Creating Astrophysical Conditions in the Laboratory

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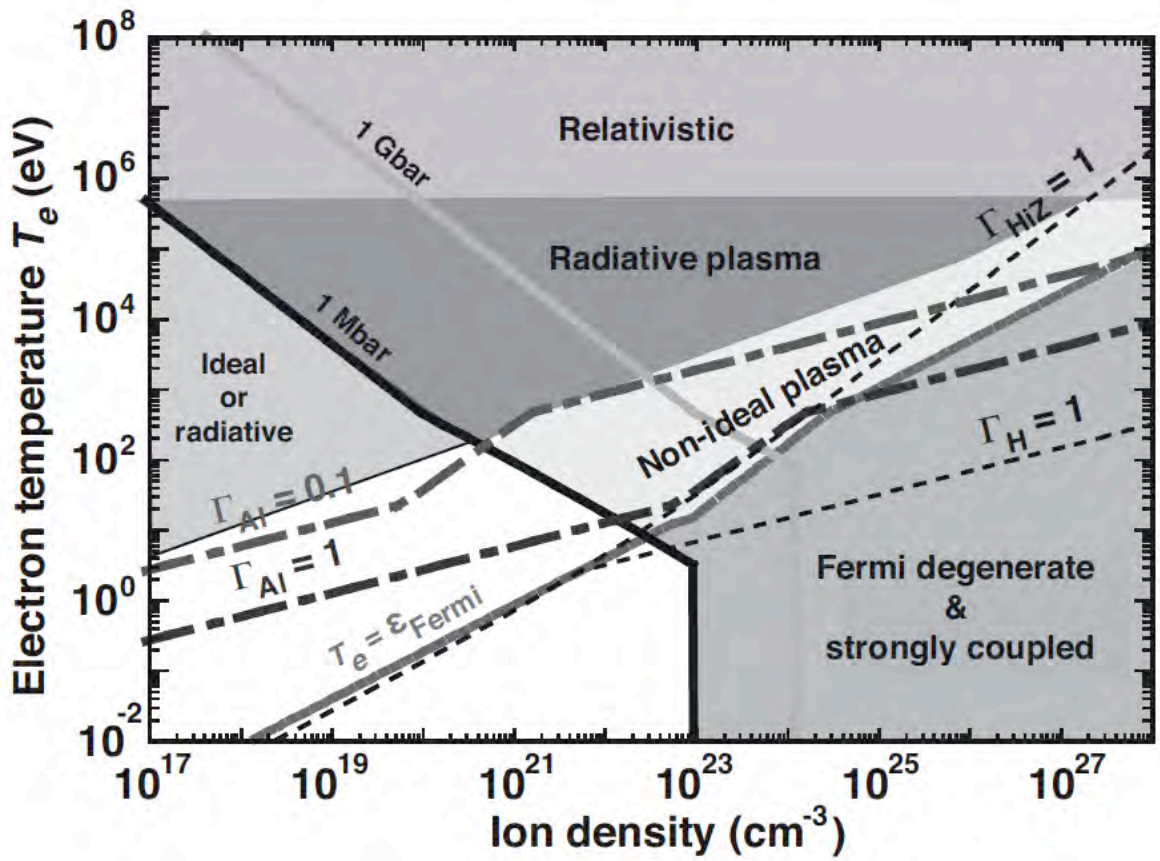
Talk Outline

- Definition of high-energy-density physics and high-energy-density laboratory astrophysics
- Mini tutorial on scaling an experiment to an astrophysical systems
- Examples of laboratory astrophysics experiments

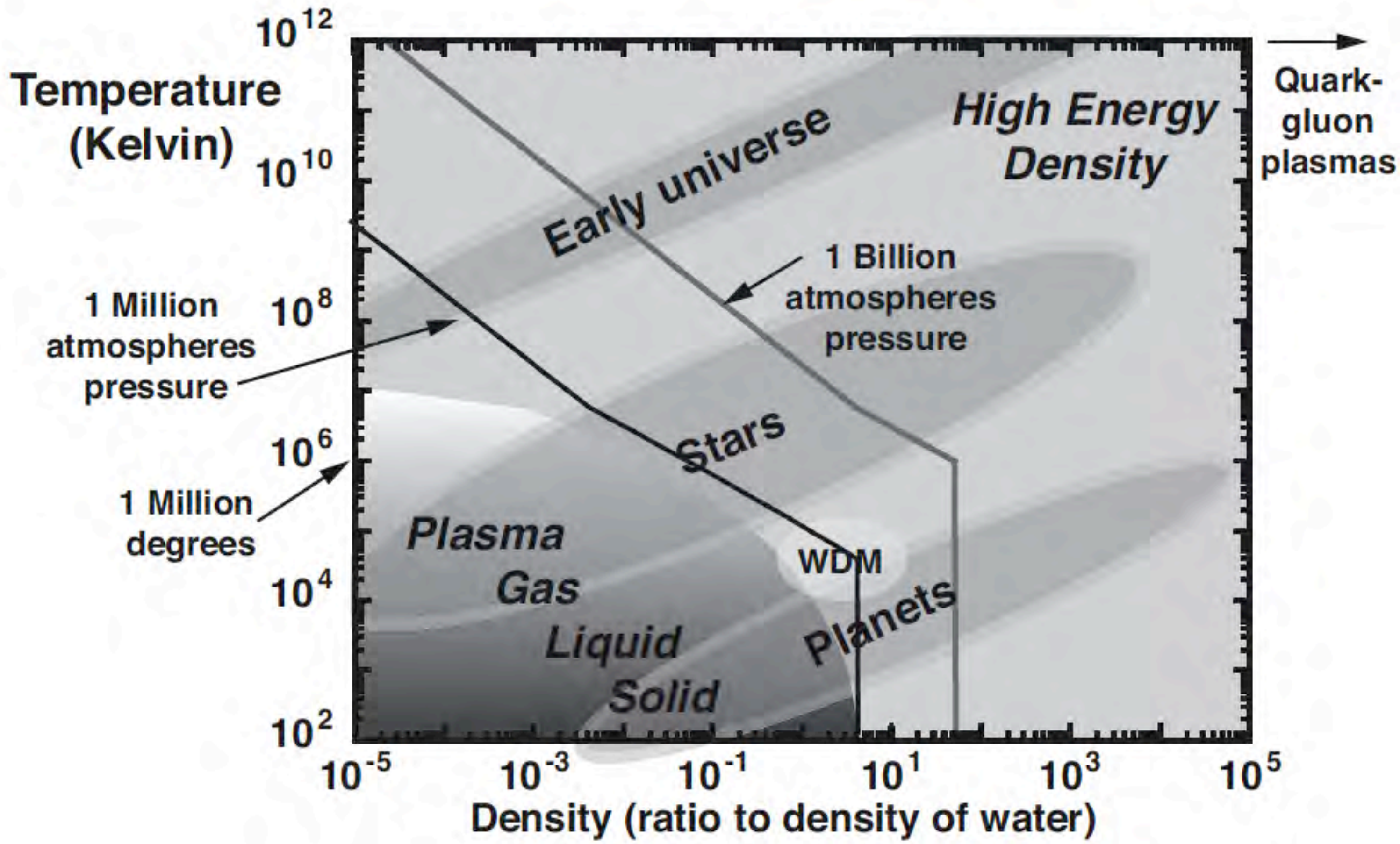
High-energy-density (HED) physics is the study of systems with pressures > 1 Mbar

1 Mbar = 0.1 Tpascal = 10^{12} dynes/cm^2 = 10^6 atm



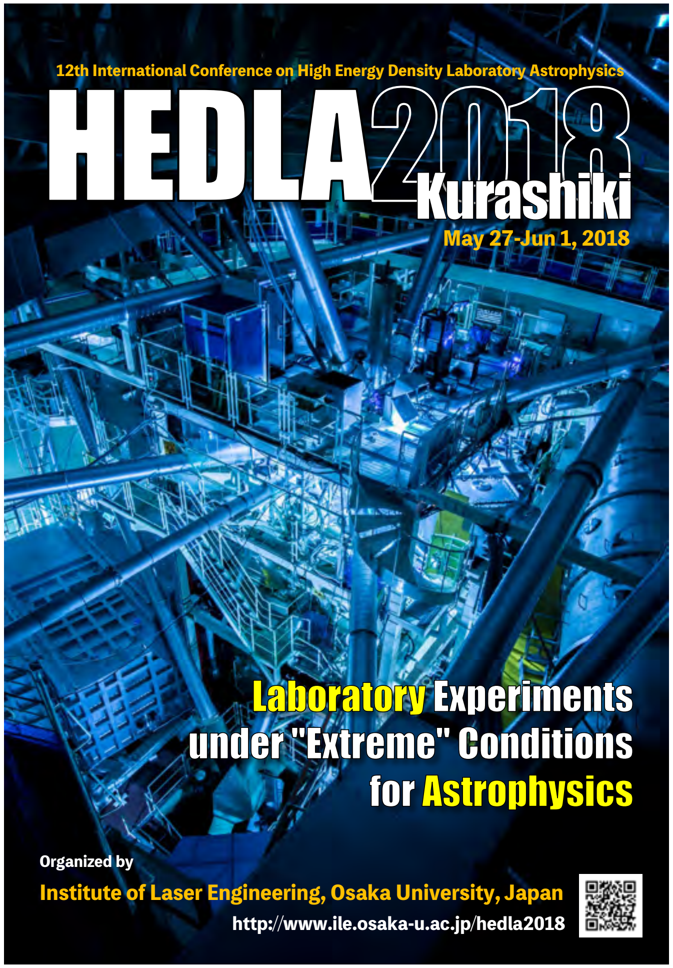
RP Drake, High-Energy-Density Physics: Foundations of Inertial Fusion and Experimental astrophysics

There is significant overlap with HED and astrophysics



RP Drake, High-Energy-Density Physics: Foundations of Inertial Fusion and Experimental astrophysics

HED Laboratory Astrophysics is a young, but growing field



- HEDLA started in 1996 focused on hydrodynamics
- Now includes planetary interiors, equation of state, atomic processes, radiation transport, photoionization, stellar opacity, magnetic reconnection, particle acceleration, collisionless plasmas, turbulent dynamos, nuclear astrophysics, pair plasmas…

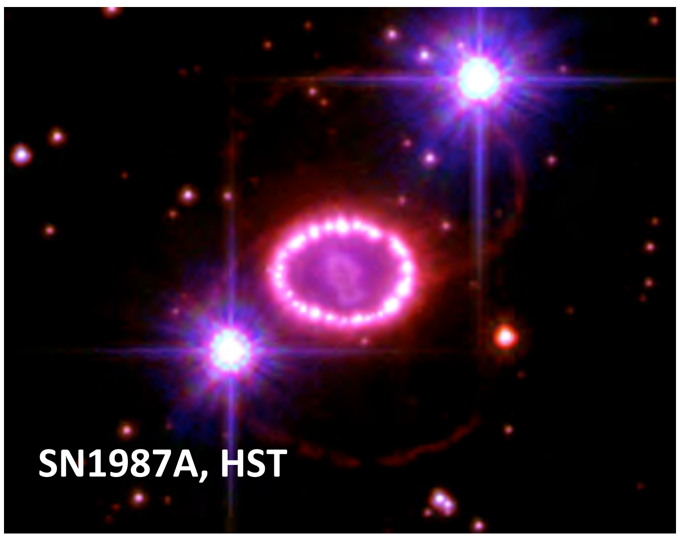
How do I scale an astrophysical system to a laboratory experiment?*

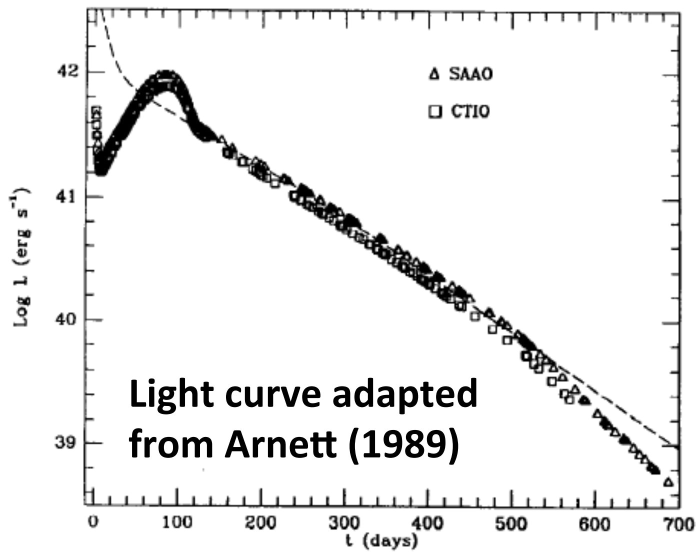
1. Can both systems validly be described by the same equations?
2. Can the two systems have good Ryutov scaling?
3. Can the two systems have good scaling with regard to the dynamics of the process of interest?

***Adapted from High-Energy-Density Physics: Foundations of Inertial Fusion and Experimental astrophysics**
See also Ryutov et al. ApJ., 518, 821 (1999)

Scaled laboratory experiments must be motivated by a specific astrophysical process

Can hydrodynamic instabilities explain the light curve of SN1987A?





Observations of ^{56}Co and ^{56}Ni were sooner than predicted and hydrodynamic mixing may explain the discrepancy

1. Can both systems validly be described by the same equations?

Hydrodynamic fluids described by single-fluid Euler Equations

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

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

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

Additional terms for radiative or magnetized systems can also be included

If the equations remain invariant under the following transformation,

$$r_{\text{astro}} = a r_{\text{expt}} \qquad P_{\text{astro}} = c P_{\text{expt}}$$

$$\rho_{\text{astro}} = b \rho_{\text{expt}} \qquad t_{\text{astro}} = a\sqrt{\frac{b}{c}}\, t_{\text{expt}}$$

then there is direct correspondence between the two systems

For the specific example, this implies characteristic time and length scales

	SN1987A	Laboratory experiment
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

2. Can the two systems have good Ryutov scaling?

Spatial relations for velocity, pressure, and density must be the scaled

$$\mathbf{v}_{t=t_o} = \mathrm{v}'\,\mathbf{F}(r/h)$$

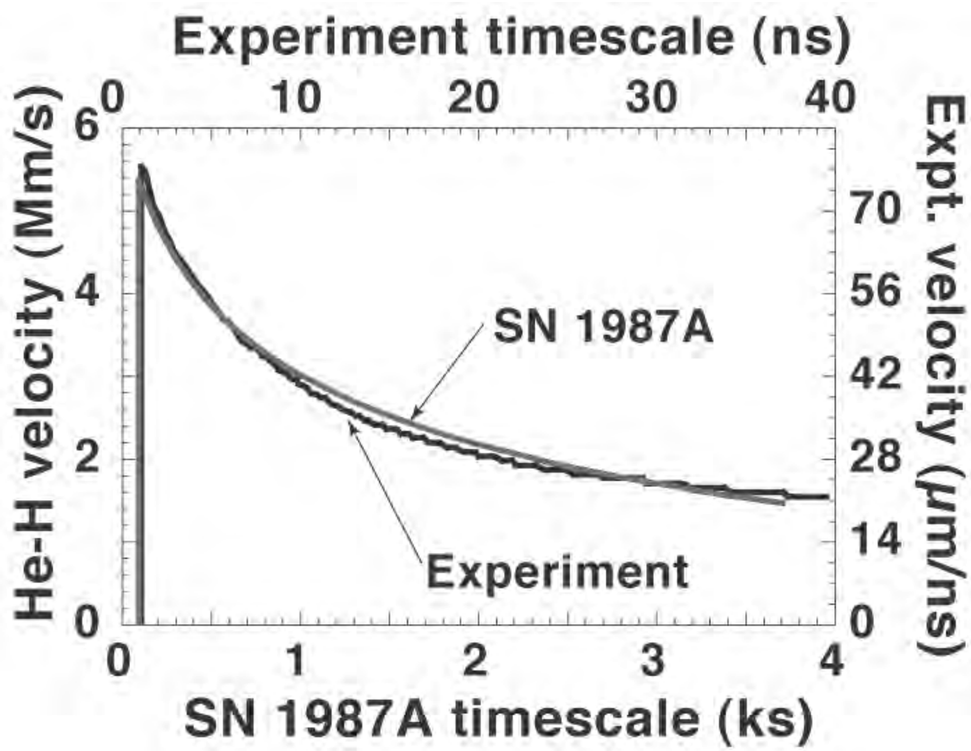
Where F(r/h), H(r/h), and G(r/h) are dimensionless functions

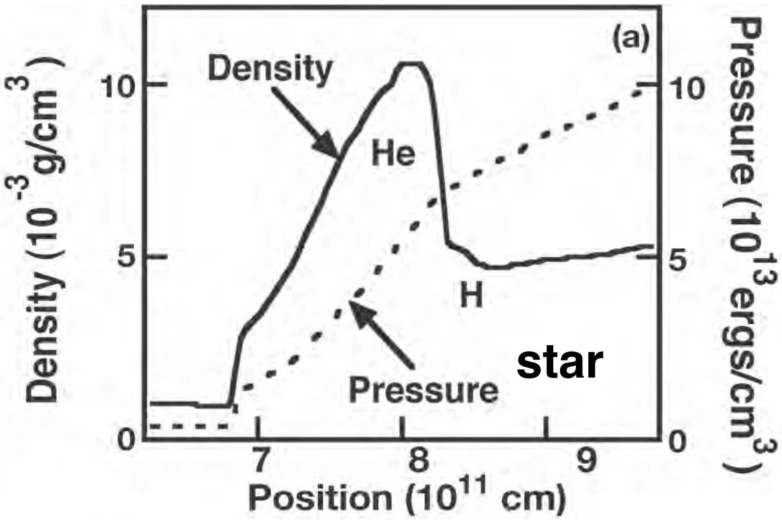
$$\rho_{t=t_o} = \rho'\,H(r/h)$$

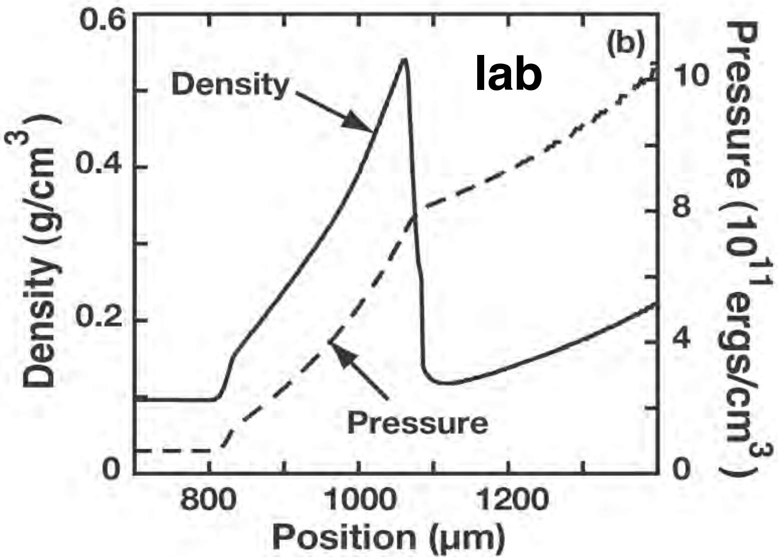
$$P_{t=t_o} = P'\,G(r/h)$$

This implies $$Ry = v'\sqrt{\frac{\rho'}{P'}}$$

1D Spatial profiles for SN1987A and laboratory experiment







3. Can the two systems have good scaling with regard to the dynamics of the process of interest?

This is determined by the dimensionless numbers key to the specific astrophysical system

For SN1987A this includes:

- **System must be highly collisional, $\lambda_c << r$**
- **Viscosity negligible, $Re >> 1$**
- **Heat conduction negligible, $Pe >> 1$**
- **Radiation flux negligible, $Pe_\gamma >> 1$**

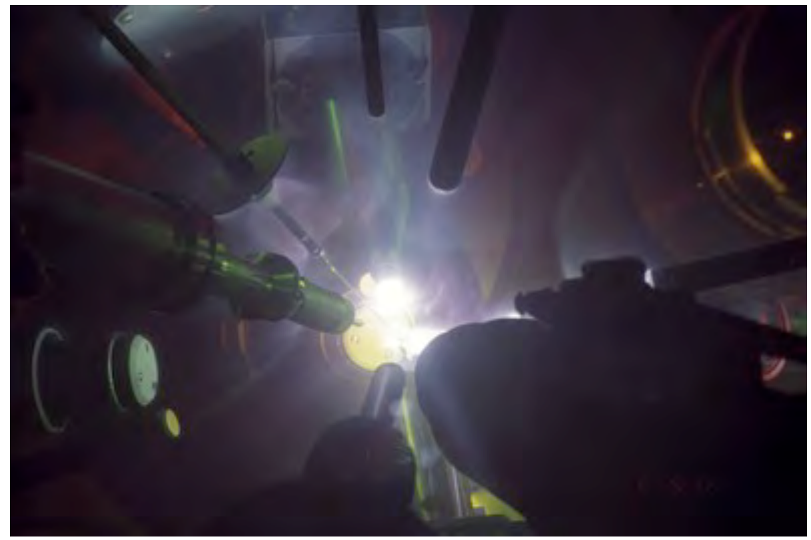
How *on Earth* do we create scaled astrophysical laboratory experiments?

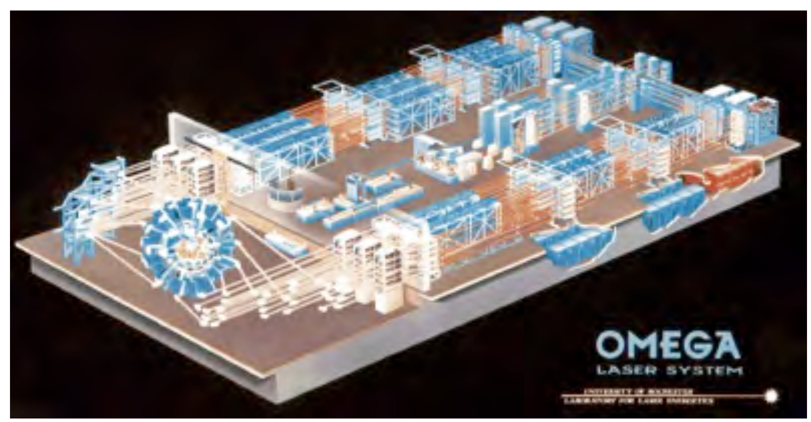
- **High-energy LASERS**
  - **Omega Laser Facility, *U. of Rochester***
  - **National Ignition Facility, *Lawrence Livermore Nat Lab***
  - **ORION Laser Facility, *UK***
  - **LMJ and LULI, *France***
  - **SGII, *China***
- **Pulsed Power machines**
  - **Z machine, *Sandia National Lab***
  - **COBRA, *Cornell University***
  - **MAIZE, *University of Michigan***
  - **Magpie, *Imperial College***

Experiments are performed at Omega laser facility

- **Ten Omega Laser beams to drive shock**
  - **~400 J each, ~4 kJ total energy**
  - **λ = .35 μm, UV light**
  - **1 ns square pulse**
- **Produce intensity of about 10^{15} W/cm^2**
- **Pressure of ~40 Mbars or 40 million atmospheres**

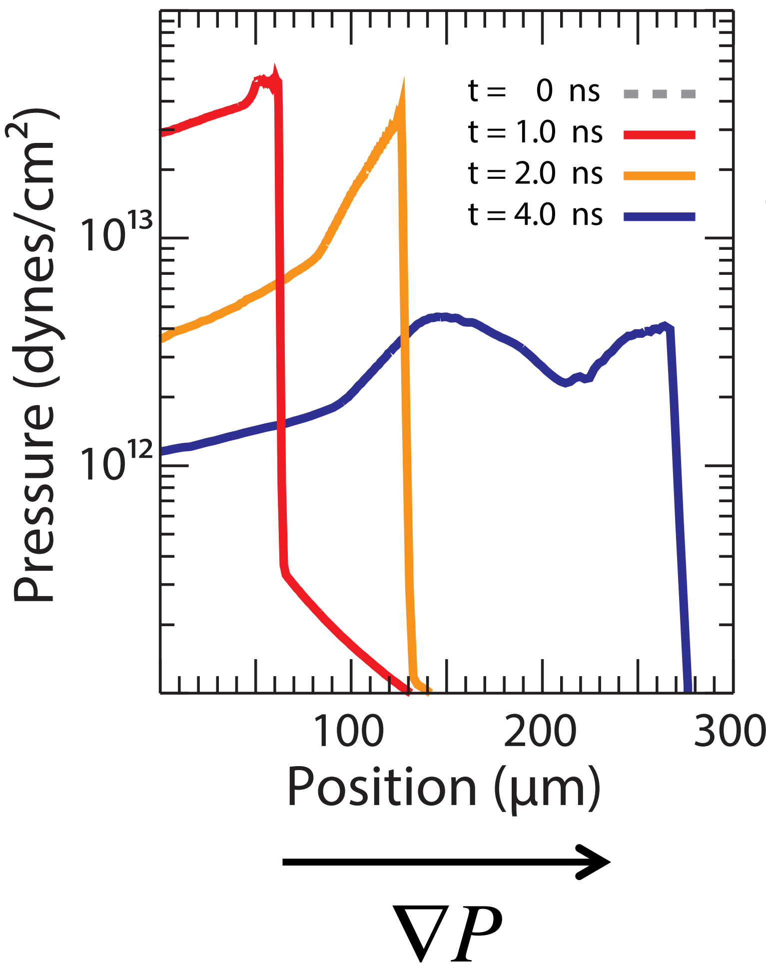
Inside the Omega target chamber

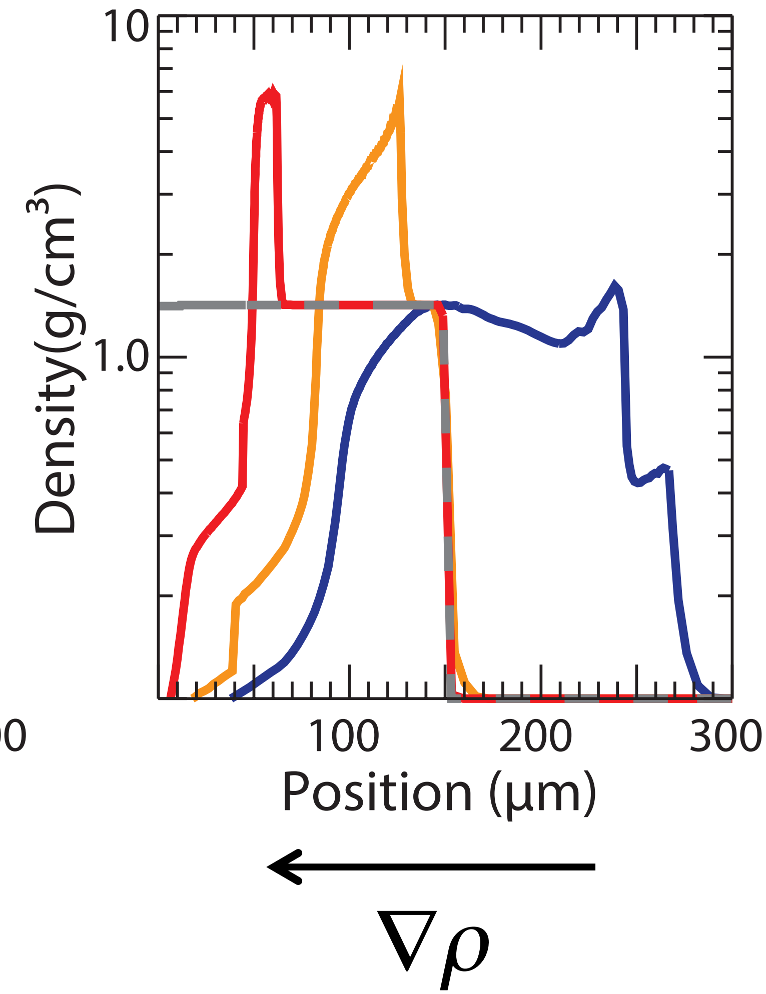




The Omega Laser System

We create a RT unstable interface under HED conditions



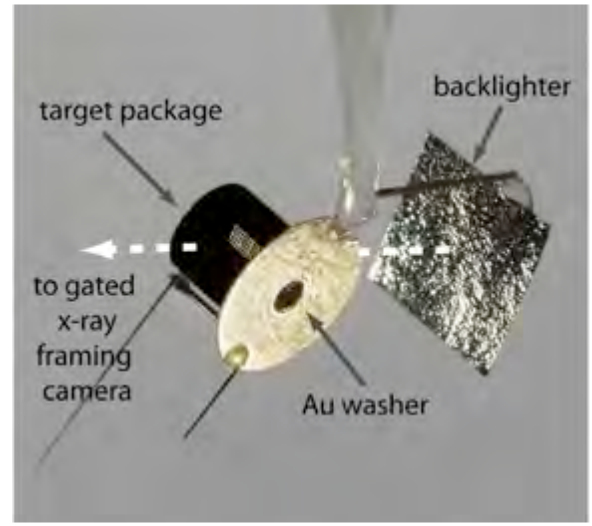


Key components of target for Rayleigh-Taylor experiment

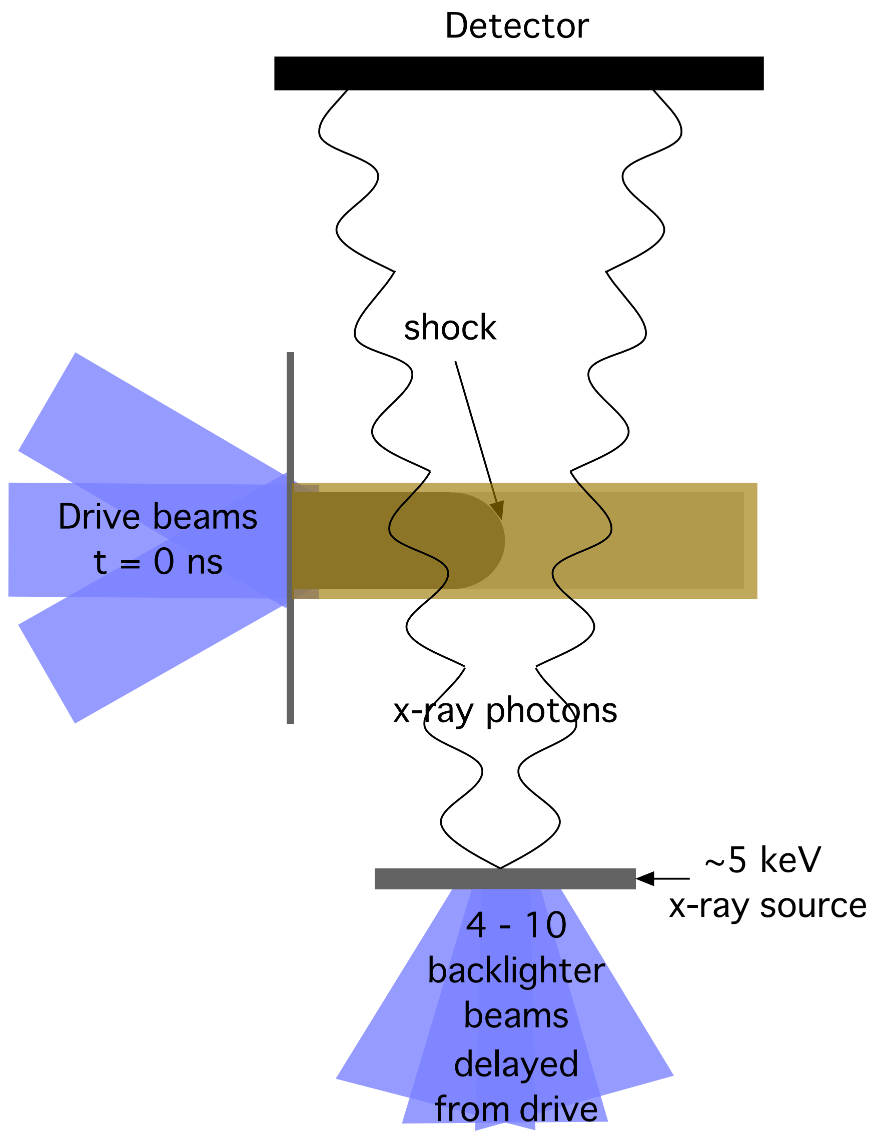
150 µm plastic (1.41 g/cc)

- **Tracer strip material: $C_{500}H_{457}Br_{43}$ (1.42 g/cc)**
- **Entire surface machined with seed perturbation**

2-3 mm carbon foam (50 - 400 mg/cc)

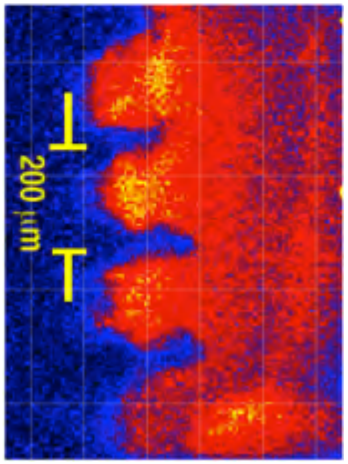


We use x-ray radiography to image the instability of the evolution

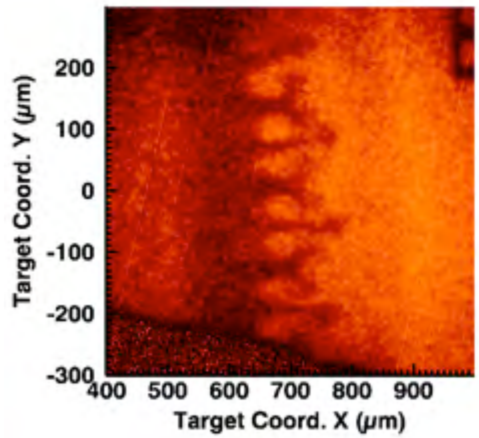


HED RT experiments have been performed on many laser facilities over the past 2 decades

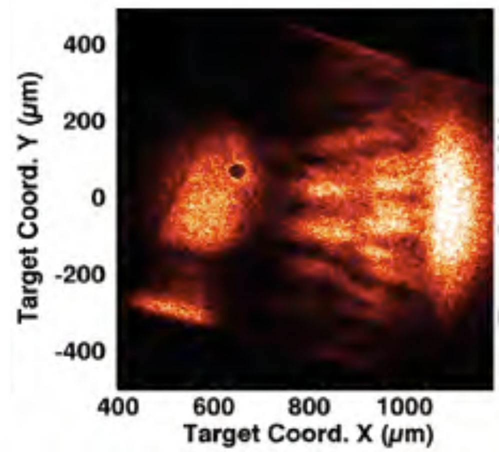
1995



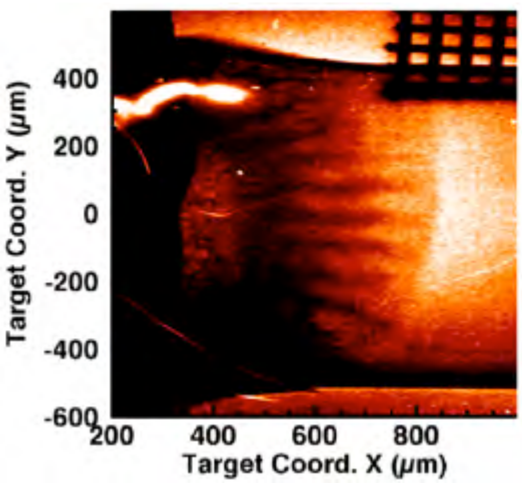
Late 90's



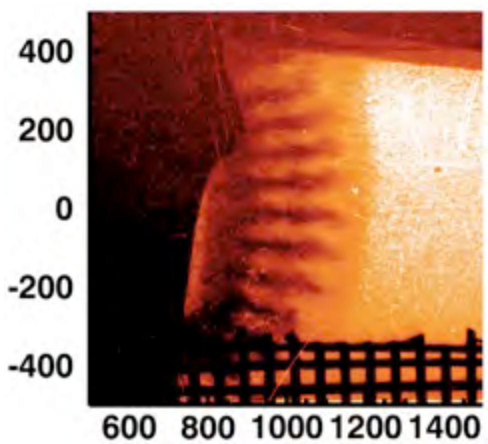
Early 2000



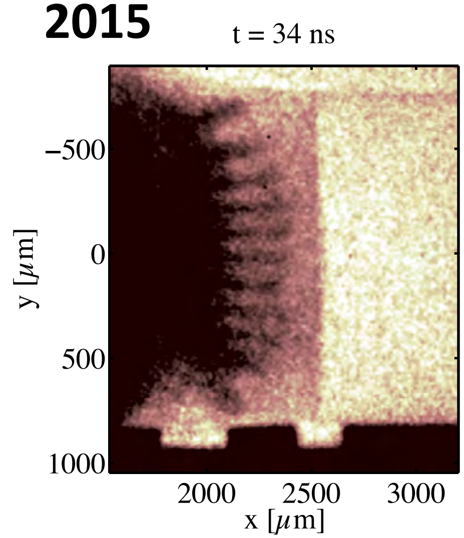
2004



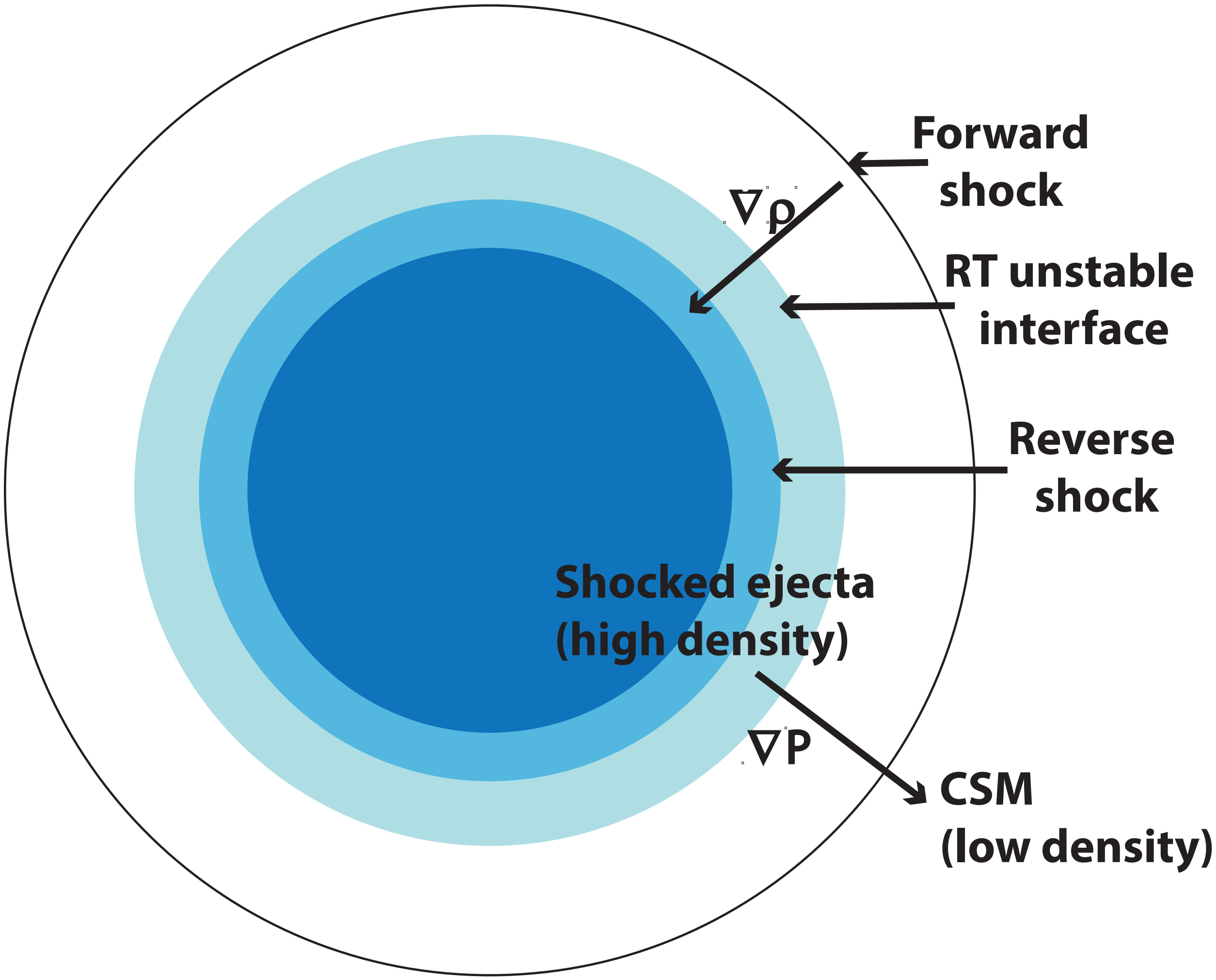
2009



2015



The study of energy transport effects on the Rayleigh-Taylor instability is relevant to SN1993J a core-collapse, red supergiant



The density profiles of the shocked ejecta and CSM are self-similar

$$\rho_{ej} = \rho_o (r_o / r)^n (t / t_o)^{(n-3)}$$

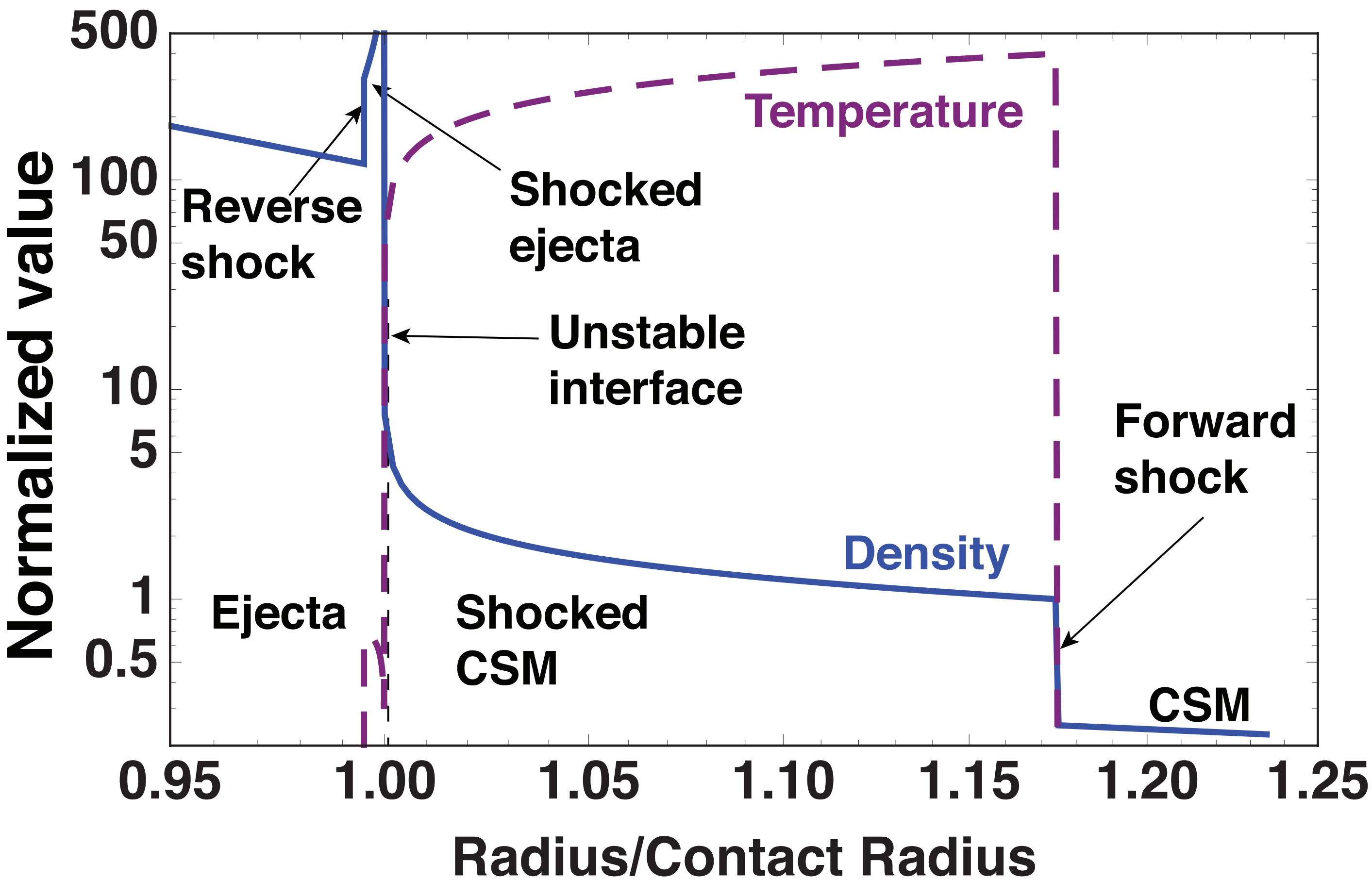
$$\rho_{CSM} = \rho_o (r_o / r)^s$$

r_o, t_o, ρ_o are the reference radius, time and density

n ~ 30 and s = 1.7 fit the observationally-determined characteristics of SN 1993J

Chevalier et al, *Astrophysical Journal*, 1992
Suzuki et al.*, Astrophysical Journal,* 1995
Fransson et al.*, Astrophysical Journal*, 1996

Relative density and temperature profiles of SN1993J



Hydrodynamic profiles

Astrophysical and experimental parameters

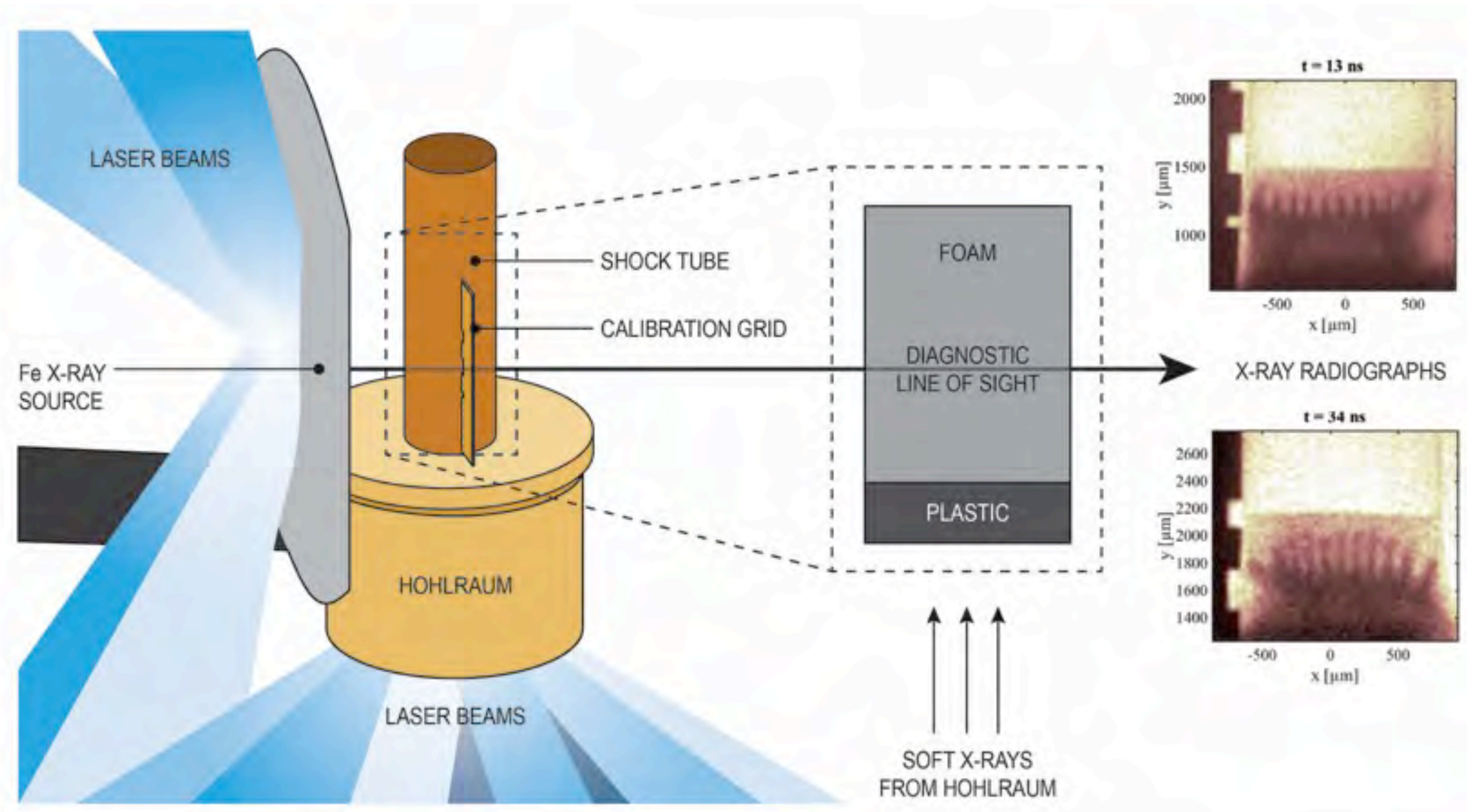
Scale Parameter	SN1993J	NIF experiment
Intershock distance L (cm)	$2.8 \times 10^{14} t_{\mathrm{yr}}^{0.95}$	0.02
Shock separation speed U (cm^{-1})	$3.0 \times 10^{8} t_{\mathrm{yr}}^{-0.046}$	6.8×10^{6}
Ejecta density at RS (g cm^{-3})	$3.4 \times 10^{-19} t_{\mathrm{yr}}^{-1.6}$	0.026
SEL Density (g cm^{-3})	$1.4 \times 10^{-16} t_{\mathrm{yr}}^{-1.6}$	0.5
SCSM Density (g cm^{-3})	$9 \times 10^{-19} t_{\mathrm{yr}}^{-1.6}$	0.18
SEL Temperature (eV)	$3800 t_{yr}^{-0.092}$	20
SCSM Temperature (eV)	$7.8 \times 10^{5} t_{\mathrm{yr}}^{-0.092}$	80
RS Velocity (km s^{-1})	$1.7 \times 10^{4} t_{\mathrm{yr}}^{-0.046}$	35
FS Velocity (km s^{-1})	$2 \times 10^{4} t_{\mathrm{yr}}^{-0.046}$	170
Z	1	2
A	1	20

Key dimensionless parameters

Dimensionless Parameter	SN1993J at 0.1 yrs	NIF experiment
λ_c/L	10^{-4}	10^{-8}
Reynolds number Re	$4 \times 10^5 t_{yr}^{-0.48}$	10^7
Energy flux ratio R	10^3	2
Peclet number Pe	1	4
Ryutov number Ry	4	5

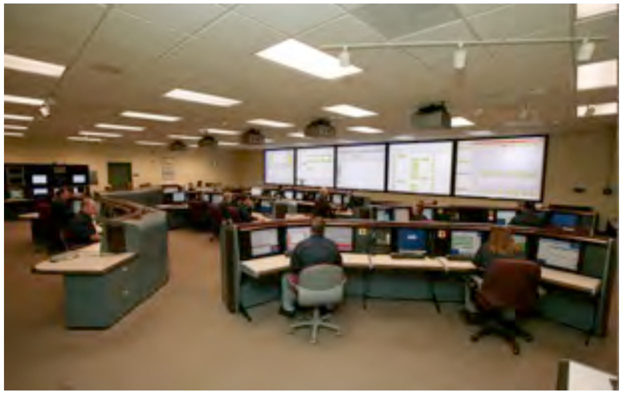
Both systems are highly collisional with negligible viscosity and energy fluxes due to radiation and heat conduction are higher or comparable to the mechanical energy flux and the hydrodynamics of the systems are similar

We use to NIF drive a create a high- and low-energy flux in an RT unstable system



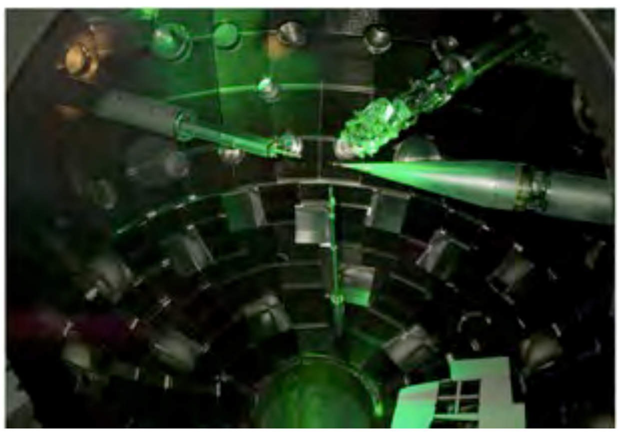
PI: Hye-Sook Park, Channing Huntington, Carolyn Kuranz

We performed these experiments at the National Ignition Facility

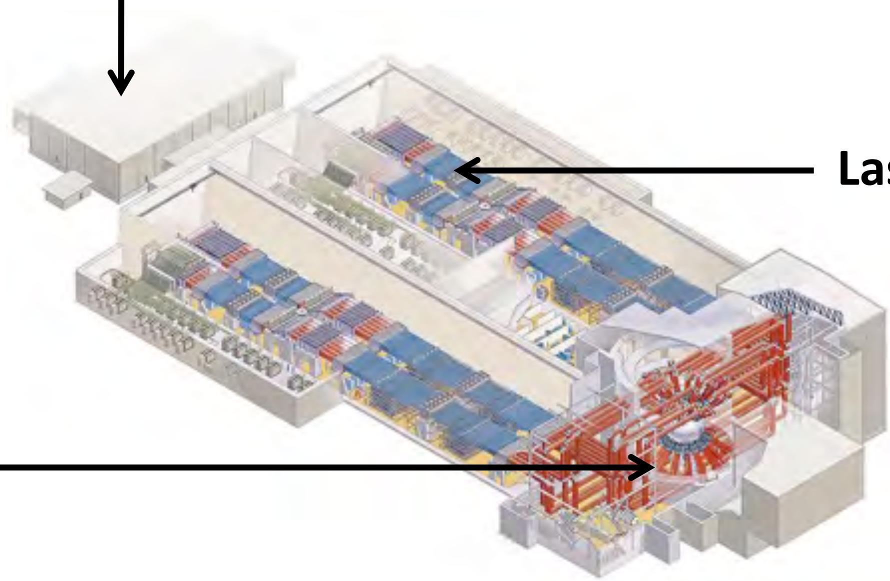


Control Rooms

Laser Bays



Target Chamber



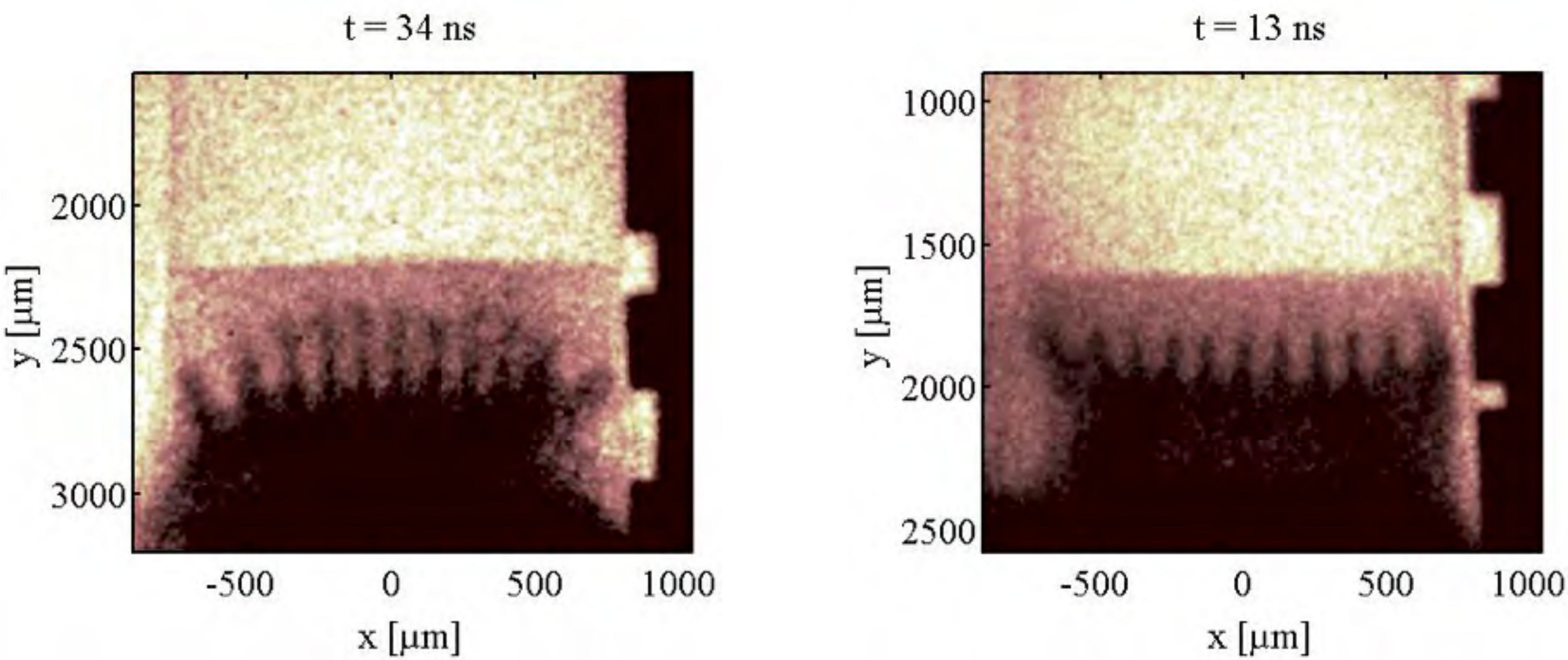
The "set" for a 23rd Century Movie!!

Laser bay

Target bay

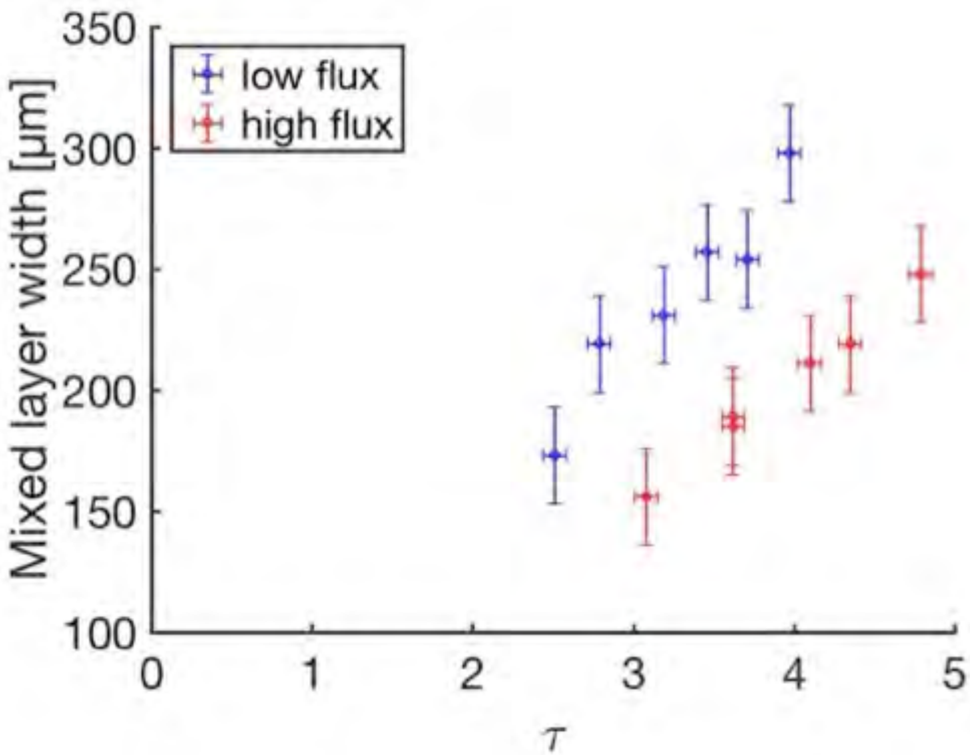
But not powered by Fusion!!!!

Typical data show qualitative and quantitative differences between cases



Low energy flux **High energy flux**

We must compare the RT growth of each case

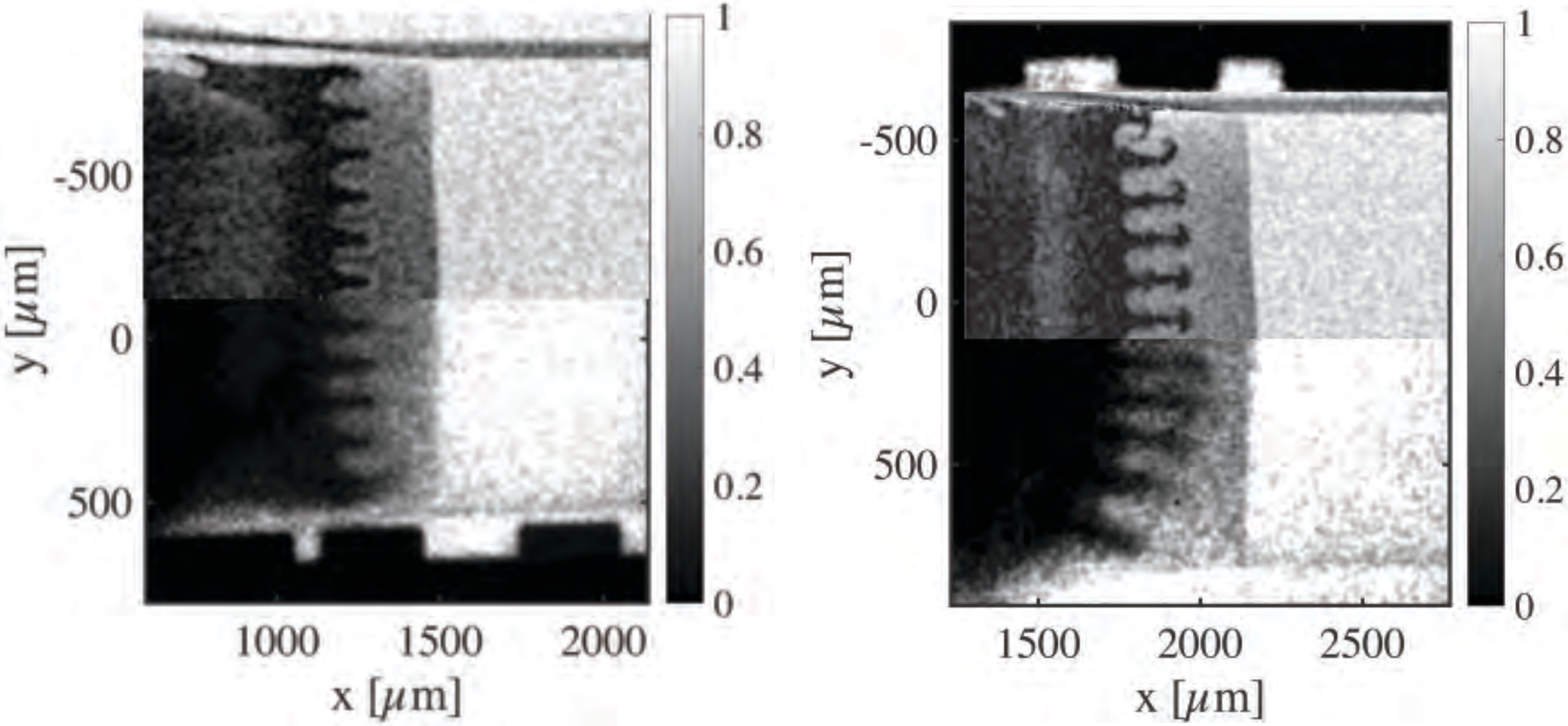


$$\tau = \int \gamma_{RT} dt$$

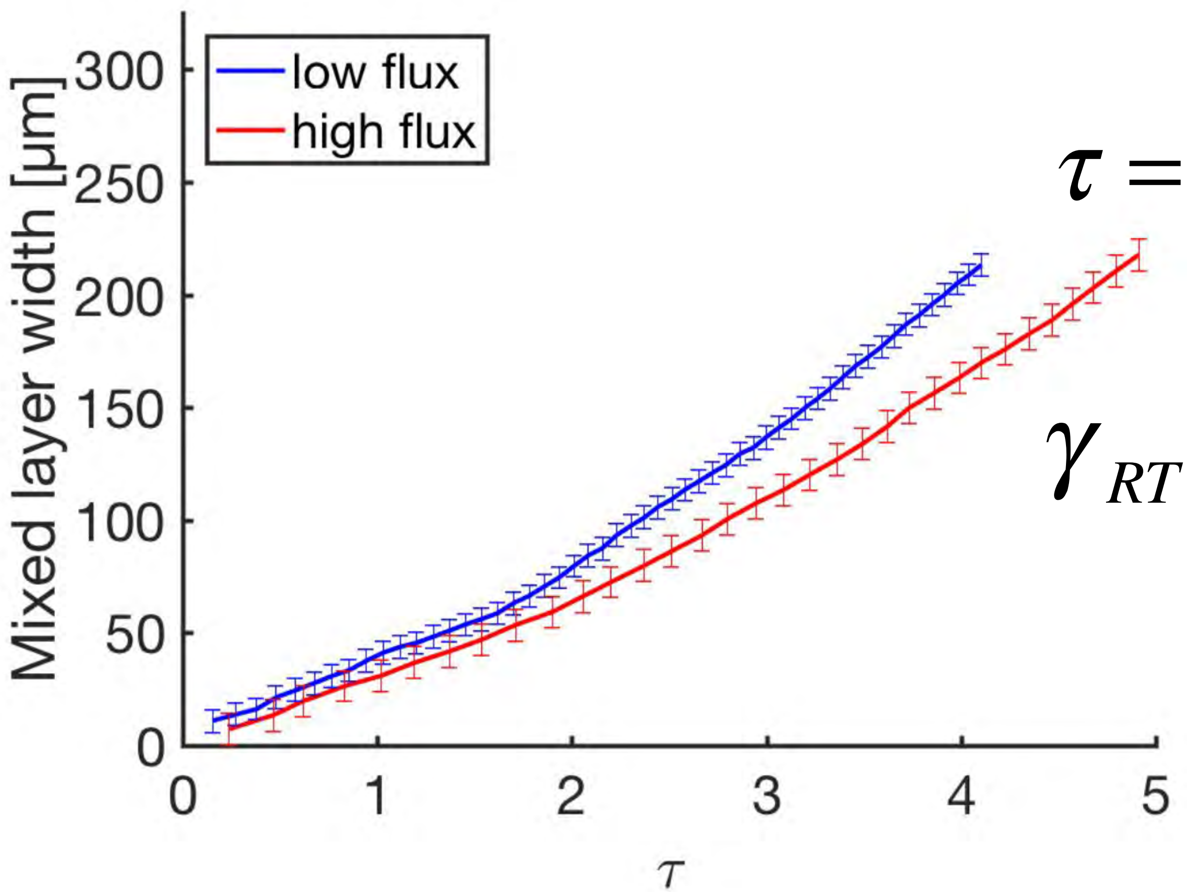
$$\gamma_{RT} = \sqrt{A(t)g(t)k}$$

A(t) is the Atwood number, g(t) is the acceleration and k is the wave number of the initial perturbation

Experimental data and CRASH simulations are in good agreement



CRASH simulations also show a reduction in RT growth



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Key dimensionless parameters

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Energy flux ratio R	10^3	2
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Both systems are highly collisional with negligible viscosity and energy fluxes due to radiation and heat conduction are higher or comparable to the mechanical energy flux and the hydrodynamics of the systems are similar

Heating is possible by radiation and electron heat conduction

$$F_{rad} = n_e n_i \Lambda D$$

Energy flux due to cooling by radiative losses from the shocked layer

$$Q_e = 0.1 n_e m_e v_{e,cs}^3$$

Electron heat flux, 10% the free-streaming heat flux

$$F_{mech} = \rho_{ej} v_{rs}^3$$

Mechanical energy flux driving the shock-heating of the shocked matter

n_e electron density

n_i ion density

Λ cooling function

D shocked layer thickness

m_e electron mass

$v_{e,cs}$ electron thermal velocity

ρ_{ej} ejecta density

v_{rs} reverse shock velocity

Radiative and heat conduction fluxes are large in SN1993J

Scale Parameter	SN1993J	NIF experiment
F_{mech} (ergs/cm^2/s)	$1.8 \times 10^5 t_{tyr}^{-1.76}$	2.8×10^{19}
F_{rad} (ergs/cm^2/s)	$3.6 \times 10^7 t_{tyr}^{-2.26}$	4.2×10^{19}
Q_e (ergs/cm^2/s)	$2.0 \times 10^8 t_{tyr}^{-1.76}$	1.7×10^{19}

$$R = \frac{Q_{ecs} + F_{rad}}{F_{mech}}$$

Energy flux ratio R	10^3	2

nature COMMUNICATIONS

ARTICLE

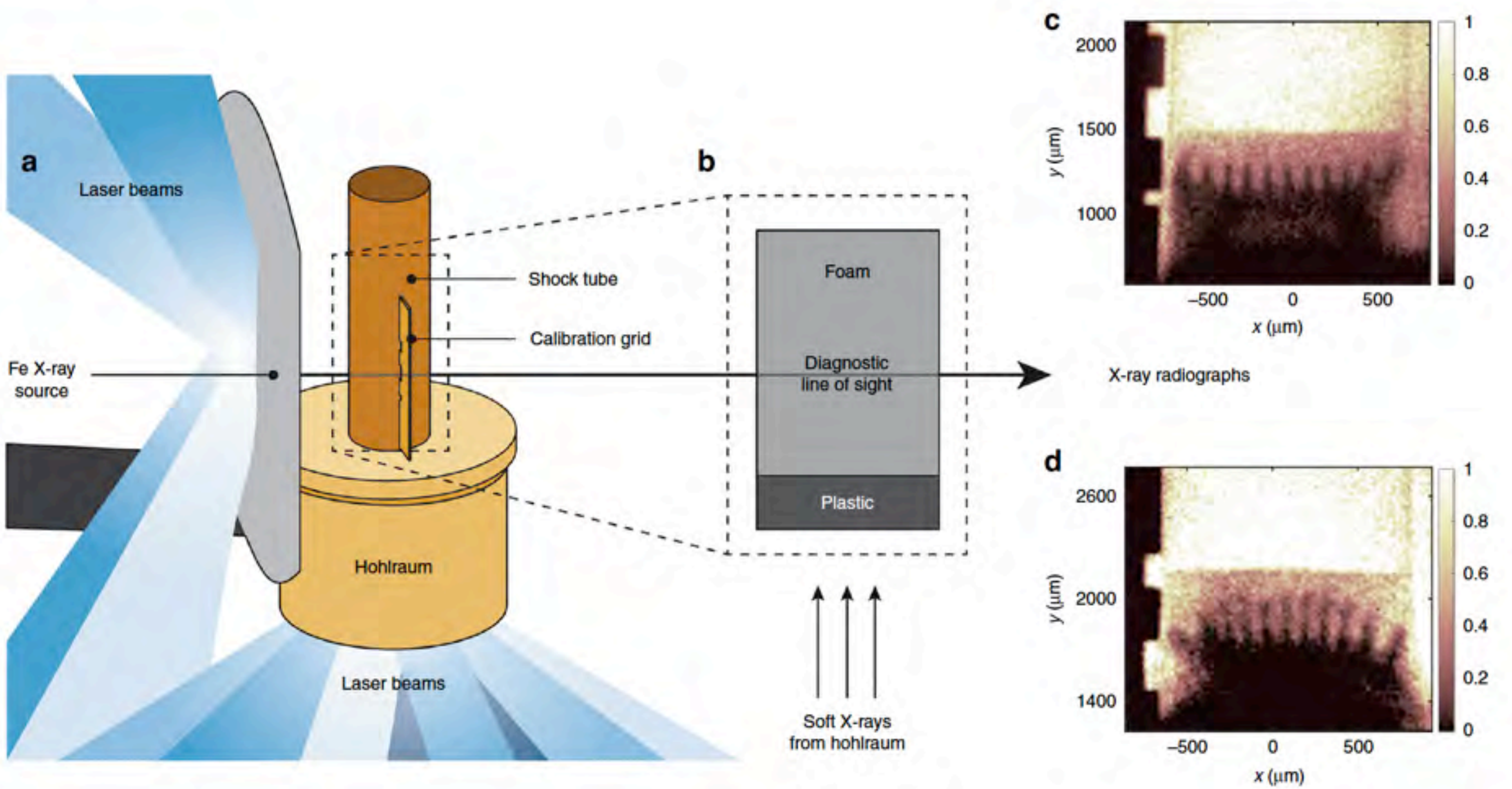
DOI: 10.1038/s41467-018-03548-7 OPEN

How high energy fluxes may affect Rayleigh–Taylor instability growth in young supernova remnants

C.C. Kuranz[1], H.-S. Park[2], C.M. Huntington[2], A.R. Miles[2], B.A. Remington[2], T. Plewa[3], M.R. Trantham[1], H.F. Robey[2], D. Shvarts[4,5], A. Shimony[4,5], K. Raman[2], S. MacLaren[2], W.C. Wan[1,6], F.W. Doss[6], J. Kline[6], K.A. Flippo[6], G. Malamud[1,5], T.A. Handy[1], S. Prisbrey[2], C.M. Krauland[7], S.R. Klein[1], E.C. Harding[8], R. Wallace[2], M. J. Grosskopf[9], D.C. Marion[1], D. Kalantar[2], E. Giraldez[7] & R.P. Drake[1]

Summary

- **We performed RT experiments in high- and low-flux regimes on NIF**
- **We found that high energy fluxes reduce the RT growth**
- **Energy fluxes due to radiative losses and electron heat conduction are large in SN1993J and the NIF experiment**
- **These fluxes should be considered in astrophysical modeling**
- **See CC Kuranz etal *Nature Communications* (2018) *and* CM Huntington et al *Physics of Plasmas* (2018)**


a
Laser beams
Fe X-ray source
Shock tube
Calibration grid
Hohlraum
Laser beams
b
Foam
Diagnostic line of sight
Plastic
Soft X-rays from hohlraum
X-ray radiographs
c
2000
1500
1000
y (μm)
−500
0
500
x (μm)
1
0.8
0.6
0.4
0.2
0
d
2600
2000
1400
y (μm)
−500
0
500
x (μm)
1
0.8
0.6
0.4
0.2
0

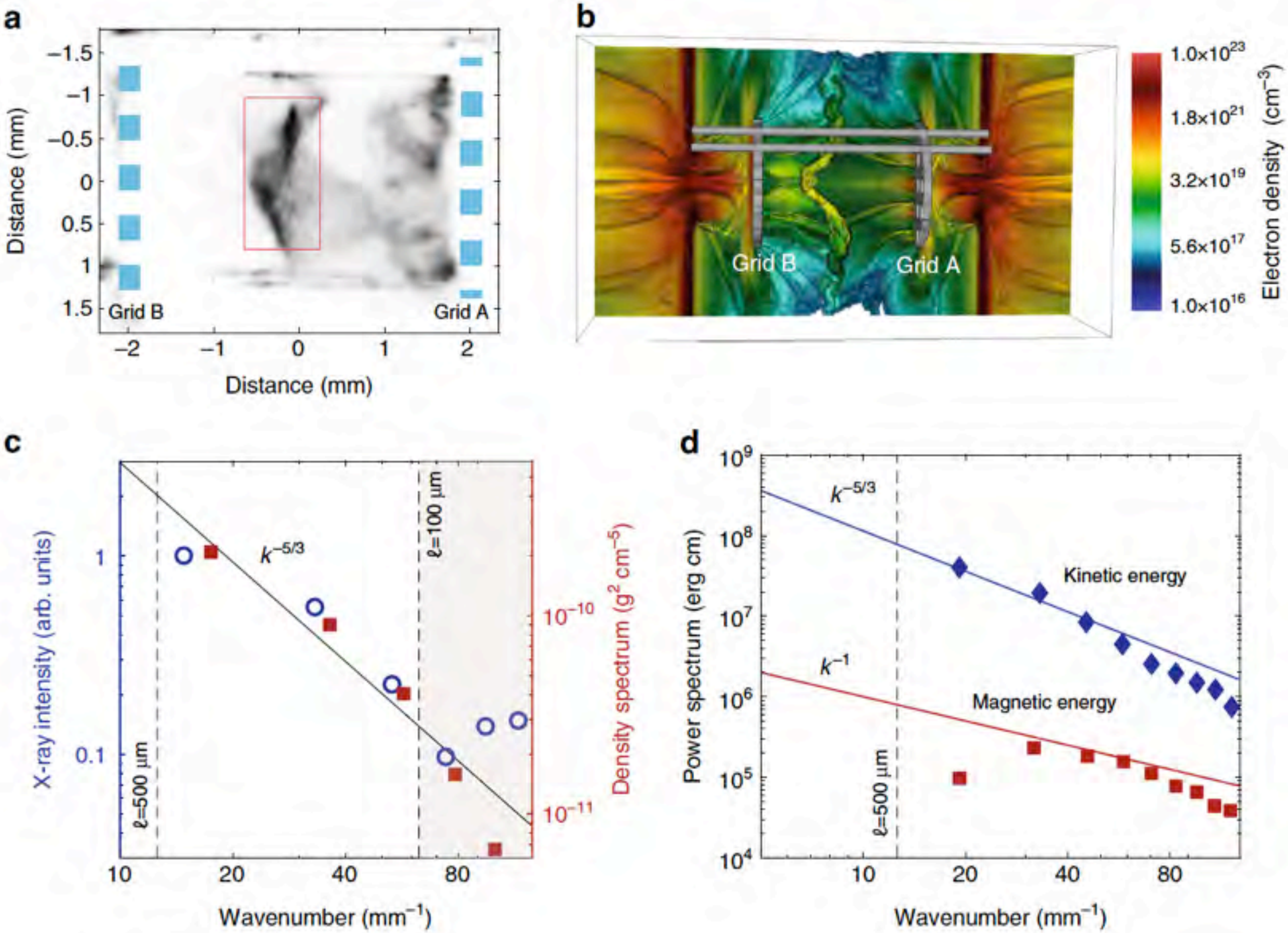
nature COMMUNICATIONS

ARTICLE

DOI: 10.1038/s41467-018-02953-2 OPEN

Laboratory evidence of dynamo amplification of magnetic fields in a turbulent plasma

P. Tzeferacos[1,2], A. Rigby[1], A. F. A. Bott[1], A.R. Bell[1], R. Bingham[3,4], A. Casner[5], F. Cattaneo[2], E.M. Churazov[6,7], J. Emig[8], F. Fiuza[9], C.B. Forest[10], J. Foster[11], C. Graziani[2], J. Katz[12], M. Koenig[13], C.-K. Li[14], J. Meinecke[1], R. Petrasso[14], H.-S. Park[8], B.A. Remington[8], J.S. Ross[8], D. Ryu[15], D. Ryutov[8], T.G. White[1], B. Reville[16], F. Miniati[17], A.A. Schekochihin[1], D.Q. Lamb[2], D.H. Froula[12] & G. Gregori[1,2]



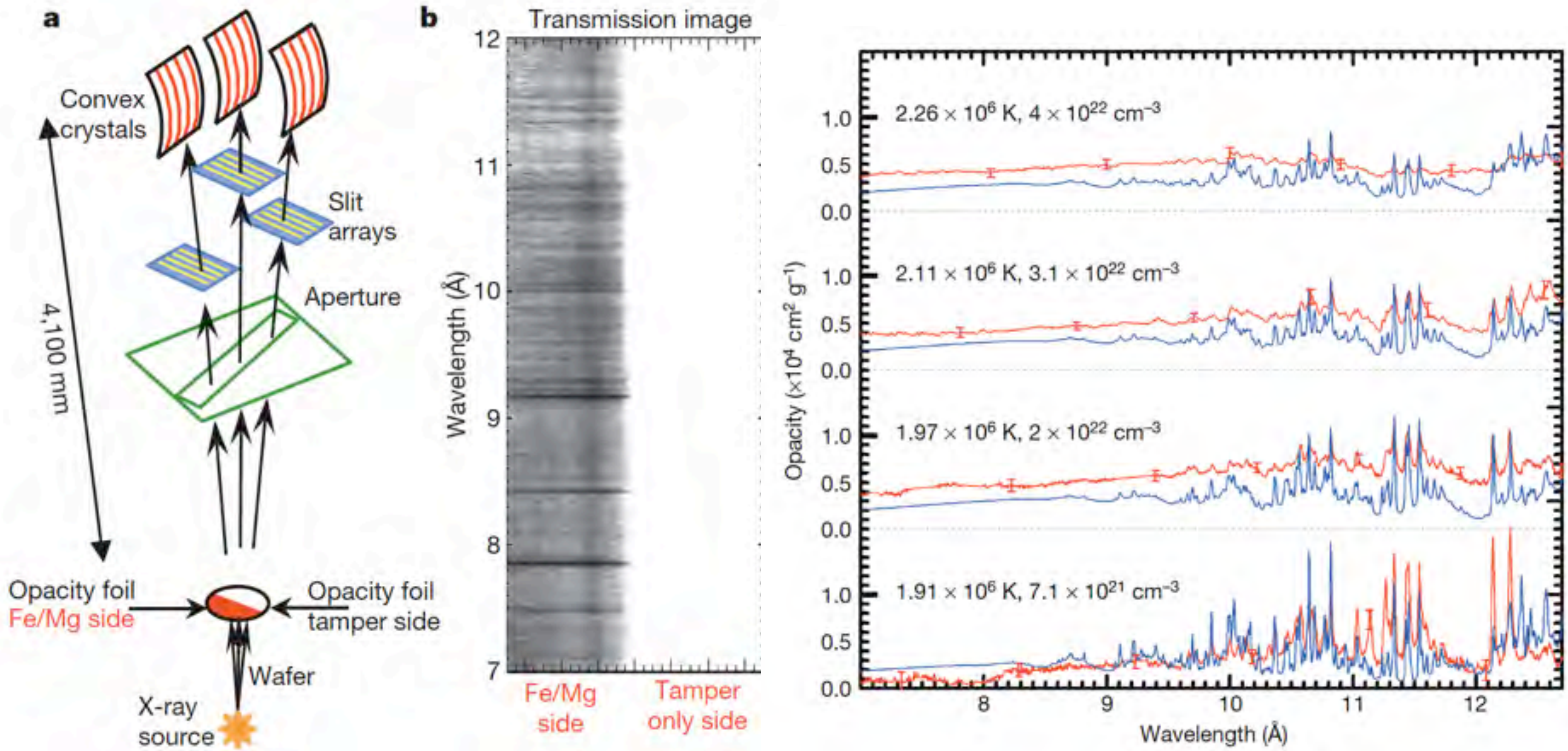
a
Distance (mm)
−1.5
−1
−0.5
0
0.5
1
1.5
Grid B
Grid A
−2
−1
0
1
2
Distance (mm)
b
Grid B
Grid A
1.0×10^23
1.8×10^21
3.2×10^19
5.6×10^17
1.0×10^16
Electron density (cm^−3)
c
X-ray intensity (arb. units)
1
0.1
ℓ=500 μm
ℓ=100 μm
k^−5/3
10^−10
10^−11
Density spectrum (g^2 cm^−5)
10
20
40
80
Wavenumber (mm^−1)
d
10^9
10^8
10^7
10^6
10^5
10^4
Power spectrum (erg cm)
k^−5/3
k^−1
Kinetic energy
Magnetic energy
ℓ=500 μm
10
20
40
80
Wavenumber (mm^−1)

LETTER

doi:10.1038/nature14048

A higher-than-predicted measurement of iron opacity at solar interior temperatures

J. E. Bailey[1], T. Nagayama[1], G. P. Loisel[1], G. A. Rochau[1], C. Blancard[2], J. Colgan[3], Ph. Cosse[2], G. Faussurier[2], C. J. Fontes[3], F. Gilleron[2], I. Golovkin[4], S. B. Hansen[1], C. A. Iglesias[5], D. P. Kilcrease[3], J. J. MacFarlane[4], R. C. Mancini[6], S. N. Nahar[7], C. Orban[7], J.-C. Pain[2], A. K. Pradhan[7], M. Sherrill[3] & B. G. Wilson[5]



a
Convex crystals
Slit arrays
Aperture
4,100 mm
Opacity foil
Fe/Mg side
Opacity foil
tamper side
Wafer
X-ray
source
b
Transmission image
Wavelength (Å)
Fe/Mg side
Tamper only side
2.26 × 10⁶ K, 4 × 10²² cm⁻³
2.11 × 10⁶ K, 3.1 × 10²² cm⁻³
1.97 × 10⁶ K, 2 × 10²² cm⁻³
1.91 × 10⁶ K, 7.1 × 10²¹ cm⁻³
Opacity (×10⁴ cm² g⁻¹)
Wavelength (Å)

nature physics

LETTERS

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Observation of magnetic field generation via the Weibel instability in interpenetrating plasma flows

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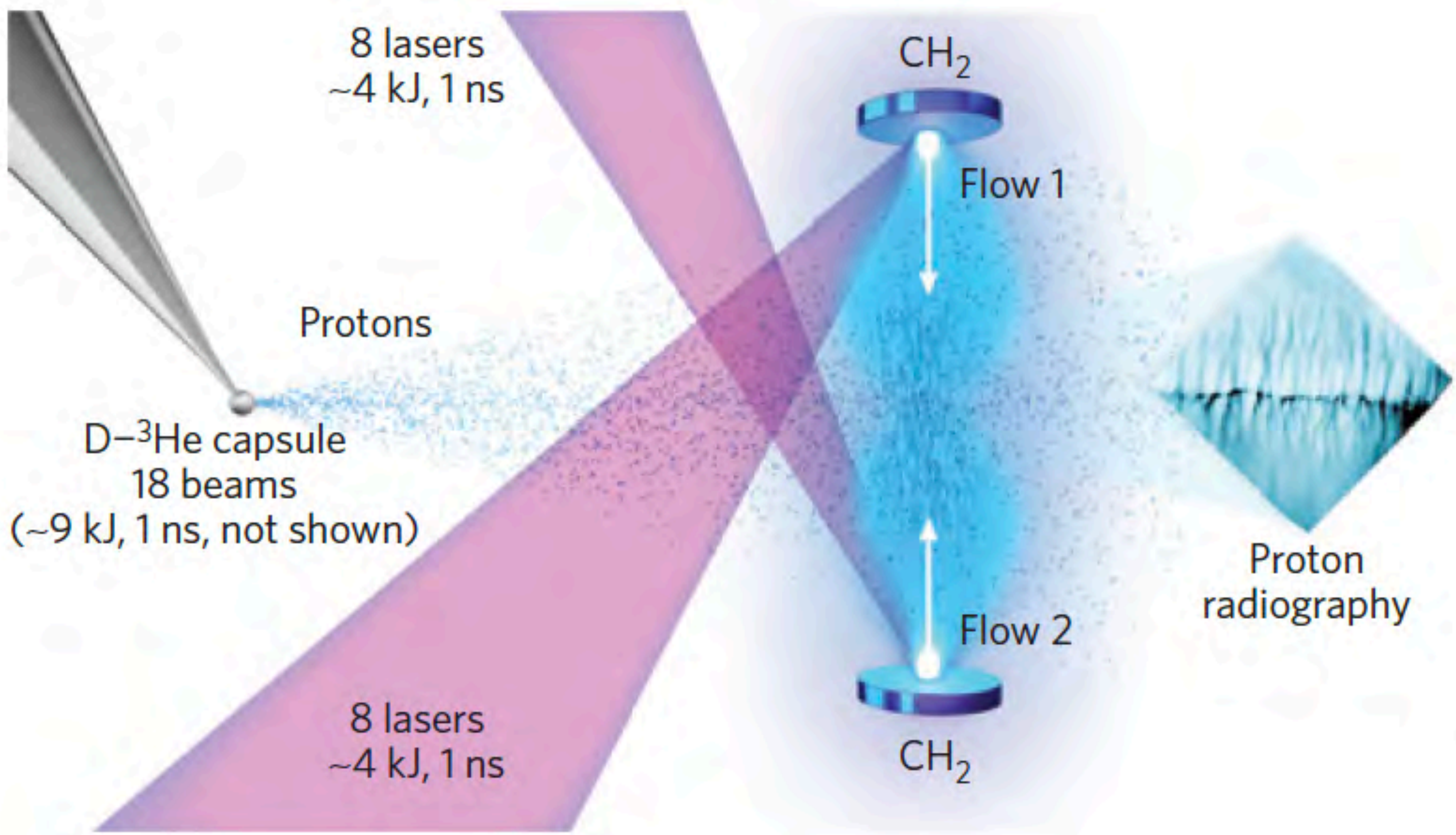
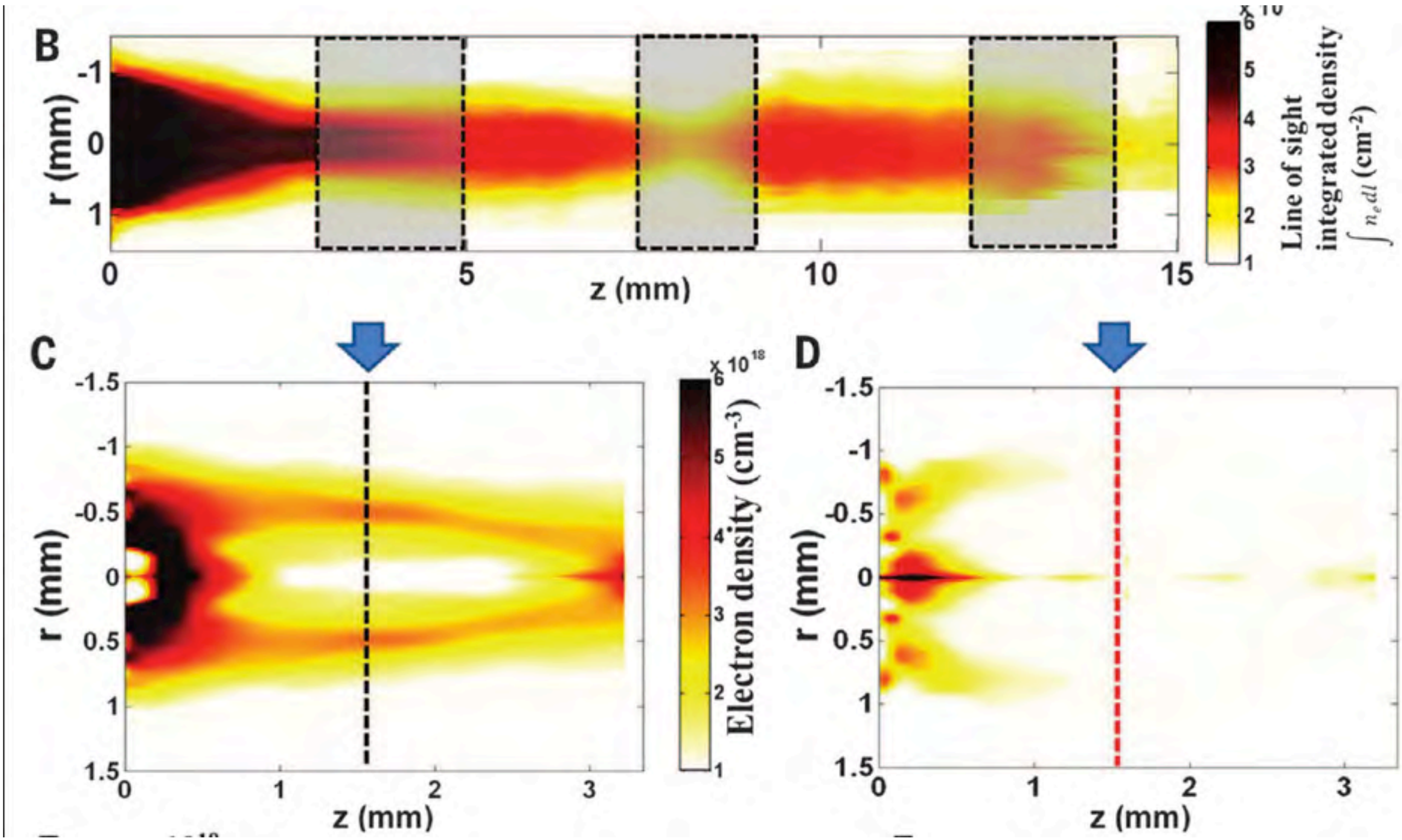

8 lasers
~4 kJ, 1 ns
CH2
Flow 1
Protons
D−3He capsule
18 beams
(~9 kJ, 1 ns, not shown)
Proton
radiography
Flow 2
8 lasers
~4 kJ, 1 ns
CH2

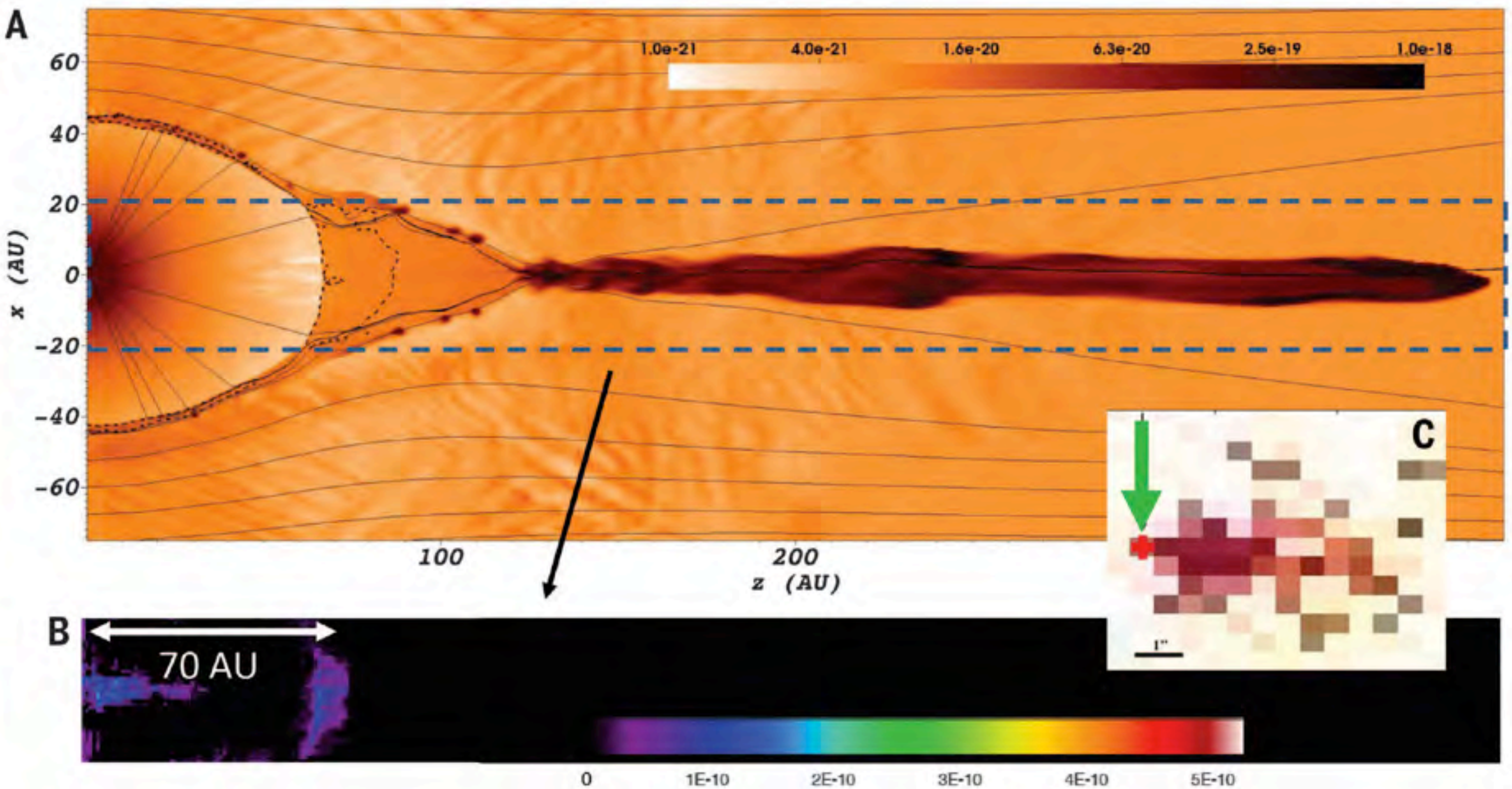
Laboratory formation of a scaled protostellar jet by coaligned poloidal magnetic field

B. Albertazzi *et al.*

Science **346**, 325 (2014);
DOI: 10.1126/science.1259694



B
r (mm)
z (mm)
Line of sight integrated density $\int n_e dl$ (cm^{-2})
C
r (mm)
z (mm)
x 10^{18}
Electron density (cm^{-3})
D
r (mm)
z (mm)



A
B
C
1.0e-21
4.0e-21
1.6e-20
6.3e-20
2.5e-19
1.0e-18
60
40
20
0
-20
-40
-60
x (AU)
100
200
z (AU)
70 AU
1"
0
1E-10
2E-10
3E-10
4E-10
5E-10

Additional HEDLA Work

"Two-dimensional blast-wave-driven Rayleigh Taylor instability: Experiment and Simulation," Kuranz et al. *Astrophysical Journal*, 2009

"Laboratory evidence of dynamo amplification of magnetic fields in a turbulent plasma," P. Tzeferacos et al. *Nature Communications* 2018

"A higher-than-predicted measurement of iron opacity at solar interior temperatures," J. Bailey et al. *Nature Letters,* 2015

"How high energy fluxes may affect Rayleigh-Taylor instability growth in young supernova remnants, " Kuranz et al. *Nature Communications,* 2018

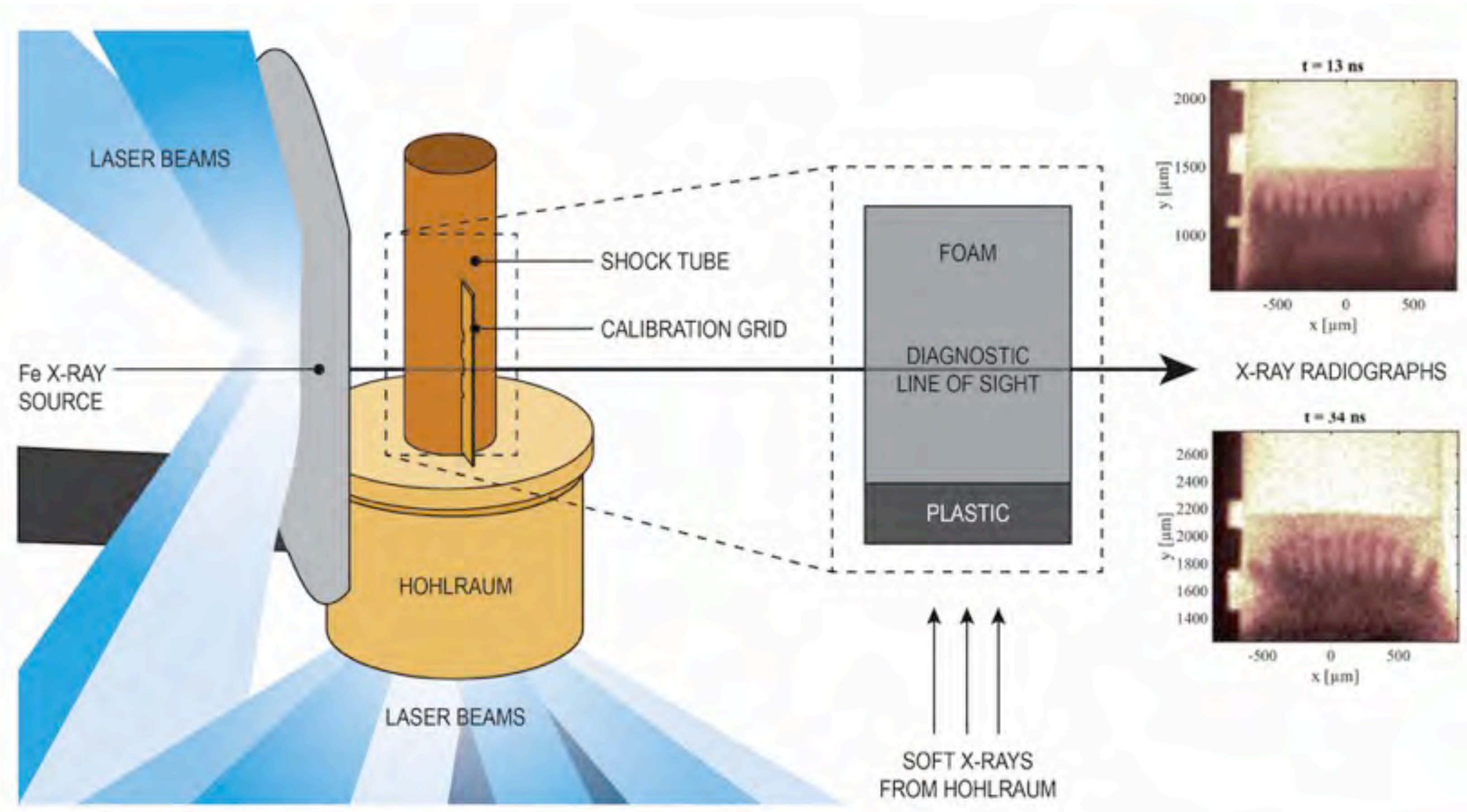
"Observation of magnetic field generation via the Weibel instability in interpenetrating plasma flows," Huntington et al., *Nature Physics,* 2015

"Laboratory formation of a scaled protostellar jet by coaligned poloidal magnetic field," *Science*, 2014

Conclusions

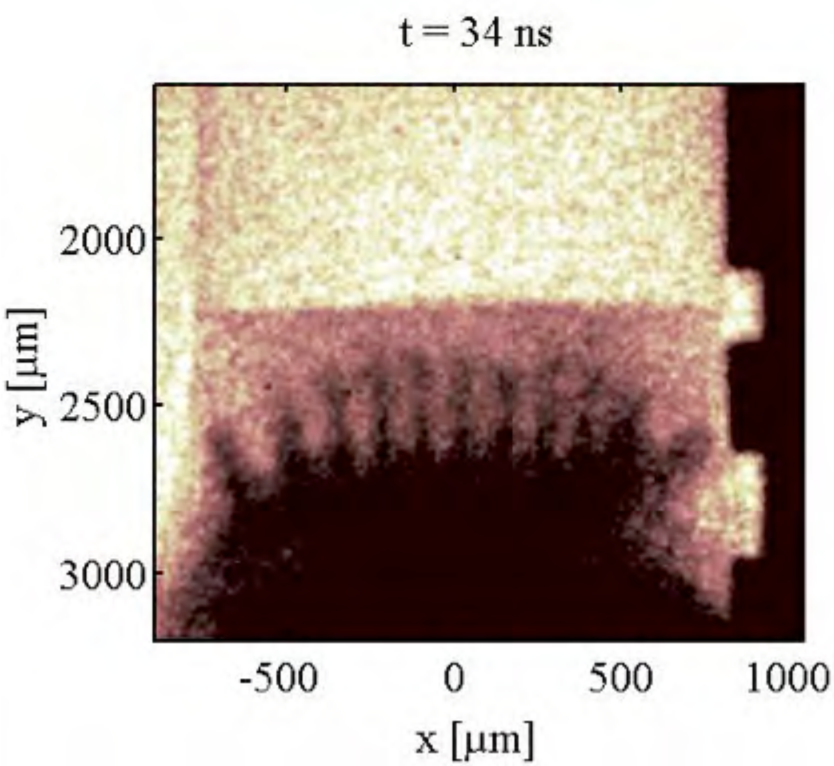
- **Laboratory experiments can garner knowledge information about specific processes in astrophysical systems**
- **HED Laboratory Astrophysics covers a vast array of physical processes**
- **There are a lot possibilities for HED experiments and collaborations**

We use to NIF drive a create a high- and low-energy flux in an RT unstable system

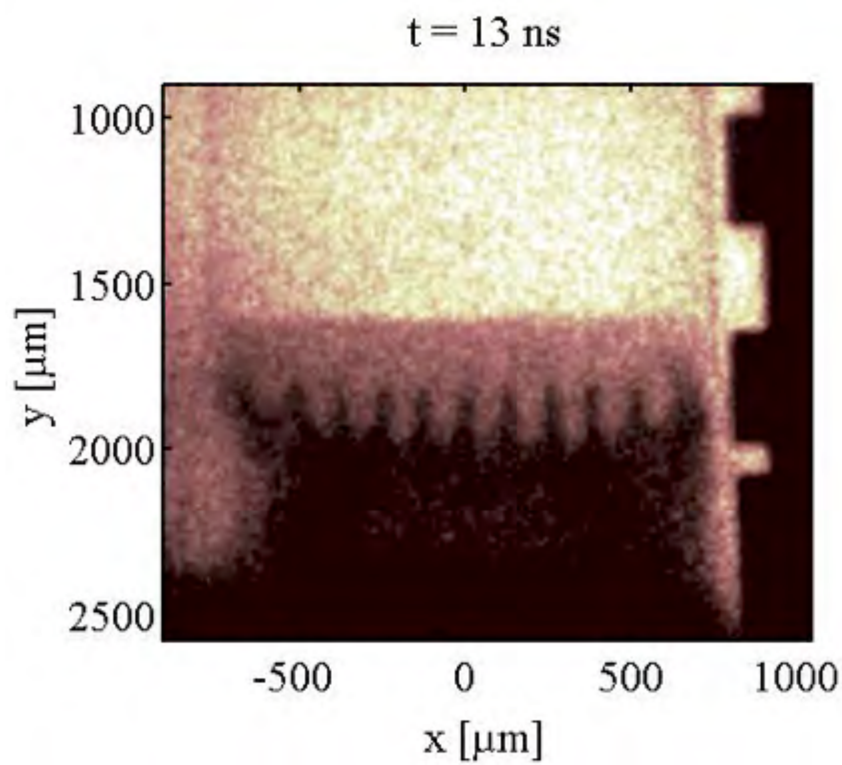


PI: Hye-Sook Park, Channing Huntington, Carolyn Kuranz, Aaron Miles, Forrest Doss, Kumar Raman

Typical data show qualitative and quantitative differences between cases

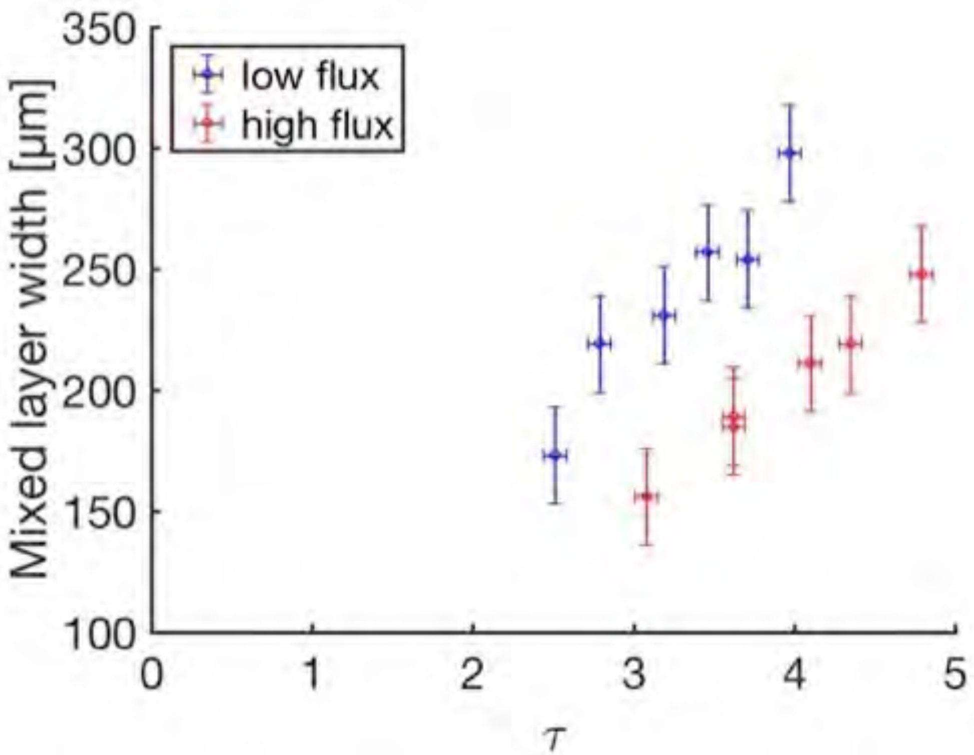


Low energy flux



High energy flux

We must compare the RT growth of each case

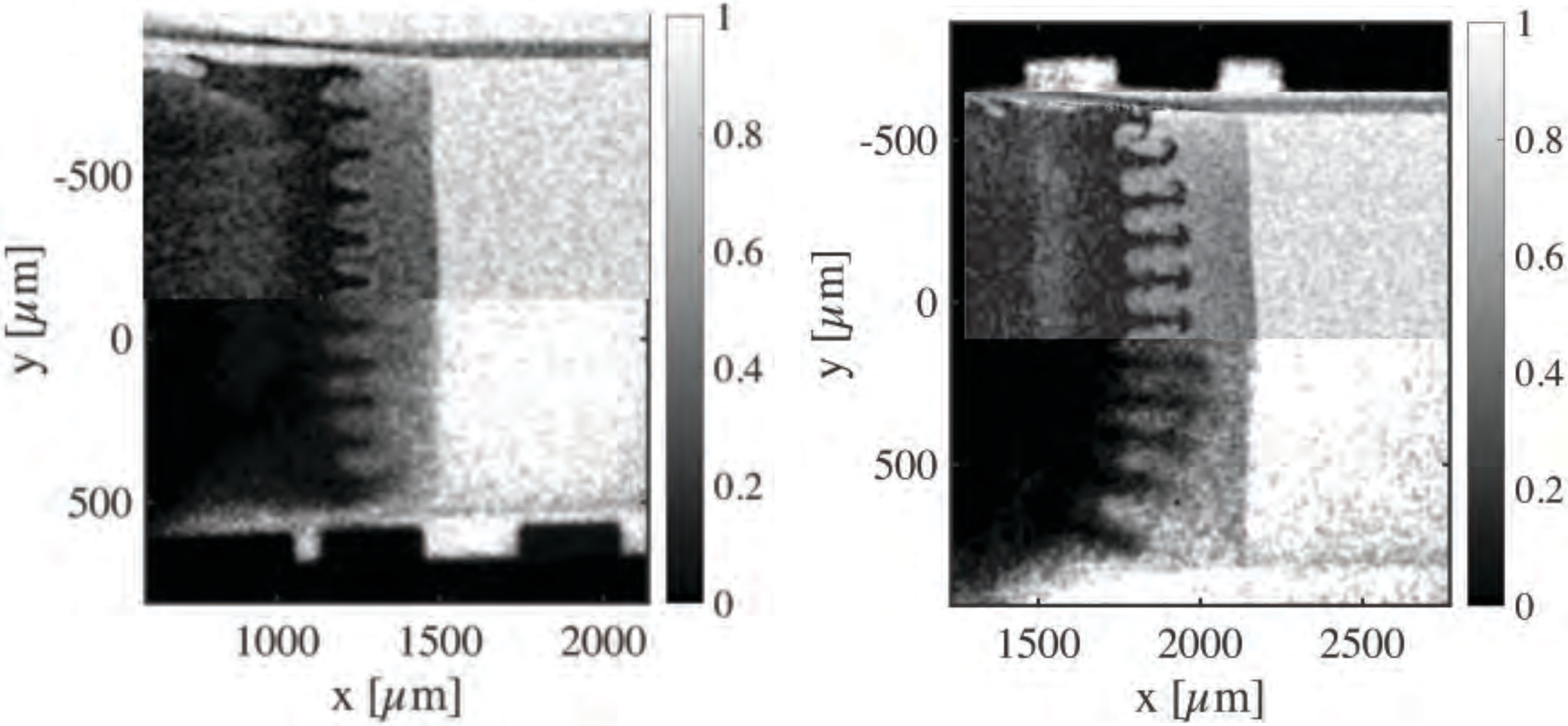


$$\tau = \int \gamma_{RT} dt$$

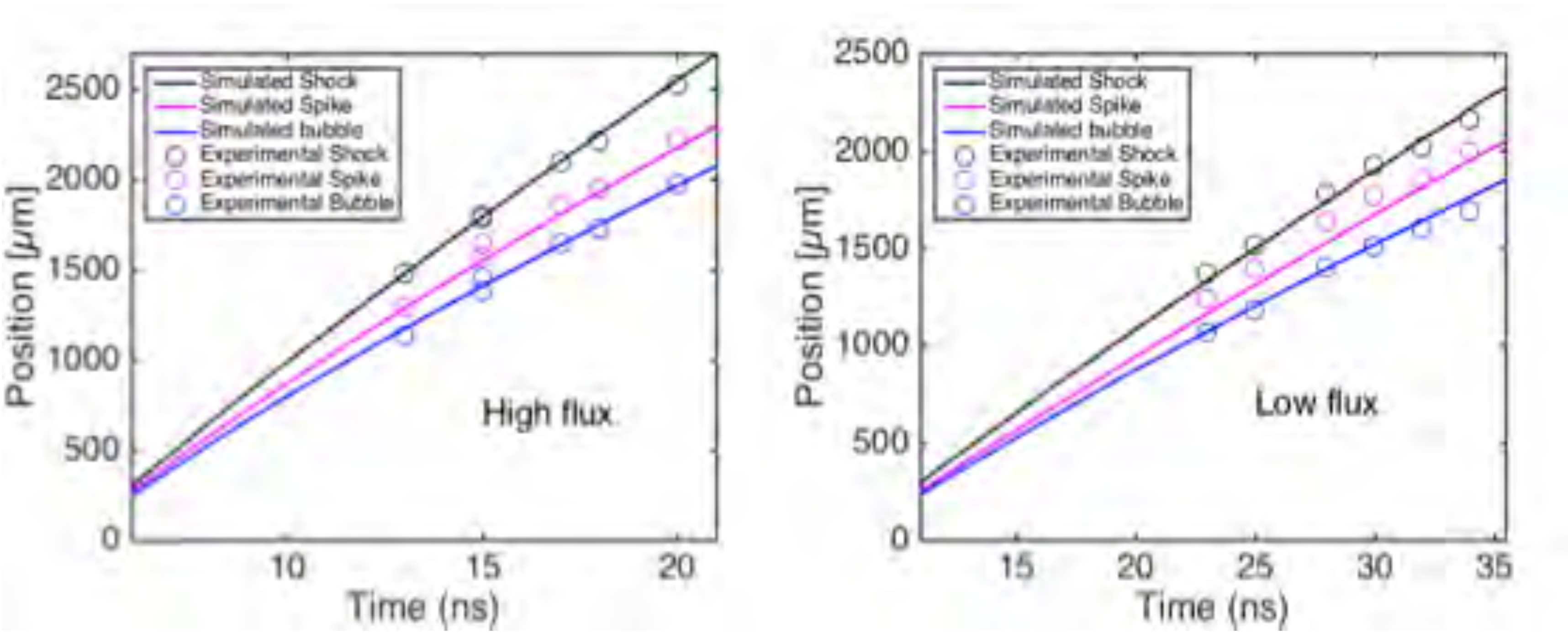
$$\gamma_{RT} = \sqrt{A(t)g(t)k}$$

A(t) is the Atwood number, g(t) is the acceleration and k is the wave number of the initial perturbation

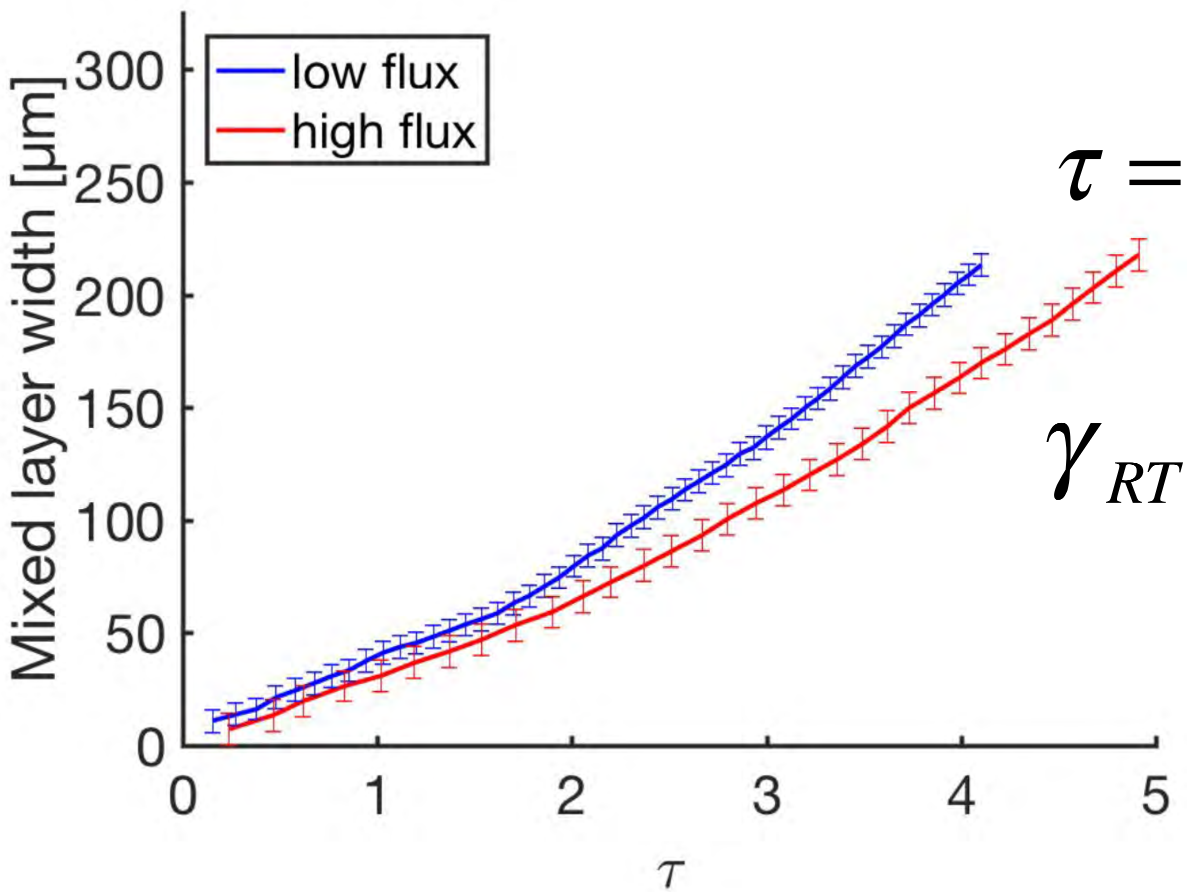
Experimental data and CRASH simulations are in good agreement



Experimental data and CRASH simulations are in good agreement



CRASH simulations also show a reduction in RT growth



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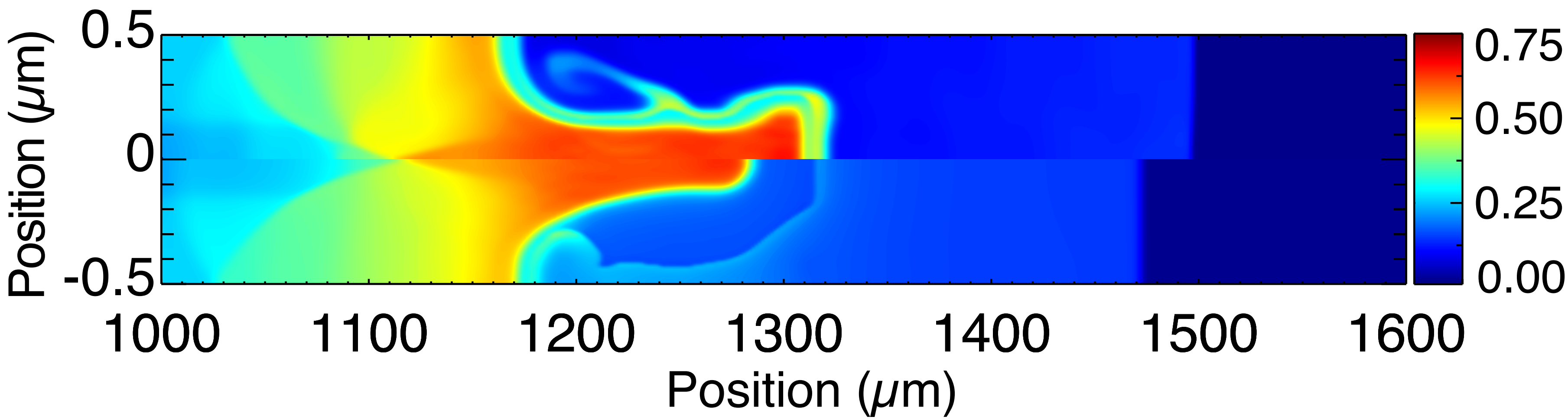

Comparison of simulated nominal and reduced opacities

Astrophysical and experimental parameters

Scale Parameter	SN1993J	NIF experiment
Intershock distance L (cm)	$2.8 \times 10^{14} t_{yr}^{0.95}$	0.02
Shock separation speed U (cm/s)	$3.0 \times 10^{8} t_{yr}^{-0.046}$	6.8×10^{6}
Ejecta density at RS (g cm^{-3})	$3.4 \times 10^{-19} t_{yr}^{-1.6}$	0.026
SEL Density (g cm^{-3})	$1.4 \times 10^{-16} t_{yr}^{-1.6}$	0.5
SCSM Density (g cm^{-3})	$9 \times 10^{-19} t_{yr}^{-1.6}$	0.18
SEL Temperature (eV)	$3800 t_{yr}^{-0.092}$	20
SCSM Temperature (eV)	$7.8 \times 10^{5} t_{yr}^{-0.092}$	80
RS Velocity (km s^{-1})	$1.7 \times 10^{4} t_{tyr}^{-0.046}$	35
FS Velocity (km s^{-1})	$2 \times 10^{4} t_{tyr}^{-0.046}$	170
Z	1	2
A	1	20

Key dimensionless parameters

Dimensionless number	SN1993J	NIF experiment
λ_c/L	$\sim 10^{-4}$	$\sim 10^{-8}$
Re	$\sim 10^{6}$	$\sim 10^{7}$
Energy flux ratio R	$\sim 10^{3}$	~ 2

Both systems are highly collisional with negligible viscosity and energy fluxes due to radiation and heat conduction are higher or comparable to the mechanical energy flux

Heating is possible by radiation and electron heat conduction

$$F_{rad} = n_e n_i \Lambda D$$

Energy flux due to cooling by radiative losses from the shocked layer

$$Q_e = 0.1 n_e m_e v_{e,cs}^3$$

Electron heat flux, 10% the free-streaming heat flux

$$F_{mech} = \rho_{ej} v_{rs}^3$$

Mechanical energy flux driving the shock-heating of the shocked matter

n_e electron density

n_i ion density

Λ cooling function

D shocked layer thickness

m_e electron mass

$v_{e,cs}$ electron thermal velocity

ρ_{ej} ejecta density

v_{rs} reverse shock velocity

Radiative and heat conduction fluxes are large in SN1993J

Scale Parameter	SN1993J	NIF experiment
F_{mech} (ergs/cm^2/s)	$1.8 \times 10^5 t_{tyr}^{-1.76}$	2.8×10^{19}
F_{rad} (ergs/cm^2/s)	$3.6 \times 10^7 t_{tyr}^{-2.26}$	4.2×10^{19}
Q_e (ergs/cm^2/s)	$2.0 \times 10^8 t_{tyr}^{-1.76}$	1.7×10^{19}

$$R = \frac{Q_{ecs} + F_{rad}}{F_{mech}}$$

Energy flux ratio R	10^3	2