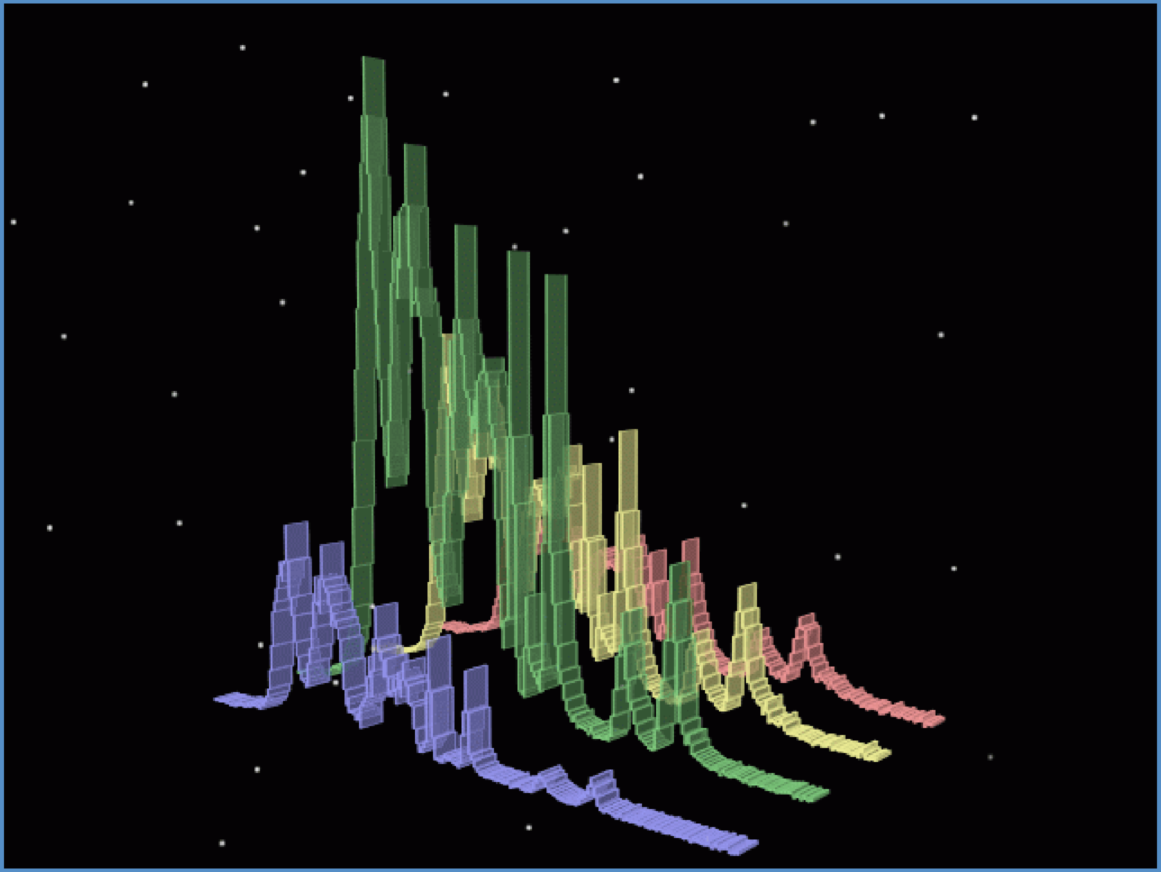
Gamma Ray Bursts
Connecting Observations and Simulations



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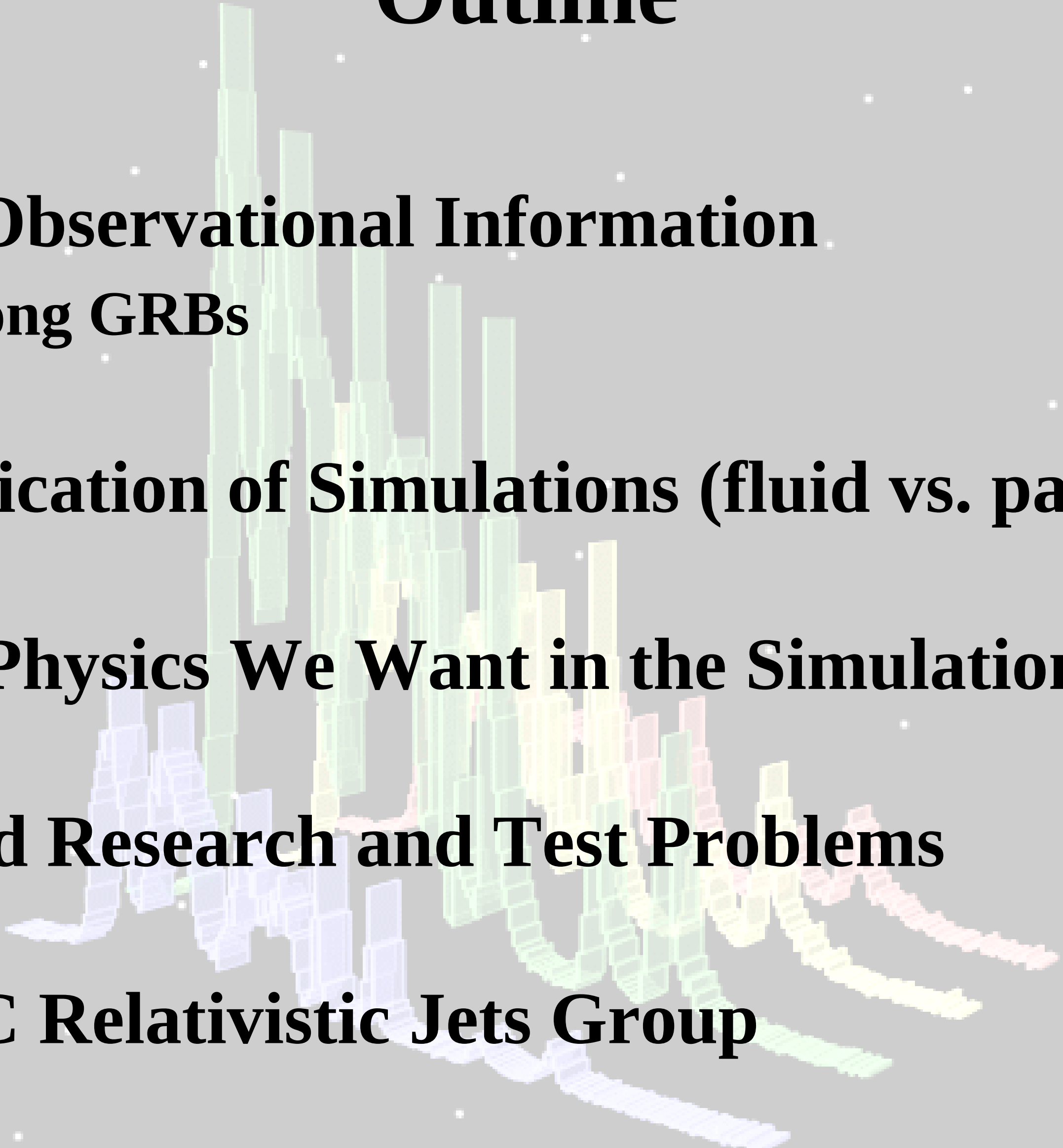
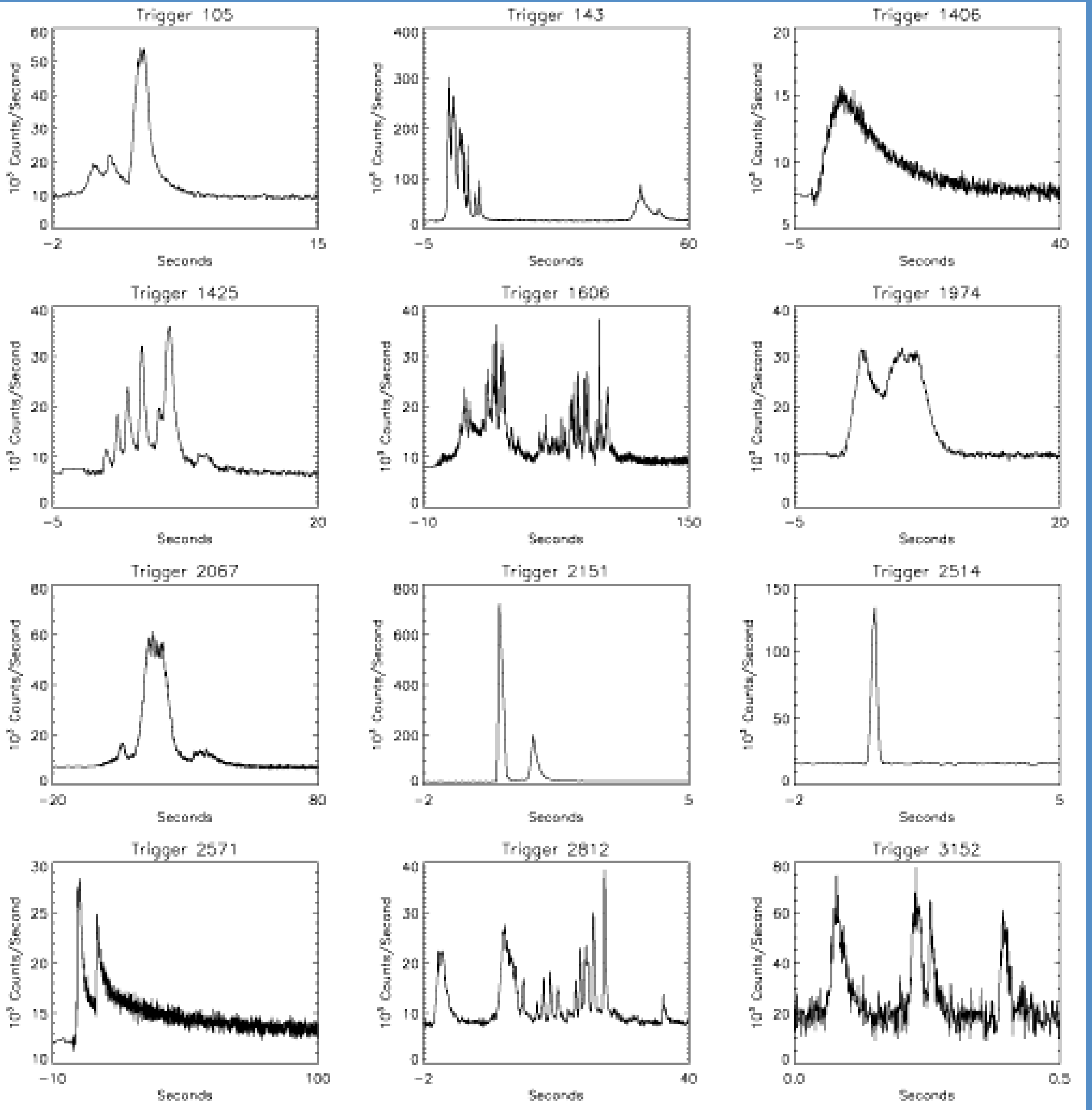
Outline



- Basic Observational Information
  - Long GRBs
- Classification of Simulations (fluid vs. particle)
- What Physics We Want in the Simulations
- Method Research and Test Problems
- NSSTC Relativistic Jets Group

A few ‘typical’ GRB light curves from BATSE



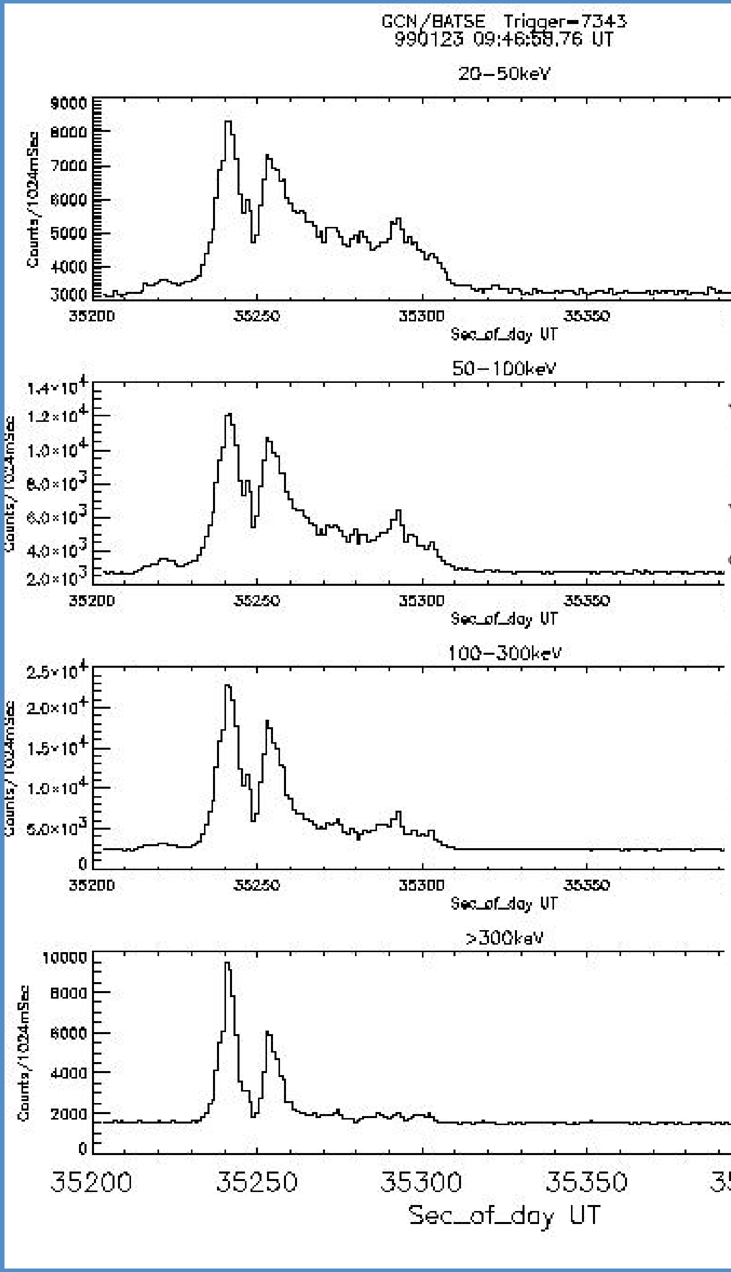
**Durations:
Milliseconds to
Hundreds of seconds**

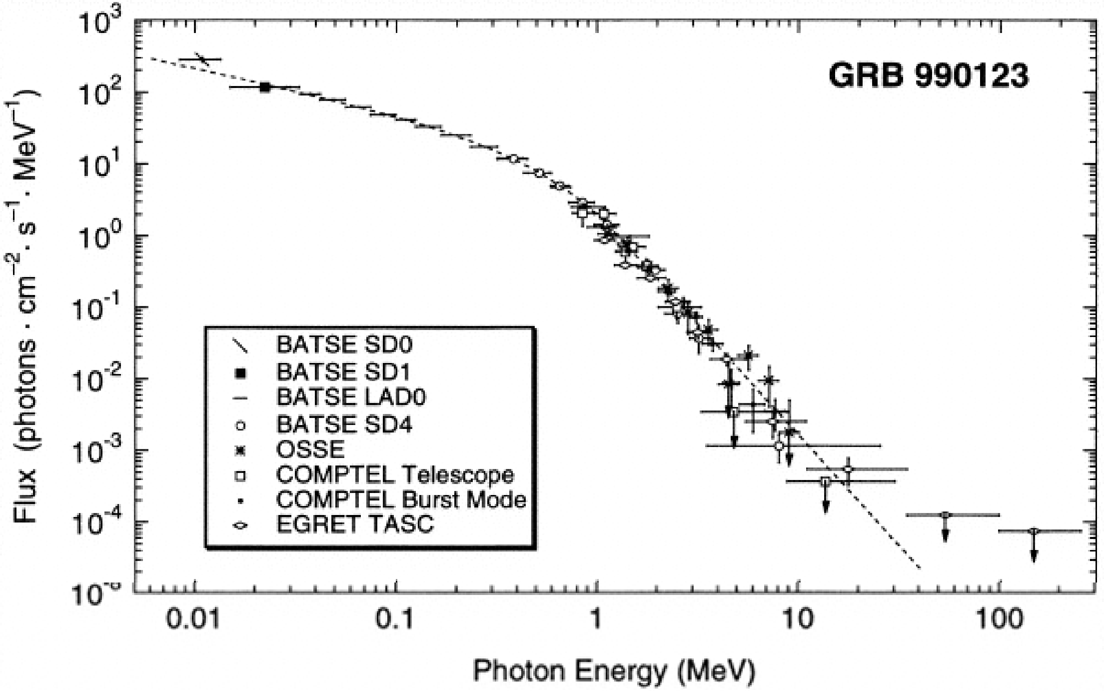
**Frequency:
One - two per day on average**

Wide range of structure

“If you have seen one burst, you have seen one burst” -Meegan

GRB990123 energy spectra



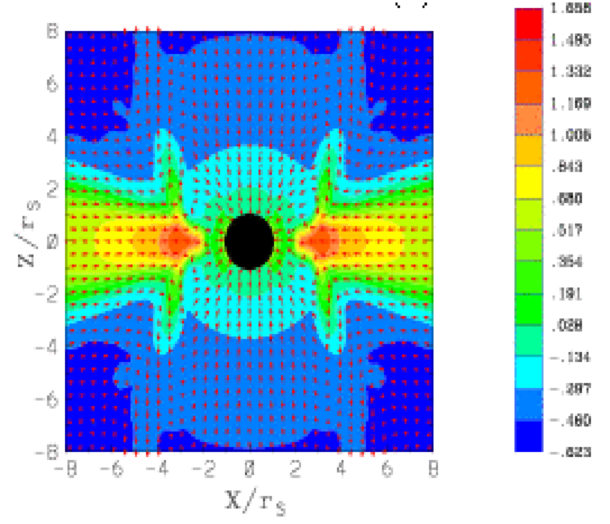


Briggs, et al. 1999

What can we simulate? Fluid vs. Particle

Fluid simulations (Hydro and MHD) – Large scale flow properties.

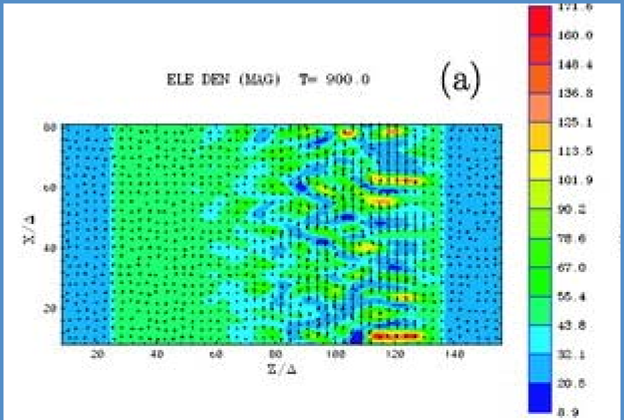
- Conservation of mass, momentum, energy and Maxwell’s equations
- Accretion and jet dynamics / formation.
- System dynamics (not the detailed physics)



Nishikawa, et al., 2005

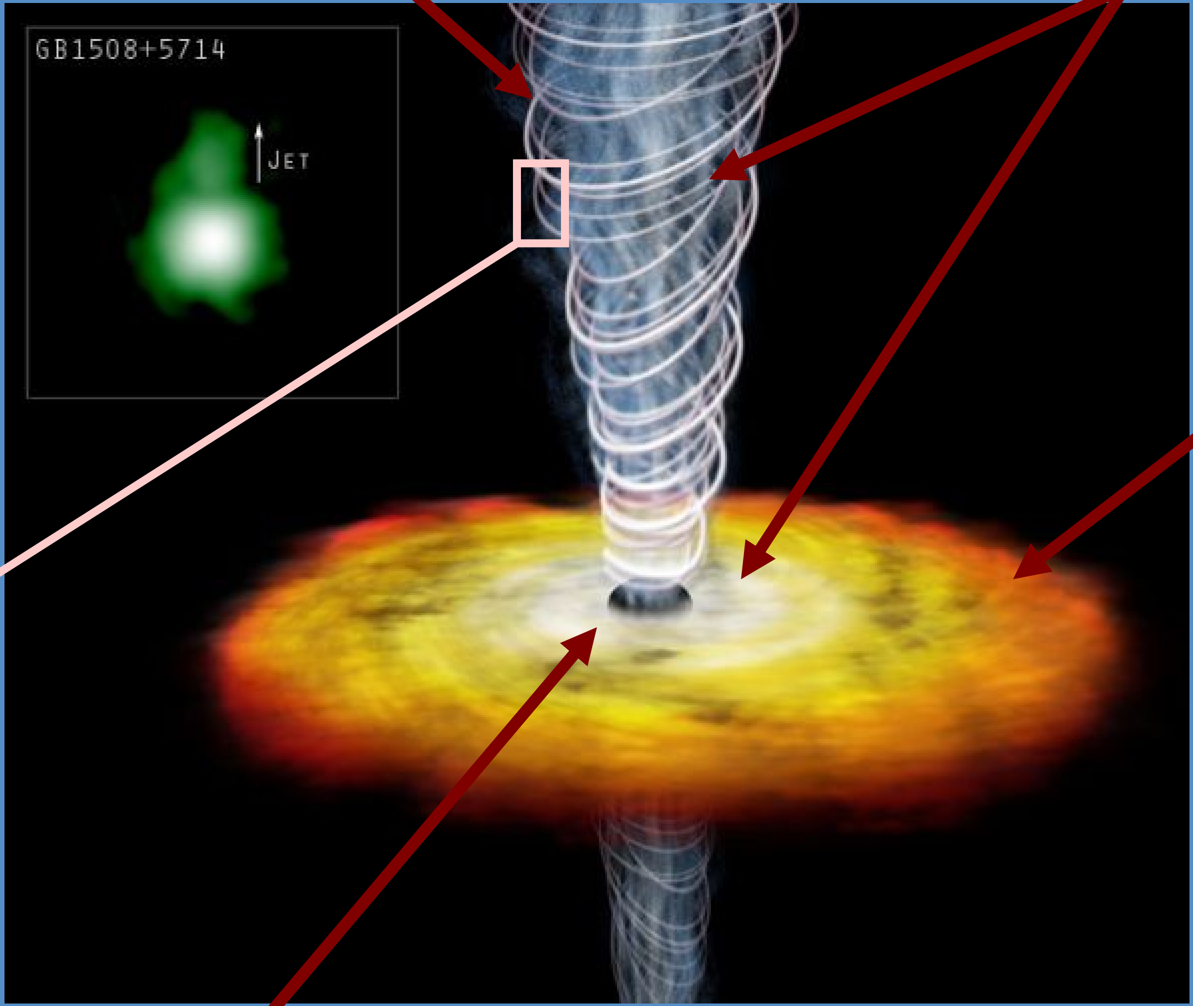
Particle simulations (PIC) – Localized simulations of particle kinetics.

- Particle equations of motion and Maxwell’s equations.
- Particle acceleration due to instabilities (small scale physics).



Nishikawa, et al., 2005

Flow Domain – Multiple Flow Regions



Fluid Instabilities

Shocks

MHD Instabilities

Particle
Domain

Strong Gravitational Force

Image Credit: A. Siemiginowska (CfA) et al., CXC, NASA
Illustration by M.Weiss (CXC)

Computational Components / GRB Relativistic Jets

- Massive explosion => Core collapse (Jet Formation)
  - General Relativity
  - Relativistic Shocks
- GRB Variability and Observational Properties
  - Shock Interactions
  - Large Lorentz Factors
  - Non-ideal – diffusion, internal heat transfer
  - Non-uniform fluid (Accretion – Jet Dynamics)
  - Equation of State (Improve fluid description)
  - Turbulence and other instabilities
- GRB Beaming
  - Magnetic fields (Non-ideal?, Divergence Constraint)
  - Rotation
- Radiation

GR-MHD Equations in Conservation Form

$$\boxed{\frac{\partial}{\partial t}\mathrm{U} = -\frac{\partial}{\partial x_i}\mathrm{F}_i - \frac{\partial}{\partial x_i}\mathrm{G}_i + \mathrm{S}}$$

U – Conservation variables
$\mathbf{F_i}$ – Flux terms
$\mathbf{G_i}$ – Diffusion terms
S – Source terms

$$F^i = \begin{bmatrix} \rho u^i \\ \rho h u^i u^1 + P g^{11}\delta_1^i - b^i b^1 \\ \rho h u^i u^2 + P g^{22}\delta_2^i - b^i b^2 \\ \rho h u^i u^3 + P g^{33}\delta_3^i - b^i b^3 \\ \rho h u^i + P g^{30} u^i - b^i b^0 \\ b^i u^1 - b^1 u^i \\ b^i u^2 - b^2 u^i \\ b^i u^3 - b^3 u^i \end{bmatrix}$$

Flowfield Dependent Variation Method

$$U^{n+1} = U^n + \Delta t \frac{\partial U^{n+s_a}}{\partial t} + \frac{\Delta t^2}{2} \frac{\partial^2 U^{n+s_b}}{\partial t^2} + O\left(\Delta t^3\right)$$

$$\Delta U^{n+1} = U^{n+1} - U^n$$

$$\Delta U^{n+1} = \Delta t \left(\frac{\partial U^n}{\partial t} + s_a \frac{\partial \Delta U^{n+1}}{\partial t} \right) + \frac{\Delta t^2}{2} \left(\frac{\partial^2 U^n}{\partial t^2} + s_b \frac{\partial \ \Delta U^{n+1}}{\partial t^2} \right) + O\left(\Delta t^3\right)$$

First order FDV Parameter

Second order FDV Parameter

$$\boxed{\frac{\partial}{\partial t} U = -\frac{\partial}{\partial x_i} F_i - \frac{\partial}{\partial x_i} G_i + S}$$

Chung - 1999
Richardson & Chung - 2002

First Order FDV Parameters

Calculated by sampling the flow physics (Lorentz factor, Reynolds number, etc.)
Indicators for shocks, instabilities (turbulence, etc.), adaptive mesh.

Diffusion parameter indicates non-ideal terms, shift in PDE form from hyperbolic to mixed.

$$s_a = \begin{cases} s_1 = 1^{st}\ order\ \ flux\ \ parameter \\ s_3 = 1^{st}\ order\ diffusion\ \ parameter \\ s_5 = 1^{st}\ order\ source\ term\ \ parameter \end{cases}$$

$$\Gamma = \frac{1}{\sqrt{1 - g_{ij} u^i u^j}}$$

$$\mathrm{Re} = \frac{u^i L \rho}{\mu}$$

Second Order FDV Parameters

Numerical instability indicator.
Controls the second order damping term.

$$\Delta U^{n+1} = \Delta t\left(\frac{\partial U^n}{\partial t} + s_a \frac{\partial \Delta U^{n+1}}{\partial t}\right) + \frac{\Delta t^2}{2}\left(\frac{\partial^2 U^n}{\partial t^2} + \boxed{s_b \frac{\partial \ \Delta U^{n+1}}{\partial t^2}}\right) + O\left(\Delta t^3\right)$$

$$s_b = \begin{cases} s_2 = 2^{nd} \ order \ convection \ parameter \\ s_4 = 2^{nd} \ order \ diffusion \ parameter \\ s_6 = 2^{nd} \ order \ source \ term \ parameter \end{cases}$$

$$s_b = \frac{1}{2}\left(1 + s_a^\eta\right)$$

With specific constant FDV parameters, the equations reduce to known solution methods.

Hydrodynamics

Relativistic shocks

Large Lorentz factors

General relativity

Non-ideal – diffusion, heat transfer

Non-uniform fluid

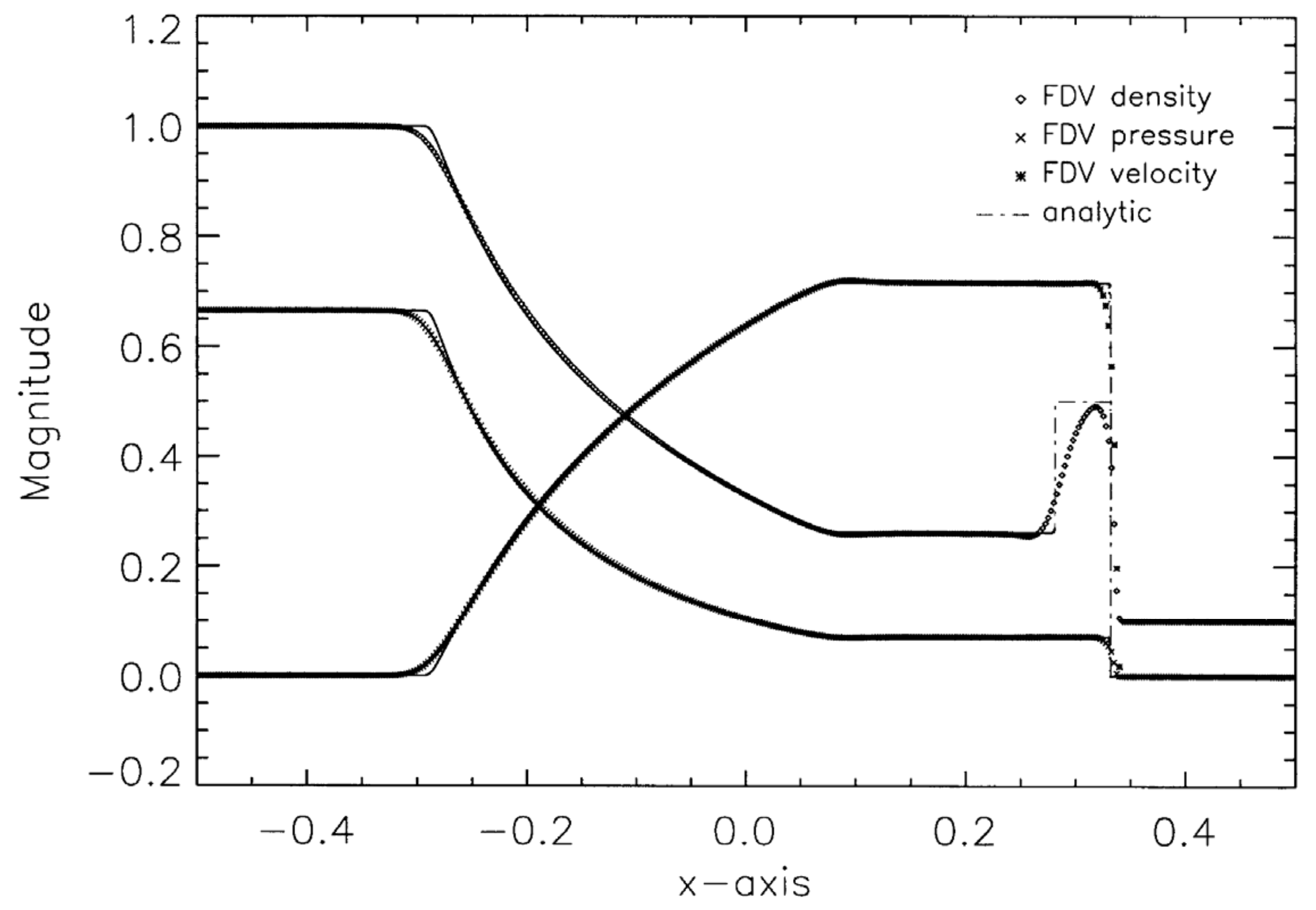
Shock Interactions

Equation of State – improve fluid description

Turbulence and other instabilities

Relativistic Shock Tube

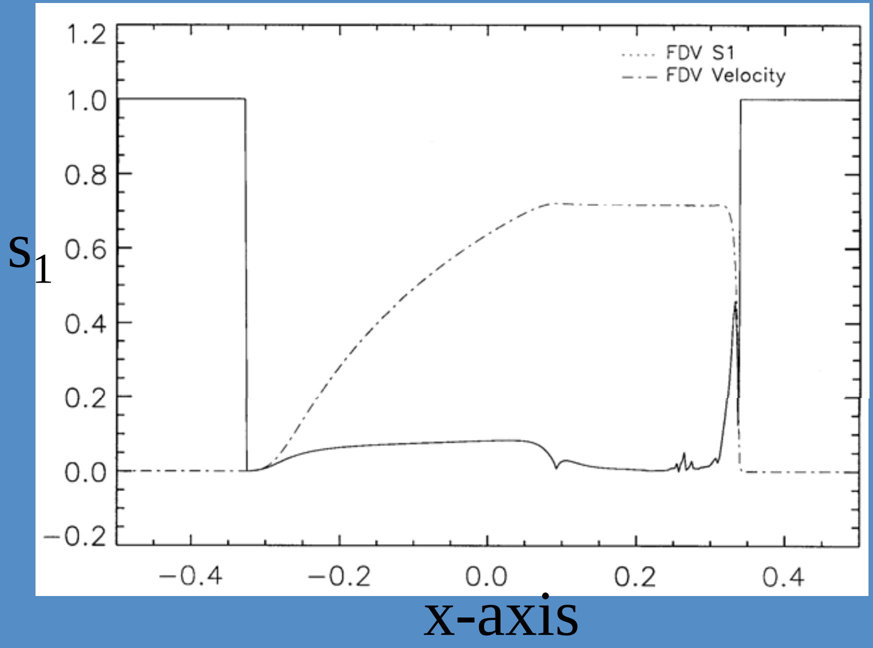
(400 nodes)

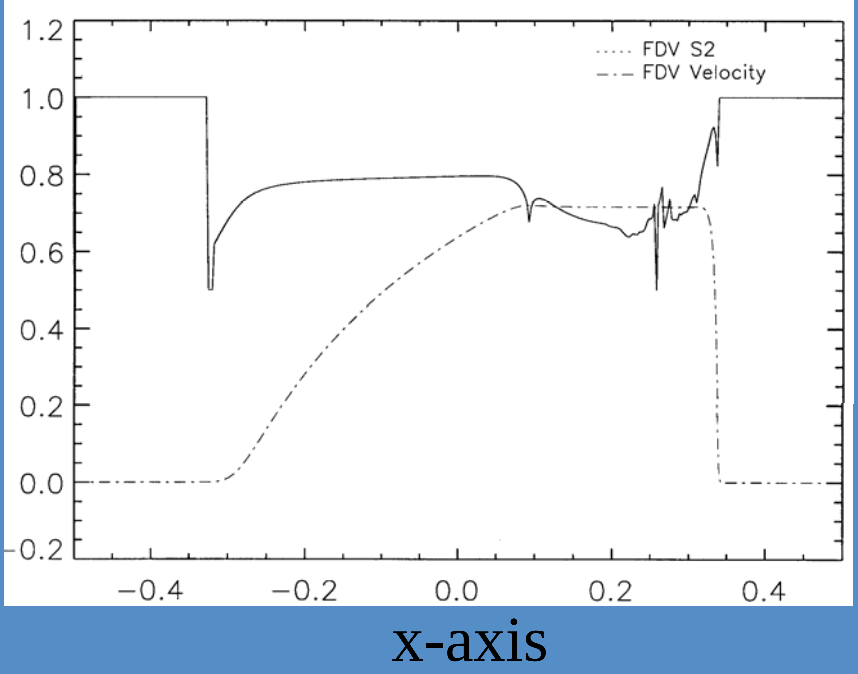


Richardson & Chung - 2002

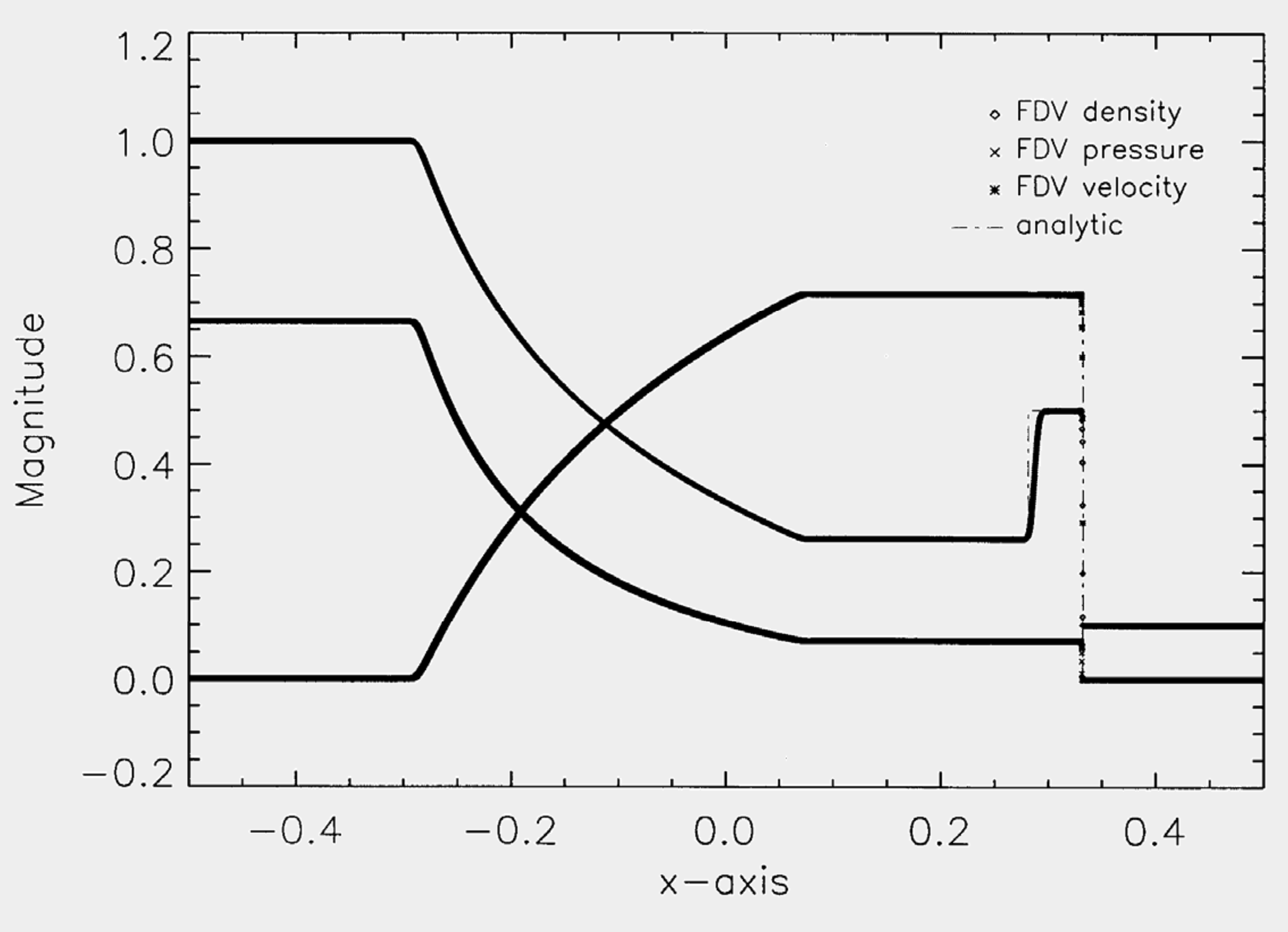
Relativistic Shock Tube – FDV Parameters

(400 nodes)





Relativistic Shock Tube – Rough Adaptive Mesh



Hydrodynamics

Relativistic shocks

Large Lorentz factors

General relativity

Non-ideal – diffusion, heat transfer

Non-uniform fluid

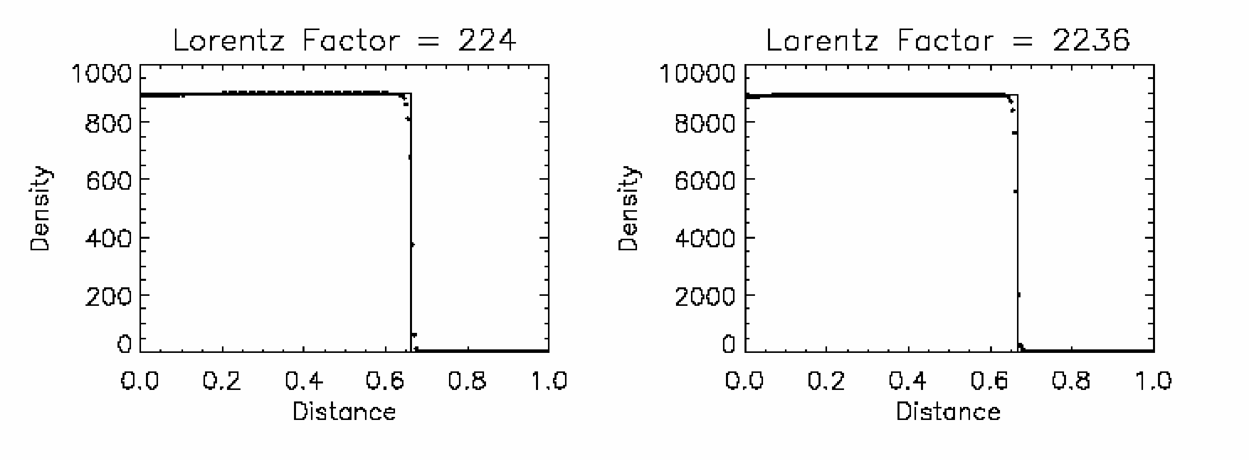
Shock Interactions

Equation of State – improve fluid description

Turbulence and other instabilities

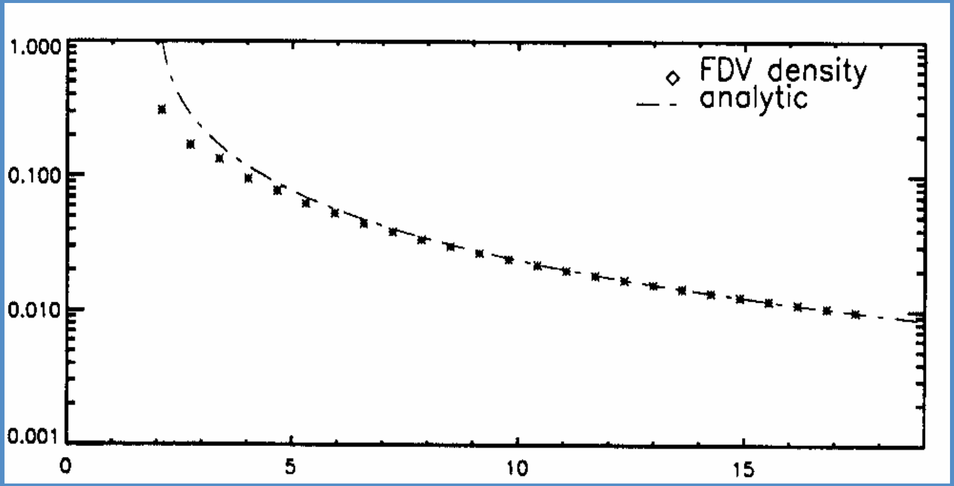
Ultra-Relativistic Wall Shock

(200 nodes)



General Relativisitc Black Hole Infall

(32 nodes)



Hydrodynamics

Relativistic shocks

Large Lorentz factors

General relativity

Non-ideal – diffusion, heat transfer

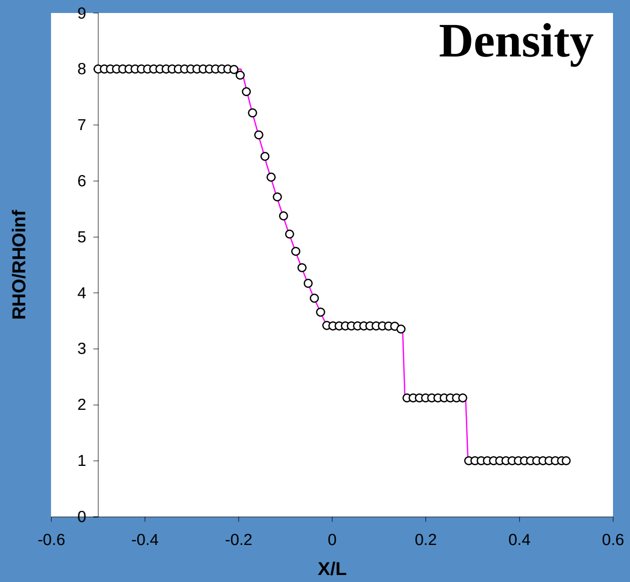
Non-uniform fluid

Shock Interactions

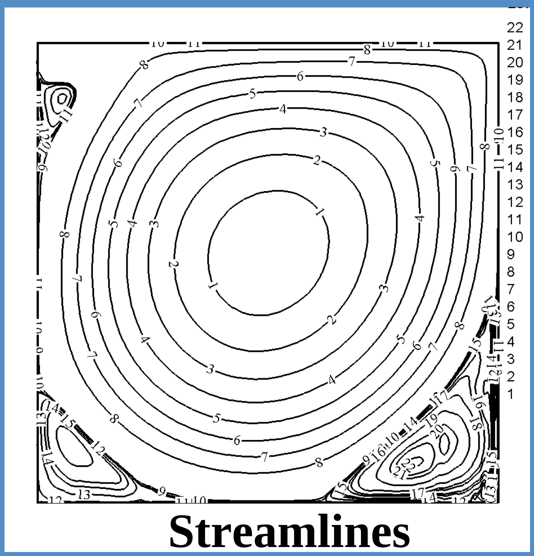
Equation of State – improve fluid description

Turbulence and other instabilities

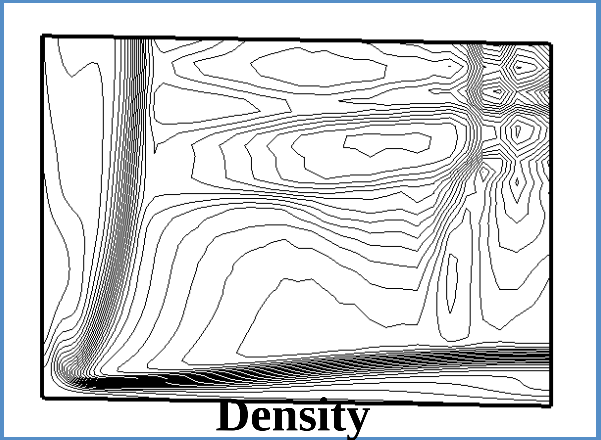
Other FDV Sample Problems

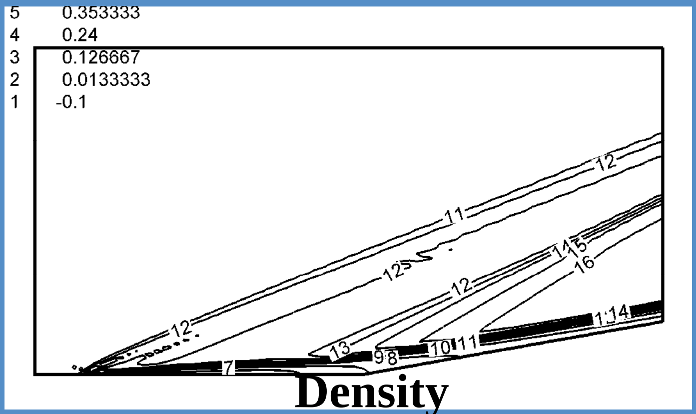


Non-Relativistic Shock Tube



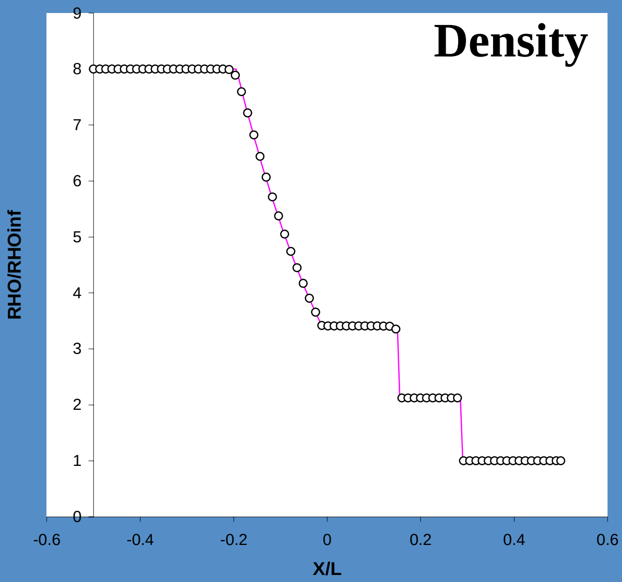
Incompressible Viscous Flow (2-D)



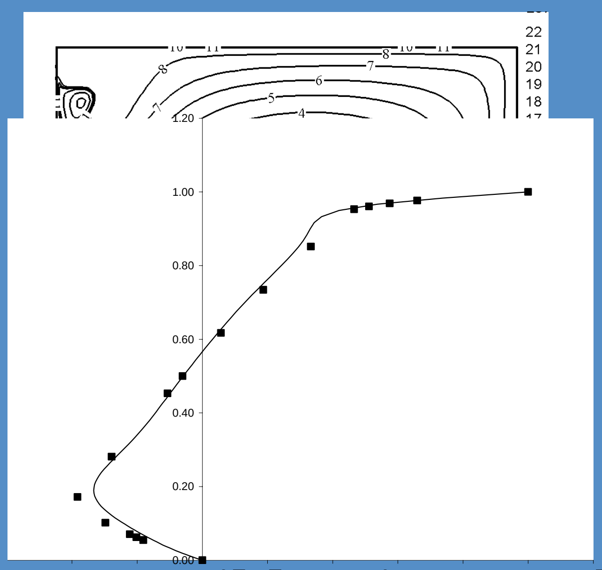


Compressible viscous flow (2-D and 3-D)

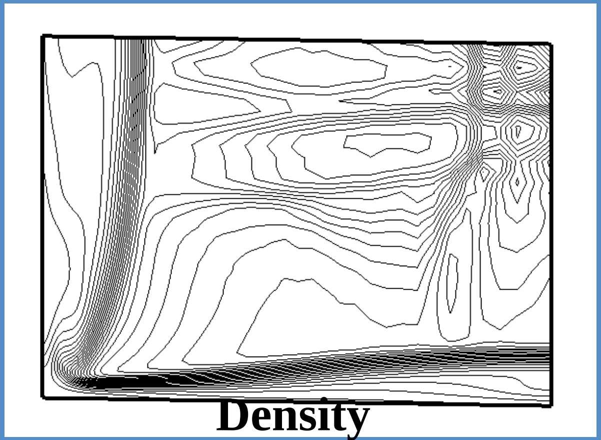
Other FDV Sample Problems

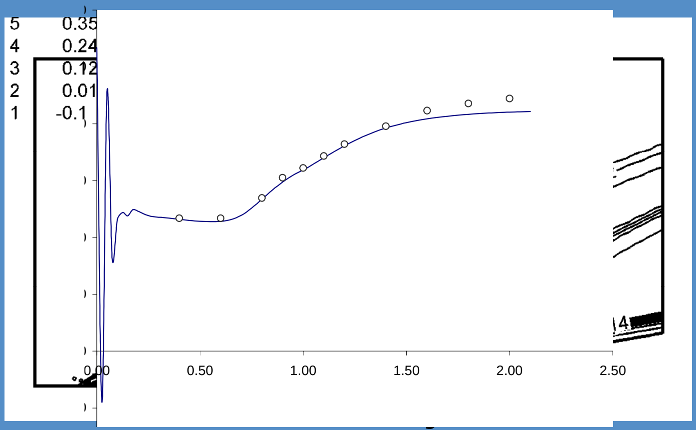


Non-Relativistic Shock Tube



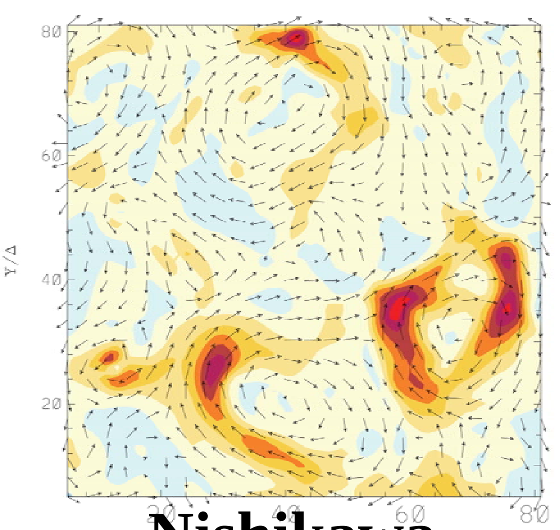
Incompressible Viscous Flow (2-D)





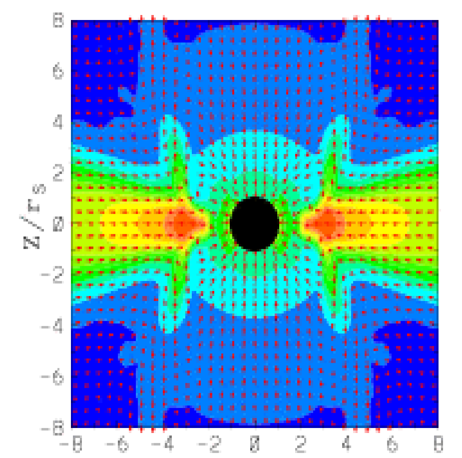
Compressible viscous flow (2-D and 3-D)

NSSTC Relativistic Jets Group

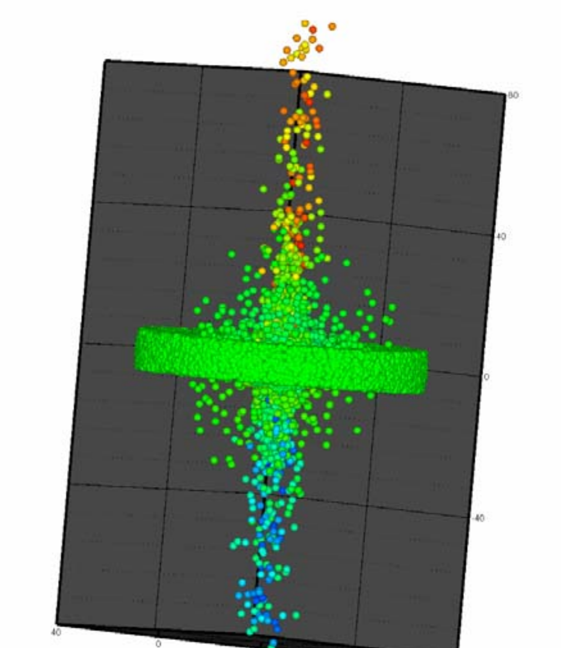


Nishikawa

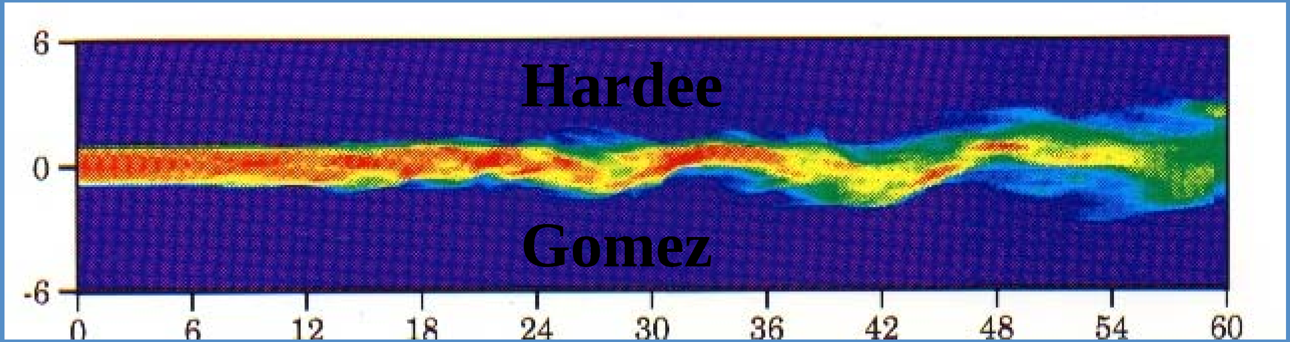
BATSE (1991 – 2000)



Mizuno



Watson



Hardee

Gomez

GLAST/GBM (2007 -)