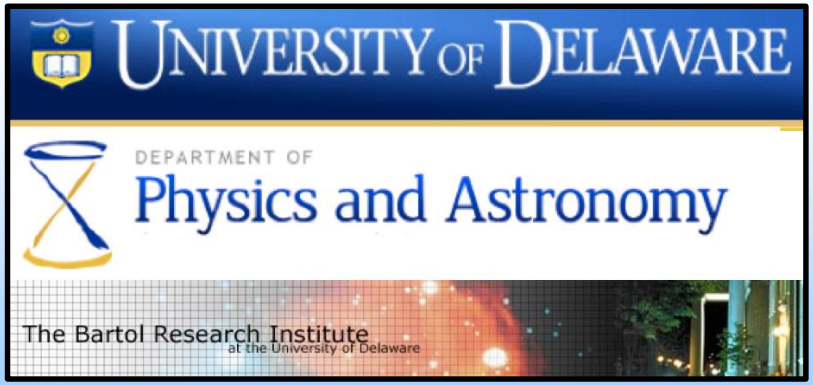


Highlights from the Current Generation of IACTs

Jamie Holder (U. Delaware/ Bartol)

CTA Symposium, Bologna
May 2019

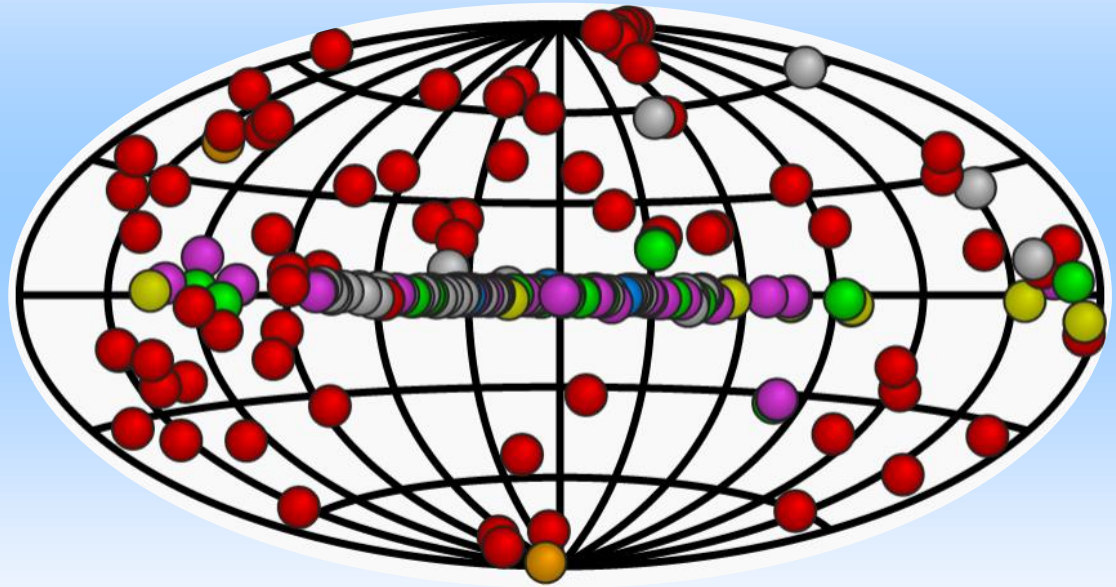

VERITAS


MAGIC II


H.E.S.S. II

The TeV Gamma-ray Source Catalog

- Over 200 sources from many different source classes and sub-categories.

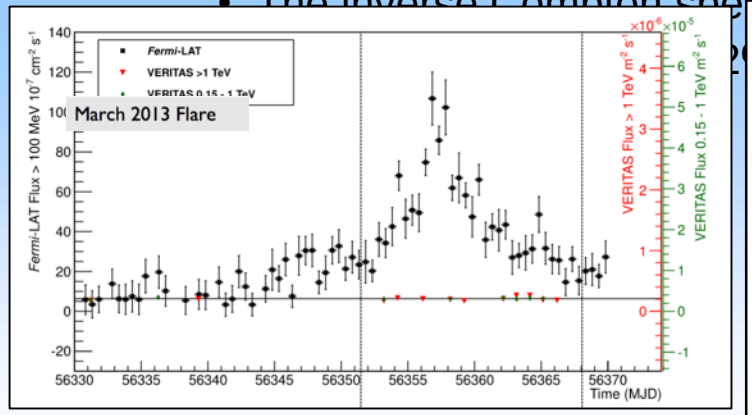


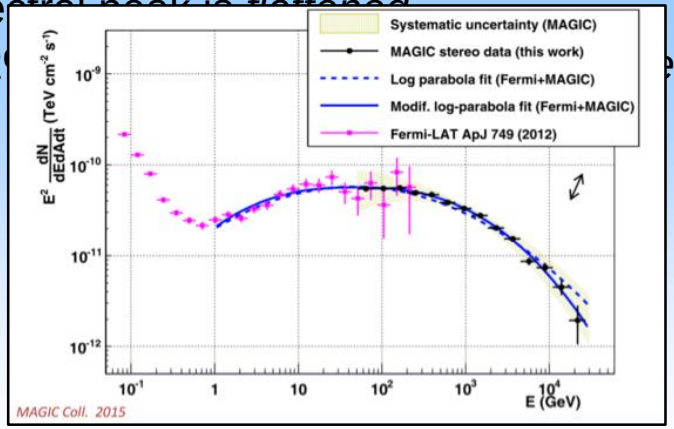
Pulsar and/or Pulsar wind Nebula
Active Galactic Nucleus
Supernova Remnant
Starburst Galaxy
Unidentified
Binary system
Stellar Cluster

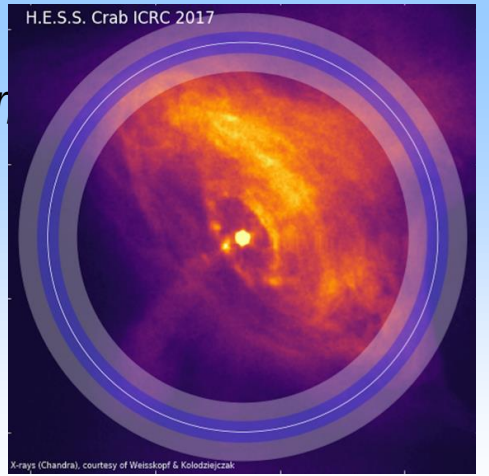
http://tevcat2.uchicago.edu/

TeV Gamma-ray emission from the Crab Nebula

- First astrophysical TeV gamma-ray source detected (Whipple Collaboration, in 1989).
- Emission is SSC of leptons accelerated near the termination shock of the pulsar wind.
- Current generation of IACTs have provided measurements of *exceptional* precision:
  - The Crab emission is *spatially resolved* at TeV energies.
  - The inverse Compton spectral peak is *flattened*



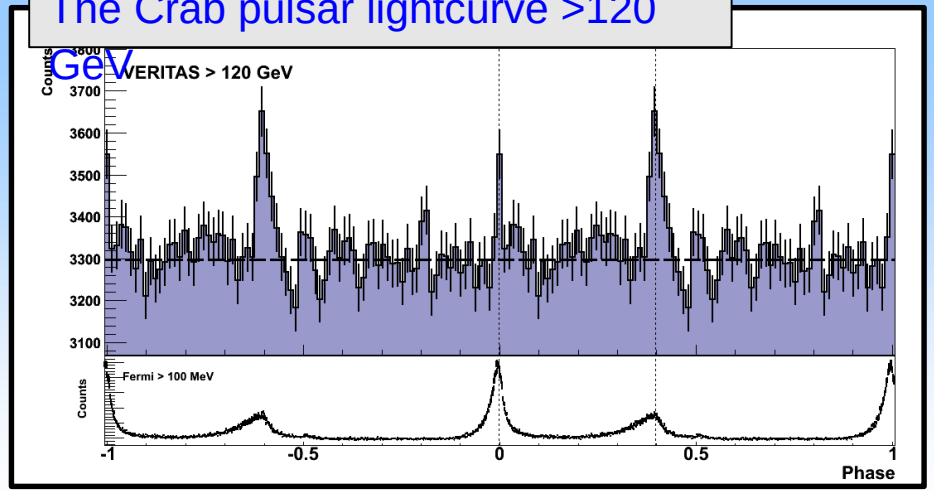




The Crab Pulsar

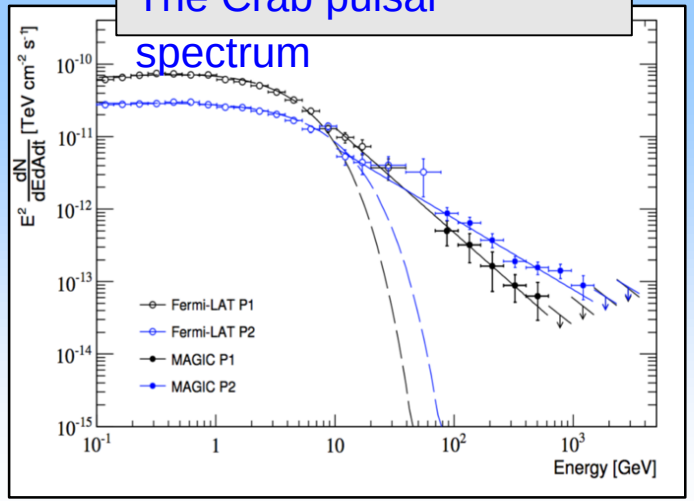
- Fermi-LAT measures a spectral break at 6 GeV
- VERITAS measured power-law emission above 100 GeV
- Implies emission region > 10 stellar radii.
- Absence of exponential cutoff makes curvature radiation unlikely.
- Latest MAGIC results extend to 1 TeV.
- H.E.S.S. has now detected Vela pulsar up to 7 TeV. The Crab is not the only TeV pulsar.
- What is the pulsar emission mechanism at the highest energies? What is the

The Crab pulsar lightcurve >120 GeV

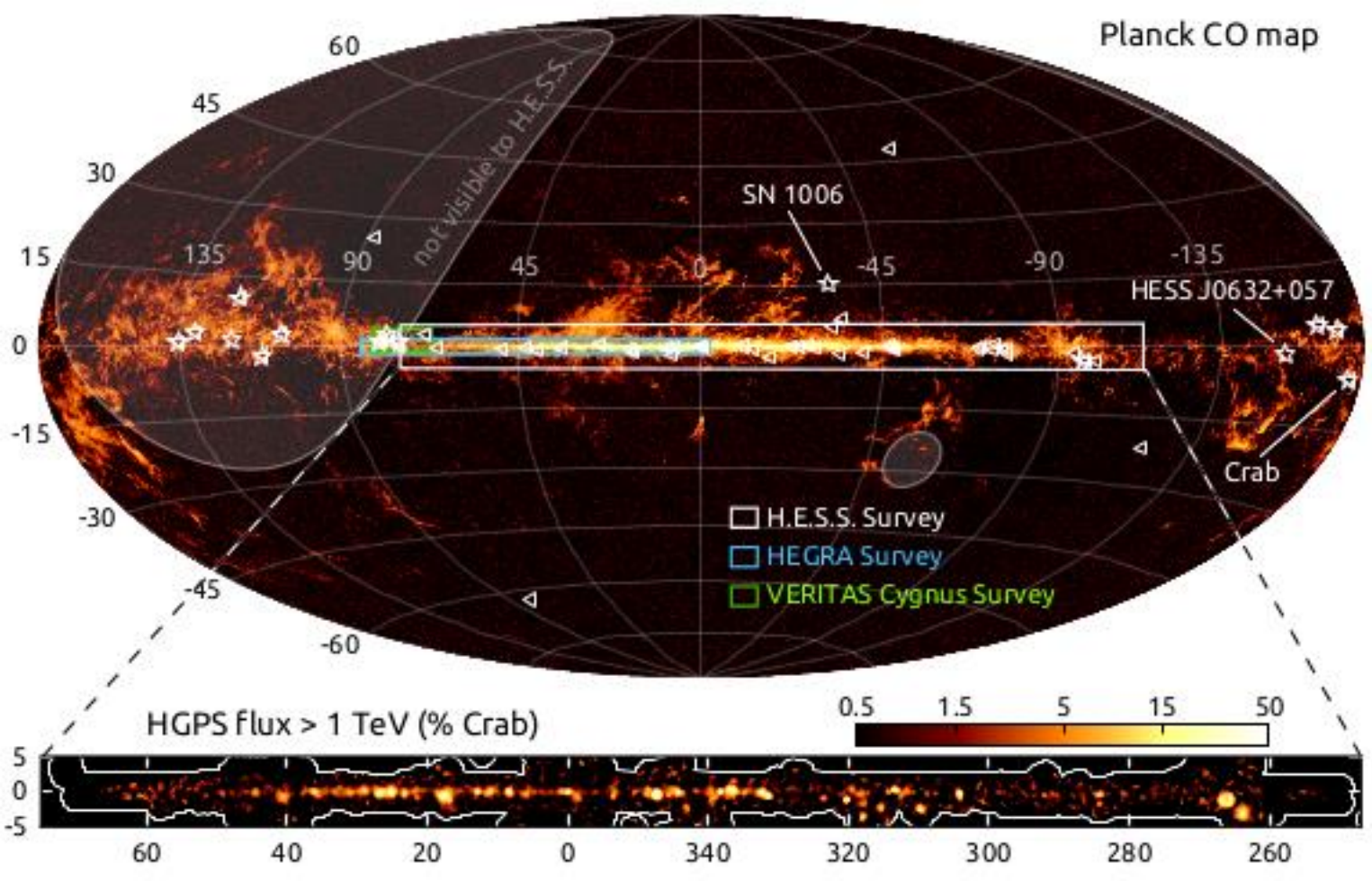


VERITAS Collaboration, Science, 334, 69, 2011.

The Crab pulsar spectrum



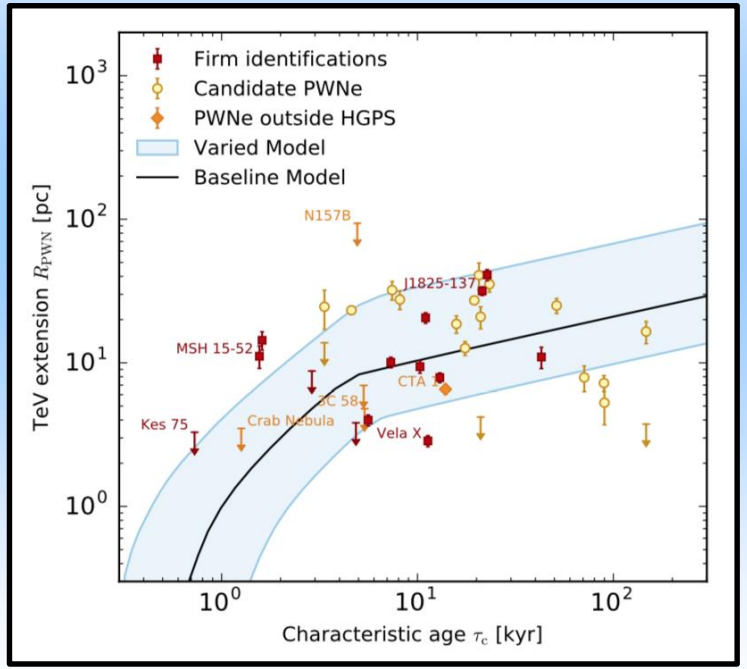
MAGIC Collaboration, A&A, 585, 133, 2016.

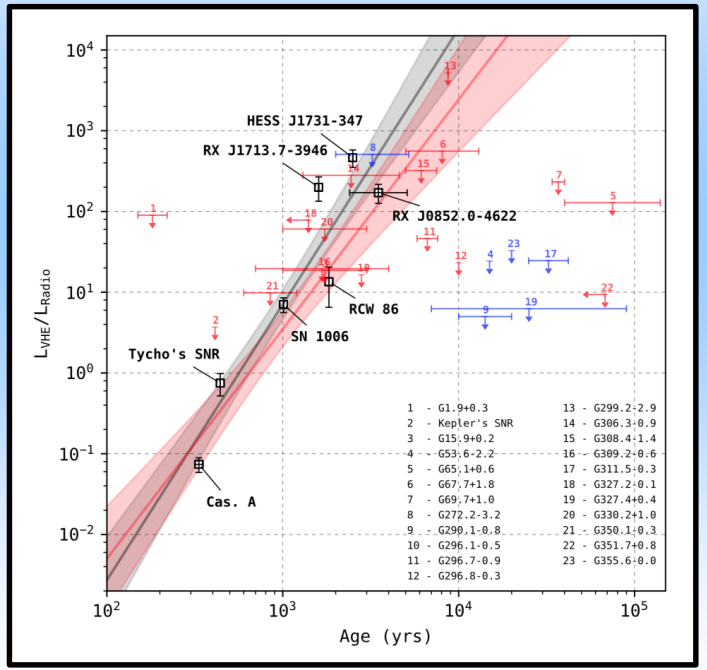


https://www.mpi-hd.mpg.de/hfm/HESS/pages/home/som/2016/01/

Galactic Population Studies

- The growing catalogue of Galactic TeV sources allows the first *population studies* of the properties and evolution of very high energy emission from pulsar wind nebulae and supernova remnants.

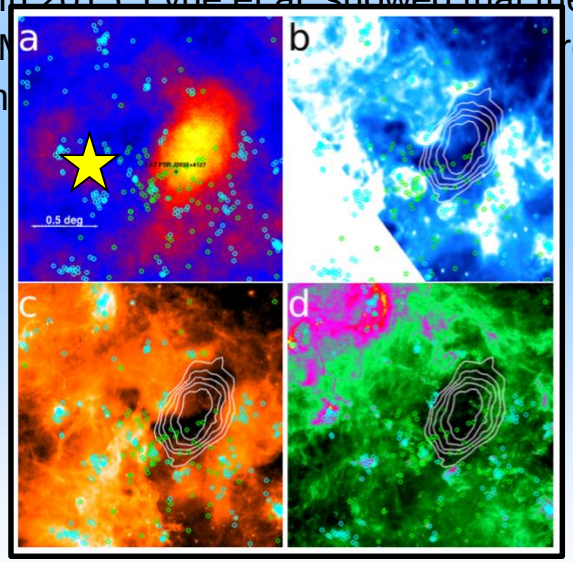


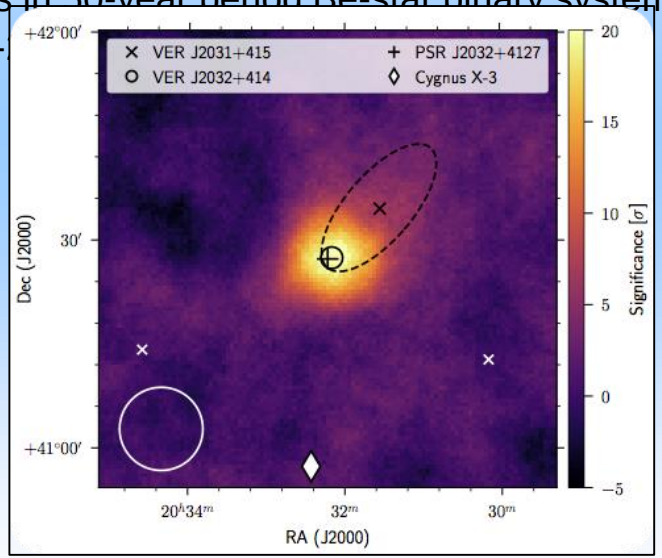


H.E.S.S. collaboration, A&A 612 (2018)

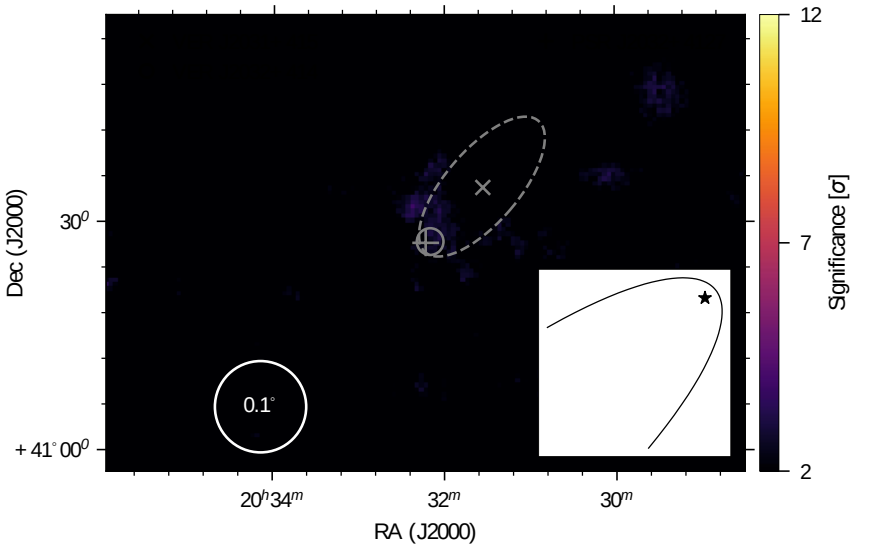
Two-for-one: a gamma-ray binary PWN

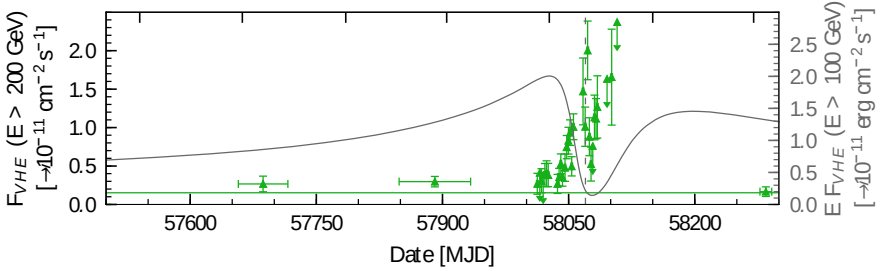
- TeV J2032+4127 was the first TeV source discovered (HEGRA) with no clear counterpart.
- VERITAS showed it to be an asymmetric, extended source, coincident with a radio/IR void.
- In 2009, Fermi discovered the likely power source: PSR J2032+4127 driving a PWN.
- In 2015, Lyne et al. showed that the pulsar is in 50-year period Be-star binary system.
- M… …rom 2016-
bin…

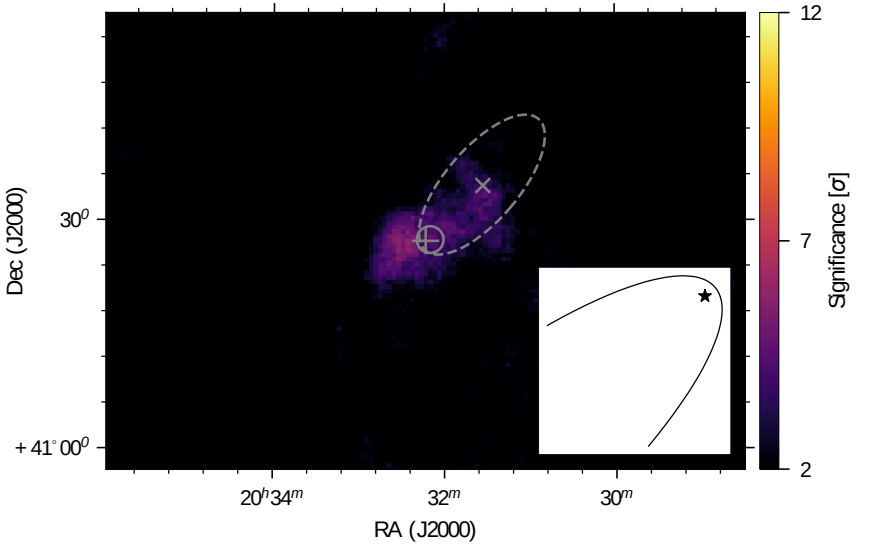


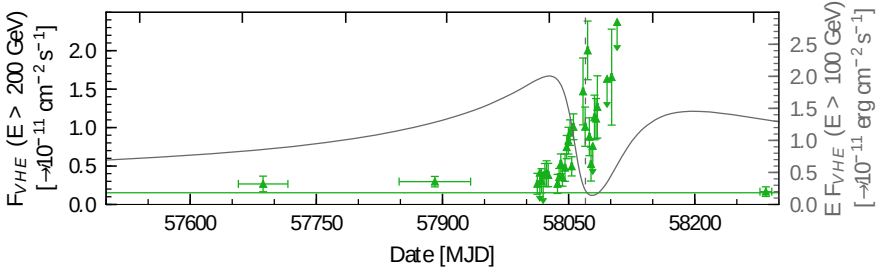


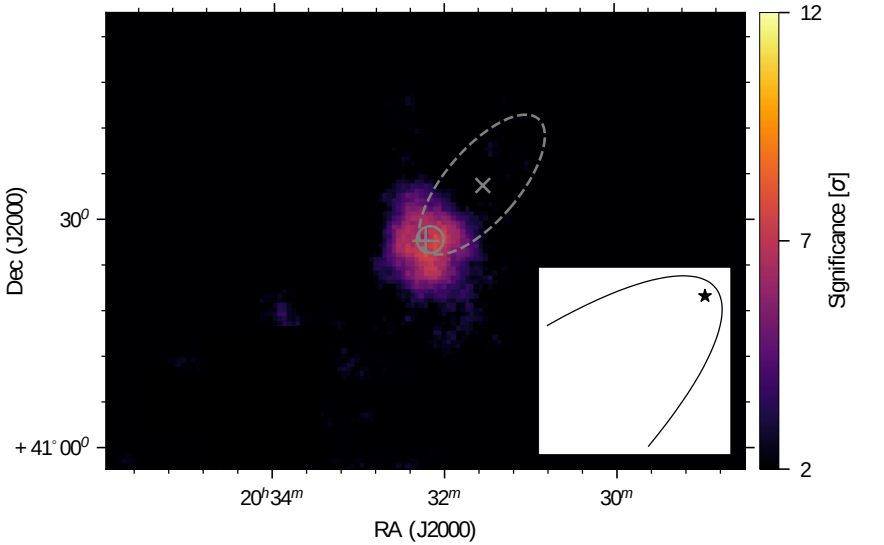
VERITAS and MAGIC Collaborations, ApJL, 867, 19, 2018.

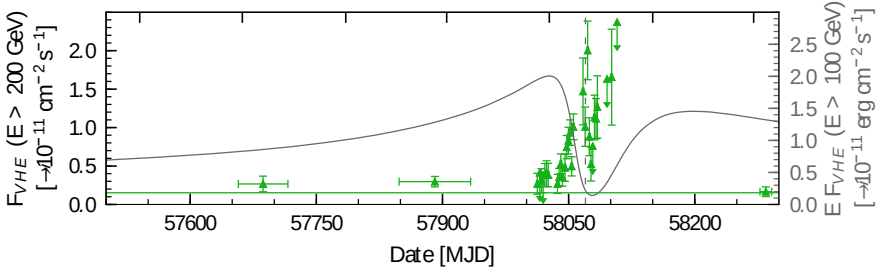

12
7
2
Significance [σ]
Dec (J2000)
30^0
+ 41° 00^0
0.1°
20^h34^m
32^m
30^m
RA (J2000)

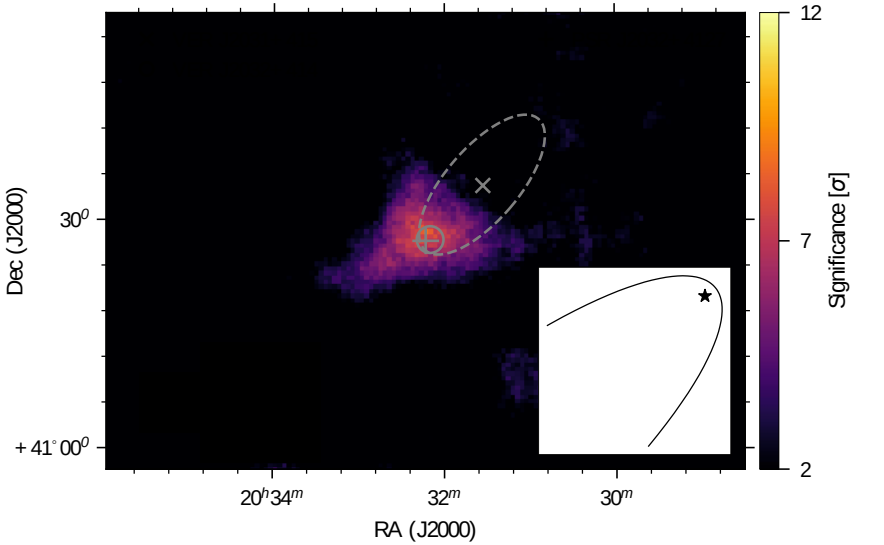

F_VHE (E > 200 GeV) [→10^-11 cm^-2 s^-1]
2.0
1.5
1.0
0.5
0.0
57600
57750
57900
58050
58200
Date [MJD]
E F_VHE (E > 100 GeV) [→10^-11 erg cm^-2 s^-1]
2.5
2.0
1.5
1.0
0.5
0.0

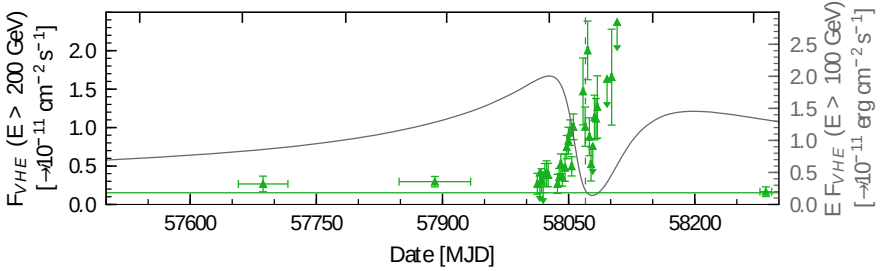

12
7
2
Significance [σ]
Dec (J2000)
30^0
+ 41° 00^0
20^h34^m
32^m
30^m
RA (J2000)

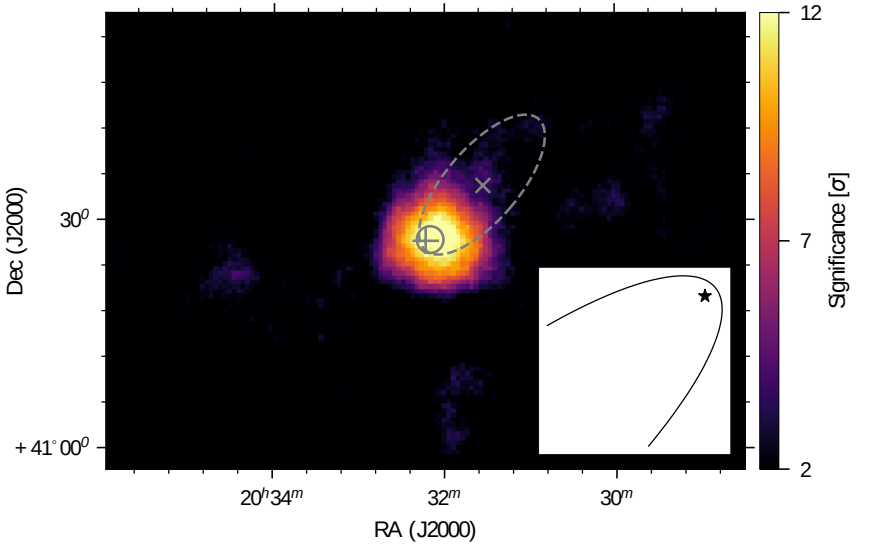

F_VHE (E > 200 GeV) [→10^-11 cm^-2 s^-1]
2.0
1.5
1.0
0.5
0.0
57600
57750
57900
58050
58200
Date [MJD]
E F_VHE (E > 100 GeV) [→10^-11 erg cm^-2 s^-1]
2.5
2.0
1.5
1.0
0.5
0.0

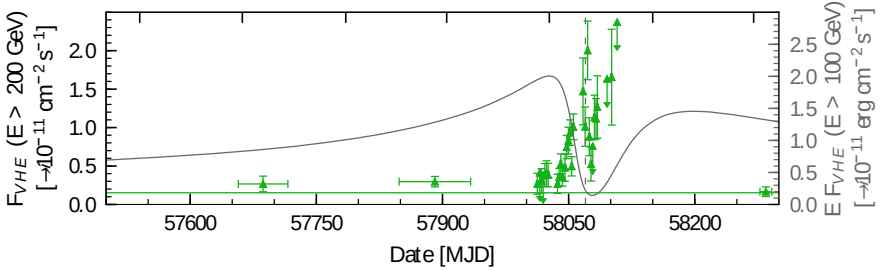

12
7
2
Significance [σ]
Dec (J2000)
30^0
+ 41° 00^0
20^h34^m
32^m
30^m
RA (J2000)

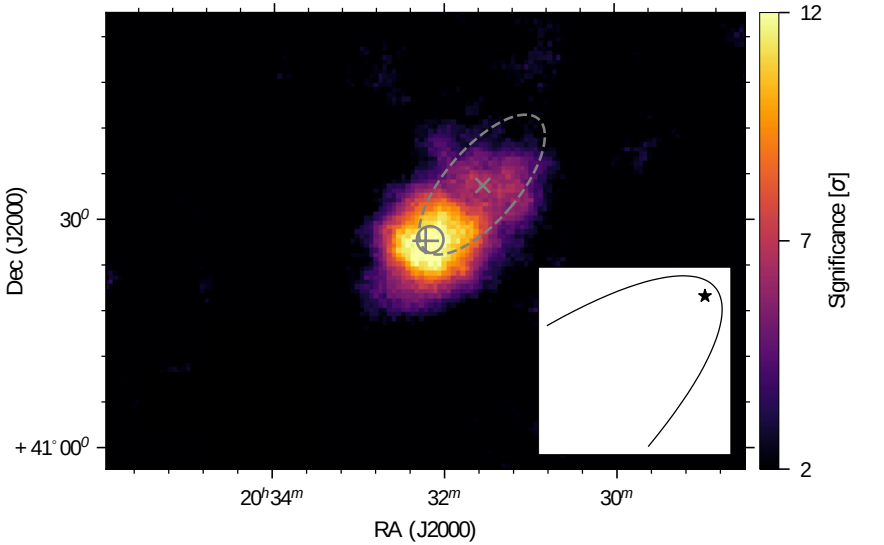

F_VHE (E > 200 GeV) [→10^-11 cm^-2 s^-1]
2.0
1.5
1.0
0.5
0.0
57600
57750
57900
58050
58200
Date [MJD]
E F_VHE (E > 100 GeV) [→10^-11 erg cm^-2 s^-1]
2.5
2.0
1.5
1.0
0.5
0.0

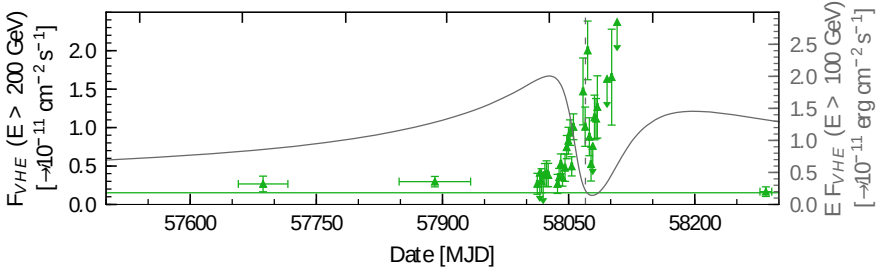

12
7
2
Significance [σ]
Dec (J2000)
30^0
+41°00^0
20^h34^m
32^m
30^m
RA (J2000)

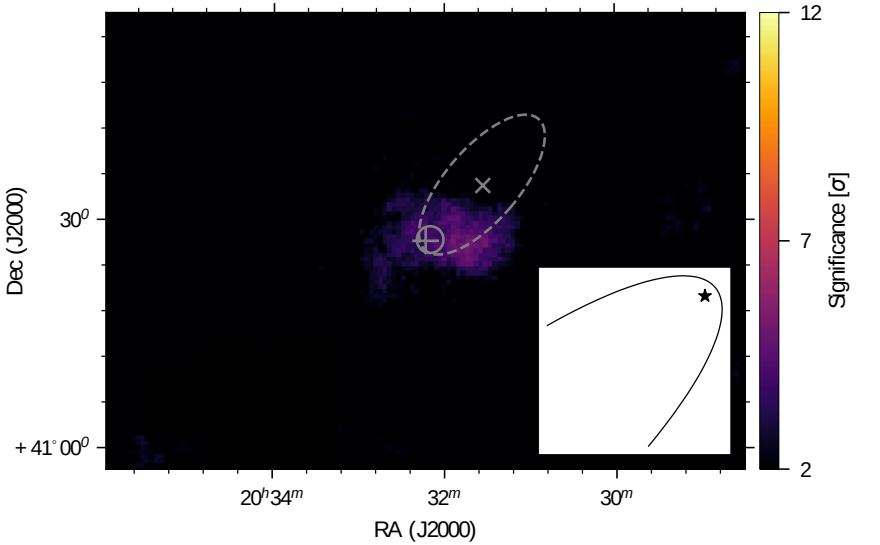

F_VHE (E > 200 GeV) [→10^-11 cm^-2 s^-1]
2.0
1.5
1.0
0.5
0.0
57600
57750
57900
58050
58200
Date [MJD]
E F_VHE (E > 100 GeV) [→10^-11 erg cm^-2 s^-1]
2.5
2.0
1.5
1.0
0.5
0.0

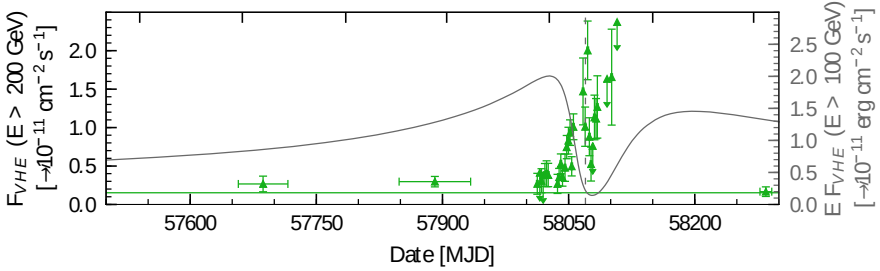

12
7
2
Significance [σ]
Dec (J2000)
30^0
+ 41° 00^0
20^h34^m
32^m
30^m
RA (J2000)


F_VHE (E > 200 GeV) [→10^-11 cm^-2 s^-1]
2.0
1.5
1.0
0.5
0.0
57600
57750
57900
58050
58200
Date [MJD]
E F_VHE (E > 100 GeV) [→10^-11 erg cm^-2 s^-1]
2.5
2.0
1.5
1.0
0.5
0.0


12
7
2
Significance [σ]
Dec (J2000)
30^0
+ 41° 00^0
20^h34^m
32^m
30^m
RA (J2000)


F_VHE (E > 200 GeV) [→10^-11 cm^-2 s^-1]
2.0
1.5
1.0
0.5
0.0
57600
57750
57900
58050
58200
Date [MJD]
E F_VHE (E > 100 GeV) [→10^-11 erg cm^-2 s^-1]
2.5
2.0
1.5
1.0
0.5
0.0

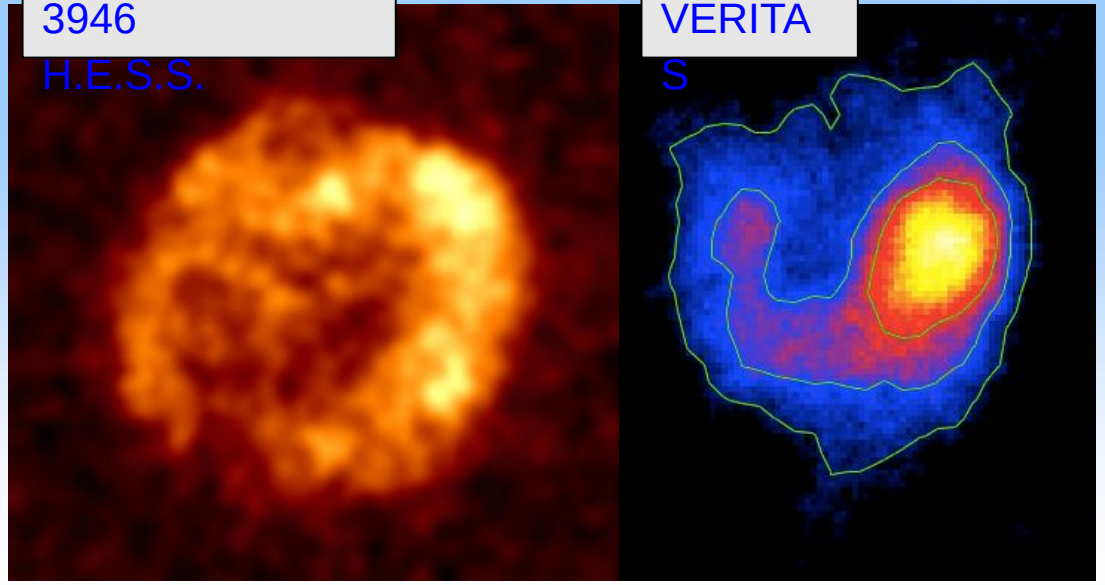

12
7
2
Significance [σ]
Dec (J2000)
30^0
+ 41° 00^0
20^h34^m
32^m
30^m
RA (J2000)


F_VHE (E > 200 GeV) [→10^-11 cm^-2 s^-1]
2.0
1.5
1.0
0.5
0.0
57600
57750
57900
58050
58200
Date [MJD]
E F_VHE (E > 100 GeV) [→10^-11 erg cm^-2 s^-1]
2.5
2.0
1.5
1.0
0.5
0.0

Shell-type Supernova Remnants

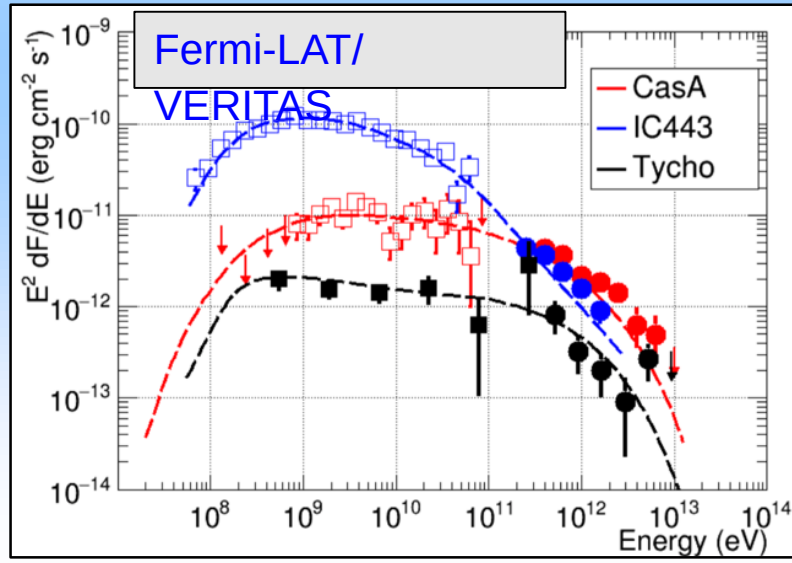
- Promising candidates to supply the majority of Galactic cosmic rays.
- A population which now includes a TeV-only detection (HESS J1912+101).
- Discrimination between leptonic and hadronic particle populations is often difficult.
- Even where hadrons are favored, the spectra do not extend to tens of TeV.

RX J 1713.7-3946
H.E.S.S.



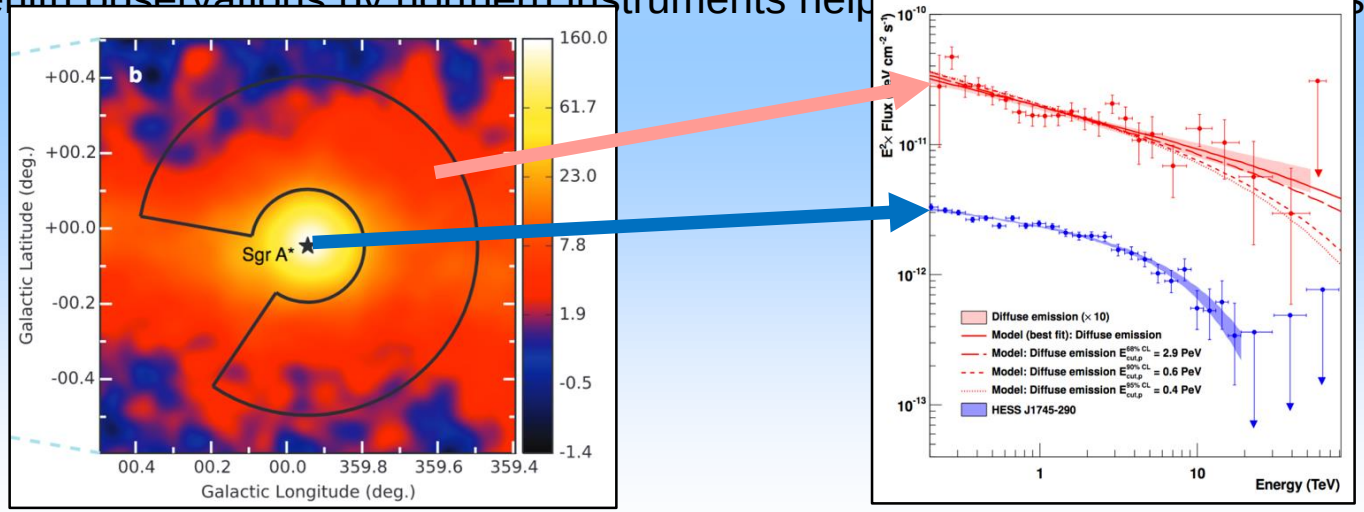
IC 443
VERITAS

Fermi-LAT/
VERITAS



The Galactic Center Region.

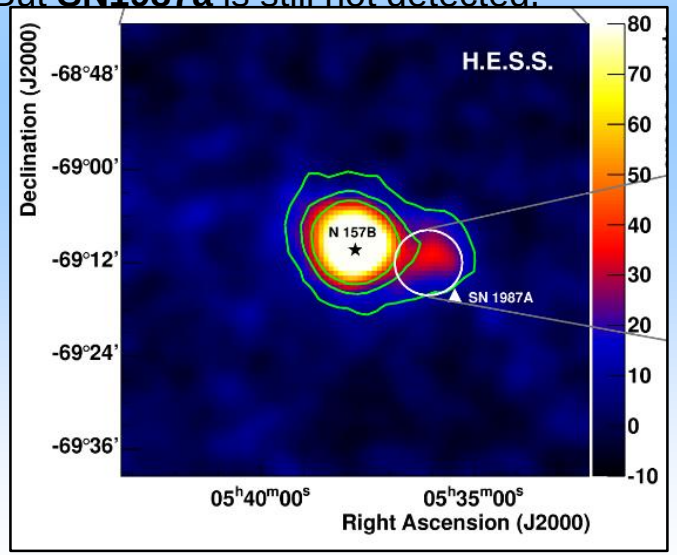
- H.E.S.S. detected a bright, steady TeV source, spatially coincident with SgrA*
- Diffuse emission is observed along the plane, within a few degrees of the Galactic Center.
- The diffuse spectrum extends to 40 TeV with no cutoff.
- Indicates presence of PeV particles – but not sufficient to explain Galactic CR flux.
- Inner Galactic halo is also a good target for dark matter - but astrophysical contamination is challenging.
- Large zenith observations by northern instruments help to study highest energies.



H.E.S.S. Collaboration, Nature 531 (2016) 476

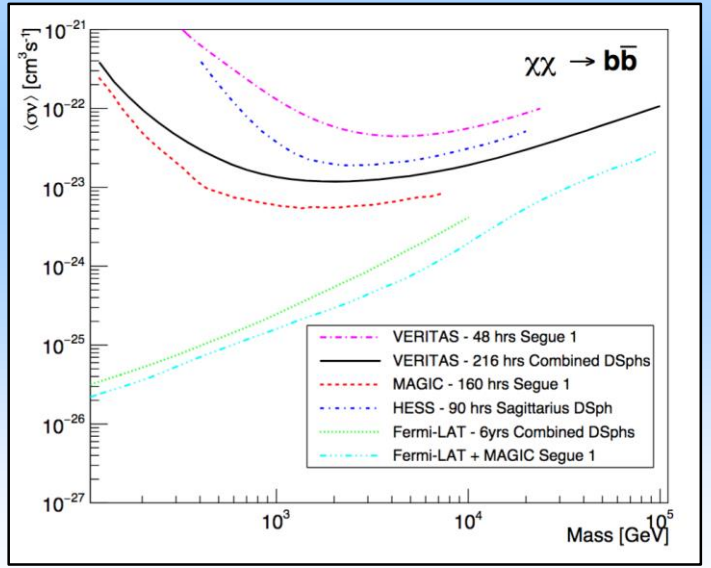
The Local Group

- The **LMC** hosts some exceptionally powerful TeV emitters:
  - **N157B**: PWN of the most energetic pulsar known.
  - **N132 D**: a radio-loud SNR.
  - **30 Dor C**: a wind-blown “superbubble”.
  - **LMC P3**: a 10-day gamma-ray binary.
  - But **SN1987a** is still not detected.



H.E.S.S. Collaboration. Science 347 (2015) 406-412

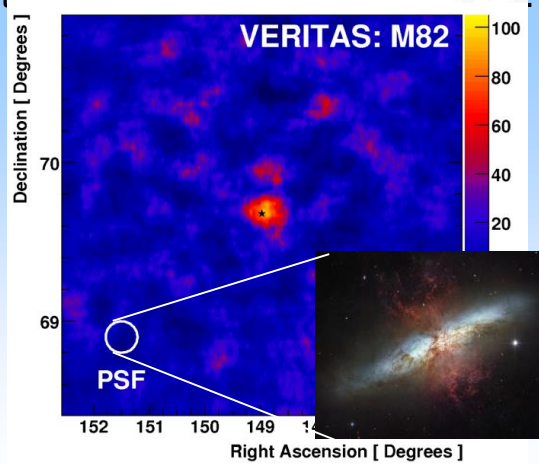
- Dark-matter dominated **dwarf spheroidal galaxies** are the preferred targets for WIMP annihilation signatures.
  - High J-factors.
  - Very low astrophysical backgrounds.



VERITAS Collaboration Phys. Rev. D, 95, 8, 2017

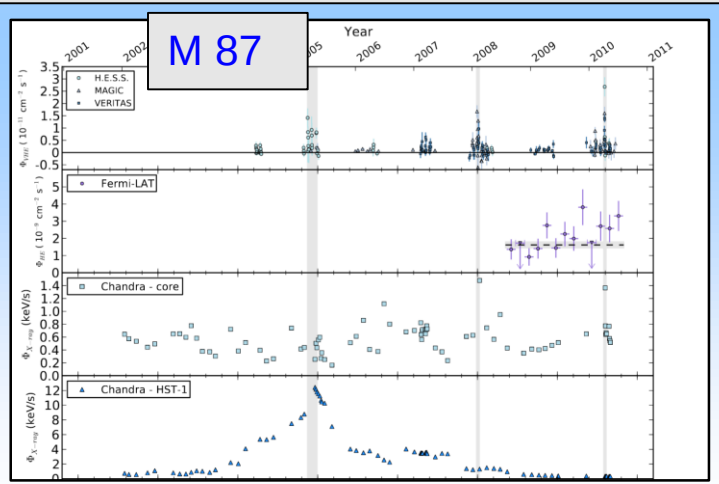
Nearby Galaxies

- **Starburst Galaxies**.
- Relatively weak TeV emission, detectable only with long exposures on nearby objects (M 82 and NGC 253).
- High rate of star formation leads to high rate of supernovae, high cosmic ray density (~500 x Galactic), and high target gas density (~150 x Galactic).
- CR interactions produce gamma-rays.



VERITAS Collaboration. Nature 462 (2009) 770

- **Radio Galaxies** have misaligned jets
- No relativistic beaming, so only nearby sources are detectable.
- For the closest, Cen A, TeV emission has recently been spatially resolved by H.E.S.S.
- For others (e.g. M 87, 3C 264), core/jet structures can be resolved in radio/X-ray, and correlated with the gamma-ray flux.

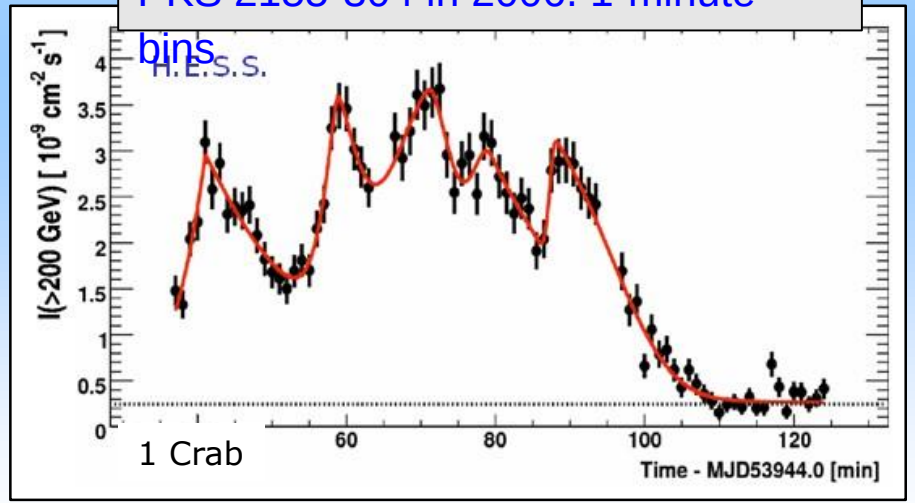


H.E.S.S./ MAGIC/VERITAS ApJ 746 (2012) 151

Blazars

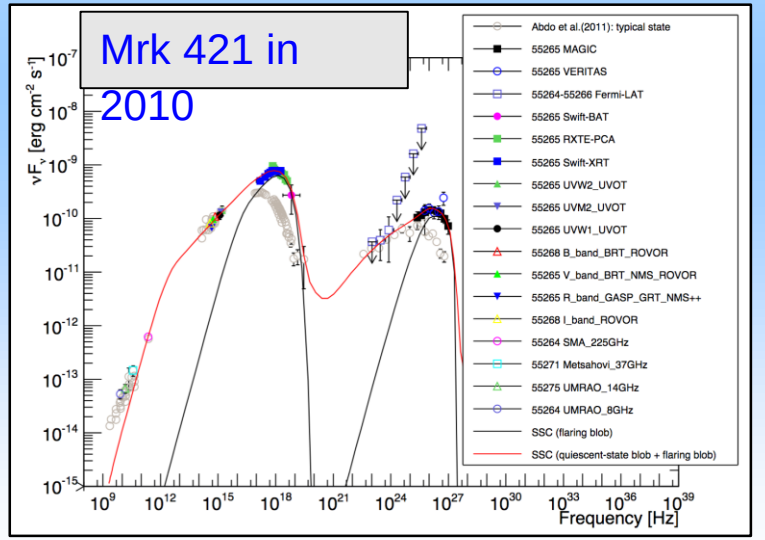
- Blazars constitute the largest extragalactic TeV source population.
- Mostly high-frequency peaked BL Lacertae objects, but also FSRQs and others.
- Exceptionally bright flares exhibit variability on all timescales, down to minutes.
- Emission characterized by double-peaked spectral energy distribution.
- Observations allow to constrain the location and size of the emission region, the acceleration mechanisms, particle populations and other parameters – but strictly contemporaneous multi-wavelength data are critical

PKS 2155-304 in 2006. 1-minute bins



H.E.S.S. Collaboration ApJL 664 L71 2007

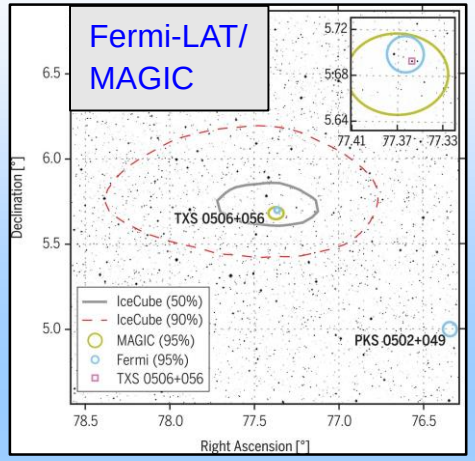
Mrk 421 in 2010

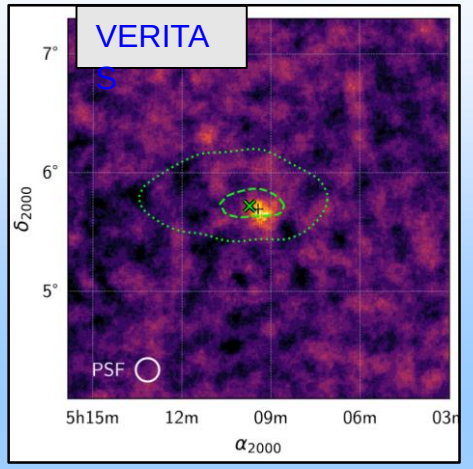


MAGIC/VERITAS A&A 578, 22, 2015.

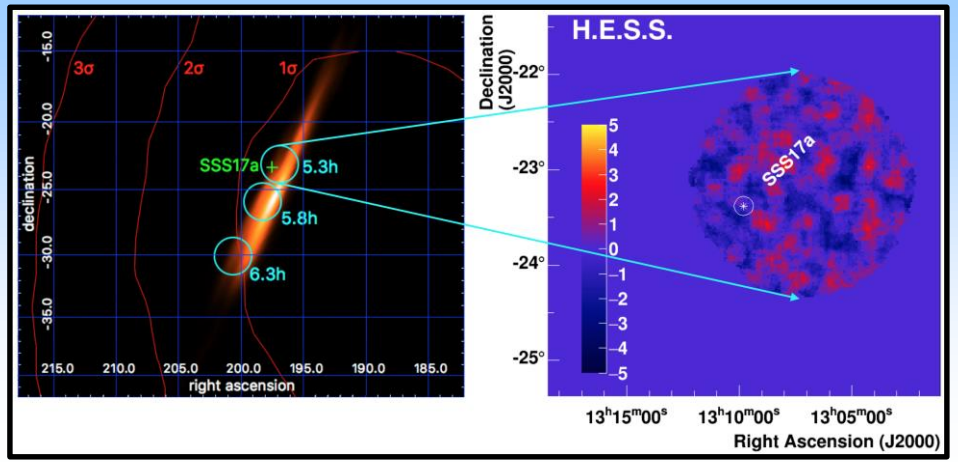
Multimessenger Astrophysics

- Blazars also play a key role in MMA
- Are they the sources of the highest energy cosmic rays?





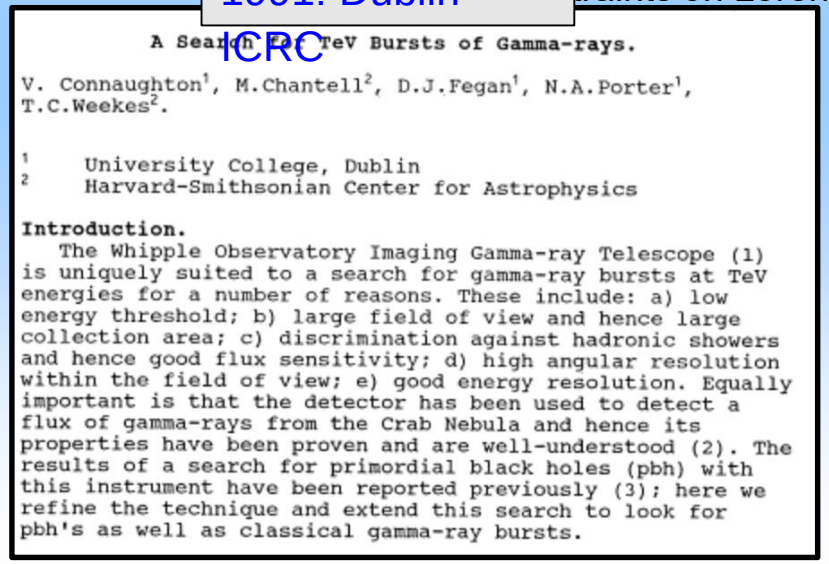
- IACTs also hunt for gravitational wave counterparts.
- Requires tiling the error region until now – but much better localization is now available.



Gamma-ray bursts

- Redshift = 0.4245 ± 0.0005. Fermi-LAT detection up to 23 GeV
- ~30-year search.
- Intrinsic absorption features and fast variability probe jet velocity and emission location.
- Time-resolved broadband spectra probe particle acceleration and emission mechanisms.
- Search for hadronic signatures – origin of UHECRs.
- traints on Lorentz invariance

1991: Dublin ICRC



A Search for TeV Bursts of Gamma-rays.

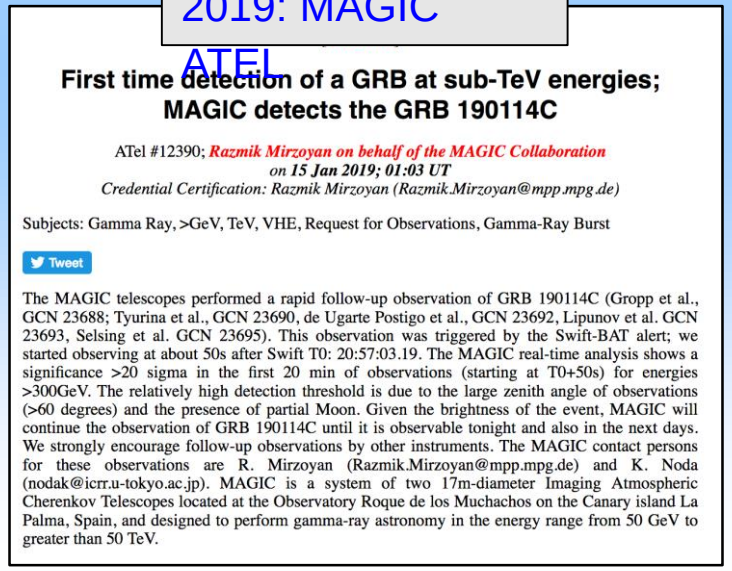
V. Connaughton[1], M.Chantell[2], D.J.Fegan[1], N.A.Porter[1], T.C.Weekes[2].

[1] University College, Dublin
[2] Harvard-Smithsonian Center for Astrophysics

Introduction.

The Whipple Observatory Imaging Gamma-ray Telescope (1) is uniquely suited to a search for gamma-ray bursts at TeV energies for a number of reasons. These include: a) low energy threshold; b) large field of view and hence large collection area; c) discrimination against hadronic showers and hence good flux sensitivity; d) high angular resolution within the field of view; e) good energy resolution. Equally important is that the detector has been used to detect a flux of gamma-rays from the Crab Nebula and hence its properties have been proven and are well-understood (2). The results of a search for primordial black holes (pbh) with this instrument have been reported previously (3); here we refine the technique and extend this search to look for pbh's as well as classical gamma-ray bursts.

2019: MAGIC ATEL



First time detection of a GRB at sub-TeV energies; MAGIC detects the GRB 190114C

ATel #12390; *Razmik Mirzoyan on behalf of the MAGIC Collaboration*
on 15 Jan 2019; 01:03 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Gamma Ray, >GeV, TeV, VHE, Request for Observations, Gamma-Ray Burst

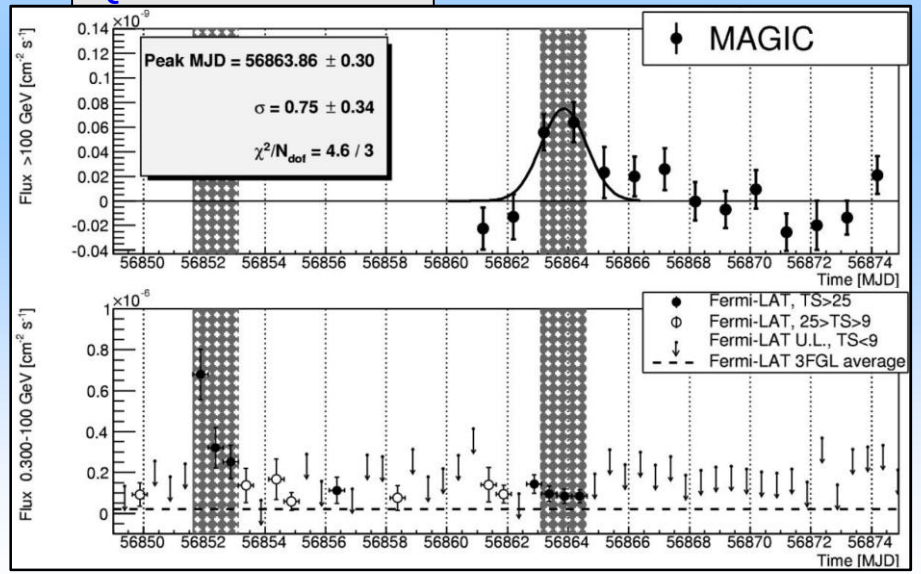
Tweet

The MAGIC telescopes performed a rapid follow-up observation of GRB 190114C (Gropp et al., GCN 23688; Tyurina et al., GCN 23690, de Ugarte Postigo et al., GCN 23692, Lipunov et al. GCN 23693, Selsing et al. GCN 23695). This observation was triggered by the Swift-BAT alert; we started observing at about 50s after Swift T0: 20:57:03.19. The MAGIC real-time analysis shows a significance >20 sigma in the first 20 min of observations (starting at T0+50s) for energies >300GeV. The relatively high detection threshold is due to the large zenith angle of observations (>60 degrees) and the presence of partial Moon. Given the brightness of the event, MAGIC will continue the observation of GRB 190114C until it is observable tonight and also in the next days. We strongly encourage follow-up observations by other instruments. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) and K. Noda (nodak@icrr.u-tokyo.ac.jp). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.

The Gamma-ray Horizon

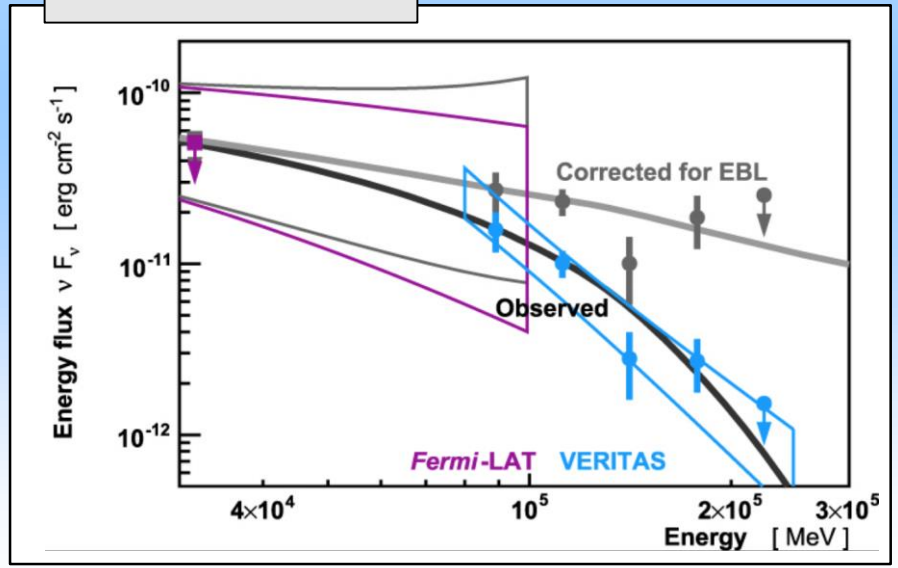
- IACTs have now observed emission from AGN up to a redshift of ~1
  - First from QSO B0218+357 (z=0.96), during a gravitationally lensed flaring event
  - Then from the FSRQ PKS 1441+25 (z=0.94)
  - This single source can be used to constrain the intensity of the extragalactic background light.

QSO



MAGIC Collaboration A&A 595 (2016) 98

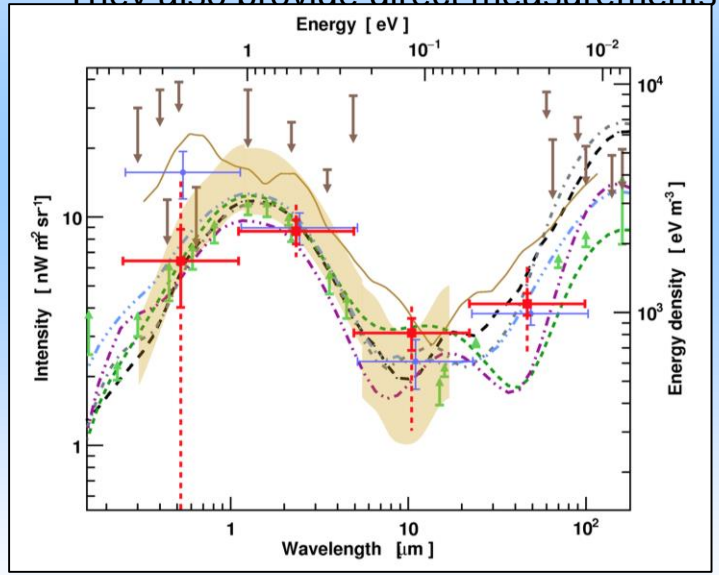
PKS 1441+25



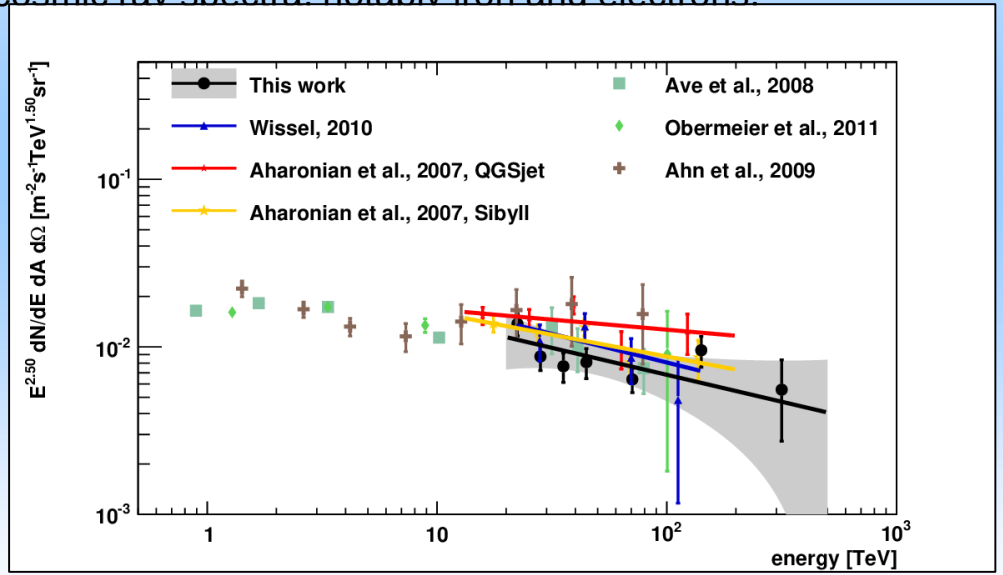
VERITAS Collaboration (+ MWL) ApJL 815 (2015) 22

IACTs as cosmological and physical probes

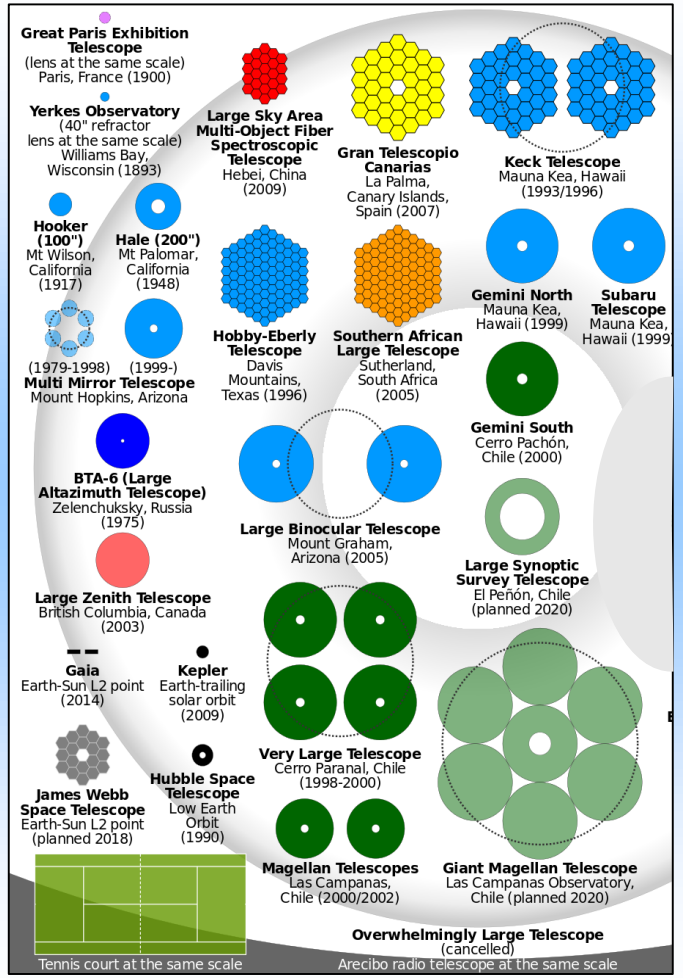
- Combining sources with a range of spectral properties and redshifts probes the EBL range from 0.1–100μm.
- IACT observations have also been used to constrain Lorentz invariance violation, the intergalactic magnetic field, axion-like particles, primordial black holes…
- They also provide direct measurements of cosmic ray spectra, notably iron and electrons.

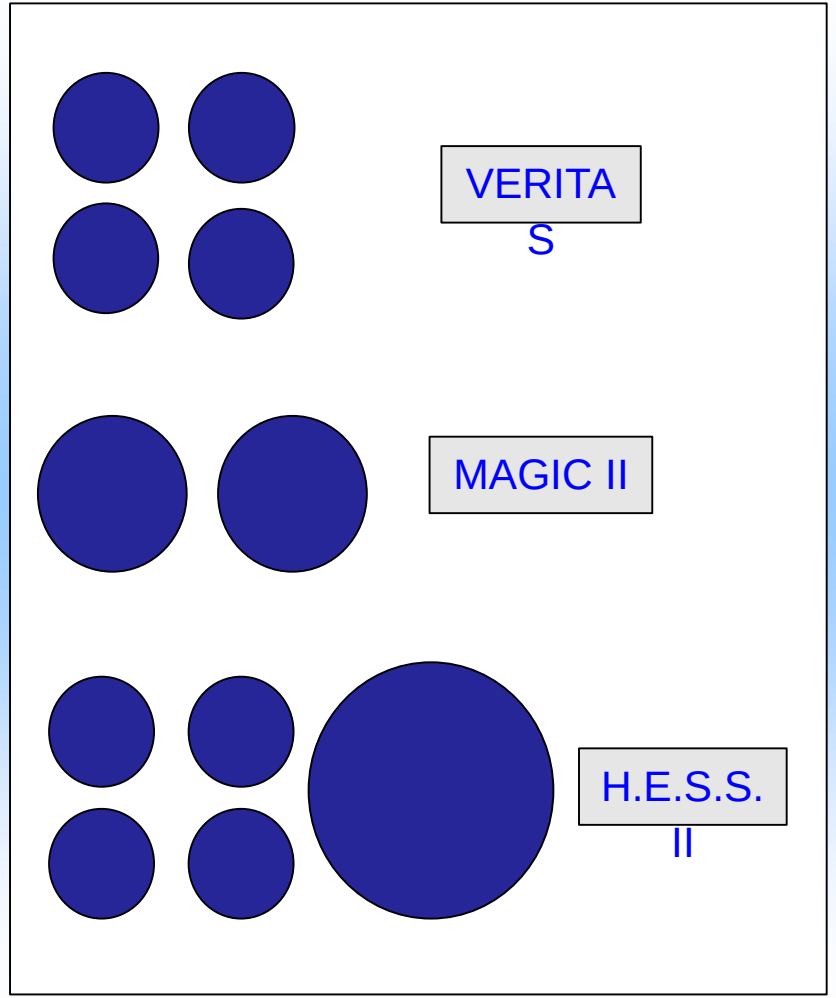


H.E.S.S. Collaboration A&A 606 (2017) 11



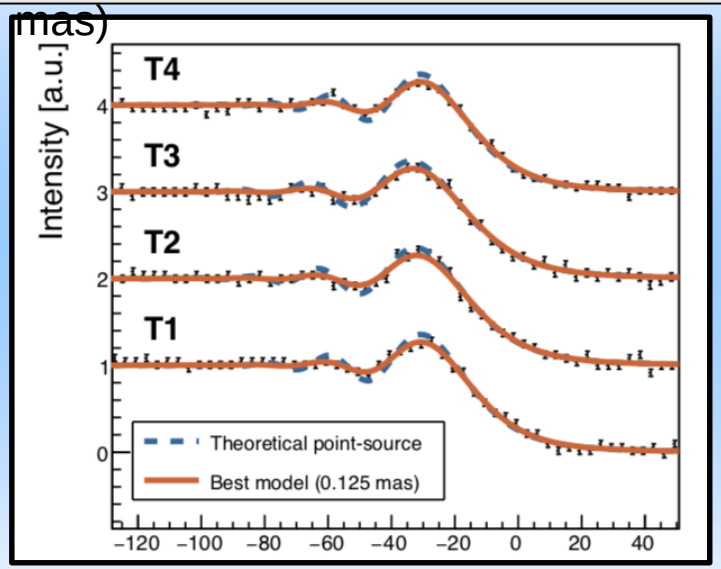
VERITAS Collaboration Phys. Rev. D., 98, 02009 (2018)


Great Paris Exhibition Telescope
(lens at the same scale)
Paris, France (1900)
Yerkes Observatory
(40" refractor lens at the same scale)
Williams Bay, Wisconsin (1893)
Hooker (100")
Mt Wilson, California (1917)
Hale (200")
Mt Palomar, California (1948)
(1979-1998)
(1999-)
Multi Mirror Telescope
Mount Hopkins, Arizona
BTA-6 (Large Altazimuth Telescope)
Zelenchuksky, Russia (1975)
Large Zenith Telescope
British Columbia, Canada (2003)
Gaia
Earth-Sun L2 point (2014)
Kepler
Earth-trailing solar orbit (2009)
James Webb Space Telescope
Earth-Sun L2 point (planned 2018)
Hubble Space Telescope
Low Earth Orbit (1990)
Large Sky Area Multi-Object Fiber Spectroscopic Telescope
Hebei, China (2009)
Gran Telescopio Canarias
La Palma, Canary Islands, Spain (2007)
Keck Telescope
Mauna Kea, Hawaii (1993/1996)
Hobby-Eberly Telescope
Davis Mountains, Texas (1996)
Southern African Large Telescope
Sutherland, South Africa (2005)
Gemini North
Mauna Kea, Hawaii (1999)
Subaru Telescope
Mauna Kea, Hawaii (1999
Gemini South
Cerro Pachón, Chile (2000)
Large Binocular Telescope
Mount Graham, Arizona (2005)
Large Synoptic Survey Telescope
El Peñón, Chile (planned 2020)
Very Large Telescope
Cerro Paranal, Chile (1998-2000)
Magellan Telescopes
Las Campanas, Chile (2000/2002)
Giant Magellan Telescope
Las Campanas Observatory, Chile (planned 2020)
Overwhelmingly Large Telescope
(cancelled)
Tennis court at the same scale
Arecibo radio telescope at the same scale


VERITAS
MAGIC II
H.E.S.S. II

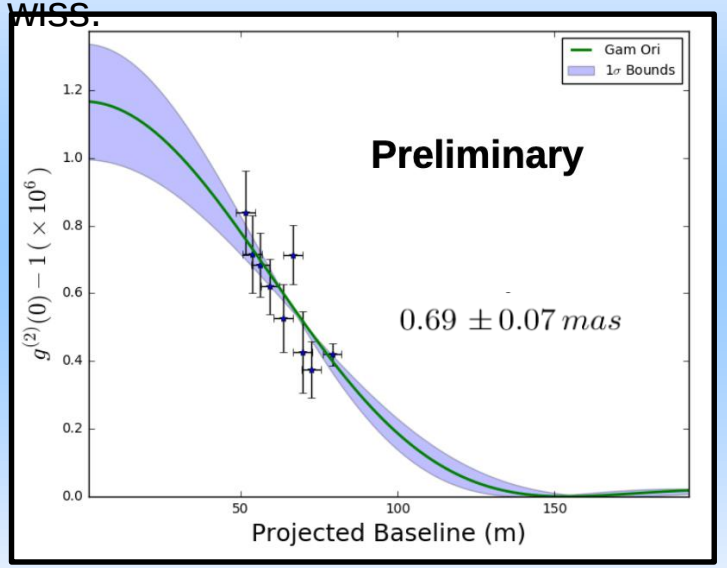
Optical Applications: Recent news

The diffraction pattern of an asteroid occultation shadow used to measure the smallest stellar diameters (0.1 mas)



The VERITAS Collaboration, Nature Astronomy
Tarek Hassan's poster, this meeting

Stellar Intensity Interferometry with light buckets successfully implemented for the first time since Hanbury Brown and Twiss.



N. Matthews for the VERITAS Collaboration.
April APS meeting, Denver, 2019
Michael Daniel's talk, this meeting.

Also optical SETI, and searches for ultra-rapid optical transients such as FRB counterparts

Conclusions

- Despite advances, TeV gamma-ray astronomy is still a young, and rapidly evolving field.
- Many surprises are still waiting, both astrophysical, and in the technical capabilities and applications of these remarkable instruments.
- As always, progress and new discoveries have opened more questions and opportunities.
- To address these questions requires better sensitivity and better precision
- C