Cosmic-ray acceleration to PeV energies

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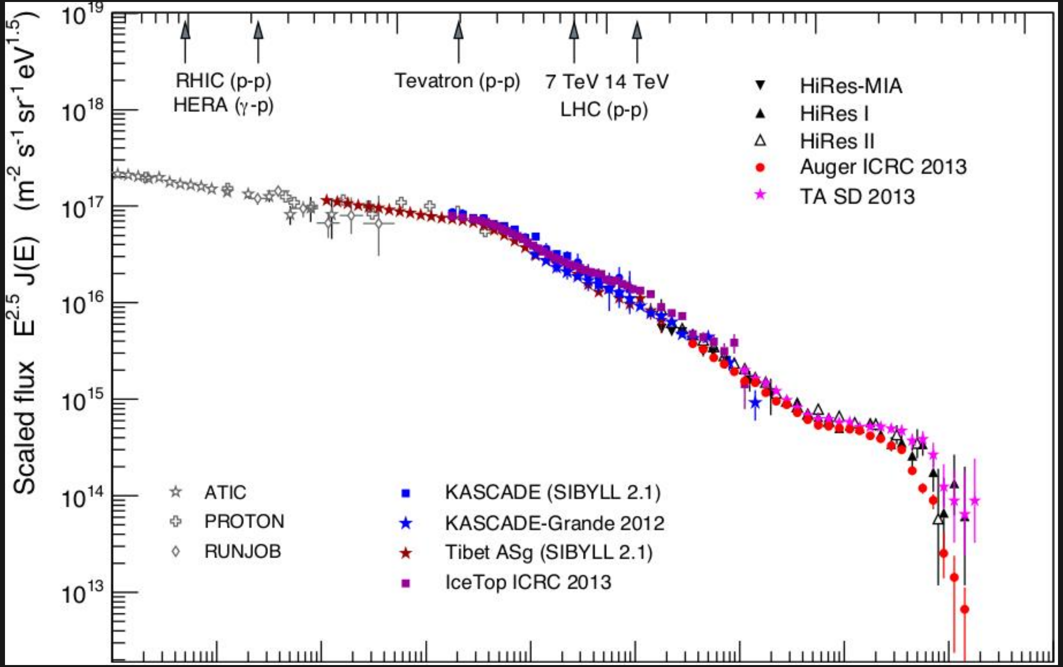
Introduction

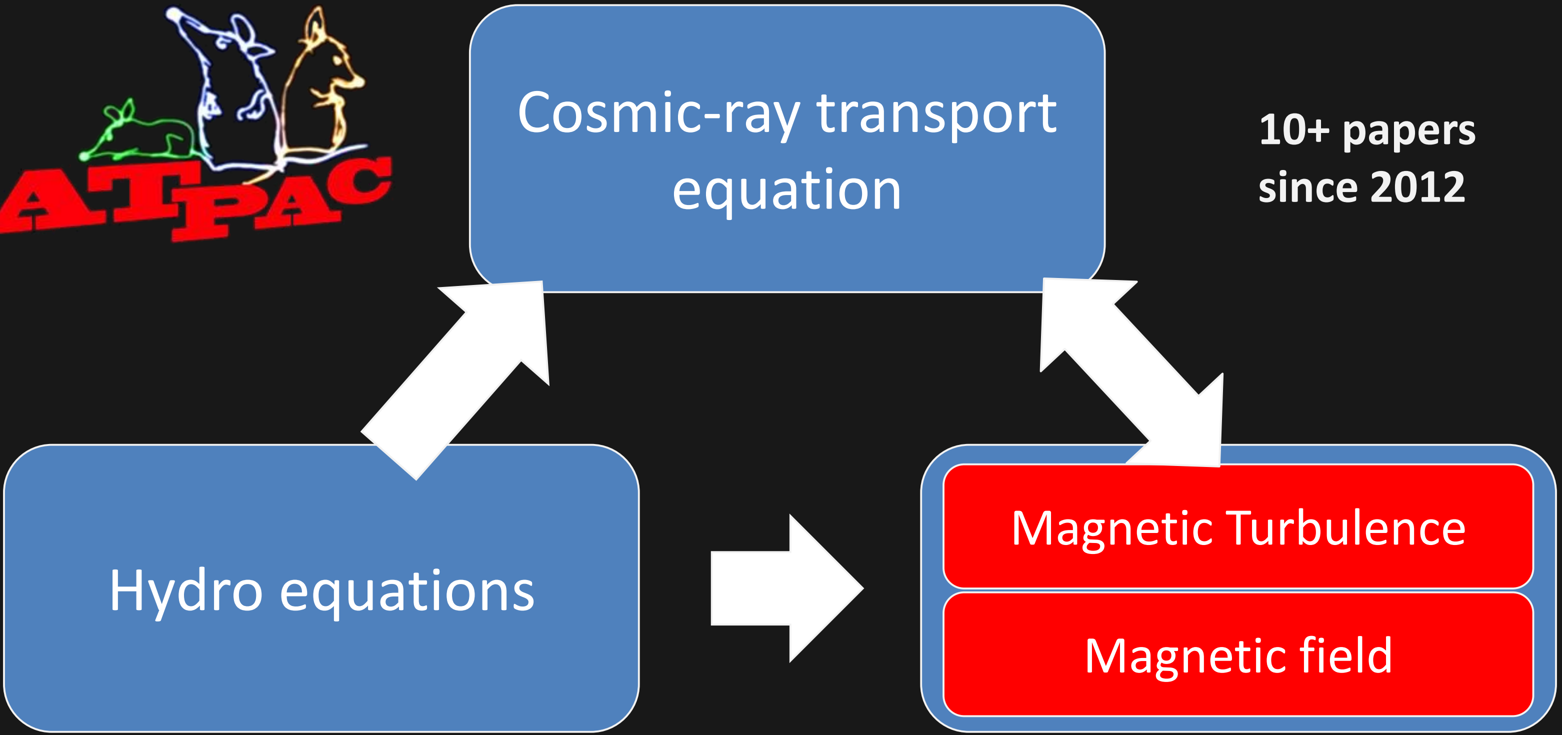
Can Galactic CR sources

Reach the knee at 3 PeV?



10 TeV 10 PeV 1 Joule

RATPaC

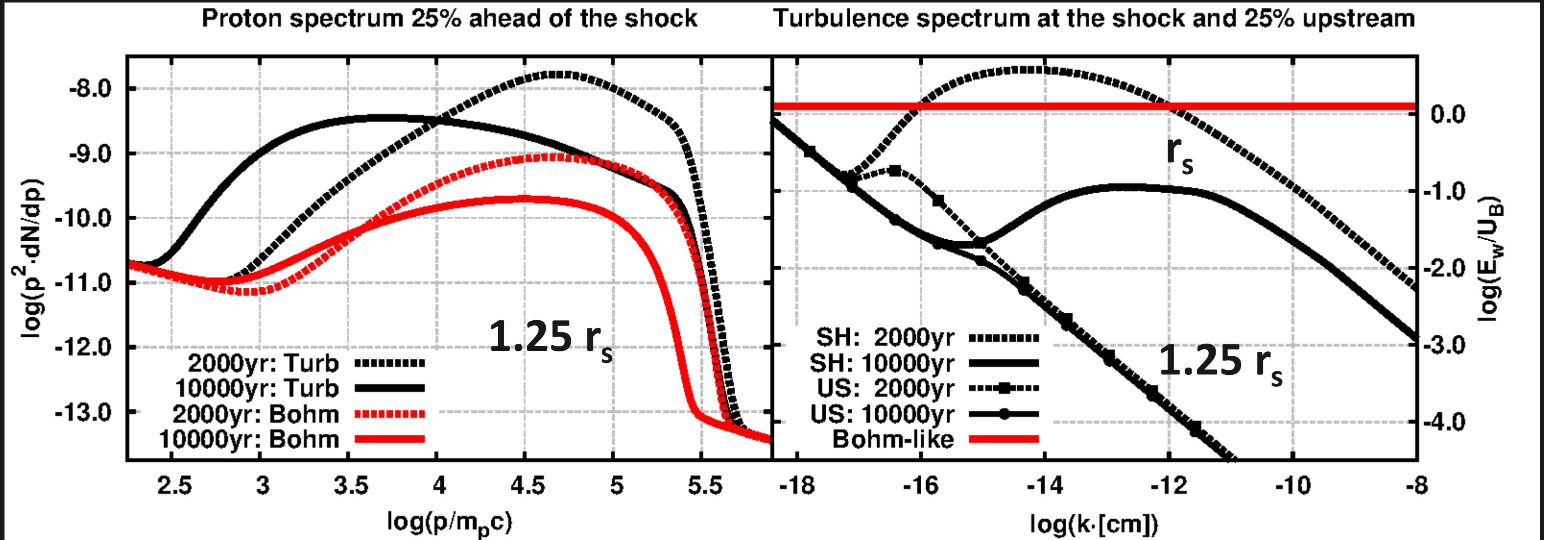


10+ papers since 2012

Type Ia SNR

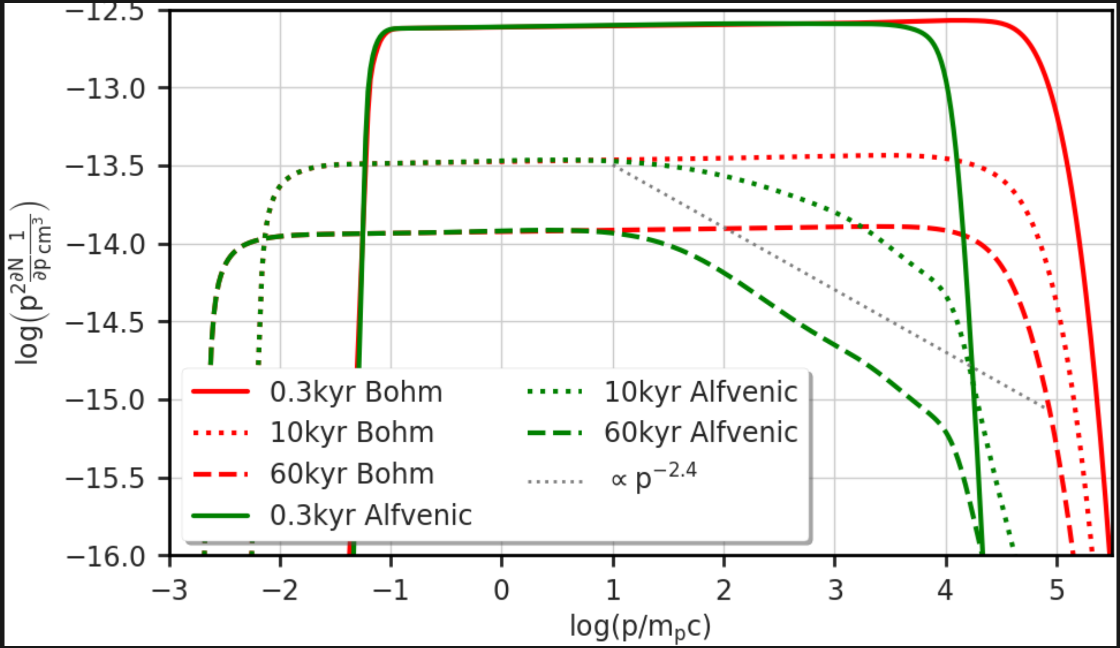
Particle spectra ahead of shock change significantly!

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



Type Ia SNR

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



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

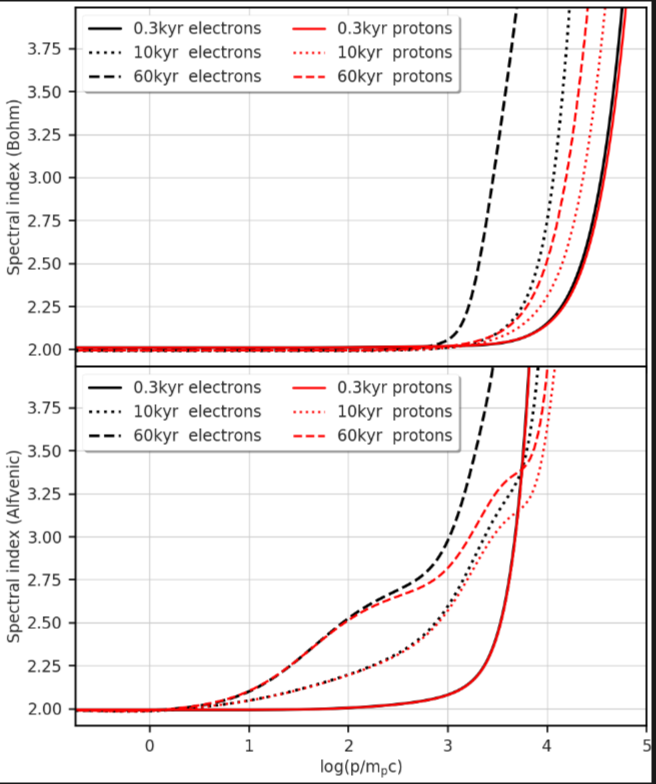
Running particle spectra

Realistic HE spectra are soft

Fits data of individual objects

Fits to Galactic propagation

Pevatrons only very early?



Bohm

Turbulence model

What do we need?

- Shock-shock collisions?
- Strong magnetic field?
- Dense gas shells?
- Clusters?
- Super-scattering or pre-existing turbulence?

Shock-shock collisions

Wind bubble of CC SNRs are full of reflected shocks

Close shocks → excess compression → very hard spectrum

CR precursor length ~D/v_{sh}

Overlap time ~D/v_{sh}^2

Acceleration time ~$8D/v_{sh}^2$

Magnetic field

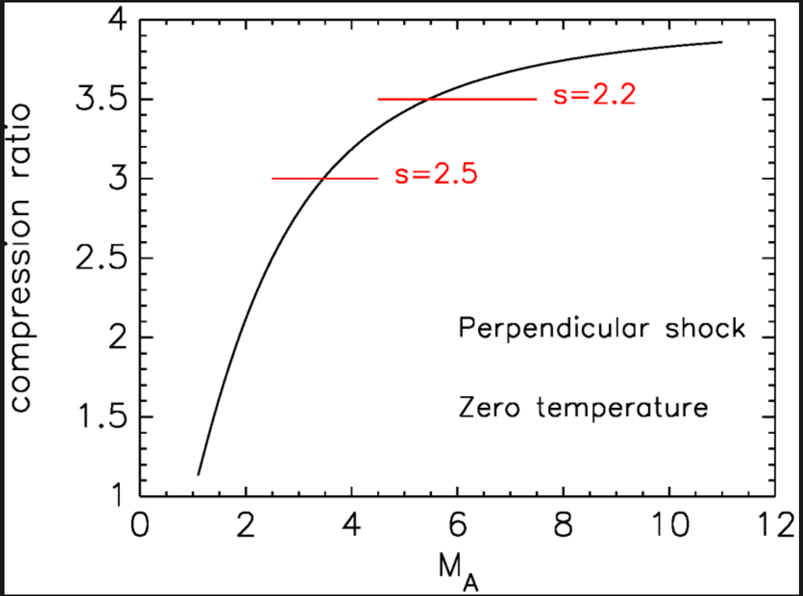
Acceleration time $t_{acc} \sim \lambda_{mfp} / v_s^2 \sim 1/B$ ➔ Want strong magnetic field

But not too strong!

Magnetic field $U_B = 0.1\, U_{kin}$

➔ $M_A = U_{kin} / U_B = 3\text{-}4$

➔ soft spectra



Dense shells

Need lots of particles with high B and V_s → Very early for CC SNR

High-density shells (1 M_{sol} at 10^{16} cm away from the star)

Gas density $n=10^{10}$ → high brightness → CR loss time 1 day

Reaccelerated shock after shell passage propagates into amplified field of previously escaped CRs → Boost to E_{max} (Brose+ 25)

Clusters

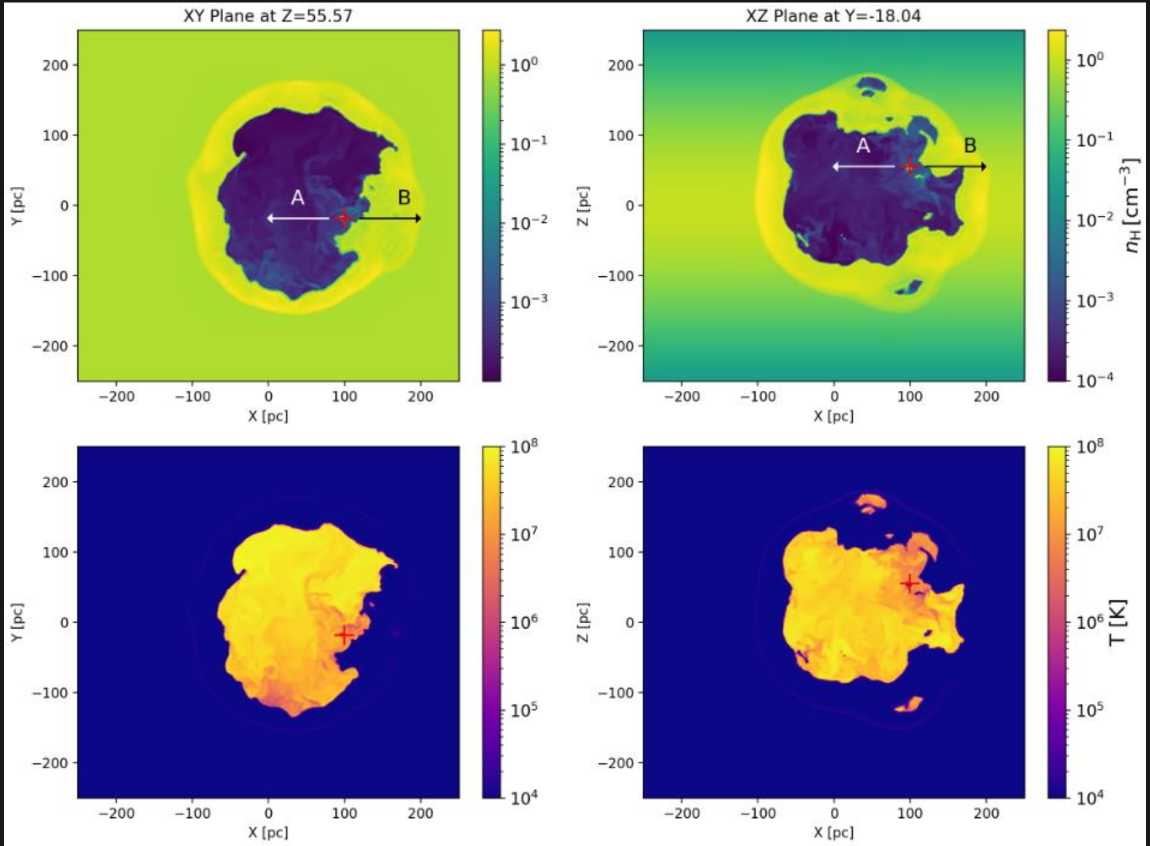
Star clusters → collective winds → long-lived termination shock

Wind speed ~1000 km/s

Warm and turbulent wind

First SN kills the structure → See local bubble

Clusters: Local bubble

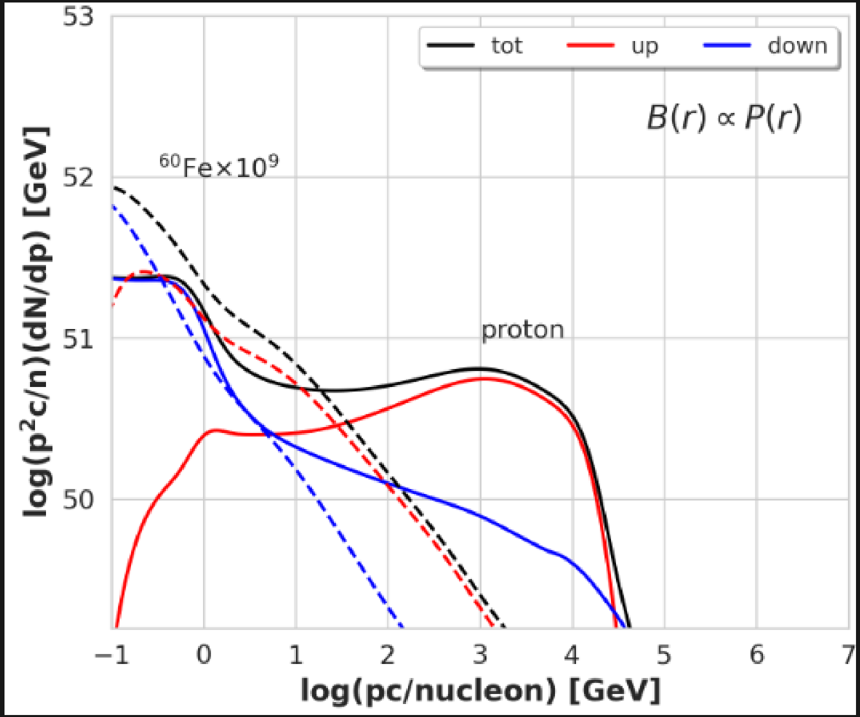


No termination shock

Schulreich ea 23

Clusters: Local bubble

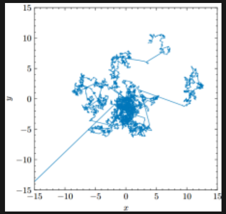
Spectral yield of
next SN is soft
and does not reach PeV



Shi ea 23

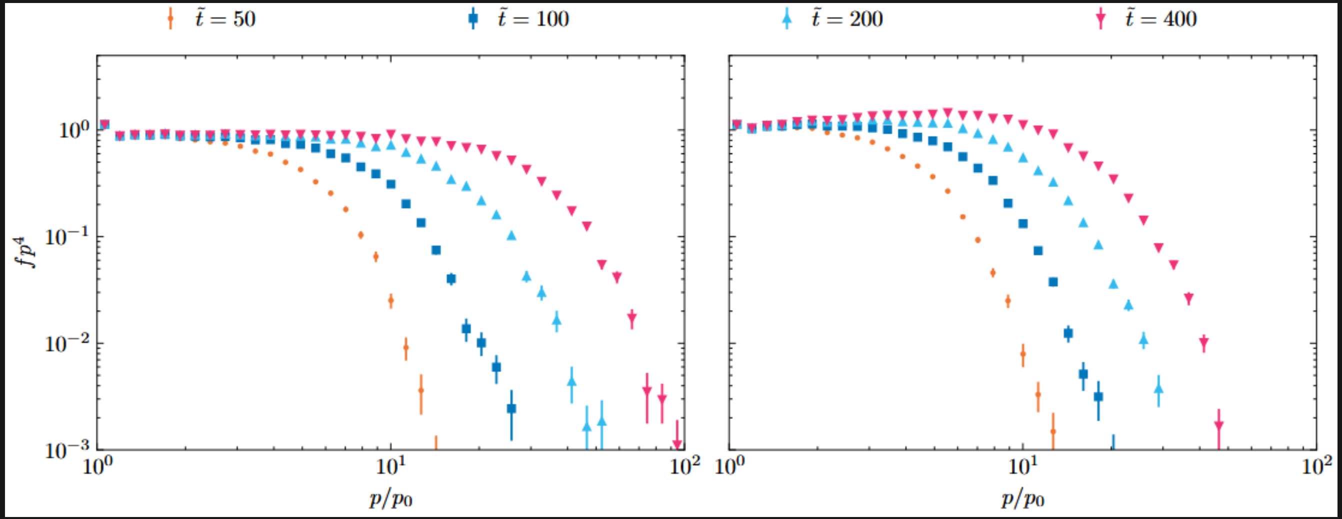
Non-standard propagation

Trapping, Levy flights, localized strong deflections



All of these have good and bad aspects

Gaussian diffusion



Non-Gaussian diffusion
α=1.7

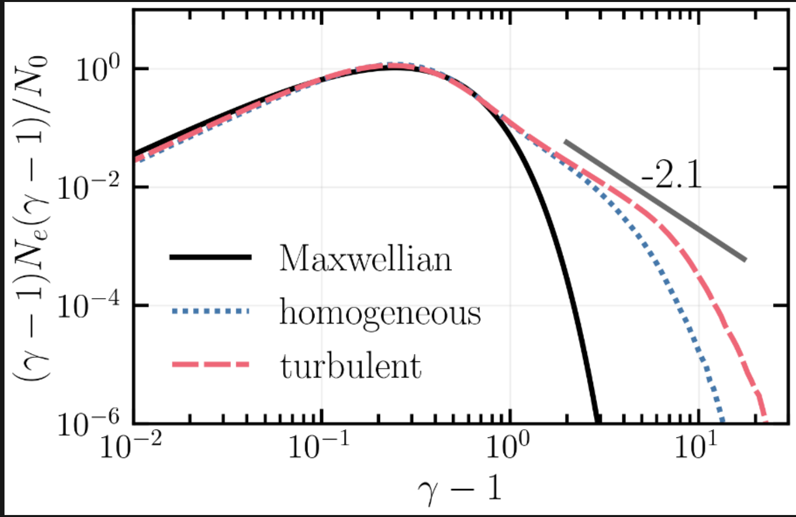
Aerdker ea 24

Pre-existing turbulence

Significantly enhance acceleration in hybrid simulations (Trotta ea, Nakanotani ea)

Moderate effect in
fully kinetic PIC simulations (Fulat ea)

Here for θ_{Bn}=60°



Summary

Shock acceleration at SNRs is a complex, non-linear process

Maximum energy likely below the knee at 3 PeV

Ageing of the objects causes spectra to become softer over time

Simple recipes for increasing E_{max} often fail to account for negative effects

Benefits of modified scattering and/or pre-existing turbulence is still unclear

E_{max} is best enhanced by a faster outflow