Recent results on particle acceleration
Part III

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Introduction

Two topics in more detail:

- Driving and transport of turbulence
- Structure of the wind bubble

Turbulence driving

Cosmic-ray anisotropy causes resonant driving of Alfven waves

Anisotropy relates to diffusive flux $\delta = -\frac{3D}{cN}\frac{\partial N}{\partial x}$

Cosmic-ray current causes nonresonant driving of Bell modes

Current relates to streaming in plasma $j = qNv_{CR}$

Threshold in streaming energy density

Both effective upstream of the shock!

Turbulence driving

Spatial part of transport equation $\frac{\partial}{\partial x}\left(vN - D\frac{\partial N}{\partial x}\right)$

In frame of upstream plasma *v*=0

diffusive flux provides streaming!

Steady-state in shock frame $N = \frac{C}{v} + N_0 \exp\left(\int^x dy\, \frac{v(y)}{D(y)}\right)$

Boundary *N*=0 at infinity → *C*=0

Exponential cut-off, because *v* < 0

Turbulence driving

If *v* and *D* are approximately constant upstream

→ cosmic ray precursor $N = N_s \exp\left(-\frac{|v_s|}{D}(x - x_s)\right)$

→ Spatial scale $D\,/\,|v_s|$

→ Determines acceleration rate

→ Energy dependence through diffusion coefficient

→ Driving rate of turbulence also falls off exponentially

Turbulence driving

What if the diffusion coefficient increases with x?

→ **Precursor scale D / v increases**

→ **Steady state streaming rate still $v_s N$**

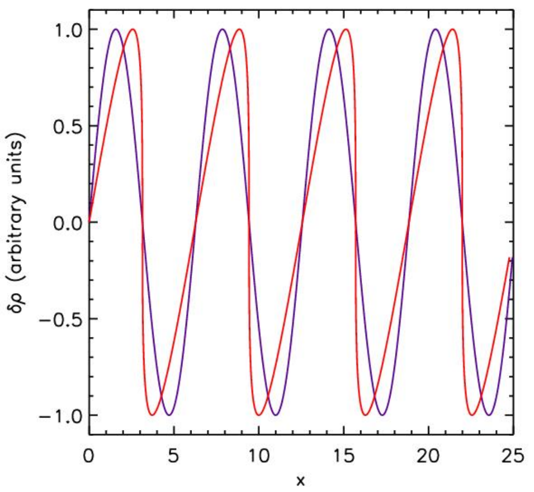
→ **Acceleration rate decreases**

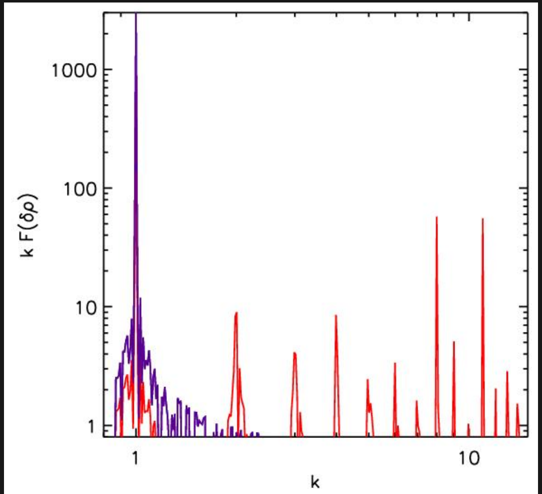
→ **Precursor unbound, if D increases at least linearly**

Magnetic turbulence

What is cascading?

Example: Adiabatic sound wave





Magnetic turbulence

$$\frac{\partial E_W}{\partial t} = -\underbrace{\left(v\nabla_r E_W + c\nabla_r v E_W\right)}_{\text{Advection + Compression}} + \underbrace{k^3\nabla_k D_k \nabla_k \frac{E_W}{k^3}}_{\text{Cascading}} + \underbrace{2\left(\Gamma_g - \Gamma_d\right)E_W}_{\text{Growth + Damping}}$$

Energy density in magnetic turbulence per unit logarithmic bandwidth

$$\boldsymbol{B_{tot}} = \sqrt{\boldsymbol{B_0^2} + 4\pi \int \boldsymbol{E_W d \ln k}}$$

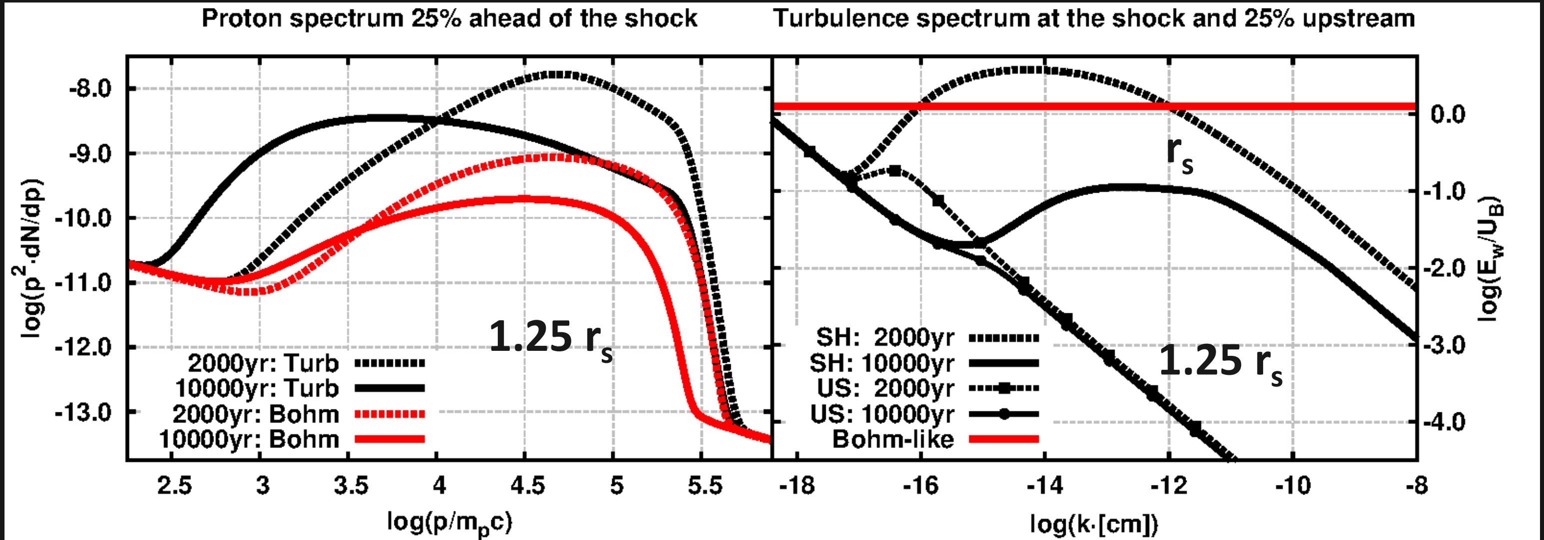
The equation describes isotropic, Alfvenic turbulence in 1D and spherical symmetry.
Same spatial grid as for cosmic rays

Turbulence growth at the largest scales takes time and limits E_{Max}!

Supernova remnants

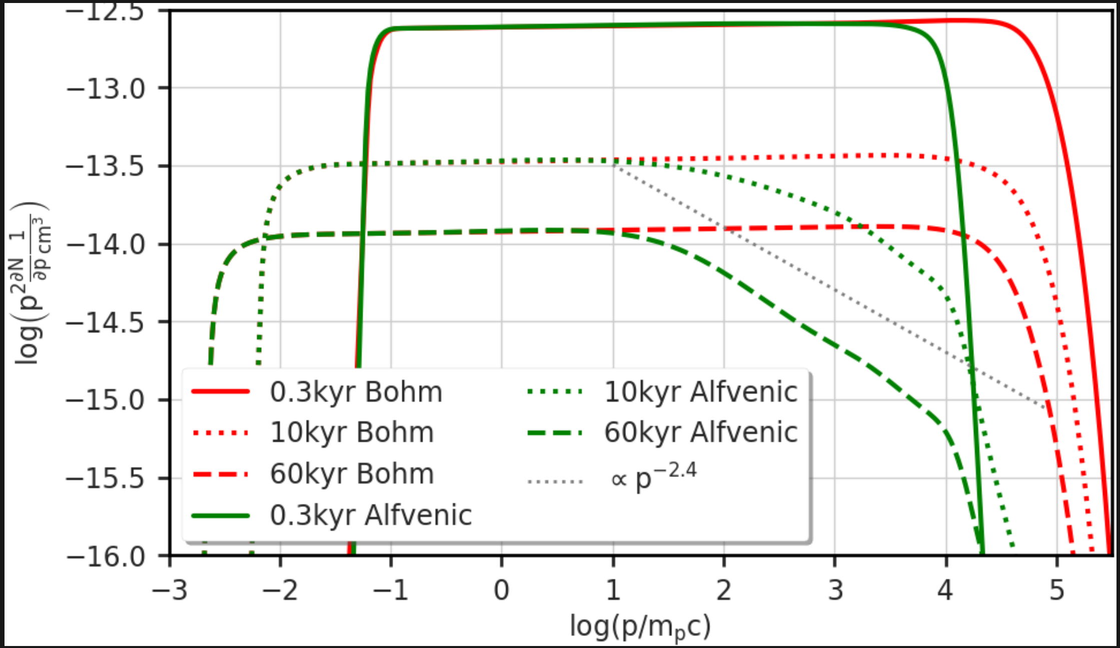
Particle spectra ahead of shock change significantly!

In total, the spectrum of accelerated particles is often softer (Brose et al.)



Supernova remnants

- Time-dependence limits E_{max}
- Fast reduction of E_{max}
- Lower cosmic-ray pressure
- Weaker cosmic-ray feedback
- Escape from far downstream
- High-energy spectrum is soft



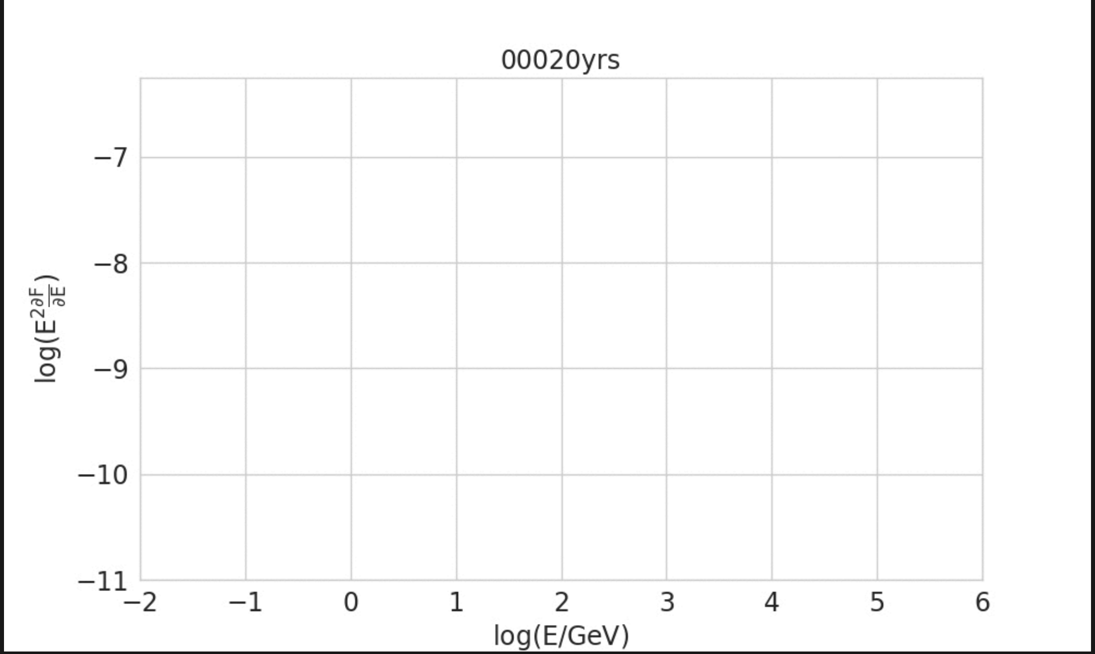
Such soft input spectra are needed for Galactic cosmic-ray propagation

Supernova remnants

Gamma-ray spectra of SNR
are generally soft at high energy

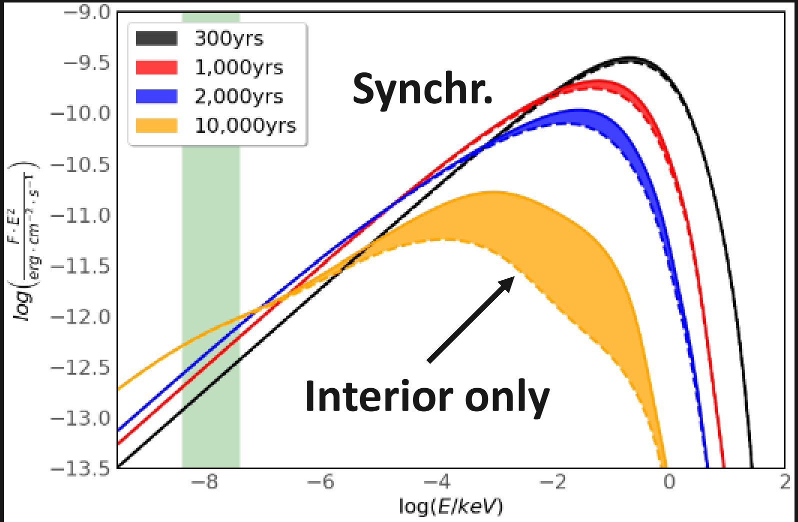
Fits data very well

Time-dependent gamma-ray spectra

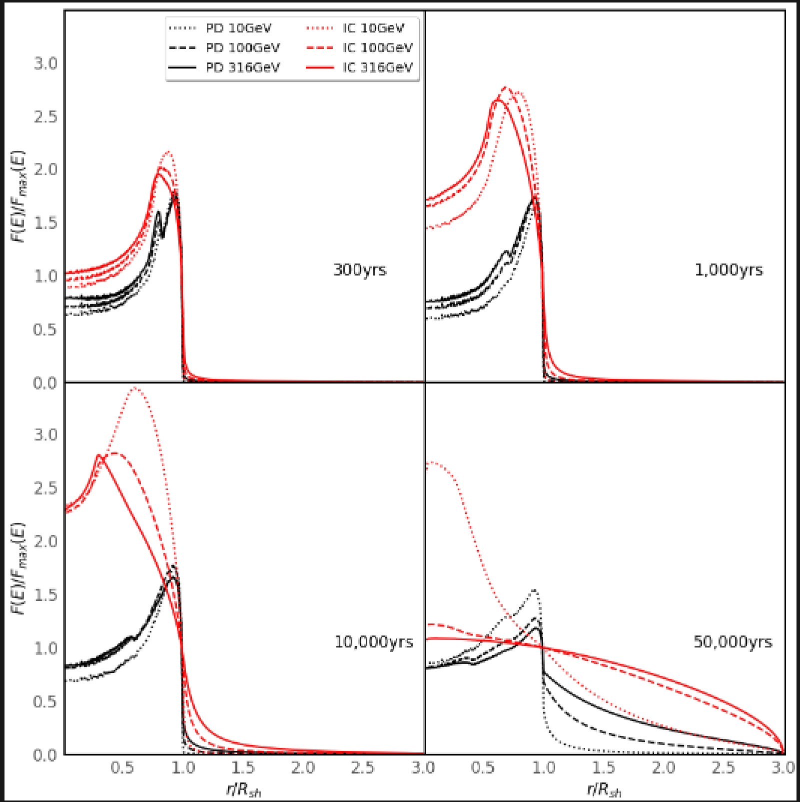


Magnetic turbulence

Appearance of haloes in source morphology



Brose et al. (2021)



Summary turbulence

Non-relativistic shocks in SNR

- Properties and spatial distribution of turbulence are important
- Steady state is probably not reached
- Particle spectra softer than in time-independent models

Wind bubble

The progenitor star goes through various evolutionary phases

The sequence of evolution depends on the initial stellar mass

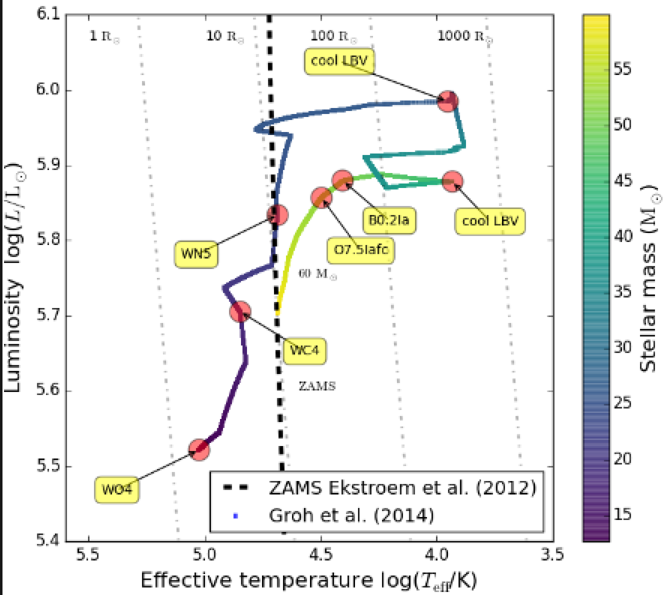
The wind bubble reflects this evolution

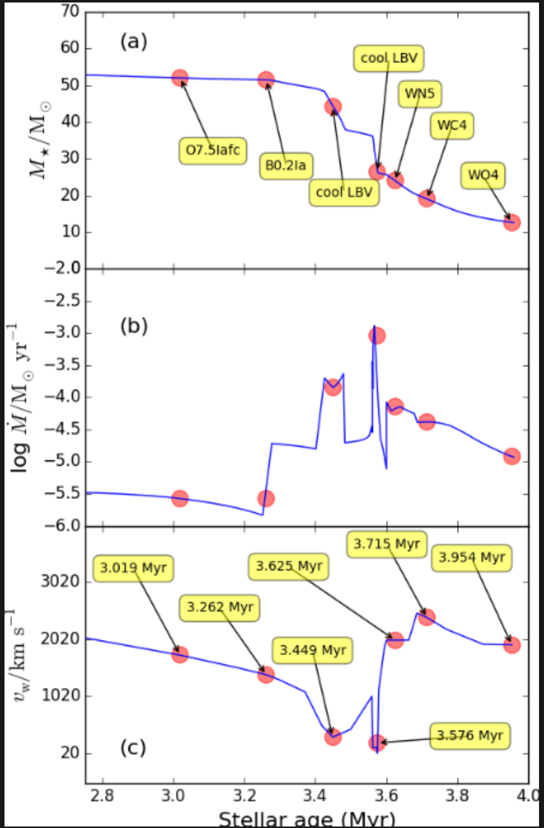
Emission from the SNR is brightest early

Most GeV-scale cosmic rays are produced late in the evolution

Wind bubble

A nonrotating 60-M_s star



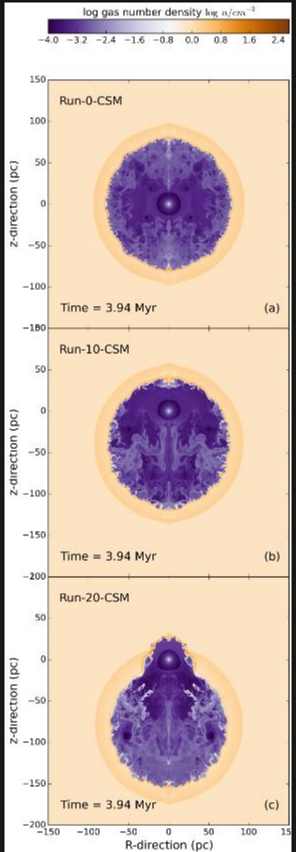


Wind bubble, 60 M_s

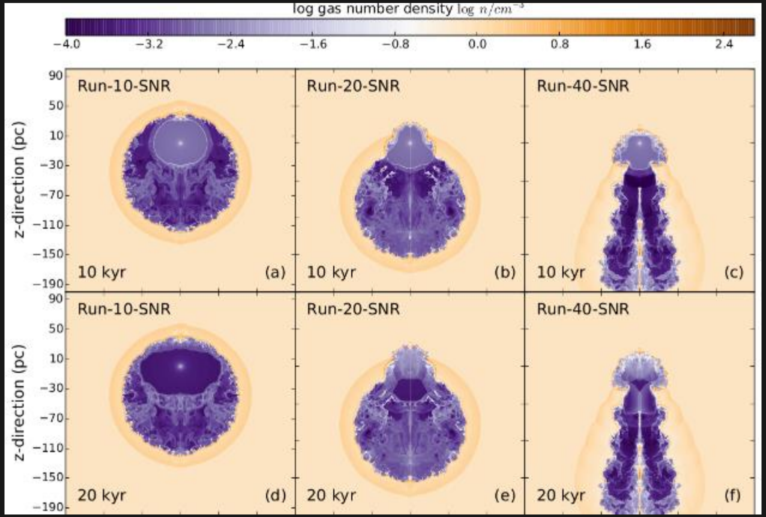
Now allow motion of progenitor

Meyer et al. (2020)

Before SN

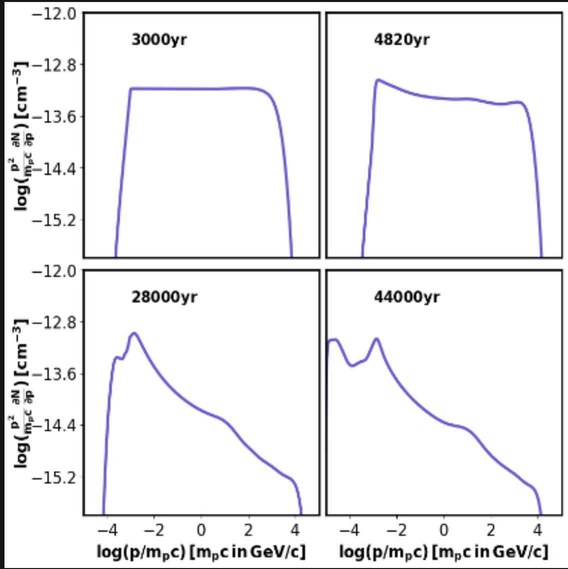


After SN



Wind bubble, 60 M_s

Acceleration model in spherical symmetry
Simplified diffusion model

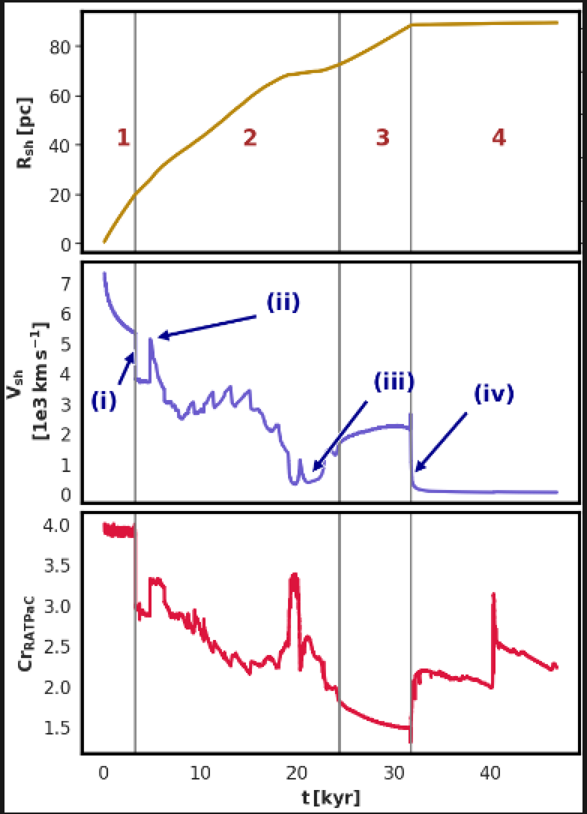


In shocked wind

Low compression

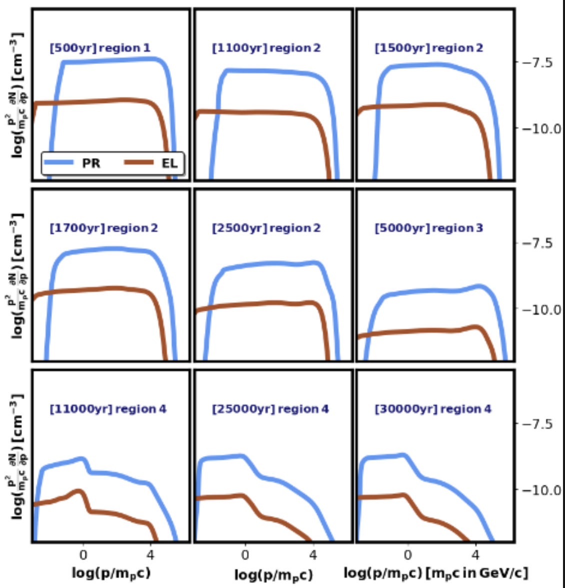
Soft particle spectra

Das et al. (2022)



Wind bubble, 20 M_s

Same for lower-mass star
but **with** turbulence transport

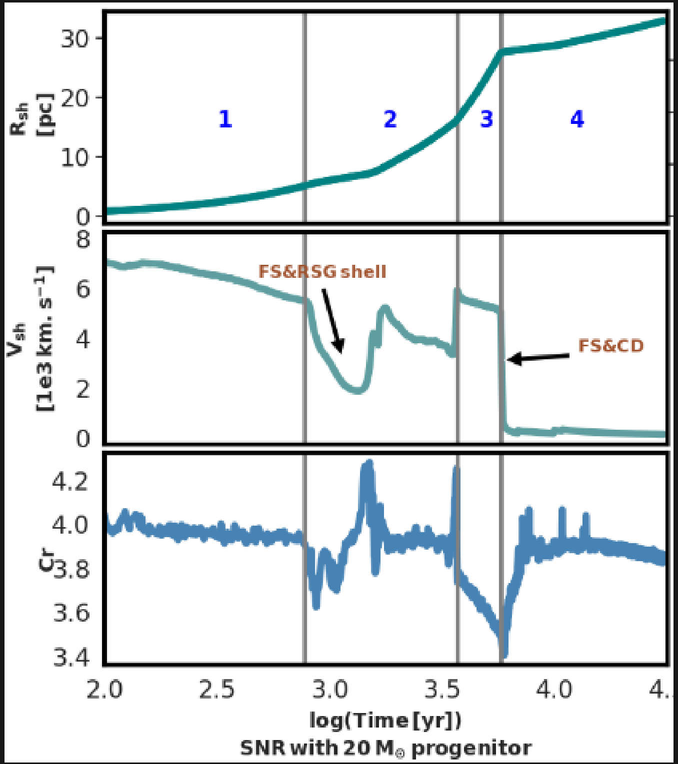


Transient bumps

Soft spectra late

In ISM low E_{max}

Das et al., in prep.



Summary Wind bubble

Wind bubbles affect

- the morphology of the SNR
- Spherical symmetry only for static progenitor
- Effect depends on stellar evolution
- Soft particle spectra in shocked wind and in ISM

Summary Part III

- Particle acceleration at reverse shock relevant only initially
- Build-up of turbulence far upstream required
- Later turbulence driving slow → reduction in E_{max}
- Wind bubble structure introduces phases of CR acceleration
- Soft particle spectra in hot shocked wind possible