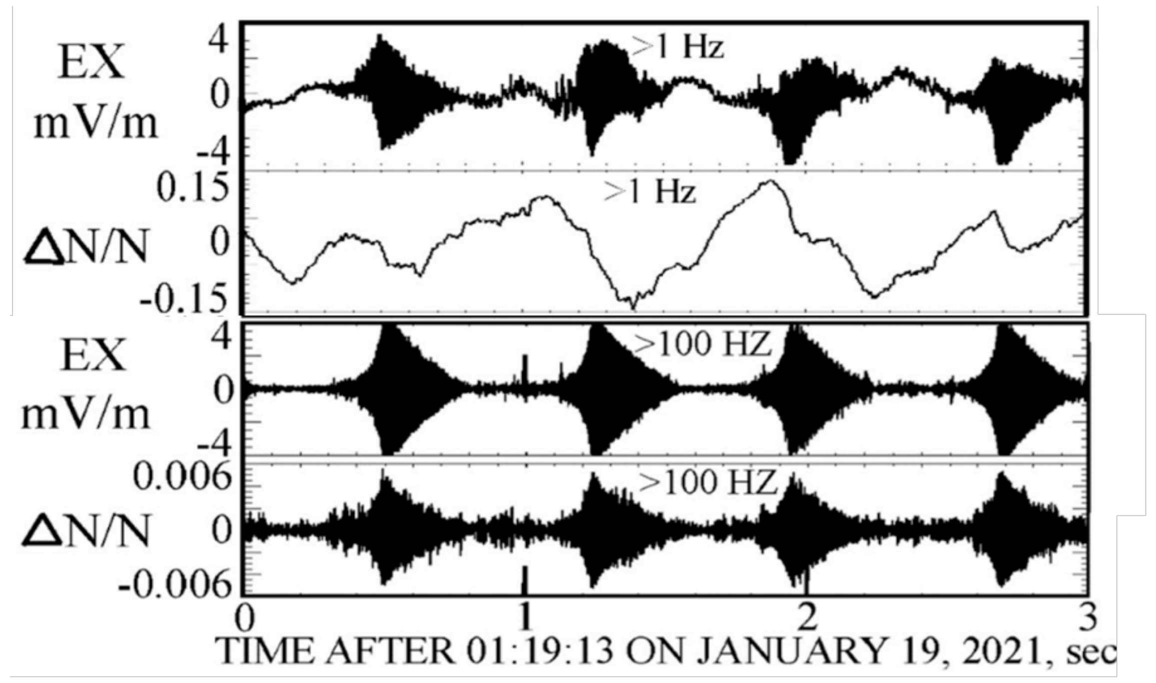
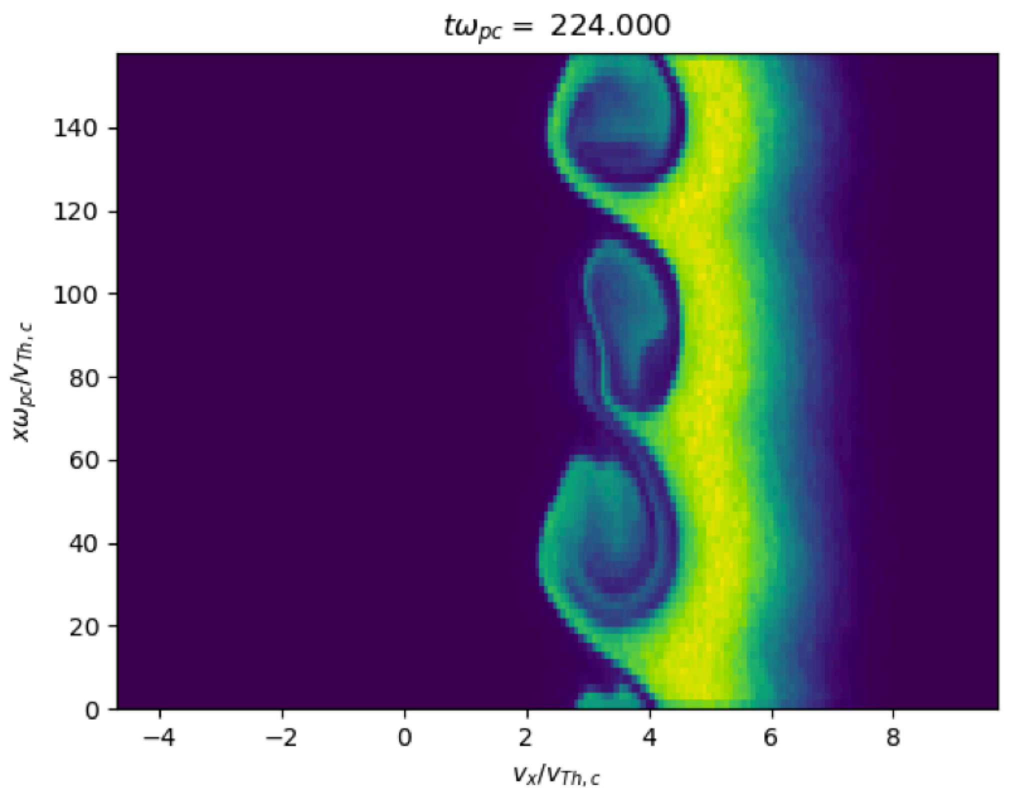
Kinetic simulations of the ion-acoustic waves observed by the Parker Solar Probe close to the Sun

MAHMOUD SAAD AFIFY
RUHR-UNIVERSITÄT BOCHUM, Germany
and BENHA UNIVERSITY, EGYPT
mahmoud.ibrahim@rub.de

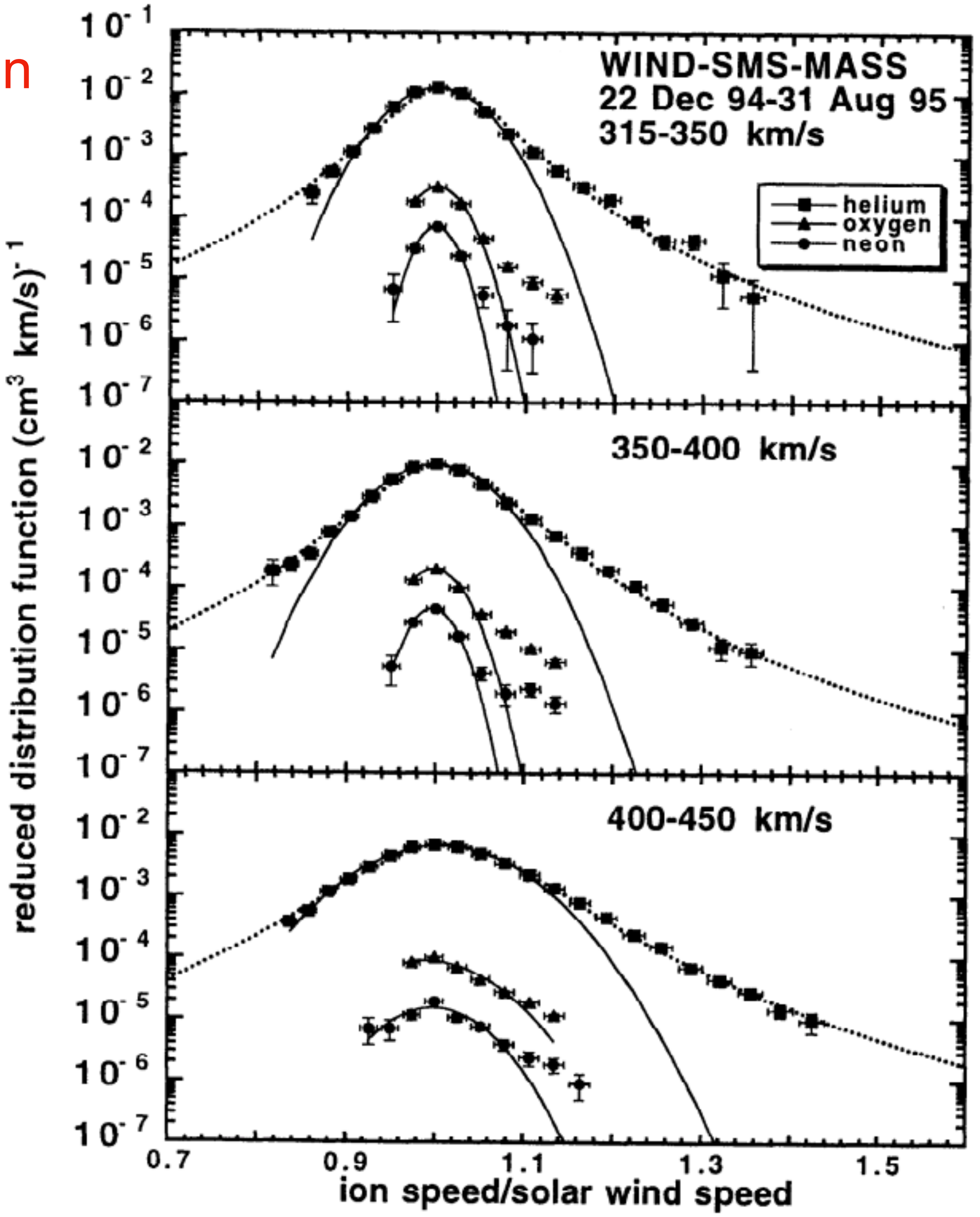


ACKNOWLEDGMENTS: MARIA ELENA INNOCENTI, JÜRGEN DREHER, KEVIN SCHOEFFLER, & ALFREDO MICERA
RUHR-UNIVERSITÄT BOCHUM, GERMANY



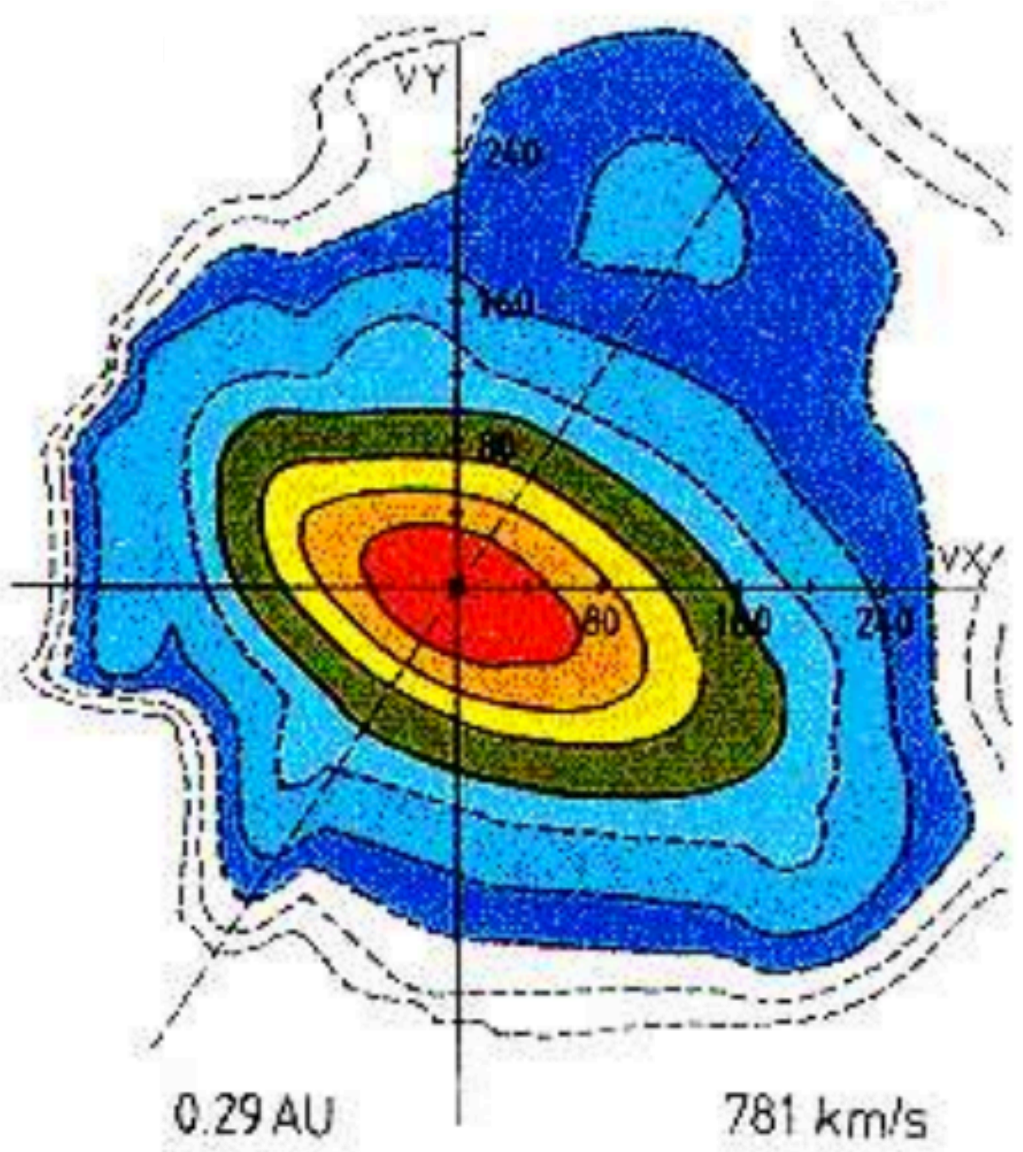
Kinetic Instabilities Matter!

- Distributions often non-Maxwellian

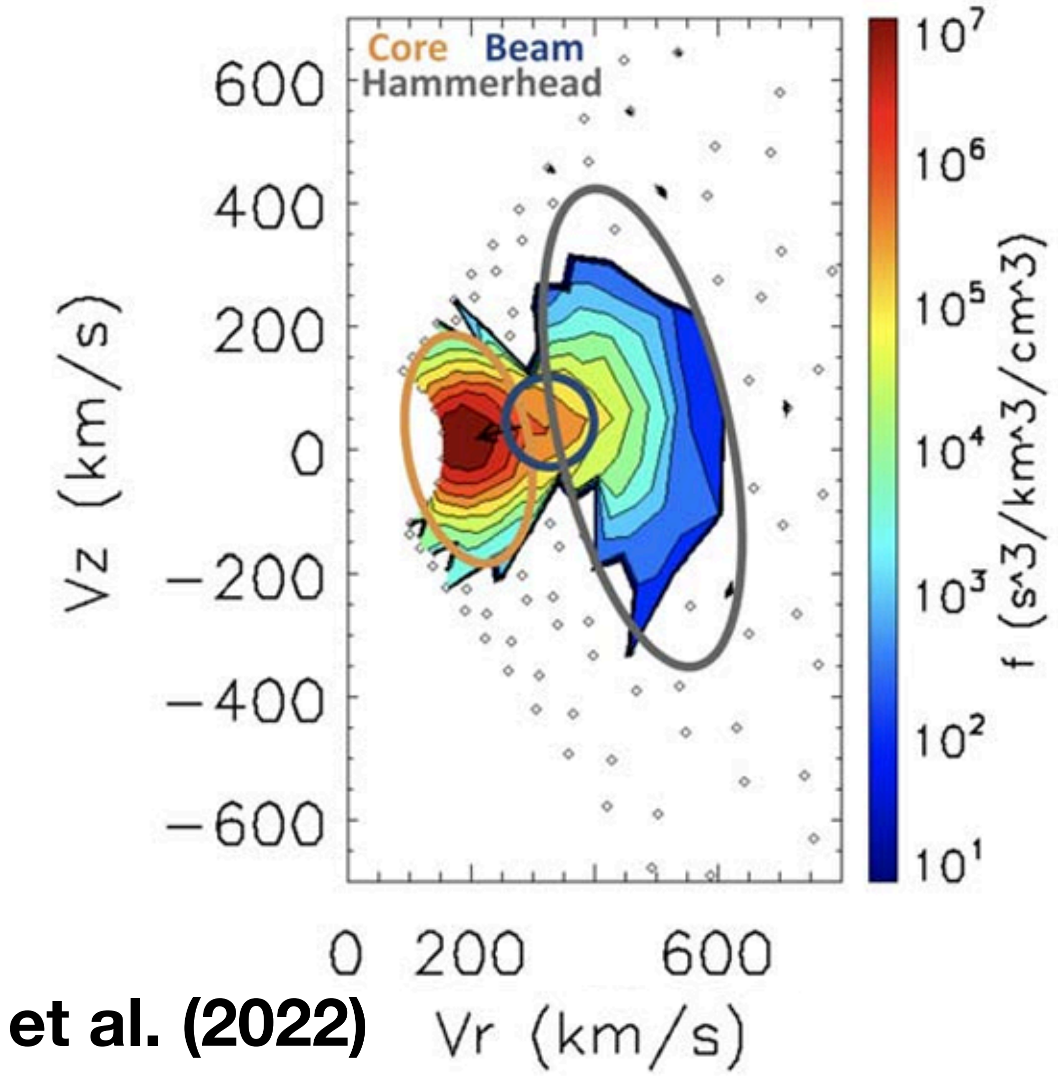


Credit: Marsch (2006)

- 2D proton velocity distribution function: temperature Anisotropy

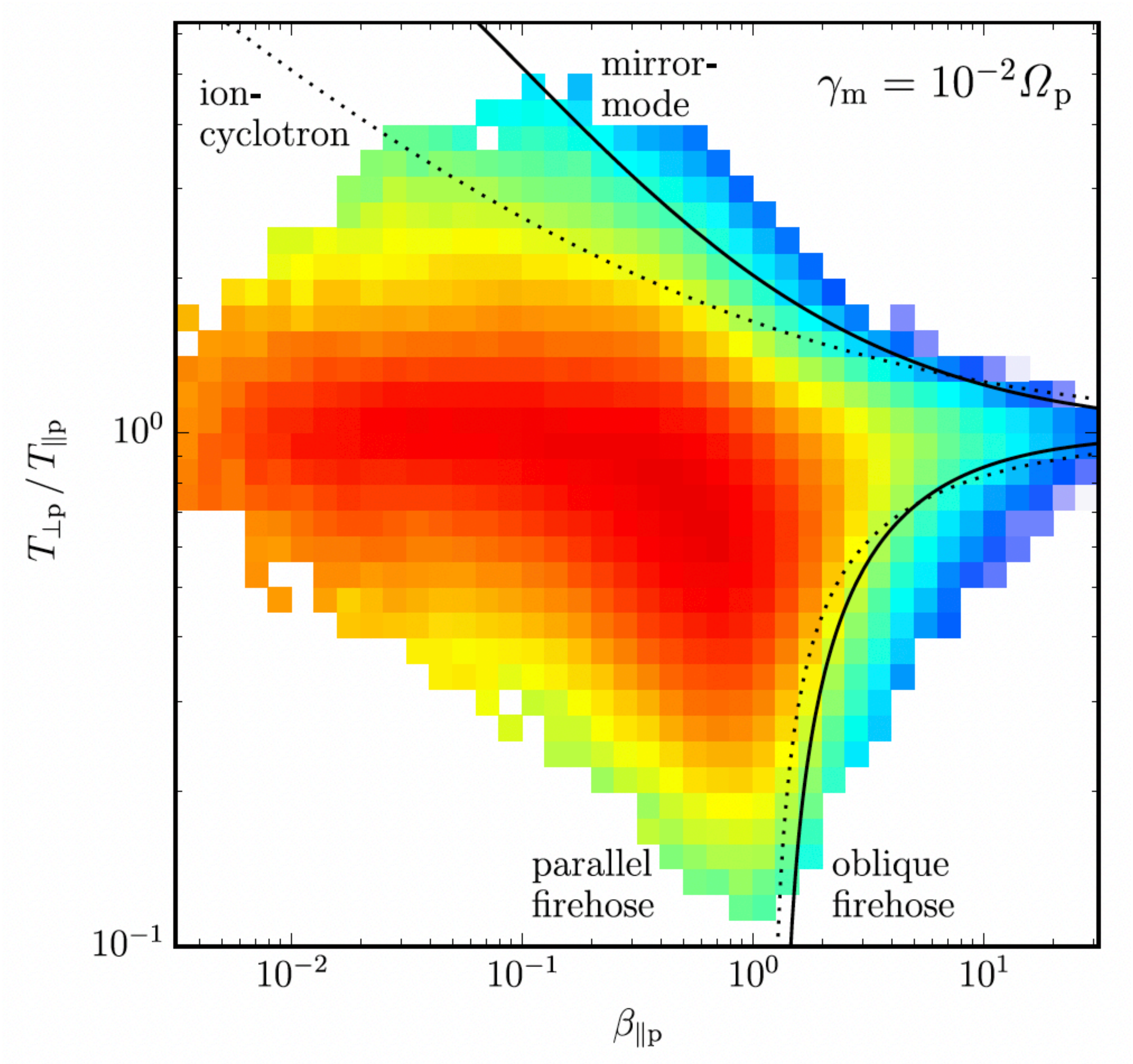


Credit: Marsch (2006)



Credit: Verniero et al. (2022)

Usual suspects include anisotropy instabilities



Credit: Verscharen et al. (2019)

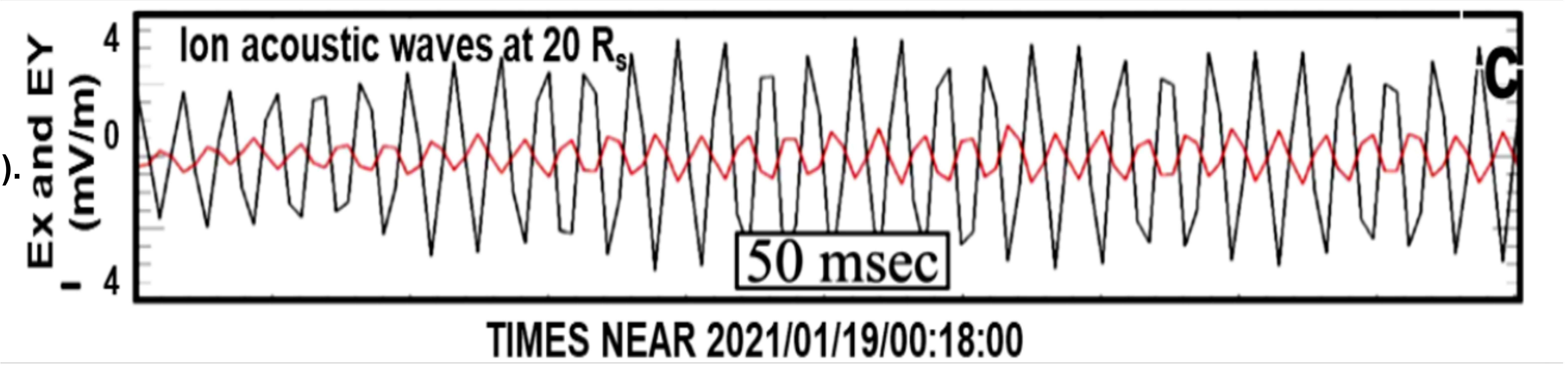
Instabilities driven by temperature anisotropy:

- ion-cyclotron
- mirror-mode
- parallel firehose
- oblique firehose

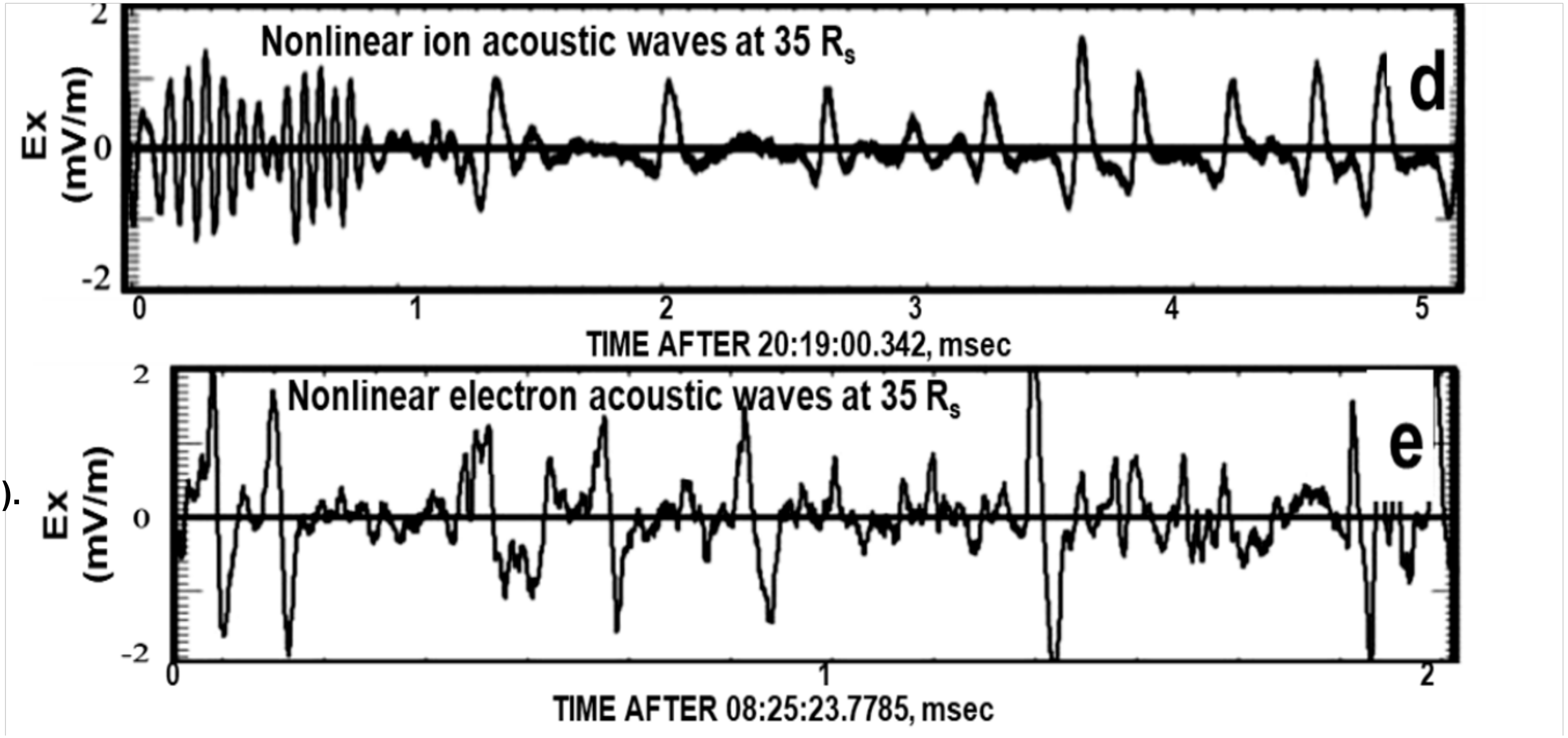
These instabilities operate on ion-scales.

In this talk: Only ion core-ion beam drift acoustic instability (electrostatic) considered.

PSP observations of ion-acoustic waves (IAWs)



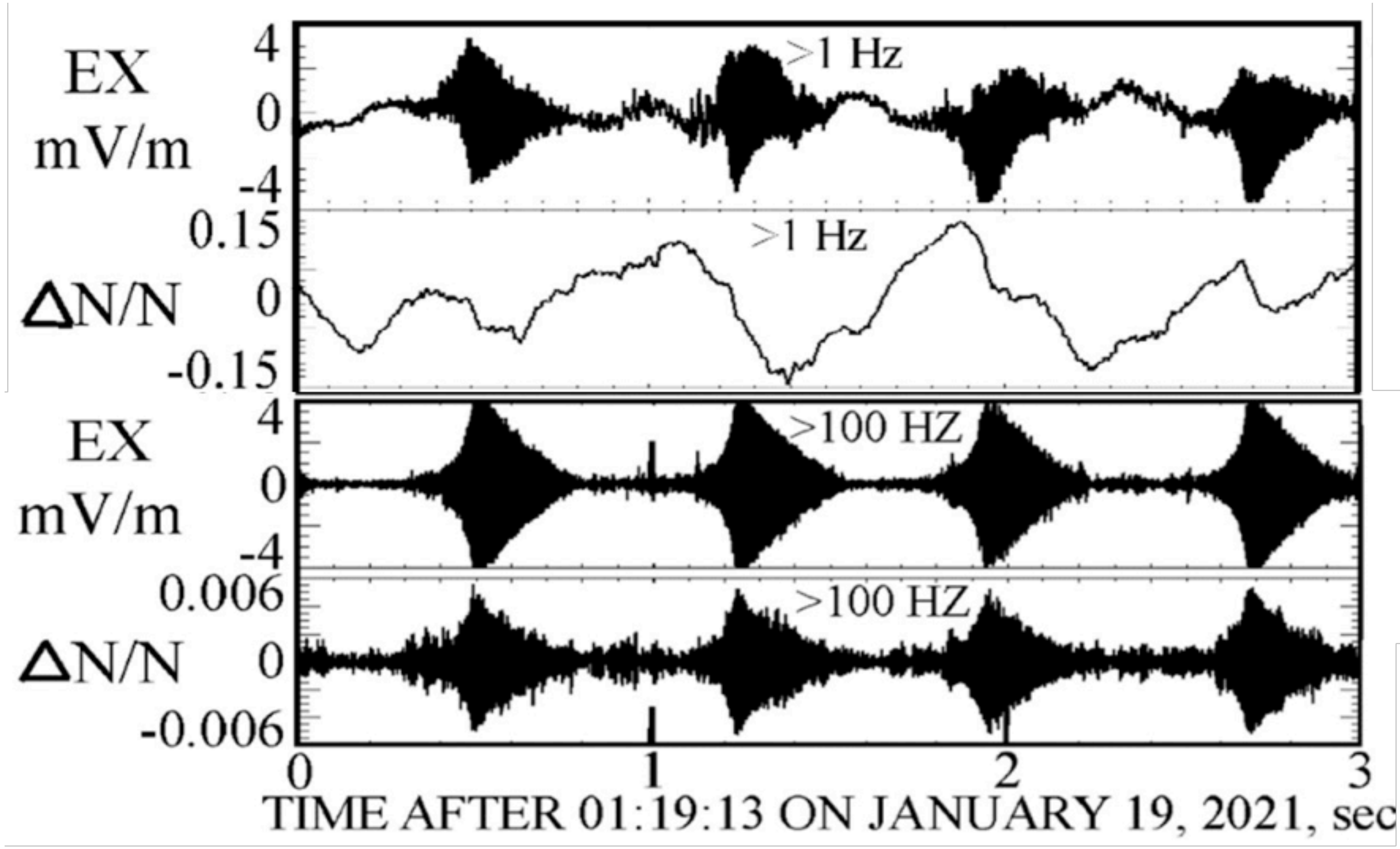
Credit: Mozer et al. (2021a).



Credit: Mozer et al. (2021b).

PSP observations of IAWs from 15-25 R_s

- A coupled pairs of low and high frequencies.
- They are observed as regular bursts.
- Each are narrow band waves.
- They can exist for several hours.
- Associated with higher electron temperature.



Credit: Mozer et al. (2023)

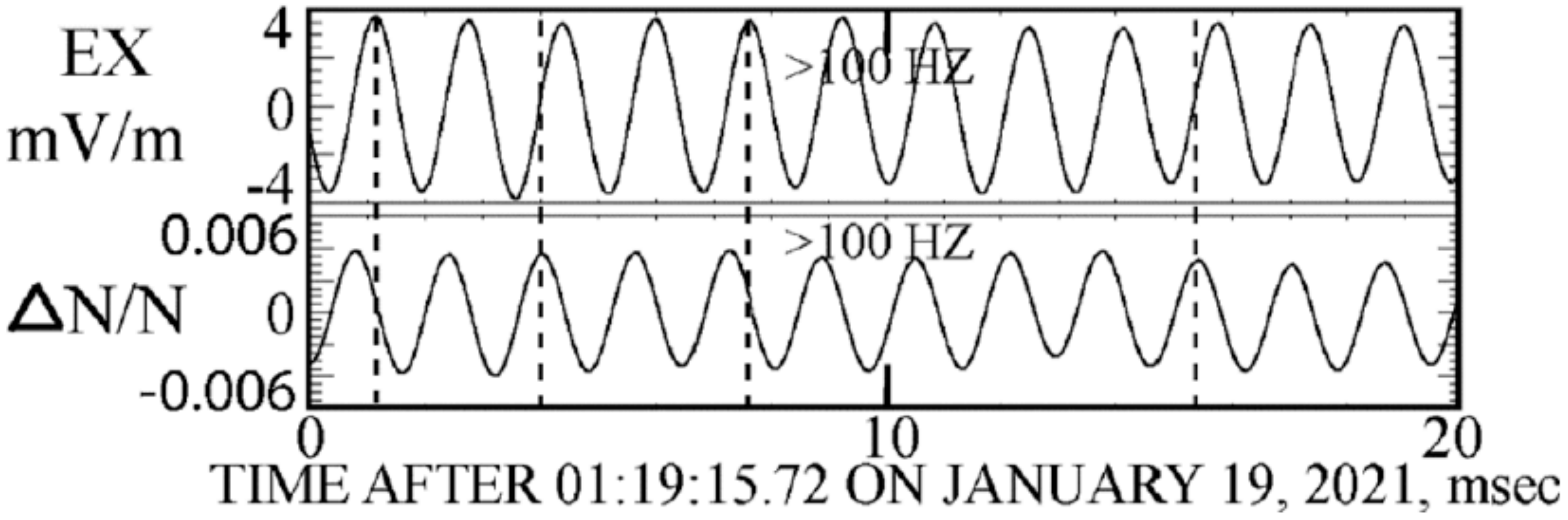
Mozer et al. arguments in favour of IAWs:

- The phase difference between the electric field and density fluctuations was $90°$.

- The waves have density fluctuations and no magnetic field component.

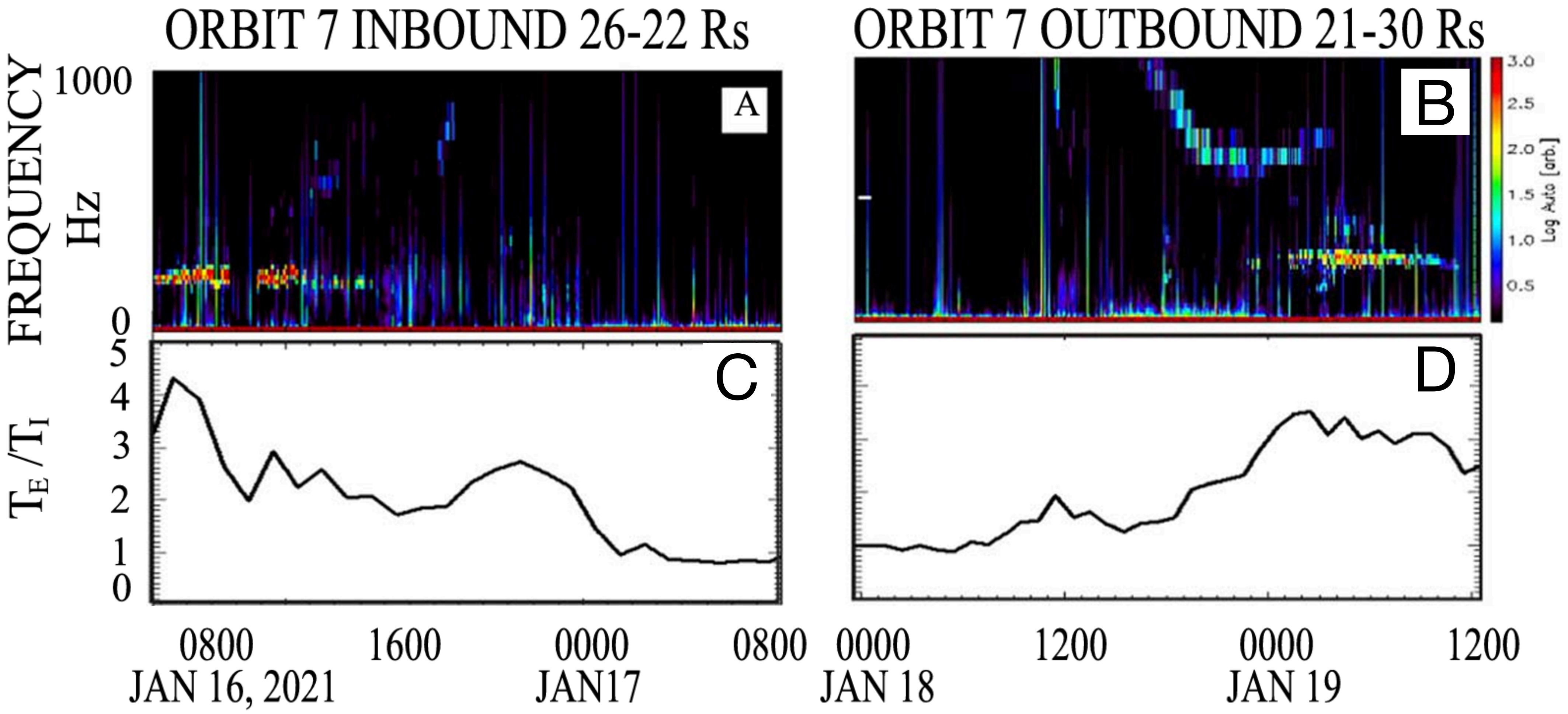
- They have the same phase velocity which is almost equal to the ion acoustic speed.

- Bursts occur during intervals of enhanced T_e/T_i which is necessary for IA modes.



Credit: Mozer et al. 2023

- Observations of IAWs through two intervals between 21 and 30 solar radii.

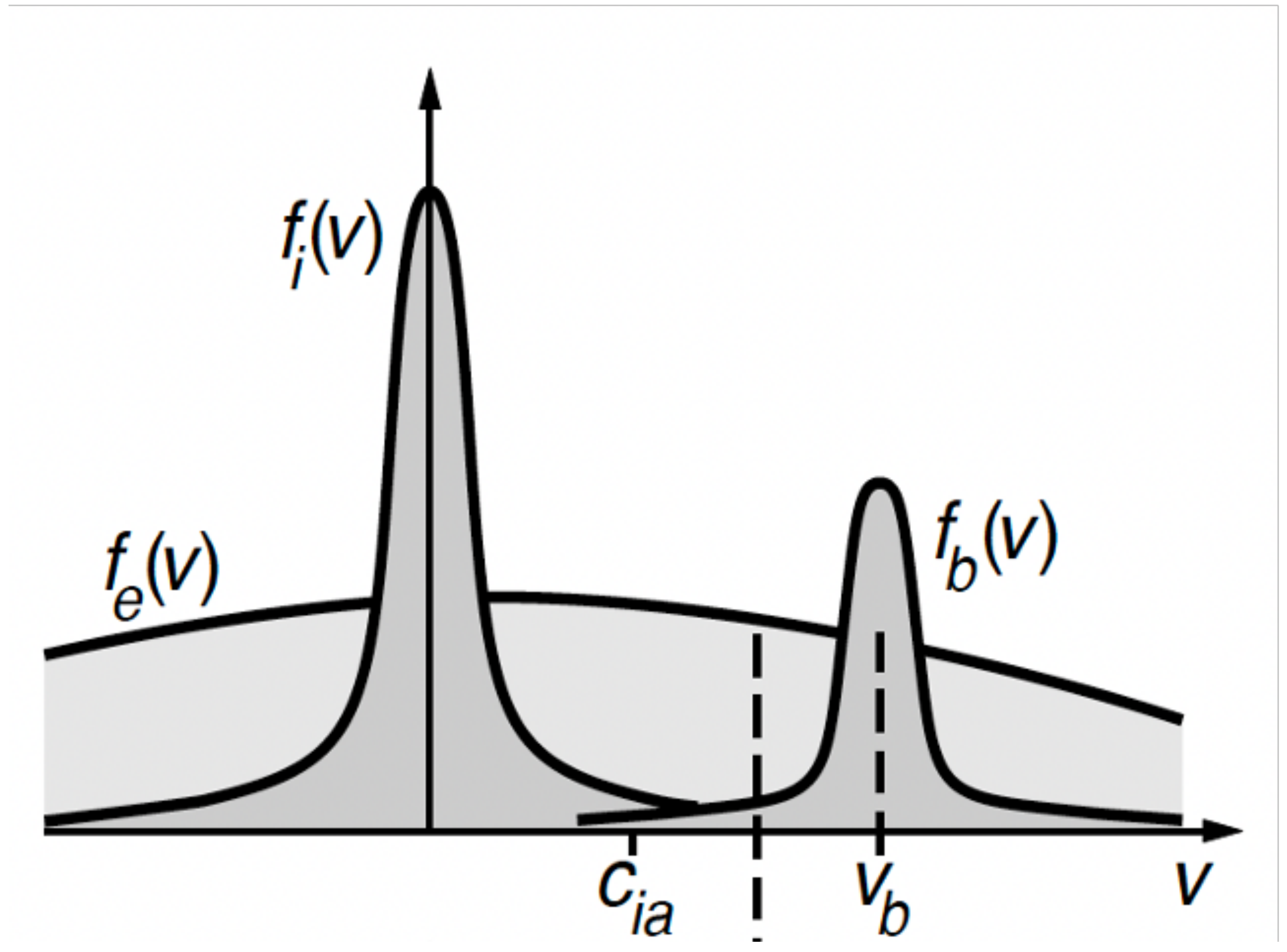


Credit: Mozer et al. 2022

IAI Mechanism

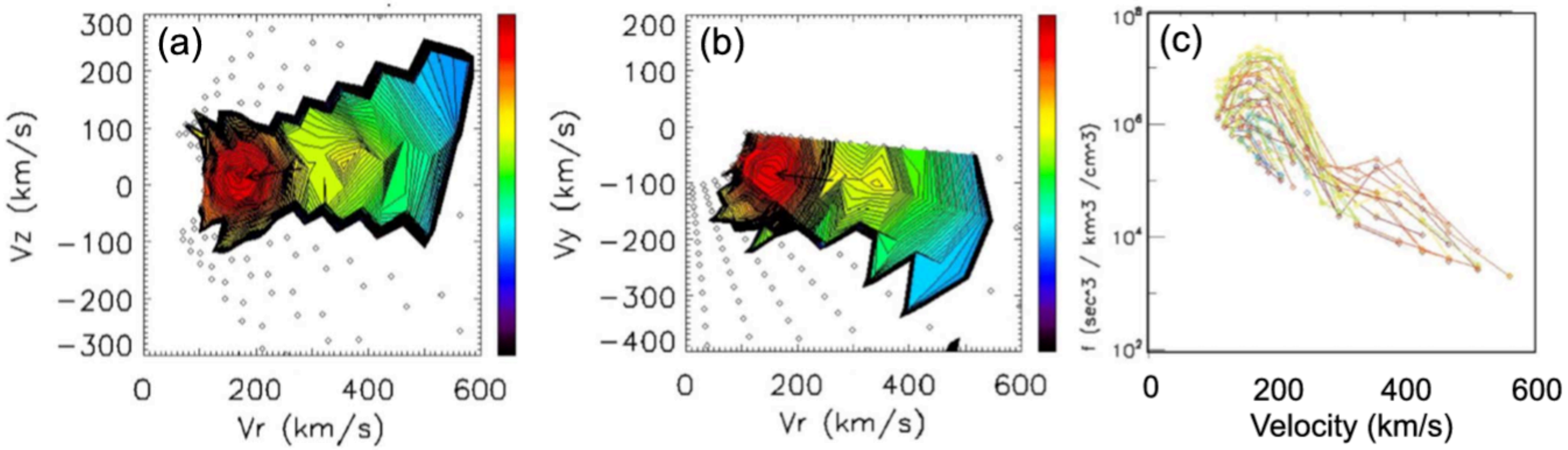
- Here: Ion-ion acoustic instability

- Triggered by a fast ion beam drifting with respect to the core plasma.
- Warm electrons as background.
- 1D electrostatic instability (e.g. parallel to B_0)



Credit: Treumann & Baumjohann (2001)

- The ion velocity distribution functions captured at 00:16:49 on January 19, 2021.



Credit: Mozer et al. (2021a)

Kinetic Theory: Vlasov-Maxwell-Landau treatment (electrostatic)

$$k^2 = \sum_\alpha \frac{\omega_{p,\alpha}^2}{n_\alpha} \int \frac{dv}{v - \omega/k} \frac{\partial f_{0,\alpha}}{\partial v}$$

$$f_{0,\alpha}(v) = \frac{n_\alpha}{\sqrt{2\pi} v_{th,\alpha}} e^{-(v - V_\alpha)^2/(2v_{th,\alpha}^2)}$$

$\alpha =$ **ion core (c), ion beam (b), electrons (e)**

See: Gary & Omidi (1987)

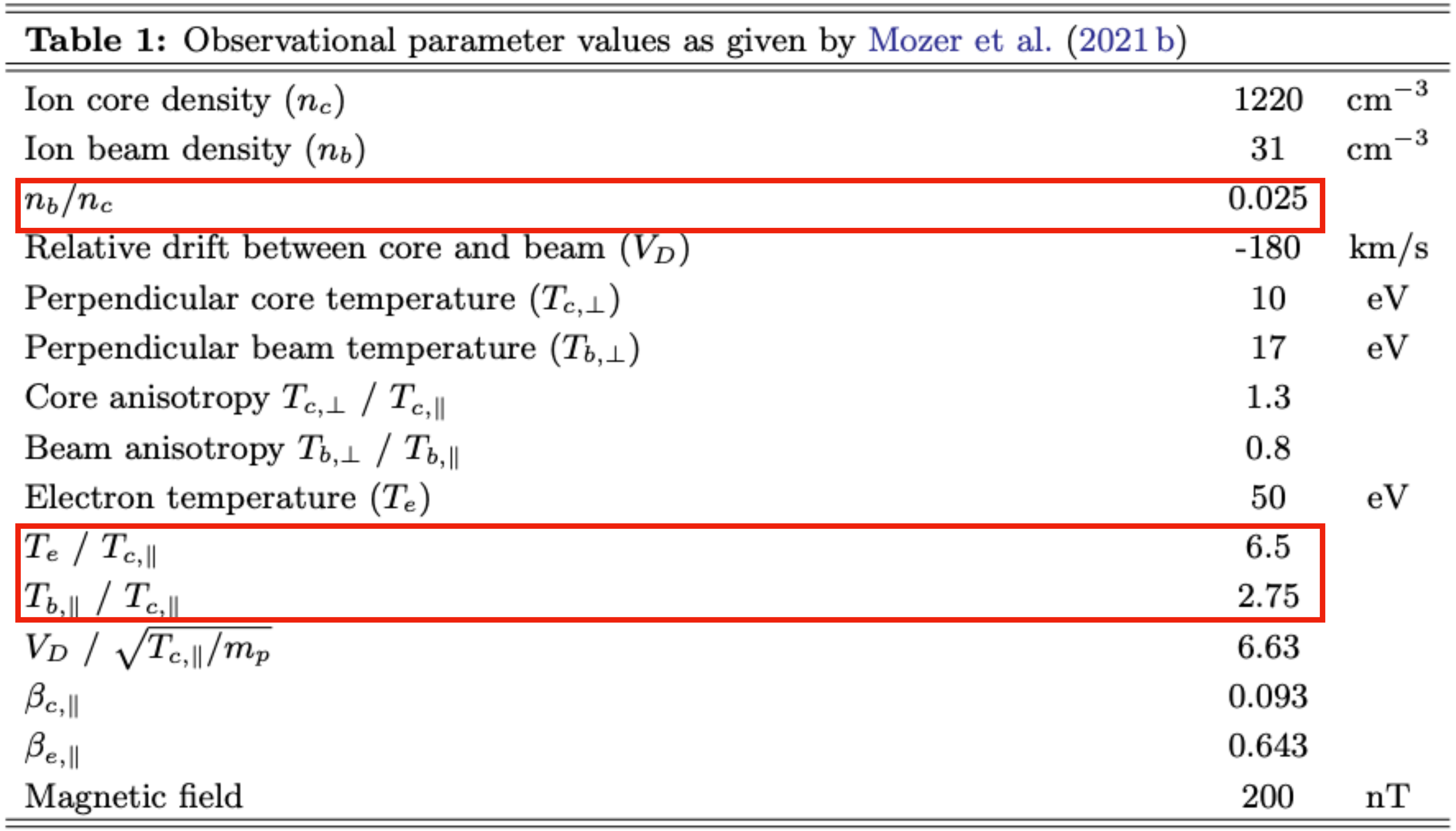


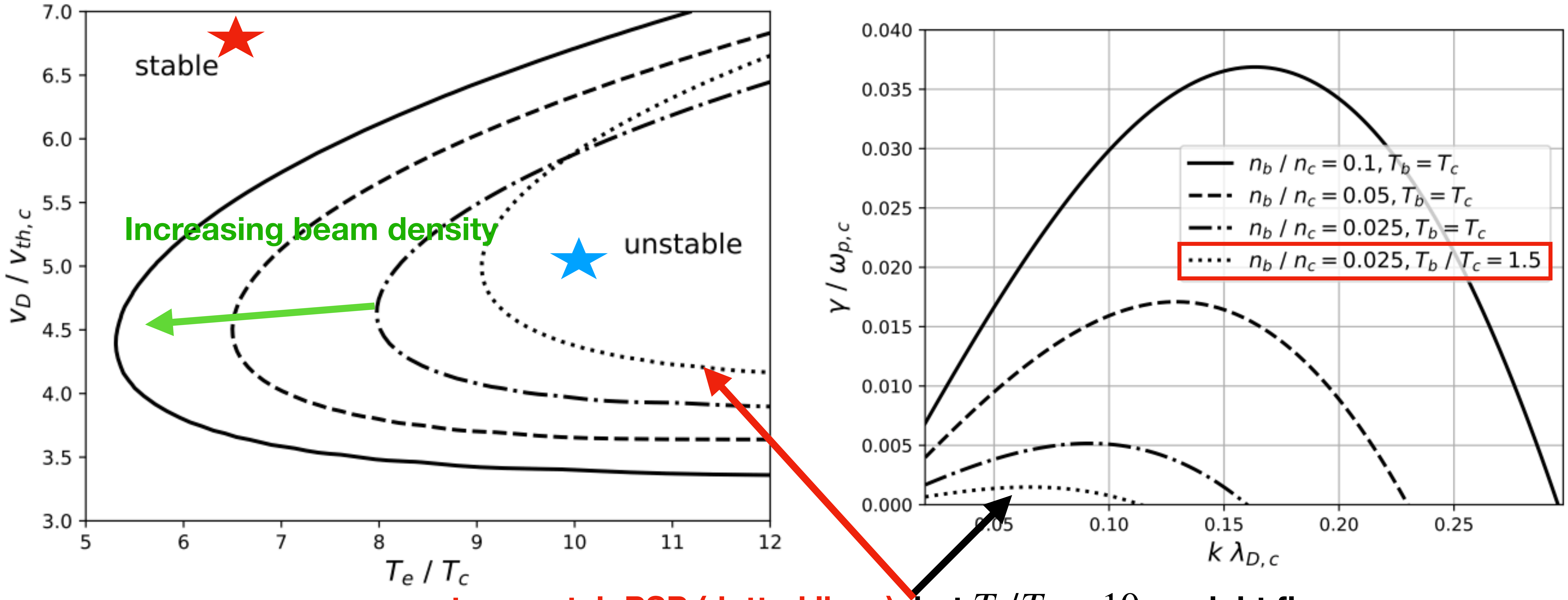
Table 1: Observational parameter values as given by Mozer et al. (2021 b)

Ion core density (n_c)	1220	cm^{-3}
Ion beam density (n_b)	31	cm^{-3}
n_b/n_c	0.025	
Relative drift between core and beam (V_D)	-180	km/s
Perpendicular core temperature ($T_{c,\perp}$)	10	eV
Perpendicular beam temperature ($T_{b,\perp}$)	17	eV
Core anisotropy $T_{c,\perp}$ / $T_{c,\parallel}$	1.3	
Beam anisotropy $T_{b,\perp}$ / $T_{b,\parallel}$	0.8	
Electron temperature (T_e)	50	eV
T_e / $T_{c,\parallel}$	6.5	
$T_{b,\parallel}$ / $T_{c,\parallel}$	2.75	
V_D / $\sqrt{T_{c,\parallel}/m_p}$	6.63	
$\beta_{c,\parallel}$	0.093	
$\beta_{e,\parallel}$	0.643	
Magnetic field	200	nT

Note: key parameters $n_b/n_c = 0.025$, $T_e/T_c = 6.5$, **and** $T_b/T_c = 2.75$

Kinetic Theory: Results

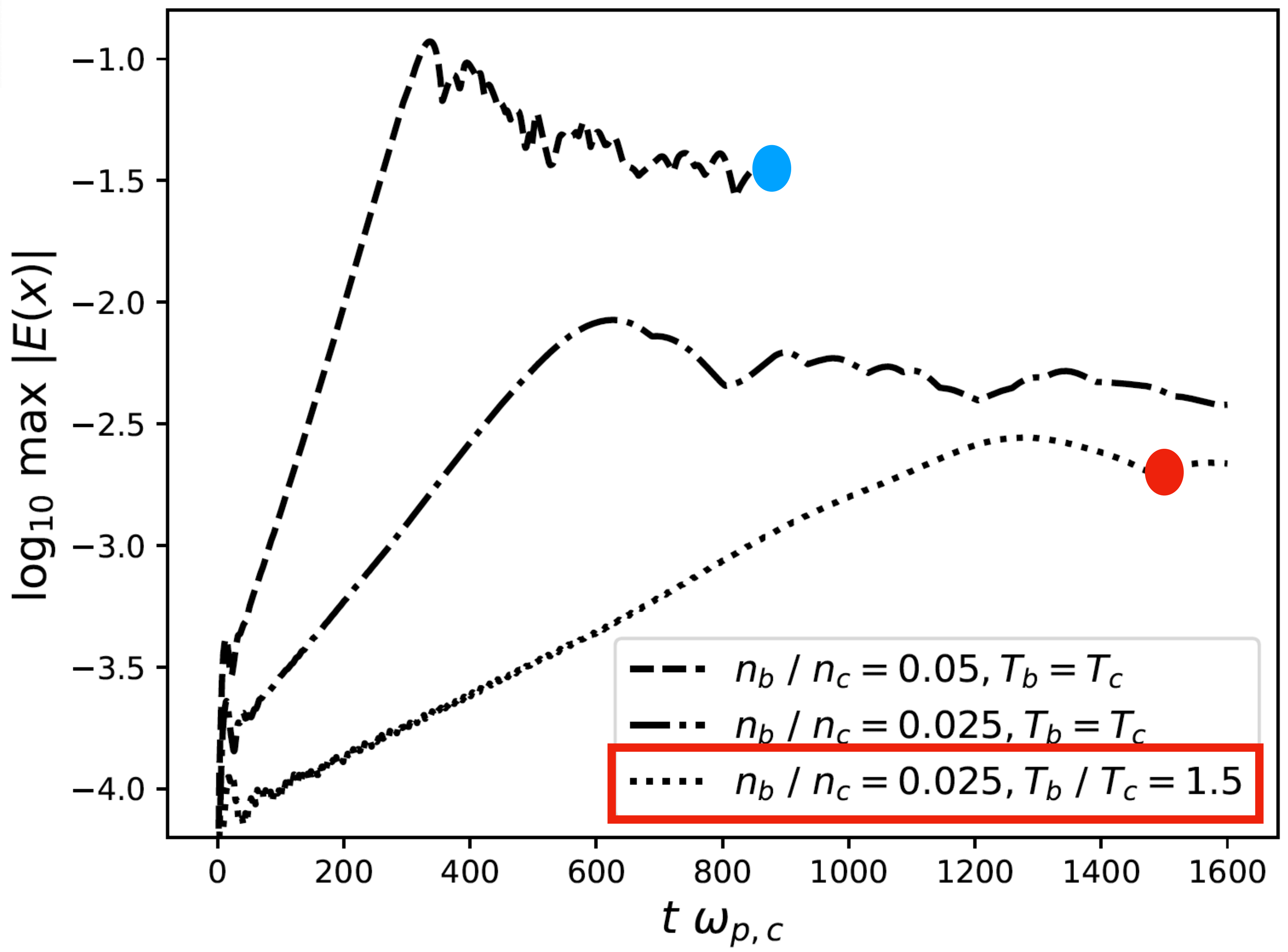
- We determine the threshold and growth rates of IAI using the linear kinetic model at different values of n_b/n_c.
- Left: stability/instability regions (same labels as on right).
- PSP observations indicate $T_e/T_c \approx 6.5$ ★ .
- Right: dispersion relations for $T_e/T_c = 10$ and $v_D/v_{th,c} = 5$ ★ .

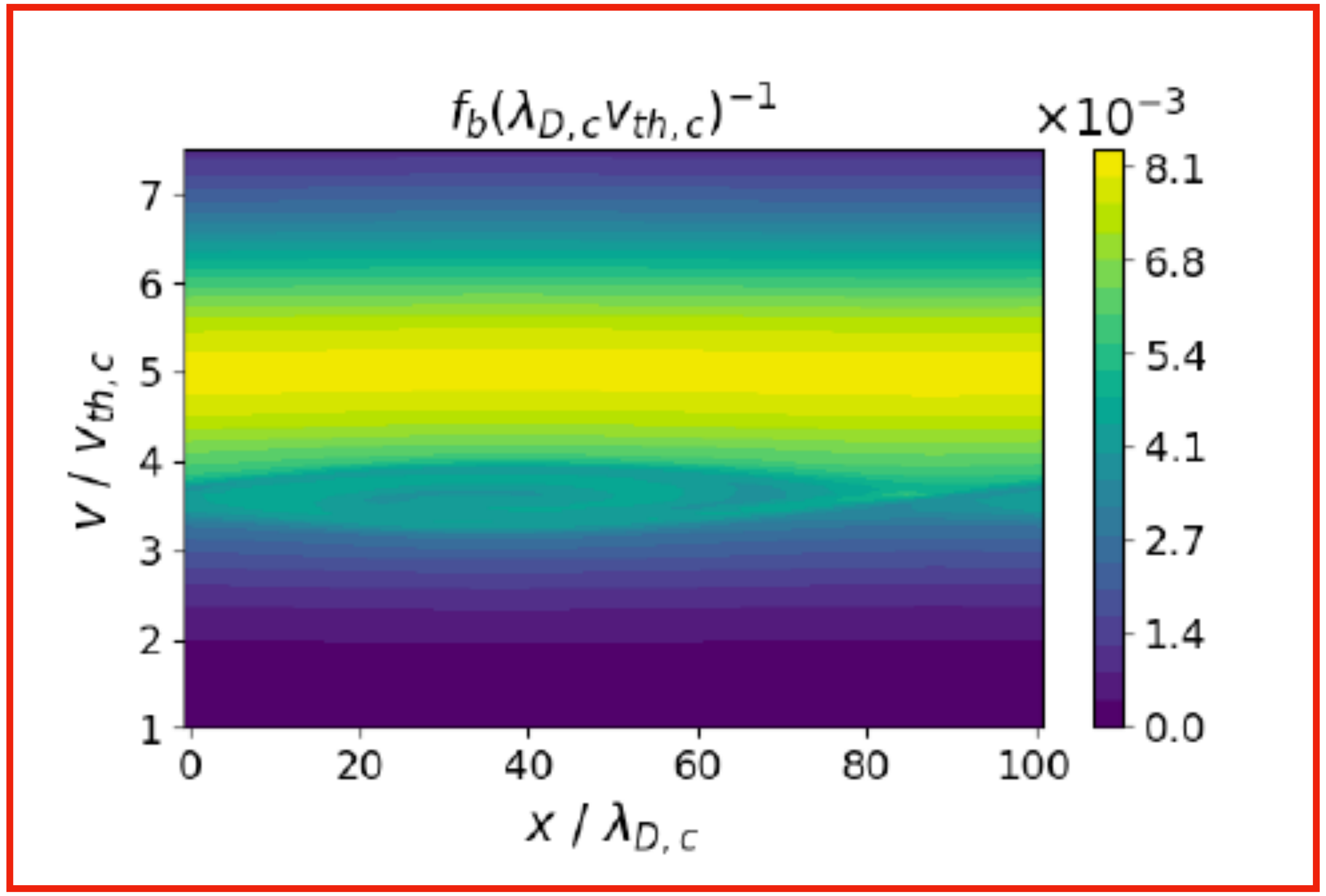


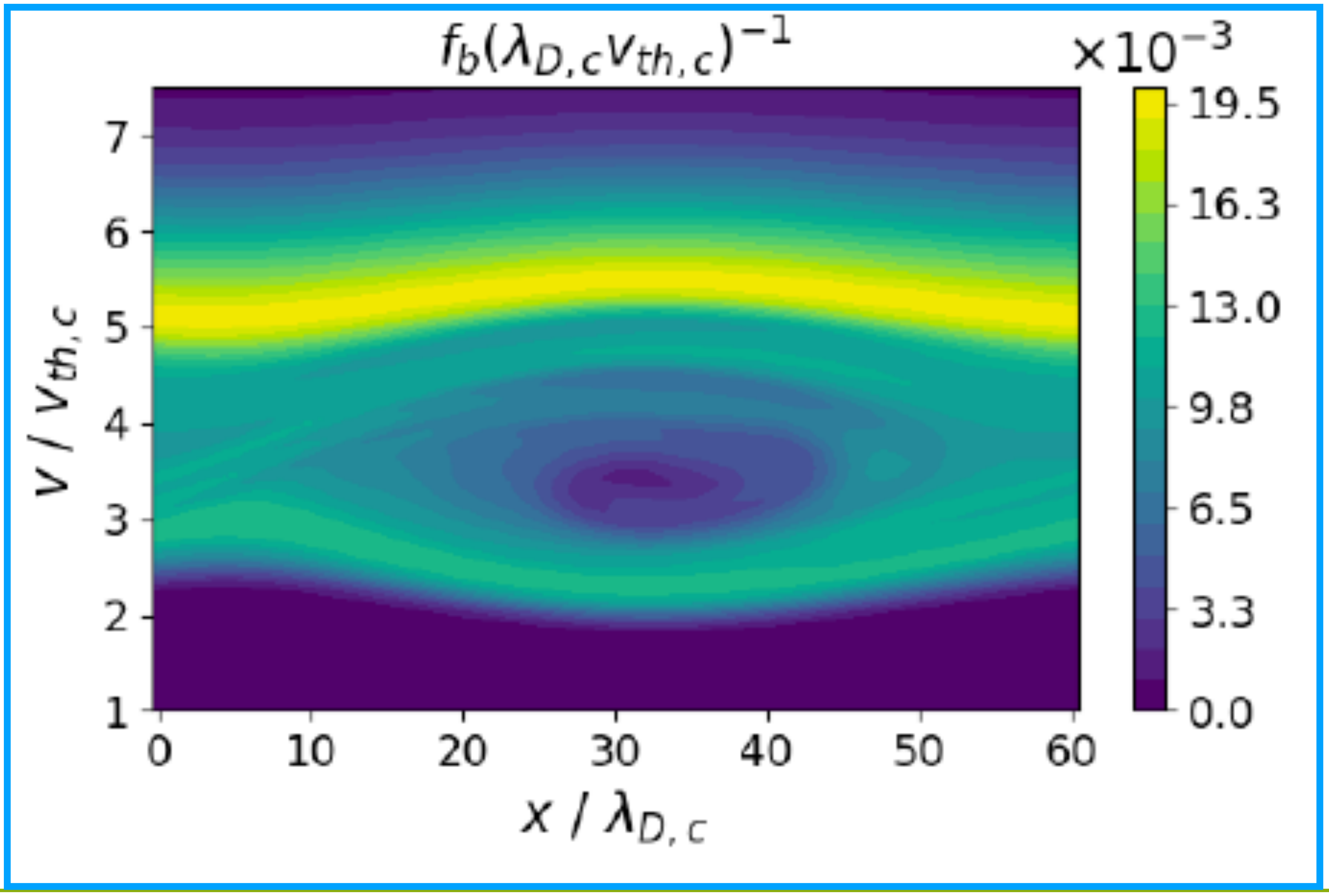
≈parameters match PSP (dotted lines), **but $T_e/T_c = 10$ on right figure**

Vlasov Simulations

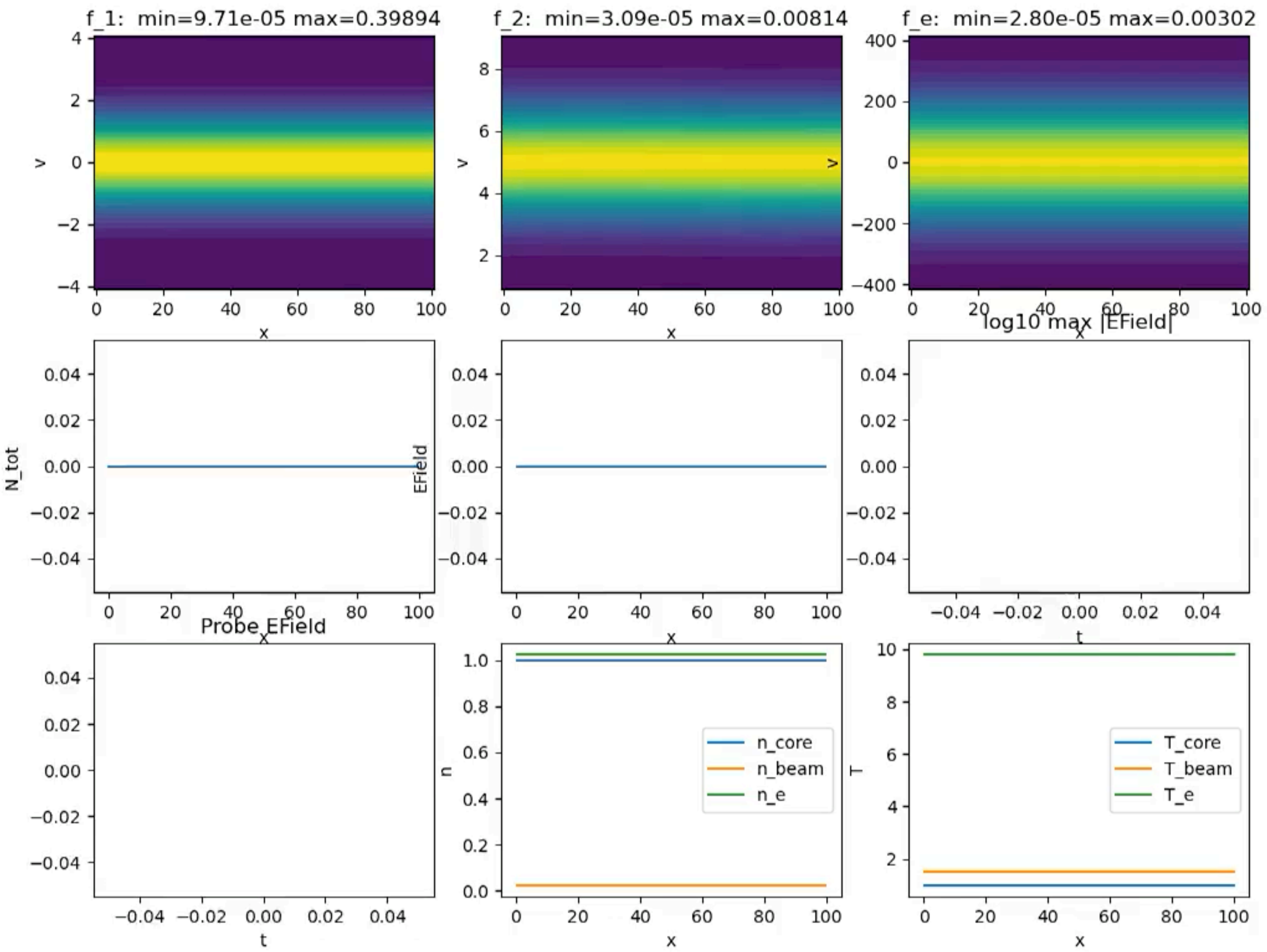
- Simulations reveal exponential growth followed by a saturation phase with small changes.
- Saturation levels are lower for “weaker” instabilities.
- Left: Weak instability, $t = 1500\omega_{pc}^{-1}$.
- Right: Stronger case with $n_b/n_c = 0.05, T_b/T_c = 1$, $t = 900\omega_{pc}^{-1}$.







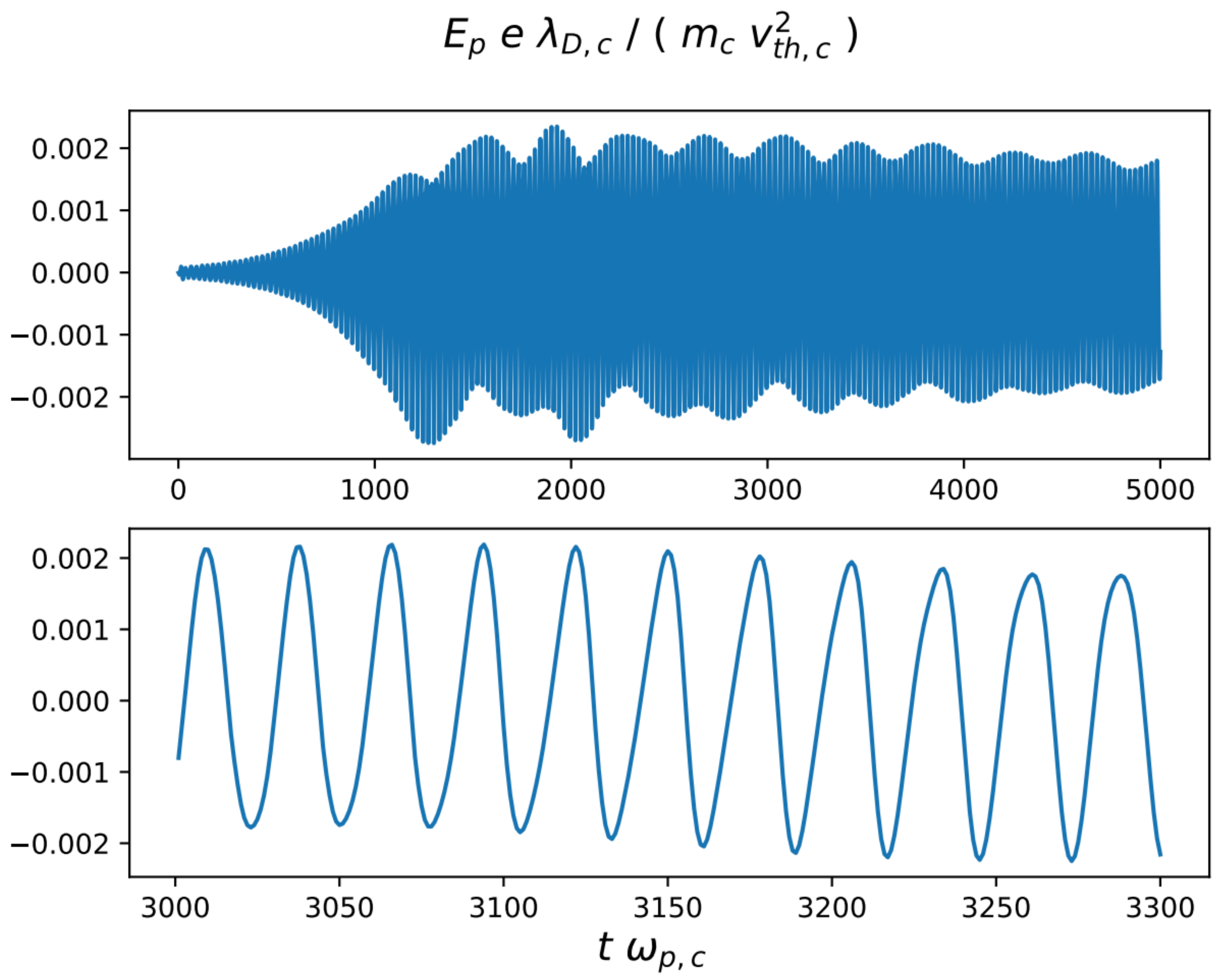
Separate phase spaces for all three components (Weak instability)

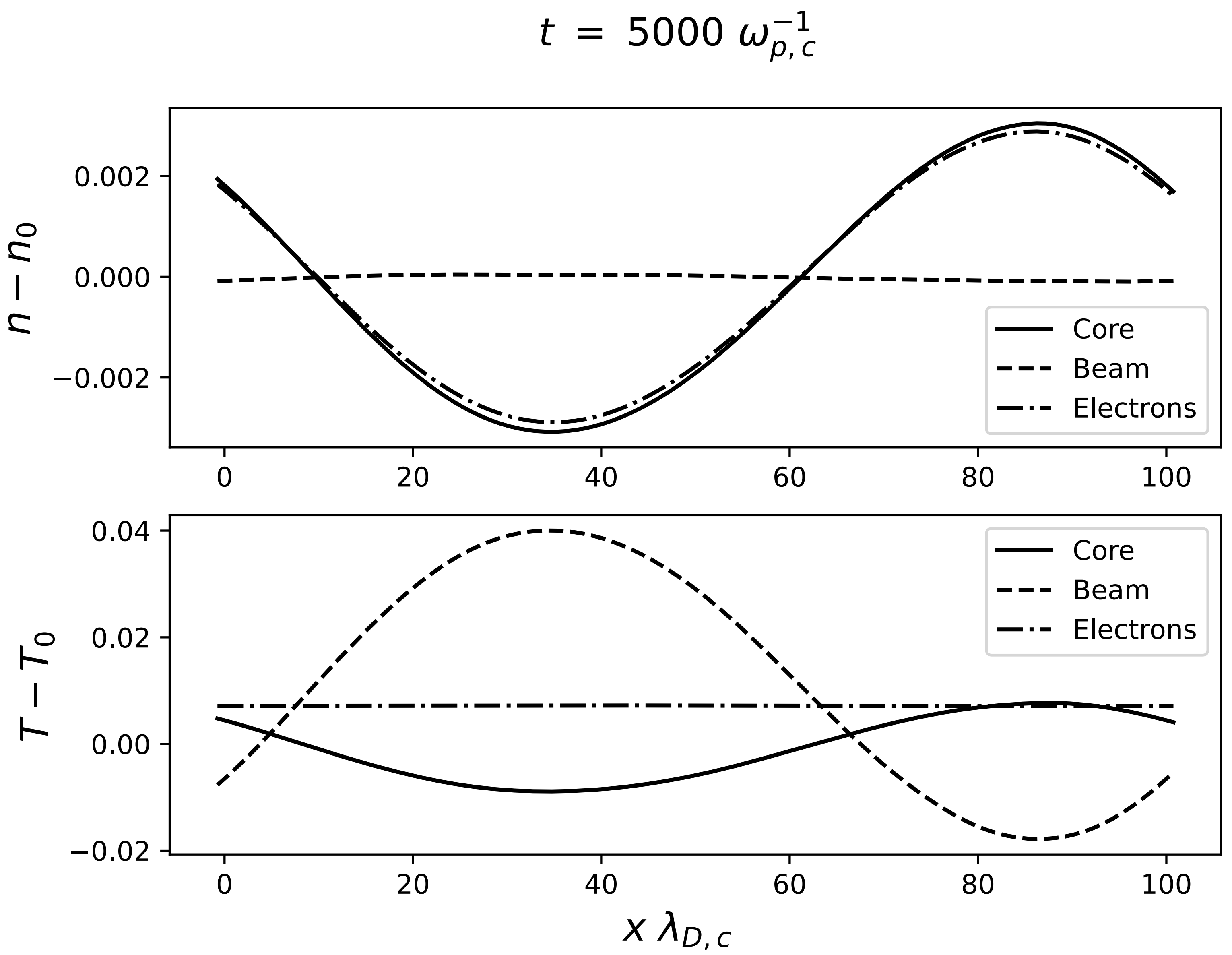


M. S. AFIFY | ISSS-15 + IPELS-16
Joint Conference (August 5-9) **MAHMOUD.IBRAHIM@RUB.DE**

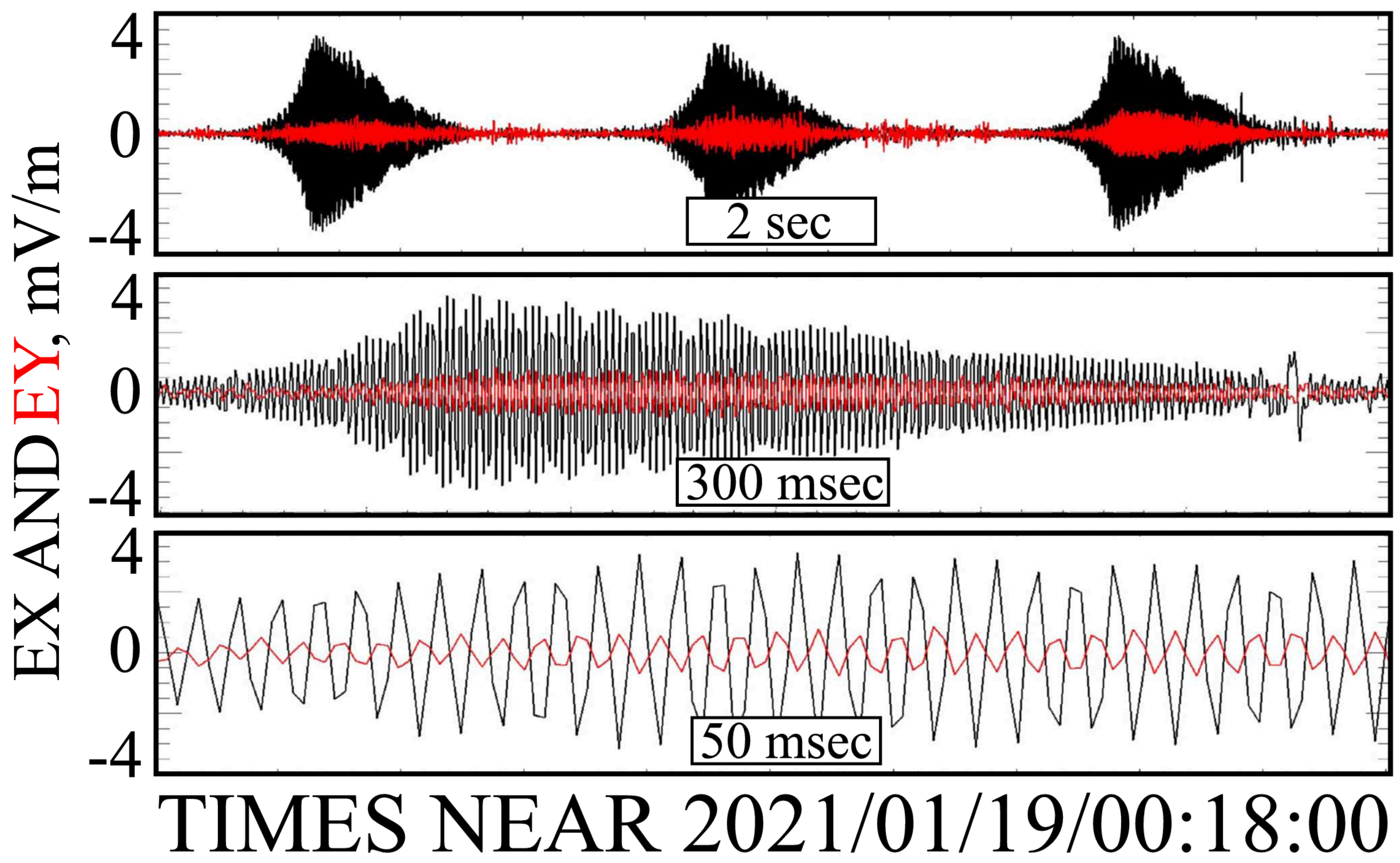
Vlasov simulation with parameters matches with PSP observations

Simulations





Observations



Credit: Mozer et al. (2021a)

Afify et al. (2024) APJ Accepted (https://arxiv.org/abs/2407.10541)

Agreements (by order of magnitude):

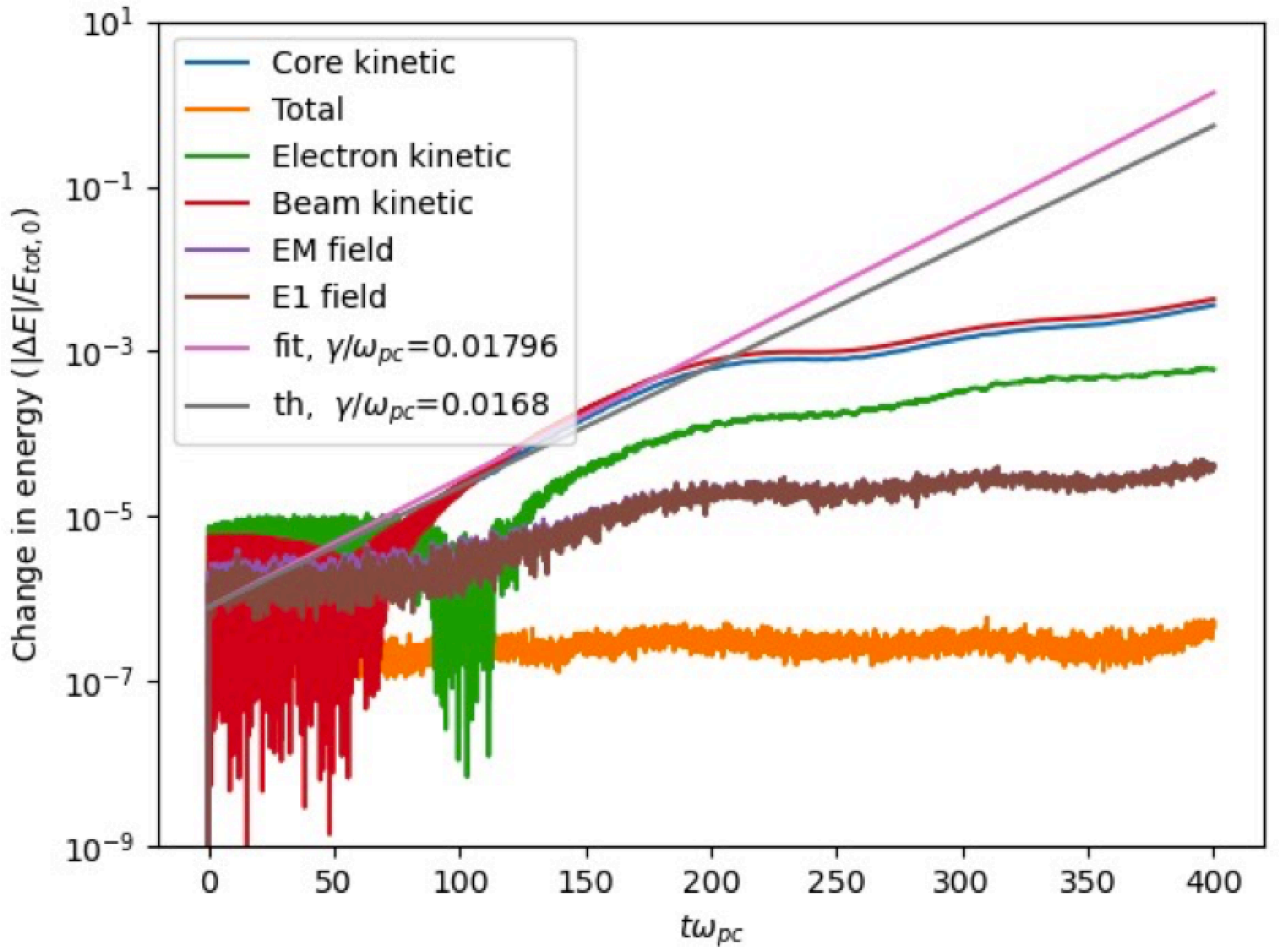
- **The growth rate/time.**
- **Saturation/maximum amplitude.**
- **Ion density perturbations.**

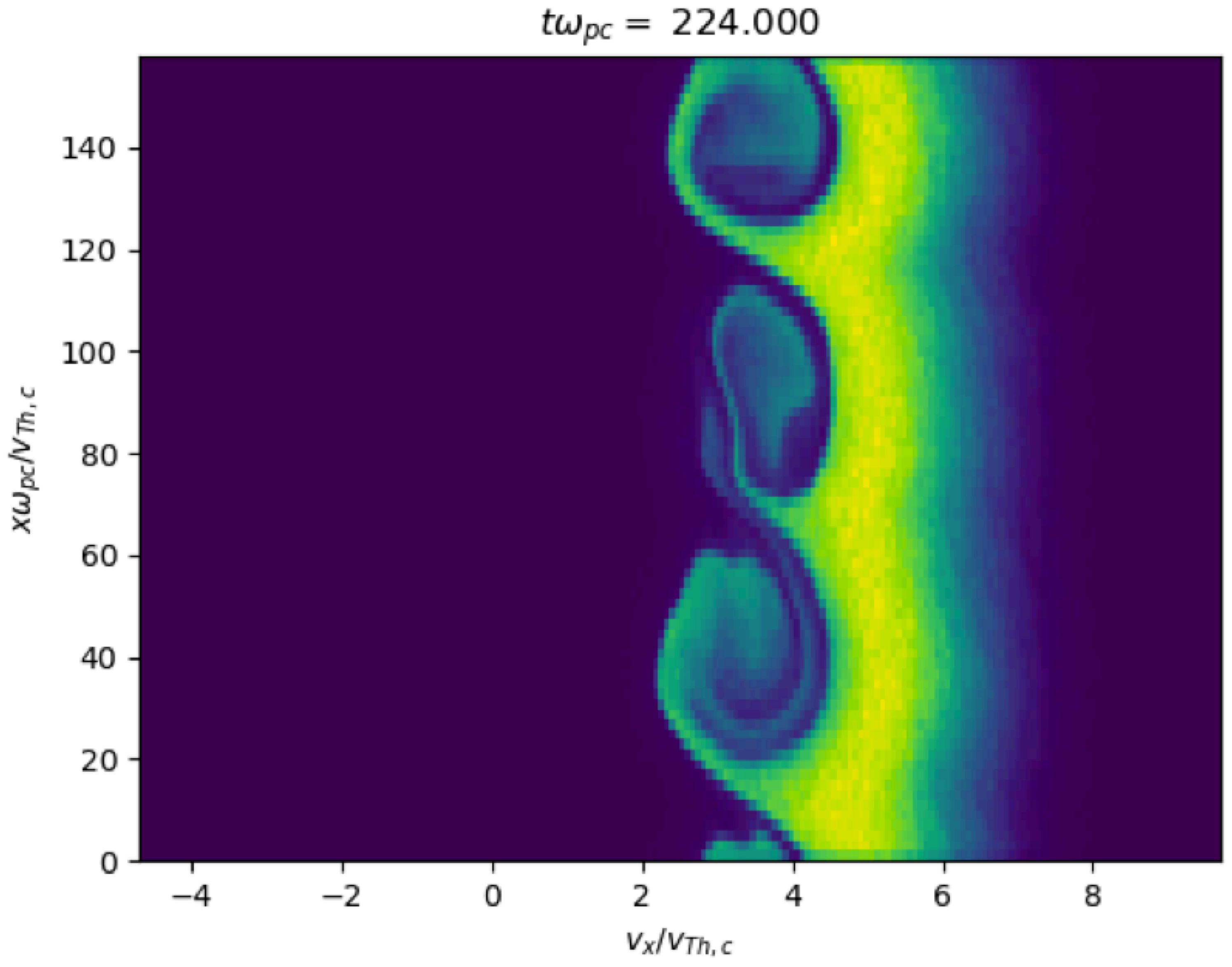
Differences:

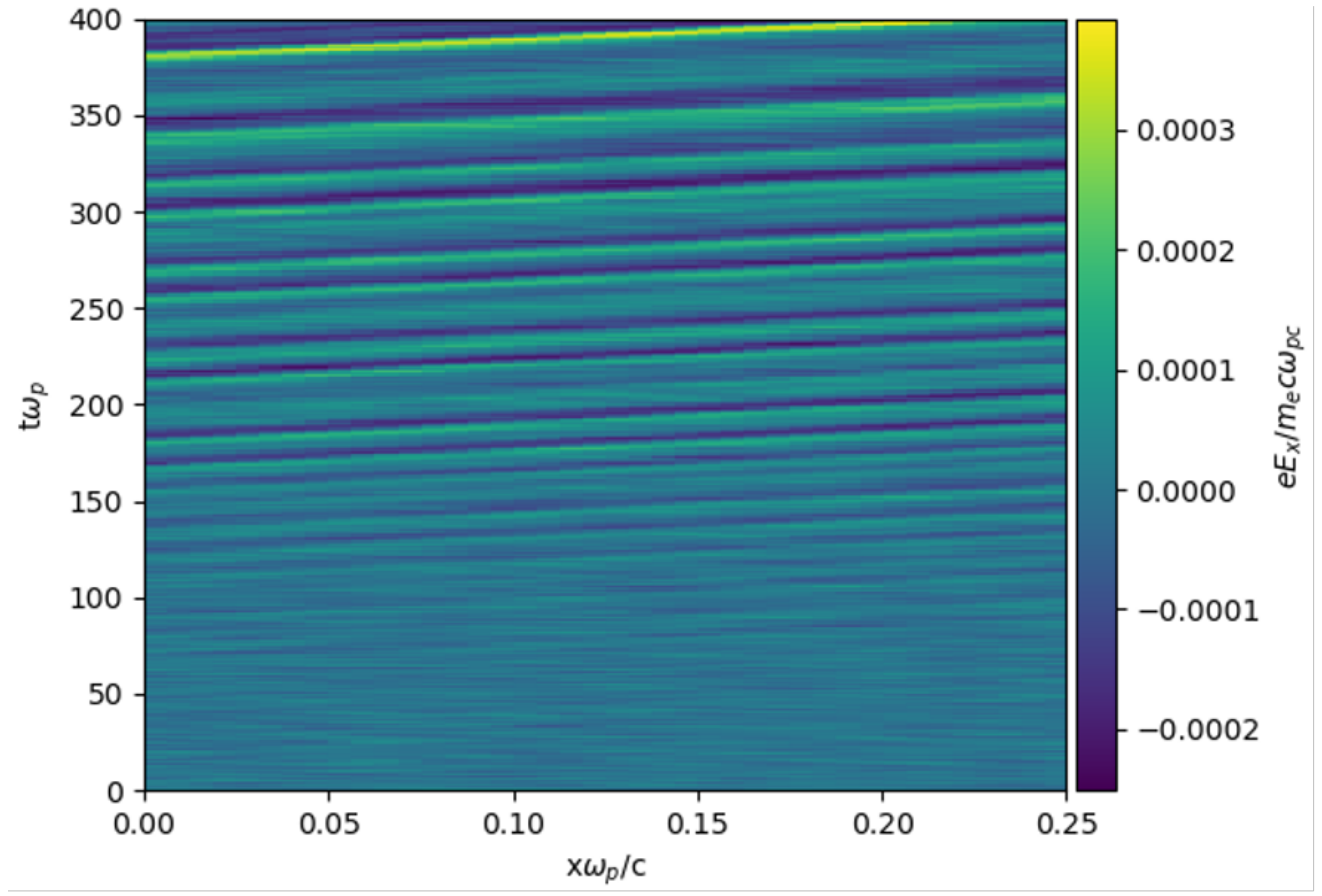
- **No rapid decay in simulated bursts.**
- **Only one burst simulated, triggering mechanism unknown**
- **Higher T_e/T_c and lower T_b/T_c in simulation**

Electromagnetic Particle-in-Cell Simulation

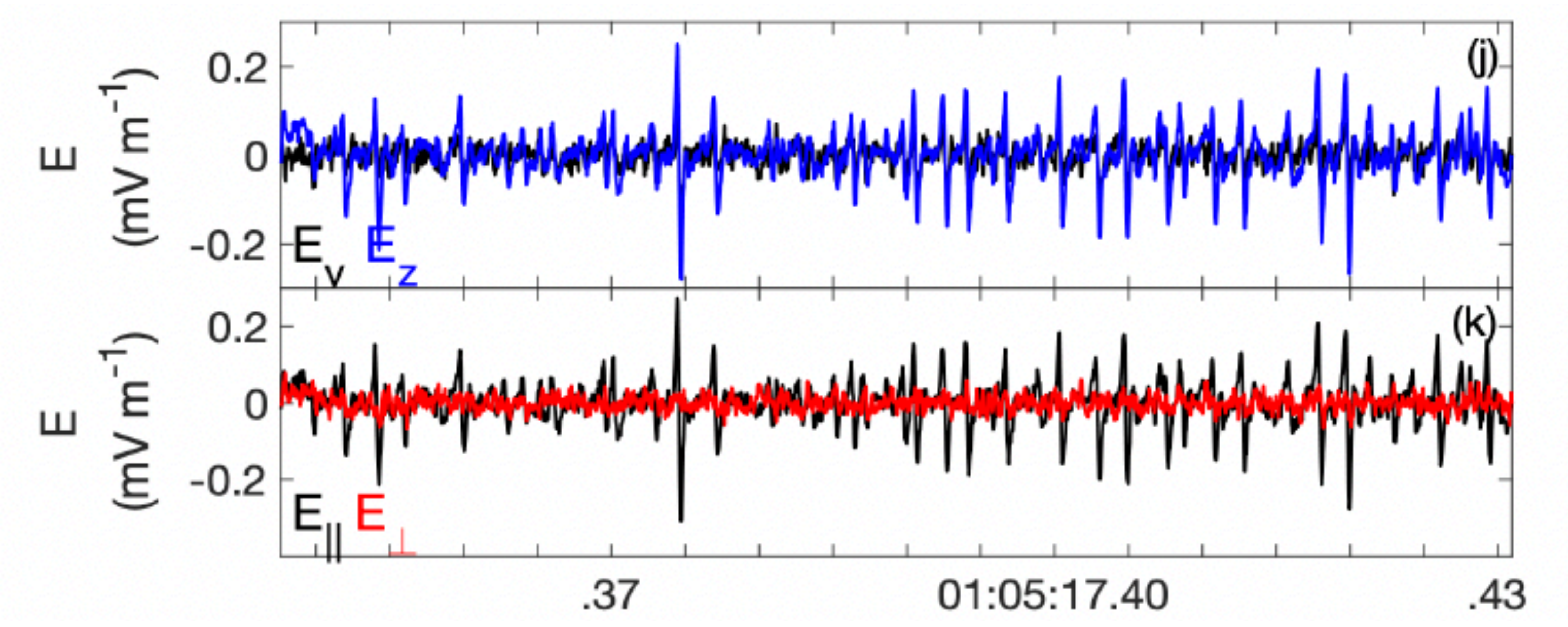
- We perform fully kinetic electromagnetic PIC simulation for validation.
- Here parameters: $T_e/T_c = 10, T_b/T_c = 1, V_D/V_{Th,c} = 5, n_b/n_c = 0.05.$
- Very good agreement between Vlasov simulation, PIC simulations, and linear theory (early phase).
- Outlook: 2D, magnetic field fluctuations.







What is the correlation between linear and nonlinear ion acoustic waves (IAWs); i.e. solitary waves, observed in the vicinity to the Sun?



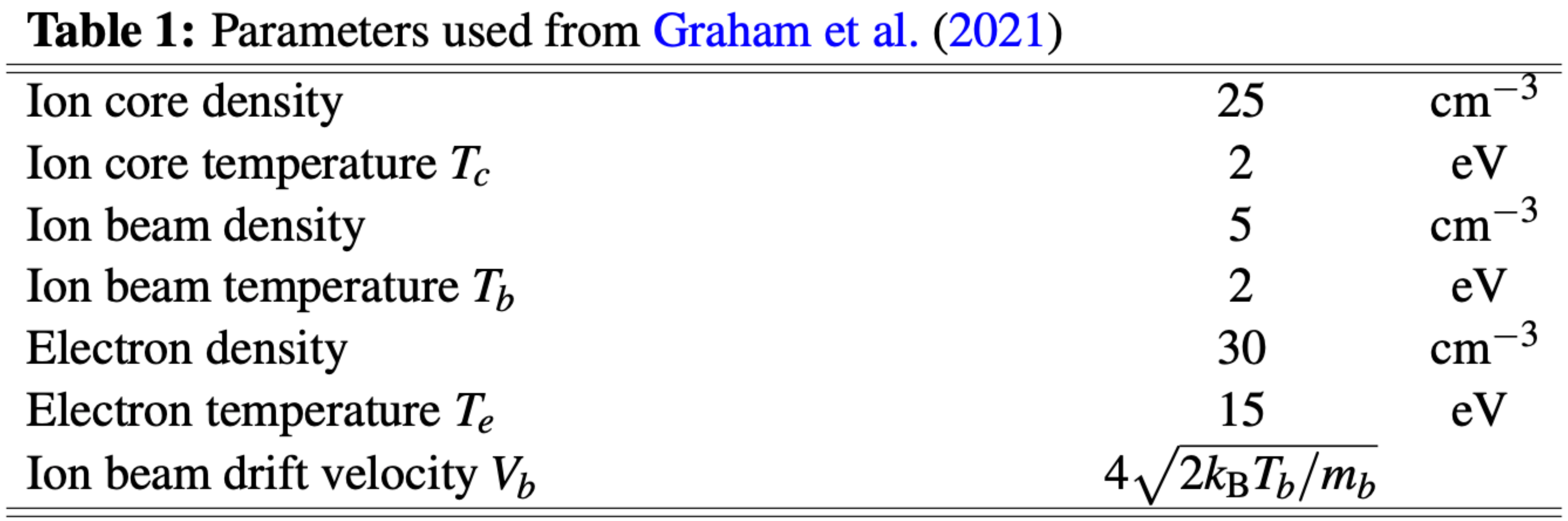
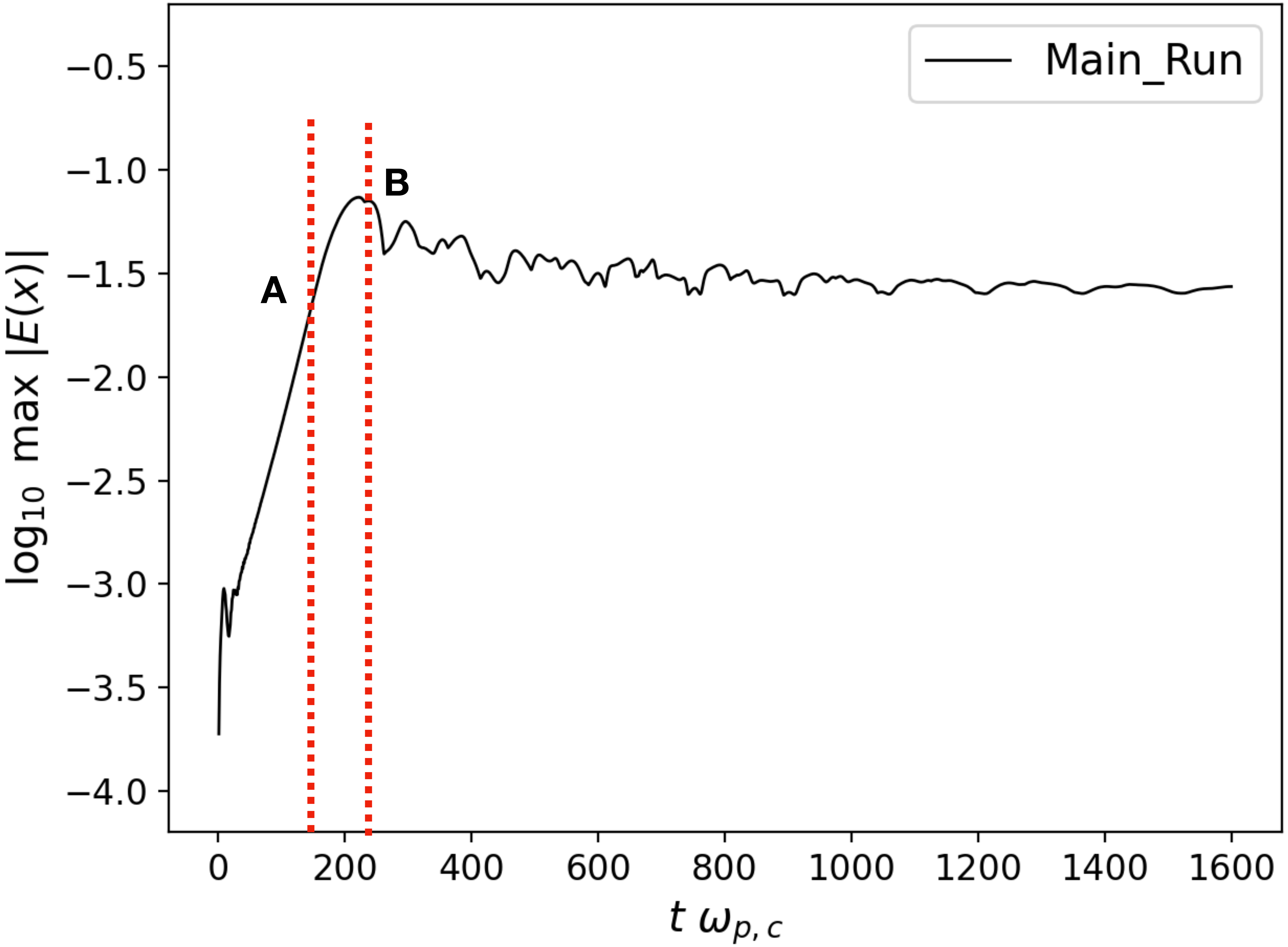


Table 1: Parameters used from Graham et al. (2021)

Ion core density	25	cm^{-3}
Ion core temperature T_c	2	eV
Ion beam density	5	cm^{-3}
Ion beam temperature T_b	2	eV
Electron density	30	cm^{-3}
Electron temperature T_e	15	eV
Ion beam drift velocity V_b	$4\sqrt{2k_B T_b/m_b}$	

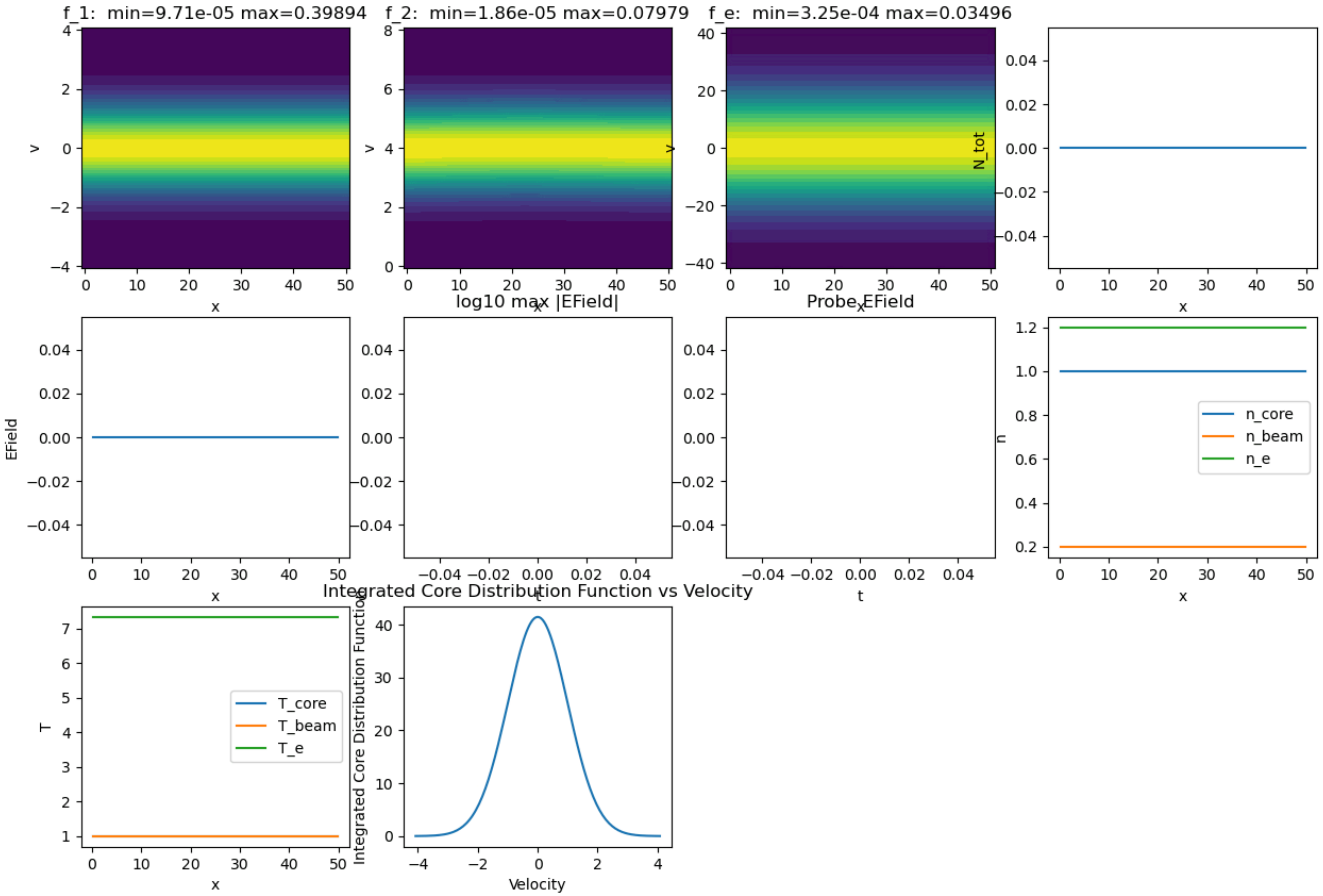
Afify et al. 2024 (Preparation)

Vlasov Simulations



M. S. AFIFY | ISSS-15 + IPELS-16
Joint Conference (August 5-9) MAHMOUD.IBRAHIM@RUB.DE

Separate phase spaces for all three components (Solar Orbiter)



MAHMOUD.IBRAHIM@RUB.DE

Conclusions

- We do observe ion acoustic instability in a regime compatible with the Mozer observations, but with $T_e/T_c = 10$, rather than $T_e/T_c = 6.5$ as observed.
- Periodic conditions in x imply creation of chain of islands in beam ion phase space.
- Oscillatory signatures in the E_x field, as seen in the observations, result from these ion holes, in the frame of the core plasma.

Open questions:

- What is the correlation between the low and high-frequency modes?
- What is the reason for the triggering and decay of the bursts?
- What is the relationship between burst occurrence and temperature ratio T_e/T_c?

Questions?

MAHMOUD.IBRAHIM@RUB.DE