Understanding the Gamma-Ray Emission around Westerlund 1

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Abstract

Young massive stellar clusters (YMCs) have come increasingly into the focus of discussions about the origin of PeV cosmic rays. Recently, HESS observed high-energy gamma ray emission around the YMC Westerlund 1, characterised by an energy independent, ring-like shape slightly off-set from the cluster position. We investigate the origin of this emission by modelling hadronic and leptonic emission processes with the open `GAMERA` library, discussing particle acceleration sites and propagation effects. Our findings support a predominately leptonic origin of the emission and highlight how the cluster's radiative and mechanical feedback facilitates particle acceleration.

TeV γ-rays around Westerlund 1 – Termination shock acceleration?

Young, massive stars have powerful, supersonic winds. In **compact clusters**, these winds and SN ejecta combine into a **cluster wind** which blows a **superbubble** (for a basic model, see Fig. 1, right). This environment enables particle acceleration, e.g., through **large-scale shocks** and **turbulence**.

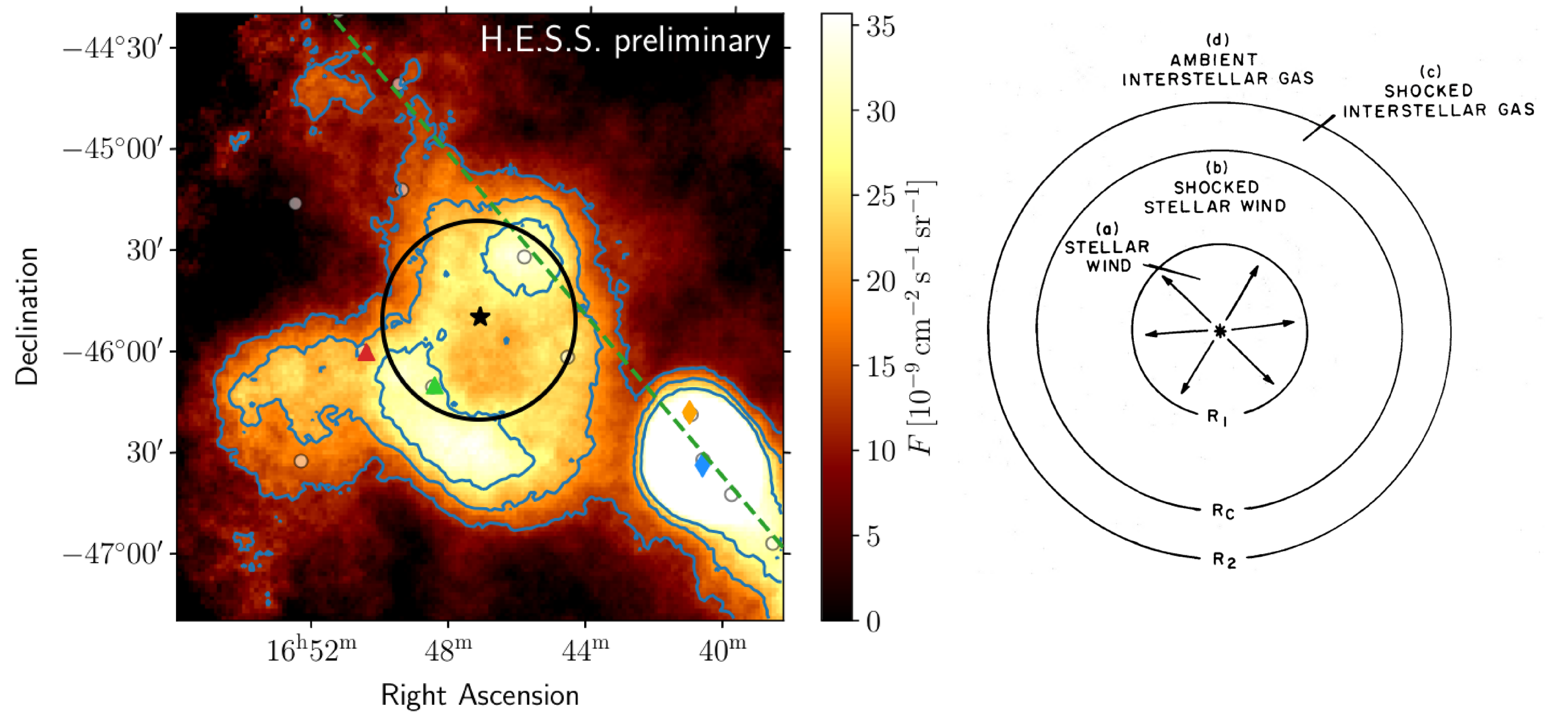

Figure 1. *Left*: H.E.S.S. observations of Westerlund 1 at $E > 0.37\,\mathrm{TeV}$ (Mohrmann et al. 2021, their Fig. 1b.). The star marks the cluster position and the dashed line the galactic plane. The black circle marks the predicted position of the termination shock, assuming spherical symmetry. *Right*: structure of a bubble blown by a continuous wind from a central object according to Weaver et al. (1977, their Fig. 1). R_1 is the wind termination shock. Note that in reality the bubble is often deformed due to inhomogeneities in the external density.

A recent analysis of H.E.S.S. data revealed **ring-like, energy and sub-region independent TeV γ-ray emission** around **Westerlund 1** (Fig. 1, left, Mohrmann et al. 2021), following up on the detection of the source by Abramowski et al. (2012). We propose particle acceleration at the **cluster wind termination shock** as source of the emission and investigate this model, assuming

1. a fraction η of the mechanical wind power, $L_\mathrm{w} = \frac{1}{2}\dot{M}v_\mathrm{wind}^2$, is converted into γ-rays at the termination shock (R_1). Model γ-ray emission processes with the open `GAMERA` library,
2. the following parameters for the cluster wind: $L_\mathrm{w} = 10^{39}\,\mathrm{erg\,s^{-1}}$, $n_\mathrm{ext} = 10\,\mathrm{cm^{-3}}$, $n_\mathrm{bubble} = 1\% \cdot n_\mathrm{ext}$, $v_\mathrm{w} = 2500\,\mathrm{km\,s^{-1}}$, $t_\mathrm{sys} = 4\,\mathrm{Myr}$, $d = 3.9\,\mathrm{kpc}$,
3. radiation fields for the CMB, direct and scattered starlight (optical and IR, Popescu et al. 2017), and the cluster (thermal spectrum for $T = 40000\,\mathrm{K}$, assume $L_\mathrm{bol} = 100 \cdot L_\mathrm{w}$).

The **position of the termination shock** is $R_1 = 30\,\mathrm{pc}$, according to Weaver et al. (1977).
Note: $R_1 \propto \dot{M}^{3/10} n_\mathrm{bubble}^{-3/10} v_\mathrm{w}^{1/10} t_\mathrm{sys}^{2/5}$.

`GAMERA` models – Results

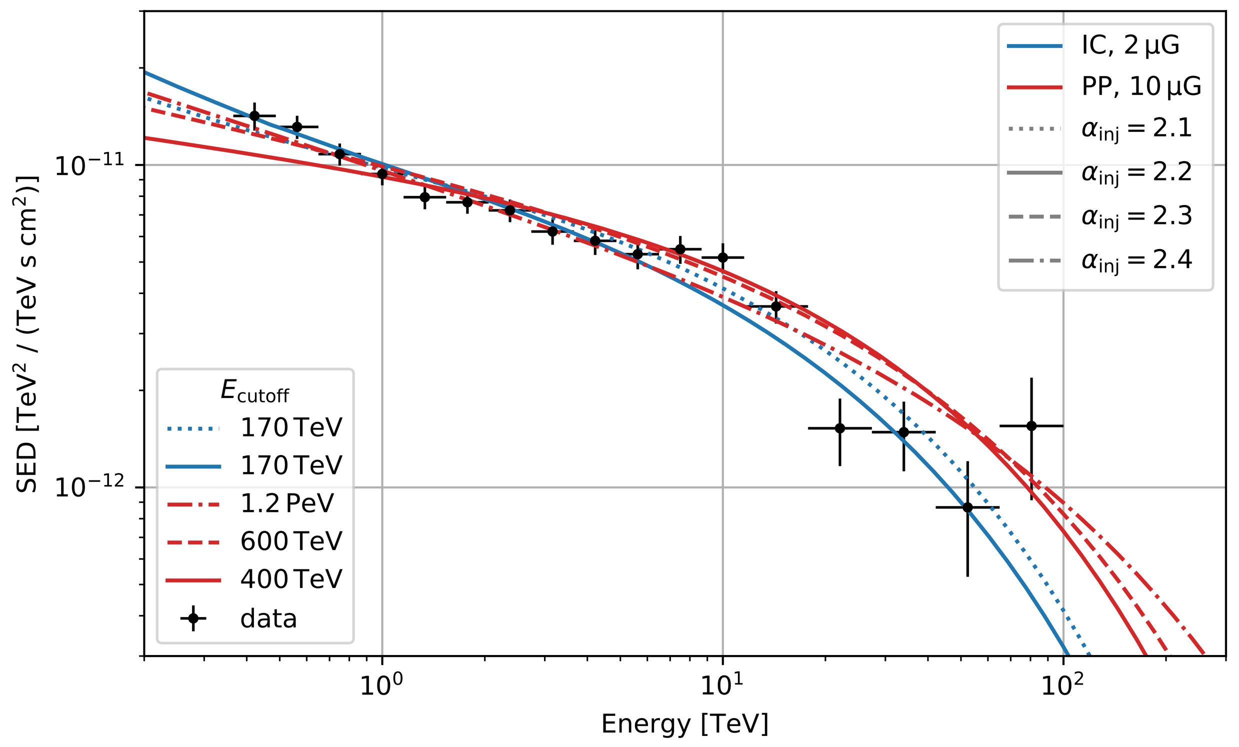

Figure 2. The H.E.S.S. spectrum of Westerlund 1 modelled with `GAMERA` (see text). The model parameters are indicated in the figure. Note that leptonic and hadronic models assume different B-fields. Data taken from Mohrmann et al. (2021).

The `GAMERA` library[2] is used to evolve a particle spectrum in time, i.e., to calculate cooling, and determine the γ-ray spectra. The injected particles are assumed to follow a **powerlaw** with index α_inj and **exp. cutoff** at E_cutoff. Figure 2 shows that the γ-ray spectrum can be modelled as Inverse Compton emission (**IC**) or emission from the decay of neutral pions, produced in proton-proton interactions (**PP**). The SEDs for two of these models, one leptonic and one hadronic, are shown in Fig. 3.

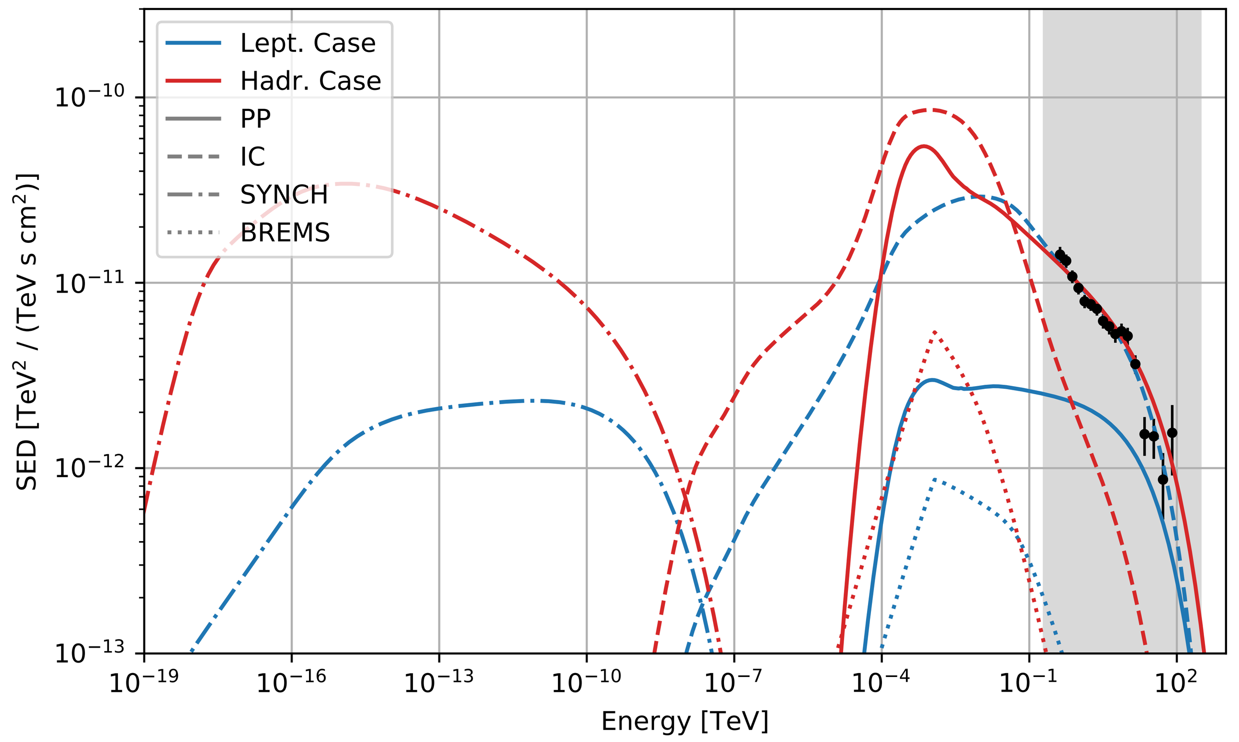

Figure 3. SEDs for the blue dotted and the red dashed models from Fig. 2. The grey band indicates the range displayed in Fig. 2.

Main takeaways

1. The PP case is only conceivable for **extreme efficiencies** of $\eta > 50\%$ (red dashed and dash-dotted models in Fig. 2).
2. IC case requires $B \lesssim 5\,\mu\mathrm{G}$, as **synch. cooling** sets E_cutoff (see right column).
3. PP models require higher B for **confinement** (see right column), causing higher radio synch. and a steep increase of the GeV–keV flux.

[2]`http://libgamera.github.io/GAMERA/docs/main_page.html`

Requirements for magnetic field and particle energies

- Energies of injected particles: $80\,\mathrm{TeV}$ γs observed
  $\Rightarrow$ energies $E_\mathrm{max} \gtrsim 100\,\mathrm{TeV}$ (leptons), $\gtrsim 6 \cdot 80\,\mathrm{TeV} = 480\,\mathrm{TeV}$ (hadrons).
- Hillas limit: the min. required B-field is
$$B \geq \frac{E_\mathrm{max} c}{e v_\mathrm{w} R_1} = 0.3\text{–}1.5\,\mu\mathrm{G}\,.$$
- Alfvénic Mach number at R_1: $M_\mathrm{A}(B_\mathrm{min}) = 100\text{–}20$, $M_\mathrm{A}(B = 30\,\mu\mathrm{G}) = 1$.
  Shock existence requires
$$M_\mathrm{A} = \frac{v_\mathrm{w}}{v_\mathrm{A}} = \frac{\sqrt{\dot{M}v_\mathrm{w}}}{BR_1} > 1\,.$$

Cooling, diffusion, and morphology

Hadrons – Cooling by pp-interactions is negligible
$$t_\mathrm{cool} = (0.5 n_\mathrm{bubble} \sigma_\mathrm{pp} c)^{-1} = 5.7 \cdot 10^7 / n_\mathrm{bubble}\,\mathrm{yr} \gg t_\mathrm{sys}\,.$$
The diffusion length is therefore determined by the age of the system, t_sys,
$$l_\mathrm{p} = \sqrt{6Dt_\mathrm{sys}} = 115\,\mathrm{pc} \cdot \left(\frac{E}{10\,\mathrm{TeV}}\right)^{0.5} \cdot \left(\frac{B}{2\,\mu\mathrm{G}}\right)^{-0.5} \overset{3.9\,\mathrm{kpc}}{=} 1.7^\circ > R_\mathrm{obs}^\mathrm{peak} = 0.45^\circ\,.$$
The diffusion length in a $2\,\mu\mathrm{G}$ field is larger than the maximum of the observed ring-like H.E.S.S. emission, $R_\mathrm{obs}^\mathrm{peak}$. If the emission is primarily hadronic, B must therefore be much larger or be structured to prevent diffusion in the radial direction.

Leptons – The cooling times for leptons are much shorter than the age of the system (Fig. 4, left). The maximum energy is reached if the acceleration time becomes equal to the total cooling time (Fig. 4, right). This energy is taken to be E_cutoff for the leptonic model. For $B > 5\,\mu\mathrm{G}$, E_cutoff drops below 100 TeV.

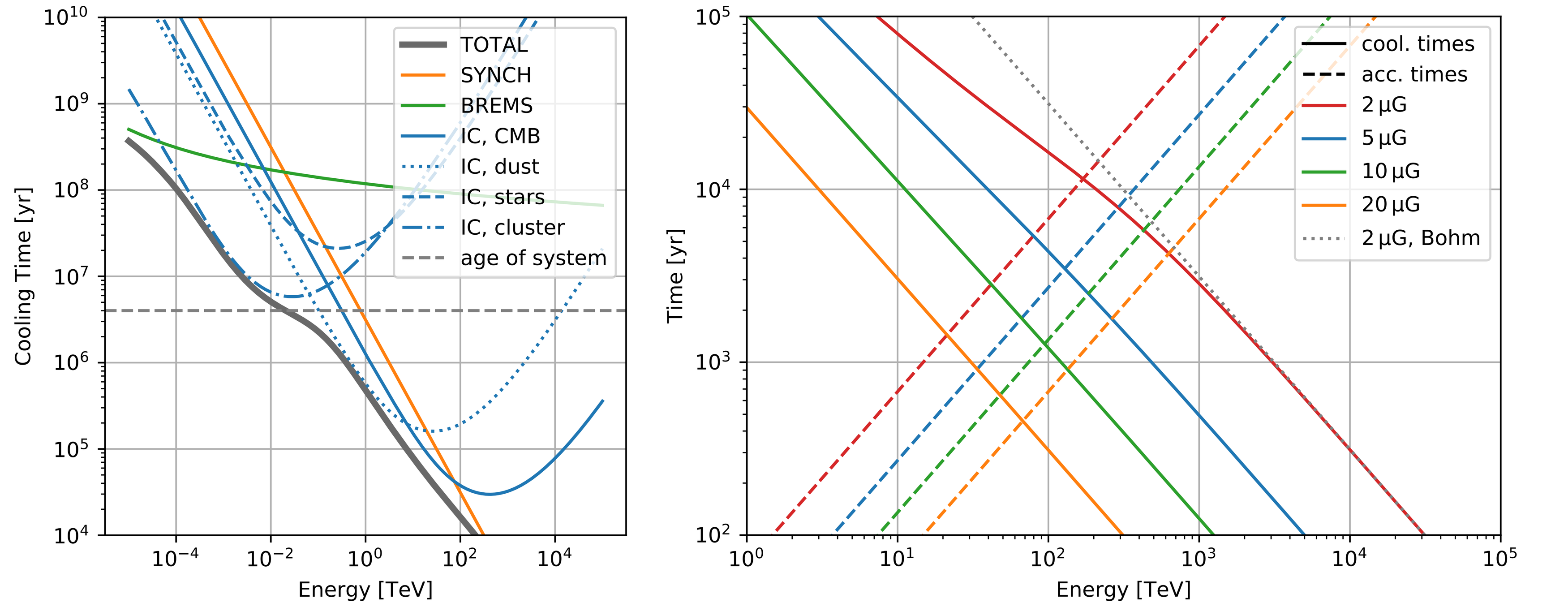

Figure 4. *Left*: cooling times for leptonic interactions at $2\,\mu\mathrm{G}$. *Right*: total cooling and acceleration times for varying B.

For $B = 2\,\mu\mathrm{G}$ and $E = 10\,\mathrm{TeV}$, the diffusion length is $l_\mathrm{e} = \sqrt{6Dt_\mathrm{cool}} = 16\,\mathrm{pc} \overset{3.9\,\mathrm{kpc}}{=} 0.24^\circ$, which is consistent with $R_\mathrm{obs}^\mathrm{peak}$ if diffusion starts at the termination shock. As the IC is in the Klein-Nishina regime at $\gtrsim 100\,\mathrm{TeV}$ (see Fig. 4, left), the morphology is expected to be energy independent for $D \propto E^{1/2}\text{–}E^{1/3}$ (Kraichnan/Kolmogorov).

Conclusions: Westerlund 1 – a leptonic accelorator?

We favour the leptonic scenario: the required efficiencies are far more plausible than in the hadronic case, although models with steep injection spectra and low cutoffs remain conceivable. In addition, confining protons in the emission region requires the B-field to be either unusually large or structured. The main constraint for the leptonic case is the low cutoff set by the synchrotron cooling. A joining of leptonic and hadronic components is also possible.

References

Abramowski, A., Acero, F., Aharonian, F., et al. 2012, A&A, 548, A38

Mohrmann, L., Ohm, S., Rauth, R., et al. 2021, in 37th International Cosmic Ray Conference. 12-23 July 2021. Berlin, 789

Popescu, C. C., Yang, R., Tuffs, R. J., et al. 2017, MNRAS, 470, 2539

Weaver, R., McCray, R., Castor, J., Shapiro, P., & Moore, R. 1977, ApJ, 218, 377