Laboratoire de Physique des Plasmas

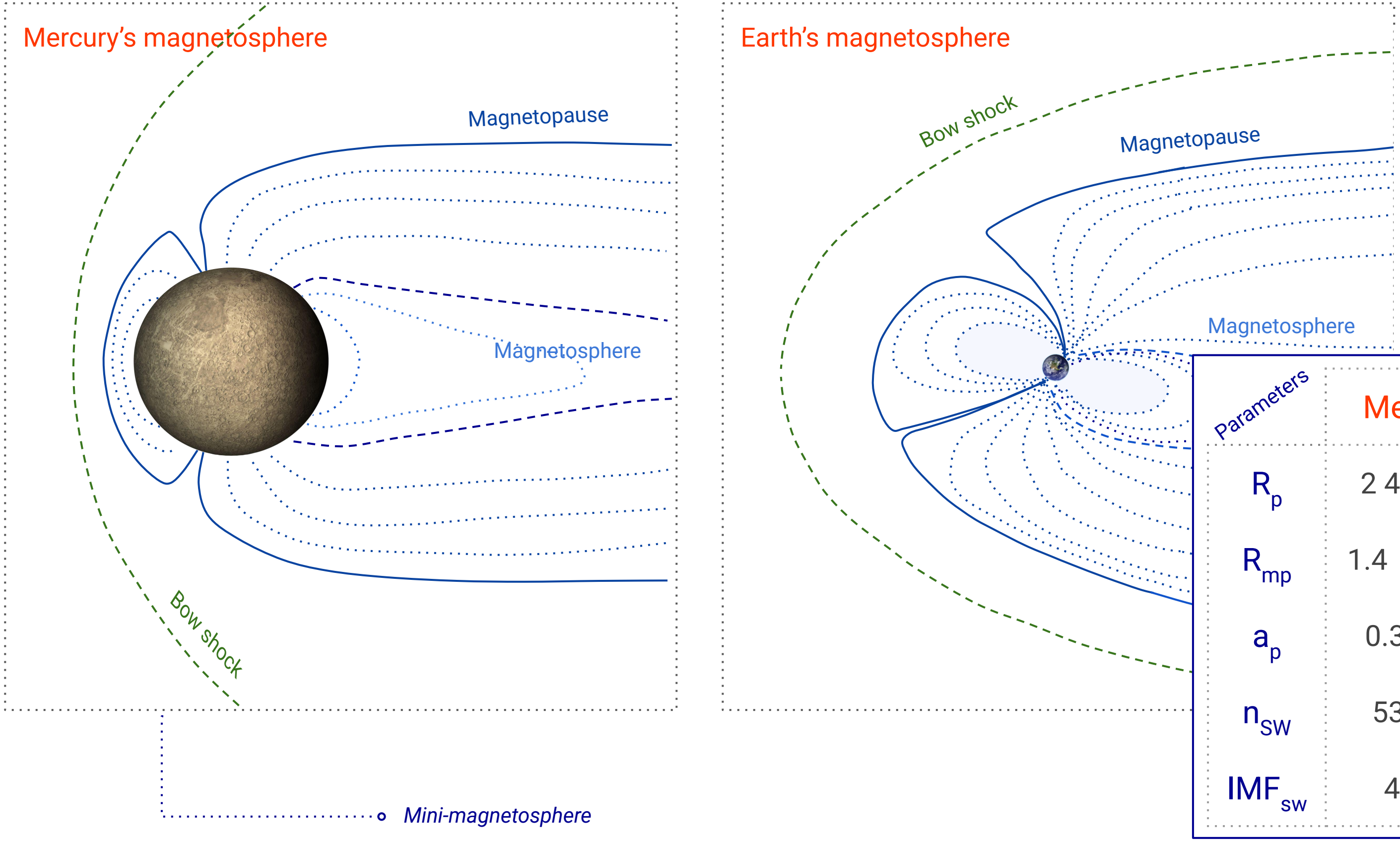
Whistler-mode waves in the tail of Mercury's magnetosphere: A numerical study

Colloque ATST, Biarritz

G. Ballerini[1,2], F. Sahraoui[1], F. Califano[2], P. Henri[3,4]

[1] Laboratoire de Physique des Plasmas, École Polytechnique, France
[2] Dipartimento di Fisica, Università di Pisa, Italy
[3] Laboratoire Lagrange, Observatoire de la Côte d'Azur, Université Côte d'Azur, CNRS, Nice, France
[4] LPC2E, CNRS, Université d'Orléans, CNES, Orléans, France

Mercury's magnetosphere



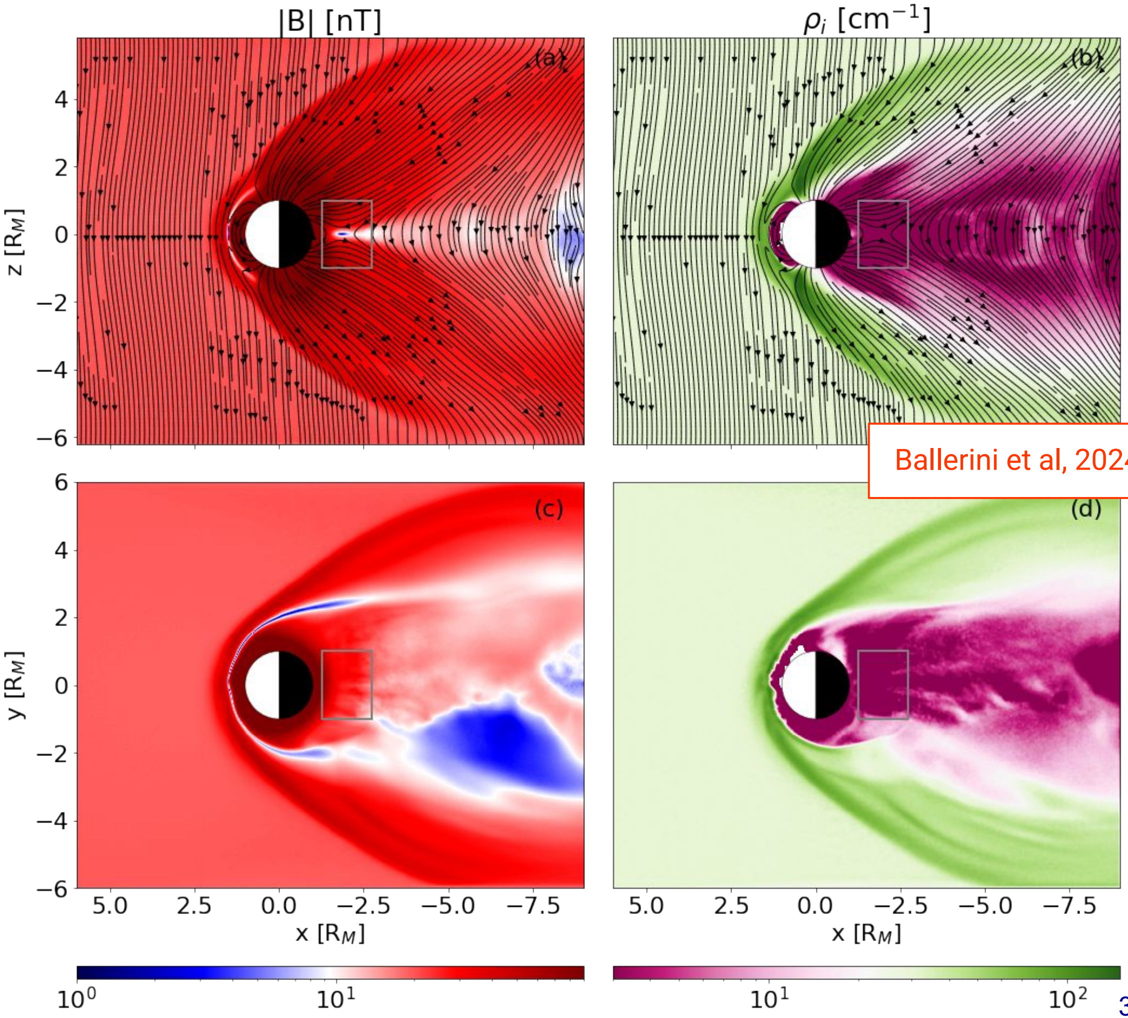
Parameters	Mercury	Earth
R_p	2 439 km	6 373 km
R_{mp}	1.4 - 1.6 R_p	10 R_p
a_p	0.39 a.u.	1 a.u.
n_{SW}	53 cm^{-3}	7 cm^{-3}
IMF_{sw}	41 nT	8 nT

Global simulation of Mercury's magnetosphere using iPIC3D

The iPIC3D solver
[Markidis et al, 2010]

iPIC3D is an full kinetic particle-in-cell (PIC) solver

- ➢ Kinetic description for both ions and electrons
- ➢ Strongly parallelized and executed on multiple CPUs (now also on **GPUs**)
- ➢ Coded to work in the planetary reference frame



Ballerini et al, 2024

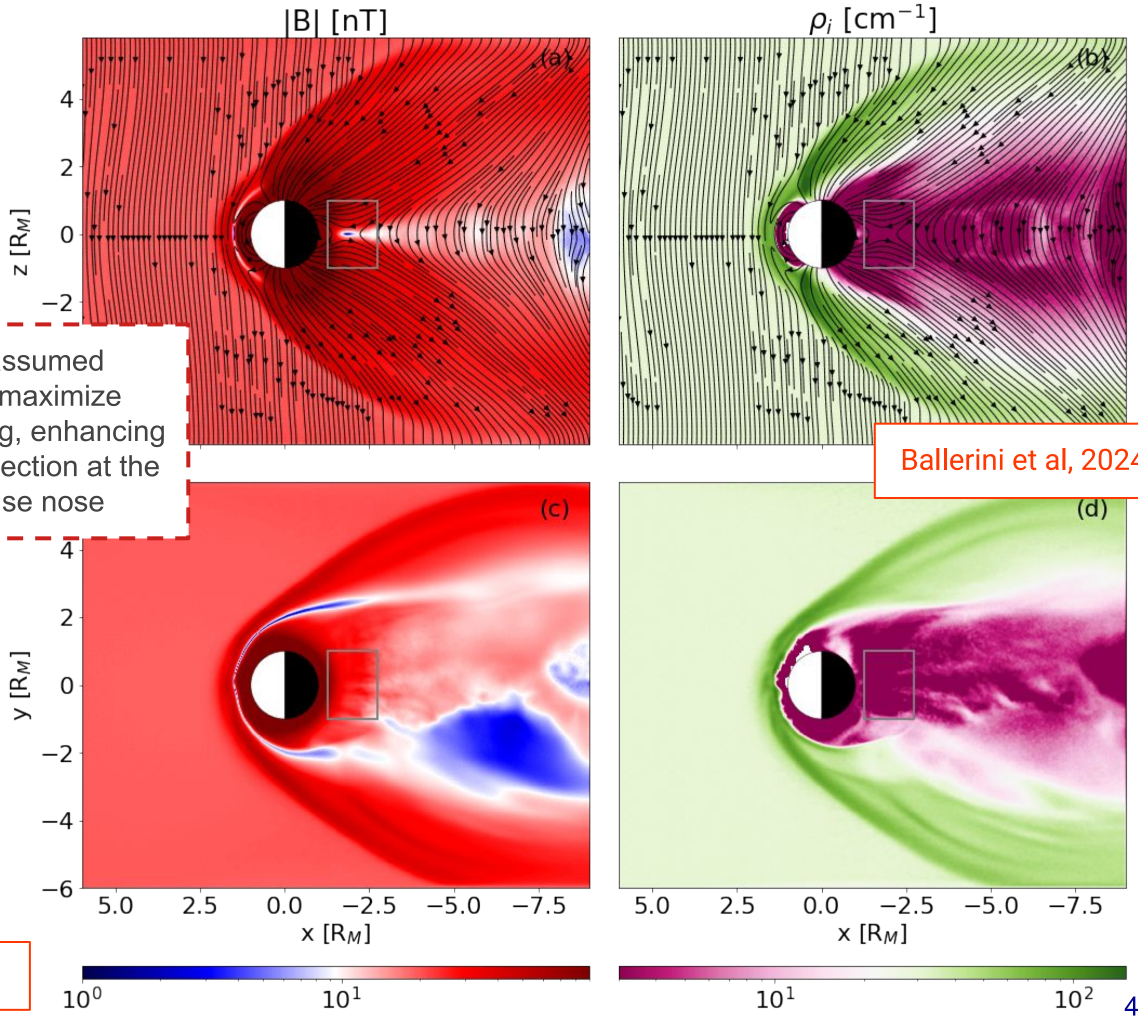
Global simulation of Mercury's magnetosphere using iPIC3D

Solar wind parameters	
n_{sw}	$30\ cm^{-3}$
$\mathbf{B}_{\mathrm{sw}}$	$[0,0,\ -20]\ nT$
$\mathbf{v}_{\mathrm{sw}}$	$400.\ km\, s^{-1}$
$T_i = T_e$	21.5 eV
$\beta_{\mathrm{sw}} = \beta_i + \beta_e$	1.3

The IMF is assumed southward to maximize magnetic coupling, enhancing magnetic reconnection at the magnetopause nose

Grid parameters	
Δx	$0.08\ d_i$
Δt	$2.8 \cdot 10^{-3}\ \omega_{c,i}^{-1}$
L_x	$82.5\ d_i$
$L_y = L_z$	$66\ d_i$
N_{pcc}	64
N_x	960
$N_y = N_z$	768

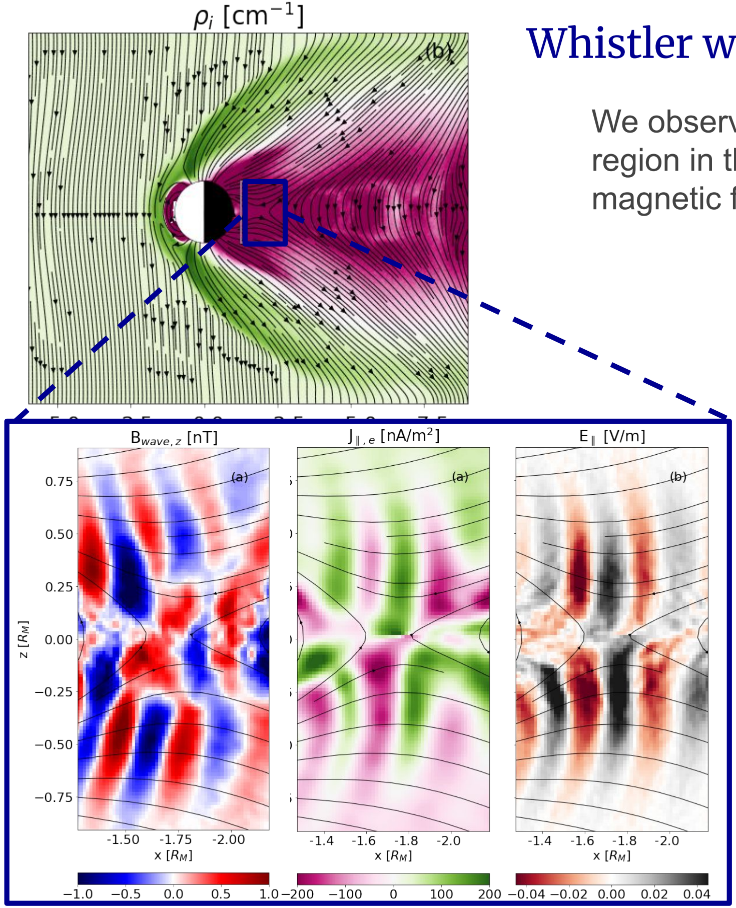
Planet parameters	
R_{planet}	$5.5\ d_i$
B_{surf}	$200\ \mathrm{nT}\ d_i$
τ_{dip} versor	$[0,0,1]$
d_{off}	0



Ballerini et al, 2024

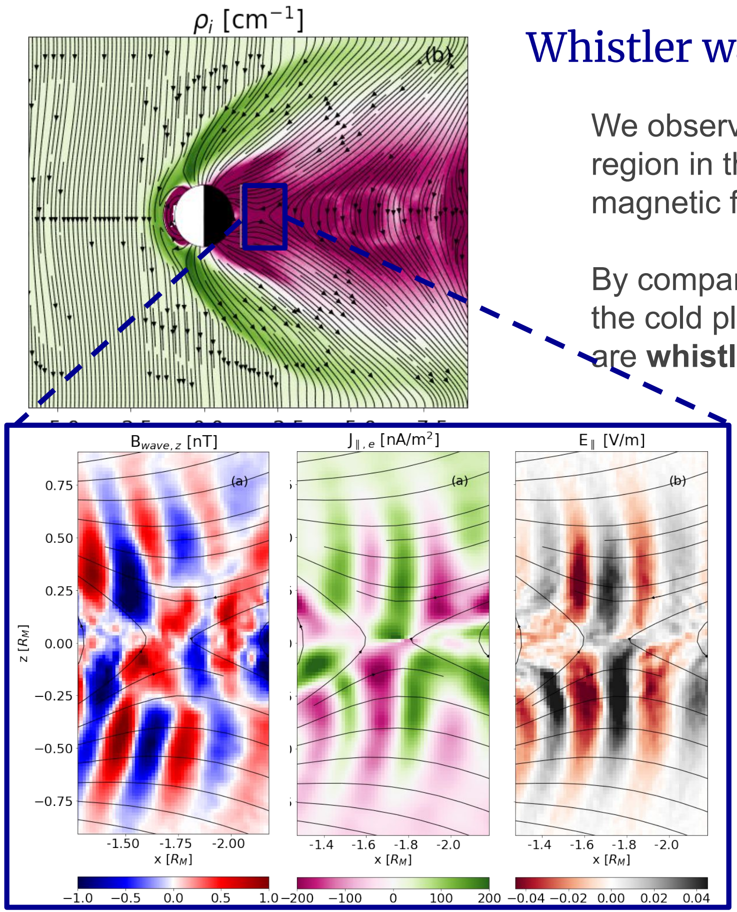
Ballerini et al, 2024

Whistler waves at Mercury's magnetotail



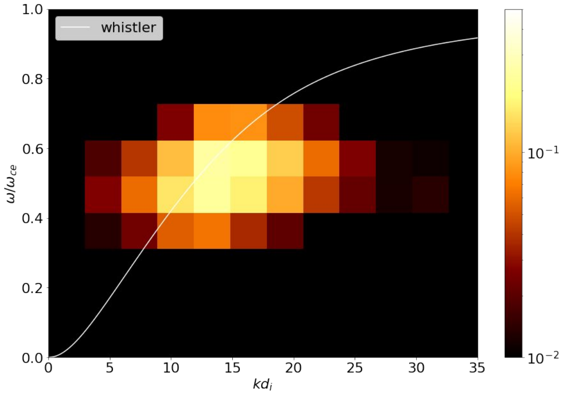
We observe waves developing nearby the X-point region in the magnetotail propagating parallel to the magnetic field

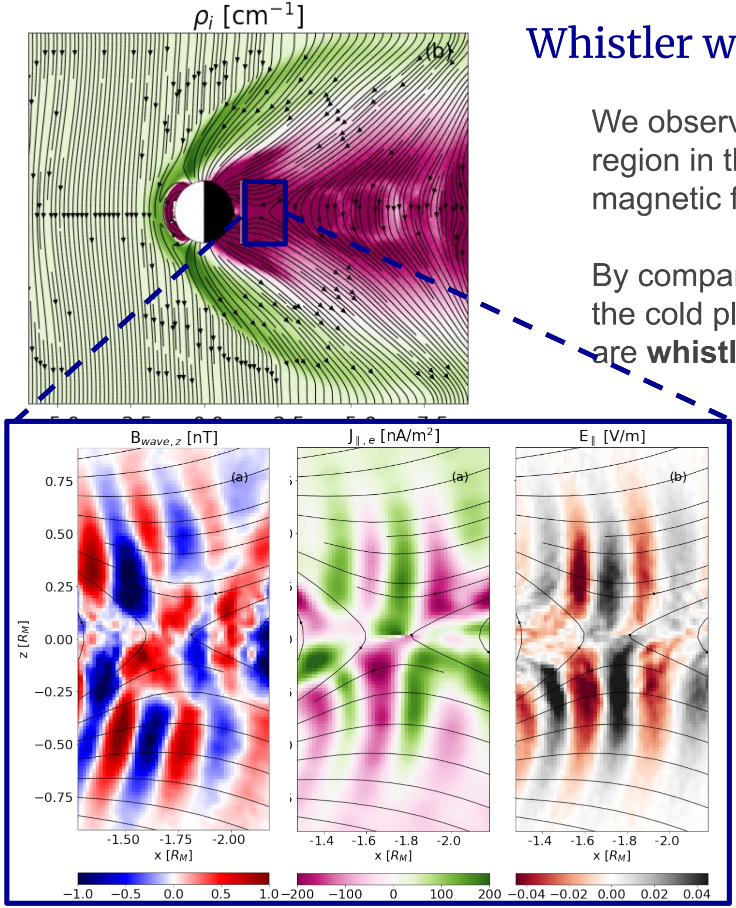
Whistler waves at Mercury's magnetotail



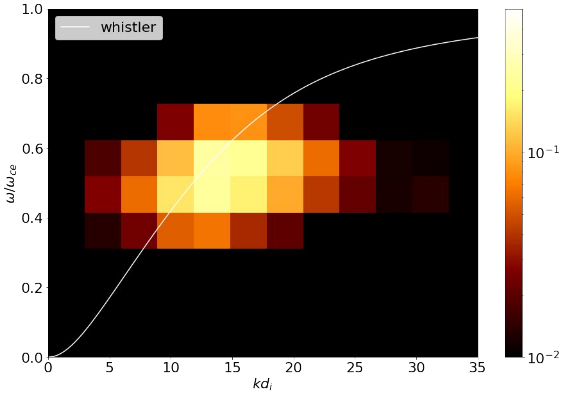
We observe waves developing nearby the X-point region in the magnetotail propagating parallel to the magnetic field

By comparing the observed dispersion relation with the cold plasma whistler mode, we conclude these are **whistler waves**





Whistler waves at Mercury's magnetotail

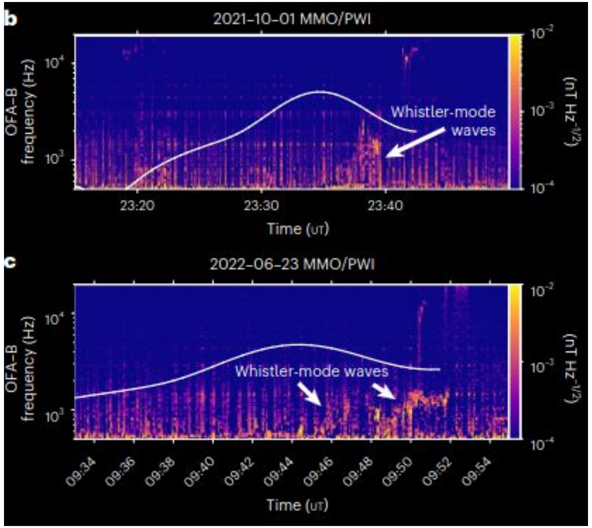


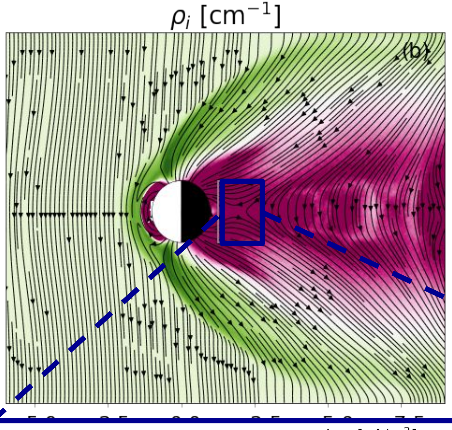
We observe waves developing nearby the X-point region in the magnetotail propagating parallel to the magnetic field

By comparing the observed dispersion relation with the cold plasma whistler mode, we conclude these are **whistler waves**

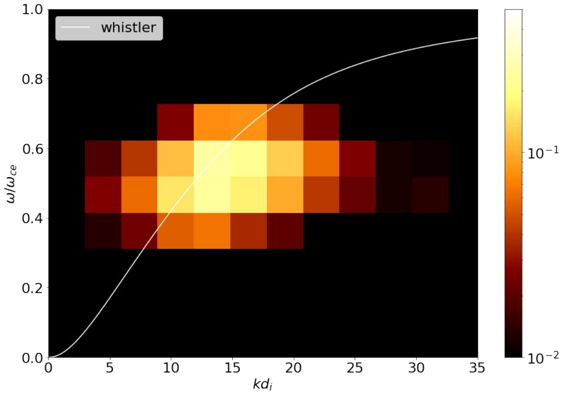
Whistler waves measurements were done by BepiColombo

[Ozaki et al, 2023]



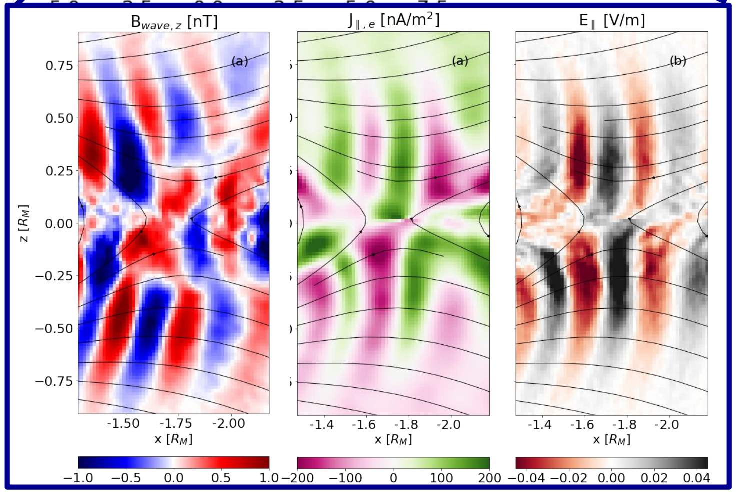


Whistler waves at Mercury’s magnetotail

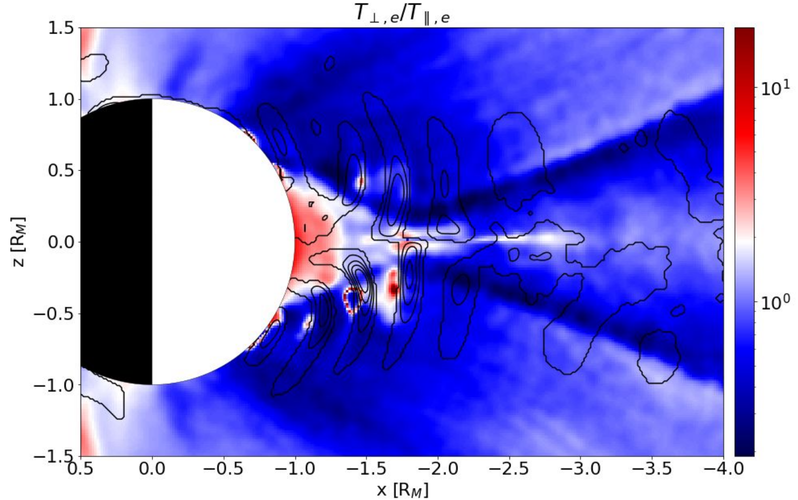


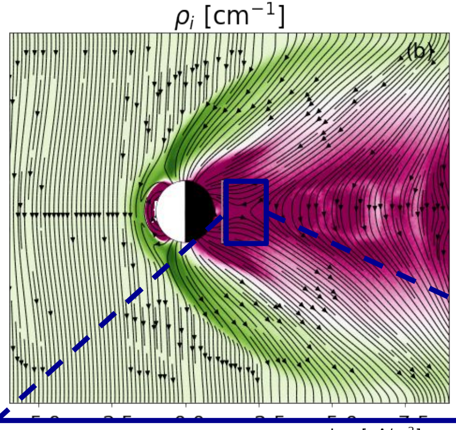
We observe waves developing nearby the X-point region in the magnetotail propagating parallel to the magnetic field

By comparing the observed dispersion relation with the cold plasma whistler mode, we conclude these are **whistler waves**



Role of electron temperature anisotropy in waves origin

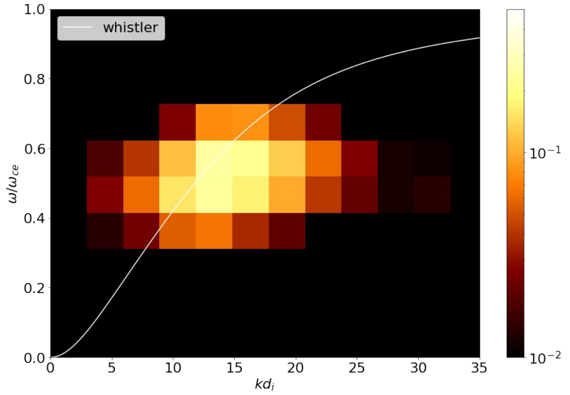


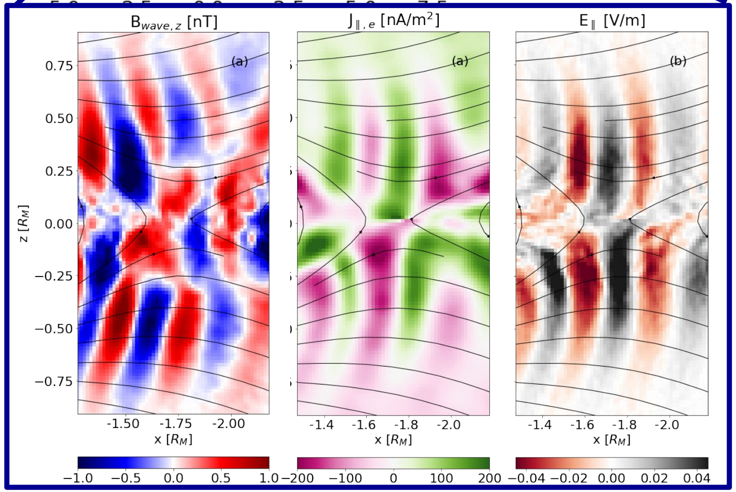


Whistler waves at Mercury's magnetotail

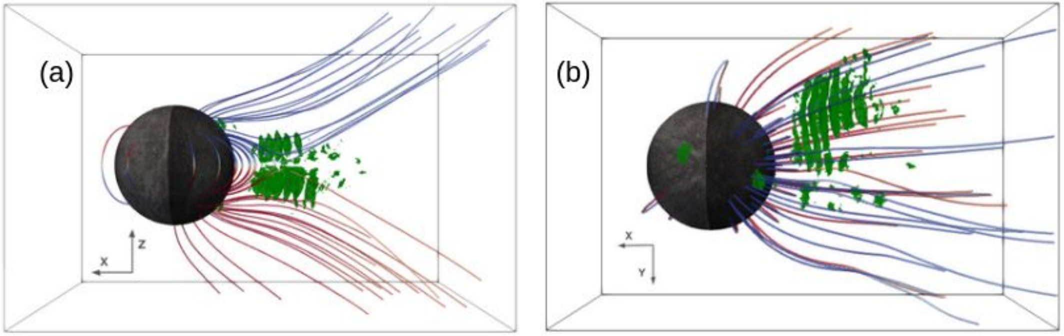
We observe waves developing nearby the X-point region in the magnetotail propagating parallel to the magnetic field

By comparing the observed dispersion relation with the cold plasma whistler mode, we conclude these are **whistler waves**



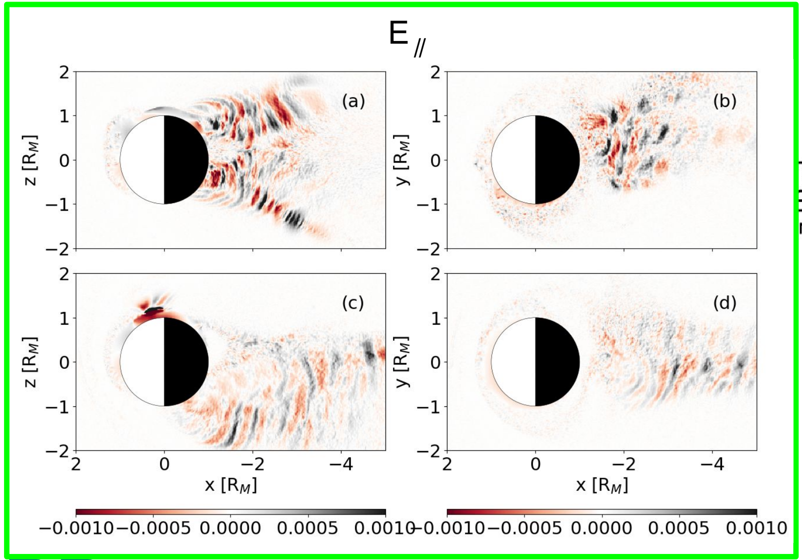


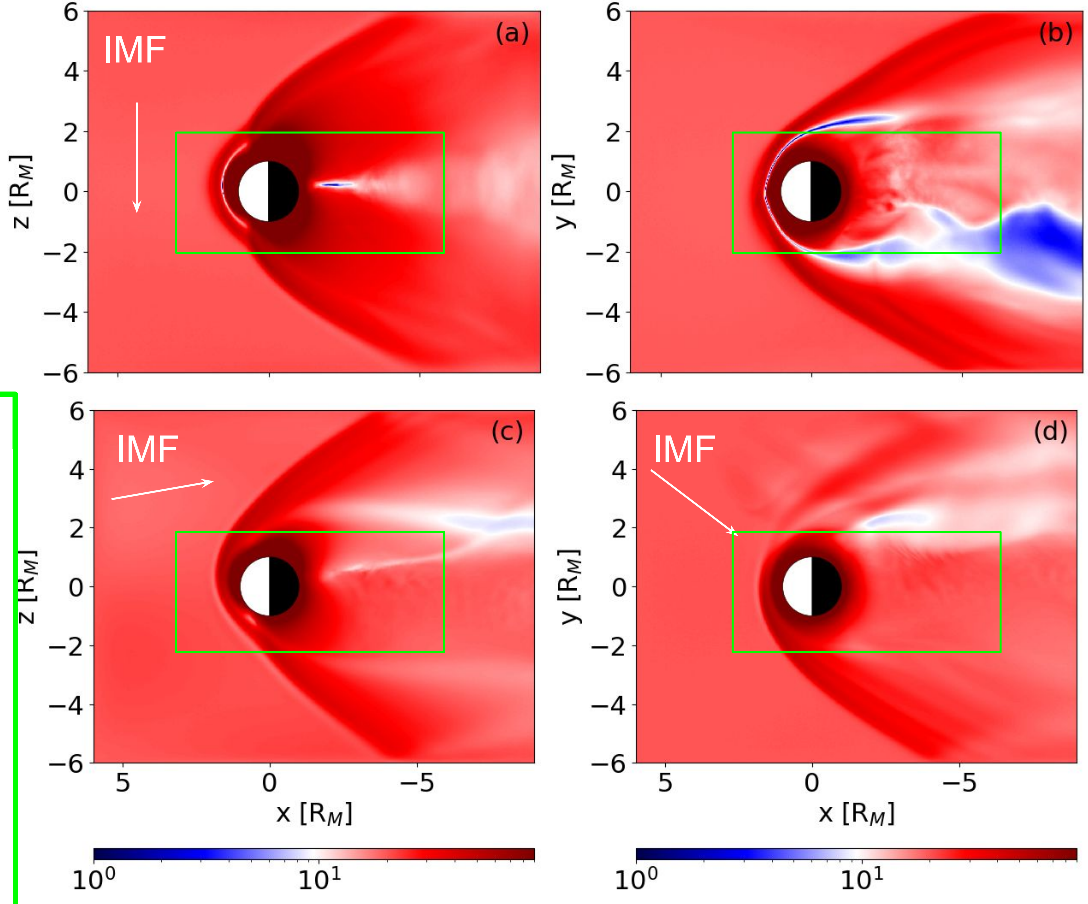
Study of whistler's geographical distribution



The role of IMF

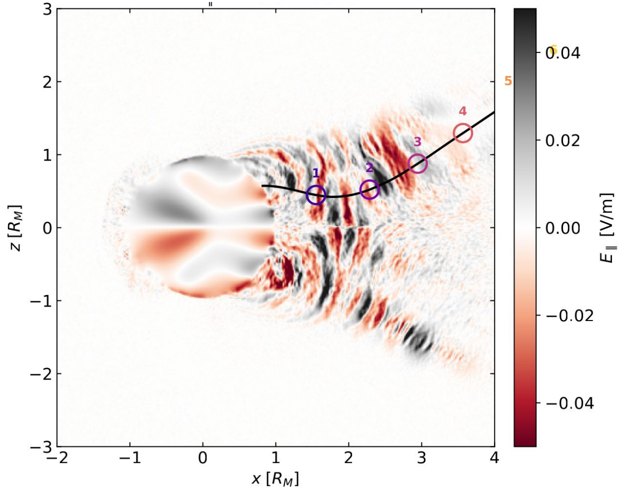
We can compare different IMF configurations to study its influence on the spatial distribution

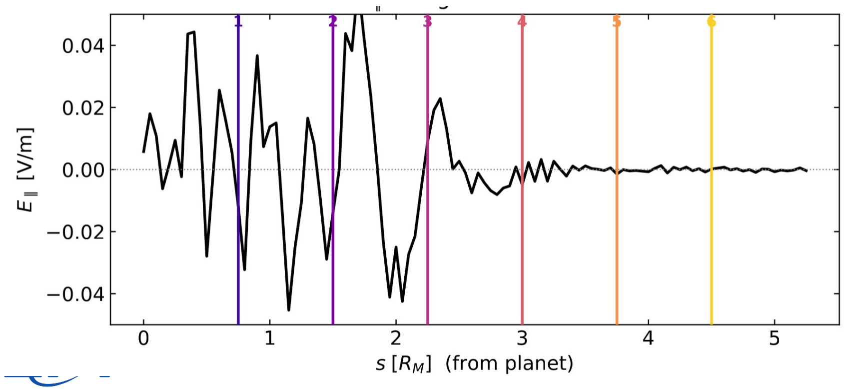




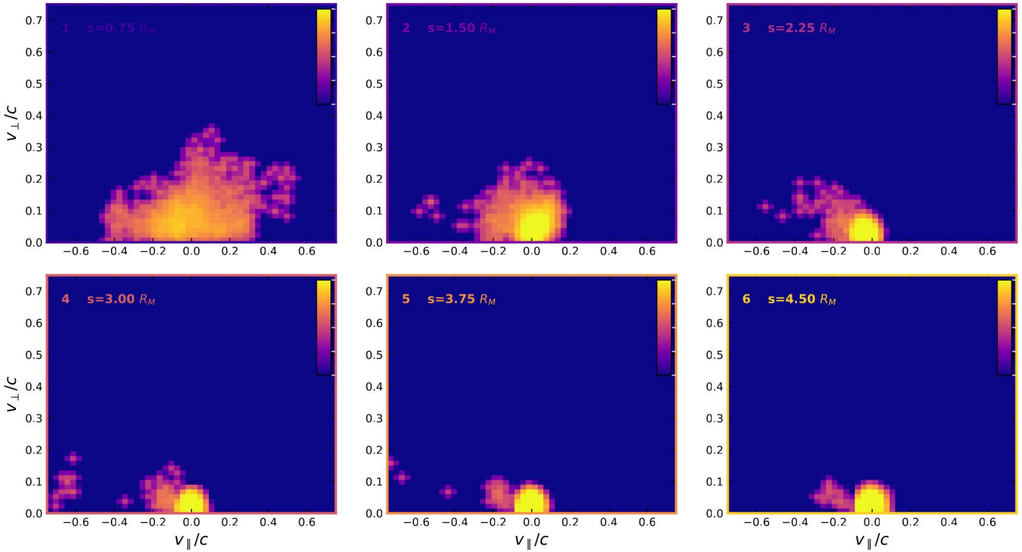
Wave particle interaction

Electron VDFs along a magnetic field line





- ➢ Electrons near the planet show **enhanced parallel temperature** in regions where the wave is present.
- ➢ Their parallel velocity $v_{//}$ is comparable to the wave phase velocity v_{ph}, indicating that closer to the planet wave-electron resonance is possible



Wave particle interaction

Electron Landau resonance

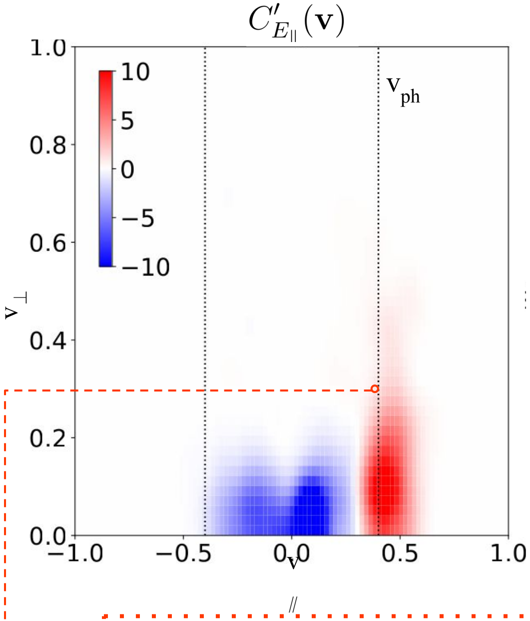
- To identify secular energy transfer from EM waves to electrons, we use the field-particle correlation technique used in data (Klein & Howes 2016; Chen et al. 2019):

$$C'_{E_\parallel}(\mathbf{v}) = \langle q_e\, v_\parallel\, E_\parallel\, \delta f_e \rangle$$

where $\delta f_s(x,v,t)$ is defined $f_s=f_{s0}(v)+\delta f_s$ with the f_{s0} the background (even, uniform, static) distribution.

- A **bipolar signature** in $C'_{E//}(v_{//})$ is the velocity-space fingerprint of Landau resonance

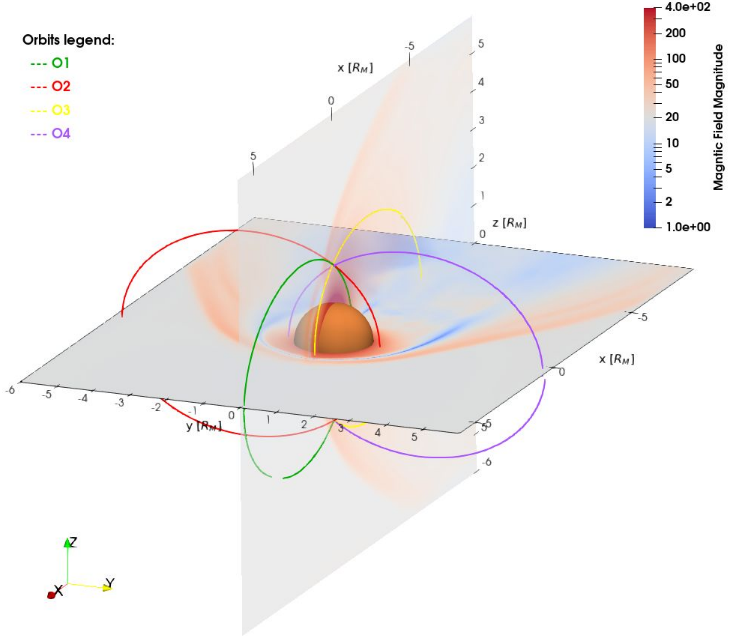
Ballerini et al, in prep

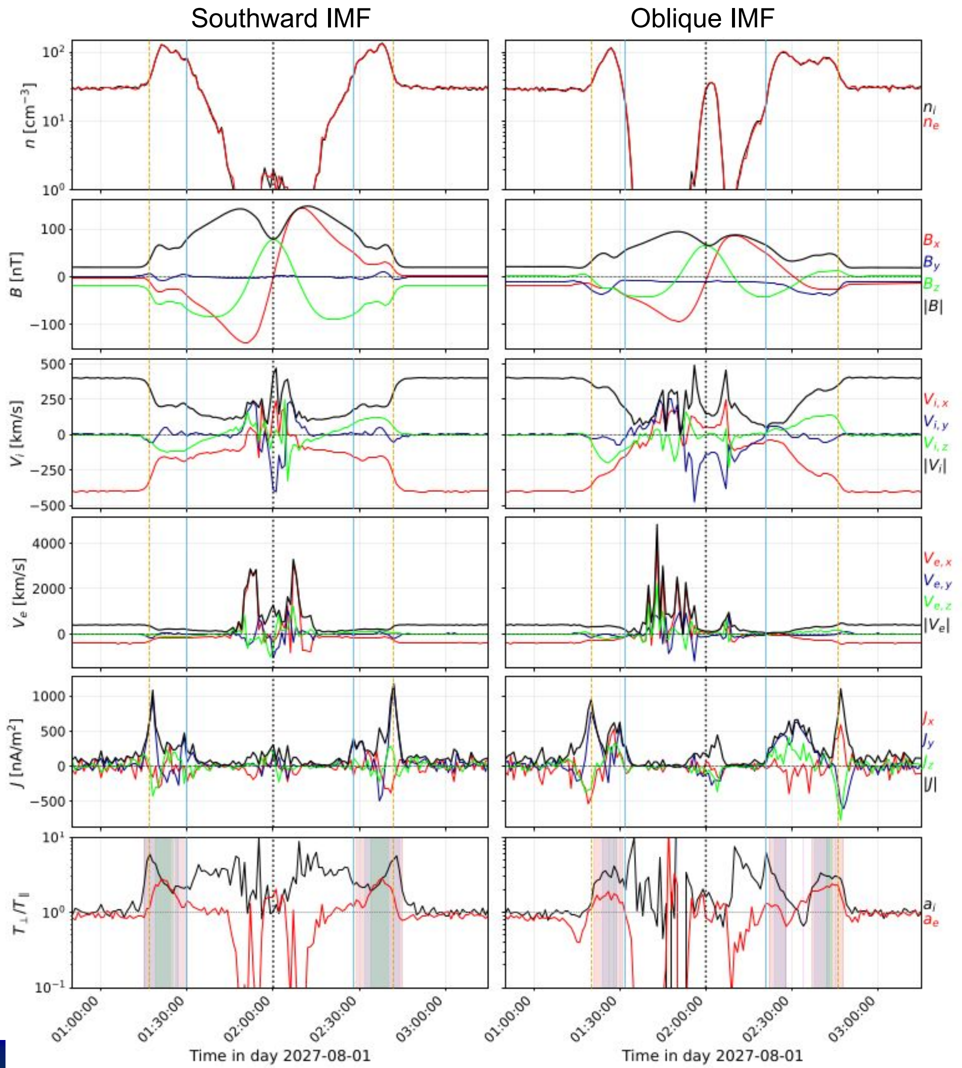


- $C'_{E//}(v_{//})$ is integrated spatially along the magnetic field line
- A clear **bipolar structure** emerges at $v_{//} \approx 0.4$ c, consistent with the **wave phase velocity** (the wave propagates quasi-parallel to B in this region).
- The **positive lobe above** the phase velocity confirms a net energy transfer from the wave to the electrons — the signature of **Landau resonance**.

Role of IMF direction in Mercury's magnetospheric measurements: virtual spacecrafts for future BepiColombo orbital phase

To support the BepiColombo mission we can use the two simulations and sample the fields along either past Flyby trajectories or future orbits to help interpret data





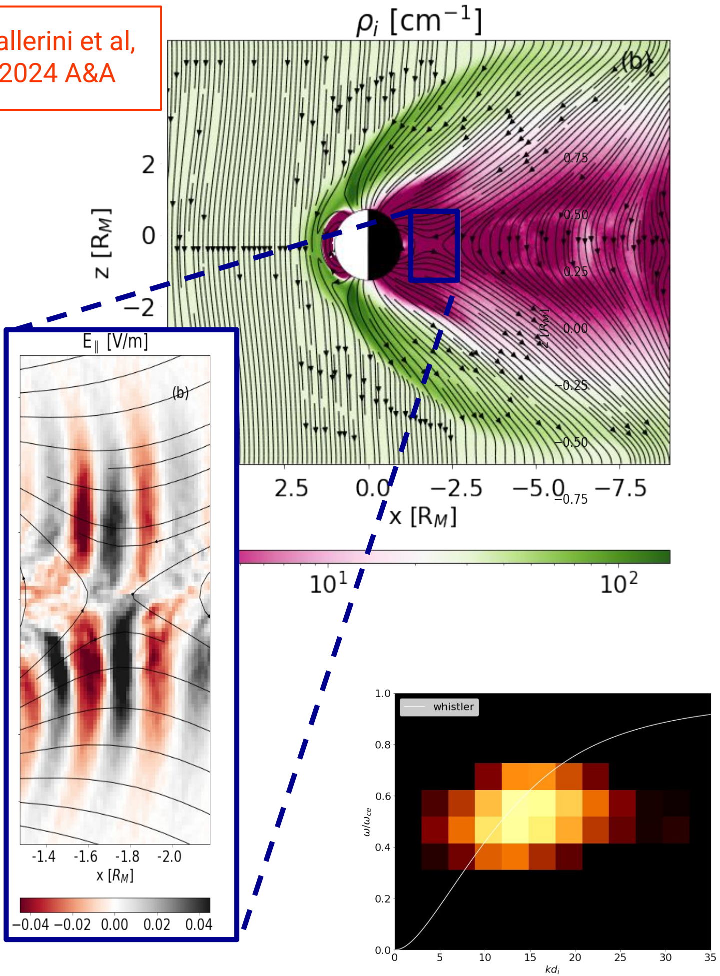
Ballerini et al, in prep

Conclusions

Two global simulations of Mercury's magnetosphere were performed to investigate magnetotail reconnection and electron dynamics.

- ➢ Narrow-band whistler-mode waves are generated at the nightside reconnection site and propagate quasi-parallel to the magnetic field.
  - ○ Wave generation is driven by electron temperature anisotropy.
  - ○ First global simulations enabling a study of the spatial distribution of whistler waves in Mercury's magnetotail.
  - ○ Local study shows Landau resonance between electrons and the mode
  - ○ Nonetheless, the rescaling of both universal and system parameters may influence the predicted wave location.
- ➢ The simulations provide a valuable tool to support the interpretation of BepiColombo observations.

Ballerini et al, 2024 A&A



“Scaling-down” as the the strategy to run large-scale PIC simulations

Even though smaller than the Earth, realistic simulations of Mercury’s magnetosphere remains not feasible due to multiple scales

➔ Universal parameters $\rho_i \sim 40\ \rho_e$ and $\omega_i \sim 2000$

➔ System parameters $L \sim 100\rho_i$

Rescaling universal parameters

- Ion-to-electron mass ratio and reduced to $m_i / m_e = 100$ (1836)
- Electron plasma-to-cyclotron frequency ratio reduced to $\omega_{pe}/\omega_{ce} = 17.8$ (83)

Rescaling system parameters

- Planetary radius scaled by a factor 10
- Use 64 macro-particles per cell

LPP

Influence of the magnetic field topology on the spatial distribution of the electrons

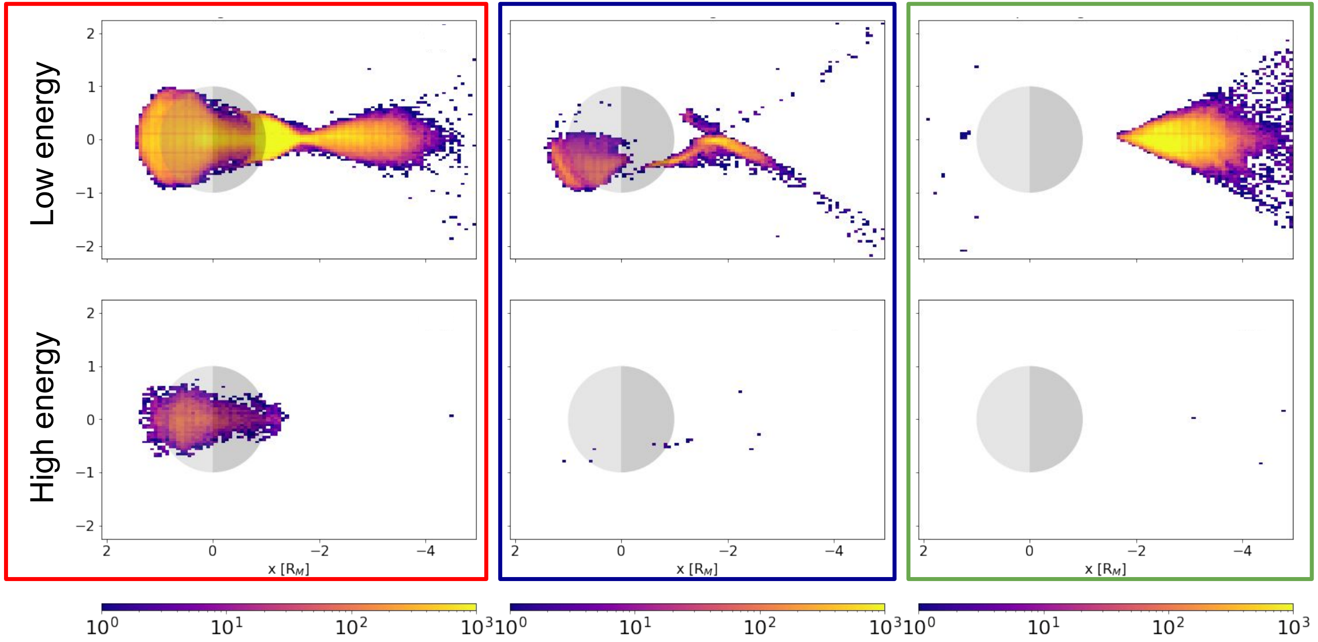
We split the domain according to the magnetic topology, selecting regions with:

A. **B**-lines closed at both ends on the planet

B. **B**-lines closed at one end;

C. magnetically open ones.

For each, we study at the distribution of electrons as a function of temperature (above and below 1 keV).



➔ Underlines a clear link between magnetic topology and electron energy distribution.

Magnetic reconnection in the magnetotail