The impact of the circumstellar magnetic field on the resulting gamma-ray 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 gamma-ray spectrum, which are usually calculated assuming a constant magnetic field far upstream of the shock

Hubble image of the Wolf-Rayet star blown bubble. (Image credit: NASA / ESA / Hubble Heritage Team / STScI / AURA)

Modelling

RATPaC - Radiation Acceleration Transport Parallel Code

- **Hydrodynamics:**
  - Gasdynamical equations solved using the Pluto code on the fly

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho\\ \vec{m}\\ E\end{pmatrix}+\nabla\begin{pmatrix}\rho\vec{v}\\ \vec{m}v+P\vec{I}\\ (E+p)\vec{v}\end{pmatrix}^{T}=\begin{pmatrix}0\\0\\0\end{pmatrix},$$

$$\frac{\rho\vec{v}^2}{2}+\frac{P}{\gamma-1}=E$$

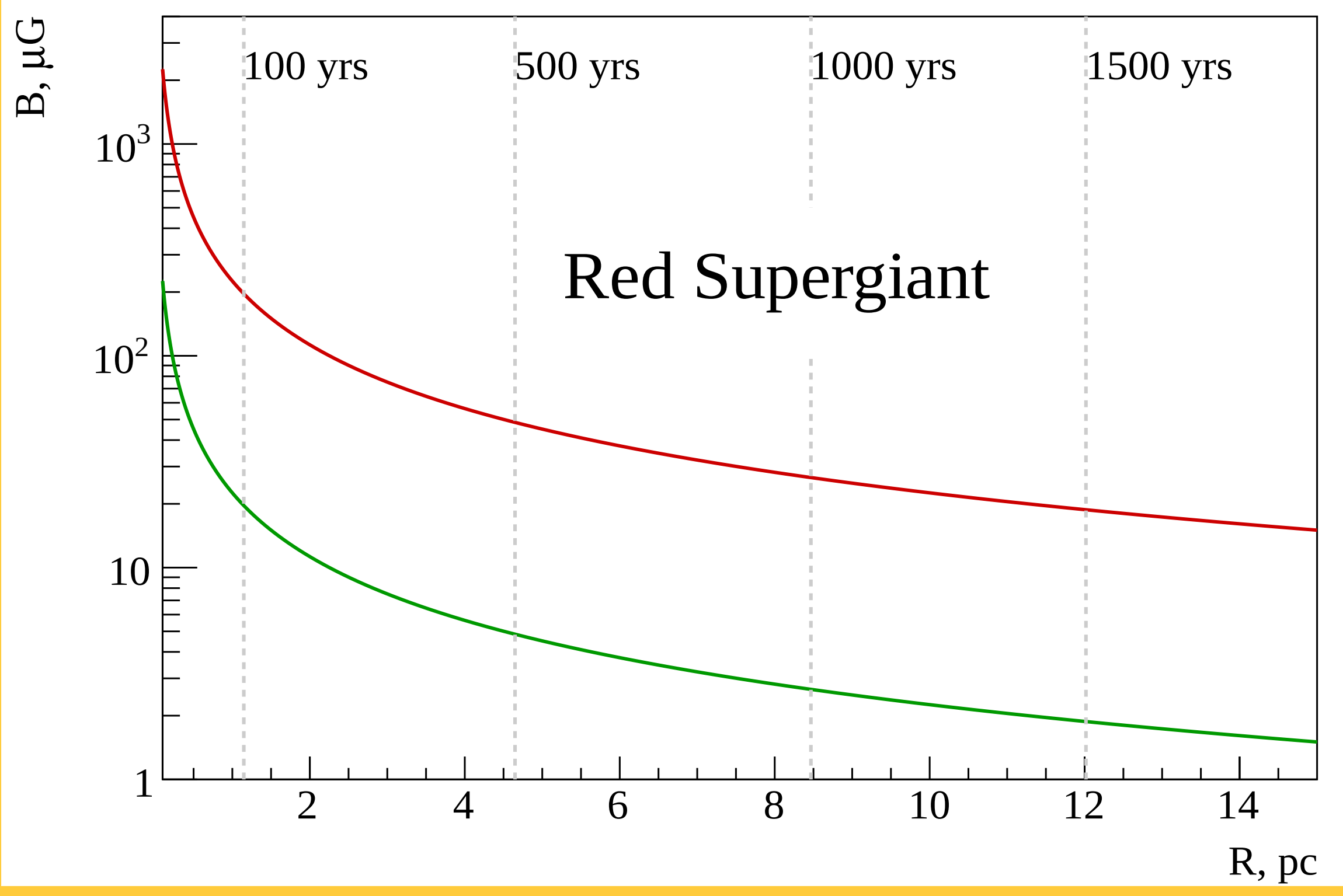
  - The SNR is expanding into a wind zone created by the progenitor star: $\rho \propto r^{-2}$
  - The boundary of the stellar wind bubble is set to be large enough to make sure the remnant is expanding inside the bubble
- **Transport equation for cosmic rays:**

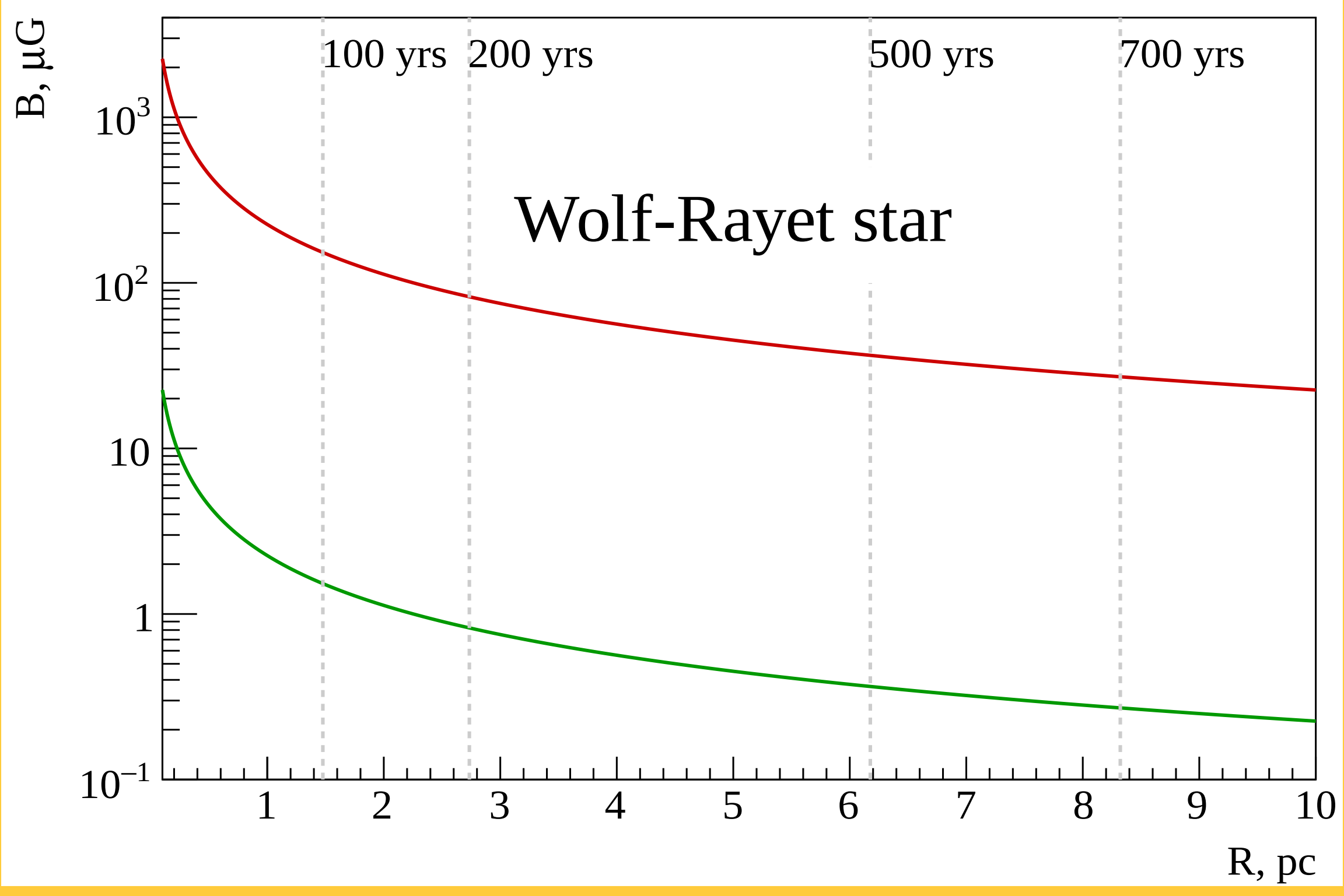
$$\frac{\partial N}{\partial t}=\nabla(D\nabla N-\vec{v}N)-\frac{\partial}{\partial p}\left((N\dot{p})-\frac{\nabla\vec{v}}{3}Np\right)+Q,$$

  - Q - source term; thermal leakage injection model
  - $\frac{\partial}{\partial p}(N\dot{p})$ - energy loss; synchrotron losses for electrons
  - D - spatial diffusion coefficient; Bohm-diffusion assumed
  - Solved in the test-particle regime - no feedback on evolution of the shock

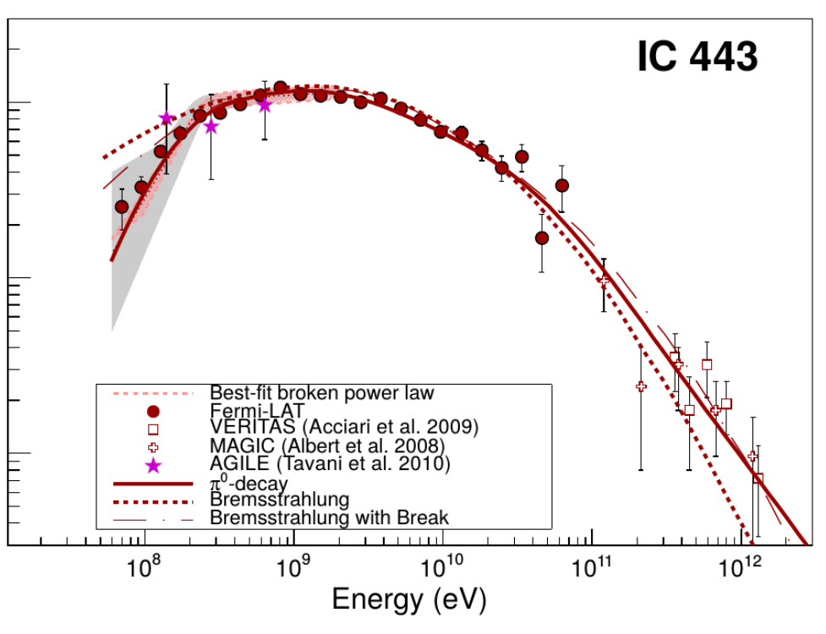
Magnetic field:

  - Upstream - circumstellar magnetic field of the stellar wind bubble assumed to follow $B = B_*(r/R_*)^{-1}$, where B_* is the magnetic field at the surface of the star and R_* is the stellar radius
  - At the shock - compressed by a factor of $\sqrt{11}$
  - Downstream - evolved following the induction equation for ideal MHD





Hadronic vs leptonic scenarios



Example of the detected pion-decay signature in the IC443 spectrum (Ackermann et al. 2013)

- Observed gamma-ray emission from SNRs can be explained either by hadronic interaction of accelerated protons with subsequent decay of neutral pions (**hadronic scenario**) or by inverse Compton emission generated by accelerated electrons scattering on ambient radiation fields (**leptonic scenario**)
- Discrimination between these two scenarios is important for understanding whether SNRs can be the sources of Galactic cosmic rays, 99 % of which are protons
- The gamma-ray spectrum in the hadronic scenario features a characteristic pion decay signature at lower energies which can be used to distinguish between two cases.

Progenitor stars

*in brackets the value used in simulations

Red Supergiants	Wolf-Rayet stars	
$\dot{M}_{\rm w} = 10^{-7} - 10^{-5} M_\odot$ (10^{-6})	$\dot{M}_{\rm w} = 10^{-6} - 10^{-4} M_\odot$ (10^{-5})	- mass-loss rate
$V_{\rm w} = 10 - 50$ km/s (20)	$V_{\rm w} = 1000 - 4000$ km/s (2000)	- wind velocity
$B_* = 1 - 10$ G	$B_* = 100 - 1000$ G	- magnetic field
$R_* = 100 - 1000 R_\odot$	$R_* = 1 - 10 R_\odot$	- stellar radius

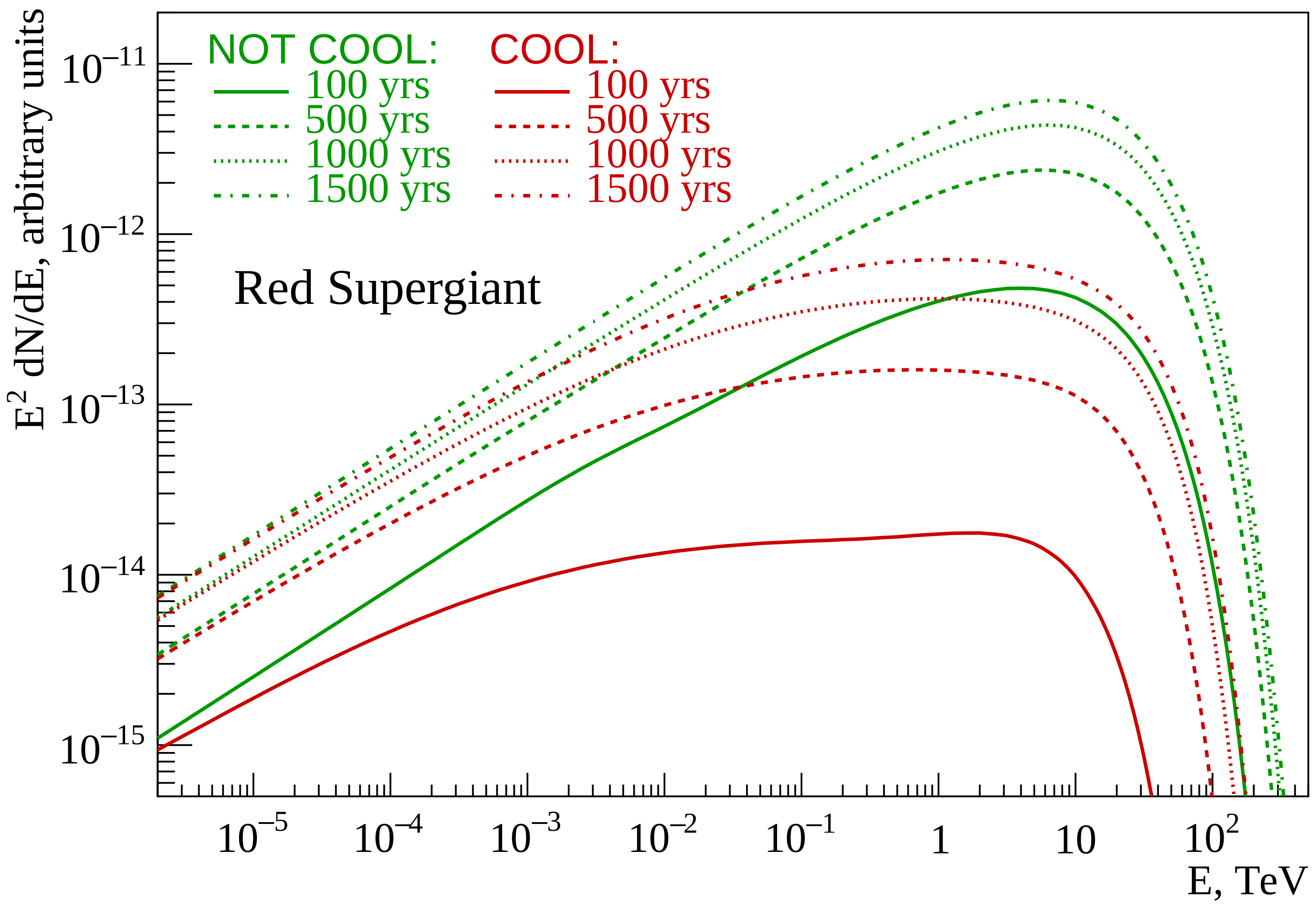
Combinations of B_* and R_* used in simulations

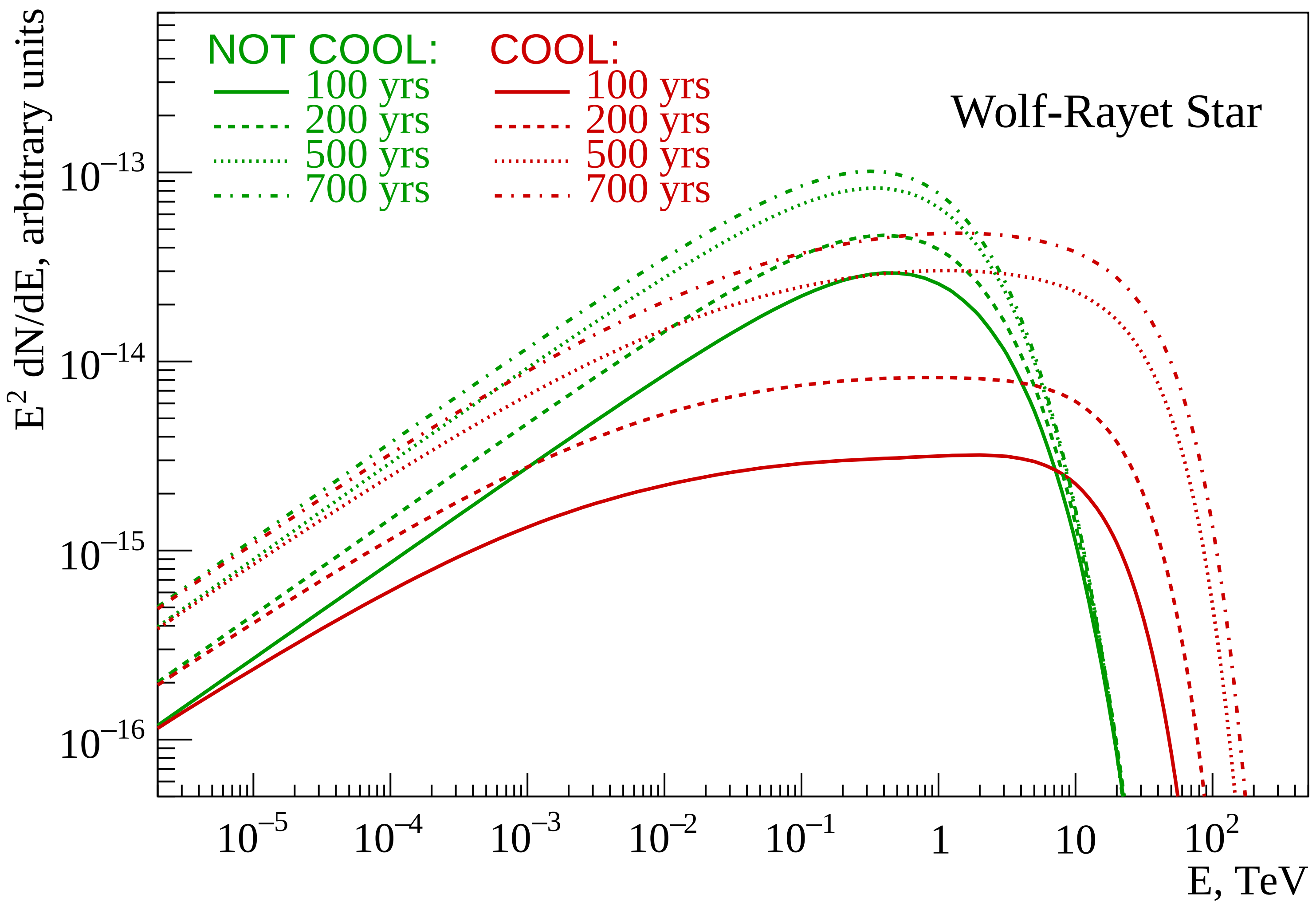
NOT COOL:	10 G and 100 $R_\odot$	NOT COOL:	100 G and 1 $R_\odot$	- weak effect
COOL:	10 G and 1000 $R_\odot$	COOL:	1000 G and 10 $R_\odot$	- strong effect

Results & Outlook

- 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 spectrum of the gamma-rays
- This characteristic synchrotron cooling feature shows up in the gamma-ray spectum as a brek at GeV energies, 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 hadroninc and leptonic scenarios in individual remnants allowing to explain hadronic-like emission within the leptonic scenario
- We plan to further investigate this effect by:
  - studying how sensitive our results are to the parameters of progenitor stars
  - examining the role of the size of the stellar bubble
  - applying this scenario to individual SNRs.

Inverse Compton emission





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