Electron Injection in Non-relativistic Shocks

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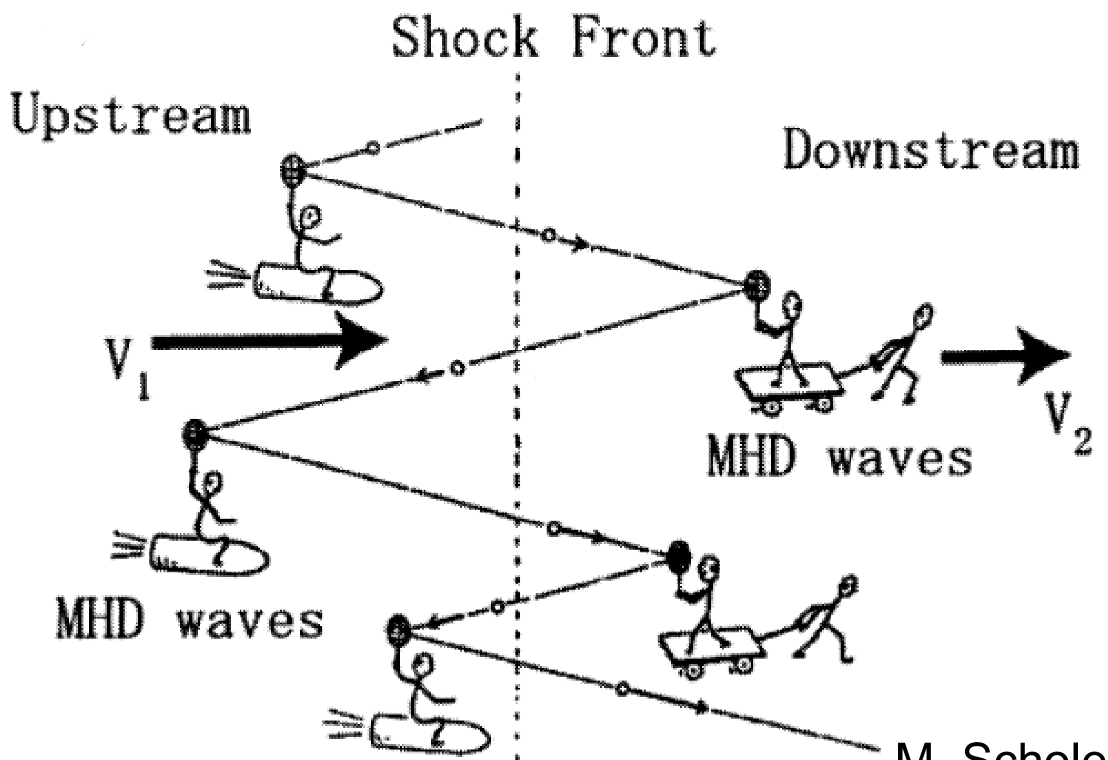
Diffusive Shock Acceleration

[e.g., Blandford and Eichler 1987]

- particles obey the diffusion-convection equation
  - particles are scattered by MHD waves
  - energy gain is due to converging velocity field

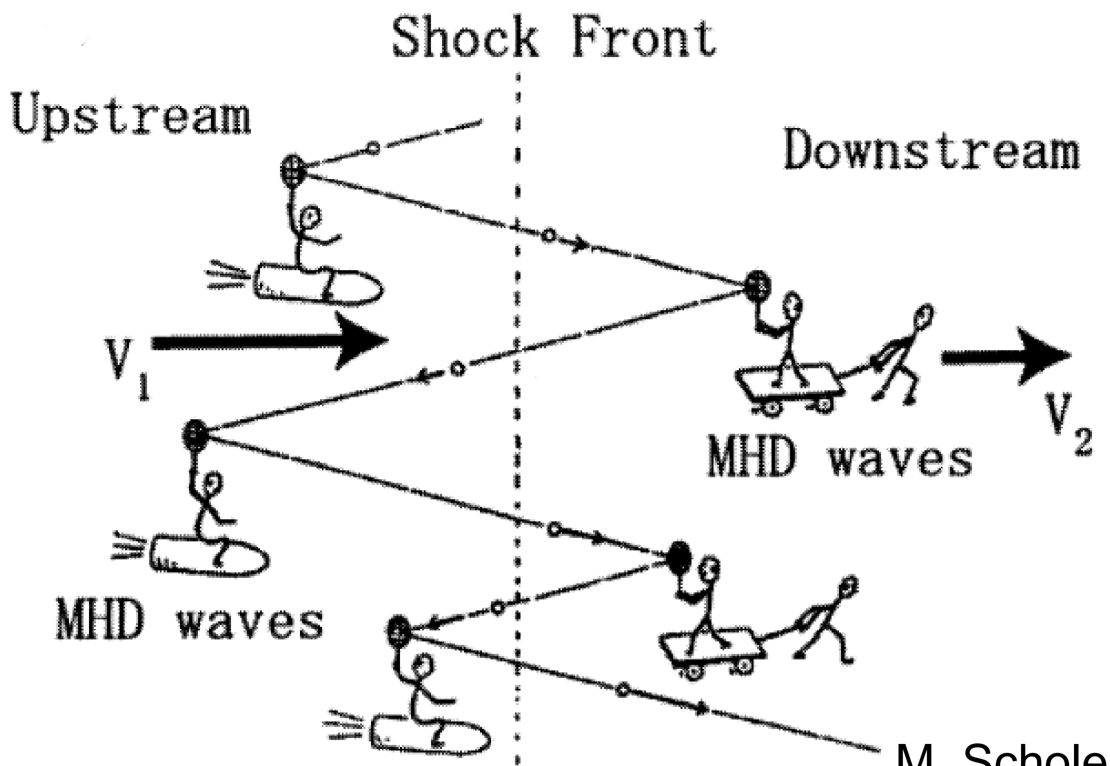


M. Scholer

Diffusive Shock Acceleration

[e.g., Blandford and Eichler 1987]

- unresolved issues
  - injection
  - back reaction from energetic particles



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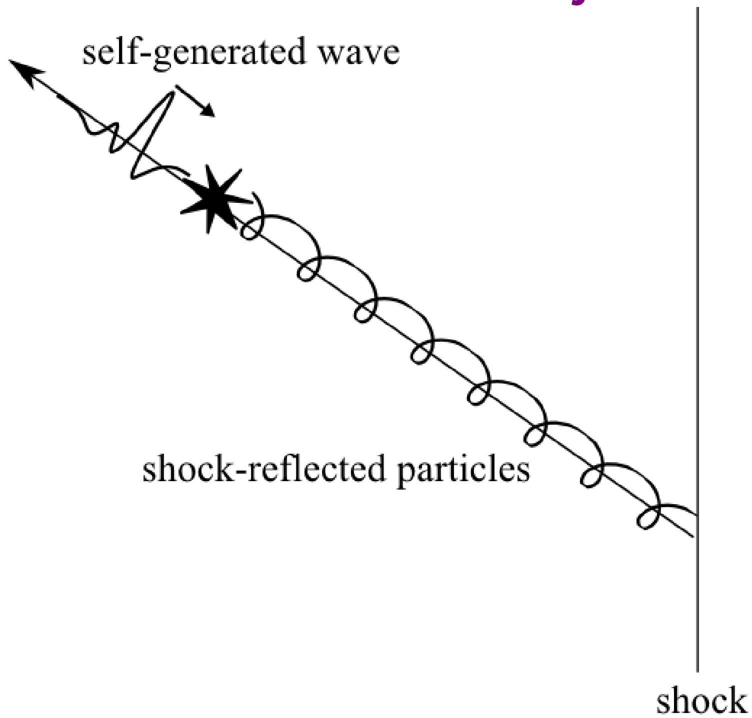
Classical Idea of Injection

- consider energetic particles streaming away from the shock front along the magnetic field line
- these energetic particles can generate waves through plasma instabilities, which induces scattering
- *the self-generation of waves (or scatterers) is the required condition for the injection*

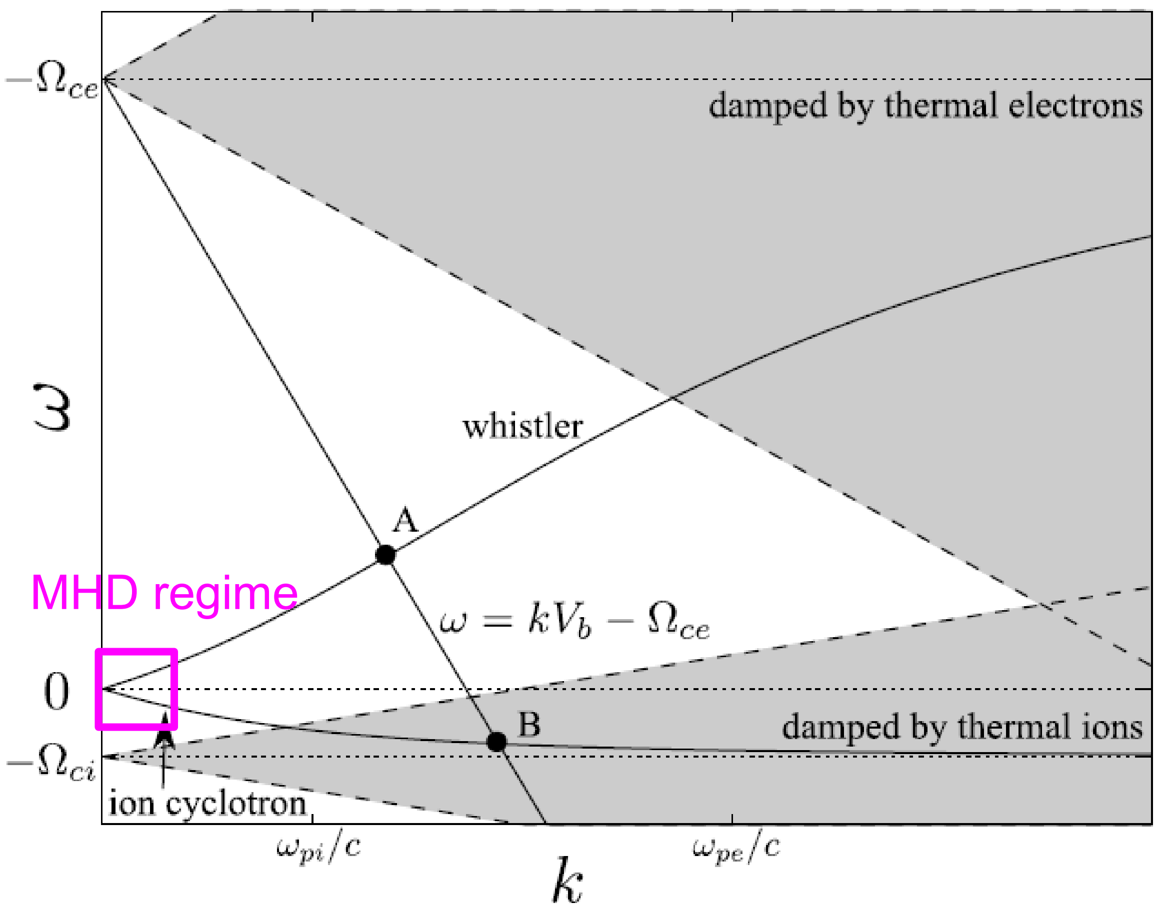


cyclotron resonance condition shold be satisfied for scattering

$$\omega - k_{\parallel} v_{\parallel} = \Omega$$

Difficulty of Electron Injection

- energetic electron beam interacts with either whistler or ion cyclotron mode (parallel propagating electromagnetic wave)



- whistler wave excitation is prohibited from the momentum conservation law
- ion cyclotron wave is heavily damped at short wave length

→ *requires very high beam velocity (v ~ c) for the injection* (interaction at MHD regime)

Requirement for Electron Injection

- *pre-acceleration to mildly relativistic energies by some other mechanisms* (most likely due to plasma microinstabilities close to the shock)
  - possible in some cases, but the required condition is too stringent (Amano & Hoshino [2007])
- *high-frequency whistler waves propagating toward the shock* (for low-energy electron scattering)
  - Levinson [1992] gives a condition for whistler excitation (but propagating away from the shock) by pre-existing CR electrons; not yet confirmed

High Mach number Q-perp shock (1D PIC)

[Amano & Hoshino 2007]

- Shock Surfing Acceleration (SSA)
  - energetic electrons are generated at the leading edge of the shock transition region

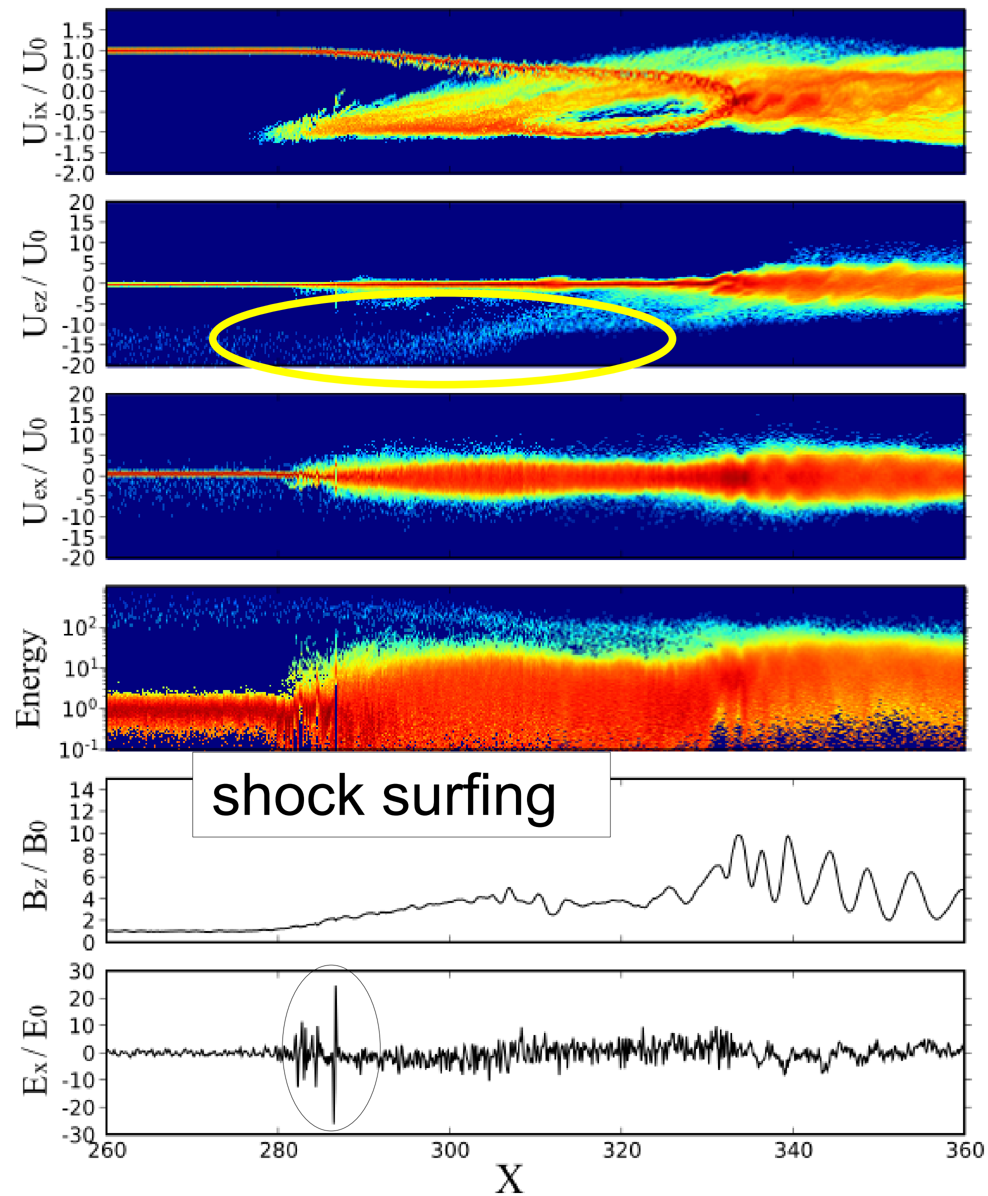
  [e.g., McClements 2001,

  Hoshino & Shimada 2002]
- Shock Drift Acceleration (SDA)
  - these electrons are further accelerated by the adiabatic mirror reflection

  [e.g., Leroy & Mangeney 1984,

  Wu 1984]

$$\Delta p = 2mV_{\rm sh} / \cos\theta_{Bn}$$



Electron Injection via Surfing and Drift

[Amano & Hoshino 2007]

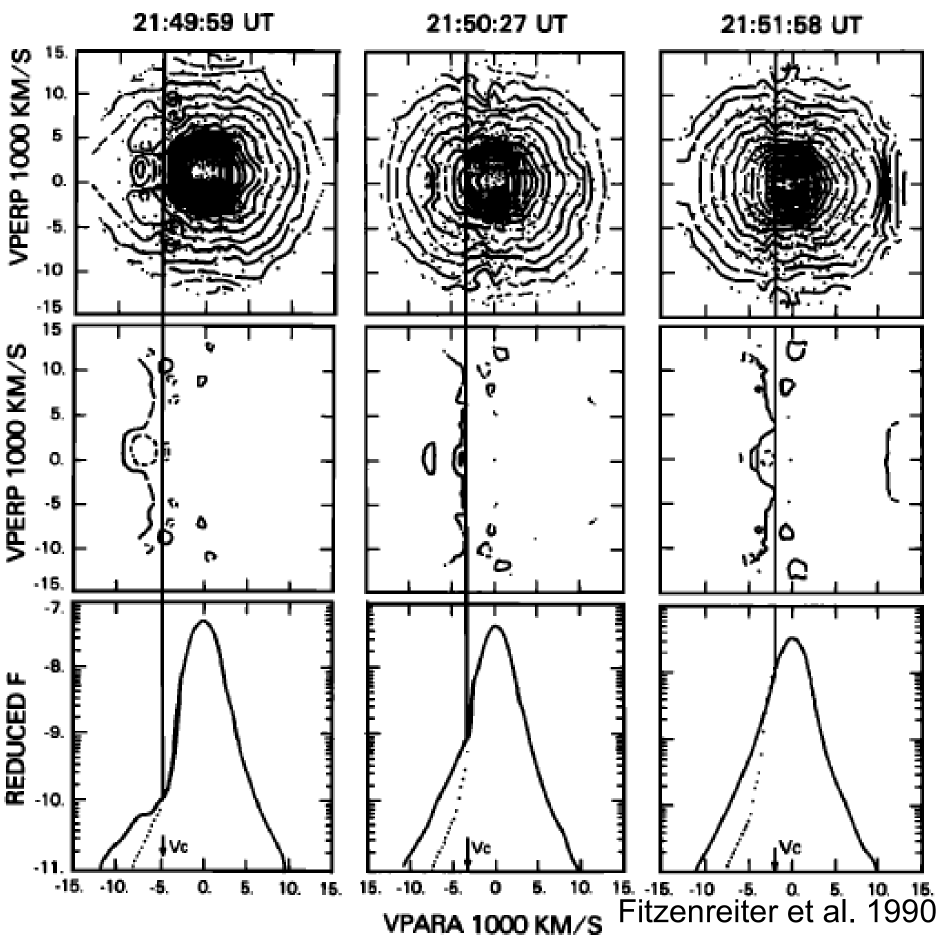
- SSA enhances the efficiency of SDA because of strong and rapid non-adiabatic heating
- shock-reflected electron may excite long-wavelength Alfven wave when

$$M_A \gtrsim \frac{\cos\theta_{Bn}}{2}\frac{m_i}{m_e}.$$

(corresponds to the condition that the beam interacts with the Alfven mode in the long wave length regime)

Idea to Relax the Requirement

- consider loss-cone type velocity distributions
    - natural consequence of mirror reflected beams



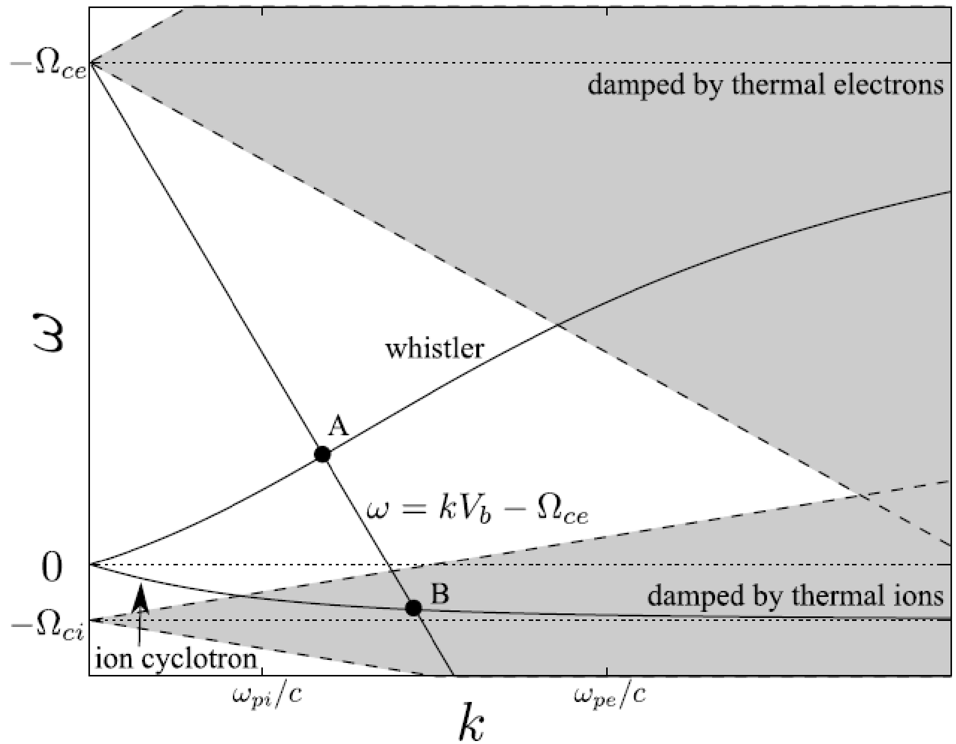
Fitzenreiter et al. 1990

loss-cone beam distribution may excite whistler waves propagating toward the shock, which we need for electron scatterers

Analytical Estimate

- whistler waves may be damped by thermal electrons
  - the condition to overcome the cyclotron damping by thermal electrons is $V_b > v_e$
  - this corresponds to the following condition:

$$M_A^{\mathrm{inj}} = \frac{\cos\theta_{Bn}}{2}\sqrt{\frac{m_i}{m_e}\beta_e}$$



reduction of Mach number by a factor of ~ 43
it is only ~20 even at purely parallel shock

Analytical Estimate

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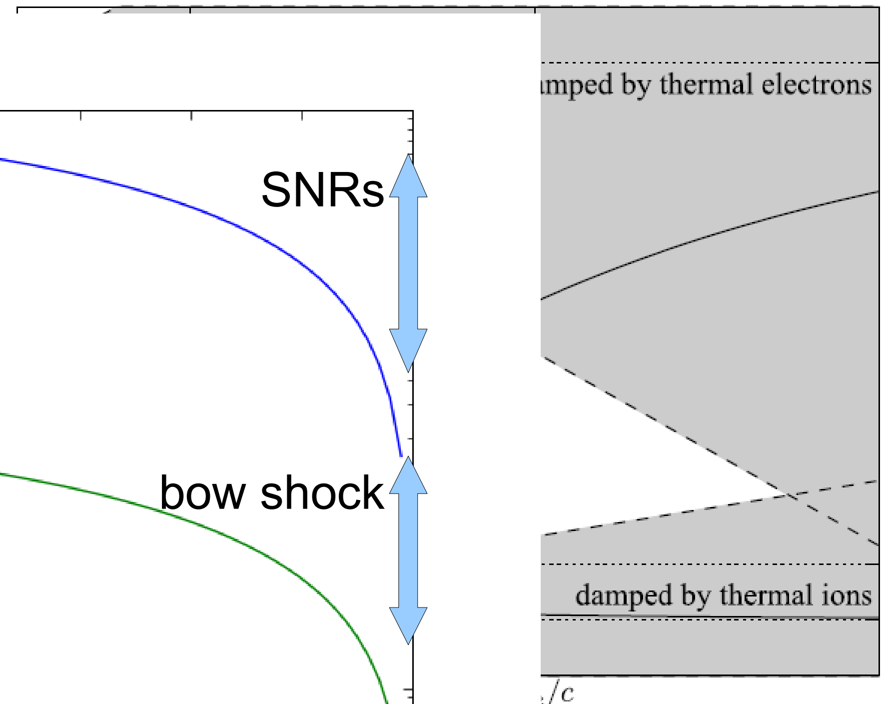
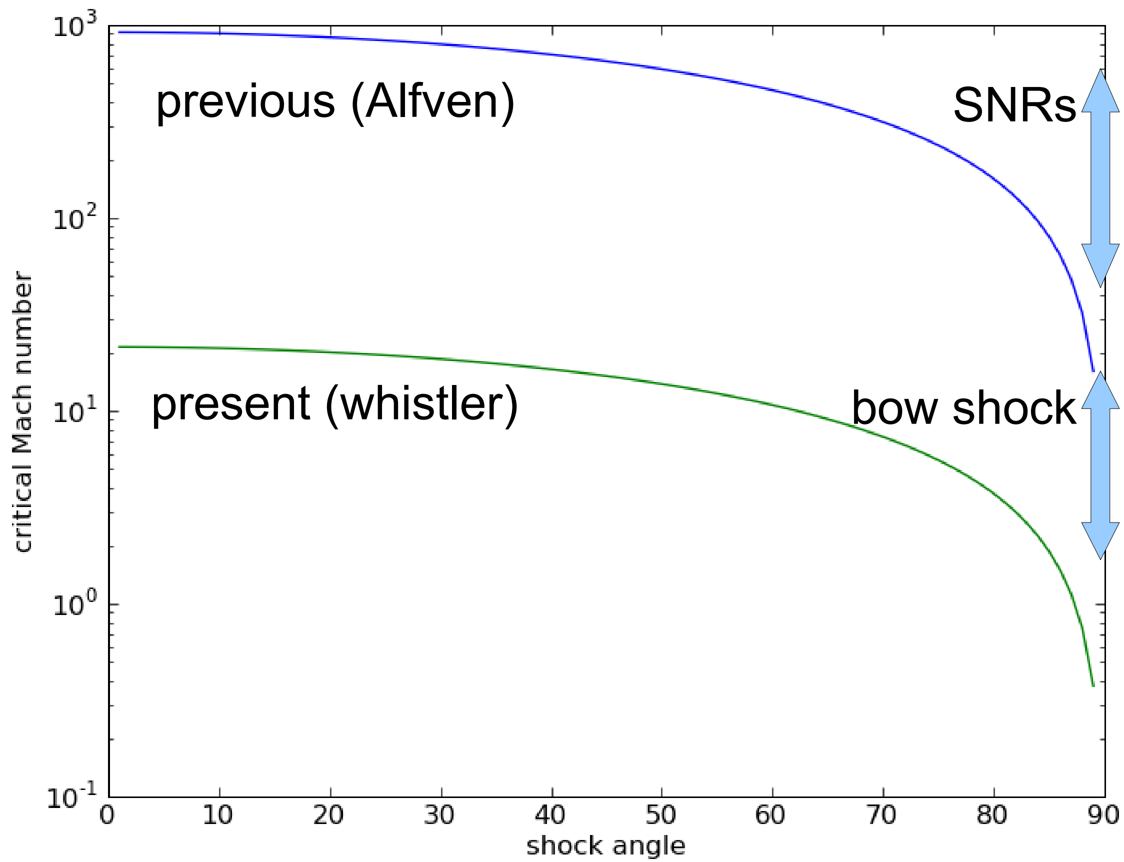
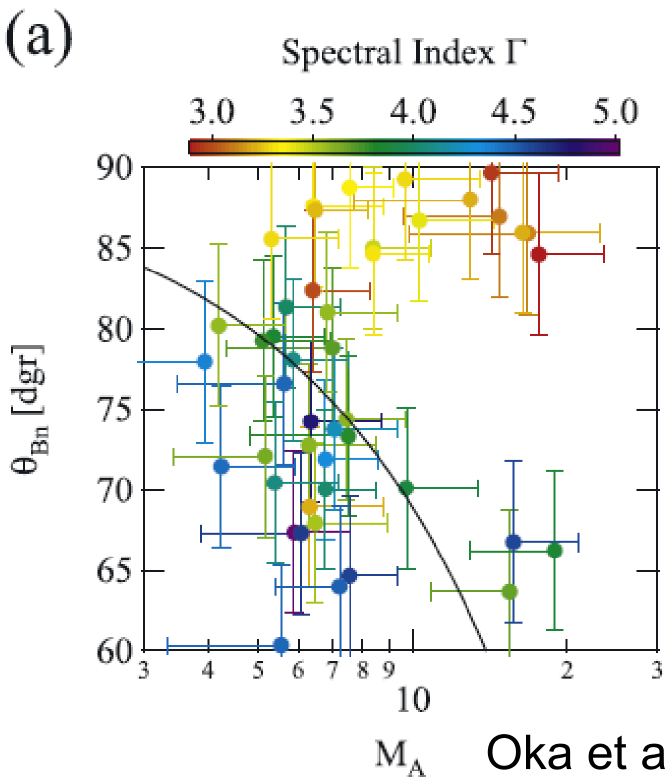


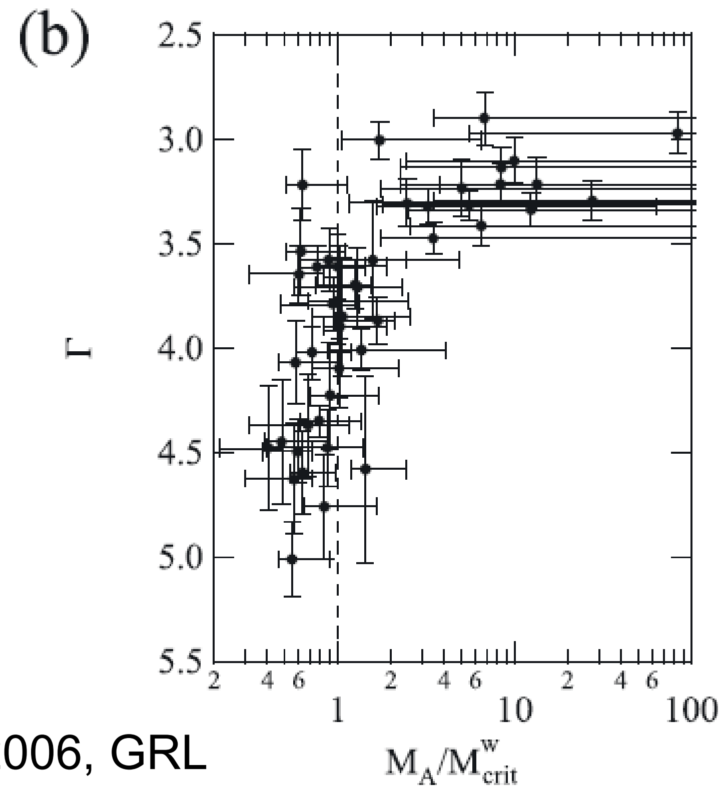


reduction of Mach number by a factor of ~ 43
it is only ~20 even at purely parallel shock

In-situ Measurements of Bow Shock

- spectral index (measured in the shock transition region) becomes harder for higher Mach number / shock angle
- regulated by *whistler critical Mach number* ...?
- no reasonable explanation at that time





Oka et al. 2006, GRL

Whistler Critical Mach Number

- it is defined as the point above which the whistler wave cannot propagate upstream (α=1 for the phase velocity, α=1.3 for the group velocity)

$$M_A^{\mathrm{whistler}} = \alpha \frac{\cos\theta_{Bn}}{2}\sqrt{\frac{m_i}{m_e}}$$

- it is very close to the critical Mach number for the electron injection (when β~1)

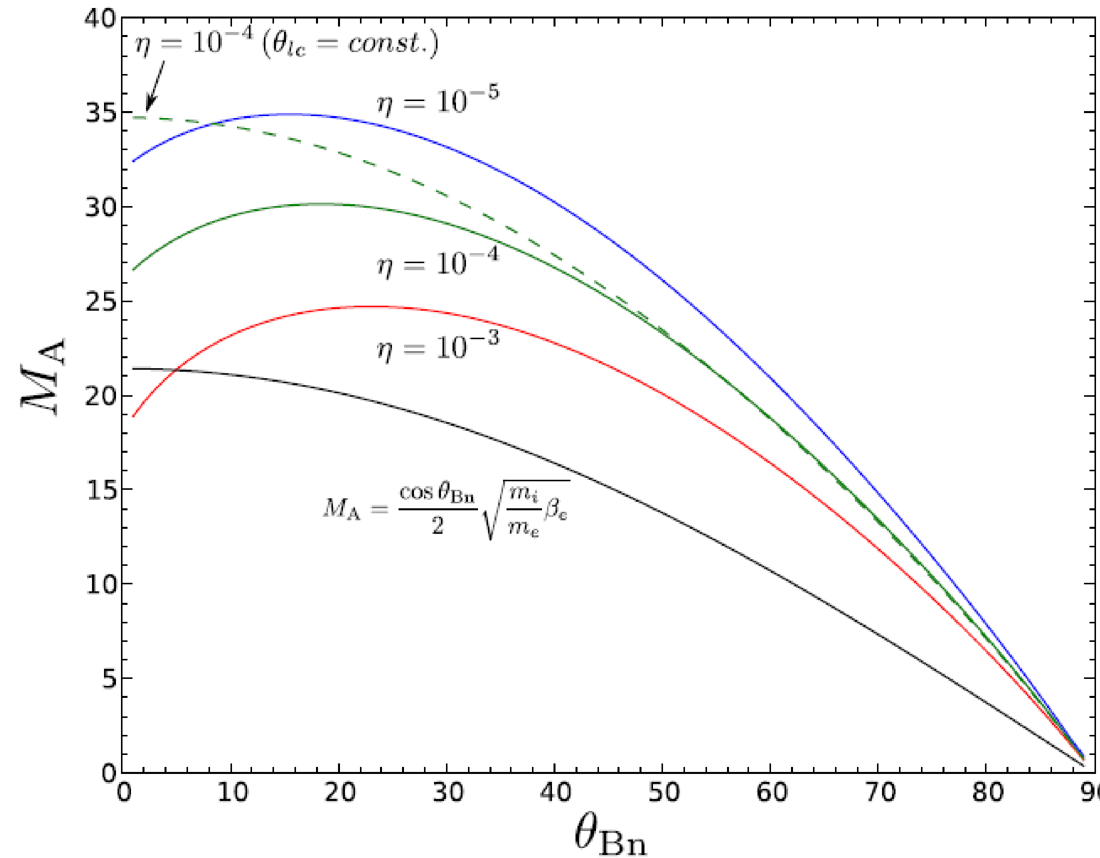
$$M_A^{\mathrm{inj}} = \frac{\cos\theta_{Bn}}{2}\sqrt{\frac{m_i}{m_e}\beta_e}$$

- *bow shock observations may be explained by this theory*

Details: Numerical Analysis

- basic caracteristics are well reproduced
- numerical solutions are typically larger than the analytical one in most cases

η: beam density



Details: Numerical Analysis

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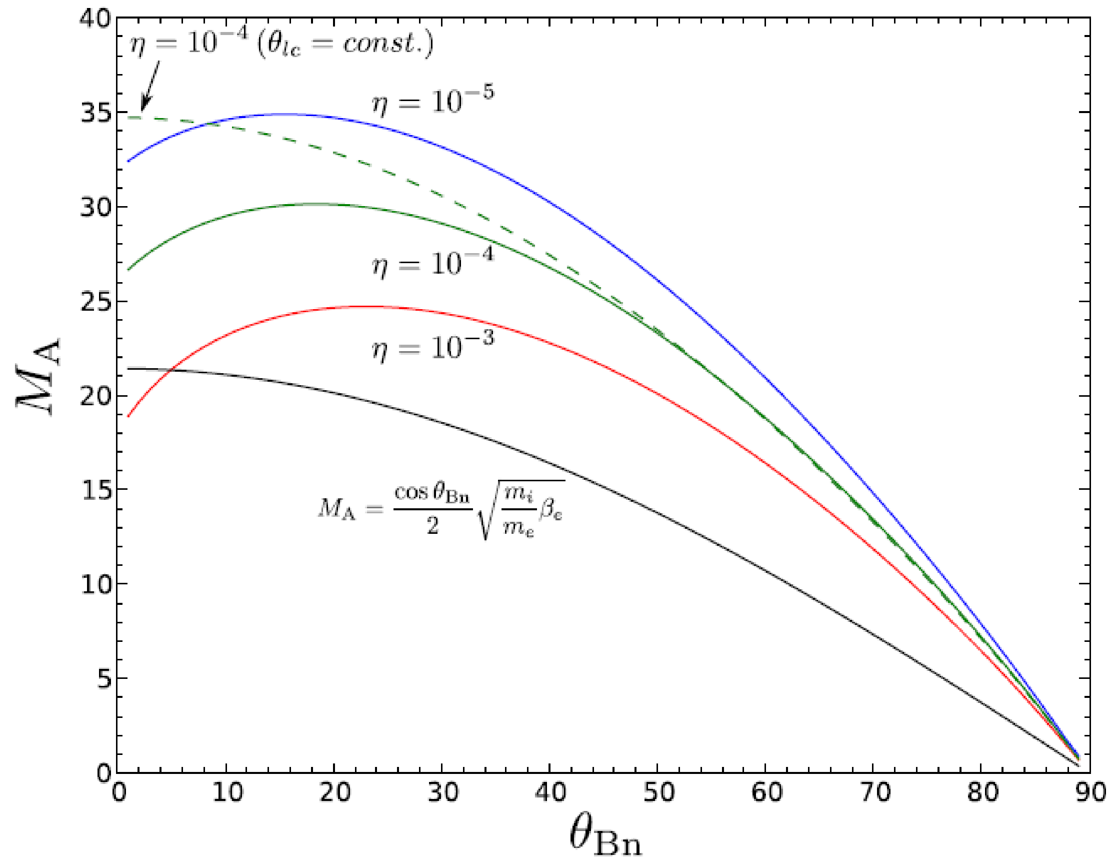
$$\xi = M_A^{\mathrm{inj*}} / M_A^{\mathrm{inj}}$$

- ξ ~ 1-3 for the parameter range of our interest

η: beam density



ξ~2 for the bow shock regime

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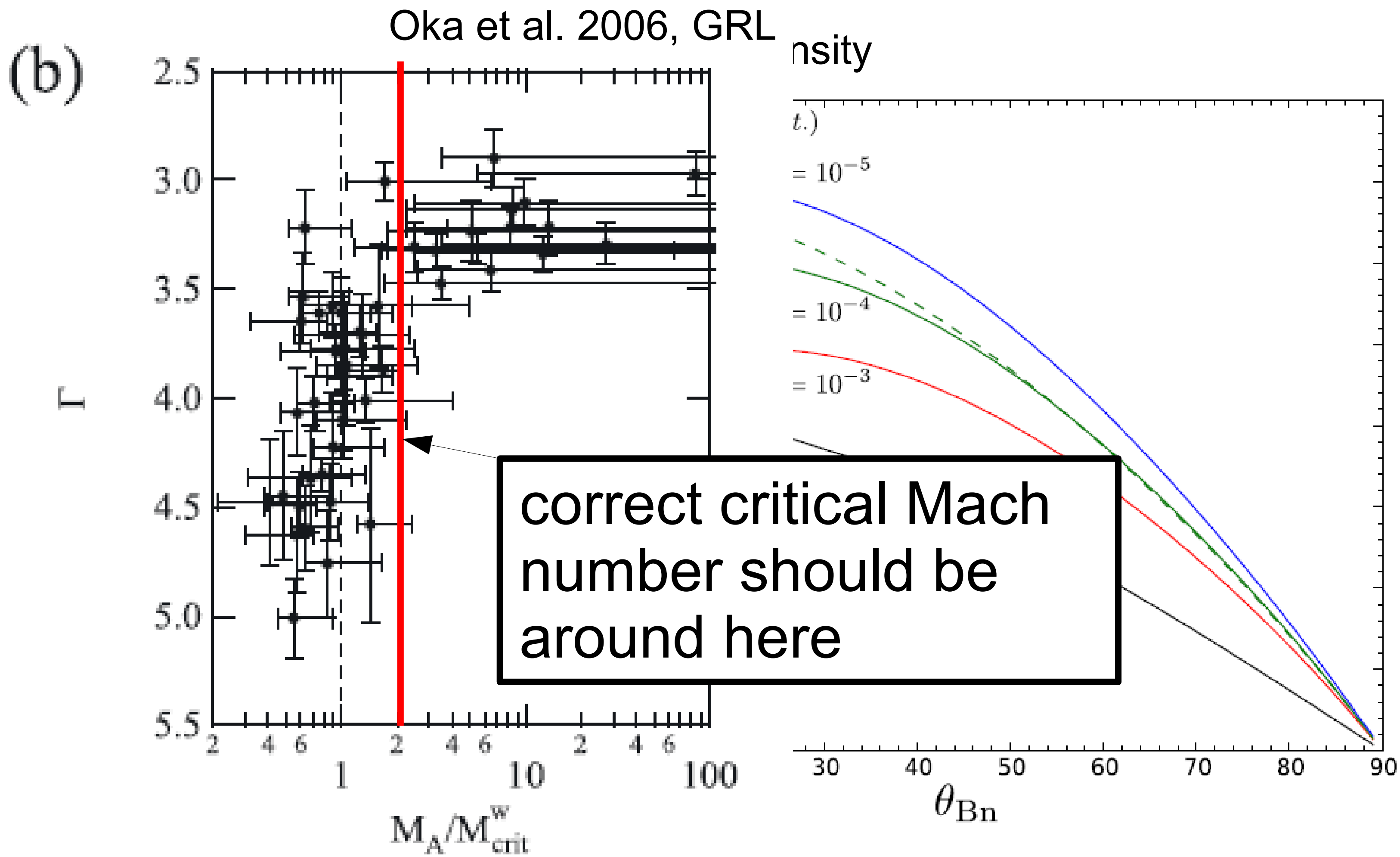


- ξ ~ 1-3
  parameter range of
  our interest

ξ~2 for the bow shock regime

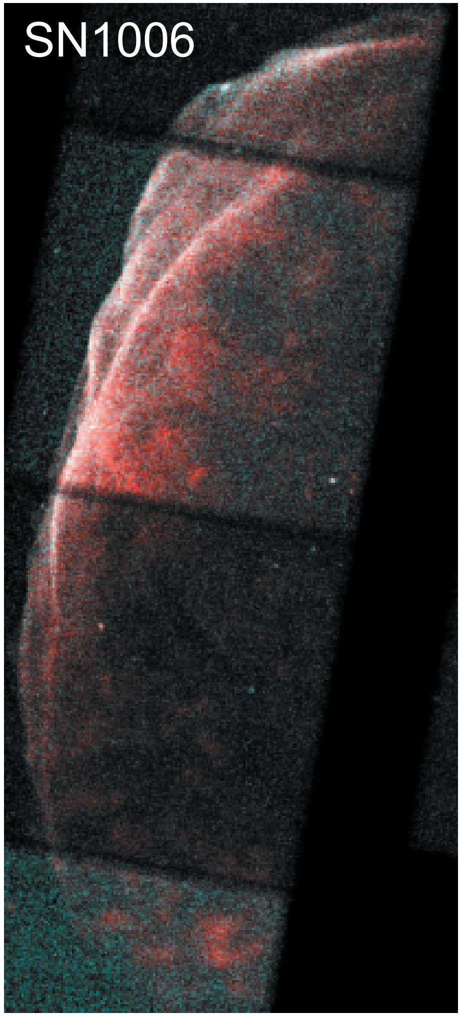
Summary

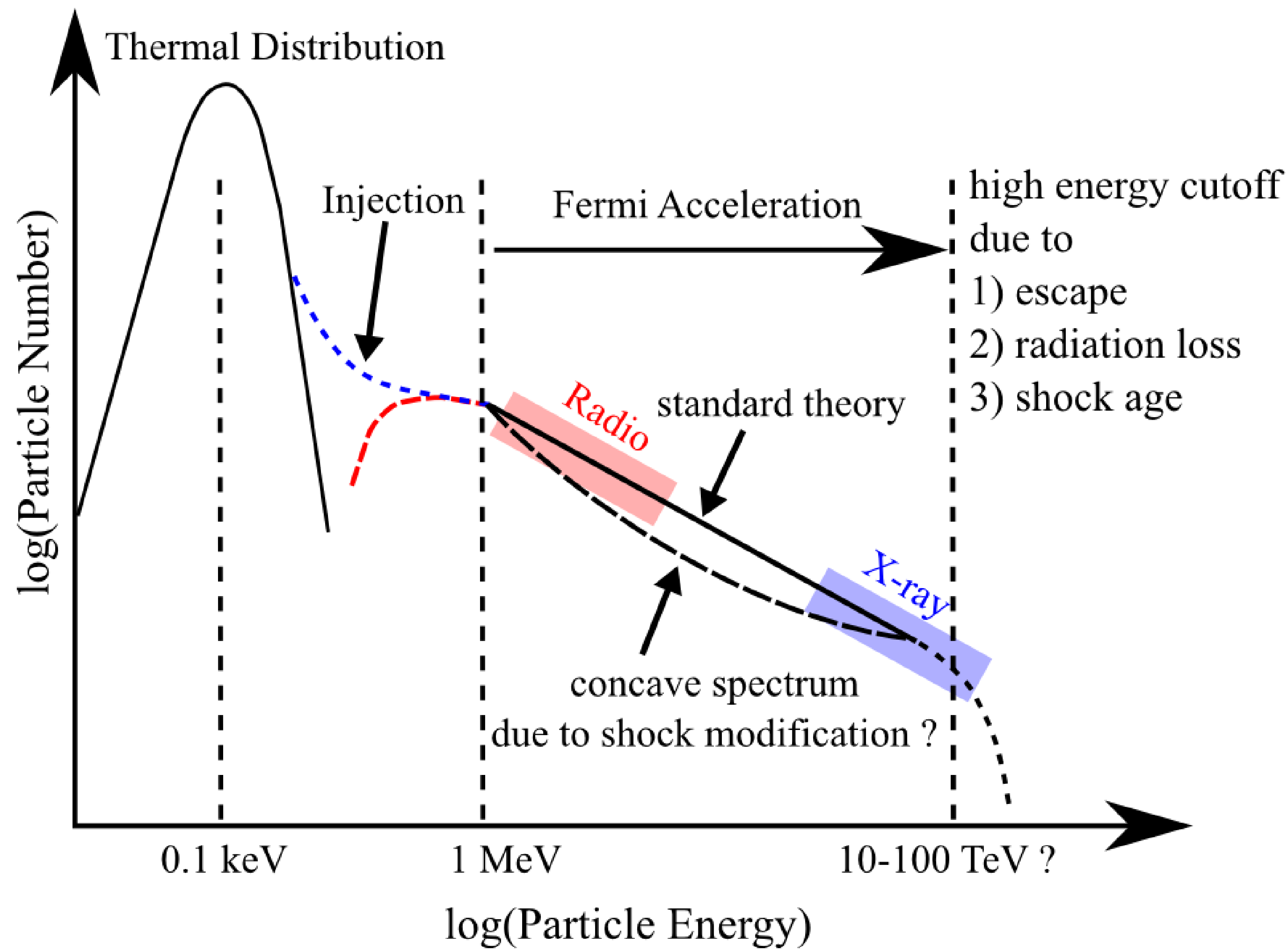
- a critical Mach number for the electron injection is obtained as a function of upstream parameters
- explains observations of the bow shock very well
- predicts that typical young SNR shocks are strong electron accelerators regardless of the magnetic field directions
- observational studies of the relationship between SNR age and acceleration efficiencies may be possible (explanation of dark particle accelerators ?)

$$\frac{M_A}{\sqrt{\beta_e}} \simeq 68 \left(\frac{V_s}{3000\mathrm{km/s}}\right)\left(\frac{T_e}{10\mathrm{eV}}\right)^{-1/2} \gtrsim 30$$

The End

Evidence for TeV energy electrons in SNRs





Electron acceleration seems to be efficient in SNR shocks, while it is not in the heliosphere probably due to the difference in Mach numbers

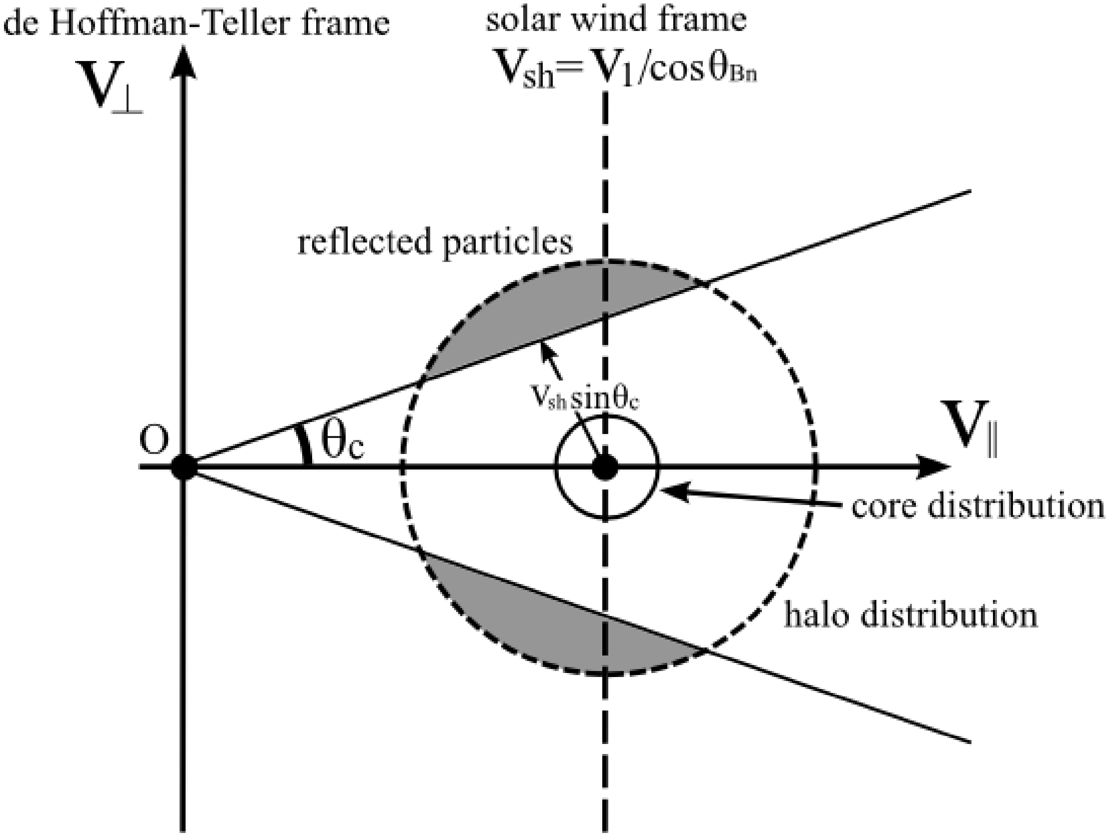
Shock Drift Acceleration (SDA)

[e.g., Wu 1984, Leroy & Mangeney 1984]

- electron dynamics is adiabatic since the gyroradius is much smaller than the shock thickness
- electron energy is conserved quantity in the HTF (where electric field = 0) → elastic reflection by the mirror force

$$\Delta p = 2mV_{\mathrm{sh}}/\cos\theta_{Bn}$$

- energy gain can be extremely large when
  - shock is nearly perpendicular
  - shock speed is high
- *the number of reflected particles decreases in these cases → shock surfing acceleration play a role*



particles outside the loss cone are adiabatically refleced back upstream due to the magnetic mirror

Numerical Modeling

- model $$f(v_\parallel, v_\perp) = \frac{1}{2\pi V_r}\delta(v_\parallel - V_b)\delta(v_\perp - V_r)$$
  - loss-cone beam is approximated by cold ring-beam velocity distribution, which is fully characterized by the upstream parameters (M_A and θ_{Bn})
  - except for the beam density, corresponding to the injection rate
  - linear cyclotron damping rate is calculated from hot plasma dispersion relation (without beam)

total growth rate should be positive to account for the electron injection → critical Mach number