SNR G39.2-0.3, an hadronic cosmic rays accelerator

diagnostic of physical properties with the gamma-ray spectrum

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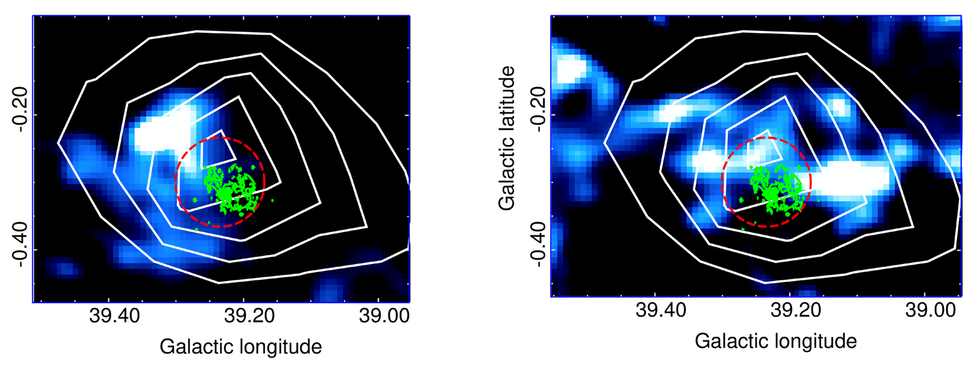
G39.2-0.3 (aka 3C 396)

A gamma-ray bright supernova remnant (SNR) detected by Fermi-LAT – one of a handful which GeV spectrum strongly favours the hadronic origin of its gamma-ray emission

Belongs to a class of core-collapse SNRs suggestively of Type IIL/b with a progenitor going through a phase of red supergiant (RSG) before the explosion (Lee et al. 2009)

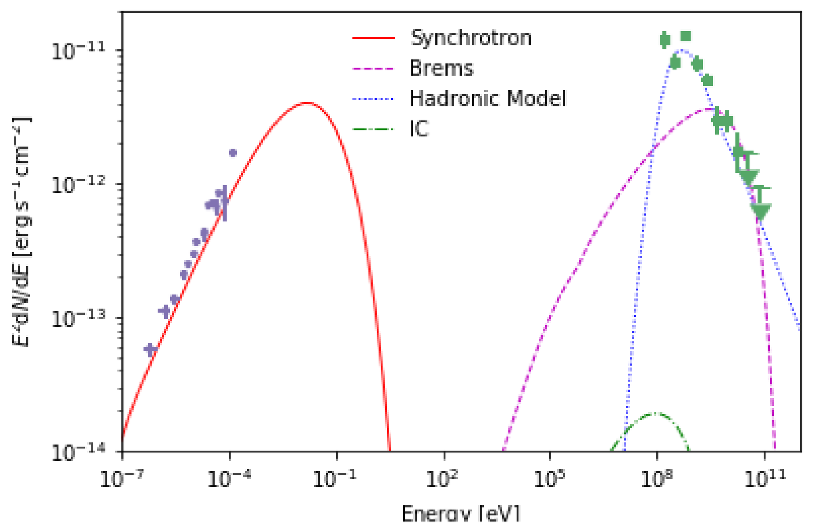
Interacts with a dense molecular cloud which provides plenty of target material for hadronic interactions

The combination of the radio and GeV data suggests a high magnetic field of at least 150 μG and undoubtfully points towards the hadronic scenario



[12]CO intensity maps of the SNR G39.2–0.3 field of view obtained from the MWISP survey for two velocity ranges: between 67 and 74 km/s (left) and between 80 and 88 km/s (right). White contours are obtained from the Fermi-LAT significance map above 3GeV, starting on TS = 25 (or ~5 σ in steps of 10). The green contours correspond to the radio shell and the red dashed-line circle marks the 99 per cent localization error of the reanalysis of 4FGL J1903.8+0531.

Intensity maps provide an estimate of the mass density of the medium in which the SNR is located to be about **400 cm^{-3}**



Spectral energy distribution fit powered by NAIMA v0.8.3 (Zabalza 2018)

- The radio spectrum is well described by synchrotron emission from a power-law electron spectrum with the spectral index of **1.8**
- The corresponding bremsstrahlung emission cannot reproduce the Fermi-LAT spectrum at high energies, but constrains the amplitude of electron population bearing in mind the estimate of the density of the medium
- The combined radio/GeV fit in the leptonic scenario then constrains the magnetic field to be at least 150 μG to be able to reproduce the level of the radio emission
- This value is comparable to the equipartition estimate of the magnetic field and although seems to be high for an evolved SNR is not really surprising for an SNR evolving in a dense cloud
- Gamma-ray spectrum is well described by hadronic interactions and subsequent pion decay from the parent particle population with a soft spectrum with the spectral index around 2.75

Heavy composition helps reconciling discrepancies

Old dynamical age scenario

The shape of the observed gamma-ray spectrum is in good agreement with theoretical expectations for dynamically old SNRs. Recent numerical simulations (Brose et al. 2020) showed that the combination of the decrease of the maximum energy of freshly accelerated particles due to the slow-down of the shock with the inefficient confinement of high-energy particles at later stages of evolution results in a broken power-law spectrum of cosmic rays with the break energy of **10-100 GeV** and the spectral index of about **2.7** above the break. This break energy corresponds to the maximum energy of particles reachable in the acceleration process at the current stage.

To analyze farther the shape of the observed spectrum we construct a toy proton spectrum which follows a broken power law in momentum

$$\frac{dN}{dp} = \begin{cases} N_0 p^{-s_1}, & if\ p < p_b \\ N_0 p_b^{-s_1+s_2} p^{-s_2}, & otherwise \end{cases}$$

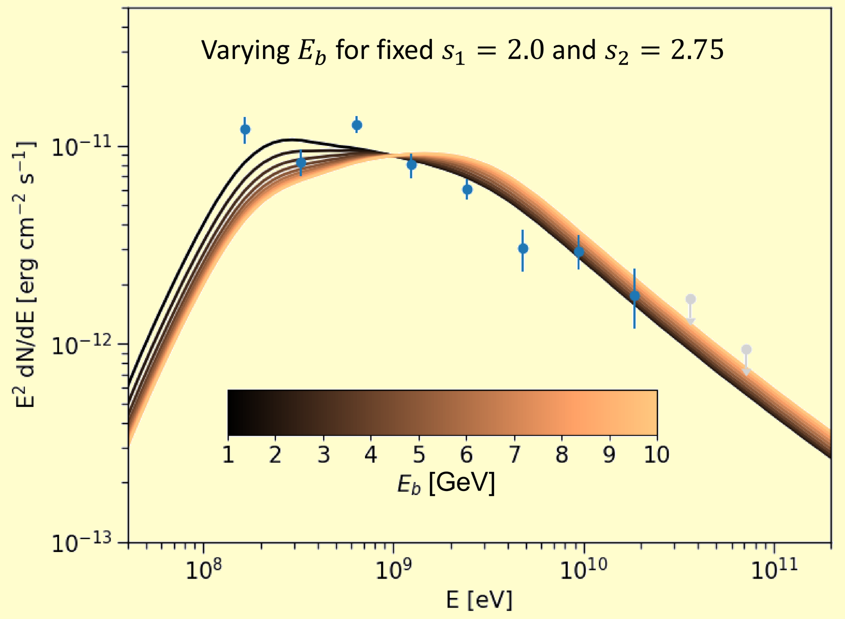
where p_b is the break momentum that corresponds to the kinetic energy E_b. We then vary E_b for fixed $s_1 = 2.0$ and $s_2 = 2.75$ (top plot) and s_1 for fixed $E_b = 10$ GeV and $s_2 = 2.75$ (bottom plot)

To calculate gamma-ray radiation from pion decays we use the post-processing radiation routine of the RATPAC code (see e.g. Brose et al. 2020 and references therein) that relies on Monte Carlo event generators for the calculation of inelastic cross-sections and differential production rates of secondary particles produced in nuclei collisions (Bhatt et al. 2020)

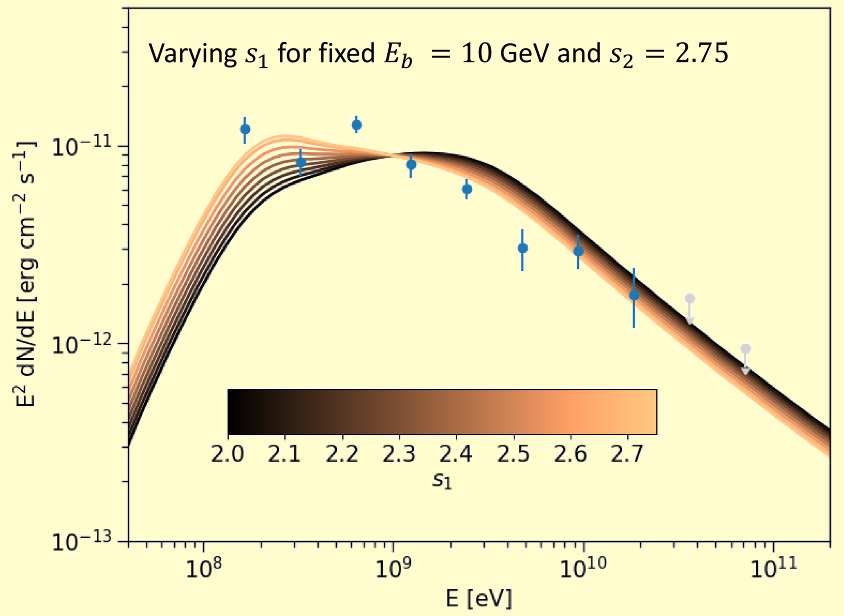
The observed spectrum suggests either a really low break energy of below 3 GeV, which:

a) points to a very old dynamical age
b) not quite easy to reach in numerical simulations

OR a soft spectrum of freshly accelerated particles (considerably softer than typical $s = 2$ expected for strong shocks through diffusive shock acceleration), which might be the case for evolved SNRs but disagrees wit the hard electron spectrum ($s = 1.8$) required to explain radio emission

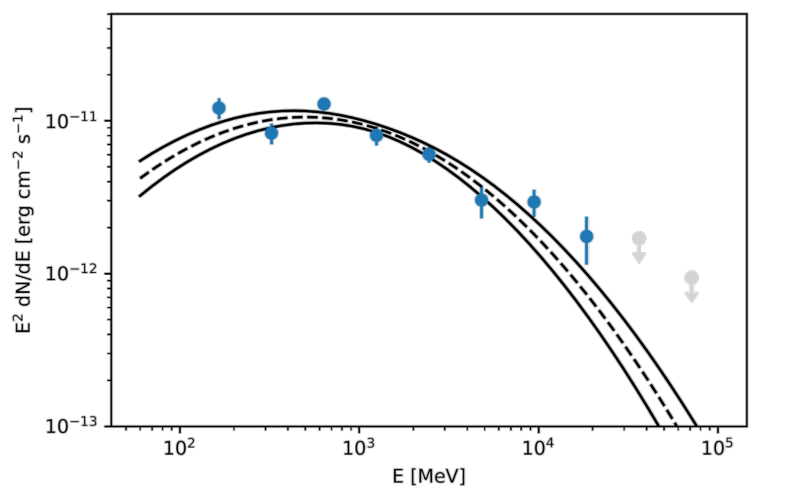


Gamma-ray spectra generated by the broken power-law proton spectrum



Powered by RATPAC

Radiation Acceleration Transport Parallel Code – a code designed for time-dependent numerical simulations of particle acceleration in SNRs



Gamma-ray spectrum of G39.2-0.3 as detected with Fermi-LAT. Well described by the LogParabola fit,

$$dN/dE = N_0 (E/E_{break})^{-(\alpha+\beta \log(E/E_{break}))}$$

with best fitting values:

$$N_0 = (8.0 \pm 0.7) \times 10^{-13}\ \text{MeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}$$
$$\alpha = 2.6 \pm 0.1$$
$$\beta = 0.20 \pm 0.03$$
$$E_{break} = 2.3\ \text{GeV}$$

?

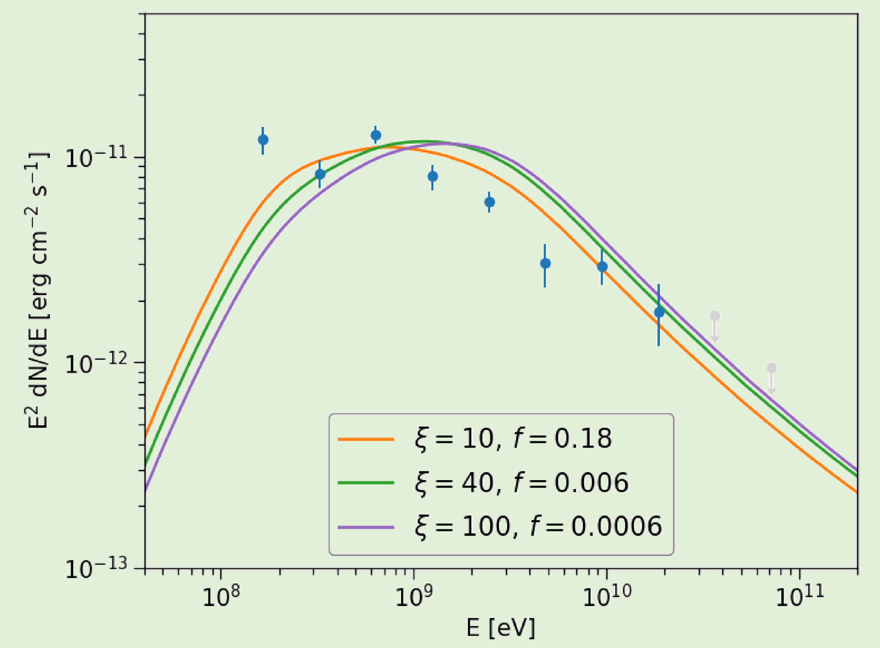
Compression of Galactic Cosmic rays?

Another mechanism which might be responsible for the gamma-ray emission from SNRs interacting with dense clouds and is widely discussed in the literature in the context of the established hadronic emitters is compression and re-acceleration of Galactic CRs in the radiative shell behind the shock front. The adiabatic compression of the pre-existing ambient Galactic CRs in the radiative shell enhances the CR spectrum both energizing particles and increasing the normalization of the spectrum as (Uchiyama et al. 2010)

$$n_{comp}(p) = \xi^{\frac{2}{3}} n_{GCR}(\xi^{-1/3} p), \xi \equiv n_{shell}/n_0$$

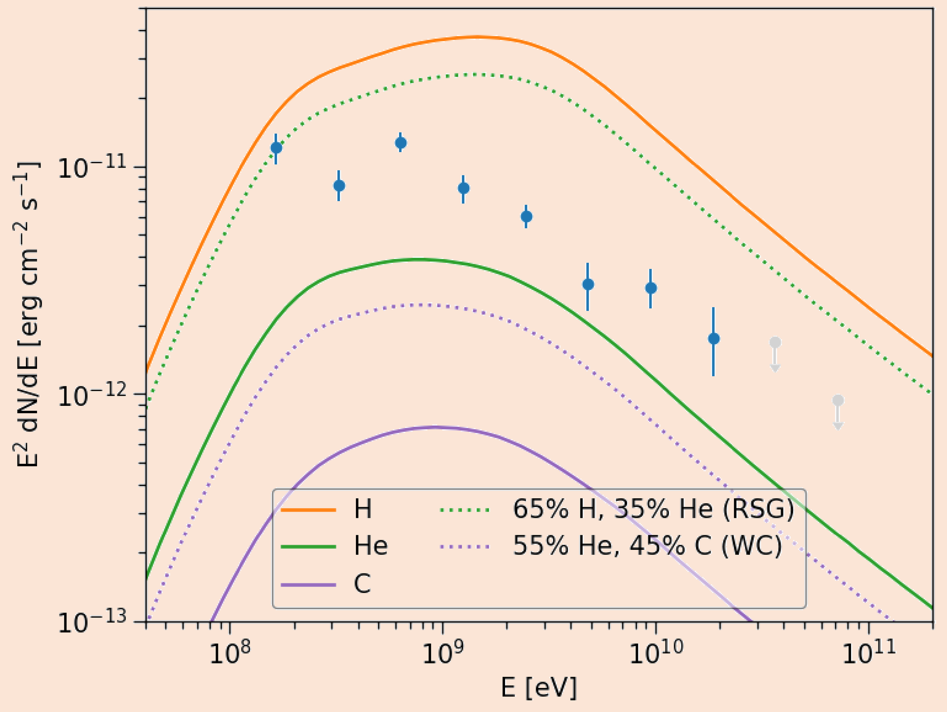
where n_{GCR} is the density of Galactic CRs, n_{shell} is the density in the shell, and n_0 is the density of the ambient medium.
The figure exhibits the computed gamma-ray spectrum for different values of the total compression ratio ξ, where the fit to the data is obtained by adjusting the volume filling factor f.

It could be seen that the break at low enough energies can be obtained only for **unrealistically** high filling factor. For such filling factor and compression ratio the total mass in the shell would exceed the maximum possible mass that can be acquired from the cloud. Therefore, we conclude that this mechanism **CANNOT** explain the observed spectrum.



Heavy composition scenario

Heavy elements, both as CRs and as target material, result in a shift of the peak in the gamma-ray spectrum to lower energies (Bhatt et al. 2020). At the same time, heavy composition is expected for core-collapse SNRs which expand into the stellar wind of their progenitor stars, mostly RSGs or Wolf–Rayet stars. Given that G39.2–0.3 is a core-collapse remnant of likely Type IIL/b with an RSG progenitor, one can expect a fair fraction of heavy elements which can be accelerated at the shock and/or act as target material for hadronic interactions. Here, we consider heavy nuclei only fo CRs accelerated at the shock, keeping the target material of typical ISM composition with H to He ratio of 10:1, motivated by the idea that CRs residing in the SNR were accelerated at earlier stages of evolution while the SNR was still evolving inside the stellar wind bubble, while at this moment of time they are interacting with the dense cloud material of the ISM composition



The figure shows gamma-ray spectra for different composition of accelerated particles for hadronic interactions. The solid lines show mono-elemental compositions for hydrogen (orange), helium (green), and carbon (purple) nuclei. Dotted lines represent mixed compositions (mass fractions) which reflect RSG and carbon rich Wolf-Rayet (WC) winds. The spectra are normalized to the same mass density of CRs (and hence the same injection efficiency) to demonstrate the difference in flux normalization when moving to heavier nuclei. There is however enough room in the parameter space to ensure that any of considered composition can match the level of observed emission. The momentum spectrum is assumed to be of the form

$$\frac{dN}{dp} = \begin{cases} N_{0,i} p^{-s_1}, & if\ p < Zp_b \\ N_{0,i} (Zp_b)^{-s_1+s_2} p^{-s_2}, & otherwise \end{cases}$$

where i denotes the type of particle, Z is the charge number and p_b is the break momentum for hydrogen nuclei. The break momentum should reflect the maximum momentum to which particles can be accelerated at this moment of time and hence should scale with rigidity. For all the cases we assume $s_1 = 2.0, s_2 = 2.75$ and $E_b =$ 10 GeV

It is clearly seen that although RSG composition is not particularly helpful in decreasing the break energy in the gamma-ray spectrum, carbon loaded WC composition does significantly shift the break to lower energies

Check the paper for more detail!
https://academic.oup.com/mnras/article/497/3/3581/5871207

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