Studying plasmas with computers

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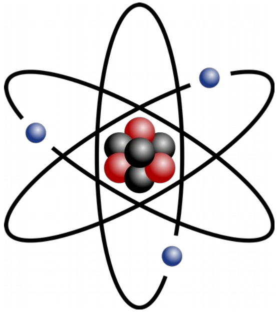
What is a plasma?



- Solids, liquids & gases: electrons stick to atoms
- With enough energy, a **plasma** forms:

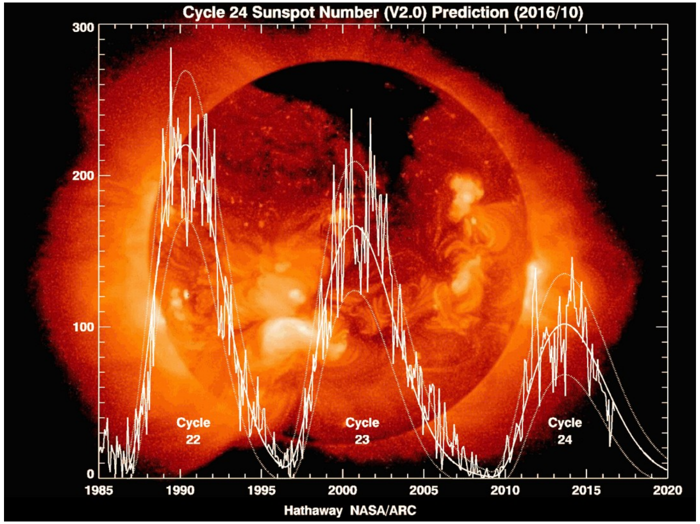
  A gas of ions, electrons (and neutral particles)

- Free charges → *electric fields*
- Moving charges → *magnetic fields*
- Lorentz force $\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$

Nonlinear interaction!

Our **plasma** energy source: Sun

- Open questions:
  - Coronal heating
  - Solar cycle

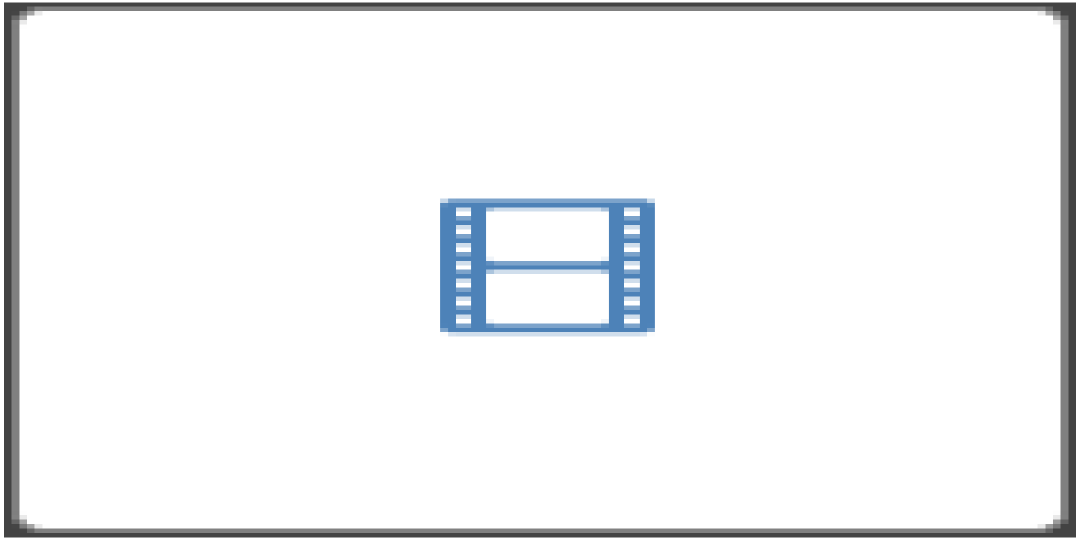


Coronal Mass Ejection

[NASA]

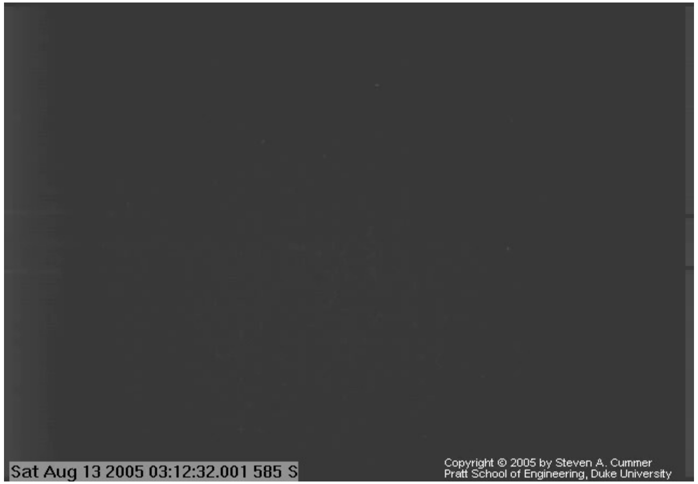
Plasmas in the sky

Lightning



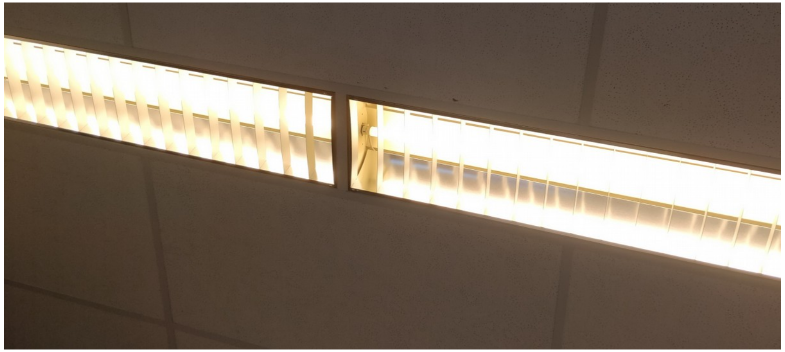
[Wu et al., GRL, 2019]

Sprites



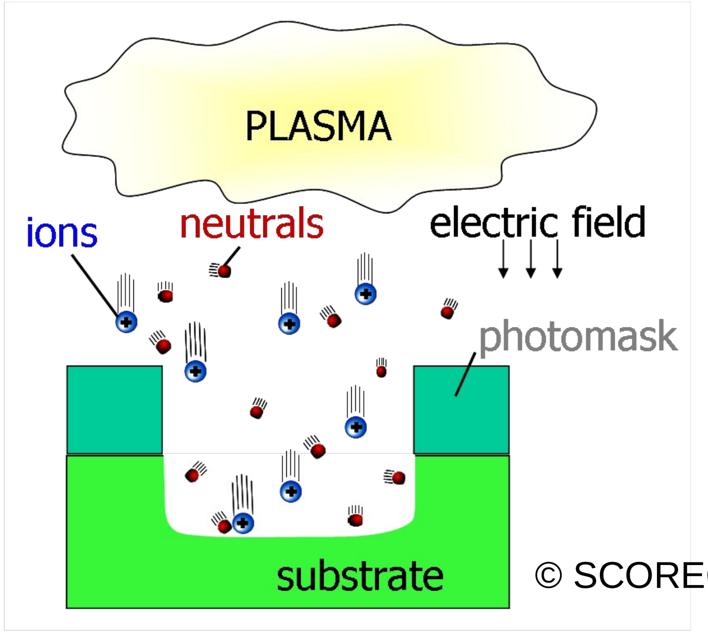
Technological plasmas

Fluorescent lamps in M133

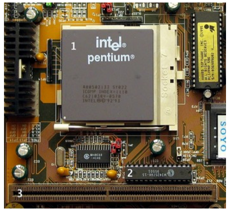


High-voltage technology

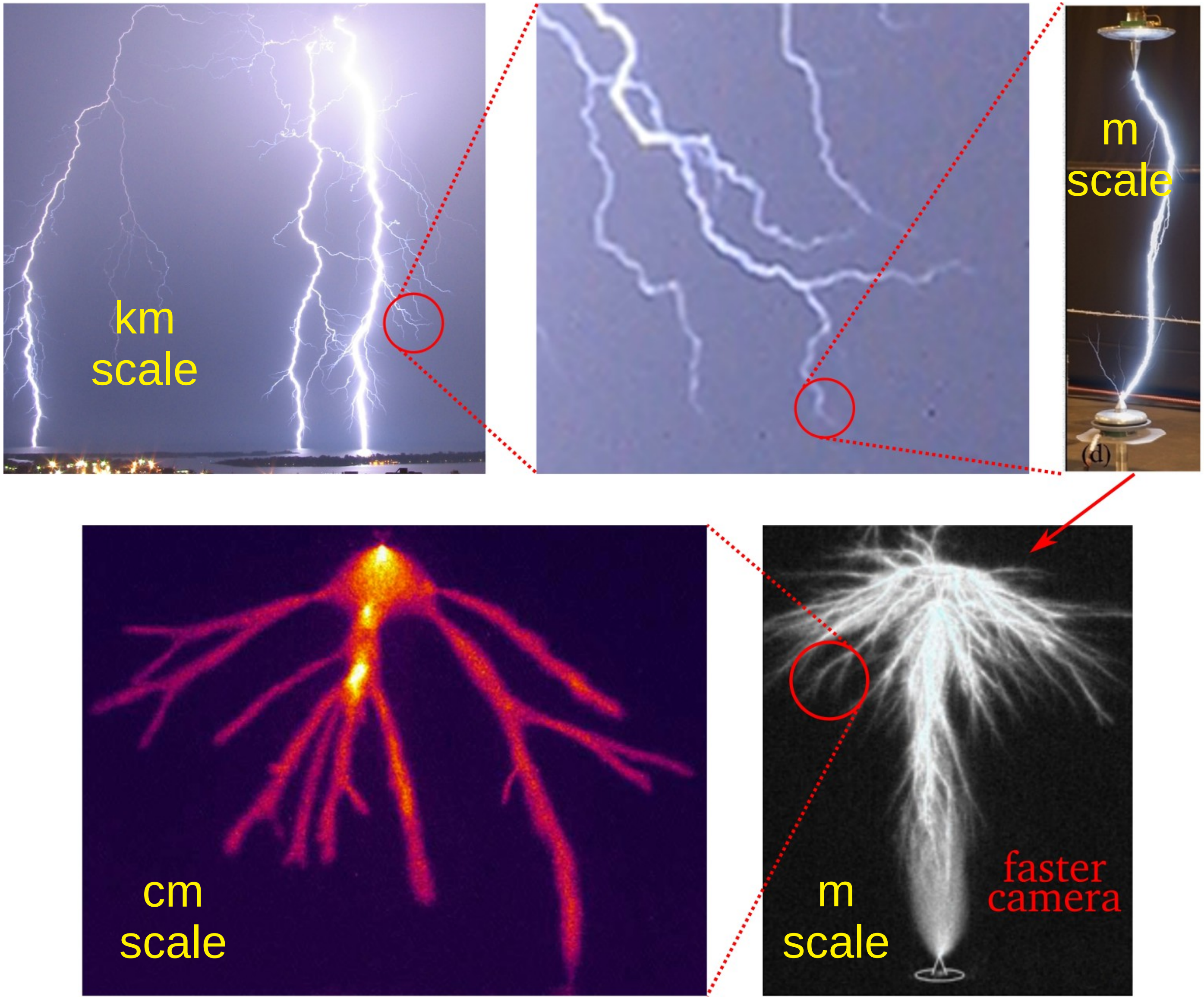
Plasma etching



© SCOREC



Plasmas are often ***multiscale***



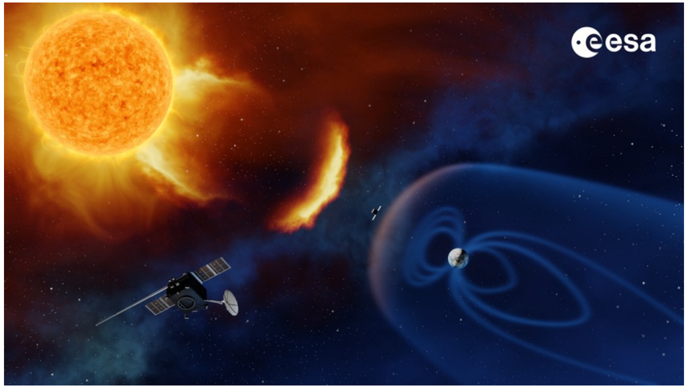
Multiscale Dynamics group

Researchers

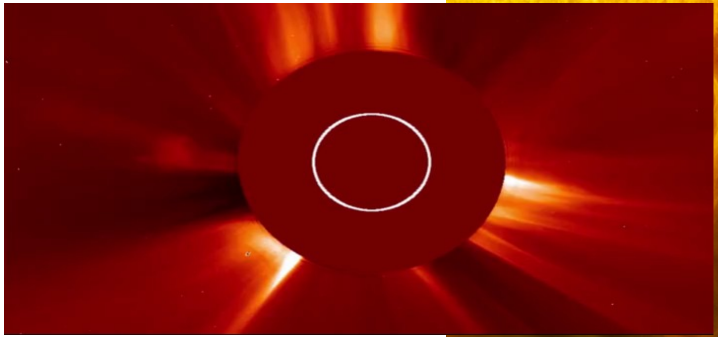
Ute Ebert (leader)
Behnaz Bagheri (pd)
Hani Francisco (phd)
Andy Martinez (phd)
Hemaditya Malla (phd)
Dennis Bouwman (phd)
Baohong Guo (phd)
Yaogong Wang (visiting)
Jannis Teunissen (staff)
Andong Hu (pd)
Rakesh Sarma (pd)
Carl Shneider (pd)
Mandar Chandorkar (phd)
Enrico Camporeale (staff, 25%)

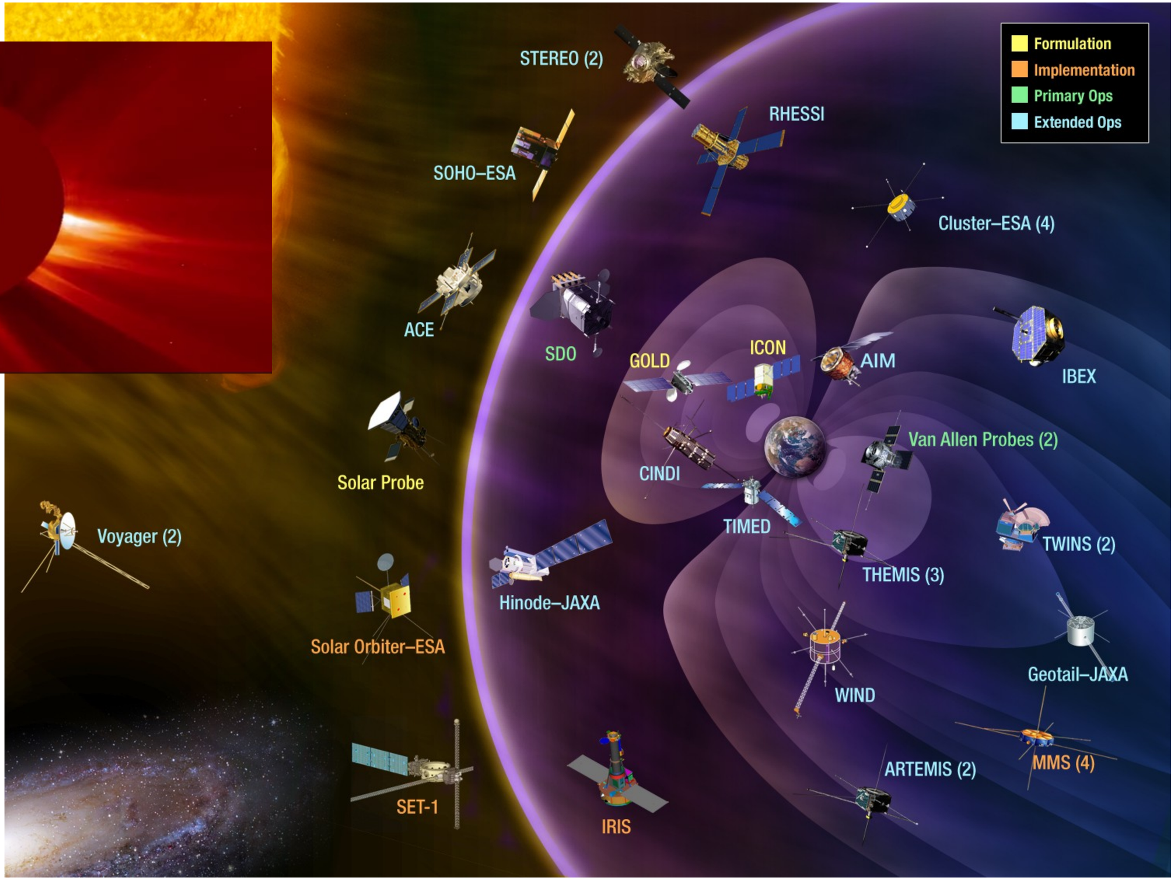
electric discharges (modeling)

space weather (machine learning)



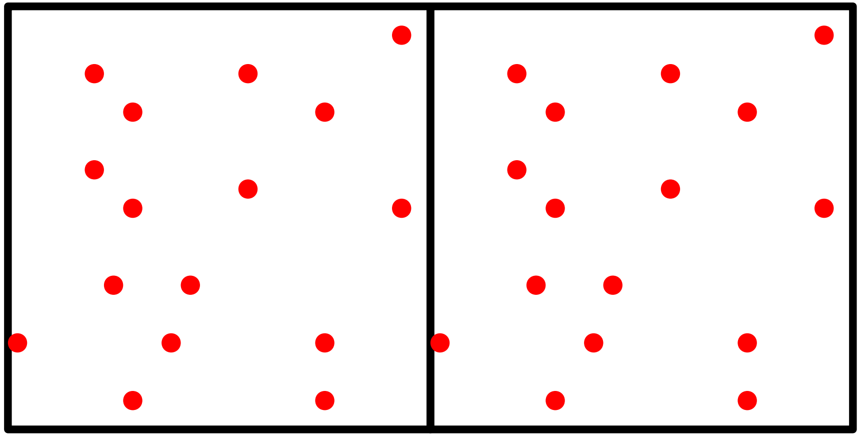
Machine learning for space weather





Physical modeling

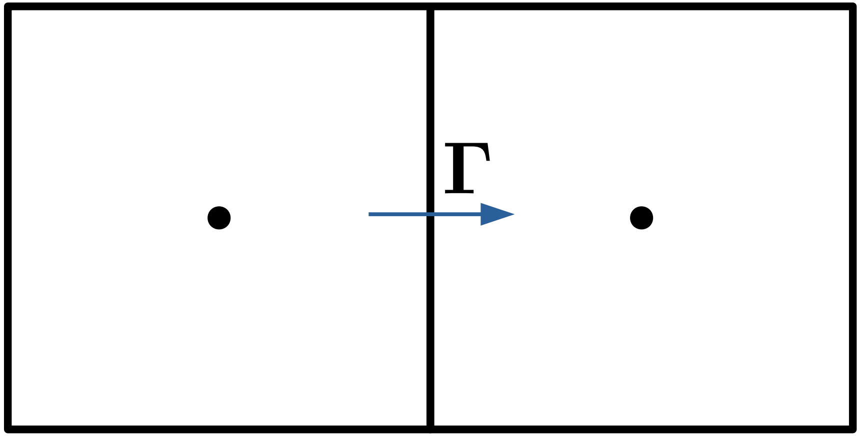
Particle models



$$\partial_t \mathbf{x} = \mathbf{v}$$

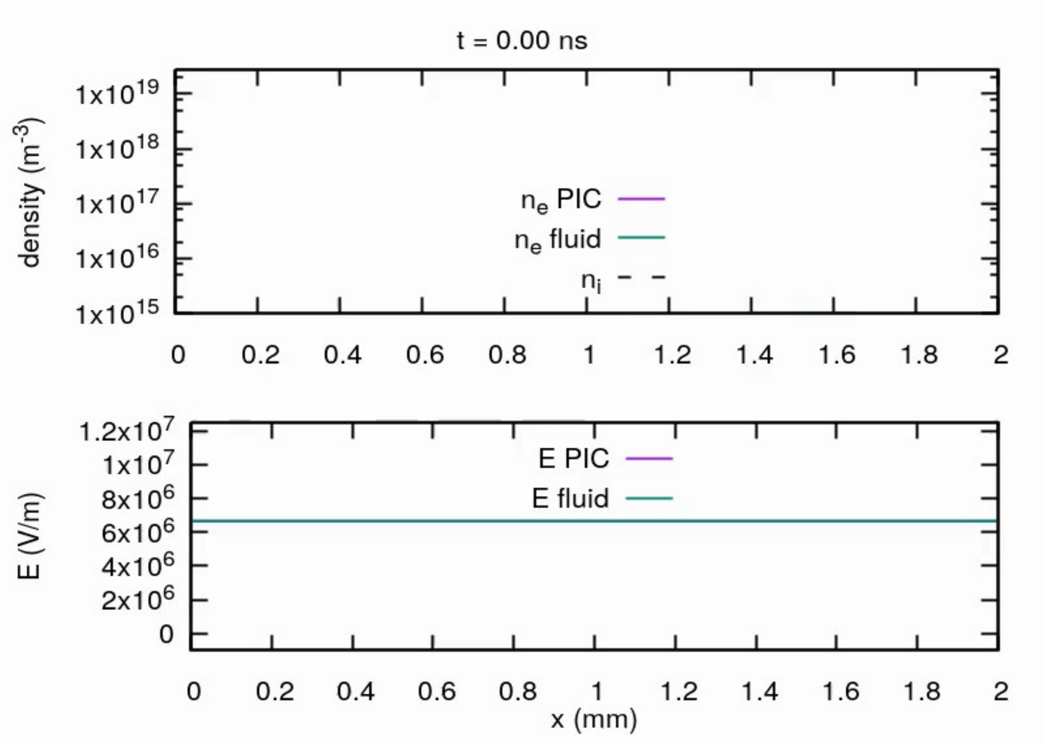
$$\partial_t \mathbf{v} = \mathbf{a}$$

Fluid models



$$\partial_t \mathbf{u} + \nabla \cdot \mathbf{\Gamma} = S$$

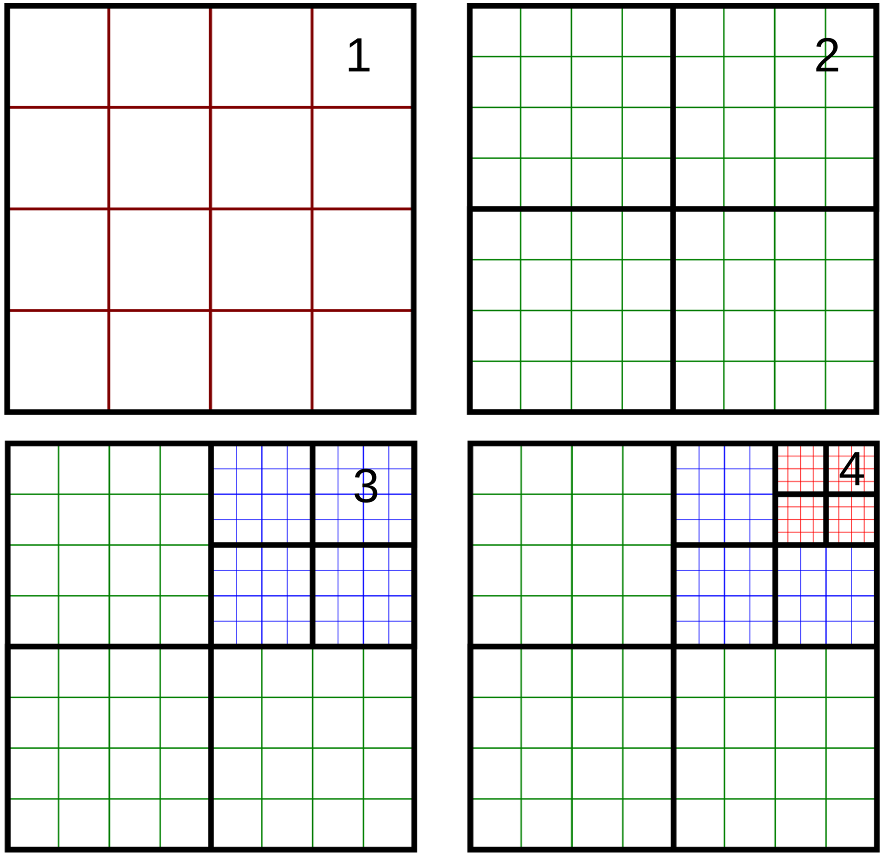
Plasmas often have steep gradients

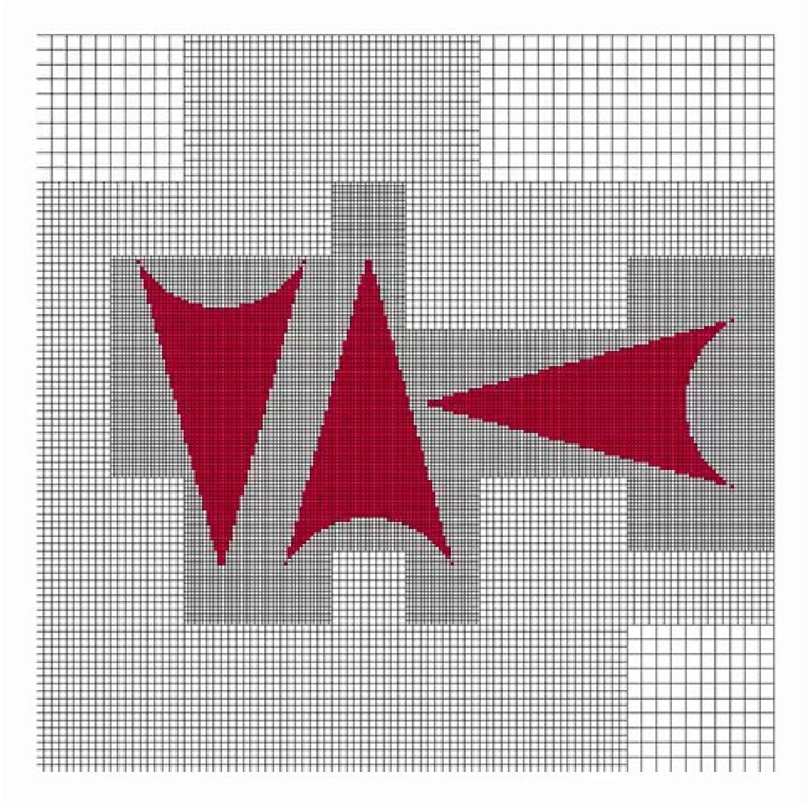


Uniform grid

$$N_{\text{cells}} = \left(\frac{L}{\Delta x}\right)^D$$

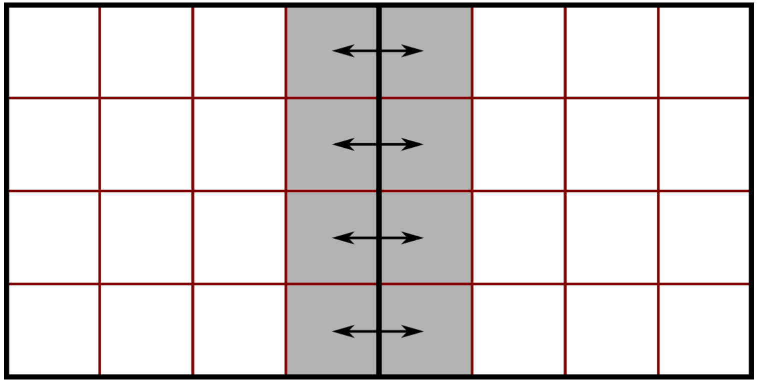
Solution: Adaptive Mesh Refinement



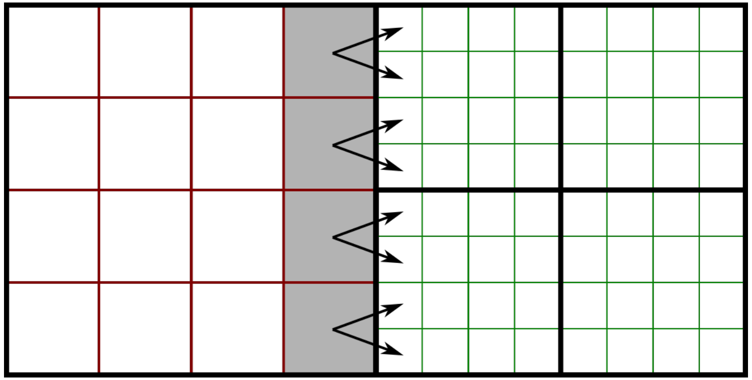


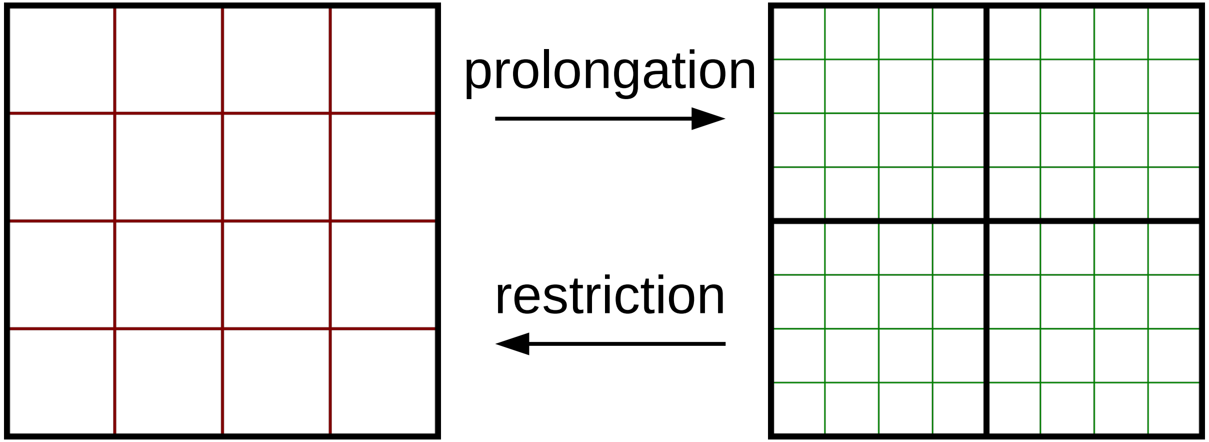
Parallel communication

ghost cells (same level)



ghost cells (level jump)





How to adapt methods near boundaries?

Elliptic Partial Differential Equations

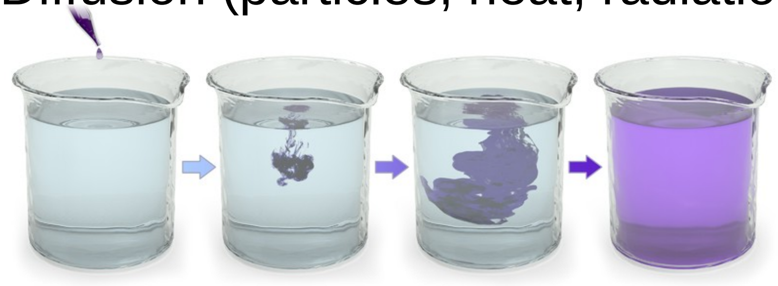
Electrostatics

$$\nabla \cdot (\varepsilon \nabla \phi) = -\rho$$

Gravity

$$\nabla^2 \phi = 4\pi G \rho$$

Diffusion (particles, heat, radiation)



$$\partial_t n = \nabla \cdot (D \nabla n)$$

Divergence cleaning

Incompressible flow

$$\partial_t \rho + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\nabla \cdot \mathbf{v} = 0$$

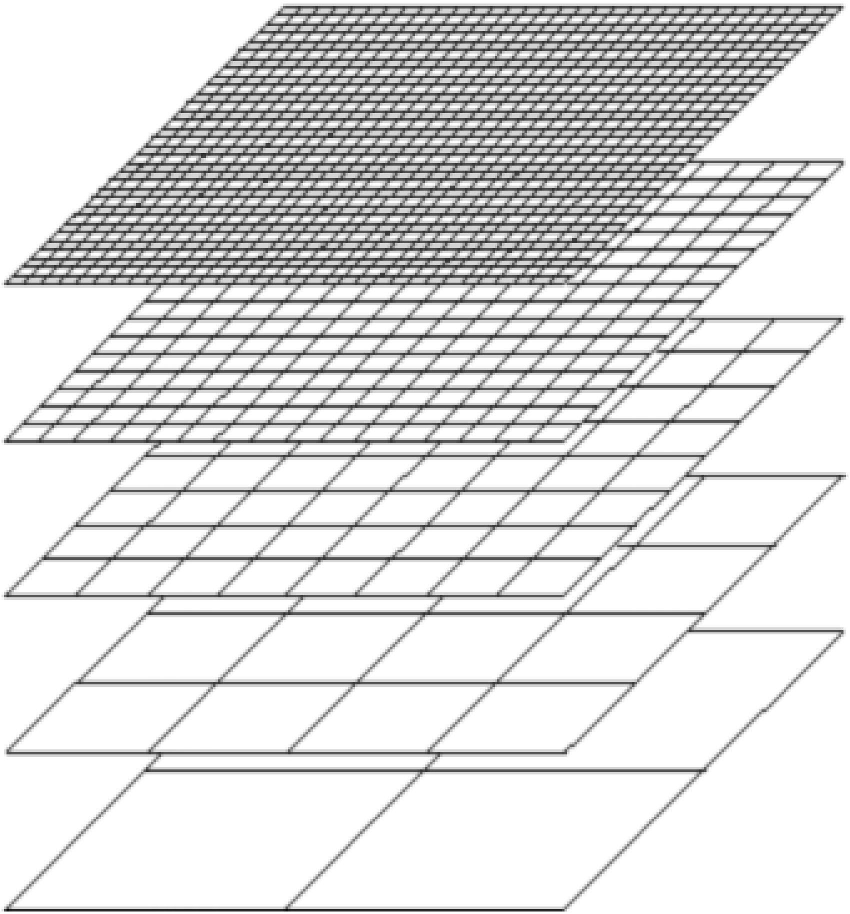
Magnetohydrodynamics (MHD)

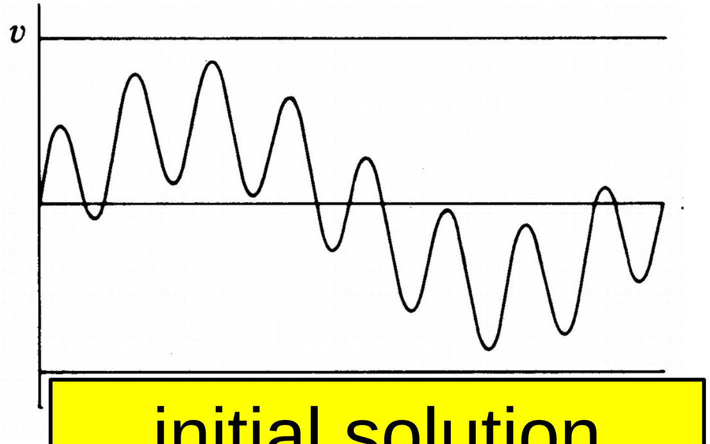
$$\nabla \cdot \mathbf{B} = 0$$

We need ***fast*** elliptic solvers

- Direct sparse solvers *(e.g. MUMPS, Pardiso)*
  - Too expensive in 3D
- FFT-based solvers *(e.g. P3DFFT, AccFFT)*
  - O(N log N), uniform grid only
- **Geometric multigrid** *(e.g. Hypre, HPGMG)*
  - O(N) scaling, AMR compatible

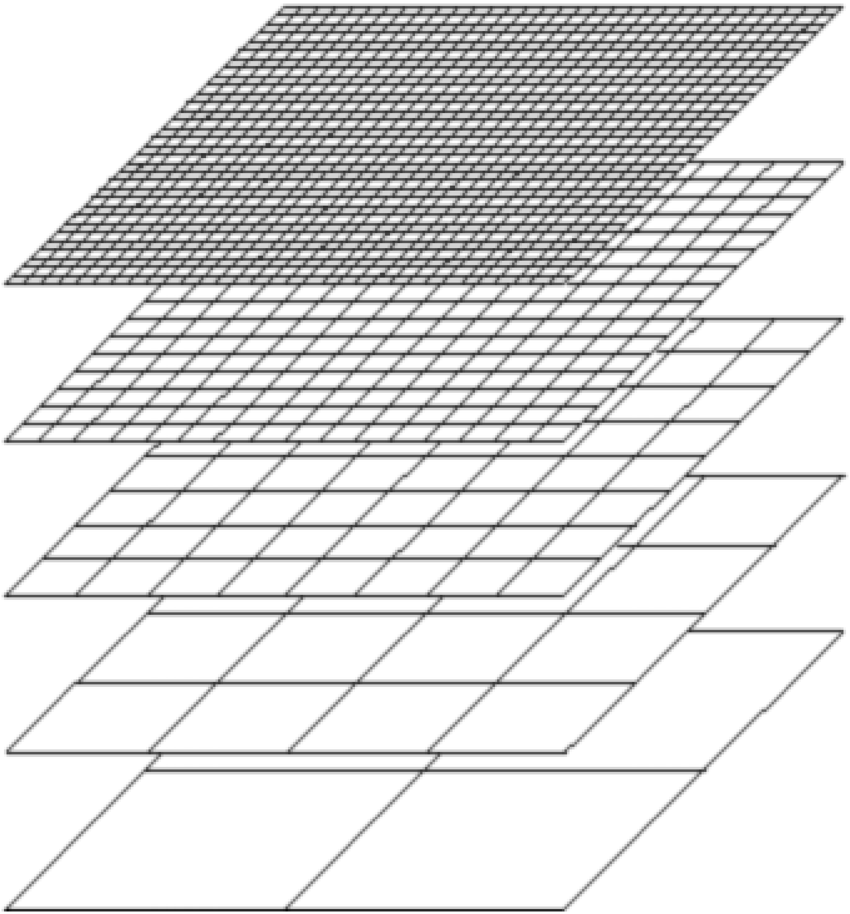
Geometric multigrid

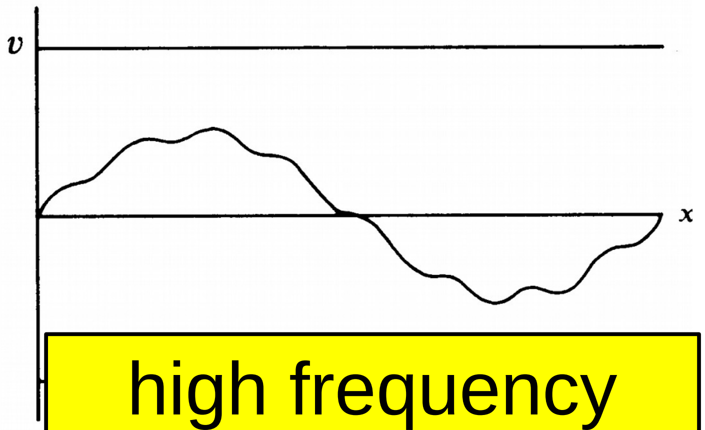




initial solution error

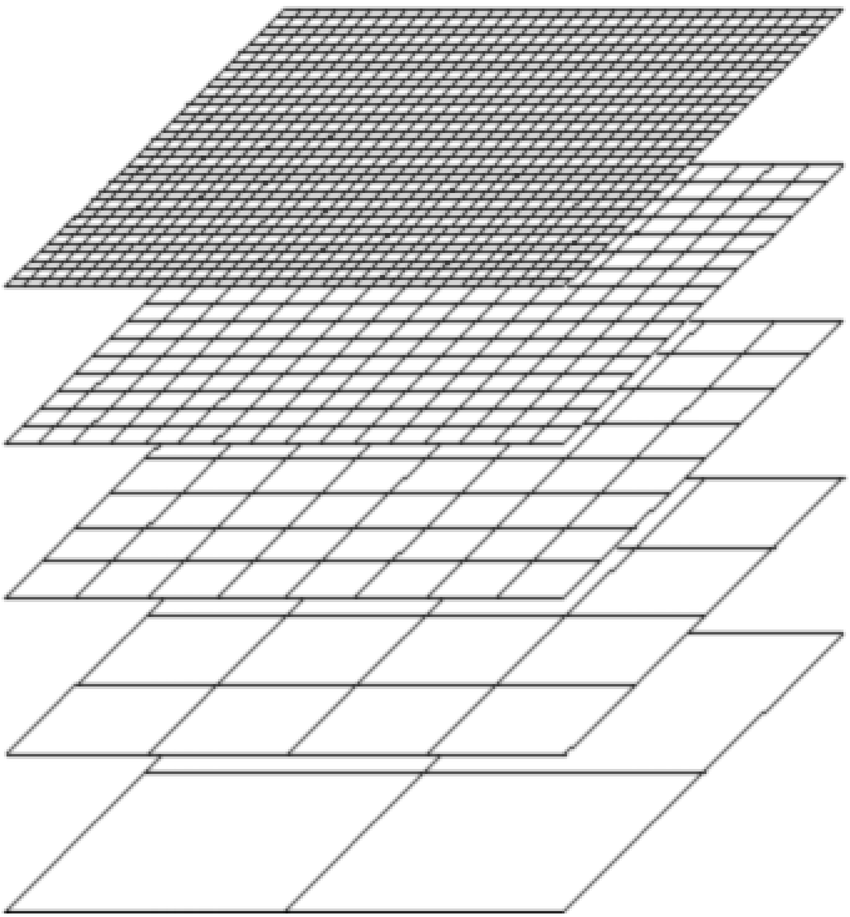
Geometric multigrid

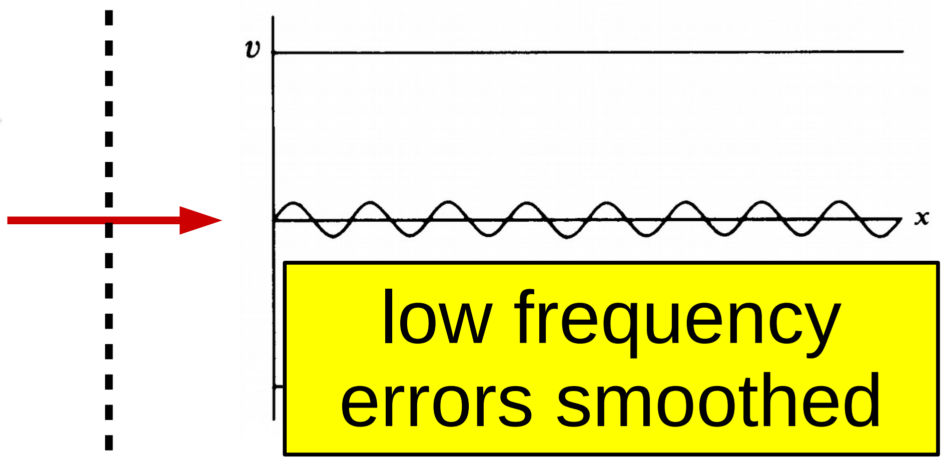




high frequency errors smoothed

Geometric multigrid

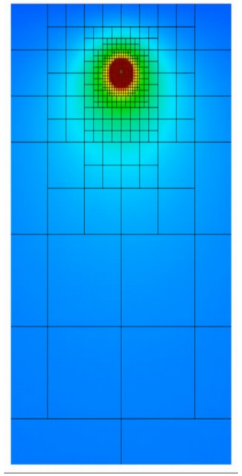




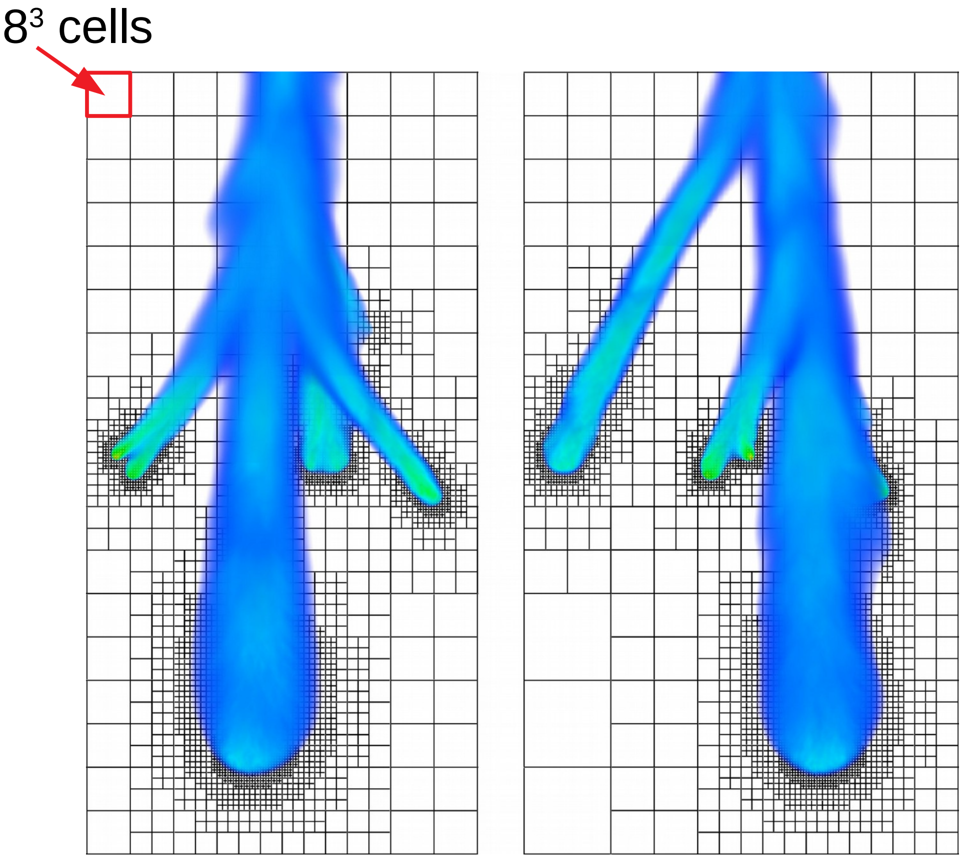
A discharge simulation code

Afivo-streamer

2D/3D
OpenMP
Quadtree/octree
Fortran (modern!)
GPL license



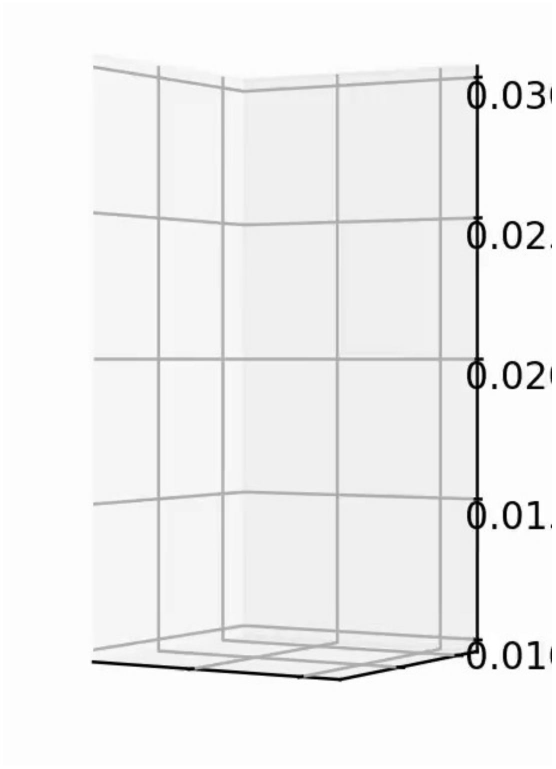
2D example



[Teunissen & Ebert, CPC, 2018]
[Teunissen & Ebert, J. Phys. D., 2017]

https://gitlab.com/MD-CWI-NL/afivo-streamer

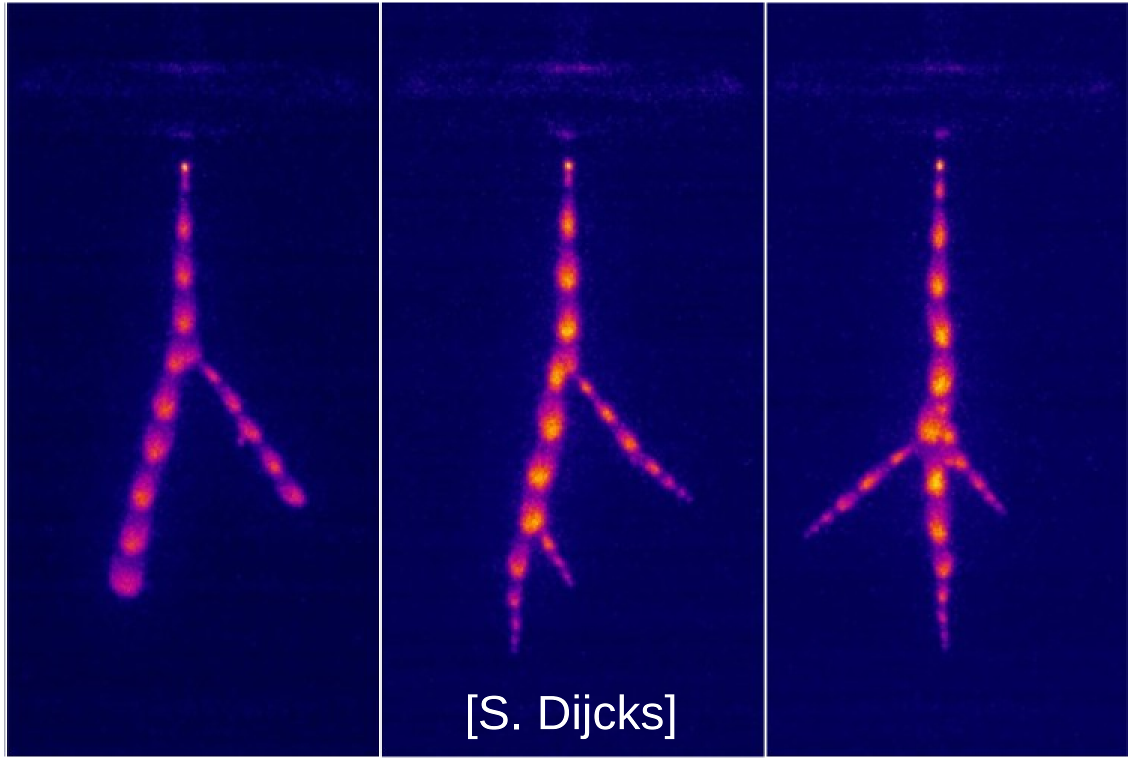
Recent study: branching



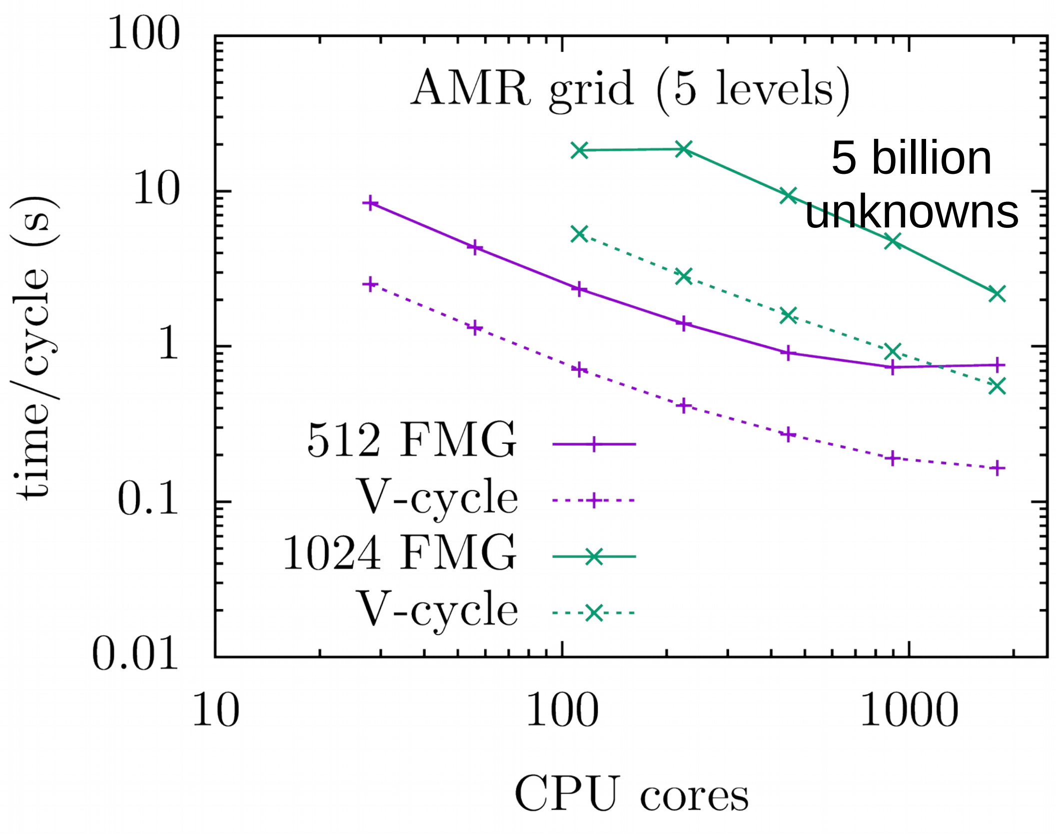
Model details: [Bagheri & Teunissen, PSST, 2019]

Experiment

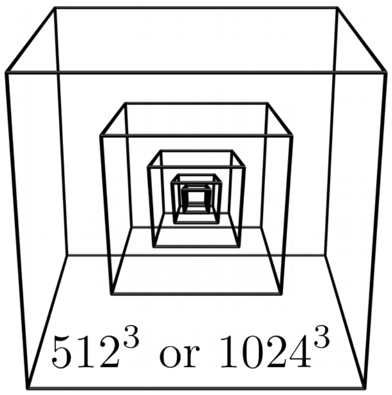
Simulation

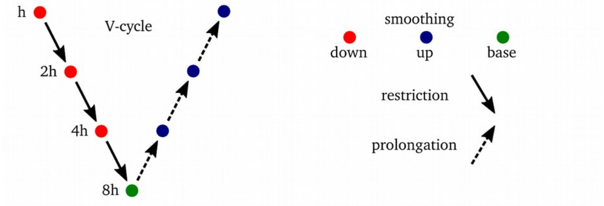


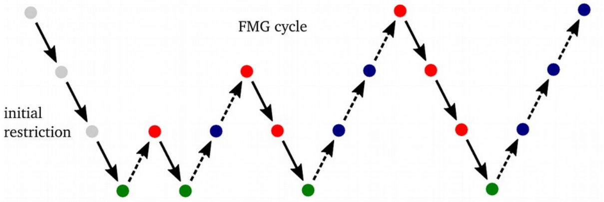
A highly parallel AMR MG solver



[Teunissen & Keppens, CPC, 2019]







http://amrvac.org

MPI-AMRVAC

$$\partial_t \boldsymbol{U} + \nabla \cdot \boldsymbol{F}_p(\boldsymbol{U}) = \boldsymbol{S}_p$$

- Shock-capturing schemes
- 1D-3D, various geometries
- Includes HD/MHD modules

AMRVAC Meeting @ CWI

Divergence cleaning

$$\nabla \cdot \nabla \phi = \nabla \cdot \boldsymbol{B}_{\text{old}}$$
$$\boldsymbol{B}_{\text{new}} = \boldsymbol{B}_{\text{old}} - \nabla \phi$$

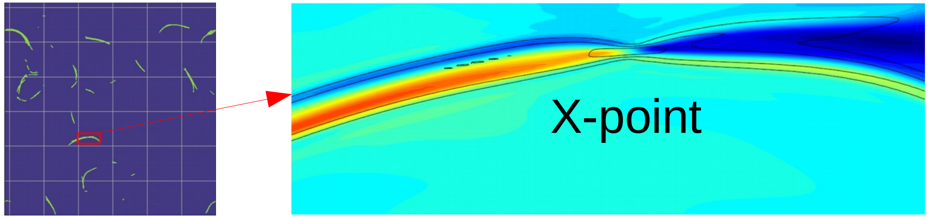
[Teunissen & Keppens, CPC, 2019]

Summary

- There exist many types of plasmas
- Plasmas have complex, multiscale behavior
- Computers play a key role in understanding them:
  - From data: machine learning
  - With simulations: physical models
- Modeling often requires **AMR** and **fast elliptic solvers**

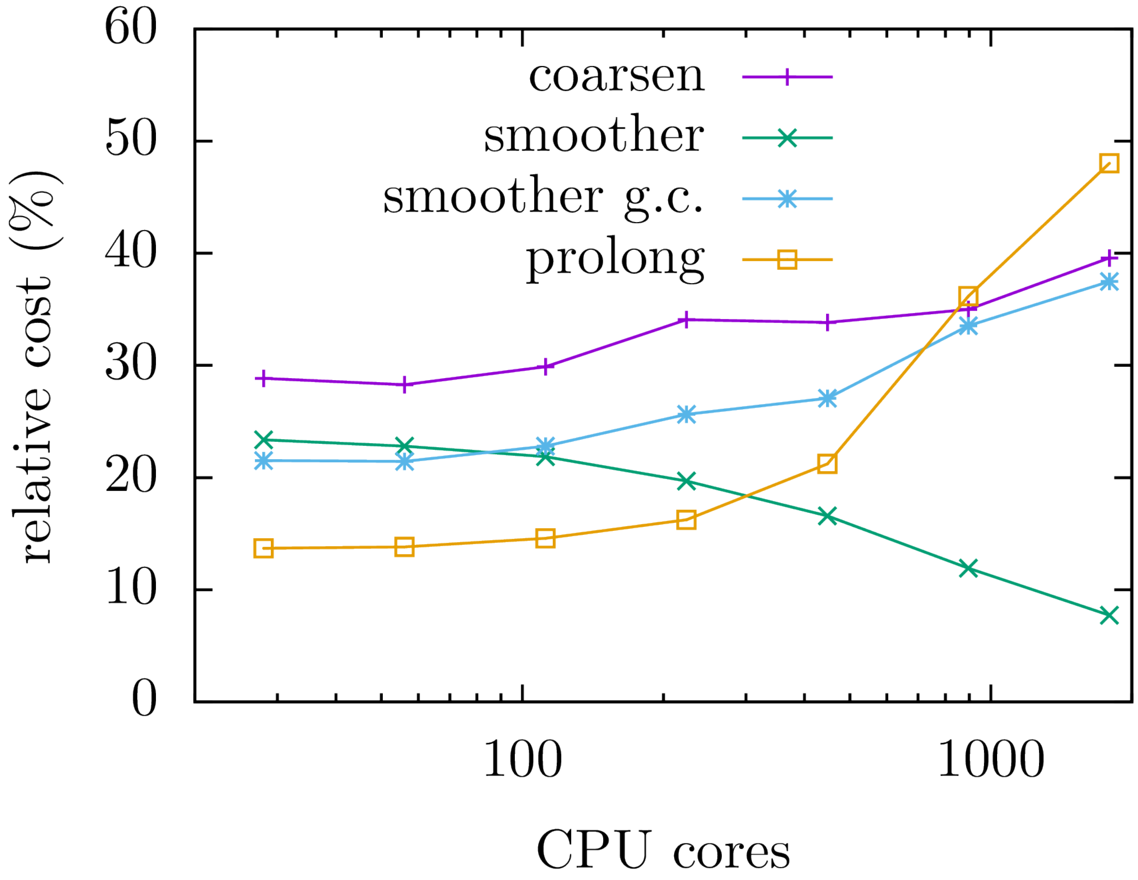
- *Outlook: combine physical models & machine learning*

Detecting reconnection
in simulations and data
(with Andong Hu)



Extra slides

Cost breakdown (1024^3 case)



Ghost cells near refinement boundaries