Kinetic Plasma Physics in the Ionosphere □

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BU Summer School on Plasma Processes in Space Physics 2012

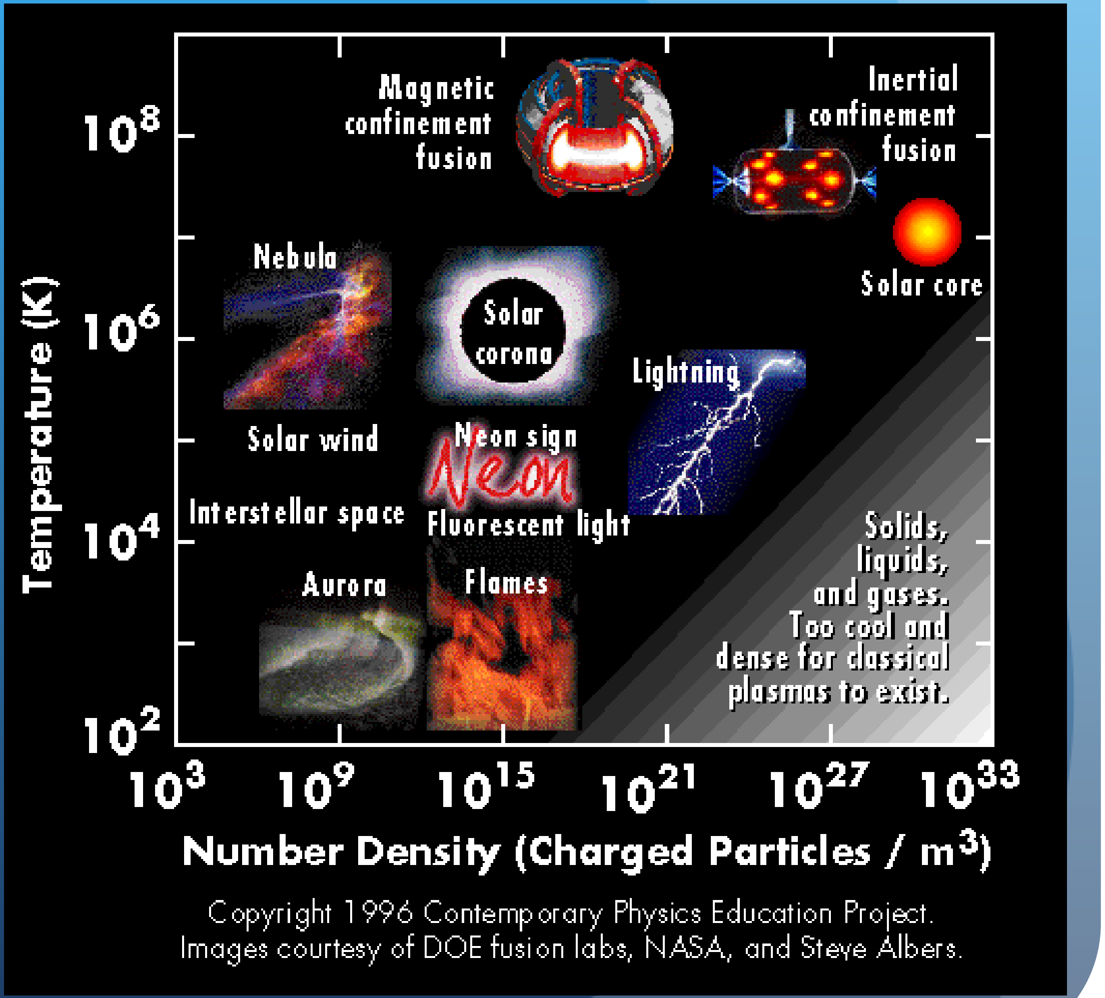
BOSTON UNIVERSITY

C S P

Center for Space Physics

Talk Outline

- Plasmas in the Ionosphere
- Kinetic vs. Fluid Physics
- Plasma Instabilities
- Kinetic Simulations
- Example problems in Space Physics
- Limitations of these methods



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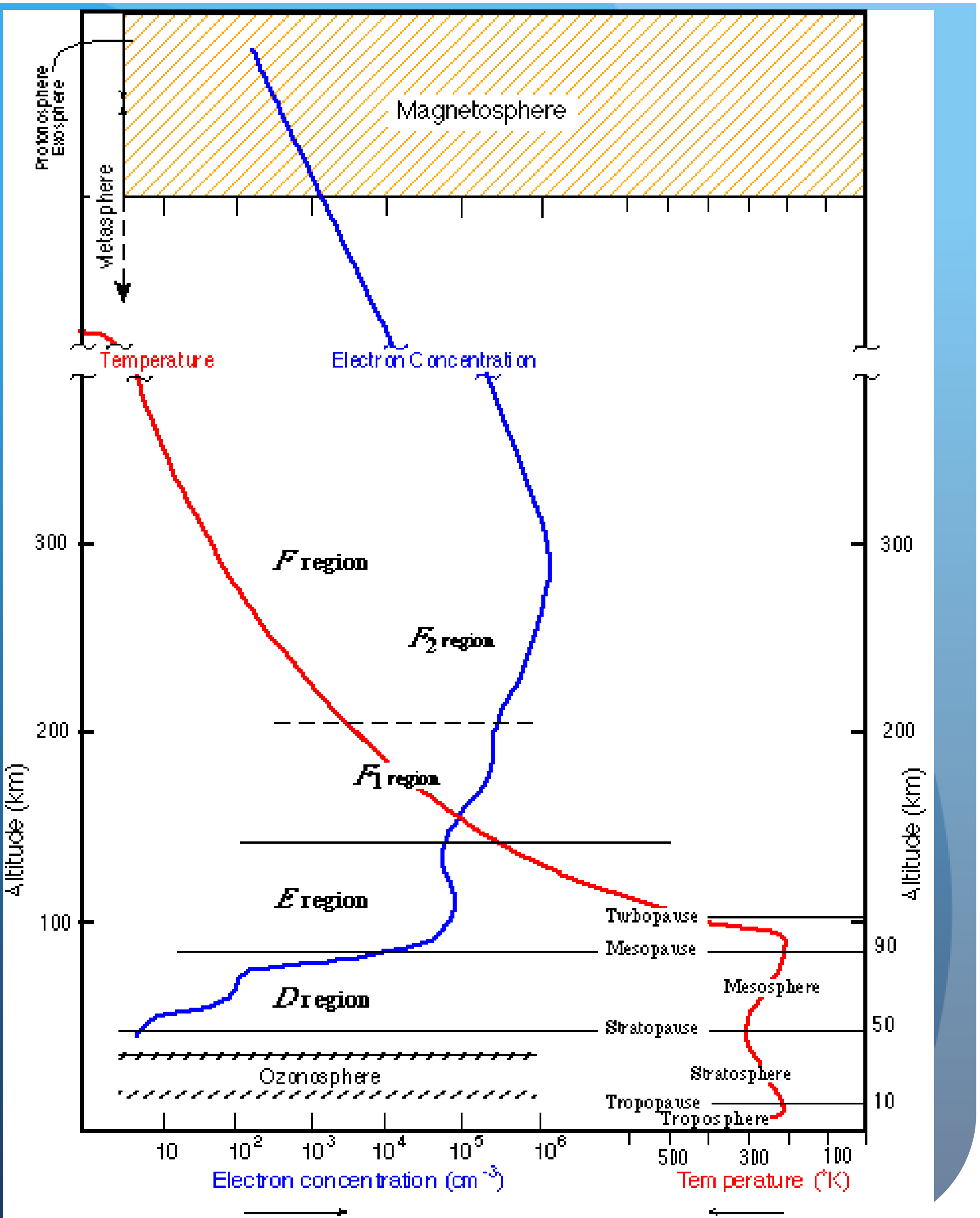
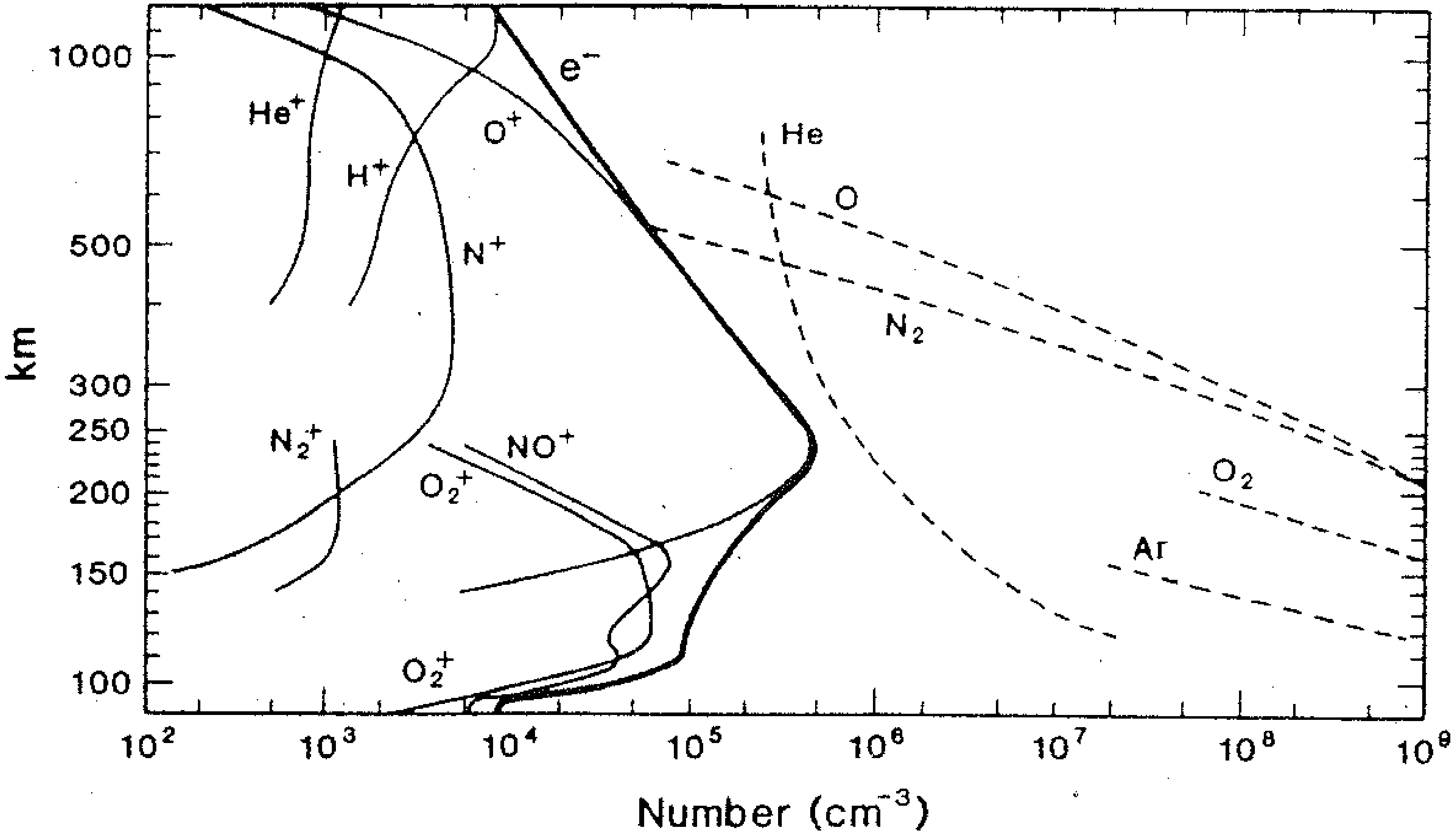
Images courtesy of DOE fusion labs, NASA, and Steve Albers.

Plasma in the Ionosphere



Ionosphere Plasma Composition



Ionosphere Plasma Density Variability

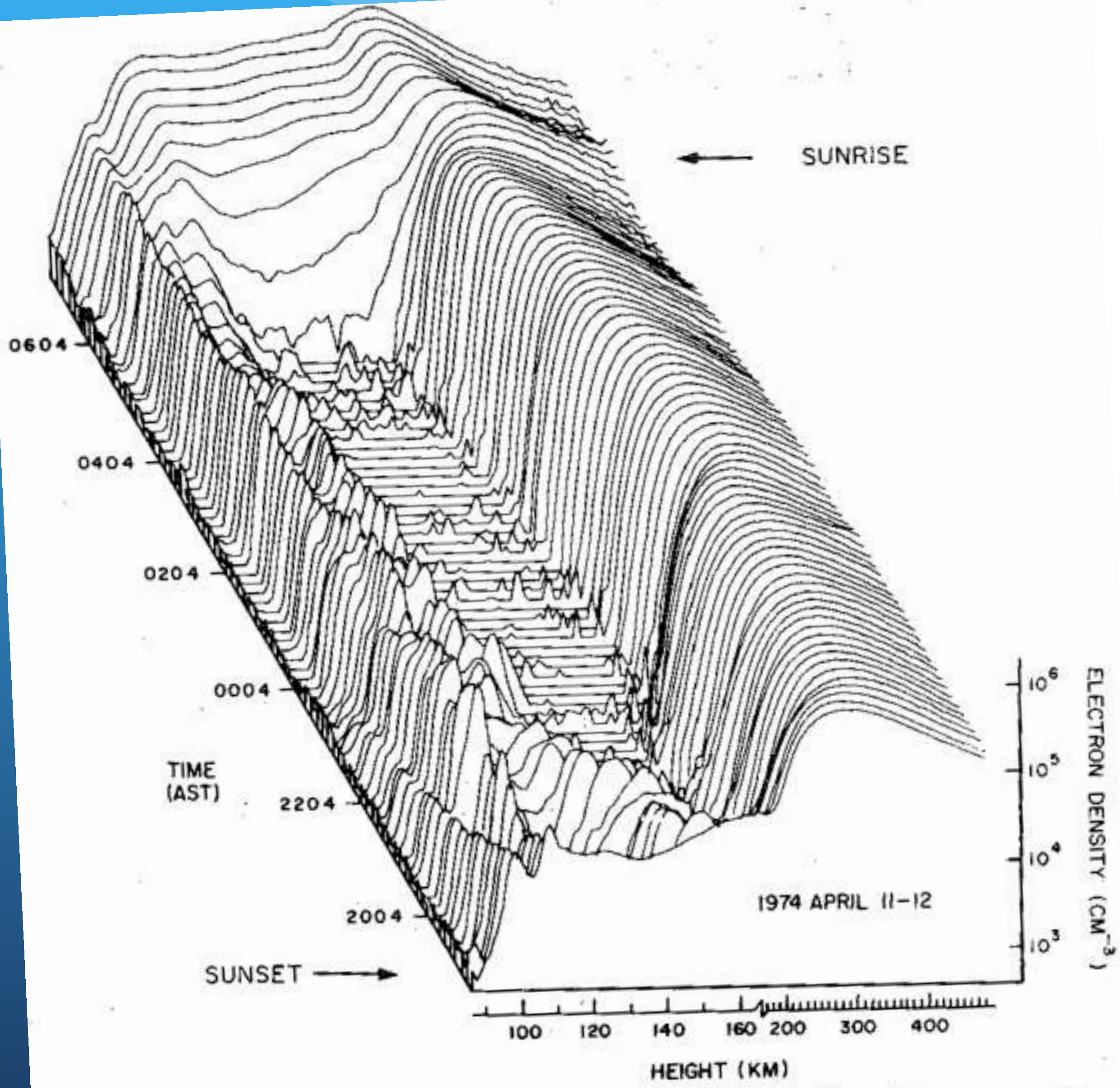
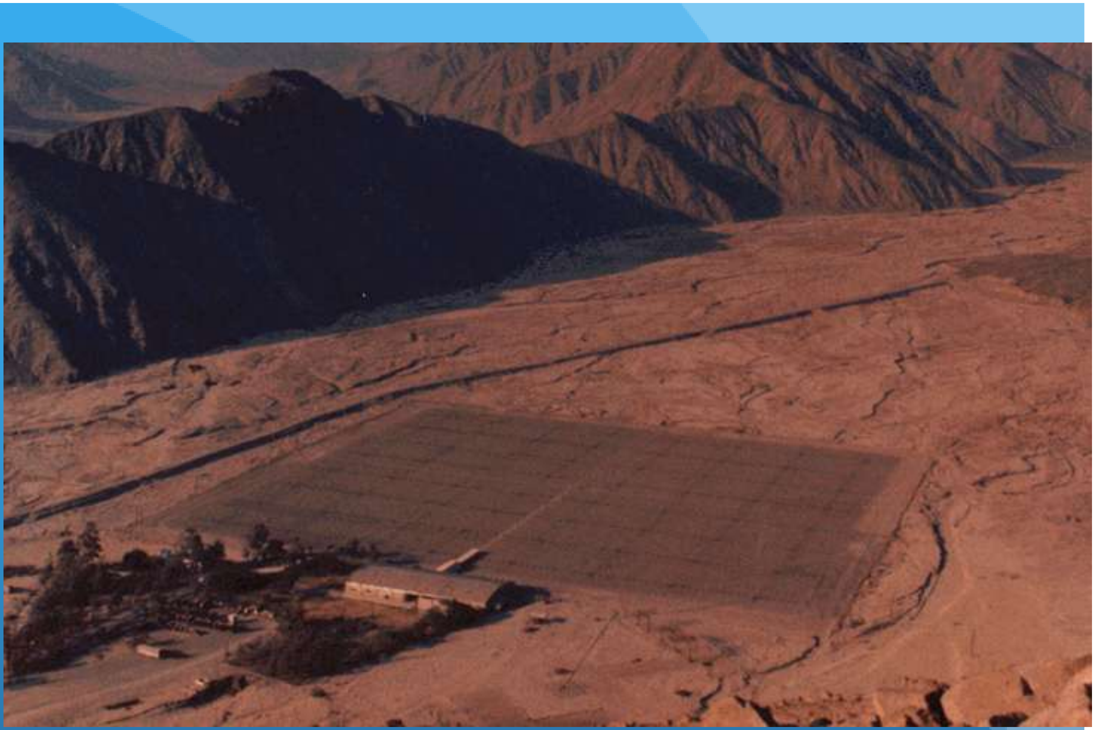


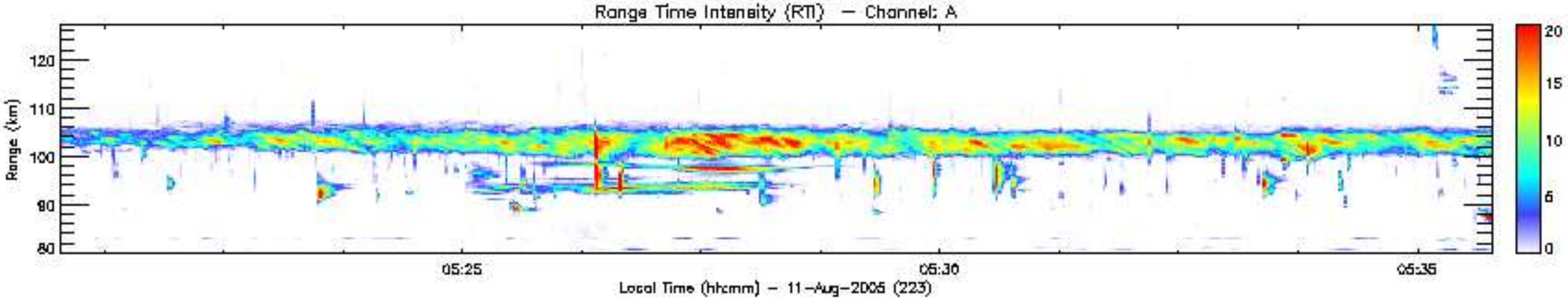
Fig. 1.3. Plasma density contours during a typical night over Arecibo, Puerto Rico. [After Shen *et al.* (1976). Reproduced with permission of the American Geophysical Union.]

Arecibo Incoherent scatter radar

Coherent Radar reflections from the Ionosphere

- Bragg Scatter: $\omega_{radar} >> \omega_p$
- Example:
    - Scatter off E-region ionosphere
        - ~90-130 km altitude
        - Electrojet irregularities
        - Meteor plasmas



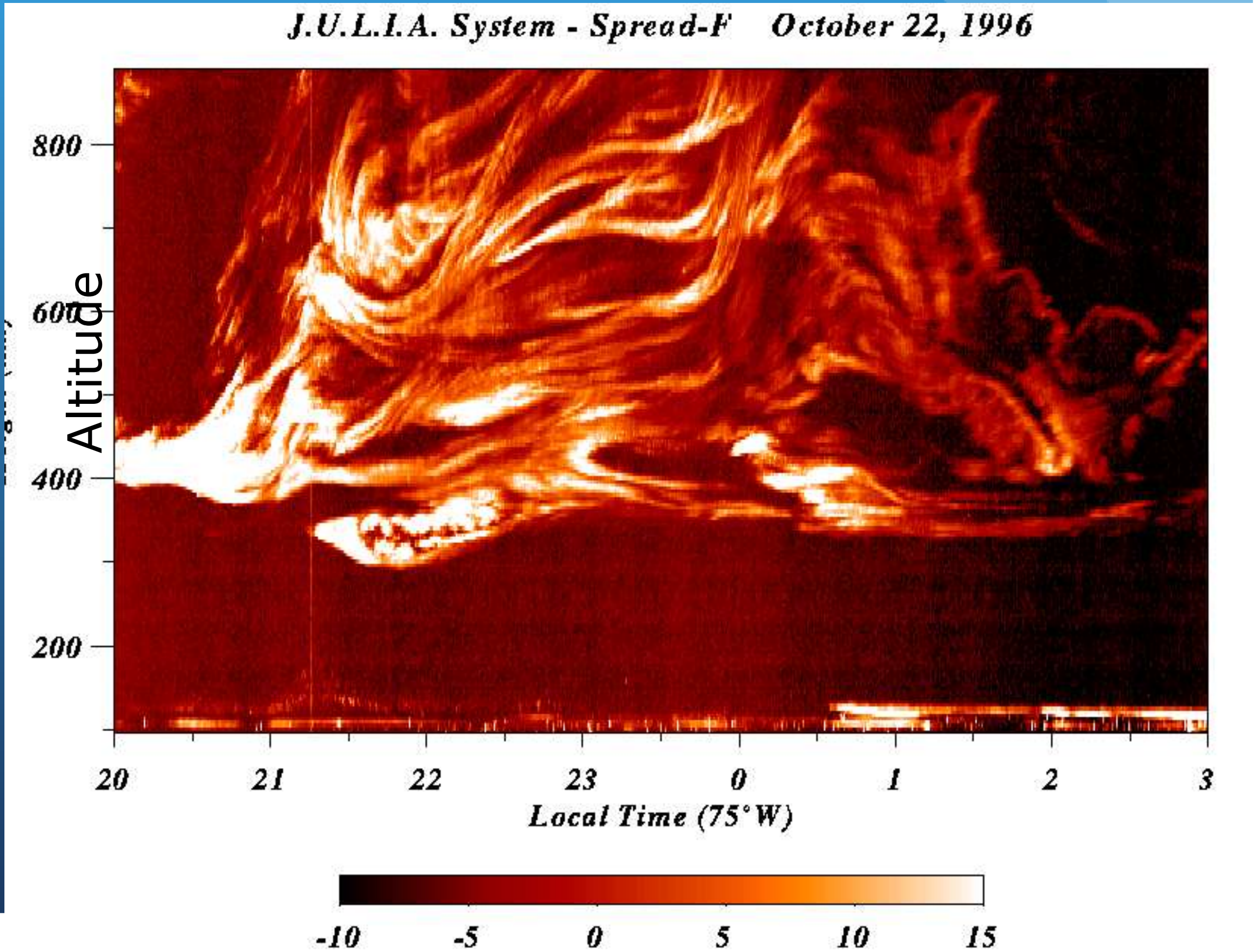

Range Time Intensity (RTI) — Channel: A
Range (km)
120
110
100
90
80
05:25
05:30
05:35
Local Time (hh:mm) – 11-Aug-2005 (223)
20
15
10
5
0

Radar measurements in the F region

Spread-F Turbulence:

Plasma Depletions which bubble up at night (sometimes)

Radar measurement of plasma density fluctuations



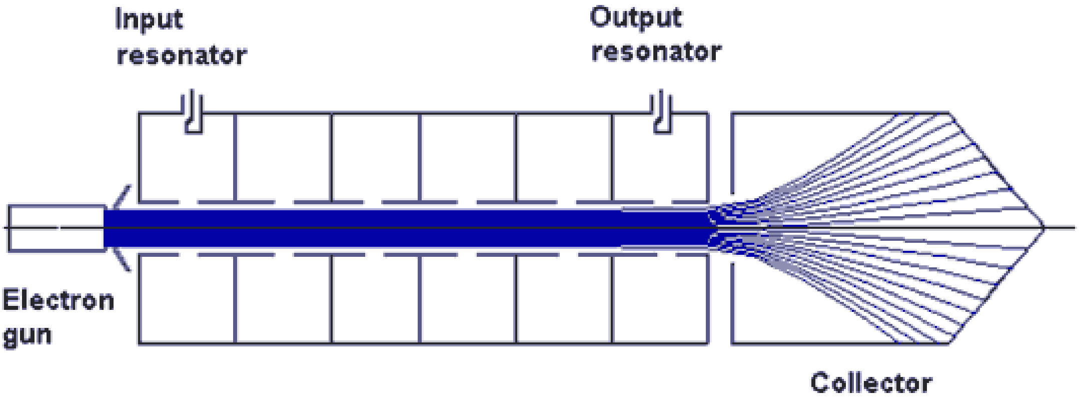
Plasma Physics Approaches

- Fluid Approaches
  - Cold
  - Warm
- MHD Approaches
  - Ideal
  - Resistive
  - Hall
- Kinetic Approaches
- What are the differences?

What are simulations?

- Views of nature:
  - Physicists think that the real world approximates equations.
  - Engineers think that equations approximate the real world.
  - Mathematicians don't care…
- Simulations are a mathematical description, or model, of a real system typically in the form of a computer program
- Simulations explore the behavior of systems too complex for analytical theory
  - Inhomogeneous systems
  - Nonlinear systems
  - Turbulence

First Plasma Particle Simulations: Klystrons



1939: Klystron inventors William Hansen and brothers Russell and Sigurd Varian examine early model

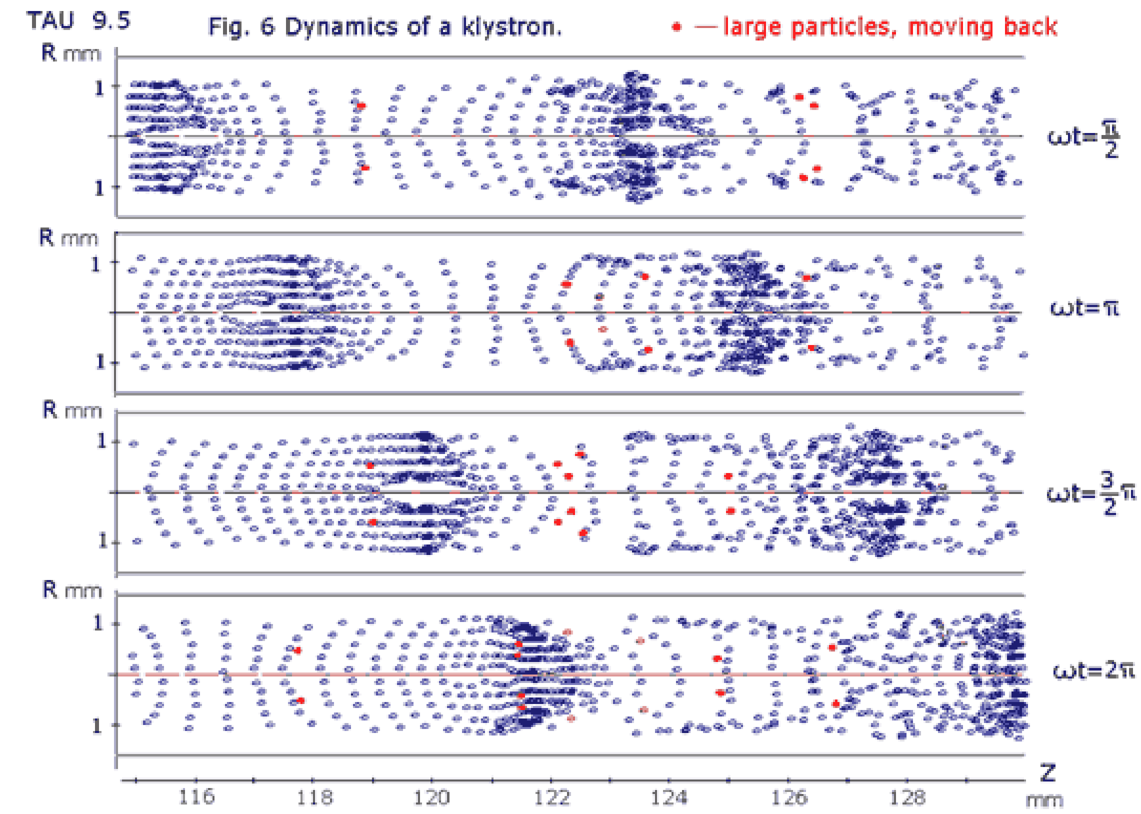


Fig. 6 Dynamics of a klystron.

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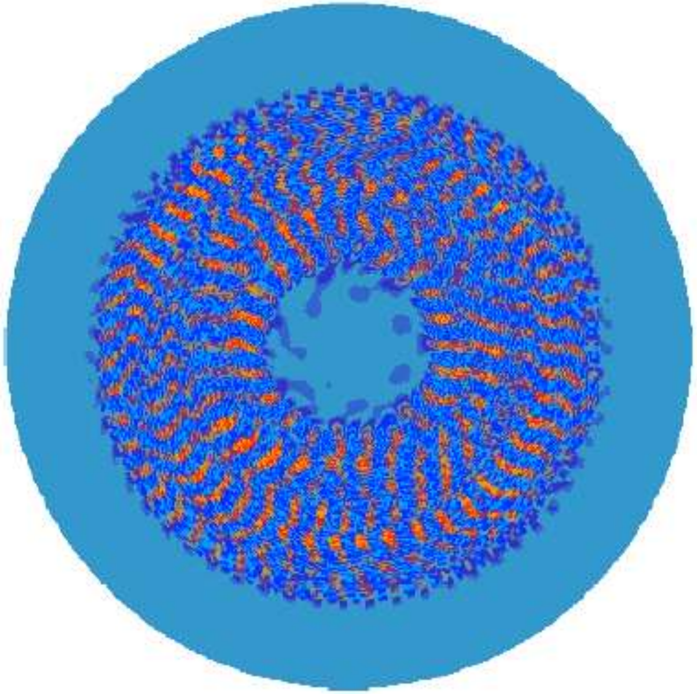
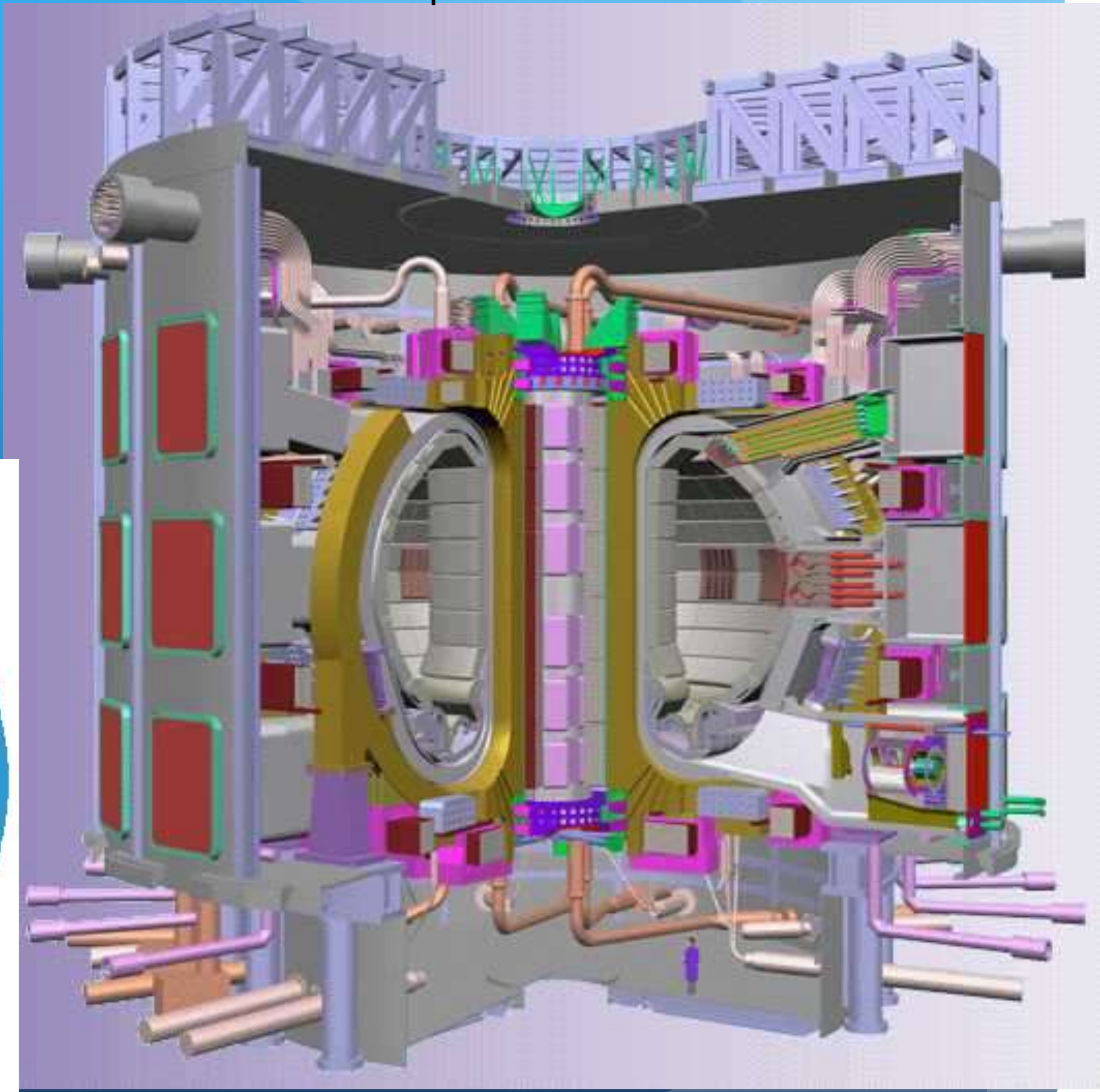
Fusion Energy Simulations



Proposed ITER Tokomak

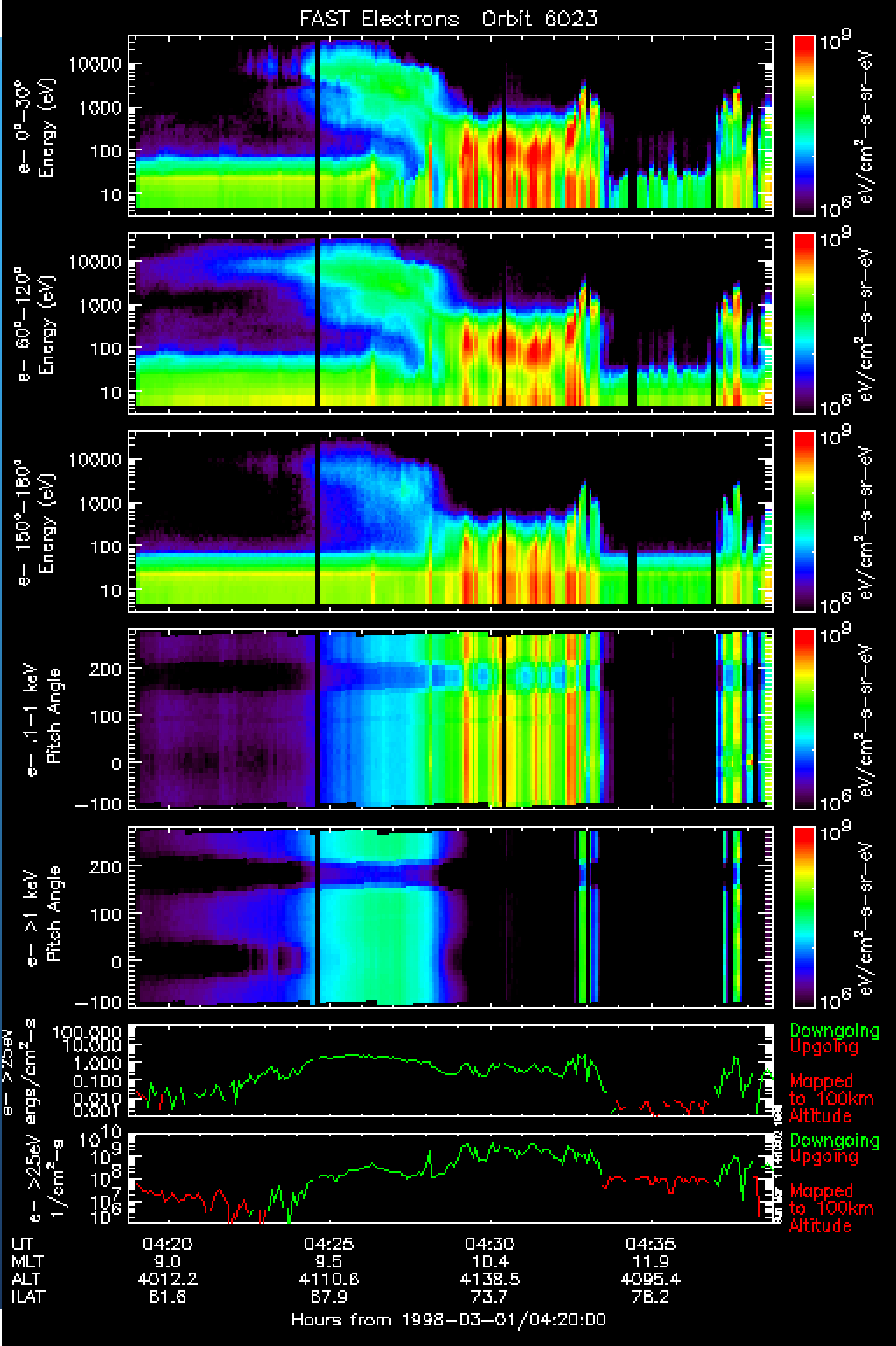


Temperature fluctuations from *Numerical Tokamak Turbulence Calculations on the CRAY T3E1* by Lynch, et al., Proceedings of the ACM/IEEE SC97 Conference (SC' 97)

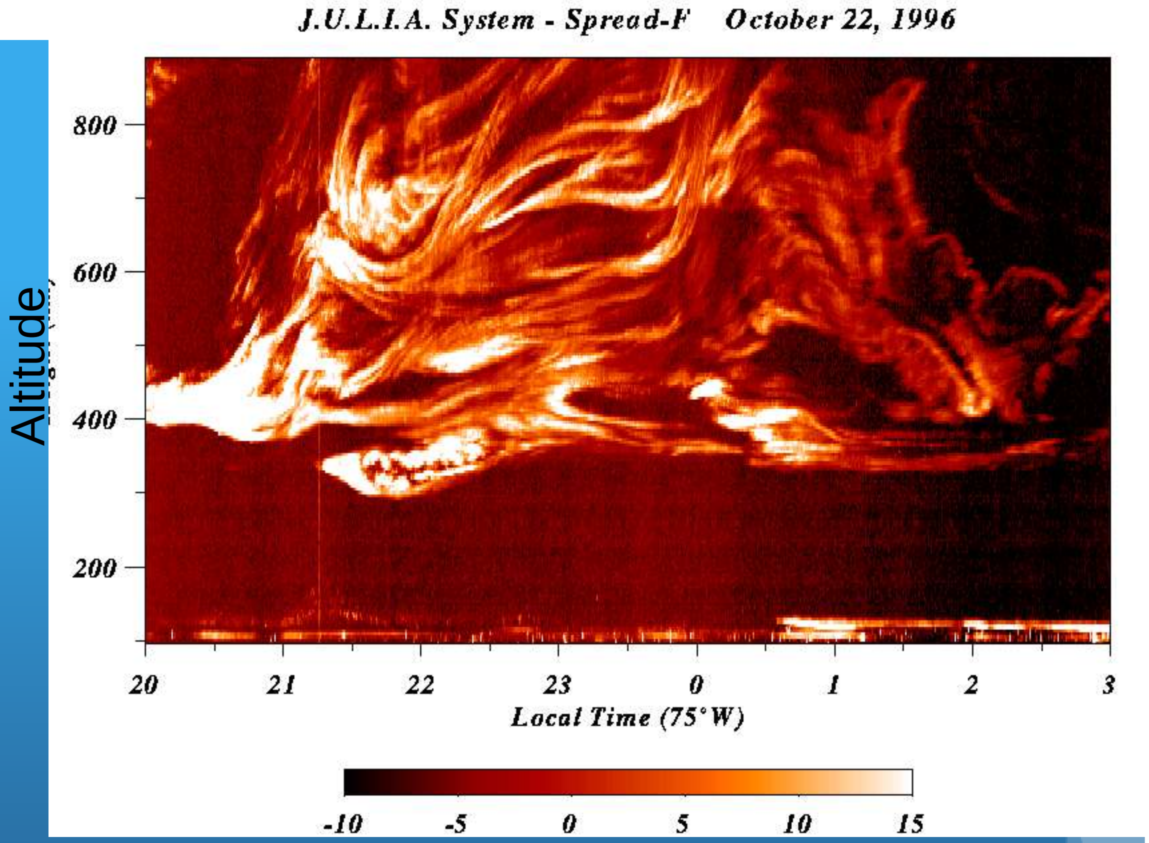
Where does one need simulations in Ionospheric Physics?

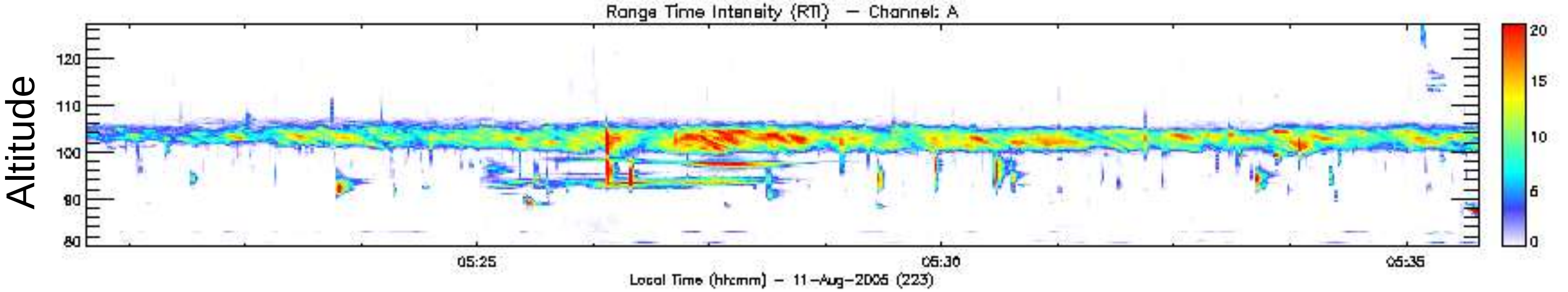
- The Auroral Ionosphere: Electrons accelerate from 3000-1500 km altitude by unknown mechanisms

FAST Spacecraft measures turbulent auroral plasmas



Radars Measure Electron Density Irregularities in Ionosphere





Plasma Theory in 5 Minutes

1. Charged particles create fields: *Maxwell's Equations*

$$\vec{\nabla} \bullet \vec{E} = \frac{e}{\varepsilon_0}(n_i - n_e) \qquad \vec{\nabla} \bullet \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \vec{\nabla} \times \vec{B} = \mu_0 \frac{\partial \vec{E}}{\partial t} + \mu_0 \varepsilon_0 \vec{J}$$

2. Lorentz Force Accelerates Particles:

$$\frac{d\vec{v}_i}{dt} = \frac{q_i}{m_i}\left[E(\vec{x},t) + \vec{v}_i \times B(\vec{x},t)\right]$$

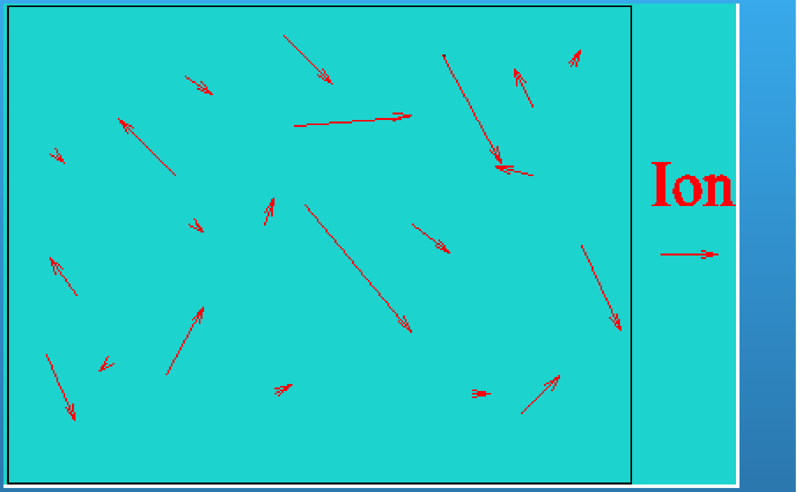
3. Equation of Motion

4. Collisions deflect particles (important in the lower ionosphere and other regimes)

Too many particles – Need simplifications!

Particle Simulations

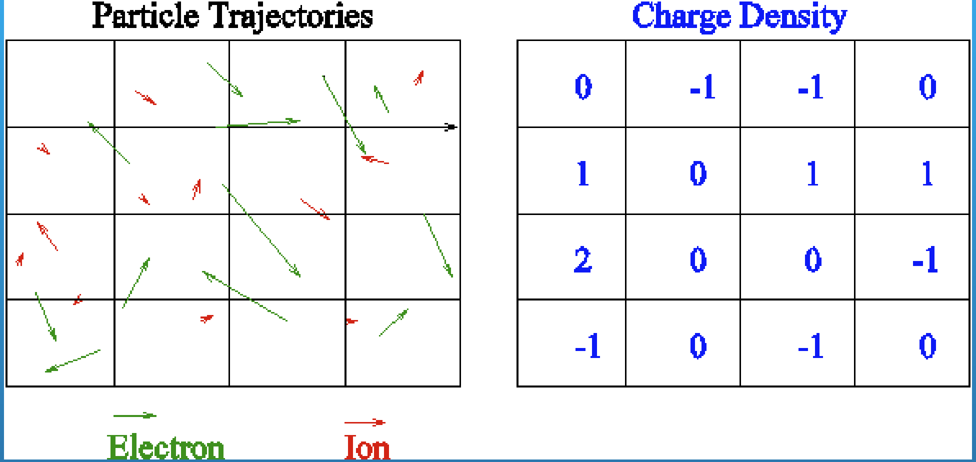
- Particles move within a box:
  - Position: $\boldsymbol{x}_i$
  - Velocity: $\boldsymbol{v}_i$
- Particles generate fields which accelerate other particles
- Too Slow! Speed proportional to the number of particles squared.



$$\vec{F}_{ij} = \frac{q_i q_j}{4\pi\varepsilon_0(\vec{x}_i - \vec{x}_j)^2}$$

Electrostatic Kinetic Simulation Method: Particle-In-Cell

1. Gather to determine charge density, ρ



0	-1	-1	0
1	0	1	1
2	0	0	-1
-1	0	-1	0

$$r(x) = \underset{particles}{\text{å}} q_i d(x - x_i)$$

2. Calculate Electric field:

$$\vec{\nabla} \bullet \vec{E} = \rho / \varepsilon_0$$

3. Update velocities:

$$\frac{d\vec{v}_i}{dt} = \frac{q_i}{m_i}\left[E(\vec{x}_i,t) + \vec{v}_i \,´\, B(\vec{x}_i,t)\right]$$

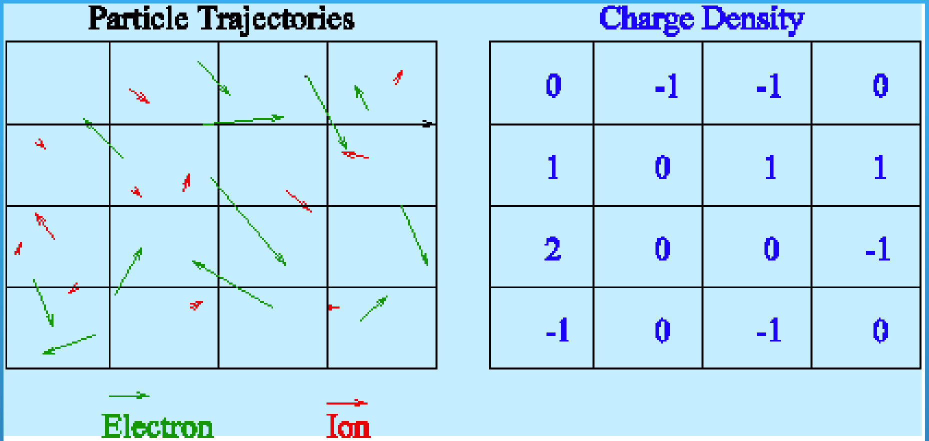
4. Update Positions:

$$\frac{d\vec{x}_i}{dt} = \vec{v}_i$$

5. Collide particles with neutrals

6. Go to Step 1

Assumptions made by PIC



Charge Density

0	-1	-1	0
1	0	1	1
2	0	0	-1
-1	0	-1	0

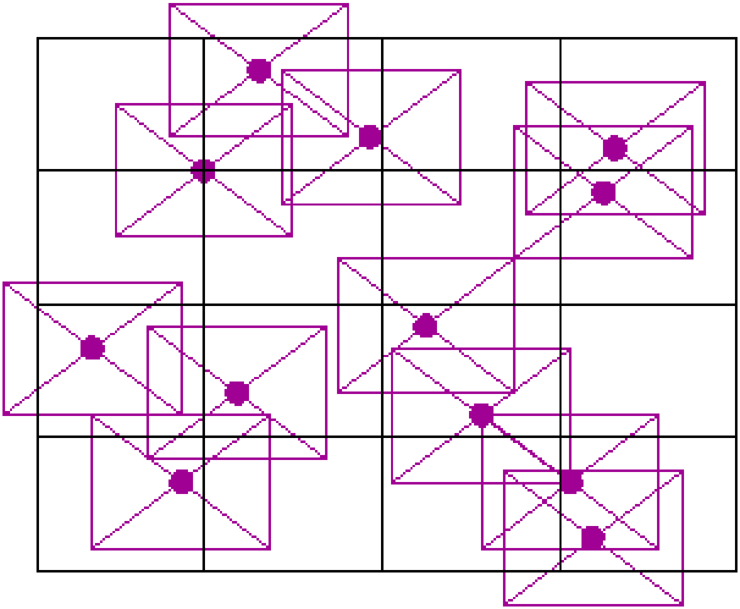
- Short range interactions eliminated
  - Simulators with a meshes cannot model behavior smaller than the mesh
  - Features must be bigger than the mesh
- Each PIC particle models the behavior of more than 10^6 real particles
- Fluid Simulators also use a mesh
  - Only one velocity in one location (unlike kinetic simulators)
  - Misses some physics but is less costly (per cell)
- Full kinetic physics represented
  - Particle trapping – resonant acceleration
  - Landau damping – resonant wave damping

One Problem with PIC

- Particle noise from limited numbers of particles
  - Random walk statistics:
  - Example n=144 particles/cell -> σ_n=8.3%
  - Fixes:
    - Nature reduces this through electrostatic shielding
    - Use non-point particles
    - Use millions and millions of particles
    - Use super computers!

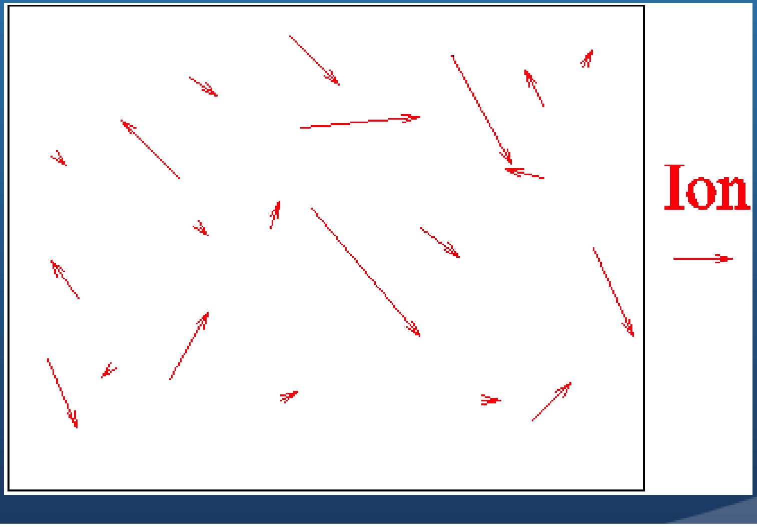
$$\sigma \propto \sqrt{n_{particles/cell}}$$

Macro-particles fill a volume



Boundary Conditions (BC)

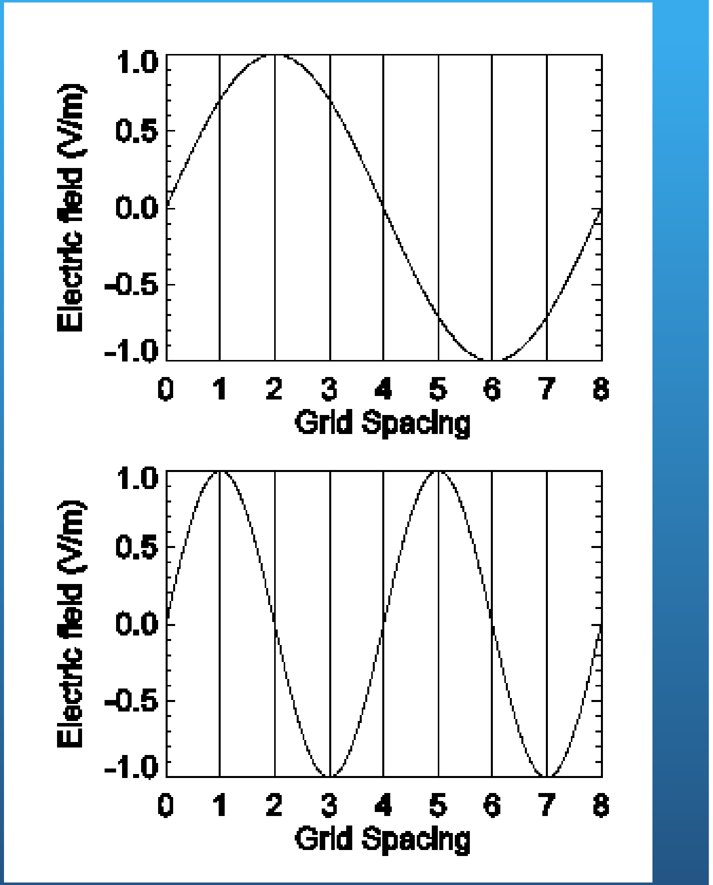
- Simulations of all types require BC
- BC introduce limitations and, sometimes, error
- Example: *Periodic* is the simplest BC
  - The right side connects to the left
  - The top to the bottom
  - Particles leaving the Left reenter on the Right and visa versa
  - Particles leaving the top -> bottom …



Boundary Conditions Cause Limitations

- Periodic boundaries quantize the simulation:
  - Only a full wave or
  - Integer multiples allowed
  - Simulations must not focus on waves spanning the system
- Other BC have other issues
- True in fluid simulators as well

Example in 1D



PIC Code…

```
 //  Read parameters from the input file:

  infile(argv[1]);

  //  Initialize the dynamic variables :

  init_misc();

  init_particles(pic, w, misc);

  init_fluid(fspecie, pic);

  init_field(Efield, rho);

//  Calculate the charges and currents on the grid.

  charges(rho, pic, fspecie, 0);

  //  Find the electric field on the grid at t=n:

  efield(Efield, rho);

 // Output any initial diagnostics:

 output (argv[1], pic, fspecie, Efield, rho, misc, w, it);
```

```
// Main timestep loop:

 for (it = it0; it <= nt; it++) {

// Apply the standard leapfrog method

    leapadv_subcycle(pic, fspecie, rho, Efield, w, misc);

   //Deal with any Boundary condition issues

   boundary(pic, Efield, w, misc, it);

   // Output data, diagnostics and restart:

   output (argv[1], pic, fspecie, Efield, rho, misc, w, it);

   }

 }//  End of main timestep loop
```

Charges.cc & density.cc

```
void charges(FArrayND &rho, particle *pic, fluid
      *fspecie, int it) {

  rho = 0.;

  for (int id=0; id<ndist; ++id) {

// Density returns the charge density of each species.

      density(den, id, pic, fspecie, qd[id]);

      rho += den;

} /* charges */
```

```
void density(FArrayND &den, int id, particle *pic, fluid
      *fspecie, FTYPE scaler) {

gather(den, INDICIES(pic[id].x, pic[id].y, pic[id].z),
      scaler*pic[id].n0);

}
```

Gather.cc

```
// 1-D Gather
void gather(FArrayND &den, PTYPEAVec &x, FTYPE n0)
{
  den=0;
  //  For each particle ...
  for (i = 0; i < np; ++i) {
    // Define the nearest grid points:
    ixl = (int) x(i);
    ixh = ixl + 1;
    if (ixh == nx) ixh = 0;
    // and the corresponding linear weighting factors:
    wxh = x(i) - ixl;
    wxl = 1. – wxh;
    // Add this particle's contribution to den:
    den(ixh) += wxh;
    den(ixl) += wxl;
  } // end for (i = 0; i < np; ++i)
  // Express in physical units:
  den *= nscale;
} // End 1-D gather
```

Field Solvers

- Electrostatic: Gauss Law

$$\nabla \bullet \vec{E} = \rho / \varepsilon_0 \Rightarrow \nabla^2 \phi = -\rho / \varepsilon_0$$

- How to solve on a mesh?
  - Spectrally:
    - Fourier Transform density, ρ

$$F(r) = \tilde{r}$$

    - Solve for Fourier Transformed potential

$$-k^2 \tilde{f} = -\tilde{r} / e_0 \text{ Þ } \tilde{f} = \tilde{r} / e_0 / k^2$$

    - Inverse transform potential

$$F^{-1}(\tilde{f}) = f$$

- Finite Difference
  - In 1D, qt the mesh point i, solve for ϕ_i,

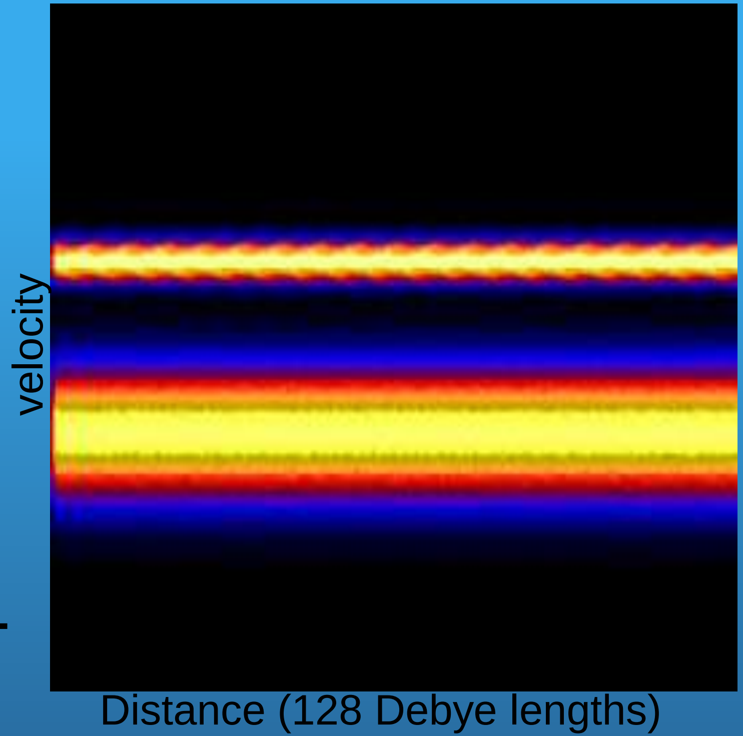
$$f_{i-1} - 2f_i + f_{i+1} = r_i / e_0$$

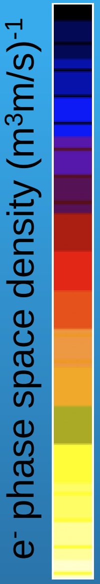
  - Requires Matrix Solve

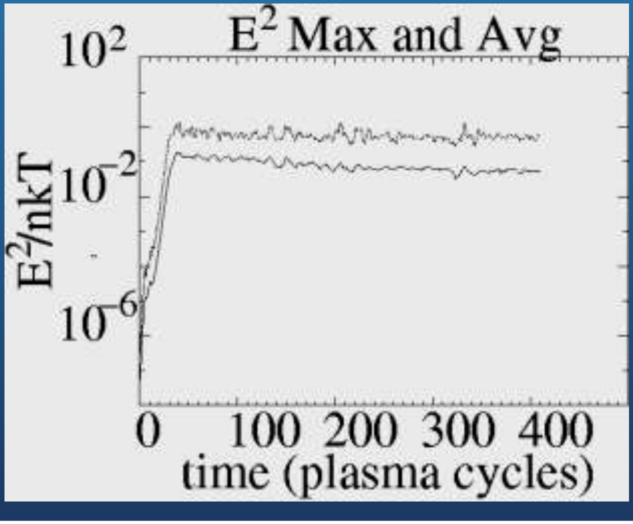
- Electromagnetic:
  - Leapfrog E and B on the mesh
  - Other Methods?

Example: 1D electron two-stream Instability

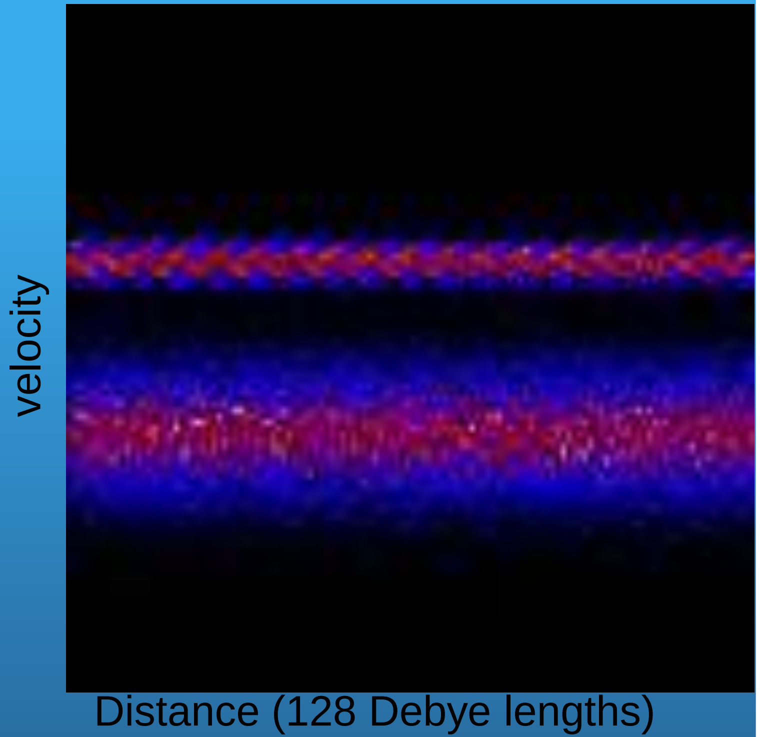
~1 Million particles

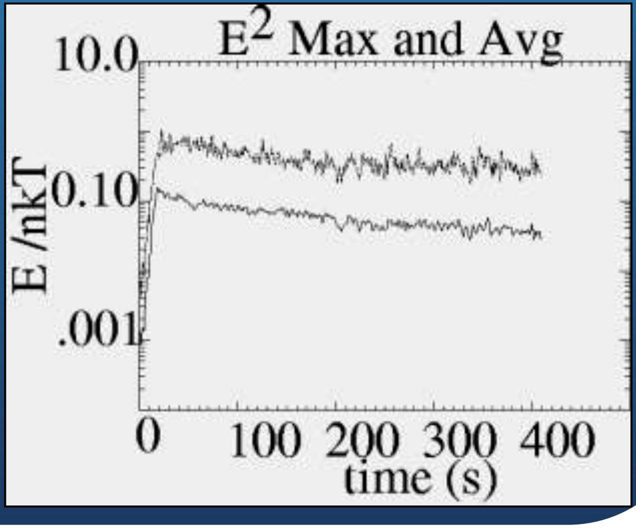




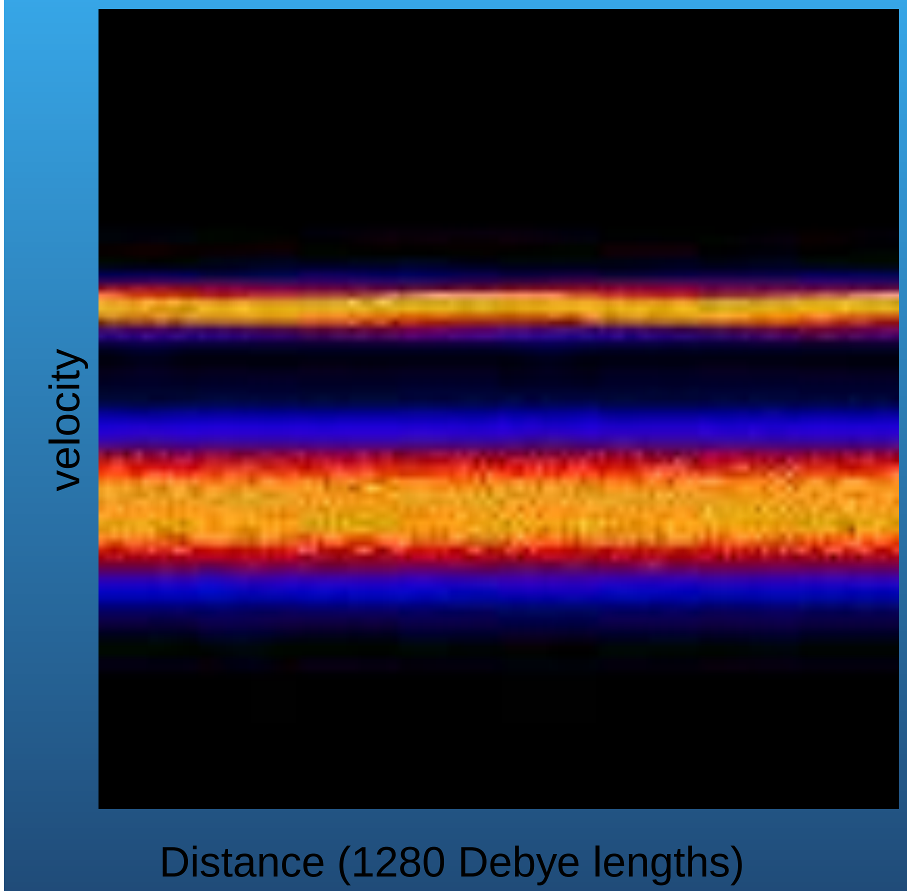


~1/64 Million particles

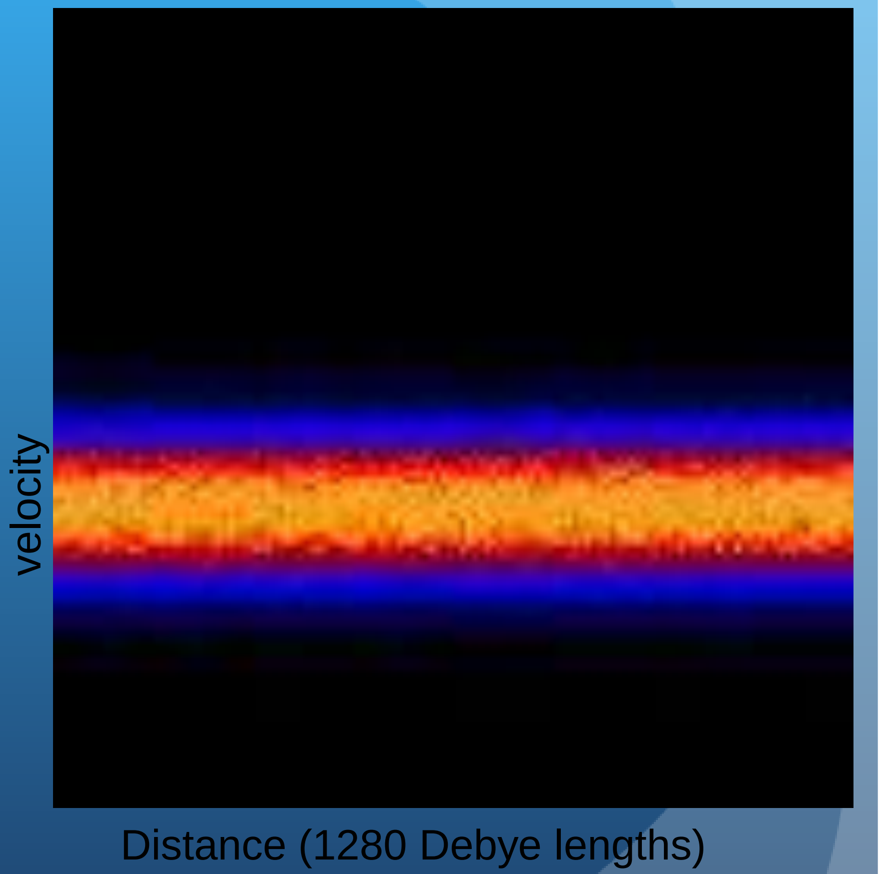




Expand grid spacing 10X



Eliminate Beam



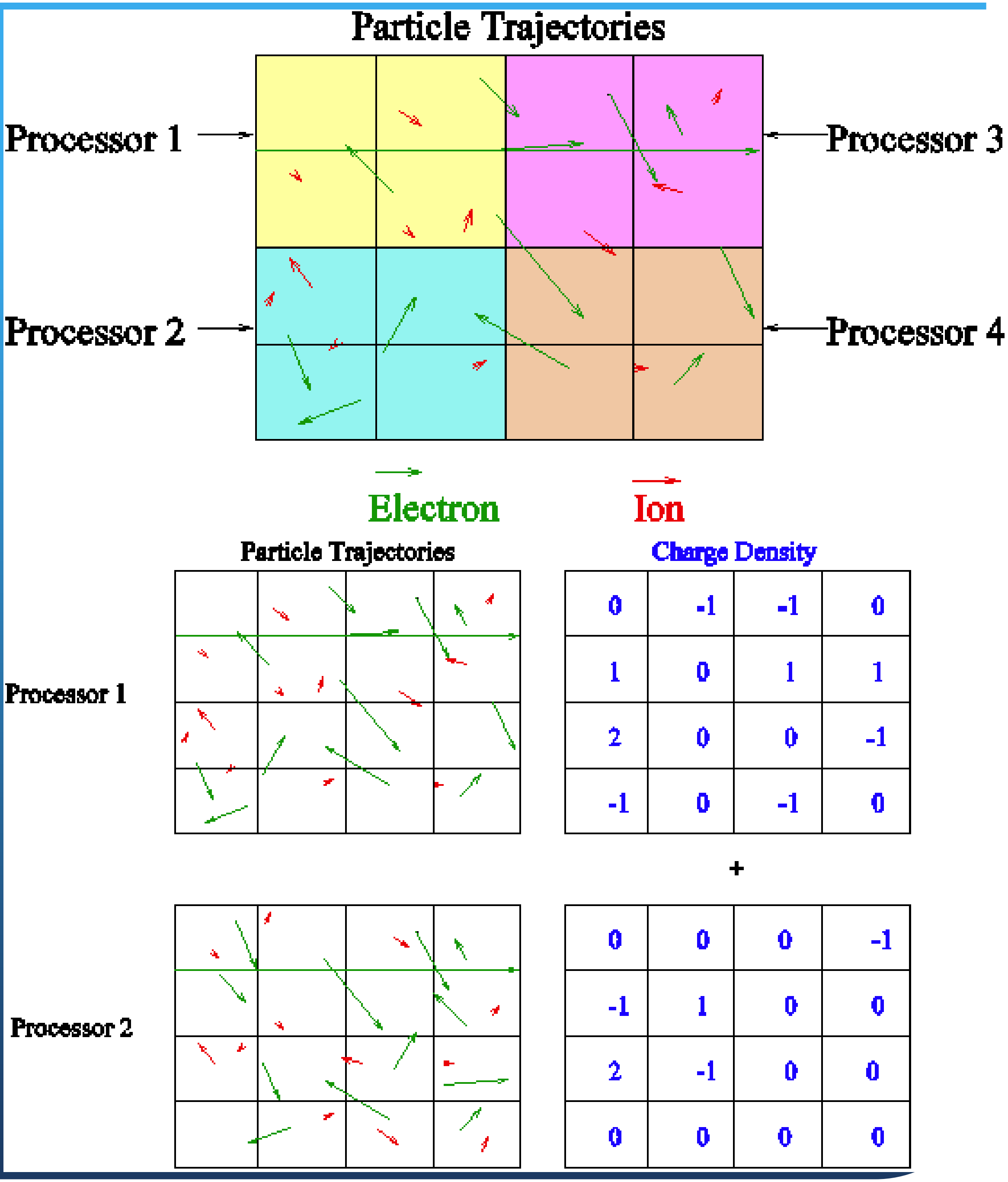
(8x longer simulation in time,
shown 16x as fast)

Simulation Limitations

- Systematic:
  - Do the equations represent the physics?
  - Do they resolve the important scales?
- Numerical:
  - Stability
  - Accuracy

Solution: Parallel Supercomputing

- Domain Decomposition
- Mesh Parallelization



Charge Density

Processor 1

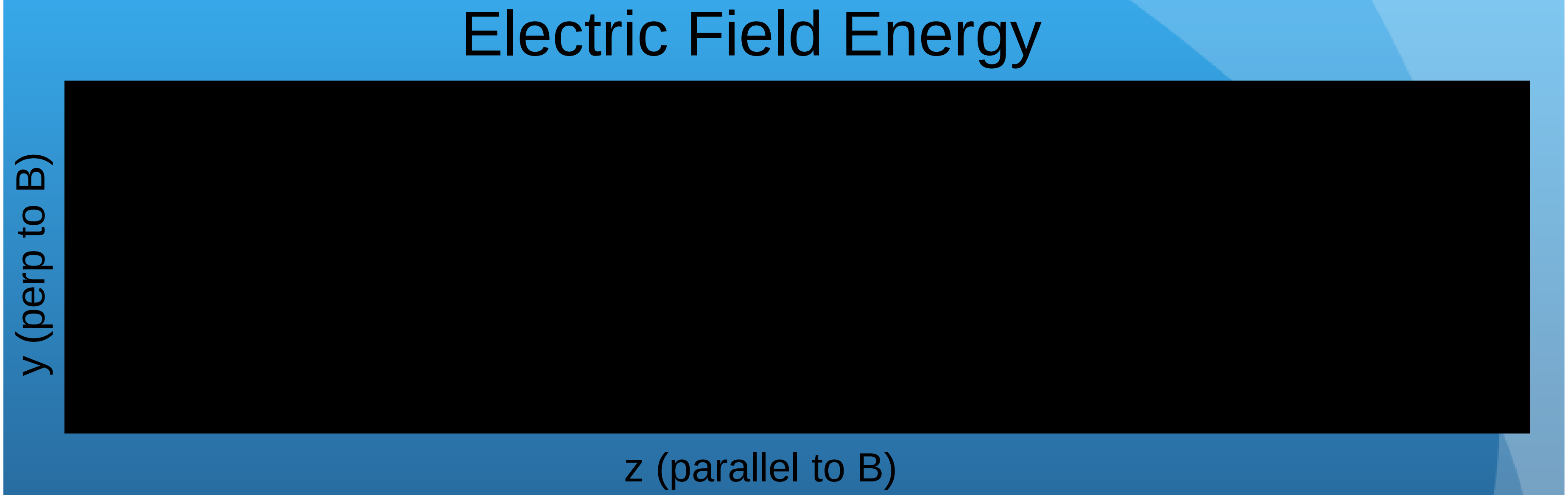
0	-1	-1	0
1	0	1	1
2	0	0	-1
-1	0	-1	0

+

Processor 2

0	0	0	-1
-1	1	0	0
2	-1	0	0
0	0	0	0

Electron Holes in 2D

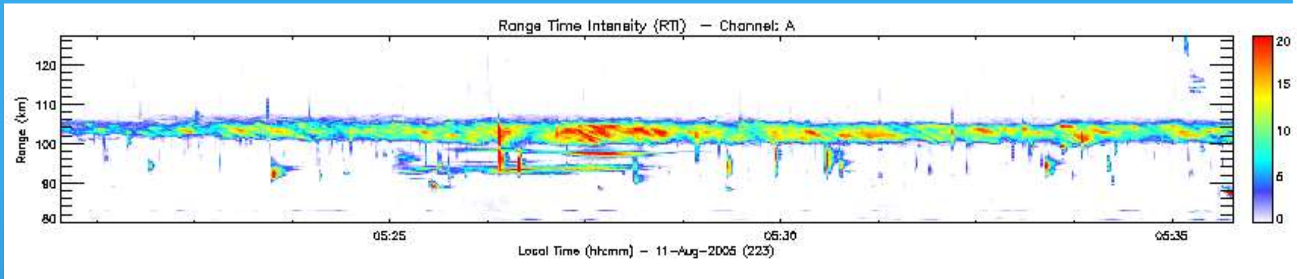


These simulations enabled us to:

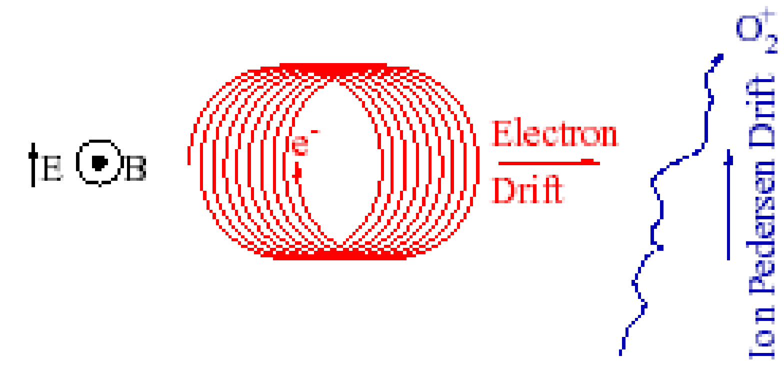
- Understand plasma evolution
- Study energy and momentum coupling
- Characterize Turbulence

Electrojet Waves

Radar Returns from Electrojet

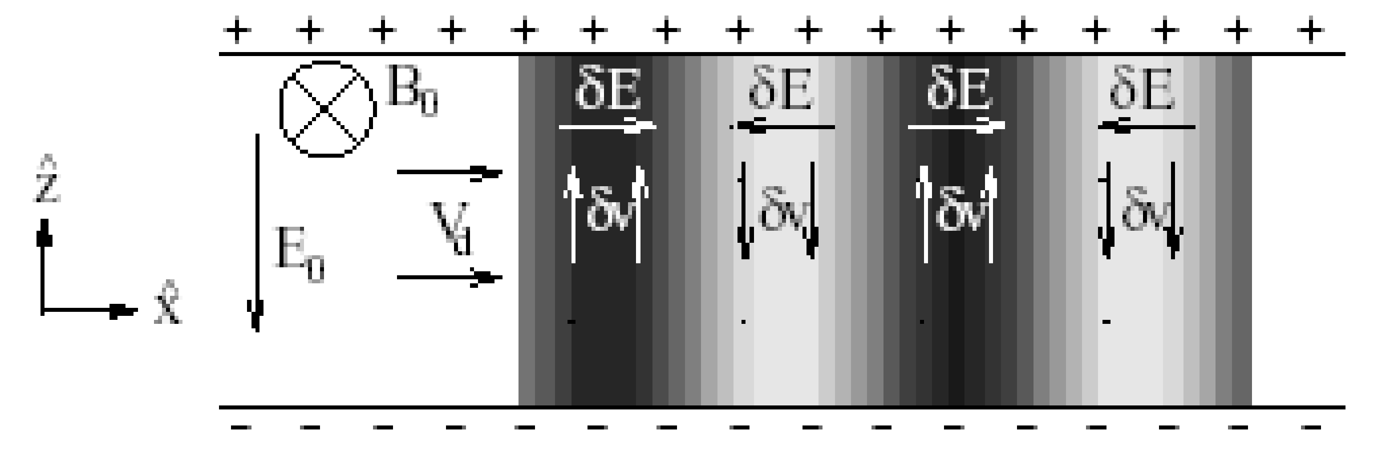


- Ions & Electrons respond differently to fields
  - Electrons remain magnetized: ***ExB*** drift
  - Ions demagnetized by collisions: flow along ***E***

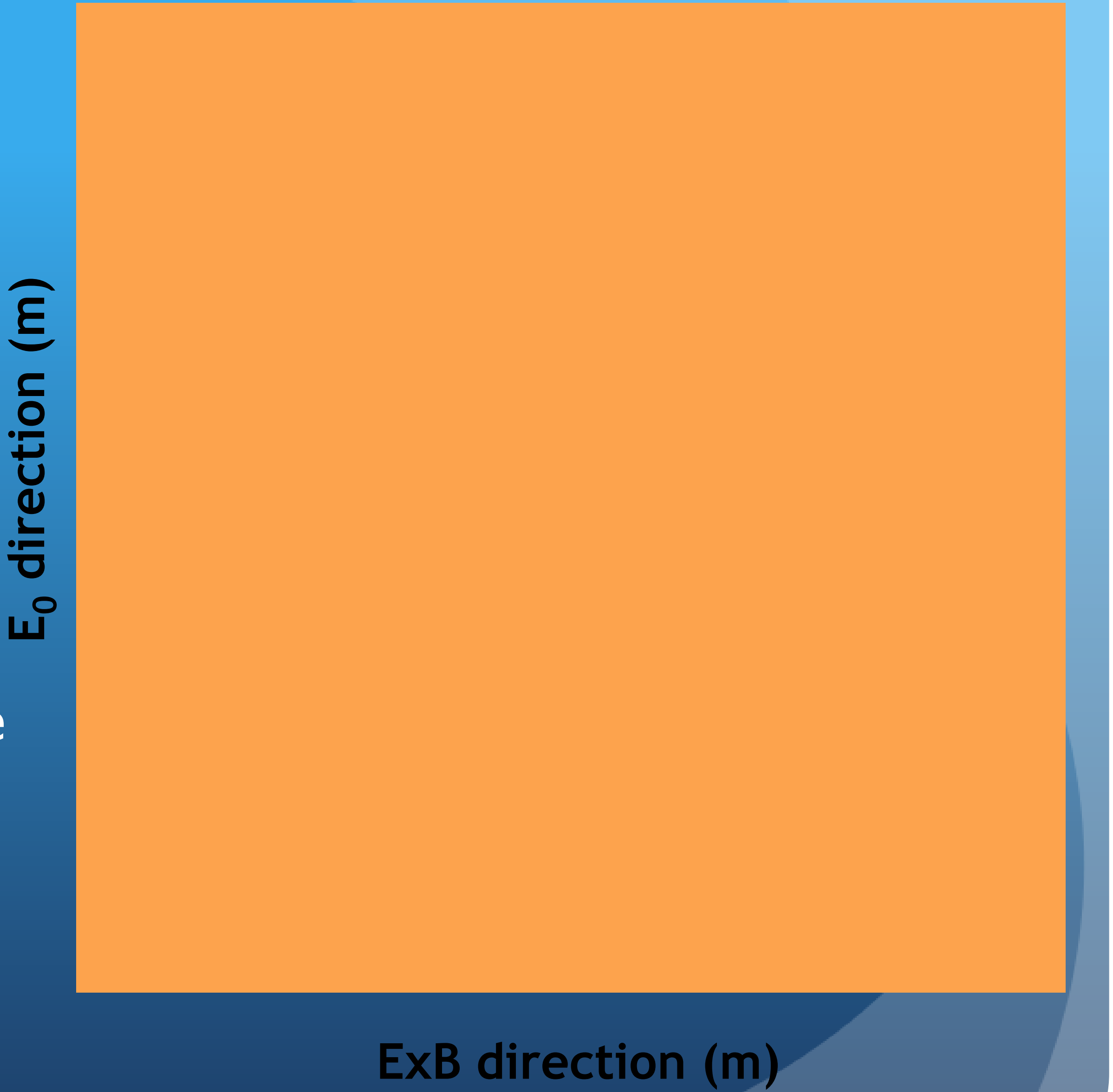


- If $V_e > C_s$, streaming instability develops

Modified two-stream or Farley-Buneman Instability



Electrojet PIC Simulation

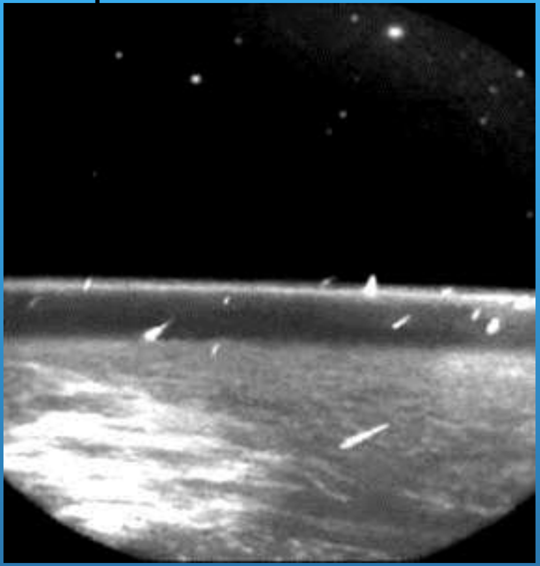


New thing learned:

- Saturation though Mode coupling
- Saturated wave speed
- Average Tilting of Wave
- Thermal Behavior

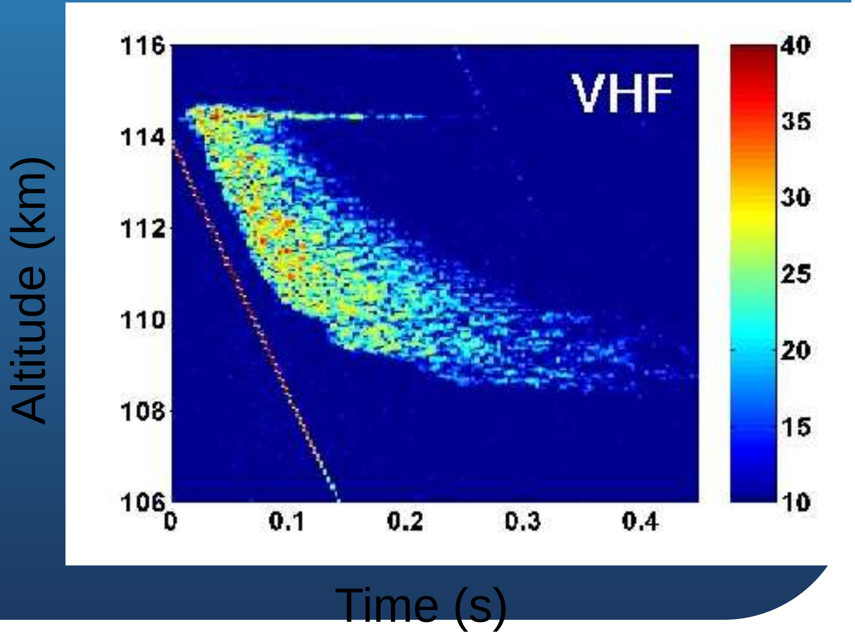
Meteor Plasma waves

Leonids picture from the shuttle

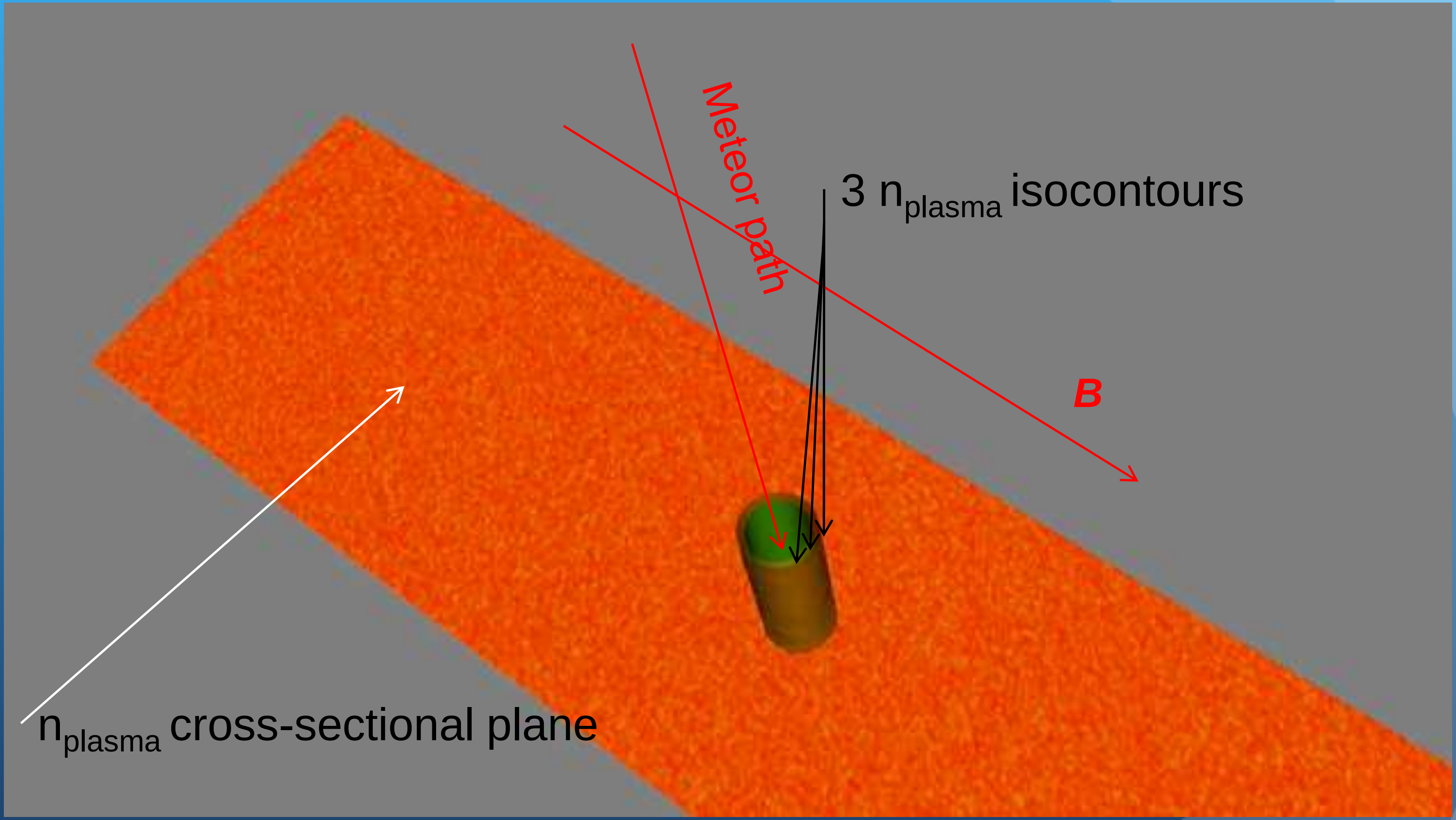


Large Aperture
Radar Detection
of a Meteor

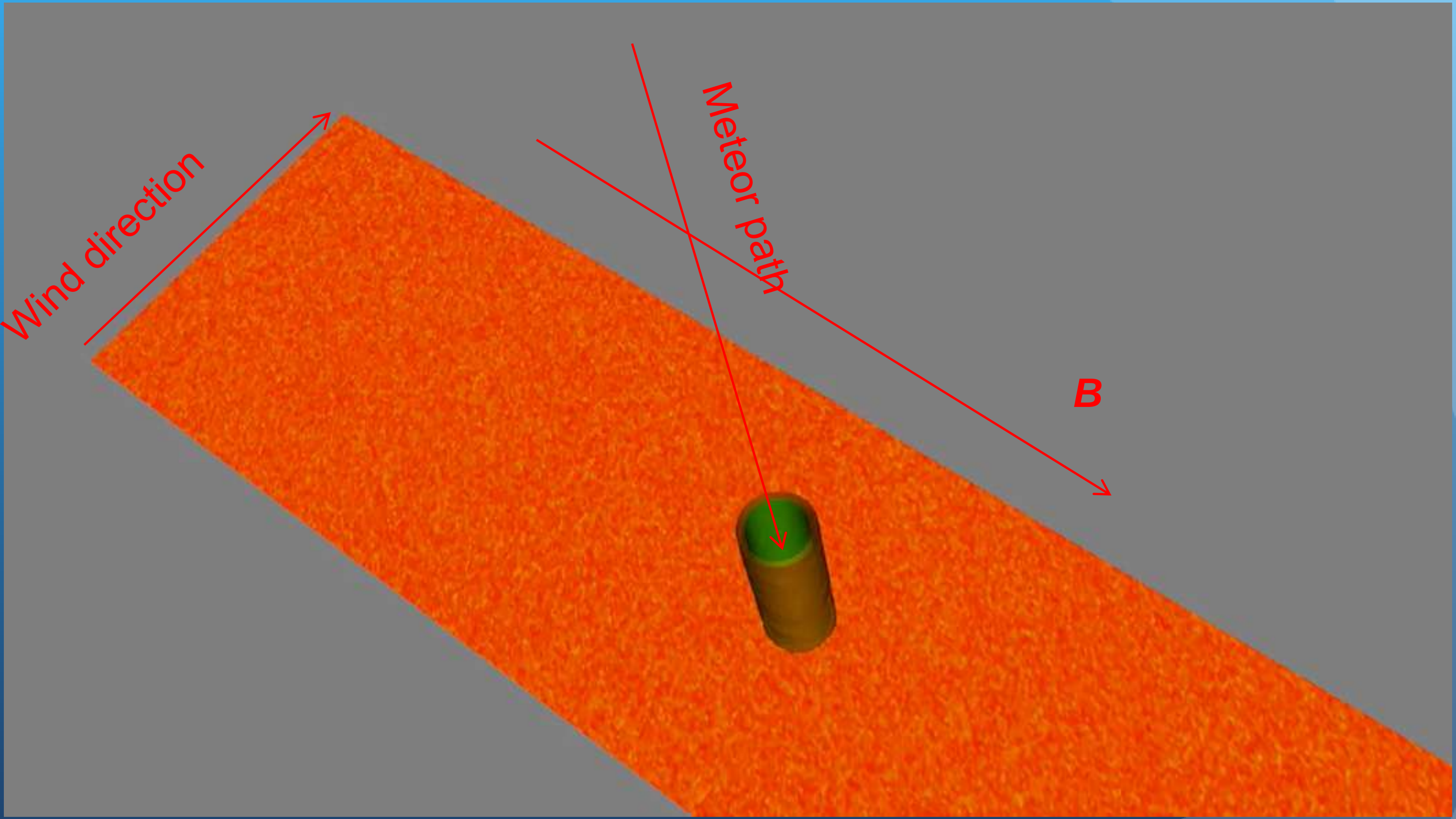
ALTAIR meteor detection



Particle in Cell Simulations of Meteor Plasma

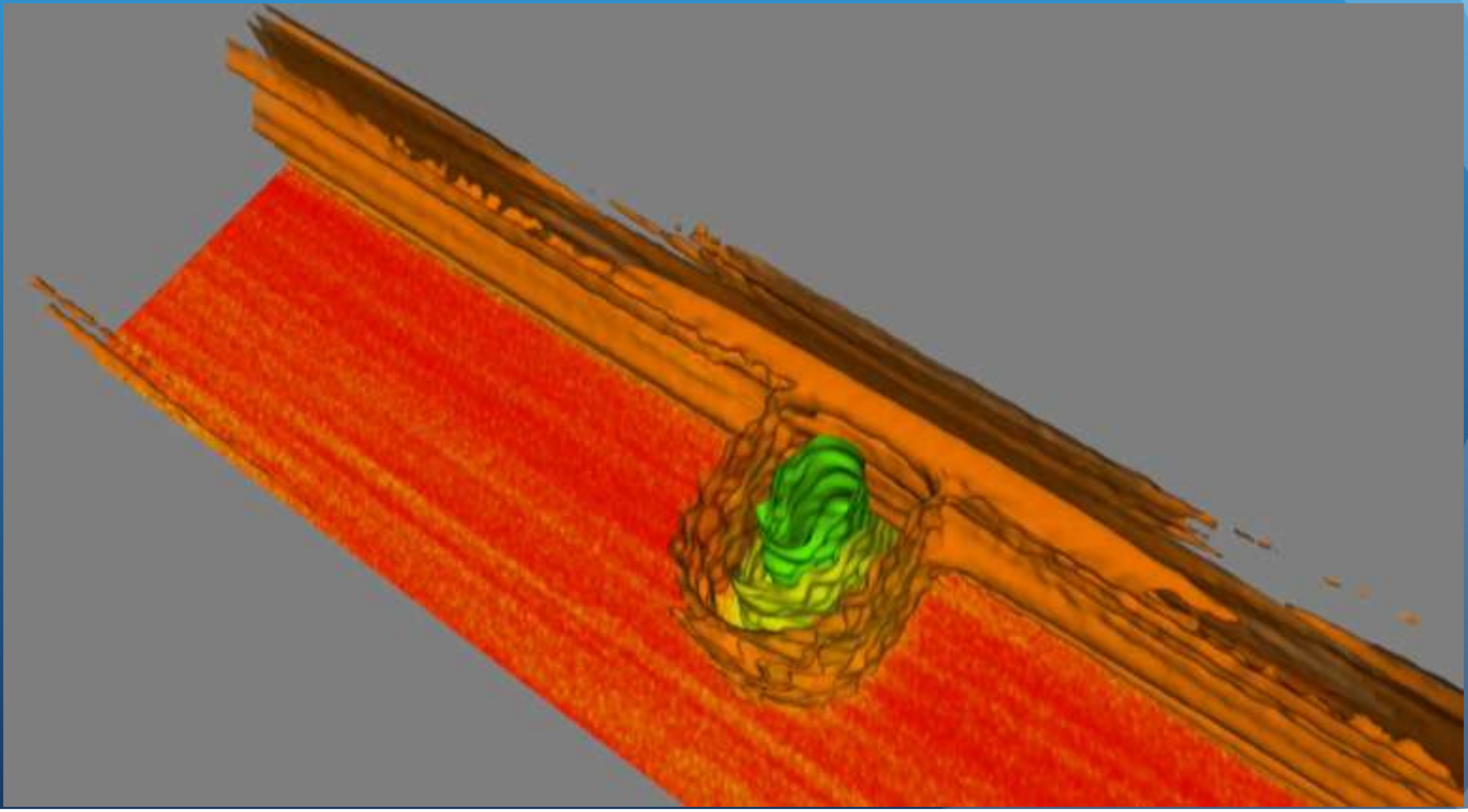

Meteor path
3 n_{plasma} isocontours
B
n_{plasma} cross-sectional plane

Particle in Cell Simulations of Meteor Plasma – with a wind



Conclusions

- New 3D Simulations
- Enables exploration of Meteor Evolution
- Future: Spectra to connect to observations



Conclusions

- Simulations enable us to explore nonlinear systems
- Simulations subject to systematic limitations and numerical errors
- Enable us to better understand our:
  - devices,
  - Models, and
  - Nature.
- Future Simulation Work:
  - Better Algorithms
  - More Parallel Efficiency
  - Vast array of applications!