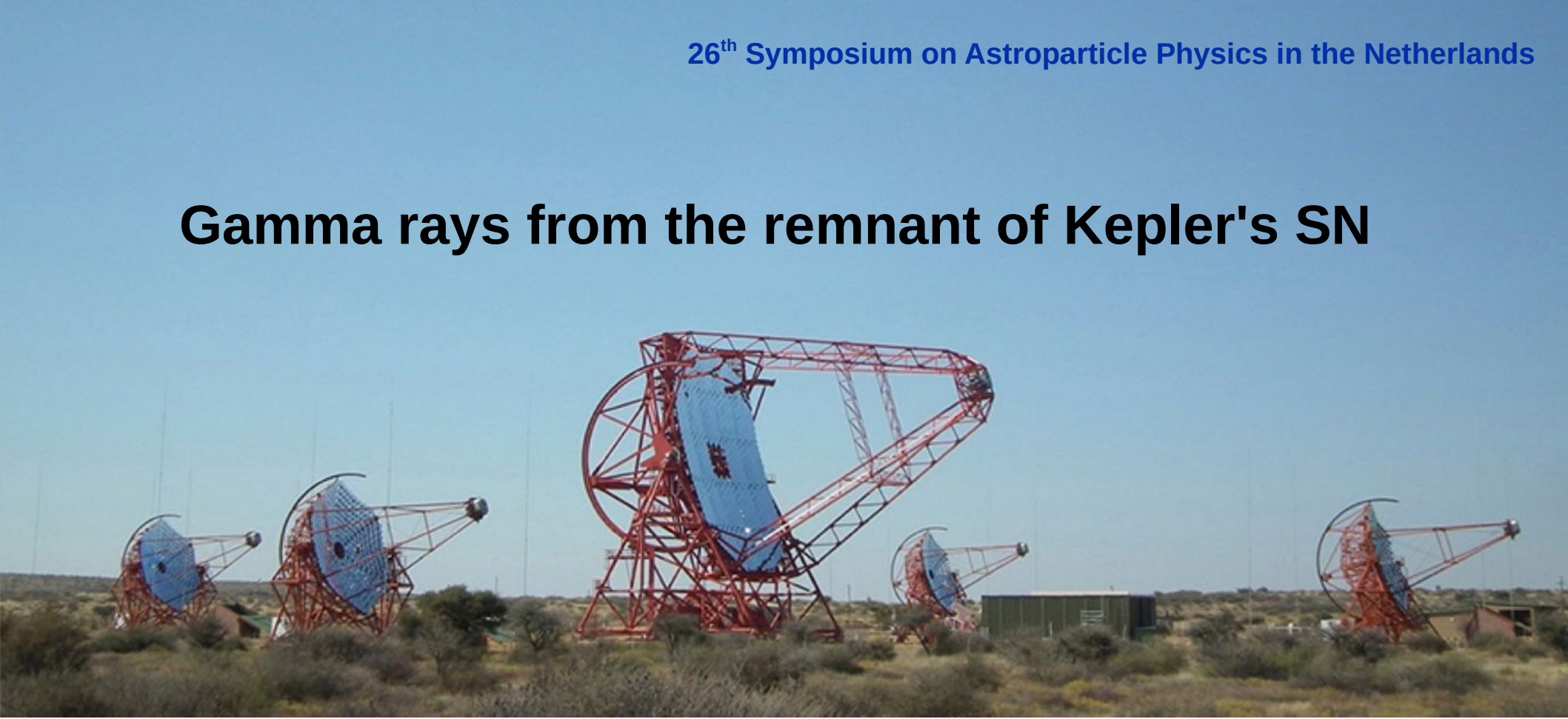
26th Symposium on Astroparticle Physics in the Netherlands

Gamma rays from the remnant of Kepler's SN



Dmitry Prokhorov, Jacco Vink, and Rachel Simoni for the H.E.S.S. Collaboration

Astronomy & Astrophysics manuscript no. manuscriptKepler_v20
January 19, 2022

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

H.E.S.S. Collaboration, F. Aharonian[1,2,3], F. Ait Benkhali[4], E.O. Angüner[5], H. Ashkar[6], M. Backes[7,8], V. Barbosa Martins[9], R. Batzofin[10], Y. Becherini[11,12], D. Berge[9], K. Bernlöhr[2], M. Böttcher[8], C. Boisson[13], J. Bolmont[14], M. de Bony de Lavergne[15], M. Breuhaus[2], R. Brose[1], F. Brun[16], T. Bulik[17], T. Bylund[12], F. Cangemi[14], S. Caroff[14], S. Casanova[18], M. Cerruti[11], T. Chand[8], A. Chen[10], O. Chibueze[8], G. Cotter[19], P. Cristofari[13], J. Damascene Mbarubucyeye[9], J. Devin[20], A. Djannati-Ataï[11], A. Dmytriiev[13], K. Egberts[21], S. Einecke[22], J.-P. Ernenwein[5], K. Feijen[22], A. Fiasson[15], G. Fichet de Clairfontaine[13], G. Fontaine[6], S. Funk[23], S. Gabici[11], Y.A. Gallant[24], S. Ghafourizadeh[4], G. Giavitto[9], L. Giunti[11,16], D. Glawion[23], J.F. Glicenstein[16], M.-H. Grondin[20], M. Hörbe[19], W. Hofmann[2], T. L. Holch[9], M. Holler[25], D. Horns[26], Zhiqiu Huang[2], M. Jamrozy[27], I. Jung-Richardt[23], E. Kasai[7], K. Katarzyński[28], U. Katz[23], B. Khélifi[11], W. Kluźniak[29], Nu. Komin[10], K. Kosack[16], D. Kostunin[9], A. Lemière[11], M. Lemoine-Goumard[20], J.-P. Lenain[14], F. Leuschner[30], T. Lohse[31], A. Luashvili[13], I. Lypova[4], J. Mackey[1], D. Malyshev[30], D. Malyshev[23], V. Marandon[2], P. Marchegiani[10], A. Marcowith[24], G. Martí-Devesa[25], R. Marx[4], G. Maurin[15], P.J. Meintjes[32], M. Meyer[26], A. Mitchell[23,2], R. Moderski[29], L. Mohrmann[2], A. Montanari[16], E. Moulin[16], J. Muller[6], K. Nakashima[23], M. de Naurois[6], A. Nayerhoda[18], J. Niemiec[18], A. Priyana Noel[27], P. O'Brien[33], S. Ohm[9], L. Olivera-Nieto[2], E. de Ona Wilhelmi[9], M. Ostrowski[27], S. Panny[25], M. Panter[2], R.D. Parsons[31], G. Peron[2], V. Poireau[15], D.A. Prokhorov[34*], G. Pühlhofer[30], M. Punch[11,12], A. Quirrenbach[4], P. Reichherzer[16], A. Reimer[25], O. Reimer[25], M. Renaud[24], B. Reville[2], F. Rieger[2], G. Rowell[22], B. Rudak[29], H. Rueda Ricarte[16], V. Sahakian[35], S. Sailer[2], H. Salzmann[30], D.A. Sanchez[15], A. Santangelo[30], M. Sasaki[23], J. Schäfer[23], F. Schüssler[16], H.M. Schutte[8], U. Schwanke[31], J.N.S. Shapopi[7], R. Simoni[34*], H. Sol[13], A. Specovius[23], S. Spencer[19], Ł. Stawarz[27], S. Steinmassl[2], C. Steppa[21], I. Sushch[8], T. Takahashi[36], T. Tanaka[37], A.M. Taylor[9], R. Terrier[11], M. Tsirou[2], Y. Uchiyama[38], T. Unbehaun[23], C. van Eldik[23], J. Veh[23], J. Vink[34*], H.J. Völk[2], S.J. Wagner[4], F. Werner[2], R. White[2], A. Wierzcholska[18], Yu Wun Wong[23], A. Yusafzai[23], M. Zacharias[13,8], D. Zargaryan[1,3], A.A. Zdziarski[29], A. Zech[13], S.J. Zhu[9], S. Zouari[11], N. Żywucka[8]

(Affiliations can be found after the references)

January 19, 2022

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.

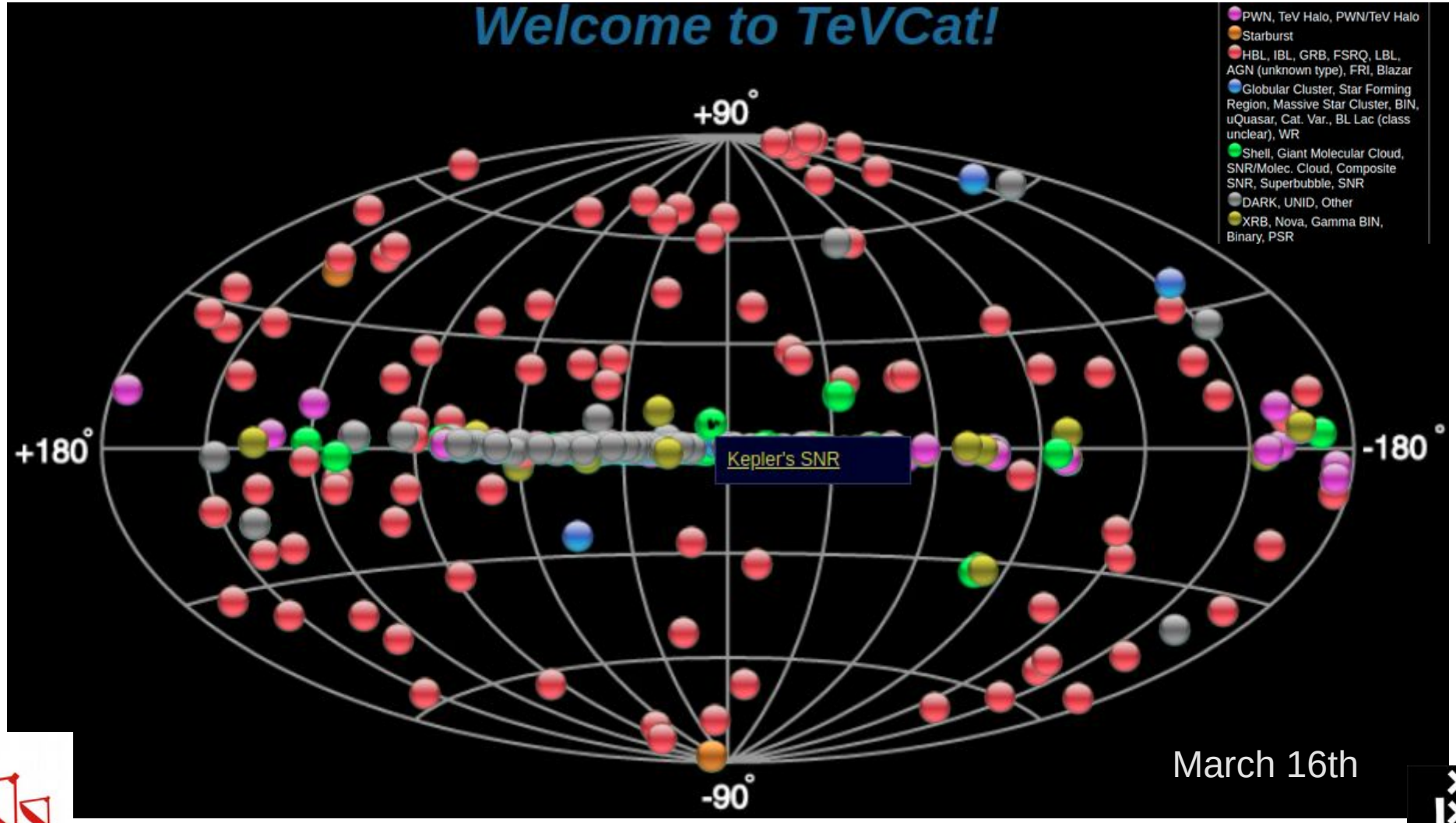
Here we report evidence at a statistical level of 4.6 σ for a VHE signal from the remnant of Kepler's SN based on deep observations by the High Energy Stereoscopic System (H.E.S.S.) with an exposure of 152 hours. The measured integral flux above an energy of 226 GeV is ~0.3% of the flux of the Crab Nebula. 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

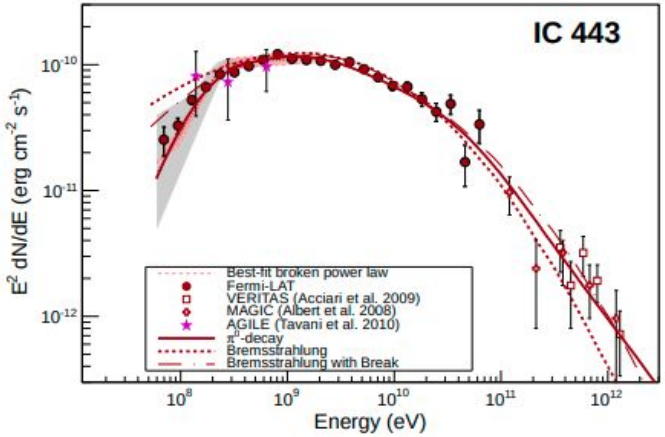
For several decades, supernova remnants (SNRs) have been considered the most likely sources of Galactic cosmic rays (CRs; e.g., Ginzburg & Syrovatskii 1964), i.e. CRs with energies at least up to 3×10^{15} eV. While the detection of radio and X-ray synchrotron radiation from SNRs does indeed prove that 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.

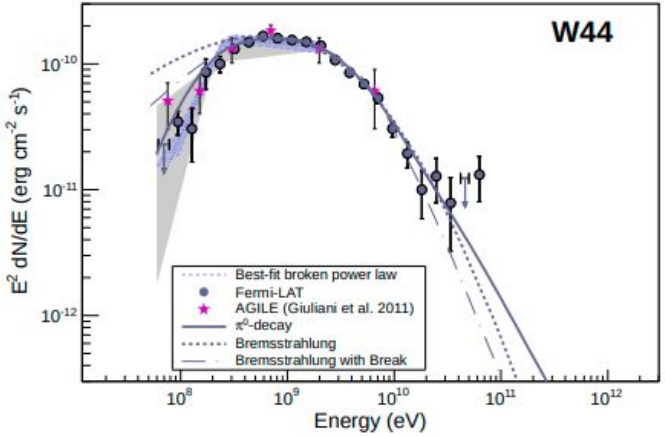
Send offprint requests to: H.E.S.S. collaboration,
e-mail: contact.hess@hess-experiment.eu;
* Corresponding authors

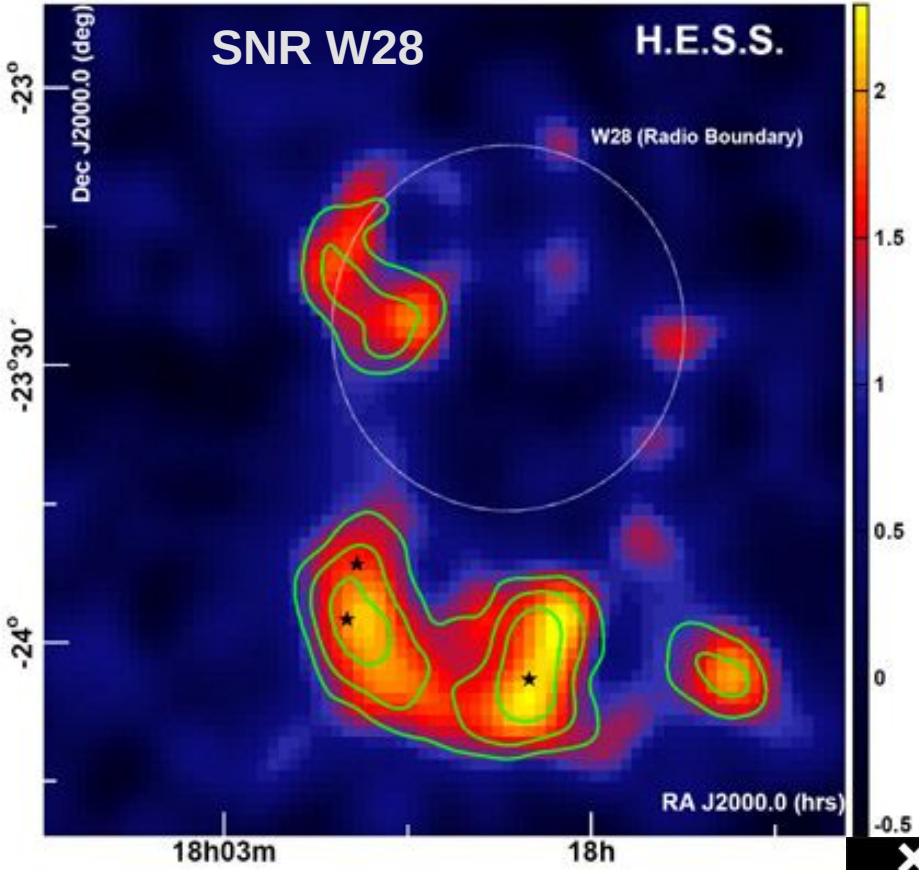

Welcome to TeVCat!
PWN, TeV Halo, PWN/TeV Halo
Starburst
HBL, IBL, GRB, FSRQ, LBL, AGN (unknown type), FRI, Blazar
Globular Cluster, Star Forming Region, Massive Star Cluster, BIN, uQuasar, Cat. Var., BL Lac (class unclear), WR
Shell, Giant Molecular Cloud, SNR/Molec. Cloud, Composite SNR, Superbubble, SNR
DARK, UNID, Other
XRB, Nova, Gamma BIN, Binary, PSR
+90°
+180°
-180°
-90°
Kepler's SNR

March 16th

SNRs as Sources of Galactic CR hadrons



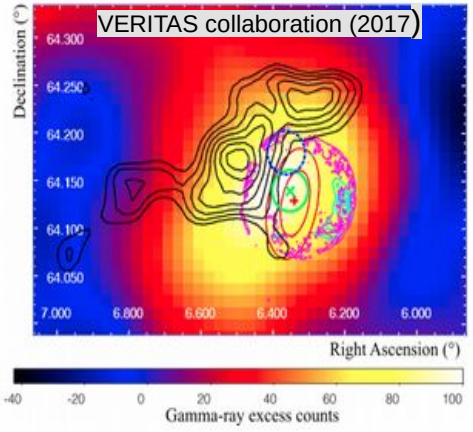




Fermi-LAT collaboration 2013

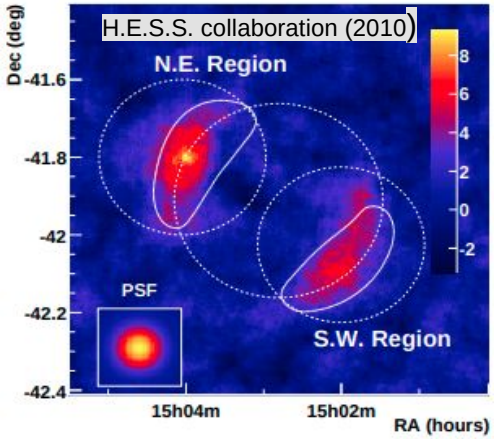
Historical SNRs detected in VHE gamma rays

Tycho SN (in 1572)



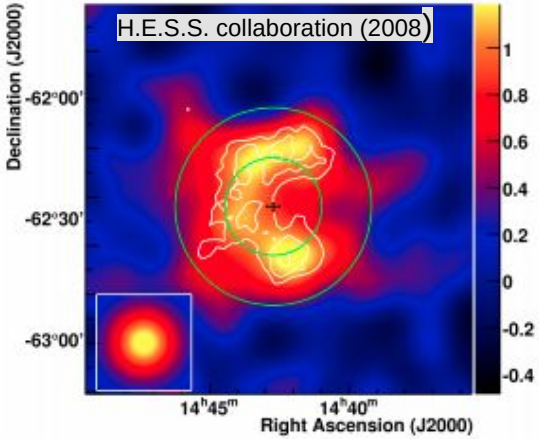
Detected at VHE with VERITAS in 2011 (67 hours)

SN 1006



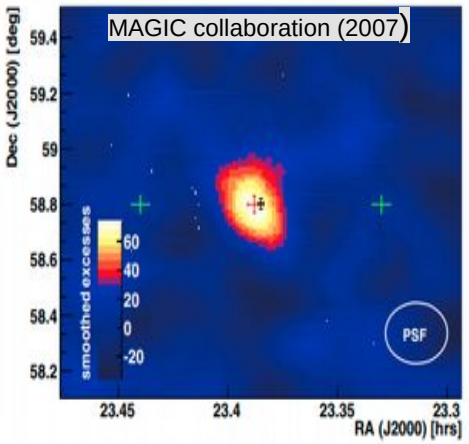
Detected at VHE with H.E.S.S. in 2010 (130 hours)

RCW 86 (SN in 185)

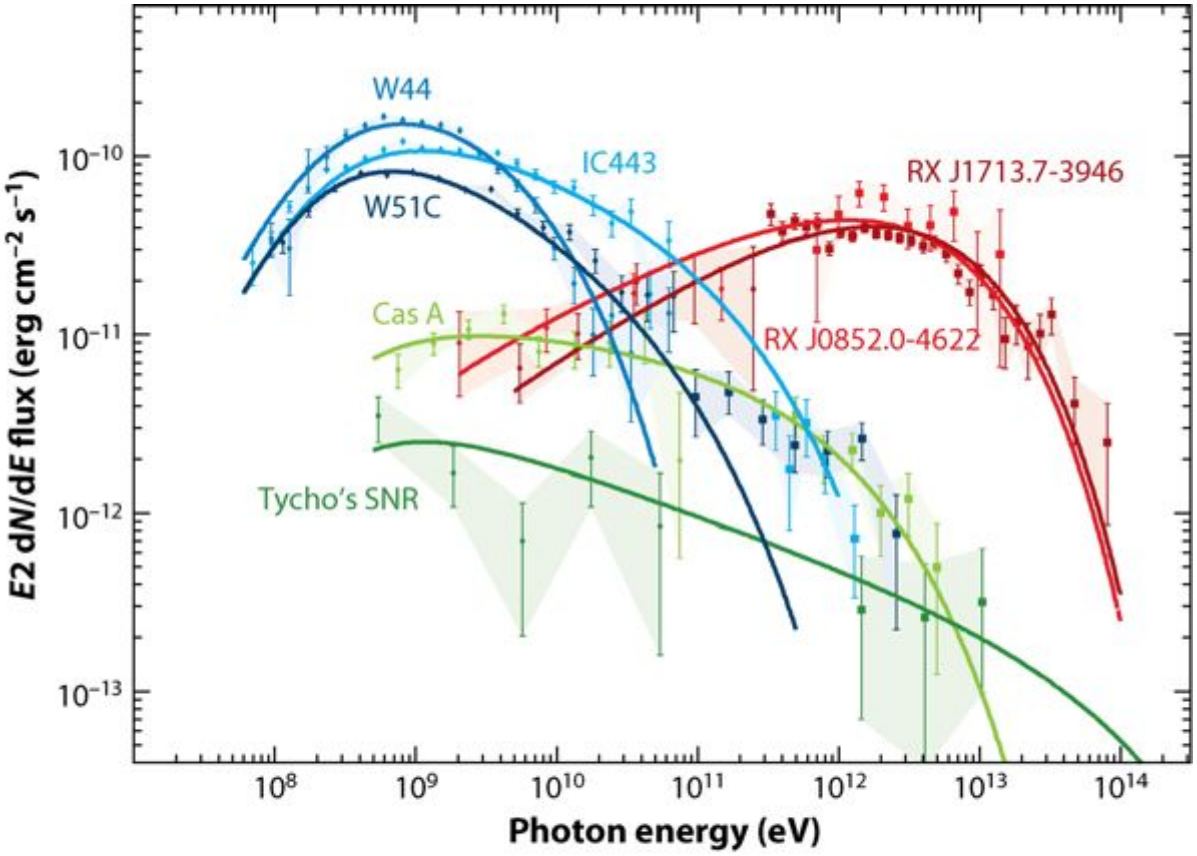


Detected at VHE with H.E.S.S. in 2008 (31 hours)

Cas A (SN around 1680)

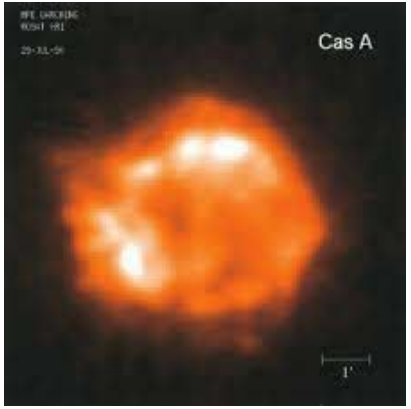


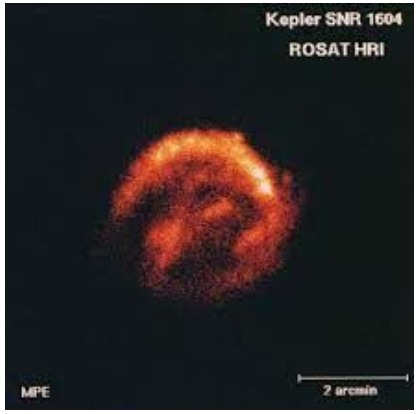
Detected at VHE with HEGRA in 2001 (232 hours)



Funk S. 2015.
Annu. Rev. Nucl. Part. Sci. 65:245–77

Cas A, Kepler, and Tycho

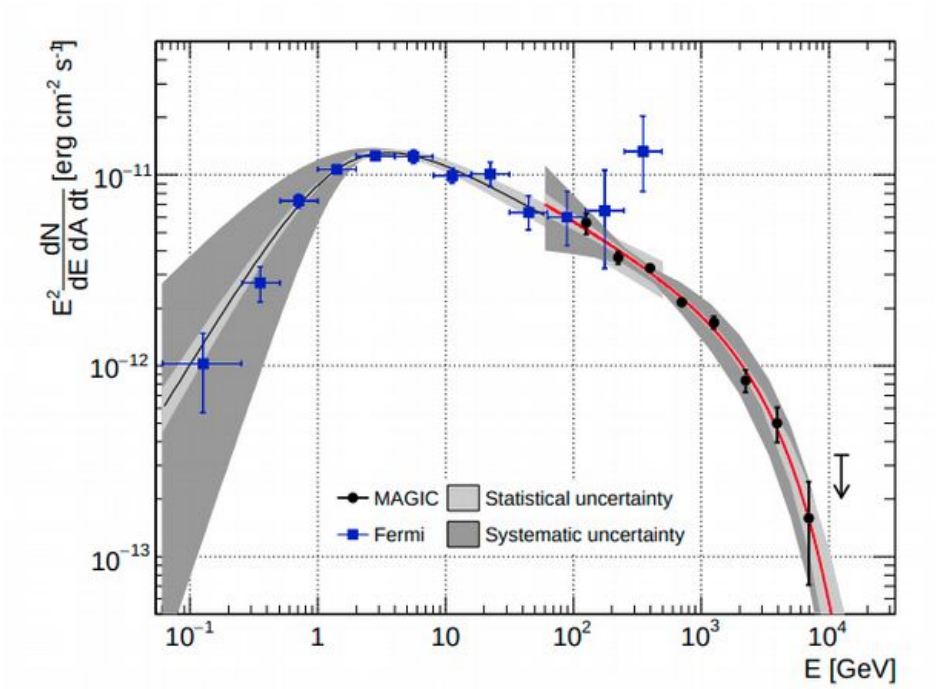




Name	Age (years)	SN Type	D, kpc	Angular diameter, arcmin
Cas A	340	core-collapse	3.4	5
Kepler	416	Ia	4.8-6.4	3.5
Tycho	448	Ia	2.5-3.3	8

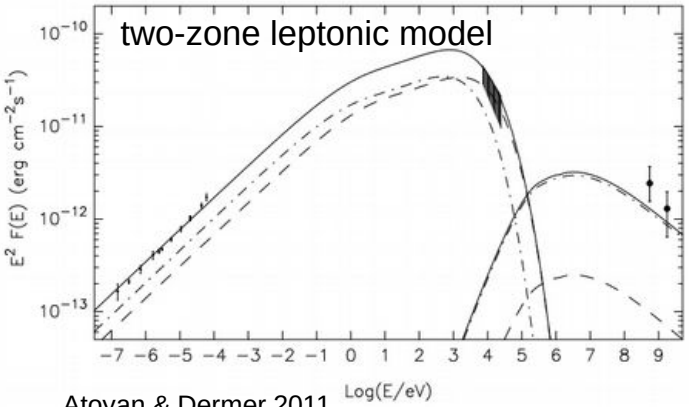
Hadronic model for Cas A and Tycho

Cassiopeia A

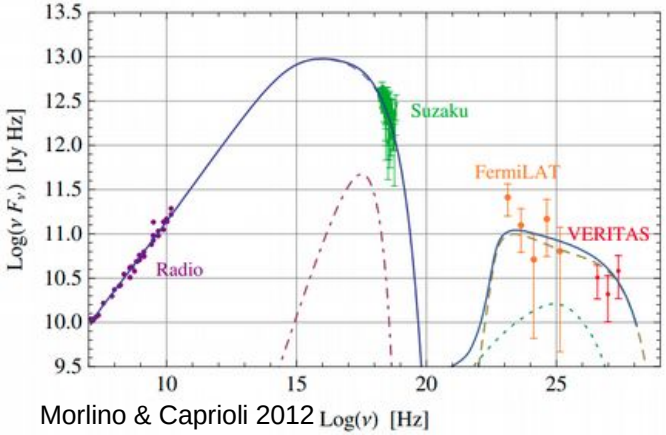


MAGIC Collaboration 2017

Tycho

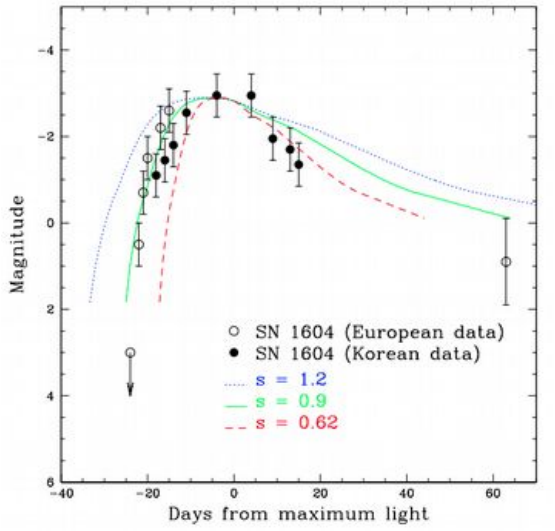


Atoyan & Dermer 2011

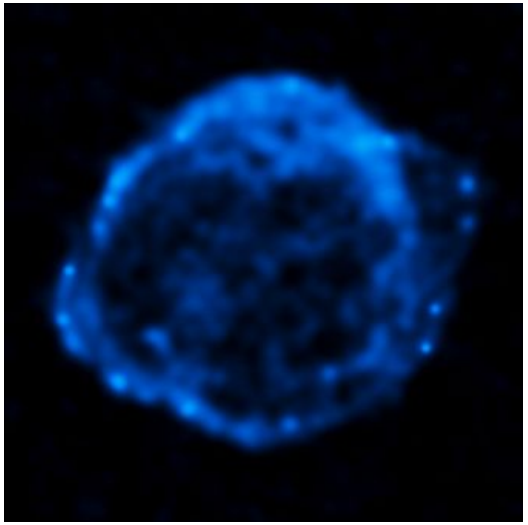


Morlino & Caprioli 2012

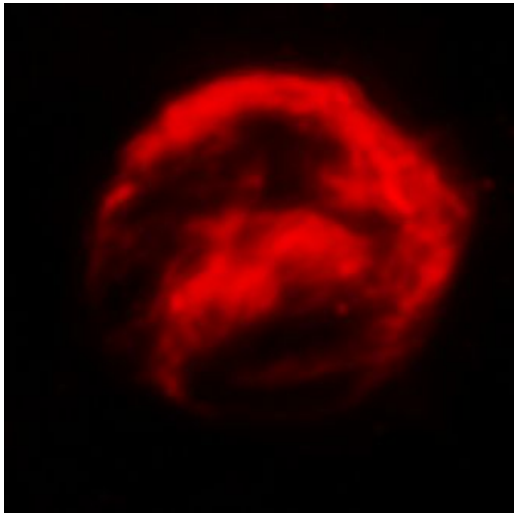
Kepler's SNR (SN 1604), the remnant of the most recent naked-eye supernova in our Galaxy



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

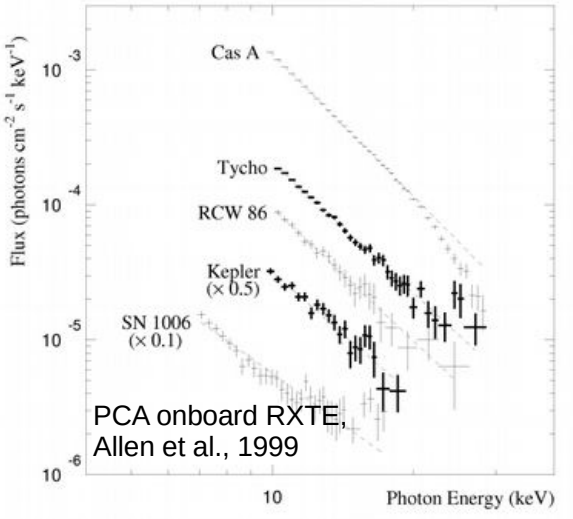
Kepler's SNR is a remnant of a thermonuclear SN located 6.8 degrees (500 pc) above the Galactic plane (at a distance of 5 kpc)
(Tycho's SNR at 3 kpc, SN 1006 - 2.2 kpc, SN 185 - 2.8 kpc, Cas A – 3.4 kpc)

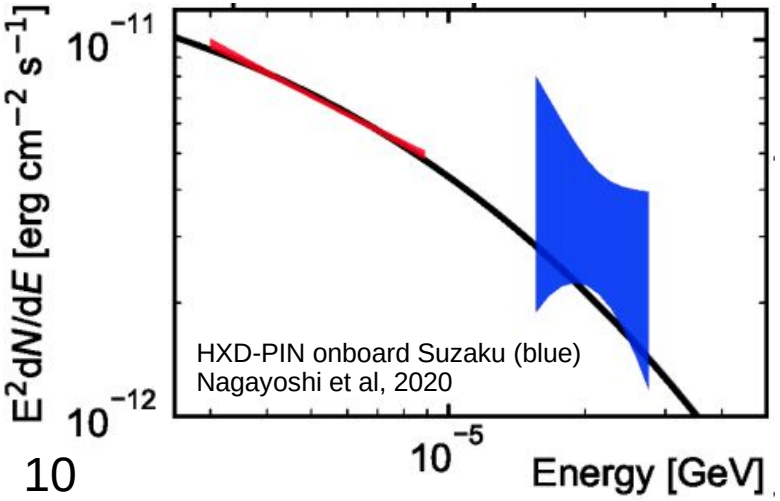
Evidence of 10-100 TeV Electrons in SNRs

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

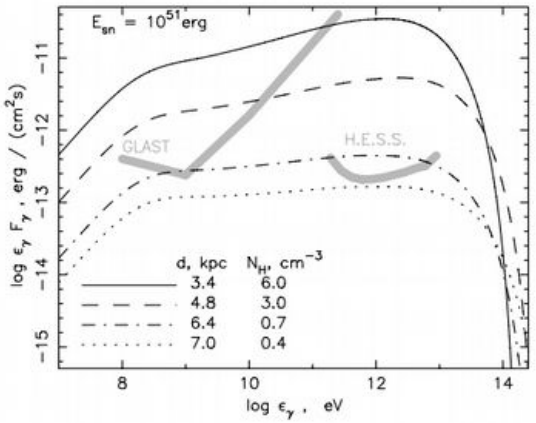
from a review by Helder at al. (2012) and based on Chandra data, see also Vink & Laming (2003) and Völk et al. (2005)



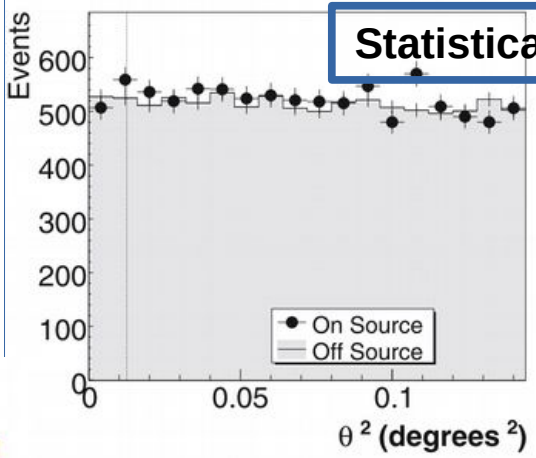


Previous searches and predictions for gamma rays from Kepler's SNR

A measurable flux of TeV gamma rays had been predicted by Berezhko, Ksenofontov, and Völk (2006)

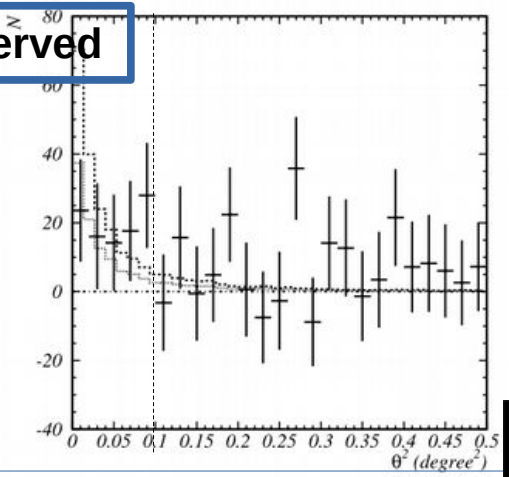


Statistically significant excess was *not* observed



H.E.S.S. search in 2004-2005
(H.E.S.S. collaboration, 2008)

CANGAROO-III search in 2005
(Enomoto et al. 2008)



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
- in wobble mode with offsets by 0.7 degree from Kepler's SNR
- Analysis chains: M++ (de Naurois and Rolland, 2009) and ImPACT (Parsons and Hinton, 2014)

Fermi-LAT observations and analysis

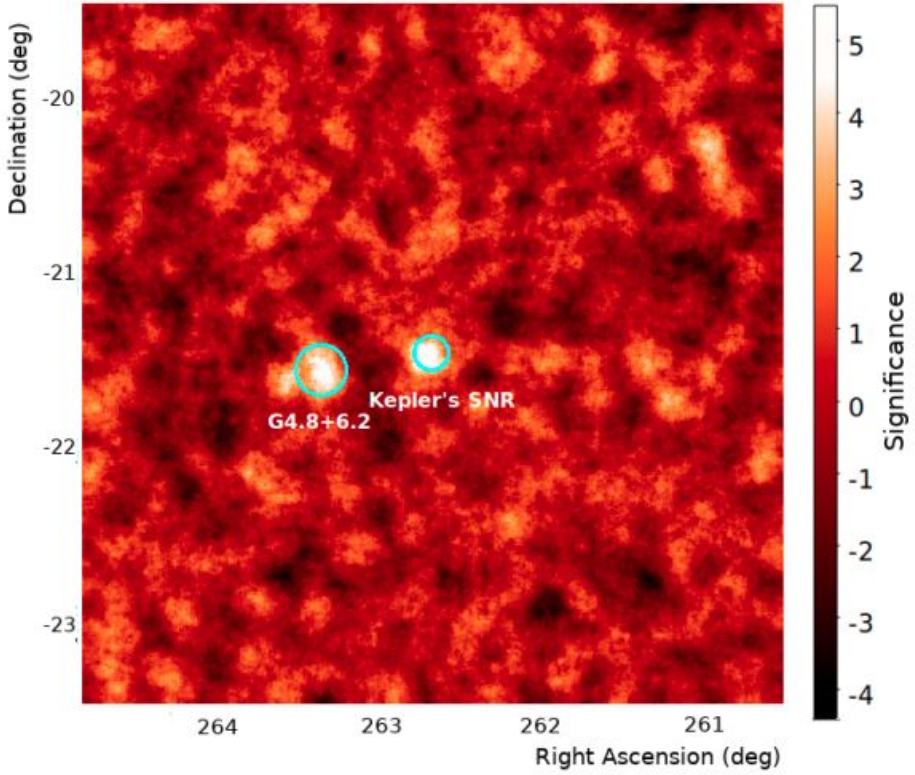
Fermi LAT Area Telescope (LAT)

- 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

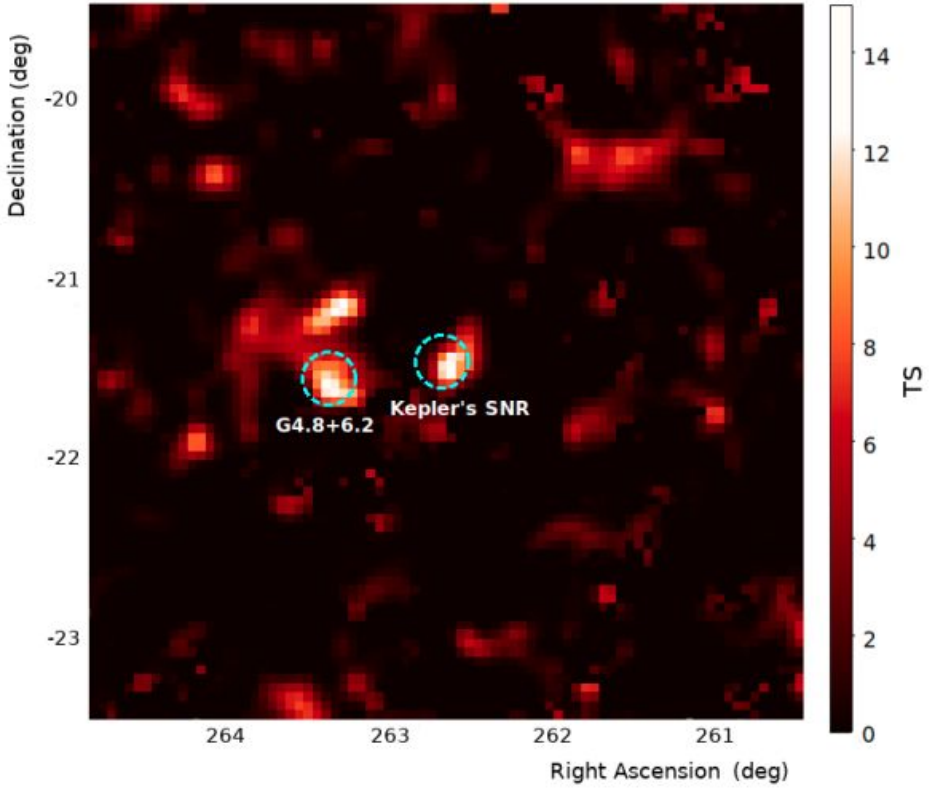
- were used by us to trigger H.E.S.S. observations in 2020
- Data with exposure of 10.7 years (August 2008-May 2019)
- Events with energies between 750 MeV and 300 GeV
- The region of interest of 10x10 squared degrees
- The model includes sources from the 4FGL catalog
- Similar Fermi-LAT excess reported by Xiang & Jiang (2021)

H.E.S.S. significance map



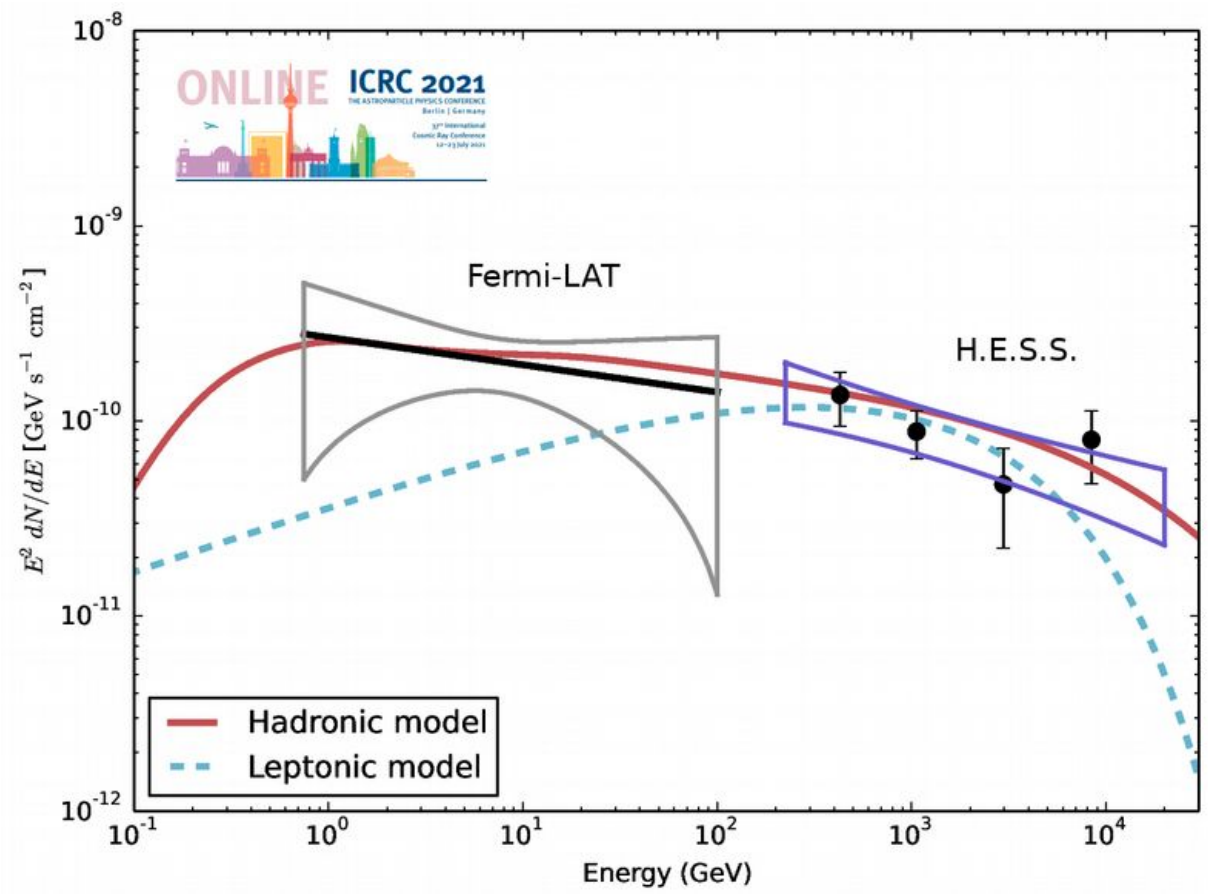
Kepler: Excess=178 gammas,
Significance=4.6 sigma

Fermi-LAT TS map (E>4.75 GeV)



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

Spectrum of Kepler’s SNR



Theoretical models

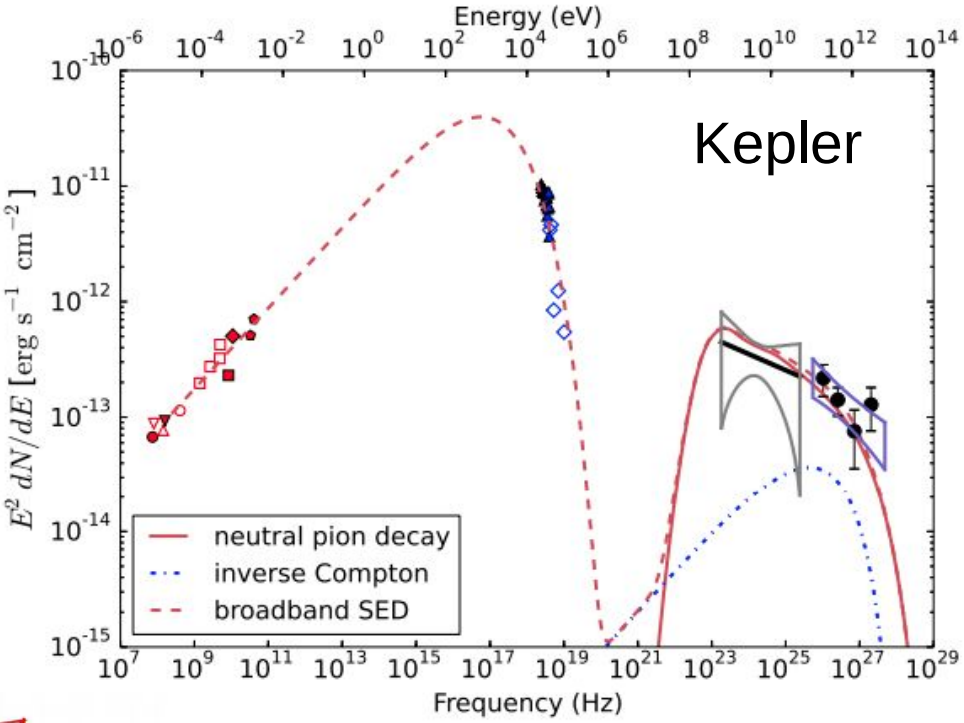
Hadronic scenario

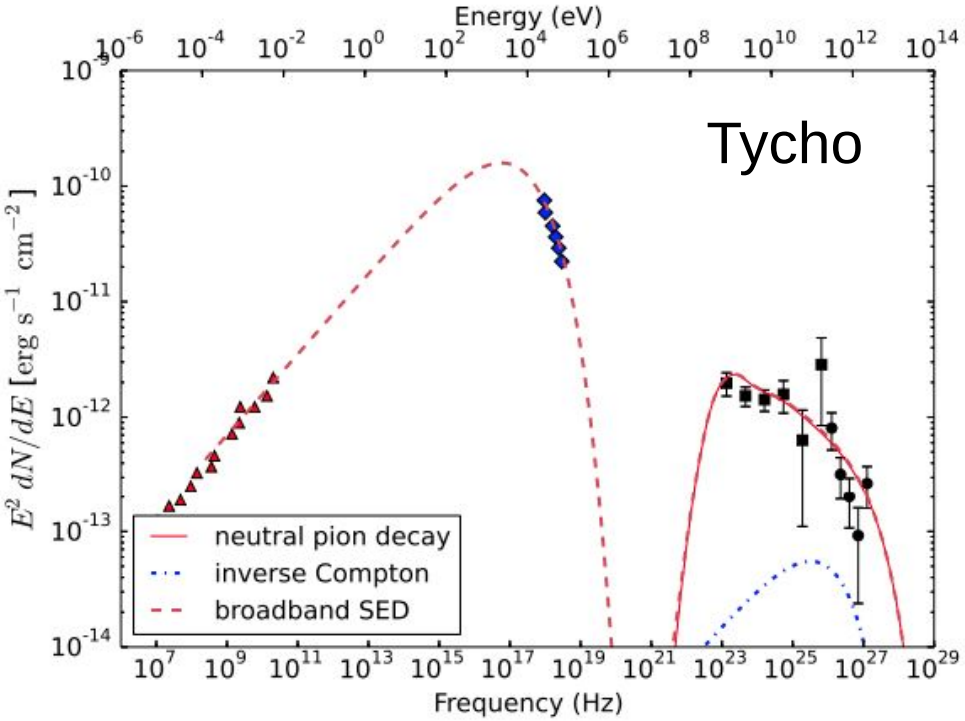
- SNIa explosion energy 10^{51}erg
- Cosmic-ray hadron energy of 7% of the explosion energy
- Target particle density 1.0 cm^{-3}
- Cosmic-ray proton spectral index, 2.2
- Exponential cut-off in the cosmic-ray proton spectrum at 100 TeV

Leptonic scenario

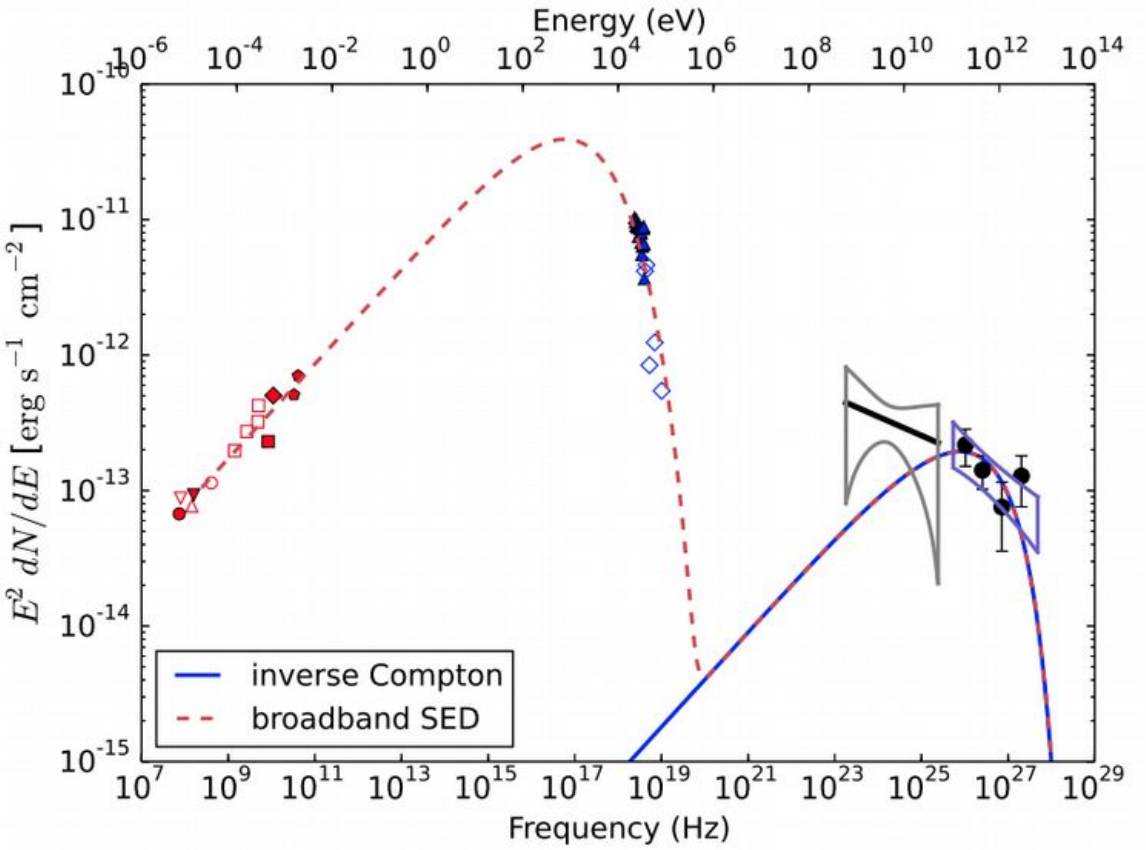
- SNIa explosion energy 10^{51}erg
- Cosmic-ray electron energy of 0.15% of the explosion energy
- Three soft photon fields, CMB, infrared emission by dust in the SNR and Galaxy
- Magnetic field strength 80μG
- Cosmic-ray electron spectral index, 2.3
- Exponential cut-off in the cosmic-ray electron spectrum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

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





Leptonic model



The lower limit on a magnetic field strength is 80 uG

Summary of Fermi-LAT analysis and conclusions by Xiang & Jiang (2021)

- Detection of Kepler's SNR at ~4 sigma significance in 0.2-500 GeV
- Insignificant flux variability in time at a 2 sigma level
- Ten new sources in the 5x5 sq.deg region (9 of them are unidentified)
- More observation data are necessary to firmly confirm the association between the gamma-ray source and Kepler's SNR in the future (at GeV and TeV)

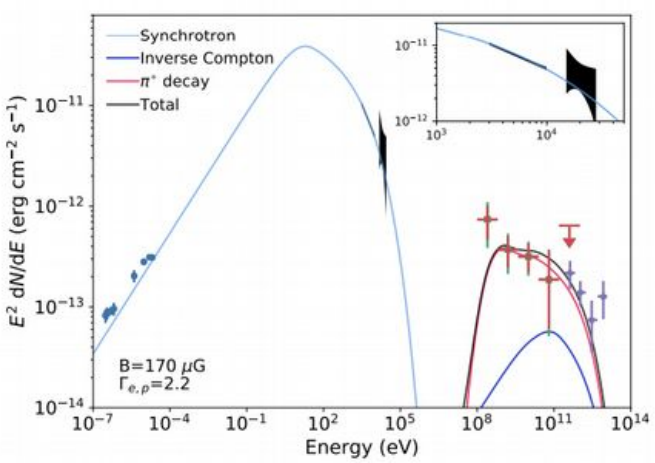
It remains unnoticed by them that among ten new sources two are with harder spectra

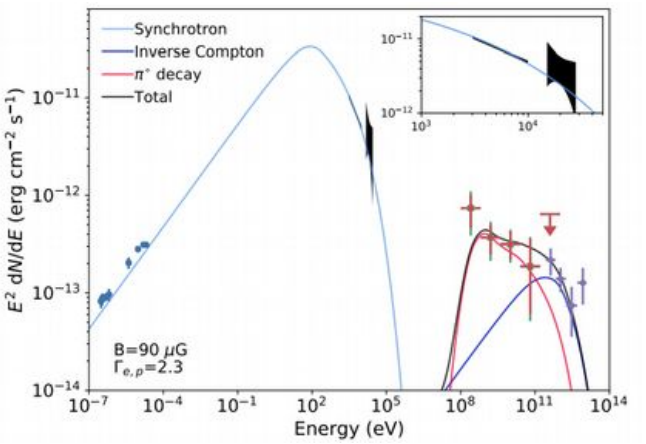
Summary of Fermi-LAT analysis and conclusions by Acero, Lemoine-Goumard, and Ballet (2022)

Detection of Kepler's SNR at 6 sigma significance in 0.1-1000 GeV 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
- using 12 years of Fermi-LAT data

SED models are similar to that we obtained





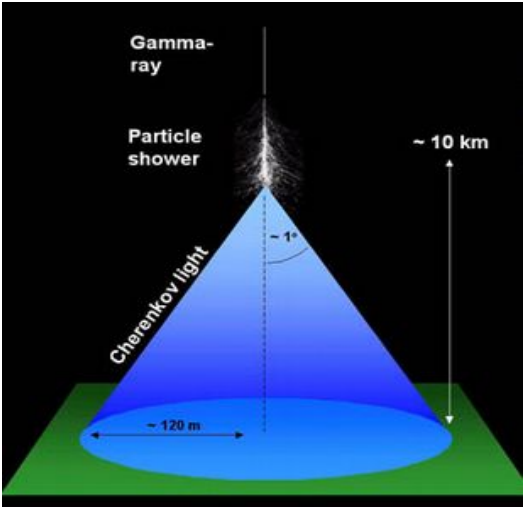
Summary

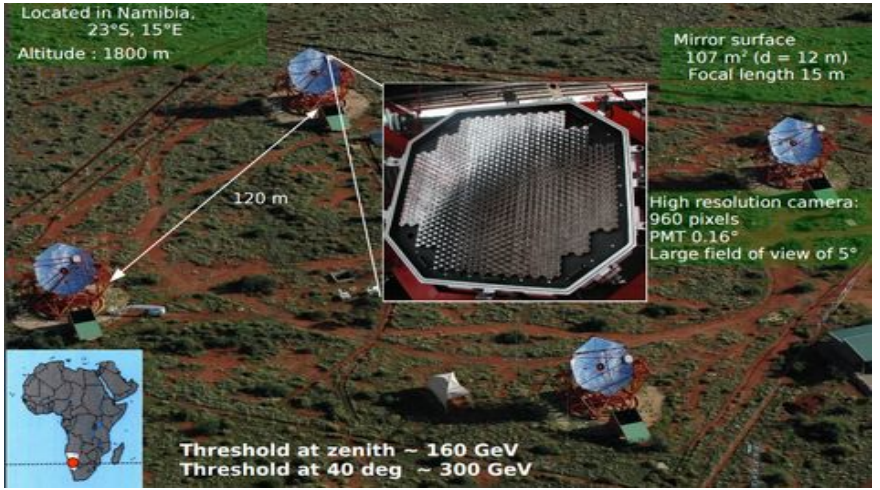
- Deep observations (152 hr) of Kepler's SNR with H.E.S.S.
- Strong evidence emission from Kepler's SNR at VHE
- Fermi-LAT data: HE gamma-ray excess
- Kepler's SNR (SN 1604) is best fit with a hadronic model, similar to Tycho's SNR (SN 1572)

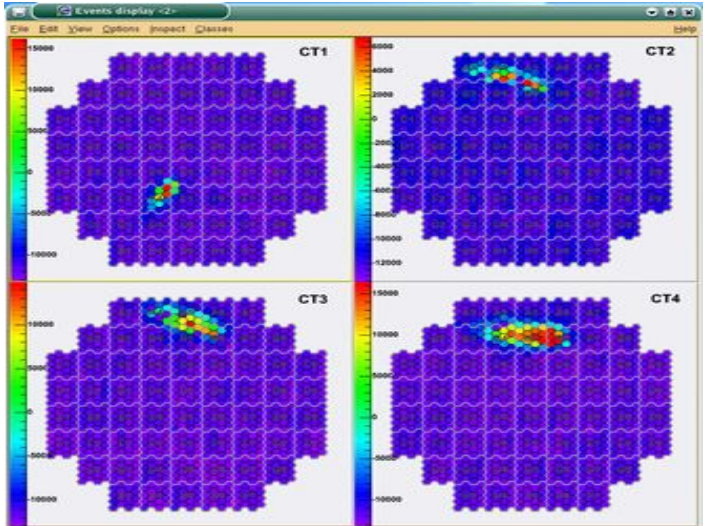
H.E.S.S. (High Energy Stereoscopic System)

The Cherenkov technique:

- a high-energy gamma ray interacts high up in the atmosphere and generates an air shower of secondary particles
- the shower particles emit Cherenkov light beamed around the direction of the incident primary particle
- produced Cherenkov light illuminates on the ground an area of about 250 m diameter
- Cherenkov photons arrive within a very short time interval, a few nanoseconds.
- the image obtained with the telescope shows the distribution of the Cherenkov light emitted by the air shower. The shape of the image is used to reject particle background.
- the geometry of the shower is reconstructed using multiple telescopes, which see the same shower from different points of view

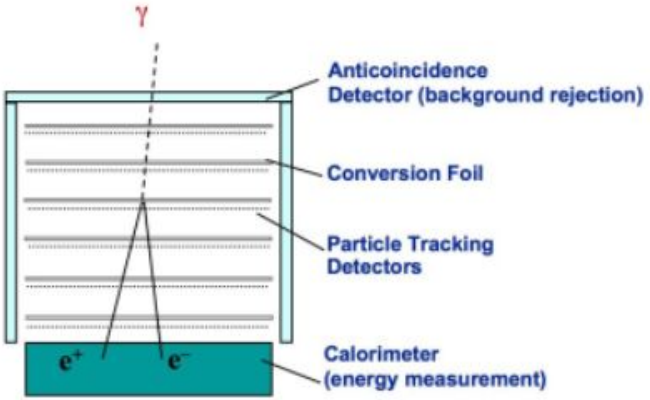


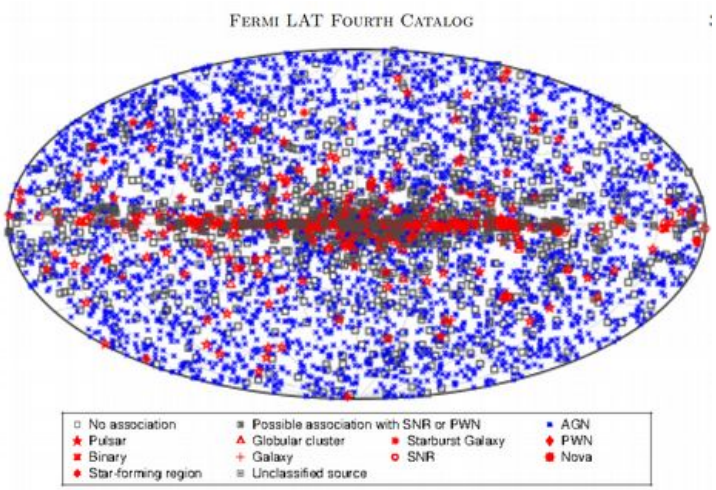




Fermi-LAT (Large Area Telescope)

- pair production telescope
  - high-Z material converts gamma-rays into electron-positron pairs
- sensitive to gamma-rays between about 20 MeV and greater than 300 GeV
  - high energy (HE)
- tracker, calorimeter, and anti-coincidence detector





- all-sky gamma-ray observatory
  - 5065 sources detected
    - 94% of associations are active galactic nuclei
    - only 42 radio galaxies (0.8%)