Theory and Simulations of Particle Acceleration in Collisionless Non-relativistic Shocks

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In collaboration with:
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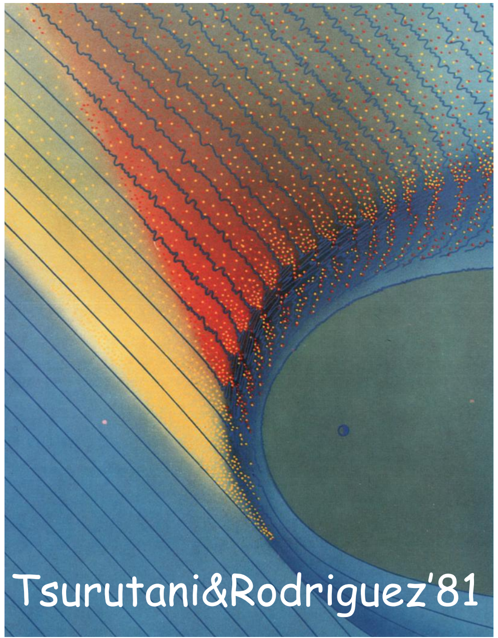
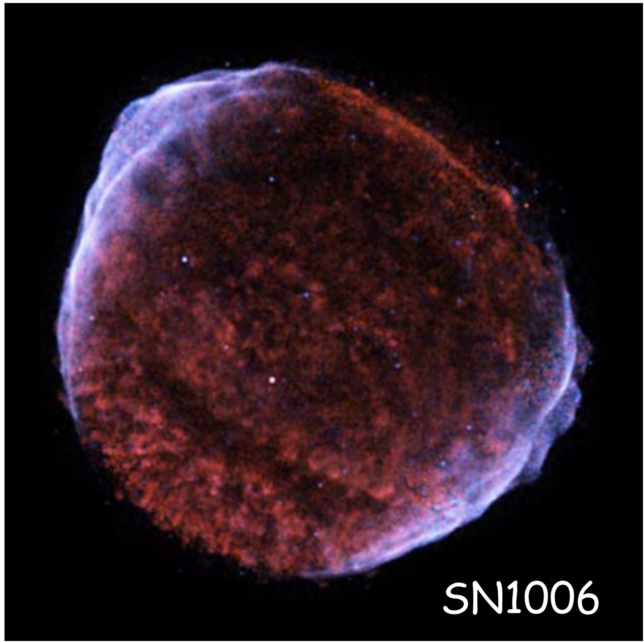
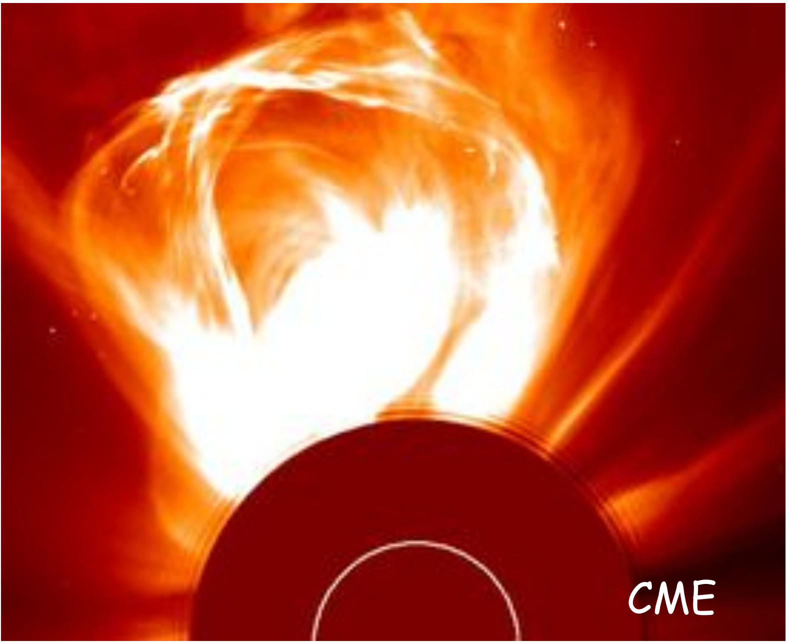
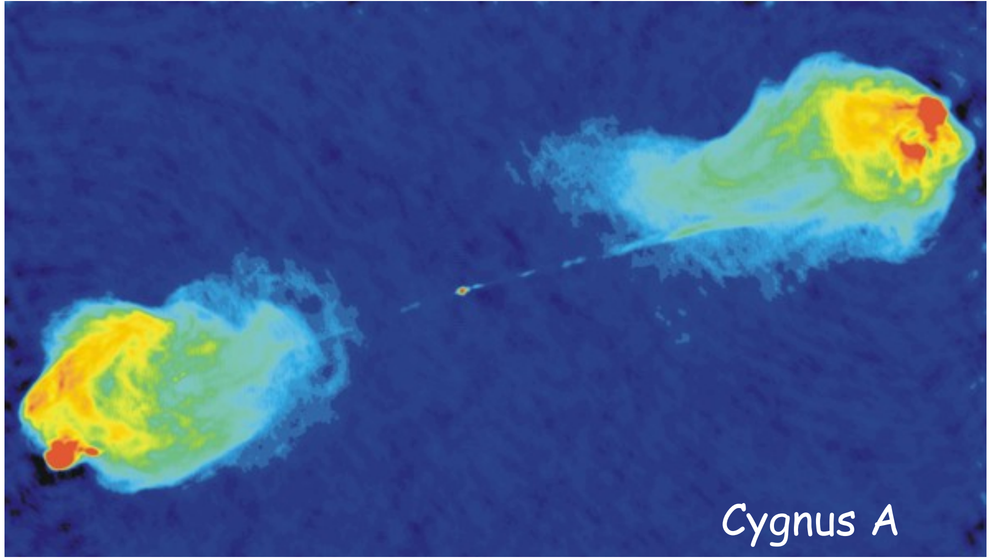
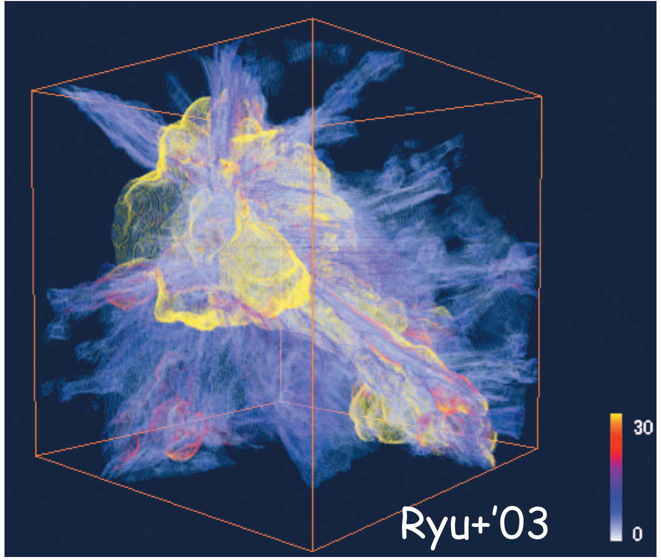
Shocks in the Universe


Tsurutani&Rodriguez'81

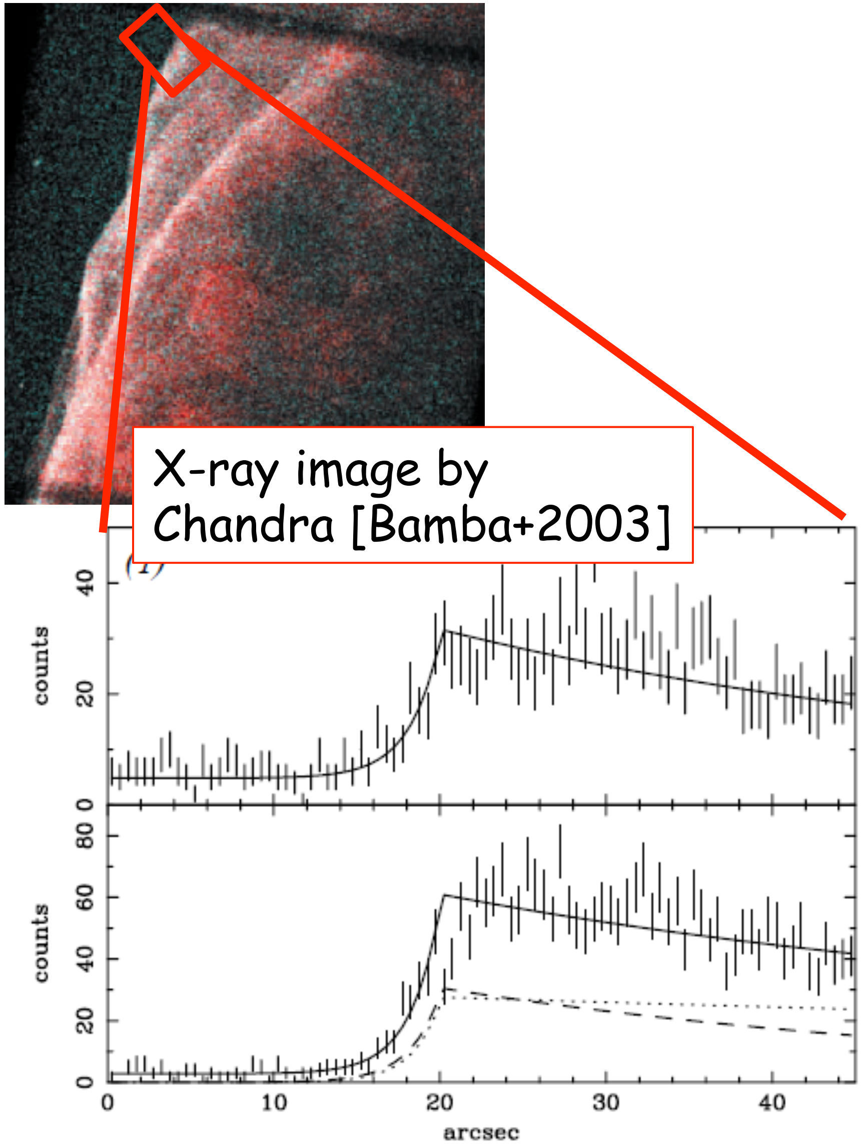

SN1006


CME

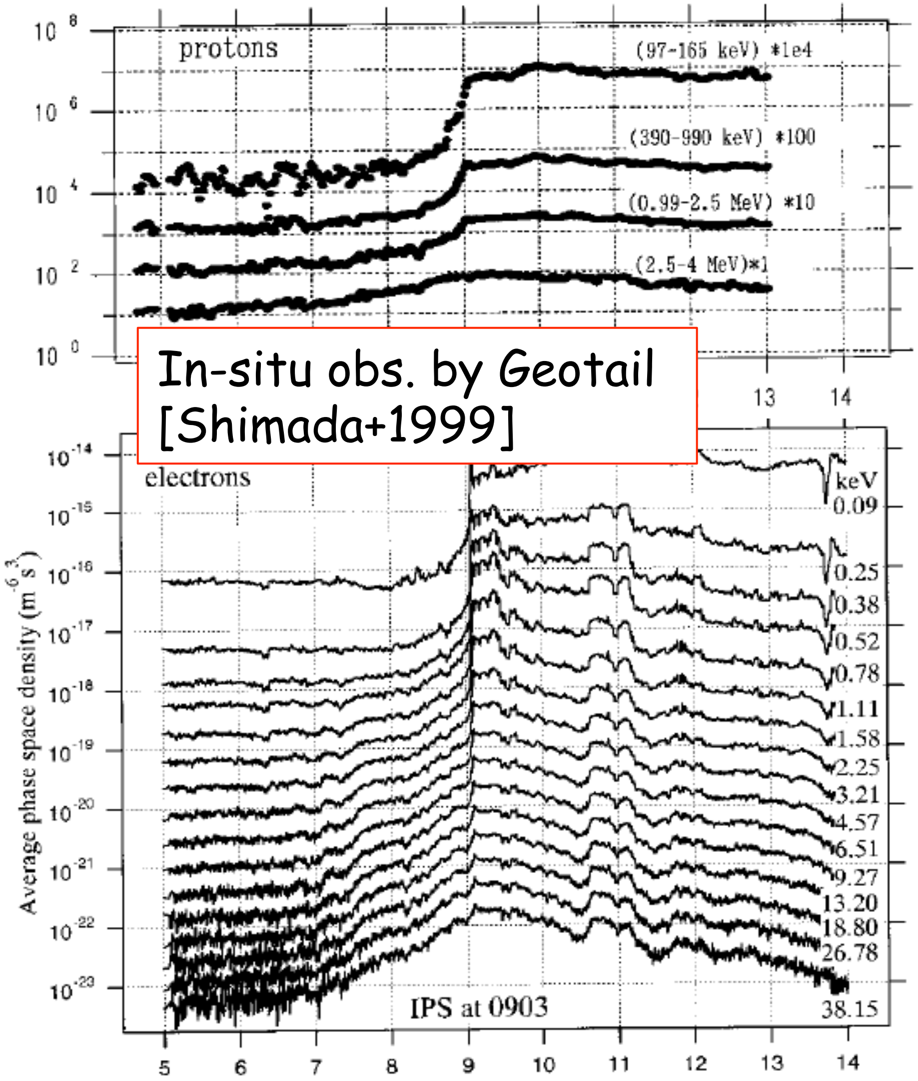

Cygnus A


Ryu+'03

Particle Acceleration



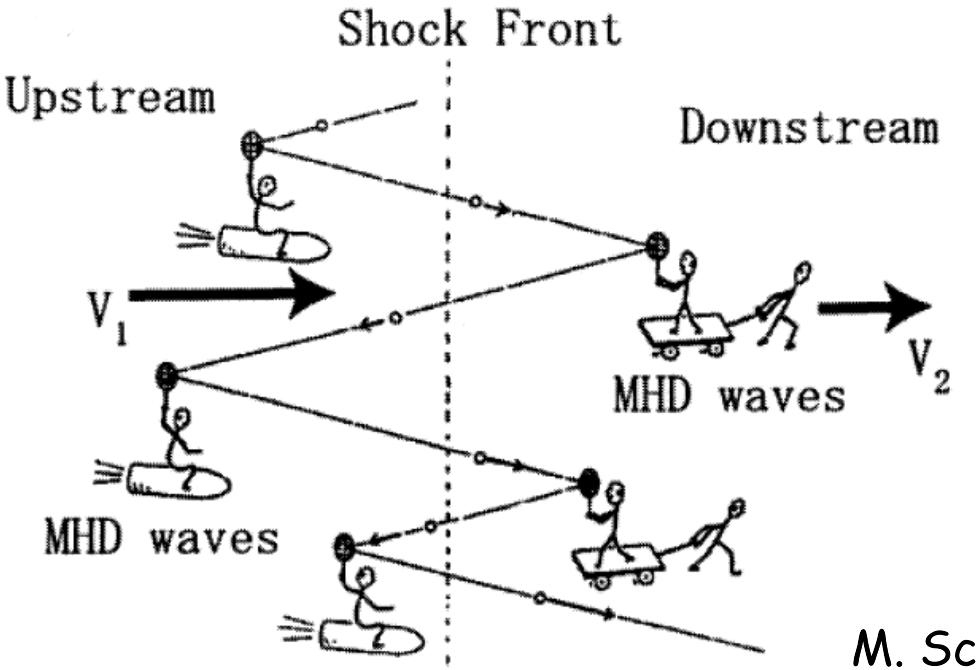
X-ray image by Chandra [Bamba+2003]



In-situ obs. by Geotail [Shimada+1999]

“Standard Model”

- Diffusive Shock Acceleration (DSA)
  - established in late 70’s [e.g., Bell ’78]
  - predicts a universal power-law; $N \propto E^{-2}$
  - simple; comparison with observations is relatively easy



M. Scholer

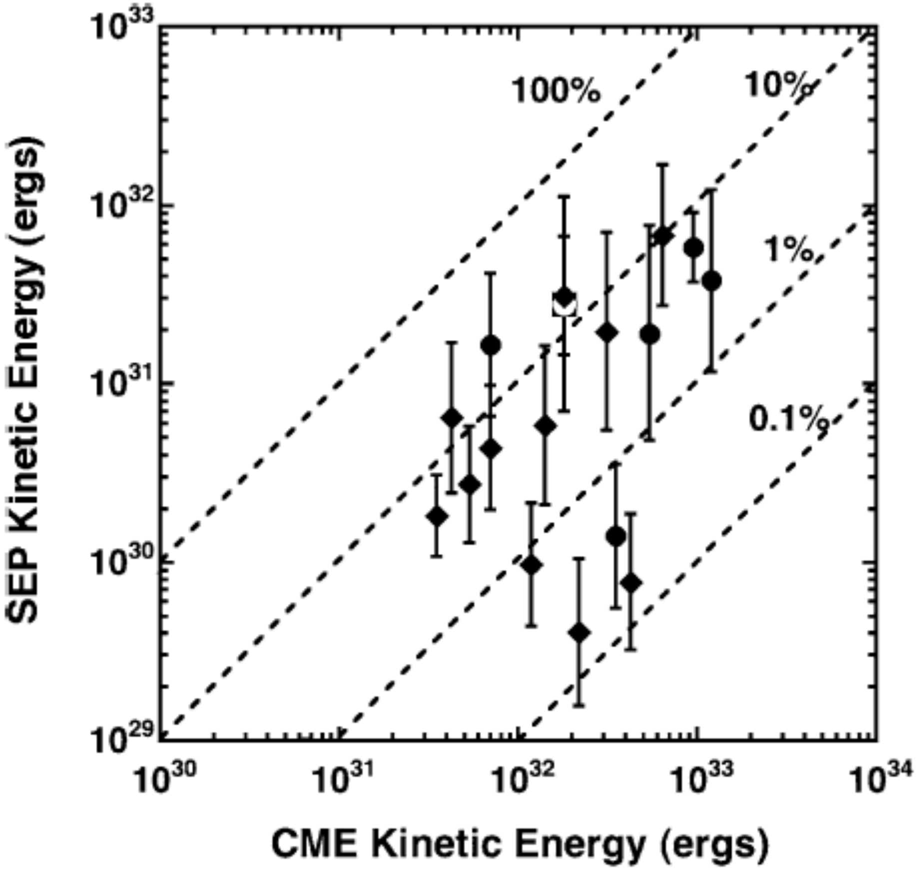
Questions

1. What fraction of the total energy is converted into accelerated particles ?
2. What is the maximum particle energy achievable ?

Key Issues

- Injection
- Nonlinear Feedback
- Particle Transport

Energetics



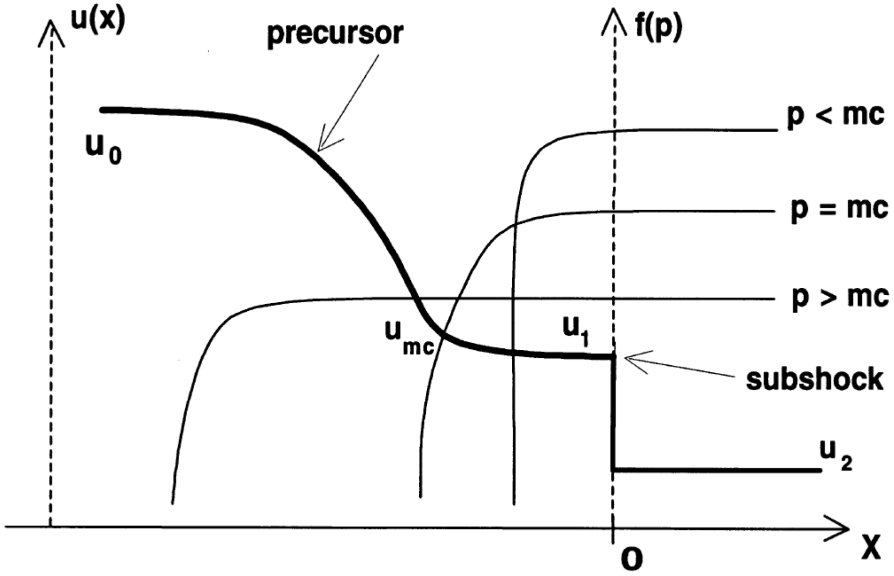
Energy conversion efficiency ~ 10% ? (needed for SNRs)

Not bad at CME-driven shocks. But, the maximum energy is much smaller.

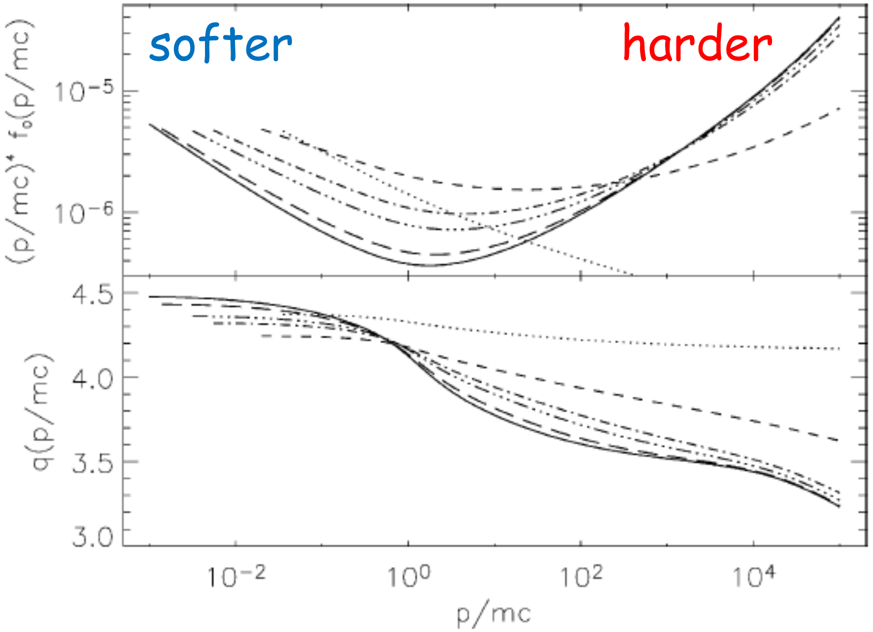
Mewaldt+(2006)

Positive Feedback

DSA is an intrinsically efficient process !



Berezhko & Ellision (1999)



Amato & Blasi (2005)

Recall that the standard DSA theory predicts the spectrum of the form:

$$f(p) \propto p^{-q} \qquad q = \frac{3r}{r-1}$$

(r is the shock compression ratio)

Possible Negative Feedback ?

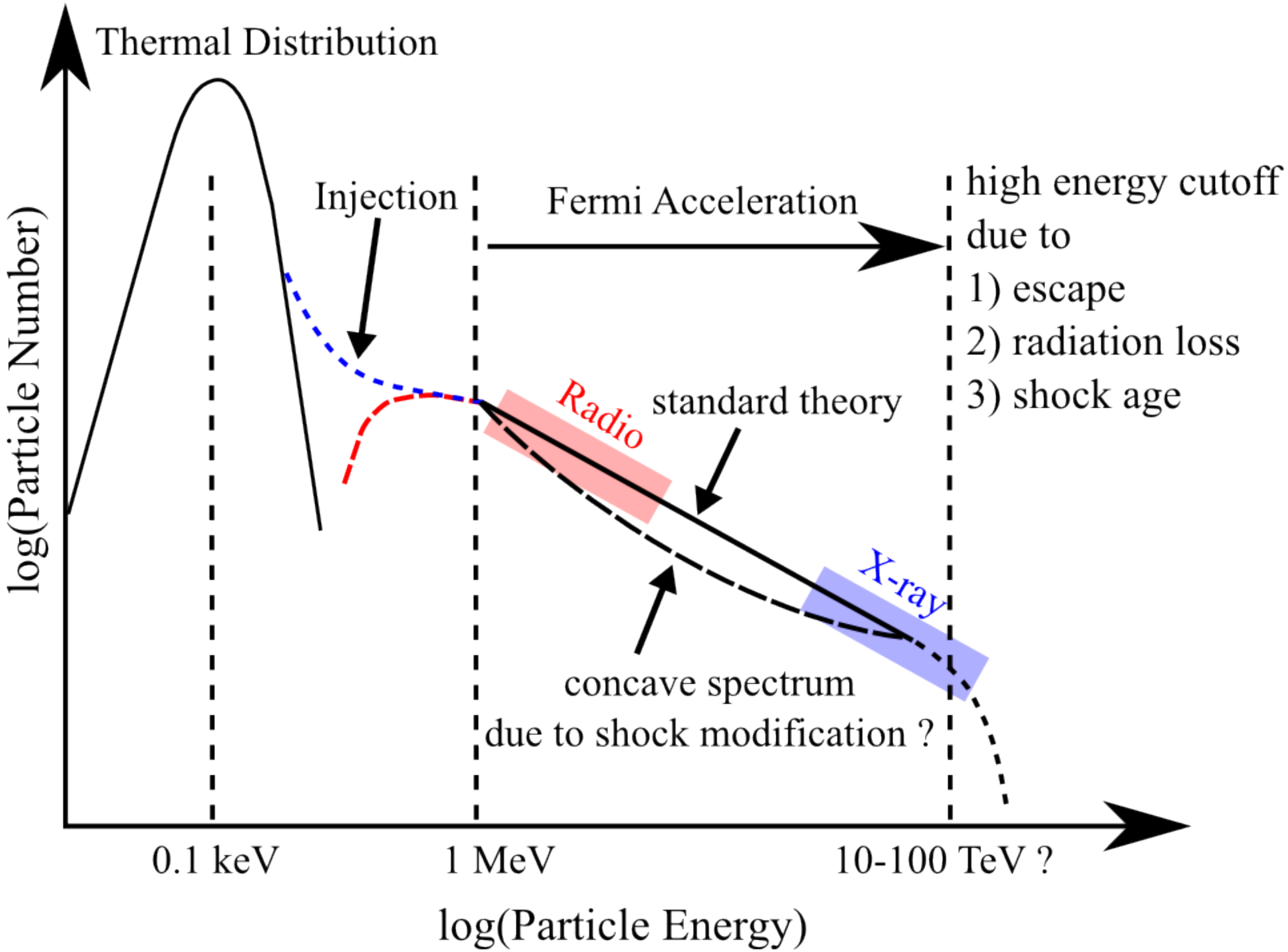
- Injection

  If the injection occurs predominantly at the subshock, the reduction of Mach number in the precursor may lower the injection rate.

- Turbulent Heating

  Turbulence driven by streaming CRs in the precursor becomes so strong, so that one expects turbulent dissipation may reduce the overall efficiency.

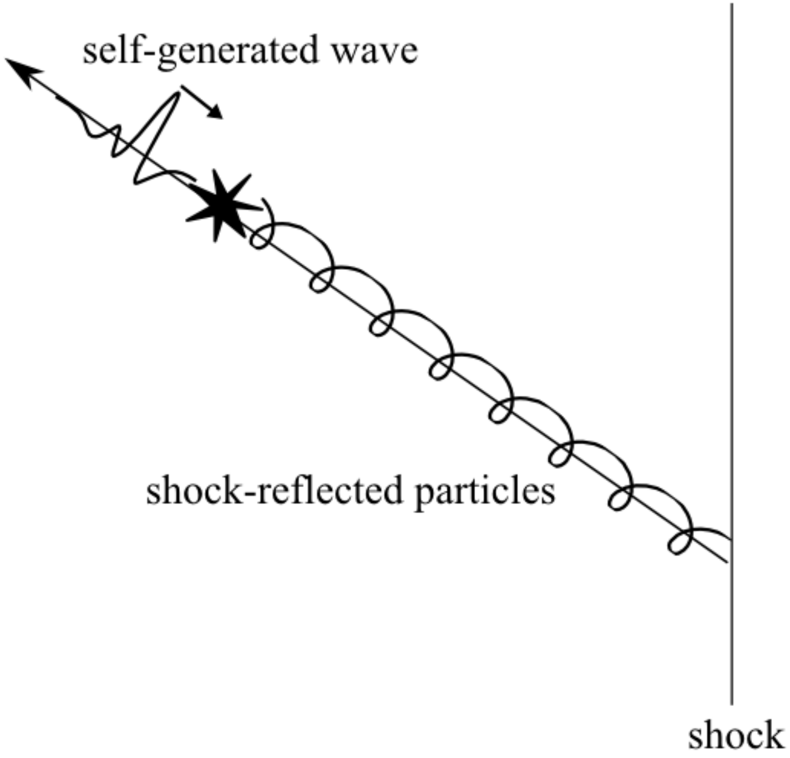
Injection


Thermal Distribution
Injection
Fermi Acceleration
high energy cutoff
due to
1) escape
2) radiation loss
3) shock age
Radio
standard theory
X-ray
concave spectrum
due to shock modification ?
log(Particle Number)
0.1 keV
1 MeV
10-100 TeV ?
log(Particle Energy)

The Injection Problem

The seed population must have sufficiently large energy so that they

- easily traverse the shock: $v \gg V_{shock}$
- scatter by waves for isotropization



cyclotron resonance condition

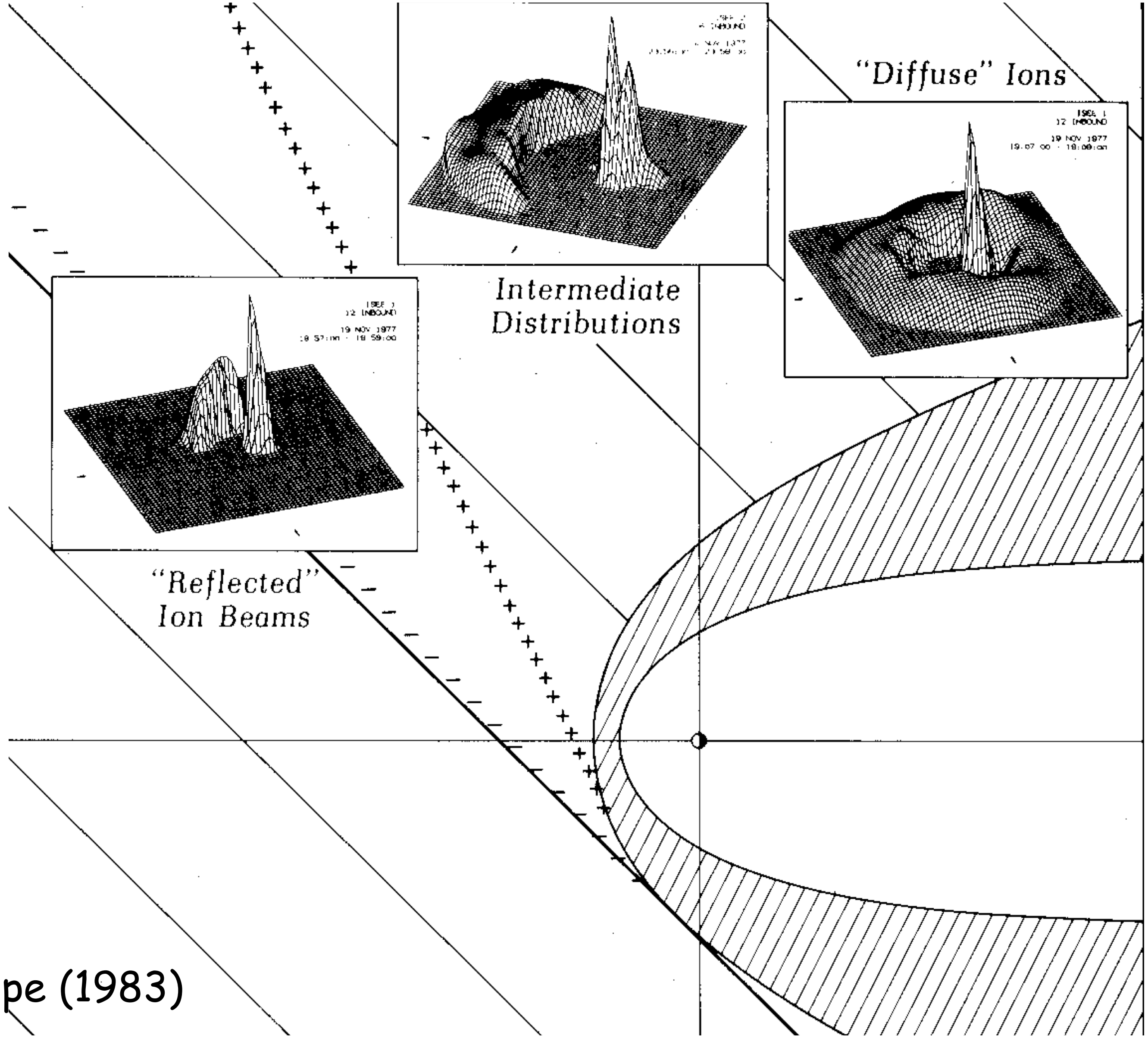
$$\omega - k v_{\parallel} = \Omega/\gamma$$

$$\Big\downarrow \quad \text{for } \omega \ll \Omega/\gamma$$

$$k r_g \sim 1$$

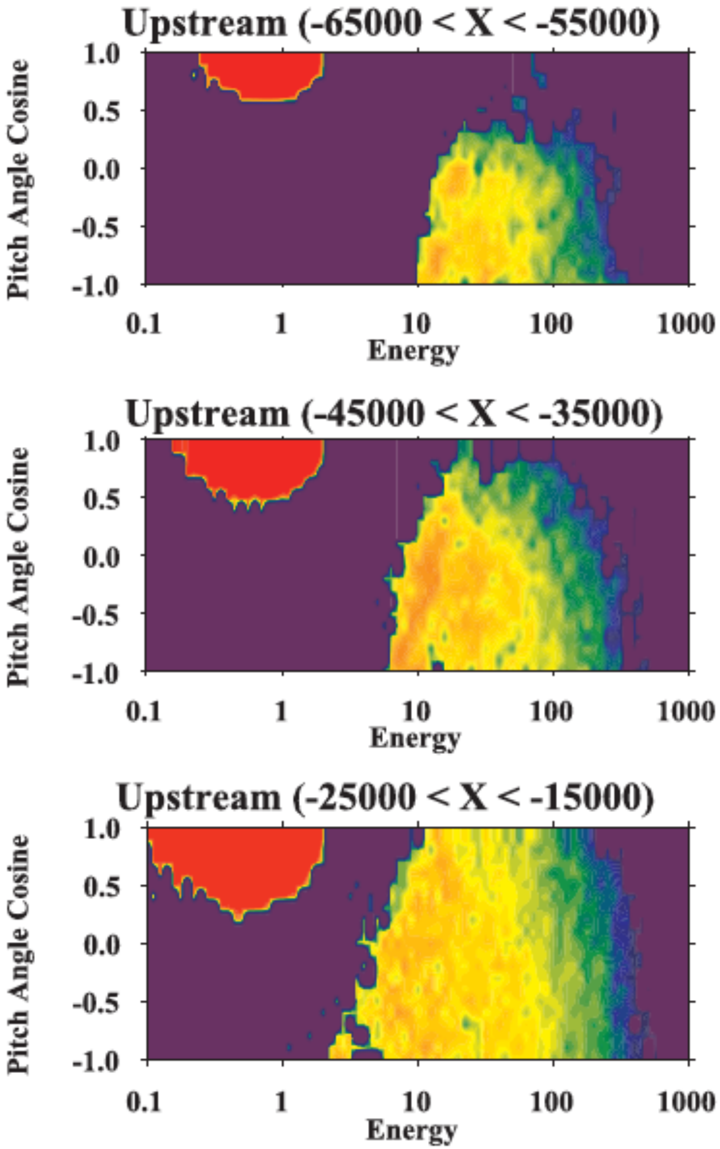
relatively easy for ions, but serious difficulty for electrons

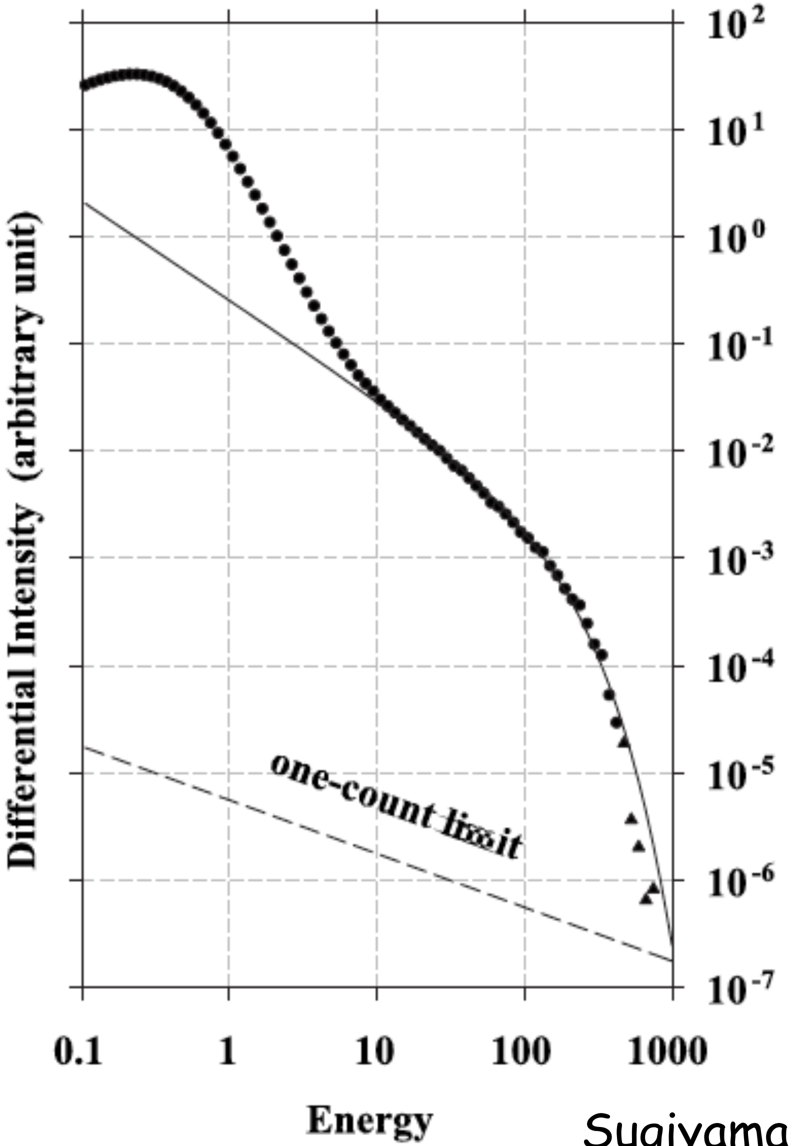
Protons



Russell & Hoppe (1983)

Protons





Sugiyama (2011)

Electrons

Only relativistic electrons can satisfy the resonance condition with low-frequency MHD waves

$$\omega - k v_{||} = \Omega / \gamma$$

Possible solutions to the electron injection problem:

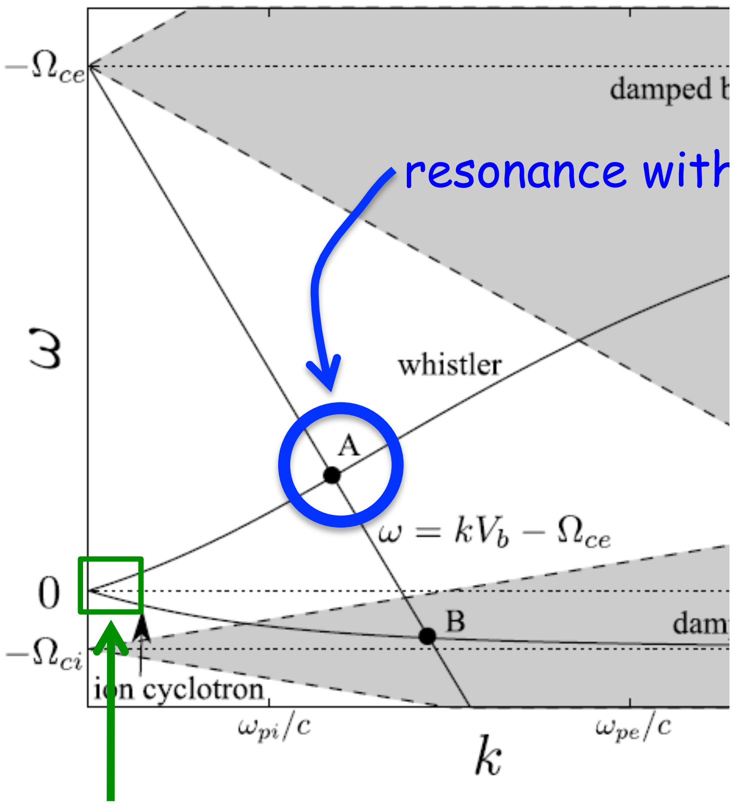
✧ Generation of high-frequency (whistler) waves

or

✧ Pre-acceleration to > 100keV

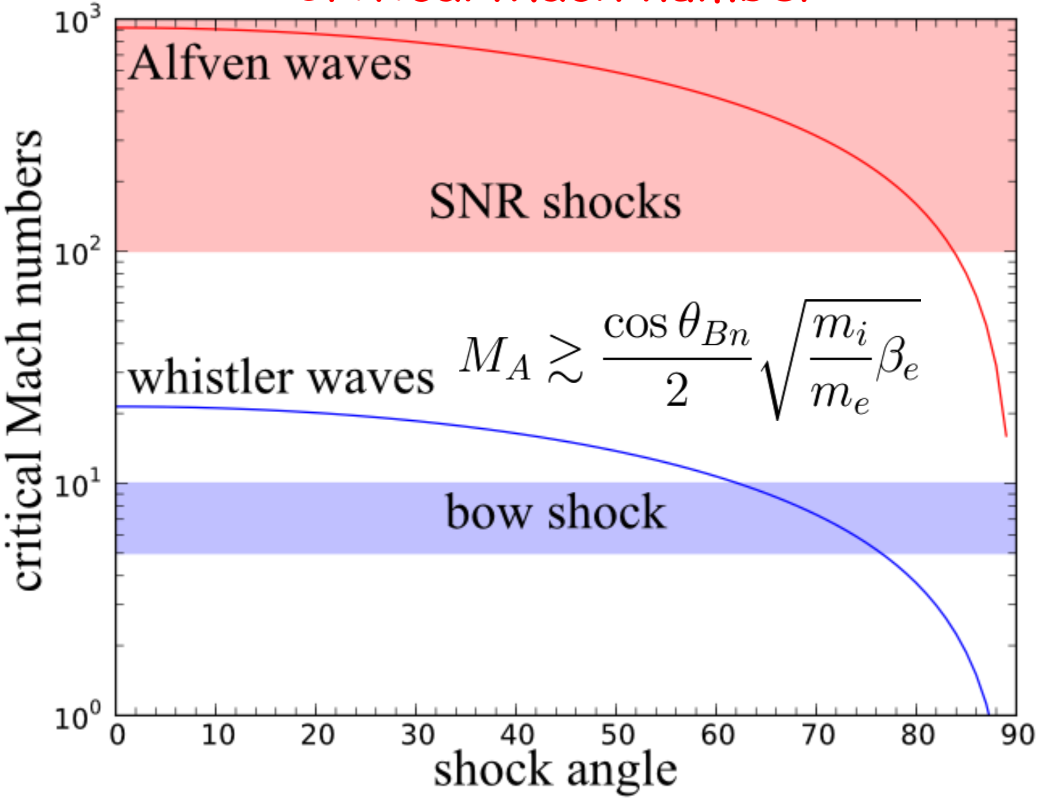
Generation of whistlers

Q : How to generate whistlers ?
A : Consider mirrorly reflected energetic electrons.



MHD regime
(Alfven waves)

Critical Mach number

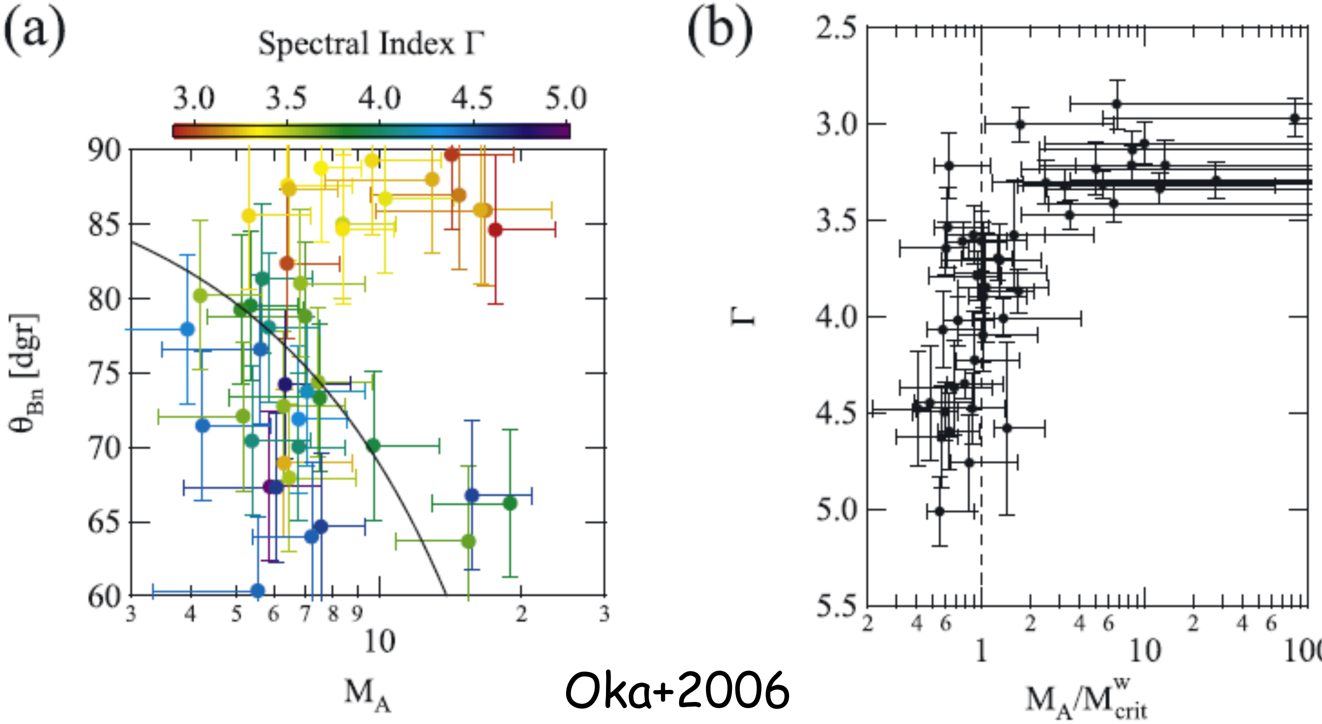


Amano & Hoshino (2010, PRL)

In-situ Observations

Oka+2006 argued that the electron acceleration efficiency at the bow shock is regulated by a whistler critical Mach number M_{crit}^{w}

This *by chance* corresponds to the critical Mach number of ours (within a numerical factor ~1)



Oka+2006

Critical Mach number used by Oka+2006

$$M_A^* \sim \alpha \frac{\cos\theta_{Bn}}{2}\sqrt{\frac{m_i}{m_e}}$$

⇕

Our definition of critical Mach number

$$M_A \sim \frac{\cos\theta_{Bn}}{2}\sqrt{\frac{m_i}{m_e}\beta_e}$$

Note: $\alpha \sim \beta_e \sim 1$

First Principles Approach

To understand possible pre-acceleration mechanisms:

- Shock internal structure
- Kinetic instabilities
- Plasma waves

must be considered. This involves extremely complicated nonlinear physics. Fully kinetic Particle-In-Cell simulation is the only option to investigate the mechanisms.

Caveat:

Any (!) simulations employ artificial parameters such as

- ion-to-electron mass ratio: mi/me
- plasma-to-cyclotron frequency ratio: $\omega_{pe}/\Omega_{ce} \propto v_A$

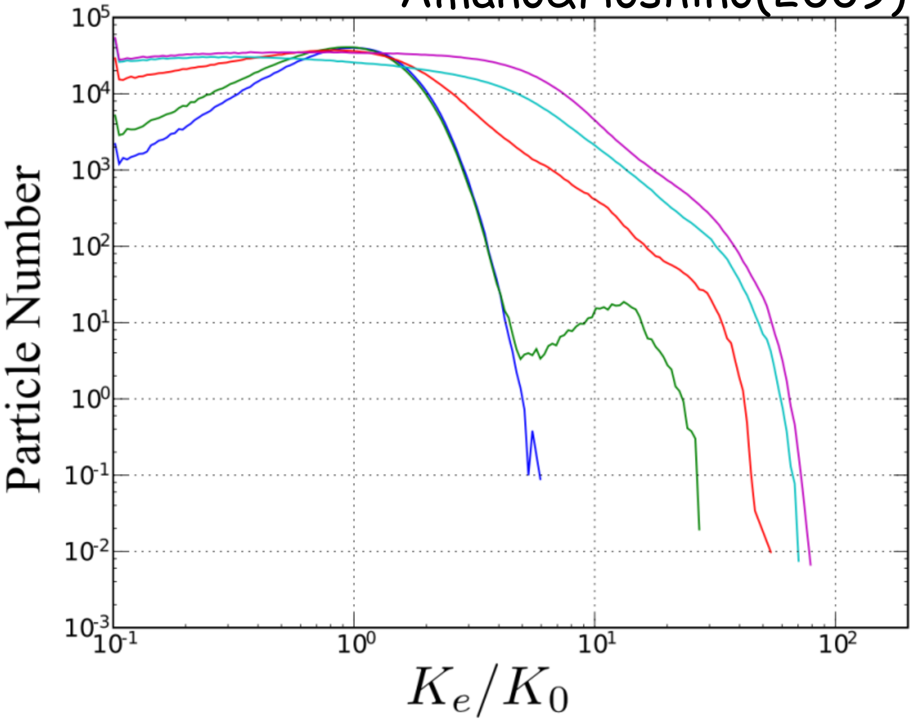
Unfortunately, plasma instabilities are sometimes sensitive to these parameters.

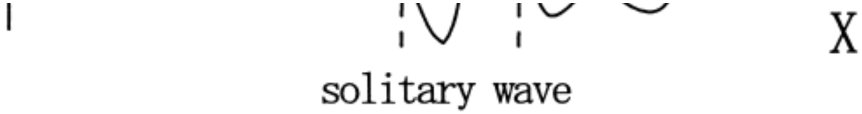
Shock Surfing Acceleration

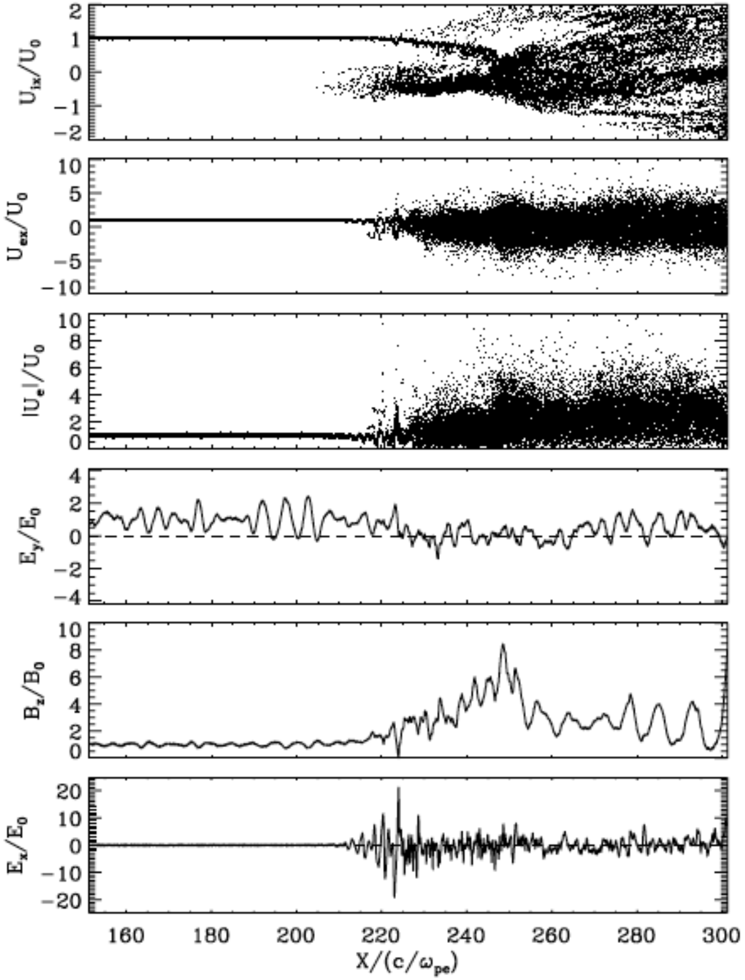
Plausible mechanism at very high Mach number shocks:

- 1D : McClements+(2001), Hoshino&Shimada(2002), Amano&Hoshino(2007)
- 2D : Amano&Hoshino(2009), Matsumoto+(2012)

Amano&Hoshino(2009)

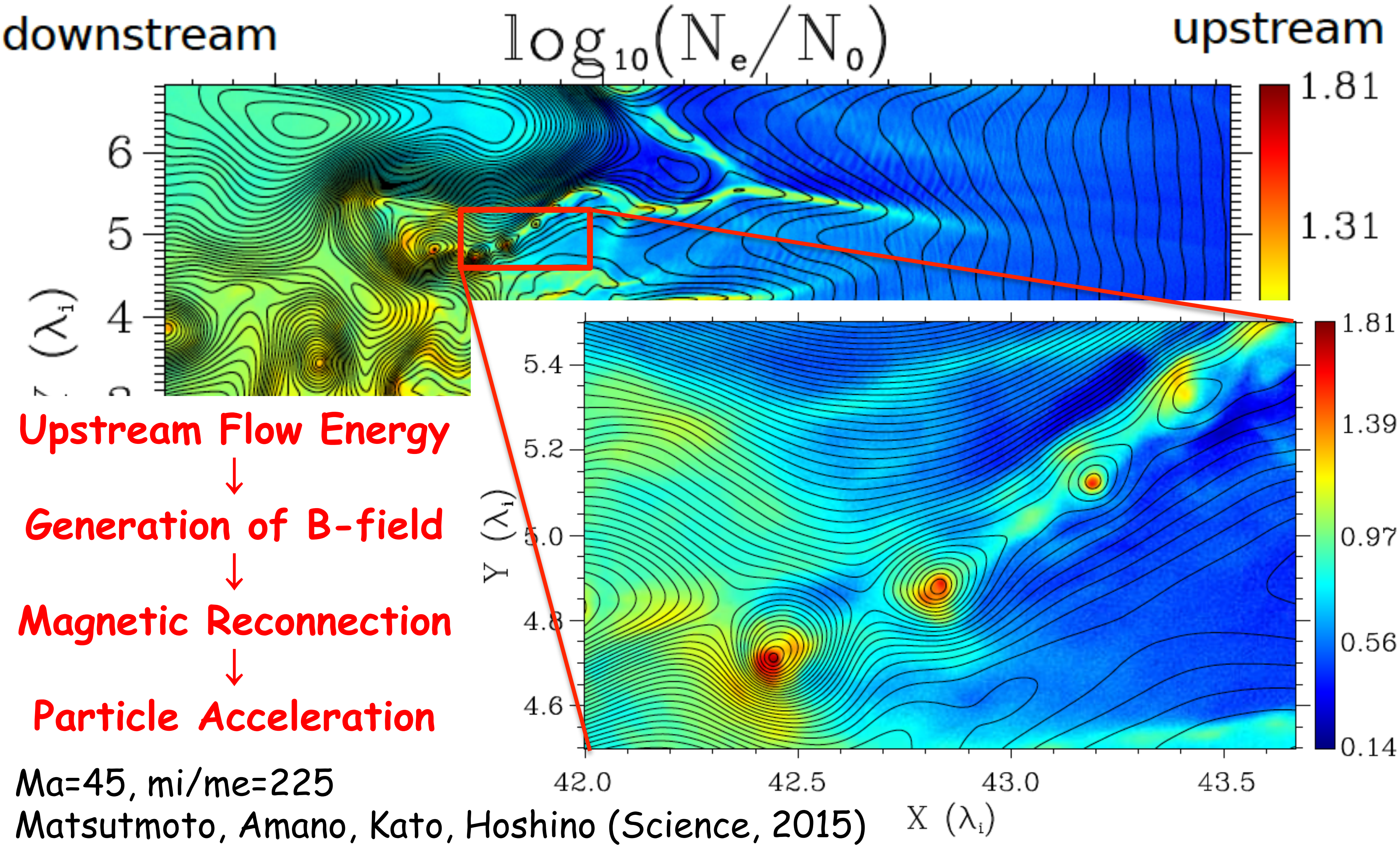






Hoshino&Shimada (2002)

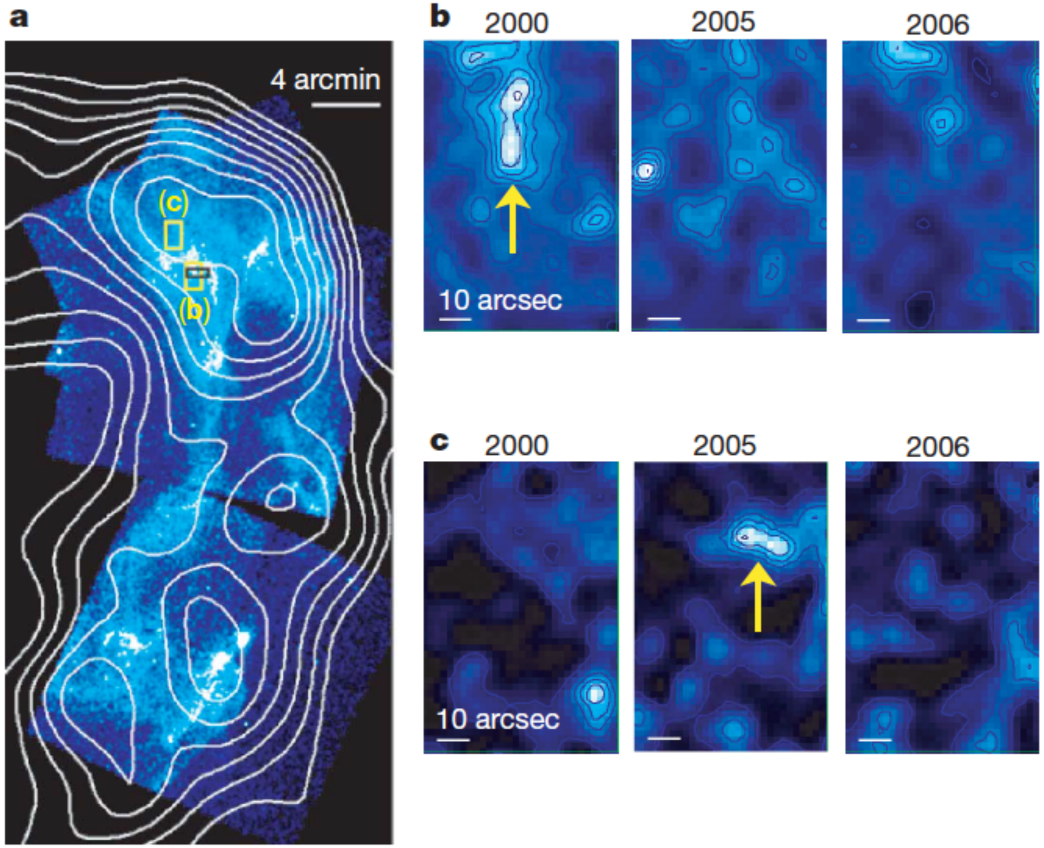
Spontaneous Reconnection



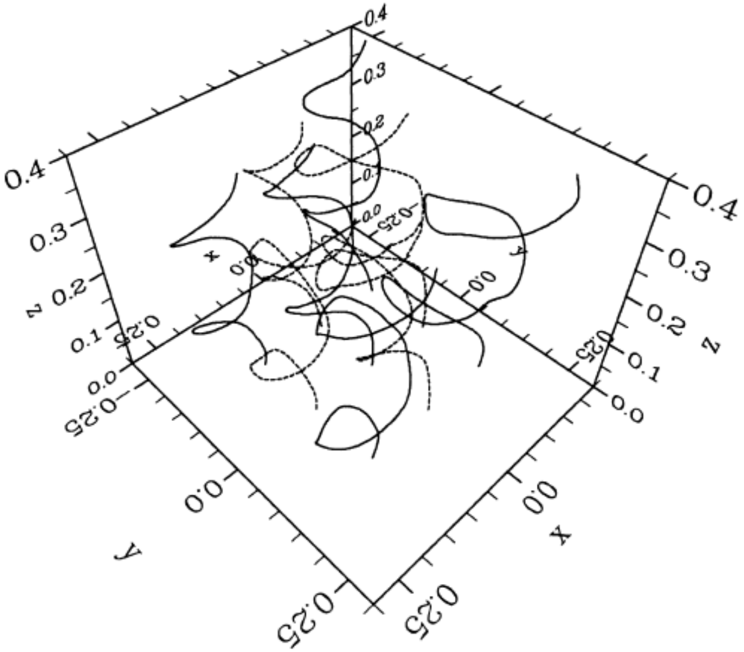
Upstream Flow Energy
↓
Generation of B-field
↓
Magnetic Reconnection
↓
Particle Acceleration

Ma=45, mi/me=225
Matsutmoto, Amano, Kato, Hoshino (Science, 2015)

Magnetic Field Amplification



Extremely fast decay of X-ray hot spots
Uchiyama+(2007, Nature)



Magnetic field amplification by CR streaming instability
Lucek&Bell(2000), Bell(2004)

Non-adiabatic Heating

Wave kinetic equation (for shear Alfven wave)

$$\frac{\partial}{\partial t}\left(\frac{\delta B^2}{4\pi}\right) + \frac{\partial}{\partial x}\left[\left(\frac{\delta B^2}{4\pi}\right)\left(\frac{3}{2}u - v_A\right)\right] = u\frac{\partial}{\partial x}\left(\frac{\delta B^2}{8\pi}\right) + \boxed{v_A\frac{\partial}{\partial x}P_c} - \boxed{L}$$

is coupled with the CR diffusion-convection and hydrodynamic equations.

Work done by CR pressure gradient (wave generation)

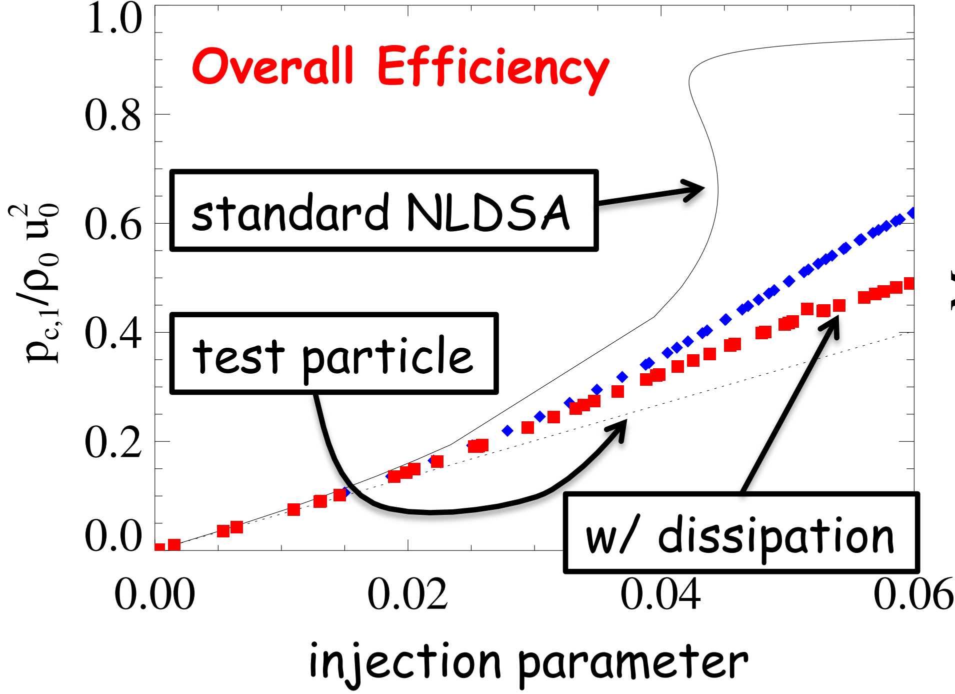
Dissipation of wave energy leading to entropy production

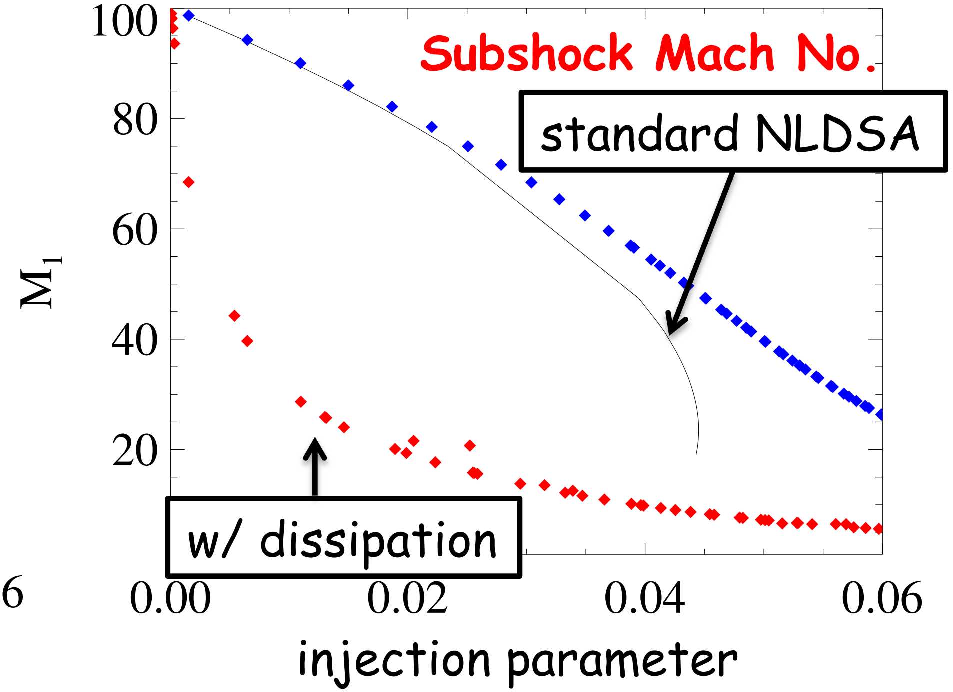
$$\frac{\rho^{\gamma-1}}{\gamma-1}u\frac{\partial}{\partial x}\left(\frac{P_g}{\rho^\gamma}\right) = L$$

Assumption of a specific form of dissipation: $L = \alpha v_A \frac{\partial P_c}{\partial x}$

[e.g., McKenzie & Voelk, 1982]

Semi-analytical Solution





Non-adiabatic heating substantially reduces the subshock Mach number ! The acceleration efficiency is degraded from the standard NLDSA solution, but yet resides above the test-particle limit.

T. Saito (Ph.D thesis)

Conclusions

- Particle acceleration efficiency of 10-20% (in terms of energy conversion rate) seems to be possible.
- Conventional understanding is that nonlinearity enhances the efficiency, in an essentially unlimited manner.
- There must be something that would suppress otherwise the unlimited acceleration.
- The injection and turbulence have yet remained the key issues in the shock acceleration theory.