Roles of whistler-mode waves for the electron injection at collisionless oblique shocks

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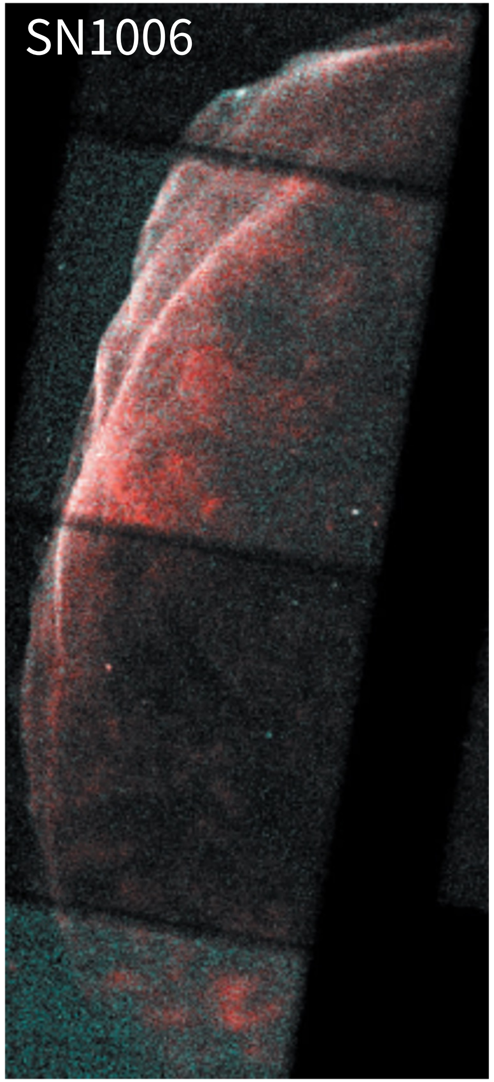
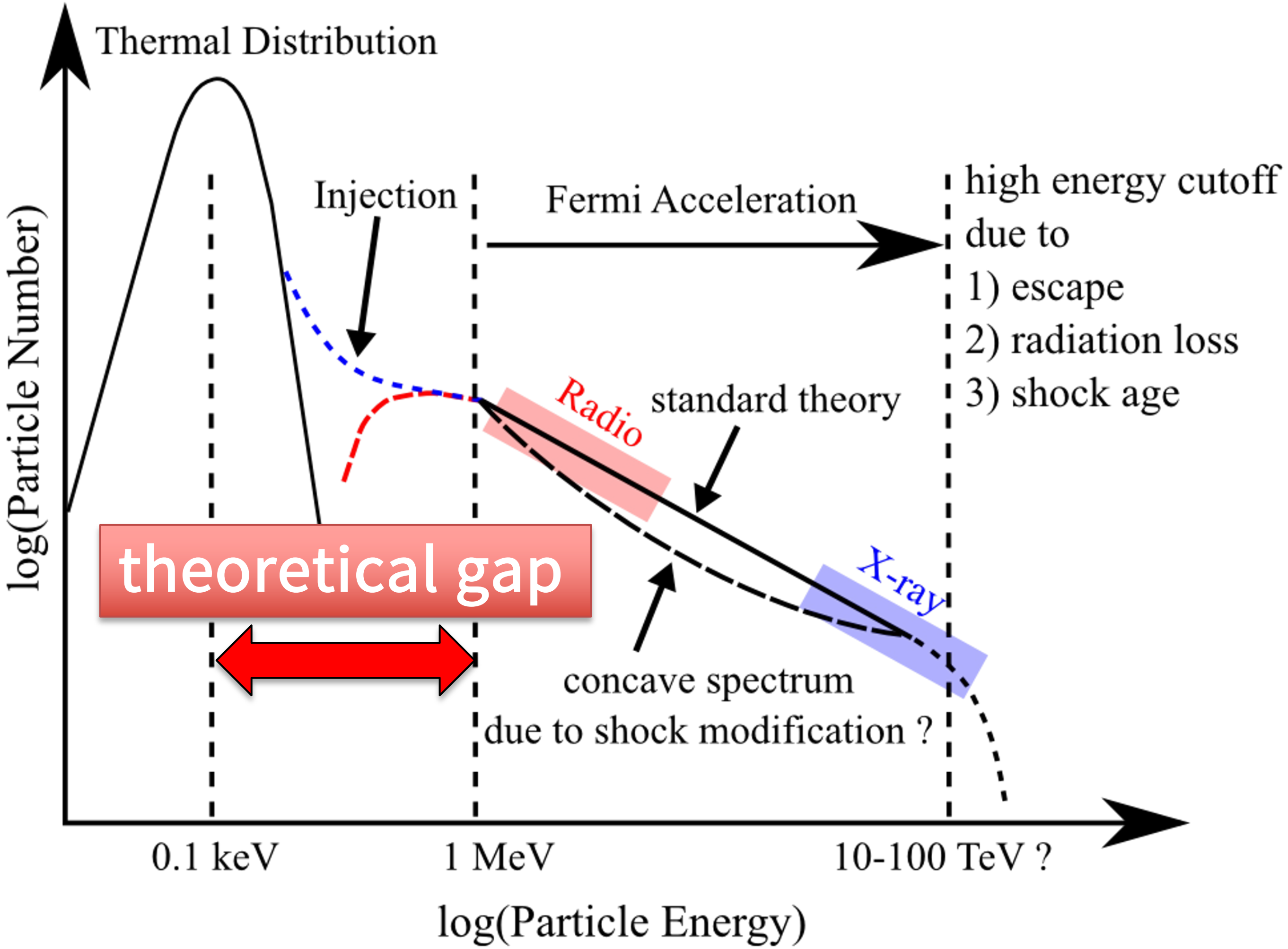
Electron Injection

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

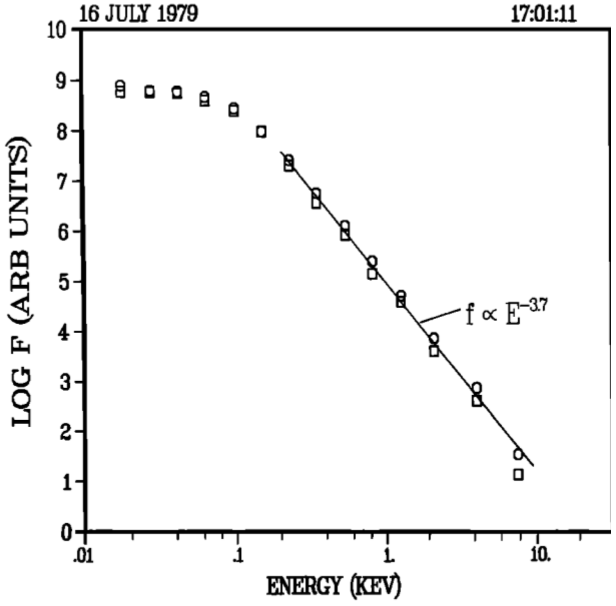




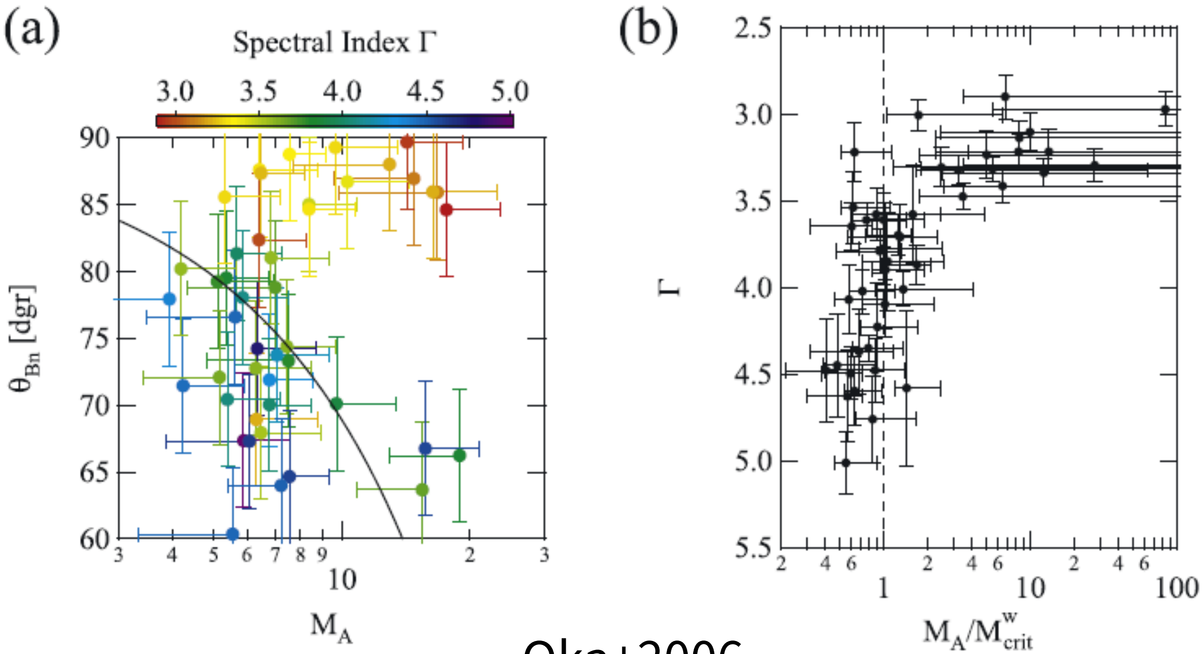
- ✓ Sub-relativistic electrons cannot be accelerated by the standard first-order Fermi mechanism.
- ✓ Substantial energy gain is needed from thermal to relativistic energies by some other mechanisms.
- ✓ Sub-relativistic suprathermal electrons are "invisible" with typical astrophysical observations,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

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

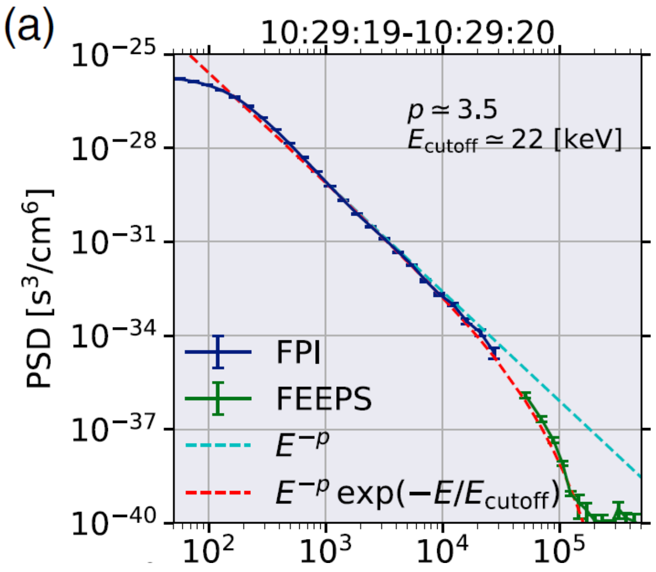
Earth's Bow Shock: Laboratory for Electron Injection



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.

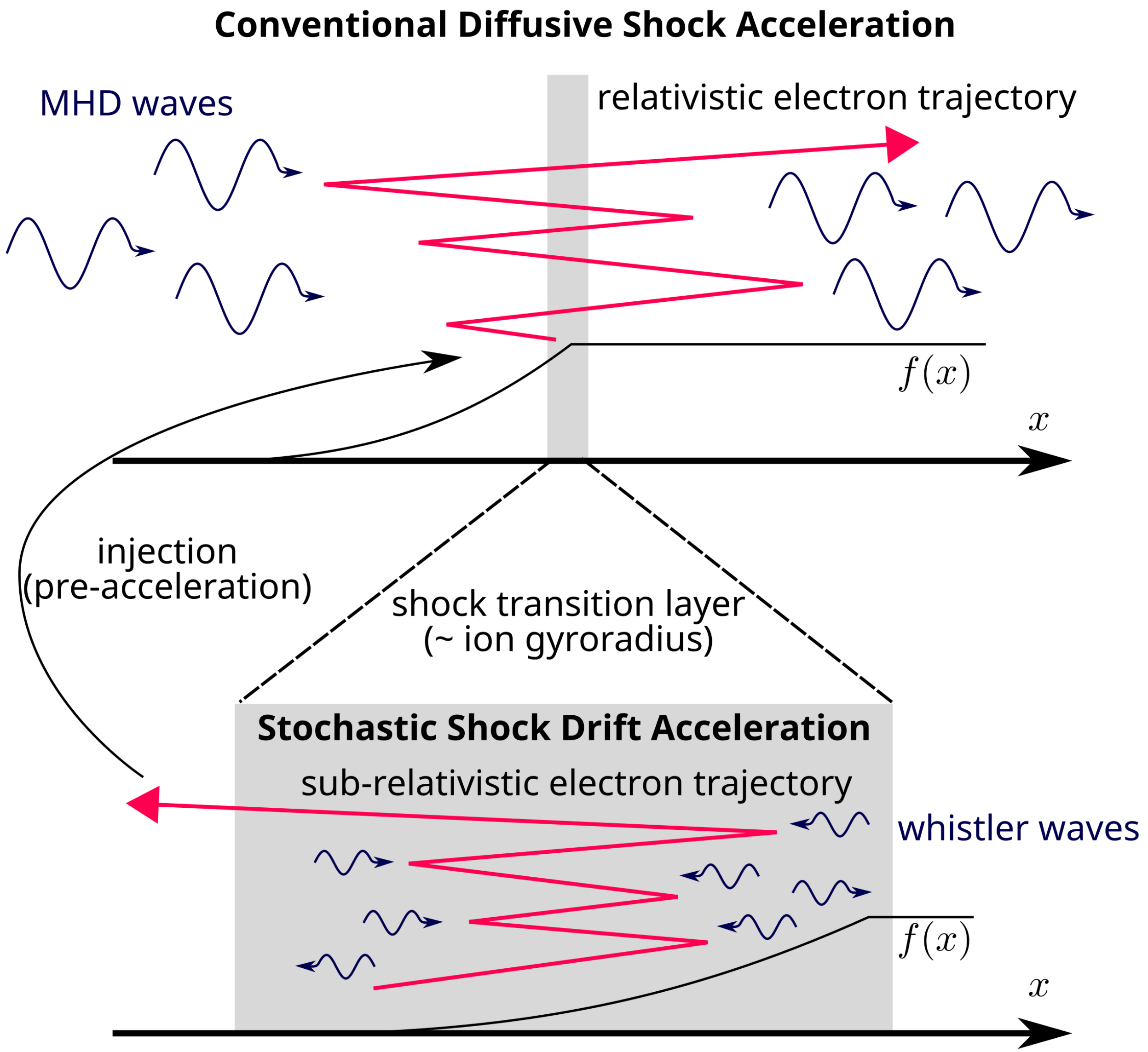
Electron Injection Scenario

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.

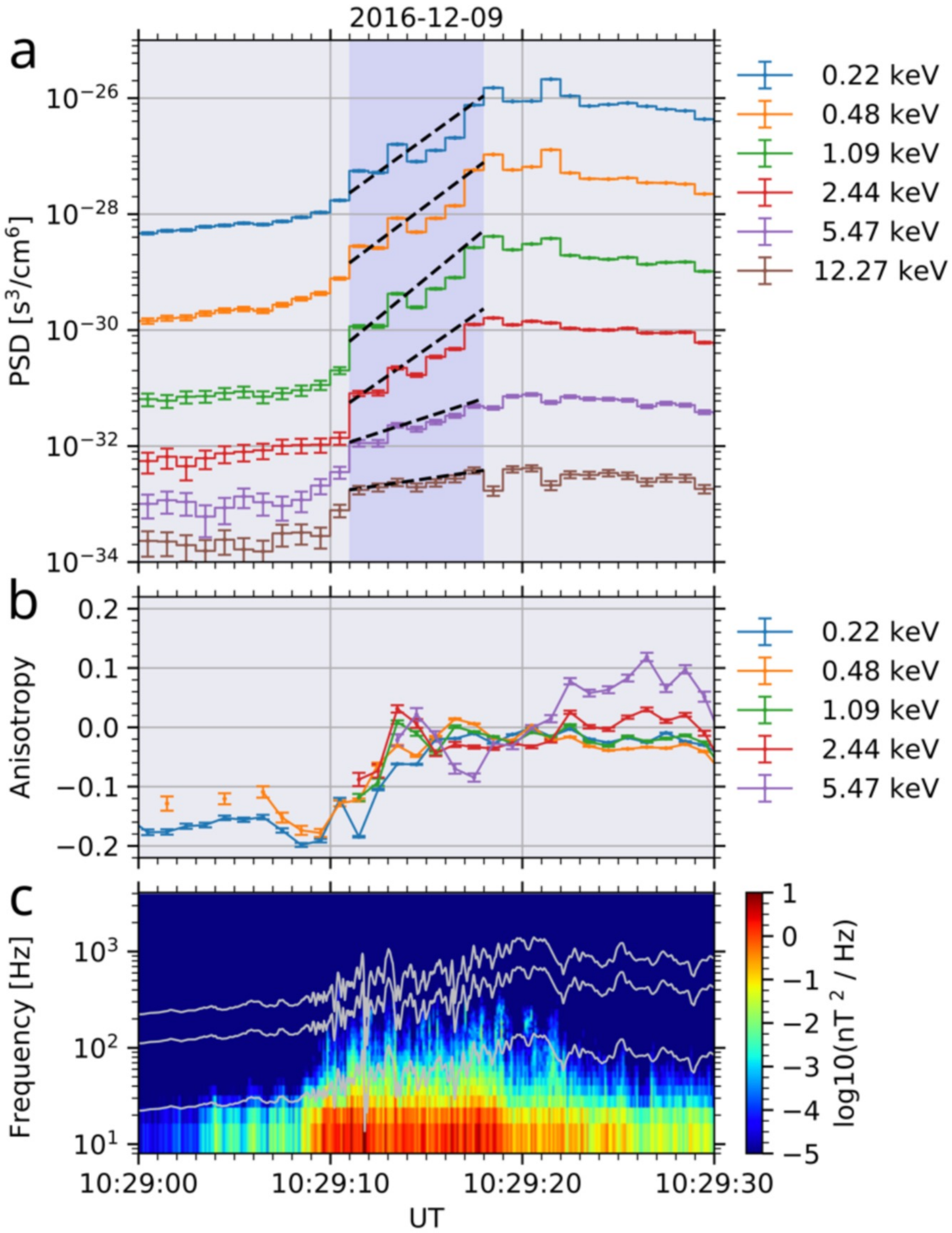
SSDA (diffusion length ~ shock thickness)

- 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)

Amano+ (PRL, 2020)



Exponential increase of particle intensity

Nearly isotropic pitch-angle distribution

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

Amano & Hoshino (2022, ApJ)

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

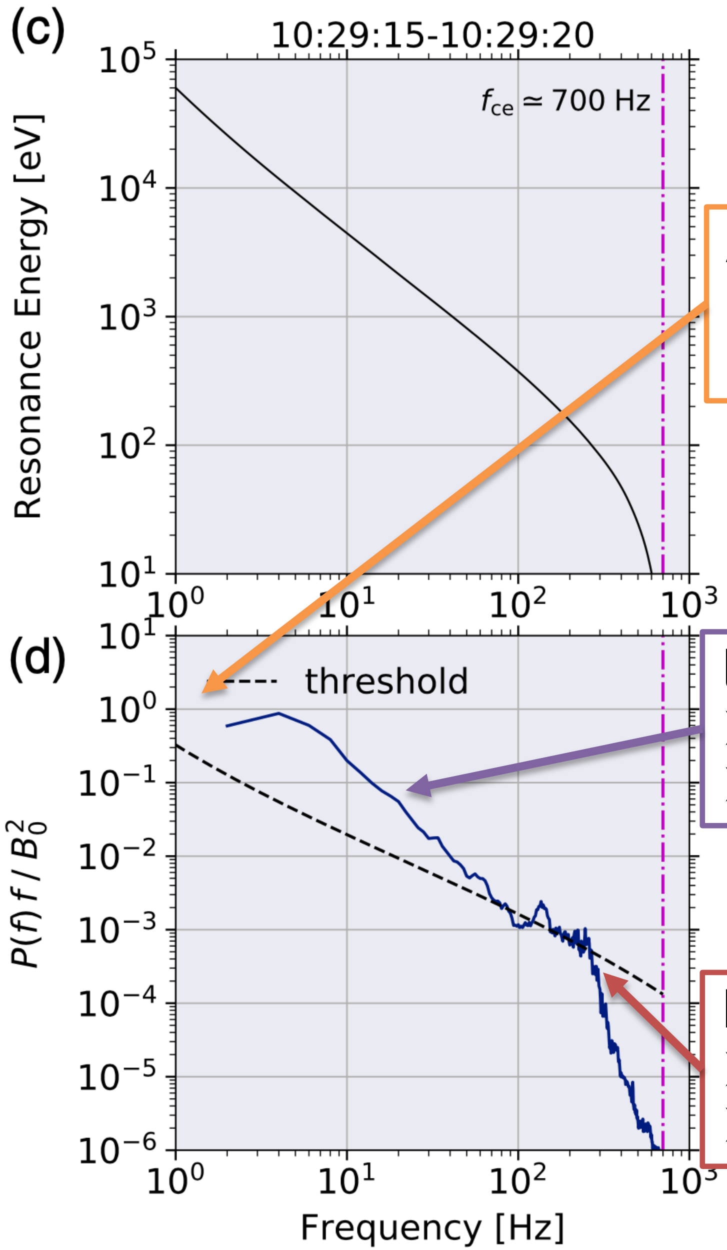
$$q \approx 3\left[1 + \left(l_{\rm diff}\left\langle\frac{\partial \ln B}{\partial x}\right\rangle\right)^{-1}\right],$$

ratio between diffusion length and shock thickness

→ predicted spectrum is steeper than DSA (q>6), but the acceleration time is much shorter

Amano+ (PRL, 2020)

Roles of Multiscale Plasma Waves



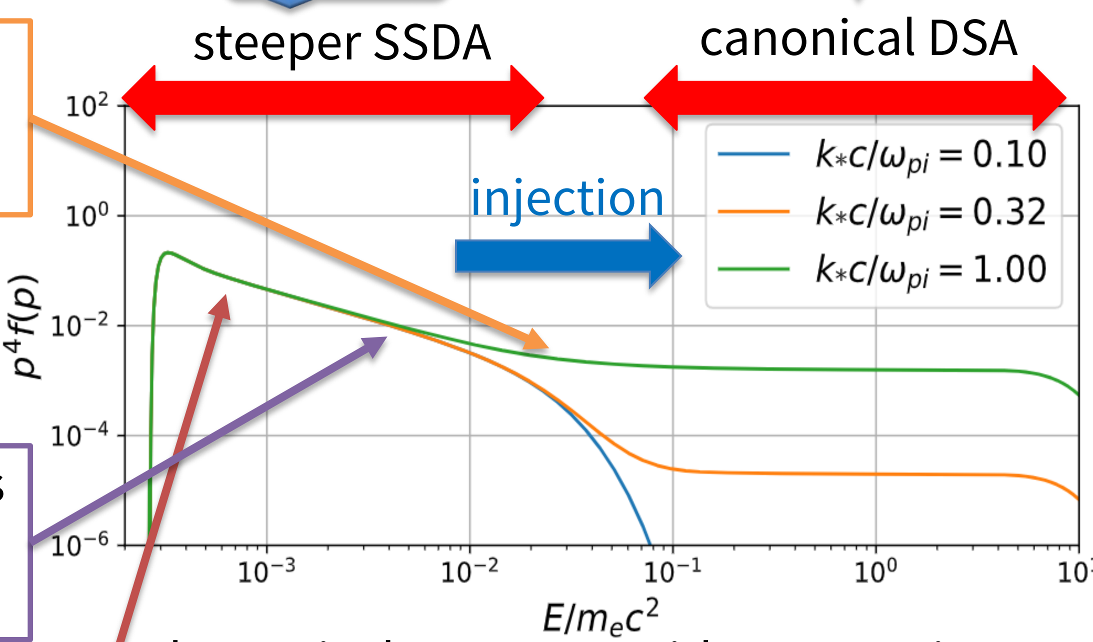
Alfven-ion-cyclotron
- ~ 1Hz
- e- energy ~ 10-100 keV

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

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

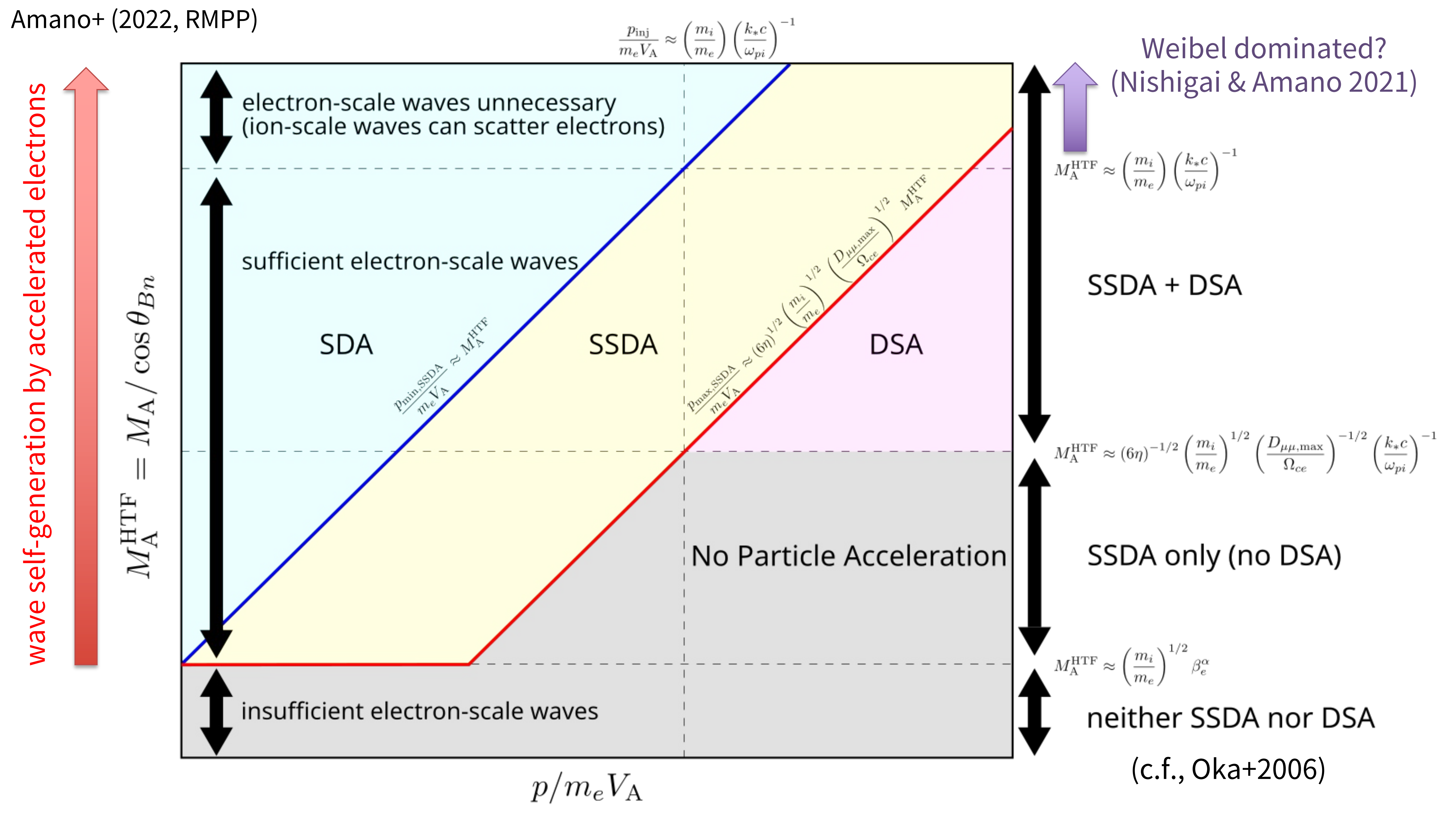
New !

MHD turbulence outside the shock layer



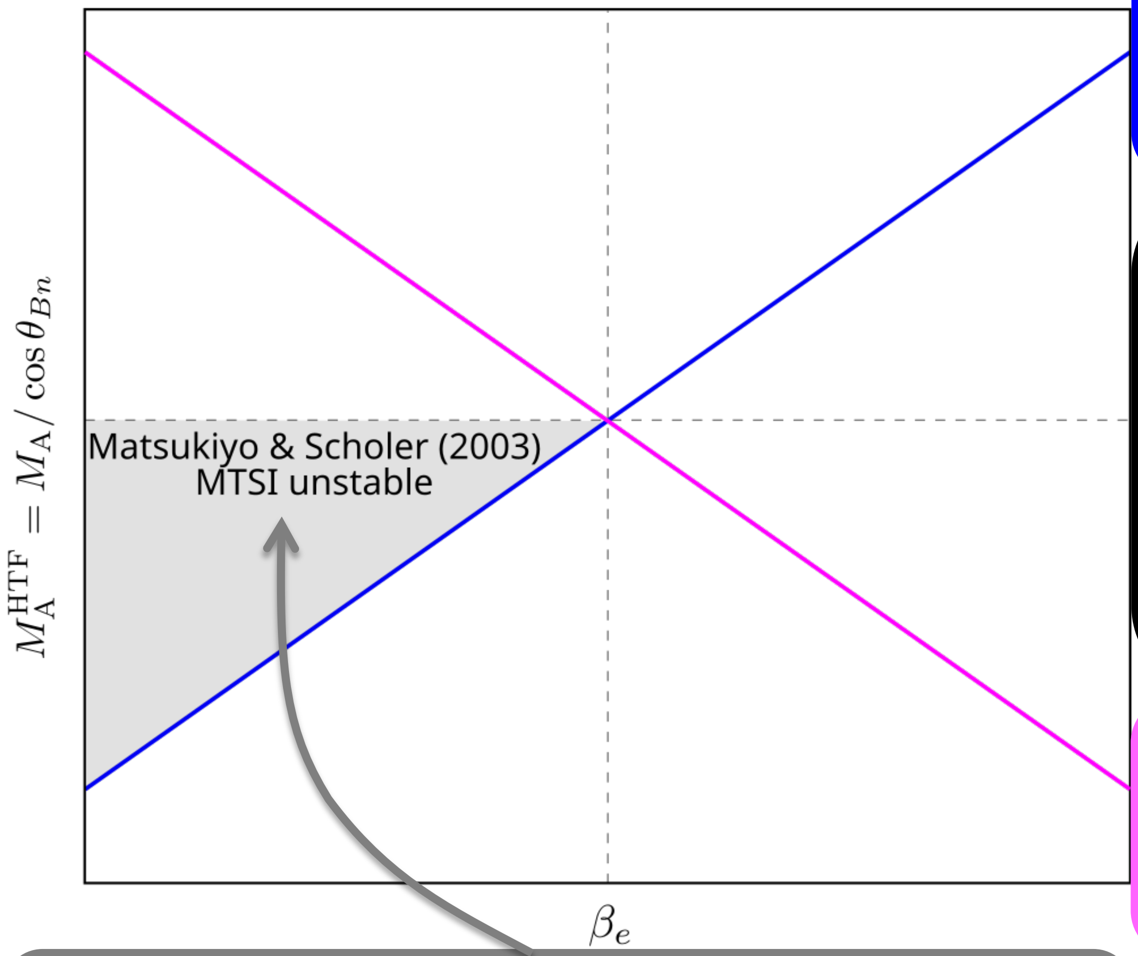
theoretical spectrum with a scattering rate estimated from MMS observation

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


Amano+ (2022, RMPP)
$\frac{p_{\rm inj}}{m_e V_{\rm A}} \approx \left(\frac{m_i}{m_e}\right)\left(\frac{k_* c}{\omega_{pi}}\right)^{-1}$
Weibel dominated?
(Nishigai & Amano 2021)
wave self-generation by accelerated electrons
$M_{\rm A}^{\rm HTF} = M_{\rm A}/\cos\theta_{Bn}$
electron-scale waves unnecessary
(ion-scale waves can scatter electrons)
sufficient electron-scale waves
SDA
SSDA
DSA
$\frac{p_{\rm min,SSDA}}{m_e V_{\rm A}} \approx M_{\rm A}^{\rm HTF}$
$\frac{p_{\rm max,SSDA}}{m_e V_{\rm A}} \approx (6\eta)^{1/2}\left(\frac{m_i}{m_e}\right)^{1/2}\left(\frac{D_{\mu\mu,\rm max}}{\Omega_{ce}}\right)^{1/2} M_{\rm A}^{\rm HTF}$
No Particle Acceleration
insufficient electron-scale waves
$p/m_e V_{\rm A}$
$M_{\rm A}^{\rm HTF} \approx \left(\frac{m_i}{m_e}\right)\left(\frac{k_* c}{\omega_{pi}}\right)^{-1}$
SSDA + DSA
$M_{\rm A}^{\rm HTF} \approx (6\eta)^{-1/2}\left(\frac{m_i}{m_e}\right)^{1/2}\left(\frac{D_{\mu\mu,\rm max}}{\Omega_{ce}}\right)^{-1/2}\left(\frac{k_* c}{\omega_{pi}}\right)^{-1}$
SSDA only (no DSA)
$M_{\rm A}^{\rm HTF} \approx \left(\frac{m_i}{m_e}\right)^{1/2}\beta_e^{\alpha}$
neither SSDA nor DSA
(c.f., Oka+2006)

Amano+ (2022, RMPP)

Conditions for Whistler Wave Generation



- Reflected/incoming ion beam
- Landau resonance
- Both upstream/downstream-directed
- Oblique low-freq. (~ 10 Hz)

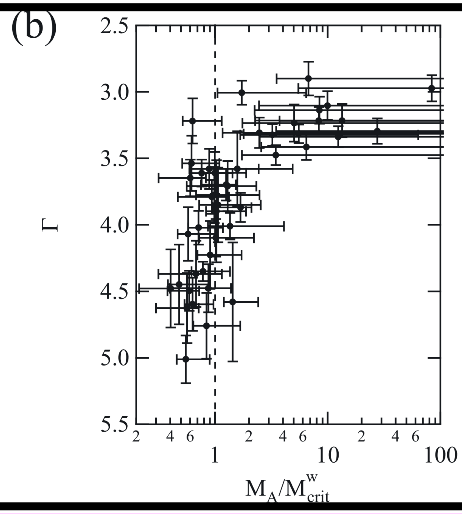
$M_A^{HTF} \approx \left(\frac{m_i}{m_e}\right)^{1/2} \beta_e^{+1/2}$

Amano & Hoshino (2010)
quasi-parallel high-freq. whistlers

- Low-energy electrons (< 1 keV)
- Normal cyclotron resonance
- Downstream-directed
- Quasi-parallel high-freq. (~ 100 Hz)

$M_A^{HTF} \approx \left(\frac{m_i}{m_e}\right)^{1/2}$

Oka et al. (2006)
whistler critical Mach number



$M_A^{HTF} \approx \left(\frac{m_i}{m_e}\right)^{1/2} \beta_e^{-1/2}$

Levinson (1992-1996)
oblique low-freq. whistlers

- Medium-energy electrons (> 1 keV)
- Anomalous cyclotron resonance
- Upstream-directed
- Oblique low-freq. (~ 10 Hz)

Conclusions

We have proposed a novel electron injection scenario at collisionless shocks that unifies SSDA (stochastic shock drift acceleration) and the standard DSA.

- It predicts a steeper spectrum at low energy (< 10-100 keV), which may be smoothly connected to the harder DSA spectrum at high energy.
- It favors shocks with high Alfven Mach numbers defined in the Hoffmann-Teller frame.
- It requires a broad spectrum of whistler waves (~ 1-100 Hz). The larger the wave power, the better the electron acceleration efficiency.

References

- Amano, T., et al. (2022). Nonthermal electron acceleration at collisionless quasi-perpendicular shocks. Reviews of Modern Plasma Physics, 6(1), 29
- Amano, T., & Hoshino, M. (2022). Theory of electron injection at oblique shock of finite thickness. The Astrophysical Journal, 927(1), 132.
- Amano, T., et al. (2020). Observational evidence for stochastic shock drift acceleration of electrons at the Earth’s bow shock. Physical Review Letters, 124(6), 065101.

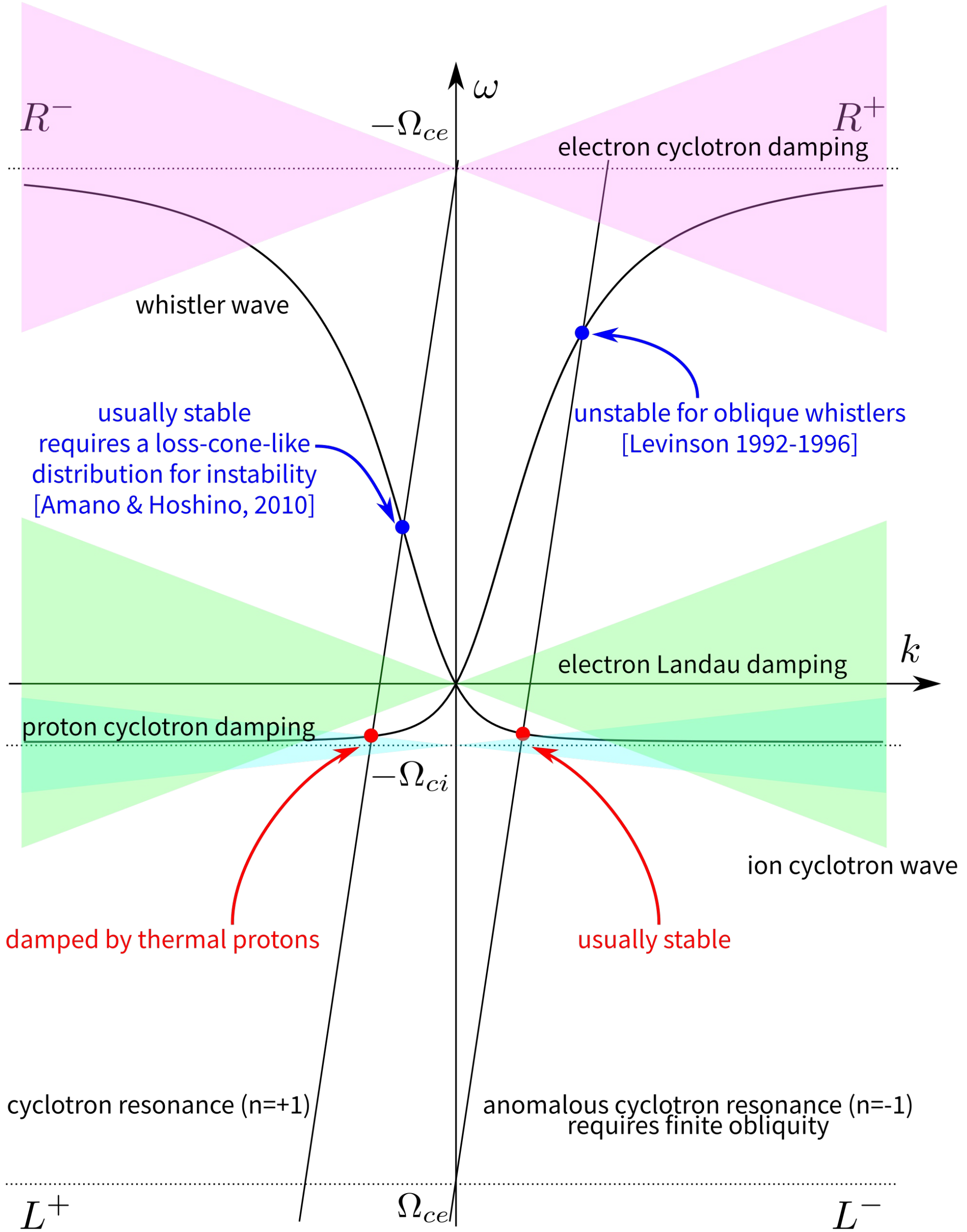
Resonance Conditions

<u>Normal Cyclotron Resonance</u>

A counter-propagating whistler wave can satisfy the resonance condition with relatively low-energy (0.1-1 keV) electrons.

The wave may become unstable if the electron beam is generated by SDA, which can produce a loss-cone-like pitch-angle anisotropy.

The ion-cyclotron wave will suffer significant damping by thermal protons unless the beam electrons are mildly relativistic.



<u>Anomalous Cyclotron Resonance</u>

A co-propagating whistler wave can satisfy the resonance condition with relatively high-energy (1-10 keV) electrons.

The wave must be obliquely propagating for the anomalous cyclotron resonance.

The ion-cyclotron wave should be stable.