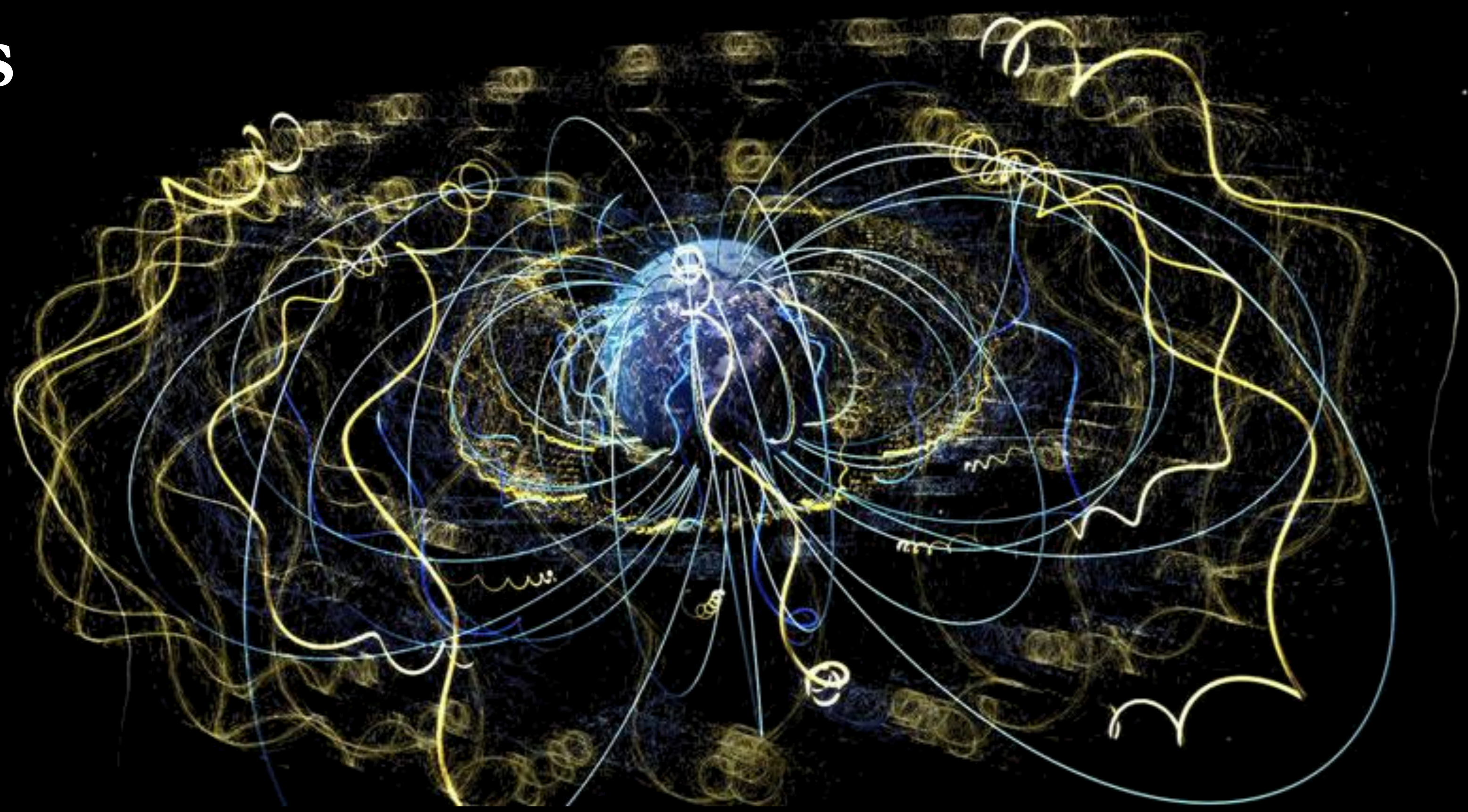
The Giant Planets as Unique Laboratories for Space Plasma Processes



Credit: NASA

Ali H. Sulaiman

CLaSP/MIPSE
Thursday, 14 Sep 2023
Ann Arbor, MI

Auroras of the giant planets

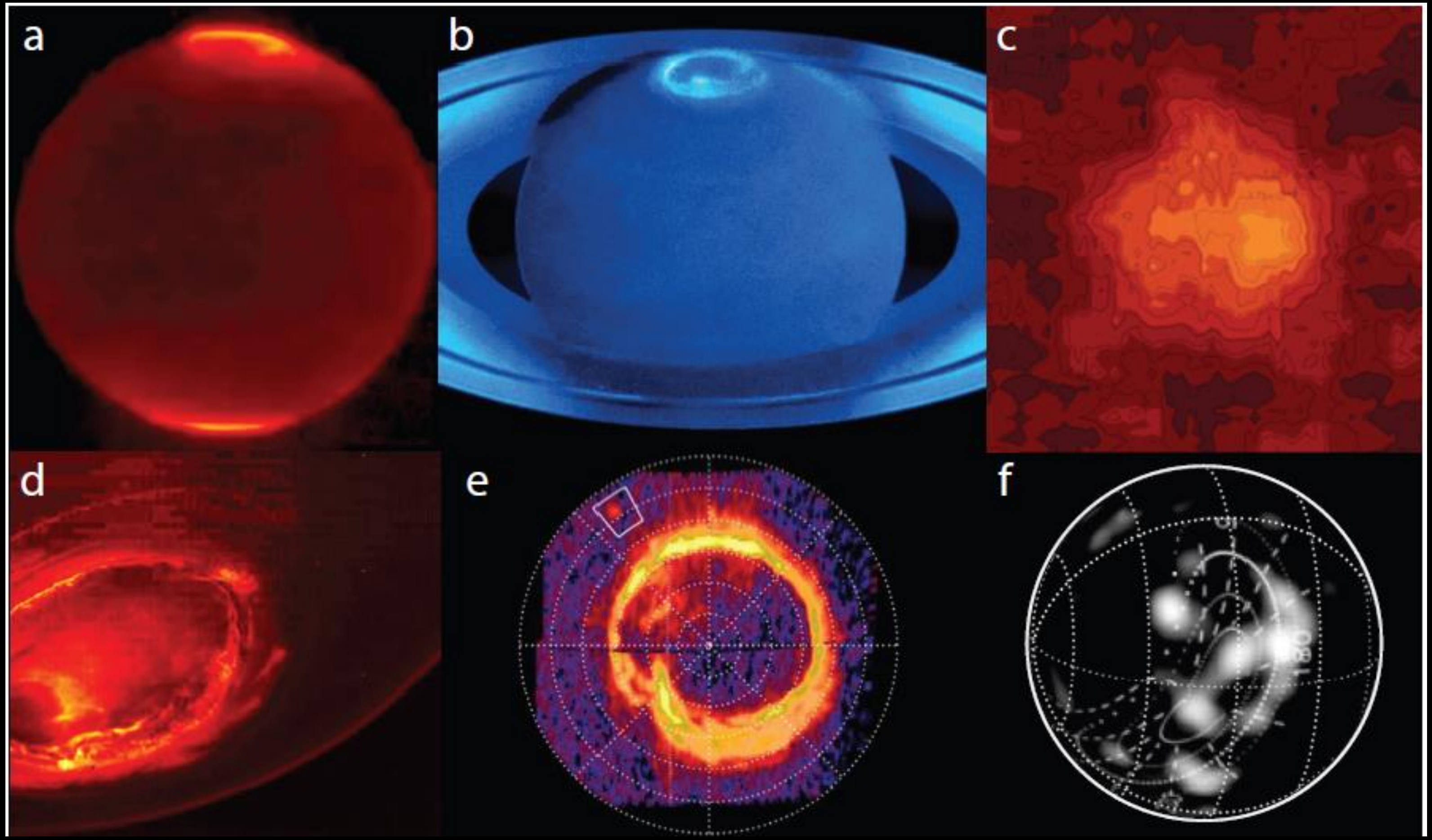
Jupiter

Saturn

Uranus

Earth-based telescopes

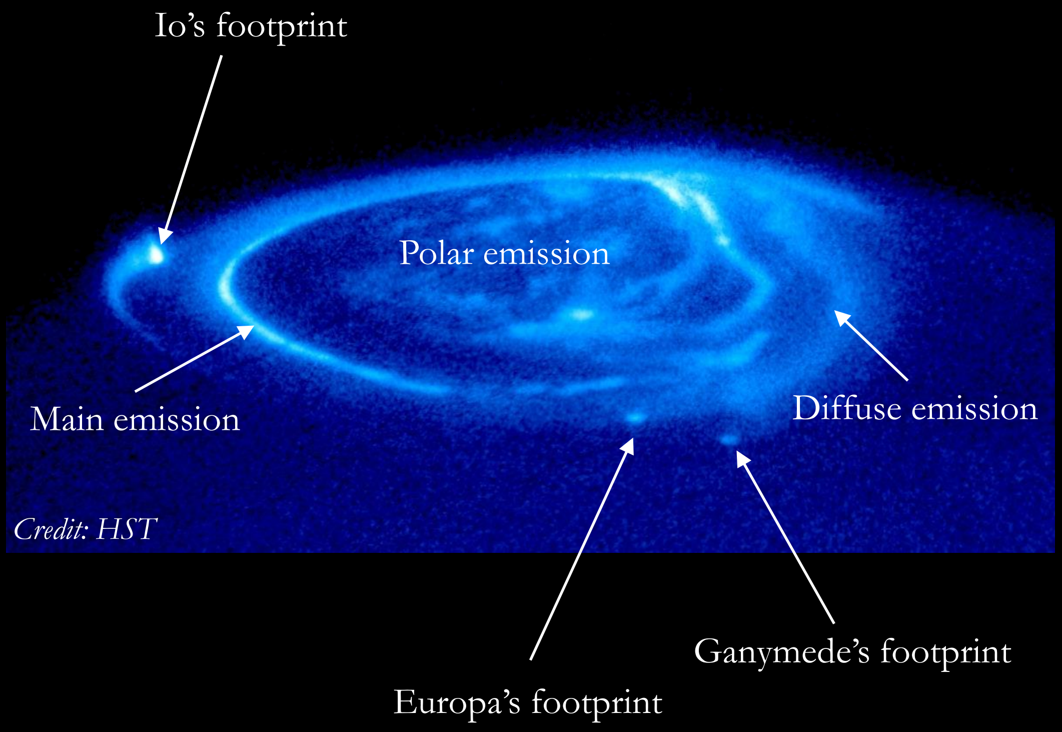
Spacecraft



Why do we care about the auroras of the giant planets?

Magnetospheres and Atmospheres

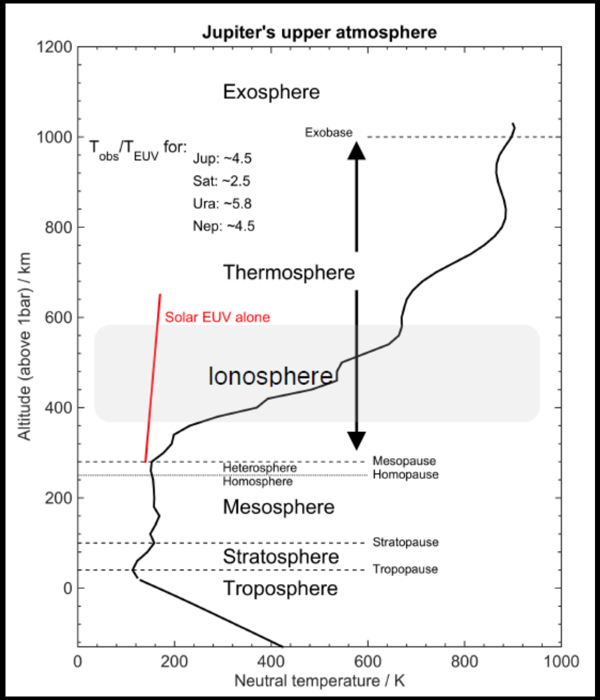
- The aurora provides the essential context to understand the dynamics of magnetospheres



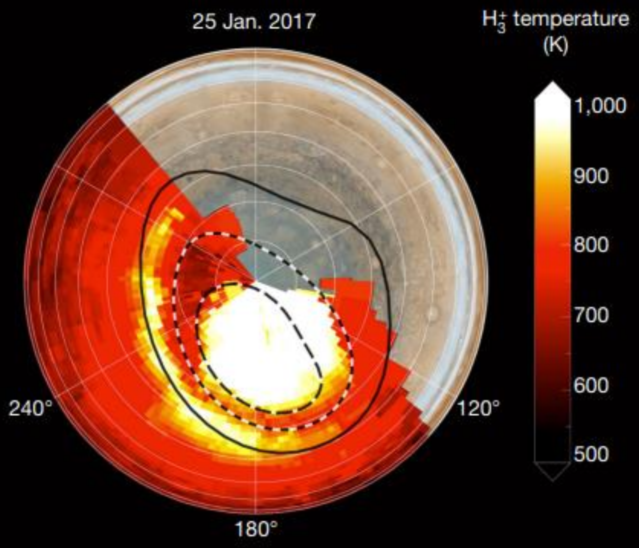
Credit: HST

"Energy Crisis"

- Jupiter's upper atmosphere is ~ 700 K or ~4.5× hotter than predicted by solar radiation models
- Saturn, Uranus, and Neptune are ~2.5×, ~5.8×, and ~4.5× hotter than predicted
- **The upper atmosphere is predominantly heated by the redistribution of auroral energy**

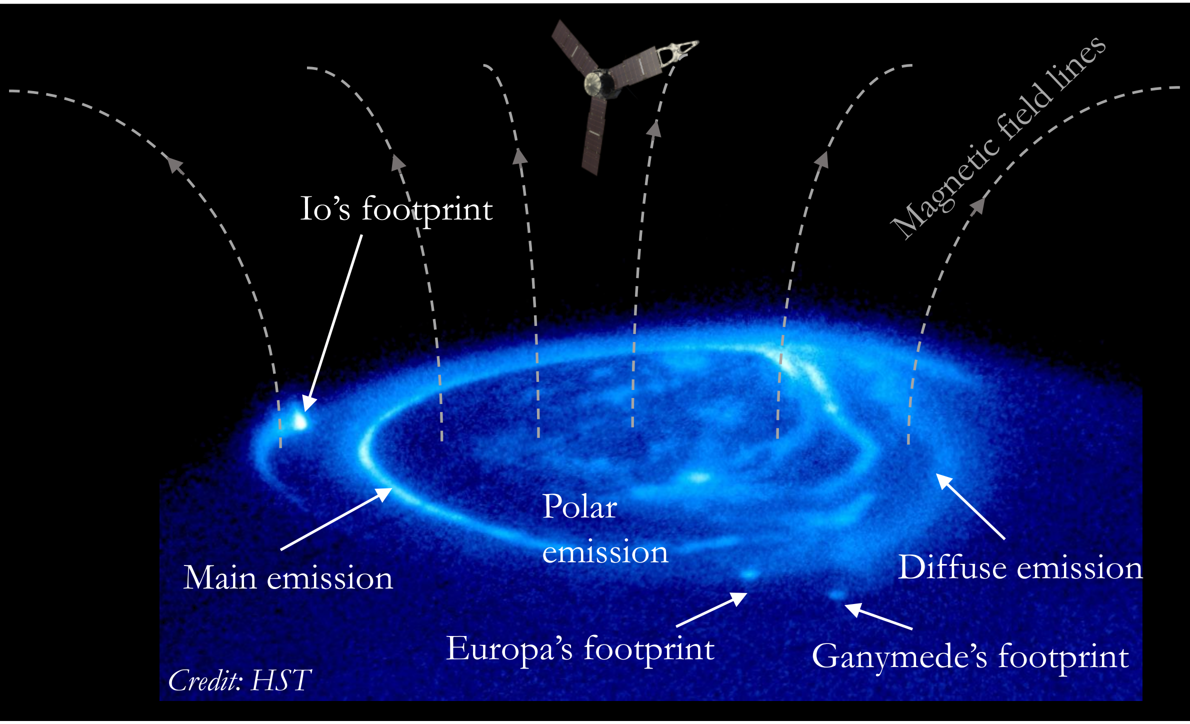


Seiff et al., 1997

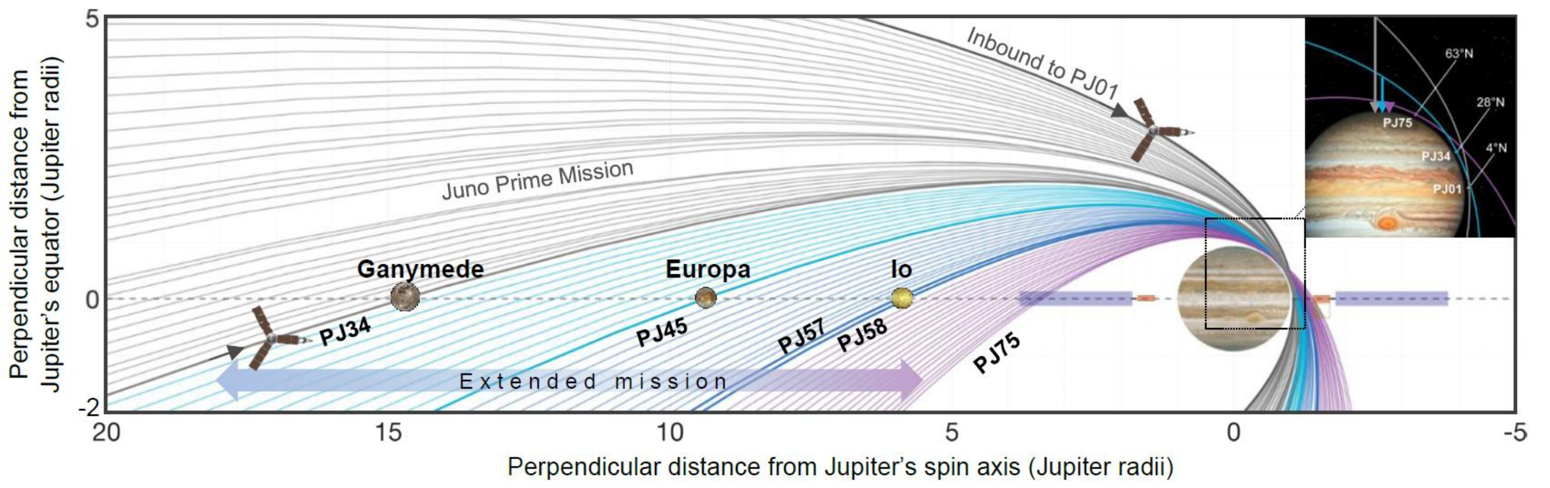


O'Donoghue et al., 2021

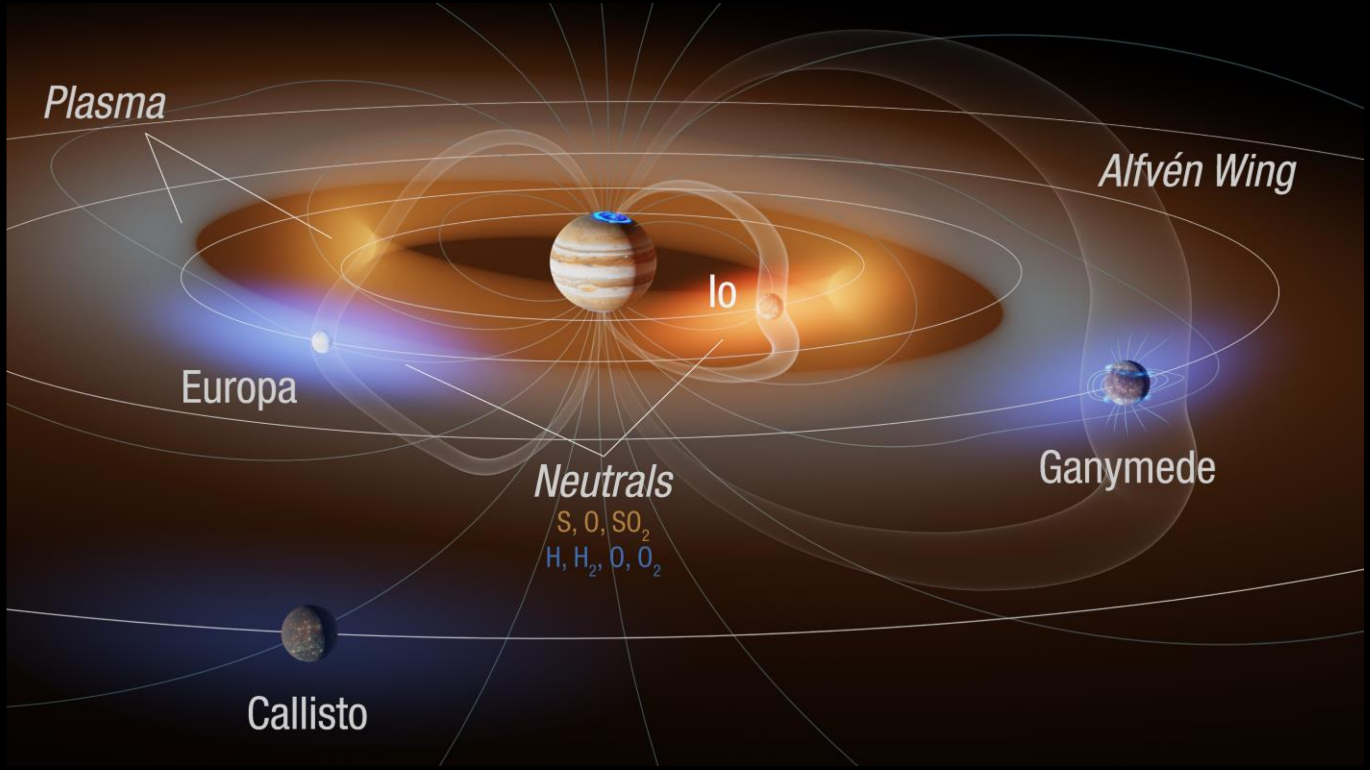
Juno's Unique View of Jupiter's Aurora



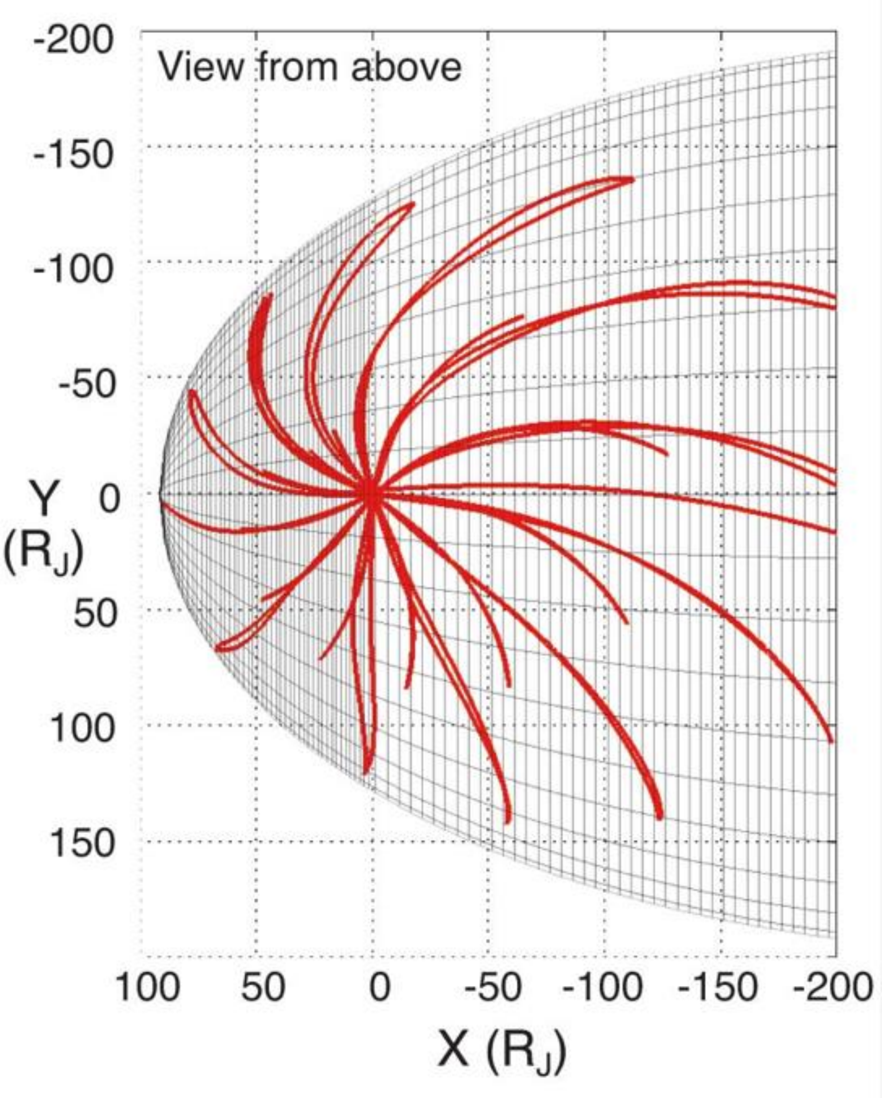
Credit: HST



The Magnetosphere of Jupiter



Credit: Szalay, Smith & Smith



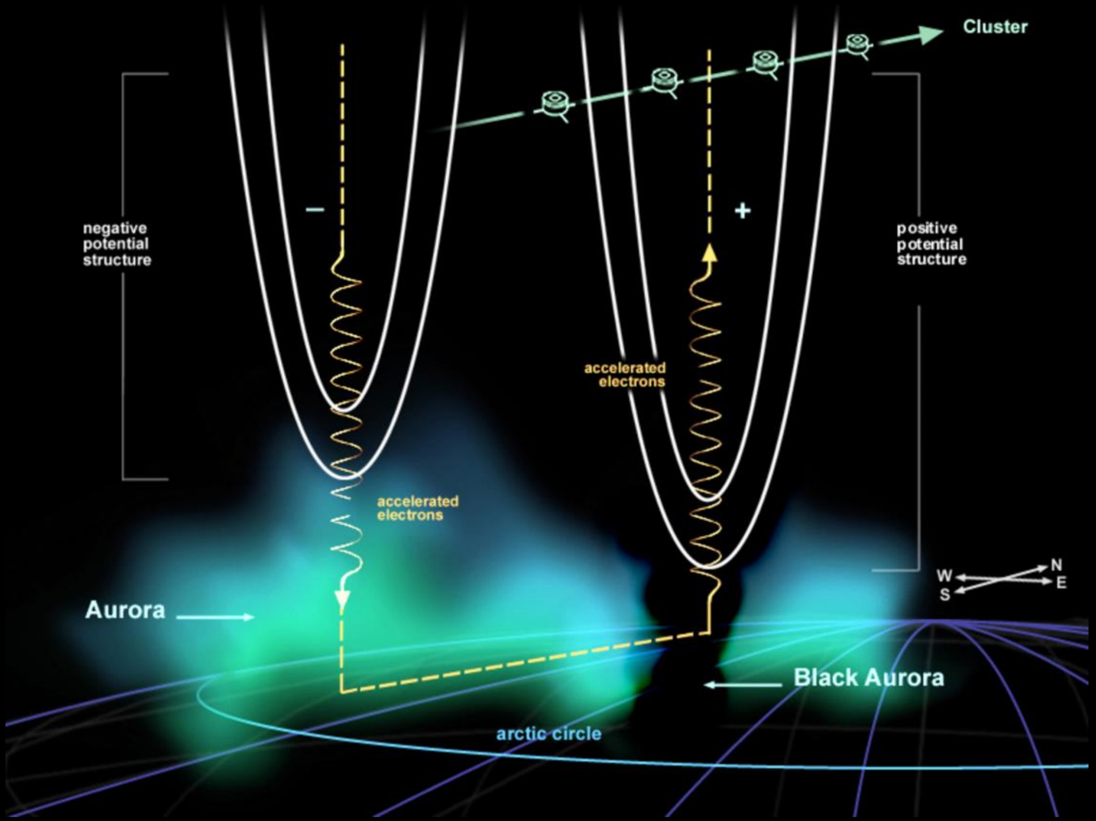
Electron Acceleration Mechanism (Peaked)

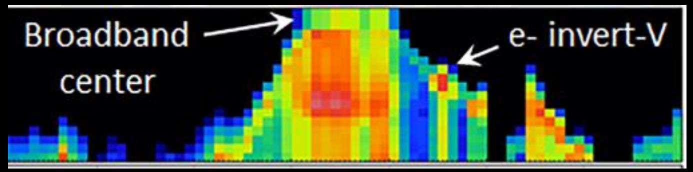
Electric Potentials (theorized as cause of peaked distributions via electrostatic acceleration)

- Quasi-static potential structures accelerate auroral particles parallel to the magnetic field. Each electron gains the same amount of energy $q\Phi$
- These potential structures develop when there are not enough charge carriers (i.e., low electron density)
- Strong electric fields accelerate electrons to compensate for their scarcity, in order to balance $\nabla \times B$ imposed by the magnetosphere

Recent statistics have shown that broadband distributions are much more common than monoenergetic distributions on main auroral field lines

Cannot be explained by a quasi-static energization mechanism

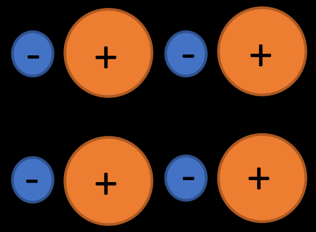




Electrostatic (inverted V) and time-dependent (broadband) acceleration over Jupiter's upward auroral zone (Zone-I) [*Mauk et al.*, 2020]

A Brief Introduction to Plasma Waves

- Due to the presence of long-range forces, various types of waves can exist in a plasma that have no counterpart in ordinary gases or dielectric media
  - In the absence of collisions, this is by virtue of electric and magnetic fields, as well as various charged particle species supported by a plasma
- One of the most fundamental plasma waves is the electron plasma frequency, ω_{pe} (the Langmuir wave)
  - When electrons are displaced relative to the ions, an electric field is set up to restore charge neutrality
  - The inertia means the response of the system is harmonic
  - The electric field is therefore oscillating, with a natural frequency, ω_{pe} that is proportional to the square root of electron number density, $\sqrt{n_e}$
  - Therefore, n_e can be inferred by simply measuring the frequency of the oscillating electric field



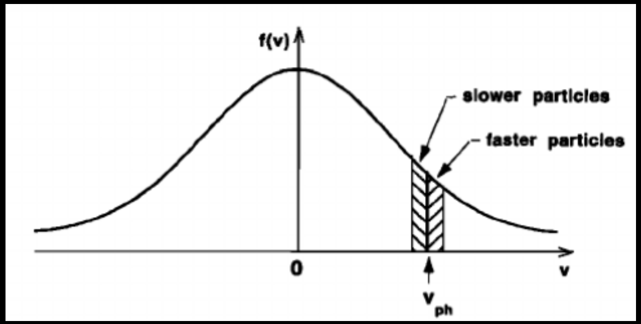
Linear response of the plasma to small perturbations

- The properties of a given plasma wave is encoded in its dispersion relation. This requires that a relationship between frequency, wavelength, and direction must be satisfied for a wave to exist. For example, a propagating Langmuir wave has a dispersion relation given by $\omega^2 = \omega_p{}^2 + 3k^2 v_{th}{}^2$

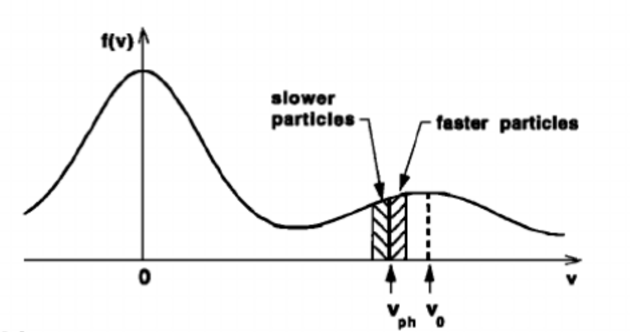
Basic Principles of Wave-Particle Interaction (1)

- The collisionless nature of space plasmas would imply that there is virtually no dissipation
- Wave-particle interactions introduce finite dissipation in a collisionless plasma
- They are thought to be play an important role in the dynamics of the radiation belts, auroral acceleration regions, magnetopause boundary layers, shock heating, etc.

- Wave-particle interaction becomes possible when a wave frequency felt by a particle is Doppler shifted by the velocity of the particle. Resonance occurs when the Doppler-shifted frequency is at the cyclotron frequency, or its harmonics, i.e., $\omega - k_{\parallel}v_{\parallel} = n\omega_c$.
  - A special case is **Landau resonance**, where $n = 0$.



Maxwellian plasma.
Wave will always suffer damping.



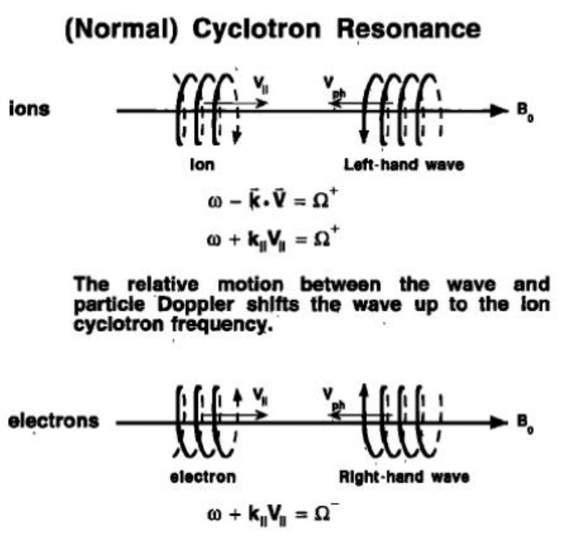
Beam-plasma system.
Resonance possible.

Tsurutani and Lakhina, 1997, *Reviews of Geophysics*

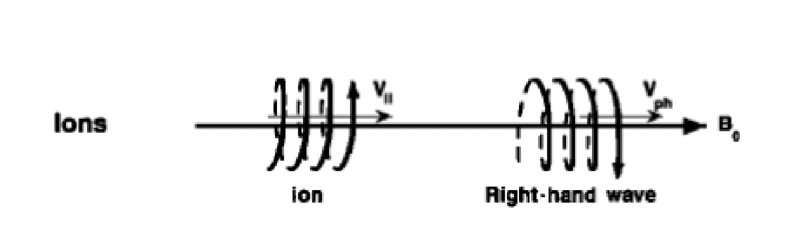
Basic Principles of Wave-Particle Interaction (2)

- Another special case worth noting is **cyclotron resonance**, where n = ±1

Normal cyclotron resonance (n = +1) occurs when an ion/electron interacts with a left/right-handed wave, i.e., the particle gyrates in the same sense as the wave's oscillating electric field.



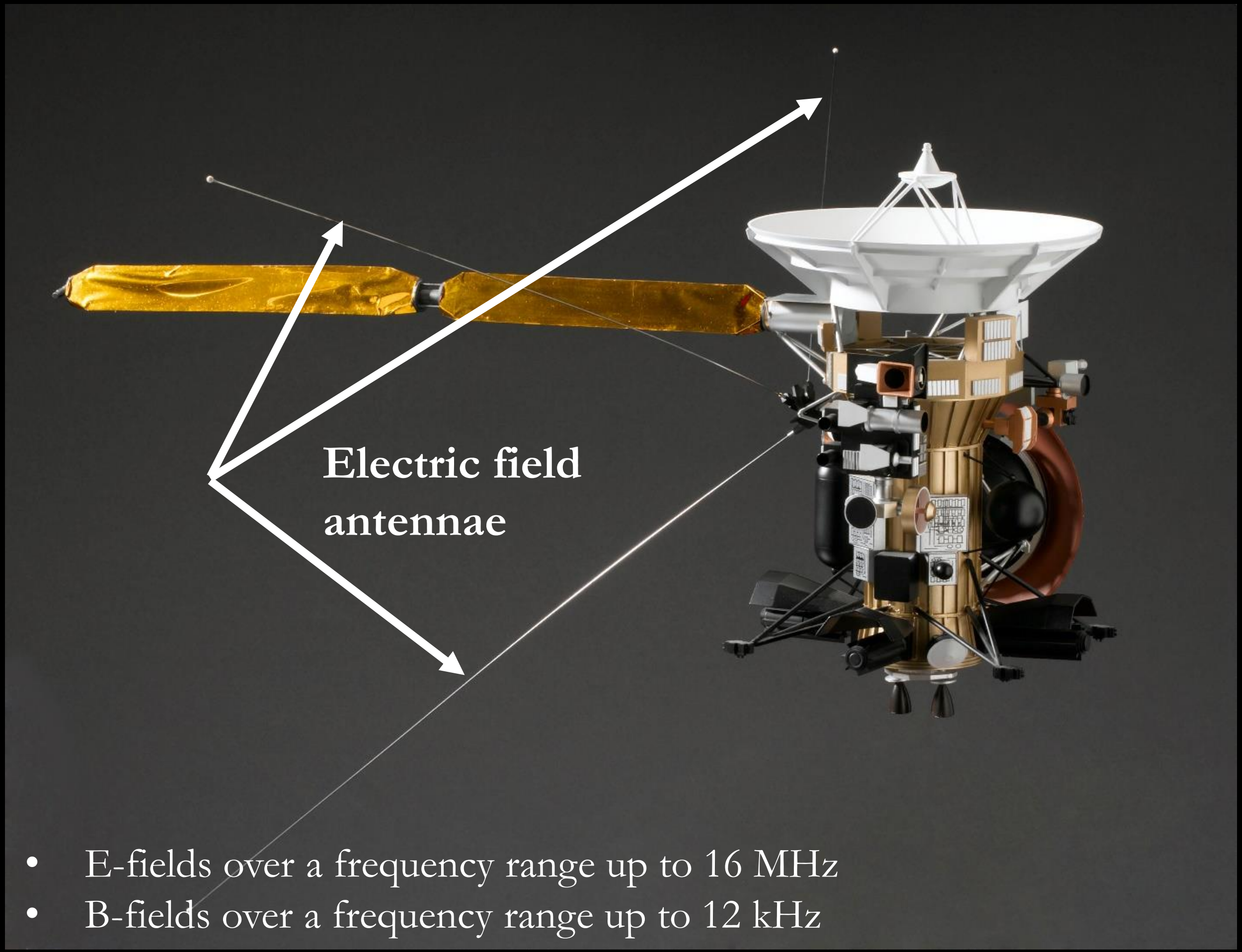
Anomalous cyclotron resonance (n = -1) occurs when an ion/electron interactions with a right/left-handed wave, i.e., the particle gyrates in the opposite sense as the wave's oscillating electric field.



Tsurutani and Lakhina, 1997, *Reviews of Geophysics*

- Distortions in particle distribution functions are unstable to plasma waves. Plasma waves act to smear out the distortions. This could be via heating (spreading out in velocity space), accelerating, and/or pitch angle scattering (reducing anisotropy).

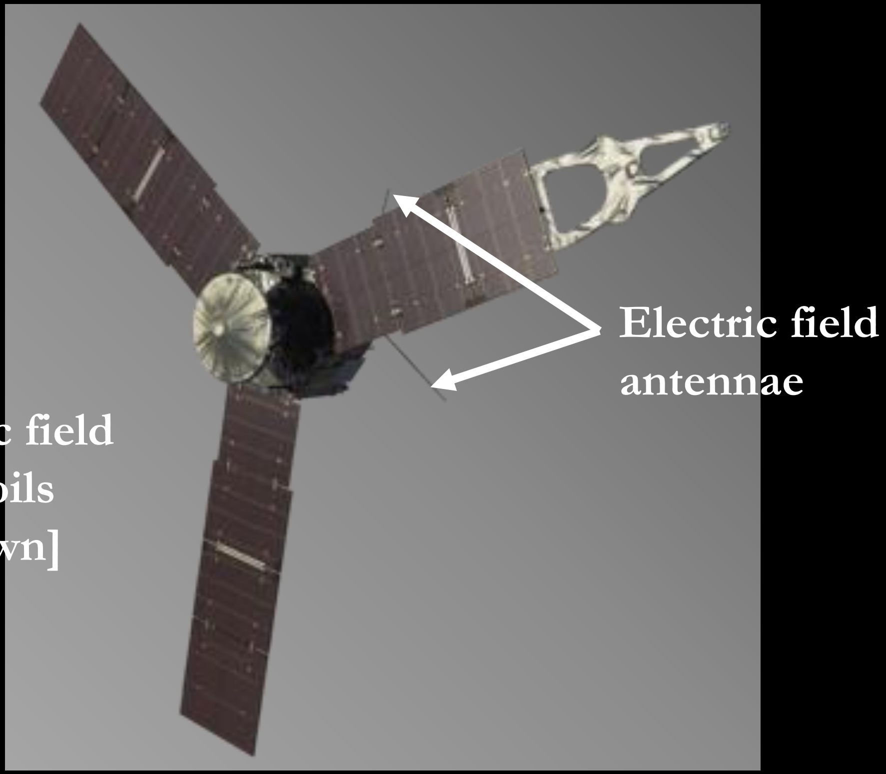
Cassini's and *Juno*'s plasma wave instruments



Electric field antennae

- E-fields over a frequency range up to 16 MHz
- B-fields over a frequency range up to 12 kHz

Gurnett et al. (2004), *Space Sci. Rev.*
Gurnett et al. (2005), *Science*



Electric field antennae

Magnetic field search coils [not shown]

- E-fields over a frequency range up to 41 MHz
- B-fields over a frequency range up to 20 kHz

Kurth et al. (2017a), *Space Sci. Rev.*
Kurth et al. (2017b), *Geophys. Res. Lett.*

Definition: Jupiter’s Auroral Zones

- The various auroral zones of Jupiter were first explicitly defined from energetic electron spectra (Mauk et al., 2020)
  - Diffuse aurora:
    - Most equatorward and broadest in latitude
    - Electron intensities greater outside the loss cone (trapped) than inside the loss cone
    - Electron intensities within the loss cone are predominantly downward (precipitating)

Main Auroral Emission

- Zone-I
  - Intermediate and narrow in latitude
  - Brightest in UV
  - Electron intensities greatest in the downward loss cone
- Zone-II
  - Poleward and narrow in latitude
  - Bright in UV (by contrast with “black” aurora at Earth and Saturn)
  - Electron intensities comparable in both upward and downward loss cones

General Plasma Properties (low altitude)

$|B| \sim O(10^5)$ nT

$n_e \sim O(10^{-3} – 10^{-2})$ cm^{-3}

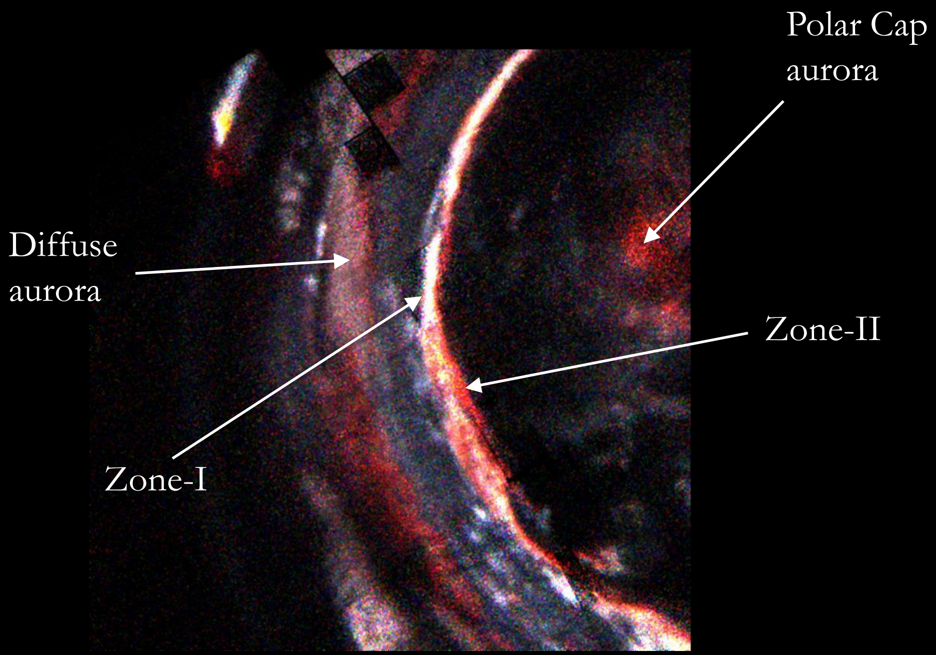
$T_e \sim O(10^3 – 10^4)$ eV

$f_{ce} \sim O(10^6)$ Hz and $f_{ci} \sim O(10^3)$ Hz

$f_{pe} \sim O(10^3 – 10^4)$ Hz

$\lambda_e \sim O(1 – 10)$ km

$v_A \rightarrow c$



False color UV image of Jupiter’s southern aurora

Electron Acceleration Mechanisms (Broadband)

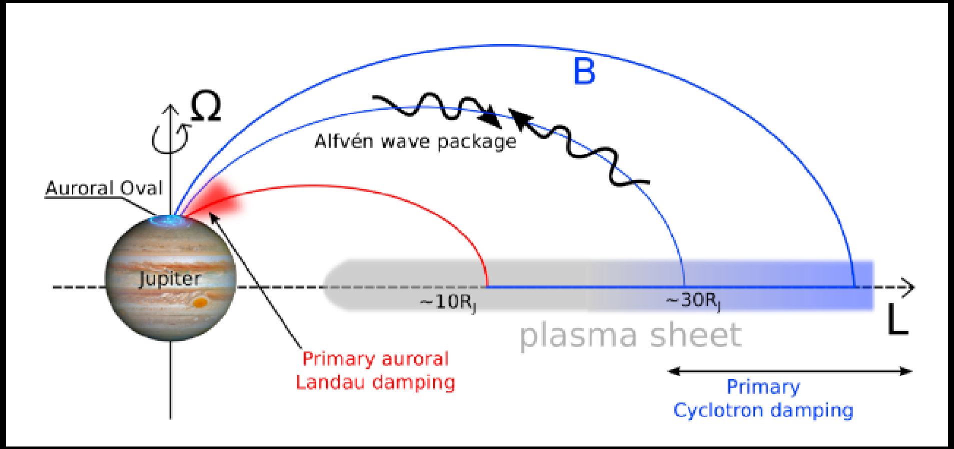
- Broadband energization calls upon a time-dependent/stochastic mechanism
- Broadband acceleration of electrons requires that the parallel electric field vary over the time it takes the electrons to pass through the acceleration region

1. **Alfvén waves**

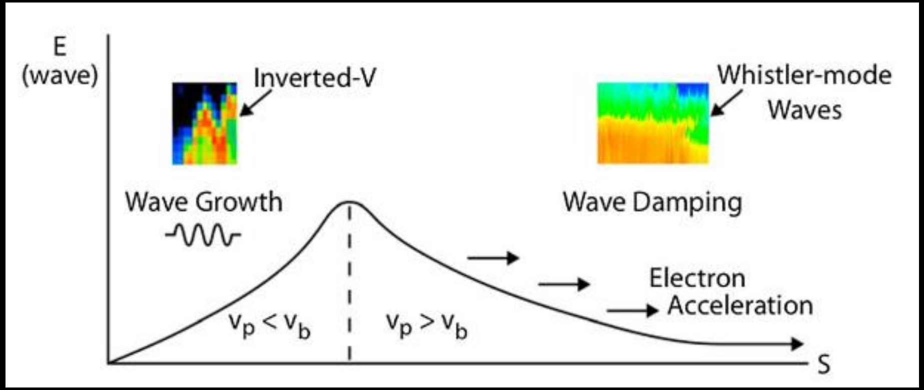
- Alfvén waves develop a $E_{\|}$ when electron mass is accounted for, which serves to accelerate electrons
- Jupiter's magnetosphere is full of disturbances that propagate in the form of Alfvén waves and these travel along magnetic field lines to higher latitudes where they can accelerate electrons

2. **Whistler-mode waves**

- Whistler-mode waves grow and then undergo damping as they accelerate electrons
- Whistler-mode waves are commonly observed in auroral regions of planetary magnetospheres

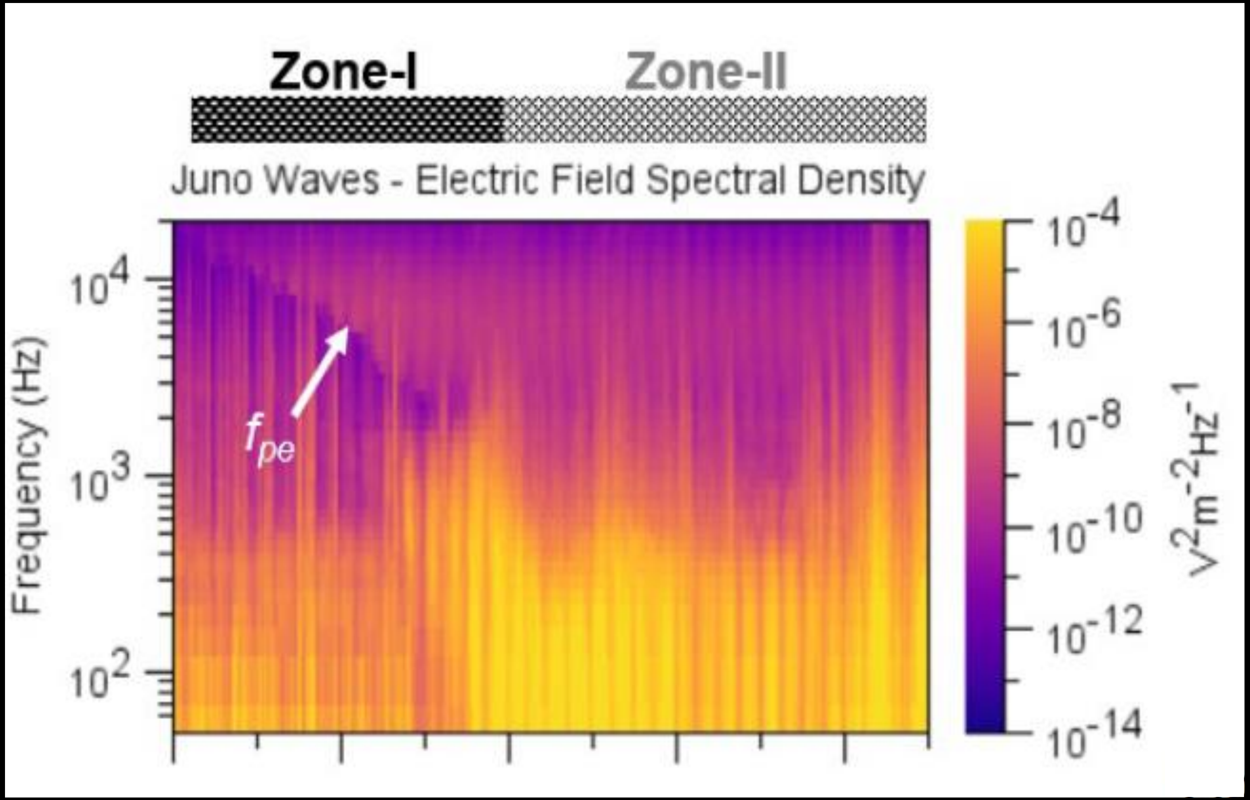


Propagation and dissipation of Alfvén waves in Jupiter's magnetosphere [*Saur et al.*, 2003; 2018]

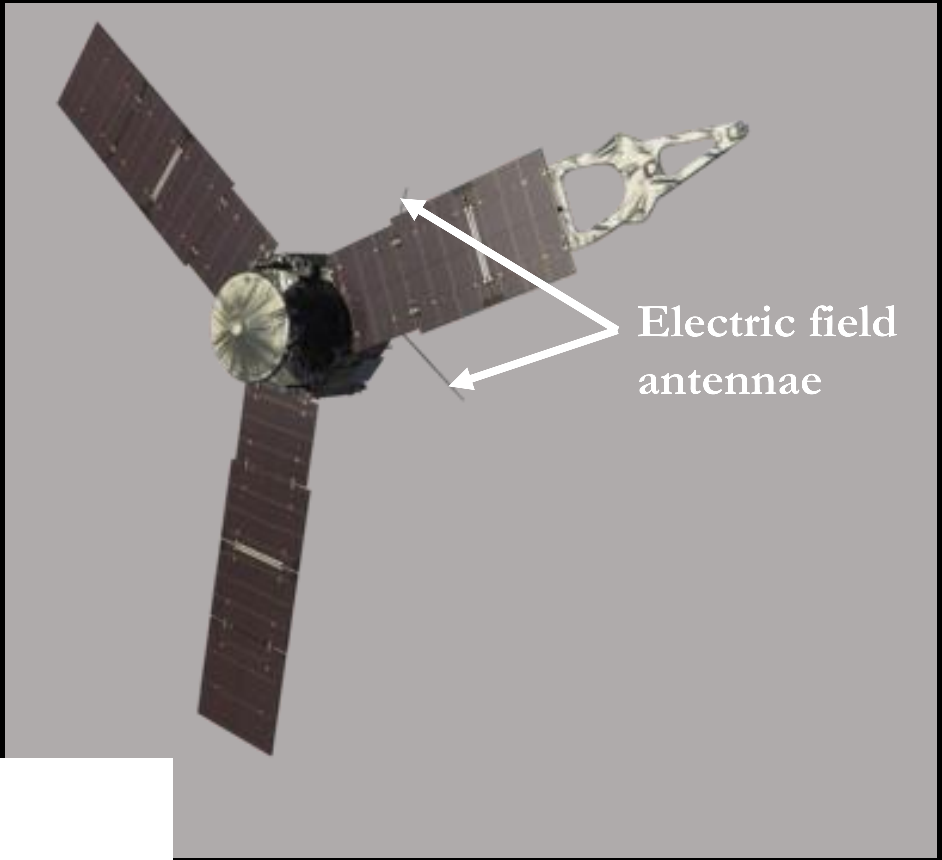


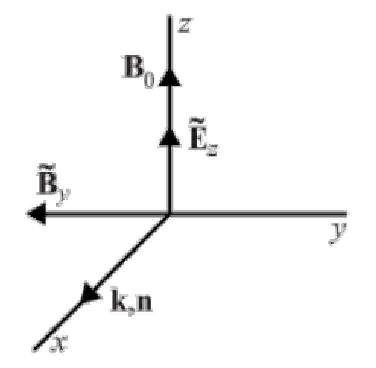
Growth and damping of whistler-mode waves in Jupiter's auroral zones [*Elliott et al.*, 2018]

Density depletions above the aurora

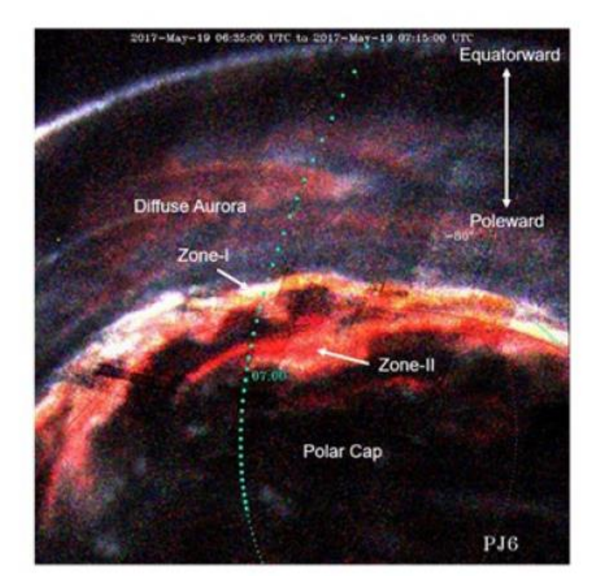


Ordinary (O) mode waves have a low-frequency cutoff at the electron plasma frequency, f_{pe} [Hz] = $8980\sqrt{n_e}$ [cm^{-3}]


Electric field antennae

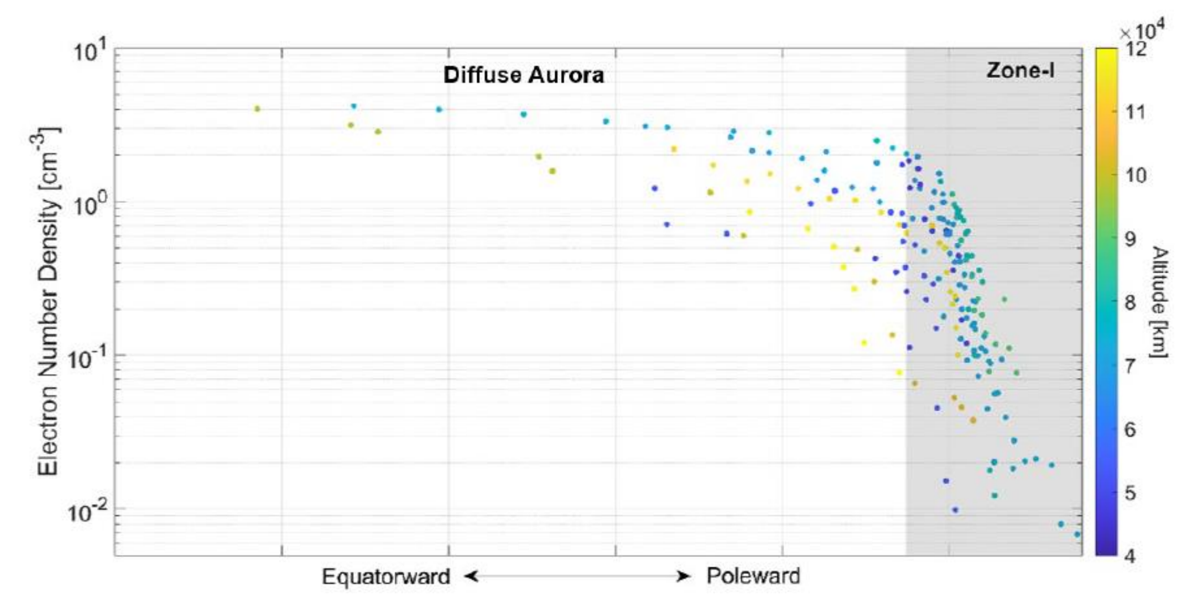


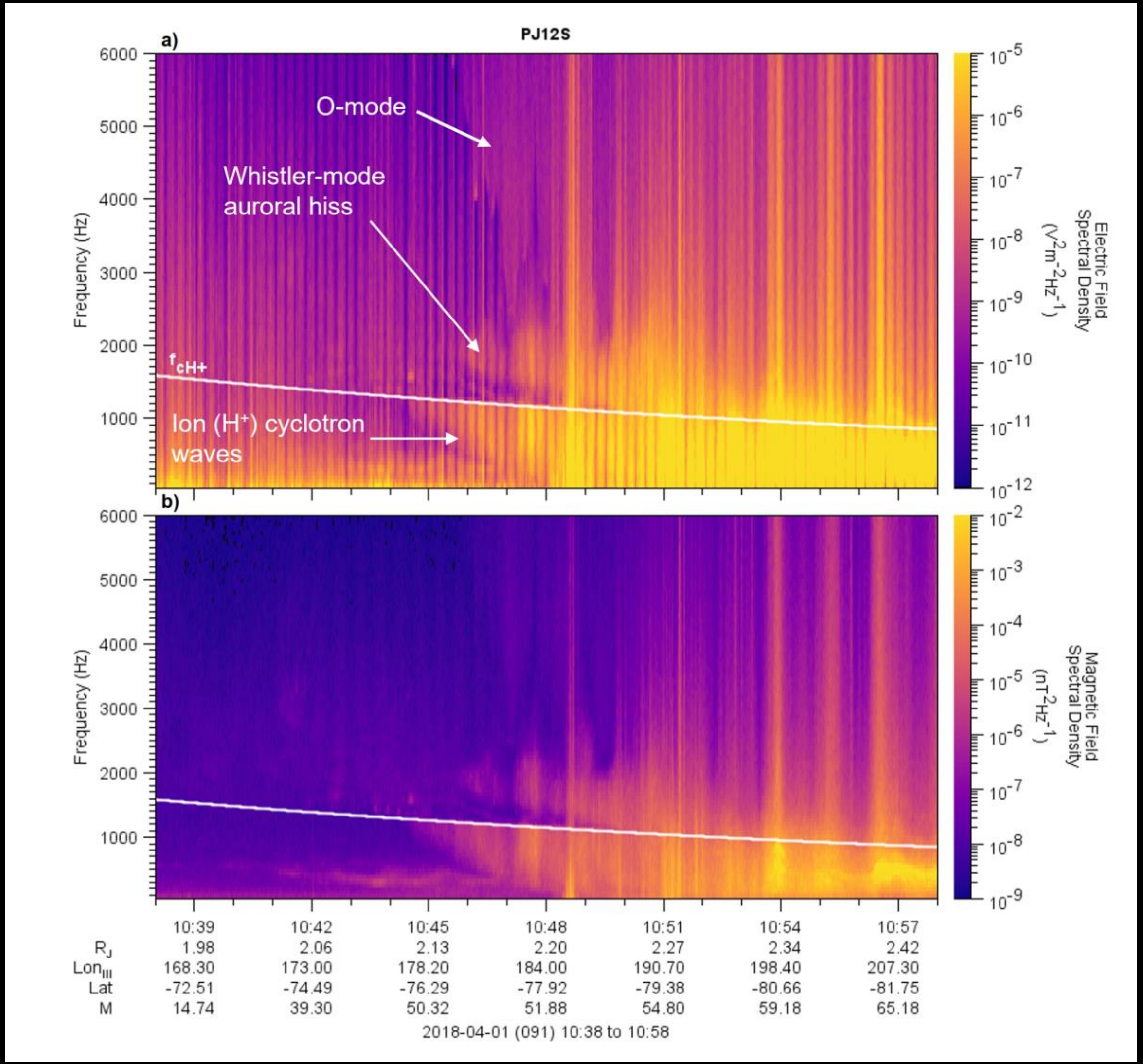
Density depletions above the aurora



The whistler mode cannot propagate above f_{pe}, leaving Alfvén waves as the leading candidate for broadband acceleration

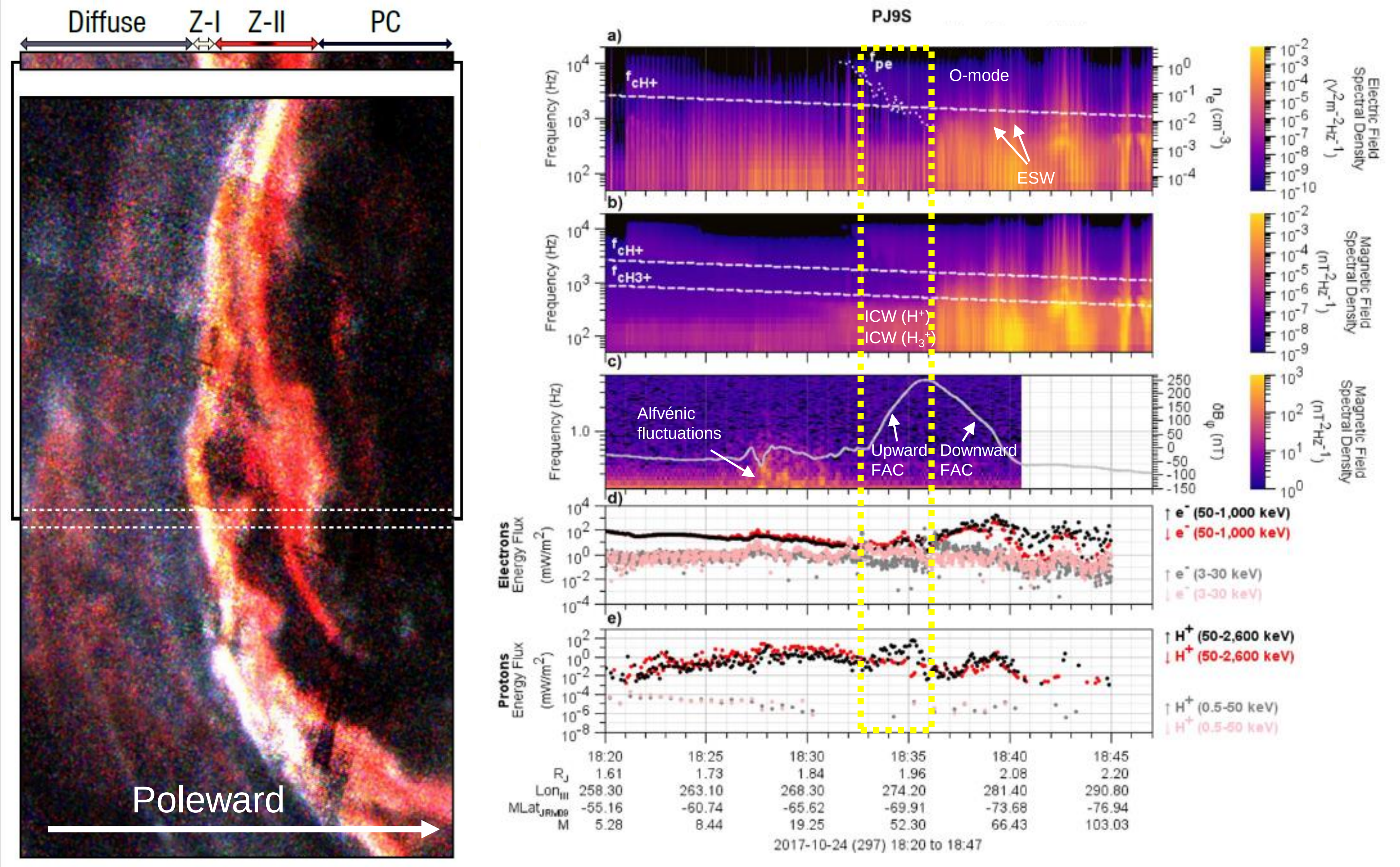
However, strong observational evidence for Alfvénic acceleration remains premature





Sulaiman et al., 2022

Fields and Particles in Zone I



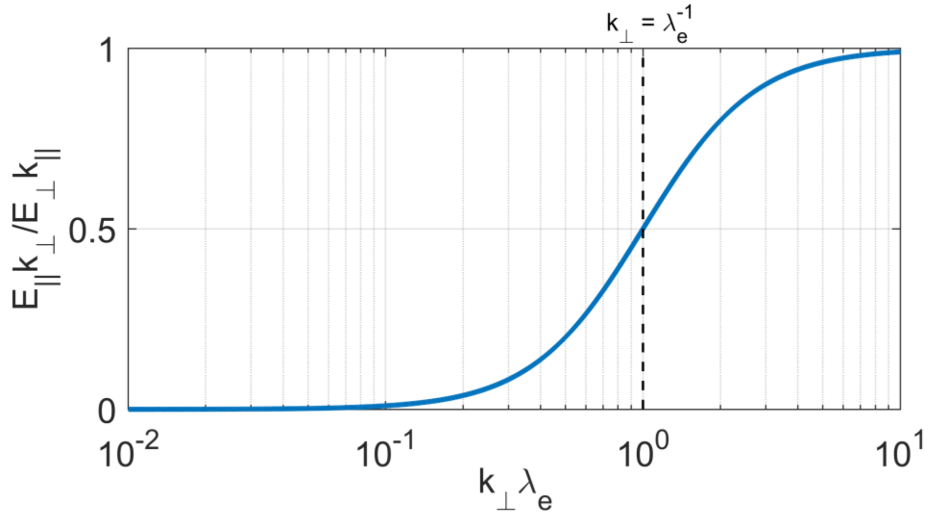
Electron acceleration: More on Alfvén Waves

Development of $E_{\|}$ due to the electron inertial effect. For a plane wave

$$E_{\|}/E_{\perp} = \frac{k_{\|} k_{\perp} \lambda_e^2}{1 + k_{\perp}^2 \lambda_e^2}$$

This parallel electric field increases with $k_{\perp}\lambda_e$

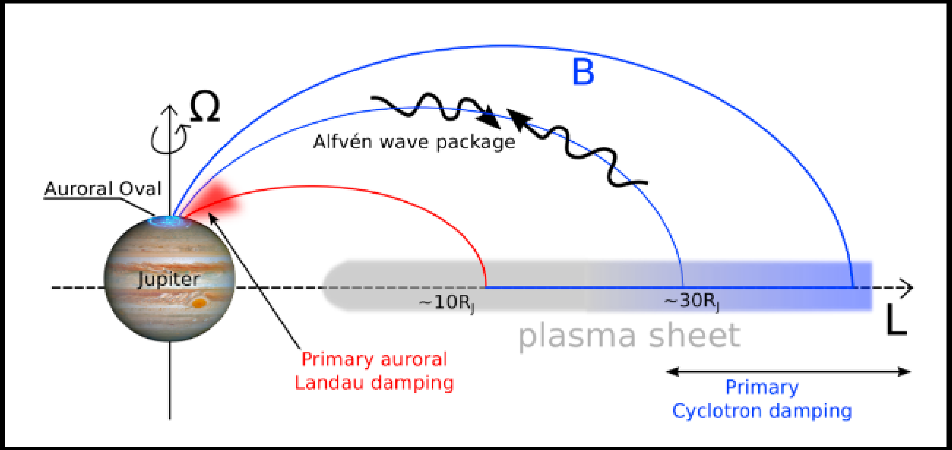
- Low n_e increases $\lambda_e\ (= c/2\pi f_{pe})$
- $k_{\perp}$ increases due to plasma turbulence cascading energy from larger to smaller scales (e.g., *Saur et al.*, 2003; 2018)
- Phase mixing due to gradients in the Alfvén speed can lead to smaller wavelengths thus increasing $k_{\perp}$ (*Lysak et al.*, 2021)



The conditions are ripe for the development of a large parallel electric field. The wave can interact with electrons resonantly or non-resonantly.

Saur et al. (2018) estimated an energization of 0.7 MeV over 1 R_J

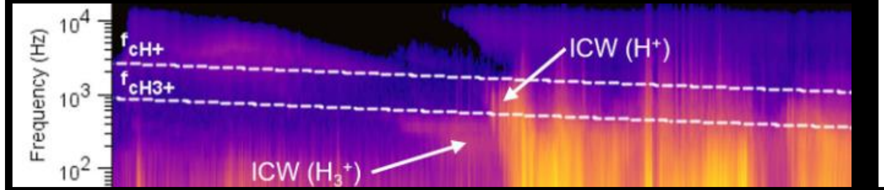
The lack of appreciable Alfvén wave power in the low-altitude (0.6 – 1.6 R_J) auroral zones supports the possibility Landau damping at higher altitudes. This is reinforced by the presence of Alfvénic fluctuations reported at much higher altitudes (> 10 R_J) that map to the main emissions (*Lorch et al.*, 2022)

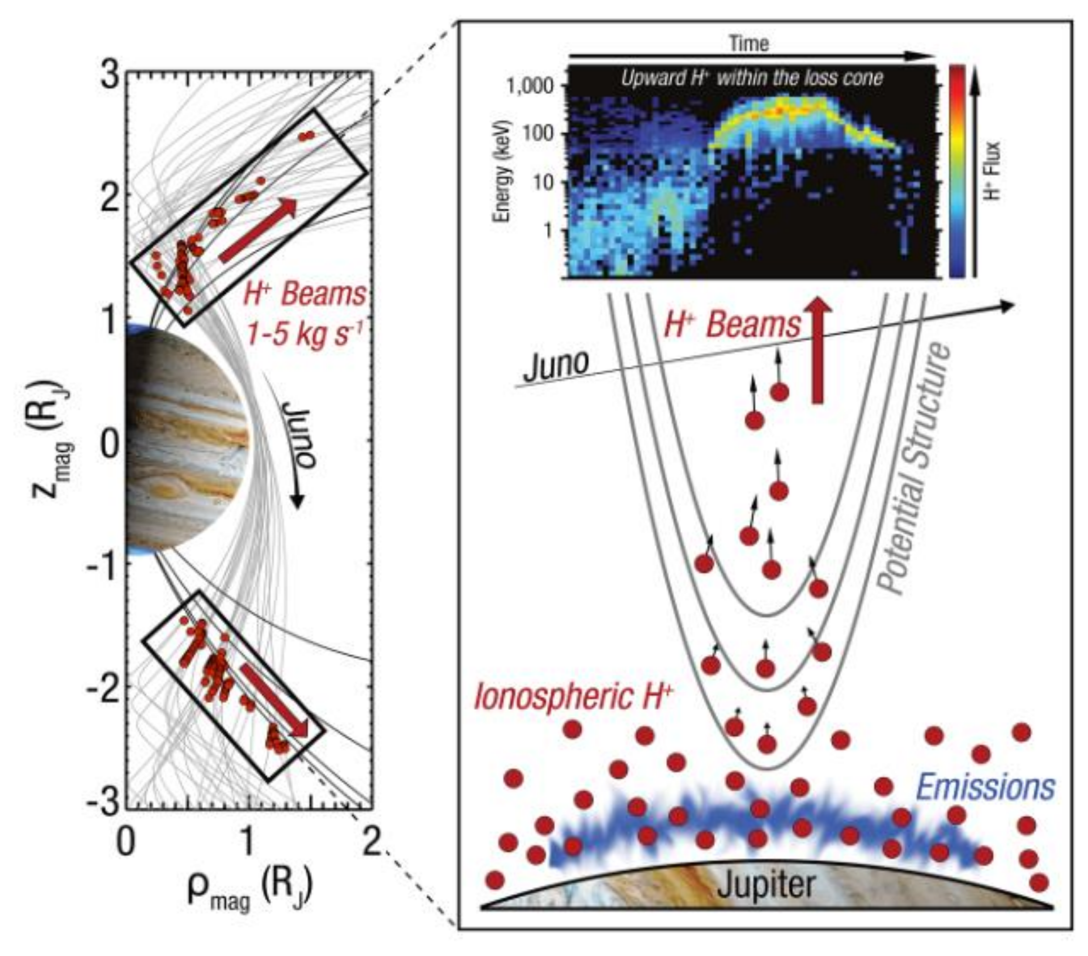


Ion acceleration in Zone-I

Persistent ionospheric H^+ accelerated over Zone-I at a rate of 1-5 kg s^{-1} [*Szalay et al.*, 2021]

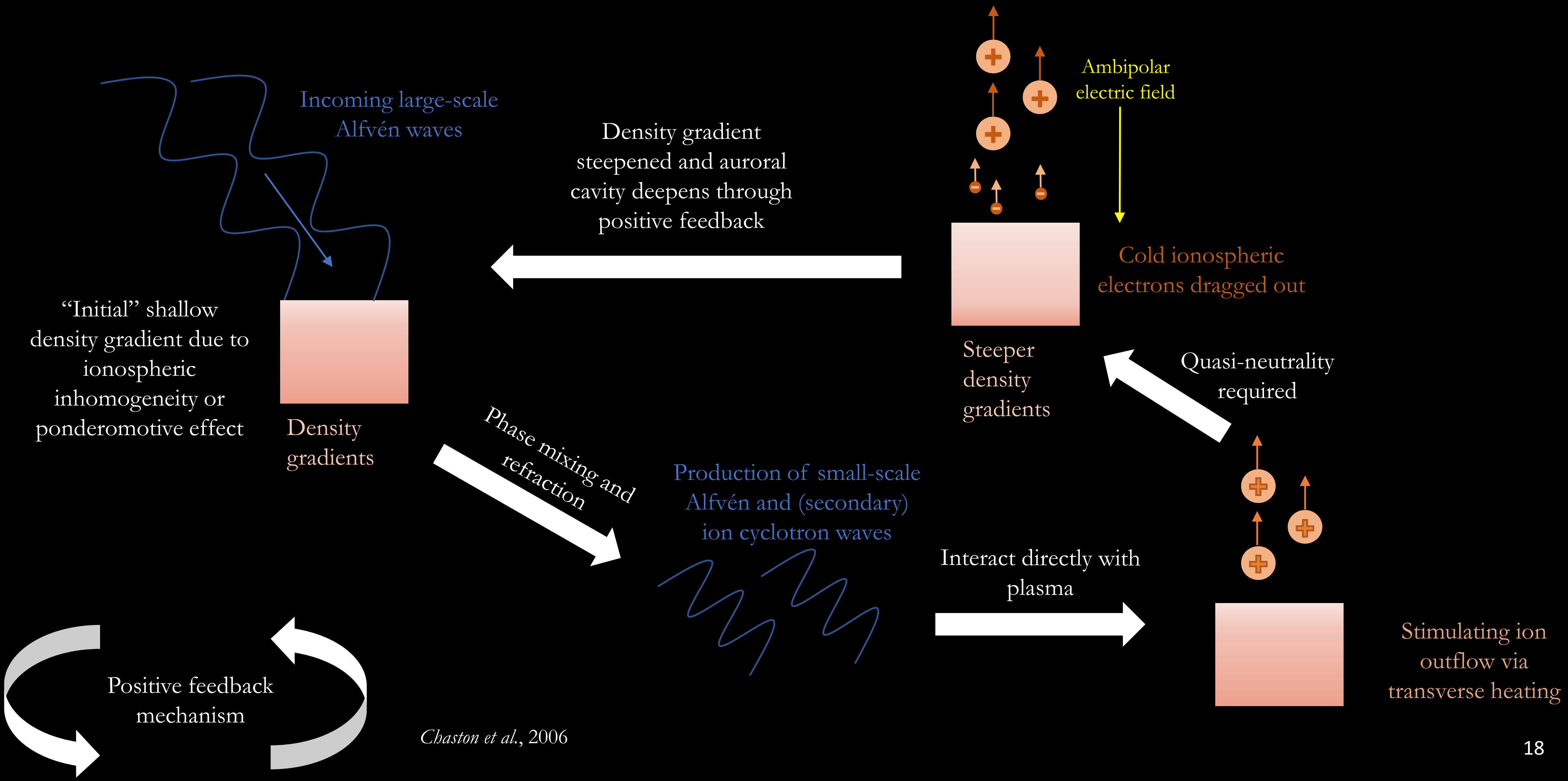
- H^+ energy distributions are peaked and pitch angles are highly collimated along the magnetic field away from Jupiter
- This indicates electrostatic acceleration by electric potentials above Zone-I
- In order to be admitted into potential structures in higher altitudes, ionospheric ions must be energized to above Jupiter's gravitation binding energy
- Presence of upward propagating H^+ and H_3^+ cyclotron waves (ICWs) suggest transverse heating of ionospheric ions which develop a parallel velocity via the action of mirror forces (conservation of the first adiabatic invariant)
- Electrostatic acceleration found to be suppressed when electron broadband acceleration occurs [*Mauk et al.*, 2020]





Ionospheric H^+ accelerated away from Jupiter along auroral field lines. The peak H^+ outflow maps to Zone I [*Szalay et al.*, 2021]

How are auroral density cavities maintained?



Incoming large-scale Alfvén waves

"Initial" shallow density gradient due to ionospheric inhomogeneity or ponderomotive effect

Density gradients

Phase mixing and refraction

Production of small-scale Alfvén and (secondary) ion cyclotron waves

Interact directly with plasma

Stimulating ion outflow via transverse heating

Quasi-neutrality required

Steeper density gradients

Cold ionospheric electrons dragged out

Ambipolar electric field

Density gradient steepened and auroral cavity deepens through positive feedback

Positive feedback mechanism

Chaston et al., 2006

Density depletions above Zone II

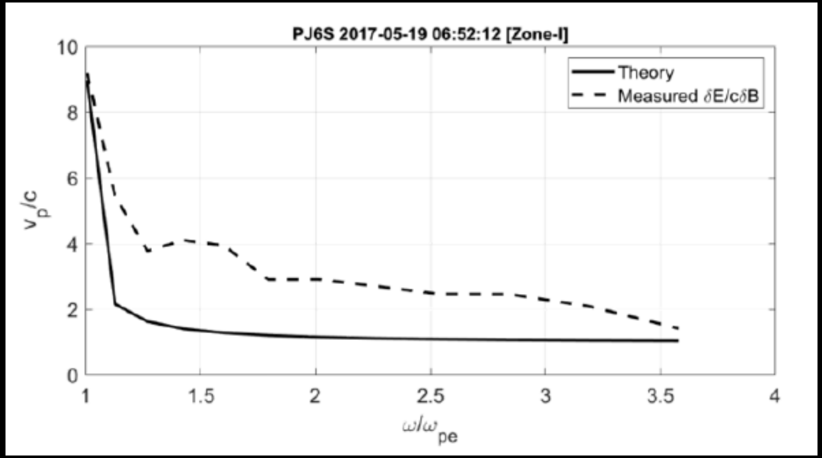
Phase speed of a transverse mode in a cold unmagnetized plasma

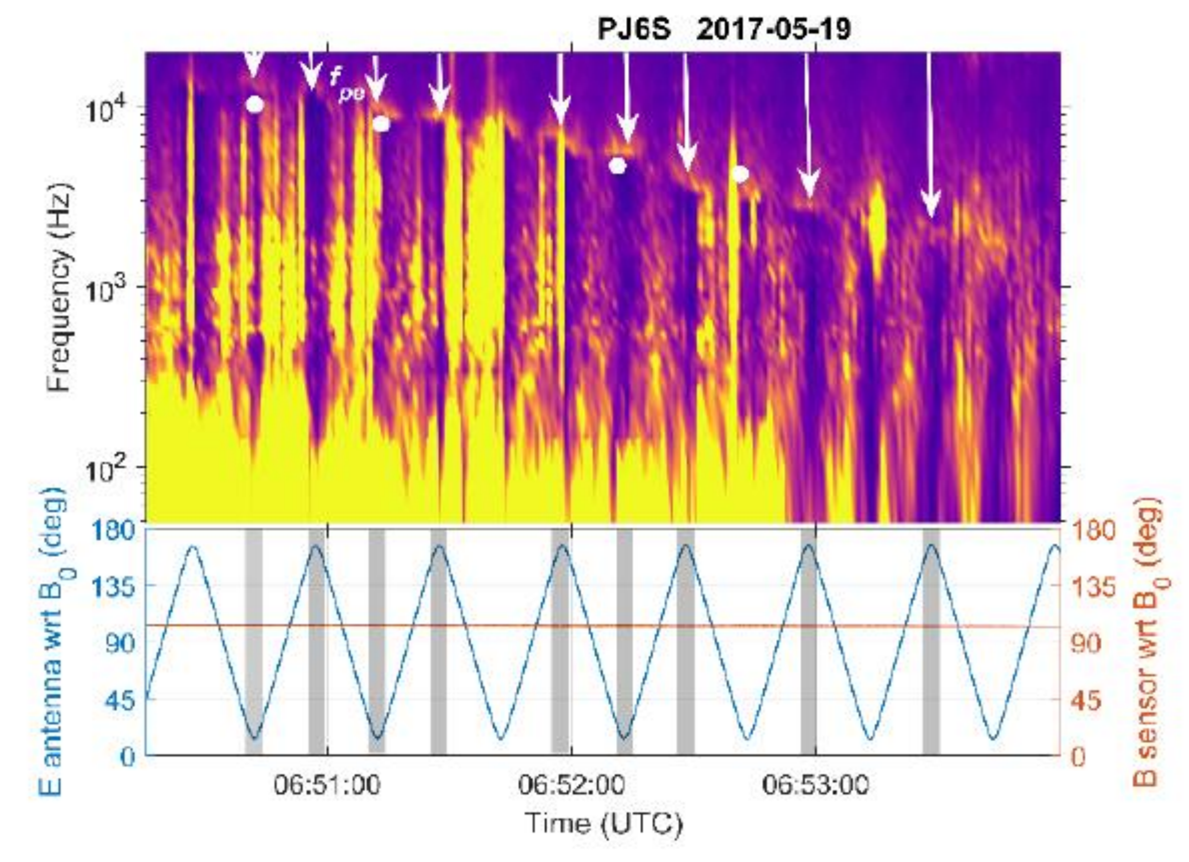
$$v_p = \frac{\omega}{k} = \frac{c}{\sqrt{1 - \frac{\omega_{pe}^2}{\omega^2}}}$$

Phase speed can be related to E and B fluctuations using Fourier's representation of Faraday's law

$$i\boldsymbol{k} \times \tilde{\boldsymbol{E}} = -(-i\omega)\tilde{\boldsymbol{B}}.$$

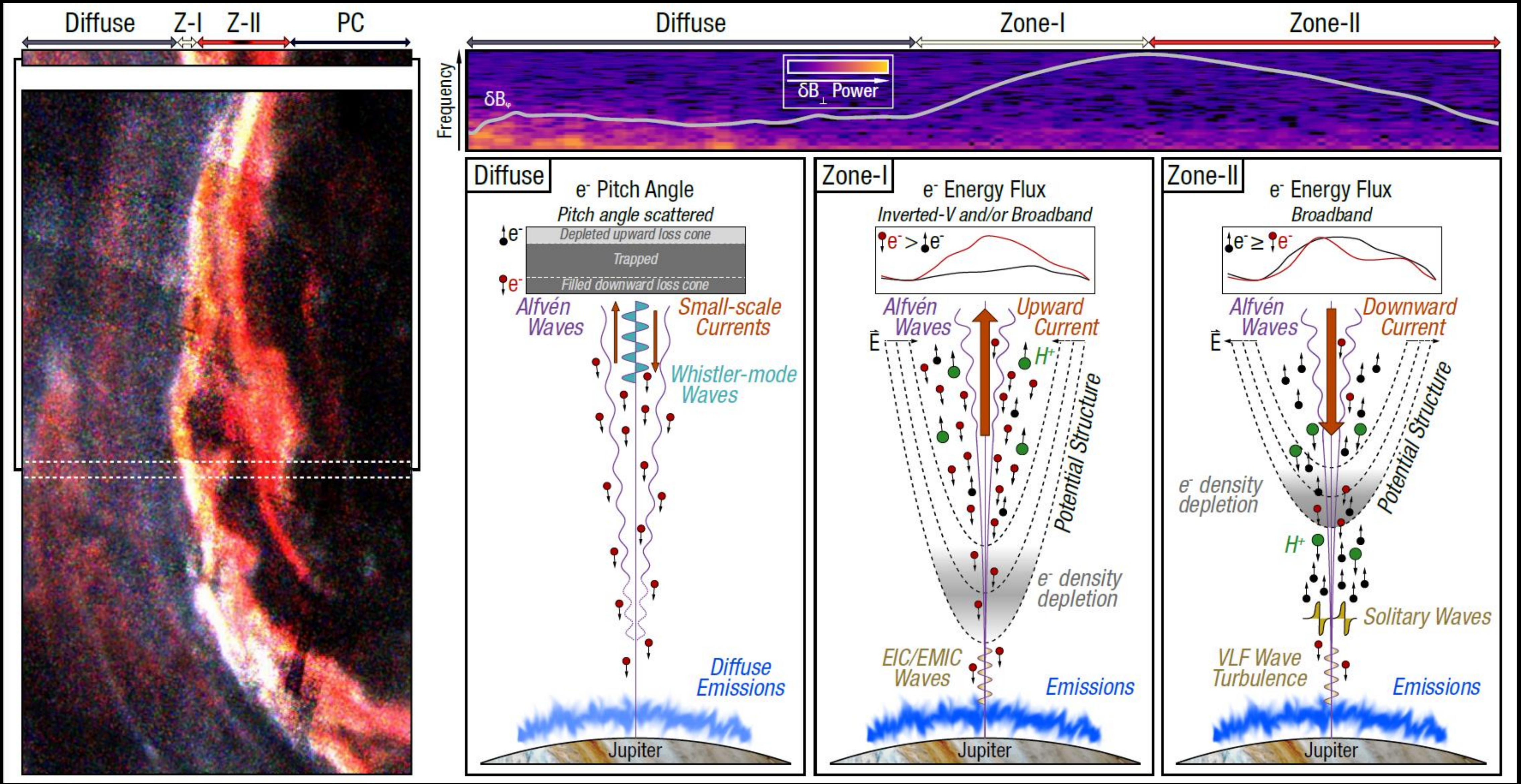
$$v_P = \frac{\omega}{k} = \frac{\tilde{E}_z}{\tilde{B}_y}$$





Sulaiman et al., 2023

Jupiter’s aurora: The present

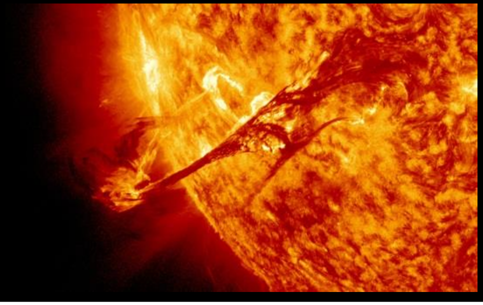


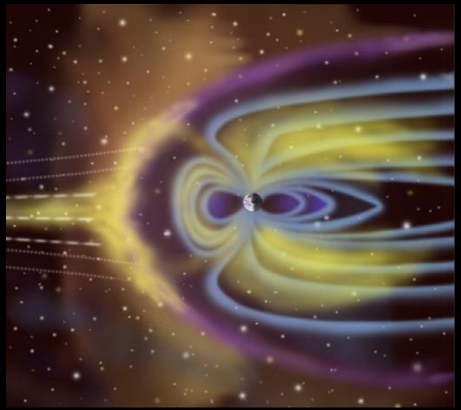
Sulaiman et al., 2022

Shock waves in the Universe

Shock waves

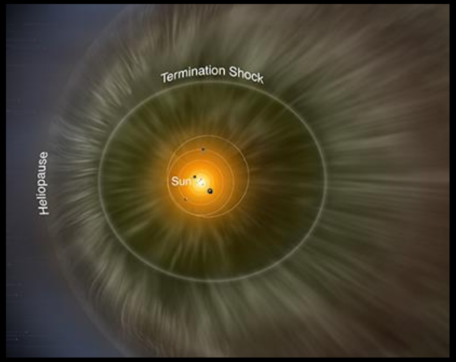
CME/IPS





Planets & Comets

Heliosphere

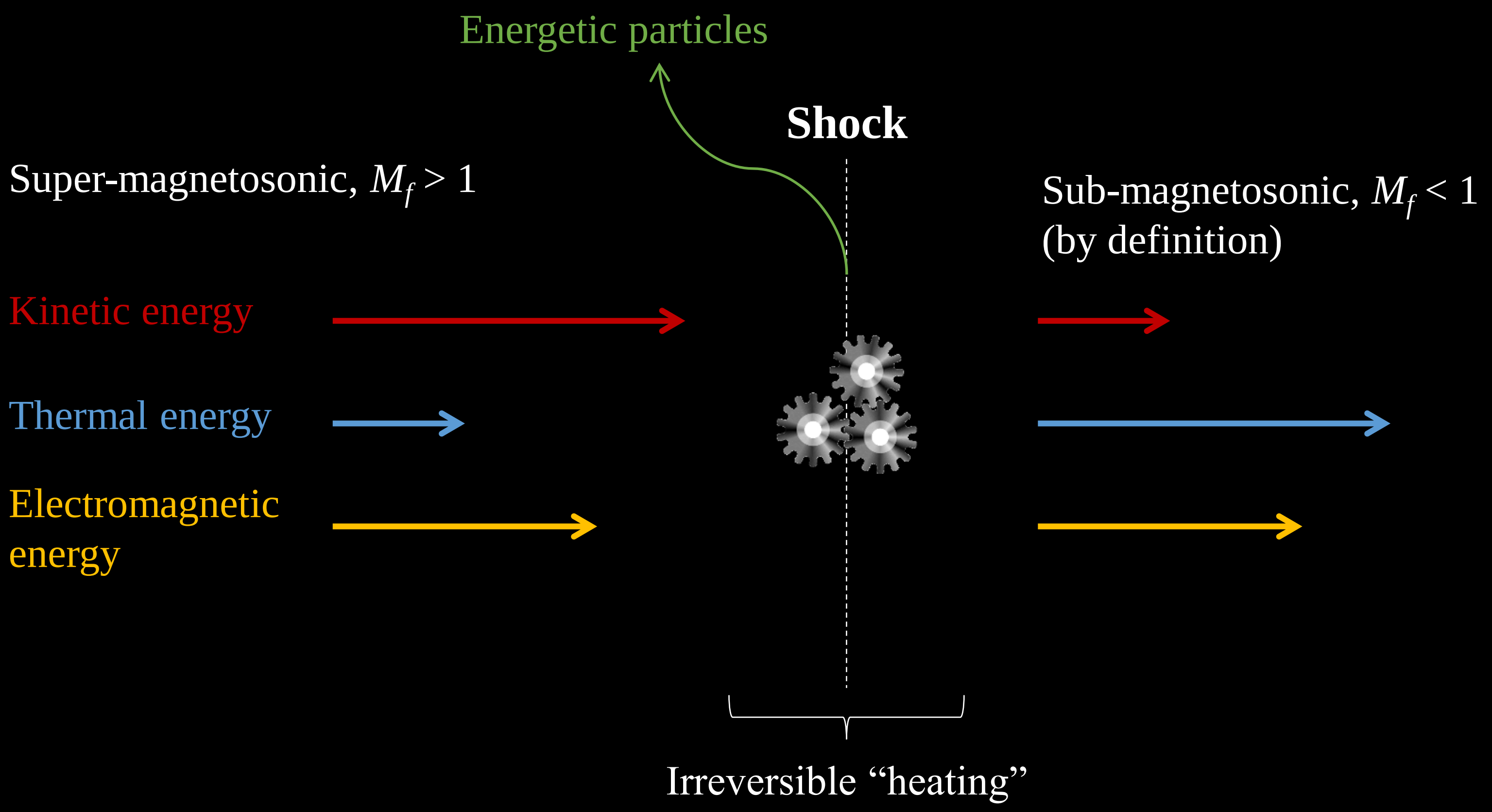


Supernovae

Size & Strength

Heliocentric Distance

Collisionless Shock Waves (Basic Principles)



Energetic particles

Shock

Super-magnetosonic, $M_f > 1$

Sub-magnetosonic, $M_f < 1$
(by definition)

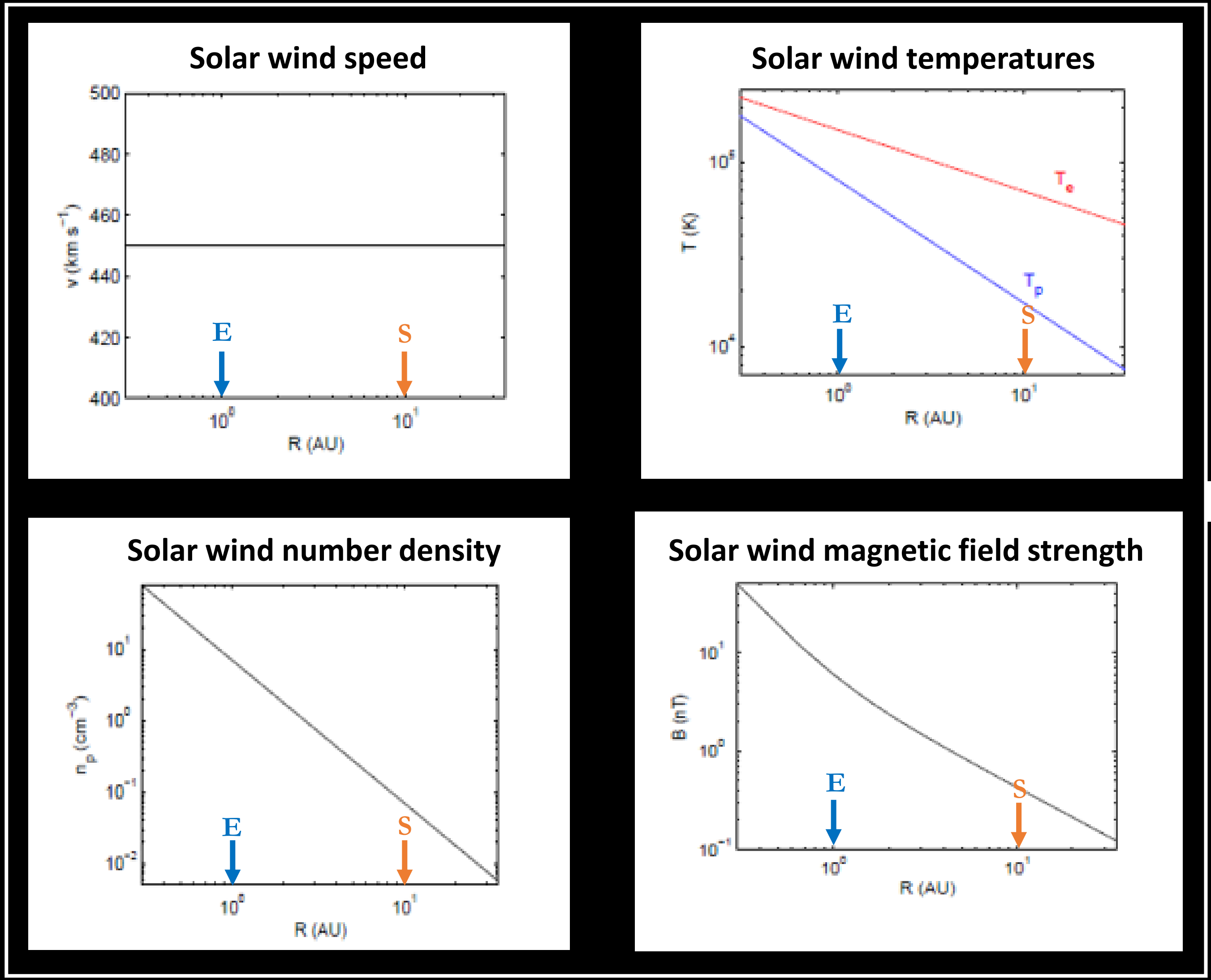
Kinetic energy

Thermal energy

Electromagnetic energy

Irreversible “heating”

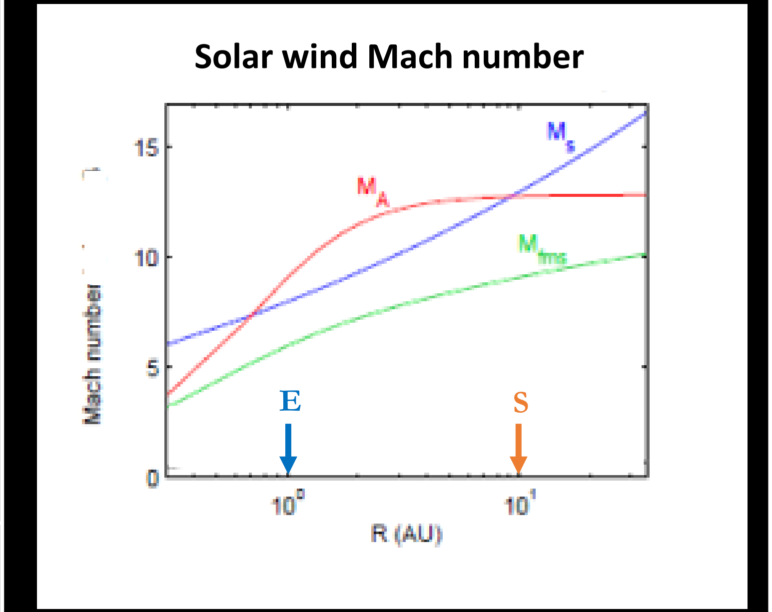
The solar wind conditions near the Gas Giants


Solar wind speed

Solar wind temperatures

Solar wind number density

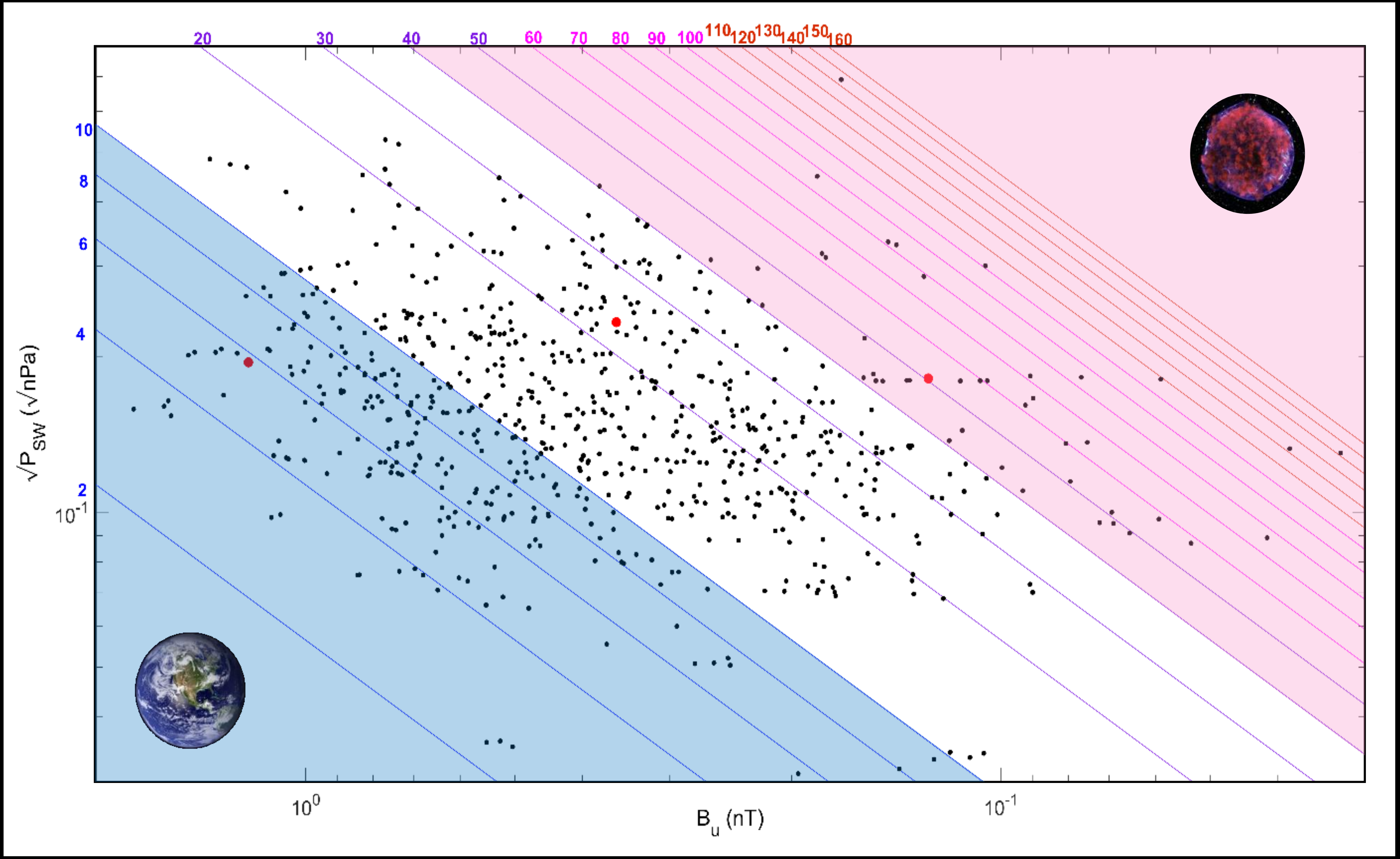
Solar wind magnetic field strength


Solar wind Mach number

$$M \equiv \frac{flow\ speed}{characteristic\ speed}$$

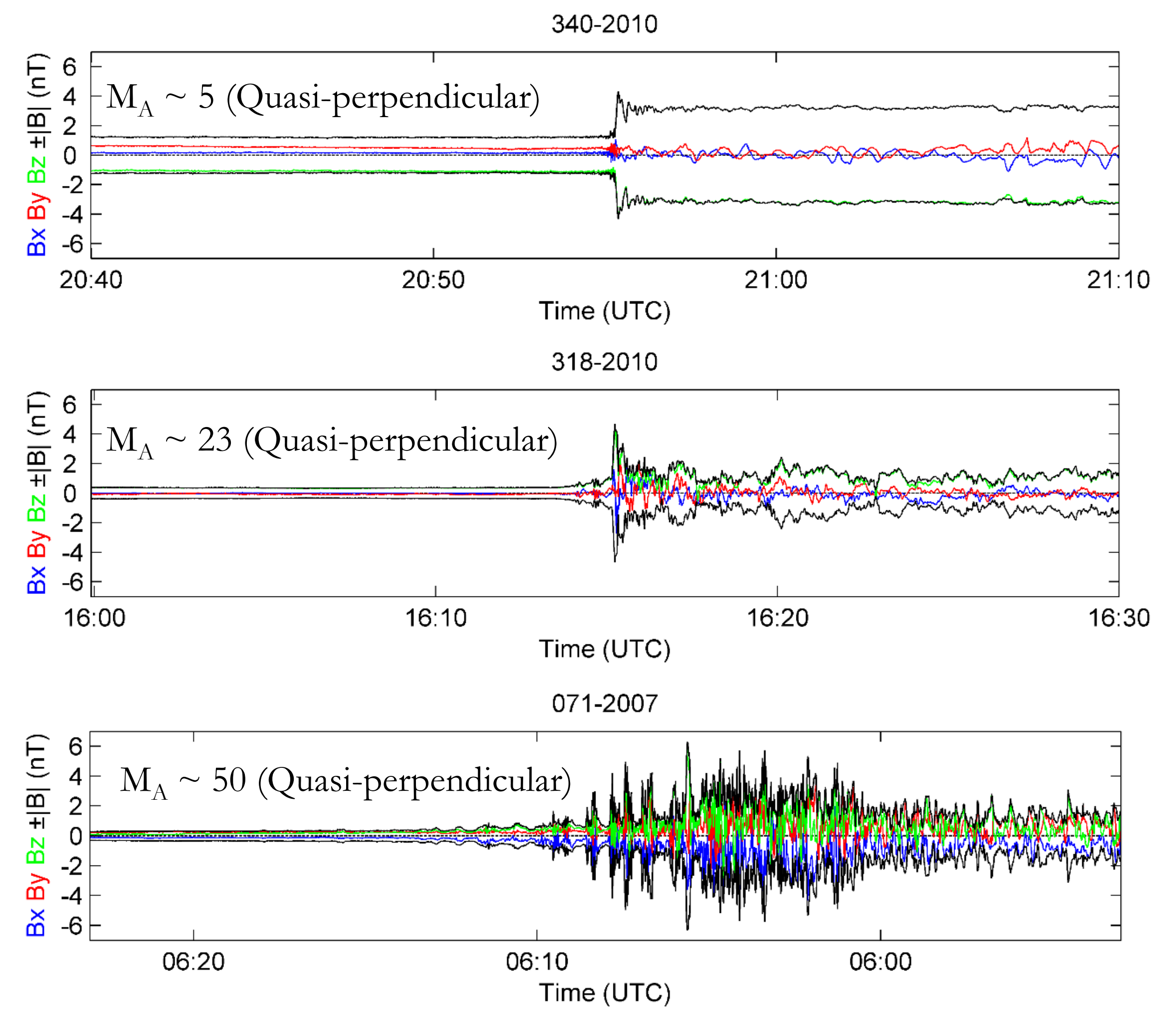
Sulaiman et al. (2017b), *Springer International Publishing*

M_A Parameter Space at Saturn

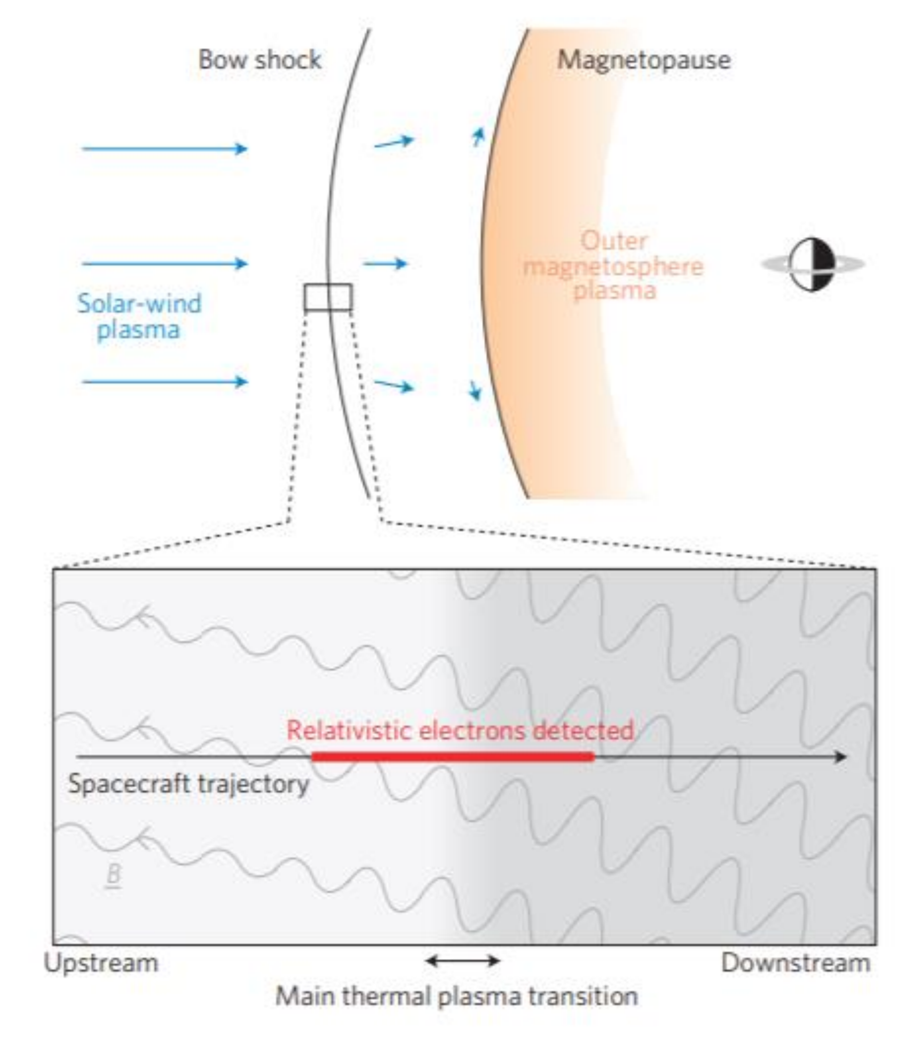


Sulaiman et al. (2016), *J. Geophys. Res.*

M_A Parameter Space at Saturn (cont'd)

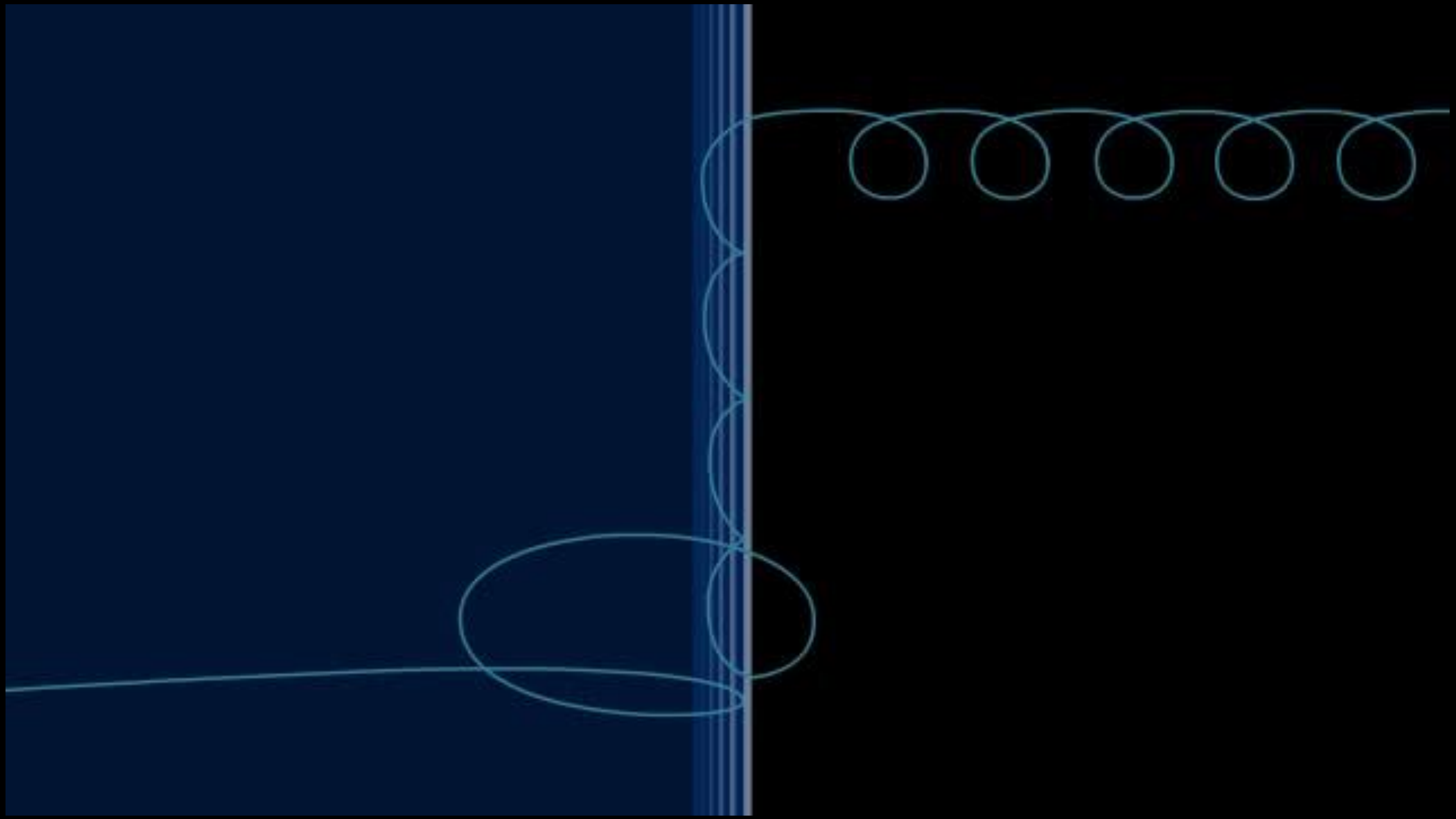


Sulaiman et al. (2015), *Phys. Rev. Lett.*



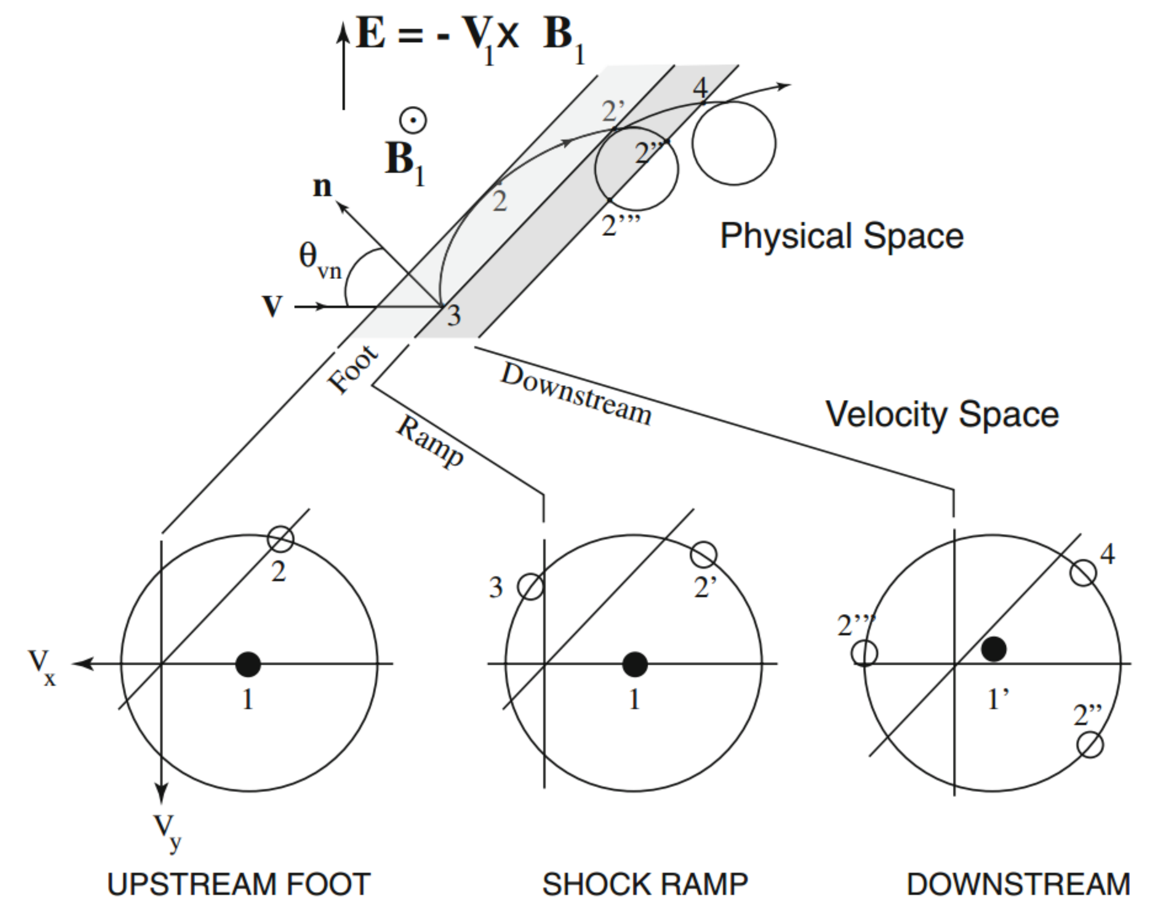
Masters et al. (2013), *Nature Physics*

Ion Reflection



Zank et al., 1996
Credit: ESA

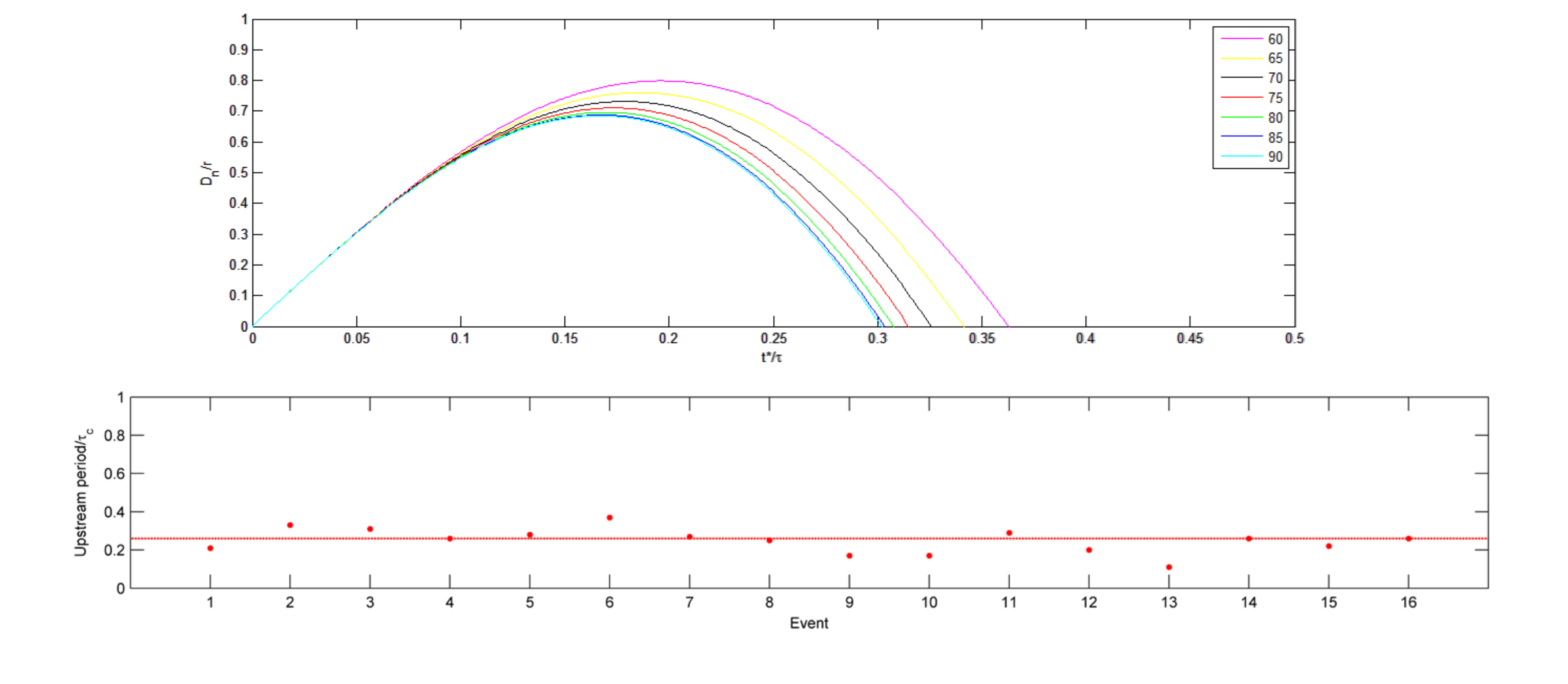
Ion Reflection



Timescale of Specular Reflection

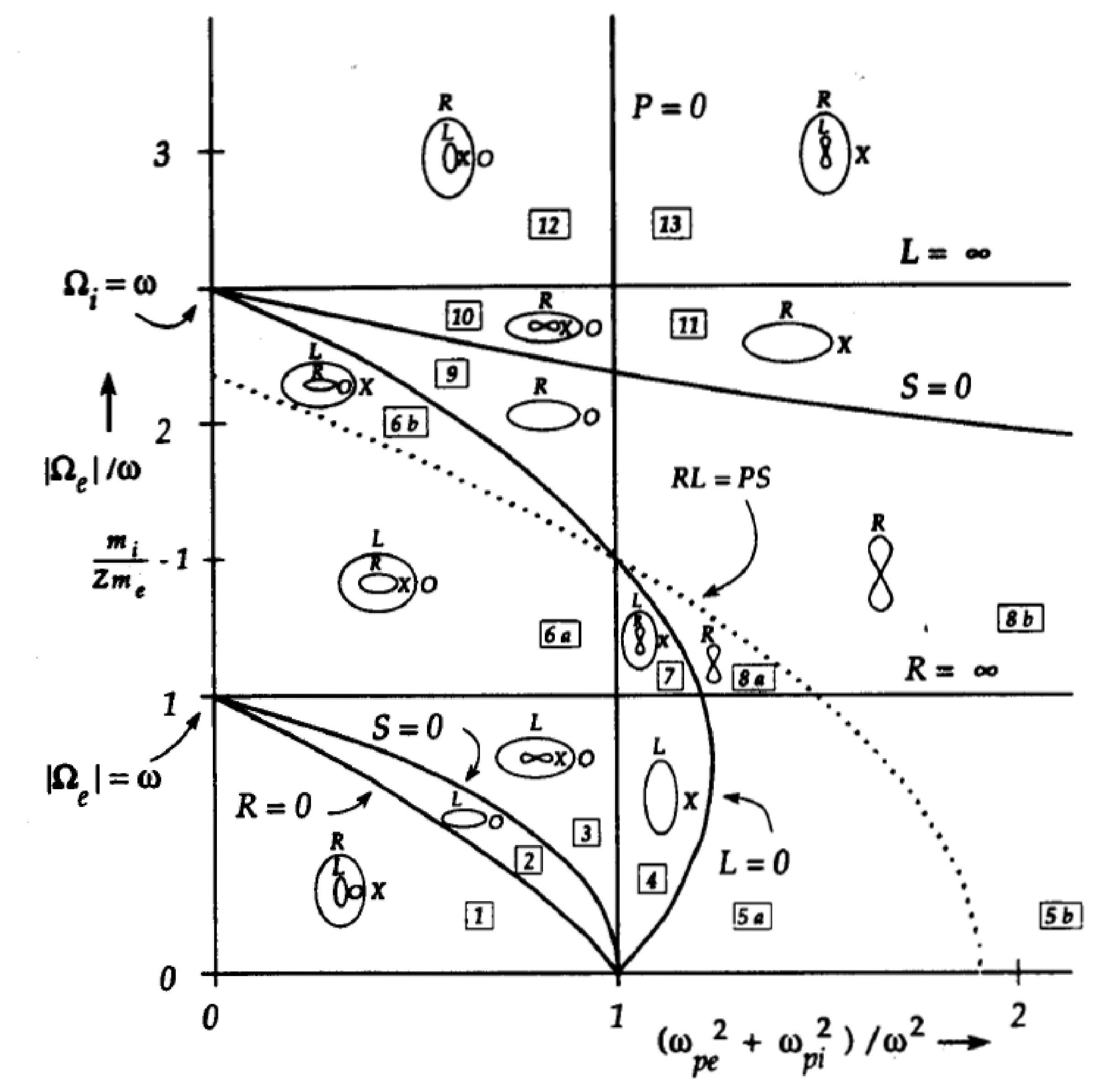
$$(2\cos^2\theta_{Bn} - 1)\frac{2\pi}{\tau}t^* + 2\sin^2\theta_{Bn}\sin\left(\frac{2\pi}{\tau}t^*\right) = 0$$

- *t** is the time of first re-encounter with the shock after specular reflection
- Solving numerically, for t*



Thank you!

CMA Diagram



$P = 0$
R
L
X
O
12
13
$L = \infty$
$\Omega_i = \omega$
10
11
9
6b
$S = 0$
$|\Omega_e|/\omega$
$RL = PS$
$\frac{m_i}{Zm_e} - 1$
6a
7
8a
8b
$R = \infty$
$S = 0$
$|\Omega_e| = \omega$
$R = 0$
$L = 0$
1
2
3
4
5a
5b
0
1
2
3
0
1
2
$(\omega_{pe}^2 + \omega_{pi}^2)/\omega^2$ →