Imperial College London

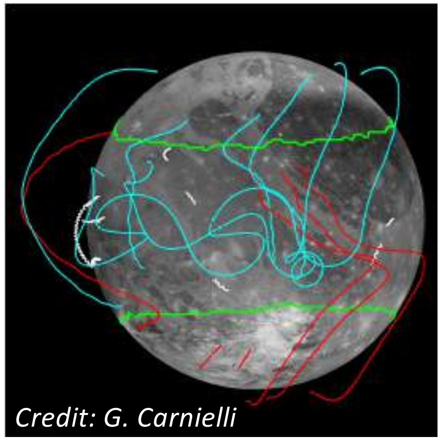
Connecting the **Galileo** particle, plasma, & field **data with** ionospheric, atmospheric, & field **models**

Marina Galand[1], **Gianluca Carnielli[1]**, François Leblanc[2], Ronan Modolo[2], Xianzhe Jia[3], & Arnaud Beth[1]

[1] Dpt of Physics, Imperial College London, London, UK (m.galand@ic.ac.uk)

[2] LATMOS/IPSL, Sorbonne Université/Université Paris-Saclay, Paris, France

[3] Dpt Climate & Space Sciences and Engineering, Université of Michigan, Ann Arbor, USA



Imperial College London

Motivation

- **Essential to have a good understanding of Ganymede's plasma environment**:
  - Ionosphere: Critical layer for coupling with magnetized environment (→ magnetospheric models – often assume spherically symmetric ionosphere)
  - In preparation to JUICE (→ operability of some plasma instruments)
- **Ionosphere of Ganymede poorly constrained**
  - Previous ionospheric models: transport neglected, chemical scheme unrealistic, only photoionization considered (e.g., Cessateur et al. 2012)

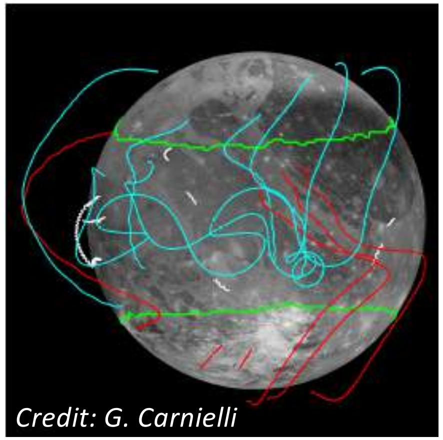
→ **Need for more realistic ionospheric models**

Imperial College London

Outline


Credit: NASA

- **3D kinetic model of Ganymede's ionosphere**
  - To calculate ion trajectories
  - To derive 3D maps of 1st moments for main ion species


Credit: G. Carnielli

- **Galileo/Model comparison (G2 flyby)**
  - To validate the B and E fields
  - To constrain the exospheric densities

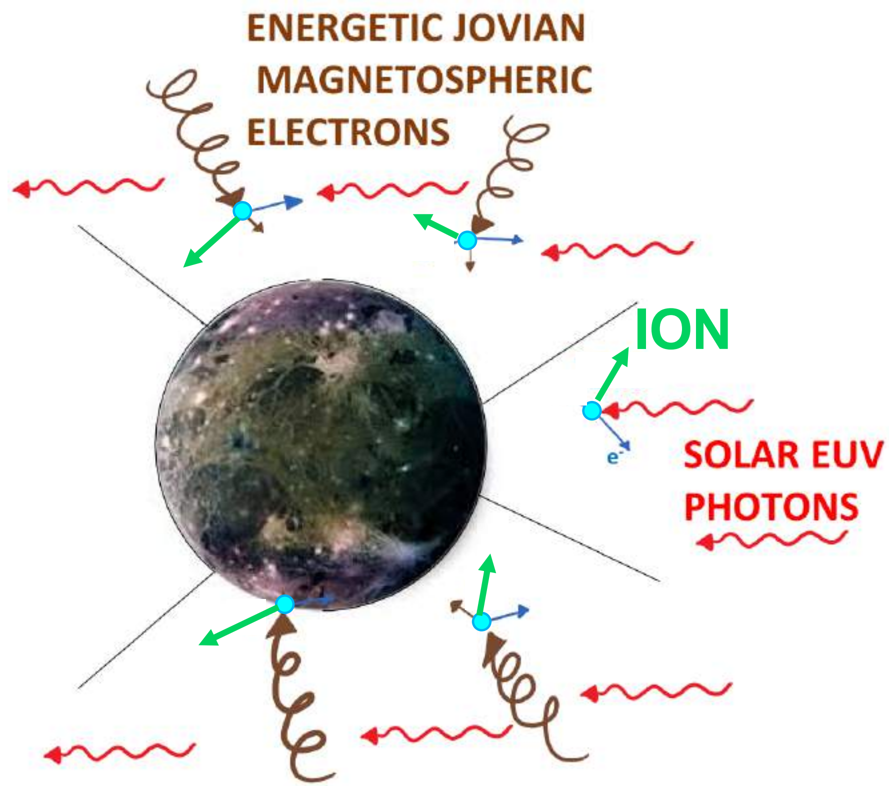
Imperial College
London

3D kinetic model of Ganymede's ionosphere

3D kinetic model of Ganymede's ionosphere

- **Inputs:**
  - **Exospheric densities:**
    O_2, H_2O, H_2, (O, H, OH)
    (Leblanc et al., 2017)
  - **Ionisation frequencies:**
    - From solar EUV radiation
    - From Jovian electrons

➢ **Creation of ionospheric ions**

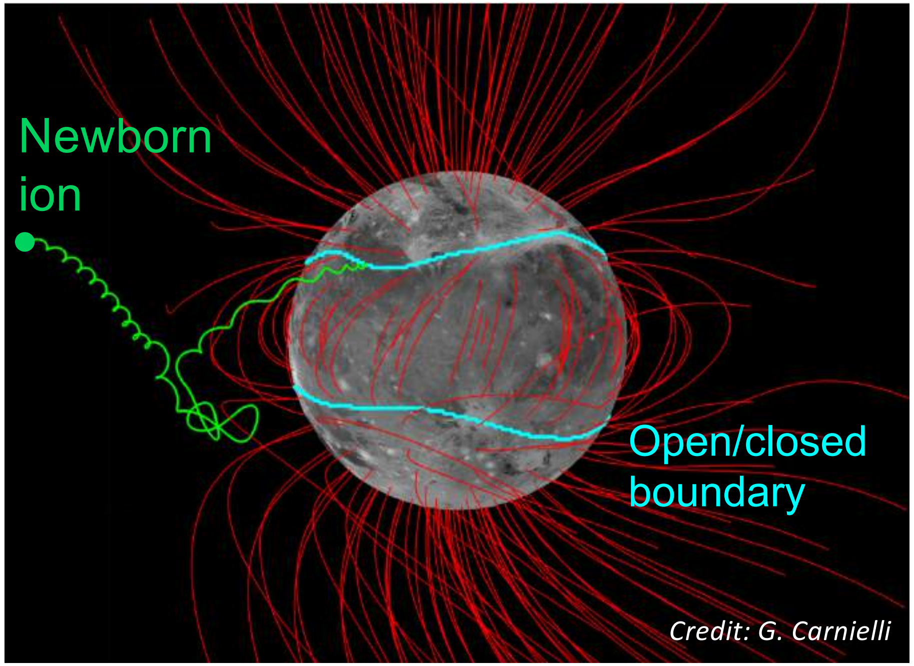


3D kinetic model of Ganymede's ionosphere

- **Inputs:**
  - Electric & magnetic fields
    - MHD: Jia et al. (2009)
    - Hybrid: Leclercq et al. (2016)
  - ➢ Ions "pushed" through the fields

- **Collisions:** charge exchange included

➢ **First 3D kinetic** test-particle **model** of the ionospheric ions

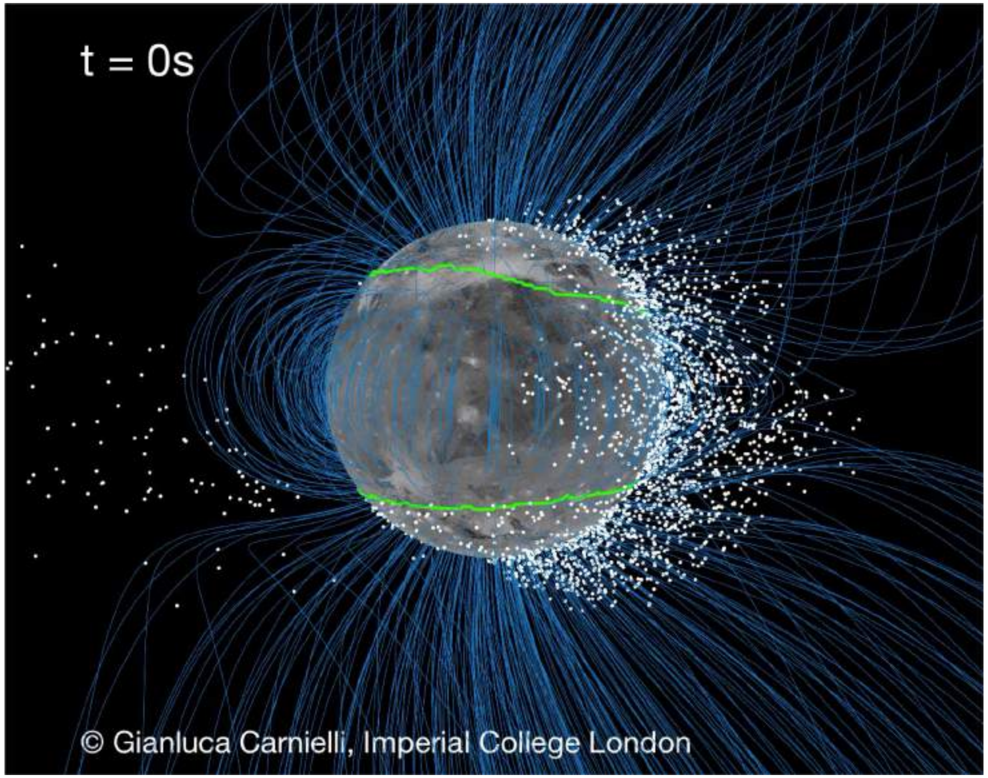


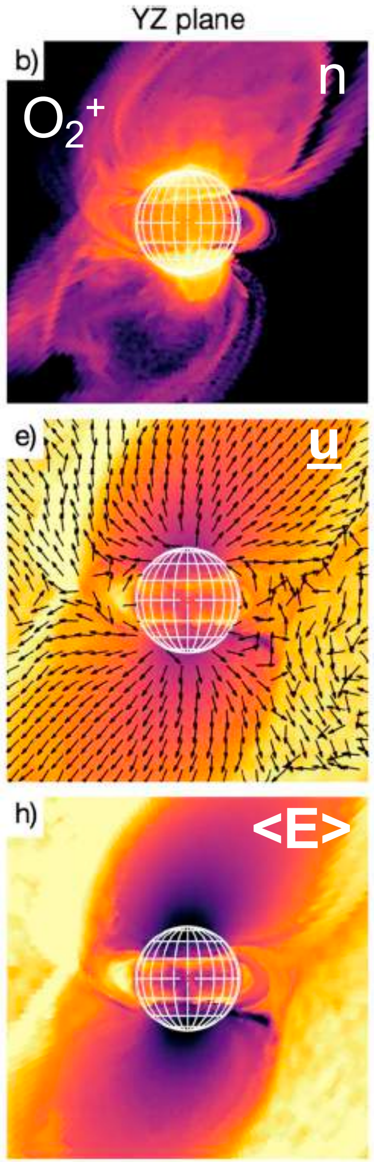
Credit for Ganymede's surface picture: NASA

Imperial College London

3D kinetic model of Ganymede's ionosphere

- **Outputs:**





Carnielli et al. (2019)

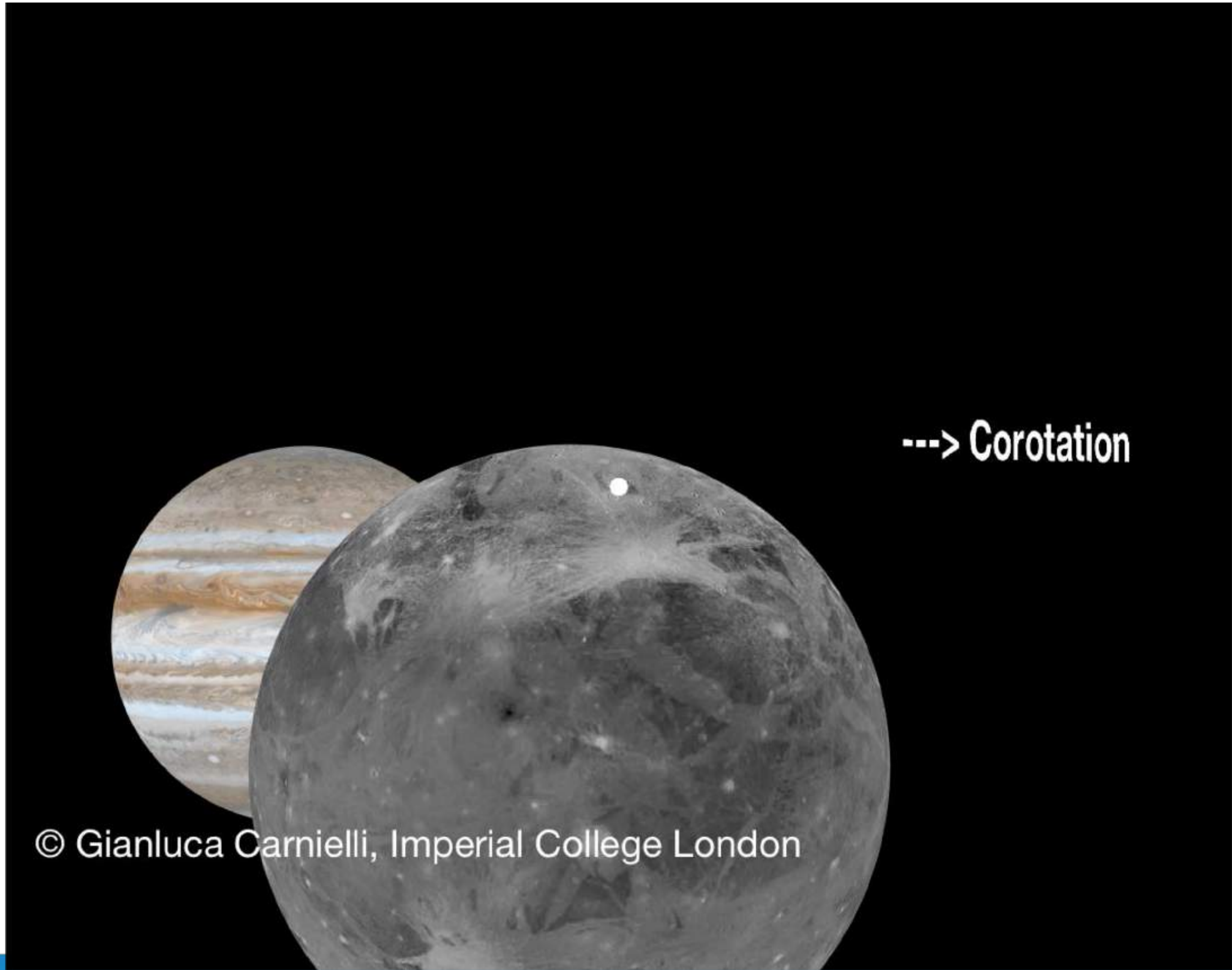
  - **O_2^+** dominant in Ganymede's ionosphere

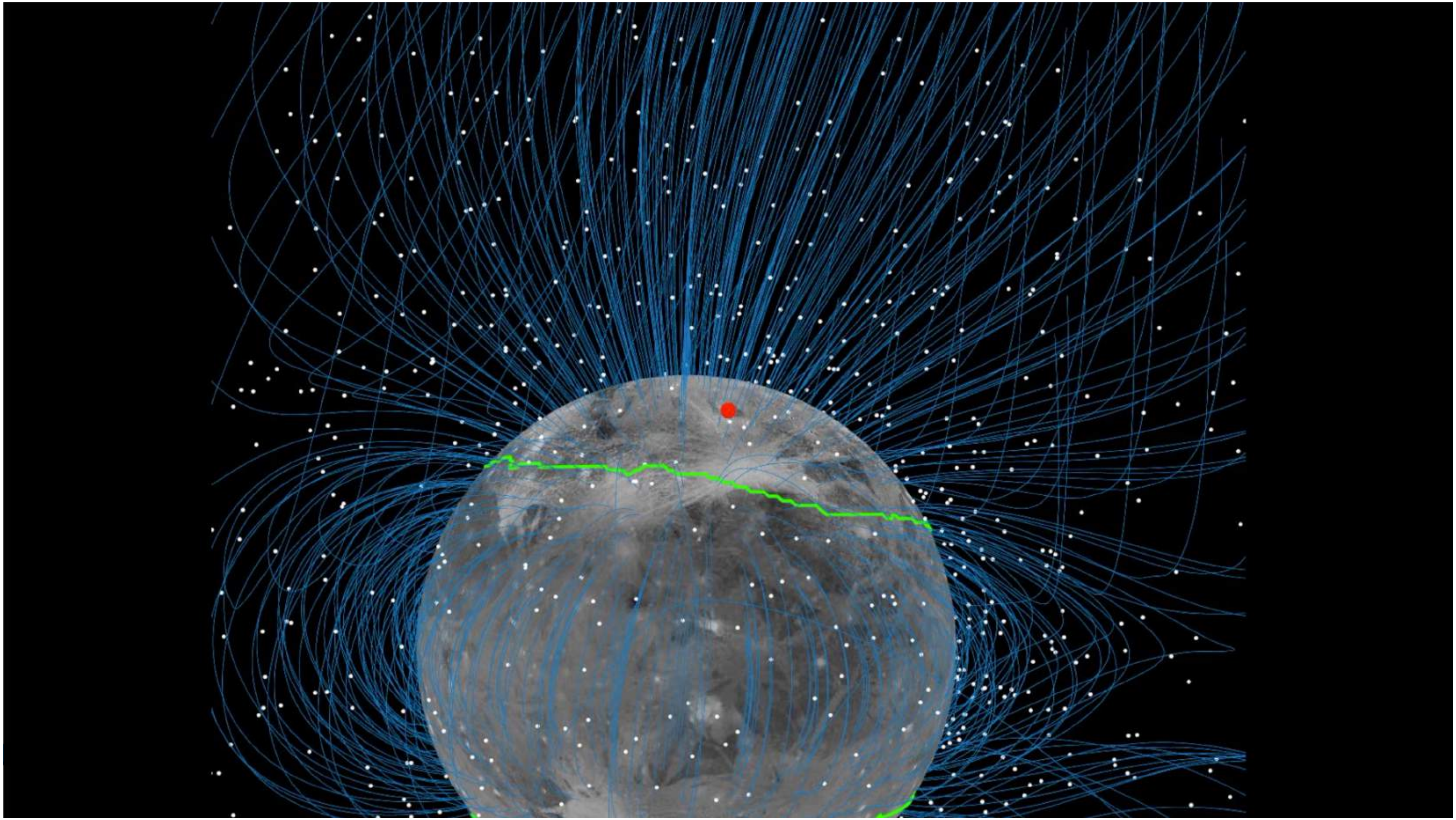
Imperial College London

Galileo/Model comparison: G2 flyby

Imperial College London

G2 flyby



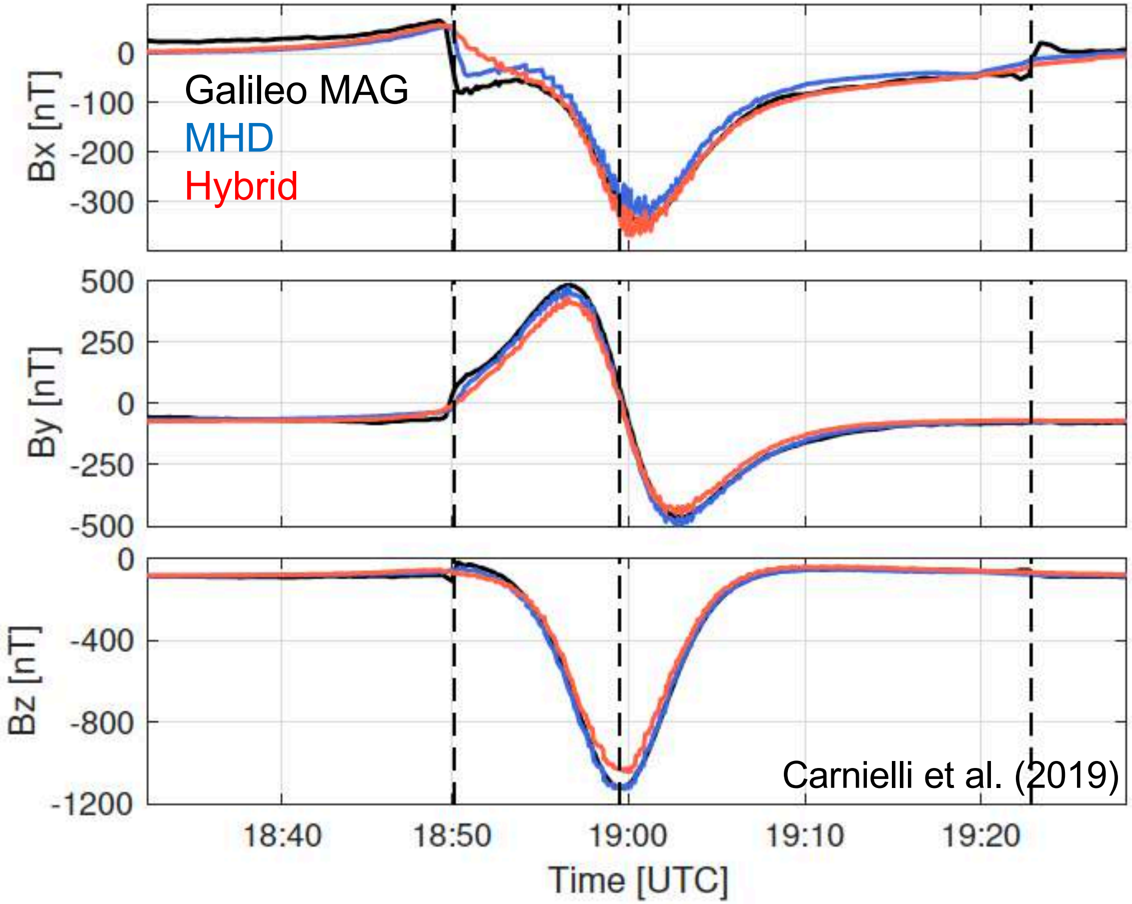


Imperial College London

Comparison: Magnetic field

✓ **Very good agreement** between Galileo/model in terms of **B** field along Galileo trajectory

Galileo/MAG: Kivelson et al. (1996,1997)
MHD: Jia et al. (2009)
Hybrid: Leclercq et al. (2016)

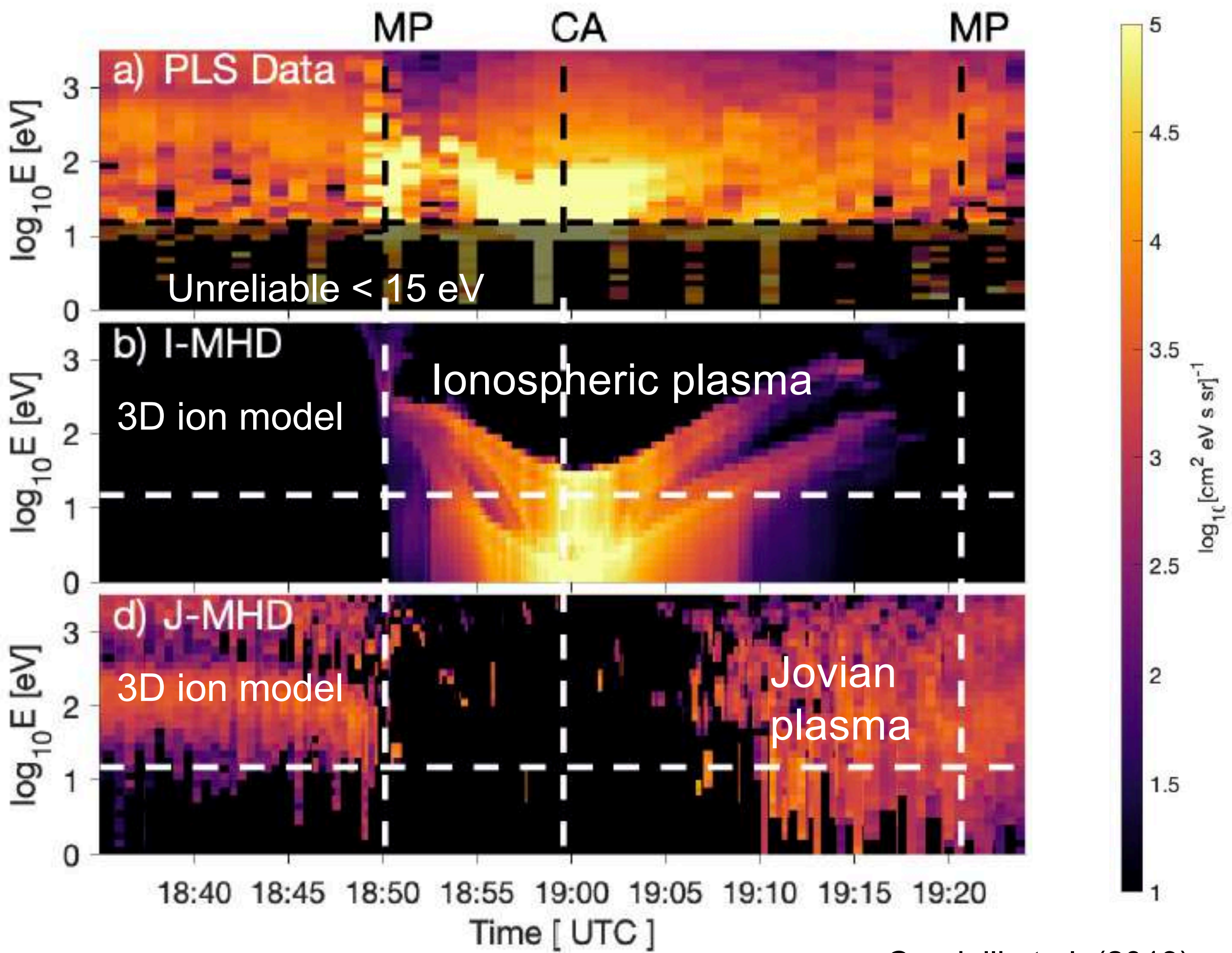


Imperial College London

Comparison: Ion energy distribution

Galileo/PLS (Frank et al. 1992): Data processing based on work by Markus Fraenz (see Carnielli et al. 2019)

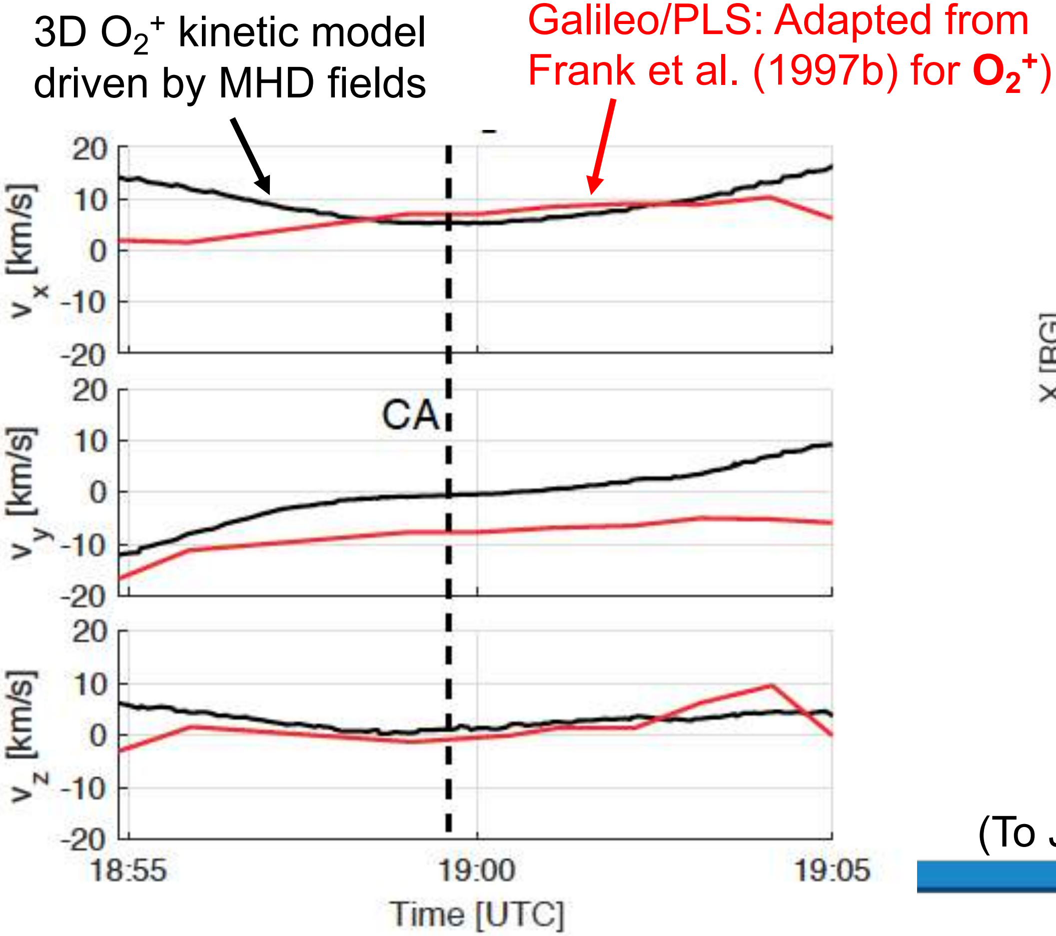
Ion model driven by fields from MHD (Jia et al. 2009)

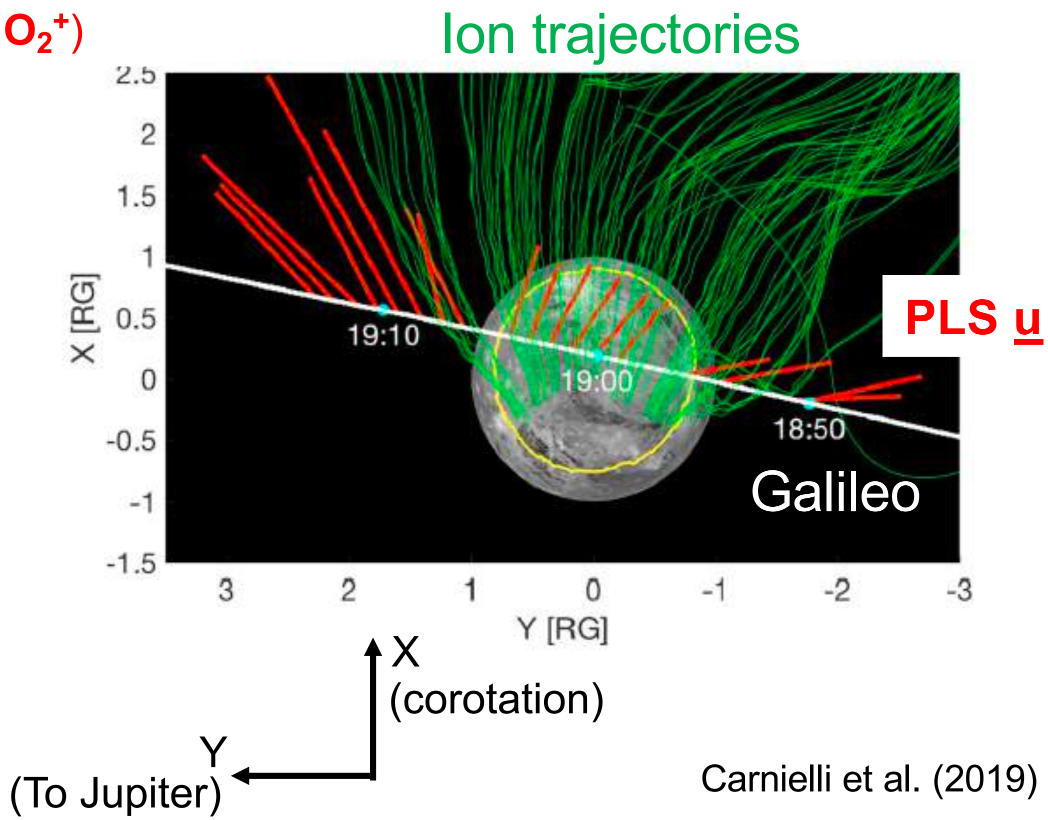


Carnielli et al. (2019)

Imperial College London

Comparison: Ion bulk velocity





Carnielli et al. (2019)

Imperial College London

Validation of E & B fields

- ✓ **Agreement** in terms of:
  - B field along the trajectory
  - Ion energy distribution & ion bulk velocity (both influenced by field in 3D environment)

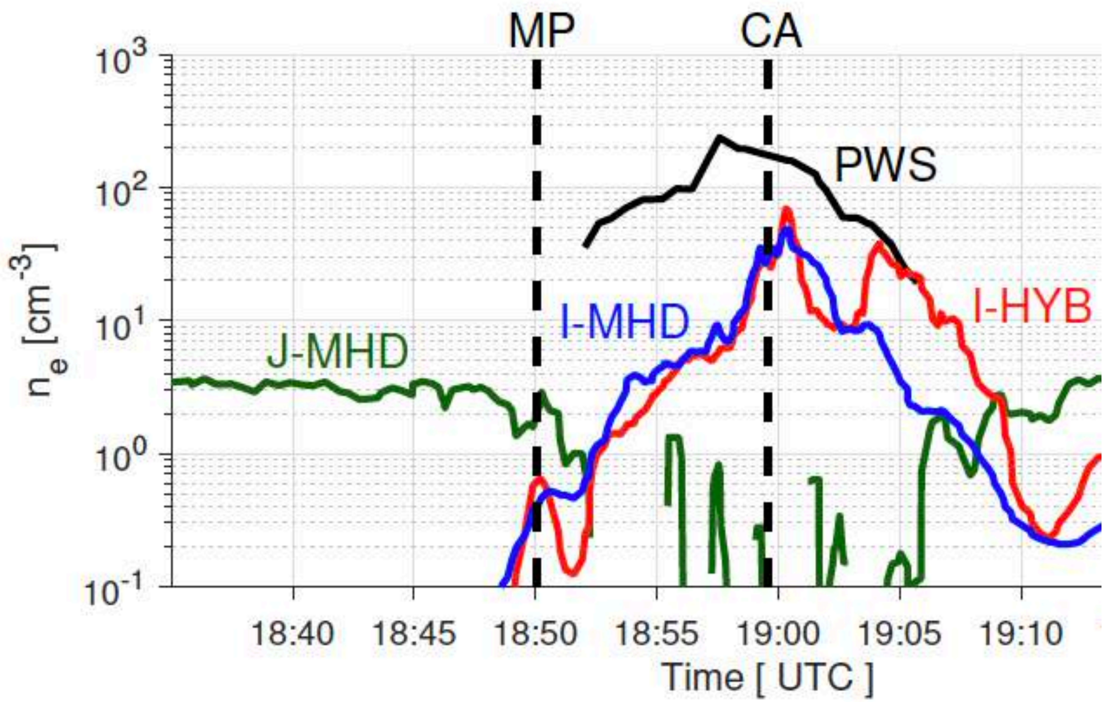
- ➢ **Validation of the MHD modelled fields*** assumed in the near environment of Ganymede (* Jia et al. 2009)

- ➢ Disagreement between obs and modelled ion energy magnitude (production?)

Imperial College London

Comparison: Plasma density

- **Galileo/PWS** (Eviatar et al., 2001)
- 3D ion kinetic model:
- Ionospheric plasma using MHD **B** field (Jia et al. 2009)
- Ionospheric plasma using hybrid **B** field (Leclercq et al. 2016)
- Jovian magnetospheric plasma using MHD **B** field (Jia et al. 2009)



Carnielli et al. (2020a)

- ➢ Agreement in terms of shape (MHD)
- ➢ Disagreement in terms of magnitude

Imperial College London

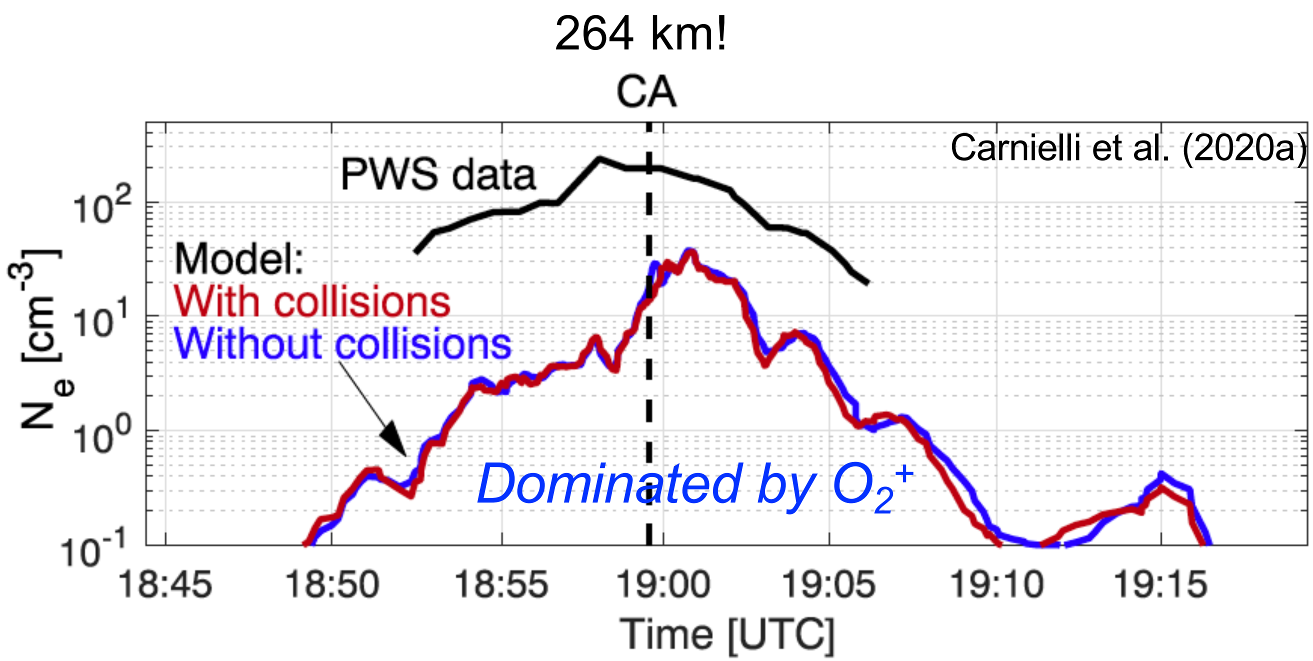
Effect of collisions

Collisions (CX):

$O_{2,f}^{+} + O_2 \rightarrow O_{2,f} + O_2^{+}$

$O_f^{+} + O_2 \rightarrow O_f + O_2^{+}$

(O^+: iono + jovian)



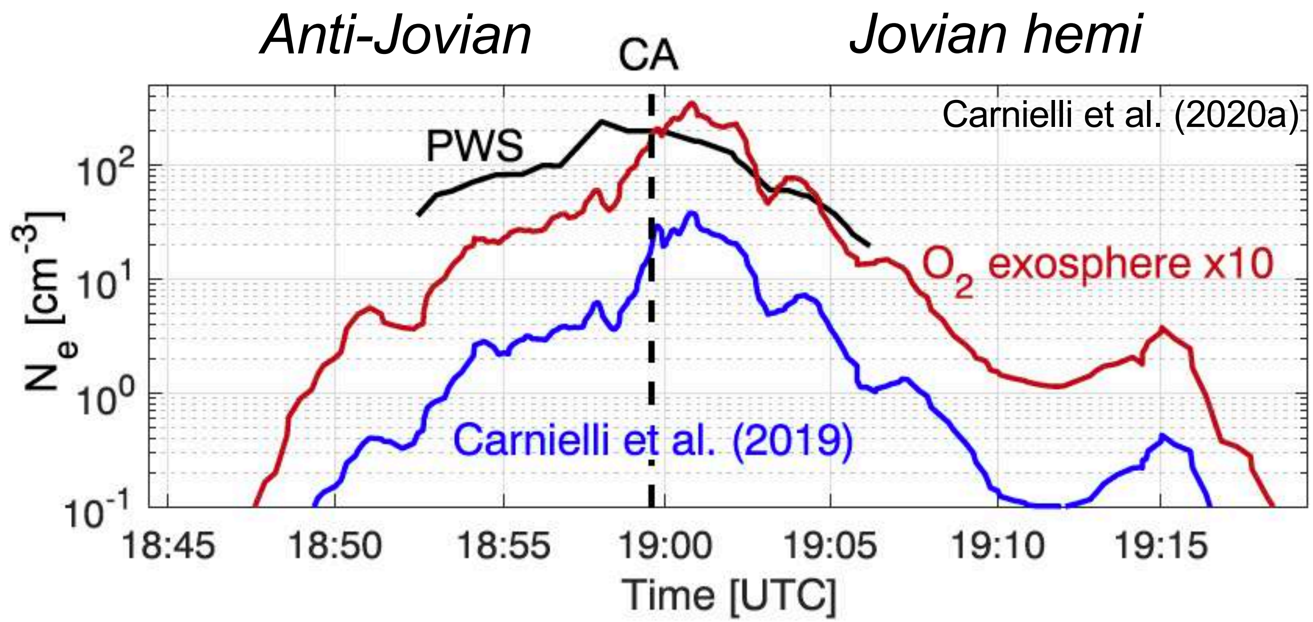
➢ No significant effect of collisions on ionospheric densities at location of Galileo

Imperial College London

Boosted exospheric O_2

Exosphere poorly constrained → **$[O_2]$x10**

Still discrepancy inbound: Unlikely explained by asymmetry in exosphere



- Good agreement outbound
- Still discrepancy inbound (factor ~ 4)

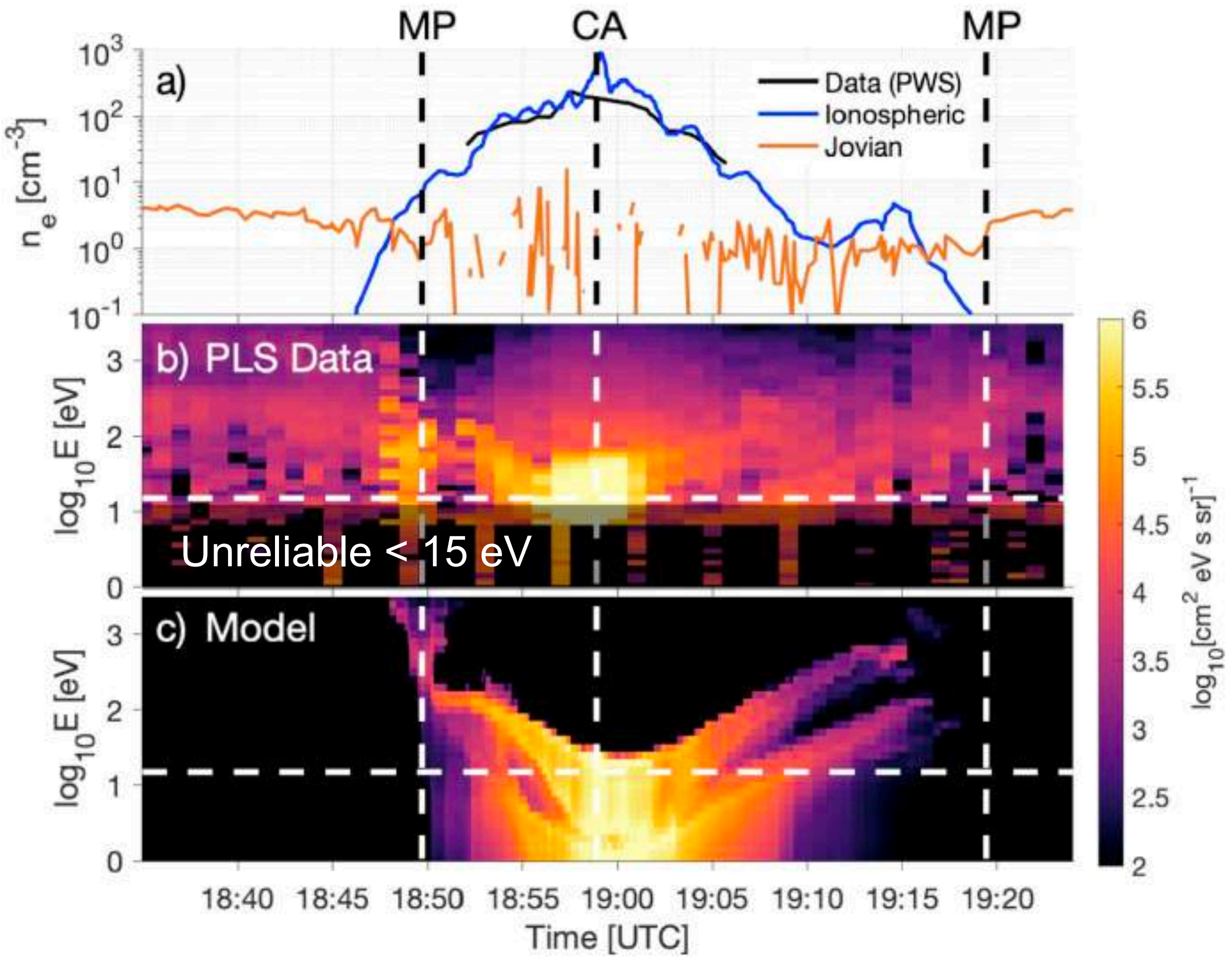
A solution

Imperial College London

10 x [O_2] everywhere

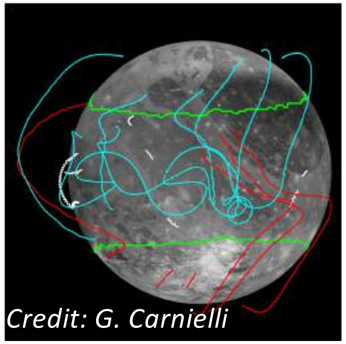
4 x electron-impact ionization in open B region around sub-solar longitude (inbound) [Galileo/EPD asymmetry around CA]

- Good agreement overall in both plasma density and ion spectrog.
- Near CA: modelled ne too low by factor ~ 2 – 3



Carnielli et al. (2020a)

Conclusion



- **First 3D kinetic ion model of Ganymede:**
  - ✓ **3D maps** (n, **u**, <E>) for **ionospheric species** derived:
    - ➢ Kinetic approach required, spatially structured distributions, O_2^+ dominates
    - ➢ Surface sputtering by ionospheric plasma dominates at low lat on leading hemisph.
  - ✓ Model also applied to **Jovian magnetospheric ions & hot O_2**
- **Comparison with Galileo multi-instrument dataset (G2 flyby):**
  - ✓ **Validation of the field environment** (B field, ion bulk velocity & ion energy distribution)
  - ✓ **[O_2] seems underestimated by factor 10** (ion energy spectrog. & plasma density)

➢ **Learn more?**

- Carnielli et al. (*Icarus*, 2019, https://doi.org/10.1016/j.icarus.2019.04.016)
- Carnielli et al. (*Icarus*, 2020a, https://doi.org/10.1016/j.icarus.2020.113691)
- Carnielli et al. (*Icarus*, 2020b, https://doi.org/10.1016/j.icarus.2020.113918)

Imperial College London

Perspective

- Improve the estimation of the **energetic electron population**
  - Improve ionospheric estimations
  - Comparison with auroral emissions (e.g., Molyneux et al. 2018)
- Coupling with **magnetospheric models**: Asymmetric ionosphere, multi-species
- Apply to **other Galileo flybys** (e.g., within jovian PS)
- Relevance to **JUICE**:
  - RPWI/MIME, 3GM, [NIM], PEP
  - J-MAG
  - UVS
- Relevance of a **multi-instrument approach**