Investigating the (lack of) gamma-ray emission from superbubbles

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Context and objectives

Superbubbles (SBs) are a possible key player in the acceleration of galactic cosmic rays (CRs). Large amounts of kinetic energy are released over short times by the many massive stars at their center, hence setting appropriate conditions for efficient shock and/or stochastic acceleration and reacceleration, possibly up to ~PeV energies and beyond. Yet, SBs did not show up as a conspicuous source class in the GeV-TeV gamma-ray sky, with only two likely associations: the Cygnus cocoon in the Galaxy, and 30 Dor C in the Large Magellanic Cloud (LMC).

Using a very simple model for CR diffusion in a SB, we investigated whether this paucity can be due to SBs actually being rare as a result of a low gamma-ray emission duty cycle. We examine under which conditions the GeV/TeV properties of 30 Dor C can be reproduced, and what these conditions imply in terms of duty cycle.

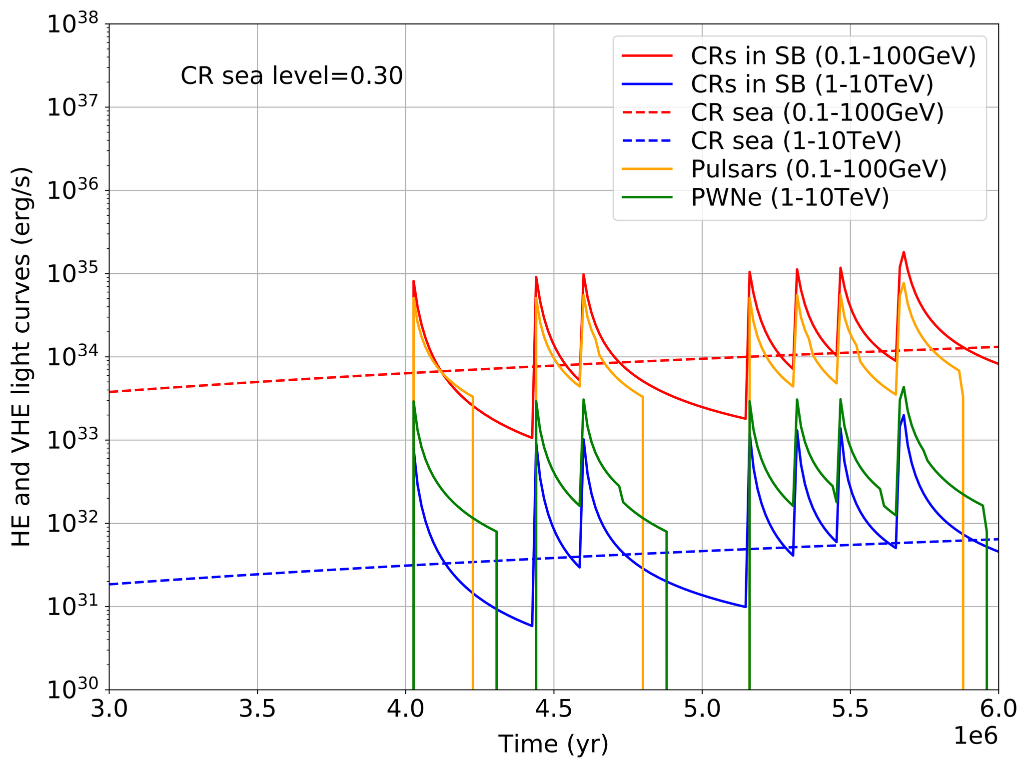


Fig 1: One 30 Dor C-like realization of the model
Spikes correspond to supernova explosions (7 over the time frame plotted here)
Red/blue is GeV/TeV hadronic emission from CRs interacting with the SB shell
Yellow/green is a simple pulsar/PWN model inspired from the LAT 2[nd] pulsar catalog and HESS PWNe catalog
GeV/TeV hadronic emission from CR background interacting wih the SB shell is shown as dashed lines

Model for SB evolution and CR diffusion

Superbubble

- Coeval massive star population 8-120 $M_\odot$
- Average mechanical power 10^{36} erg/s/massive star
- Dynamical SB model, uniform ambient density (Weaver-1977)

Cosmic rays (nuclei only !)

- Uniform supernova (SN) rate over 3-37 Myr (see Ferrand-2010)
- Impulsive release of 10^{50} erg/SN in $\geq$1GeV CRs
- Power-law CR spectrum, index α=2.0…2.5, cutoff 100TeV…1PeV
- Spatial diffusion with $D(p)=D_0(p/10GeV/c)^\beta$, $D_0=10^{25}\ldots10^{28}$ cm²/s, β=1/3
- No CR forward escape and/or reacceleration, no energy losses
- Two limiting spatial injection scenarios:
  - S1 – at SB center (SNR dissolves quickly in SB interior)
  - S2 – in SB shell (SNR expands up to colliding with SB shell)

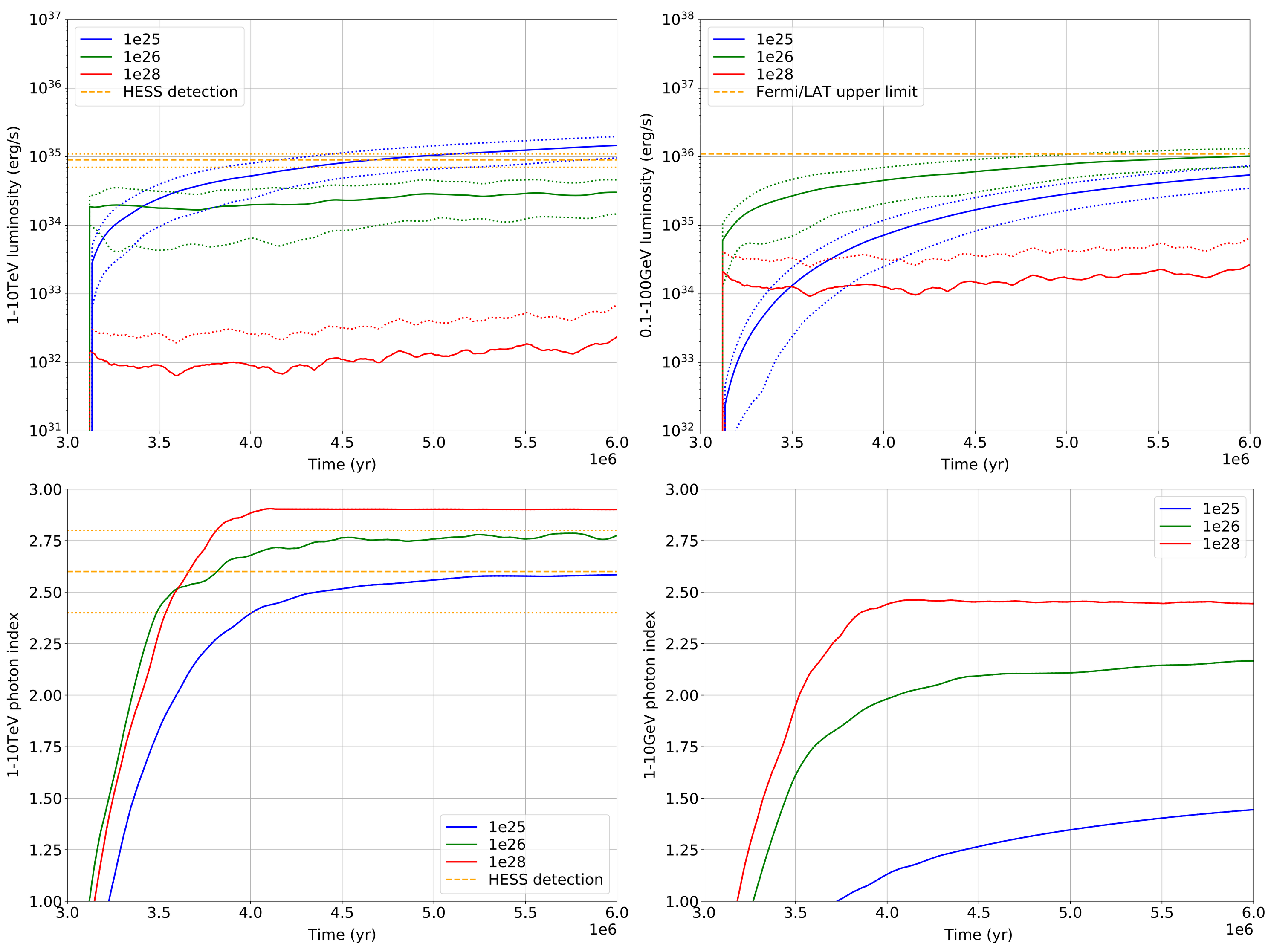
Gamma rays (hadronic only !)

- From CRs interacting with SB shell (where 99% of the mass is)
- Pion decay computed using Naima

30 Doradus C simulations

- 33 O/WR stars (Testor-1993, Walborn-1999), translates into SN rate 3-4/Myr
- Assumed age ~5 Myr
- Ambient density 30 cm^{-3} so as to get a shell mass 3-5x10^5 $M_\odot$ (Sano-2017)
- Shell radius 45pc, thickness 10pc (Sano-2017)

Scenario 1 - CRs injected at SB center



Scenario 2 - CRs injected in SB shell

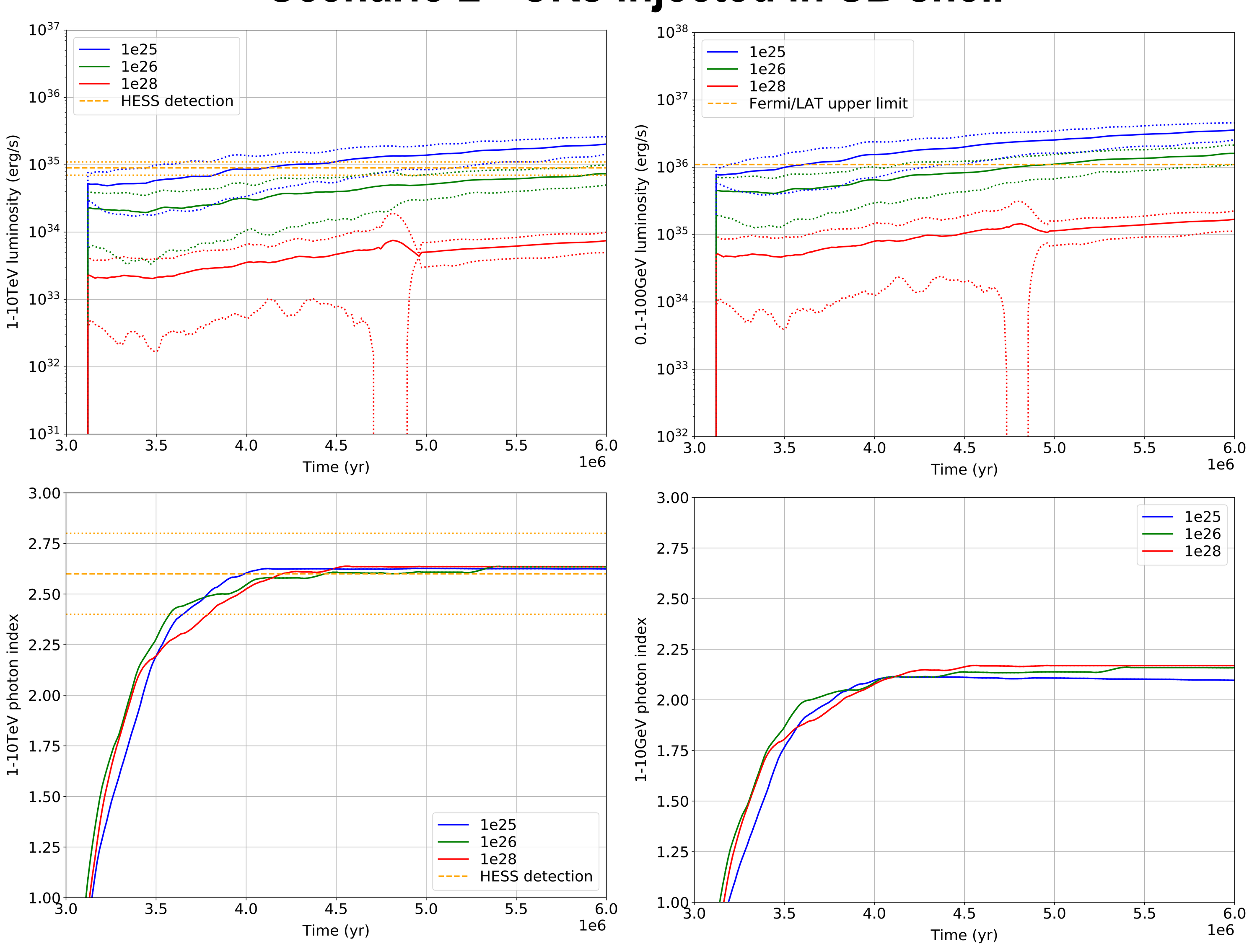


Fig 2 : Results of statistical analysis of 100 SB realizations (random variable is the SNe explosion dates)
Two injection scenarios are compared: injection at the SB center (4 upper panels) or in the SB shell (4 lower panels)
For each scenario, several diffusion normalizations were tested: 10^{28} cm²/s (ISM-like), 10^{26} and 10^{25} cm²/s
Plots show the means of the luminosity and photon index in the GeV and TeV bands (+standard deviation for the luminosity)
Results are compared to HESS measurements and Fermi-LAT upper limit
Curves were smoothed for readability. Luminosity mean/variance estimates for the 10^{28} cm²/s cases suffer from insufficient statistics.

Gamma-ray emission duty cycle

- Fraction of time the SB shell shines above level resulting from CR background
- Depends on CR background level (aka CR sea, ~3x lower in LMC than locally)
- Depends on CR confinement inside SB (diffusion coefficient)
- Depends on average time between SNe (stellar population)

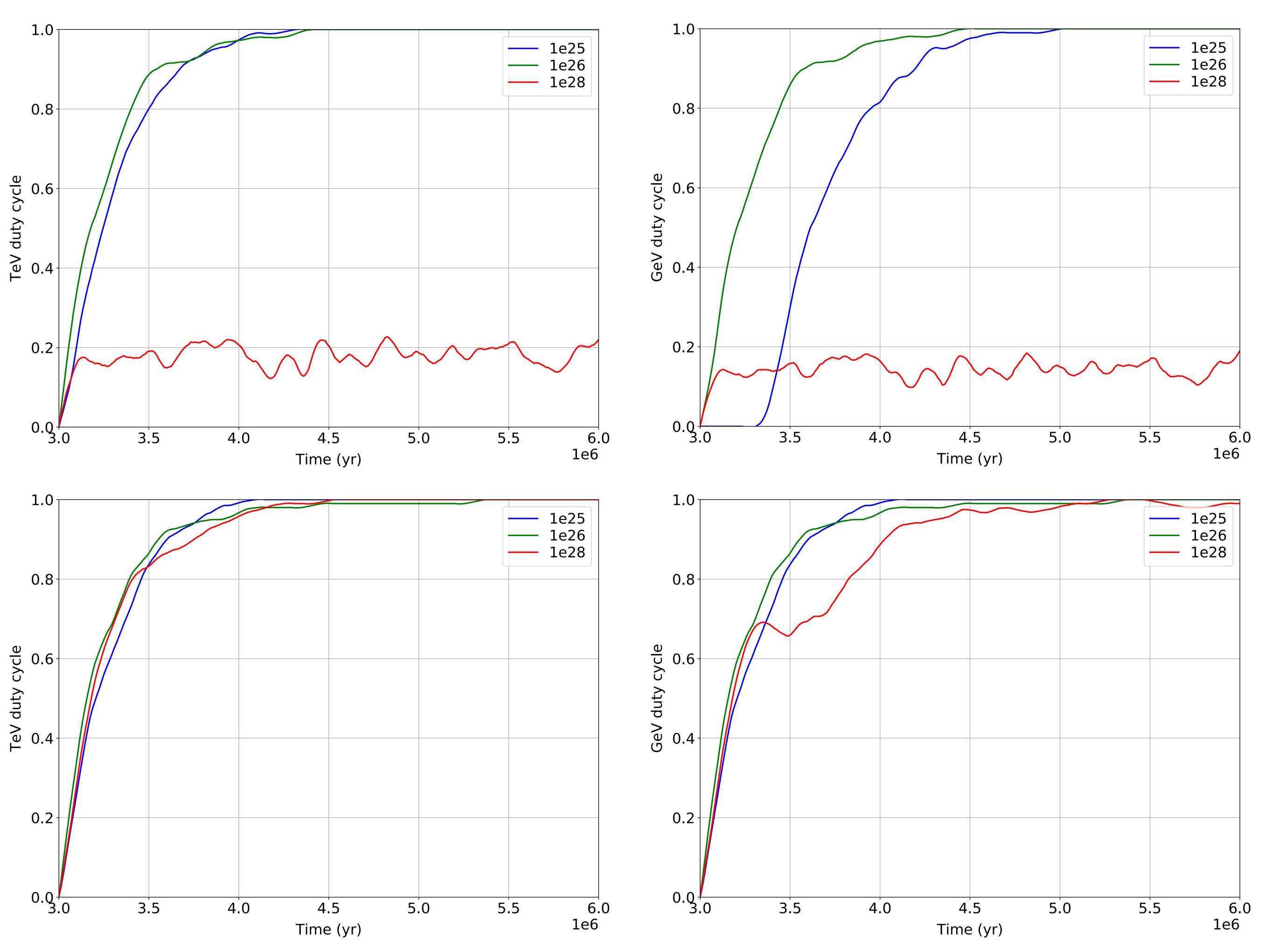


Fig 3 : gamma-ray duty cycle
Top row corresponds to CR injection at the SB center, bottom row to CR injection in the SB shell

Preliminary conclusions

- Scenario 1: strong confinement ($D_0<10^{26}$ cm²/s) reproduces the TeV luminosity of 30 Dor C while suppressing/delaying GeV luminosity. Implies a >90% duty cycle with high GeV/TeV luminosities, a priori not consistent with observed paucity of SBs.
- Scenario 2: moderate or no confinement ($D_0>10^{26}$ cm²/s) needed to avoid GeV CRs accumulating in SB shell and radiating above LAT upper limit. High >90% duty cycle dominated by low GeV/TeV luminosities. TeV emission from 30 Dor C at the level observed by HESS corresponds to a duty cycle < a few %.