Study of the GeV to TeV morphology of the γ Cygni SNR (G 78.2+2.1) with MAGIC and Fermi-LAT

Evidence for cosmic ray escape

Abstract

- **CONTEXT**: Diffusive shock acceleration (DSA) is the most promising mechanism that accelerates Galactic Cosmic Rays (CRs) in the shocks of Supernova Remnants (SNRs). It is based on particles scattering caused by turbulence ahead and behind the shock. The turbulence upstream is supposedly generated by the CRs, but this process is still not well understood. The dominant mechanism may depend on the evolutionary state of the shock and can be studied via the CRs escaping upstream into the Interstellar Medium (ISM).

- **AIMS**: Previous observations of the γ Cygni SNR showed a difference in morphology between GeV and TeV energies. Since this SNR has the right age and is at the evolutionary stage for a significant fraction of CRs to escape, our aim is to understand γ-ray emission in the vicinity of the γ Cygni SNR.

- **METHODS**: We observed the region of the γ Cygni SNR with the MAGIC Imaging Atmospheric Cherenkov telescopes between 2015 May and 2017 September recording 87 h of good-quality data. Additionally, we analysed *Fermi*-LAT data to study the energy dependence of the morphology as well as the energy spectrum in the GeV to TeV range. The energy spectra and morphology were compared against theoretical predictions, which include a detailed derivation of the CR escape process and their γ-ray generation.

Cosmic Rays and SNRs

- Identification of the origin of Galactic Cosmic Rays (CRs) : → supernova remnants (SNRs) prime candidates with the mechanism of Diffusive Shock Acceleration (DSA), which can transfer a fraction of the kinetic energy of the SNR shock wave to CRs.
- DSA predicts that CRs self-generate magnetic turbulence upstream of the shock that scatter them back downstream. The process of DSA is connected to the escape of CRs into the interstellar medium (ISM).
- It is expected that both in the initial and finale stages of the evolution of SNRs at least a fraction of the highest energy CRs escapes from the shock upstream, but the mechanism of CR escape from the accelerator is not well understood, also due to the lack of clear observational signatures.
- Evidence could be provided by γ rays produced from the interaction of escaping particles with the ISM surrounding the SNR
    - **Young SNRs** → Number of CRs escaping is small. Not expected to show clear signatures of CR–ISM interaction.
    - **Mature SNRs** → The shock has already encountered molecular clouds and even low-energy CRs have escaped from the accelerator.
- Optimal candidates are SNRs with intermediate age, during the adiabatic or Sedov–Taylor phase, in which the shock velocity decreases significantly and large fractions of particles are released into the ISM.

γ Cygni supernova remnant

Characteristic	Value used in this work	Value range
Radius (°)	0.53	0.51–0.56
Distance (kpc)	1.7	1.5–2.6
Age (kyr)	7	4–13
Shock speed (km s^{-1})	1000	600–1500
Gas density at γ Cygni (1 cm^{-3})	0.2	0.14–0.32
Explosion energy (10^{51} erg)	1	0.8–1.1

- The γ Cygni SNR is located in the heart of the Cygnus region, which also hosts the pulsar PSR 2021+4026,.
- It is believed to be the debris of a core collapse supernova.
- At radio wavelengths it shows a distinctively circular shell.
- The emission is brighter towards the south-east and north-west of the shell than along the north-east–south-west axis
- X-ray observations confirm that the SNR is in its adiabatic phase. The structure of the X-ray emission correlates with the radio band.
- No optical counterpart of the SNR has been detected and this could be ascribed to the hot dust and absorbing matter lying in the foreground of the SNR, which possibly obscures most of the optical emission.
- Together with the other observed properties, the γ Cygni SNR is an interesting target to search for signatures of escaping CRs.

MAGIC analysis

Observation

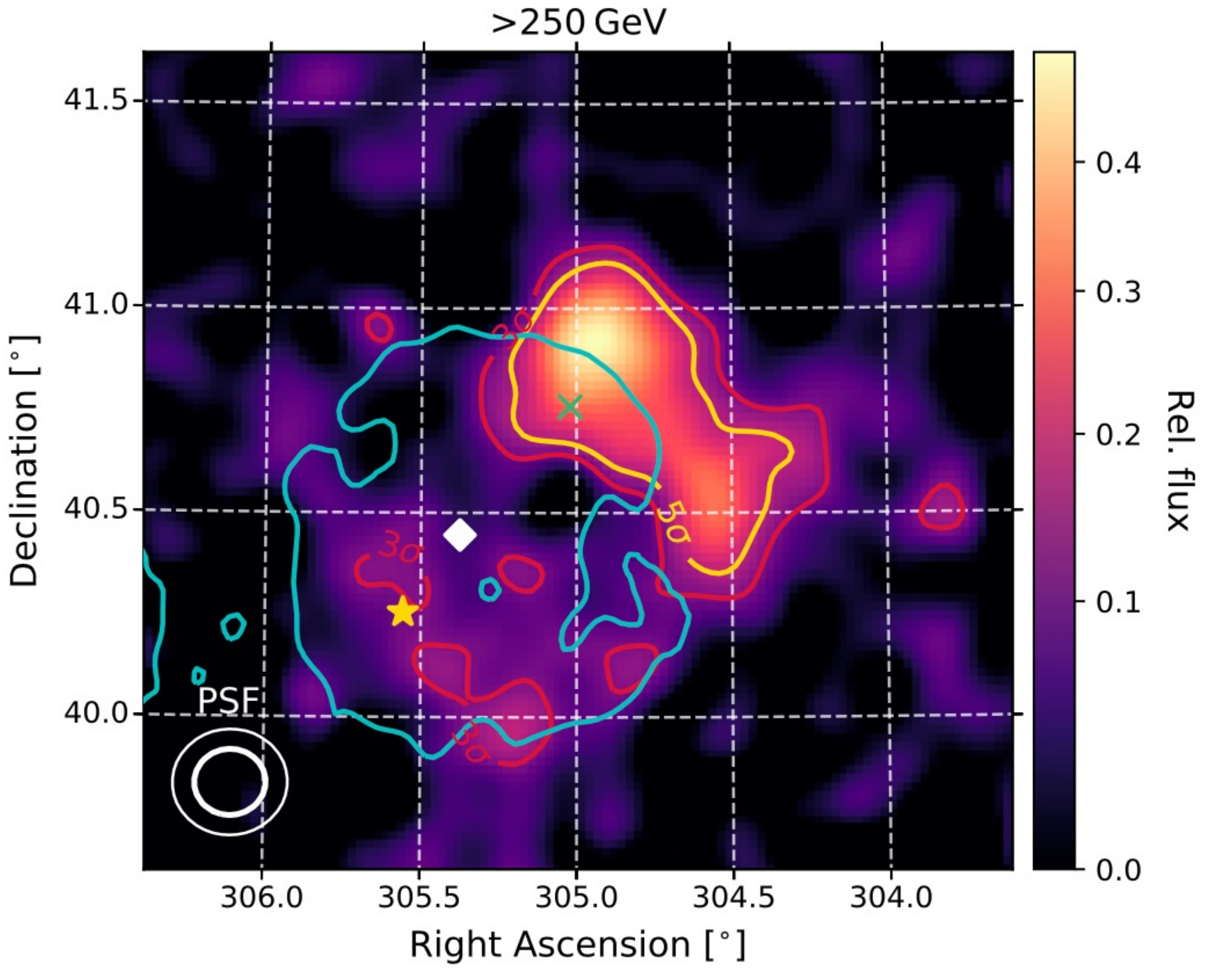
Observational periods: between 2015 May and November and
between 2017 April and September
Pointing positions: offset of 0.6 deg from VERITAS source location
Total dead-time corrected observation time: 85 hours
Energy threshold: 250 GeV

Morphological results

The emission is extended and patchy, especially along the north-western rim of the radio shell, with a bright roundish component centred on the rim and an adjunct arc-like appendix extending beyond the shell.
There are faint emission areas inside the southern part, but they are below the detection level for a point source.

The brighter region could be modelled by a radially symmetric Gaussian. Point source detected with 17.1 σ (MAGIC J2019+408).

The arc-like source can be modelled in two different ways:
- annulus segment (detection significance 10.3σ)
- second Gaussian (detection significance 9.2σ)



Fermi-LAT analysis

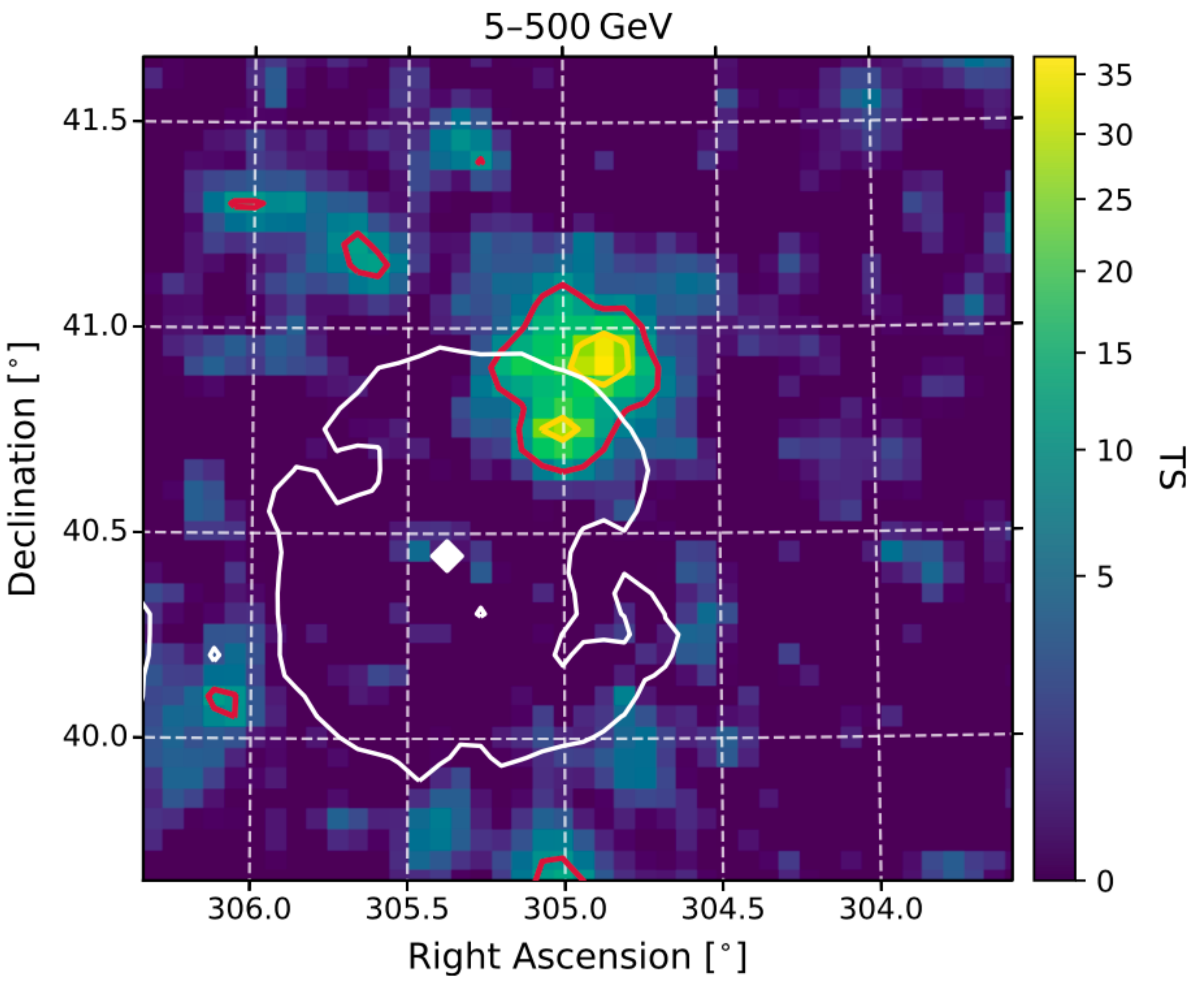
Observation

Observational periods: ∼ 9yr of observation, between 2008 October 27 and 2017 September 12 .
Energy range: to reliably disentangle the two components (pulsar and SNR), energy range is limited to 5–500 GeV.

Morphological results

A point source search on top of the radio disc, suggests the presence of a source of similar morphology to MAGIC-J 2019+408. Assuming a point source, the source search resulted in the detection at a 6.1σ.
Fitting the extension of the source with a radially symmetric Gaussian source model, the obtained values agree within errors with the position and extension of the MAGIC-J 2019+408, so we associate the Fermi-LAT and MAGIC source.

To account for the extended uniform emission that is visible in the 15 to 60GeV skymap, previous analyses of the Fermi-LAT data used a radially symmetric disc model.



Energy dependence

Observations with MAGIC provide a more precise image of the source at hundreds of GeV to TeV and its morphology differs from previously published Fermi-LAT skymaps.

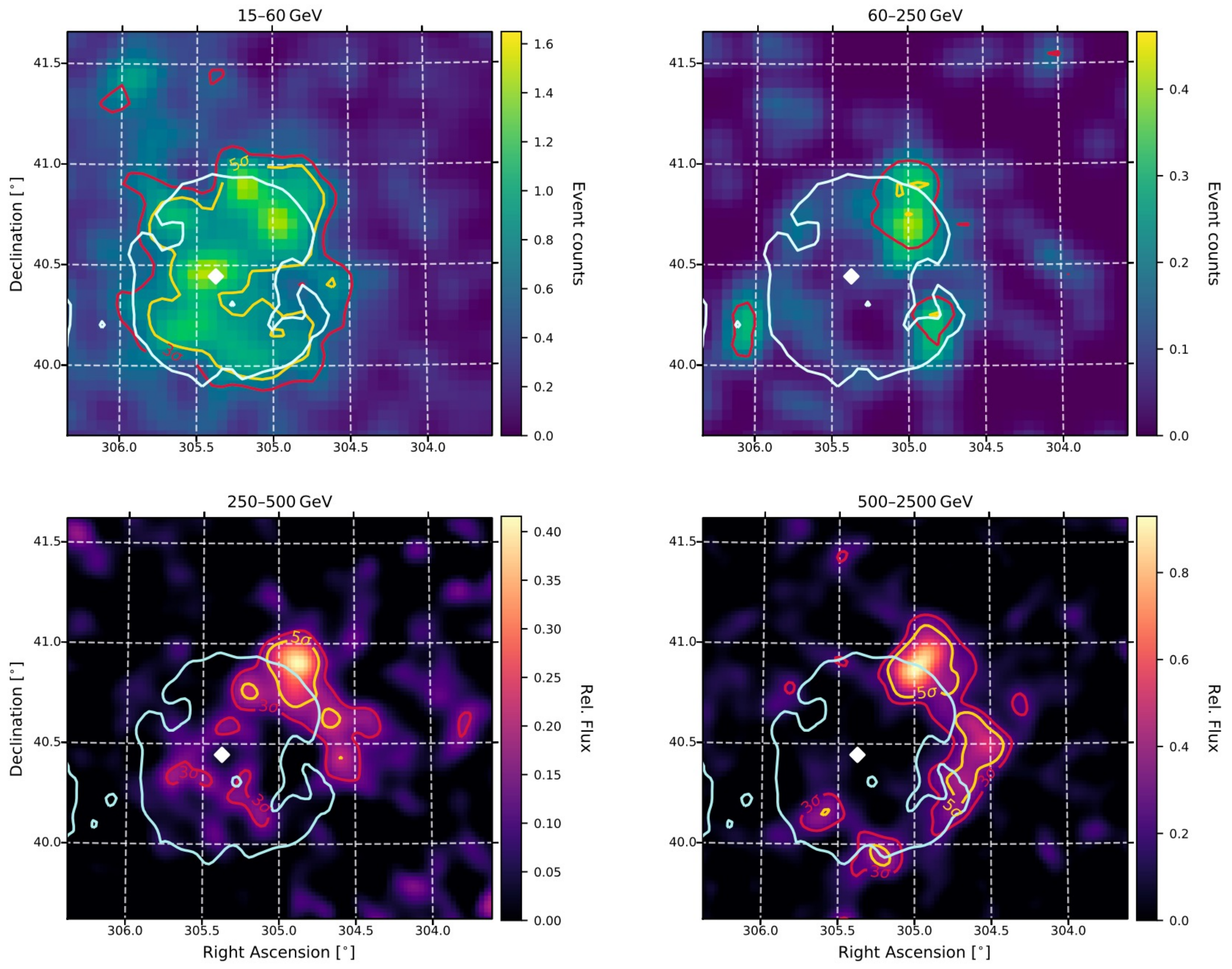
The Fermi-LAT and MAGIC data were split into two energy ranges:
15–60 GeV and 60–250 GeV for the former
and 250–500 GeV and 500–2.5 TeV for the latter

In the 15–60GeV range the emission predominantly comes from a region agreeing with the SNR radio shell, with a nearly uniform intensity.

At 60 to 250 GeV the shell emission weakens, and an extended emission at the north-western rim stands out near MAGIC J2019+408.
The position at which MAGIC observes the arc-like structure, however, does not show any significant emission.

MAGICJ2019+408 is the main component in the 250 to 500 GeV map. Emission at the arc position is becoming visible, but at a lower level.

At 500 GeV to 2.5 TeV, the arc-like region brightens and some emission towards the south of the shell becomes visible.

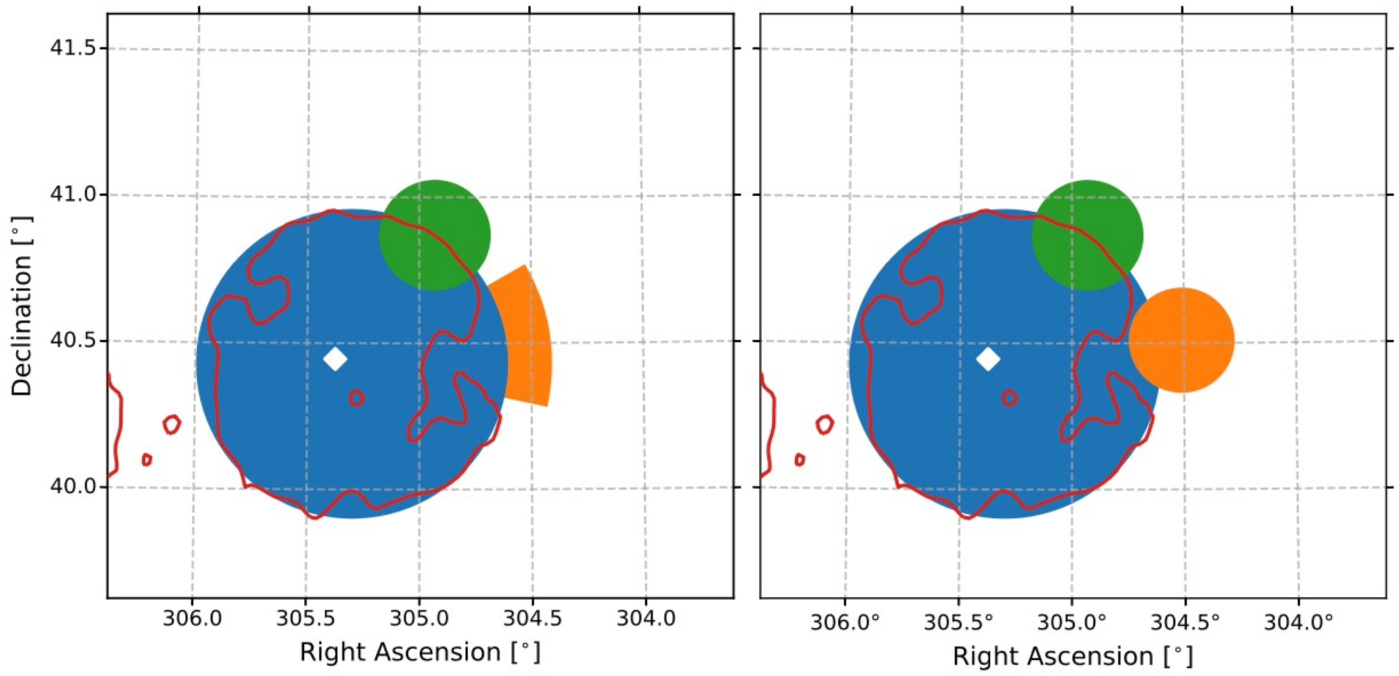


Source common model and spectra

To extract the spectra in the entire GeV to TeV range, the previous findings need to be combined into a common source model .
The γ-ray emission in the region is assumed to consist of three components:
the interior of the SNR shell, MAGIC J2019+408, and emission west of the shell (arc or second Gaussian).

The developed theoretical model in the article indicates that the annular sector is a better spatial representation for this model.

Flux points: Fermi-LAT data split in nine bins per decade over the range from 5 to 500 GeV.
MAGIC data split in four bins per decade ranging from 250 GeV to 12.5 TeV.



Power law spectral model:

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0} \right)^{-\Gamma}$$

with spectral index Γ,
normalisation constant N_0,
and scaling energy (or pivot energy) E_0.

Interpretation and modelling

The radio emission proves the presence of high-energy electrons inside the shell.

- Leptonic scenario:
  - origin of the γ-ray emission via Inverse Compton scattering
  - origin of the γ-ray emission via bremsstrahlung radiation

- Even if a leptonic explanation cannot be completely ruled out, its realisation requires extreme conditions

- Hadronic scenario:
  - emission due to the CR precursor in front of the shock
  - emission due to particles escaping from the shock

- The former interpretation seems unlikely for two different reasons:
  - spectrum from the arc region is softer than the one detected from the SNR interior. But theoretically the spectrum from the arc region should be harder than the one inside.
  - the comparison of the SNR age with the acceleration time shows that the acceleration time needed to produce particles at 8 TeV is estimated to be 4×10^4 yr, which is ~5 times the estimated SNR age

By *precursor* we mean the region upstream of the shock where particles diffuse, but are still bound to the shock.

Simplified approach for particle propagation

- The shock converts the bulk kinetic energy to relativistic particles.
- The distribution function of CRs accelerated at the shock is determined by the DSA theory and is predicted to be a power law in momentum (DSA predicts α ~ 4)up to a maximum value, $p_{max,0}$:

$$f_0(p,t) = \frac{3\,\xi_{CR} u_{sh}(t)^2 \rho_0}{4\pi\, c (m_p c)^4 \Lambda(p_{max,0}(t))} \left(\frac{p}{m_p c}\right)^{-\alpha} \Theta\left[p_{max,0}(t) - p\right],$$

- Shock position R_{sh} and the shock speed u_{sh} as a function of time are:

$$R_{sh}(t) = \left(\xi_0 \frac{E_{SN}}{\rho_0}\right)^{1/5} t^{2/5}, \qquad u_{sh}(t) = \frac{2}{5}\left(\xi_0 \frac{E_{SN}}{\rho_0}\right)^{1/5} t^{-3/5},$$

- The internal structure of the SNR is determined by adopting the linear velocity approximation, in which the gas velocity profile for r < Rsh is given by: where σ is the compression factor at the shock

$$u(r,t) = \left(1 - \frac{1}{\sigma}\right) \frac{u_{sh}(t)}{R_{sh}(t)} r,$$

- The escaping time, when particles with momentum p can no longer be confined and start escaping, is defined as:

$$t_{esc}(p) = t_{ST}\,(p/p_M)^{-1/\delta}$$

- The escaping radius, the radius of the forward shock when particles with momentum p start escaping, is defined as:

$$R_{esc}(p) = R_{sh}\,(t_{esc}(p))$$

Simplified approach for particle propagation

Assuming spherical symmetry inside and outside the remnant, the transport equation for accelerated protons in spherical coordinates is:

$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial r} = \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D\frac{\partial f}{\partial r}\right] + \frac{1}{r^2}\frac{\partial(r^2 u)}{\partial r}\frac{p}{3}\frac{\partial f}{\partial p},$$

Resolution of the transport equation using two different approximations leads to two solutions, one for particles confined inside the remnant and one for the escaping particles.

- ## Confined particles:

- When t < t_{esc}(p), particles with momentum p are confined inside the SNR and do not escape.
- A reasonable approximation for the distribution of these confined particles can be obtained from transport equation by neglecting the diffusion term.

$$f_c(t,r,p) = f_0(p,t)\left(\frac{t'}{t}\right)^{2\alpha(\sigma-1)/5\sigma-6/5}\Theta\left[p_{\max}(t,r)-p\right]$$

- ## Escaping particles:

- When t > t_{esc}(p), particles with momentum p cannot be confined anymore and start escaping.
- An approximate solution can be obtained assuming that particles are completely decoupled from the SNR evolution and only diffuse, so all terms including u in the transport equation are dropped.

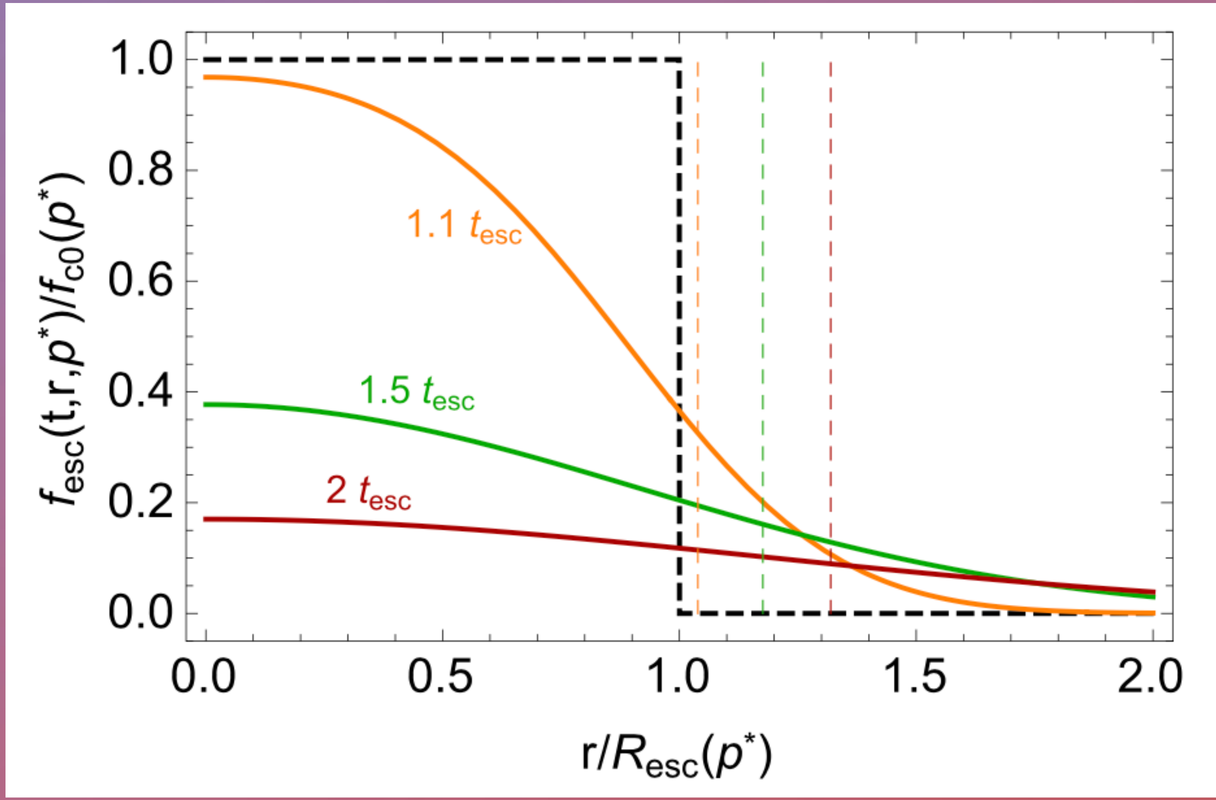
$$f_{esc}(t,r,p) = \frac{f_{c0}(p)}{2}\Theta\left[t-t_{esc}(p)\right] \times\left\{\frac{R_d}{\sqrt{\pi}\,r}\left(e^{-R_+^2}-e^{-R_-^2}\right)+\mathrm{Erf}\left(R_+\right)+\mathrm{Erf}\left(R_-\right)\right\},$$

Simplified approach for particle propagation

- Examples of f_{esc} are plotted for different escape times.
- For all plots we assume a strong shock ($\sigma = 4$) and the test particle limit ($\alpha = 4$).

- In particular, the distribution of escaping particles is observed at one arbitrary fixed momentum, $p^* = 10$TeV, as a function of the radial coordinate normalised to $R_{esc}(p^*) = 13$ pc.

- Different lines refer to different times in units of $t_{esc}(p^*) = 4000$ yr.
- The vertical dashed lines correspond to the shock positions at those times.

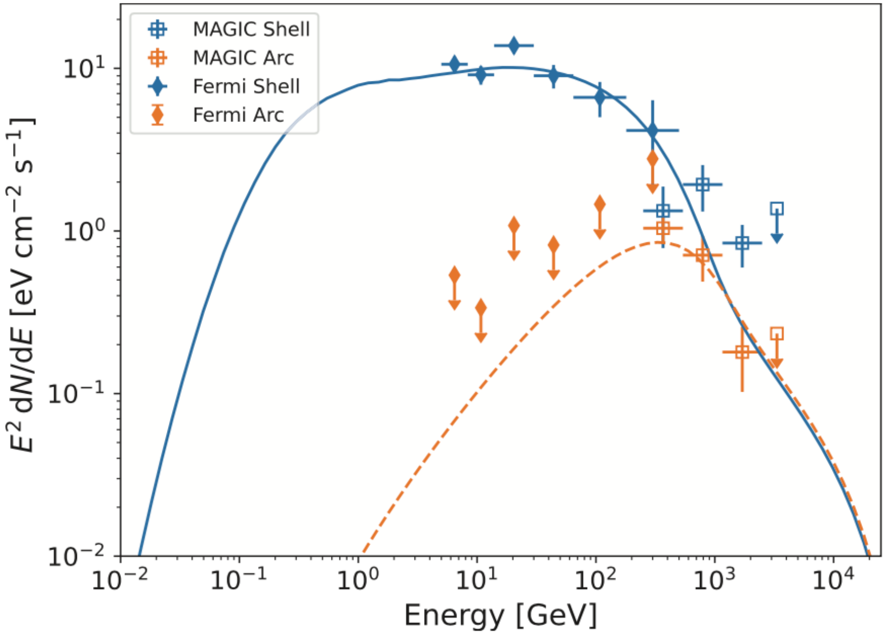


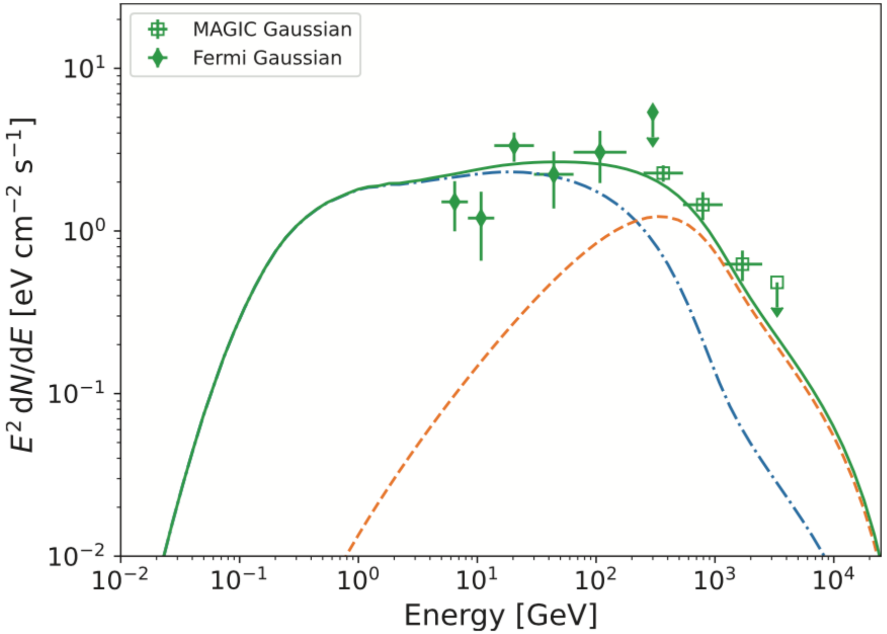
Gamma Ray spectra

- Once the particle distribution is known at any position inside and outside the FSNR, the calculation of γ-ray emissivity due to hadronic collisions is straightforward. The rate of emitted photons from a given region is :

$$\Phi_\gamma(E_\gamma, t) \equiv \frac{dN_\gamma}{dE_\gamma\, dt} = 4\pi \int \frac{d\sigma(E_p, E_\gamma)}{dE_\gamma} J_p(E_p, t) dE_p.$$

- F_p is the proton distribution in momentum convoluted with the target density in the region of interest. In particular, we distinguish two regions, the interior of the SNR and the external spherical shell which include the arc.





Summary

- Combining MAGIC and Fermi-LAT data, we investigated the γ-ray emission in the vicinity of the γ Cygni SNR and identified three main source components: the SNR interior, an extended emission outside the SNR (the arc), and a Gaussian-shaped extended source MAGIC J2019+408 in the north-west .
- The brightness ratio between the source components is energy dependent with the SNR shell dominating below ~60GeV and the arc only being observed by MAGIC above 250 GeV.
  The morphologies and spectra of MAGIC J2019+408 and the arc suggest an association with the SNR.
- The indices for a power-law model for MAGIC J2019+408 and the shell are ~2 in the Fermi-LAT energy range and ~2.8 for the three components in the MAGIC energy range.
- We interpret the three components as the result of CRs escaping the shock of the SNR upstream into the ISM, while the shock is still capable of confining less energetic CRs.
- In this context, the differences between MAGIC J2019+408 and the arc can be understood as a combination of emission from the remnant interior plus a contribution from escaping particles located outside the SNR, in particular by the presence of an over-dense cloud partially engulfed by the SNR and partially still outside of it.
- Alternatively, MAGIC J2019+408 could result from two (or more) clouds, spatially separated, one inside and one outside the SNR

Summary

- We further presented a theoretical model to interpret the data in the framework of DSA with the inclusion of time-dependent particle escape from the SNR interior.
- While a leptonic origin for the γ-ray emission cannot be ruled out, given the morphologies and spectra of the source components a hadronic scenario seems more plausible.
- Hadronic collisions can account for the γ-ray emission from all three regions provided the following criteria are met:
  - the spectrum of accelerated particles is $\propto p^{-4}$ and the acceleration efficiency is $\xi_{CR} \simeq 3.8\%$;
  - the maximum energy of accelerated particles decreases in time as $\propto t^{-2.55}$ and, at the present moment, it is a few TeV while at the end of the free-expansion phase it reached an absolute maximum of about 100 TeV;
  - the level of magnetic turbulence in the shock region at the present moment is $\delta B/B_0 \lesssim 1$ and has to decrease in time, pointing towards the presence of self-exited magnetic waves from accelerated particles;
  - the diffusion coefficient in the region immediately outside the SNR has to be ∼10–35 times smaller than the average Galactic value inferred from the boron-to-carbon ratio in the local CR spectrum;
  - the region around the SNR has to be patchy with extended clouds, with densities between 5 and 200 times higher than the average density of the circumstellar medium.
- All these findings agree well with the standard DSA applied to a middle-aged SNR produced by a core-collapse explosion, except the quite steep time dependence of the maximum energy: the theory usually predicts flatter dependences.
- We note, however, that the description of the particle escape is not completely understood yet.

Future prospects

- The understanding of the γ Cygni SNR could profit from future observation particularly of the radio emission and the molecular material, the uncovered hard X-ray to sub-GeV energy range, and very high-energy γ rays.
- Deep radio observations could help to better understand the connection between the radio and the very high-energy emission from the region, and thus provide further information on the nature of the γ-ray emitter.
- Improved knowledge of the target material can reduce the uncertainty of our proposed model and determine the contribution from hadrons.
- Given that hard X-rays or MeV γ rays can resolve the SNR shell under the background from the pulsar, they may clarify the remaining uncertainties about a hadronic or leptonic origin by searching for possible bremsstrahlung, a cooling break in the spectrum of the SNR shell, or a pion cut-off.
- To validate our proposed model future γ-ray studies could test whether the extension of the arc region is energy-dependent.
- Hence, γ Cygni might be a prime target to study the particle escape process from SNRs particularly for deeper γ-ray observations with improved angular resolution.