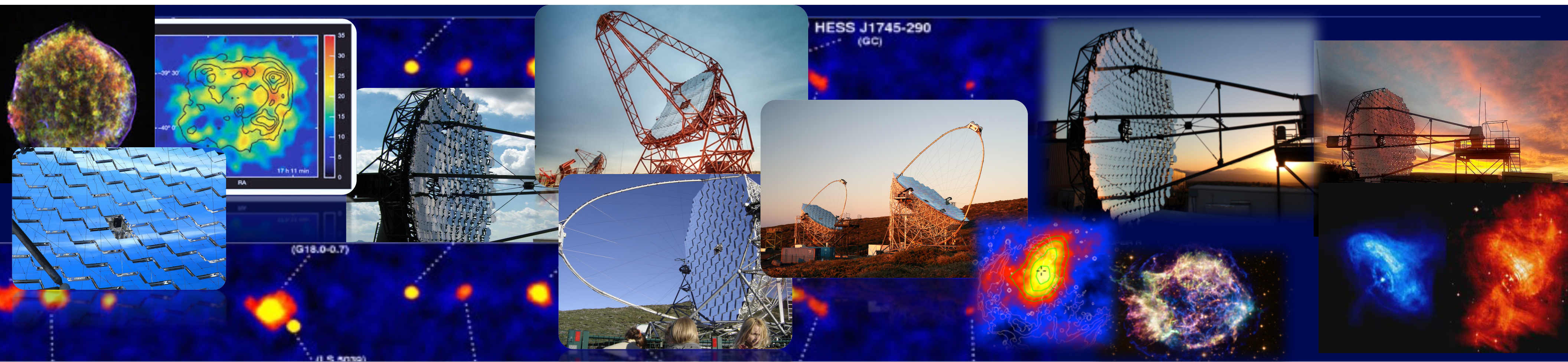
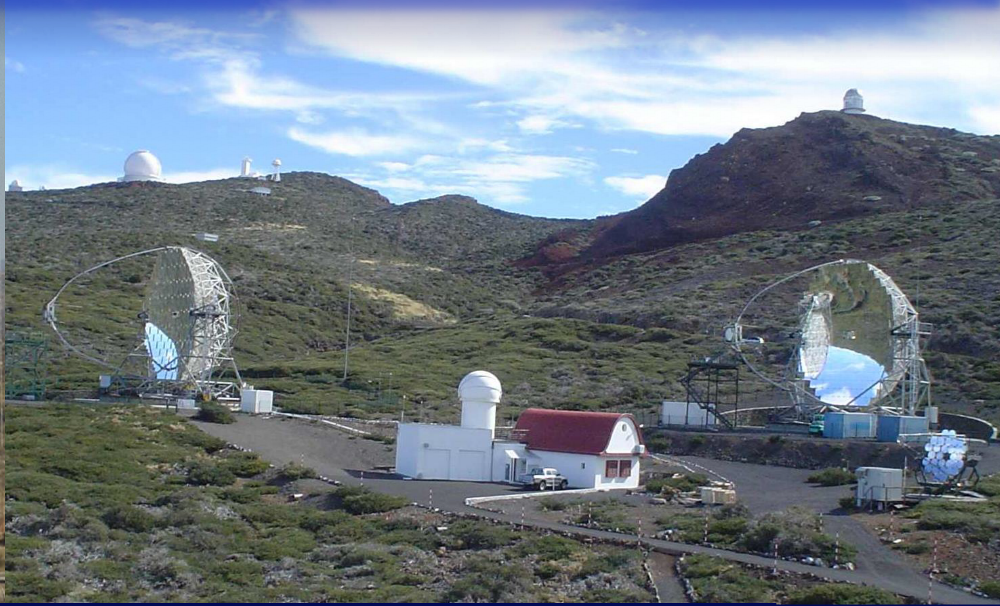
Galactic Sources of VHE Gamma-Ray Emission: Highlights from IACTs

Reshmi Mukherjee
Barnard College, Columbia University



The Three Major IACTs



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

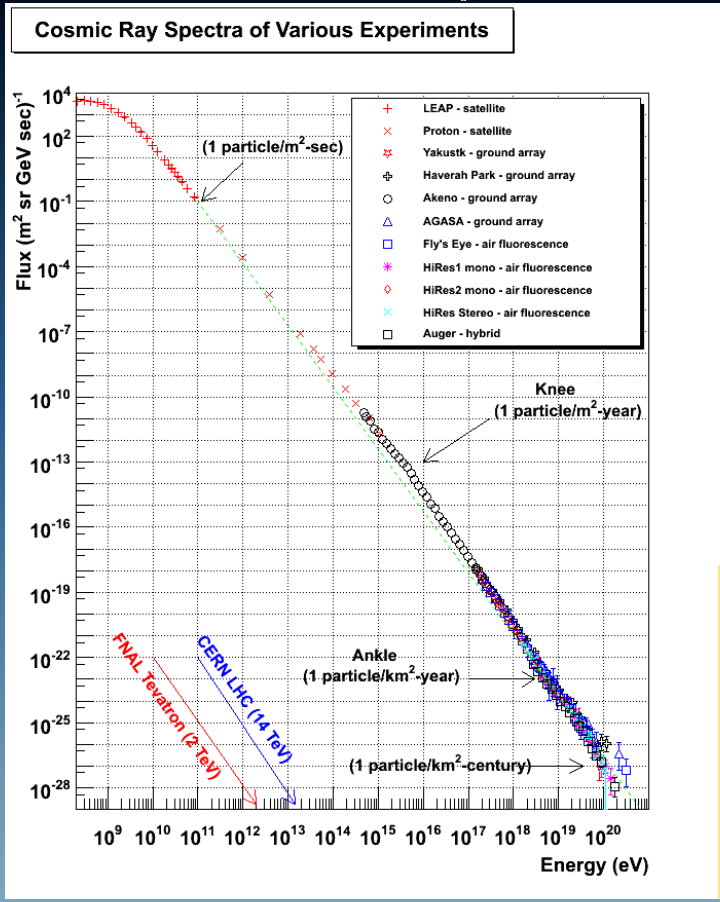
H.E.S.S.

MAGIC

VERITAS

Gamma Rays as Tracers of Cosmic Rays

- What are the sources of the highest energy cosmic rays?
- Are there "PeVatrons" in our Galaxy → young supernova remnants that can accelerate particles up to PeV (~10^{15} eV) energies?
- Is there yet a robust evidence of acceleration of nucleonic component of cosmic rays in supernova remnants?
- What is the maximum particle energy
  → acceleration efficiency?
- What is the nature of the supernova progenitor and the magnetic field environment?



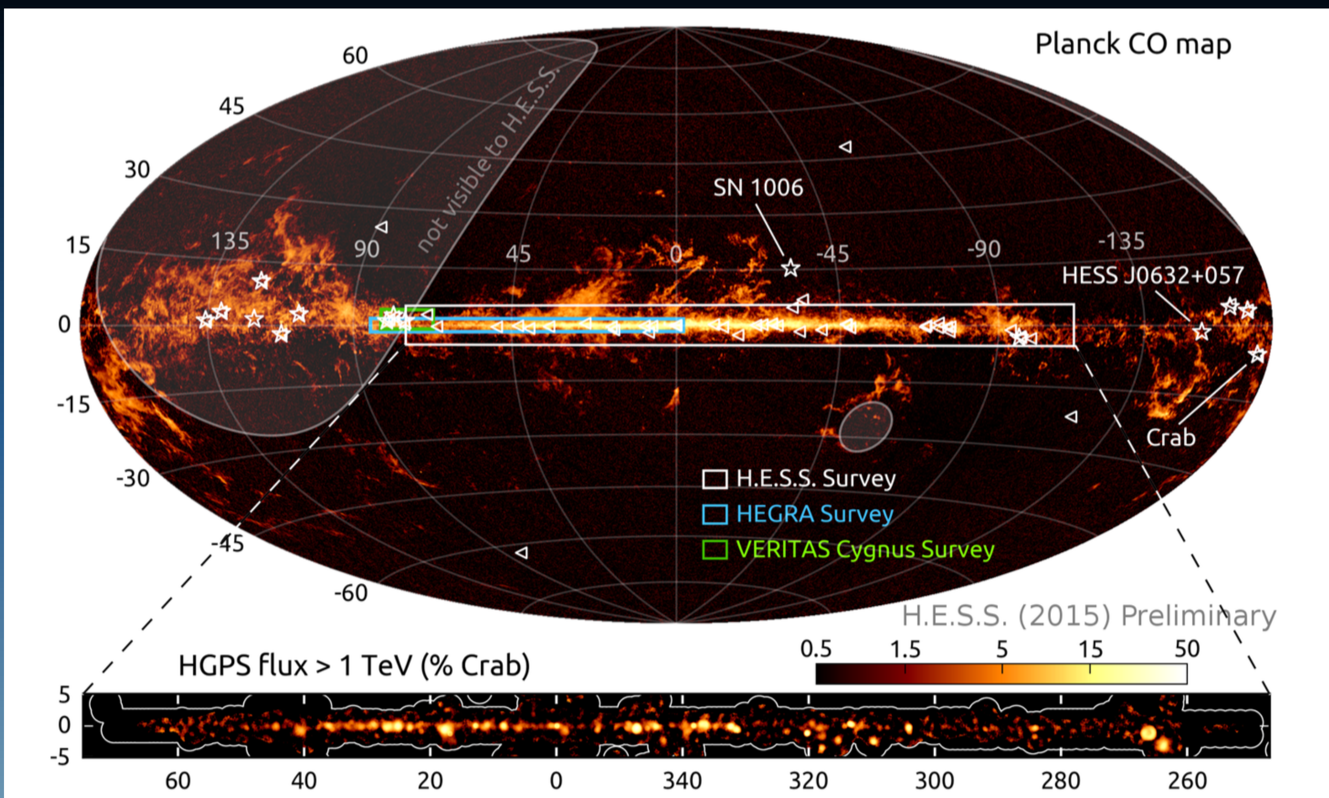
Courtesy Dr. Hanlon

Galactic Plane Survey, 0.2 – 100 TeV

H.E.S.S. survey

See Chavez, TeVPA 2015

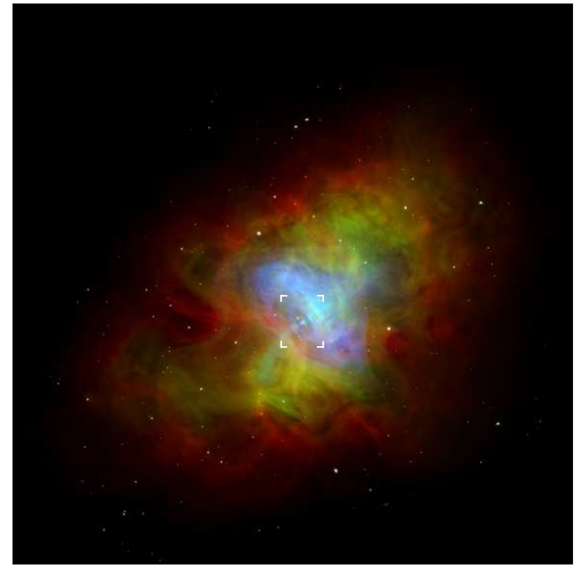
- The deepest and most comprehensive, high resolution (~ 0.1°) and sensitive (<2% Crab Nebula) survey of the Milky Way in very-high-energy γ-rays.



- Large catalog (~100) of Galactic sources →opportunity to carry out particle acceleration studies.
- Different classes of Galactic sources.
- Population studies are now starting to become possible.

de Naurois, ICRC 2015

Rich Variety of Galactic Science at > 100 GeV



- Supernova remnants/PWNe/Supernova products
  - Non-thermal shells.
  - Shell-molecular cloud interactions.
  - TeV PWNe associated with high E_{dot}/d^2 pulsars.

- Gamma-ray pulsars
- TeV observations of binaries
  - Binaries are the *only* variable Galactic TeV sources.
  - Jets or colliding winds? TeV emission probes the highest energy particles accelerated.
- Unidentified Galactic sources
  - TeV unidentified sources from Galactic plane surveys.
  - Fermi unidentified sources & transients in the Galactic plane.
- Synergistic Studies with Fermi-LAT & HAWC
  - Unprecedented opportunities for spectral studies in the 100 MeV – 100 TeV.

Rich Variety of Galactic Science at > 100 GeV

However,

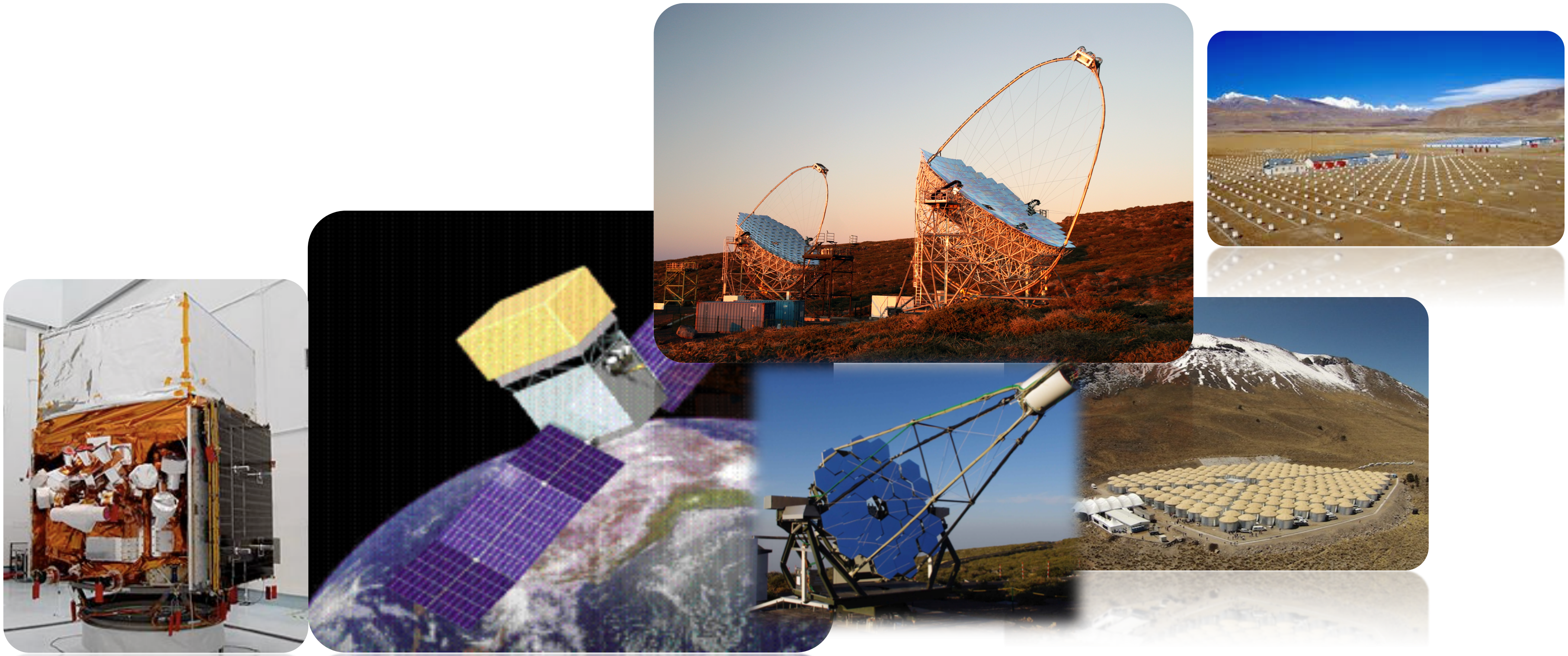
*this talk will focus on only a few topics** ….*

(not a comprehensive review)

*** Handful of highlights*

**** See for e.g. de Naurois ICRC 2015 for a recent review*

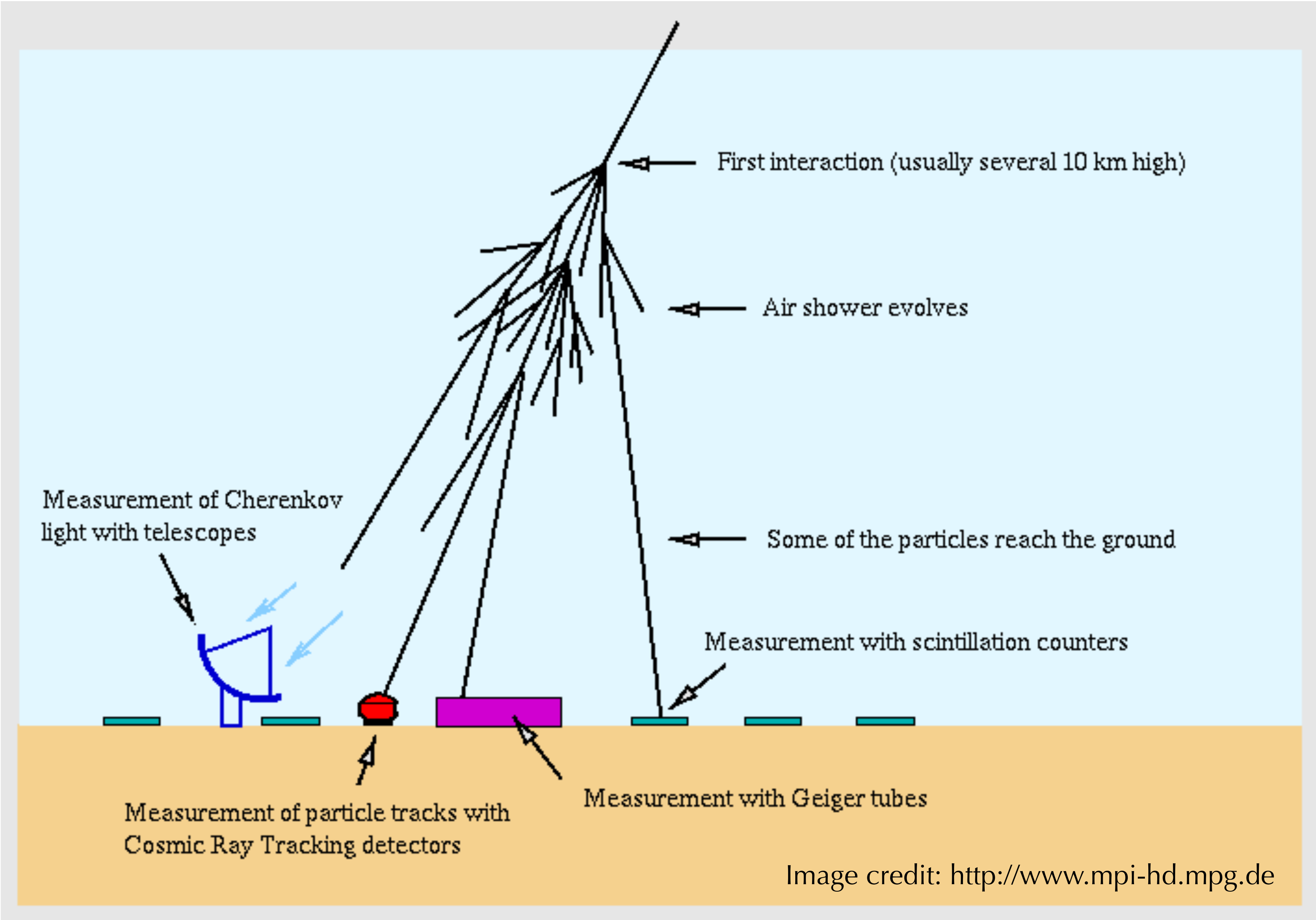
IACTs in Context



10^{-12} 10^{-14} 10^{-16} 10^{-18} 10^{-20} m

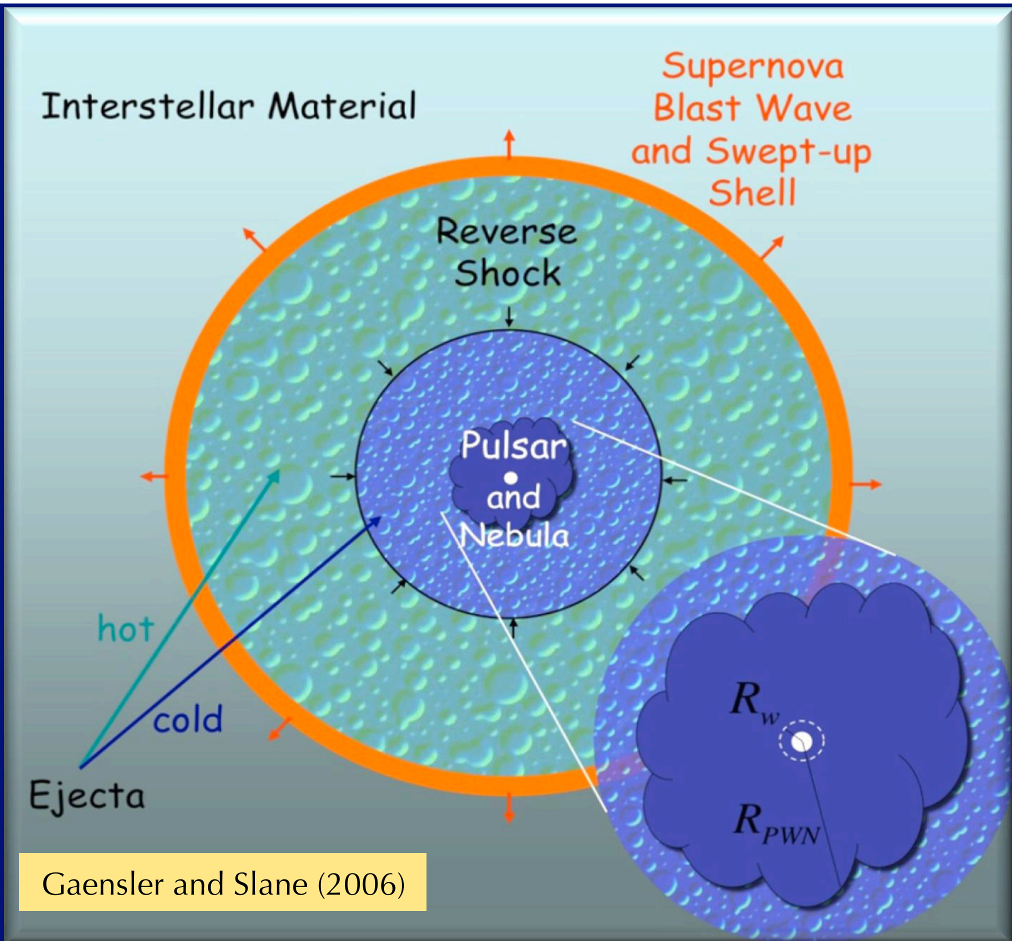
0.5 MeV 100 TeV

IACTs in Context



Sources of Cosmic rays: SNRs

Power Source: Supernova Remnants



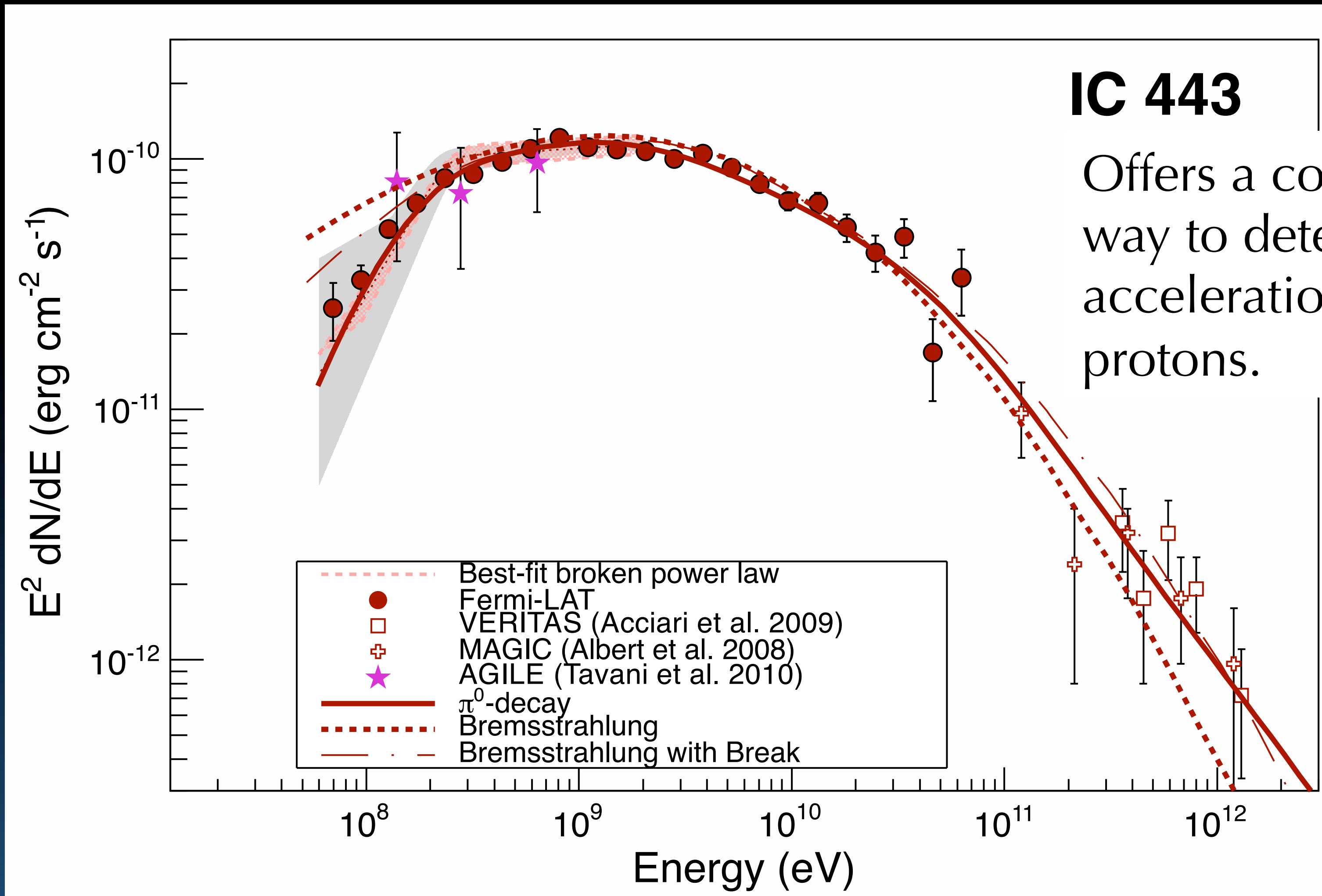
Gaensler and Slane (2006)

- Collapse of massive star in our Galaxy (~ every 50 yrs).
- One of the most violent events in our Universe.
- Outer layers ejected: v~1-2 x10^4km/s.
- Shell expands and shock front forms as it sweeps up material from ISM.

- Supernova shocks accelerate e^- and protons.
- Relative efficiency of e^- vs p acceleration not well-understood. What are the maximum energies obtained?

Gamma-ray production by IC scattering or π^0 decays from inelastic interactions of protons with ambient gas.

Cosmic rays?

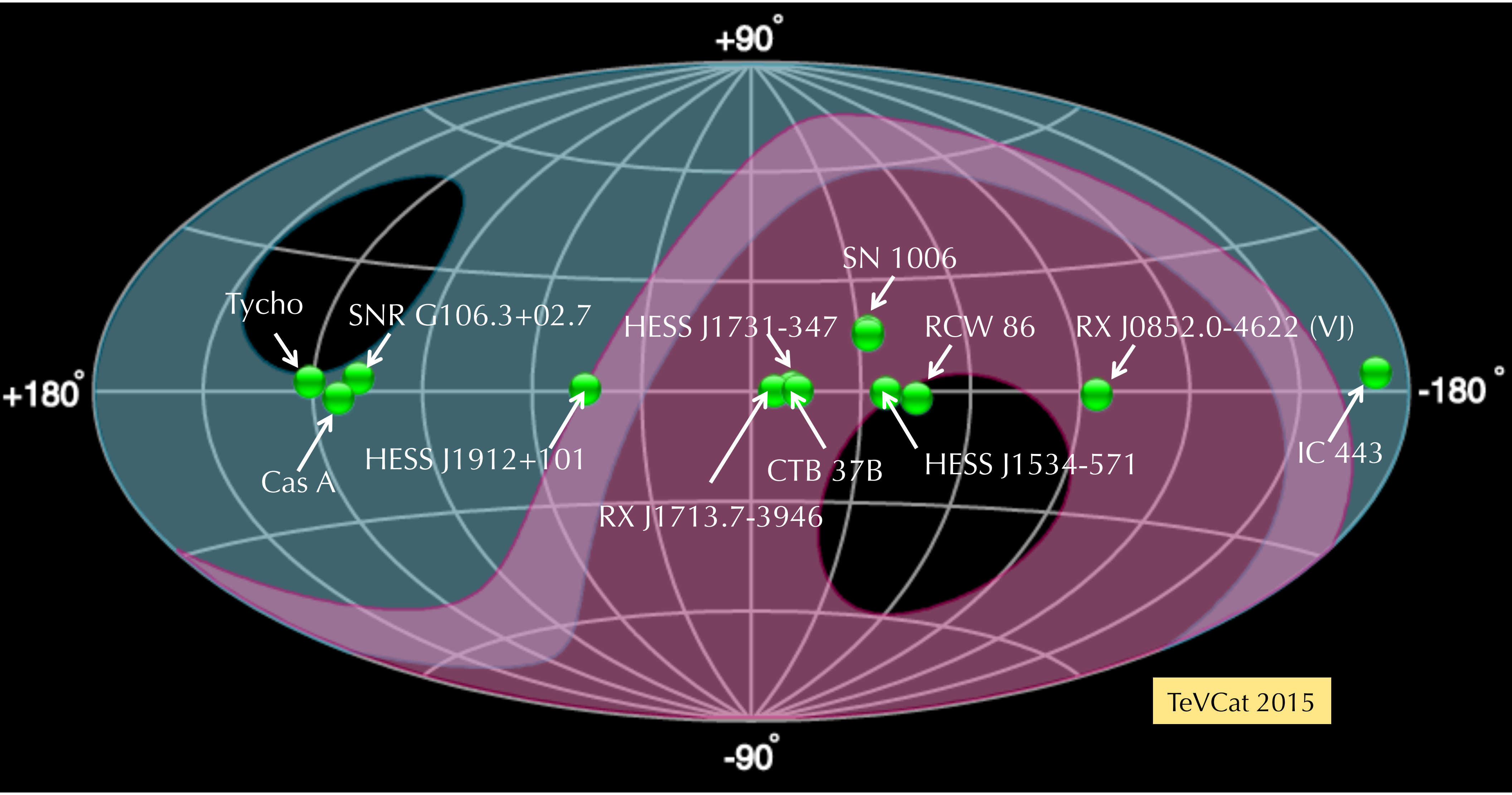


Offers a compelling way to detect the acceleration sites of protons.

Ackermann et al. 1302.3307

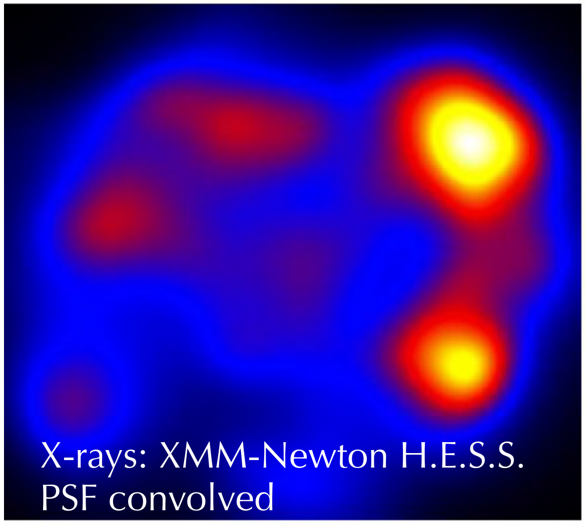
- Fermi-LAT SED cutoff around 200 MeV, "pion bump," is direct indication of hadronic interactions.

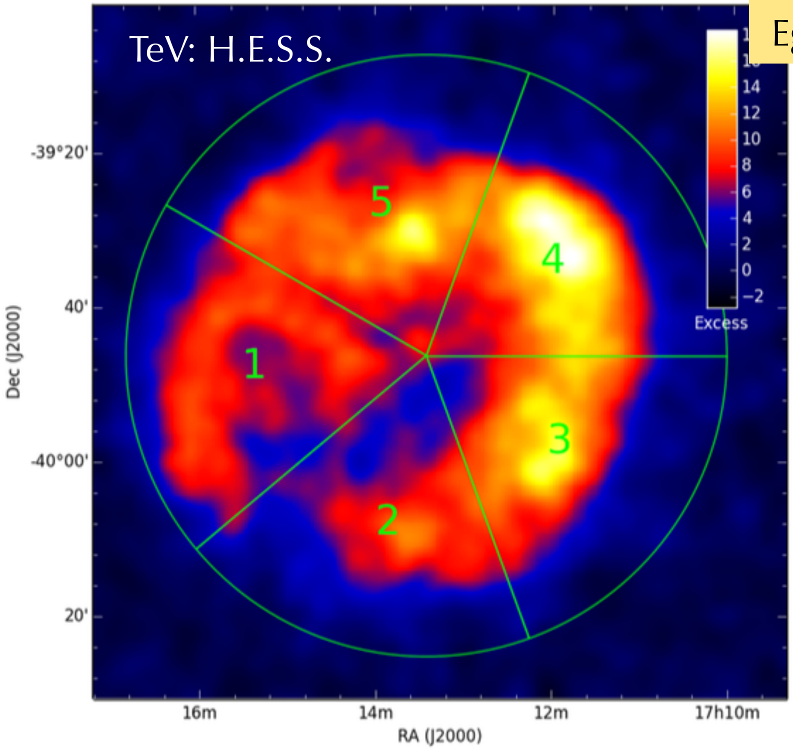
Sources of Cosmic rays: SNRs (Shells)



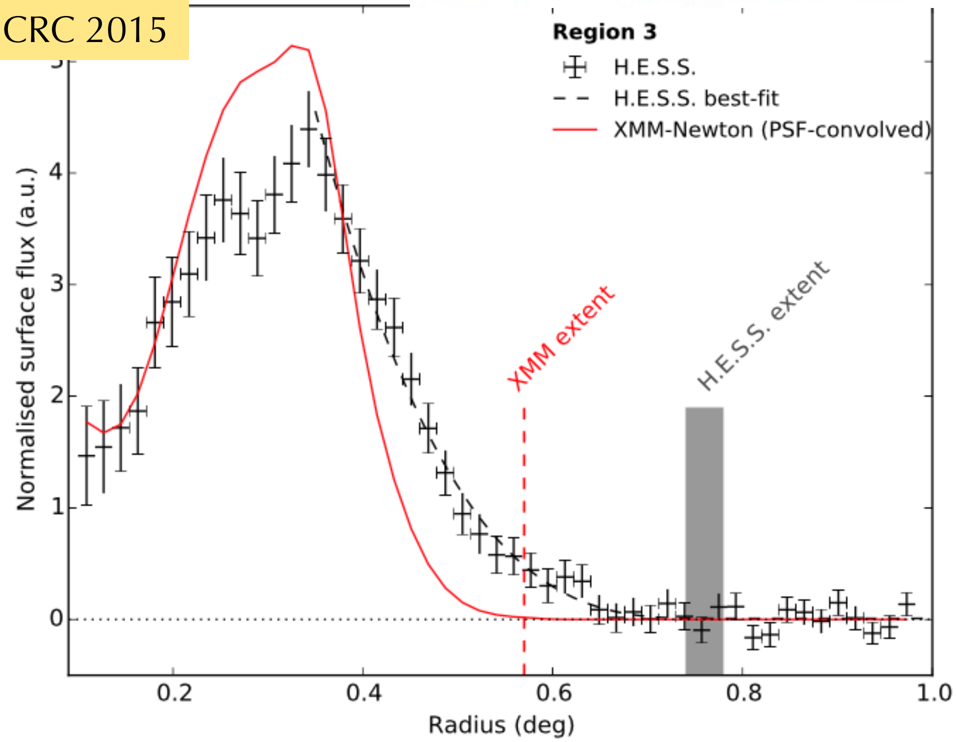
SNR RX J1713.7-3946: *First shell-type resolved in TeV*

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





Eger et al. ICRC 2015



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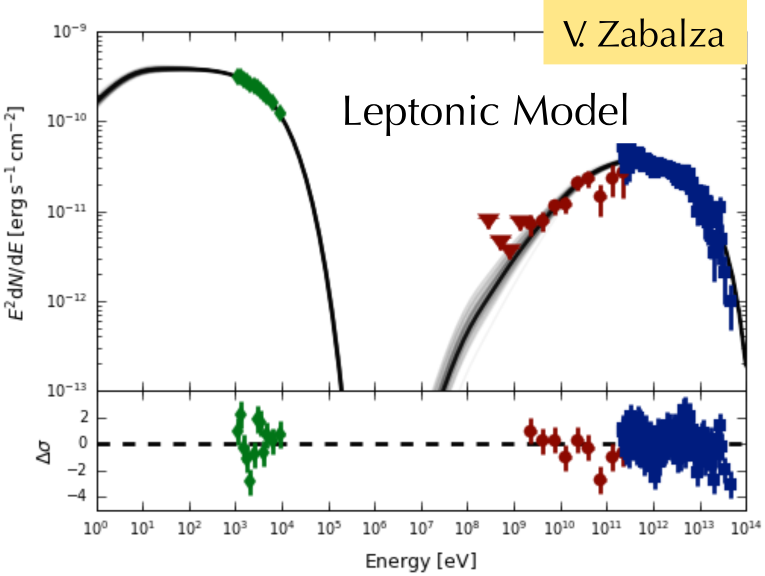
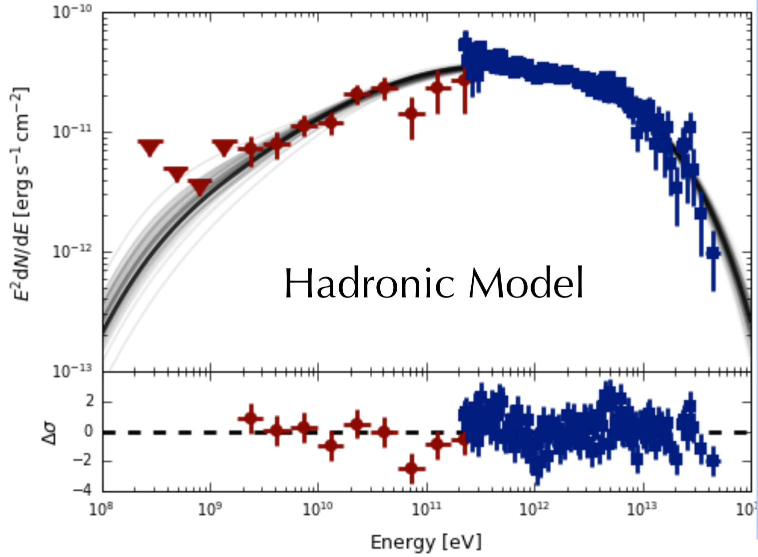
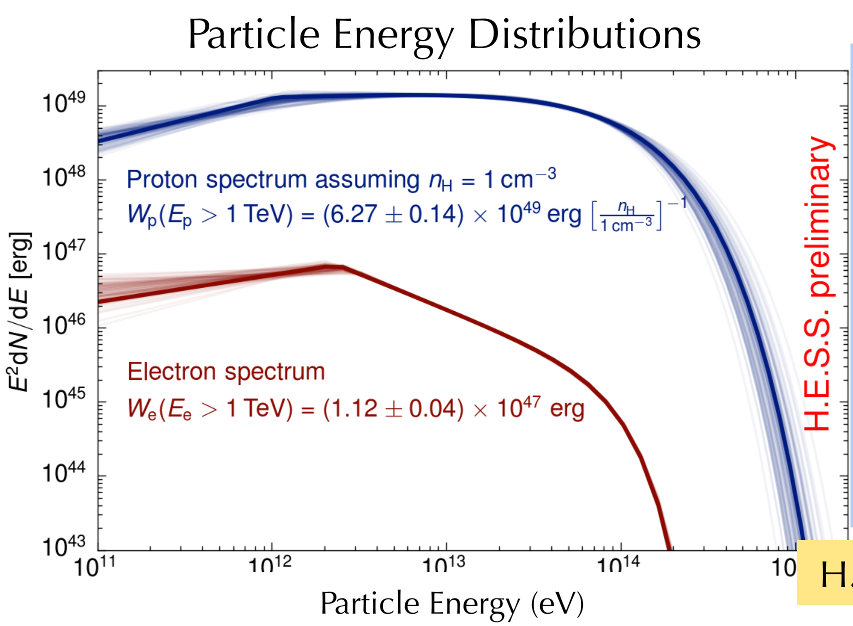




- TeV spectrum extends to ~100 TeV. Purely leptonic model with single-population of electrons not good explanation for Fermi-LAT + HESS spectrum



- Models require break in in electron spectrum @ 2.5 TeV
- If Synchrotron cooling, required B-field: ~140 μG

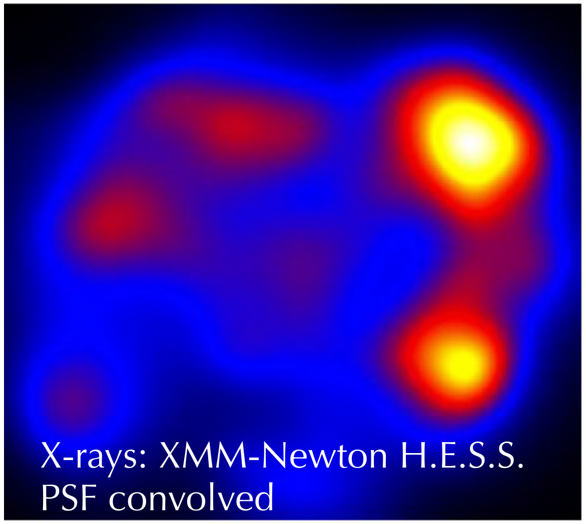
  → at odds with X-ray measurement (B = 14.8 ± 0.2 μG)

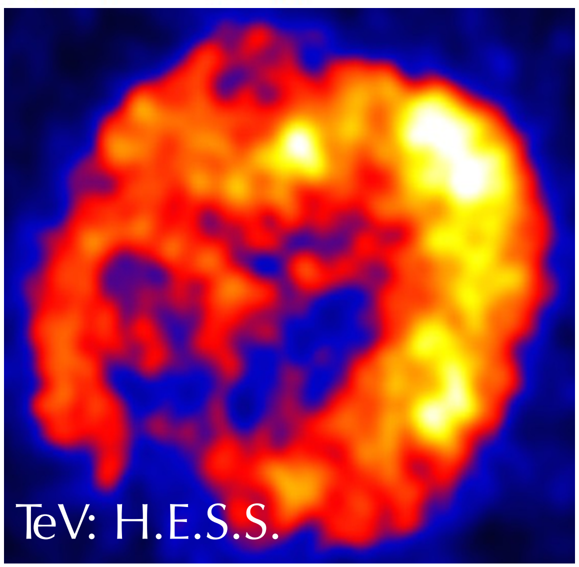
- Additional target photon field?
  → required energy density: 140 eV cm^{-3}
  → 10^2 times larger than in all previous estimates

H.E.S.S., V. Zabala ICRC 2015

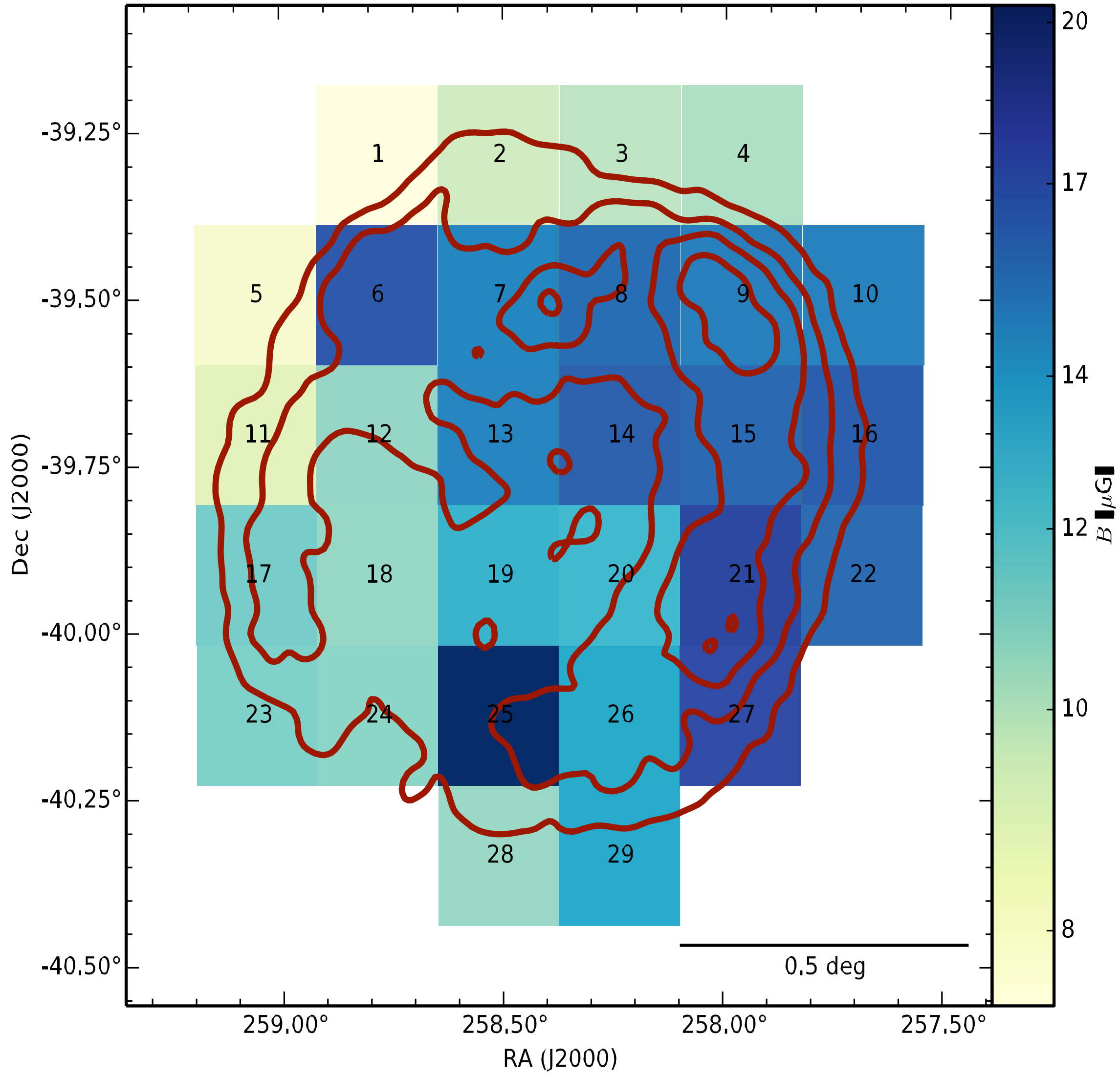
Mapping the Magnetic Field

Eger et al. ICRC 2015

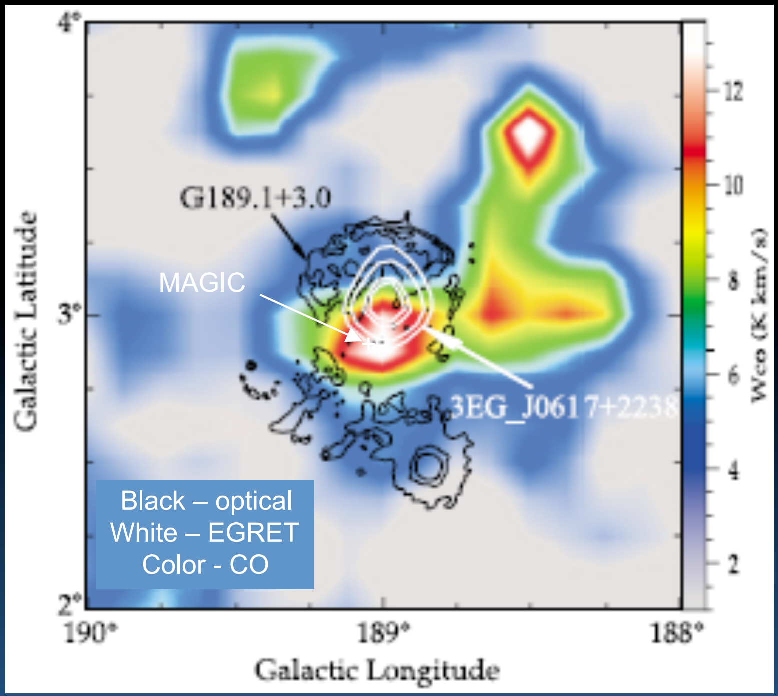


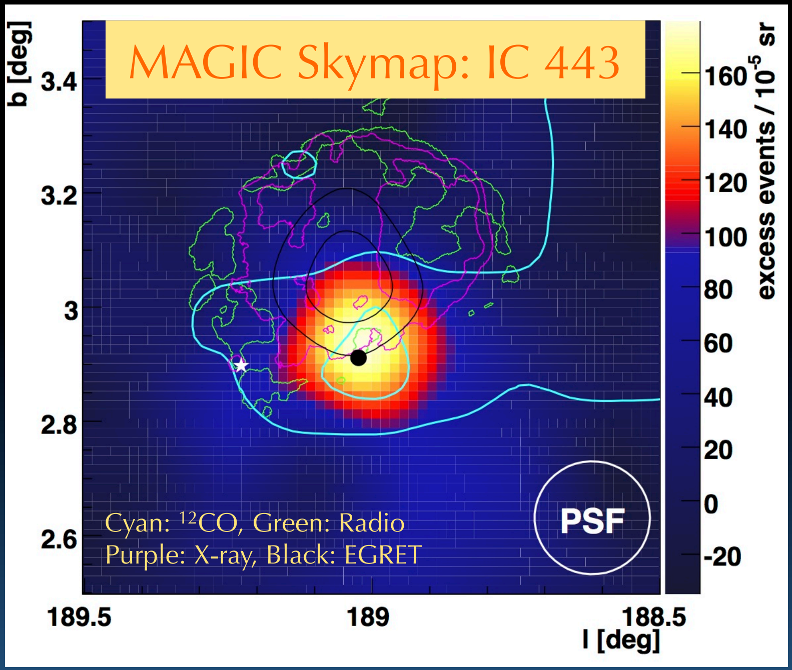


B-field map



IC 443: Jellyfish Nebula

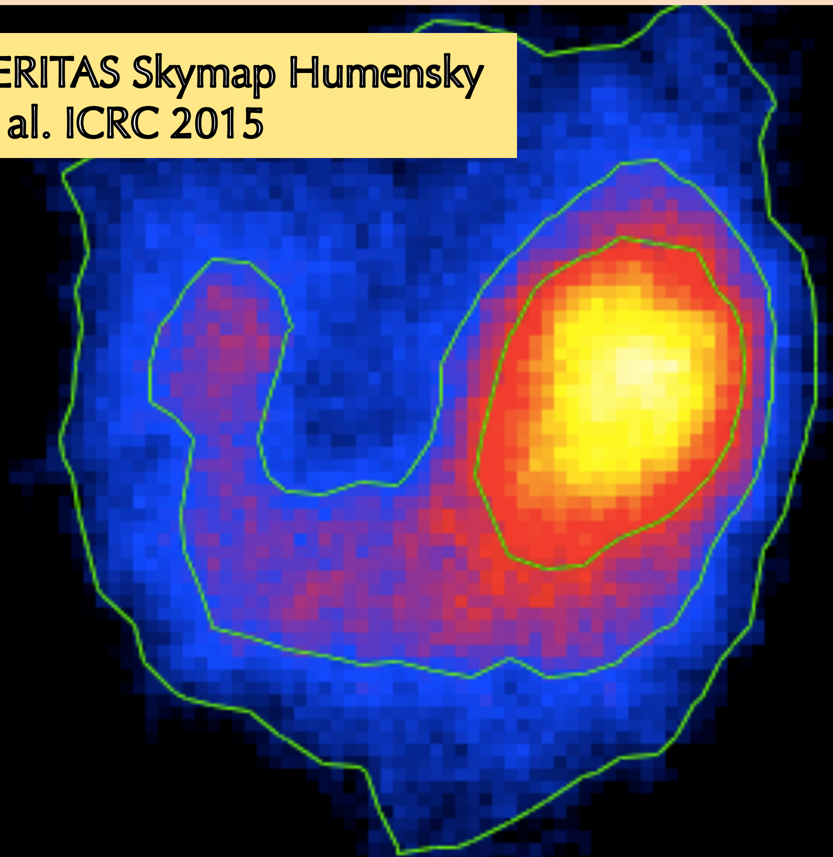


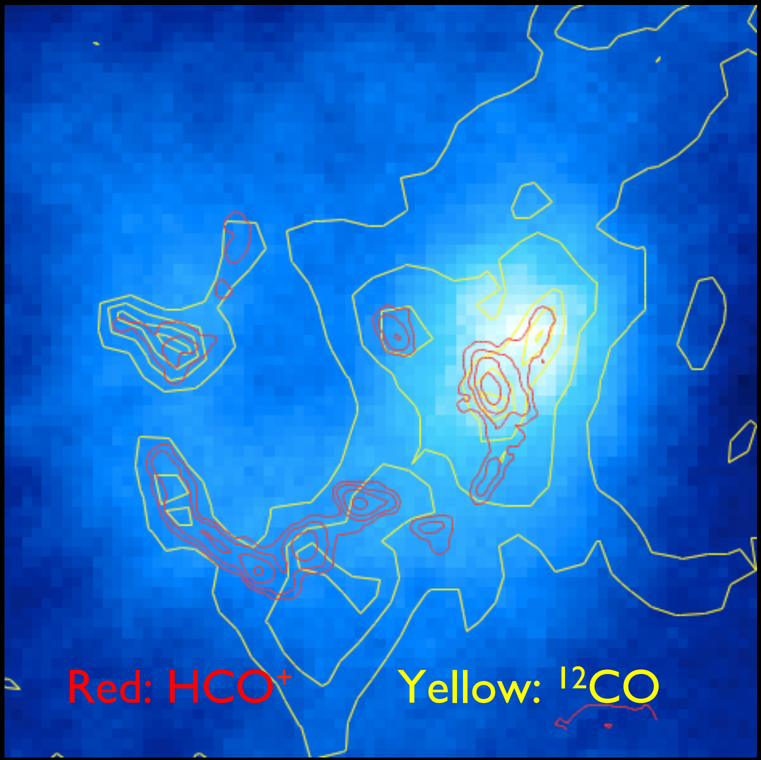


- Distance ~ 1.5 kpc. Age ~ 30,000yr. Distinct shell in radio, optical.
- Shell interacting with molecular cloud → potential target material.
- PWN at southern edge of shell.
- Maser emission suggests SNR shock interacting with cloud.

- Discovery in TeV by MAGIC, followed by VERITAS (2007).
- Fermi Observations, 5-50 GeV.
- Fermi location consistent with VERITAS – Angular Extent ~ 0.27°.
- *Compelling reasons to search for TeV emission from IC 443: γ s from cosmic rays, or from the PWN?*

Resolving the Jellyfish Nebula in TeV γ-rays

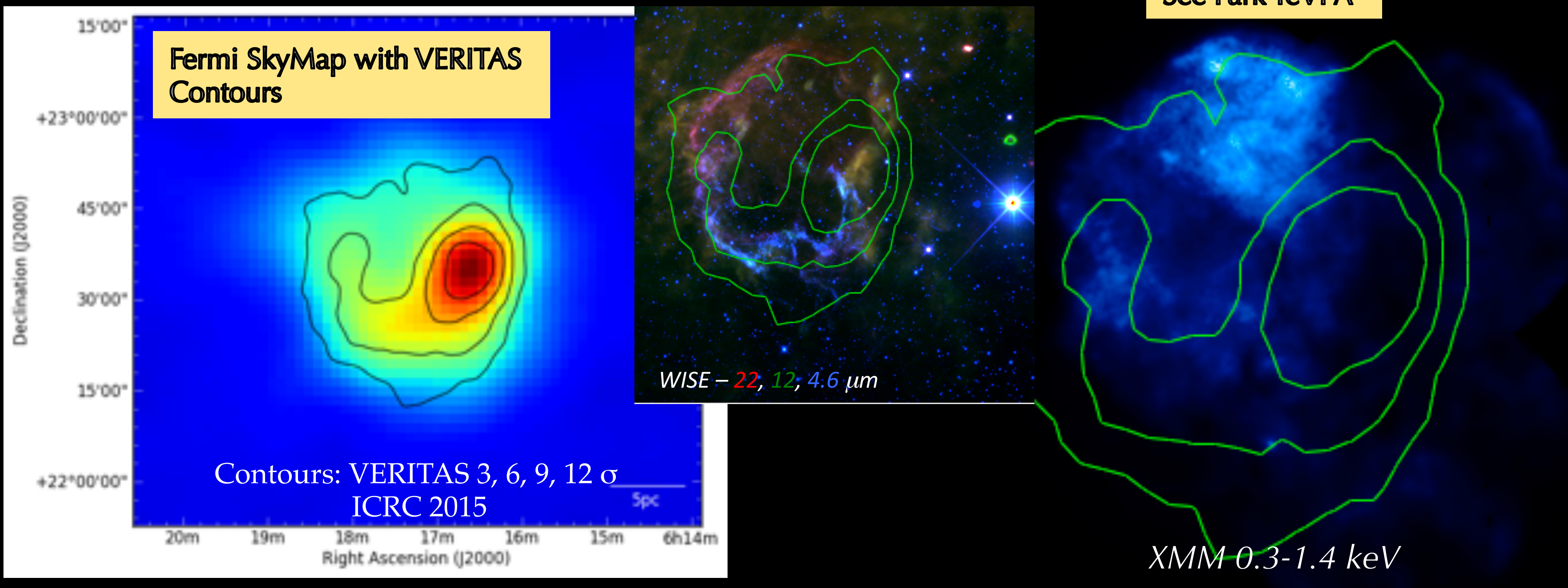




- Strong spatial correlation of γ-ray emission with masers and molecular gas.
- The centroid of the emission corresponds to the densest part of the MC.
- TeV emission fills the northeast lobe and SNR/MC interaction regions.
- Strongest where maser emission brightest.
- Entire shell appears to be accelerating particles.

Resolving the Jellyfish Nebula (IC 443) in TeV γ-rays

See Park TeVPA

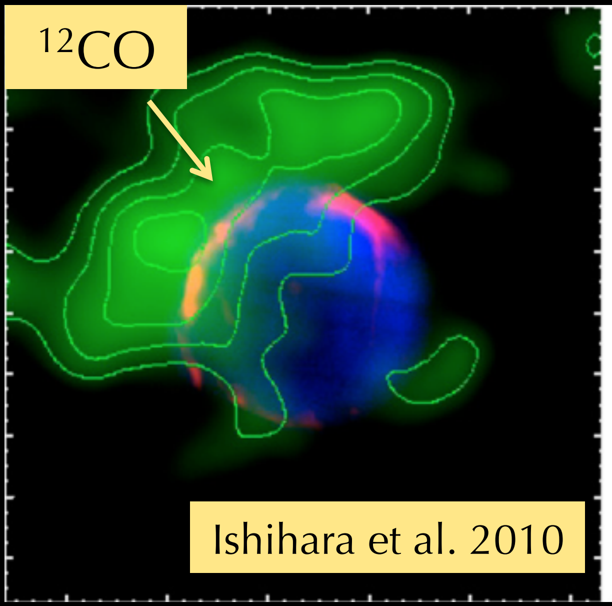


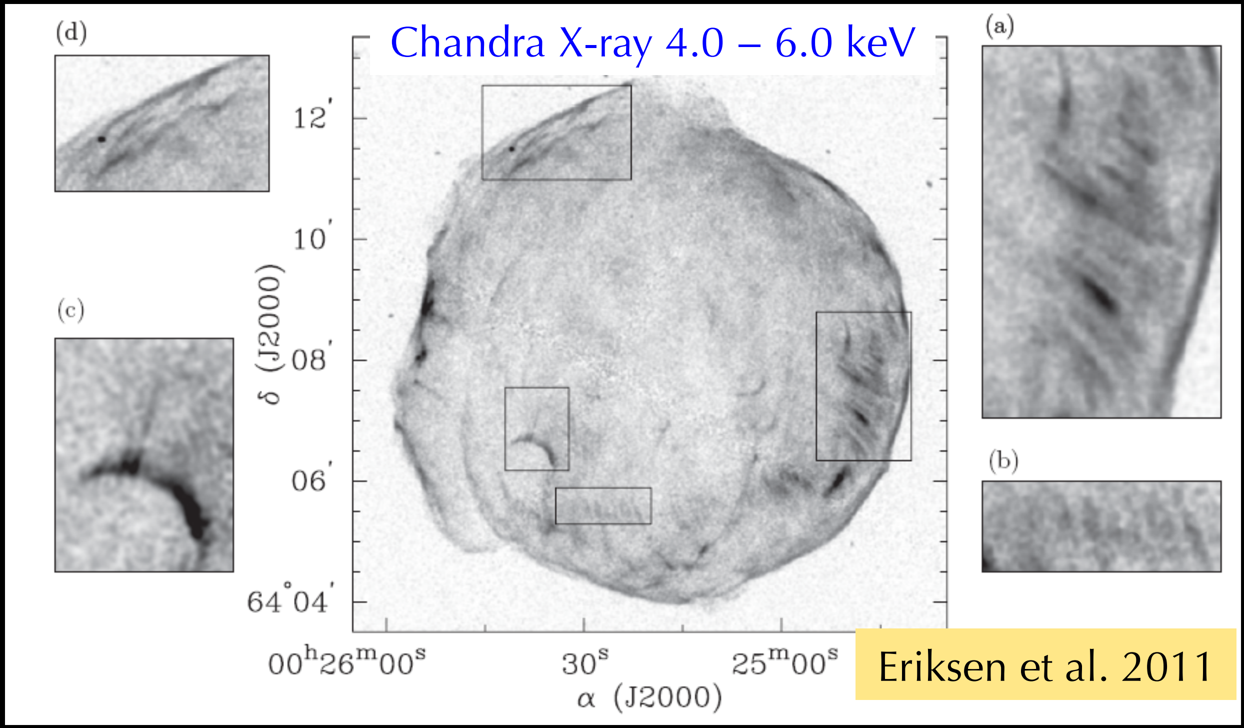
Humensky et al. ICRC 2015

- GeV/TeV emission show remarkable spatial correlation
- Anti-correlation with thermal X-rays
- Spectra from different regions within the remnant will help to probe the environmental dependence of cosmic-ray diffusion.

Single population of CR interacting with swept up / shocked gas?

Tycho: Well-Studied SNR

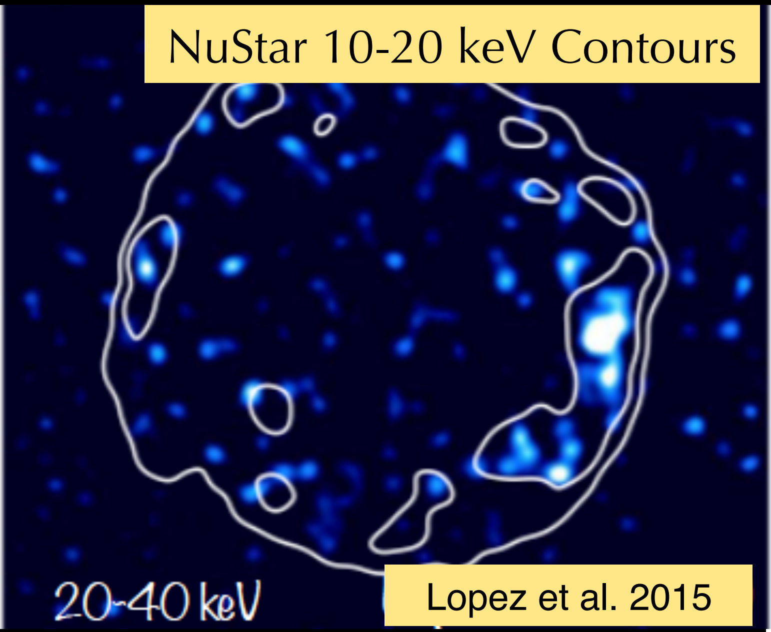


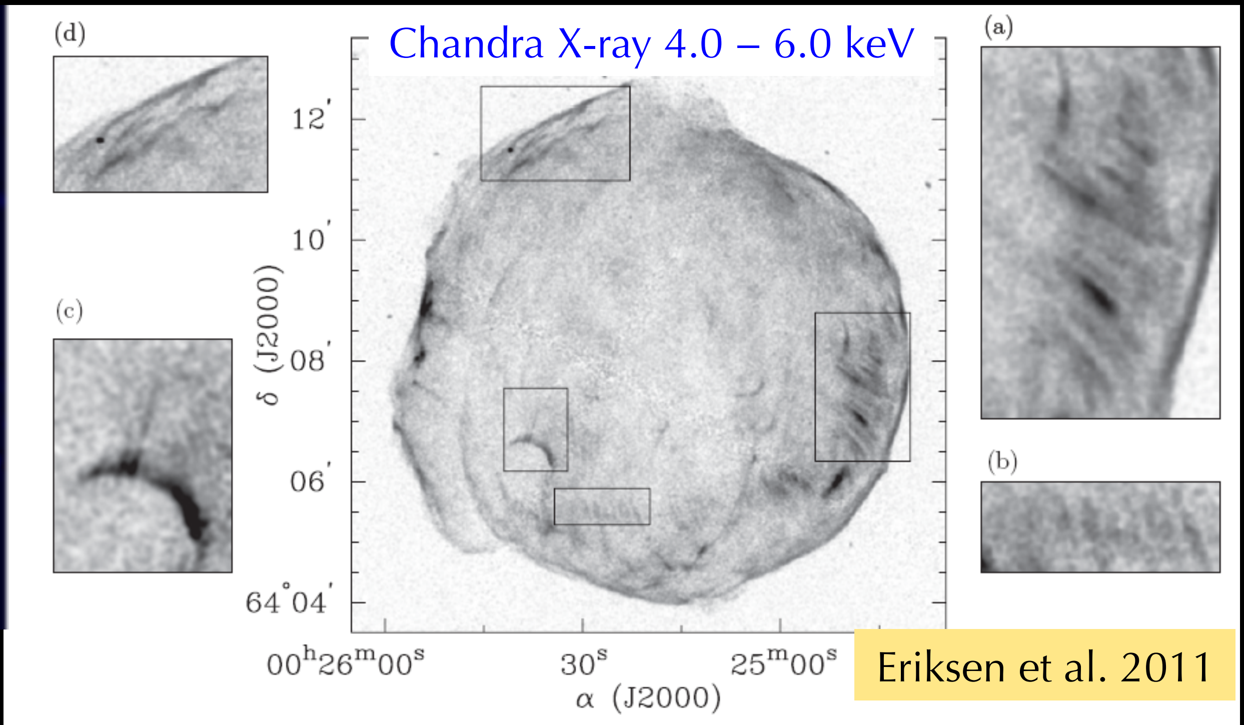


- Age : ~ 440 yr
- Distance of 2-5 kpc
- Type Ia SNR, exploded in a relatively clean environment
- Nearby MC in NE side?

- X-ray shows detailed non-thermal emitting features, manifesting the shock fronts
- Hard X-ray emission up to 40 keV
- Bright X-ray rims and filaments likely evidence for electrons up to ~100 TeV

Tycho: Well-Studied SNR

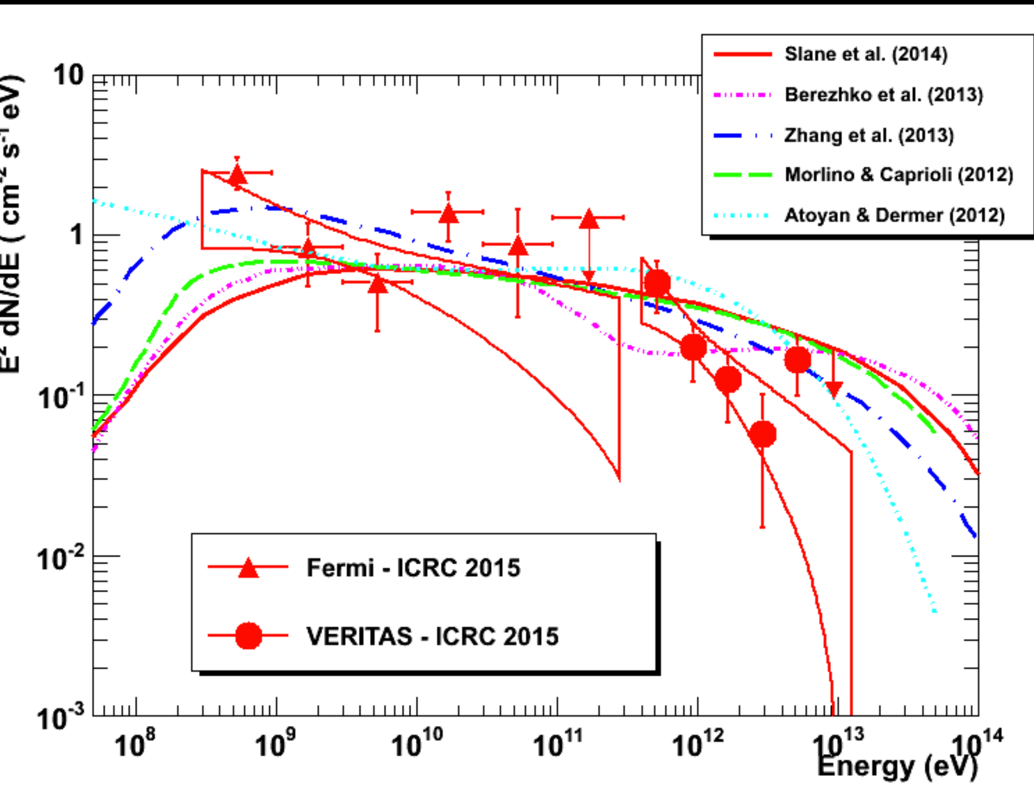


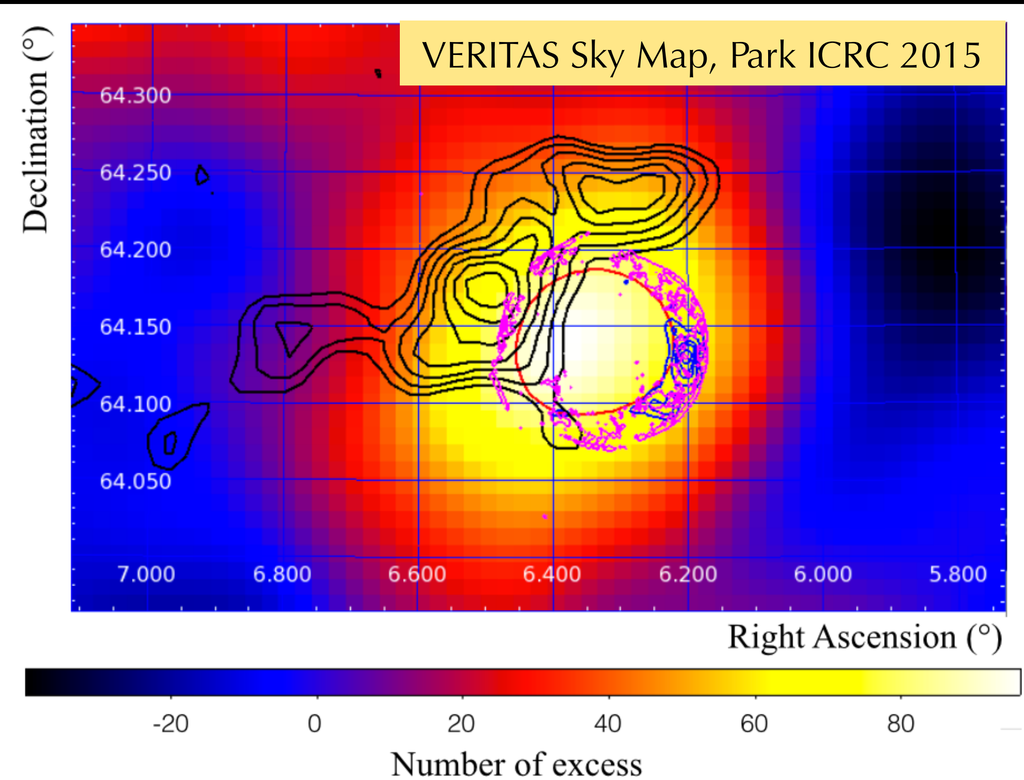


- Hard X-ray emission (NuStar) up to 40 keV
- Evidence of magnetic turbulence
- Bright X-ray rims and filaments likely evidence for electrons up to ~100 TeV

What is the maximum energy of particles accelerated in Tycho?

Tycho: Hadronic Accelerator?





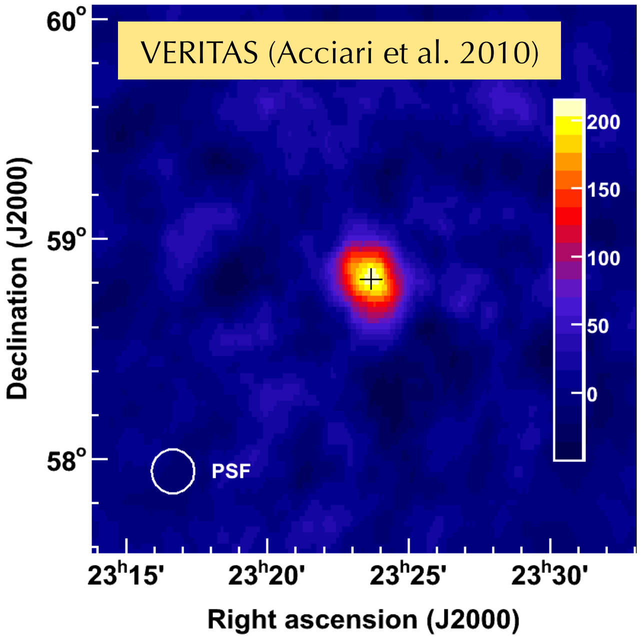
CO cloud / X-ray (Chandra, E>4.1 keV) / X-ray (NuSTAR, 20 keV<E<40 keV)/Red (Fermi, 95% C.L. centroid)

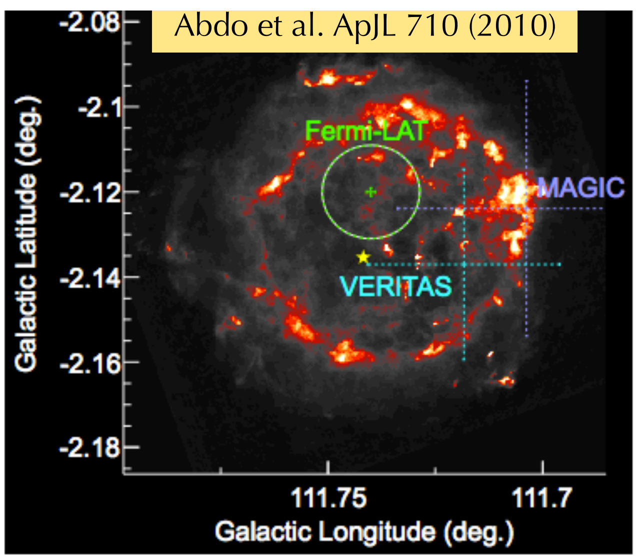
Softness of γ-ray emissions for energies higher than 400 GeV produced tension with all of the models

- Possible interaction with Molecular Cloud
- Detection in GeV-TeV energy by Fermi & VERITAS
- Spectrum favors hadronic models

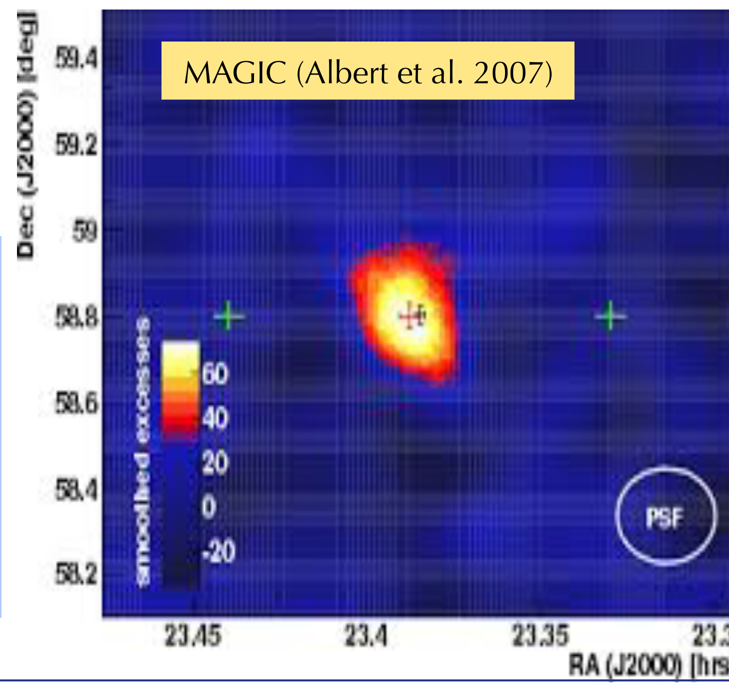
Supernova Remnants: Cas A

- Young (330 yr), shell-type SNR. D ~ 3.4 kpc.
- Radio – sub mm – IR to X-ray emission is synch.
- Morphology of non-thermal X-ray emission is dominated by faint, well-defined filaments and knots, which are sites of CR acceleration.
- First detected in TeV by HEGRA (Aharonian et al. 2001)
- MAGIC & VERITAS detections in TeV (~ 3.5% Crab)
- Fermi detection: Point source. No pulsations from CCO.

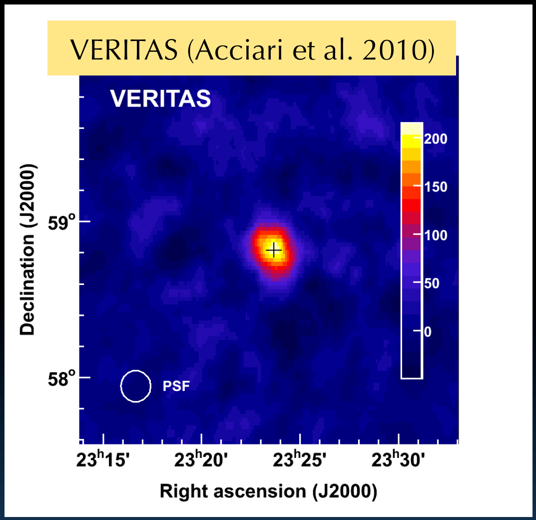


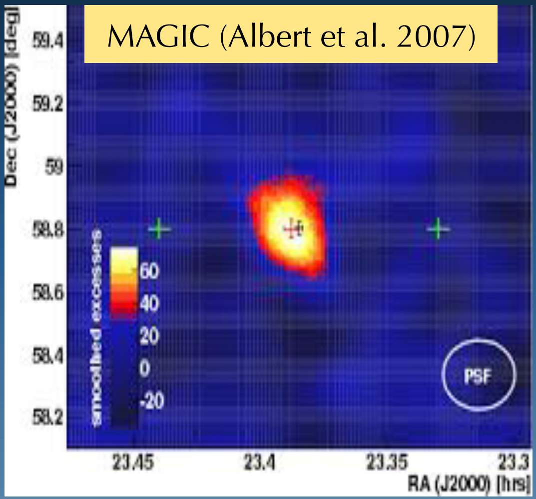


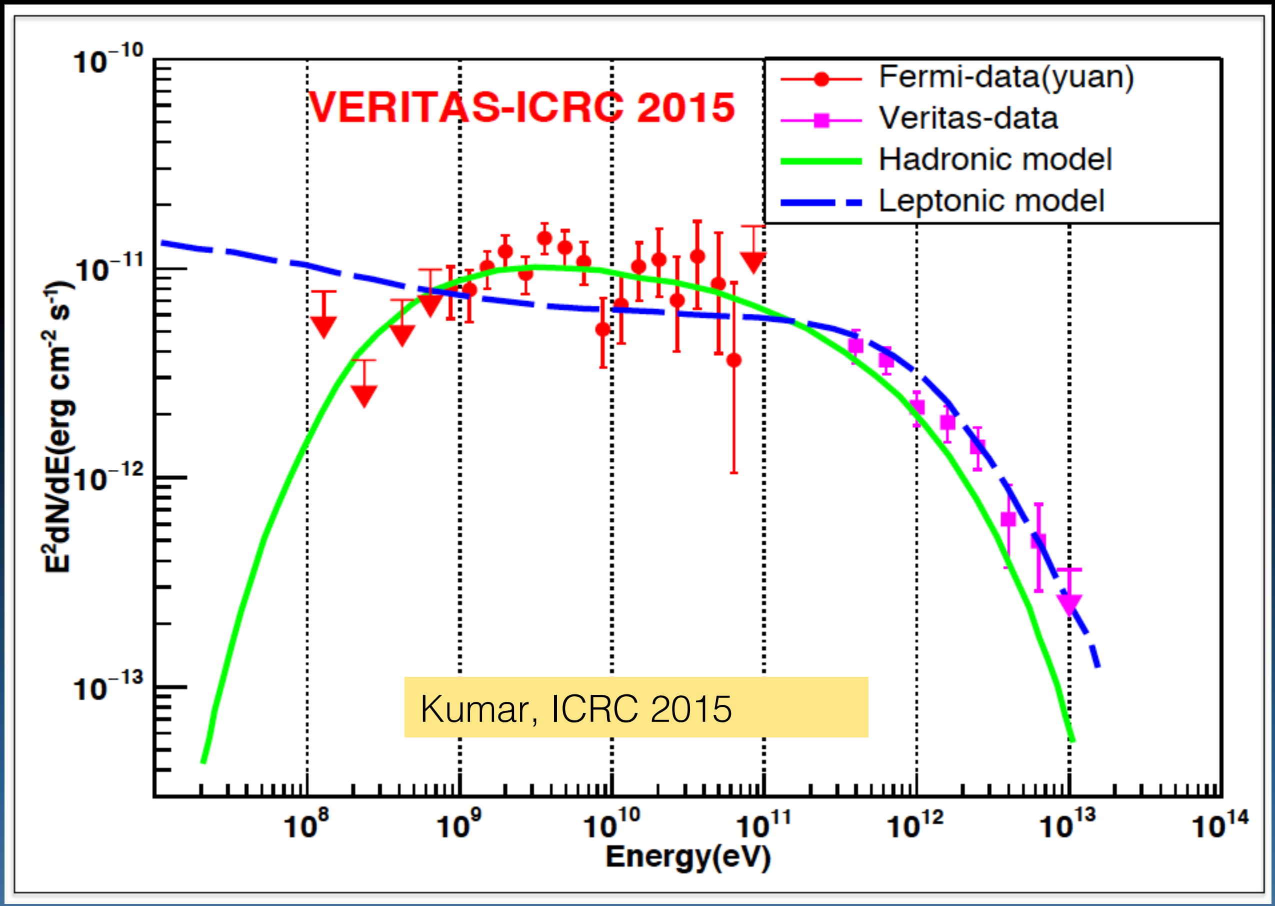
- *Fermi spectrum favors scenario in which the GeV γ rays are emitted in the shell of the SNR.*
- *Hadronic model is favored, but leptons not ruled out.*



Deep exposures of Cas A: Radiation Models





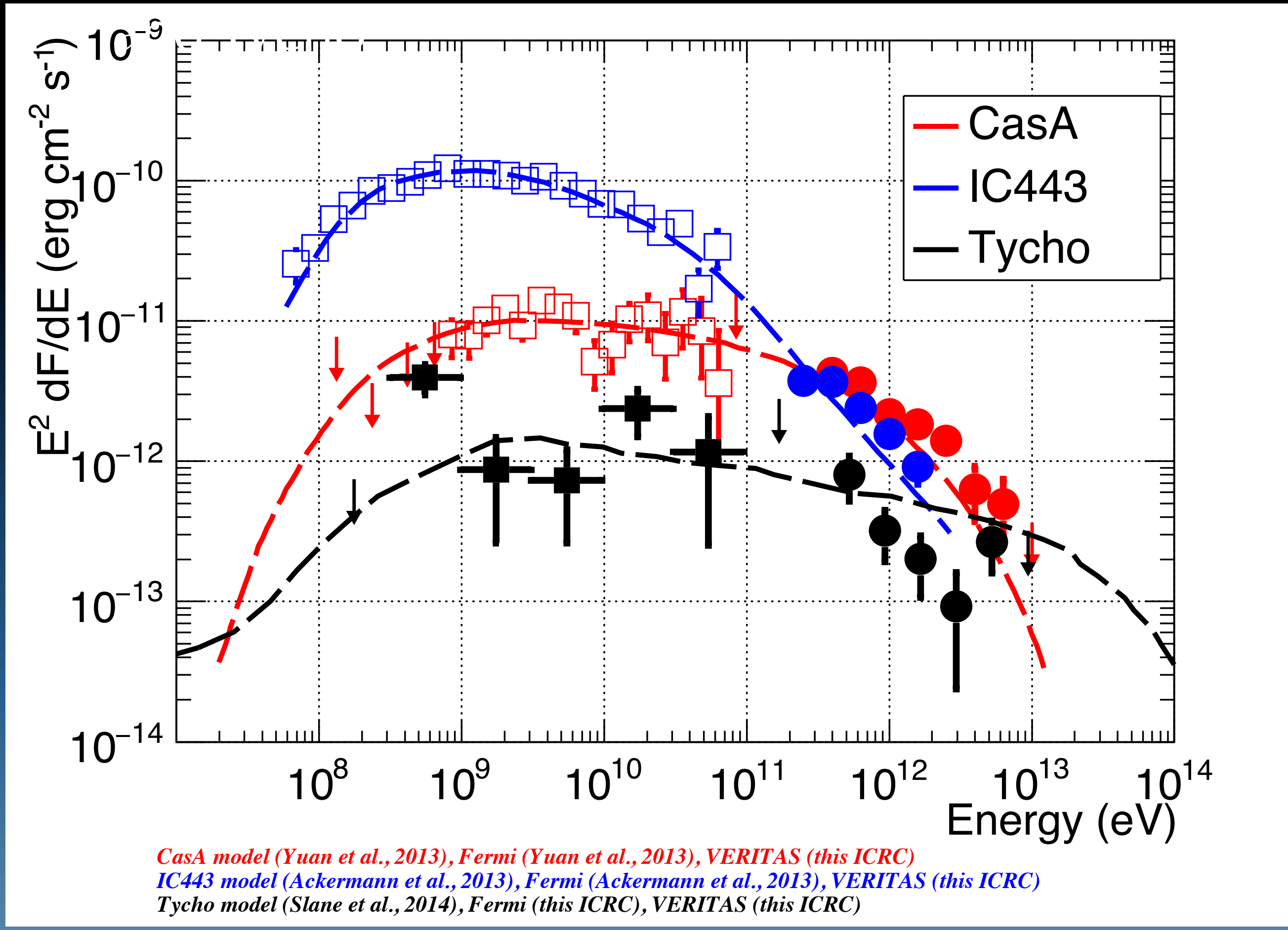


- Hadronic model is preferred at lower energy (Yuan et al. 2013)
- At higher energy both leptonic and hadronic mechanisms may contribute (Saha et al. 2013)

Deep exposures of three northern SNRs

- New, precise spectra of young and interacting SNRs will Investigate the mechanisms of cosmic-ray acceleration .
- Probe the distribution of energetic particles in the acceleration region
- Study the importance of SNR type, age, target material, magnetic fields, progenitor

VERITAS: 150 hours of exposure for IC443

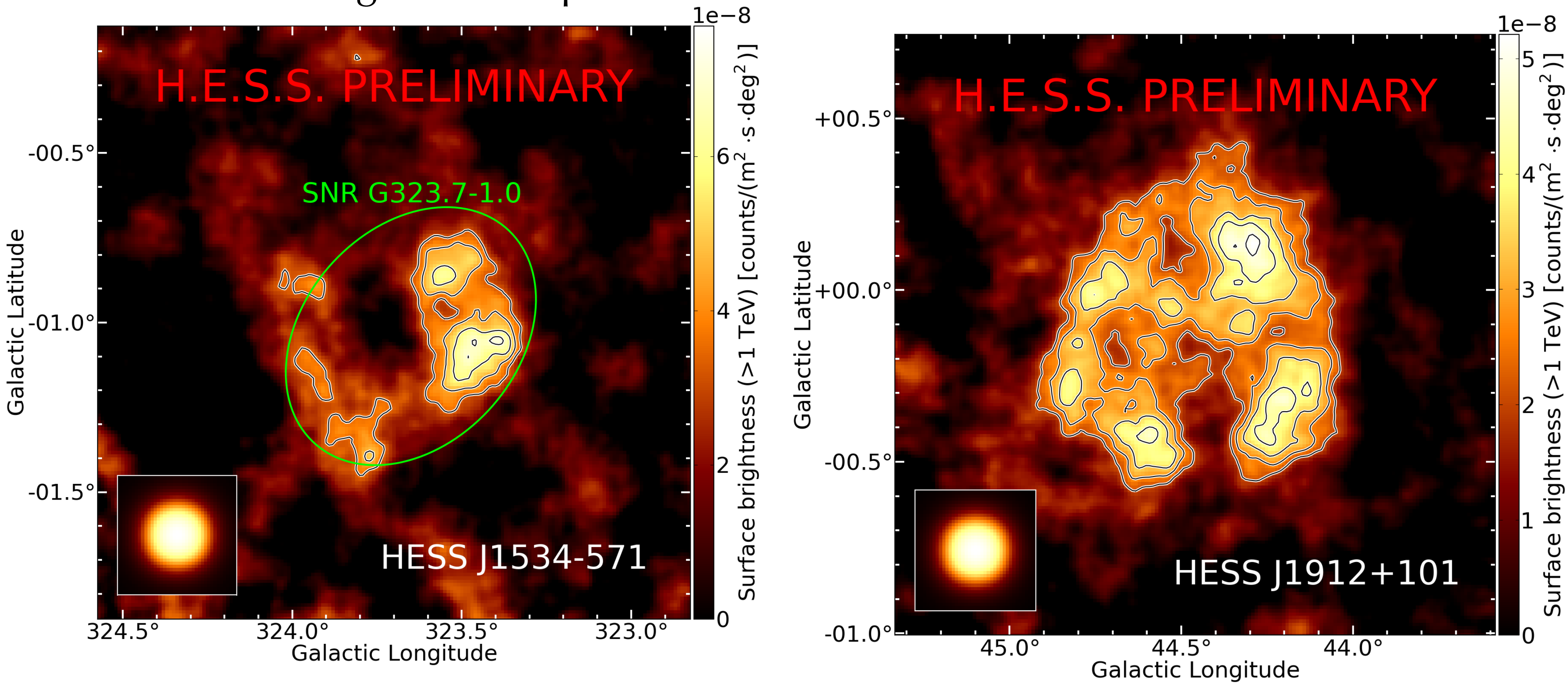


Humensky, Park, Kumar, ICRC 2015

H.E.S.S. SNRs discovered in GPS

TeV surface brightness maps of two unidentified sources

Pühlhofer et al. arXiv 1509.03872

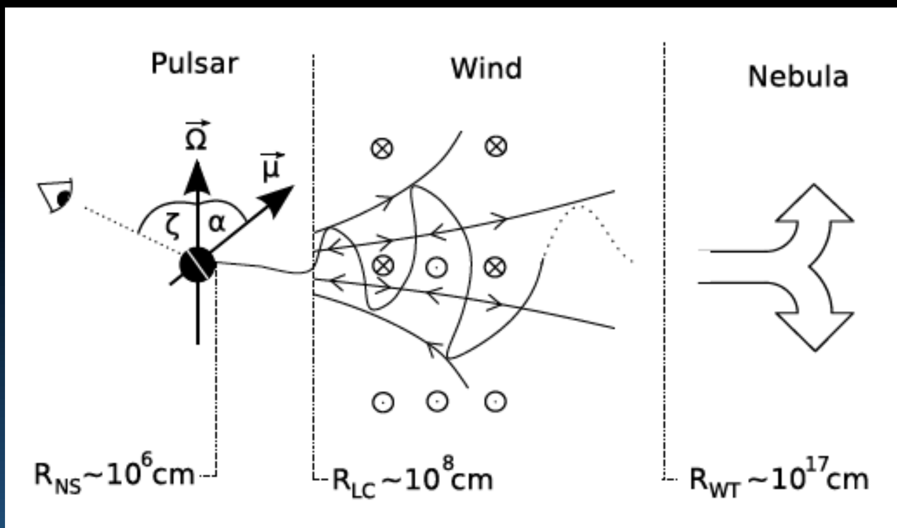


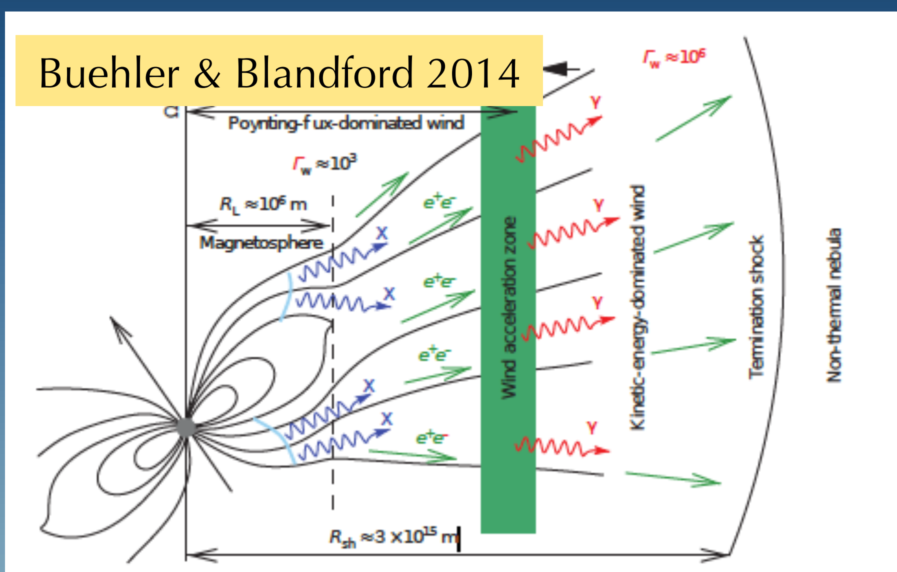
- HESS J1534-571: No X-ray emission is found from the source region, excluding non-thermal X-ray emission at the level detected from the other known TeV SNR. Excellent candidate for proton-dominated processes.
- HESS J1912+101: New data shows shell-like morphology, first TeV-only shell candidate

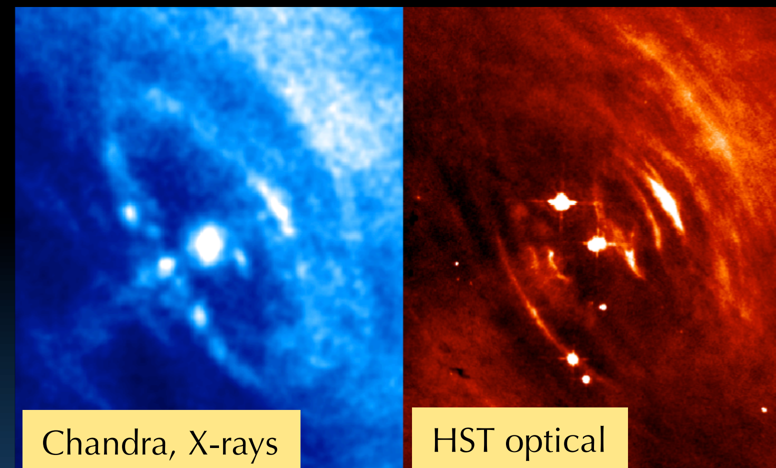
Pulsed Radiation at TeV

The Crab Pulsar at TeV Energies

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



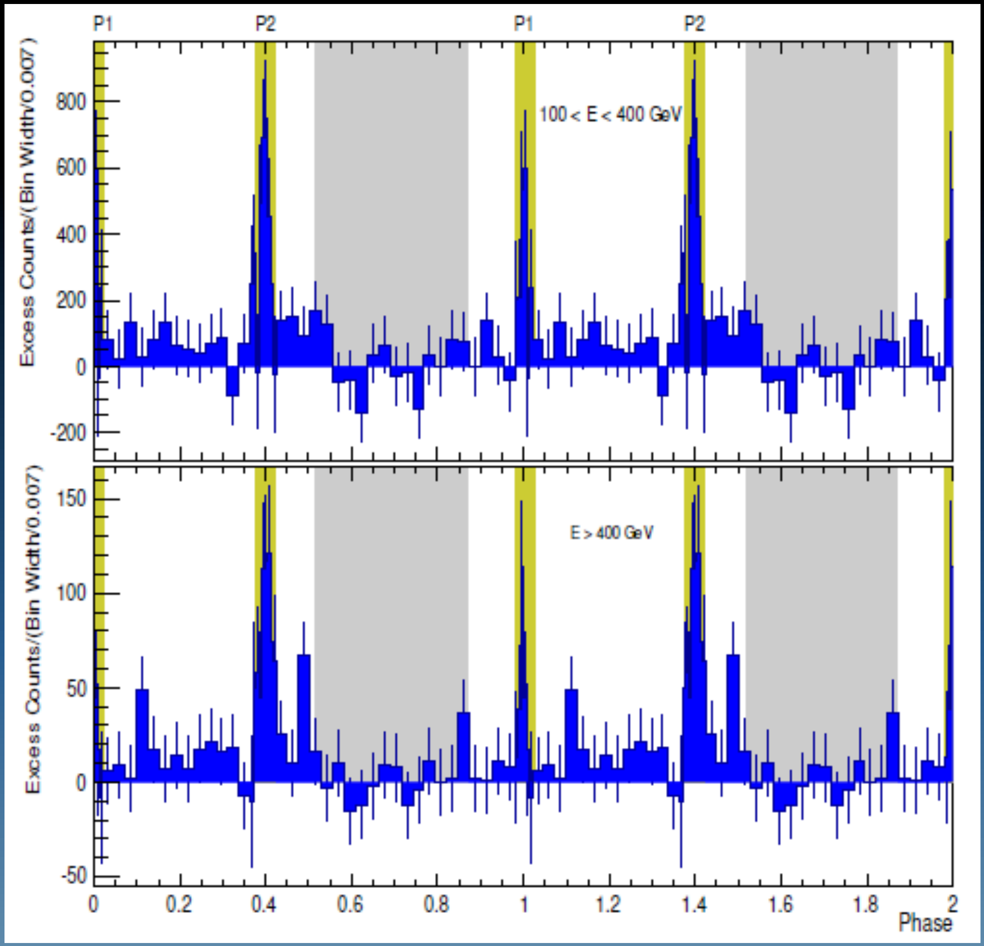




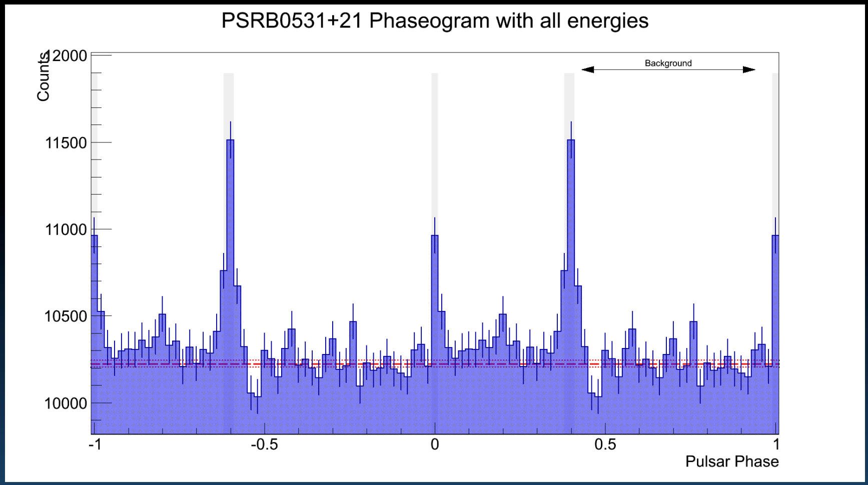
- First detection of emission above 25 GeV from a pulsar by MAGIC (2008, Science)
- Detection of pulsed emission in the 120-400 GeV by VERITAS (2011, Science)
- Spectrum between 25-500 GeV by MAGIC Bridge emission detected >50 GeV by MAGIC

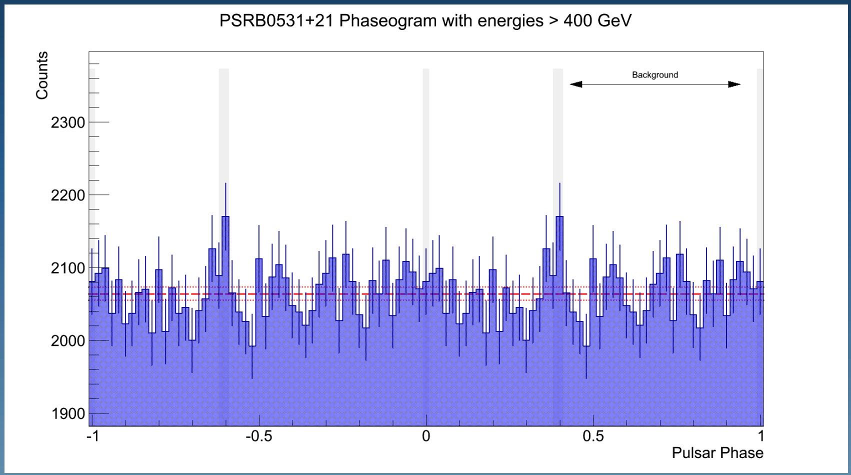
The Crab Pulsar at TeV Energies

- Pulsed emission in the 120-400 GeV range not expected theoretically – challenge to pulsar models.



MAGIC, de Oña Wilhelmi, ICRC 2015

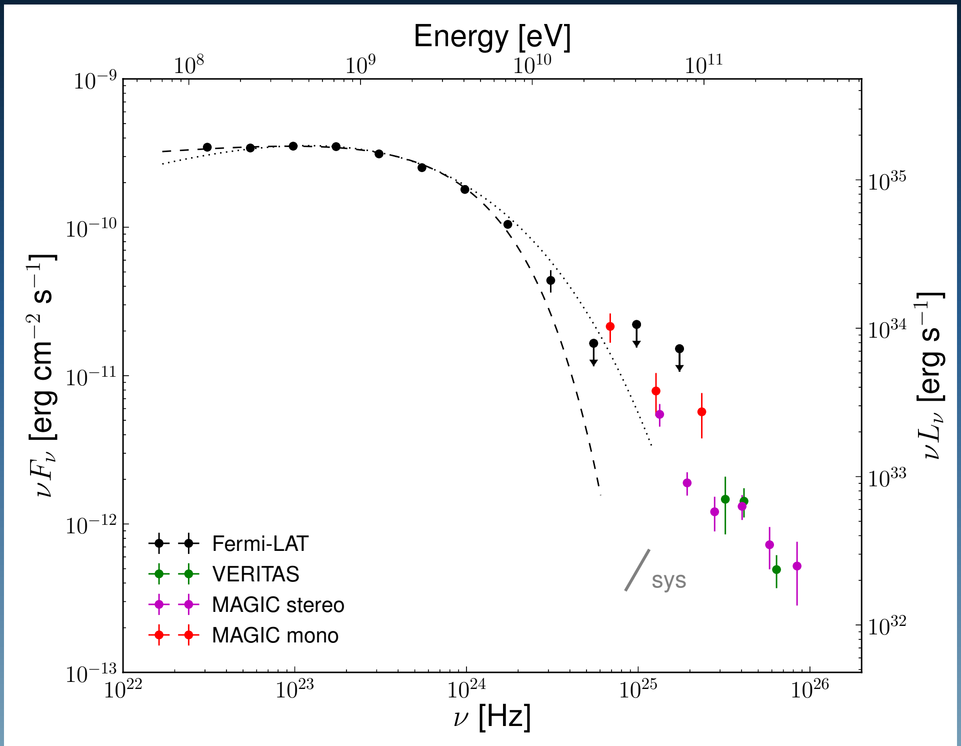




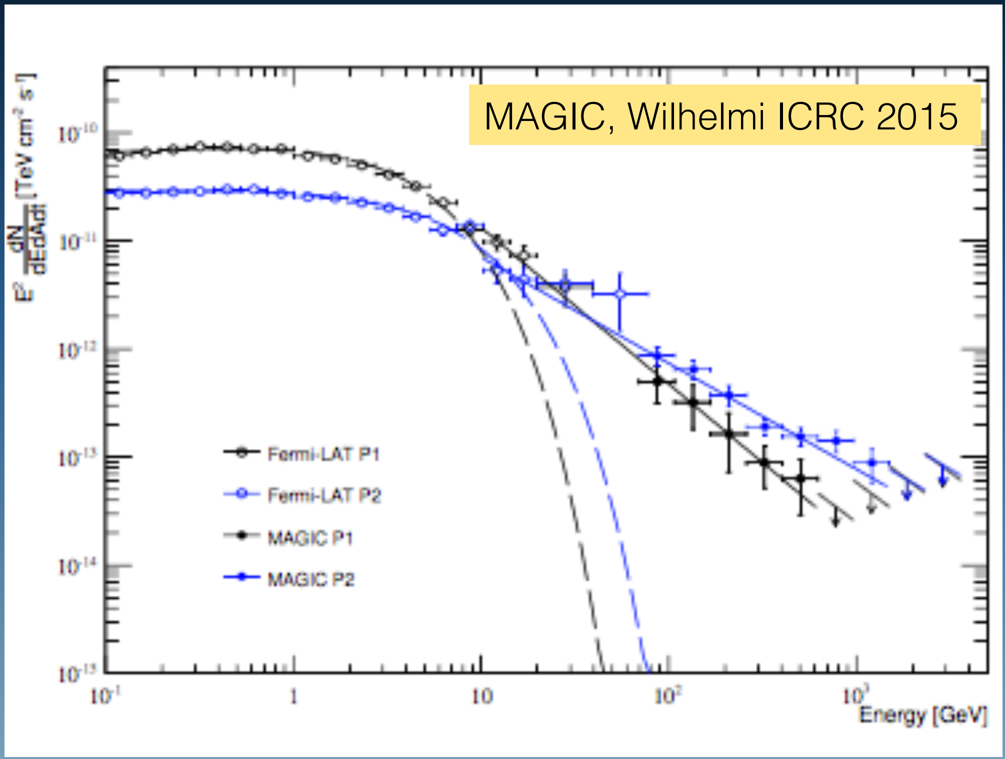
VERITAS, Nguyen, ICRC 2015

The Crab Pulsar Spectrum at TeV Energies

- Challenges emission models: Curvature radiation unlikely to be responsible for pulsed VHE emission.
  - Emission from the neighborhood of Light Cylinder (r ~1600km) .
- MAGIC measures spectrum for pulsar > 1.2 TeV
- Fermi-TeV fits show IC emission from ~ 10 GeV to > 1 TeV.
- TeV pulsations may be used to put quadratic limits for LIV.



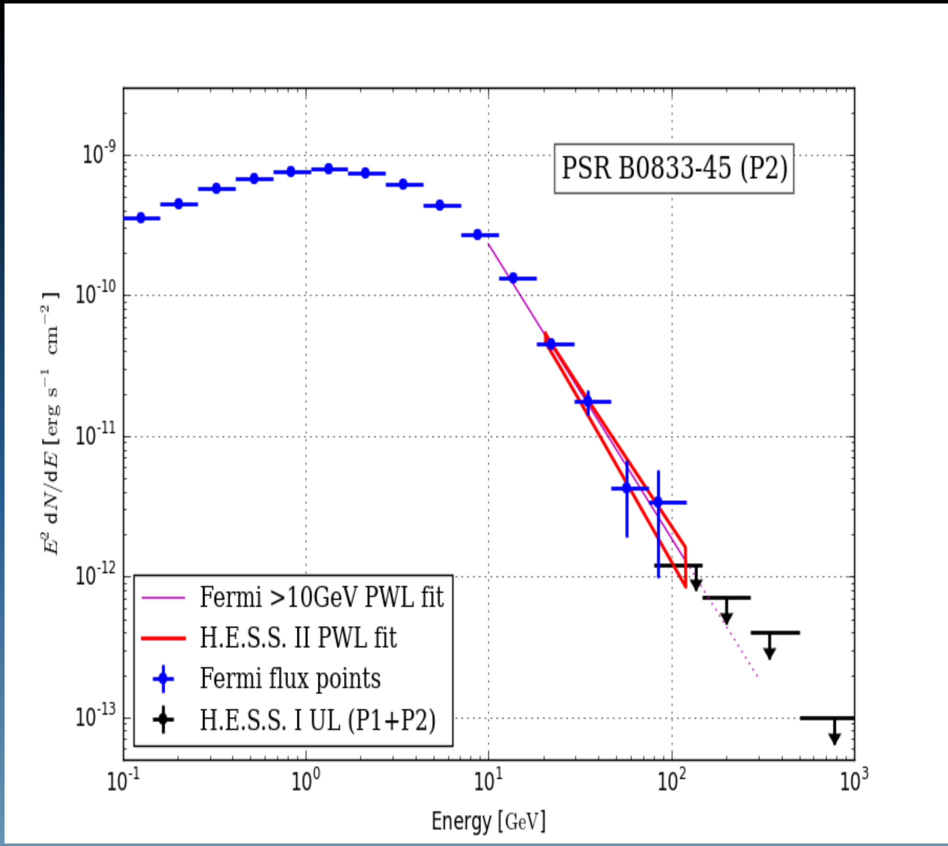
Buehler & Blandford 2014



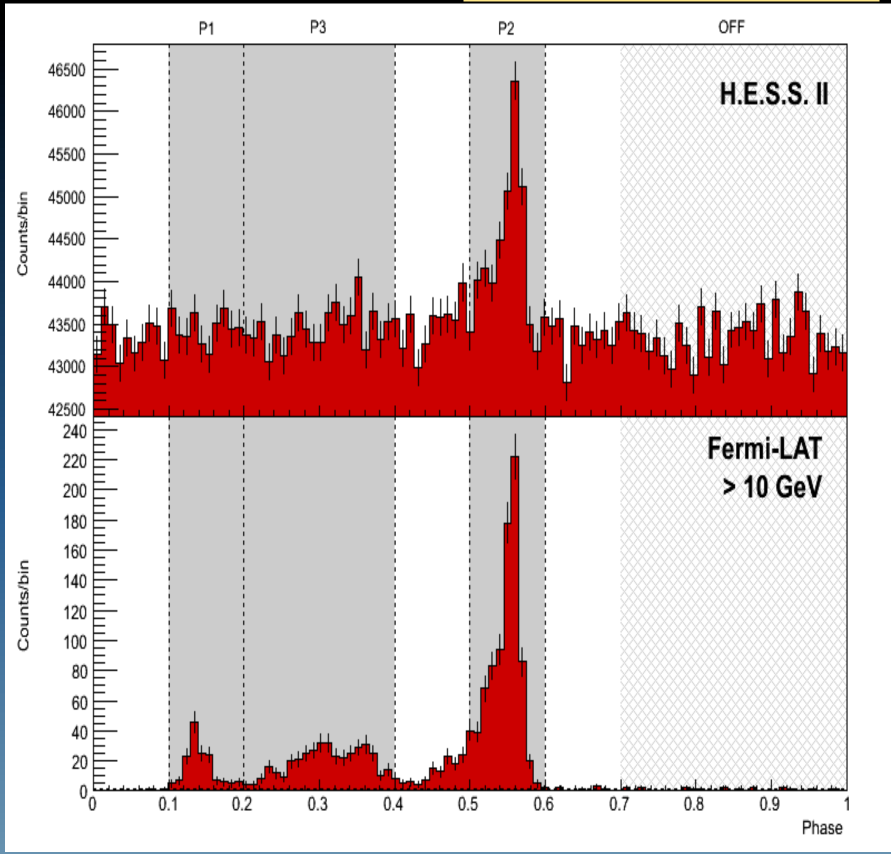
Vela Pulsar (Second VHE Pulsar)

- Calibration source for H.E.S.S at the threshold in standard observation mode
- γ-rays detected as low as 10 GeV!

See Rudak, TeVPA



Gajdus, ICRC 2015



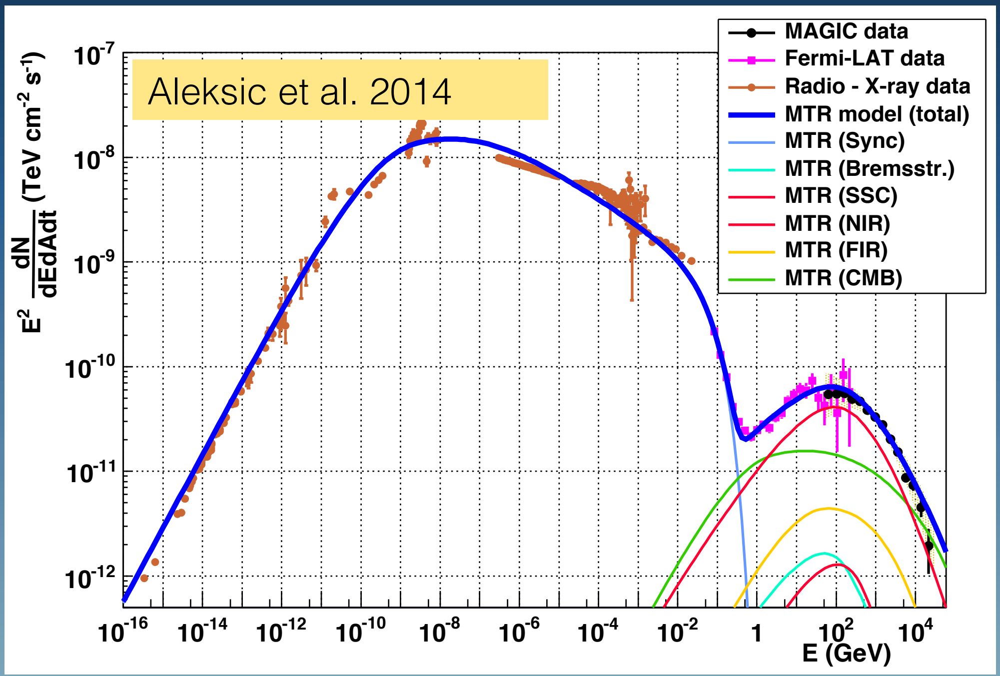
Phase-folded distribution of events of the Vela Pulsar with H.E.S.S.-II and Fermi- LAT

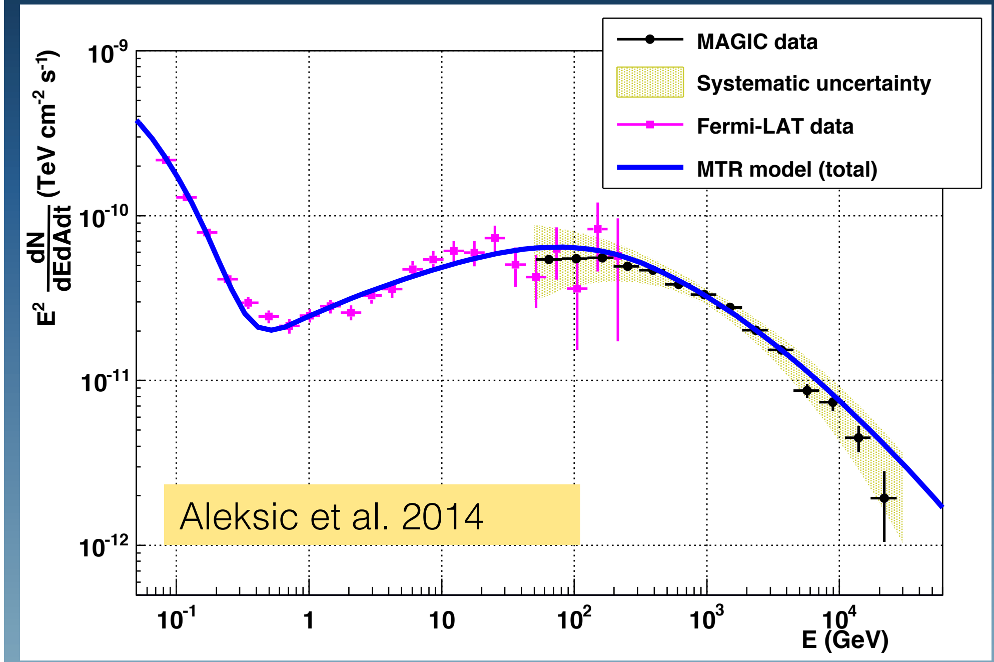
Pulsar Wind Nebulae

dominant population of Galactic VHE sources

The Crab PWN: 50 GeV – 30 TeV

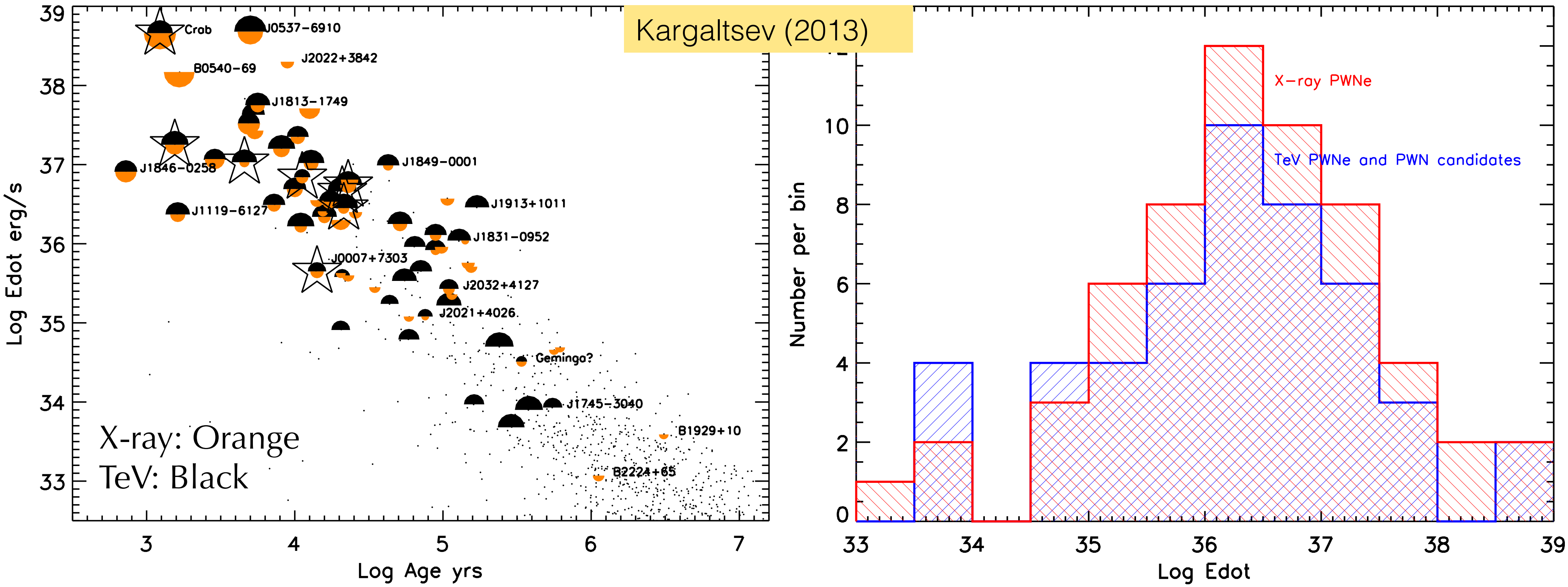
- Crab Nebula is a very effective accelerator but not an effective IC gamma-ray emitter.
- The Crab has a large spin-down reservoir (~10^{38} erg s), but γ-ray lum. << spin-down power, because of a large magnetic field.
- In the future, CTA is expected to detect a zoo of PWNe, allowing detailed population studies: less powerful pulsar --> weaker magnetic field --> higher gamma-ray efficiency.





TeV PWNe

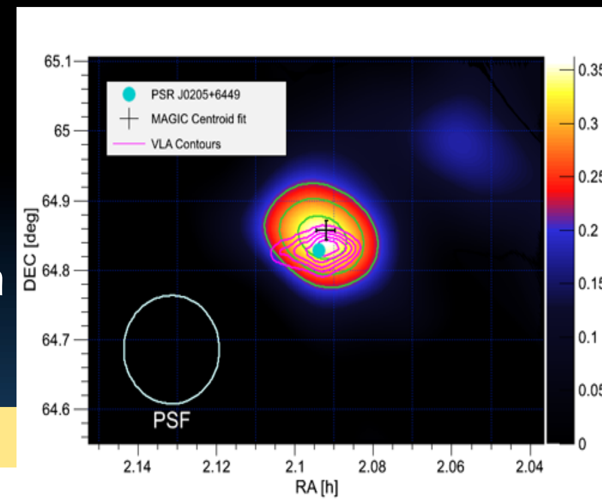
- What is the connection between pulsar winds and TeV emission?
- Are pulsars a source of local leptonic cosmic rays?



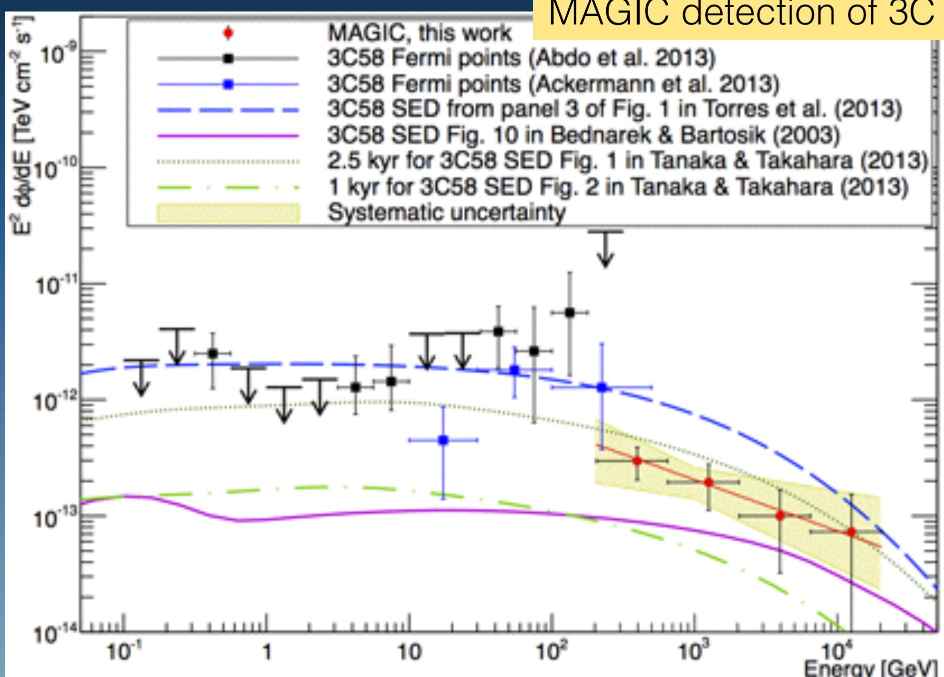
- Are all young and high spin-down power ($\dot{E} > 10^{37}$ erg/s) PWNe high-energy γ-ray emitters? If not, why not?
- Do we understand the evolution of PWNe?

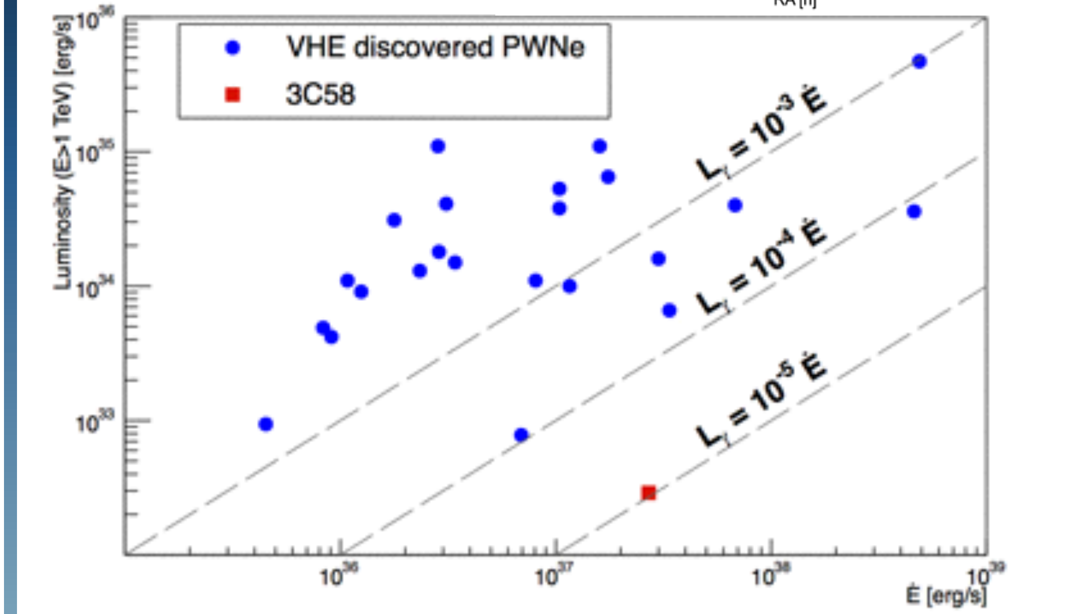
3C 58: MAGIC Detection of the Least Luminous PWN

- Powered by high spin down pulsar PSR J0205+6449, $\dot{E} = 2.7 \times 10^{37}$ erg.s^{-1}
- ~2 kpc (~2 % of Crab pulsar, similar morphology)
- MAGIC discovered TeV emission in 100h of observations (0.65 % CU)
- Magnetic field drawn from models is far from equipartition and low for a young PWN



MAGIC detection of 3C 58 (Lopez-Coto, ICRC 2015)





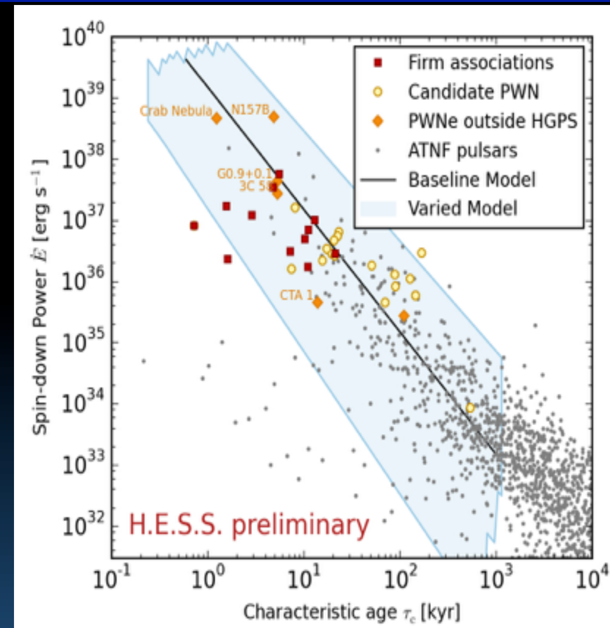
Surveys: PWN population studies

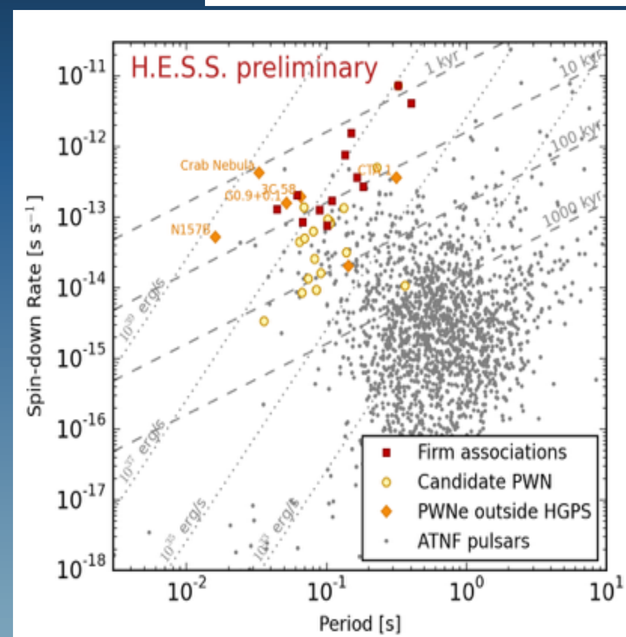
Surveys are good for populations studies

- Statistical behaviour:
  - Most young pulsars associated with PWN

- Some PWN exhibit peculiar characteristics
  - 3C58: very low luminosity (Least luminous TeV PWN) compared to spin-down power
  - (Not efficient accelerator? Weak B Field?)

From de Naurois, ICRC 2015



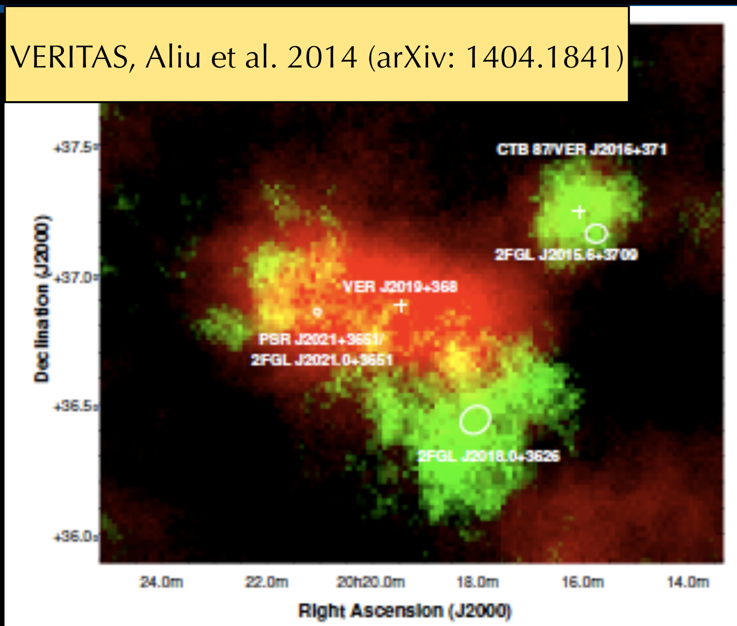


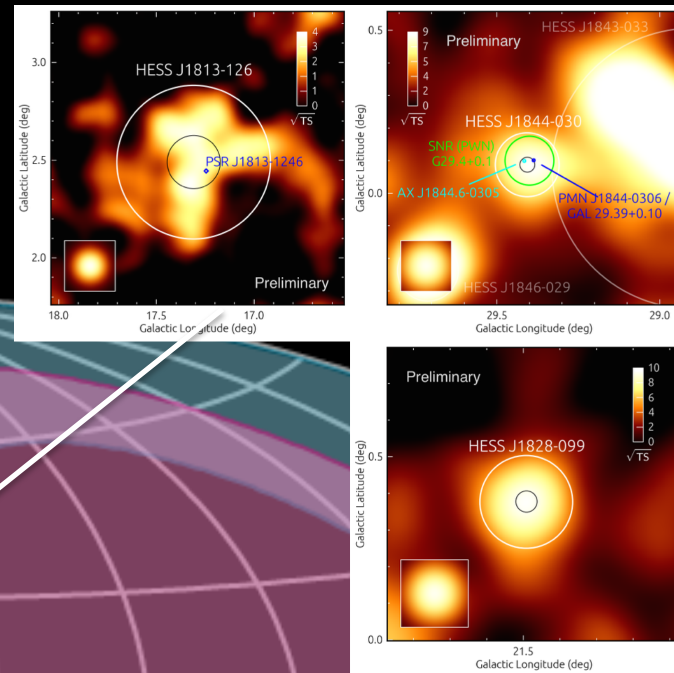
Klepser, ICRC 2015

Unidentified Sources

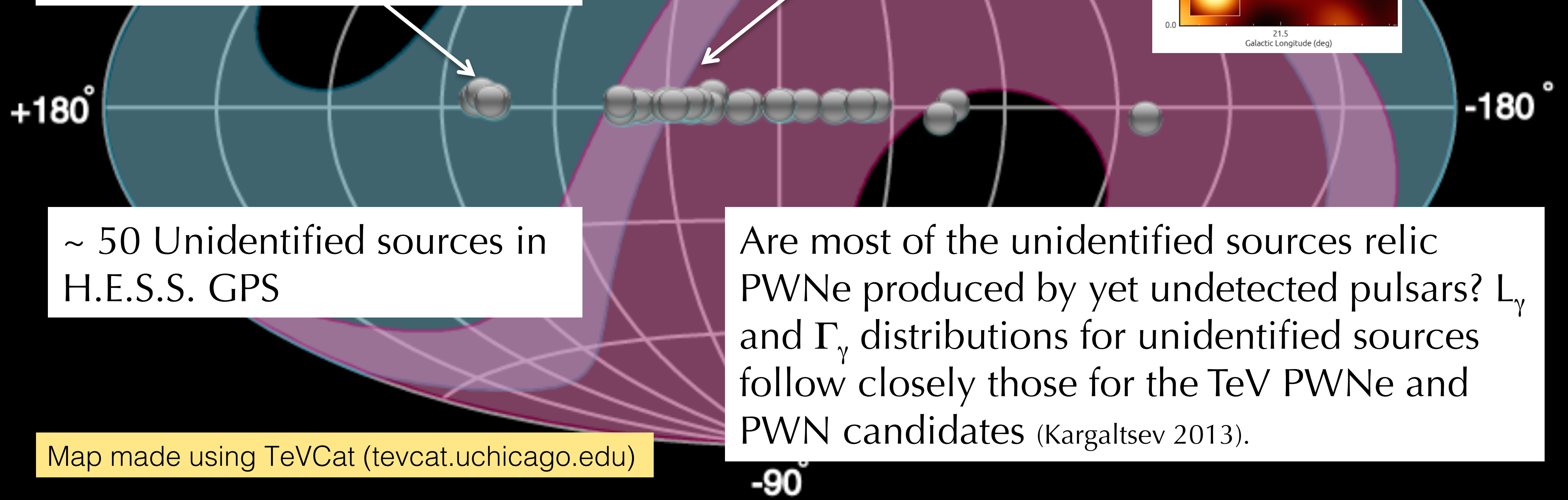
Unidentified TeV Sources

VERITAS, Aliu et al. 2014 (arXiv: 1404.1841)





H.E.S.S., Brun et al., ICRC 2015



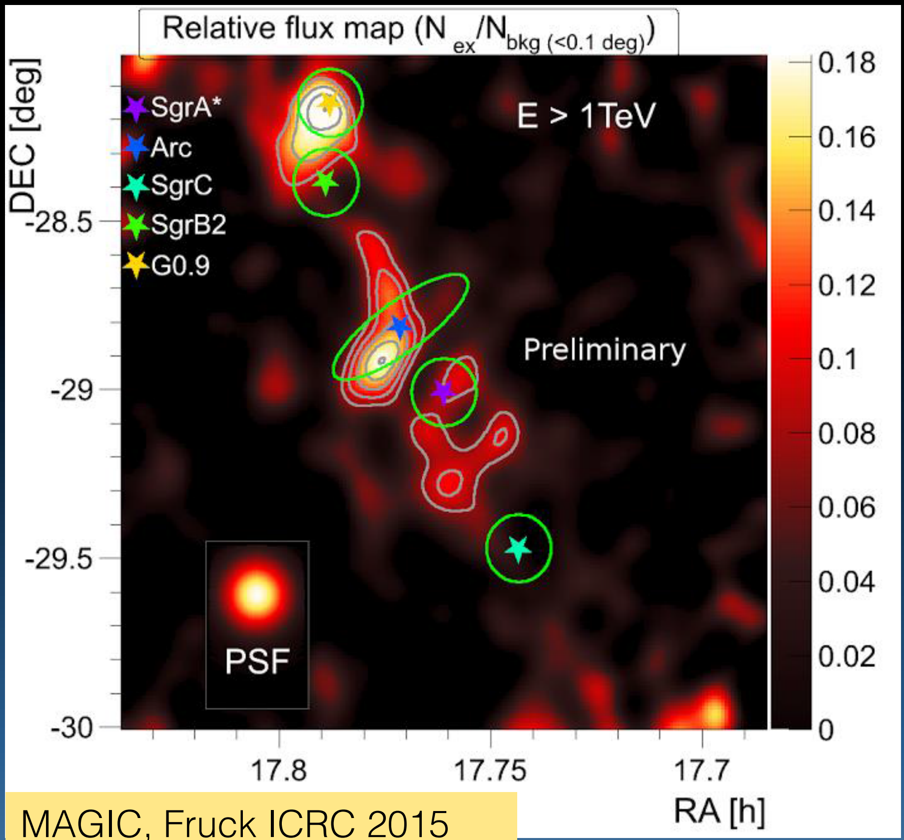
~ 50 Unidentified sources in H.E.S.S. GPS

Are most of the unidentified sources relic PWNe produced by yet undetected pulsars? L_γ and Γ_γ distributions for unidentified sources follow closely those for the TeV PWNe and PWN candidates (Kargaltsev 2013).

Map made using TeVCat (tevcat.uchicago.edu)

The Galactic Center

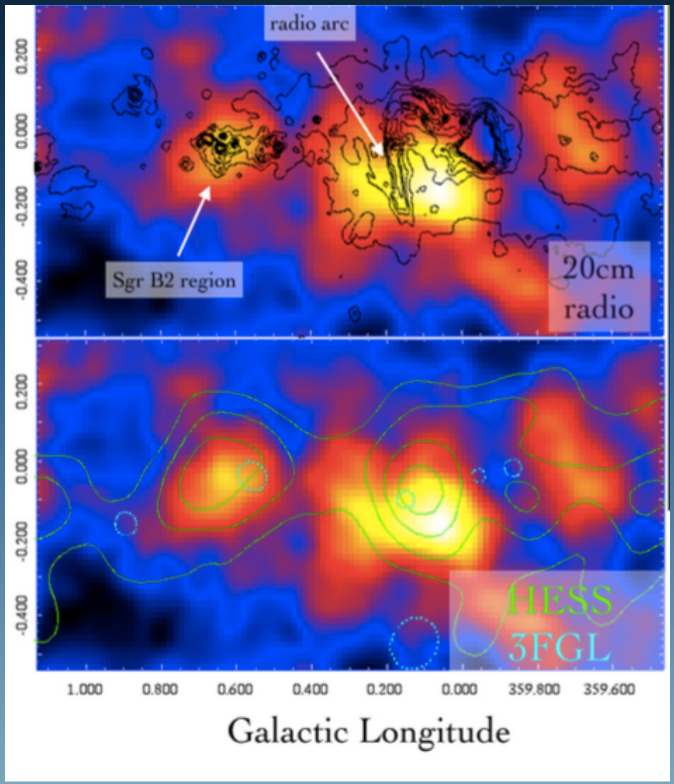
TeV View of the Galactic Center



MAGIC, Fruck ICRC 2015
Also: Fruck TeVPA

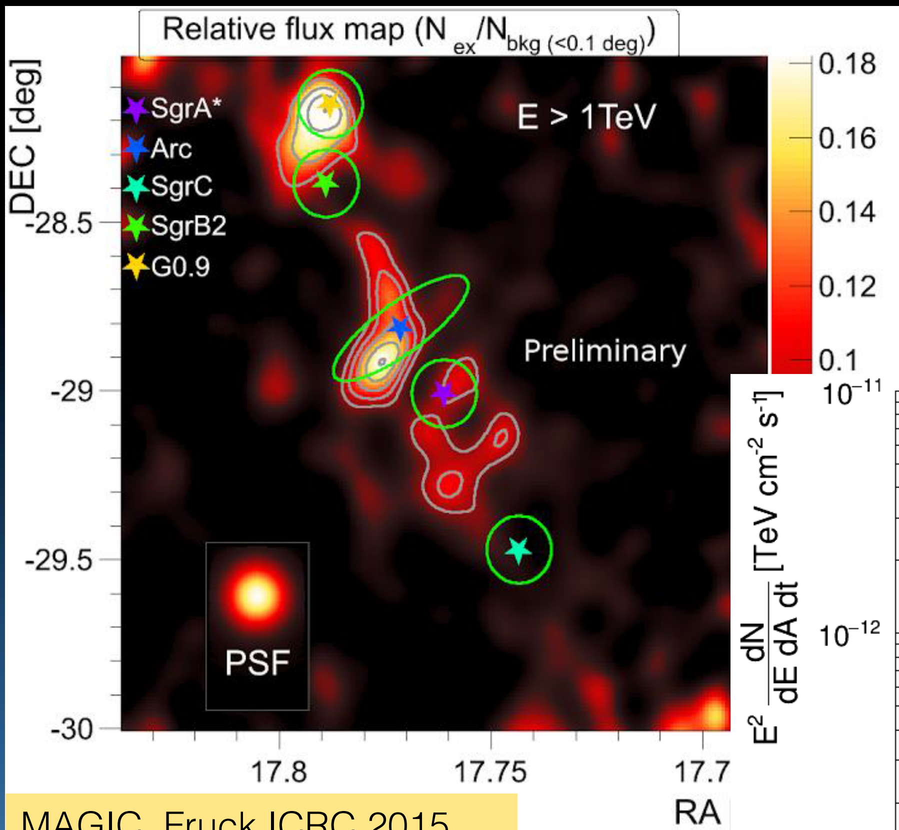
- MAGIC observed the Galactic center under large zenith angle range of 58°-70°
- Observed good correlation between 90cm radio image and TeV sky map
- Radio arc seem to have a TeV counterpart

VERITAS, Smith ICRC 2015



VERITAS: good correlation with radio, 3FGL & HESS

TeV View of the Galactic Center



MAGIC, Fruck ICRC 2015

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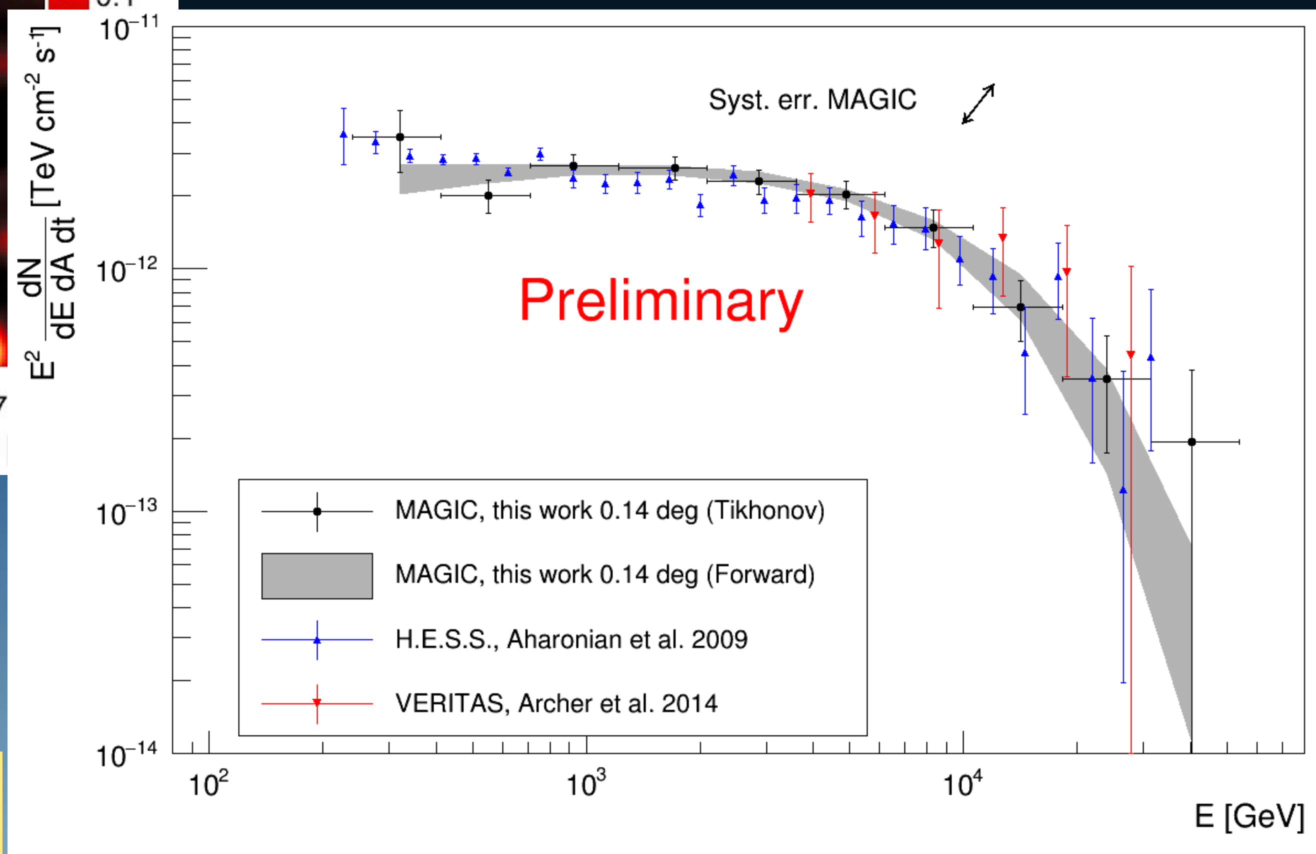
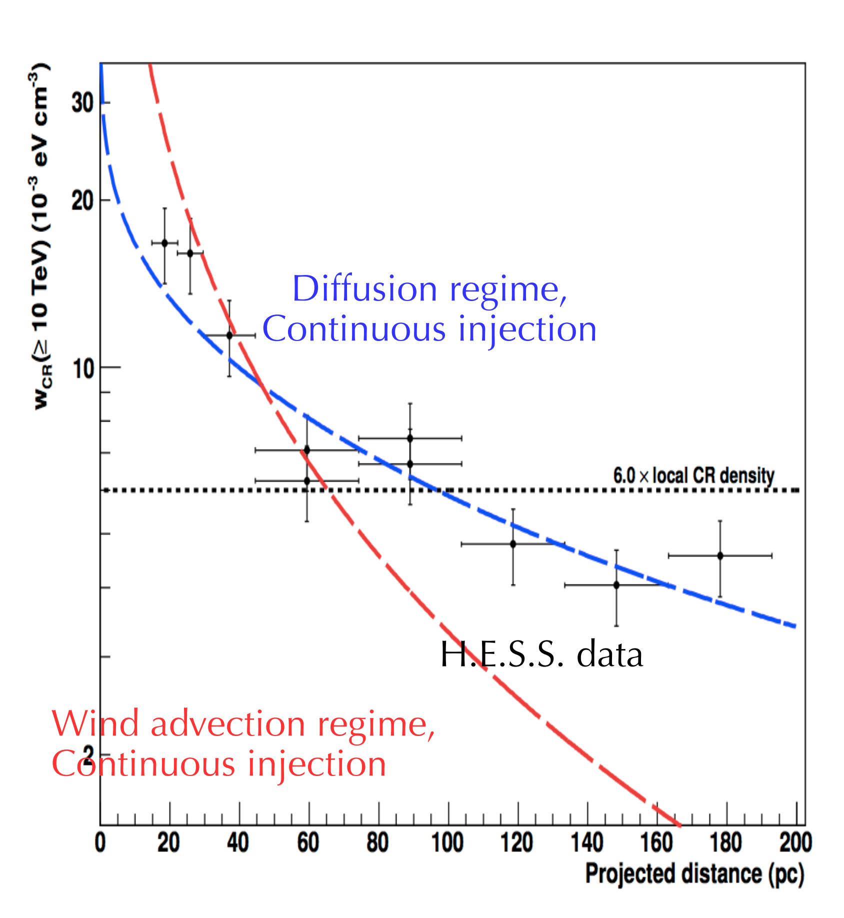


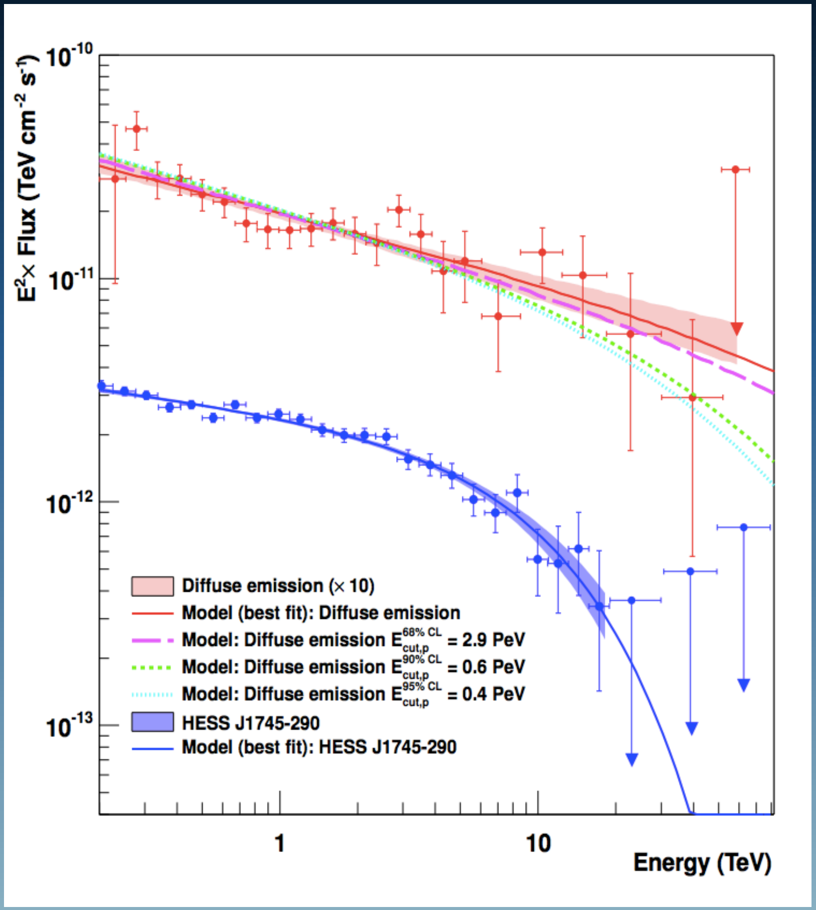
See Fruck TeVPA 2015 for details

Galactic Centre with H.E.S.S.

- Central source: cut-off @ 10 TeV
- Diffuse emission shows no cut-off well > 10 TeV
- Emission likely due to 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)

Viana ICRC 2015





Summary & Conclusion

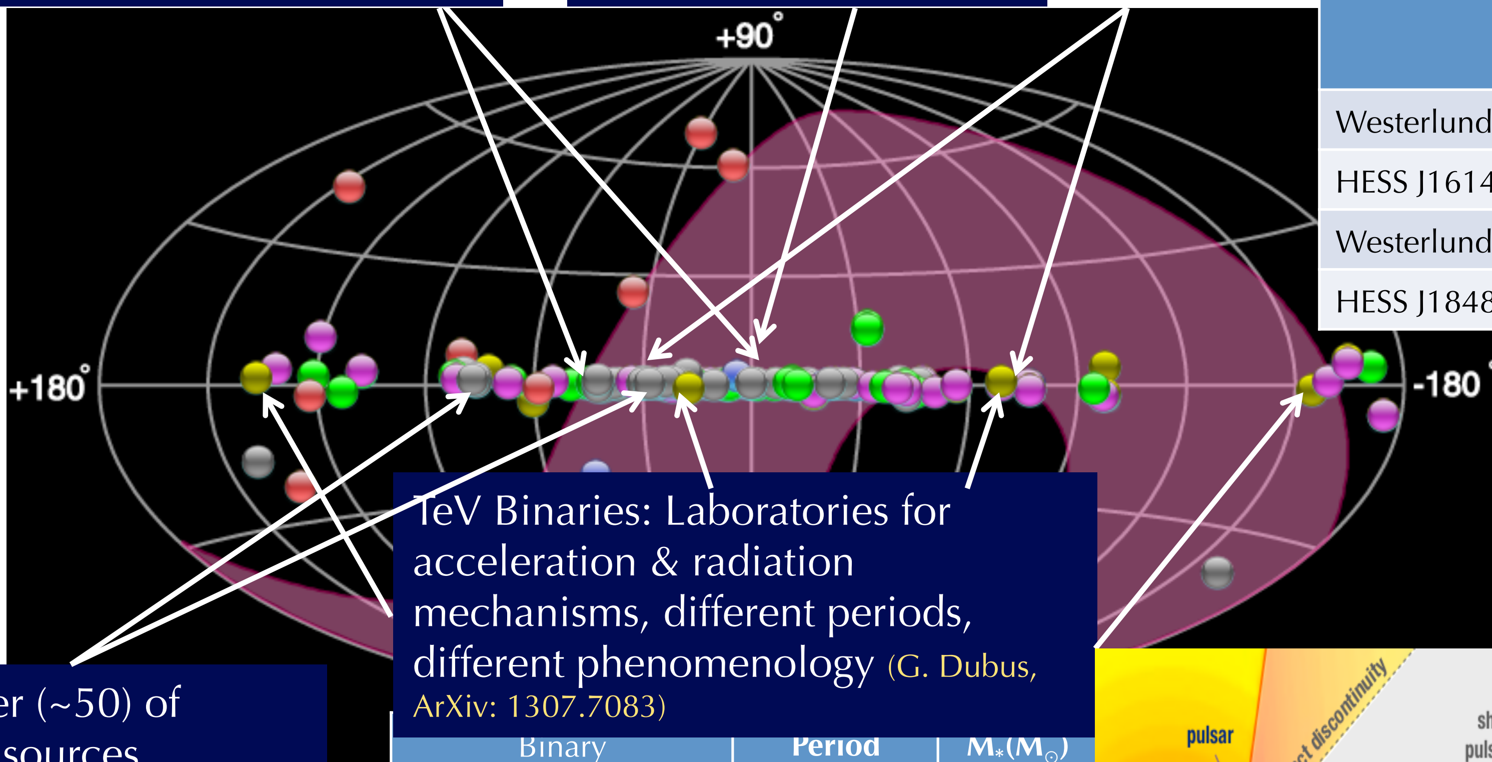
What went unsaid ……

SNR/Molecular cloud interactions (11) (e.g. W49B, W51, SNR G318.2+00.1, SNR G349.7+00.2 (H.E.S.S.)

Globular Cluster (Terzan 5, HESS J1747-248)

Massive star clusters: potential acceleration sites of VHE particles (de Naurois arXiv:1104.1680v1)

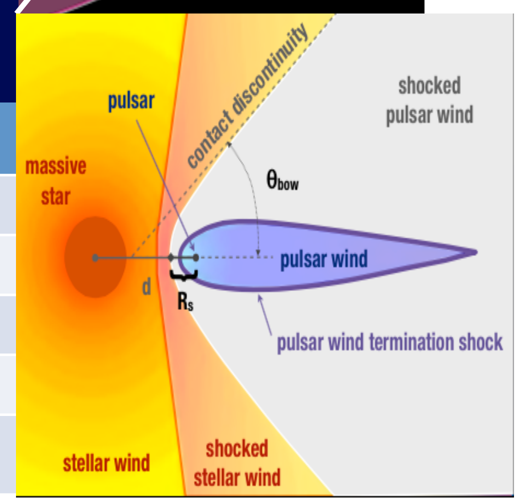
	Distance (kpc)
Westerlund 2	8
HESS J1614-518	-
Westerlund 1	4
HESS J1848-018	5.3



TeV Binaries: Laboratories for acceleration & radiation mechanisms, different periods, different phenomenology (G. Dubus, ArXiv: 1307.7083)

Large number (~50) of unidentified sources (unassociated. "Dark accelerators"?, H.E.S.S. GPS)

Binary	Period (days)	$M_*(M_\odot)$
PSR B1259-63	1236	31
LS 5039	3.9	23
LS I +61 303	26.4	12
HESS J0632+057	315	16
1FGL J1018.6-5856	16.6	31

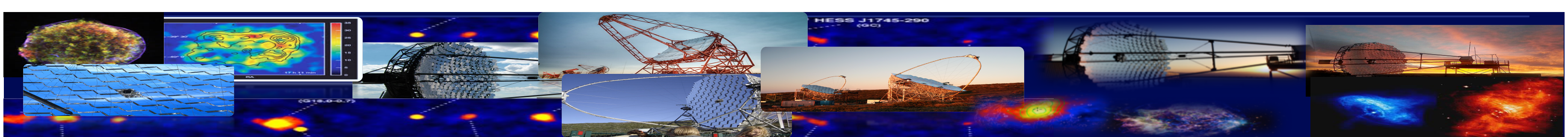


See Viana TeVPA 2015 for binaries

See Hasdasch TeVPA 2015 for transients & variable sources

Summary & Future Prospects

- The field of ground-based γ-ray astronomy is active and vibrant.
- With major improvements in sensitivity, new Galactic discoveries + deep studies of targeted sources.
- The field continues to evolve:
  - Learning new things from complementary experiments (X-ray, HAWC & Fermi-LAT).
- Several open questions remain:
  - Definite proof of acceleration of hadrons
  - Definitive proof of cosmic Pevatrons
- Outlook for Galactic Astrophysics with CTA is extremely promising.



Extra/Backup slides