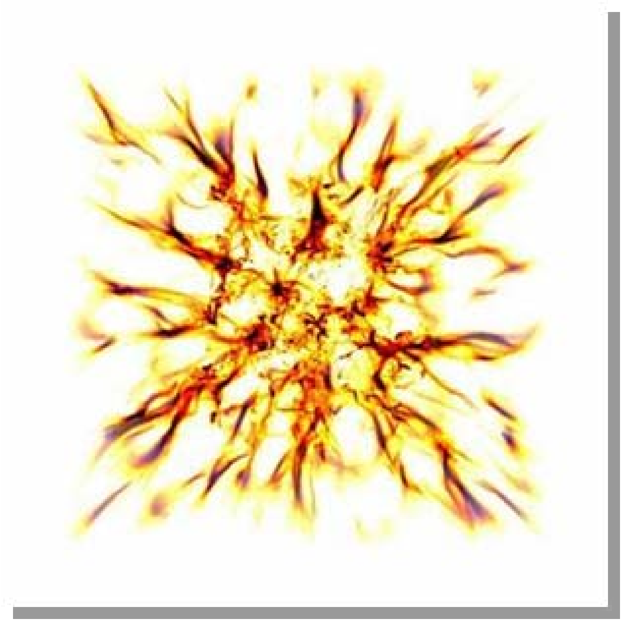
Imag(en-)ing the Structure of Relativistic Collisionless Shocks



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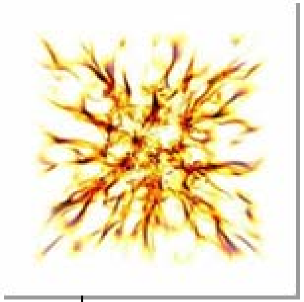
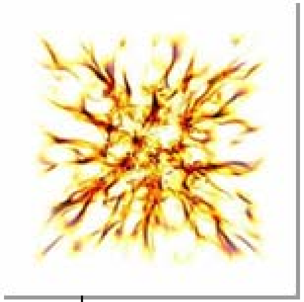
The structure of relativistic collisionless shocks

Topics and sub-topics



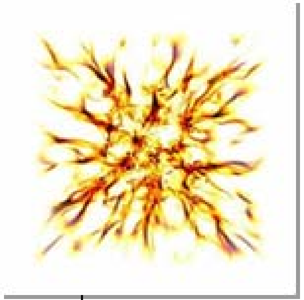
- Particle-in-cell simulations in general
  - Current capabilities – future expectations
  - Can we trust the results?
- Collisionless shock structure
  - 3-D vs. 2-D; structural differences
  - Radiation spectra
- Imaging the radiation output
  - Spatial and temporal structure



Particle-In-Cell Simulations Capabilities and Concerns

The structure of relativistic collisionless shocks

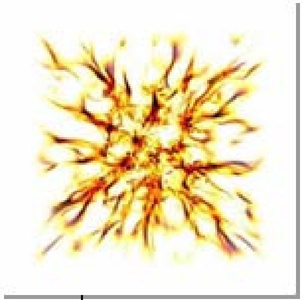
Current capabilities



- Compute cluster (fraction) ~1000 cores 24/7
  - ≈ 10 million core-hours / year

- Current CPUs; Intel Nehalem / IBM Power-6, ...
  - of the order of **1 micro-second / particle-update**
  - with **GPUs**; a factor of **10-30 faster expected**

- Total particle-updates per year: **3** x **10^{16}**
  - With, say, **10 experiments** & e.g. **10^{10} particles**
    - can afford **about 300,000 time steps per experiment**
    - **10^{10} particles:** **enough for serious 3-D experiments**



Potential problems with (all) PIC Codes

- Numerical grid heating
  - too low temperature $\Rightarrow$ Debye length not resolved
  - particles are perturbed and heated by the grid
    - ”heating continues until the Debye length is resolved” ..
    - .. so, when is the Debye length ”resolved”?
- Numerical Cherenkov radiation
  - if particles travel faster than the (grid-) speed of light
    - electro-magnetic ”wakes” are generated
    - characteristic criss-cross pattern

The structure of relativistic collisionless shocks
Potential problems with (all) PIC Codes

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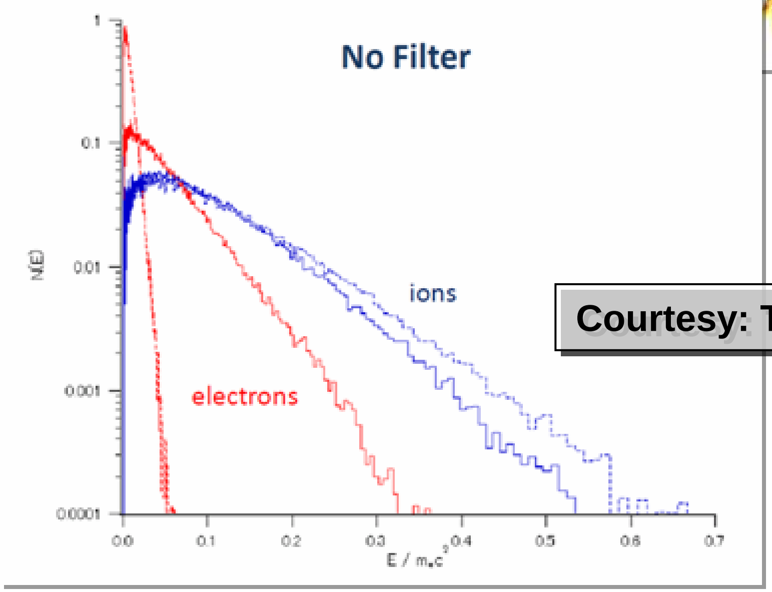

Courtesy: T. Kato

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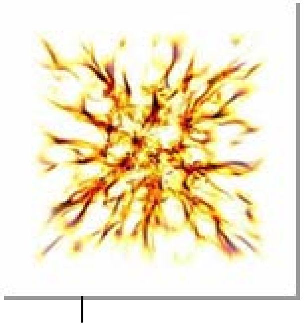
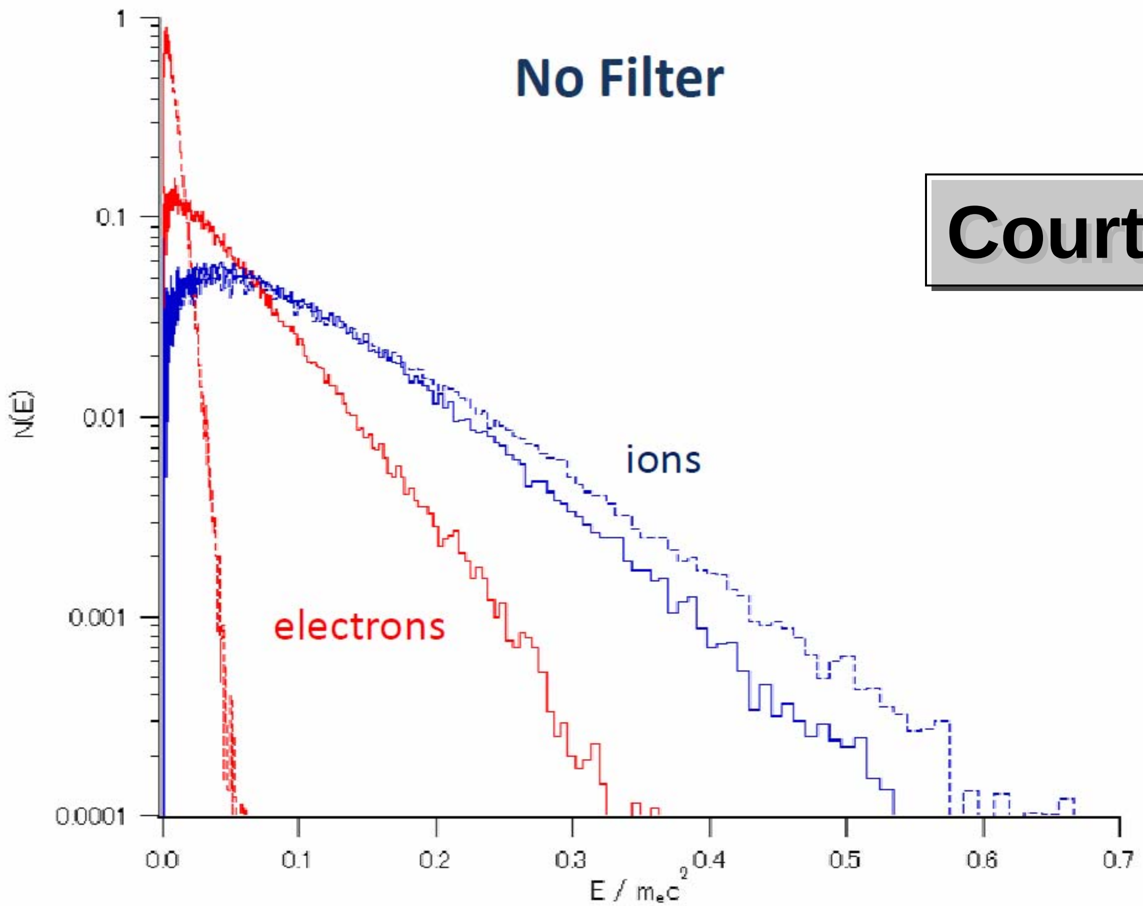
Numerical Collision Effect



N_{PPC} = **1**, NGP

m_i/m_e=**16**, v_{the}=v_{thi}=**0.1c**



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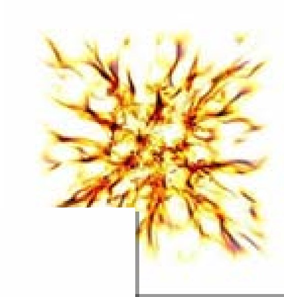
The structure of relativistic collisionless shocks

Potential problems with (all) PIC Codes



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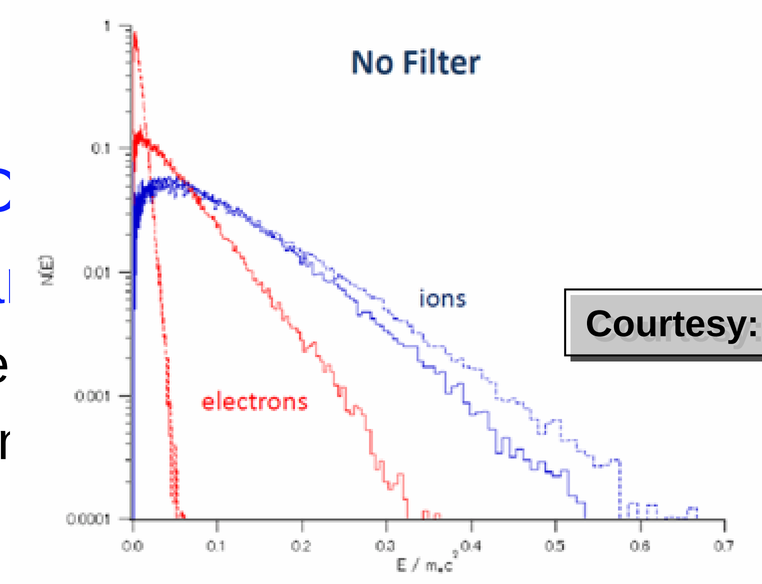

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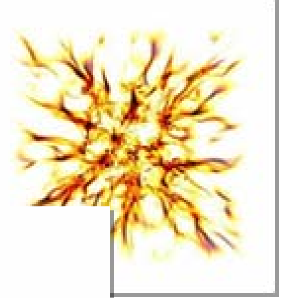
Potential problems with (all) PIC Codes



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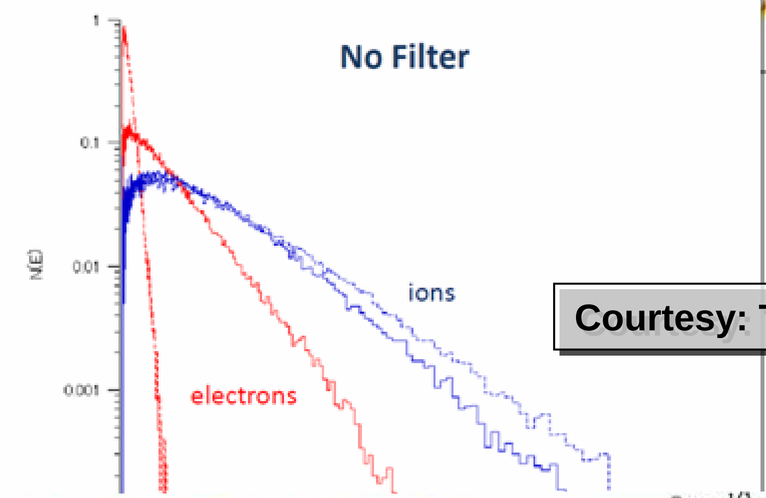
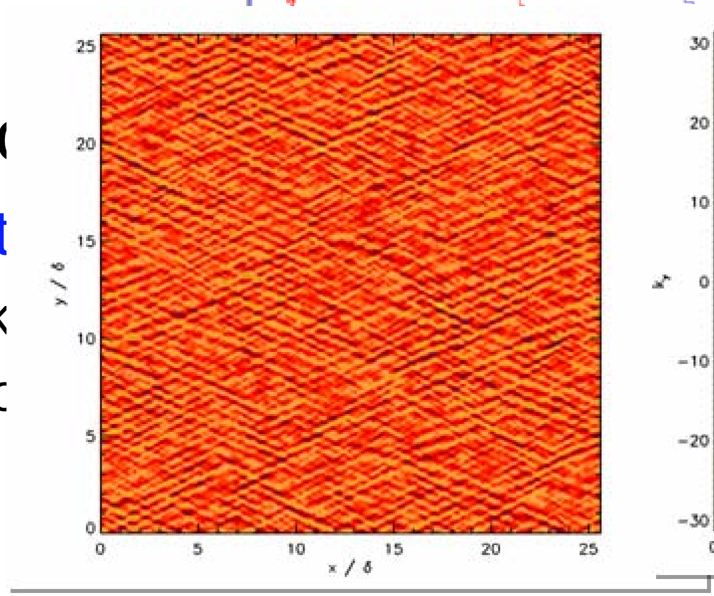
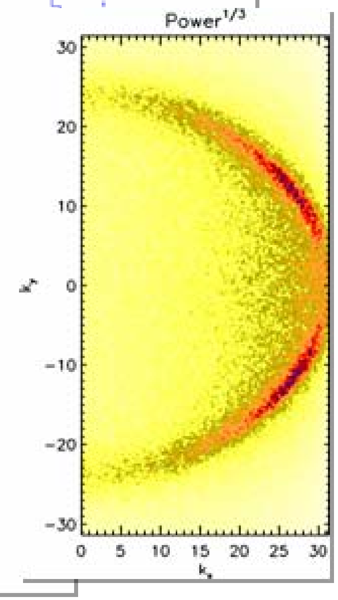


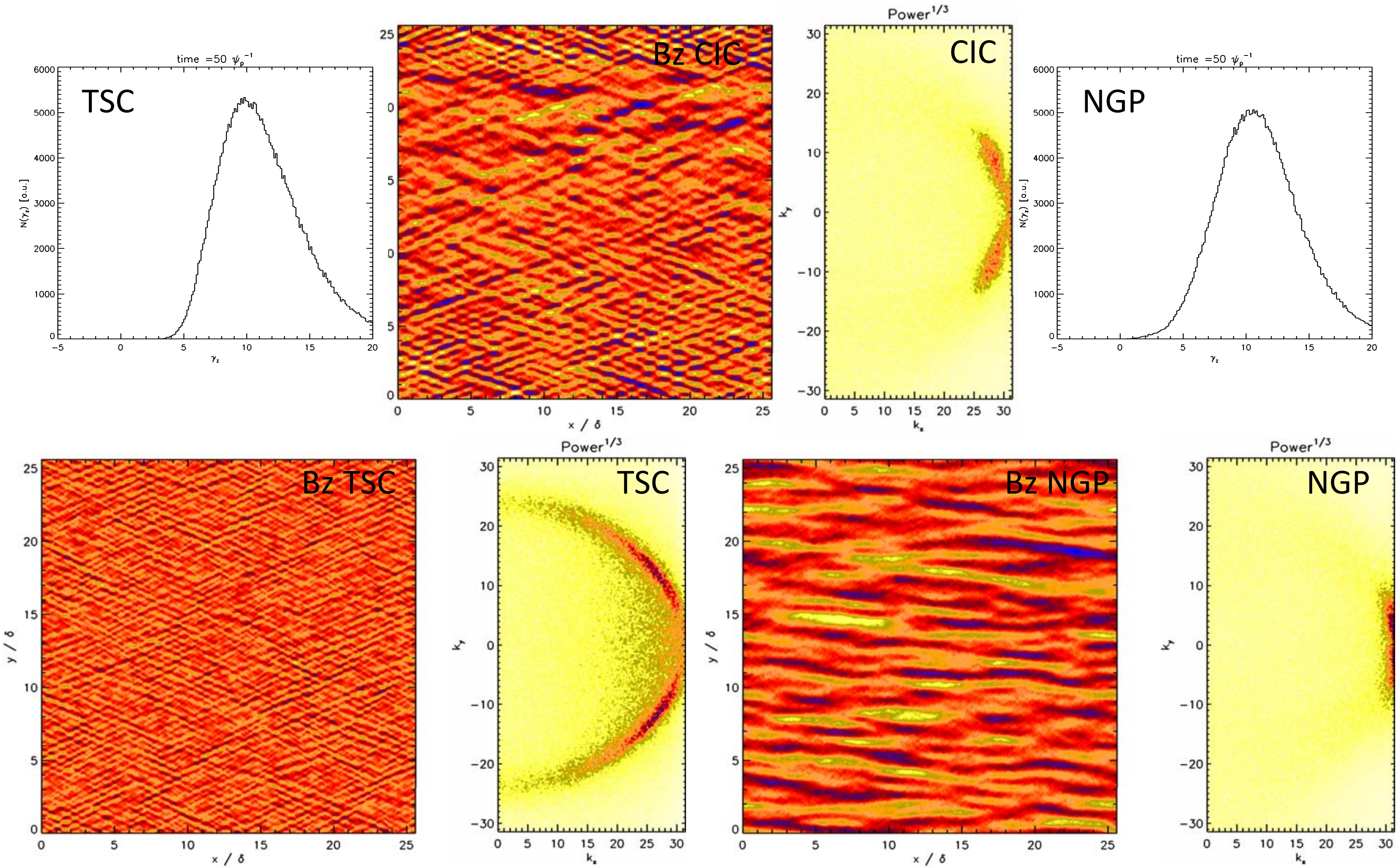
- Numerical Cherenk
  - if particles travel fast
    - electro-magnetic ”wak
    - characteristic criss-cr

Courtesy: T. Kato





Streaming beam test Γ=10



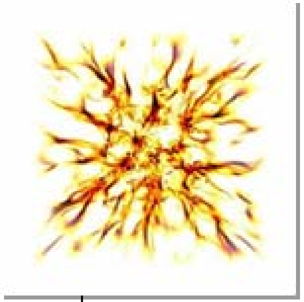
Cold beam instability is another concern

The initial temperature of the plasma is set artifically high, with $v_{e,th} = 0.01c$, in order to mitigate Buneman-type electrostatic effects arising from the drift between the stationary population of ions and the slowly drifting electrons. Our simulations in N08 demonstrated that cooler plasmas were heated through such effects on a much shorter timescale than any turbulent magnetic-field amplification, but the resulting anisotropy of the ion distribution function in particular persisted on such timescales. A higher initial temperature leads to better preservation of isotropy against the intra-plasma drift. Additionally, using a density ratio N_i/N_{CR} of 50 instead of 3 (the value in N08) significantly reduces v_d.

Strohman et al arXiv: 0909.5212

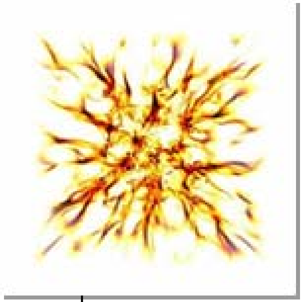
The structure of relativistic collisionless shocks

Spatial resolution



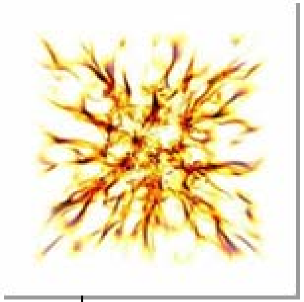
- As always, spatial resolution $\Leftrightarrow$ cost!
  - Need to balance **spatial extent & spatial resolution!**
- Number of cells per e-skin depth
  - Important parameter – ***but not the only one!***
- Number of cells per Debye length
  - Also crucial; and generally ***more demanding!***
    - **unless T already relativistic, the Debye length is smaller!**

Spatial resolution

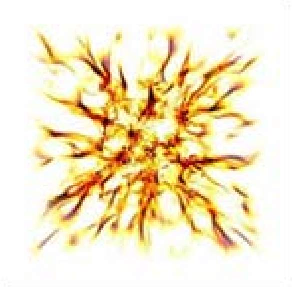


- Spatial and temporal order of field operators
  - Often only 2nd order in space & time (classical Boris')
    - **Should probably rather be similar to MHD codes!**

- Spatial order of scatter/gather (particle/field) operators
  - Very coarse (nearest-grid-point) or "2-D tent" methods sometimes used
    - Probably sub-optimal – a small improvement in resolution translates into a ***large factor in computing time*** (~ N^4)
  - Higher order $\Rightarrow$ larger footprint / support volume
    - But re-using things in cache is good (especially with GPUs!)



The case for a ”KITP comparison” of PIC codes

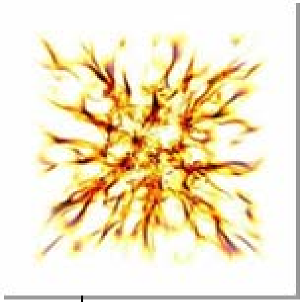


Code comparisons

- 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

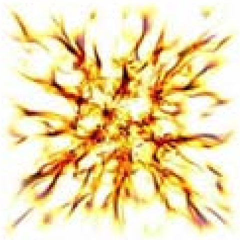
Follow-up:
Workshop in Copenhagen



- Small informal workshop at the Niels Bohr Inst.
  - Sometime in the spring – TBD

- Deciding on test problems
  - ”Now”, or ”soon”

- Come ***with solutions*** to the test problems
  - Experience from previous comparisons!

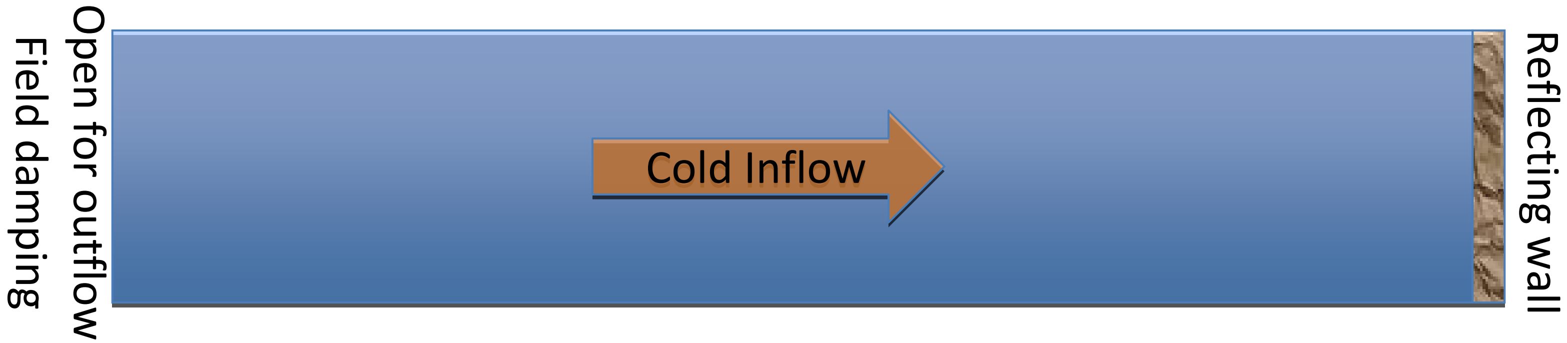


Structure(s) of Relativistic Collisionless Shocks

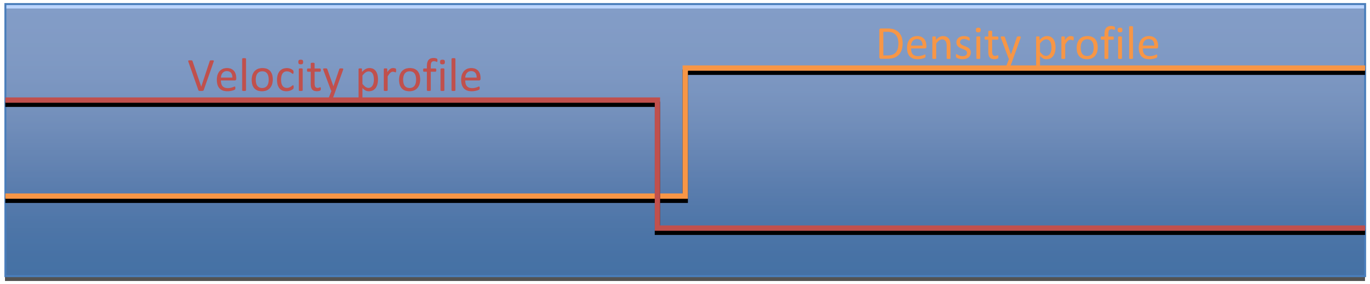
Collisionless shocks

Two alternative setups

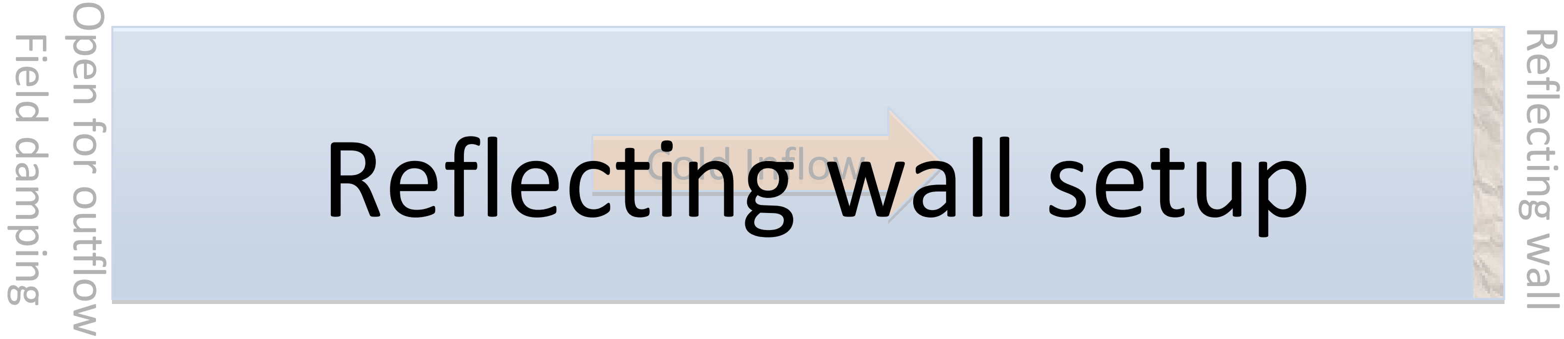
1. Reflecting wall setup – easy initial conditions



2. Steady state setup – for long time evolution



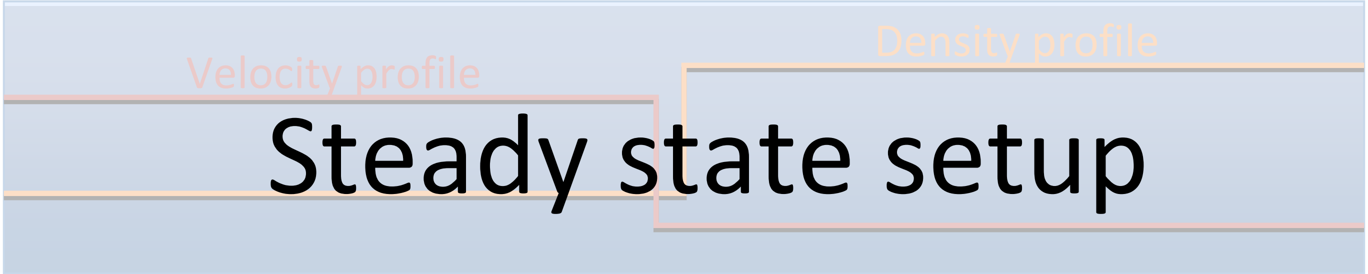
Reflecting wall setup



- PROs of the setup :
  - The initial conditions are extremely simple
  - Can validate 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
  - Up to 50,000 cells necessary in the streaming direction
    - up to 20 billion particles needed
    - in order to follow long time behavior with “expanding box”

Steady state setup



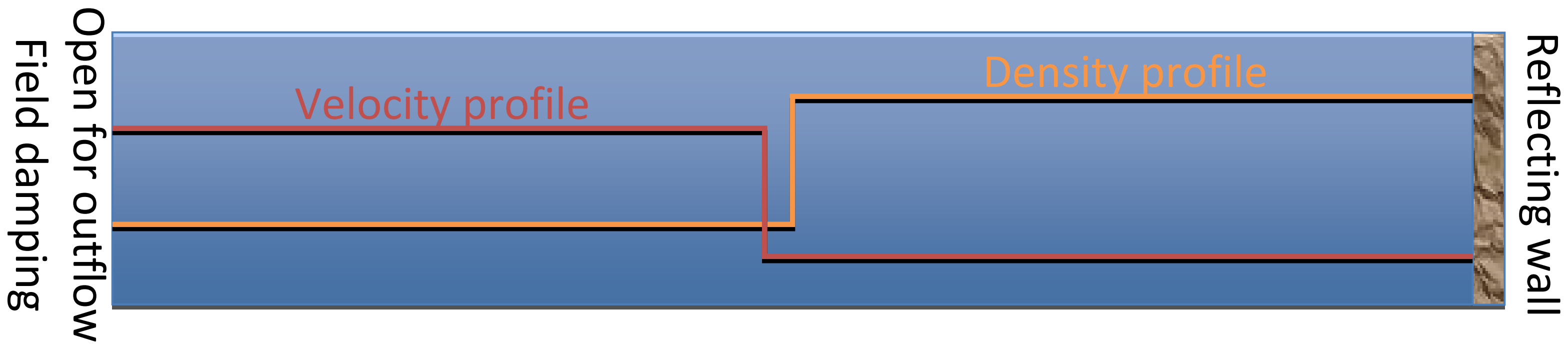
- Alternative to reflecting wall
  - Allows much longer runs
    - For studying secular trends and evolution

- Need to conserve mass, momentum and energy fluxes from left to right boundaries
  - Outflow boundary condition is crucial
    - **.. and difficult!**

Collisionless shocks

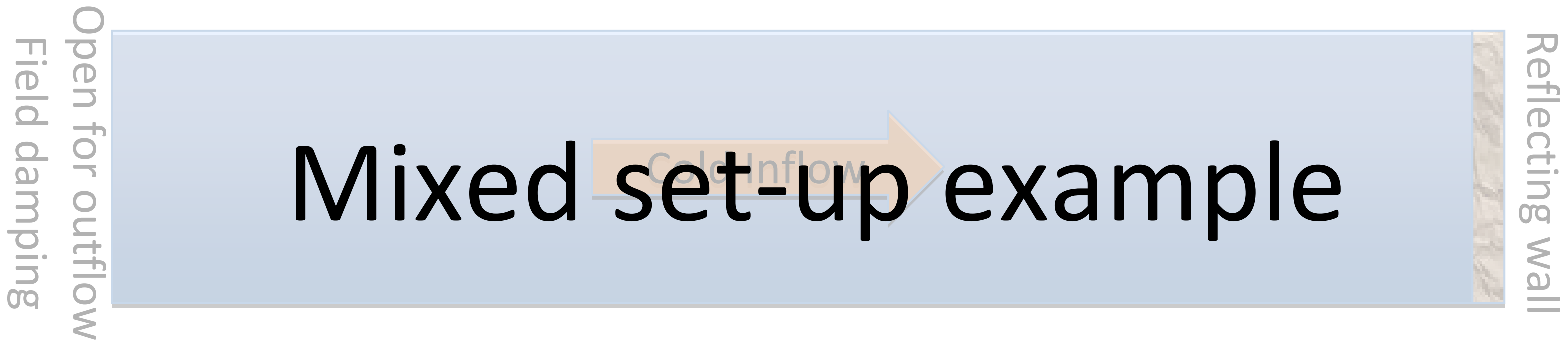
Mixed setup

- Reflecting wall setup – **with peel-off!**

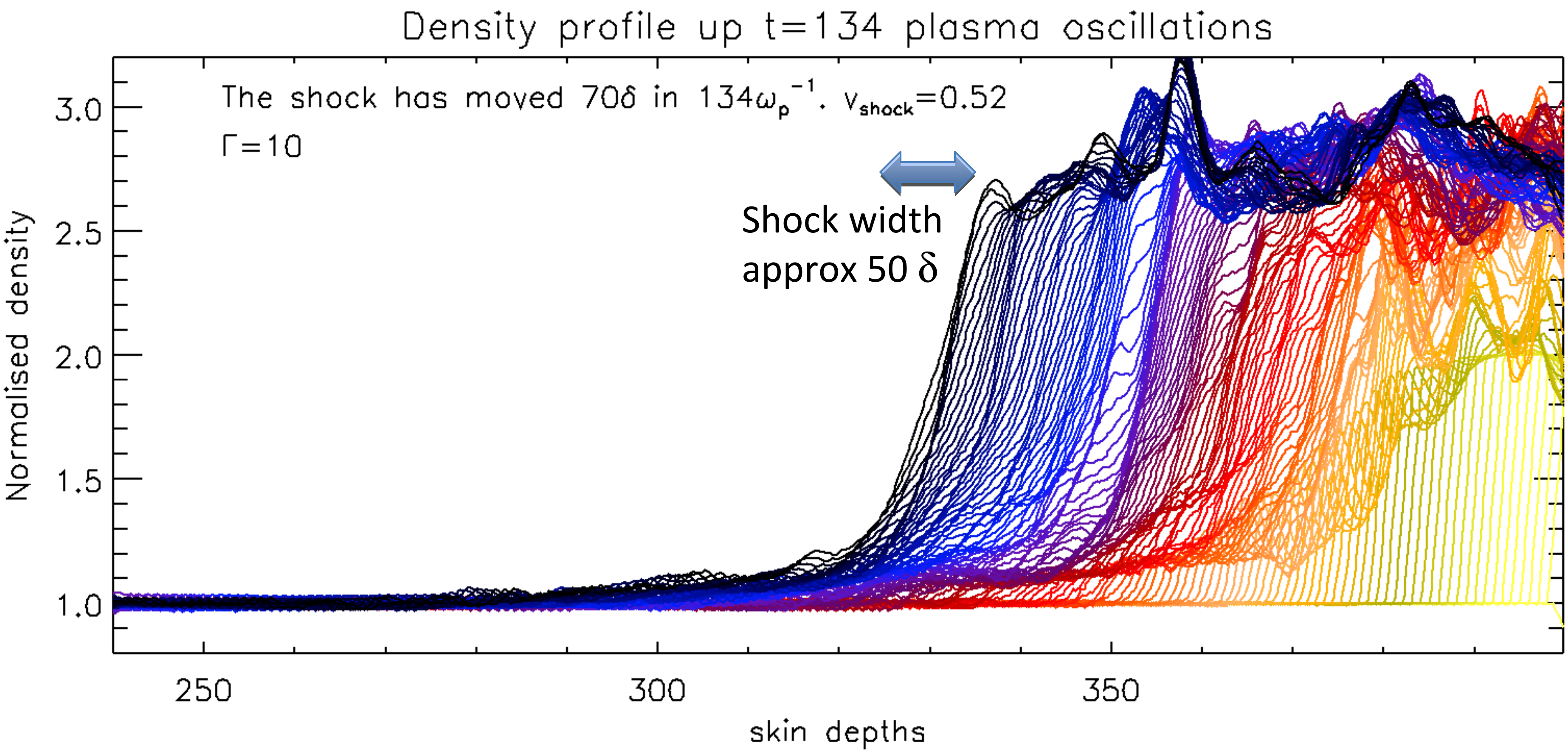


- Stay in the down-stream frame
  - Shock moves to the left with ~ 0.5 c
  - ”Peel-off” fractions of the box to the right
  - Add new inflow layers at the inflow boundary
  - Avoid reflection of EM-fields
    - damping near the inflow boundary

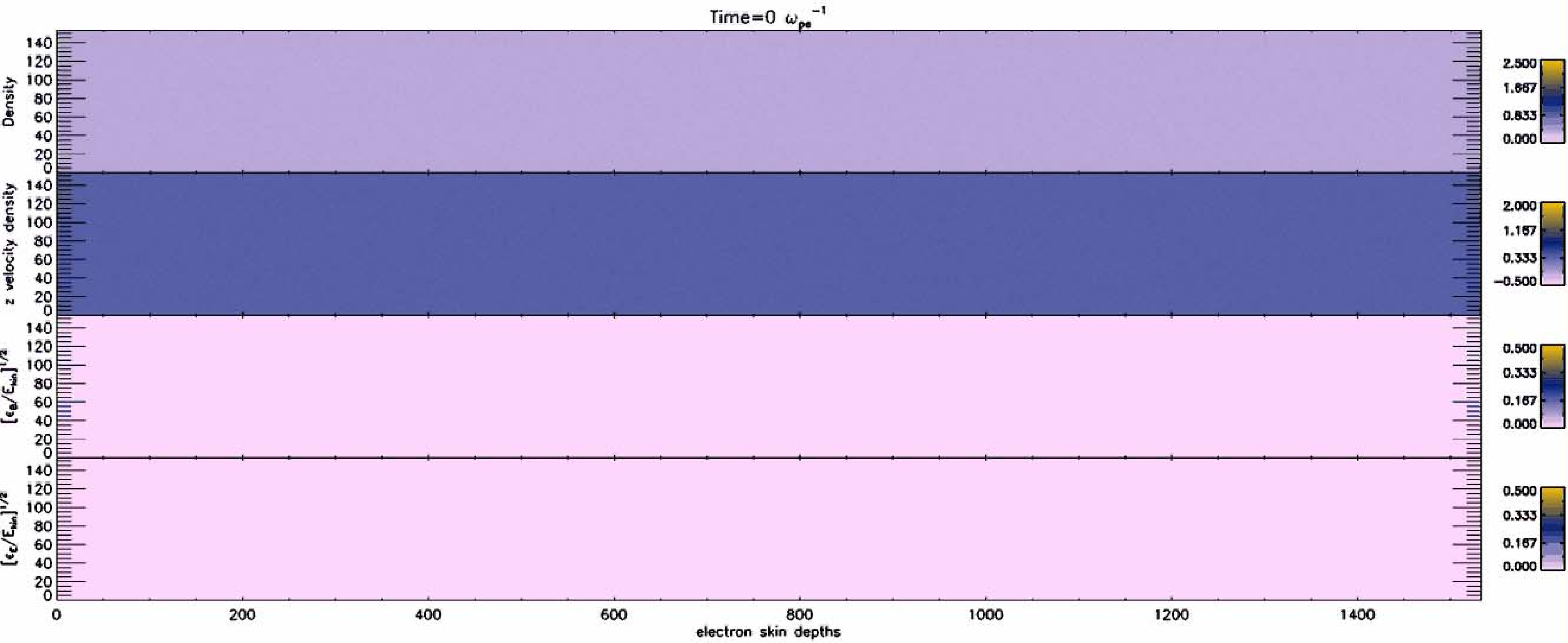
Mixed set-up example



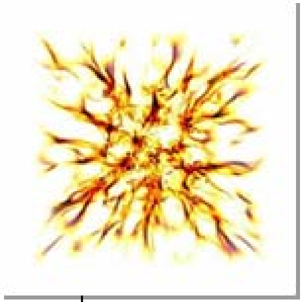
- Density evolution



Movie, peel-off 2-D setup, Γ=15 ion-electron plasma



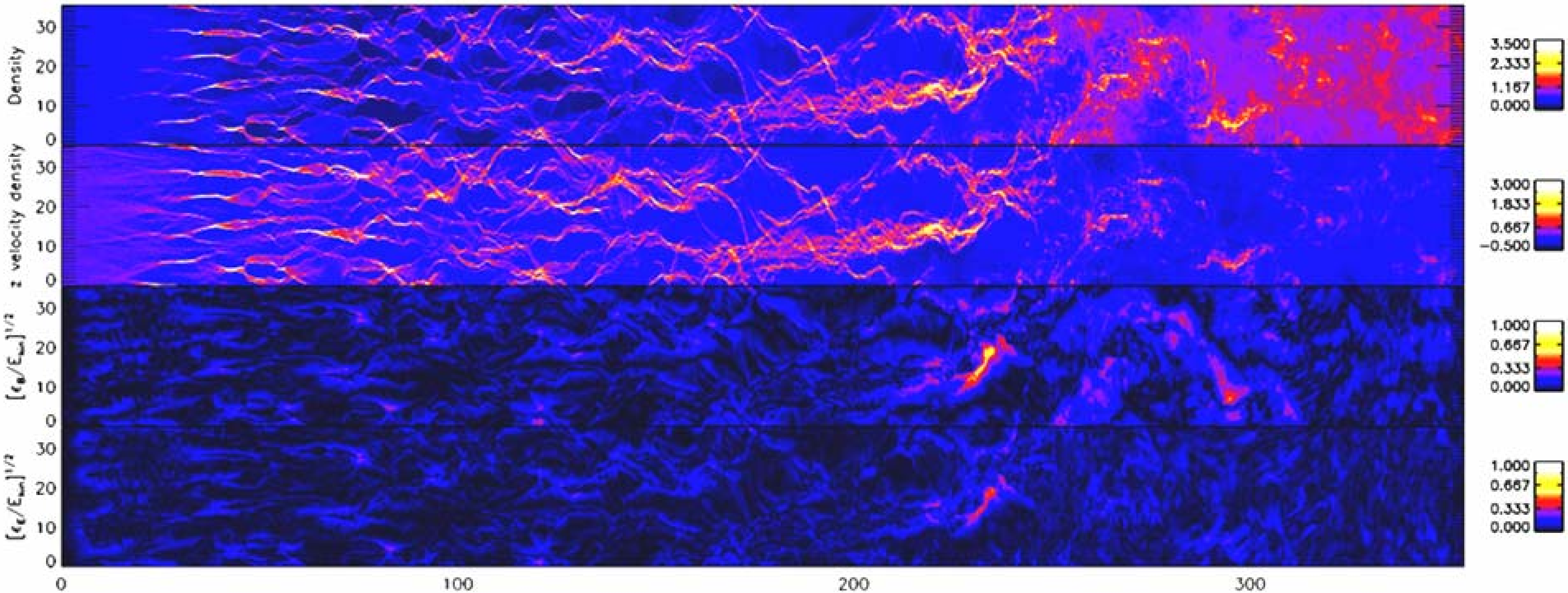
2D vs. 3D
One-on-one comparison



- Reflecting wall, $\Gamma = 15$
  - Resolved to the same extent in 2-D and 3-D
- 2D is much cheaper, but is it quantitatively OK?
  - Different jump conditions
  - Different synthetic spectra
  - Different particle acceleration(?)
- ”Cheap” 3D-demo used here
  - Using relatively ”flat” 3-D box – aspect ratio 100:10:1

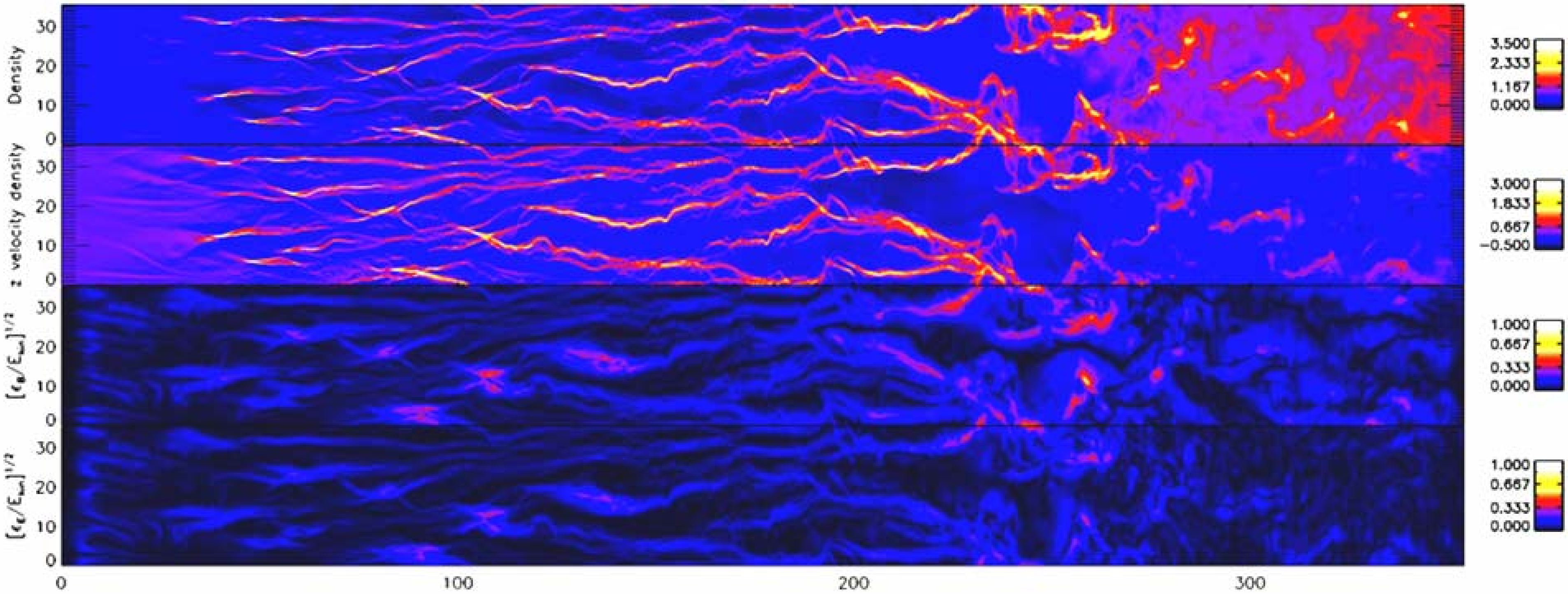
2D vs. 3D – same particles-per-cell and cells-per-skindepth

2-D: 3540 x 354 cells



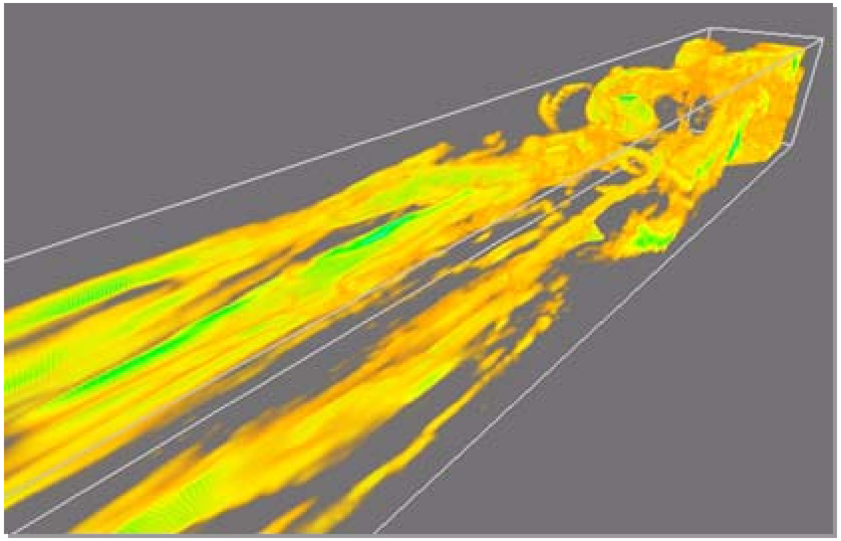
2D vs. 3D – same particles-per-cell and cells-per-skindepth

3-D: 3540 x 354 x 35 cells



3-D Visualization (NCAR Vapor)

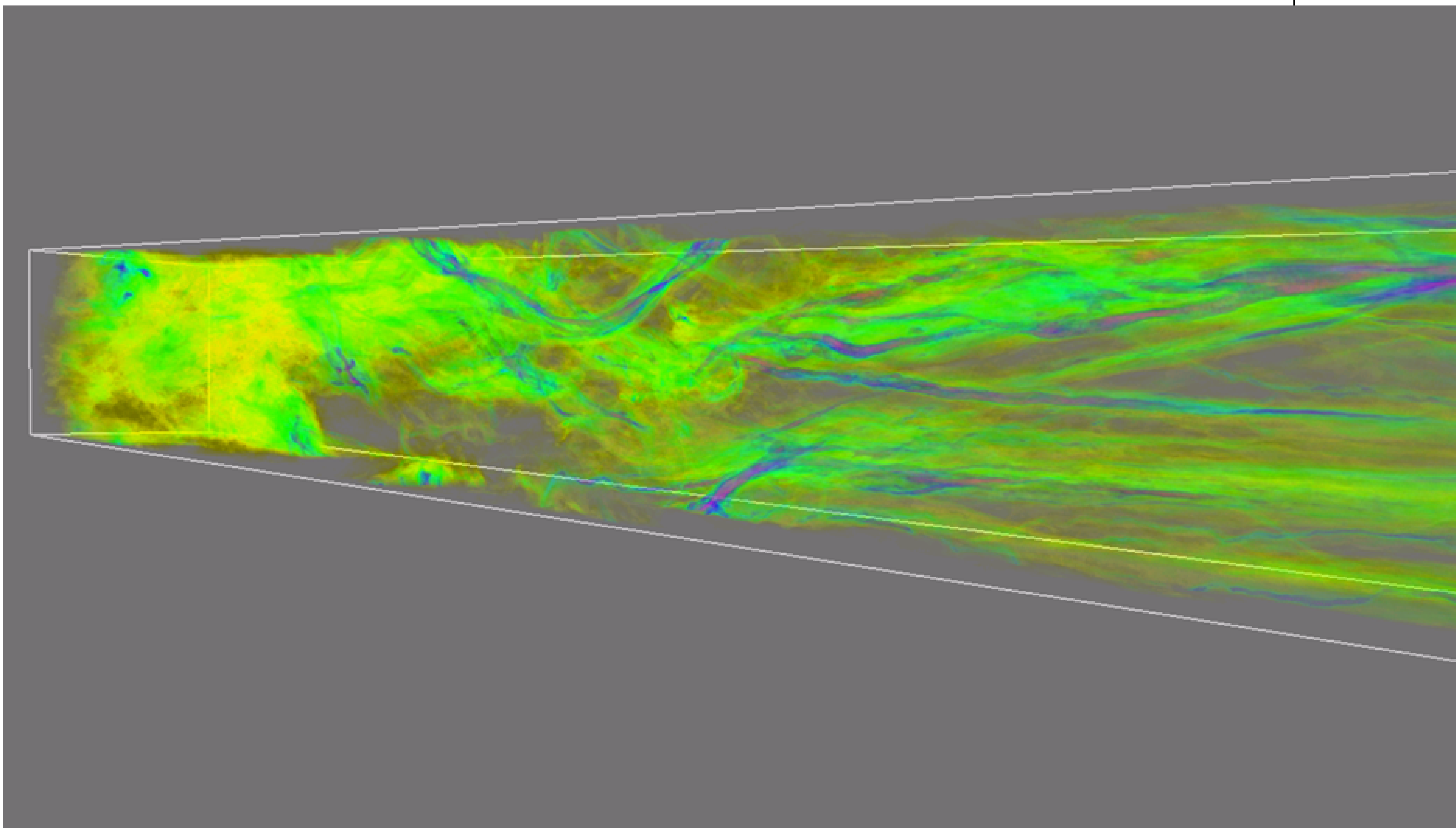
- Γ = 15

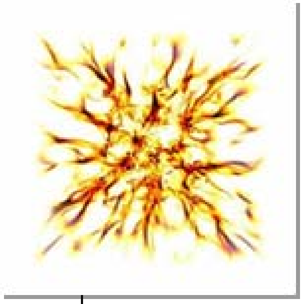


- 20 billion particles
  - 6 ppc upstream
- 7000 x 250 x 250
  - showing only 2900 x 250 x 250
  - t = 290 skin times
  - 10 cells per e-skin depth
  - mass ratio 16:1

3-D Visualization (NCAR Vapor)

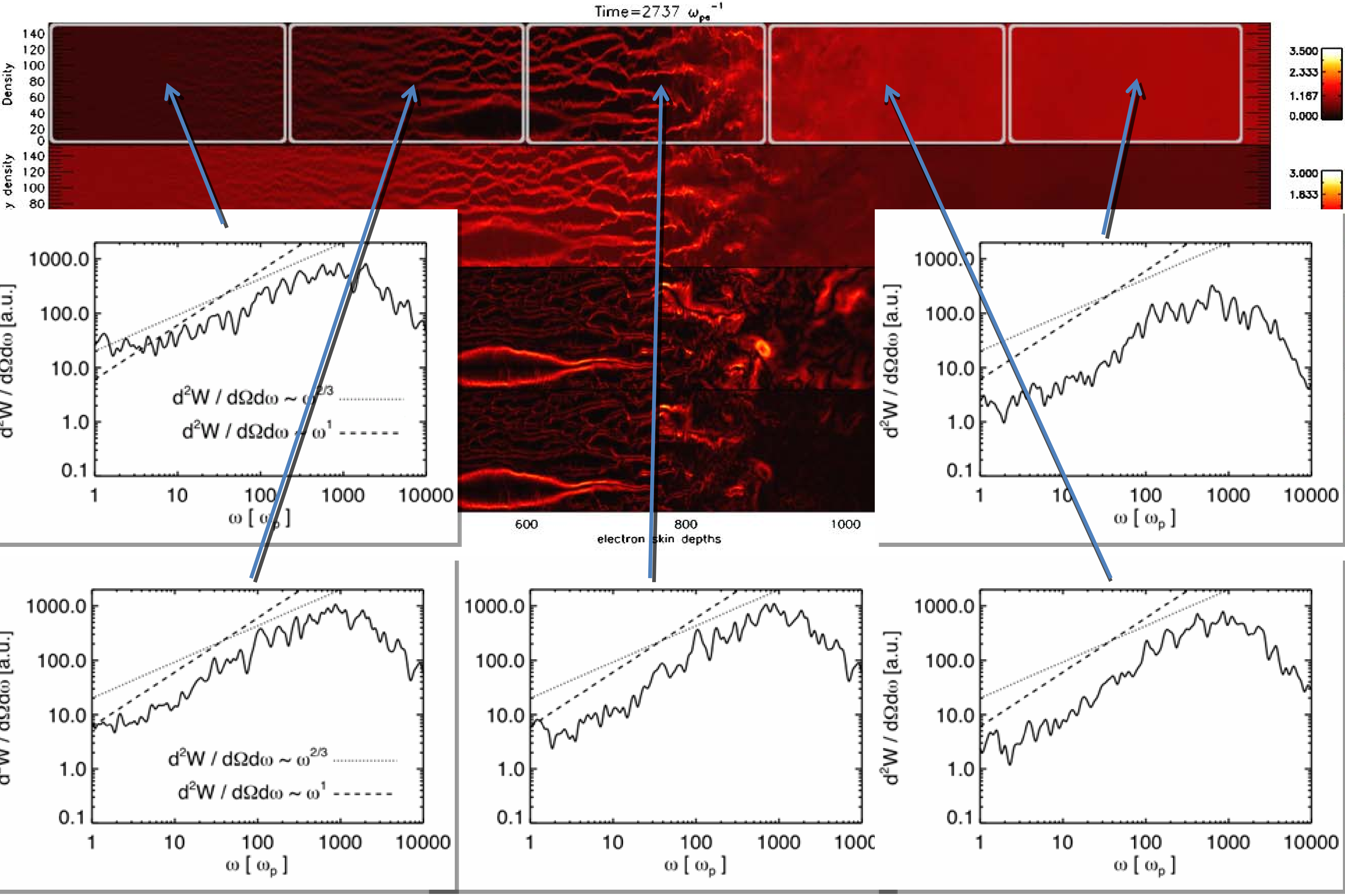
Proton density in $\Gamma = 15$ 3-D case



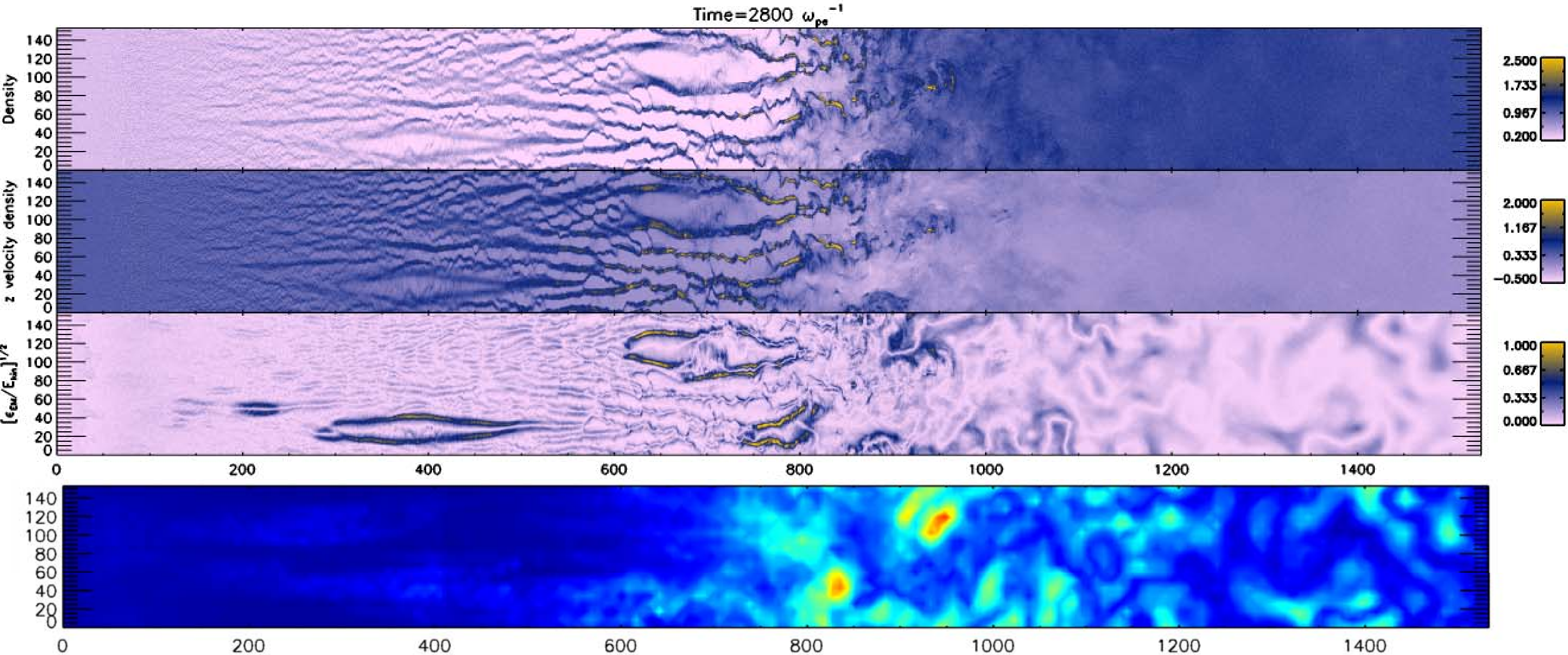


Imag(en)ing the Radiation Structure of Relativistic Collionless Shocks

Synthetic spectra



Imagining Synthetic spectra

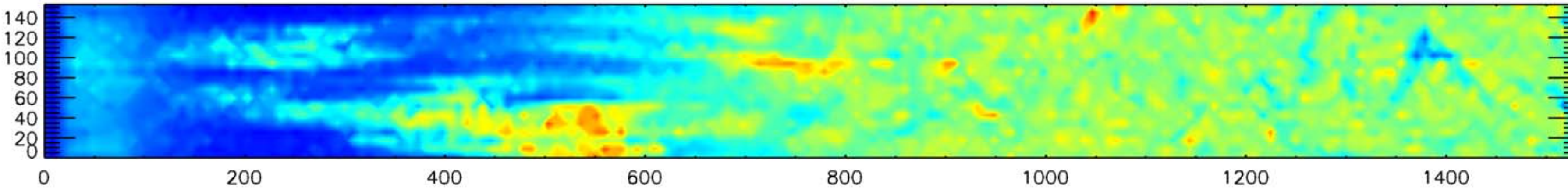


- Sampling particles in different regions
- Not only synthetic spectra but also *synthetic images*
- Gives us an understanding of where radiation arises

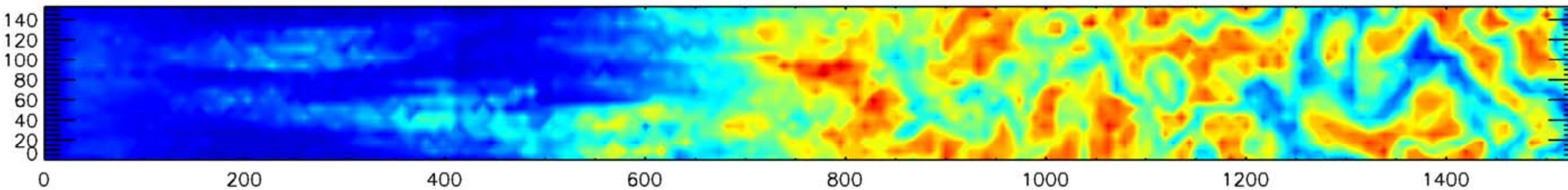
Imagining Synthetic spectra

Images show power $P^{0.3}$

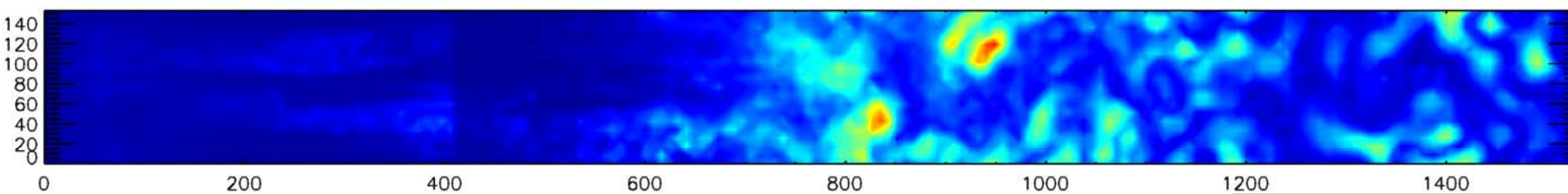
ω= [10, 100]



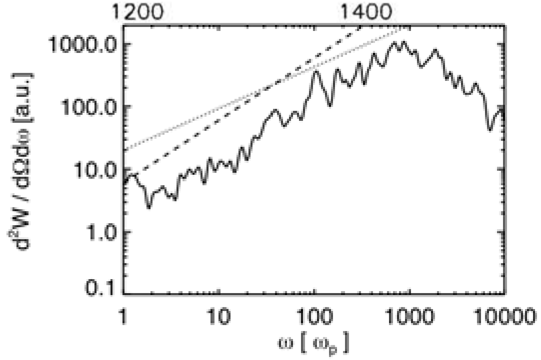
ω= [100, 1000]



ω= [1000, 10000]

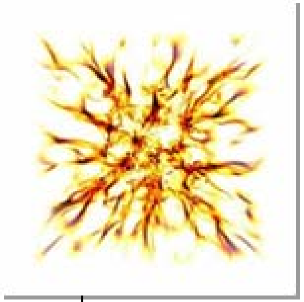


- It's the high frequencies that dominates energy budget
- Different bands sample different structures



The structure of relativistic collisionless shocks

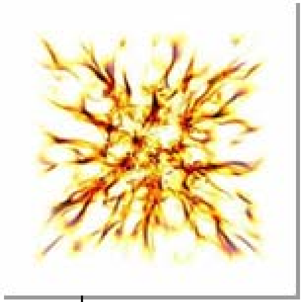
Summary and Conclusions



- Particle-in-cell simulations in general
  - Current capabilities: **large enough for serious 3D!**
  - Can we trust the results? **Yes, after comparisons!**

- Collisionless shock structure
  - 3-D vs. 2-D: **major structural differences!**
  - Radiation spectra: **Need high resolution 3D!**

- Imaging the radiation output
  - Spatial and temporal structure: **can be retrieved!**



Thanks for your attention!