PIC Simulations
Round Table Discussions

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Agenda

- Åke
  - Short intro – towards a Santa Barbara PIC-comparison
  - Structure of relativistic collisionless shocks
- Anatoly
  - Particle acceleration
- Ken
  - Synthetic spectra

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This is a discussion session, so feel free to interrupt!

Particle-in-Cell codes and the case for a new KITP comparison

What to learn about relativistic shocks from PIC-simulations

- Physical mechanisms active in shock transitions
  - Which mechanism are there & how do they interact?
  - What is the resulting shock structure?

- Specifically: Particle Acceleration
  - How does injection and main acceleration work?!

- Diagnostics: Synthetic Spectra
  - How can we use PIC-codes to get an observational handle on the items above?

Problems and Tuning of PIC Codes

- Numerical grid heating
  - particles perturbed and heated by the grid
- Numerical Cherenkov radiation
  - particles travel faster than the (grid-) speed of light
- Tuning parameters & code properties
  - Mass ratio
  - Number of particles per cell – method of initialization
  - Number of cells per e-skin depth
  - Number of cells per Debye length
  - Spatial and temporal order of field operators
  - Spatial order of scatter/gather (particle/field) ops

The case for a KITP PIC-code comparison

- Usefulness of previous comparisons
  - Cosmology, turbulence, radiative transfer, star & planet formation, ...
  - All have been very useful!

- The need for PIC-comparisons is even larger
  - Larger number of issues, and more subtle!
    - MHD codes; relatively few and more easily identified issues
    - PIC-codes (and the underlying physics!) have several, and they are harder to get a grip on
      - More *bona fide* parameters
      - Further from ’reality’; ~no ’direct comparisons’ available
      - Impact of numerical techniques and ’tricks’ harder to diagnose

Previous comparisons

- KITP comparisons
  - Cosmology – SB cluster comparison (1999)
    - **arXiv:astro-ph/9906160**
  - MHD turbulence
    - Kritsuk et al (2009-2010)
- Others
  - Wengen comparisons
    - Agerts et al (2007)
  - Proto-planetary disk dynamics
    - (de Val-Borro, MNRAS 2006)
  - Radiative transfer / cosmological re-ionization
    - Illiev et al (2006, 2009)
  - Radiative transfer / molecular cloud diagnostics
    - on-going (Heidelberg and others)

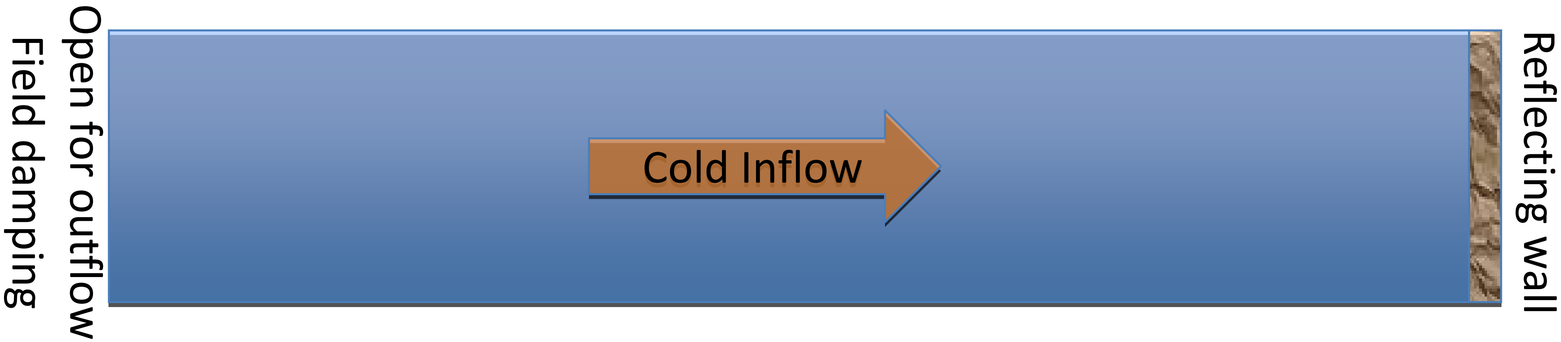
The Structure(s) of Relativistic Collisionless Shocks

Niels Bohr Institute Associates

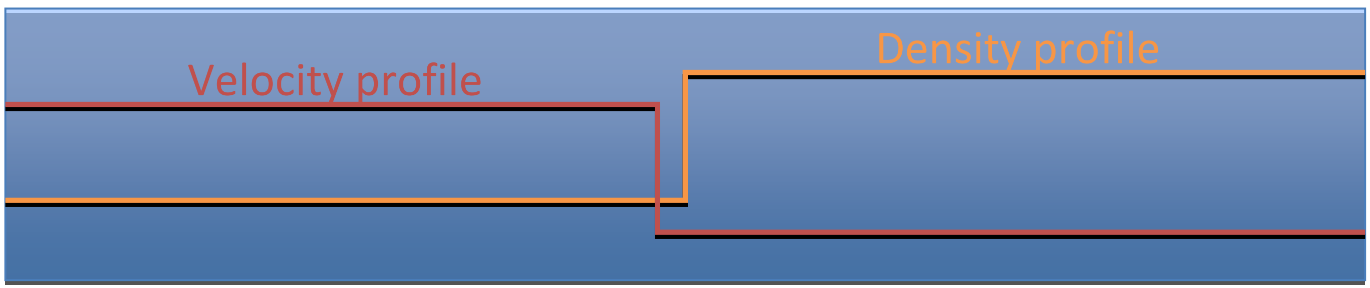
- **Jacob Trier Frederiksen**
  - GRB shocks, wakefield acceleration, solar flares
- **Troels Haugbølle**
  - GRB shocks, PIC code development, cosmology ...
- **Klaus Galsgaard**
  - MHD of the solar corona and flares, reconnection
- **Gisela Baumann**
  - Particle acceleration in solar flars

Collisionless shock setups

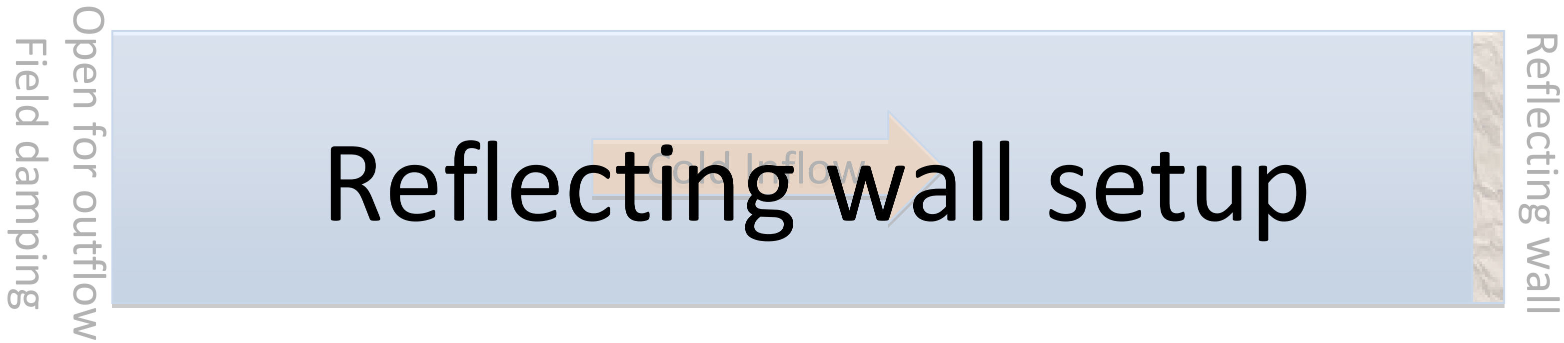
- Reflecting wall setup – easy initial conditions



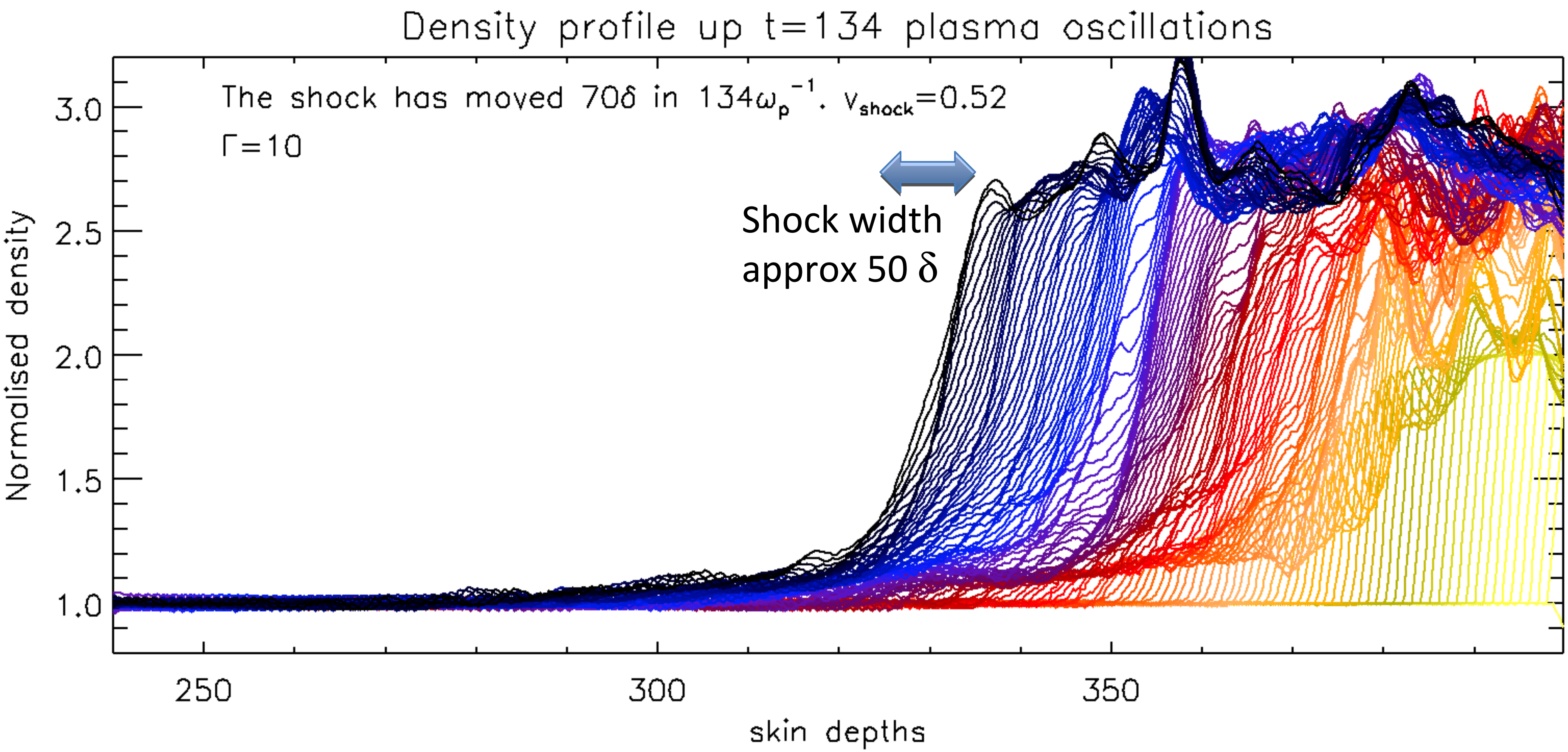
- Steady state setup – for long time evolution



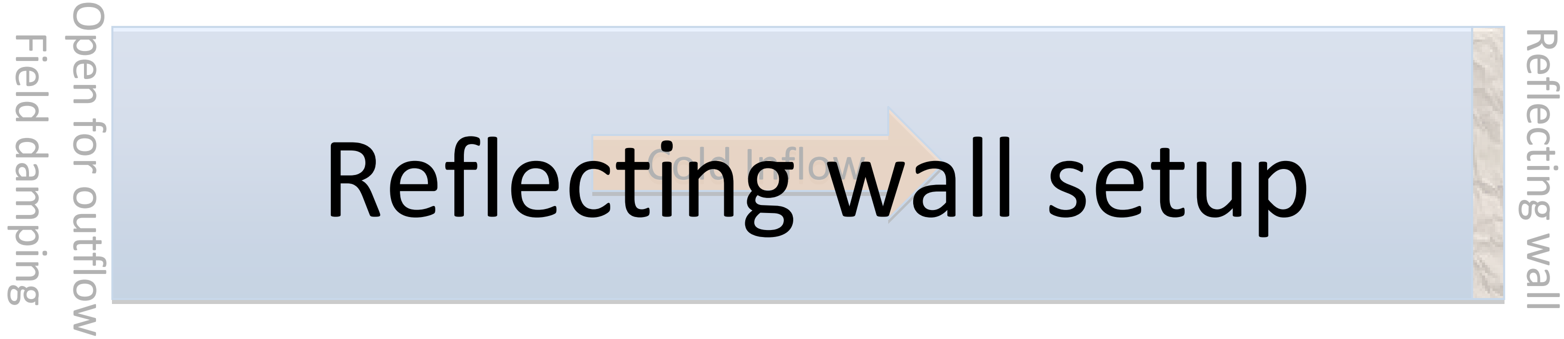
Reflecting wall setup



- Density evolution:

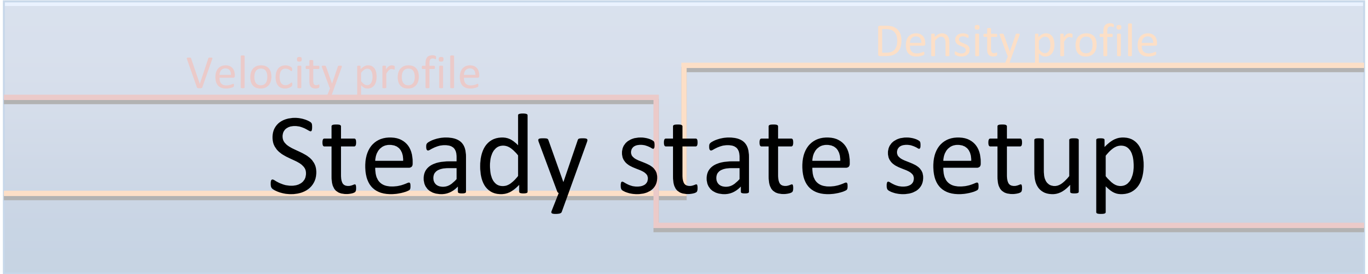


Reflecting wall setup



- PROs of the setup :
  - The initial conditions are extremely simple
  - We can validate the code against published results
  - Compare the shocks obtained in one restframe (wall setup) against another restframe (steady state)
- CONs of the setup :
  - Long boxes: The shock is propagating with v_{shock} = 0.5 c
  - Anatoly has been running with a 2D grid of 6000x60000 (equivalent to 700^3) to examine long time behavior, and with up to 20 billion particles.
  - Silva et al with 16000x3000 for electron-ion setup.

Steady state setup



- Alternative to reflecting wall

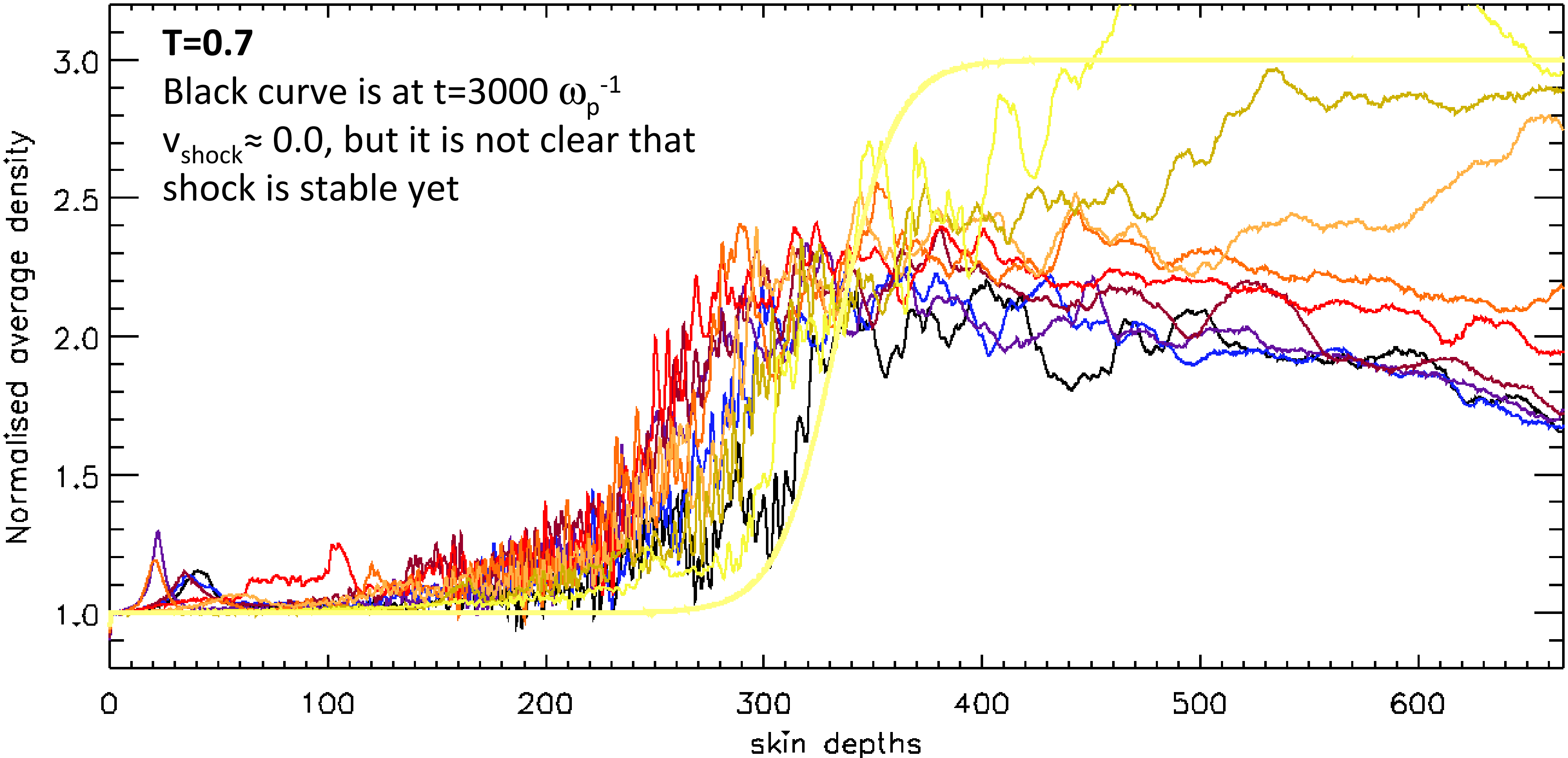
- The crucial point is to get conserved mass, momentum and energy fluxes across the shock jump. I.e. we need to tune the outflow velocity and the temperature correctly. 1D does not give the same as 2D and 3D for the temperature!

- Cost-benefit analysis in terms of :
  - Minimum #parts/cell without noise dominating
  - Minimum cells/skin depth without getting spurious effects

- It is not clear if the same conditions apply in 2D and 3D. We still need to test that

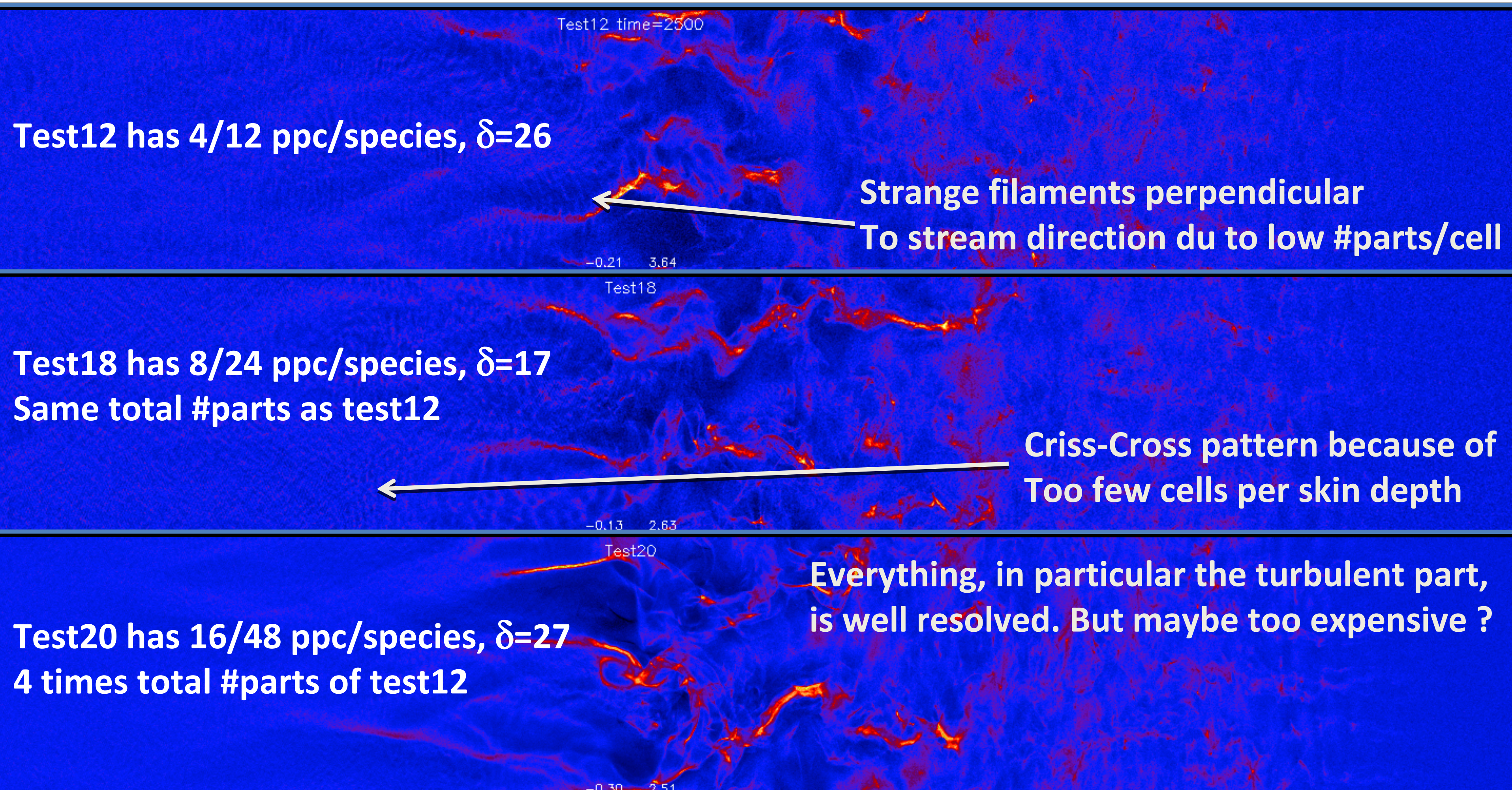
Steady state setup

- Steady state : Inflow Γ=3; outflow v ≈ 0.33 c



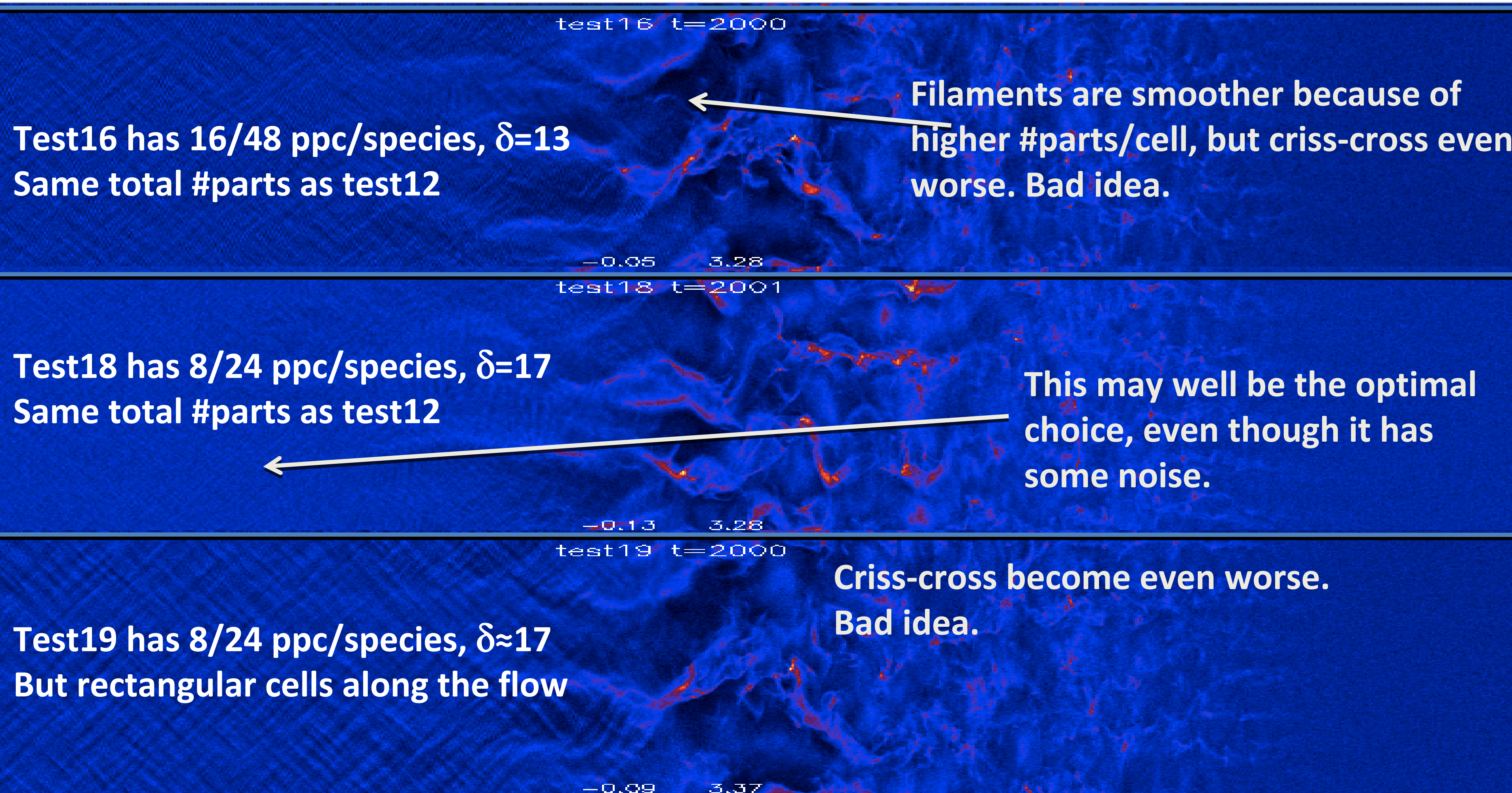
Pair-plasma, Steady state setup, $\Gamma=3$

- Microphysics - current density at $t=100\ \omega_p^{-1}$



Pair-plasma, Steady state setup, $\Gamma=3$

- Microphysics - current density at $t=212\ \omega_p^{-1}$



One-on-one comparisons
Reflecting wall, $\Gamma = 15$

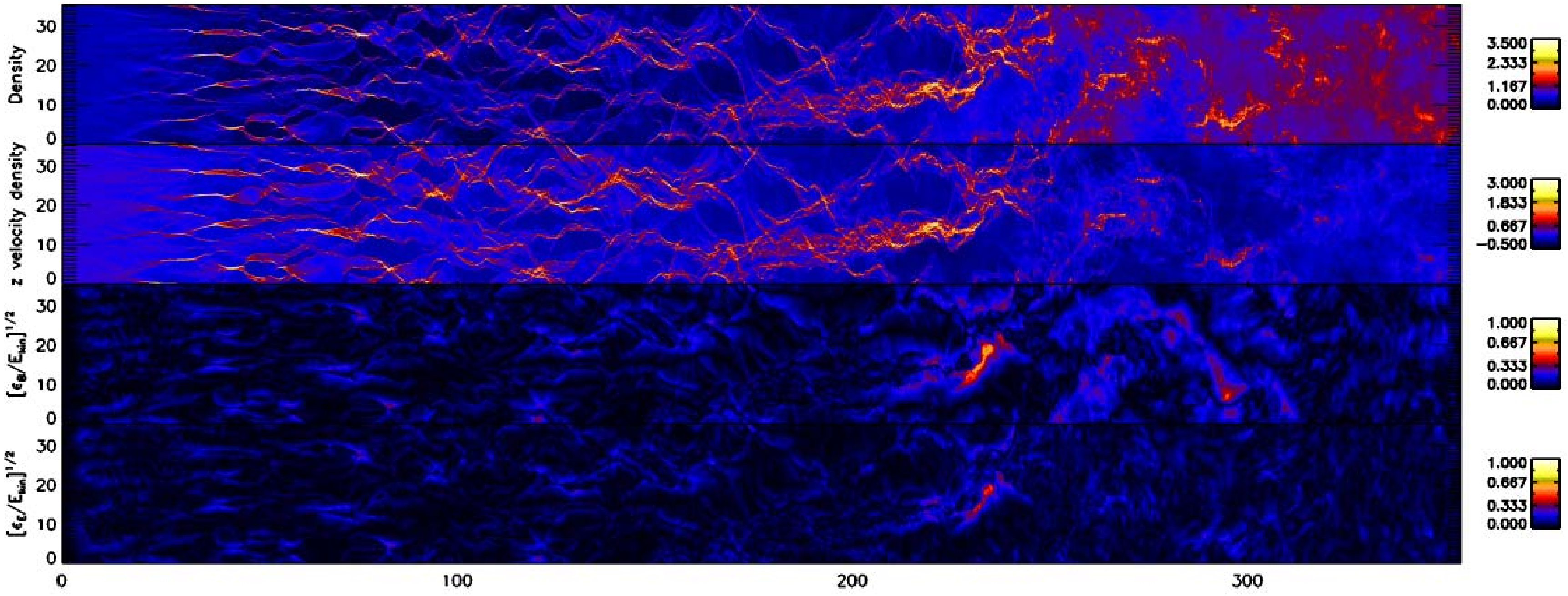
- 2D vs. 3D
  - 2D is much cheaper, but is it quantitatively OK?

- Resolution / computing cost
  - Number of particles (per species) per cell
  - Number of cells per e-skin depth
  - (Number of cells per Debye length)

- Grid aspect ratio

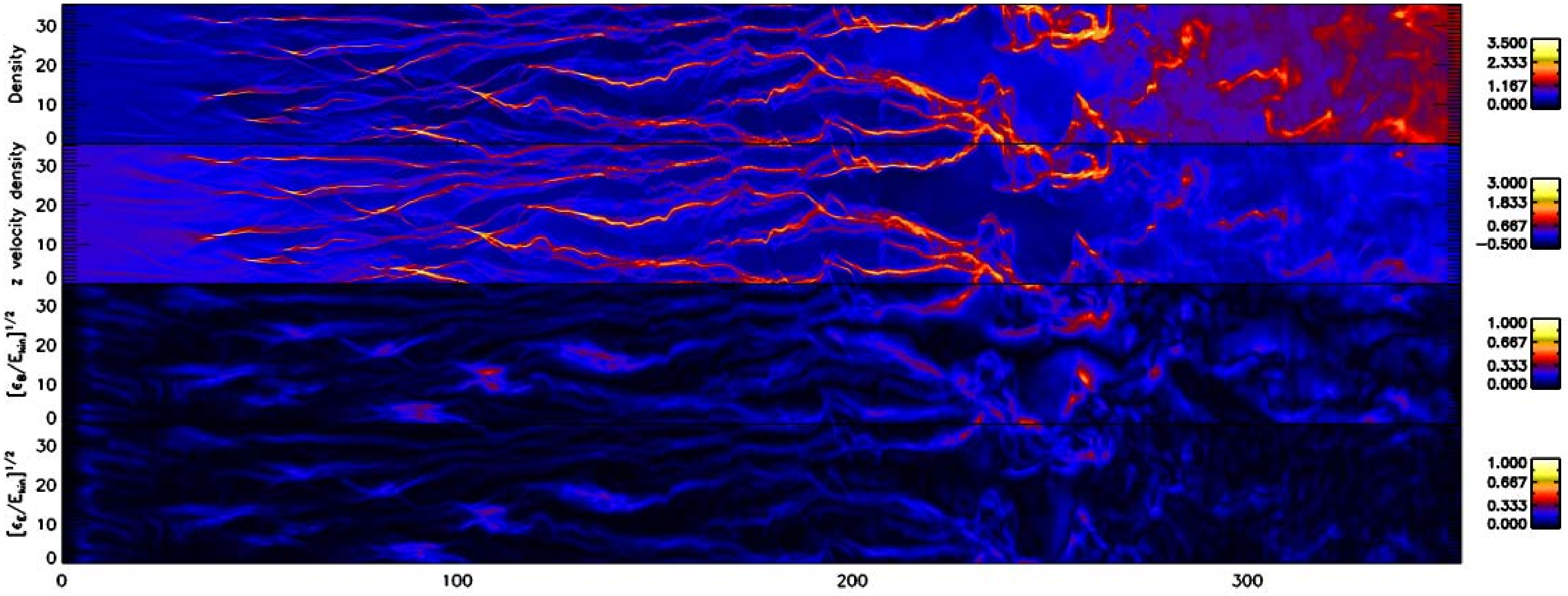
2D vs. 3D – same particles-per-cell and cells-per-skindepth

2-D



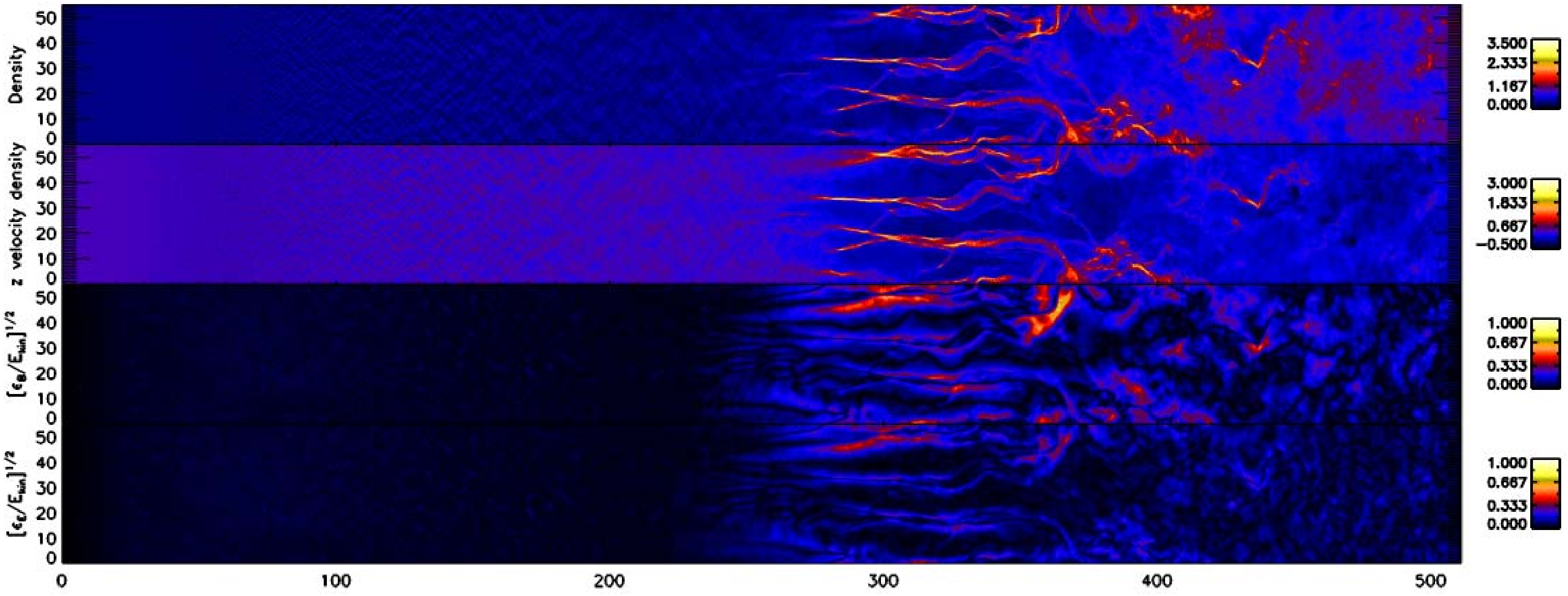
2D vs. 3D – same particles-per-cell and cells-per-skindepth

3-D



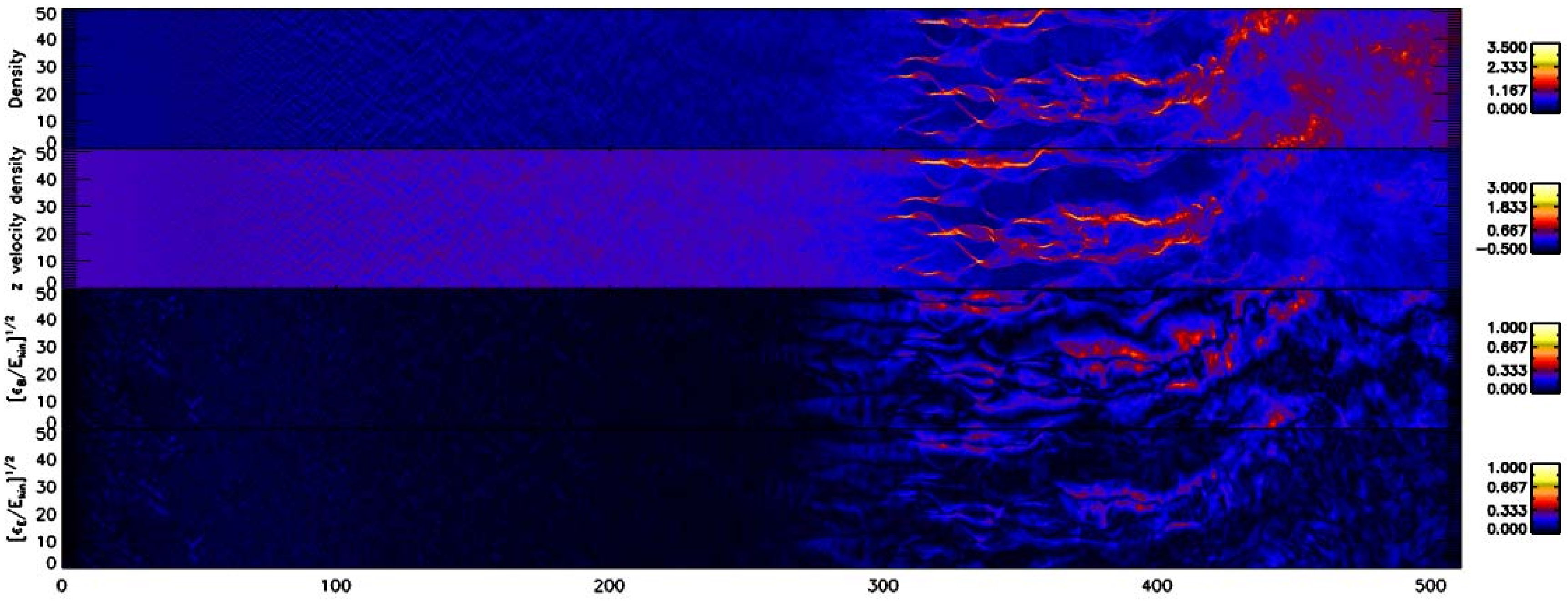
Resolution – dependence on particles-per-cell and cells-per-skindepth

60 particles-per-cell, 10 cells-per-skindepth



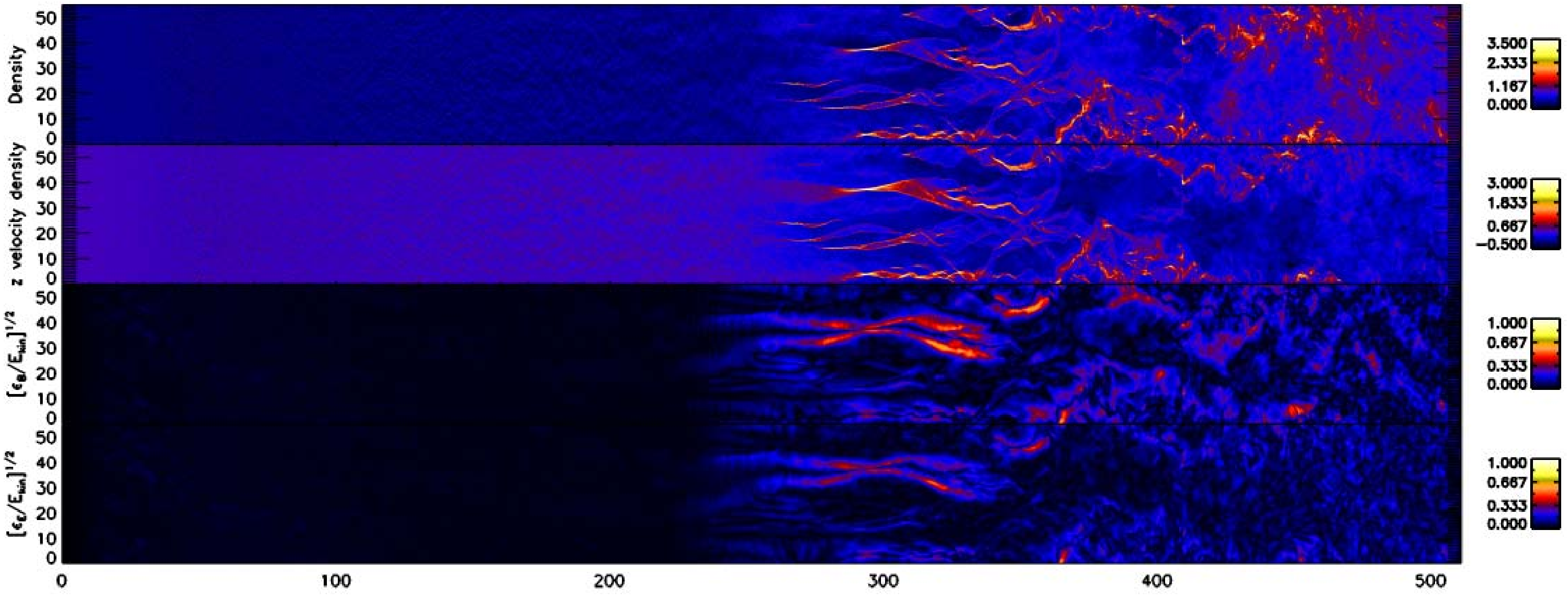
Resolution – dependence on particles-per-cell and cells-per-skindepth

8 particles-per-cell, 10 cells-per-skindepth

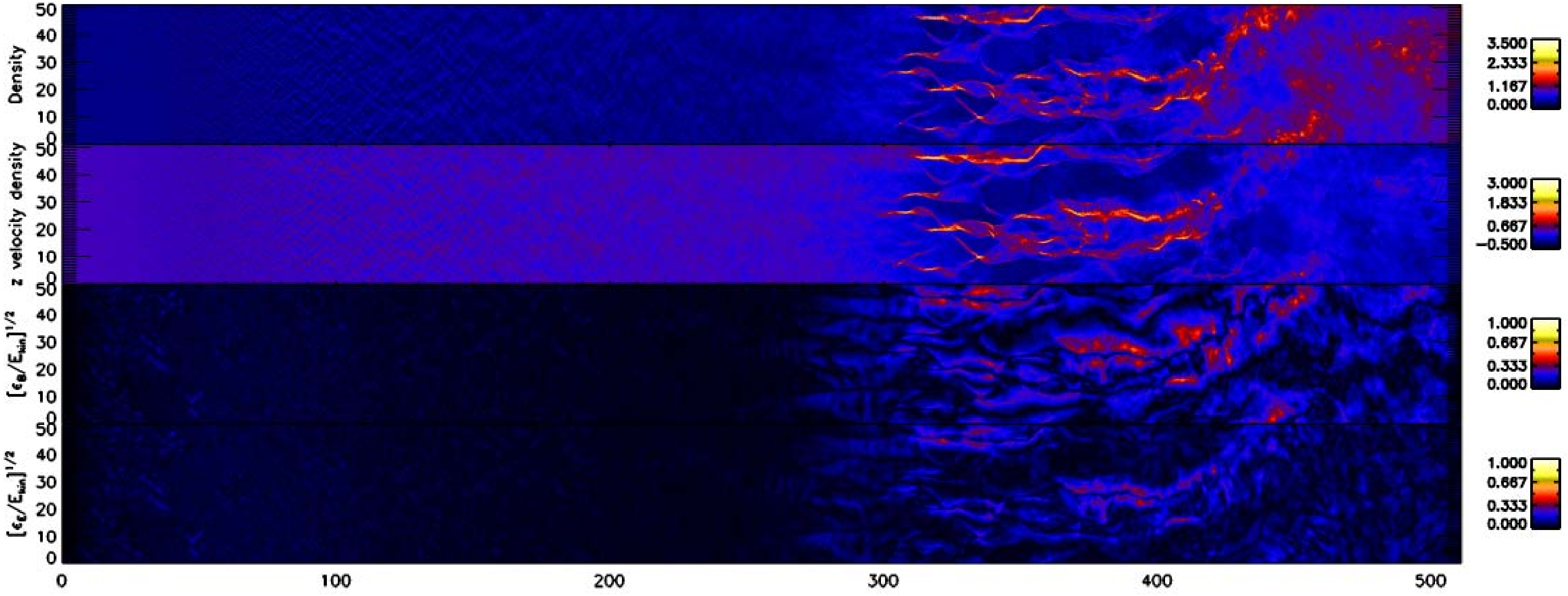


Resolution – dependence on particles-per-cell and cells-per-skindepth

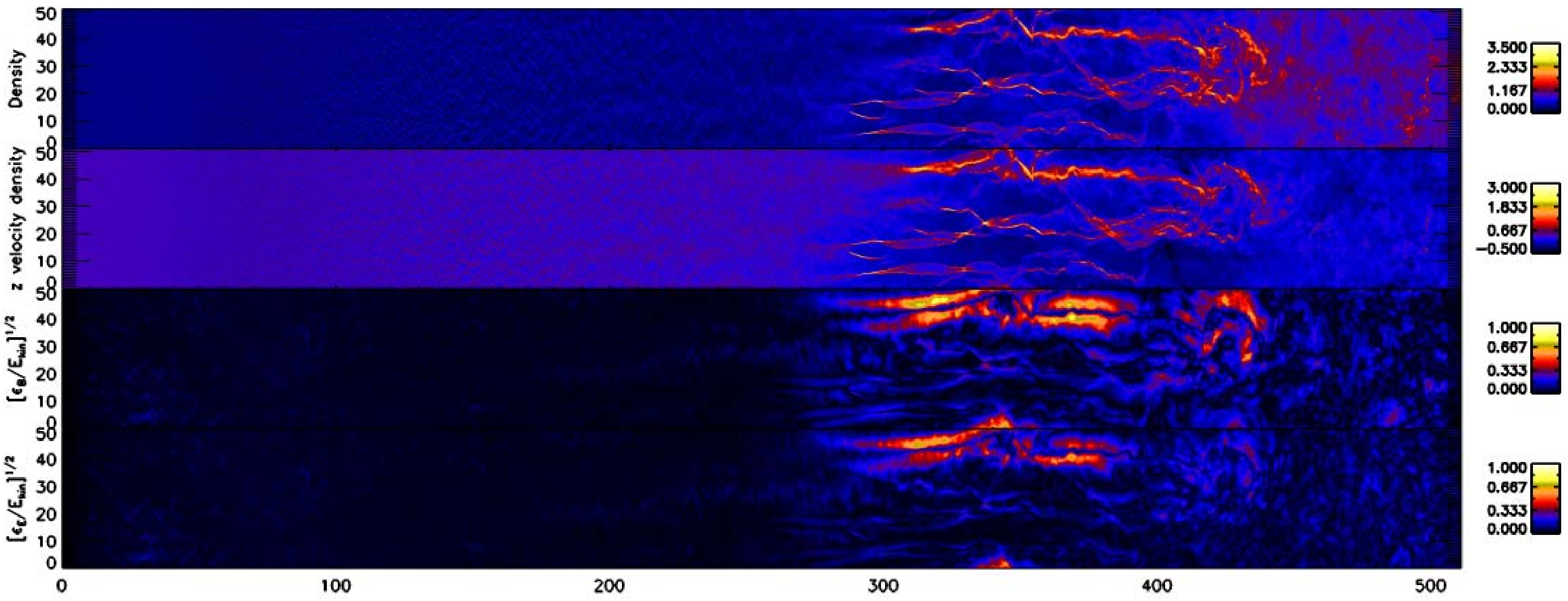
8 particles-per-cell, 27 cells-per-skindepth



Aspect ratio: uniform



Aspect ratio: flat (1:2)



Briefly about Particle Acceleration in the Solar Corona

Solar Corona Conditions

- **MHD approximations valid or not?**
  - Enough charged particles to make a plasma?
    - Certainly! ***Typical Debye lengths are a few mm*****!**
  - Slow enough motions relative to the speed of light?
    - Well ”yes, most of the time!”
  - Frequent enough collisions for thermal behavior?
    - ***No!!*** Mean-free-paths similar to loop lengths
    - Coulomb collisions dominate
      - ***Run-away behavior possible***
    - **Excellent nearby lab for studying particle acceleration!**

Moreno-Insertis et al 2008: ”Jets in coronal holes: ...”

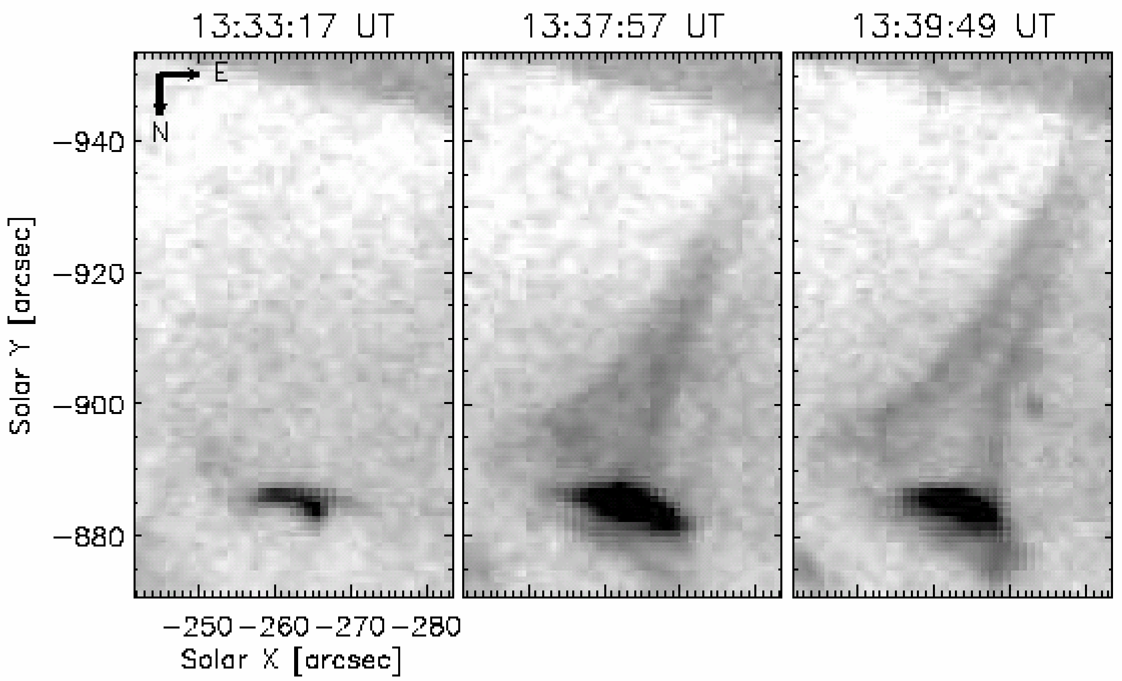


Fig. 1.— Polar coronal jet observed with XRT Al_poly/Open filter combination on the South coronal hole on January 20 2007. Color scale is reversed.

3-D Corona Jet Simulations

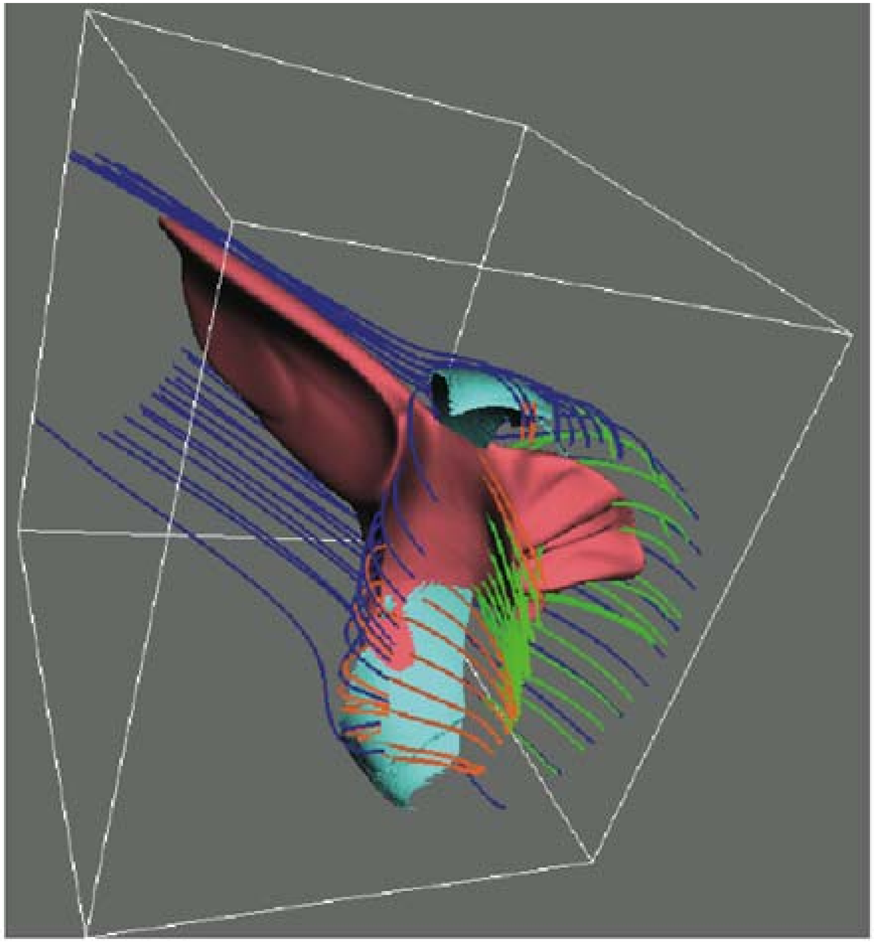
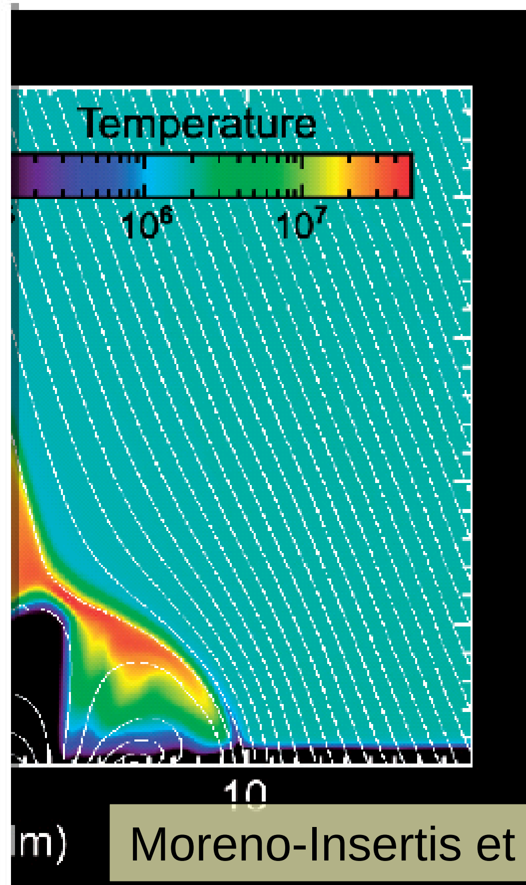


FIG. 3.—Three-dimensional view of the emerged region, the reconnection site, and the jet at the time of peak reconnection activity (*top:* side view; *bottom:* view from below). The isosurface of *j*/*B* (*in blue*) delineates the collapsed current sheet on the side of the emerged volume. The temperature isosurface ($T = 6.5 \times 10^6$ K; *in red*) encompasses both the reconnection site and the jet volume. Underlying the jet and current sheet, a double set of current loops (emerged and reconnected, with field lines in orange and green, re-



Moreno-Insertis et al 2008

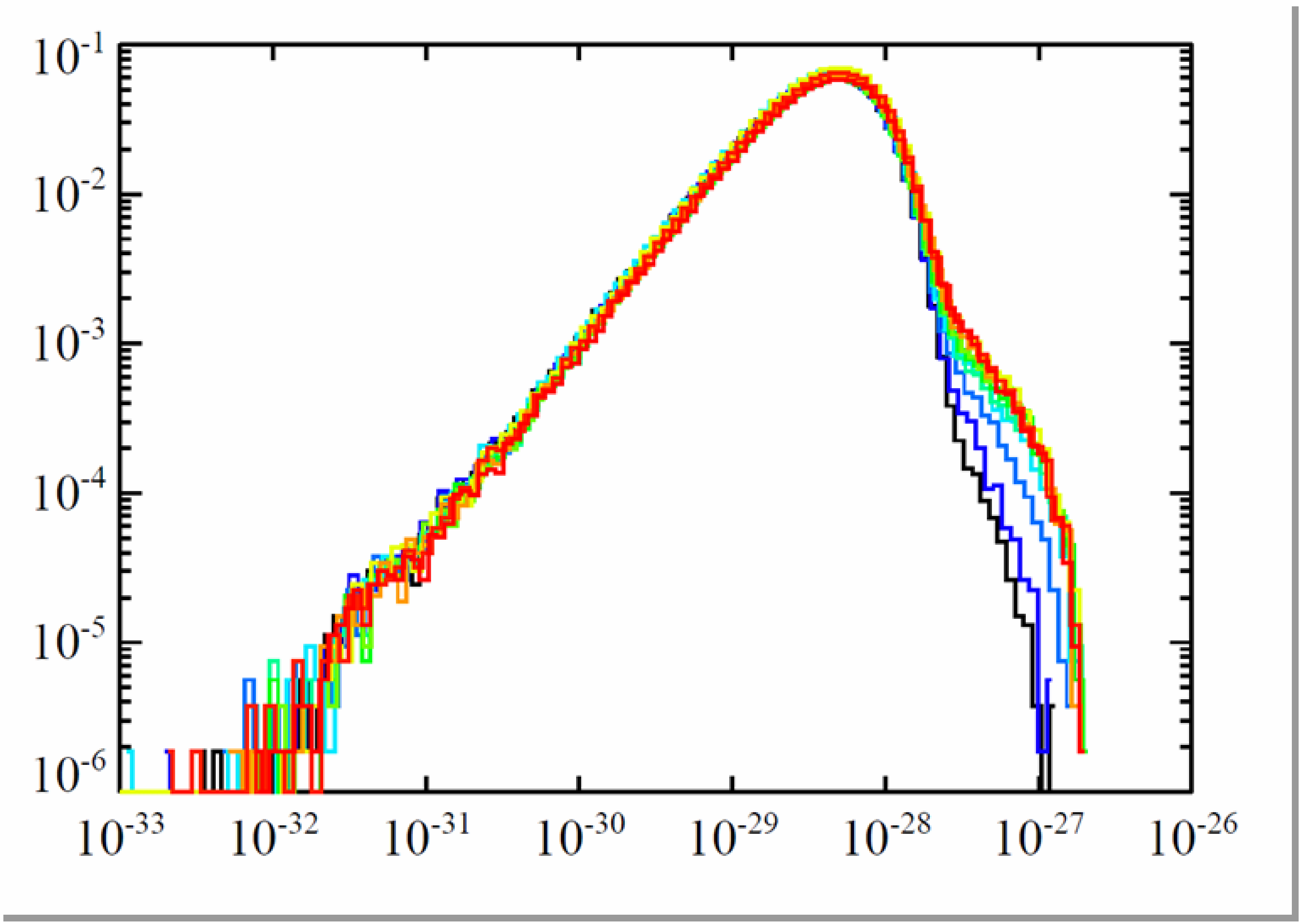
of the evolution. *Top: j/B* distri-
age. A thin current sheet is situated
ps. The diffuse, elongated current
erged volume correspond to pre-
al velocity map and field line pro-

Recent and current work:
Large scale PIC-simulations

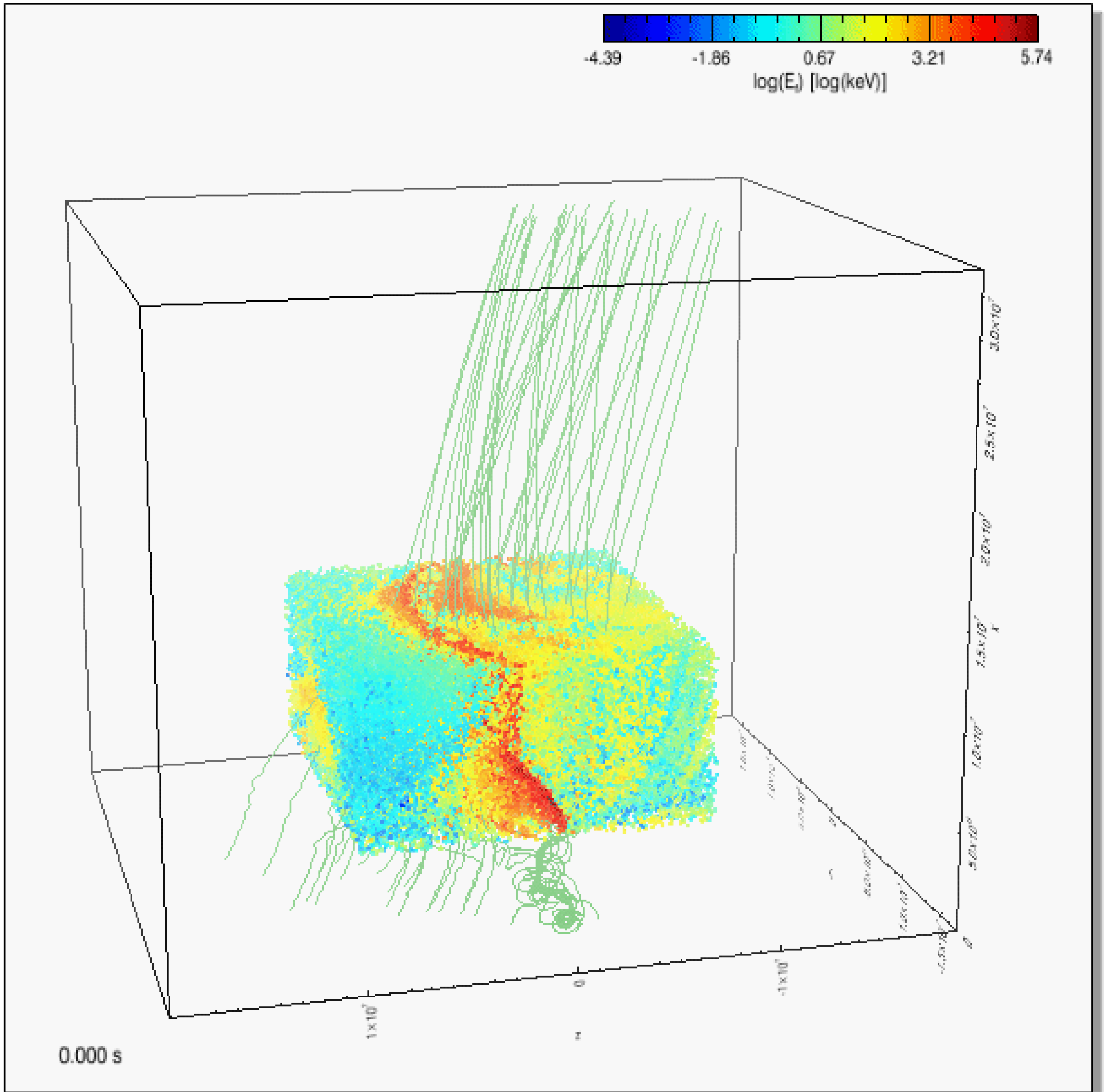
- Copenhagen ”PhotonPlasma” code
  - MPI-parallelized PIC code
    - Includes *particle-interactions*
      - Most relevant in the corona: ***Coulomb scattering***
      - **Modular**: also Compton scattering, pair creation & annihilation, ...
    - ***Scales to thousands of cores***
      - Pleiades (NASA/Ames); ~47.000 cores, tested up to ***2.000 cores***
      - Uses ***about 2 core-microseconds per particle-update***
        - *nearly independent of problem size!*

  - Developed in Gamma-Ray Burst context
    - Weibel instability (Hededal et al 2004, Frederiksen et al 2005)
    - Wakefield acceleration (Frederiksen 2008)

PIC-simulation particle acceleration in the Corona Jet



Test particle animation



Joakim Rosdahl,
(2008 master thesis)

Important!
The solar case vs. DSA

- The solar case is accessible only after rescaling
  - Renormalized fundamental constants
  - Scaled to actual solar dimension (conventional scaling)

- Can one do the same with DSA?!
  - Make a ***resolvable*** DSA case
  - Theory should apply there too!
  - Accessible to simulations!

Summary

- Resolution and parameters studies
  - 3D is significantly different from 2D!
  - Need significant resolution beyond the e-skin depth!
  - Need to check anisotropic meshes for high gamma

- Suggested KITP comparisons
  - PIC-codes on well defined, non-trivial problems
  - Possibly a scaled DSA setup, accessible to PIC-sim

Thanks for your attention, and now over to Anatoly and Ken ..