Space & Planetary Physics | Lancaster University

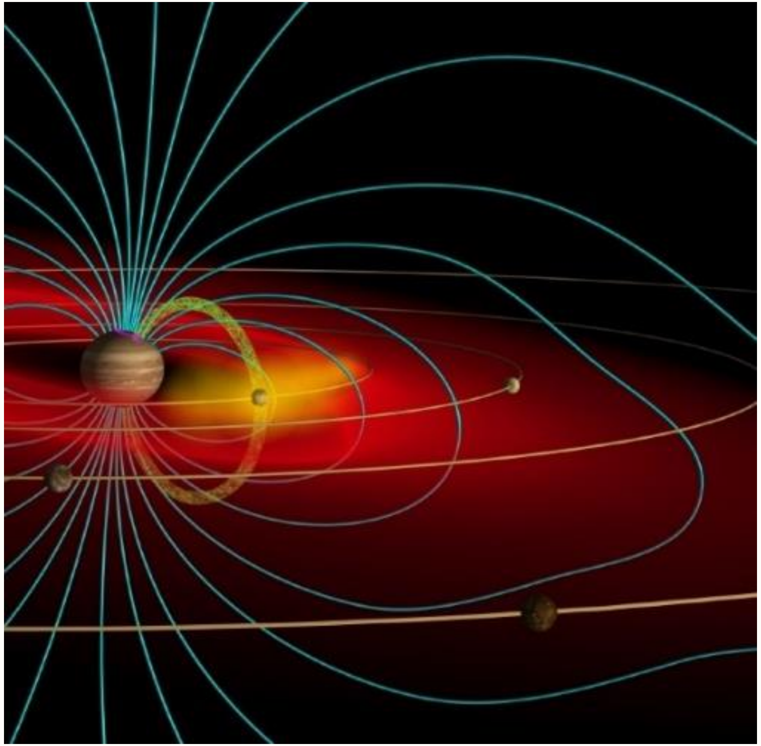
JERICHO: a Kinetic-Ion, Fluid-Electron Hybrid Plasma Model for the Outer Planets

8th October 2021

Josh A. Wiggs & C. S. Arridge
Department of Physics, Lancaster University, Lancaster, LA1 4YB, UK

j.wiggs@lancaster.ac.uk JAWiggs JoshWiggs

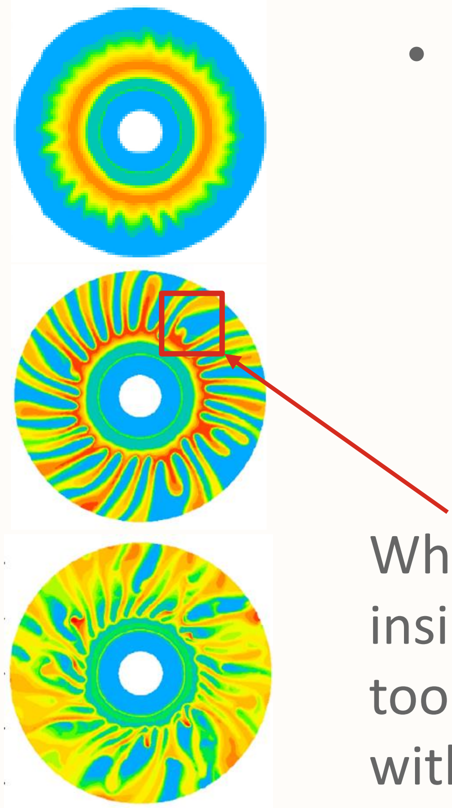
The Jovian Magnetosphere



Credit: J. Spencer

- Jupiter's inner magnetosphere is loaded with plasma associated with the volcanic moon Io
- Magnetosphere is deformed into a magnetodisk by internal plasma sources & centrifugal forces
- Plasma forms a torus at Io's orbital distance and loses a proportion via radial transport

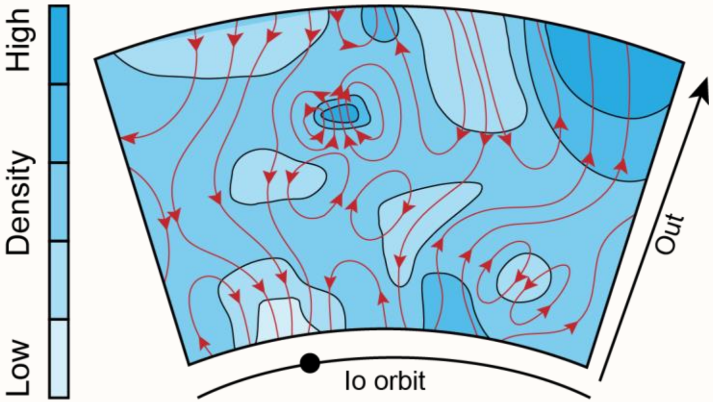
Radial Transport



Liu et al, 2010

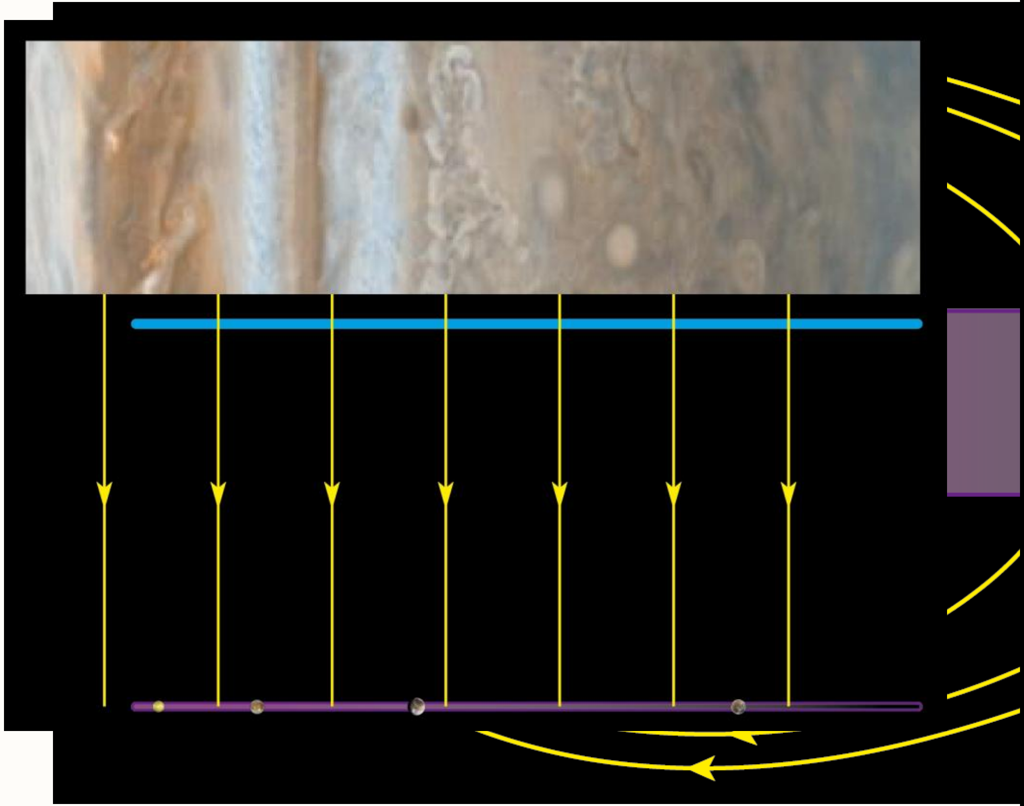
- Various models for transporting plasma from near Io to the outer magnetosphere
  - Diffusive gradients
  - Large-scale 'interchange fingers'

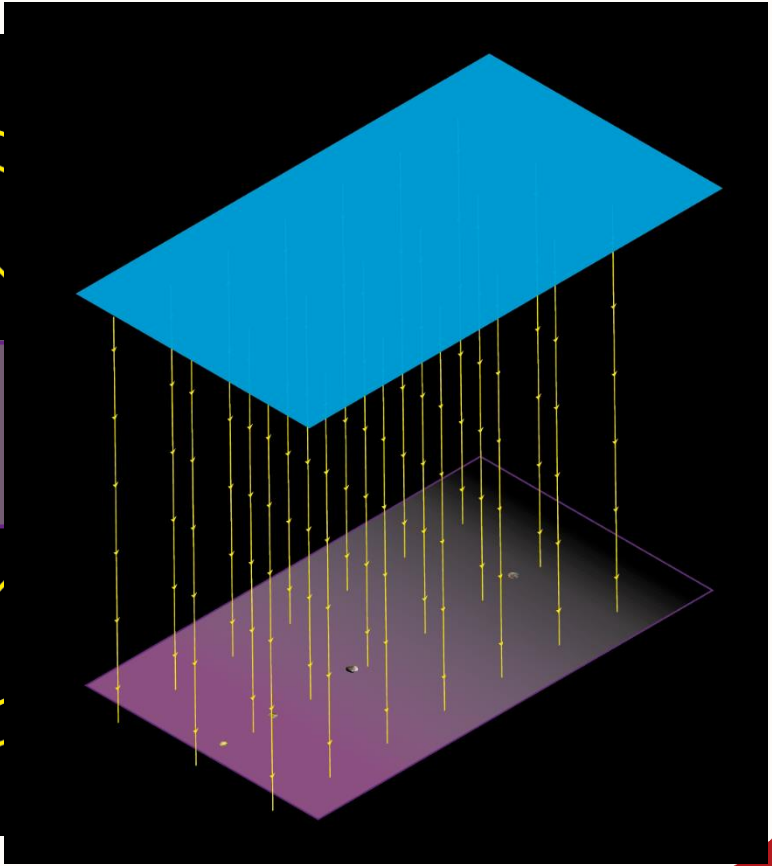
What's happening inside here? Region is too small to probe with current state-of-the-art



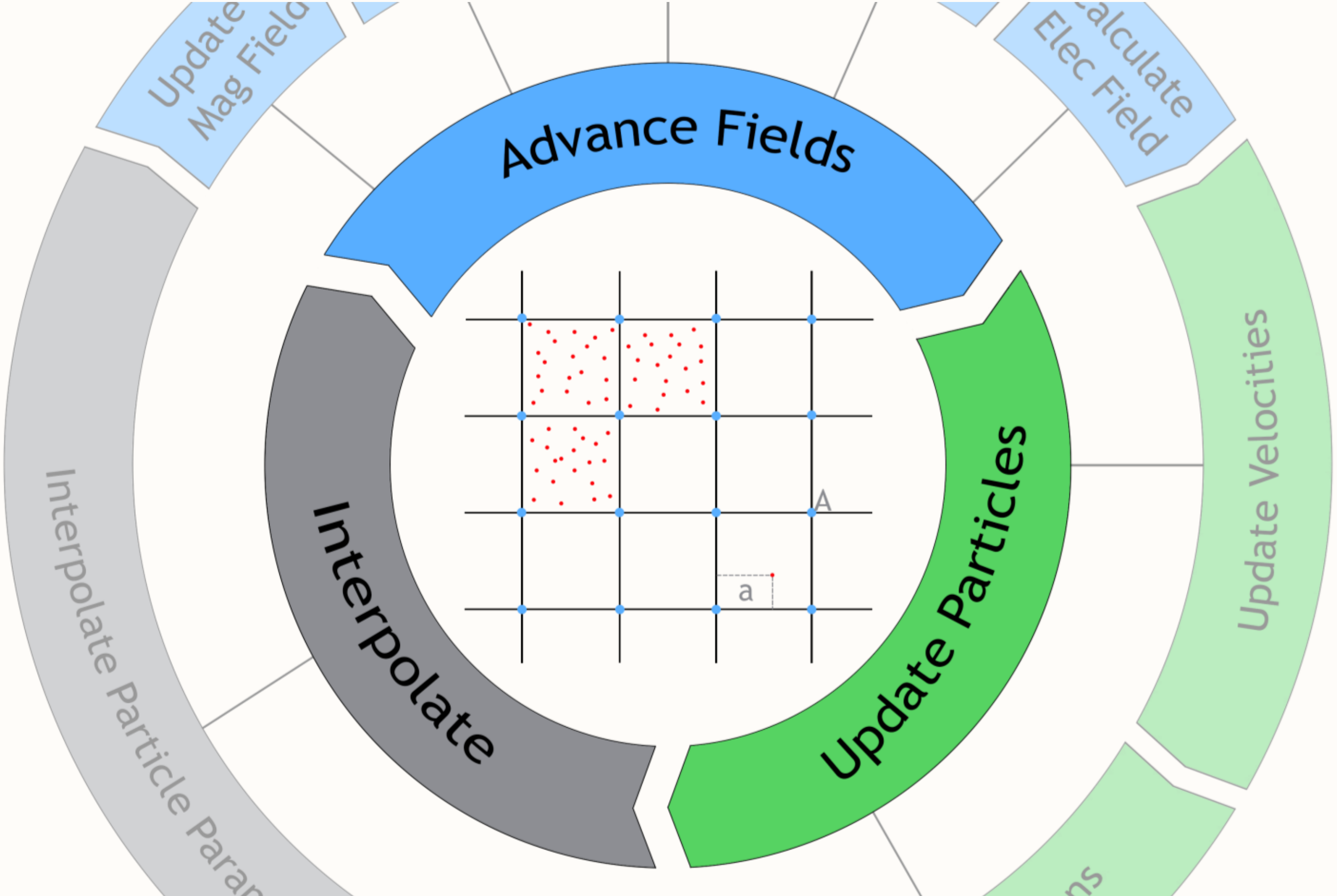
After: Southwood & Kivelson, 1989

Geometry –
What is 2.5D?



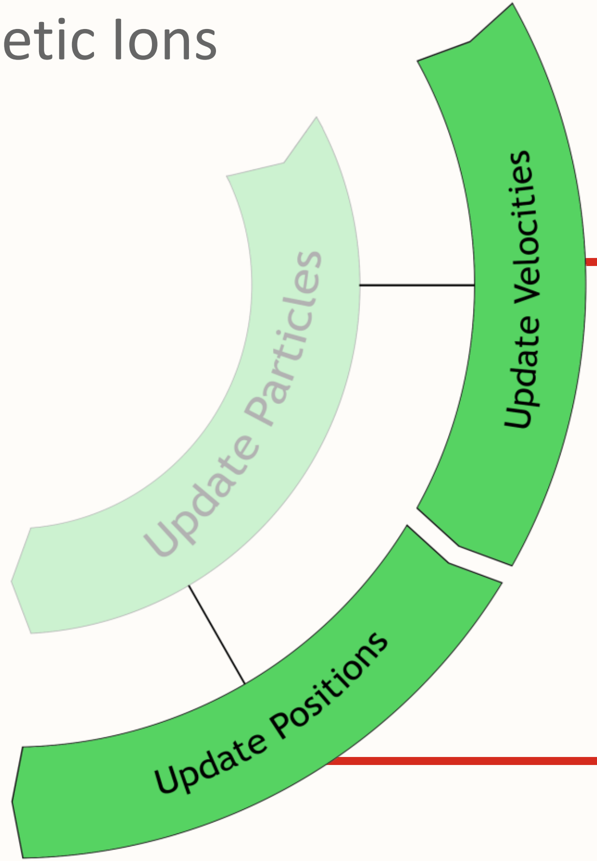


JERICHO – Kinetic Ion, Fluid Electron



JERICHO – Particle Numerics

Kinetic Ions



Lorentz

$$\frac{d\underline{v}}{dt} = \frac{q}{m}(\underline{E} + \underline{v} \times \underline{B}) - \underline{\Omega} \times (\underline{\Omega} \times \underline{x}) - 2\underline{\Omega} \times \underline{v}$$

Centrifugal　　Coriolis

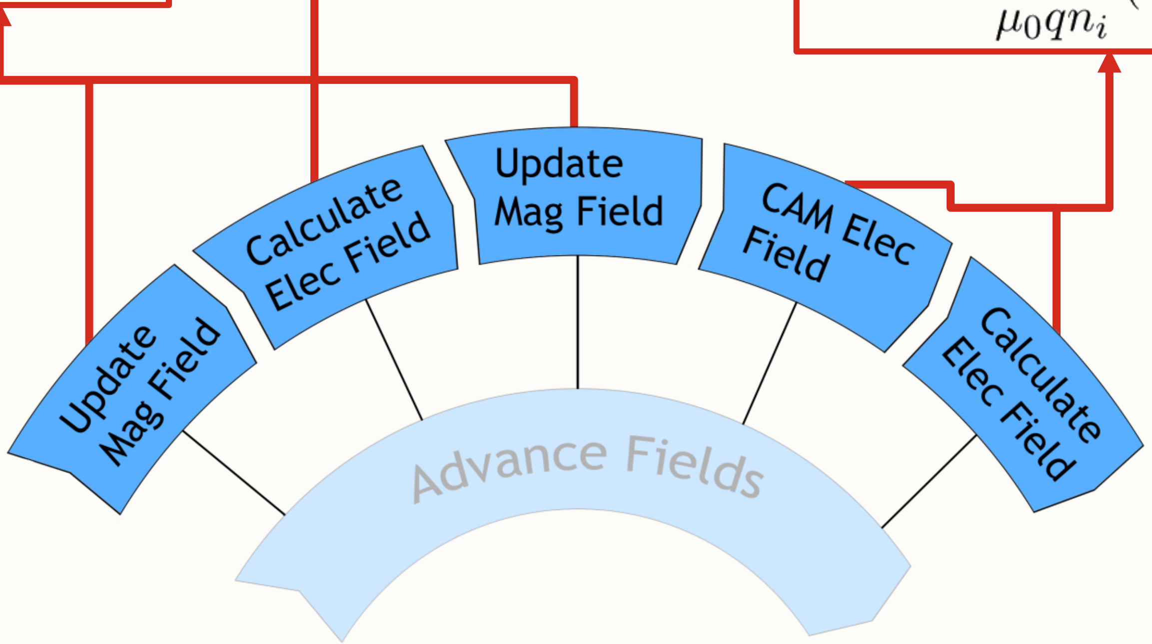
$$\frac{d\underline{x}}{dt} = \underline{v}$$

JERICHO - Electromagnetic Numerics

Electromagnetic Fields

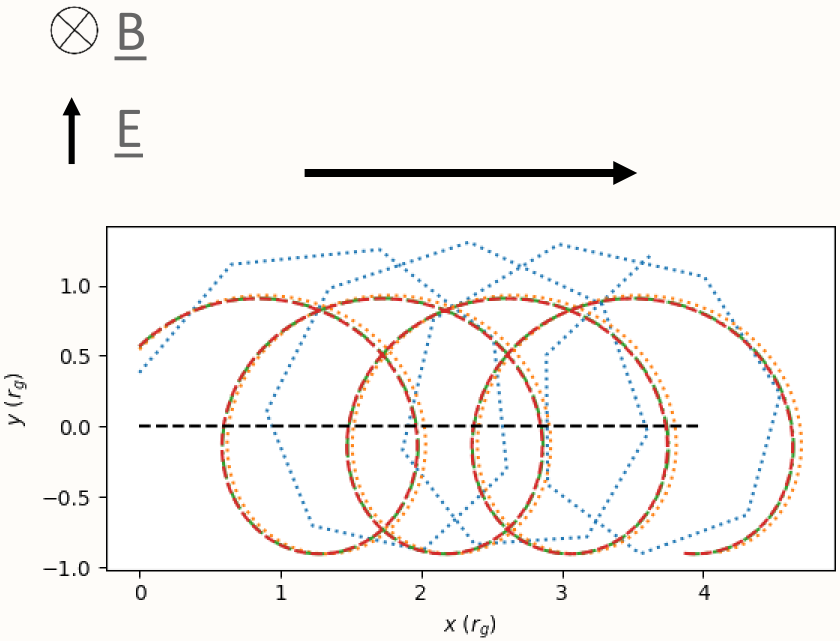
$$\frac{\partial \underline{B}}{\partial t} = -\left(\nabla \times \underline{E}\right)$$

$$\underline{E} = -\frac{1}{q n_i} \nabla \cdot \underline{\underline{P_e}} - \left[\underline{U_i} \times \underline{B} - \frac{1}{\mu_0 q n_i} \left(\nabla \times \underline{B}\right) \times \underline{B} \right]$$

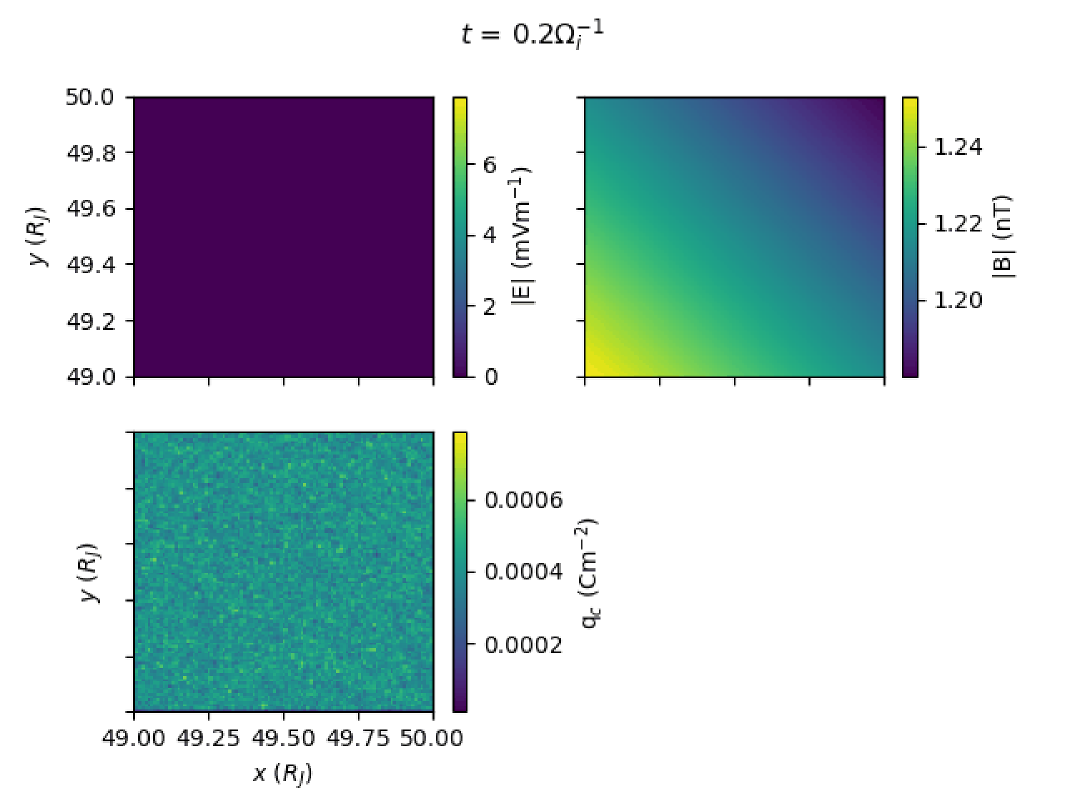


Model Validation – Single Particle Motions

- Important to check that model is reproducing well defined physics
- Gyro-motions of single particles can be obtained analytically
- Therefore these are a sensible set of plasma properties to check



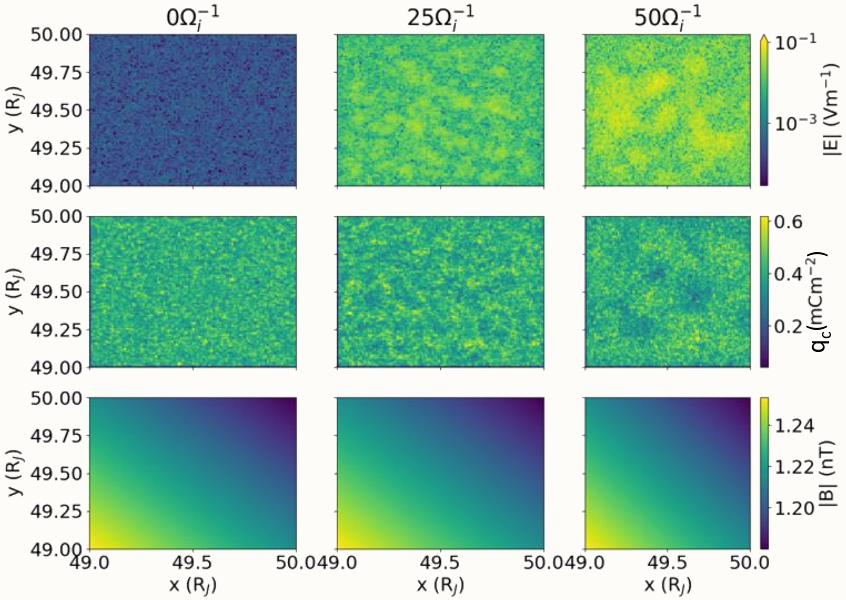
Model Validation – Energy Conservation

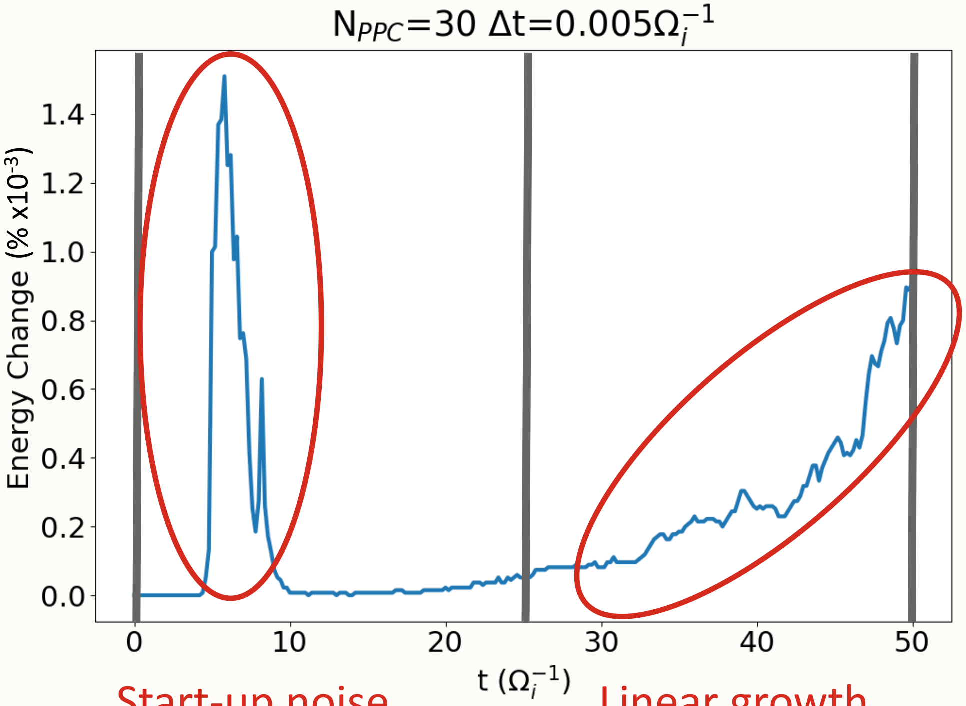


- Energy change is inevitable as parameters in the model are progressed numerically
- Ensure that the total energy change over the period of interest does not overpower dynamics in run

Model Validation – Energy Conservation

Space & Planetary Physics | Lancaster University





Start-up noise

Linear growth

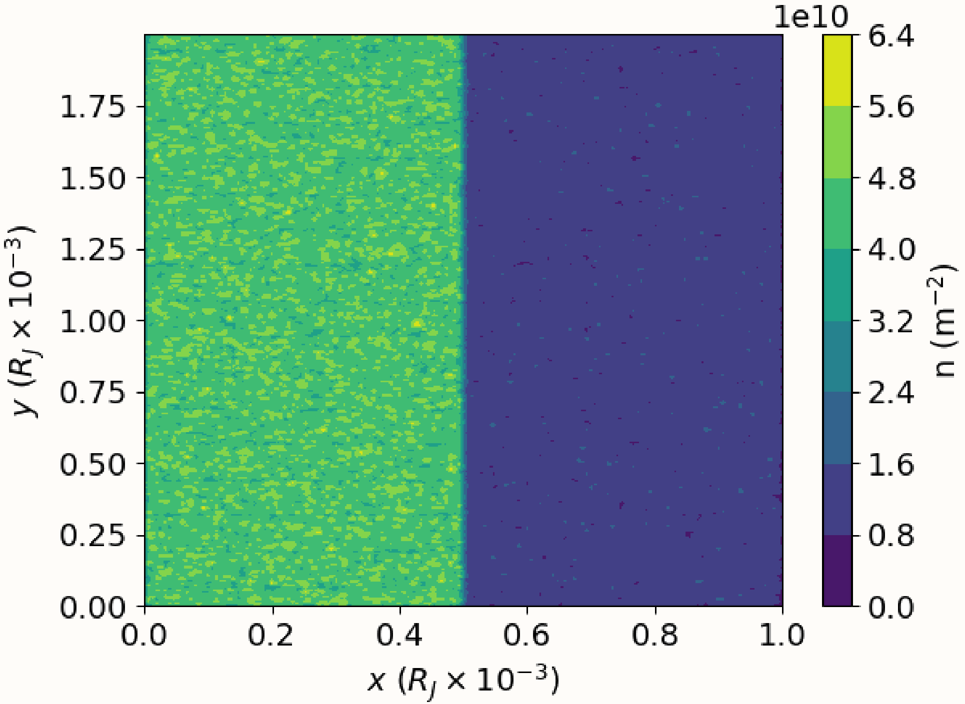
Model Validation – Rayleigh-Taylor Instability

Space & Planetary Physics | Lancaster University

- Process of interest for radial transport is centrifugal-interchange instability

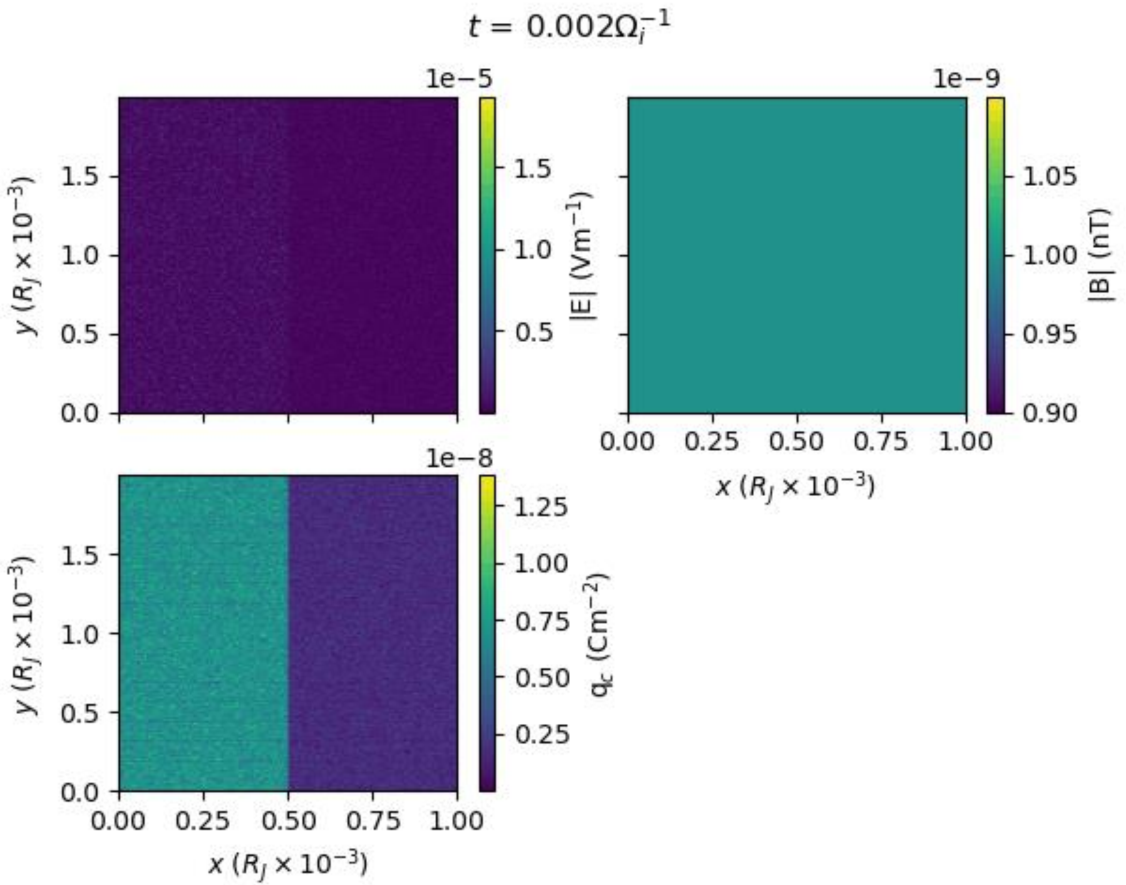
- This instability is analogous to an RT instability with centrifugal force replacing gravity

- No gravity in model only centrifugal force



Interchange Instability – Latest Results

Space & Planetary Physics | Lancaster University



Summary

- We have developed a 2.5D ion-kinetic, fluid-electron hybrid plasma model [*in prep, Wiggs & Arridge 2021*]

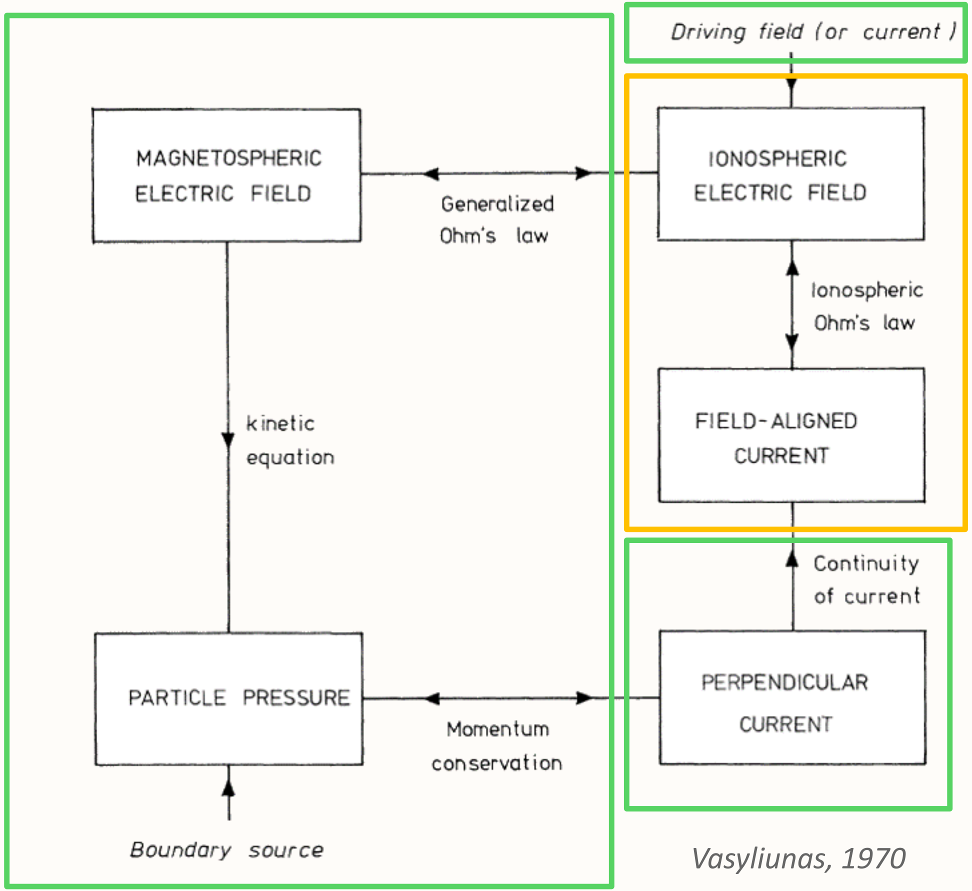
- A series of test simulations have demonstrated that both plasma properties are accurately reproduced by the model over the time period of interest

- Centrifugal-interchange instability with Jovian parameters is currently being investigated with JERICHO (visit us at AGU to see results)

j.wiggs@lancaster.ac.uk JAWiggs JoshWiggs

Backup Slides

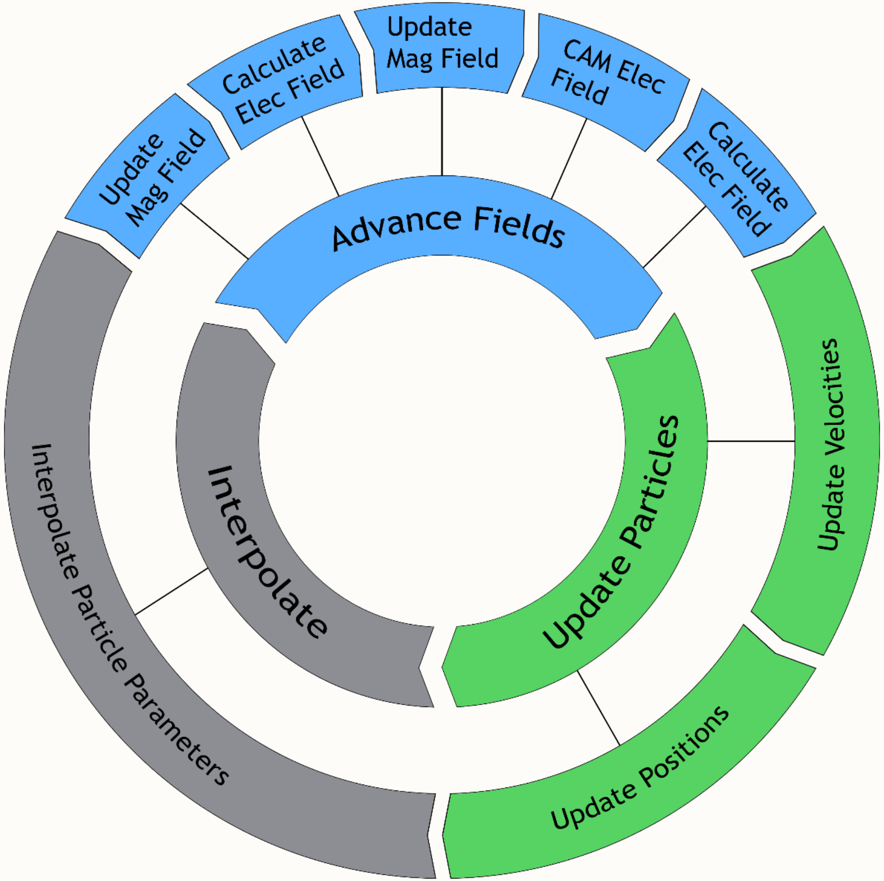
Vytenis Chart Updated



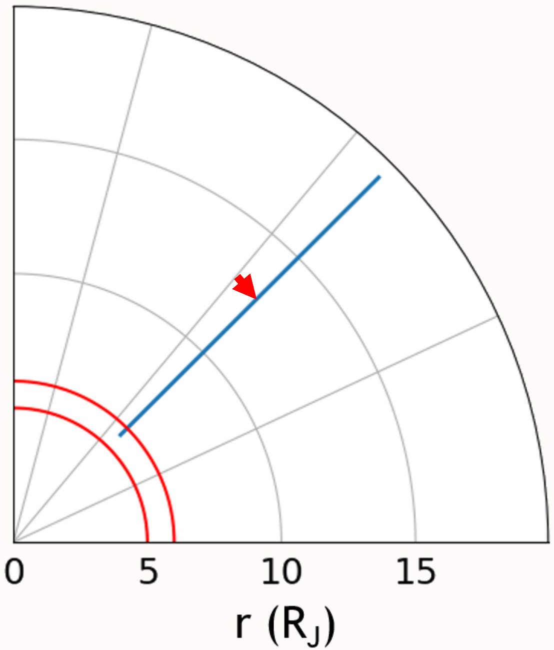
Vasyliunas, 1970

JERICHO – Model Logic

Space & Planetary Physics | Lancaster University



Rotational Forces



- Tracer particle only ‘feeling’ centrifugal and Coriolis forces

$$\underline{v}^{n+\frac{1}{2}} = K\left\{\left(1-h^2\alpha^2\right)\underline{v}^{n-\frac{1}{2}} + h\left[2\alpha\left(\underline{v}^{n-\frac{1}{2}}\times\hat{\underline{z}}\right)\right] + \Delta t|\Omega|^2\left[\underline{x}^2 + \left(\underline{x}^n \times h\alpha\hat{\underline{z}}\right)\right]\right\}$$

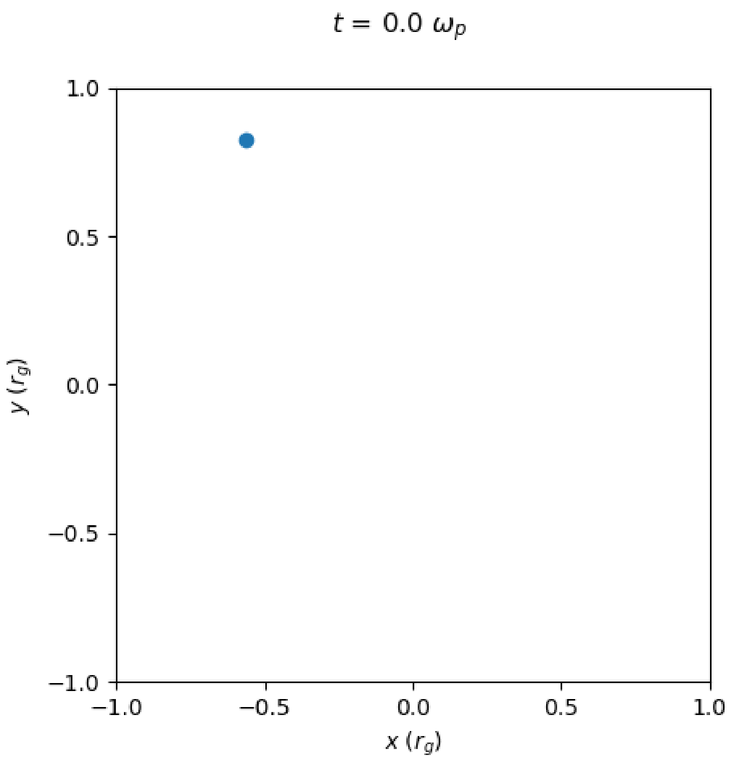
Centrifugal

$$\alpha = \frac{m}{q}\Omega_z$$

Coriolis

- Ray trace of particle path over 3 hours simulated time in a system with Jovian parameters

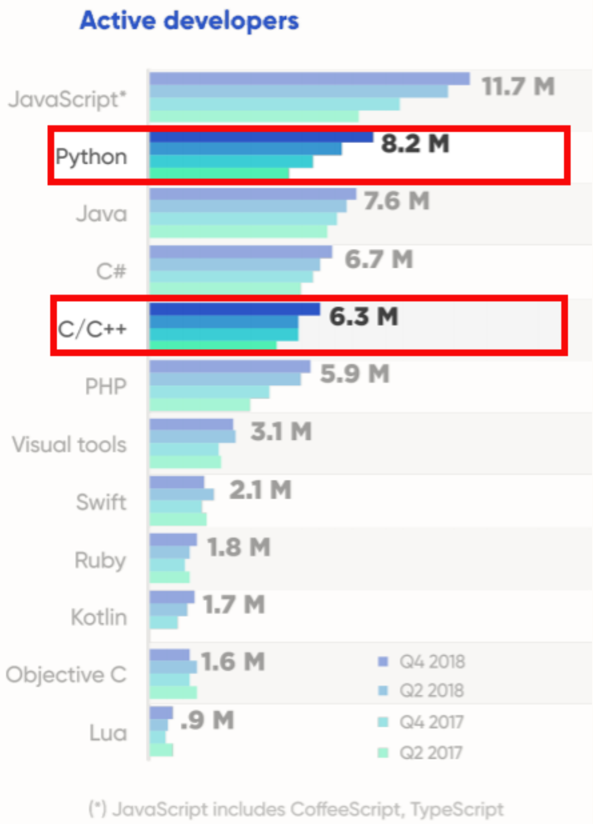
Model Validation – Single Particle Motions



Why Python?

Space & Planetary Physics
Lancaster University

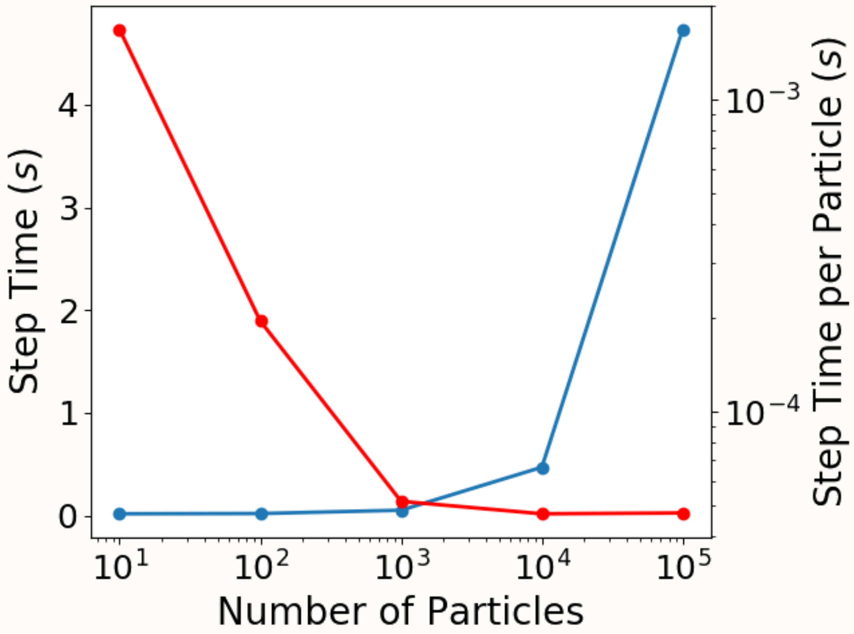
- One of the fastest growing and most popular programming languages
- High-level, dynamic language allowing for quick modification for prototyping
- Easy-to-read, modular nature makes code very accessible for a wide range of users such as students and researchers



SlashData, 2019

Computational Efficiency

- As number of simulated particles increases, particle operations dominate run time
- At ~1000 particles no notable decrease in step time per particle
- ~2 orders of magnitude slower per particle operation than highly optimised PIC code [Decyk & Singh, 2014]

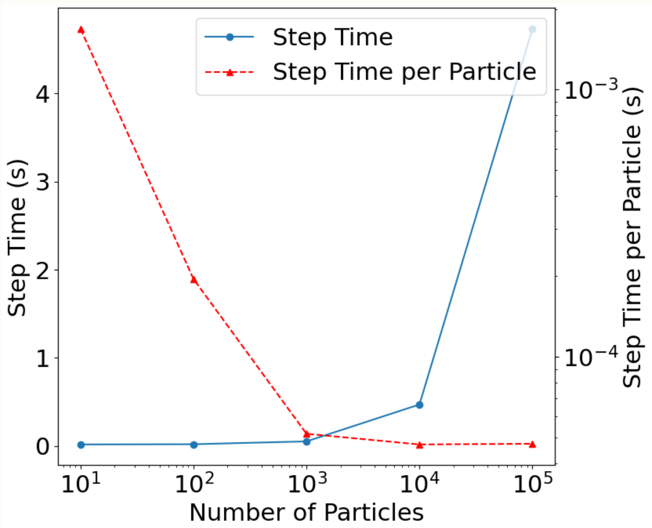


Simulation Parameters:

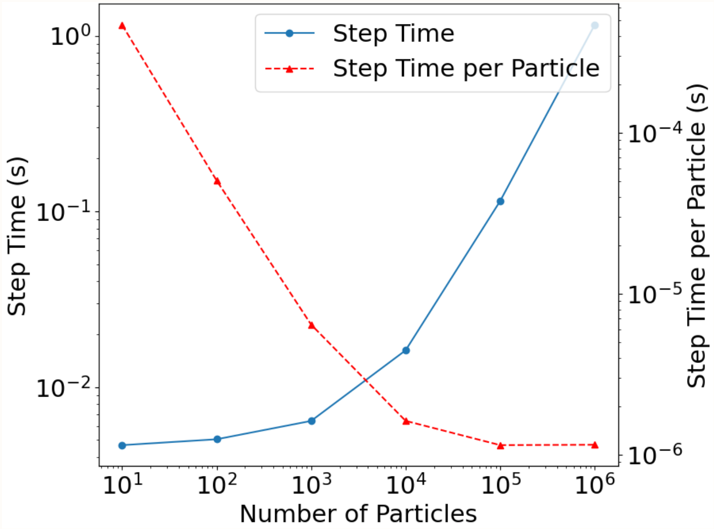
- Fully electrodynamic
- 51x51 grid
- 10x10m surface

From Python to c++

Space & Planetary Physics | Lancaster University



Python



c++