Simulations using FLASH

(… and other considerations regarding numerical modeling)

FLASH center for Computational Science, University of Chicago

Outline

- ...
- ...
- ...

~~Outline~~ Bunch of questions

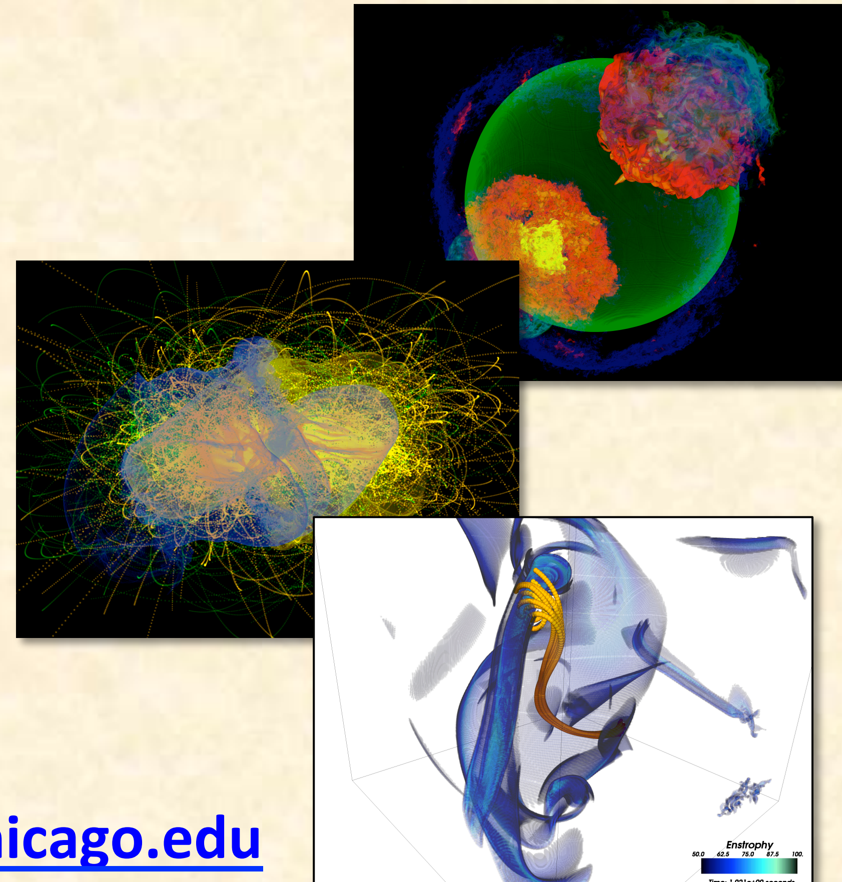
- ❑ Why do we need numerical simulations?
- ❑ What does it take to make a simulation?
- ❑ What can be learned from them?

The FLASH code

FLASH is a portable, multi-physics, shock-capturing code with extended capabilities:

- ❑ HD, MHD (1 & 3T)
- ❑ Block-structured AMR
- ❑ Implicit diffusion solvers (HYPRE)
- ❑ Particles, Flame, Self-gravity, etc...
- ❑ HEDP suite, including
  - radiation diffusion,
  - laser deposition, ray-tracing,
  - multi-material support and
  - tabulated EoS and opacities.

Publicly available @ http://flash.uchicago.edu



Compact MHD

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$$\frac{\partial \boldsymbol{U}}{\partial t} = -\nabla \cdot \mathbf{F}\,(\boldsymbol{U}) + \boldsymbol{S}(\boldsymbol{U})$$

$$\boldsymbol{U} = \begin{pmatrix} \rho \\ \boldsymbol{m} \\ \boldsymbol{B} \\ E \end{pmatrix}, \quad \mathbf{F}\,(\boldsymbol{U}) = \begin{bmatrix} \rho\boldsymbol{v} \\ \boldsymbol{m}\boldsymbol{v} - \boldsymbol{B}\boldsymbol{B} + p_t\mathbf{I} \\ \boldsymbol{v}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{v} \\ (E + p_t)\boldsymbol{v} - (\boldsymbol{v}\cdot\boldsymbol{B})\boldsymbol{B} \end{bmatrix}^T$$

Compact MHD

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Non linear…

$$\frac{\partial \boldsymbol{U}}{\partial t} = -\nabla \cdot \mathbf{F}(\boldsymbol{U}) + \boldsymbol{S}(\boldsymbol{U})$$

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Numerical treatment because…

- ❑ This sort of system of equations can be solved analytically only under restrictive assumptions (e.g. self-similarity, stationarity).
- ❑ Follow both linear and non linear phase of evolution.
- ❑ Validation of theoretical models.
- ❑ Predictive science & design.

Setting up a numerical project

Filament structures in SN remnants!

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Setting up a numerical project

Filament structures in SN remnants!

<u>Motivation:</u>
Probably caused by the Rayleigh-Taylor instability.

<u>Simple model:</u>
Two fluids of different density inside a gravitational Potential.

Setting up a numerical project

Before starting, go through a short checklist:

- Timescales of the problem?

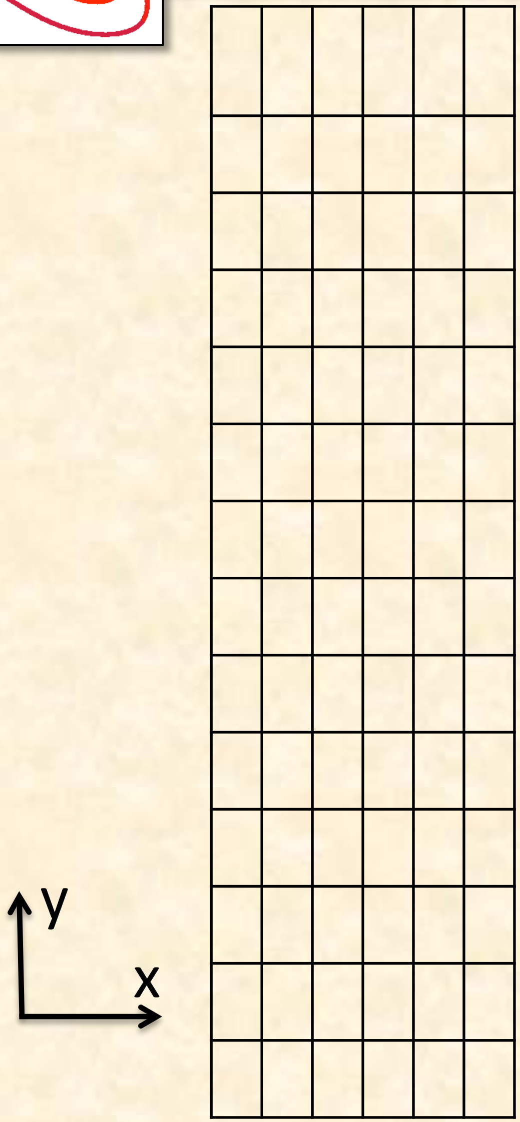
$$\Delta t_{\rm adv} \sim \frac{\Delta x}{\lambda_{\rm max}}\ , \quad \Delta t_{\rm dff} \sim \frac{\Delta x^2}{\eta}\ , \quad \Delta t_{\rm rad} \sim \frac{p}{\Lambda_{\rm cool}}$$

- Normalize! Normalize! Normalize!

$$L_0\,({\rm cm})\ , \quad \rho_0\,({\rm gr/cm^3})\ , \quad v_0\,({\rm cm/s}) \quad \Longrightarrow \quad t_0 = L_0/v_0$$

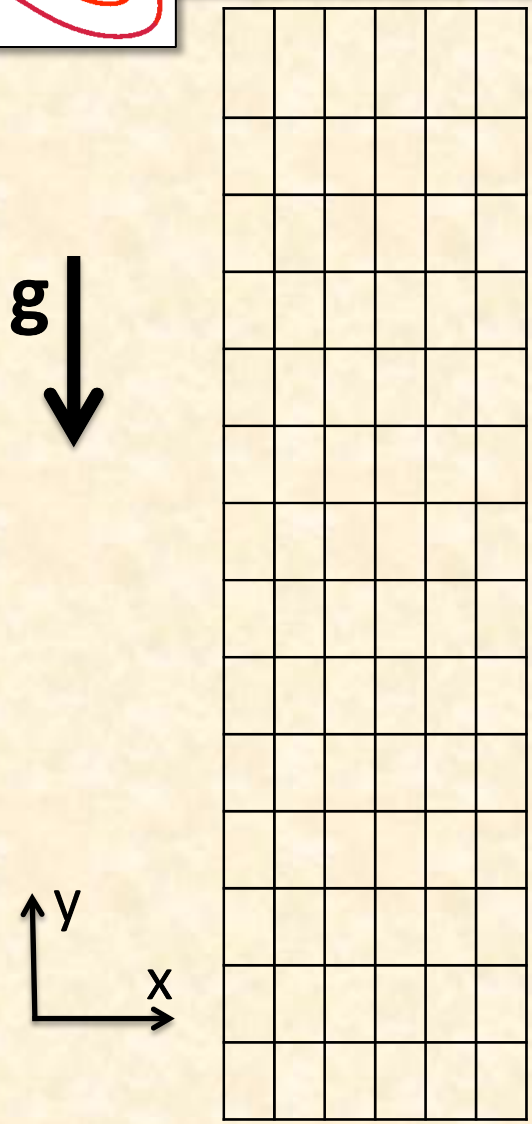
- Resolution: What features do you want to see?
- Non dimensional parameters are your knobs! Plasma β, Mach number, density contrasts, etc.

Setting up a numerical project



✓ Simulate a single filament in a Cartesian "domain". Mesh resolution? Physical size?

Setting up a numerical project



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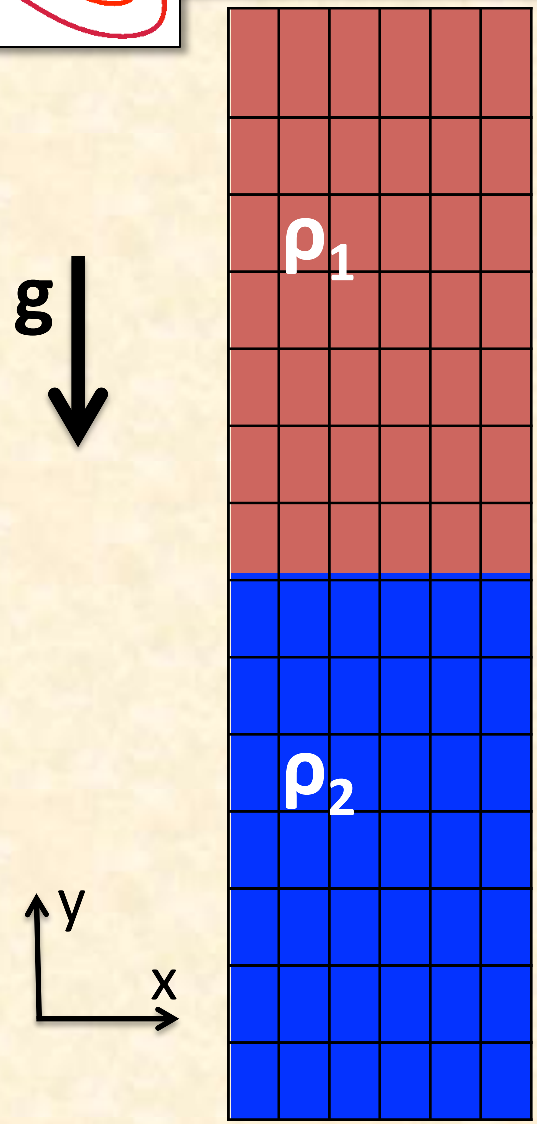
✓ Physics: Hydrodynamics + Gravity (uniform gravity, in the y direction)



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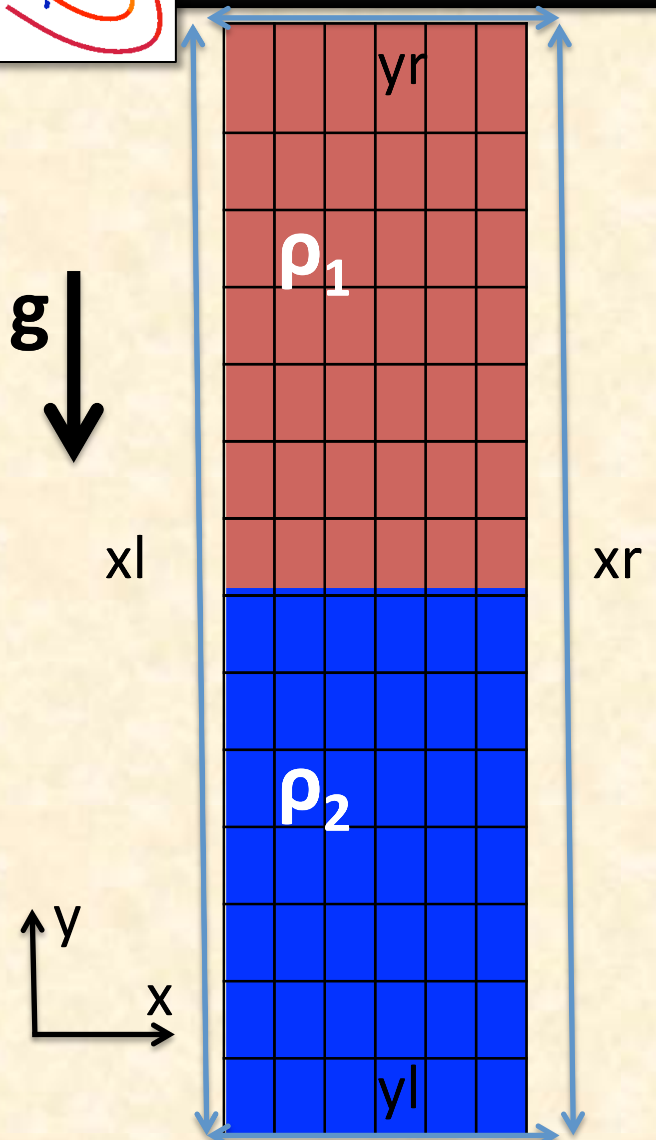
Setting up a numerical project



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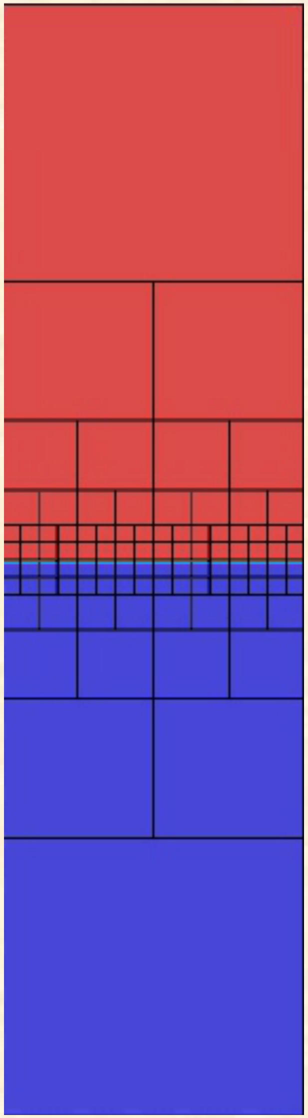
Setting up a numerical project



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✓ **Crunch numbers!**

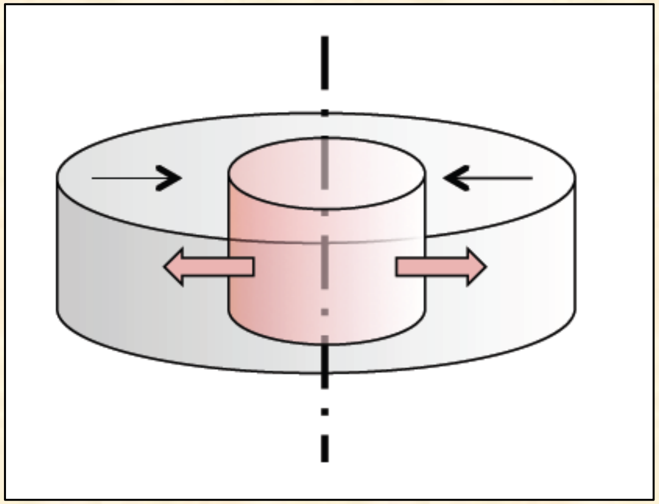
Learn by examples

- ❑ Validation, comparison with analytic models
  -- Magnetized Noh Z-pinch
- ❑ Validation, code to code comparison
  -- Accretion Tori
- ❑ Predictive science & Design
  -- LULI/Vulcan experiments

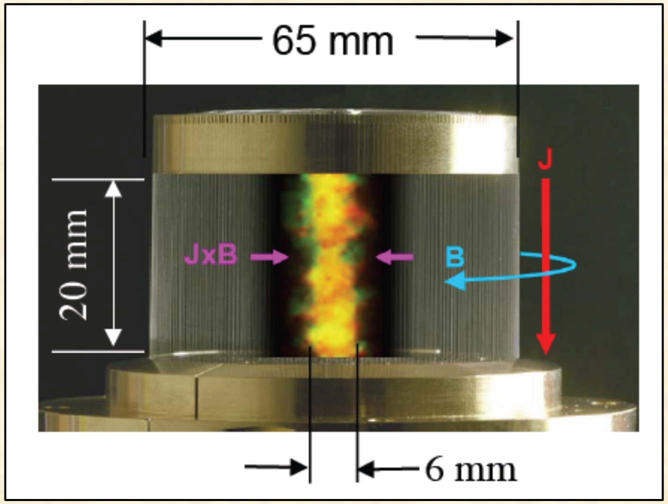
Magnetized Noh

Consider a pressure-less gas which implodes radially in a cylindrical chamber, retaining the symmetry

Hydro, Noh JCP 1987

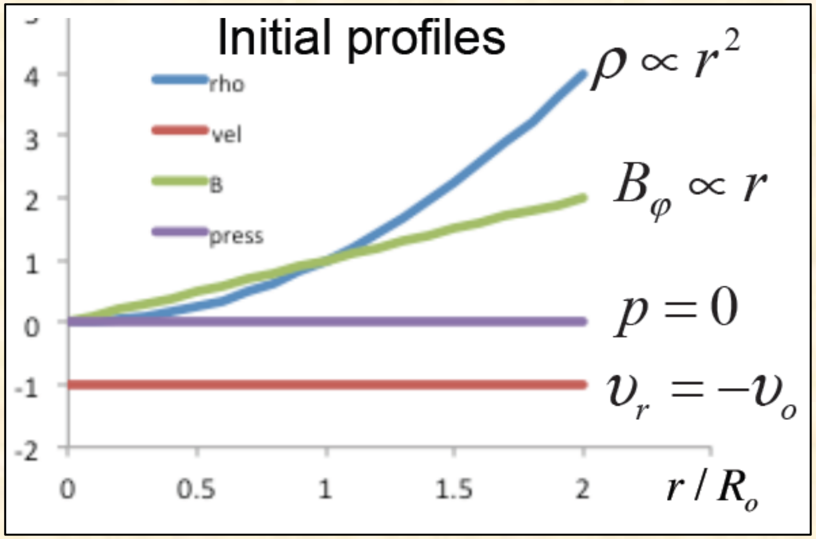


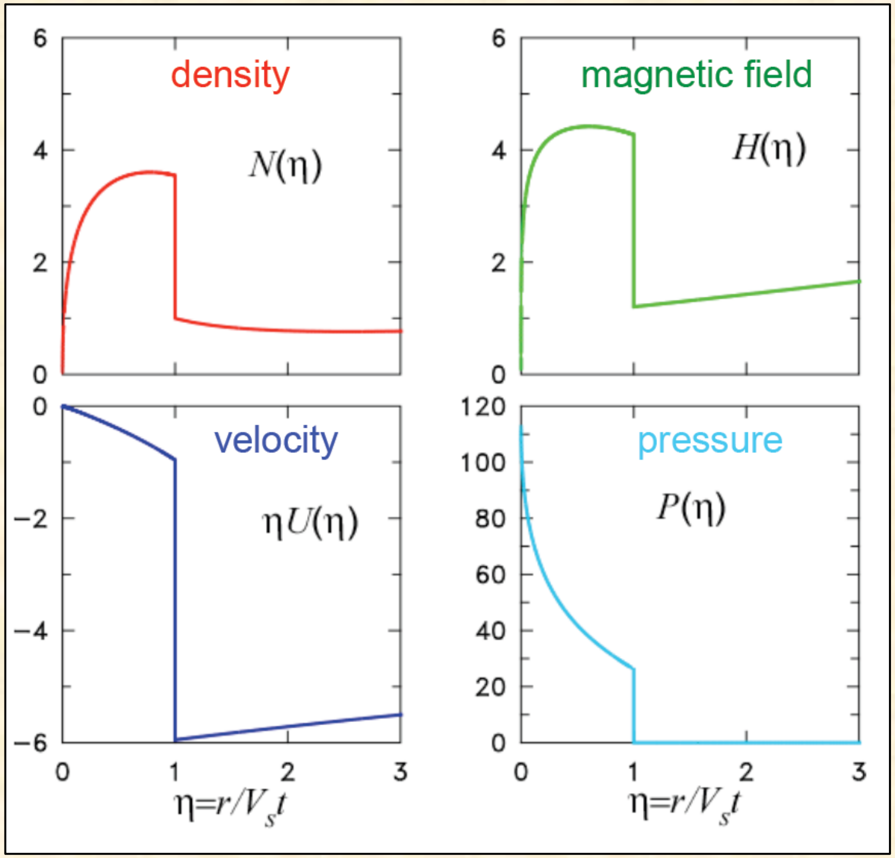
MHD, Giuliani et al. 53rd APS 2011



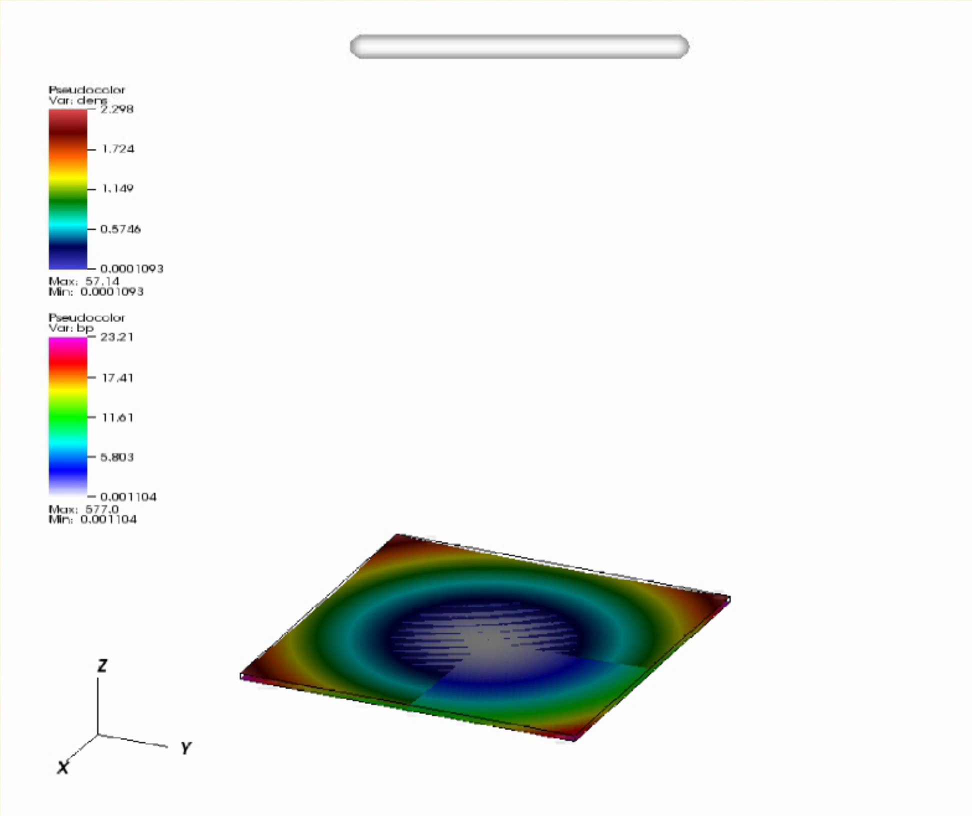
Magnetized Noh

Velikovich et al. 2012 discovered a class of SS solutions that describe the expansion of the accretion shock.

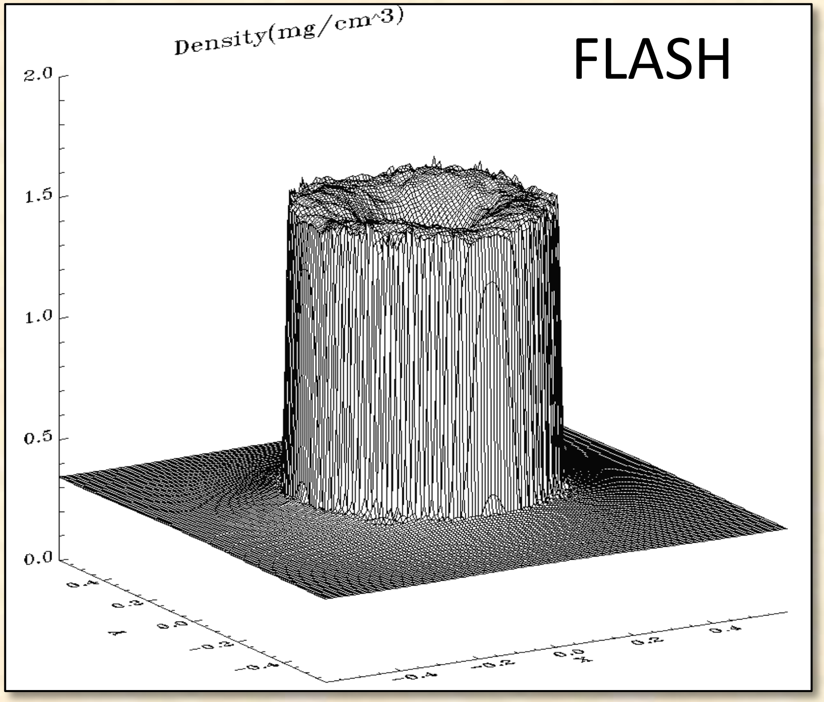


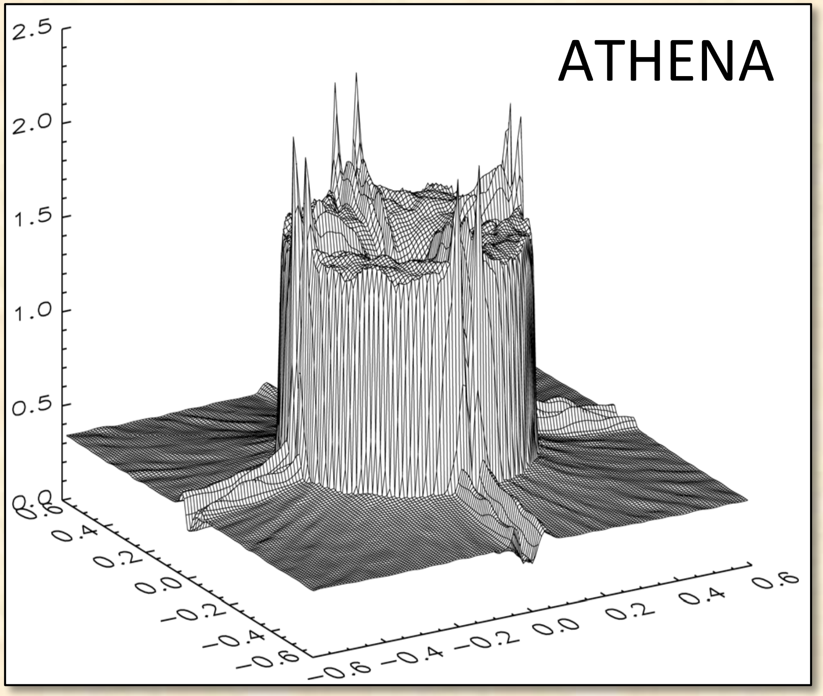


Magnetized Noh



Magnetized Noh

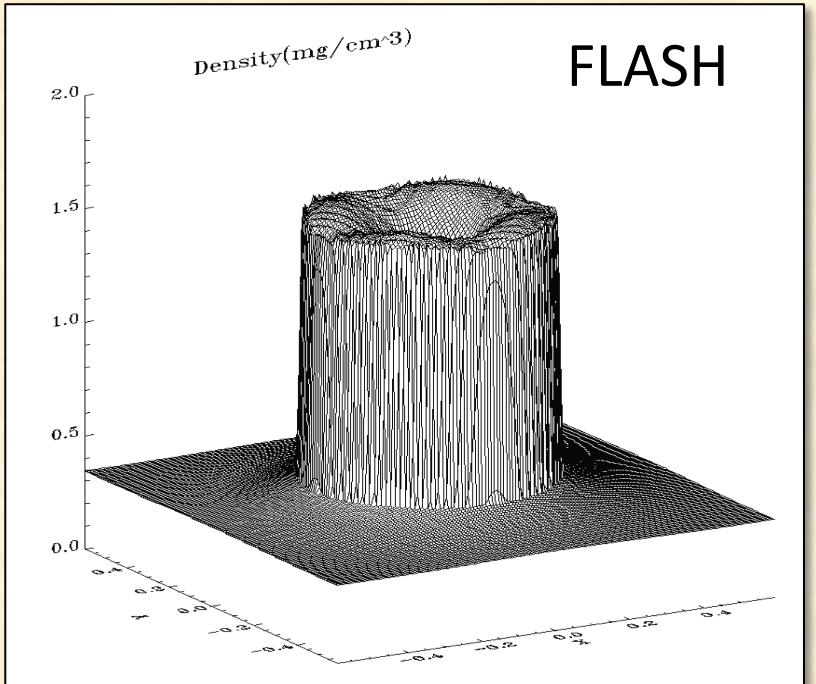


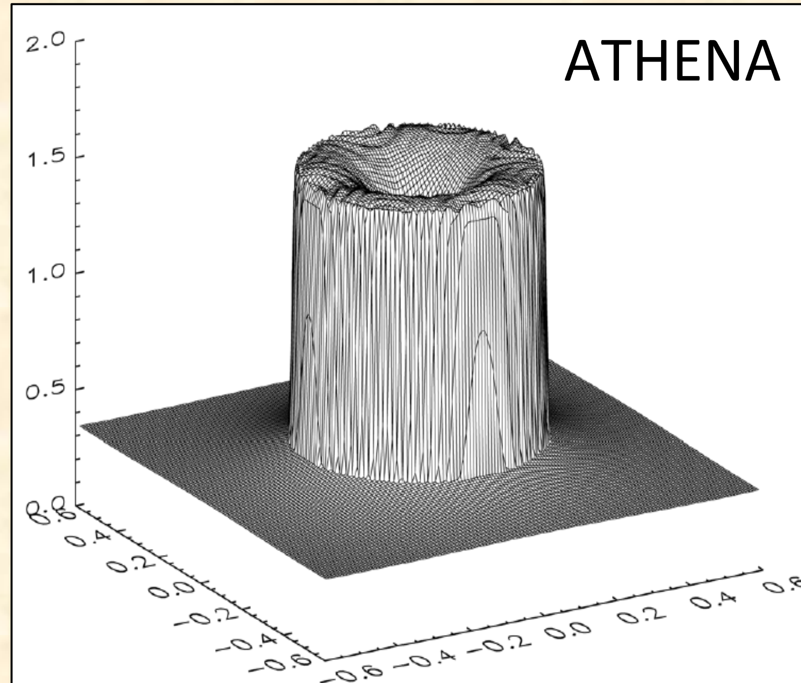


- HLLD, characteristic limiting at CFL = 0.8

- HLLD, characteristic limiting at CFL = 0.4

Magnetized Noh

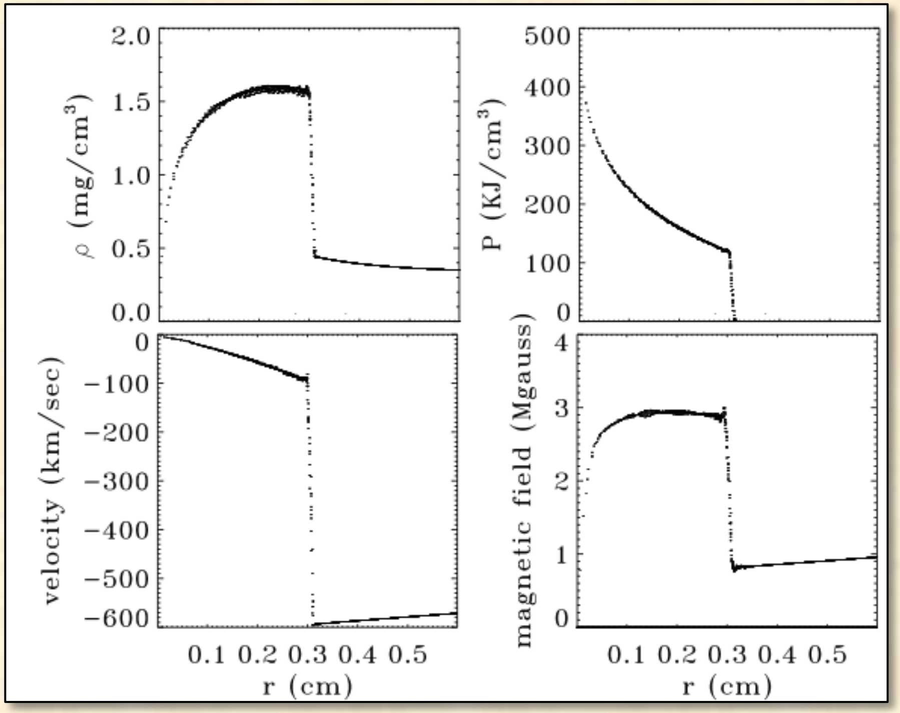


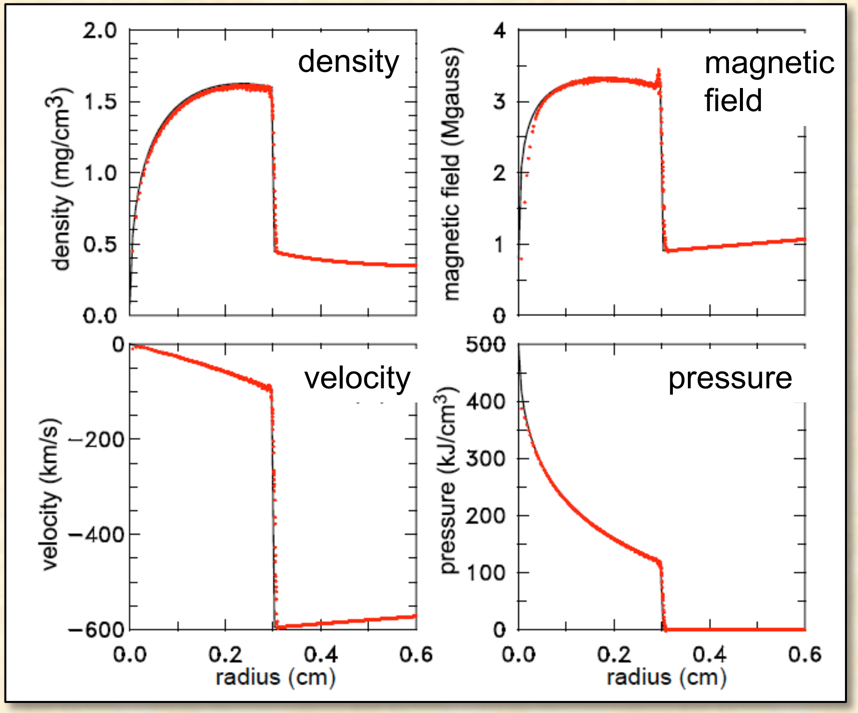


- HLLD, primitive limiting at CFL = 0.8

- HLLD, primitive limiting at CFL = 0.4

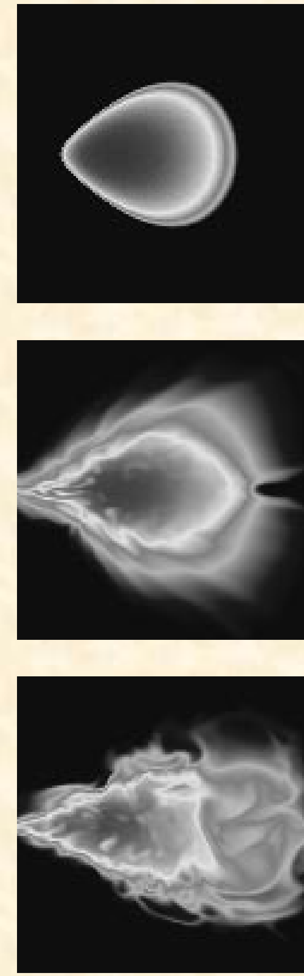
Magnetized Noh





✓ Both codes exhibit good agreement with the analytical solutions although FLASH remains stable with higher CFL and performs equally well, even with more accurate RS such as Roe!

On a more astrophysics related problem, we examine the magnetized accretion torus simulation proposed by Hawley 2000.



THE ASTROPHYSICAL JOURNAL, 528:462–479, 2000 January 1

GLOBAL MAGNETOHYDRODYNAMICAL SIMULATIONS OF ACCRETION TORI

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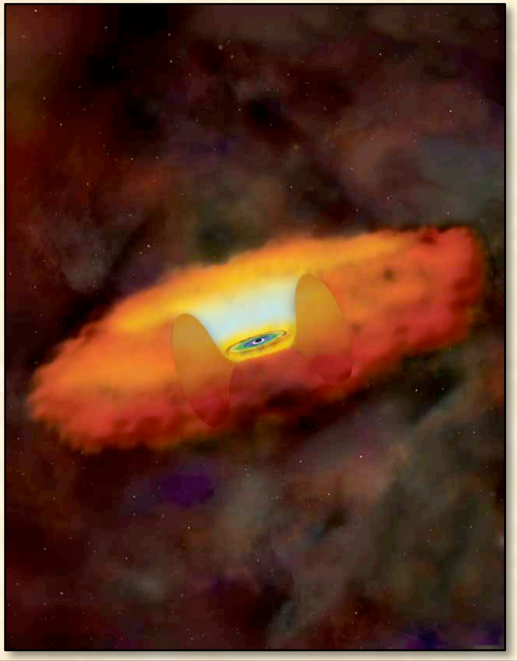
Received 1999 July 15; accepted 1999 August 17

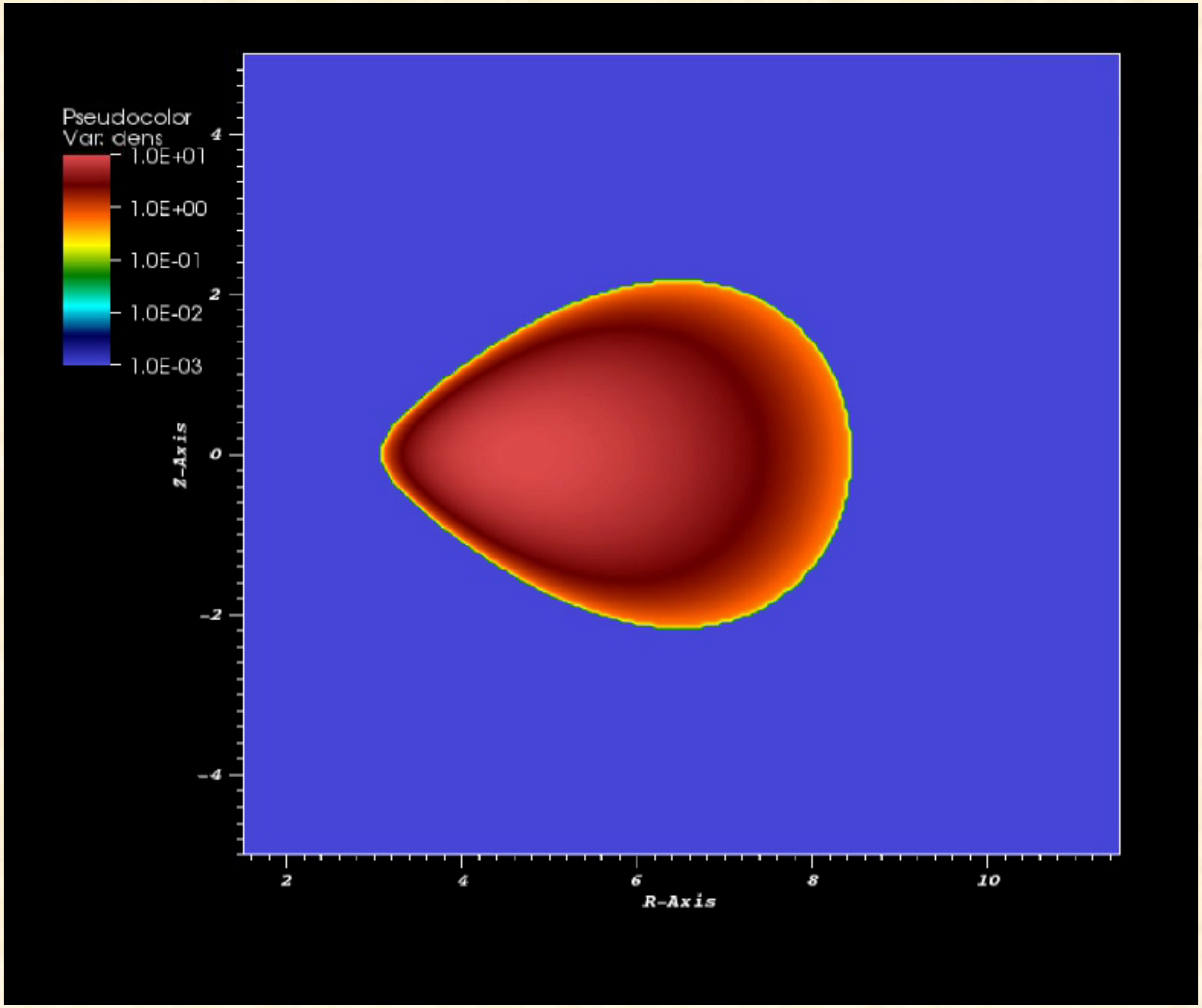
ABSTRACT

Global time-dependent simulations provide a means to investigate time-dependent dynamic evolution in accretion disks. This paper seeks to extend previous local simulations by beginning a systematic effort

- ✓ constant angular momentum torus, whose initial equilibrium configuration is dictated by $$\frac{\Gamma p}{(\Gamma - 1)\rho} = C - \Phi - \frac{1}{2}\frac{l_{\rm kep}^2}{r^2 \sin^2\theta}$$
- ✓ The gravitational potential is pseudo-Newtonian of the form $$\Phi = -\frac{GM}{r - r_g}$$
- ✓ The torus is threaded by an initially poloidal magnetic field

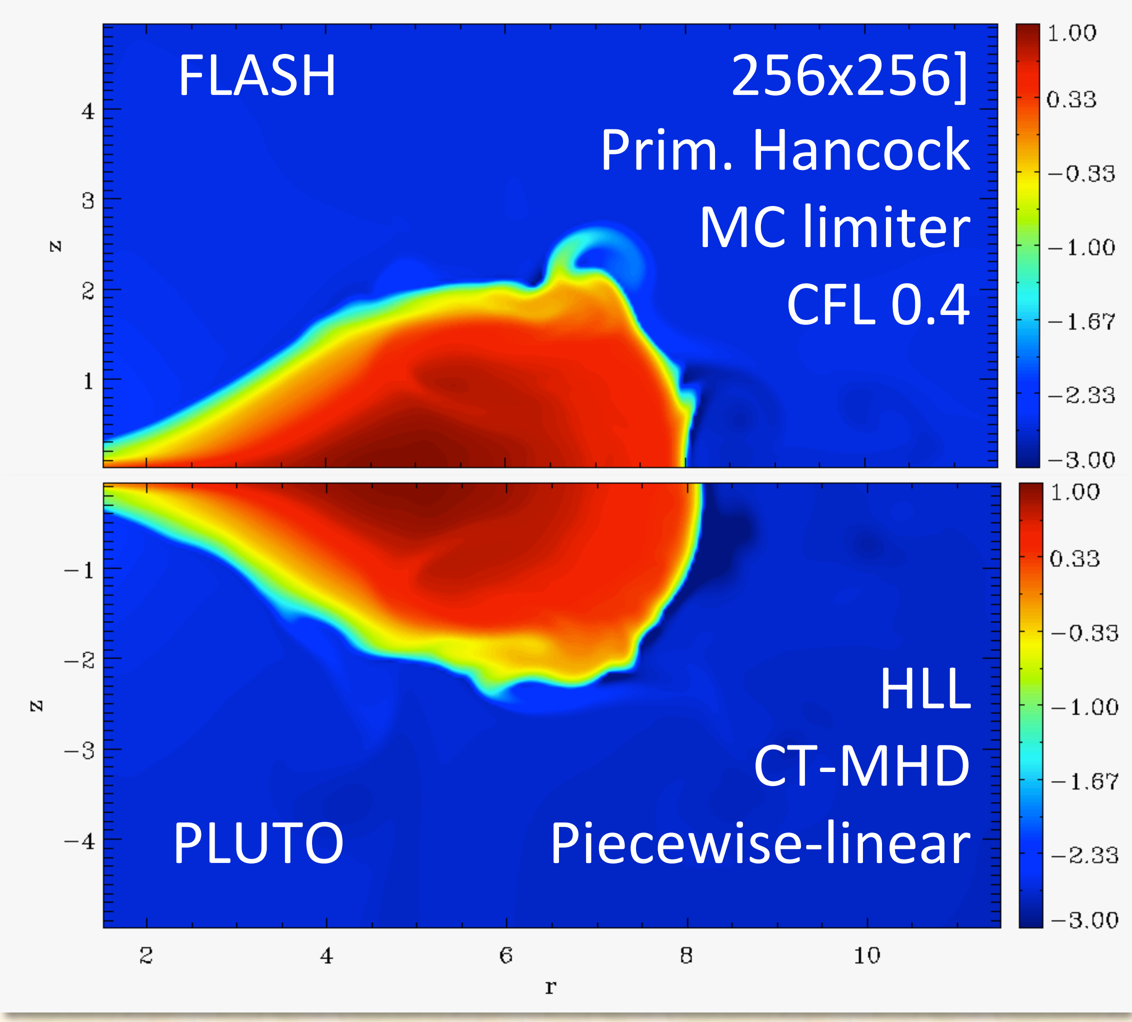


Accretion Torus



Accretion Torus

- ✓ Strong shear creates an azimuthal field
- ✓ The torus is MRI unstable
- ✓ Angular momentum re-distribution, accretion
- ✓ Good agreement between codes.



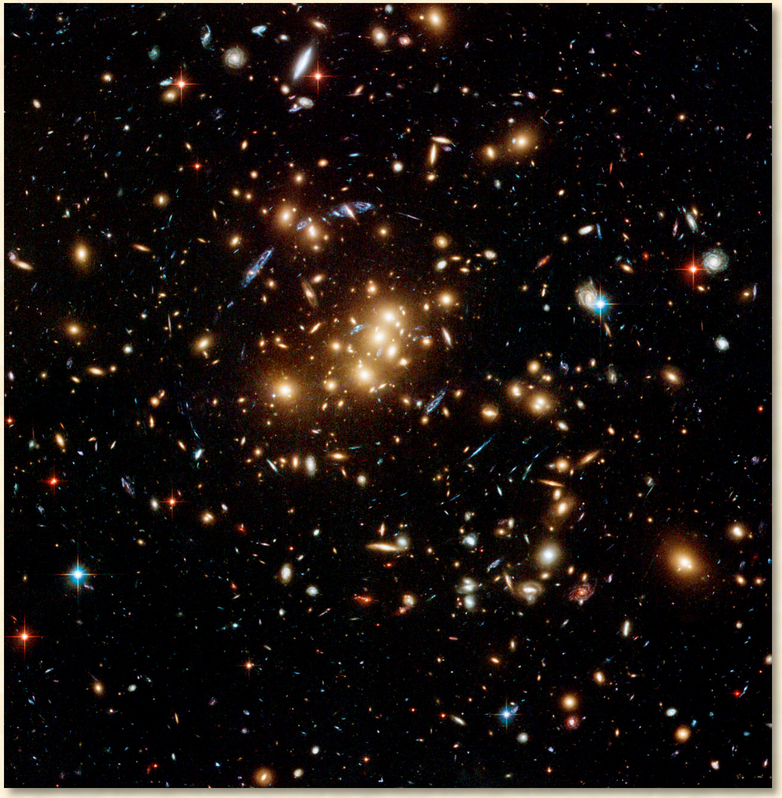
Gianluca experiments @LULI!

Study the generation of magnetic fields in the context of galaxies and clusters.
Gregori et al., Nature 2012

Biermann Battery mechanism:

$$\frac{\partial \mathbf{B}}{\partial t} \sim \frac{\nabla P_e \times \nabla n_e}{e\, n_e^2}$$

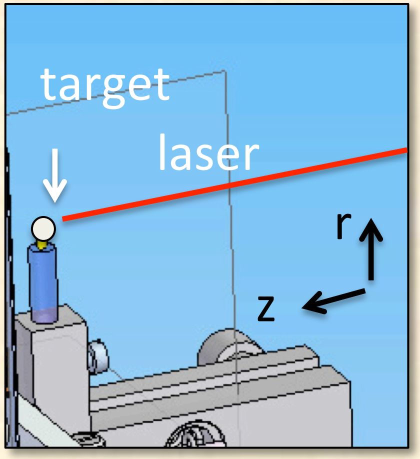
Generation of **B** at shocks



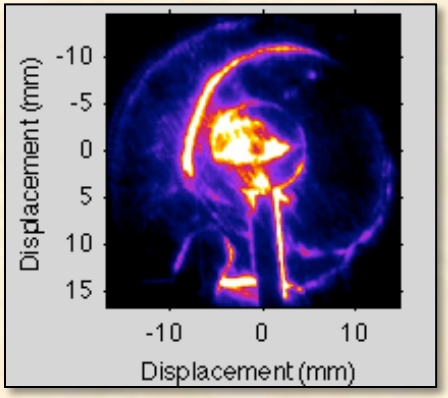
Cl 0024+17 (ZwCl 0024+1652)

Gianluca experiments @LULI!

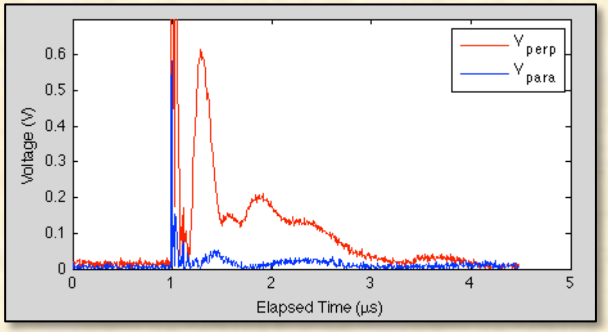
- ✓ 500 µm plastic sphere (among other)
- ✓ 0.5 mbar Argon filled chamber
- ✓ 400J, 2ω, 1.5ns square pulse laser
- ✓ Ablation and shock front creation
- ✓ Quantitative measurements of magnetic field generation!



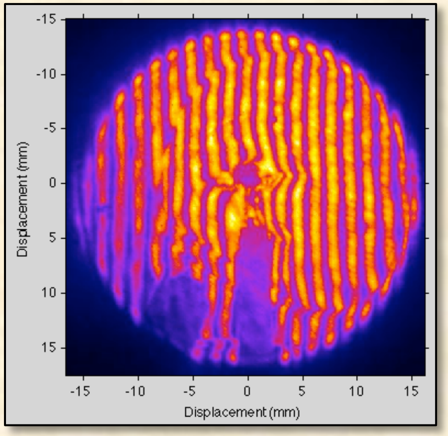
Experimental setup



Schlieren

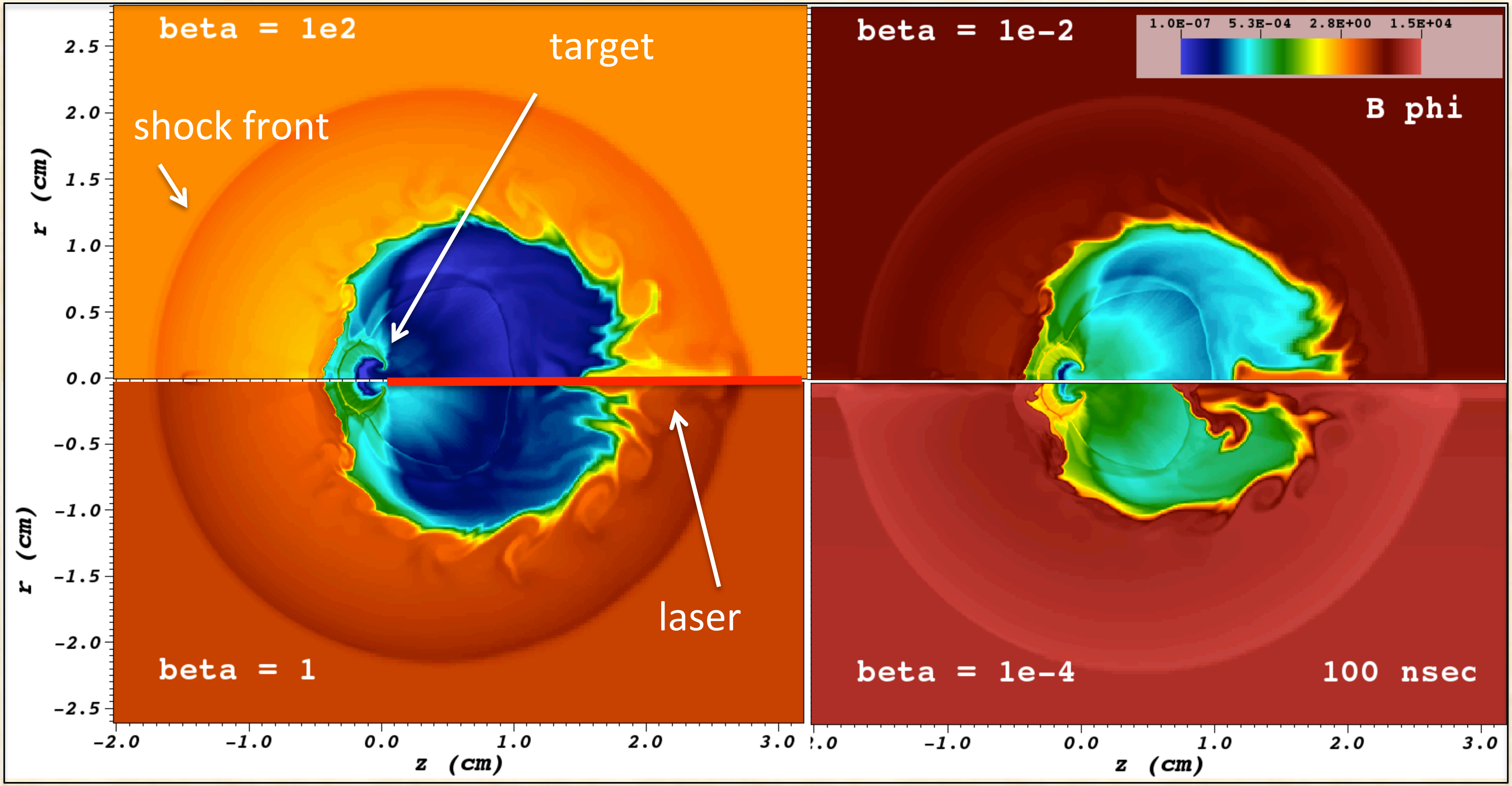


Bdot probes

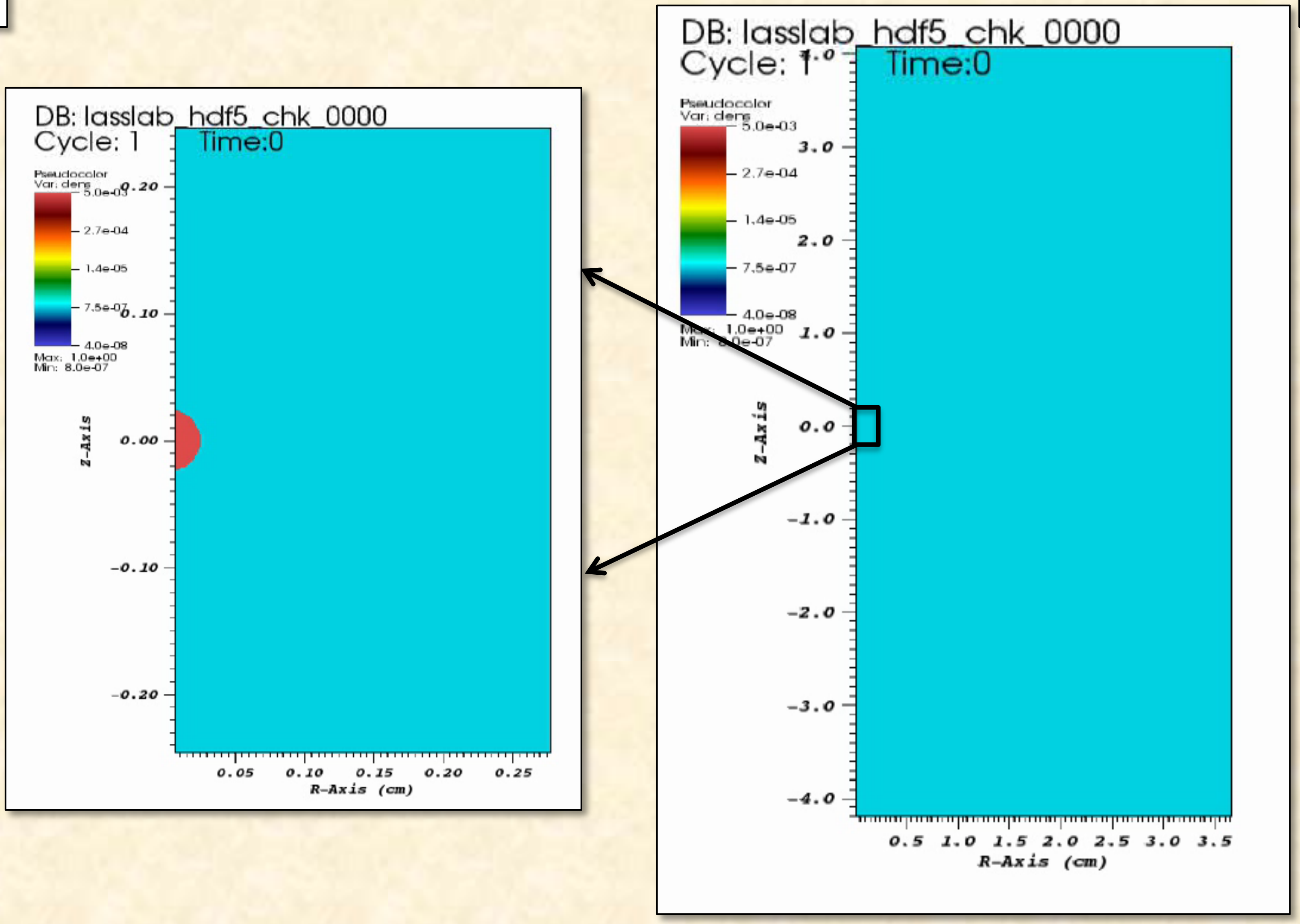


Interferometry

+external azimuthal field



+grid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Cycle: 1
Time:0
Pseudocolor
Var: dens
5.0e-03
2.7e-04
1.4e-05
7.5e-07
4.0e-08
Max: 1.0e+00
Min: 8.0e-07
0.20
0.10
0.00
-0.10
-0.20
Z-Axis
0.05
0.10
0.15
0.20
0.25
R-Axis (cm)
DB: lasslab_hdf5_chk_0000
Cycle: 1
Time:0
Pseudocolor
Var: dens
5.0e-03
2.7e-04
1.4e-05
7.5e-07
4.0e-08
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
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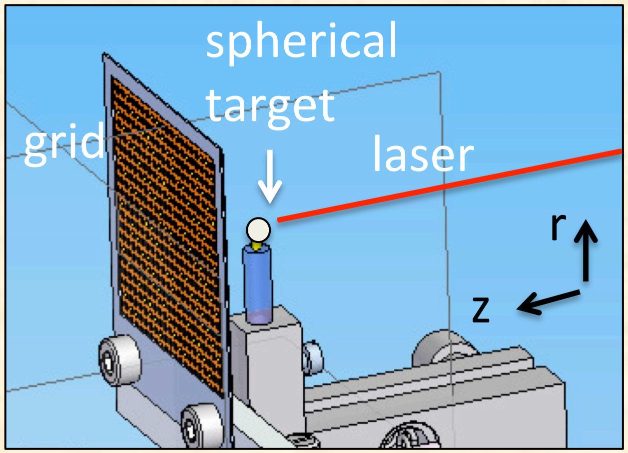
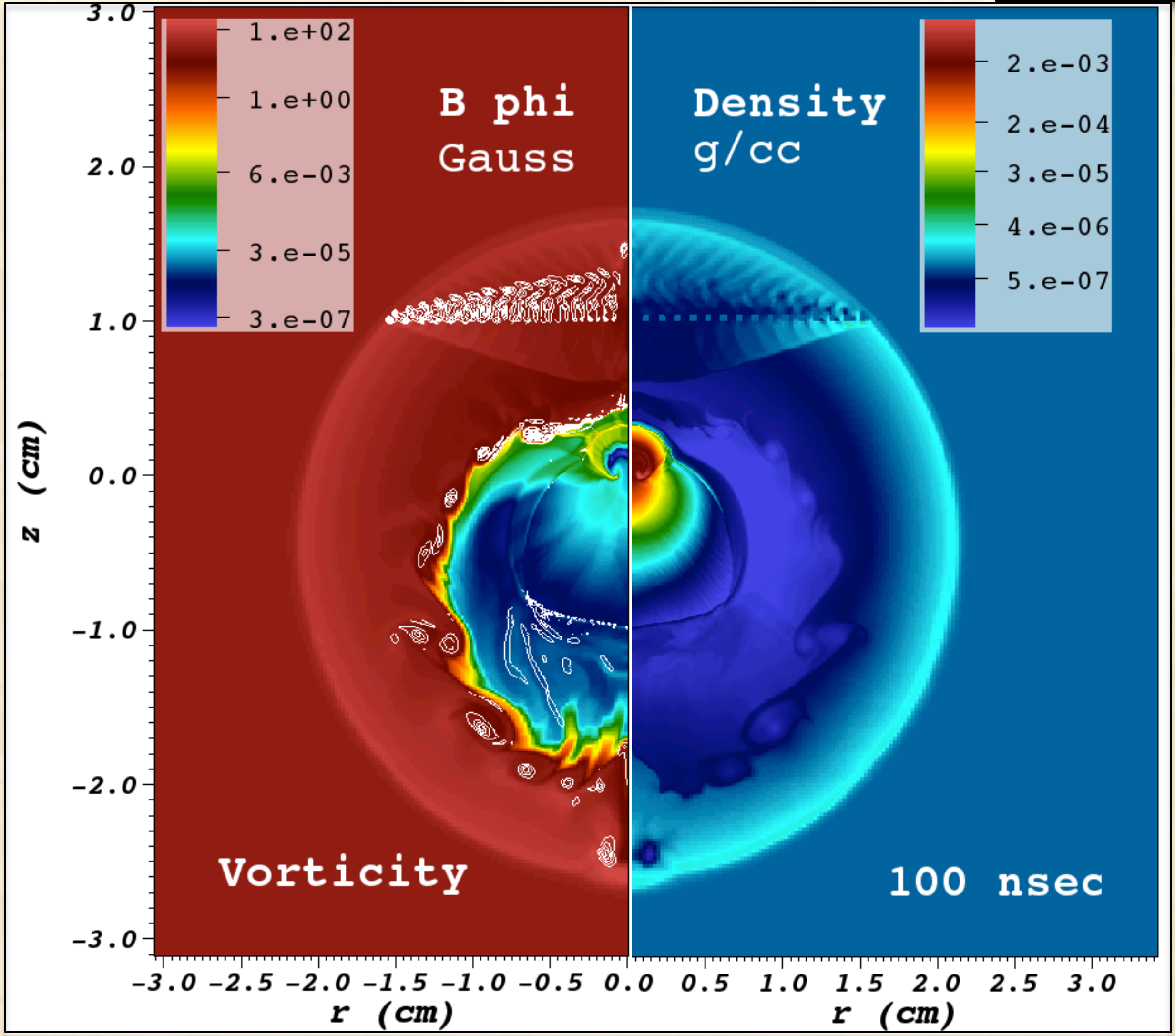
Z-Axis
0.5
1.0
1.5
2.0
2.5
3.0
3.5
R-Axis (cm)

+grid


spherical
target
grid
laser
r
z


B phi
Gauss
1.e+02
1.e+00
6.e-03
3.e-05
3.e-07
Density
g/cc
2.e-03
2.e-04
3.e-05
4.e-06
5.e-07
Vorticity
100 nsec
z (cm)
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-3.0 -2.5 -2.0 -1.5 -1.0 -0.5 0.0
0.0 0.5 1.0 1.5 2.0 2.5 3.0
r (cm)
r (cm)

Takeaways

- Simulations can be a valuable tool
- Simulate responsibly
- Code verification & validation is not optional
- Experimental design and data analysis