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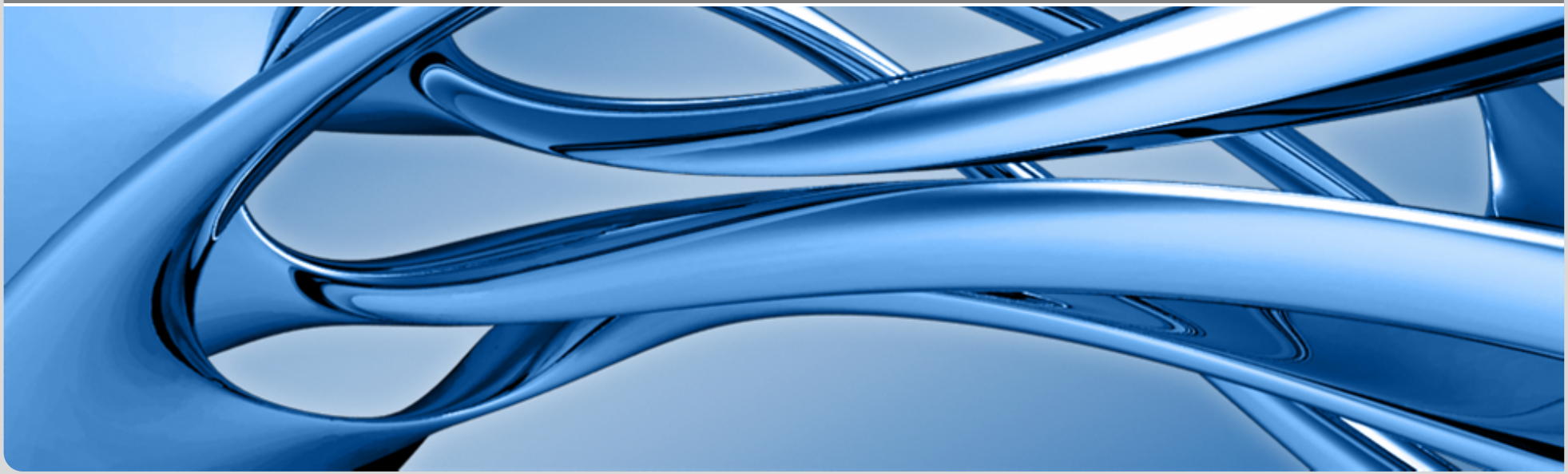
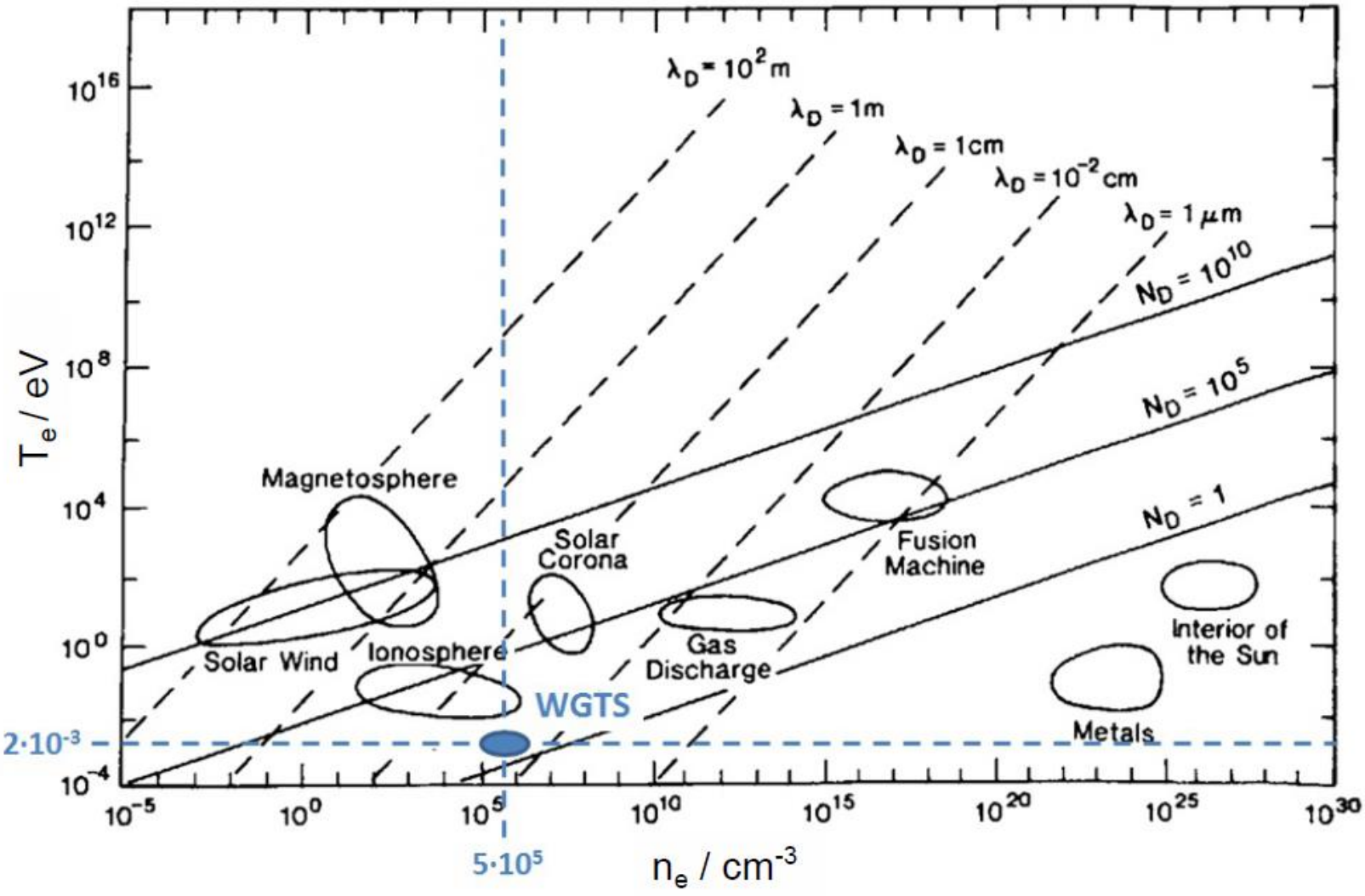
Plasma physics with KATRIN

Institut für Kernphysik



What is plasma physics?



What is plasma physics?

99% of the universe is in the plasma state

- Basically every system outside of Earth's crust is a plasma
- The plasma definition requires a *collective behaviour*, which is quasi-neutral
- The plasma state is not a state of matter in the physical sense (no first order phase transition)

The plasma state

- Plasma is a description of collective behaviour
- There is not a single plasma description
- Plasmas may show different behaviour depending on various parameters

Different plasma regimes

Hot vs. cold

- Most theoretical plasma descriptions assume $T = 0$
- Change in temperature changes the sound velocity in first place
- Absolute value of the temperature not too relevant
- Thermal energy has to be compared with magnetic field energy, particle rest mass

Different plasma regimes

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Unmagnetized vs. magnetized

Is there a strong magnetic background field?

- Magnetic field yields a preferential direction
- More different wave modes exist in a magnetic field
- Important parameter β: Ratio of thermal and magnetic energy
- Particles are tied to magnetic field lines in lowest order

Different plasma regimes

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Collisional vs. collisionless

Do collisions play a role?

- Strong collisional influence makes the plasma act like a fluid
- Collisions produce Maxwellian particle spectra
- Collision-free plasmas can support nonthermal particle populations

Different plasma regimes

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Fully vs. partially ionized

- There is no specific limit on the how ionized a plasma has to be
- Neutral particles and plasma couple only through collisions
- Minor fractions of neutrals only act as damping agent
- Ionization fraction is not identical for all species
- Saha equation relates ionization and temperature, but other effects (UV radiation, beta decay electrons) can increase the ionization

Different plasma regimes

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Fluid vs. kinetic

- Fluid = no single particle effects observable
- Kinetic = single particle effects (gyromotion etc.) relevant
- More collisions $\rightarrow$ fluid like plasma
- On large scales similar behaviour

Different plasma regimes

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Thermal vs. nonthermal

- Thermal plasmas show pure Maxwellian distribution functions
- Nonthermal plasmas have deviations from that, typically power-law tails
- Prerequisite for nonthermal plasmas: Low collision rate
- Nonthermal plasmas are prone to instabilities

Different plasma regimes

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Bound vs. unbound

Boundaries change stuff. . . (not a surprise after all)

Different plasma regimes

Single- vs. Multispecies

- Simple models assume either electro-positron or electro-proton plasmas
- A simple plasma has either species with identical mass/charge ratios or very large differences
- More species make a more diverse plasma

Different plasma regimes

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Typical analysis

- Theoretical approach to understanding a plasma: Find the eigenmodes of the plasma
- Neutral gas: One eigenmode, the sound wave
- Thermal electron-proton fluid plasma: Three eigenmodes with different behaviour depending on orientation to the magnetic field

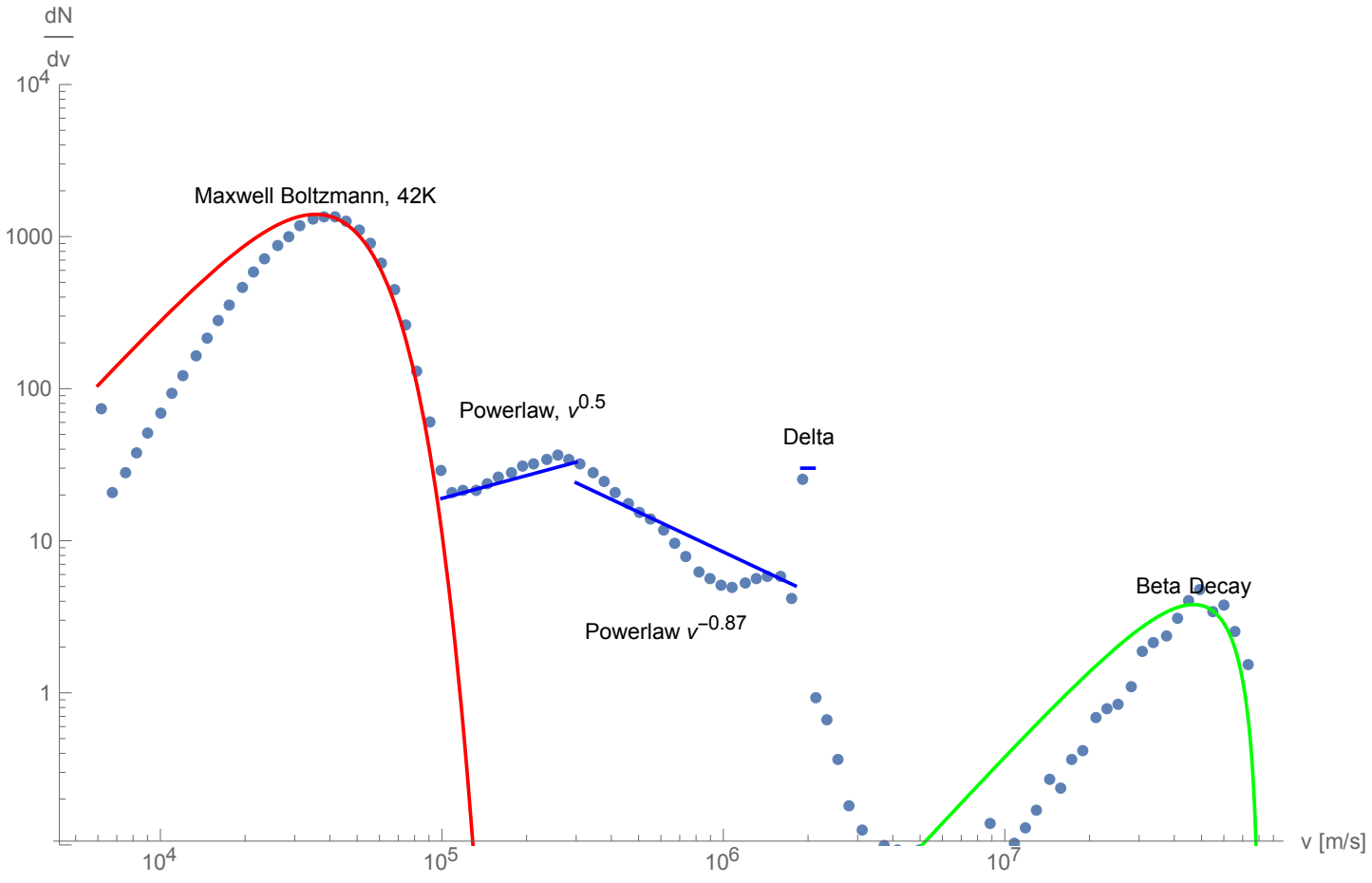
Some details about KATRIN's plasma

KATRIN parameter set

- $T = 30$ K
- $n_{T_2} \approx 10^{14}$ cm^{-3}
- $n_e \approx 10^5 - -10^6$ cm^{-3}
- $B = 2.5 \cdot 10^4$ G

Some details about KATRIN's plasma

Energy spectrum



Some details about KATRIN's plasma

Stability criterion

For

$$\frac{\partial f}{\partial v} > 0$$

the plasma is unstable and waves are excited at

$$\vec{k} \cdot \vec{v} = \omega$$

where ω and $\vec{k}$ have to fulfill the dispersion relation of an Eigenmode

The KATRIN plasma is obviously in an unstable configuration.

Some details about KATRIN's plasma

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Boundary conditions

- Grounded walls
- Rear wall...

The plasma inside KATRIN is

- Low temperature
- Strongly magnetized
- Multi-species
- Partially collisional
- Nonthermal
- Bound
- Partially ionized

Previous modeling attempts

Multi-fluid approach

$$\frac{\partial n_j}{\partial t} + \nabla \vec{\Gamma}_j = R_j$$

$$\vec{\Gamma}_j = \pm \mu_j n_j \vec{E} - \nabla (D_j n_)$$

with n_j particle density per species, $\vec{\Gamma}_j$ particle flux density
μ_j mobility tensor
D_j diffusivity tensor

Previous modeling attempts

Pros and Cons

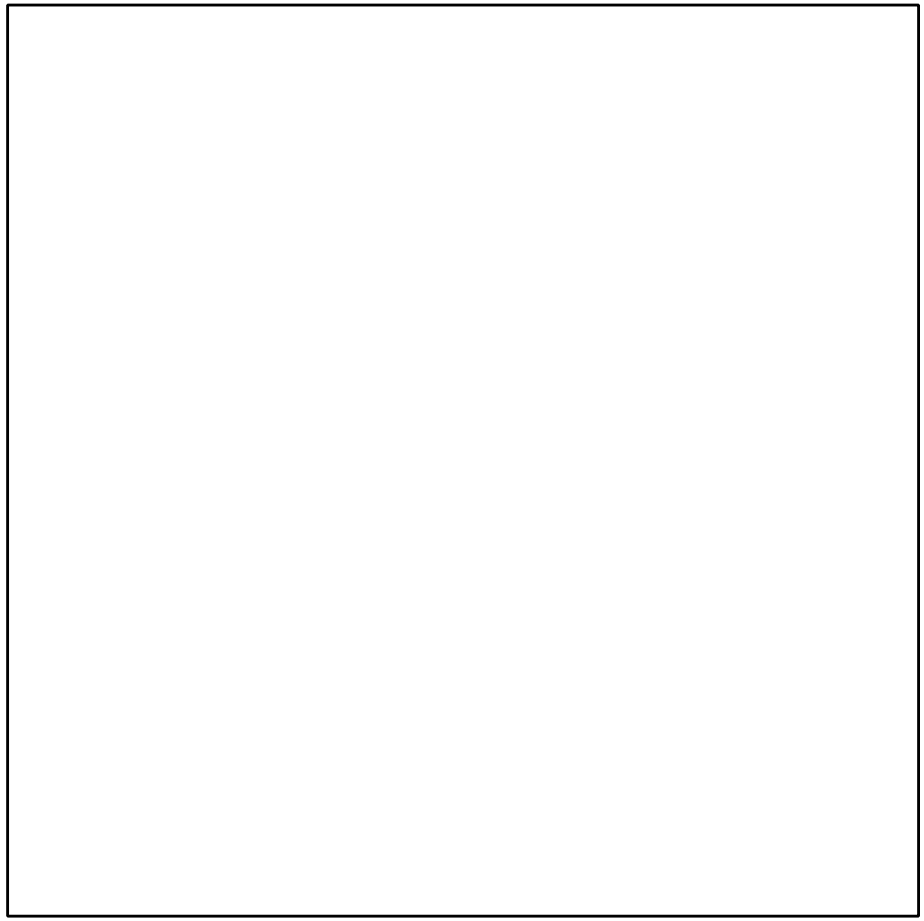
- Good description of a multi-species thermal fluid plasma
- Limited to the drift-diffusion approximation
- Model requires knowledge about microphysics
- Non-maxwellian parts of the distribution function are not covered

New modeling attempt

- Electric fields are mostly dominated by the electrons
- Non-maxwellian distribution of electrons
- Distribution of electrons in the plasma sheath at the wall presumably complicated

$\Rightarrow$ **kinetic approach is a good choice**

Particle-in-Cell



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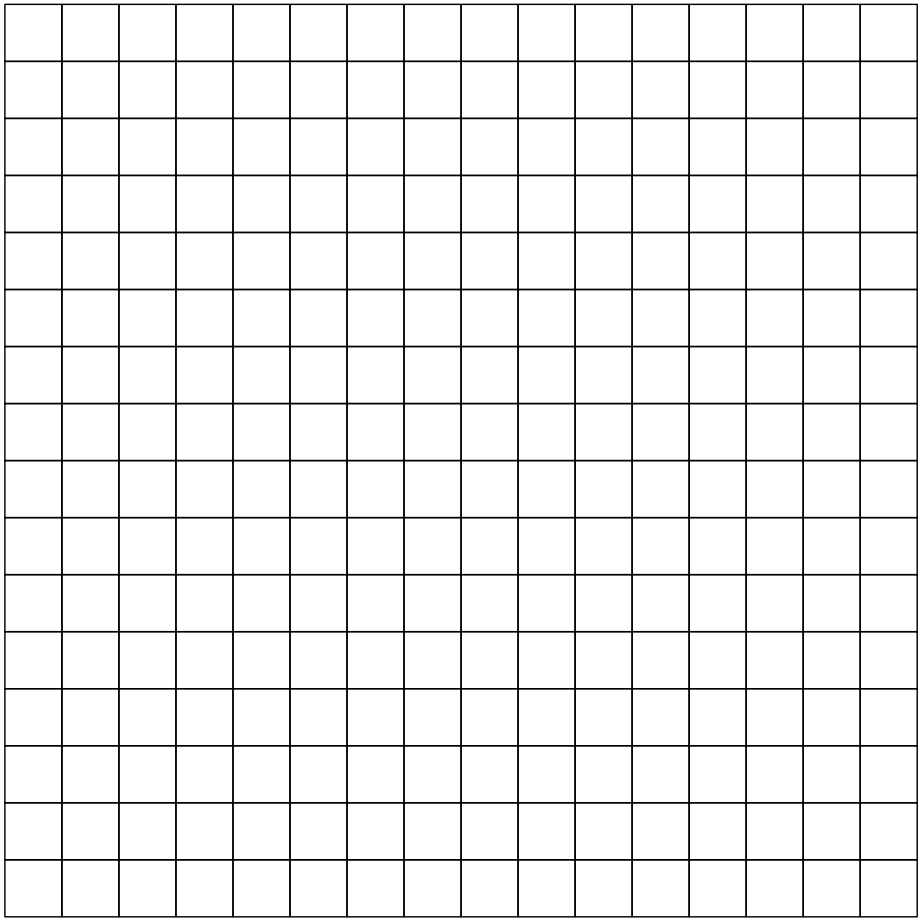

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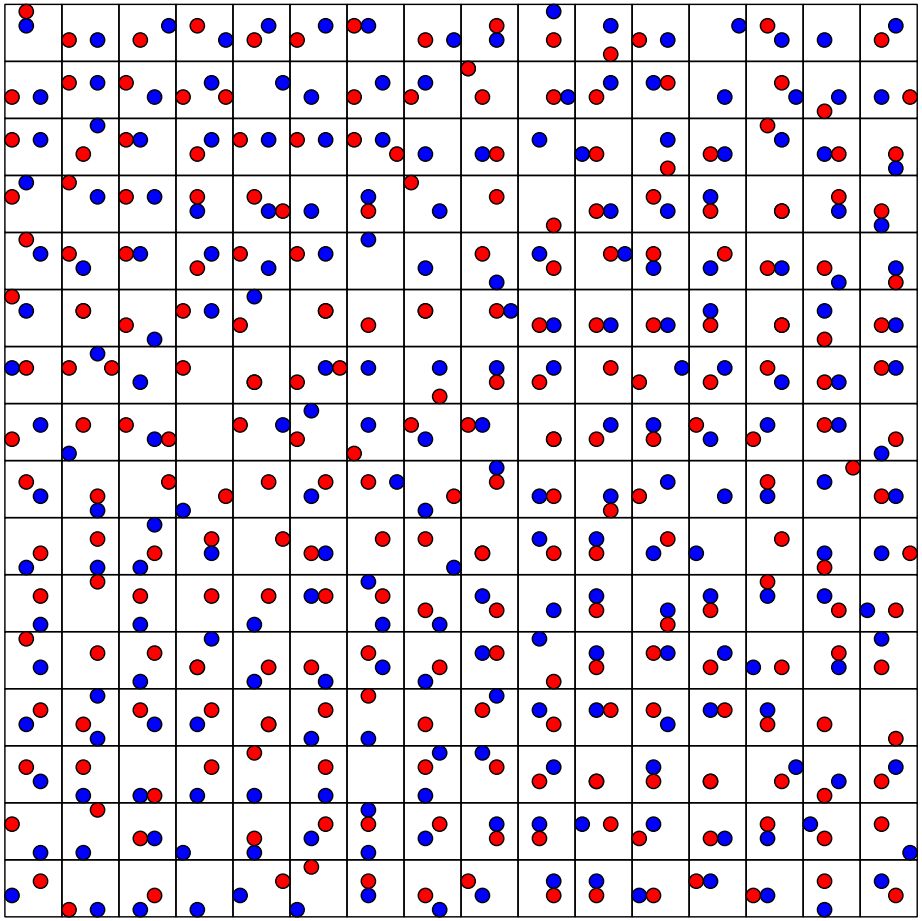

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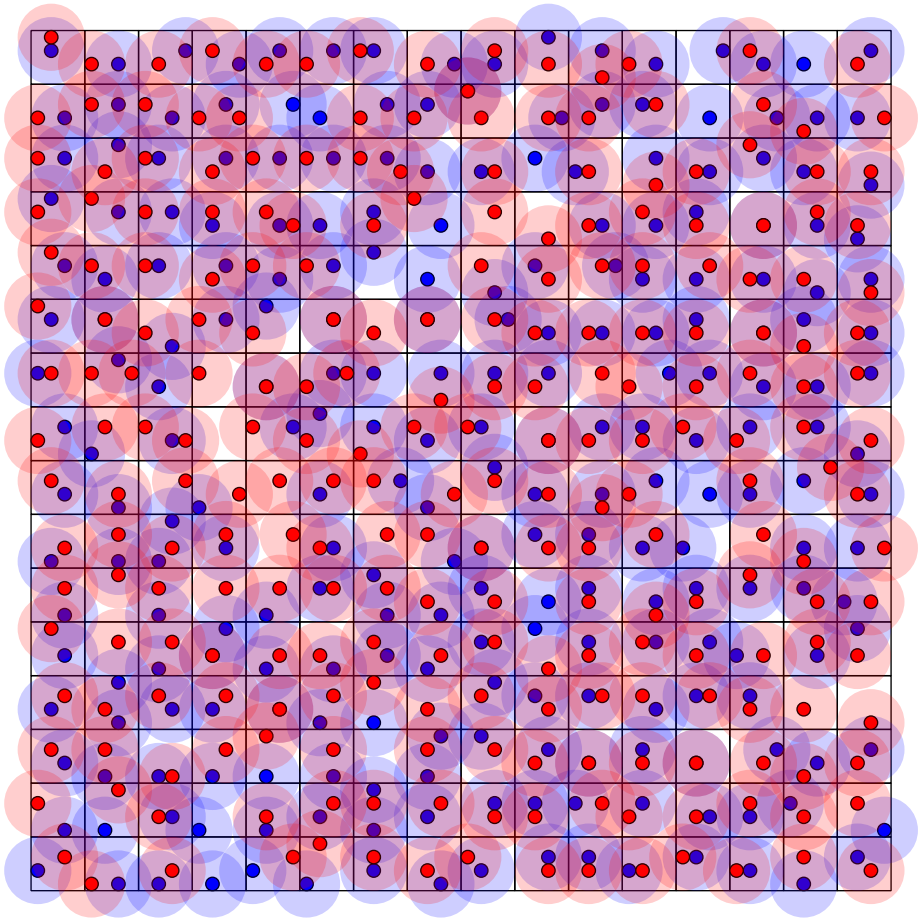

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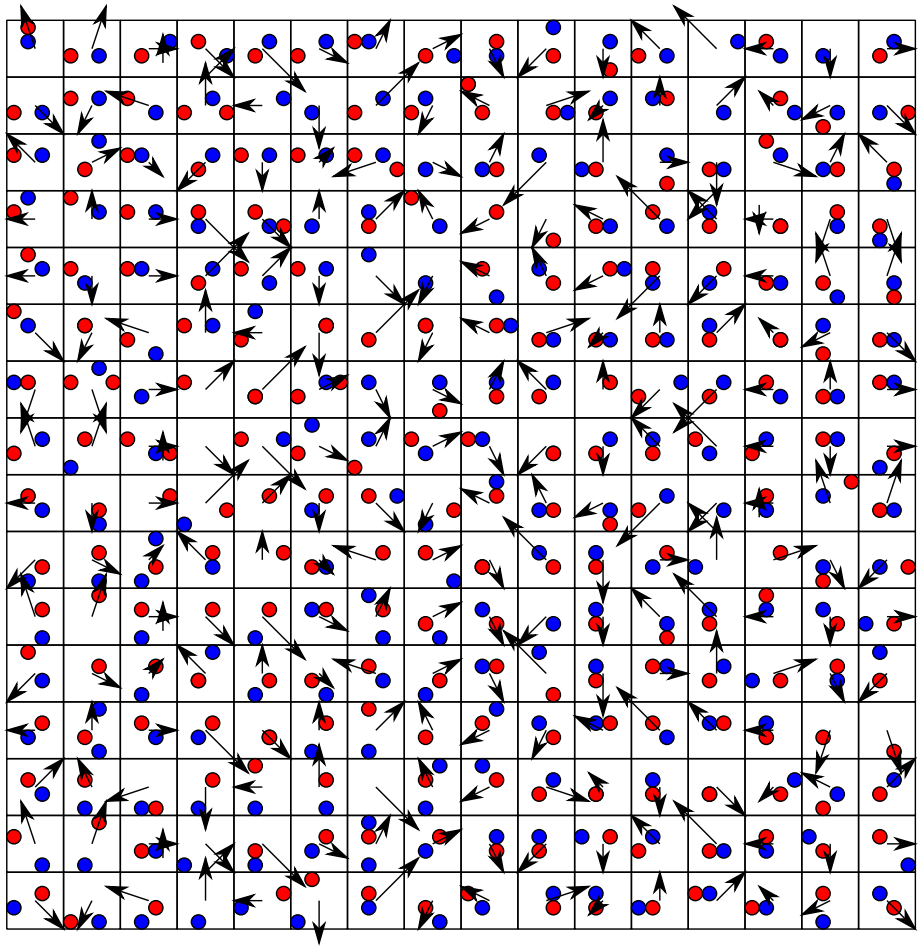

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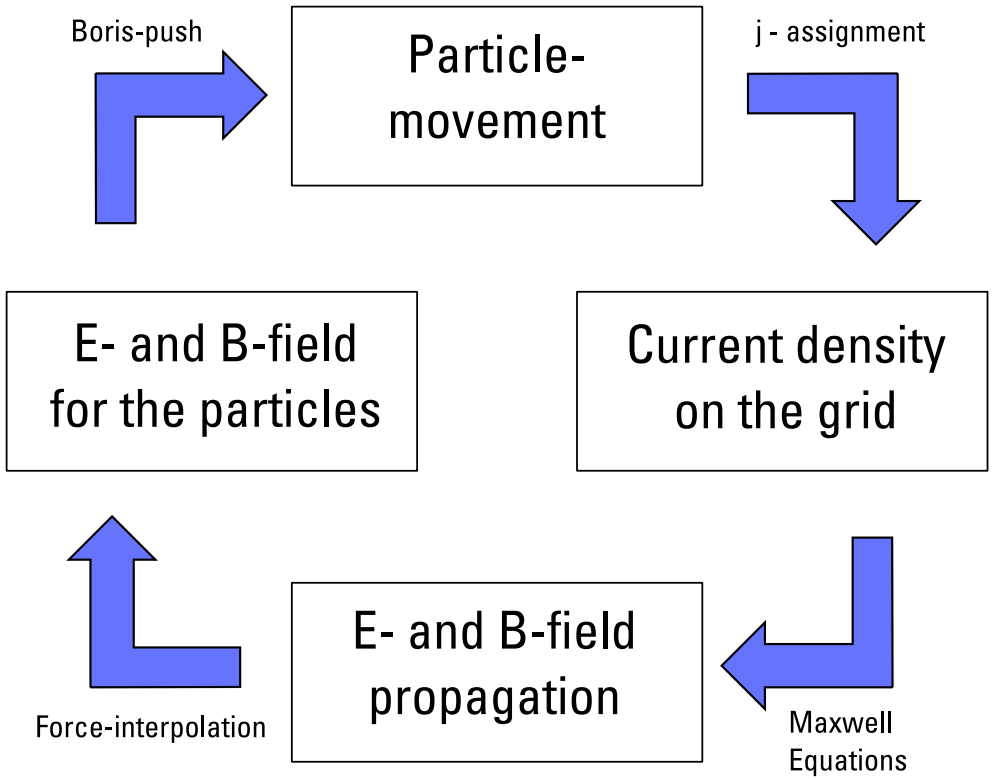

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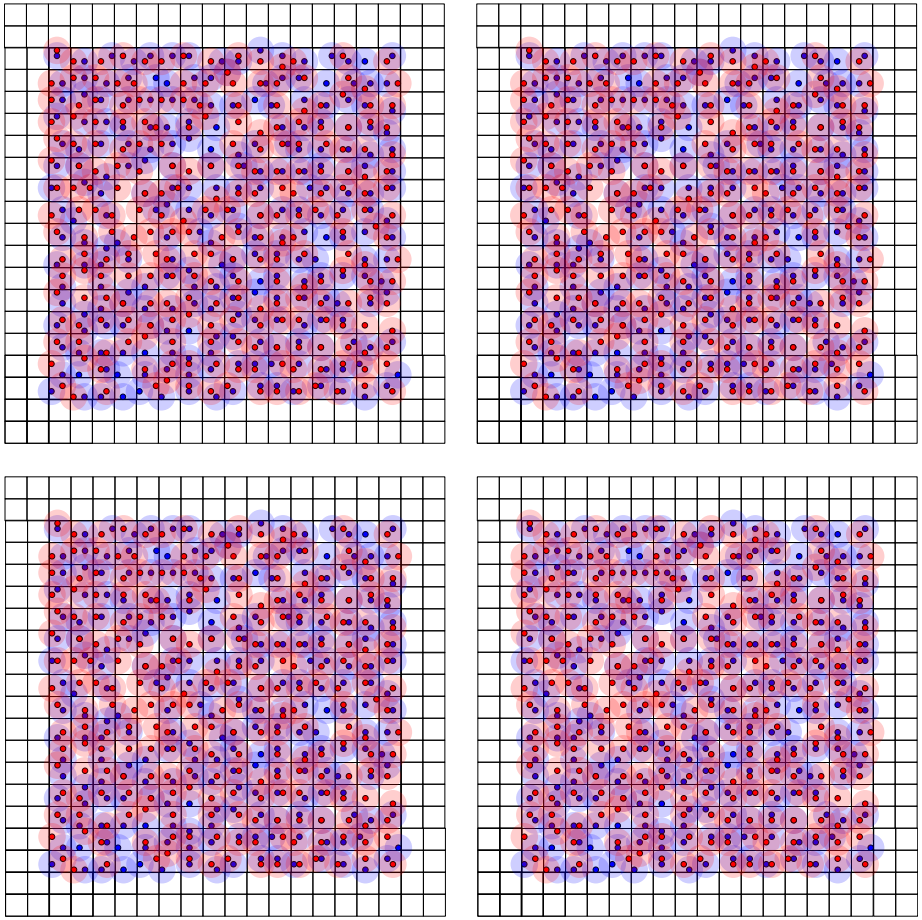


PiC Characteristics

General characteristics of PiC codes:

- Domain decomposition
- Ghost cells
- Nearest neighbor communication
- Good scaling is expected

ACRONYM

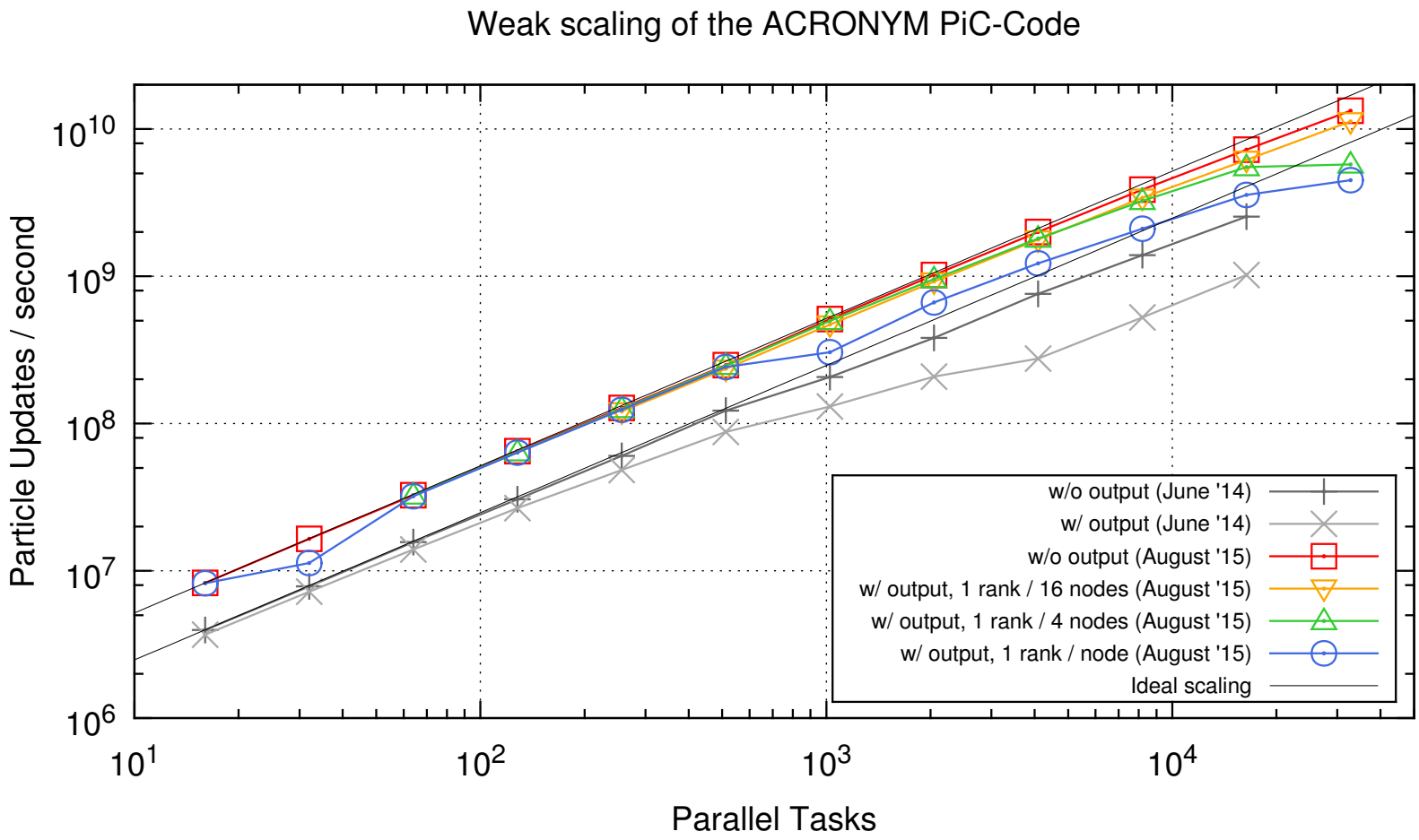
Another Code for moving Relativistic Objects,
Now with Yee lattice and Macroparticles

- Maxwell Solver: electromagnetic and electrostatic
- Shape Function: NGP, CIC, TSC, PQS or half order.
- 1d3v, 2d3v, or 3d3v phase space
- Periodic, reflecting (PEC) and absorbing (CFS CPML) boundaries
- Wave launching
- Optional Gauss cleaning or current smoothing
- Massively parallel, scales from 1 to 65536 cores
- Esirkepov current deposition
- Boris Push
- Relativistically correct

ACRONYM

- Explicit PiC code
- Portable C++
- Libraries: blitz++, MPI, HDF5, FFTW
- Running on several HPC systems

Weak scaling - SuperMUC



Challenges with PiC

Density and temperature

- Very high (charged particle) density
- ω_{pe} is very small
- cR/ω_{pe} is a very small number!
- Radial direction dominated by the boundary

Solutions:

- Make KATRIN wider by at least a factor of 10

Challenges with PiC

Density and temperature

- Plasma is extremely cold
- Very low (charged particle) density[1]
- λ_D is very small
- L/λ_D is very large number!
- Kinetic simulations require many cells

Solutions:

- Shorten KATRIN by at least a factor of 10
- Heat plasma by a factor of 100

[1] Yes, contradiction to the previous slide

Challenges with PiC

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Magnetic field

- Very high, makes Ω_i very large
- Gyroradius very small

Everything happens on scale above the gyroradius. That's good news!

Modeling approach

- Full KATRIN simulation not possible
- Take large enough 3D slice of KATRIN
- Assume ion currents as given background
- Implement boundary conditions
- Calculate electromagnetic field configuration from electron motion
- Use new EM field as seed for the iteration of ion currents

Known unknowns...

- Is the plasma stable on long time scales? Will there be large scale structures/filaments?
- How do nonthermal electrons diffuse?
- What kind of modes do actually exist in the KATRIN configuration?
- Is the assumption of adiabatic electron motion in the magnetic field justified?