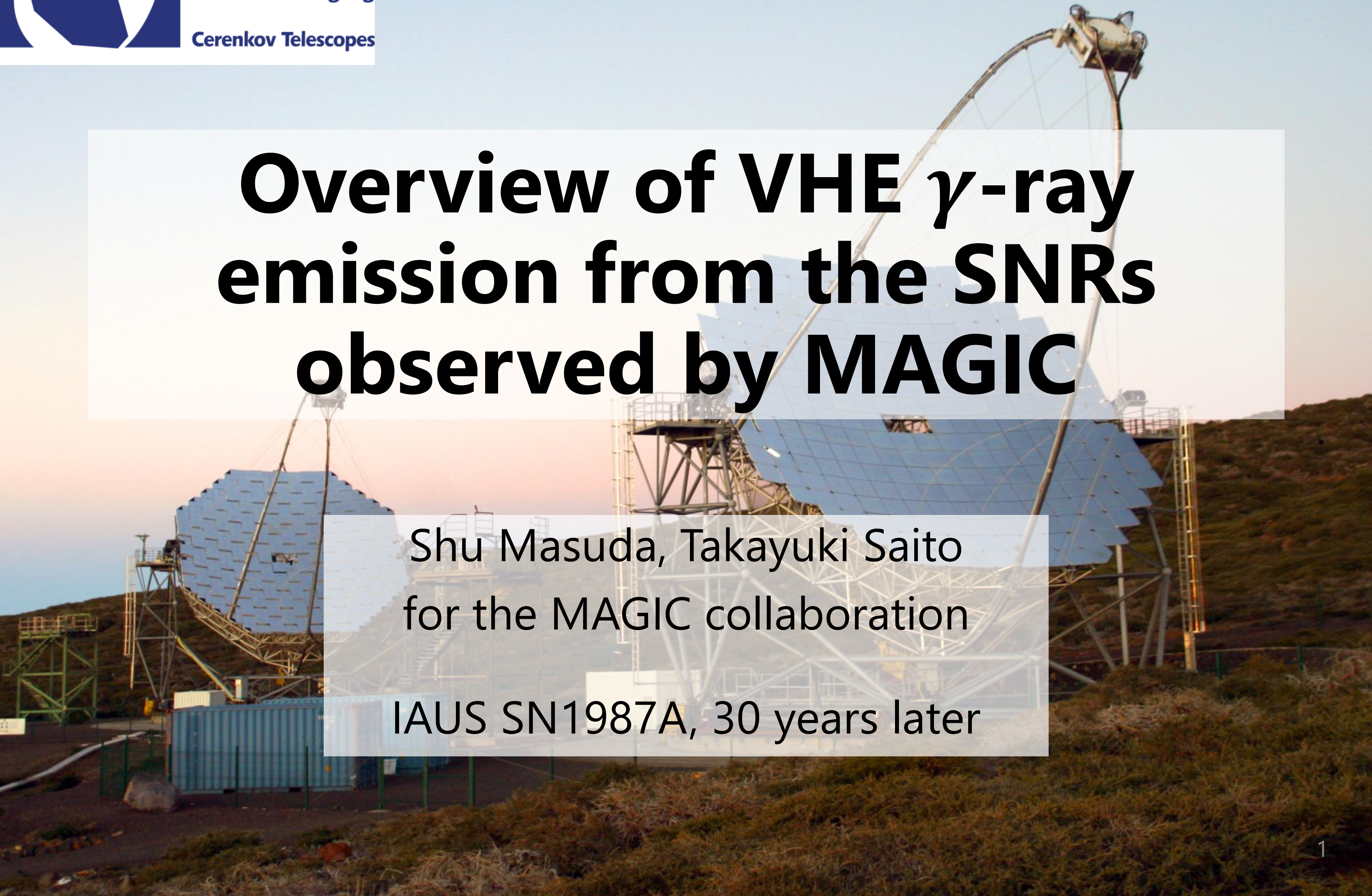


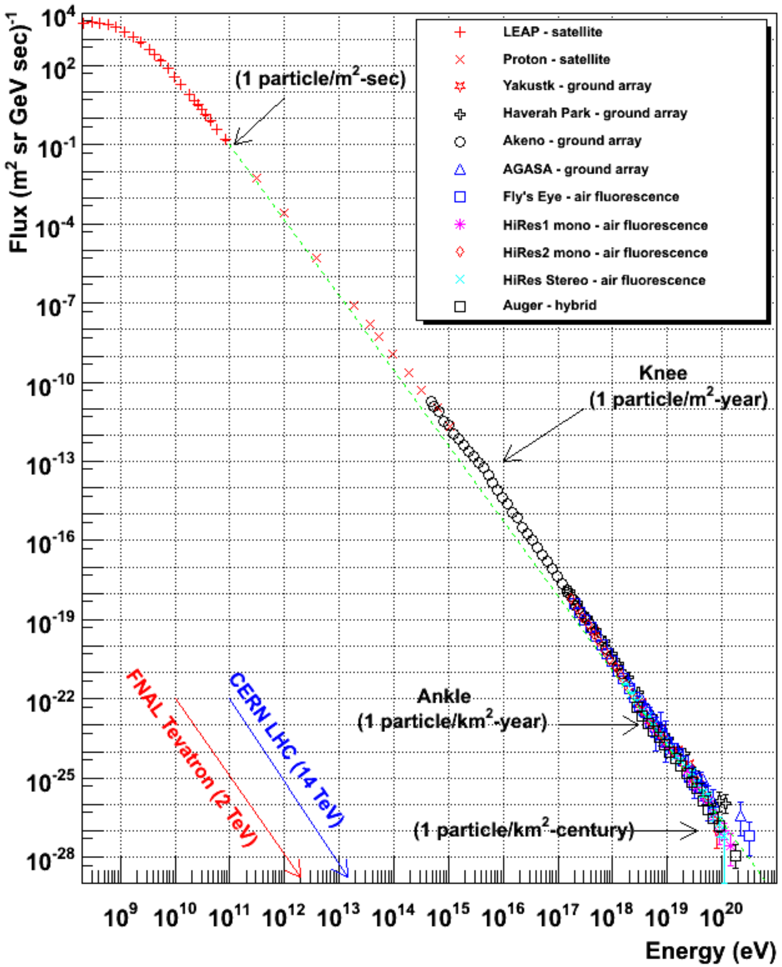
Overview of VHE γ-ray emission from the SNRs observed by MAGIC

Shu Masuda, Takayuki Saito
for the MAGIC collaboration

IAUS SN1987A, 30 years later

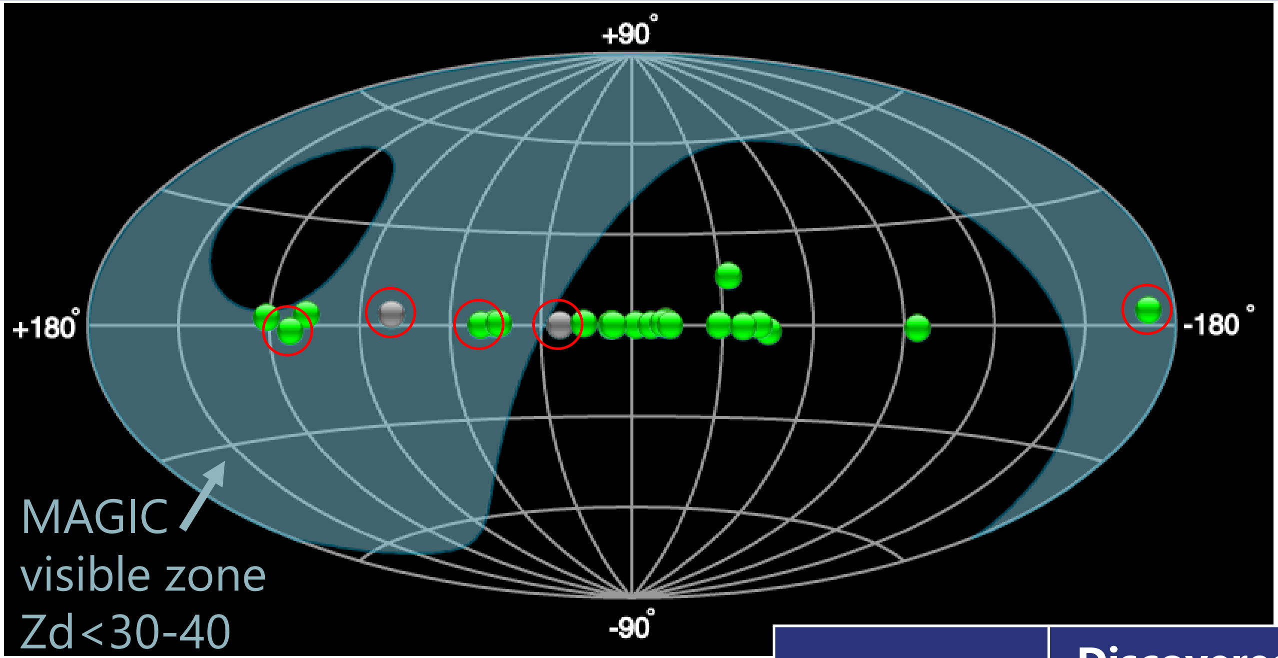
Origin of Galactic cosmic rays

- Up to the knee (10^{15} – 10^{16} eV) the spectrum of the cosmic rays is thought to be dominated by accelerated particles produced in Galactic SNRs.
- However the charged particles do not tell us their source location due to interaction with magnetic fields
- At the acceleration sites there would be detectable emission of very high energy γ rays. They result from:
  - **leptonic** processes: caused by energetic electrons or positrons such as inverse Compton upscattering of soft photons or Bremsstrahlung
  - **hadronic** processes: such as pion decay induced by collisions between cosmic rays and the ambient medium.



http://www.physics.utah.edu/~whanlon/spectrum.html

Very high energy (VHE) γ-ray SNR

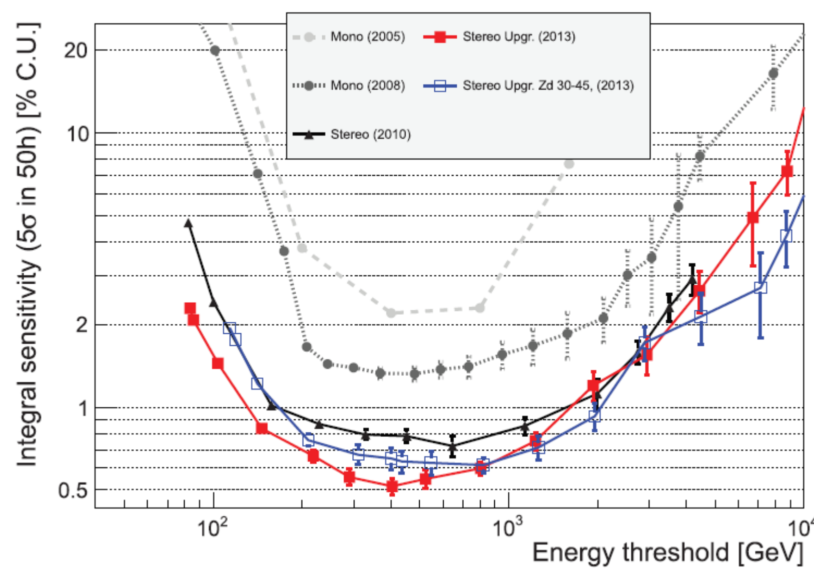


- Up to the present day, about 20 SNRs have been detected at very high energies, a fair fraction of them by the MAGIC telescope system
- Using broadband spectral energy distribution (radio – VHE γ ray) and/or morphological information, we can learn about the energetics and acceleration mechanisms at play.

	Discovered by	MAGIC detection
HESS J1834	H.E.S.S.	✓ (2005)
Cas A	HEGRA	✓ (2007)
IC 443	MAGIC	✓ (2007)
W51	H.E.S.S.	✓ (2011)
W44	–	–
γ Cygni	VERITAS	✓ (2015)

The MAGIC telescopes

- Two 17 m diameter telescopes
- Located at Observatorio del Roque de los Muchachos @2200 m a.s.l.
- Camera of 1.05 m diameter, with 1039 PMTs each
- 50 GeV – 50 TeV
- FoV: 3.5°
- Angular resolution: ≲0.06° @1 TeV
- Energy resolution: 15 – 25 %
- Continuous improvement
  - 2004: start of MAGIC-I operations
  - 2007: upgrade of MAGIC-I readout
  - 2009: MAGIC-II built, start of stereo operations
  - 2011-12: upgrade of MAGIC-I camera and both readout systems

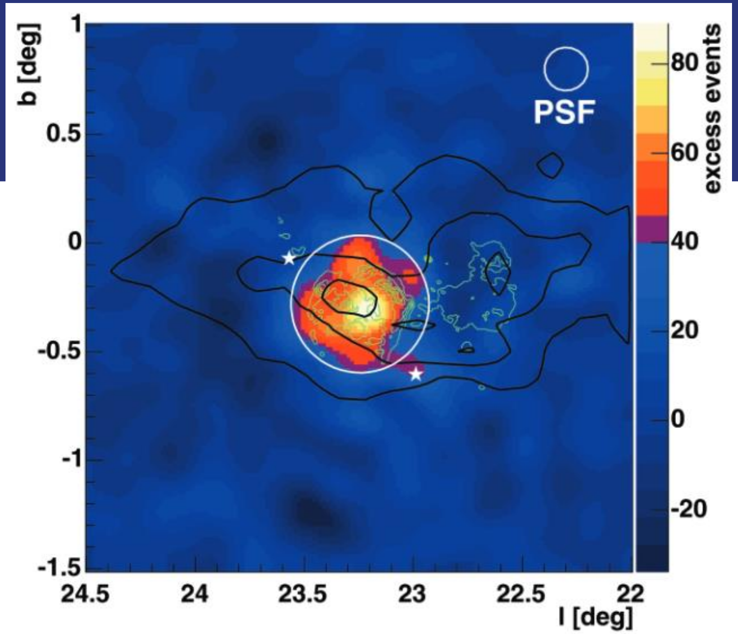


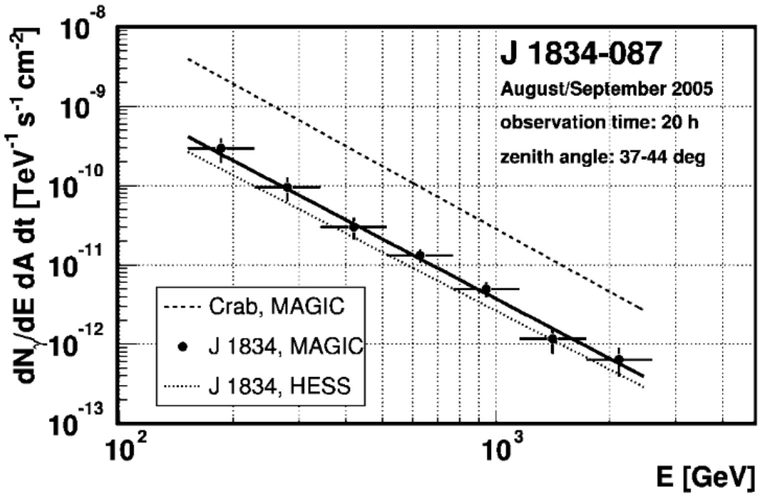
Aleksić et al. Astropart. Phys, 72, 2016

SNRs observed by the MAGIC telescopes

HESS J1834–087 (W41) mono

- Discovered by H.E.S.S. Galactic plane survey, coincide with SNR W41 which is an asymmetric shell-type SNR
- Distance: 3.8 – 4.5 kpc
- Age: 60 – 200 kyr
- a massive molecular cloud (~$8.8\text{x}10^4$ $M_{\odot}$) has been identified in the region. There is enough mass to generate the high-energy radiation hadronically, even if only part of the gas is interacting with the SNR shock.
- On the other hand, in X-ray, pulsar/PWN candidate is detected within the extent of TeV emission, which suggests leptonic scenario. (Mukherjee et al. 2009)



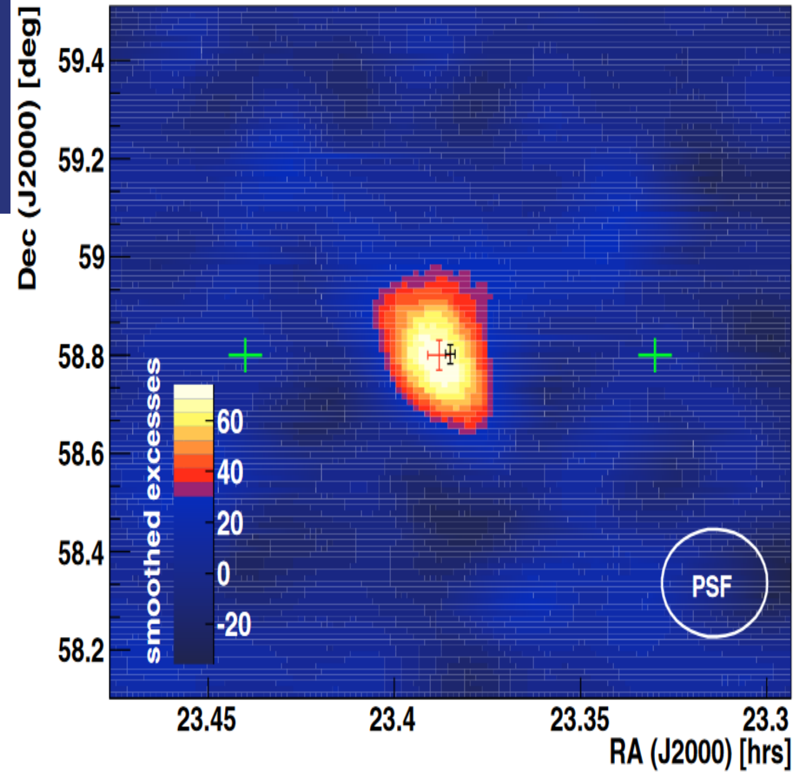


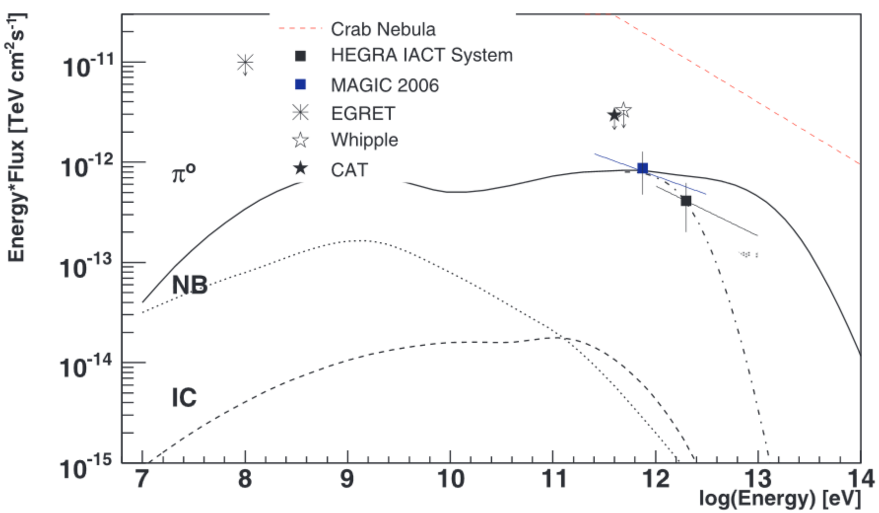
Albert et al. AsJ 643 L53–L56, 2006

Cassiopeia A

mono

- a shell type supernova remnant and a bright source of synchrotron radiation observed at radio frequencies and in the X-ray band
- Distance: 3.3 – 3.7 kpc
- Age: 316 – 352 yr
- $B \lesssim 1$ mG $\Rightarrow$ Leptonic modeling predicts a steep cutoff @a few TeV (Atoyan+ 2000), which is not seen in HEGRA or MAGIC data, disfavoring a leptonic origin of the radiation.
- However in hadronic case (using the model of Berezhko+ 2003), The predicted slope for the dominating nucleonic-produced γ–rays too hard to provide a good fit.



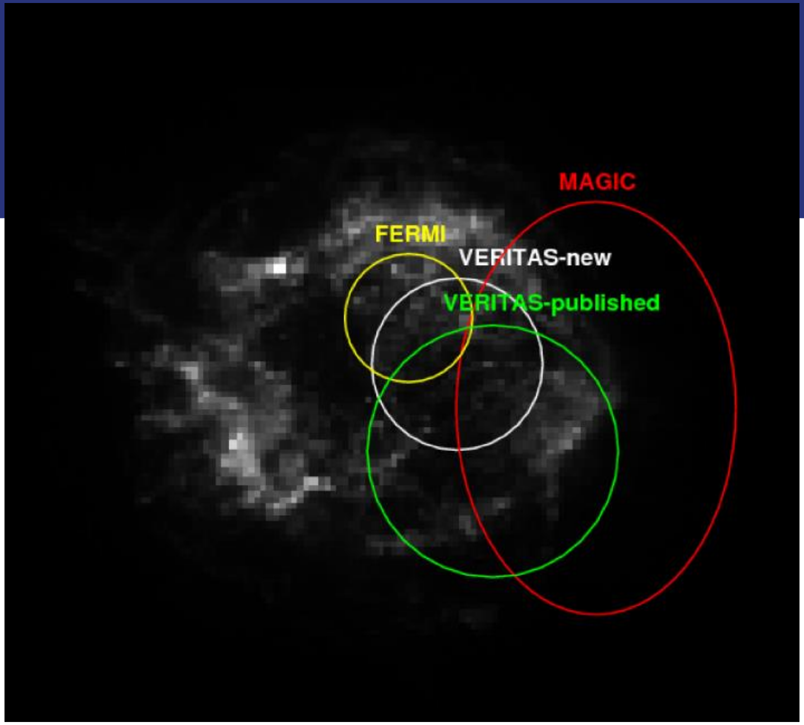


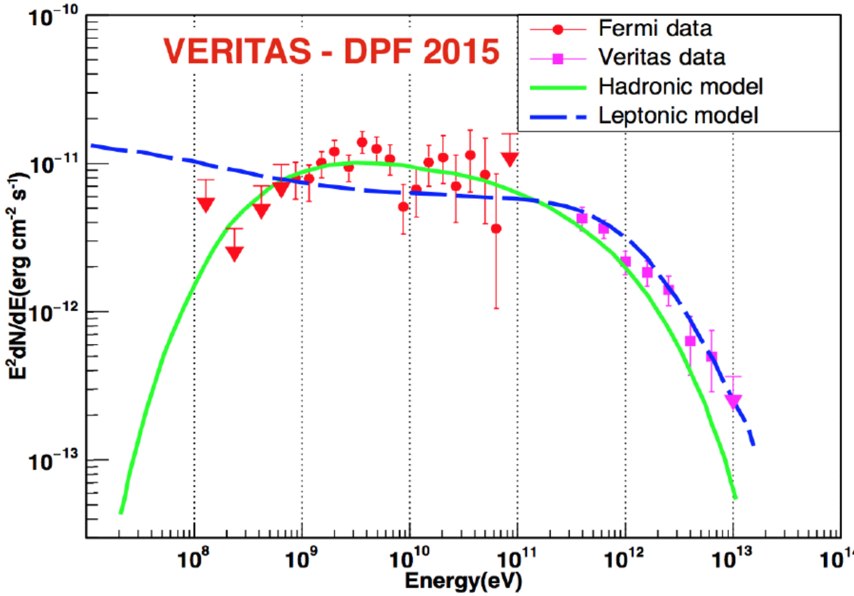
Albert et al. A&A 474, 937–940, 2007

Cassiopeia A

mono

- a shell type supernova remnant and a bright source of synchrotron radiation observed at radio frequencies and in the X-ray band
- Distance: 3.3 – 3.7 kpc
- Age: 316 – 352 yr
- VERITAS updated the result
- In order for the data to be consistent with the current hadronic emission model, the cut off energy would have to be higher than 10 TeV.
- The updated map does not confirm the suggestion in Grefenstette et al. 2015 that the TeV emission is associated with synchrotron knots.



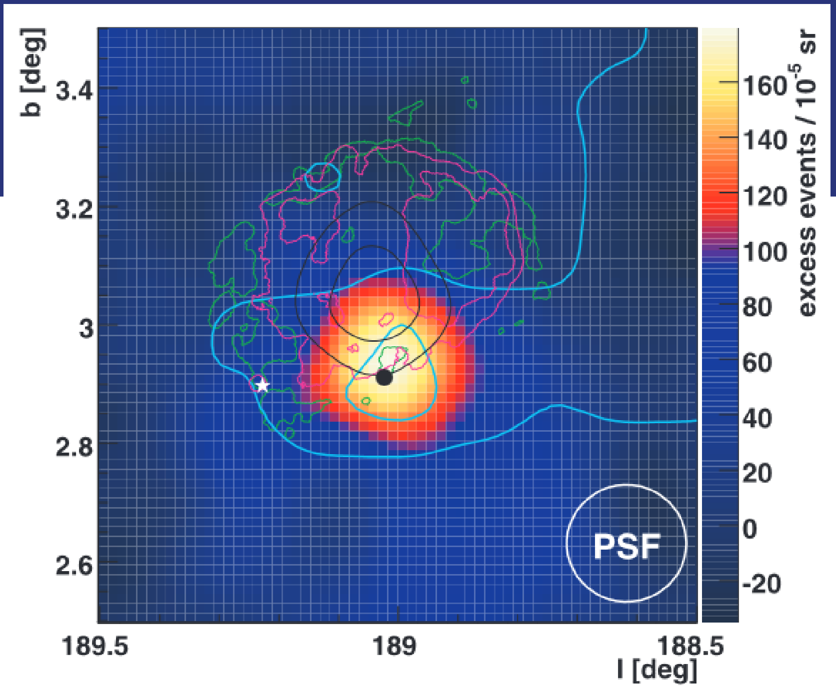


Ghiotto et al., DPF 2015

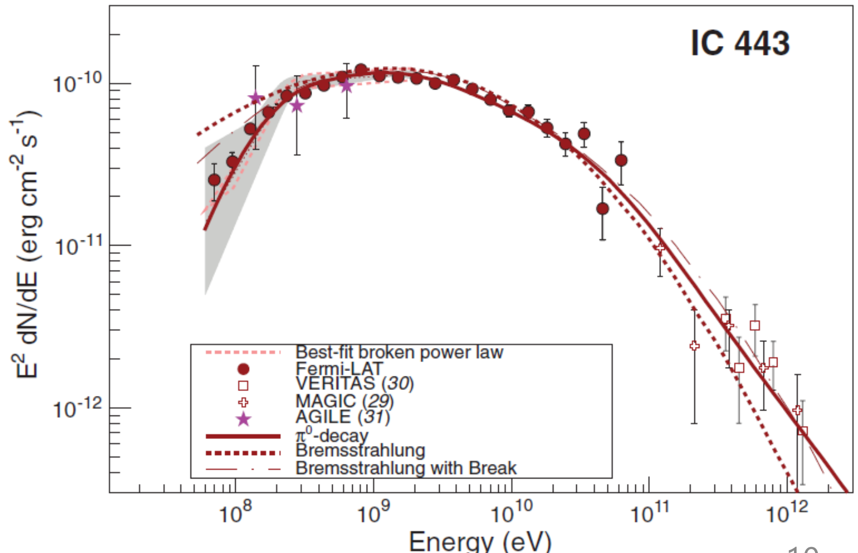
IC 443

mono

- asymmetric shell-type SNR
- discovered by MAGIC in VHE
- Distance: 0.7 – 2 kpc
- Age: 3 – 30 kyr
- A massive molecular cloud and OH maser emissions are located at the same sky position as that of the MAGIC detection, and they suggest hadronic origin of VHE γ rays. A *Fermi*-LAT result supports this scenario (Ackermann et al., 2013)



Albert et al. AsJ 664 L87–L90, 2007



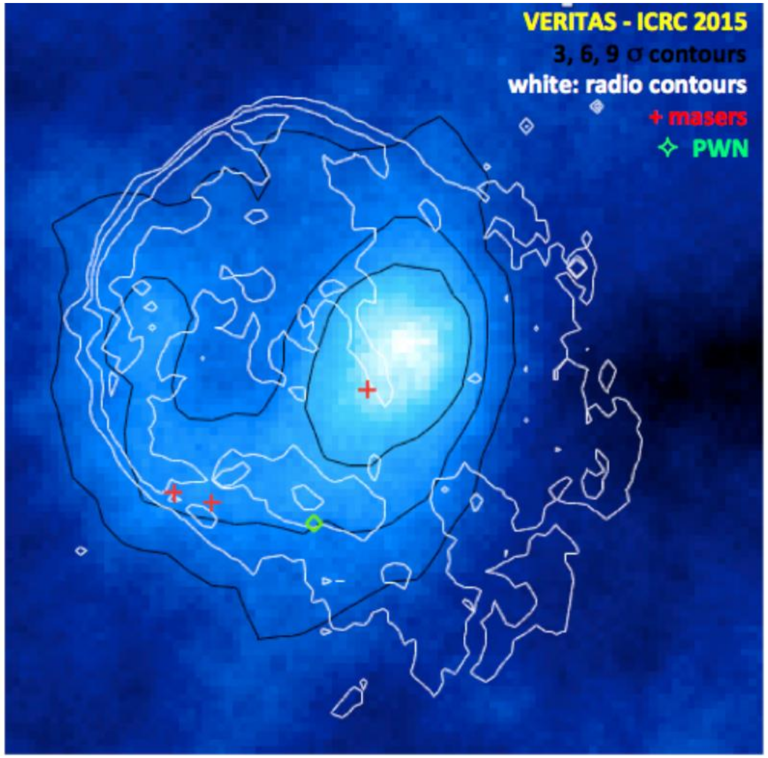
Ackermann et al., Science 339, 2013

IC 443

mono

- asymmetric shell-type SNR
- discovered by MAGIC in VHE
- Distance: 0.7 – 2 kpc
- Age: 3 – 30 kyr

- VERITAS updated the result
- GeV / TeV emission correlate most strongly with shocked gas, which suggests emission dominated by CRs interacting with gas in contact with shock front. (Humensky et al., ICRC, 2015)

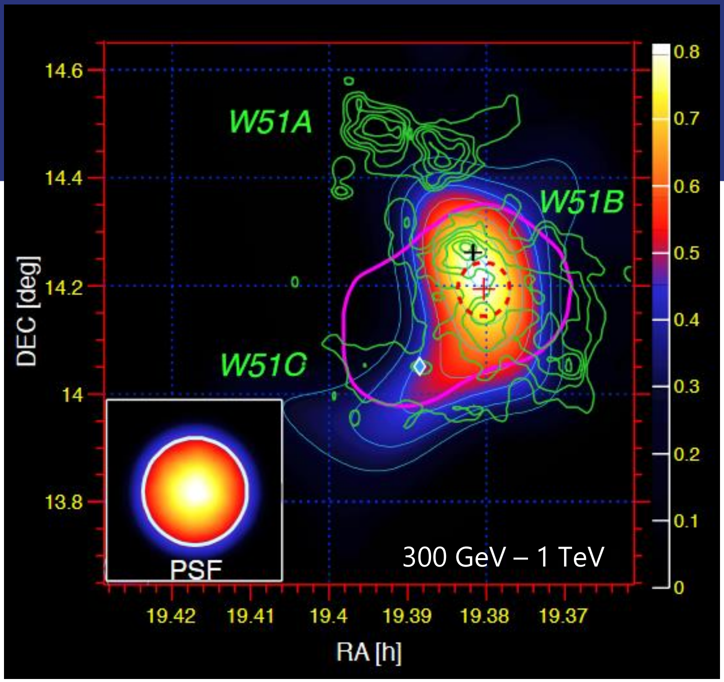


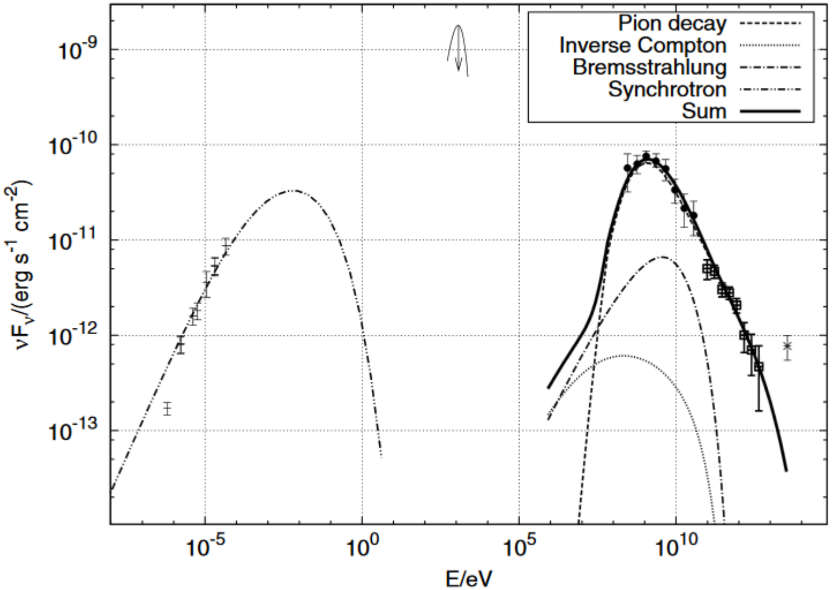
Humensky et al., ICRC, 2015

W51

stereo

- a massive molecular complex which is composed of the star-forming regions W51A and W51B and, attached to the south-eastern boundary of W51B, the SNR W51C.
- Distance: 4.3 – 6 kpc
- Age: 18 – 30 kyr
- the VHE emission from W51C cannot be explained by any of the considered leptonic models.
- In the hadronic model, the SNR has converted about 16% of the explosion energy into kinetic energy for proton acceleration and the emission zone includes a 10% of a molecular cloud of $10^5\ M_\odot$. In this scenario, protons are required to reach at least ~100 TeV.



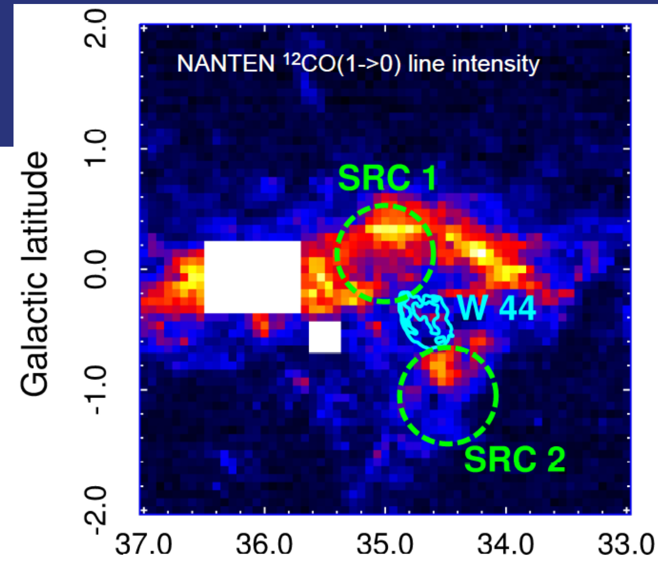


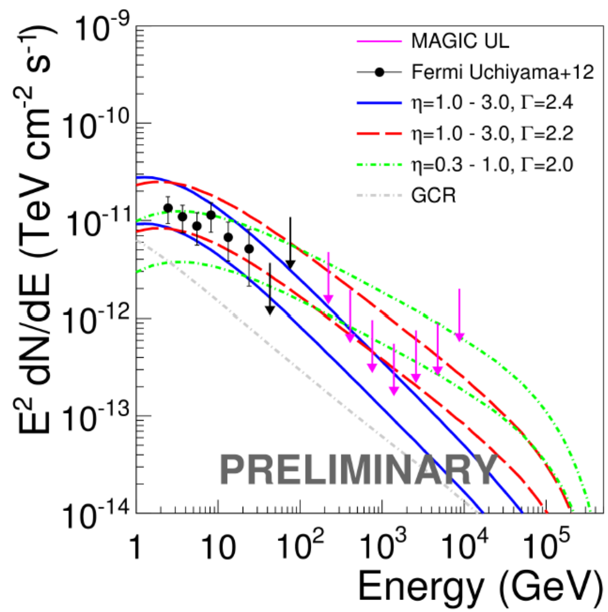
Aleksić et al. A&A 541, A13 2012

W44

stereo

- Fermi/LAT observations reveal emission from two additional regions after the subtraction of a model for the main emission of W44,. The HE emission (2-10 GeV) can be modelled with cosmic rays that have escaped from W44 and are diffusing in the surrounding molecular cloud (Uchiyama et al. 2012)
- From NANTEN2 $^{12}CO(1\rightarrow0)$ datasets (Yoshiike et al. 2013), $M \sim 2\text{x}10^5\ M_{\odot}$
- MAGIC observation was performed toward W44 SRC 1. No significant emission has been detected.
- Fermi data were modeled so that it is compatible with MAGIC upper limits using the approach of Torres et al. 2010.



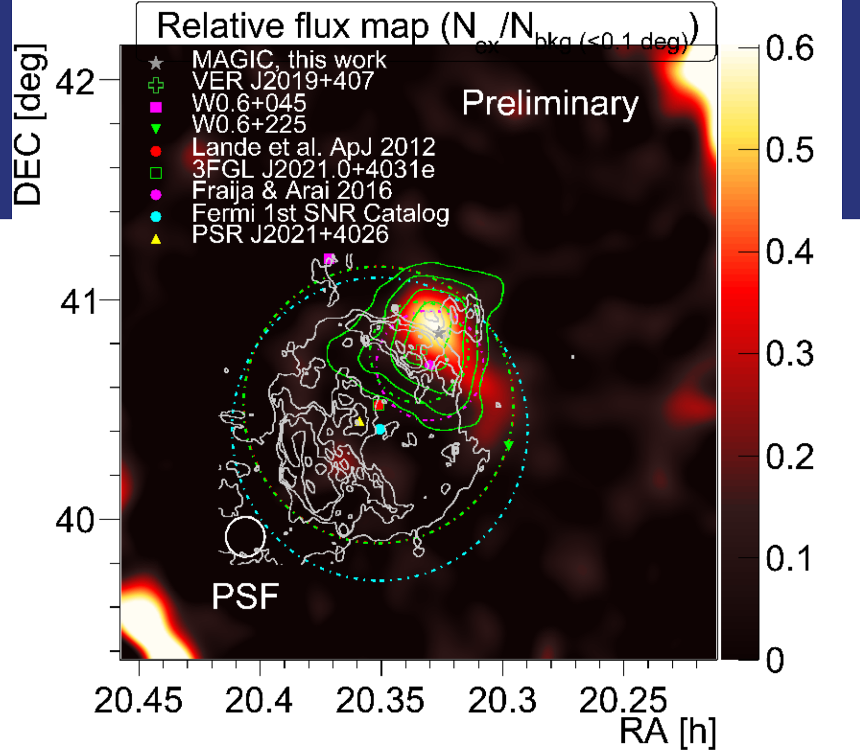


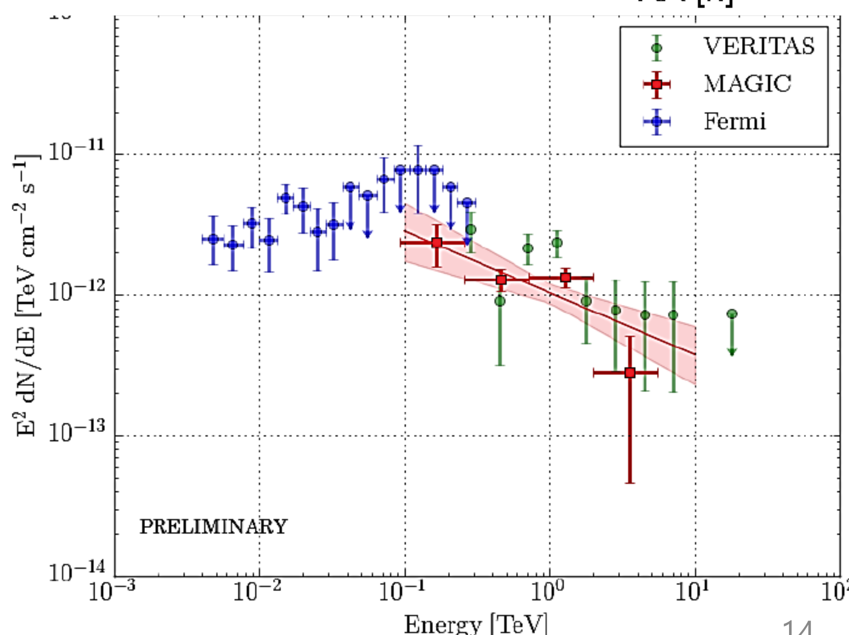
Gozzini et al. ICRC 2015

γ Cygni

stereo

- Very bright radio shell SNR. Discovered by Cygnus region survey performed by VERITAS (Aliu et al. ApJ 770, 93, 2013)
- Distance: 1.7 – 2.6 kpc
- Age: 7 – 16 kpc
- MAGIC brightest spot overlaps the VERITAS main spot.
- The interaction of the supernova shock with the ambient HI shell are found by [S II] lines and thermal X-ray. Hadronic scenario is favored.
- difficult for the emission to be explained by leptonic scenario due to missing nearby pulsar/PWN but energetics is no problem.
- Broadband spectrum modeling is necessary.





Strzys et al. TeVPa 2016

Summary

- CR spectrum up to knee is thought to be dominated by particles accelerated in Galactic SNRs, but sufficient proofs are still missing. Multi wavelength study from radio up to TeV regime can help the understanding of particle acceleration at the SNRs.
- To date MAGIC telescopes have observed several SNRs, 5 of which are detected. These observations and results have helped to provide hints for spectrum of hadronic process, especially IC443 and W51.
- The emissions from these objects can be explained by hadronic process, although some of them still can be explained by leptonic scenario.

Thank you for your attention!

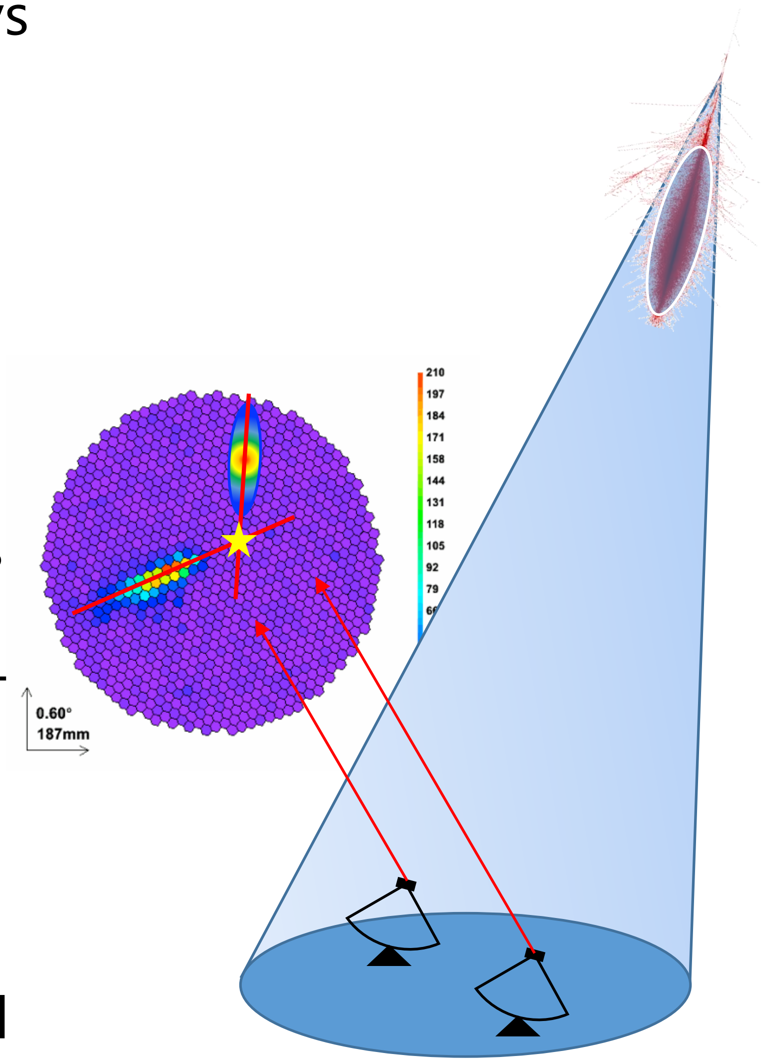
The MAGIC telescopes

- Two 17 m diameter telescopes
- Located at Observatorio del Roque de los Muchachos @2200 m a.s.l.
- Camera of 1.05 m diameter, with 1039 PMTs each

- 50 GeV – 50 TeV
- FoV: 3.5°
- Angular resolution: ≲0.06° @1 TeV
- Energy resolution: 15 – 25 %

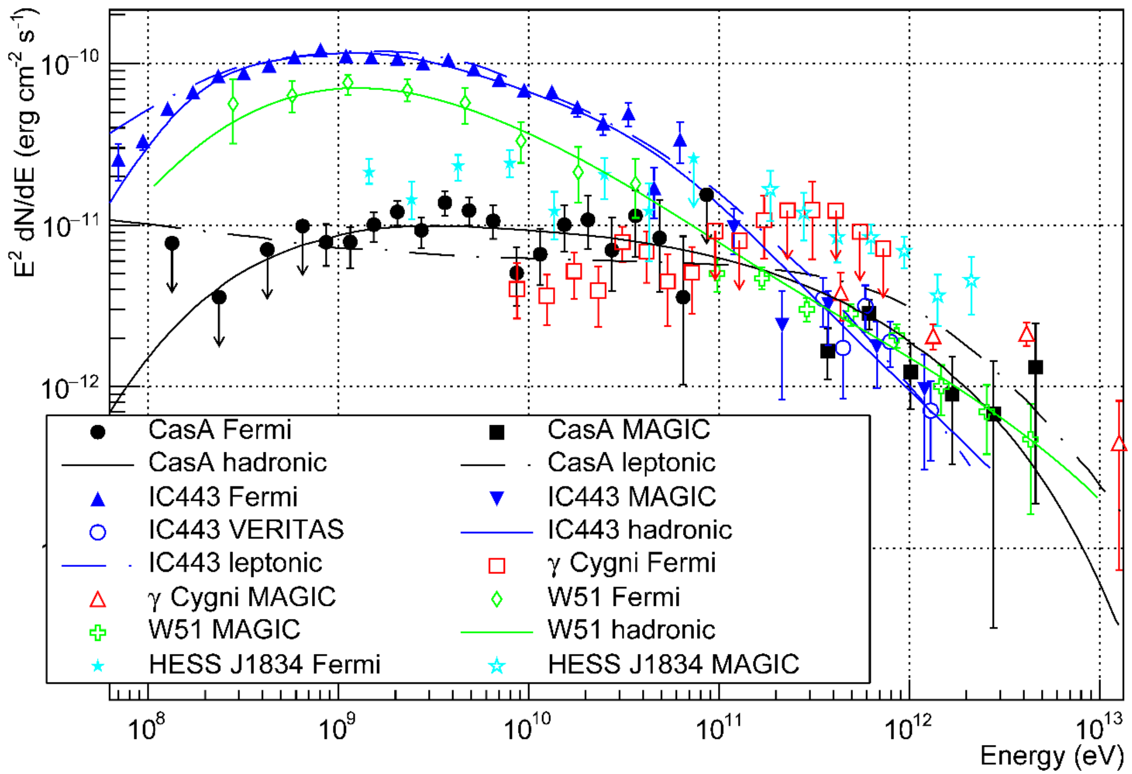
Imaging air Cherenkov telescopes

- Electromagnetic cascade shower: γ rays entering the atmosphere interact with nucleus and primarily create e^+e^- pair. the high-energy e^+e^- emit γ rays via Bremsstrahlung. These two processes last until the particles reach the critical energies.
- Cherenkov radiation: the cascade of high-energy charged particles exceeds the speed of light in the material (the atmosphere) and emits flashes of blue-UV light.
- Imaging air Cherenkov telescopes: Cherenkov flashes of showers can be taken by ground-based telescopes. From the images, arrival directions and estimated energies are obtained.



Spectra of 5 SNRs

	Age [kyr]
Cas A	0.316 – 0.352
IC 443	3 – 30
γ Cygni	7 – 16
W51	18 – 30
HESS J1834	60 – 200



Although following could be attributed to selection bias, what we can say from the figure are:

- to be detected by MAGIC, either extremely high flux or hard spectrum above TeV is required.
- no clear correlation between parameters like age and spectral index was found.