Recent and prospective laboratory studies of compressible turbulence
(using high-energy-density facilities)

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Center for Radiative Shock Hydrodynamics

Center for Laser Experimental Astrophysics Research

The Michigan team we work with

- **Experimental Program**
  - **Grosskopf, Marion, Gillespie**
  - **Grad students:**
    - **Harding, Visco, Doss, Huntington,**
    - **Krauland, DiStefano, Gamboa, Young**
  - **Many undergrads**

- **Center for Radiative Shock Hydrodynamics (CRASH)**
  - **Staff: Fryxell, Myra, Toth, Sokolov, van der Holst, Andronova, Torralva, Rutter**
  - **Grad students: Patterson, Chou, and many others**
  - **Professors: Powell, Holloway, Stout, Martin, Larsen, Roe, van Leer, Fidkowsky, Thornton, Nair, Karni, Gombosi**
  - **TAMU: Adams, Morel, McClarren, Mallick, Amato, Raushberger, Hawkins**
  - **Simon Frazer: Bingham**

We value our scientific and financial collaborators

Scientific collaborators:

LLE/Rochester – ***Knauer, Boehly***
LLNL – ***Park, Remington, Robey, Miles, Hansen, Froula, Glenzer, others***
LANL – ***Montgomery, Lanier, Workman***
Arizona – ***Arnett, Meakin***
NCAR –***Hearn***
Florida State – ***Plewa***
Stony Brook – ***Glimm, Swesty***
NRL – ***Aglitskiy, Weaver***
France – ***Bouquet, Koenig, Michaut***
Texas – ***Ditmire, Wheeler***

Financial collaborators:

Joint DOE HEDLP program

Predictive Science Academic Alliance Program

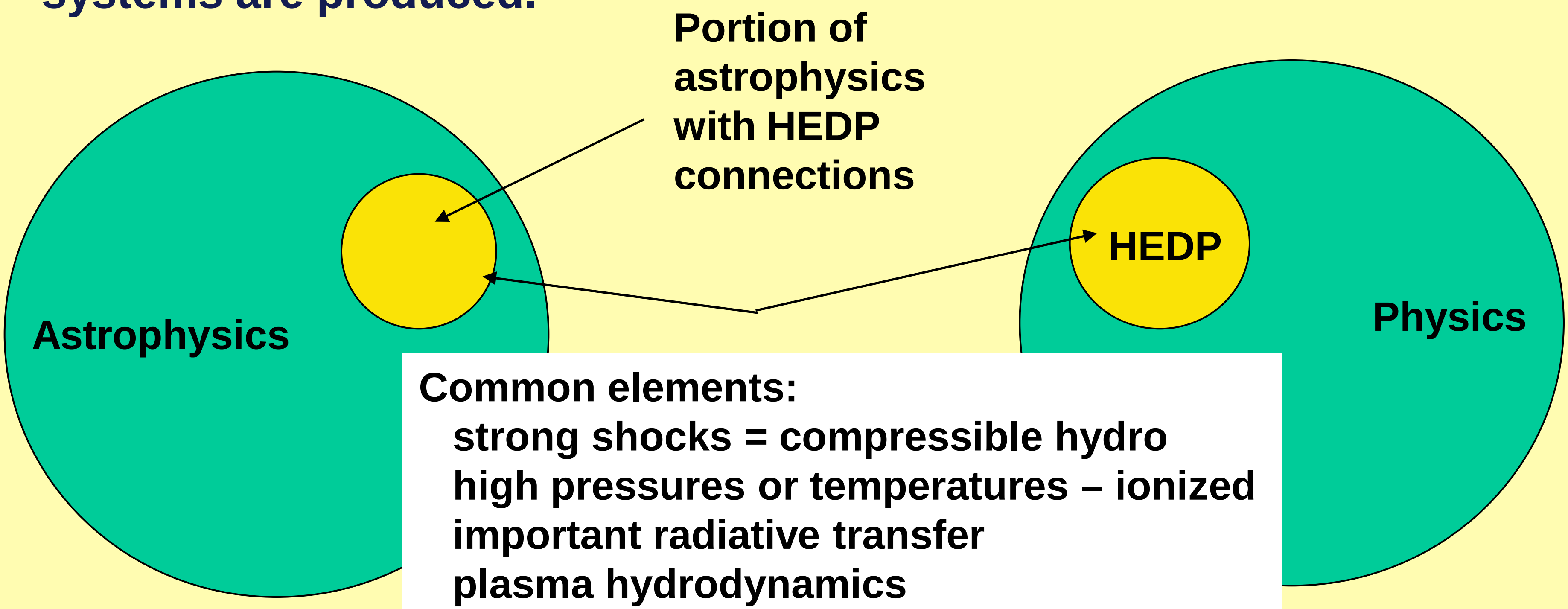
National Laser User Facility

DTRA

Past support:
Lawrence Livermore Nat. Lab.
Naval Research Lab.

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

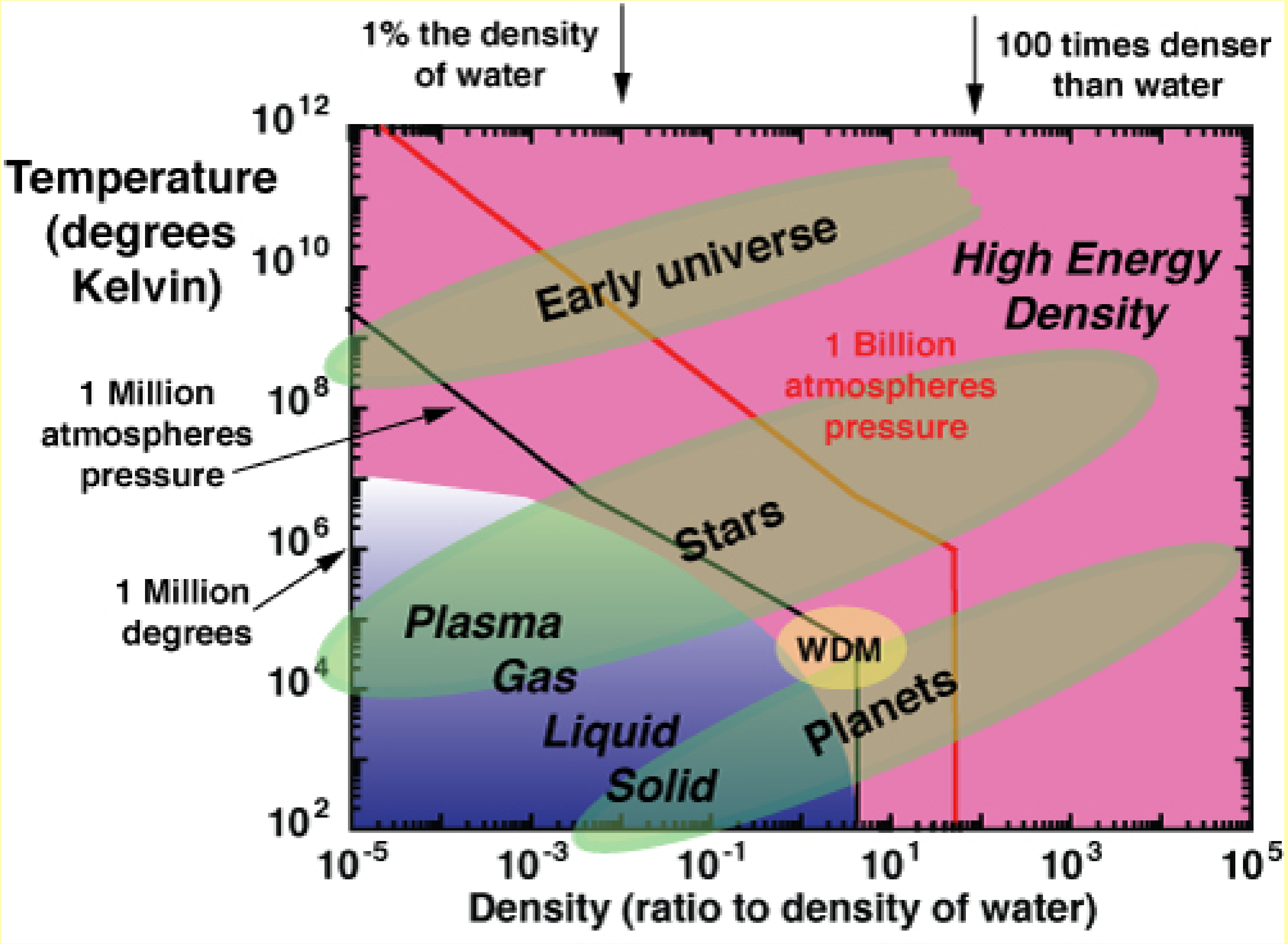
HEDP involves the study of systems having a pressure > 1 Mbar (= 0.1 Tpascal = 10^{12} dynes/cm^2), and of the methods by which such systems are produced.



Common elements:
- strong shocks = compressible hydro
- high pressures or temperatures – ionized
- important radiative transfer
- plasma hydrodynamics

The “sexy” questions tend to arise from the connections
Nearly every problem in HEDP has astrophysical connections

The high energy density regime

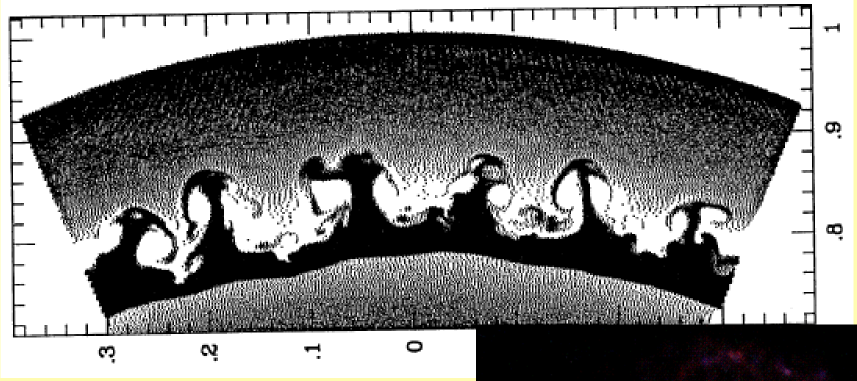


R.P. Drake,
Physics Today
June 2010

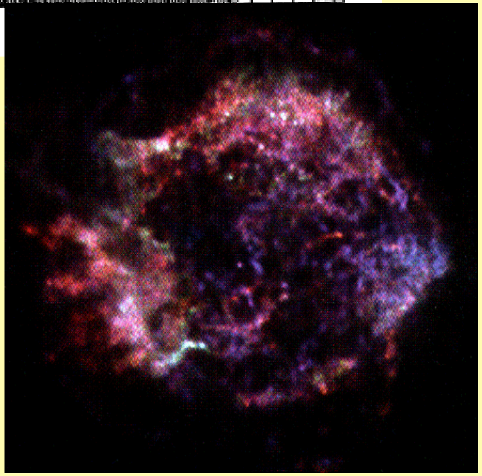
Decelerating forward shock / reverse shock systems are often unstable

- This may produce turbulence
- They can be driven by blast waves or flow

In supernova remnants

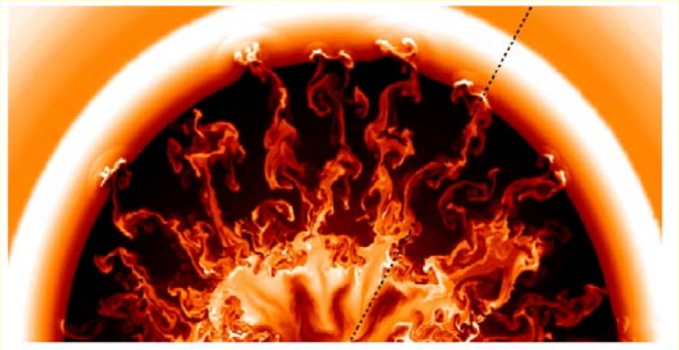


Chevalier, et al. ApJ <u>392</u>, 118 (1992)



Cass. A

and supernovae



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

These systems can be globally hydro

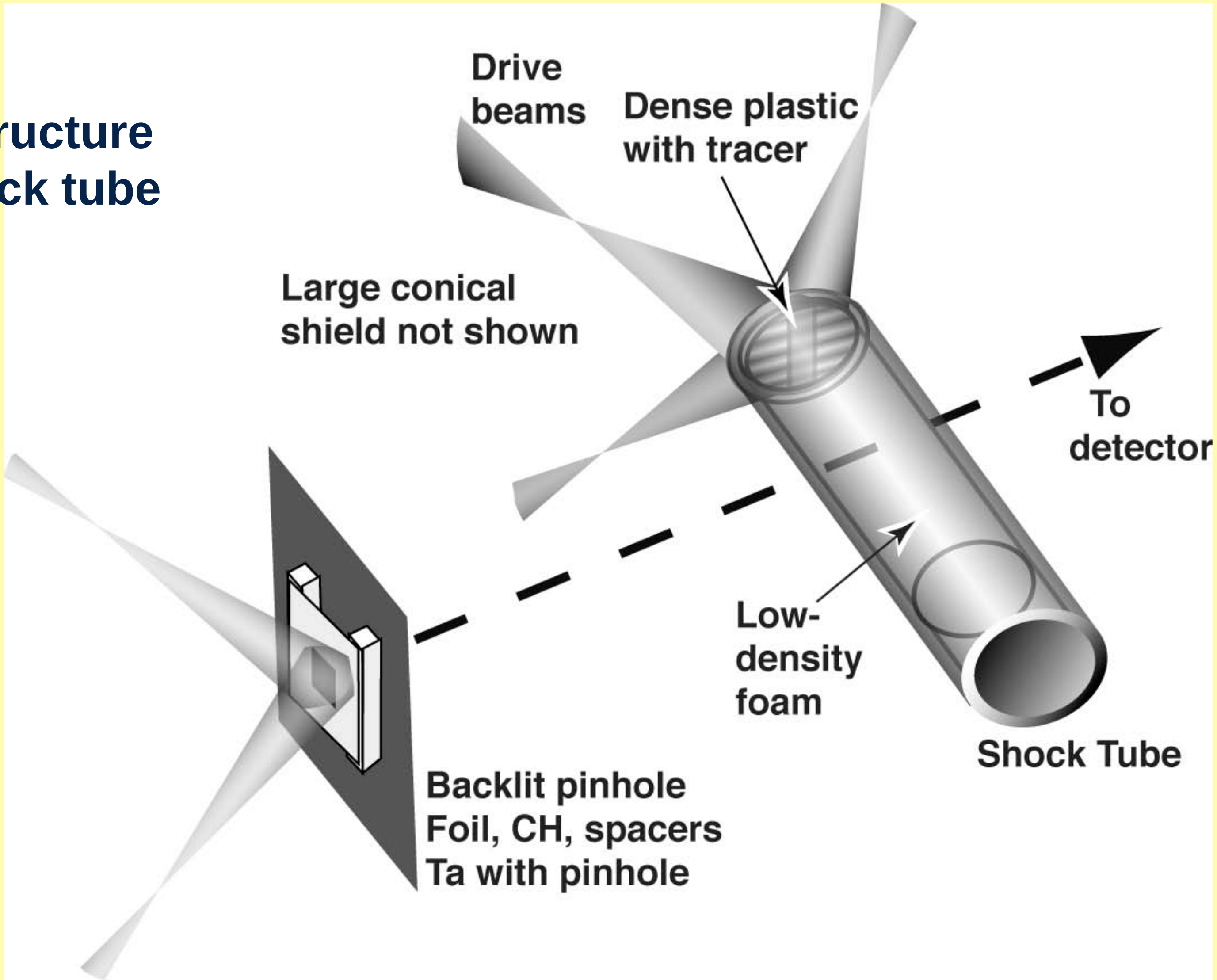
- **System must be highly collisional, $\lambda_c << r$**
- **Viscosity negligible, Re >> 1**
- **Heat conduction negligible, Pe >> 1**
- **Radiation flux negligible, Pe_γ >>1 or τ_{BB}/τ >> 1**
- **Gravitational and magnetic forces negligible**

	SN	lab
h/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	…
τ_{BB}/τ	…	580

Ryutov et al. ApJ., 518, 821 (1999)

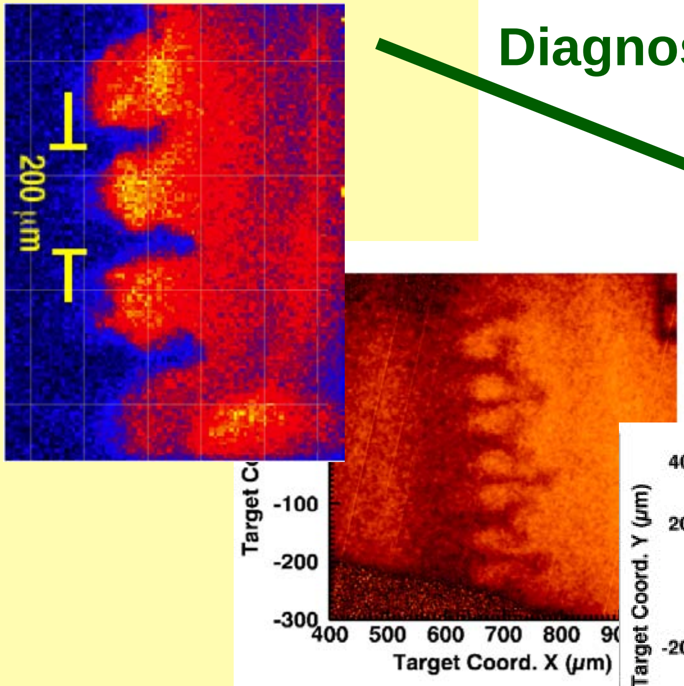
We often create plasmas in shock tubes to study such hydrodynamic processes

- **Precision structure inside a shock tube**



Well scaled experiments have produced variable spike shape and penetration

~ 1995

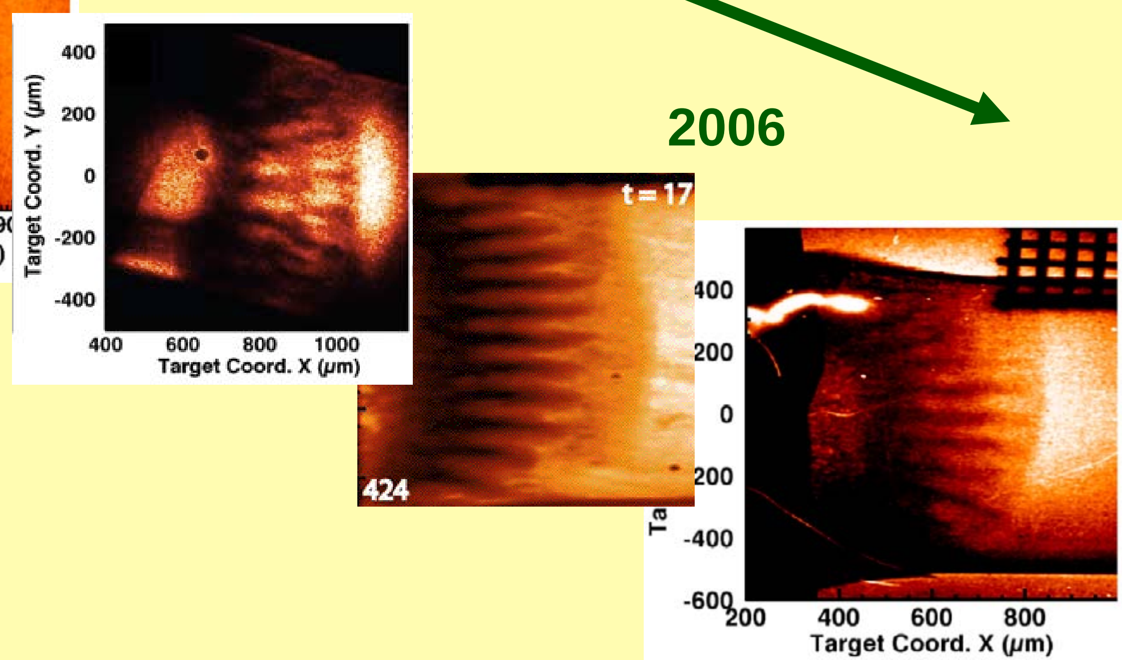


Diagnostic improvements

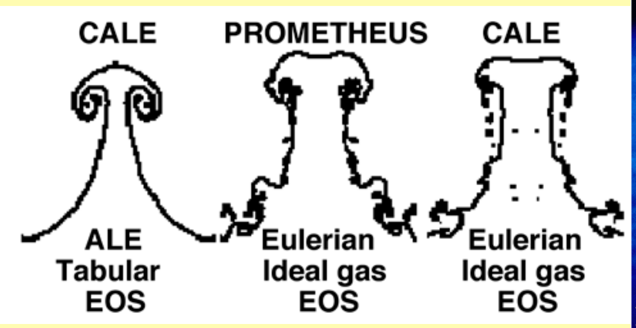
and

better, more complex targets

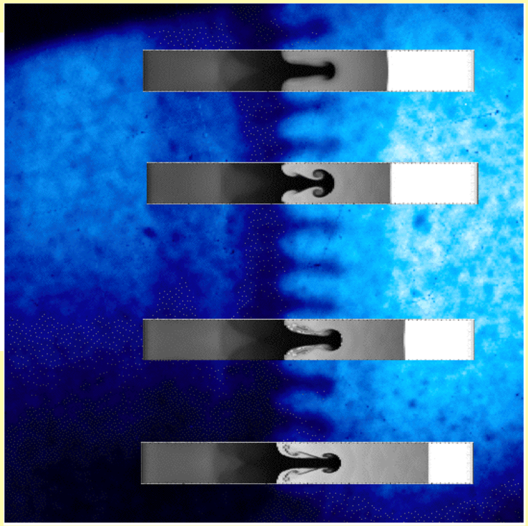
2006



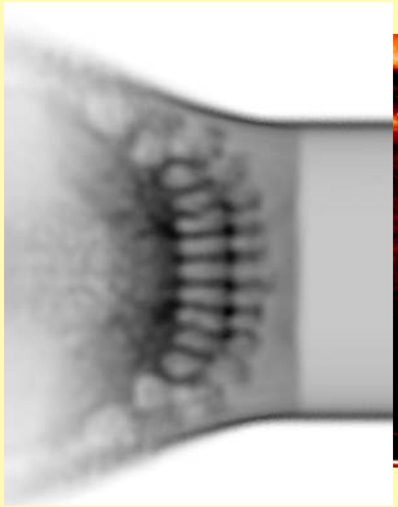
Simulations also see variable spike shape and penetration



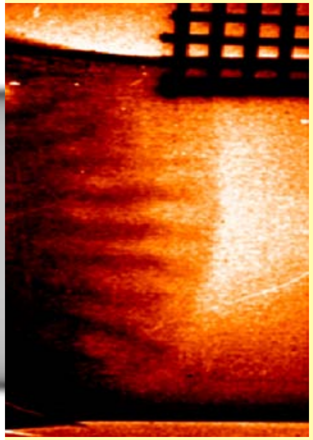
Credit: Jave Kane



Credit: Aaron Miles



Credit: Nathan Hearn



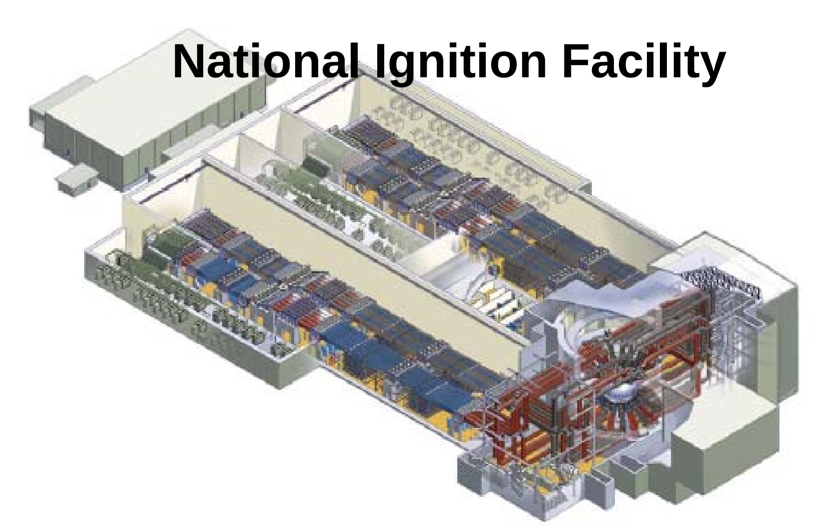
Credit: Carolyn Kuranz

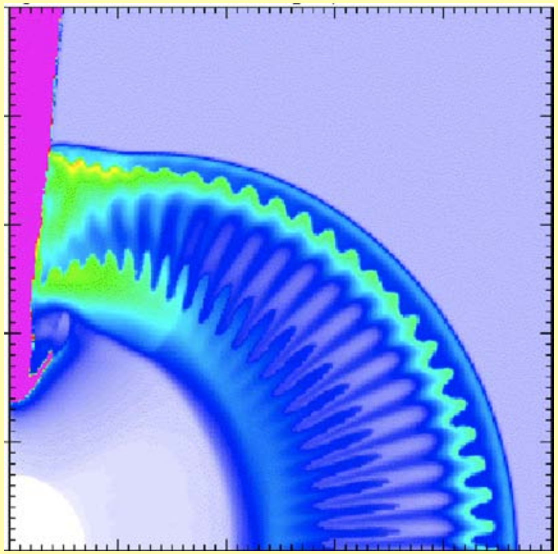
In some experimental cases the spikes reach the shock, which would explain the astrophysical results

Kuranz, ApJ 2009, Phys. Plasmas 2009, Phys. Plasmas 2010
Miles, Phys. Plasmas 2004, ApJ 2009

We have designed a diverging multi-interface experiment for the National Ignition Facility

- **Addresses**
  - The 3D behavior of a diverging explosion
  - With multiple, structured interfaces
  - Too complex, too high Reynolds number for complete computer simulation
  - NIF can do a very relevant experiment

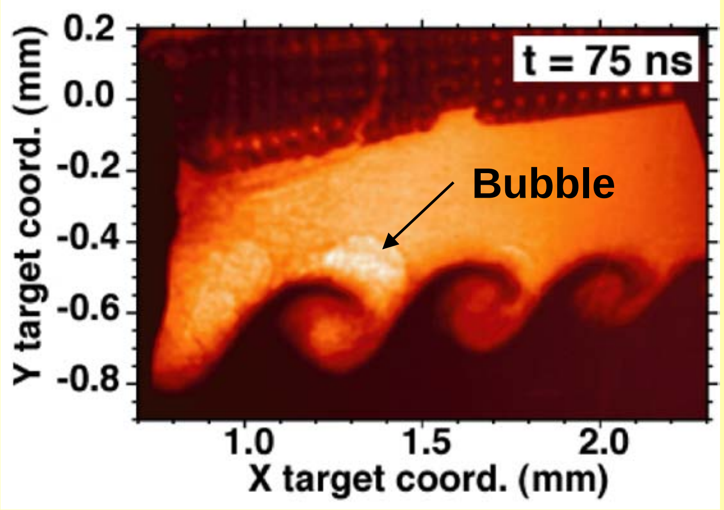


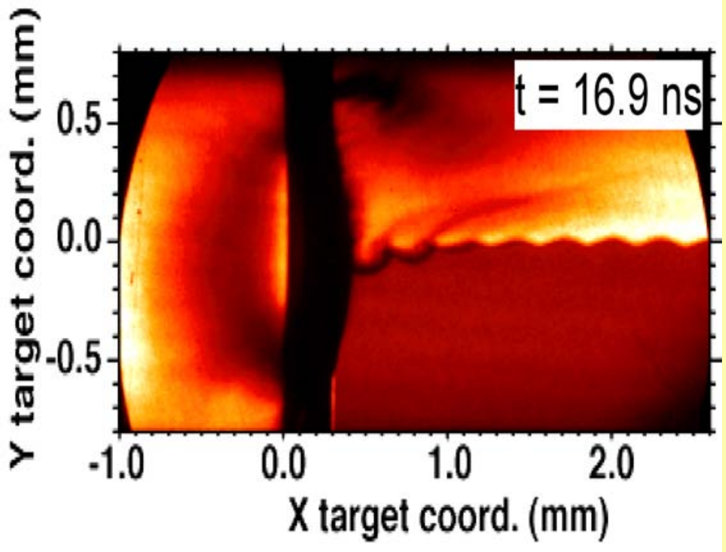


Michigan design calculation for NIF experiment (using CALE)
M.J. Grosskopf, ApSS 2009

We also have initial designs of a Rayleigh-Taylor-driven turbulence experiment

We have begun to explore both subsonic and supersonic Kelvin-Helmholtz (KH)



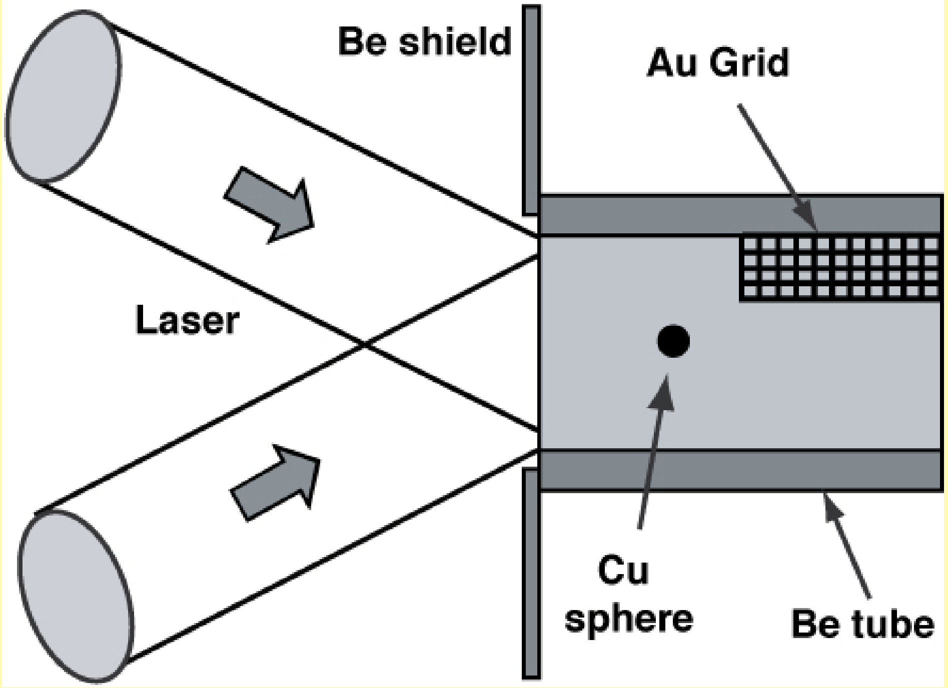


- **Omega experiment**
  - Subsonic flow
  - Classic KH through apparent onset of turbulence
  - Mysterious bubble might be related to equation of state
- **Nike experiment**
  - Supersonic flow
  - Shape of shocks in flow is sensitive to Mach number

Harding, Phys. Rev. Lett. 2009
Hurricane, Phys. Plasmas 2009
Harding, Phys. Plasmas 2010

Other researchers have pursued clump destruction by blast waves

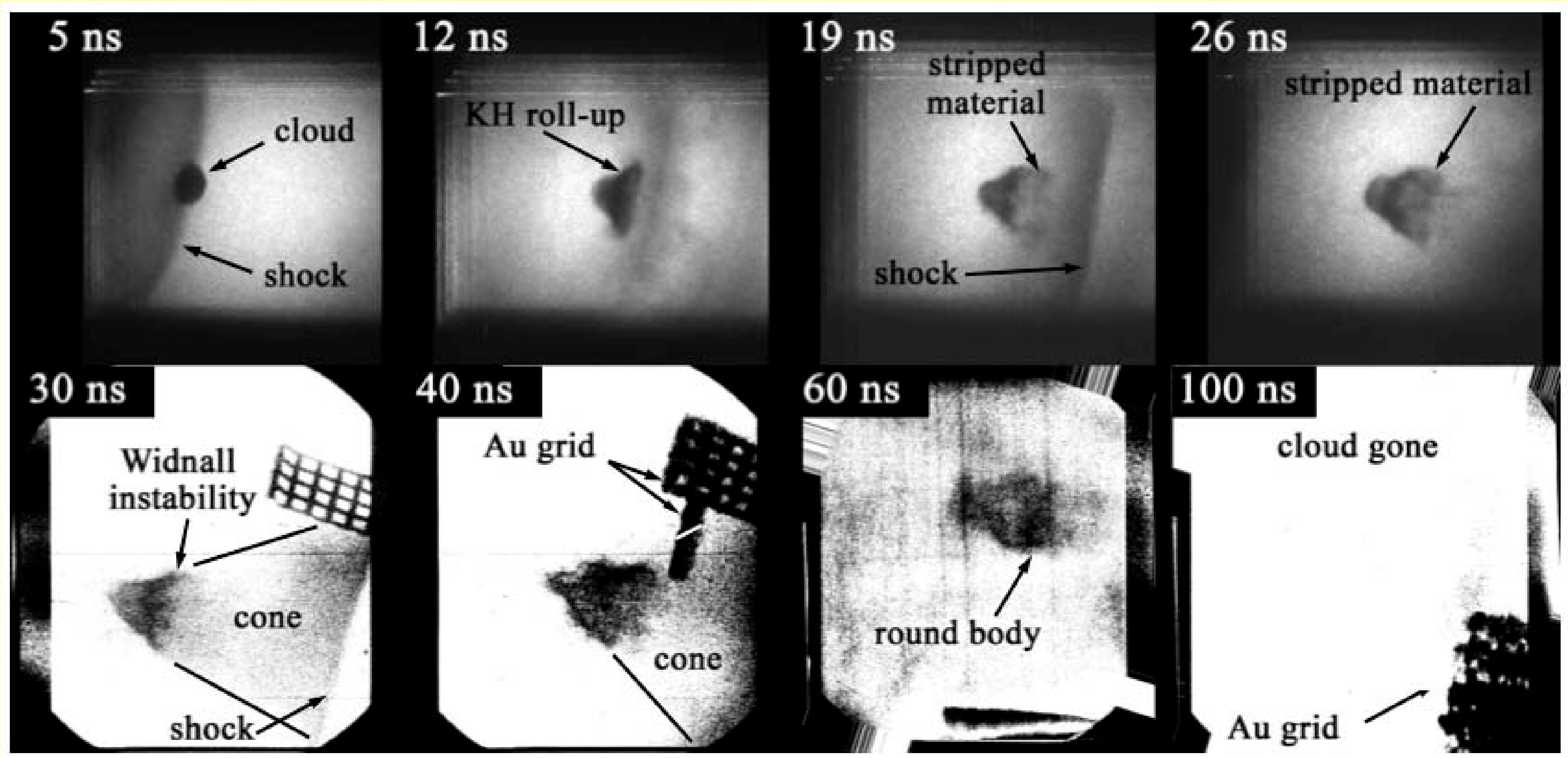
- **The experiment involves blast-wave-driven mass stripping from a sphere**
- **Early experiments used Cu in plastic; later experiments used Al in foam**



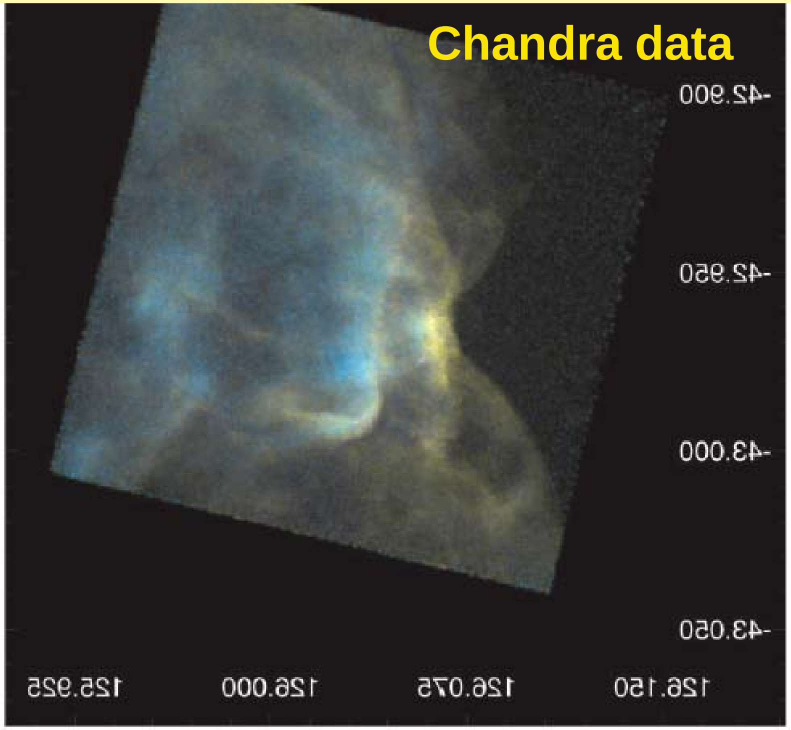
Robey, Phys. Rev. Lett 2002
Klein, ApJ 2003

The cloud is crushed, stripped, and destroyed

- **Hansen et al., ApJ 2007, Phys. Plasmas 2007**



This work has had direct applicaton to astrophysical data

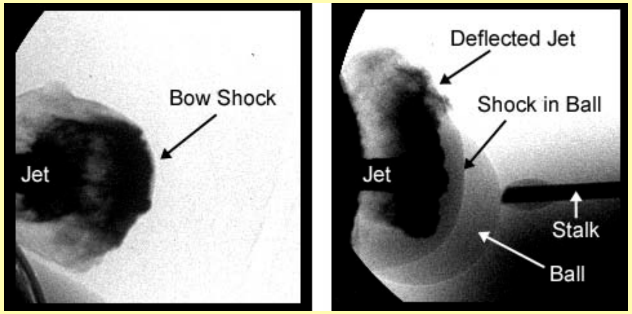


Lab Experiment

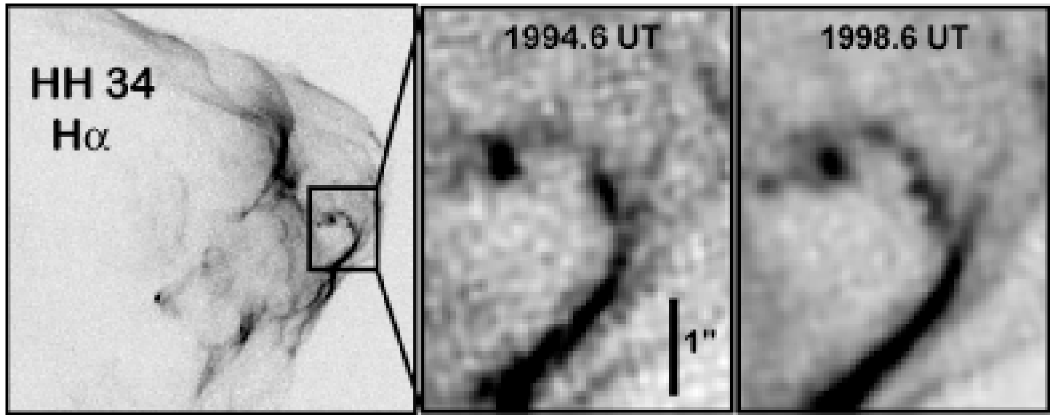
Klein et al., ApJS 2007
Robey et al., PRL 2002

- **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)**

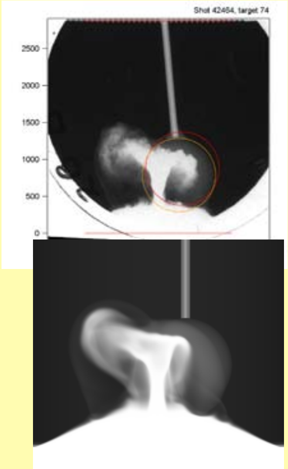
Project led by Patrick Hartigan to study bow shocks and jets using experiments, simulations, and observations



Laser experiment of deflected jet and bow shock



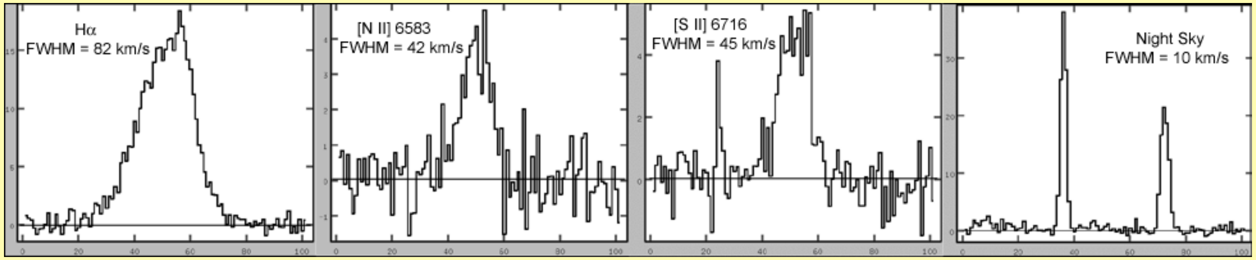
Hubble Space Telescope project to obtain 3rd epoch to follow instabilities, clumps, and shear



Data

RAGE Code

Numerical Simulations



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

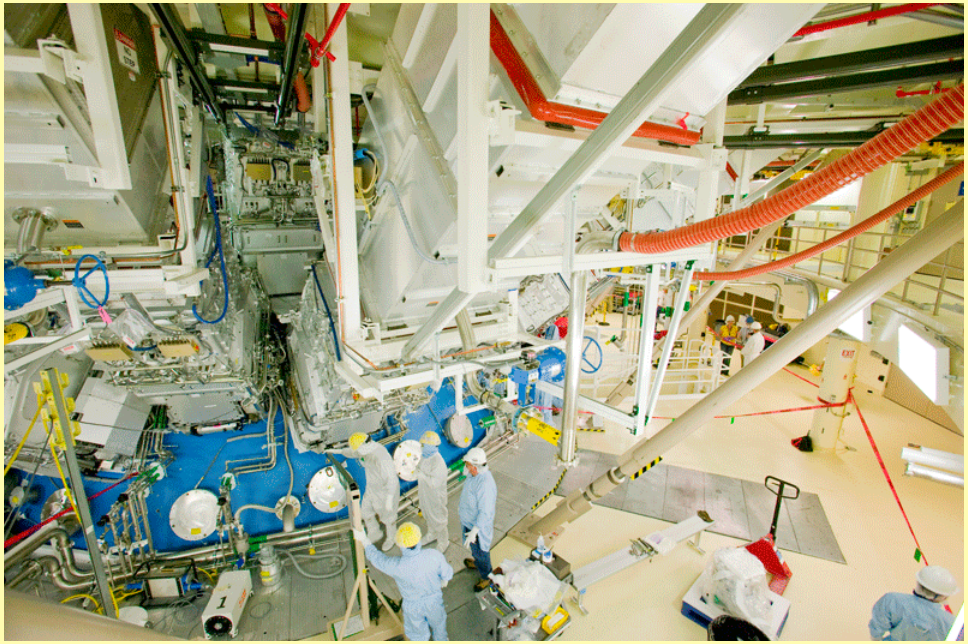
see Hartigan, et al. ApJ 2009

Our experiments at the National Ignition Facility unify our two lines of inquiry

- **Hydrodynamic instabilities**
  - Rayleigh Taylor
  - As in supernovae

- **Radiation hydrodynamics**
  - Radiative shocks
  - As in Red Giant supernova remnants

NIF Target Bay

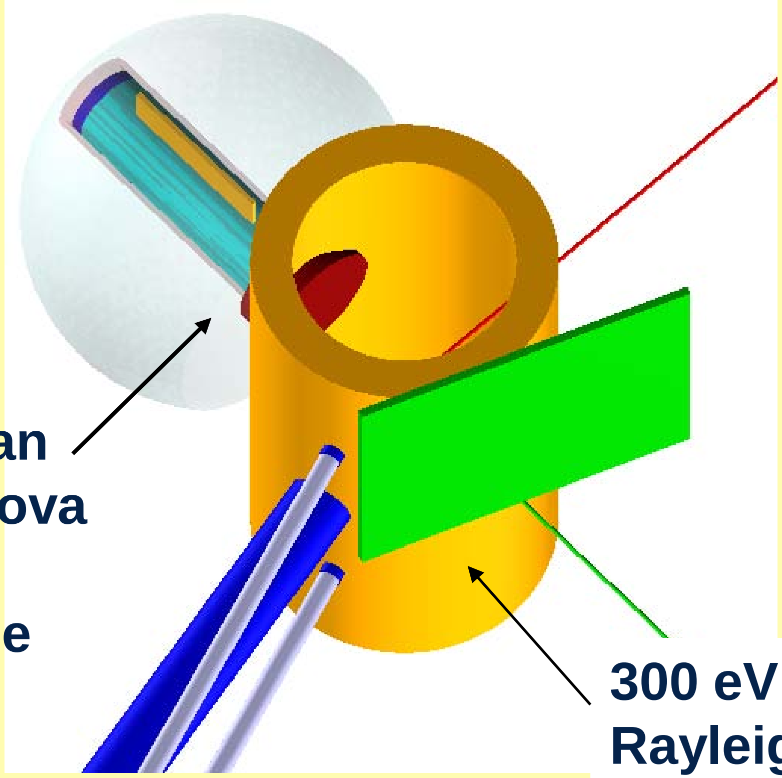


Led by Carolyn Kuranz

Depend on very extensive LLNL involvement by Hye-Sook Park and many others.

We use a NIF hohlraum to drive one of our target packages

- A hydrodynamically unstable system altered by radiation hydrodynamics



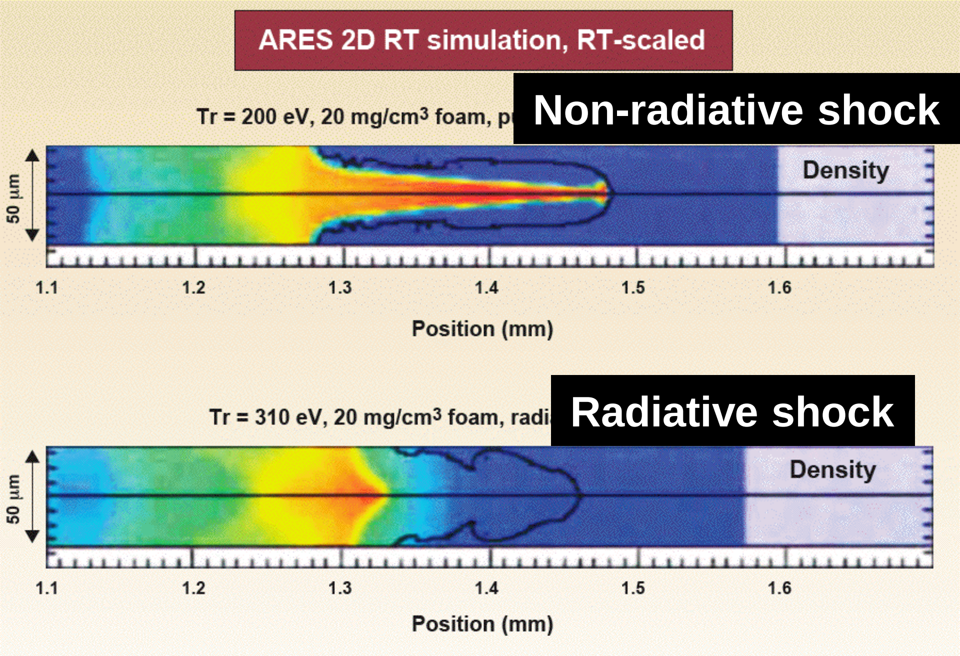
Michigan supernova target package

300 eV hohlraum drives Rayleigh Taylor instability behind radiative shock

The stronger drive produces a radiative shock that changes the hydrodynamic instability

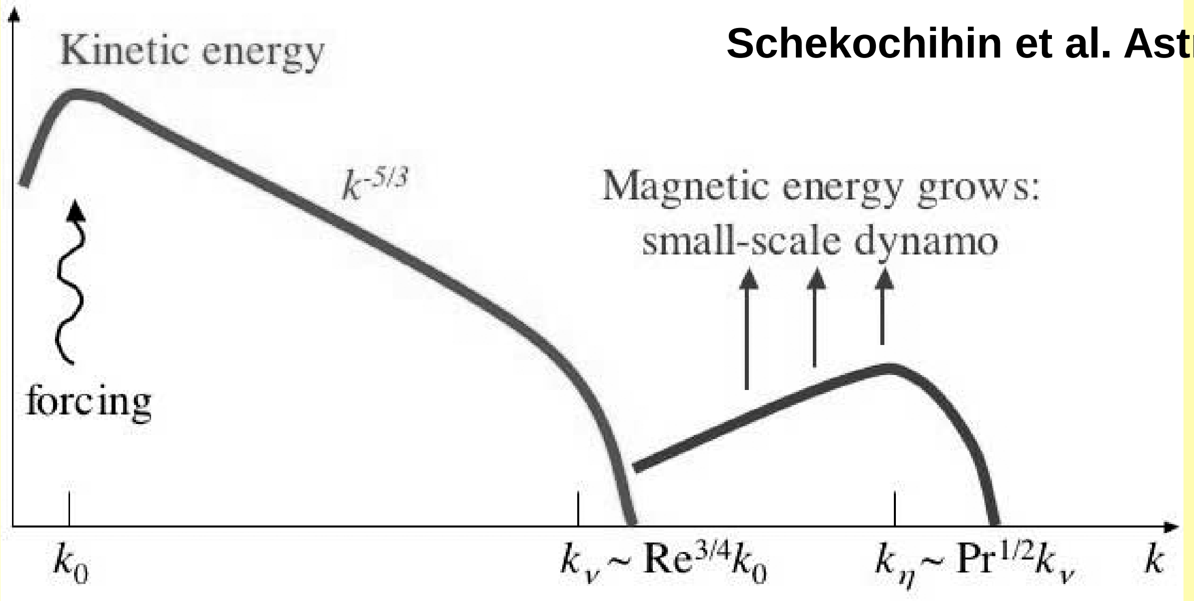
- **Two shots to date for technique development needed by many programs**
  - Backlit pinhole radiography
  - 300 eV, low-stagnation hohlraum
- **We are on the NIF schedule this next year for integrated system demonstration and physics**

Two simulations having the same linear Rayleigh Taylor growth



Connecting more strongly here: we have done some design work relevant to the turbulent dynamo

- **Astrophysical systems:** ***L*** **>>** d_o **>>** d_ν **>>** d_η **;** ***Re*** **>> 1,** Pr_m **>> 1**

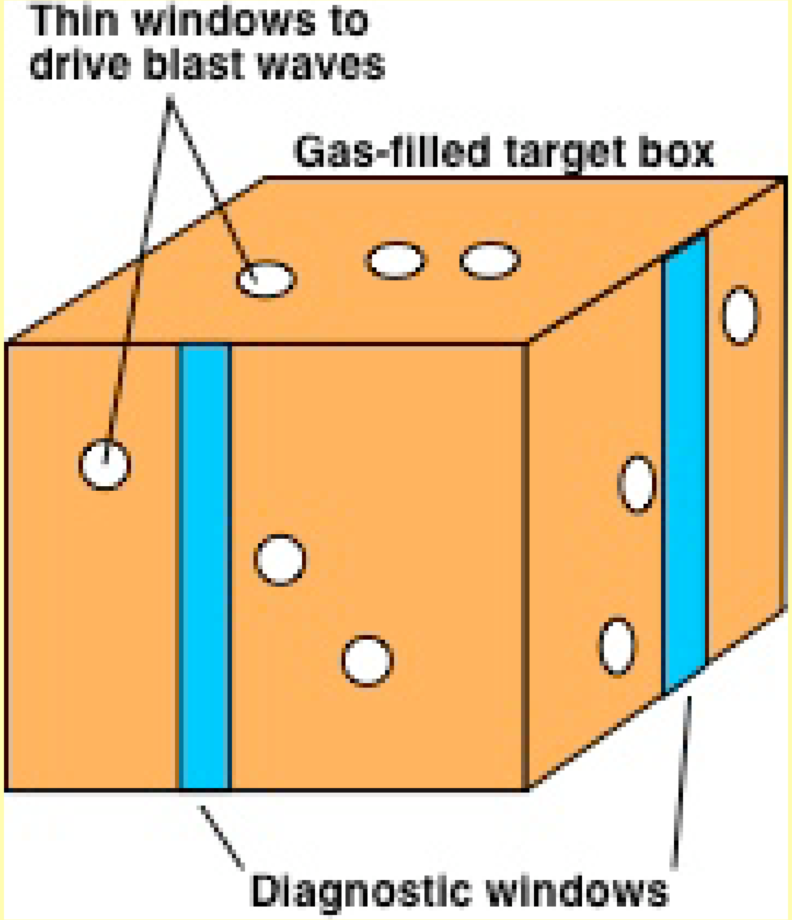


Schekochihin et al. Astrophys. J 2004

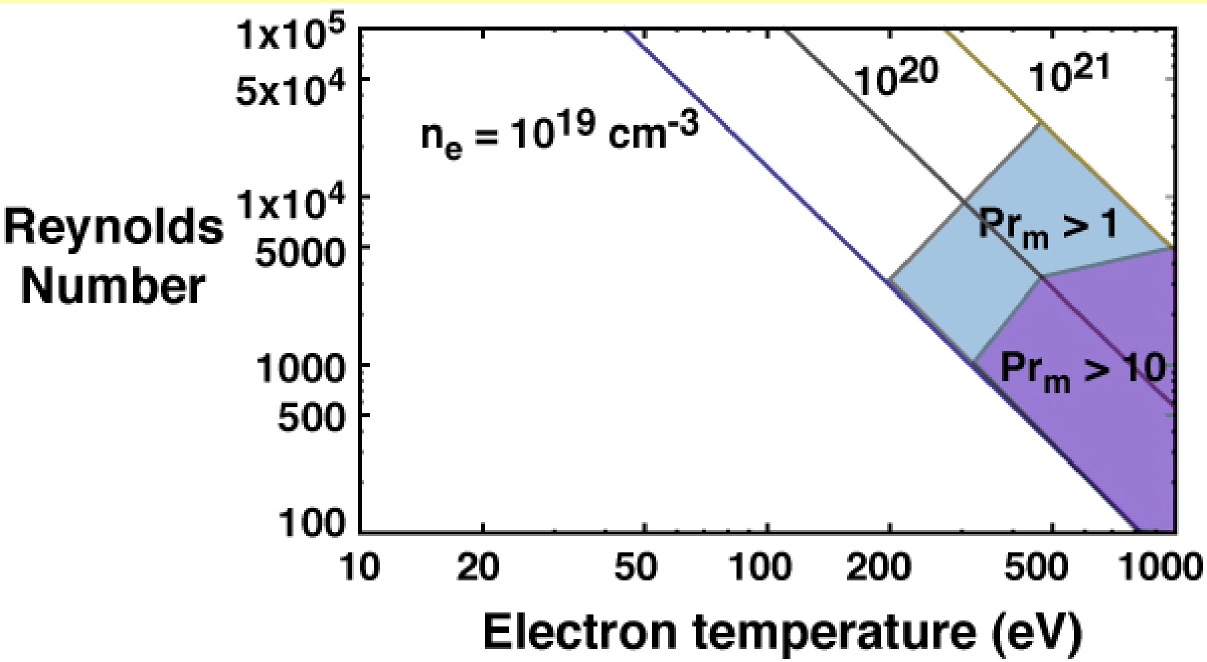
- **Simulation studies:** ***Re*** **>> 1 and** Pr_m **~ 1 or** Pr_m **>> 1 and** ***Re*** **~ 1**

The question here: what can laser experiments do?

Schematically, the laser target is a box with thin windows to be exploded by lasers



There is a regime worth shooting for



Kinematic viscosity

ν

Kinematic magnetic diffusivity

η

Reynolds number

$Re = UL/\nu$

Magnetic Prandtl number

$Pr_m = \nu / \eta$

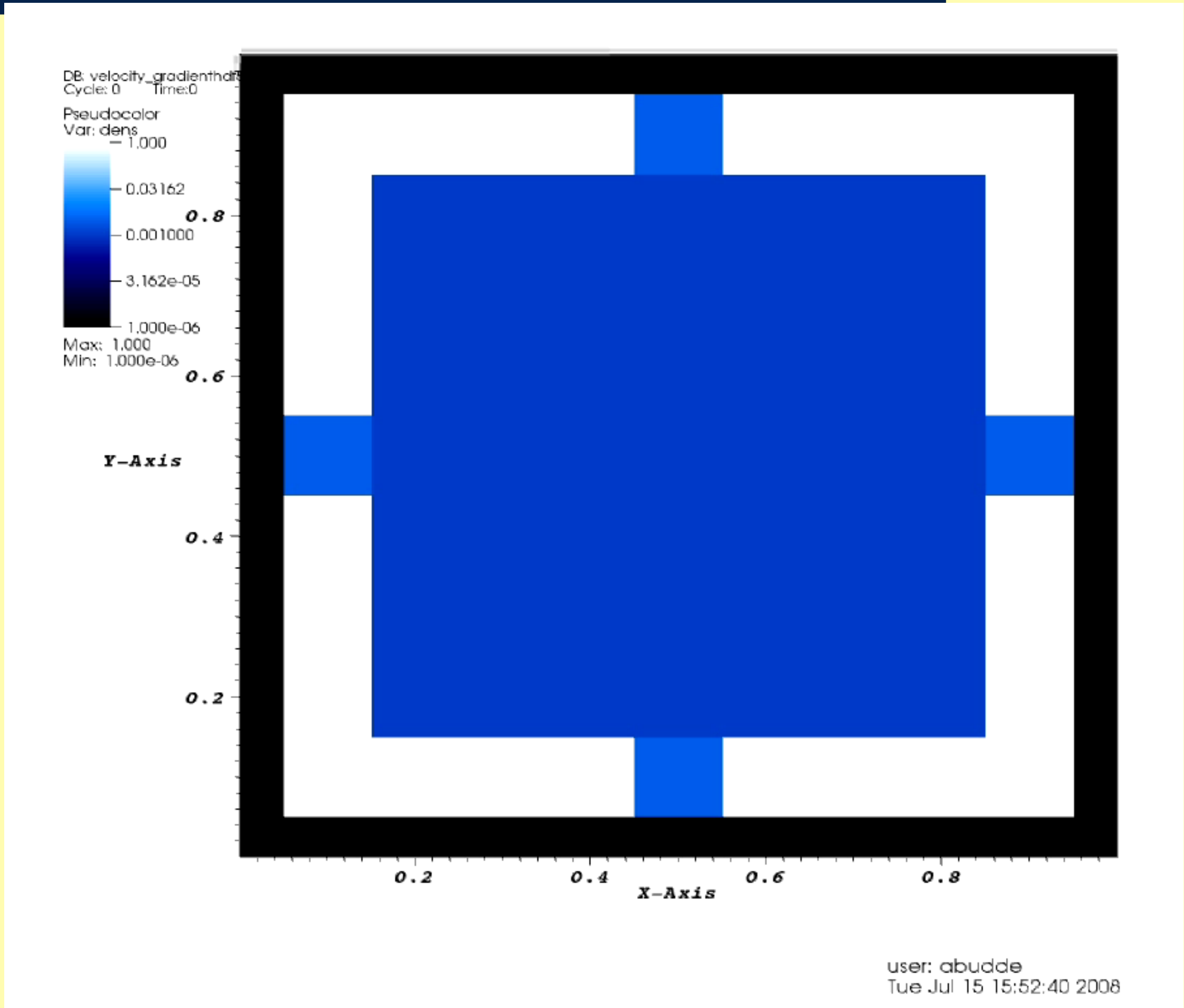
Magnetic Reynolds number

$R_m = UL/\eta = Re\ Pr_m$

- ***Re*** **could be made higher by using higher Z plasma, but** Pr_m **would be very small**

Multi-dimensional simulations will be key to design an actual experiment

- **Preliminary work with 2D FLASH**



Laser experiments can study instabilities and (probably) turbulence in shocked media

- **Past, present and pending compressible instability work**
  - Rayleigh Taylor driven by blast waves
  - Kelvin Helmholtz
  - Clump destruction
  - Jet-cloud interactions

- **More preliminary and speculative:**
  - Plausible parameters can produce *Re* > 1,000 and Pr_m ~ 10
    - Adequate to explore turbulent dynamo
  - Purely hydrodynamic experiments could have larger *Re*
    - Better to explore evolution of highly turbulent state