High-Energy-Density Laboratory Astrophysics Experiments: Interface and Shear Instabilities

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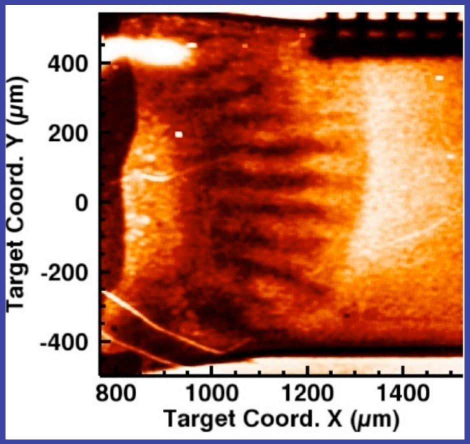
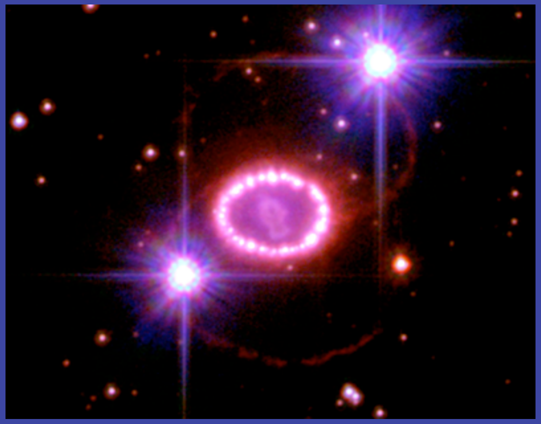
High-energy-density (HED) facilities allow access to astrophysical conditions in a controlled setting

- High-energy-density physics devices deposit kJ of energies in mm-scale volumes
- Create ionized, high pressure systems
- Produce processes in the laboratory that occur in astrophysical systems
  - Sometimes in a well-scaled environment





In order to for the systems to be described by Euler's equations certain conditions must be met

- System must be highly collisional, $\lambda_c \ll r$
- Viscosity negligible, Re >> 1
- Heat conduction negligible, Pe >> 1
- Radiation flux negligible, $Pe_\gamma \gg 1$
- Gravitational and magnetic forces negligible

	SN	lab
r/λ_c	10^6	10^4
Re	2.6×10^{10}	1.9×10^6
Pe	1.5×10^{12}	1.8×10^3
$Pe\gamma$	2.6×10^5	…
$\tau_{(\text{Black body})}/\tau_{(\text{hydro})}$	…	580

Euler Equations are invariant under transformation

If two systems are hydrodynamic and related by the transformation below then there is a direct correspondence between the two systems*

$$r_{SN} = a r_{lab} \qquad p_{SN} = c p_{lab}$$

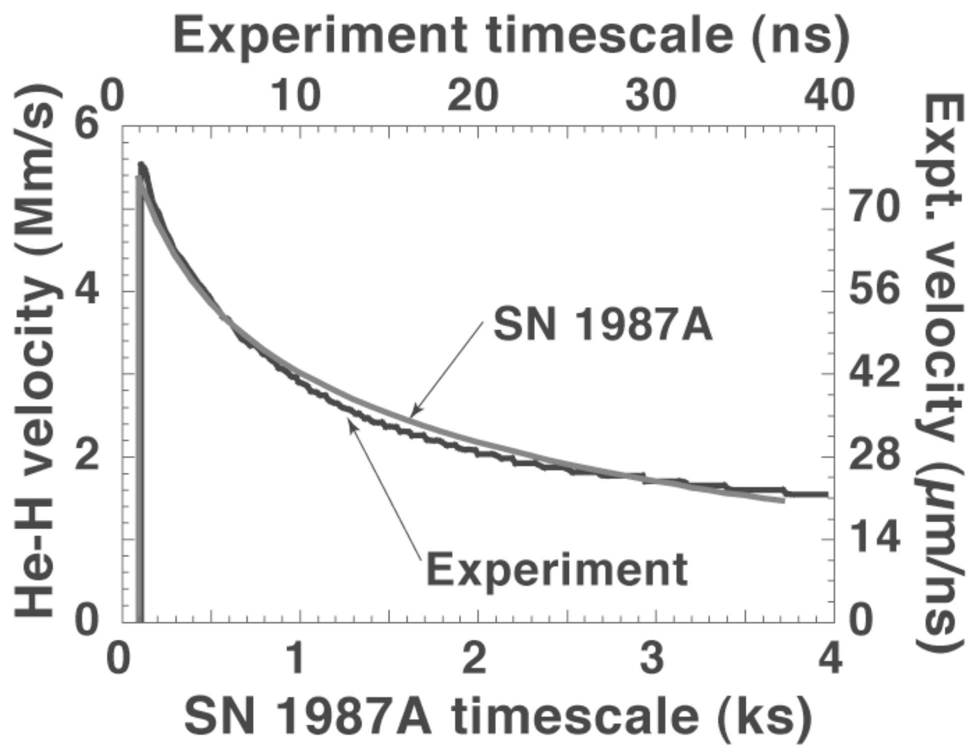
$$\rho_{SN} = b \rho_{lab} \qquad t_{SN} = a\sqrt{\frac{b}{c}}\, t_{lab}$$

	SN	lab
r	10^{11} cm	10^{2} μm
ρ	10^{-2} g/cc	1 g/cc
p	10 Mbar	1 Mbar
t	1000 s	10 ns

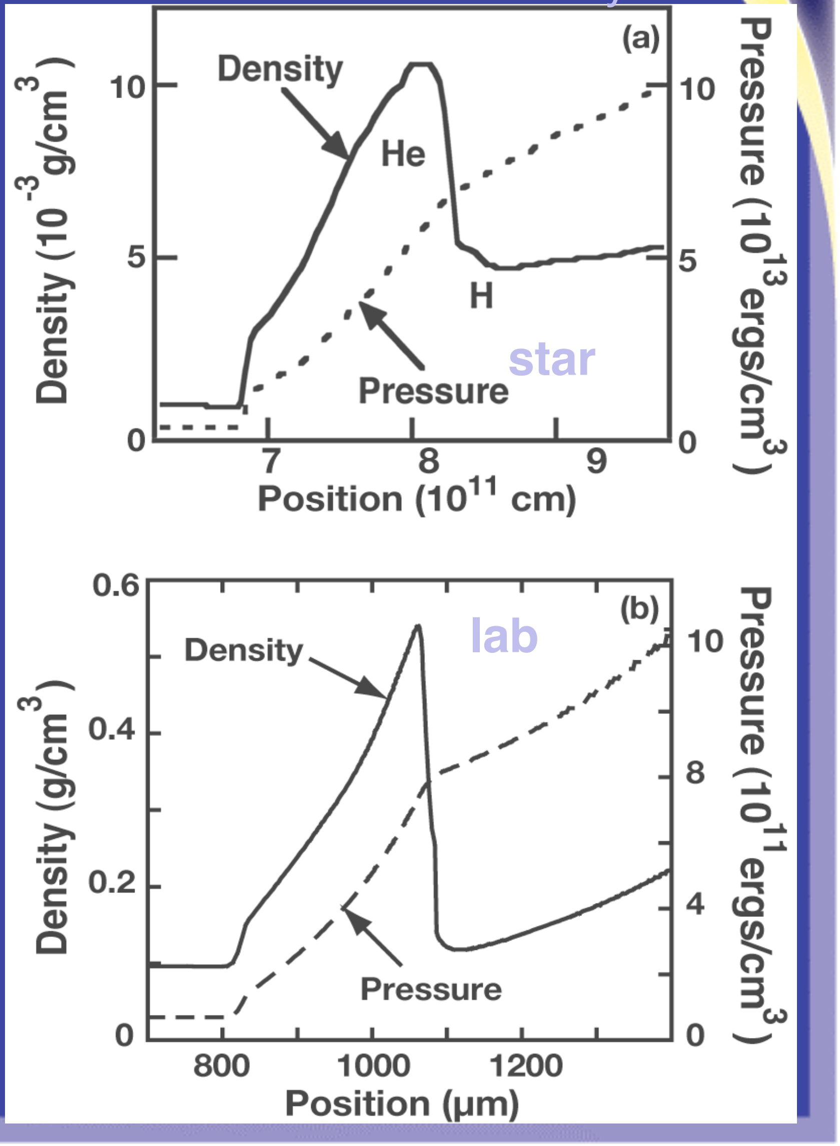
*Ryutov (1999)

Boundary conditions in space and time must also be well-scaled

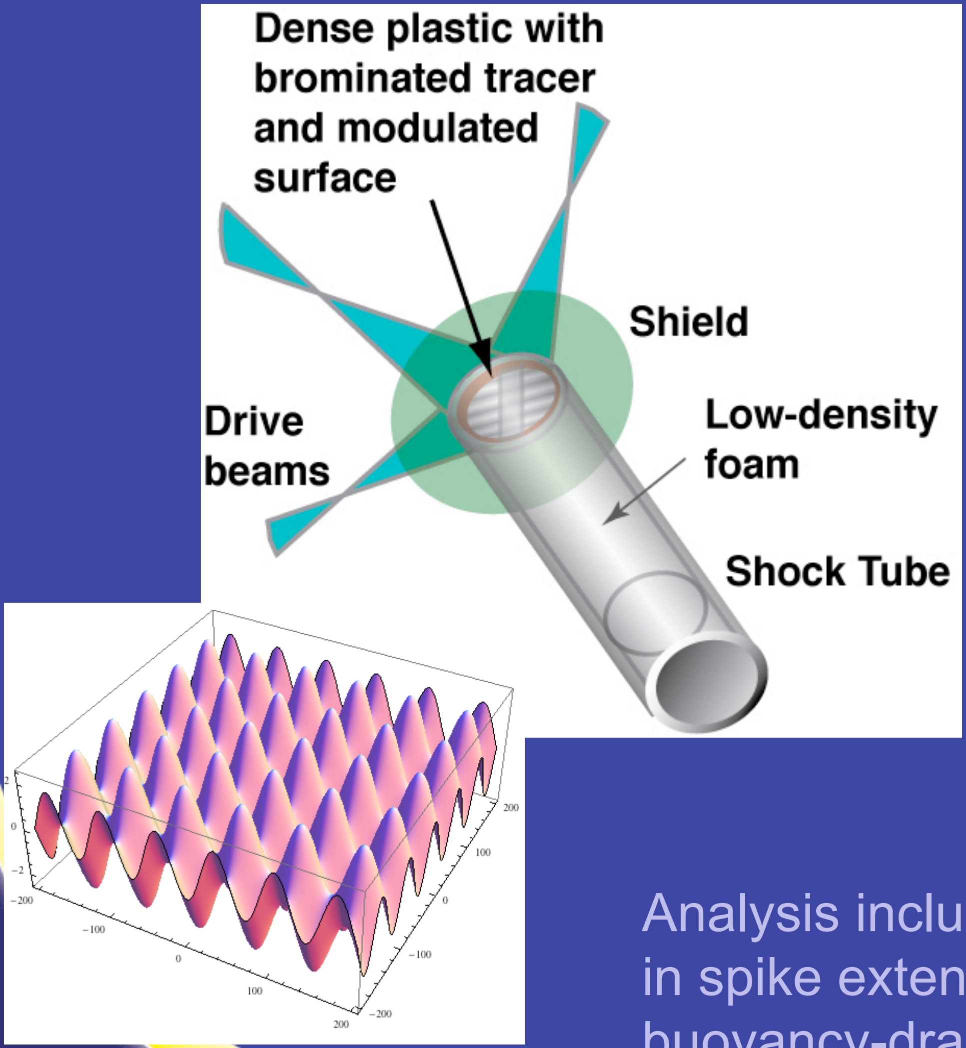
Interface velocity vs time

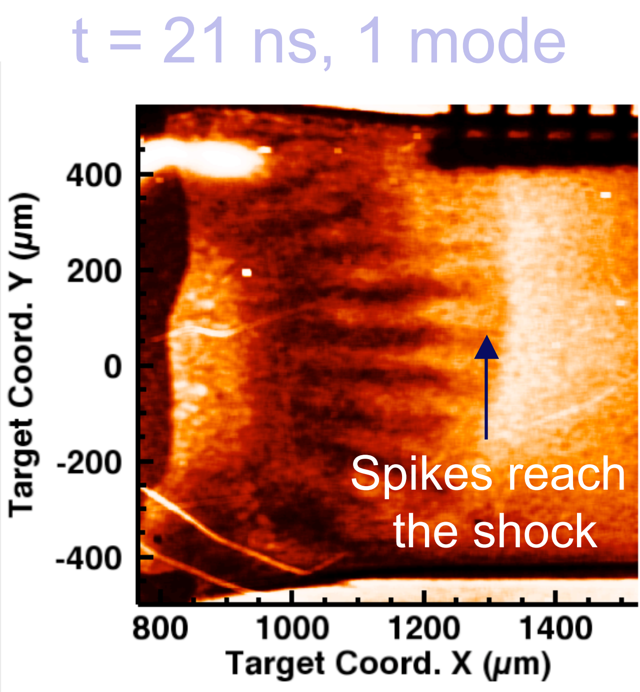


Pressure and density



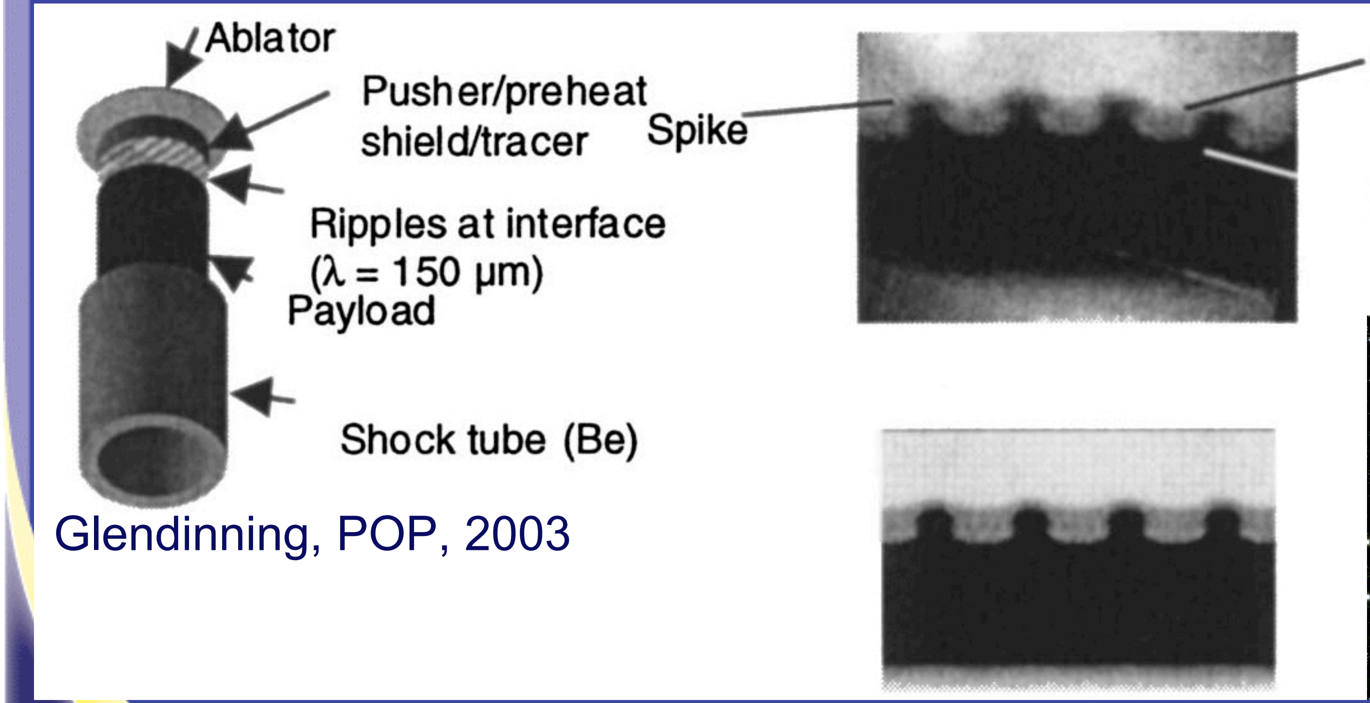
Rayleigh-Taylor instability: Core-collapse supernova explosions





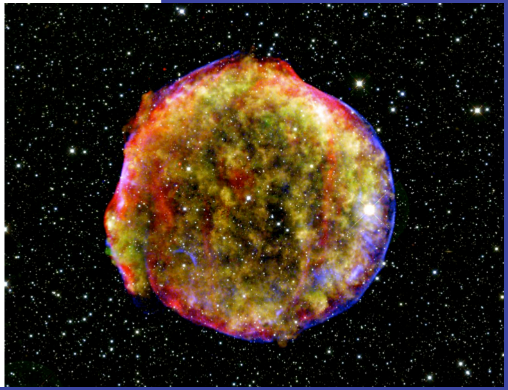
Analysis includes finding amount of mass in spike extensions and comparison to buoyancy-drag model and simulations

Richtmyer-Meshkov instability: core-collapse supernova, molecular cloud morphology, early star formation

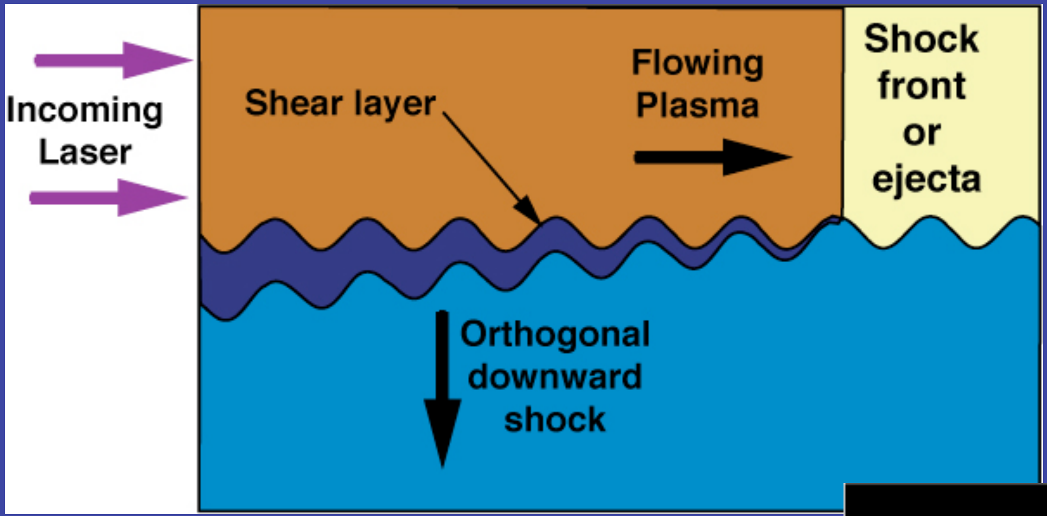


Glendinning, POP, 2003

Tycho, SNR

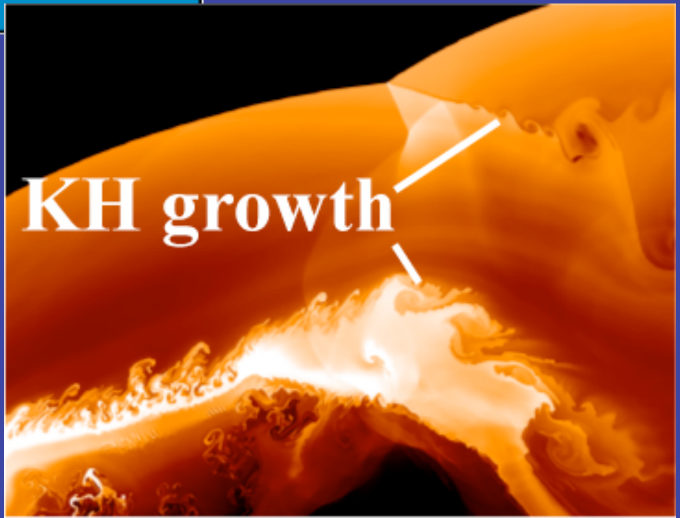


Kelvin-Helmholtz instability: core-collapse supernova, shear flow



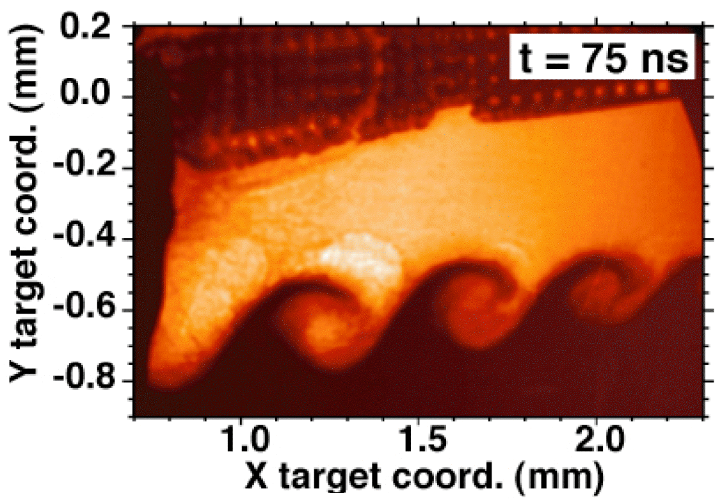
Design of experiment to observe KHI in HED regime

Core-collapse supernova simulation results showing Kelvin-Helmholtz roll-up due to velocity shear created by RMI and RTI

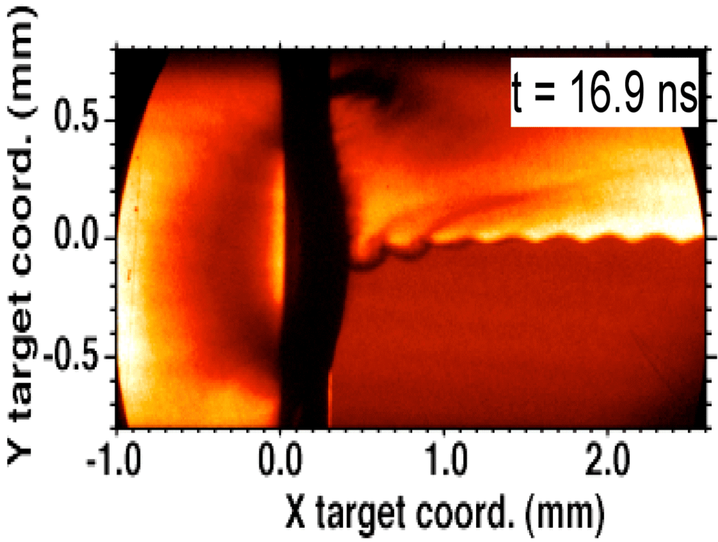


Supernova simulation (Guzman and Plewa, *2009*)

Subsonic and supersonic Kelvin-Helmholtz is being studied



Harding, PRL, 2009



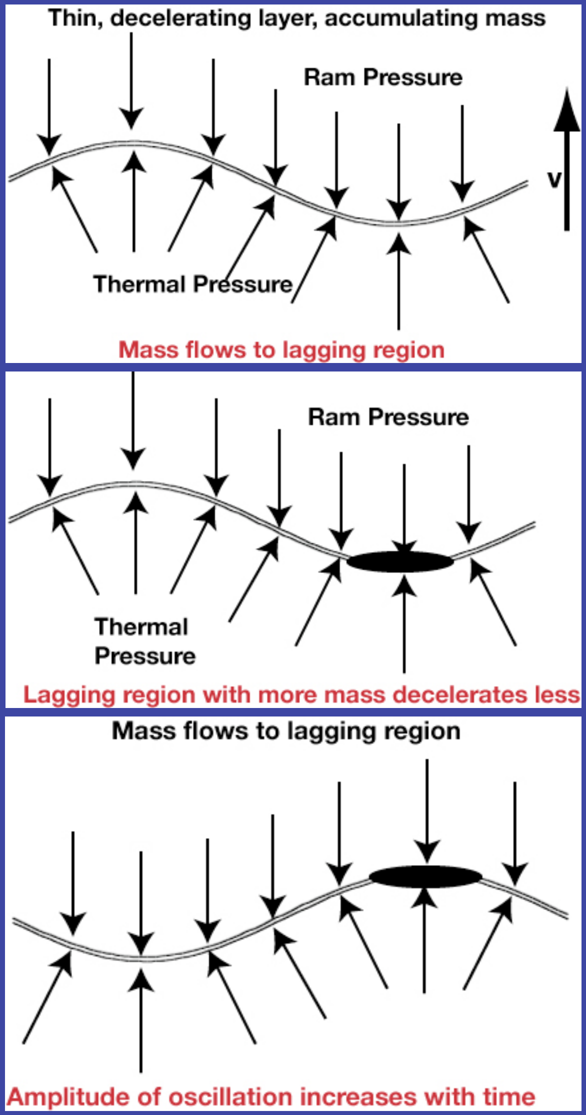
Harding, HEDP, 2010

- Omega experiment
  - Subsonic flow
  - Classic KH through apparent onset of turbulence
  - Mysterious bubble might be EOS related
- Nike experiment
  - Supersonic flow
  - Shape of shocks in flow is sensitive to Mach number

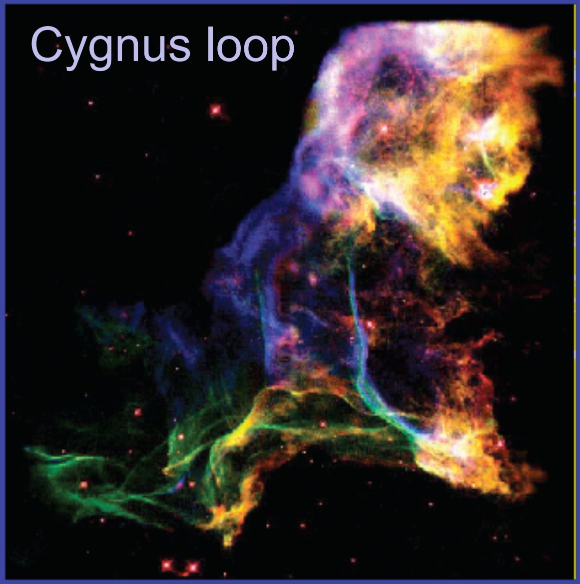
Vishniac-like instability: supernova remnants and radiative shocks

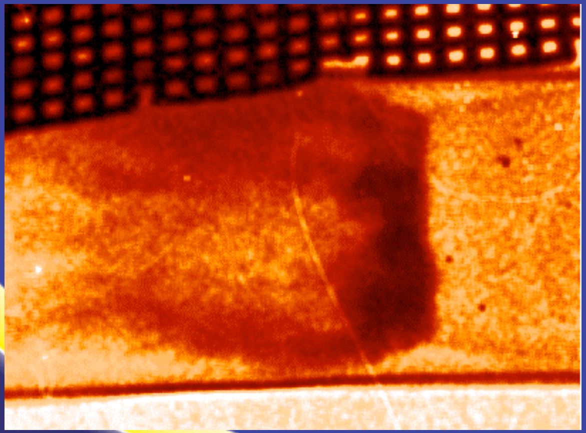
- Accreting shocks are unstable to velocity perturbations
- Mass flows to lagging regions
- Lagging region with more mass decelerates less
- Amplitude of oscillation increases with time

See E. Vishniac, ApJ 1983



Vishniac-like instabilities may be present in supernova remnants

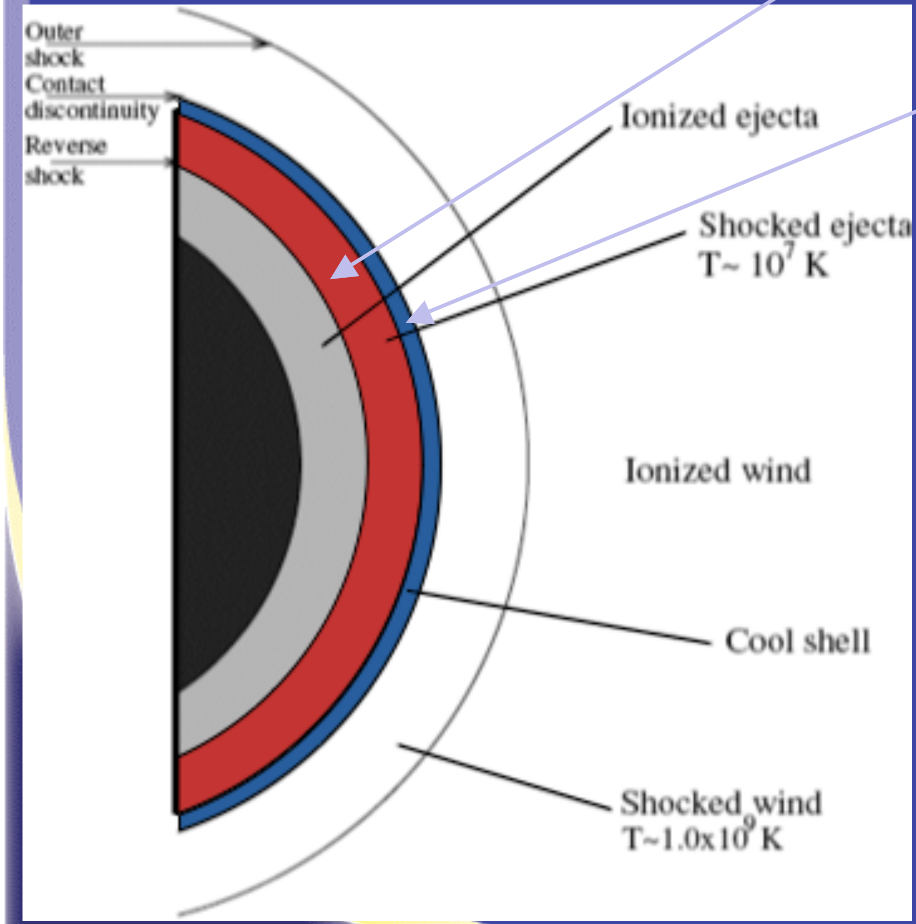




- Clumpiness in supernova remnants may be due to Vishniac-like instabilities.
- Radiative shock experiments have been performed on Omega and are investigating the structure in the shock

Radiative effects on RTI: core-collapse, red supergiant

Nymark et al., A&A 2006



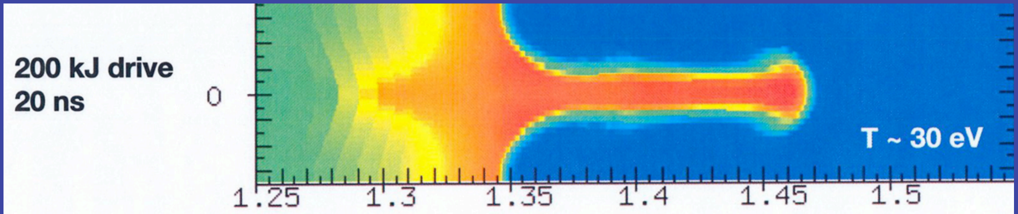
Shocked layer is strongly radiative

Cool shell is Rayleigh Taylor unstable (not shown)

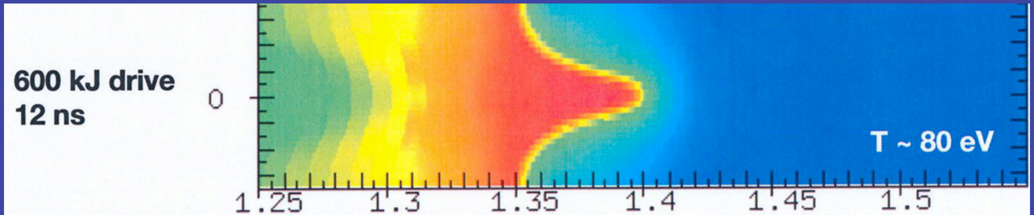
- These dynamics are relevant in other astrophysical systems where there are high temperatures and low densities

- This regime is only accessible on the NIF

Simulations show NIF experiment will demonstrate the new regime of RT suppression by x-ray ablation driven by radiative shock-heated material



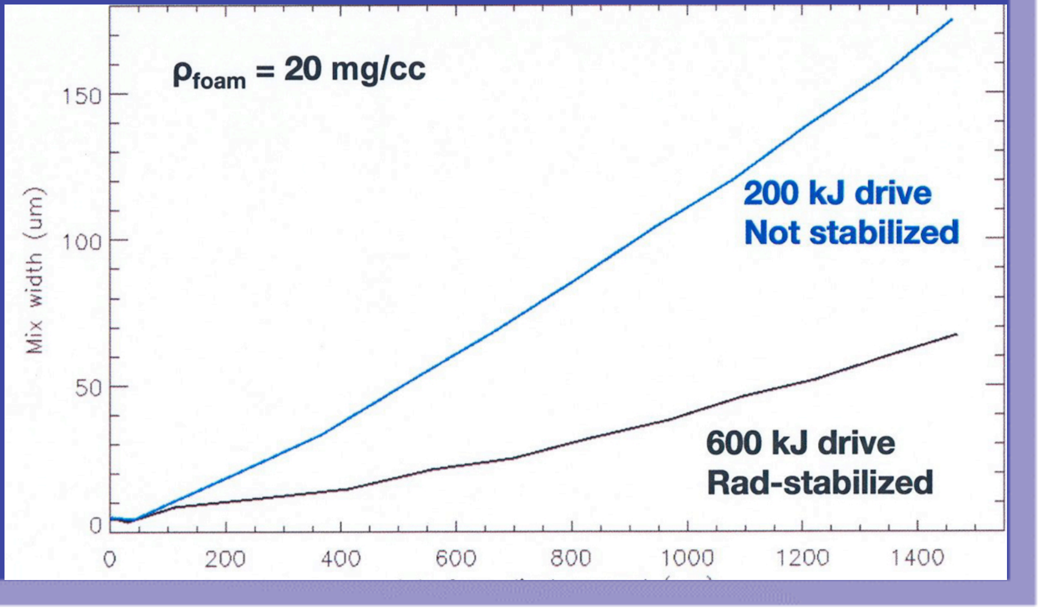
Low-temperature drive creates a non-radiative shock and hydro-dominated growth



High-temperature drive creates a radiative shock, causing a difference in RT growth

RT growth curve shows ablative and density gradient stabilization

ARES 2D simulations by A. Miles

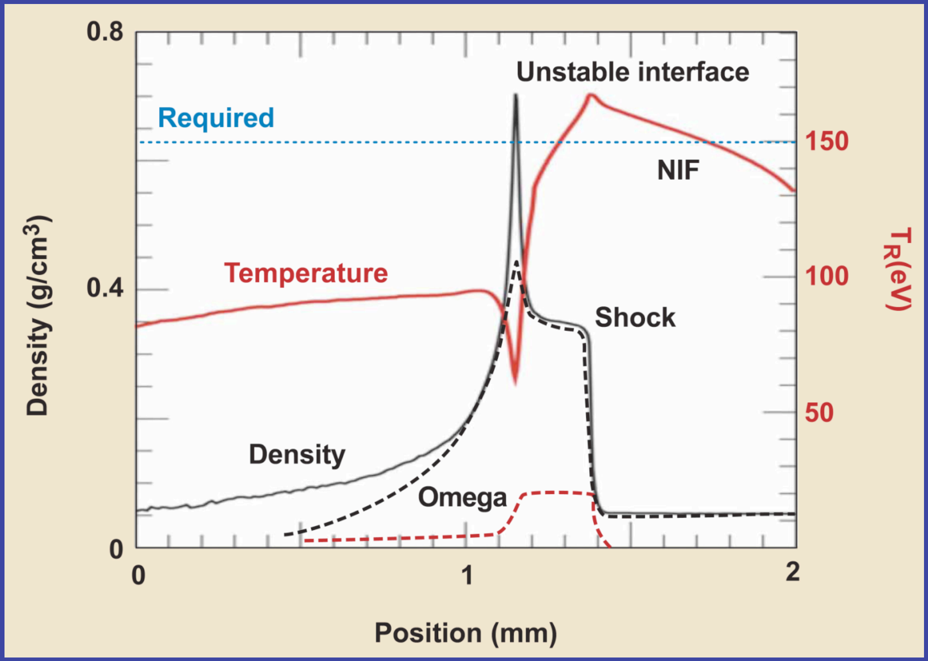


Summary of Research Opportunities

- Laboratory Astrophysics experiments need to further develop techniques to seed and measure magnetic fields
- Laboratory Astrophysics on the NIF will allow access to new regimes of experiments
  - Radiation hydrodynamics experiments
  - Instabilities at multiple, coupled interfaces in a spherically divergent geometry
  - Turbulent flow experiments
- Success at NIF requires funding at smaller-scale facilities
- Continued and further interaction with astrophysicists
  - HEDLA meeting, Pasadena, CA, March 15th-18th, 2010
  - AAS, MiM, “Bridging the Laboratory and Astrophysics: Frontiers in Plasma Astrophysics,” Miami, FL, May 23rd-27th

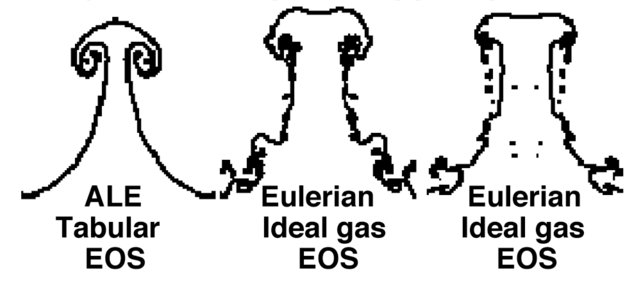
NIF can probe how supernovae eject matter into the universe and create novel HED systems

- Relevant to dynamics in core-collapse supernovae of red supergiant stars
  - Radiation from the driven, radiative shock interacts with denser emerging material.
  - Radiation affects how the materials mix.
- Forefront high-energy-density physics

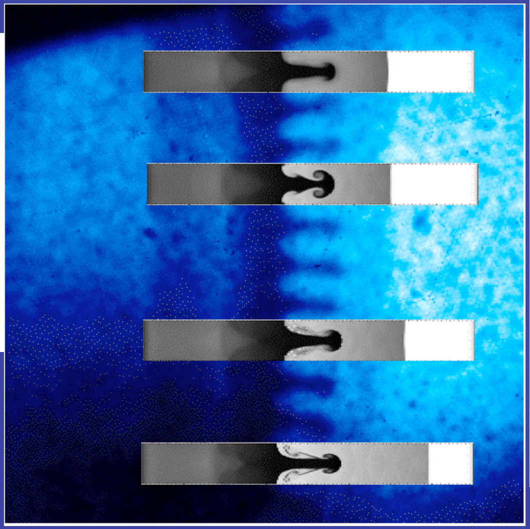


Simulation of NIF experiment where an unstable interface is heated by a 150 eV shock

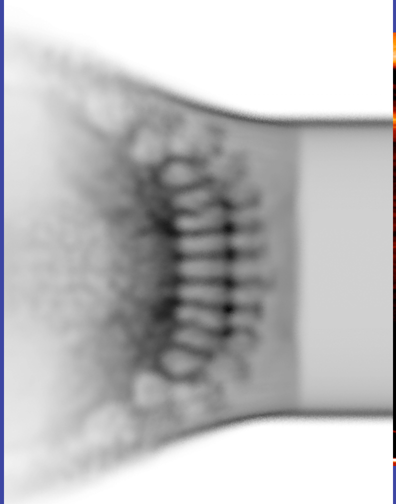
Simulations also see variable spike shape and penetration



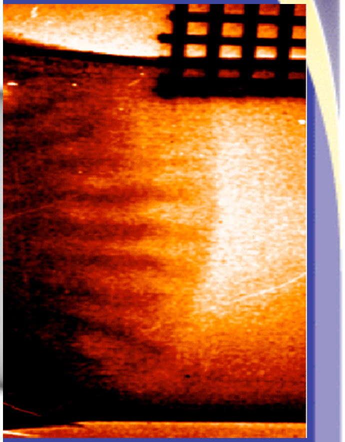
Jave Kane



Aaron Miles



Nathan Hearn

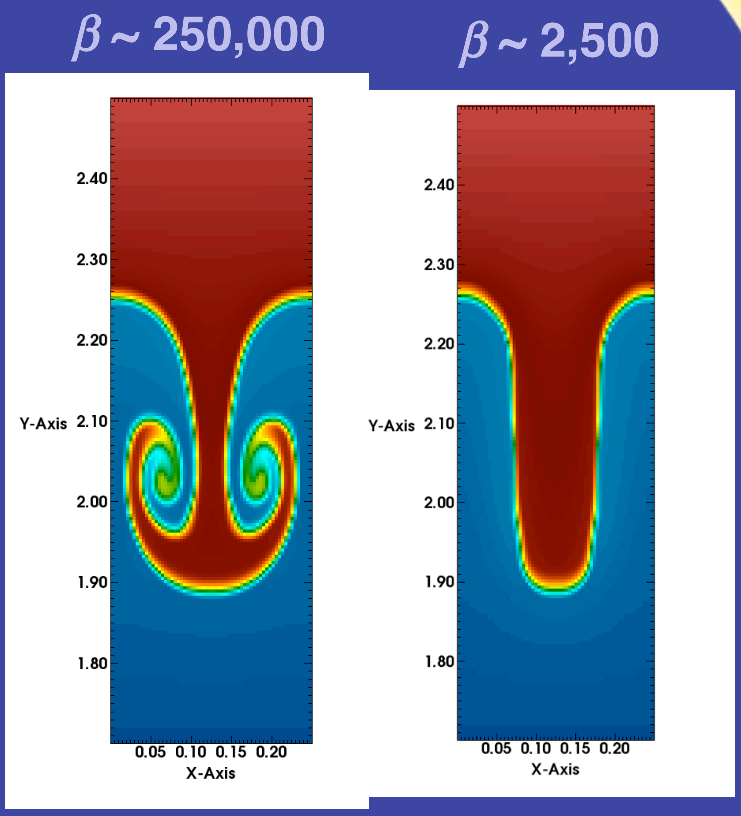


Carolyn Kuranz

In some experimental cases the spikes reach the shock, which would explain the astrophysical results

Self-generated magnetic fields may explain some observed details

- Magnetic fields have recently been seen in several laser experiments
- For our experiments, the “Biermann battery effect” generates a significant source term, but nonlinear heating and diffusion add complexity
- Magnetic fields would affect the scaling from the lab to astrophysics



Simulations using FLASH

Hydrodynamic fluids described by single-fluid Euler's Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v}\right) = -\nabla p$$

$$\frac{\partial p}{\partial t} - \gamma \frac{p}{\rho}\frac{\partial \rho}{\partial t} + \mathbf{v} \cdot \nabla p - \gamma \frac{p}{\rho}\mathbf{v} \cdot \nabla \rho = 0$$

- A good approximation for an ionized gas
- See Ryutov et al. ApJ., 518, 821 (1999)