Supernova Remnants: Cosmic-ray Accelerators in the Milky Way

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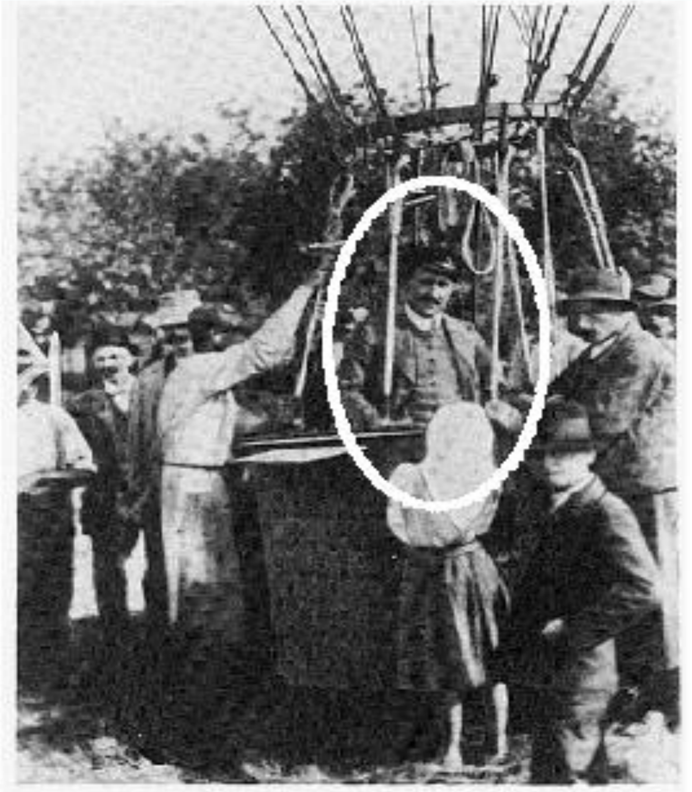
Outline

- Cosmic Ray Origin
- Gamma Rays
  - Production Processes
  - Detection Instruments
- Supernova Remnants
  - Definition and General Classes
  - Gamma-ray Emission Mechanisms
- Example Studies
  - Multi-waveband Modeling of Cas A
  - Finding Hadronic Emission from 3C 391

Non-thermal Radiation

- Particle radiation:
  - Solar Energetic Particles: protons, electrons, heavy ions
  - Neutrinos
  - Cosmic Rays (CRs): protons (86%), nuclei, electrons)
- Photon Radiations:
  - Radio emission (by cosmic ray electrons)
  - X-rays and gamma rays (by cosmic ray electrons, protons, and ions)

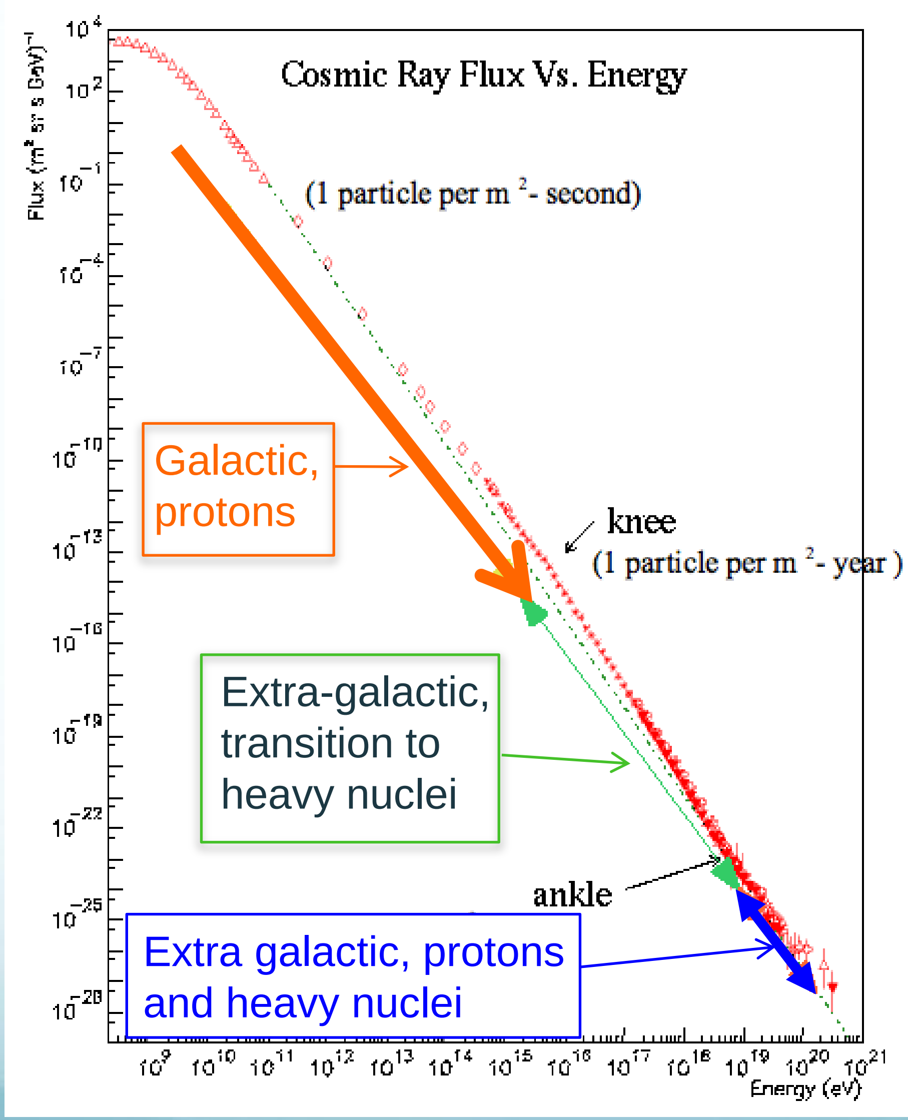


Victor F. Hess

Measurements of ionization intensity during balloon flights (1912).

Nobel prize 1936

The Origin of CRs

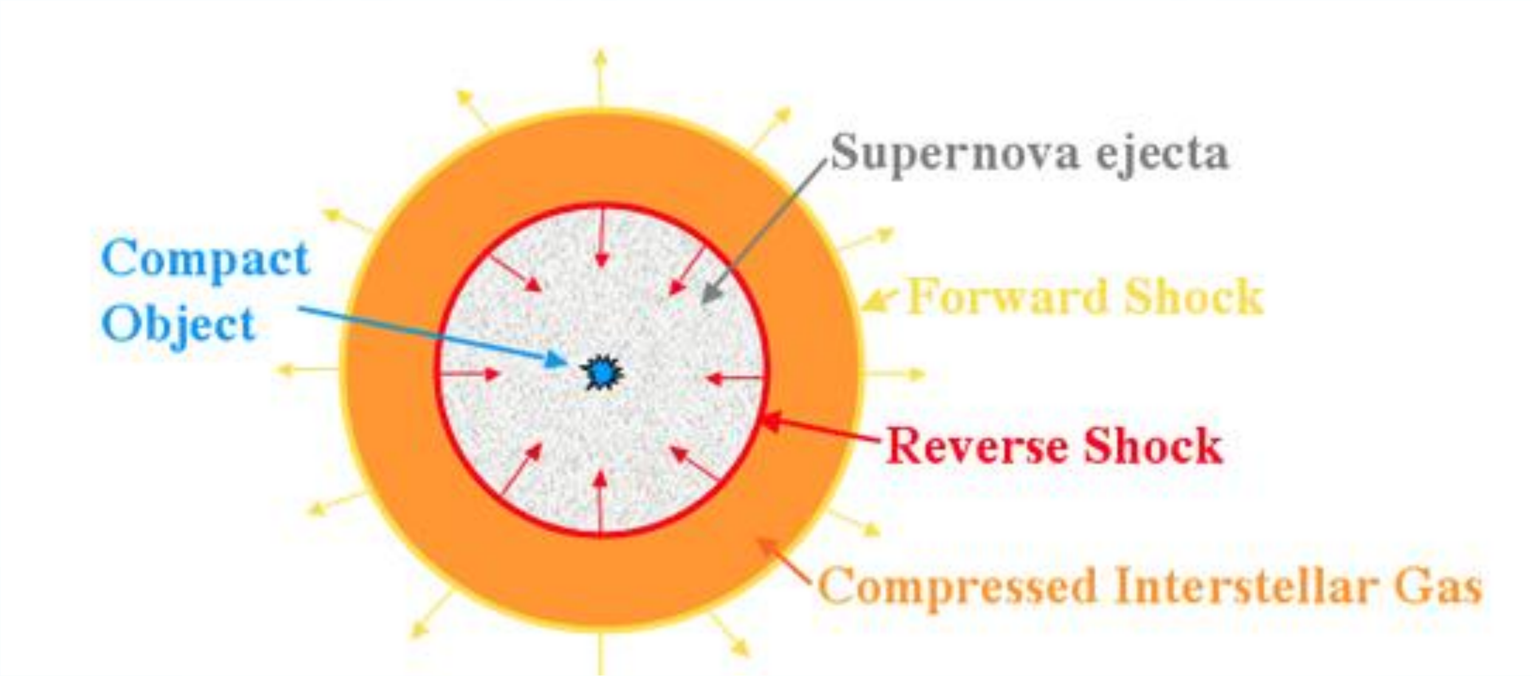


Shock-wave acceleration in supernova remnants (SNRs) ?

The Origin of Galactic CRs

- Supernova explosion
  - 10 billion times brighter than the Sun
  - **Type-Ia: energy = thermonuclear fusion**
    - E = 2 MeV/nucleon
    - Total energy: 10^{51} erg
  - **Type II, Ib, Ic : energy = gravity**
    - E = 200 MeV/nucleon
    - Total energy: 10^{53} erg
    - Kinetic energy: 10^{51} erg
- Kinetic energy (~10^{51} erg) released as expanding stellar material (ejecta, ~$M_{\odot}$) creates an SNR
  - Sources of (heavy) elements
  - Sources of kinetic energy in the ISM
  - **Sources of cosmic rays**

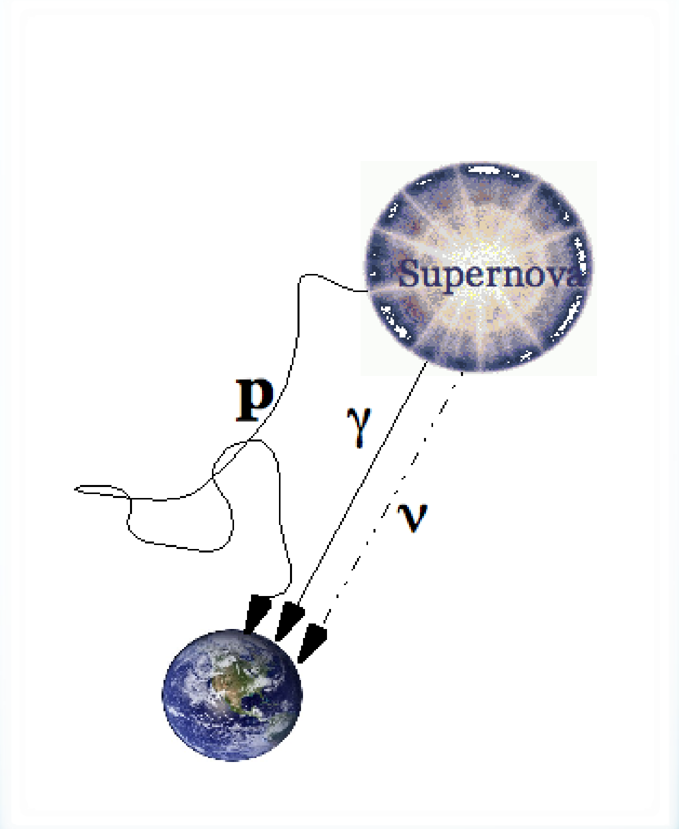
Supernova Explosion



A forward and a reverse shock are created when the supernova shock wave interacts with the interstellar medium (ISM). The forward shock continues to expand into the ISM, the reverse shock travels back into the freely expanding supernova ejecta.

Finding CR Sources

- Protons, Nuclei
  - Deflected by galactic/intergalactic magnetic fields → Isotropic distribution
  - Exception: CR with energies above the "ankle" → Auger project
- Neutrinos
  - Direct signature from hadronic interactions, and not absorbed by intergalactic IR fields
  - Weak emission → difficult to detect
- Gamma & X-rays
  - Not deflected → Point back to its source



Gamma-ray Production

- Charged particles in strong electromagnetic fields
  - Bremsstrahlung (Leptonic)
    - VHE charged particles accelerated in electric field
  - Synchrotron radiation
    - VHE electrons moving in strong magnetic field
- Inverse Compton scattering (Leptonic)
  - Up-scattering of photons of lower energy through collision with VHE particles
- Decays and annihilation
  - Pair annihilation
    - Particle + Anti-Particle → $\gamma + \gamma$
  - Pion production and decay (Hadronic)
    - Proton + Matter → $\pi°$ → $\gamma + \gamma$

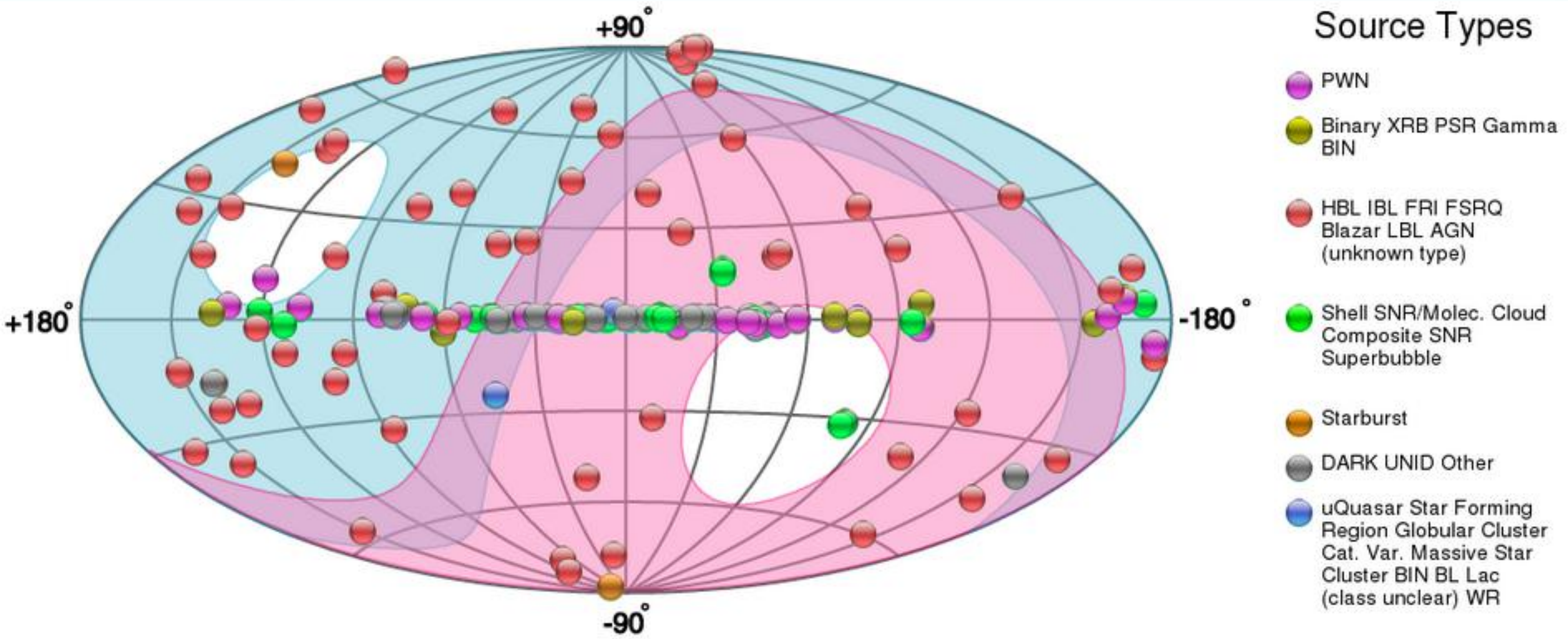
Ground-based Observatories of IACTs*

* Imaging Atmospheric Cherenkov Telescopes

VERITAS

Geographic Location: 31° 40´ North, 110° 57´ West, Altitude: 1268 masl.
Energy range: 100 GeV < E < 10 TeV
Sensitivity: ~1% of the flux of the Crab Nebula detected in 25 hours

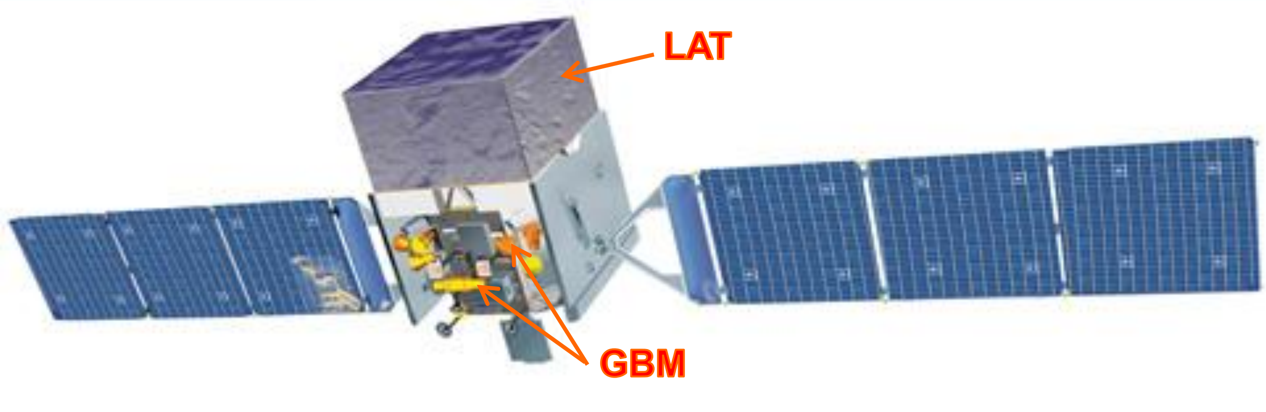
TeV Sources 2015

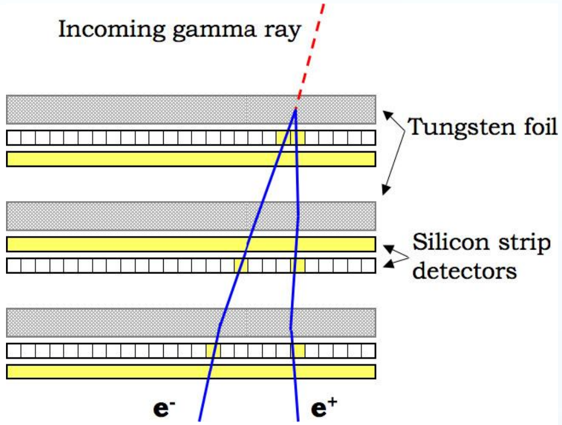


http://tevcat.uchicago.edu/

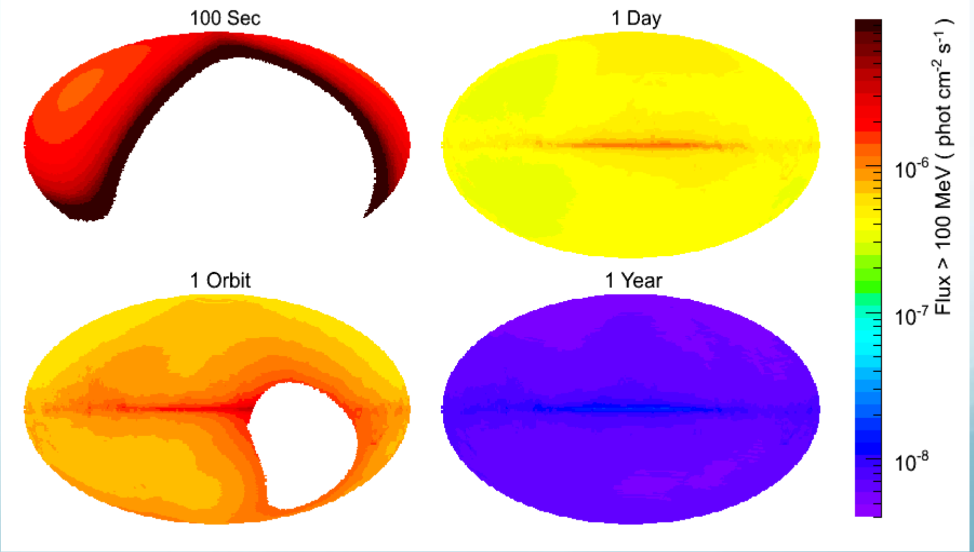
Currently 177 sources in total. Detected farthest distance object at z=0.944.

Fermi Gamma-ray Space Telescope





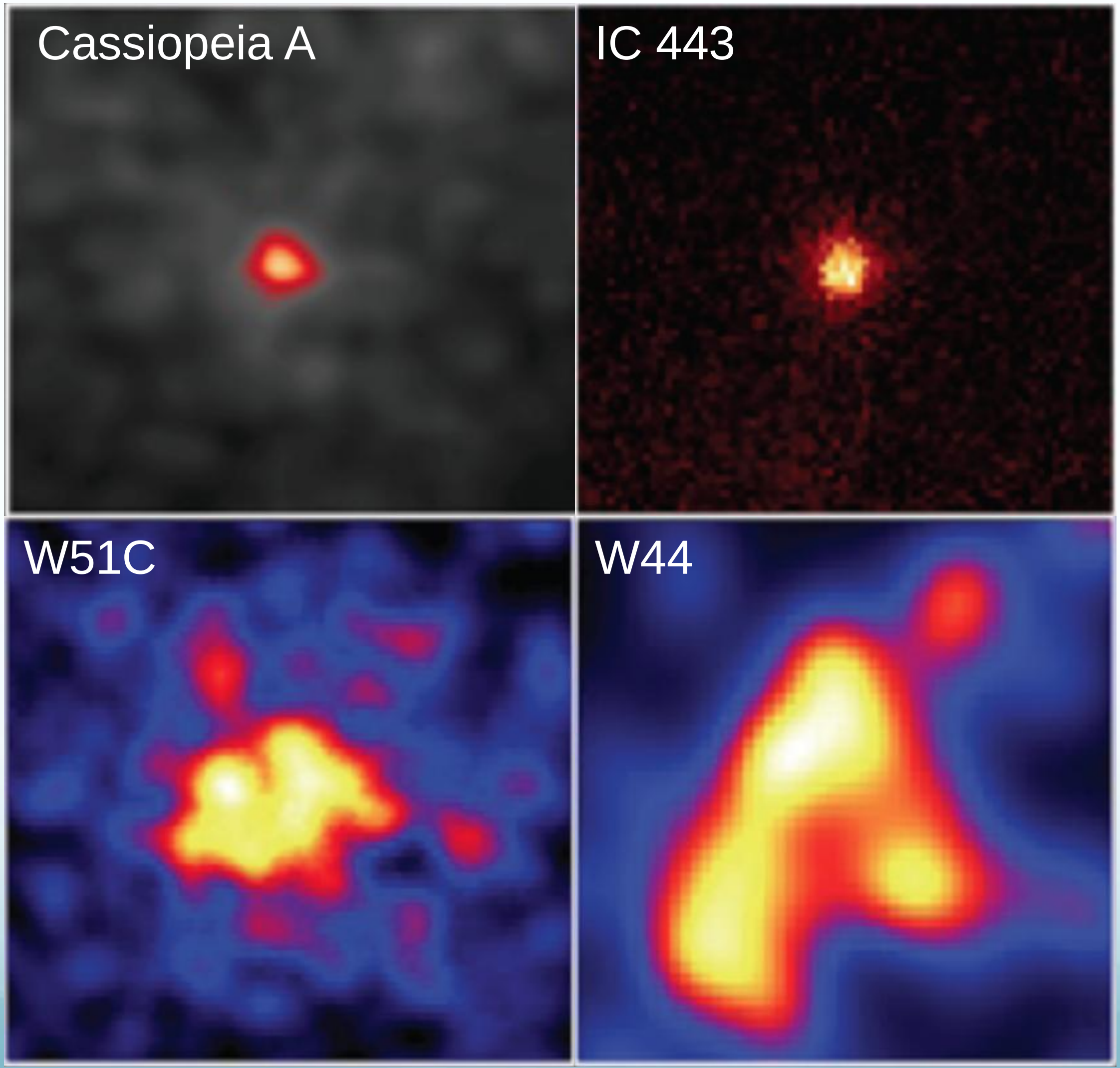
- Launched on June 11, 2008
- Two instruments
  - Large Area Telescope (LAT)
    - 20 MeV − 300 GeV
  - Gamma-ray Burst Monitor (GBM)
    - 10 keV − 25 MeV



Sensitivity to Point Sources

Atwood et al. (arXiv:0902.1089)

First Detected SNRs by Fermi-LAT



The SNR Classification

- According to Origin
  - Core-collapse or Type-Ia SNR
- According to Radio & X-ray Morphology

SNR	Shell-like	Center-like
Shell-type	yes	no
Plerion-type	no	yes
Composite-type	yes	yes
Mixed Morphology (Radio)	yes	no
Mixed Morphology (X-rays)	no	yes

Why do we study SNRs?

- SNR interactions with dense clouds to study cosmic rays
  - Type & maximum energy of emitting population (electrons or ions)
  - Propagation / diffusion of cosmic rays in interstellar medium
- Plerion science
  - Measure magnetic field strength
  - Study cooling breaks and cut-offs in broad-band spectra
- Broad-band spectral and morphological studies
  - Spatially resolved properties of non-thermal populations
  - Common population of objects across GeV / TeV

Shell-type SNRs

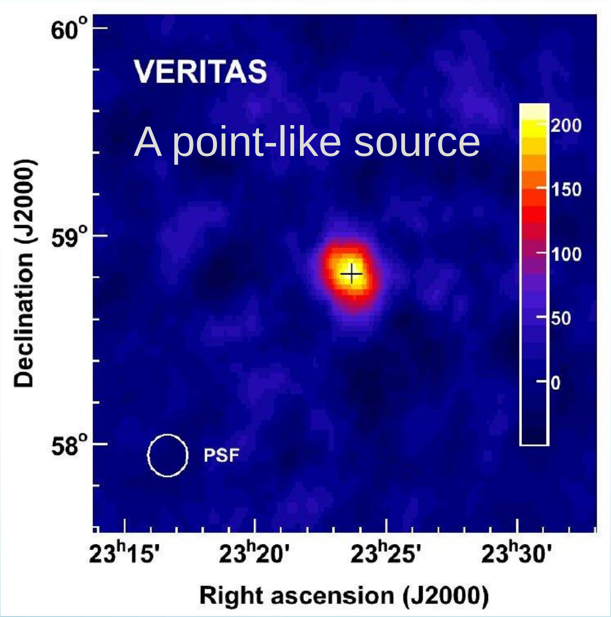
- No electrons supplied by the pulsar wind
- Shells of the remnants possibly hadron or electron acceleration sites
  - Gamma rays from hadrons through $\pi^\circ \rightarrow 2\gamma$
  - Gamma rays from electrons through inverse Compton scattering
- Gamma-ray signal from shell regions may give hints for hadron acceleration
  - Signal could be enhanced by shell interacting with nearby molecular clouds
  - Gamma-ray source spectrum

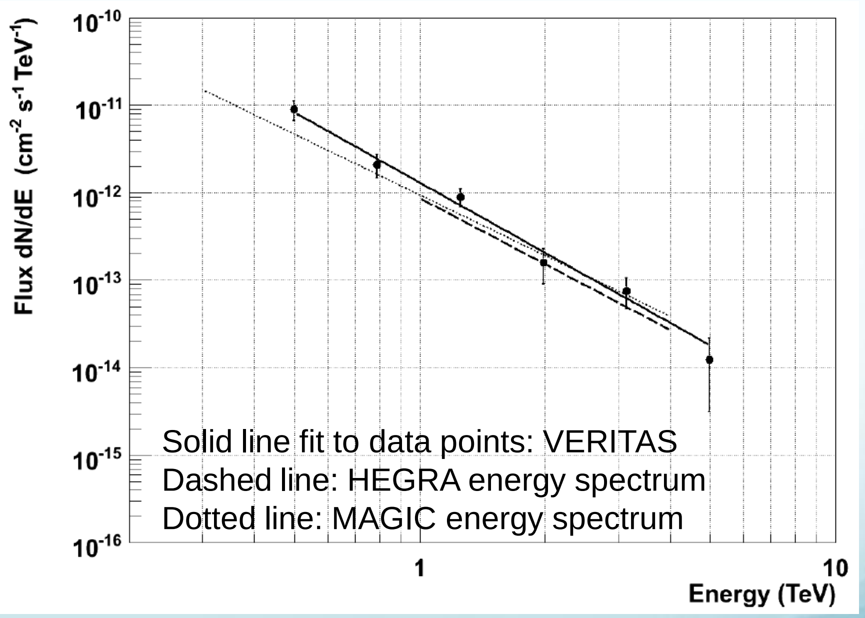
Cassiopeia A: A Young Shell-type Remnant

- One of the youngest SNRs in our Galaxy (1680)
- One of the brightest radio sources in the sky
- Angular size of 2’.5 in radius
  - Size of 2.34 pc at a distance of 3.4 (+0.3 −0.1) kpc
- Strong magnetic fields implied from X-ray variability on short timescales

VERITAS View of Cas A

- Previously detected by HEGRA, MAGIC
- VERITAS detection
  - 8.3 σ in 22 hours
  - Spectral Index: $\Gamma = 2.61 \pm 0.24^{stat} \pm 0.2^{sys}$
  - Flux above 1 TeV: $(7.76 \pm 0.11) \times 10^{-13}$ cm^{-2} s^{-1} (3% of Crab Nebula flux)

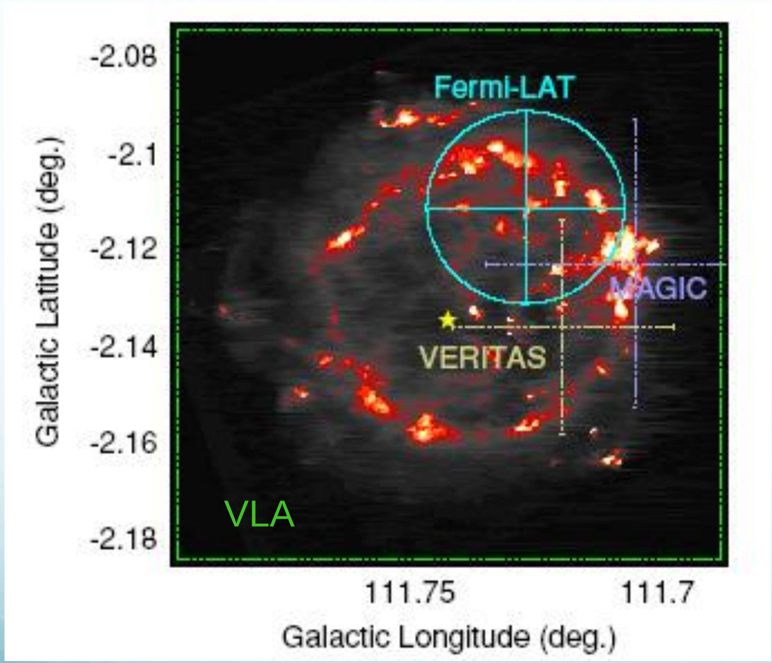


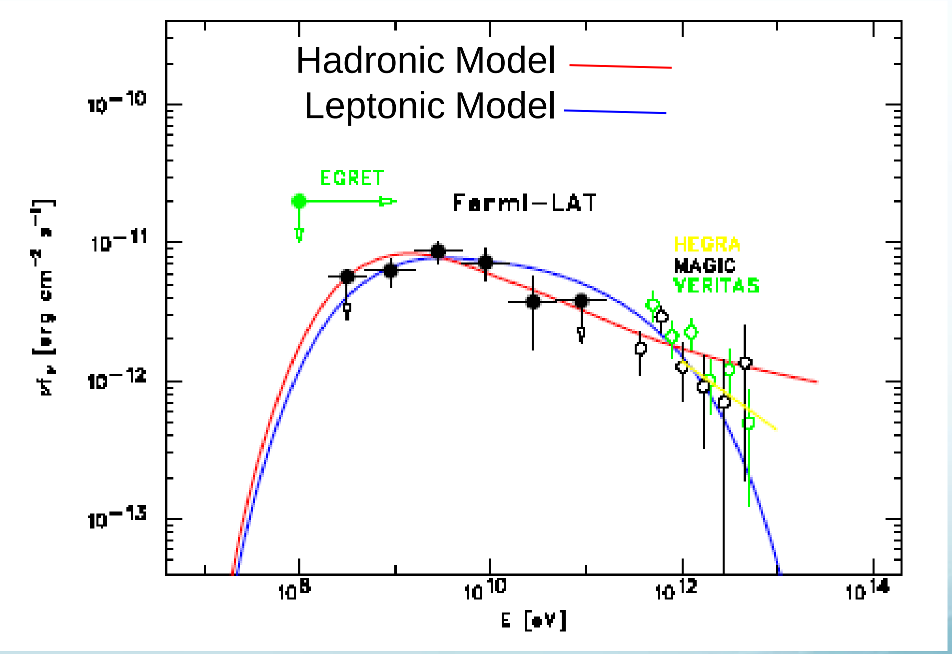


HEGRA: Aharonian, F. et al., A&A, 370:1,112, MAGIC: Albert, J. et al.,A&A, 474:3,397(2007), VERITAS: Acciari, V.A. et al.,submitted(2010).

2 Years of Fermi-LAT Data

- Fermi detection (~12σ) is consistent with a point source (3’.5)
  - Pulsar? No sign for a cut-off as in many pulsar spectra
- Spectrum does not rule out leptonic models
  - Bremsstrahlung models need B ~ 0.1 mB to fit the measured spectrum





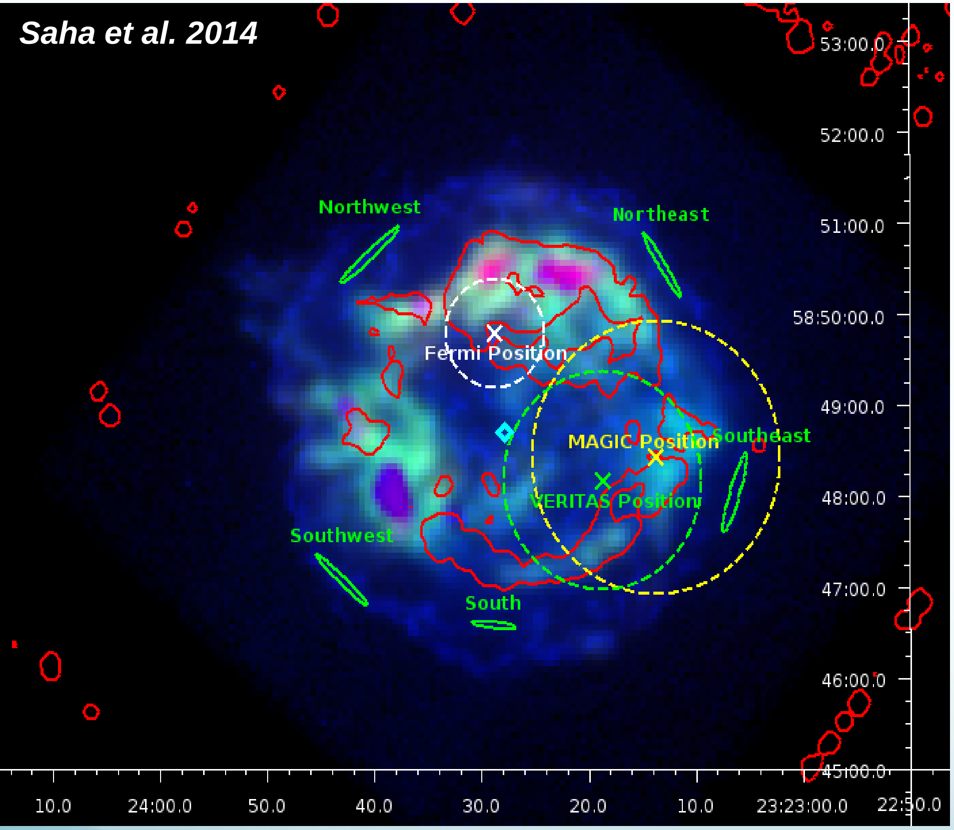
Abdo et al. 2010, ApJ, 710, L92

Locating the Source of Gamma Rays on the Shell of Cas A

- Aim: To locate the origin of gamma rays based on the X-ray data of the shell of Cas A, and to explain the GeV & TeV gamma-ray data in the context of both leptonic and hadronic scenario.

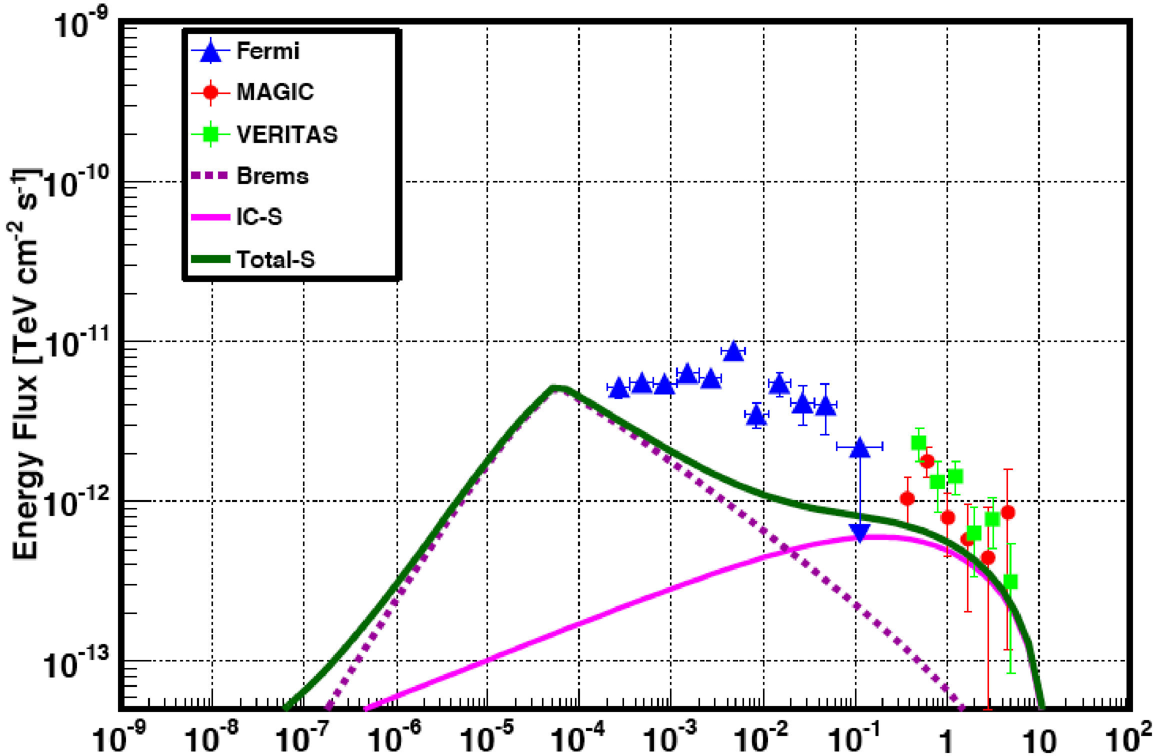
- Our Related Papers:
  - Saha, L., Ergin, T., Majumdar, P., Bozkurt, M., Ercan, E. N. (2014). “Origin of gamma-ray emission in the shell of Cassiopeia A”, Astronomy & Astrophysics, 563, 88.
  - T. Ergin, L. Saha, P. Majumdar, M. Bozkurt, E. N. Ercan, “Modeling the Shell of Cassiopeia A to find the TeV Gamma-ray Emission Region”, 33rd International Cosmic Ray Conference Proceedings, arXiv:1308.0195 [astro-ph.HE].
  - M. Bozkurt, T. Ergin, M. Hudaverdi, E. Ercan, ”High Energy Studies on the Non-Thermal Emissions from Cassiopeia A & Tycho”, International Journal of Astronomy and Astrophysics, Vol. 3 No. 1, 2013, pp. 34-48.

Selecting X-ray Regions on the Shell of Cas A



- The red, green, and blue color hues: The energy ranges of [0.7, 1.0], [1.0, 3.5], and [3.5, 8.0] keV, respectively.
- The green ellipses: selected S, SW, SE, NW, and NE regions
- The green and yellow crosses and dashed circles: The VERITAS and MAGIC locations and approximated location error circles.
- The white cross and dashed circle: The GeV gamma-ray emission best-fit location and the location error circle
- Cyan open diamond: The CCO location
- Red contours: The derived CO data from Spitzer-IRAC starting from a value of 0.4 MJy/sr and higher

Modeling the Total Leptonic Emission for the S Region

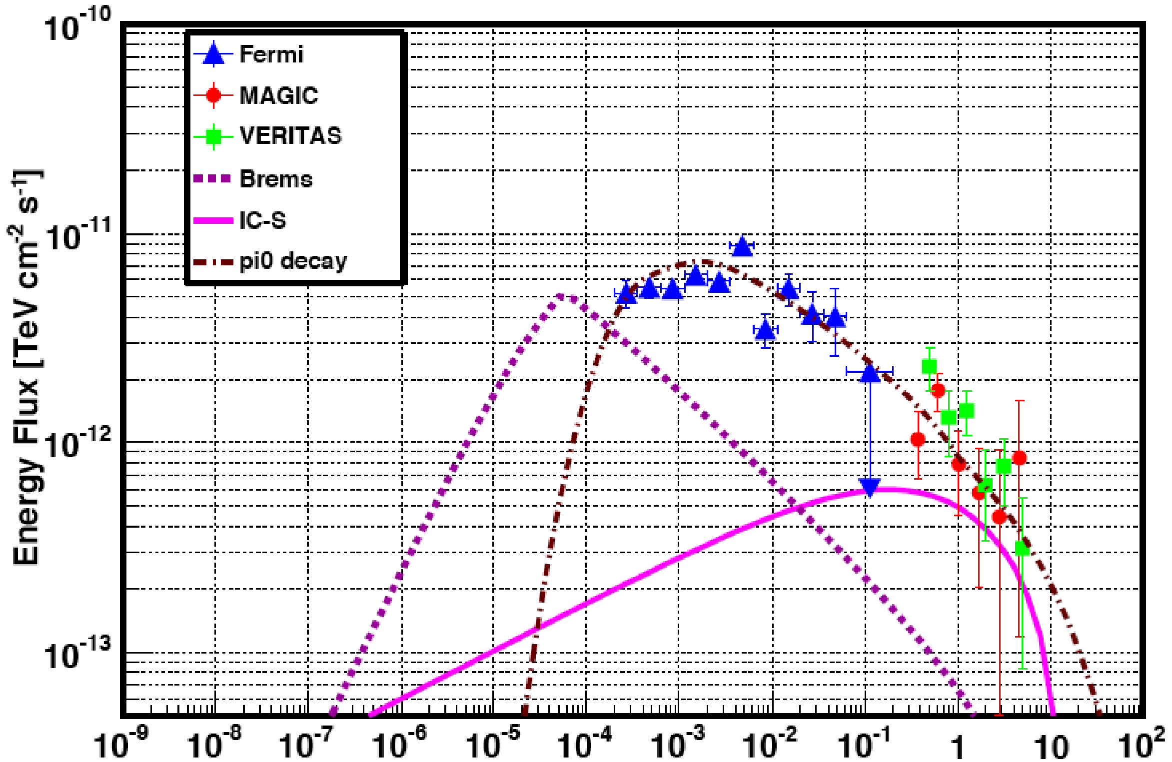


Saha et al. 2014

But the total leptonic model does not fit to the GeV gamma-ray data from Fermi-LAT!

- IC (solid line) and bremsstrahlung (dashed line) spectra are estimated for the whole remnant.
- Electron spectrum parameters are based on S region.
- Bremsstrahlung spectrum calculated for n_H = 10 cm^{-3}
- The thick solid line corresponds to total contribution to gamma rays from leptons (electron)
- The parameters for radio emitting electrons are α = 2.54 and γ_{max} = 3.2 x 10^7 (Lorenz fact. of cutoff energy)

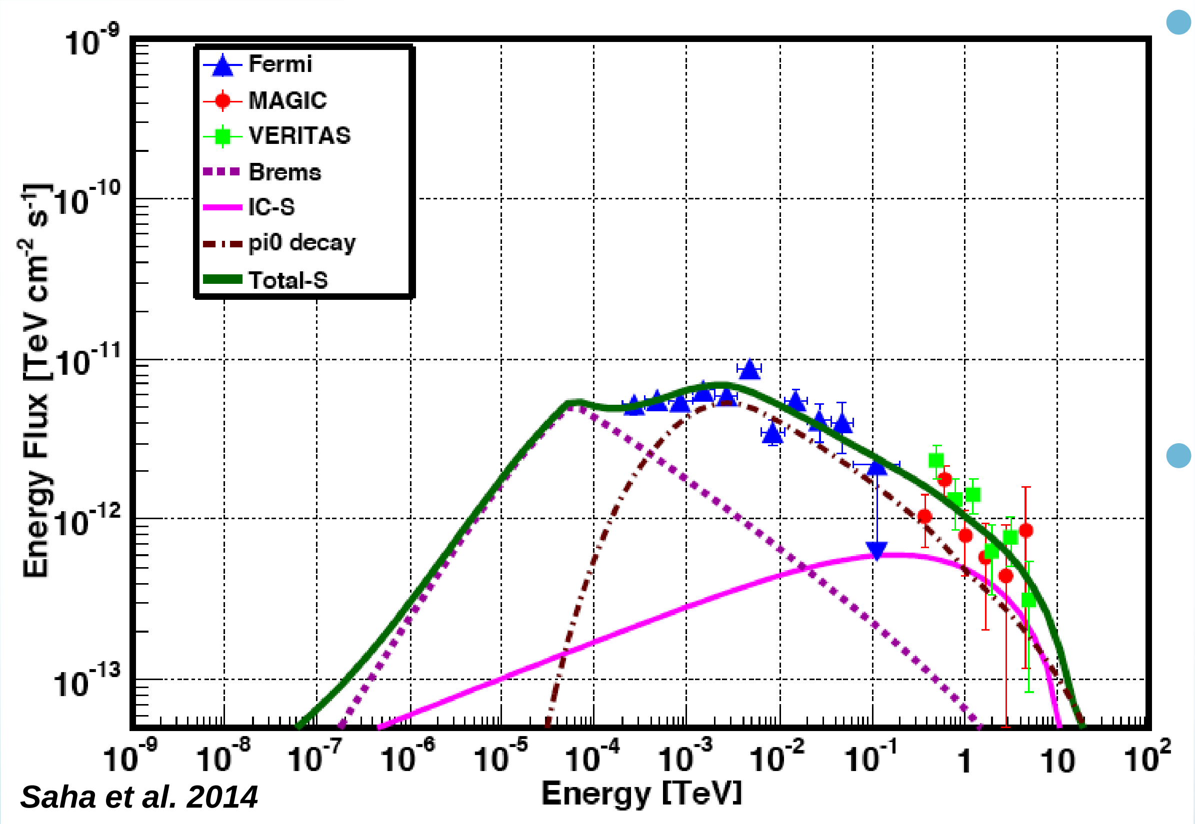
The Hadronic Gamma-ray Emission Model



Saha et al. 2014

- π° decay spectrum for the power-law distributed proton spectra shown as long dash-dotted line.
- The estimated total energy of the protons, $W_p = 5.7 \times 10^{49}$ erg
- The total energy of the electrons was estimated to be $W_e = 4.8 \times 10^{48}$ erg

The Lepto-hadronic Gamma-ray Emission Model



- Gamma-ray spectrum (thick solid line) of Cas A for combining both leptonic and hadronic contribution to the whole remnant data.
- The total energy of the charged particles is $W_e + W_p = 3.4 \times 10^{49}$ erg
  - Gives a conversion efficiency of supernova explosion energy to be < 2%

Mixed-Morphology (MM) SNRs

- Different Morphology in X-ray and radio band: Thermal X-rays from the central region and radio emission from the shell.
- 10% of all Galactic SNRs and 25% of all X-ray detected Galactic SNRs are MM-type.
- First detected SNRs by Fermi-LAT were mostly middle-aged MM-type SNRs: W44, IC 443, W28, W49B, and W51C.
  - Interactions of these MM-type SNRs with molecular clouds (MC) proven by the 1720 MHz OH masers.
  - MM SNRs interacting with MC are targets for detecting gamma rays of hadronic origin.
    - Provides clear evidence for these SNRs to be sites of proton acceleration.

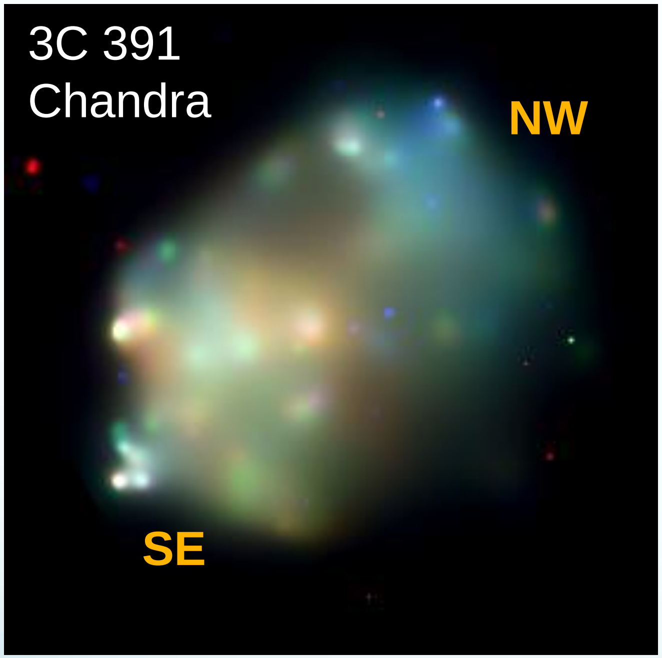
Origin of MM-type SNRs

- Interactions with MC hint associations with star forming regions (SFRs)
  - SFRs contain massive stars with strong stellar winds surrounded by circumstellar matter (CSM)
  - Possibly these massive stars are the progenitors of MM-type remnants.
- When the supernova blast wave breaks out of the CSM into the ISM, the particle acceleration increases.

Our Work related to MM SNRs

- Ergin, T. & Ercan, E. N. (2012). “GeV Analysis of Mixed Morphology Supernova Remnants Interacting with Molecular Clouds”, AIP Conference Proceedings, 1505, 265.
- Ergin, T., Sezer, A., Saha, L., Majumdar, P., Chatterjee, A., Bayirli, A., Ercan, E. N. (2014). “Recombining Plasma in the Gamma-ray Emitting Mixed-Morphology Supernova Remnant 3C 391”, Astrophysical Journal, 790, 65.
- Ergin, T., Saha. L., Majumdar, P. (2015). “Discovery of GeV Gamma-ray Emission from the Galactic Supernova Remnant Kes 41“, Türkiye Ulusal Astronomi Kongresi.
- Sezer, A. & Ergin, T. (2015). “Searching for the Recombining Plasma in the Supernova remnant G357.7−0.1”. Türkiye Ulusal Astronomi Kongresi.

3C 391: A Middle-aged MM SNR

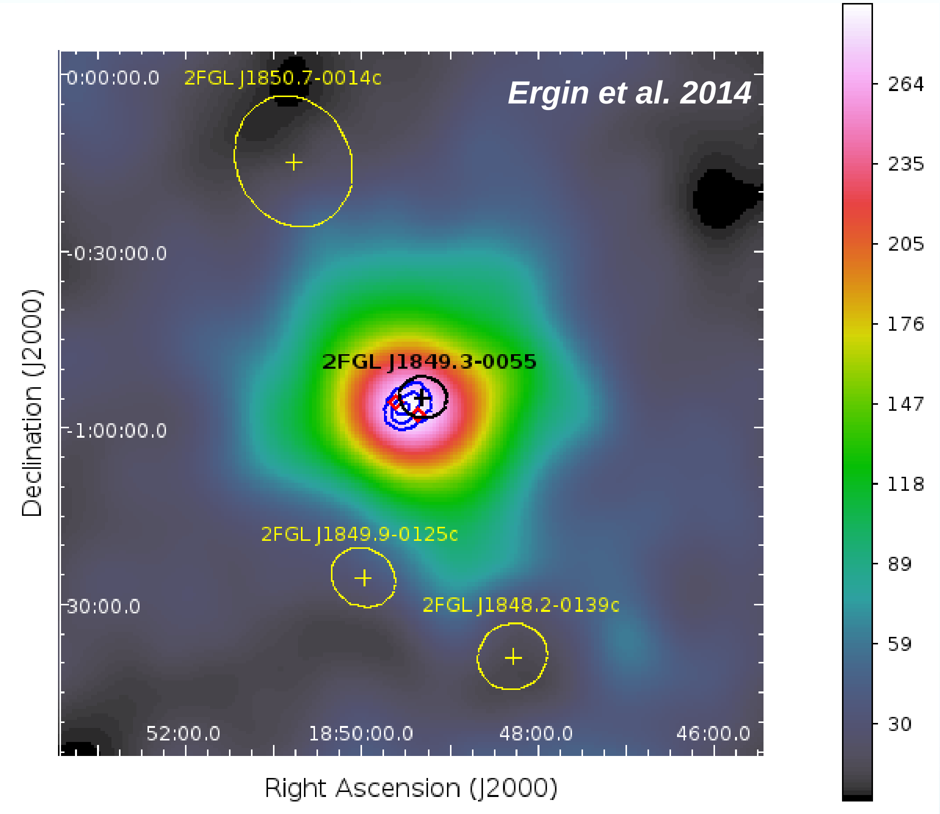


- A MM-type SNR at a distance between 7.2 and 11.4 kpc
- A partial radio shell of 5’ diameter with breakout morphology
  - Intensity of the radio emission in the shell rises in the bright northwest rim (NW) and drops and vanishes toward the southeast rim (SE).
- Observed in X-rays by Einstein, ROSAT, Chandra, ASCA
  - Revealed brightest X-ray peak interior to the weak SE rim and a fainter one in the interior of the bright NW radio shell.
- Two OH masers at 1720 MHz coincident with the SE and NE rim of 3C 391.
  - First clear evidence for 3C 391 interacting with an MC.

Fermi-LAT View of 3C 391

- Listed in the 2nd Fermi-LAT catalog as a point-like source
  - 2FGL J1849.3−0055
- Castro & Slane (2010) reported
  - ~ 12σ detection
  - The peak of the significance map was shifted 4' away from the NW edge of the radio shell.
  - Power-law model spectral index: $\Gamma = -2.33 \pm 0.11$
  - Integrated flux: $F(0.1-100\ \mathrm{GeV}) = (1.58 \pm 0.26) \times 10^{-7}$ ph cm^{-2} s^{-1}
- TeV observation results from H.E.S.S.
  - Integral flux upper limit (at the 95% CL) = 0.8 Crab Nebula flux units

Fermi-LAT Analysis Results

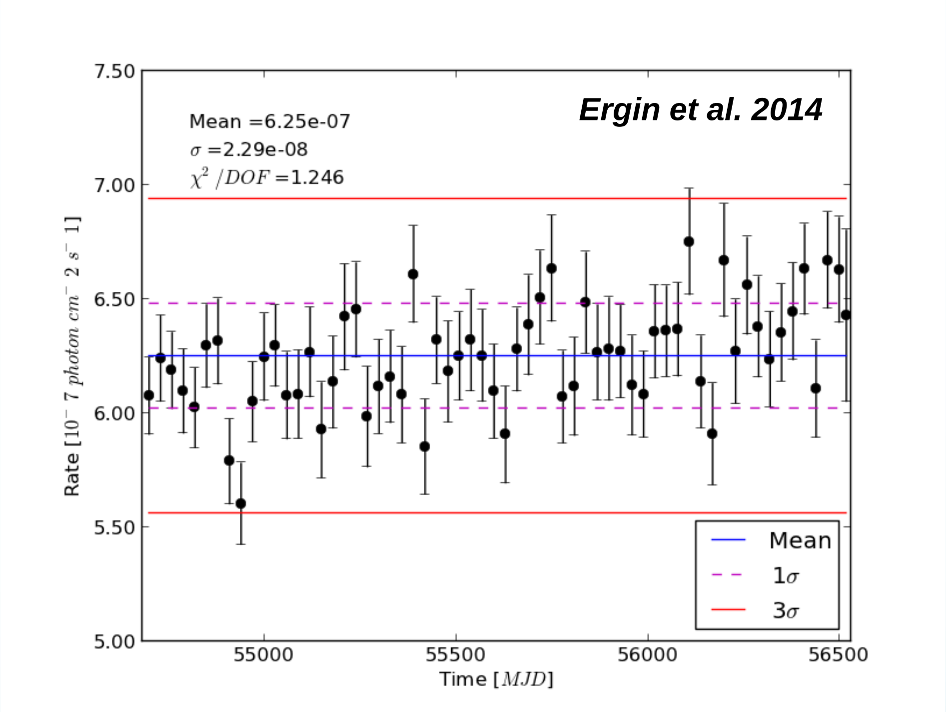


Test statistics (TS): Larger TS values indicate that the null hypothesis (maximum likelihood value for a model without an additional source) is incorrect. Source significance is approximately the square-root of the TS value.

- 5 years of Fermi-LAT data
- ~18σ signal detection
- Motivation:
  - Is the gamma-ray emission is hadronic in origin due to the interaction between the SNR & MC?
    - Can we obtain information about the parent proton spectrum?
  - Is 3C 391 extended in gamma rays?
  - Is the gamma-ray emission form 3C 391 variable in time?

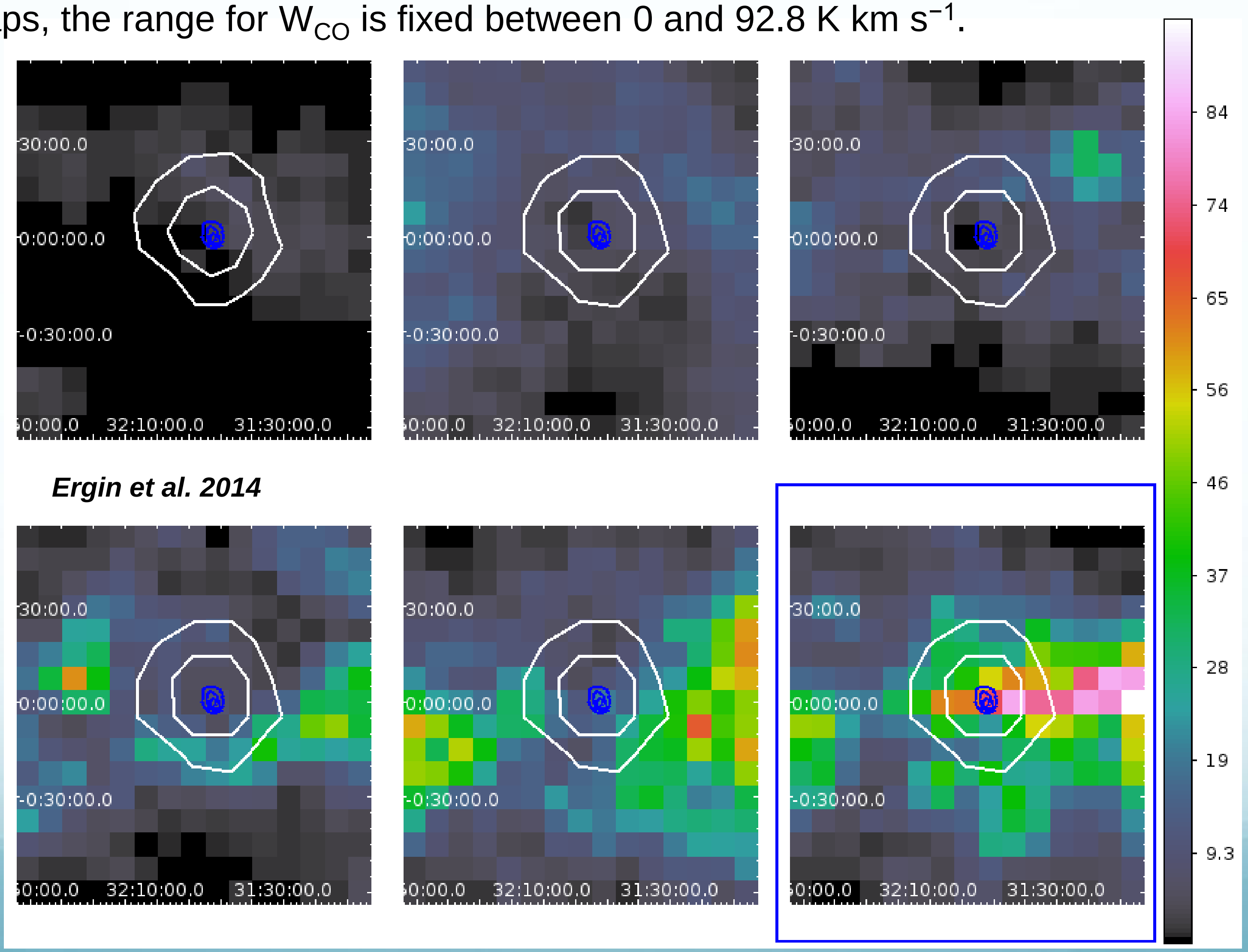
Gamma-ray Light Curve

- Checked data from the circular region of 1° around the best-fit position
- Fitting 3C 391 spectrum assuming standard spectrum of a pulsar (PLEC)
- Best-fit cutoff energy found to be 28.80 ± 6.73 GeV
  - An order of magnitude away from the range of typical pulsar cutoff energies
- Fitting the flux points to a straight line yields a X^2/dof of ~1.25 assuming a PLEC type spectrum for 3C 391
  - No long term variability observed for 3C 391



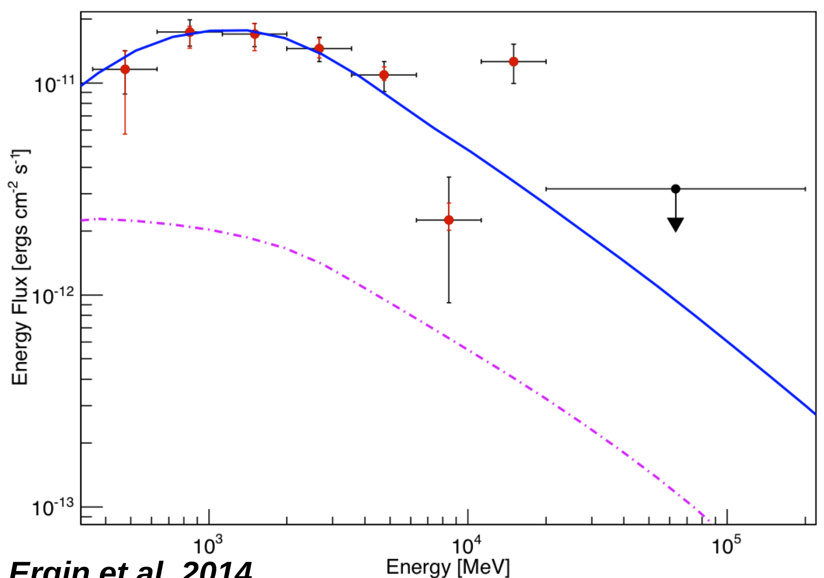
Molecular Map around 3C 391

Top from left: [−*50,0], [0,15],*[15,35]; Bottom from left: [35,60], [60,90], [90,120] km s^{-1}
For all maps, the range for W_{CO} is fixed between 0 and 92.8 K km s^{-1}.



Ergin et al. 2014

Modeling the Gamma-ray Spectrum



Ergin et al. 2014

Spectral Model	Photon Flux (10^{-8} photon cm^{-2} s^{-1})	Γ_1	Γ_2	E_b (MeV)	TS
PL	15.0 ± 1.7	2.30 ± 0.03	...	...	337
LP	7.14 ± 0.34	2.27 ± 0.04	0.15 ± 0.45	2430	337
BPL	4.89 ± 0.57	1.28 ± 0.50	2.50 ± 0.04	1060	338

- Red filled circles are spectral data points with black statistical errors and red systematic errors.
- Blue line: the fit to the spectrum from the decay of π° decay using a BPL distribution of protons. Dashed dotted line is the Bremsstrahlung model.
- Different spectral shapes tested
  - Best-fit TS value of 338 for BPL
- Total energy of protons

  $W_p \sim 5.8 \times 10^{48}$ erg x (387 cm^{-3} /n_H)

  n_H : Effective gas number density for p-p collision

The Proton Spectrum

- The luminosity of 3C 391 is L = 1.34 x 10^{36} erg s^{-1}
  - In the same ballpark with other middle-aged MM SNRs detected by Fermi-LAT, e.g. IC443, W44, W51C, etc.
- Spectral break at ~ 12 GeV in the parent BPL proton spectrum with index parameters of α = 2.48 and β= 3.0
  - Particles are escaping from the acceleration site to the rarefied ISM from the shell broken-out from the dense MC
    - TeV particles can only be confined during early stages of the SNR → But 3C 391 middle-aged SNR
    - Interaction between MC and SNR can speed up particle escape
- Assuming the BPL spectrum of protons without any spectral cut-off
  - The differential flux of gamma rays at 1 TeV ~ 0.06% of Crab nebula flux
  - TeV observations of 3C 391 with the upcoming Cherenkov Telescope Array (CTA) will provide more robust constraints of the various parameters of the input proton spectrum.

Conclusion

- Gamma rays gives an opportunity to study the acceleration processes of high-energy particles inside astrophysical sources, such as SNRs.
- Gamma-ray data from the young shell-like Cas A was analyzed to determine the exact location of TeV and GeV gamma rays inside Cas A.
  - The multi-wavelength spectrum of Cas A can be best described by the lepto-hadronic emission model.
  - The TeV and GeV gamma-ray emission may dominantly come from the southern region of Cas A's shell.
- We have studied the gamma-ray emission the middle-aged MM-type SNR 3C 391
  - Modeling the spectrum revealed gamma-ray emission that can be explained by the hadronic emission model.

COSPAR Committee on Space Research

- Turkey is a member of COSPAR since 1996.
- The 41st COSPAR Scientific Assembly will be held in İstanbul between 30 July and 7 August 2016.
- Around 3000 participants from 60 countries are expected.

https://cosparhq.cnes.fr/