Is Supernova Remnant Cassiopeia A a PeVatron?

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INTRODUCTION

Supernova remnants (SNRs) are thought to be the dominant sources of Galactic cosmic rays (CRs, mainly protons) below the "knee" energy of 3 PeV. However the lack of evidence for PeV particles in SNRs pose a challenge to this paradigm. Moreover, a cutoff at ~3.5 TeV in the gamma-ray spectrum of Cas A was detected by MAGIC [1], suggesting that if the TeV gamma-rays have a hadronic origin, Cas A can only accelerate particles to tens of TeV.

In this work, we propose a two-zone emission model for regions associated with the forward (zone 1) and inward/reverse shocks (zone 2). Given the low density associated with the forward shocks, it dominates high-frequency radio emission, soft X-ray rim via the synchrotron process and TeV γ-ray via the inverse Comptonization. The reverse shocks are associated with a high density zone. With a relatively softer particle distribution and a higher cut-off energy for electrons, it dominates low-frequency radio, hard X-ray via the synchrotron process and GeV γ-ray via the hadronic processes.

MODEL DESCRIPTION

- Two emission zones:
  Zone 1 (z1): the outer thin rim (the forward shocks)
  Zone 2 (z2): rest of the emission regions, in particular regions containing inward-moving shocks, see Fig 1.
- Particles' distribution: power-law with a cutoff

$$N(p) = A \cdot p^{-\alpha} \exp[-(p/p_c)^{\beta}]$$

p : the momentum; p_c: the cut-off momentum
α : the index; β : cut-off shape parameter

- Considering the radiative cooling effect

$$E_{bre} = 4\,(B_{\rm SNR}/100\,\mu{\rm G})^{-2}(t/340\,{\rm yr})^{-1}\,{\rm TeV}$$

In z1, t is the SNR age; in z2, t is a free parameter

- Including four radiation processes:
  > synchrotron (Syn)
  > inverse Compton (IC)
  > bremsstrahlung (Bre)
  > proton-proton collision (p-p)

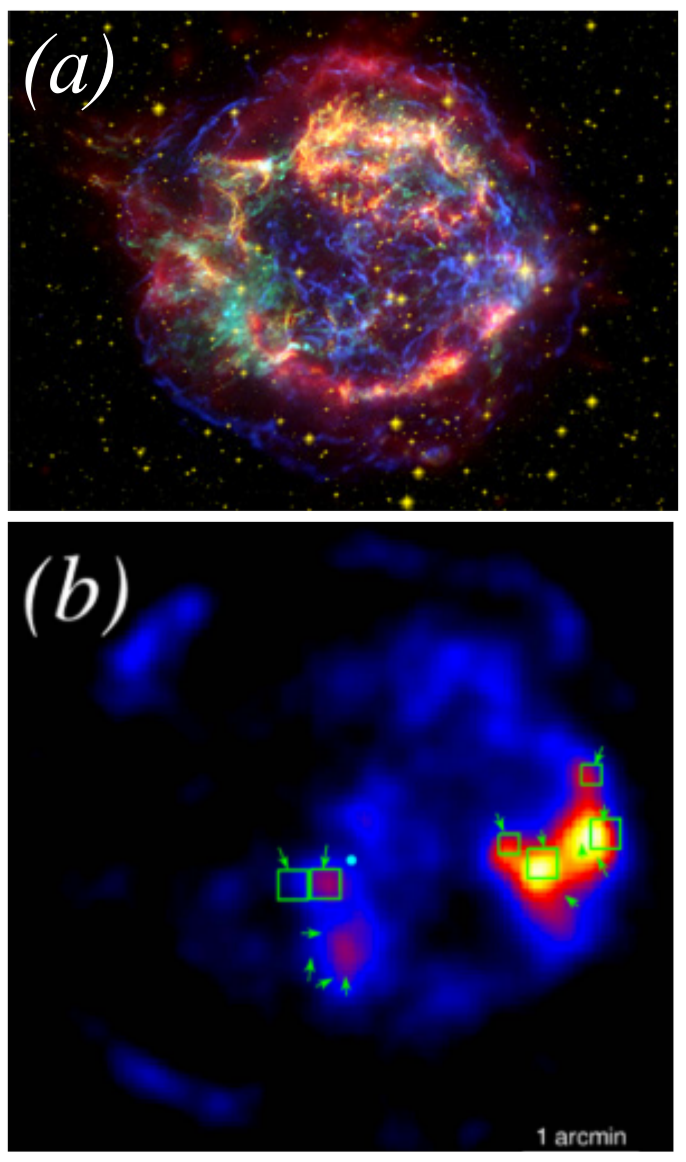

Fig 1. (a) Image of Cas A. from NASA; (b) NuSTAR 15-40 keV. Green arrows and boxes show the inward-shock positions [2].

RESULTS

Model A

Zone 2: dominates GeV via p-p process, low-energy cutoff ($p_{lc,p} = 15$ GeV/c and $p_{lc,e} = 1$ MeV/c)

zone	α	β_e	$p_{c,e}$ (TeV/c)	B_{SNR} (μG)	W_e (10^{47} erg)	W_p (10^{48} erg)	n_t (cm^{-3})
1	2.1	1 (2)	7.0 (10.0)	250	7.0	1.0	4
2	2.7	1	9.0	1000	0.4	180	10

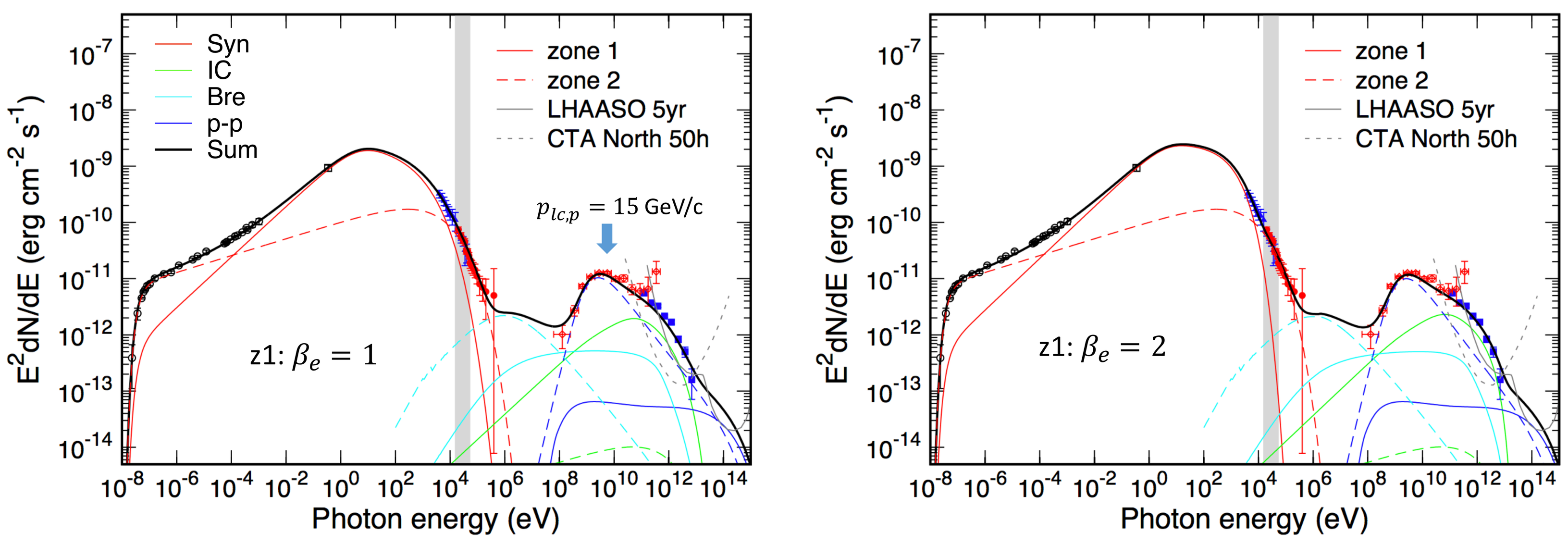

Figure 2. SED of SNR Cas A for Model A. The black solid line represents the total emission from zone 1 (solid) and 2 (dashed) with various components considered in this work: synchrotron (red), inverse Compton (green), bremsstrahlung (cyan) and p-p collision (blue). Also shown are the radio data (open circle) given in Vinyaikin (2014), infrared data from IRAC 3.6 μm (open square; De Looze et al. 2017), X-ray data from Suzaku (filled triangle; Maeda et al. 2009) and INTEGRAL-IBIS (filled circle; Wang & Li 2016), γ-ray data from Fermi-LAT and MAGIC (open diamond and filled square, respectively; Ahnen et al. 2017). The gray region represents the energy range 15–55 keV.

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DISCUSSION

Model B

Zone 2: dominates GeV via p-p process, same low-energy cutoff for electrons and protons

zone	α	β_e	$p_{c,e}$ (TeV/c)	B_{SNR} (μG)	W_e (10^{47} erg)	W_p (10^{48} erg)	n_t (cm^{-3})
1	2.1	1 (2)	7.0 (10.0)	260 (280)	7.0 (6.0)	1.0	4
2	2.7	1	22.0	160	10.0	180	10

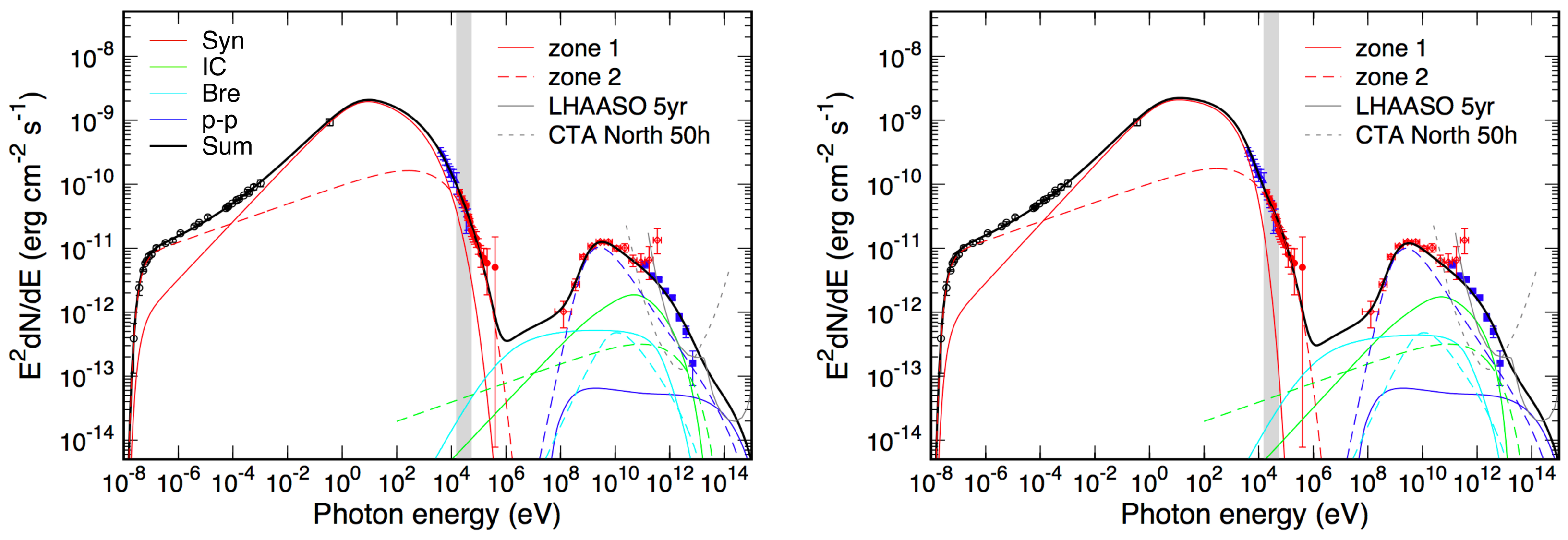

Figure 3. Same as in Figure 2 but for **Model B**.

Model C

Zone 2: dominates GeV via bremsstrahlung process, same low-energy cutoff for electrons and protons

zone	α	β_e	$p_{c,e}$ (TeV/c)	B_{SNR} (μG)	W_e (10^{47} erg)	W_p (10^{48} erg)	n_t (cm^{-3})
1	2.1	1 (2)	7.0 (10.0)	260 (280)	7.0 (6.0)	1.0	4
2	2.7	1	22.0	160	10.0	1.0	100

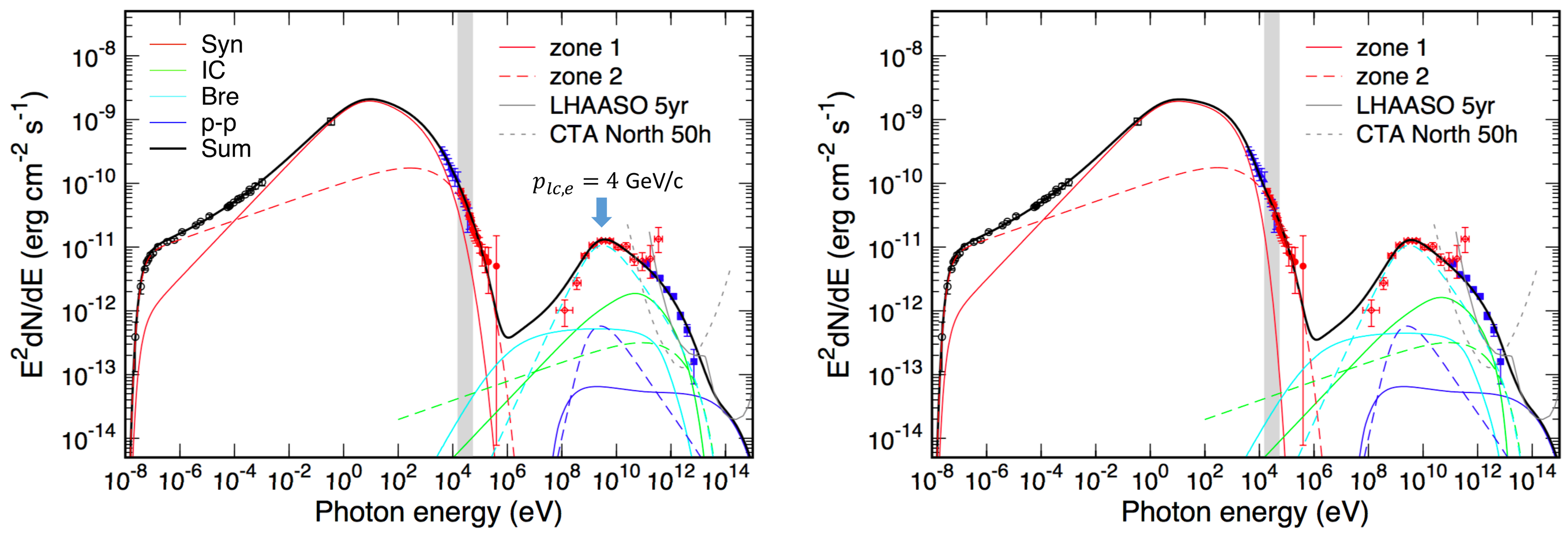

Figure 4. Same as in Figure 2 but for **Model C**.

Model D

Zone 2: similar to Model A but include cooling and $\beta_e = 2$

zone	α	β_e	$p_{c,e}$ (TeV/c)	B_{SNR} (μG)	W_e (10^{47} erg)	W_p (10^{48} erg)	n_t (cm^{-3})
1	2.1	1 (2)	8.0 (10.0)	260 (280)	7.0	1.0	4
2	2.7	2	25.0	950	0.4	200	10

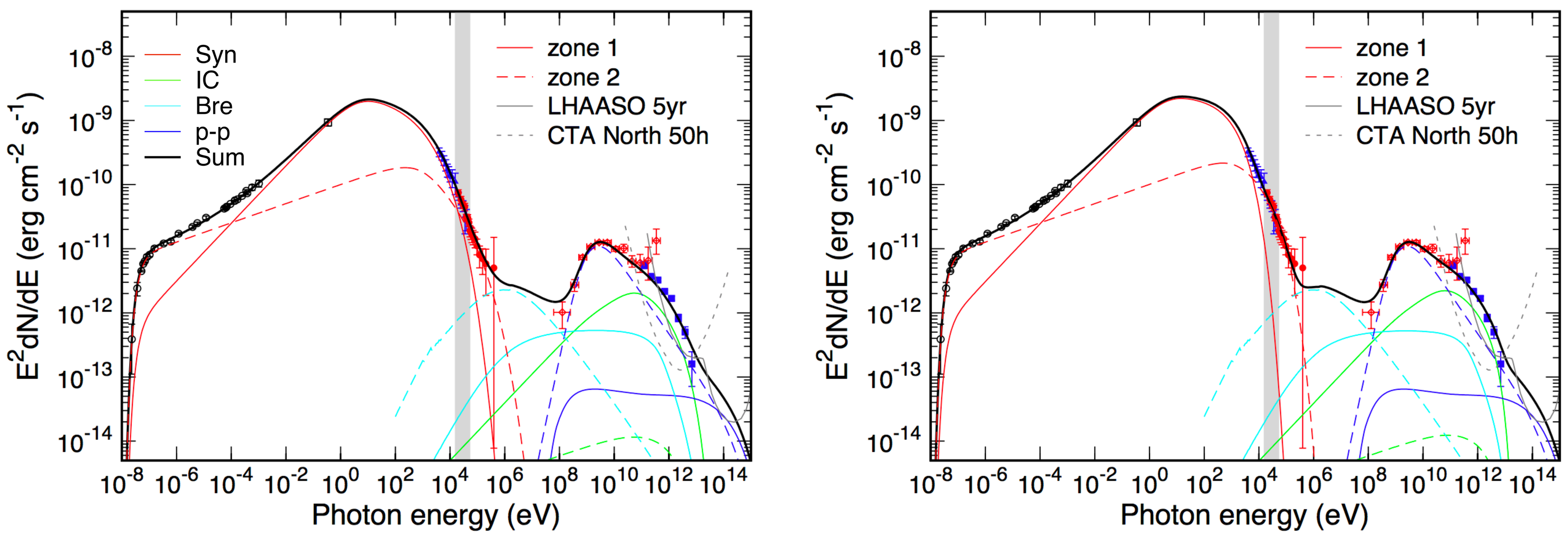

Figure 5. Same as in Figure 2 but for **Model D**. The age of the inward shocks is 5 (left) and 3 (right) years.

CONCLUSION

- Zone 1 (forward shock): high-frequency radio (Syn), infrared, soft X-rays (Syn), and TeV gamma-rays (IC)
- Zone 2 (reverse/inward shock): low-frequency radio (Syn), hard X-rays (Syn), and GeV gamma-rays (p-p)

There is no evidence for high-energy cutoffs in the proton distributions implying that Cas A can still be a PeVatron! (also see ***Zhang_2019_ApJ_874_98***)