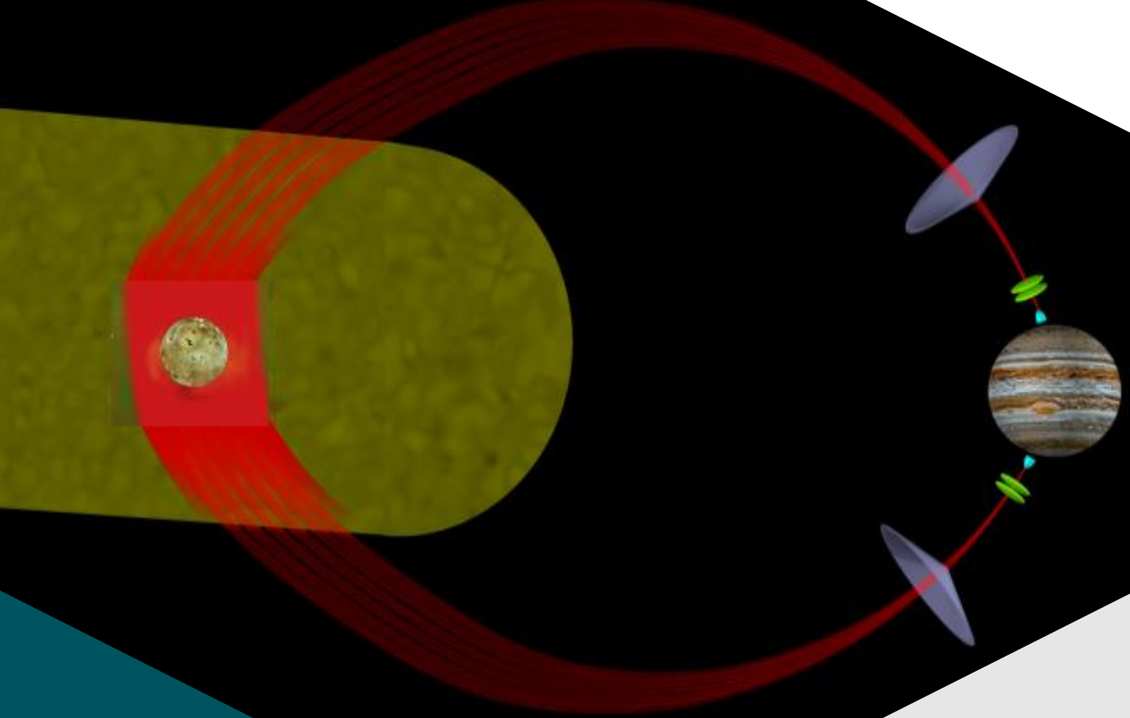
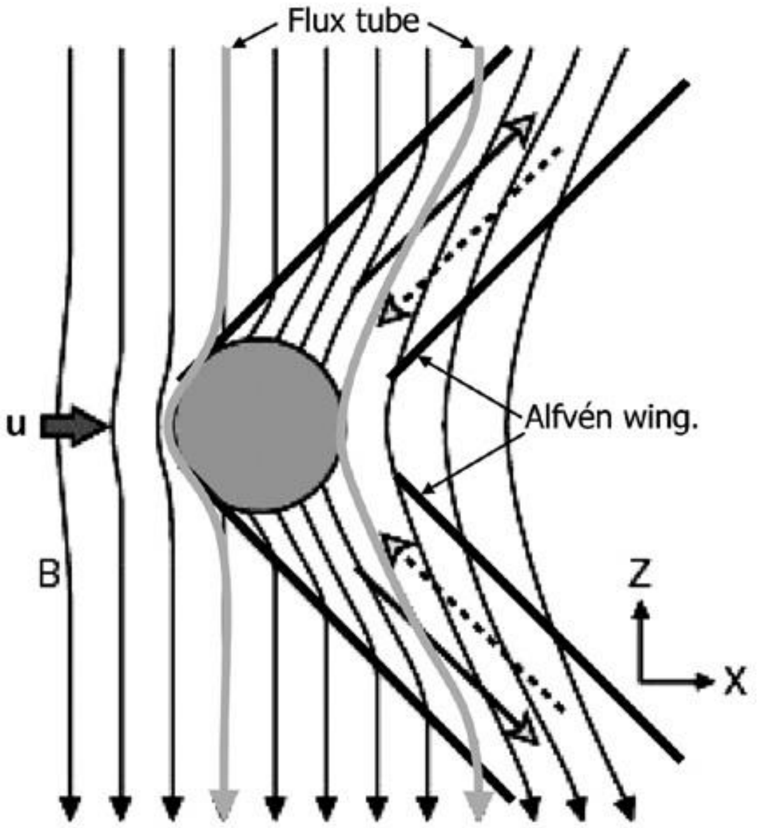


Alfvén waves related to moon-magnetosphere interactions

Bertrand Bonfond and Ali Sulaiman

Take home message 1

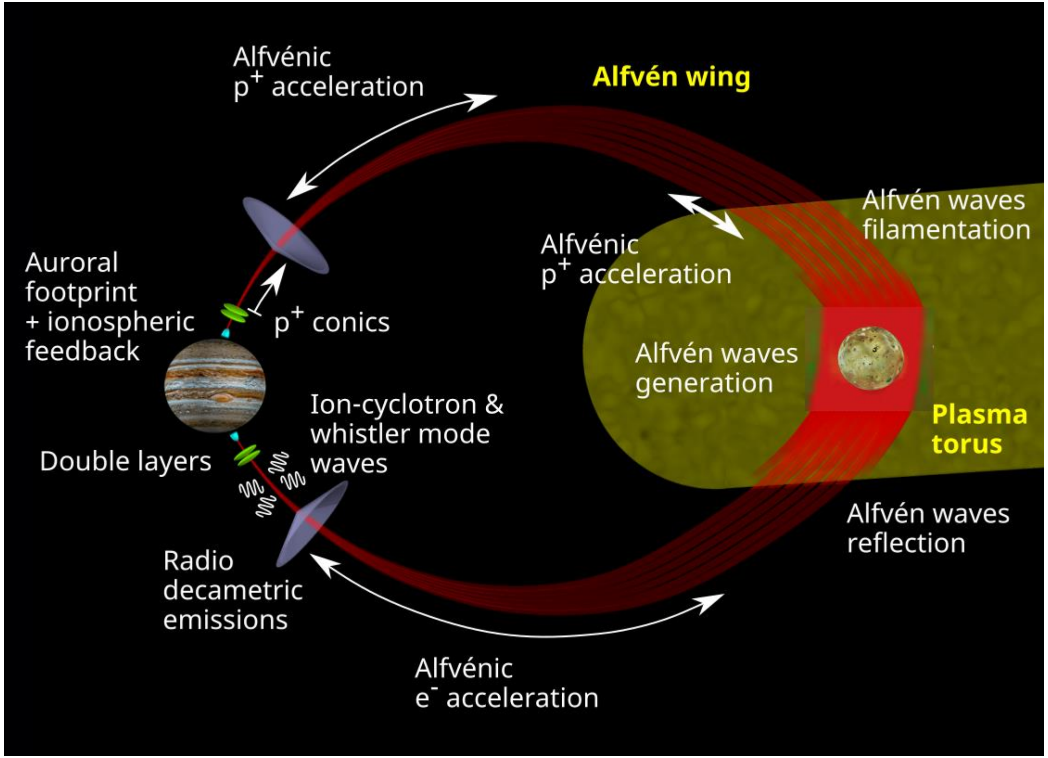
- The obstacle formed by a moon (or a planet) in a plasma flow can generate powerful Alfvén waves propagating along the field lines.



Kivelson et al. 2004

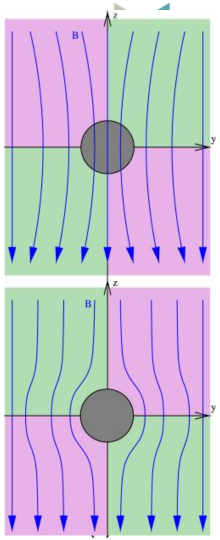
Take home message 2

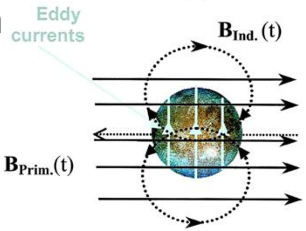
- On their path to the parent planet, these waves trigger a wealth of intriguing phenomena.

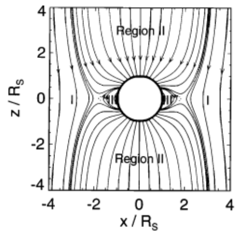


Large moons form obstacles to the plasma flow

- Obstacle formed by the moon
  - Mechanical obstacle
    - Inert body
    - Mass loading /conductive body
  - Electromagnetic obstacle
    - Induced magnetic field
      - Subsurface ocean
      - Ionosphere
      - Astenosphere
    - Intrinsic magnetic field



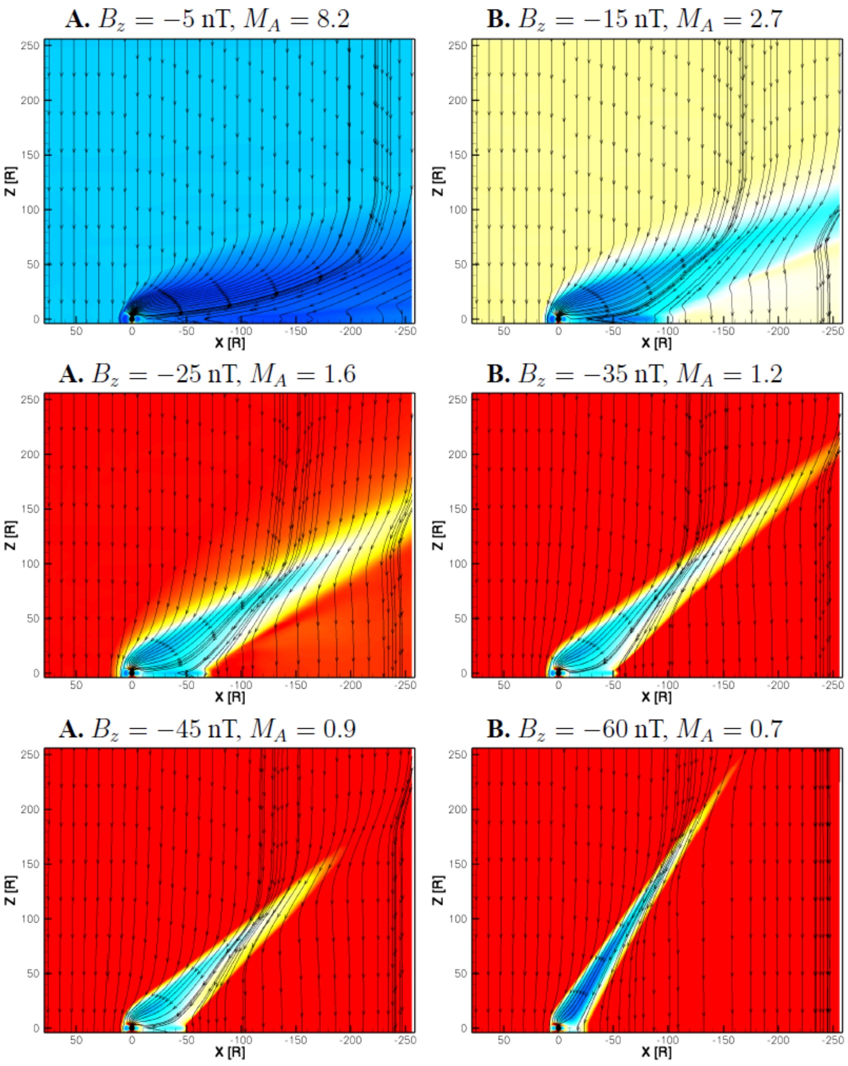




Inspired by Saur et al. 2021/Simon et al. 2015/Jia et al. 2009

A smooth transition

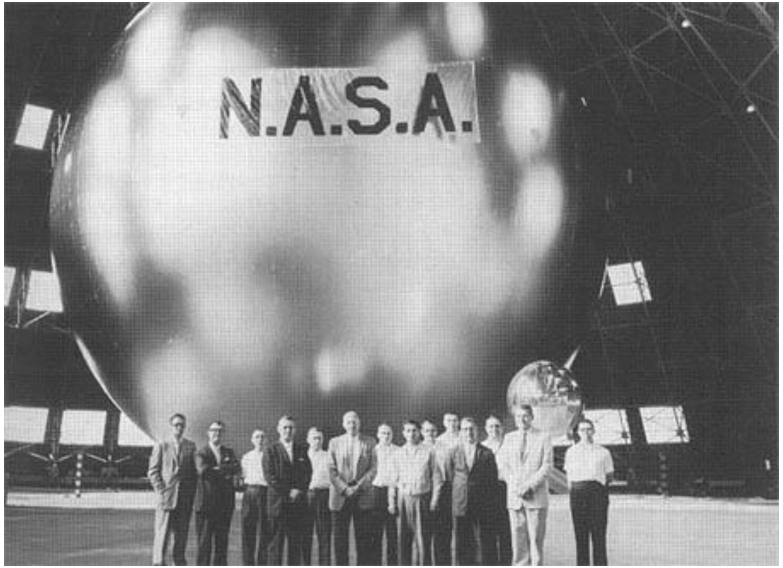
- As the Alfvén Mach number decreases, the interaction region transitions from a magnetosheath into Alfvén wings



Ridley 2007

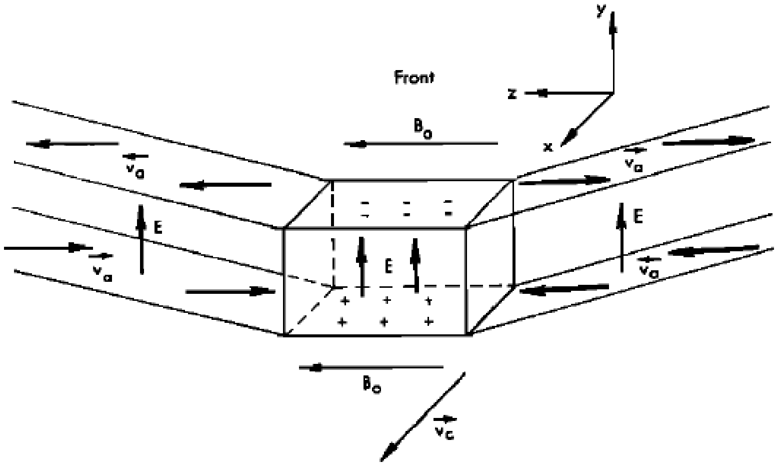
History of the moon-magnetosphere interactions

- Io controlled radio emissions (Bigg 1964)
- Echo 1 and the invention of Alfvén wings (Drell et al. 1965)
- The unipolar inductor model (Goldreich and Lynden-Bell 1969)



History of the moon-magnetosphere interactions

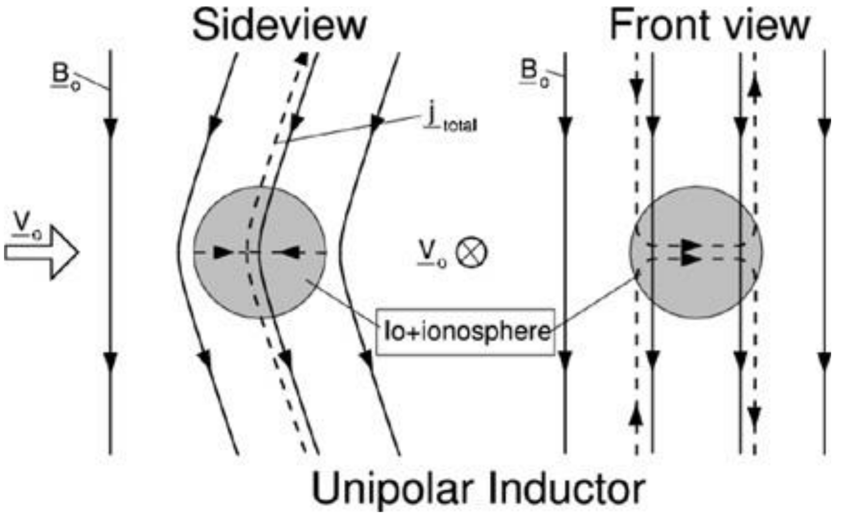
- Io controlled radio emissions (Bigg 1964)
- Echo 1 and the invention of Alfvén wings (Drell 1965)
- The unipolar inductor model (Goldreich and Lynden-Bell 1969)



Drell 1965

History of the moon-magnetosphere interactions

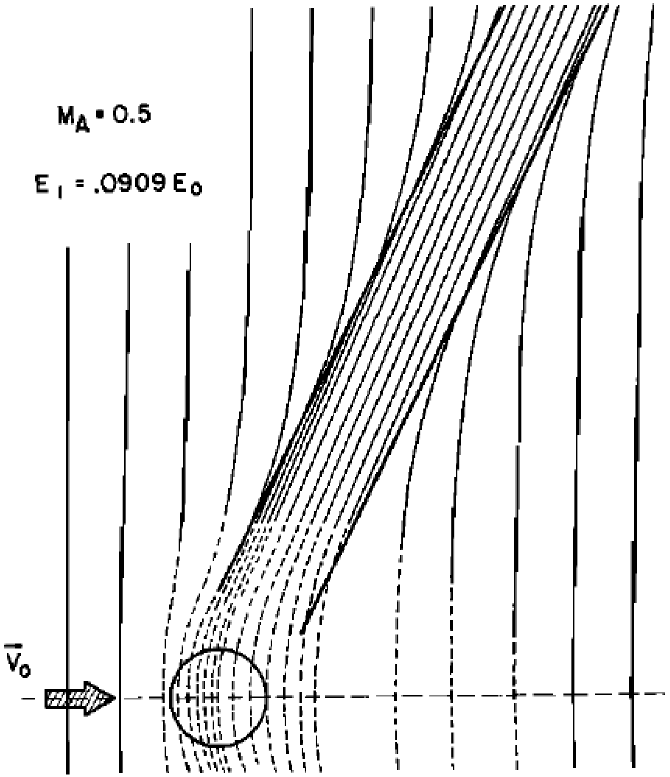
- Io controlled radio emissions (Bigg 1964)
- Echo 1 and the invention of Alfvén wings (Drell et al. 1965)
- The unipolar inductor model (Goldreich and Lynden-Bell 1969)



Saur et al. 2004

History of the moon-magnetosphere interactions

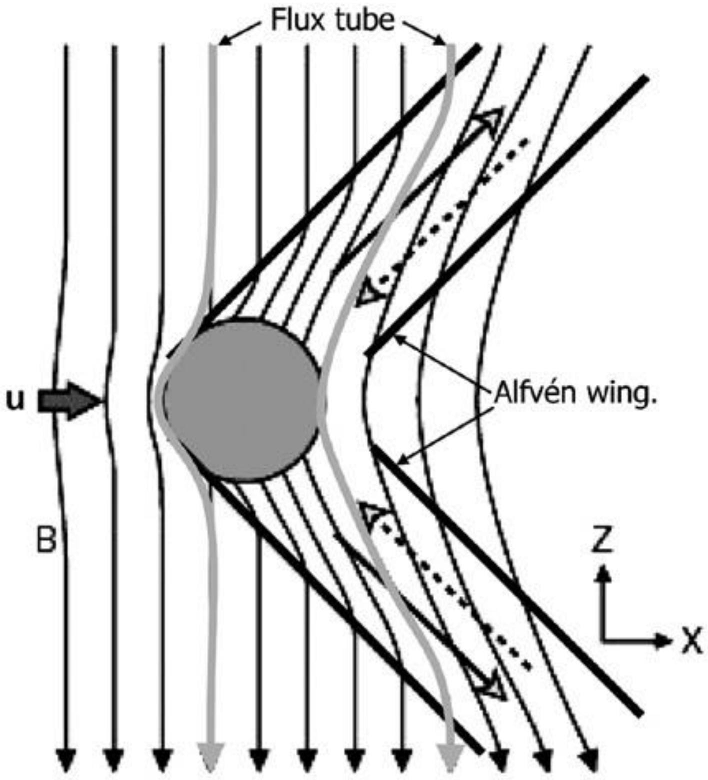
- Voyager probes: Io plasma torus => ideal Alfvén wings model (Neubauer 1980)
  - Possibility for reflections
- Galileo: stagnant wake downstream of Io => the return of the unipolar inductor



Neubauer 1980

History of the moon-magnetosphere interactions

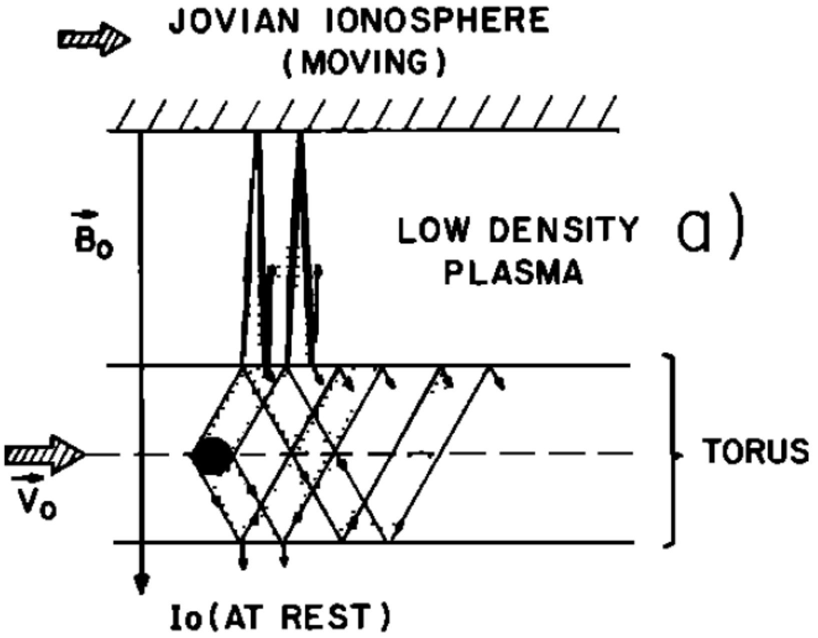
- Voyager probes: Io plasma torus => ideal Alfvén wings model (Neubauer 1980)
  - Possibility for reflections
- Galileo: stagnant wake downstream of Io => the return of the unipolar inductor



Kivelson et al. 2004

History of the moon-magnetosphere interactions

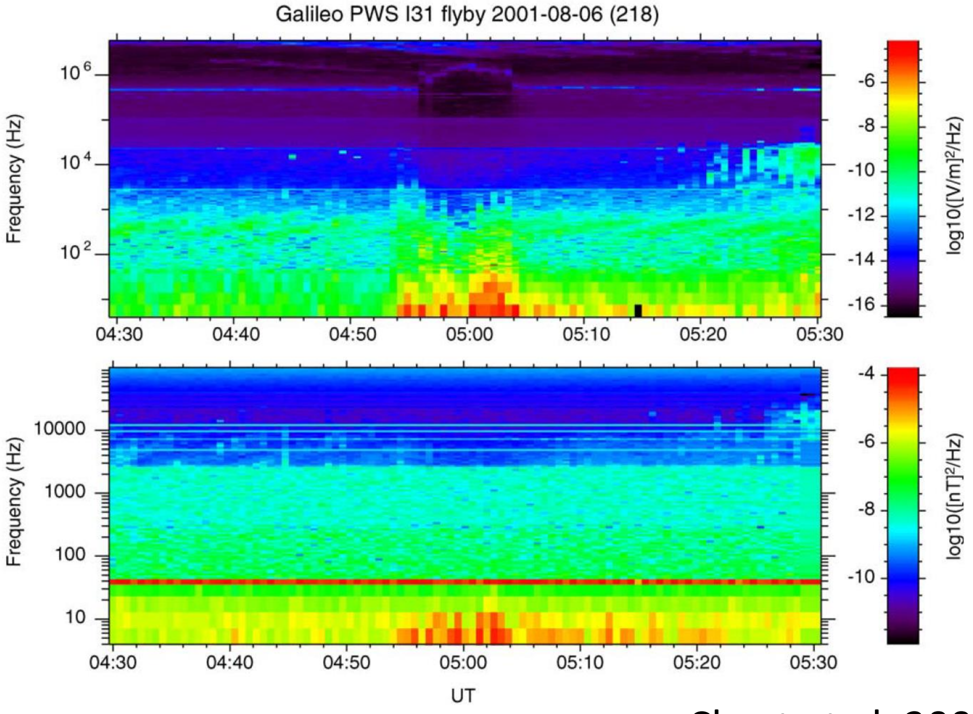
- Voyager probes: Io plasma torus => ideal Alfvén wings model (Neubauer et al. 1980)
  - Possibility for reflections
- Galileo: stagnant wake downstream of Io => the return of the unipolar inductor



Neubauer 1980

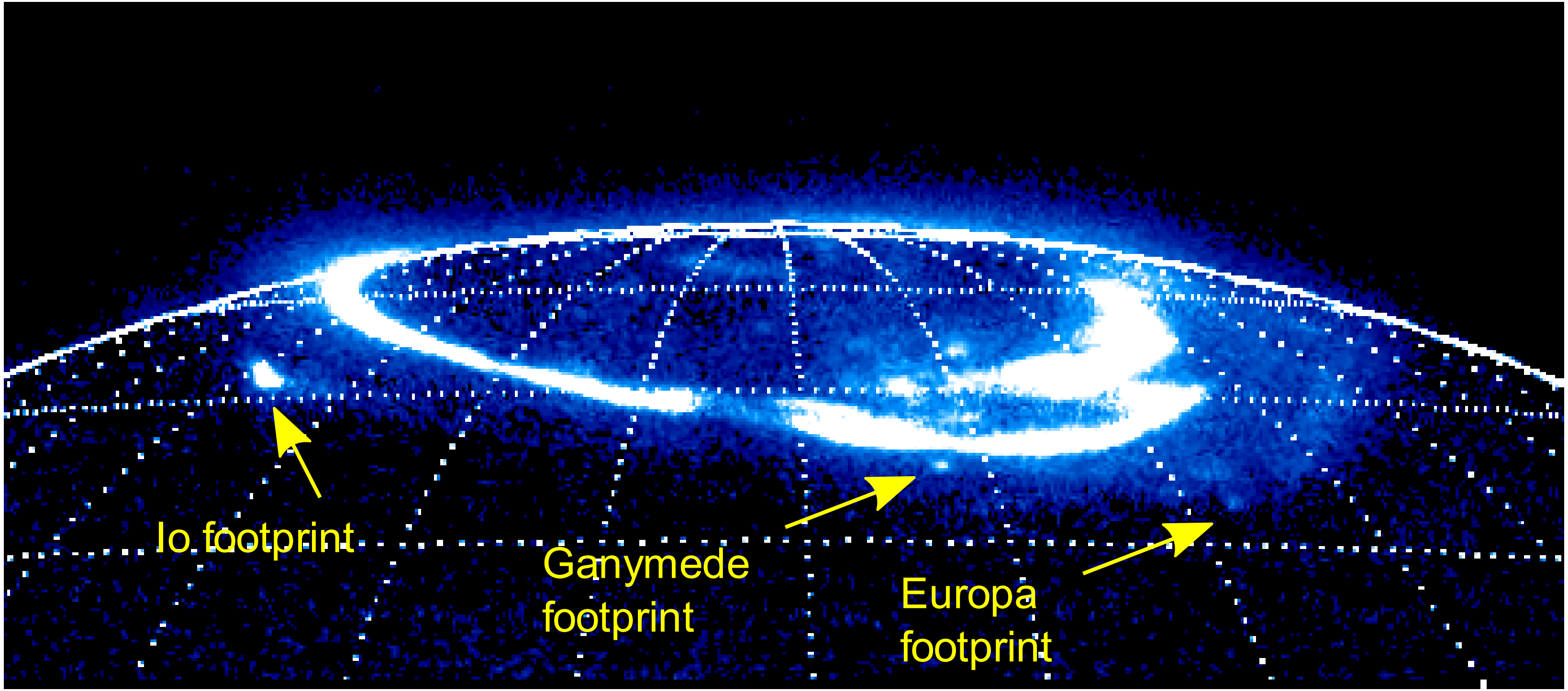
Alfvén waves filamentation

- Galileo observed fast fluctuations of the electric and magnetic fields during the Alfvén wings crossing
- Interpreted as signatures of the turbulent filamentation of the AW (Chust et al. 2005)
- This filamentation is necessary for energy to cross the torus density gradient (Hess et al. 2010, 2013, Sulaiman et al. 2023).



Chust et al. 2005

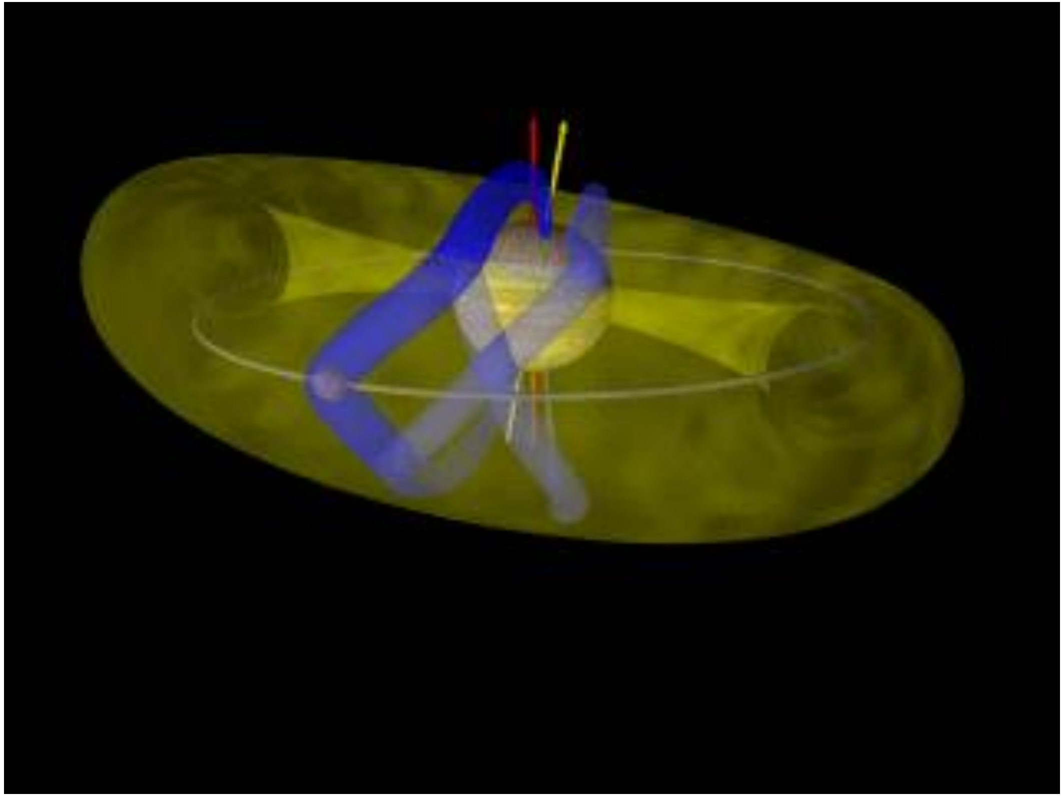
The satellite footprints



Bonfond 2012

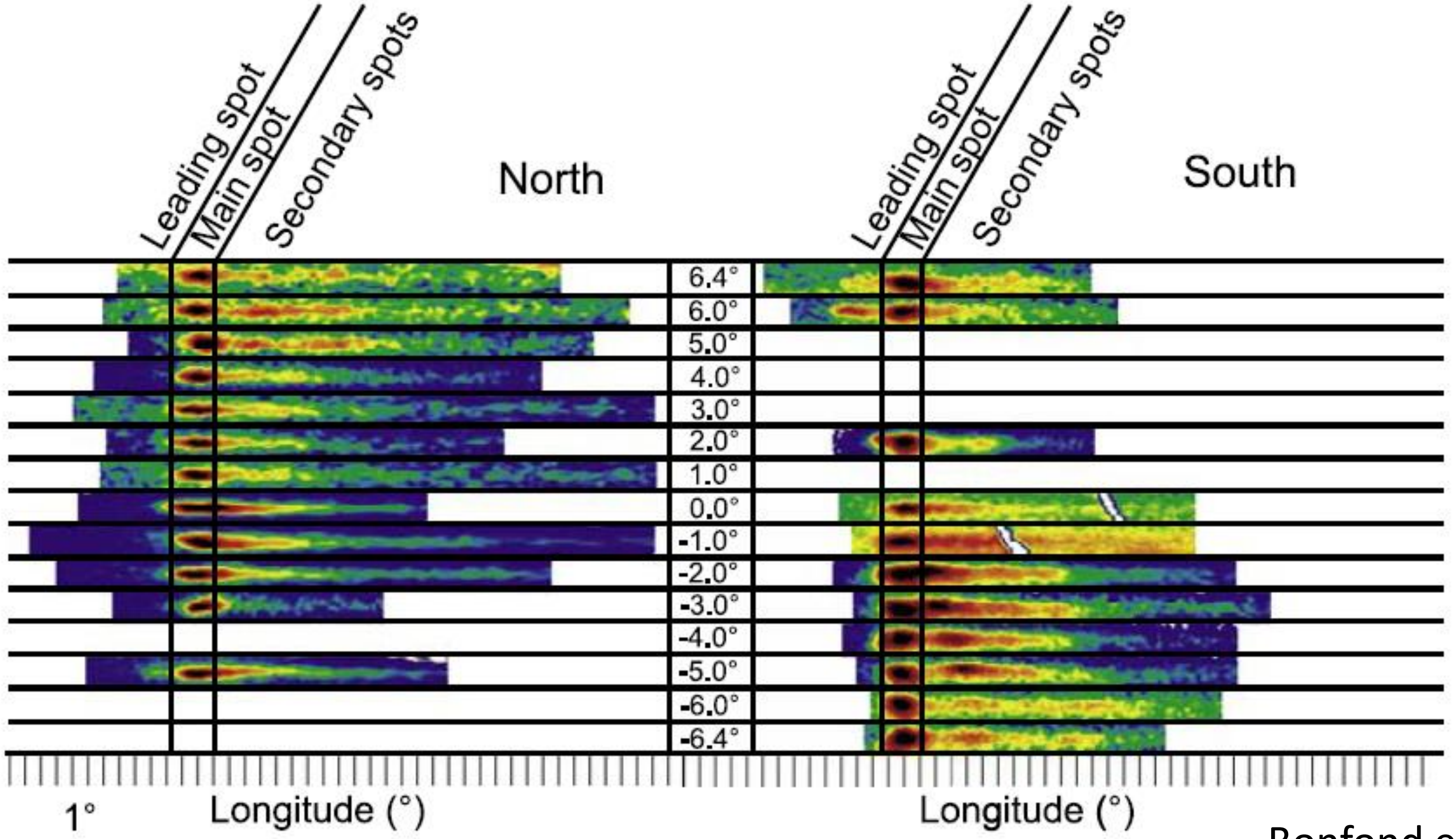
Io in the plasma torus

- Io moves across the torus because of the tilt of the Jovian magnetic field.
- The AW reflection pattern evolves with time.



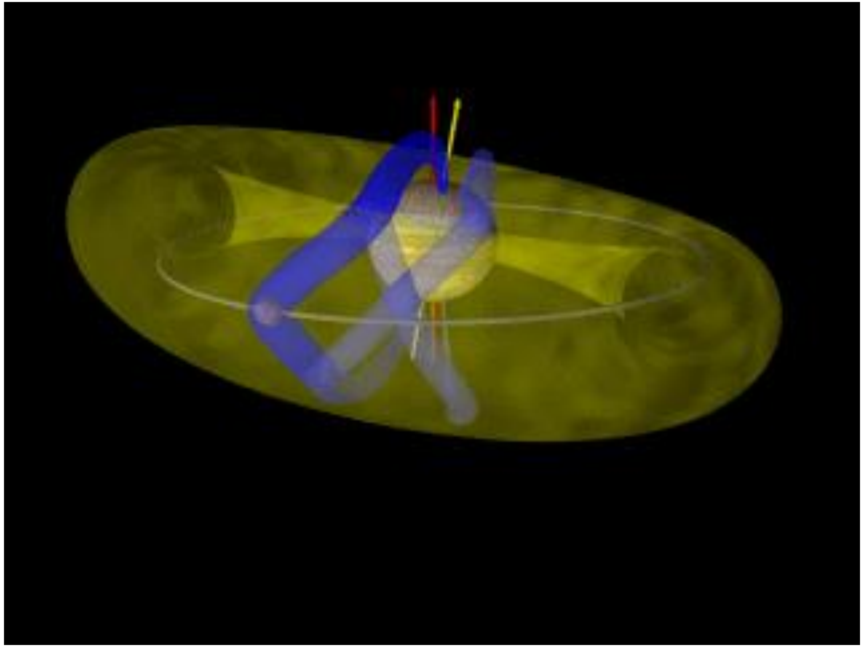
Bonfond et al. 2013

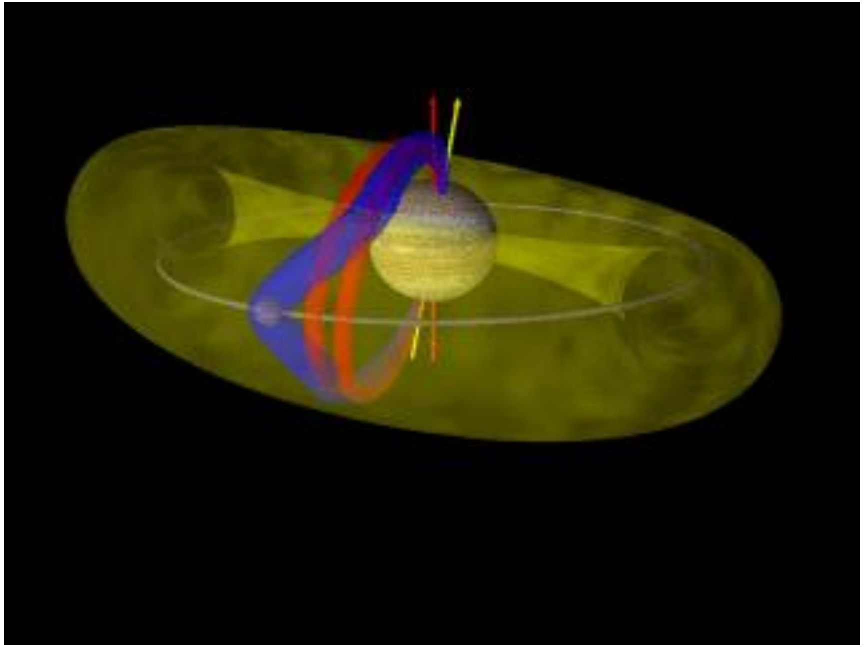
The Io footprint



Bonfond et al. 2008

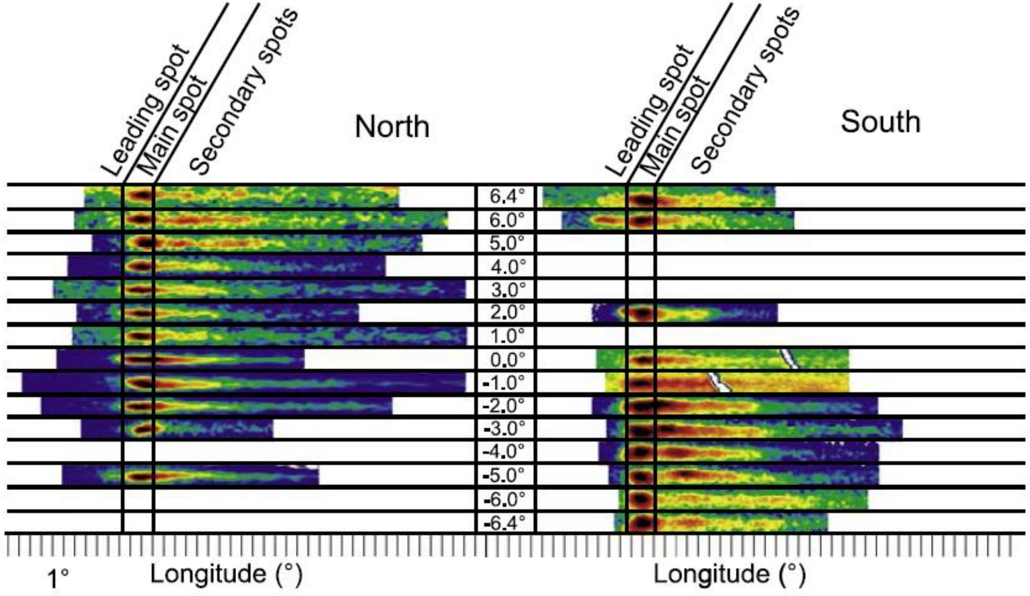
Transhemispheric electron beams

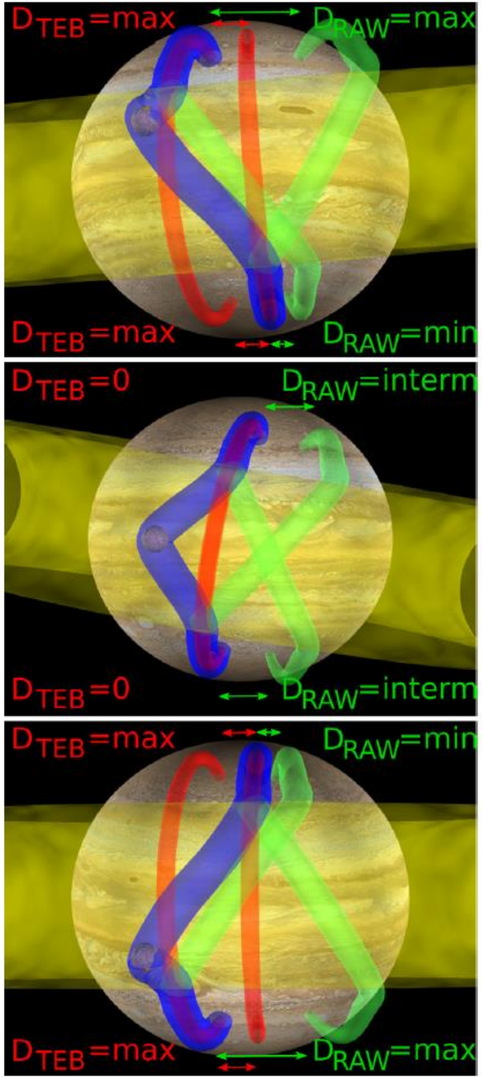




Bonfond et al. 2013

The Io footprint

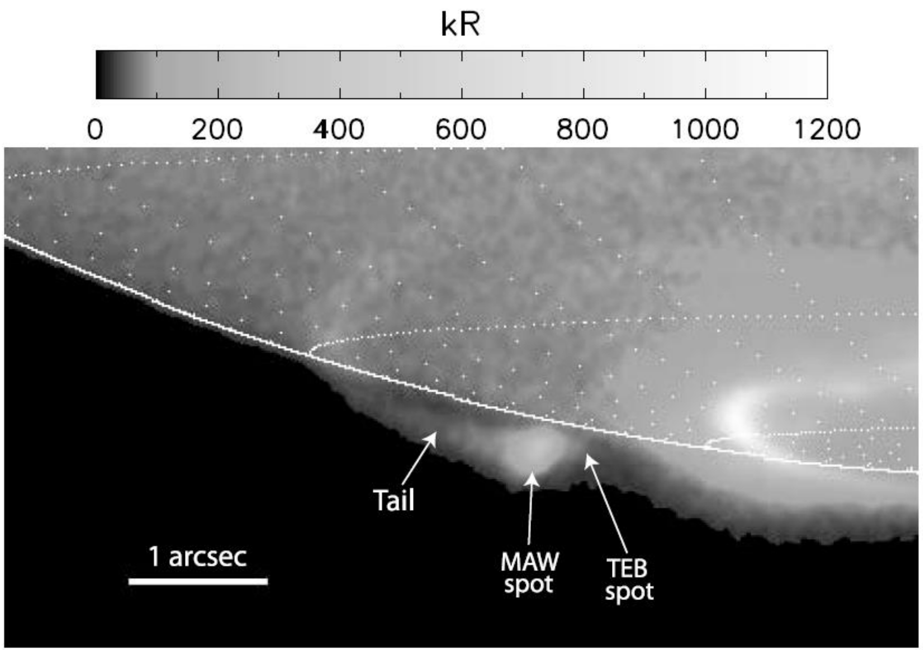




Bonfond et al. 2013

Energy distribution

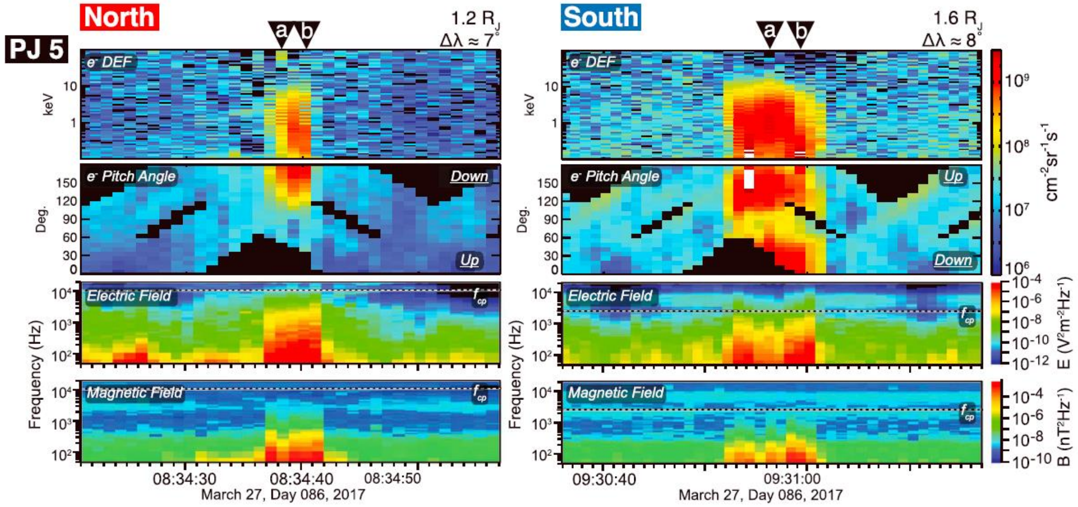
- Only a broadband energy distribution can explain the auroral vertical profile.



Bonfond et al. 2009

Particle and field measurements

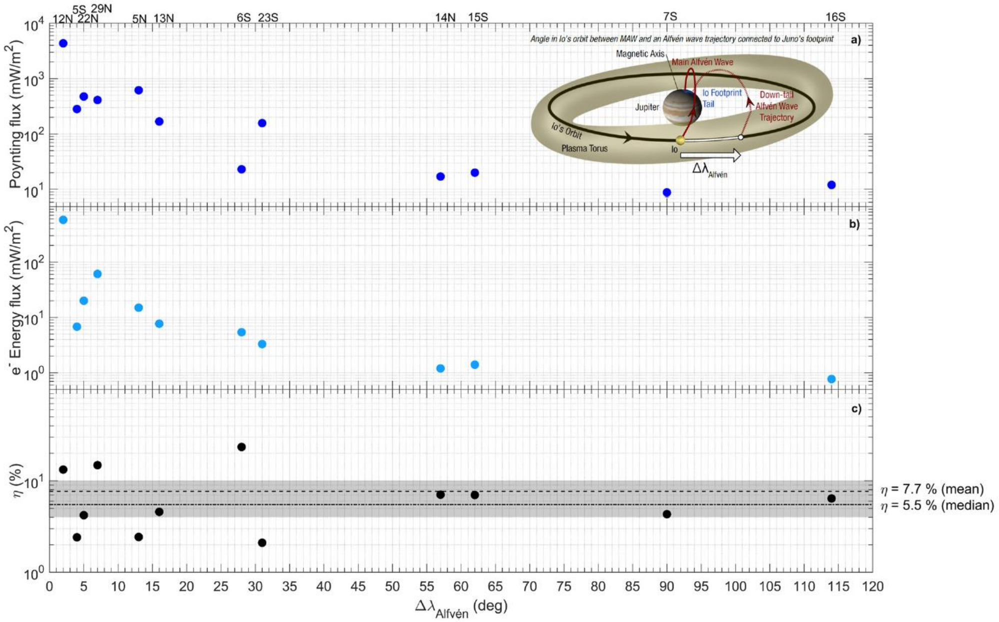
- The Juno crossings of the Io footprint confirmed the broadband distribution and the presence of Alfvén waves



Szalay et al. 2018

Alfvén waves, particle fluxes and turbulence

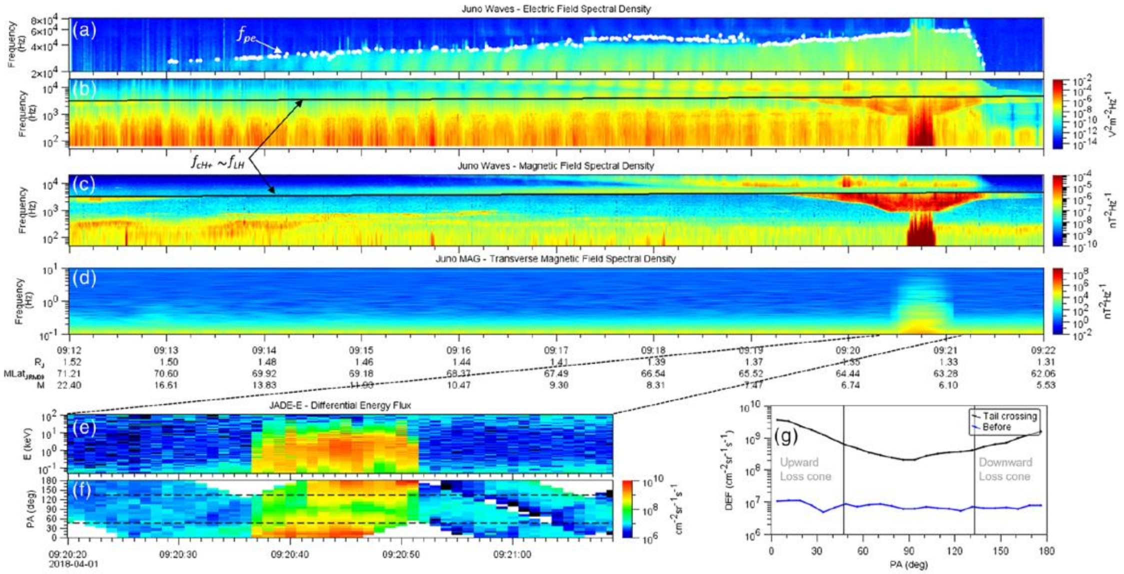
- The AW Poynting fluxes and the particle energy fluxes are well correlated.
- The efficiency (~10%) is consistent with AW filamentation via a turbulent cascade.



Sulaiman et al. 2022

Auroral hiss over the Io footprint

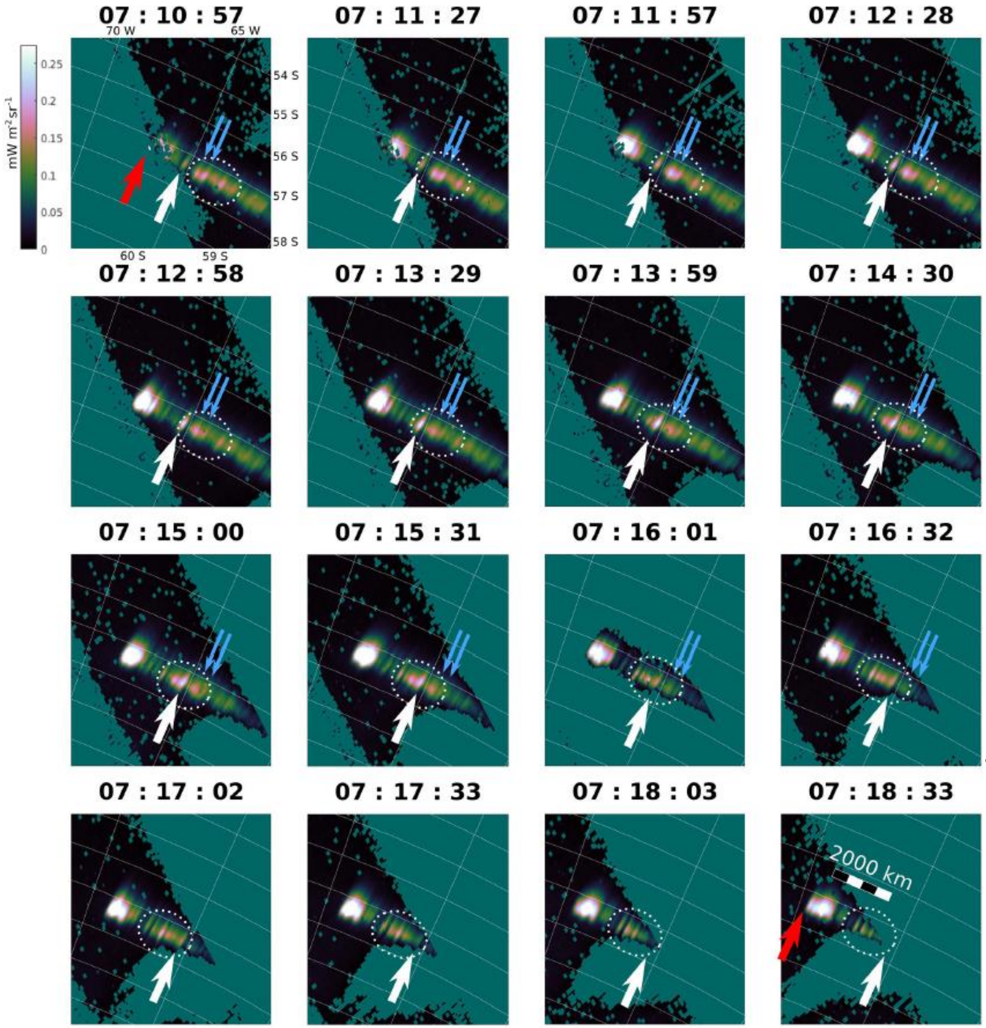
- Intense ion-cyclotron and whistler mode waves related to the accelerated ions and electrons



Sulaiman et al. 2020

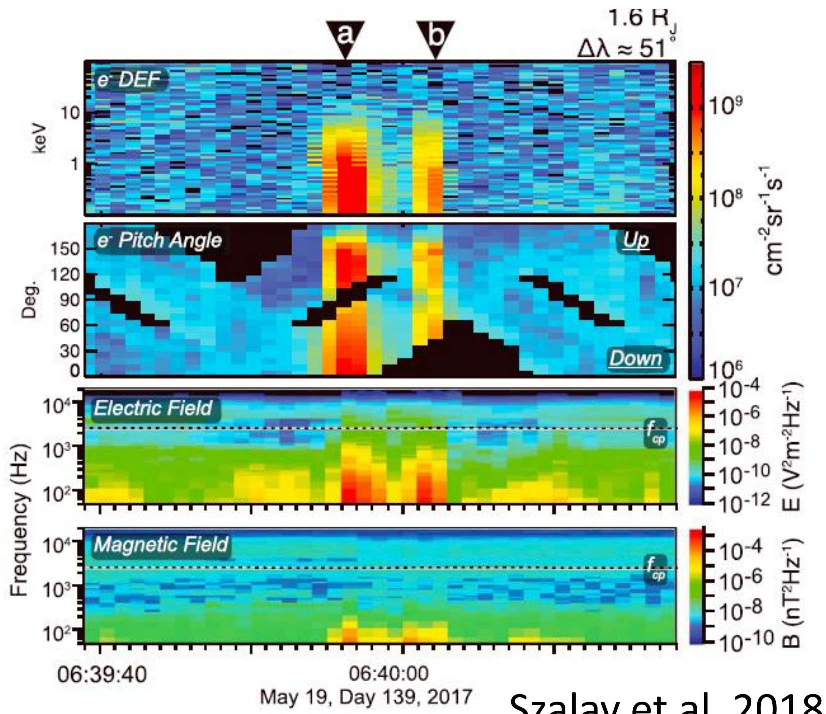
A Juno surprise: sub-dots

- High resolution IR images show sub-structures fixed with the planet.
- Since the sub-dots are fixed with the planet, some forms of ionospheric feedback are expected.



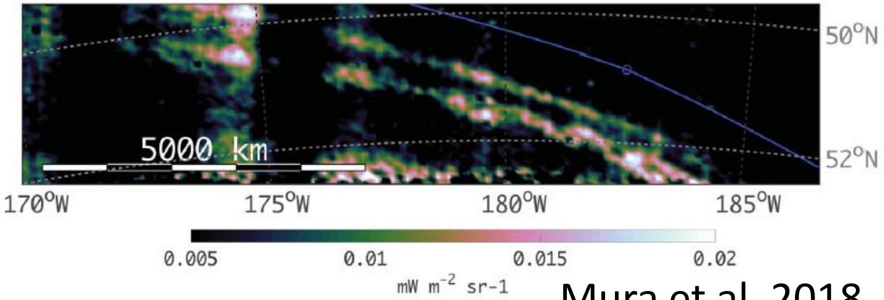
Moirano et al. 2021

Another Juno surprise: a dual tail



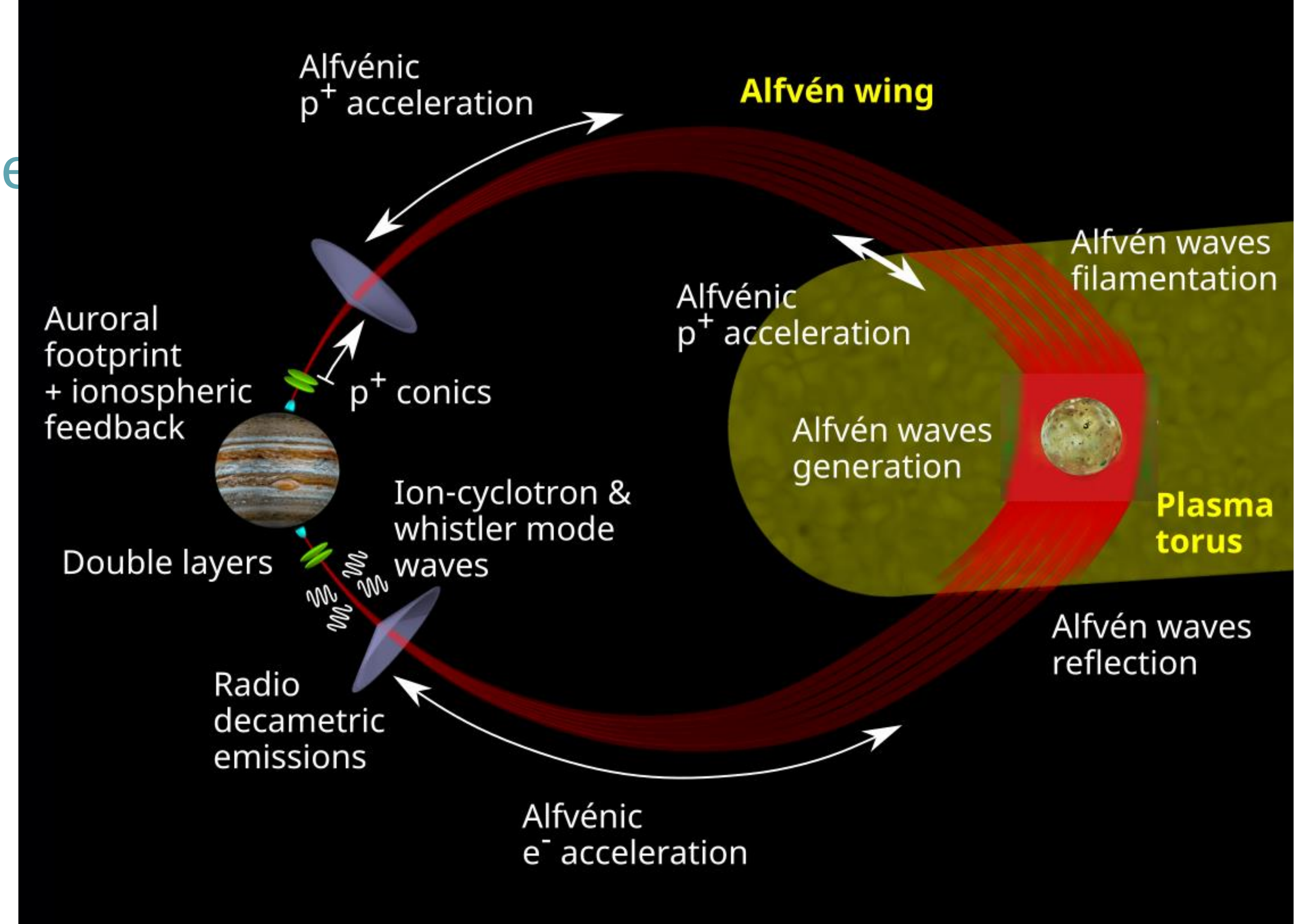
Szalay et al. 2018

- Both high resolution IR images and particle measurements sometimes show a double structure



Mura et al. 2018

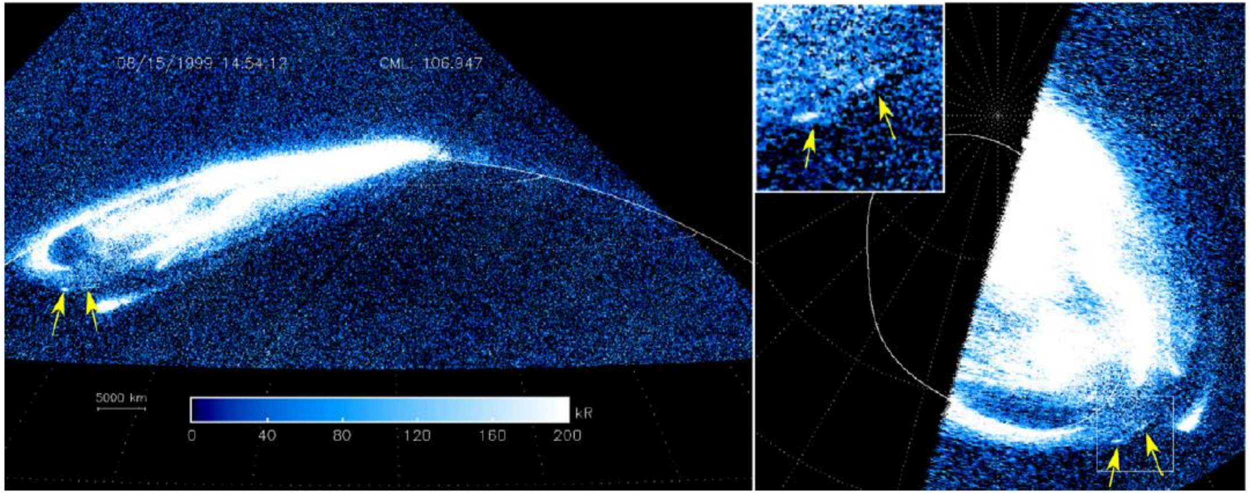
The



Alfvénic
p+ acceleration
Alfvén wing
Auroral
footprint
+ ionospheric
feedback
p+ conics
Alfvén waves
filamentation
Alfvénic
p+ acceleration
Alfvén waves
generation
Ion-cyclotron &
whistler mode
waves
Plasma
torus
Double layers
Alfvén waves
reflection
Radio
decametric
emissions
Alfvénic
e- acceleration

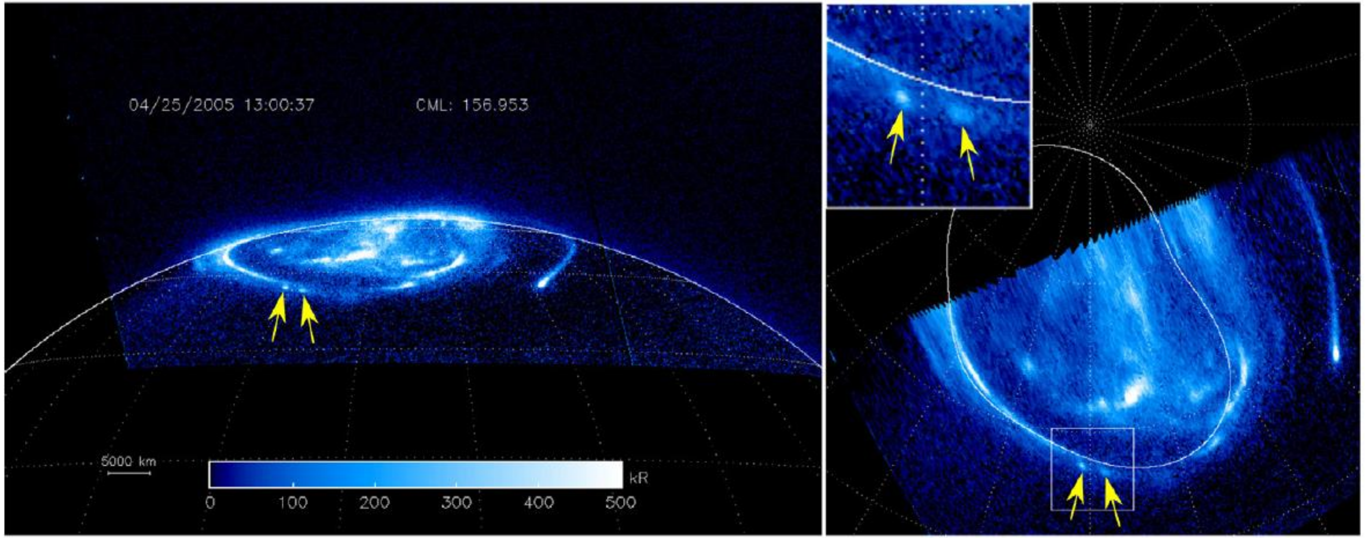
Multiple spots of the Europa footprint

Bonfond et al. 2017



- While it is much weaker than Io’s, the Europa footprint sometimes shows a tail and a pair of spots

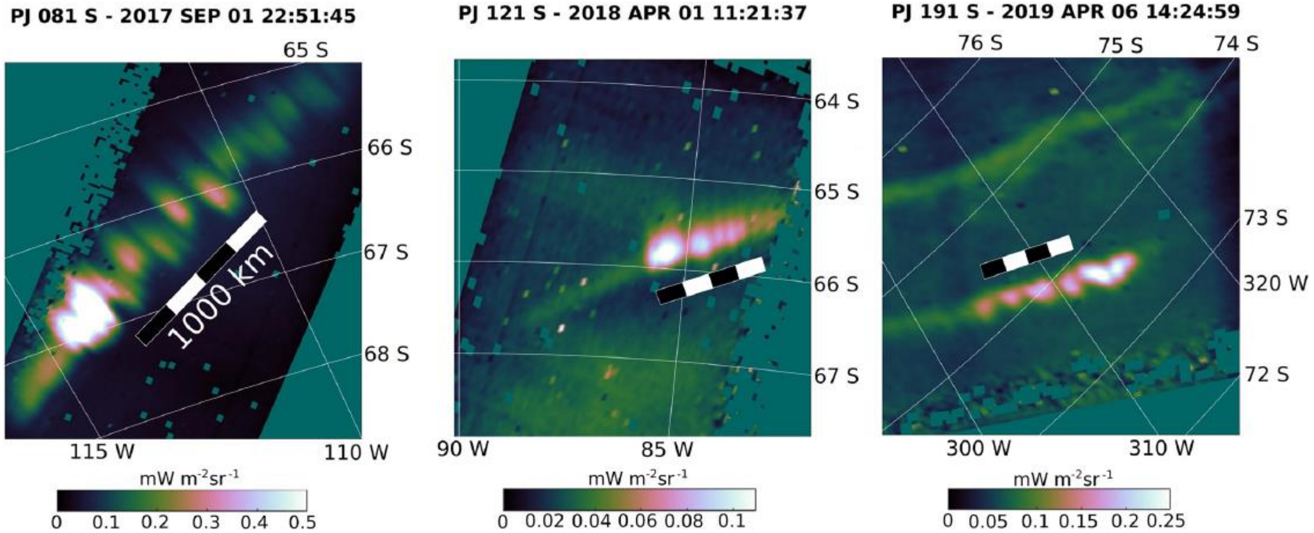
Multiple spots of the Ganymede footprint



Bonfond et al. 2017

- The Ganymede footprint also often dispas a tail and a pair of spots.

The Europa and Ganymede footprints

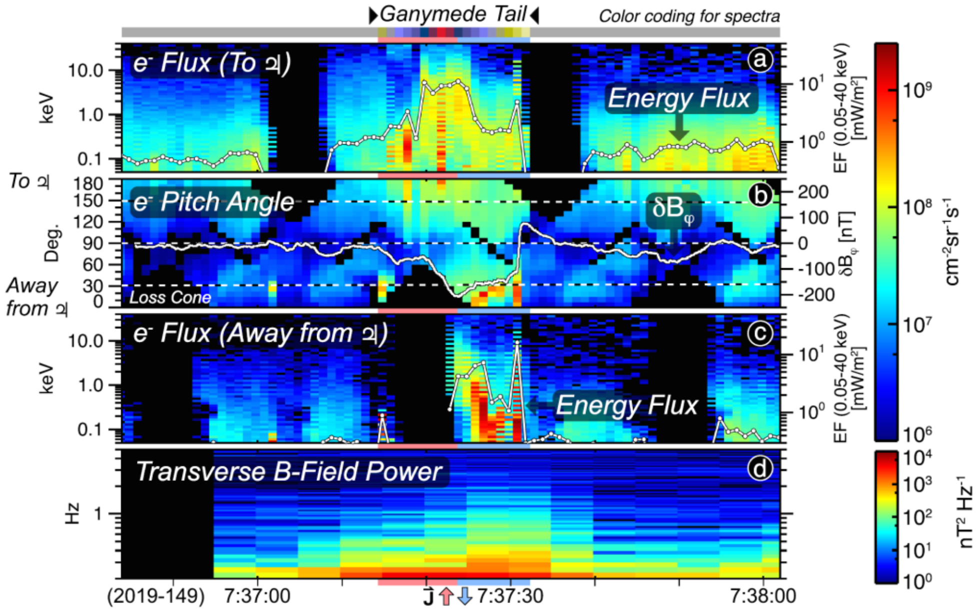


Moirano et al. 2021

- All three footprints show the sub-dots features

Juno crossing of the Ganymede footprint tail

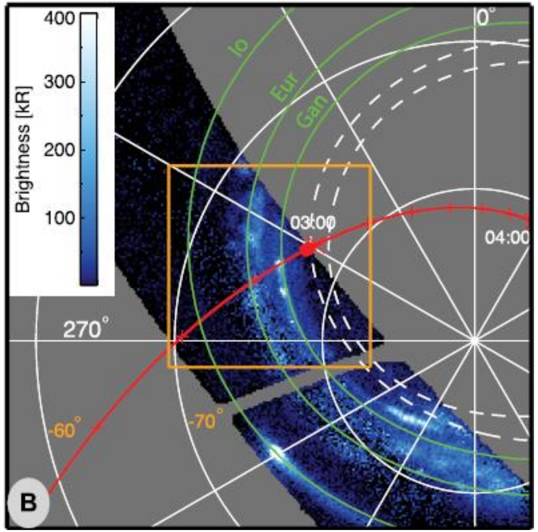
- Broadband field aligned electron beams, electric currents and Alfvén waves are observed over the Ganymede footprint tail

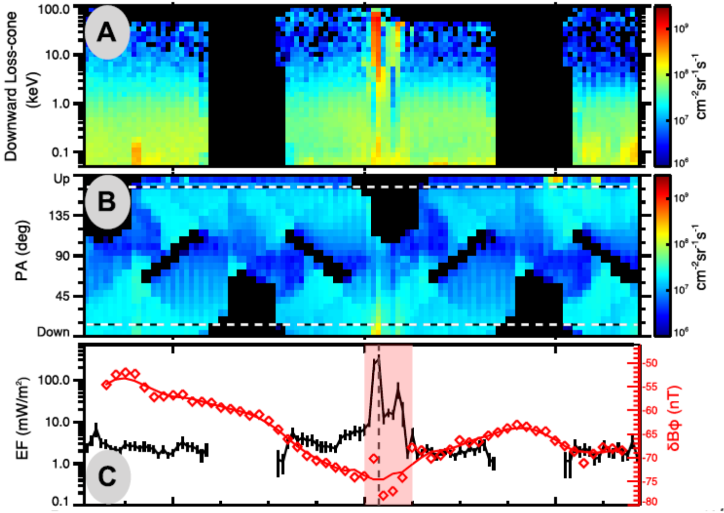


Szalay et al. 2020

Flying through the Ganymede footprint trans-hemispheric electron beam spot

- When Juno flew across the GFP TEB spot, it observed a significant particle flux, but very weak currents
- This is very strong evidence in favor of the TEB theory

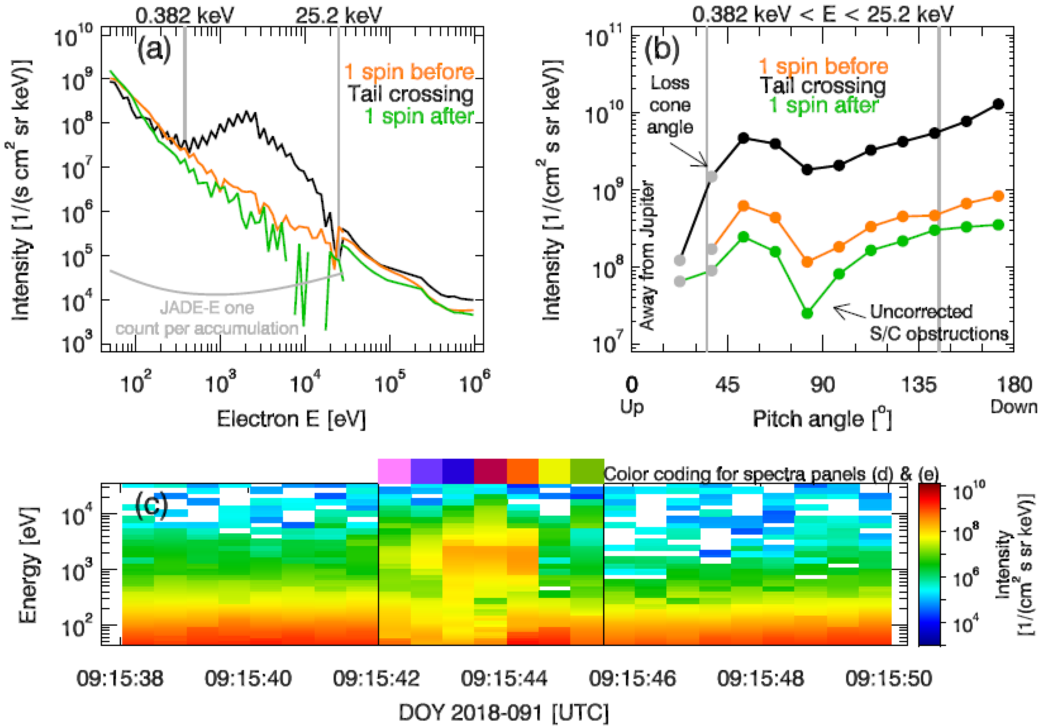




Hue et al. 2022

Juno crossing of the Europa footprint tail

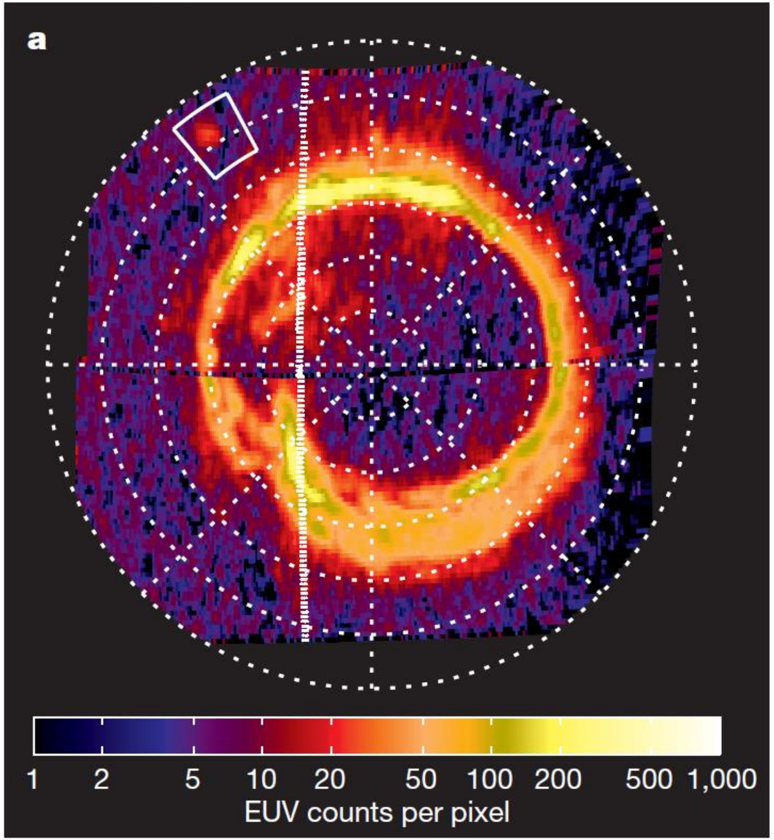
- While broadband distributions dominated over the Io and Ganymede footprint tails, the JADE data over the Europa tail showed signatures of electrostatic acceleration.



Allegrini et al. 2020

The Enceladus footprint

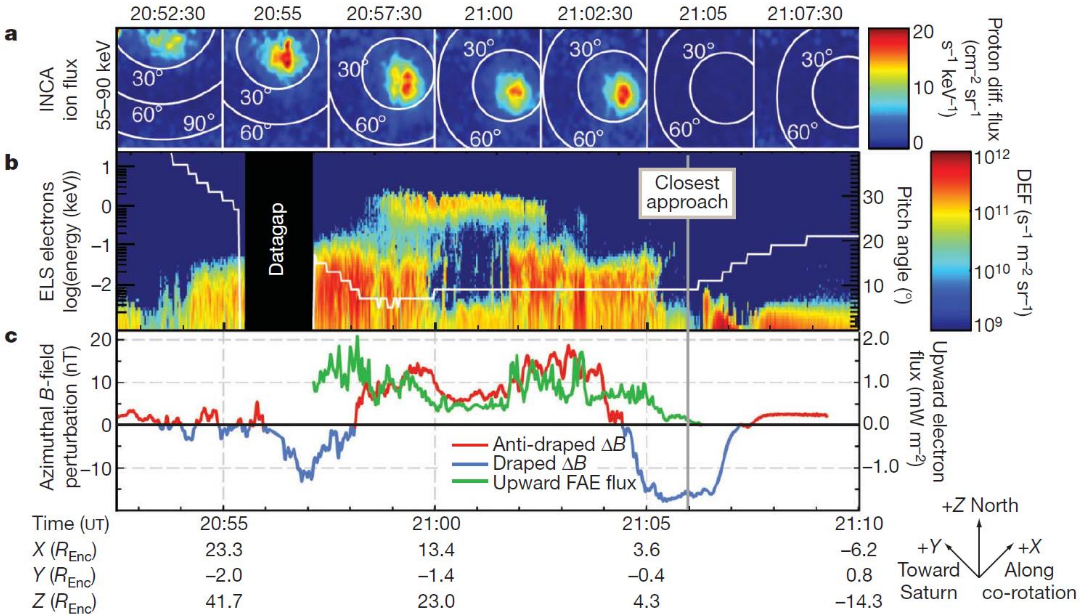
- Kronian satellites were not expected to show as clear signatures at the Jovian ones.
- However, Cassini UVIS detected the UV signature of the Enceladus footprint in Saturn’s aurora.



Pryor et al. 2011

Enceladus electron beam

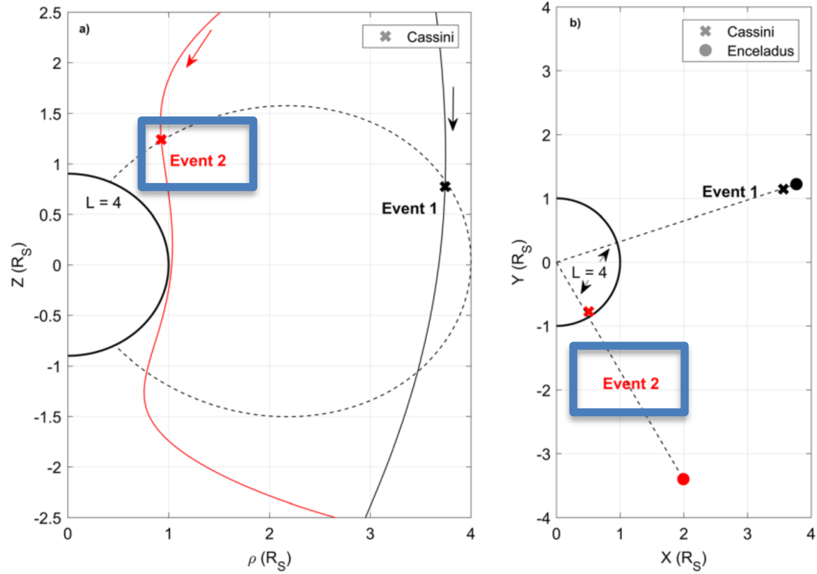
- Cassini detected an electron beam related to the Enceladus-Saturn interaction

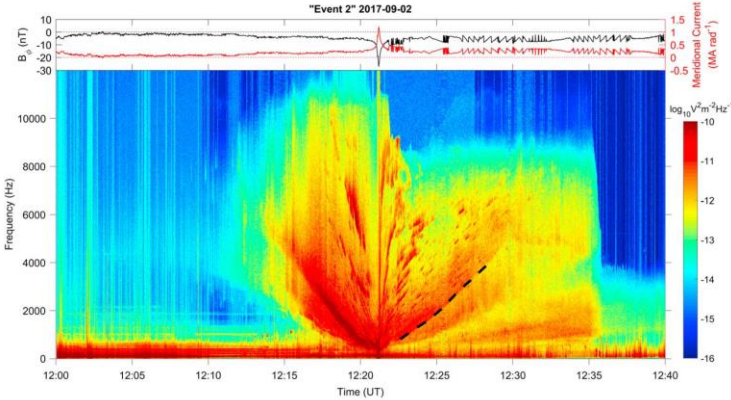


Pryor et al. 2011

Enceladus auroral hiss

- Similarly to what Juno detected at Io, beautiful signatures of auroral hiss were observed when Cassini crossed the Enceladus AW



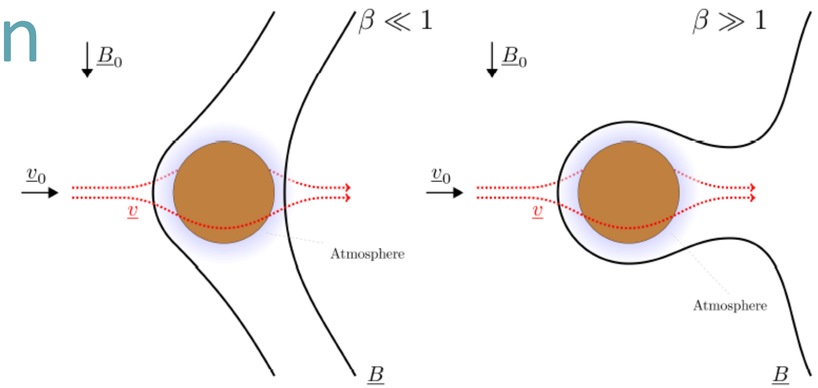


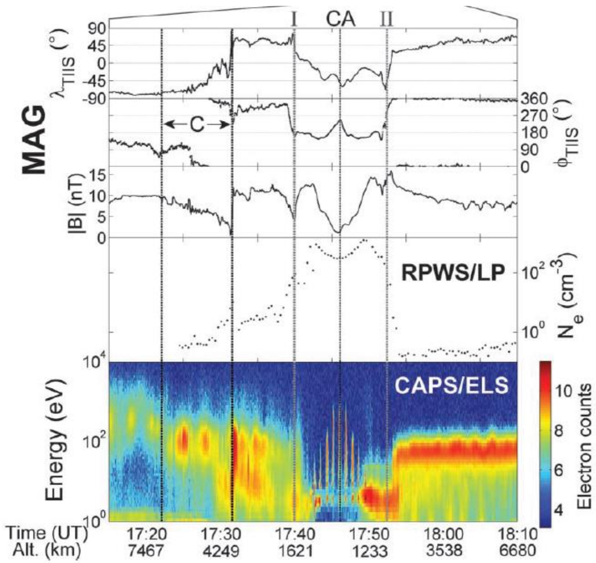
Sulaiman et al. 2018

A high-β situation: Titan

- Titan can be either in the plasma sheet, the lobes or the magnetosheath.
- Because of the convection timescale is larger than the timescale of the changes of the external field, previous magnetic field configurations remain fossilized in the thick ionosphere

Saur et al. 2021



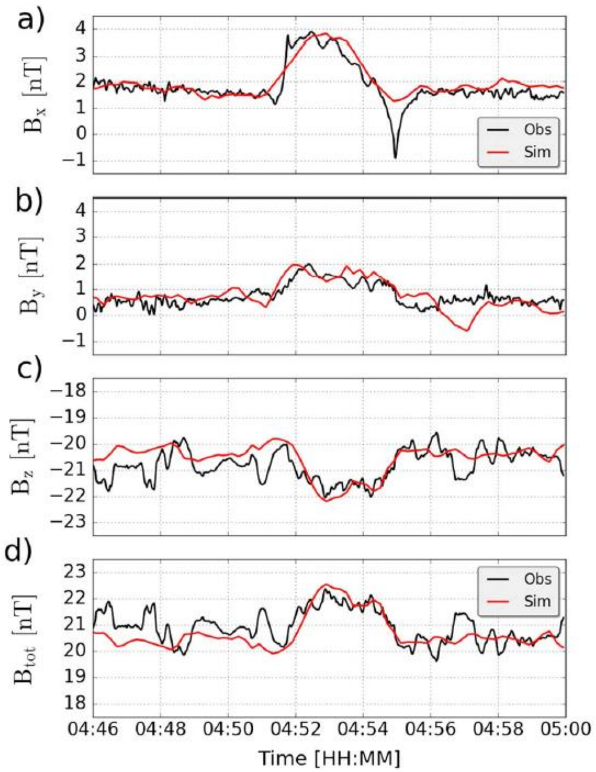


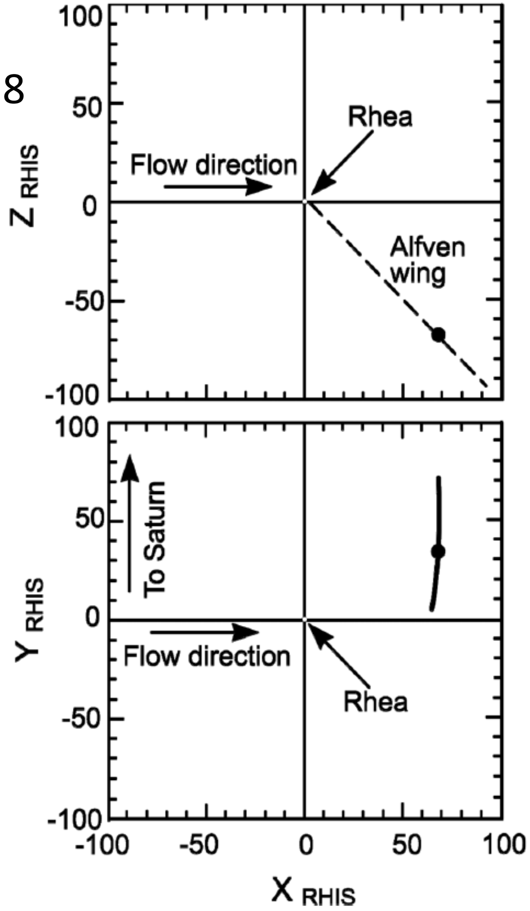
Bertucci et al. 2008

An inert obstacle: Rhea

- Inert satellite
- Distant magnetic field signature of an Alfvén wing
- The AW originate from the density gradient in the wake

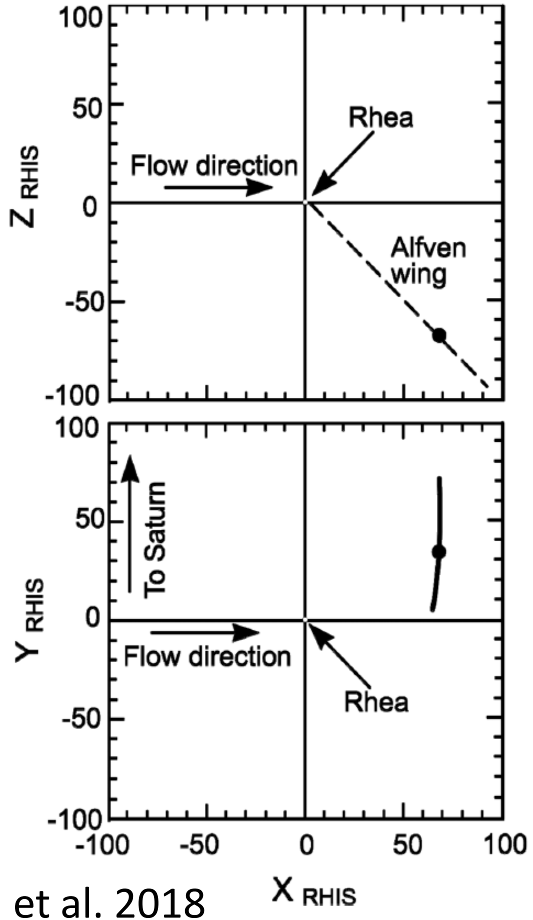
Khurana et al. 2018



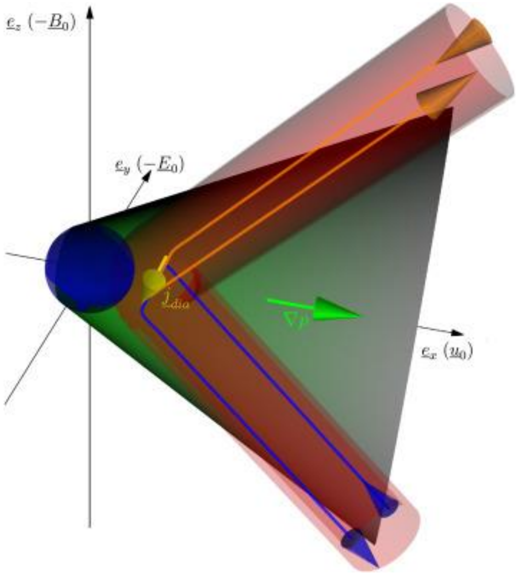


An inert obstacle: Rhea

- Inert satellite
- Distant magnetic field signature of an Alfvén wing
- The AW originate from the density gradient in the wake



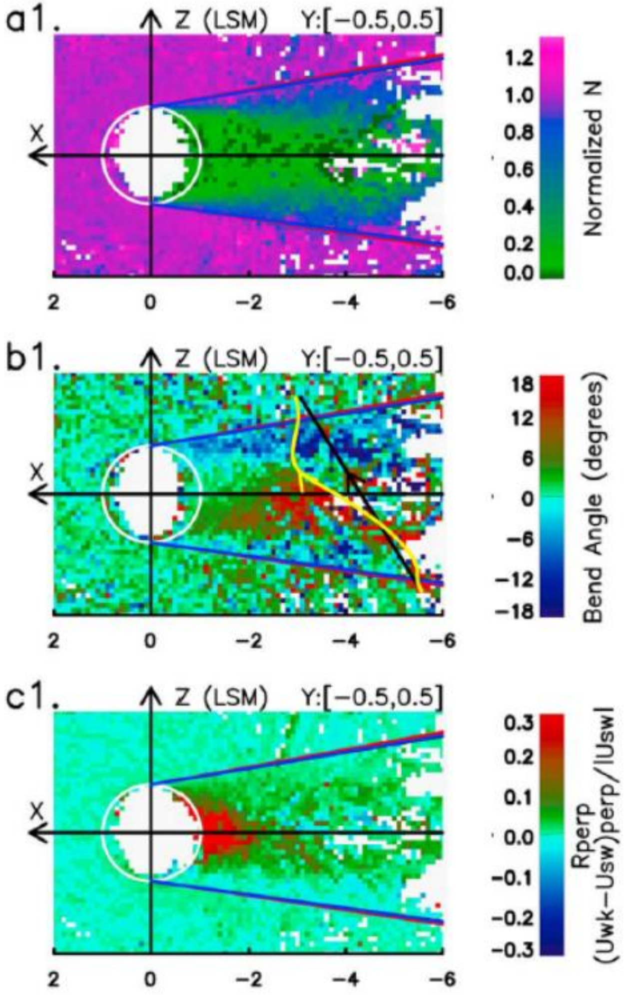
Khurana et al. 2018



Simon et al. 2015

Our Moon

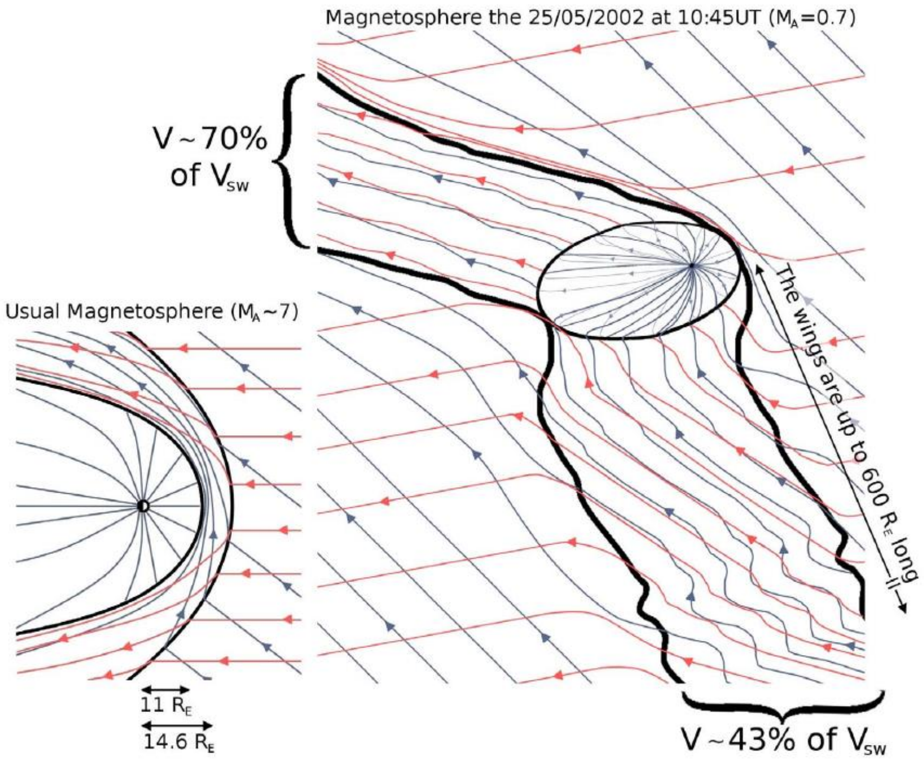
- Super-Alfvénic regime
- The Alfvén wings are folded on themselves in the wake.



Zhang et al. 2016

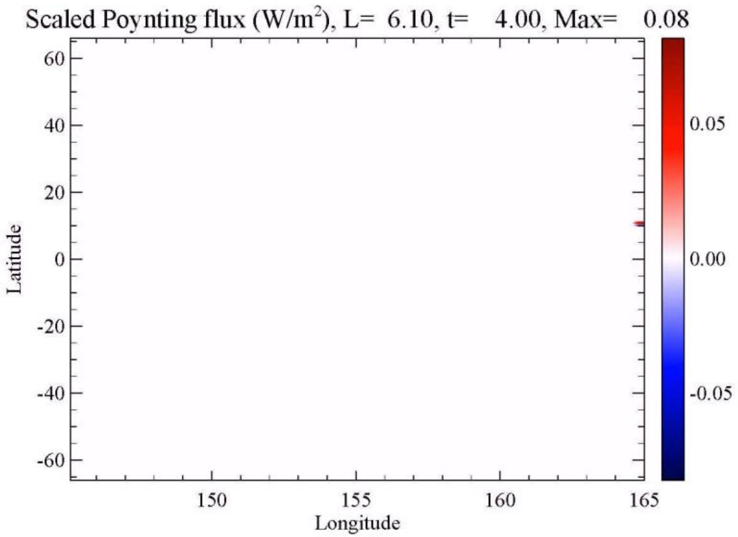
Alfvén wings at Earth?

- During 4 hours, the Earth entered a sub-Alfvénic regime and started forming Alfvén wings (Chané et al. 2012)
- It should also happen at Mercury.



Conclusions

- The moon-magnetosphere interactions are valuable laboratories for the Alfvén waves generation, filamentation, transmission and energy conversion.
- We do not have all puzzle pieces for all satellites, but commonalities are getting obvious.
- Similar interactions are ubiquitous throughout the solar system and probably beyond.



Lysak et al. 2023