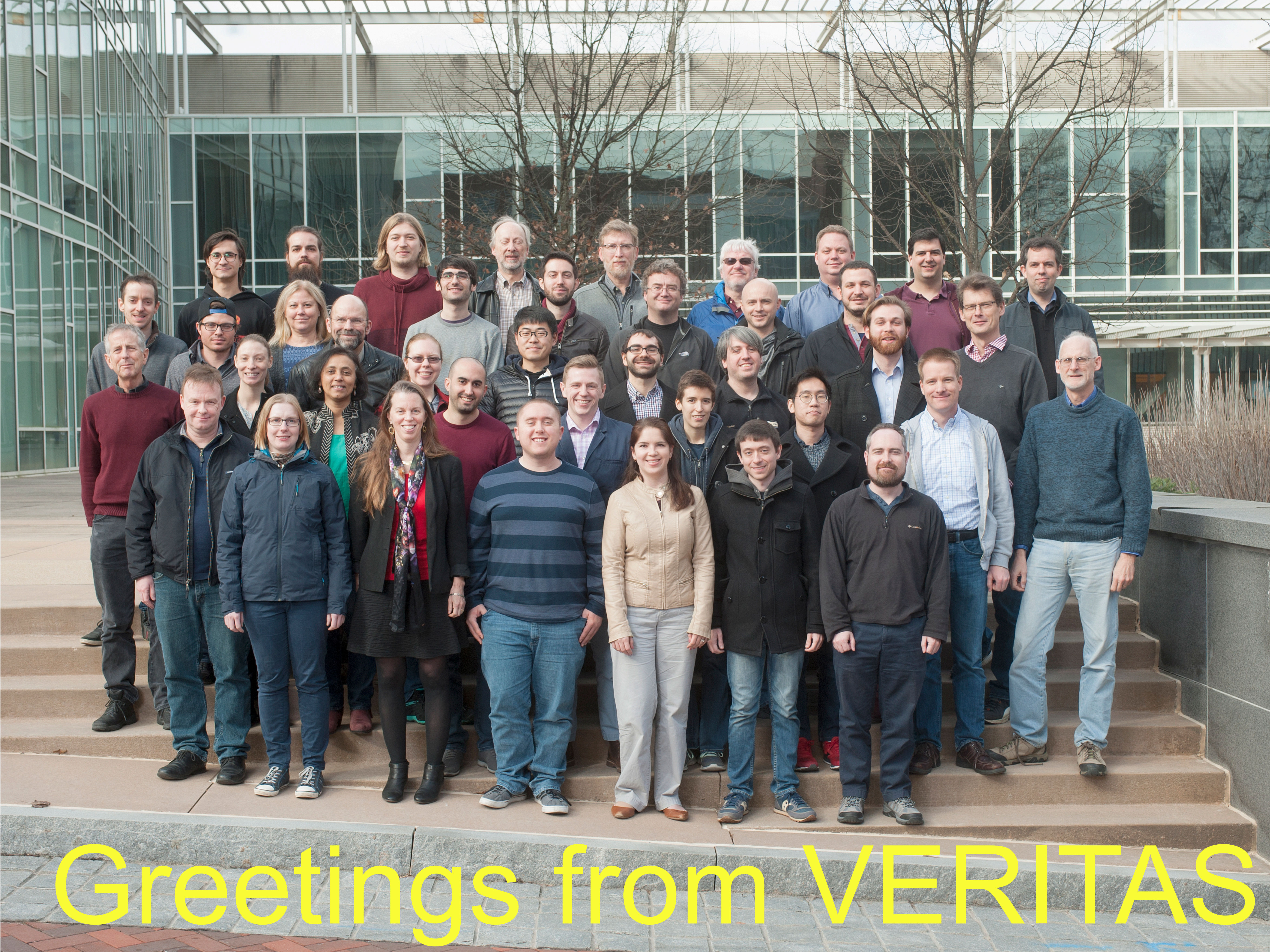
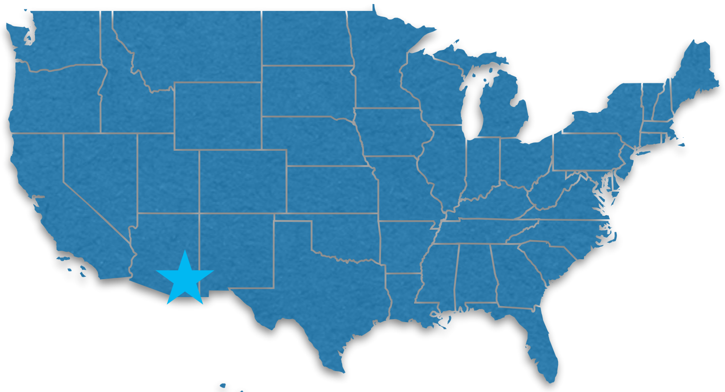

Greetings from VERITAS

Science Highlights from VERITAS

Stefan Schlenstedt
June 27, 2018

VERITAS

Mount Hopkins, 1300m, Southern Arizona, 31°N 111°W



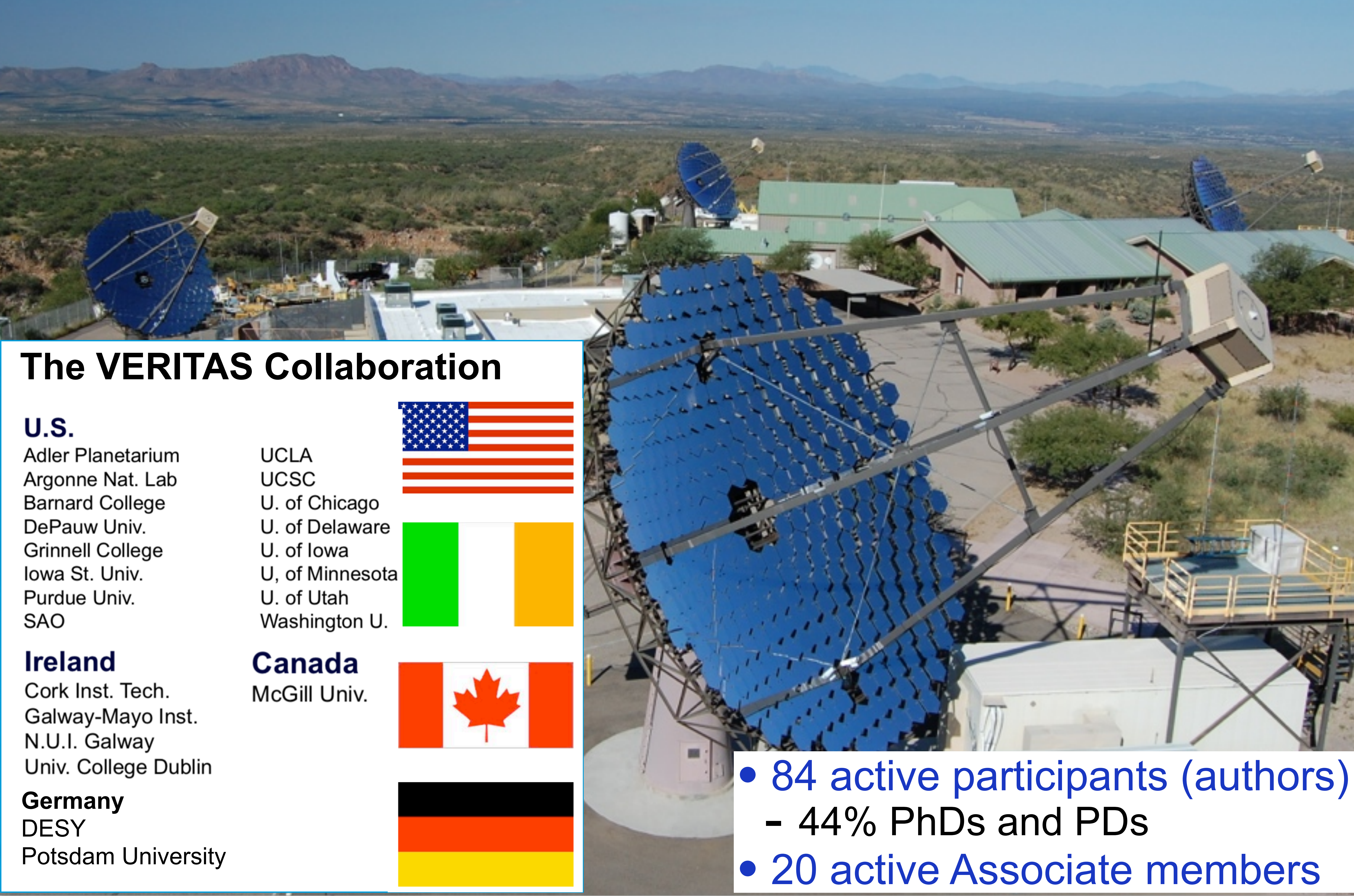
- Four 12 m diameter telescopes in operation for > ten years
- 350 mirrors → 110 m^2
- 3.5° cameras with 500 PMT pixels – 500 Msps FADC readout
- Sensitivity <1% Crab in 25 h
- Energy range 100 GeV to 30 TeV
- Excellent performance:
  - Observe > 1300h/ year
  - Included moon time ~350h
  - This season four telescopes 97%

VERITAS

The Very Energetic Radiation Imaging Telescope Array System

VERITAS

The Very Energetic Radiation Imaging Telescope Array System



The VERITAS Collaboration

U.S.

Adler Planetarium	UCLA
Argonne Nat. Lab	UCSC
Barnard College	U. of Chicago
DePauw Univ.	U. of Delaware
Grinnell College	U. of Iowa
Iowa St. Univ.	U, of Minnesota
Purdue Univ.	U. of Utah
SAO	Washington U.

Ireland

Cork Inst. Tech.
Galway-Mayo Inst.
N.U.I. Galway
Univ. College Dublin

Canada

McGill Univ.

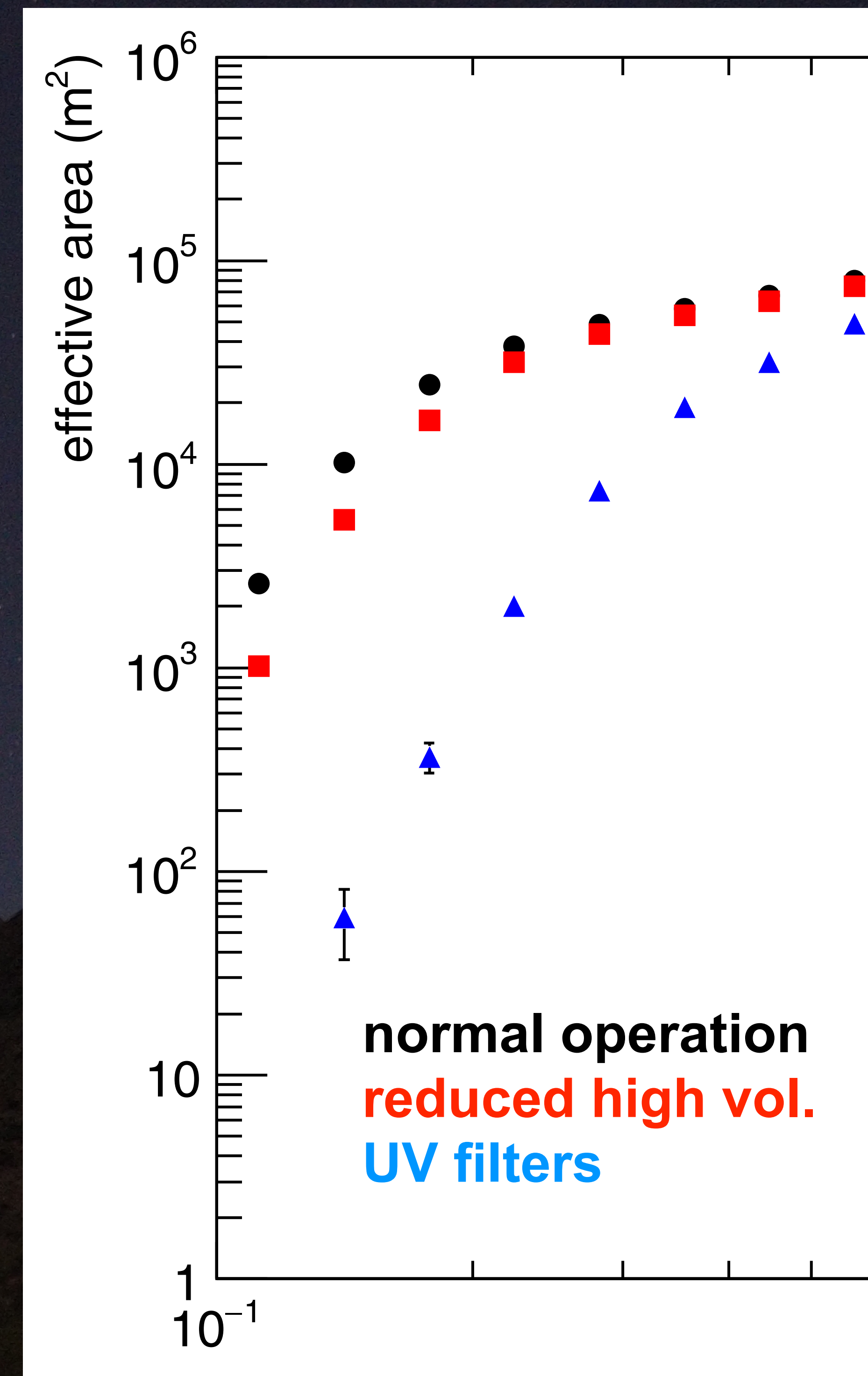
Germany

DESY
Potsdam University

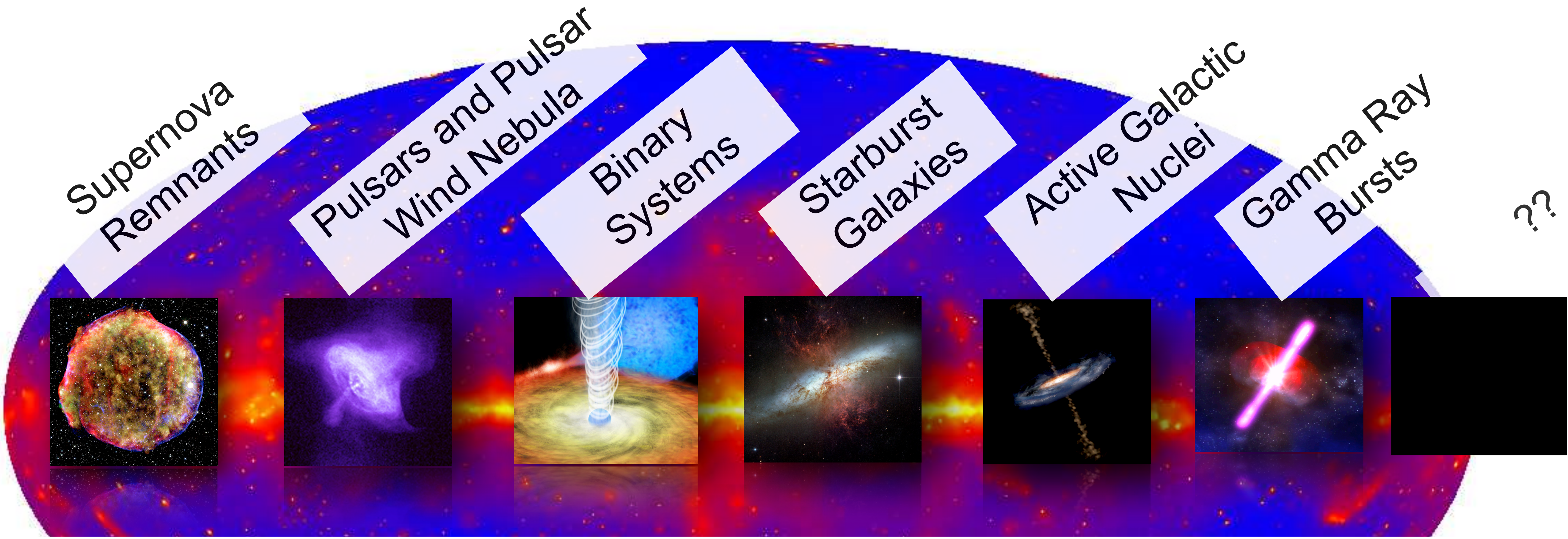
- 84 active participants (authors)
  - 44% PhDs and PDs
- 20 active Associate members

VERITAS Observations during Moonlight

VERITAS Observations during Moonlight

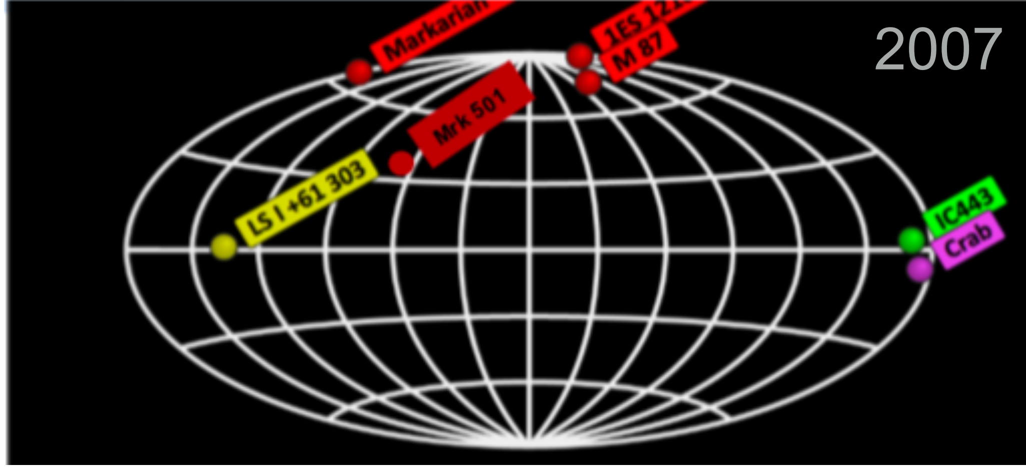


Gamma-Ray Observations - General Approach



- Census of particle accelerators
  - How many? What types of objects? Where?
- Detailed observation and modeling of individual objects:
  - How do particle accelerators work?
  - Which astrophysical conditions lead to efficient acceleration?

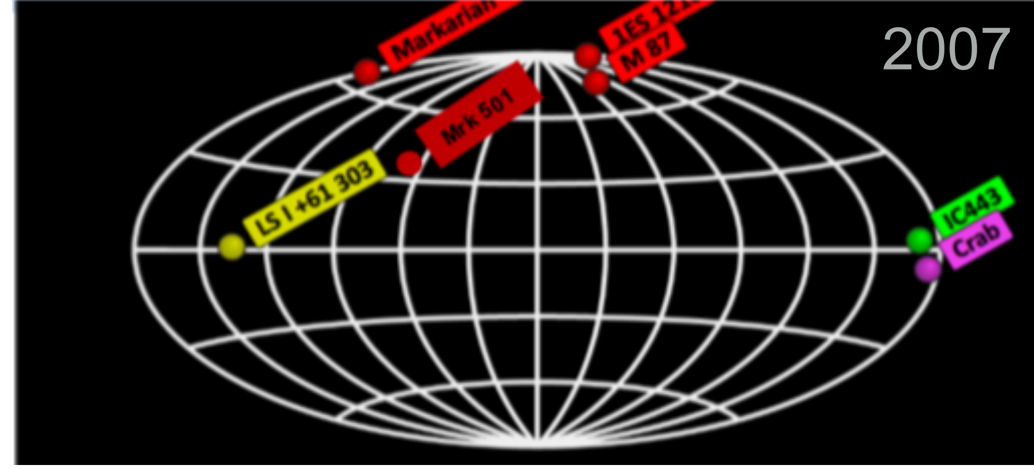
VERITAS Catalogue

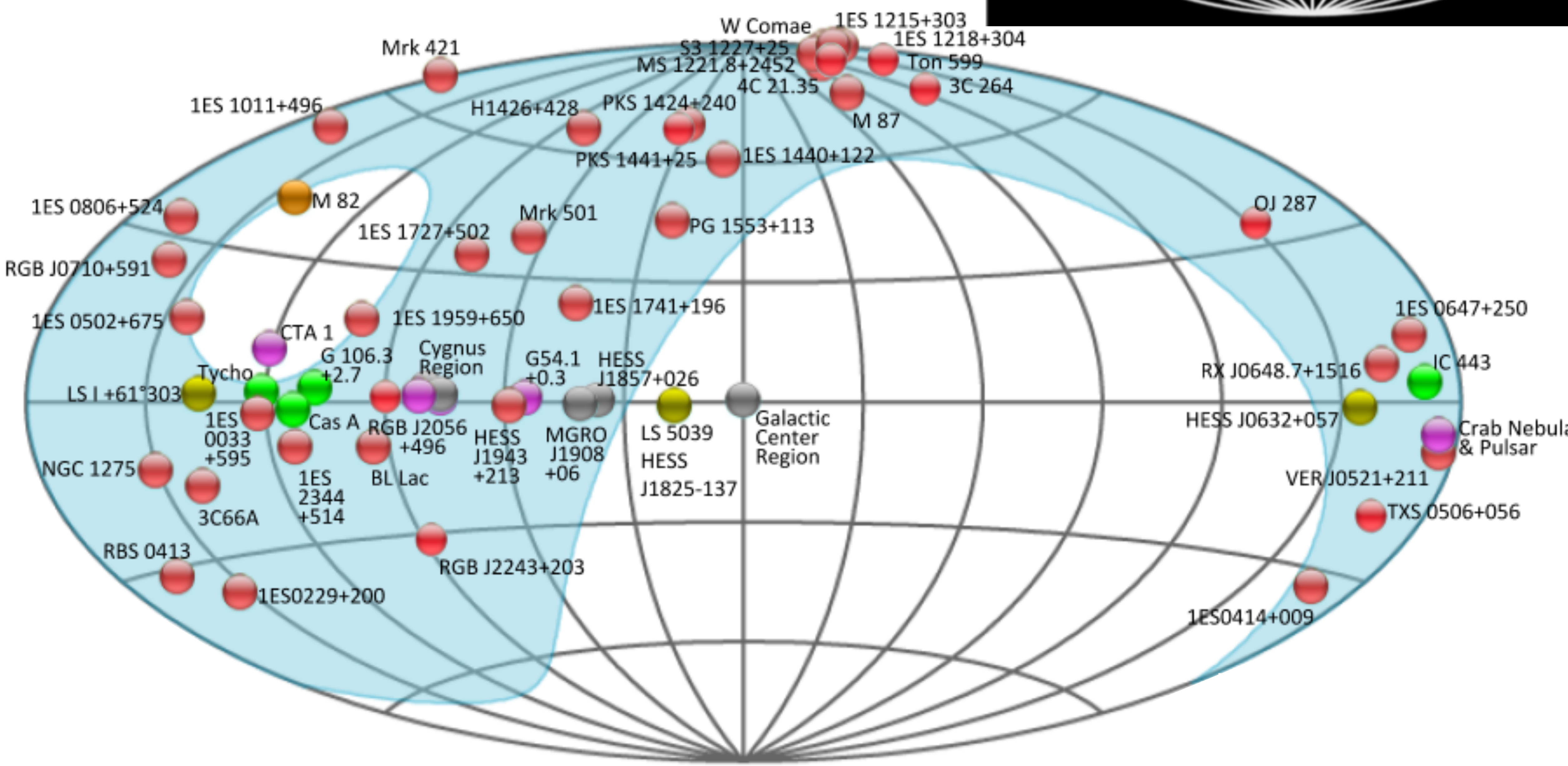


June 2018

VERITAS Catalogue

63 Detections with at least eight Source Classes





June 2018

VERITAS Catalogue

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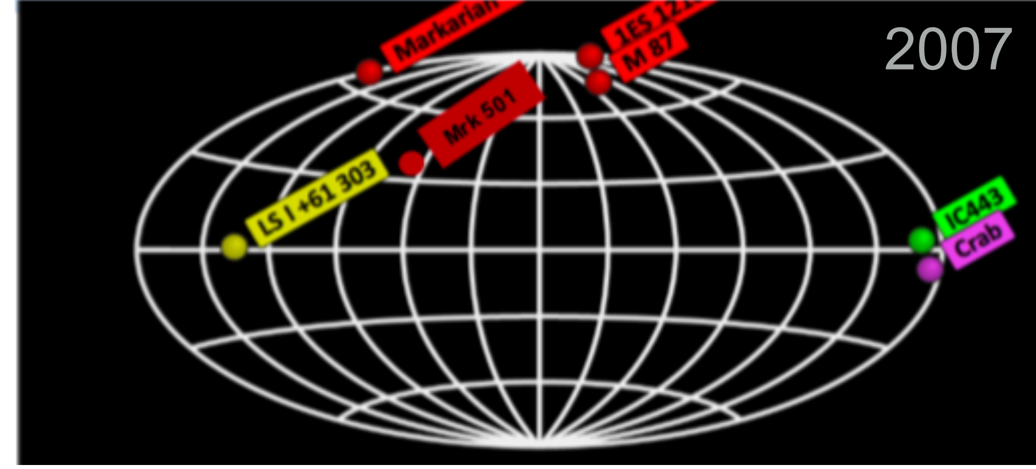
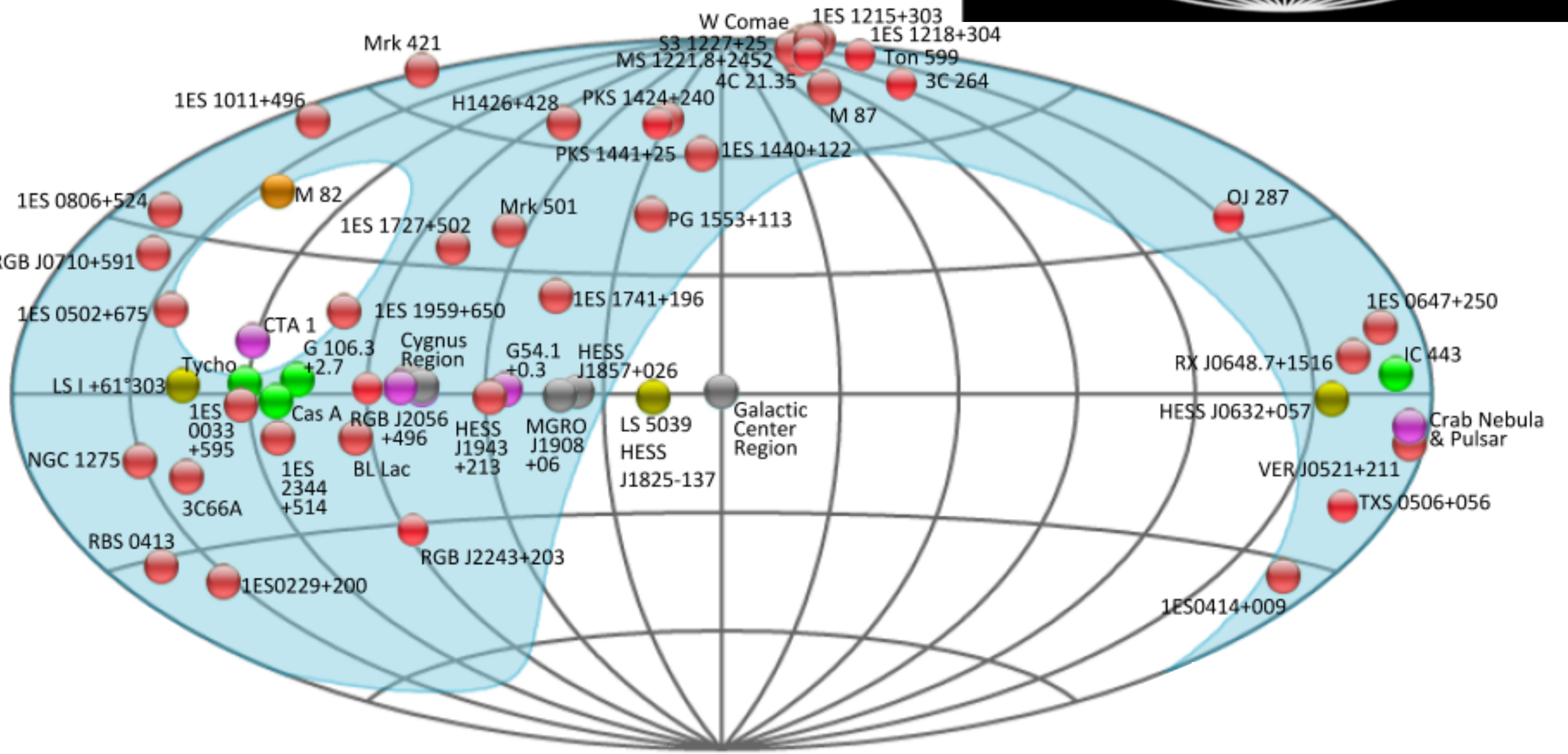




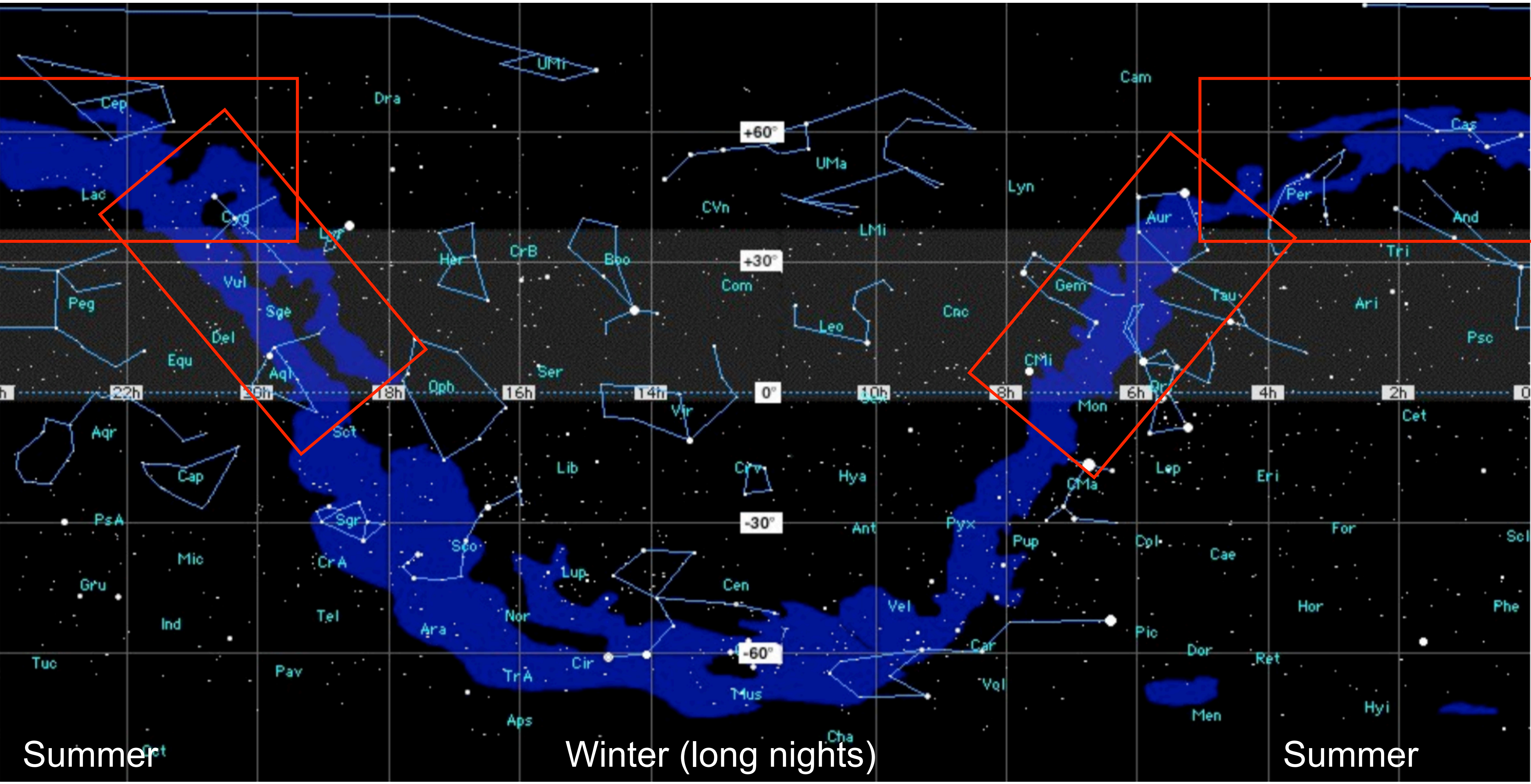
>20 galactic sources by VERITAS

June 2018

Galactic Observations with VERITAS

- Rich galactic science

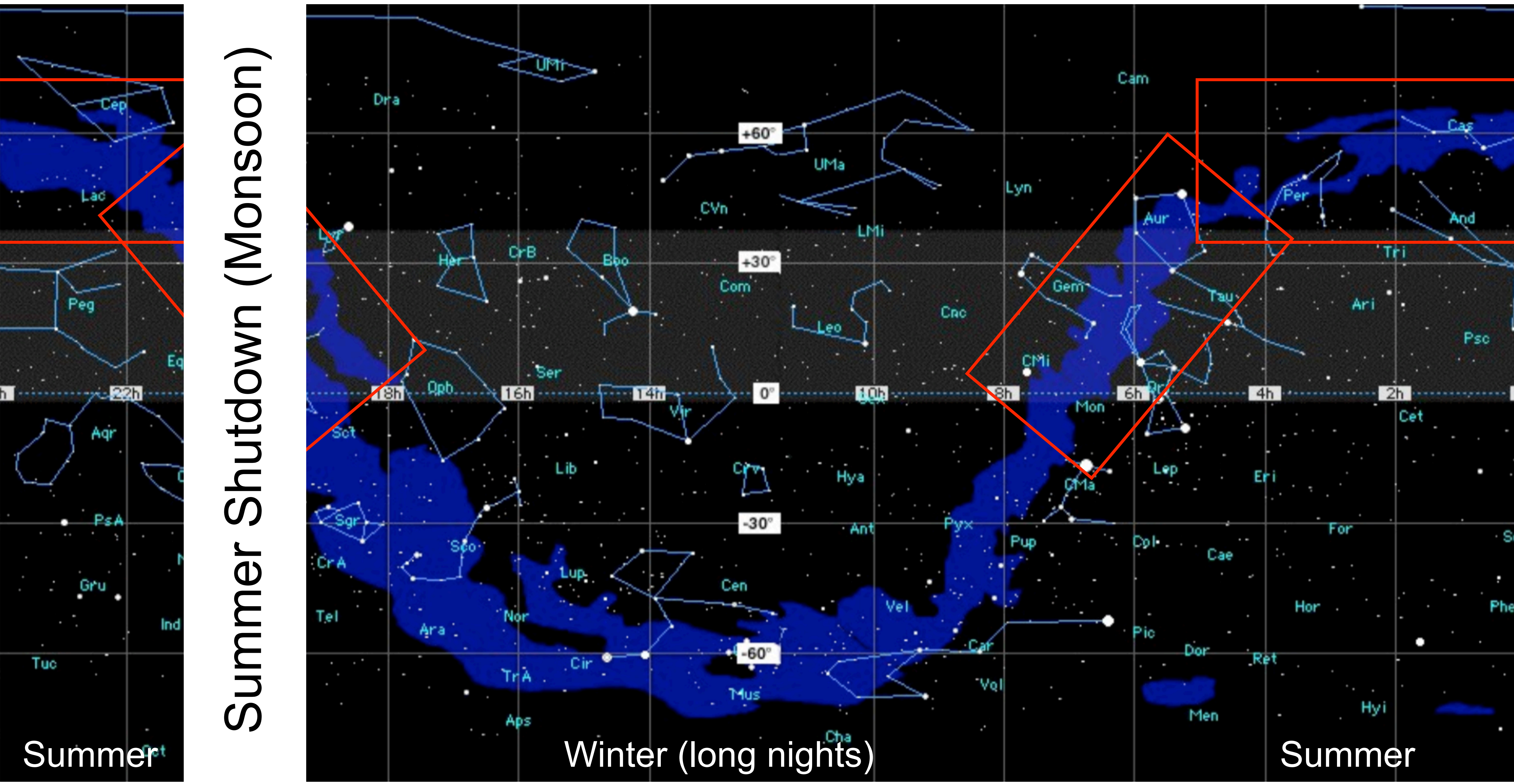
Milky Way Equatorial Coordinates



Galactic Observations with VERITAS

- Rich galactic science

Milky Way Equatorial Coordinates



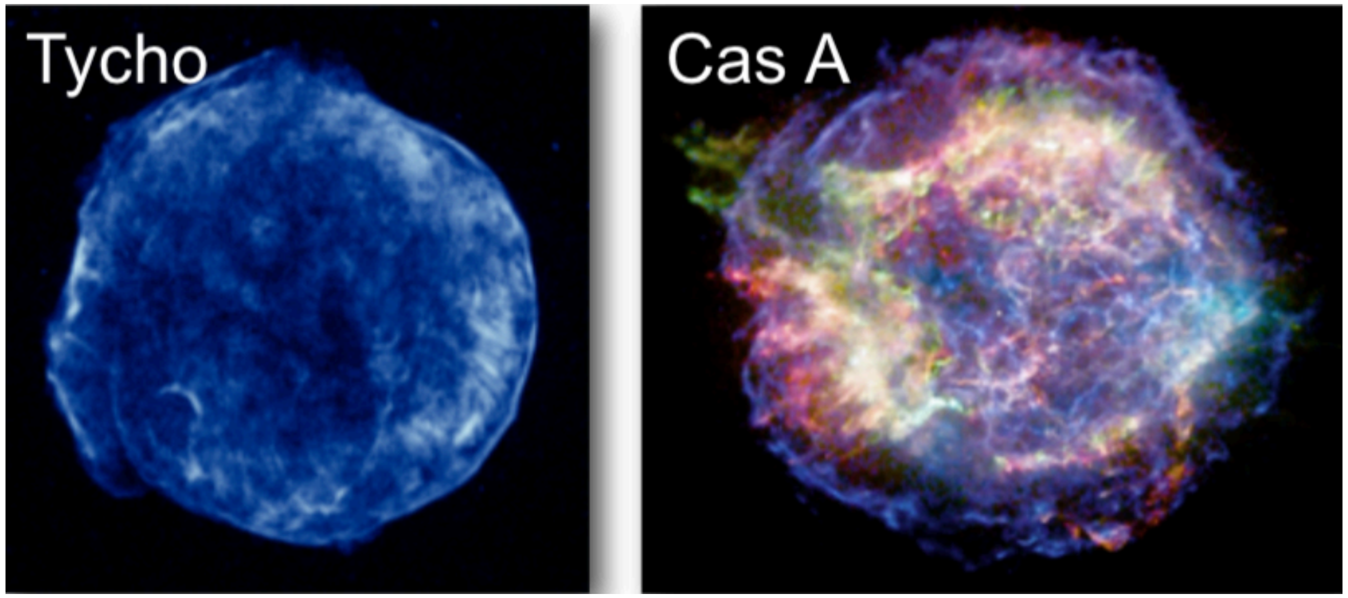
G Maier

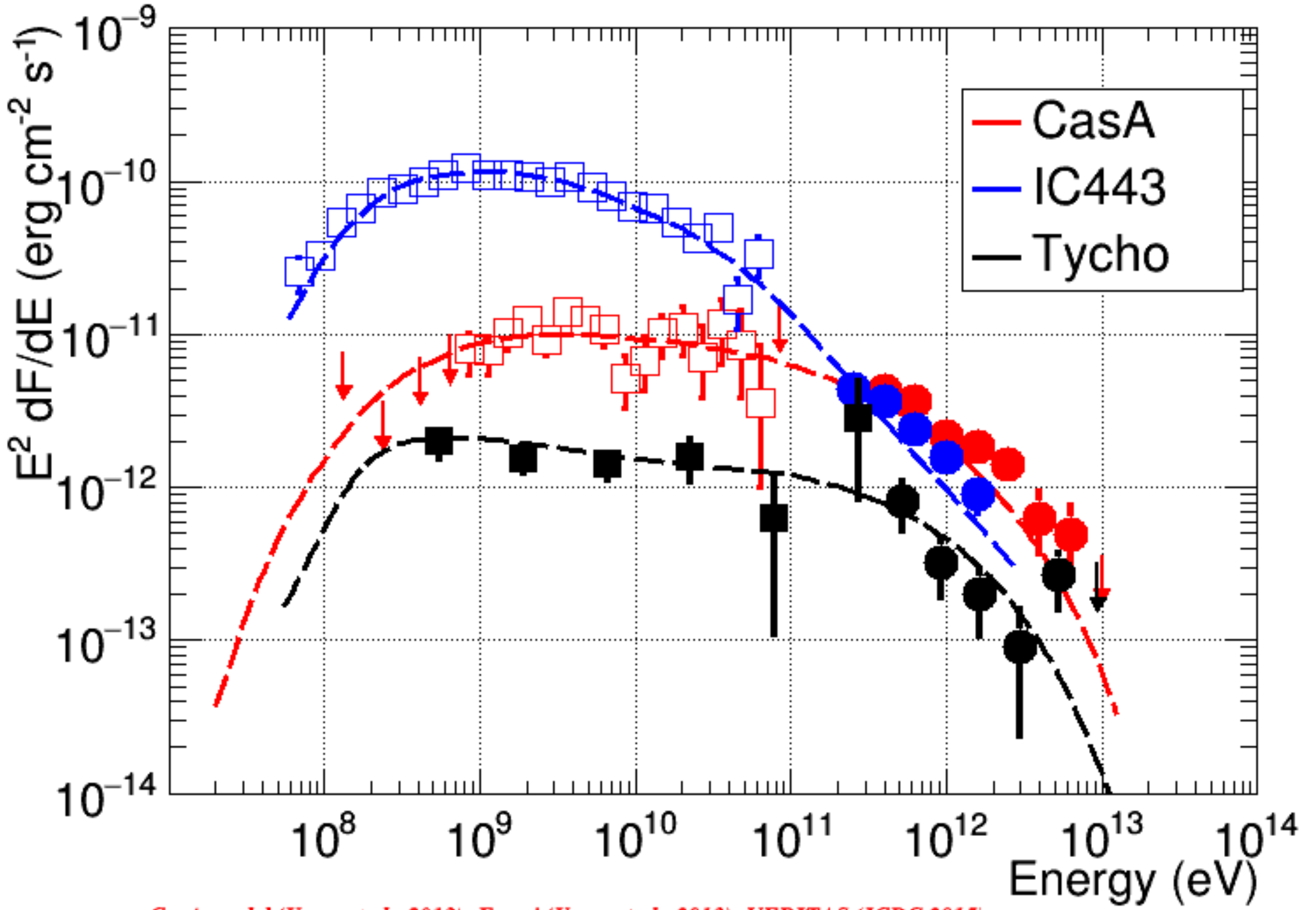
VERITAS – Flagship Galactic Themes

- What are the main Cosmic Ray accelerators & Where are the PeVatrons?
  - Supernova Remnants
  - Pulsar Wind Nebulae
  - Highest-Energy HAWC sources
  - Galactic Center
- What are the sources of the local electrons & positrons?
  - Geminga PWN
  - Cosmic Ray electron/positron spectrum
- What is the physics of Gamma-Ray Binaries?
  - Conditions for efficient radiation in VHE band?
  - Is the power source a pulsar wind or accretion?

Galactic Sources: Particle Acceleration in Supernova Remnants

- Efficient cosmic-ray acceleration observed in many supernova remnants
  - in different environments and evolutionary stages
- Gamma-ray observations can:
  - probe the distributions of high-energy particles in the acceleration region
  - study the evolution of SNRs as cosmic-ray accelerators
  - study the importance of progenitor, SNR type, age, target material, magnetic fields, ...
  - study the propagation of cosmic rays away from the acceleration site

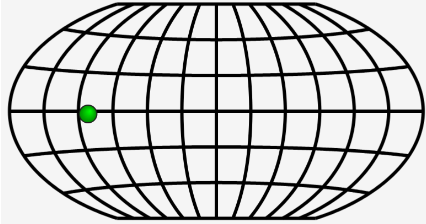


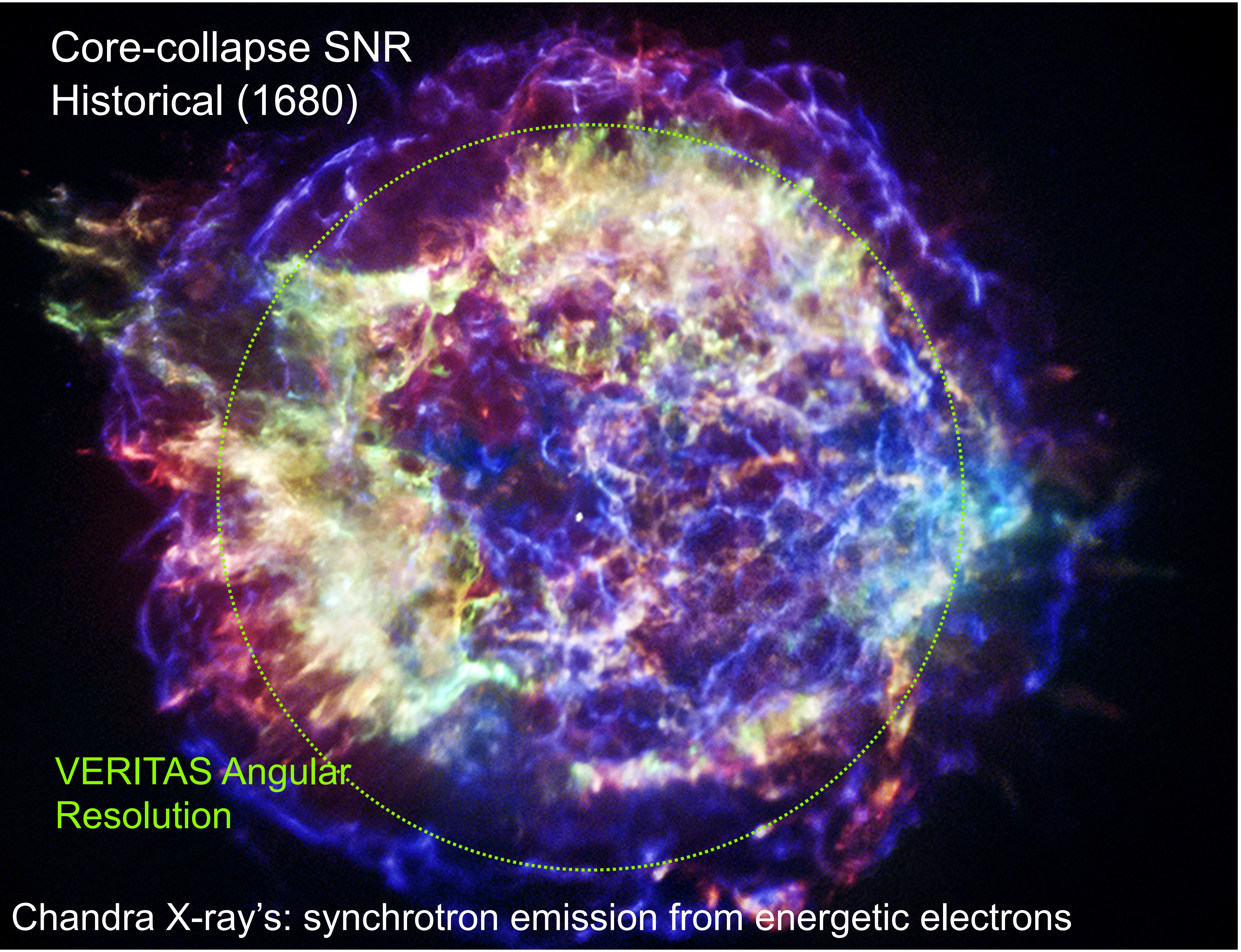


CasA model (Yuan et al., 2013), Fermi (Yuan et al., 2013), VERITAS (ICRC 2015)
IC443 model (Ackermann et al., 2013), Fermi (Ackermann et al., 2013), VERITAS (ICRC 2015)
Tycho model (Slane et al., 2014), Fermi (Archambault et al, 2017), VERITAS (Archambault et al, 2017)

Galactic Sources: Supernova Remnants

Cassiopeia A





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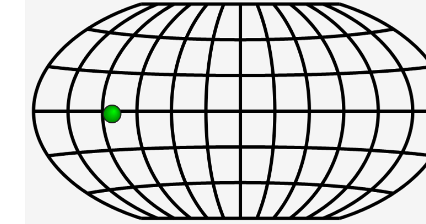
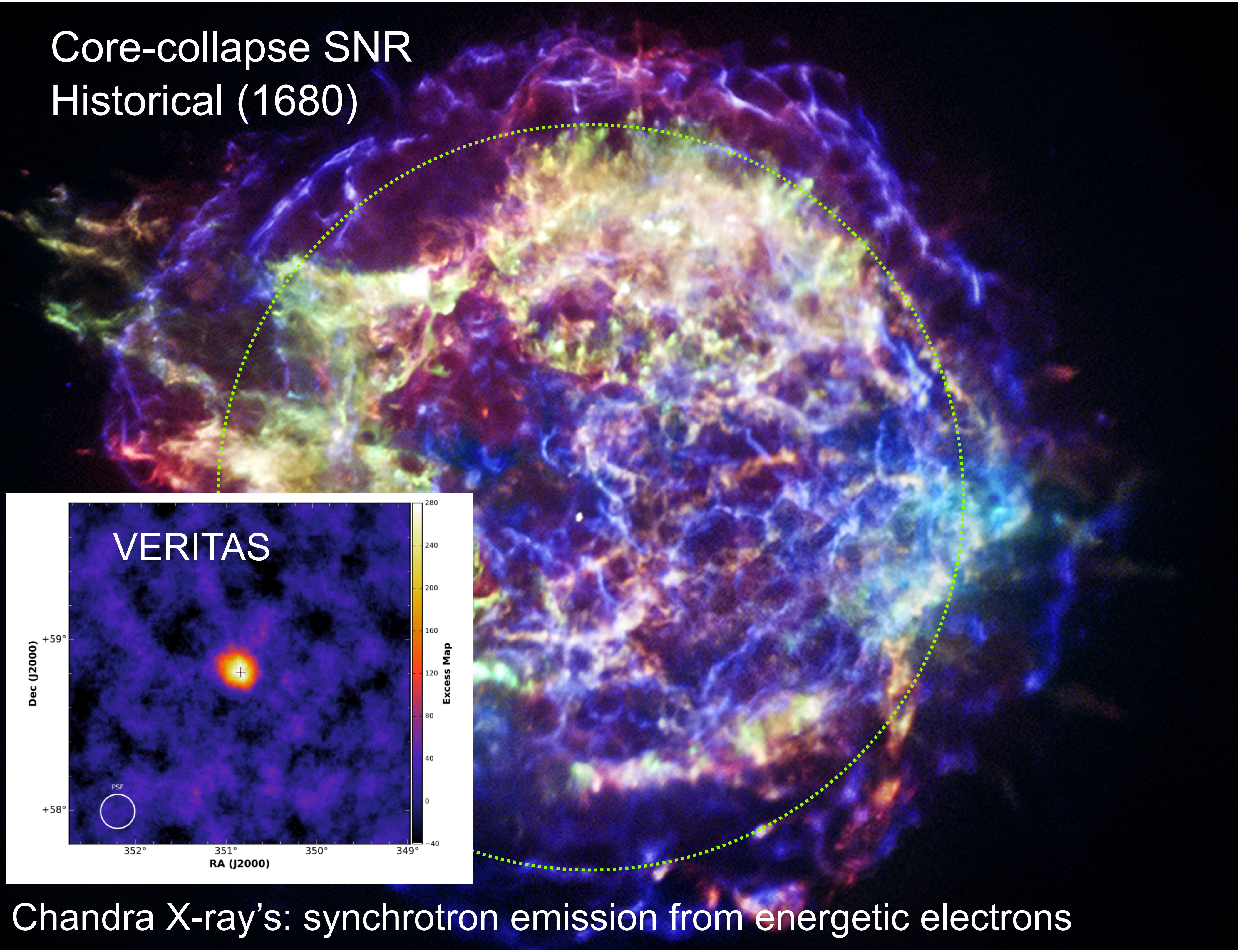
Galactic Sources: Supernova Remnants

Cassiopeia A





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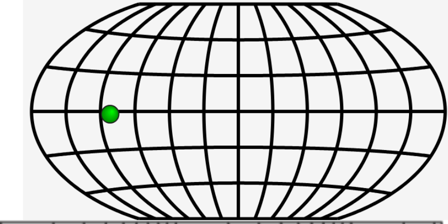
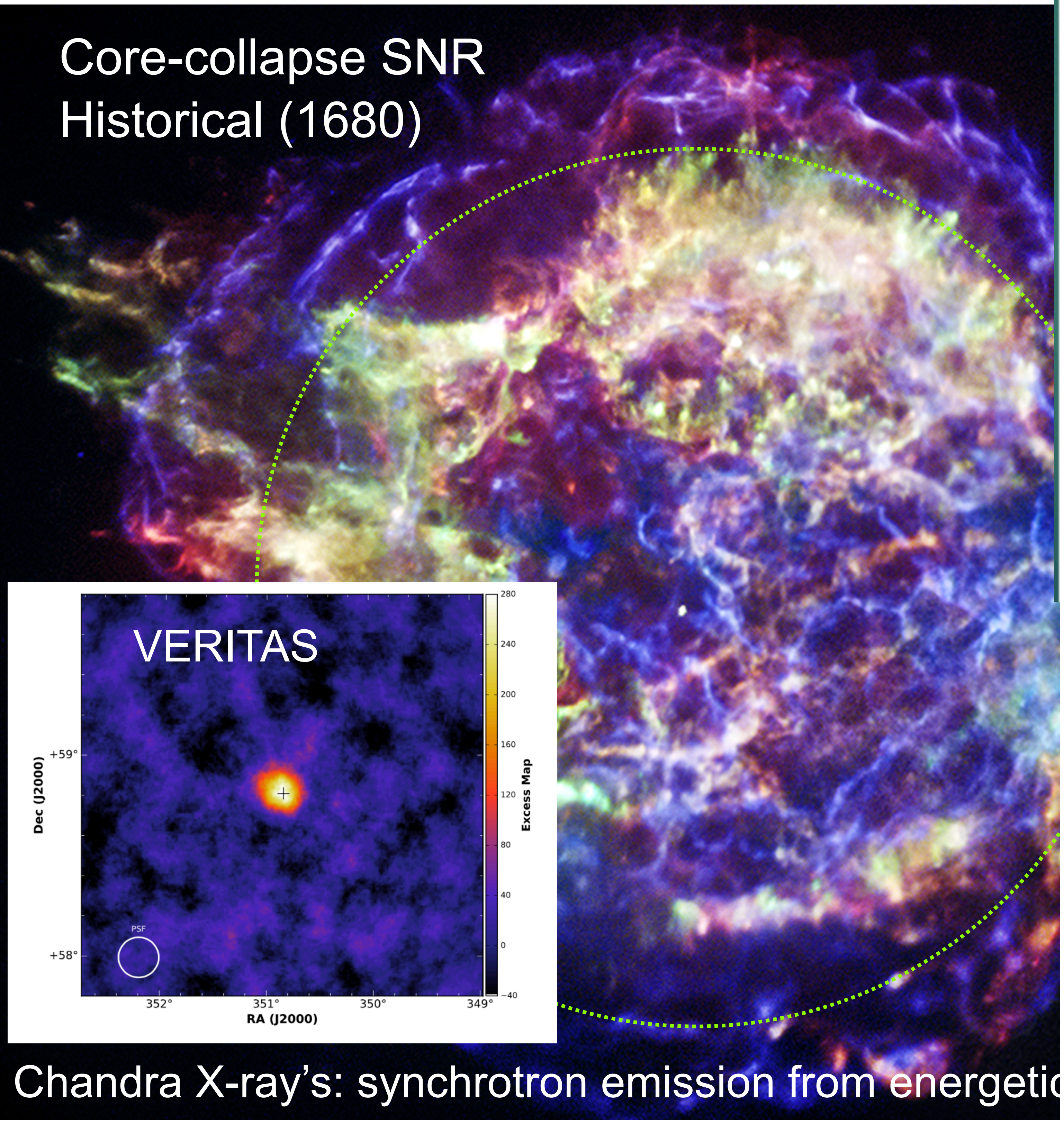
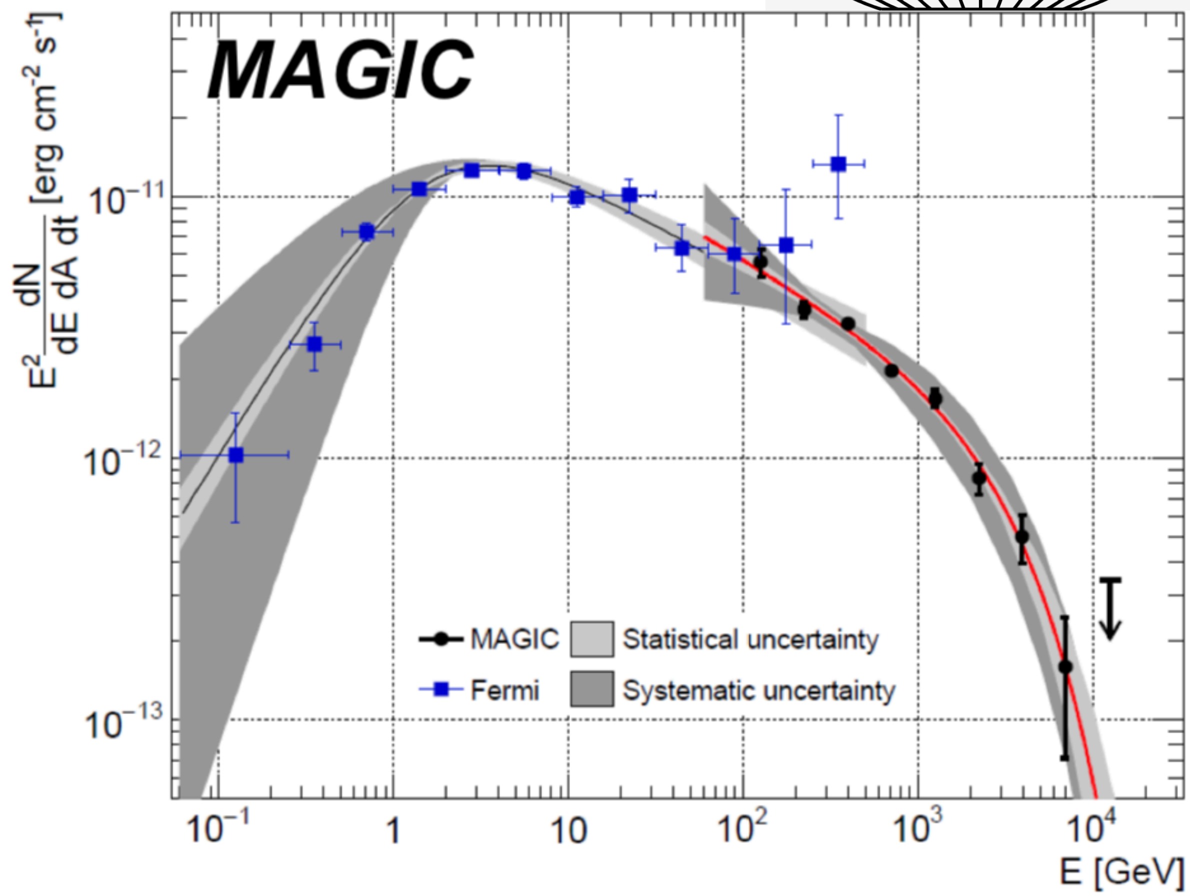
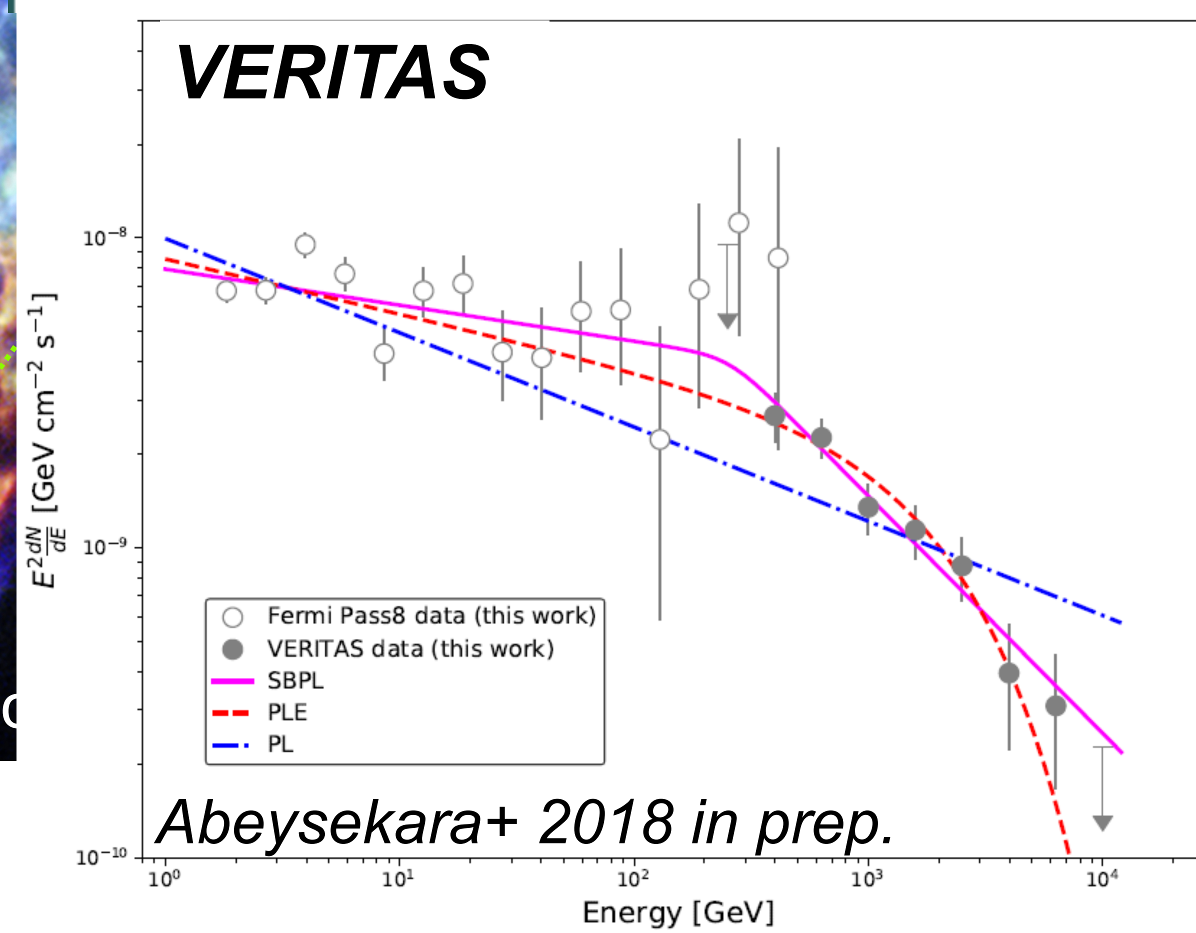
Galactic Sources: Supernova Remnants

Cassiopeia A









Abeysekara+ 2018 in prep.

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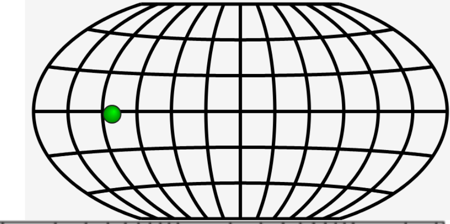
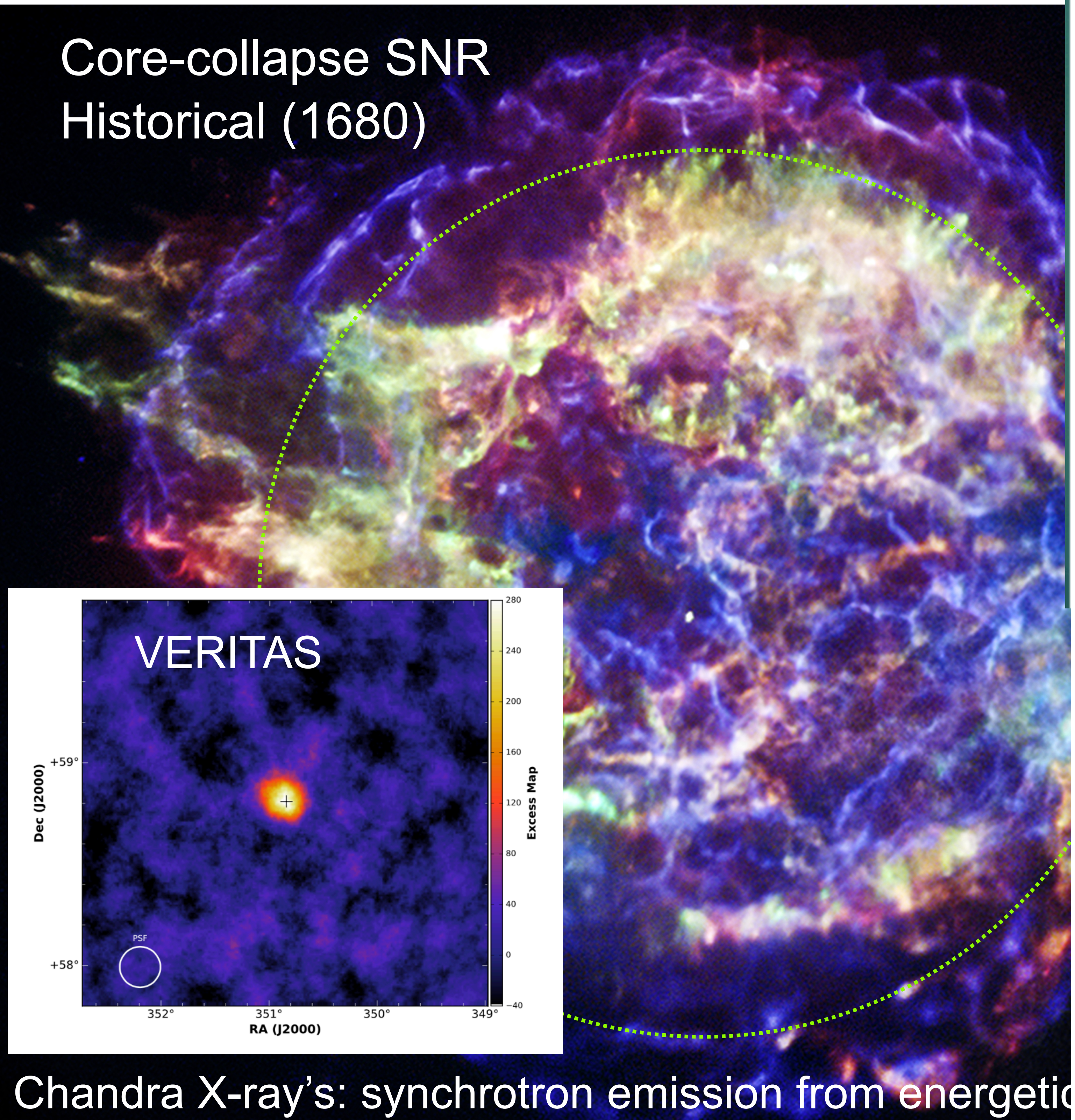
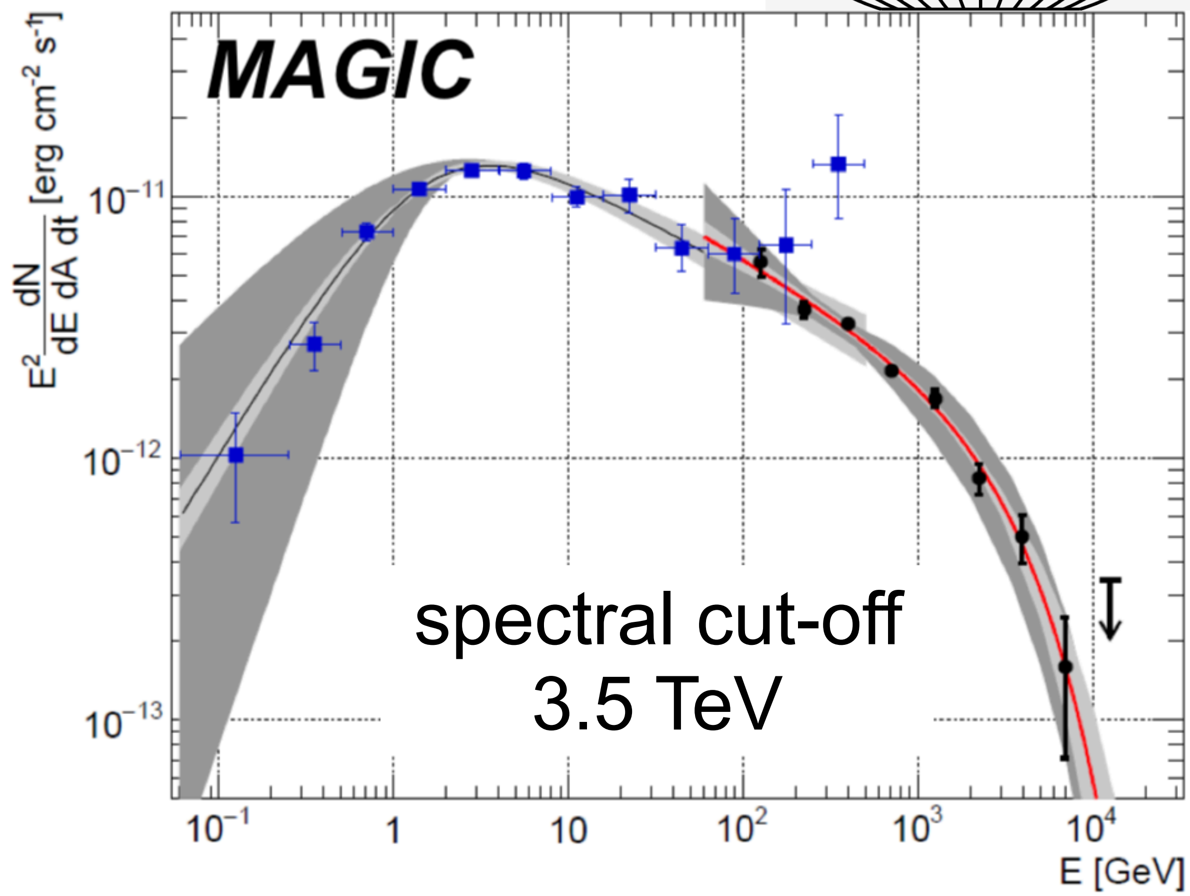
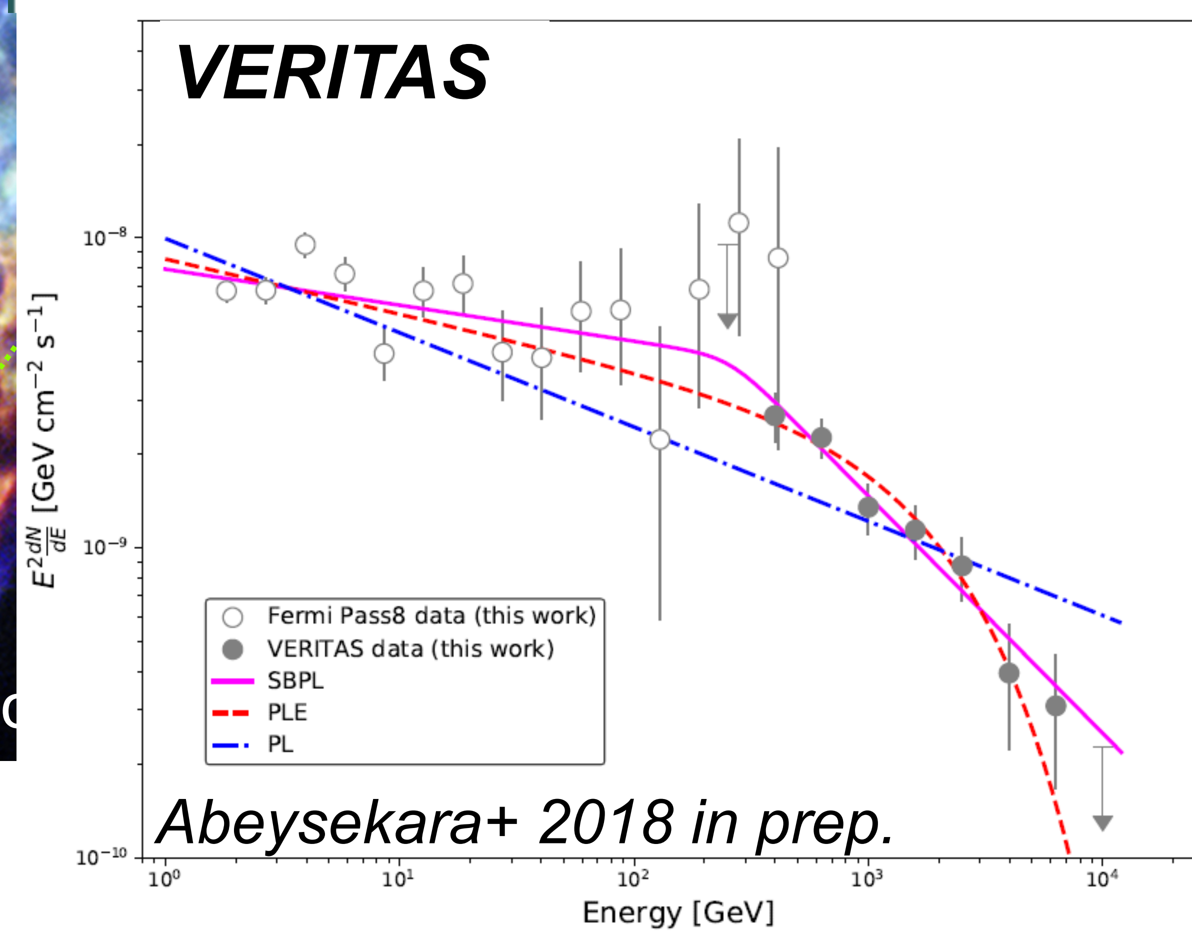
Galactic Sources: Supernova Remnants

Cassiopeia A









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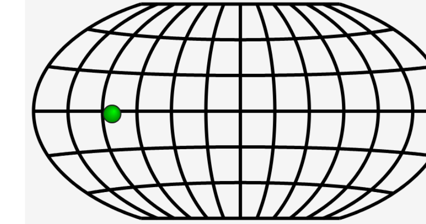
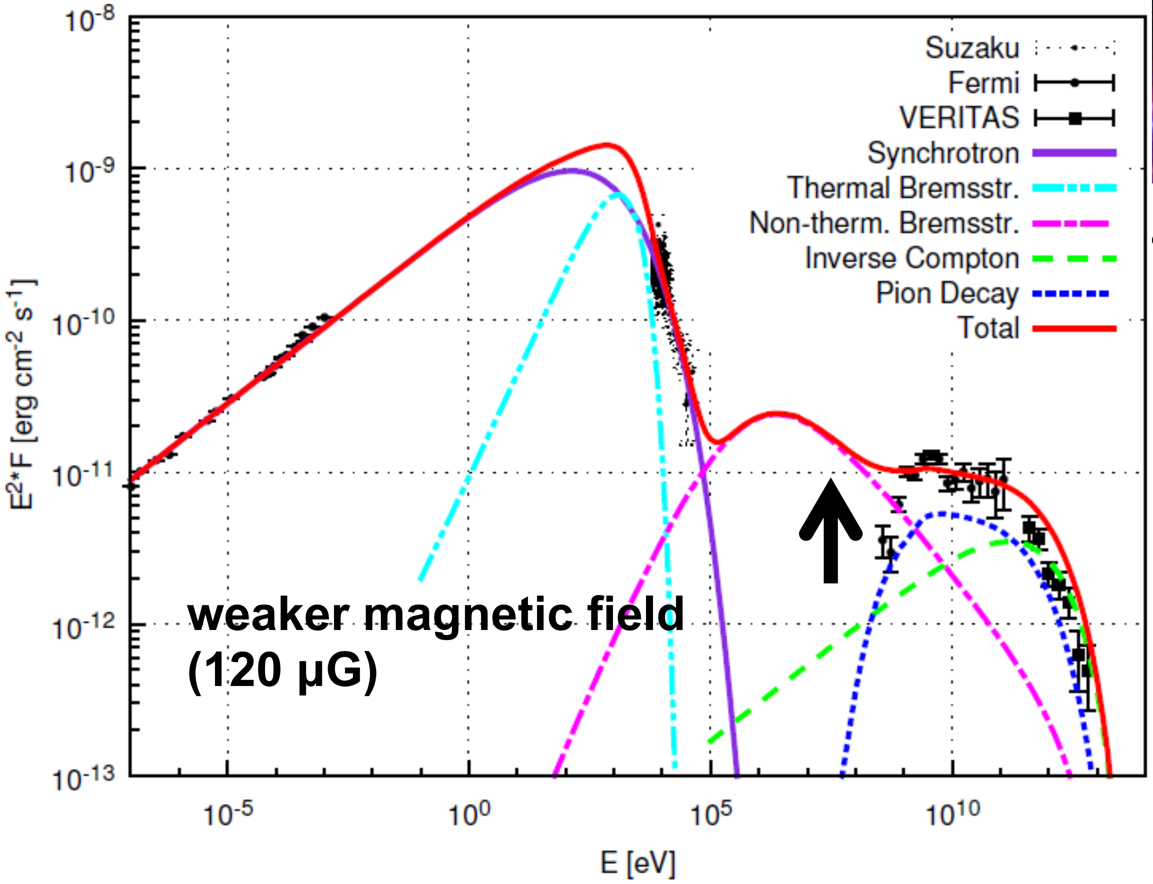
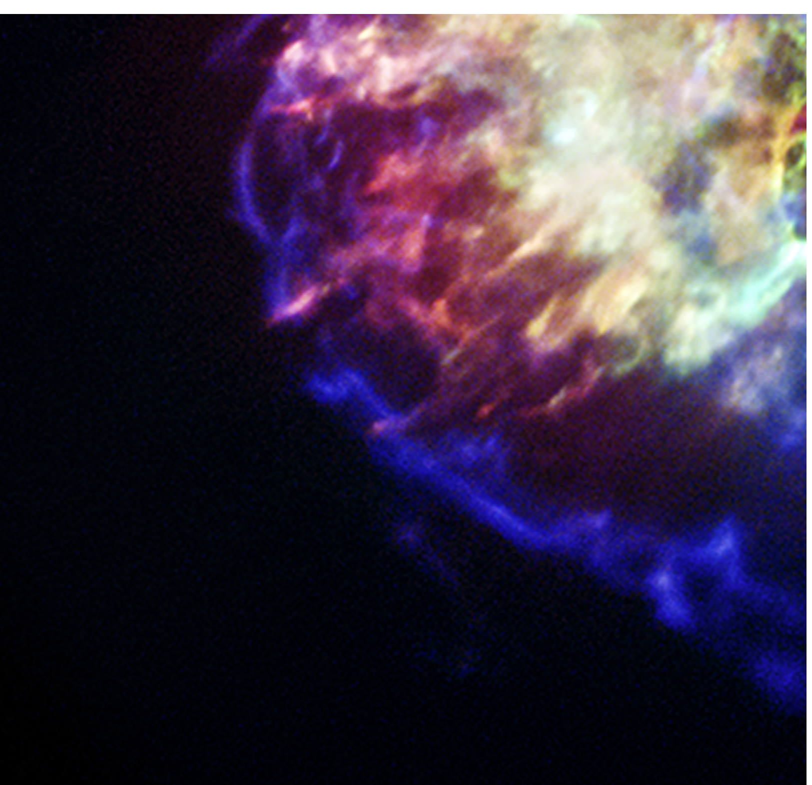
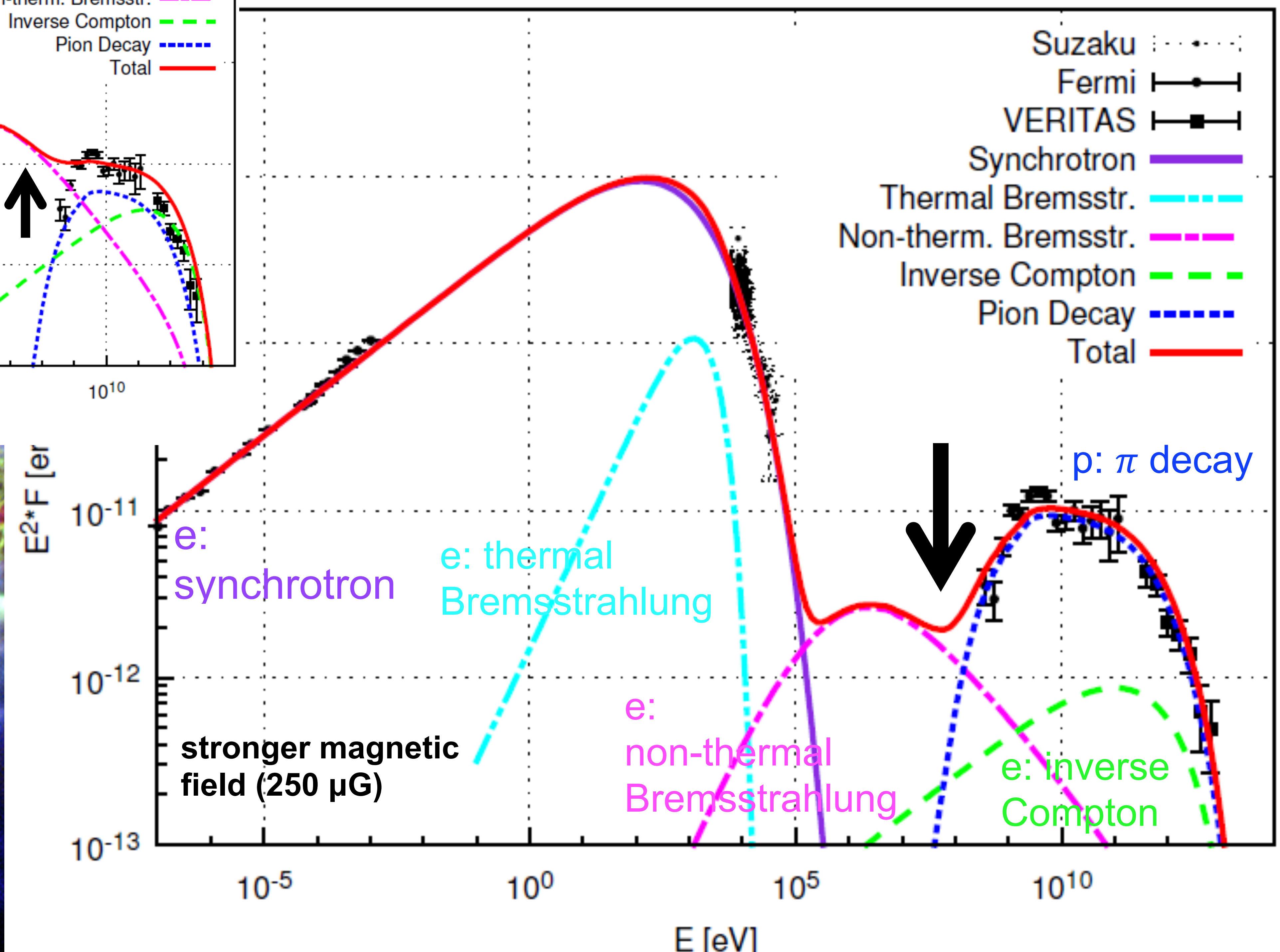
Spectral Energy Distribution

Cassiopeia A



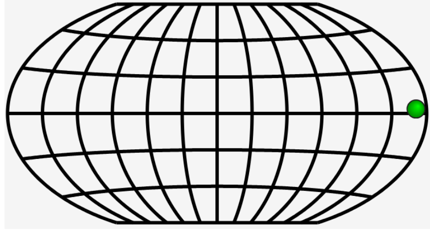


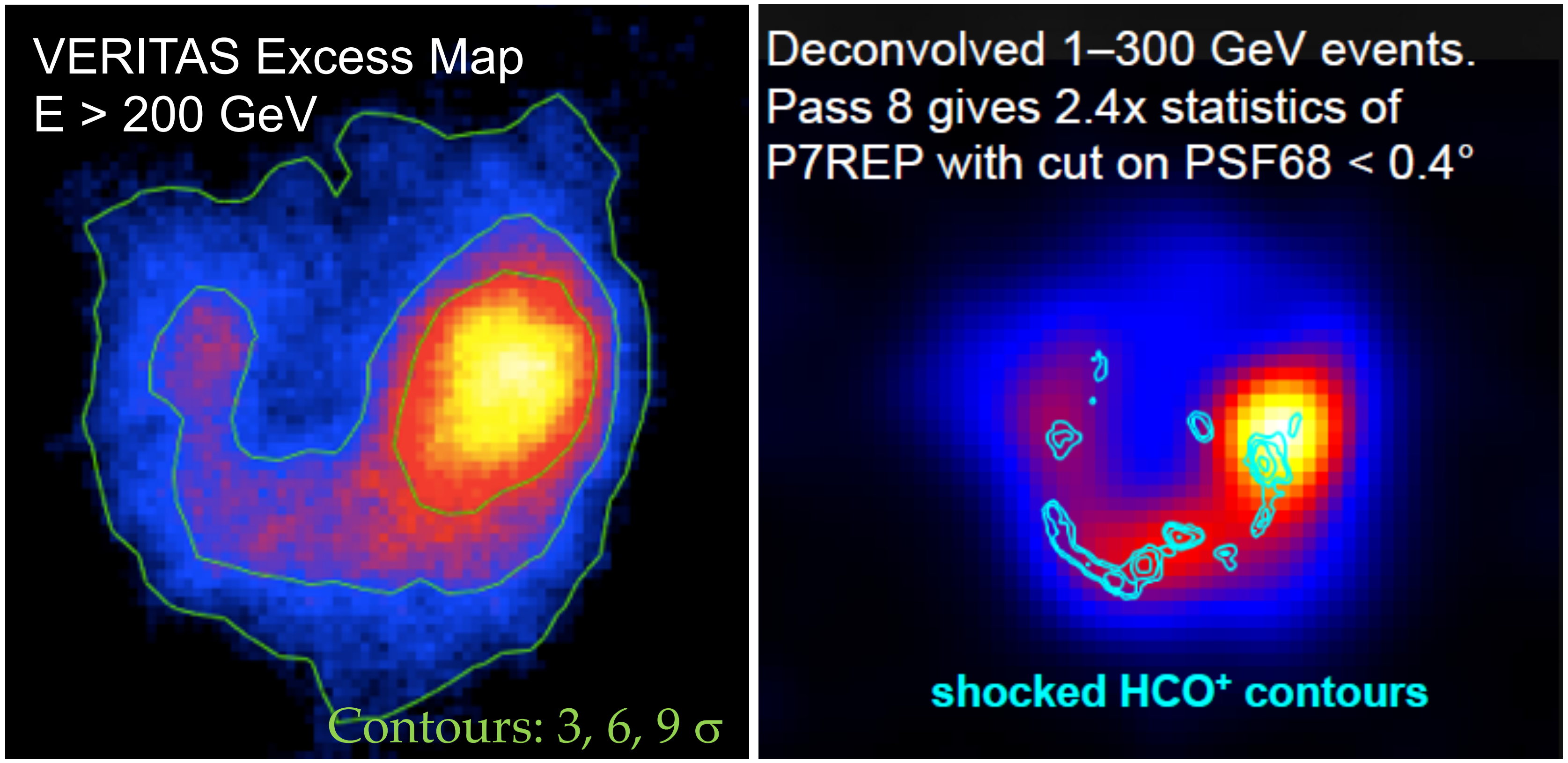




Galactic Sources: Supernova Remnants

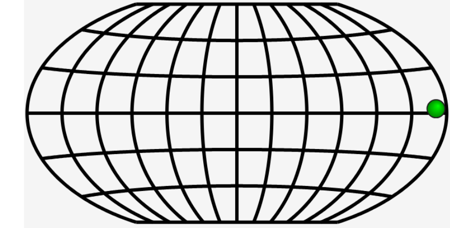
Interacting SNR IC 443 – Resolved Middle-aged Shell





- Emission dominated by CRs interacting with gas in/ with shock front
- Strong differences in environment – comparable spectral shape
- Huge intensity variation but TeV/GeV integral flux ratios consistent
- Common morphology from GeV to TeV → single CR population

Galactic Sources: Supernova Remnants



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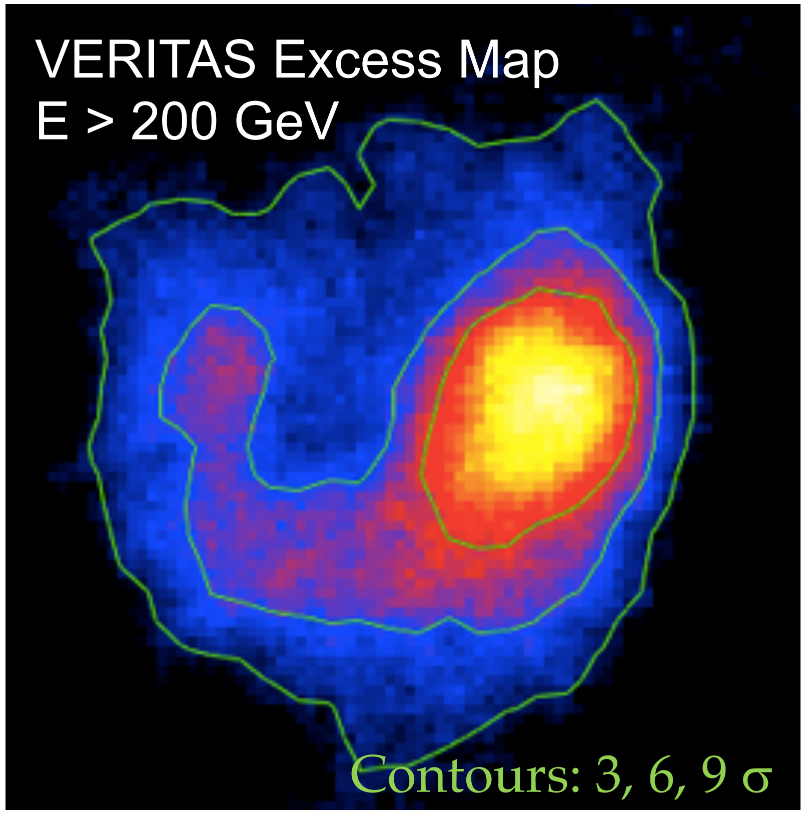
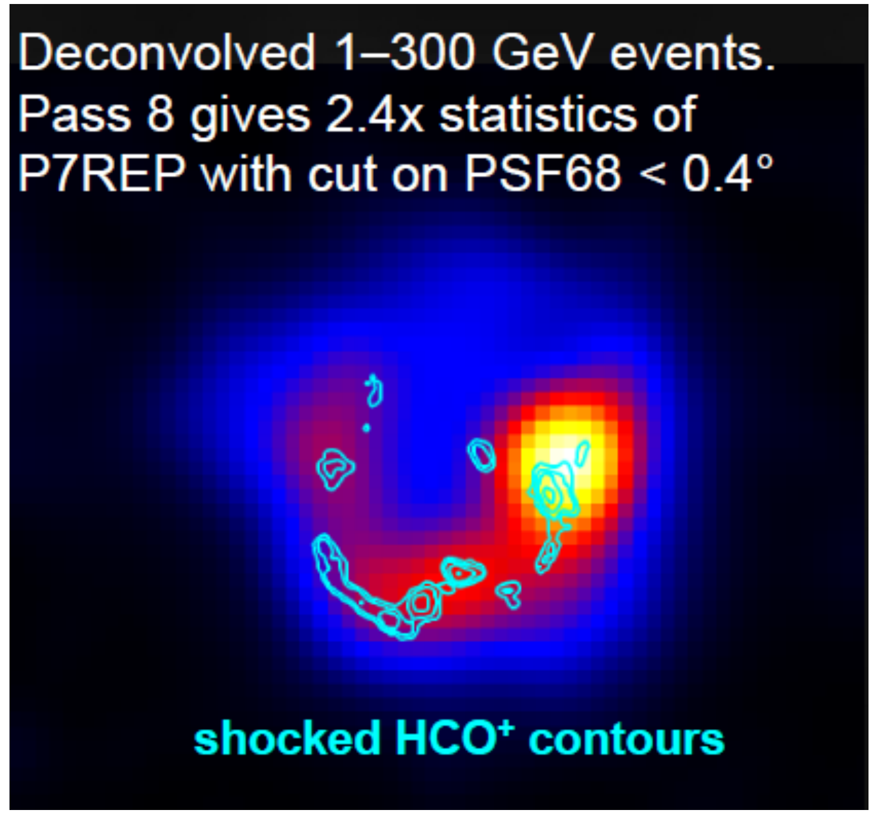
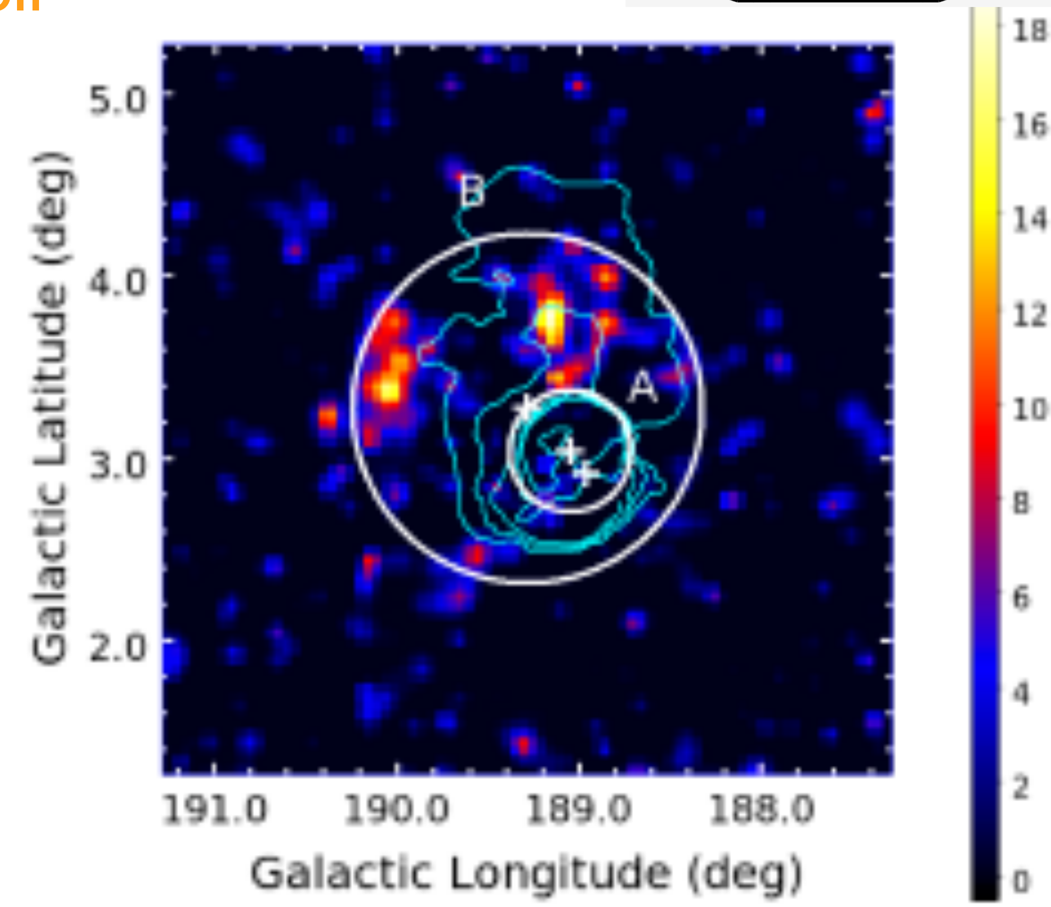
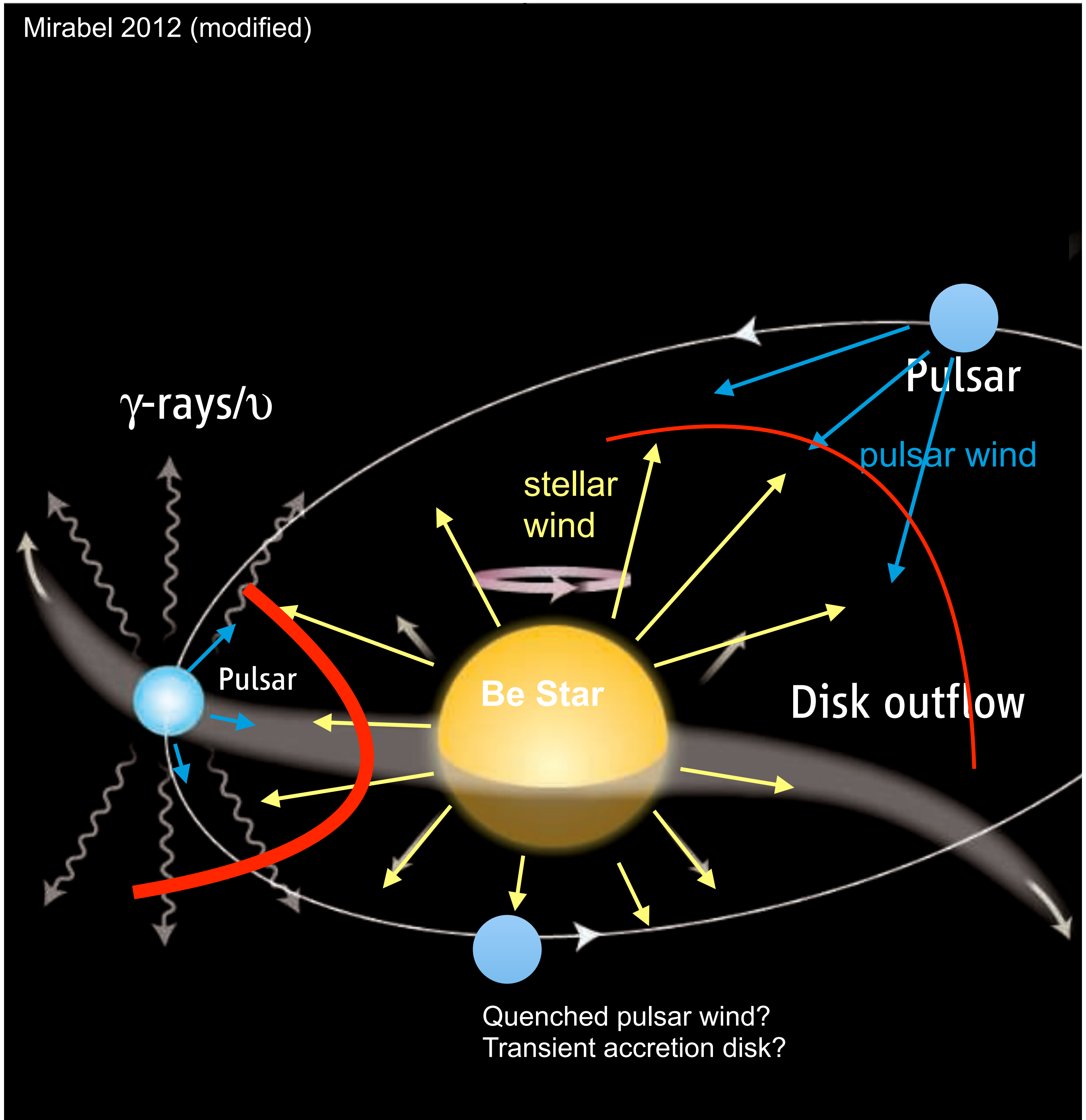






- Emission dominated by CRs interacting with gas in/ with shock front
- Strong differences in environment – comparable spectral shape
- Huge intensity variation but TeV/GeV integral flux ratios consistent
- Common morphology from GeV to TeV → single CR population
- Fermi-LAT reports a second, hard-spectrum extended source FGES J0619.6+2229 encompassing IC 443
  - CR escape signature? Or a separate SNR?

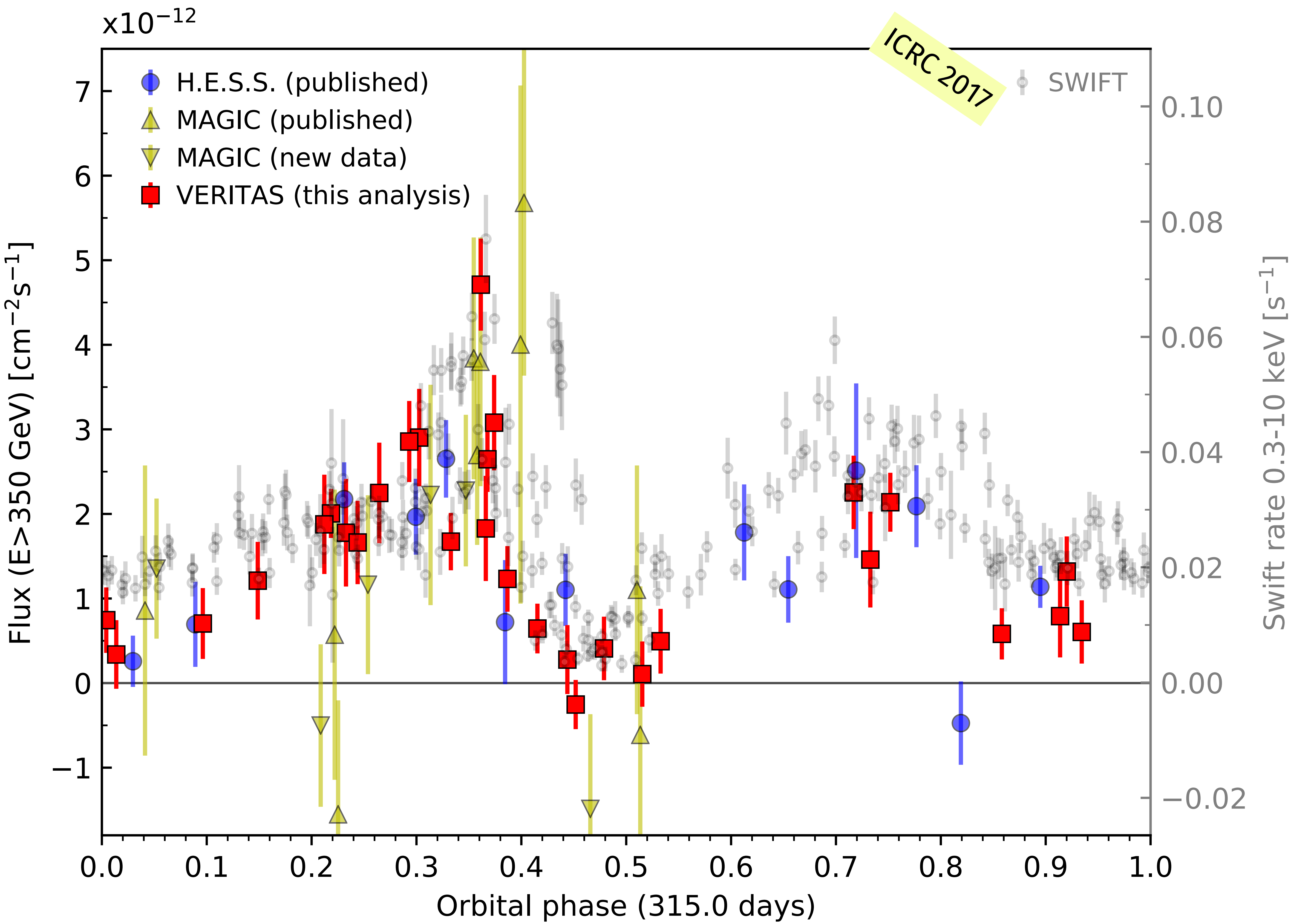
Galactic Sources: Binary Systems
Accretion or wind powered?



- Acceleration in regularly repeating changing conditions
- Probe structure of pulsar wind
- Seven gamma-ray binaries known to emit gamma-rays > 100 GeV

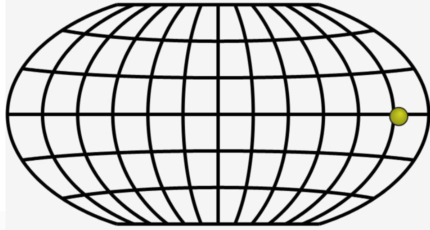
Long Observation of a Binary System

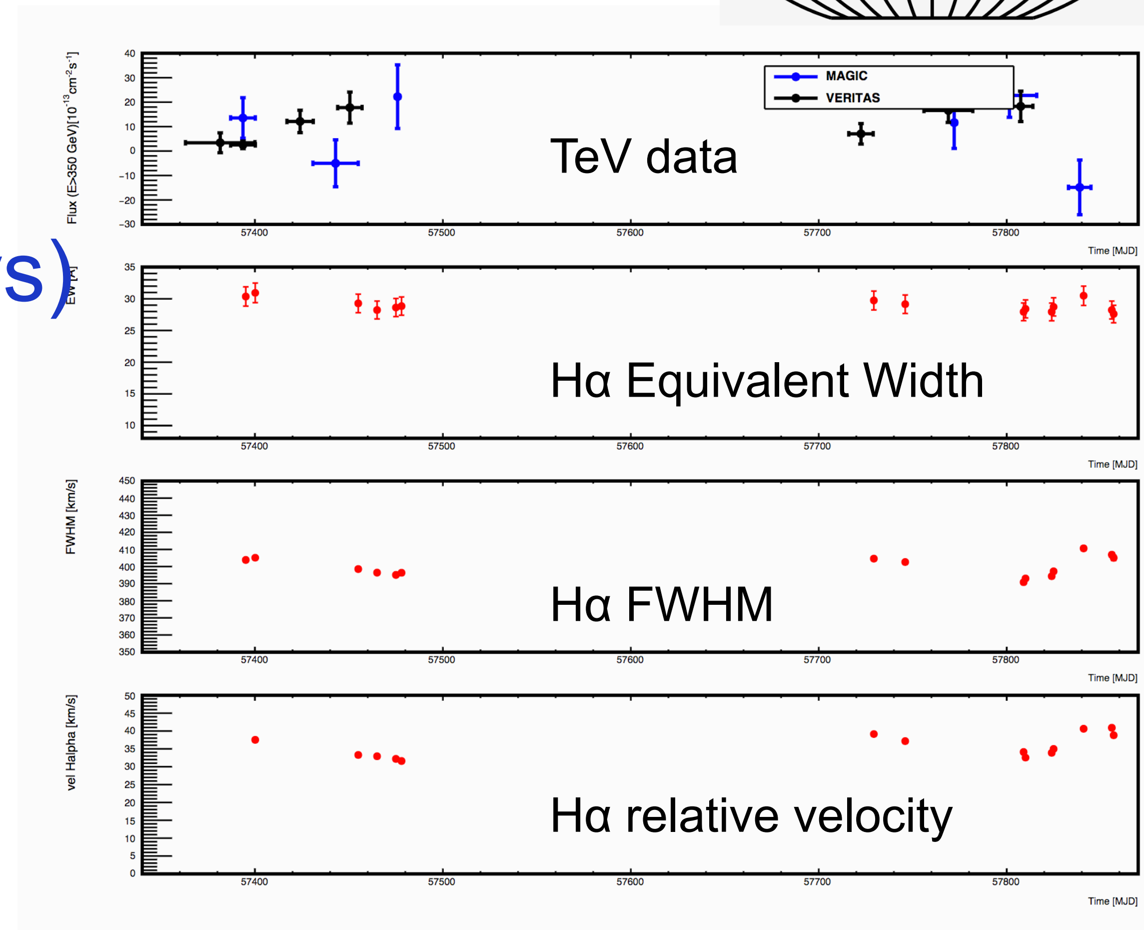
HESS J0632+057 - Monoceros Loop – MWC 148: B0pe star



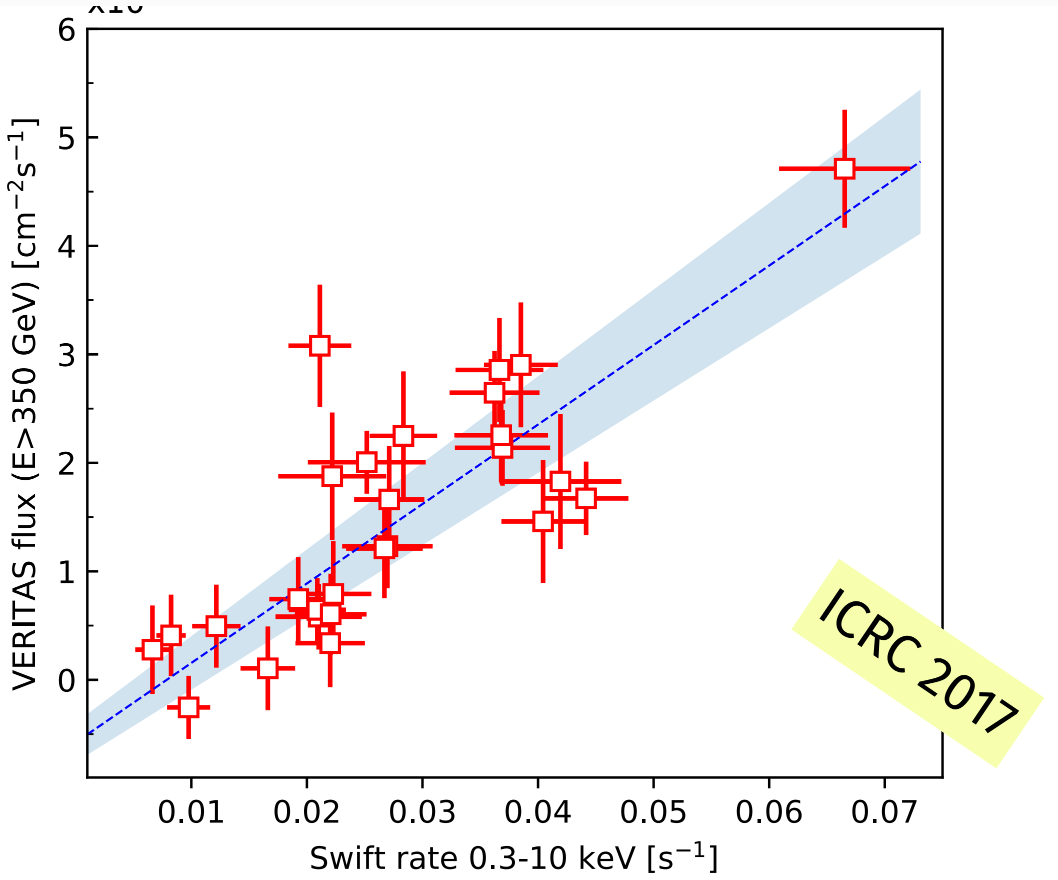
H.E.S.S. /MAGIC /VERITAS Publication

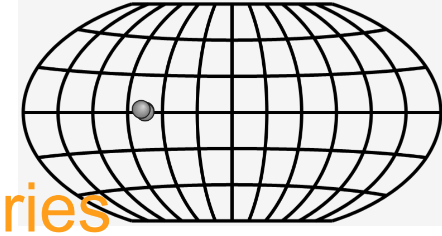
HESS J0632+057





- Joint publication with main focus on light curve analysis and (optical, X-rays) multi-wavelength analysis
- New (unpublished) data:
  - H.E.S.S. ~50 hours
  - MAGIC ~15 hours (joint campaign in 2014 with VERITAS, XRT, optical and infrared observations)
  - VERITAS ~76 hours (plus 2017/18 data)
- Paper status:
  - Monthly meetings and milestone preparation (coordinated by D Hadasch)
  - Attempt first draft in summer

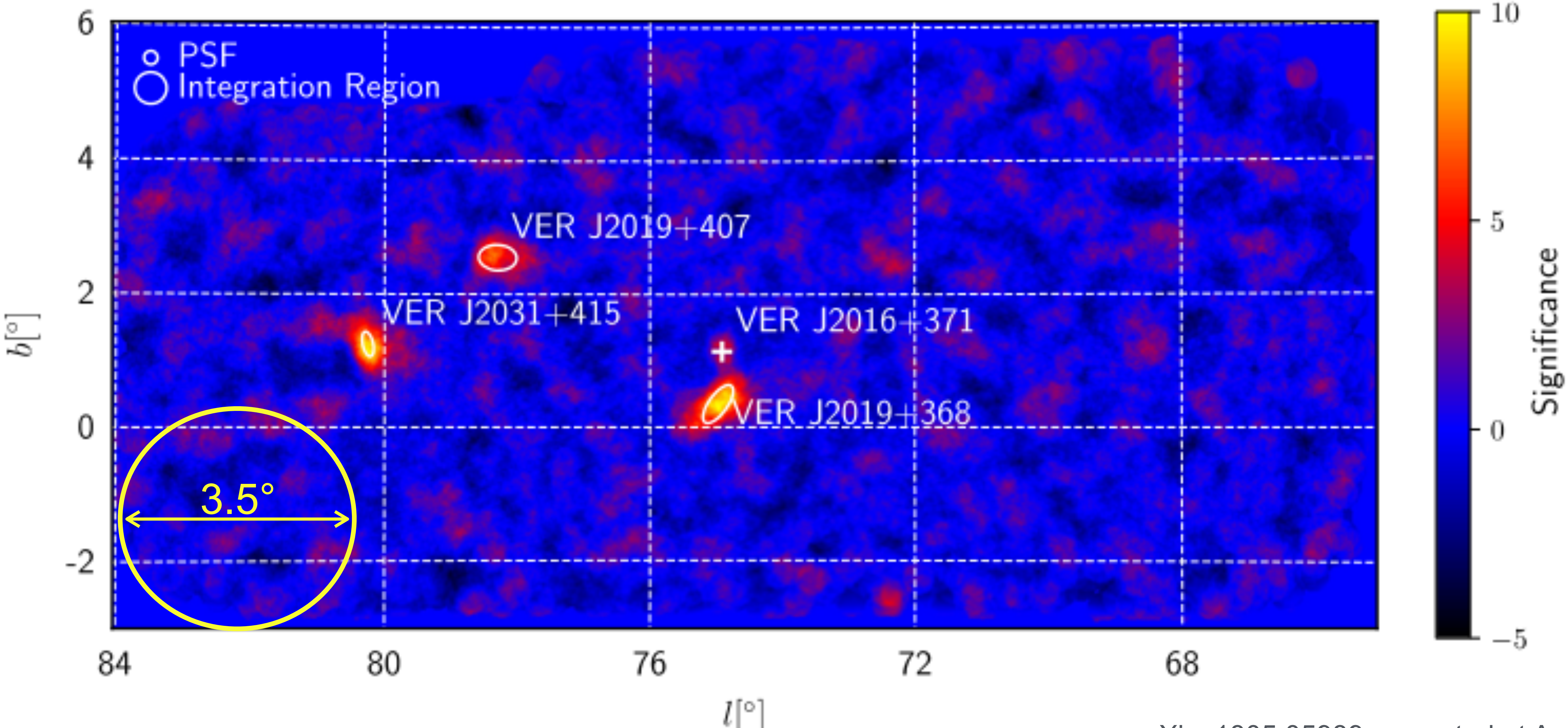




Galactic Physics: Cygnus Region

Densest Region of the Galactic Plane accessible for Northern Observatories

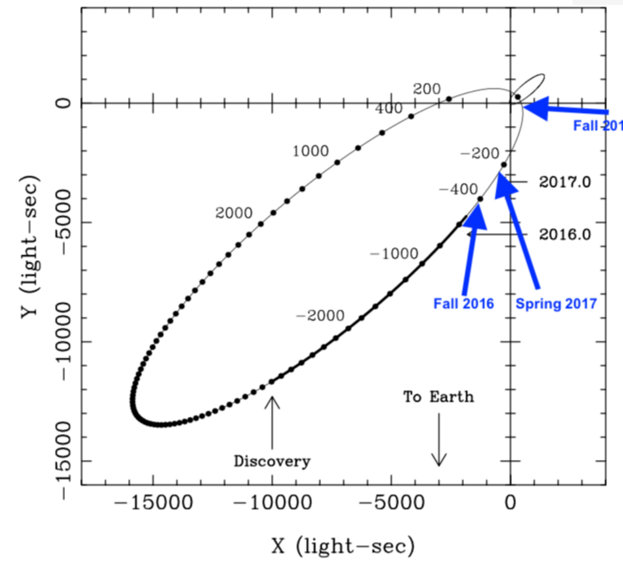
- A Survey covering a 15×5° area – a key VERITAS project
- Data from 2007–2008 + follow-ups till 2012
- Four sources (resolved) and upper limits for 71 locations

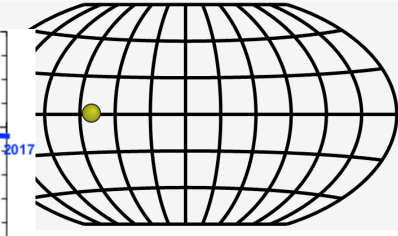


arXiv: 1805.05989, accepted at ApJ

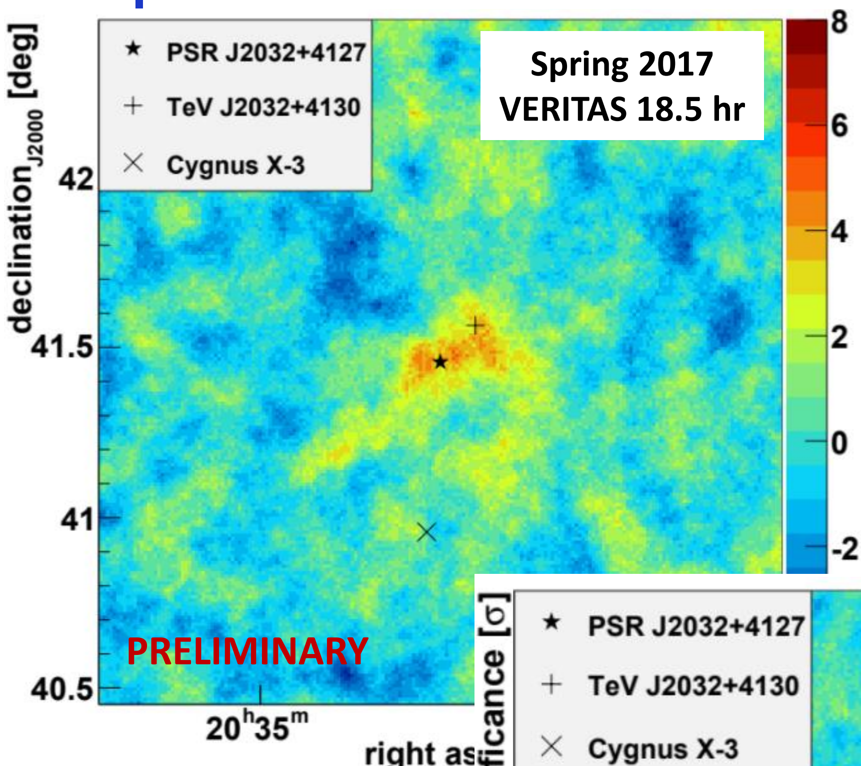
Galactic Sources: Binary System with a Pulsar

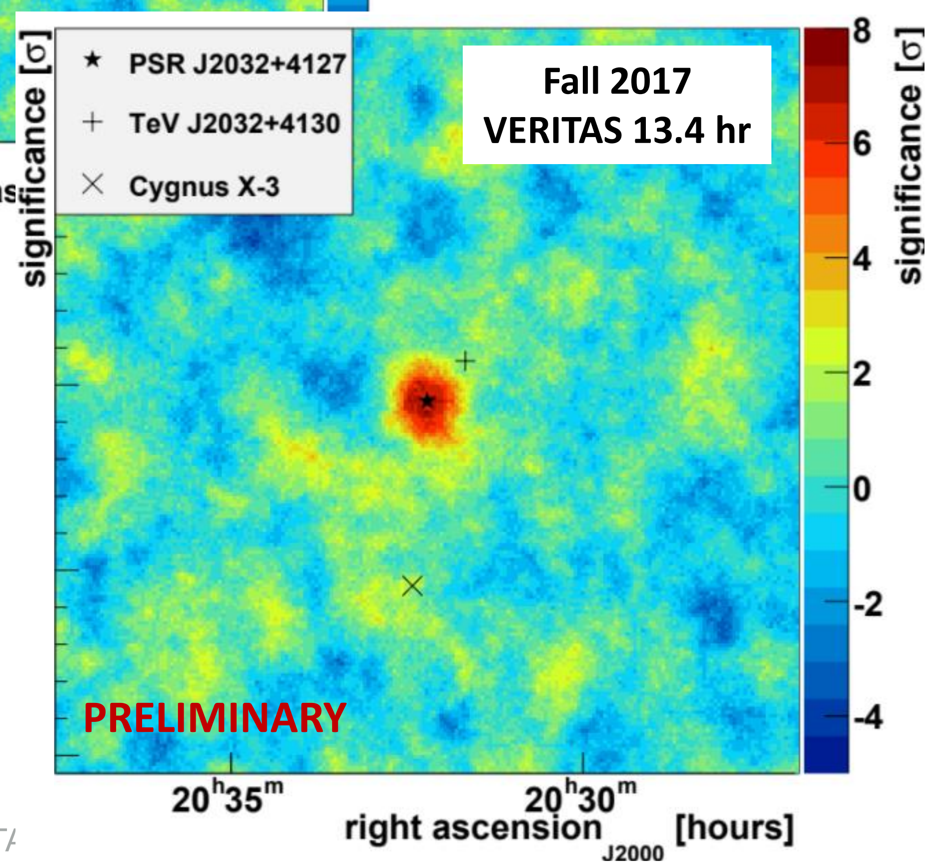
PSR J2032+4127 and Be Star MT91 213





Identified as a member of a binary in 2015 with orbit period ~50 years – periastron in November 2017

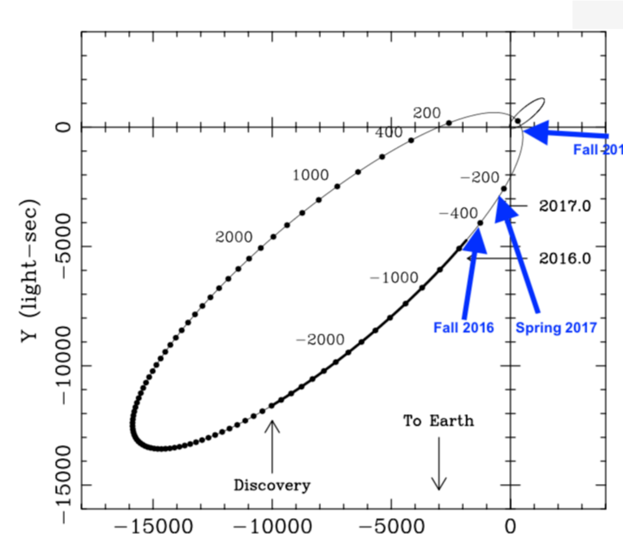


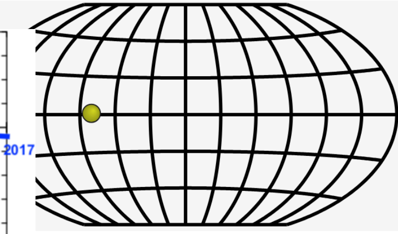


MAGIC and VERITAS ATel #10810 → paper in preparation

Galactic Sources: Binary System with a Pulsar

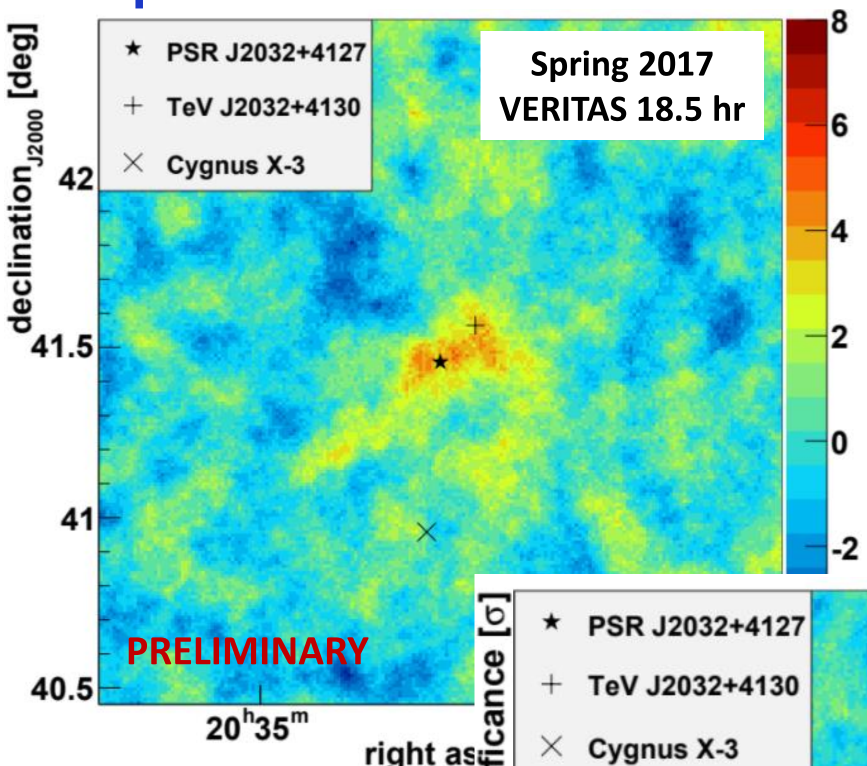
PSR J2032+4127 and Be Star MT91 213

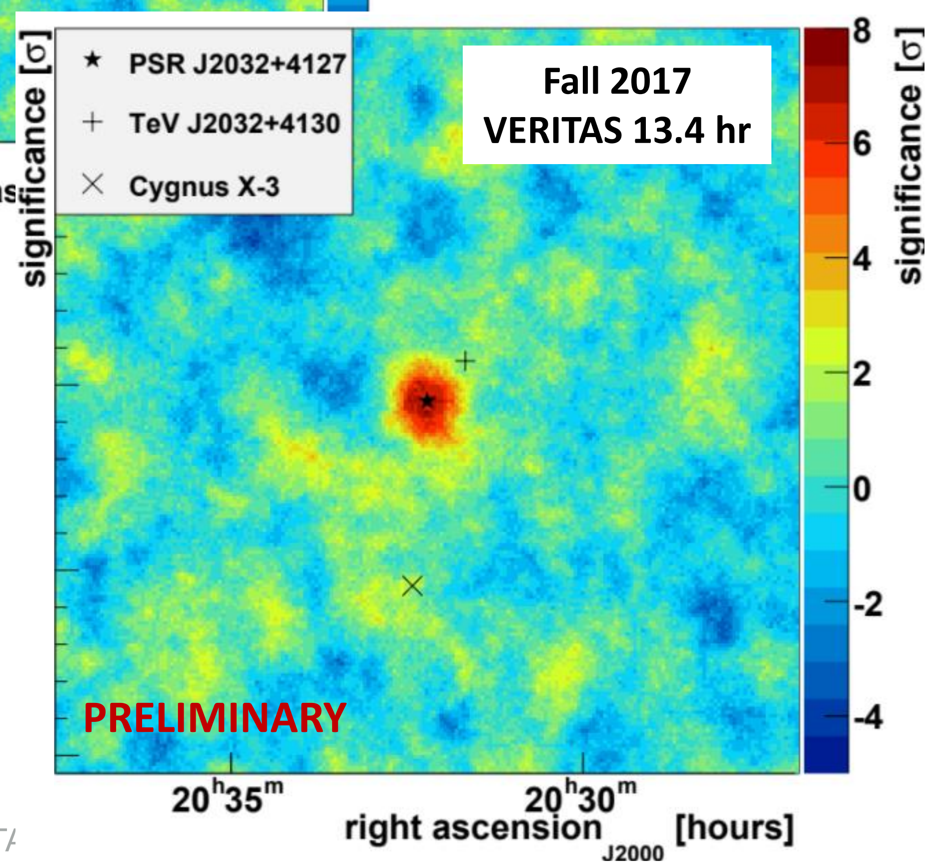


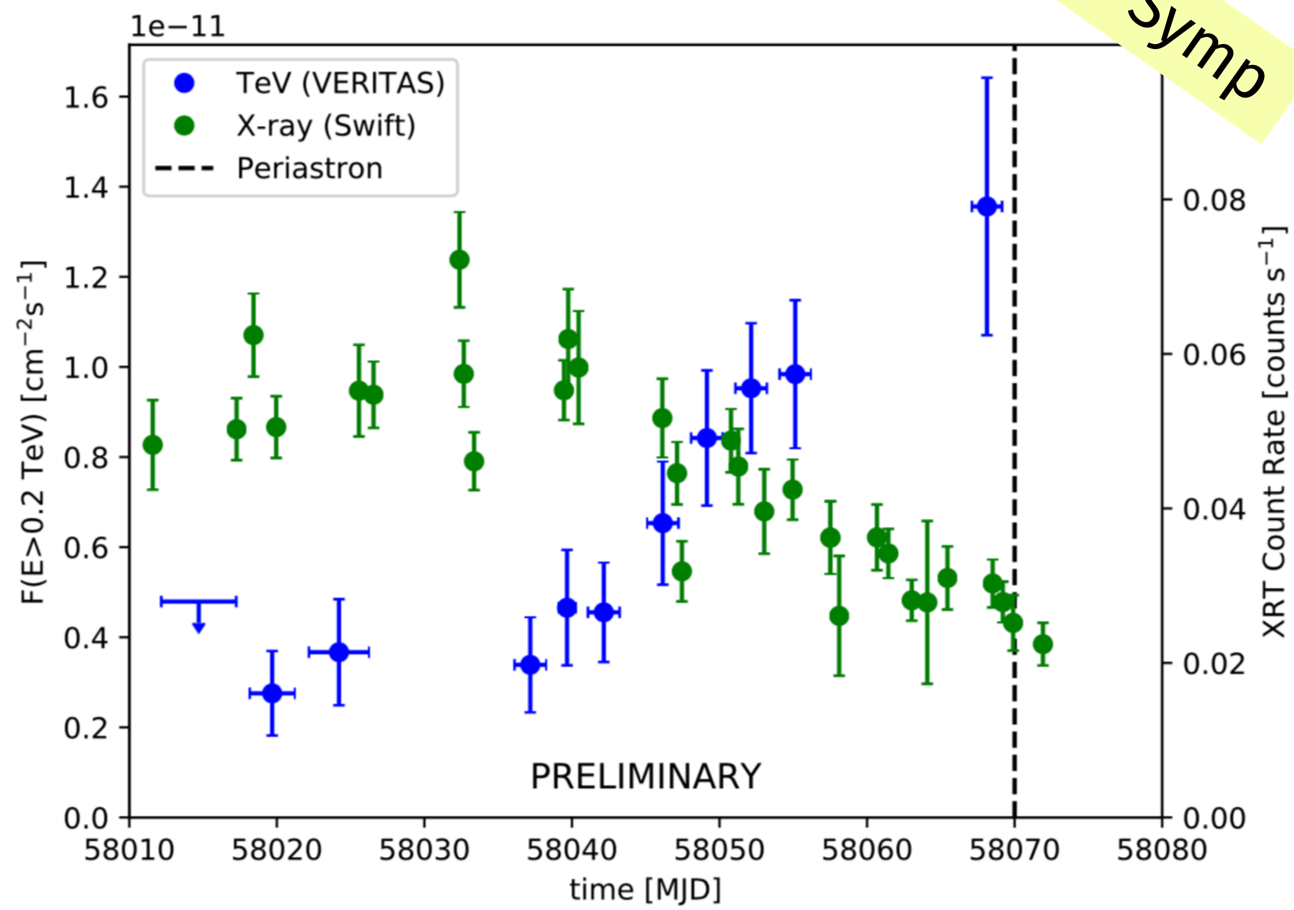


Texas Symp

Identified as a member of a binary in 2015 with orbit period ~50 years – periastron in November 2017







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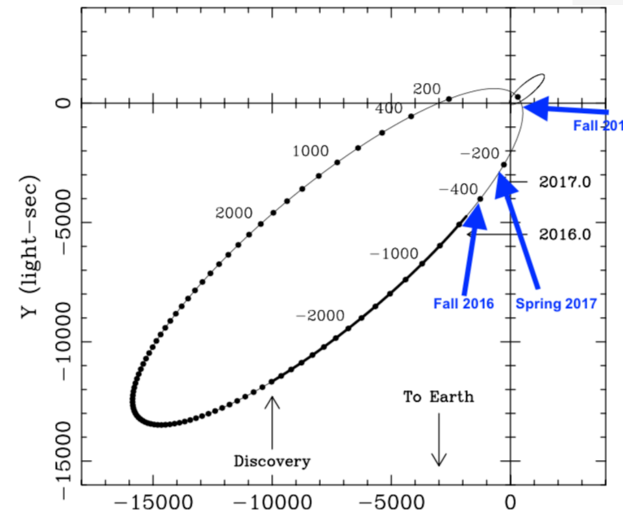

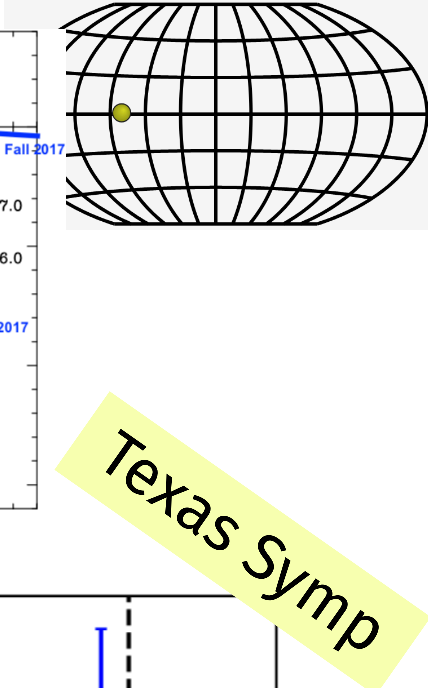

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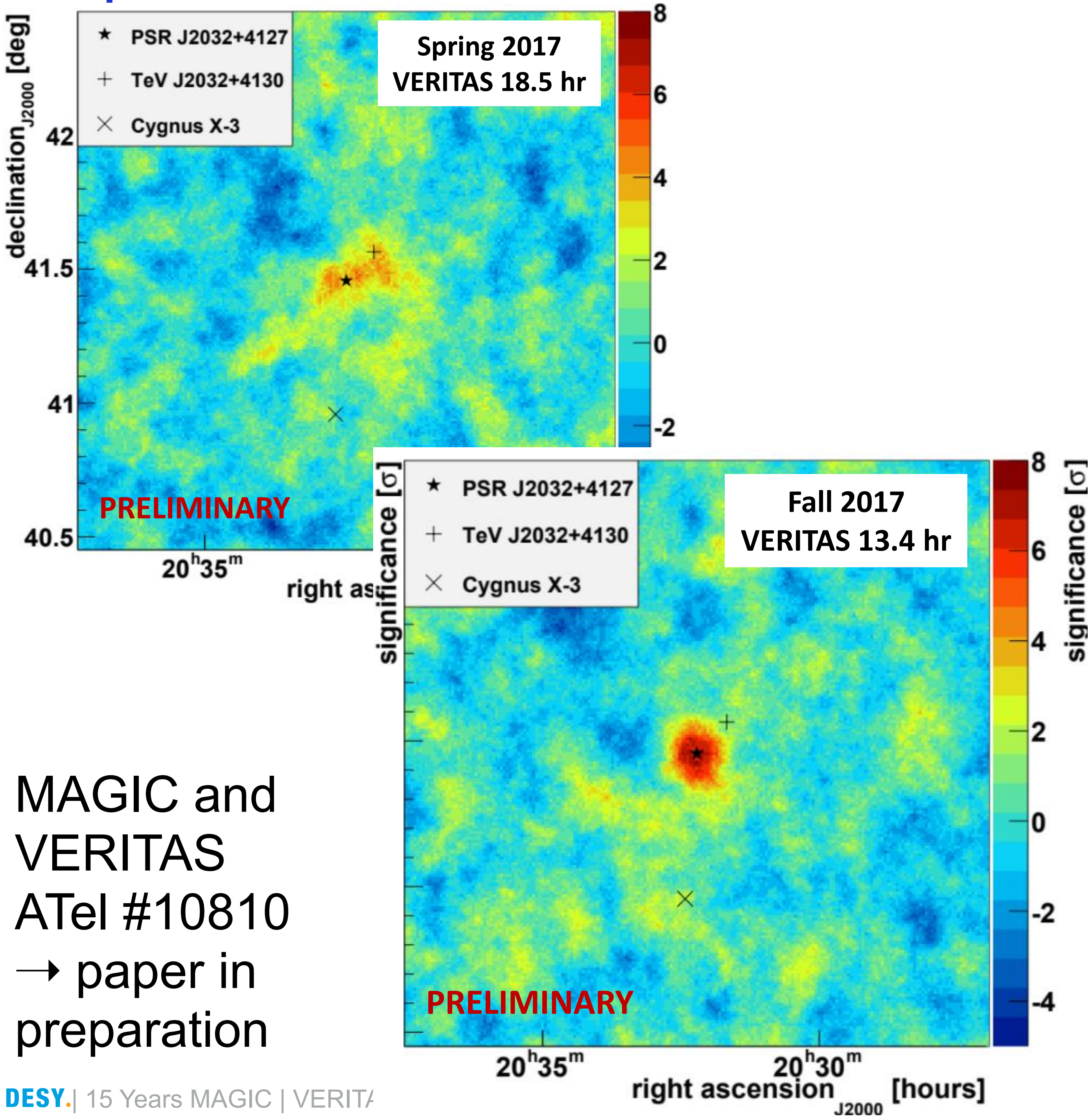
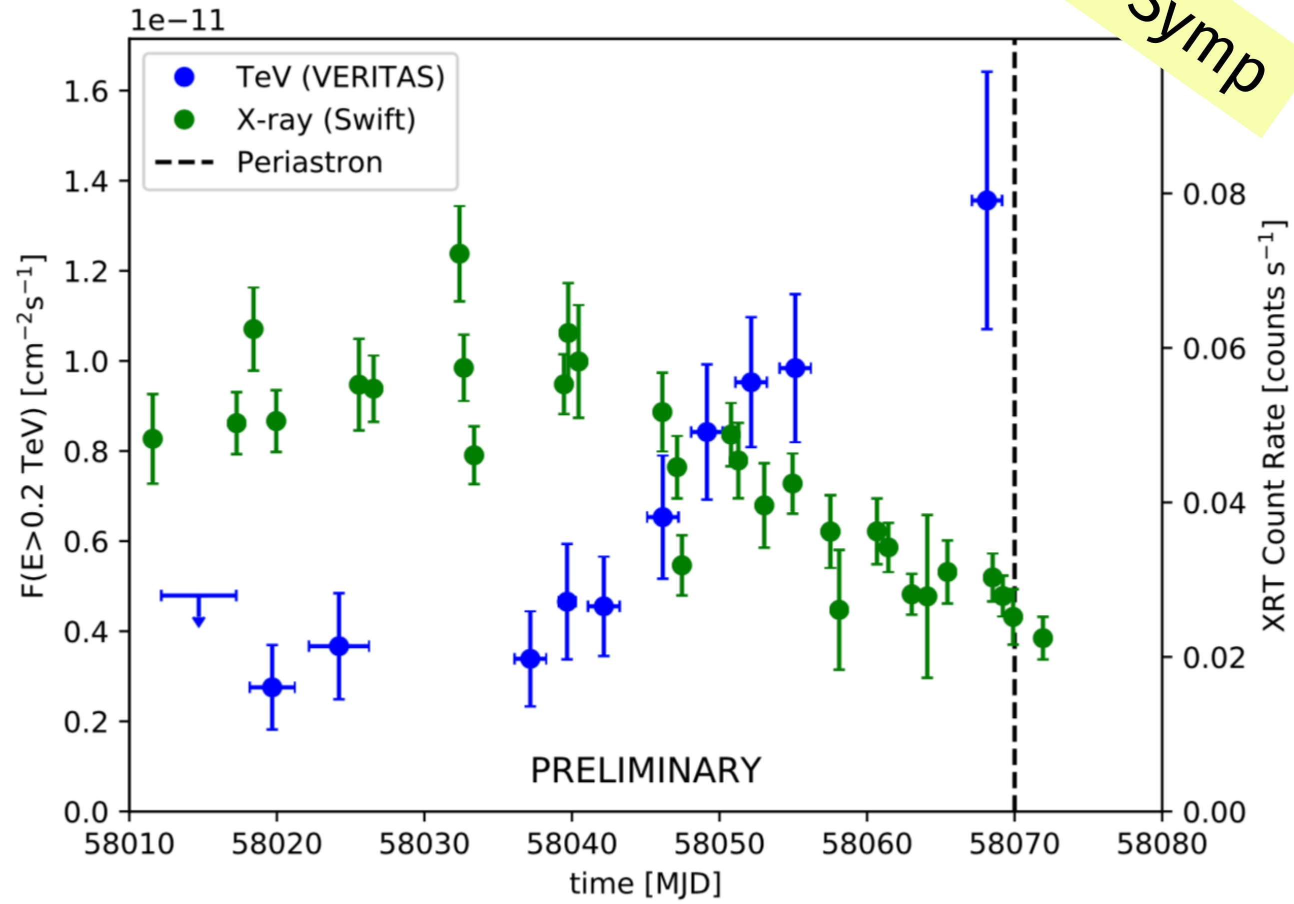
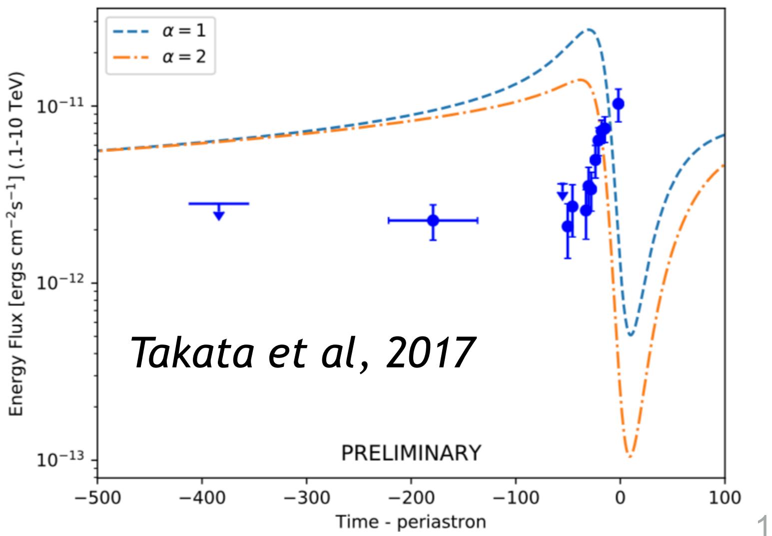


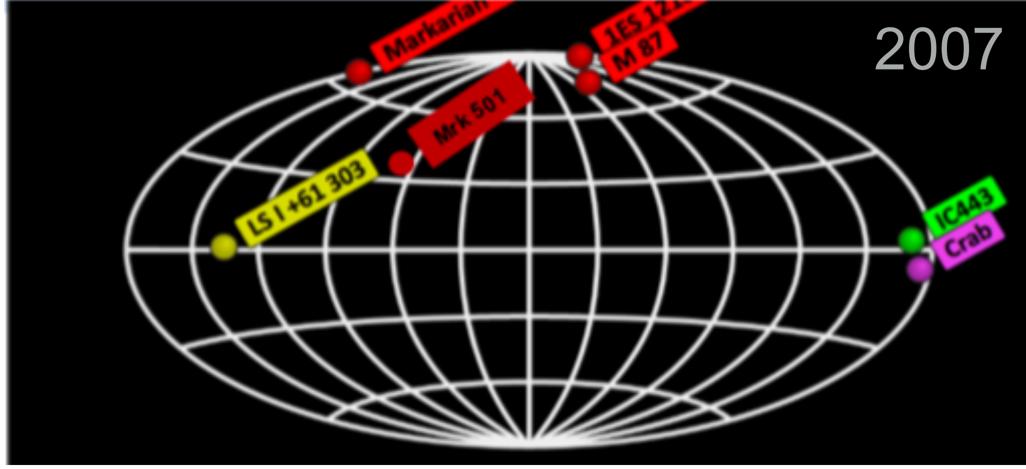


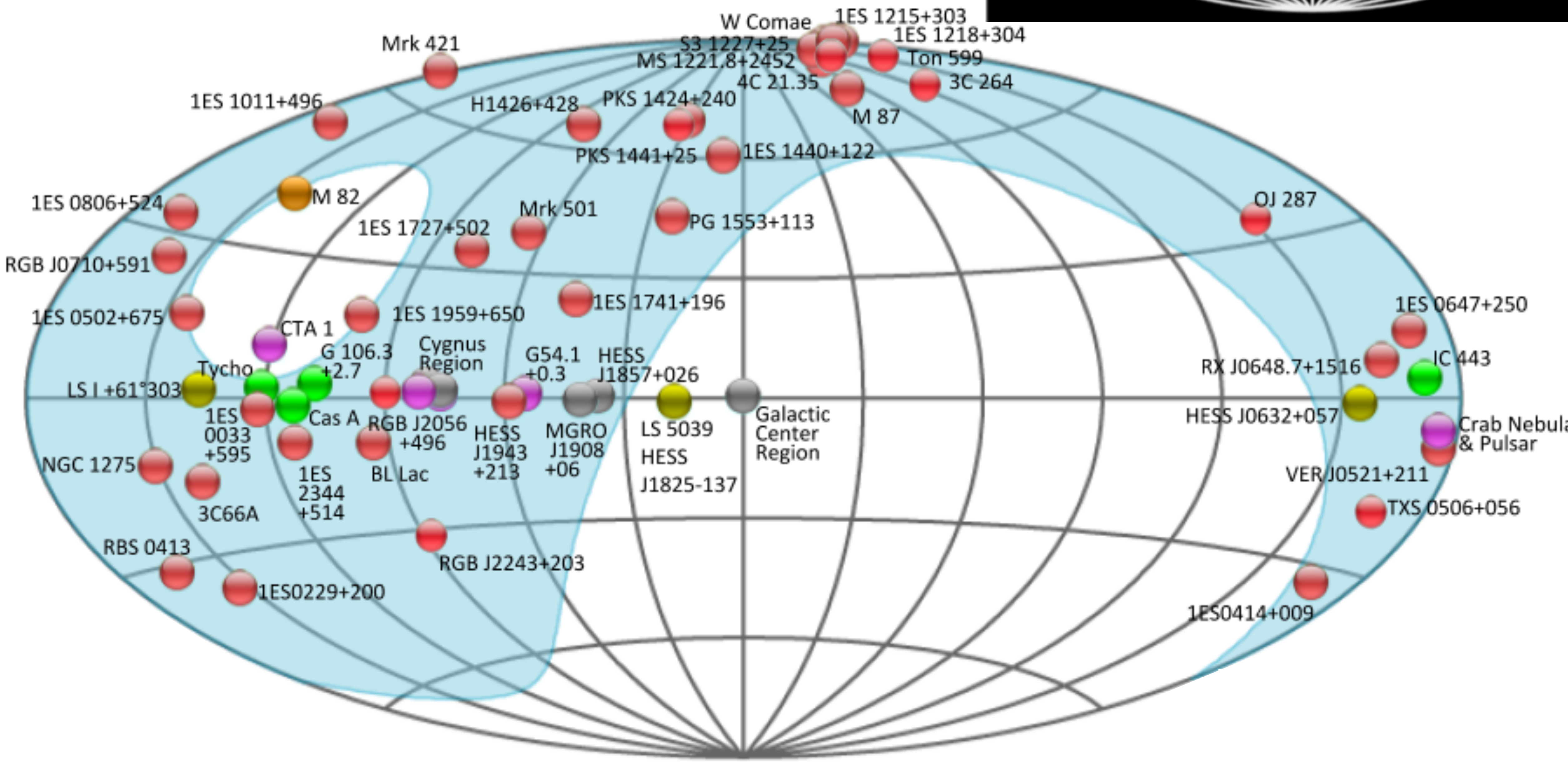
MAGIC and VERITAS ATel #10810 → paper in preparation

Significant revision of models required



VERITAS Catalogue

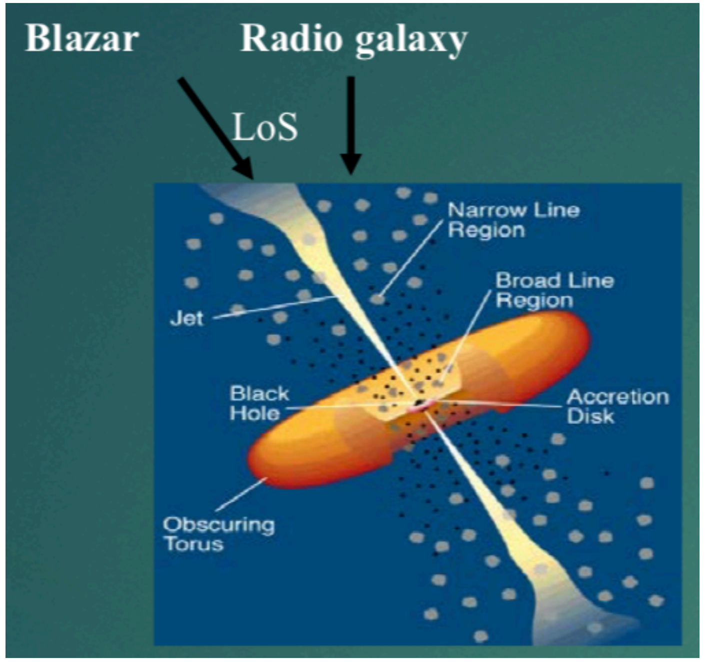




35 extragalactic sources by VERITAS
>20 extragalactic sources discovered

June 2018

VERITAS – Extragalactic Highlights



- Flaring activities – study the dynamics of relativistic particles in blazars
- A highly elevated flux increases the chance to get a glimpse of the extragalactic γ-ray horizon, enabling cosmological studies and the propagation studies of γ-rays

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#11436 VERITAS discovery of VHE emission from the FRI radio galaxy 3C 264

Reshmi Mukherjee for the VERITAS Collaboration 17 Mar 2018

#11075 VERITAS Detection of VHE Emission from Ton 599

Reshmi Mukherjee for the VERITAS Collaboration 18 Dec 2017

#10051 VERITAS Detection of VHE Emission from OJ 287

Reshmi Mukherjee for the VERITAS Collaboration 5 Feb 2017

#9931 VERITAS detection of the radio galaxy NGC 1275 with elevated very-high-energy gamma-ray emission

Reshmi Mukherjee for the VERITAS Collaboration 4 Jan 2017

#9721 VERITAS Discovery of VHE Emission from RGB J2056+496

Reshmi Mukherjee for the VERITAS Collaboration 6 Nov 2016

VERITAS – Extragalactic Physics
Fundamental Questions

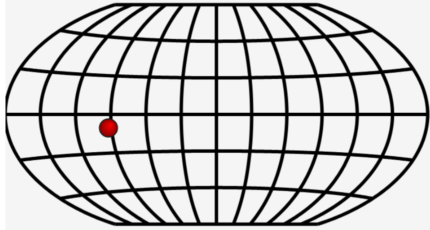
VERITAS collects data on all visible VHE-detected galaxies every year, providing a vast dataset on sources in both low and high emission states

- What types of galaxies produce gamma-ray emission?
- Where does the gamma-ray emission originate within radio galaxies and blazars?
- How is the gamma-ray emission produced within these sources
- What drives blazar variability?
- How is the gamma-ray emission related to the lower-energy emission emerging from these sources?
- How do the spectral signatures of these sources changes as the sources evolve?

A Furniss

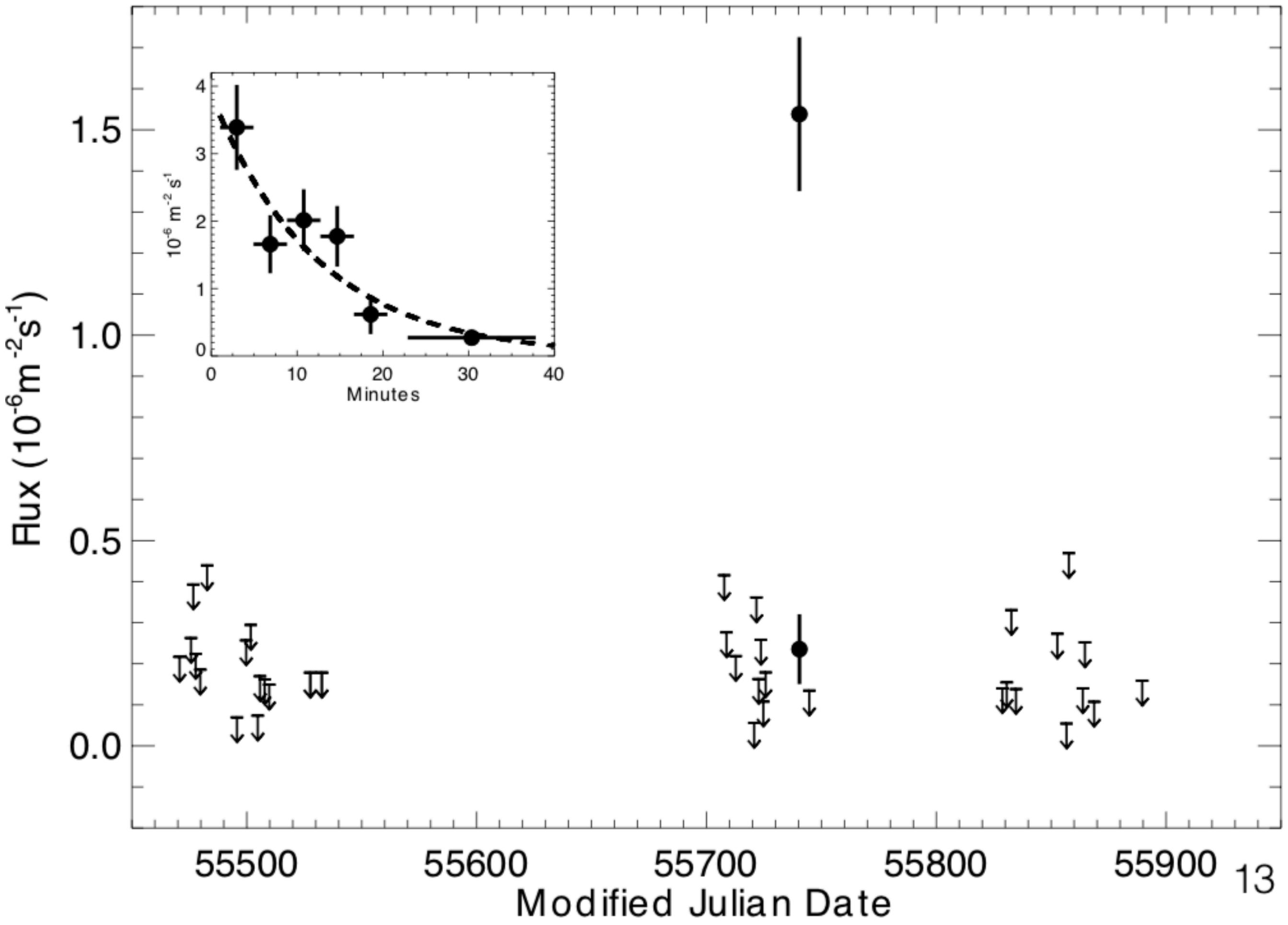
Extragalactic Sources: Blazars

The BL Lacertae



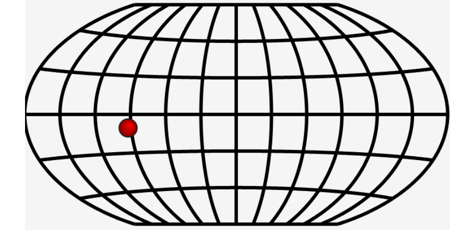
High variability of the gamma- ray emission from these sources

- Discovered in TeV by MAGIC in 2005
- Observed by VERITAS May 2011



Extraglactic Sources: Blazars

The BL Lacertae



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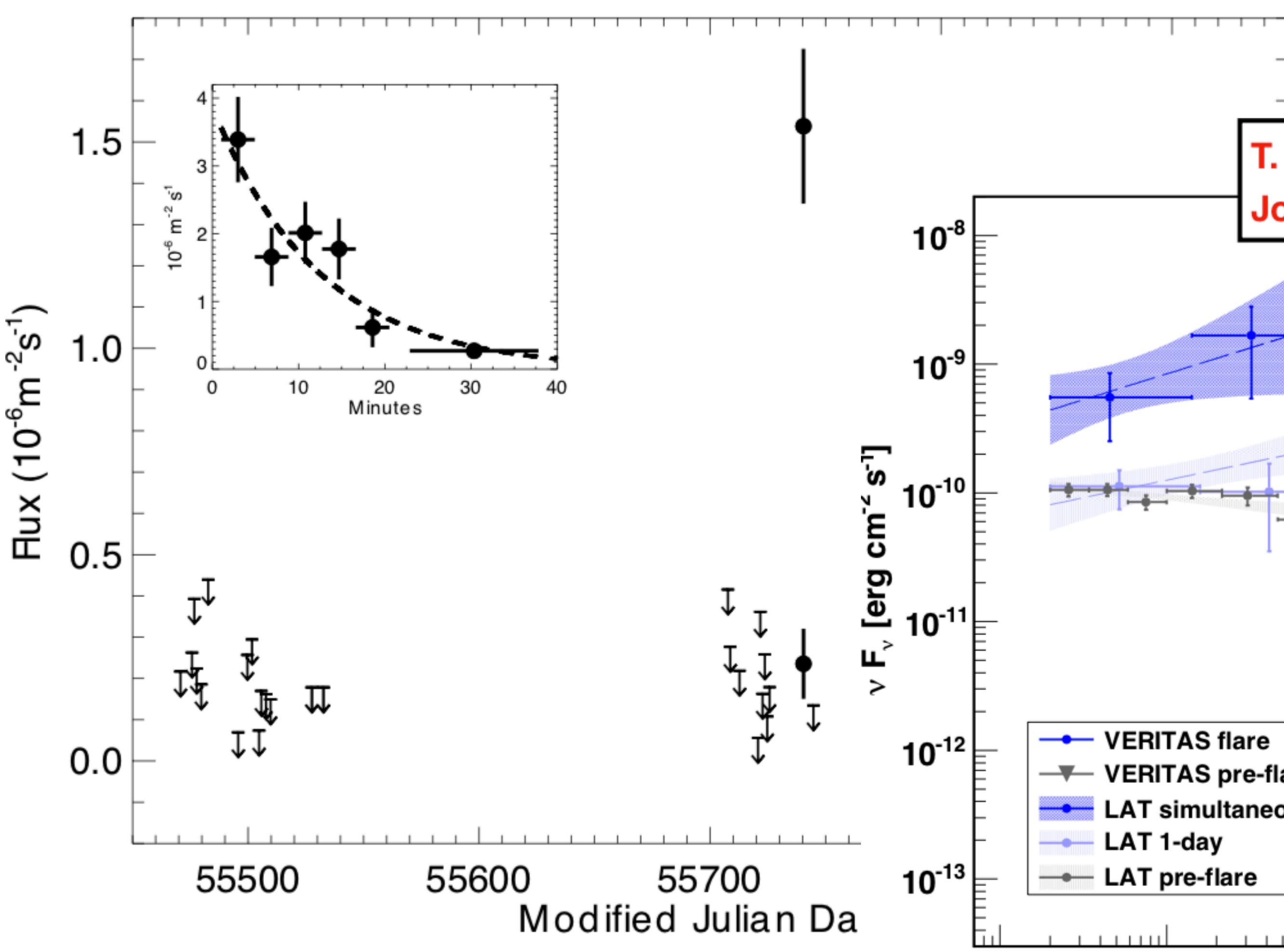
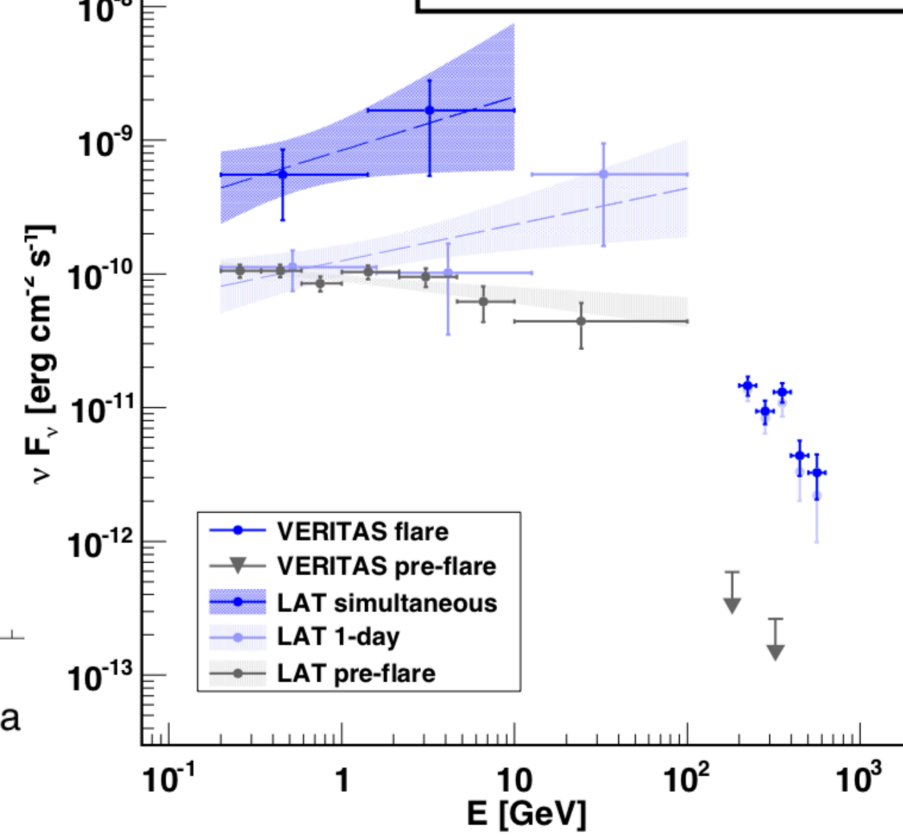
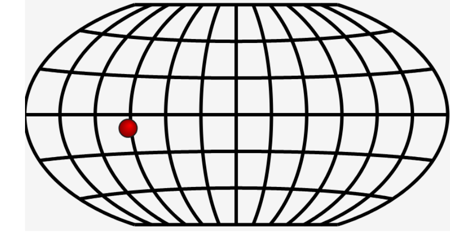


T. Arlen et al., Astrophysical Journal 762: 92, 2012



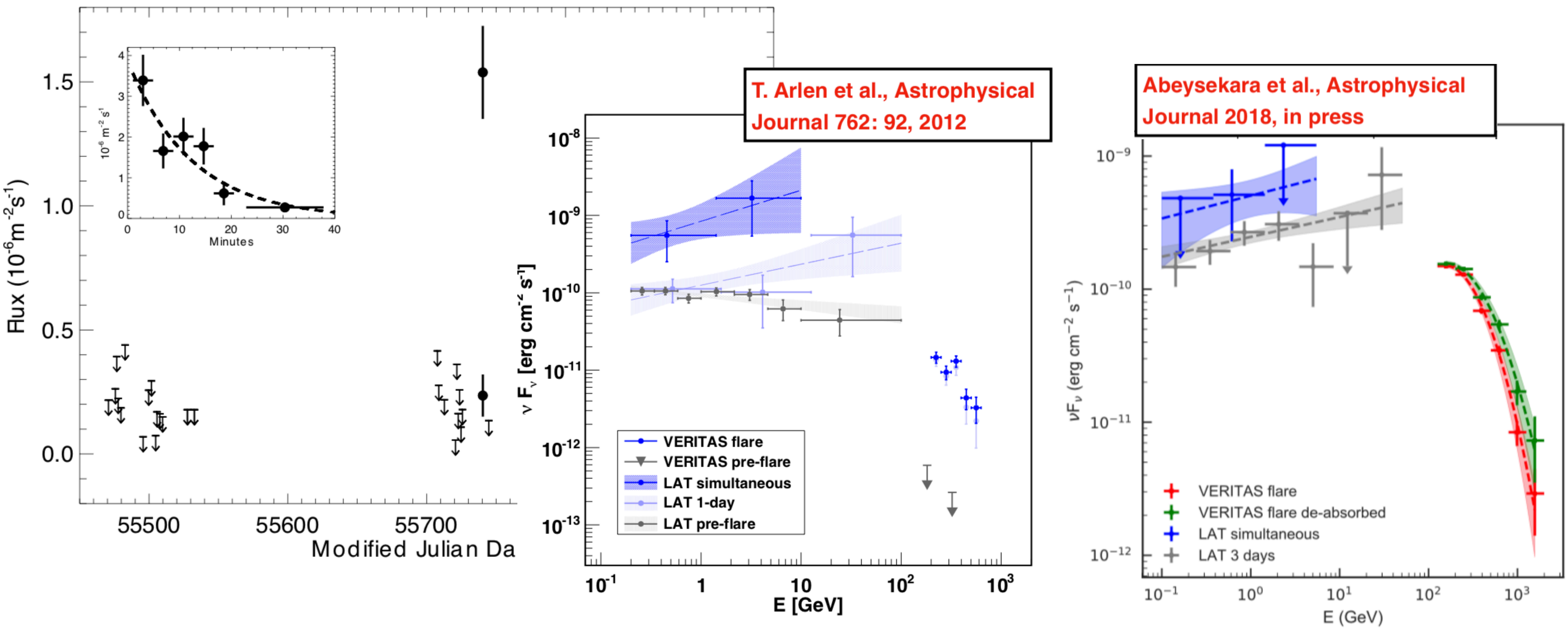
Extragalactic Sources: Blazars

The BL Lacertae



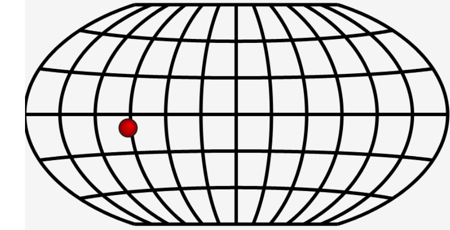
High variability of the gamma- ray emission from these sources

- Discovered in TeV by MAGIC in 2005
- Observed by VERITAS May 2011 significant flare in Oct 2016

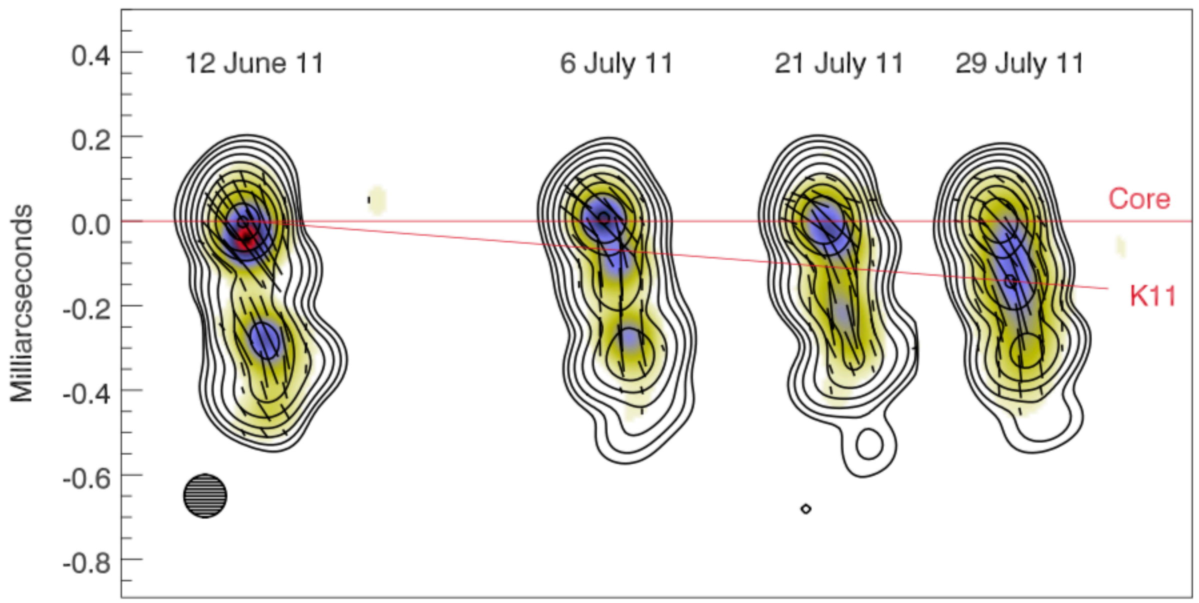


Extragalactic Sources: Blazars

The BL Lacertae

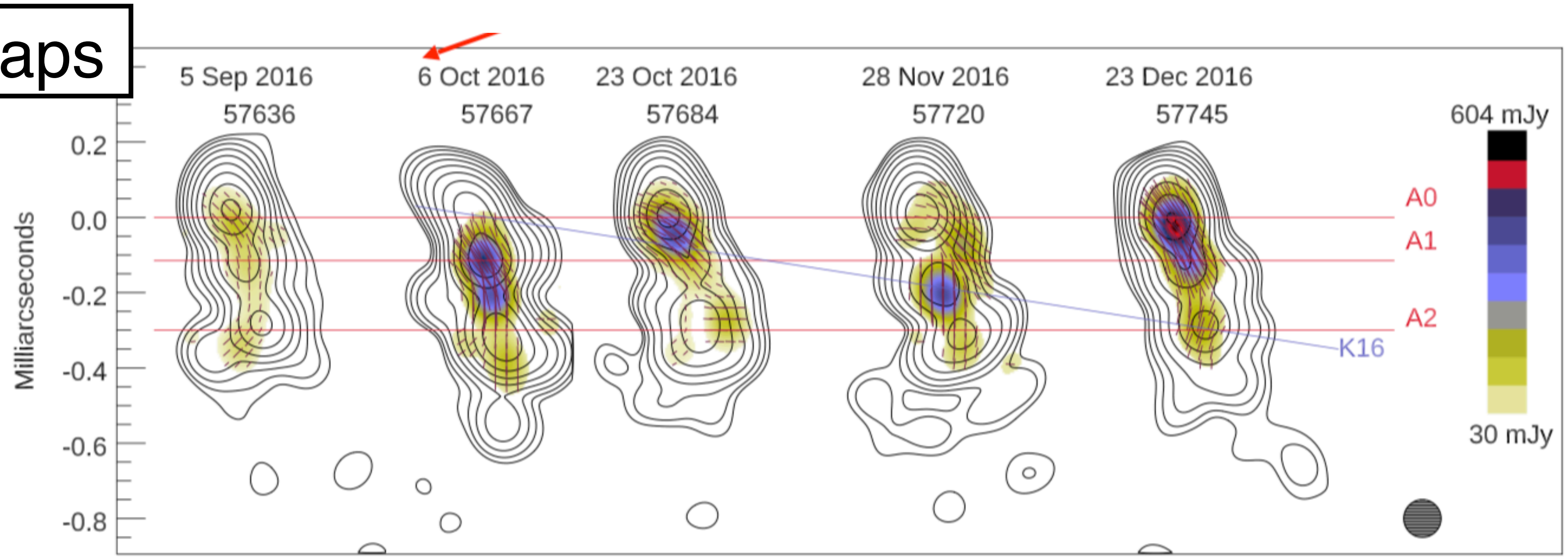


High variability of the gamma- ray emission from these sources

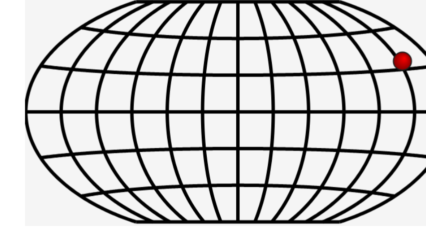


Flaring episodes display unique qualities - is every one from a different region?

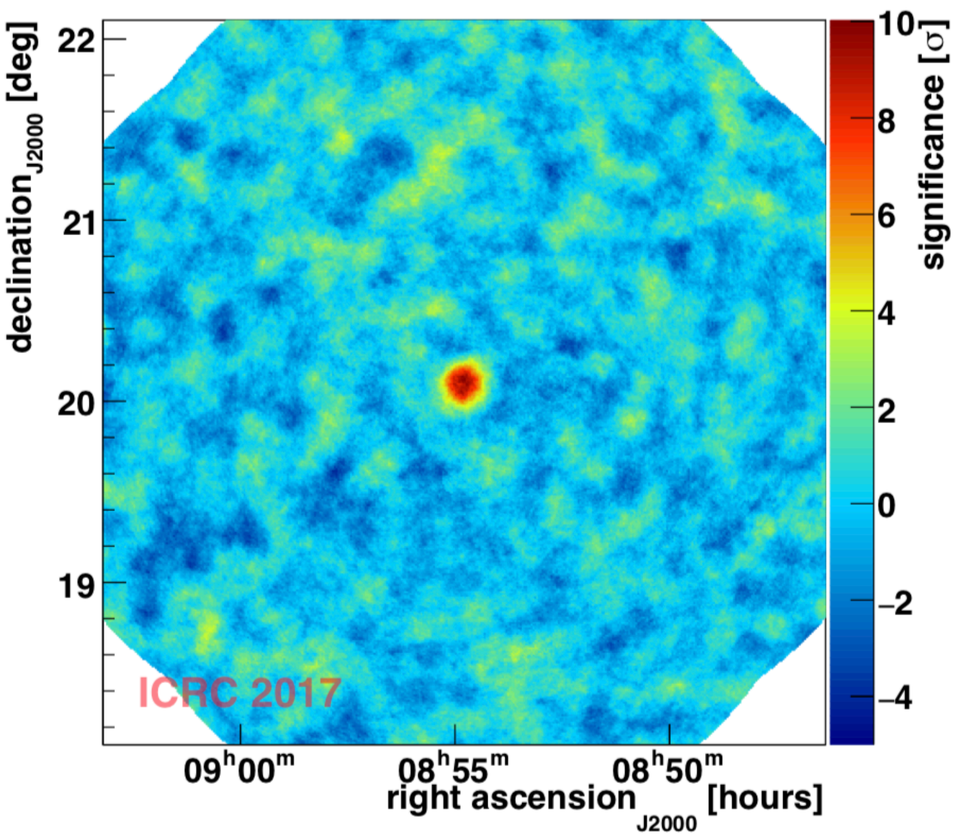
VLBA 43 GHz Maps

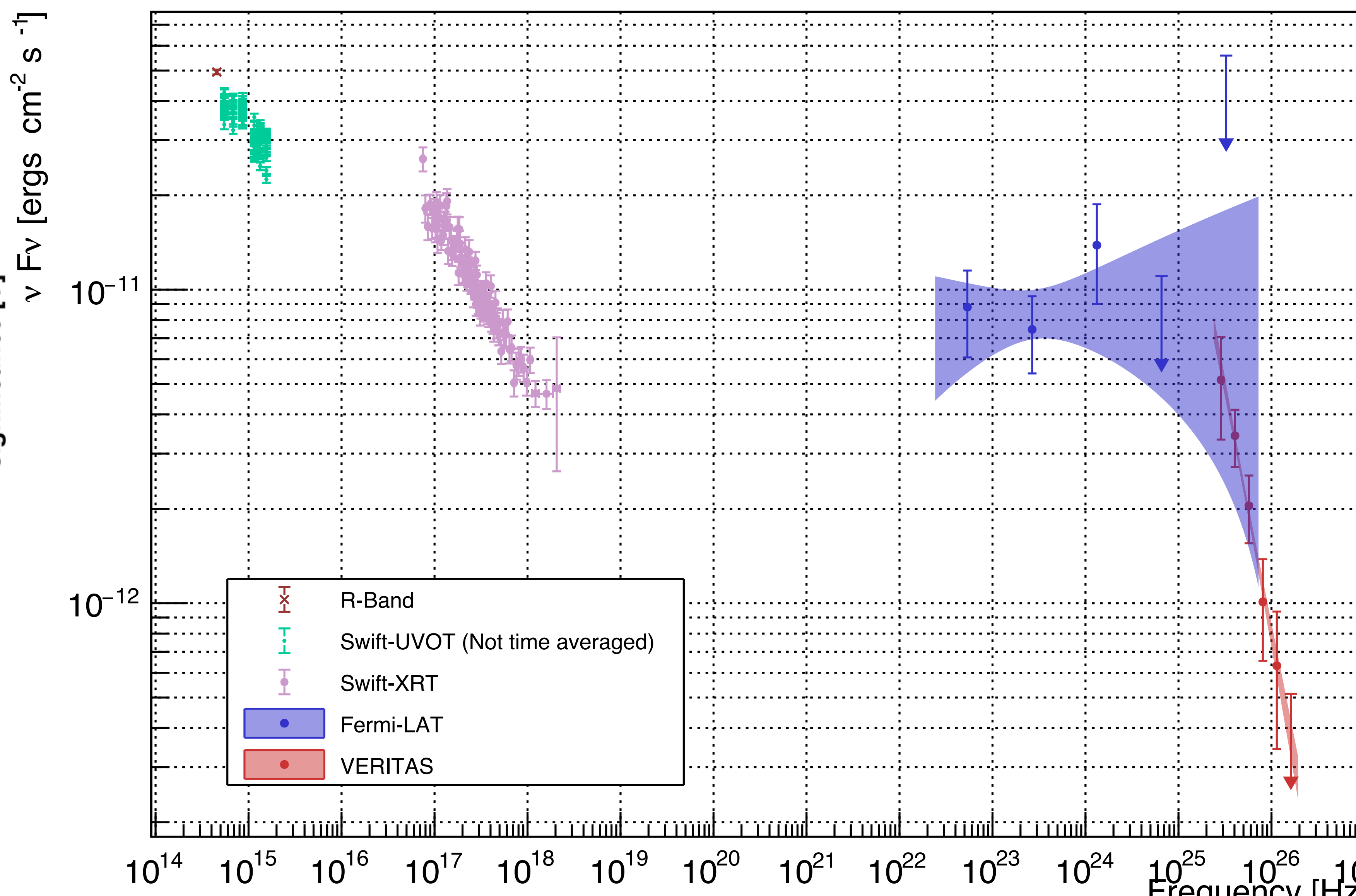


Extragalactic Sources: BL Lacertae
The VERITAS Detection of OJ 287



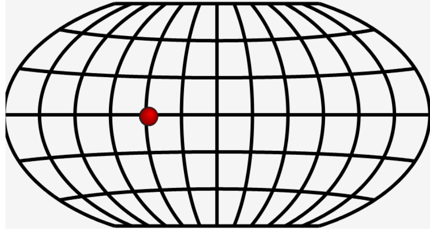
- Optically bright quasar – archival observations dating back > 100 years → ~12 year outburst cycle
- Proposed binary black hole system and a helical jet
- Detected during high X-ray activity/low Fermi-band activity
- Observed variability by VERITAS over the last 10 years?



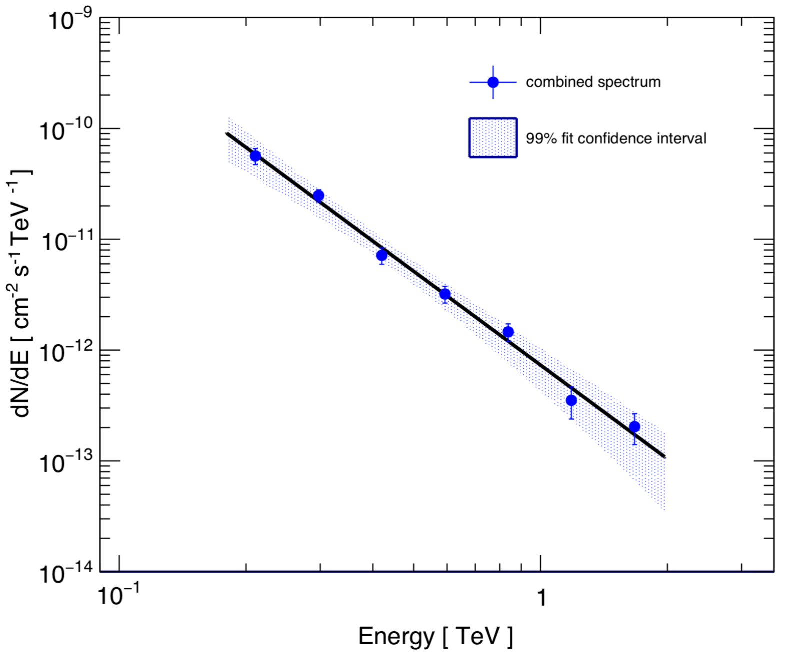


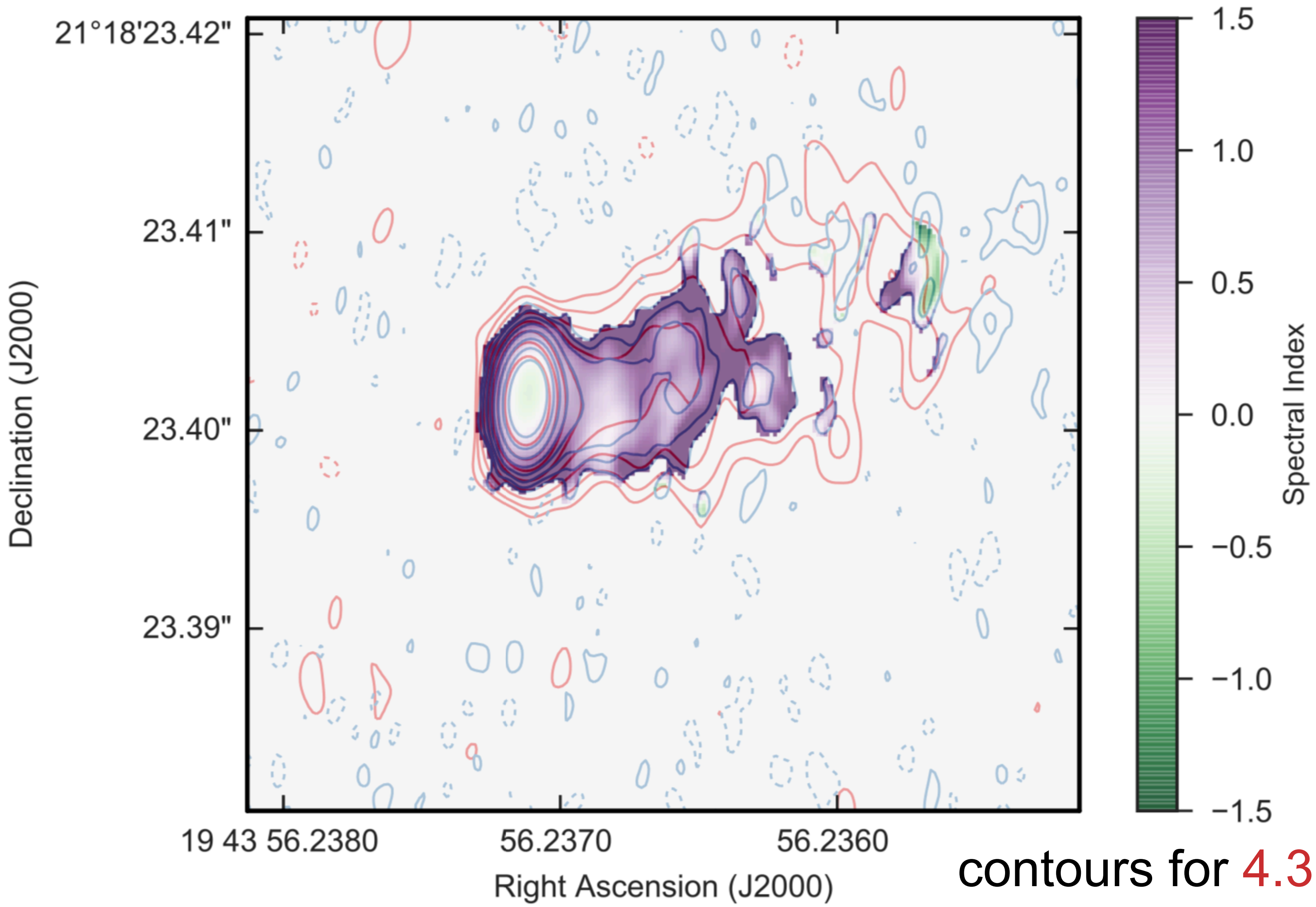
Extragalactic Sources: Blazars

HESS J1943+213 – Shining Through The Galactic Plane



- Extreme synchrotron BL Lac object
- Multi-frequency very-long-baseline array (VLBA) observations of the source confirm the extended, jet-like structure

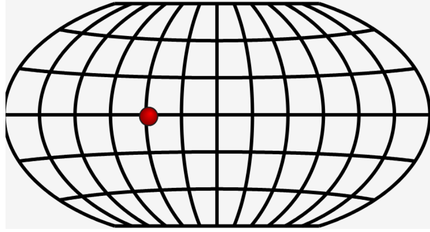




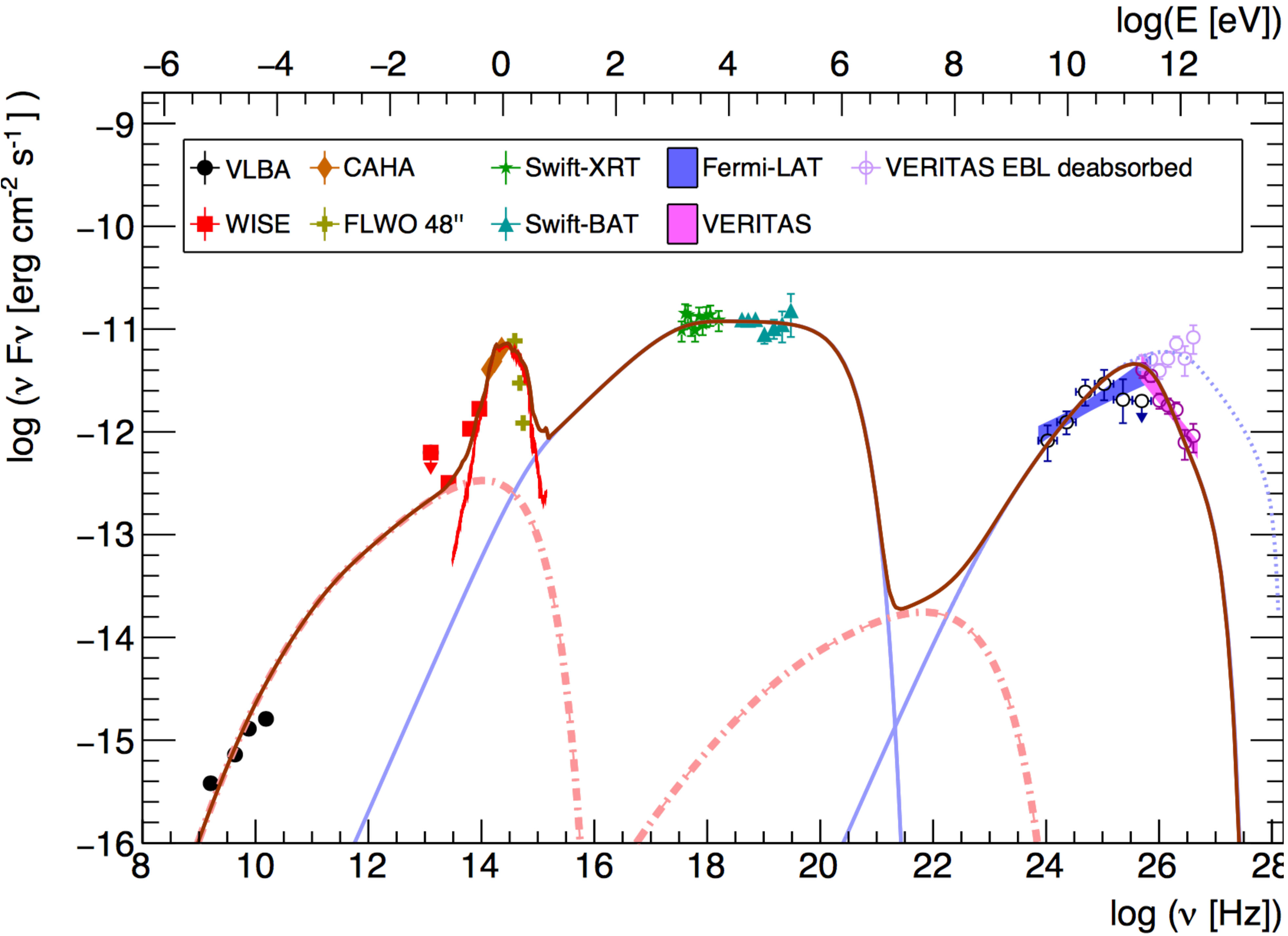
contours for 4.3 GHz and 7.6 GHz

Extragalactic Sources: Blazars

HESS J1943+213



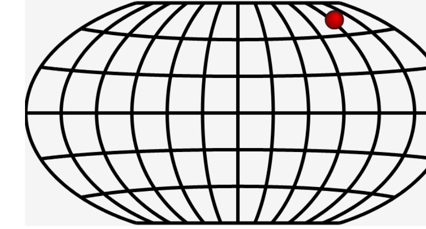
- Data from VERITAS, Fermi-LAT, Swift-XRT, FLWO 48" telescope, and archival infrared and hard X-ray observations →



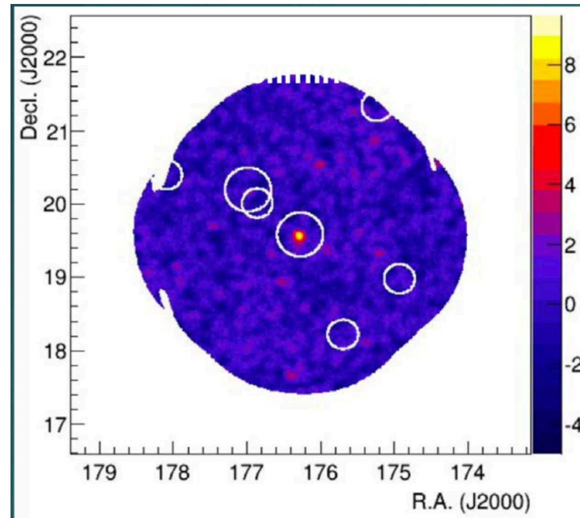
describe spectral energy distribution with a synchrotron -self-Compton model with two zones (described by homogenous, compact blob within a conical wider jet)

1806.04144
accepted by ApJ

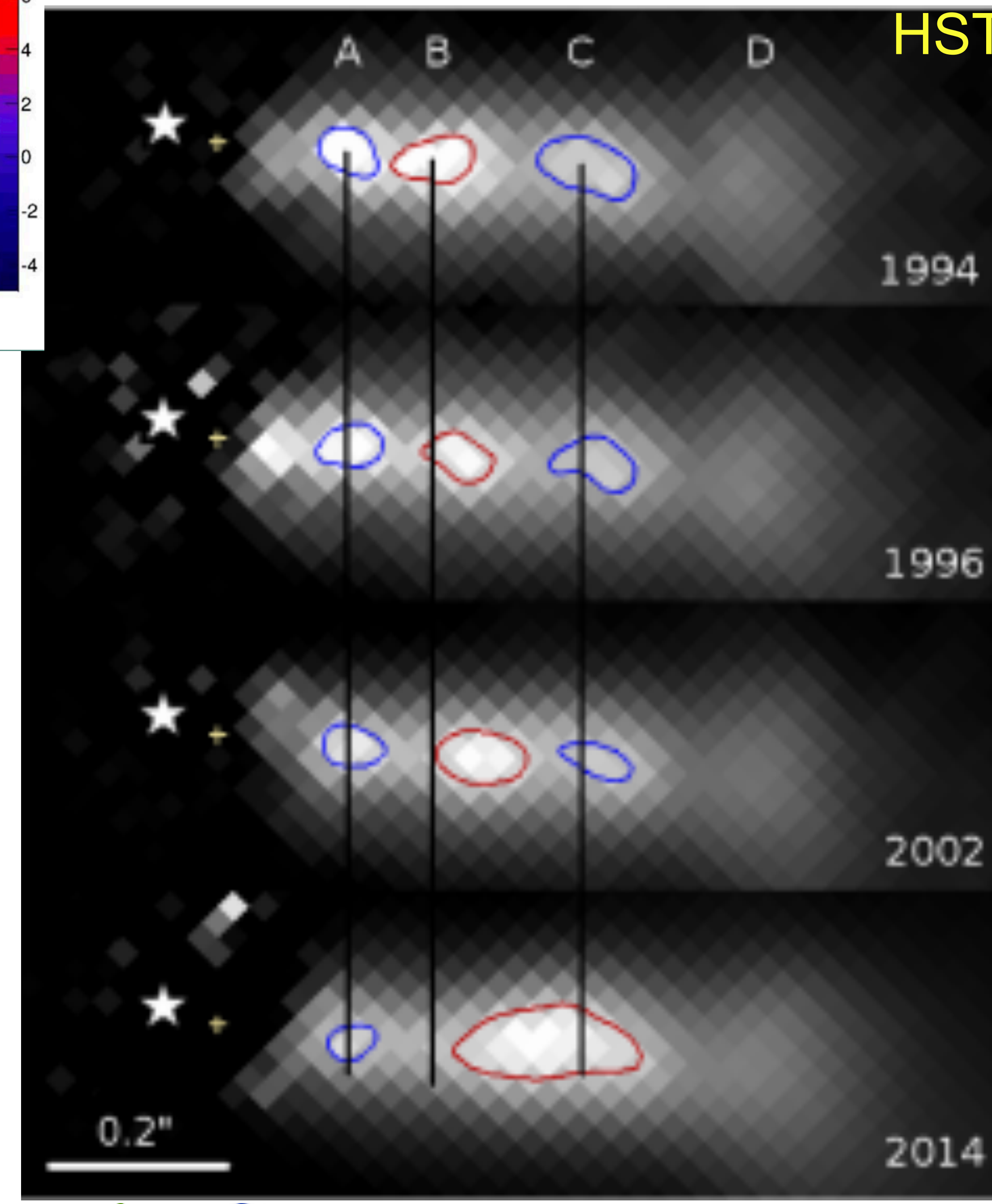
Extragalactic Sources: The Newest Radio Galaxy

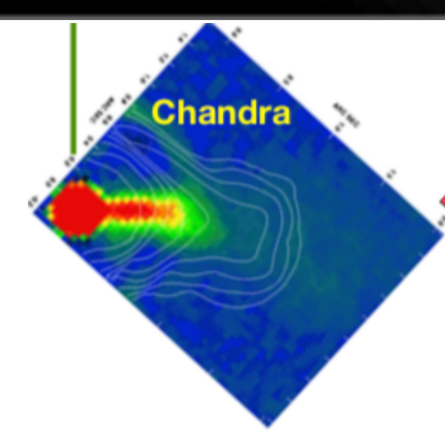


3C 264 (NGC 3862)



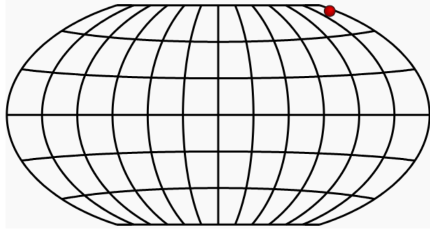
- Detected at a flux of ~1% Crab; flaring ~month-scale variations
- Rapidly evolving knot structure
- Triggered fantastic MWL effort including *Chandra*, *NuSTAR*, *Swift*, HST, RCT, Steward Observatory, VLBA, and VLA
- Radio galaxies are mis-aligned: strong beaming not necessarily a requirement for VHE detection?



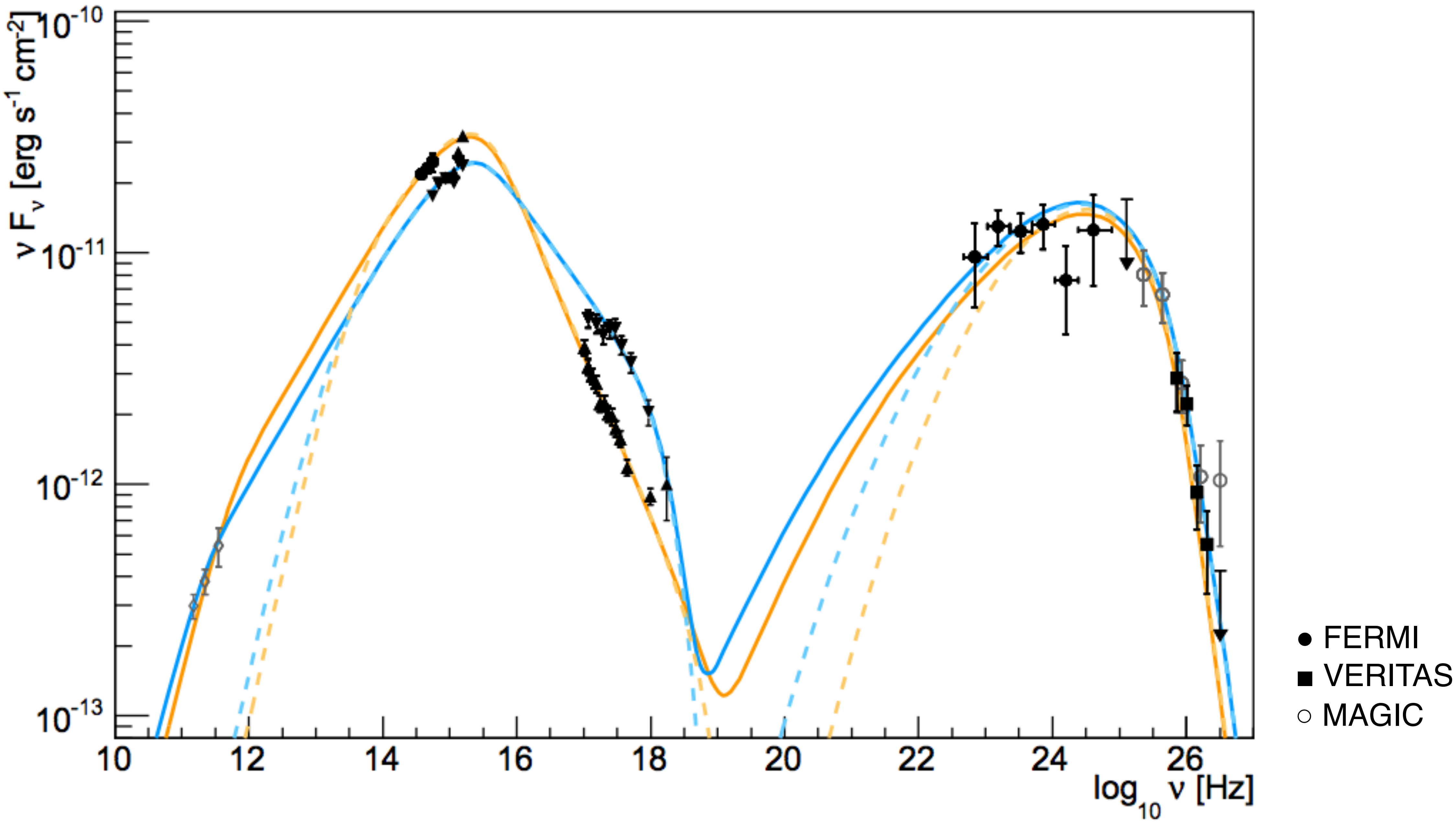


Extraglactic Sources: Long-Term Observations

1ES 1215+303 (BL Lac type)



- Discovered by MAGIC in VHE band in 2011
- VERITAS data set started 2008, high significance early 2011, huge flare 2014 → analyzing ten years of data



Extragalactic Sources: Is there a Single Answer?

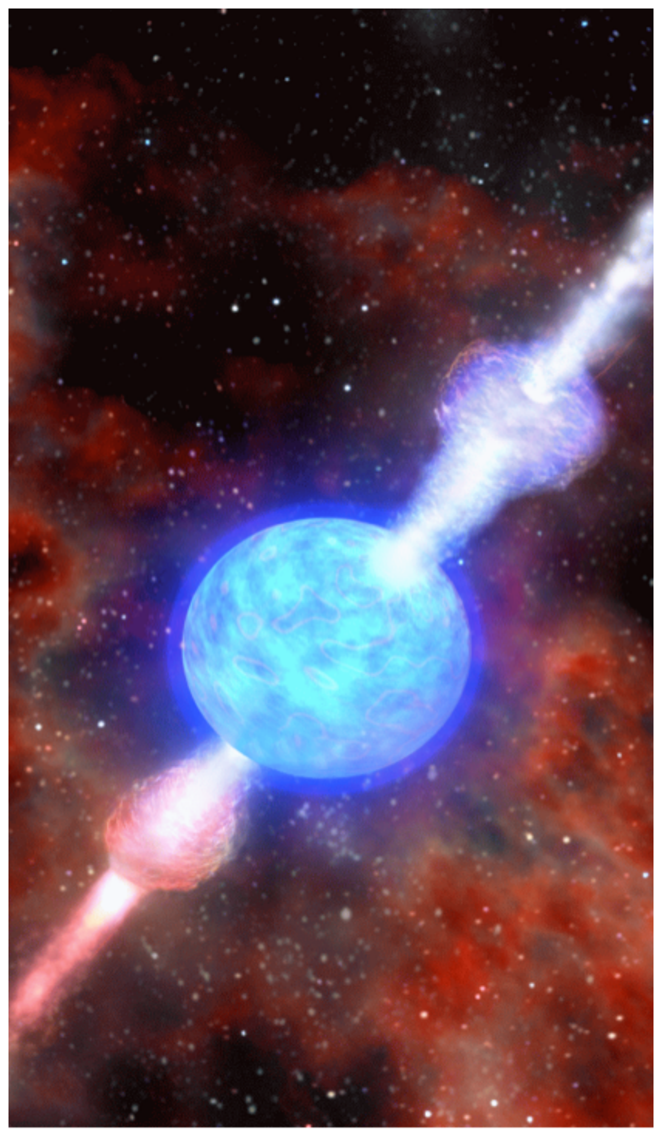
- What types of galaxies produce gamma-ray emission?
  - New source discoveries are still being made...
- Where does the gamma-ray emission originate within radio galaxies and blazars?
  - Multiple regions undergoing different processes?
- How is the gamma-ray emission produced within these sources?
  - Single-zone SSC emission not sufficient/sub-class specific?
- What drives the variability of the gamma-ray emission from these sources?
  - Source specific?
- How is the gamma-ray emission related to the lower-energy emission emerging from these sources?
  - Gamma-ray/X-ray correlations not simple – open questions

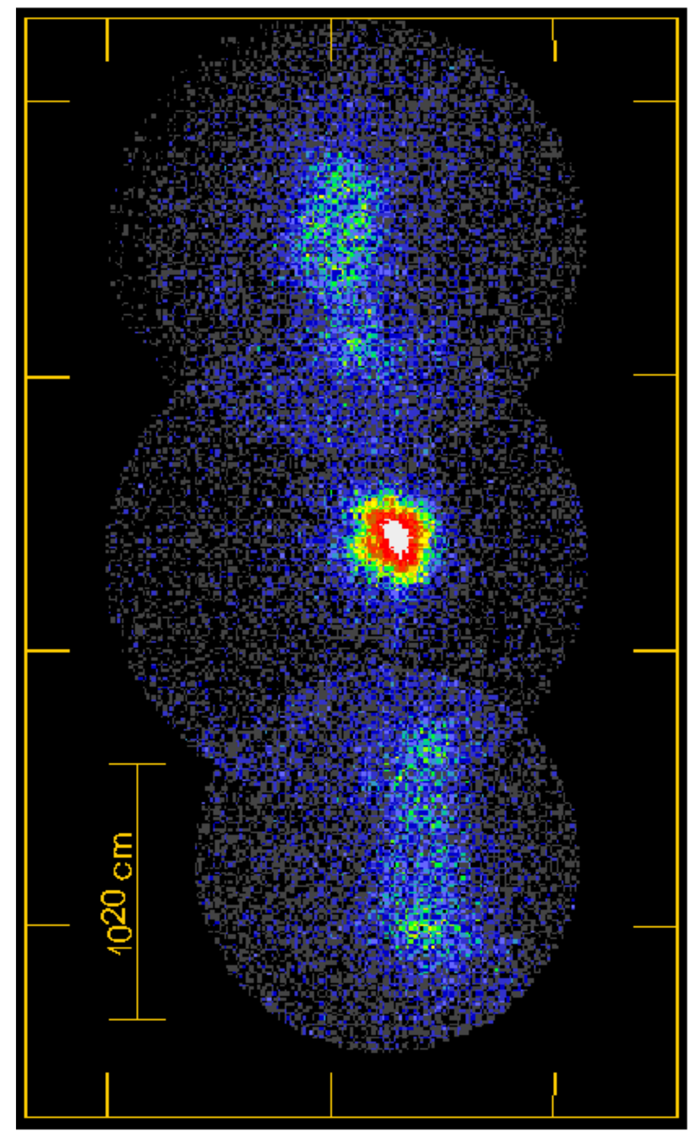
A Furniss

Jets on all Scales

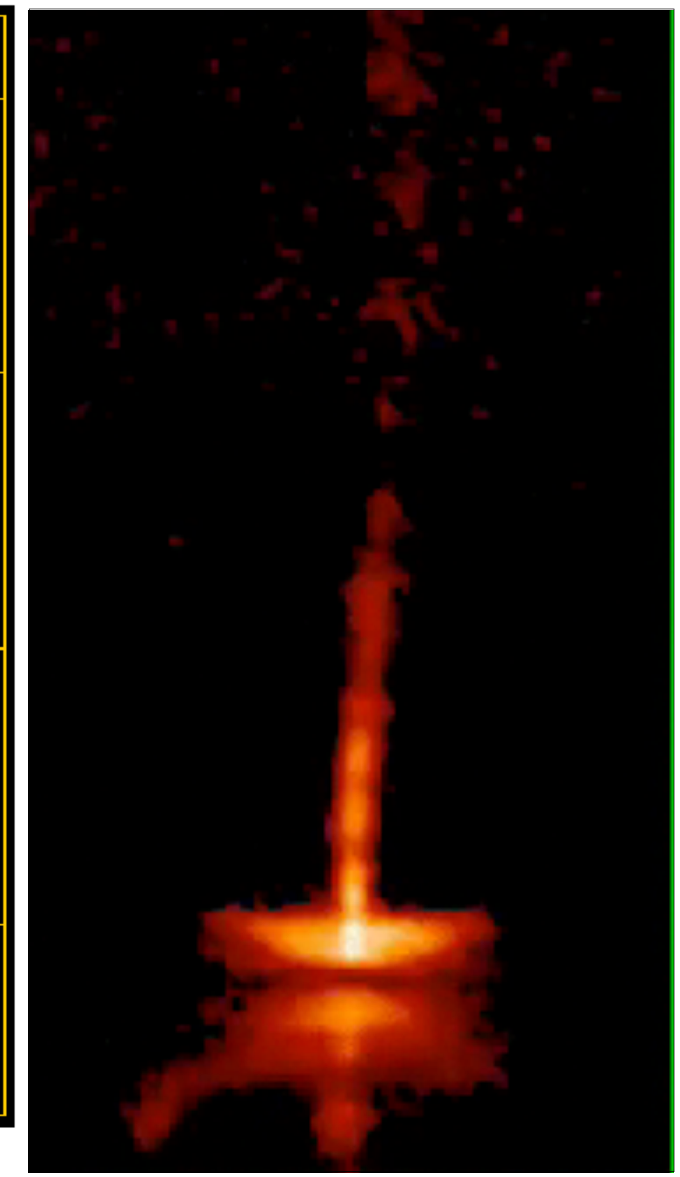
Active Galactic Nuclei	Gamma Ray Bursts (hypernovae)	Microquasars (X-ray binaries)	Young Stars (Herbig-Haro)

M87
(optical)





SS 433
(2-10 keV)



HH30:
1995 - 2000

G Maier

Jets on all Scales

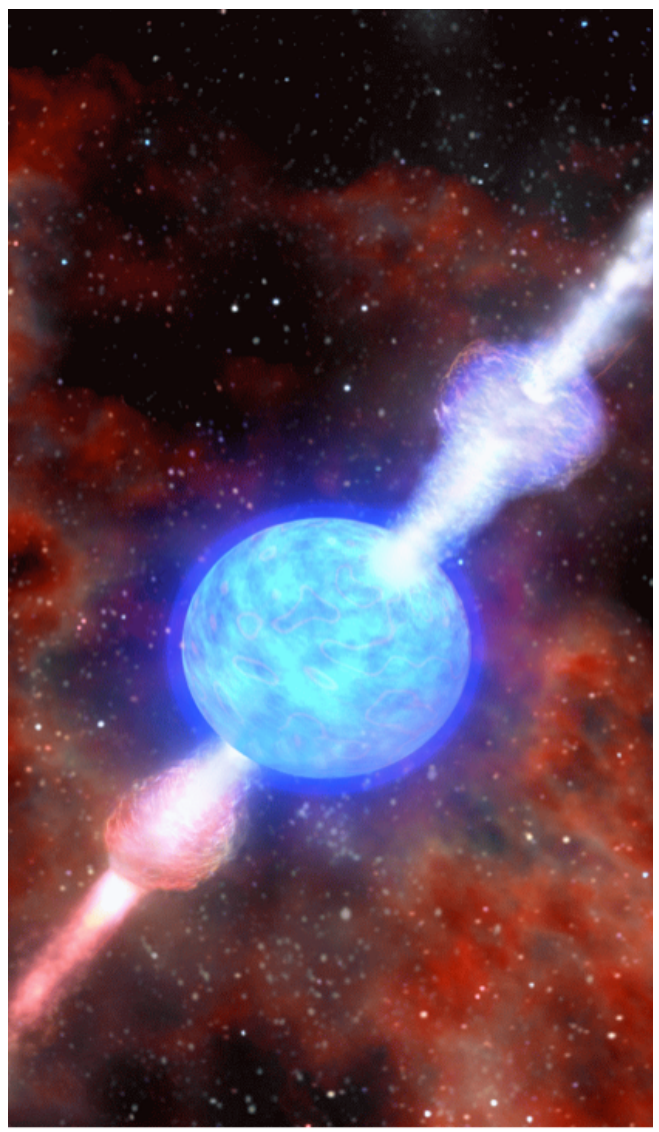
Active Galactic Nuclei

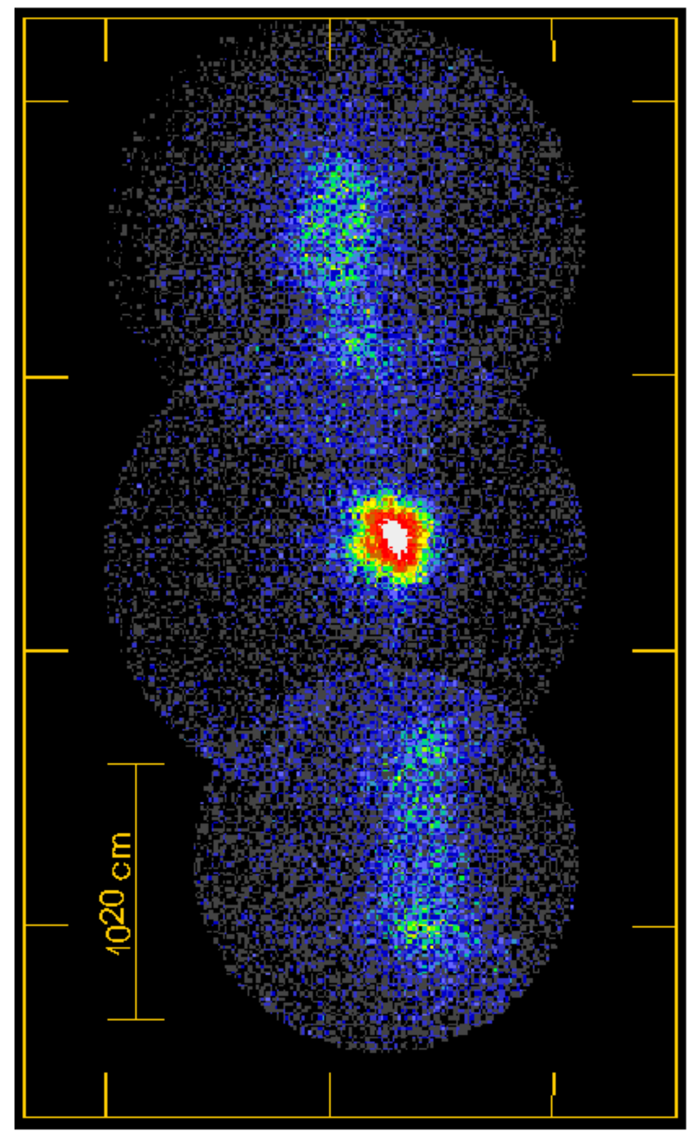
Gamma Ray Bursts (hypernovae)

Microquasars (X-ray binaries)

Young Stars (Herbig-Haro)

M87 (optical)





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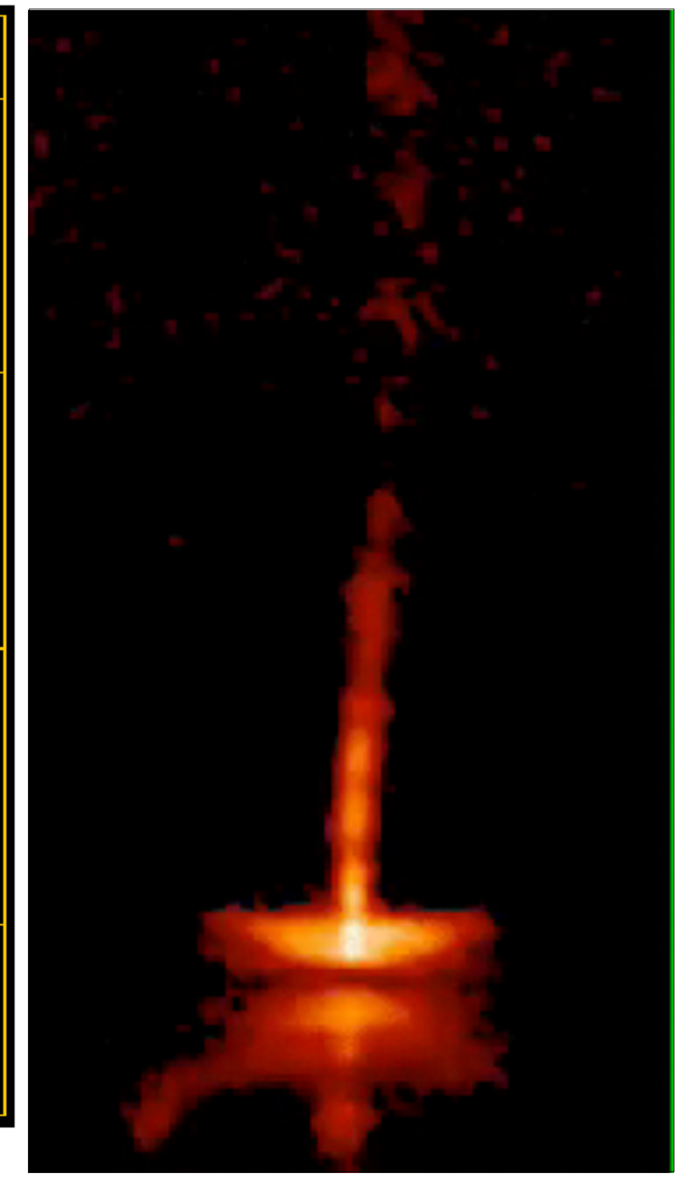

HH30: 1995 - 2000

G Maier

VERITAS Program

- Galactic Particle Accelerators
  - Supernova remnants, pulsar & pulsar wind nebula, binaries, diffuse emission
  - Galactic transients
  - Origin of Cosmic Rays
- Extragalactic Particle Accelerators
  - Active galactic nuclei - blazars and radio galaxies - black holes & jet physics
  - Gamma-ray emission from starburst galaxies
  - Origin of Ultra-high energy Cosmic rays
  - Extragalactic Magnetic Field and Pair halos
  - Gamma-ray bursts
- Astroparticle Physics
  - Dark-matter searches (WIMP, Axions)
  - History of star formation - cosmology - measurement of the EBL density
  - Primordial Black Holes
  - Heavy Nuclei Cosmic Rays - direct Cherenkov light measurement
- Search search for optical transients

Summary

- VERITAS has been operated successfully for over ten years and continues to observe the Northern sky
  - Proposing to run for three more years, until 2022.
- The scientific goals of VERITAS include understanding the acceleration, interactions, and propagation of TeV particles
  - by observing very-high-energy gamma rays from extreme environments in both Galactic and extragalactic sources
  - A large variety of different particle accelerators are observed today and new ones are continuously discovered
- Deep studies & sophisticated modeling: long-term observing plan
- Synergies with Fermi LAT and HAWC and other observatories
- Increasing collaboration with H.E.S.S. and MAGIC