Gamma rays from the remnant of Kepler's SN

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Evidence for γ-ray emission from the remnant of Kepler's supernova based on deep H.E.S.S. observations

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ABSTRACT

Observations with imaging atmospheric Cherenkov telescopes (IACTs) have enhanced our knowledge of nearby supernova (SN) remnants with ages younger than 500 years by establishing Cassiopeia A and the remnant of Tycho's SN as very-high-energy (VHE) γ-ray sources. The remnant of Kepler's SN, which is the product of the most recent naked-eye supernova in our Galaxy, is comparable in age to the other two, but is significantly more distant. If the γ-ray luminosities of the remnants of Tycho's and Kepler's SNe are similar, then the latter is expected to be one of the faintest γ-ray sources within reach of the current generation IACT arrays.

Here we report evidence at a statistical level of 4.6 σ for a VHE signal from the remnant of Kepler's SN based on deep observations by the High Energy Stereoscopic System (H.E.S.S.) with an exposure of 152 hours. The measured integral flux above an energy of 226 GeV is ~0.3% of the flux of the Crab Nebula. The spectral energy distribution (SED) reveals a γ-ray emitting component connecting the VHE emission observed with H.E.S.S. to the emission observed at GeV energies with *Fermi*-LAT. The overall SED is similar to that of the remnant of Tycho's SN, possibly indicating the same non-thermal emission processes acting in both these young remnants of thermonuclear SNe.

Key words. gamma-rays: general, supernovae: individual: Kepler's SN, ISM: supernova remnants, radiation mechanisms: non-thermal

1. Introduction

For several decades, supernova remnants (SNRs) have been considered the most likely sources of Galactic cosmic rays (CRs; e.g., Ginzburg & Syrovatskii 1964), i.e. CRs with energies at least up to 3×10^{15} eV. While the detection of radio and X-ray synchrotron radiation from SNRs does indeed prove that electrons are accelerated to GeV or even of order 10 TeV energies (e.g. Reynolds 2008, Helder et al. 2012, Dubner & Giacani 2015, Vink 2020, for reviews), further insight into the particle acceleration in SNRs comes from γ-ray astronomy, which inter alia provides a probe of CR protons and nuclei through observations of GeV to TeV emission resulting from the decay of secondary neutral pions produced in CR interactions.

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Characterization of the GeV emission from the Kepler supernova remnant

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ABSTRACT

The Kepler supernova remnant (SNR) is the only historic supernova remnant lacking a detection at GeV and TeV energies which probe particle acceleration. A recent analysis of *Fermi*-LAT data reported a likely GeV γ-ray candidate in the direction of the SNR. Using approximately the same dataset but with an optimized analysis configuration, we confirm the γ-ray candidate to a solid $> 6\sigma$ detection and report a spectral index of $2.14 \pm 0.12_{stat} \pm 0.15_{syst}$ for an energy flux above 100 MeV of $(3.1 \pm 0.6_{stat} \pm 0.3_{syst}) \times 10^{-12}$ erg cm^{-2} s^{-1}. The γ-ray excess is not significantly extended and is fully compatible with the radio, infrared or X-ray spatial distribution of the SNR. We successfully characterized this multi-wavelength emission with a model in which accelerated particles interact with the dense circumstellar material in the North-West portion of the SNR and radiate GeV γ-rays through π^0 decay. The X-ray synchrotron and inverse-Compton (IC) emission mostly stem from the fast shocks in the southern regions with a magnetic field B~100 μG or higher. Depending on the exact magnetic field amplitude, the TeV emission could arise from either the South region (IC dominated) or the interaction region (π^0 decay dominated).

Key words. supernovae: individual : Kepler – ISM: supernova remnants – ISM: cosmic rays – Gamma rays: general – Astroparticle physics –Shock waves

1. Introduction

The last Galactic supernova to be observed from Earth occurred on October 9, 1604 and a detailed report was produced by Johannes Kepler whose name is now attached to the supernova and its remnant. The Kepler SNR is most certainly the remnant of a Type Ia explosion but the large scale asymmetry with brighter emission towards the North from radio to X-rays (DeLaney et al. 2002; Cassam-Chenaï et al. 2004; Blair et al. 2007; Reynolds et al. 2007) has caused some confusion with a core collapse origin (see Vink 2017, for a review). This asymmetry is now thought to be associated with circumstellar medium (CSM) from a runaway supernova progenitor system with significant mass loss prior to the explosion in a single degenerate scenario (e.g. Bandiera 1987; Burkey et al. 2013; Katsuda et al. 2015).

Estimates for the distance to the SNR range widely, from 3 to 7 kpc in the literature (e.g. Reynoso & Goss 1999; Sankrit et al. 2005; Katsuda et al. 2008). The measurement of the proper motion of Balmer-dominated filaments using the Hubble space telescope at a 10-year interval combined with the independently derived shock velocity from spectroscopy (Hα line width) provides the most robust estimation at $d = 5.1^{+0.8}_{-0.7}$ kpc (Sankrit et al. 2016). Throughout the paper we will use a distance of 5 kpc and rescale the values from the literature (e.g. shock speed) to match this distance whenever possible.

In the X-ray band, the emission is dominated by thermal emission with strong lines and in particular Fe lines supporting a Type Ia origin (e.g. Cassam-Chenaï et al. 2004; Reynolds et al. 2007). Non-thermal emission from thin synchrotron-dominated filaments was later revealed by Chandra observations (Bamba et al. 2005; Reynolds et al. 2007). Proper motion studies of these synchrotron rims (Vink 2008; Katsuda et al. 2008) show fast shocks with velocities[1] ranging from ~2000 km s^{-1} in the northern region to ~5000 km s^{-1} in the South.

The slower velocities in the North are related to the higher CSM density in this direction. Measurement of the thickness of these filaments suggests a high magnetic field of 150-300 μG if the width is energy loss limited (Bamba et al. 2005; Parizot et al. 2006).

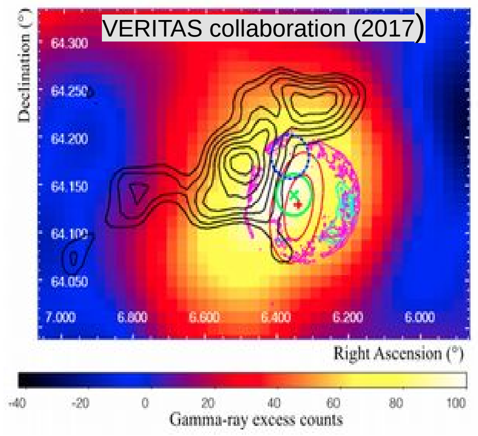
Despite being one of the youngest SNRs in our Galaxy with high velocity shocks and signs of dense material and interaction, Kepler was the only historic SNR without detected γ-ray emission until now. This has changed with the recent report by Xiang & Jiang (2021) of a ~ 3.8σ detection[2] with *Fermi*-LAT in the direction of the Kepler SNR. In addition, the recent detection of TeV γ-rays after a deep exposure with the H.E.S.S. telescopes (152 hours, Prokhorov et al. 2021, H.E.S.S. collaboration submitted) opens the window for a detailed γ-ray study of this young and historic SNR.

In this work we aim to transform the status of the *Fermi*-LAT discovery from likely candidate to solid detection by using a more sophisticated analysis with approximately the same dataset (see Sect. 2). In addition to the modest significance, Xiang & Jiang (2021) find a slightly offset best-fit position from the SNR. We thus analyze in detail if this offset is statistically compatible with the SNR morphology, as realized by multi-wavelength spatial templates. We conclude in Sect. 3 by modeling Kepler's multi-wavelength emission under the assumption that γ-rays are

[1] Velocities were rescaled to a 5 kpc distance.
[2] Significance associated to a Test Statistic of 22.94 with 4 degrees of freedom.

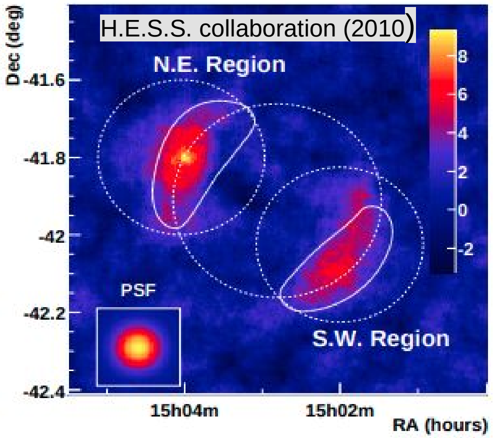
Historical shell-type SNRs detected in VHE gamma rays

Tycho SN (in 1572)



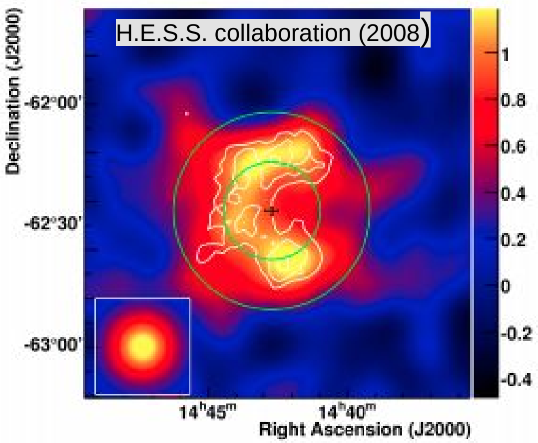
Detected at VHE with VERITAS in 2011 (67 hours)

SN 1006



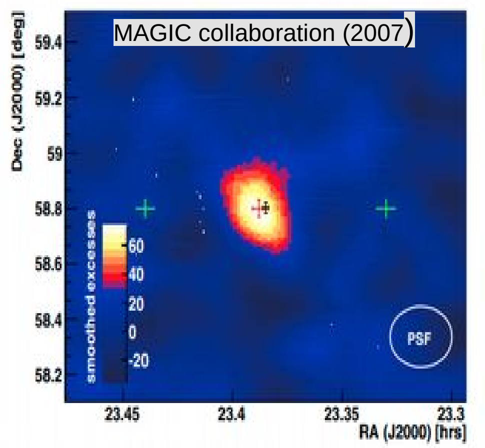
Detected at VHE with H.E.S.S. in 2010 (130 hours)

RCW 86 (SN in 185)



Detected at VHE with H.E.S.S. in 2008 (31 hours)

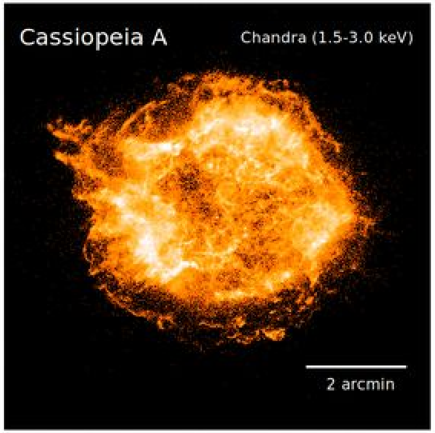
Cas A (SN around 1680)

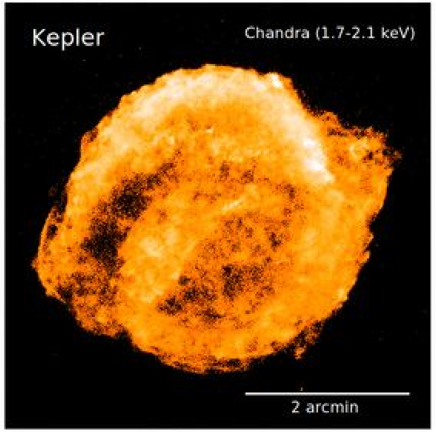


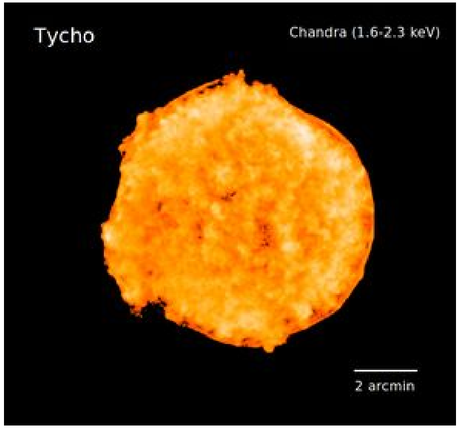
Detected at VHE with HEGRA in 2001 (232 hours)

Cas A, Kepler, and Tycho:

the remnant of Kepler’s SN is the most distant of the three



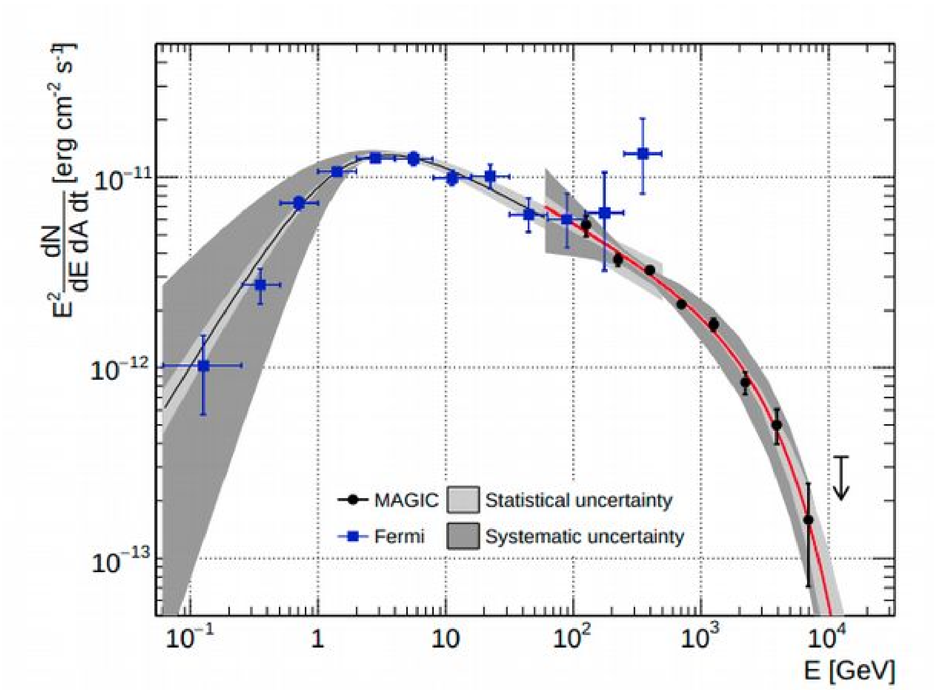




Name	Age (years)	SN Type	D, kpc	Angular diameter, arcmin
Cas A	~340	core-collapse	3.4	5
Kepler	417	Ia	4.8-6.4	3.5
Tycho	449	Ia	2.5-3.3	8

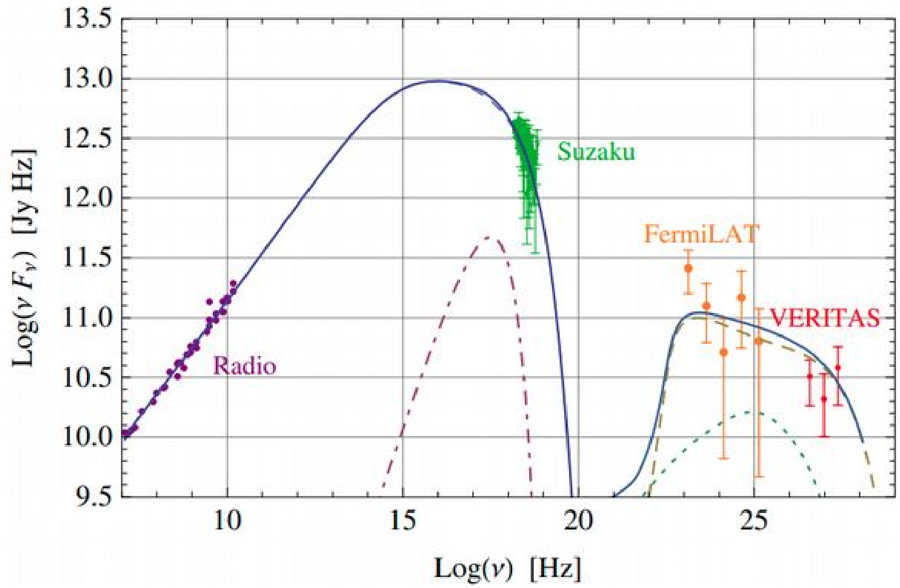
Hadronic model for Cas A and Tycho

Cassiopeia A



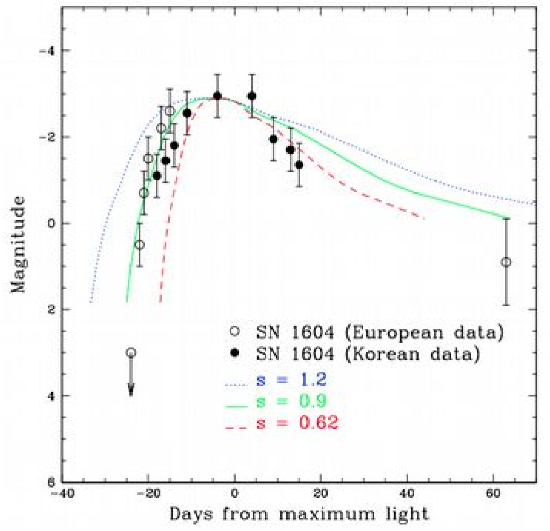
MAGIC Collaboration 2017

Tycho

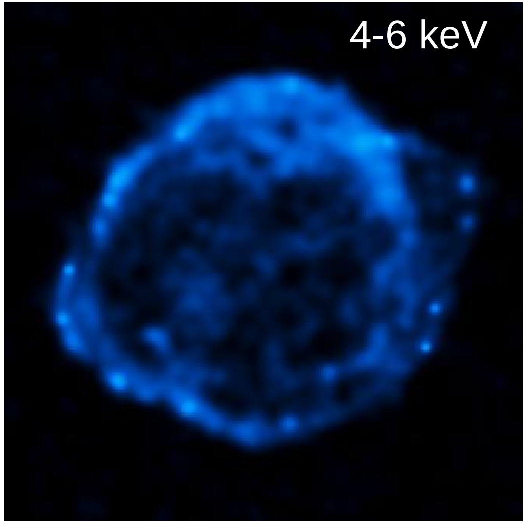


Morlino & Caprioli 2012

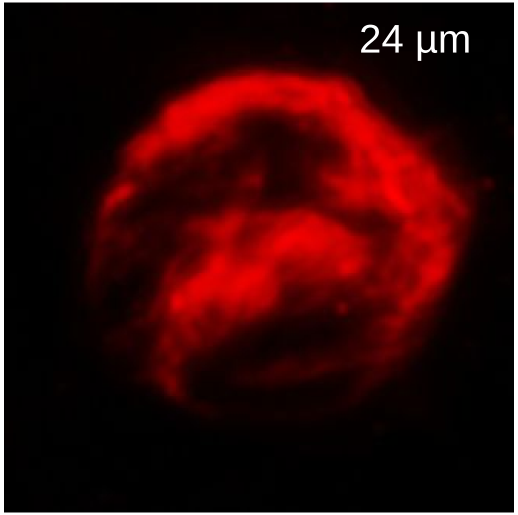
Kepler's SNR (SN 1604), the remnant of the most recent naked-eye supernova in our Galaxy



The visual light curve of SN 1604 (from Ruiz-Lapuente 2016)



Remnant of SN 1604 seen in the HE X-ray band with Chandra



Remnant of SN 1604 seen in the infrared band with Spitzer

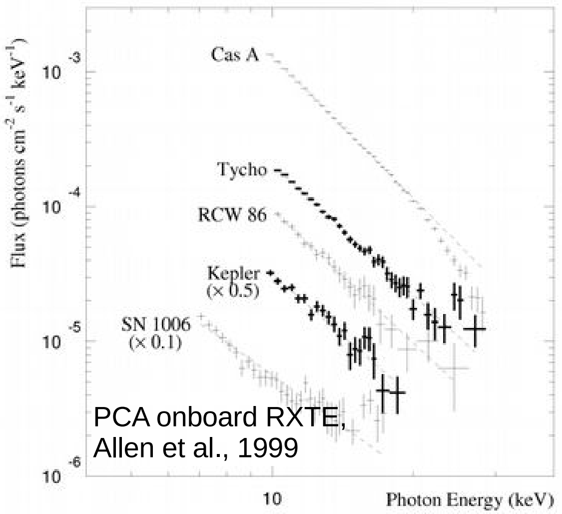
Kepler's SNR is a remnant of a thermonuclear SN located 6.8 degrees (500 pc) above the Galactic plane (at a distance of 5 kpc)
(Tycho's SNR at 3 kpc, SN 1006 - 2.2 kpc, SN 185 - 2.8 kpc, Cas A – 3.4 kpc)

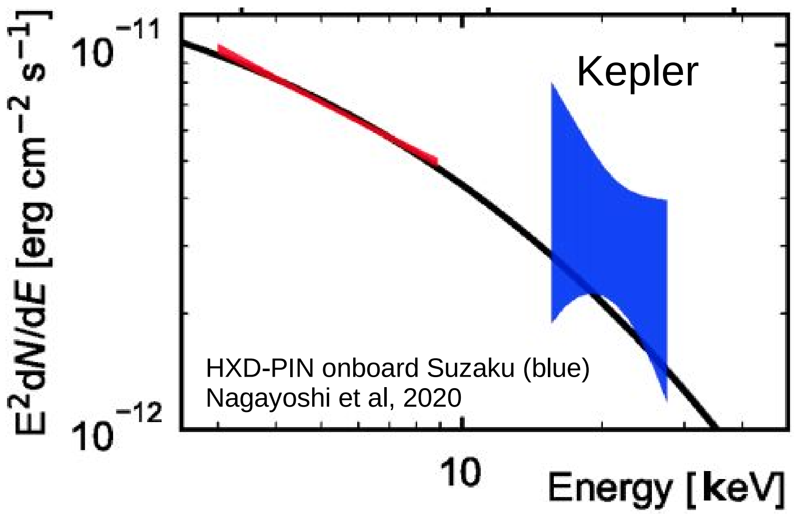
Evidence of 10-100 TeV Electrons in SNRs

Table. Observed widths of synchrotron filaments and downstream inferred magnetic field strength.

SNR	Age (yr)	Dist (kpc)	Radius (pc)	R_w (")	l_{adv} (10^{17} cm)	B_2 (μG)	E_{el} (TeV)	τ_{syn} (yr)
G1.9+0.3 (SW)	110	8.5	1.8	3.1	2.8	67	33	86
Cas A (NE)	334	3.4	2.5	1.1	0.4	246	17	12
Kepler (SE)	401	6.0	3.7	1.8	1.1	122	24	35
Tycho (W)	433	3.0	3.7	1.6	0.5	207	19	16
SN1006 (E)	999	2.2	9.1	9.1	2.1	81	30	64
RX J1713.7-3946 (SW)	1612	1.0	7.8	63.5	6.7	37	44	206
RCW 86 (NE)	1820	2.5	16.0	28.6	7.6	35	46	232
RX J0852.0-4622 (N)	2203	1.0	16.3	28.4	3.0	64	34	92

from a review by Helder at al. (2012) and based on Chandra data, see also Vink & Laming (2003) and Völk et al. (2005)





H.E.S.S. observations and analysis

H.E.S.S.- a system of imaging Cherenkov Telescopes

- located in Namibia at an altitude of 1800m
- well-suited for VHE (>100 GeV) observations of SNRs in the Southern sky, including Kepler's SNR
- with the 12m-diameter telescopes (2016)

Observations and analysis of Kepler's SNR with H.E.S.S.

- Data with exposure of 122 hours were taken in 2017-2020
- The total amount of data is 152 hours since 2004
- ~10 times longer than the observations in 2004-2005
- Analysis chains: M++ (de Naurois and Rolland, 2009) and ImPACT (Parsons and Hinton, 2014)

Fermi-LAT observations and analysis

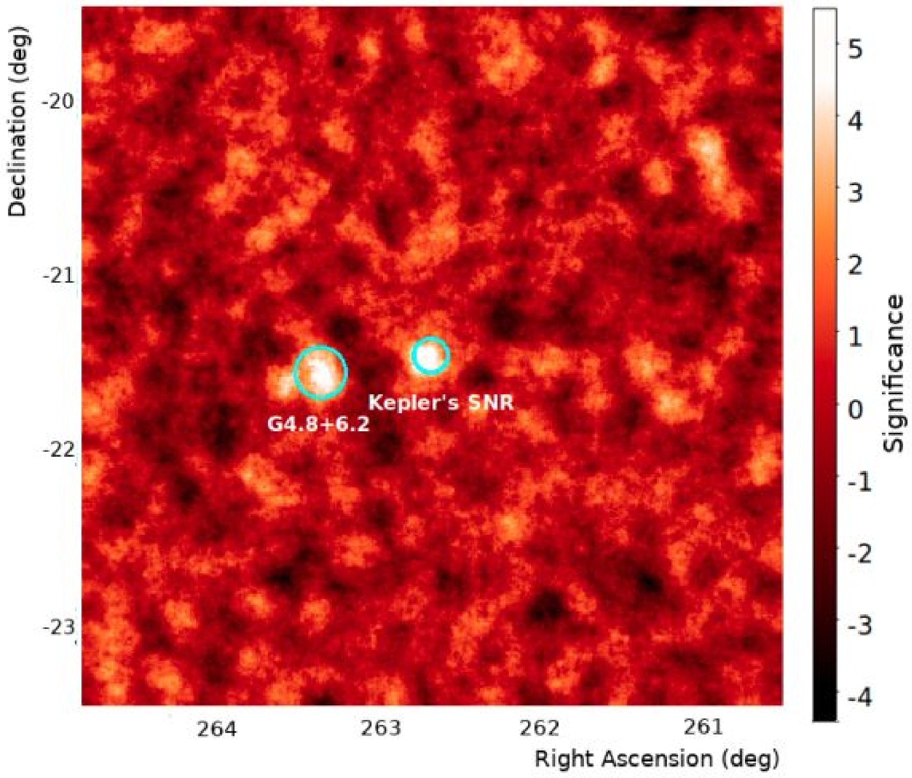
Fermi LAT Area Telescope (LAT)

- is a pair-conversion telescope
- has been scanning the entire sky since August 2008 from about 20 MeV to more than 300 GeV

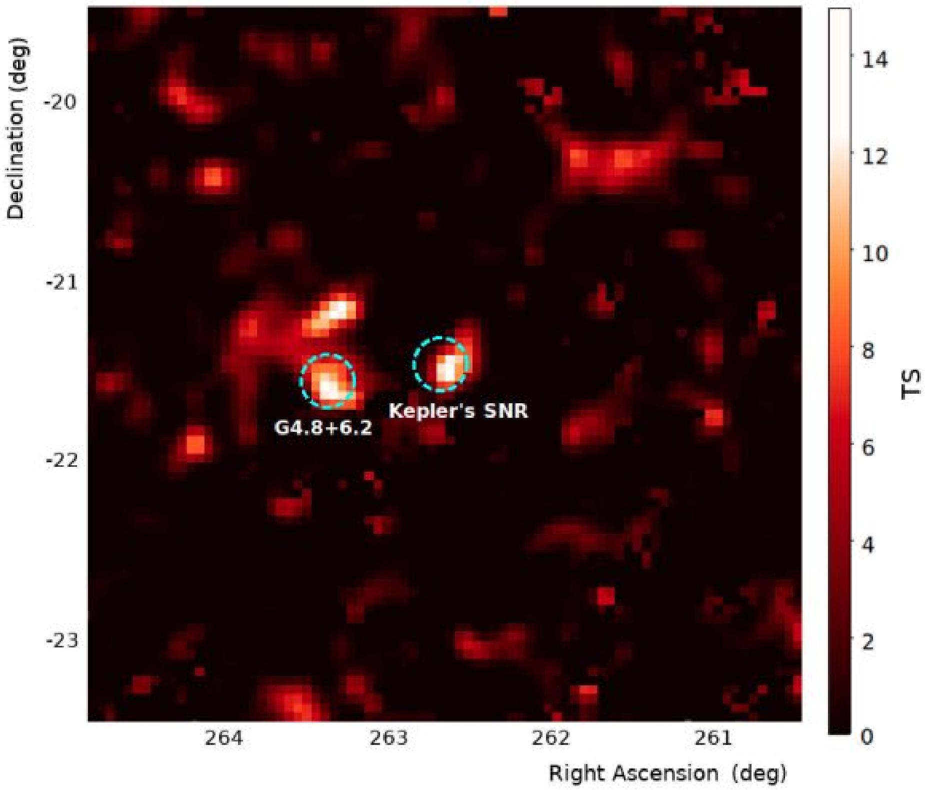
Observations and analysis of Kepler's SNR with Fermi-LAT

- 10.7 years of LAT data were used by the H.E.S.S. team to trigger H.E.S.S. observations in 2020
- Data with exposure of 12 years are analyzed in Acero et al. (2022)
- Events with energies between 100 MeV and 1 TeV
- Similar Fermi-LAT excess reported by Xiang & Jiang (2021)

H.E.S.S. significance map



Fermi-LAT TS map (E>4.75 GeV)



Kepler: Excess=178 gammas,
Significance=4.6 sigma

Kepler: TS=16.8 for E>0.75 GeV,
Significance=4.1 sigma

Theoretical models

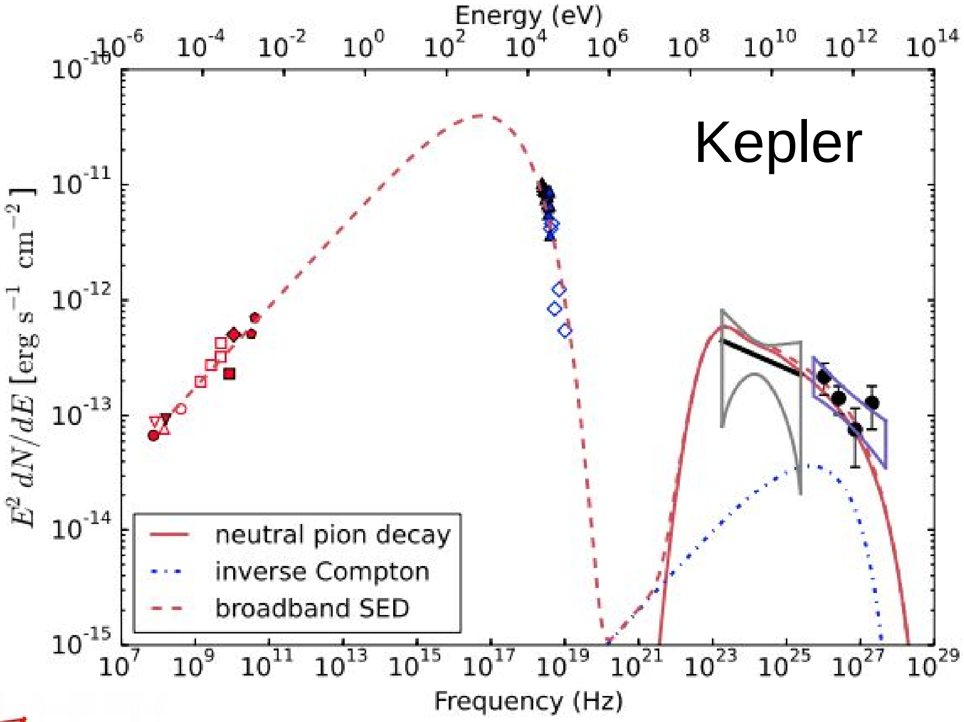
Hadronic scenario

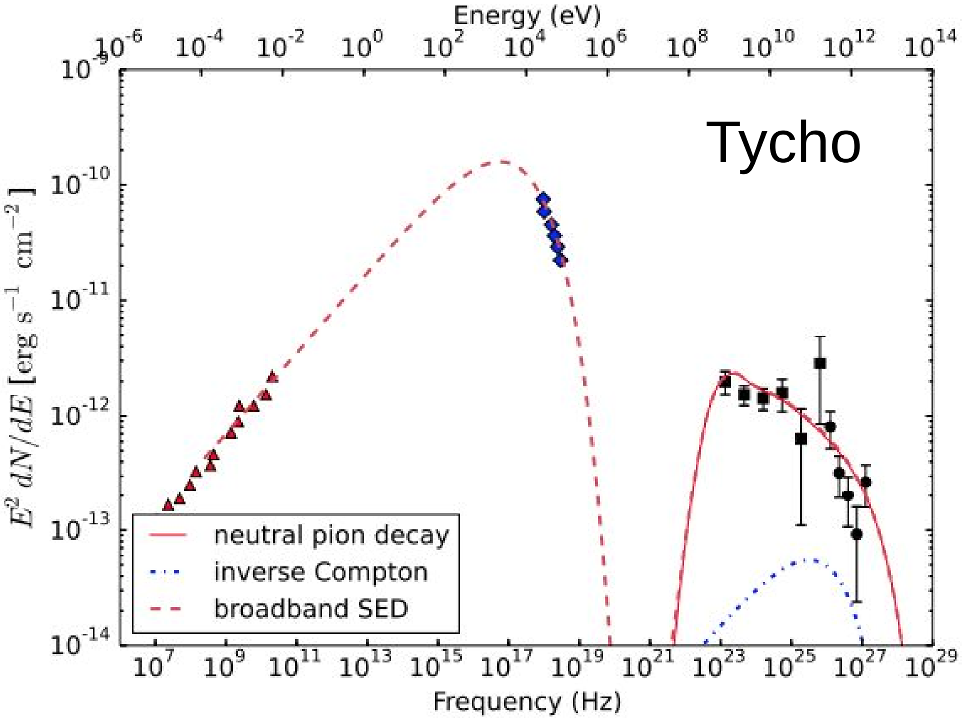
- SNIa explosion energy 10^{51}erg
- Cosmic-ray hadron energy of 7% of the explosion energy
- Target particle density 1.0 cm^{-3}
- Cosmic-ray proton spectral index, 2.2
- Exponential cut-off in the cosmic-ray proton spectrum at 100 TeV

Leptonic scenario

- SNIa explosion energy 10^{51}erg
- Cosmic-ray electron energy of 0.15% of the explosion energy
- Three soft photon fields, CMB, infrared emission by dust in the SNR and Galaxy
- Magnetic field strength 80μG
- Cosmic-ray electron spectral index, 2.3
- Exponential cut-off in the cosmic-ray electron spectrum at 11 TeV

The same hadronic model scaled with distance works for Kepler and Tycho



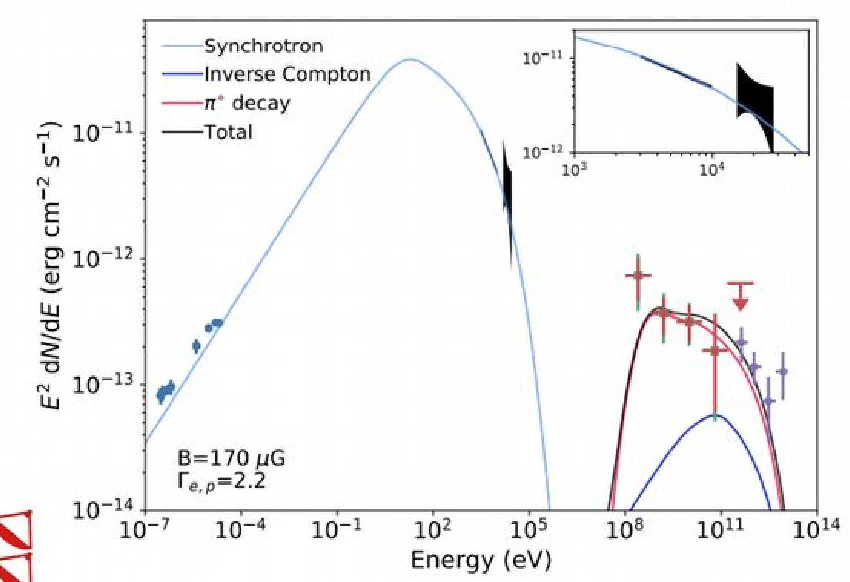


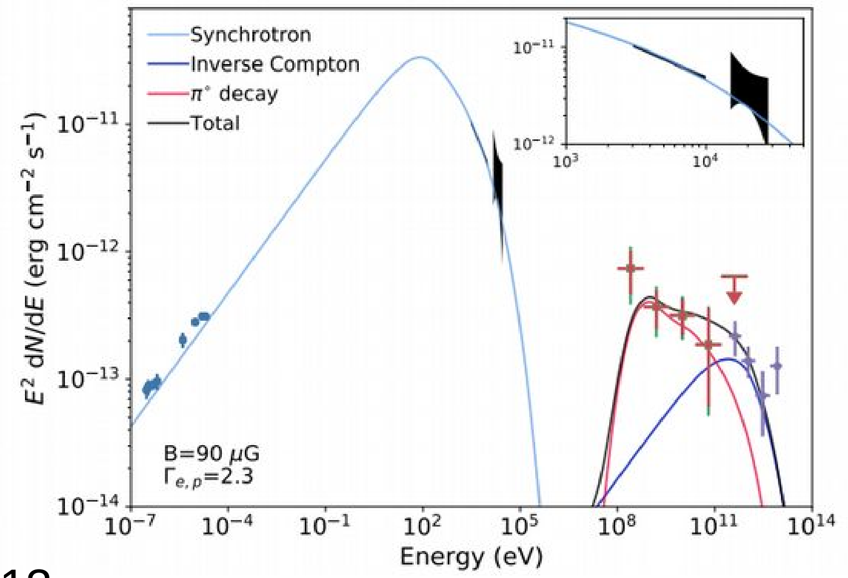
Fermi-LAT analysis by Acero, Lemoine-Goumard, and Ballet (2022)

Detection of Kepler's SNR at 6 sigma significance after

- applying a max zenith angle of 90 deg below 1 GeV and 105 deg above 1 GeV
- using the summed likelihood method for events with different reconstruction quality

Fermi-LAT spectral points: 5 log bins from 100 MeV to 1 TeV:





Summary

- Deep observations (152 hr) of Kepler's SNR with H.E.S.S.
- Strong evidence emission from Kepler's SNR at VHE
- Fermi-LAT data: HE gamma-ray detection
- Kepler's SNR (SN 1604) is best fit with a hadronic model, similar to Tycho's SNR (SN 1572)
- Now all historical SNRs have gamma-ray detections