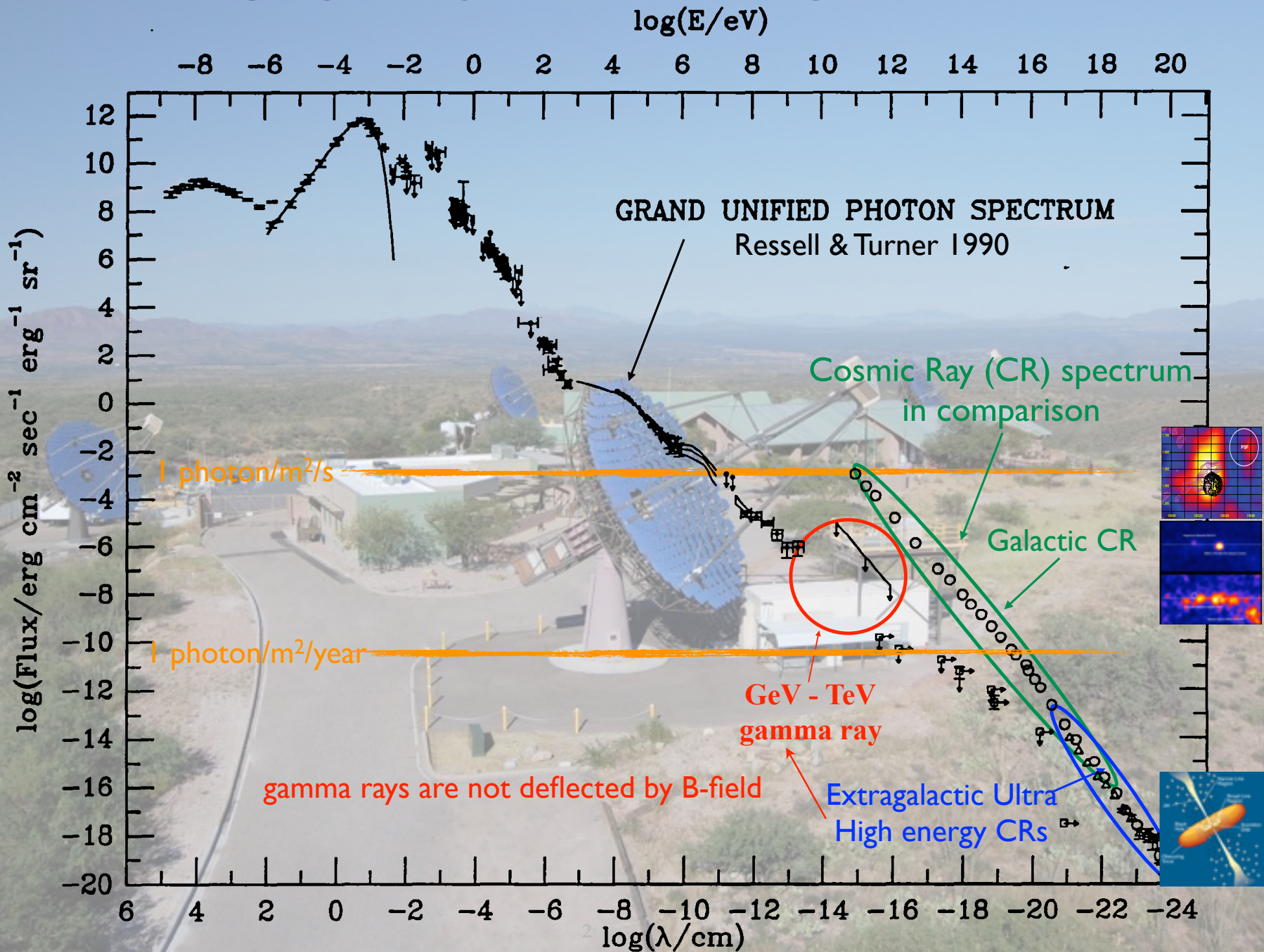
# RECENT HIGHLIGHTS FROM THE VERITAS GAMMA-RAY OBSERVATORY

Qi Feng, McGill University  
for the VERITAS Collaboration



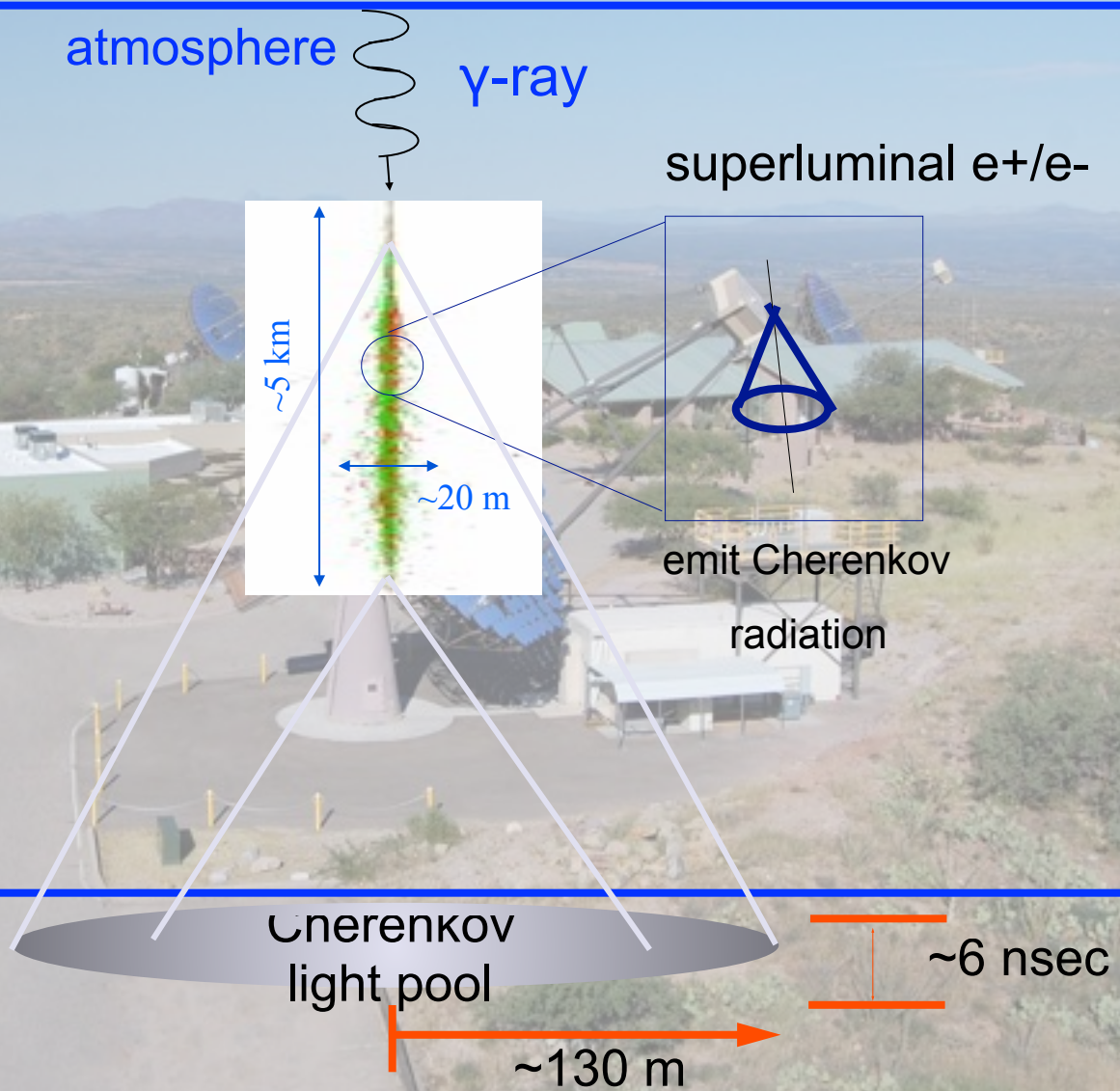


# WHY STUDY GAMMA RAYS

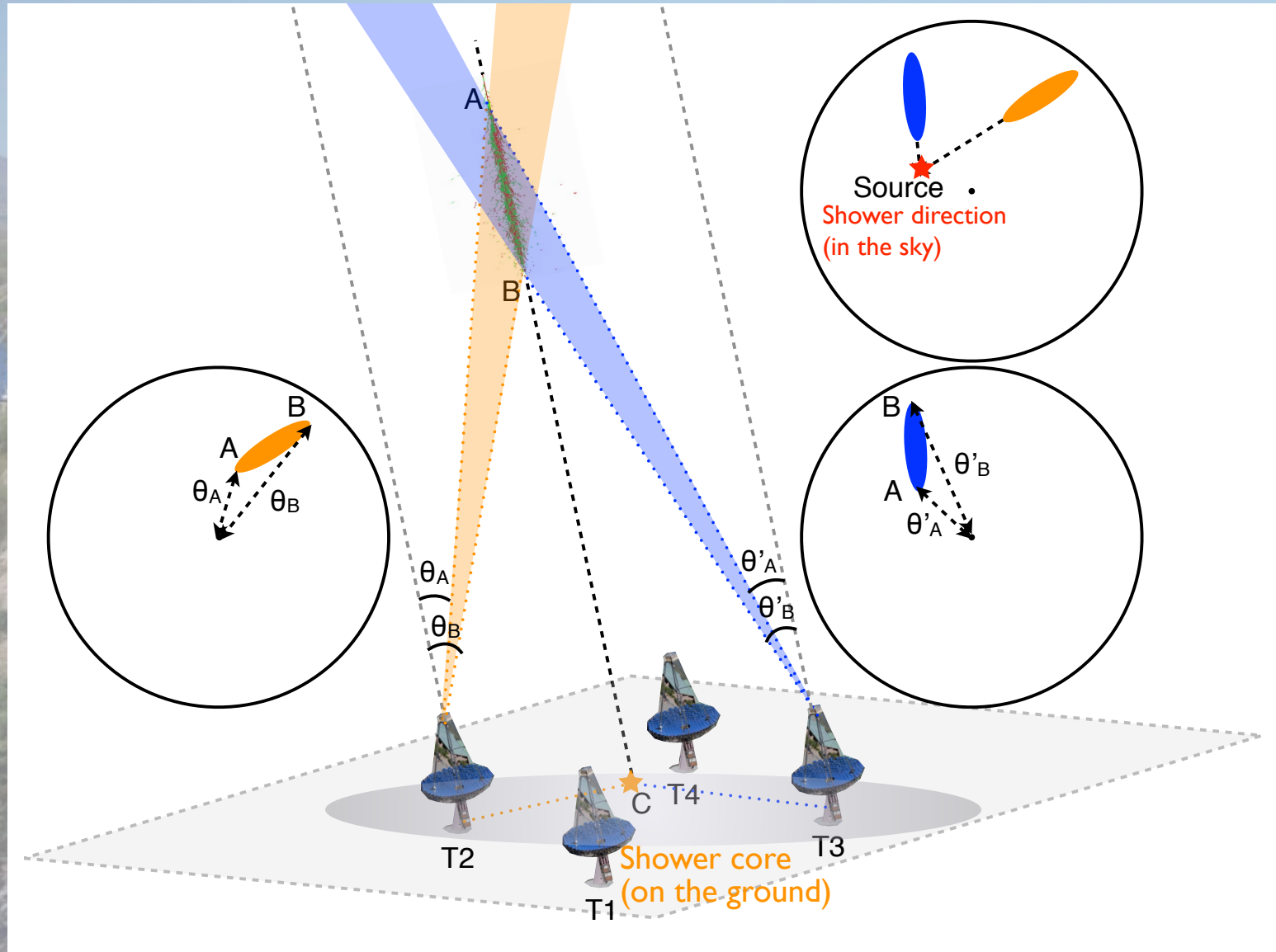




# Fast Cherenkov flash from air showers



# Stereo image of the shower gives the direction of the incoming gamma ray.



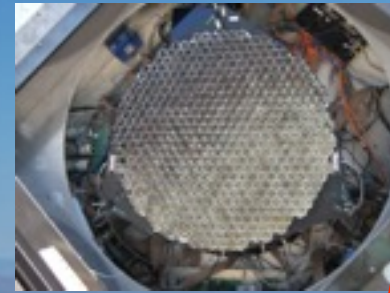




# VERITAS OVERVIEW

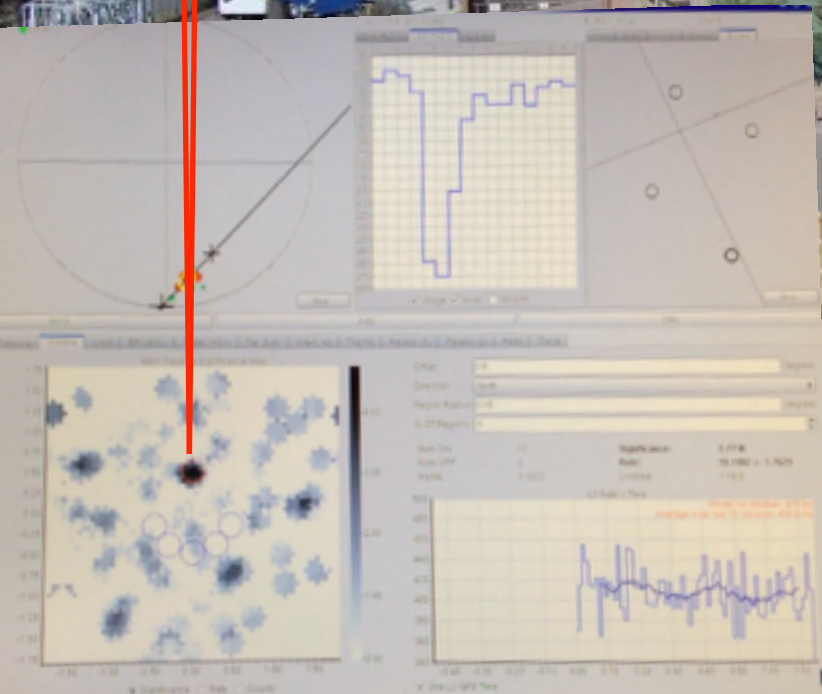
Very Energetic Radiation Imaging Telescope Array System (VERITAS)  
in southern Arizona

12-m mirrors,  
 $\sim 10^5$  m<sup>2</sup> effective area.



cameras:  
499 photomultiplier tubes (PMT),  
 $\sim 3.5$  deg field of view,  
 $\sim 0.08$  deg angular resolution  
@ 1 TeV.

real-time analysis:  
5-sigma detection on Crab  
with 1-minute exposure.



15-20% energy resolution;  
 $\sim 85$  GeV-30 TeV energy range;  
1% Crab detection in  $\sim 25$  hr;  
10% Crab detection in  $\sim 25$  min;  
 $\sim 20\%$  systematic uncertainty on flux;  
 $\sim 0.1$  sys. unc. on spectral index.

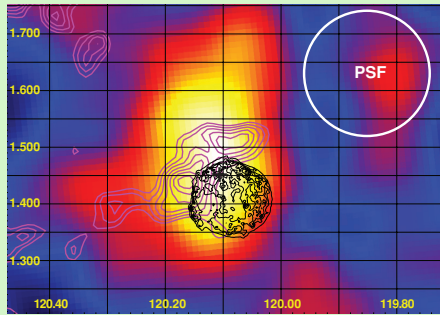


# VERITAS SCIENCE PROGRAM

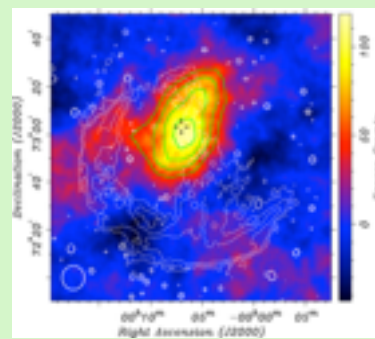
Galactic

54 sources detected

Extragalactic

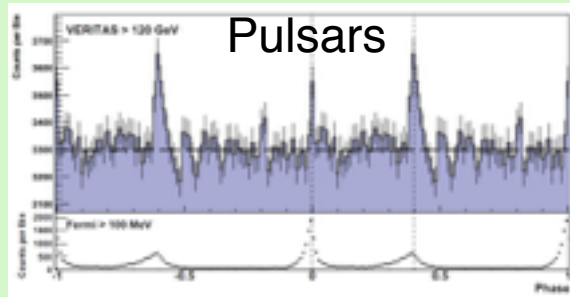


Supernova remnants



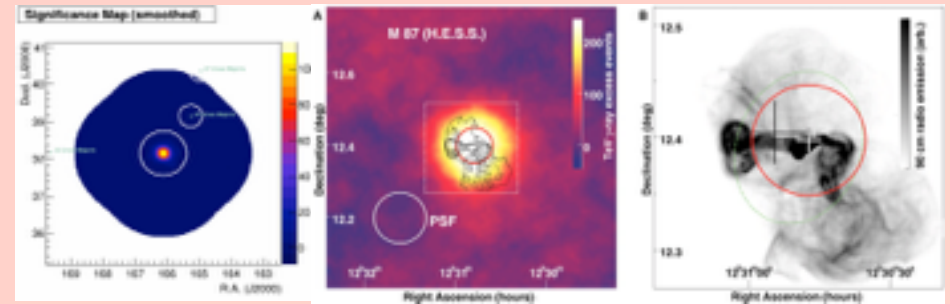
Pulsar wind nebulae

Supernova explosions



Pulsars

Radio-loud AGN



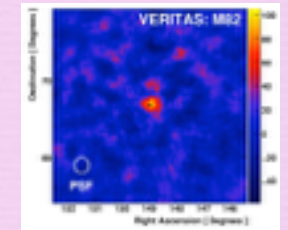
Blazars

Radio Galaxies

Transients follow-up

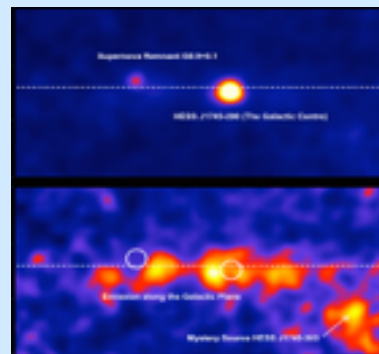
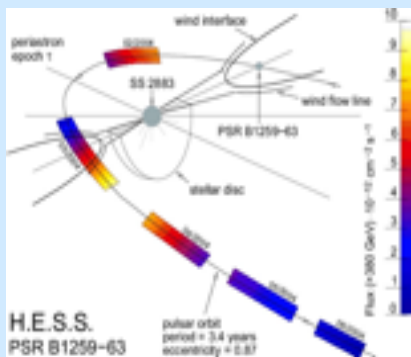
- Gamma-ray bursts;
- IceCube neutrino events;
- LIGO;
- HAWC.

Starburst galaxies



TeV binaries

Galactic center



Dark matter candidate

- Dwarf spheroidal galaxies;
- Galaxy clusters;
- Galactic center;
- DM subhalos.

Astroparticle physics

- Primordial black holes;
- Cosmic e+/e- spectrum;
- Lorentz invariance (violation).

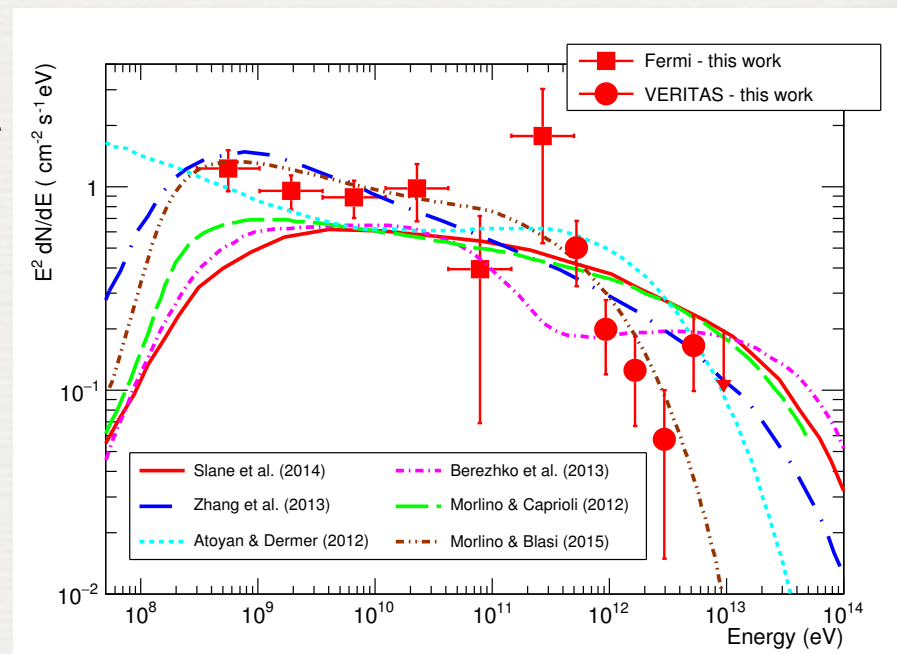
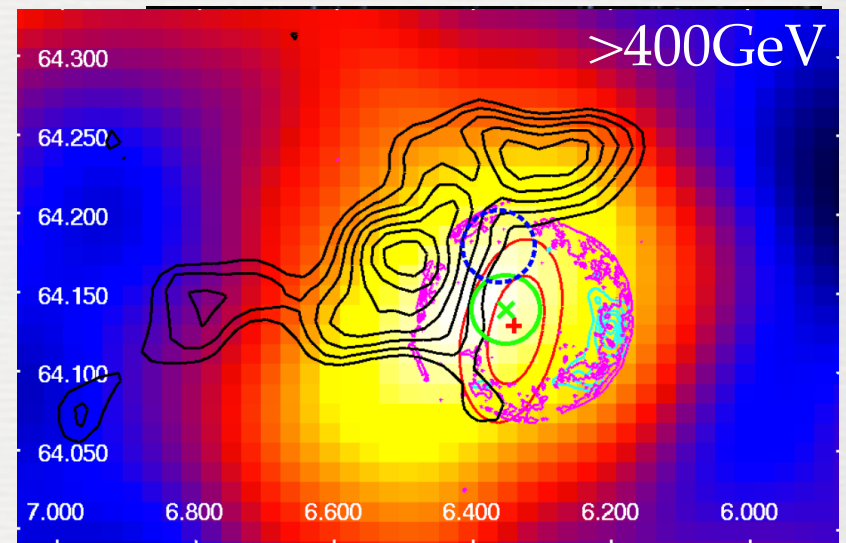


# SUPERNOVA REMNANTS

- Potential accelerators of Galactic cosmic ray particles
- Shock structure (e.g. X-ray)
- Young SNRs

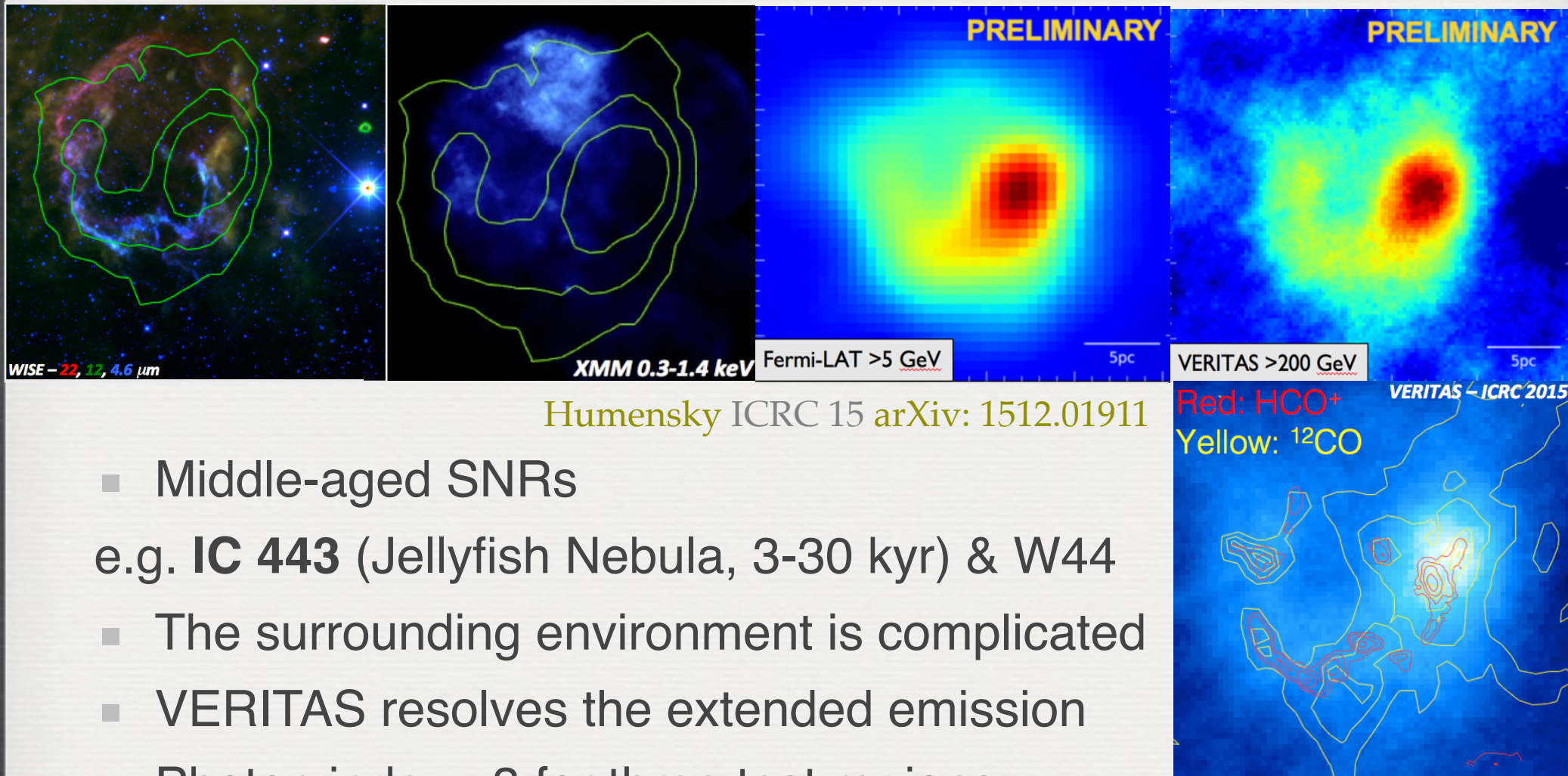
e.g. **Tycho** ( $\sim 444$  yr) & Cas A

- Both leptonic and hadronic models can describe the gamma-ray SED
- Photon index:  $2.92 \pm 0.42 \pm 0.20$



Park ICRC 15 arXiv: 1508.07068

# SUPERNOVA REMNANTS



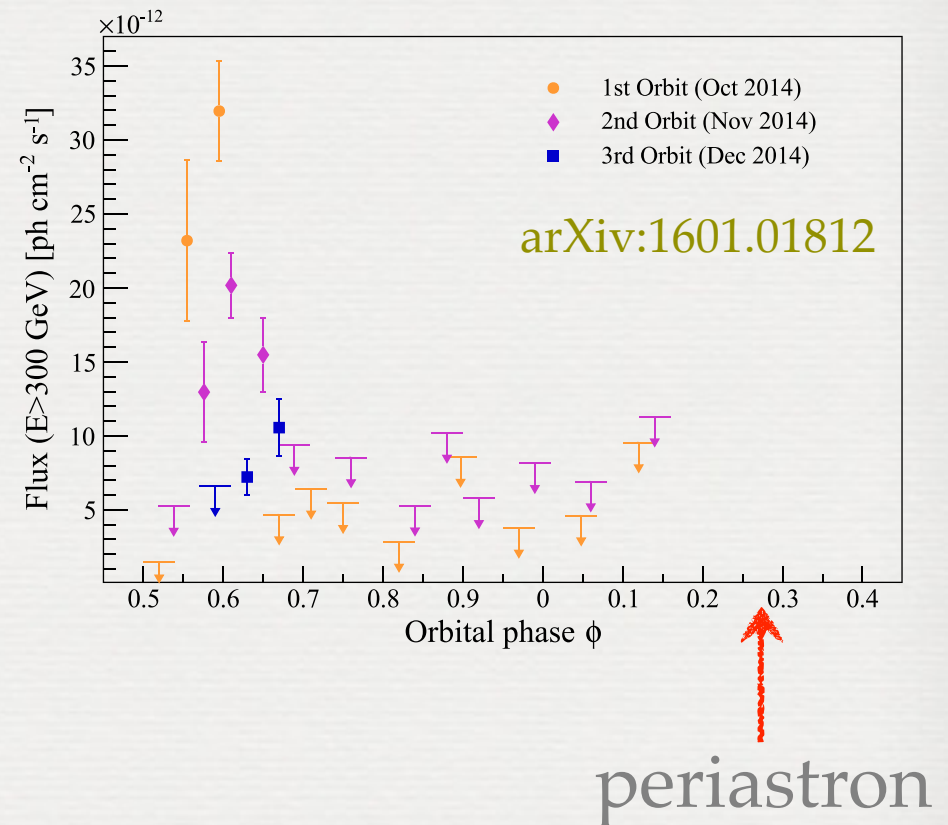
Humensky ICRC 15 arXiv: 1512.01911

- Middle-aged SNRs
- e.g. **IC 443** (Jellyfish Nebula, 3-30 kyr) & W44
- The surrounding environment is complicated
  - VERITAS resolves the extended emission
  - Photon index  $\sim 3$  for three test regions



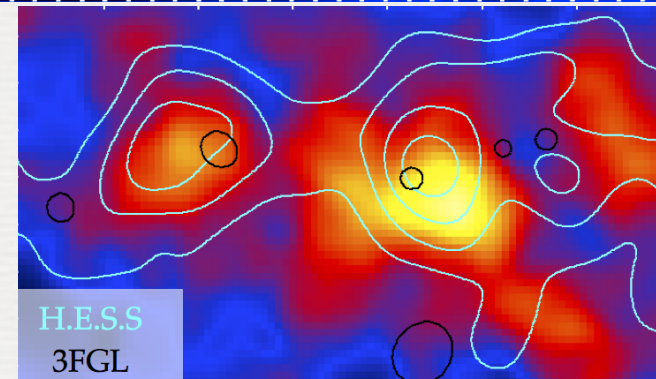
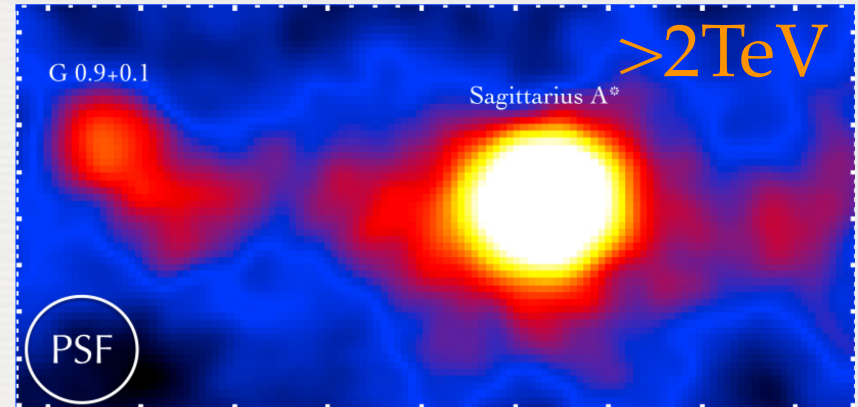
# GAMMA-RAY BINARIES

- e.g. **LS I +61 303** (and HESS J0632+057):
  - orbital period: 26.5 days
  - periastron: 0.1 AU
  - apastron: 0.7 AU
  - TeV activities correlated with X-ray, but not GeV.
- Possible scenario:
  1. micro-quasar with a jet
  2. pulsar binary with shock from interactions between stellar and pulsar wind



# GALACTIC CENTER

- Large zenith angle observations (large effective area at high energies)
- Point sources: Sgr A\* and G0.9+0.1 (composite SNR)
- Residual diffuse emission: VER J1746-289  
 $l = 0.86^\circ \pm 0.015^\circ \pm 0.013^\circ$   
 $b = 0.067^\circ \pm 0.02^\circ \pm 0.013^\circ$   
(Sgr B2 not detected at 4.1 sigma)
- Dark matter search

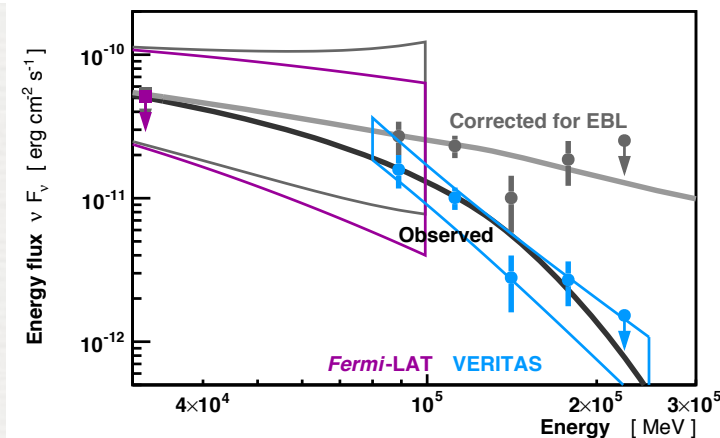
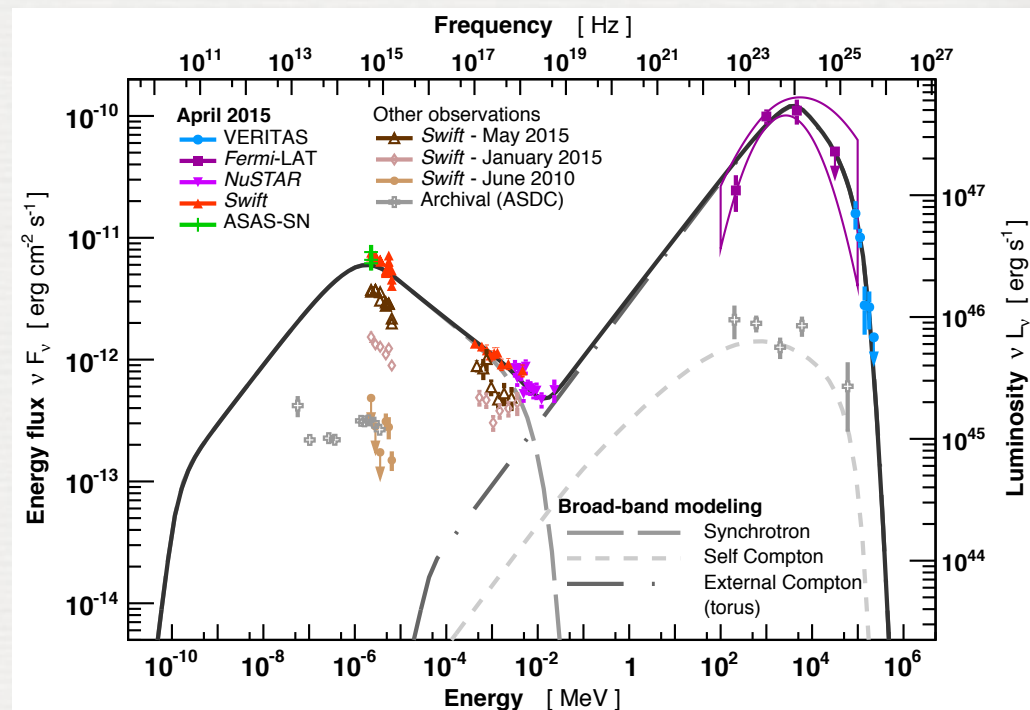


Archer+ 2016, arXiv: 1602.08522



# ACTIVE GALACTIC NUCLEI

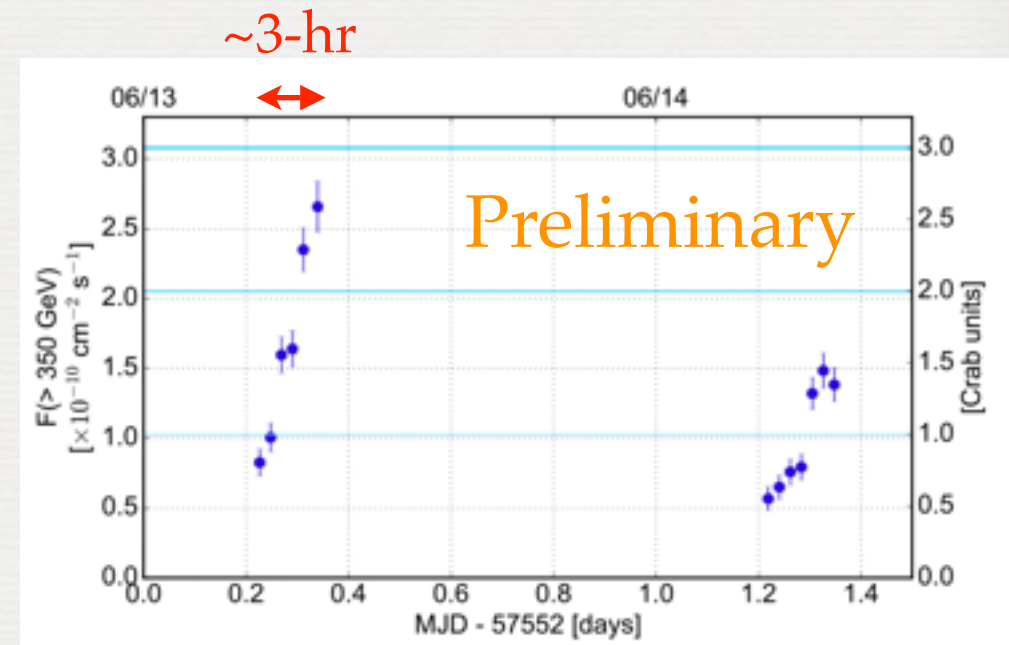
- Double-peak SEDs
- Variable; MWL important
- Distant blazars: constraints on extragalactic background light
- PKS 1441+25 ( $z \sim 0.94$ )
- VERITAS detection at  $8\text{-}\sigma$  in  $\sim 15$  hr, spectral index  $-5.3 \pm 0.5$  puts constraint on EBL density



Abeysekara+ 2015, arXiv: 1512.04434

# ACTIVE GALACTIC NUCLEI

- Flaring blazars:  
constraints on size and emitting models
- **1ES 1959+650** flare in 2016 June (Atel #9148)  
>2.5 Crab peak flux
- BL Lacertae flare on 2016 Oct 5 (Atel #9599)  
>1 Crab peak flux, sub-hour variability

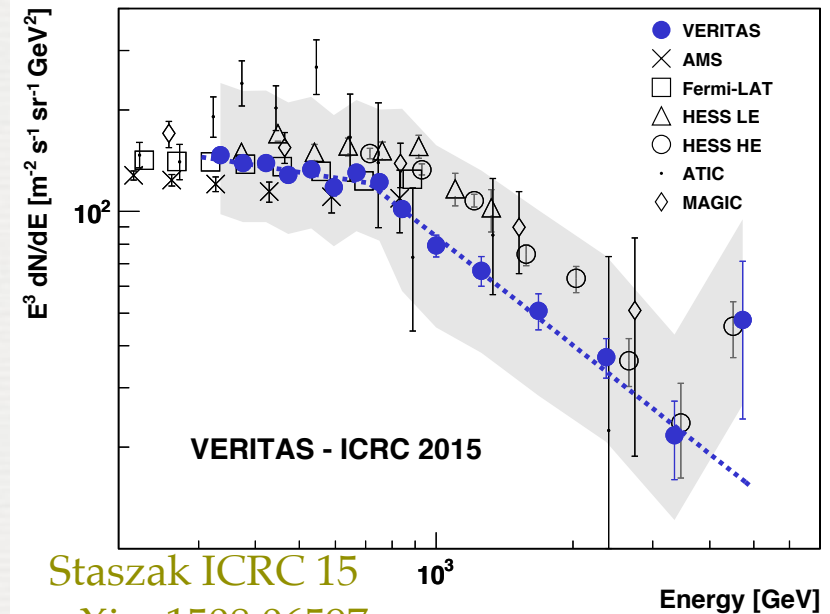


arXiv: 1609.02881

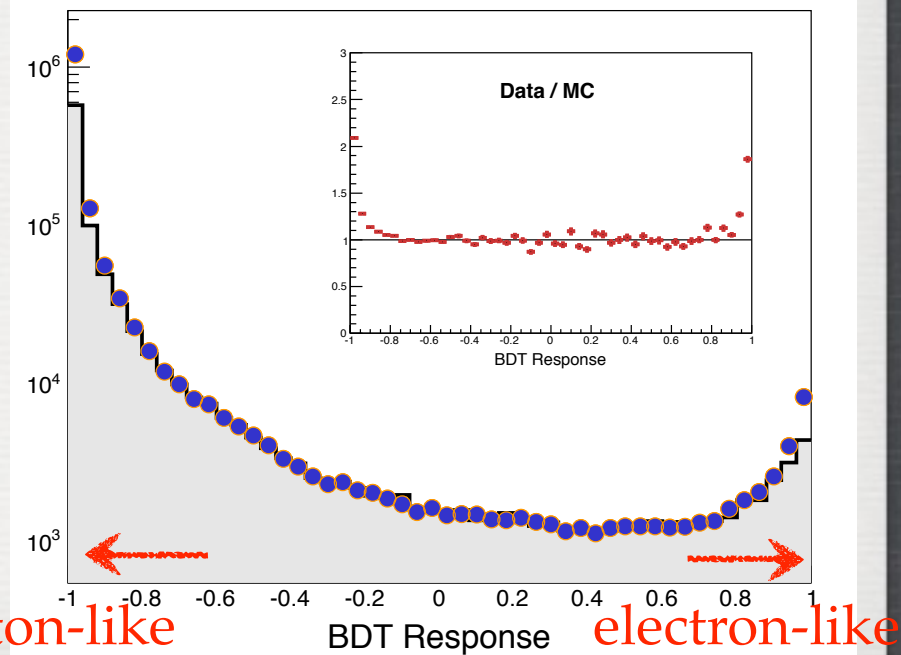


# COSMIC-RAY ELECTRONS

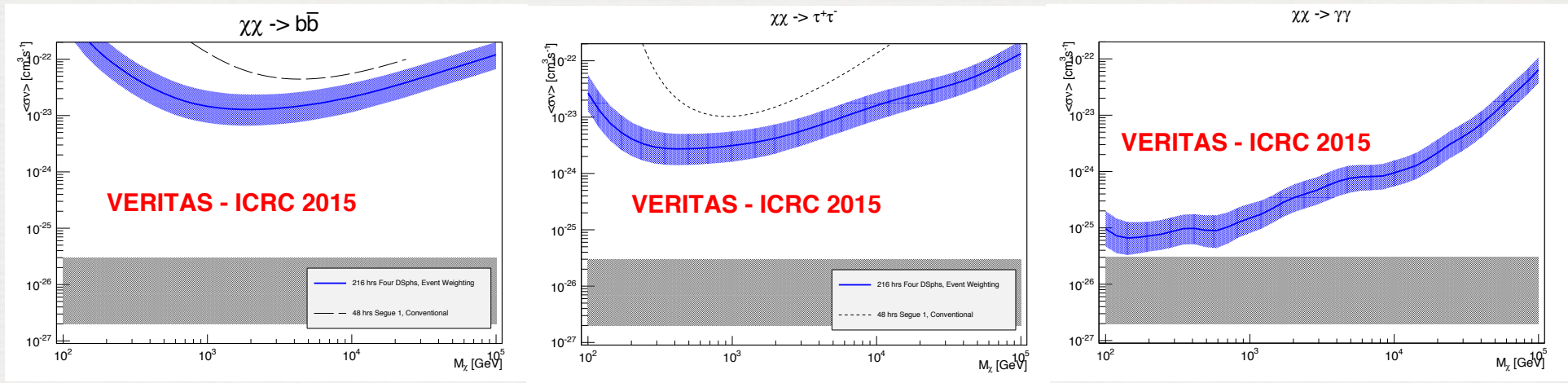
- Probes local  $e^+/e^-$  (cool fast)
- Isotropic: challenge on background estimation; use BDT
- 296 hrs of data after quality cuts
- Spectral break at  $710 \pm 40$  GeV, spectral index  $-3.2 \rightarrow -4.1$ , statistical uncertainty  $\sim 0.1$ , systematic uncertainty  $\sim 20\%$ .



Staszak ICRC 15  
arXiv: 1508.06597



# DARK MATTER

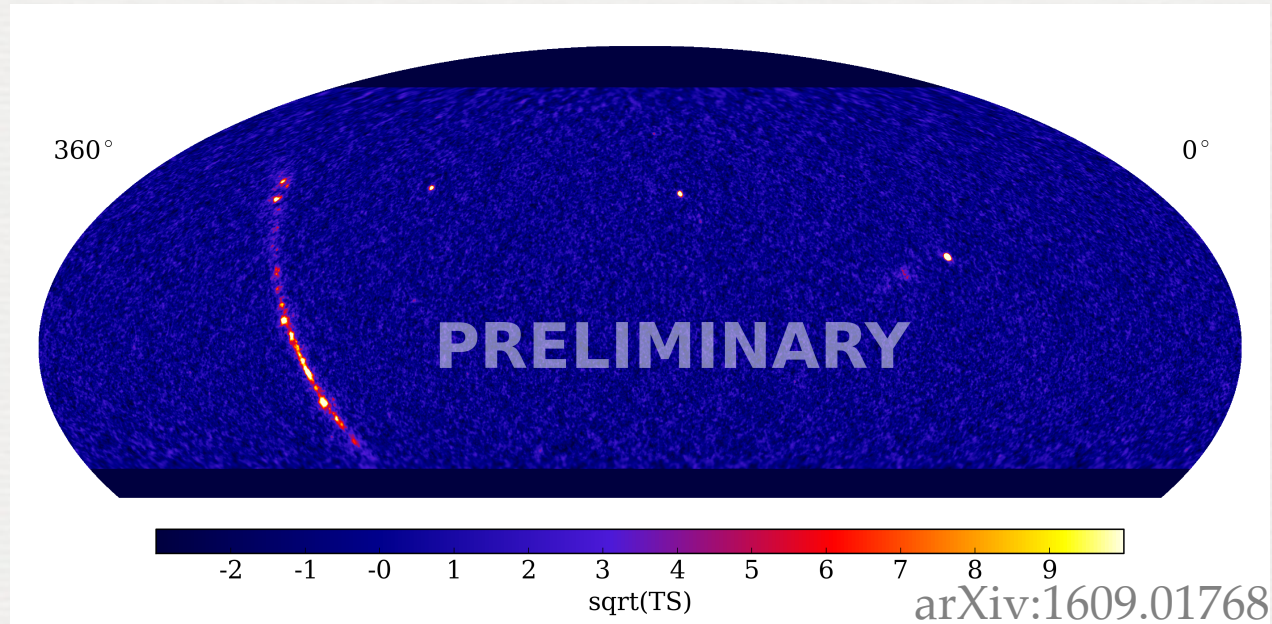


Zitzer ICRC 15 arXiv:1509.01105

- Dwarf spheroidal galaxies (dSphs):  
high M/L ratio, low astrophysical background
- Combined  $\sim 216$ -hr data on 4 dSphs, no detection
- Constraints on DM annihilation cross section derived



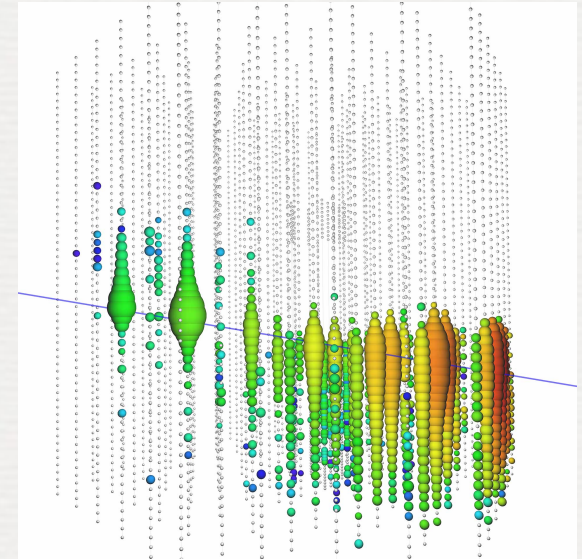
# HAWC FOLLOW-UP



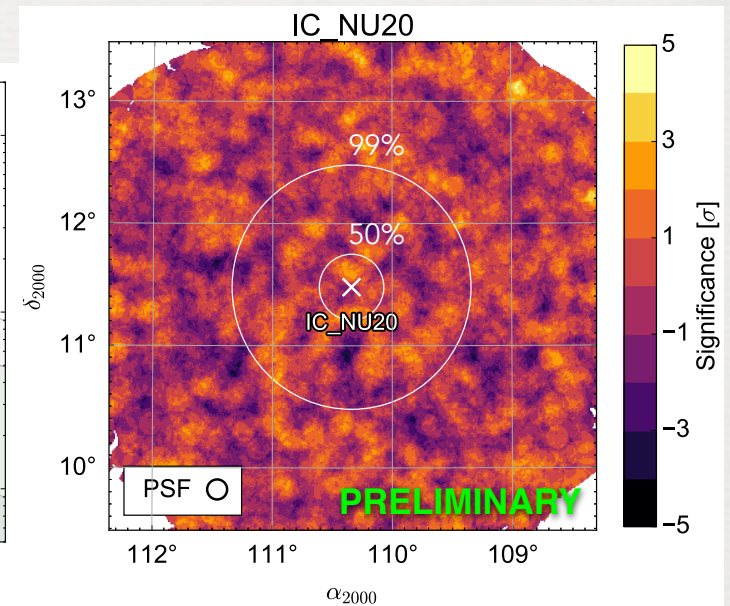
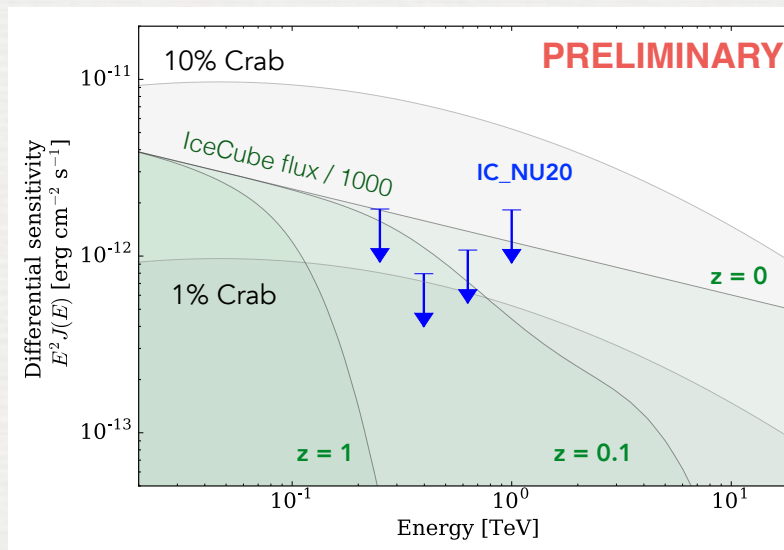
- HAWC: ground-based gamma-ray survey instrument.
- VERITAS is searching the archival data for previously unidentified HAWC sources.
- VERITAS can also trigger ToO on HAWC alerts.

# ICECUBE FOLLOW-UP

- VERITAS followed up 28 northern muon track events, no detections so far
- Multi-PeV muon neutrino detected on 2014 Jun 11,  $\sim 1.8$  hr VERITAS data on 2016 Mar 27, UL at 0.1% all-sky astrophysical neutrino flux.



$2.6 \pm 0.3$  PeV (arXiv:1607.08006)



Santander ICRC 15  
arXiv:1509.00517

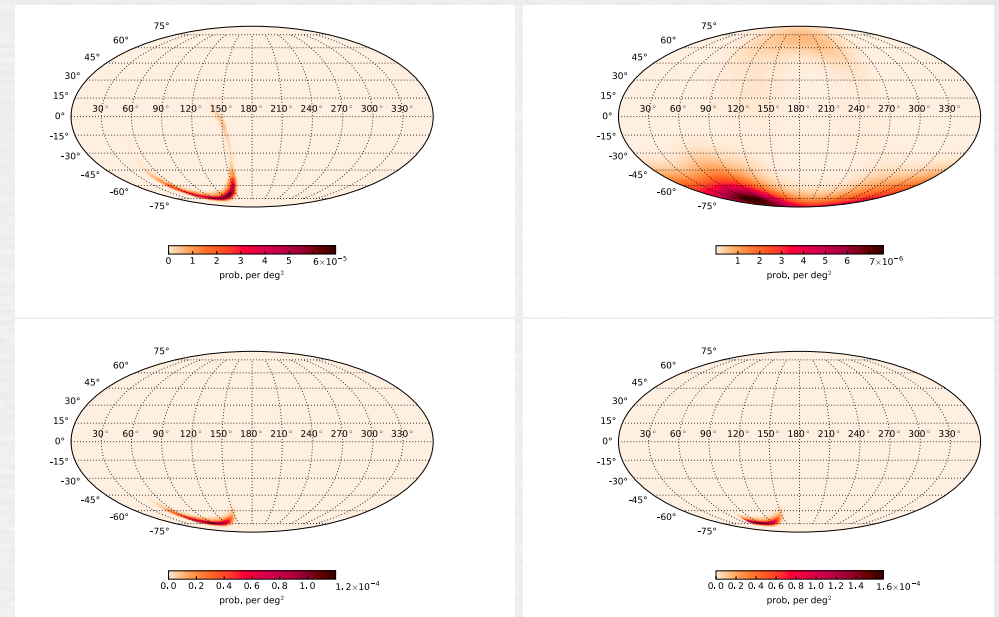
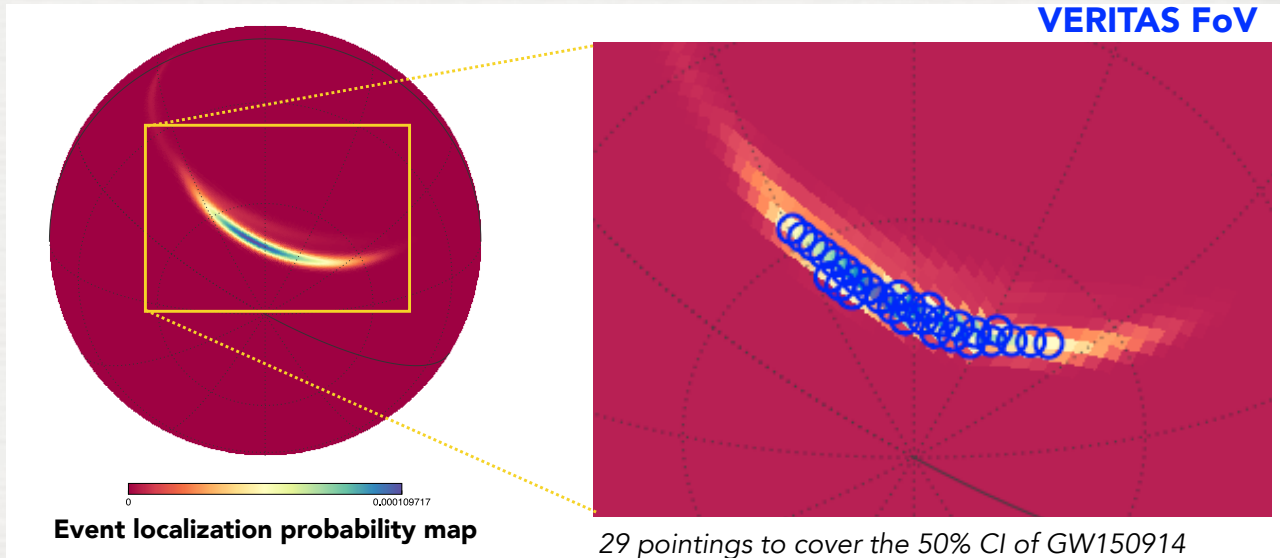


# ICECUBE FOLLOW-UP

- High-energy starting event (HESE); 14 track events in 4-year IceCube data
- Fast: VERITAS followed up IceCube event 160427A within ~3 minutes of its detection (<http://gcn.gsfc.nasa.gov/gcn3/19377.gcn3>)
- Angular error: 90% of the time 8.9 deg (50% of the time 1.6 deg)

# LIGO FOLLOW-UP

- GW150914:
- BH-BH merger:  
**no** strong gamma-ray emission predicted.
- NS-NS/NS-BH merger:  
possible short GRB,  
GBM event 0.4 s after.
- ~30 VERITAS  
pointings to follow up.



arXiv: 1602.03920



# SUMMARY AND OUTLOOK

- VERITAS continues to run smoothly and contribute actively to a wide range of scientific topics
- Existing and new multi-wavelengths and multi-messenger partnerships are emphasized
- Funding secure until 2019
- A mid-size CTA prototype is being built on site