GROUND BASED GAMMA RAY ASTRONOMY WITH IMAGING AIR CHERENKOV TELESCOPES

Sabrina Casanova
IFJ PAN Krakow & MPIK Heidelberg

7th Workshop on Air Shower Detection at High Altitude

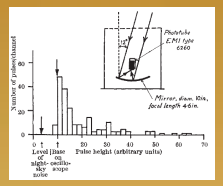
1st Dec 2016

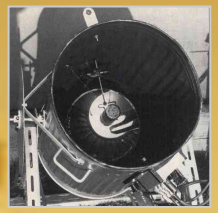
Overview

- Brief history of ground based imaging gamma-ray astronomy
- Detection technique and current imaging air Cherenkov telescopes
- Searching for the Galactic particle accelerators
- HESS 2, MAGIC 2, VERITAS upgrade : the low threshold era
- The CTA gamma-ray observatory

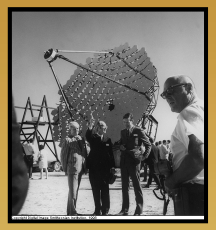
Brief history

First years Whipple HEGRA Phase I Phase 2 CTA

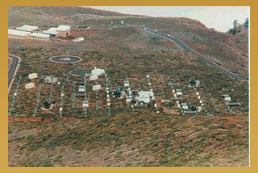




Galbraith and Jelley, 1953

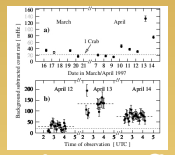


1968

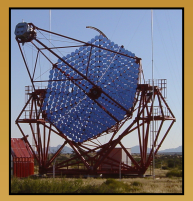


1987

Crab 1989



Mrk 501 flare 1997



2003

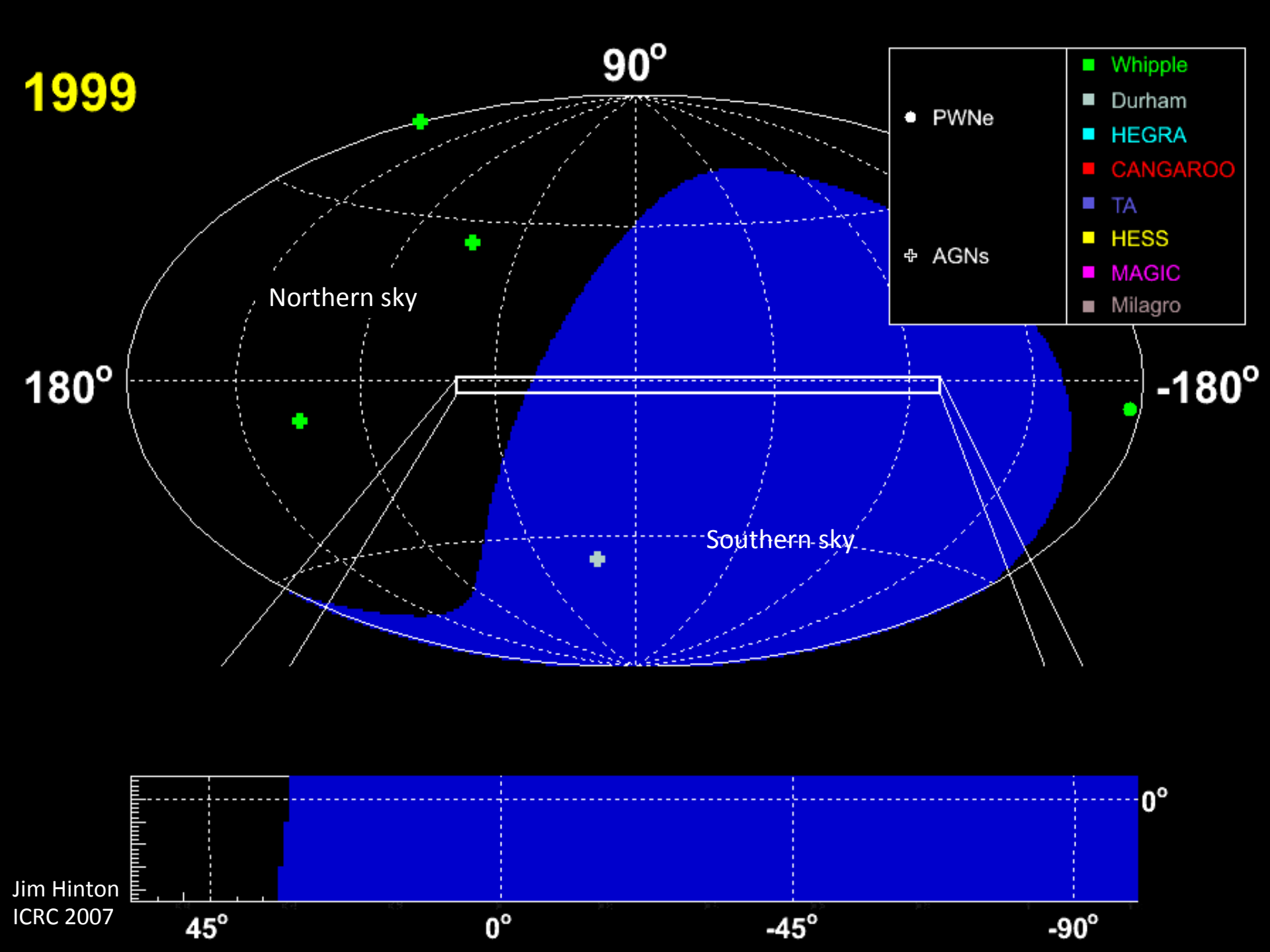
2012
Low energy threshold era

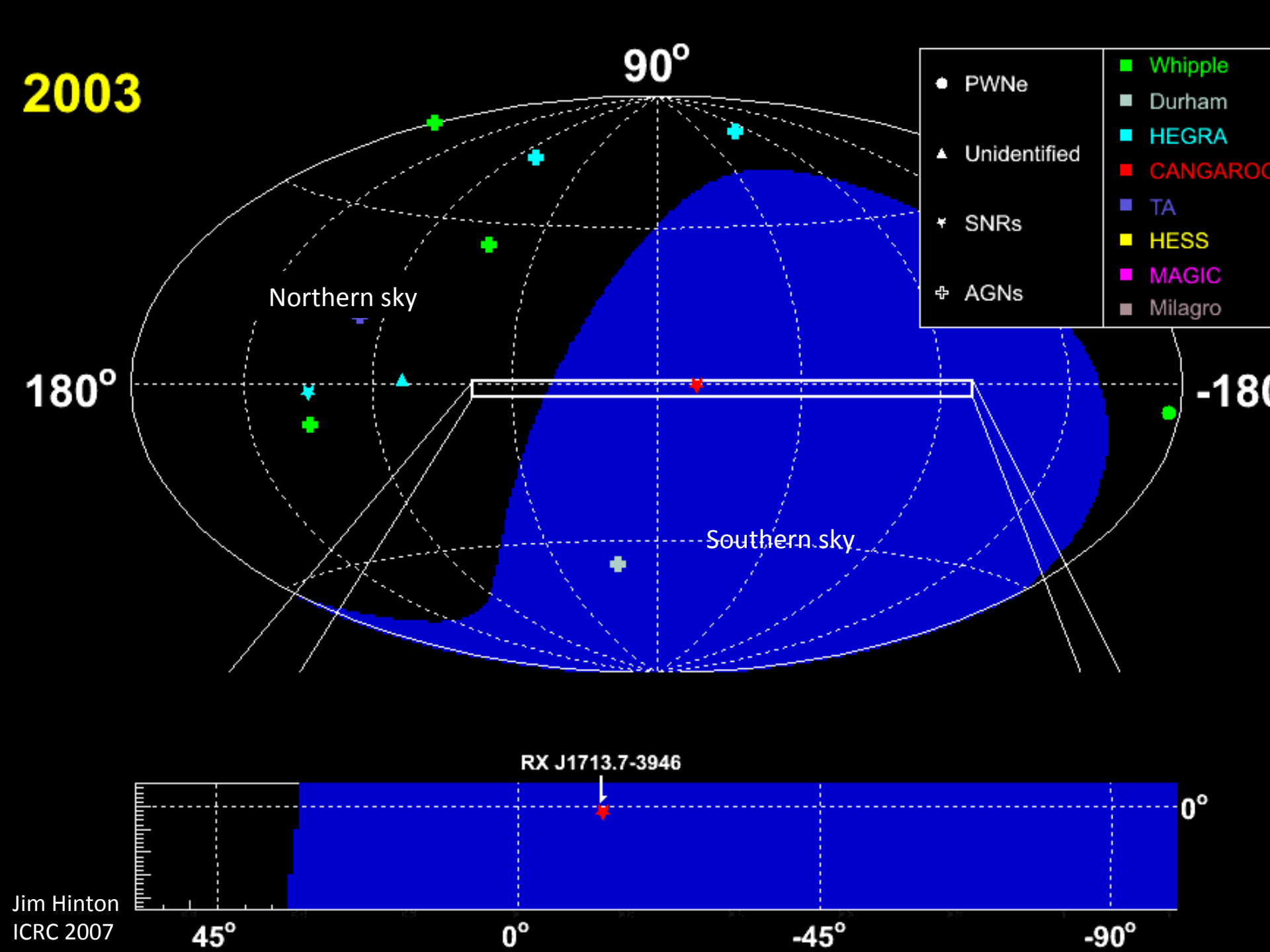
Single source astronomy

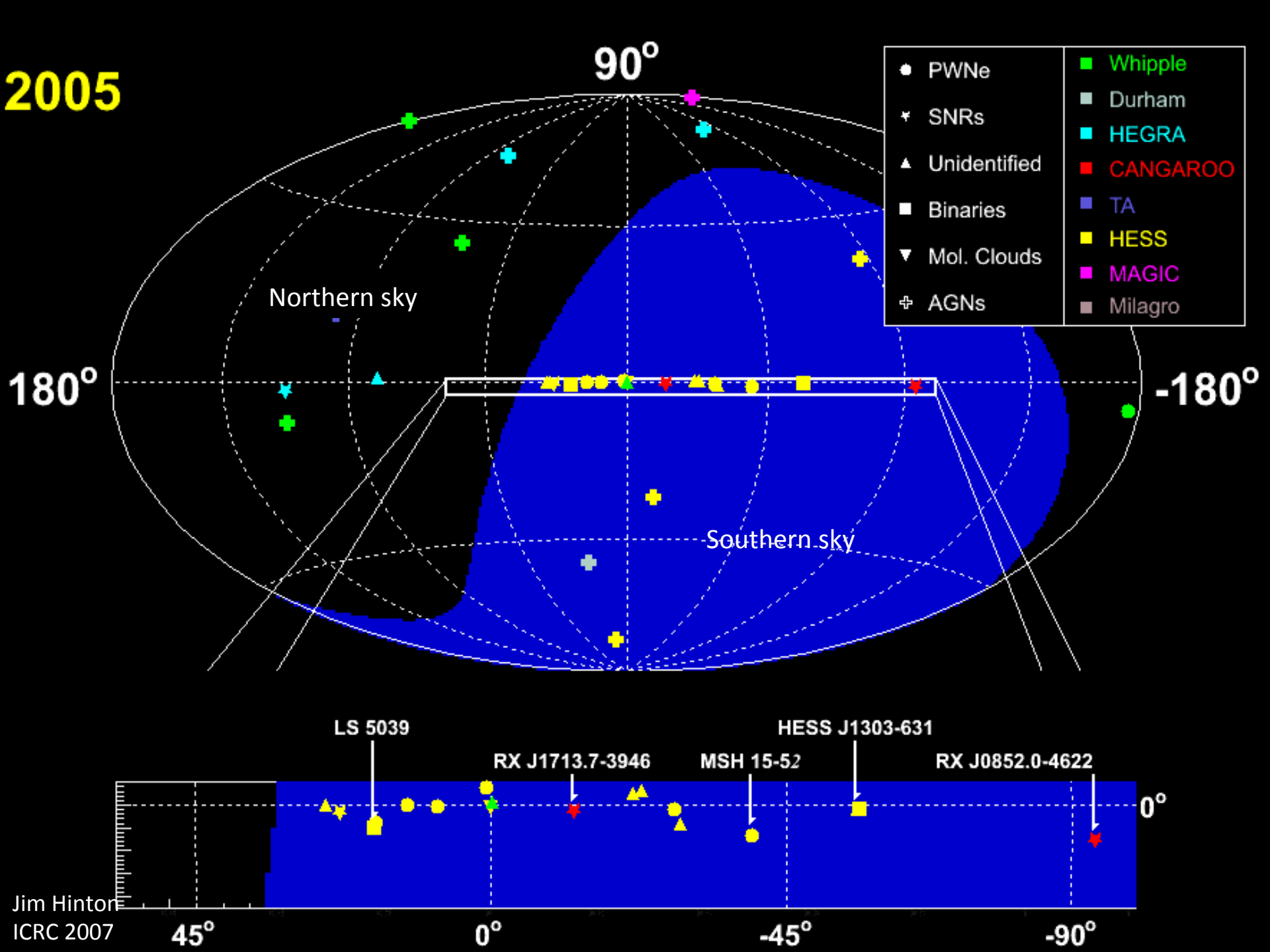
10 sources

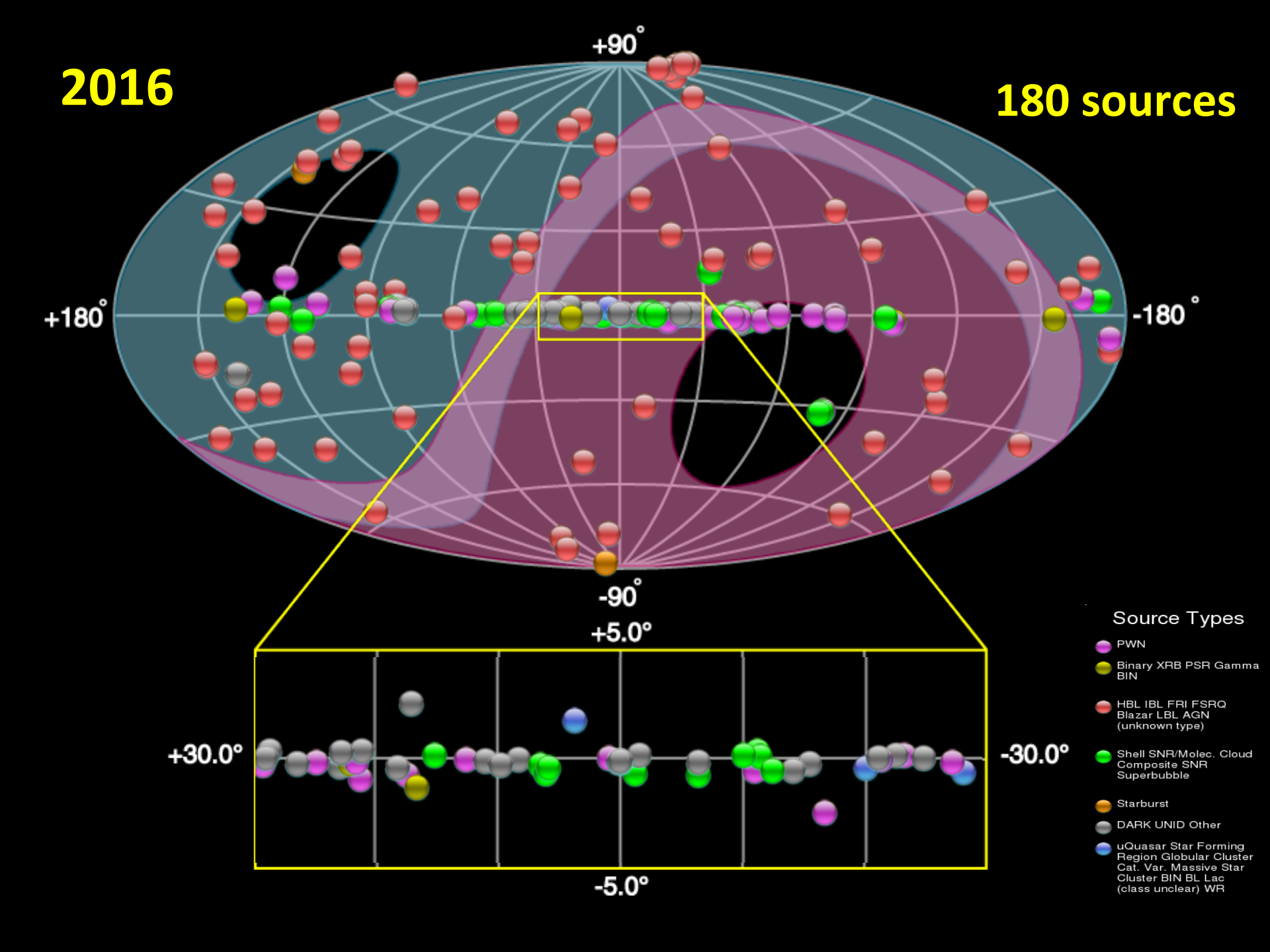
180 sources

50s 60s 70s 80s 90s 2000 2010 2020


1999
90°
180°
-180°
Northern sky
Southern sky
PWNe
AGNs
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
0°
45°
0°
-45°
-90°
Jim Hinton
ICRC 2007


2003
90°
180°
-180
Northern sky
Southern sky
PWNe
Unidentified
SNRs
AGNs
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
RX J1713.7-3946
0°
45°
0°
-45°
-90°
Jim Hinton
ICRC 2007


2005
90°
180°
-180°
Northern sky
Southern sky
PWNe
SNRs
Unidentified
Binaries
Mol. Clouds
AGNs
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
LS 5039
RX J1713.7-3946
MSH 15-52
HESS J1303-631
RX J0852.0-4622
0°
45°
0°
-45°
-90°
Jim Hinton
ICRC 2007


2016
180 sources
+90°
+180°
-180°
-90°
+5.0°
+30.0°
-30.0°
-5.0°
Source Types
PWN
Binary XRB PSR Gamma BIN
HBL IBL FRI FSRQ Blazar LBL AGN (unknown type)
Shell SNR/Molec. Cloud Composite SNR Superbubble
Starburst
DARK UNID Other
uQuasar Star Forming Region Globular Cluster Cat. Var. Massive Star Cluster BIN BL Lac (class unclear) WR

Motivations of the success of IACTs

1 Cherenkov telescopes

Good cosmic ray detectors

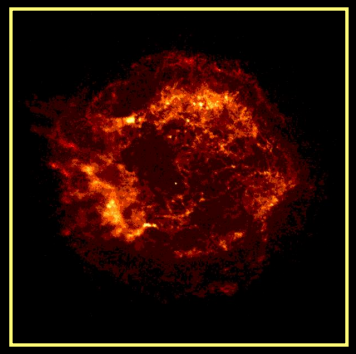
2 Imaging

Good gamma-ray detectors!

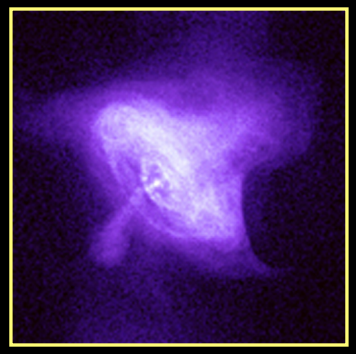
3 Stereoscopy

IACTs are great gamma-ray telescopes !

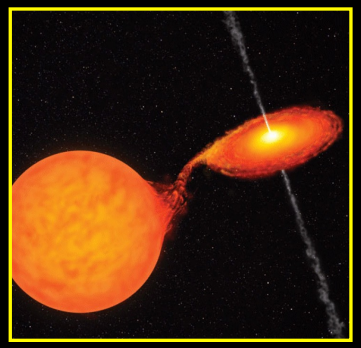
A big help from nature: many extreme accelerators



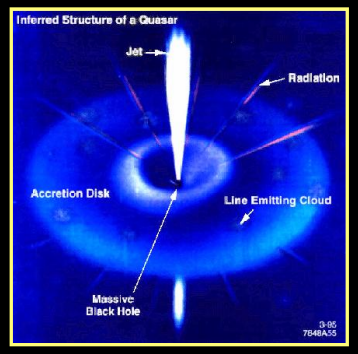
SNRs



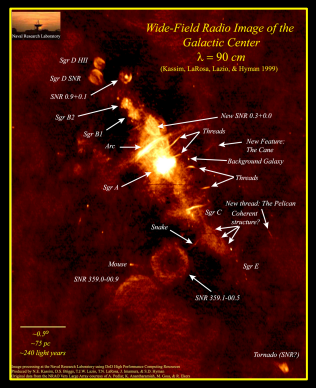
Pulsars and PWN



Micro quasars X-ray binaries

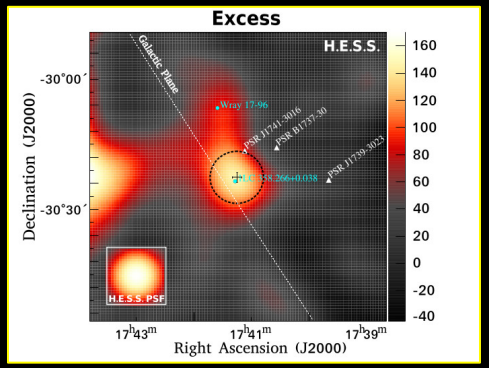


AGNs

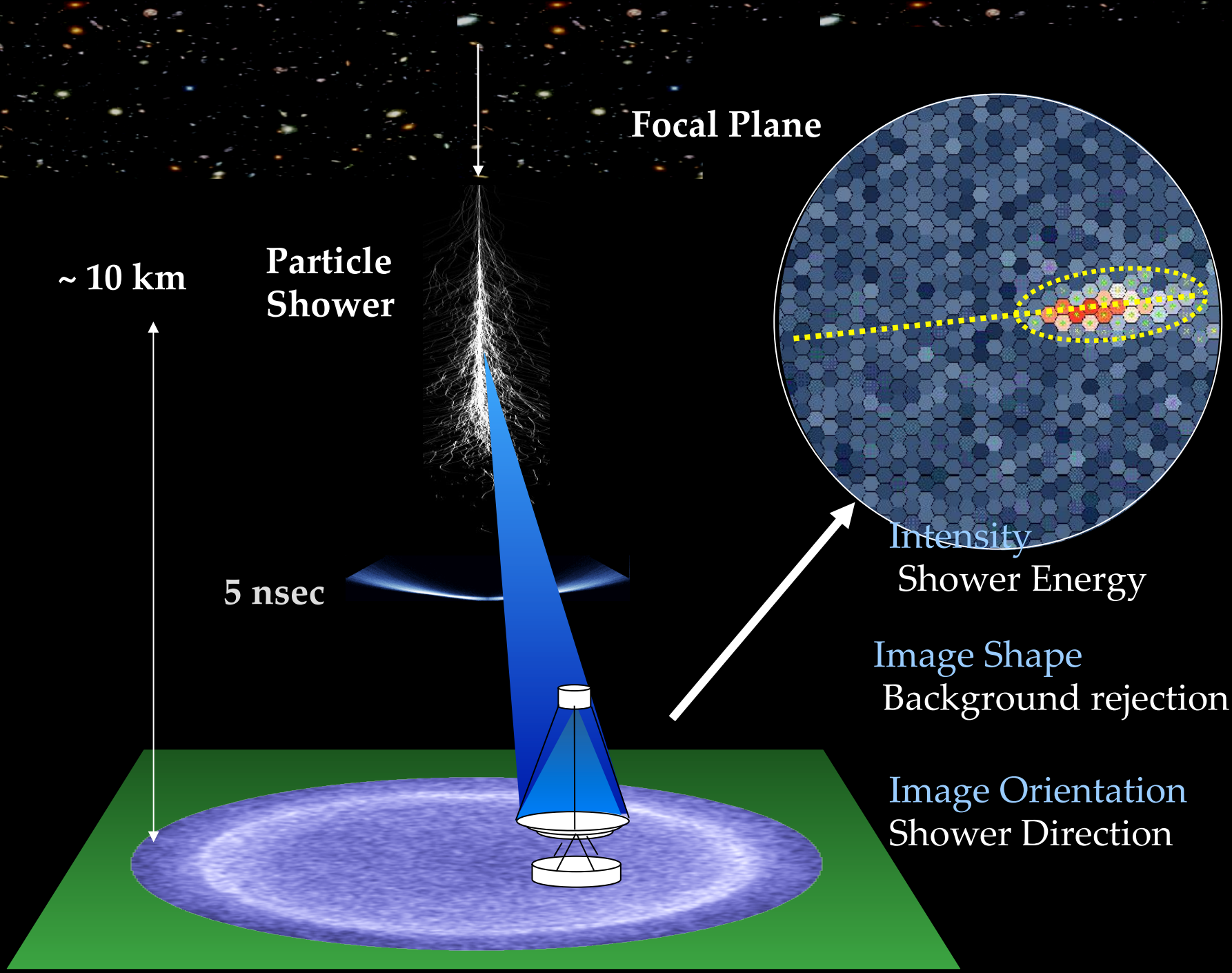


GC

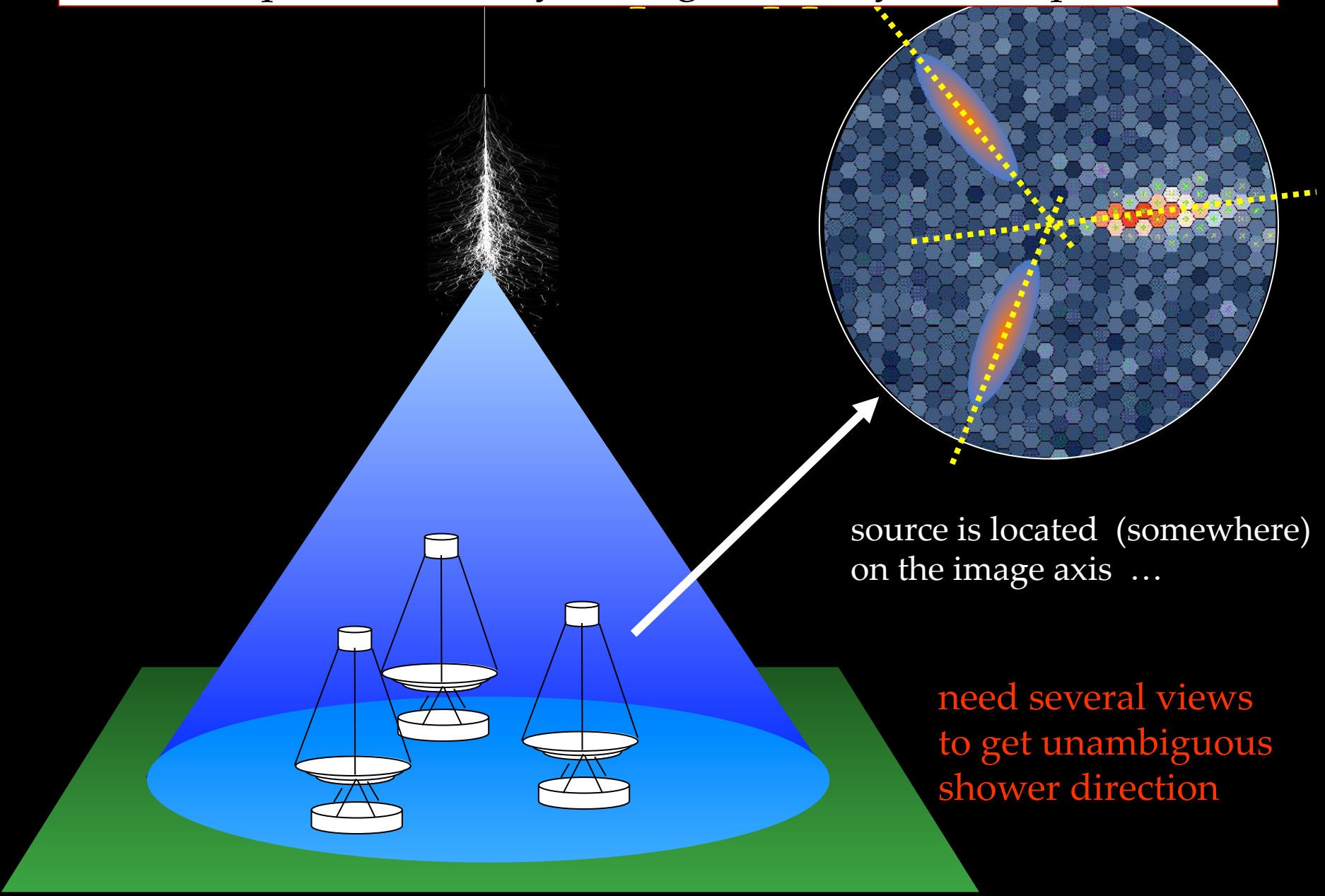
Stellar clusters



Dark sources


Focal Plane
~ 10 km
Particle Shower
5 nsec
Intensity
Shower Energy
Image Shape
Background rejection
Image Orientation
Shower Direction

Stereoscopic IACT arrays are great γ-ray-telescopes !



source is located (somewhere) on the image axis …

need several views to get unambiguous shower direction

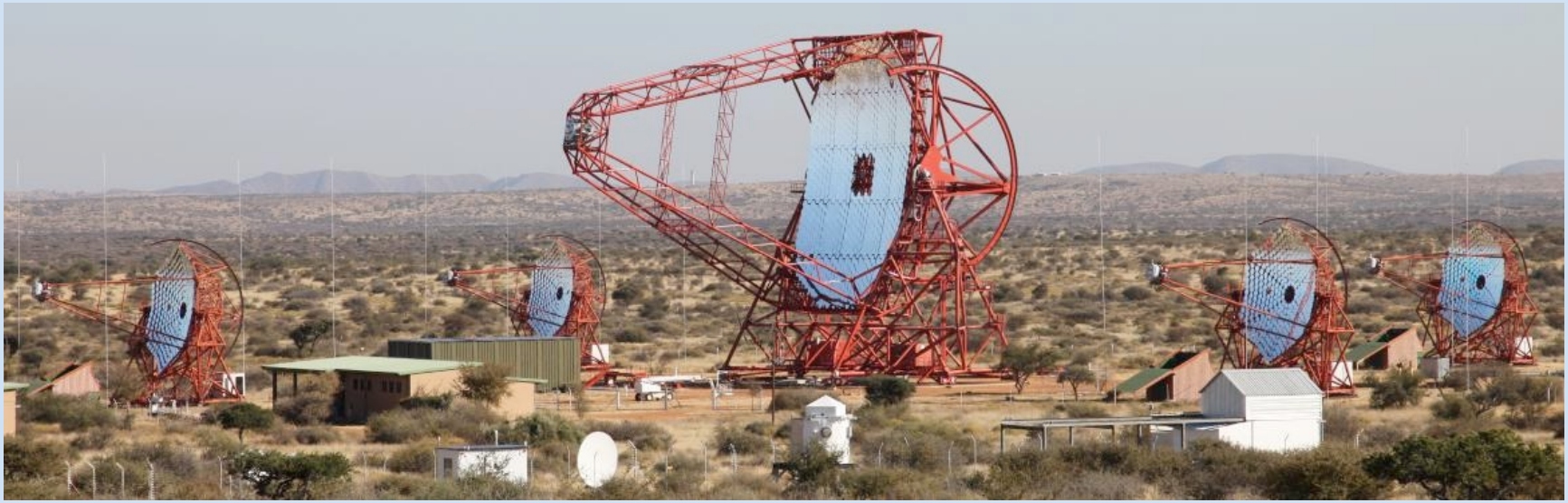
VERITAS

- Array of four atmospheric Cherenkov telescopes based on Whipple
- 350 individual mirrors on each telescope reflector
- Each telescope aperture: 12m
- 499 pixel camera on each telescope
- Field of view of 3.5 degrees
- Energy range of 85 GeV to 30 TeV

MAGIC

- 17m diameter dish
- Energy range: 30 GeV-30 TeV
- Angular resolution: <0.08°;
- Energy resolution: ~15-25%
- Pointed mode observations (Field of View: ~3.5°)
- stereo-mode since 2009
- Designed optimized for: low-energy, fast repositioning

HESS



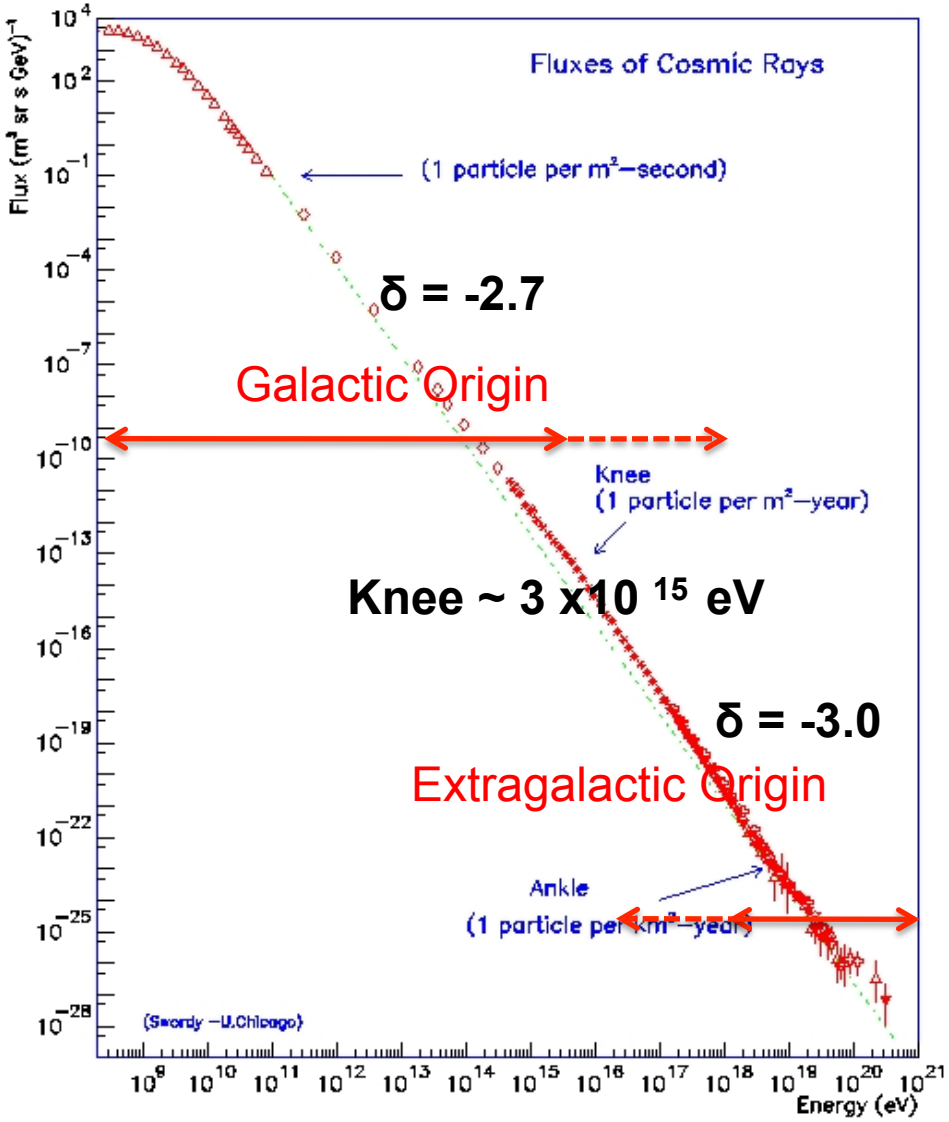
- H.E.S.S. phase 1:
  - 4 telescopes: Ø 12 m,107 m^2
  - Stereoscopic reconstruction
  - 960 PMTs/camera, field of view: 5°
  - Source position : ~ 10”
- H.E.S.S. phase 2:
  - addition of a 5th telescope, Ø 28 m, 600 m^2
  - 2048 PMTs, field of view : 3.5°
  - Energy threshold (zenith) ~ 30 GeV

Observations : ~1000 h/year

Searching for the Galactic accelerators

- Almost featureless spectrum
- CRs up to the knee are believed to have a Galactic origin
- Galactic accelerators have to inject particles up to at least to the knee at PeV = 10^{15} energies

J. Cronin, T. Gaisser, S. Swordy, Sci. Amer. 276 (1997) 44.



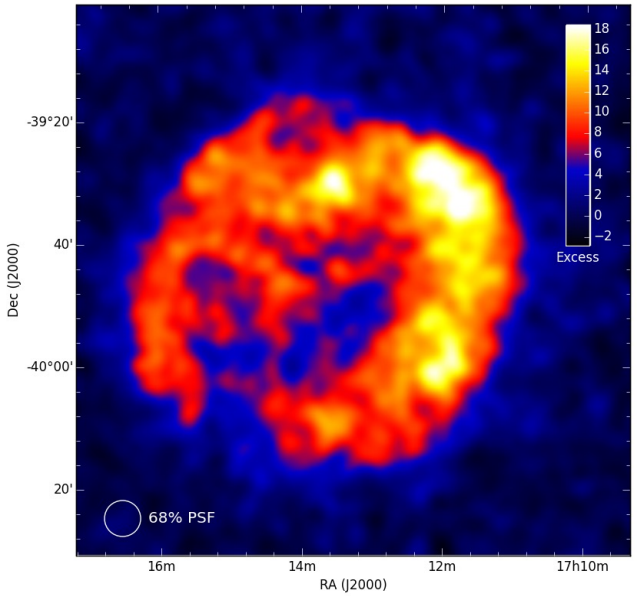
The first suspect: SNR RX J1713-3946

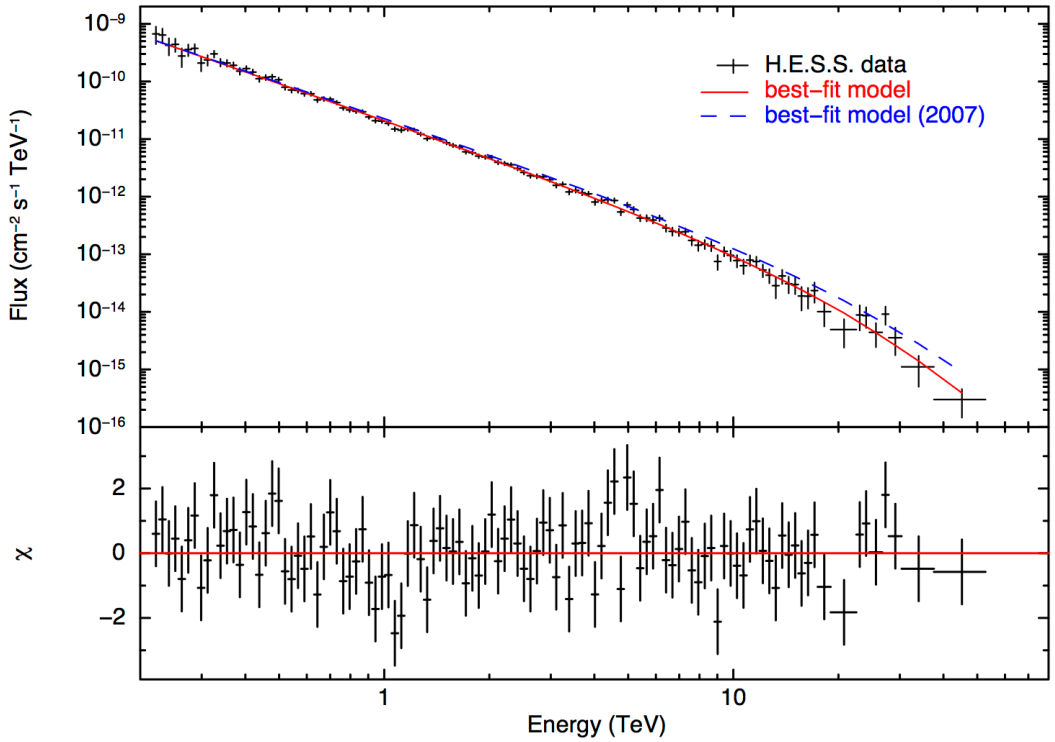
Young (~1.5 kyr) and nearby (~1 kpc) SNR

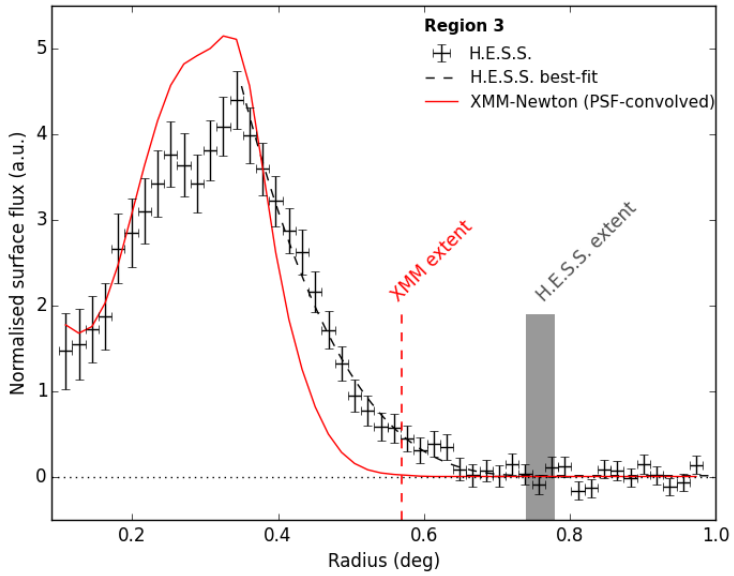
First, and brightest resolved TeV shell

10 years of H.E.S.S. data

- Factor 2 improvement in statistics over last publication (> 27 000 γ's)
- Spectrum up to ~50 TeV: cuts off ~ 15 TeV
- Spatially resolved spectra!

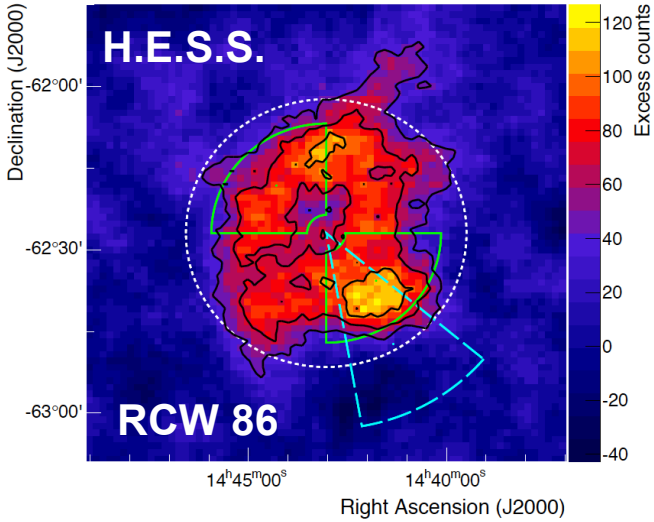


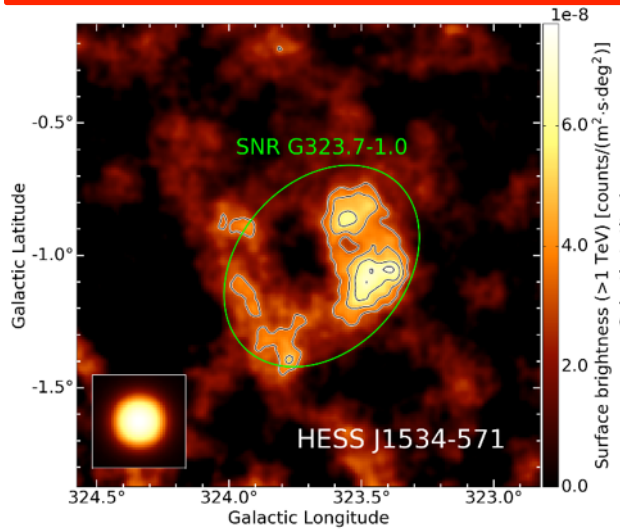


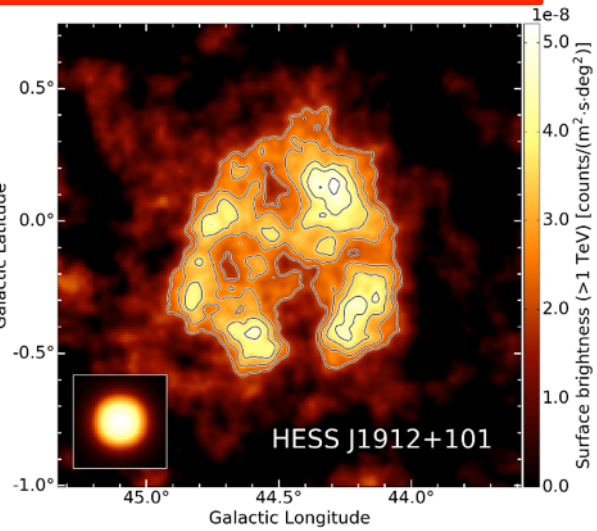


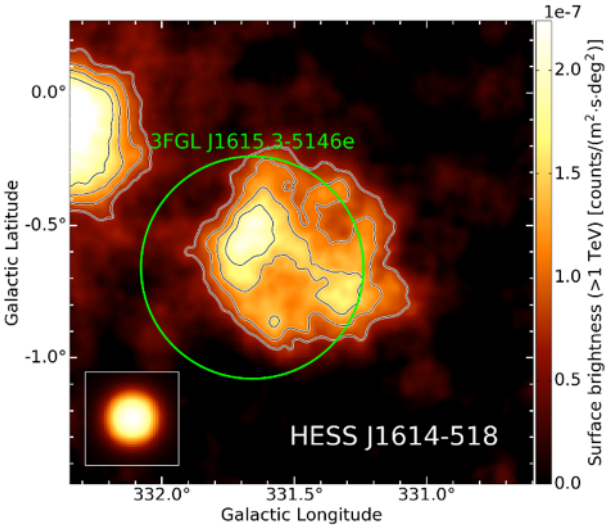
New shell-type SNRs resolved with H.E.S.S.

- RCW 86:
  deep exposure **confirms** TeV shell appearance
  - Good correlation between TeV and hard X-ray (IC vs. synchrotron), likely leptonic dominated, B ~20 μG
  - Maximum energy ~ 3 TeV
- New TeV shells:
  HESS J1534-571, HESS J1614-518, HESS J1912+101
  - Identified in the HESS Galactic Plane Survey (HGPS) data set
  - HESS J1912+101 likely the only TeV SNR w/o counterparts in other wavebands
  - Lack of nonthermal X-ray synchrotron emission (at least for HESS J1534-571): hints at proton emission(?)





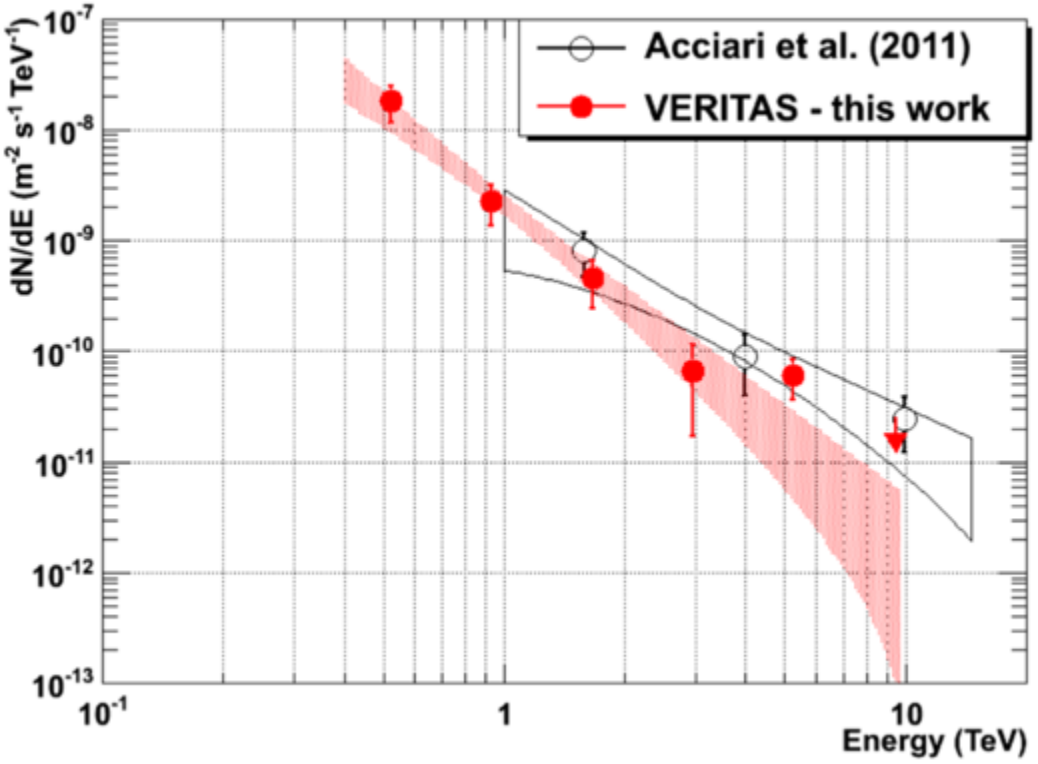




VERITAS Supernova Remnants

Exposures on Tycho, IC 443 and Cas A have all more than doubled since the original publications, and the new data are more sensitive.

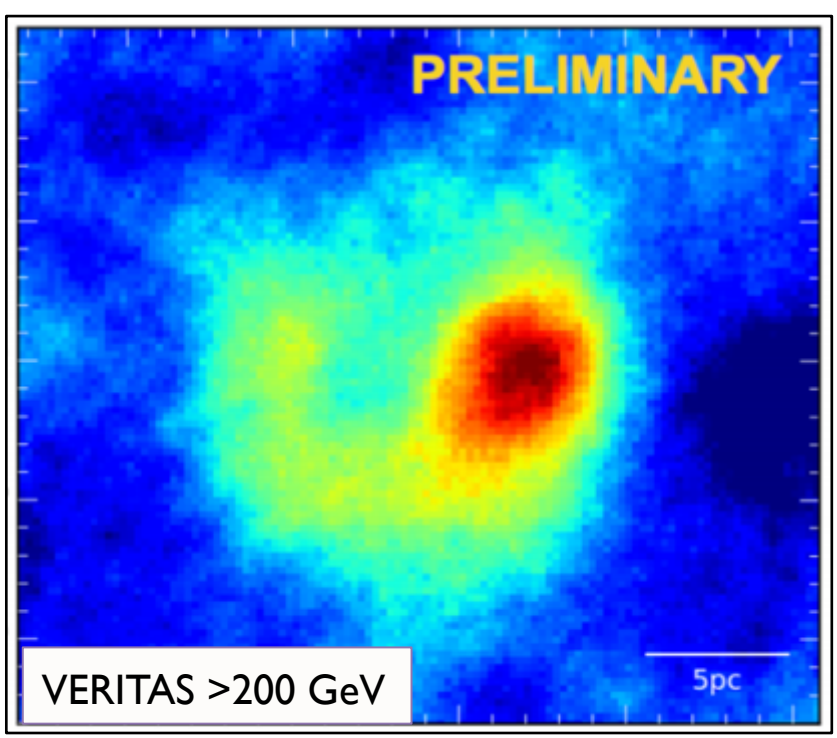
- The **Tycho** spectrum now extends to lower energies.
- Consistent with published results, but…
- Softer power-law fit implies a lower maximum particle energy.

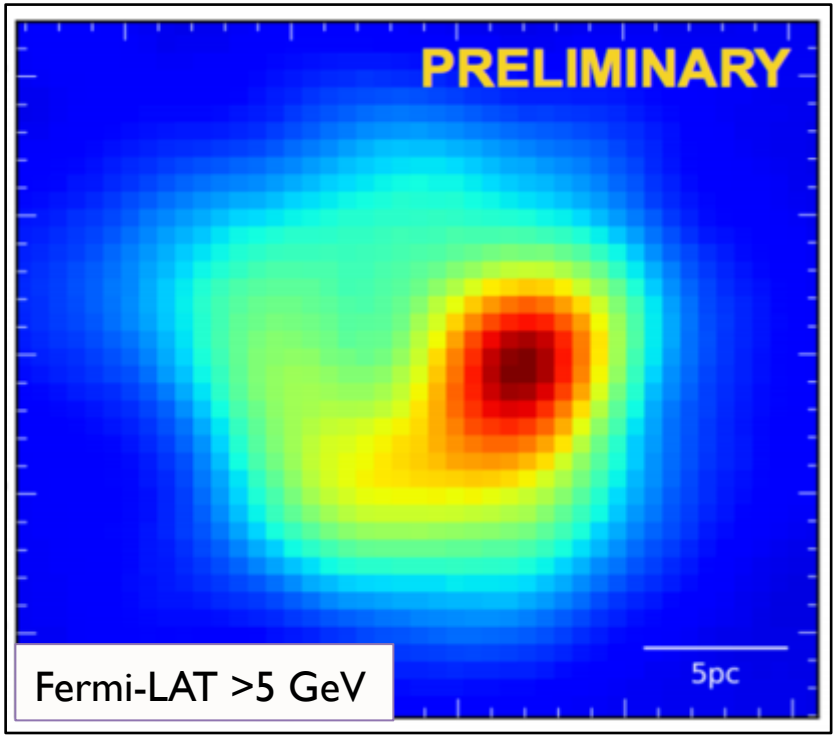


Jamie Holder

VERITAS Supernova Remnants

- **IC 443** is the first shell-type SNR to be resolved by VERITAS.
- Low energy pion-decay bump confirms hadronic acceleration.
- TeV and GeV (Fermi-LAT) fluxes correlate closely across the remnant, despite a wide variety of environmental conditions, and a factor of 30 change in flux.

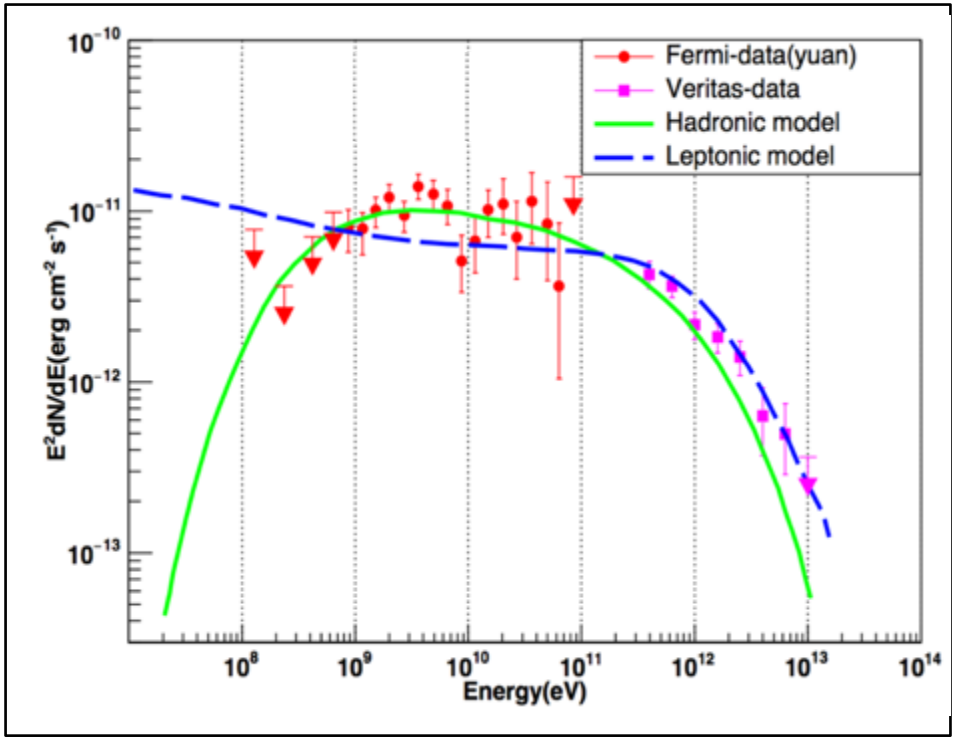


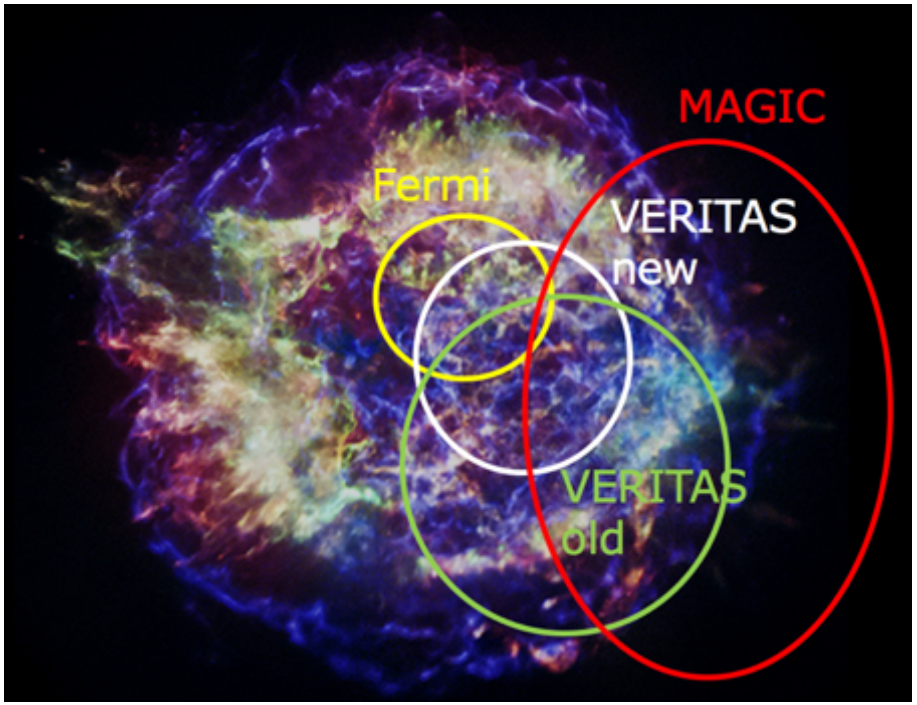


Jamie Holder

VERITAS Supernova Remnants

- **Cas A**, first detected by HEGRA.
- Statistical errors on the VHE spectrum reduced by 60%. Energy range extended.
- Spectral break preferred (3.5 σ).
- Localization limited by systematic errors.

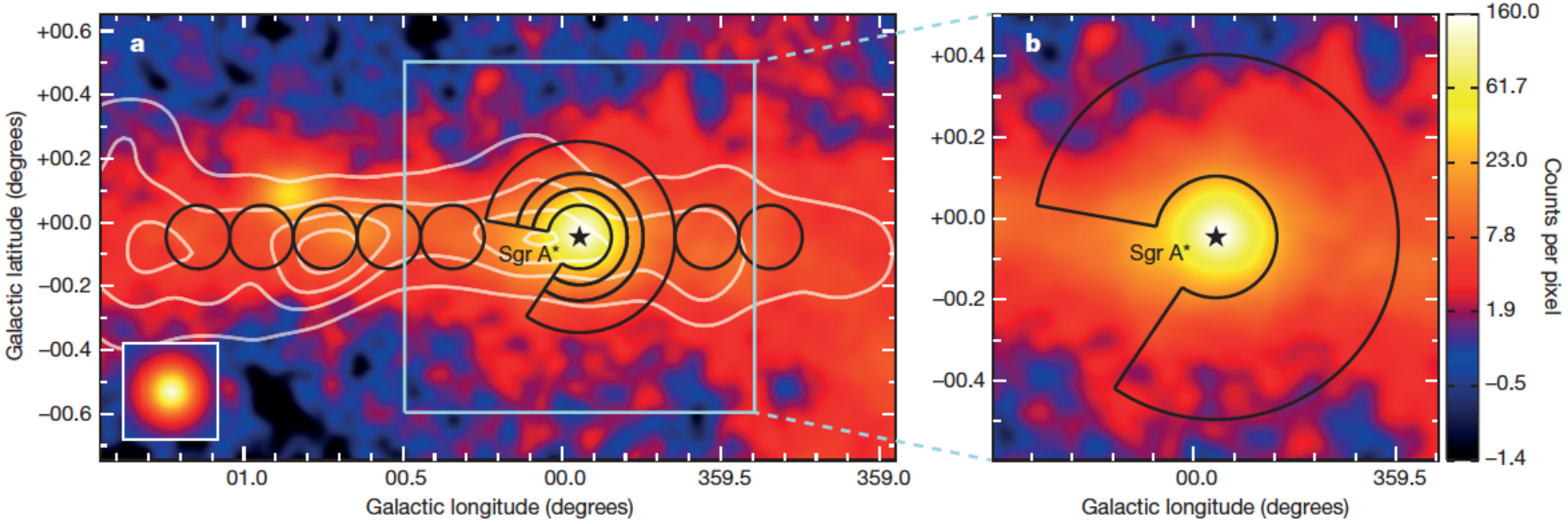




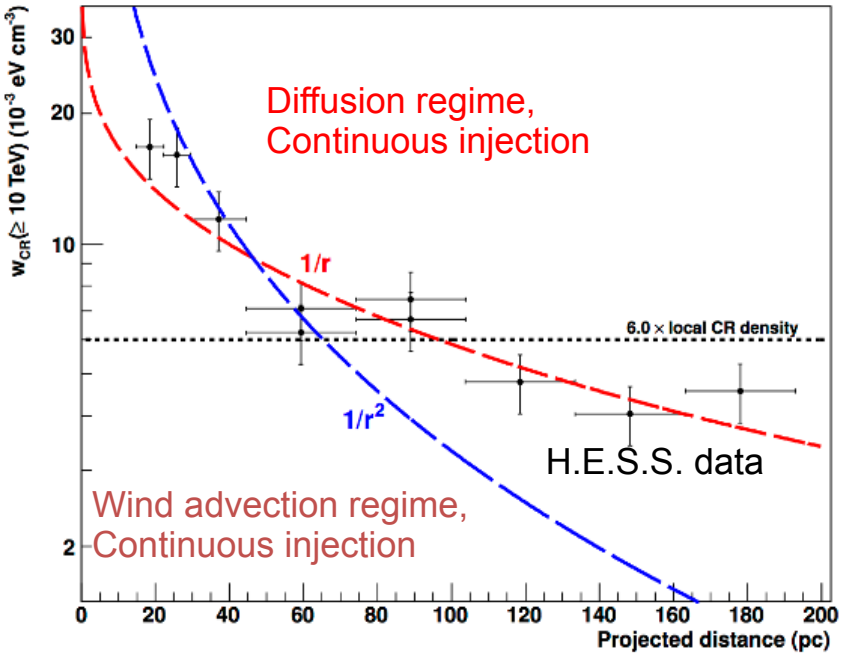
Jamie Holder

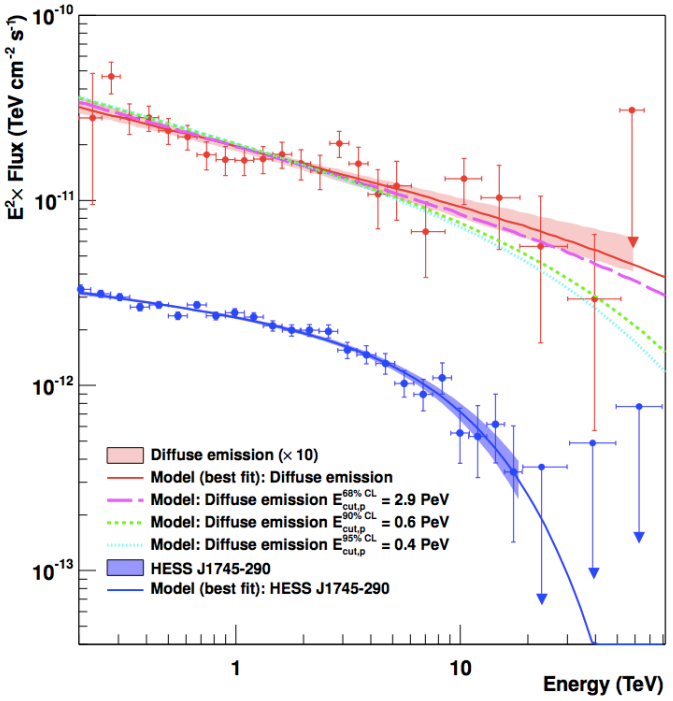
Acceleration up to PeV energies : Galactic Centre with H.E.S.S.

- Point like, central source on top of extended (ridge) emission
- Origin of diffuse emission:
  - Interaction of CR (from central BH) with interstellar medium
  - CR acceleration in CMZ (and in particular star forming regions)
  - …



Galactic Centre with H.E.S.S.: a pevatron

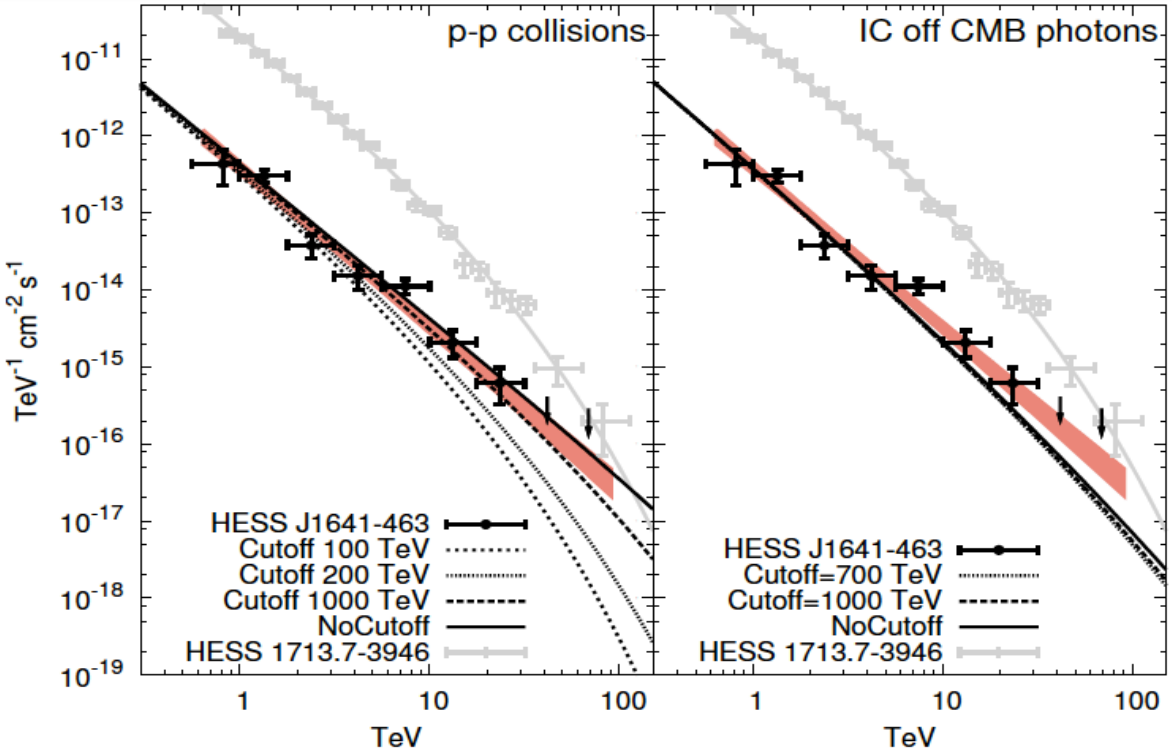


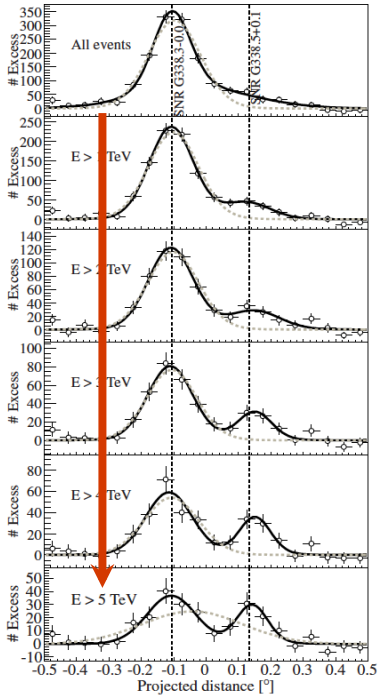


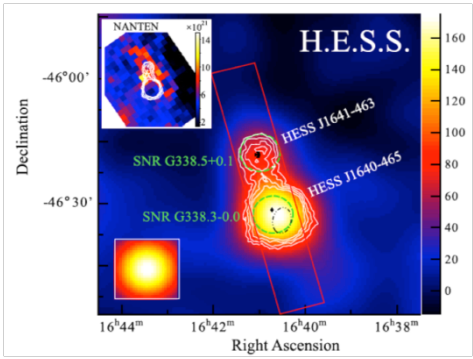
- Central point source: cut-off @ 10 TeV
- Diffuse emission shows no cut-off well > 10 TeV
- Emission profile consistent with propagation of protons accelerated around central black hole and diffusing away (projected radial distribution matches)
- Parent proton population up to 1 PeV (2.9 PeV @ 68% CL)

HESS J1641-463: a potential pevatron

- Very hard spectrum, index 2.07
- Data points until 20 TeV
- Lower limit on cutoff energy: 100 TeV

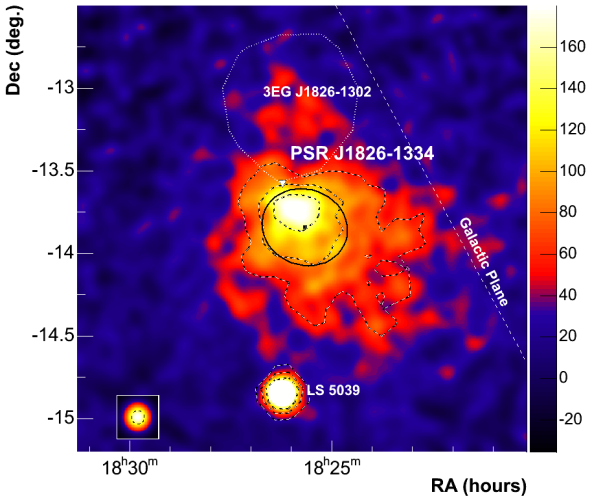


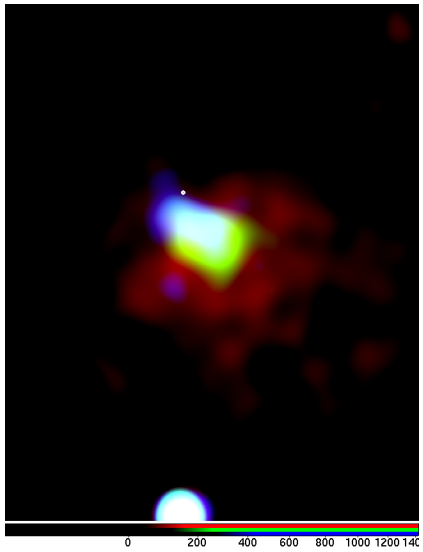




H.E.S.S., 2014
http://iopscience.iop.org/2041-8205/794/1/L1/

A good laboratory to study TeV PWNe: HESS J1825 (PSR J1826-1334)





the γ-ray luminosity is comparable to the TeV luminosity of the Crab Nebula, while the spindown luminosity is two orders of magnitude less ! -> magnetic field should be significantly less than 10mG.

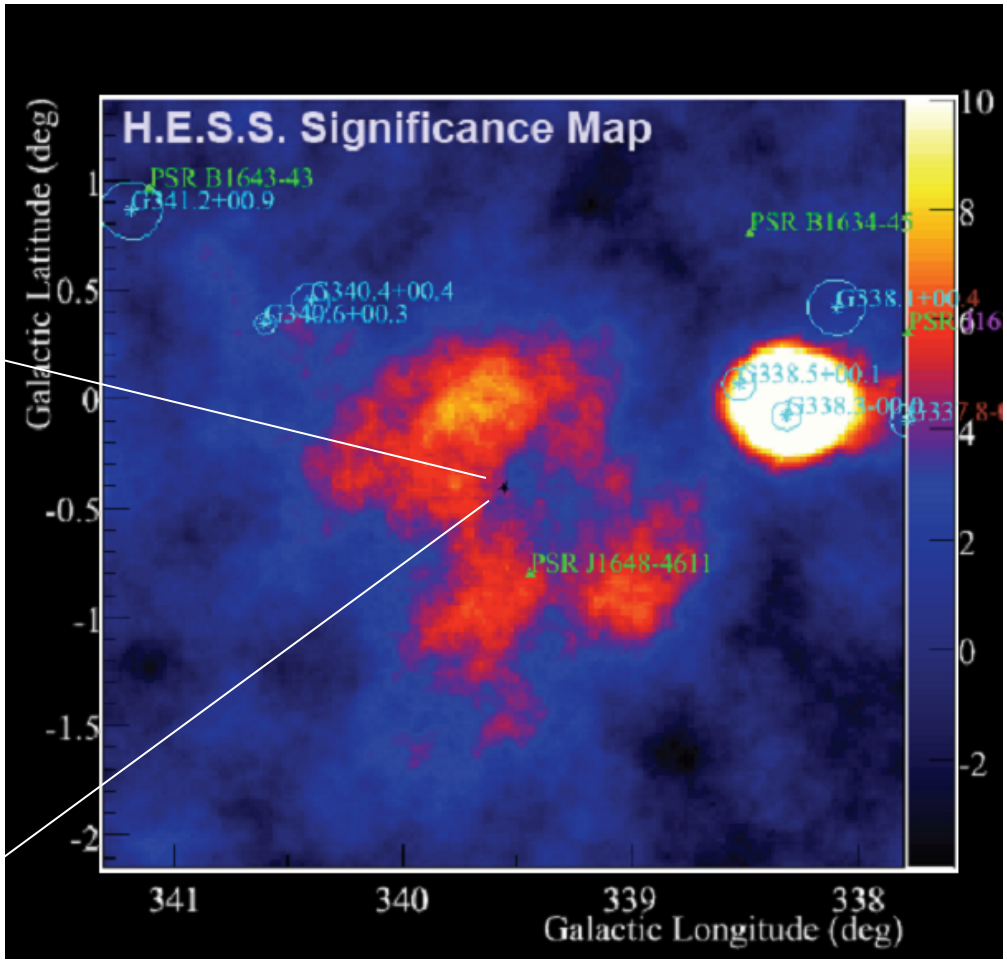
even for $L_e=L_{rot}$ this condition alone is not sufficient to achieve the γ-ray production efficiency (Compton cooling time of electrons on 2.7K CMBR exceeds the age of the source) -> the spin-down luminosity in the past was much higher.

energy-dependen image !

red – below 0.8 TeV
yellow – 0.8TeV -2.5 TeV
blue – above 2.5 TeV

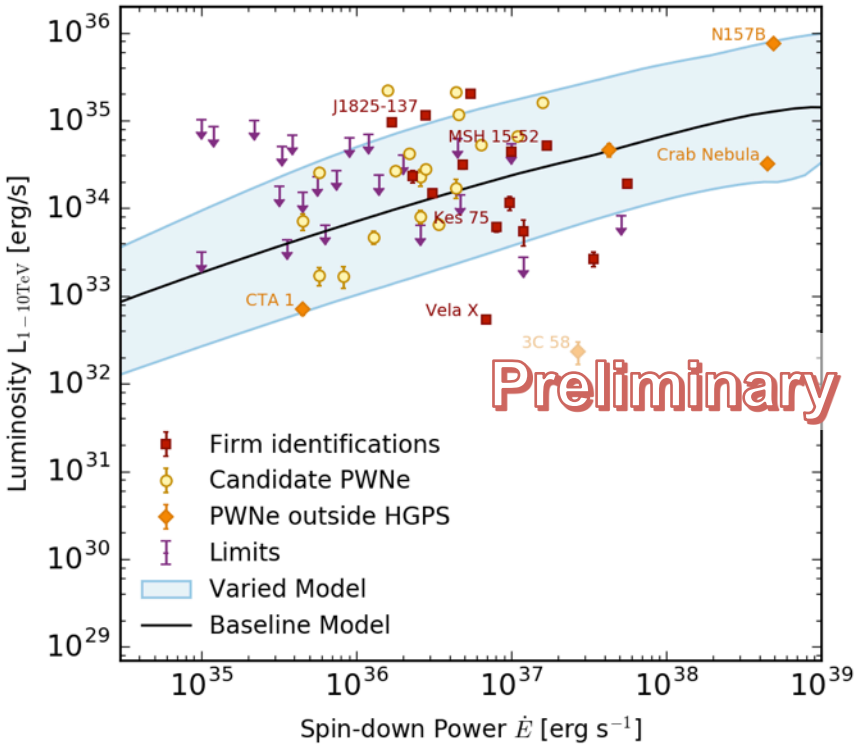
Westerlund 1 Stellar Cluster

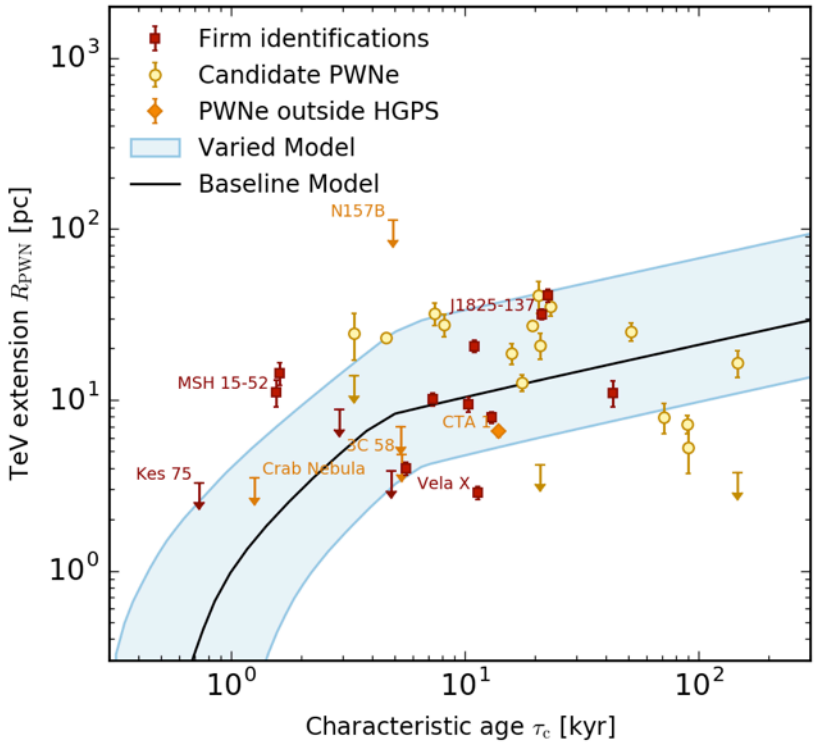
- most massive compact young star cluster
- 5 kpc distance
- 13 WR stars, ~30 hot supergiant stars
- in 0.5° gas bubble



HESS PWNe population study

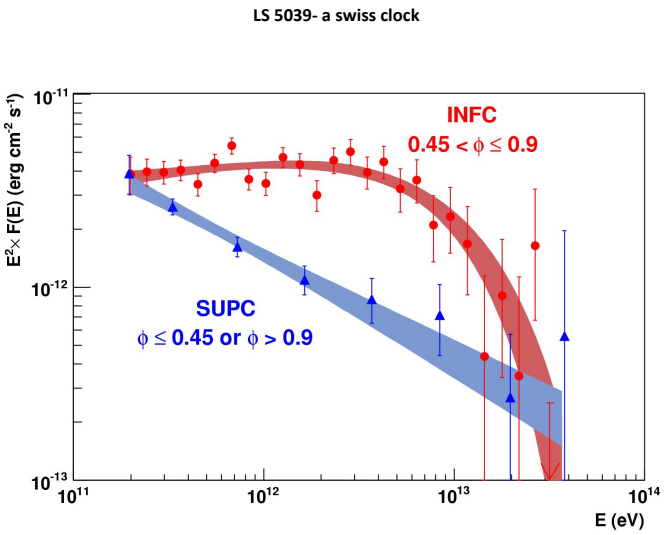
- Surveys are good for population studies
- Most young, energetic pulsars are detected
- Observables consistent with simple evolution model:
  - Time-dependent $e^{\pm}$ injection
  - Analytical radius evolution
  - Cooling mechanisms: synchrotron, adiabatic, Inverse Compton & escape





HESS TeV gamma-ray binaries

- Gamma-ray binaries: small class of objects
- H.E.S.S. TeV detections from well-known HMXBs:
  PSR B1259-63, LS 5039
- New discoveries of binary systems in the Gamma-ray band:
  HESS J0632+057, 1FGL 1018.6-5856, HESS J1832-093 (?)



- Accretion/ejection in binary systems.
- Anisotropic radiation fields
- Absorption by pair creation
- Variable conditions

- Very different periods
- Very different phenomenology
- Laboratories for acceleration & radiation mechanisms on human timescales

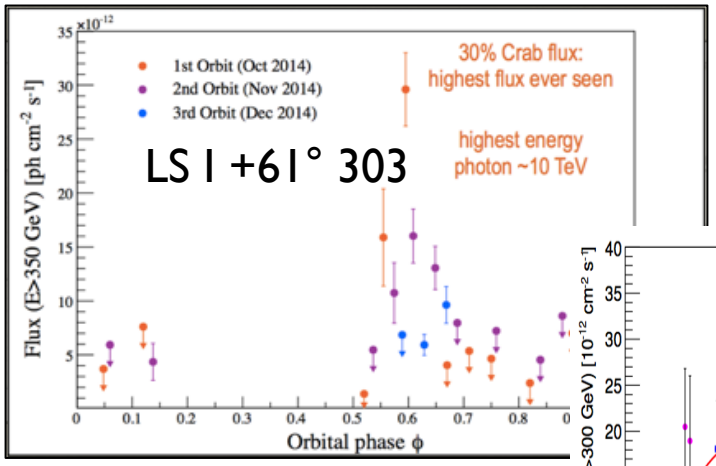
Binary Systems in the Northern Sky

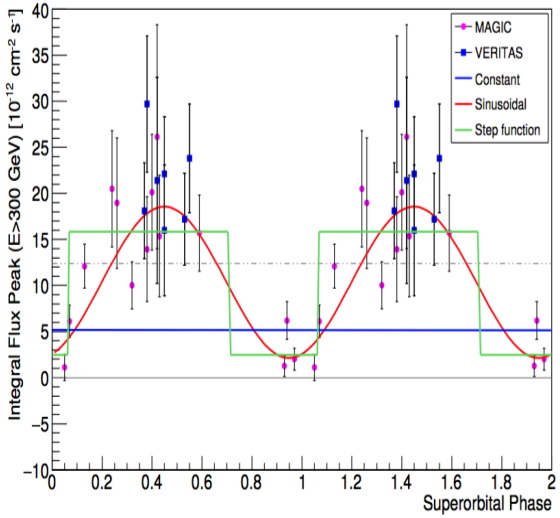
LS I +61◦303 is a system of a Be star and a compact object of unknown nature [MAGIC Science 312 (2006)]

→ **First detection of super-orbital variability** (1667 days) in the TeV regime compatible with radio data witin 8%

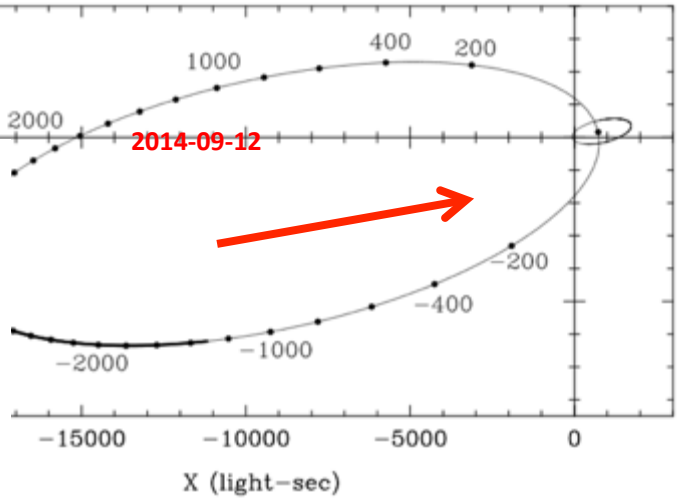
- Ongoing monitoring of LS I +61° 303.
- PSR J2032+4127 – a 20-30 year-period binary coincident with TeV 2032+4130.
- Periastron predicted 2017-2018. VERITAS will be observing.

Periastron
Feb-March 2018





PSR J2032+4127

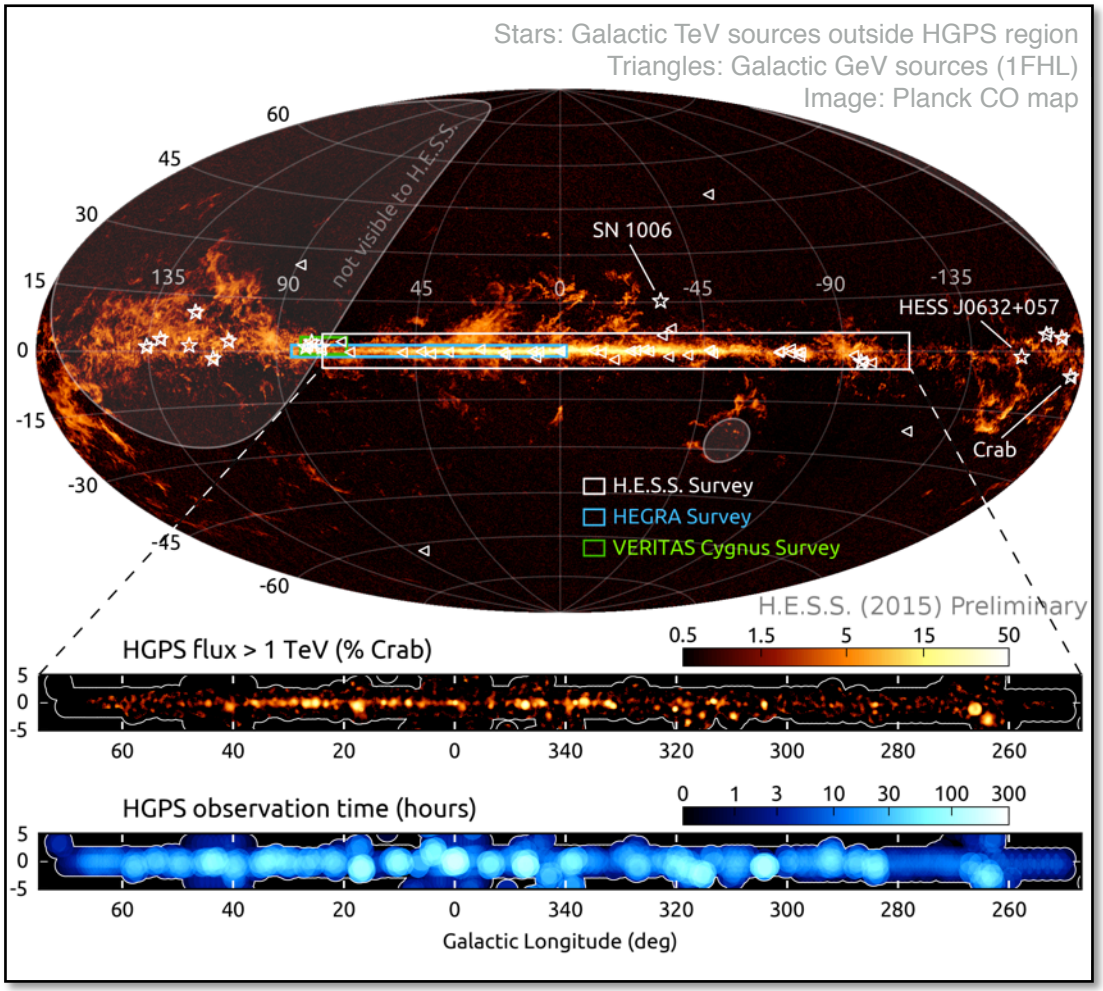


Astron.Astrophys. 591 (2016) A76

Archambault, S. et al., ApJL, 817, 7, 20__.

HGPS: The H.E.S.S. I Galactic Plane Survey

- H.E.S.S. I telescope system (CT1 – CT4)
- 2673 hours of (good quality) observations, years 2004-2013
- -110° < l < 65°
  -3.5° < b < 3.5°
- 0.2-100 TeV, $R_{68\%}$ ~ 0.07°
- Inhomogeneous exposure (sources of particular interest included)

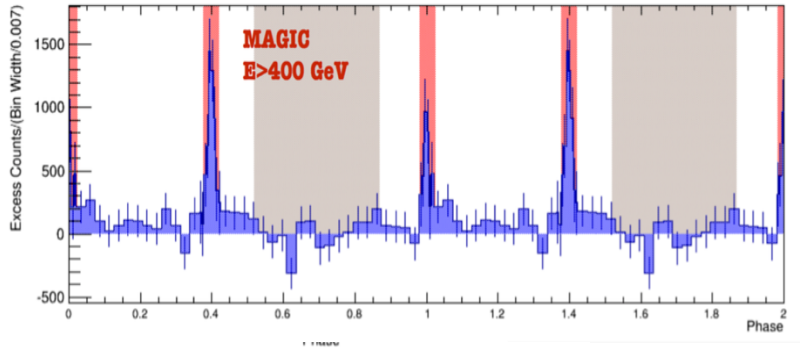


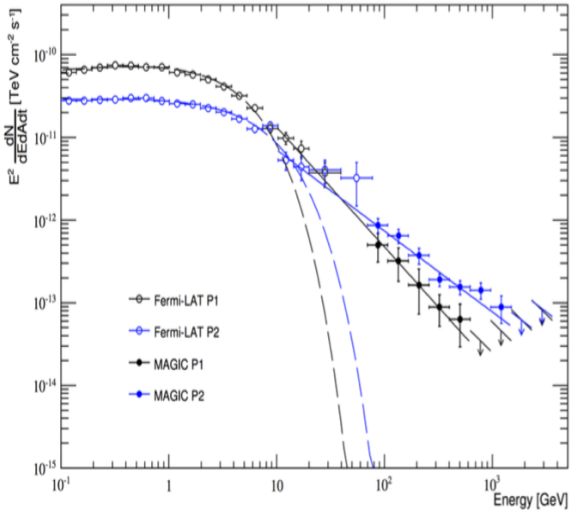
Lowering the energy threshold

- 2012 MAGIC stereo upgrade:
- 2012 HESS-II New 28m telescope:
- 2012 VERITAS upgrade
- HAWC now online and FACT monitoring
- ....and Fermi, AGILE....

MAGIC Crab and Geminga pulsars and pwne

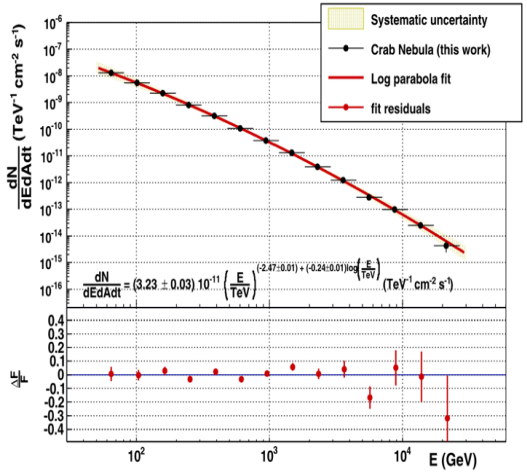
Teraelectronvolt pulsed emission from the Crab pulsar detected by MAGIC
MAGIC Collaboration (M.L. Ahnen *et al.*). Oct 23, 2015. 6 pp.
Published in **Astron.Astrophys. 585 (2016) A133**

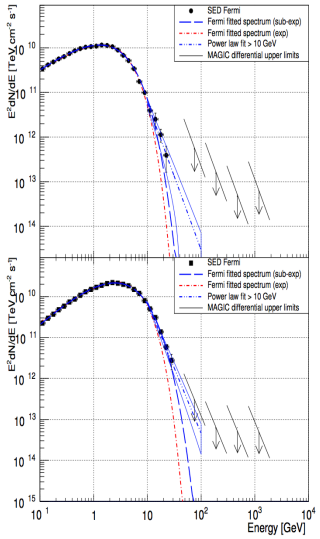




MAGIC (300h) pulsed emission close to 1 TeV on the Crab Pulsar

- MAGIC Crab Nebula log-parabola spectrum from 70 GeV to 30 TeV.





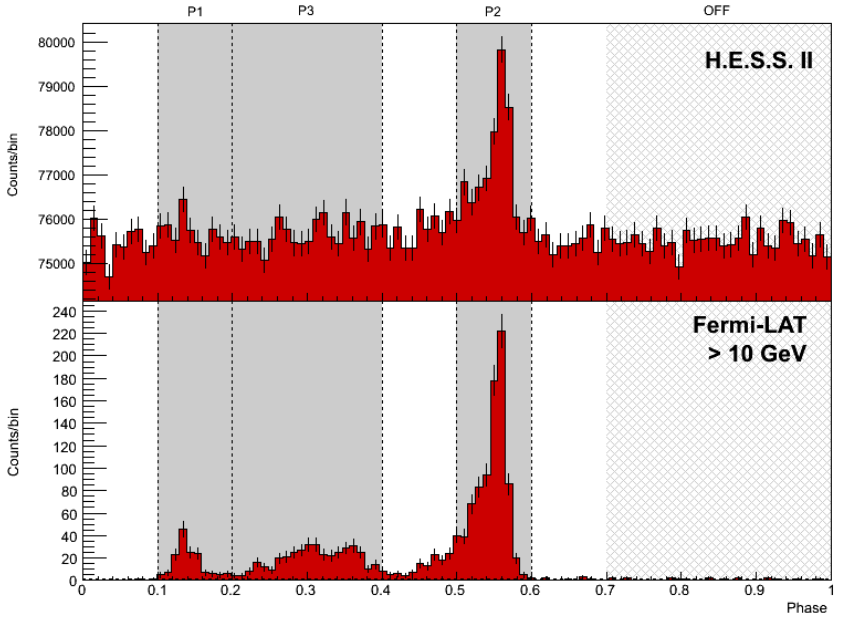
Nothing from the **Geminga pulsar** (nor Nebula) in 70h of data [MAGIC 2016]

Vela pulsar with H.E.S.S.

- Second VHE pulsar (after Crab)
  - Calibration source at the threshold in standard observation mode
  - Deep observation campaign needed to investigate maximum energy and variation of pulse profile with energy
  - Very different regime than Fermi-LAT: huge statistics over a huge background

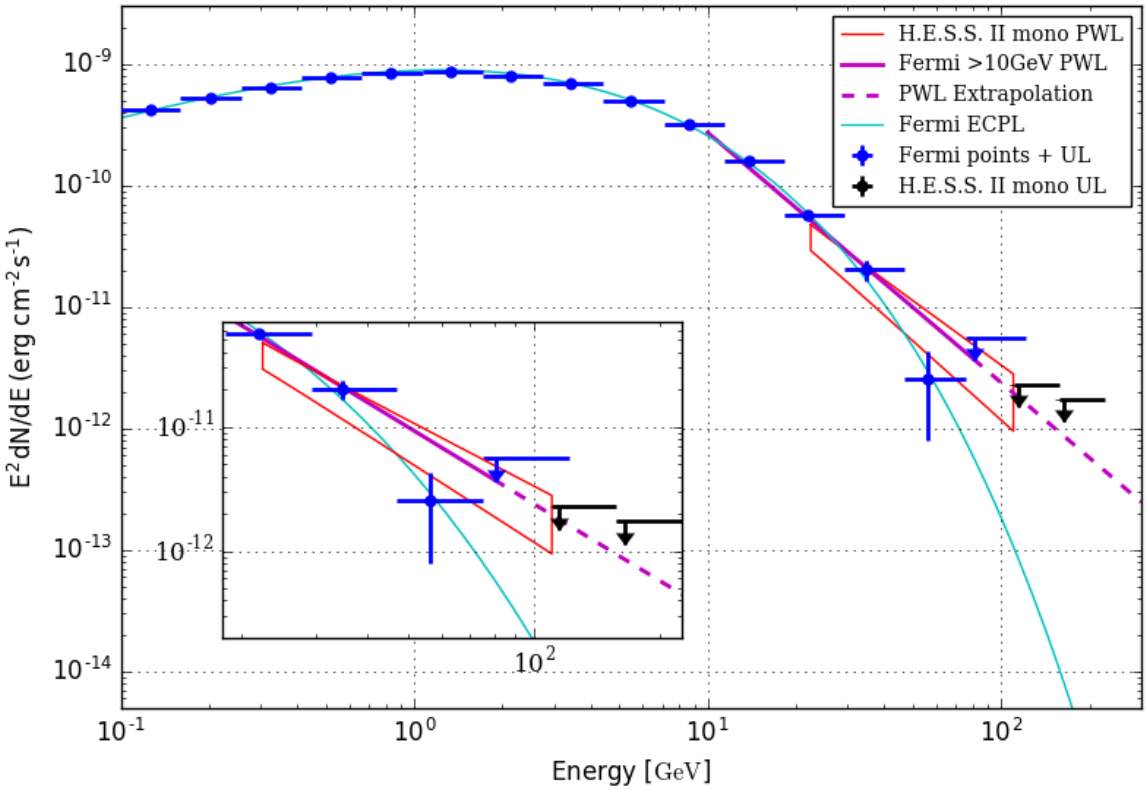
~16 000 γ's

> 15 σ



Vela pulsar – energy spectrum

- Good agreement with Fermi-LAT
- Consistent with steep power law, no indication of hard component so far
- Extensive observation campaign started

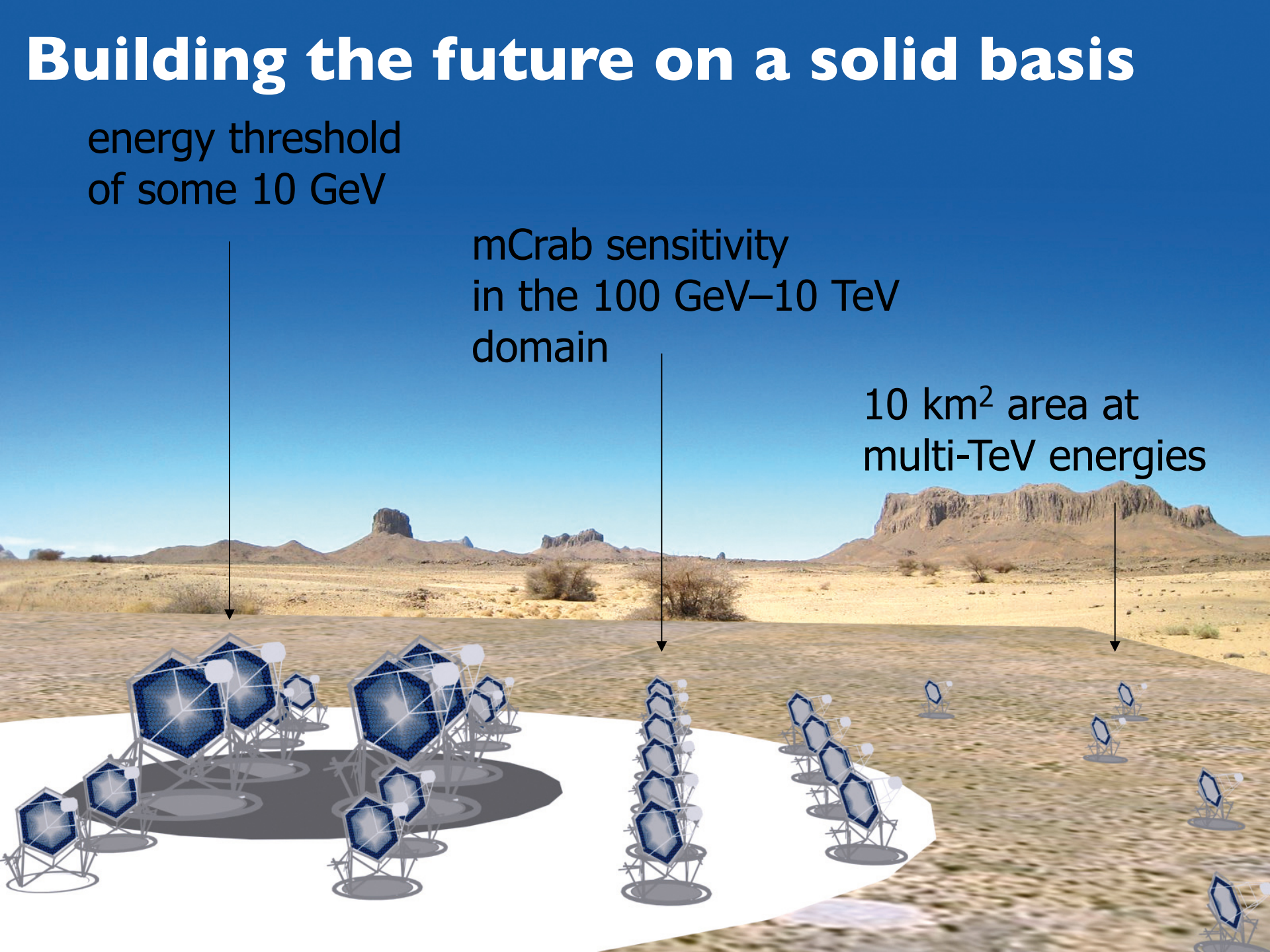


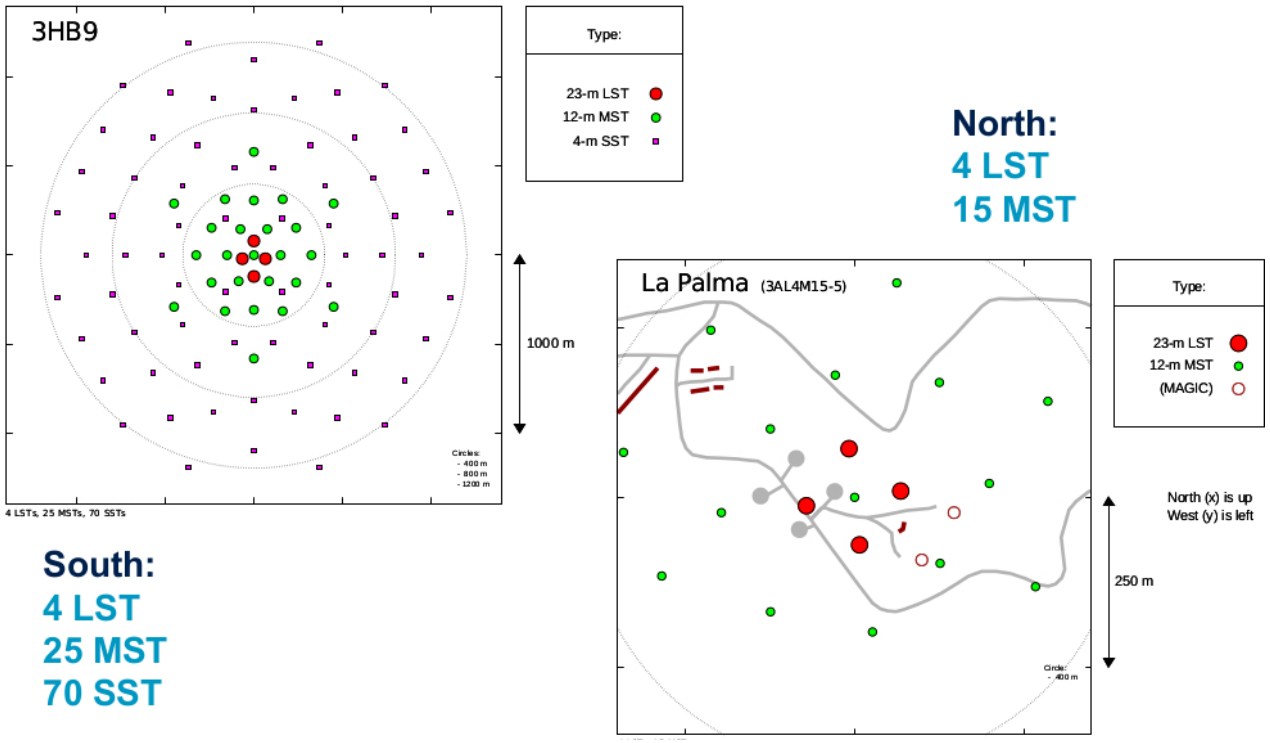
Building the future on a solid basis

energy threshold
of some 10 GeV

mCrab sensitivity
in the 100 GeV–10 TeV
domain

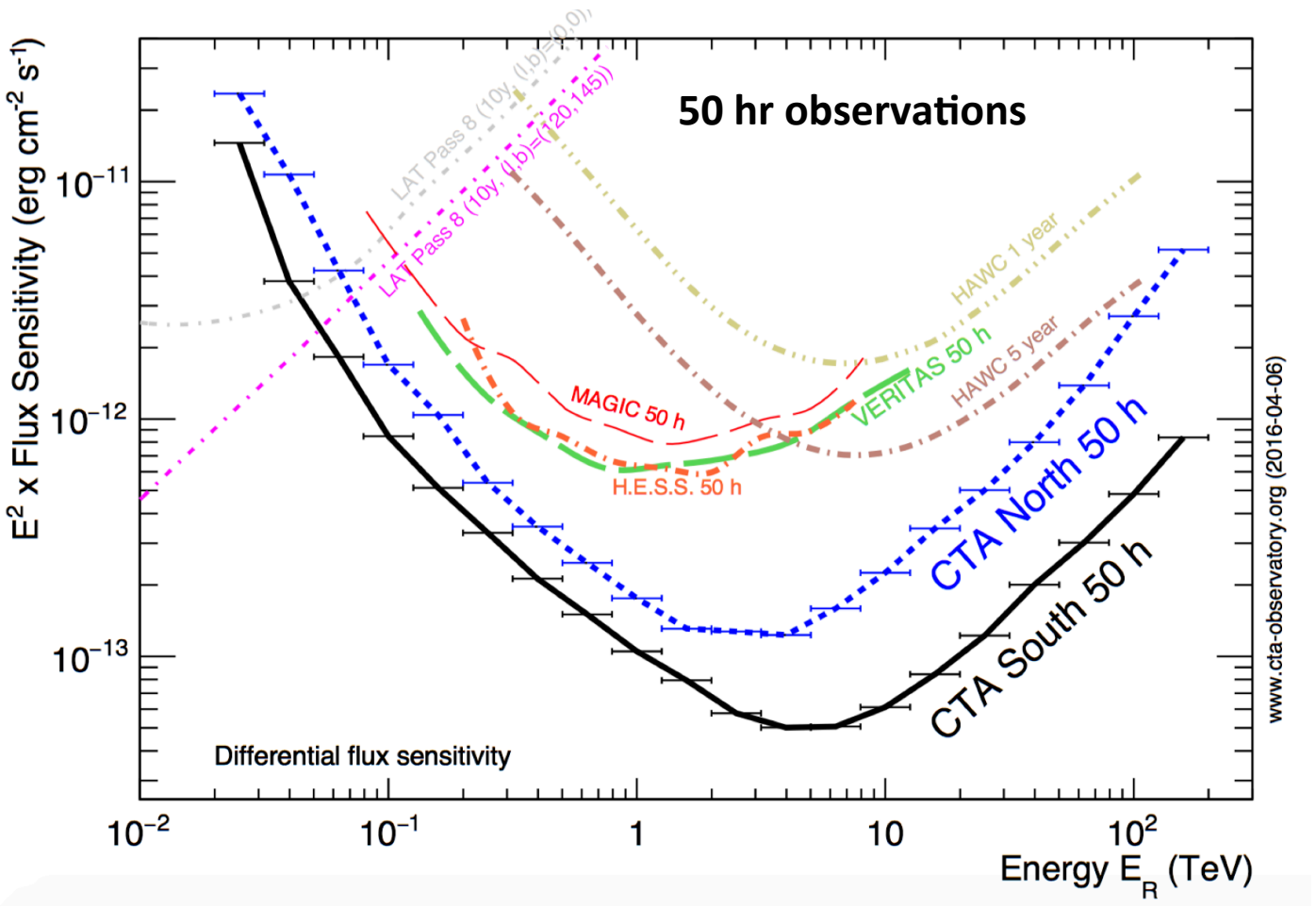
10 km^2 area at
multi-TeV energies



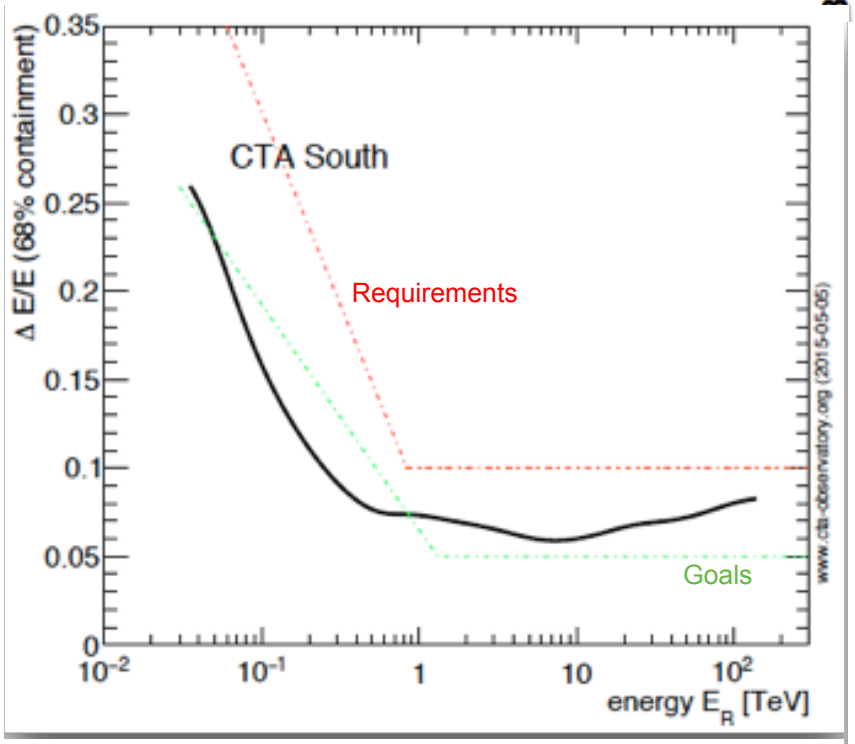


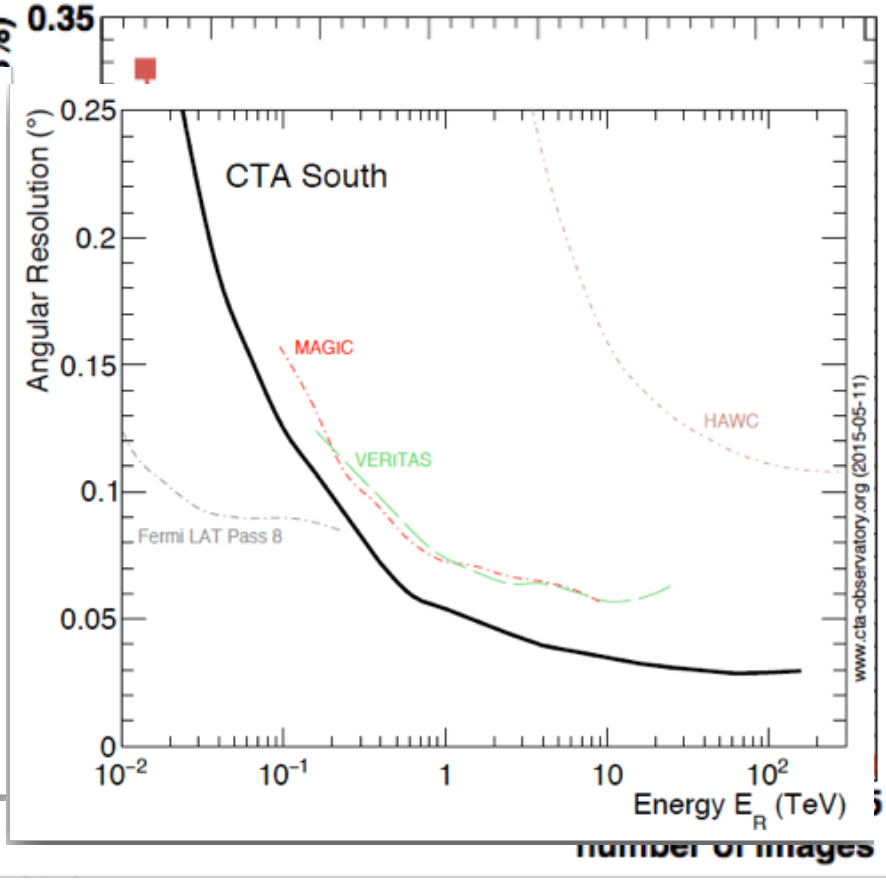
- 10 times sensitivity at TeV energies
- Lower threshold (20-30 GeV)
- Higher energy reach (100s of TeV)
- Wider field of view
- Improved angular resolution
- Higher detection rates

Boosting sensitivity



Boosting angular and energy resolution





An observatory for ground based gamma-ray astronomy

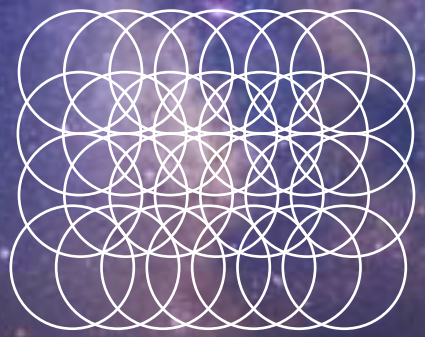
Monitoring
4 telescopes

Monitoring
4 telescope

Deep field
~1/2 of telescopes

Deep field
~1/3 of telescopes

Monitoring
1 telescope



Survey
mode

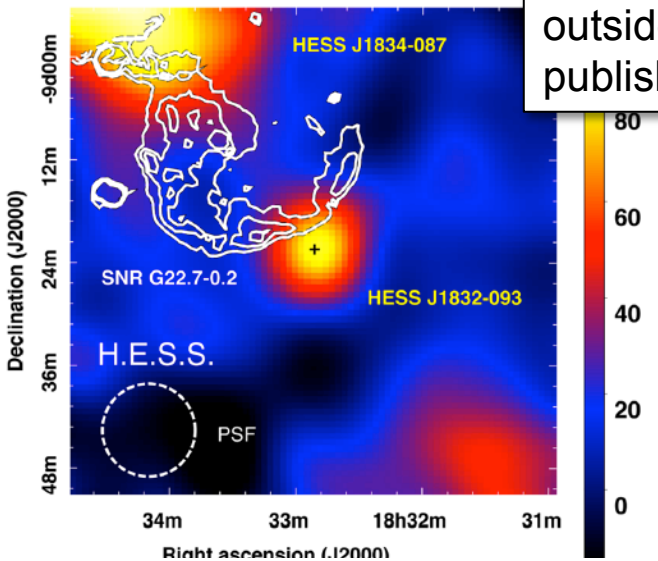
Conclusions

- The results of current IACTs have demostrated the power of the imaging Cherenkov technique
- Current IACTs have recently extended their domain to few tens of GeV
- CTA will be the VHE observatory built on this solid and well-known basis

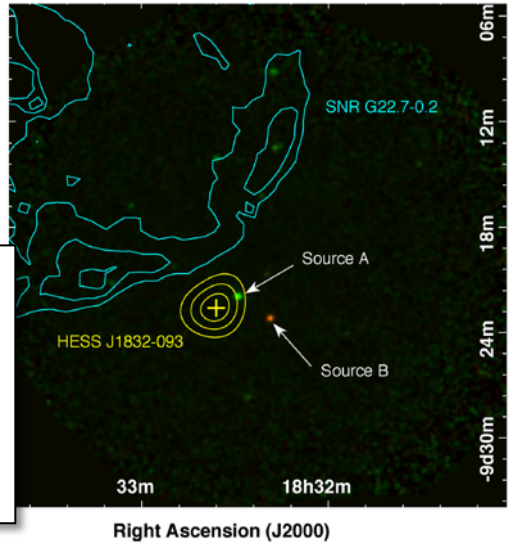
HESS J1832-093: a new TeV gamma-ray binary ?

1. TeV point source just outside SNR G22.7-0.2, published 2015

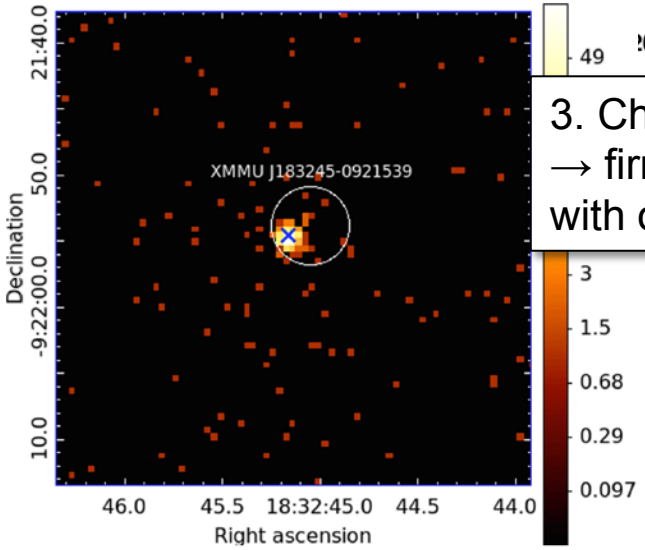
HESS coll. 2015



2. XMM-Newton (point-source) localisation
→ likely identification with TeV source + likely identification with optical counterpart

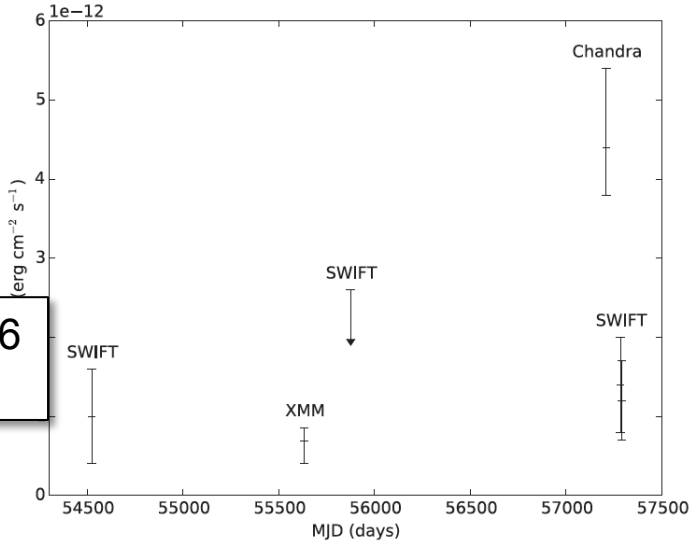


Eger at al., MNRAS 457 (2016)



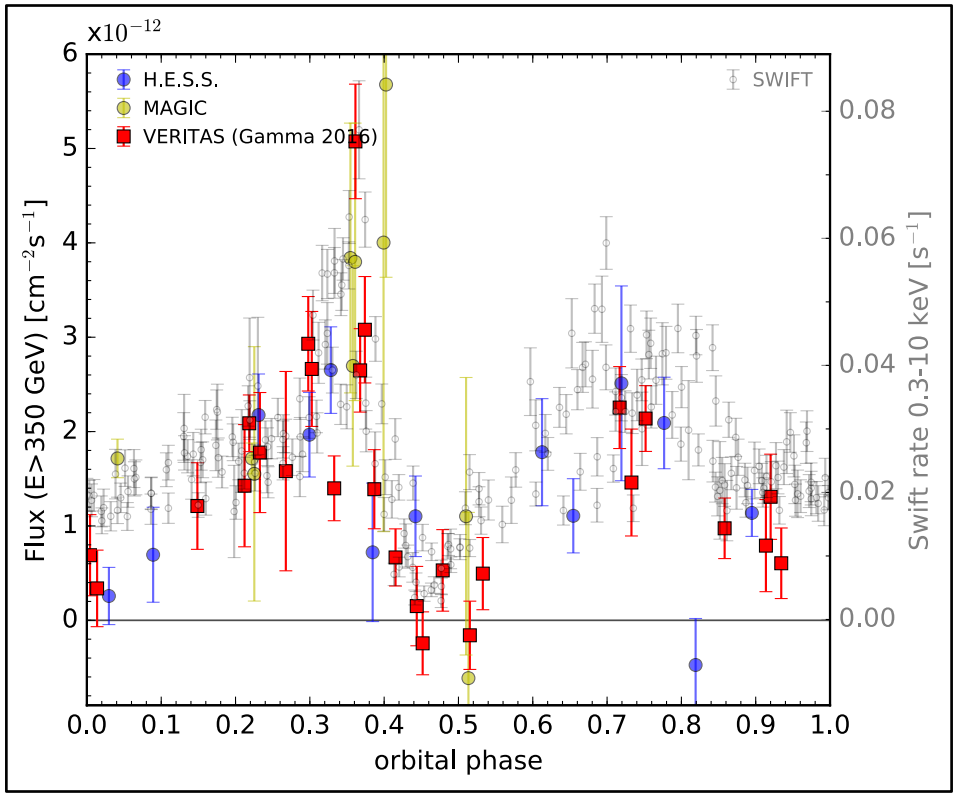
3. Chandra localisation
→ firm identification with optical counterpart

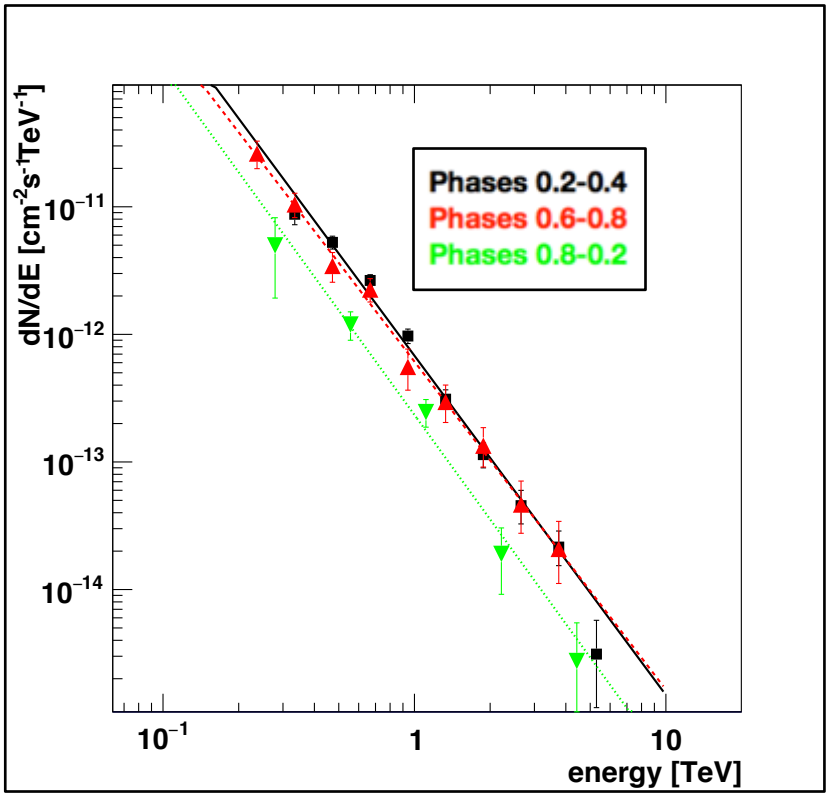
4. X-ray variability by × 6
→ likely a new binary



Binary Systems with VERITAS

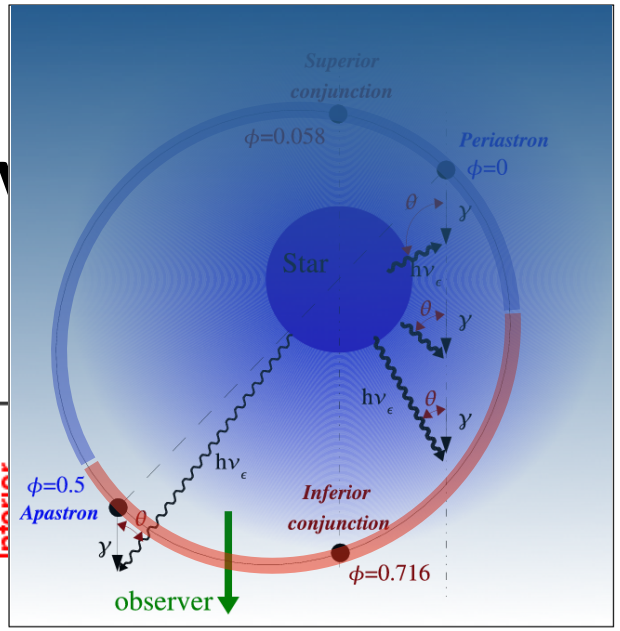
- HESS J0632+057. Full 315-day orbit now sampled.
- Clear detection and spectral measurements over almost all phases.

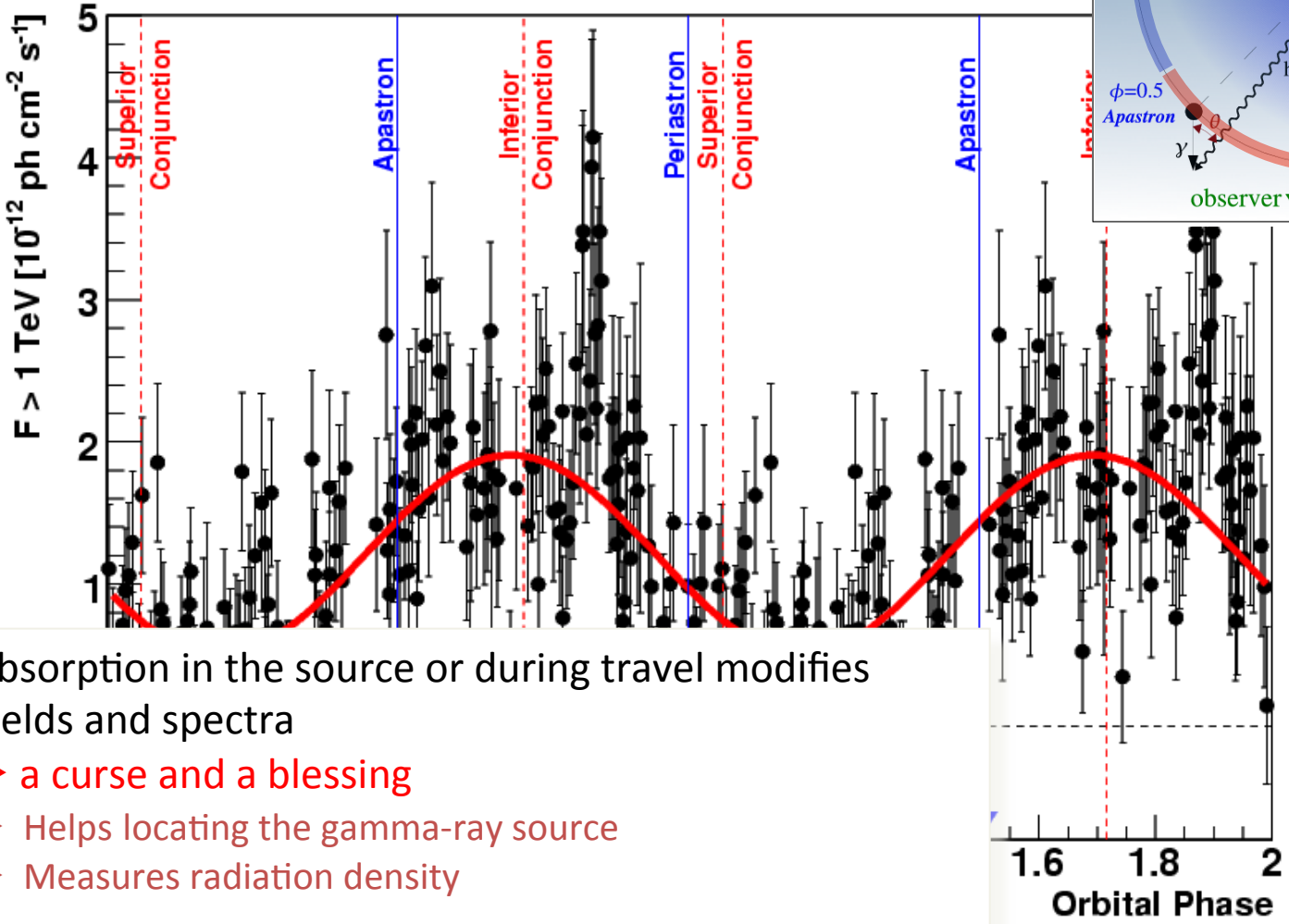




S. Schlenstedt: Long-term TeV Observations of the Gamma-ray Binary HESS J0632+057 with VERITAS

LS 5039 lightcur





Absorption in the source or during travel modifies yields and spectra

- a curse and a blessing
- Helps locating the gamma-ray source
- Measures radiation density

Folded using optical period

Data repeated for 2 cycles