Investigating the Origin of the TeV γ-rays in the PeVatron Source LHAASO J2002+3244

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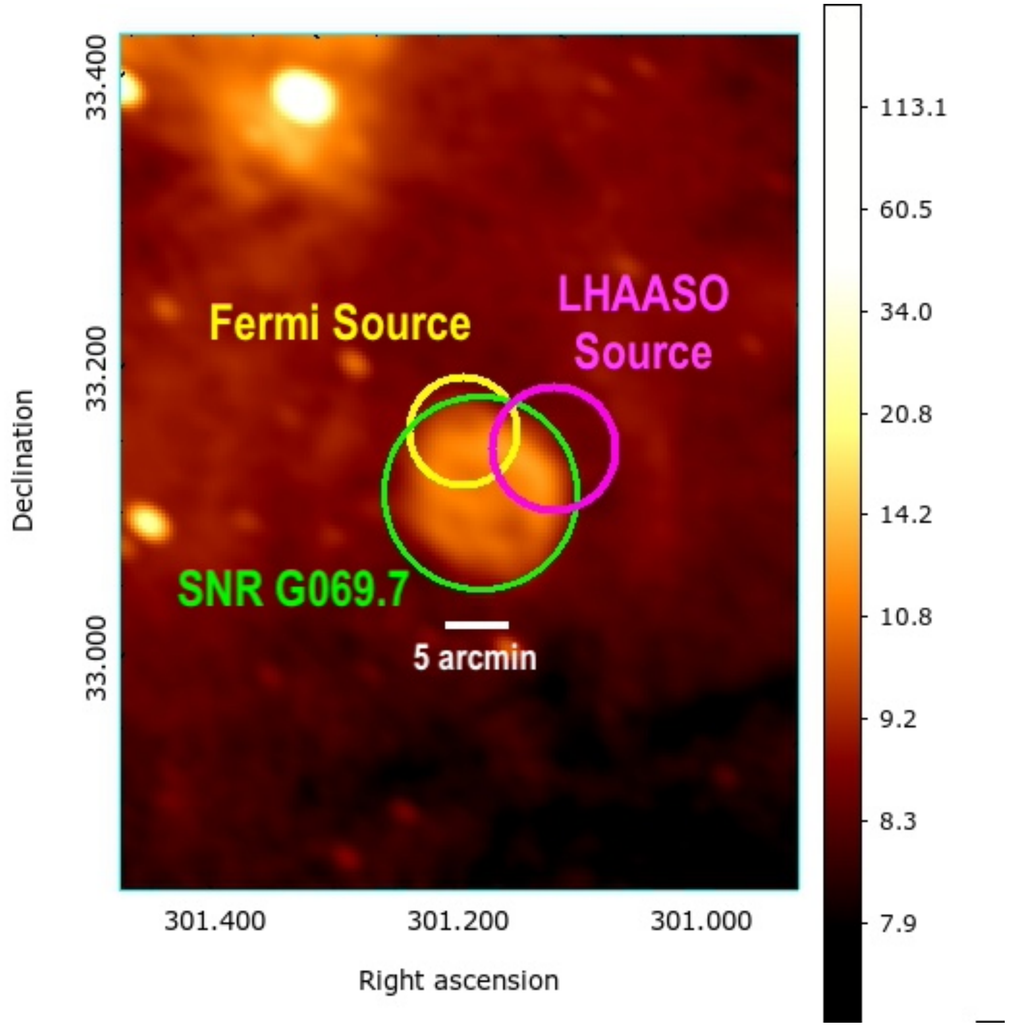
Outline:

- Background Information
- Possible Emission Scenarios
- Multi-wavelength Analysis:
  - Jansky Very Large Array (JVLA) Radio Observation
  - Archival ASCA X-ray Observation
  - Cumulative Fermi-LAT γ-ray Observations
- Next Steps
- Conclusions

Background Information

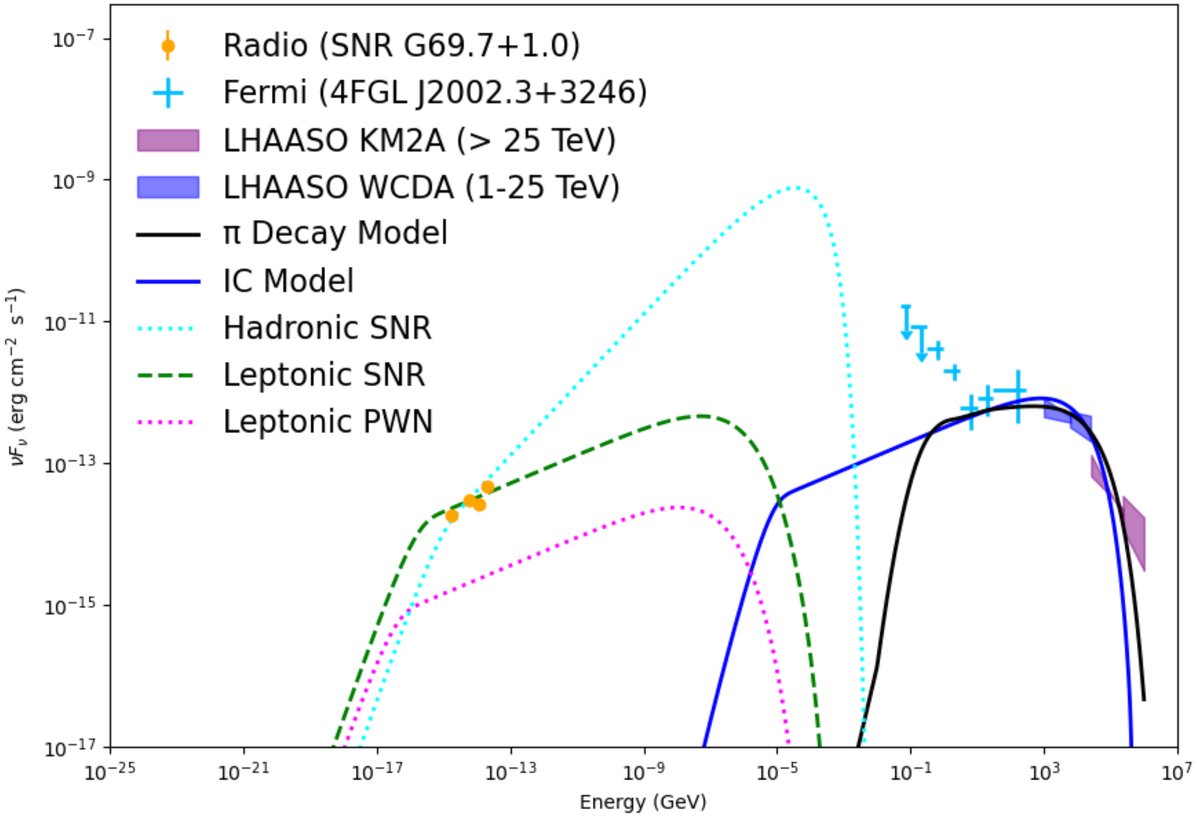
- 1LHAASO J2002+3244u is one of the UHE LHAASO sources
  - Significance: 5.8 σ > 25 TeV & 6.8 σ > 100 TeV
- Spatially coincident (0.07° away) with a shell-type SNR G069.7+1.0
  - Steep radio spectrum ($\alpha = -0.7 \pm 0.05$)
  - Distance is uncertain: (7.8—14.4 kpc)
- Spatially coincident (0.05° away) with 4FGL J2002.3+3246:
  - Potentially associated with an SNR or a PWN by Fermi-LAT



Radio image of the FoV around SNR G069.7 at 1.4 GHz from the Canadian Galactic Plane Survey (CGPS) along with the LHAASO and Fermi Sources

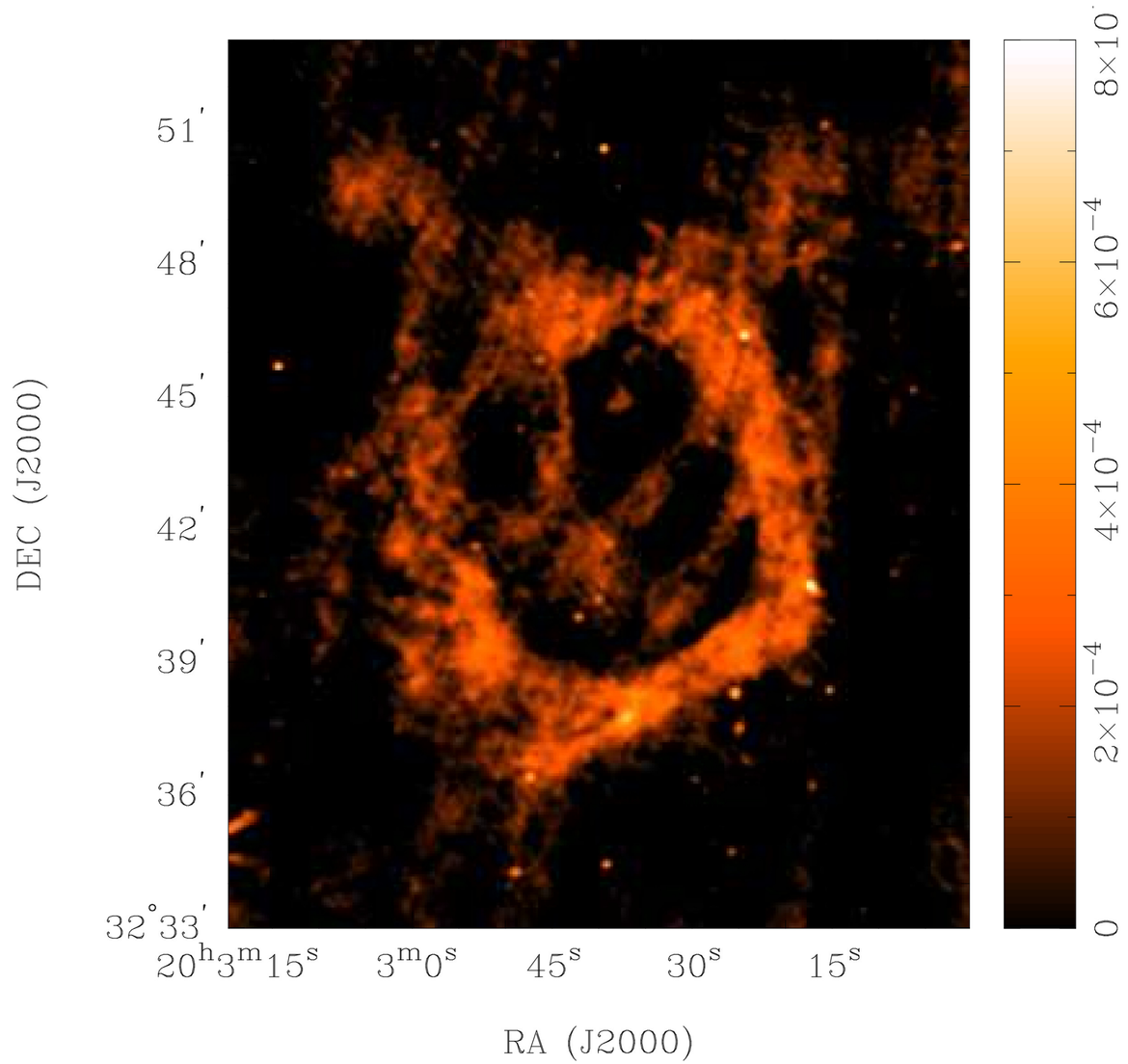
Possible Emission Scenarios

- UHE TeV γ-rays can result from leptonic or hadronic processes
- Hadronic Scenario:
  - Accelerated CR protons/hadrons interact with the surroundings such as molecular clouds to produce γ-rays through π^0 decay
  - Can arise from SNRs
- Leptonic Scenario:
  - ICS where $e^{\pm}$scatter off low-energy photons from the CMB or other near-by photon fields
  - Can arise from SNRs or PWNe



VLA Analysis Results

- Observation was made in January 2024 at 1.4 GHz in the C configuration
- Results:
  - SNR is clearly detected & no evidence of PWN inside
  - We place an upper limit on the radio emission from the PWN
  - SNR morphology hints at an interaction with a molecular cloud on the Eastern side

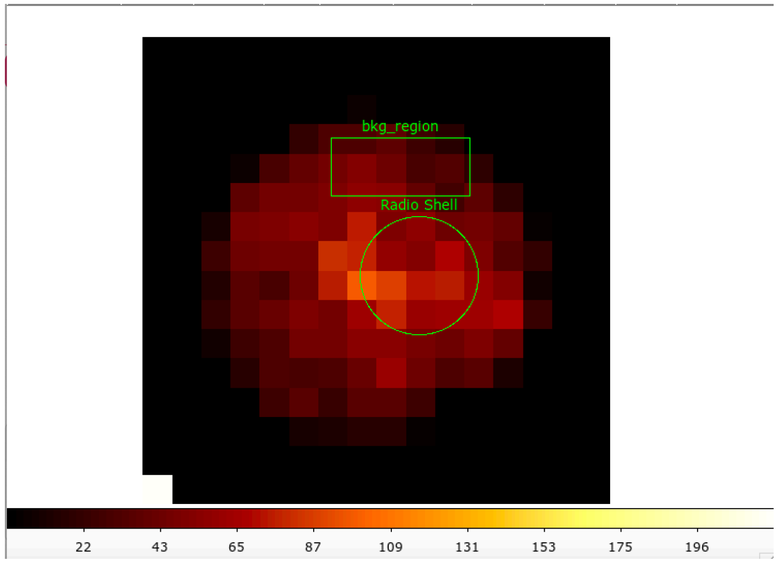


VLA image of SNR G69.7 at 1.4 GHz

We can exclude scenario 1: Leptonic PWN

Archival ASCA X-ray Observations

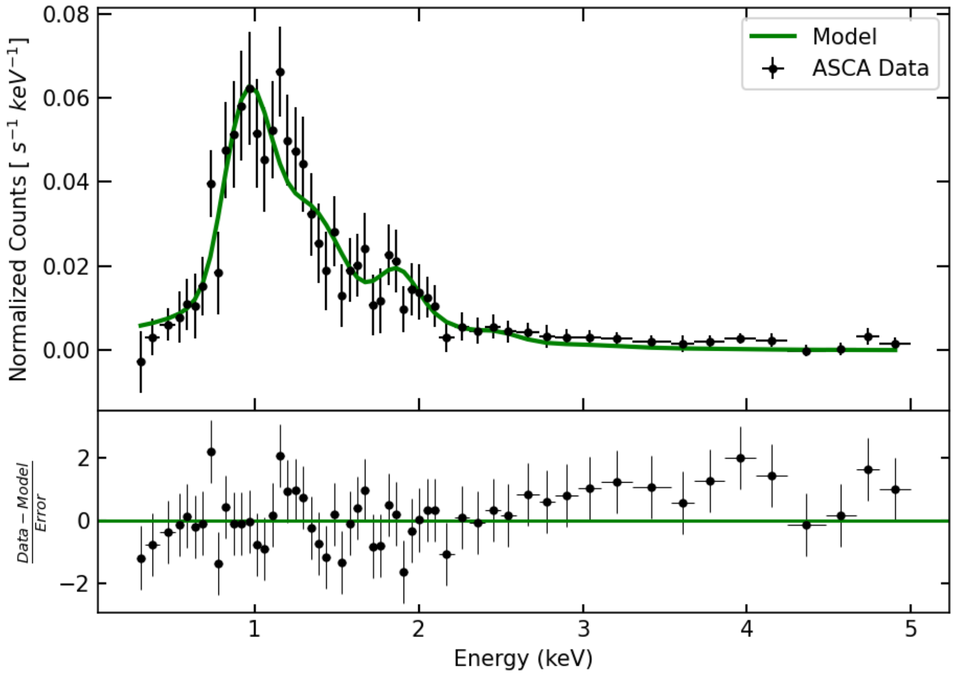
- Exposure time of ASCA Observation ~ 20 ks
- Flux value is probably a lower limit on X-ray emission from the SNR
- New X-ray observations are important in lifting the degeneracy



X-ray ASCA image of the SNR

Model Parameter	Value
$N_H(\mathrm{cm}^{-2})$	$(0.39 \pm 0.2) \times 10^{23}$
kT (Kev)	0.75 ± 0.11
Abundance	1 (Frozen)
Redshift	0 (Frozen)
Norm	$(3.69 \pm 1.09) \times 10^{-3}$
Flux (0.2-5 KeV)	$3.06^{+0.08}_{-0.6} \times 10^{-13}$ erg cm$^{-2}s^{-1}$

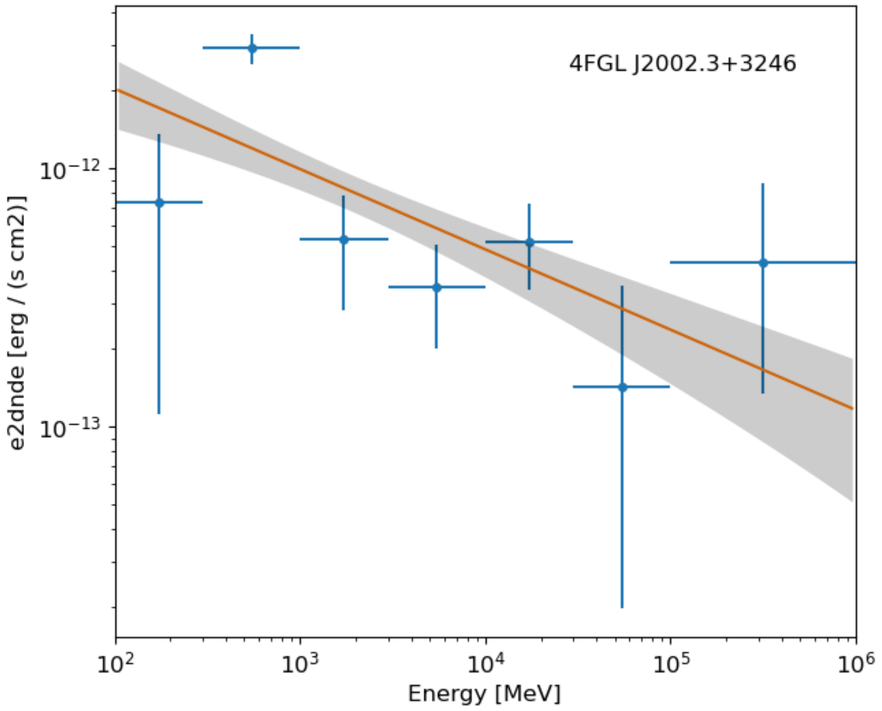
Table 3: XSPEC Fit Results of an Absorbed Raymond-Smith Model



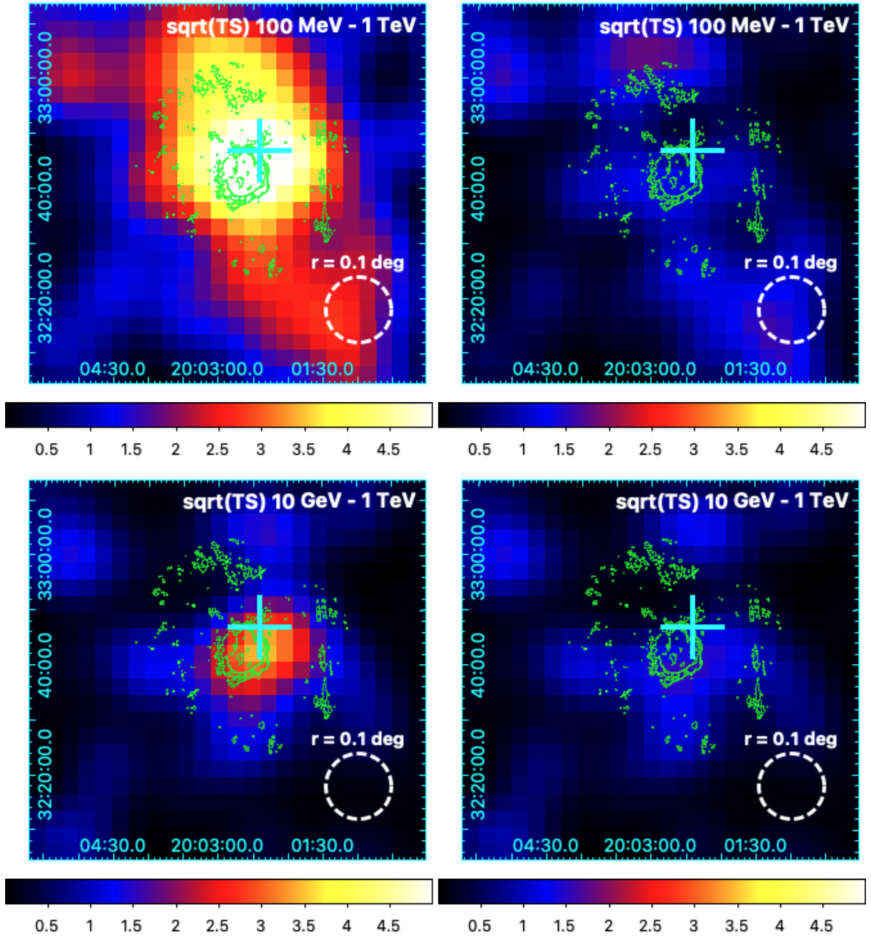
Cumulative Fermi-LAT γ-ray Observations

Analysis done by Jooyun Woo (Columbia University)

- Re-analyzed 14 years of Fermi-LAT data
- Left panels show emission in the region when it isn't modeled
- Right panels are when the Fermi source is added to fit the gamma-ray emission
- Spectrum of the source is well fitted with a power law with an index ~ 2.3
- No evidence of contribution from a pulsar



SED of the Fermi Source fitted with a power law with an index ~ 2.3



Significance maps in two different energy bands (100 MeV-1 TeV & 10 GeV- 1 TeV) with the VLA radio contours overlaid on them. Cyan cross is the position of the Fermi source. The white circle is the LAT PSF at 10 GeV

Next Steps

1. Model the SED using NAIMA with the updated data:
    - Updated Fermi-LAT spectrum
    - ASCA X-ray lower limits
    - VERITAS & HESS upper limits
2. Get better X-ray data to constrain the SED (*NuSTAR* proposal in January!)
3. Look into *CO* observations around the SNR

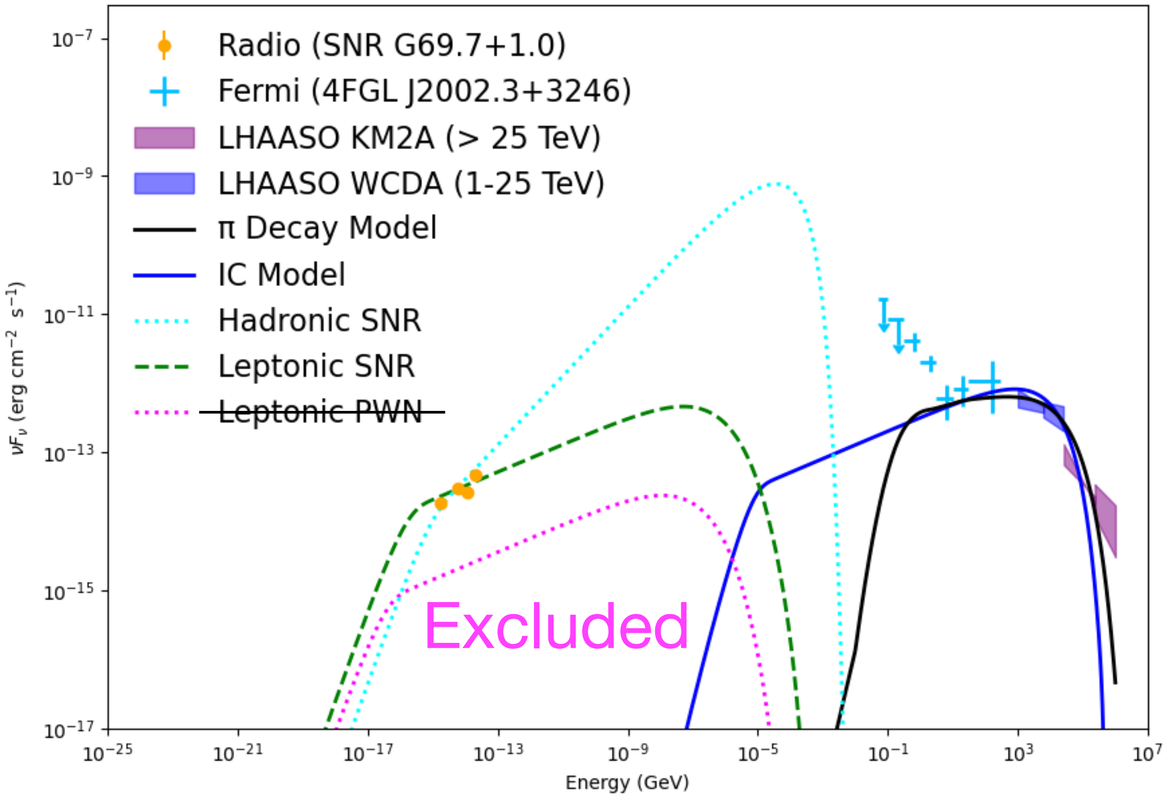
Conclusions

1. No detection of radio PWN: Exclude the leptonic PWN scenario

2. Radio morphology hints at a molecular cloud interaction with the SNR

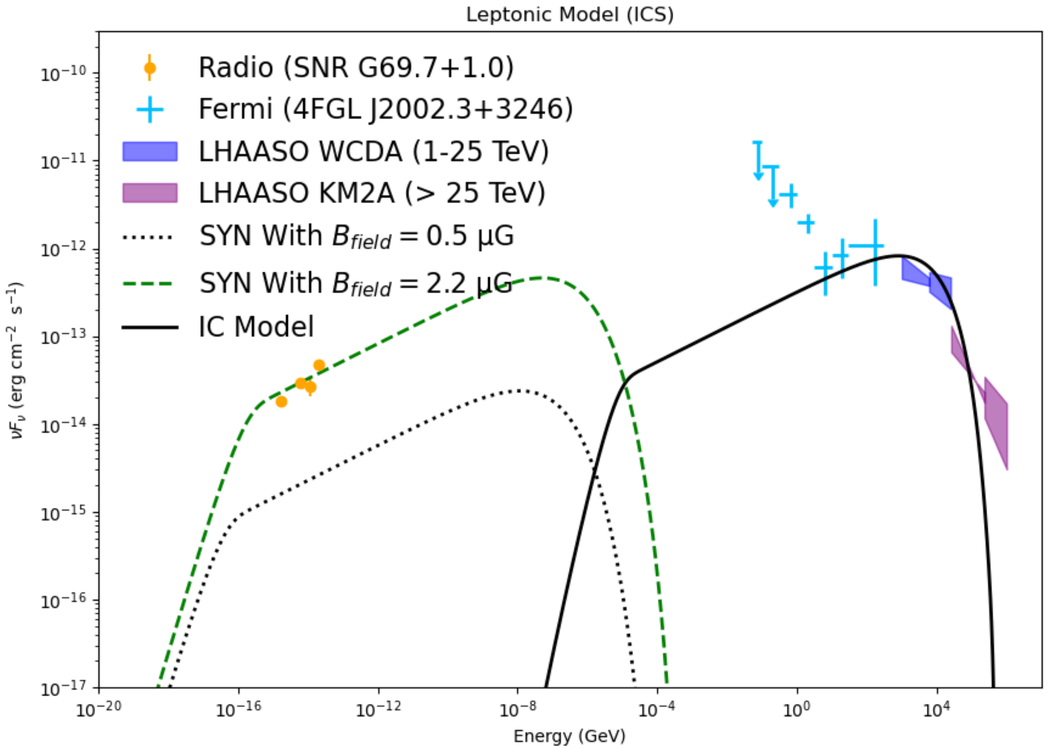
3. TeV emission most likely arises from the SNR either through:

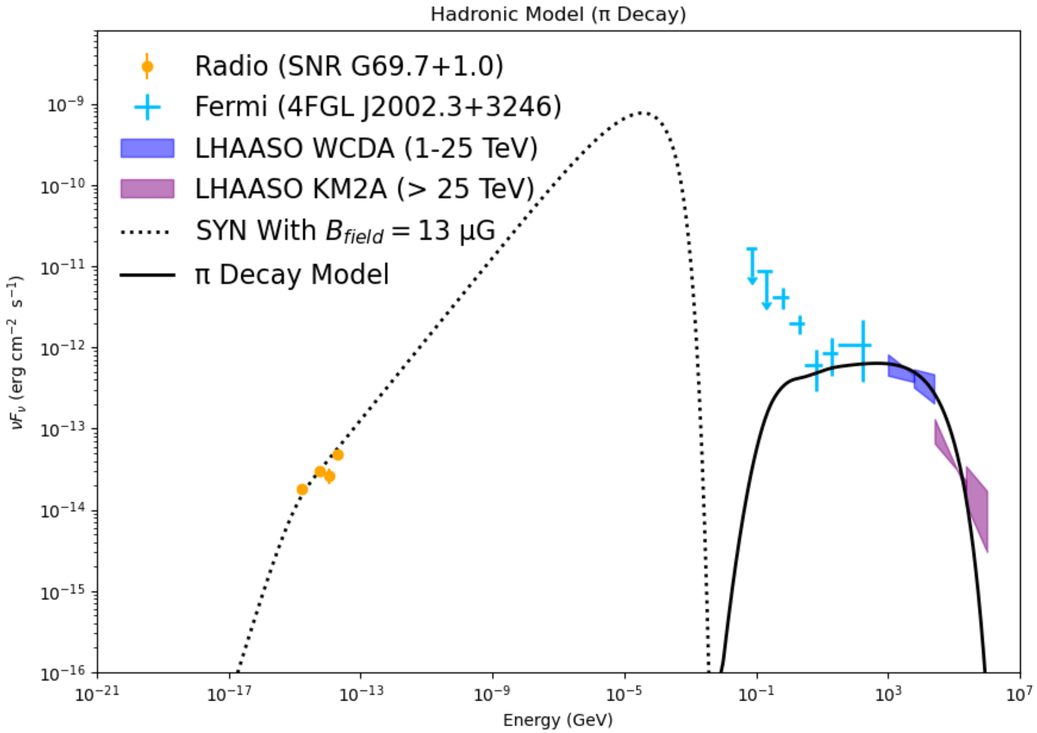
   - Hadronic scenario
   - Hybrid (hadronic + leptonic)

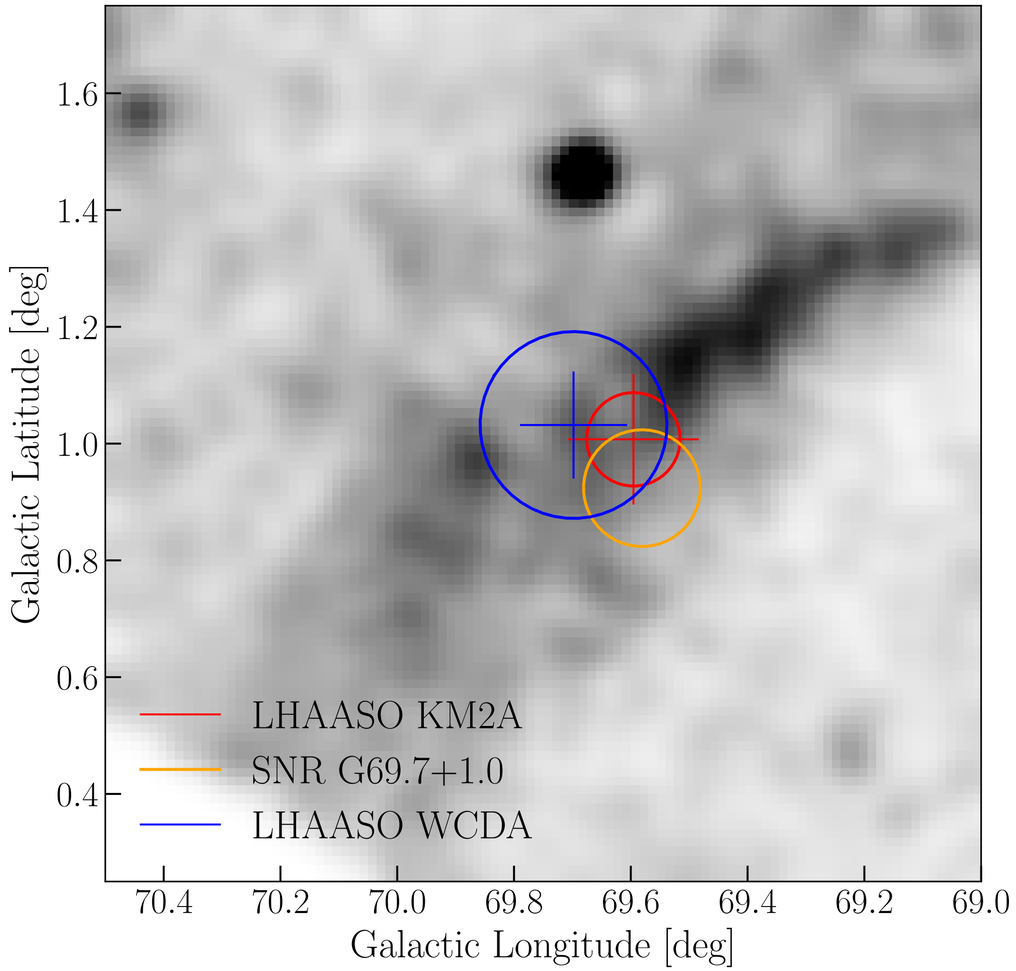


Thank you

Results & Insights:






1.6
1.4
1.2
1.0
0.8
0.6
0.4
Galactic Latitude [deg]
LHAASO KM2A
SNR G69.7+1.0
LHAASO WCDA
70.4
70.2
70.0
69.8
69.6
69.4
69.2
69.0
Galactic Longitude [deg]