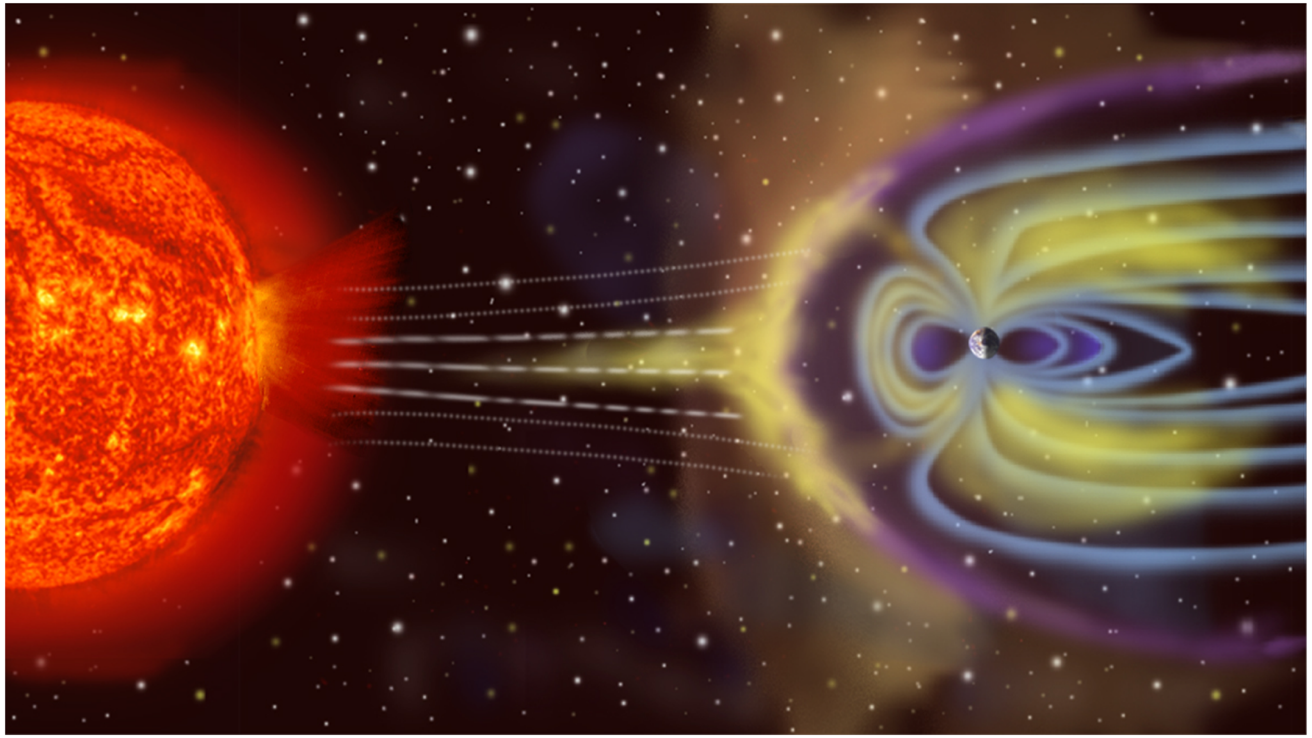
# Numerical simulations in space plasmas: from plasma physics studies to space missions support.

Pierre HENRI

*(LPC2E, CNRS, Orleans)*

# Sun / solar wind interactions with system solar bodies



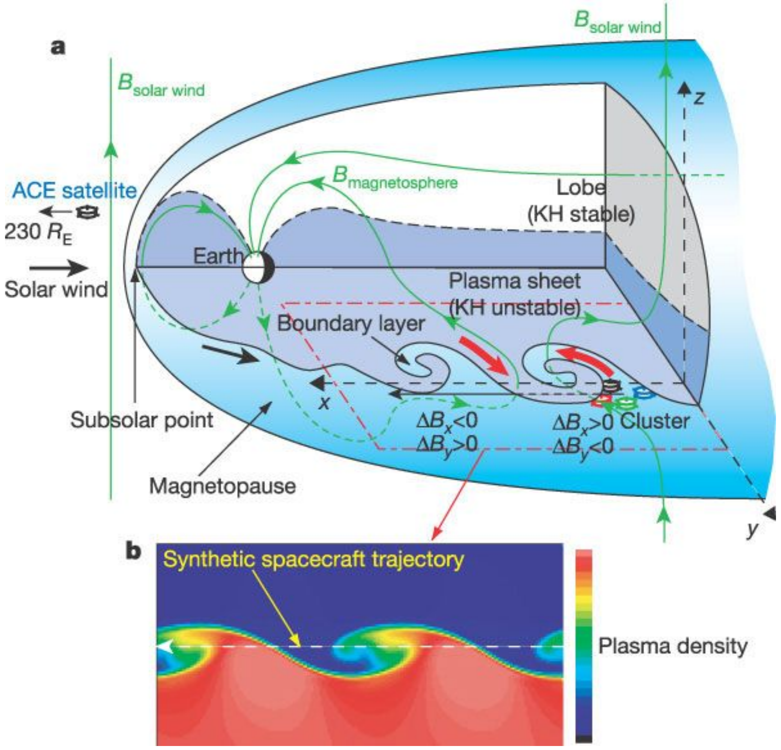
→ **Solar Physics** [Sophie Masson]
(scales are such that MHD is a good model)

→ **Interaction with solar system bodies: Magnetosphere / Induced magnetospheres**
(may require to go to smaller scale processes ➔ increases (i) complexity in modelling or/and (ii) computational time so that HPC quickly becomes a requirement)

# Solar wind – magnetosphere interactions

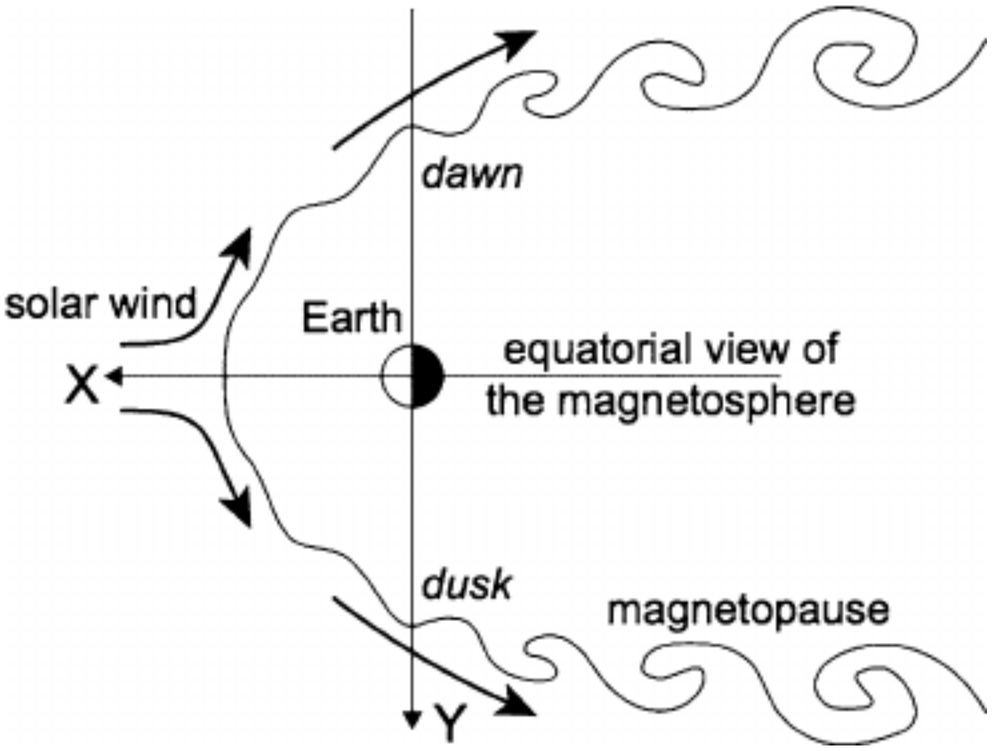
**Goal: Understand physical processes at play in mass / energy exchange with incoming solar wind**

→ **Collisionless shocks**
→ **Turbulence**
→ **Magnetic reconnection** [e.g. Roch Smets]
→ **<u>Fluid instabilities at the interface</u>**
(e.g. shear flow instabilities)




[Hasegawa et al., Nature, 2004]

# Solar wind – magnetosphere interactions
# Magnetized Kelvin-Helmholtz instability



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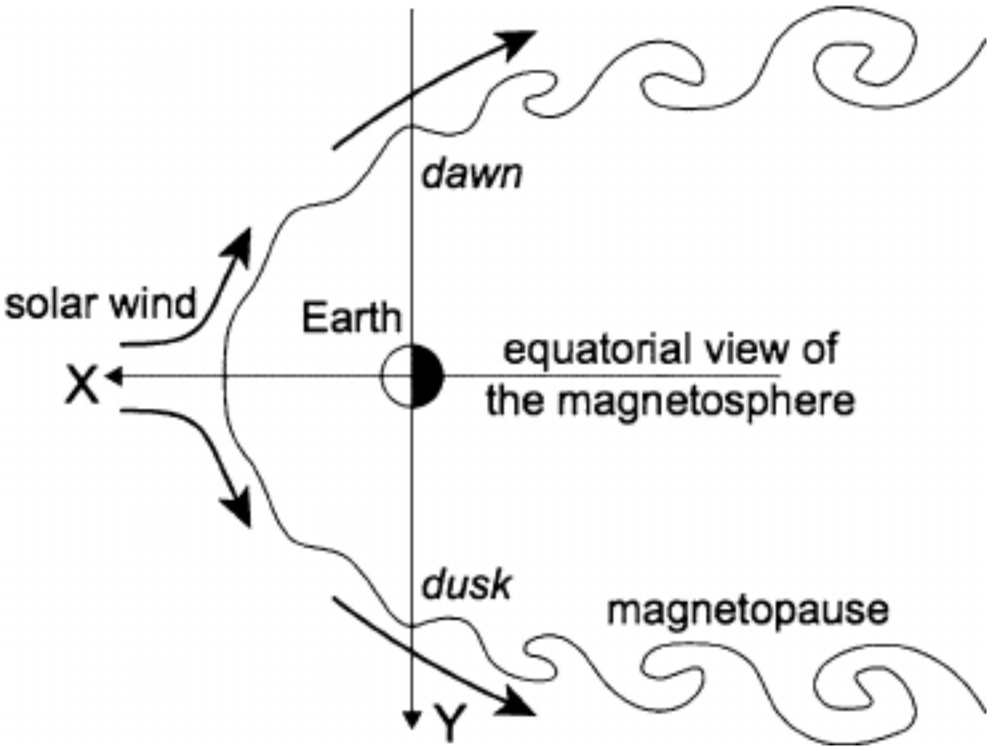
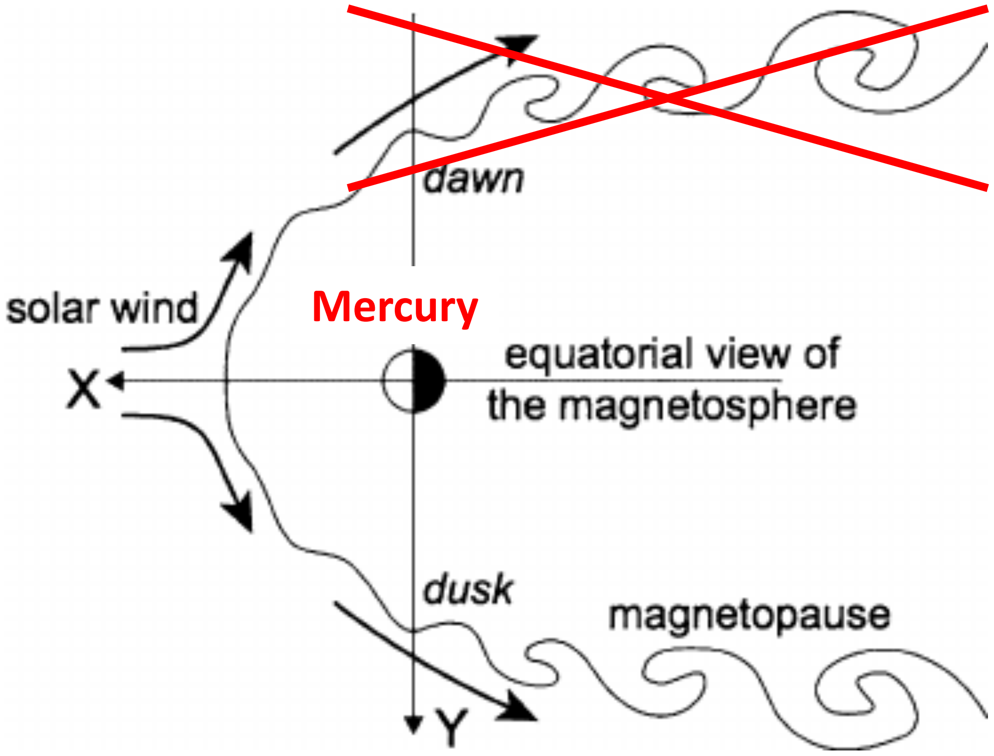



MESSENGER data:
Dawn-Dusk asymmetry and KH vortices seen on one side only



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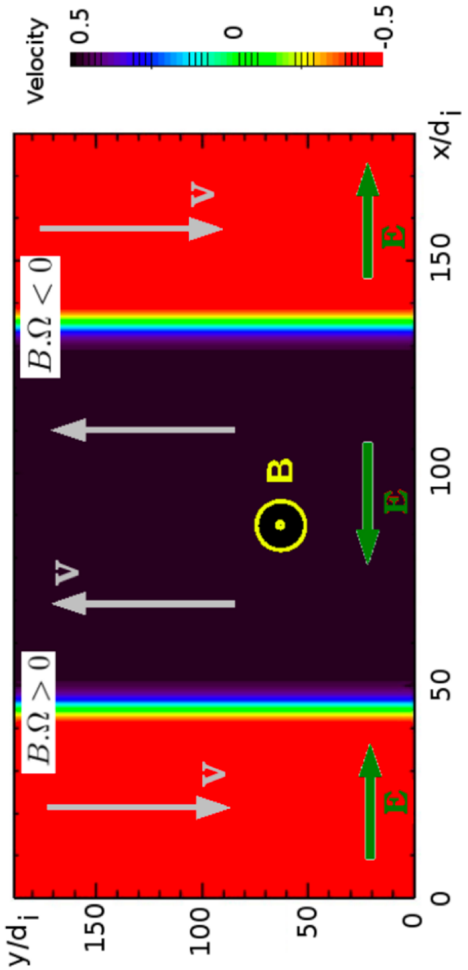
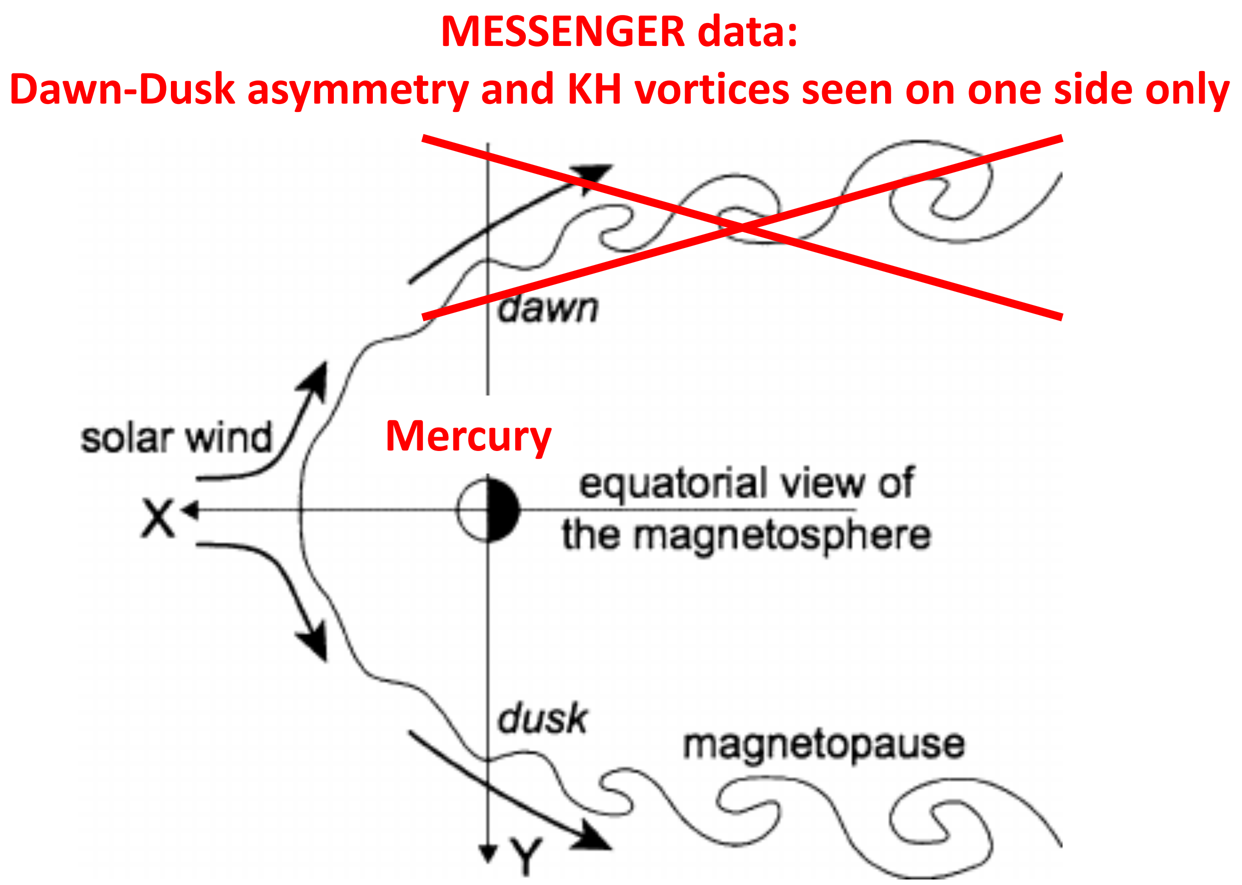
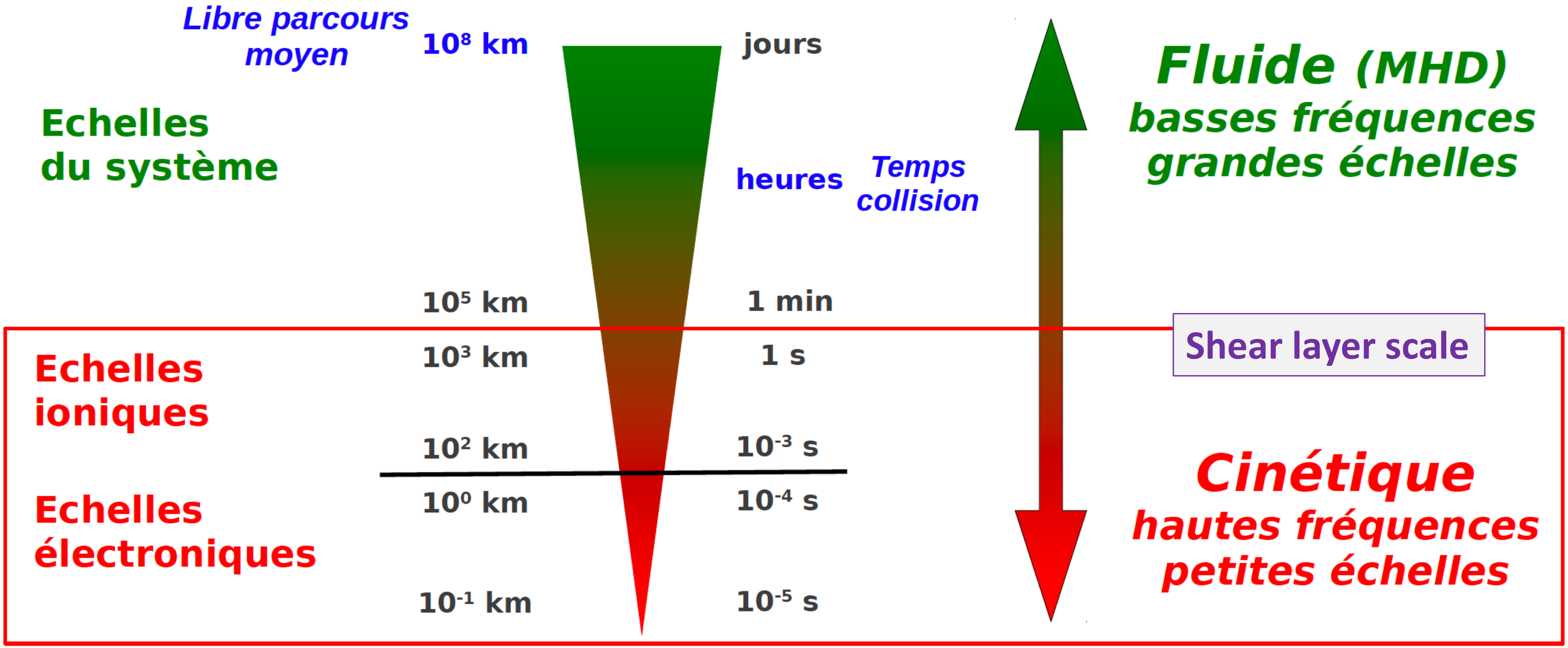



~~Global simulation~~ → Local setup



# Plasmas (spatiaux, astrophysiques) multi-échelles :

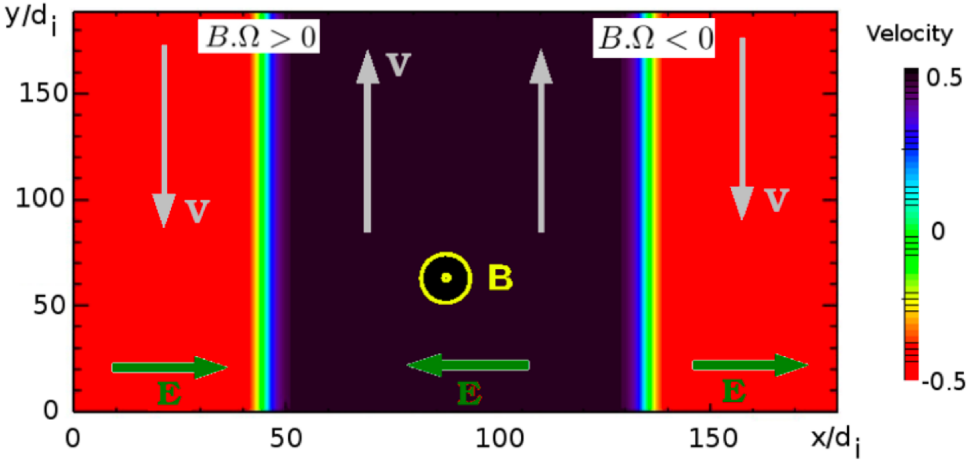


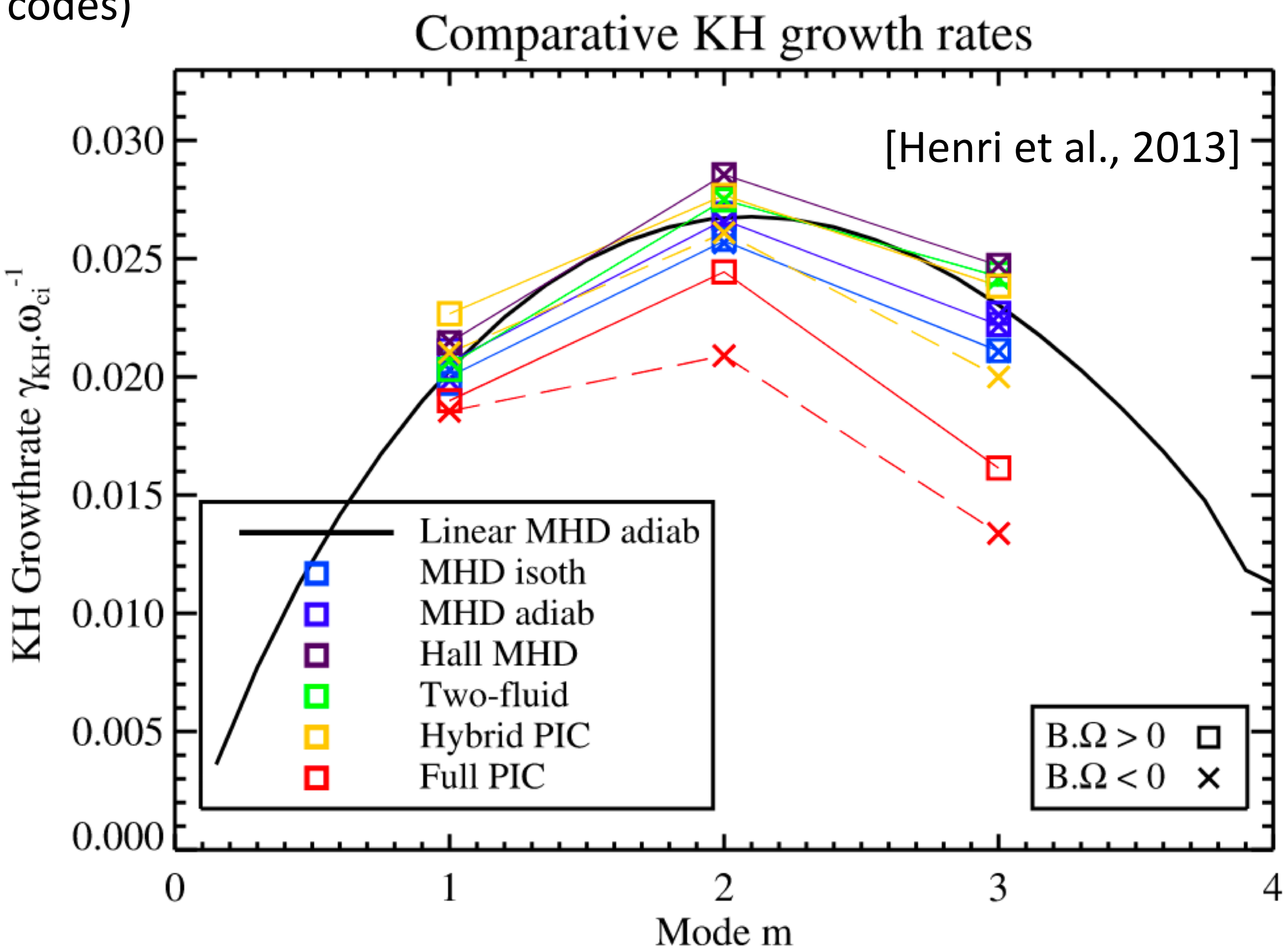
# Solar wind – magnetosphere interactions
# Magnetized Kelvin-Helmholtz instability

→ **Code comparisons** (requires same model)
→ Different **models comparisons** (with obviously different codes)

**Goal is to identify *minimal* key physical process**

Similar problematics in defining same initial and boundary conditions, with issues associated to the models discrepancies themselves.

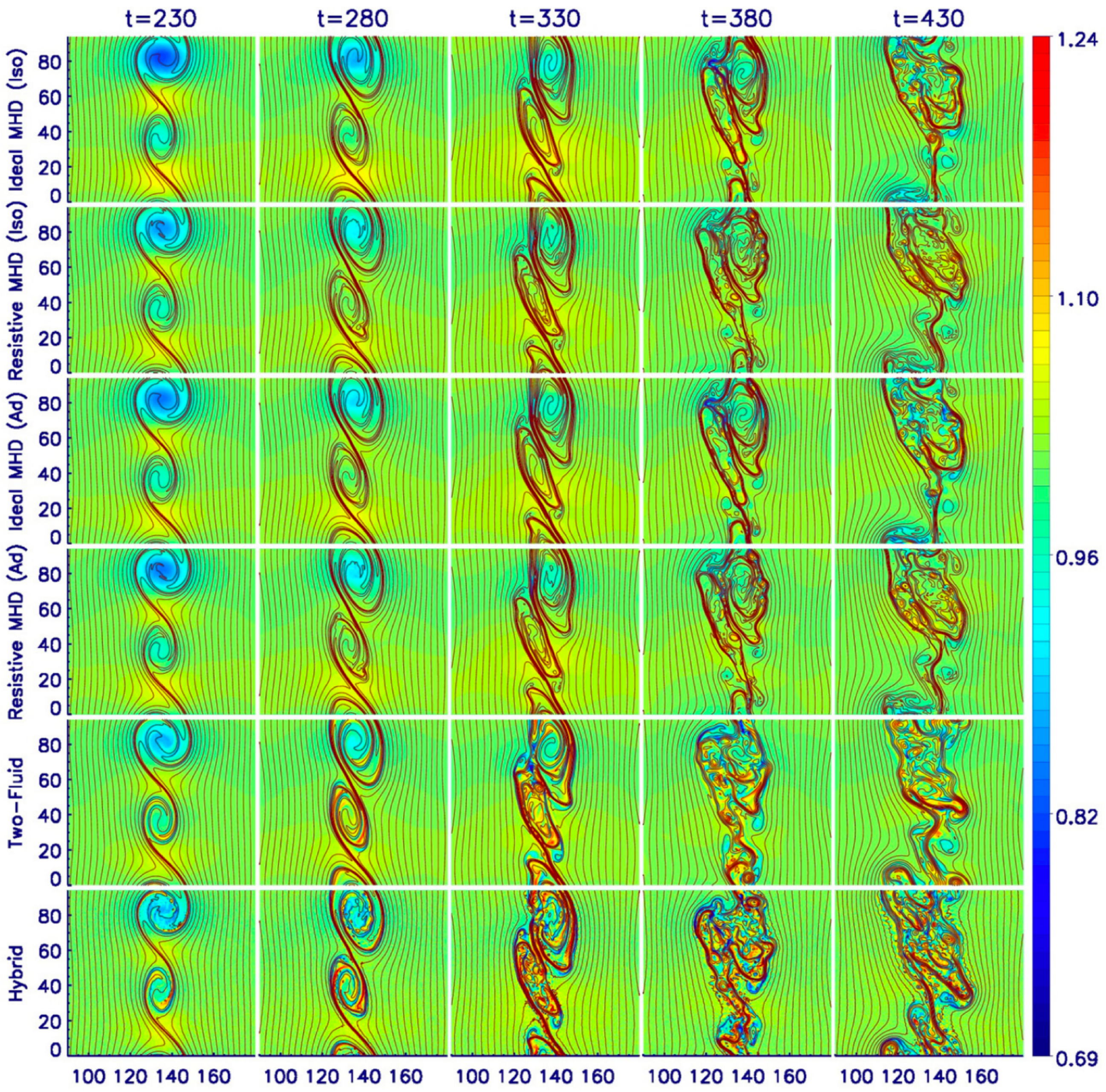



→ Mercury Dawn-Dusk asymmetry understood as **difference in growth rates associated to Finite Ion Larmor Radius effects**

# Role of different physics in the generation of a turbulent layer

Time




Ideal/resistive MHD
with isothermal or adiabatic closure

Two-fluid model

Hybrid model
(kinetic ions, massless fluid electrons)

Model complexity

*Do not require HPC*

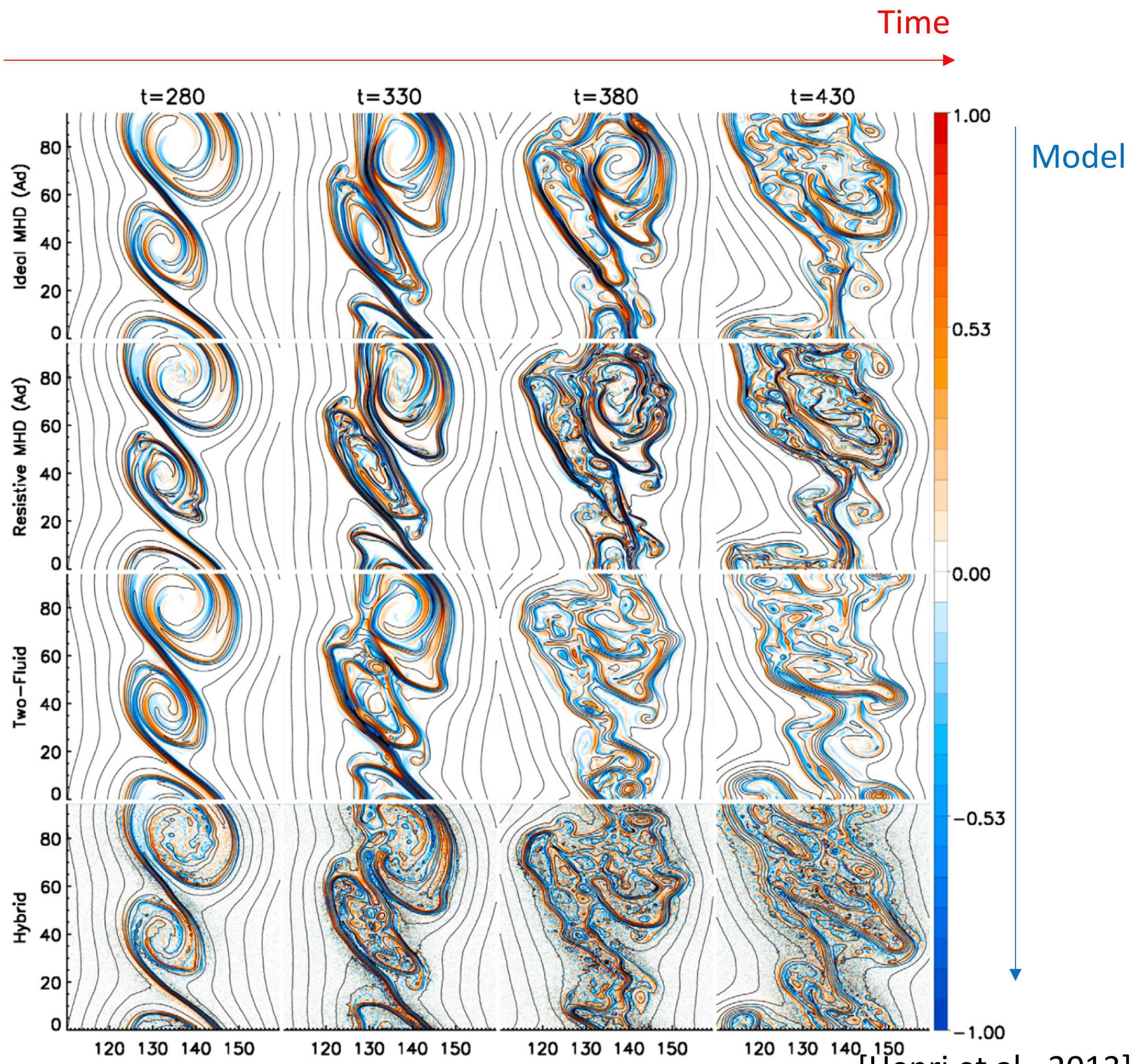
*Requires HPC (Tier-1 ok)*

# Role of different physics in the generation of a turbulent layer

Comparison of abundance of current sheets → dissipation sites generation (**efficiency of dissipation in collisionless plasma**)

**Goal is to validate reduced model or identify regime of validity**

Here it succeeds in large scale structure, fails in reproducing dissipation sites (small-scale structures) – as one could expected




[Henri et al., 2013]

(Unmagnetized bodies → Induced magnetosphere )

# Sun-comet interactions - Rosetta mission

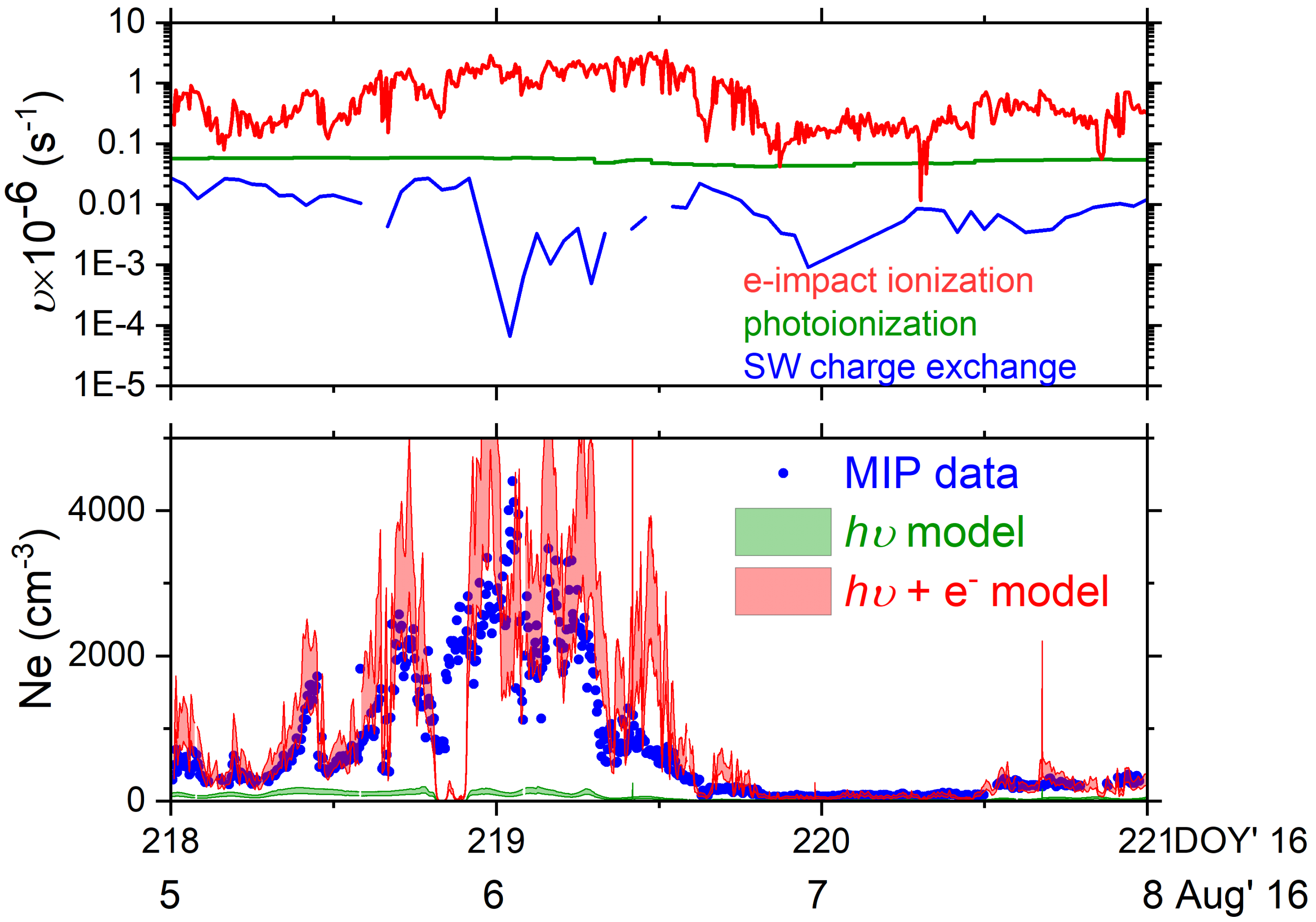
## What generates the cometary plasma?

$$
\begin{array}{rlcl}
\text{Photoionisation:} & X + h\nu & \longrightarrow & X^{+} + e^{-} \\
\text{Charge exchange:} & X + Y^{n+} & \longrightarrow & X^{+} + Y^{(n-1)+} \\
\text{Electron ionisation:} & X + e^{-} & \longrightarrow & X^{+} + 2e^{-}
\end{array}
$$

[Galand et al. 2016 , Vigren et al. 2016, Héritier et al 2017]

# What generates the cometary plasma?

Electron impact ionization >> Photo-ionization >> Charge exchange




[Hajra et al., 2018]

- **Electron-impact** ionization frequency is ~1 order of magnitude higher than **photo-ionization** frequency and ~2 orders of magnitude higher than **solar wind charge exchange** rate.

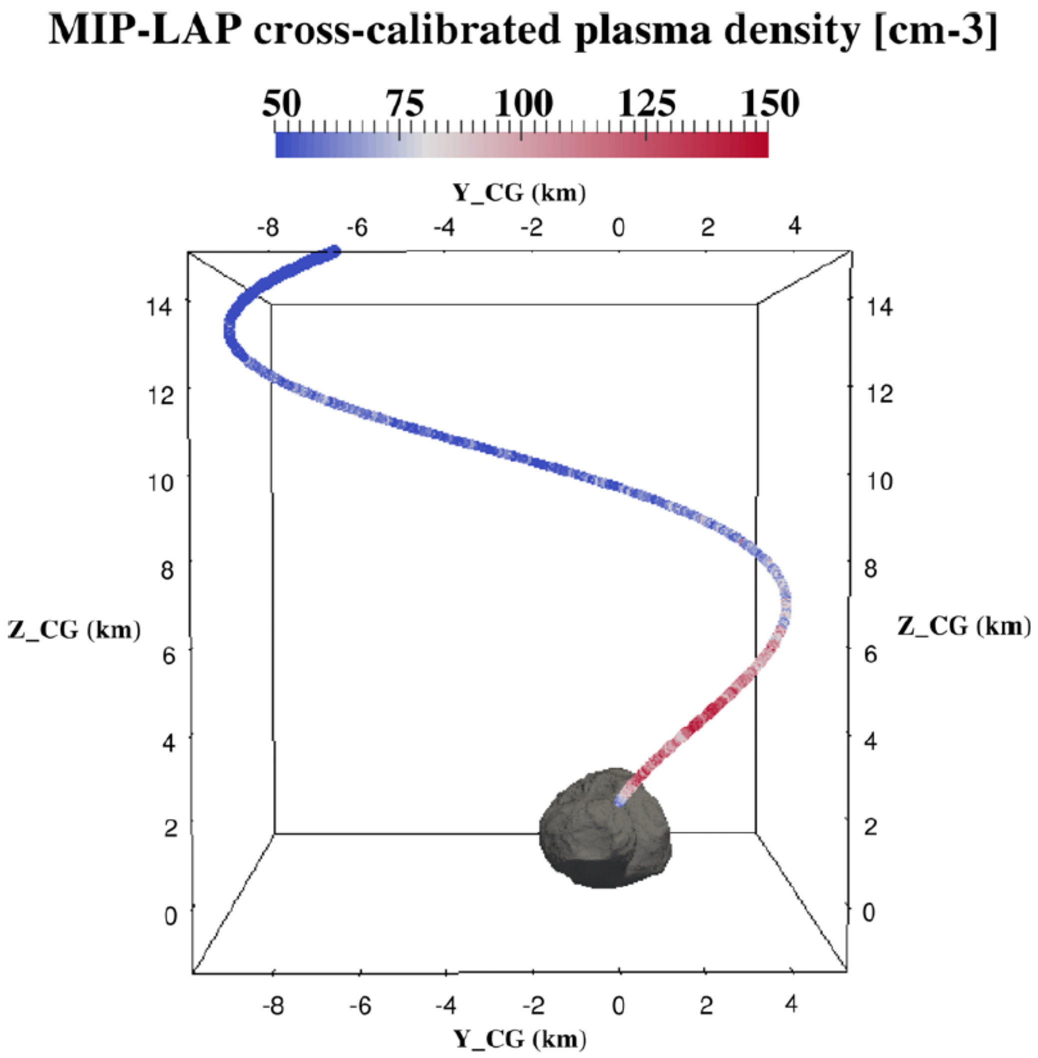
- Large suprathermal electron flux

→increase in the electron-impact ionization rate

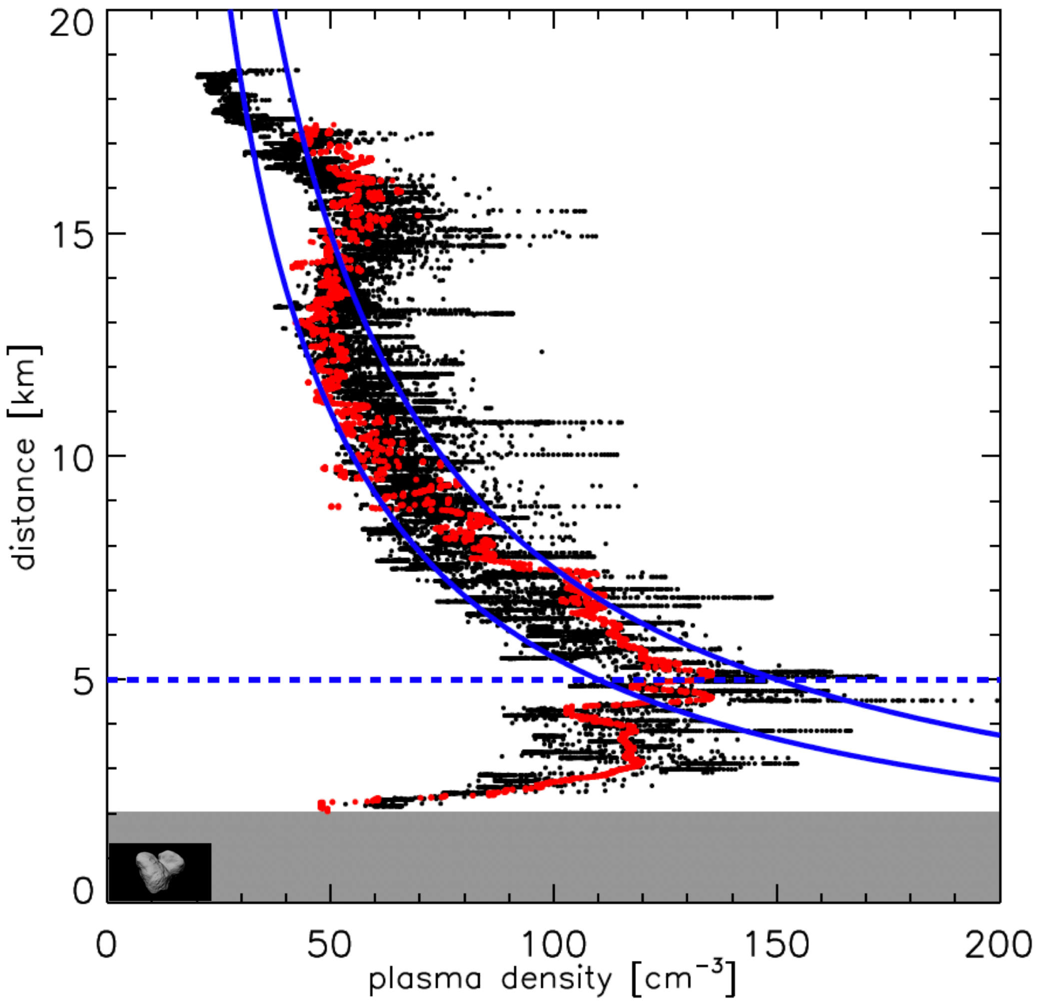
→ increase in cometary plasma density

# What generates the cometary plasma?

Another example: End of mission and controlled crash to the comet surface [30/09/2016]




[Héritier et al., 2017]



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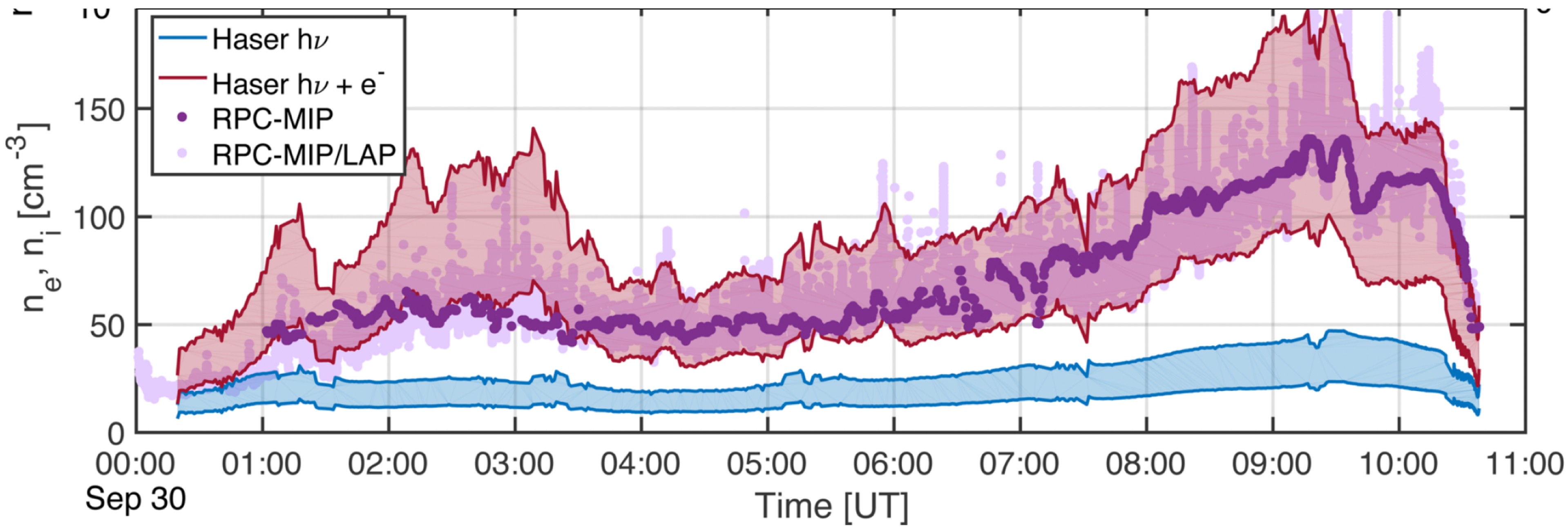


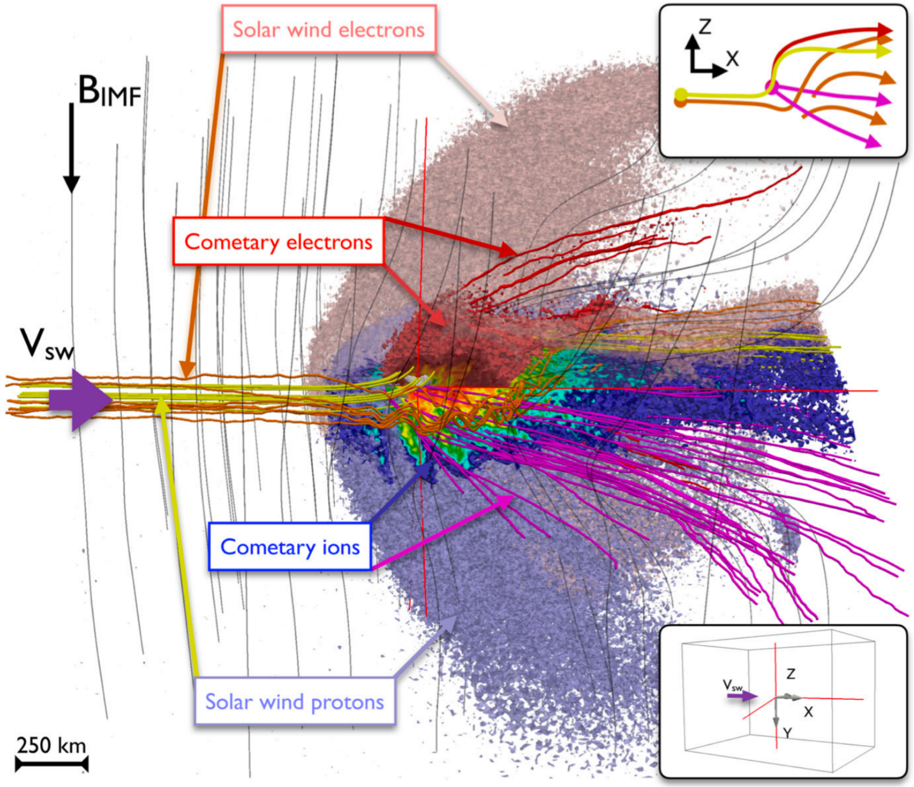

[Héritier et al., 2017]

***Issue*: Pristine solar wind or cometary electrons do not enable to ionise that efficiently**

**➔ Were do these ionizing electrons come from?**

# What is the origin of those ionizing (=suprathermal) electrons?

~~Local simulations~~ → **Need to move to global simulation** of solar wind-comet interaction **(Tier-1 → Tier-0)** [PRACE - 15M CPU hours on TGCC Curie]



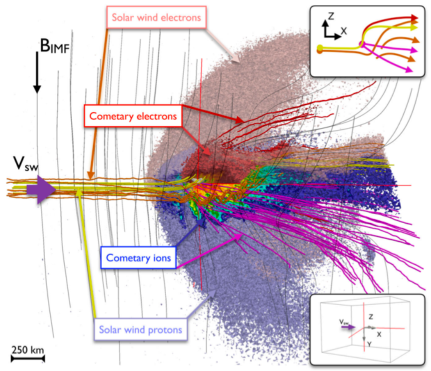

[Deca et al., PRL, 2017]

3D Full kinetic simulations of solar wind-comet interactions

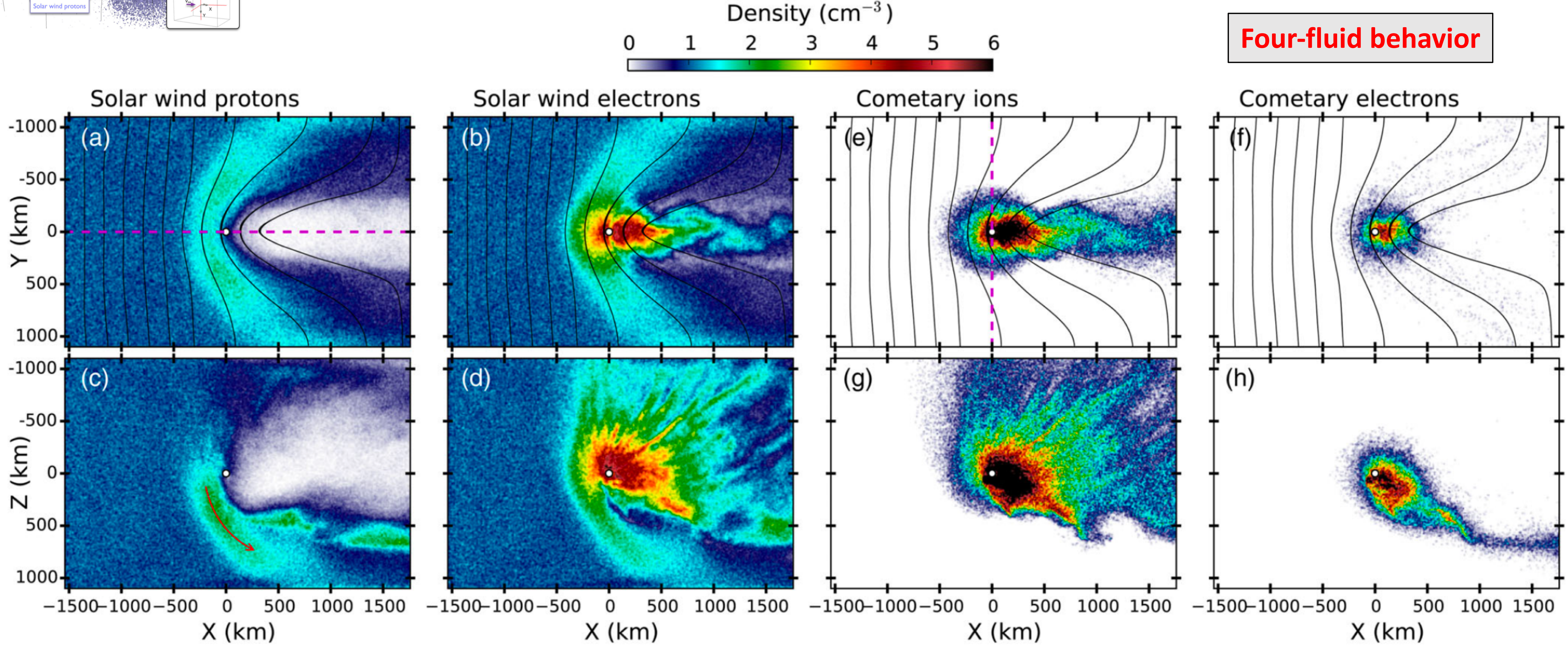
→ *Collisionless (ionizing → suprathermal)*

→ Vlasov-Maxwell equations solved with PIC simulations using a semi-implicit scheme (Krylov solver) [Markidis et al., 2010]

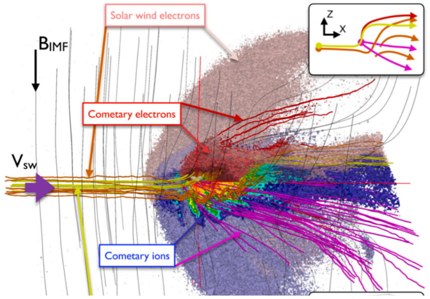
# What is the origin of those ionizing (=suprathermal) electrons?




**Four-fluid behavior**




[Deca et al., PRL, 2017]

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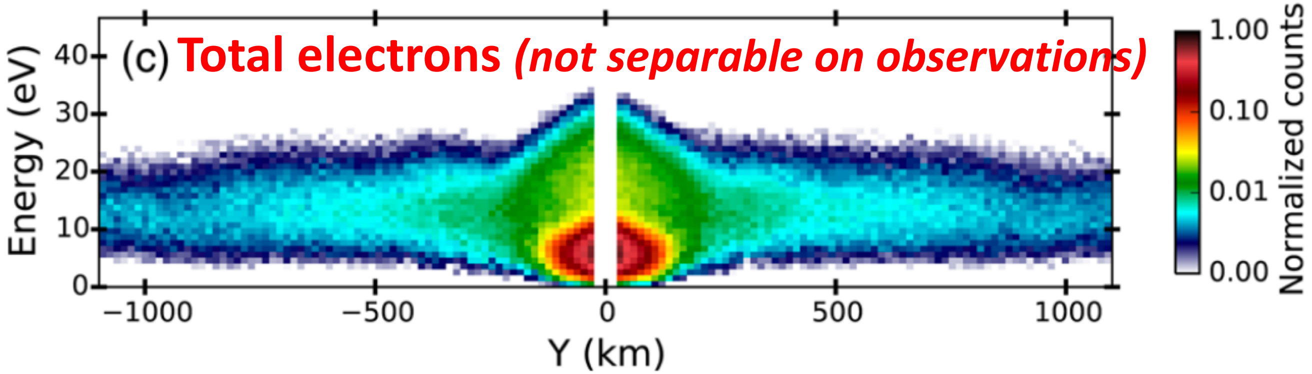

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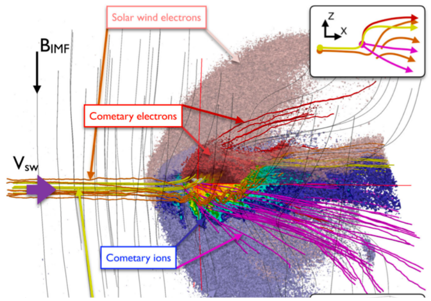
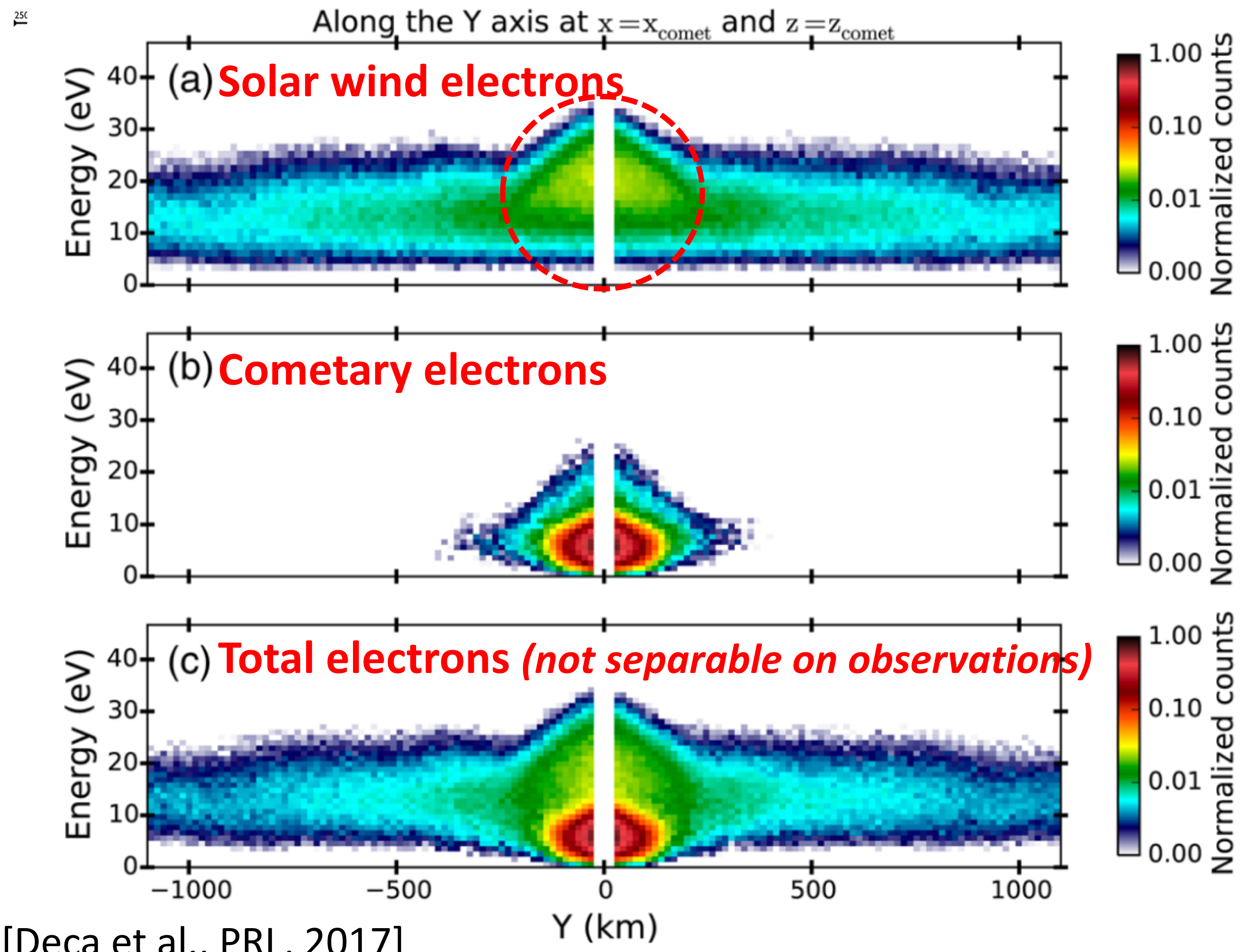



[Deca et al., PRL, 2017]

→Full kinetic simulations of solar wind-comet interactions shows **acceleration of solar wind electron** to ionizing energies in the close coma environment. [Deca et al., PRL, 2017]

→Role of ambipolar electric field [Madanian et al., 2016]

$$E = -\mathbf{u_e} \times \mathbf{B} - \frac{1}{en_e} \nabla p_e + \eta \mathbf{J}$$

# HPC Numerical simulations in support to space ~~observations~~ operations

*Example: Rosetta bow shock excursion [oct. 2015]*
~ 1 month of operations (over 2 years of total operation time)

Use of AIKEF (Adaptive Ion-Kinetic Electron-Fluid) code
Hybrid code : - ions → Vlasov eq. through PIC
- electrons → through Ohm's law

To predict cometary bow shock position in front of comet CG/67P
[Koenders et al, 2013]

**==> used as tool to decide spacecraft operations**
(very direct feedback to space mission definition and operations planning)

# HPC Numerical simulations in support to space operations

In reality no shock was found… ☹

*Worst:*

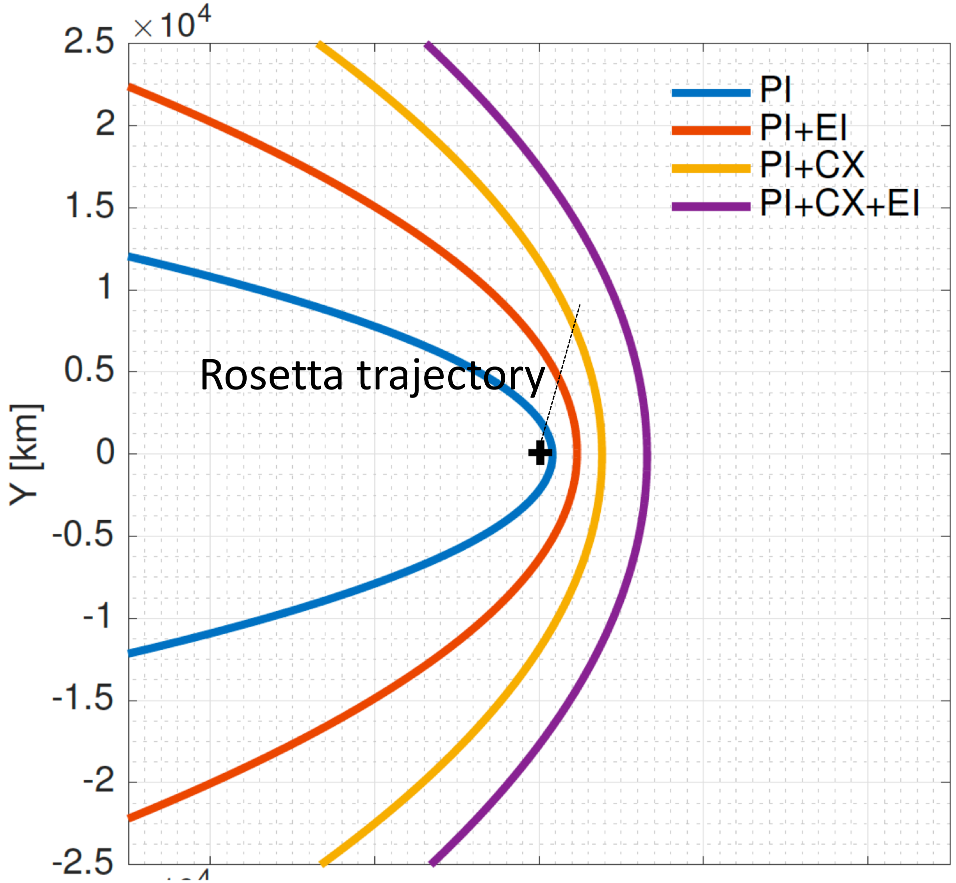
no shocked solar wind ions were found… ☹

*Worst:*

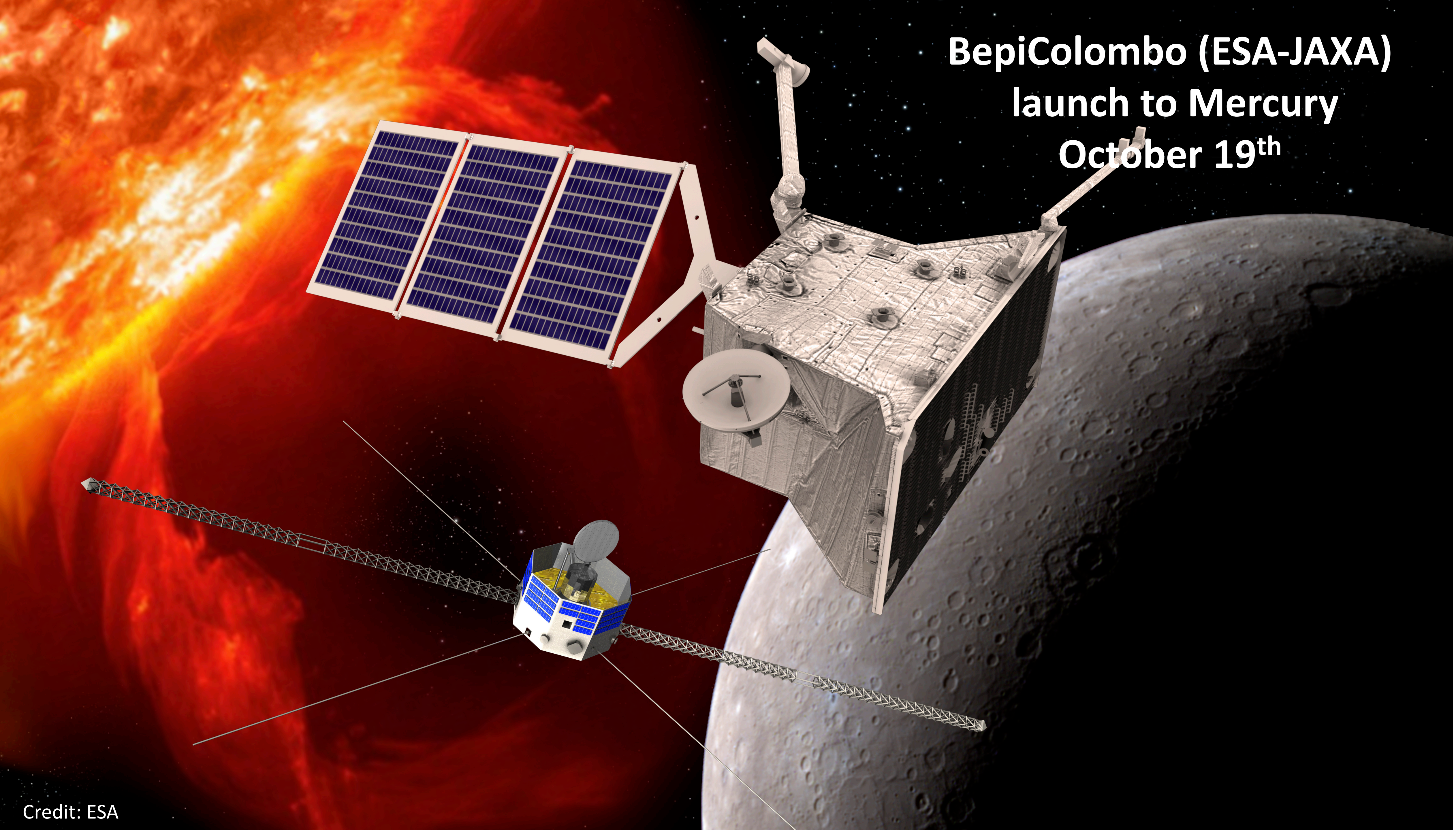
no solar wind ions were found… ☹

➔ Science to find… ☺

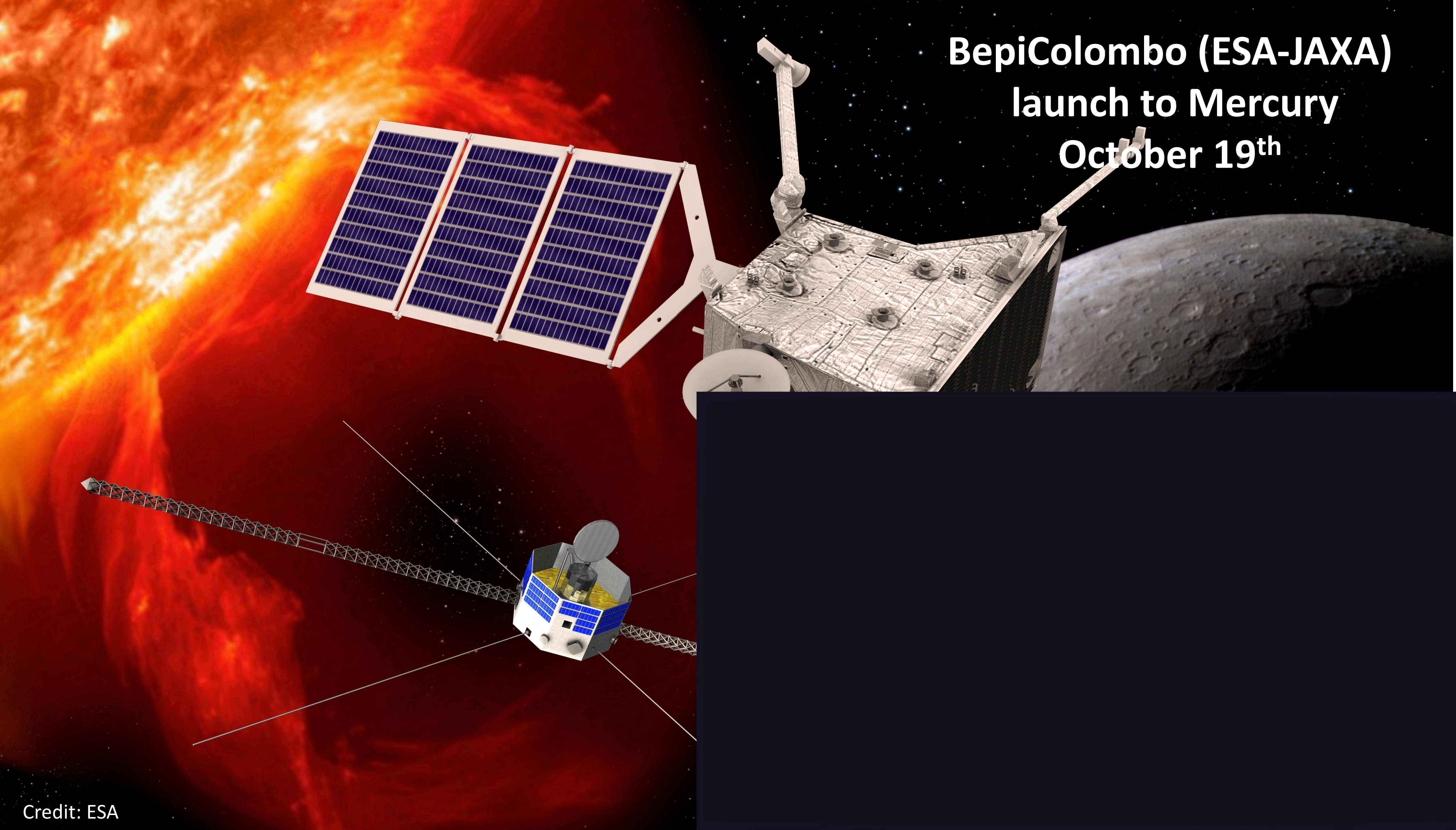
(existence of a shock structure?)




[Simon Wedlund et al.:, 2017]

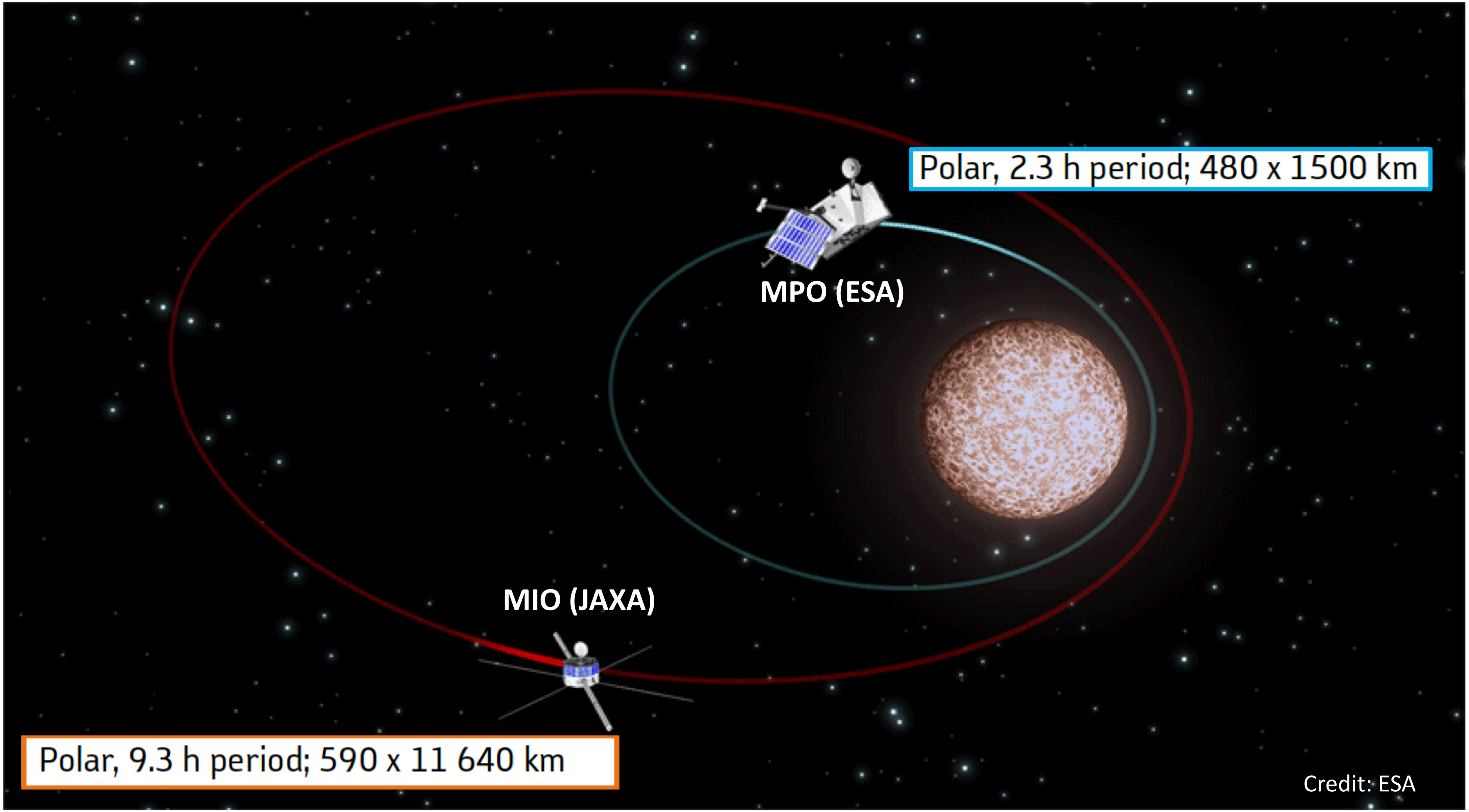

BepiColombo (ESA-JAXA)
launch to Mercury
October 19th
Credit: ESA

# BepiColombo (ESA-JAXA) launch to Mercury October 19th



Credit: ESA

# BepiColombo @ Mercury in 2025



**Some examples of efforts within the PNST community to develop and share numerical simulations data in support to space missions.**

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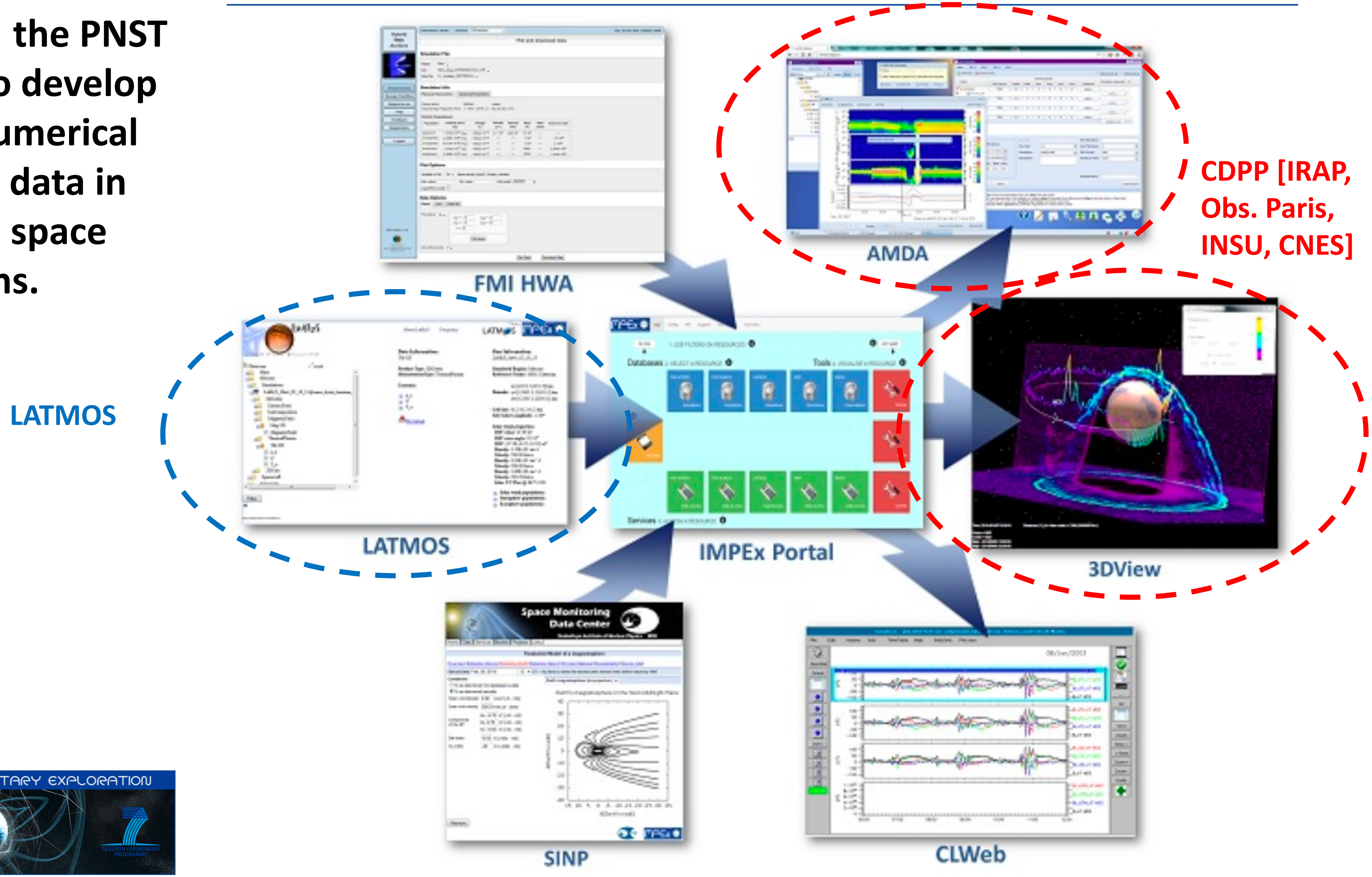
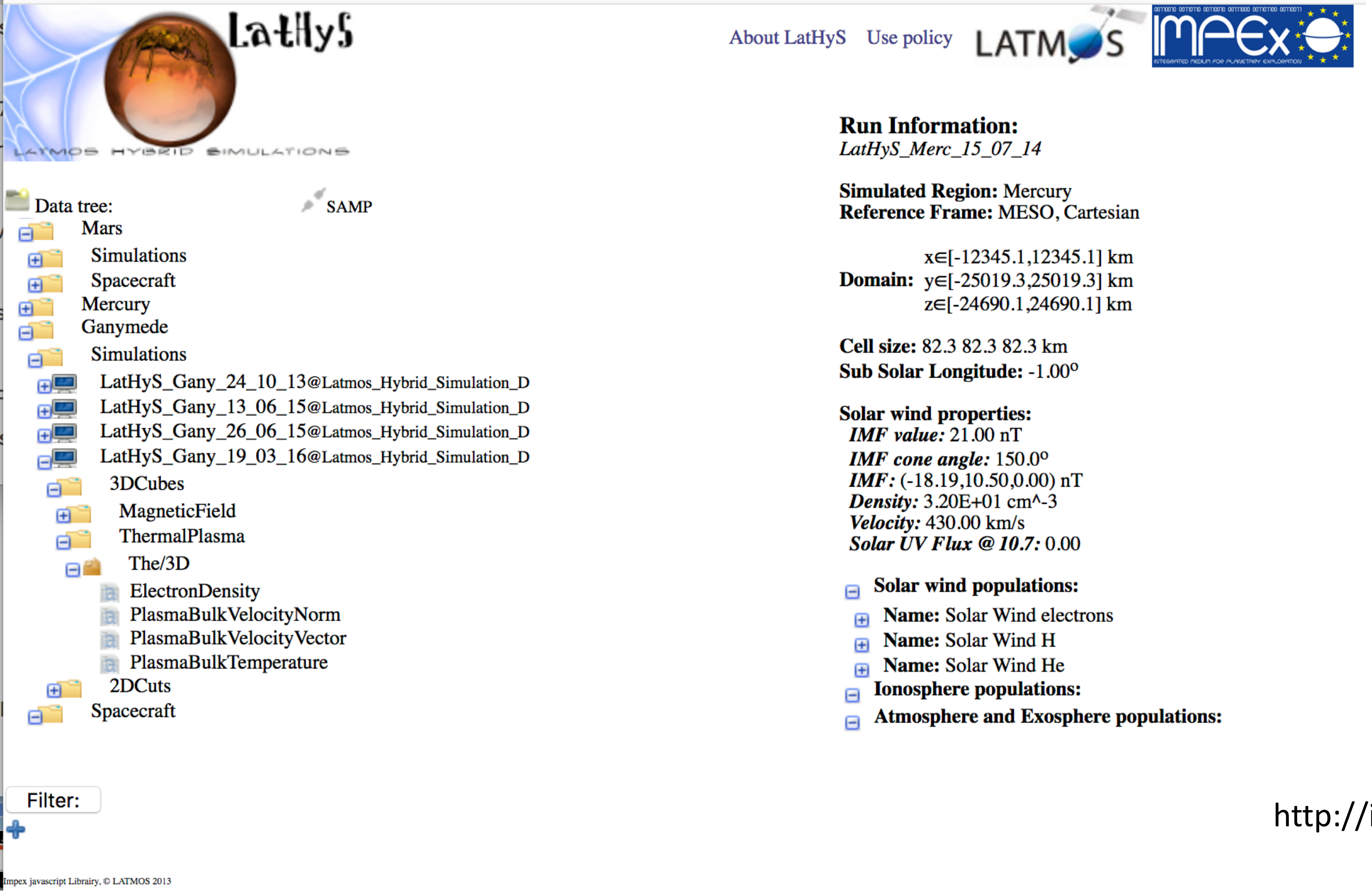
## IMPEx Tools and Data




INTEGRATED MEDIUM FOR PLANETARY EXPLORATION

[R. Modolo]




http://impex.latmos.ipsl.fr/LatHyS.htm

***The LatHyS database for planetary plasma environment investigations: Overview and a case study of data/model comparisons***
Modolo, Hess, Génot, Leclercq, Leblanc, Chaufray et al., *Planetary and Space Science* (2018)

CDPP

http://www.cdpp.eu/

[Vincent Génot]

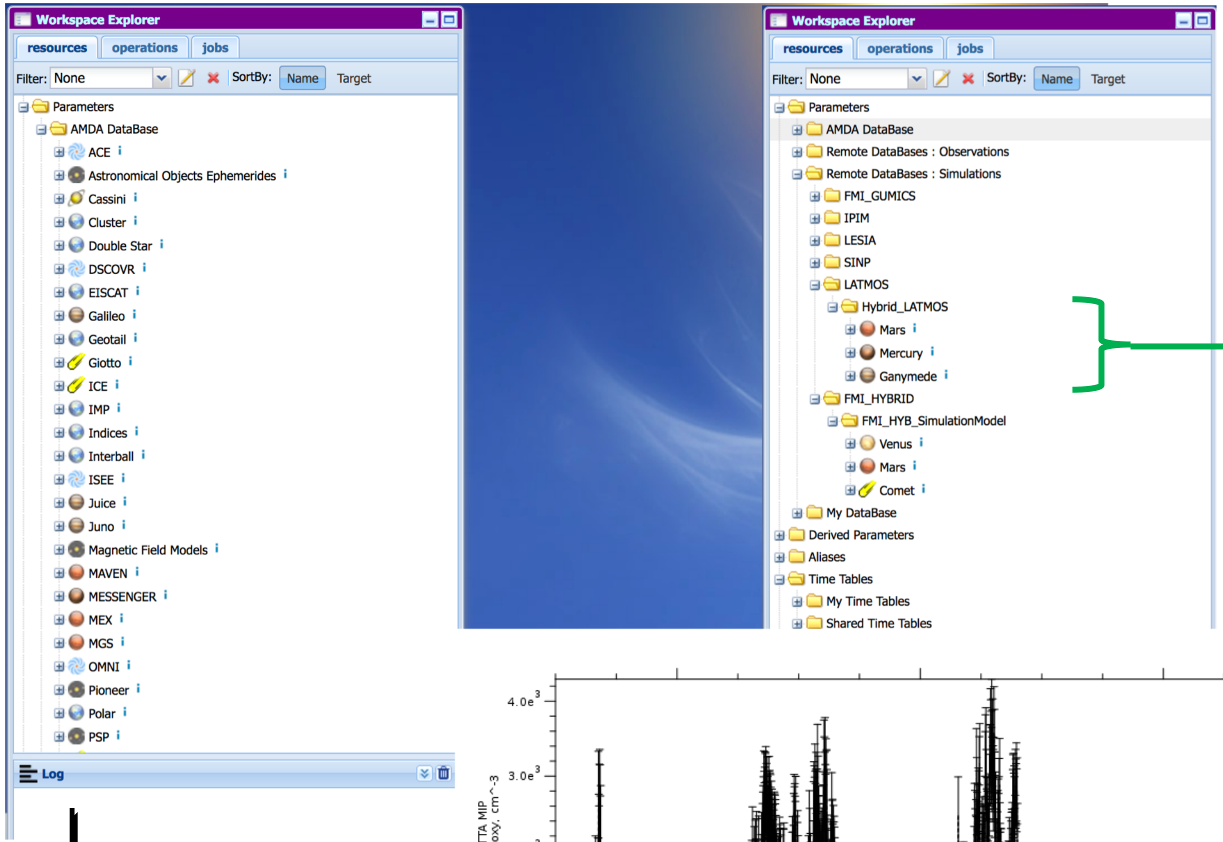

→ **SNO labellisé (SO5 / SO6)**

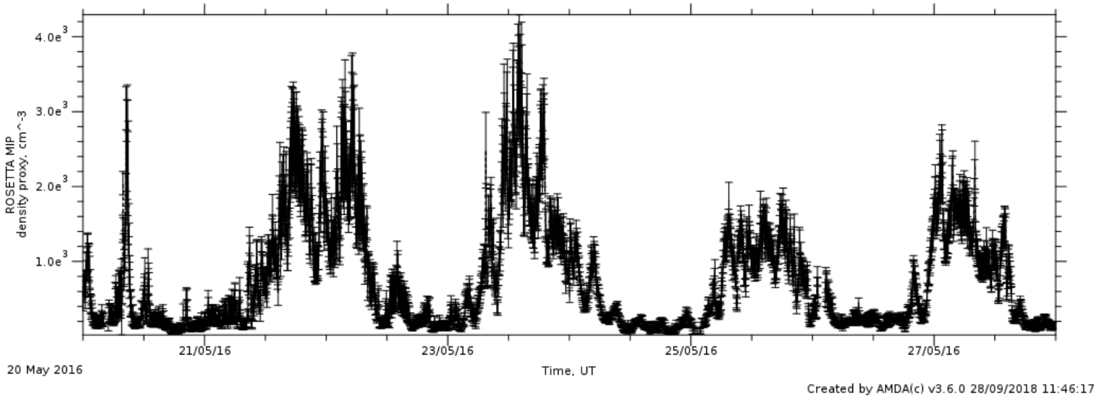
→ **CDPP and ESA/SSA: Integrating the ESA space weather portal**

→ Useful examples for data analysis tools to access and manipulate **observations and simulation data : AMDA & 3DView** http://www.cdpp.eu/

[Vincent Génot]

→ ***AMDA*** (Automated Multi-Dataset Analysis service): data visualisation, merging, computation, search and extraction on data (among which **simulation data**) content.



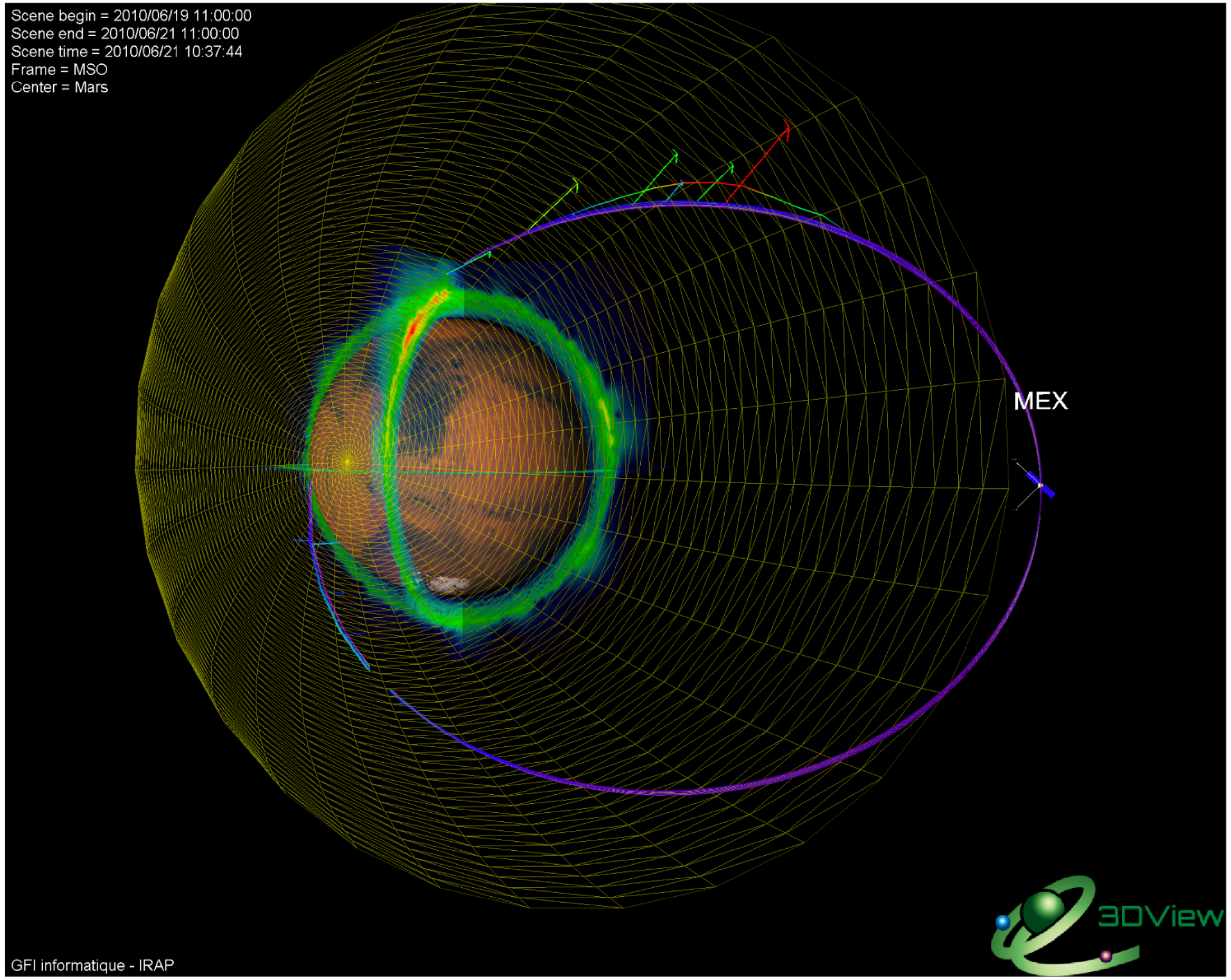




Ex. Rosetta - plasma density

CDPP

http://www.cdpp.eu/

[Vincent Génot]

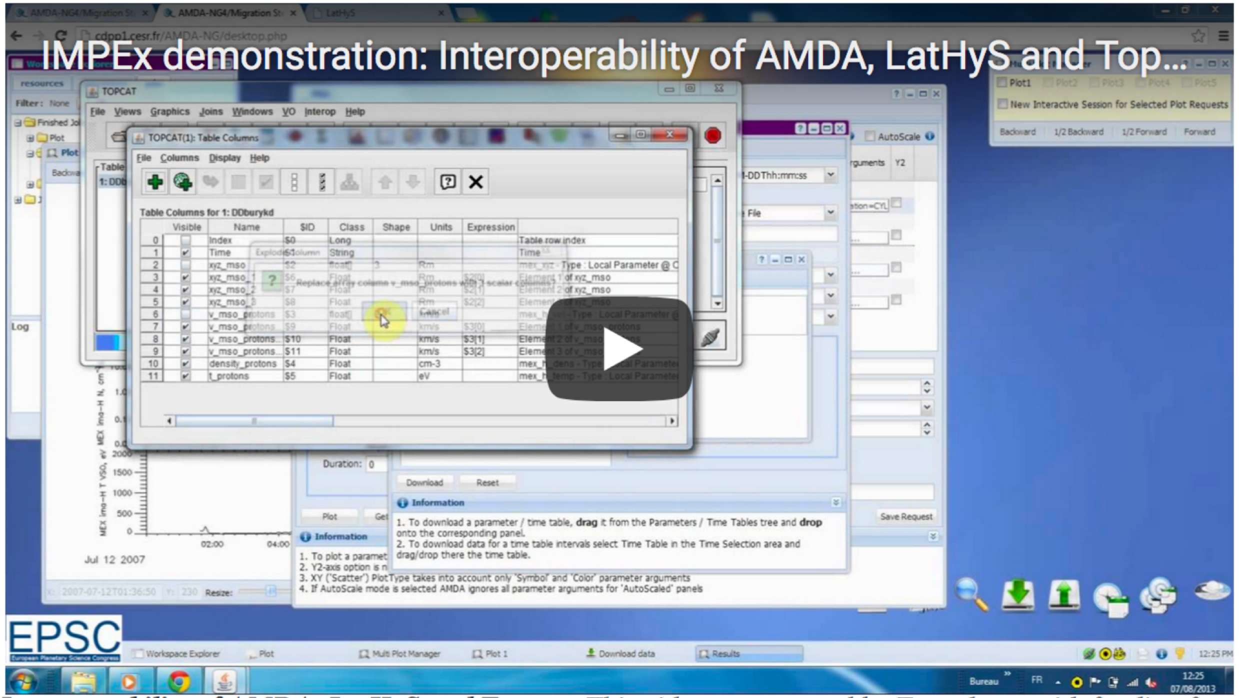



***3DView***:
visualize **data and models** in 3D planetary context.

Amda
Propagation Tool
SpaceWeather Tool
3DView
SIPAD
TREPS

# Dissemination efforts


***AMDA, 3DView and Simulation Databases (SMDBs)*** *- This video was created by Europlanet with funding from FP7/REA and presented at EPSC 2013*




***Interoperability of AMDA, LatHyS and Topcat*** *- This video was created by Europlanet with funding from FP7/REA and presented at EPSC 2013*

Les services nationaux d’observation et les moyens nationaux labellisés


AA- ANO-1 Métrologie de l'espace et du temps........................................

AA-ANO2 Instrumentation des grands observatoires au sol et spatiaux .....

II-1 Instrumentation des télescopes, sondes et observatoires spatiaux...

II-2 Instrumentation des grands télescopes et interféromètres au sol.....

AA-ANO-3 Stations d’observation...................................................

AA-ANO-4 Grands relevés, sondages profonds et suivi à long terme .........

AA-ANO-5 Centres de traitement, d'archivage et de diffusion de données .

AA-ANO-6 Surveillance du Soleil et de l'environnement spatial de la Terre.

Les services nationaux d'observation et les moyens nationaux labellisés

OCEAN, ATMOSPHERE et CLIMAT ........ 15
AO-ANO-1 : SERVICES DE SURVEILLANCE DE L'ATMOSPHERE ........ 16
I-I : INDAF : "International Network of Deposition and Atmospheric chemistry in Africa" .. 16
I-2 : IAGOS (In service Aircraft for a Global Observation System) ........ 17
I-3: NDACC (Network for the Detection of Atmospheric Composition Change) ........ 18
I-4 : PHOTONS/AERONET (Observatoire de Recherche sur les Aérosols) ........ 18
I-5 : ICOS (integrated Carbon Observation System) ........ 20
I-6- CLAP (CLimate relevant Aerosol Properties from near surface observations) ........ 21
AO-ANO-2: SERVICES D'OBSERVATION DE L'OCEAN ........ 22
II-1 :OISO/CARAUS (Océan Indien Service d'Observation / Carbon Austral) ........ 22
II-2 : MOOSE (Mediterranean Ocean Observing System on Environment)) ........ 22
II-3 : SSS (Service d'Observation de la Salinité des Océans, Sea Surface Salinity) ........ 23
II-4 : SOMLIT (Service d'Observation en Milieu LIToral) ........ 24
II-5 : PIRATA (PIlot Research moored Array in the Tropical Atlantic) ........ 25
II-6 : MEMO (Mammifères Echantillonneurs du Milieu Océanique) ........ 26
II-7 : SONEL ........ 26
II-8 : ARGO ........ 27
II-9 : CORAIL ........ 28
AO-ANO-3 : CODES NUMERIQUES COMMUNAUTAIRES ........ 29
III-1 : CODE NUMERIQUE MESO-NH (Modélisation à moyenne échelle de l'atmosphère) ........ 29
III-2: Code numérique NEMO (Nucleus for European Model of the Ocean) ........ 29
III-3 : CODE NUMERIQUE CHIMERE (Modélisation de la pollution atmosphérique) ........ 30
III-4 : CODE NUMERIQUE SIROCCO (Simulation réaliste de l'océan côtier) ........ 31
AO- ANO-4 : Centres de Traitement et d'archivage des données ........ 31
IV-1 : CTOH (Centre de Topographie des Océans et de l'Hydrosphère) ........ 31
AO- ANO-5 : Sites nationaux d'observation ........ 32
V-1: SIRTA (Site instrumental de recherche par télédétection atmosphérique) ........ 32
V-2: CO-PDD (Site d'observations atmosphériques Puy de Dôme/Opme/Cézeaux) ........ 32