Electron Injection via Stochastic Shock Drift Acceleration: Theory, Simulation, and Observation

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Collaborators

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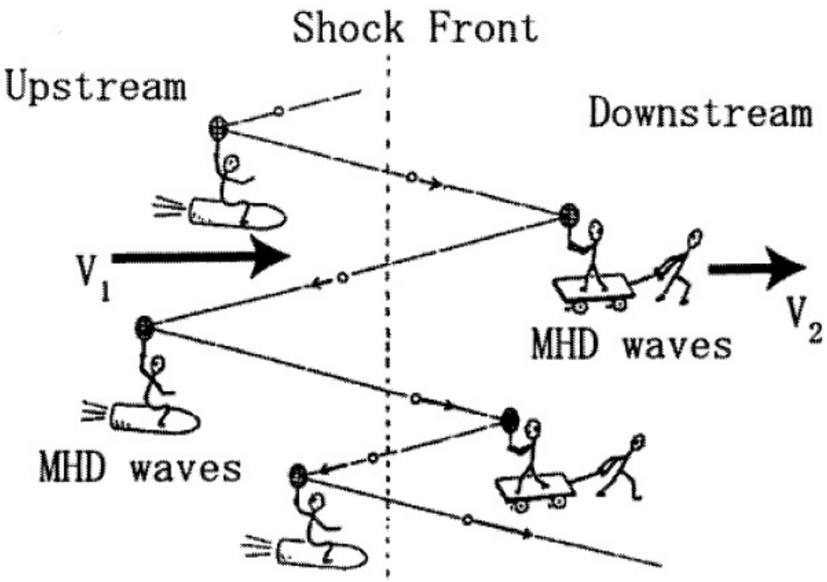
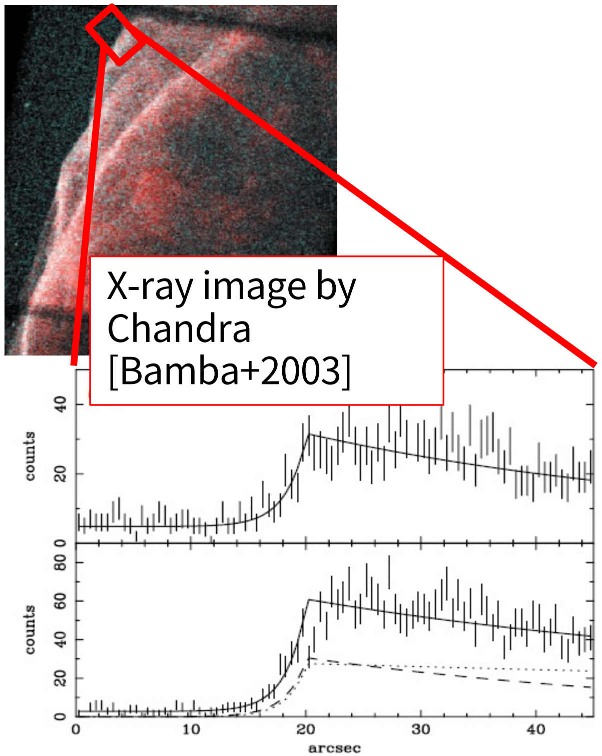
The Standard Shock Acceleration Theory

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

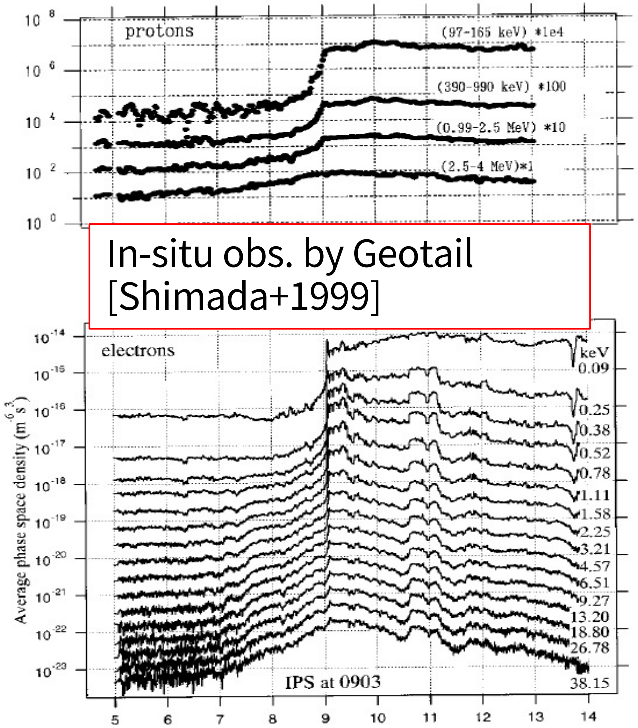
[e.g., Bell 1978, Blandford & Ostriker 1978]



M. Scholer



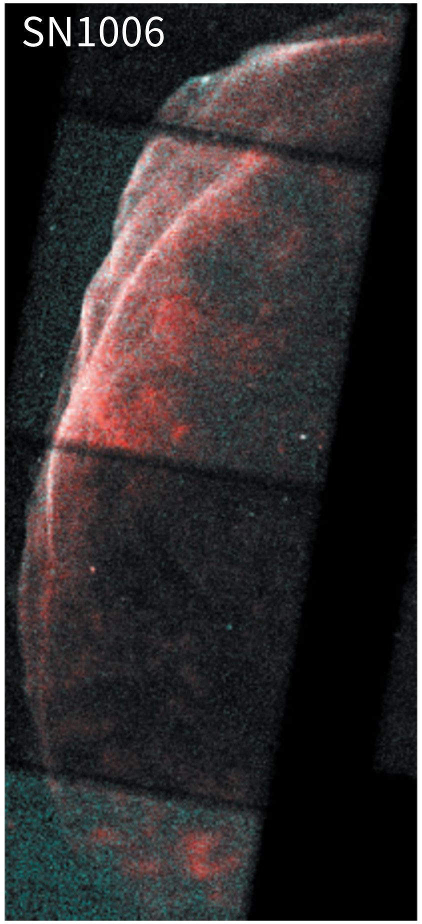
X-ray image by Chandra [Bamba+2003]

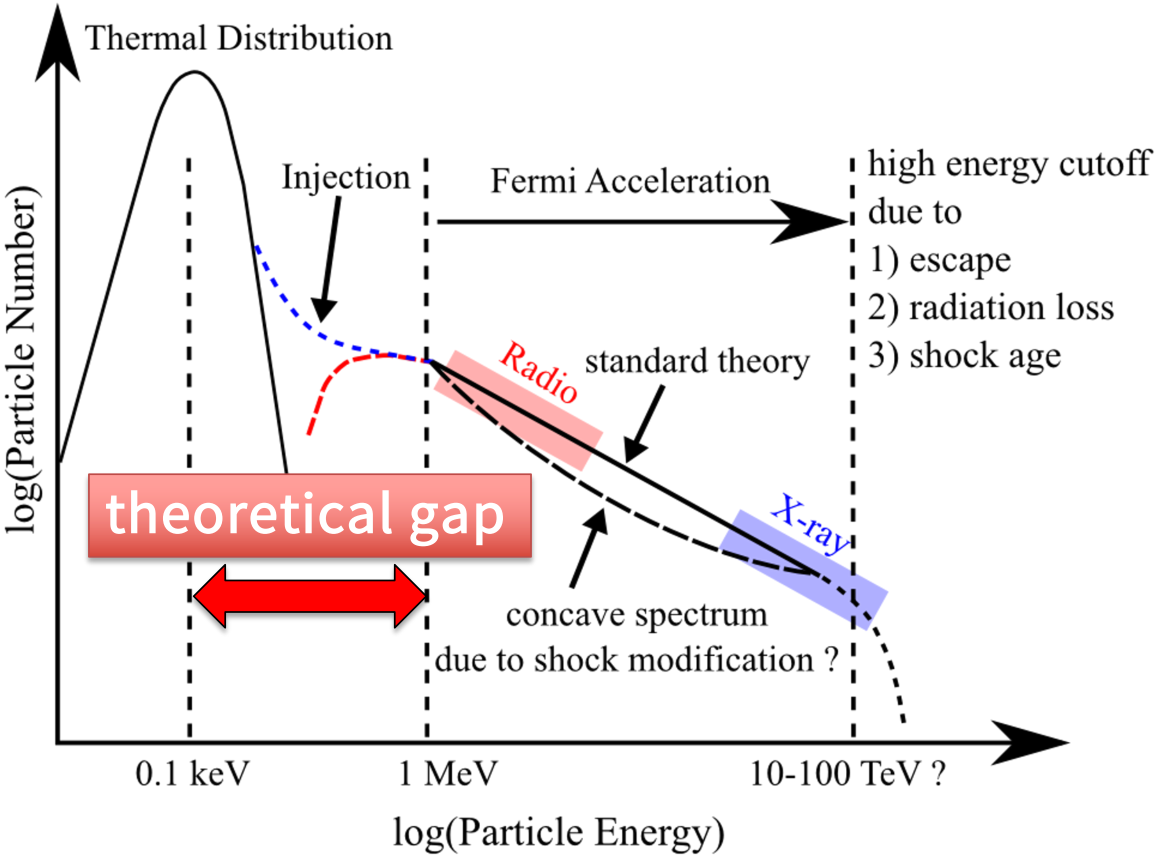


In-situ obs. by Geotail [Shimada+1999]

The Electron Injection

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

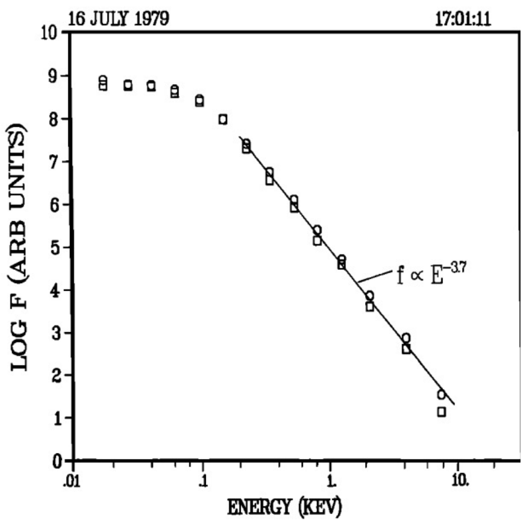




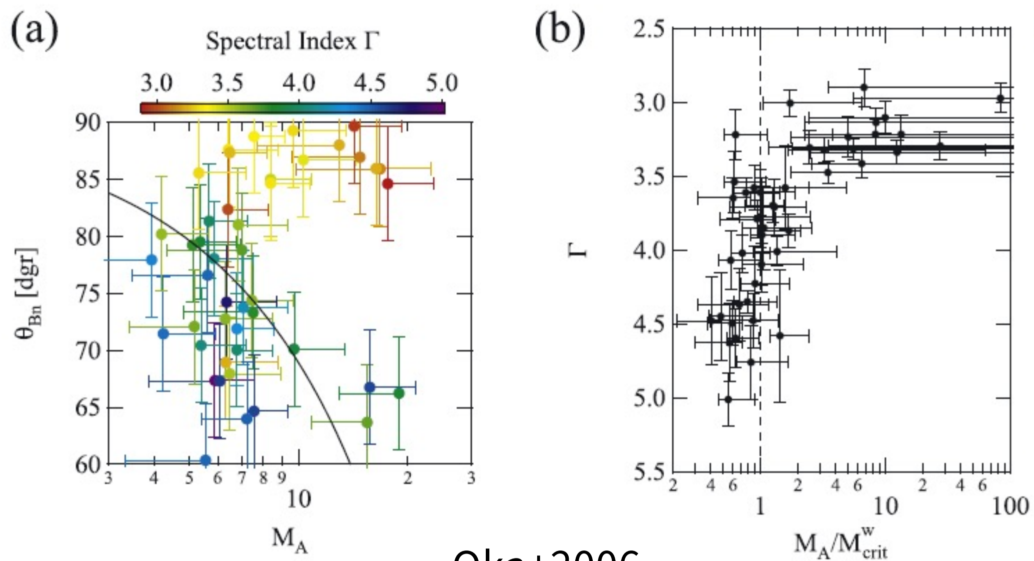
- ✓ Sub-relativistic electrons cannot be accelerated by the standard first-order Fermi mechanism.
- ✓ Substantial energy gain is needed from thermal to relativistic energies by some other mechanisms.
- ✓ Sub-relativistic suprathermal electrons are "invisible" with typical astrophysical observations,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

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

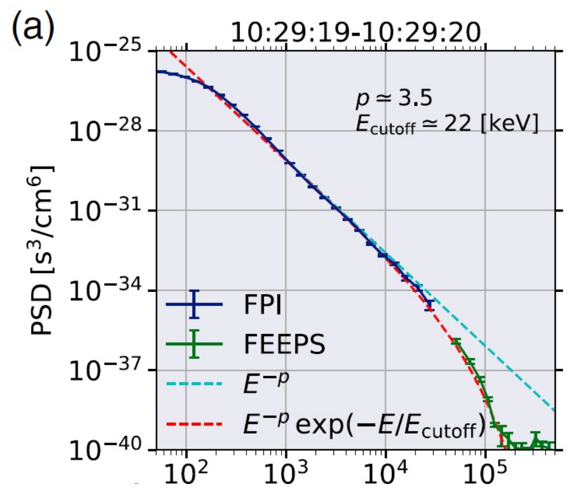
Earth's Bow Shock: Laboratory for Electron Injection



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.

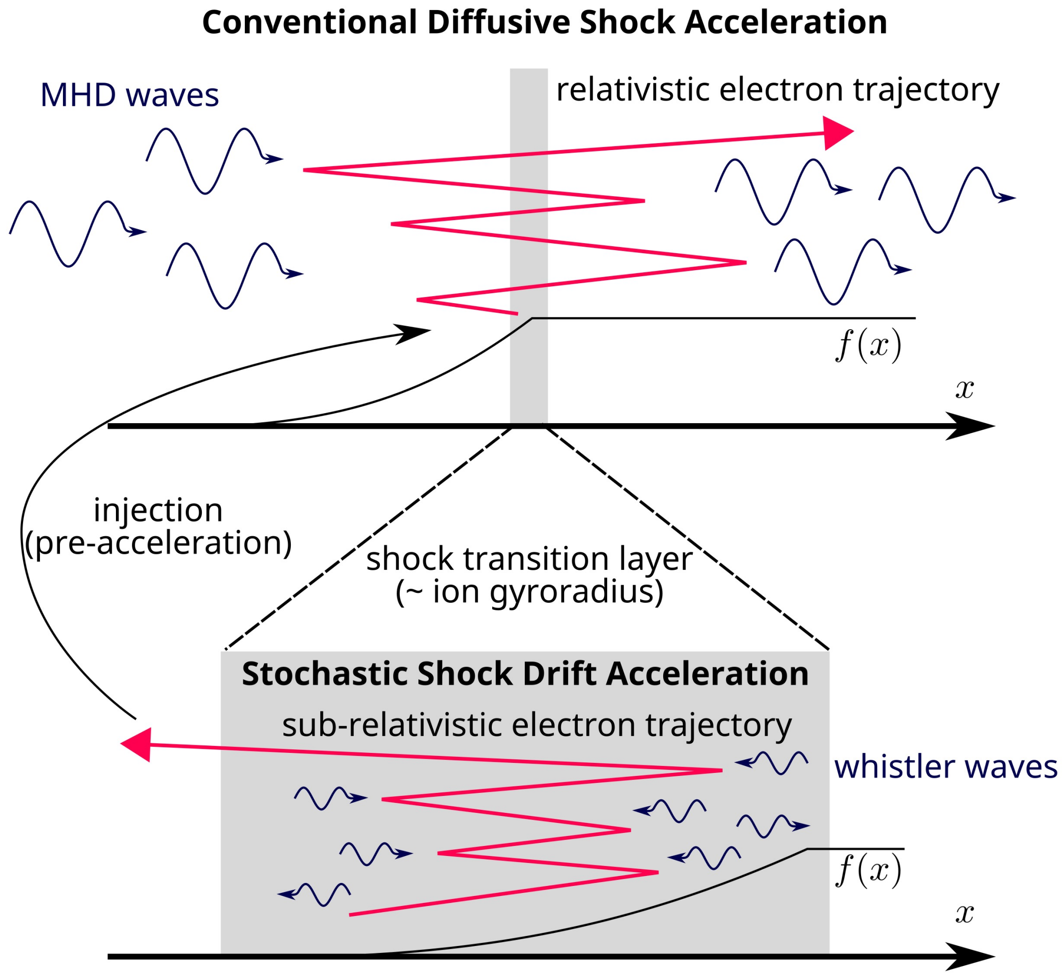
Electron Injection Scenario

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 & Hoshino (2022, ApJ), Amano+(2020, PRL), Katou & Amano (2019, ApJ), Kobzar+(2021, ApJ), Matsumoto+(2017, PRL)

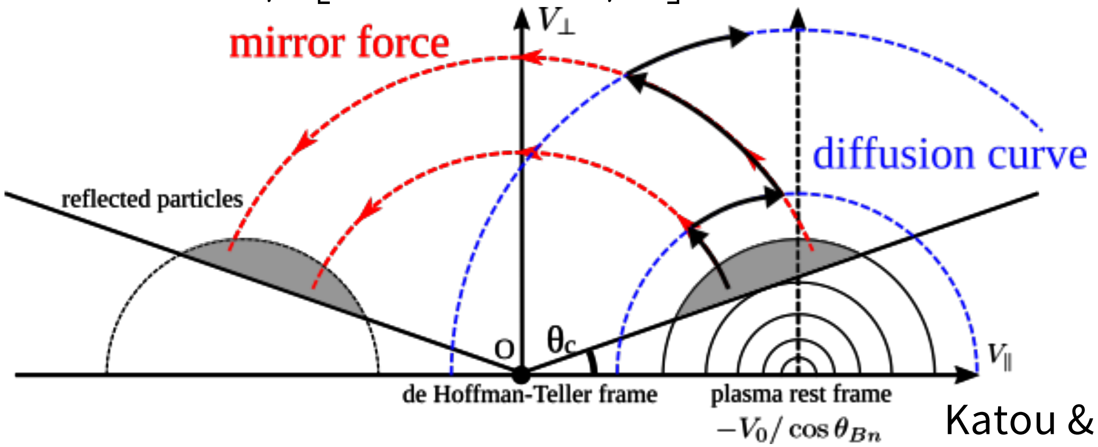
Stochastic SDA (SSDA)

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

negligible at Qperp shock
(major term for DSA)

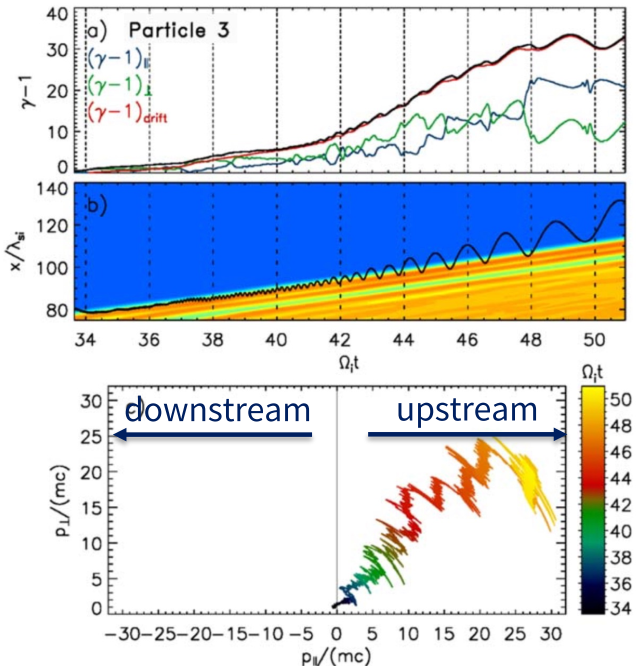
mirror force

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



Katou & Amano (2019)

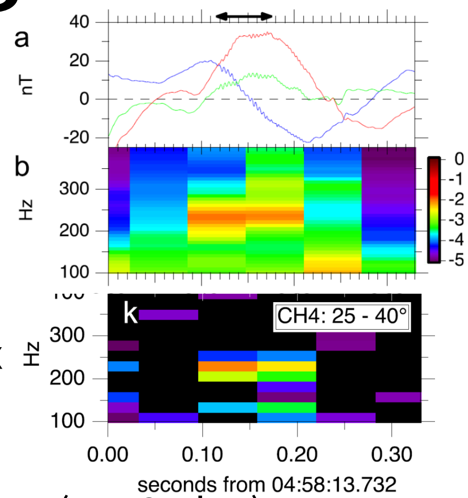
SSDA Signatures



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

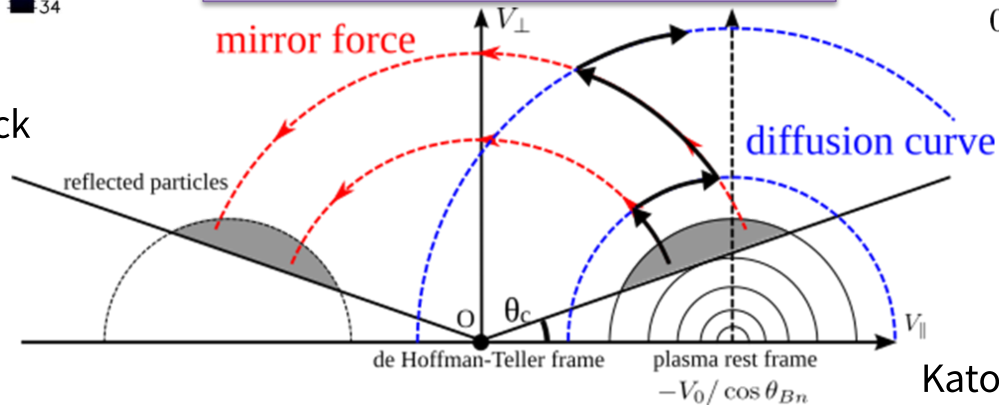
B field

particle flux

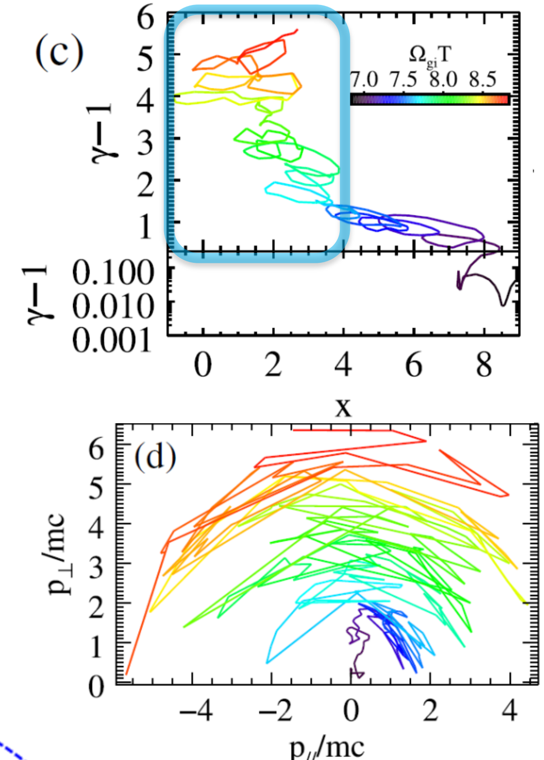


Oka+2017 (MMS obs.)

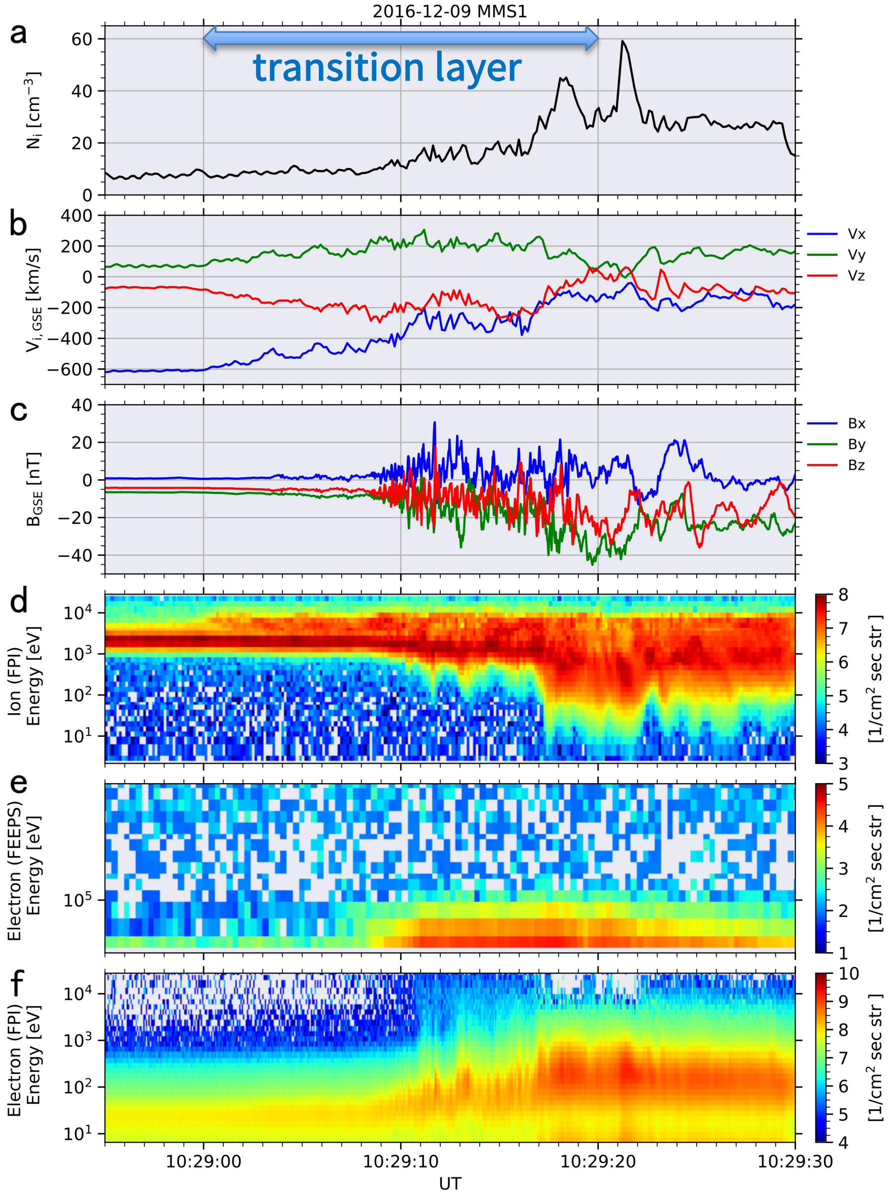
Stochastic Shock Drift Acceleration
mirror reflection + scattering



Katou & Amano 2019



Matsumoto+2017
3D Weibel-dominated shock

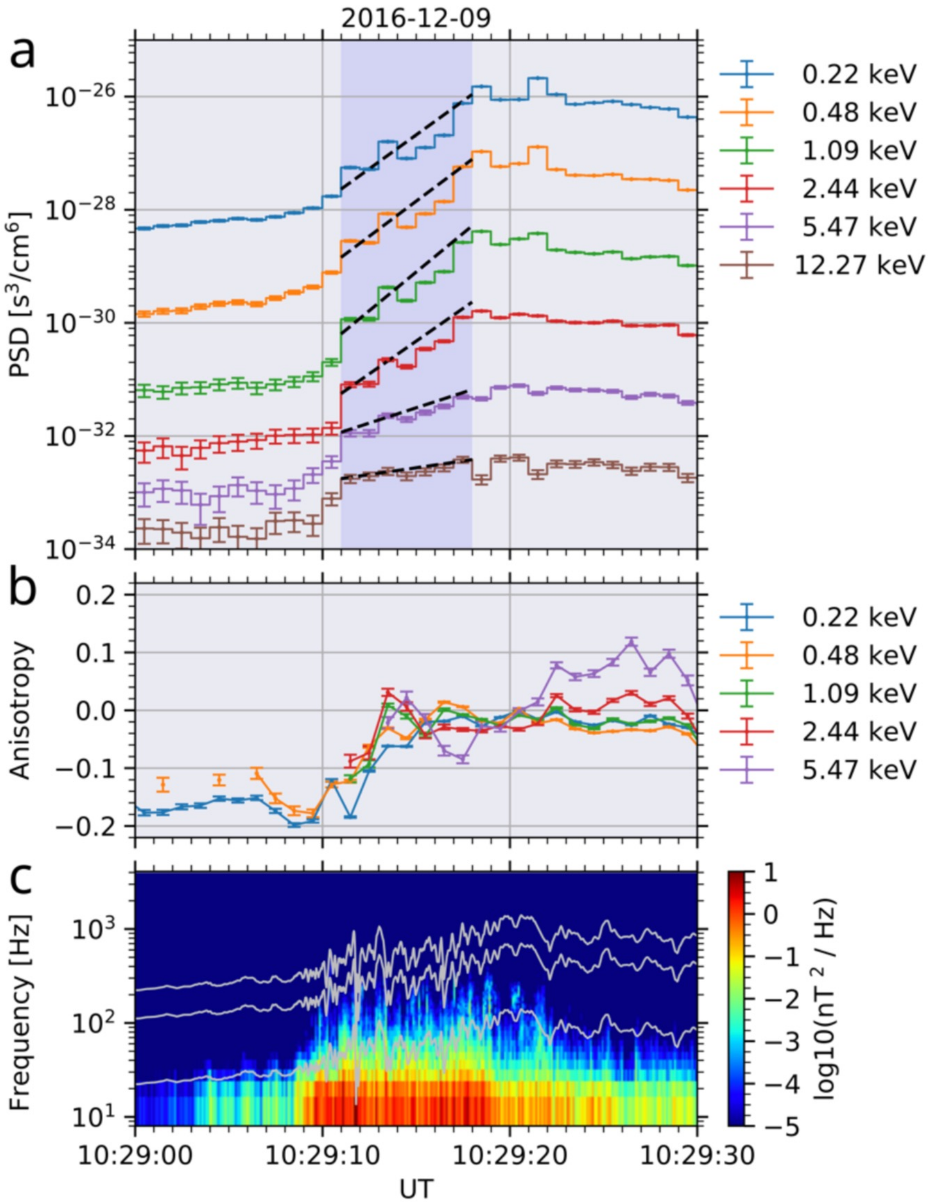


Bow Shock Crossing measured by MMS spacecraft

- 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.

Evidence for the proposed electron injection scenario by MMS observation at Earth's bow shock [Amano+2020, PRL]



Exponential increase of particle intensity

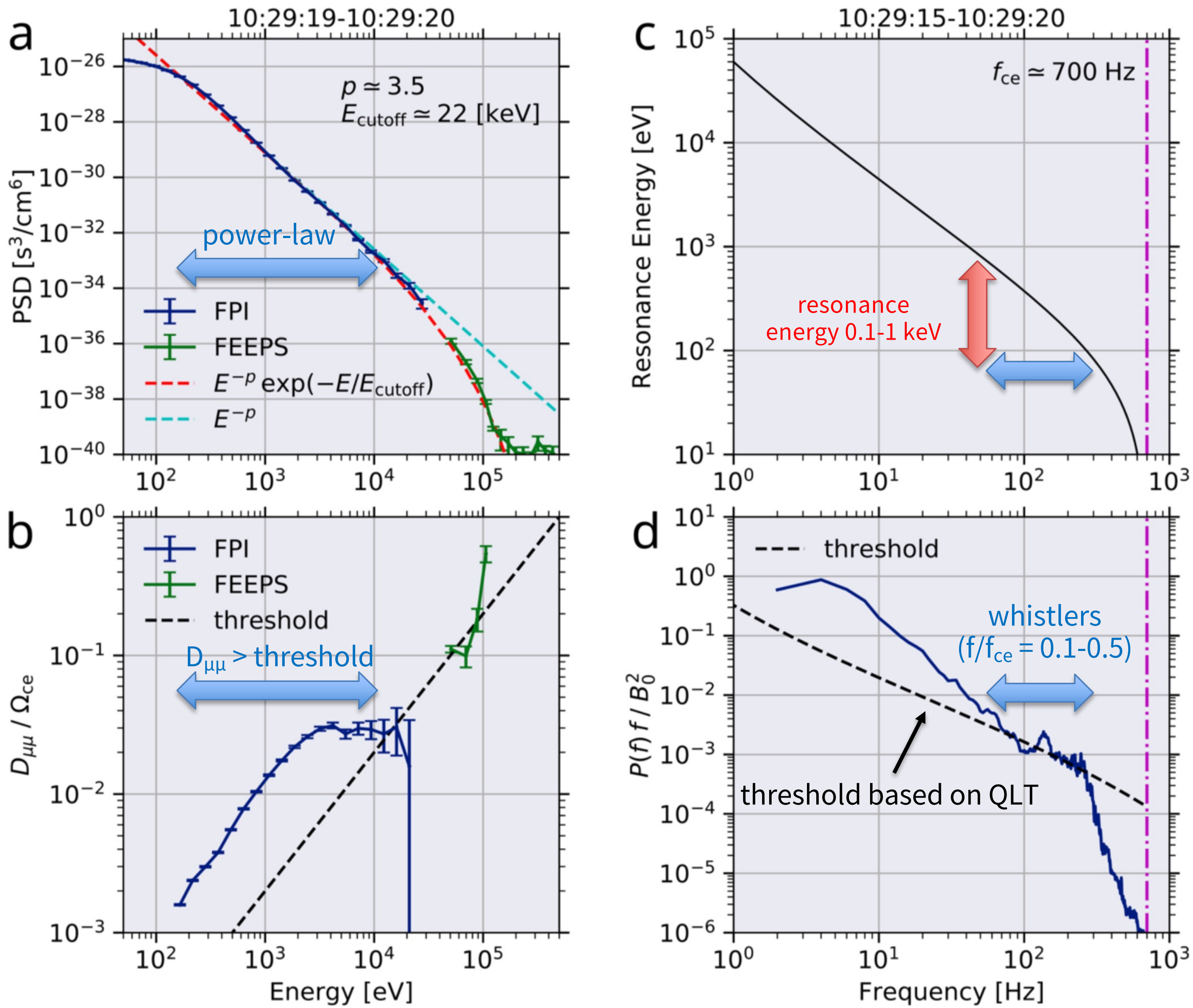
Nearly isotropic pitch-angle distribution

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 $D_{\mu\mu}$

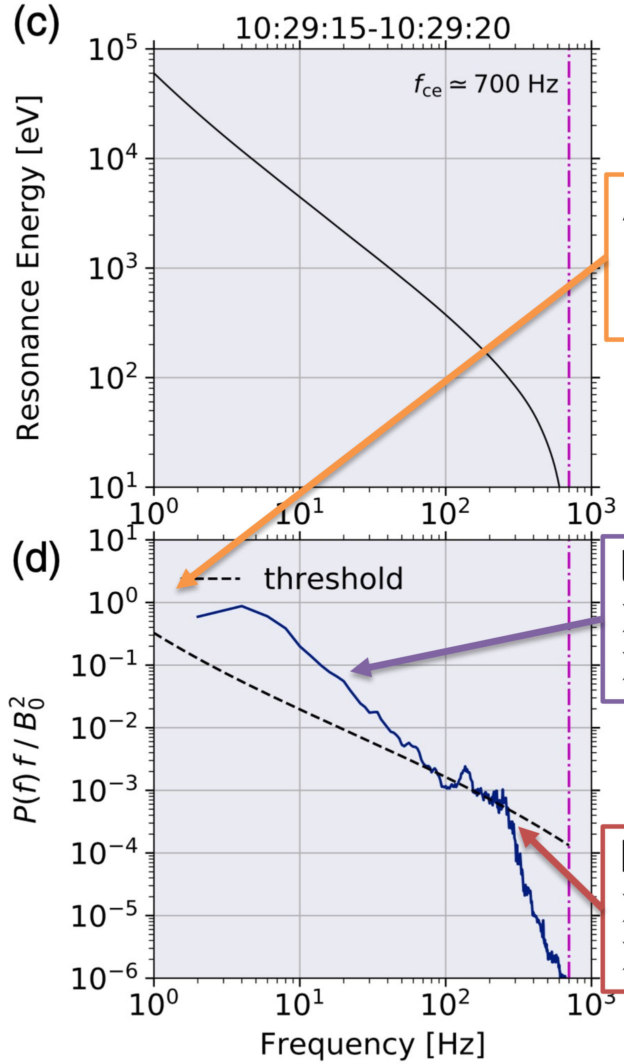
$$E_{\mathrm{cutoff}} \sim E_{\mathrm{sh}} \left(\frac{m_i}{m_e}\right) \left(\frac{D_{\mu\mu}}{\Omega_{\mathrm{ce}}}\right) = \frac{1}{2} m_i \left(\frac{u_0}{\cos\theta_{\mathrm{Bn}}}\right)^2 \left(\frac{D_{\mu\mu}}{\Omega_{\mathrm{ce}}}\right)$$



Amano+(2020, PRL)

Ref: Amano+2020 (PRL), Amano & Hoshino (2022), Amano+(submitted)

Unifying SSDA and DSA

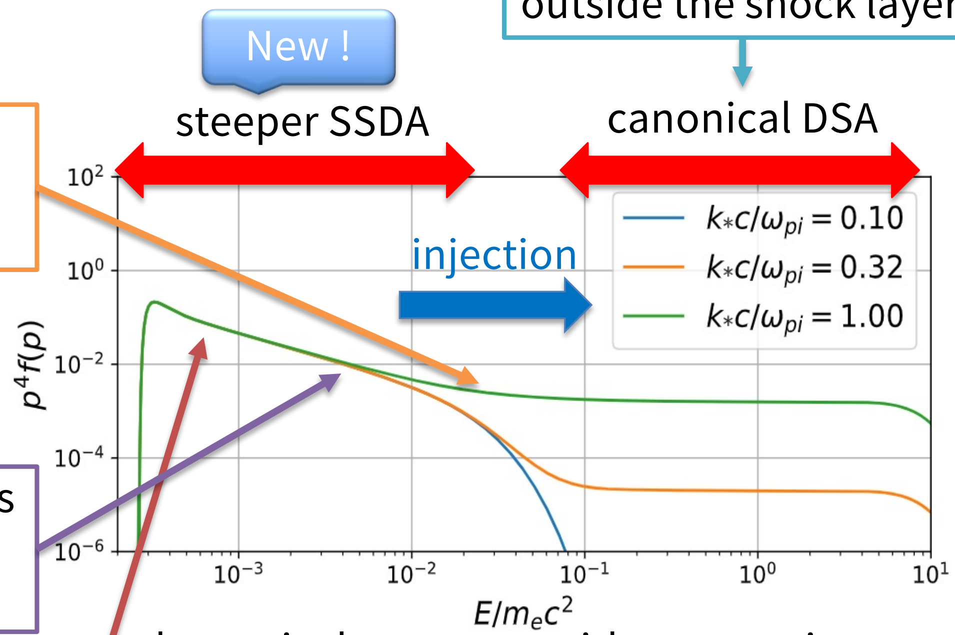


Alfven-ion-cyclotron
- ~ 1Hz
- e- energy ~ 10-100 keV

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

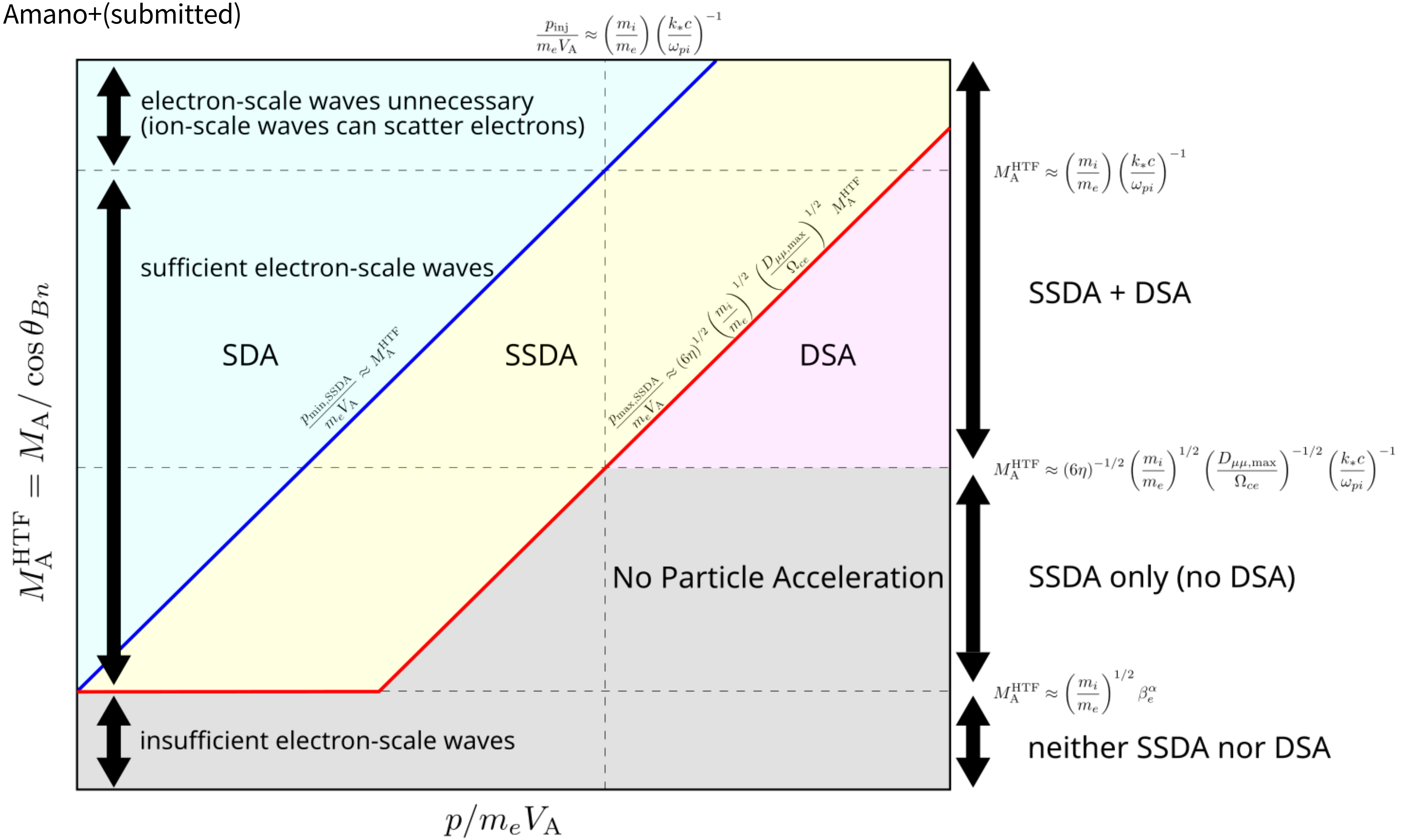
high-freq. parallel whistlers
- ~100 Hz
- e- energy ~ 0.1-1 keV

MHD turbulence outside the shock layer



theoretical spectrum with a scattering rate estimated from MMS observation

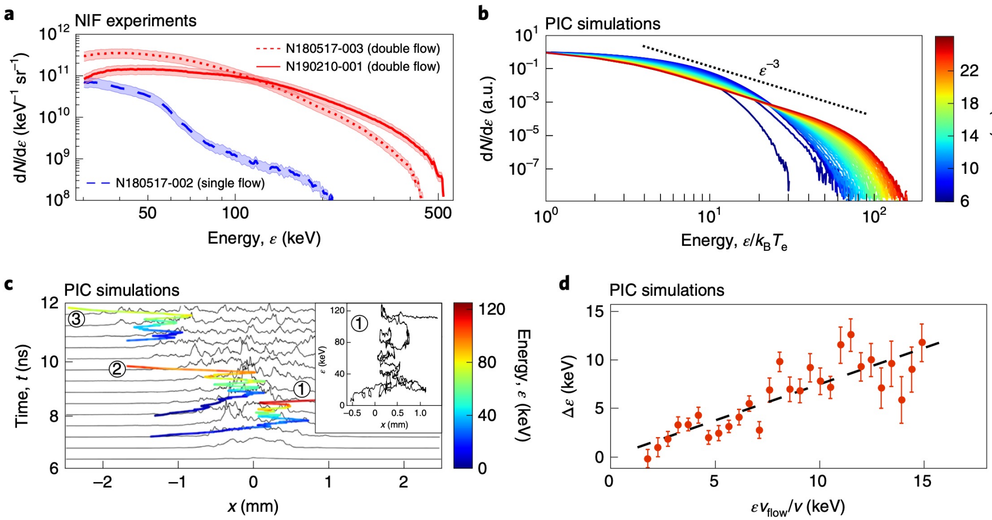
Ref: Amano+(submitted)



Conclusions

- We believe that, at present, Stochastic Shock Drift Acceleration (SSDA) is the most promising mechanism for electron injection at shocks.
- 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.
- It may be tested not only with in-situ spacecraft observations but also future astrophysical observations as well as laboratory laser experiments.

Fiuza+2020 (Laser Experiments @ NIF)



Tanaka+2018 (NuSTAR obs for W49B)