The impact of the circumstellar magnetic field on the nonthermal emission from SNRs

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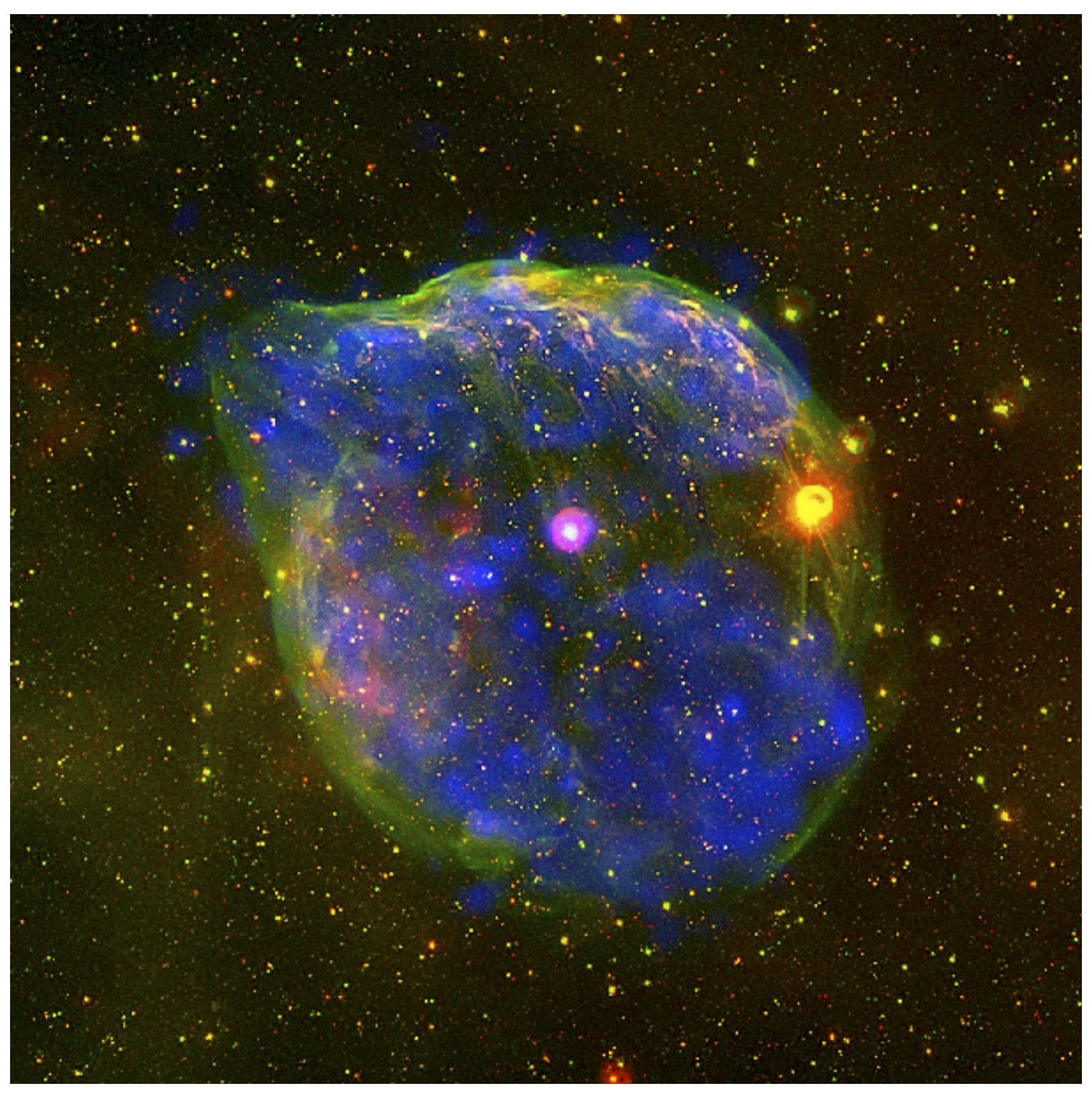
Environments of core-collapse SNRs

- Progenitors are mainly red supergiants or Wolf-Rayet stars
- Feature large blown-up stellar wind bubbles
- Properties of the circumstellar medium differ from those of the the interstellar medium, in particular magnetic field is dependent on the distance from the star.
- This might have an impact on the resulting particle and subsequently nonthermal spectrum, which are usually calculated assuming a constant magnetic field far upstream of the shock



Stellar bubble blown around the Wolf-Rayet star HD 50896. (Copyright: ESA, J. Toala M. Guerrero (IAA-CSIC), Y.-H. Chu & R. Gruendl (UIUC), S. Arthur (CRyA–UNAM), R. Smith (NOAO/CTIO), S. Snowden (NASA/GSFC) and G. Ramos-Larios (IAM)

Modelling

RATPaC - **R**adiation **A**cceleration **T**ransport **Pa**rallel **C**ode
– a numerical toolset to study particle acceleration in SNRs

- **Hydrodynamics:**
  Gasdynamical equations solved in 1D using the Pluto code on-the-fly
- **Transport equation for cosmic rays:**
  Solved in 1D, in the test-particle regime, assuming Bohm diffusion
- **Magnetic field:**
  passively transferred downstream following the induction equation for ideal MHD

Progenitor stars

Typical properties of progenitor stars:
*in brackets the value used in simulations

Red Supergiants

- $\dot{M}_{\rm w} = 10^{-7} - 10^{-5} M_\odot$ (10^{-6}) - mass-loss rate
- $V_{\rm w} = 10 - 50$ km/s (20) - wind velocity
- $B_* = 1 - 10$ G - magnetic field
- $R_* = 100 - 1000 R_\odot$ - stellar radius

Wolf-Rayet stars

- $\dot{M}_{\rm w} = 10^{-6} - 10^{-4} M_\odot$ (10^{-5})
- $V_{\rm w} = 1000 - 4000$ km/s (2000)
- $B_* = 100 - 1000$ G
- $R_* = 1 - 10 R_\odot$

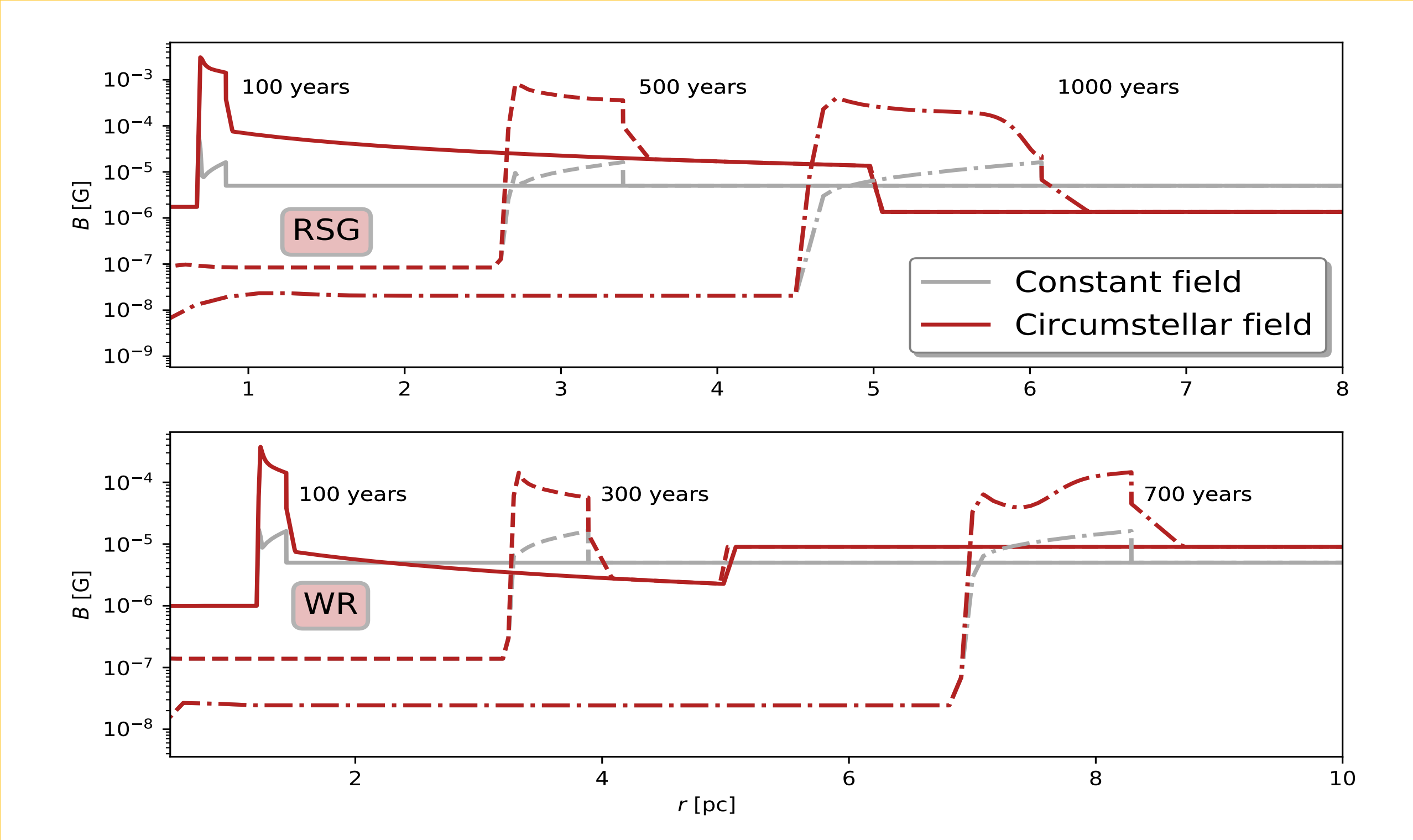
Circumstellar magnetic field

– prescribed as $B = B_0 (r/R_*)^{-1}$ in the free wind where R_* is the radius of the progenitor star and B_0 is the fraction of the surface magnetic field accounting for the fact that very close to the star magnetic field is radial and falls off as $1/r^2$.
– beyond the free-wind wind zone (assumed to end at 5 pc) magnetic field either abruptly decreases (RSG) or abruptly increases (WR) and then stays constant in the shocked wind part of the wind bubble
– three models are constructed for both RSG and WR progenitor type:

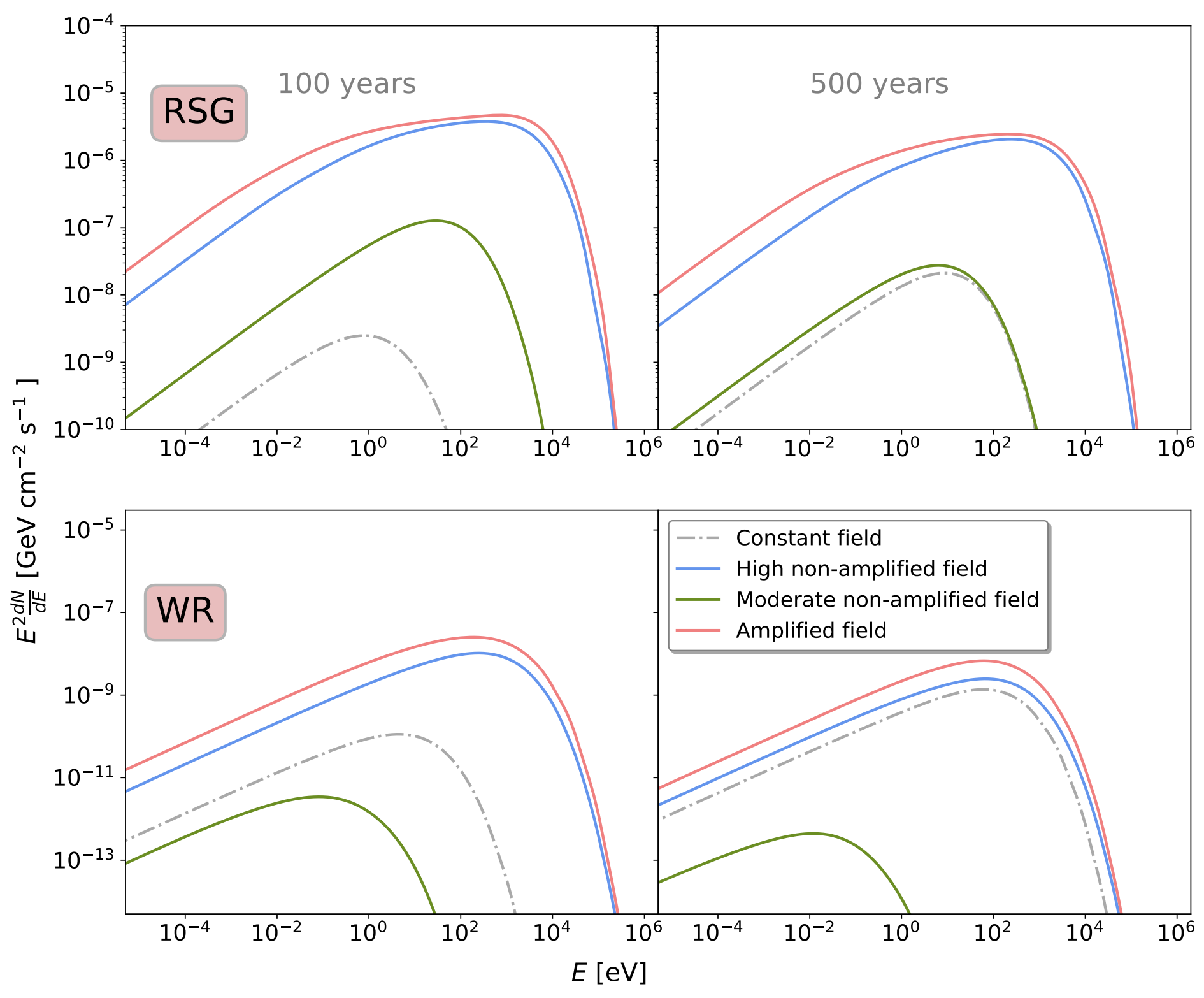
- HNM - high non-amplified magnetic field (high end of the parameter space)
- MNM - moderate non-amplified magnetic field
- AMP - moderate magnetic field additionally amplified in the upstream of the shock by a factor of 5

	Red Supergiant			Wolf-Rayet		
Parameter	HNA	MNA	AMP	HNA	MNA	AMP
B_0 [G]	7	1	3	100	10	50
R_* [$R_\odot$]	1000	500	1000	10	5	10

Figure: Magnetic field radial profiles for AMP models with the reference model assuming the constant field of 5 μG shown in grey



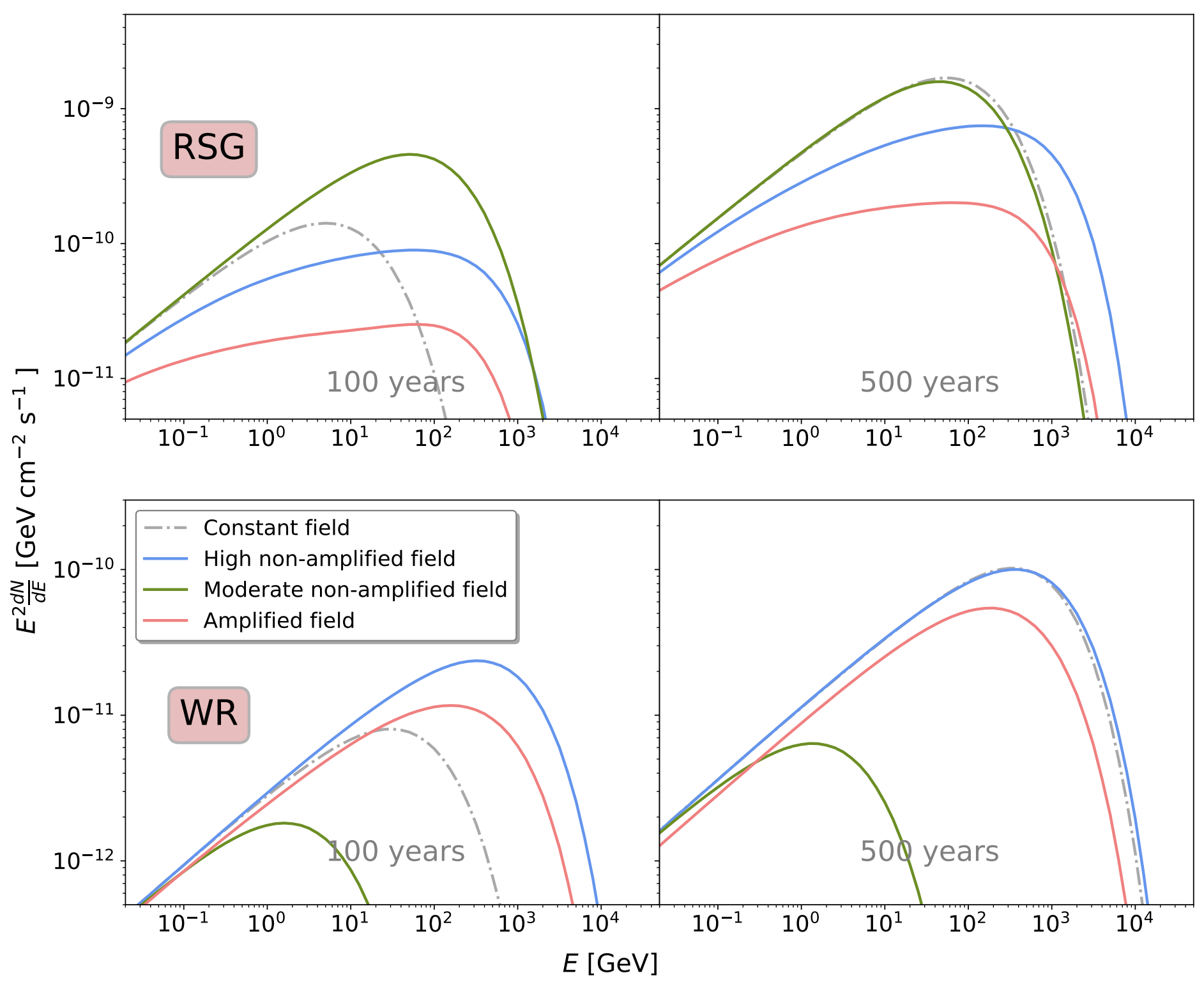
Synchrotron emission



Volume averaged synchrotron spectra at 100 and 500 years for an SNR evolving in a free wind of the progenitor star obtained for different models of the magnetic field. The reference model for the constant magnetic field of 5 μG is shown in grey

- Strong magnetic field encountered at early stages of the SNR evolution implies substantial synchrotron cooling which may considerably modify the electron spectrum and thus leave a characteristic imprint in the observed synchrotron spectrum
- The magnetic field of the WR progenitor is not strong enough for a substantial effect
- The decrease of the magnetic field with distance implies fading of the synchrotron emission from young SNRs with time. Fading of observed radio and X-ray emission with time is observed e.g. in the Cas A SNR
- The latter should be studied in detail examining to what degree it can explain the observed fading

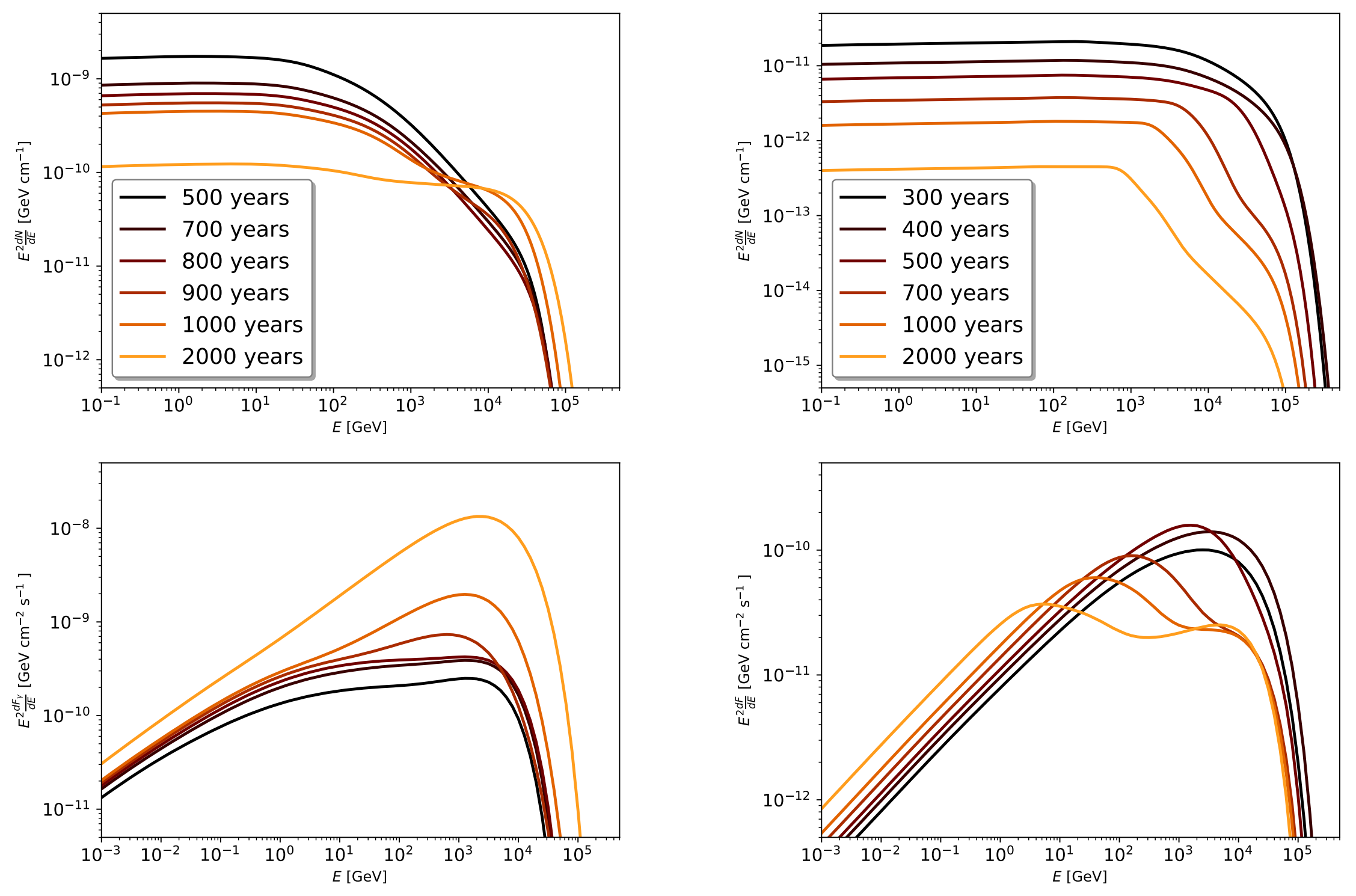
Inverse Compton emission



Volume averaged inverse Compton spectra at 100 and 500 years for an SNR evolving in a free wind of the progenitor star obtained for different models of the magnetic field. The reference model for the constant magnetic field of 5 μG is shown in grey

- The characteristic synchrotron cooling feature shows up in the gamma-ray spectum as a break at GeV energies (for an SNR with an RSG progenitor), similar to energies where a pion-decay signature is expected in hadronic scenarios
- Above the break energy the gamma-ray spectrum hardens resulting in a similar spectral shape to the gamma-ray emission produced in hadronic interactions
- This similarity can potentially make it more difficult to distinguish between hadronic and leptonic scenarios in individual remnants allowing to explain hadronic-like emission within the leptonic scenario
- For the WR progenitor the effect is not pronounced even for the magnetic field values at the high end of the parameter space

Transition spectra



Volume averaged particle (top) and inverse Compton (bottom) spectra for SNRs with the RSG (left) and WR (right) progenitor for the transitioning period between the free-wind and shocked wind zones

- **RSG:** The transition happens at around 800 years. As the forward shock of the SNR starts to expand into the medium with much lower magnetic field, particle acceleration switches from the synchrotron-cooling-limited regime to the age-limited regime which on one hand reduces slightly the maximum electron energy due to the low magnetic field, but on the other hand increases the amount of high-energy particles as they are not being cooled effectively.
- **WR:** The transition happens at around 500 years. Higher ambient magnetic field leads to the increase of the magnetic field farther downstream activating effective synchrotron cooling of the particles advected far from the shock. At the same time, freshly injected particles can still be accelerated to high energies at the shock. This again creates a two-component particle spectrum which translates into the concave gamma-ray spectrum.

Note, to isolate the effect of the magnetic field we assume that an SNR keeps expanding into the $1/r^2$ density profile characteristic for the free wind, ignoring the transition to the shocked wind with an accompanying jump/drop in density.

Outlook

The full modelling taking into account both density and magnetic field profiles is currently undergoing. We also plan to take advantage of MHD simulations of progenitor stellar wind bubbles to obtain realistic MHD profiles of SNR environments

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