Electron Dynamics Throughout The Solar System

Jan Deca

Laboratory for Atmospheric & Space Physics
University of Colorado Boulder

The 15th International Symposium for Space Simulations (ISSS-15) and the 16th International Workshop on the Interrelationship between Plasma Experiments in the Laboratory and in Space (IPELS-16).
@ Max Planck Institute for Plasma Physics. August 7, 2024.

Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

Outline

Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

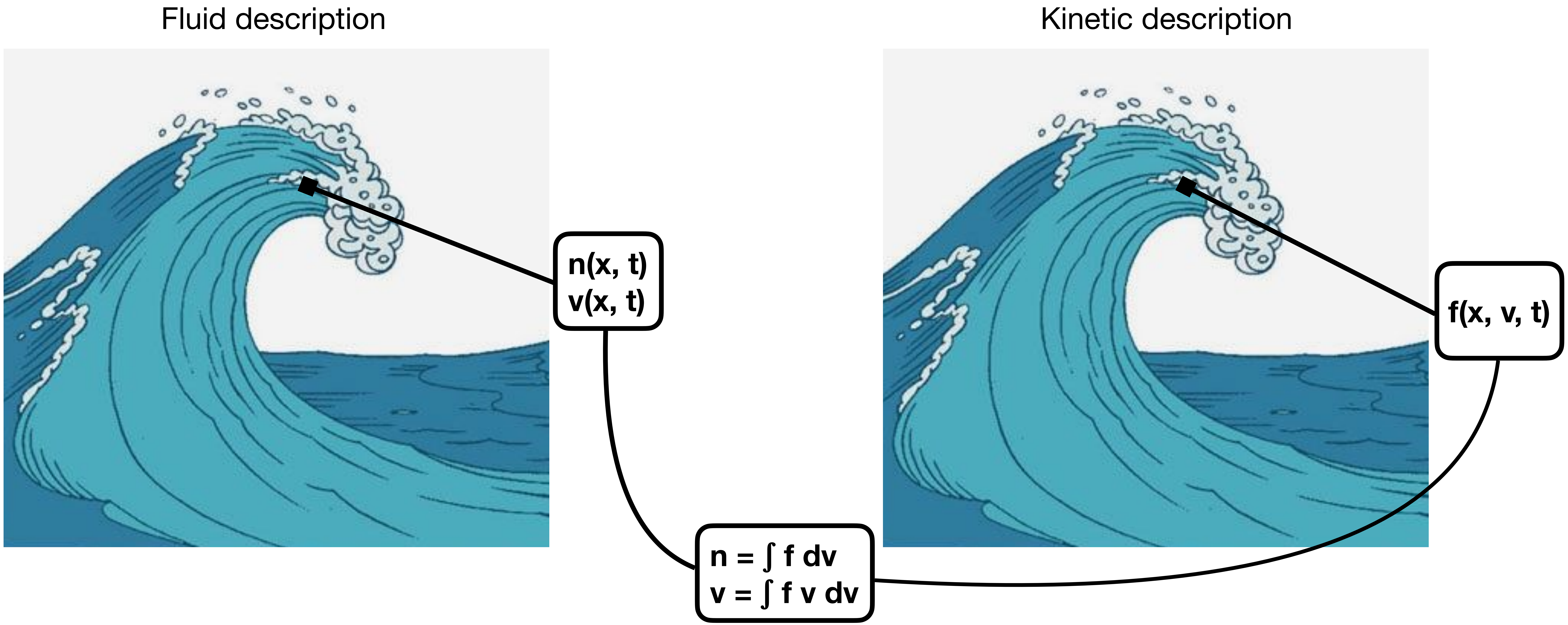
- *Local electron dynamics shapes the global structure of a system.*

  - Modeling a plasma: a problem of scales.
    - Obtaining self-consistent electron dynamics.
  - Research highlights:
    - Dust and spacecraft charging.
    - The solar wind interaction with the lunar plasma environment, comet 67P, and the planet Mercury.

- *Numerical models provide a complimentary opportunity to understand a problem from a basic physics point of view.*

Introduction

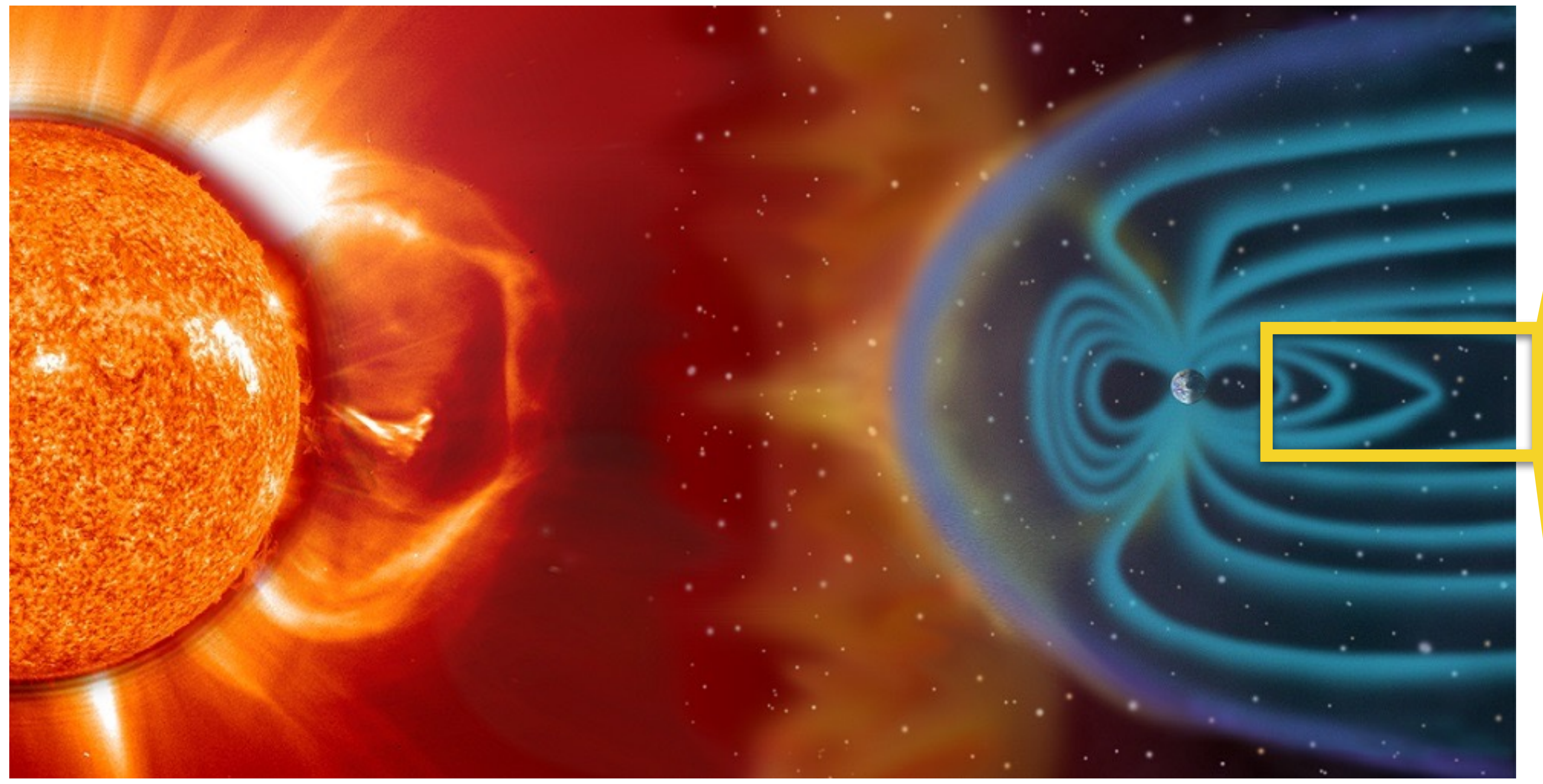
- A **plasma** can be described in different ways:

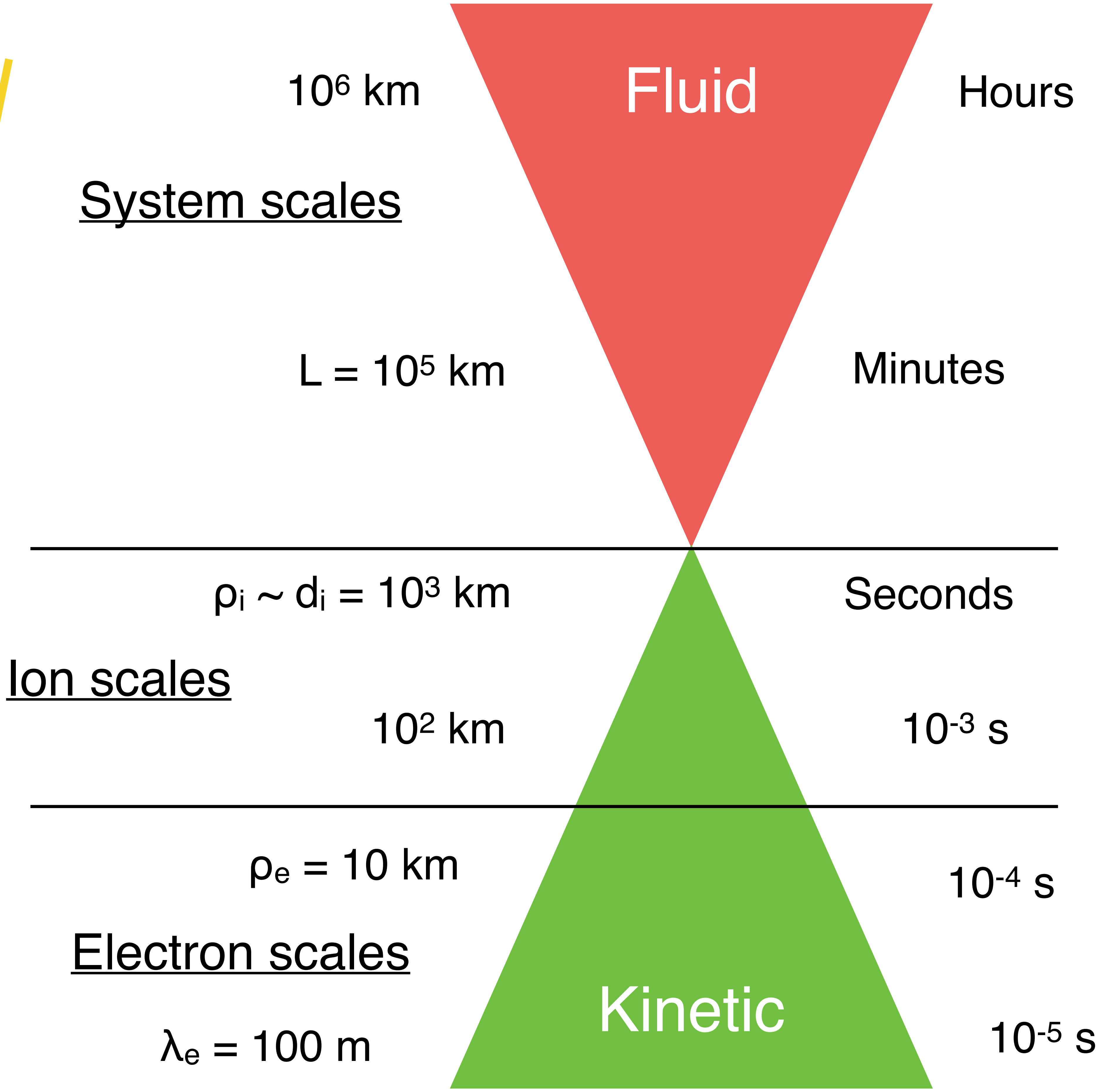


Introduction

- **Self-consistent** electron dynamics for a macroscopic system: **a problem of scales**.

Two-way coupling between the electromagnetic fields and the motion of the plasma particles.





Introduction

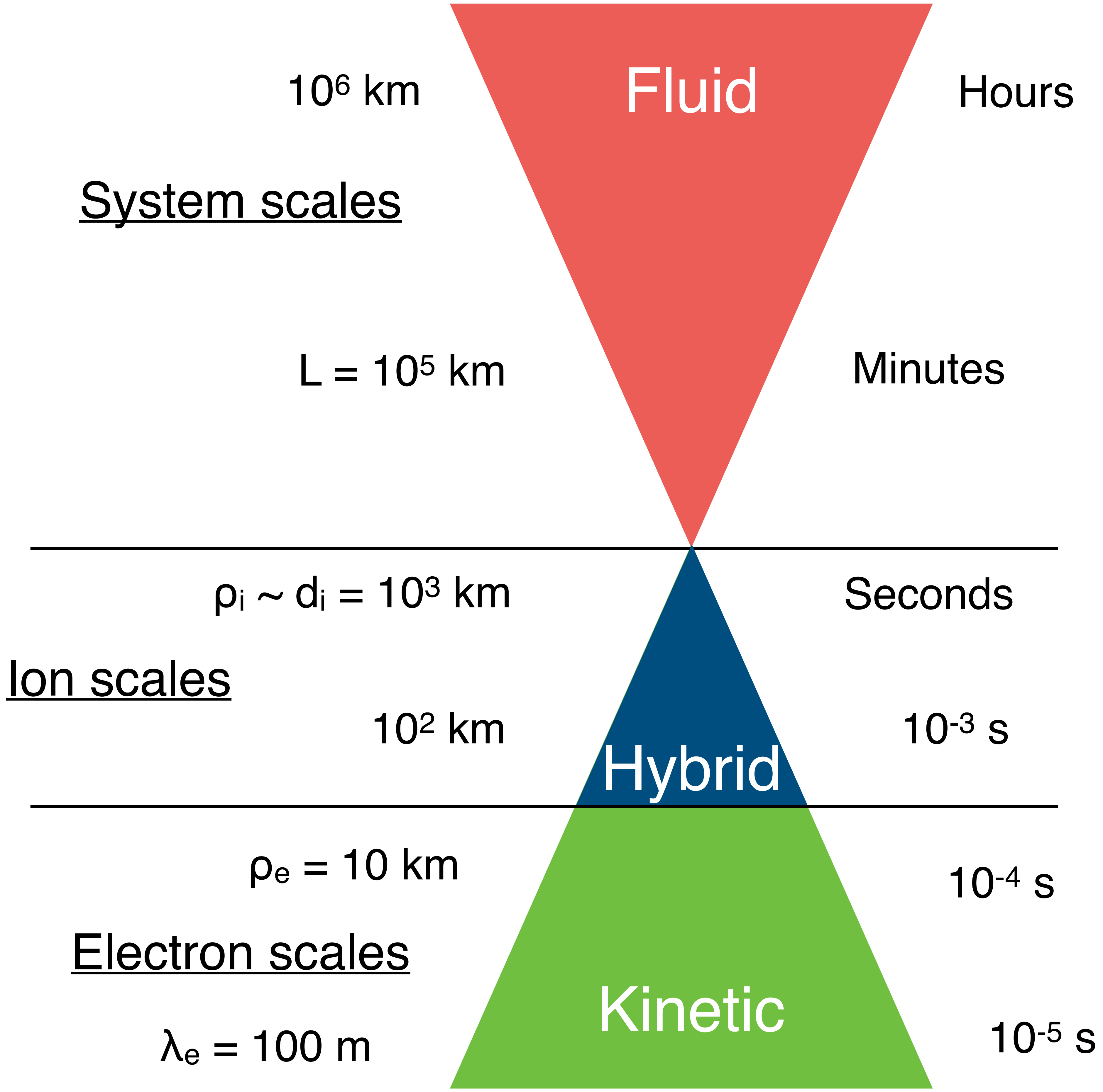
Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

- **Self-consistent** electron dynamics for a macroscopic system: **a problem of scales**.

▸ **Fluid models** (n_i, n_e, v_i, v_e)
- Computational effort manageable, even at large scales.
- Miss the small-scale physics.
- Fudge parameters reduce the predictive value.

▸ **Hybrid models** (f_i, n_e, v_e)
- Do bit of both.

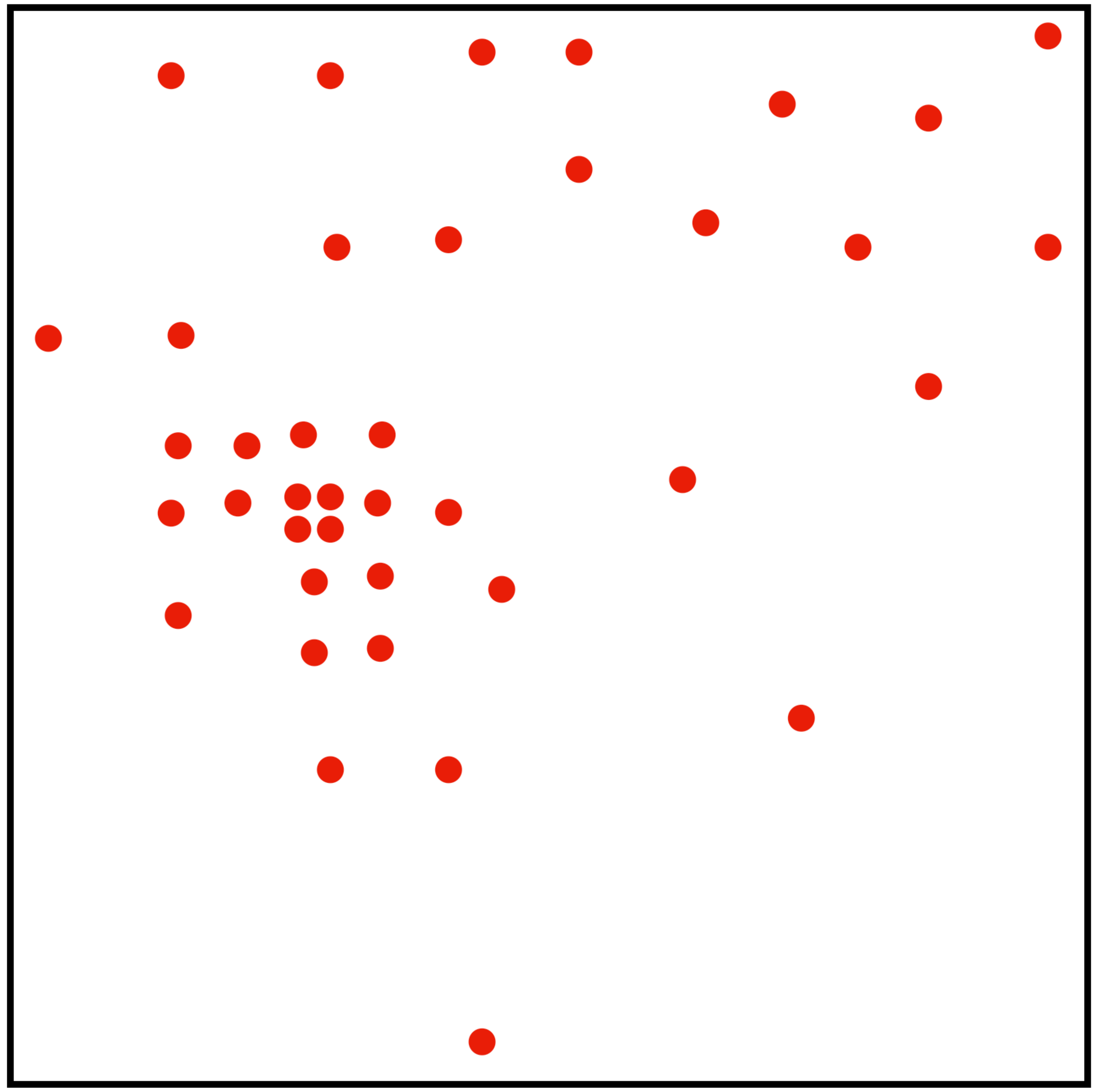
▸ **Kinetic models** (f_i, f_e)
- First principles: include all physics, in particular what we do not yet understand.
- Surprisingly simple to conceive and implement in computers.
- Not economical at large scales.



Modeling electron dynamics

Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

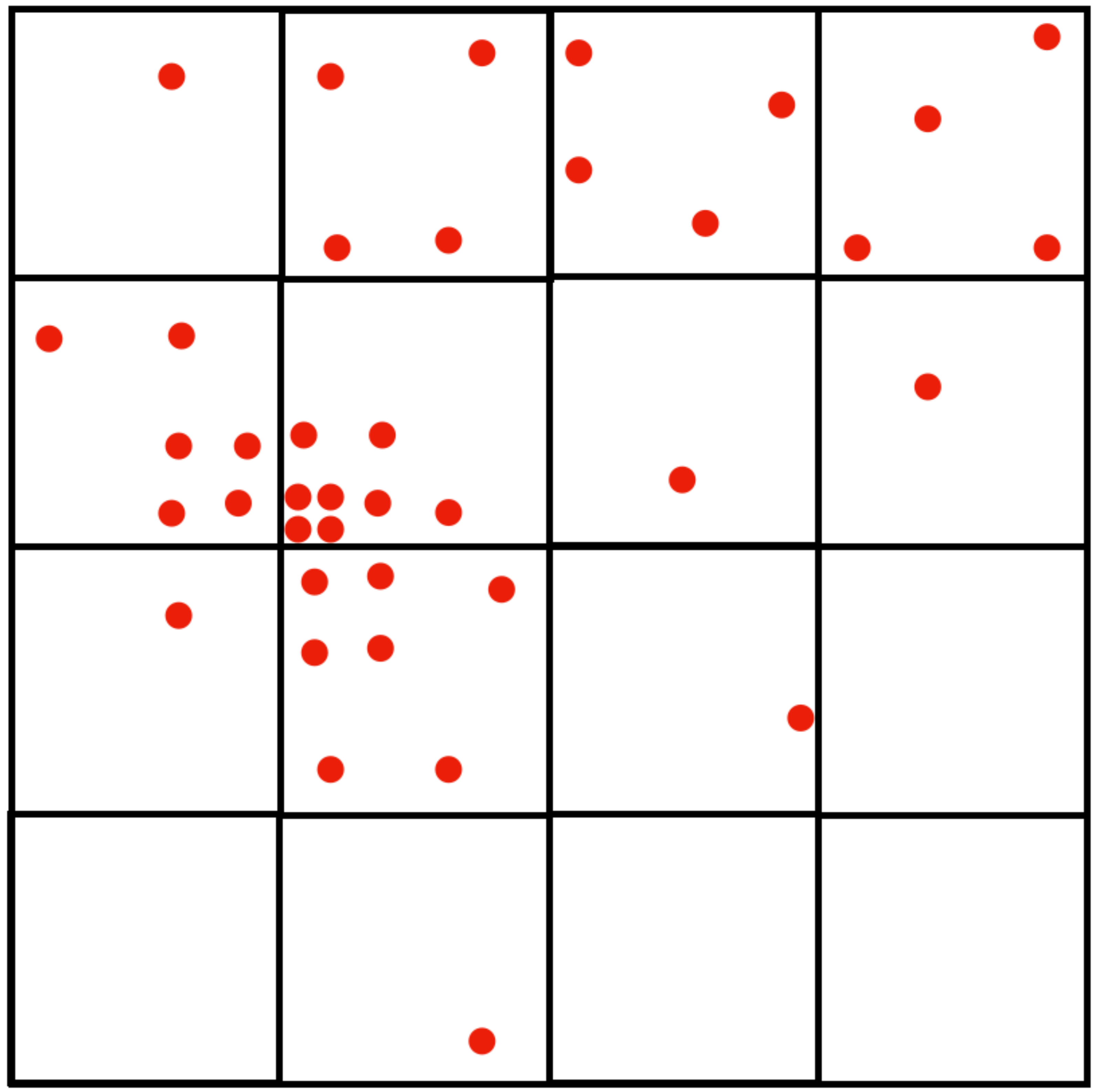
- A Particle-Particle/Particle-Mesh code + appropriate algorithms + a big computer.



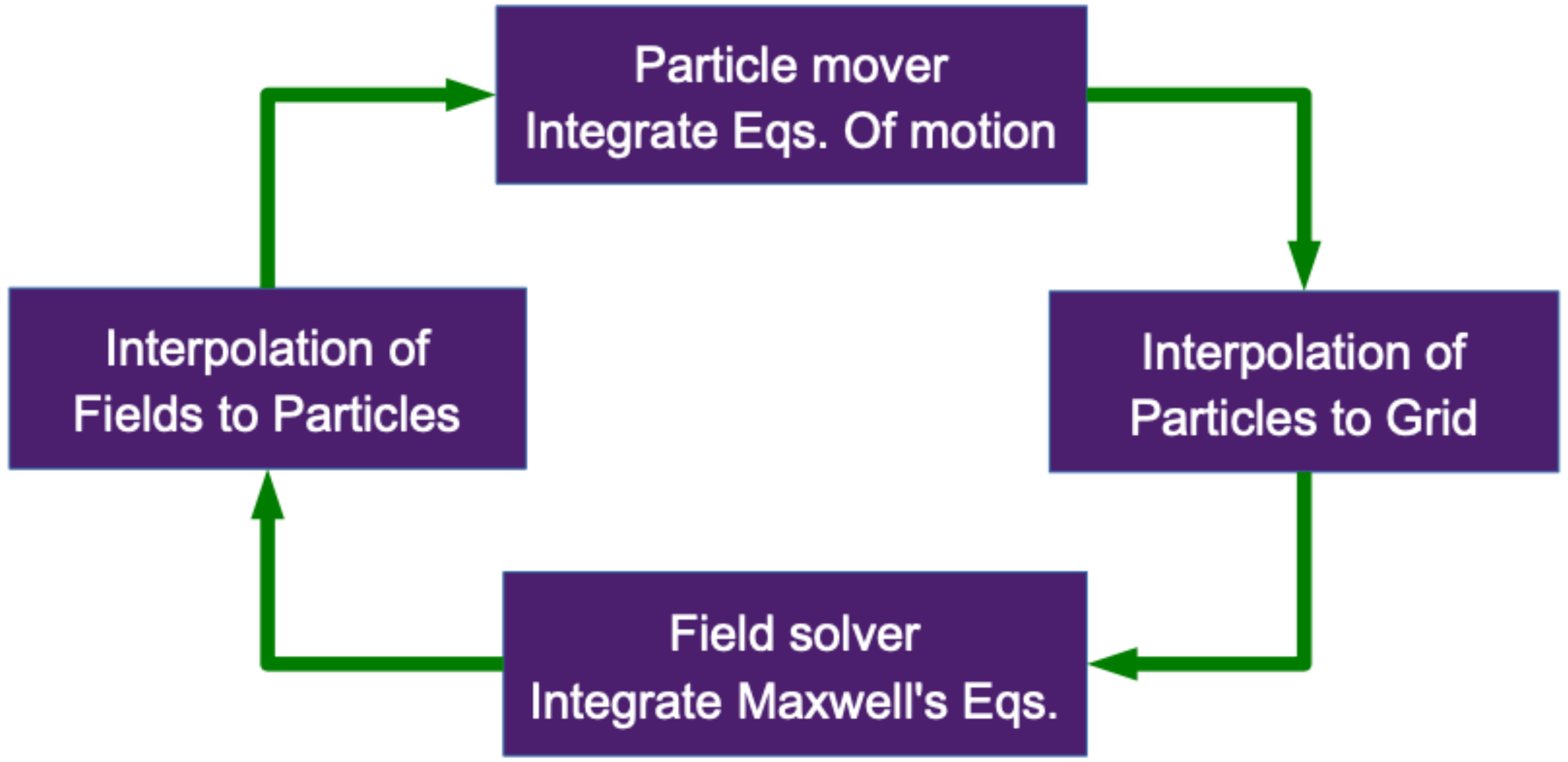
Modeling electron dynamics

LASP
Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

- A Particle-Particle/Particle-Mesh code + appropriate algorithms + a big computer.



Particle-in-cell (PIC) approach

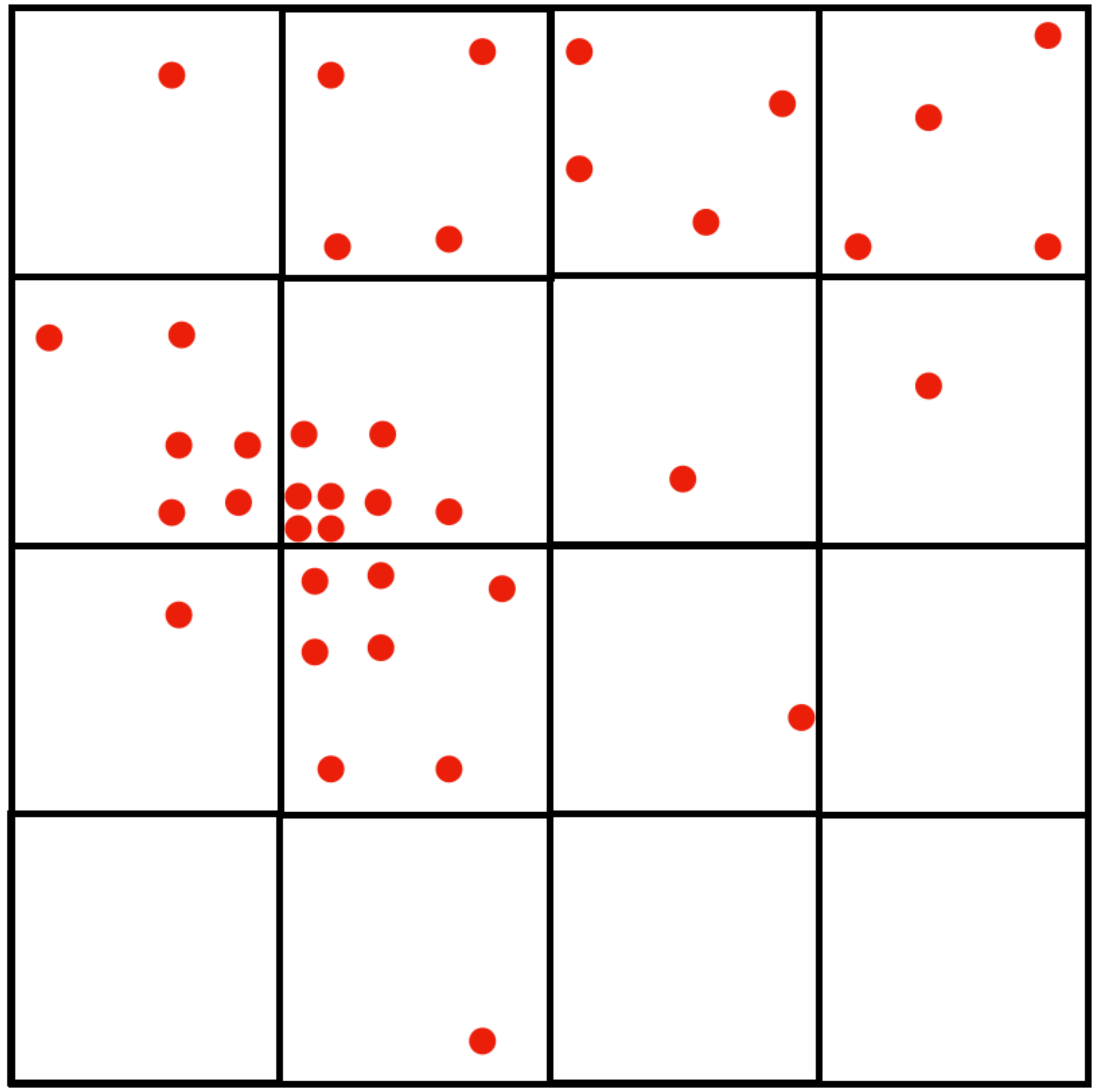


Explicit PIC

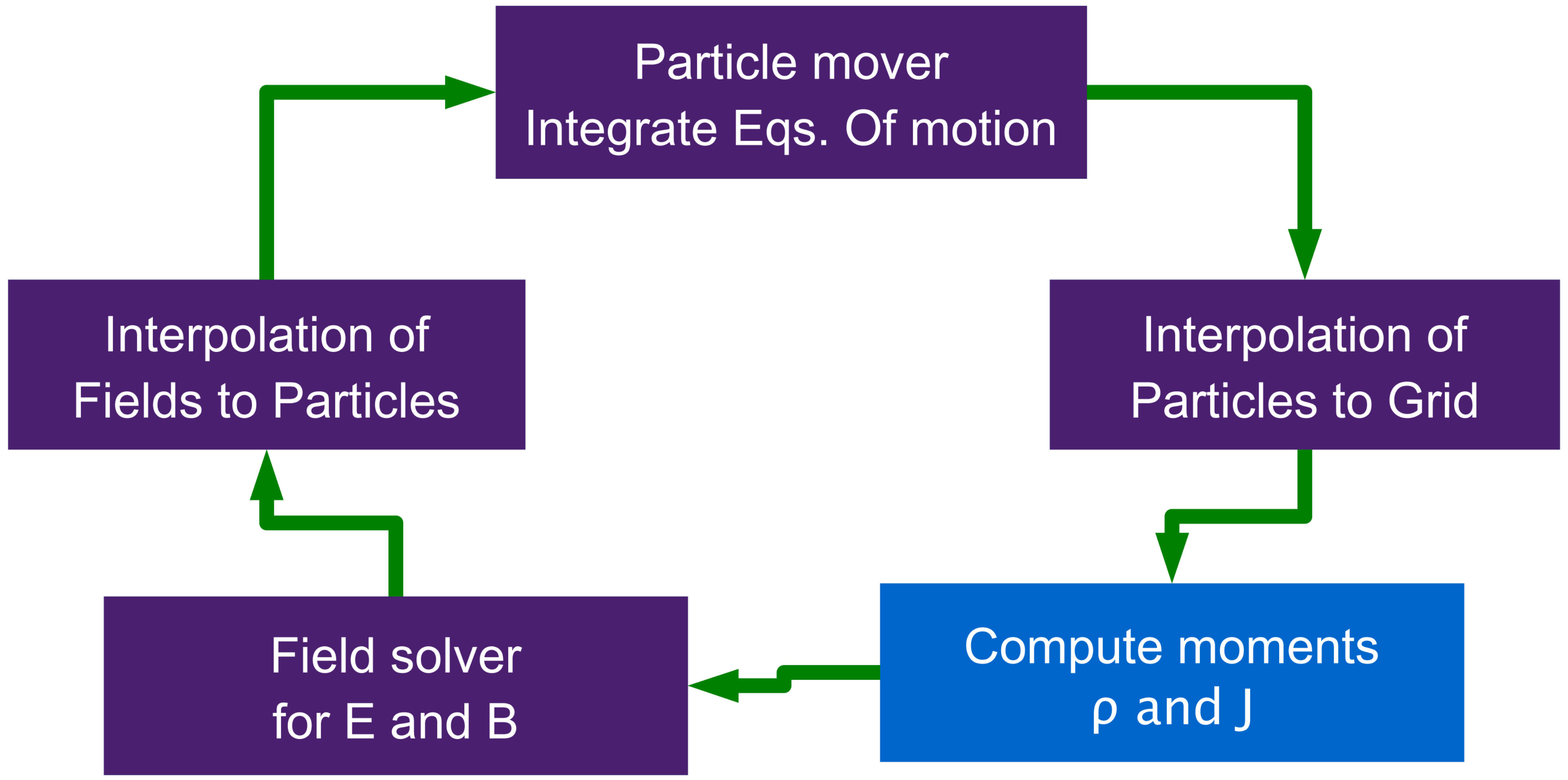
$$c\Delta t < \Delta x$$
$$\omega_{pe}\Delta t < \Delta x$$
$$\Delta x < \zeta\lambda_D$$

Modeling electron dynamics

- A Particle-Particle/Particle-Mesh code + appropriate algorithms + a big computer.



Particle-in-cell (PIC) approach



Explicit PIC

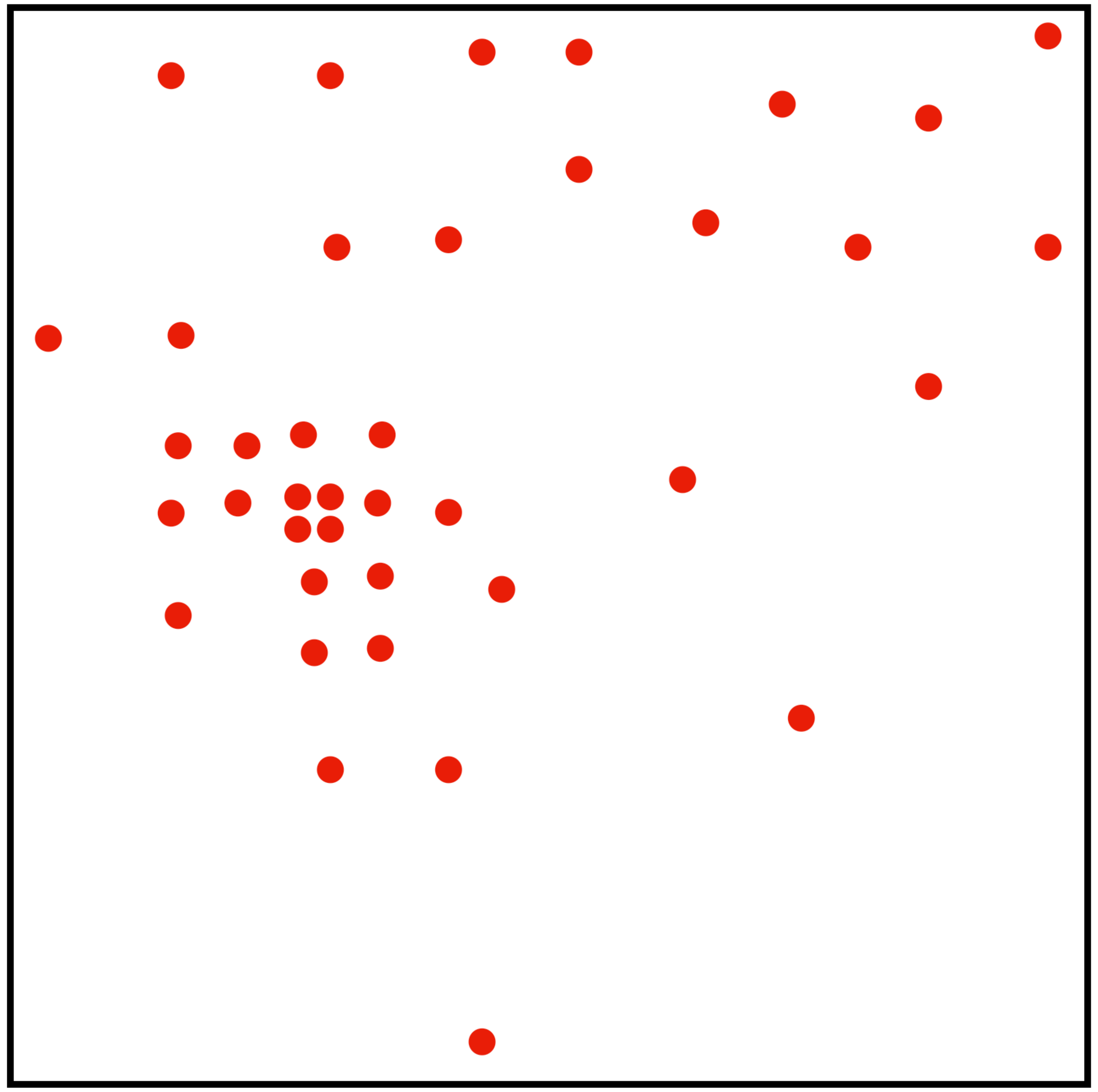
$$c\Delta t < \Delta x$$
$$\omega_{pe}\Delta t < \Delta x$$
$$\Delta x < \zeta\lambda_D$$

Semi-implicit PIC

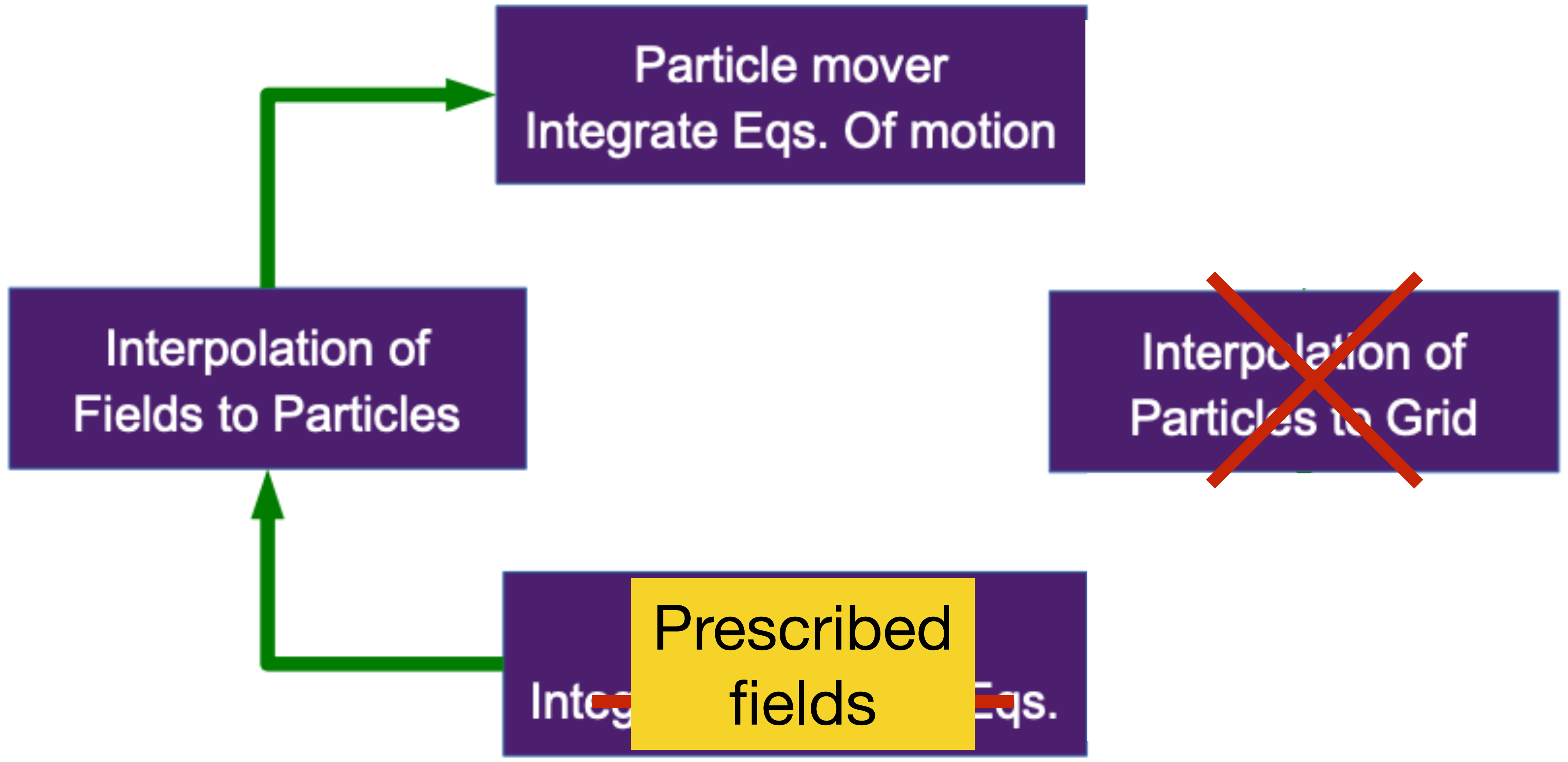
$$0.1 < v_{the}\,{}^{\Delta t}/_{\Delta x} < 1$$

Modeling electron dynamics

- A Particle-Particle/Particle-Mesh code + appropriate algorithms + a big computer.



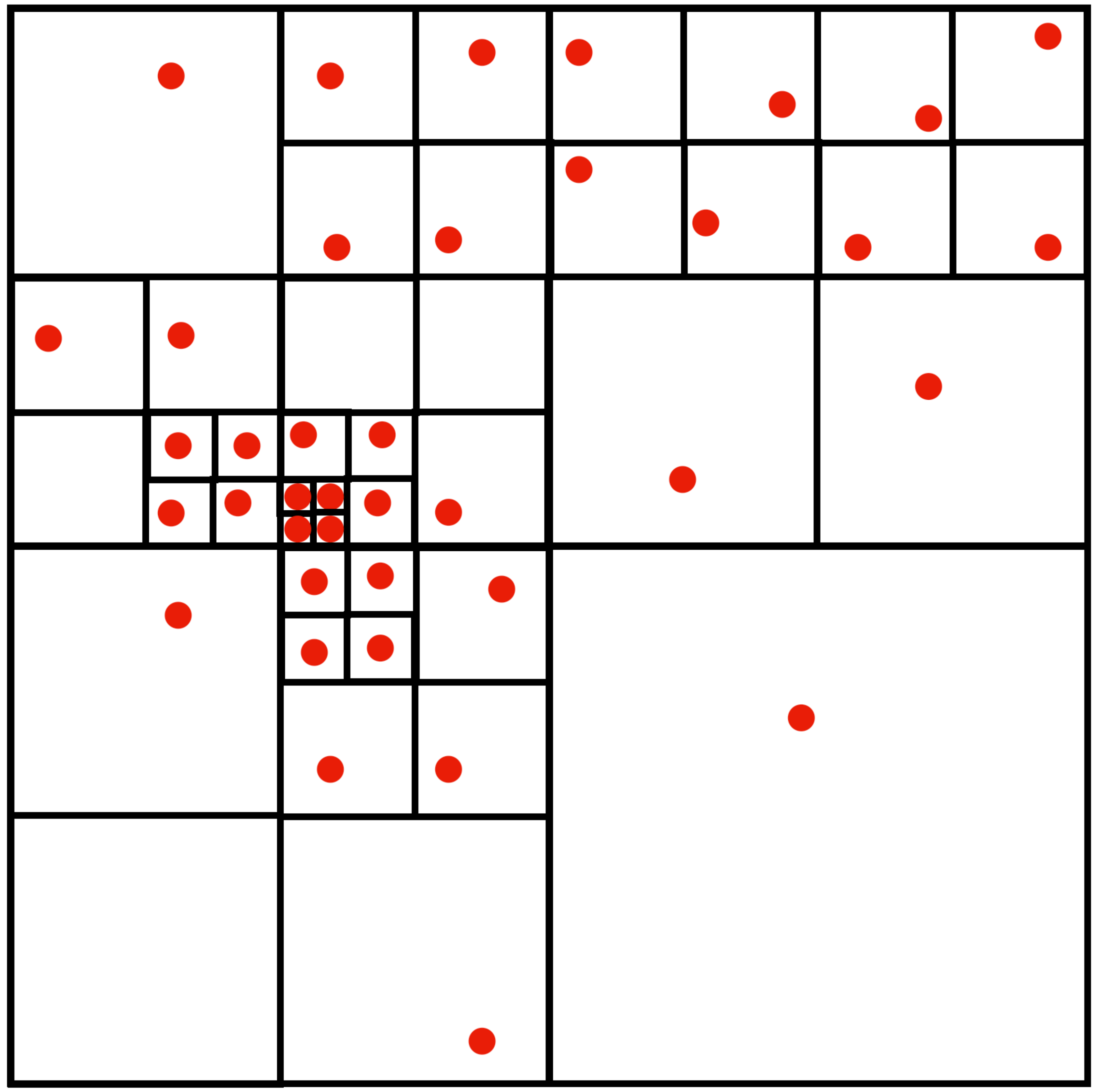
Test-particle approach

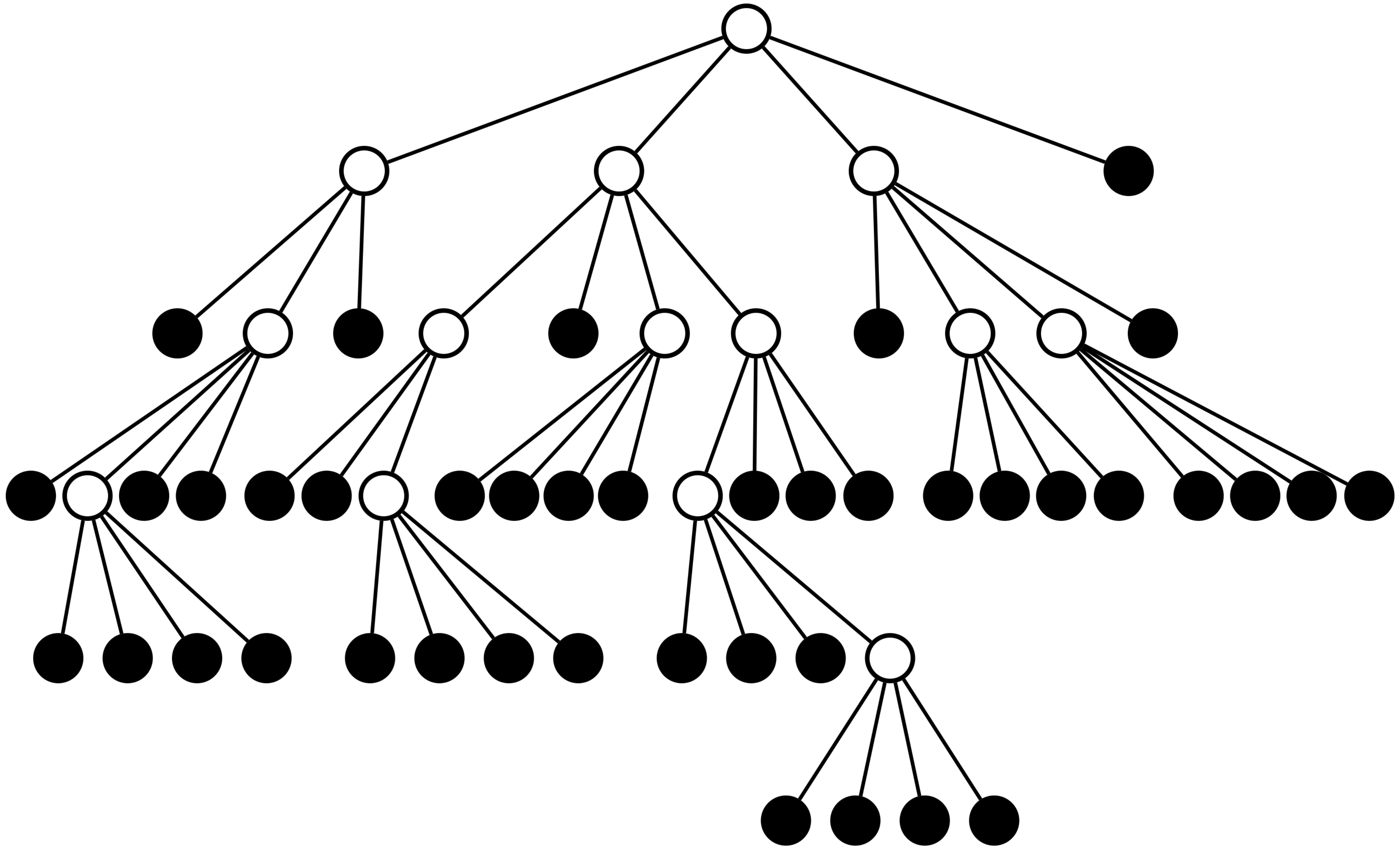


No self-consistent plasma dynamics…

Modeling electron dynamics

- Barnes-Hut tree algorithm: no fixed grid, so not bound globally by CFL constraints.
  - Divisions are constructed depending on plasma particle and surface segment density.

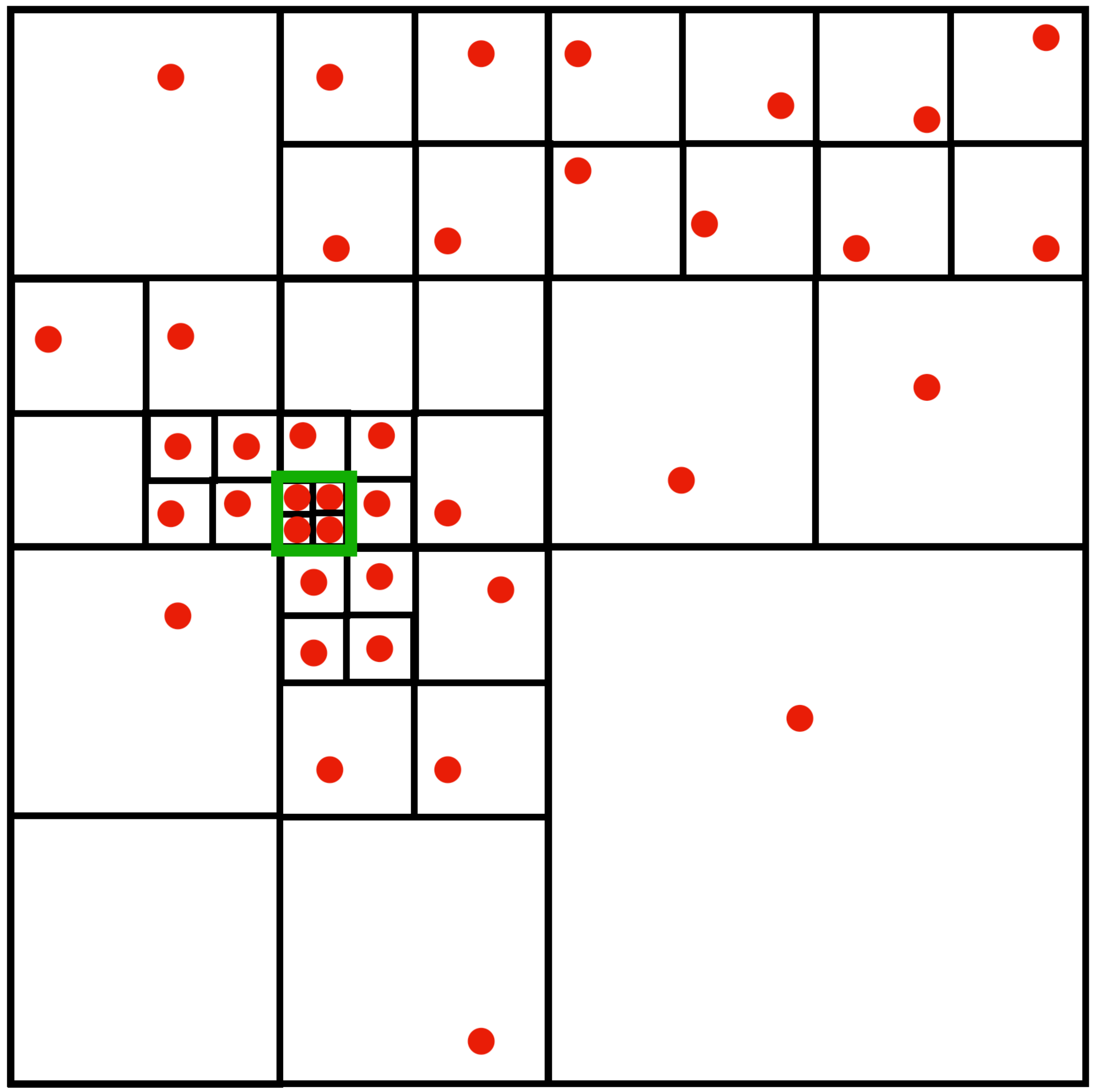


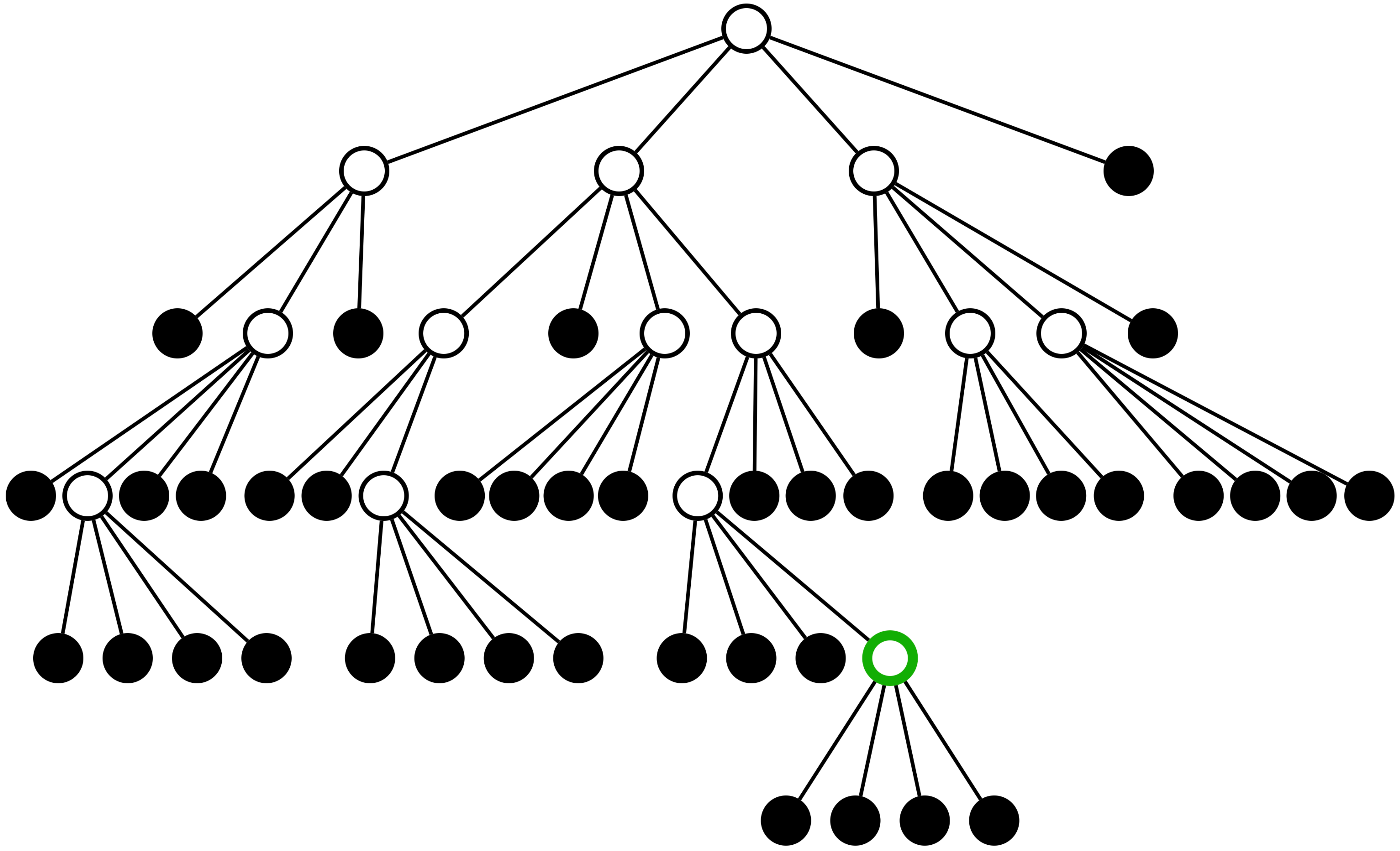


Modeling electron dynamics

Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

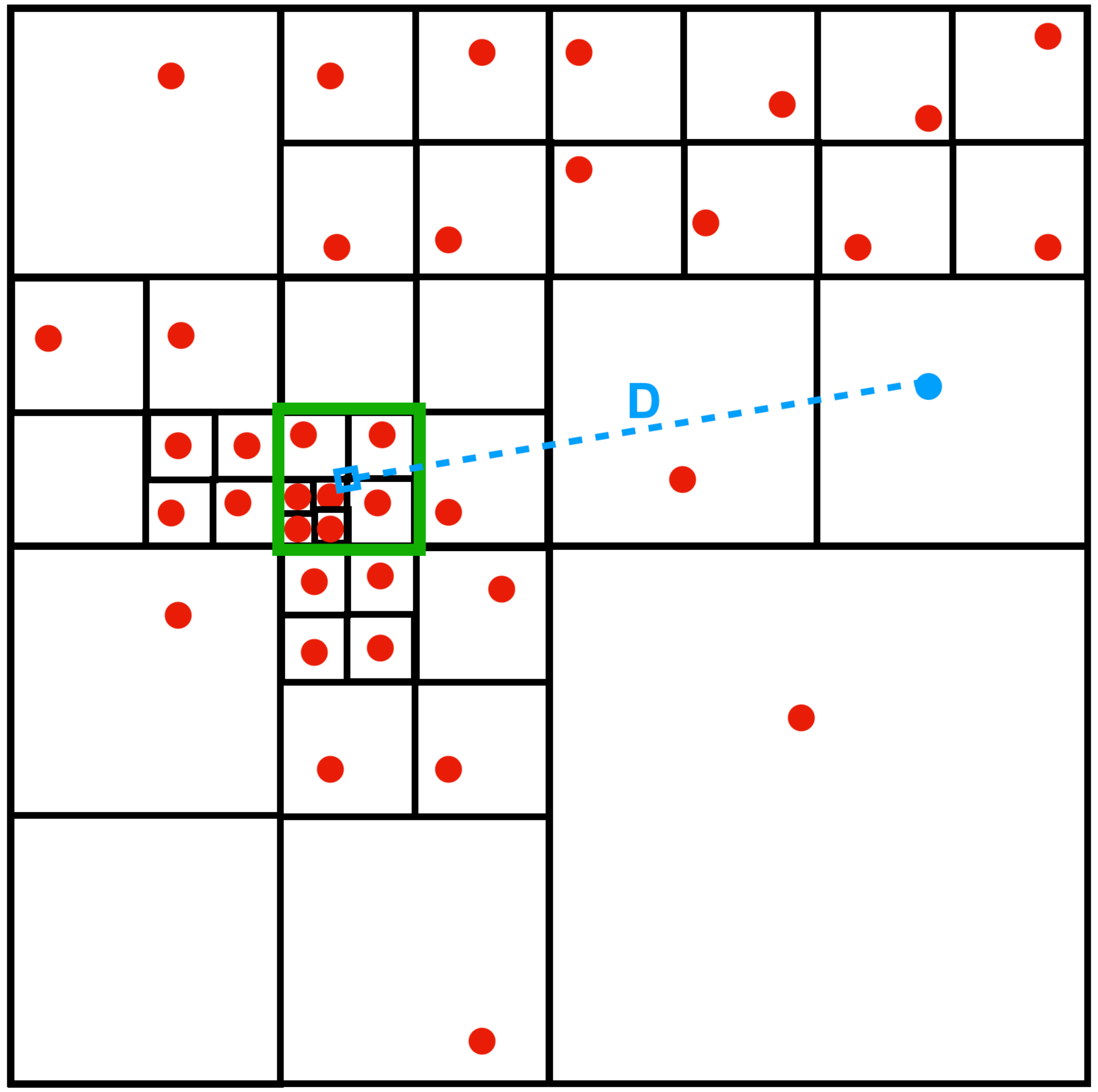
- Barnes-Hut tree algorithm: no fixed grid, so not bound globally by CFL constraints.
  - **Short range** interactions, use **brute force**, i.e., Coulomb's Law.

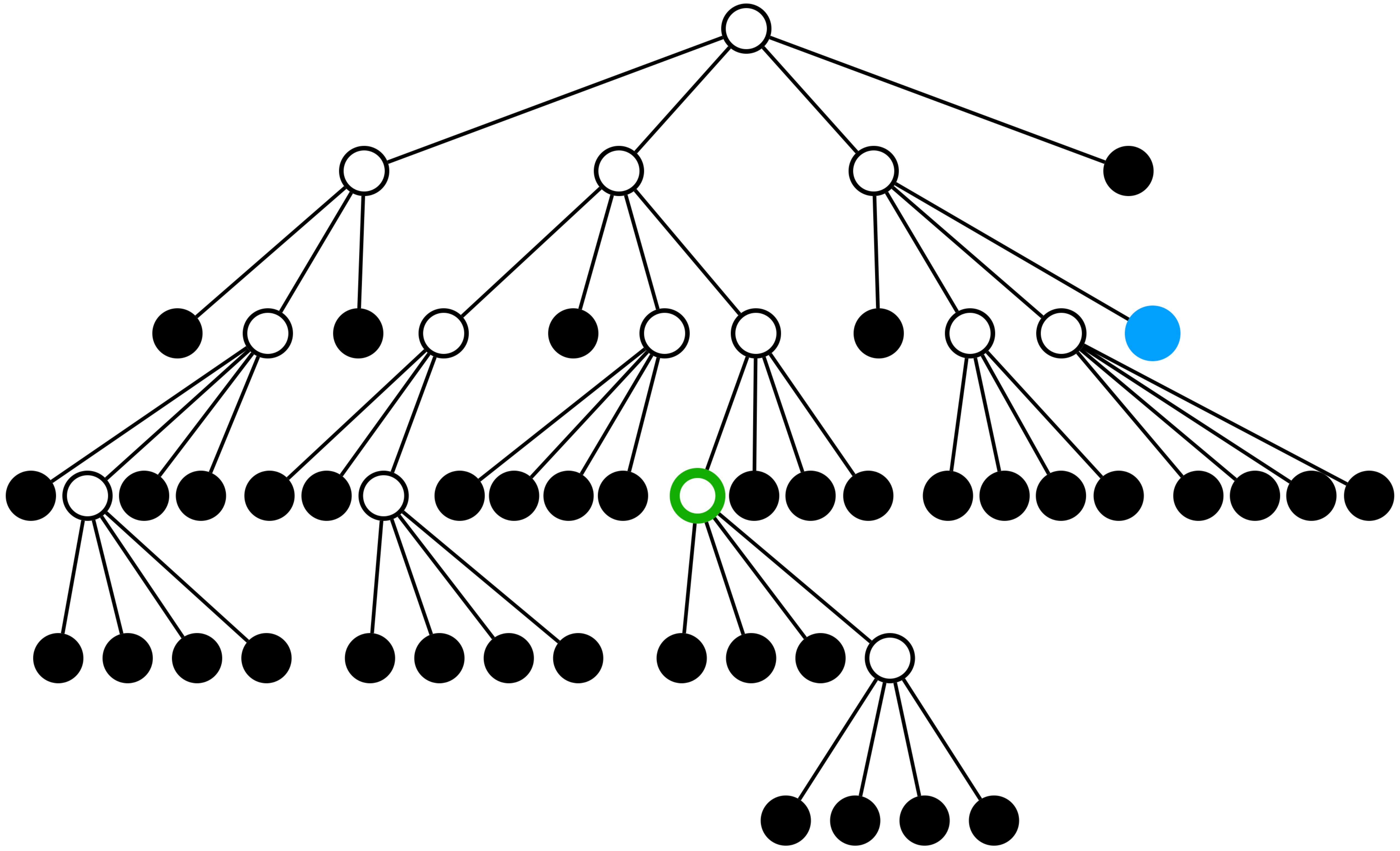




Modeling electron dynamics

- Barnes-Hut tree algorithm: no fixed grid, so not bound globally by CFL constraints.
  - **Long-range** interactions, use **multipole** expansion [Zimmerman et al. (JGR 2016)].

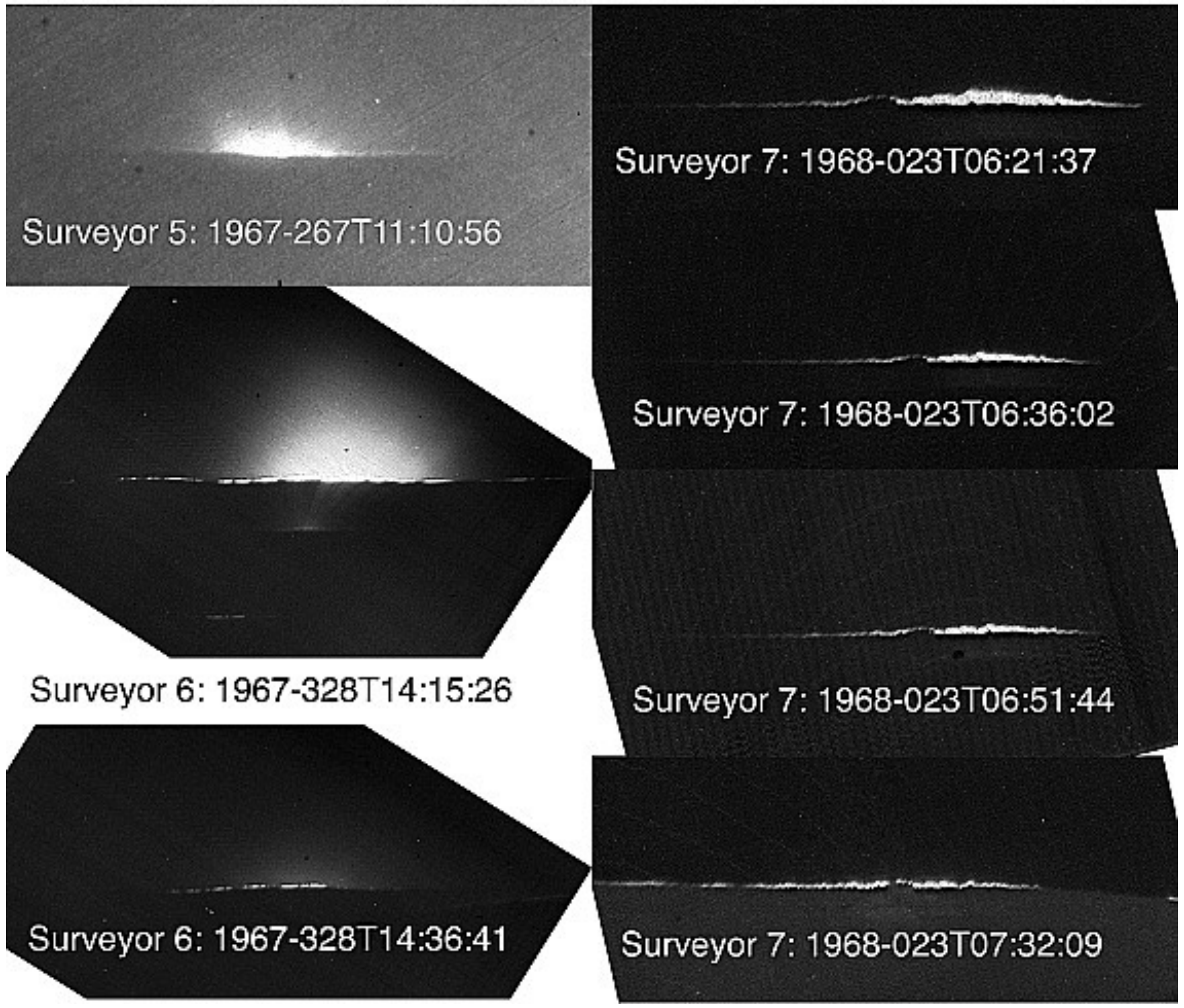




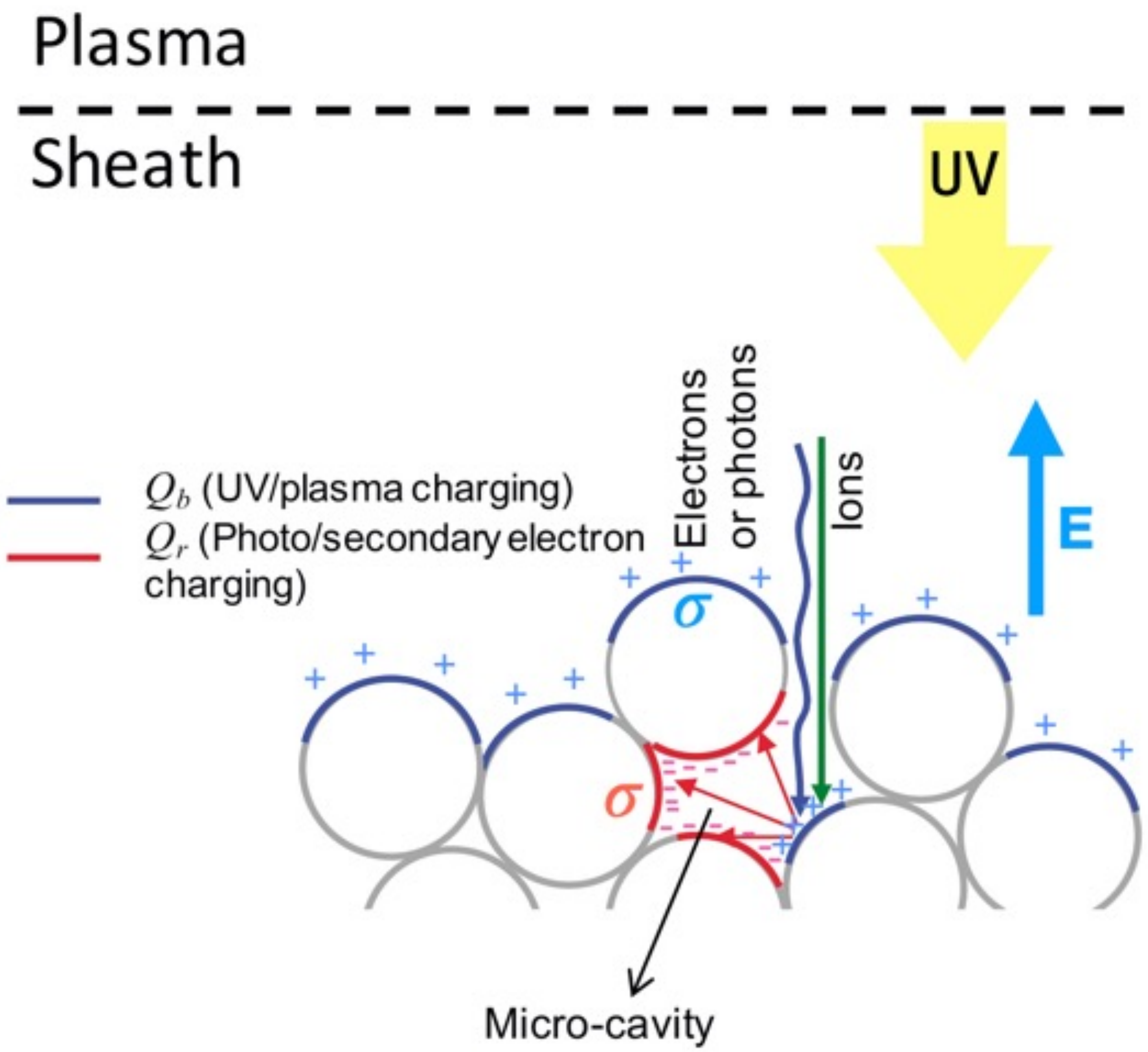
Regolith-plasma interactions

Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

- **The lunar horizon glow**: naturally lofted electrostatically charged dust, transported by surface electric fields.



[Criswell (Springer, 1973); Colwell et al. (Rev. Geophys. 2007)]



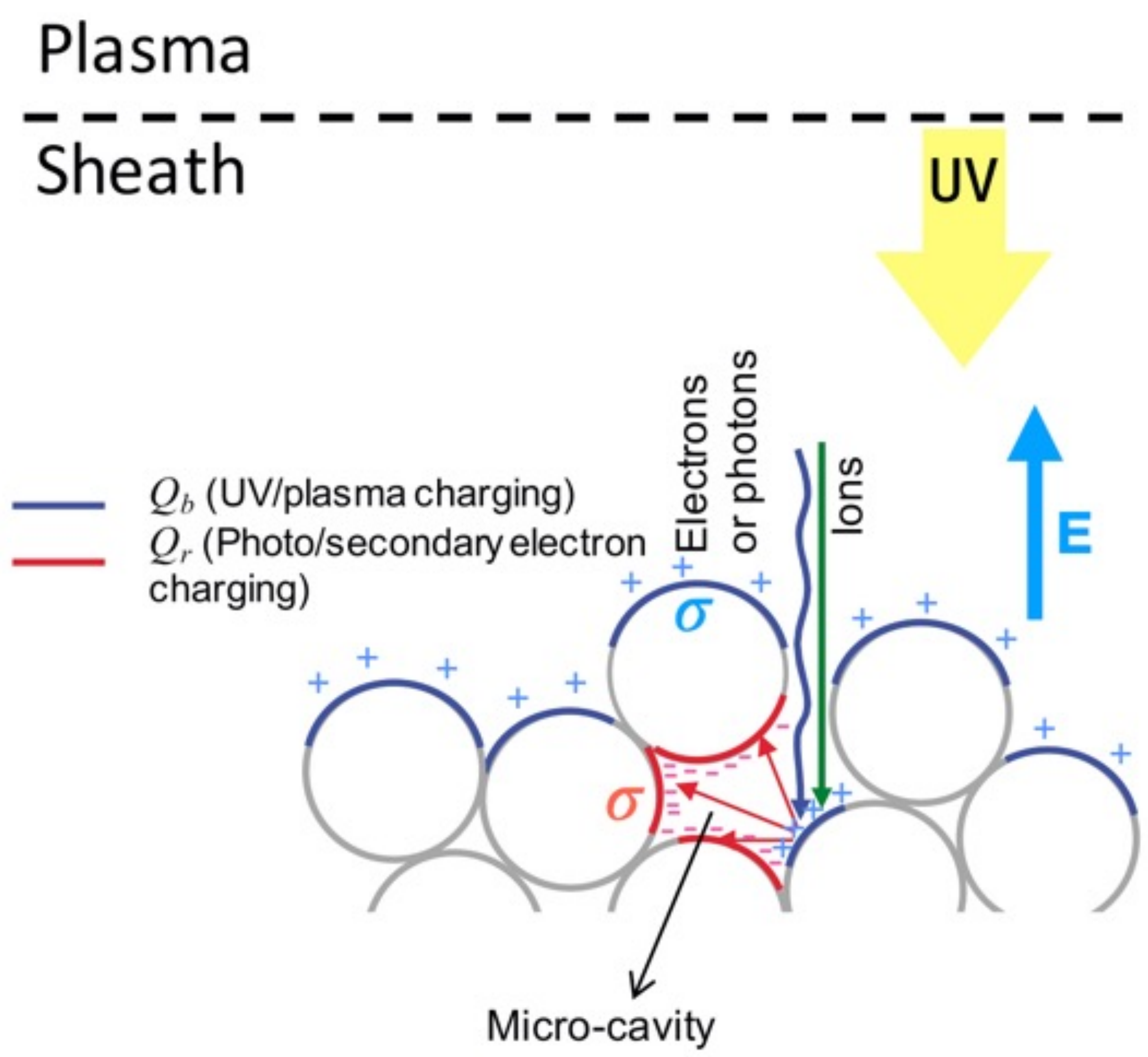
Lofting Criterium: $Q_d\mathbf{E} = \mathbf{F}_e + \mathbf{F}_c > \mathbf{F}_g + \mathbf{F}_{co}$

[**Patched Charge Model**, Wang et al. (GRL 2016)]

Regolith-plasma interactions

Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

- Dust transport - driven by impacts, exposure to solar wind plasma and ultraviolet radiation - shapes the properties of the lunar regolith.
- Dust is also mobilized by human activities, representing both a technical and a health hazard.



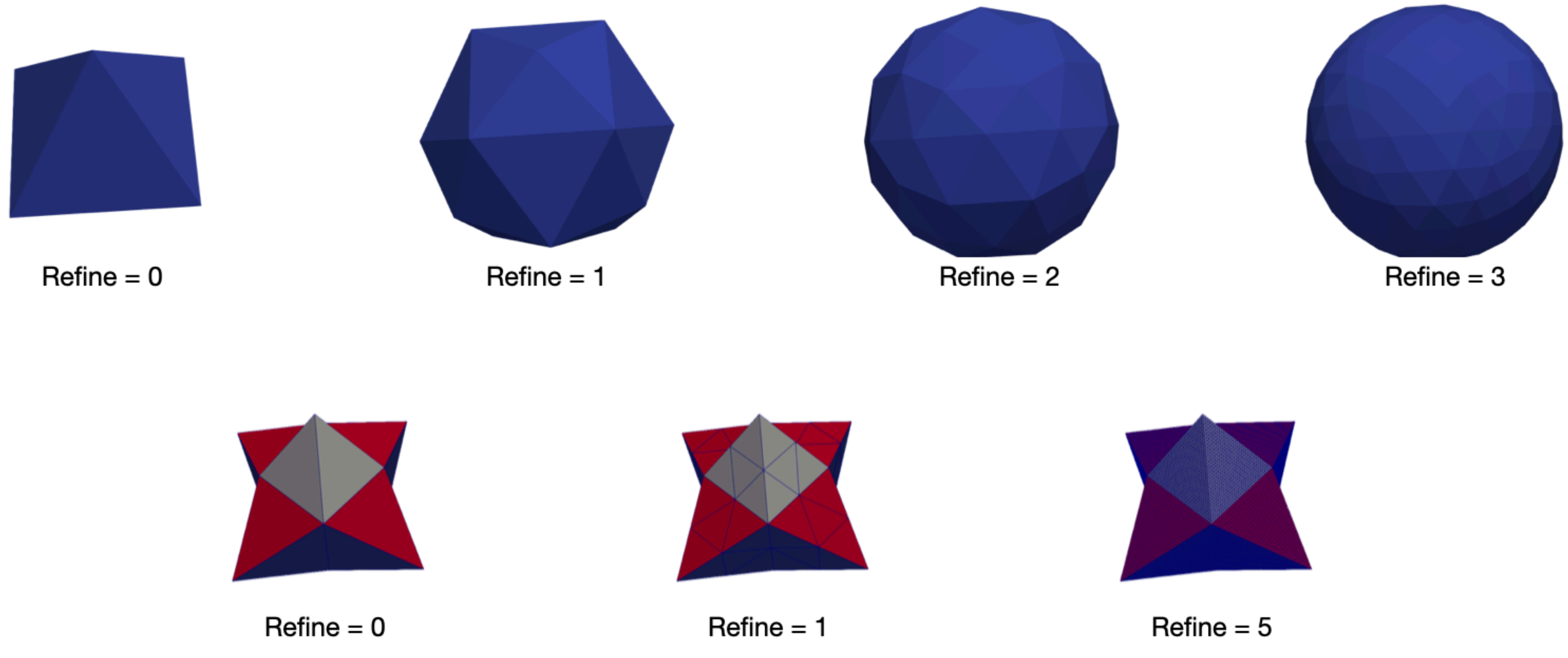
Lofting Criterium: $Q_d\mathbf{E} = \mathbf{F}_e + \mathbf{F}_c > \mathbf{F}_g + \mathbf{F}_{co}$

[**Patched Charge Model**, Wang et al. (GRL 2016)]

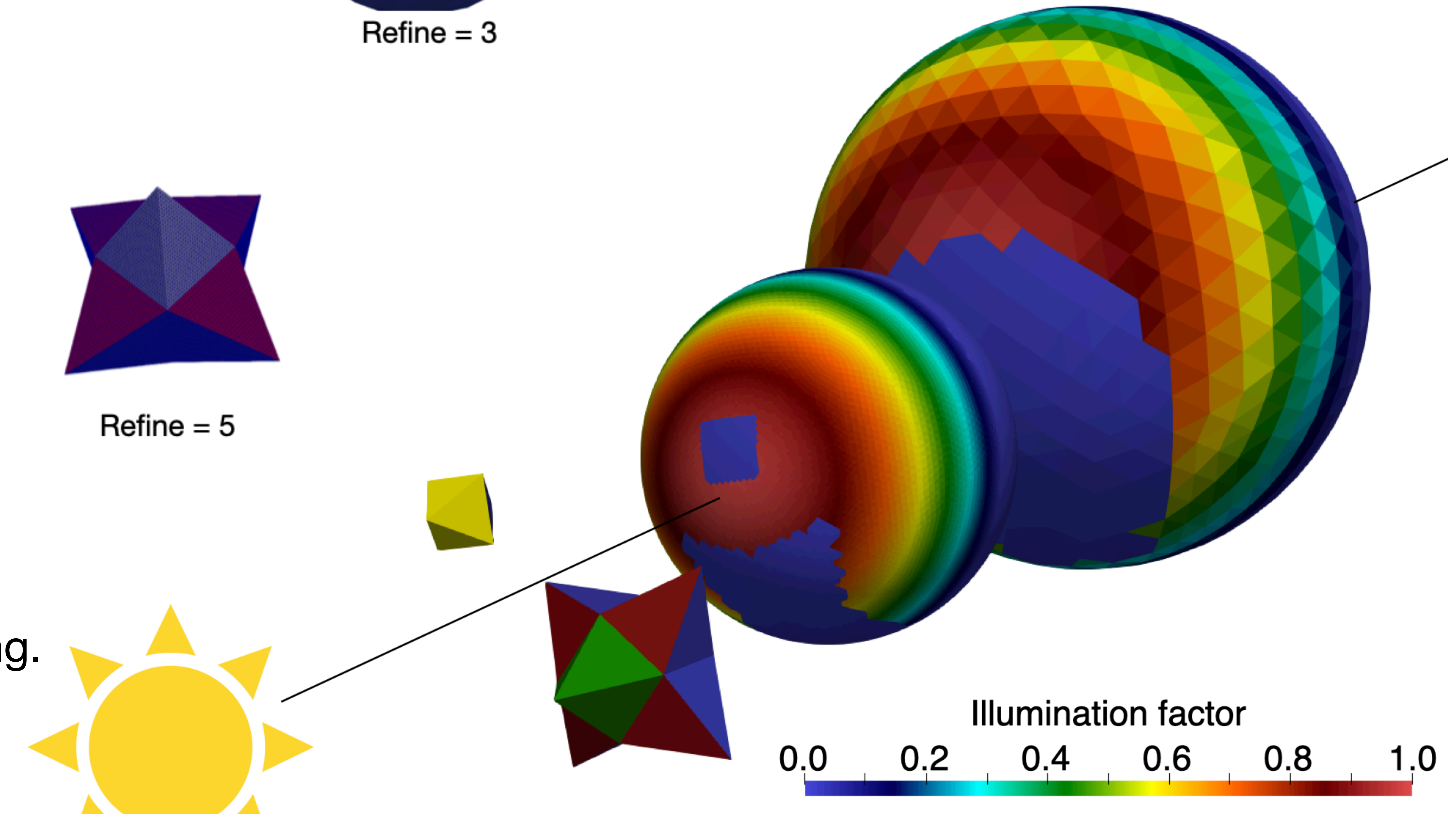
Dust covered Harrison Schmitt's spacesuit
[NASA]

Irregular-shaped dust

Illustration of the mesh refinement for spherical and irregularly shaped dust grains.



- Mesh refinement to obtain preferred resolution.
- Raytracing to obtain grain illumination/shadowing.



[Deca et al. (AGU 2023; URSI AT-RASC 2024)]

Particle mobilization

Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

Regolith grain configuration
(shape, arrangement, …)

1. Grain facet charging

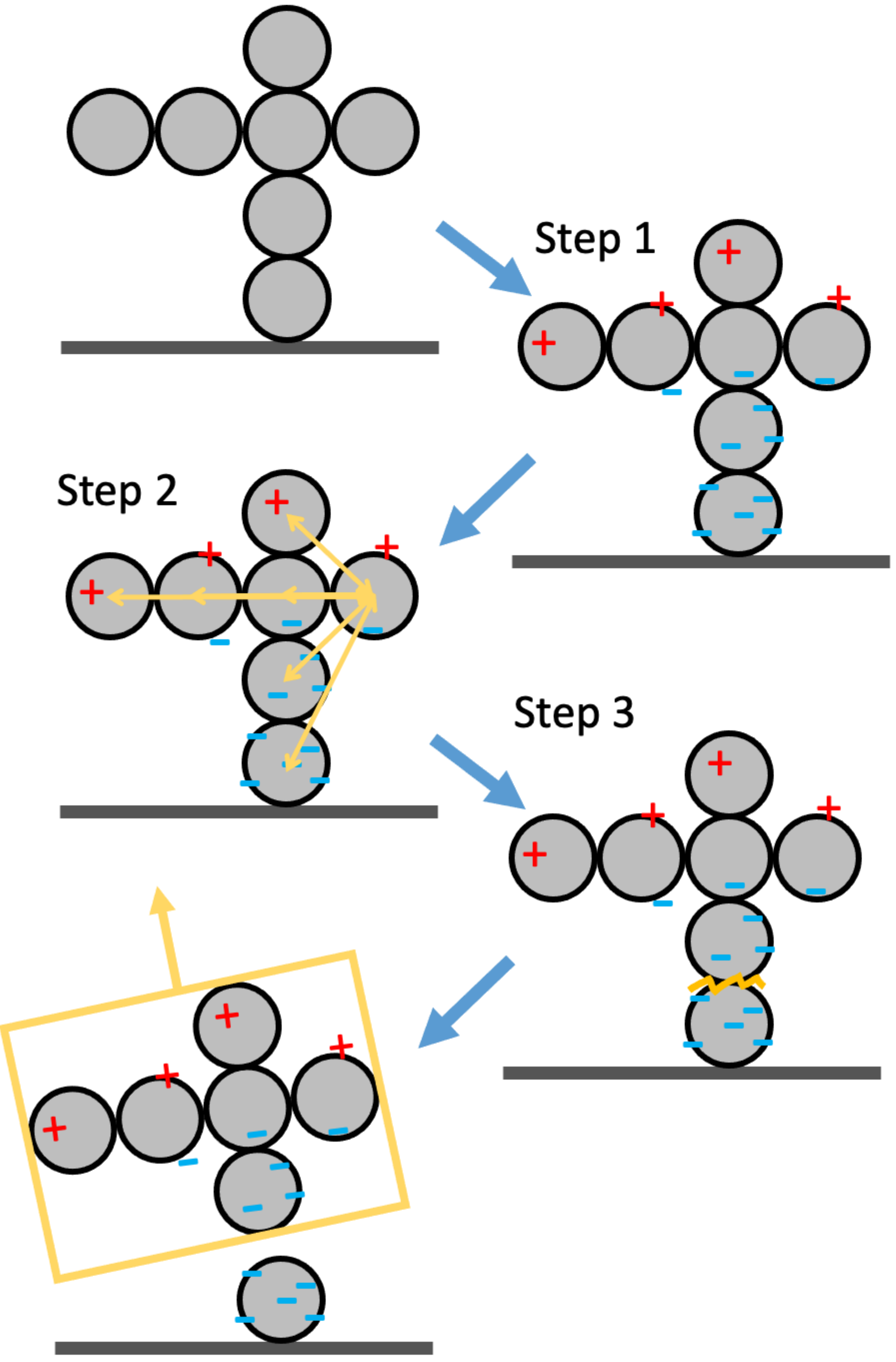
2. Force balance
(Coulomb vs cohesion)

3. Detachment identification
(Coulomb vs cohesion)

NO → Time → back to 1. Grain facet charging

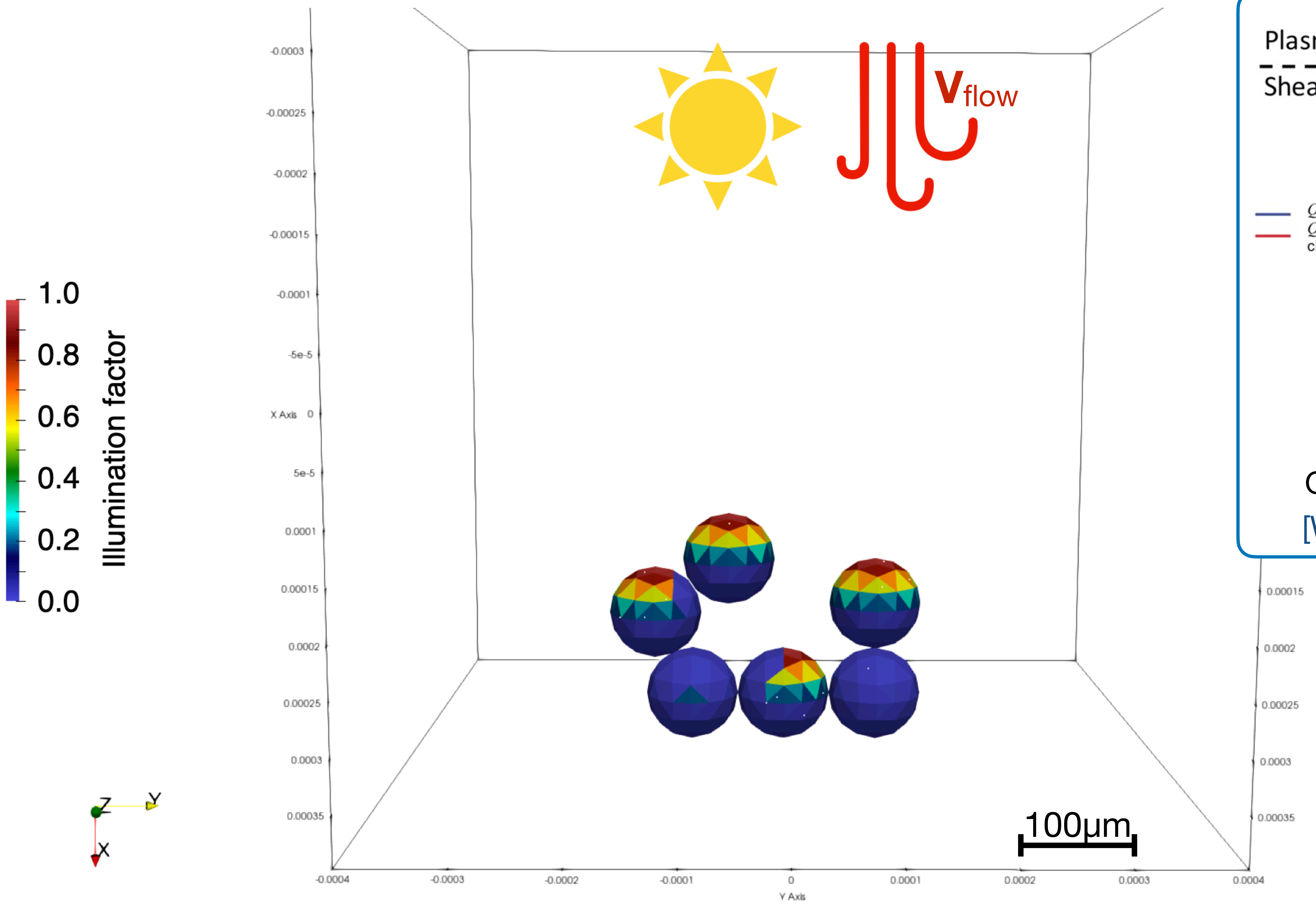
YES ↓

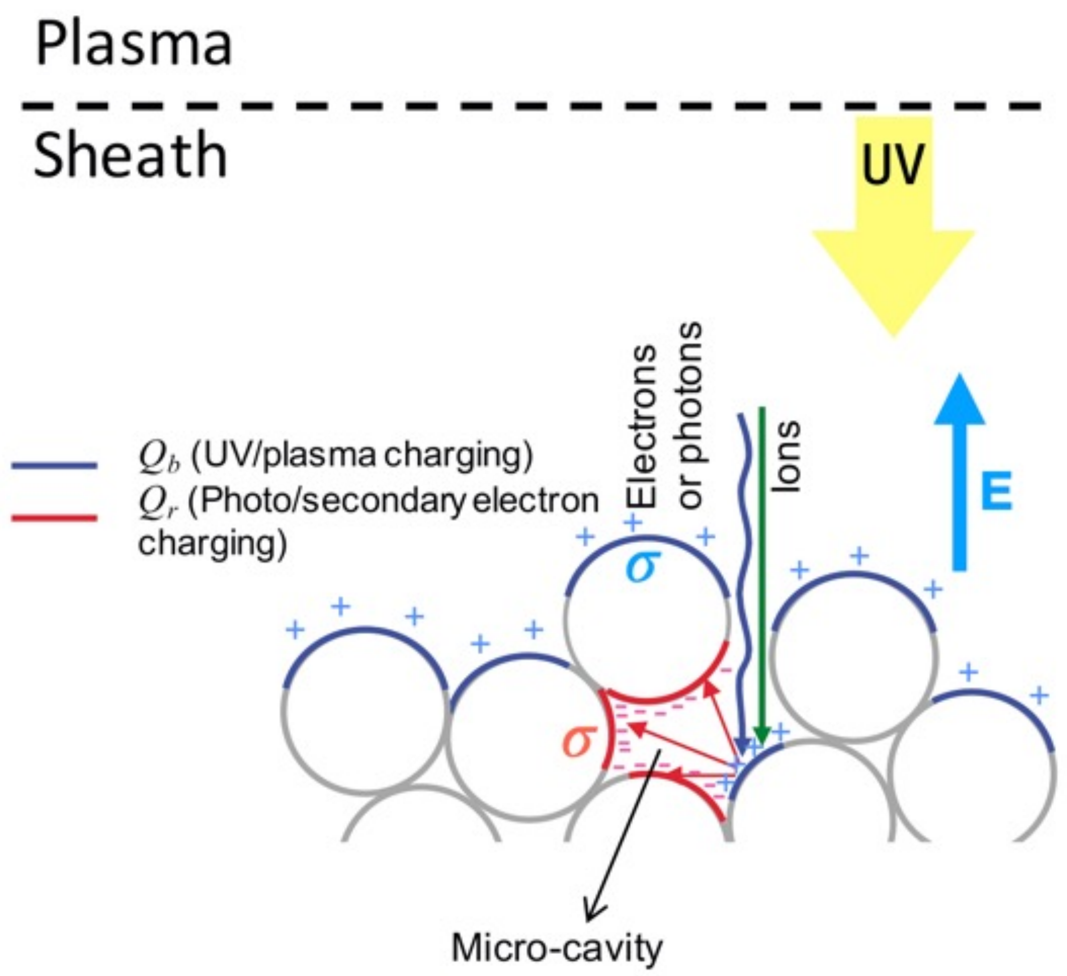
Output: Lofted grain parameters
(Size, shape, lofted acceleration, grain charge)



Patched Charge Model benchmark

Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**



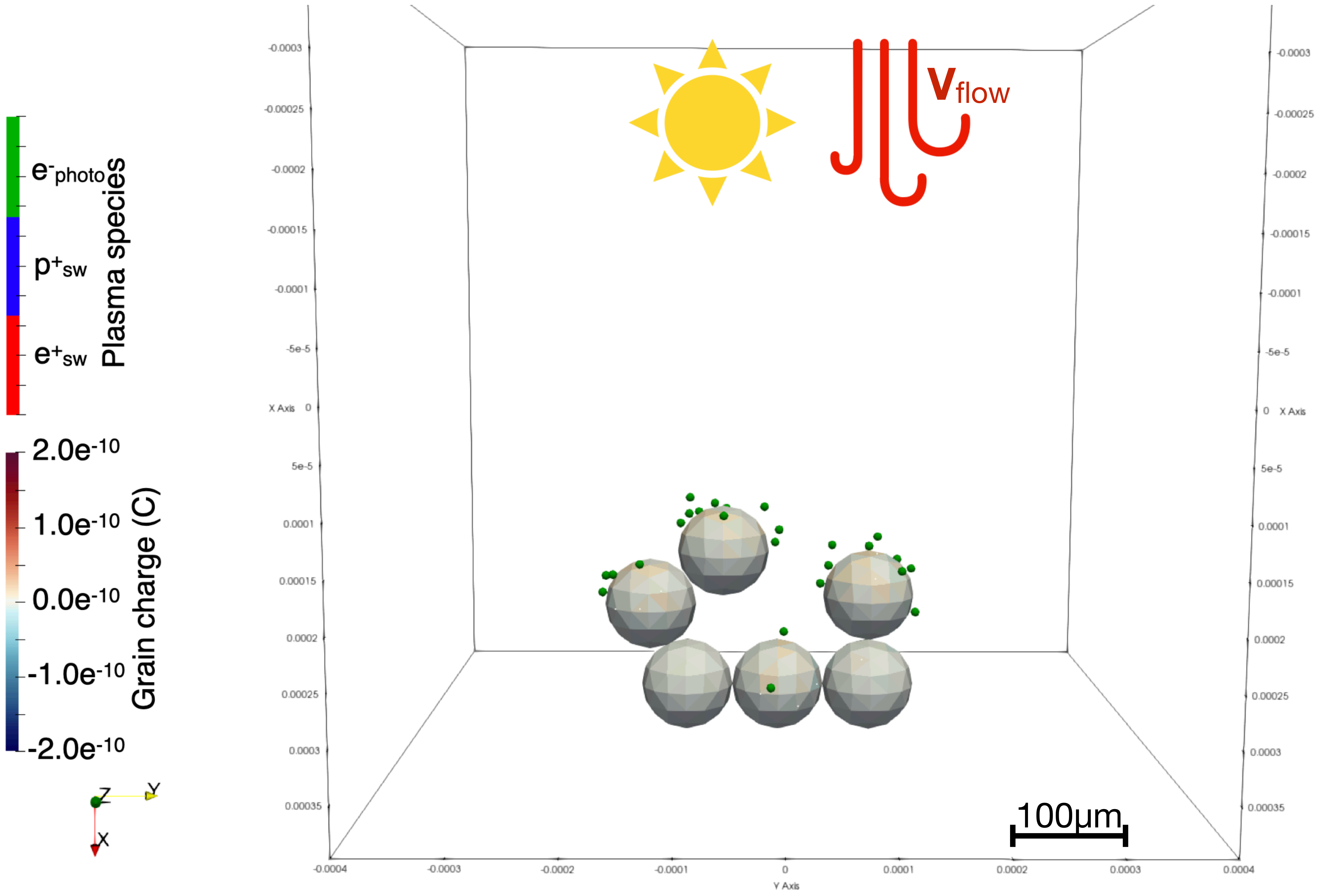


Lofting Criterium:

$Q_d\mathbf{E} = \mathbf{F}_e + \mathbf{F}_c > \mathbf{F}_g + \mathbf{F}_{co}$

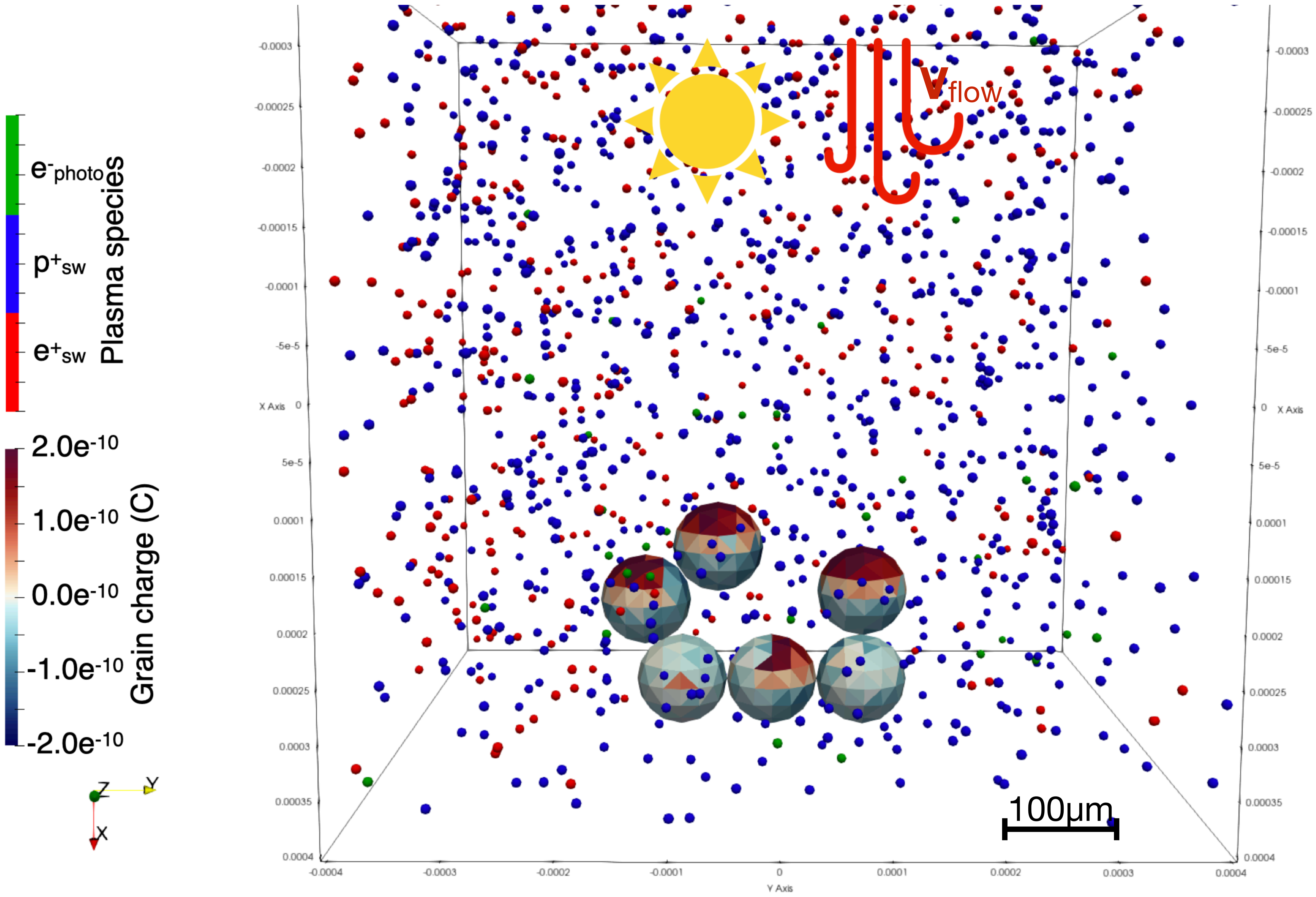
[Wang et al. (GRL 2016)]

Patched Charge Model benchmark.



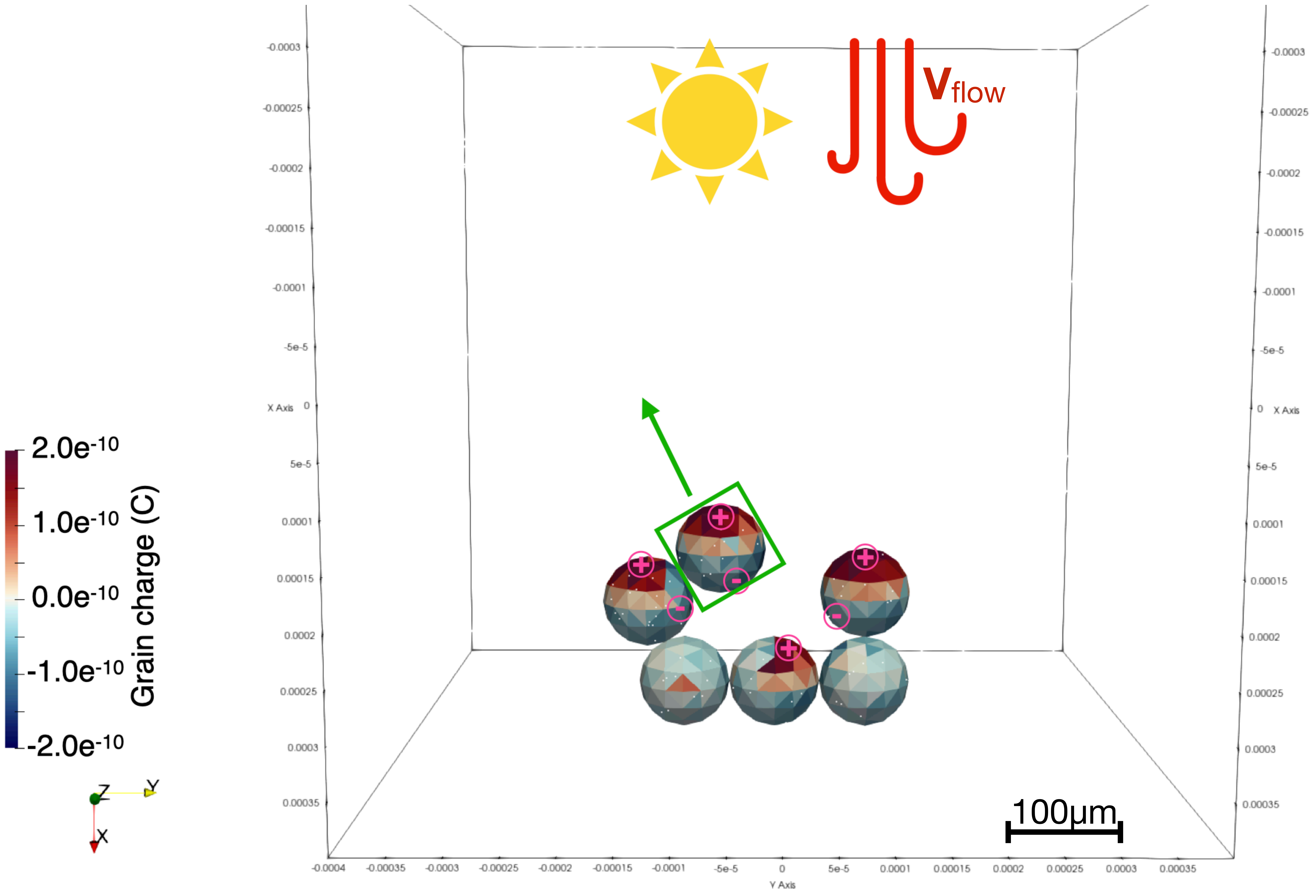
Patched Charge Model benchmark.

$\mathcal{O}(10^1)$



Patched Charge Model benchmark.

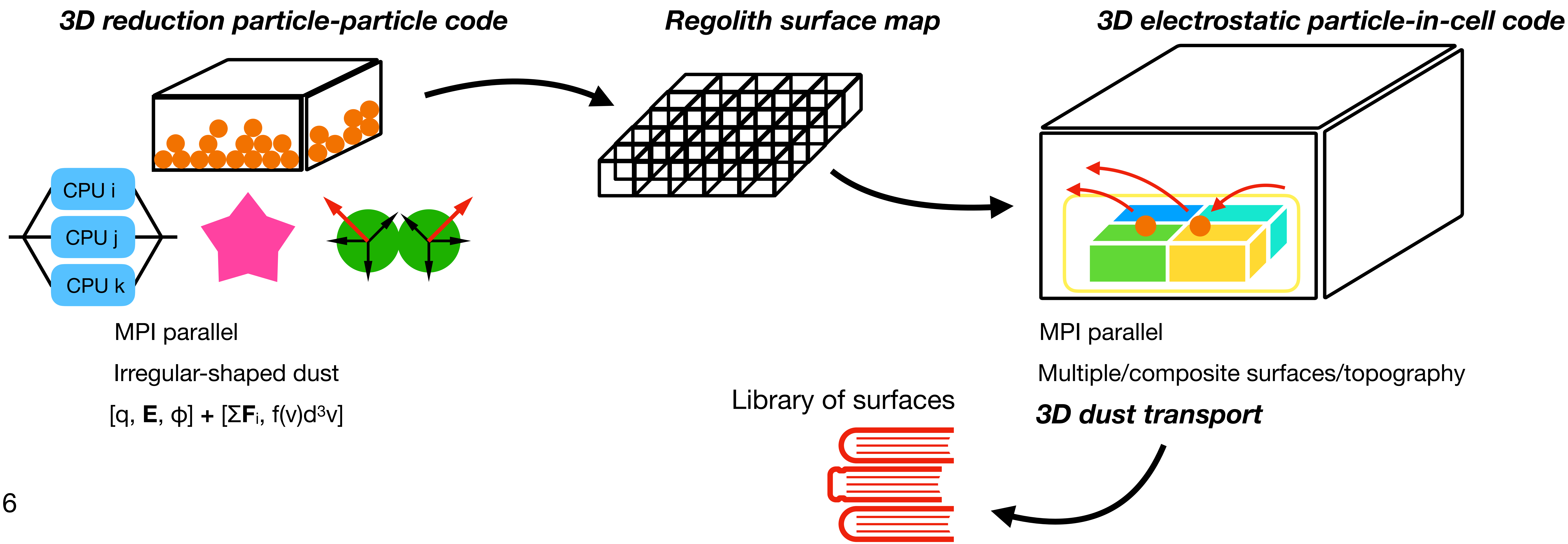
Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**



Modeling regolith-plasma interactions

Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

- **Needs self-consistent electron dynamics!**
- **Objective:** Develop a framework of numerical models that couple the microphysics of grain-scaled processes with the self-consistent solution of the near-surface plasma environment.

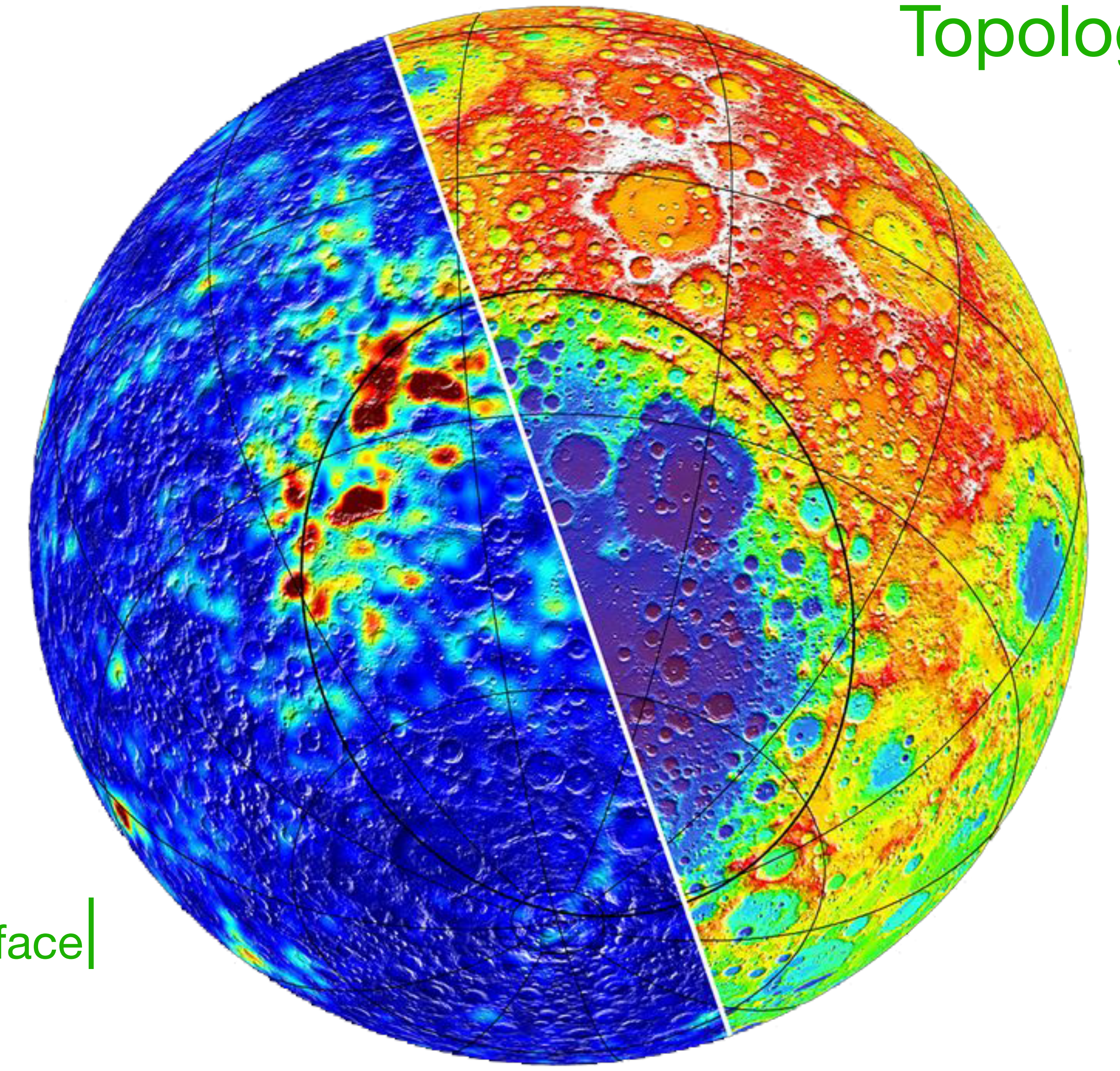


Moon - plasma interaction

Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

- The Moon has no intrinsic magnetic field, but does possess regions of local magnetization, called **Lunar Magnetic Anomalies** (LMAs).
  - Non-dipolar, small-scale, $|\mathbf{B}_{surface}|$ ~ 0.1nT -> 1000nT.
  - Linked with mini-magnetosphere formation.
- All **lunar swirls** - the peculiar high-albedo markings on the Moon's surface - have been associated with LMAs. The opposite does *NOT* hold.

Topology



$|\mathbf{B}_{surface}|$

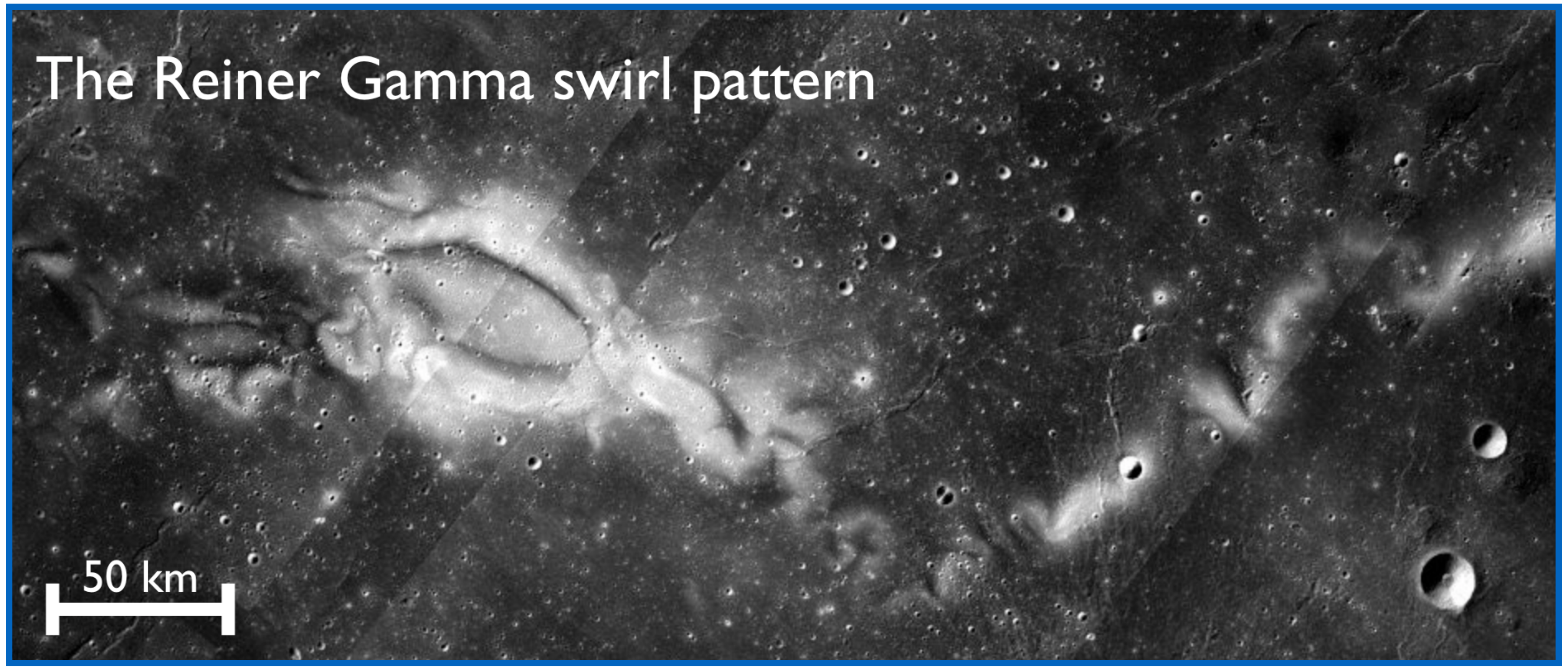
Albedo

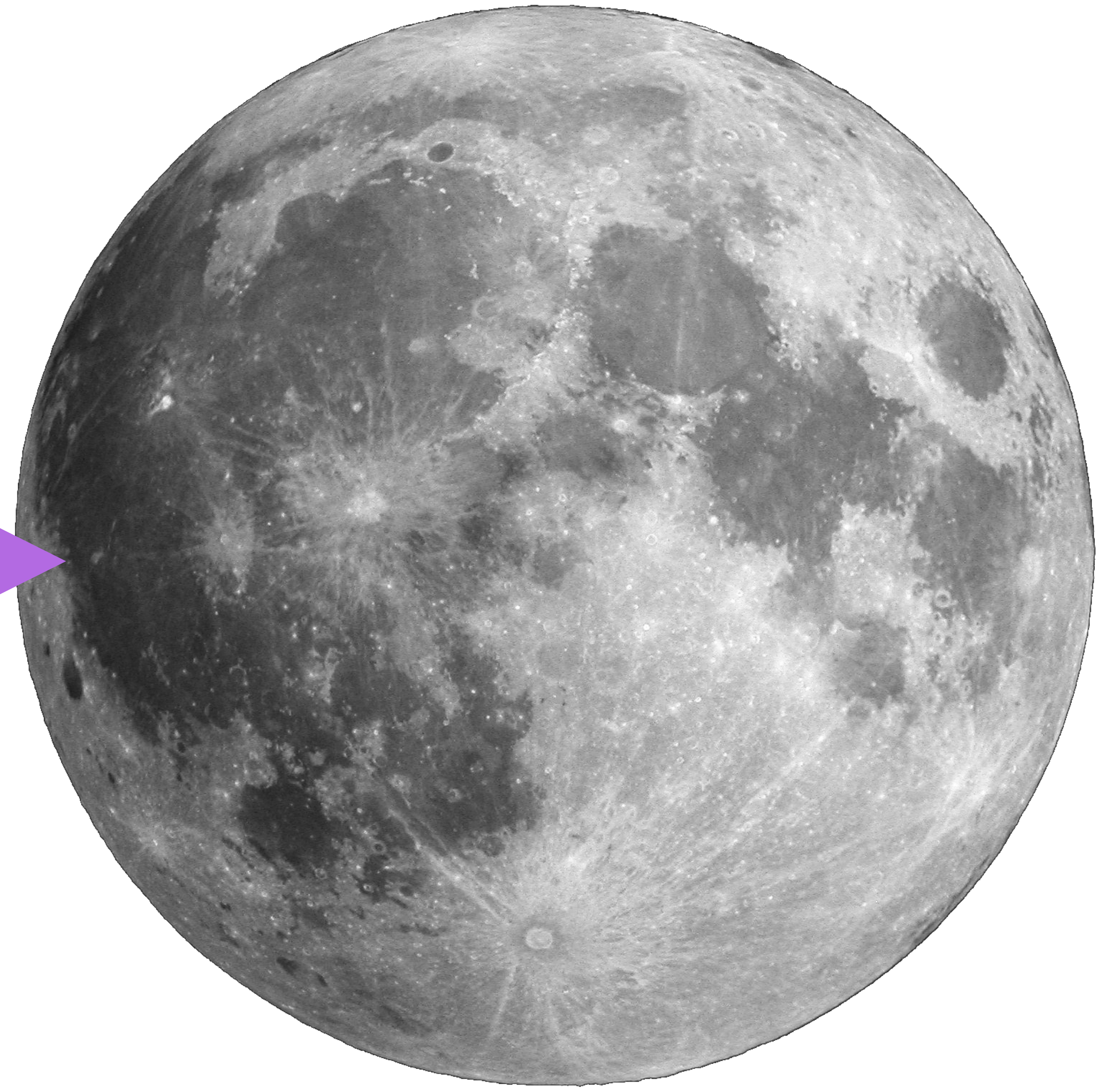
Moon - plasma interaction

Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

- The Moon has no intrinsic magnetic field, but does possess regions of local magnetization, called **Lunar Magnetic Anomalies** (LMAs).
  - Non-dipolar, small-scale, $|\mathbf{B}_{surface}|$ ~ 0.1nT -> 1000nT.
  - Linked with mini-magnetosphere formation.
- All **lunar swirls** - the peculiar high-albedo markings on the Moon's surface - have been associated with LMAs. The opposite does *NOT* hold.

Hic ego sum!



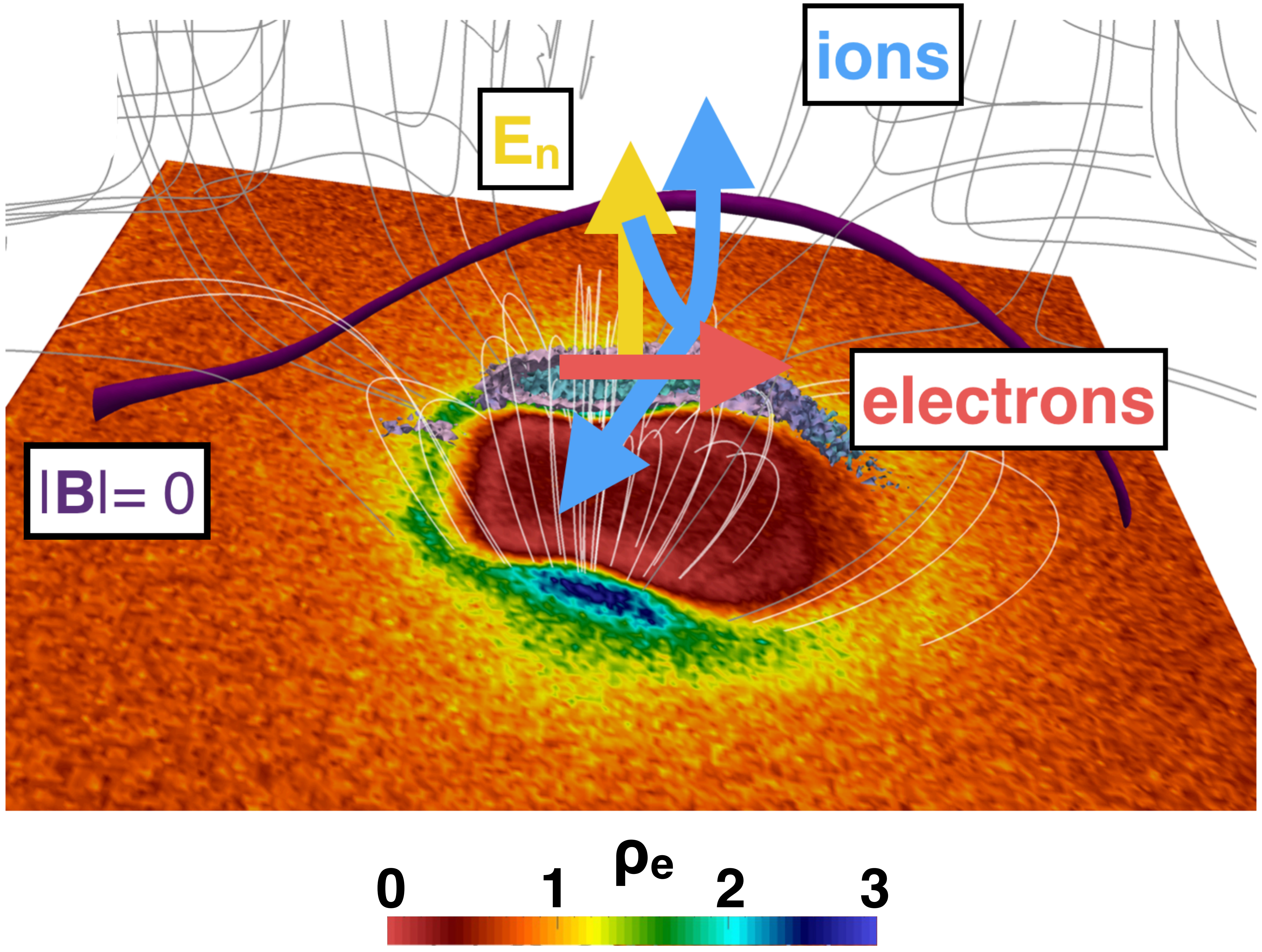


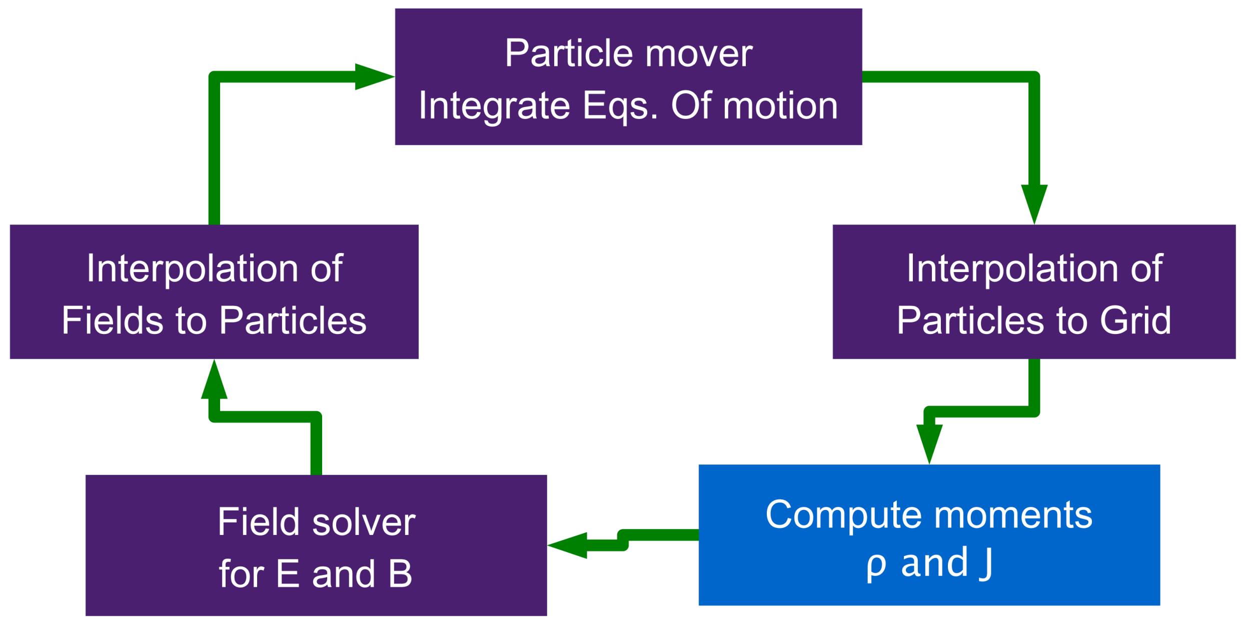
Plasma interaction with a dipole

$\mathcal{O}(10^3)$

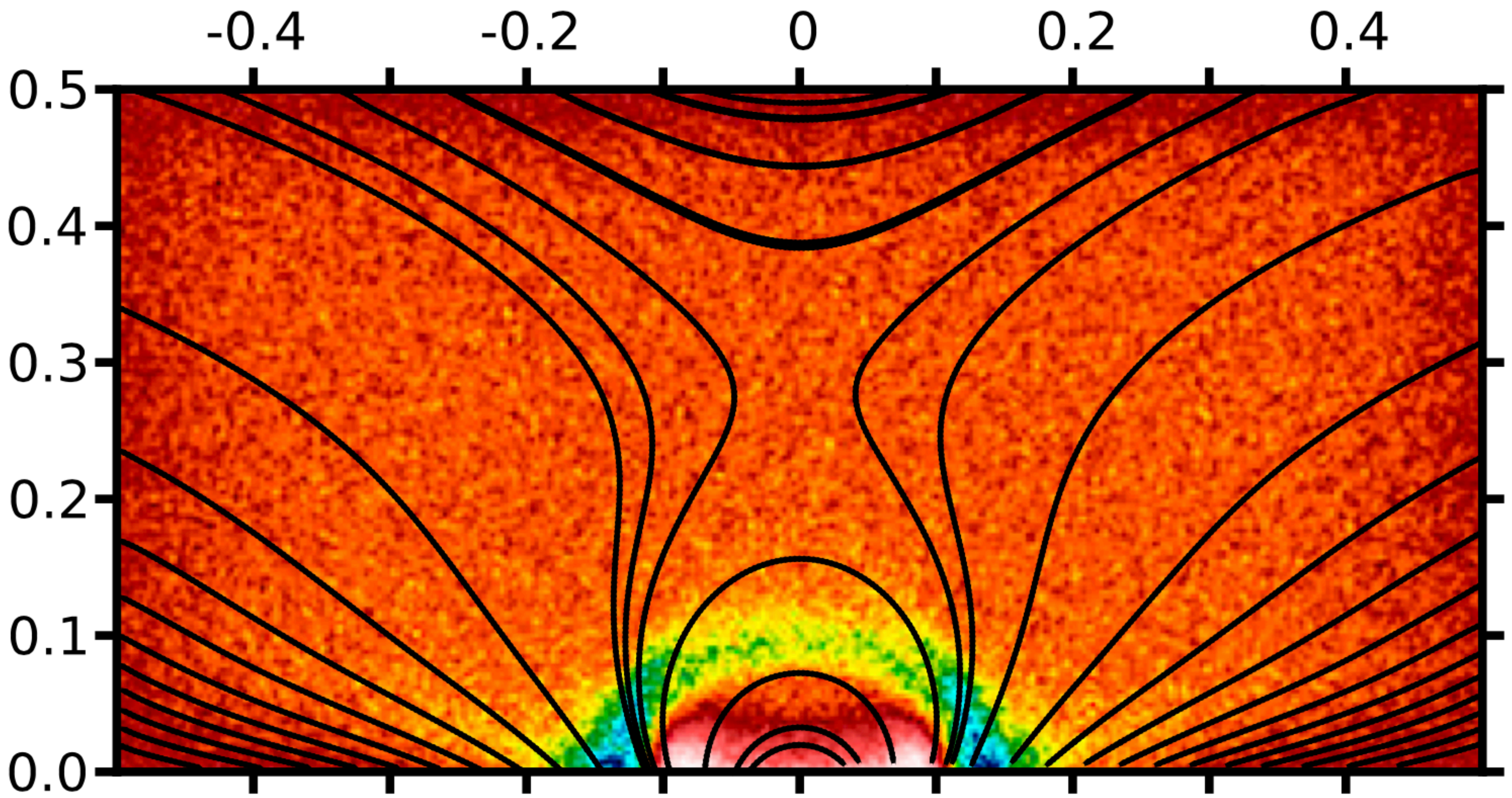
Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

- Mini-magnetosphere formation





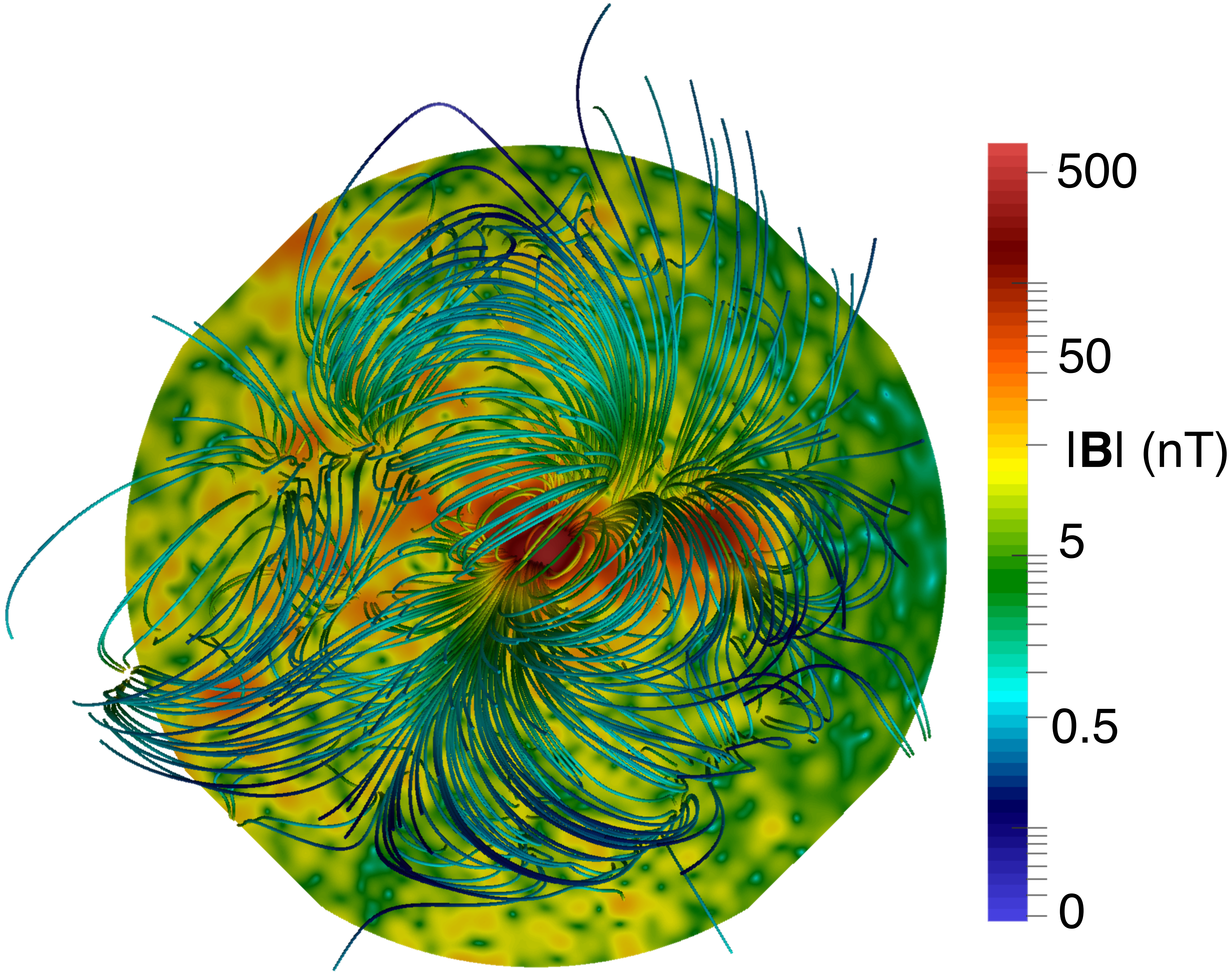
Semi-implicit PIC
+ Open boundaries
+ Magnetic field model
+ Surface interaction model
[Deca et al. (PRL 2014)]



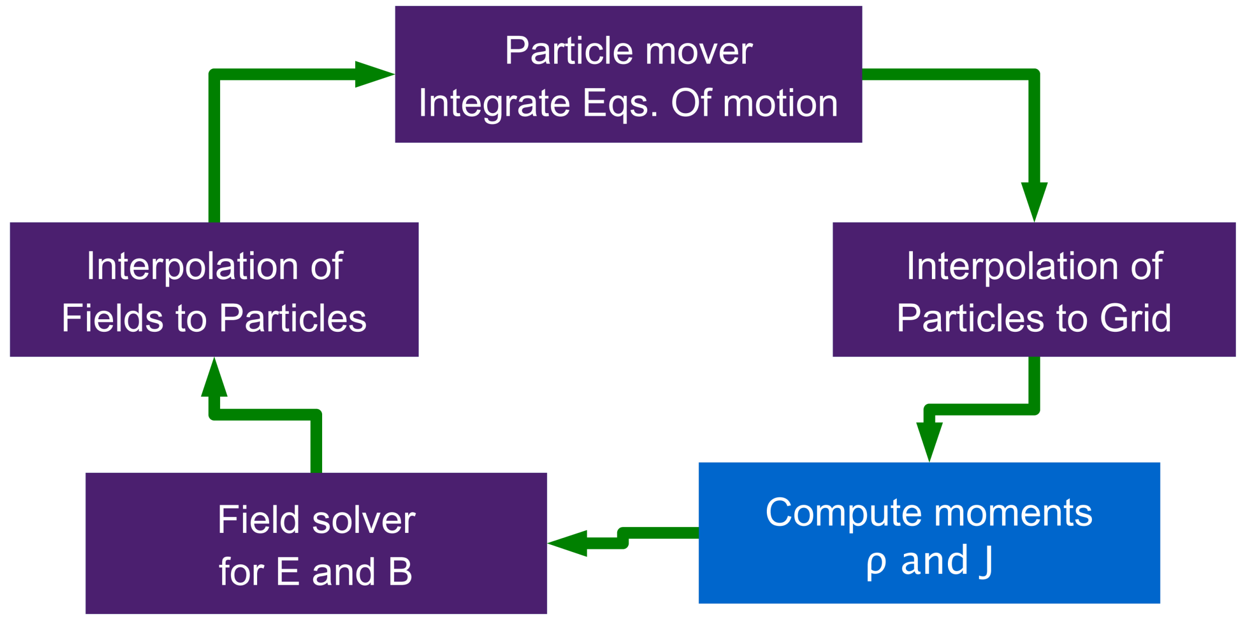
Solar wind interaction with Reiner Gamma

Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

- The Tsunakawa model.

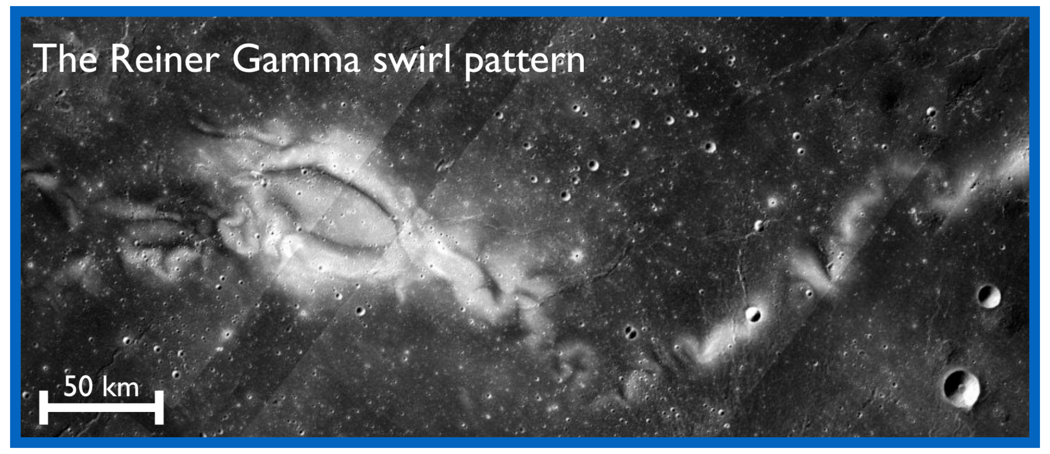


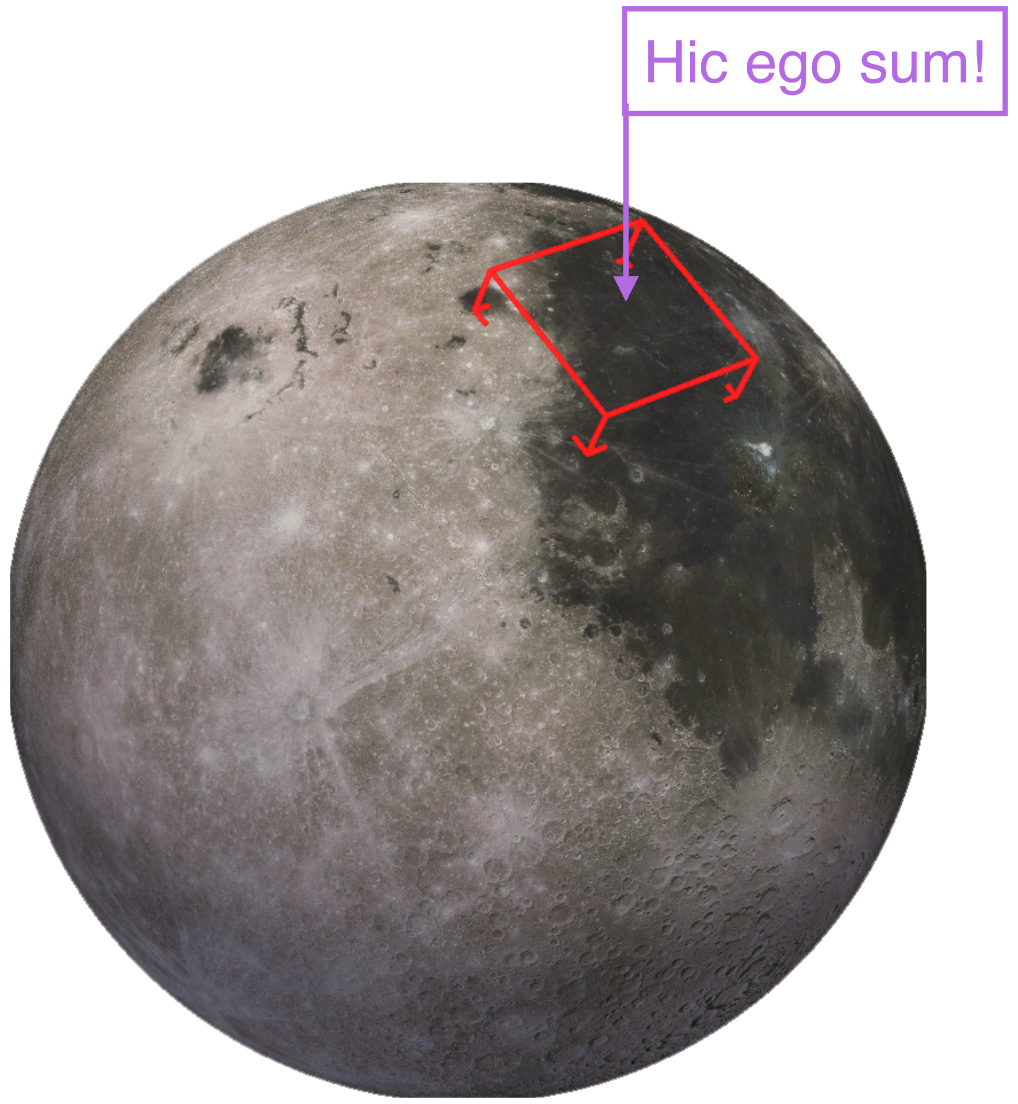
[Tsunakawa et al. (JGR 2015)]



Semi-implicit PIC

+ Open boundaries
+ Magnetic field model
+ Surface interaction model

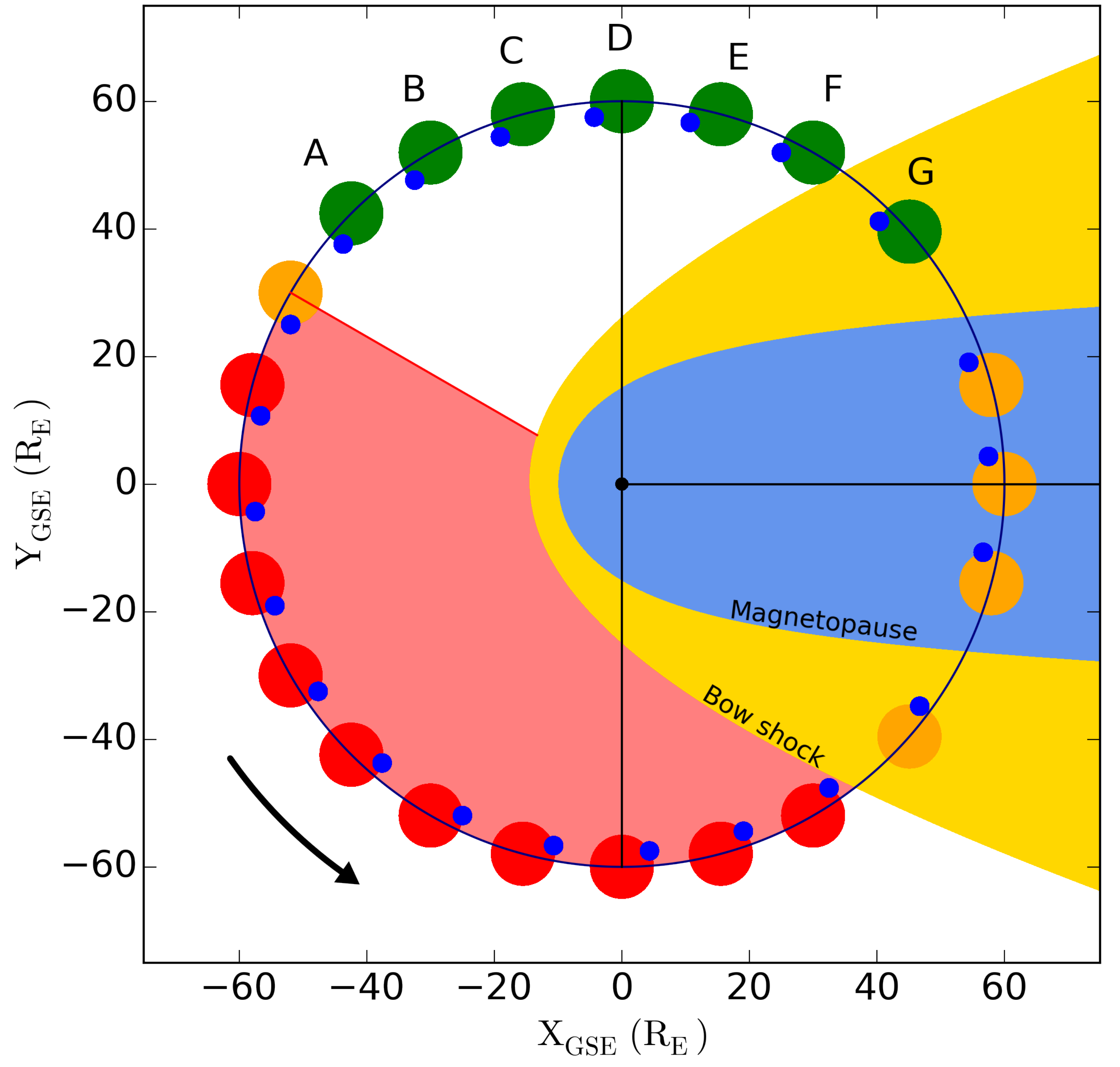


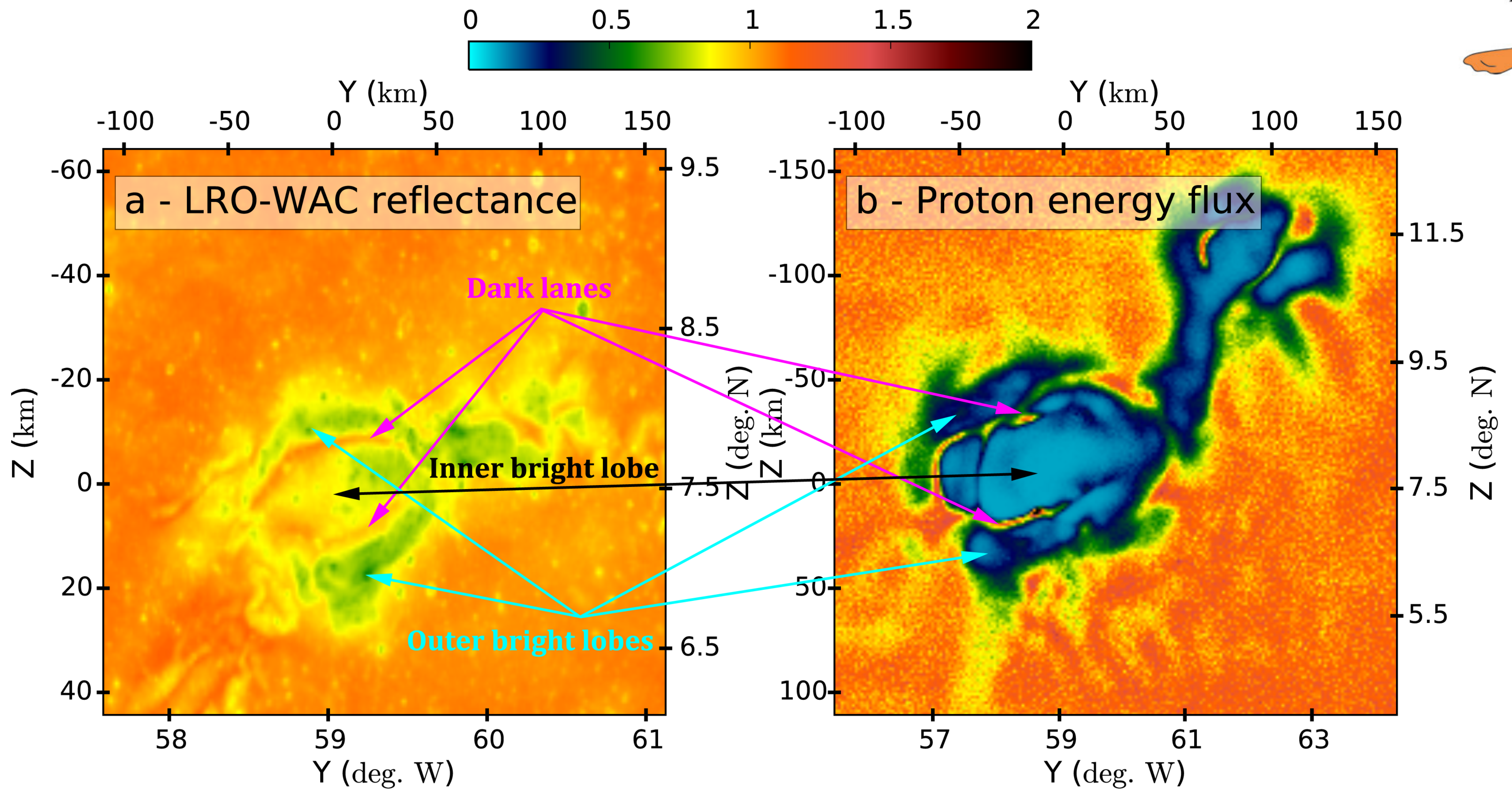


The long-term effect of solar wind standoff

Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

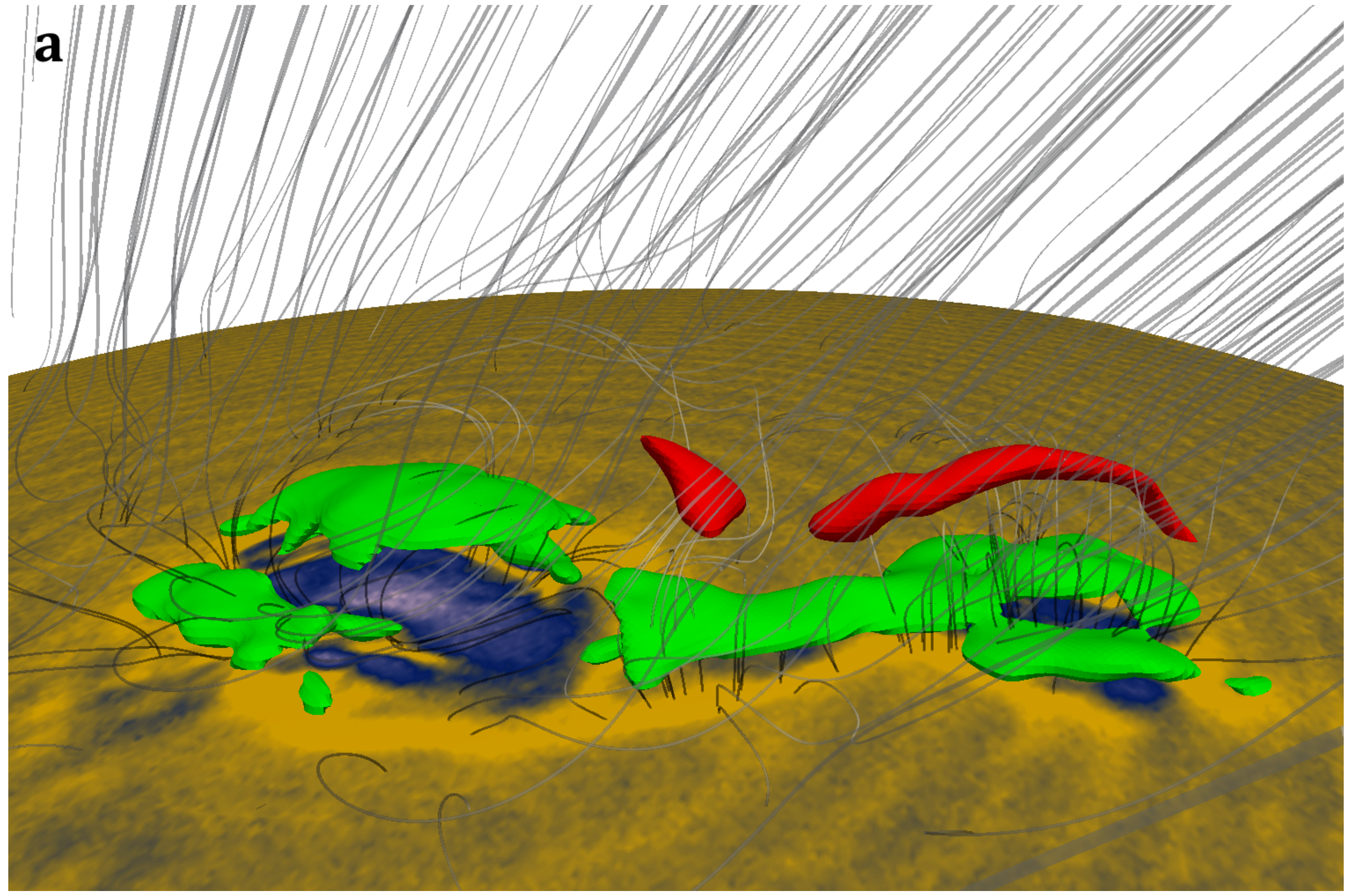
- Integrate over the lunar orbit.

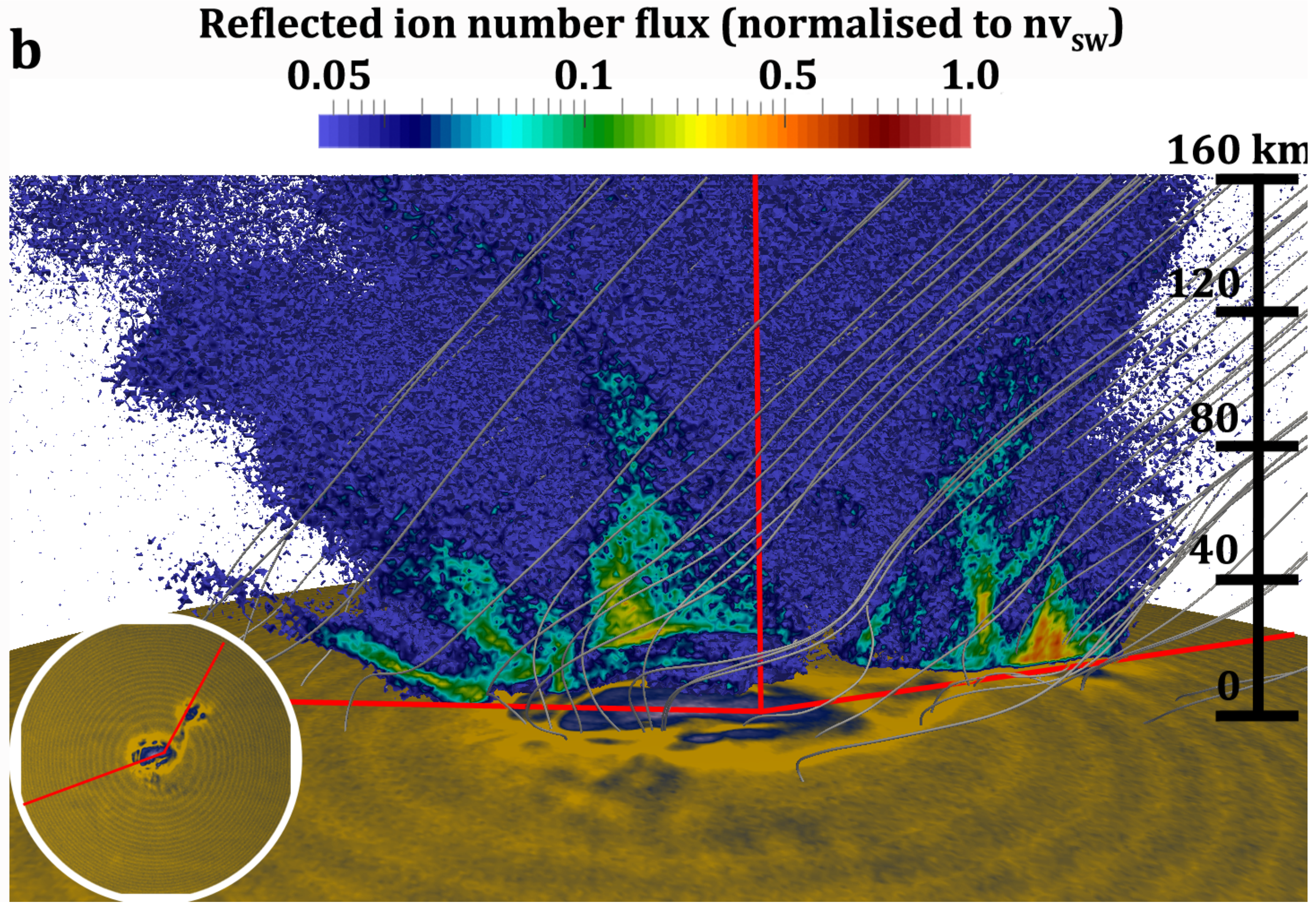


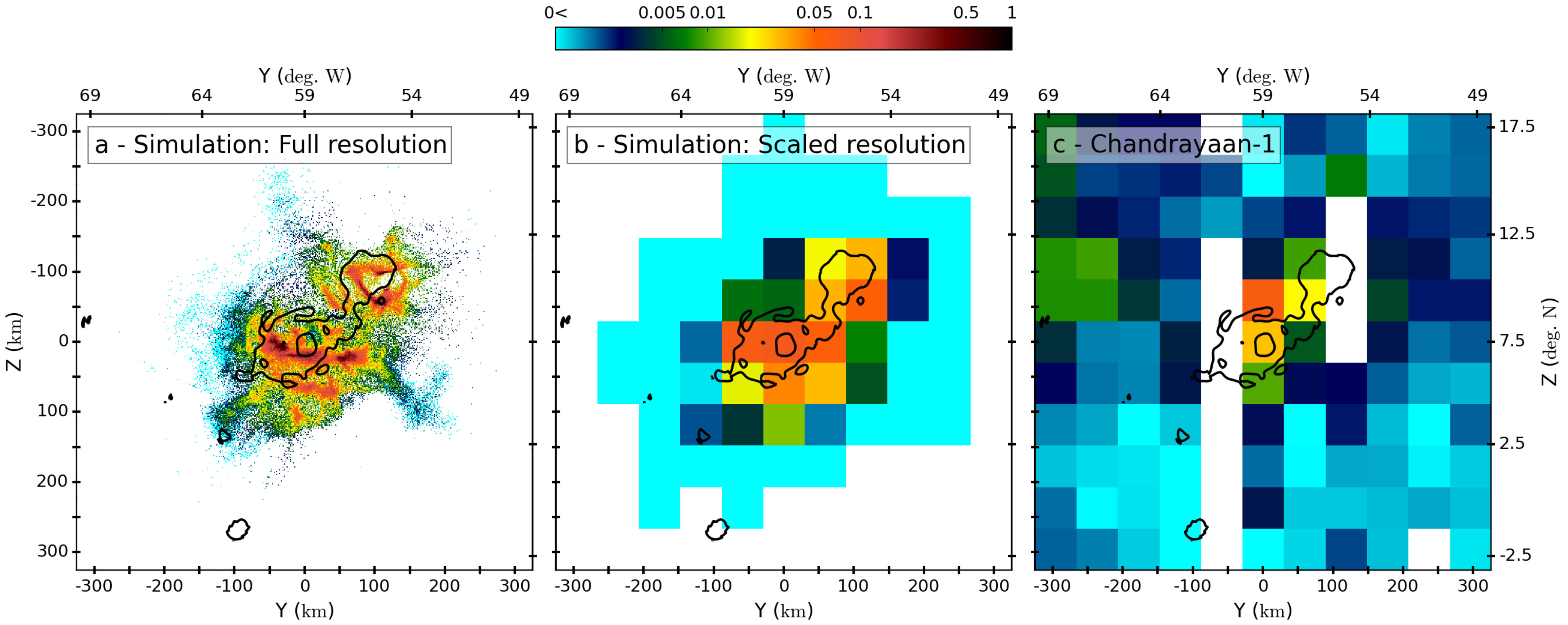


[Deca et al. (Nat. Comm. Phys. 2018; JGR 2020)]

Predict the presence and shape of the swirl pattern







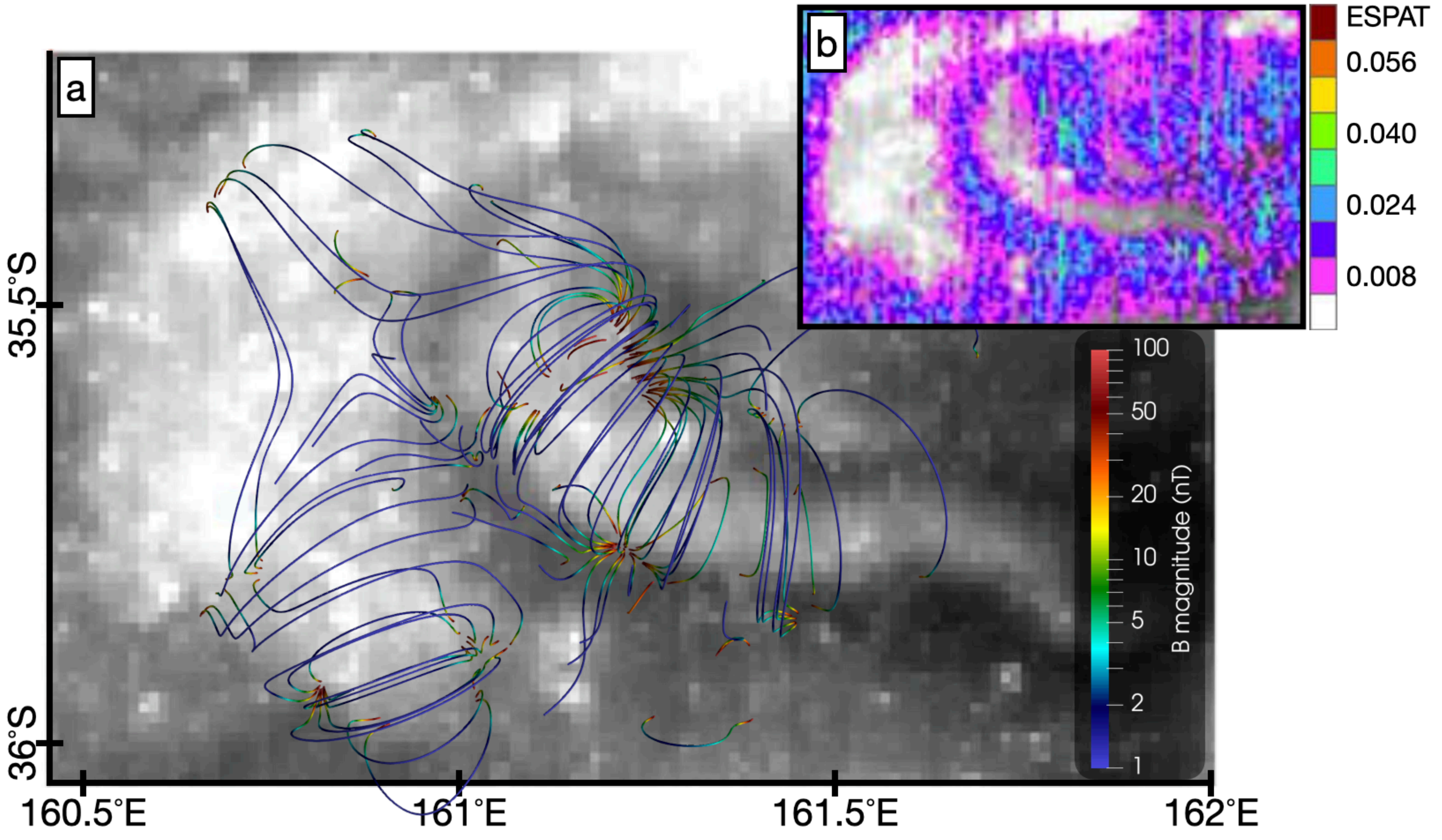
[Deca et al. (Nat. Comm. Phys. 2018; JGR 2020)]

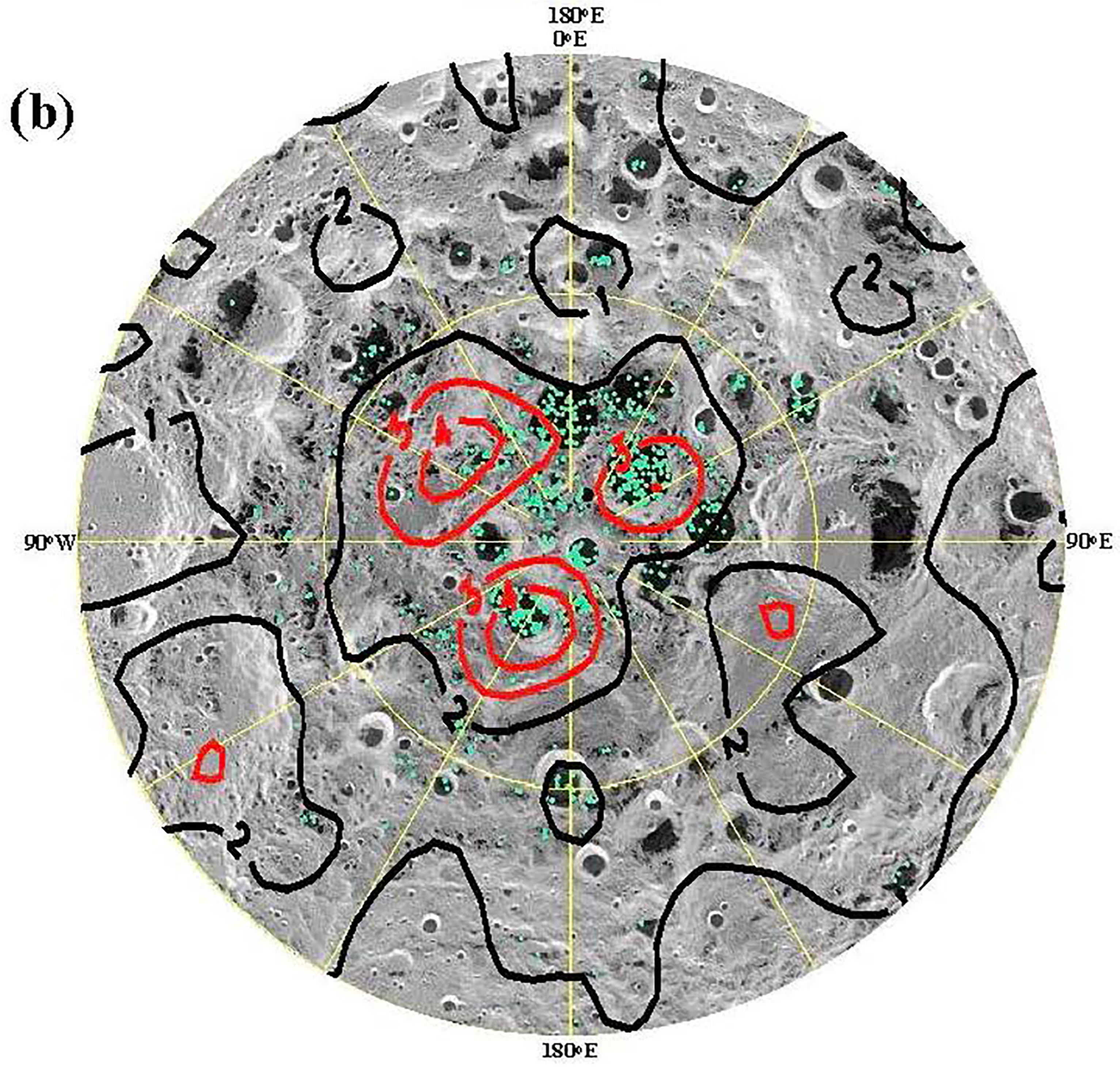
The charge separation electric field:
(a) explains why not all LMAs form a swirl,
(b) predicts the shape of the albedo pattern.

Water ice in the lunar polar regions

Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

- Current water ice lifetime models do not include the effects of lunar magnetic anomalies co-located with permanently shadowed regions.
- Proof of concept for Mare Ingenii:





Solar wind ion bombardment in the polar regions may be a dominant loss process rather than a supplier of water ice.

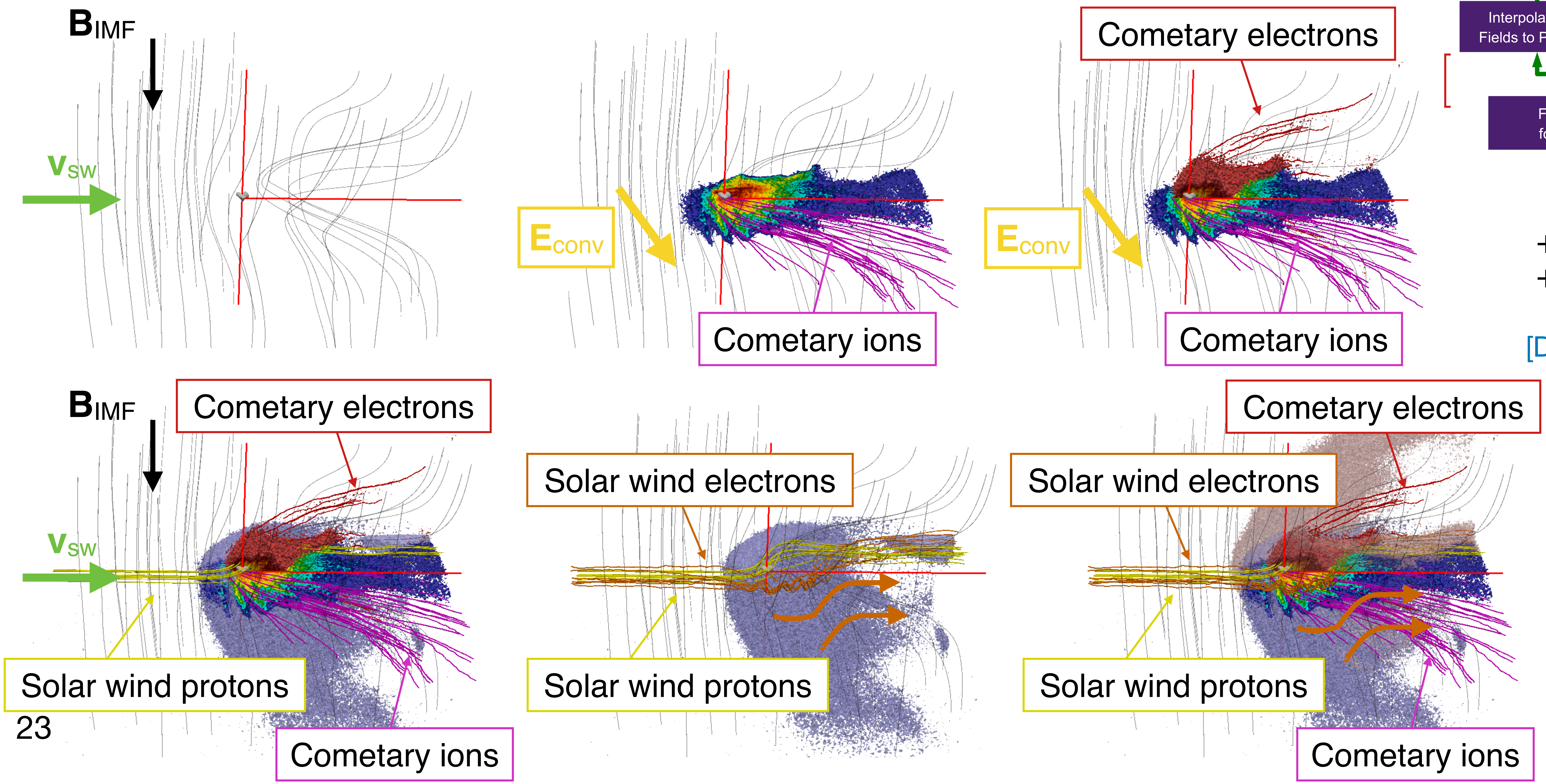
[Li&Milliken (Sci. Adv. 2017); Hood et al. (GRL 2022); Li&Garrick-Bethell (GRL 2019); Deca et al. (AGU 2024)]

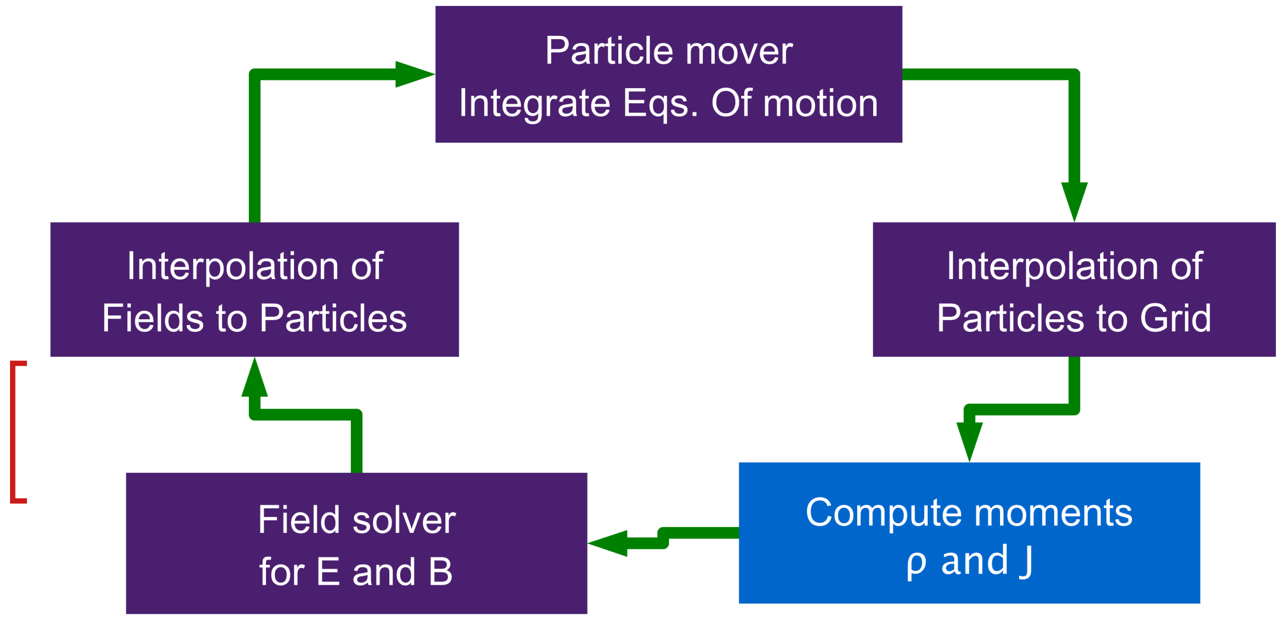
Solar wind interaction with comets (67P)

Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

$\mathcal{O}(8\cdot10^3)$

- The dynamics resembles that of a four-fluid coupled system.

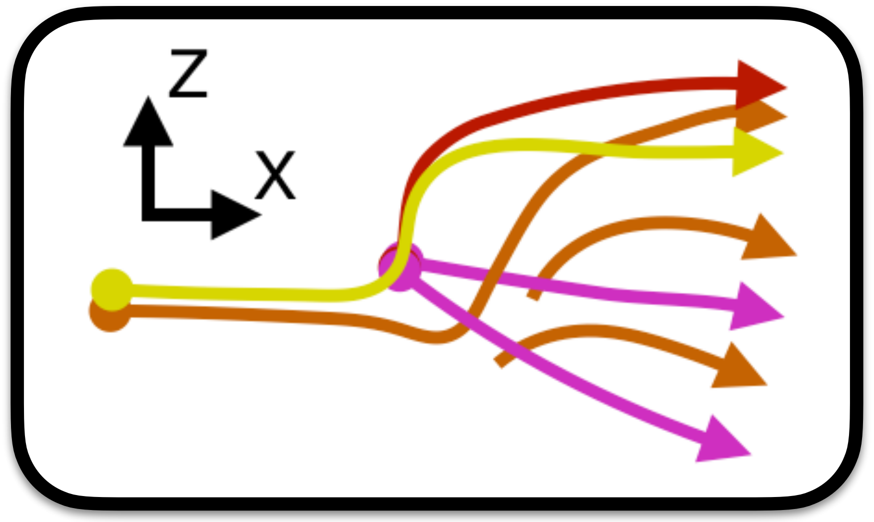




Semi-implicit PIC

+ Open boundaries
+ Cometary plasma injection model

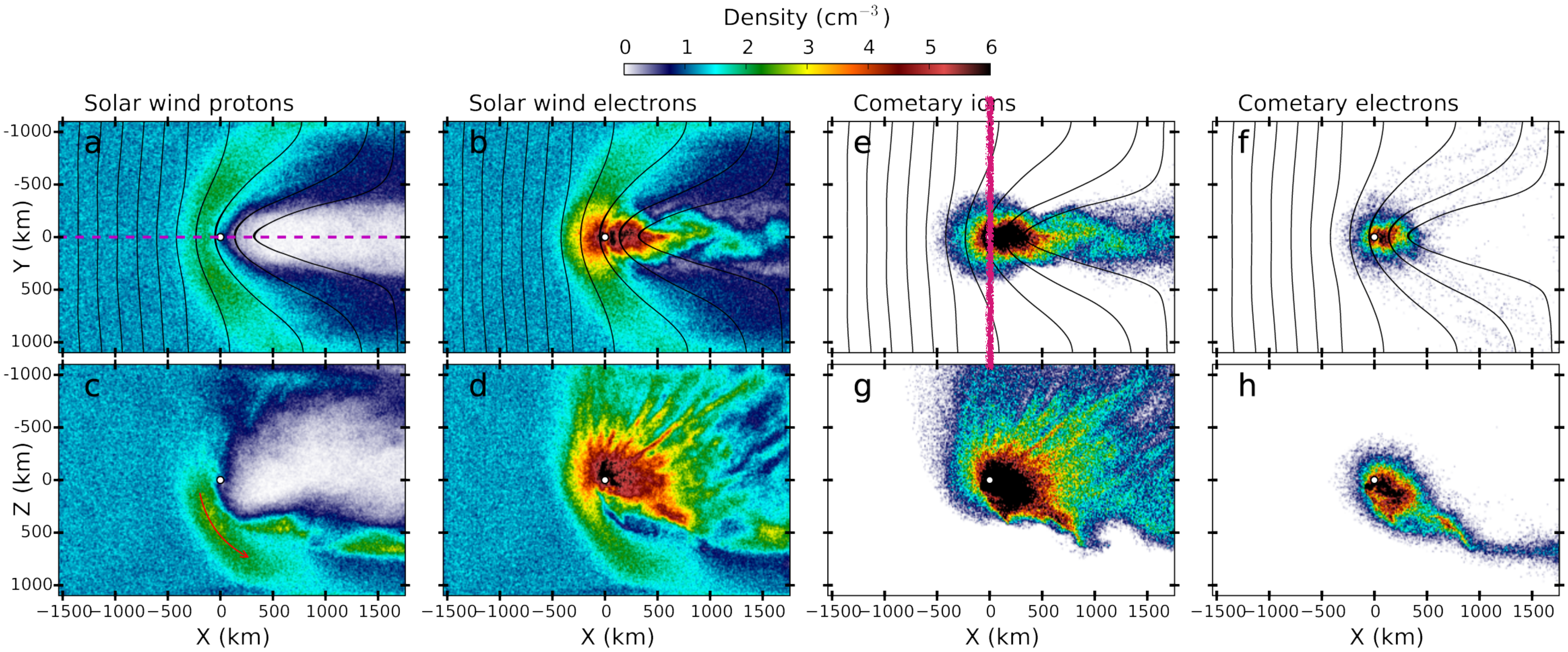
[Deca et al. (PRL 2017, 2019)]



Solar wind interaction with comets (67P)

Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

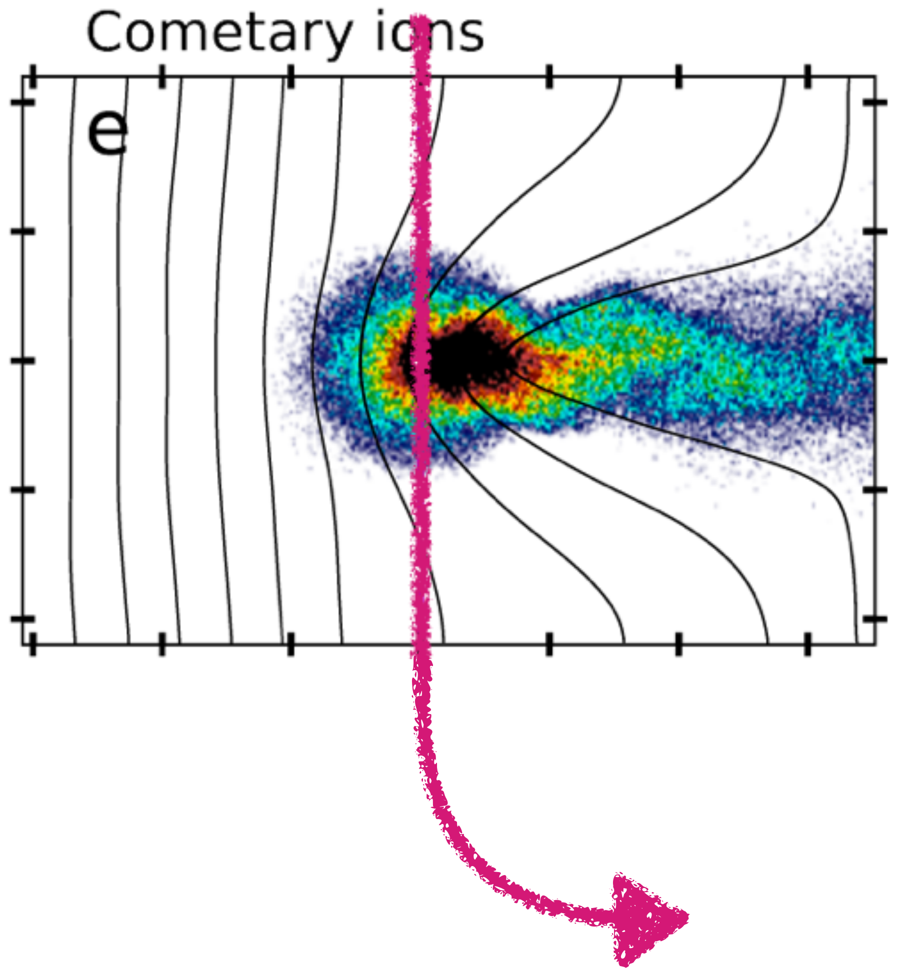
- Disentangle complex electron measurements from Rosetta.

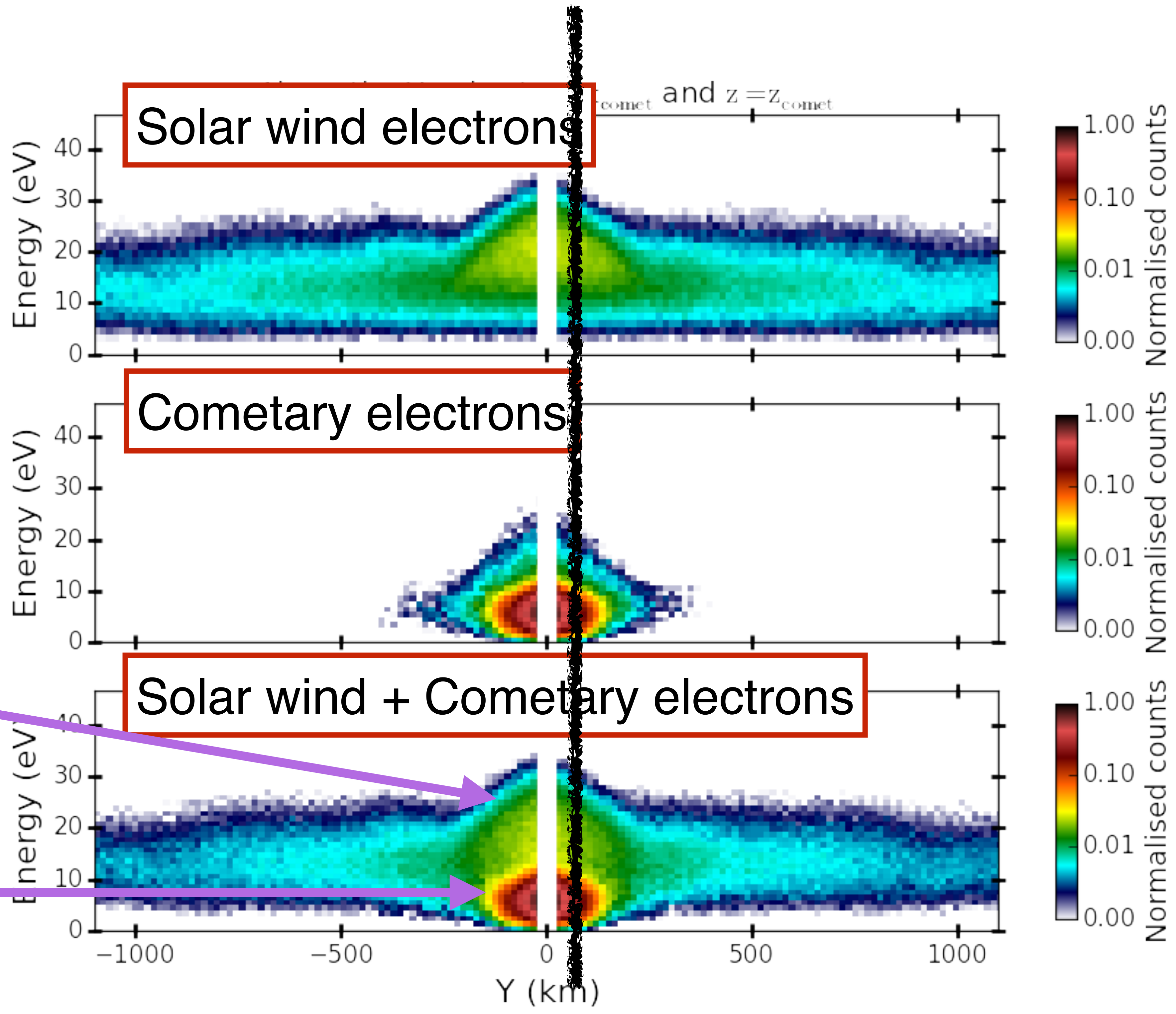


[Deca et al. PRL 2017]

Solar wind interaction with comets (67P)

- Disentangle complex electron measurements from Rosetta.

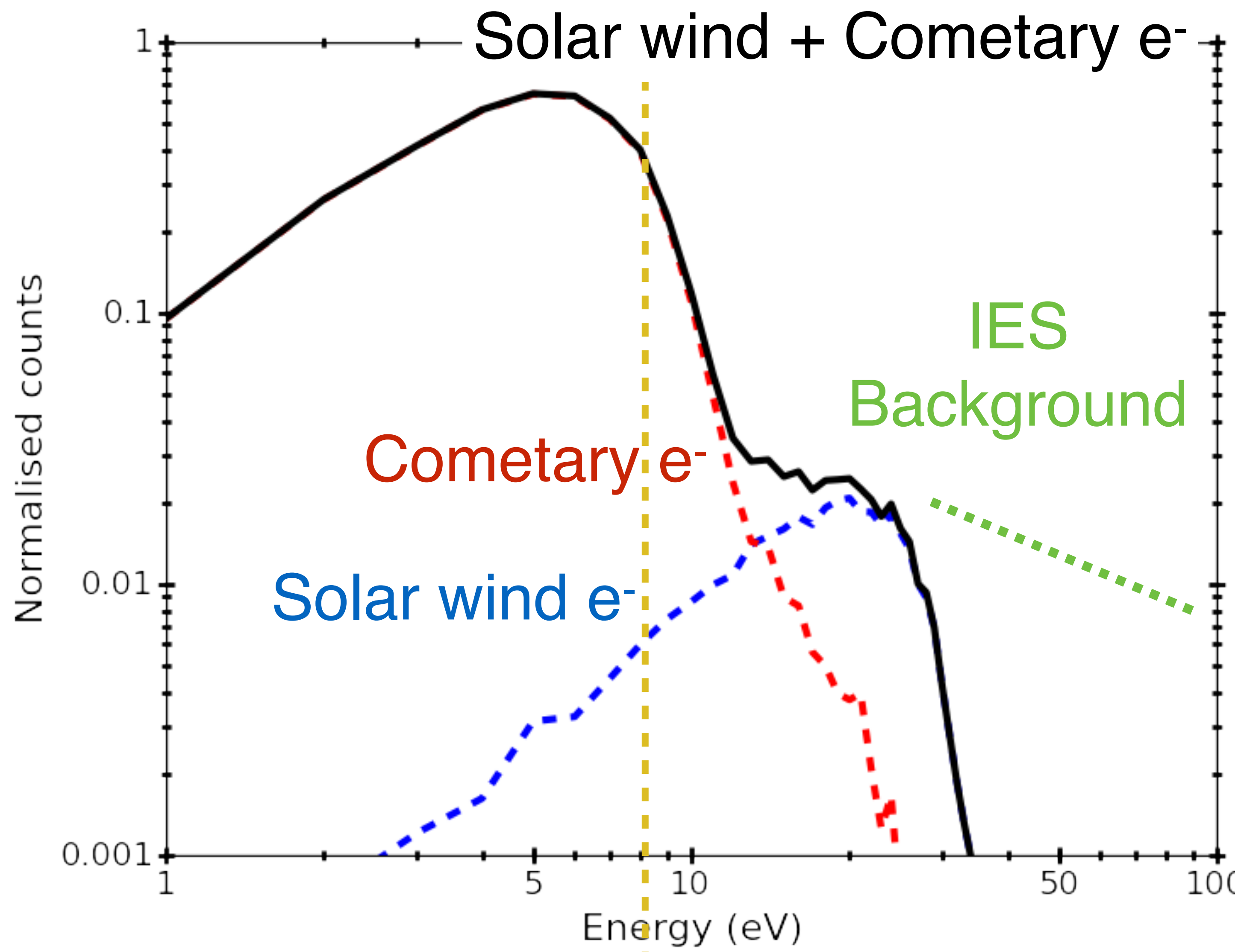


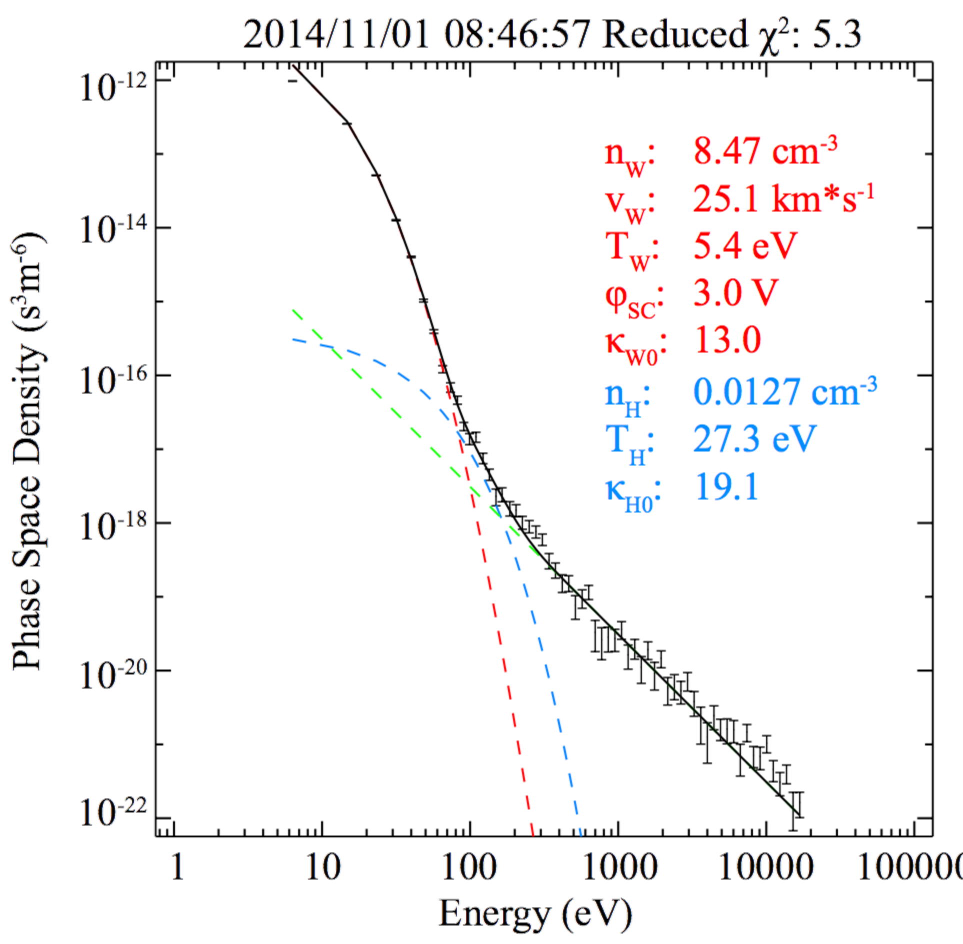


Suprathermal e-, solar wind origin.

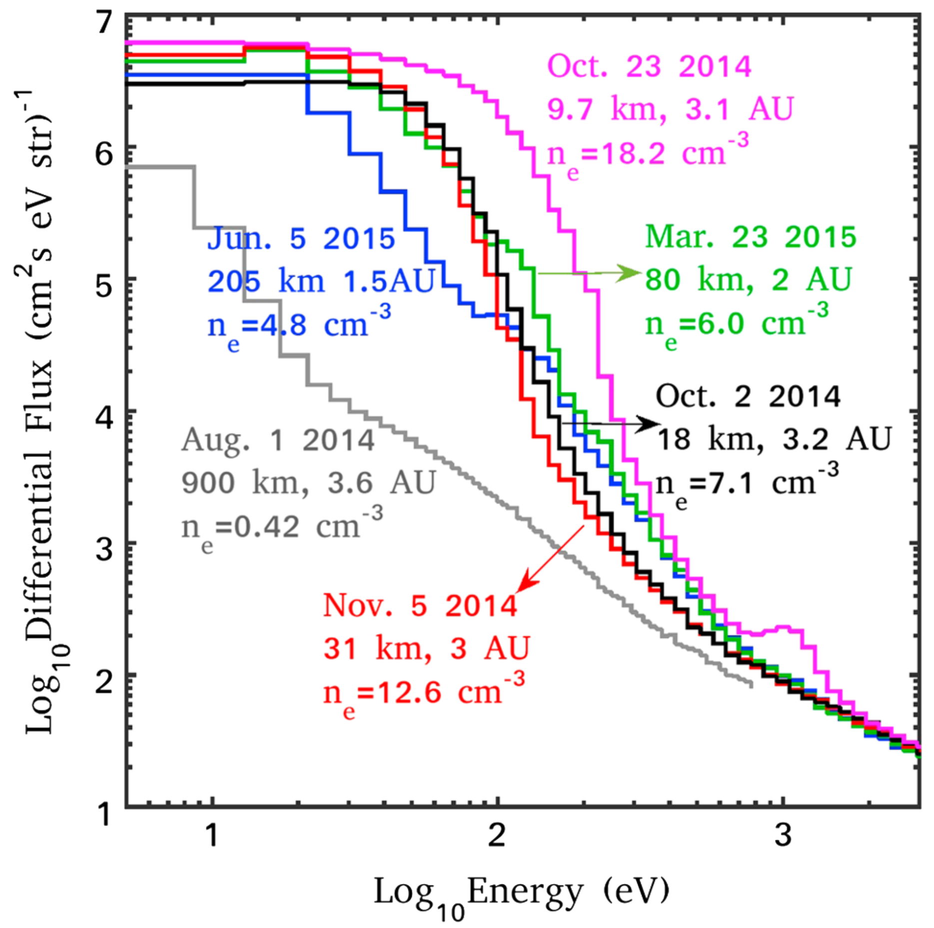
Warm e-, cometary origin.

[Deca et al. PRL 2017]





[Broiles et al. JGR 2016]



[Madanian et al. JGR 2016]

As observed by RPC-IES/ALICE/LAP/MIP.

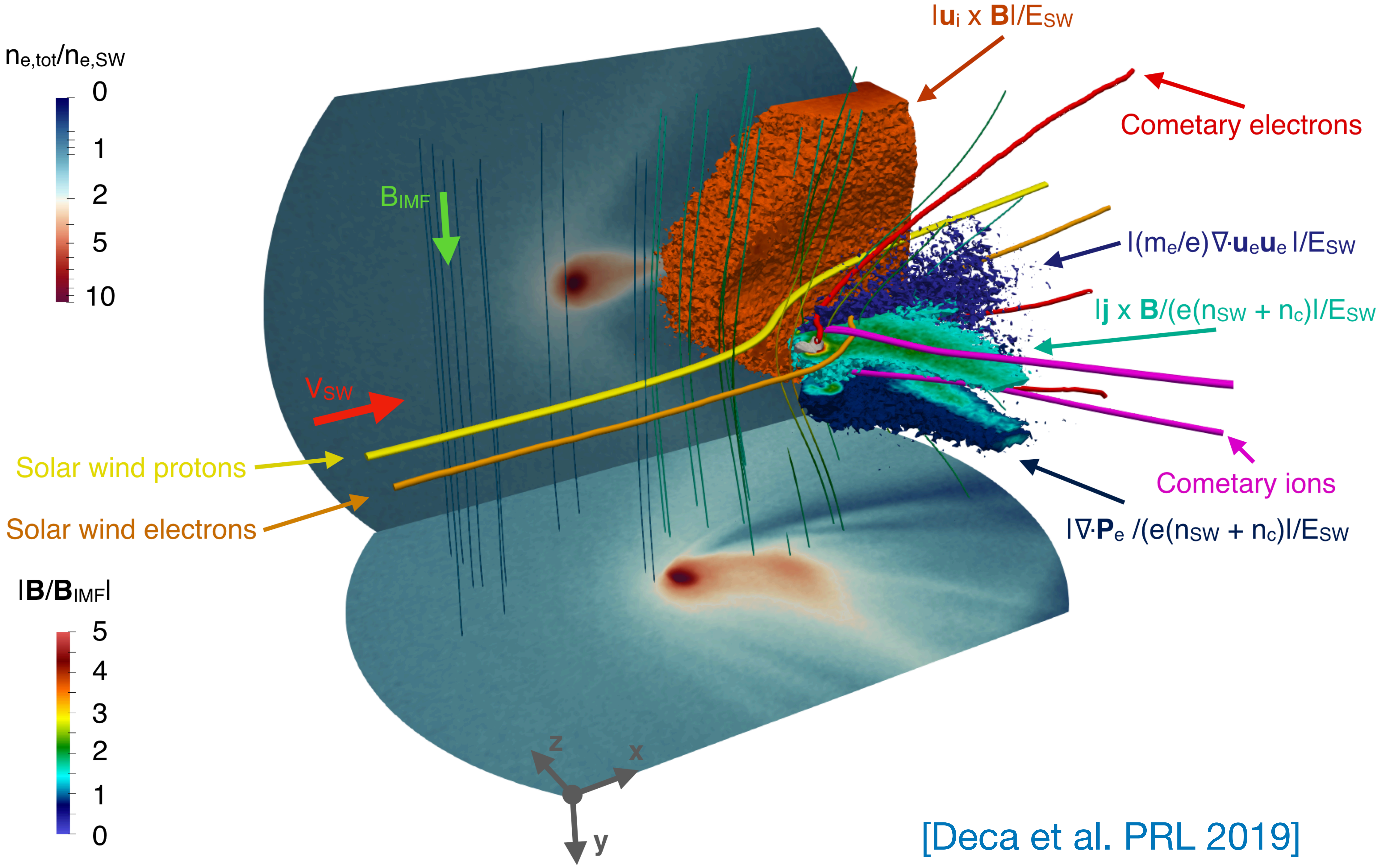
Solar wind interaction with comets (67P)

$\mathcal{O}(8{\cdot}10^3)$

- Advice non-fully kinetic simulation approaches on where reduced plasma models can be safely used.

- **Example**: generalized Ohm's law computed from particle data.

$$\mathbf{E} = -(\mathbf{u}_\mathrm{i} \times \mathbf{B}) + \frac{1}{en}(\mathbf{j} \times \mathbf{B}) - \frac{1}{en}\nabla \cdot \mathbf{\Pi}_\mathrm{e}$$

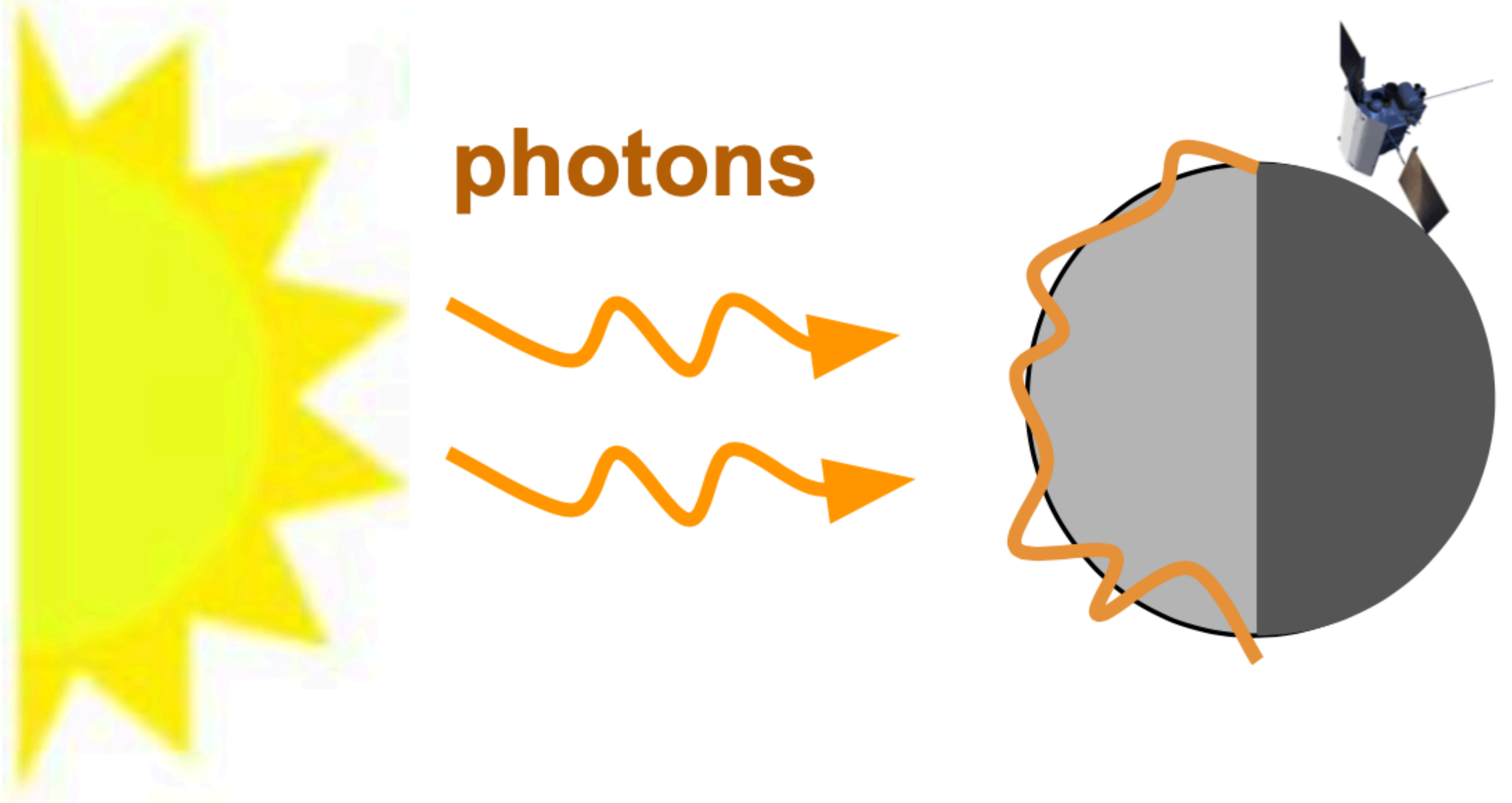


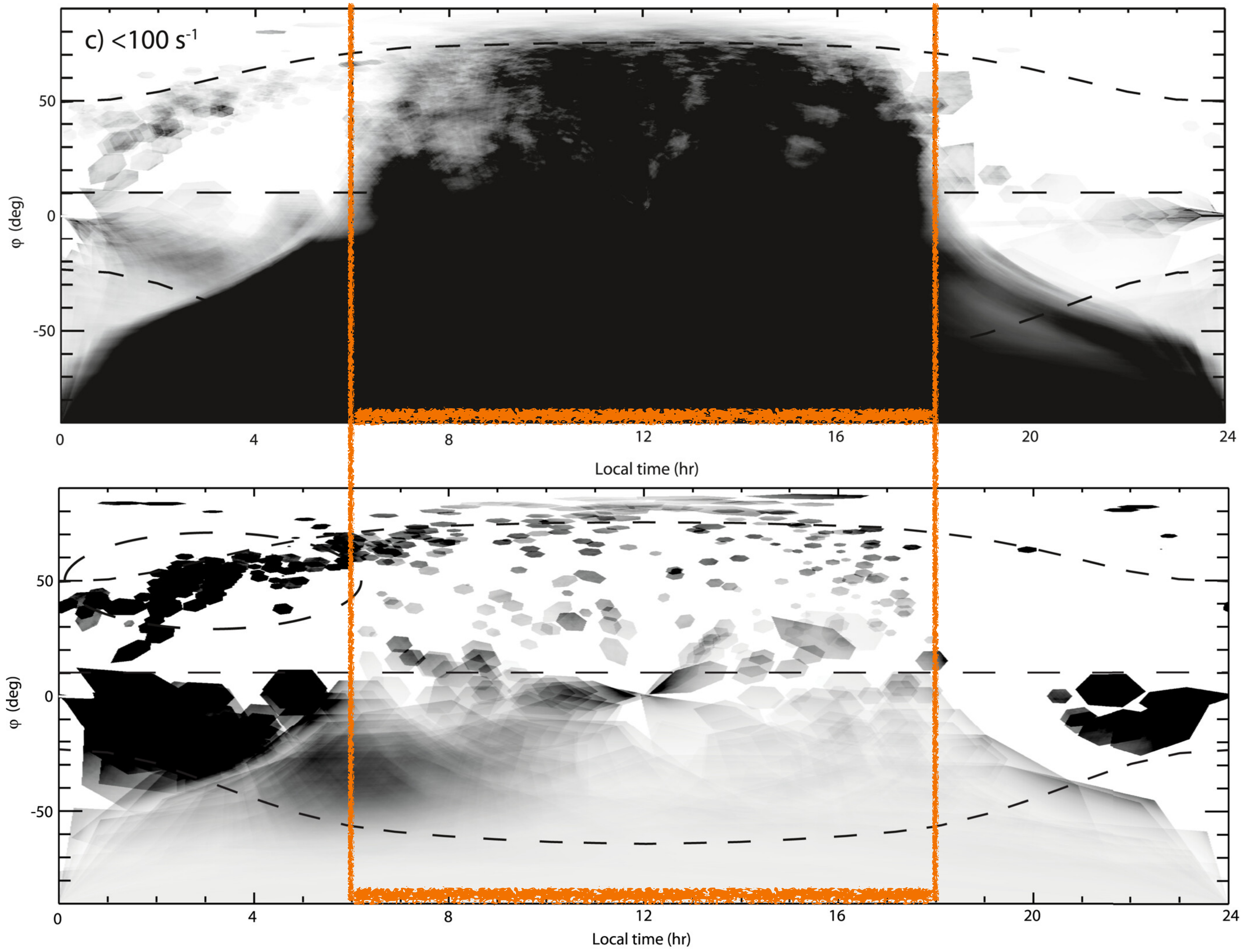
[Deca et al. PRL 2019]

Electron dynamics at Mercury

Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

- The lack of electron measurements at Mercury left many enigmas.





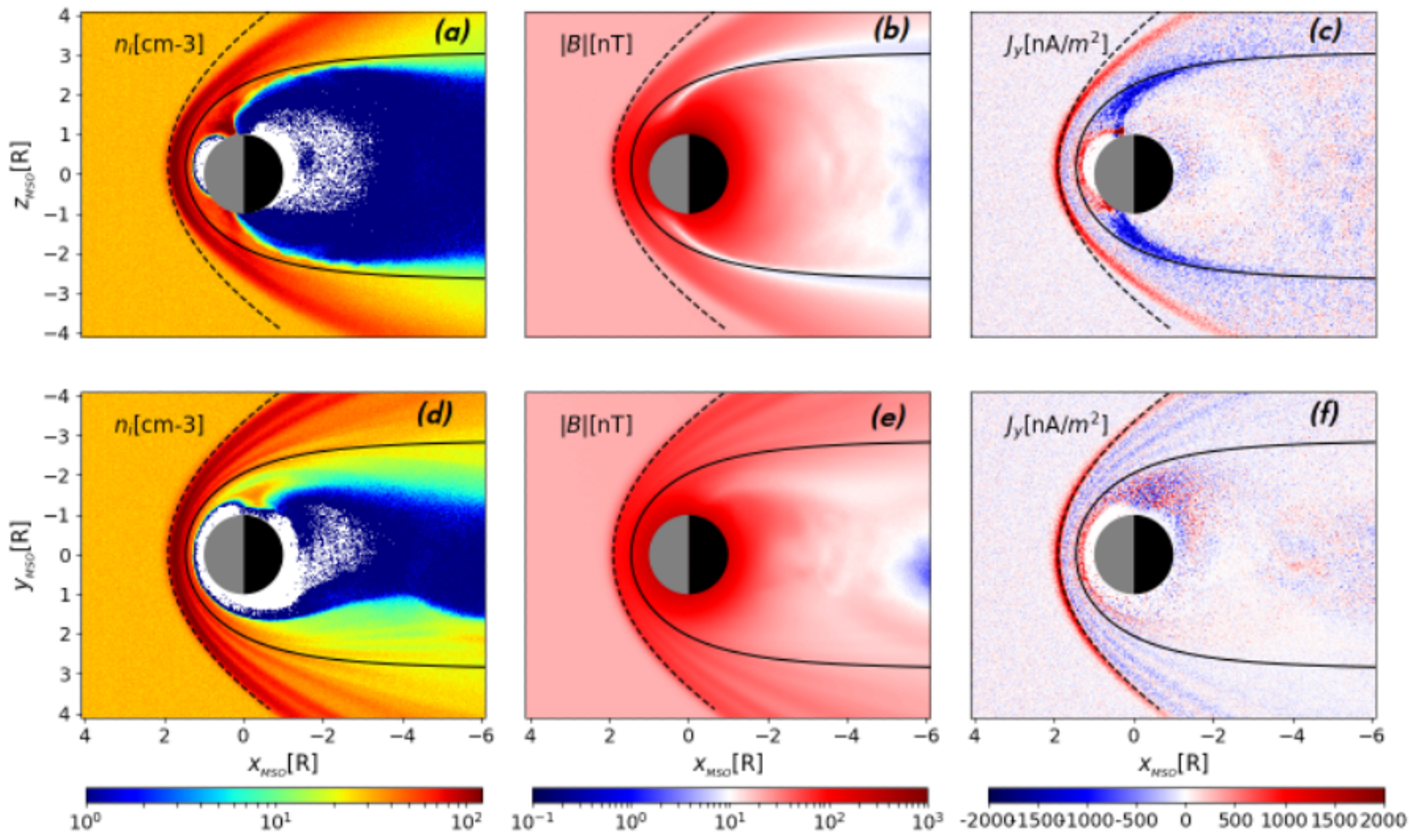
MESSENGER/XRS
[Lindsay et al. JGR 2022]

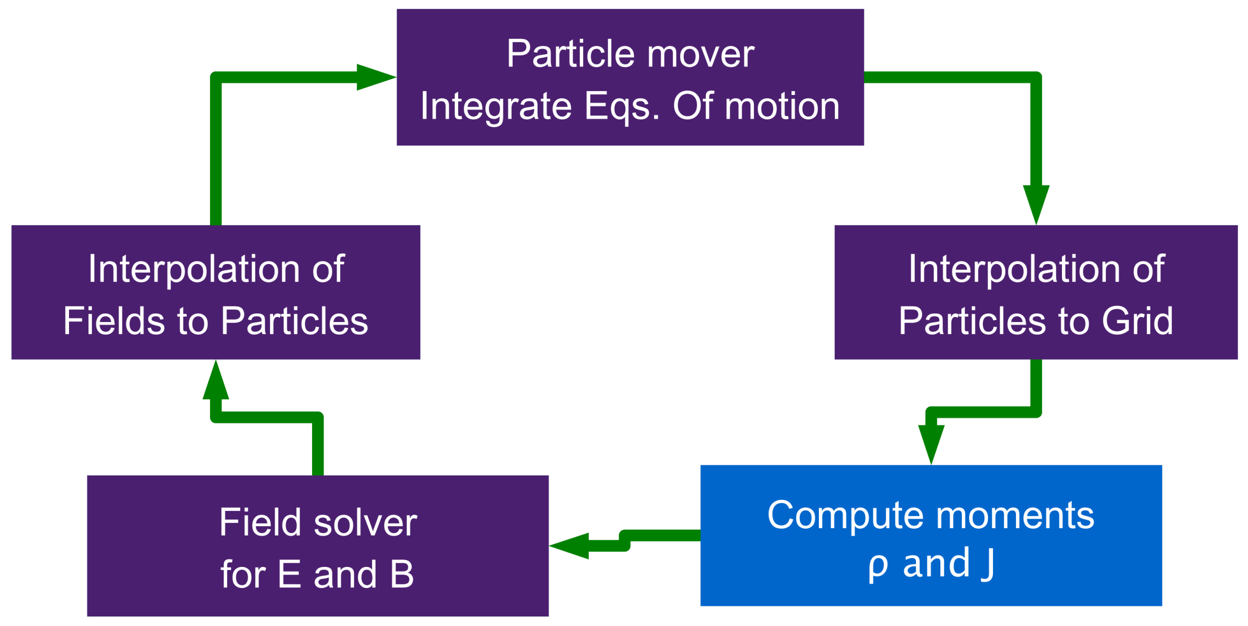
Electron dynamics at Mercury

$\mathcal{O}(3\cdot10^4)$

Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

- Simulation overview for northward IMF.



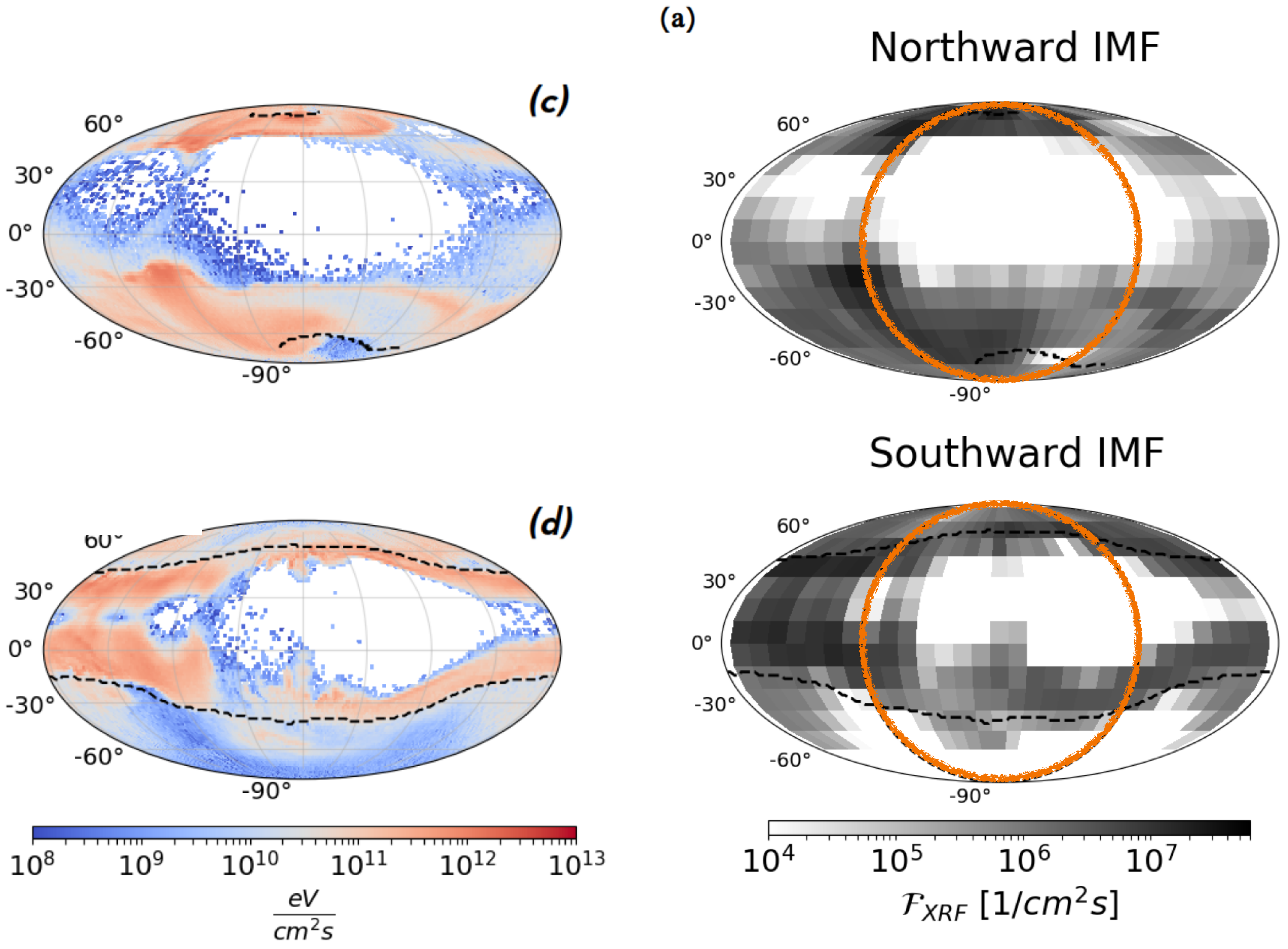


Semi-implicit PIC
+ Open boundaries
+ Magnetic field model
+ Exosphere model

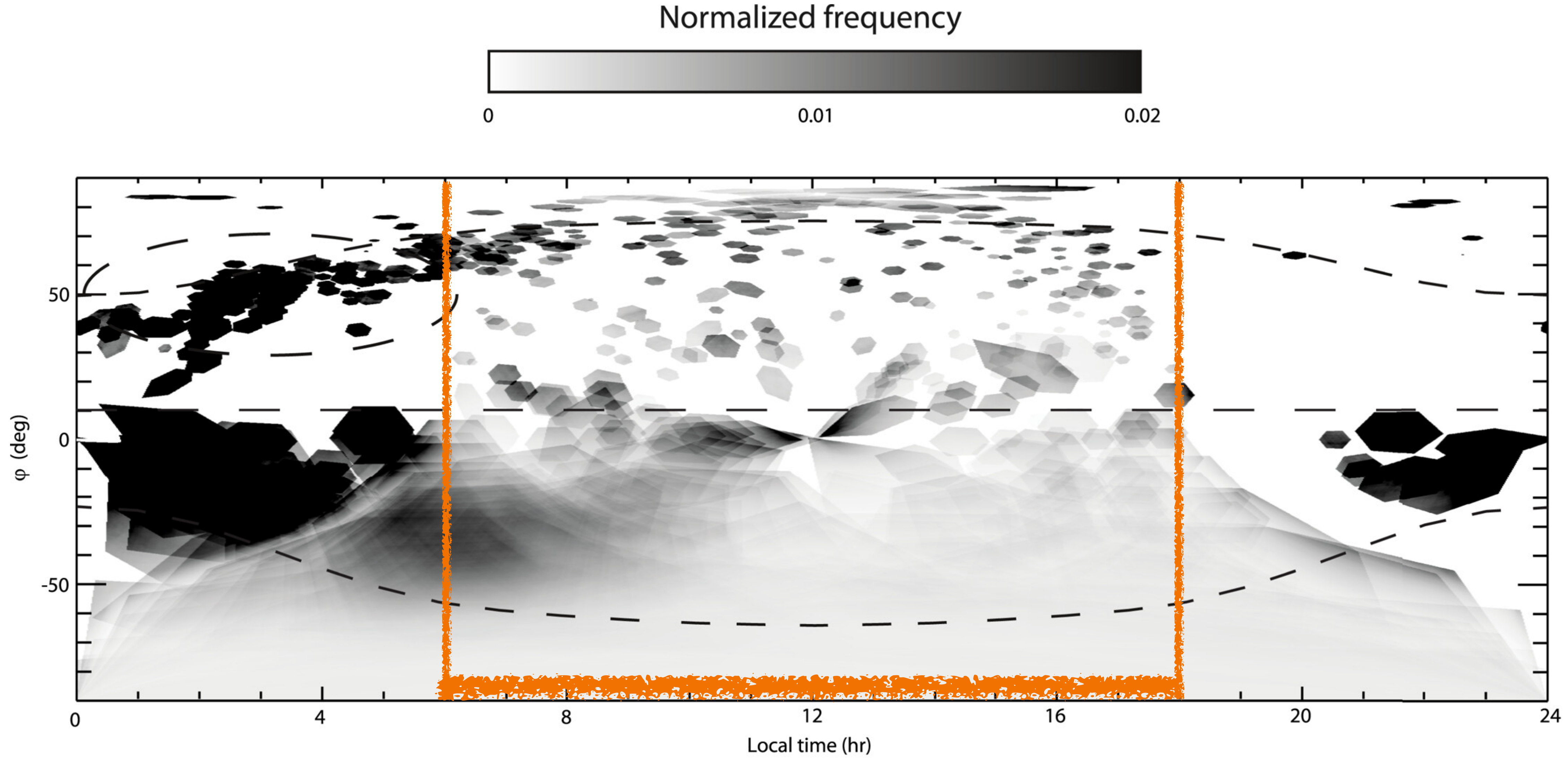
[Lavorenti et al. (A&A 2023)]

Electron dynamics at Mercury

- Electron precipitation drives the emission of X-rays



[Lavorenti et al. (A&A 2023)]



MESSENGER/XRS
[Lindsay et al. JGR 2022]

Take-aways

Simulations are fun, use them!

Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

- Local electron dynamics shapes the global structure of a system.

Dust - Comets - Lunar magnetic anomalies - Magnetospheres

- Fully kinetic models can help interpret complex plasma measurements from a basic physics point of view.

- “If you have a problem, if no one else can help, and if you can find them…
maybe you can try the **A** (kinetic modeling) **Team**.”

Thank you for your attention!

(What happens when you push the red button? - No clue…)