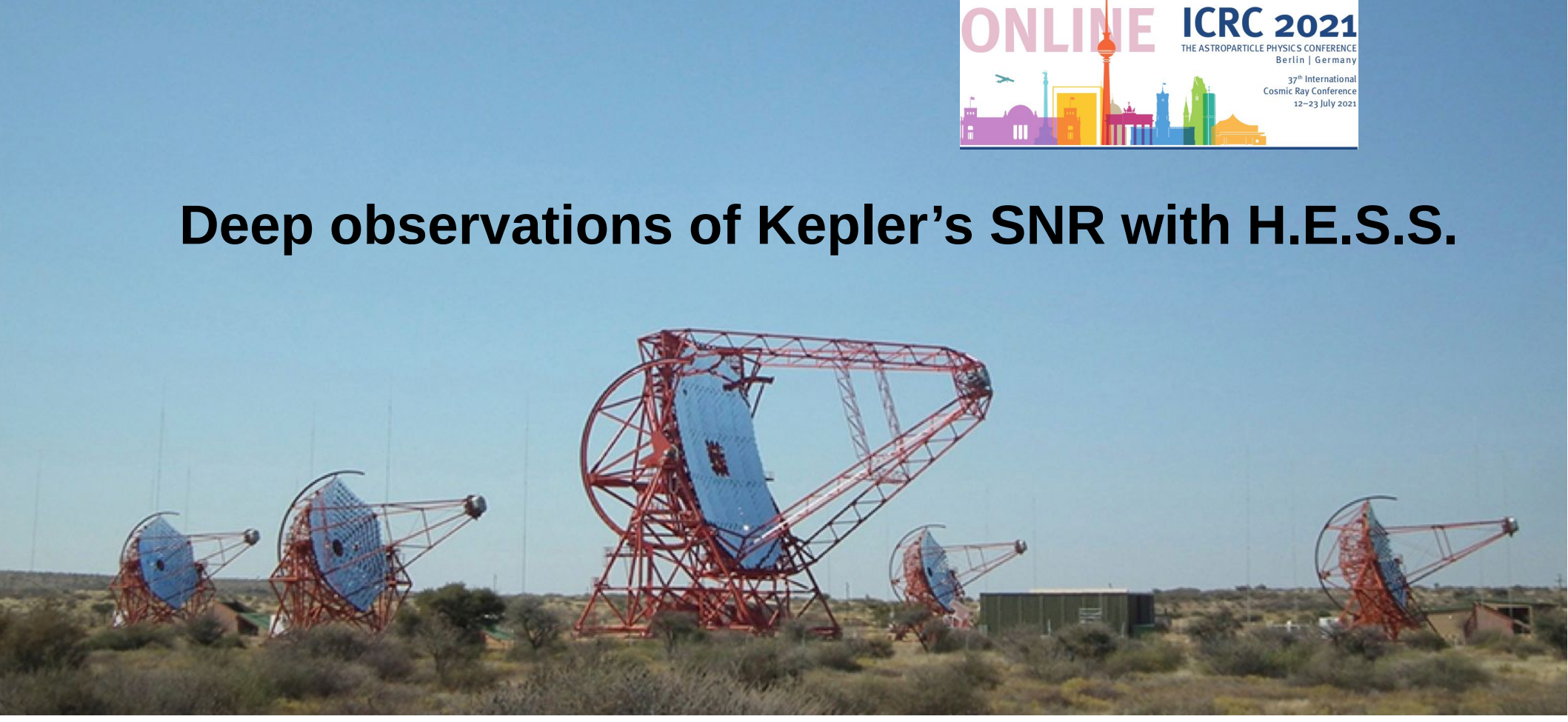
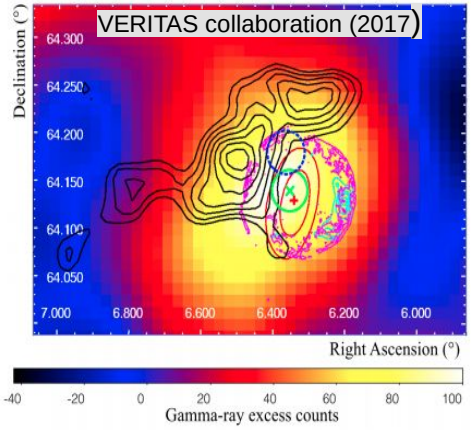


Deep observations of Kepler's SNR with H.E.S.S.

Dmitry Prokhorov, Jacco Vink, Rachel Simoni, Nukri Komin, Stefan Funk,
Denys Malyshev, Lars Mohrmann, Stefan Ohm, Gerd Pühlhofer, and Heinrich Völk
for the H.E.S.S. Collaboration

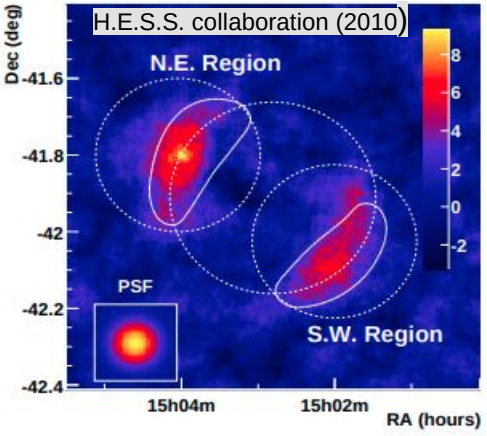
Historical SNRs detected in VHE gamma rays

Tycho SN (in 1572)



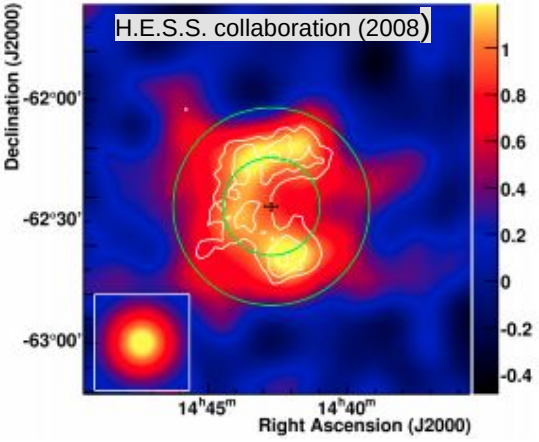
Detected at VHE with VERITAS in 2011 (67 hours)

SN 1006



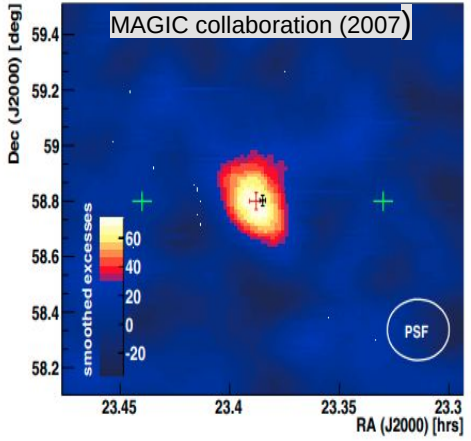
Detected at VHE with H.E.S.S. in 2010 (130 hours)

RCW 86 (SN in 185)



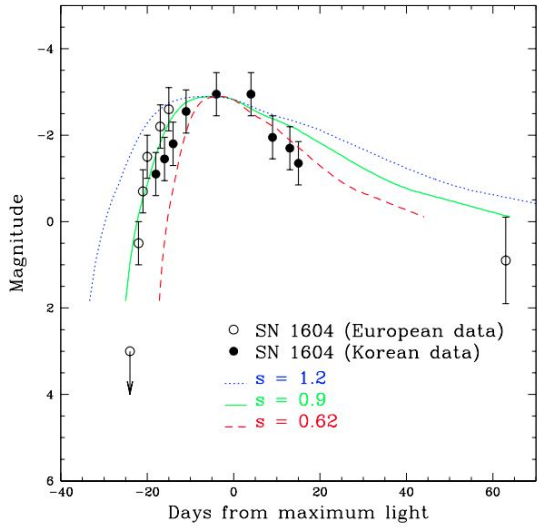
Detected at VHE with H.E.S.S. in 2008 (31 hours)

Cas A (SN around 1680)

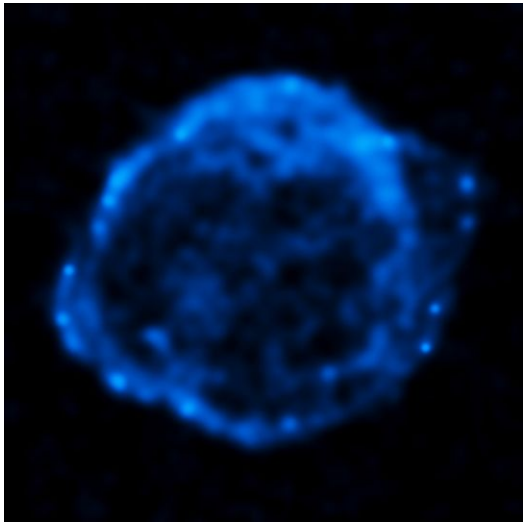


Detected at VHE with HEGRA in 2001 (232 hours)

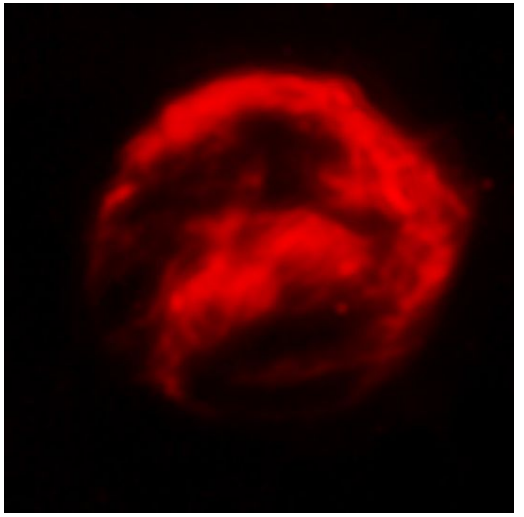
Kepler's SNR (SN 1604), the remnant of the most recent naked-eye supernova in our Galaxy



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

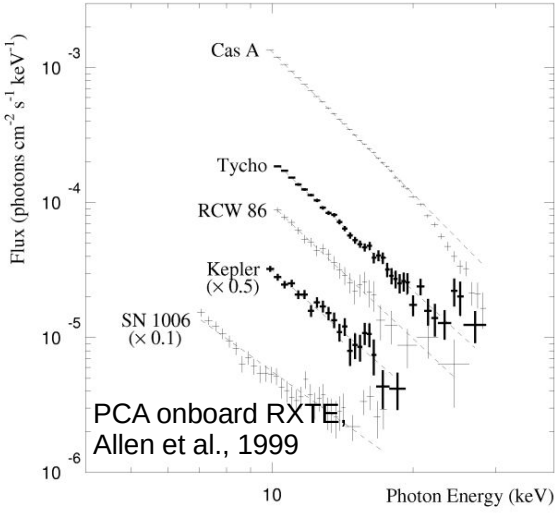
Kepler's SNR is a remnant of a thermonuclear SN located 6.8 degrees (500 pc) above the Galactic plane (at a distance of 5 kpc)
(Tycho's SNR at 3 kpc, SN 1006 - 2.2 kpc, SN 185 - 2.8 kpc, Cas A – 3.4 kpc)

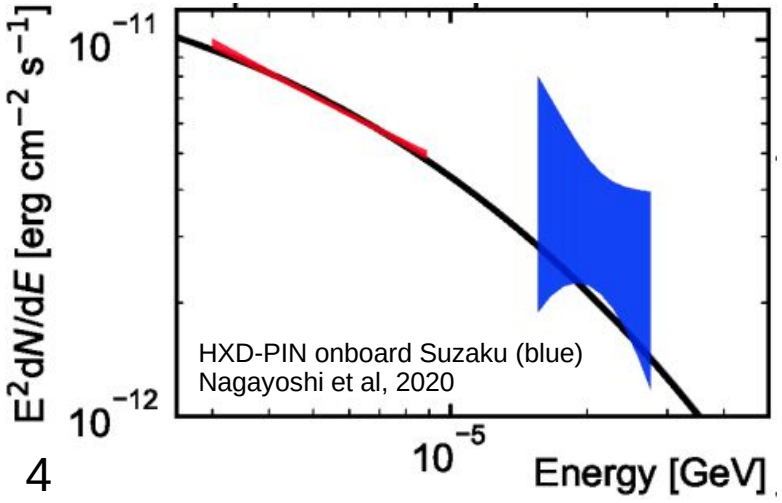
Evidence of 10-100 TeV Electrons in SNRs

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

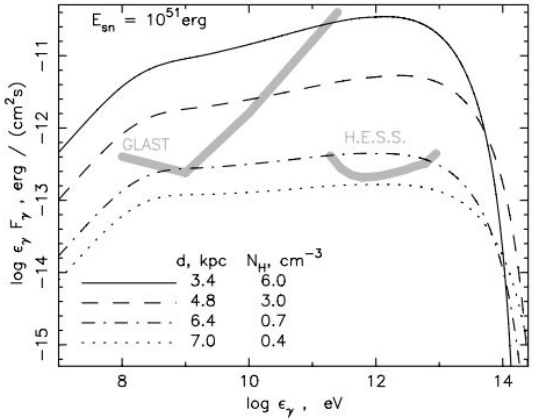
from a review by Helder at al. (2012) and based on Chandra data, see also Vink & Laming (2003) and Völk et al. (2005)



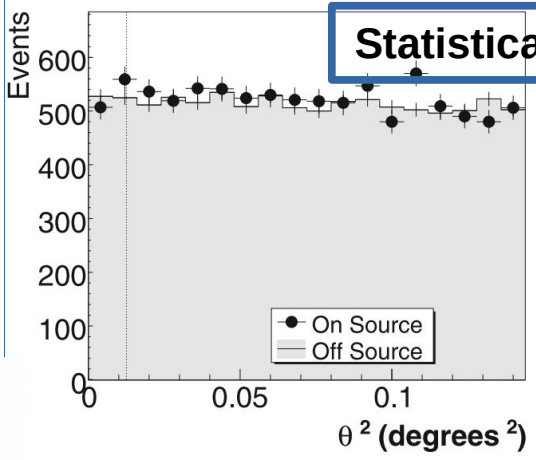


Previous searches and predictions for gamma rays from Kepler's SNR

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

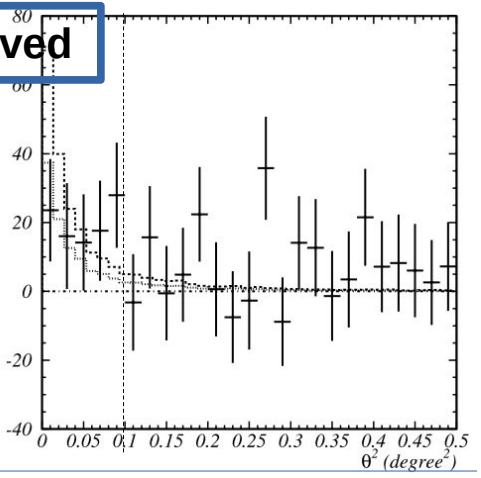


Statistically significant excess was *not* observed



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 upgraded cameras of 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)

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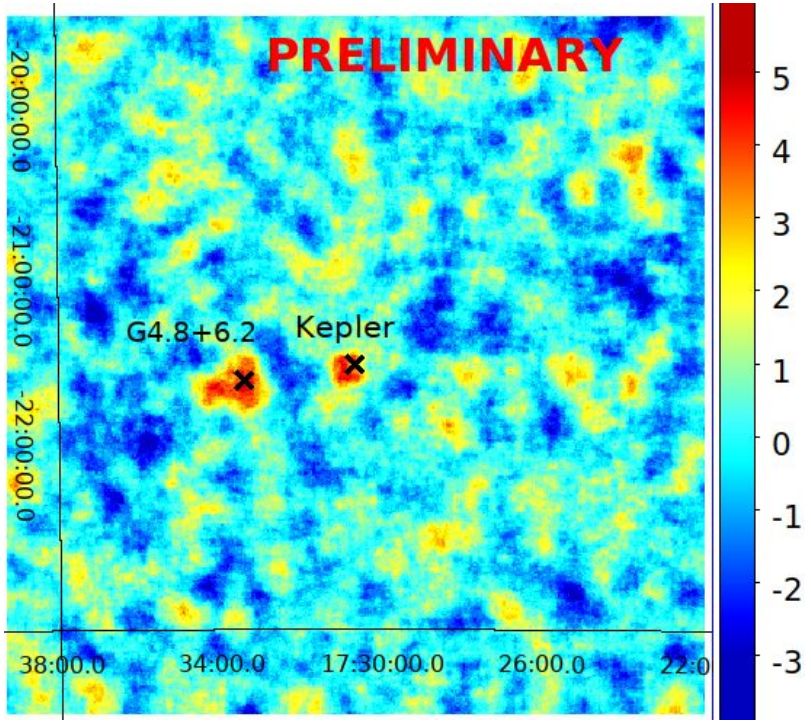
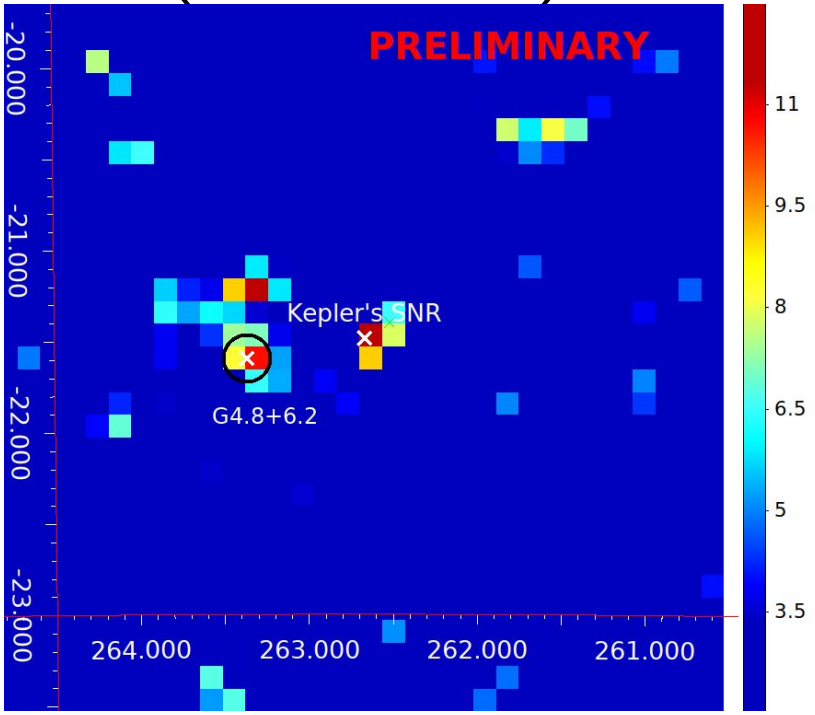
H.E.S.S. significance map



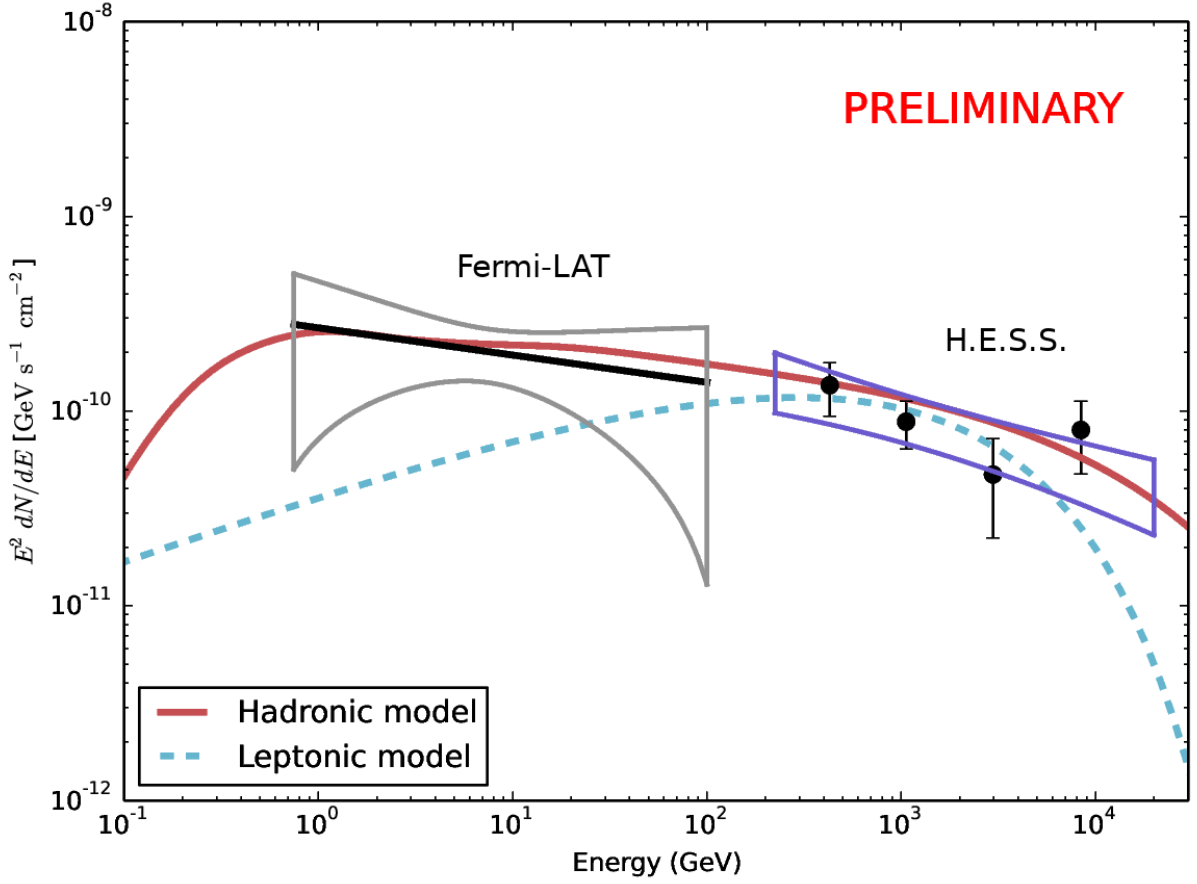
Kepler: Excess=178 gammas,
Significance=4.6 sigma

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 10% of the explosion energy
- Target particle density 0.5 cm^{-3}
- Cosmic-ray proton spectral index, 2.2
- Exponential cut-off in the cosmic-ray proton spectrum at 300 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

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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: GeV excess at 4. sigma level
- Kepler's SNR (SN 1604) is best fit with a hadronic model, similar to Tycho's SNR (SN 1572)

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