



TeV Emission in NGC 4278: Are Shocks the Source?

Alberto Domínguez
(IPARCOS & UC Madrid)

This work was supported by the Spanish Ministry of Science and Innovation (MCIN) and the State Research Agency (AEI) through project PID2021-126536OA-I00 (MCIN/AEI/10.13039/501100011033).



IV IPARCOS Congress
December 10, 2025

An Overview of NGC 4278

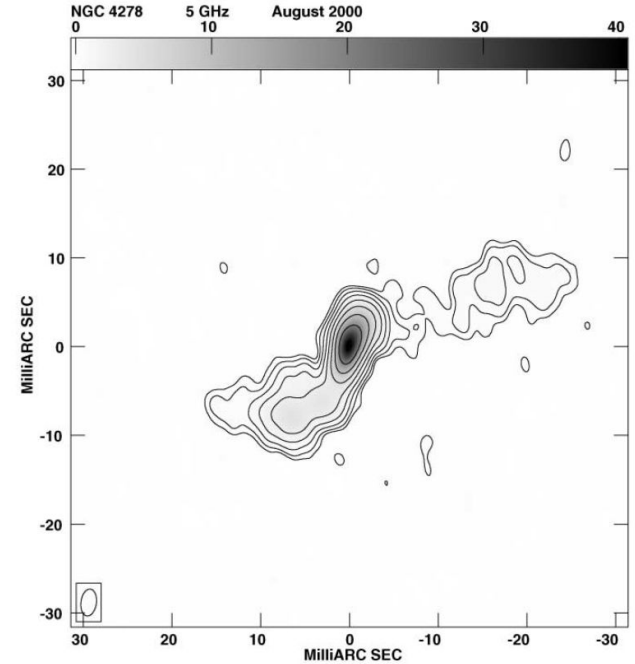
- Elliptical galaxy with a low-ionization nuclear emission-line region (LINER).
- Distance: ~16.4 Mpc (Tonry et al. 2001).
- Central engine: Low-luminosity AGN (LLAGN) with inefficient accretion and weak jets (Ho 2008, Yuan et al. 2009).
- Radio morphology: Compact radio core with small-scale jets (Giroletti et al. 2005).



Hubble Space Telescope Image, ACS/WFC filters F475W and F850LP

An Overview of NGC 4278

- Elliptical galaxy with a low-ionization nuclear emission-line region (LINER).
- Distance: ~16.4 Mpc (Tonry et al. 2001).
- Central engine: Low-luminosity AGN (LLAGN) with inefficient accretion and weak jets (Ho 2008, Yuan et al. 2009).
- Radio morphology: Compact radio core with small-scale jets (Giroletti et al. 2005).



VLBA+Y1 Image at 5 GHz

Detection at TeV by LHAASO

- First LINER/LLAGN detected at TeV energies (LHAASO collaboration 2024, Cao et al. 2024)
- Two states identified (Cao et al. 2024):

Active state: $L_{1-10 \text{ TeV}} \approx 8 \times 10^{40} \text{ erg s}^{-1}$

Quiescent state: $L_{1-10 \text{ TeV}} \approx 2 \times 10^{40} \text{ erg s}^{-1}$

Spectrum: power law, $\Gamma \approx 2.4$ (active) to 2.7 (quiescent)

$$L_{\gamma} = 4\pi d^2 \int_{E_1}^{E_2} E \phi(E) dE,$$

- TeV emission now extends to LINER/LLAGN population



LHAASO high on the Tibetan Plateau

Detection at TeV by LHAASO

- First LINER/LLAGN detected at TeV energies (LHAASO collaboration 2024, Cao et al. 2024)
- Two states identified (Cao et al. 2024):

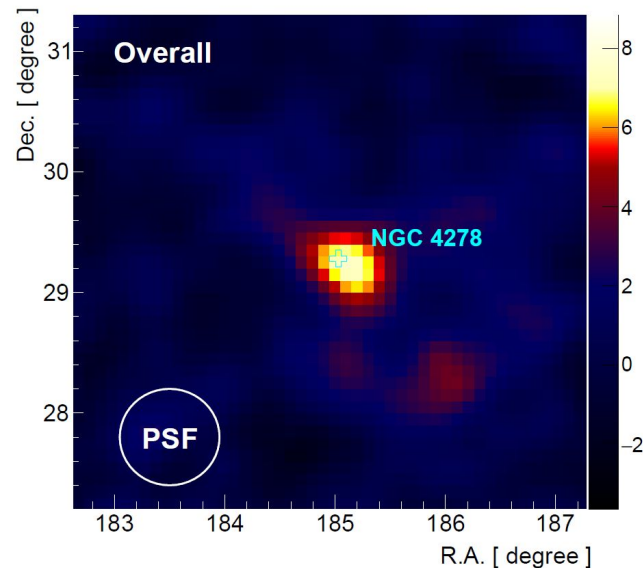
Active state: $L_{1-10 \text{ TeV}} \approx 8 \times 10^{40} \text{ erg s}^{-1}$

Quiescent state: $L_{1-10 \text{ TeV}} \approx 2 \times 10^{40} \text{ erg s}^{-1}$

Spectrum: power law, $\Gamma \approx 2.4$ (active) to 2.7 (quiescent)

$$L_{\gamma} = 4\pi d^2 \int_{E_1}^{E_2} E \phi(E) dE,$$

- TeV emission now extends to LINER/LLAGN population



LHAASO Test Statistics Map at 1 - 10 TeV (Cao et al. 2024)

Detection at TeV by LHAASO

- First LINER/LLAGN detected at TeV energies (LHAASO collaboration 2024, Cao et al. 2024)

- Two states identified (Cao et al. 2024):

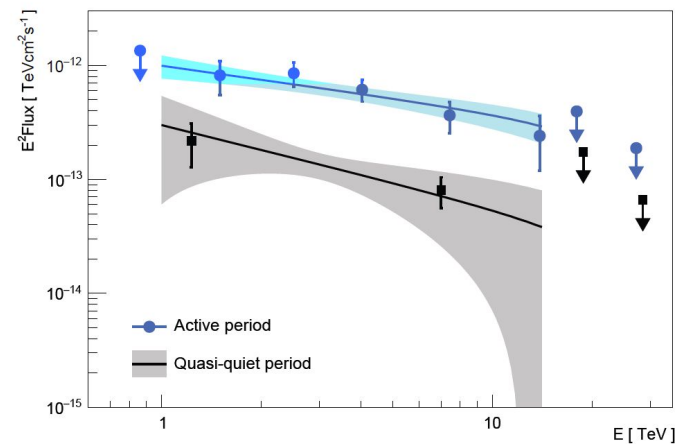
Active state: $L_{1-10 \text{ TeV}} \approx 8 \times 10^{40} \text{ erg s}^{-1}$

Quiescent state: $L_{1-10 \text{ TeV}} \approx 2 \times 10^{40} \text{ erg s}^{-1}$

Spectrum: power law, $\Gamma \approx 2.4$ (active) to 2.7 (quiescent)

$$L_{\gamma} = 4\pi d^2 \int_{E_1}^{E_2} E \phi(E) dE,$$

- TeV emission now extends to LINER/LLAGN population



LHAASO gamma-ray spectrum (Cao et al. 2024)

Possible Scenarios for the TeV Production

1. *Extended jet-ISM shocks*: TeV photons could be produced where the radio jets interact with the interstellar medium (ISM) of the host galaxy. In this case, shocks at hundreds of parsecs from the nucleus accelerate particles that emit gamma rays through synchrotron or inverse-Compton processes (e.g., Bykov et al. 2018).
2. *Compact jet zones producing inverse-Compton emission*: The TeV emission could instead originate in compact regions close to the base of the jet, where relativistic electrons upscatter lower-energy photons (from synchrotron radiation or the accretion flow) to TeV energies via inverse-Compton scattering (e.g., Abdalla et al. 2018).
3. *Magnetospheric gap accelerators near the black hole*: In this scenario, strong electric fields in charge-starved regions (gaps) of the black hole's magnetosphere directly accelerate particles to ultra-relativistic energies, leading to TeV emission through curvature or inverse-Compton radiation very close to the event horizon (e.g., Aharonian et al. 2006).

Integral-Field Spectroscopy with MEGARA

- GTC/MEGARA observed nine LINERs including NGC 4278 (Hermosa Muñoz et al. 2024)
- MEGARA found outflows in six out of nine.

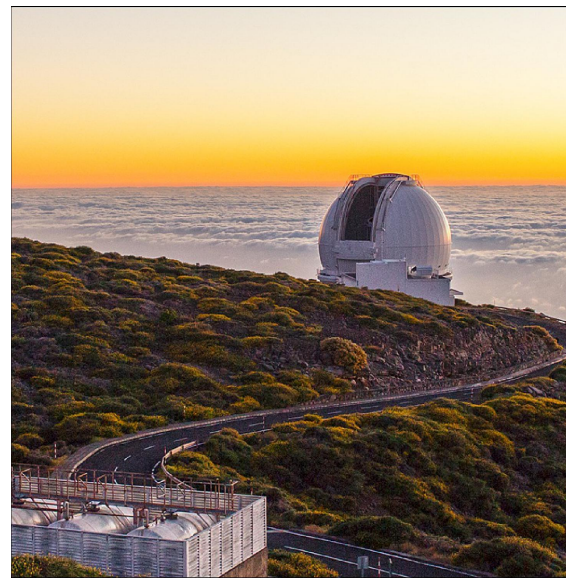
$$\dot{E}_{\text{shock}} = \frac{1}{2} \dot{M} (v^2 + 3\sigma^2),$$

shock kinetic power

ionized gas mass outflow rate

outflow velocity

velocity dispersion



Gran Telescopio de Canarias at the Roque de los Muchachos Observatory, Spain

Integral-Field Spectroscopy with MEGARA

- GTC/MEGARA observed nine LINERs including NGC 4278 (Hermosa Muñoz et al. 2024)
- MEGARA found outflows in six out of nine.

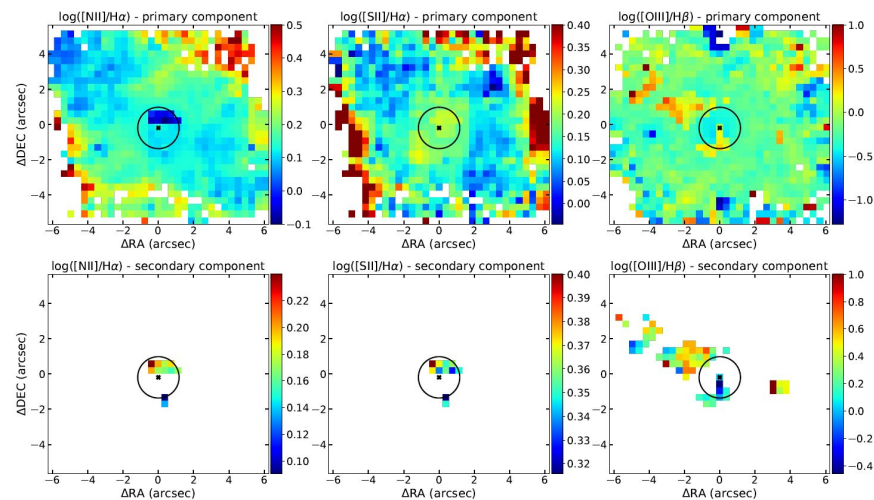
$$\dot{E}_{\text{shock}} = \frac{1}{2} \dot{M} (v^2 + 3\sigma^2),$$

shock kinetic power

ionized gas mass outflow rate

outflow velocity

velocity dispersion



Line ratios measured with MEGARA (Hermosa Muñoz et al. 2024)

Results (I)

Quantity	Value	Reference
L_γ (1–10 TeV)	$0.8 \times 10^{41} \text{ erg s}^{-1}$	Cao et al. (2024)
\dot{E}_{shock}	$(7.2 \pm 1.7) \times 10^{37} \text{ erg s}^{-1}$	Hermosa Muñoz et al. (2024)

$$\eta = \frac{L_\gamma}{\dot{E}_{\text{shock}}} \gtrsim 1000,$$

Putative efficiency

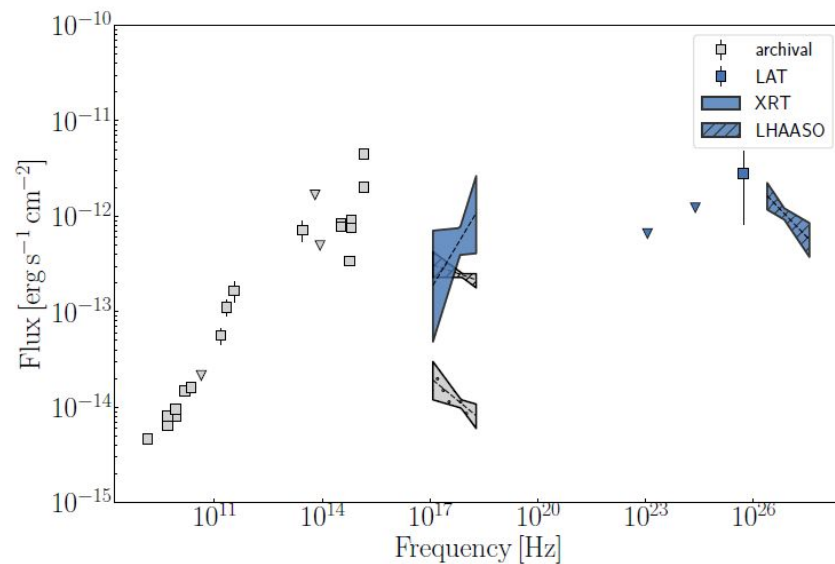
Note that EBL-corrected TeV luminosity will be larger (less than 10% at these short distances)

The efficiency values required in NGC4278 are unphysical, thereby excluding extended jet–ISM interactions as the TeV source.

This energy comparison is presented for the first time in Domínguez (2025, RNAAS)
<https://arxiv.org/abs/2509.07527>

Results (II)

Broad-band SED modeling, including contemporaneous Swift + Fermi-LAT data (Bronzini et al. 2024), together with the observed month-scale variability, point to a compact nuclear origin of the TeV emission.



Broad-band SED (Bronzini et al. 2024)

Possible Scenarios for the TeV Production

1. *Extended jet-ISM shocks*

Not supported by Bronzini et al. (2024) and our work

2. *Compact jet zones producing inverse-Compton emission*

Supported by Bronzini et al. (2024) - broadband SED modeling and monthly-time scale

3. *Magnetospheric gap accelerators near the black hole*

Not supported by Bronzini et al. (2024)

Conclusions

1. TeV photons arise from a compact nuclear accelerator, while optical outflows trace larger-scale jet-ISM interactions that coexist but do not power the TeV radiation. We used an argument based on energy comparisons.
2. NGC 4278 may represent a broader class of LINERs with ionized outflows.
3. There are 6/9 LINERs that show ~100 pc outflows (Hermosa Muñoz et al. 2024), but only NGC 4278 is detected so far at TeV energies.
4. Its detection extends TeV emission to the population of LINERs and LLAGNs, beyond the previously known cases of blazars and FR I radio galaxies such as M87, establishing NGC 4278 as a benchmark source and a prime CTAO target.

Master's Thesis ongoing "Can Quiet Active Galaxies Shine in Gamma Rays? A Study with NASA's Fermi-LAT" by Alejandra León León supervised by Armando Gil de Paz & Alberto Domínguez

Backup

1. Ionized gas mass (M_{gas}):

- Obtained from recombination-line luminosities (typically $H\alpha$), assuming case B recombination and an electron density n_e from diagnostic line ratios (e.g., [S II] doublet).
- Formula:

$$M_{\text{gas}} \approx \frac{m_p L_{H\alpha}}{n_e \alpha_{H\alpha}^{\text{eff}} h\nu_{H\alpha}}$$

where m_p is the proton mass, $\alpha_{H\alpha}^{\text{eff}}$ the recombination coefficient, and $h\nu_{H\alpha}$ the photon energy.

2. Outflow rate (\dot{M}):

- Divide the gas mass by the dynamical time of the outflow:

$$\dot{M} \approx \frac{M_{\text{gas}} v}{R}$$

where v is the bulk outflow velocity (from line shifts) and R the size of the outflowing region (from spatially resolved spectroscopy).

3. Kinetic power (\dot{E}_{shock}):

- Includes both bulk motion and turbulence:

$$\dot{E}_{\text{shock}} = \frac{1}{2} \dot{M} (v^2 + 3\sigma^2)$$

where v is the outflow velocity and σ the velocity dispersion (line broadening beyond instrumental resolution).

- The factor $3\sigma^2$ accounts for the contribution of random/turbulent motions to the total kinetic energy per particle.