astrophysique & planétologie

Modelling global plasma transport in the magnetospheres of gas giant planets

Marie Devinat, M. Blanc, N. André

Kinetic physics for astrophysical plasma
18/05/2026

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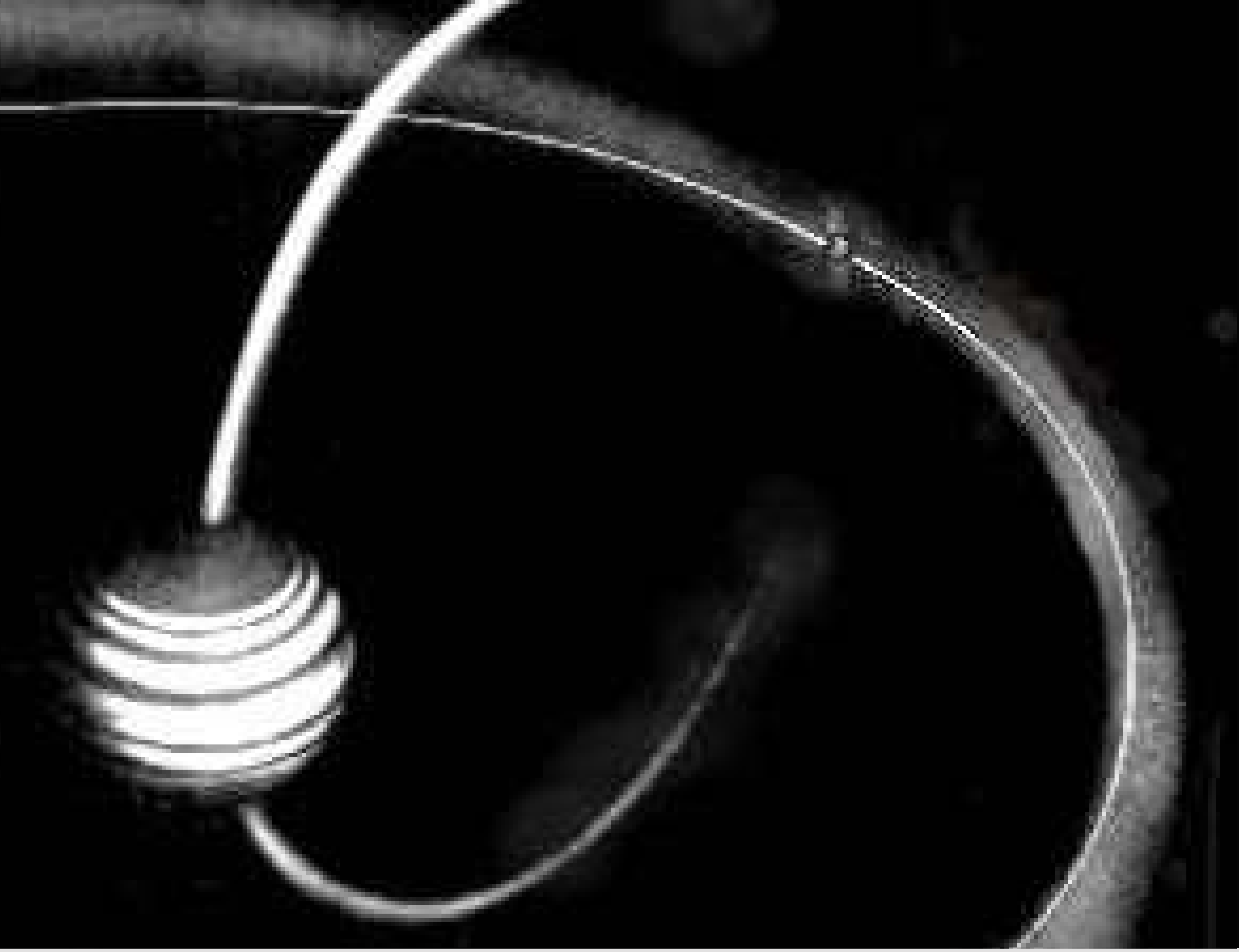
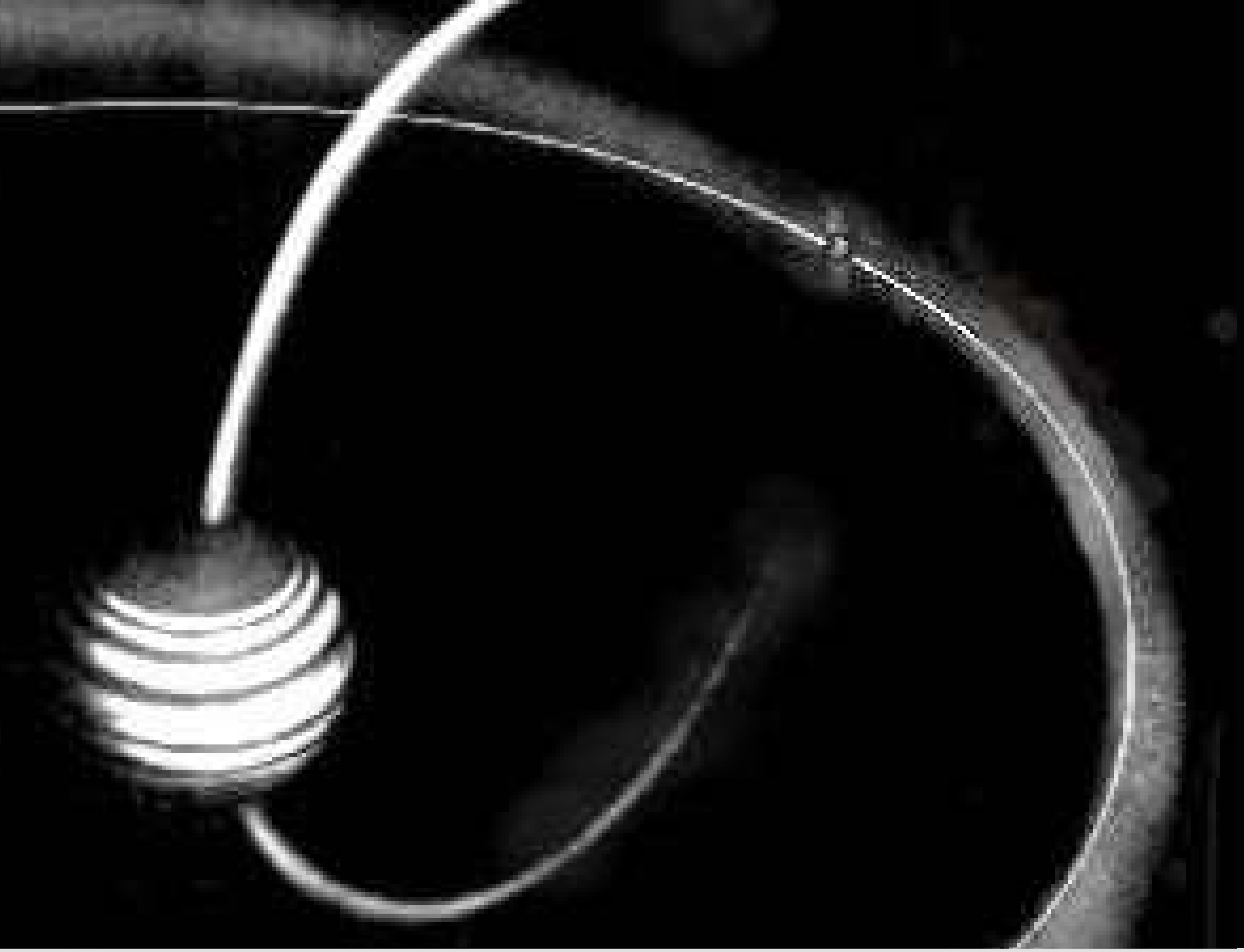


Topic of this presentation

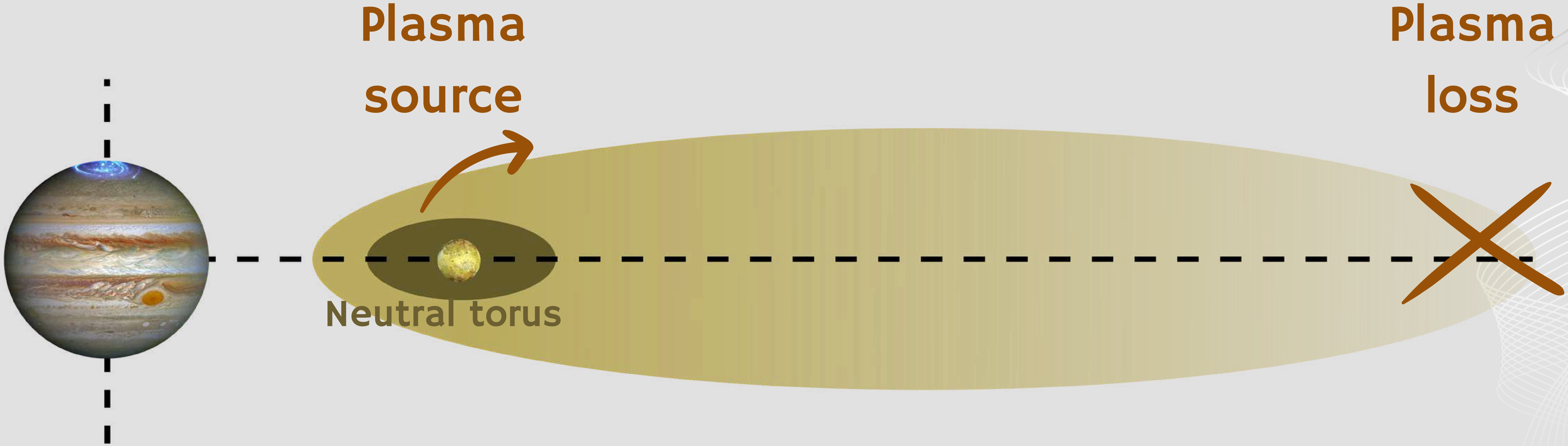
- Discuss the various pieces of evidence for plasma cycles in gas giant magnetosphere
- Show the modelling effort at IRAP
- Through the prism of the Jovian magnetosphere



Jovian magnetospheric plasma cycles: evidence

- "Internally-driven" plasma cycle
- "Solar-Wind-driven" plasma cycle

"Internally-driven" plasma cycle



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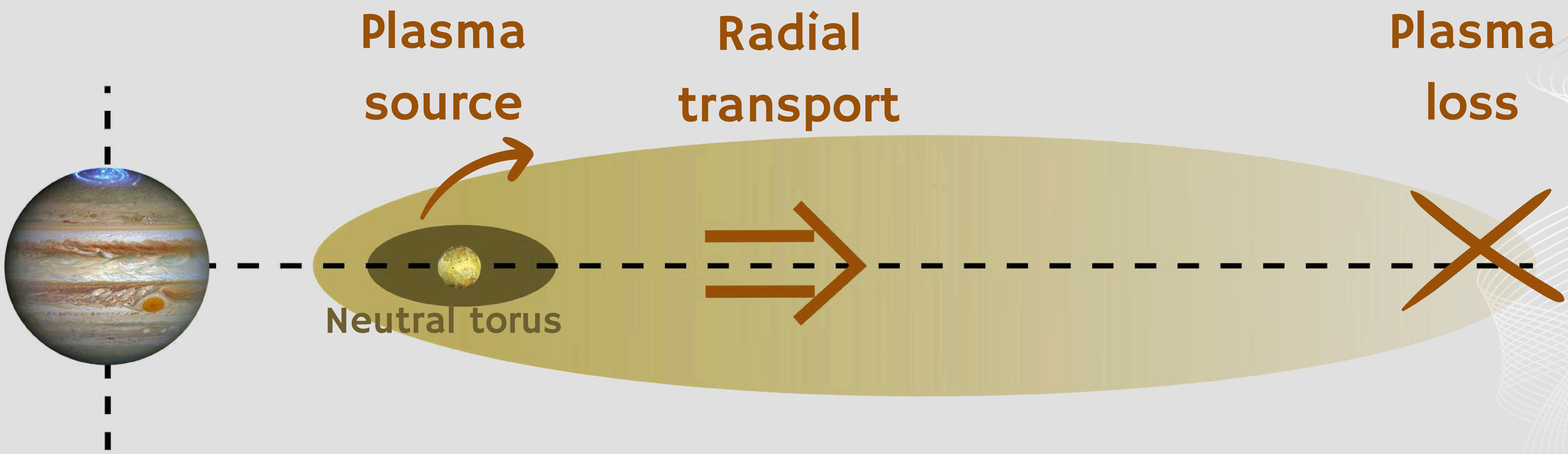
"Internally-driven" plasma cycle



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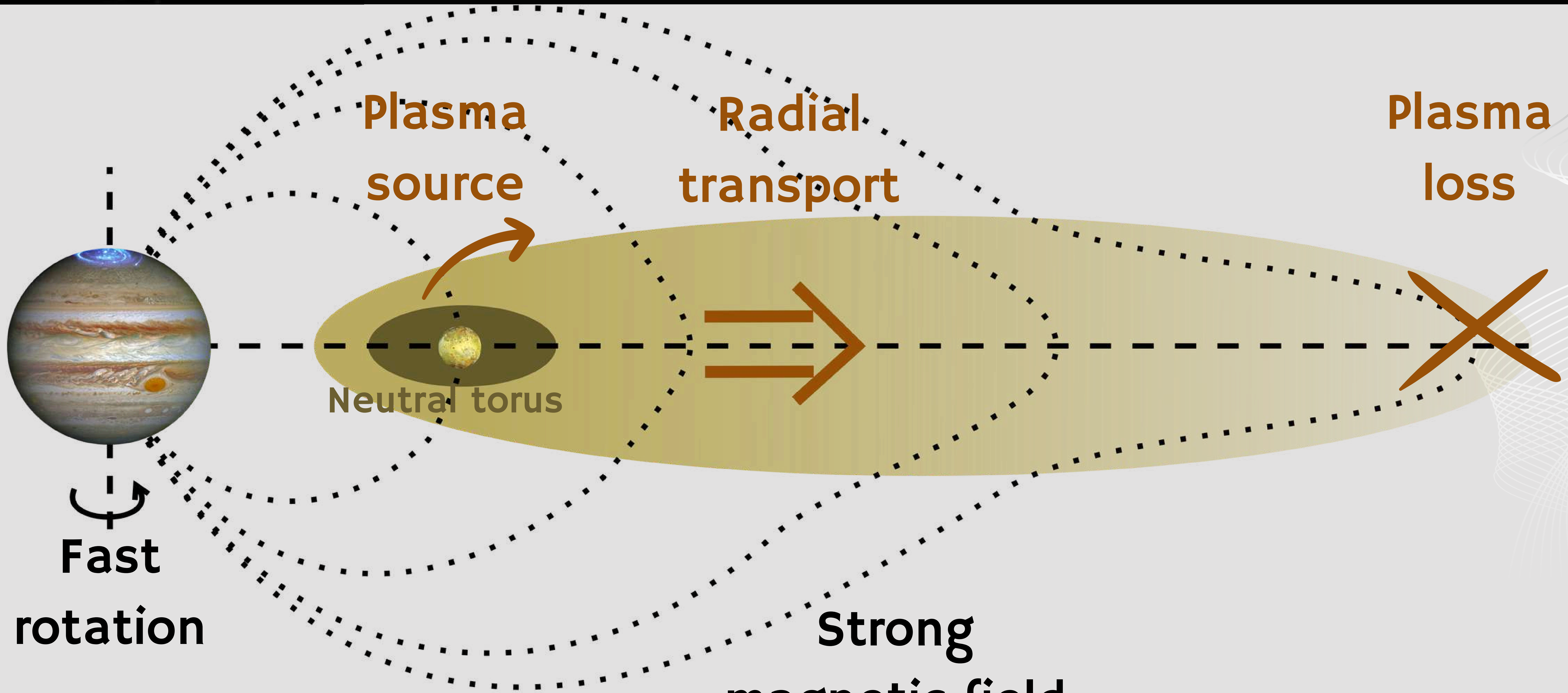
"Internally-driven" plasma cycle



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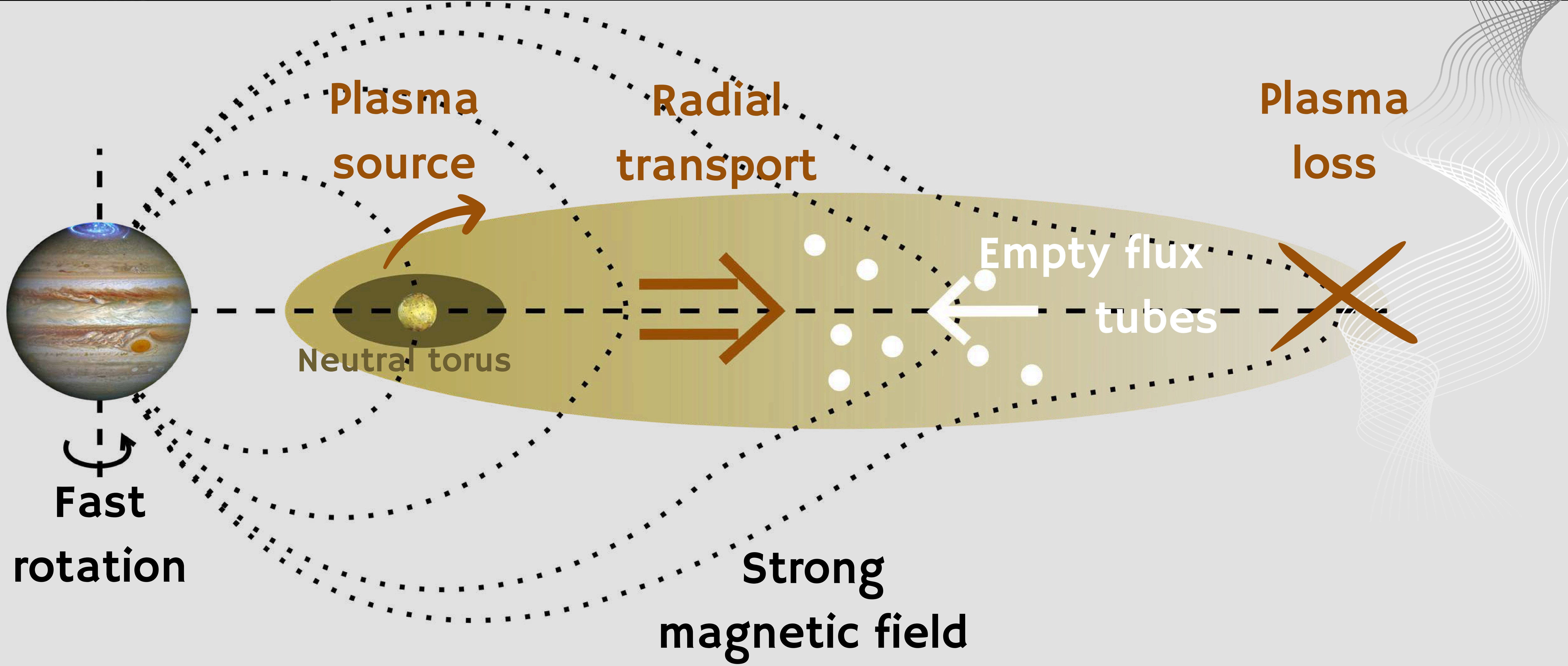
"Internally-driven" plasma cycle



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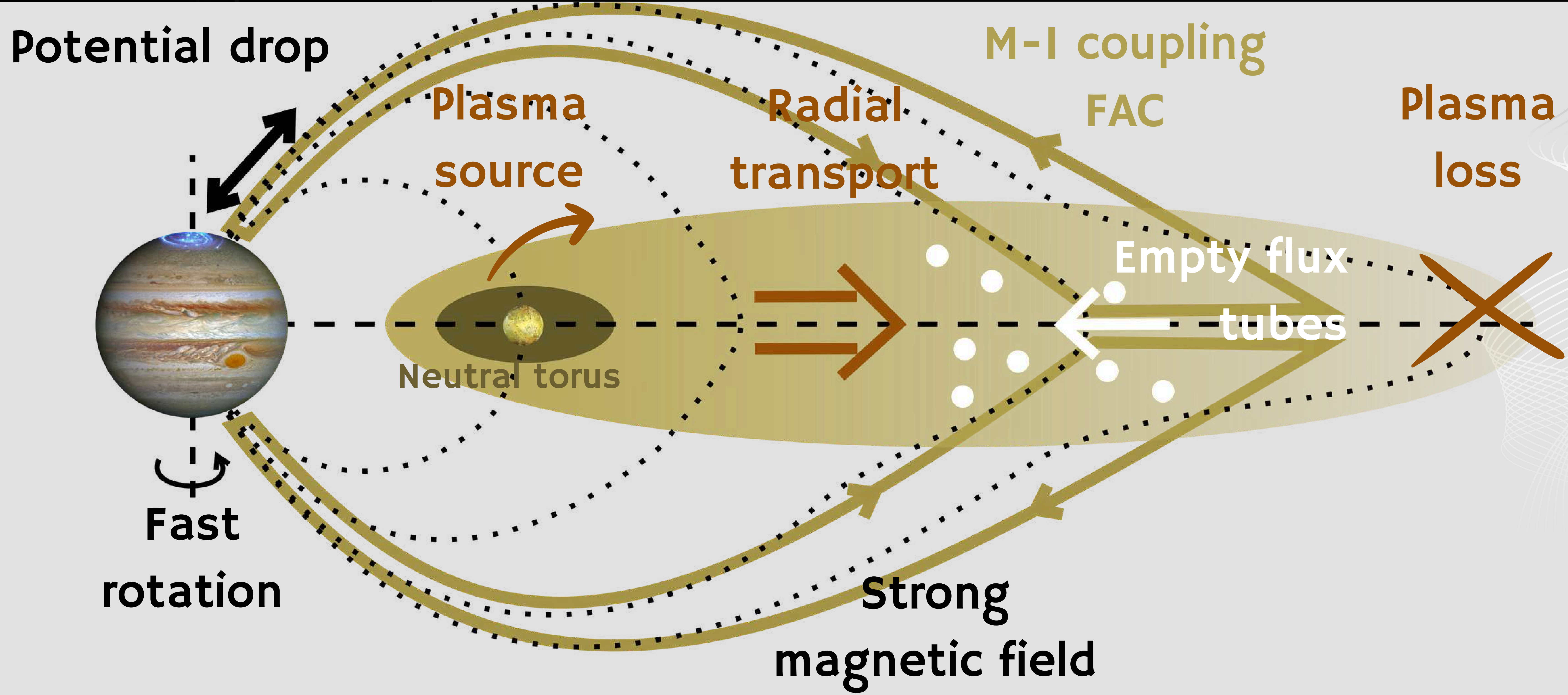
"Internally-driven" plasma cycle



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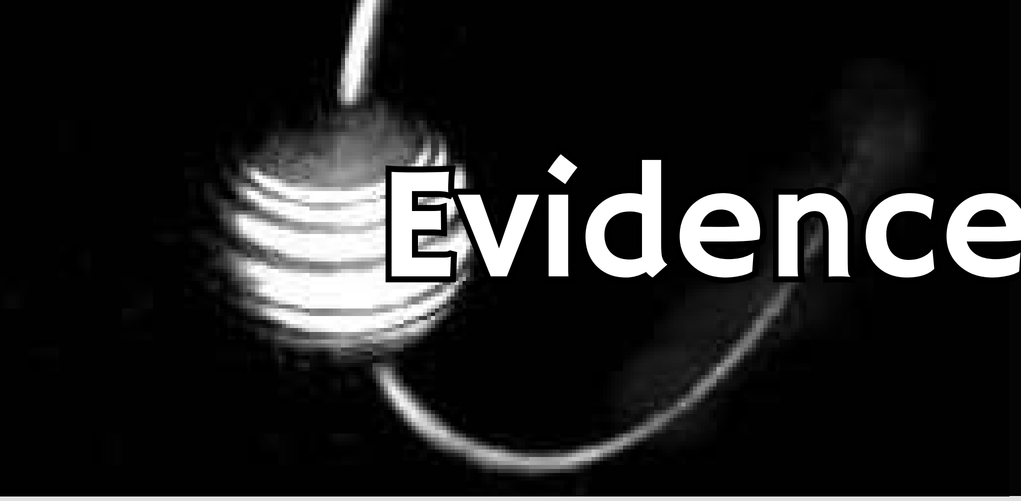
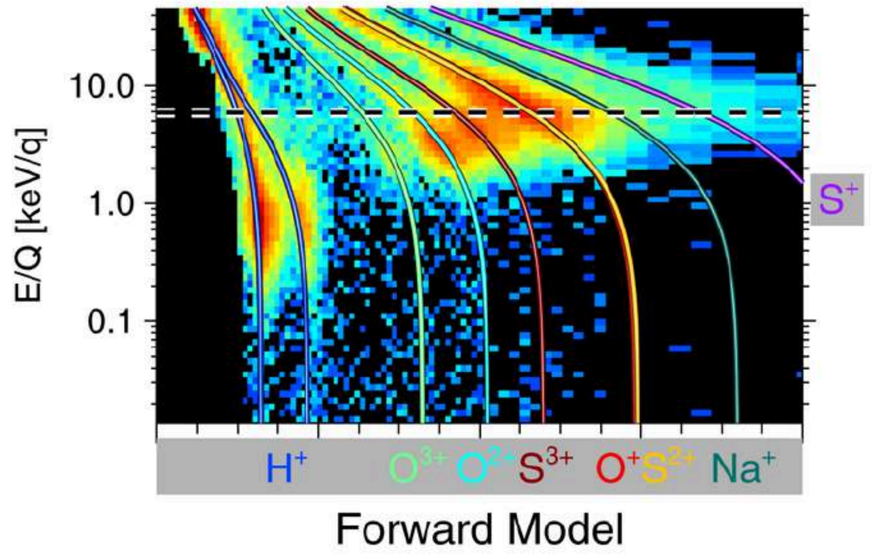
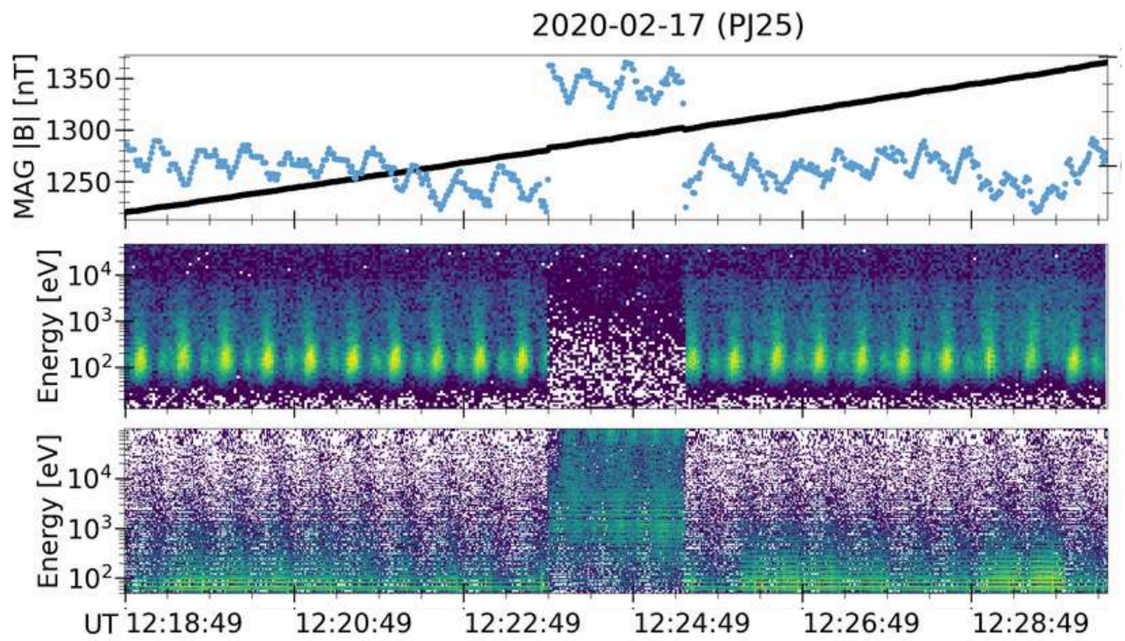


Evidence for the "internally-driven" cycle

Inner source

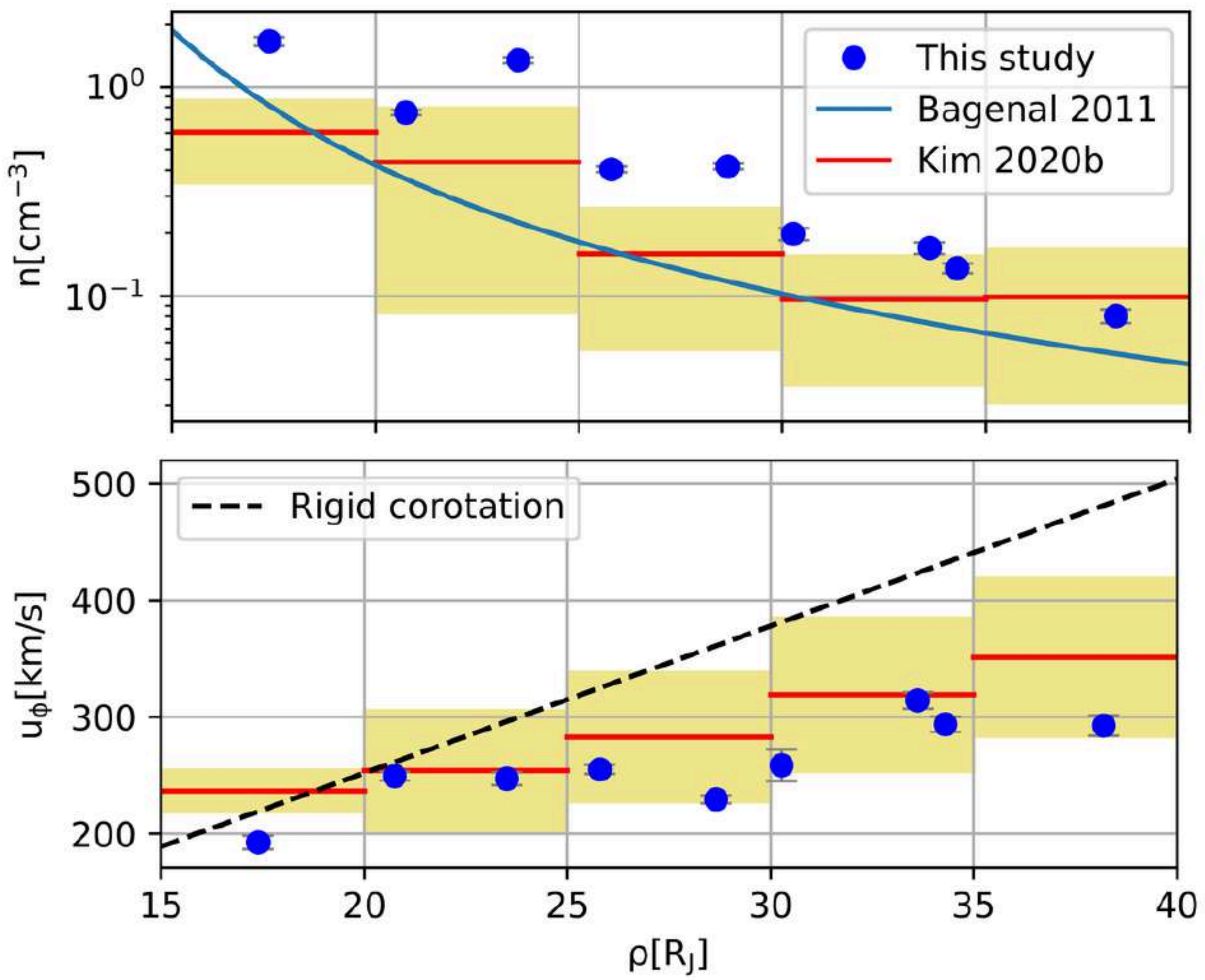


Kim et al. (2020)



Devinat et al. 2025

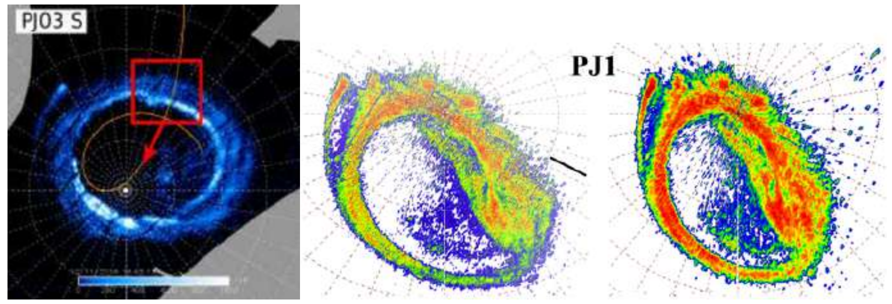
Radial transport



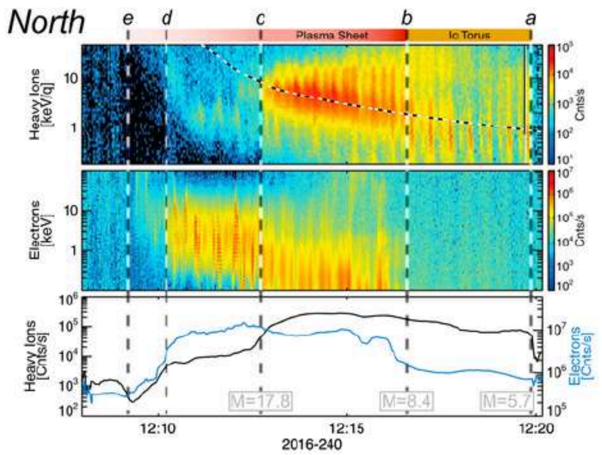
Wang et al. 2024

Empty flux tubes

M-I coupling, FAC



Al Saati et al 2022,
Gerard et al. 2020



Szalay et al. 2017

Juno, Galileo, ...

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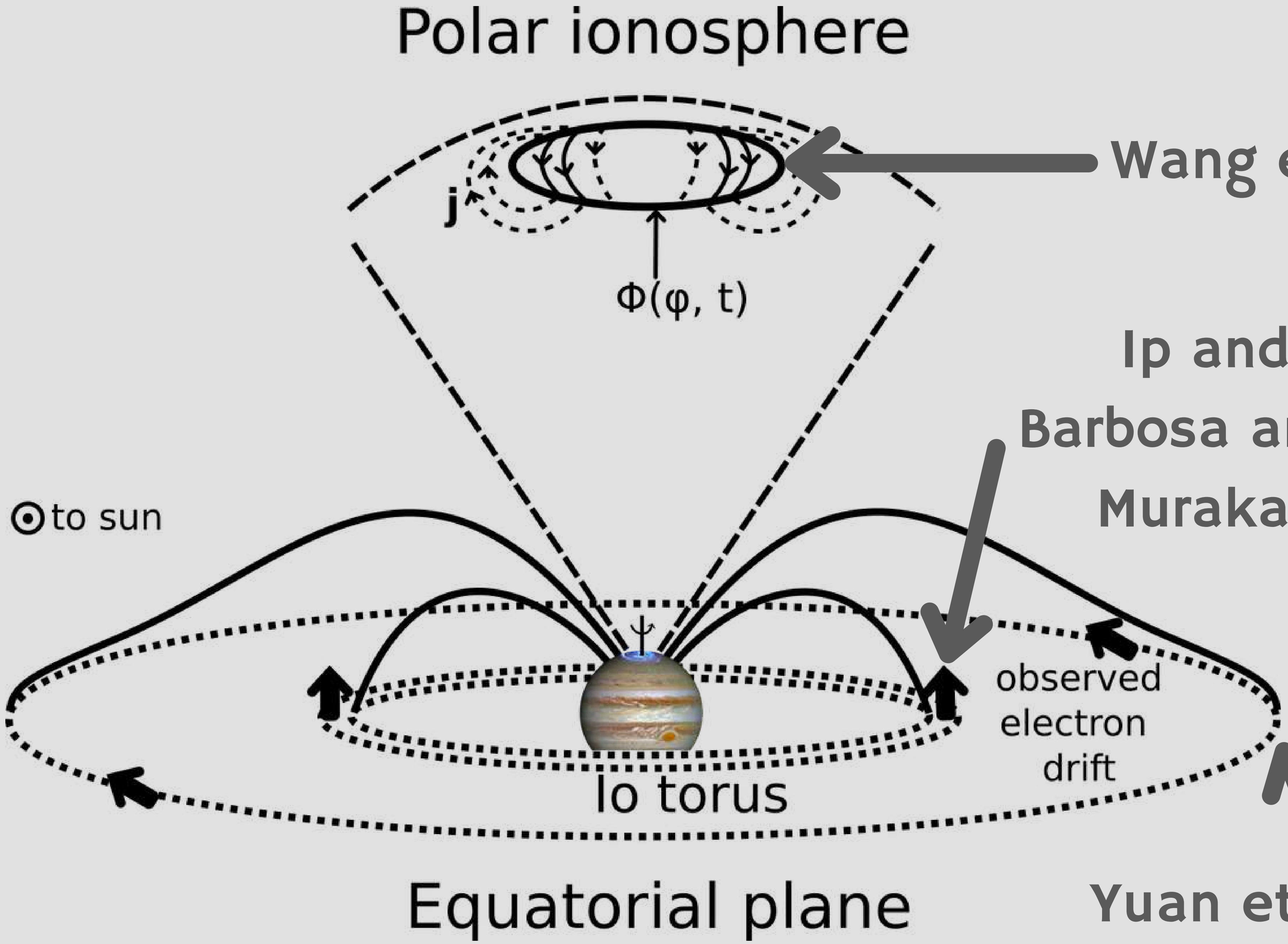
"Solar-Wind-driven" plasma cycle ?

At Jupiter: hints towards Solar-Wind driven cycle



Wang et al. (2023)

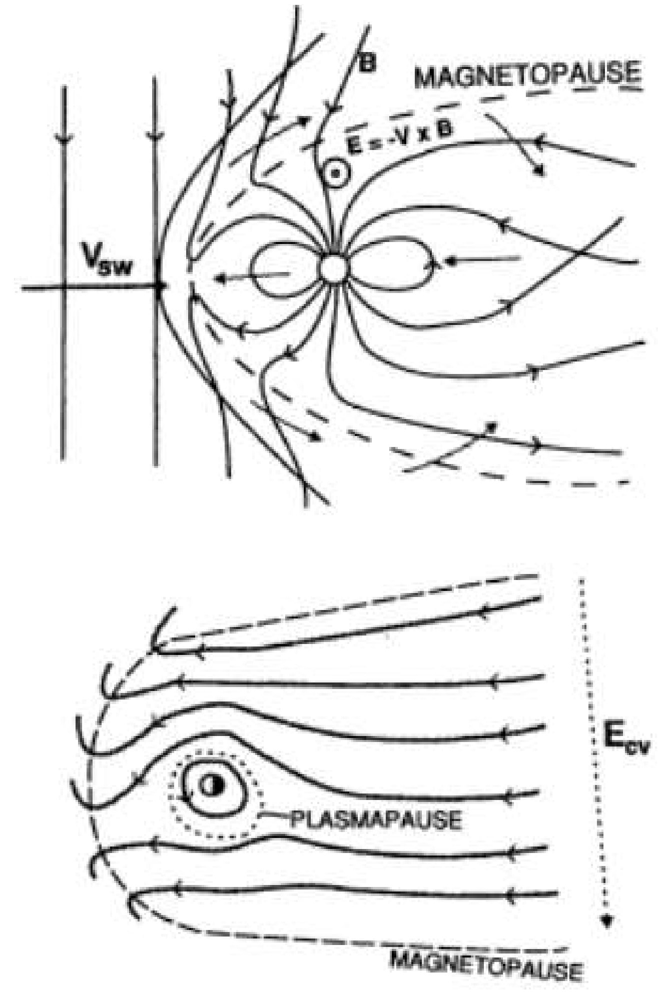
Ip and Goertz (1983)

Barbosa and Kivelson (1983)

Murakami et al. (2016)

Yuan et al. (2024)

Dungey cycle at Earth



Bagenal et al. (1992)

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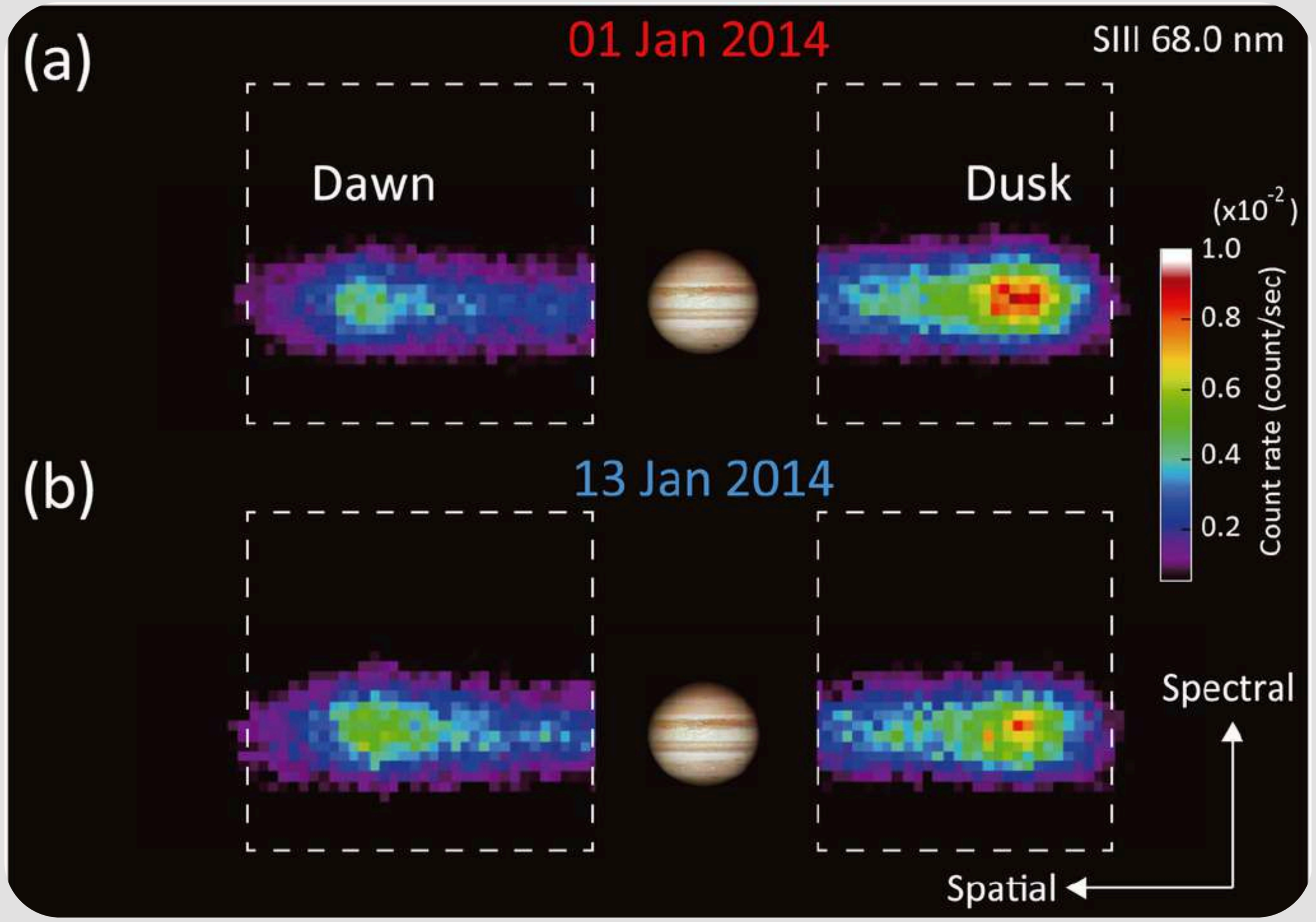
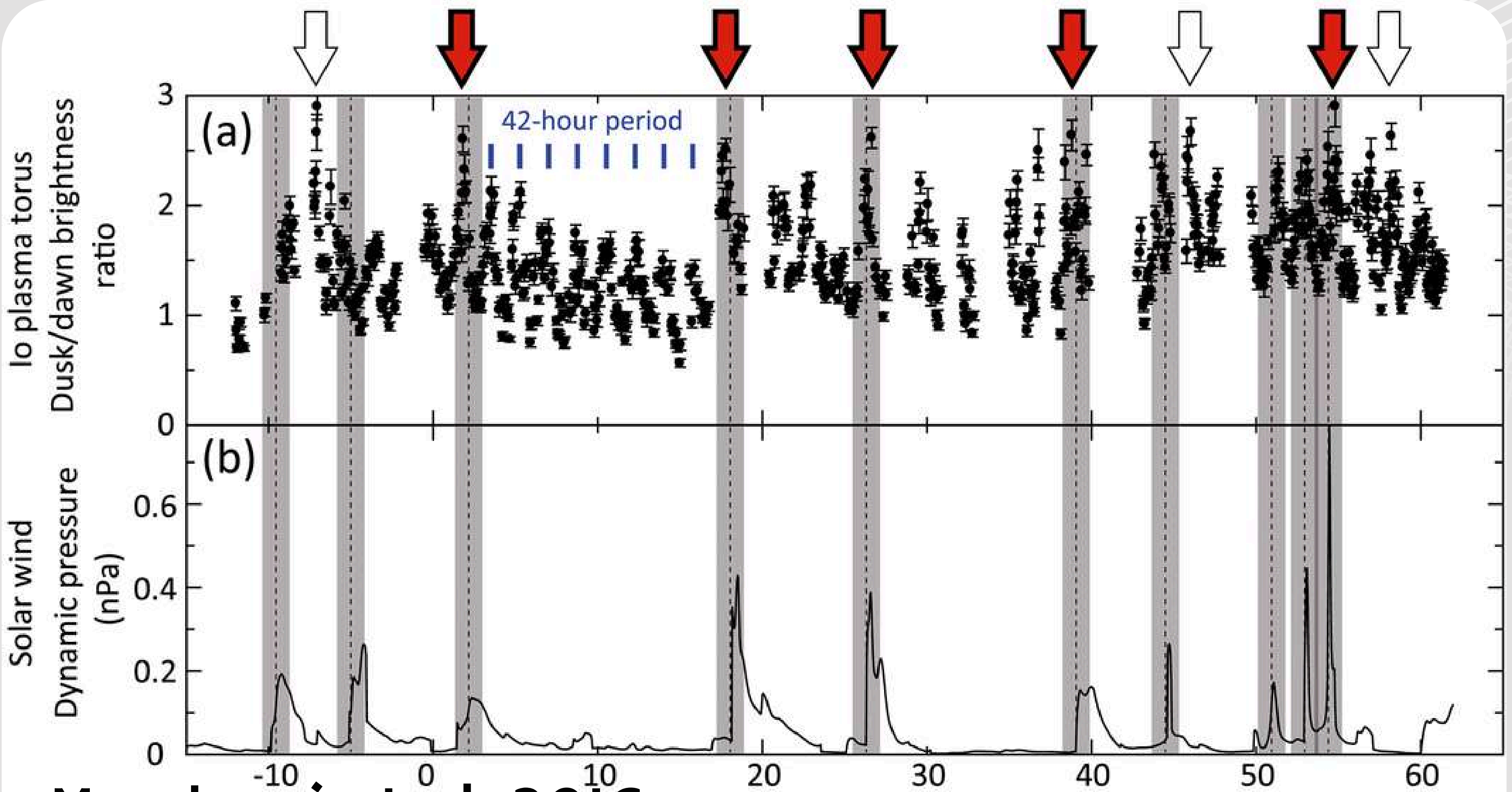
"Solar-Wind-driven" plasma cycle ?

How deep can the solar wind influence penetrate inside the Jovian magnetosphere ?

Observations of inner asymmetries in the Jovian magnetosphere...

... which seem to be modulated by the Solar Wind





Murakami et al. 2016

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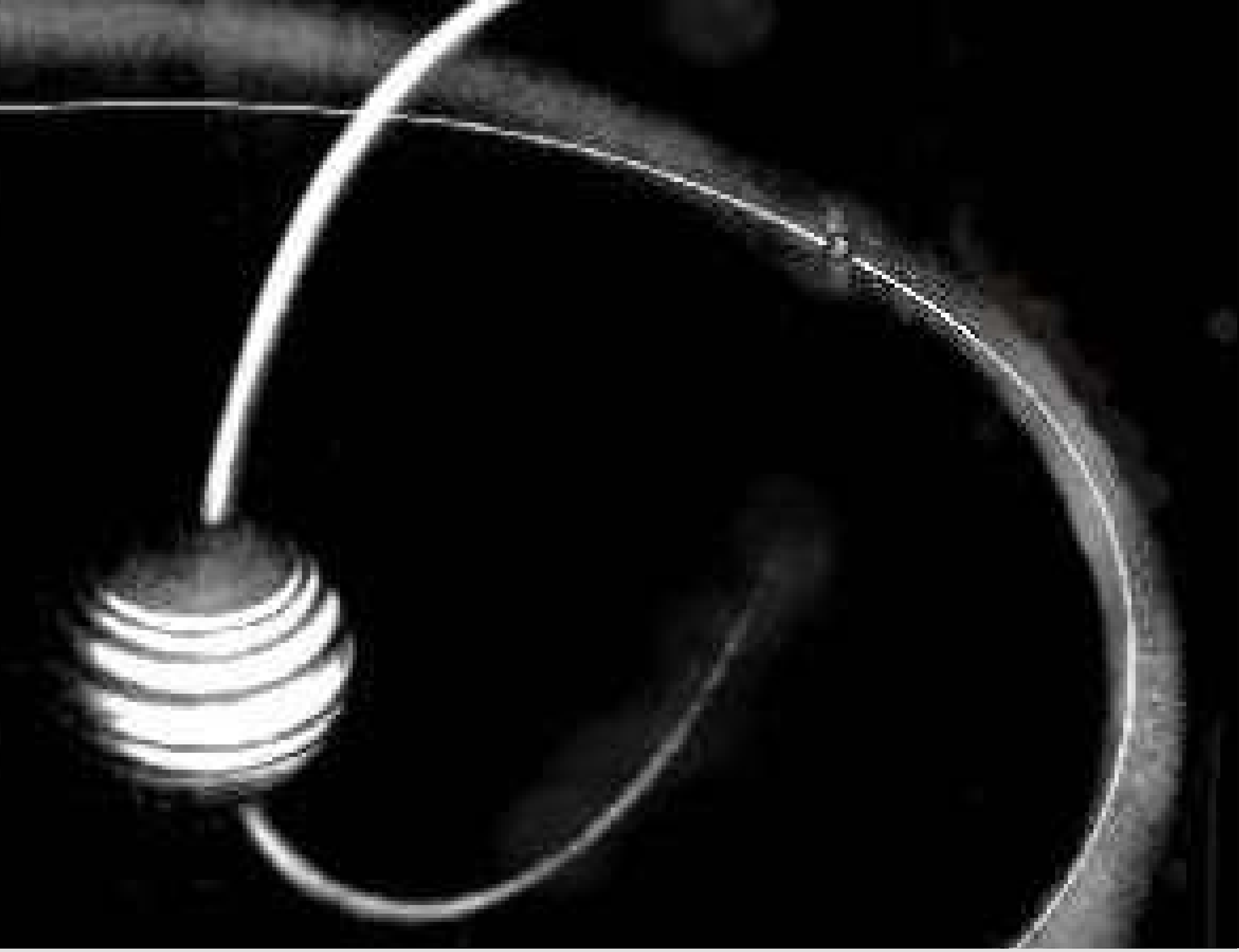
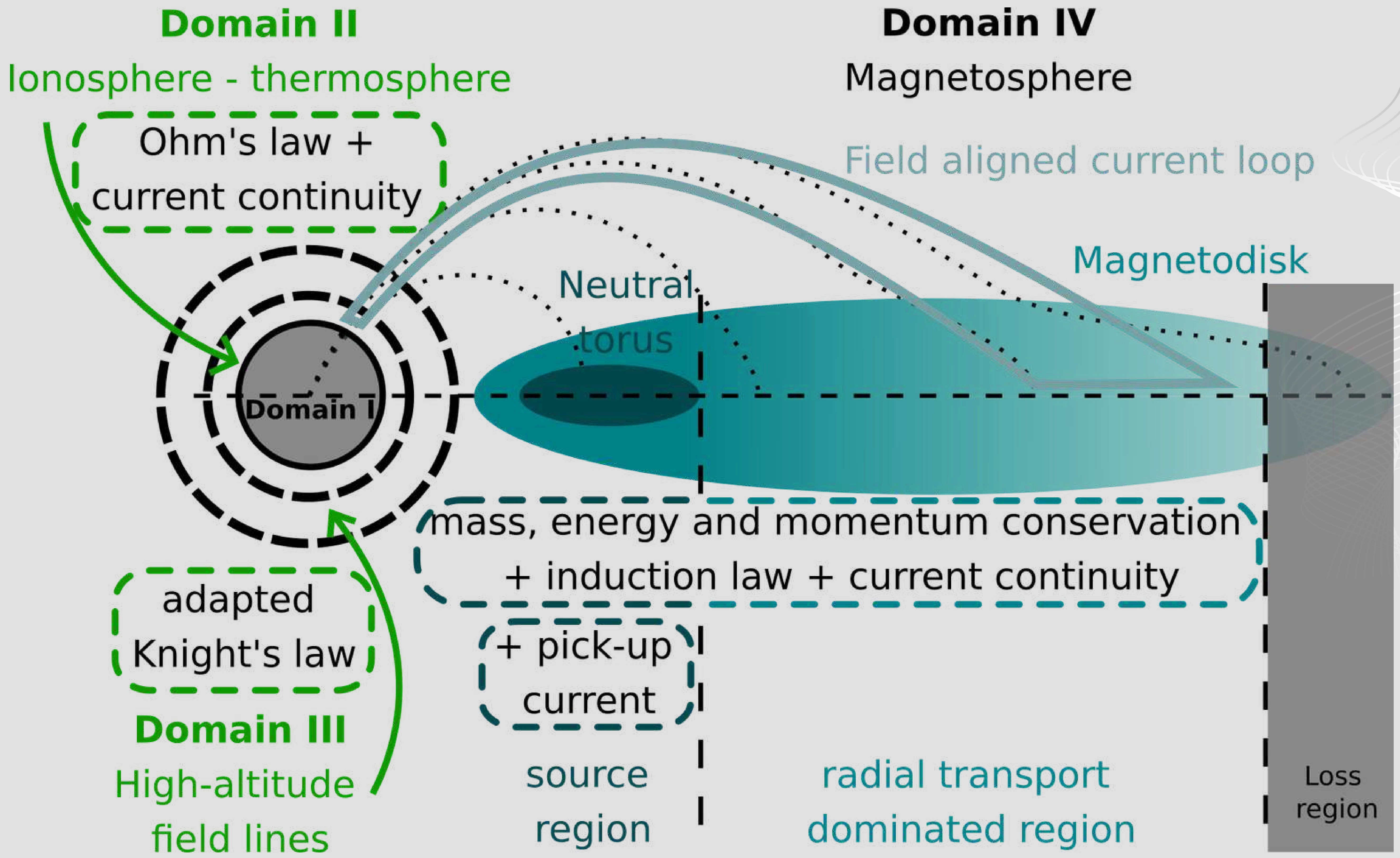


Modelling approach

System, physics, assumptions



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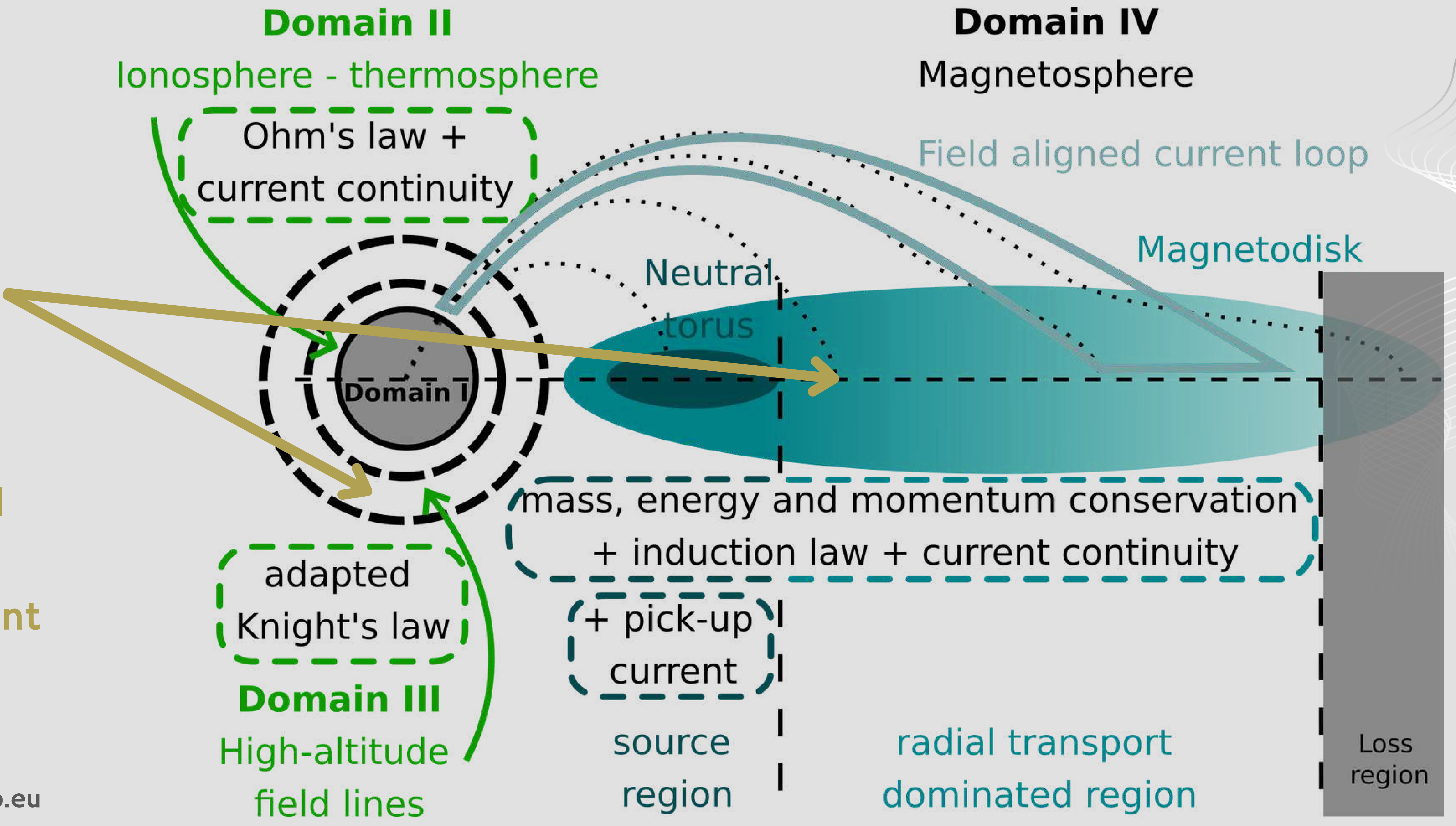
System, physics, assumptions

Kinetic description

High-latitude acceleration

Plasma vertical distribution

Plasma turbulent heating



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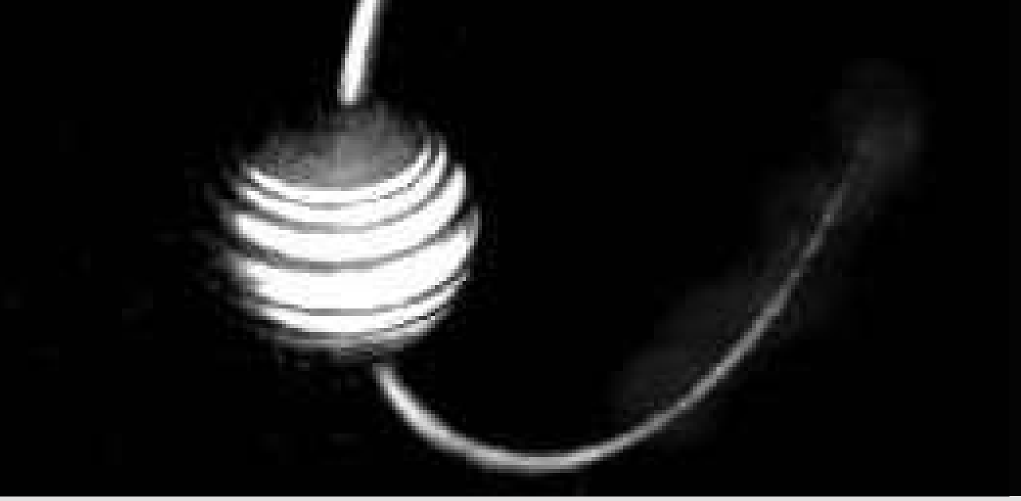

Method

Fundamental local equations

↓

Integrate over a flux tube M, W, Ω

↙ ↘

Mean quiet state

Averages over flux shells

(2π longitude)

Axisymmetrical

Perturbations

(flux tube interchange)

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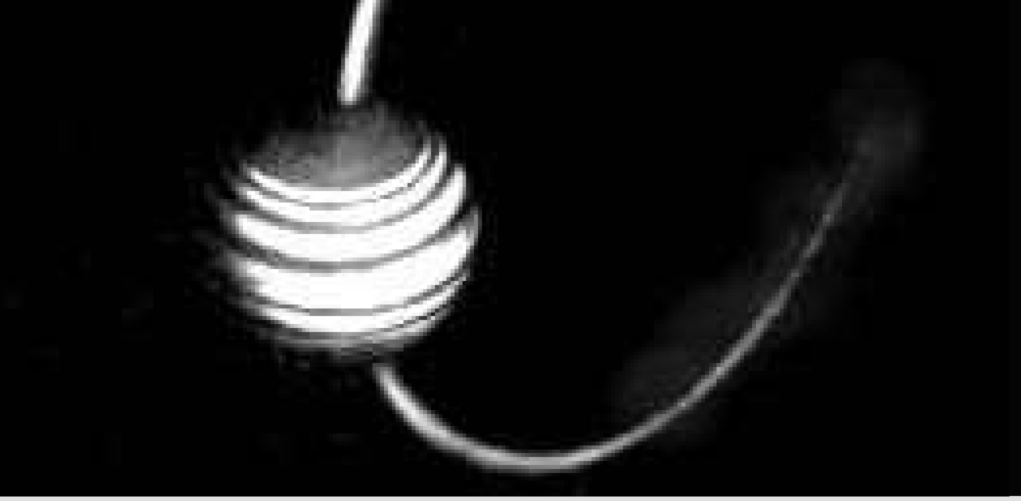

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Mean quiet state
Averages over flux shells
(2π longitude)
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Perturbations
(flux tube interchange)

← Transport

↓ Departure from axisymmetry

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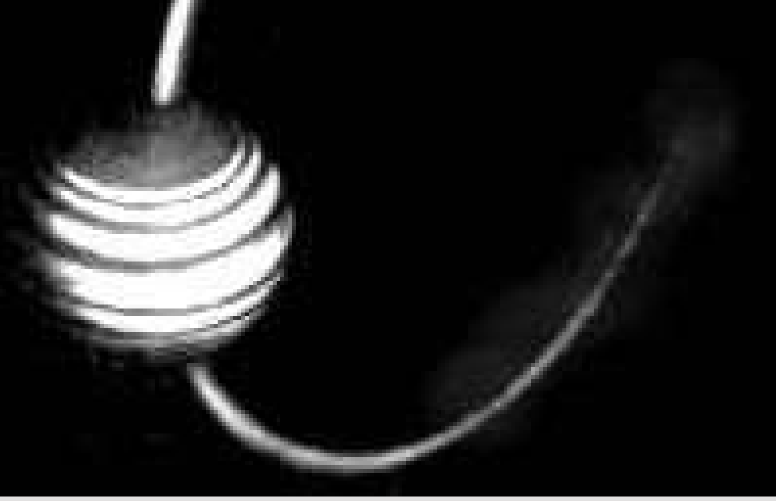

Method

Fundamental local equations

↓

Integrate over a flux tube M, W, Ω

↙ ↘

Mean quiet state
Averages over flux shells
(2π longitude)
Axisymmetrical

Perturbations
(flux tube interchange)

← Transport "internally-driven" cycle

↓ "Solar-Wind-driven" cycle

Departure from axisymmetry

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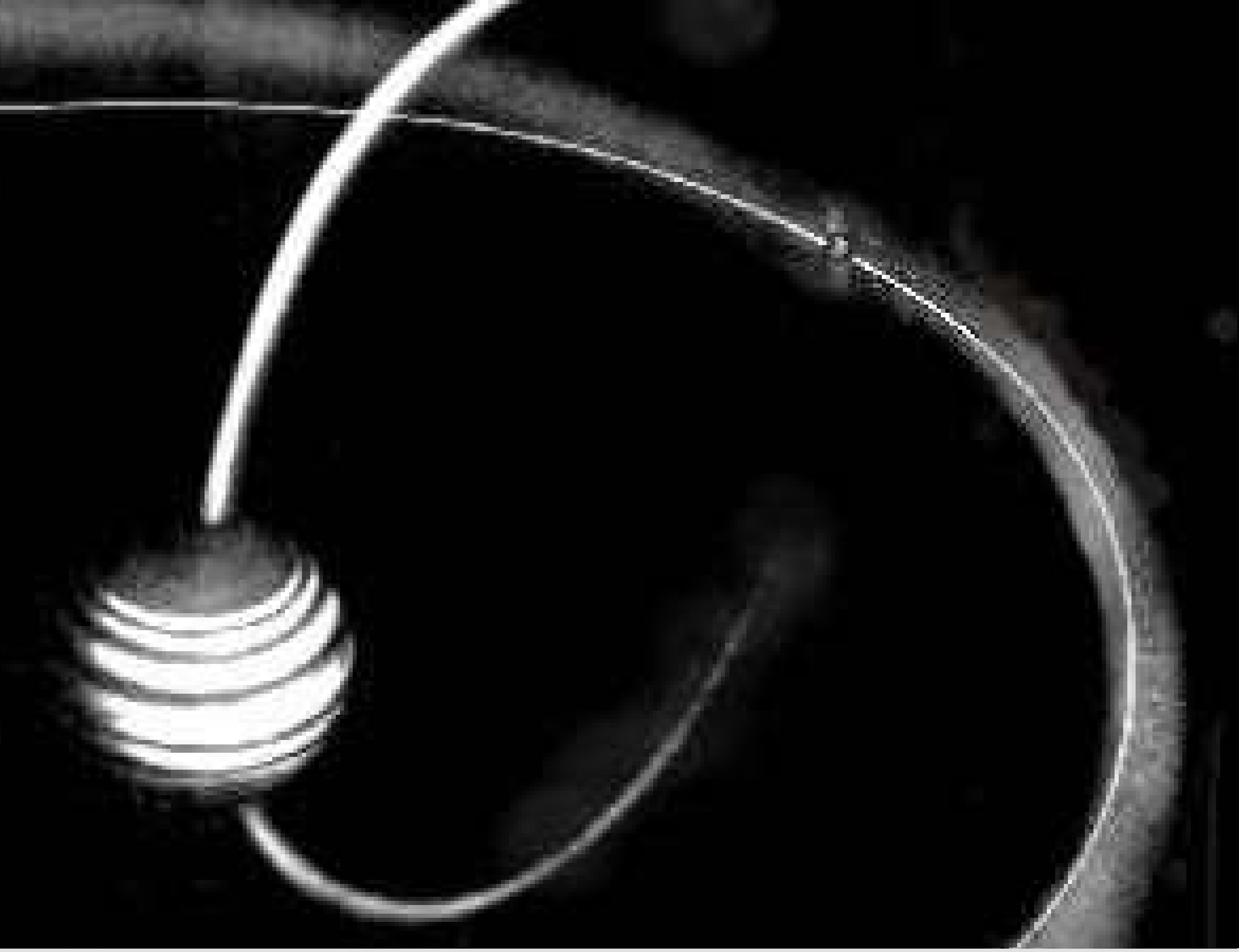

"Internally-driven" cycle model

"Internally-driven" transport equations

(Single-fluid)

$$\frac{\partial\, \text{Mass}}{\partial t} + \frac{\partial}{\partial \text{shell}}\left(\text{Diffusion} \, \frac{\partial\, \text{Mass}}{\partial \text{shell}} \right) = \text{Source - Loss}$$

$$\frac{\partial\, \text{Energy}}{\partial t} + \frac{\partial}{\partial \text{shell}}\left(\text{Diffusion} \, \frac{\partial\, \text{Energy}}{\partial \text{shell}} \right) = \text{Heating}$$

$$2\pi \mathcal{T}_{FT} \frac{\partial\, \Omega}{\partial t} + \mathcal{M}_{\perp} \frac{\partial\, \Omega}{\partial \text{shell}} + \mathcal{M}_{\text{shell}}\, \Omega = \text{Source} + \underbrace{2\pi \left(\Omega_{in} - \Omega \right) \frac{\Sigma_P R_i^2 R_P B_i}{\sin I}}_{\text{ionospheric properties}}$$

ionospheric properties
conductances, magnetic field, rotation

+ partial coupling with ionosphere
(currents, potential drops)

Magnetospheric transport	MI coupling	Source region

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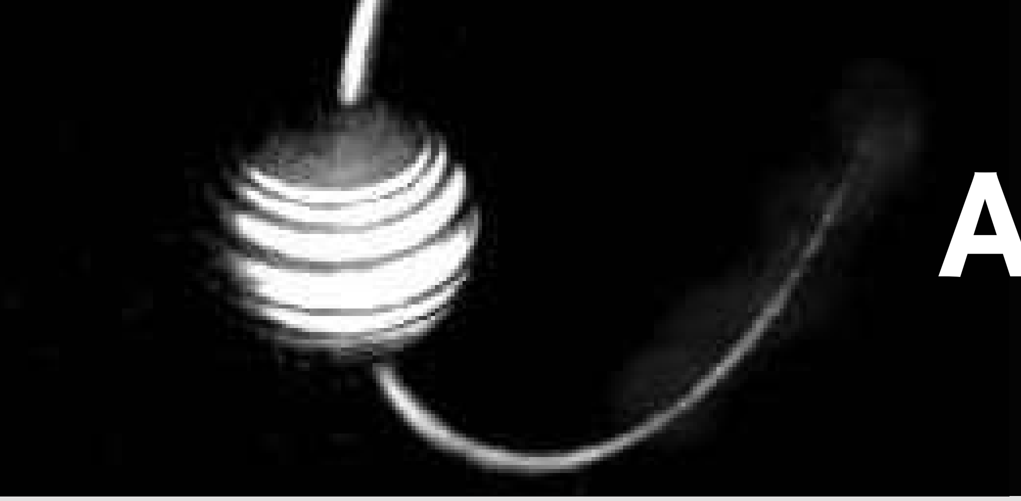
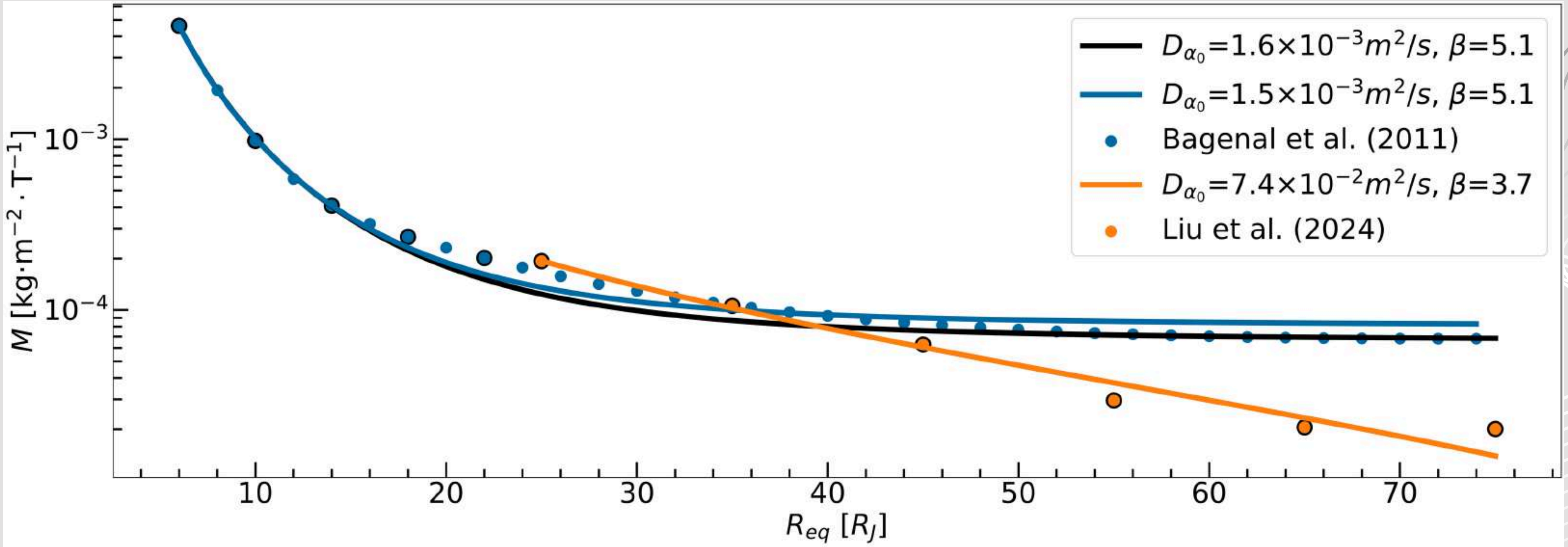


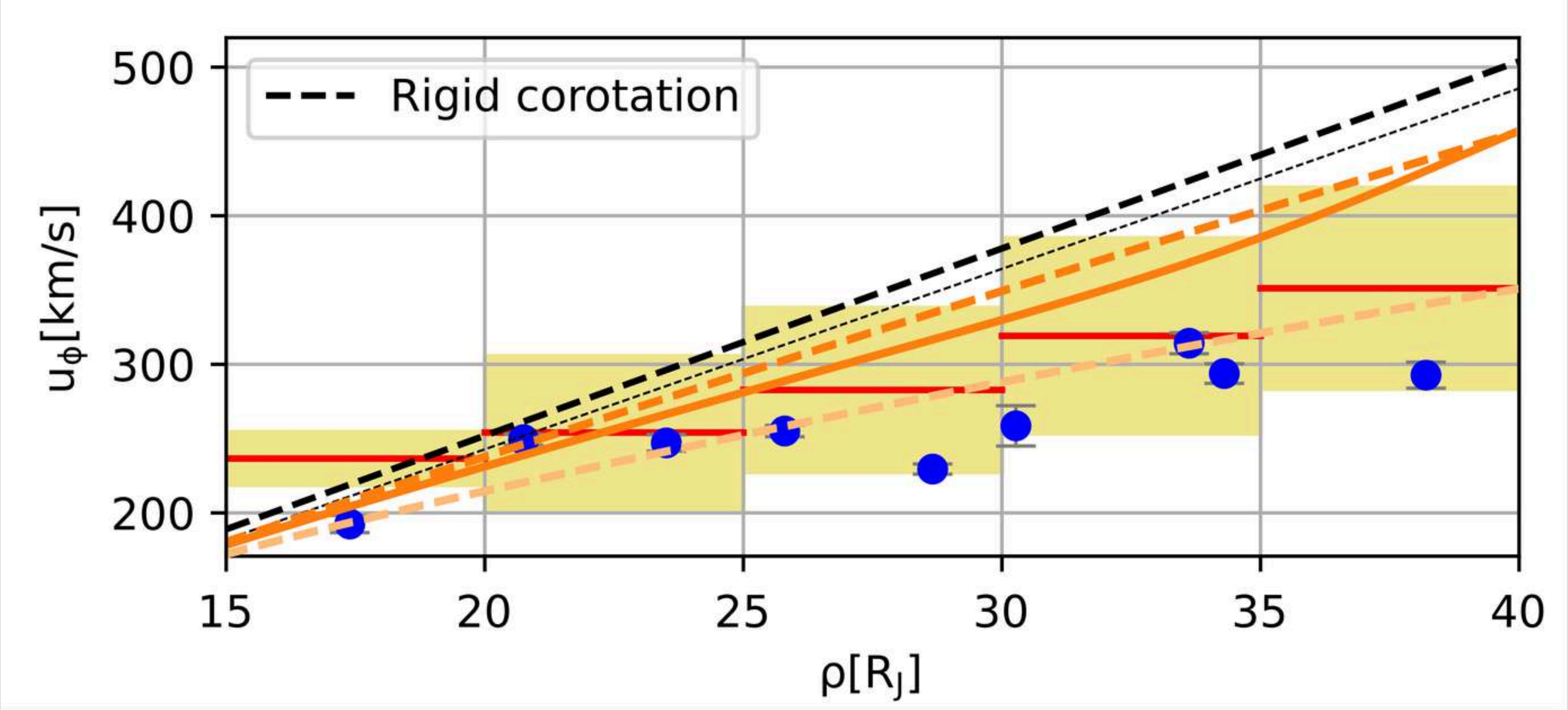
Application to Jovian data

Steady-state

Mass transport



Angular momentum transport



Canonical model

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Io source and temporal variations

$$\frac{\partial\,\text{Mass}}{\partial t} + \frac{\partial}{\partial\,\text{shell}}\left(\text{Diffusion}\ \frac{\partial\,\text{Mass}}{\partial\,\text{shell}}\right) = \text{Source - Loss}$$

(simple) modelling of the torus region

time-space propagation (in the magnetosphere) of the time variations in Io torus plasma production

$$2\pi\,\mathcal{I}_{FT}\,\frac{\partial\,\Omega}{\partial t} + \dot{\mathcal{M}}_{\perp}\,\frac{\partial\,\Omega}{\partial\,\text{shell}} + \dot{\mathcal{M}}_{\text{shell}}\,\Omega = \text{Source} + 2\pi\left(\Omega_{in} - \Omega\right)\frac{\Sigma_P\, R_i^2\, R_P\, B_i}{\sin I}$$

time-space propagation of the time variations in Io torus plasma production

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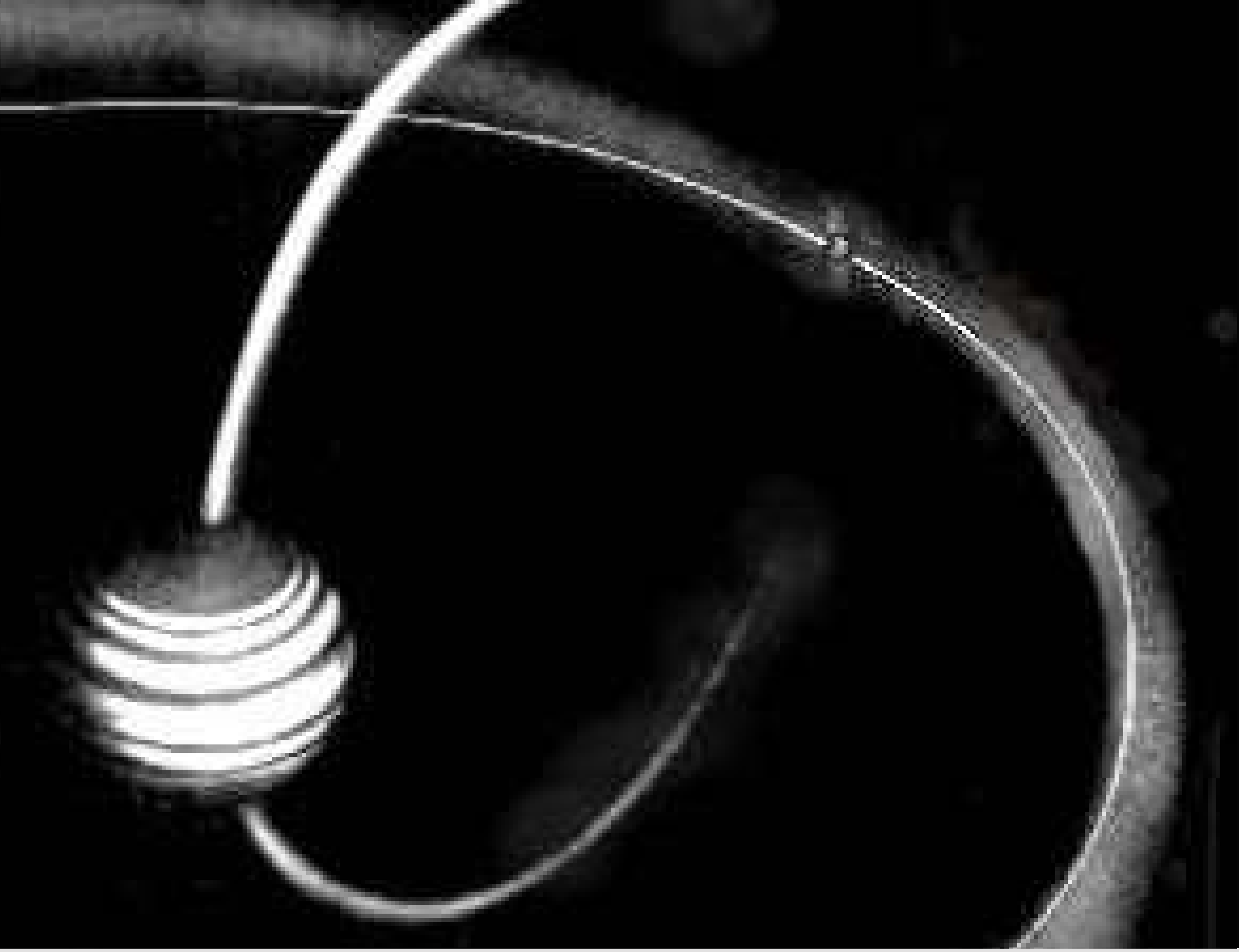

"Solar-Wind-driven" cycle model

Solving for currents and electric field

(2-fluid)

<u>Equilibrium state:</u>

subcorotation equilibrium computed previously

<u>Linear, first order decomposition</u>

- Electric field E
- Electrostatic potential Φ
- Current j
- (magnetospheric plasma pressure, velocity)

Explicit solutions

<u>Current-voltage relationship</u>

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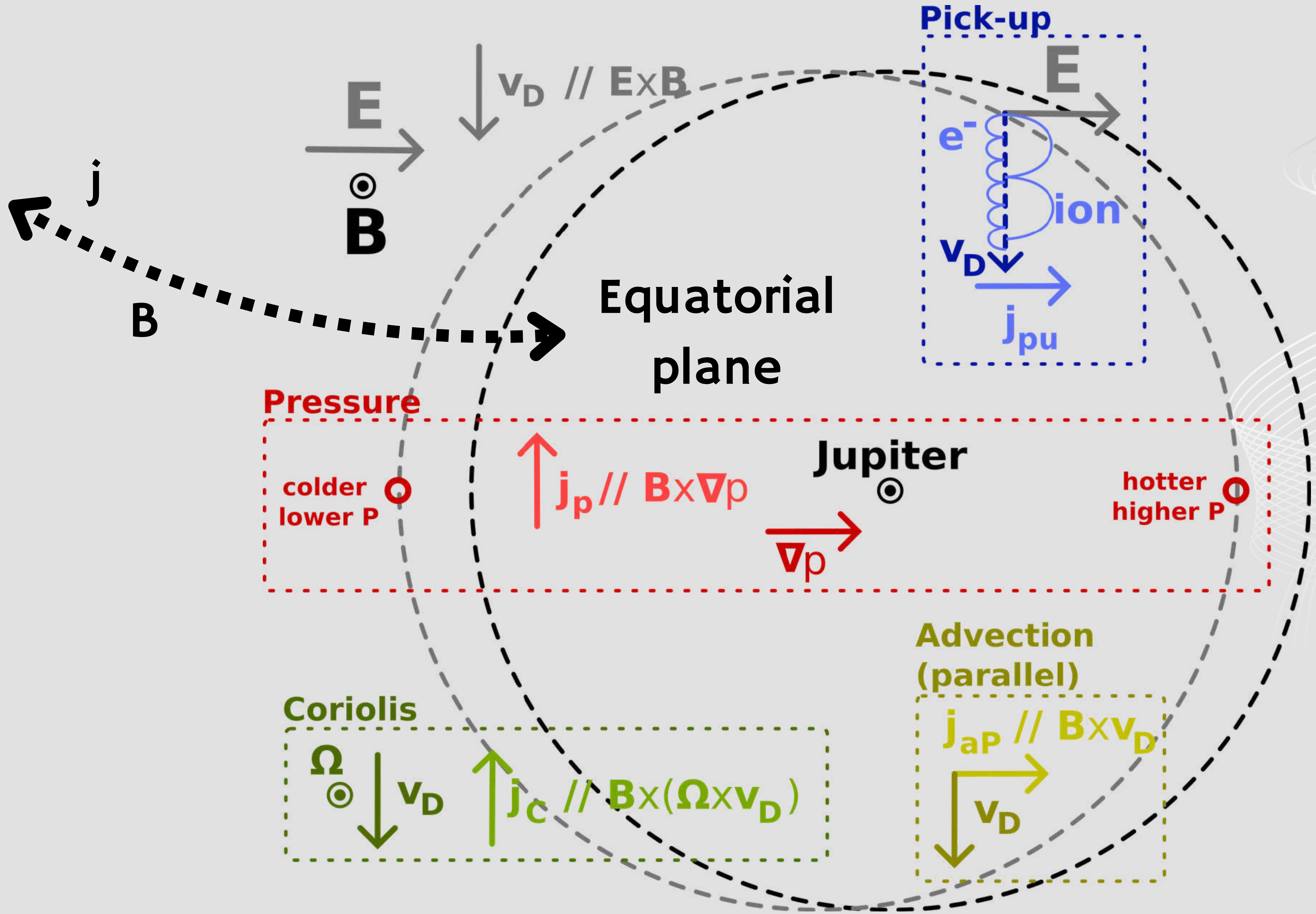
Solving for currents and electric field

Coupling to the planet
upper atmosphere



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Electrostatic potential equation

Ionospheric current = Magnetospheric current

$$\nabla_i \cdot \left(\Sigma_P \nabla_i \tilde{\Phi}\right) + \left(\nabla_i \Sigma_H \times \nabla_i \tilde{\Phi}\right) \cdot e_\zeta = -\left(2 m_i \Omega\, \nabla_e \cdot \left(\frac{N_i}{B_{\mathrm{eq}}}\right) \times \nabla_e \tilde{\Phi}\right) \cdot e_\zeta$$
$$- \left(\frac{1}{\gamma} \frac{\omega_D}{\omega - \omega_D} \nabla_e (q_i N_i) \times \nabla_e \tilde{\Phi}\right) \cdot e_\zeta$$
$$- \nabla_e \cdot \left(\frac{\dot{N}_i m_i}{B_{\mathrm{eq}}} \nabla_e \tilde{\Phi}\right),$$

<u>**Linear, first order**</u>

perturbative decomposition

Fourier transform

$$\Phi_1 = \sum_k \int Re\left(\tilde{\Phi} e^{i\left(k \frac{\beta}{R_J} + \omega t\right)}\right) d\omega.$$

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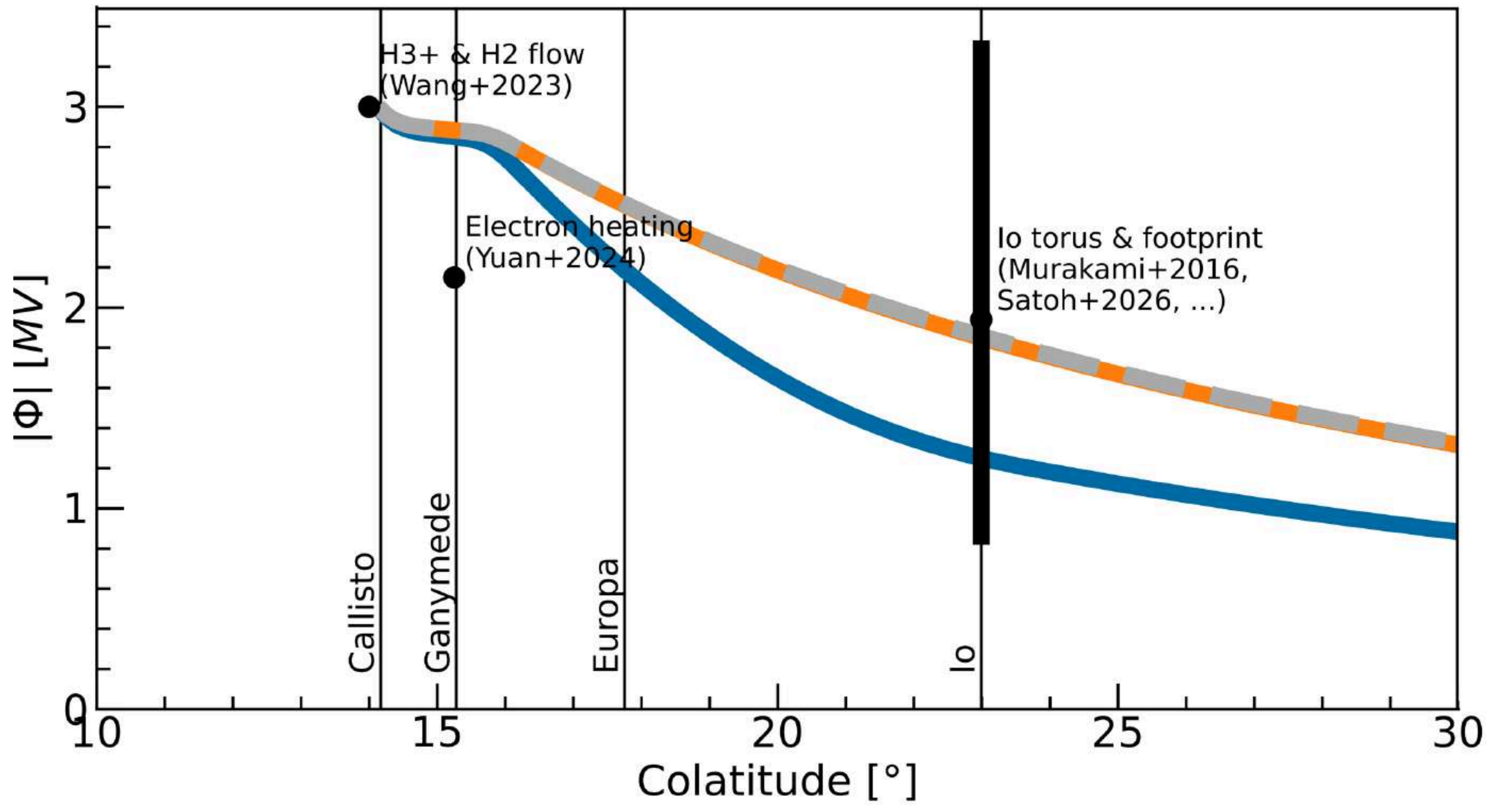
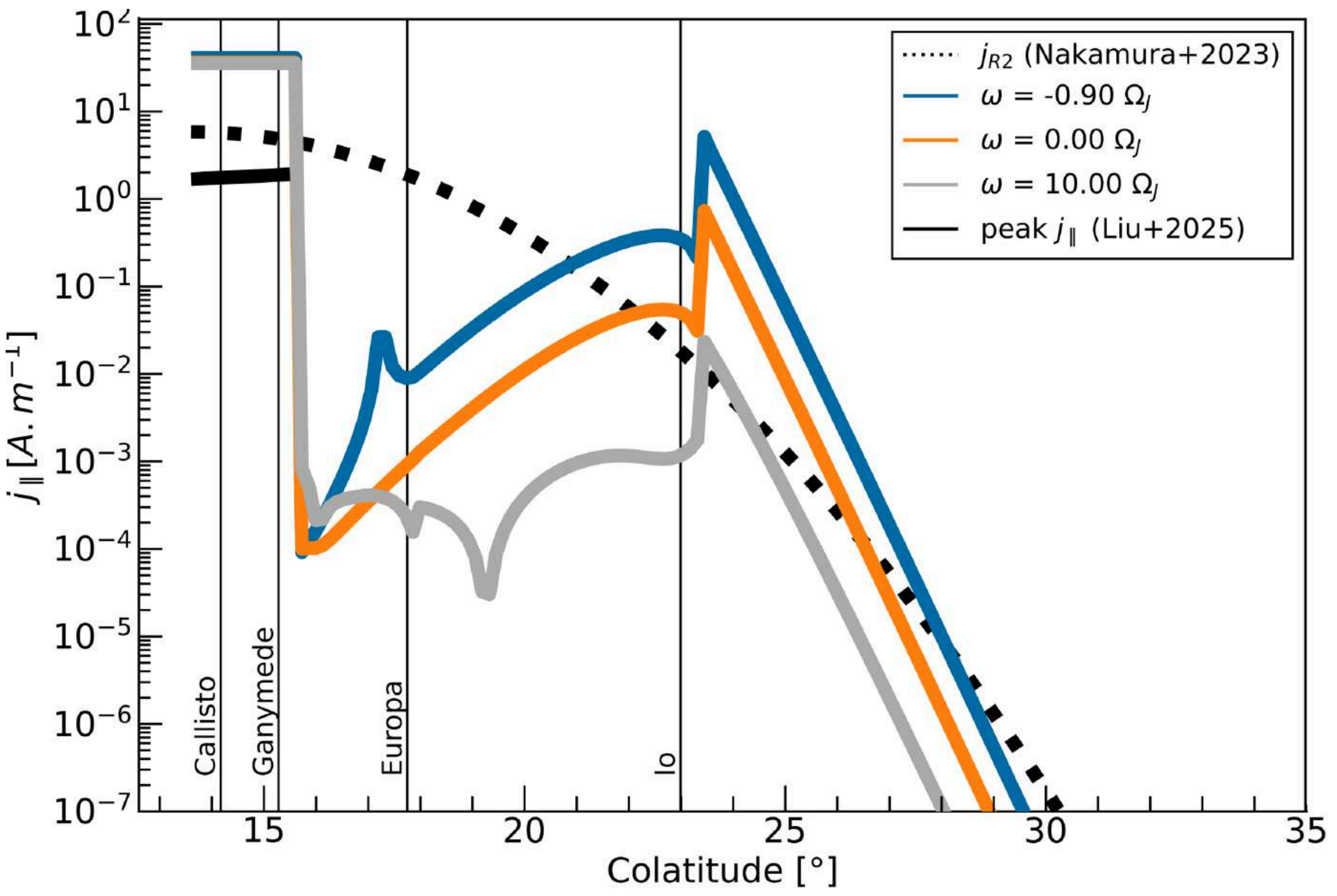
Comparison to observations



Electrostatic potential amplitude



Field-aligned currents

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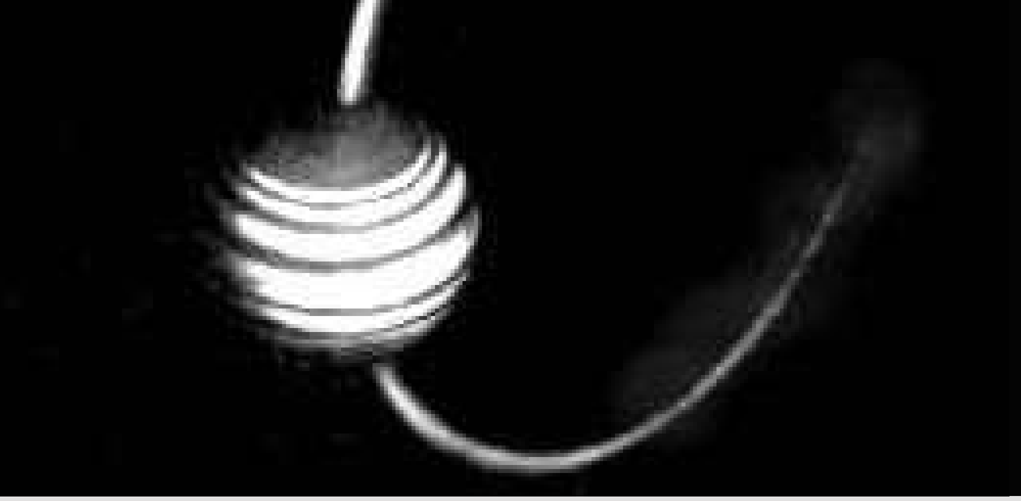
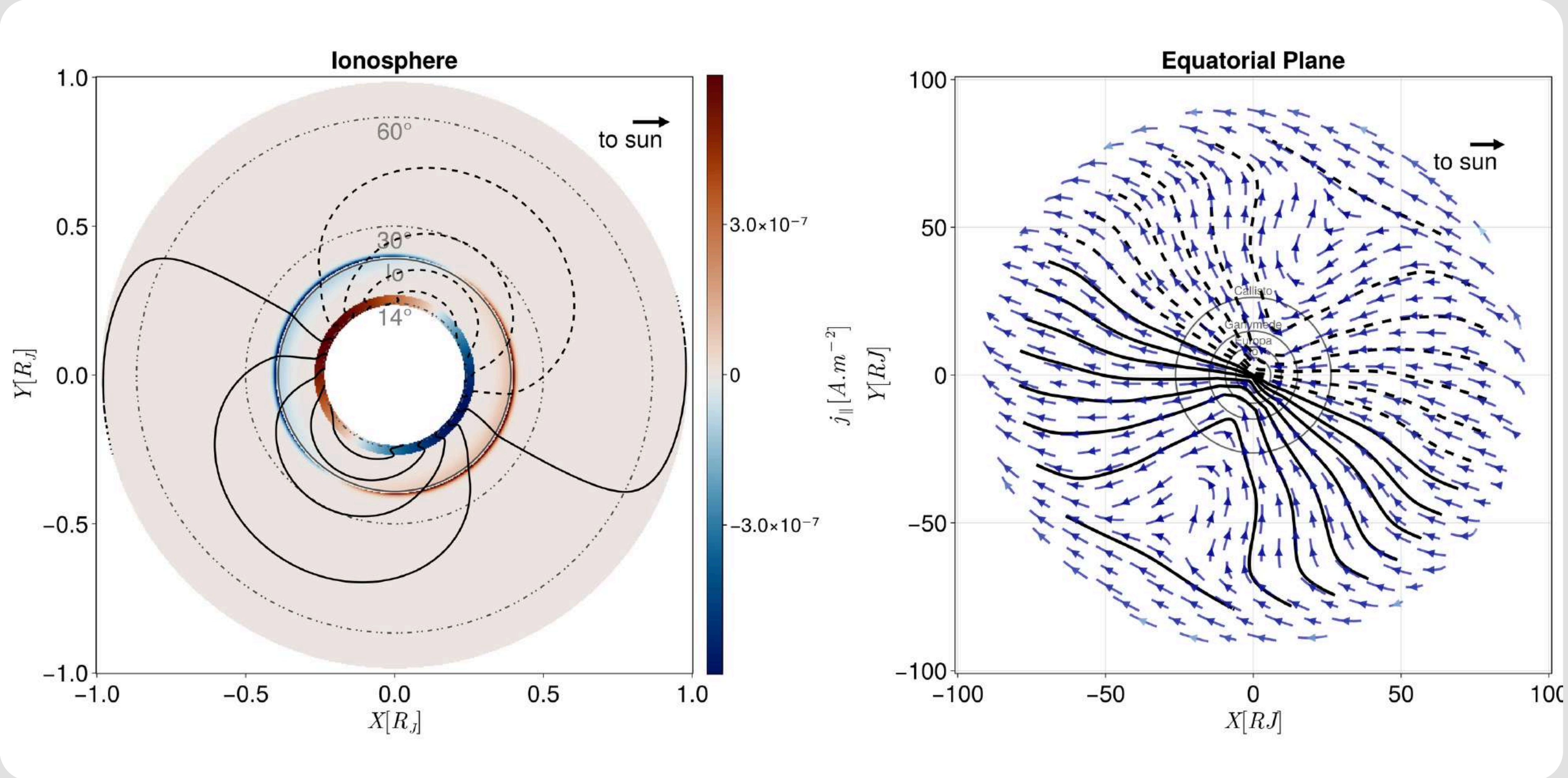
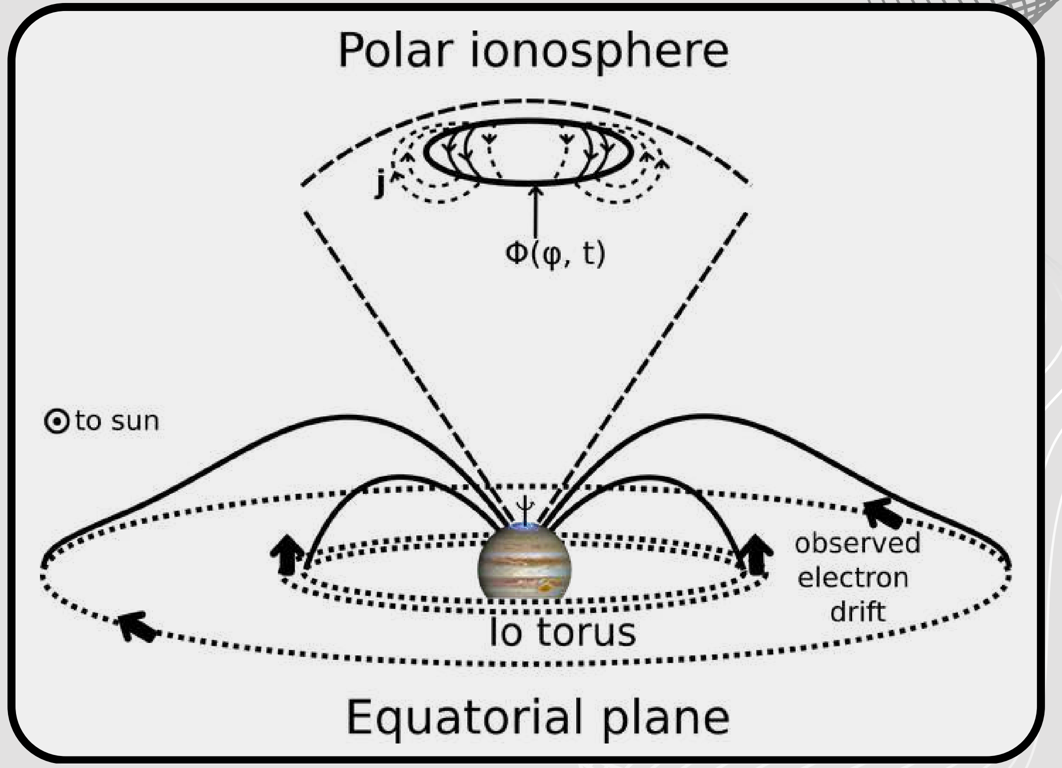


Numerical solution

$$\omega = 0$$





Observations

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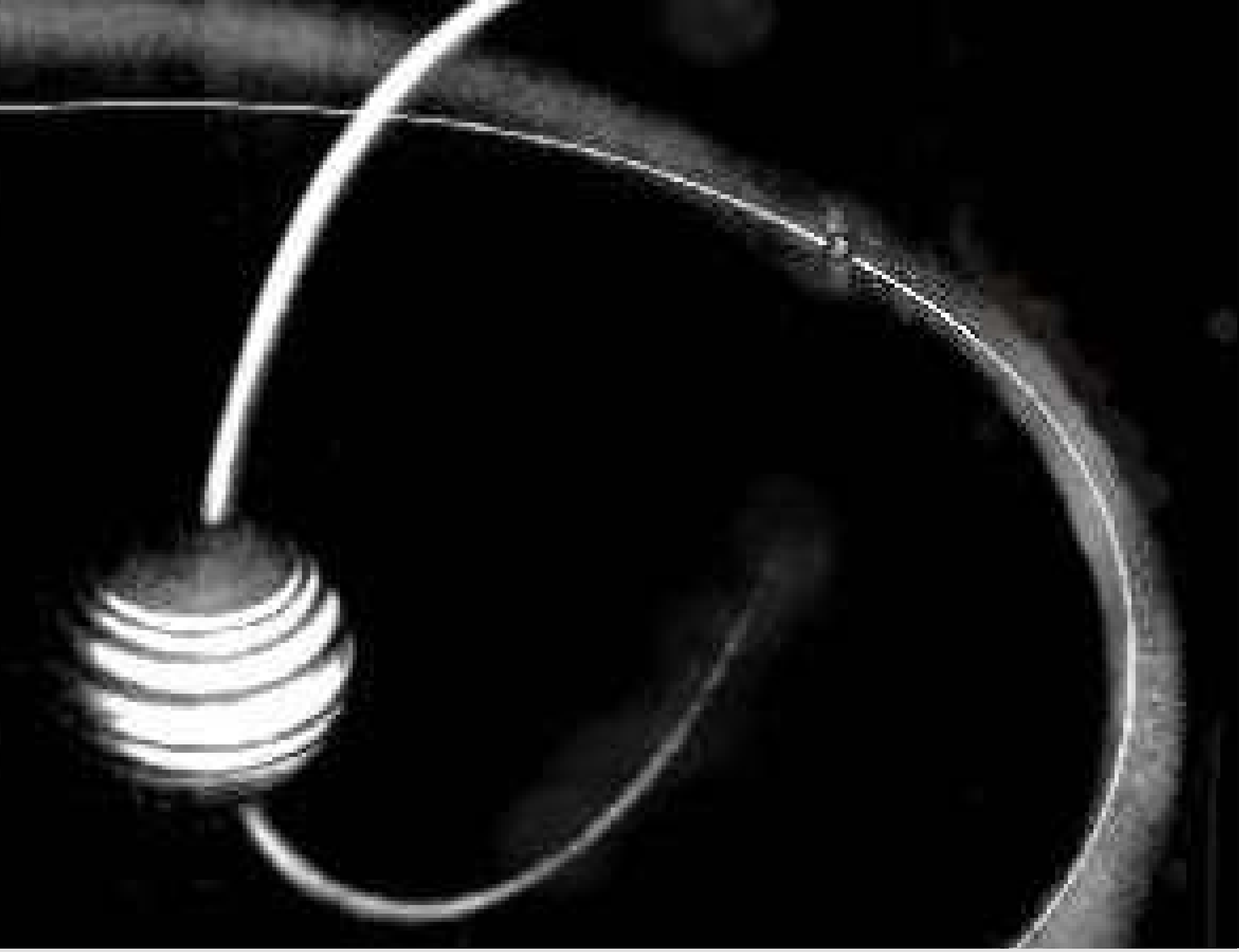

Conclusions and perspectives

Summary and ways forward

- The Jovian magnetospheric plasma cycle is the combination of a rotation driven transport and an asymmetrical convection in the outer regions
    - We model axisymmetrical transport based on a quasi-linear approach
    - We model asymmetrical convection as a first order departure from the symmetrical equilibrium

→ Consistently combine both approaches to describe non-axisymmetrical outward transport

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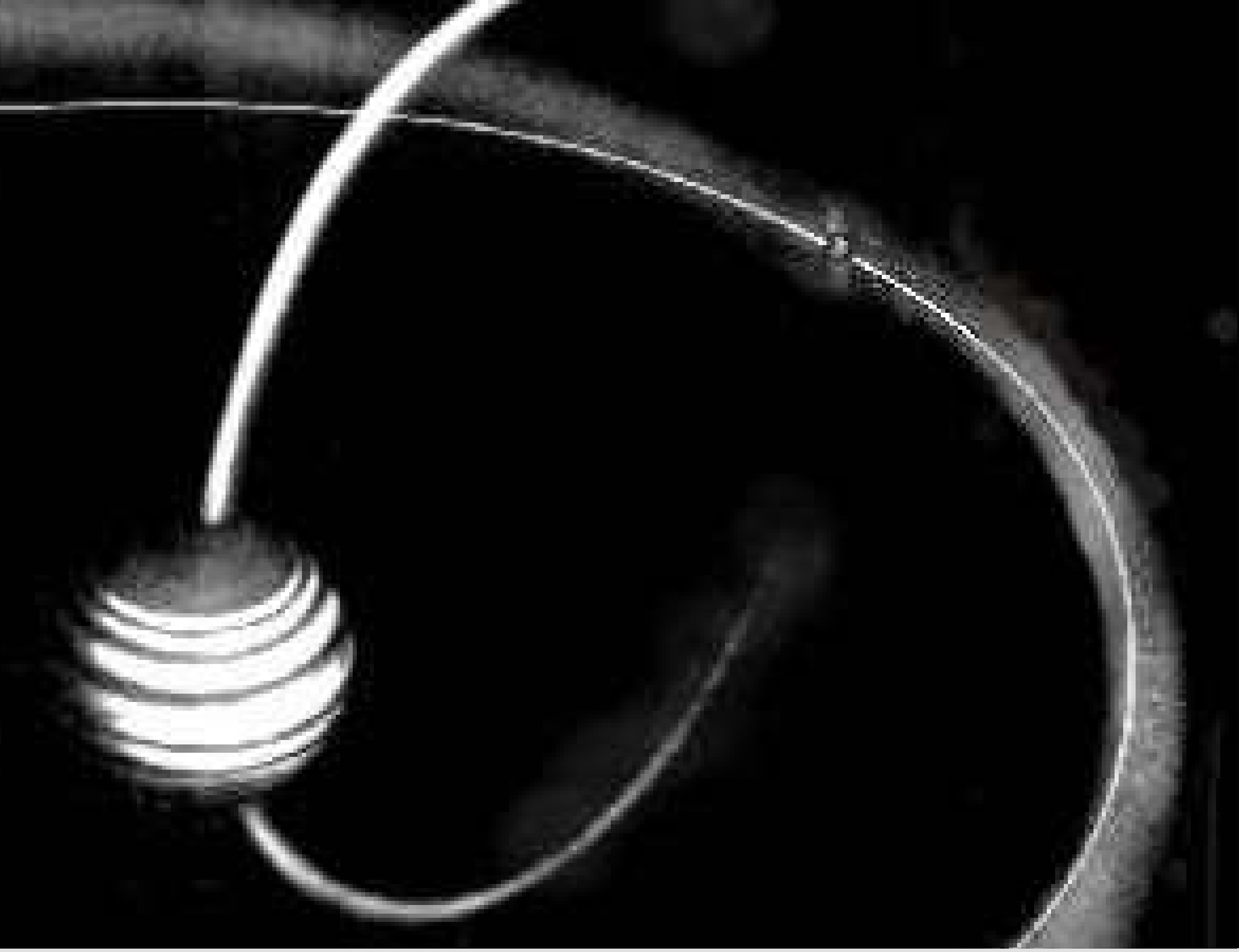
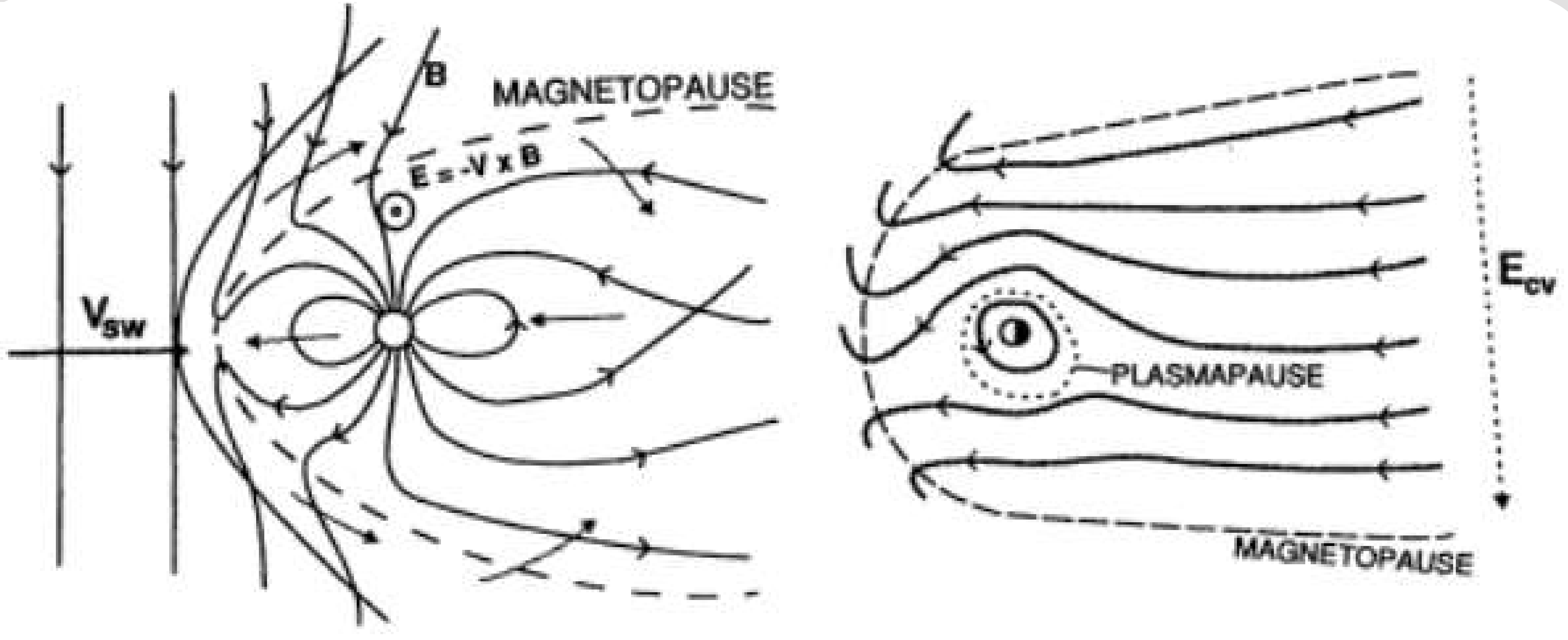


Backups

Plasma cycle in Earth magnetosphere

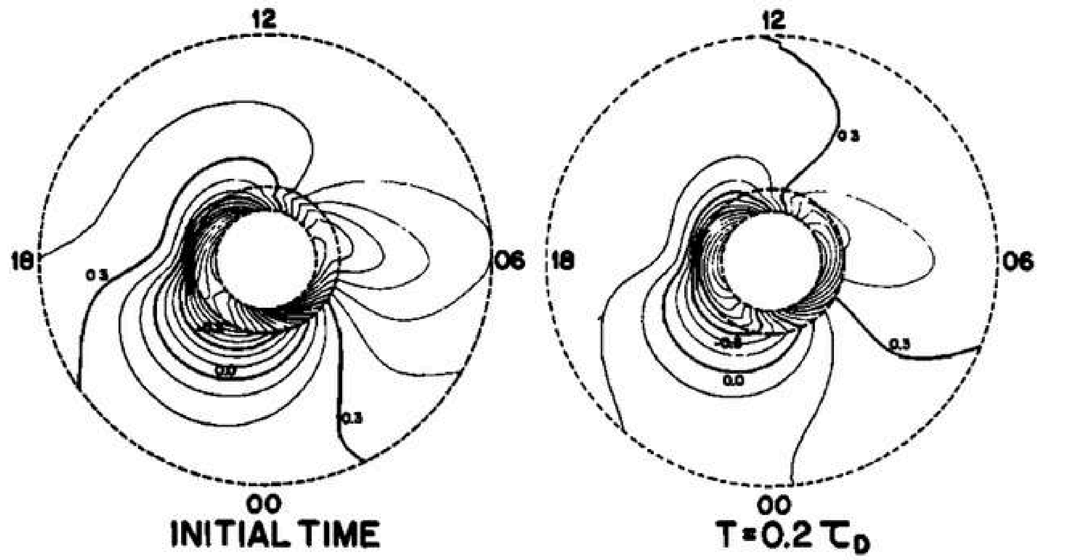
At Earth

Dungey cycle & modulations, solar-wind driven



Bagenal et al. (1992)

Response to temporal variation well described



Senior et Blanc (1984)

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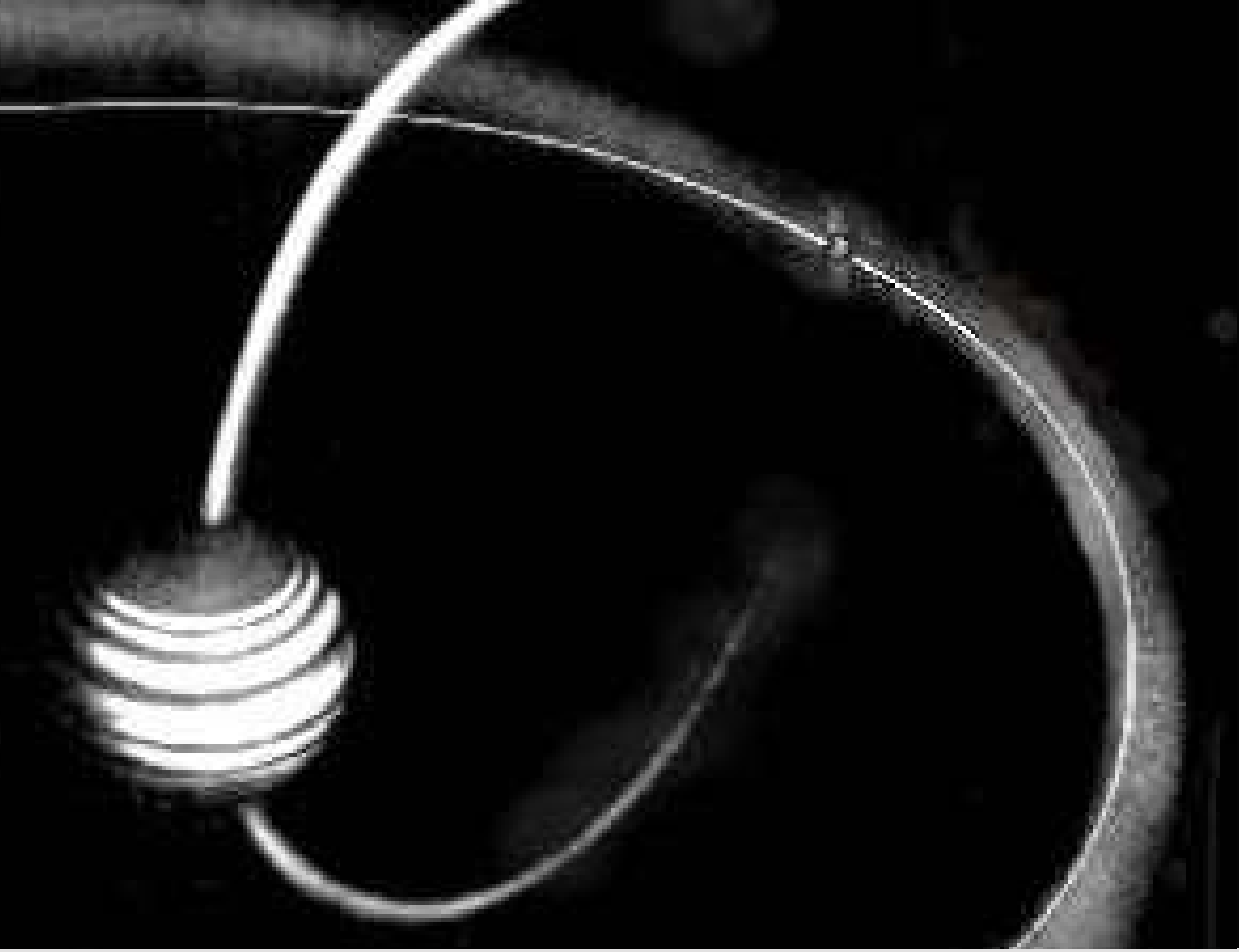
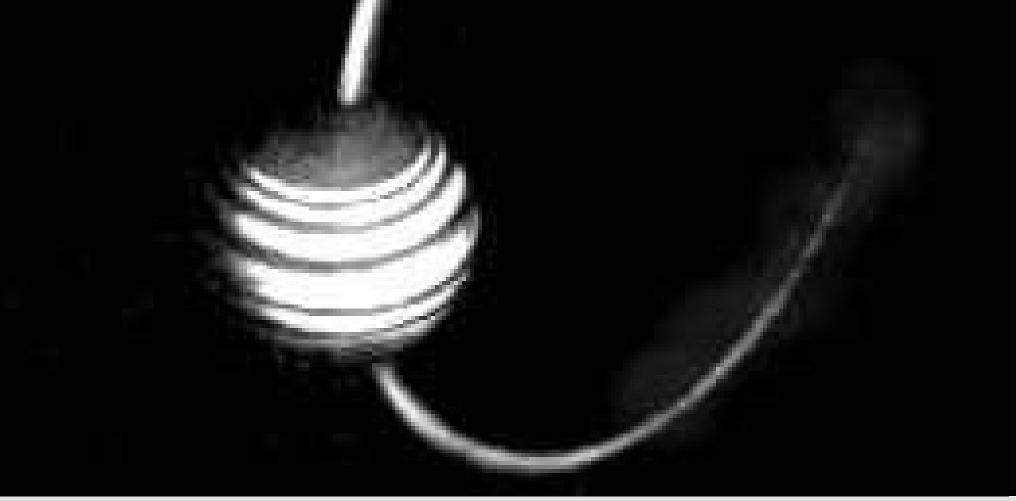


Internally driven cycle model : details

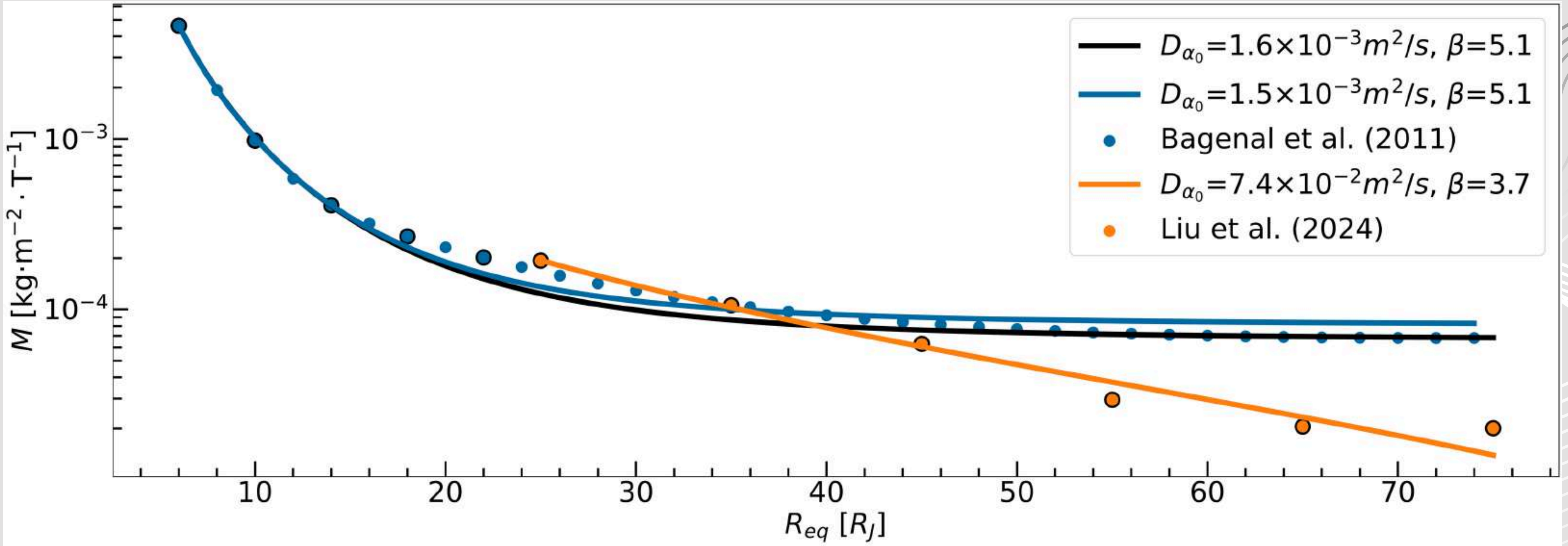


Jovian model

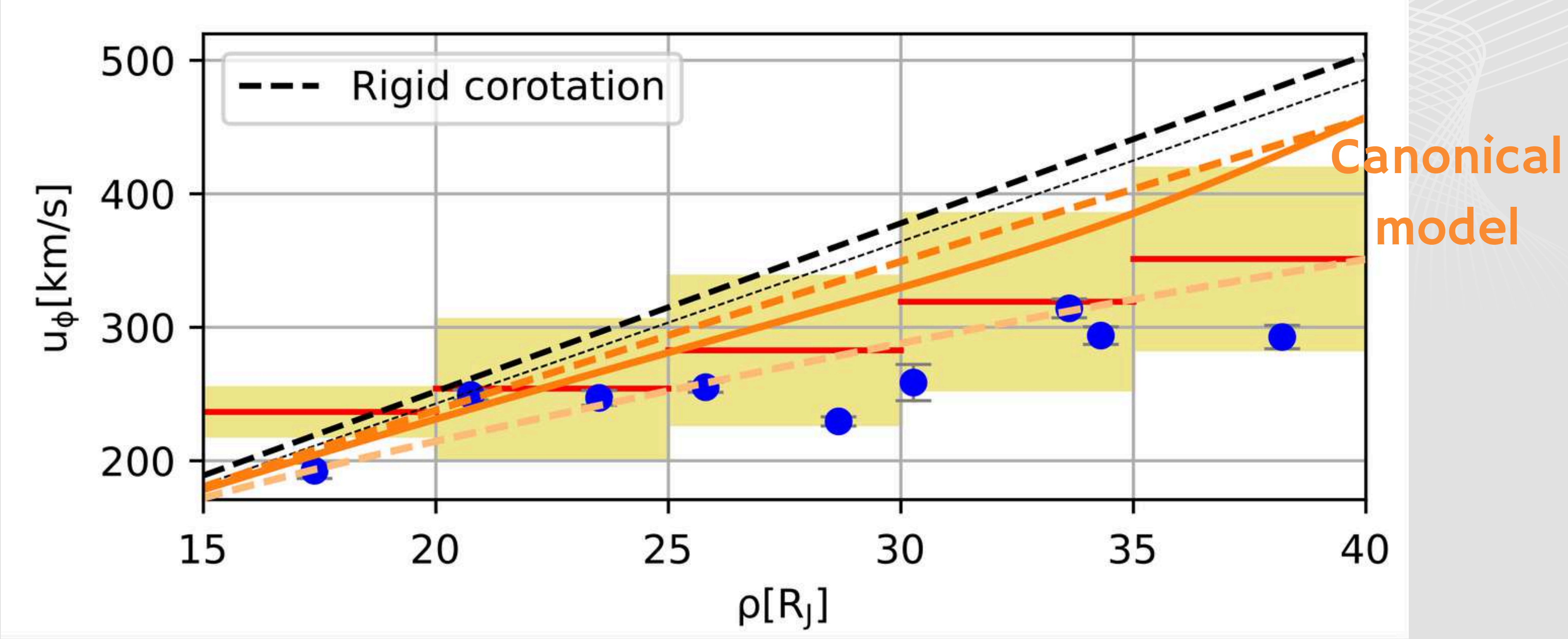
Steady-state

Constant mass flux

Mass transport



Angular momentum transport



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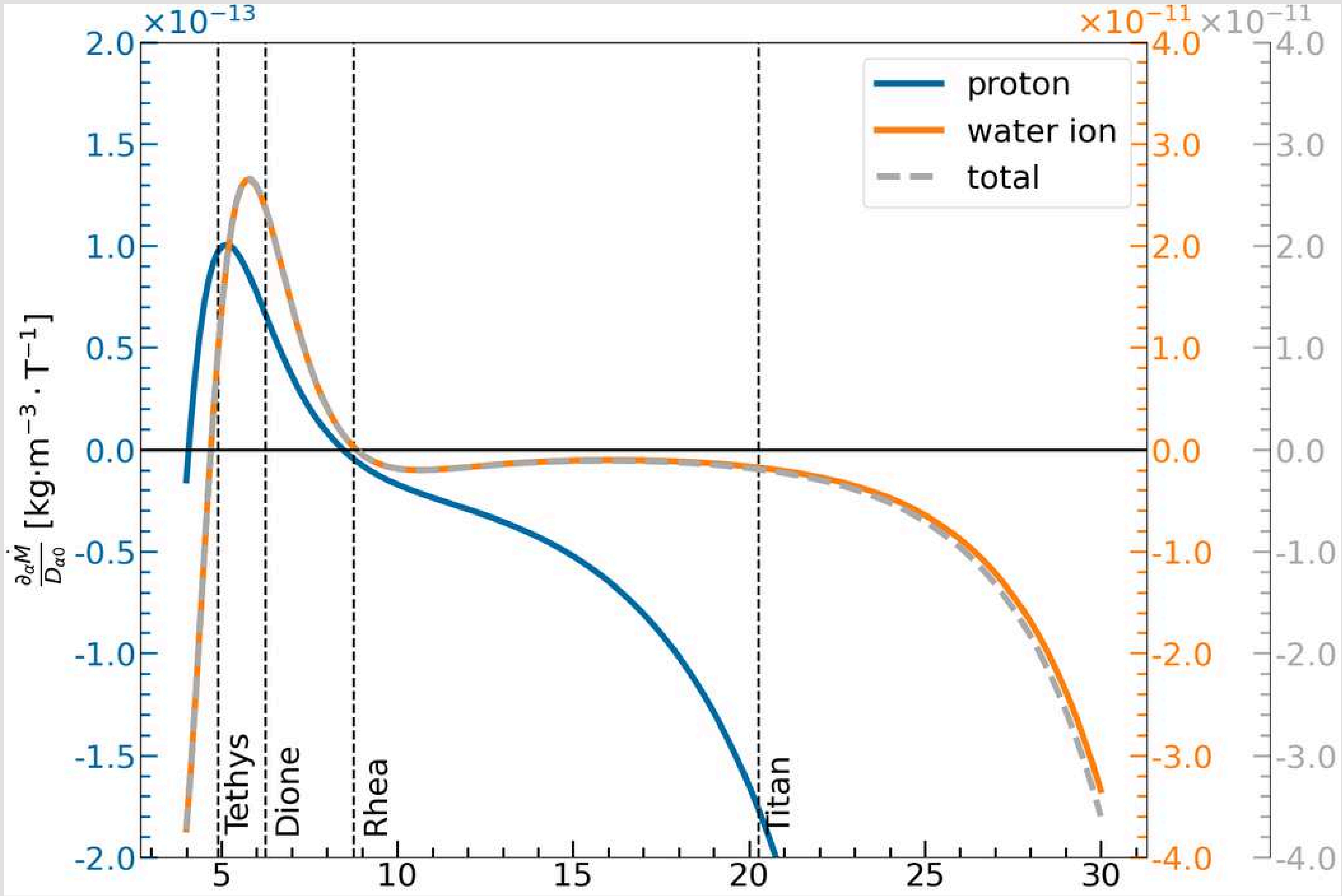
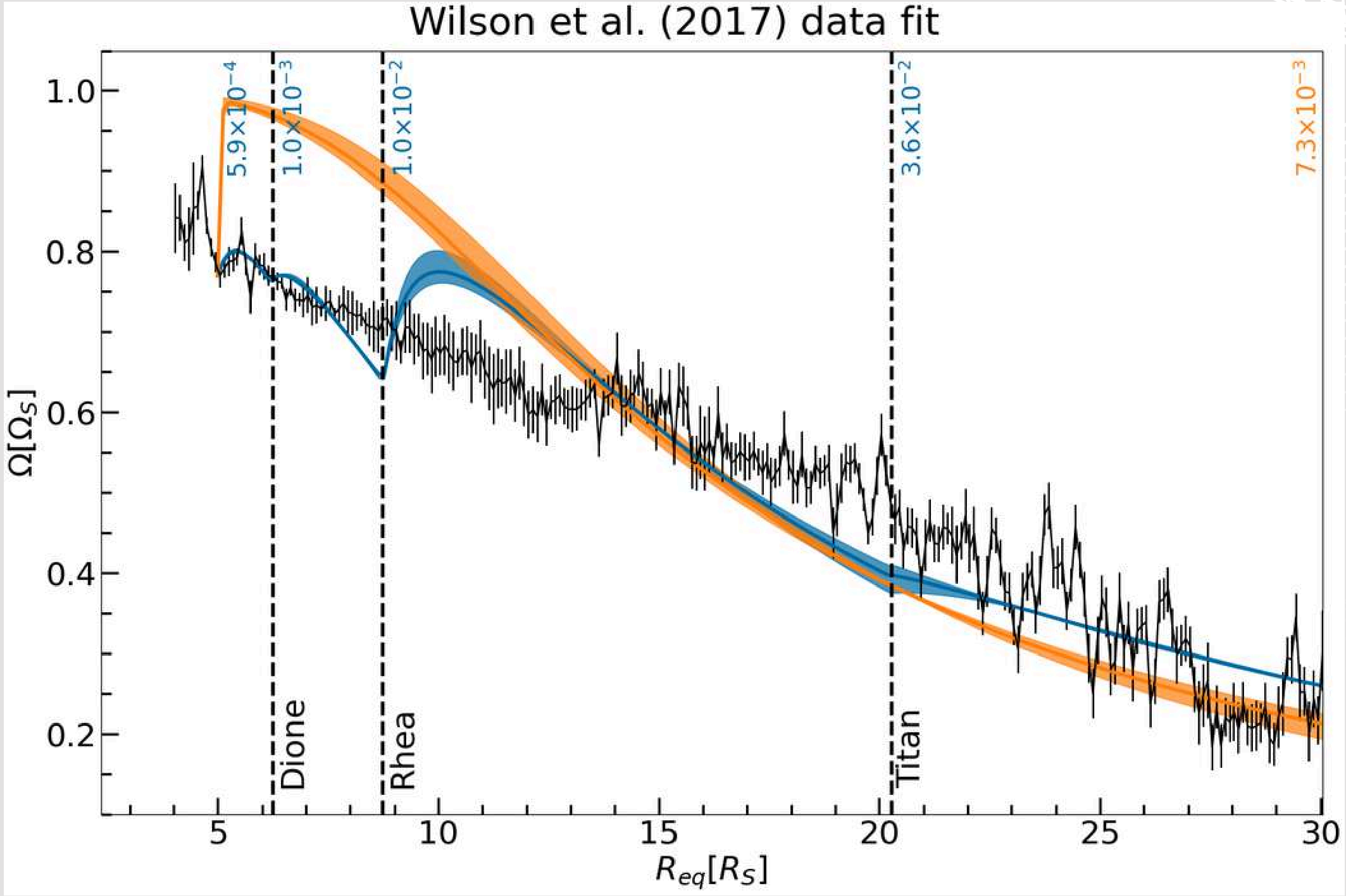
Kronian model

Steady-state

Mass transport: plasma source



Angular momentum transport



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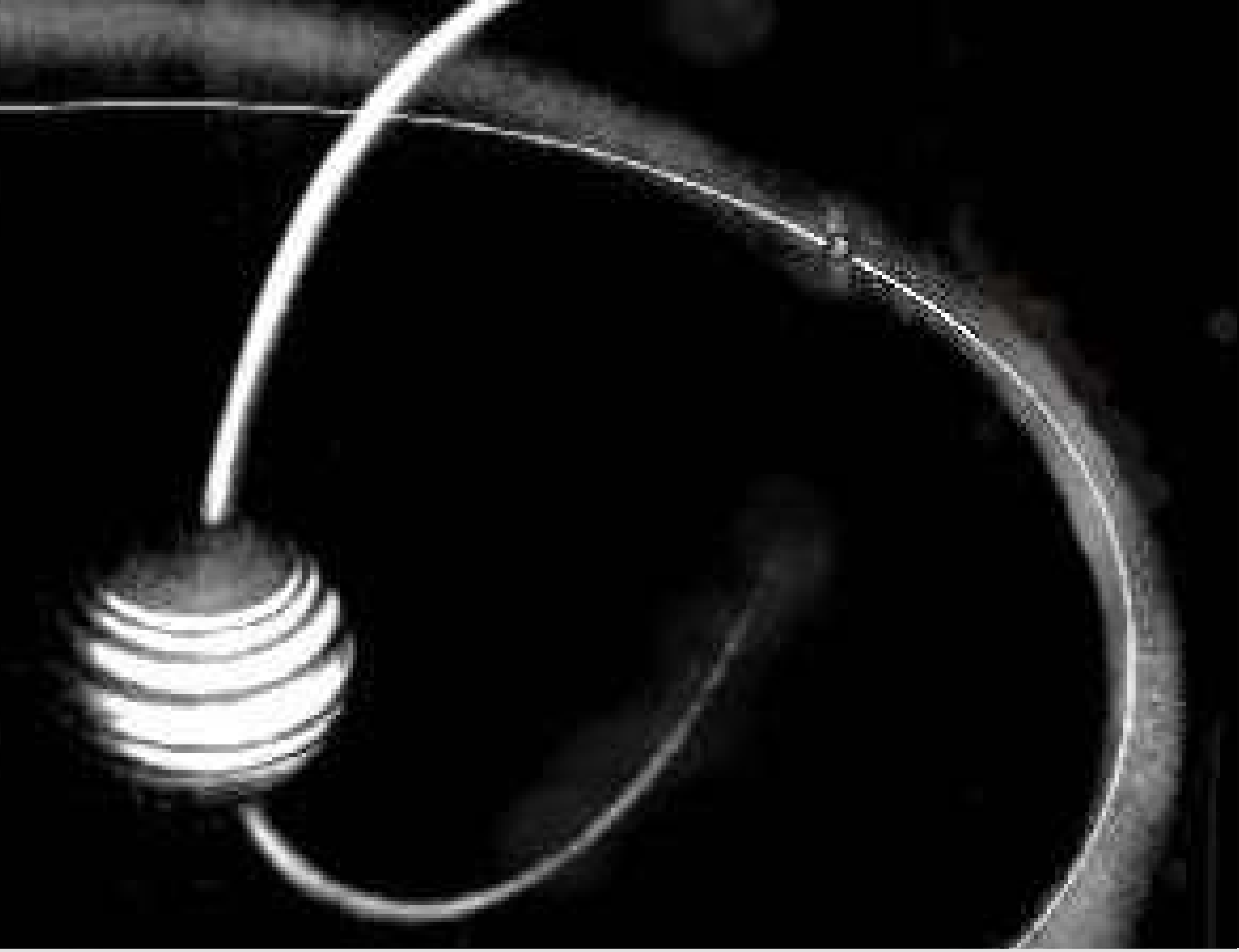
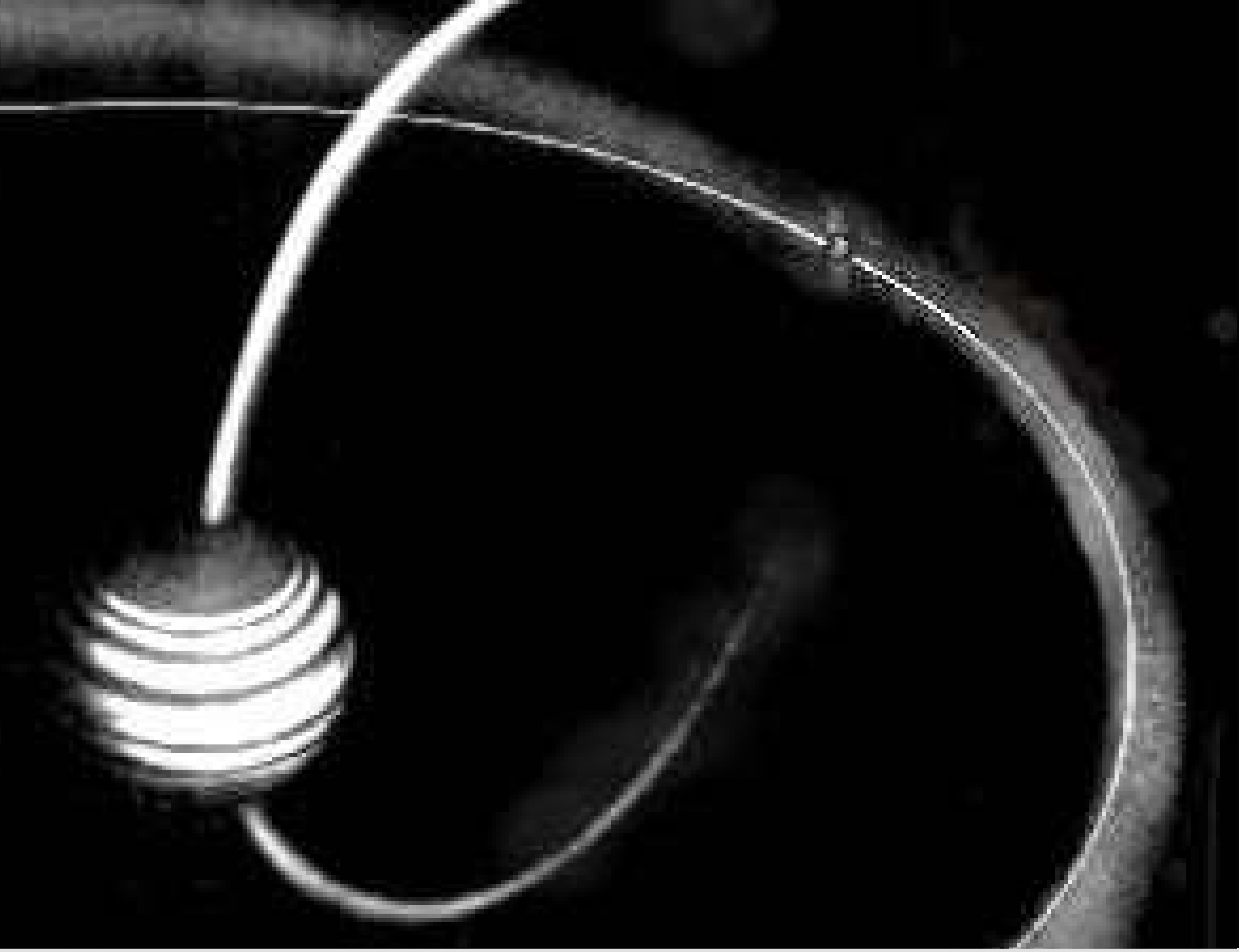


Solar-Wind driven cycle model : details

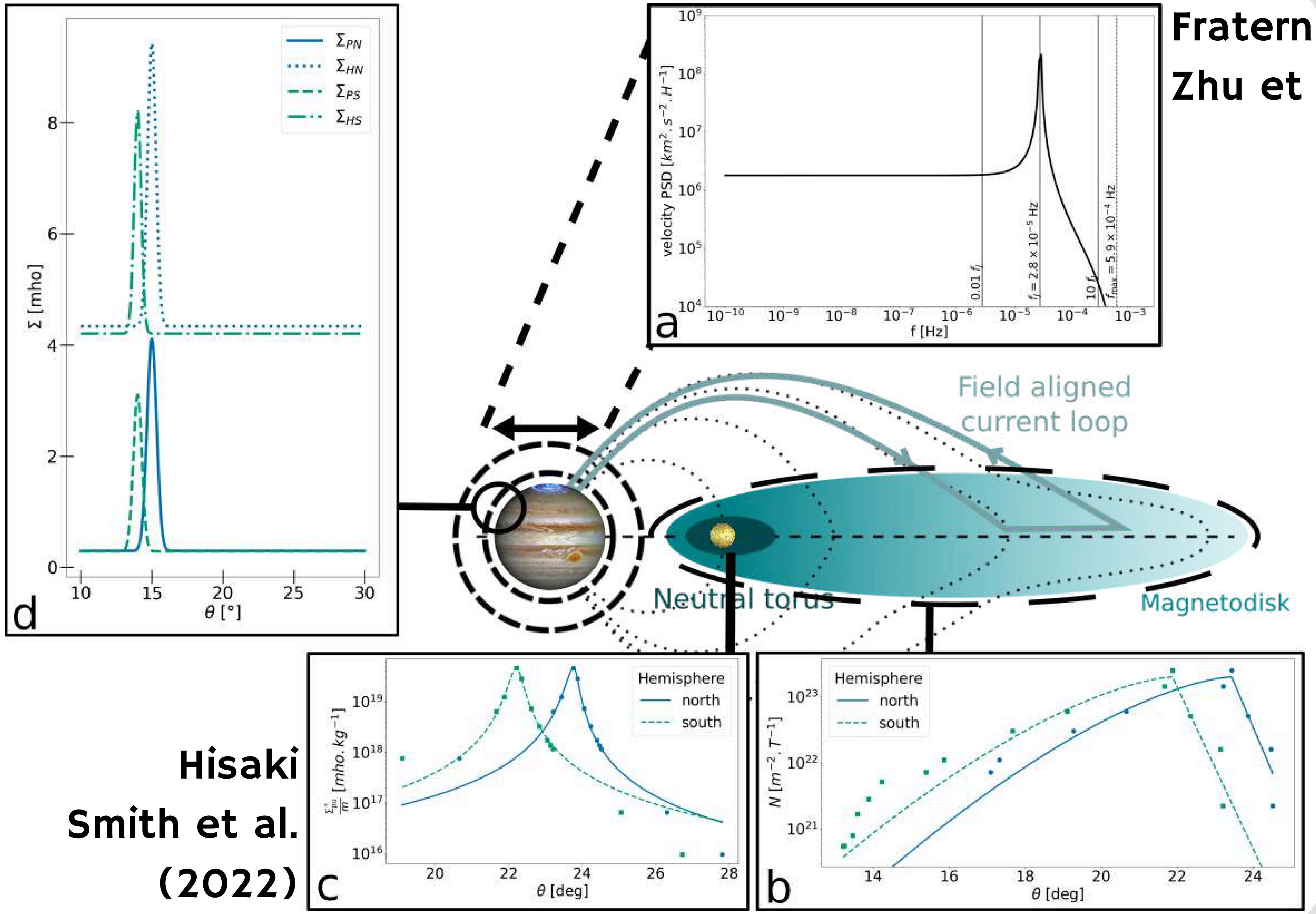


"Solar-Wind driven" cycle Numerical applications

Input parameters

Juno
Al Saati et al. (2022)
Nakamura et al. (2022)

Fraternale et al. (2016)
Zhu et al. (2024)



Juno
Liu et al. (2021, 2024)

Hisaki
Smith et al. (2022)

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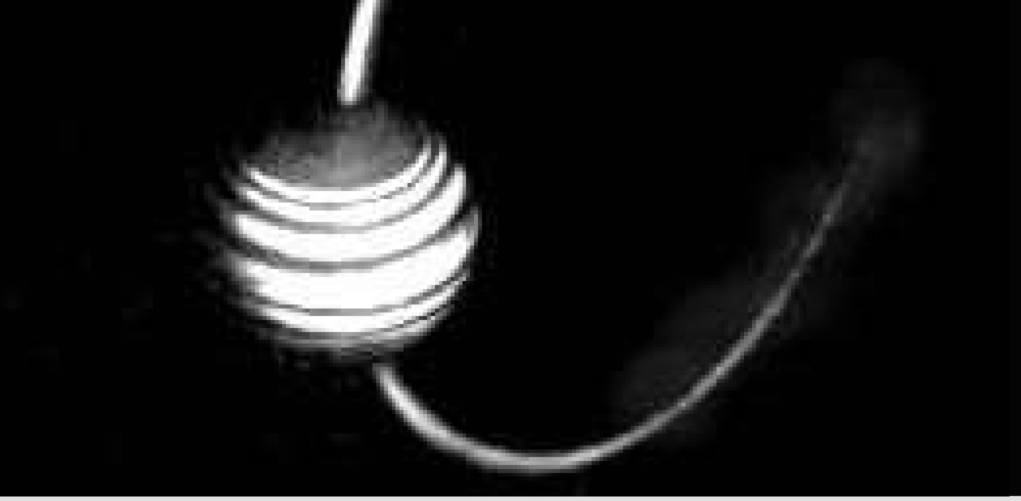
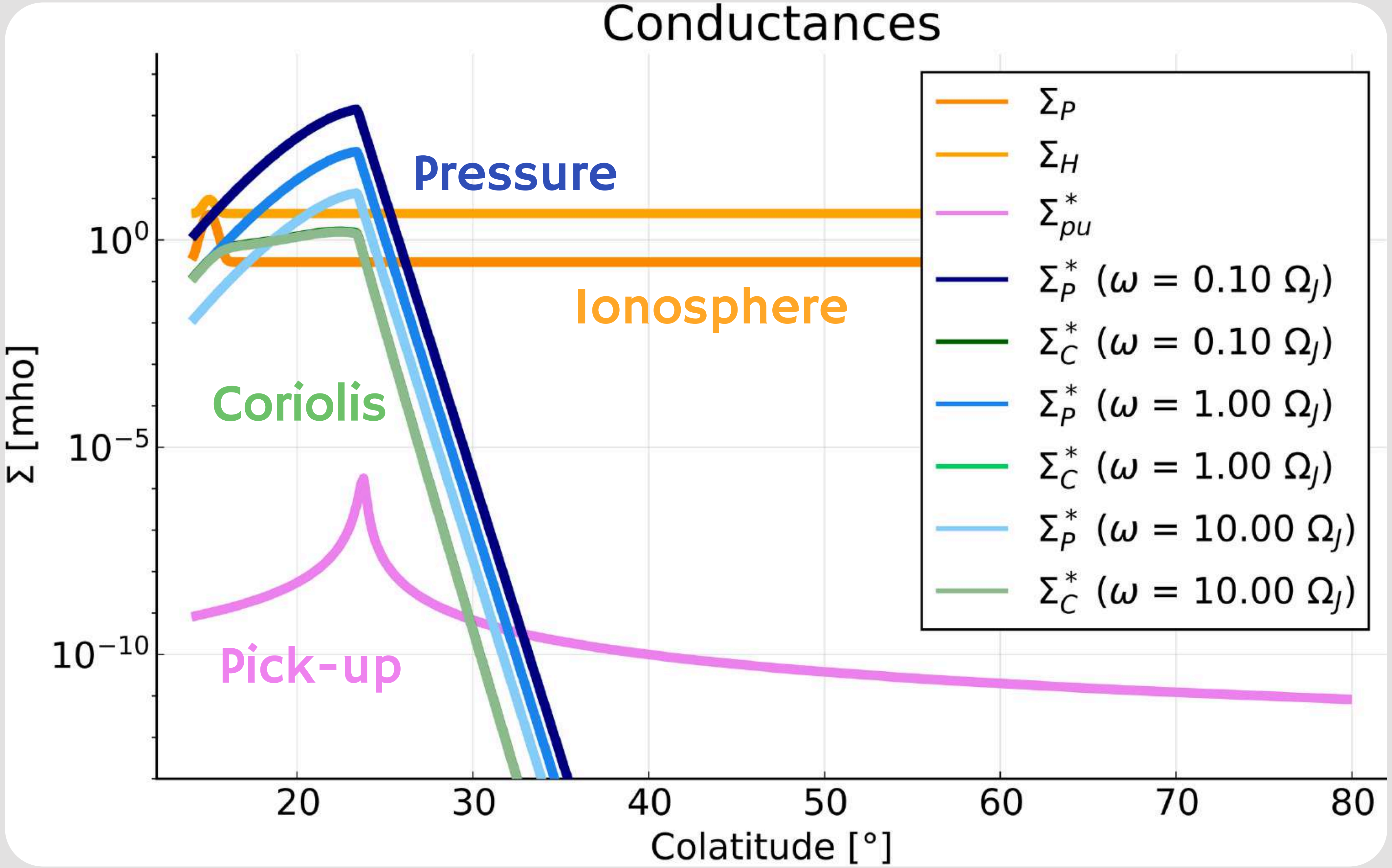


Contributions

$$\boldsymbol{\nabla_i} \cdot \left(\Sigma_P \boldsymbol{\nabla_i} \tilde{\Phi}\right) + \left(\boldsymbol{\nabla_i} \Sigma_H \times \boldsymbol{\nabla_i} \tilde{\Phi}\right) \cdot \boldsymbol{e_\zeta} = -\left(2 m_i \Omega \, \boldsymbol{\nabla_e} \cdot \left(\frac{N_i}{B_{\mathrm{eq}}}\right) \times \boldsymbol{\nabla_e} \tilde{\Phi}\right) \cdot \boldsymbol{e_\zeta} - \left(\frac{1}{\gamma} \frac{\omega_D}{\omega - \omega_D} \boldsymbol{\nabla_e}(q_i N_i) \times \boldsymbol{\nabla_e} \tilde{\Phi}\right) \cdot \boldsymbol{e_\zeta} - \boldsymbol{\nabla_e} \cdot \left(\frac{\dot{N}_i m_i}{B_{\mathrm{eq}}} \boldsymbol{\nabla_e} \tilde{\Phi}\right)$$



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