HESS J1640-465

An exceptionally luminous TeV γ-ray SNR

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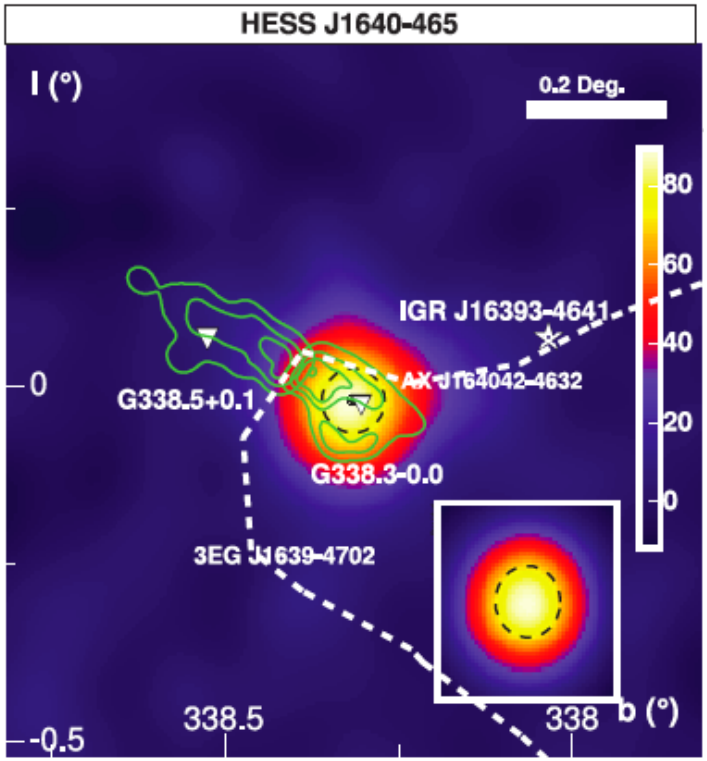
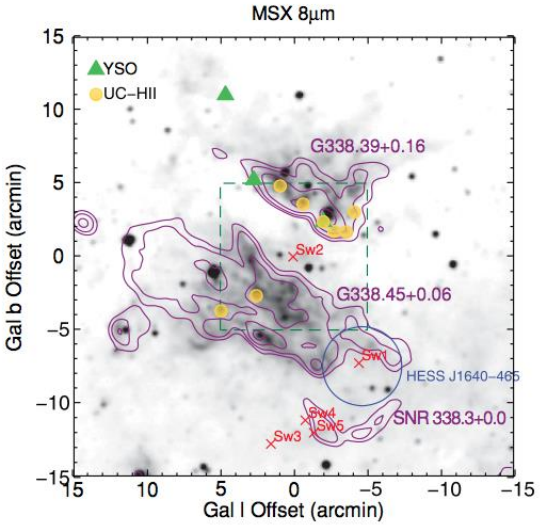
On behalf of the H.E.S.S. collaboration

Introduction: HESS J1640-465

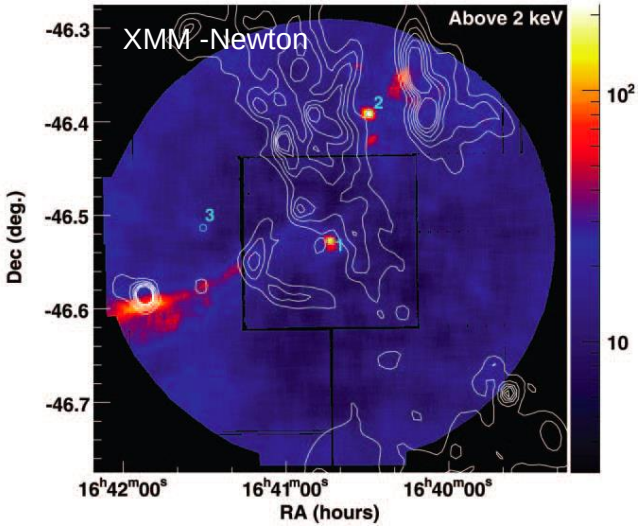
- HESS
  - Original discovery in 2006
  - 14σ in 14 hours of observations
  - Compact (~2.7'), strong (~10% Crab) γ-ray emitter
  - Γ = -2.40 ± 0.15
- Environment
  - In complex region (HII region, stellar cluster)
  - Coincident with incomplete shell-type SNR
  - No non-thermal emission reported at time of HESS discovery



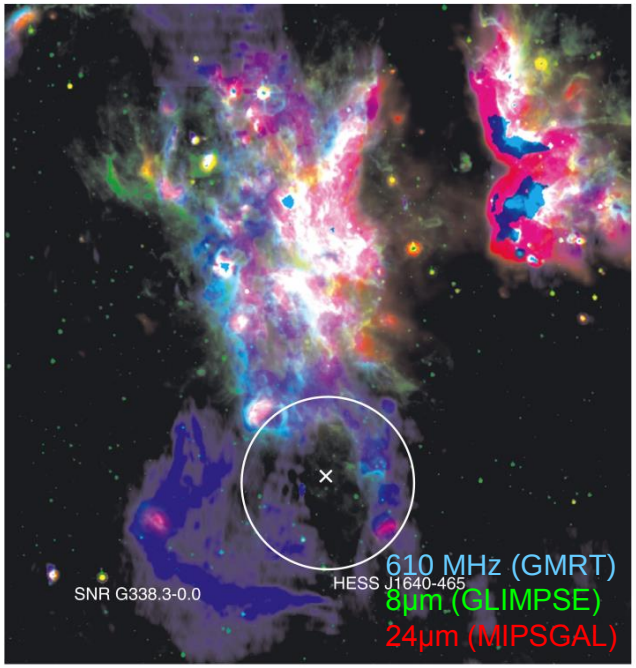


X-ray and radio follow-up observations

- X-rays (Swift, XMM and Chandra)
  - Detection of compact source + extended nebula
  - No non-thermal X-ray emission from SNR shell
  - Highly absorbed → large distance
  - Pulsar wind nebula interpretation of TeV signal



Swift (Landi et al. 2006)
XMM (Funk et al. 2007)
Chandra (Lemiere et al. 2009)



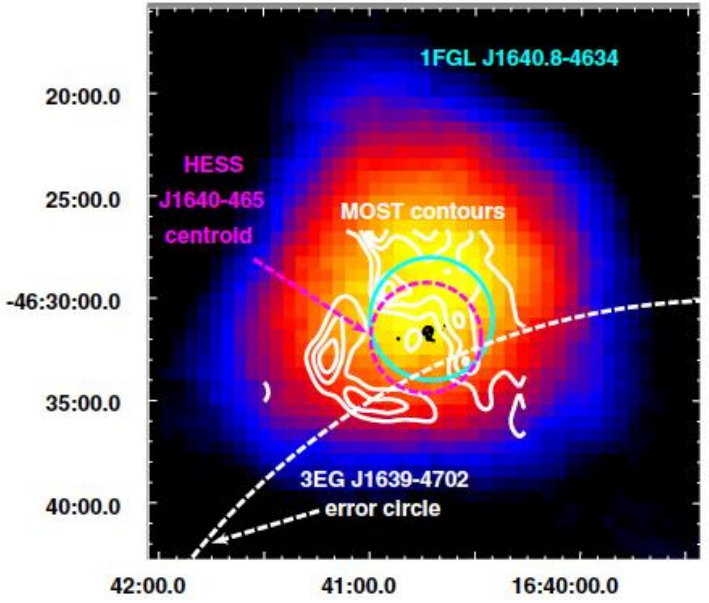
GMRT, ATCA (Castelletti et al. 2011)

- Radio (SGPS, GMRT, ATCA)
  - Detection of non-thermal shell emission
  - No non-thermal emission from PSR or PWN
  - Absorption features of SNR throughout line-of-sight
  - Distance estimate: 8 – 13 kpc

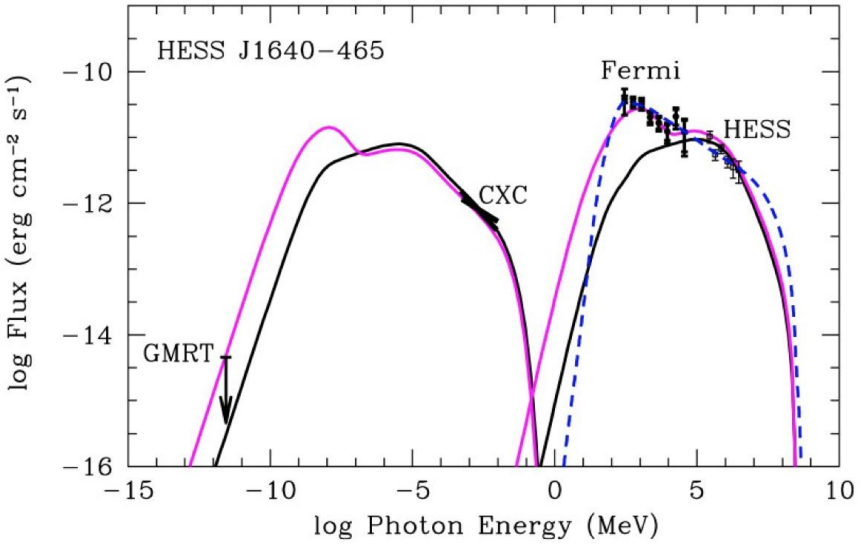
→ Most luminous Galactic TeV γ-ray source

Fermi-LAT observations

- Morphology
  - Detection of luminous GeV source
  - Coincident with HESS source
  - Consistent with point source
- Spectrum
  - Spectral points between 200 MeV and 50 GeV
  - Spectral index compatible with HESS (Γ = -2.3 ± 0.1)



Fermi-LAT (Slane et al. 2010)

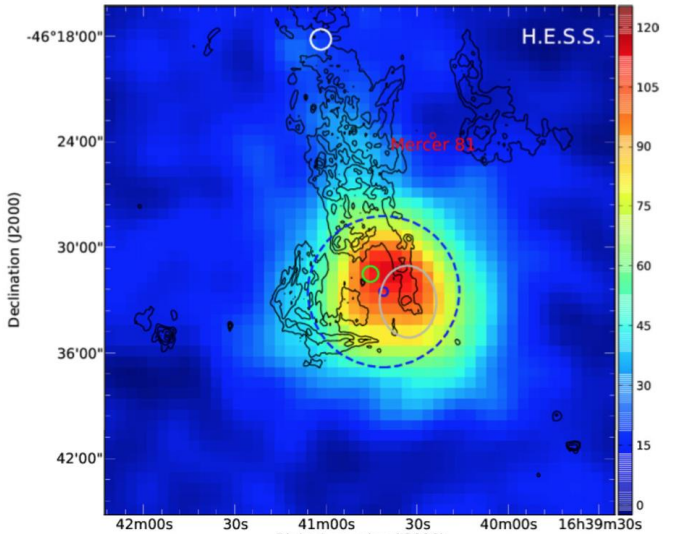


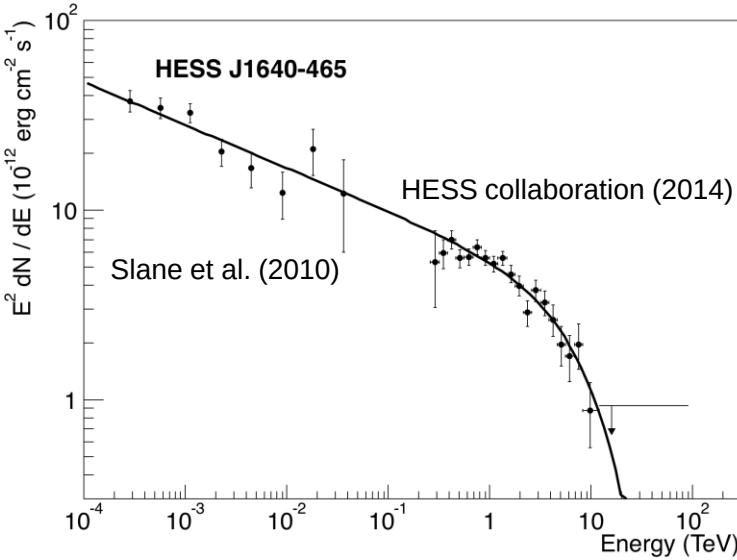
- Interpretation and modelling
  - GeV + TeV spectrum interpreted as IC emission from PWN
  - Smooth connection of Fermi and HESS spectrum requires additional low-energy relativistic Maxwellian component

New HESS results

- Data set
  - Quadrupled data set (>60 hours of observations)
  - More sensitive analysis methods (40σ, ~1800 γ-rays)

  → detailed spectral and morphological studies possible
- TeV spectrum
  - Power-law has low probability p = 1%
  - Exponential cut-off power-law (ECPL) fits data much better (fit probability p = 36%)
  - At 10 kpc distance, luminosity L = 7.8 x 10^{34} erg/s
- GeV – TeV spectrum
  - Simultaneous ECPL fit to Fermi and HESS spectrum gives consistent results → no break required in γ-ray spectrum





Data	E_{min}	E_{max}	Γ	Φ_0 (10^{-12} cm^{-2} s^{-1})	E_c (TeV)
HESS	260 GeV	90 TeV	2.11 ± 0.09	3.3 ± 0.1	$6.0^{+2.0}_{-1.2}$
HESS + *Fermi*-LAT	200 MeV	90 TeV	2.23 ± 0.01	3.7 ± 0.2	$8.8^{+2.3}_{-1.5}$

DESY

Discussion: Age and environment of G338.3-0.0

- SNR evolution in wind-blown bubble
  - Scenario that has also been invoked for RCW 86, Cygnus SNR, or RX J1713-3946
  - Bubble size of 10 pc typical for 20 $M_{\odot}$ mass O-type star (Chevalier, 1999)
  - Lifetime of 7 Myrs, 2600 km/s, 10^{-7} $M_{\odot}$ per year
  - Lower age limit for wind material inside the bubble, the shock speed of 5000 – 10000 km/s of 1 – 2 kyr (Slane et al. estimate 5 – 8 kyrs)
  - And free expansion until shock hits wall of swept up material
- Density
  - Large density required to explain γ-ray emission as hadronic
  - Thermal radio: Castelletti et al. infer electron densities of 100 – 150 cm^{-3}
  - Thermal X-rays: not seen from the shell, detected in this source, but also not expected given the large distance, high absorption and possible evolution in wind-blown bubble
  - HI: absorption gives upper limit on neutral gas density of ~600 cm^{-3}
  - No indication for molecular gas densities ($n > 10^4$ cm^{-3})
  - Measurements consistent with gas densities of ≥ 150 cm^{-3}

Interpretation I: PWN scenario

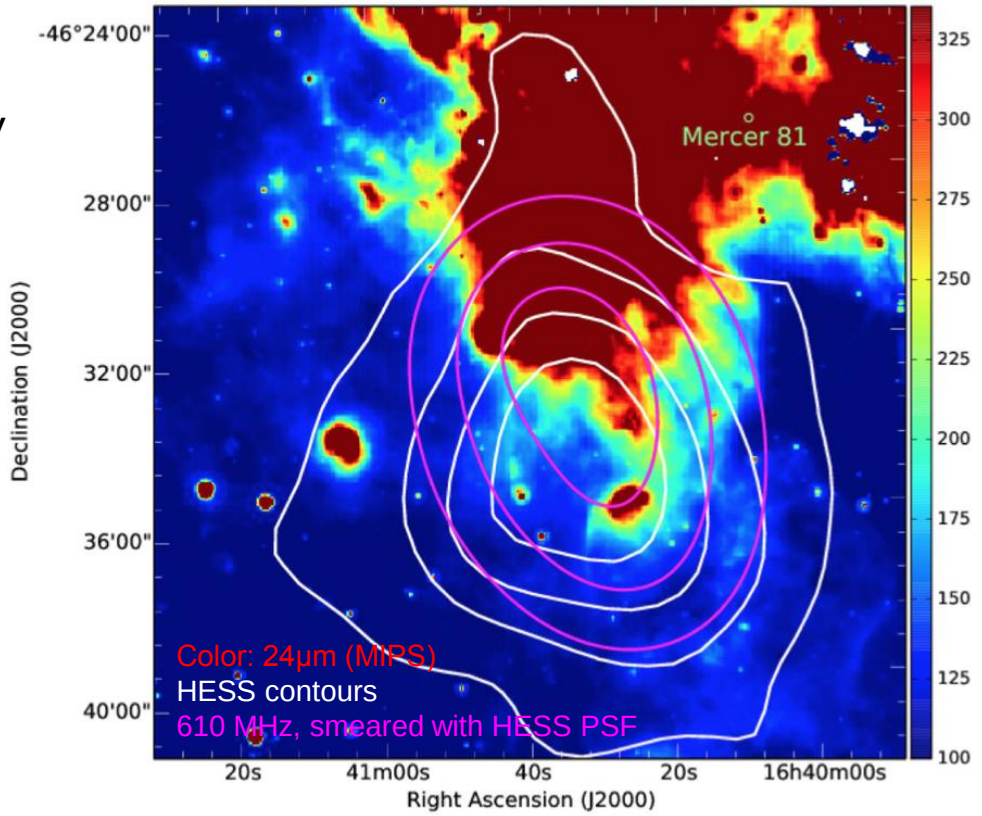
- PWN scenario
  - Existence of point-like X-ray source + extended nebula (but no pulsations detected)
  - Positional coincidence of X-ray PWN candidate, GeV source and HESS source
- But…
  - IC peak is seen for all TeV-emitting PWN, but not for this one
  - Smooth power-law from hundreds of MeV to multi-TeV energies requires $\Gamma_e \sim -3.4$
  - HESS spectrum also excludes the proposed low-energy relativistic Maxwellian
  - TeV extension of all TeV emitting PWN is smaller than SNR shell, this one is larger
  - No energy-dependent morphology seen in HESS data
  - Scaled radio limit factor ~5 lower than model predictions

  → PWN-only interpretation of GeV and TeV emission hard to realise

  → different origin of Fermi and HESS emission is possible, but requires fine-tuning
- Explore alternative scenario

Interpretation II: SNR scenario

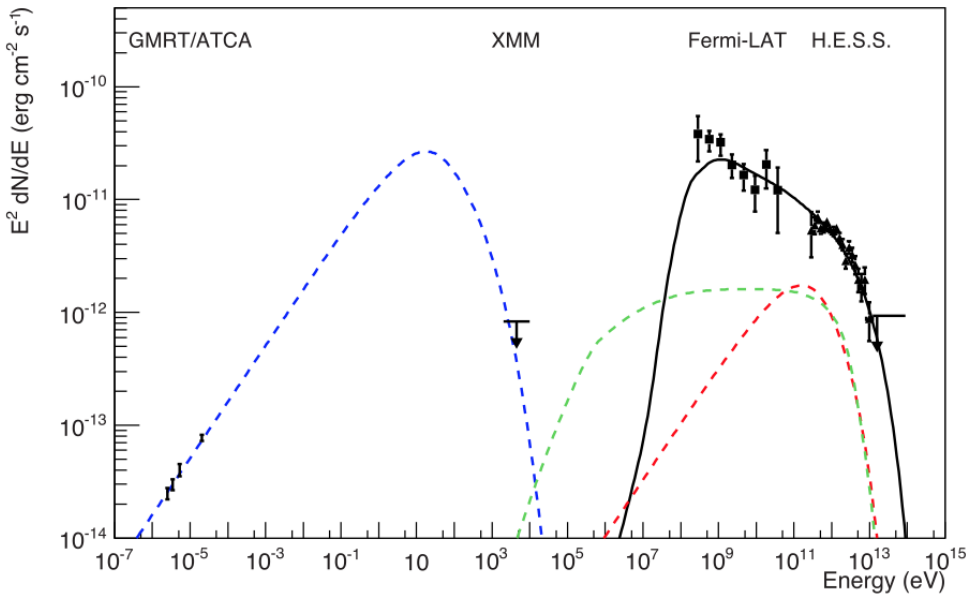
- Supported by
  - Positional coincidence of GeV and TeV source and north-western SNR shell
  - Spectral and morphological similarity with other Galactic SNRs interacting with molecular clouds
- Hadronic origin
  - Efficient particle acceleration in low-density medium inside wind-blown bubble
  - Requires large densities (interior of wind-bubble not sufficient)
  - Target: a) dense wind shell, or b) dense and clumpy surrounding material
  - cf. RX J1713-3946 (Zirakashvili & Aharonian, 2010)
  - Higher IR flux from north-western shell consistent with TeV morphology



Interpretation II: SNR scenario

Modelling

- X-ray UL on non-thermal shell emission from archival XMM data
- Scale non-thermal radio flux from shell
- Apply time-dependent one-zone model
- Continuous injection of electrons and protons over assumed SNR age of 2.5 kyrs



Leptonic scenario

- Magnetic field and electrons spectral index from radio (B = 35μG, Γe = 2.0)
- Cut-off energy from XMM ($E_{c,e}$ = 10 TeV)
- Predicted IC emission much lower than HESS data
- Larger e/p ratios and lower field help with the level of emission, but not with the shape

Hadronic scenario

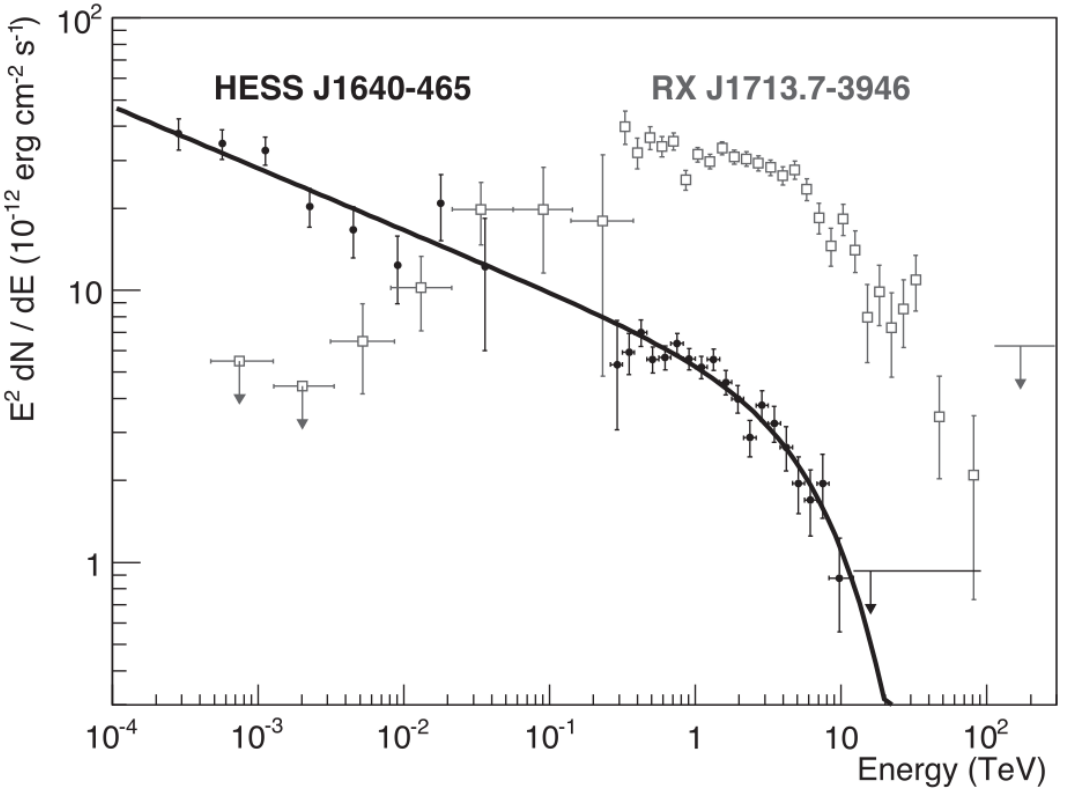
- For n_H = 150 cm^{-3}, 4 x 10^{50} erg in protons required to explain γ-ray spectrum

→ very efficient accelerator, and/or

→ very energetic SN explosion

Interpretation III: Comparison with RX J1713-3946

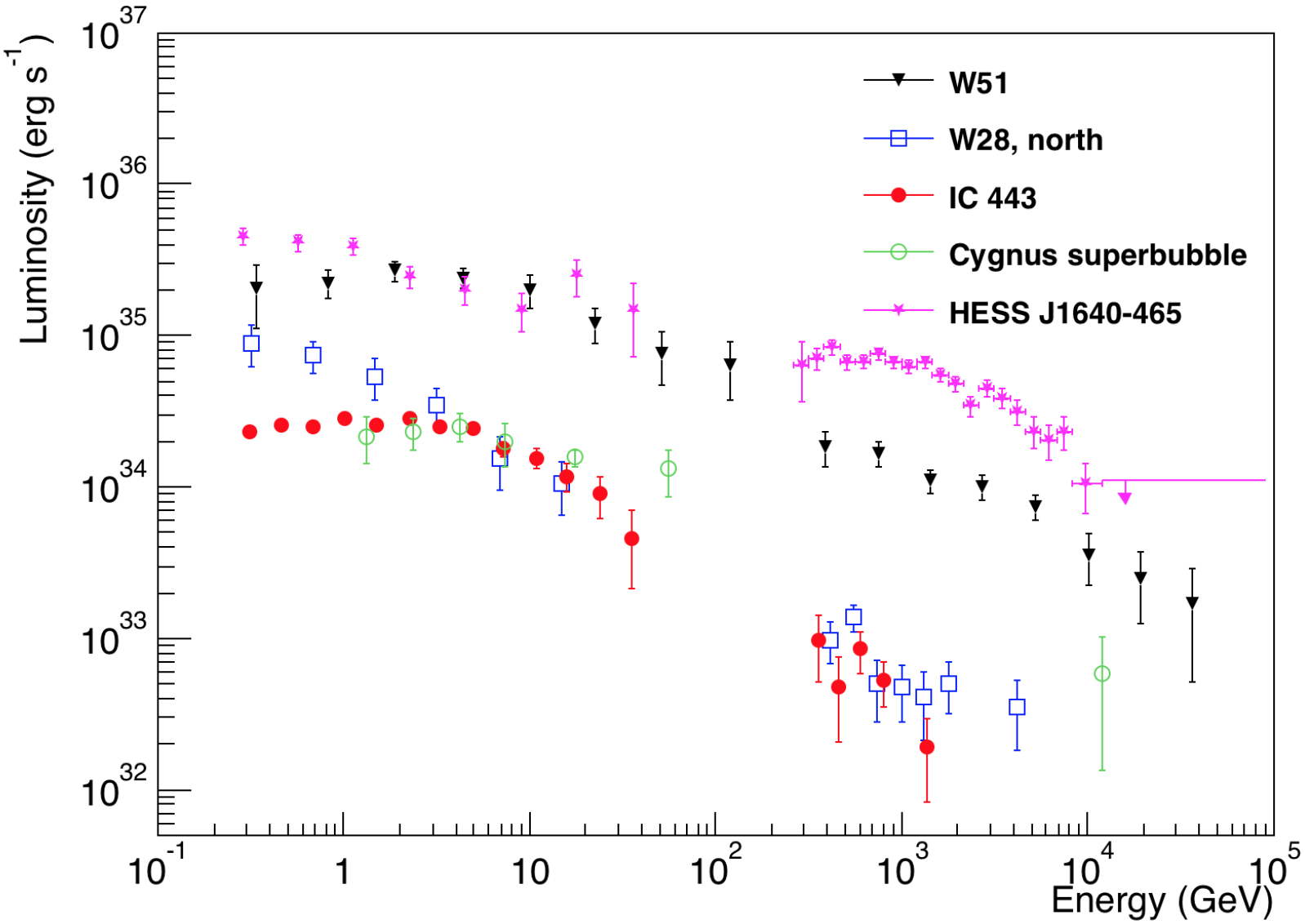
- Comparion
  - Similar TeV spectra
  - Different GeV spectra
- Possible Explanation
  - Diffusion of low-energy CRs into dense clumps in HESS J1640-465
  - ‘Shielding’ of lower-energy CRs in RX J1713-3946?
  - Different ages?
  - Different diffusion properties?



Summary and Conclusion

- HESS J1640-465 is the most luminous Galactic TeV source
- TeV morphology
  - significantly extended
  - overlapping with SNR shell
  - more extended than shell
- GeV – TeV spectrum consistent with one featureless power-law over 6 orders of magnitude
- PWNe interpretation challenging, but contribution to TeV spectrum not excluded
- New HESS results + MWL data suggests dominant hadronic emission from SNR shell
  - Morphology and spectrum well reproduced
  - Requires high energy in CRs and high ambient densities

Comparison of HESS J1640 with other SNRs



NuSTAR discovery of PSR in HESS J1640-465

- Gotthelf et al. (2014) reported discovery of pulsation from PSR in HESS J1640-465
  - $\dot{E}$ = 4.4 x 10 erg/s, τ_c = 3350 yrs, P = 206 ms
  - With n = 2, >10 GeV spectrum can be described with PWN model for PSR birth period of P_0 = 15ms
- Requires middle-aged PWN, 6% of current $\dot{E}$ to be converted into γ-rays
- Spin-down power and age considerably smaller than in previous models
- Authors argue that the Fermi spectrum below 10 GeV is likely not correct in HESS paper, but without presenting a reanalysis
- Revised preliminary analysis of 5 years of Fermi-LAT data confirms significant emission below 10 GeV (as also presented in 2FGL)