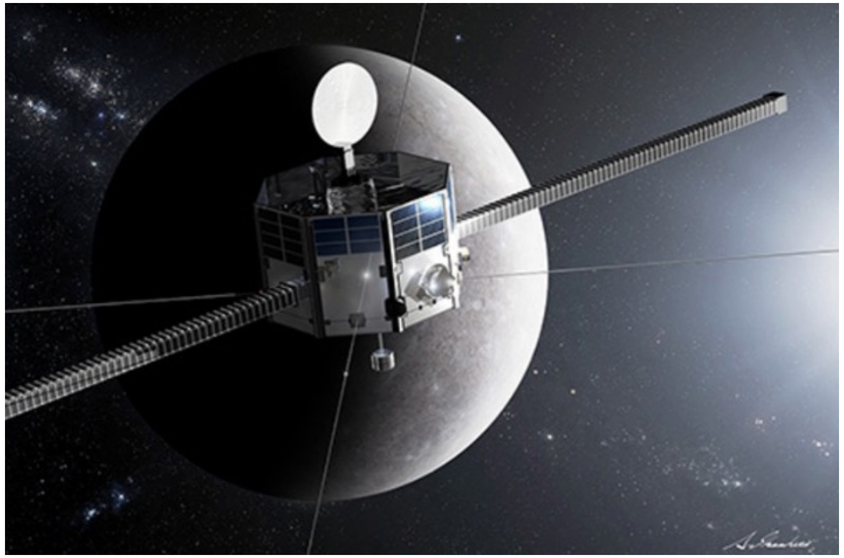
Mutual Impedance Modeling for BepiColombo: Including Ion Dynamics Effects

Mélody PALLU[1], Pierre HENRI[1,2], Pietro DAZZI[3]

[1]*LPC2E, Université d'Orléans, Orléans*
[2]*Observatoire de la Côte d'Azur, CNRS, UCA, Nice*
[3]*Centre for Mathematical Plasma Astrophysics, KU Leuven, Belgium*

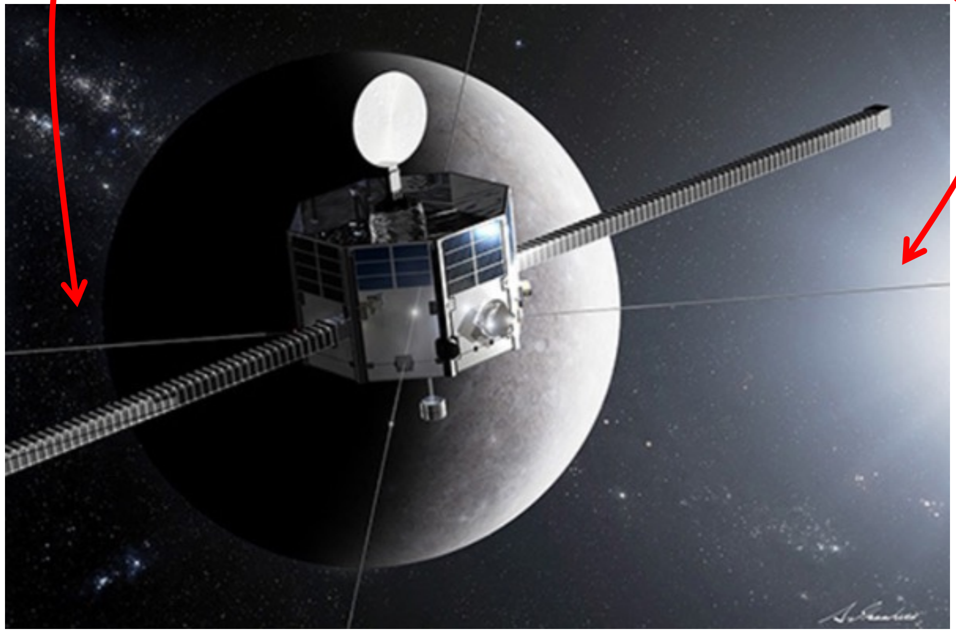


Tuesday 2nd June 2026 – ATST Colloque, Biarritz

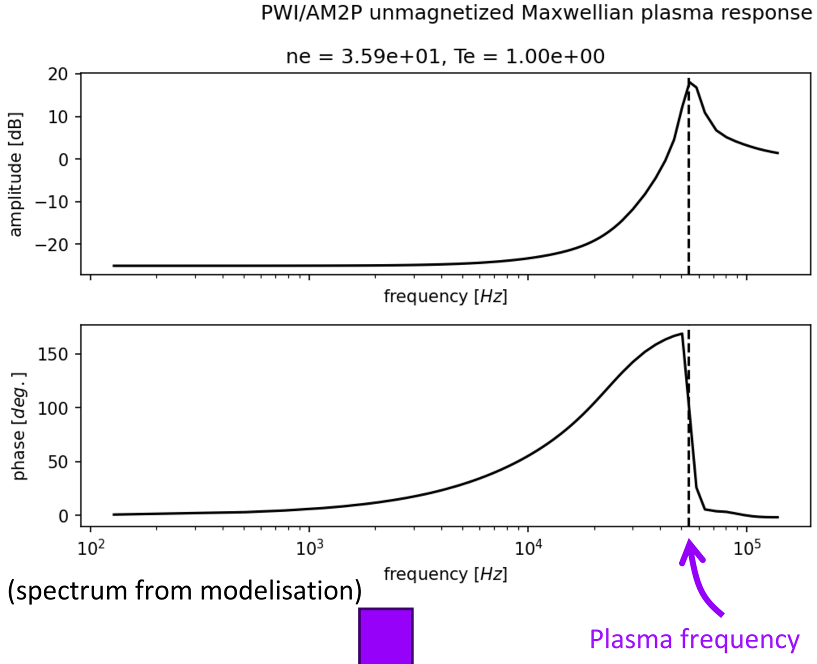
Context

BepiColombo will arrive **end of 2026** at Mercury

PWI/AM²P antennas developped by LPC2E (uses MEFISTO Swedish antennas)



Mutual impedance measurements to probe the plasma surrounding Mercury



(spectrum from modelisation)

We deduce:
Electron density n_e
Electron temperature T_e
+ if multiple electron populations exist

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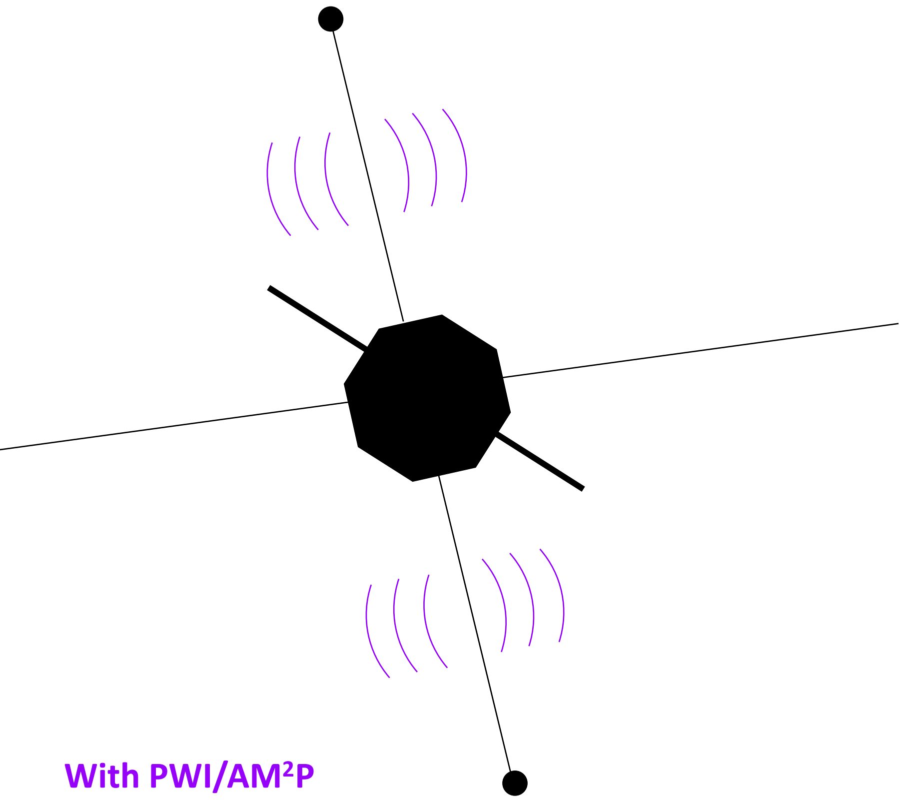
Mutual Impedance

Measurement principle:

1. Current emitted by the emitting wires at a frequency ω

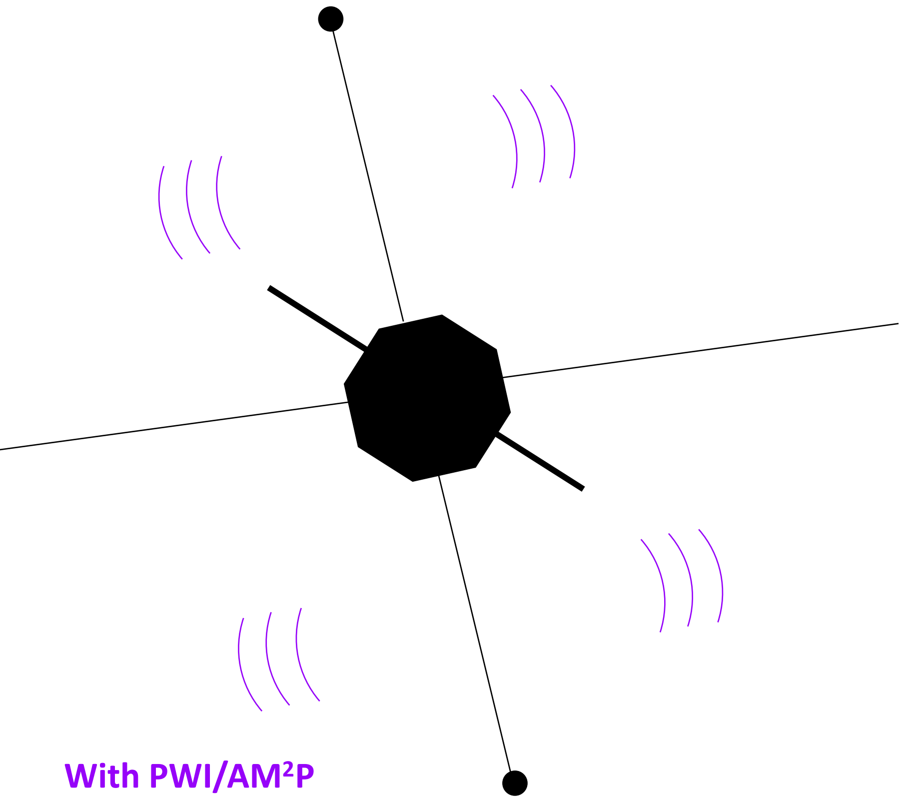


With PWI/AM²P onboard BepiColombo

Mutual Impedance

Measurement principle:

1. Current emitted by the emitting wires at a frequency ω
2. The signal is propagating through the plasma → dielectric response



With PWI/AM²P onboard BepiColombo

Mutual Impedance

Measurement principle:
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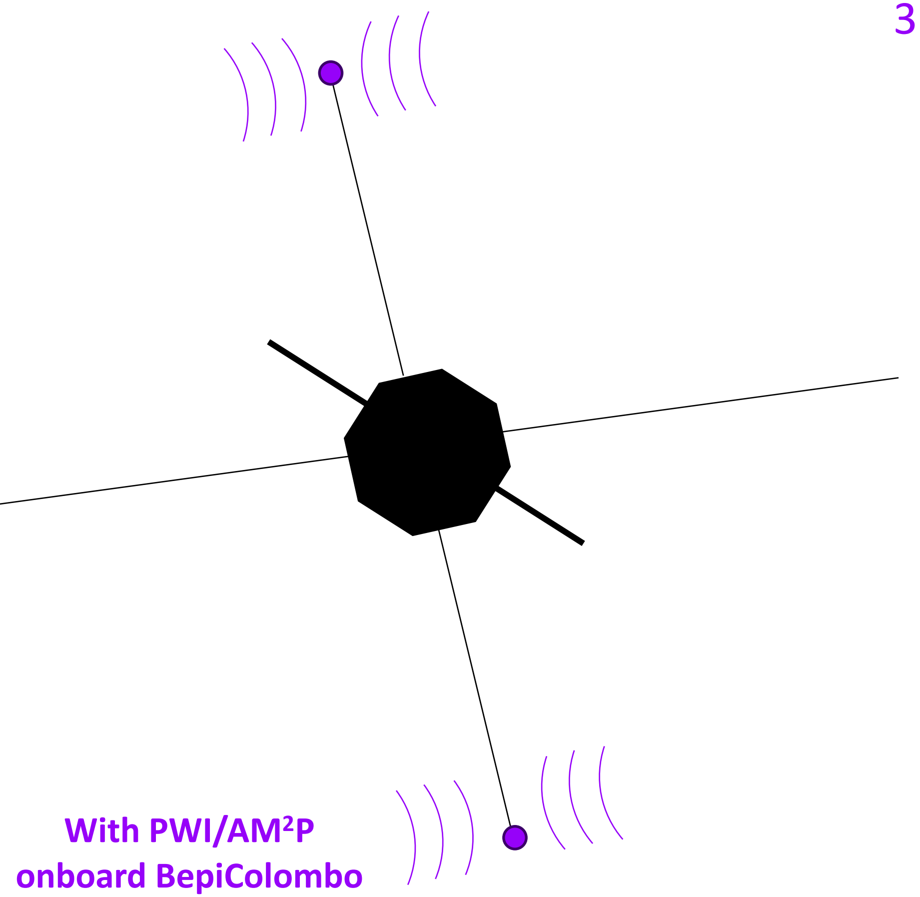
2. The signal is propagating through the plasma → dielectric
3. We measure the potential seen by the receiving spheres



With PWI/AM²P onboard BepiColombo

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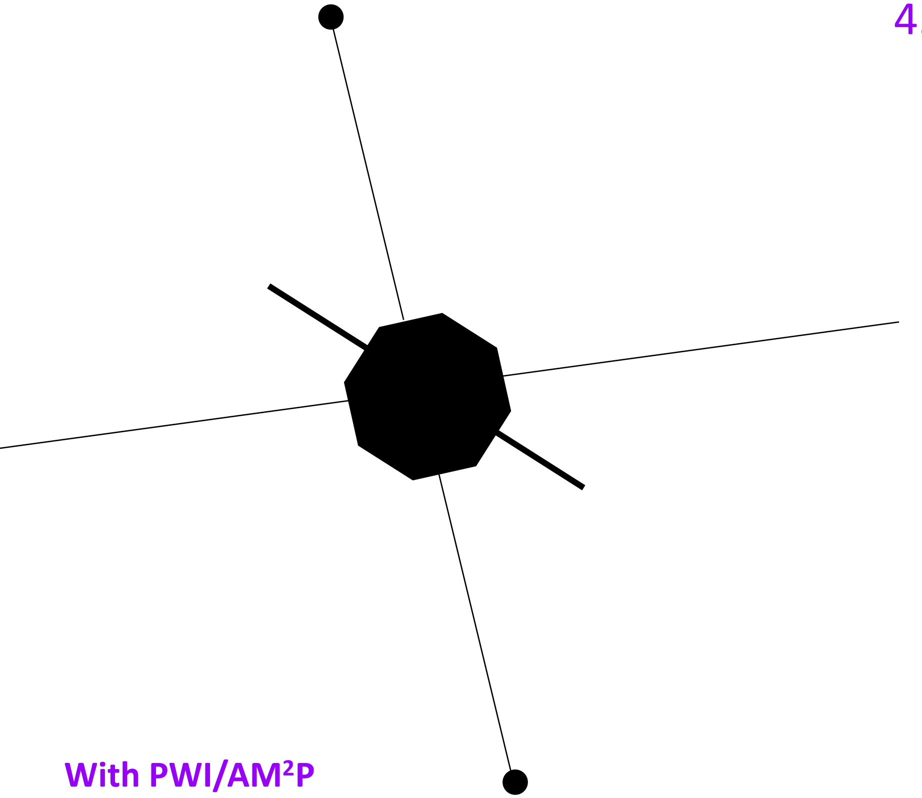
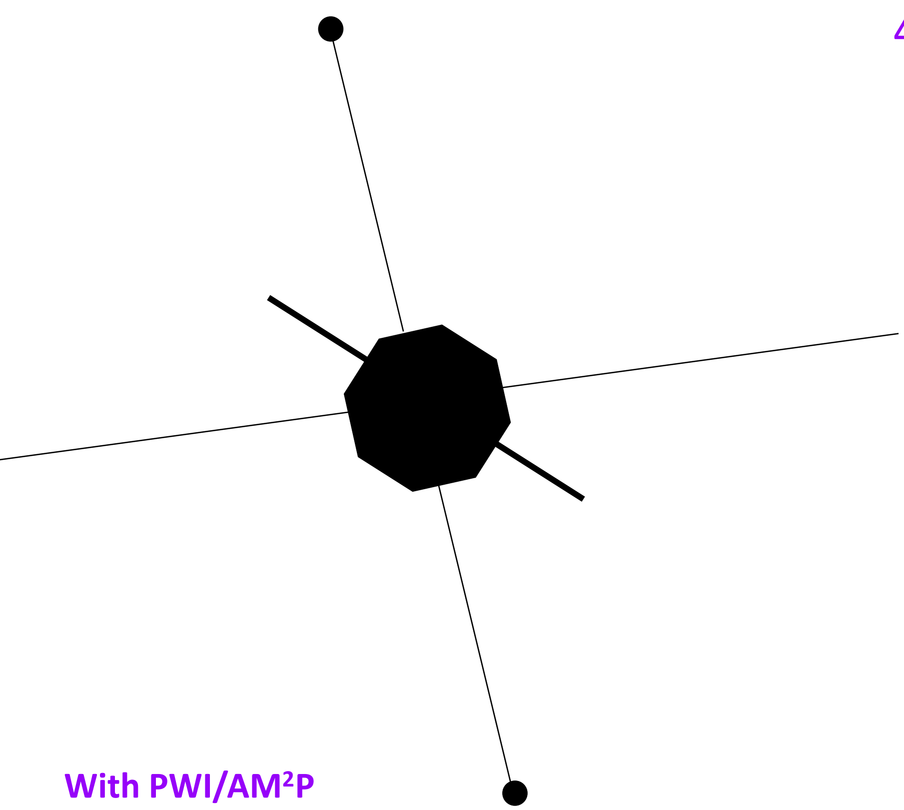
2. The signal is propagating through the plasma → dielectric
3. We measure the potential seen by the receiving spheres
4. We calculate the mutual impedance H(ω):

$$H(\omega) = \frac{\Delta Z}{\Delta Z_0} = \frac{V_{R_2}(\omega) - V_{R_1}(\omega)}{V_{R_2,0} - V_{R_1,0}}$$



With PWI/AM^{2}P onboard BepiColombo

Mutual Impedance



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At several frequencies:

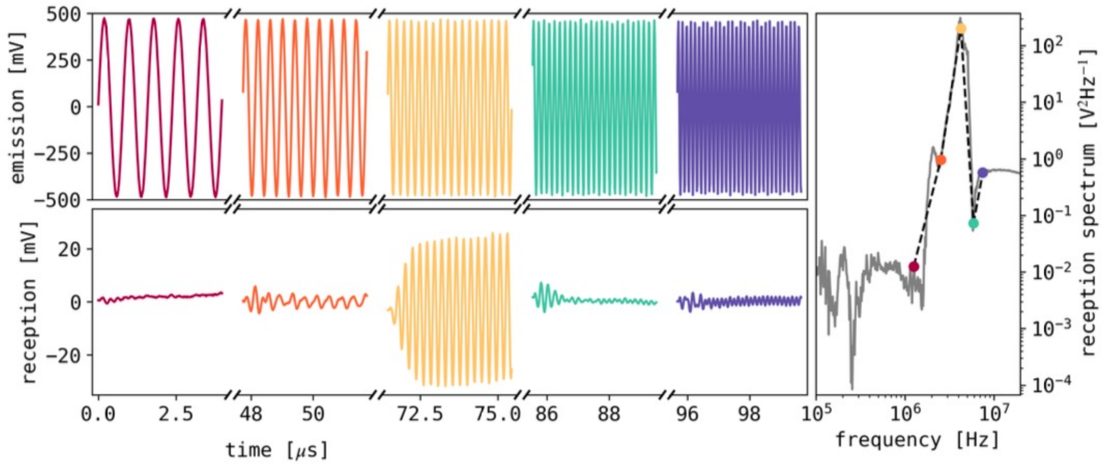
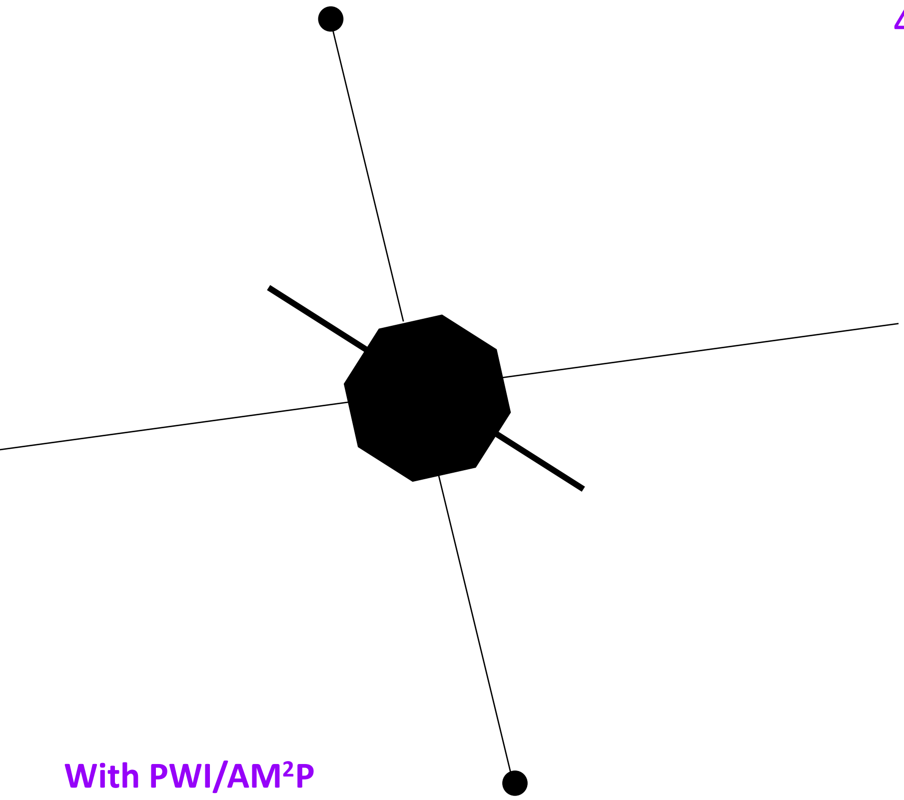


Fig. from P. Dazzi's thesis (2025)

With PWI/AM²P onboard BepiColombo

Mutual Impedance



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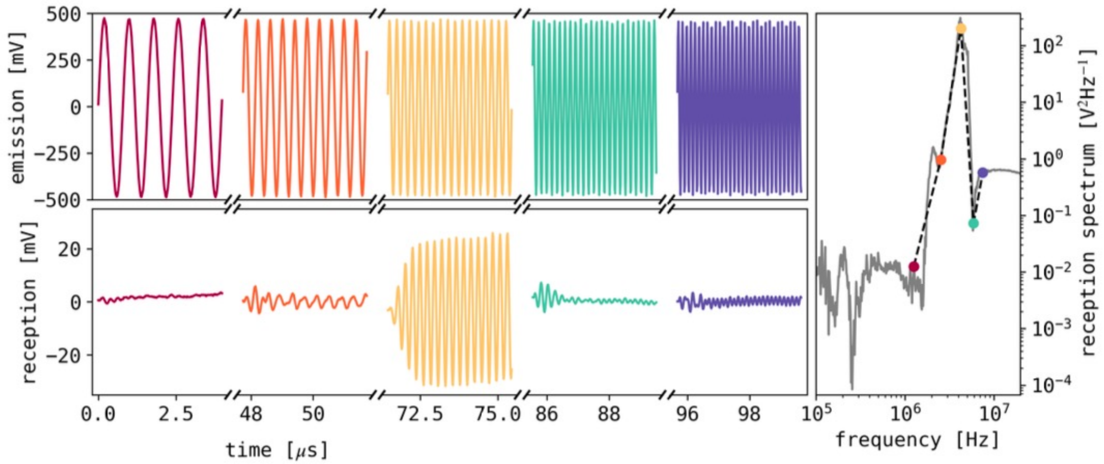

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Electron density n_e
Electron temperature T_e
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With PWI/AM²P onboard BepiColombo

Mutual Impedance

Te =

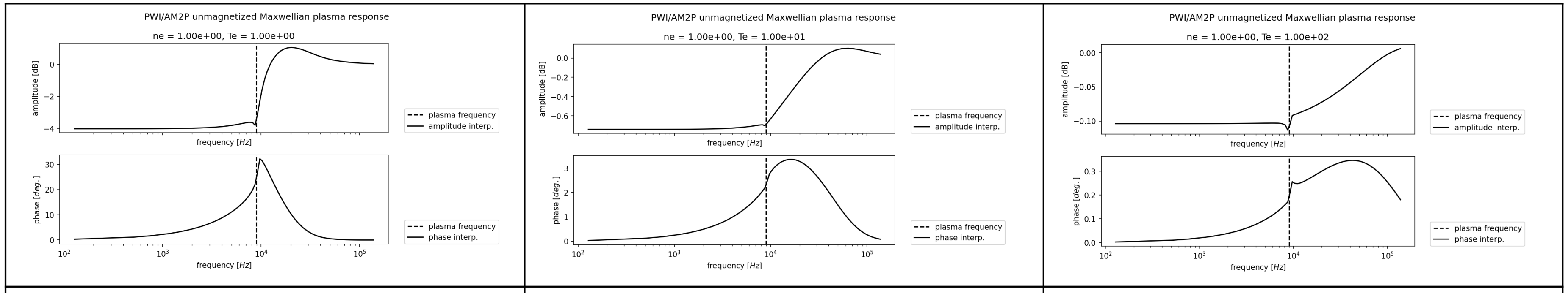
ne =

1 eV

10 eV

100 eV

$1\ cm^{-3}$



Spectrum shape depends on electron temperature
→ inverse problem

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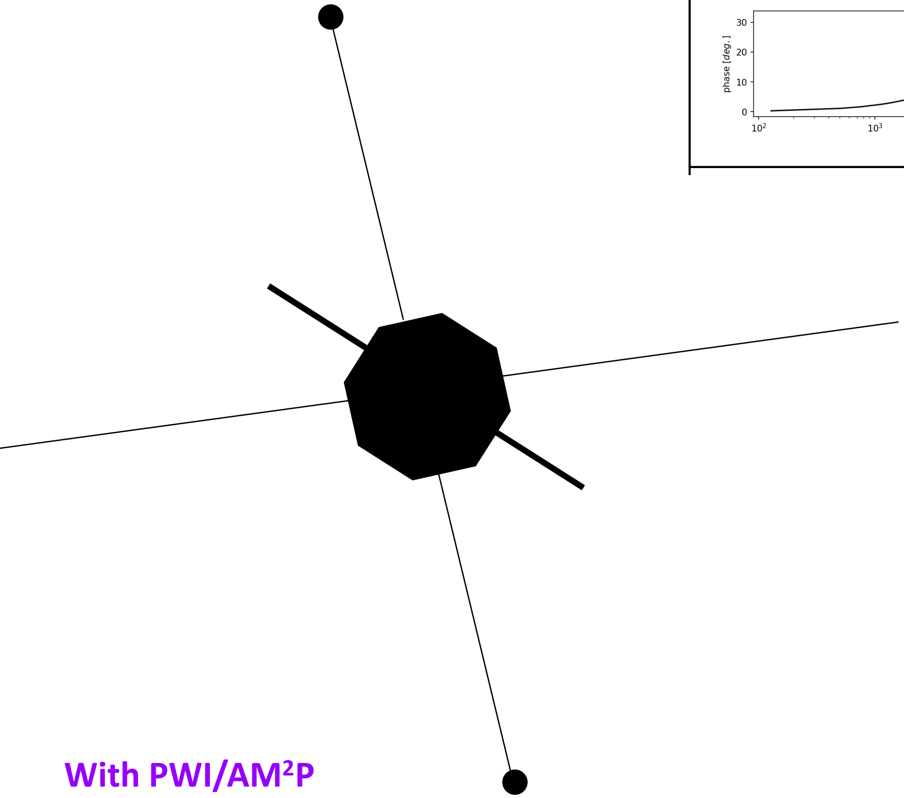

With PWI/AM²P onboard BepiColombo

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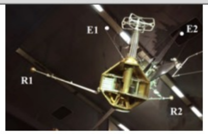
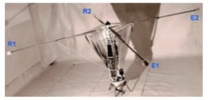
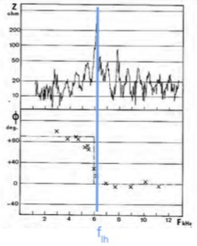
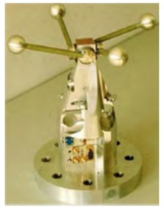
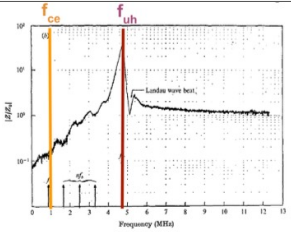
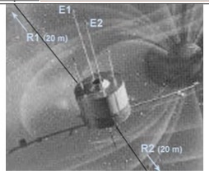
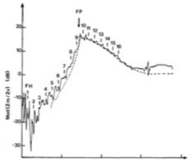
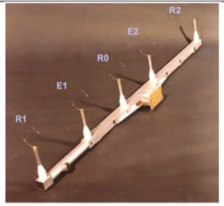
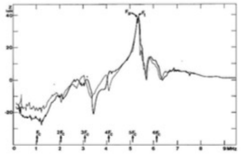
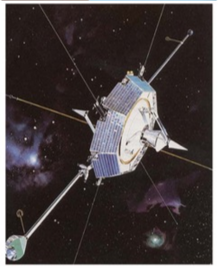
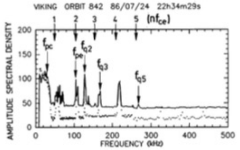
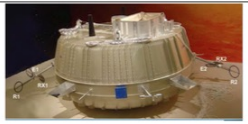
Historic of Mutual Impedance

Rocket sounding since 1969

Instrument	Géométrie	Exemple de données
Sonde quadripolaire à bord de la fusée French FR-1 [Storey et al., 1969]		
Sonde quadripolaire à bord de la fusée DRAGON-3 [Beghin, 1971]		
Sonde CISASPE à bord d'une fusée Véronique [Chasseriaux et al., 1972]		

Tables from N. Gilet's thesis (2017)

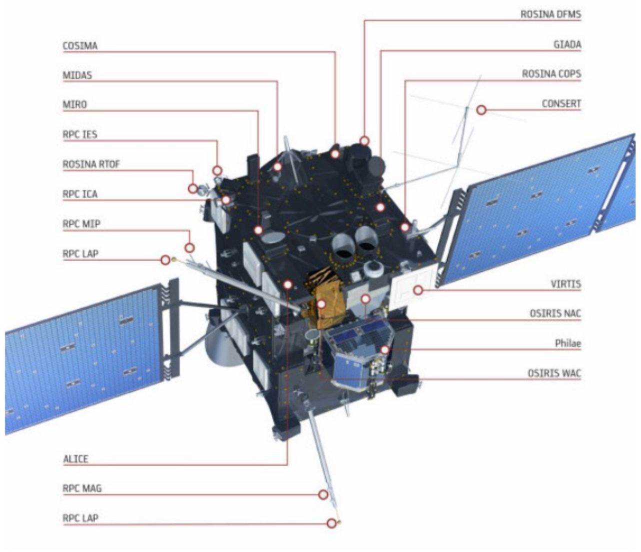
Onboard satellites since 1978

Instrument	Géométrie	Exemple de données
Sonde S-304 à bord de GEOS-1 [Décréau et al., 1978a]		
Sonde ISOBPROBE-3 à bord de ARCAD-3 [Beghin et al., 1982]		
Sonde à bord du satellite Viking [Bahnsen et al., 1986; Perraut et al., 1990]		
Sonde PWA à bord du satellite HUYGENS [Hamelin et al., 2007]		

Historic of Mutual Impedance

Recent space missions equiped with mutual impedance:

Instrument RPC-MIP, onboard Rosetta,
on 67P comet (up to 2016)



(Crédit : ESA/Science)

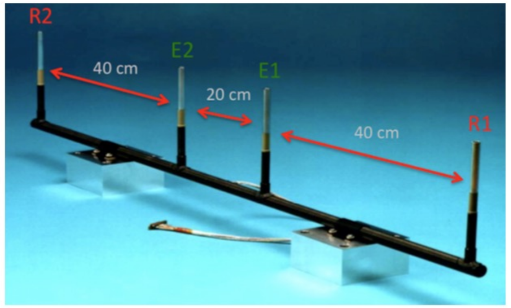


FIGURE 2.8 – La sonde à impédance mutuelle RPC-MIP à bord du satellite spatial *Rosetta* : sonde d'un mètre de long possédant deux émetteurs E_1 et E_2 et deux récepteurs, R_1 et R_2 à ses extrémités. Adaptée de Trotignon et al. [2007].

Figure from N. Gilet's thesis (2017)

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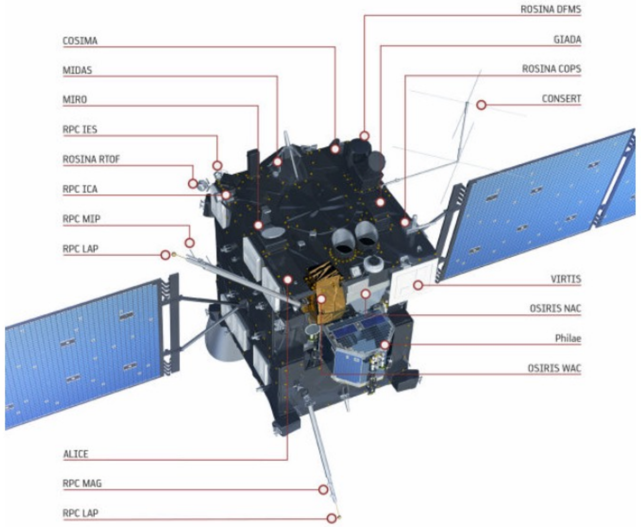

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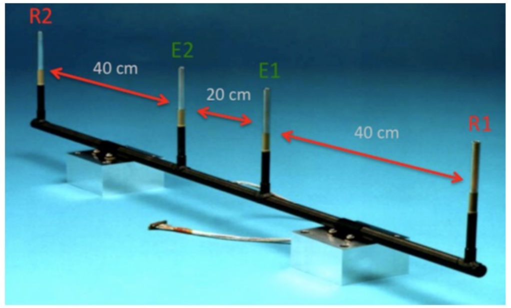

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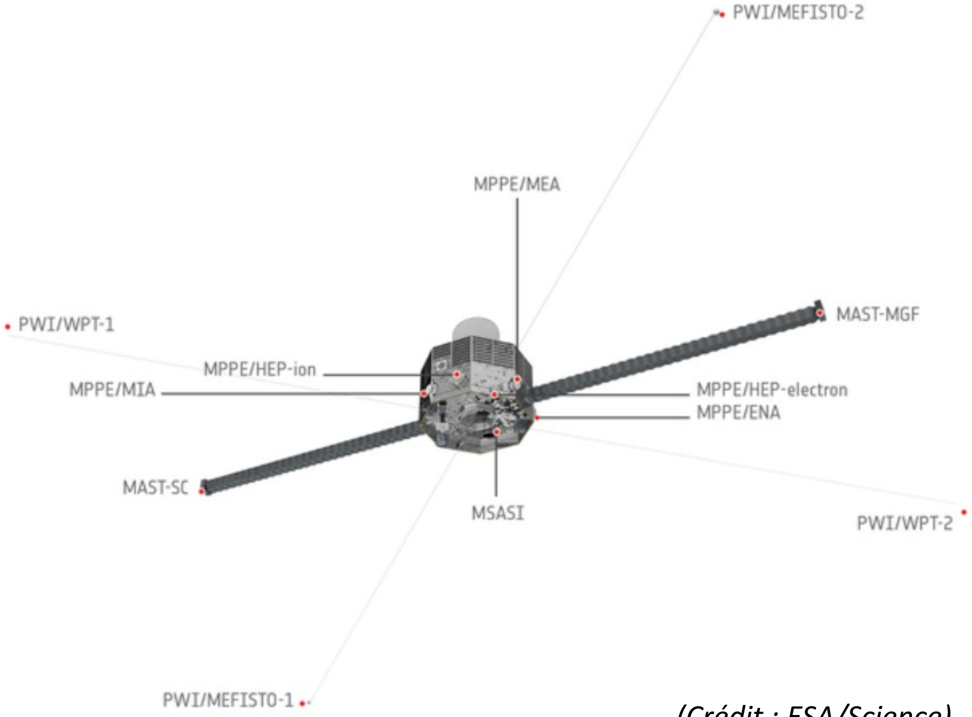
Figure from N. Gilet's thesis (2017)

Instrument PWI/AM2P, onboard BepiColombo,
soon around Mercury (in 2027)

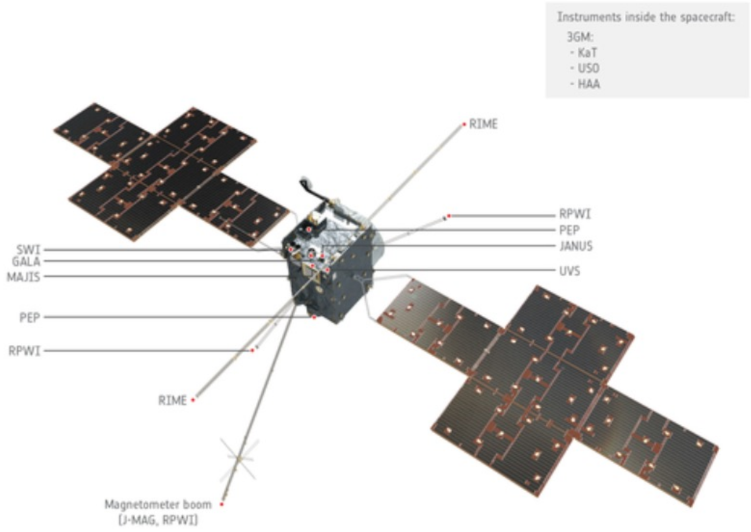


(Crédit : ESA/Science)

Historic of Mutual Impedance

Recent/future space missions equiped with mutual impedance:

Instrument RPWI/MIME, onboard JUICE, around Jupiter and his moons (from 2031)



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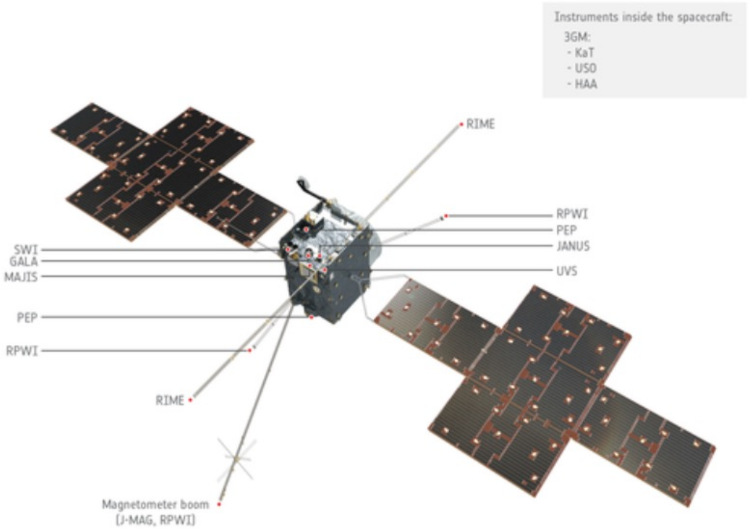
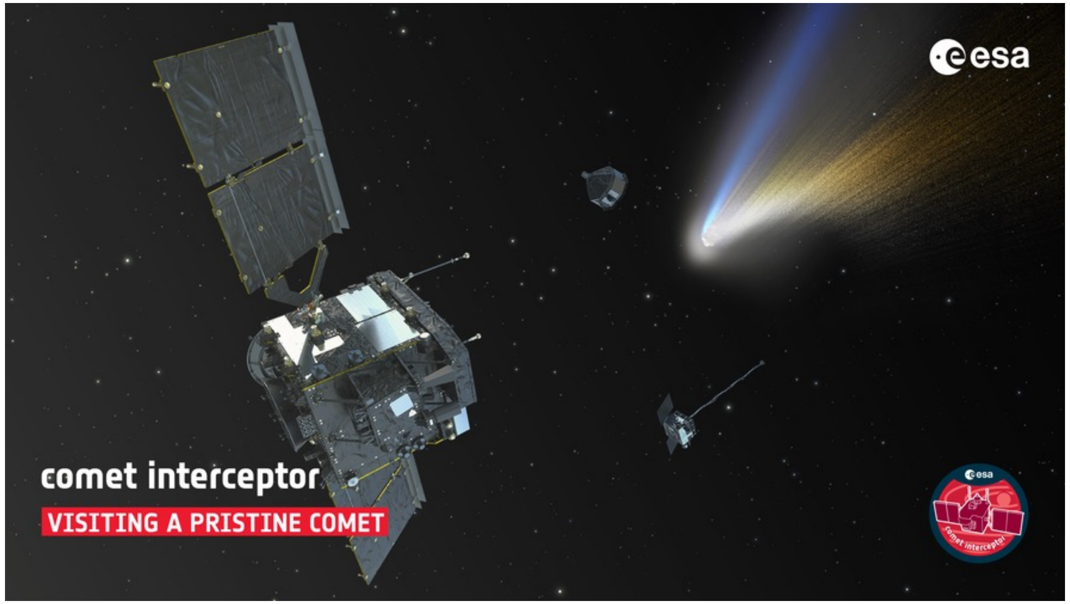


(Crédit : ESA/Science)

Instrument DFP/Compliment, onboard Comet Interceptor, through a pristine comet (launch ~2029)



Objectives

Prepare the BepiColombo future data

- Diagnostic of electron populations

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But also:

- Try to make a diagnostic of ions *in some configurations*!

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Why?

- the response is dominated by electrons
- ions oscillate at lower frequencies
  → frequencies not in the instrumental frequency range

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How:

We need to add the ion contribution in AM^{2}P response model

Instrumental Response **Modeling** of Mutual Impedance

We measure: $V_R(\omega)$
which depends on: $\varepsilon(k, \omega)$

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We need to calculate $\varepsilon(k,\omega)$ theoretically:

Vlasov + Poisson equations

$$\begin{cases} \dfrac{\partial f}{\partial t}(\mathbf{x},\mathbf{v},t) + \mathbf{v}.\nabla_{\mathbf{x}} f(\mathbf{x},\mathbf{v},t) + \dfrac{e}{m_e}\mathbf{E}.\nabla_{\mathbf{v}} f(\mathbf{x},\mathbf{v},t) = 0 \\ \nabla.\mathbf{E} = \dfrac{e}{\varepsilon_0}\displaystyle\int f(\mathbf{x},\mathbf{v},t)\,d\mathbf{v} \end{cases}$$

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Instrumental Response **Modeling** of Mutual Impedance

We measure: $V_R(\omega)$
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We need to calculate $\varepsilon(k,\omega)$ theoretically:

$$\phi(\omega, r) = \frac{Q}{4\pi\varepsilon_0}\frac{2}{\pi}\lim_{\mathrm{Im}(\omega)\to 0}\int_0^{+\infty}\frac{\sin(kr)}{kr}\frac{dk}{\varepsilon_l(\omega,k)}$$

Vlasov + Poisson equations → Linearisation + Fourier → Use Maxwellian velocity function → Calculate dielectric $\varepsilon(k,\omega)$ → Calculate the wave potential V/V_0

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\+ We take into account the spacecraft influence (with DSCD code)

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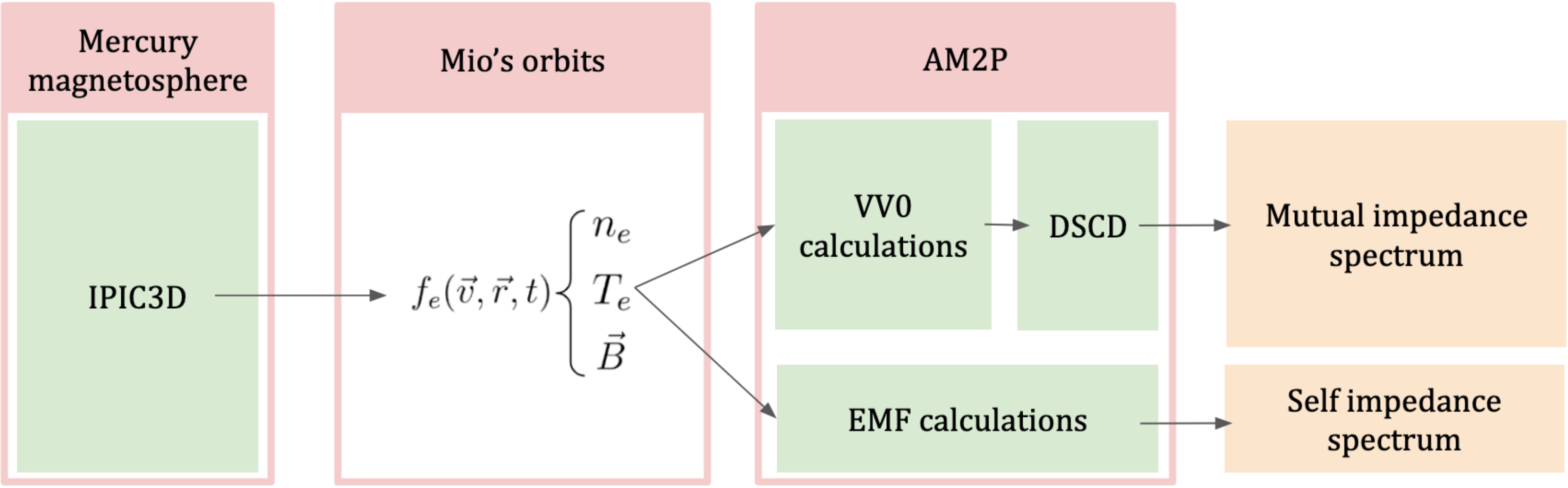
→ Diagnostic of electron population:

currently working on simulations of the future data measured by BepiColombo:

[Pallu et al., to be submitted in July]



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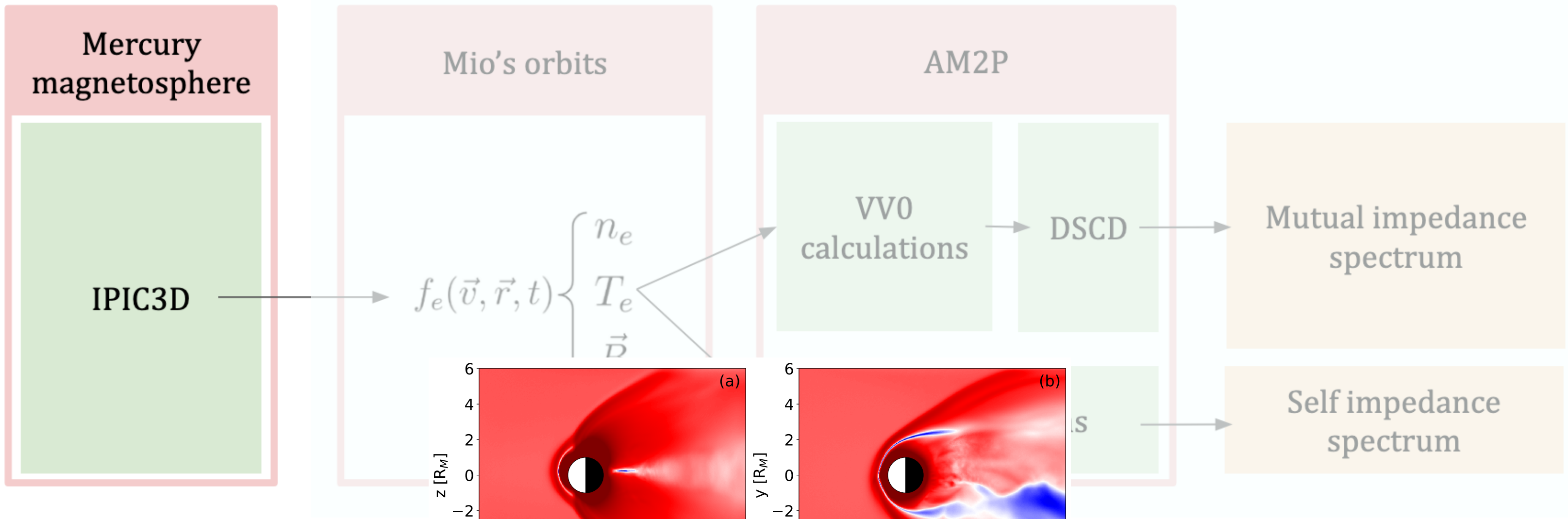

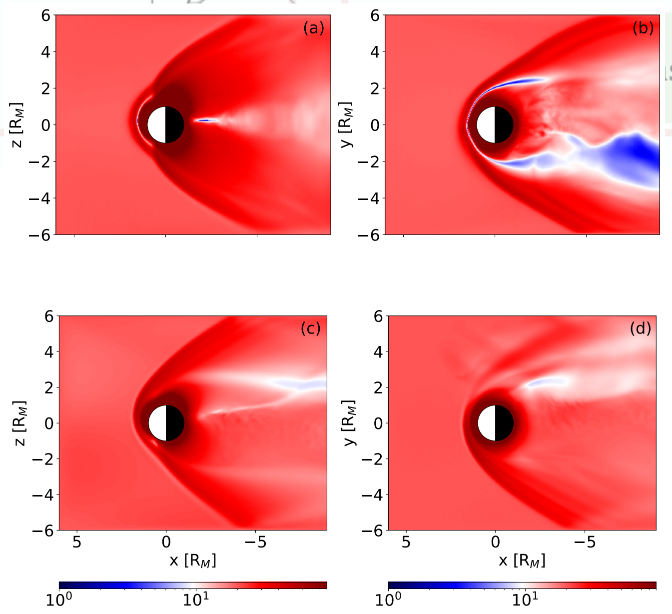

[Ballerini et al., 2024]

Instrumental Response **Modeling** of Mutual Impedance

→ Diagnostic of electron population:

currently working on simulations of the future data measured by BepiColombo:

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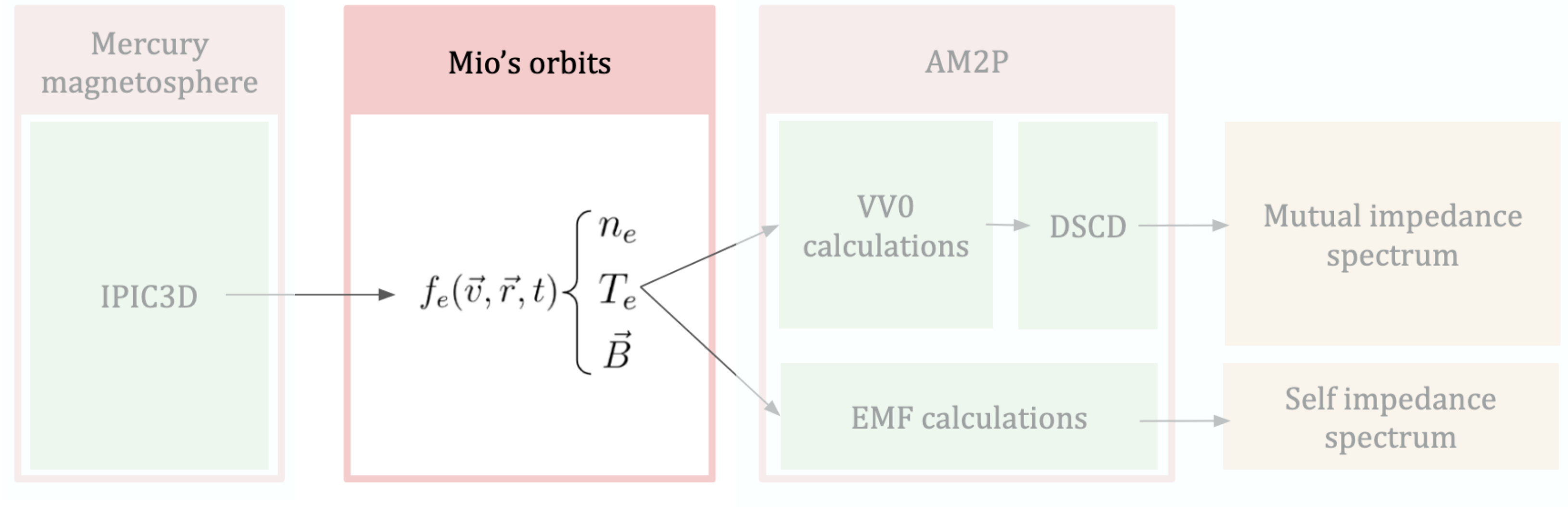

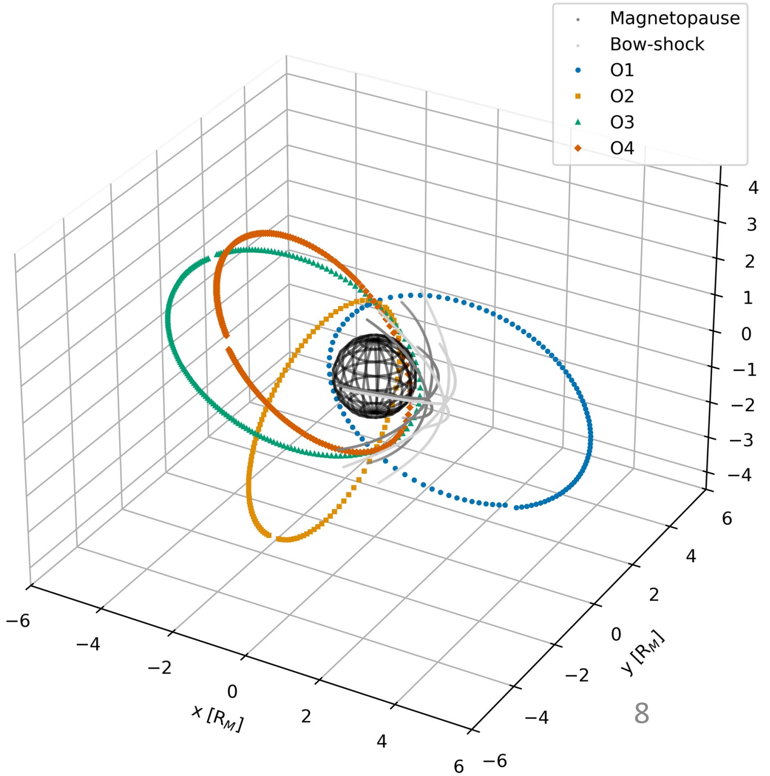

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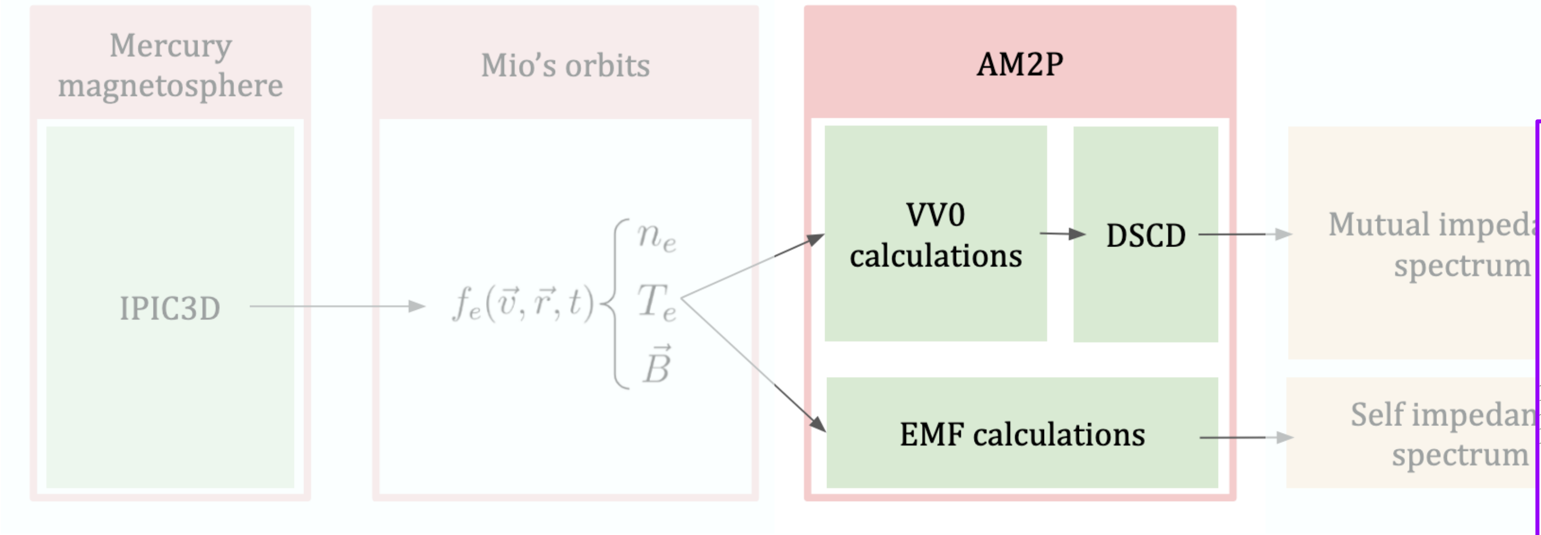

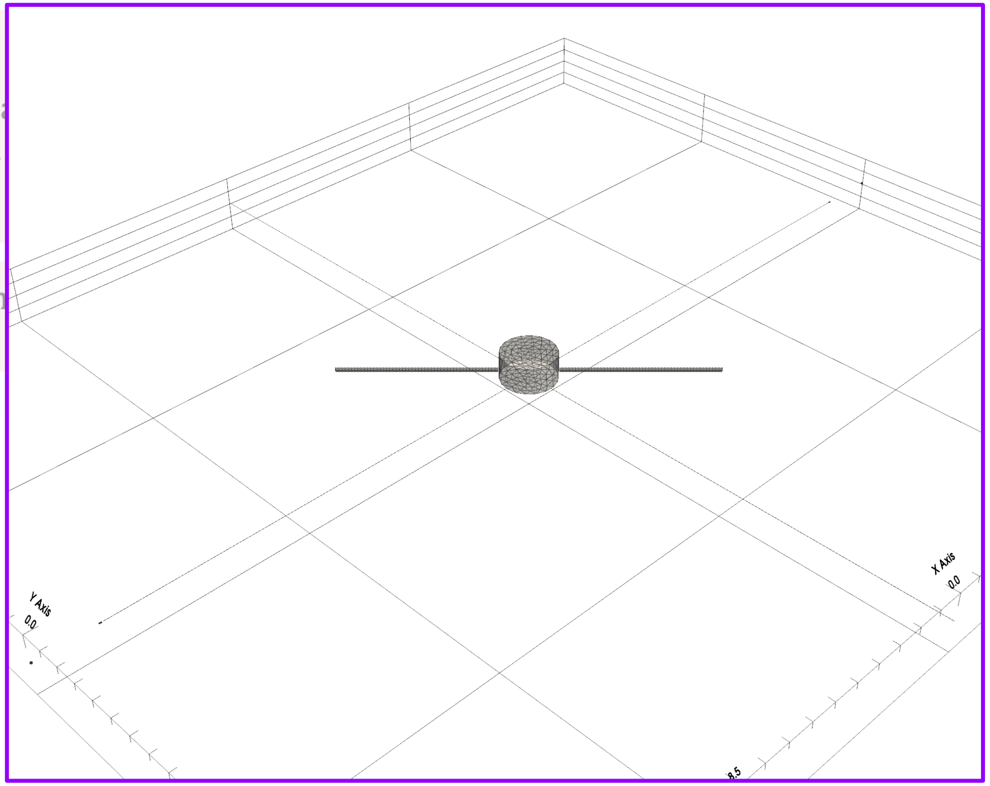

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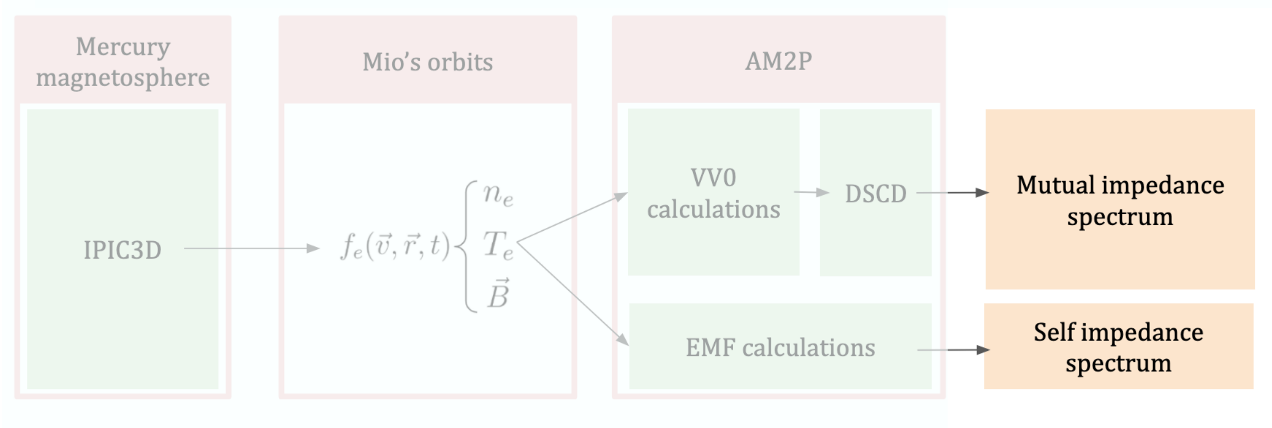

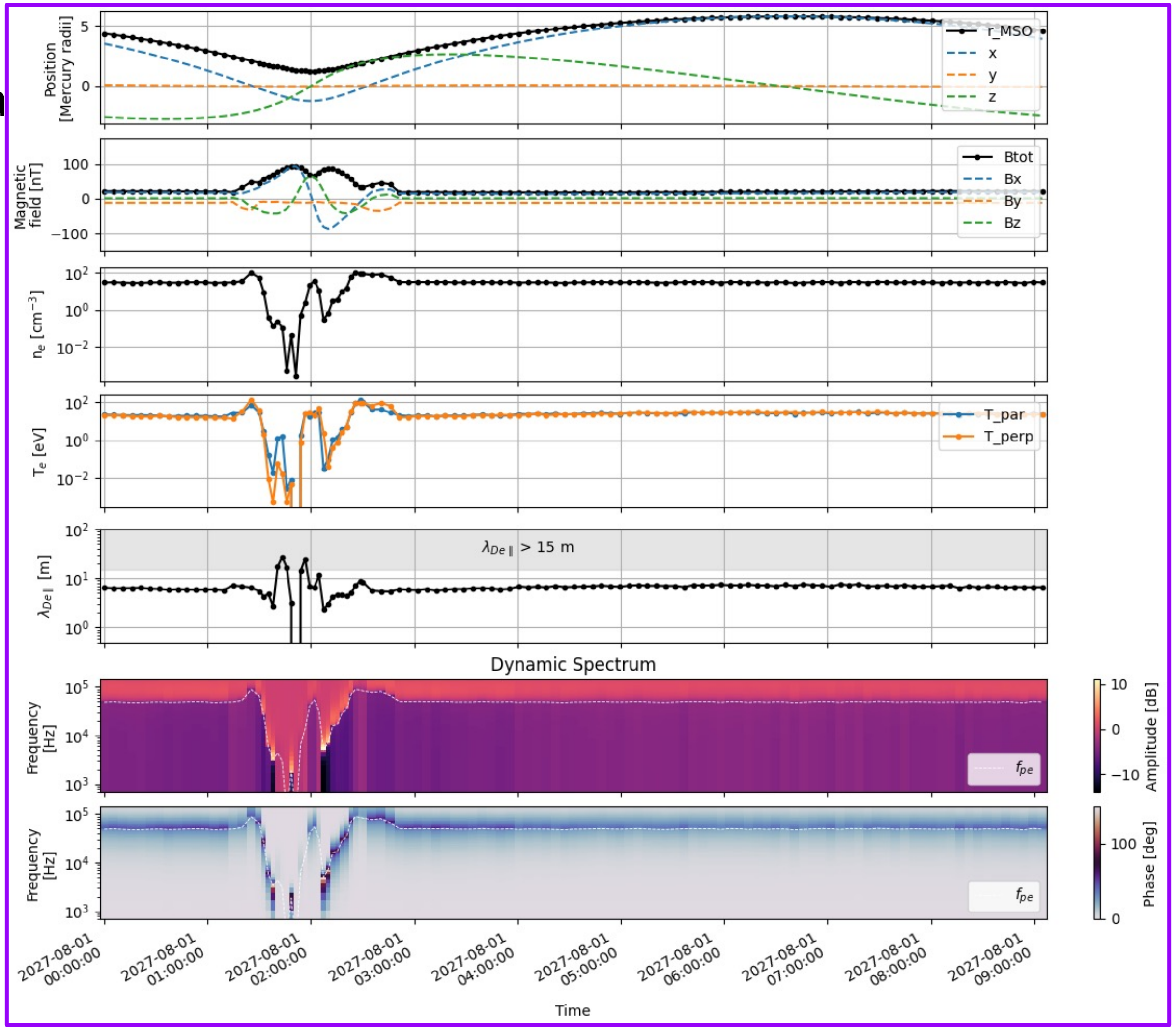

[Pallu, Dazzi, Henri, Vallières, Ballerini, Carme, Elliott, et al., to be submitted in July]

Objectives

Prepare the BepiColombo future data

- Diagnostic of electron populations

But also:

- Try to make a diagnostic of ions *in some configurations*!

Why?

- the response is dominated by electrons
- ions oscillate at lower frequencies
  → frequencies not in the instrumental frequency range

How:

We need to add the ion contribution in AM^{2}P response model

Instrumental Response Modeling

We measure: $V_R(\omega)$
which depends on: $\varepsilon(k,\omega)$

We need to calculate $\varepsilon(k,\omega)$ theoretically:

Vlasov + Poisson equations → Linearisation + Fourier → Use Maxwellian velocity function → Calculate dielectric $\varepsilon(k,\omega)$ → Calculate the wave potential V/V_0

$$\begin{cases} \frac{\partial f}{\partial t}(\mathbf{x},\mathbf{v},t) + \mathbf{v}.\nabla_{\mathbf{x}} f(\mathbf{x},\mathbf{v},t) + \frac{e}{m_e}\mathbf{E}.\nabla_{\mathbf{v}} f(\mathbf{x},\mathbf{v},t) = 0 \\ \nabla.\mathbf{E} = \frac{e}{\varepsilon_0}\int f(\mathbf{x},\mathbf{v},t)d\mathbf{v} \end{cases}$$

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Also done for two **maxwellian** distribution functions!

→ **Use this code and adapt it for 2 populations:**
- one electron population
- one ion population

Comparison of cases

Electron maxwellian:

2 Electron maxwellian:

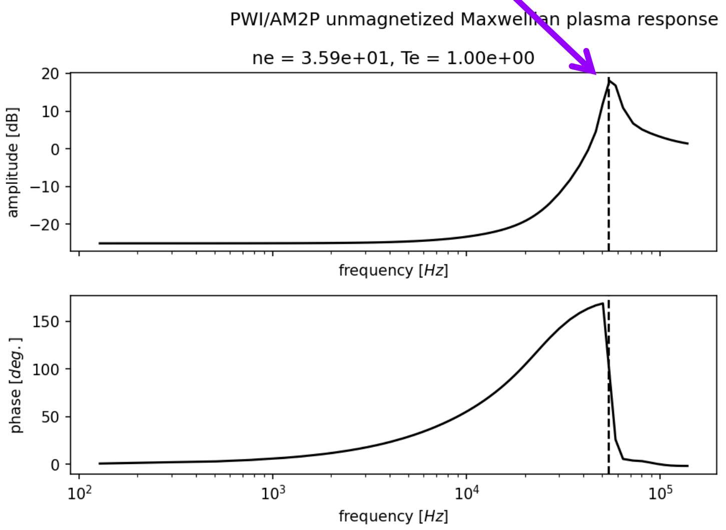
2 Electron/ion maxwellian:

Comparison of cases

Electron maxwellian:

e^- population with (T_e, n_e)

Only Langmuir waves and f_{pe} visible



Spectrum from modelisation

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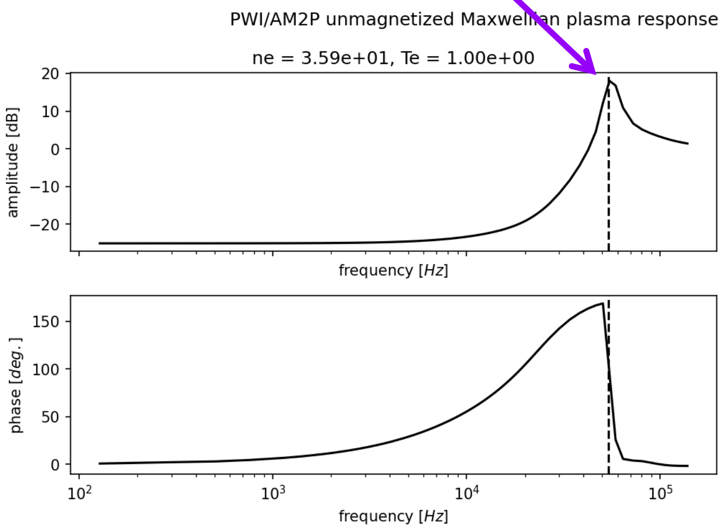

Spectrum from modelisation

2 Electron maxwellian:

e_H population with (T_H, n_H)
e_C population with (T_C, n_C)

These parameters were used:

$\mu = n_H/n_C$
$\tau = T_H/T_c$

Necessary: $T_H >> T_C$

2 waves:
Langmuir and electron acoustic waves

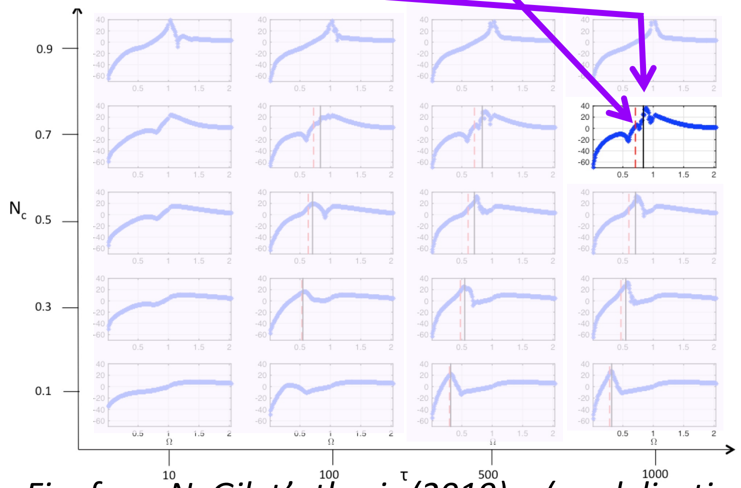

Fig. from N. Gilet's thesis (2019) – (modelisation)

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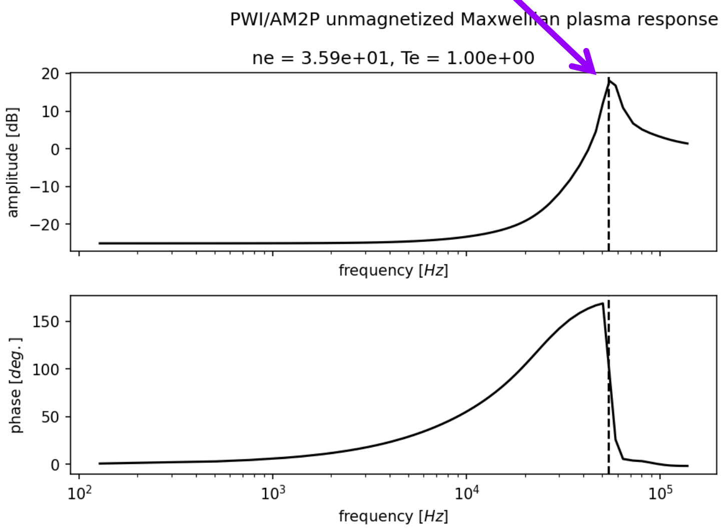

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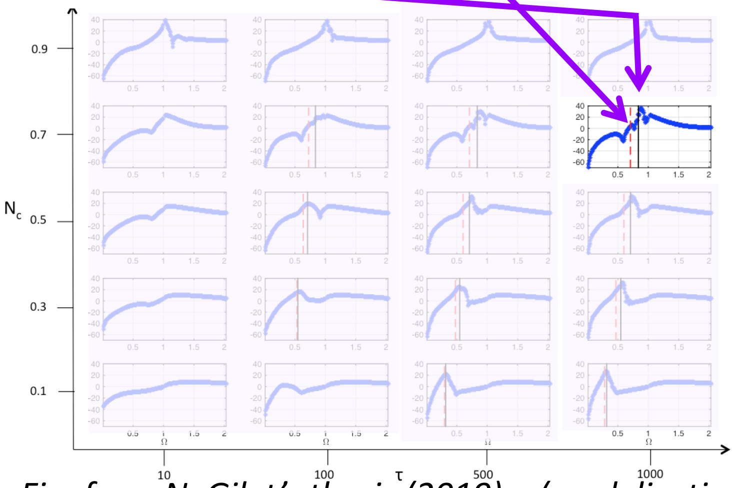

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$$\epsilon(k,\omega) = 1 - \frac{1}{k^2} Z'(\mathrm{Xi}_e) - \frac{1}{k^2}\frac{T_e}{T_i} Z'(\mathrm{Xi}_i)$$

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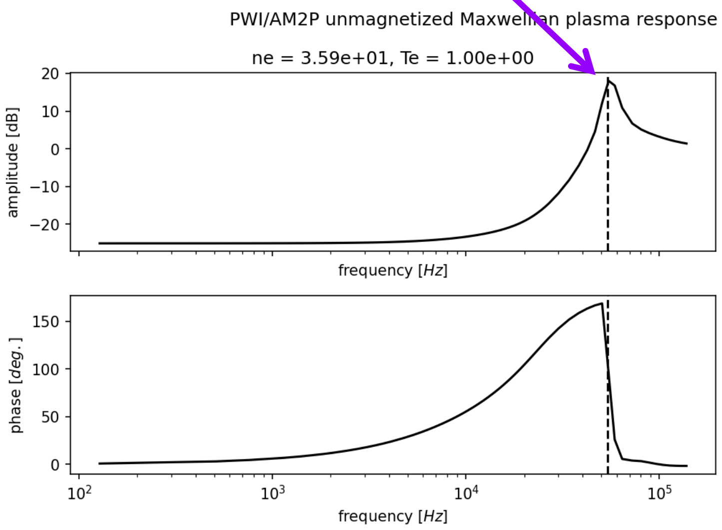

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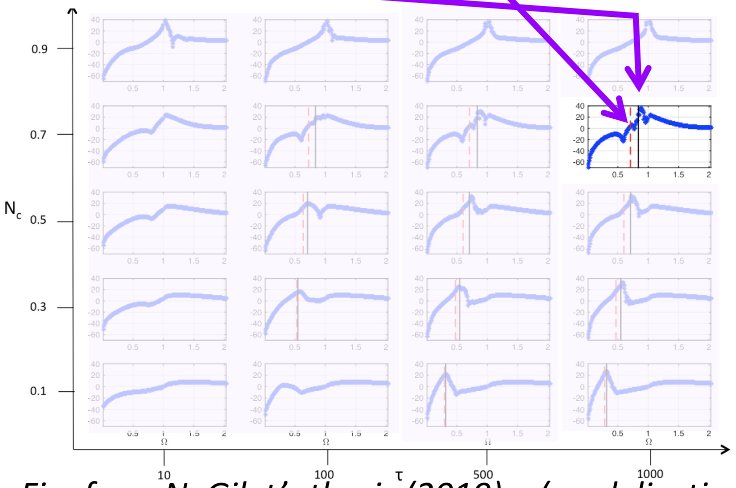

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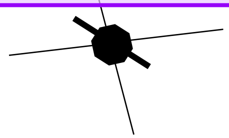
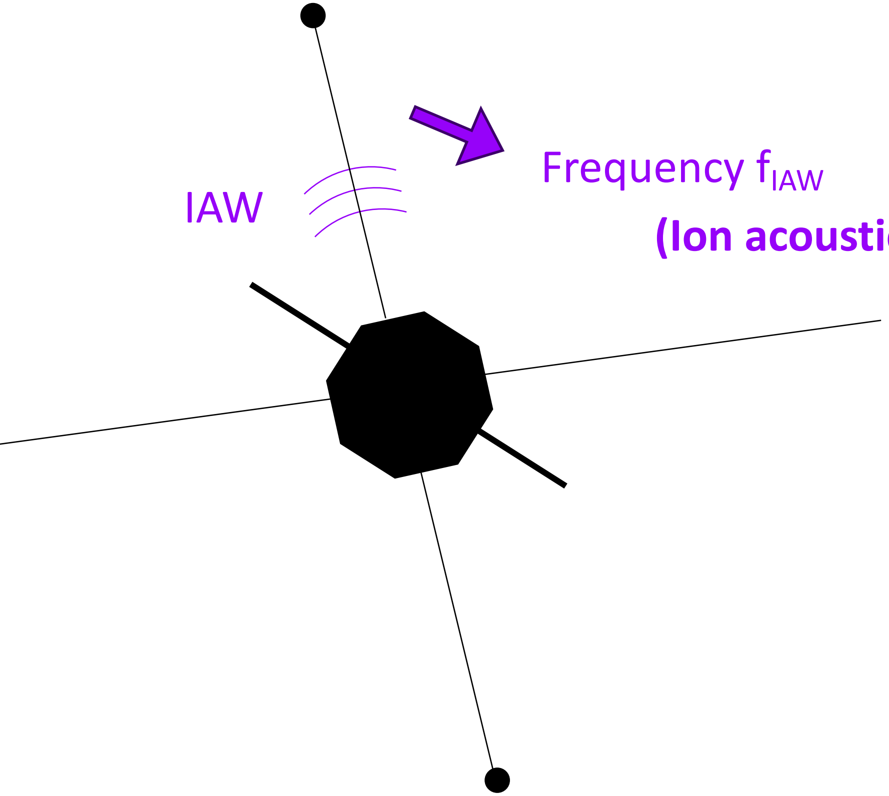
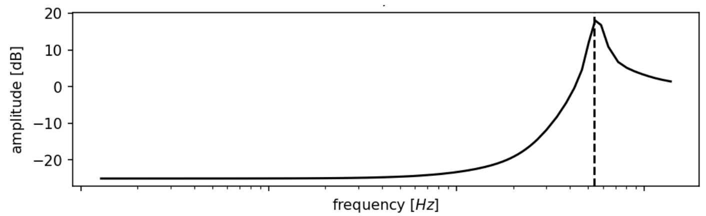
→ Possible in the solar wind with BepiColombo

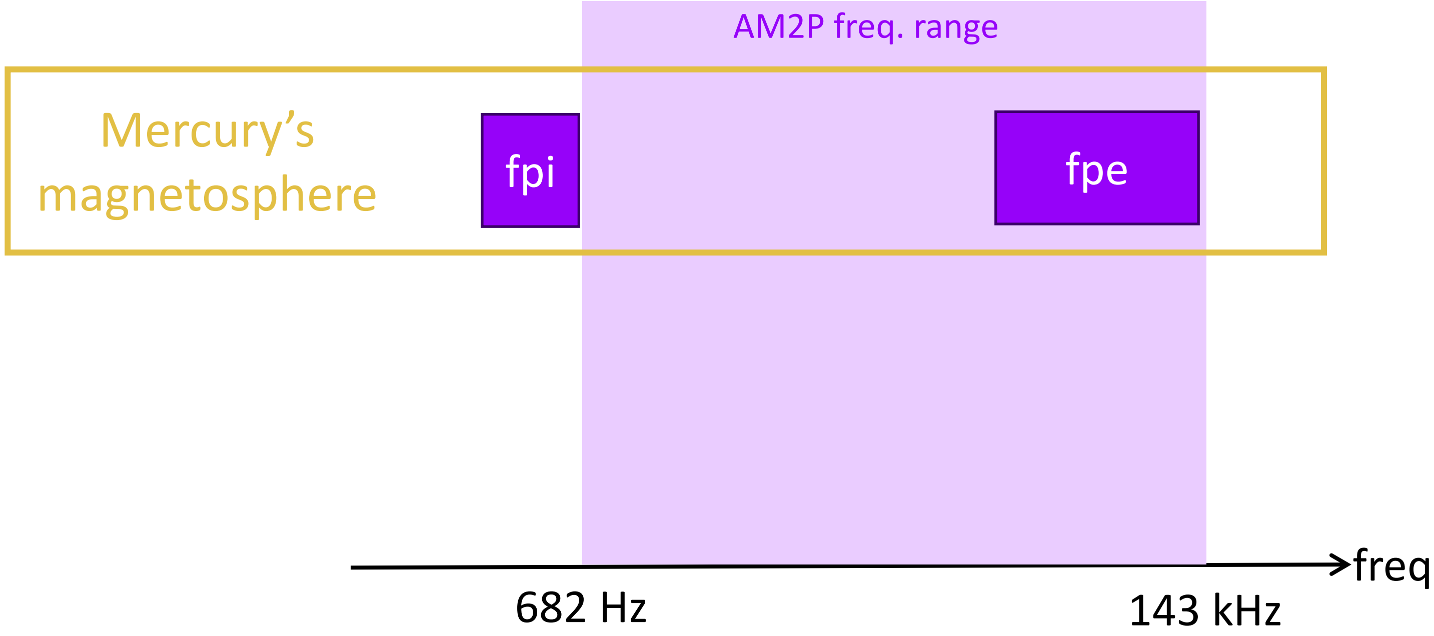


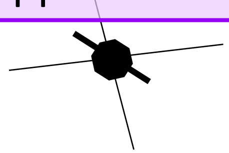


Frequency f_{IAW}

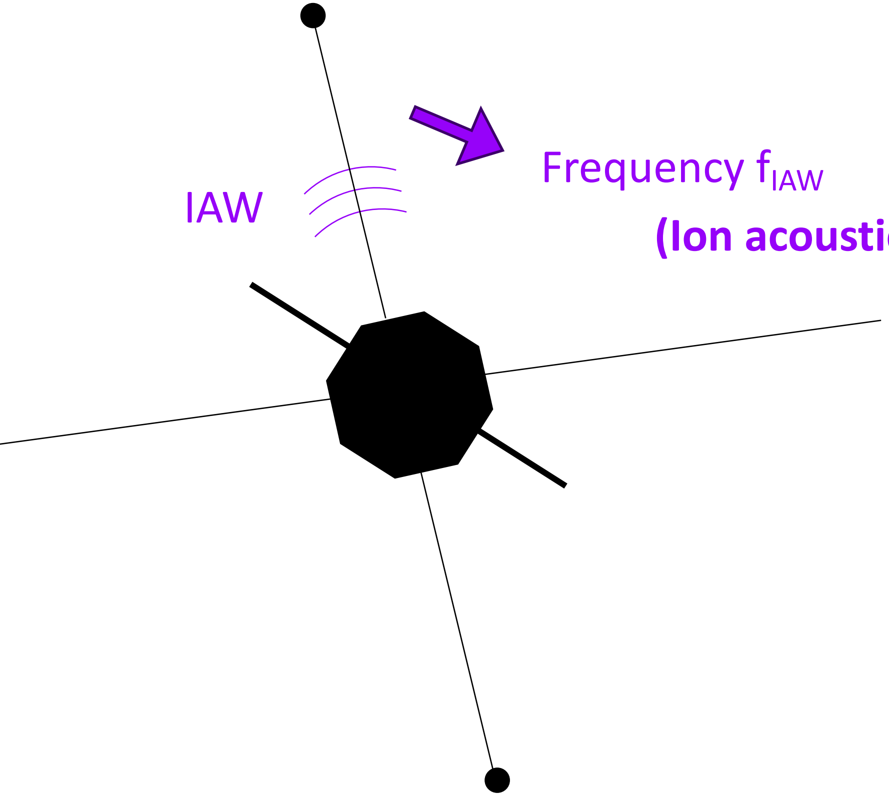
(Ion acoustic wave frequency)







BepiColombo will go
in the solar wind
for a big part of its orbits:



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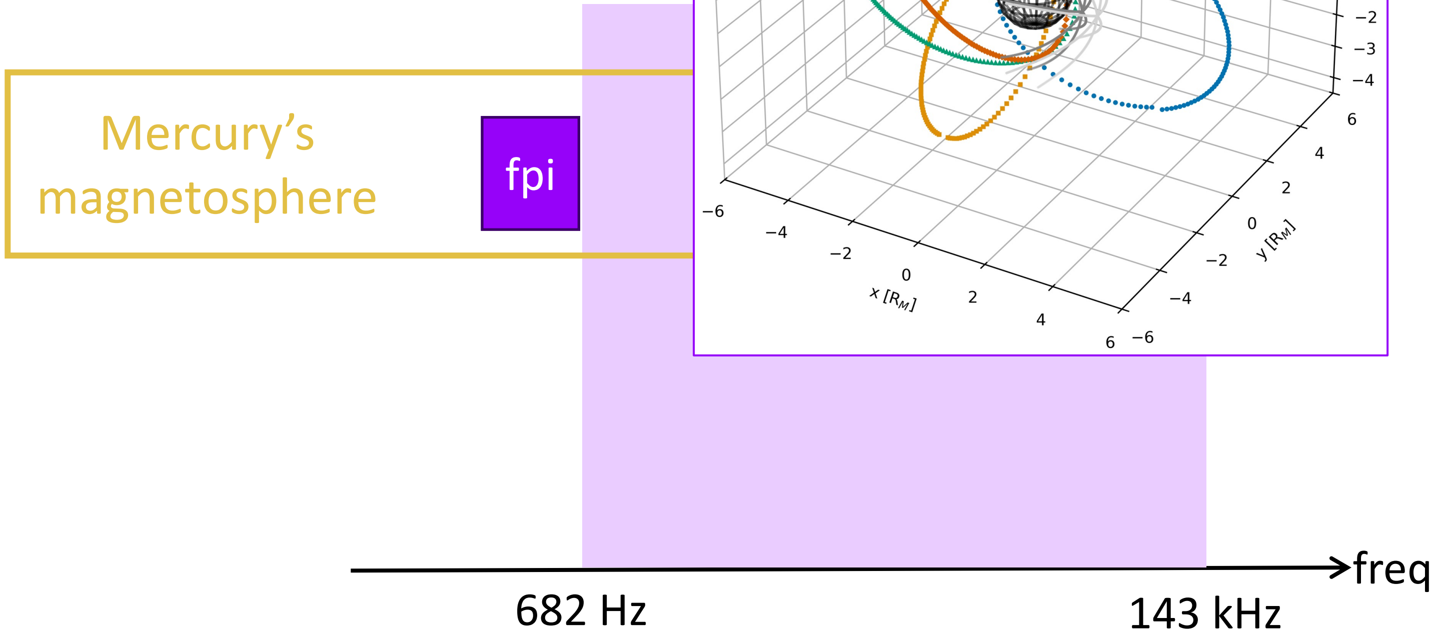
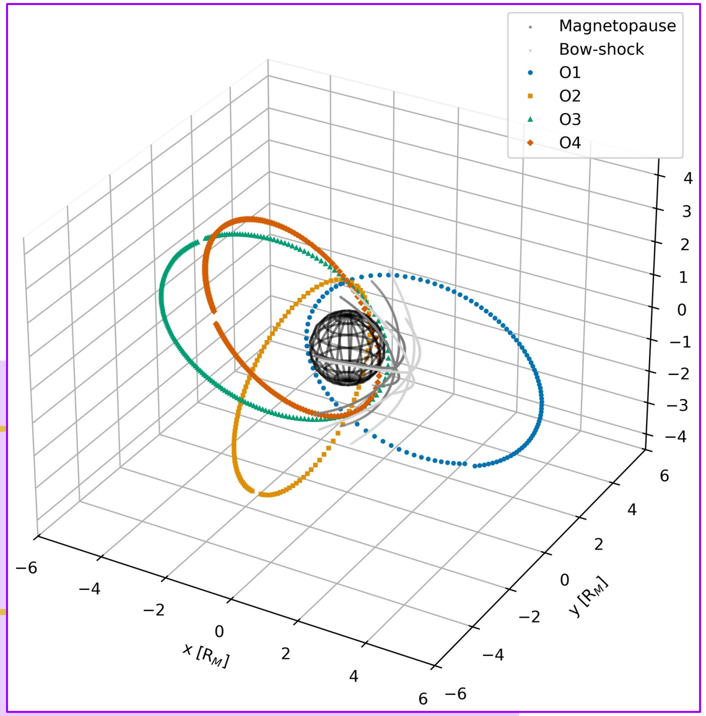
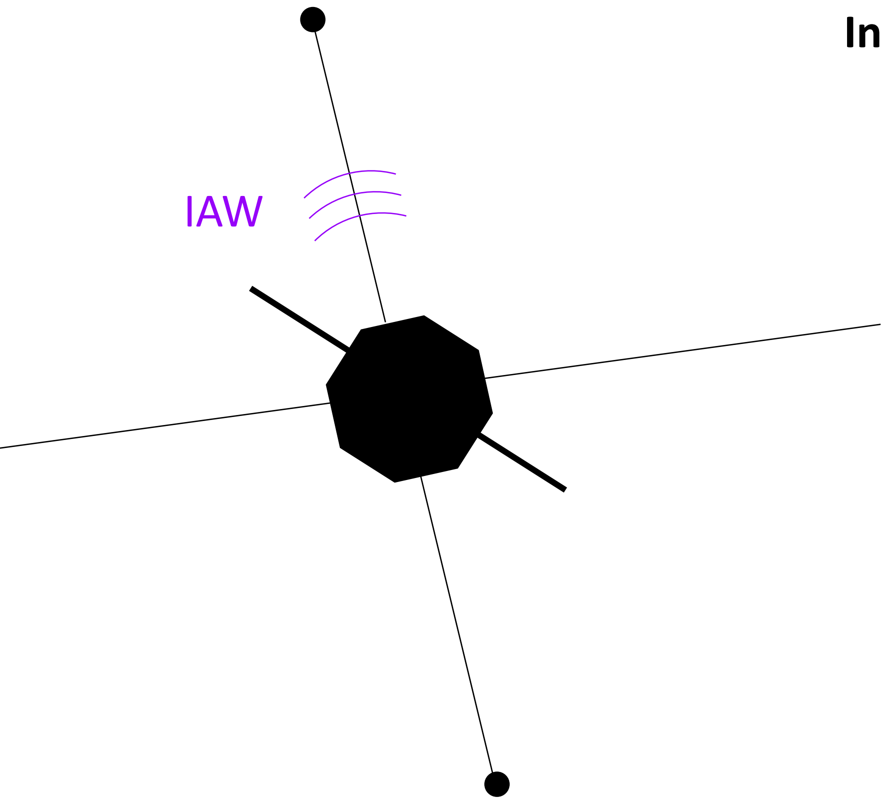
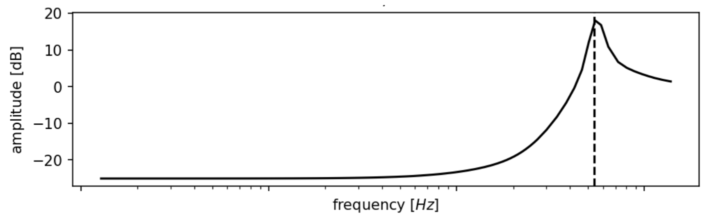


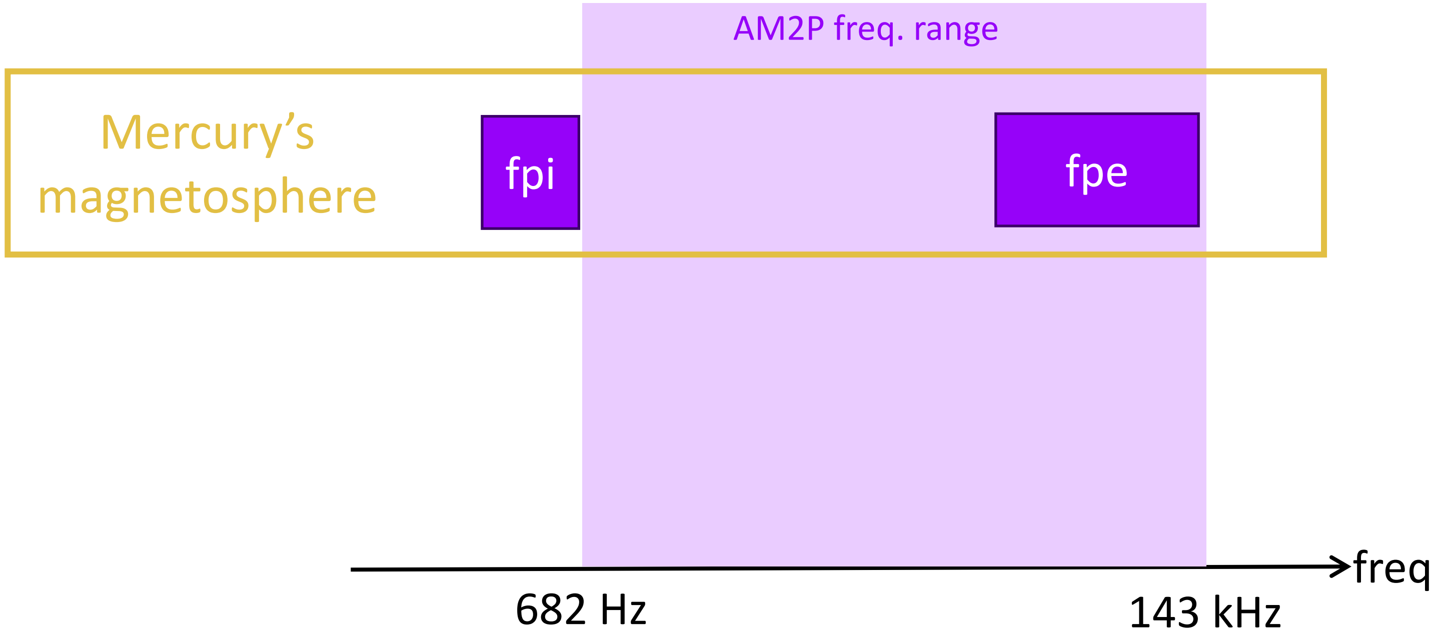


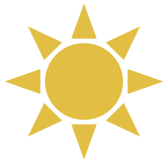
The power of the Doppler shift

In the solar wind:









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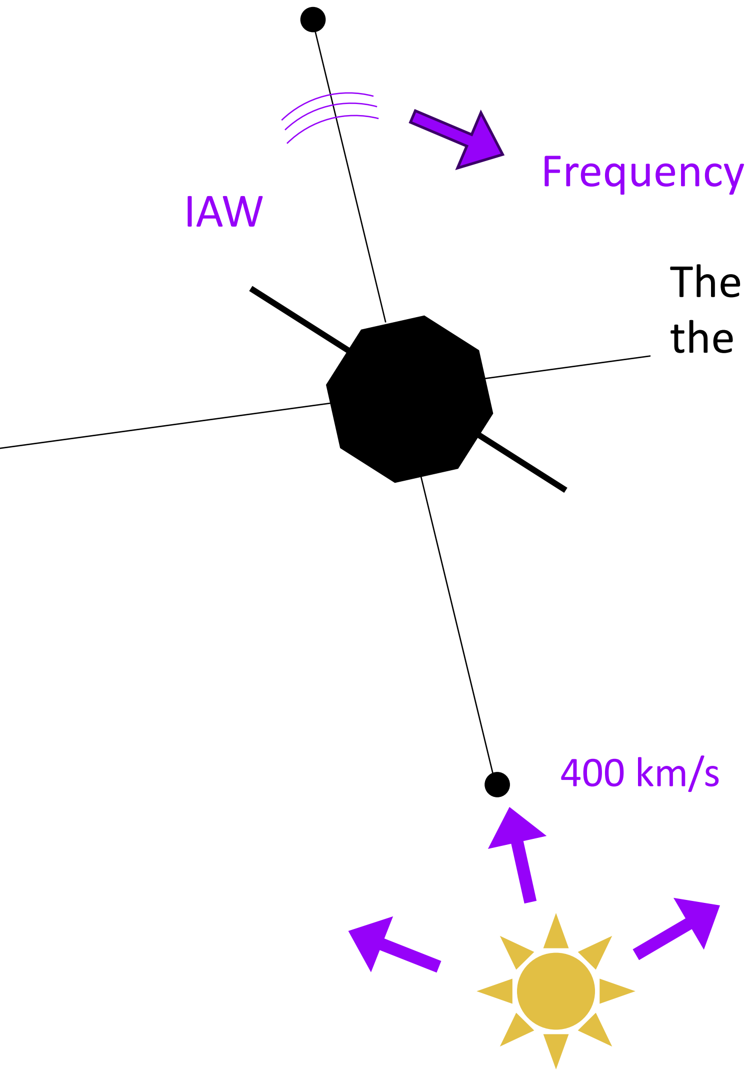
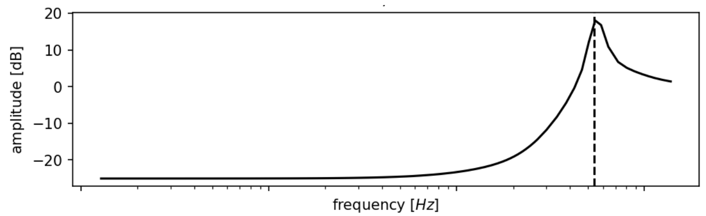


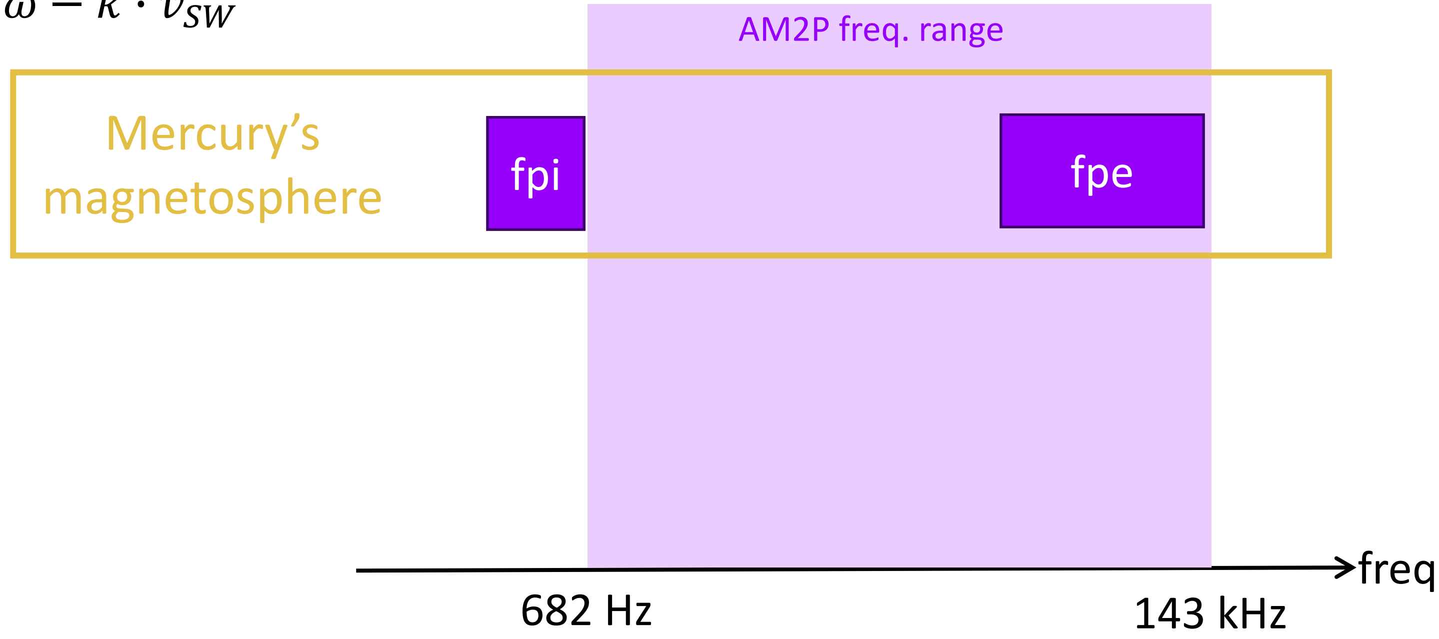
Frequency seen > f_{IAW} !

Solar wind

The spacecraft appears to be stationary, but the plasma is flowing with the solar wind:

$$\omega \rightarrow \omega' = \omega - \vec{k} \cdot \vec{v}_{SW}$$





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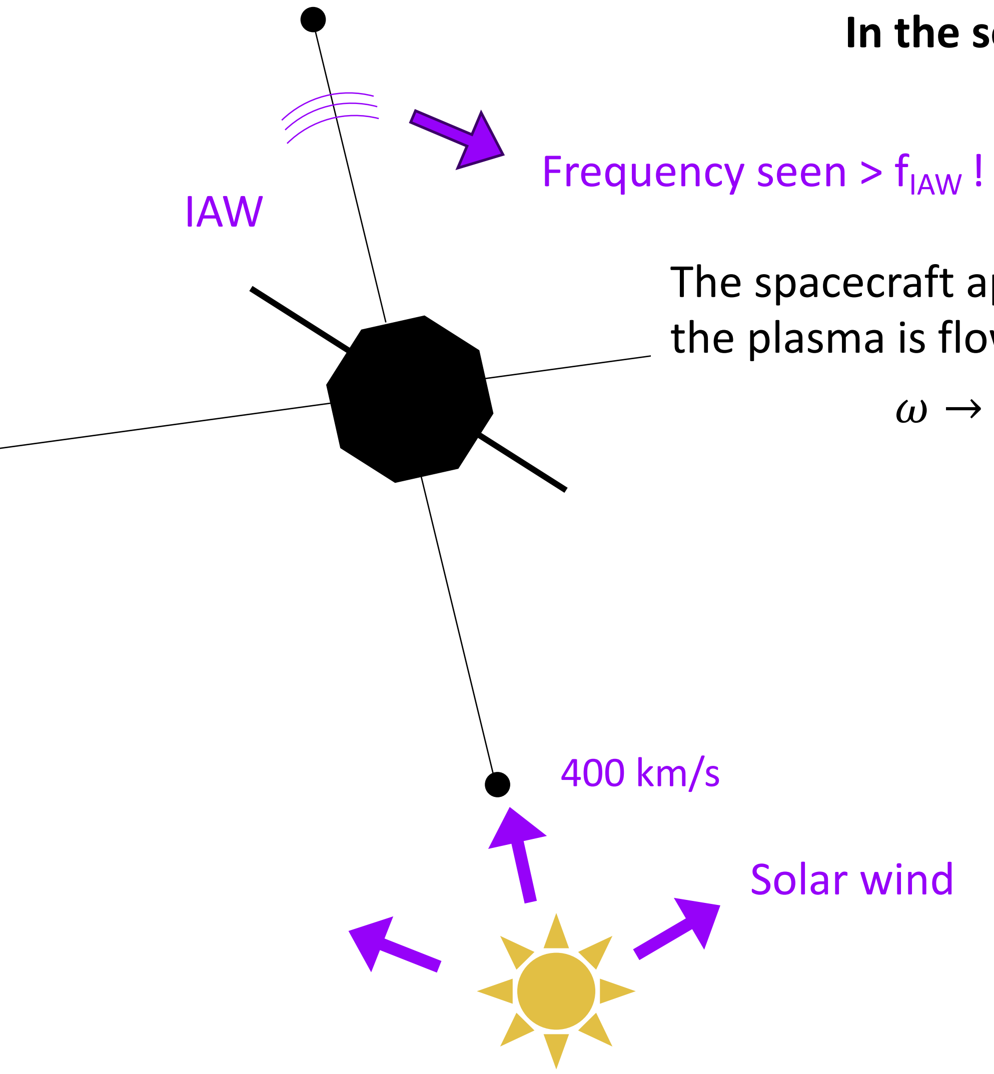

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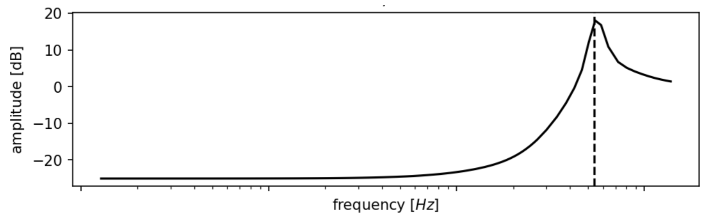

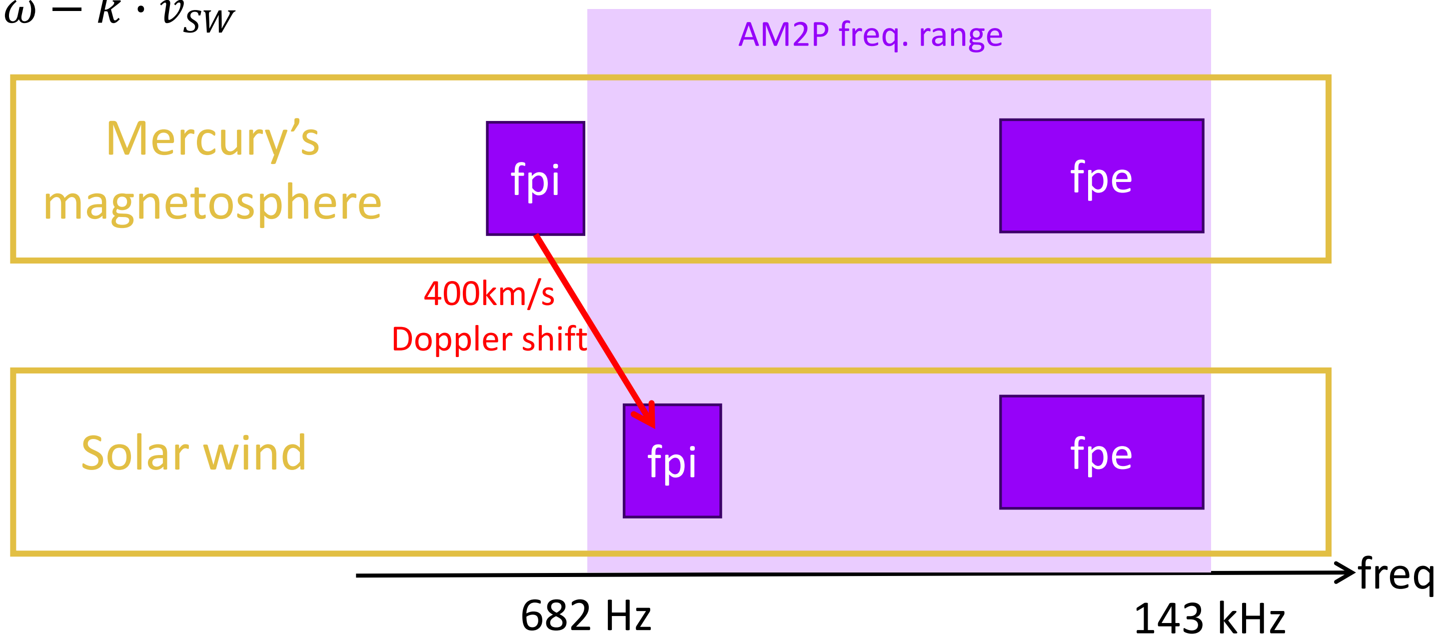

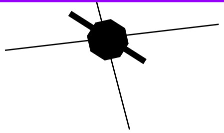

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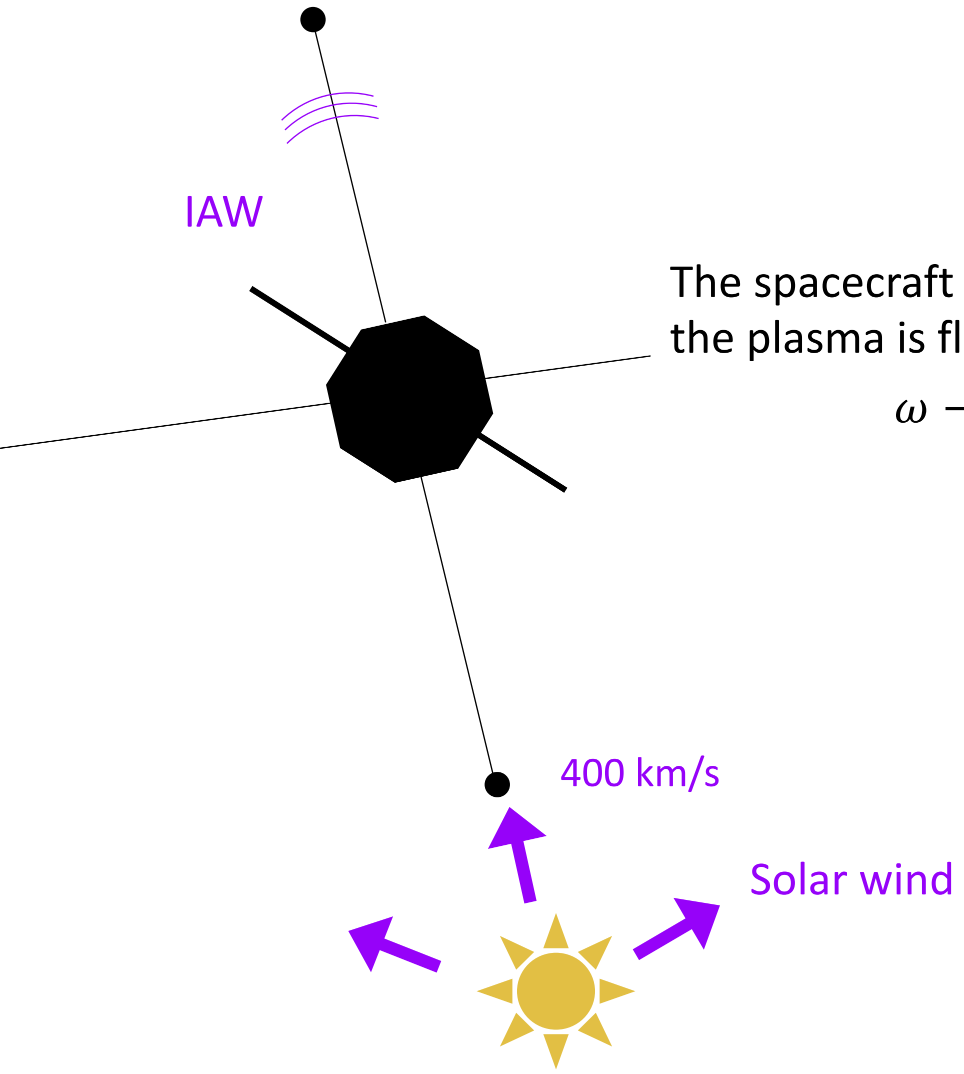

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→ Particular configurations that should be tested:
- k and v_{SW} in the same direction
- k and v_{SW} in the opposite direction
- k perpendiculary to v_{SW}

Preliminary results

- Calculation of the dielectric ε
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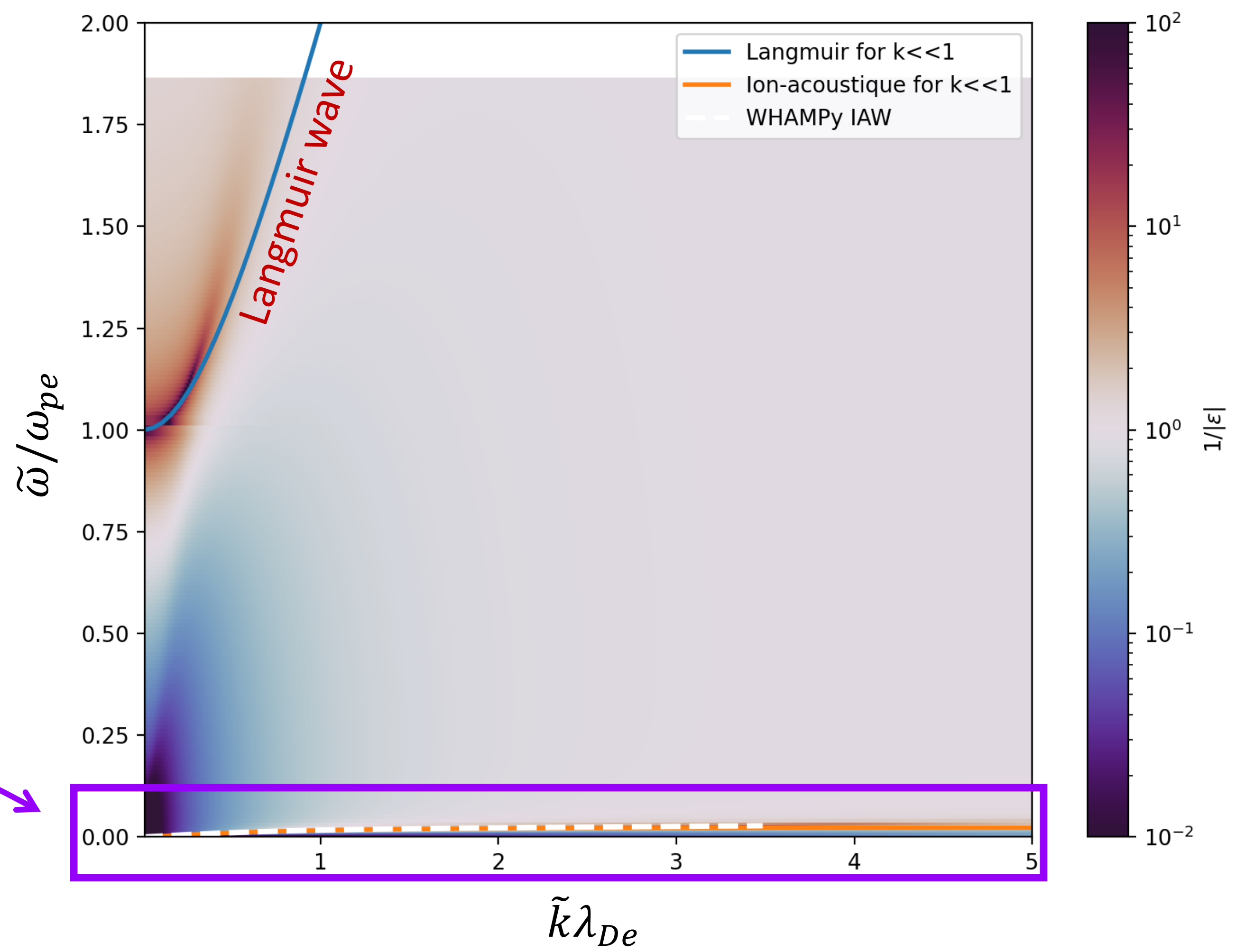
The color map shows:
$1/|\varepsilon|$ as a function of normalized wavenumber $\tilde{k}\lambda_{De}$ and normalized frequency $\tilde{\omega}/\omega_{pe}$

Red peaks = plasma normal modes,
i.e. solutions of the dispersion relation $\varepsilon(\tilde{k}, \tilde{\omega}) = 0$

Ion acoustic wave dispersion relation is located here



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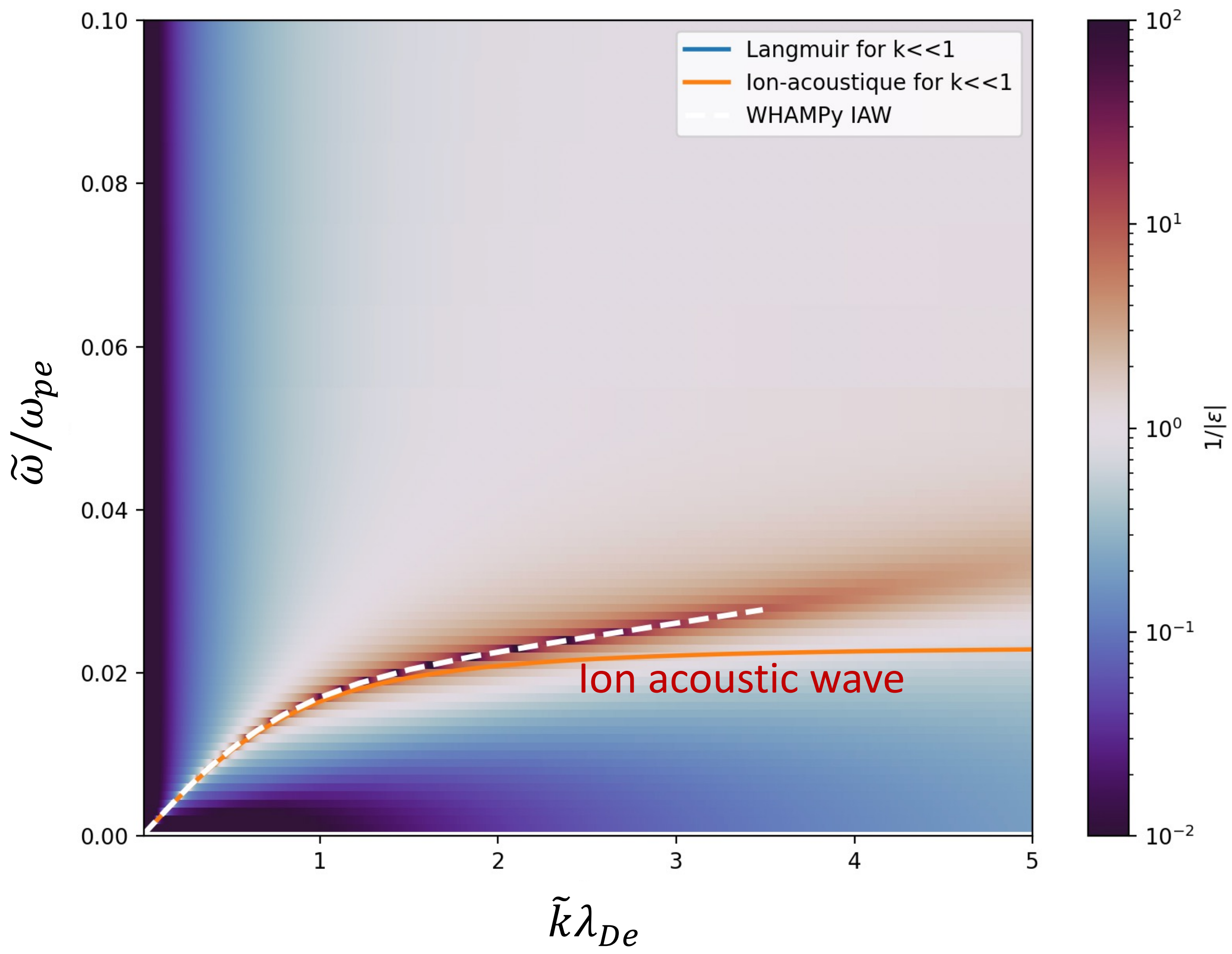
→ Great agreement between:
- our calculations
- theory for k<<1
- simulation results from Whamp

(Zoom)



Conclusions:

- We have used a global kinetic simulation of mercury magnetosphere to produce synthetic spectra that should be measured by BepiColombo/AM^{2}P
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