Electron Injection at Shocks: Transition from Stochastic Shock Drift Acceleration to Diffusive Shock Acceleration

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Collaborators

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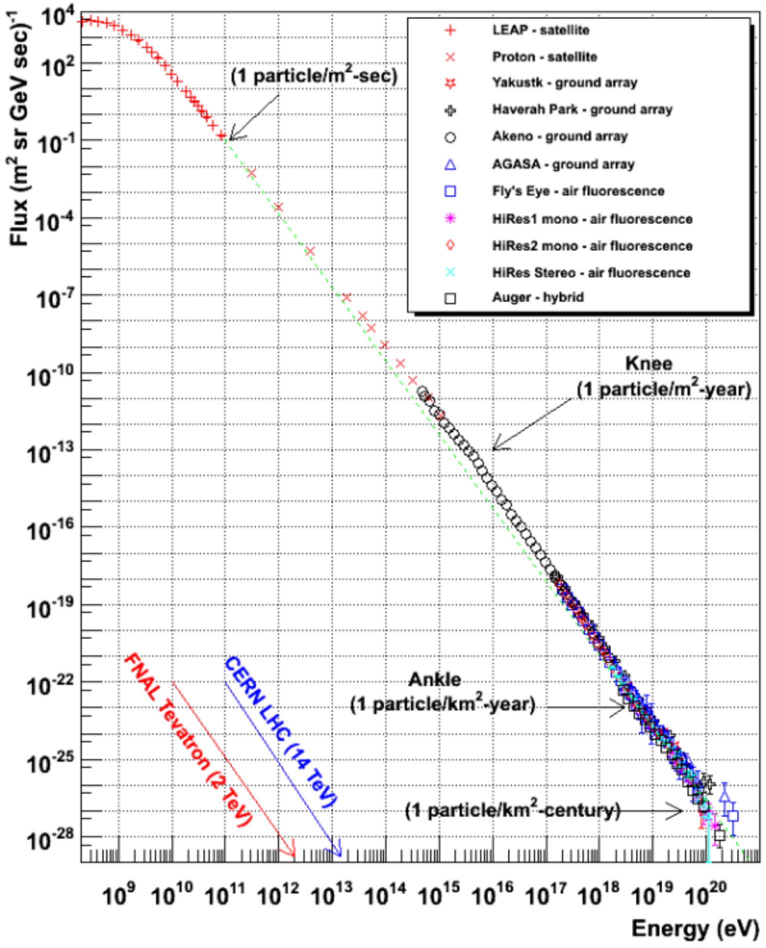
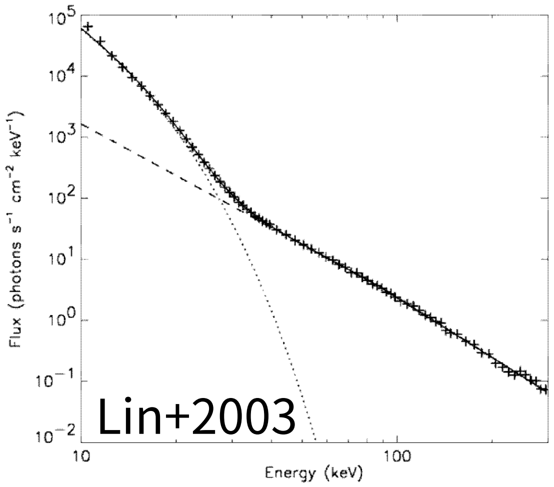
Non-thermal Particles

Highly energetic charged particles with energies much larger than the thermal energy are ubiquitous in many astrophysical phenomena. The energy density of the non-thermal populations can be comparable to the thermal component.

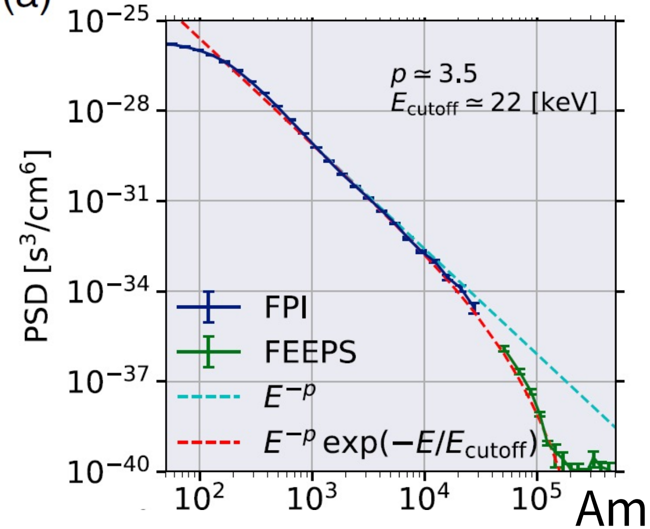


Blasi (2013), Amato (2014)

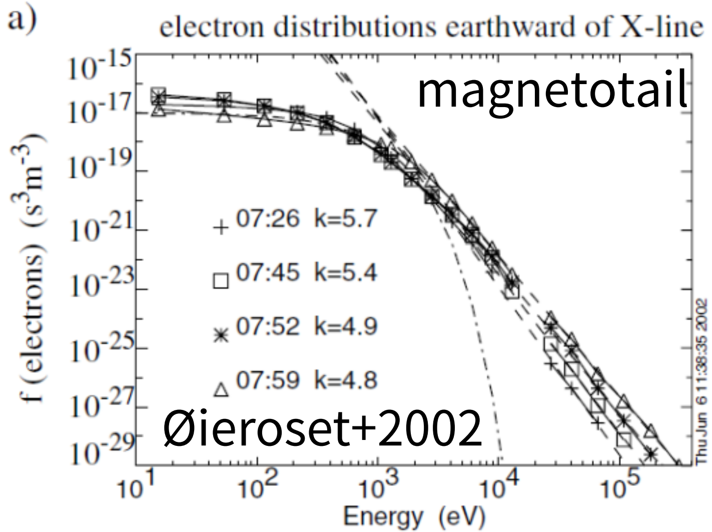
solar flare



Earth bow shock



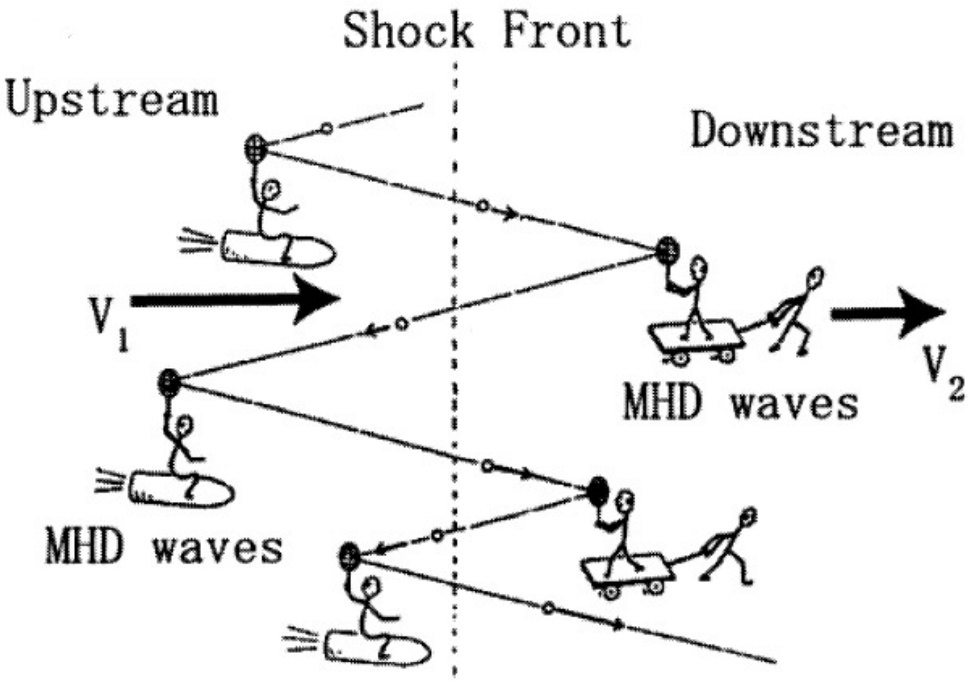
Amano+2020



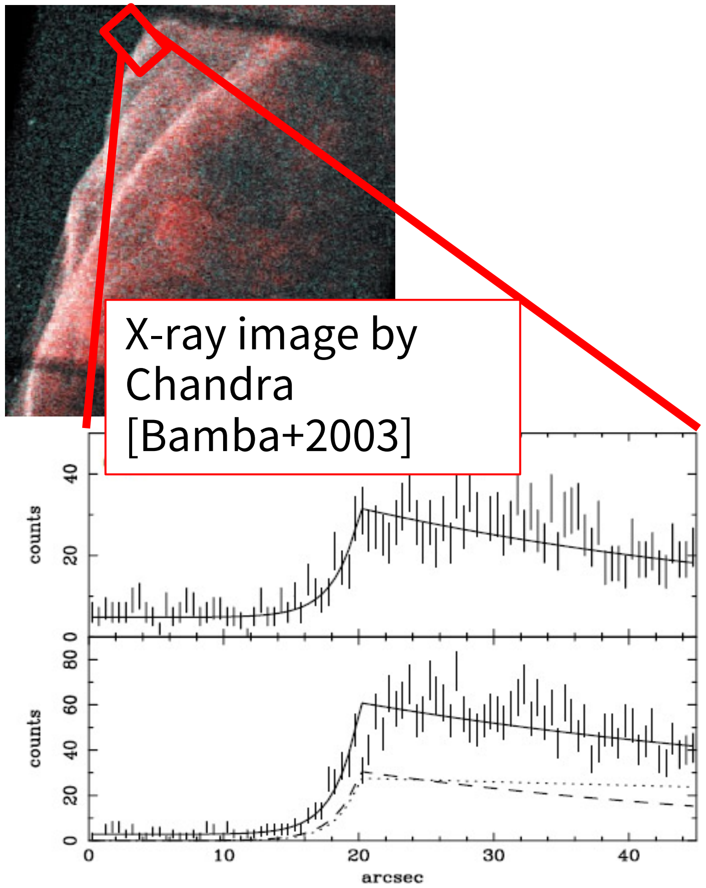
The Standard Shock Acceleration Theory

- Diffusive Shock Acceleration (DSA)
  - A simple yet powerful model that predicts a nearly universal power-law; $N(E) \propto E^{-2}$

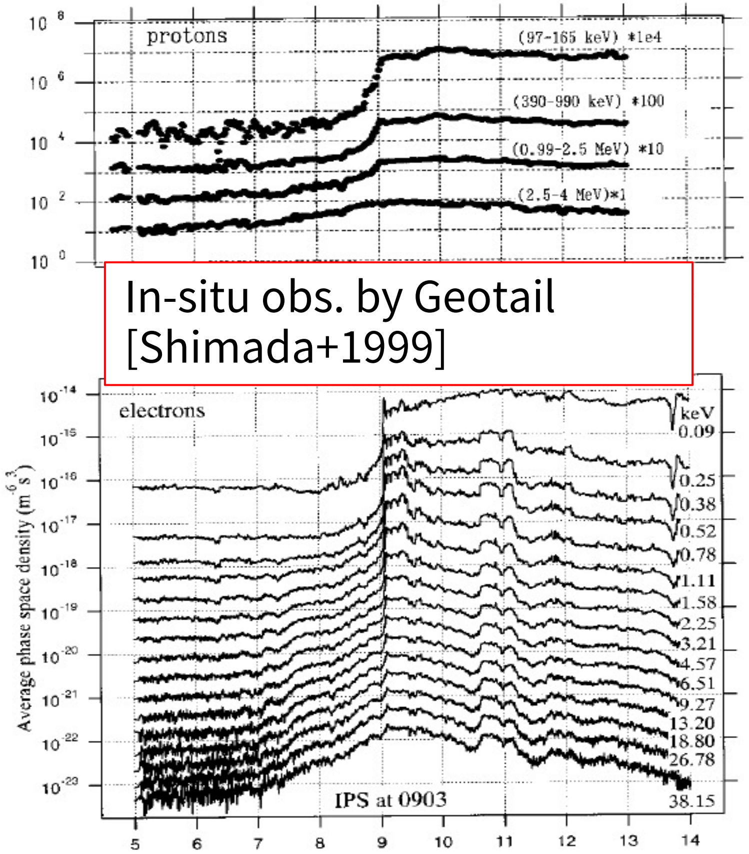
[e.g., Bell 1978, Blandford & Ostriker 1978]



M. Scholer



X-ray image by Chandra [Bamba+2003]



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

Acceleration Time and Injection Problem

$$\tau_{acc}(p) = \int_{p_0}^{p} \frac{dp'}{p'} \frac{3}{V_1 - V_2} \left[\frac{\kappa_1}{V_1} + \frac{\kappa_2}{V_2} \right] \sim \frac{\kappa}{V^2} \propto \left(\frac{v}{V} \right)^2 \frac{1}{D_{\mu\mu}}$$

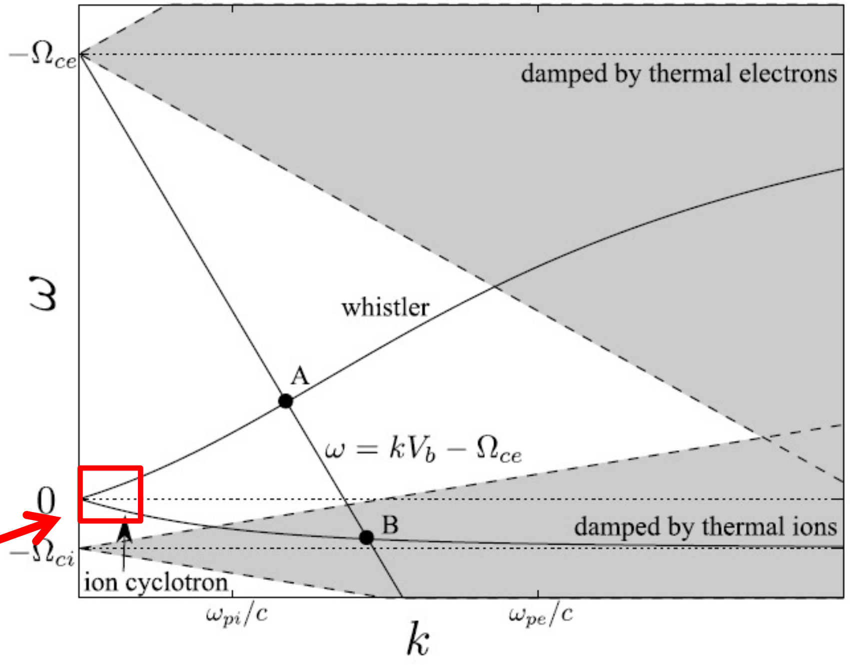
Quasi-linear estimate: $D_{\mu\mu} = \frac{\pi}{4} \frac{k_R P(k_R)}{B_0^2} \Omega_0 \quad \text{where} \quad k_R = \Omega_0 / v\mu$

The gyroradii of low-energy electrons are very small and will be well below the dissipation range of MHD turbulence.

→ no electron acceleration should be expected?

- MHD waves cannot resonantly scatter sub-relativistic electrons.
- Intense high-frequency (whistler) waves to scatter low-energy electrons?
- Any other mechanisms to energize low-energy electrons to mildly relativistic energies?

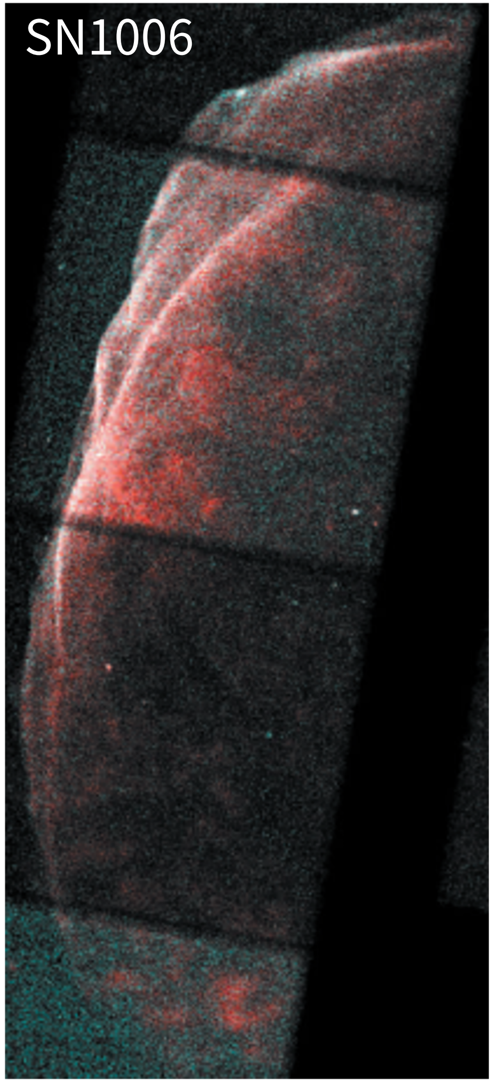
MHD regime (Alfven waves)

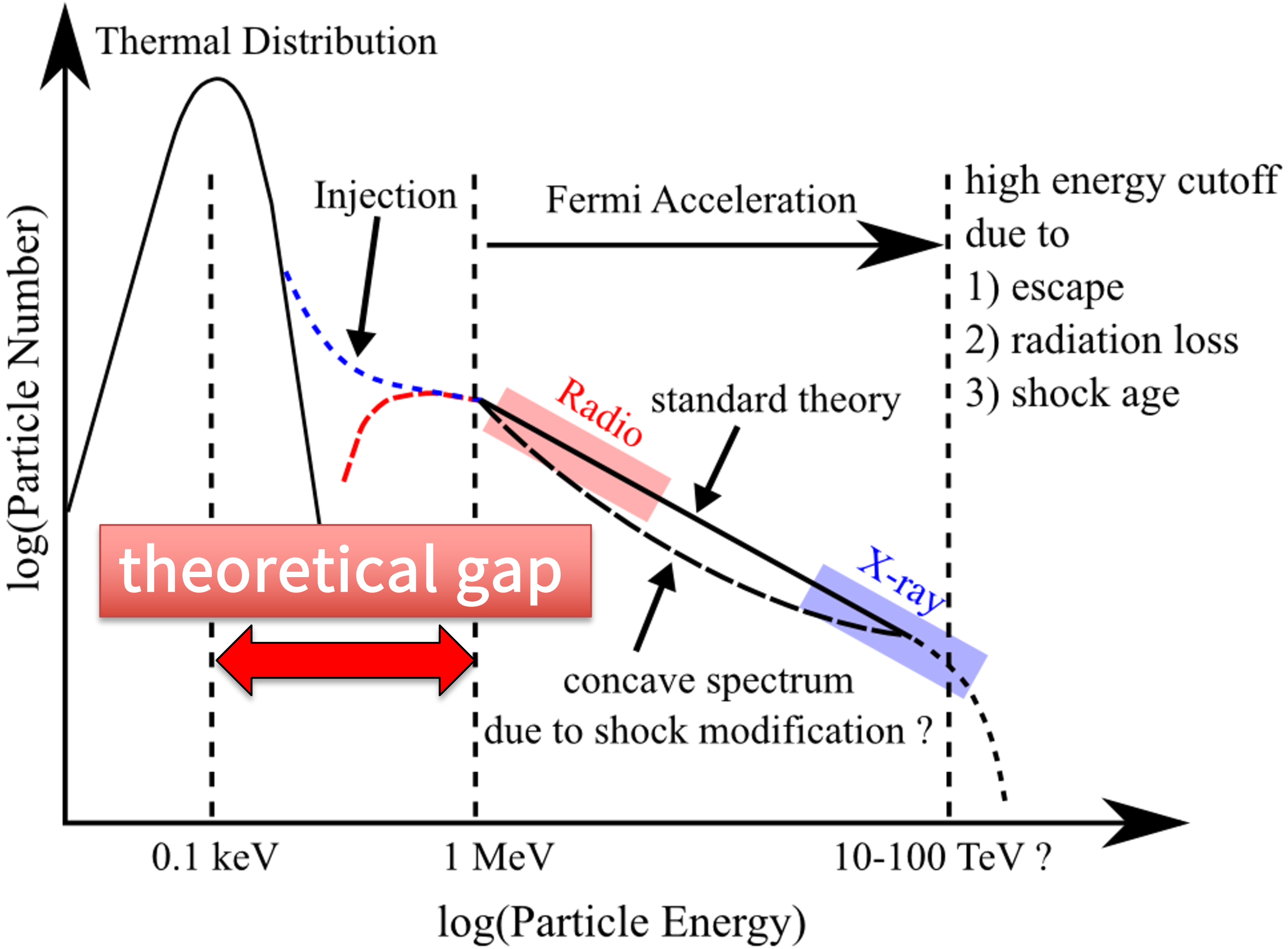


Amano & Hoshino (2010)

The Electron Injection

electrons with < 0.1-1 MeV cannot be scattered by MHD waves $\omega - kv_{\parallel} = \Omega/\gamma$

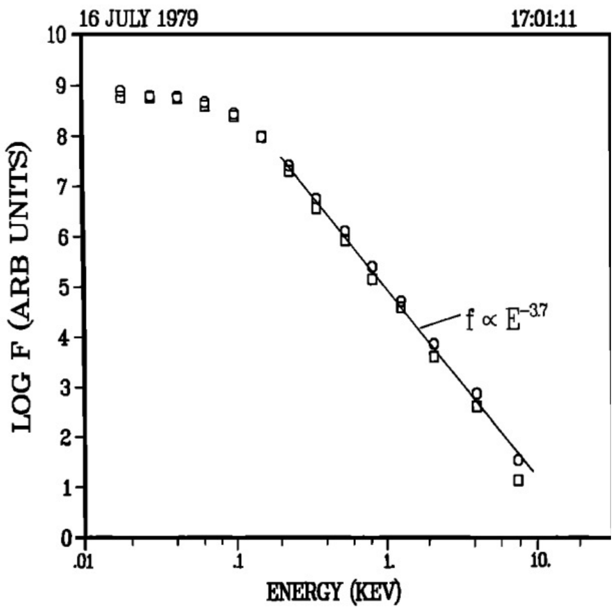




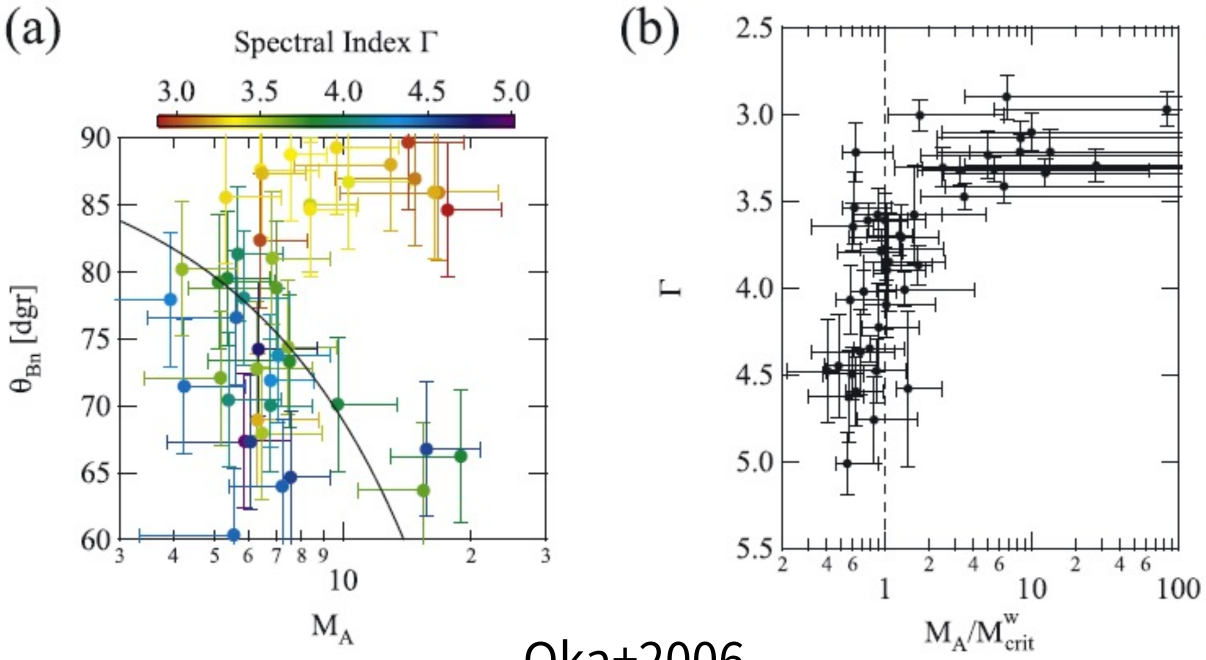
- ✓ Sub-relativistic electrons cannot be accelerated by the standard first-order Fermi mechanism.
- ✓ Substantial energy gain is needed from thermal to relativistic energies by some other mechanisms.
- ✓ Sub-relativistic suprathermal electrons are "invisible" with typical astrophysical observations, while they are observable with in-situ spacecraft measurement.

Ref: Levinson 1992, Amano & Hoshino 2010, Shimada+1999, Lario+2003, Dresing+2016

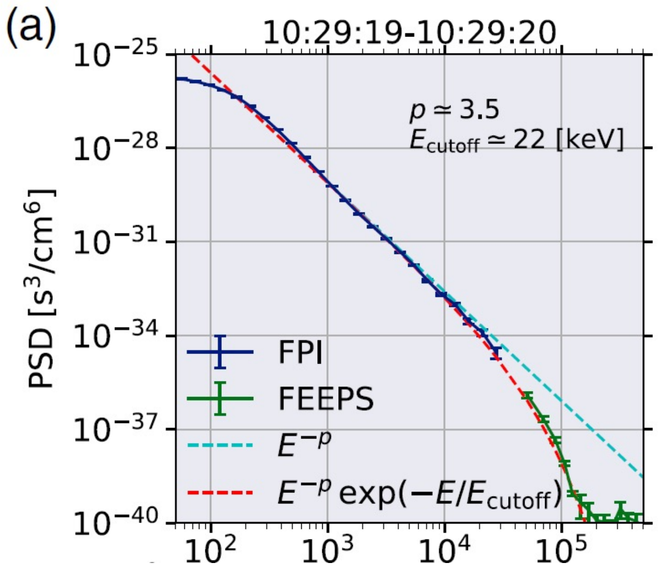
Earth’s Bow Shock: Laboratory for Electron Injection



Gosling+1989



Oka+2006



Amano+2020

- Non-thermal electrons with a clear power-law spectrum have been observed occasionally at the bow shock.
- The typical energy range of non-thermal electrons measured at the bow shock is the most important energy range for the injection.

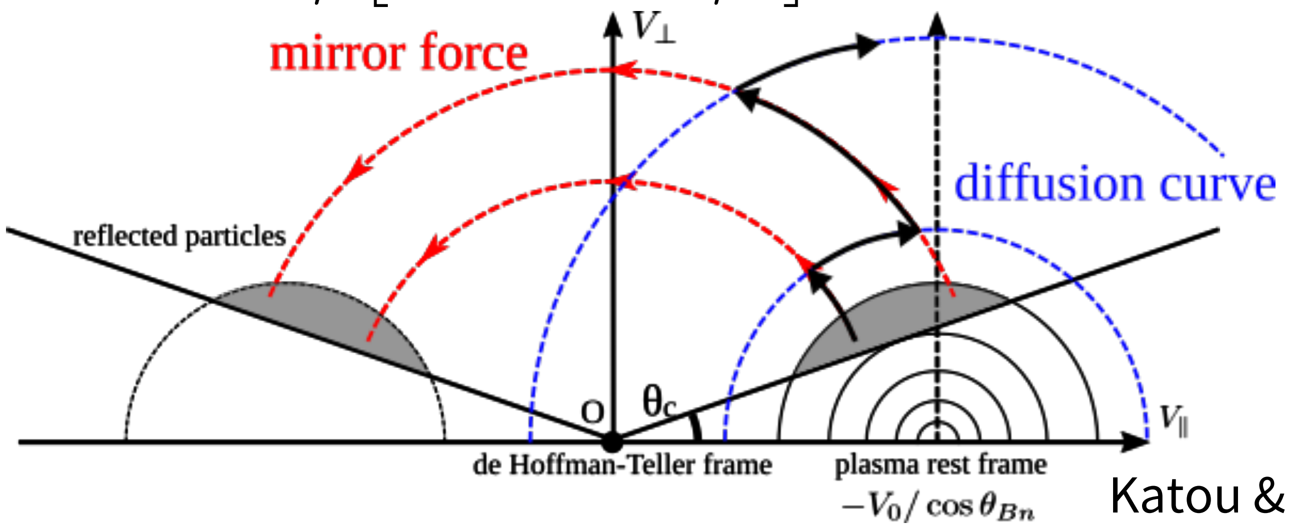
Stochastic SDA (SSDA)

The transport of electrons in the de Hoffmann-Teller frame ($\boldsymbol{u} = u_\parallel \boldsymbol{b}$) may be governed by

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

mirror force

negligible at Qperp shock
(major term for DSA)



Katou & Amano (2019)

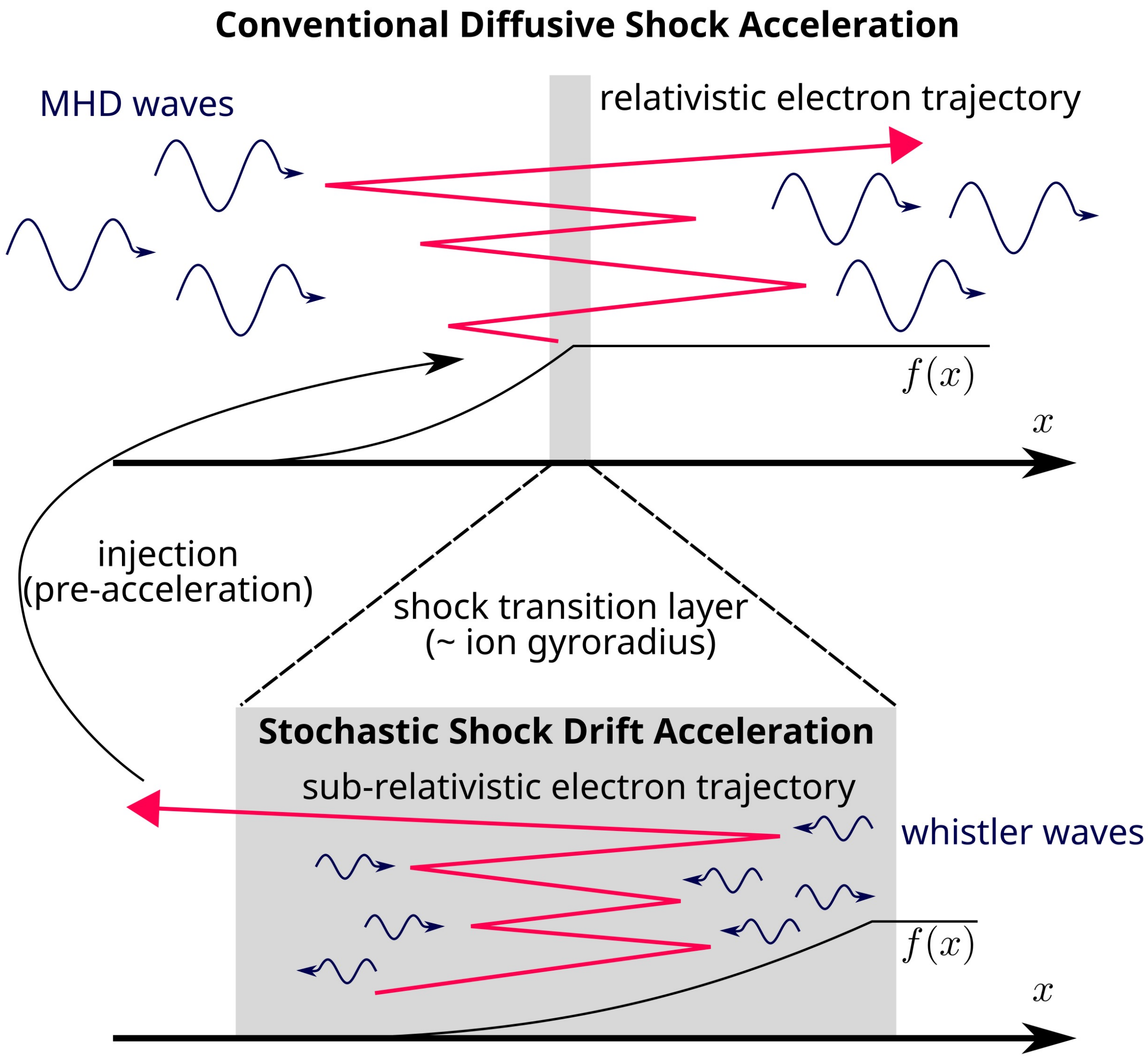
Electron Injection Scenario

DSA (diffusion length >> shock thickness)

- Diffusive and slow particle acceleration well beyond the shock thickness.
- The canonical power-law: $f(p) \propto p^{-4}$
- It may operate only when SSDA provides sufficiently energetic electrons.

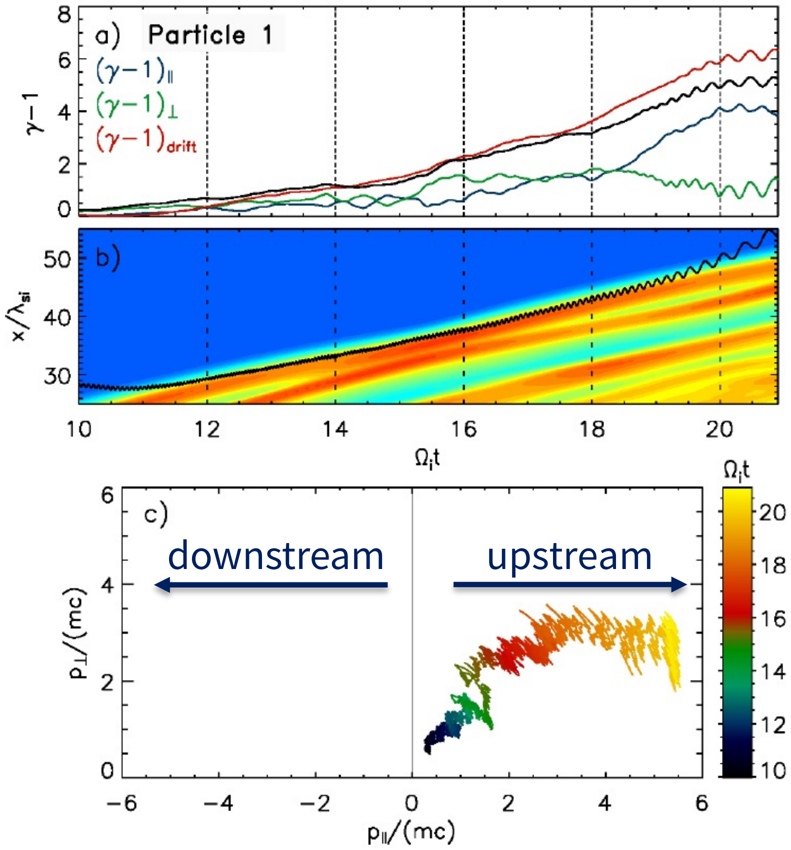
SSDA (diffusion length ~ shock thickness)

- Diffusive and fast particle acceleration within the shock transition layer.
- It results in a steeper power-law for energy-independent diffusion (consistent with observations at the bow shock.)
- Higher-energy electrons will eventually escape toward upstream because of diffusion lengths longer than the shock thickness.



Amano+(2020, PRL), Katou & Amano (2019, ApJ), Kobzar+(2021, ApJ), Matsumoto+(2017, PRL)

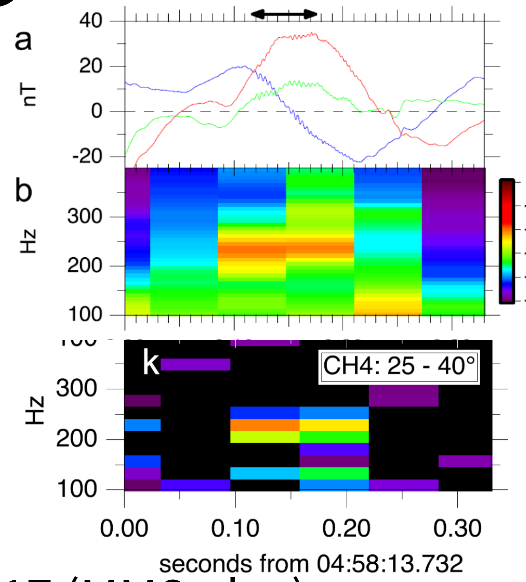
SSDA Signatures



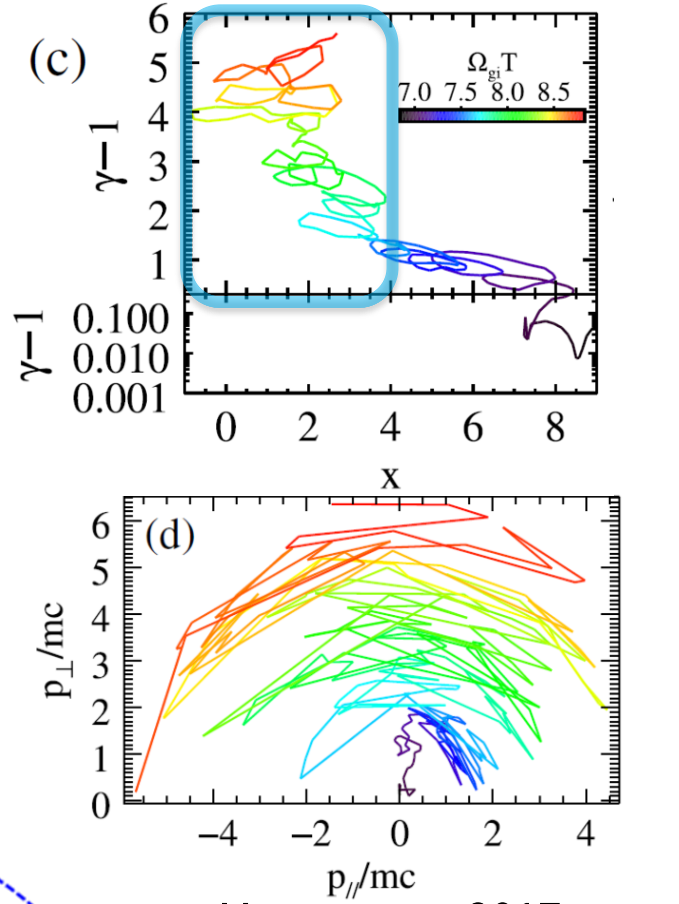
Kobzar+2021
2D high-beta and low Mach no. shock

B field

particle flux

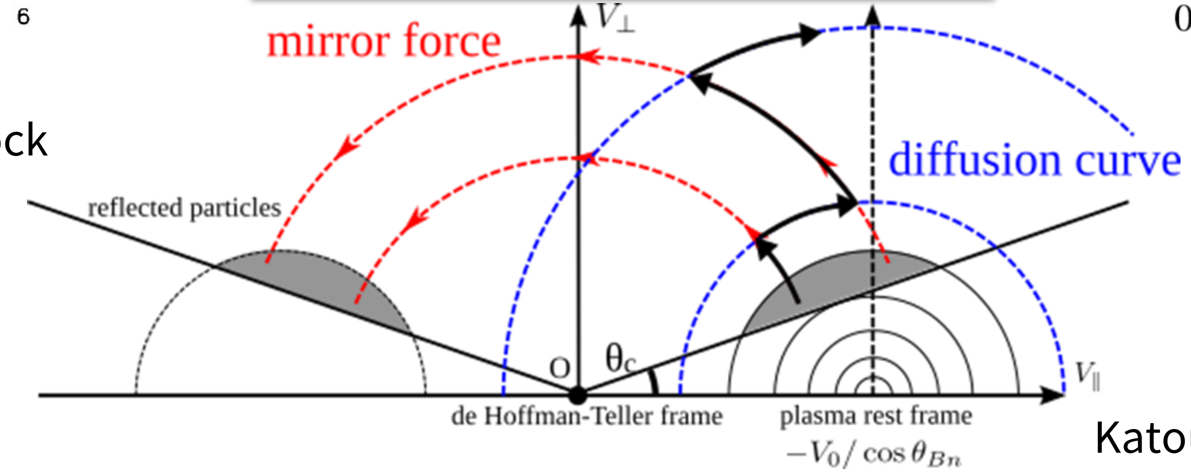


Oka+2017 (MMS obs.)

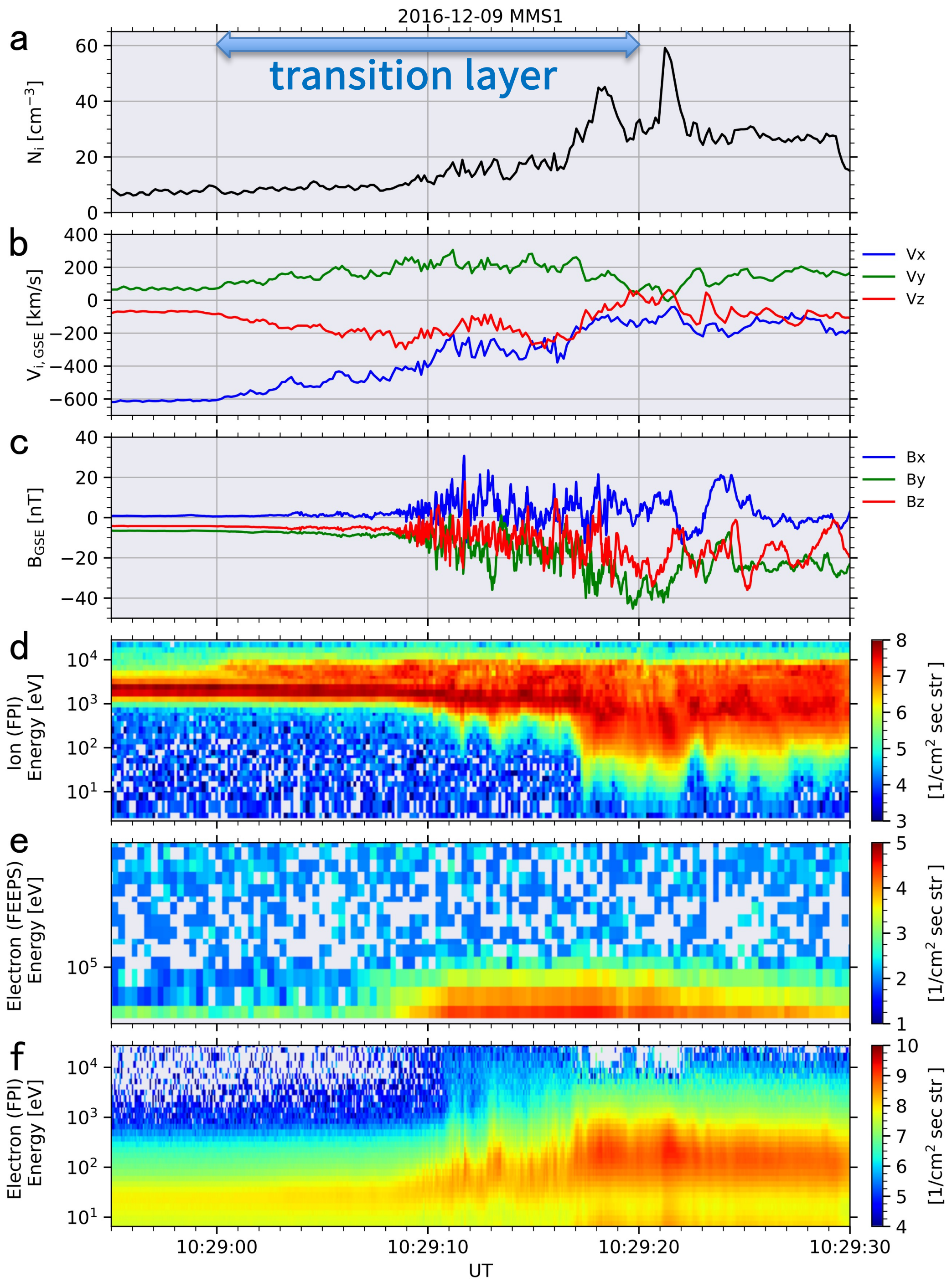


Matsumoto+2017
3D Weibel-dominated shock

Stochastic Shock Drift Acceleration
mirror reflection + scattering



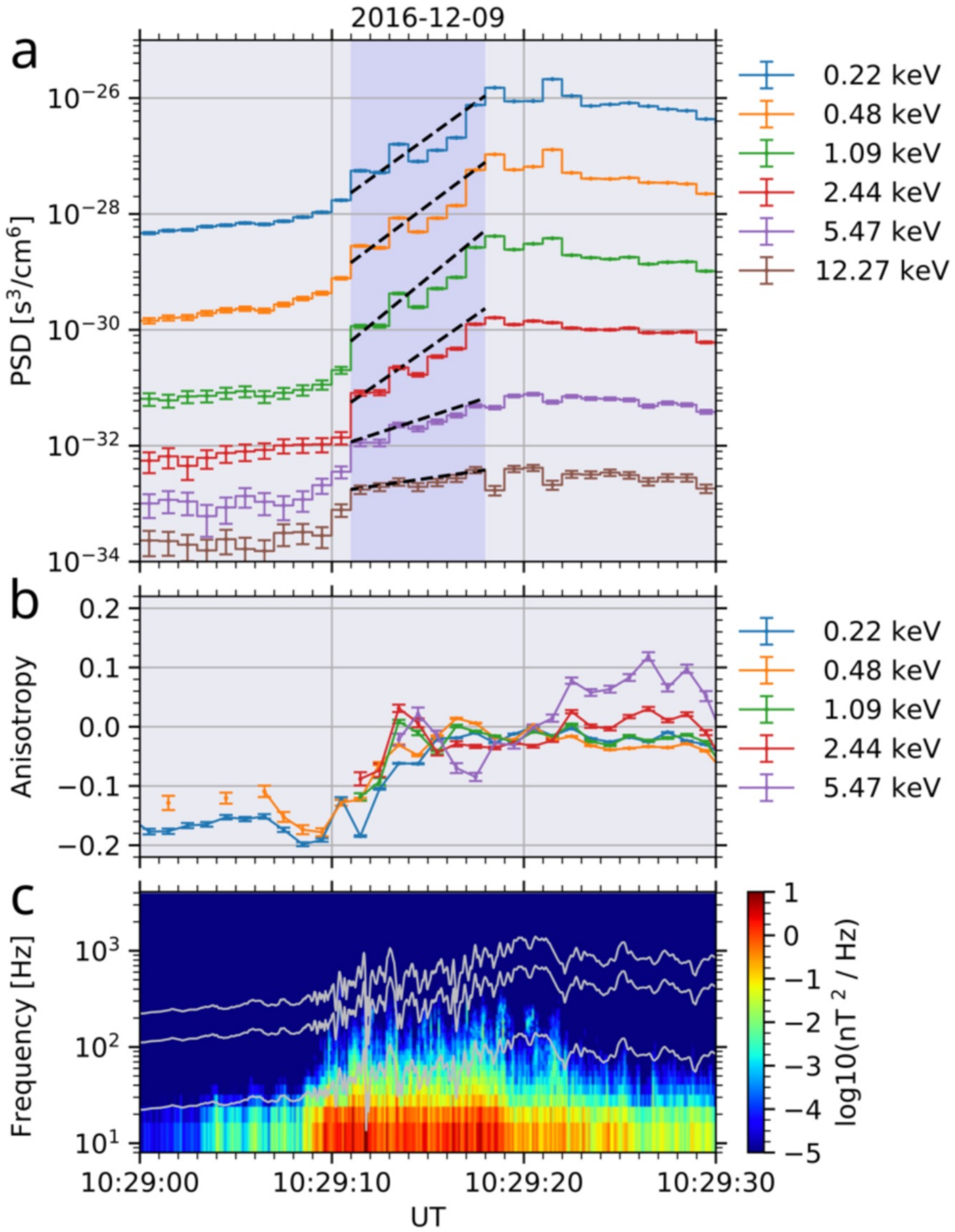
Katou & Amano 2019



Bow Shock Crossing measured by MMS spacecraft

- Vsw ~ 600 km/s
- θ_{Bn} ~ 85 (quasi-perp.)
- M_A ~ 8.9 (high Mach num.)

Substantial flux enhancements for high energy (>1 keV) electrons.
FEEPS also detected electrons up to ~100 keV.
Unusual for bow shock crossings.



Exponential increase of particle intensity

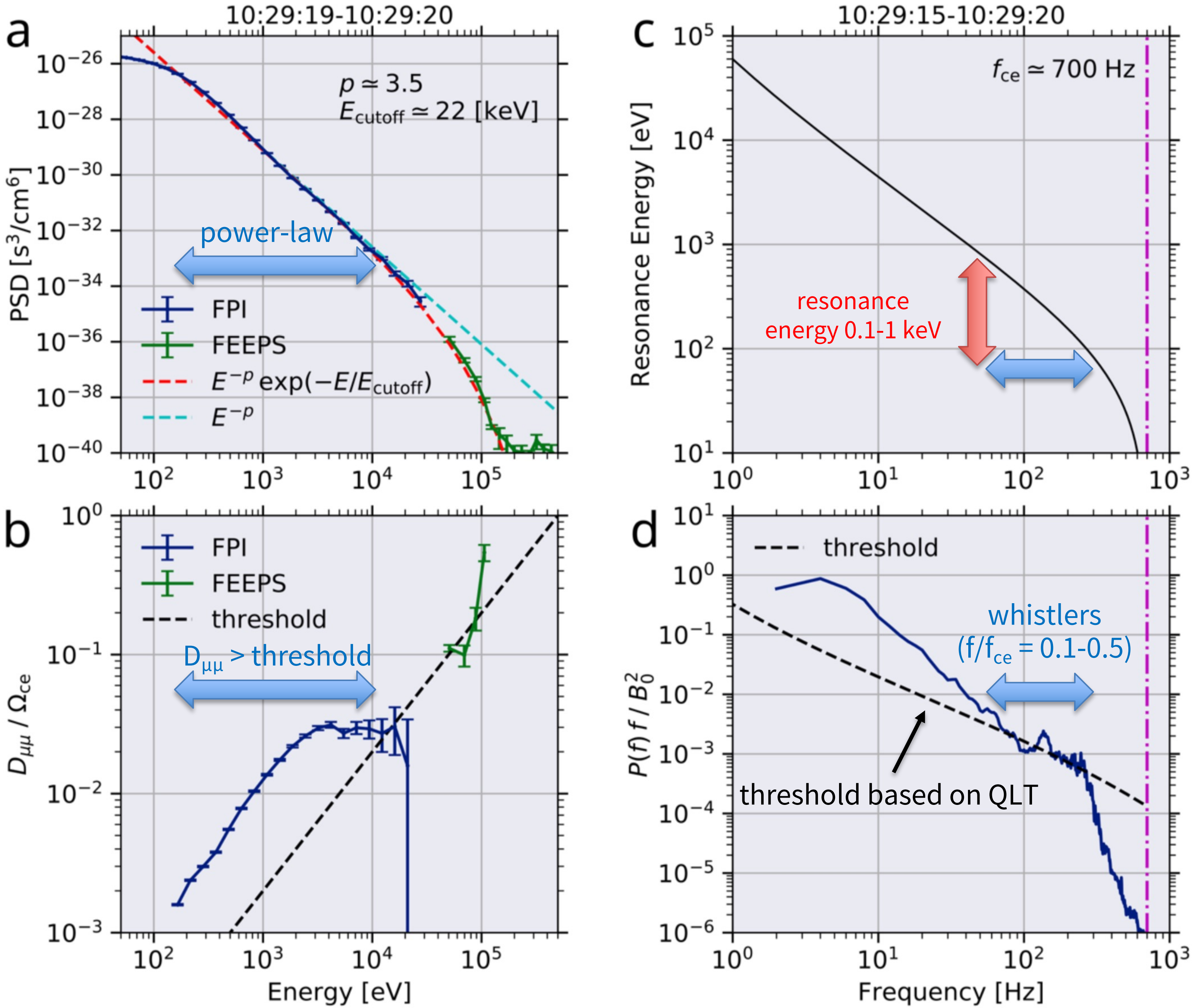
Nearly isotropic pitch-angle distribution

Enhanced wave power (in particular, high-frequency whistlers)

Smoking-Gun Evidence ?

- Simultaneous appearance of energetic electron profiles, weak anisotropy, enhanced wave power are all consistent with the theory. However, the agreement is only qualitative.
- The observed power-law index is roughly consistent with the theory. But it does not necessarily identify the mechanism.
- The theory predicts that the high-energy cutoff of the spectrum is determined by the single parameter $D_{\mu\mu}$

$$E_{\rm cutoff} \sim E_{\rm sh} \left(\frac{m_i}{m_e}\right) \left(\frac{D_{\mu\mu}}{\Omega_{\rm ce}}\right) = \frac{1}{2} m_i \left(\frac{u_0}{\cos\theta_{\rm Bn}}\right)^2 \left(\frac{D_{\mu\mu}}{\Omega_{\rm ce}}\right)$$



Amano+(2020, PRL)

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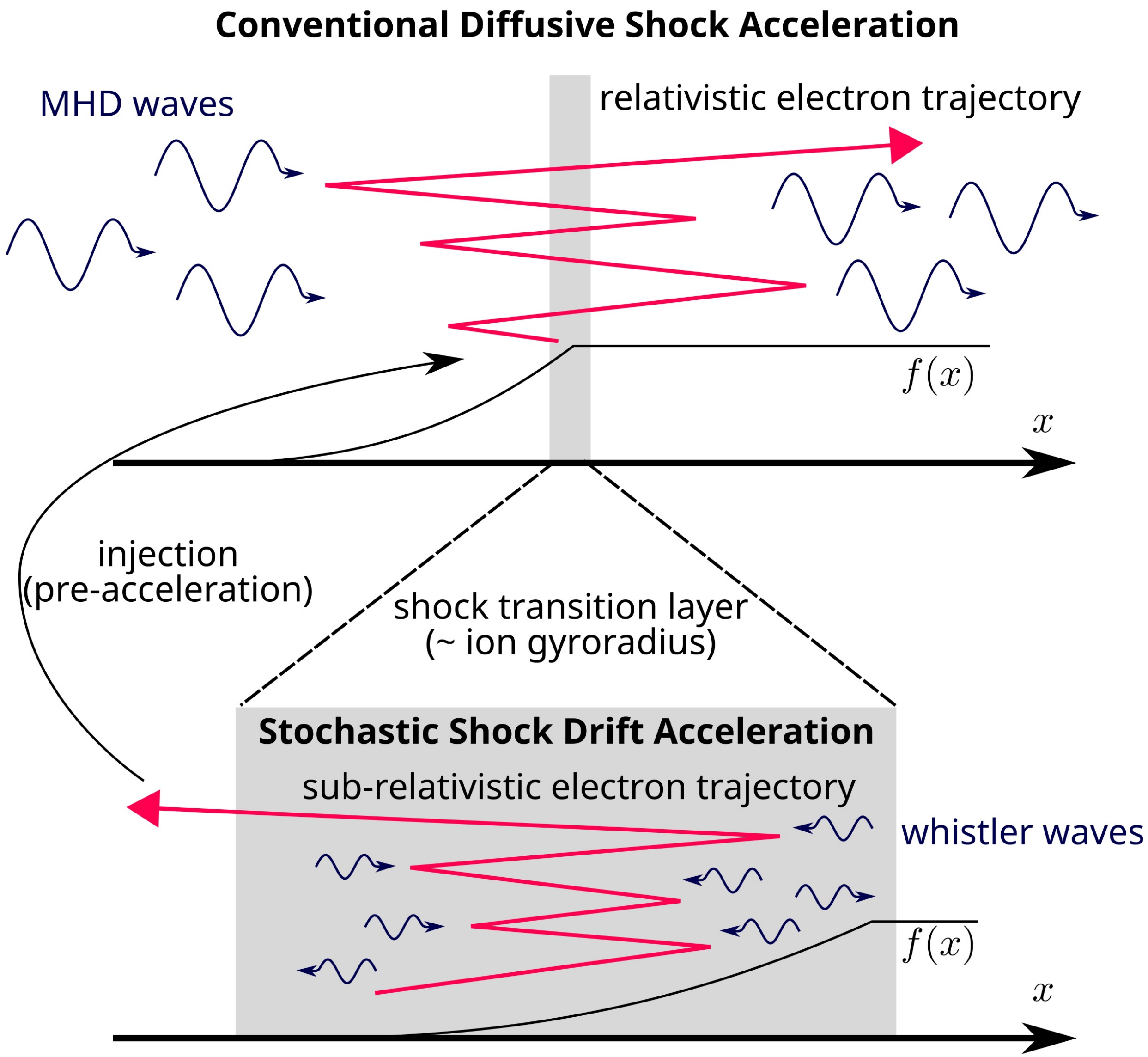


Amano+(2020, PRL), Katou & Amano (2019, ApJ), Kobzar+(2021, ApJ), Matsumoto+(2017, PRL)

Amano & Hoshino (submitted)

Unifying SSDA and DSA

Both SSDA and DSA may be described by the diffusion-convection equation:

$$\frac{\partial f_0}{\partial t} + V\cos\theta \frac{\partial f_0}{\partial x} + \frac{1}{3}\left(\frac{\partial \ln B}{\partial x} - \frac{\partial \ln V}{\partial x}\right) V\cos\theta \frac{\partial f_0}{\partial \ln p} = \frac{\partial}{\partial x}\left(\kappa \cos^2\theta \frac{\partial f_0}{\partial x}\right)$$

energy gain = flow divergence   diffusion along B

$$\frac{\partial}{\partial x}(V\cos\theta) = -V\cos\theta\left(\frac{\partial \ln B}{\partial x} - \frac{\partial \ln V}{\partial x}\right),$$

→ Both SDA (∇B) and first-order Fermi (∇V) contributes to the energy gain but ∇B is dominant at quasi-perp shocks

The steady-state spectrum may be estimated as $f_2(p) \propto p^{-q}$ with

diffusion length >> shock thickness
→ standard DSA (q=4)

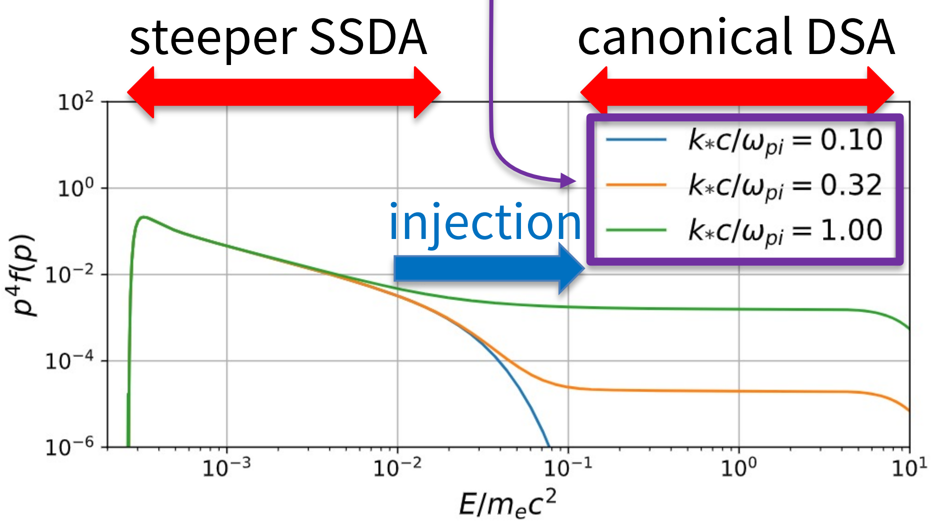
$$q = \frac{3V_1\cos\theta_1}{V_2\cos\theta_2 - V_1\cos\theta_1} = \frac{3r}{r-1},$$

diffusion length ~ shock thickness
→ SSDA

$$q \approx 3\left[1 + \left(l_{\rm diff}\left\langle\frac{\partial \ln B}{\partial x}\right\rangle\right)^{-1}\right],$$

ratio between diffusion length and shock thickness
→ predicted spectrum is steeper than DSA (q>6), but the acceleration time is much shorter

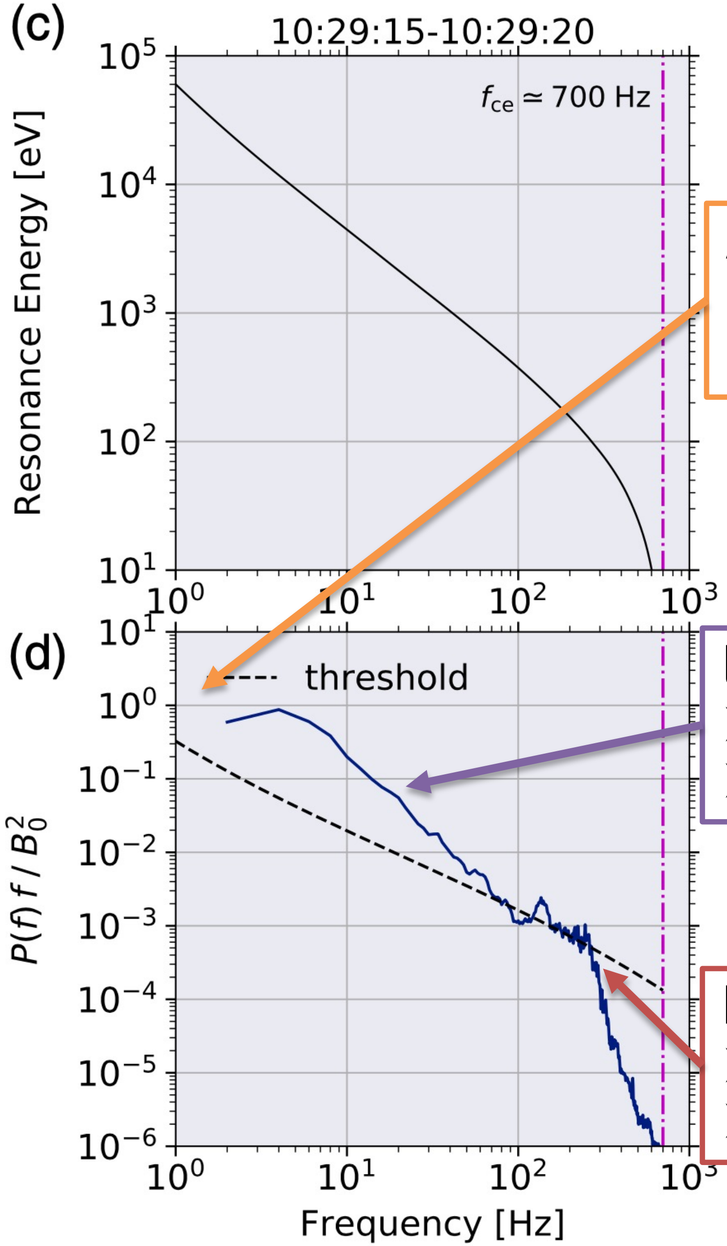
dissipation scale of MHD turbulence for DSA (outside the shock layer)



downstream spectrum

Ref: Amano+2020 (PRL), Amano & Hoshino (submitted)

Roles of Multiscale Plasma Waves



Alfven-ion-cyclotron
- ~ 1Hz
- e- energy ~ 10-100 keV

low-freq. oblique whistlers
- ~10 Hz
- e- energy ~ 1-10 keV

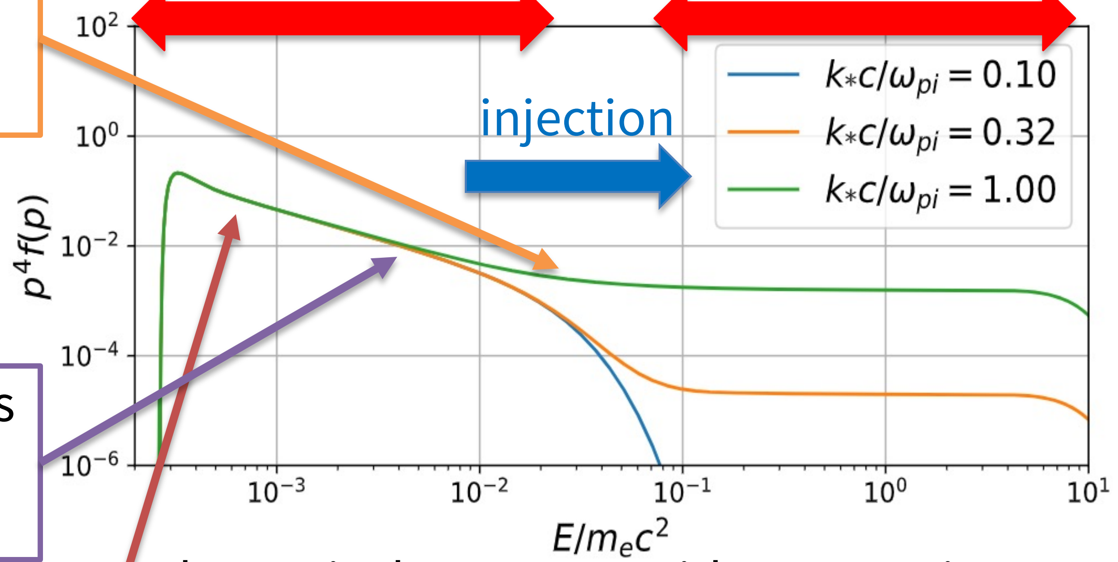
high-freq. parallel whistlers
- ~100 Hz
- e- energy ~ 0.1-1 keV

MHD turbulence outside the shock layer

New !

steeper SSDA

canonical DSA



theoretical spectrum with a scattering rate estimated from MMS observation

Question:
Does the generation of various waves happen just by chance? Are there any causal relations with the accelerated electrons?

Amano & Hoshino (submitted)

Condition for Electron Injection

Earth's bow shock

SNR shock

no electron acc.

electron acc. by SSDA but not DSA
(injection is impossible)

electron acc. by SSDA and DSA
(injection is possible)

$$M_A^{HTF} = M_A / \cos\theta_{Bn}$$

$$M_A^{HTF} \gtrsim (6\eta)^{-1/2} \left(\frac{D_{\mu\mu}(p)}{\Omega_{ce}}\right)^{-1/2} \left(\frac{p}{m_e V_{A,e}}\right)$$

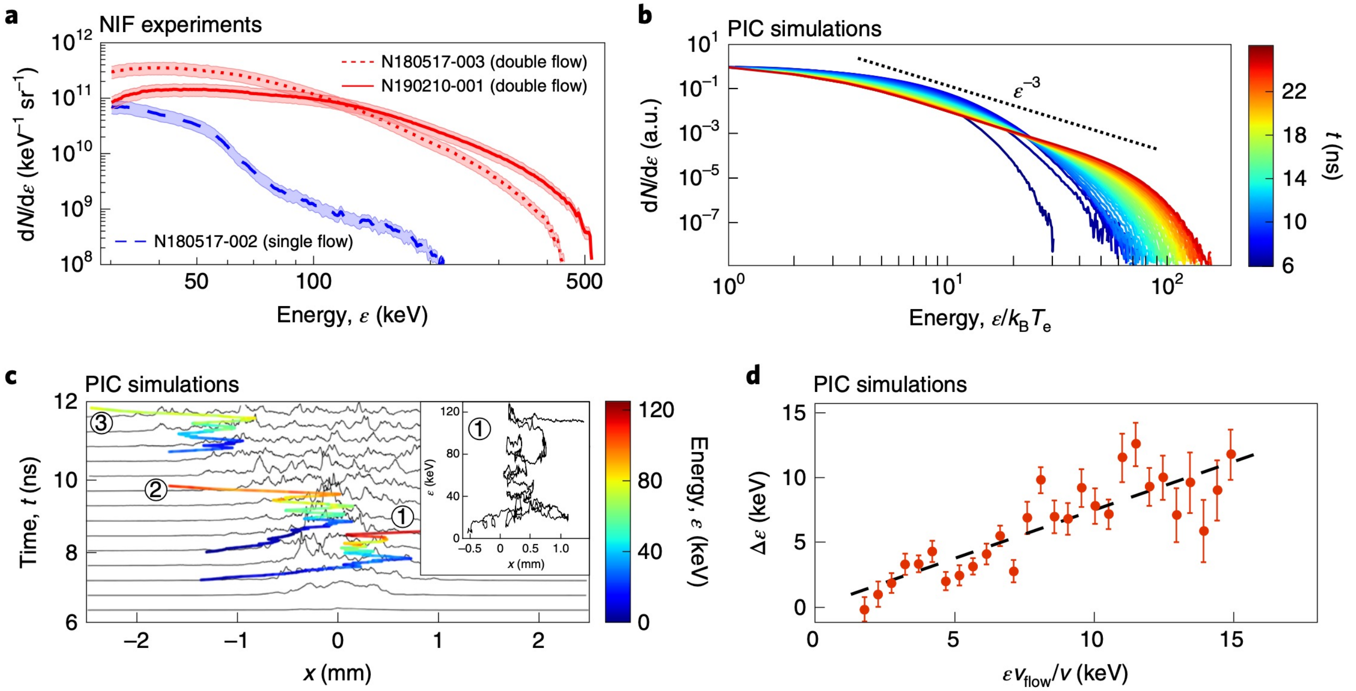
$$M_A^{HTF} \gtrsim (6\eta)^{-1/2} \left(\frac{D_{\mu\mu}(p)}{\Omega_{ce}}\right)^{-1/2} \left(\frac{m_i}{m_e}\right)^{1/2} \left(\frac{k_* c}{\omega_{pi}}\right)^{-1}$$

- The most important parameter is the Alfven Mach number in HTF: $M_A^{HTF} = M_A / \cos\theta_{Bn}$
  - Importance of this parameter for electron acceleration has been suggested both in theory and observations [Levinson 1992-1996, Oka+2006, Amano & Hoshino 2010]
- The specific transition Mach number depends on $D_{\mu\mu}$.
  - Wave intensity and associated scattering efficiency must be known for making a quantitative theoretical prediction.

Conclusions

- At present, Stochastic Shock Drift Acceleration (SSDA) is the most promising mechanism for electron injection.
- The theory predicts a steeper-than-DSA spectrum at sub-relativistic energies, which will be connected smoothly to the harder DSA at the transition energy of 0.1-1 MeV, if efficient electron injection is realized.

Fiuza+2020 (Laser Experiments @ NIF)



Tanaka+2018 (NuSTAR obs for W49B)