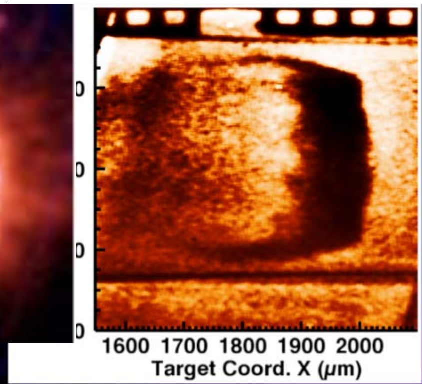
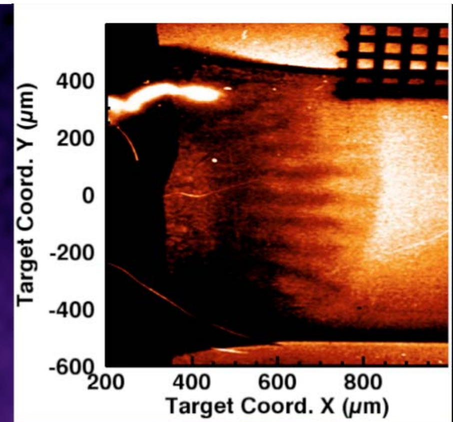
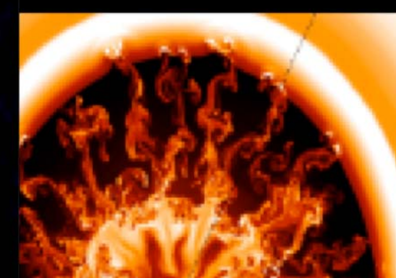
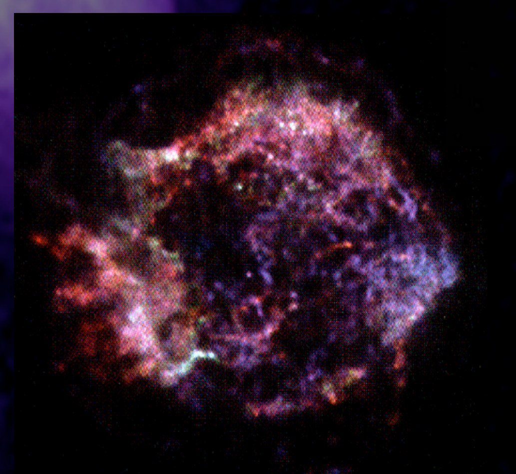




Laboratory Astrophysics at Omega 60 and EP

R. Paul Drake
University of Michigan

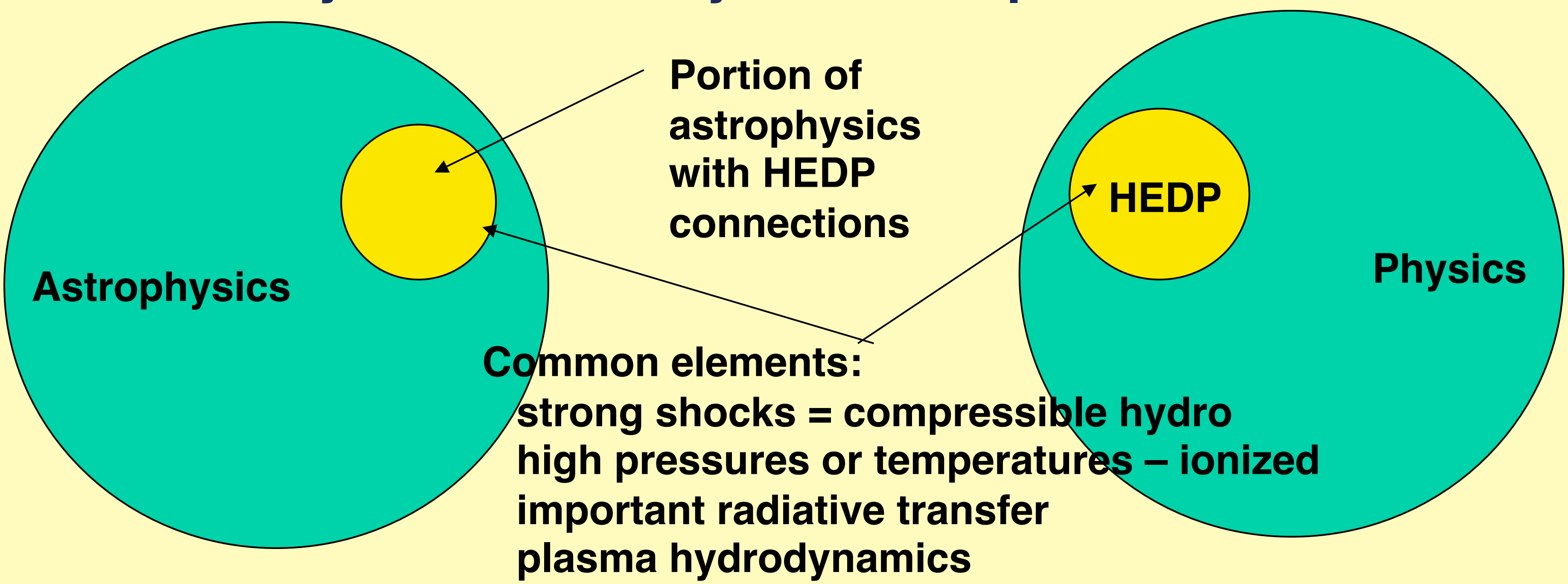




Work supported by the U.S. Department of Energy under grants DE-FG52-03NA00064, DE-FG52-07NA28058 and other grants and contracts

High-Energy-Density Physics (HEDP) and its connection to Astrophysics

HEDP involves the study of systems having a pressure > 1 Mbar (= 0.1 Tpascal = 10^{12} dynes/cm^2), and of the methods by which such systems are produced.



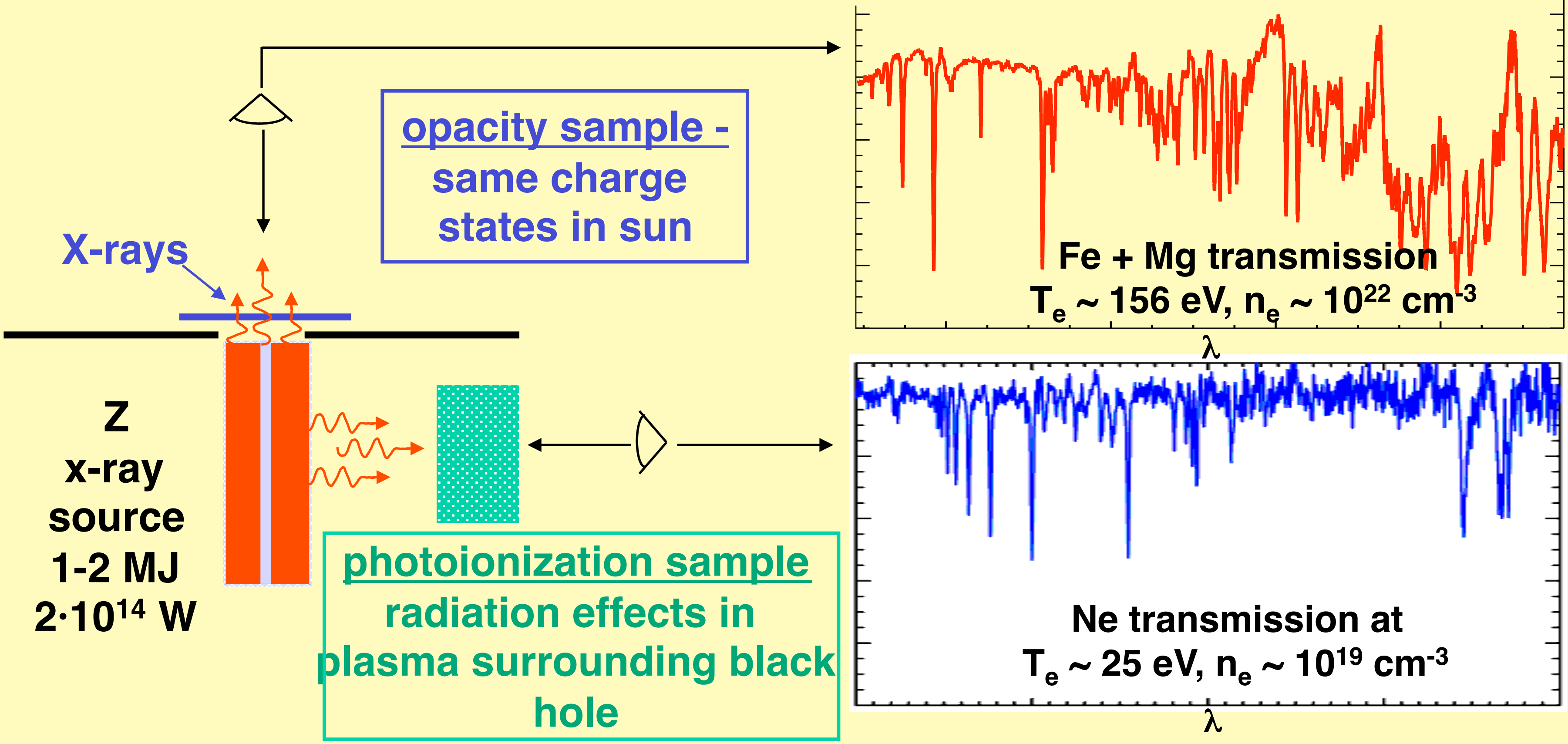
The "sexy" questions tend to arise from the connections

Nearly every problem in HEDP has astrophysical connections

Here we focus on issues where Omega can contribute

- **Properties of matter: opacity & Equation of State (EOS)**
- **Some general perspective**
- **Hydrodynamics**
- **Radiation Hydrodynamics**
- **Relativistic plasmas**
- **Credits:**
  - **Much of the HEDLA (High Energy Density Laboratory Astrophysics) community**
  - **My group and our collaborators (DrakeLab)**
- **My Affiliations:**
  - **Department of Atmospheric, Oceanic, and Space Sciences**
  - **Applied Physics Program**
  - **Michigan Institute for Plasma Science and Engineering**
  - **Center for Radiative Shock Hydrodynamics**

Opacity and photoionization experiments, relevant to stellar interiors and accretion powered objects, have been done at Z and could be done at Omega

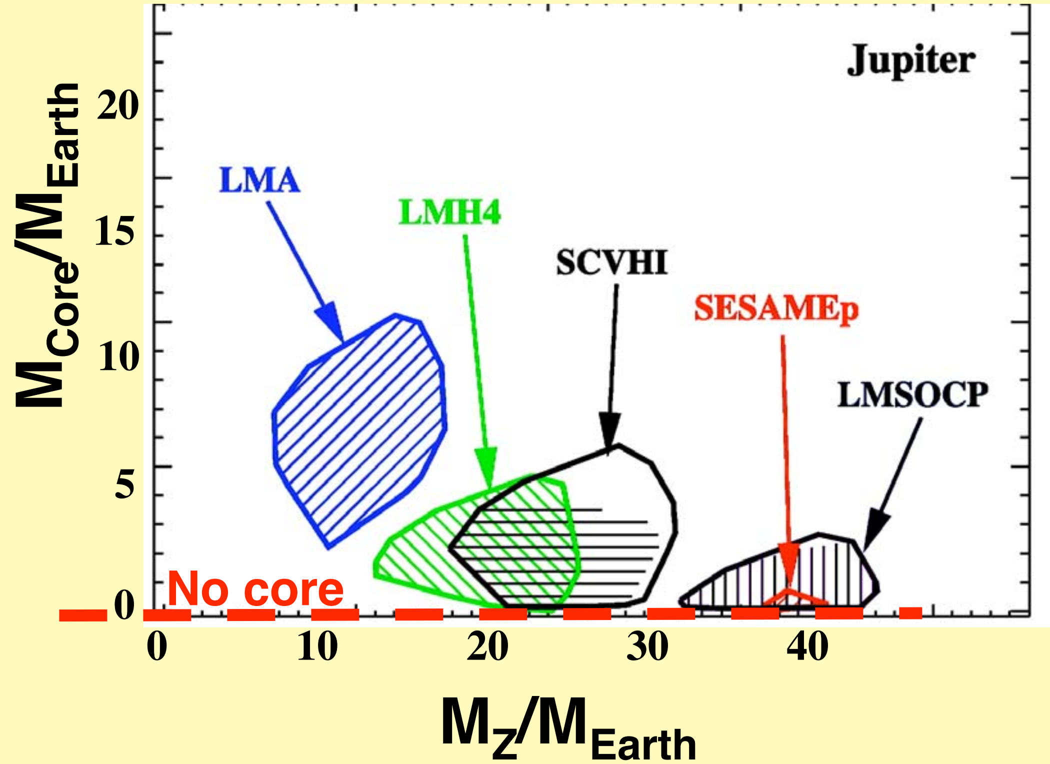


The importance of radiation for creation and diagnosis is a unifying theme for these very different plasmas

[Jim Bailey, PRL (2007); and PoP 13, 056301 (2006)]

Slide credit: James Bailey

The different EOS models for hydrogen directly impact whether Jupiter is predicted to have a central dense core or not

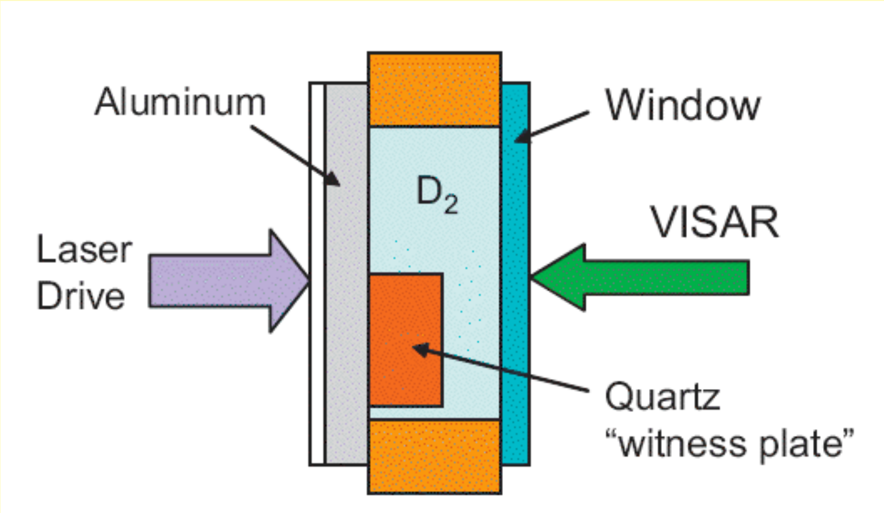


- Outlines show range of models matching Jupiter's properties within 2σ of observed
- Cannot yet tell whether Jupiter has a core
- The predicted age of Jupiter is is also sensitive to the H EOS, which affects luminosity

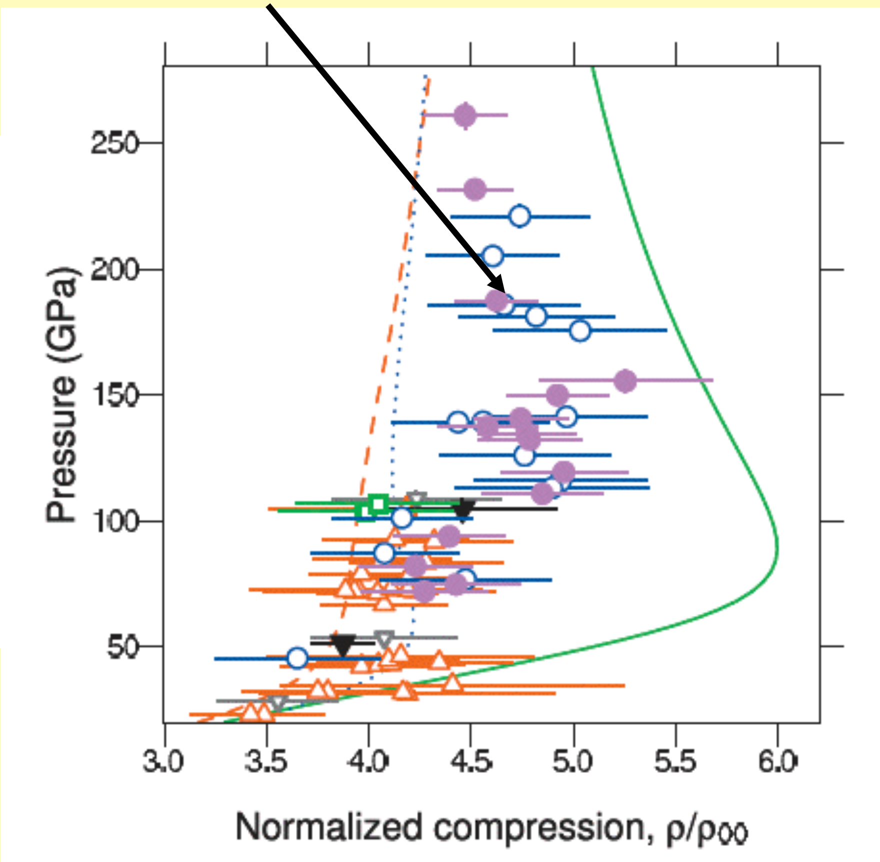
[D. Saumon and T. Guillot, Ap. J. 609, 1170 (2004)]

Adapted from slide by Bruce Remington

Equation of state experiments have been and will be common at Omega



Single-shock and double-shock Omega data



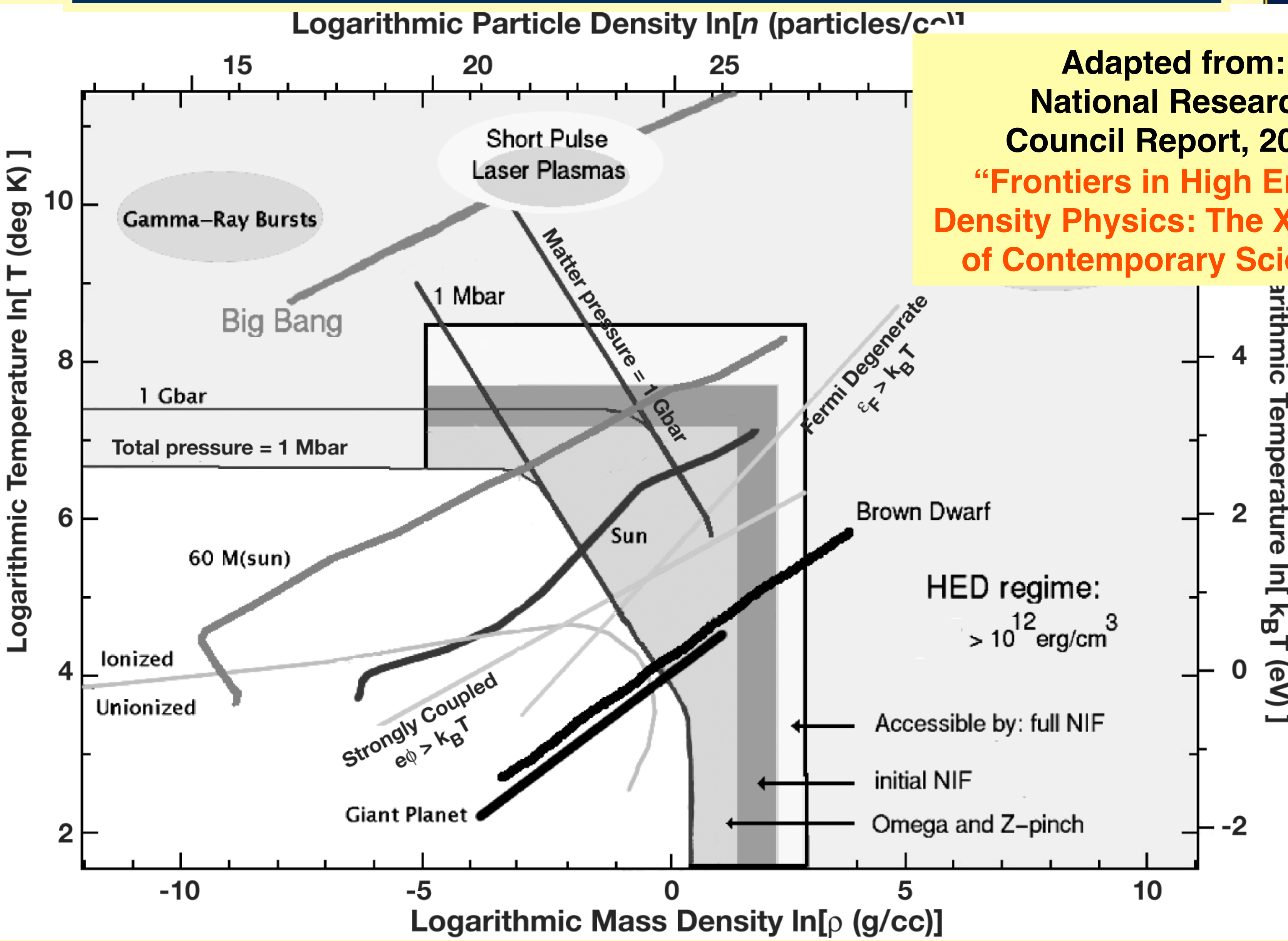
D. Hicks, et al., PHYS. REV. B 79, 014112 (2009)

These experiments are an example of a direct measurement of a relevant property

- **This is one of several types of measurement one can do**

- **One can measure**
  - **Properties directly;**
    - **Opacity (stellar structure, Cepheid variable pulsations)**
    - **Photoionized plasma properties**
    - **Equation of State (planetary structure)**
    -
  - **Scaled properties; e.g., He-like ion photoionization**
  - **Scaled dynamics; e.g., hydrodynamic phenomena**
  - **Dynamics with key dimensionless parameters; e.g. radiative shocks**

For properties: the equilibrium HEDP regimes

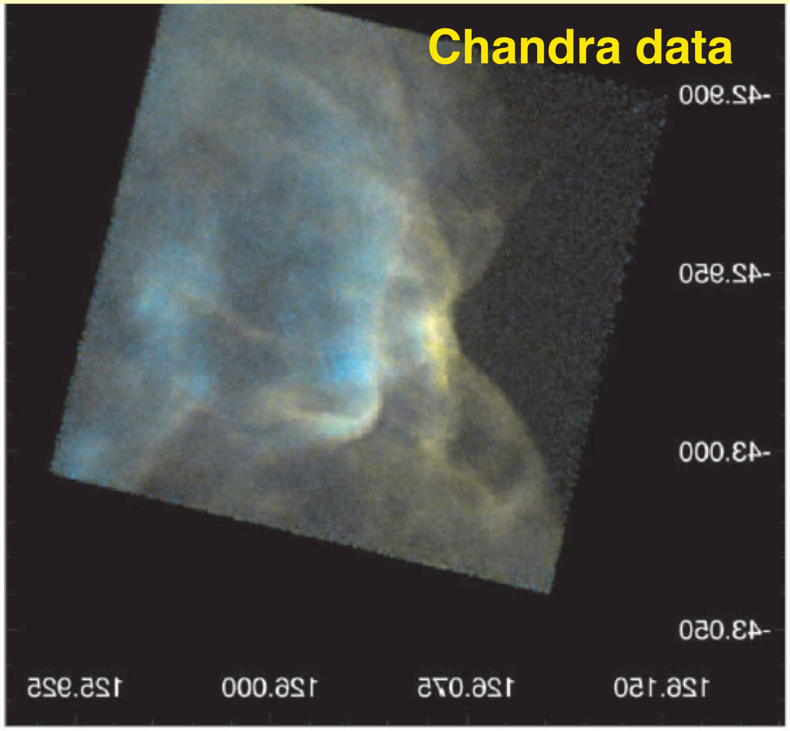


Adapted from:
National Research
Council Report, 2002
"Frontiers in High Energy Density Physics: The X Games of Contemporary Science"

Many potential areas of impact in HEDP come from dynamical processes

- Shock waves and other hydrodynamic effects
- Hydrodynamic Instabilities
- Dynamics involving radiation (radiation hydrodynamics)
  - Radiative heat waves
  - Collapsing shock waves
- Relativistic dynamics

Destruction of clumps in post-shock flow has been a research area with impact



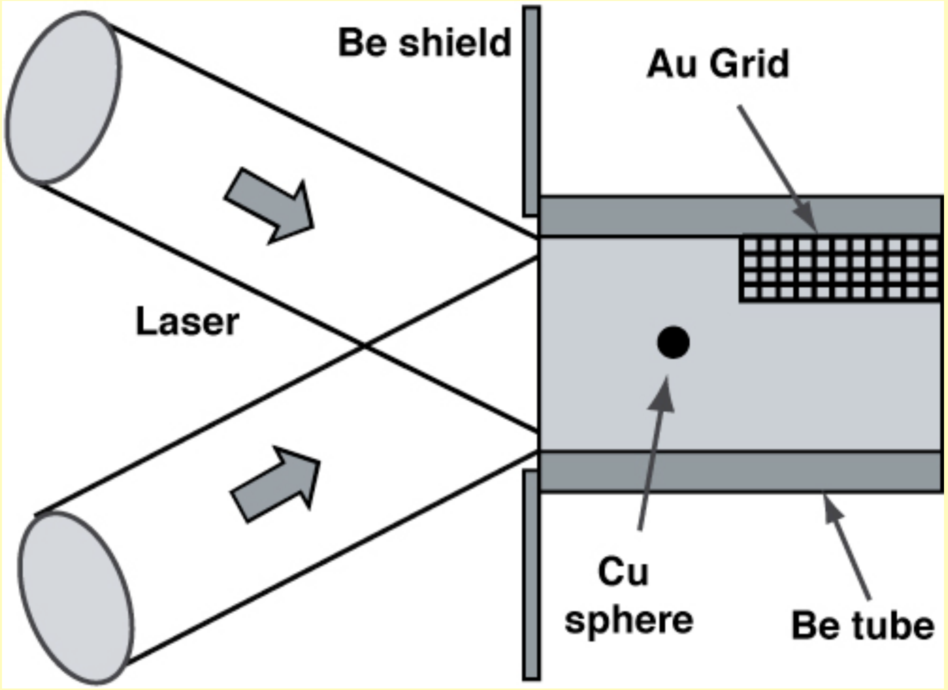
Lab Experiment

Klein et al., ApJ 2003
Robey et al., PRL 2002

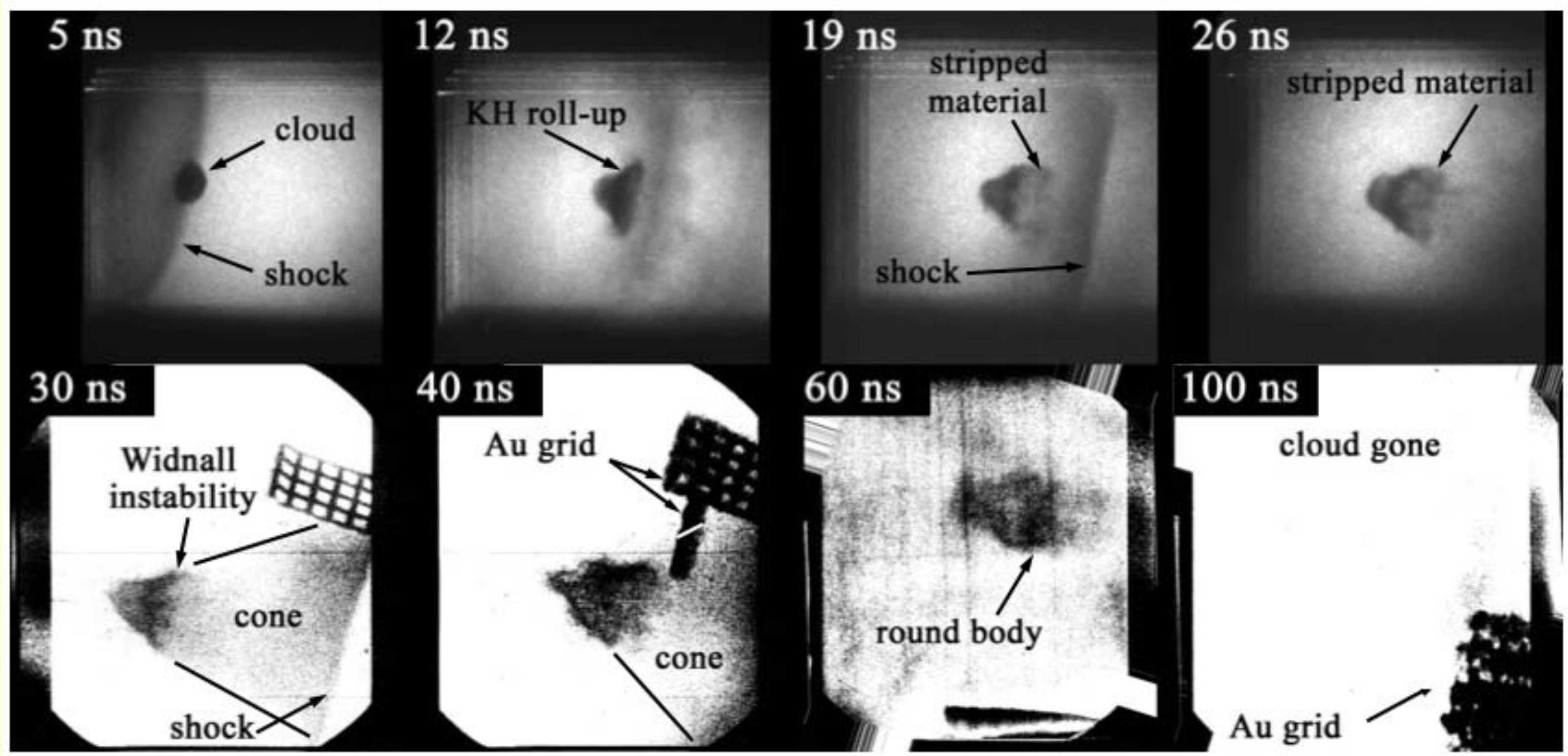
- **Experimental results used to help interpret Chandra data from the Puppis A supernova remnant**
- **Well-scaled experiments have deep credibility**
- **Una Hwang et al., Astrophys. J. (2005)**

How shock-clump experiments are done

- … but not in a way that lets one diagnose details
- The experiment involves blast-wave-driven mass stripping from a sphere
- Early experiments used Cu in plastic; recent experiments use Al in foam



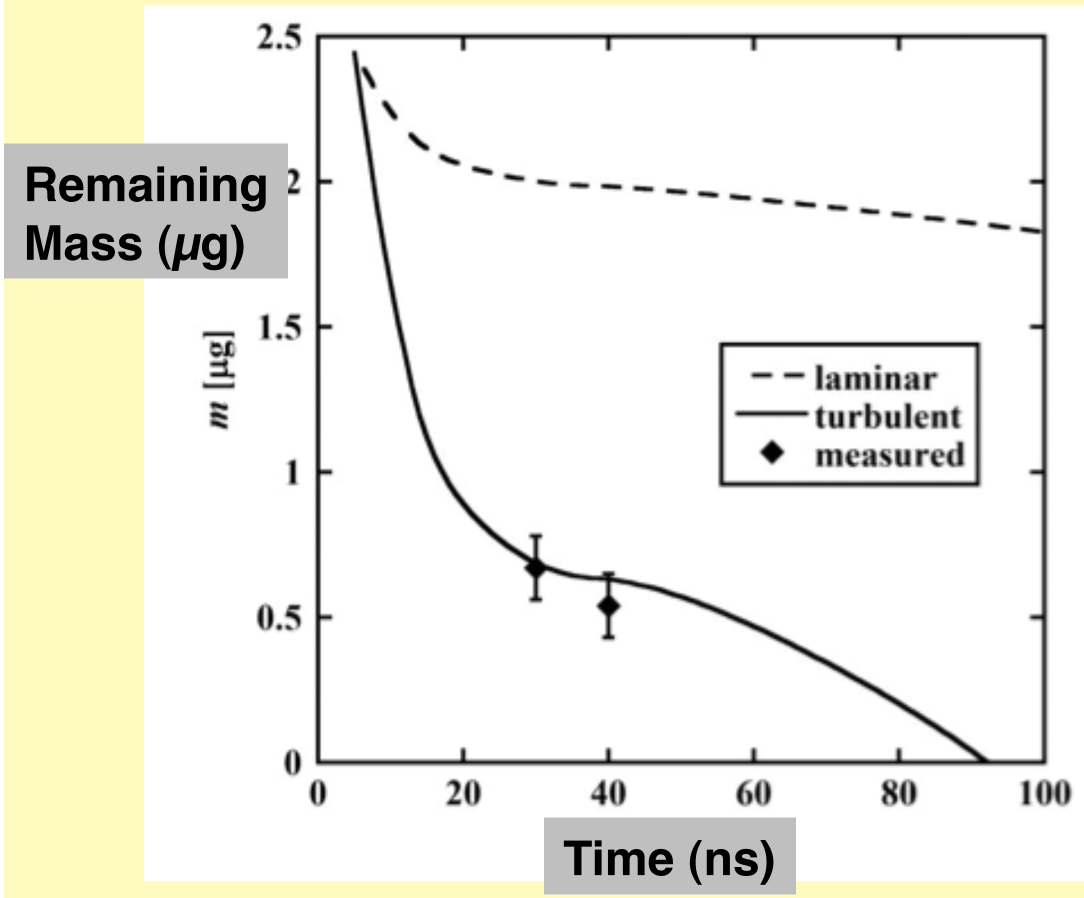
Observations of the Al/foam case continued until mass stripping had destroyed the cloud



- **Hansen et al., ApJ 2007, PoP 2007**

The stripping is clearly turbulent, consistent with the necessary conditions

Hansen et al., ApJ 2007



- The turbulent model is based on “Spalding’s law of the wall”, Spalding (1961)

- Parameters

  $Re \sim 10^5$ to 10^6

  $U \sim 10$ km/s

  $\nu \sim 10^{-5}$ to 10^{-6} m^2/s

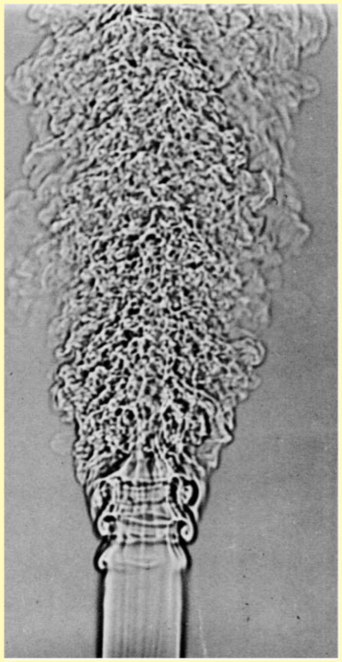
  δ ~ Sphere ~ 60 μm radius

- $\delta / U \sim 6$ ns ~ rollup time (data)

- Robey/Zhou time is ~ 1 ns

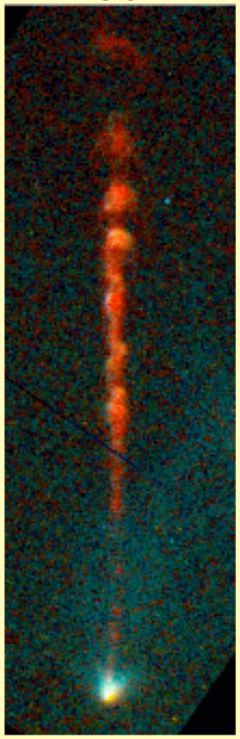
Astrophysical jets do not appear turbulent

Turbulent jet in gas

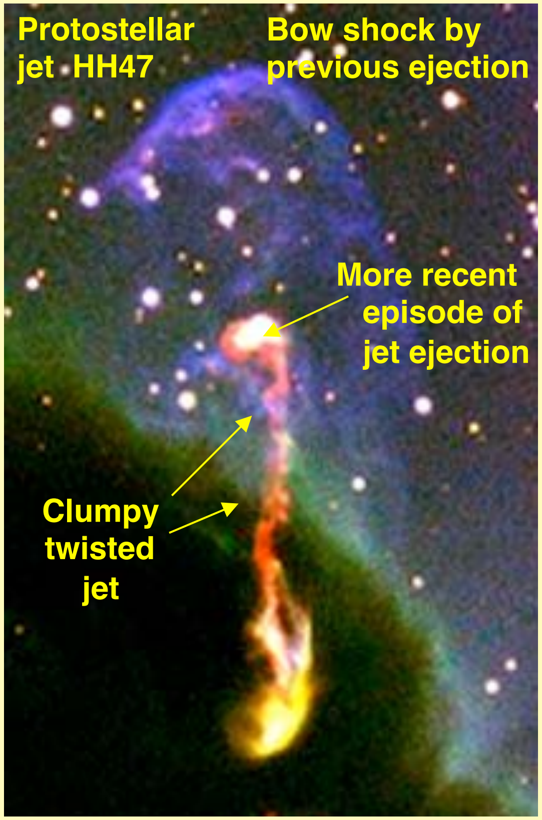


Van Dyke, Album of Fluid Motion (1982)

HH34 Astro Jet



Burrows, Hester, Morse, WFPC2 Hubble



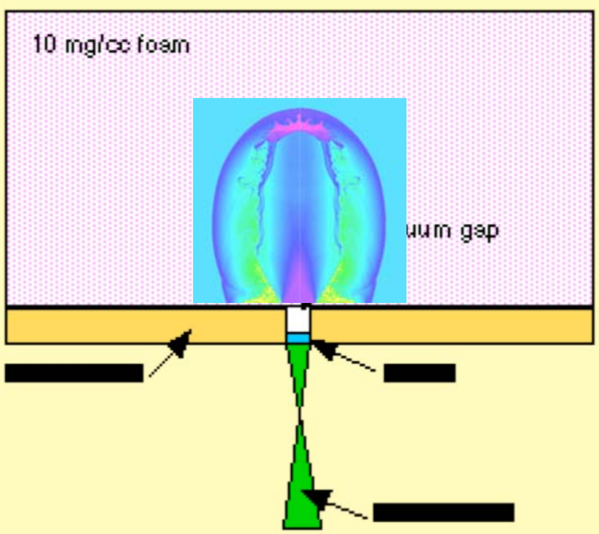
[Reipurth & Bally, ARAA 39, 403 (2001)]

Here is one of several approaches to jet experiments

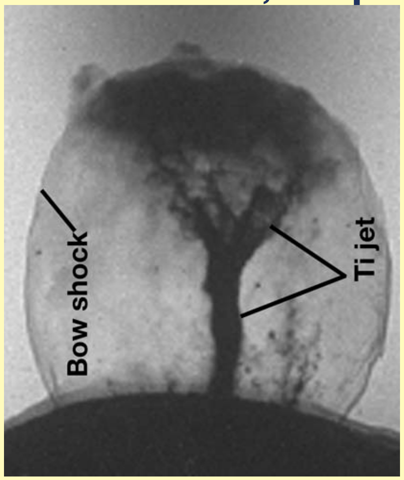
- **Basic idea**
  - Irradiate a thin layer of material to launch a plasma down an expansion tube
  - Plasma expands and accelerates to form supersonic, directed flow (jet)
  - Jet interacts with low-density medium

Initial design work

Harding and Drake, 2000
Khokhlov, 2001



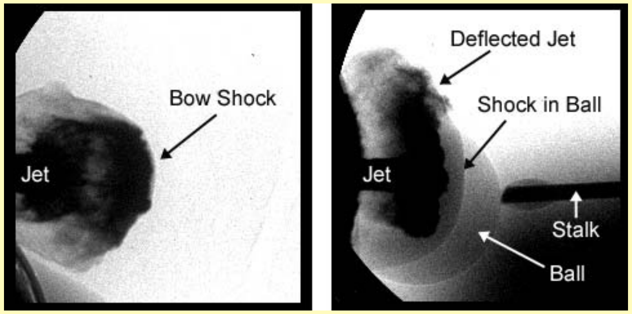
- **This has worked well**
  - Work by Hartigan, Foster, et al.
  - Ph.D. thesis, Stephanie Sublett, U. Rochester



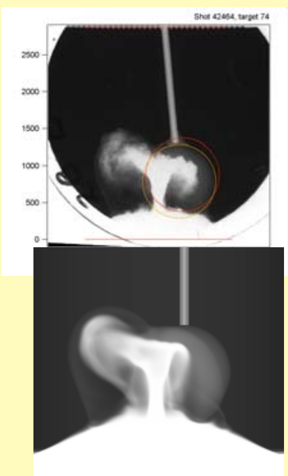
Foster et al. ApJL 2005

This led to …

Project led by Patrick Hartigan to study bow shocks and jets using experiments, simulations, and observations



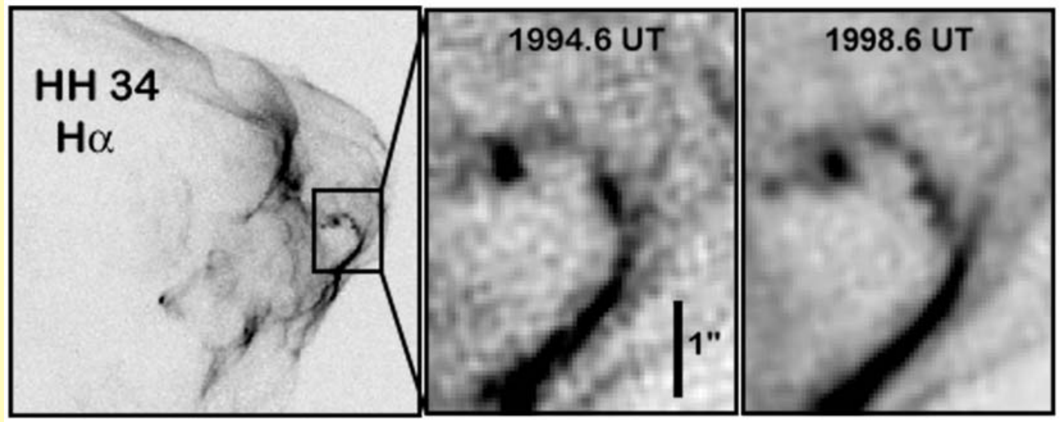
Laser experiment of deflected jet and bow shock



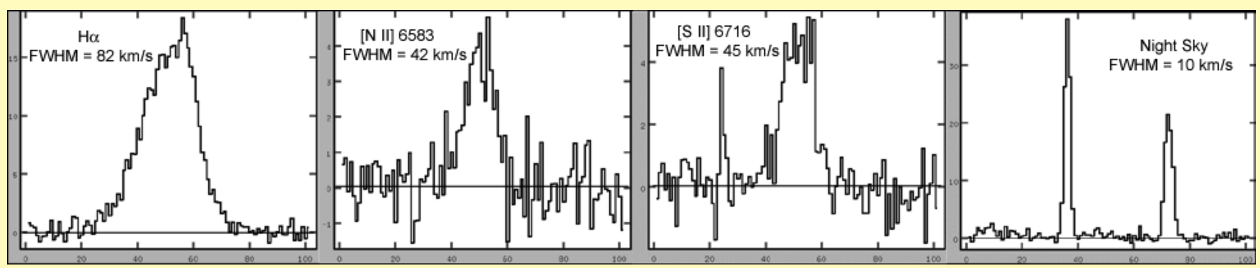
Data

RAGE Code

Numerical Simulations



Hubble Space Telescope project to obtain 3rd epoch to follow instabilities, clumps, and shear

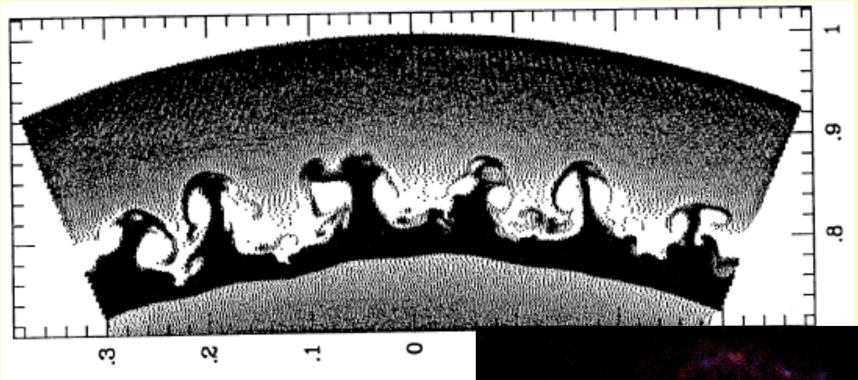


Kitt Peak 4-m spectral mapping to quantify supersonic turbulence in wake of a deflected jet

Our own work has focused on supernovae and related systems

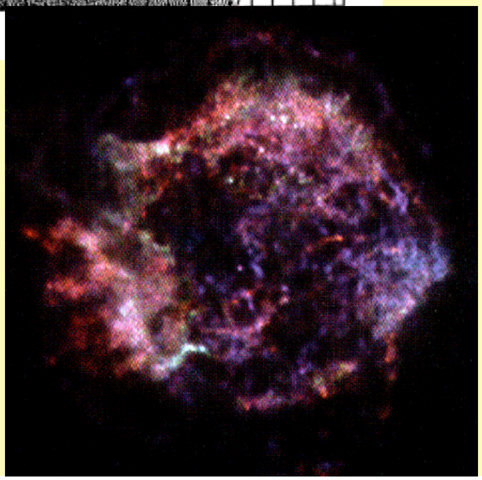
- **The degree to which hydrodynamic processes can produce outward penetration of high-Z stuff**
  - **Initial conditions and explosion symmetry have been shown to matter**

In supernova remnants



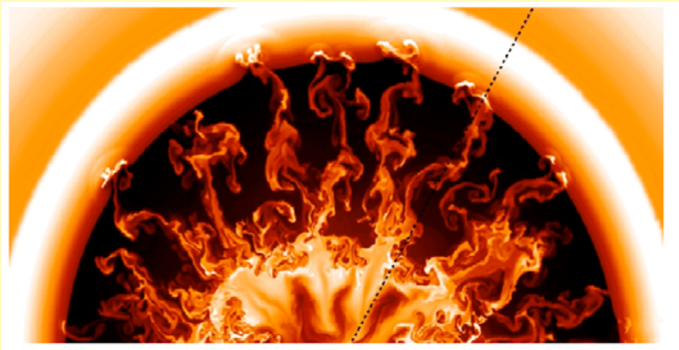
Chevalier, et al. ApJ 392, 118 (1992)

and supernovae remnants



Cass. A

and supernovae



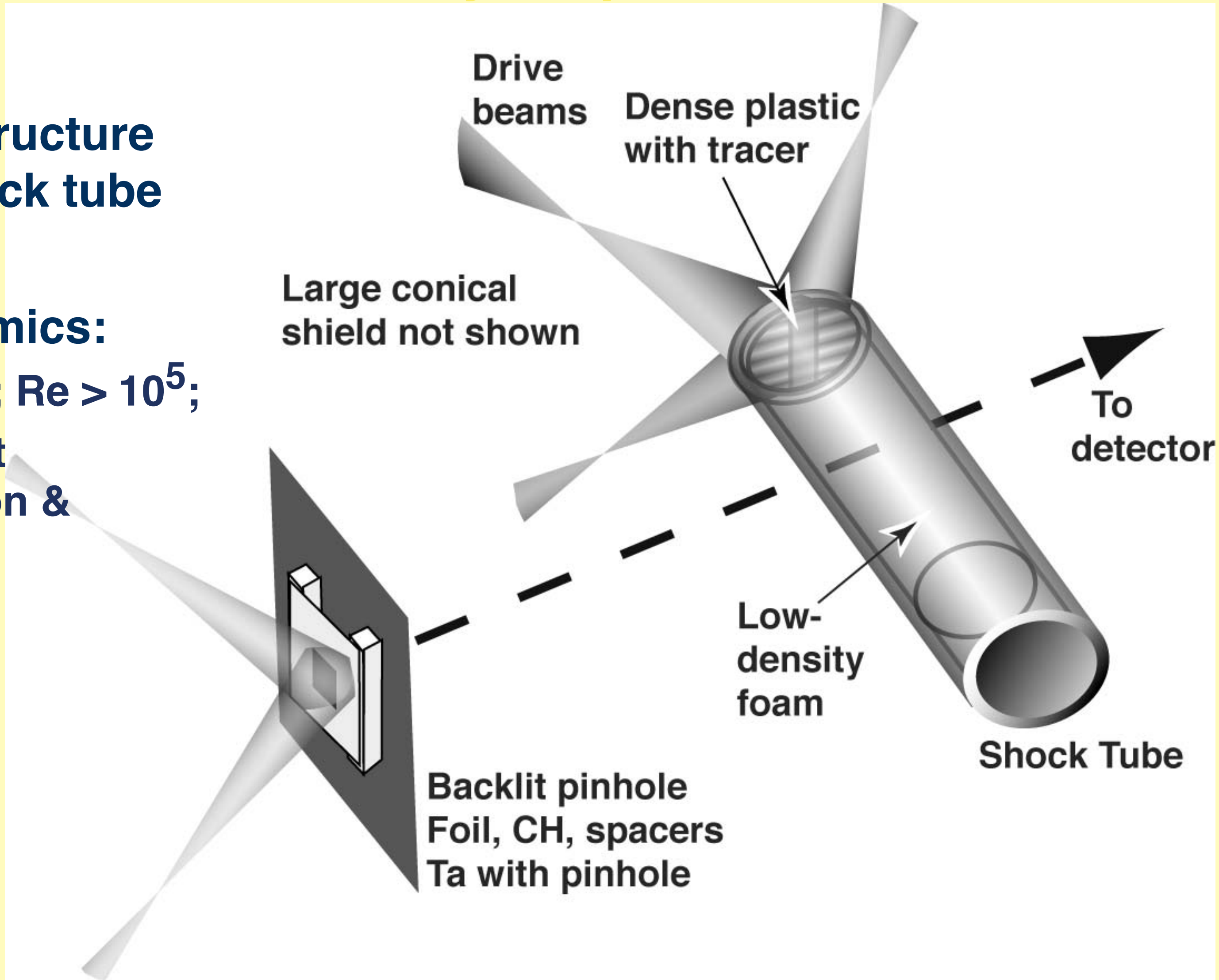
Kifonidis, et al. A&A (2003) SN 1987A

All these systems are globally hydro

One can often do very well scaled hydrodynamic studies of hydro processes

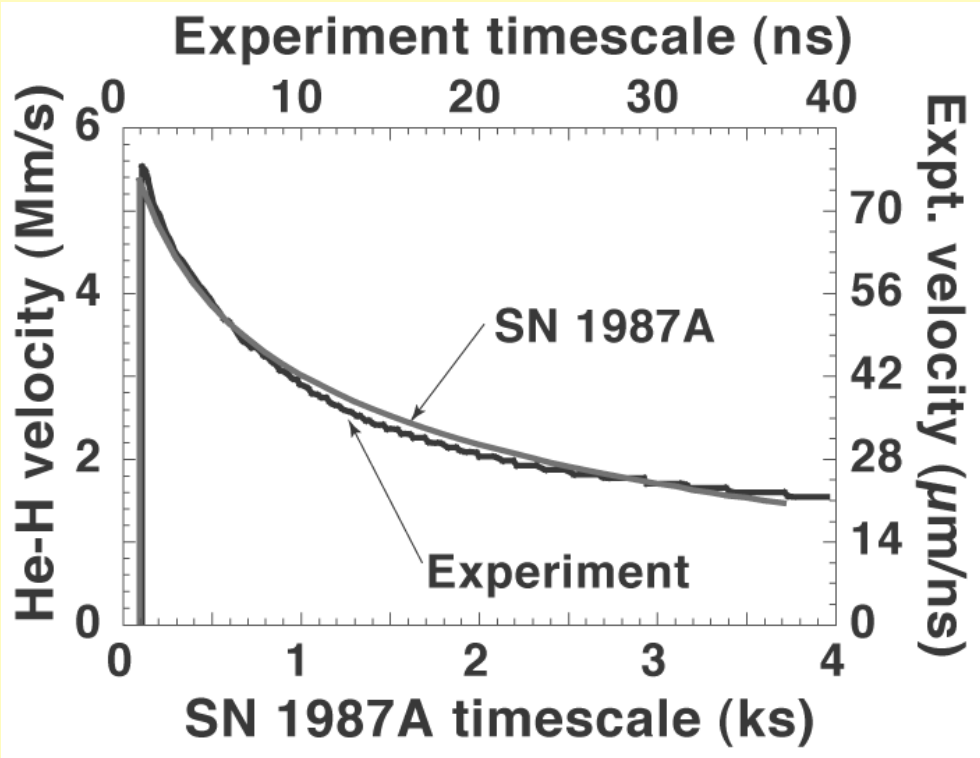
- **Precision structure inside a shock tube**

- **Hydrodynamics:**
  - **$L >> \lambda_{mfp}$; $Re > 10^5$;**
  - **small heat conduction & radiation**

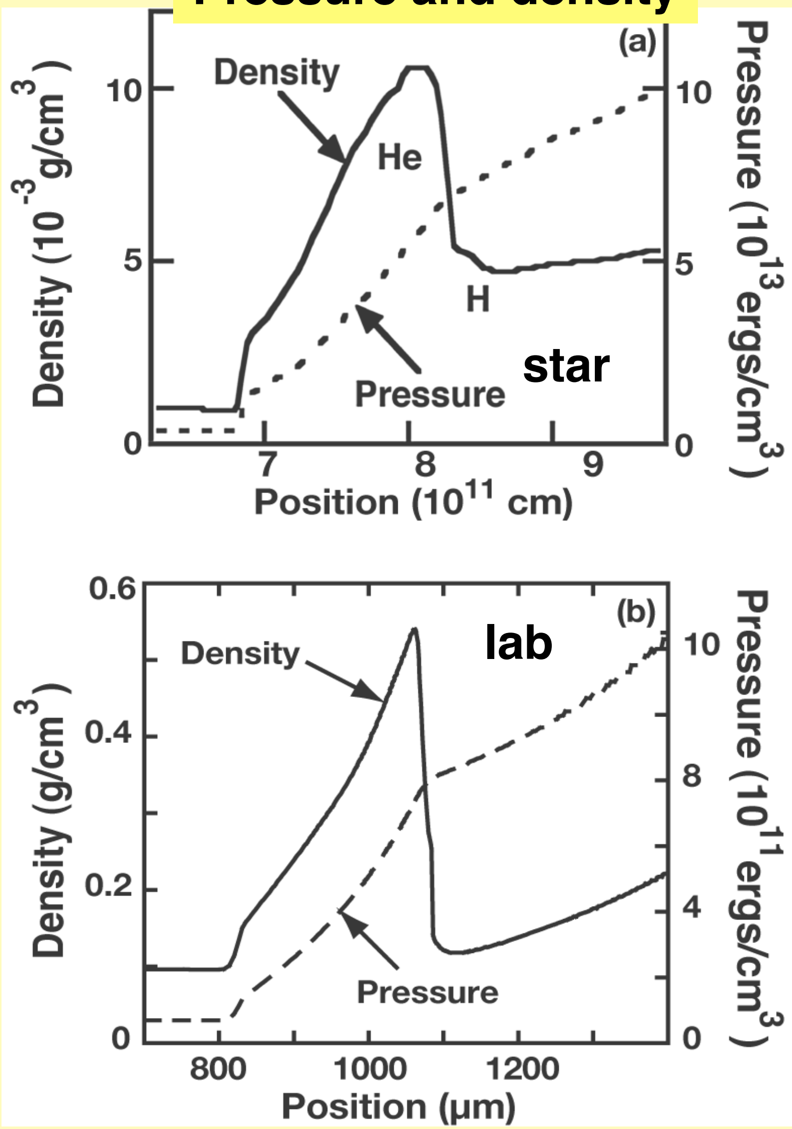


Boundary conditions in space and time must also be well-scaled

Interface velocity vs time

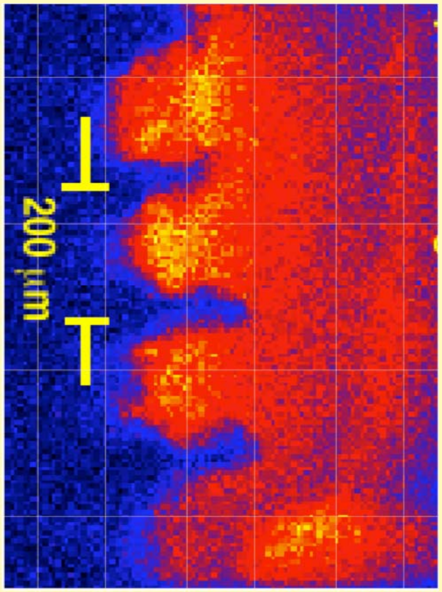


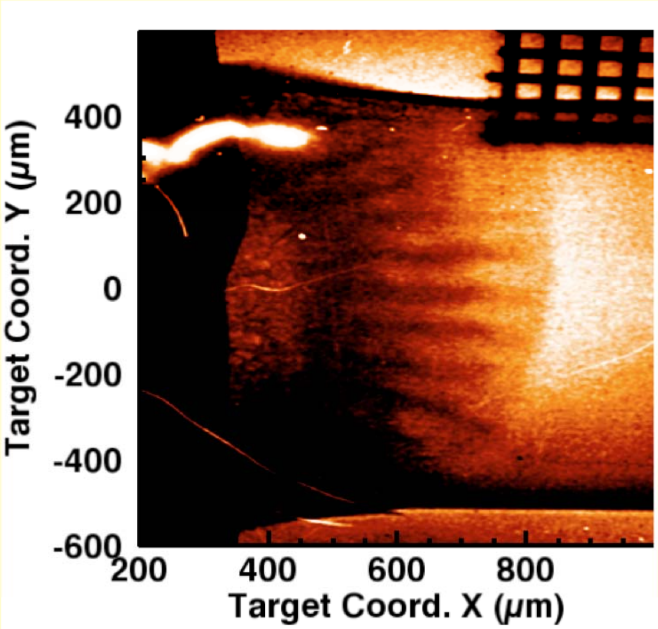
Pressure and density



Our ability to measure the resulting structures has advanced greatly

mid-90's



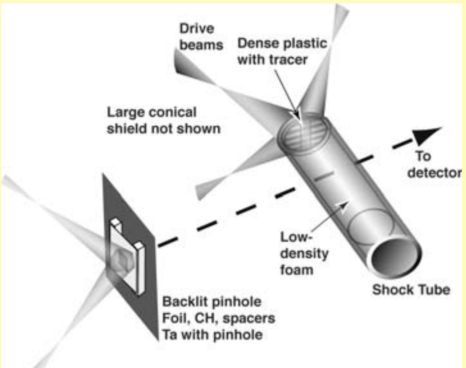


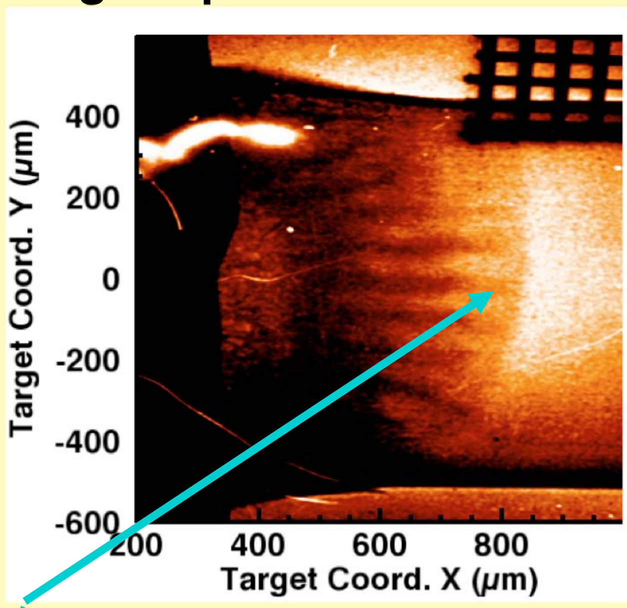
Dec 2006

Many groups contributed to these advances

We see morphology that differs greatly from expectations

Kuranz Omega experiment

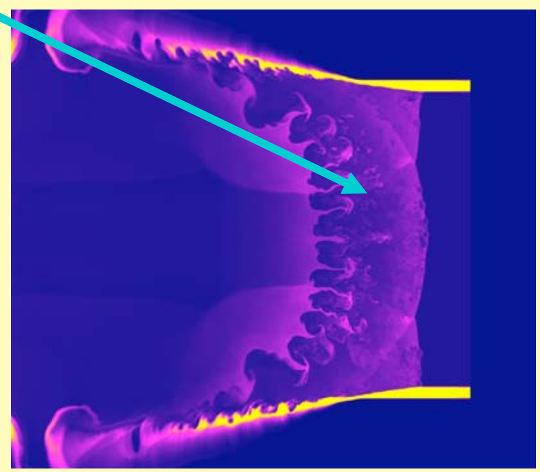




Omega scale:
Experiments to establish mechanisms

Penetration to shock !
No mushroom caps!

NIF scale:
Penetration in diverging multi-interface case



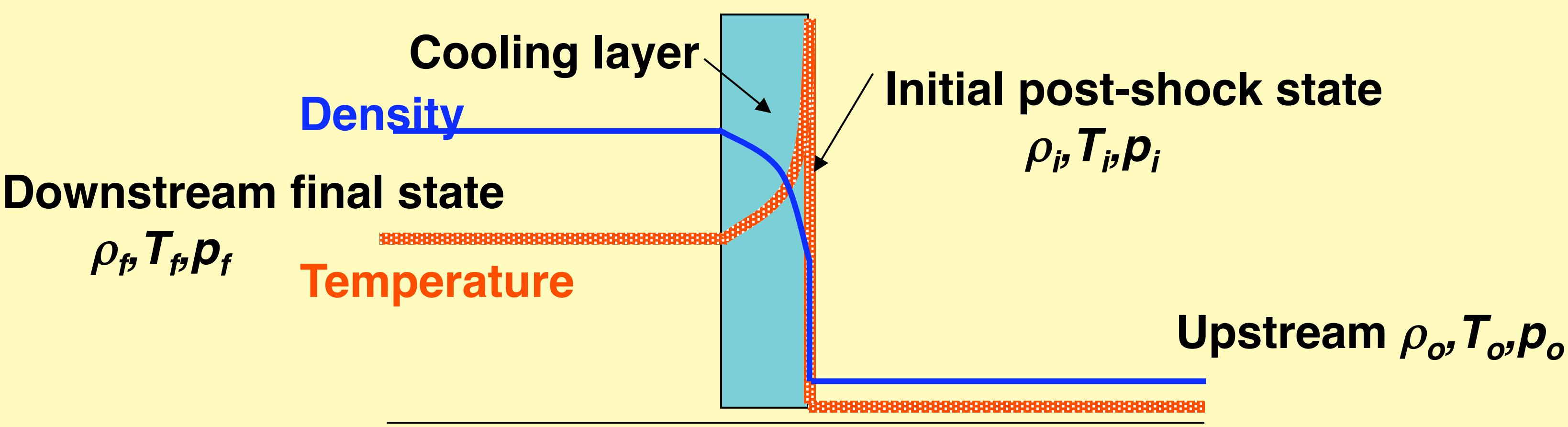
Hearn 3D FLASH simulation

Radiative shocks are a harder problem in both astrophysics and the laboratory

- **Radiative shocks**
  - Radiation alters the structure and dynamics of the shock
  - A radiation-hydrodynamic phenomenon
  - Inherently nonlinear
  - Sometimes unstable
- **Motivation from astrophysics**
  - Supernova shocks
  - Stellar shocks
  - Some accretion phenomena
- **Modeling them is difficult**
  - Widely varying scales
  - Radiation transport regimes
  - Ionizing media and 3D effects
- **Astrophysical modelers called for experiments in this area**
- **Experiments are a major challenge**
  - Novel experimental systems
  - Need innovation in targets and diagnostic approaches
- **Matching key dimensionless parameters is what one can do**

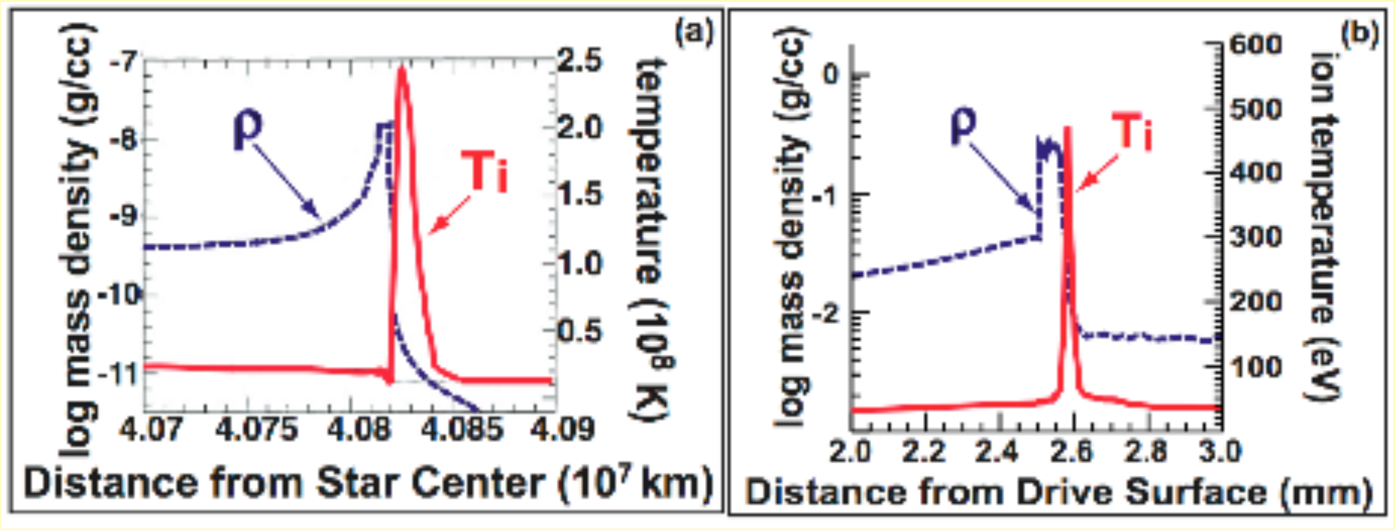
There are three key dimensionless parameters for radiative shocks

- The ratio radiation flux at the initial postshock temperature to the incoming material energy flux
- The upstream optical depth
- The downstream optical depth



(Ignoring ion-electron decoupling near the density jump)

Shocks in SNe pass through the regime of our experiments as they emerge



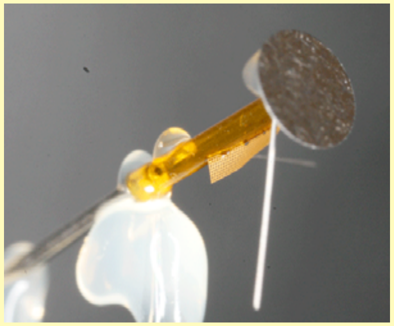
1987A simulation **Xe experiment simulation**

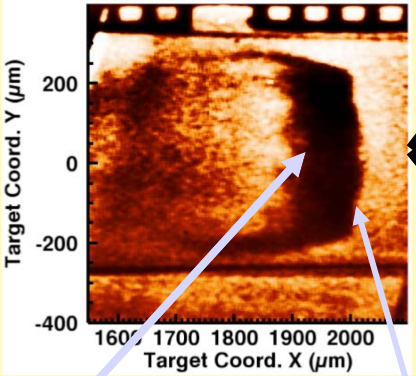
- **Core collapse SNe shock passing through outer layers becomes radiative**
  - **Once radiation ahead of the shock can escape**
- **Associated with luminosity burst; radiation escaping to optically thin region**

A.B. Reighard, Ph.D. Thesis, 2007 **Ensman and Burrows*, ApJ.,* 393,742-755,1992**

Radiative shocks have been produced and can now be studied and understood

Reighard Omega experiment





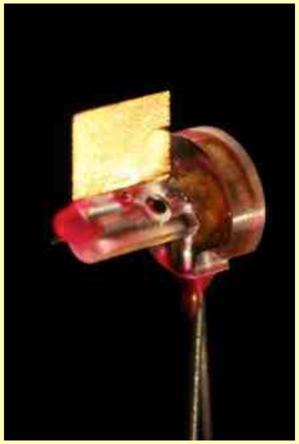
shock

Continuously radiating shock produces dense xenon layer at > 30 times initial density.

Omega scale:

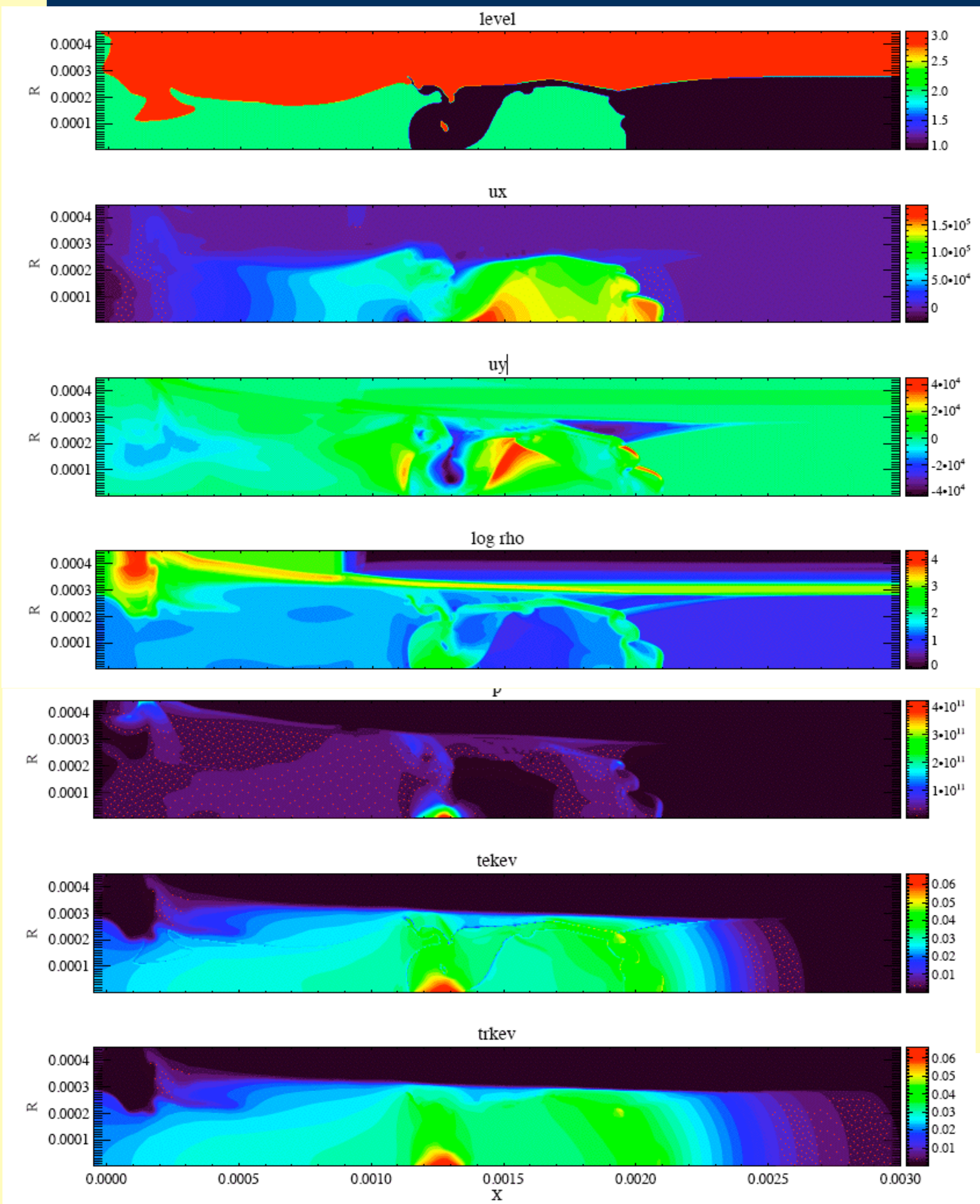
- Determine structure and dynamics
- Both axial and lateral
- Create more complex systems

Target for Visco X-ray Thomson scattering experiment



Omega has the potential to do other radiation hydrodynamics

CRASH 1.0 2D Simulation of Experiment



Level

Axial vel.

Radial vel.

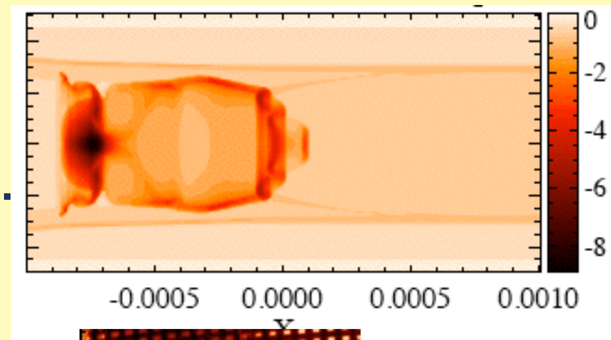
Density

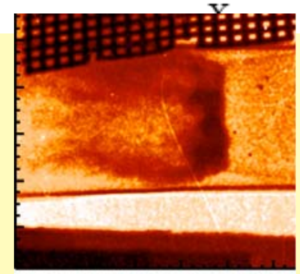
Pressure

Te

Tr

Xe radiograph
(of rotated output)





1400 1600 1800 2000 2200 2400
Target Coord. X (μm)

The agreement here is too good

Omega EP opens the potential for experiments on relativistic laboratory astrophysics

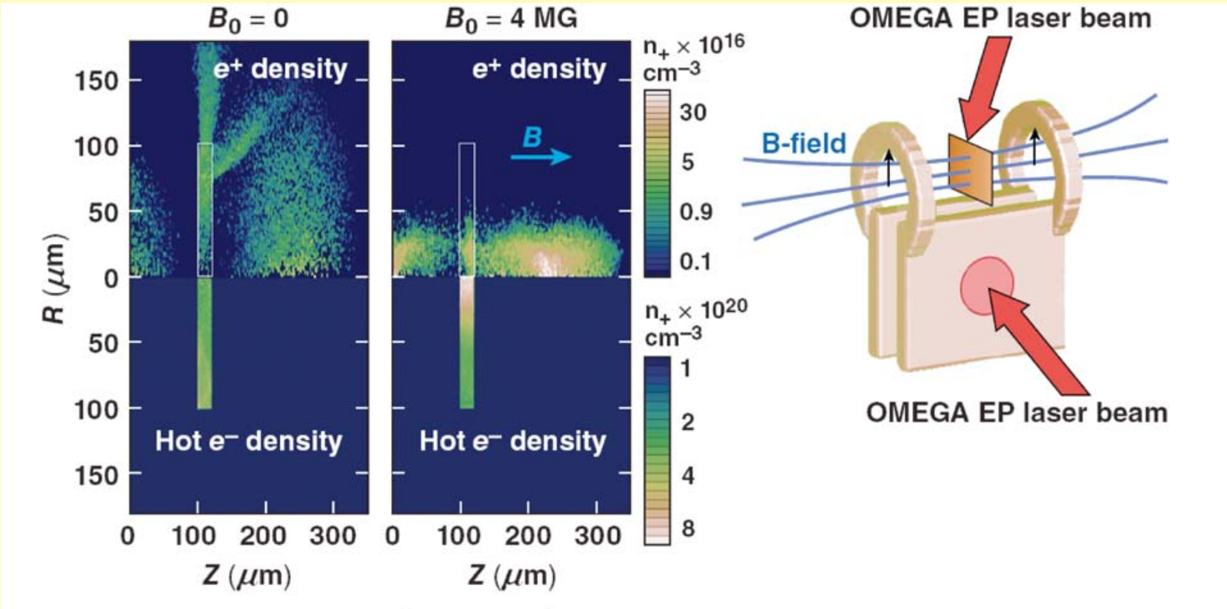
- **The capability to combine long, short, and ultrashort laser pulses, producing strongly relativistic electrons, opens the potential for novel experiments.**
- **Some examples**
  - **Relativistic electron acceleration**
  - **Ion acceleration**
  - **Light transmission through high-density plasma**
  - **Drilling holes in dense plasma**
  - **Electron-positron pair production**
  - **Induced photo-nuclear reactions**
  - **GigaGauss magnetic-field creation**
- **"Relativistic" laser beams**
  - **Quiver momentum**

$$a_o = \frac{p_e}{m_e c} = \sqrt{\frac{I_L \lambda_\mu^2}{1.37 \times 10^{18} \mathrm{W} \mu^2 / \mathrm{cm}^2}}$$

  - **Lorentz factor**

$$\gamma_r = \sqrt{1 + a_o^2}$$

Experiments on OMEGA EP will study the formation of electron-positron jets and plasmas



D. Welch *et al.*, Nucl. Instrum. Methods Phys. Res. A 464, 134 (2001).

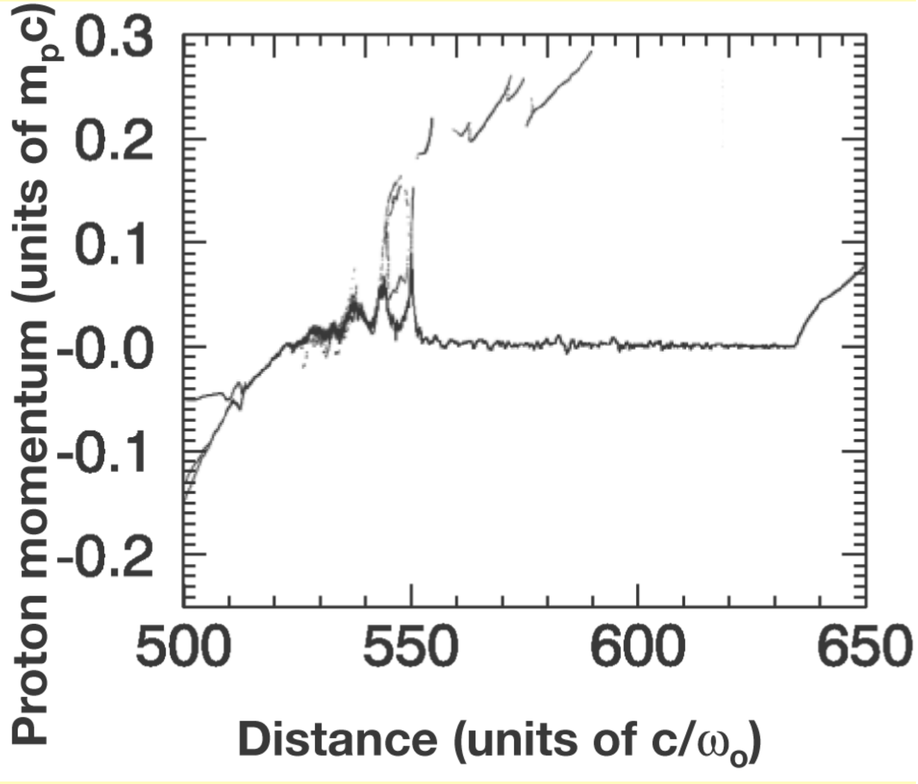
- **A significant number of electron positron pairs can be produced with 10 ps OMEGA EP beamline interacting with a high-Z target.**
- **Initial electron-postiron pair production from OMEGA EP is encouraging (LLNL/LLE collaboration, P.I. H. Chen).**
- **Addition of a magnetic field should allow production of a confined electron-positron plasma (J. Myatt APS/DPP 2007).**
  – **Many pairs in a Debye sphere and plasma size >> Debye Length**

Slide credit: D.D. Meyerhofer

Collisionless shocks might prove feasible?

- **Simulated by Particle-In-Cell or PIC codes**
- **PIC codes simulate motion of actual or representative particles with correct mechanical equations and EM equations**
- **An example of simulated momentum vs distance for a collisionless shock**

Collisionless shock driven by ultrafast laser



Credit: Louis Silva

Facility issues that have emerged in our laboratory astrophysics experiments

- Need to be able to drive any legs from any driver
  - Now can only drive one leg with backlighter driver
  - Becomes a major problem for X-ray Thomson Scattering
- Dedicated lab space for visiting groups
  - Enable preparations without conflicts
- Computer linkages in this lab or wherever preparations occur
- More SG8 DPPs would be useful