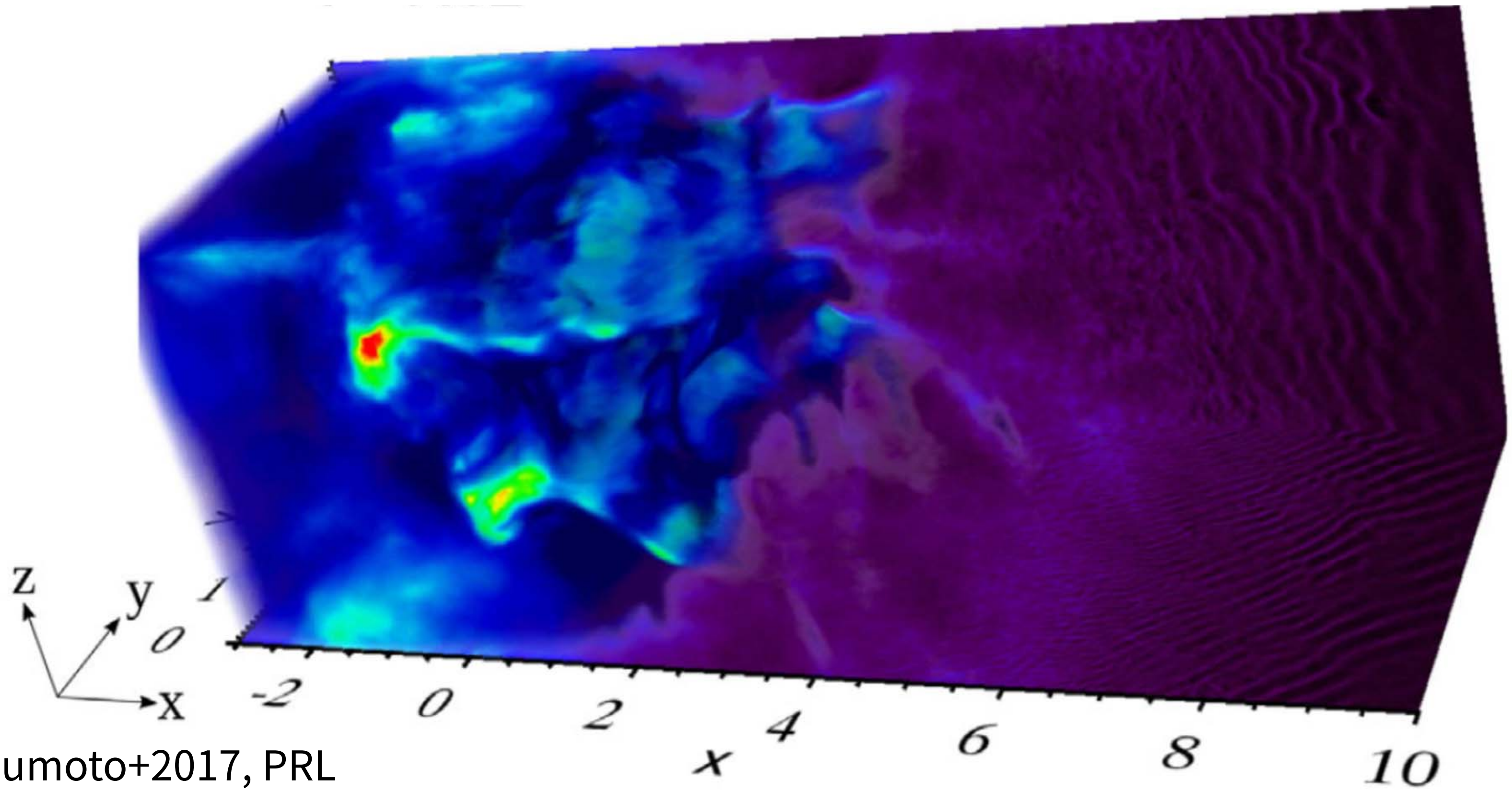
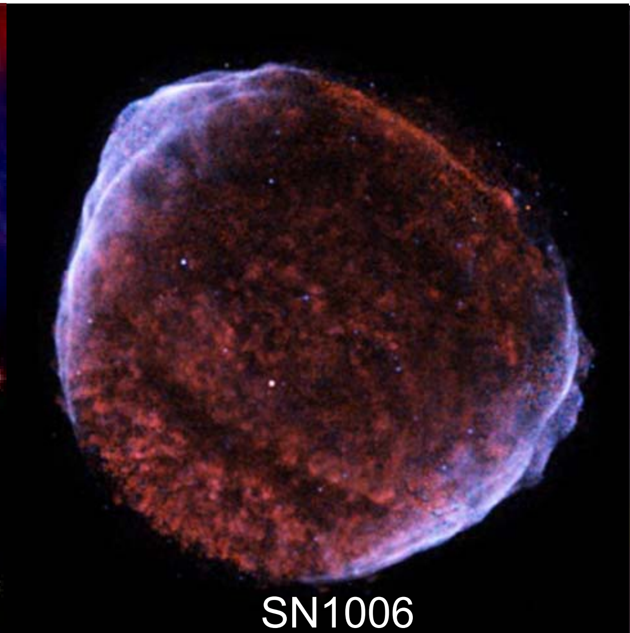
Stochastic Shock Drift Acceleration

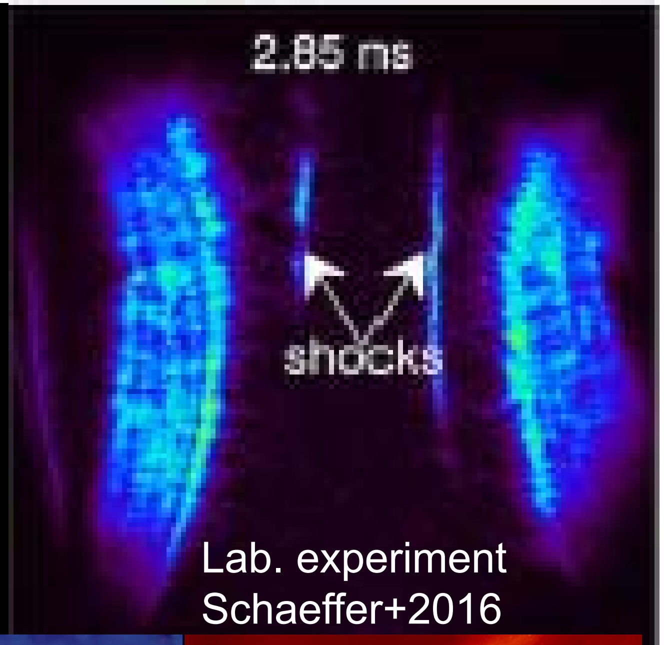


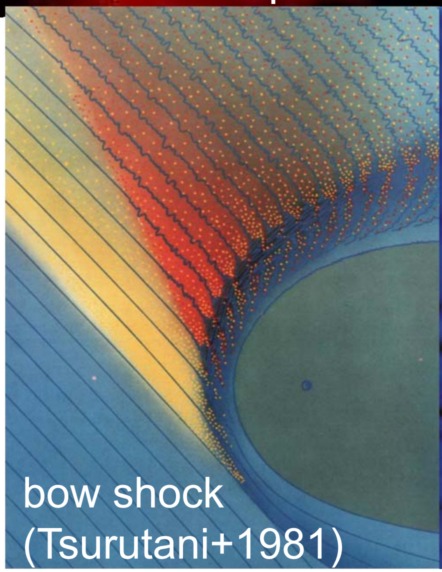
Matsumoto+2017, PRL

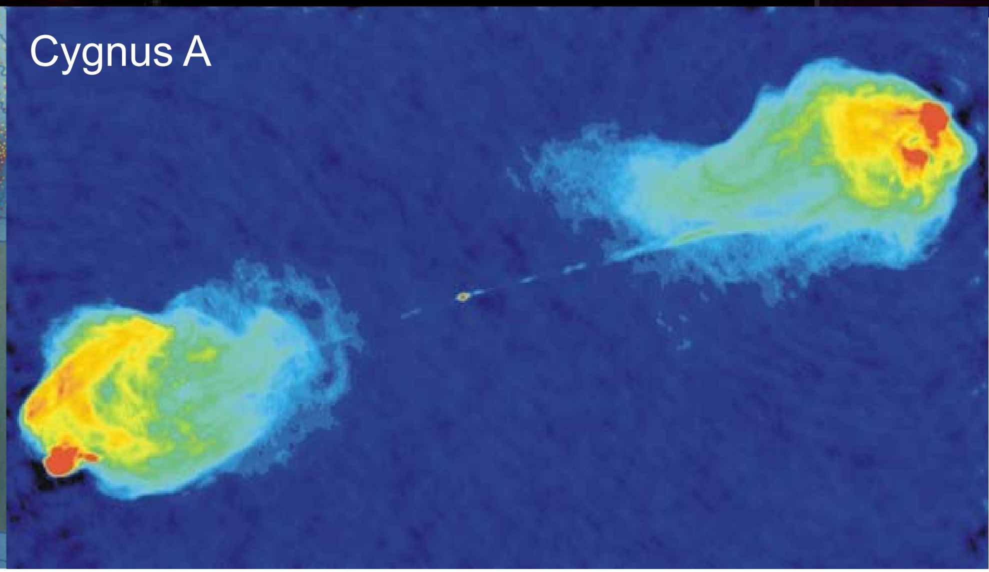
Takanobu Amano[1]
T. Katou[1], Y. Matsumoto[2], M. Oka[3], M. Hoshino[1]
[1] University of Tokyo, [2] Chiba University [3] UC Berkeley

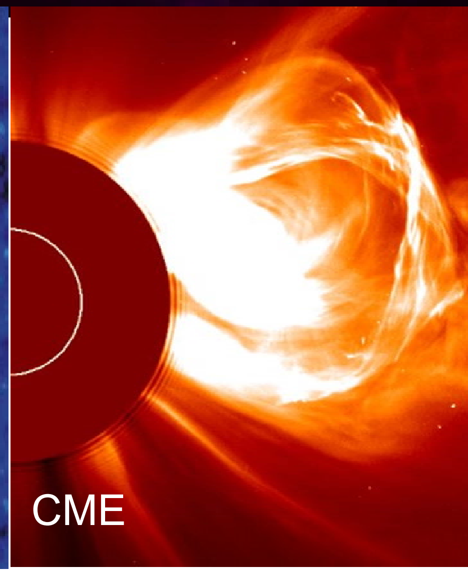
Shocks as Natural Particle Accelerators



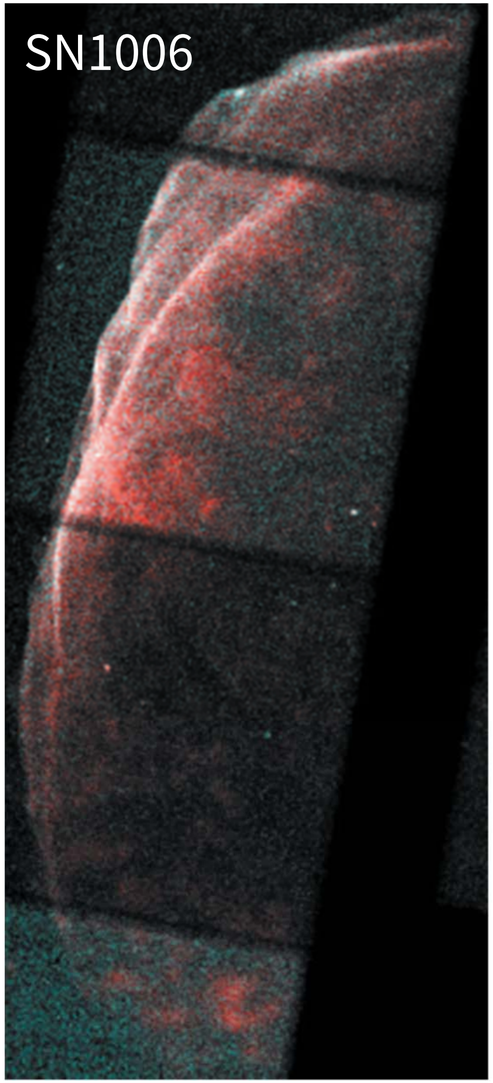


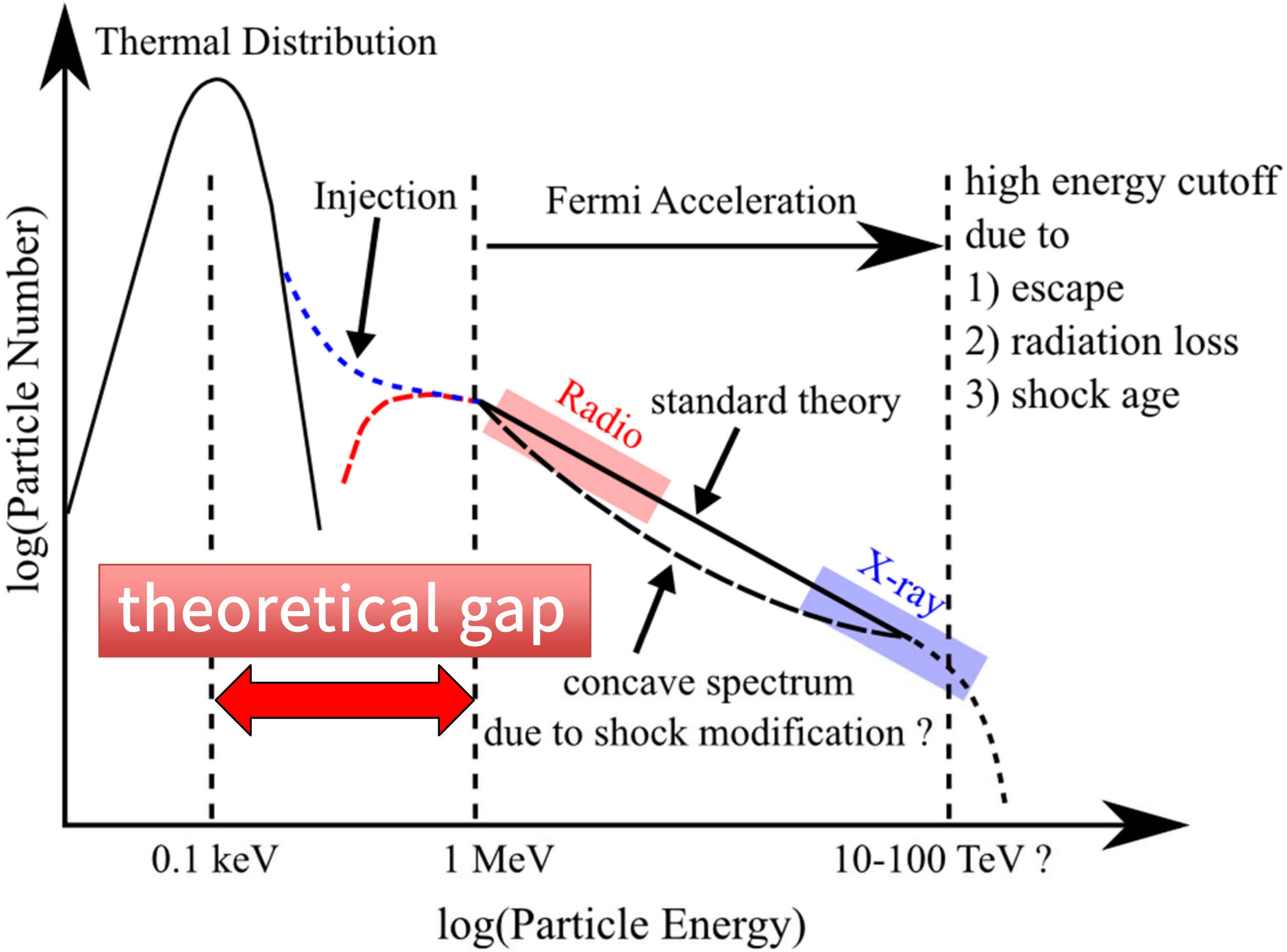






The Electron Injection

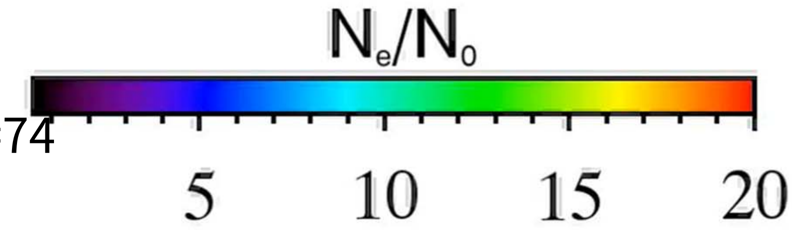


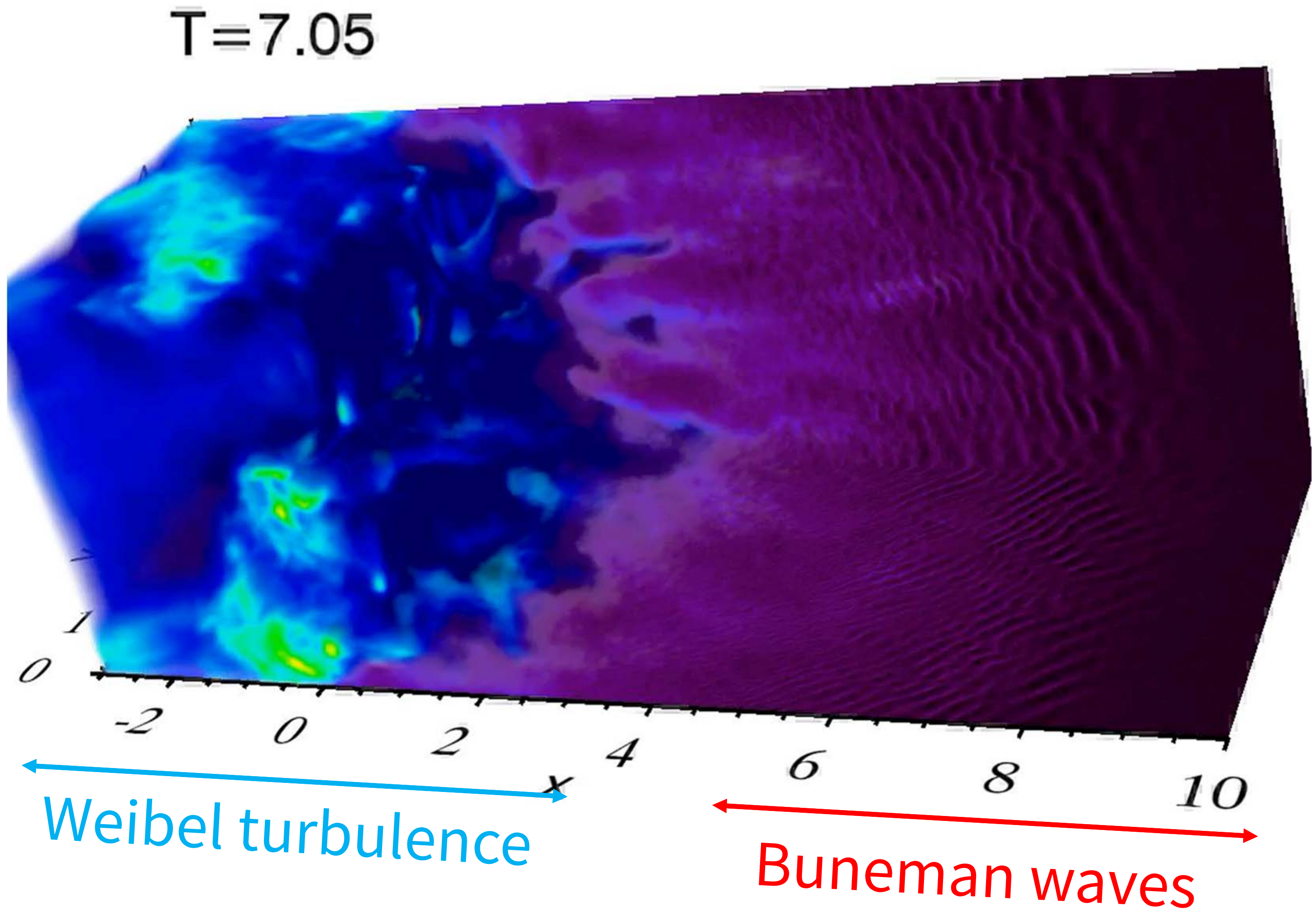


electrons with < 0.1-1 MeV cannot be scattered by MHD waves

10^{12} particles in
8800 x 768 x 768 cells
($55d_i$ x $4.8d_i$ x $4.8d_i$)
mi/me=64, Ma=20, theta=74

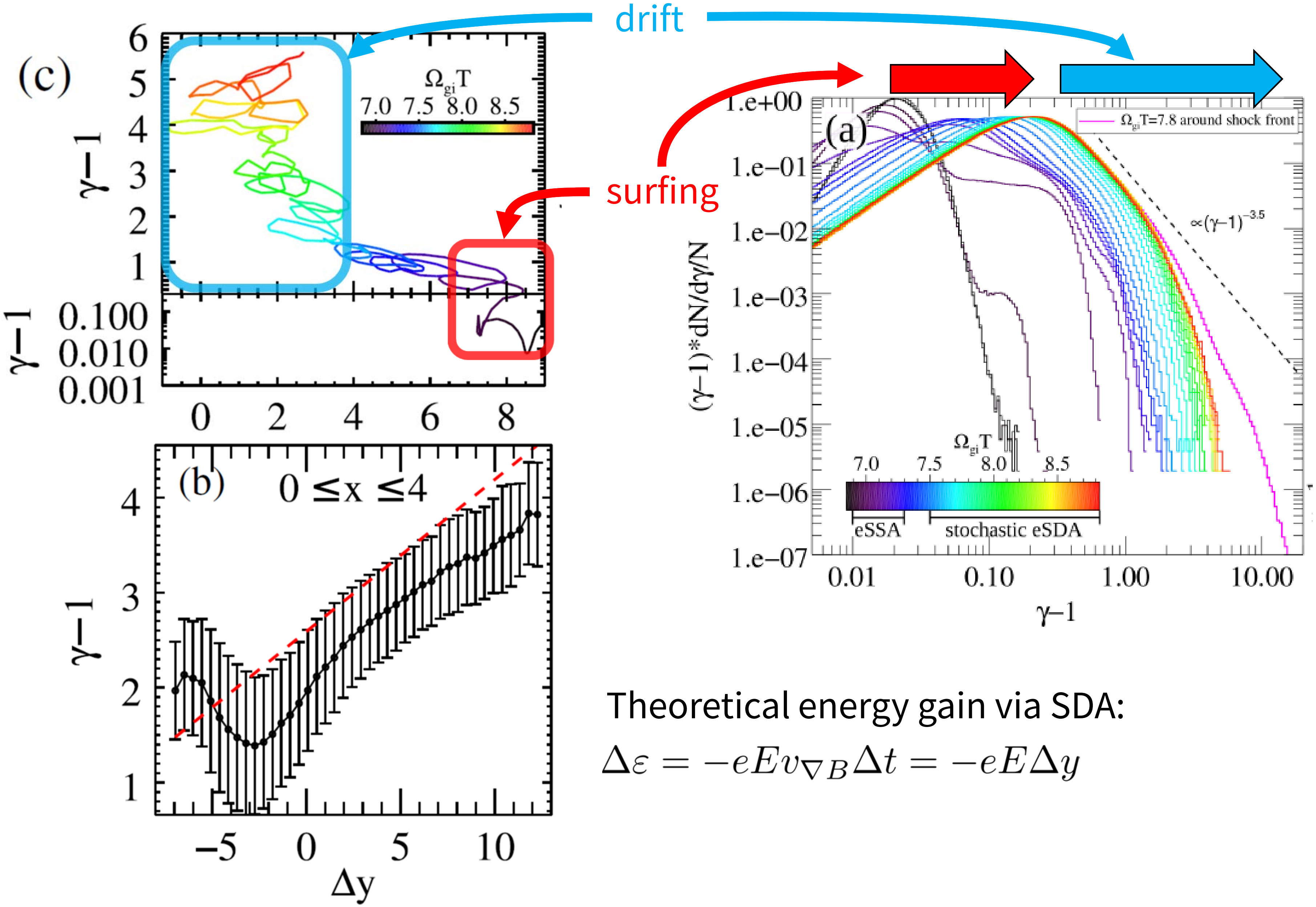
3D PIC on the K computer (Matsumoto+2017, PRL)





3D PIC on the K computer (Matsumoto+2017, PRL)

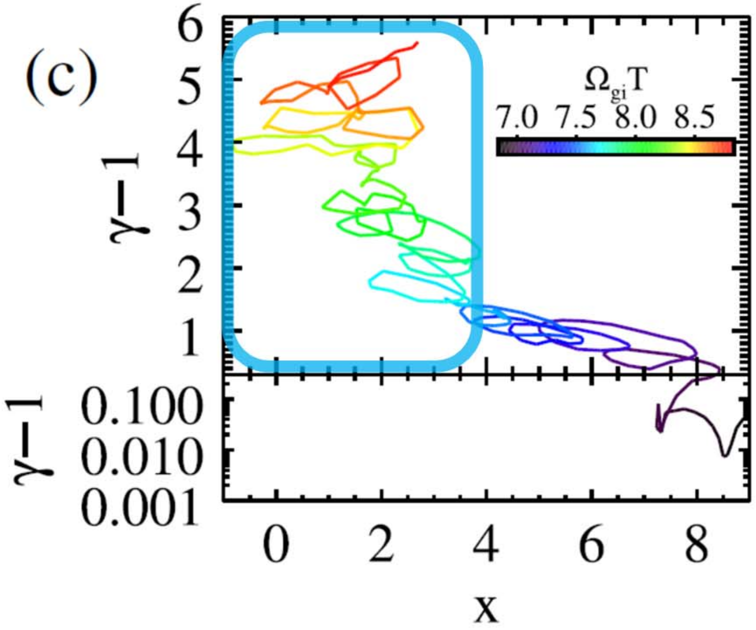
"Stochastic" Shock Drift Acceleration

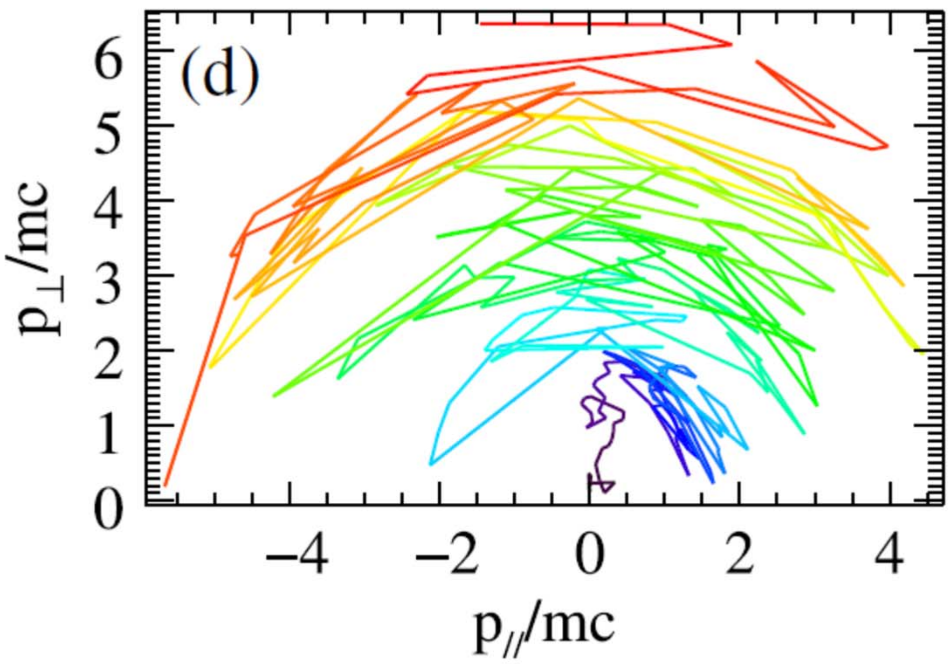


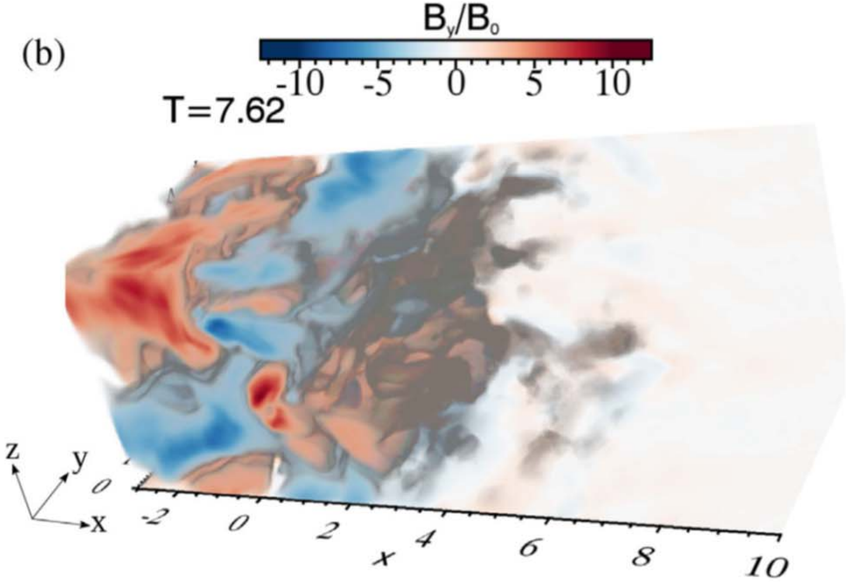
Theoretical energy gain via SDA:

$$\Delta\varepsilon = -eEv_{\nabla B}\Delta t = -eE\Delta y$$

Scattering by Weibel Turbulence



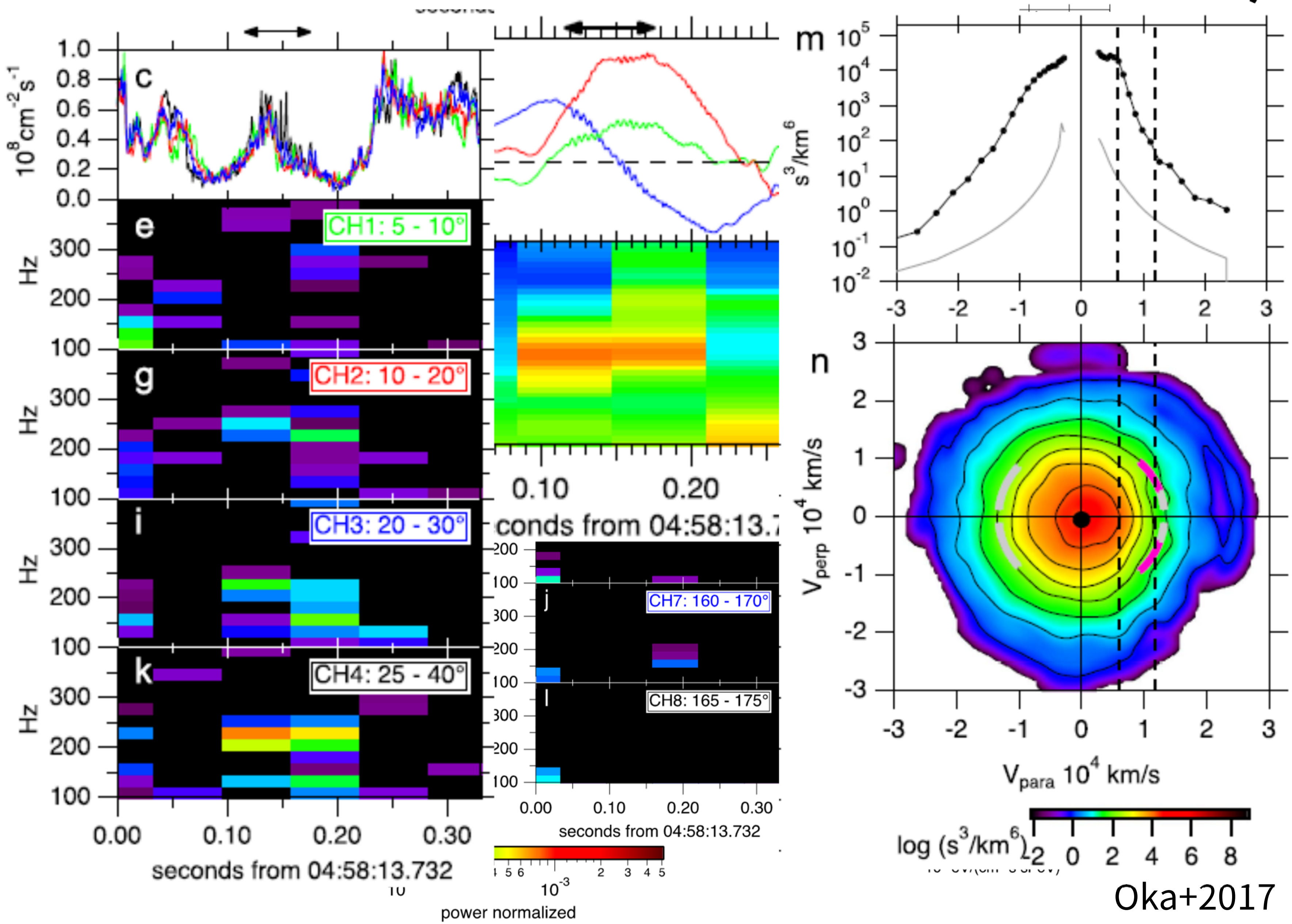




The strong Weibel turbulence play the role for the pitch-angle scattering.

More effective confinement of the particles in the acceleration region becomes possible.

Whistler-Electron Interaction (MMS obs.)

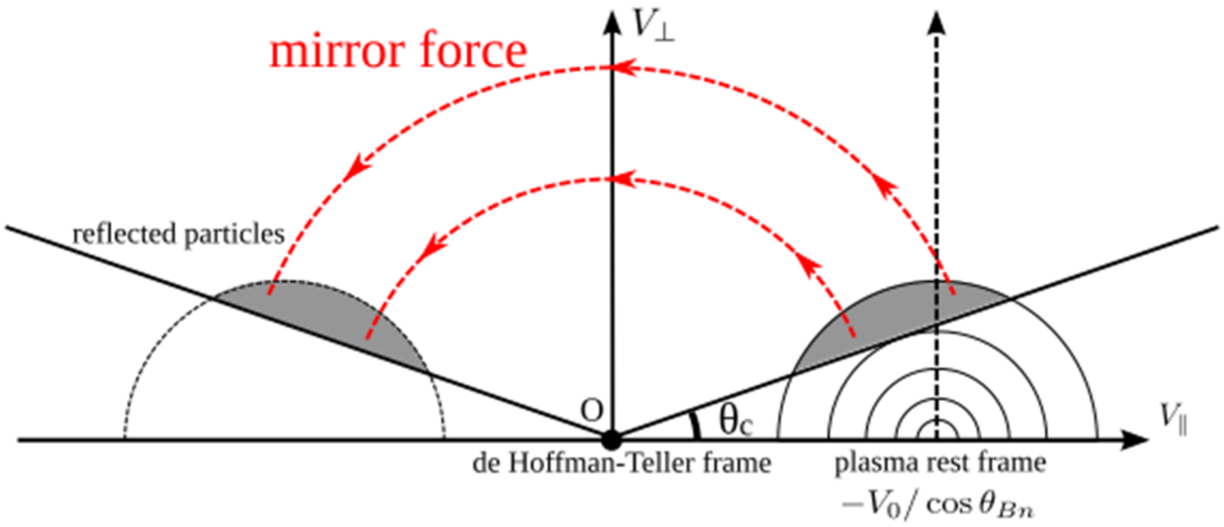


Oka+2017

c.f., Wu 1984, Leroy&Mangeney 1984

Shock Drift Acceleration (SDA)

- Adiabatic magnetic mirror reflection process.
  - Magnetic moment and energy (in the HTF) are conserved.
  - Pitch angle should be large enough for reflection to occur.
- Loss-cone type distribution for the reflected electrons.
- The energy gain measured in the upstream rest frame may be understood as the gradient-B drift in the direction of the motional E-field (–V x B).



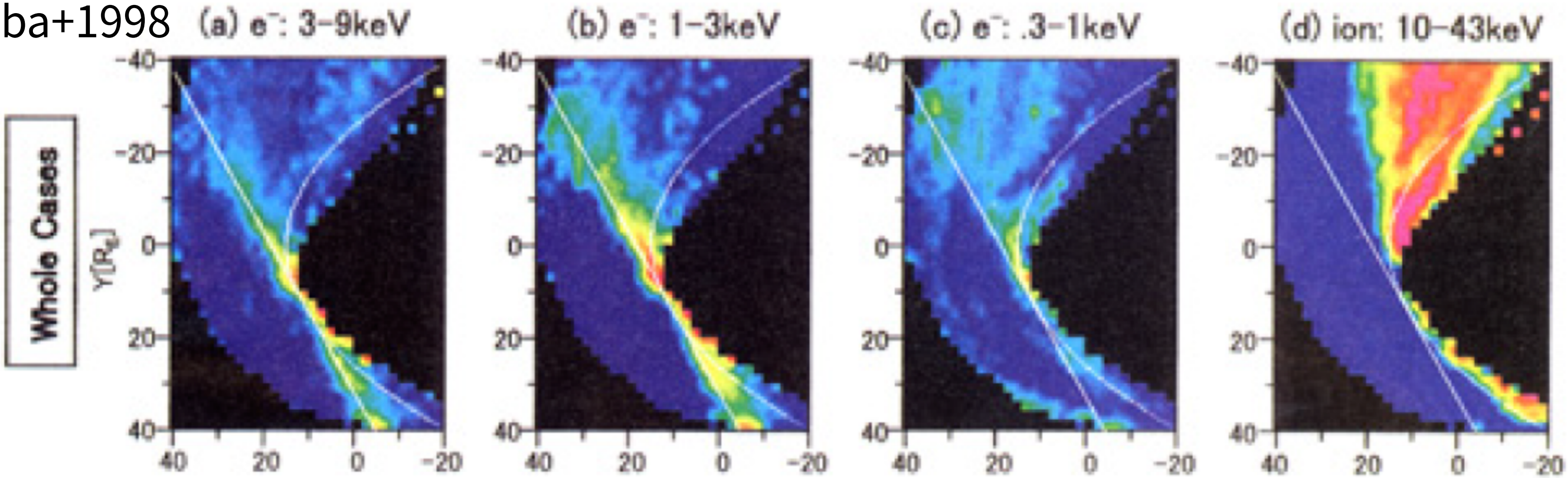
Expected momentum gain by the reflection

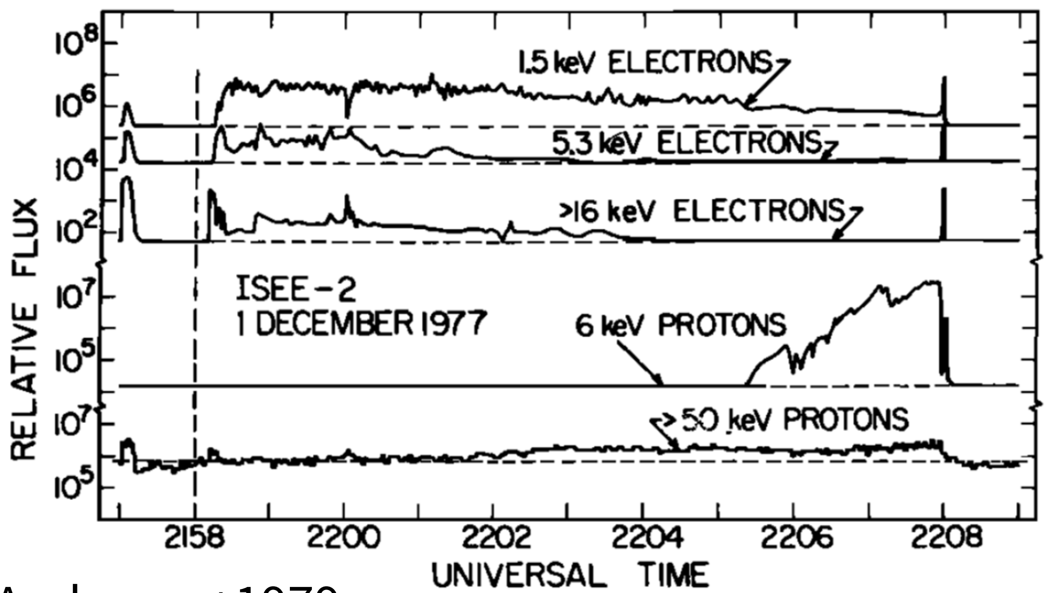
$$\Delta p = 2mV_0/\cos\theta_{Bn}$$

A reflected electron population forms an upstream propagating beam with loss-cone

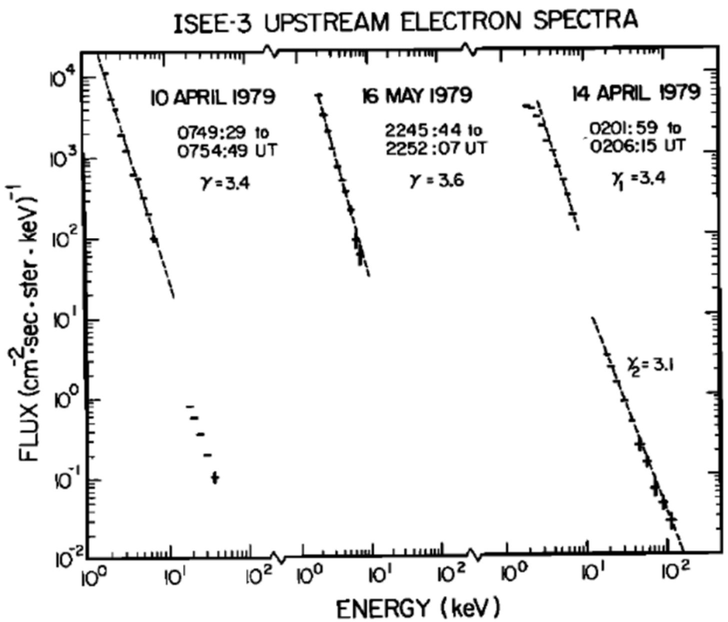
Energetic Back-streaming Electrons

Kasaba+1998





Anderson+1979



Anderson 1981

Stochastic SDA

The electron transport in the shock transition region may be described by the following focused transport equation (Skilling 1975, Isenberg 1997):

$$
\begin{aligned}
&\frac{\partial}{\partial t} f + (\boldsymbol{u} + v\mu\boldsymbol{b}) \cdot \nabla f \\
&\quad + \left[\frac{1-3\mu^2}{2}\boldsymbol{bb} : \nabla\boldsymbol{u} - \frac{1-\mu^2}{2}\nabla\cdot\boldsymbol{u} - \frac{\mu}{v}\boldsymbol{b}\cdot\frac{d}{dt}\boldsymbol{u}\right] v\frac{\partial f}{\partial v} \\
&\quad + \frac{1-\mu^2}{2}\left[v\nabla\cdot\boldsymbol{b} + \mu\nabla\cdot\boldsymbol{u} - 3\mu\boldsymbol{bb} : \nabla\boldsymbol{u} - \frac{2\boldsymbol{b}}{v}\cdot\frac{d}{dt}\boldsymbol{u}\right]\frac{\partial f}{\partial \mu} \\
&\quad = \frac{\partial}{\partial\mu}\left[(1-\mu^2)D_{\mu\mu}\frac{\partial}{\partial\mu}f\right] + Q.
\end{aligned}
$$

plasma flow divergence

mirror force

inertial force

pitch-angle scattering

In the de Hoffmann-Teller frame, the plasma flow may be written as

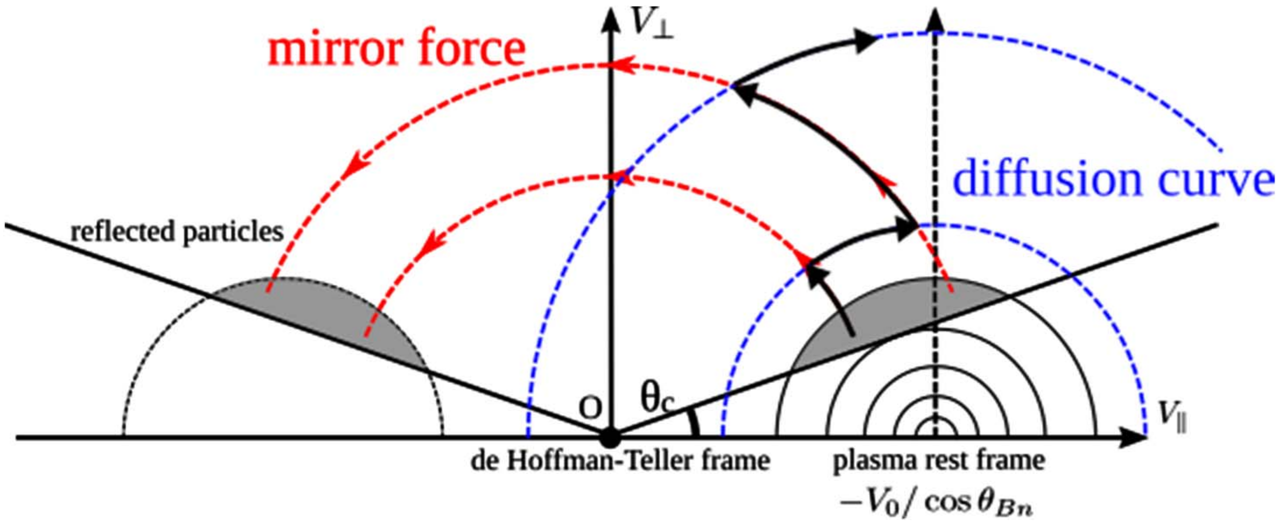
$$\boldsymbol{u} = u_{\|}\boldsymbol{b}.$$

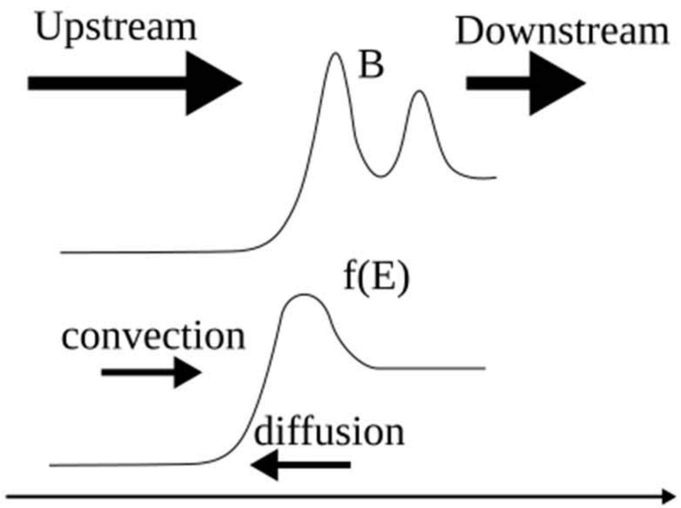
Ignoring the inertial term $d\boldsymbol{u}/dt$ ($v \gg u_{\|}$), the transport equation becomes:

$$\frac{\partial}{\partial t} f + (v\mu + u_{\|}) \frac{\partial}{\partial s} f + \left(\frac{1-\mu^2}{2} u_{\|} \frac{\partial \ln B}{\partial s} - \mu^2 \frac{\partial u_{\|}}{\partial s} \right) v \frac{\partial f}{\partial v} - \frac{1-\mu^2}{2} \left((v\mu + u_{\|}) \frac{\partial \ln B}{\partial s} + 2\mu \frac{\partial u_{\|}}{\partial s} \right) \frac{\partial f}{\partial \mu} = \frac{\partial}{\partial \mu} \left[(1-\mu^2) D_{\mu\mu} \frac{\partial}{\partial \mu} f \right] + Q.$$

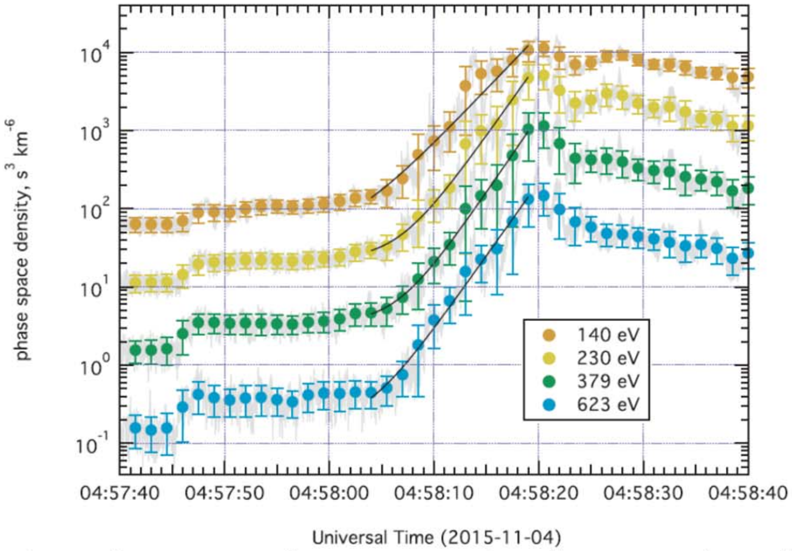
negligible at Qperp shock

mirror force





MMS observation (Oka+ unpublished)



The spatially-integrated spectrum in the steady state is determined by the two typical time scales:

- The escape time $\frac{1}{\tau_{esc}} \sim \frac{V}{L}$ (convective escape)
- The acceleration time $\frac{1}{\tau_{acc}} \sim \frac{2}{3}\frac{V}{L}\left(L\frac{d\ln B}{dx}\right)$ (SDA with isotropy)

The energy spectrum becomes a power-law:

$$f(\varepsilon) \propto \varepsilon^{-\frac{3}{2}(1+\eta)} \qquad \eta^{-1} \equiv L\frac{d\ln B}{dx}$$

The maximum energy may be estimated as

$$\frac{\varepsilon_{\max}}{1/2m_e(V_0/\cos\theta_{Bn})^2} \approx \frac{m_i}{m_e}\frac{D_{\mu\mu}}{\Omega_{ce}}$$

Summary of Stochastic SDA Theory

- A power-law spectrum with its index independent of details of scattering.
  - When does the scattering becomes efficient ?
- The maximum energy scales as

$$\varepsilon_{\mathrm{max}} \sim 10\,\mathrm{keV} \left(\frac{V_0}{400\mathrm{km/s}} \right)^2 \left(\frac{\cos\theta}{\cos 85} \right)^{-2} \left(\frac{D_{\mu\mu}}{0.1\Omega_{ce}} \right)$$

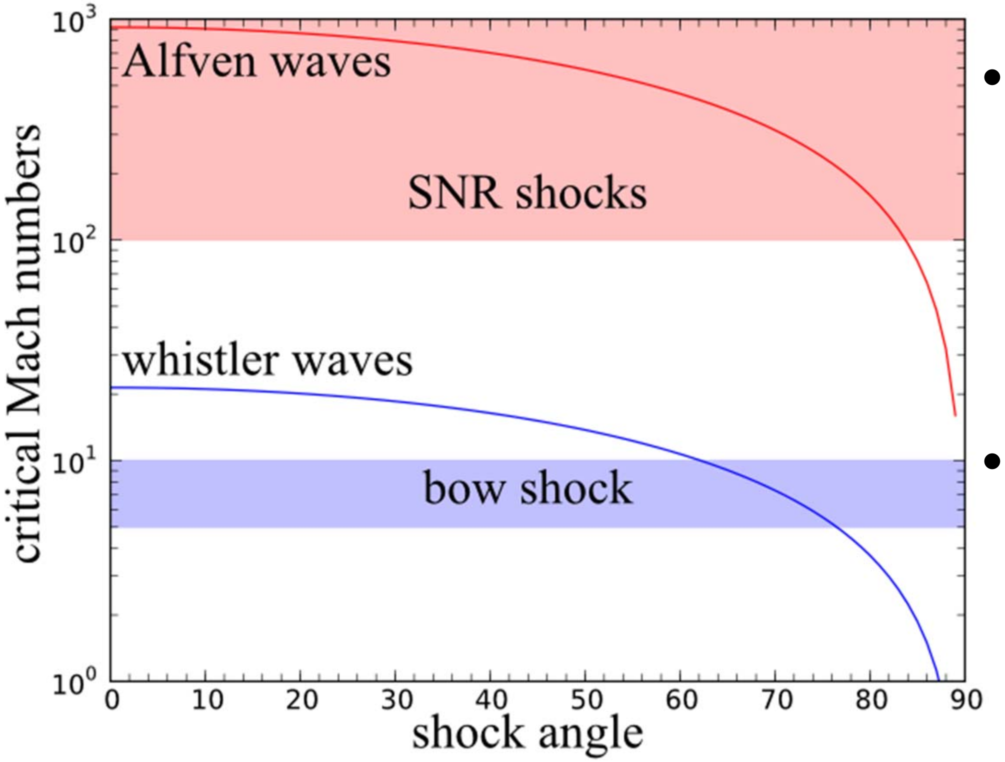
  - mildly relativistic energy possible at SNR shocks.
  - can be tested with the bow shock observations.
- The highest energy particles (~at cut-off) primarily escape toward upstream.
  - Consistent with the back-streaming electrons observations.

A Critical Mach Number

To overcome electron cyclotron damping of whistler waves, the following condition should be met:

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

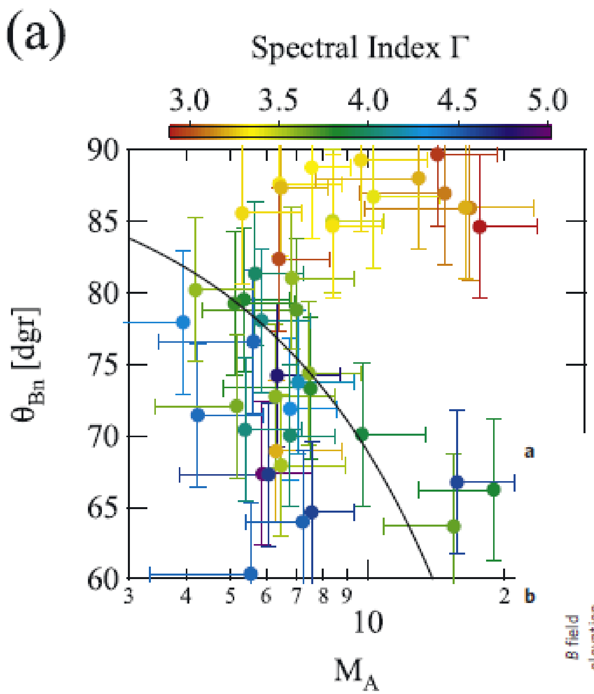
This defines a critical Mach number for injection

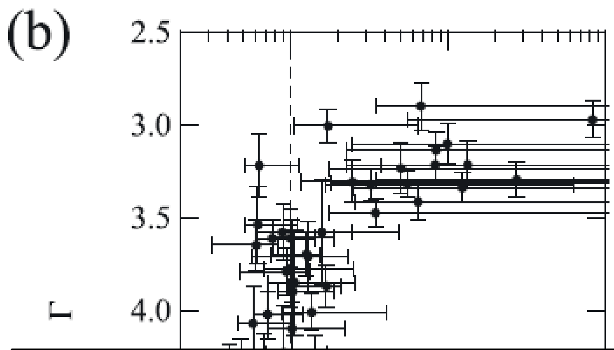


- Typical SNR shocks are super-critical; Naturally explains radio/X-ray synchrotron emission
- Bow shock is marginal; <u>Theory can be tested using in-situ observations</u>

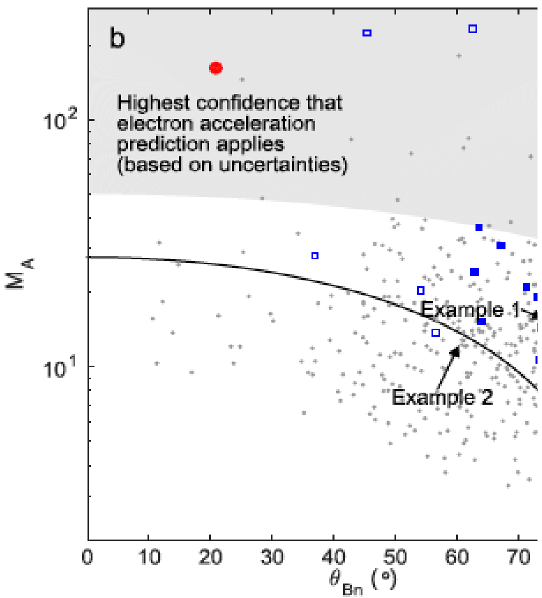
Amano & Hoshino 2010

Geotail obs. for Earth's bow shock (Oka et al. 2006)

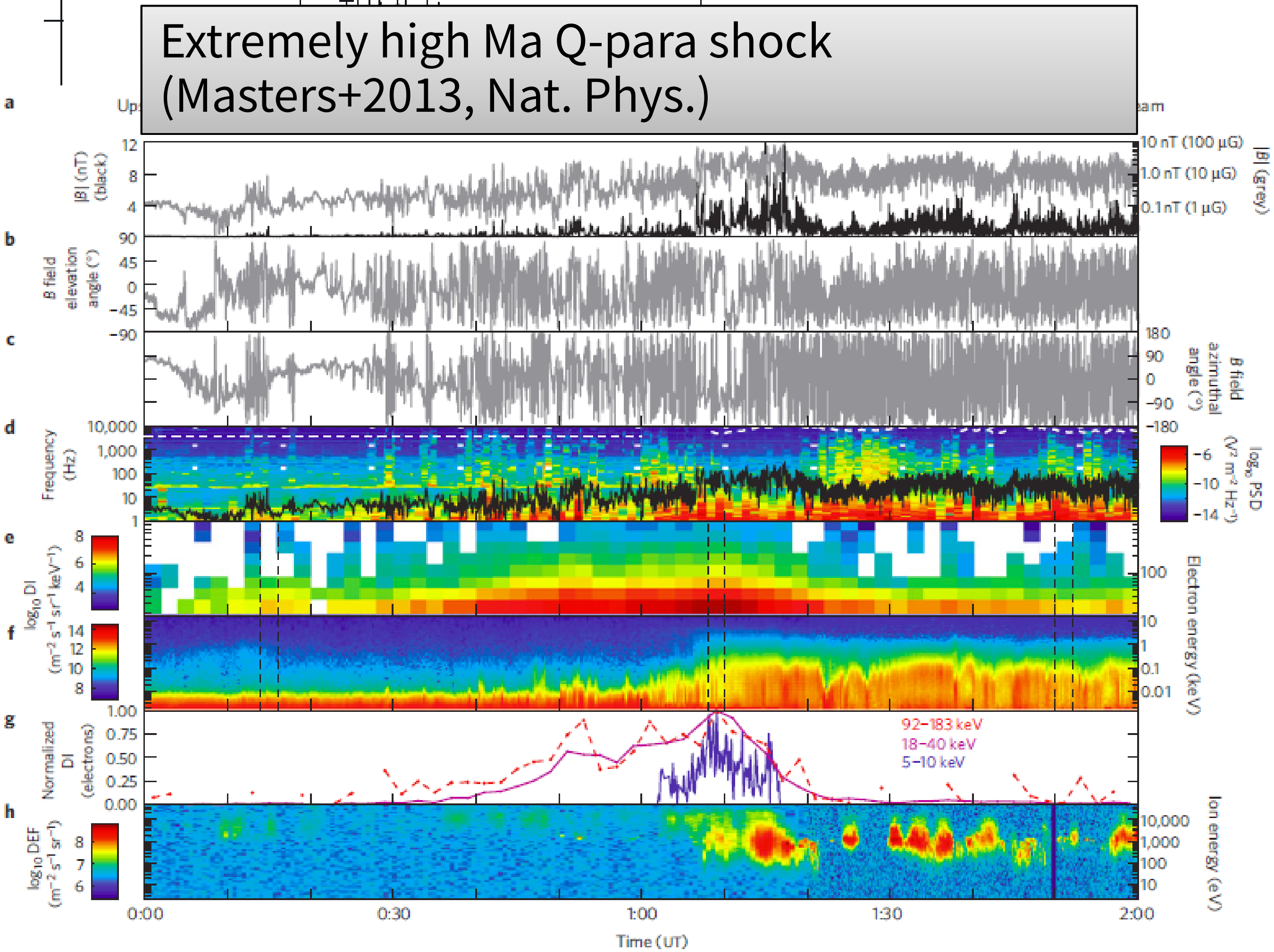




Cassini obs. for Saturn's



Extremely high Ma Q-para shock
(Masters+2013, Nat. Phys.)



Conclusions

- The efficiency of the SDA is enhanced by introducing the pitch-angle scattering.
- The result provides a better agreement both with PIC simulations and in-situ observations.
- The maximum energy may reach mildly relativistic energies at SNR shocks, which may thus explain astrophysical observations.
- More detailed comparisons with MMS observations are ongoing.