Máster Universitario en Ingeniería Aeronáutica

The Space Environment

Plasma Simulation

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Based on the work by Luis Conde

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POLITÉCNICA

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Motivation

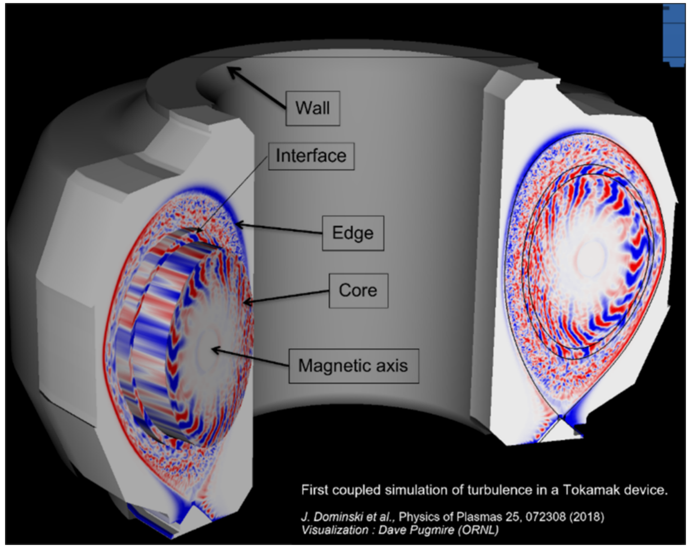
Plasmas are very complex systems:

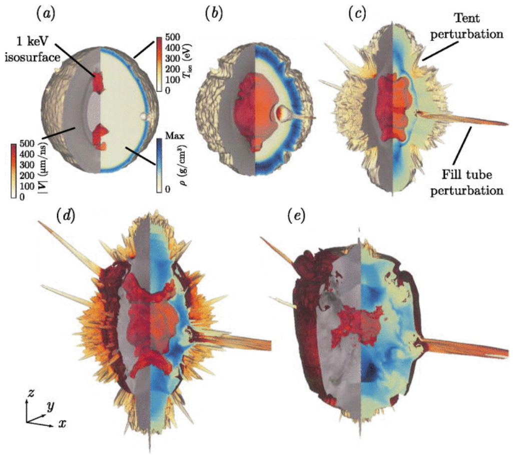
- Let’s take a fluid and add
  - a mixture of species with **disparate time and spatial scales** (electrons, ions and neutrals)
  - many **collisions** between them (ionization, recombination, charge-exchange, excitation…)
  - the **electromagnetic field** (Maxwell’s equations)
  - Sometimes interaction with **radiation** is also required to be taken into account (photoionization)

Simulations are often required to understand the behaviour, analyse experiments and generate artificial plasmas

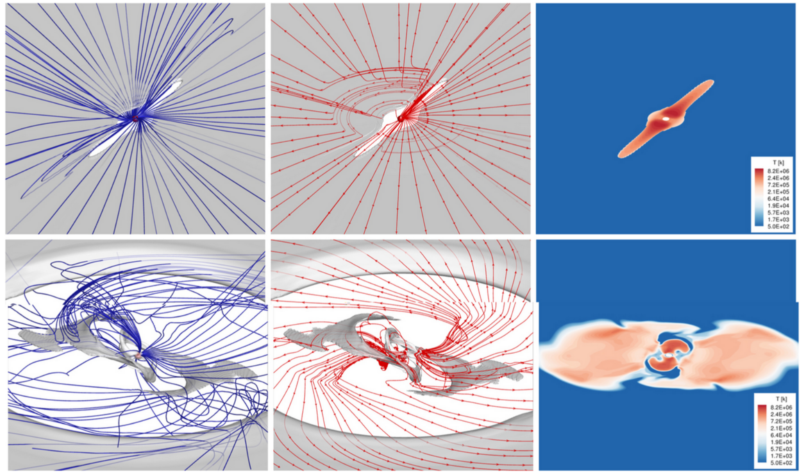
Even the simpler descriptions of plasmas require a significant amount of computational and theoretical resources.

Simulations of complex systems might require days, weeks or even months to run in supercomputers



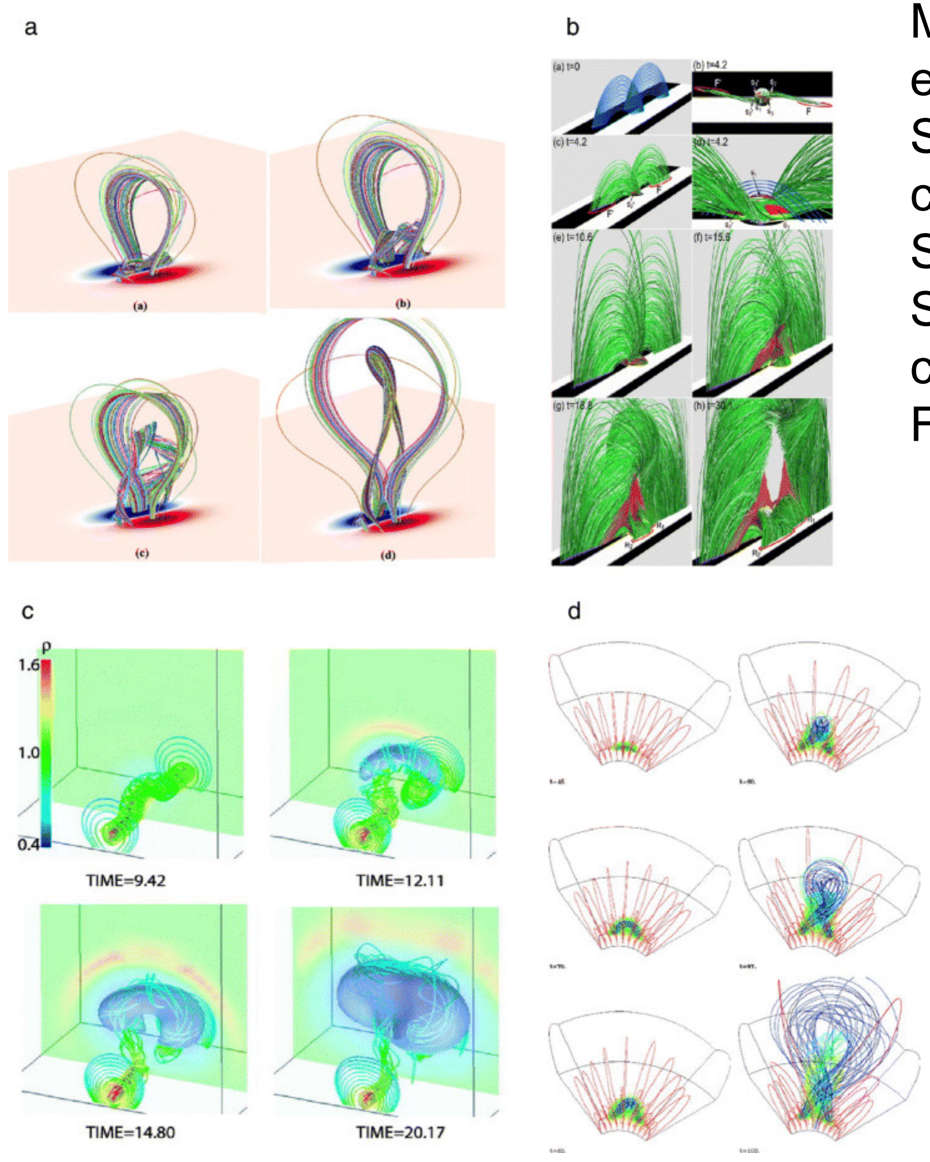


Phys. Plasmas 22, 032702 (2015)



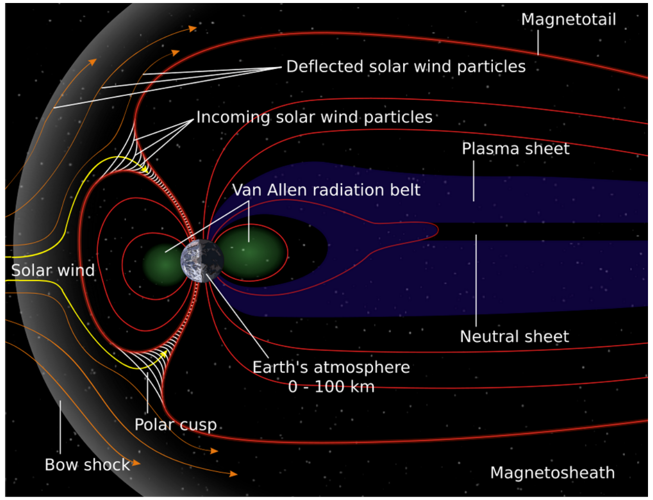
Ofer Cohen et al 2023 ApJ 949 54

Plasmas as a fluid



Inoue, S. Magnetohydrodynamics modeling of coronal magnetic field a nd solar eruptions based on the photospheric magnetic field. Prog. in Earth and Planet. Sci. 3, 19 (2016).

Magneto Hydro-Dynamics (MHD) is a fluid approach used in the space environment: stellar plasma (astrophysics), solar wind…
Solution of conservation equations based on charge density and current, plus the equations for EM field
Simplifications are required (ideal MHD)
Similar to solving Navier-Stokes: continuity, momentum, energy plus clousure.
Finite differences, finite volumes...



A simulation of a charged particle being deflected from the Earth by the magnetosphere. NASA

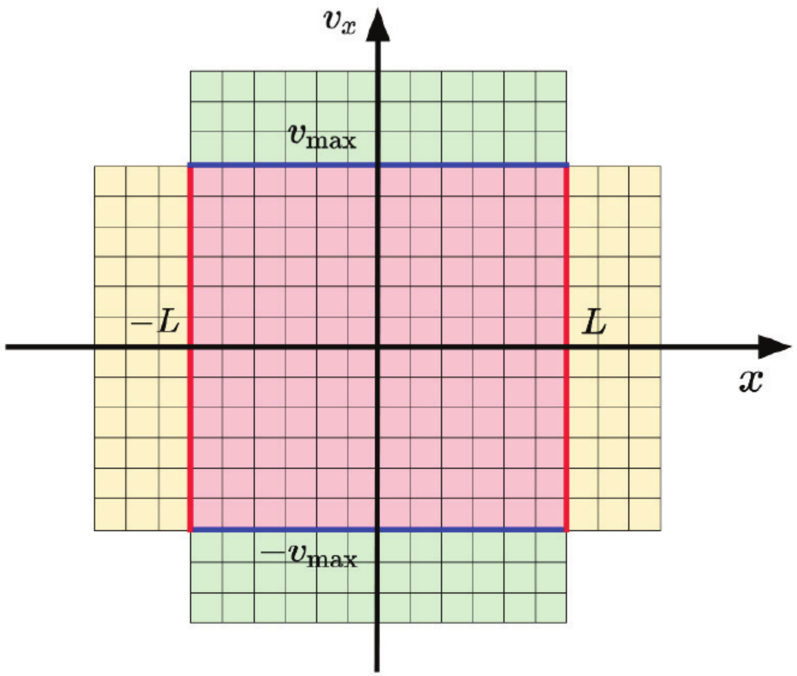
Always remember fluid models carry assumptions and simplifications

Plasmas from a kinetic POV

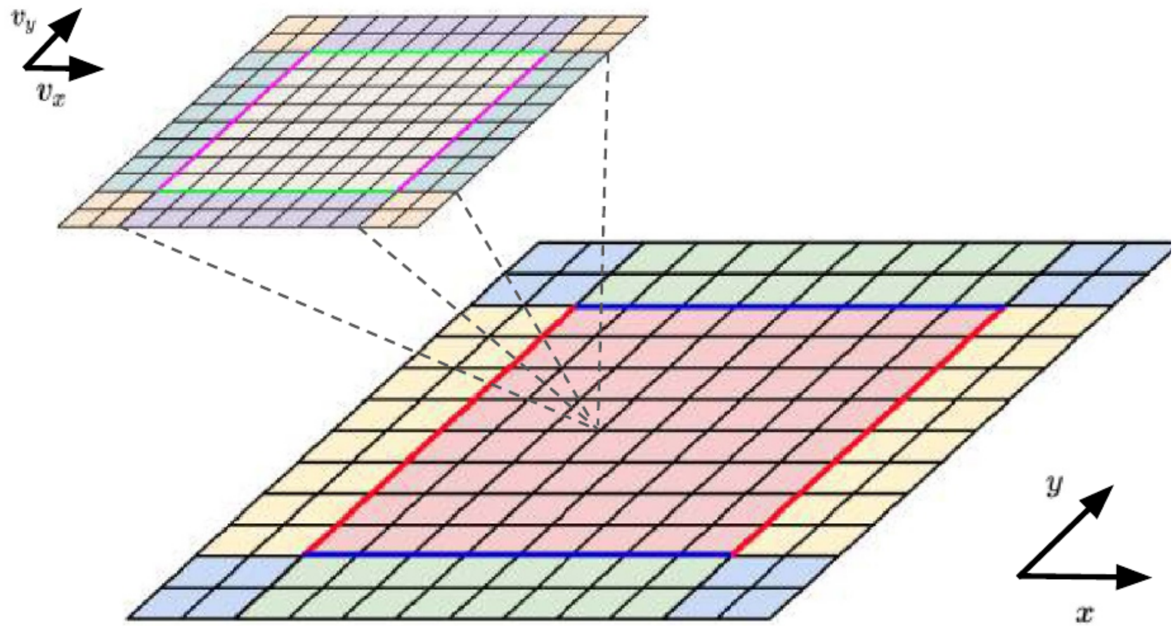
Aim: Solve the Vlasov equation associated to the evolution of a species.
Plus EM field and collisions (when needed)
The velocity space has to be discretized too. Remember: $f_\alpha(\boldsymbol{r}, \boldsymbol{v}, t)$

This usually limits the dimensionality of the model

$$\frac{\partial f_\alpha}{\partial t} + \nabla_{\mathbf{r}} \cdot (\mathbf{v}_\alpha f_\alpha) + \nabla_{\mathbf{v}} \cdot (\mathbf{a}_\alpha f_\alpha) = C_\alpha$$



Phys. Plasmas 28, 093510 (2021); doi: 10.1063/5.0058635

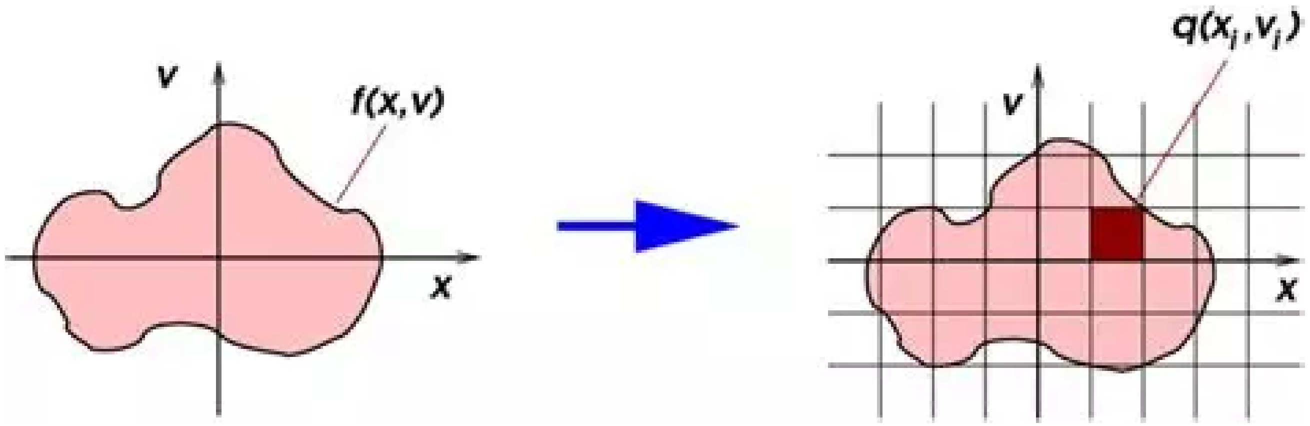


Plasma Sources Sci. Technol. 33 (2024) 125005

Plasmas as (macro) particles

Instead of distretizing the full r-v domain, we follow a number of macro-particles in the spatial domain
Each macro-particle represents a large num... es that follow a similar path.
A large number of macro-particle is required ... distribution function for a species (sometimes even millions of particles).
Macro-particles carry charge and mass (momentum).
Effects between particles both local (collisions) and collective (EM forces) must be considered.

$$\frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t} = \mathbf{v}, \quad \frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = \mathbf{a}$$



Long-Range Interactions in Many-Particle Simulation

Particle-in-cell method

Four main steps:
1)Particle push

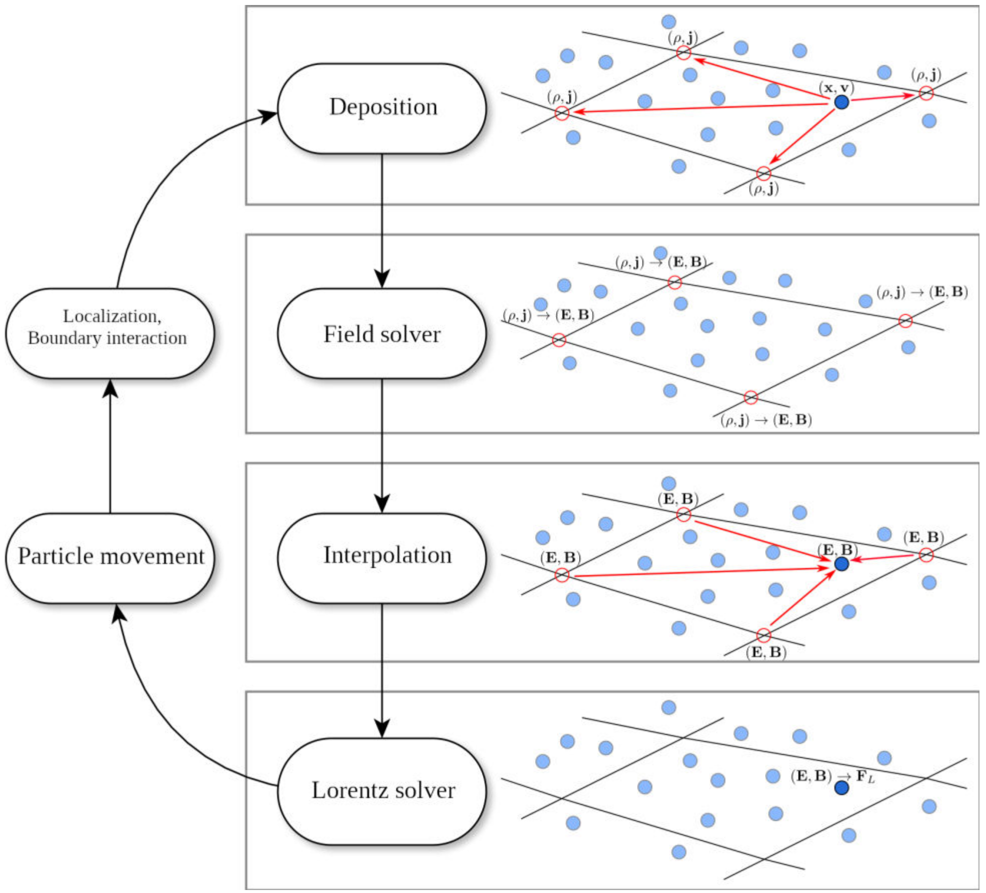
2)Charge (and current) deposition

3)Field solver

4)Field interpolation (and force calculation)

Collisions between particles in the same cell.
- Coulomb scattering
- Elastic and inelastic collisions

Sometimes, electrons are treated as a fluid to save computational time.



Introduction to the Particle-in-Cell (PIC) method