On the Fermi acceleration process in collisionless shocks

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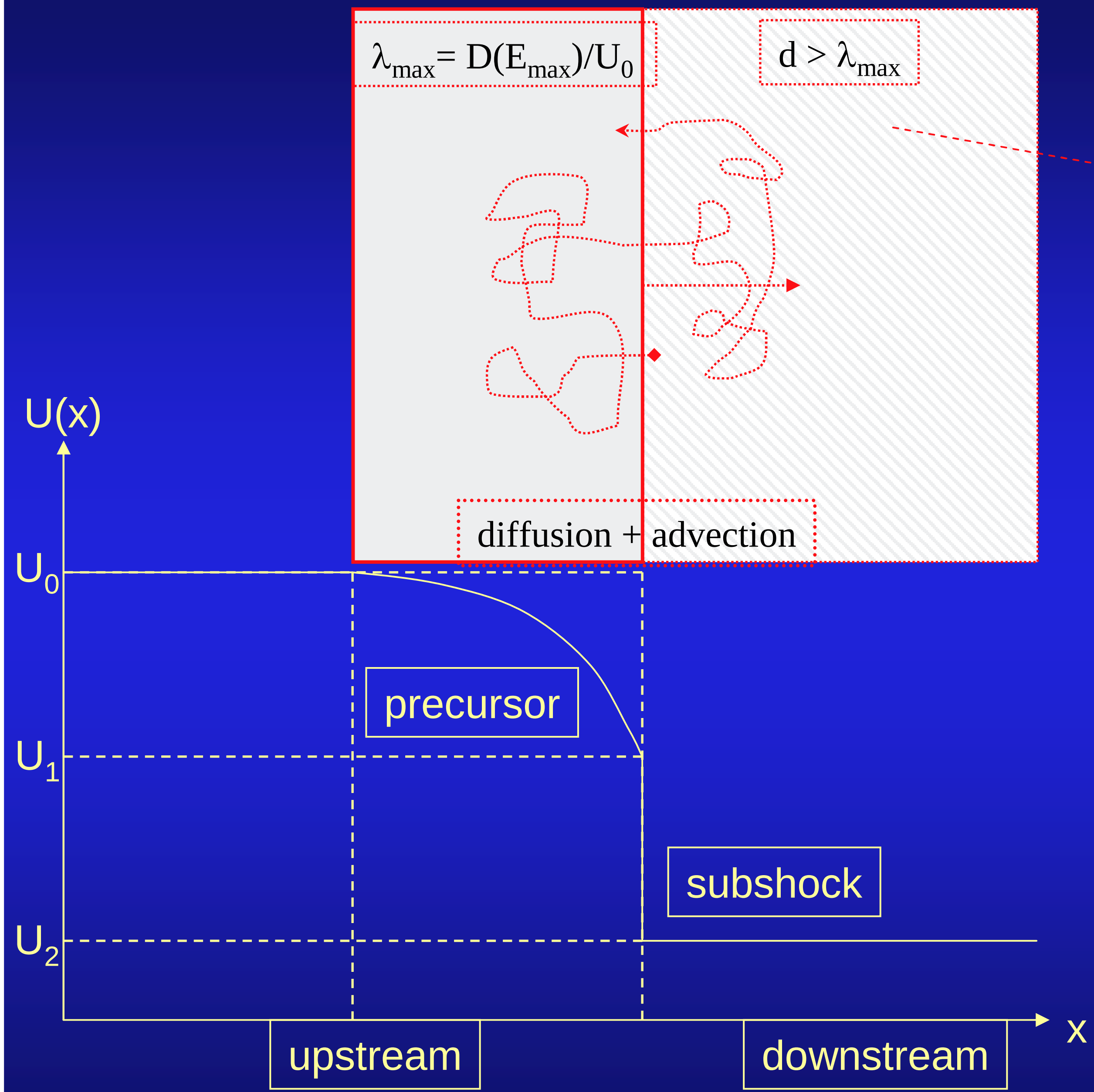
(Super-Alfvenic shocks)
(In the shock rest-frame)



$\Delta E/E = cst$
$= 4/3\ V_{sh}/c$

• NR shocks: $D(E) \propto E^{2-\beta}$
(! Quasi-linear solutions)
Test particle results
s(r)=3r/(r-1) Drury'83

• UR shocks:
- regular deflection in large scale turbulence.
- diffusive regime in small scale turbulence; $D(E) \propto E^2$
Test particle results s=2.2
Achterberg et al'01

The two regimes of CR streaming instability upstream

⇔ CR self-generated waves

- Resonant (r) regime: [Skilling '75]

⇨ wave-particle Landau-synchrotron resonance:

$$k_{//} r_g \cos(\alpha) \approx 1$$ ⇨ $r_g > \lambda_{res}$

Particle gyro-radius $r_g = E/(e\, B_{tot})$; $B_{tot} = (B_\infty{}^2 + \delta B^2)^{1/2}$
[Bell & Lucek'01, Ptuskin & Zirakashvili '03]

Fast shock regime: $(\delta B/B_\infty)^2 = M_{a\infty}{}^2 \; (P_{CR}/\, \rho u^2)^2 > 1$
$\rightarrow$ B ~ mG $\leftrightarrow$ numerical simulations [Lucek& Bell'00]

- <u>Non-resonant (nr) regime</u>: [Bell'04]

➢ Driving force: J_{ret} x B/c

<u>Saturation</u>: MF tension $B^2/4\pi l_0$

⇨ $(\delta B/B_\infty)^2 = M_{a\infty}^{\ 2}\ u_{sh}/c\ (P_{CR}/\ \rho u_{sh}^{\ 2}) > 1$

- <u>nr modes</u>:

⇨ $\xi\ M_{a\infty}^{\ 2} > kr_g > 1;\ \xi = u_{sh}\ \zeta_{CR}\ /c$

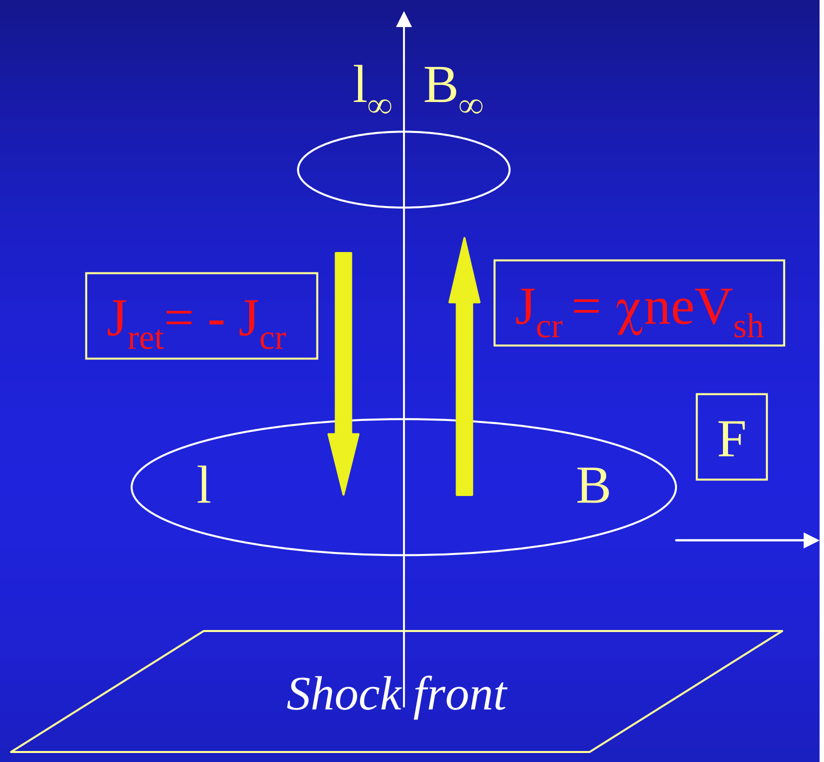
⇨ Grow faster than the r modes

⇨ circular polarisation → helicity # 0

⇨ ion-neutral damping [Reville et al '07]

⇨ thermal effects [Reville et al'06]

✓ δB_{sat} is debated and requires further simulations.

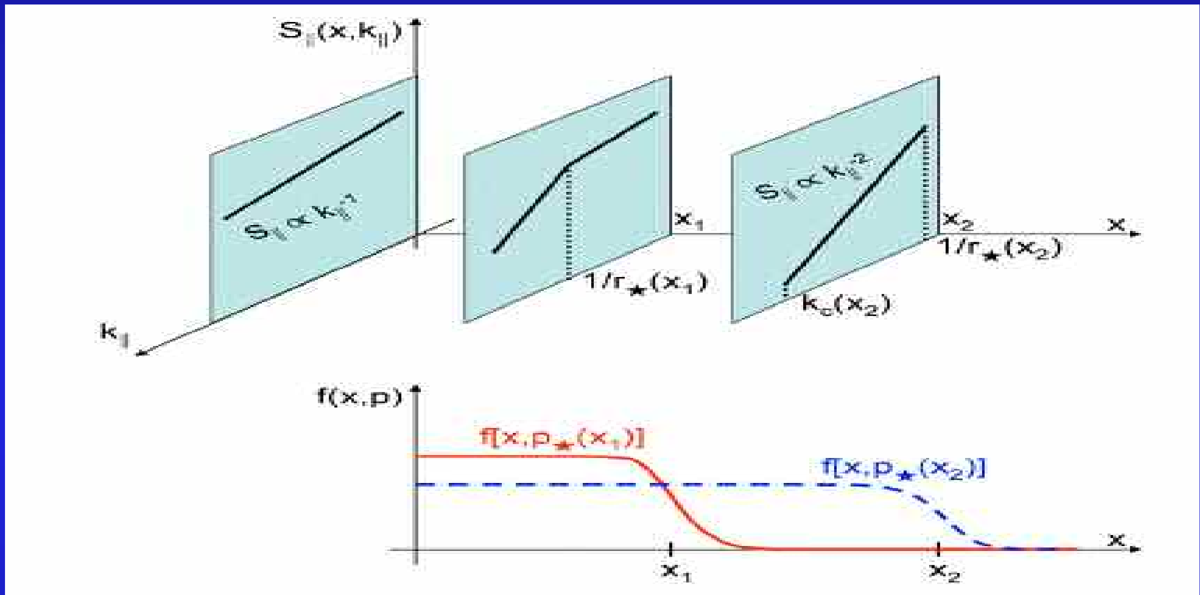


Bell'04
Milosavljevic & Nakar '06

(thermal & magnetic pressures are neglected)

Non relativistic (SNR) shocks

- Both regimes should operate *jointly* [Pelletier et al '06]



(parallel shock)

Saturation criterium:
$\Gamma_{nr}(k)=[kV_a(k)]^{-1}$

If $V_{sh} \geq \zeta_{CR}\, c$

- The level of turbulence is fixed by the nr instability: B = B(Bell'04)
- The spectrum is fixed by the r instability: $S_{1D} \propto k_{//}^{-1}$
- Once $S(k_{//},k_{\perp})$ is fixed ⇨ D(E,x) [Marcowith et al'06]

Ultra relativistic (GRBs) shocks

= shocks with Lorentz factors > 100   Pelletier et al in prep.

- The resonant regime alone *does not* work:

  $X(r_g)$ distance travelled by CRs at r_g ($= k_{res}^{-1}$) << k_{res}^{-1}

- The non-resonant regime:

⇨ Coherence scale $\lambda_{coh} << r_g$ ⇨ upstream transport in the diffusive regime; $D \propto r_g^2$ [Milosavljevic & Nakar'06]

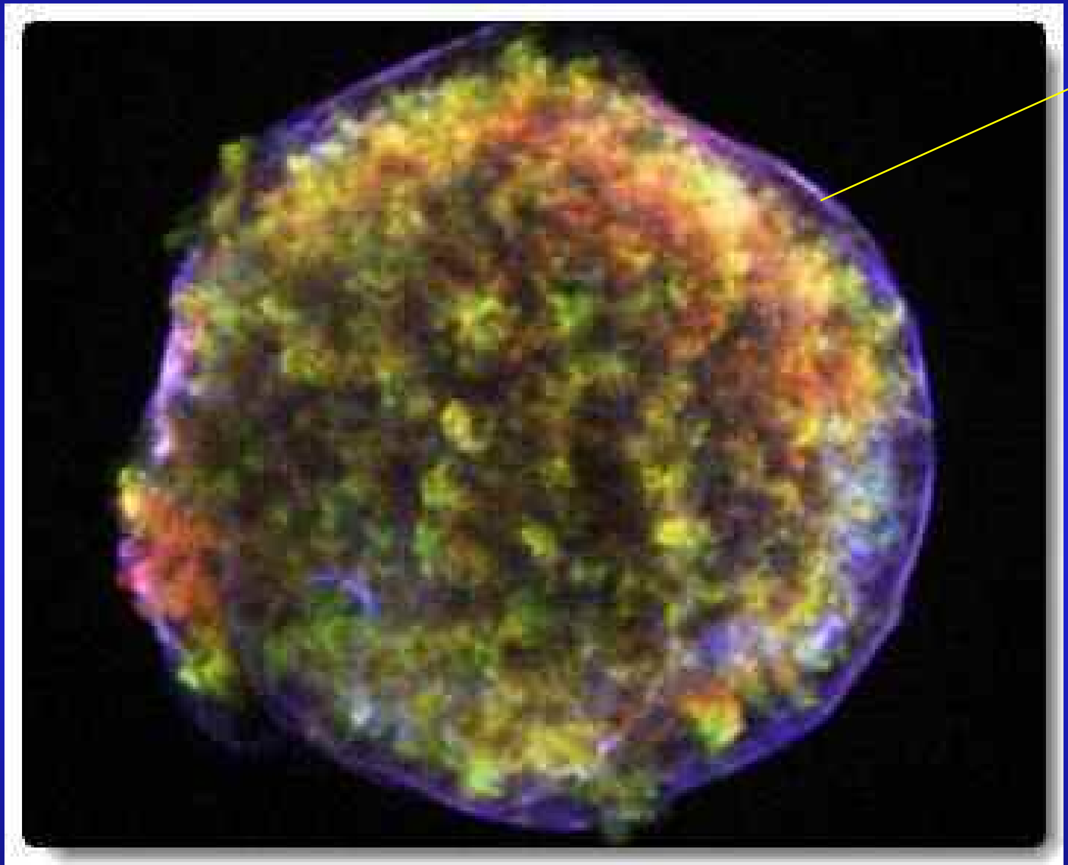
⇨ The only way the Fermi process can work in UR shocks

(regular deflection produces at best 1-1/2 cycle) [Lemoine et al '06]

⇨ *Not expected* to produce UHE CRs.

Observational constraints

Tycho SNR as observed by Chandra: blue = [4-6] keV images



Thin X-ray filaments tracing the forward shock:

- size (de-projected) ~ % shock radius = 0.01 pc.

- observed in several SNRs (CasA, Képler, SN1006, G347.5, RCW86, RXJ1713).

- synchrotron radiation of 10-100 TeV electrons.

! Other constraints: Gamma-ray vs X & radio radiation [Aharonian et al'07, Katz this conference]

X-ray filaments in SNR shocks

- Thinness ⇨ B_{up} *amplified* & B_d *compressed* by $(1/3+2/3r^2)^{1/2}$ [Berezhko & Völk '03, Vink'04, Völk et al.'05, Parizot et al.'06]
- Support the theoretical investigations.

  ⇨ Downstream medium contributes the most to the synchrotron radiation

  ⇨ lower limits on $B_d \rightarrow 500\ \mu$Gauss; 2 orders of magnitude above B_∞

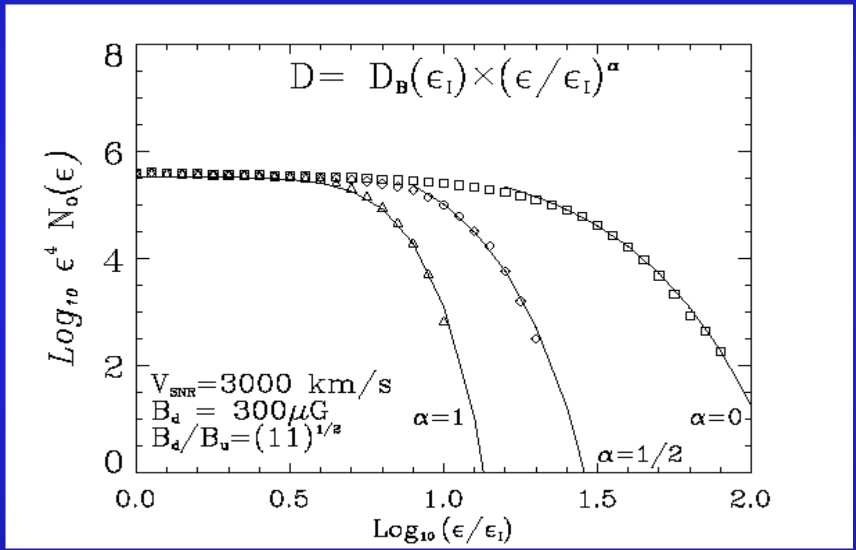
  ⇨ Constraints on D(E) only @ $E_{obs} \sim$ 10-100 TeV

  $$D(E_{obs}) \sim k\, D_{Bohm}\,,\ k > 1$$

  ⇨ Maximum CR energies ~ PeV (CR knee yes but CR ankle no !)

The downstream medium

- Synchrotron cut-off ↔ transport law [Zirakashvili & Aharonian '07] (test-particle solutions) ⇨ important for the particle acceleration/loss diagnostics



Square: D cst
Circle: Kraichnan
Triangle: Bohm

Solid: SDE-hydro simulations
Marcowith & Casse in prep.

⇨ SimbolX

- Turbulence relaxation over a length scale = ΔR_X [Pohl et al'05] ⇨ produce lower B_d (lower limits) : $t_{Sync} \propto B^{-2}$, $t_{diff} \propto B^{\beta-2}$

Marcowith & Casse in prep.

Ultra relativistic (GRBs) shocks

- Hints for MF amplification:

- Afterglow synchrotron radiation: B_d ~ 7 orders of magnitude above B_∞ [Waxman'06]

- Inverse Compton losses & synchrotron cut-off:

B_u amplified by ~ 2 orders of magnitude [Li & Waxman'06]

⇨ CRs ahead the UR shock

- Downstream: Compression vs Relaxation [Lemoine & Revenu'06]

- Numerical investigation in a prescribed turbulence (Kolmogorov compressed turbulence)

⇨ Unless $v_a > \sim 0.1\ c \longrightarrow t_{ret} < t_{relax}$

- Return probability ↘

Conclusions

1. Upstream: *in the streaming instability framework*:

• Continuous (?) sequence

➢ NR shocks *non-resonant dominated* (early stages)→ *resonant dominated* (late stages).

➢ *resonant dominated* (NR shocks) → *non-resonant dominated* (UR shocks).

! Numerical simulations have to confirm $\delta B > B_\infty$ in r & nr regime (see the result of Niemiec & Pohl '07 and discussions in Reville et al'07, '06, Bykov & Toptyghin'05)

2. Downstream:

➢ Compression (introduces anisotropy), relaxation or growth → D(x)

✓ *Numerical & analytical calculation for both UR & NR shocks*

UR shocks: tests of Fermi acceleration in a different turbulence configuration [Lemoine & Revenu'06, Niemiec et al'06, Keshet & Waxman'05, Blasi & Vietri'05]

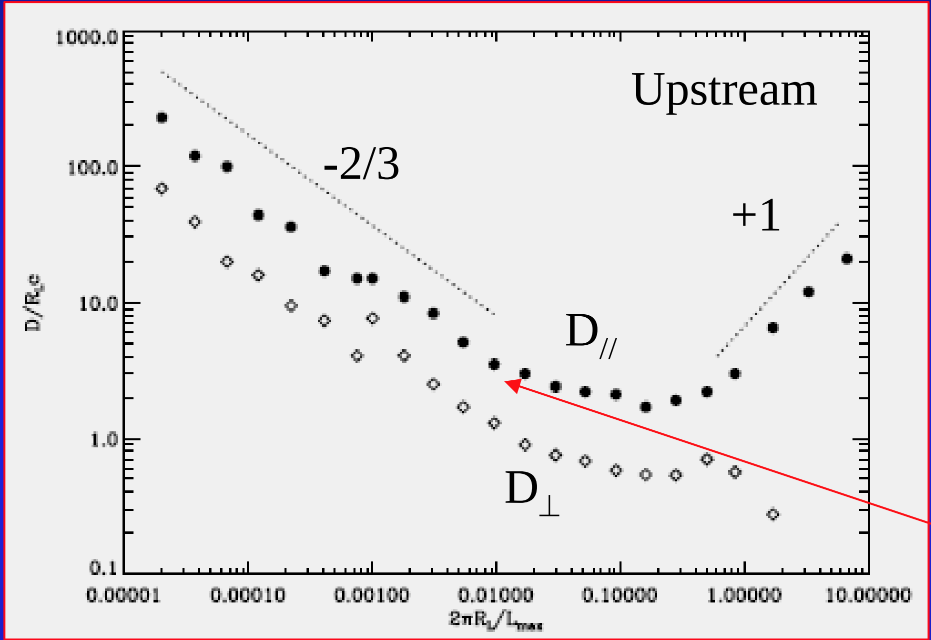
NR shocks: Non-linear effects

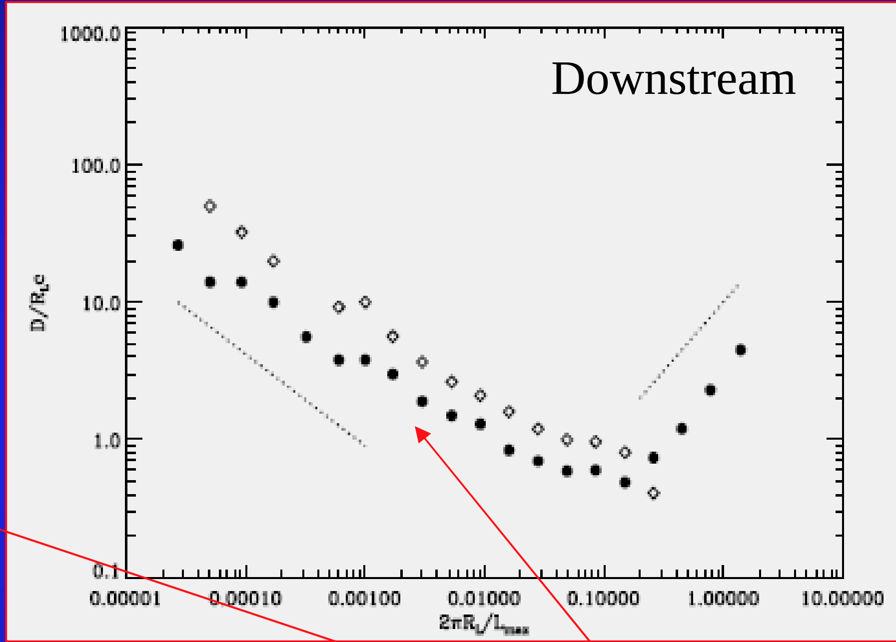
➢ "Self-consistent" calculation of D from f(x,p) [Vladimirov et al'06, Amato & Blasi'06]

➢ MHD turbulence theory ⇨ D in strong turbulence [Marcowith et al'06] ! No CR back- reaction

Transport & CR spectrum

Goldreich-Sridhar scaling





Scale compression

$D/(r_L c)= D/(3\ D_{Bohm})$

Code developed by M.Lemoine (IAP): FFT of a given MF configuration + diffusion coefficients reconstructed from particle paths [see Casse et al'02]

Effects of turbulence on CRs

- Bohm diffusion if no correlation: $S_{//} \propto k_{//}^{-1}$ ⇨ $D \propto r_L$ only // and ⊥ scales are independent
- Kolmogorov-like diffusion if Golreich-Shridar correlation applies: ⇨ $D \propto r_L^{1/3}$ (interaction at $k_\perp r_L \sim 1$)
- Turbulence production within the Fermi cycle produces softer CR spectra.

⇨ $s \sim 4\,(1+ 2/3\, M_a^{-1}) + o(M_a^{-2})$; M_a renormalised Alfvén Mach number.

- Maximum CR energies including the MF compression.

⇨ $E_{CR\text{-}max} \leq$ CR knee.