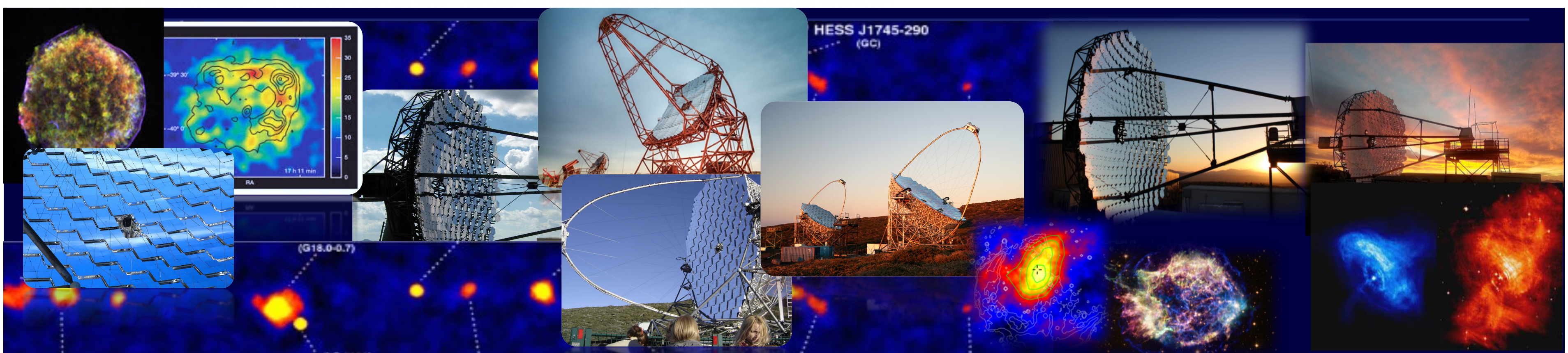
The Current Generation of Imaging Atmospheric Cherenkov Telescopes

Reshmi Mukherjee
Barnard College, Columbia University



The Legacy of Michael Hillas

It is shown that it should be possible to distinguish very effectively between background hadronic showers and TeV gamma-ray showers from a point source on the basis of the width, length and orientation of the Cerenkov light images of the shower, seen in the focal plane of a focusing mirror, even with a relatively coarse pixel size such as employed in the Mt. Hopkins detector.

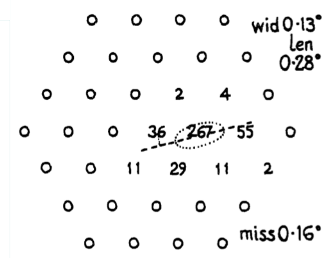


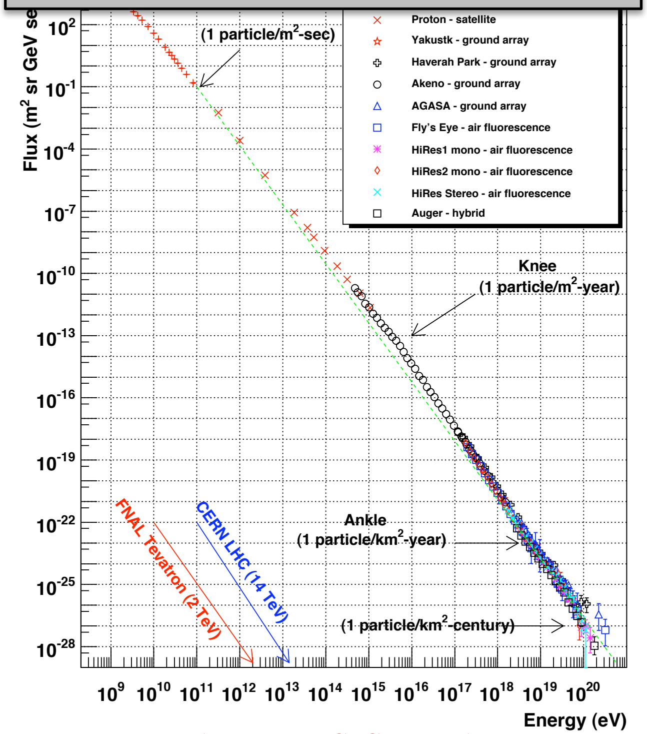
Figure 1.

Michael Hillas, OG 9.5-3, ICRC 1985

- Michael Hillas' work (1985) has directly led to the development of the sensitive IACTs, MAGIC, VERITAS, and H.E.S.S.
- First γ–ray source, the Crab Nebula, was unambiguously detected by the Whipple telescope in 1989.
- The current-generation IACTs have opened a new window on the universe. We now have a catalog of more than 200 TeV sources.
- The successes of the current IACTs has propelled the development of CTA, the next-generation VHE instrument.
- There are now more than 1400 scientists in 31countries working in the field of very-high-energy gamma-ray astrophysics.

Astrophysical Drivers for E > 100 GeV

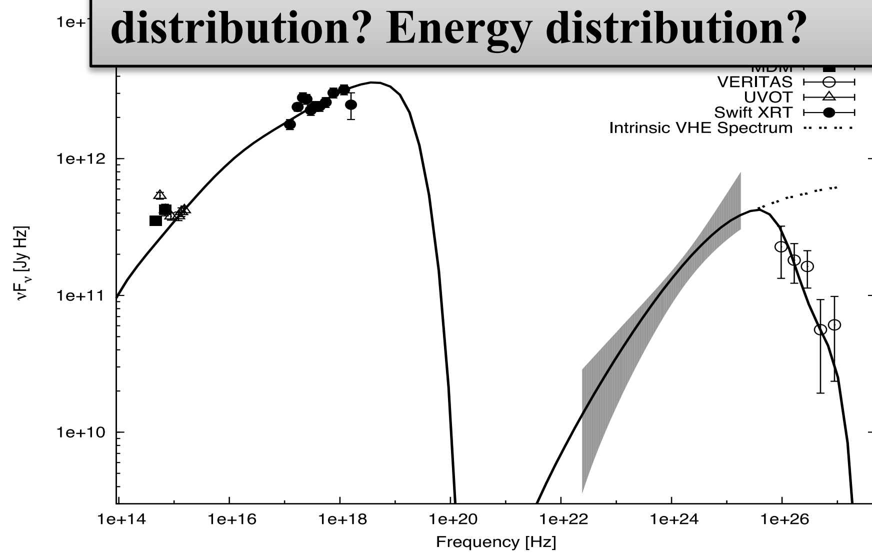
Origin of Cosmic Rays? Diffuse, all particle spectrum



Whanlon (based on S. Swordy)

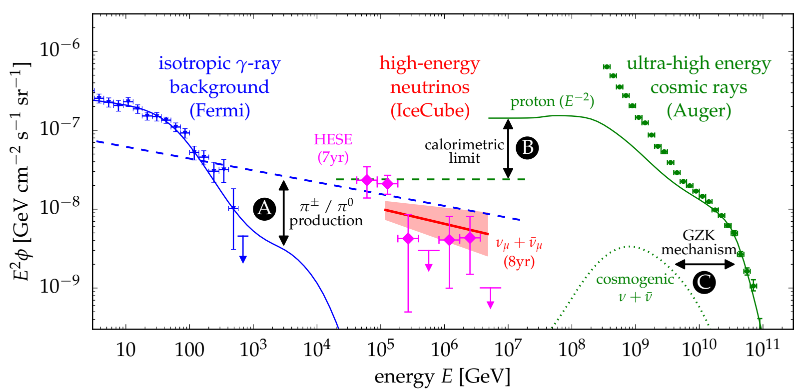
Neutral messengers: γ, ν are required to directly observe cosmic accelerators.

Nature of primary particles? Spatial distribution? Energy distribution?



Acciari et al. ApJL 2010

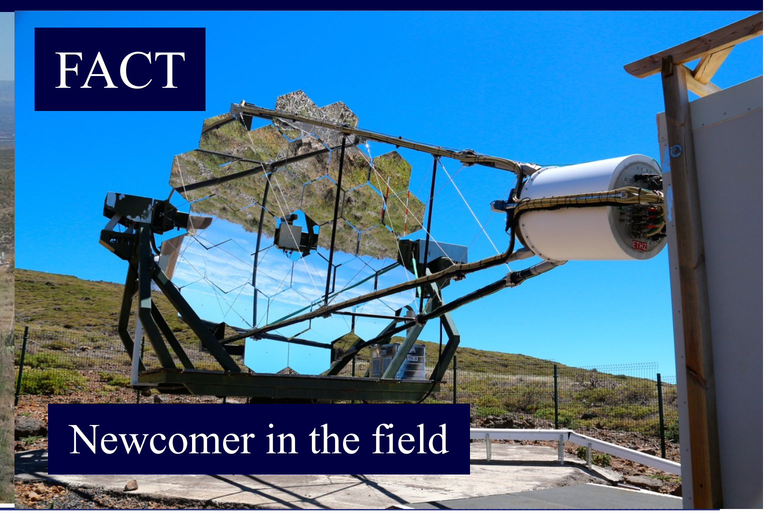
Diffuse HE backgrounds



Ahlers et al. (2018)

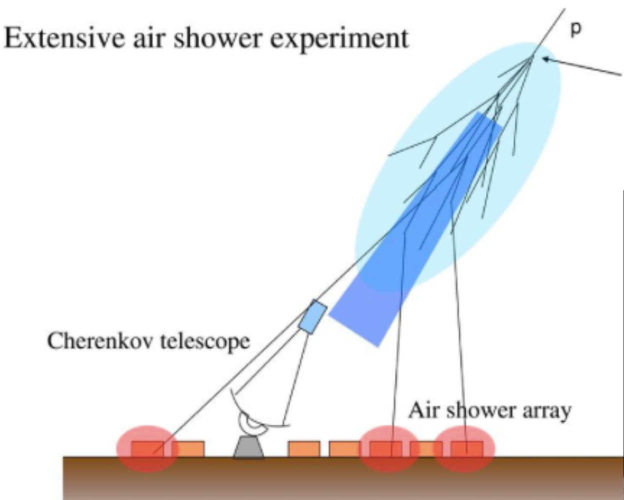
The Three Major IACTs

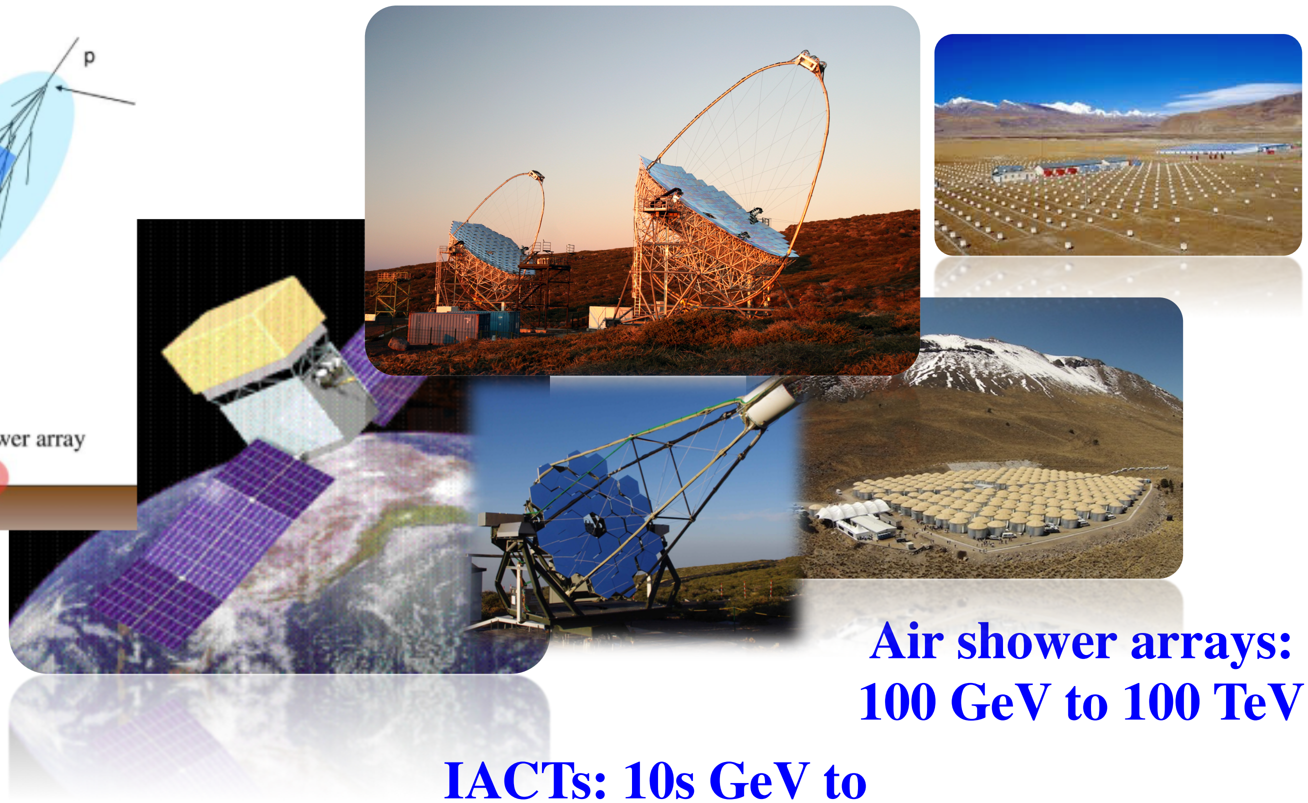
Viewing Cosmic Particle Acceleration from ~ tens of GeV to ~30 TeV



IACTs in Context

IACTs offer large effective area (~ 10^5 m^2) over a wide energy range.





Air shower arrays: 100 GeV to 100 TeV

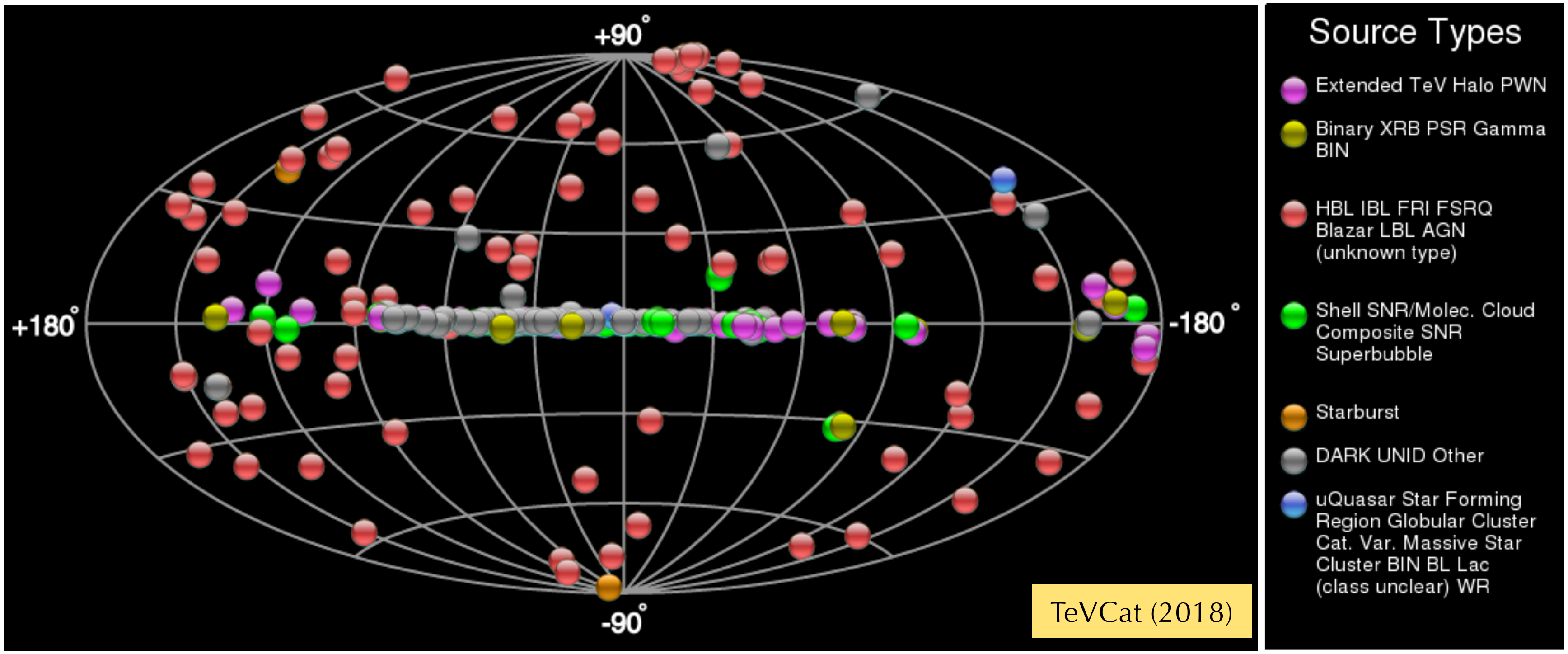
IACTs: 10s GeV to > 30 TeV

Satellites: 100 MeV to > 30 GeV

Some Highlights from the last 10 years

VHE Gamma-Ray Sky (2018)

γ-rays: Highly effective tracers of particle acceleration. Several different classes of TeV emitters.

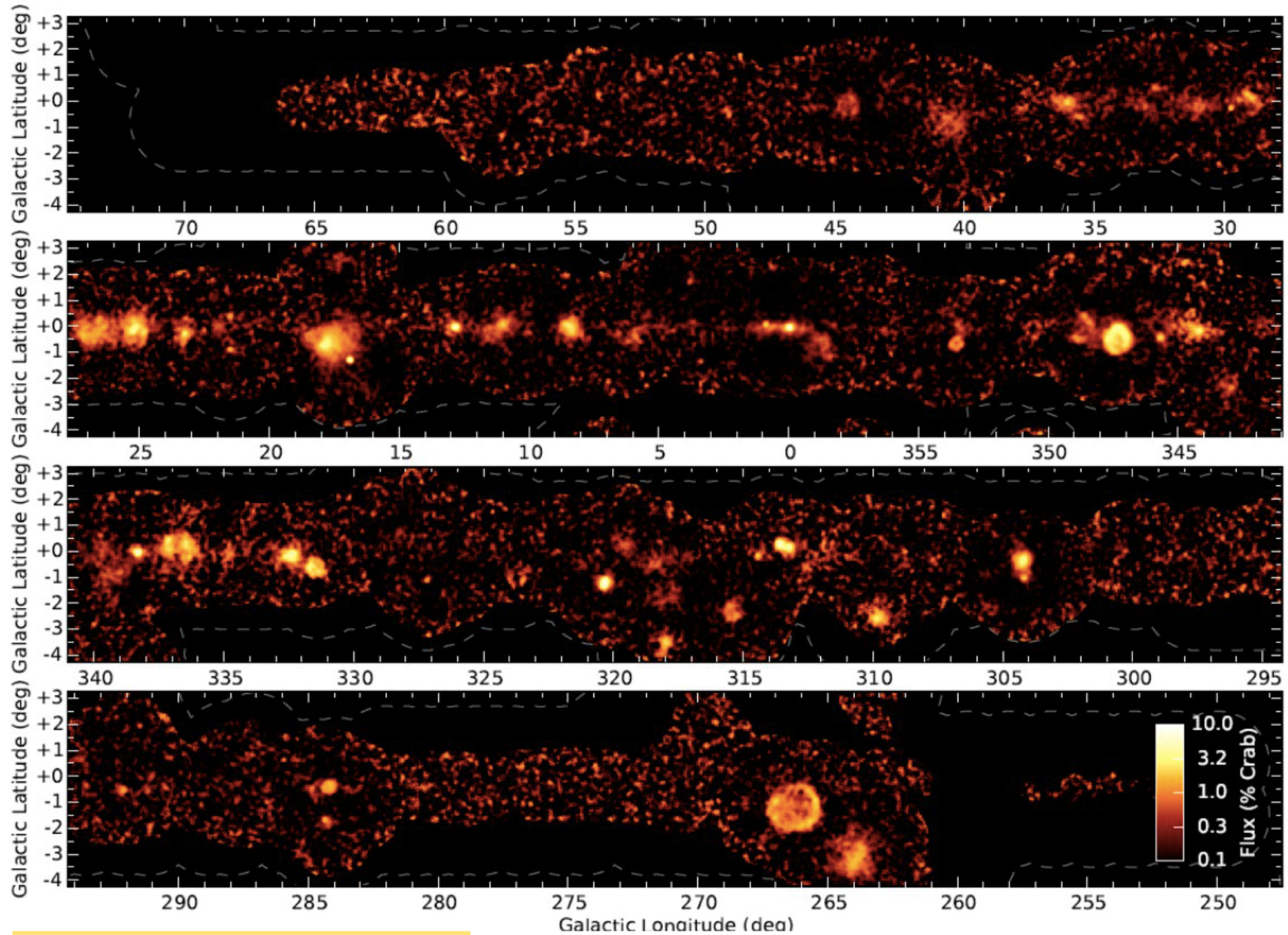


Key Capabilities of IACTs:

- Best sensitivity for observing γ-ray emission on short time scales
- Detection of AGN out to cosmological redshifts
- Excellent spectral coverage
- Best angular resolution

Gamma-Ray Surveys: H.E.S.S. GPS

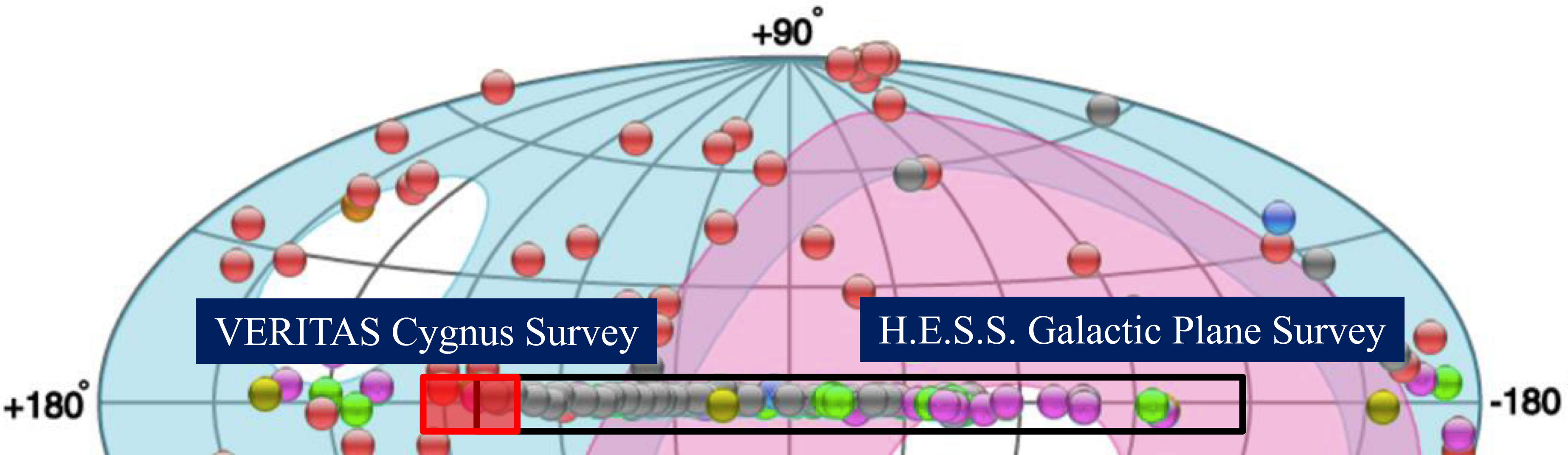
The deepest and most comprehensive, high resolution (~ 0.1°) and sensitive (<2% Crab Nebula) survey of the Milky Way in very-high-energy γ-rays.

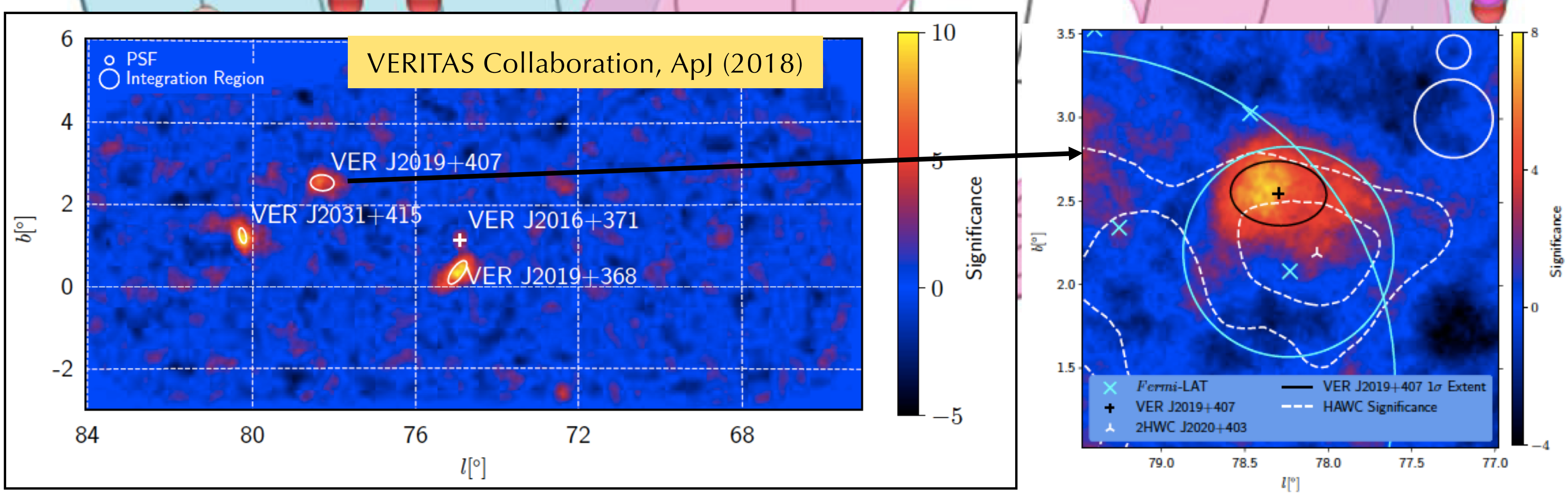


H.E.S.S. Collaboration (2017)

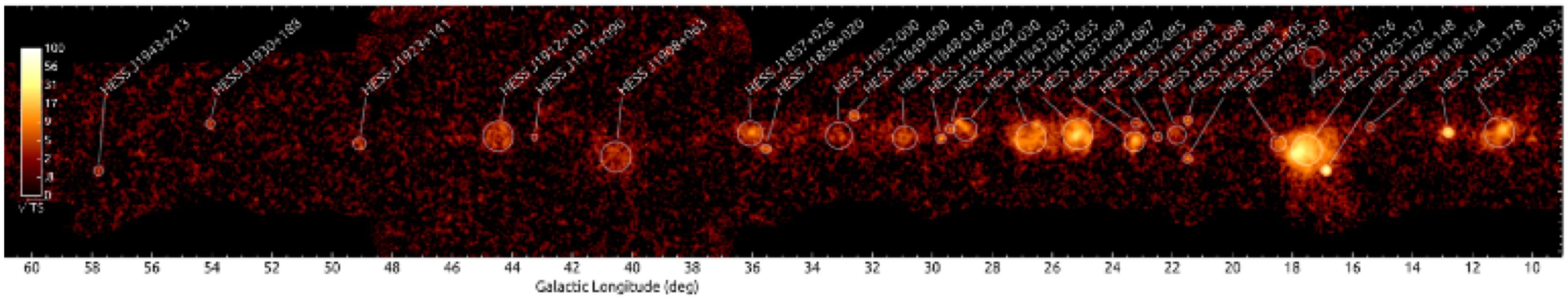
- The first high resolution survey of our Galaxy.
- Different classes of Galactic sources.
- The Milky Way is aglow with TeV γ-ray emission!
- 78 sources, 36 unidentified.
- Population studies are now possible.

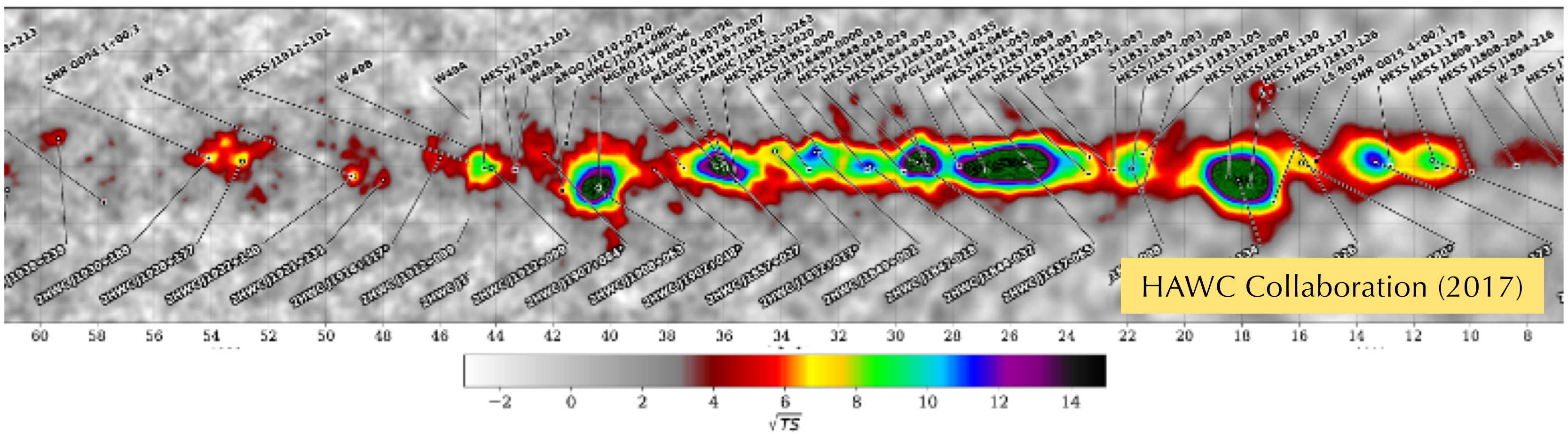
Gamma Ray Surveys: Cygnus Region





HAWC Galactic Plane Survey Follow-ups



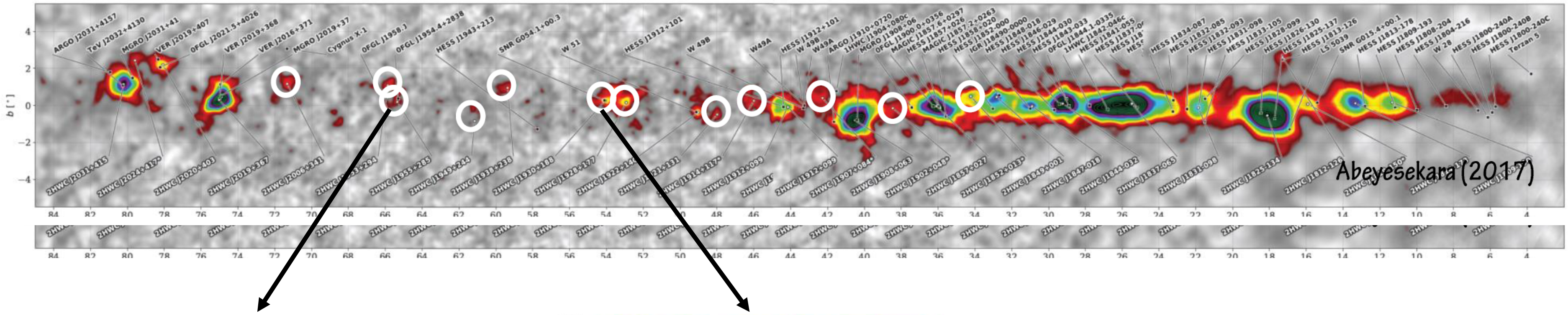


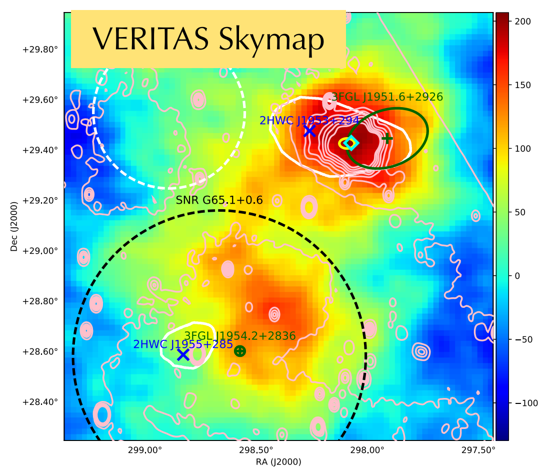
- 15 HAWC sources associated with H.E.S.S. sources.
- 7 HAWC sources undetected by IACTs
  - lack of sensitivity to very extended sources?
  - energy-threshold effects?

H.E.S.S. Collaboration, A&A (2018)

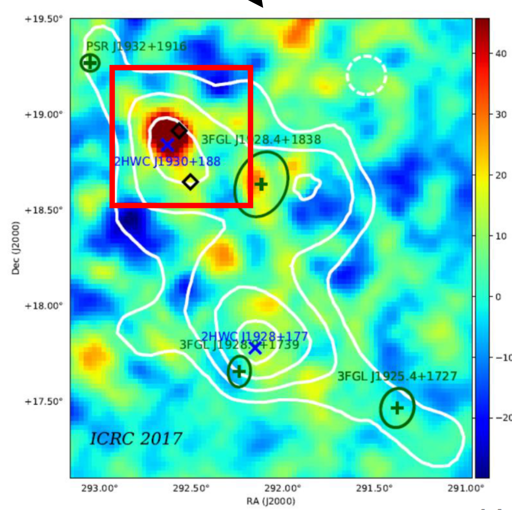
In-depth Studies of HAWC Sources

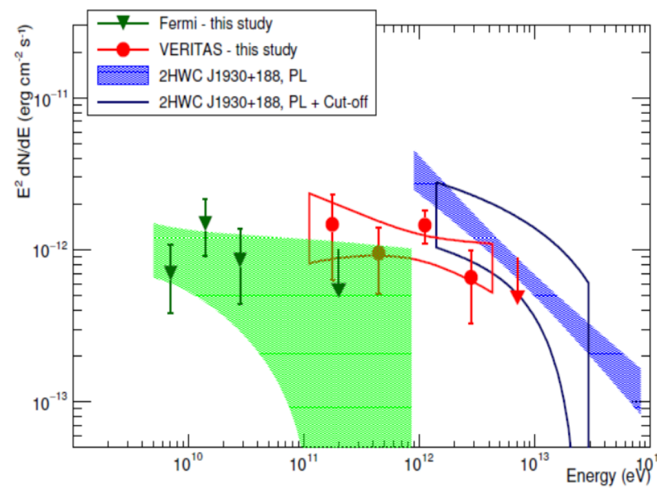
HAWC: 507 days of observation, found 39 γ-ray sources





Detection: 2HWC J1953+294 = VER J1952+294 (DA 495)



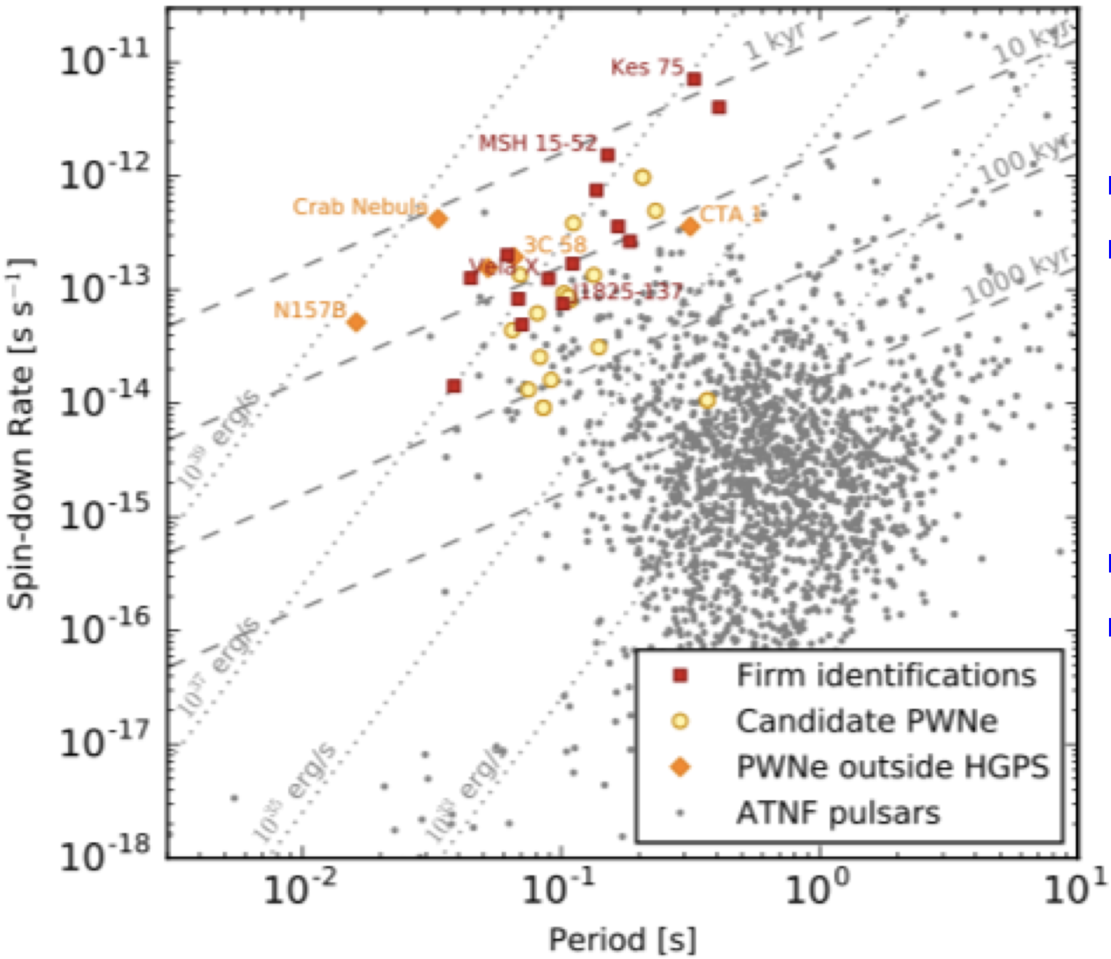


SNR G54.1+0.3, PWN of PSR J1930+1852

VERITAS + HAWC Collaborations, ApJ (2018)

Population Studies – Pulsar Wind Nebulae

Galactic cosmic accelerators: Population of TeV PWNe in the H.E.S.S. GPS



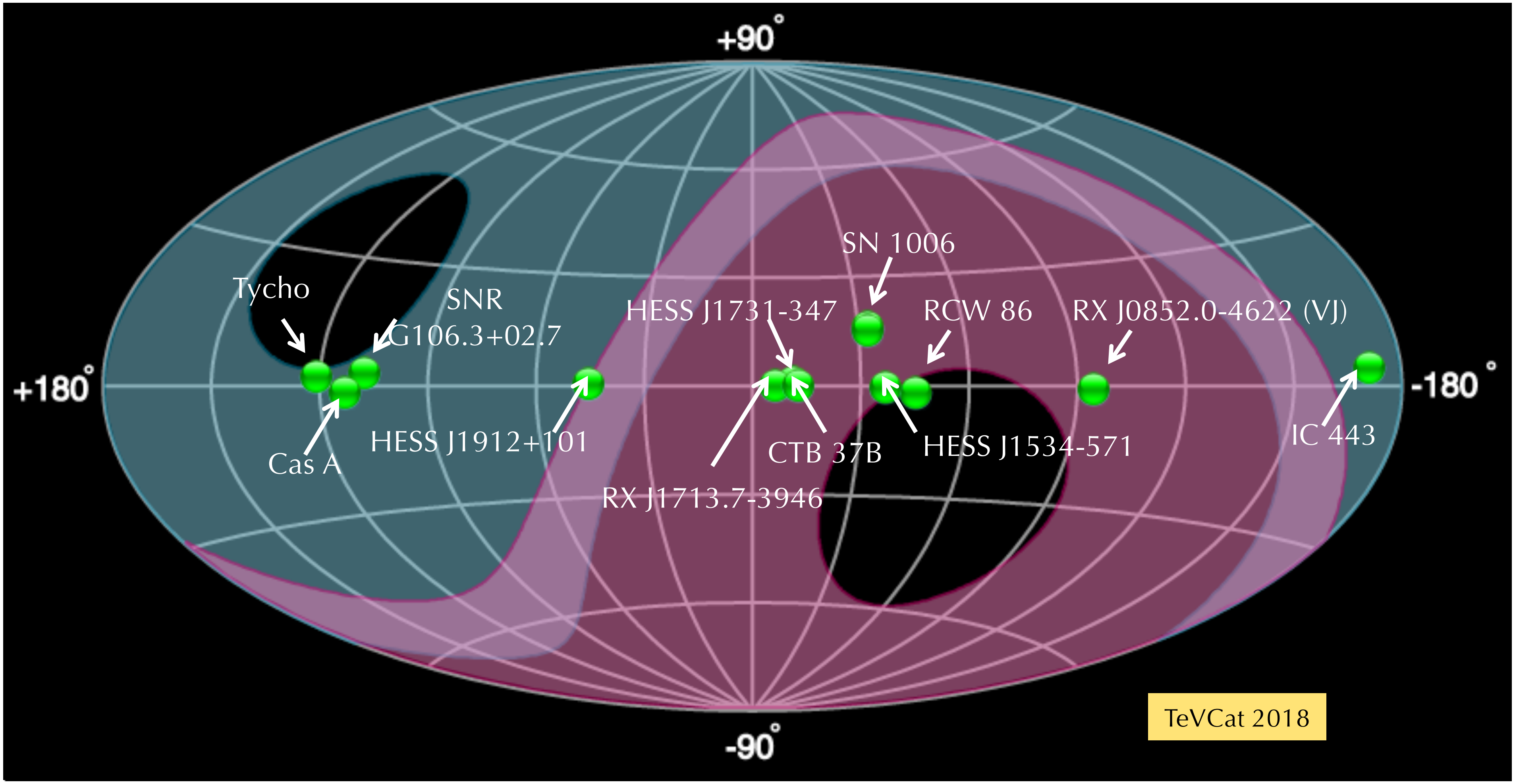
- Best studied: Crab Nebula
- Only young, energetic pulsars grow TeV PWNe that are bright enough for detection with the current IACTs.

- ~ 50% have $E_{dot} > 10^{37}$ ergs s^{-1}
- ~ 2/3 have $E_{dot} > 10^{36}$ ergs s^{-1}

H.E.S.S. Collaboration A&A (2018)

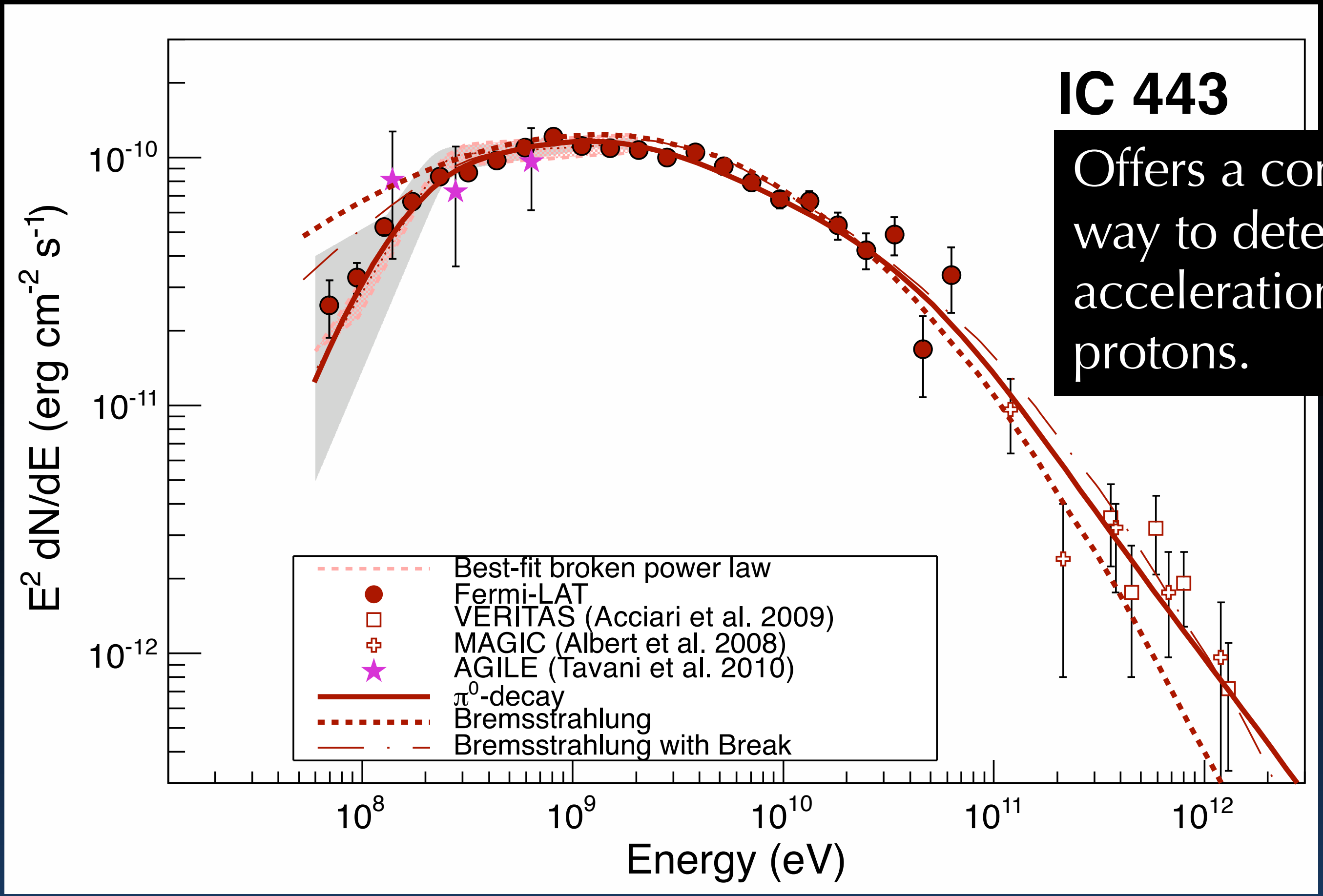
Sources of Cosmic rays: SNRs (Shells)

Galactic cosmic ray accelerators: Supernova Remnants



Protons Interacting with Clouds?

Ackermann et al. 1302.3307

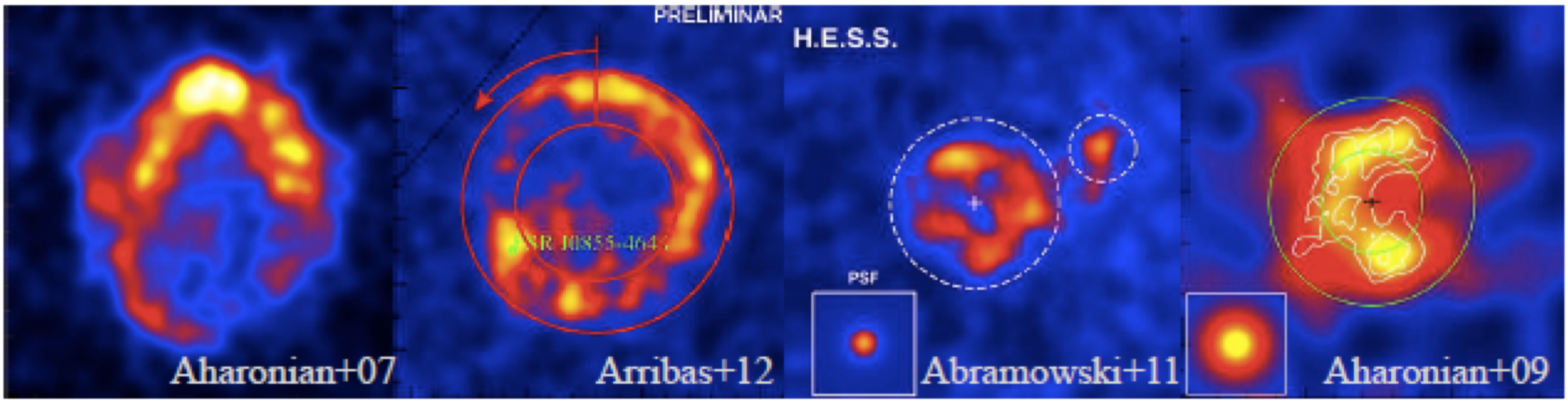


Offers a compelling way to detect the acceleration sites of protons.

- Fermi-LAT SED cutoff around 200 MeV, "pion bump," is direct indication of hadronic interactions.

Young Shell-type SNRs

- 4 TeV gamma ray SNRs age 2000yrs
- They are interacting with ISM

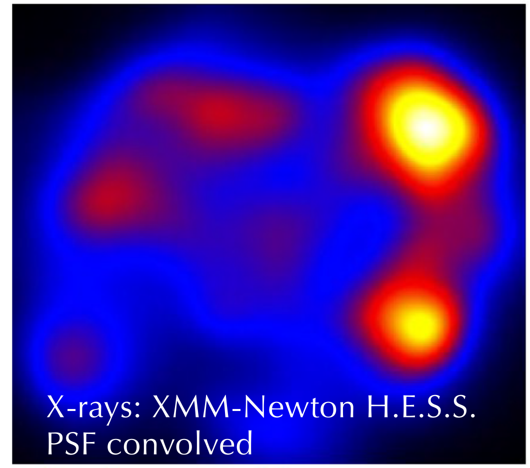


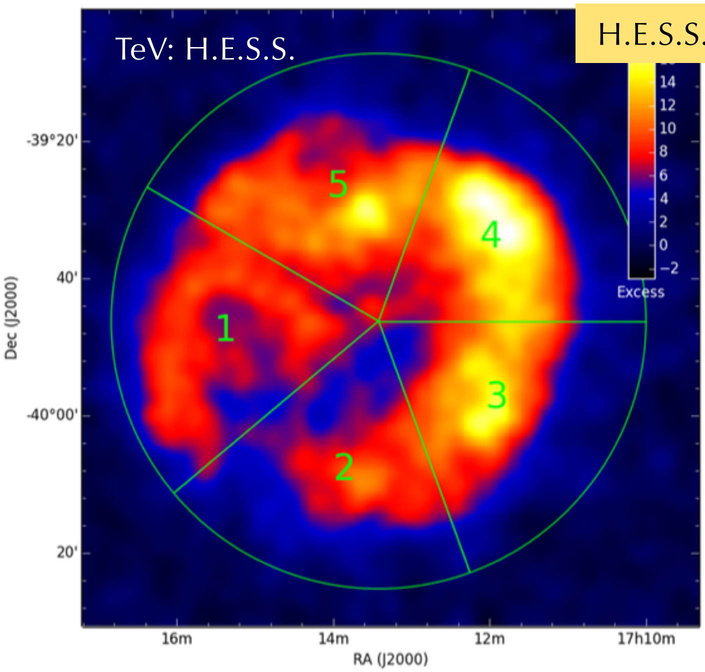
RX J1713.7–3946	RX J0852.0–4622	HESS J1731–347	RCW 86
diamter: ~1 deg.	~2 deg.	~0.5 deg.	~0.5 deg.
age: ~1600 yr	~1700–4300 yr	~3600–7200 yr	~1800 yr
ISM: rich CO + cold HI	rich HI + little CO	rich CO + HI cavity	rich HI + little CO
X-rays: pure synchrotron	pure synchrotron ?	pure synchrotron	thermal + non-thermal

slide from L. Fukui (2017)

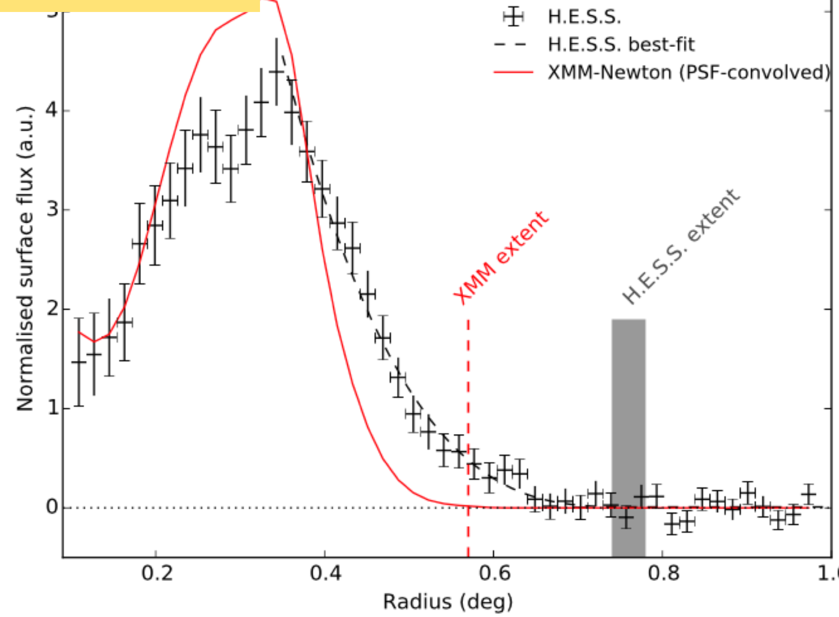
SNR RX J1713.7-3946: *First shell-type resolved in TeV*

- Spatially resolved spectra with unprecedented resolution (<0.05°).
- TeV shell morphology - close correlation with X-rays.
- Dominant emission likely to be leptonic?
- Difference in X-ray/γ radial profiles: Particle escape and/or B field geometry.





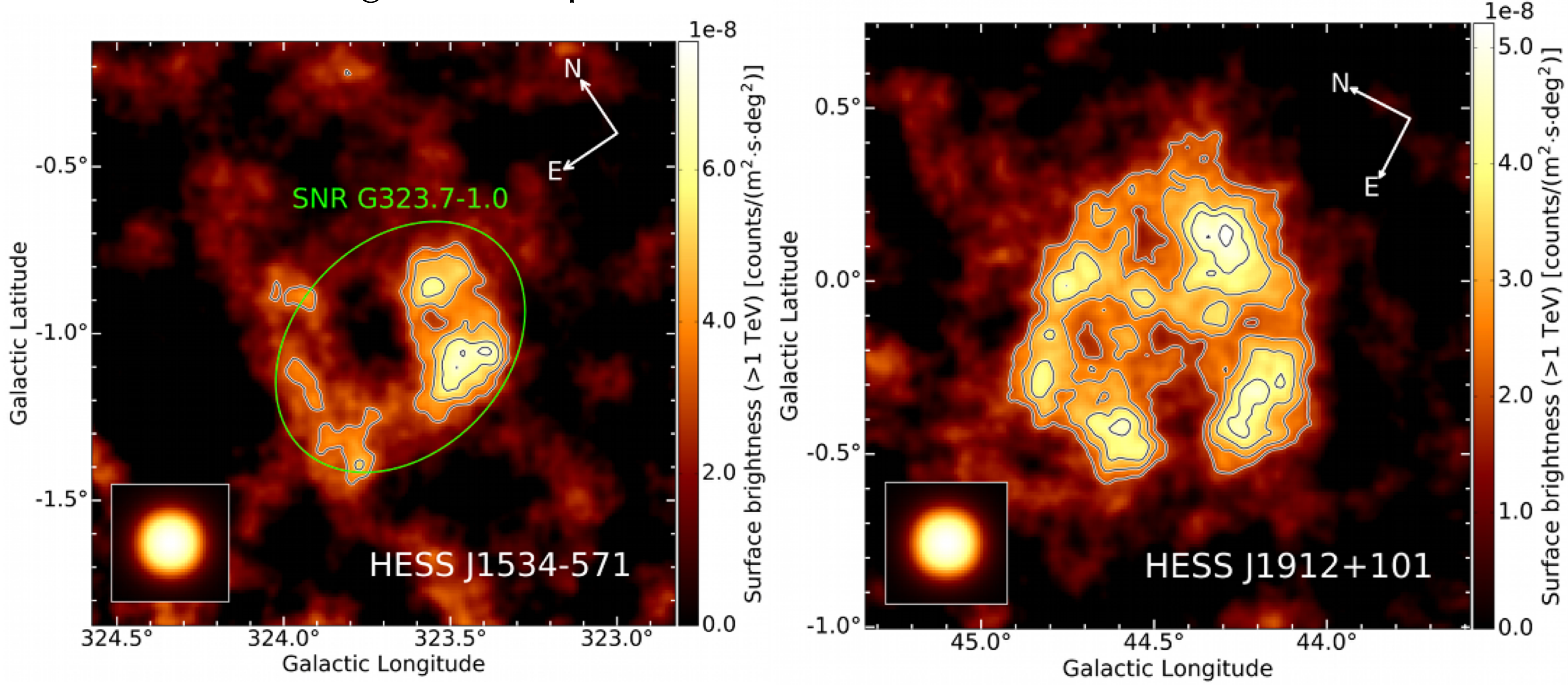
H.E.S.S. Special Issue A&A (2018)



Shell-Type SNRs discovered in H.E.S.S. GPS

TeV surface brightness maps of two unidentified sources.

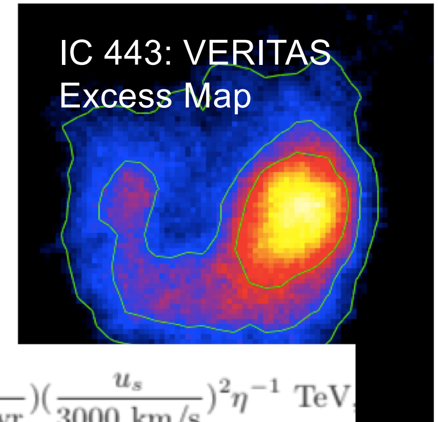
H.E.S.S. A&A (2018)

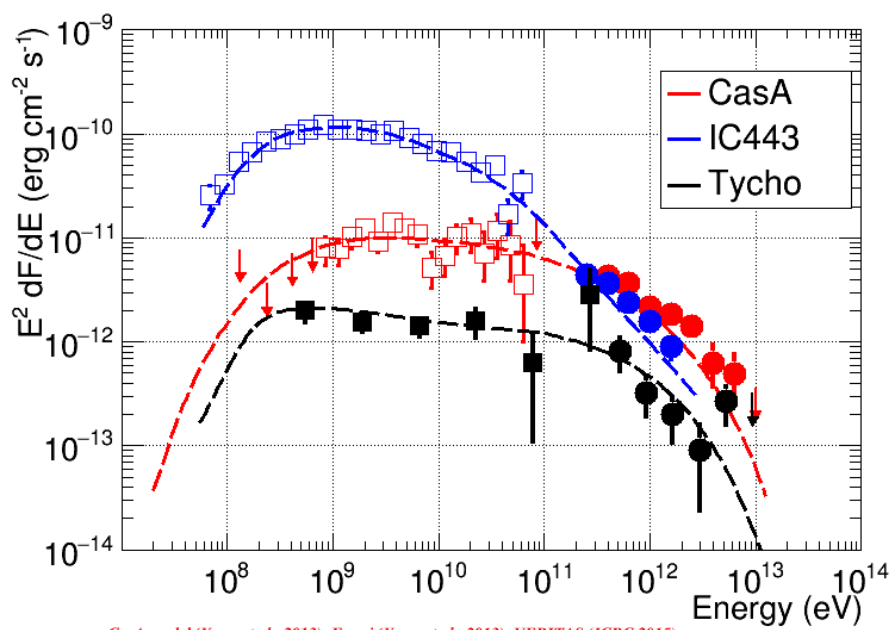


- HESS J1534-571: No X-ray emission is found from the source region, excluding non-thermal X-ray emission at the level detected from the other known TeV SNR. Excellent candidate for proton-dominated processes.
- HESS J1912+101: New data shows shell-like morphology, first TeV-only shell candidate.

Northern Supernova Remnants

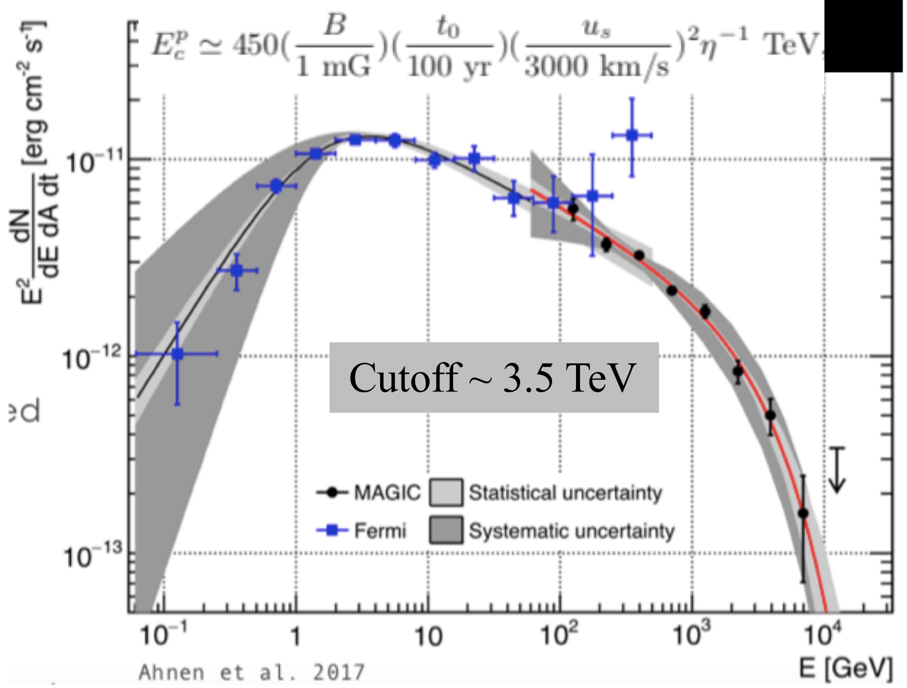
- Spectra of Cas A, Tycho, IC 443 all break above ~100 GeV.
- Spectra are too soft to explain acceleration of CRs to the "knee" at 3×10^{15} eV.
- Proton energy is ~ 0.2% of estimated explosion KE.
- **Where are the PeVatrons?**





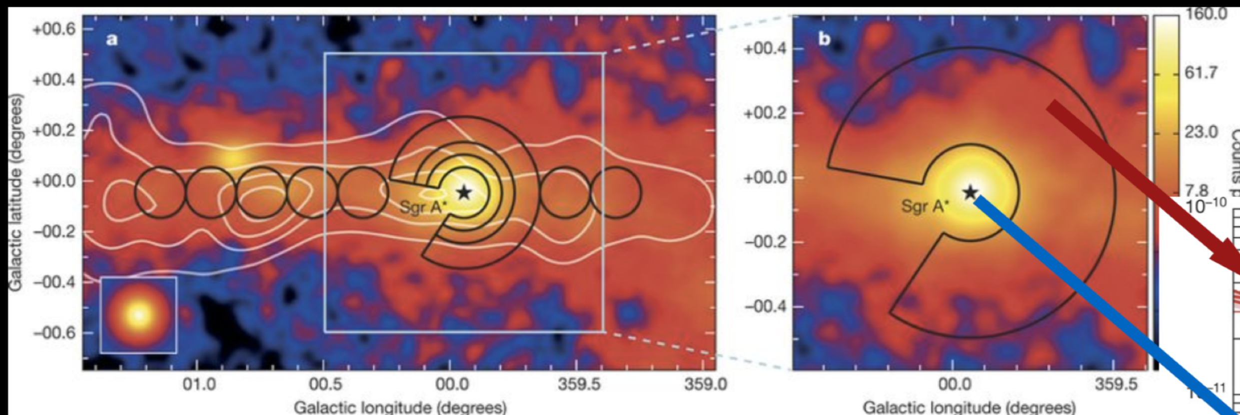
CasA model (Yuan et al., 2013), Fermi (Yuan et al., 2013), VERITAS (ICRC 2015)
IC443 model (Ackermann et al., 2013), Fermi (Ackermann et al., 2013), VERITAS (ICRC 2015)
Tycho model (Slane et al., 2014), Fermi (Archambault et al, 2017), VERITAS (Archambault et al, 2017)

VERITAS Collaboration 2017

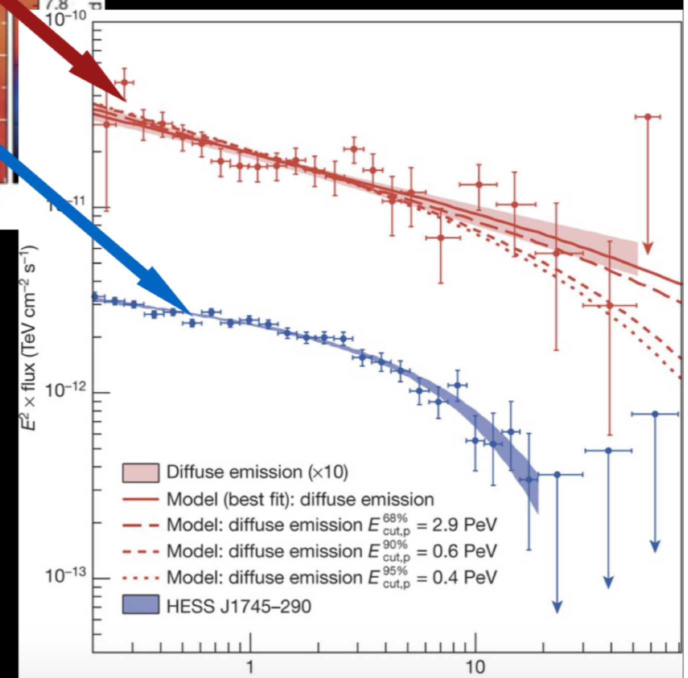


MAGIC Collaboration 2017

Acceleration of PeV Protons in the Galactic Center

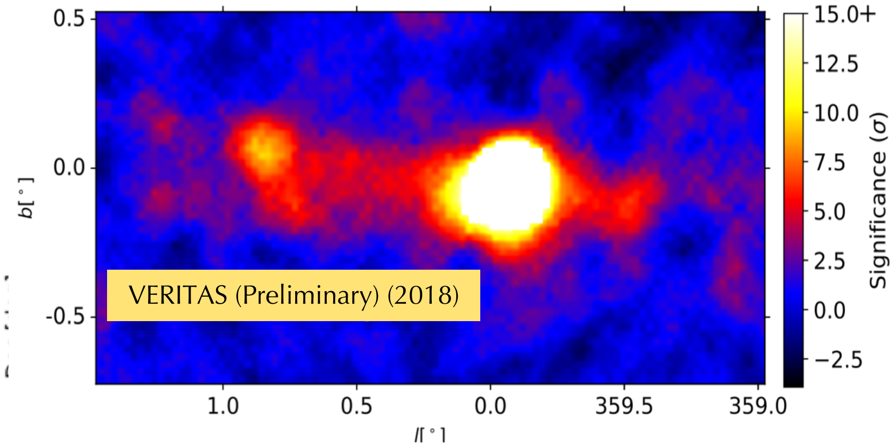


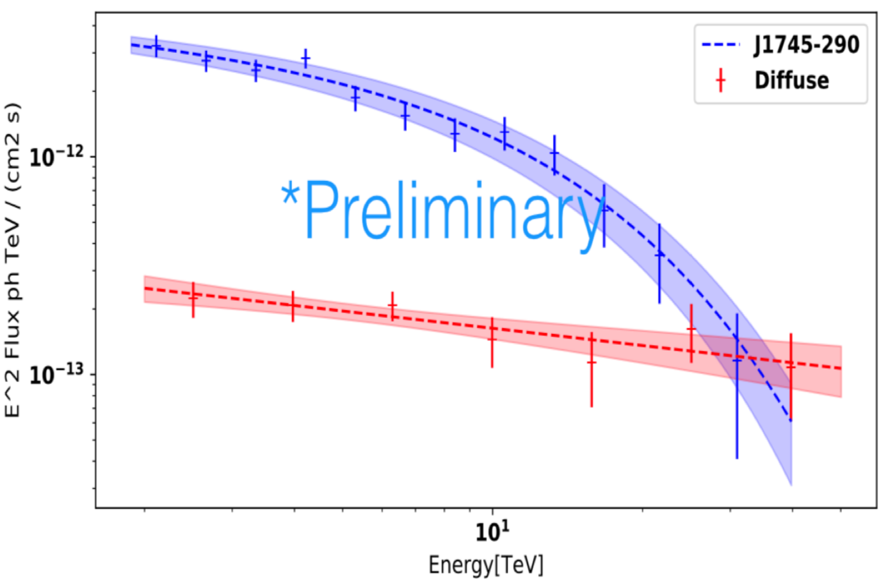
H.E.S.S. Collaboration, Nature (2017)



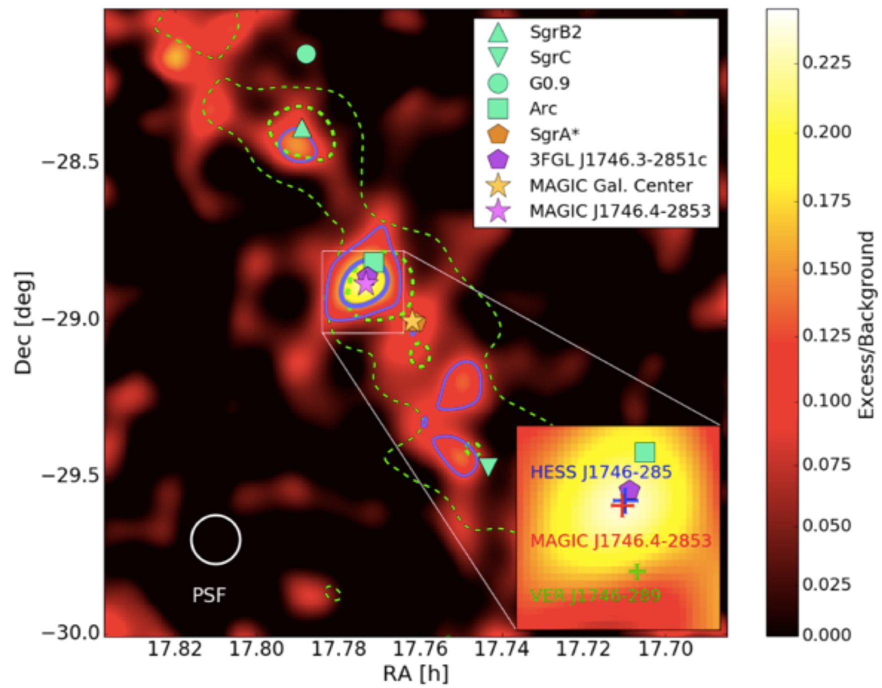
- H.E.S.S. analyzed the diffuse pacman region above, extracting a spectrum pictured right (Abramowski et al. 2016)
- Spectrum was best fit by power law w/ no sign of a cutoff up to 40TeV
- Hypothesized center could be accelerator of PeV cosmic rays, which interact with MC gas to create gamma rays

Large Zenith Angle Observations of the Galactic Center





VERITAS Collaboration, COSPAR (2018)

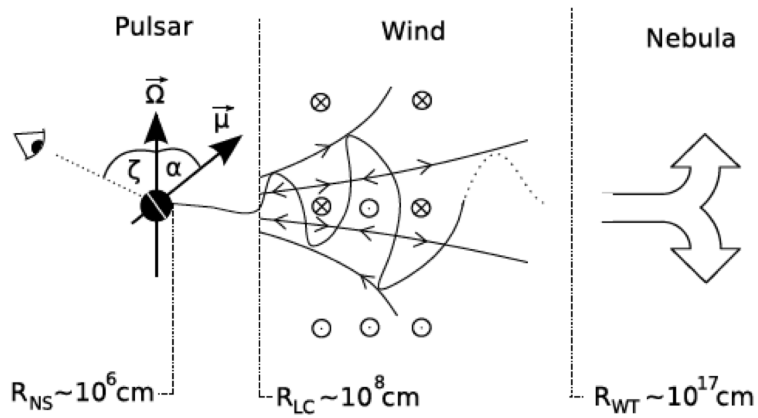


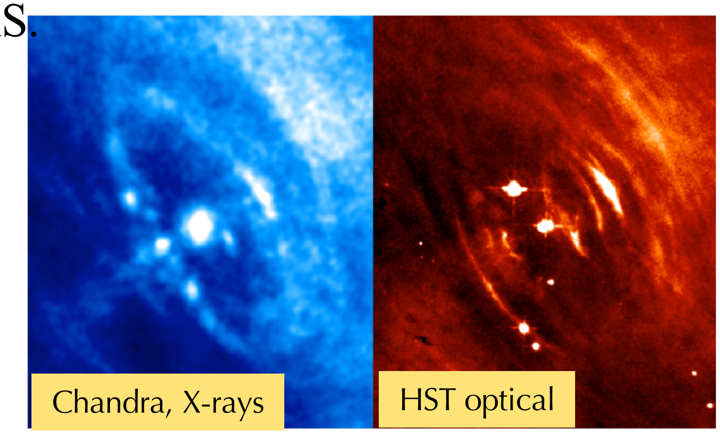
MAGIC Collaboration Texas Symp (2017)

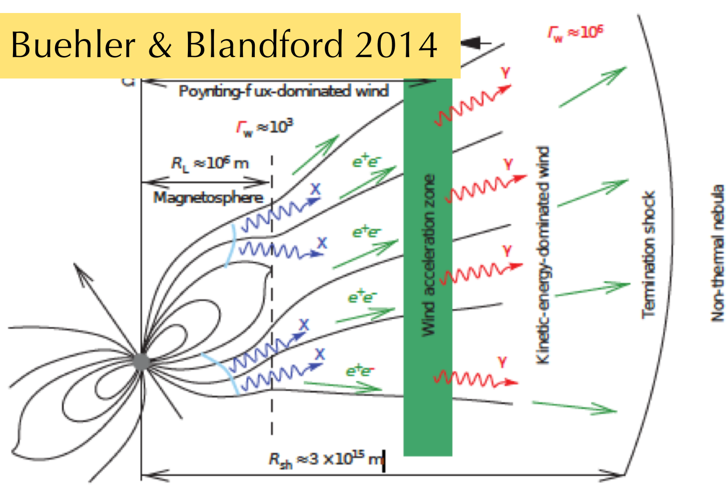
- No cutoff observed up to 40 TeV.
- Further observations planned at LZA.

The Crab Pulsar at TeV Energies

- Search for pulsed emission in VHE since EGRET detection of pulsed emission.
- Dedicated observations by MAGIC & VERITAS.



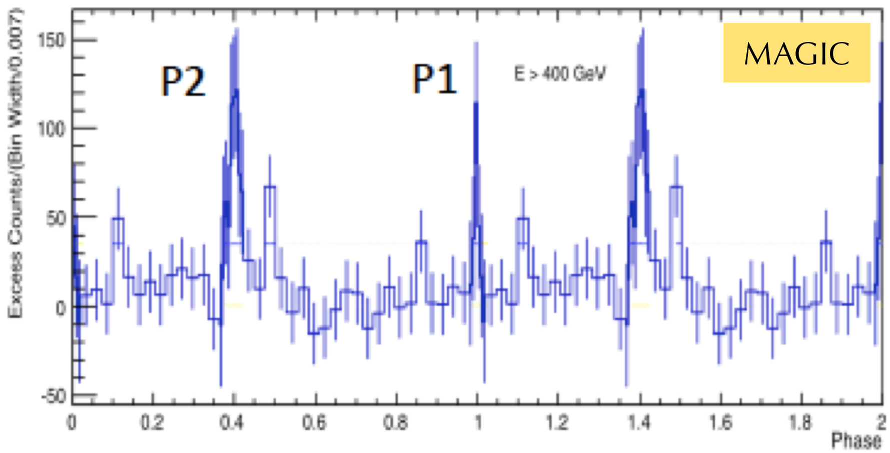




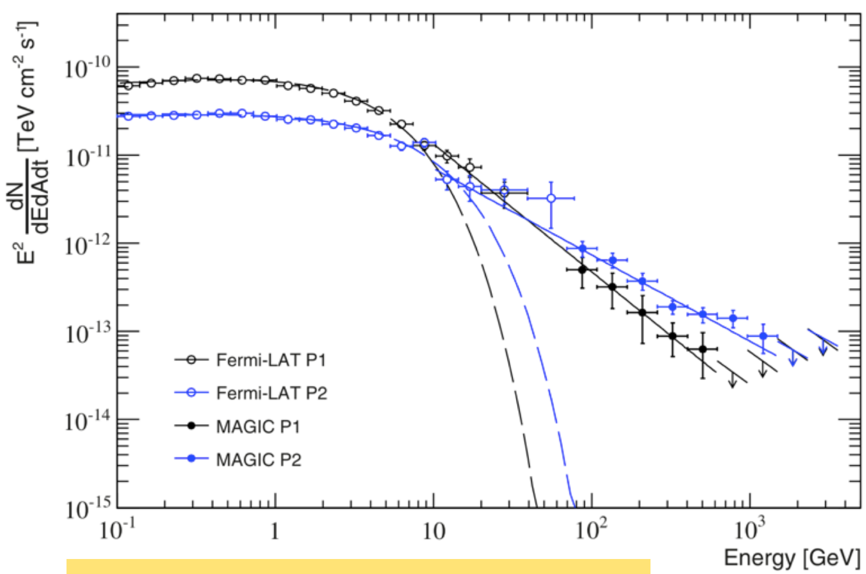
Buehler & Blandford 2014

- First detection of emission above 25 GeV from a pulsar by MAGIC (2008, Science).
- Detection of pulsed emission in the 120-400 GeV by VERITAS (2011, Science).
- Spectrum between 25-500 GeV by MAGIC Bridge emission detected >50 GeV by MAGIC.

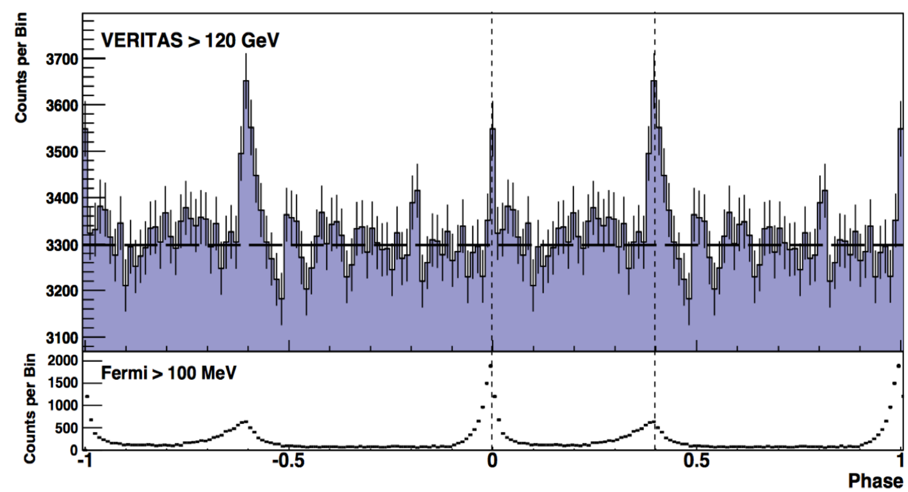
The Crab Pulsar at TeV Energies



- MAGIC and VERITAS measure pulsed emission >100 GeV.
- MAGIC measured pulsed emission >1 TeV.
- Pulsed emission in the 120-400 GeV range not expected theoretically – challenge to pulsar models.
- MAGIC-Fermi fit shows IC emission 10GeV to ≥ 1 TeV. Emission from the vicinity of LC (r ~ 1600 km).



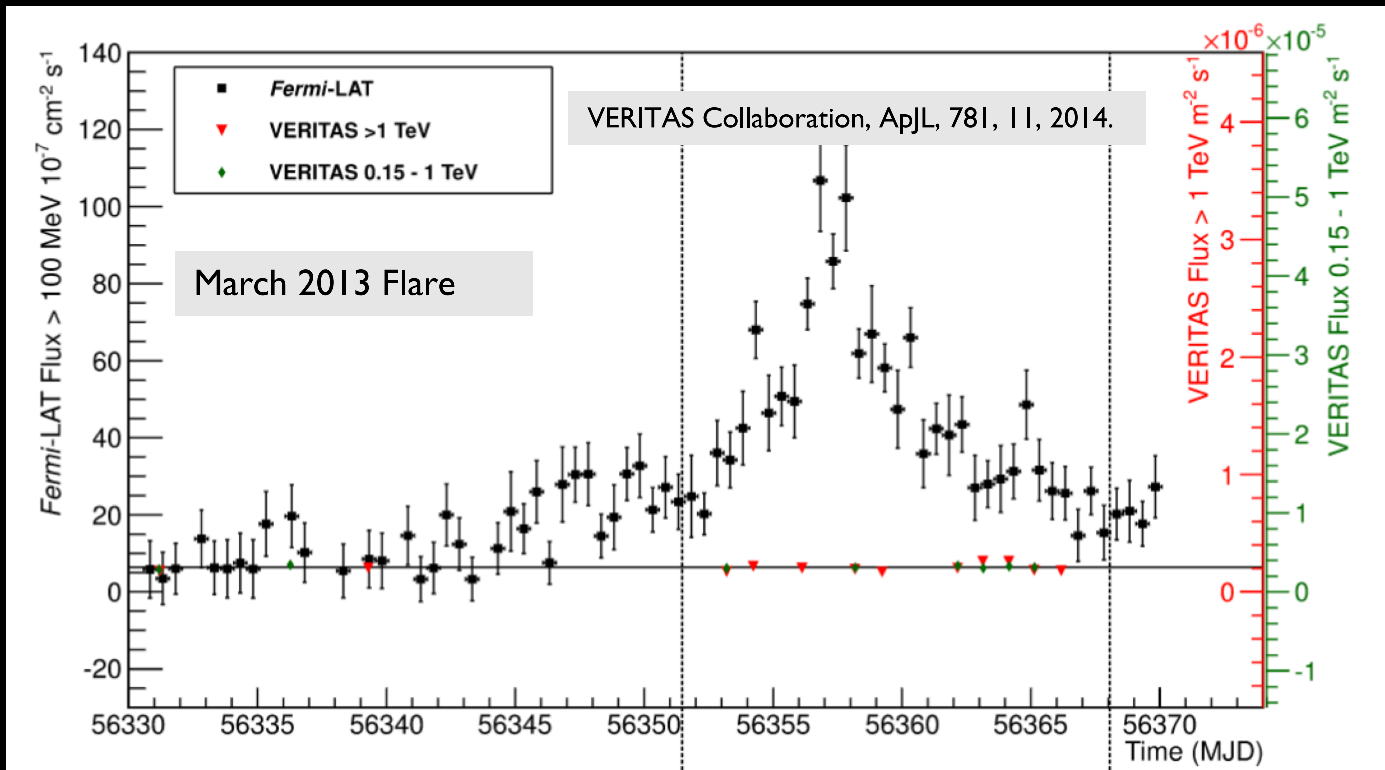
MAGIC, Science (2008), A&A (2016)



VERITAS Collaboration, Science (2011)

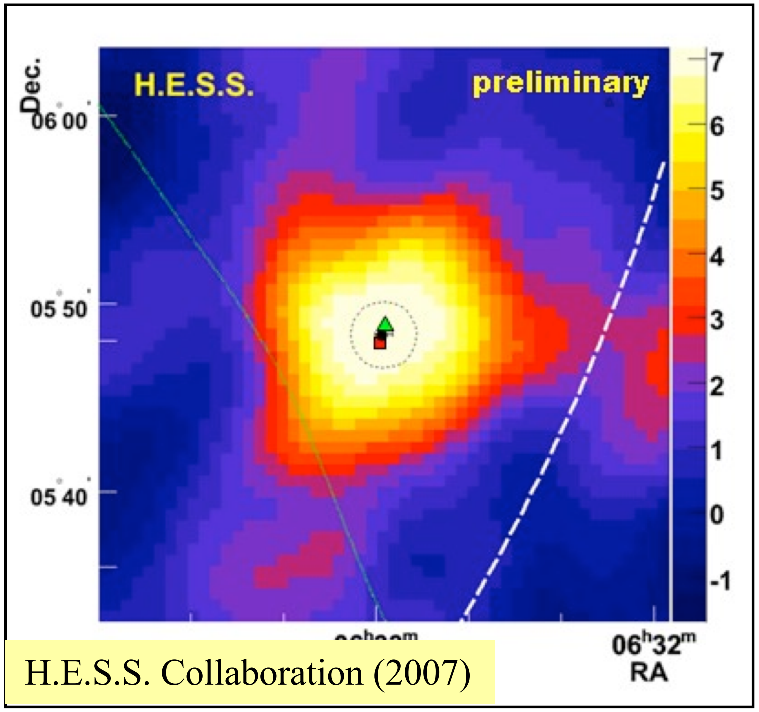
The Steady Crab: No Flares at TeV

- The Fermi-LAT measured Crab flares have no counterpart at TeV.

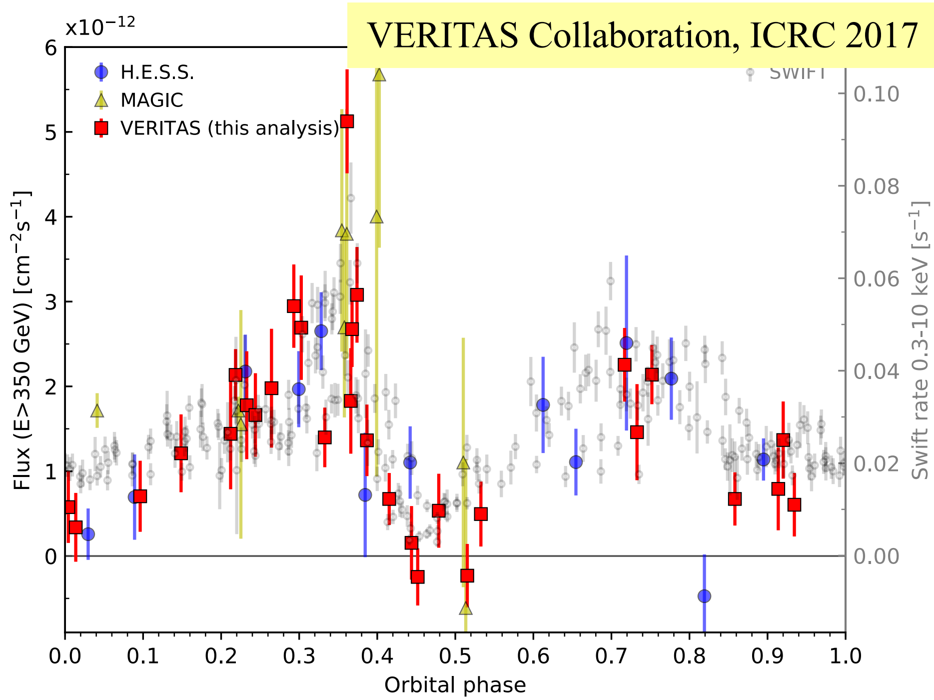


- Light curve and reconstructed energy spectrum in between 1 TeV and 10 TeV do not indicate any flux enhancement at TeV energies.
- Flux above 100 MeV was six times elevated during observations.

Identification of a Gamma Ray Binary



H.E.S.S. Collaboration (2007)

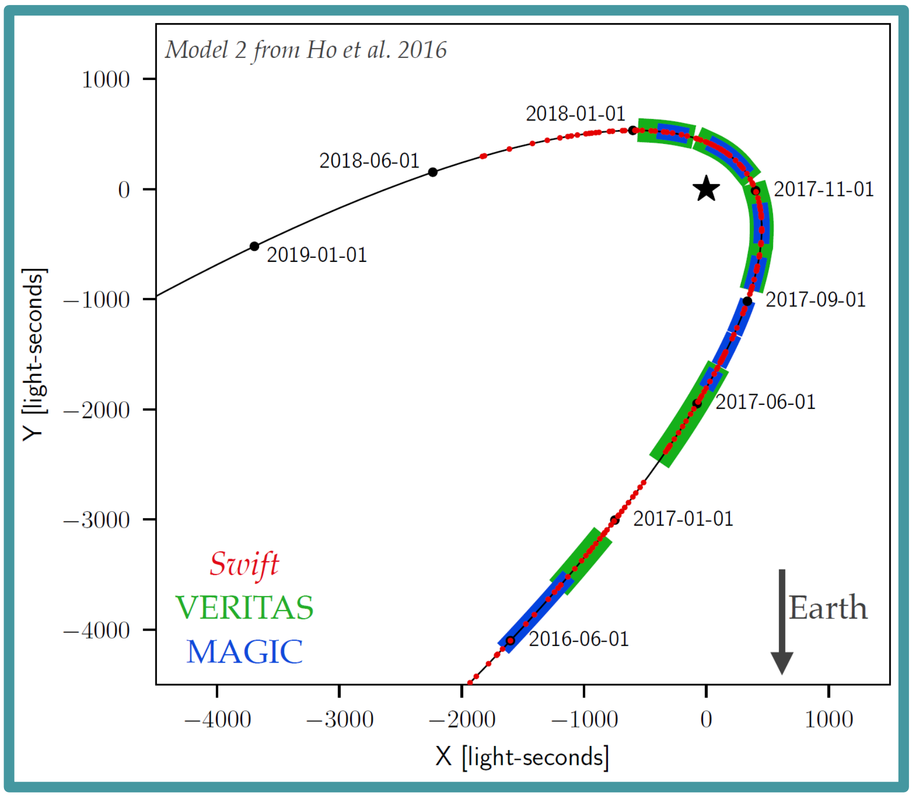


VERITAS Collaboration, ICRC 2017

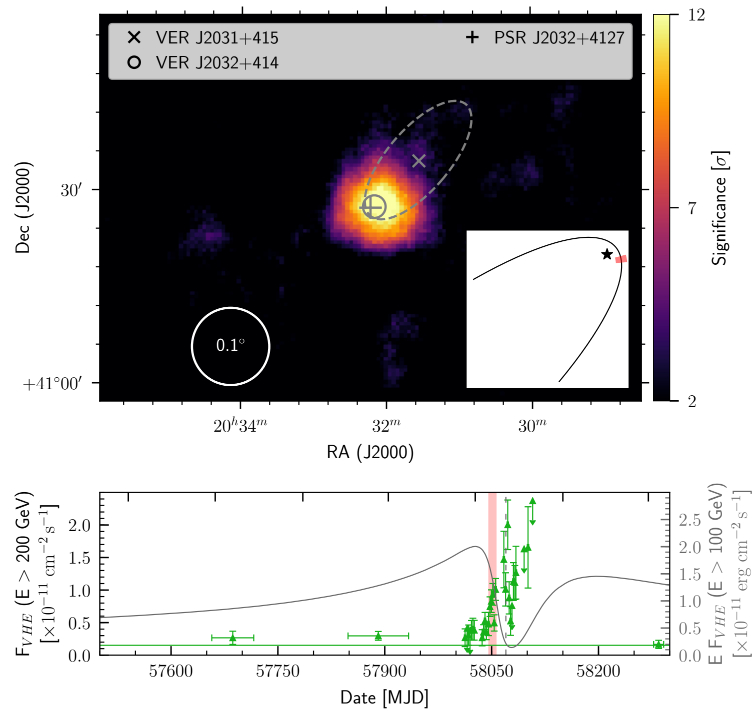
- HESS J0632+057: unidentified, located in the Monoceros region.
- Associated with massive Be star MWC 148. Hypothesized to be a new γ-ray binary (Hinton et al. 2008).
- X-ray & γ-ray data over 10 years. VHE & Swift X-ray data indicate that the source is a binary period of 315 days.
- VERITAS has more than 220 hours of observations.

TeV J2032+4130 is a binary!

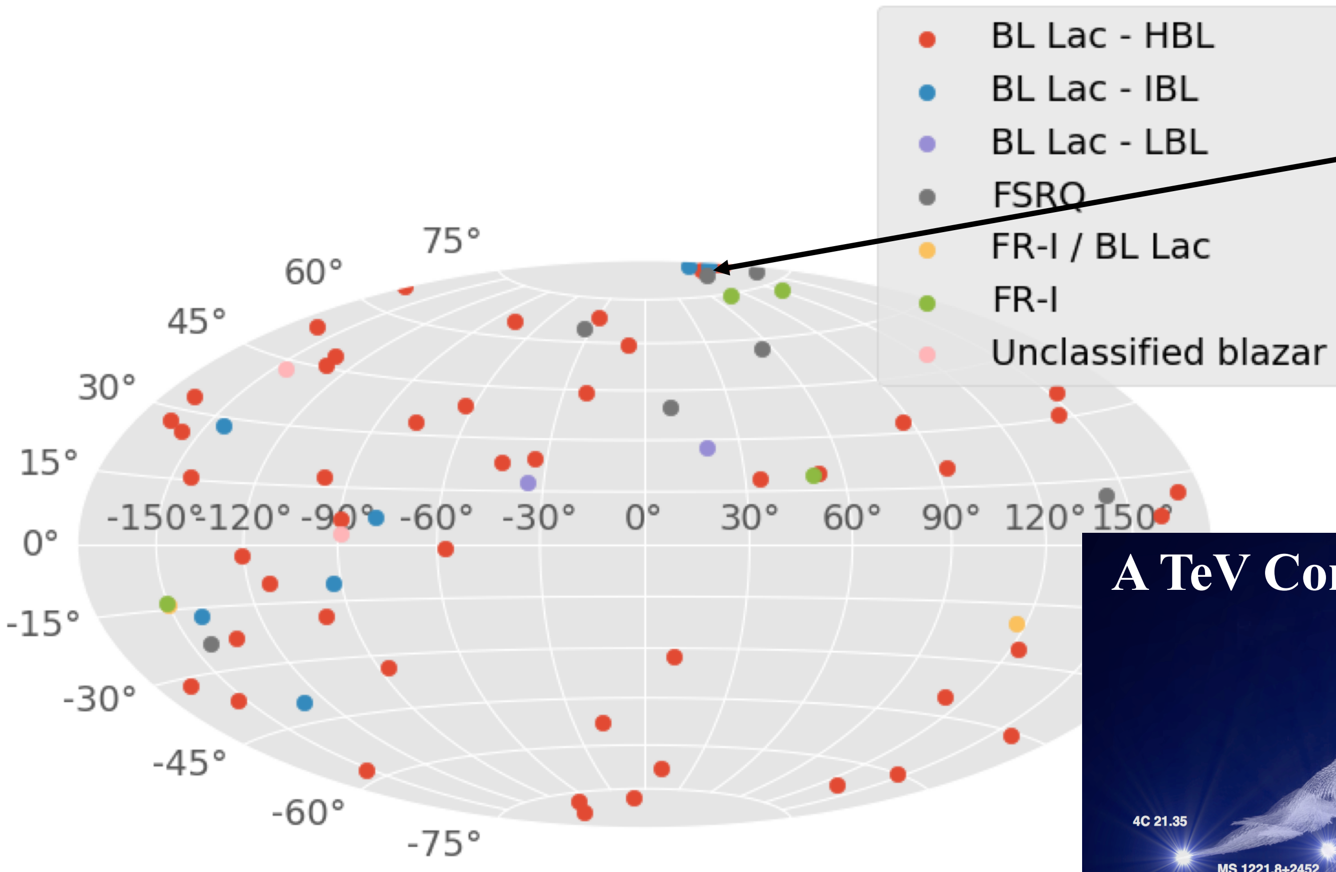
- 2002 detection of an unidentified source (first unidentified TeV source!).
- In 2009, Fermi discovered the likely power source: PSR J2032+4127.
- In 2015, Lyne et al. showed that the pulsar is in a long period binary system with MT91 213.
- Further monitoring gave an orbital period of 45-50 years, with periastron in fall 2017.
- Collected 140 hours from 2016-2018.

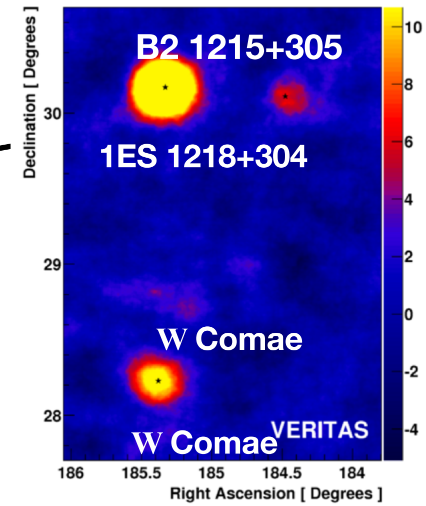


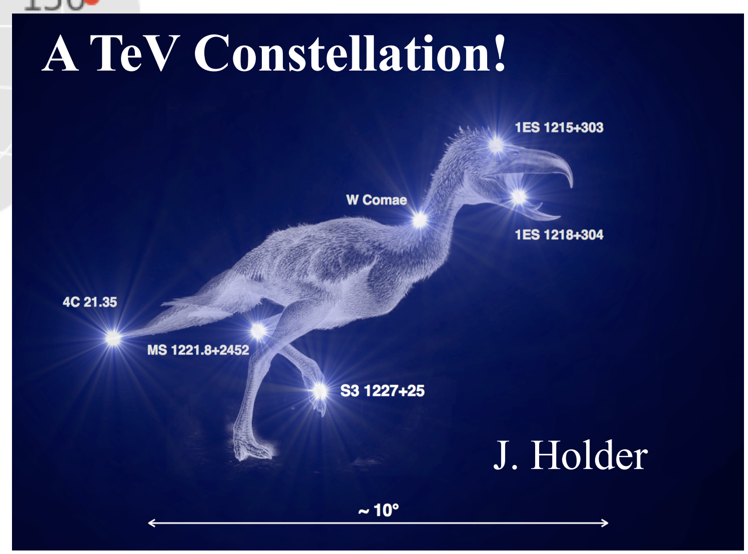
MAGIC + VERITAS ApJ Letters (2018)



The Extragalactic TeV Sky

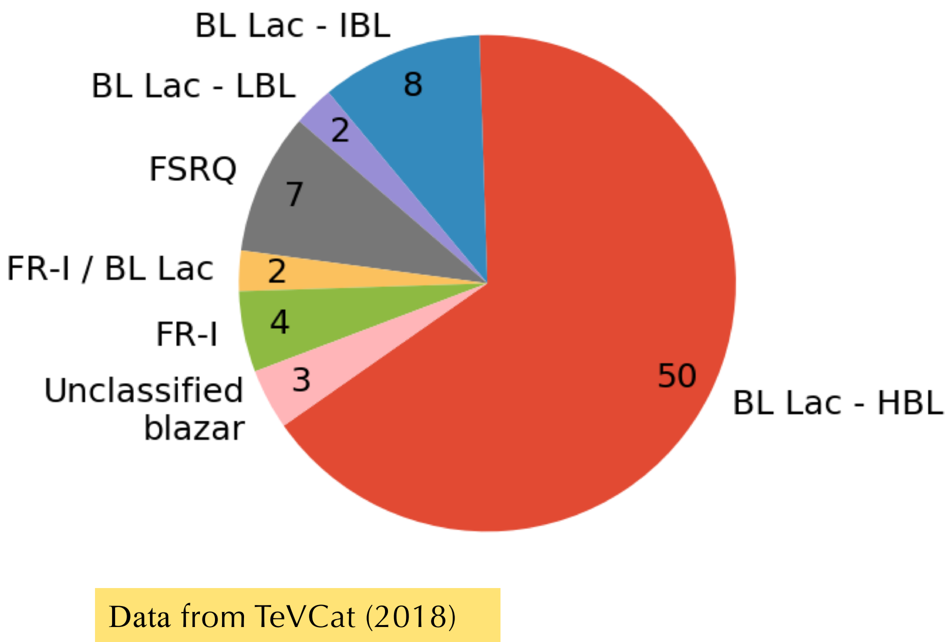


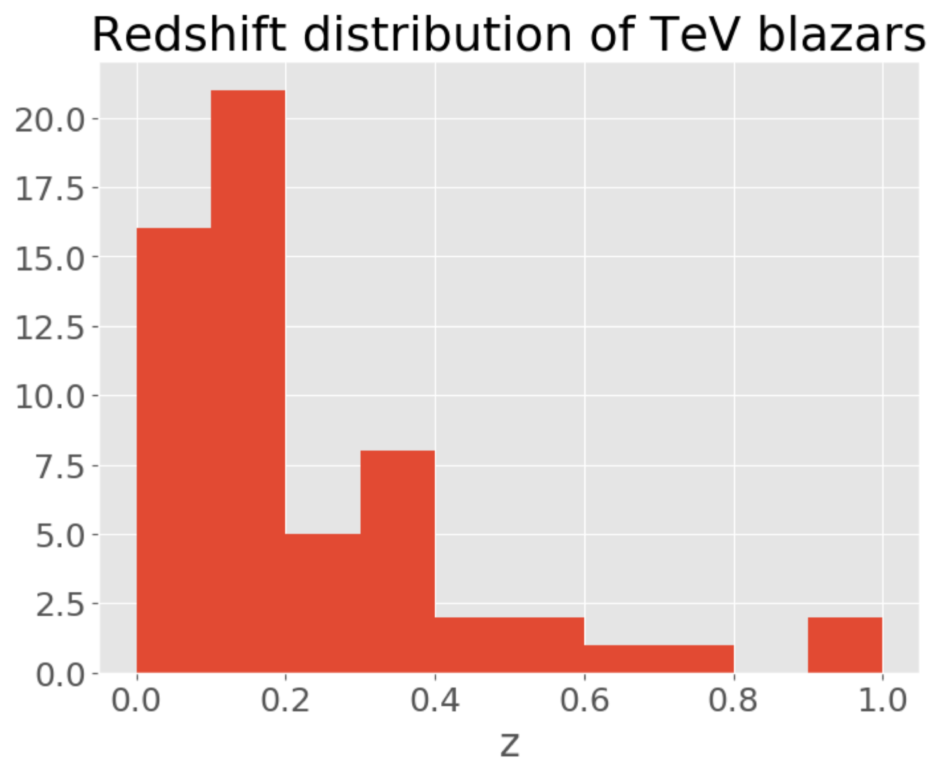




The Terabird – A TeV Constellation!

The Extragalactic TeV Sky

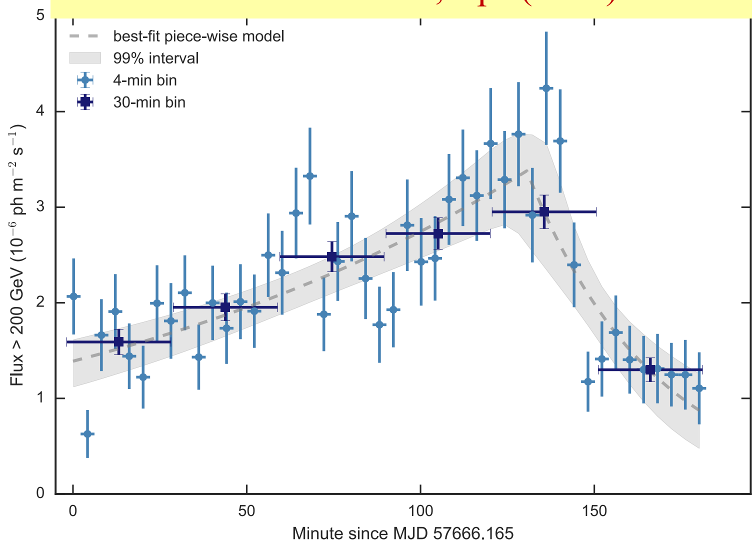


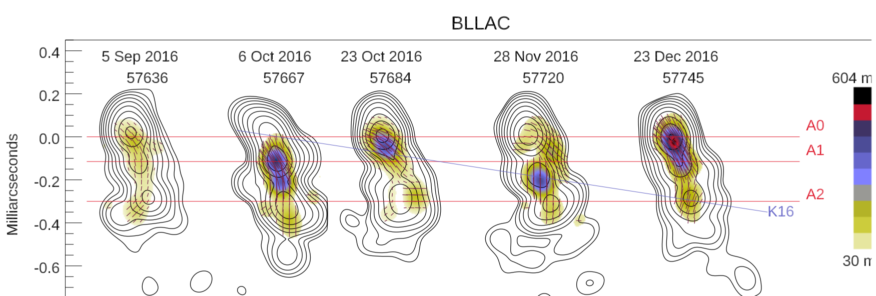


- BL Lacs are still the largest source class, comprising 60/76 TeV sources.
- 90% of blazars with known redshift have $z < 0.5$.
- CTA should be able to detect more FSRQs & radio galaxies.

Unique Capabilities: Short time scale variability

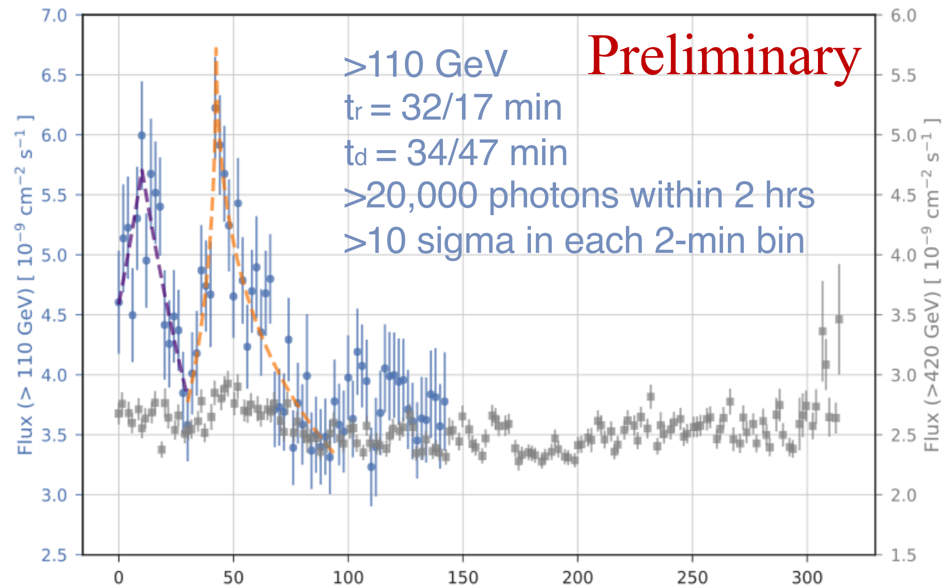
VERITAS Collaboration, ApJ (2018)





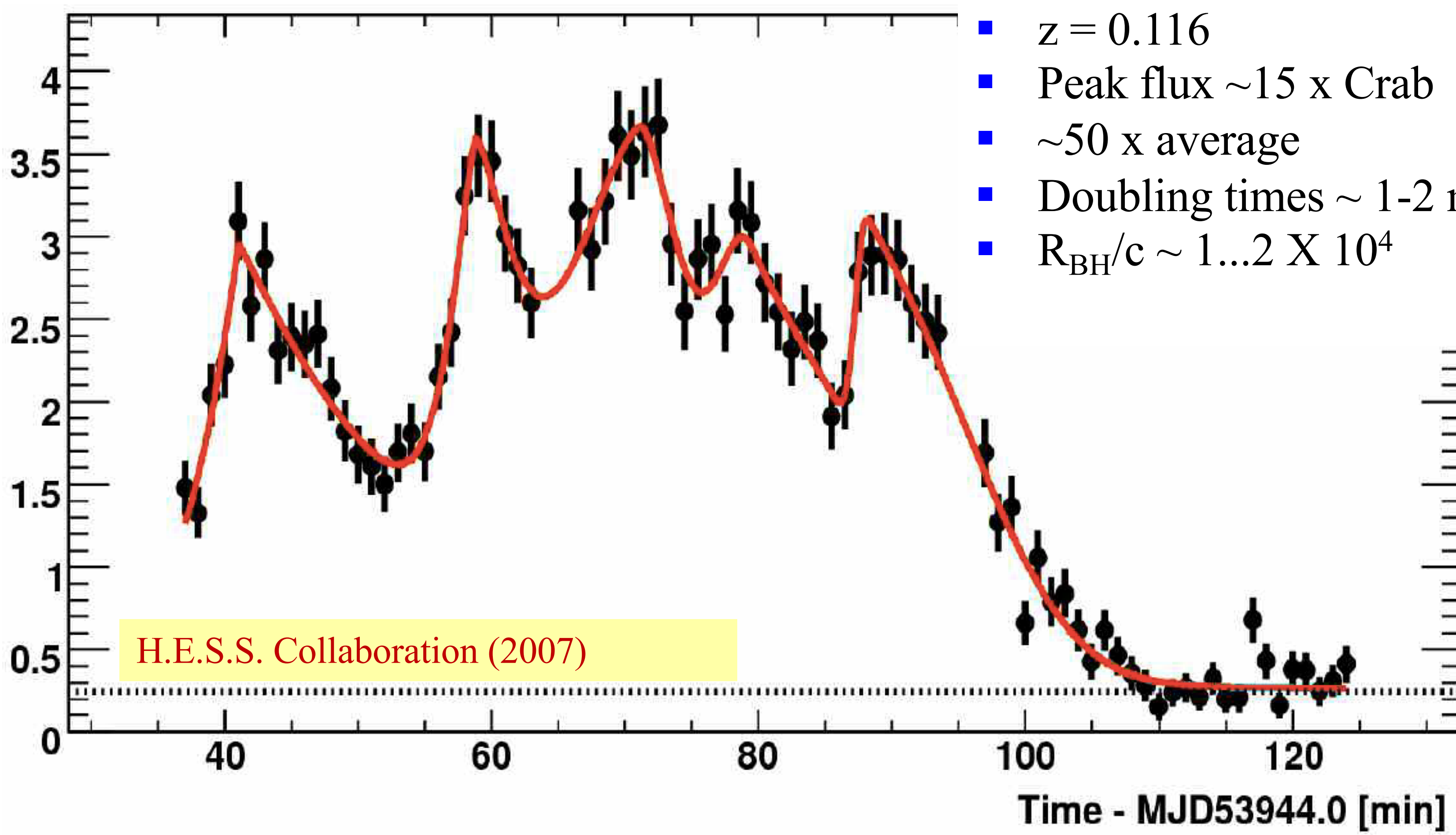
- BL Lac: Major flare in Oct 2016
- 150% Crab flux, τ ~ 36 min.
- 43 GHz VLBA imaging, coincident knots
- $R < ct\delta/(1+z) < 12\ R_{Sch.}$

- Locating the emission region in the jets.
- Measuring minute-scale variability.



Mrk 421: Iconic TeV blazar.
Fast flares during a major outburst.

Short time scale variability

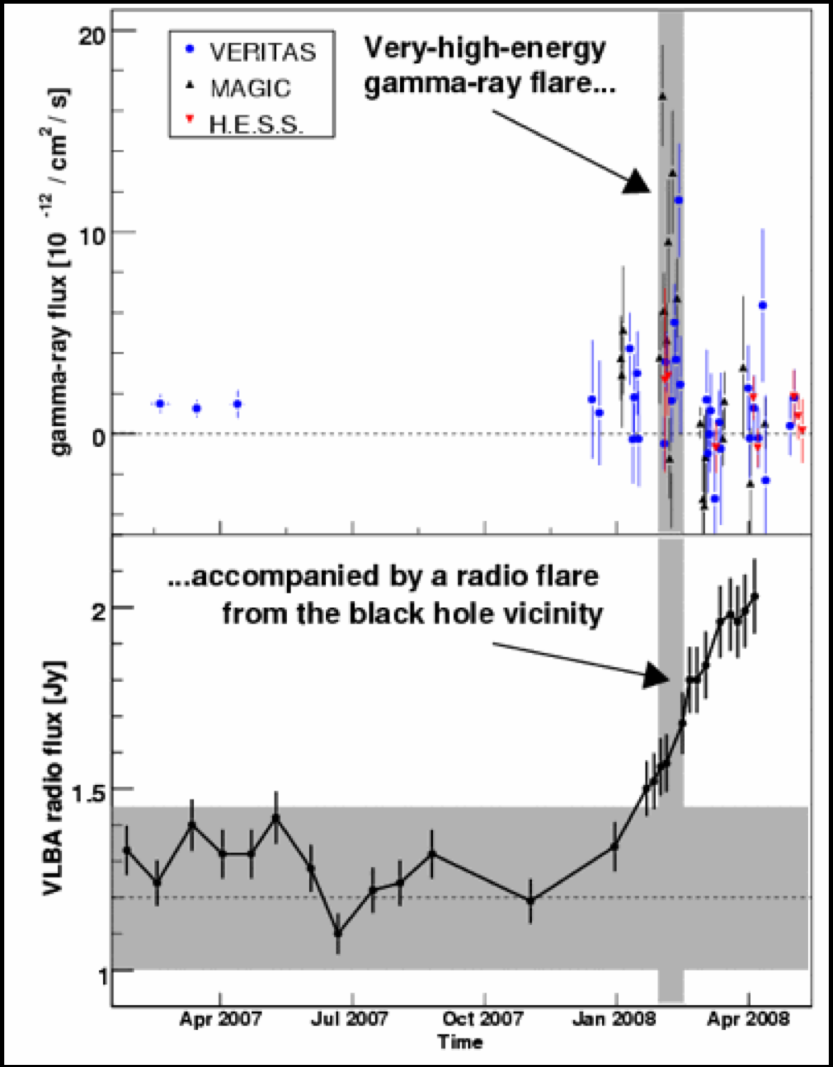


- PKS 2155-304
- z = 0.116
- Peak flux ~15 x Crab
- ~50 x average
- Doubling times ~ 1-2 min
- $R_{BH}/c \sim 1...2 \times 10^4$

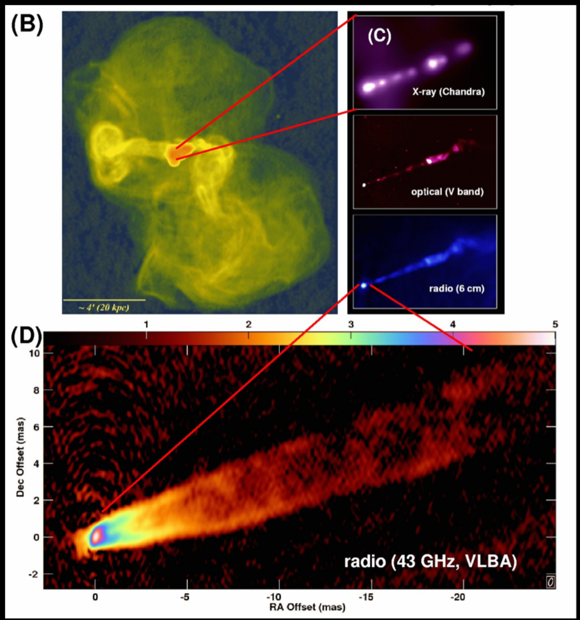
Slide from W. Hoffman (2007)

M 87: Gammas from the Edge of a Supermassive Black Hole

- High-resolution radio and gamma-ray observations reveal the site of relativistic particle acceleration in the galaxy M87.

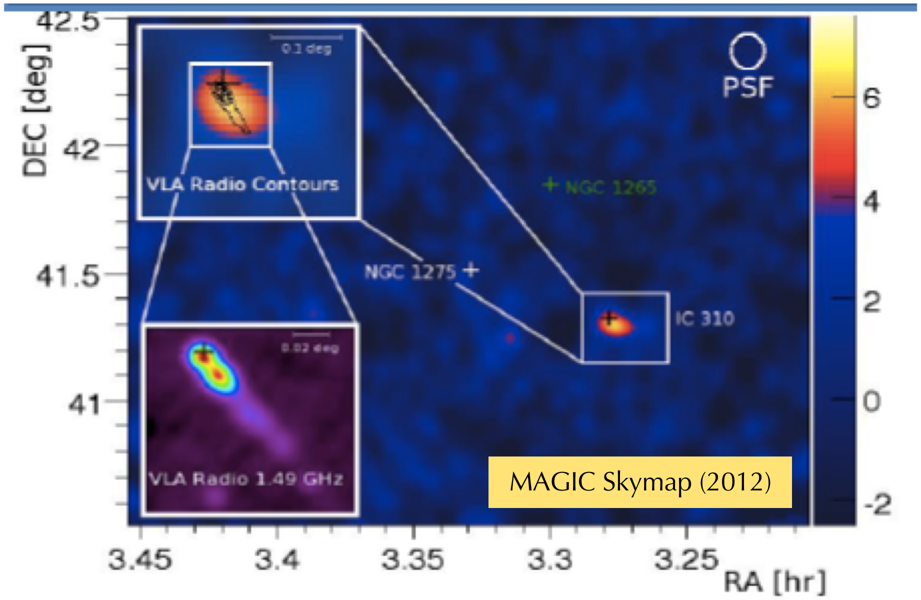


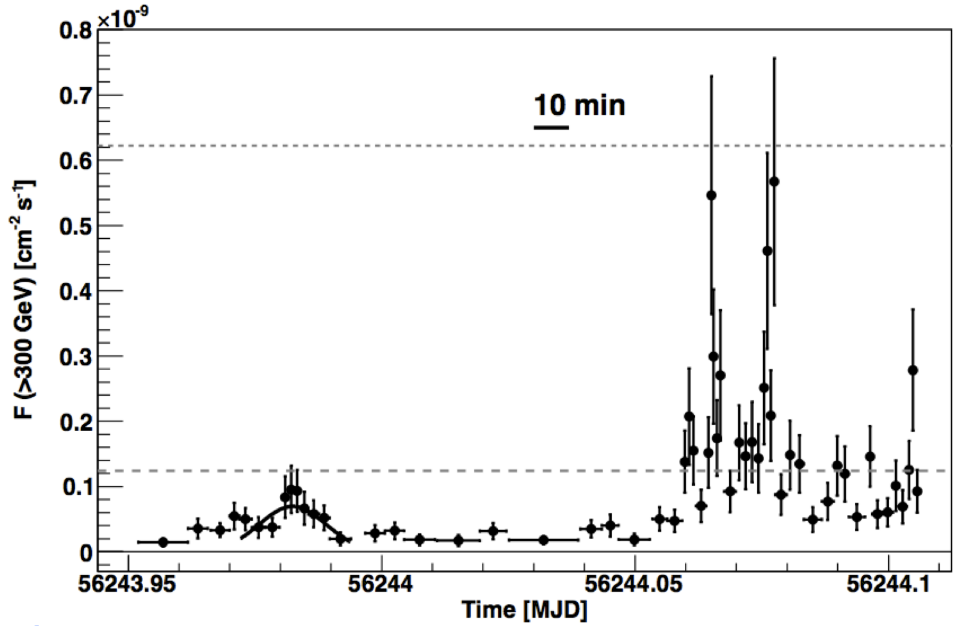
TeV flare occurred simultaneous with the birth of a knot in radio. (VLBA) on the "rim" of the central SMBH of M87.



VERITAS, VLBA, H.E.S.S. + MAGIC, Science (2009)

IC 310: Unexpected Discovery in the Perseus Cluster of Galaxies



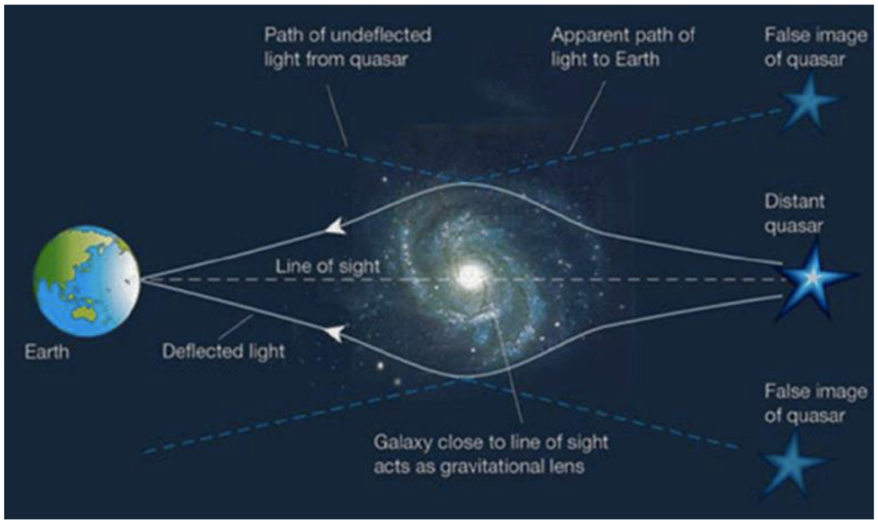


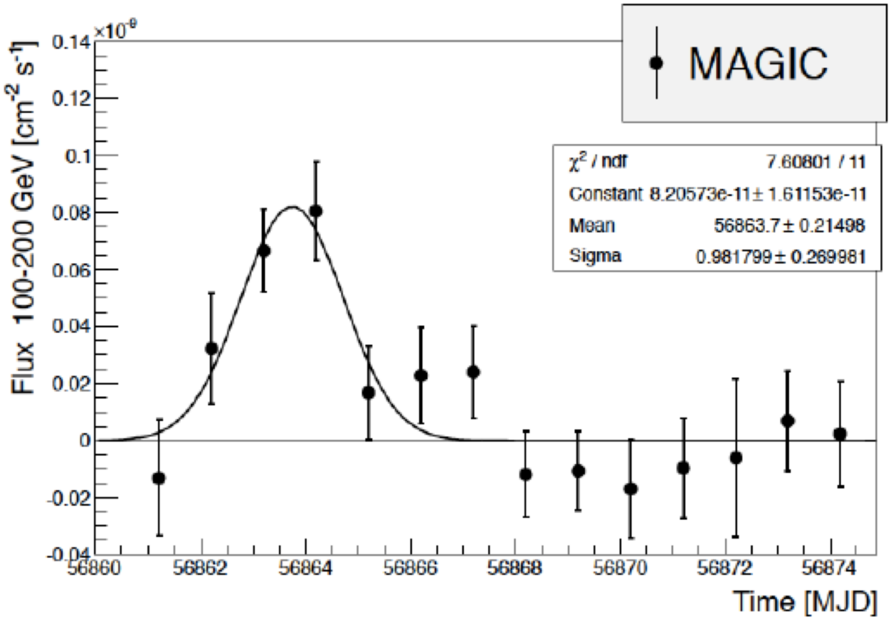
- Detection at > 260 GeV by MAGIC. MWL campaign in 2012-2013.
- VLBI reports parsec-scale blazar-like structures; $\theta \leq 38^\circ$.
- Light curve with 1-min bins shows extreme variability; unusual for a radio galaxy.
- No curvature in spectrum from 60 GeV – 10 TeV.
- Difficult to explain with current (standard) theoretical scenarios.

MAGIC Collaboration, Science (2012)

Gravitationally lensed blazar QSO B0218+357

- Detection of very high energy γ-ray emission from the gravitationally lensed blazar QSO B0218+357 by MAGIC at a redshift of 0.944.
- Fermi-LAT flare in July 2014. MAGIC observed delayed signal, as predicted.

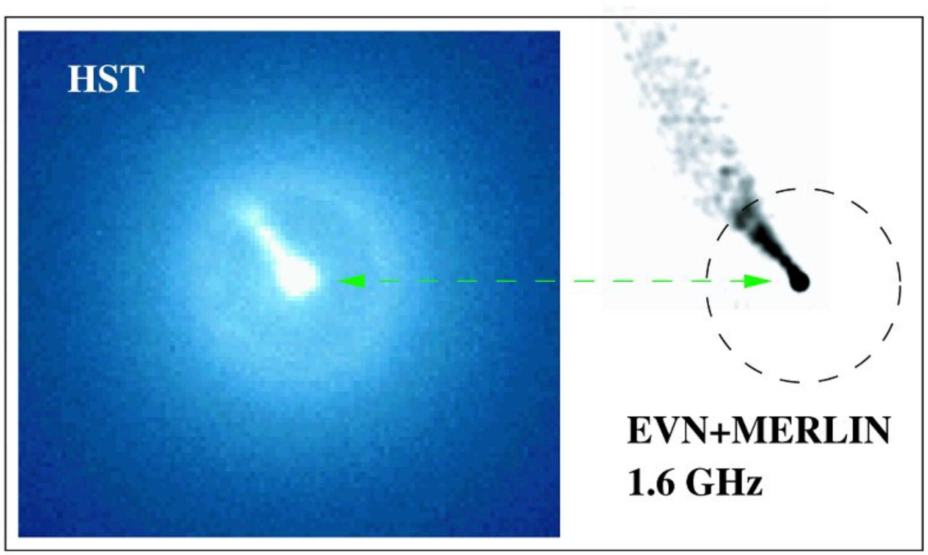




MAGIC Collaboration A&A 2016

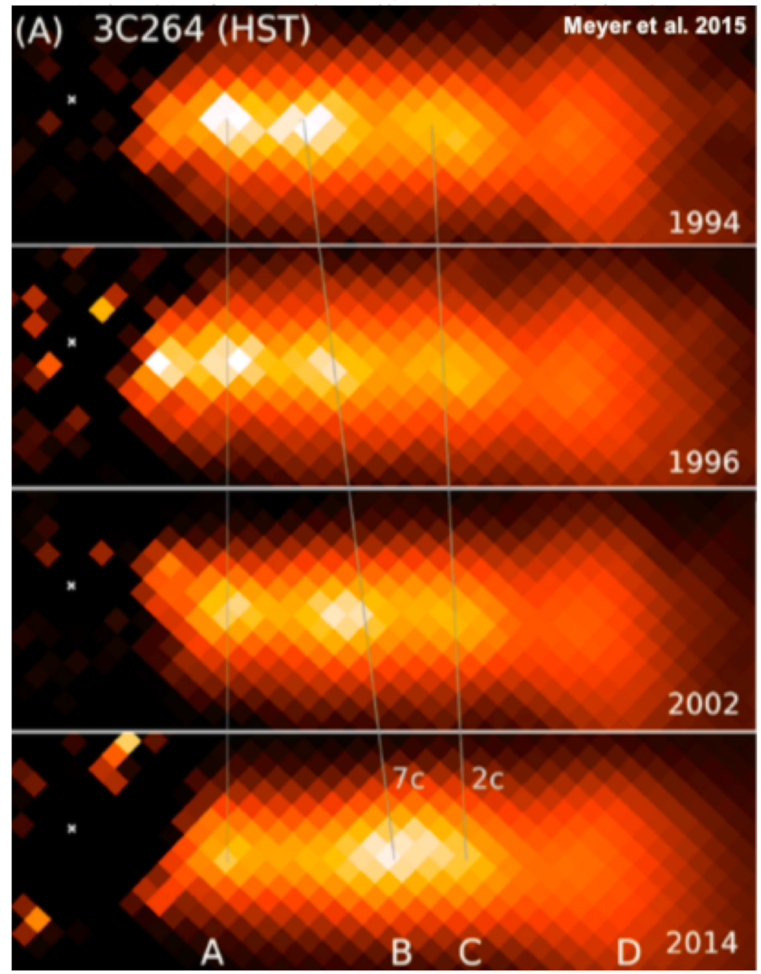
Farthest TeV Radio Galaxy: 3C264

- FR-I radio galaxy, z = 0.0216.
- More distant (~6x) “M87” analog, kpc scale jet, SL motion ~ 7c.
- Rapidly evolving knot-structure MeV-GeV source (Γ_{3FHL} ~ 1.65 → F(>200 GeV) ~1.6% Crab).
- VERITAS detection in 2018 + MWL.



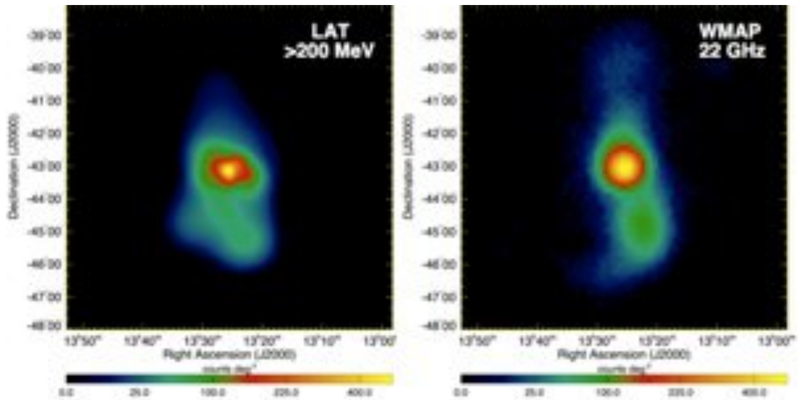
VERITAS discovery of VHE emission from the FRI radio galaxy 3C 264

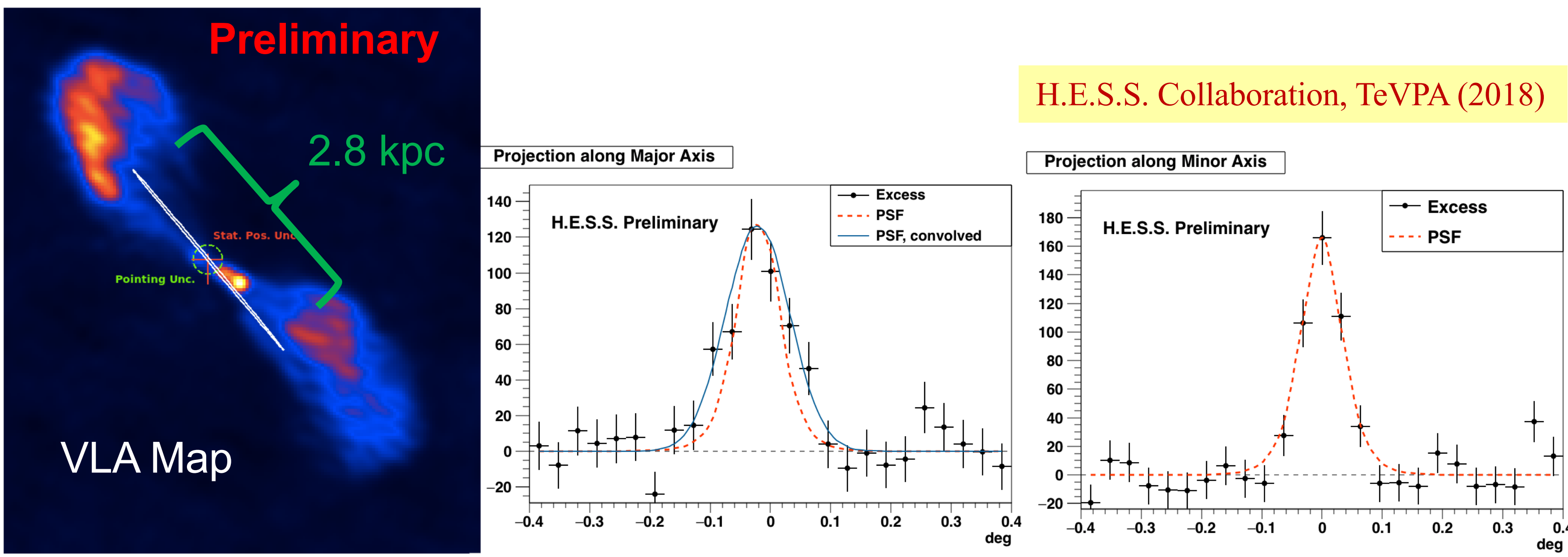
ATel #11436; *Reshmi Mukherjee (Barnard College) for the VERITAS Collaboration*
on 17 Mar 2018; 00:25 UT



Centaurus A: Resolved emission

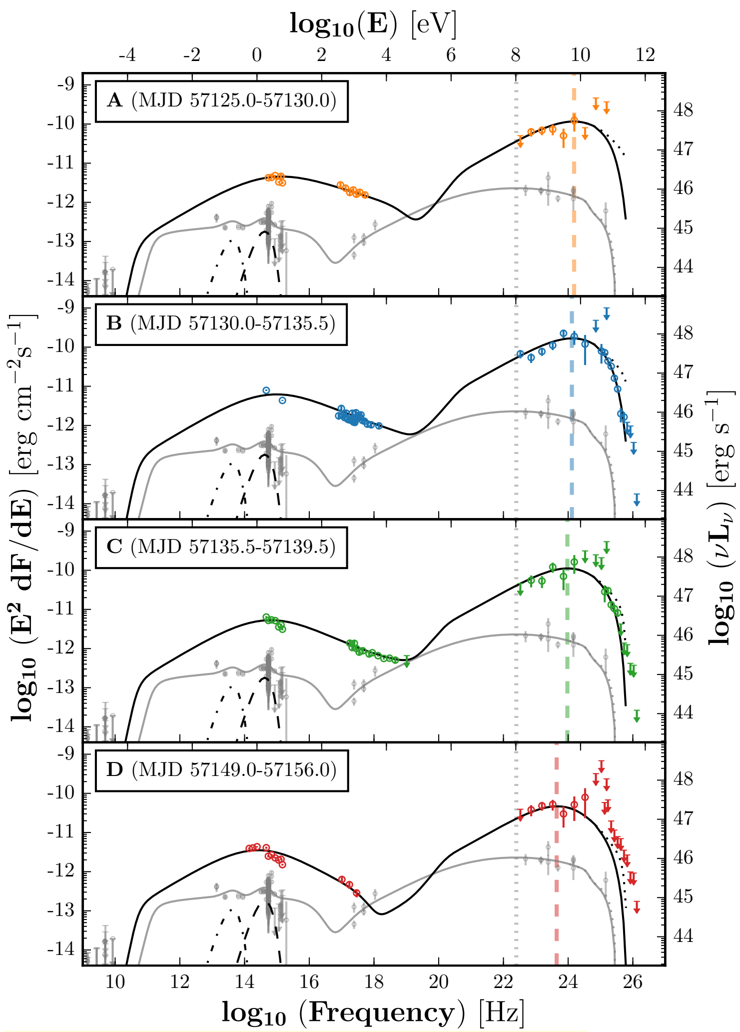
- Radio Galaxy (NGC 5128) of FRI type.
- Nearest active galaxy, distance of 3.7 Mpc.
- Fermi-LAT : extended lobes.
- Deep H.E.S.S. observations from 2004 to 2013.
- Resolved emission, aligned with radio jets.





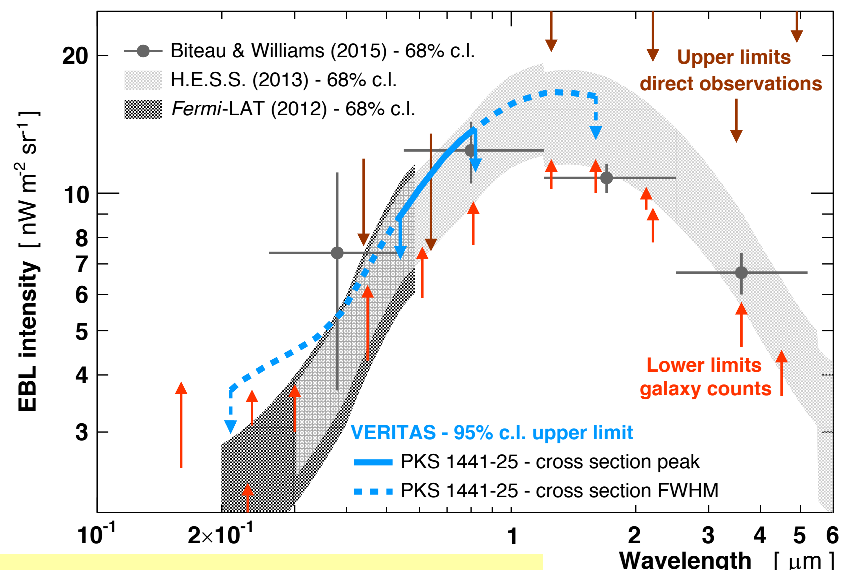
H.E.S.S. Collaboration, TeVPA (2018)

Gamma-ray Horizon: Blazar detection at z ~ 1



MAGIC Collaboration, ApJL (2015)

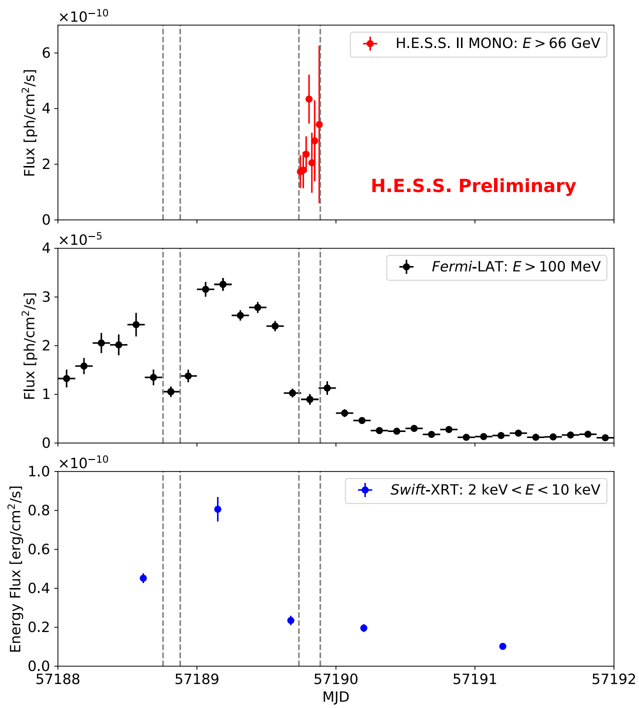
- Unexpected discovery of FSRQ PKS 1441+25 by MAGIC and VERITAS, z = 0.939.
- Powerful cosmological constraints from a single source, $\gamma + \gamma \rightarrow e^+ + e^-$.
- Location of emitting region constrained to be far from the center. Gamma rays must be from outside BLR.

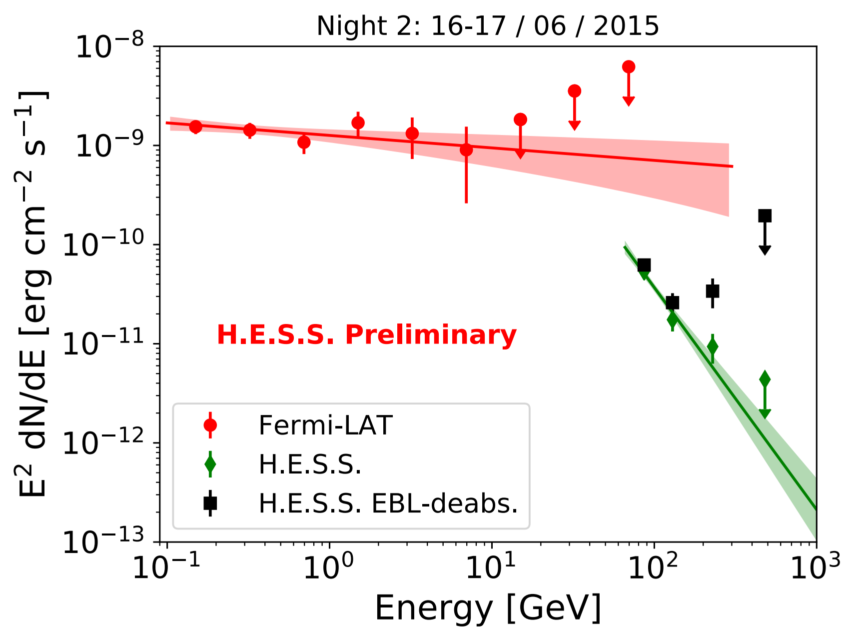


VERITAS Collaboration, ApJL (2015)

Flat-Spectrum Radio Quasars at TeV Energies

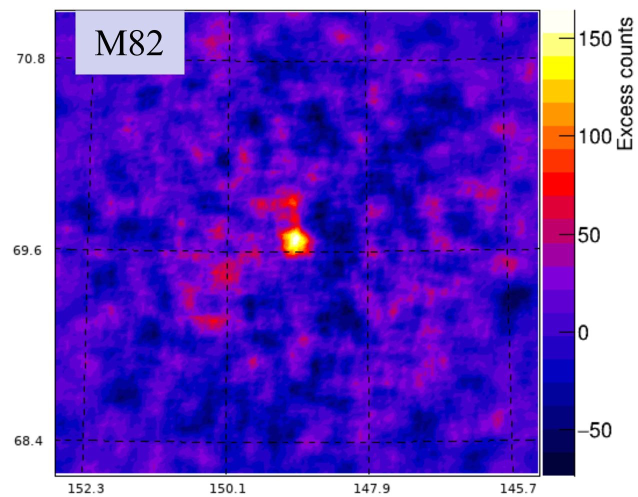
- Most luminous γ-ray sources, characterized by jets with high Doppler factors, superluminal motion, emissions that include high radio and optical polarizations.
- 3C 279 detected at its historical maximum by Fermi-LAT in 2015. TeV detections by MAGIC and H.E.S.S.
- TeV measurements can provide information about opacity in the source region.

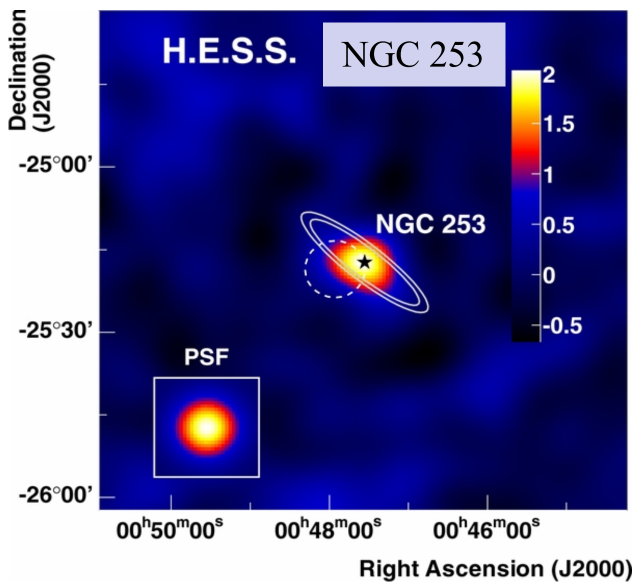


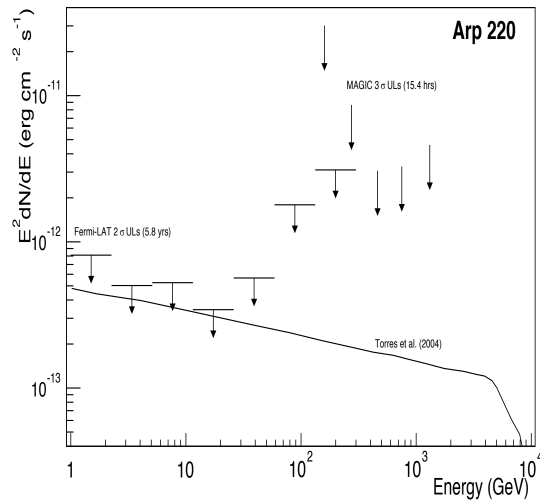


H.E.S.S. Collaboration, ICRC (2017)

New Source Classes: Starburst Galaxies







VERITAS, Science (2009), TeVPA 2018

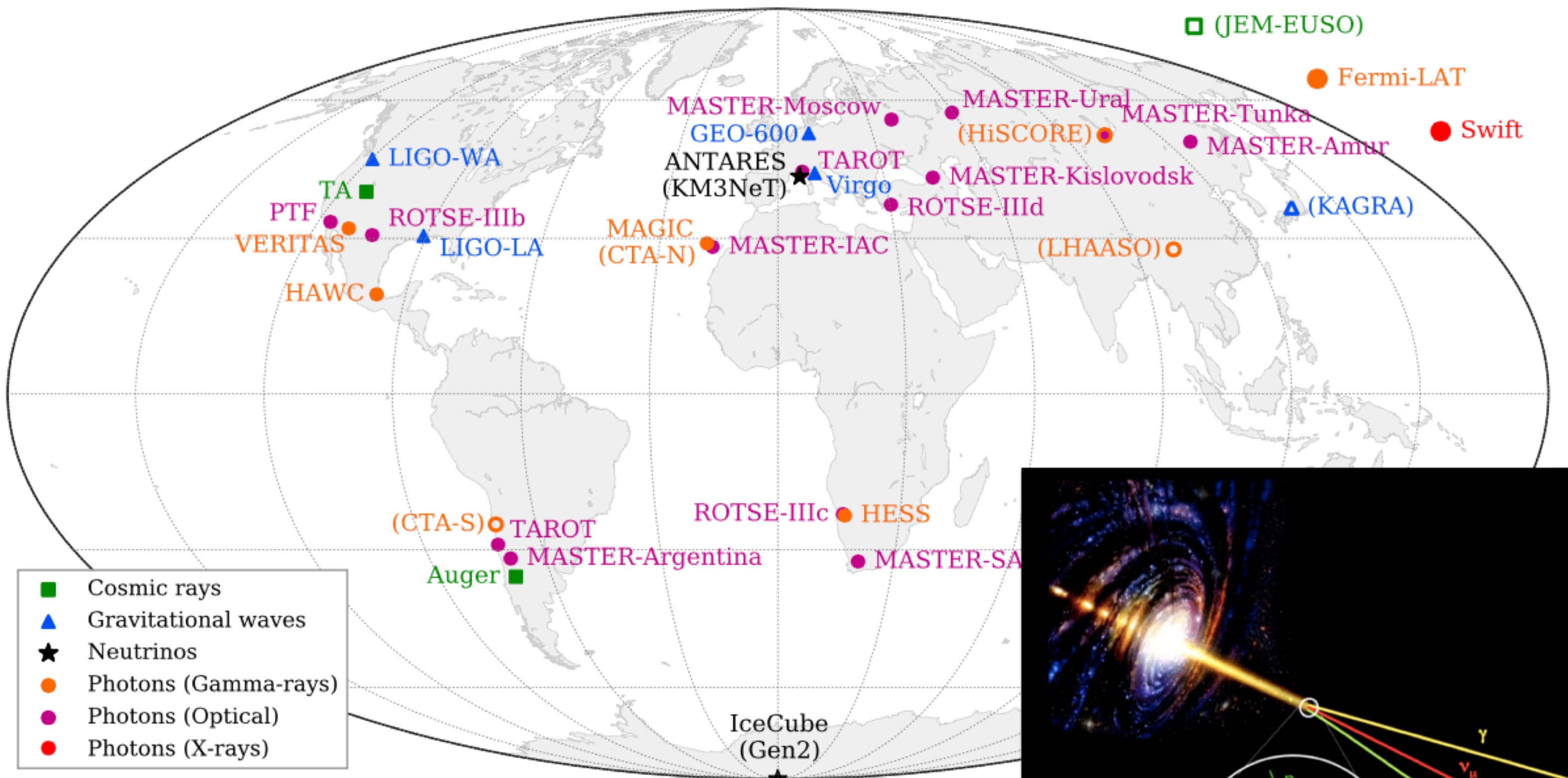
H.E.S.S.

MAGIC

- Only 2 starburst galaxies detected at VHE.
- Among the weakest VHE sources detected, < 1% Crab Nebula flux.
- Cosmic ray density ~ 250 eV cm^{-3} (~ 500 times average Galactic density).
- The active regions of starburst galaxies have exceptionally high rates of star formation.
- High supernova rate: ~0.1-0.3/year, high gas density: ~150 particles/cm^3
- Starbursts galaxies offer an independent probe for the SNR paradigm for CR origin.

Era of Multi-Messenger Astronomy

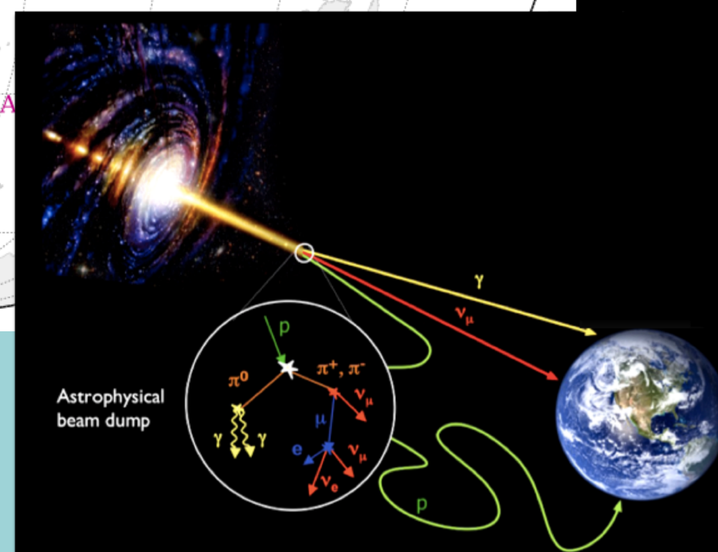
From "Dawn of Multi Messenger Astronomy," Santander, 2016



$$p + \gamma \rightarrow p + \pi_0$$

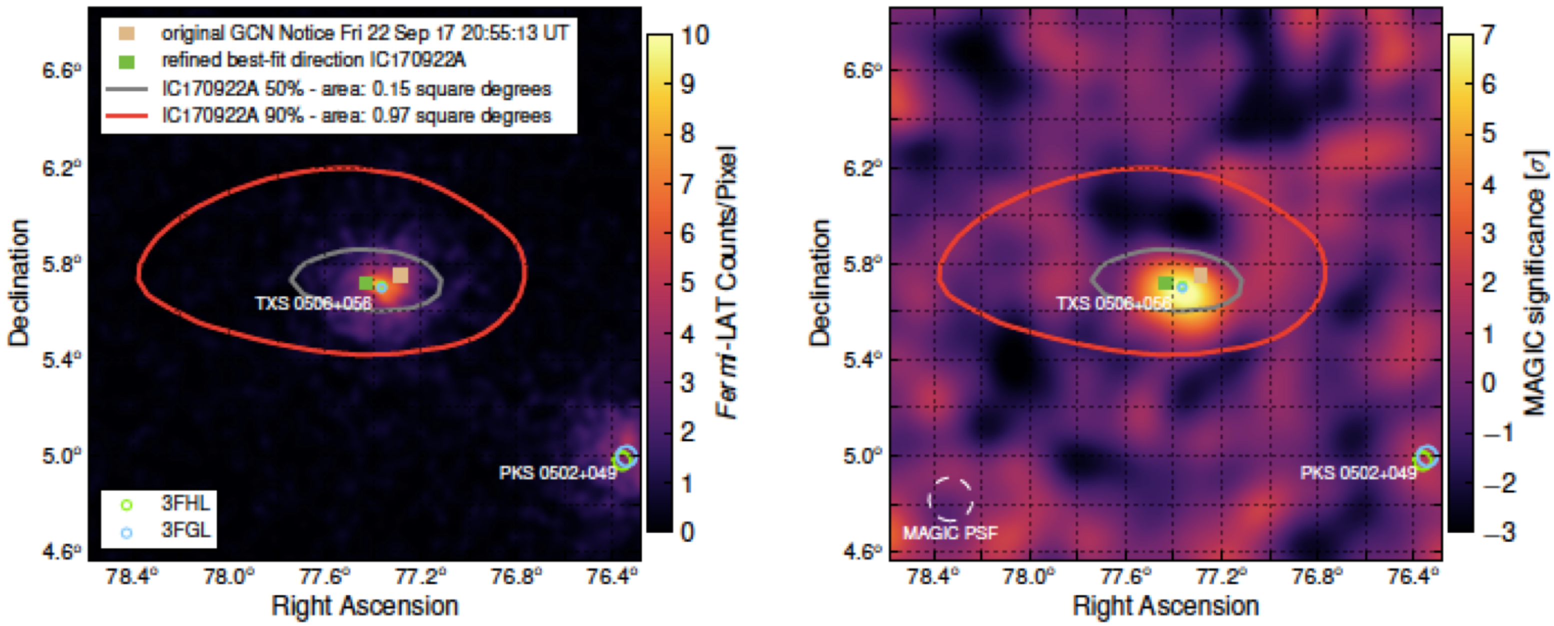
$$\rightarrow n + \pi^+$$

$$\pi^0 \rightarrow \gamma\gamma \quad \pi^+ \rightarrow \mu^+ + \nu_{\mu.} \quad \mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$$



Possible γ-ray – HE Neutrino Association

IC170922 and TXS 0506+056: First evidence (3σ) for a neutrino source

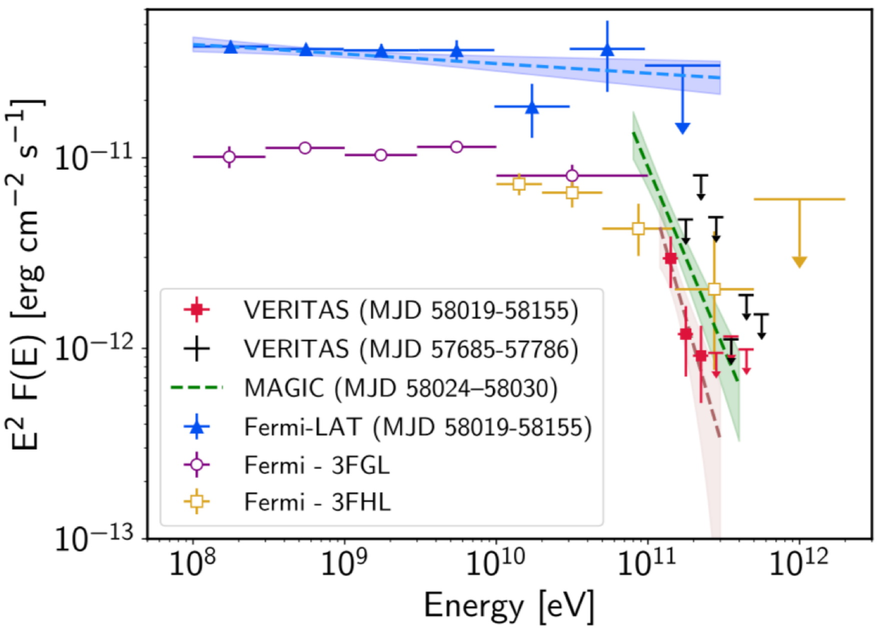


- On Sept 22, 2017, IceCube detected a high-energy ν ≅ 290 TeV energy!
- Fermi LAT reported that TXS 0506+056 was in a flaring state.
- An extensive multi-wavelength campaign followed.
- Detected at TeV energies first by MAGIC.

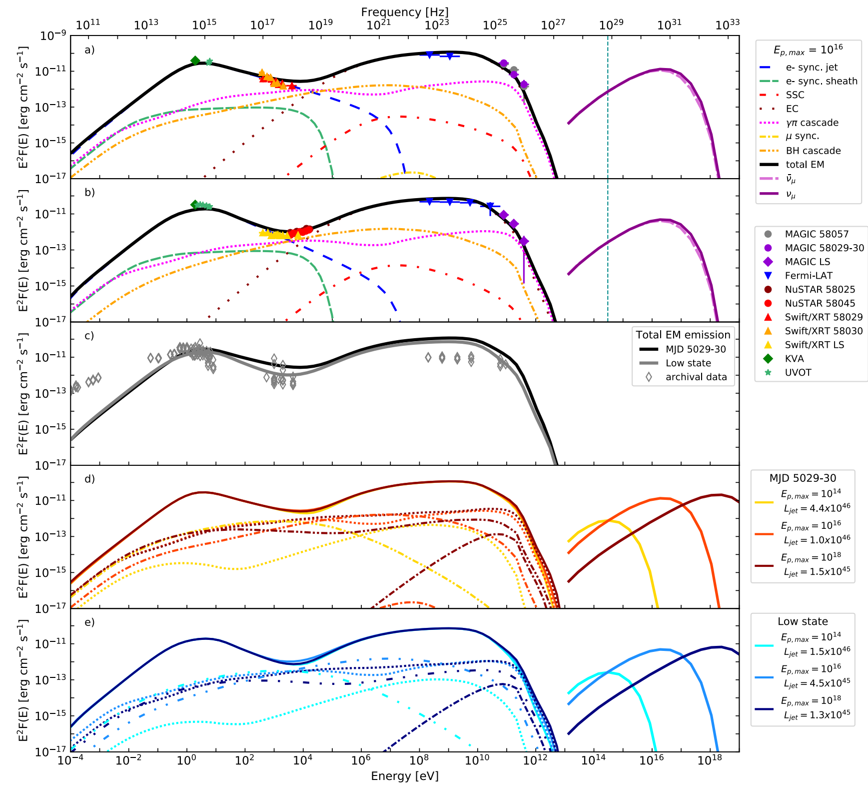
IceCube + MWL partners, MAGIC Collaboration (2018)

Monitoring the blazar TXS 0506+056 with VERITAS

VERITAS Collaboration, ApJL (2018)



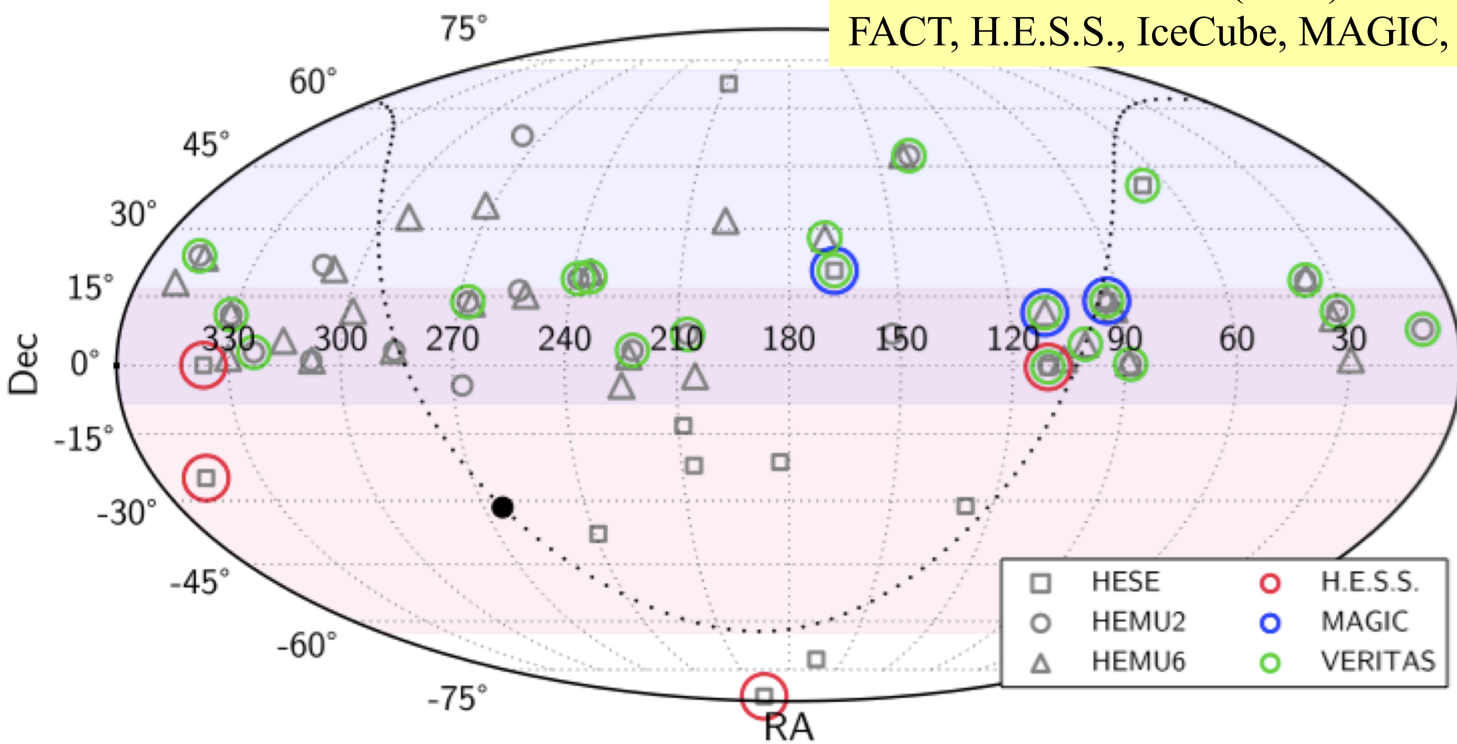
MAGIC Collaboration, ApJL (2018)



- Sharp break between GeV and TeV energies, not consistent with EBL alone.
- If there is hadronic γ-ray emission, it could attenuated at the source, and potentially cascades down to energies lower than the Fermi-LAT band.
- MAGIC data: detailed lepto-hadronic model. Max $E_p \sim 10^{14} - 10^{18}$ eV, $\Gamma_{jet} \sim 20$.

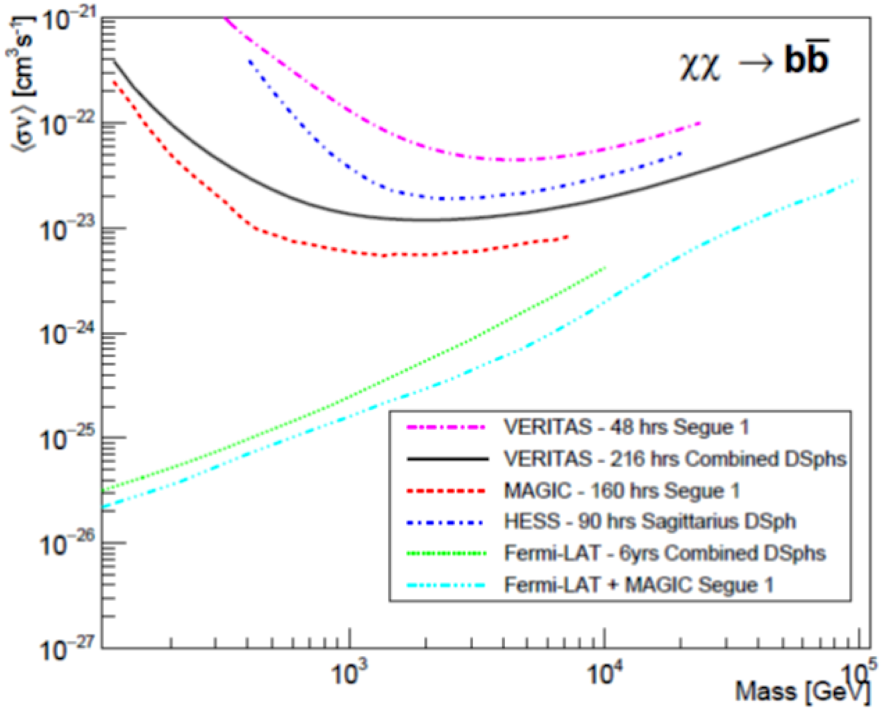
Searching for VHE Neutrino Point Sources

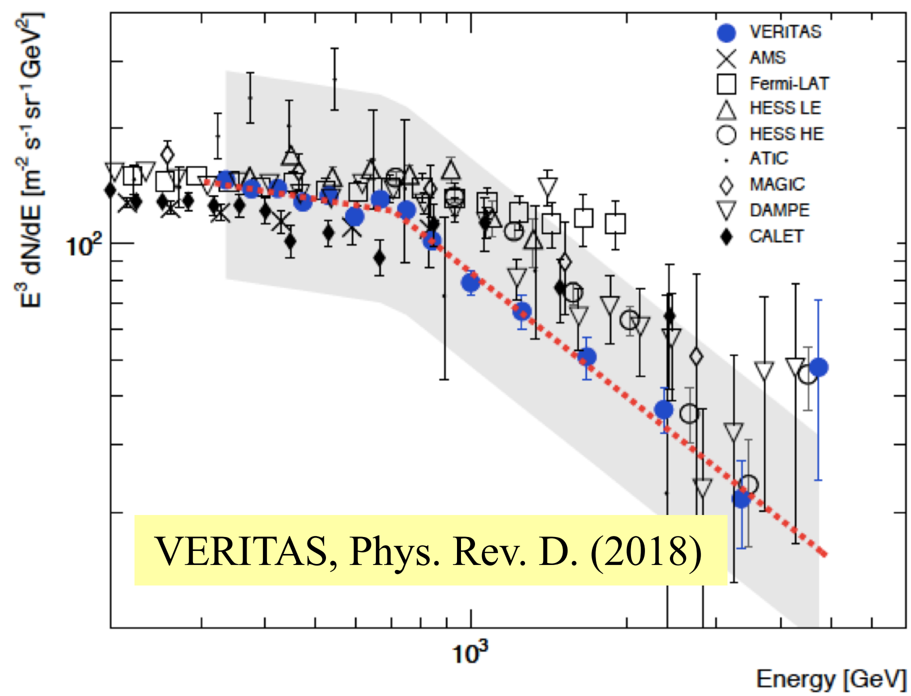
Santander et al. ICRC (2017)
FACT, H.E.S.S., IceCube, MAGIC, VERITAS



- Over the last four years, FACT, H.E.S.S., MAGIC and VERITAS, have searched for γ-ray emission associated with high-energy neutrino events, potentially astrophysical ($p_{astro} > 50\%$) and have good localizations (~1°).
- No significant excess was found within any of the neutrino regions of interest.

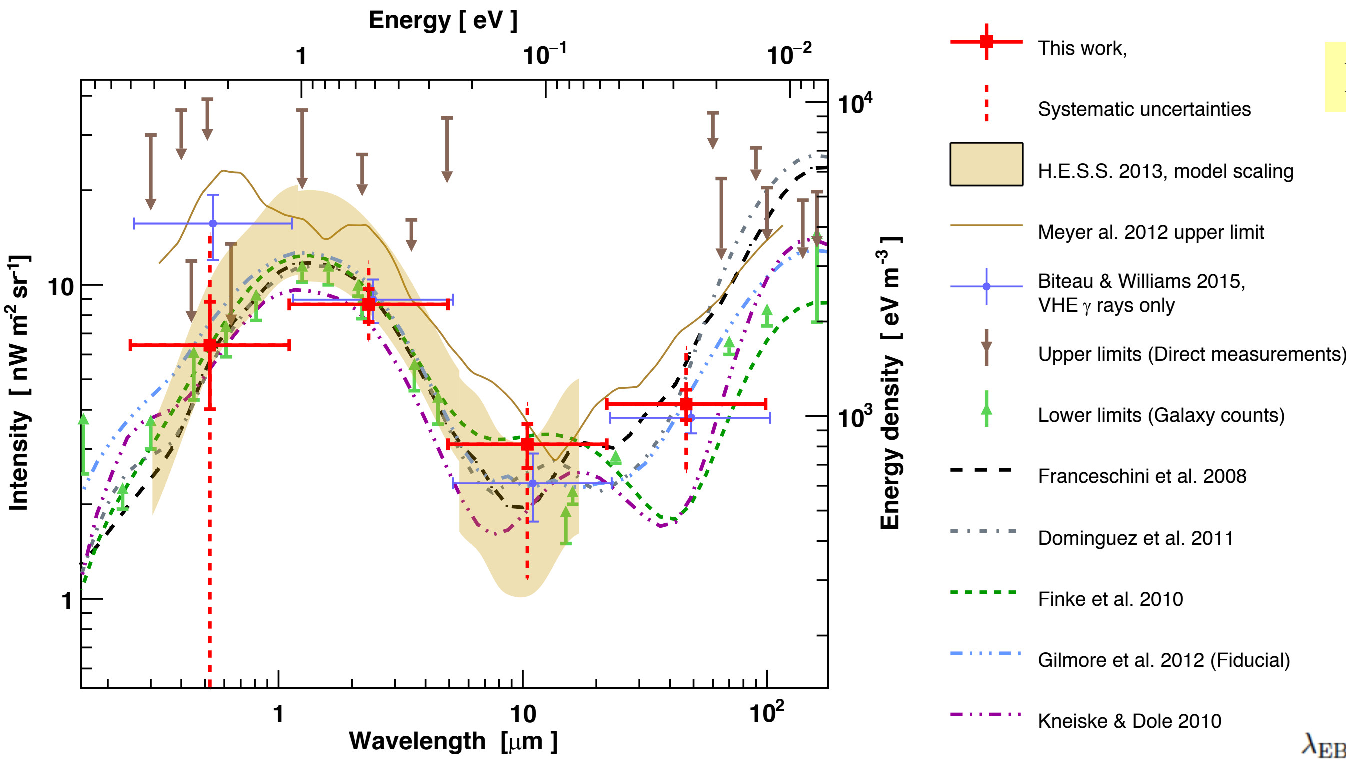
Large Data Sets Allow Fundamental Physics Studies





- Combined result from four dwarf galaxies, Segue1, Ursa Minor, Draco, Boötes, studies by H.E.S.S., MAGIC, VERITAS.
- Spectrum of CREs between 300 GeV and 5 TeV, as measured by VERITAS along with previously published measurements.

Large Data Sets Allow Fundamental Physics Studies



H.E.S.S. Collaboration (2017)

$$\lambda_{\rm EBL} \simeq 0.5 - 5\,\mu{\rm m} \times \left(\frac{E_\gamma}{1\,{\rm TeV}}\right) \times (1+z)^2$$

- The current generation of IACTs has probed a large fraction of the EBL spectral energy distribution, covering a range from 0.1–100μm.
- Measurement of extragalactic background light, imprint on blazar spectra.
- IACTs probe the long wavelengths where the theoretical models disagree.

Future Prospects

- After more than 10 years of continued operations, current-generation IACTs are still going strong.
- Productive science programs covering Galactic, Extragalactic, Dark Matter, Cosmic Rays and Fundamental Physics.
- LZA observations - sensitivity to VHE (e.g. Galactic Center). Search for PeVatrons.
- Sensitivity to transients, rapid response, combination of spectral and angular resolution make IACTs a powerful tool in MM astronomy.
- H.E.S.S. II and MAGIC sensitivity to lower energy threshold, higher-redshift AGN.
- Continued operations of IACTs are critical at this time of contemporaneous observations with multi-messenger instruments, before CTA.
- Exciting prospects for transients, GRBs, FRBs.

Thank you

- To the VERITAS Collaboration
- Razmik Mirzoyan for providing slides from MAGIC
- Mathieu de Naurois for providing slides from H.E.S.S.
- Thank you to the organizers of the symposium

Extra/Backup slides