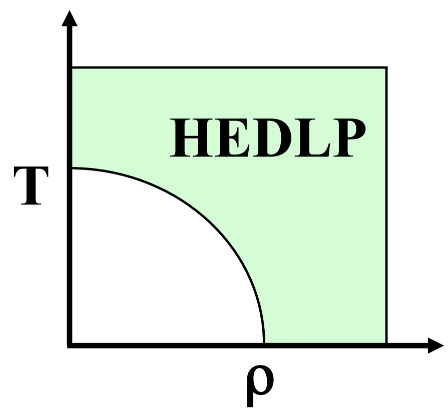
# Radiative hydrodynamics - experiments

**Workshop on Opportunities in Plasma Astrophysics**
**Princeton Plasma Physics Laboratory**
**January 18-21, 2010**




**Bruce A. Remington**
**Lawrence Livermore National Laboratory**

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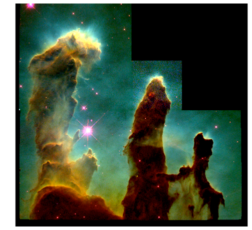
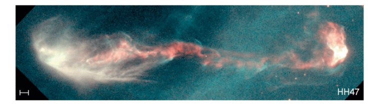
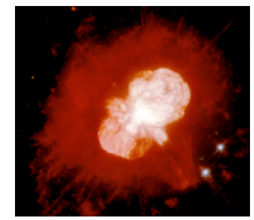
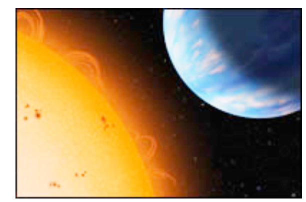
# HED facilities open up unique experimental opportunities to study radiative hydrodynamics relevant to astrophysics

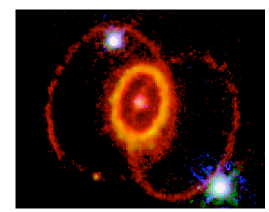
- **Star formation dynamics: molecular cloud radiative hydrodynamics**
- **Stellar evolution: stellar interior opacities, location of radiative zone**
- **Stellar evolution: white dwarf opacities, EOS, cooling rates**
- **Radiation (UV, x-ray) driving exoplanet atmospheres**
- **Core-collapse SNe: neutrino "rad–hydro", shock break out rad-hydro**
- **Rad-hydro in Type-1A SNe: nuclear burn propagation, light curve evol.**
- **Supernova remnants: radiative shocks, shock processing of the ISM**
- **Protostellar jets: high-M-#, radiative, MHD or rad-hydro jets**
- **Radiation (UV, x-ray) destruction of dust grains near GRBs**
- **Black hole accretion disks; photoionized plasmas; (e+, e-) pair fireball**







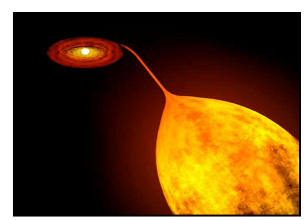


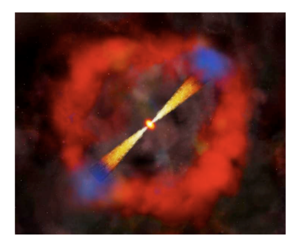


H. Takabe, "Astrophysics with intense and ultra-intense lasers: laser astrophysics," Prog. Theor. Phys. Suppl. 143 202 (2001)

Remington, Drake, Ryutov," Experimental astrophysics with high power lasers and Z pinches," Rev. Mod. Phys. 78, 755 (2006)

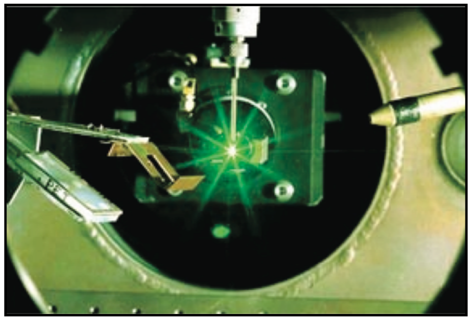
Mark E. Koepke, "Interrelated laboratory and space plasma experiments," Reviews of Geophysics 46, No. 3, RG3001 (July 16, 2008)



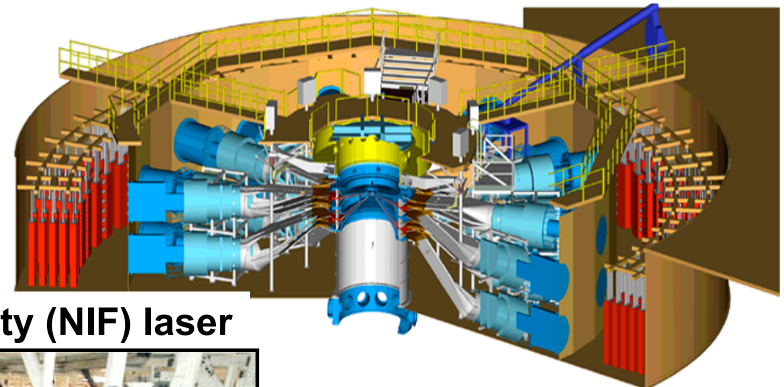


# This frontier science is being pursued on a wide range of high energy density facilities around the world

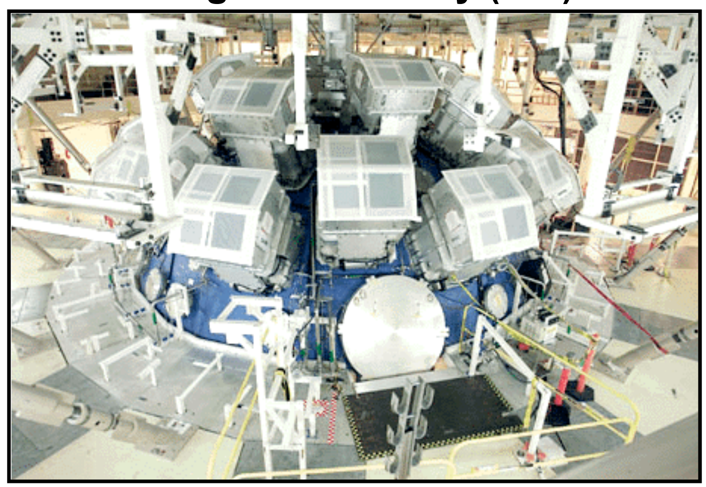
**Jupiter, Trident, Z-Beamlet, Vulcan, LULI, Gekko lasers**



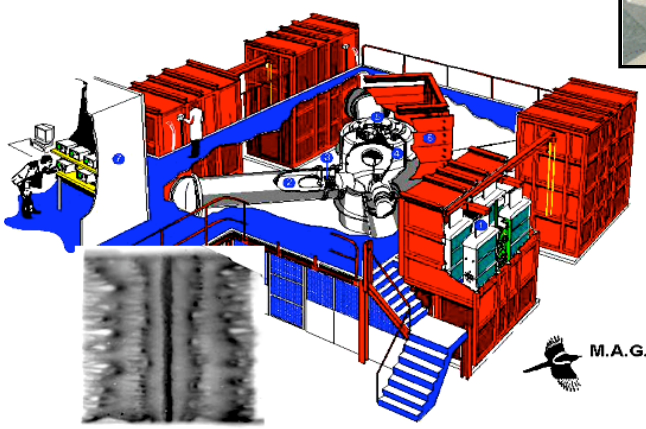
**Z, ZR magnetic-pinch facility**



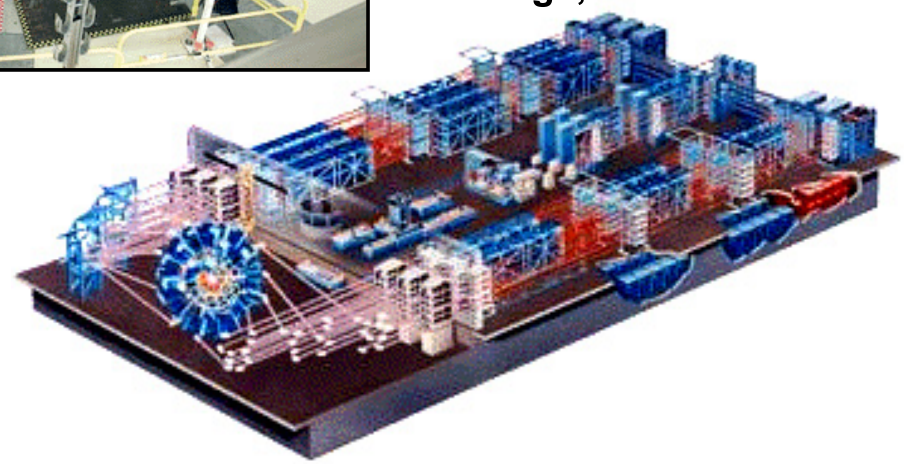
**National Ignition Facility (NIF) laser**



**Magpie magnetic-pinch facility**

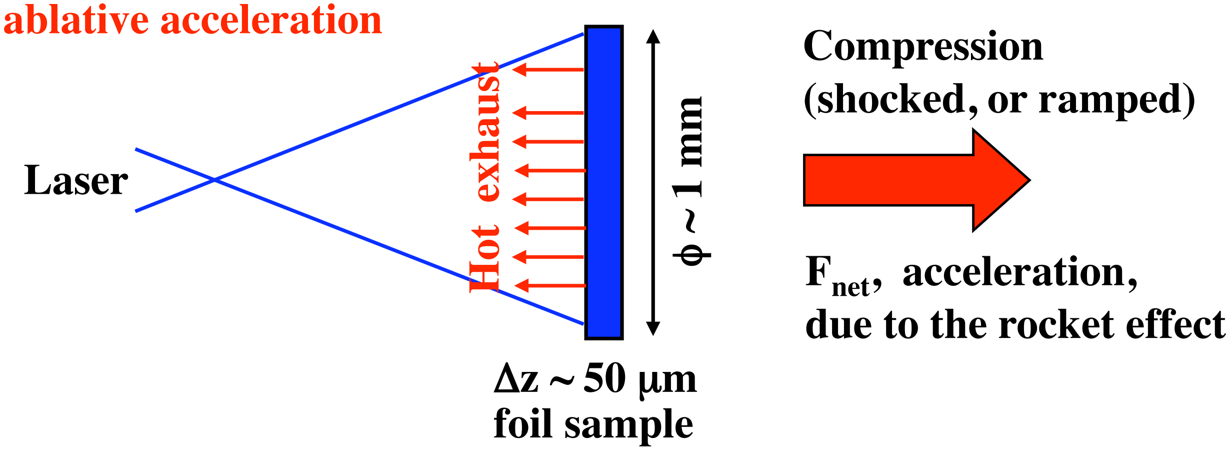



**Omega, EP lasers**



# HED facilities, such as lasers, are ideal for producing localized regions of high pressure to "drive" experiments

**Example: laser driven, ablative acceleration**




**Assume $E_L \sim 1$ kJ, $\lambda_L = 1/3\ \mu$m, a 1 mm diameter spot, for 1 ns:**

$$I_L = \frac{10^3\ \mathrm{J}}{\pi(0.05\mathrm{cm})^2(10^{-9}\mathrm{s})} = 1.3\mathrm{x}10^{14}\ \mathrm{W/cm^2}$$

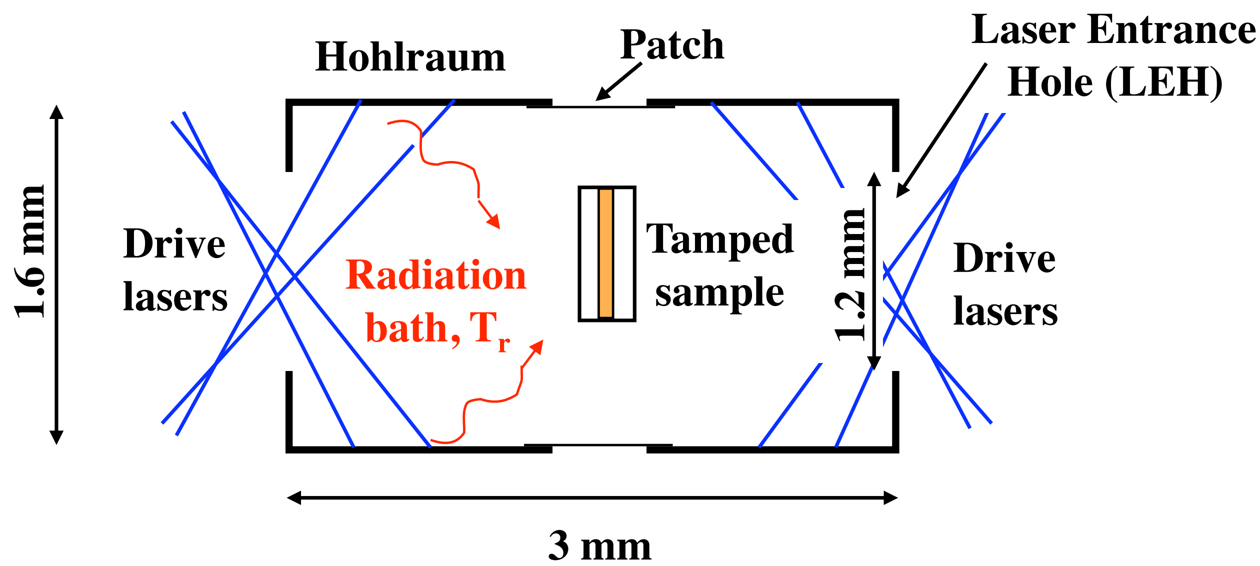
$$P_{abl}(\mathrm{Mbar}) \approx 40\left[\frac{I_{15}}{\lambda_{(\mu m)}}\right]^{2/3} = 40\left[\frac{0.13}{1/3\ \mu m}\right]^{2/3} \approx 21\ \mathrm{Mbar} = 21\ \mathrm{x}\ 10^{12}\ \mathrm{dyne/cm^2} = 2.1\ \mathrm{TPa}$$

- **Newton's 2nd law, $P = \rho \cdot \Delta z \cdot g$, gives $g = 4.2 \times 10^{15}$ cm/s$^2$ = 42 μm/ns$^2$ ~ $(10^{12} - 10^{13})\ g_0$, yielding very high accelerations over ~1-10 ns**
- **Compare with the acceleration due to gravity at the surface of a neutron star: $g_{NS} = GM_{NS}/r^2 \sim G(1.5M_{Sun})/(15\mathrm{km})^2 \sim 10^{11} g_0$ .**

[Lindl, PoP 2, 3933 (1995), Eq. 47; *Inertial Confinement Fusion* (Springer, 1998); Rosen, PoP 6, 1690 (1999)]

# Lasers and Z-pinches can also generate high temperature, radiation conditions for heating or “driving” samples

**Example: laser driven radiation cavity or “hohlraum”**




Laser power

$$\eta P_{Laser}(kJ/ns) = 4.4A_{wall}(cm^2)T_r^{3.3}(heV) + 6.25A_{holes}(cm^2)T_r^4(heV)$$

X-ray conversion efficiency

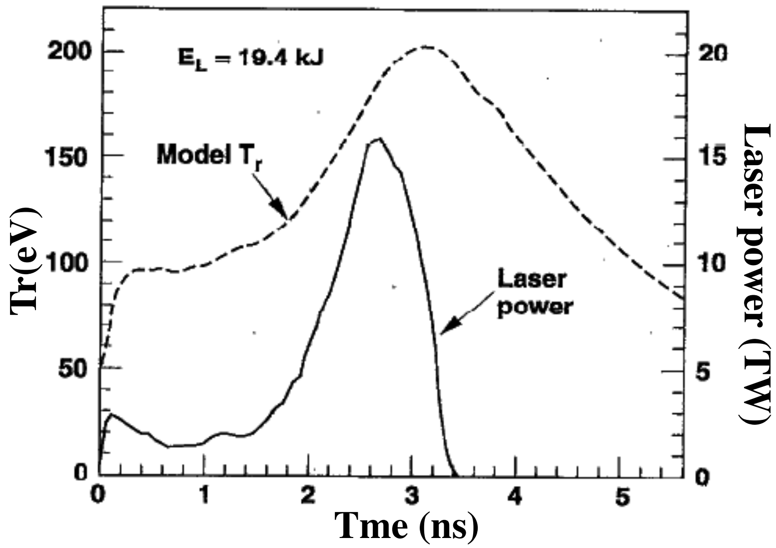
Heat loss into the wall

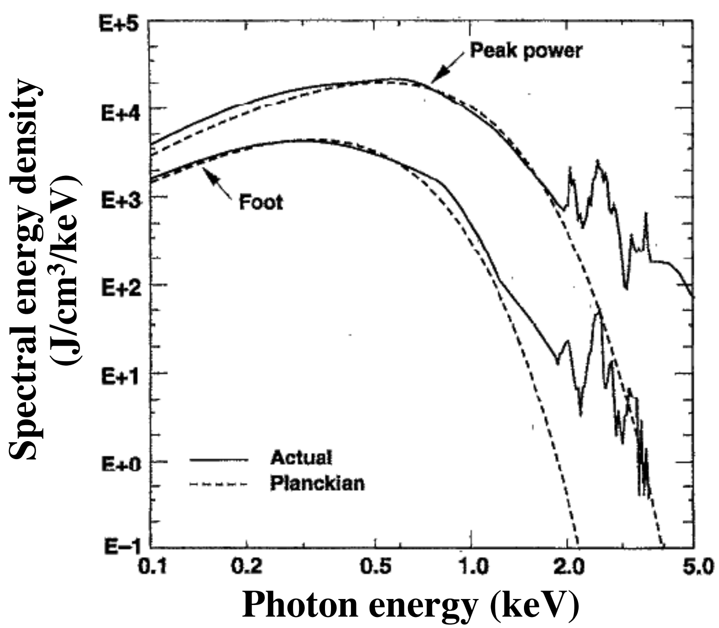
Heat loss out the holes (Stefan’s Law: $P/A \sim \sigma T^4$)

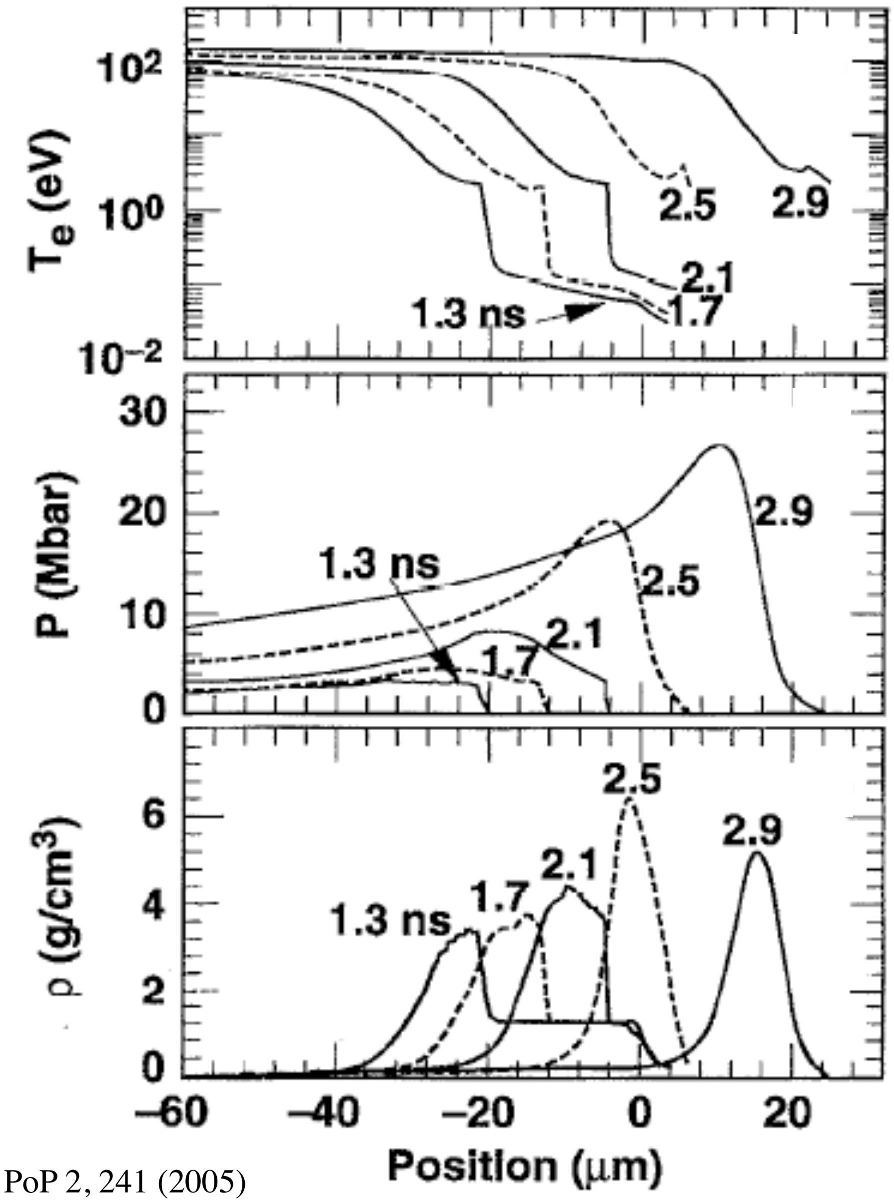
- Typical drive of $P_L$= 20 kJ / 1 ns at $\eta \sim 0.6$ gives $T_r \sim 2.16$ heV = 216 eV
- Corresponding ablation pressure: $P_{abl} \sim (3\ \text{Mbar})T_r^{3.5} = (3\text{Mbar})(2.16\ \text{heV})^{3.5} = 44$ Mbar

[Lindl, *Inertial Confinement Fusion* (Springer, 1998); PoP 2, 3933 (1995); Rosen, Phys. Plasmas 6, 1690 (1999)]

# Generic example of parameters for a radiatively ablated, CH(3%Br) foil compression, acceleration

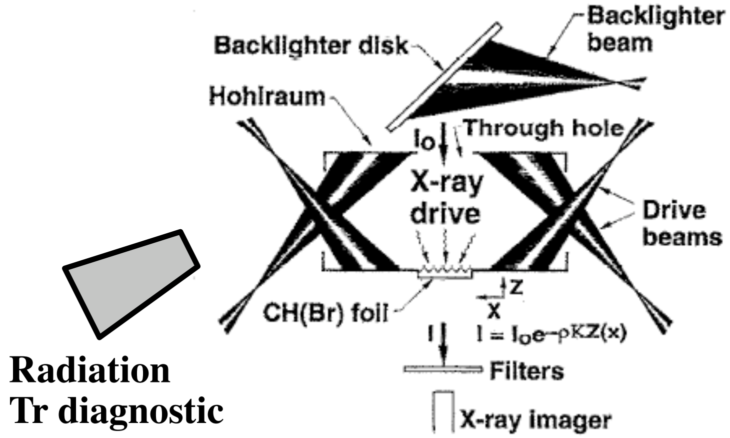


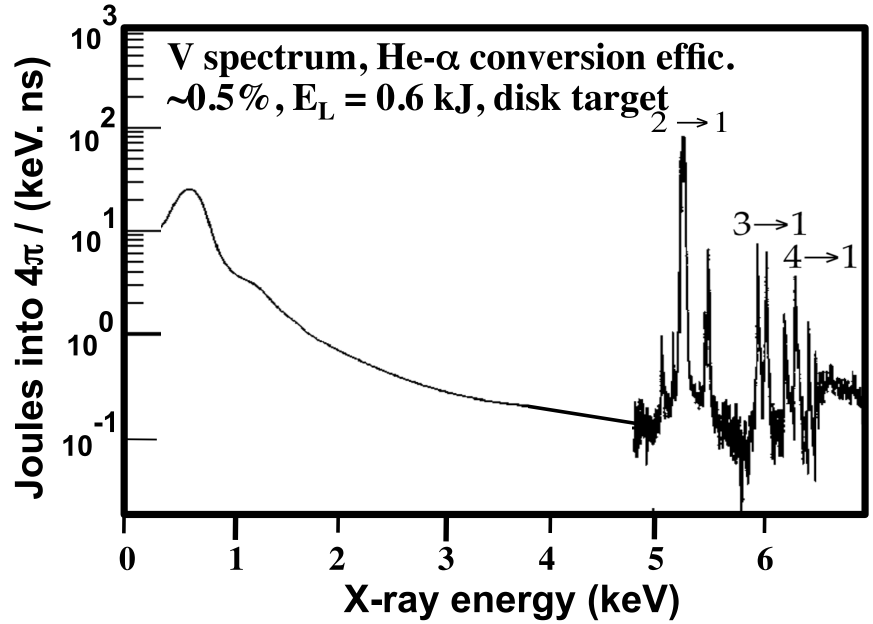



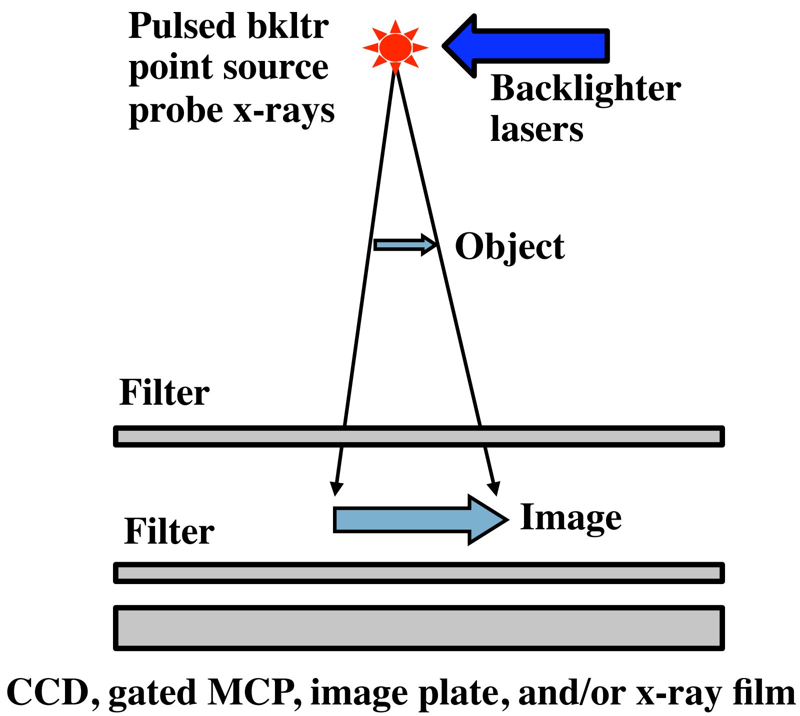



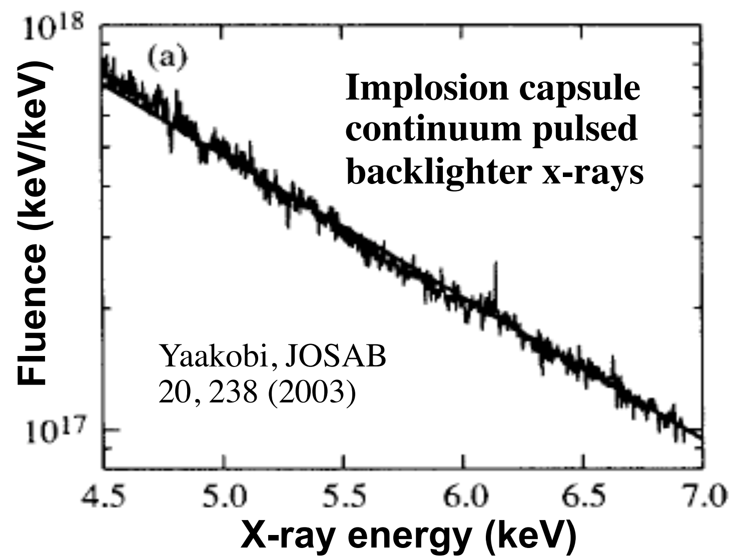

Remington, PoP 2, 241 (2005)

# One way to diagnose laser experiments is will a bright, pulsed source of "backlighter" x-rays



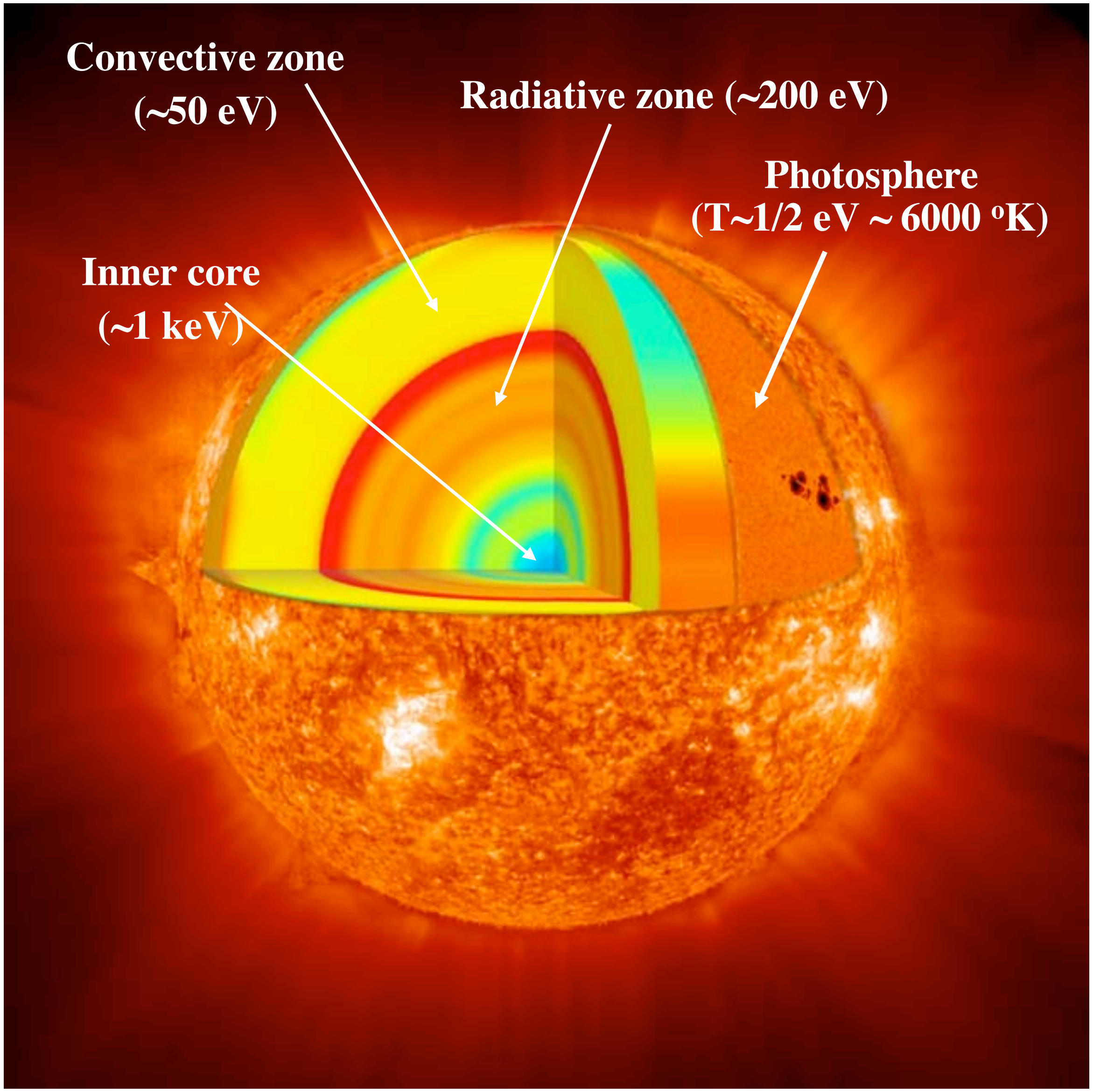



# Hohlraum temperatures are put into perspective by comparing with the temperature of the sun

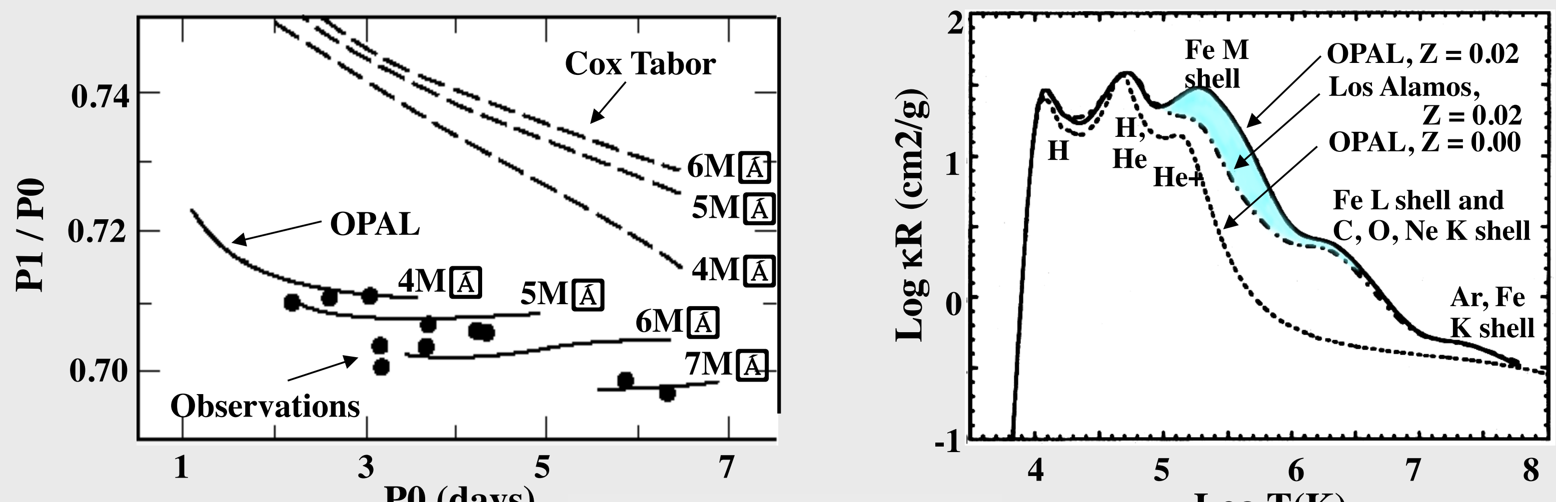
## Sun




## How hot is 200 eV?

- 200 eV = 400 x temperature at the surface of sun
- 200 eV = 2 million deg., which is the temperature at about half way to the center of the sun, in the radiative zone

# Opacity experiments have led to an improved understanding of Cepheid Variable pulsation and stellar dynamics




[Rogers & Iglesias, Science 263, 50 (1994); Da Silva et al., PRL 69, 438 (1992)]

- The original simulations of Cepheids predicted pulsation periods longer than observed
- The measured opacities of Fe under relevant conditions were larger than calculated:

$$P \sim D_{star} / c_s \sim T_e^{-1/2} \sim \kappa_\nu^{-1/2n}, \text{ if } \kappa_\nu \sim T_e^n$$

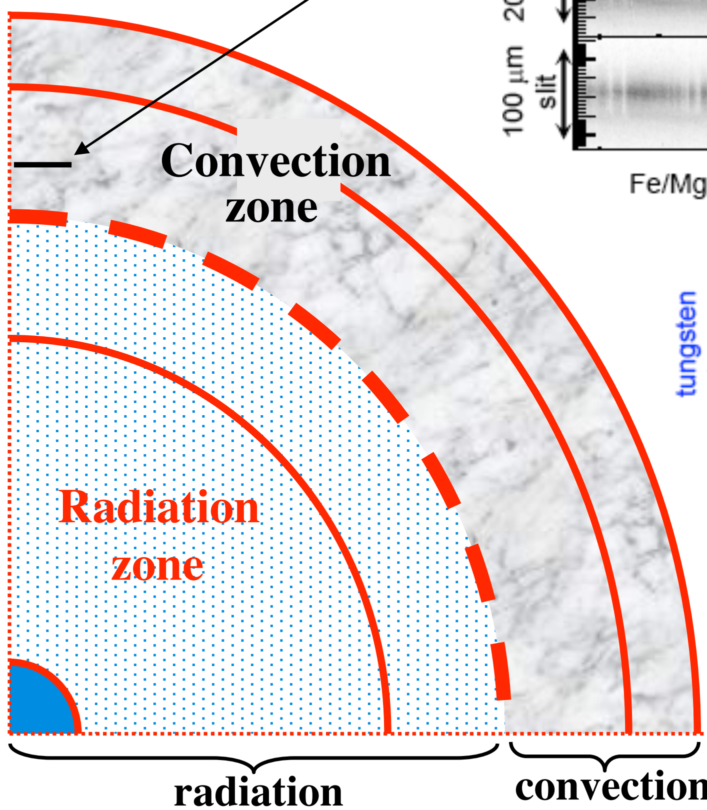
- Exprmts were done on the Nova laser and Saturn facility

- New OPAL simulations of the opacity of Fe reproduced the data
- This allowed Cepheid Variable pulsations to be correctly modeled
- NIF should allow opacities to be measured under stellar radiative zone conditions

# Opacity and radiation transport control the temperature profile inside the star, which affects all aspects of the stellar dynamics

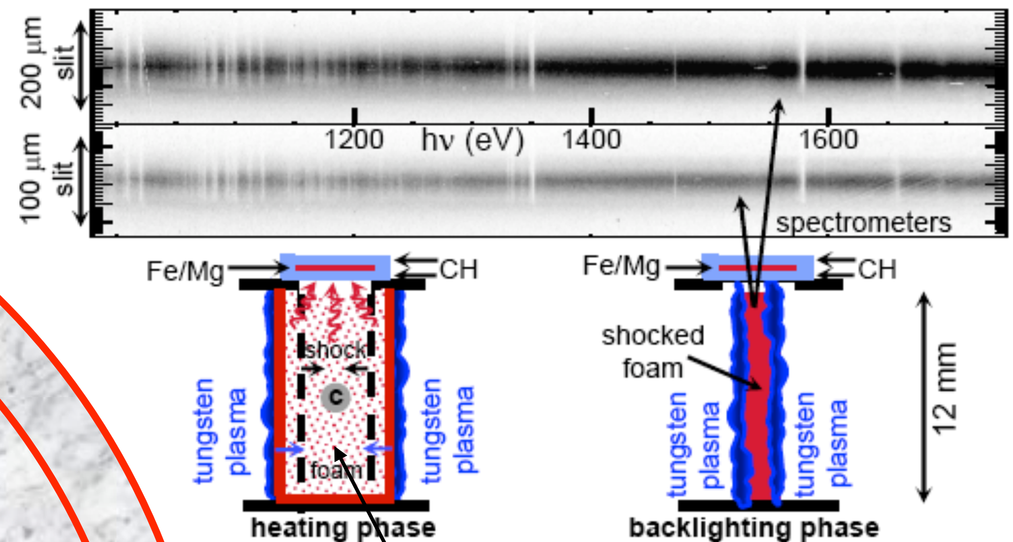
| T(eV) | $n_e$($cm^{-3}$) | $r/R_0$ |
|---|---|---|
| 54 | $1\times10^{22}$ | 0.90 |
| 182 | $9\times10^{22}$ | 0.71 |
| 293 | $4\times10^{23}$ | 0.55 |
| 1360 | $6\times10^{25}$ | 0 |

Solar model :
J.N. Bahcall,
RMP 54, 767 (1982)




[Courtesy of Jim Bailey (2007)]

**Opacity experiment at Z: Fe+Mg at 156 eV**



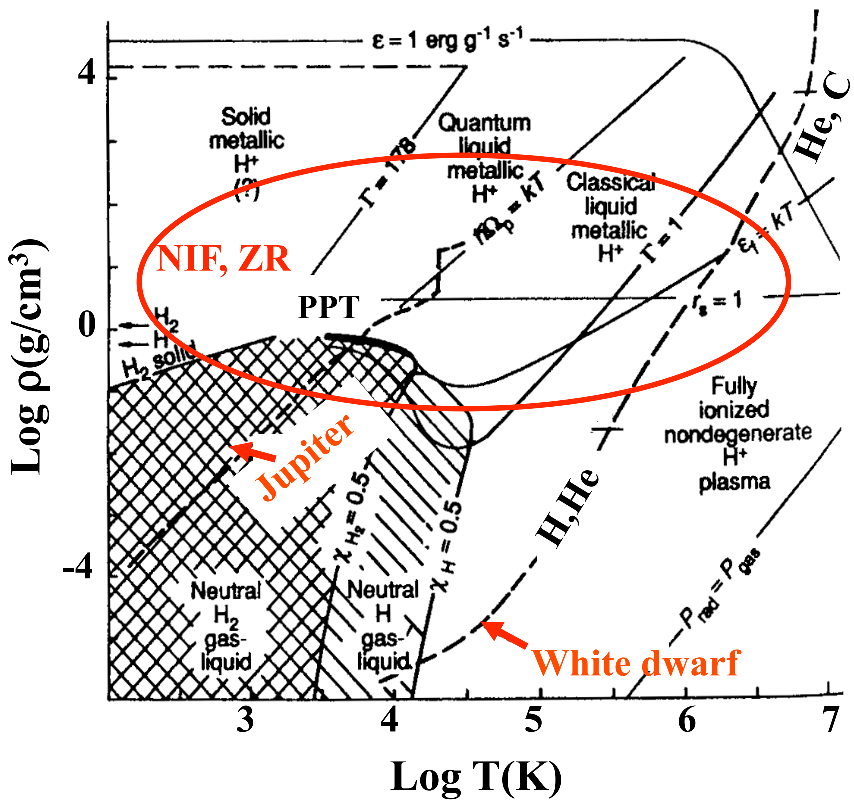

**Radiative shock launched into low-density foam, creates a "dynamic hohlraum" rad. source, heating the Fe/Mg opacity sample**

[Jim Bailey, PRL 99, 265002 (2007); and PoP 13, 056301 (2006)]

- **Hohlraums driven by Z-pinches or lasers are ideal for opacity measurements at stellar interior conditions**
- **Next generation facilities - ZR, NIF - will reach conditions relevant to the stellar radiative zone**

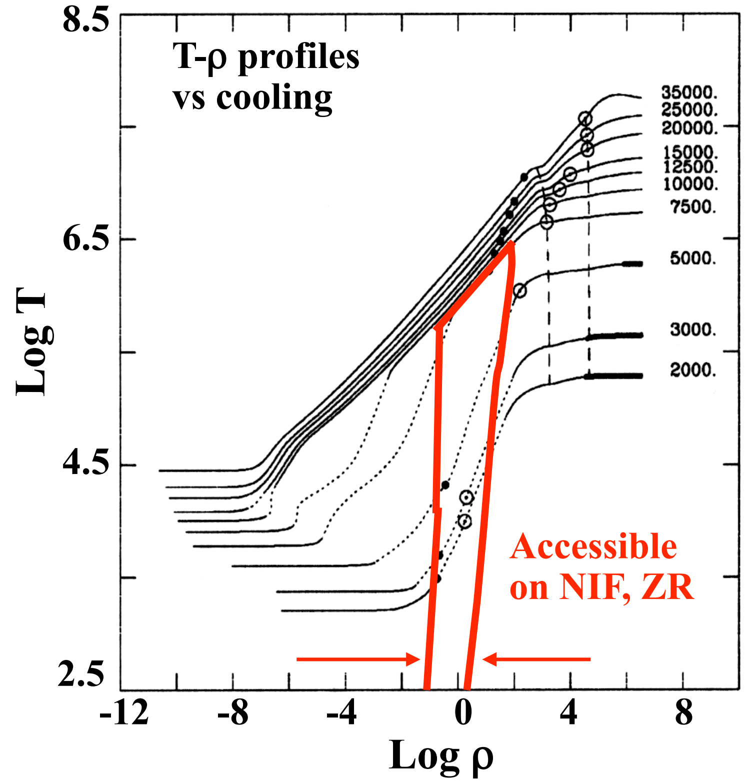
# Experiments relevant to white dwarf envelope properties (EOS, opacity) should be possible on NIF, ZR

**Phase diagram of hydrogen**




Van Horn,
Science 252, 384 (1991)

**Phase diagram for white dwarfs**

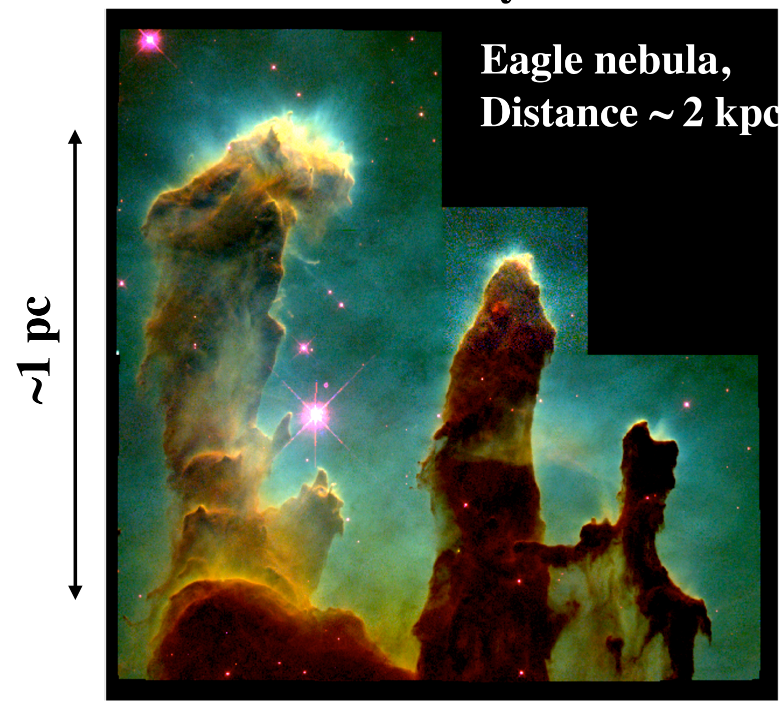



Fontaine et al.,
Pub. Astron. Soc. Pacific 113, 409 (2001)

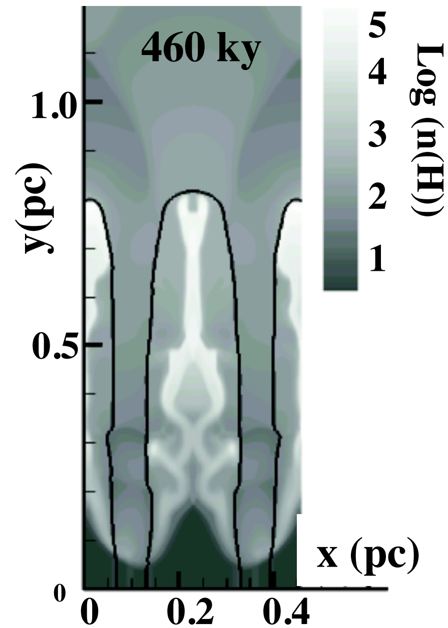
- **NIF, ZR can access WD conditions in the envelope, where the EOS and opacity are uncertain**

# Unique regimes relevant to radiatively driven molecular can also be achieved

## Stellar birth dynamics?

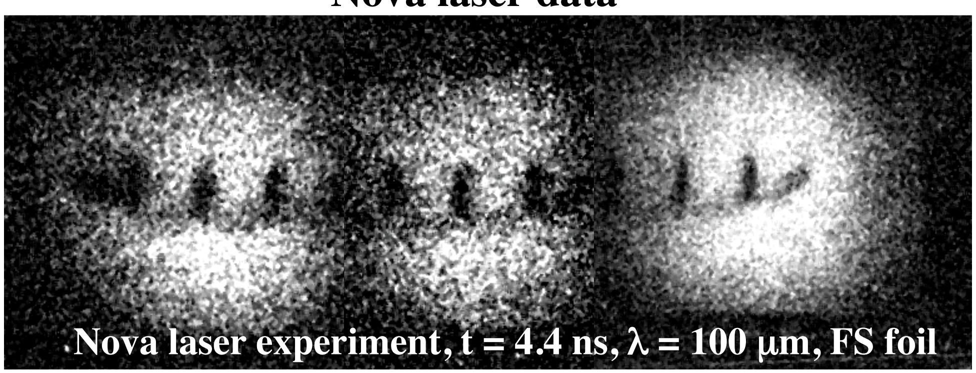



[J. Hester et al., AJ 111, 2349 (1996)]

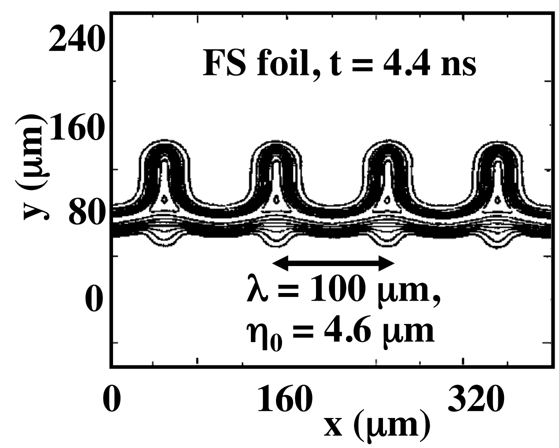



[A. Mizuta, ApSS 298, 197 (2005);
D.D. Ryutov, ApSS 307, 173 (2007)]

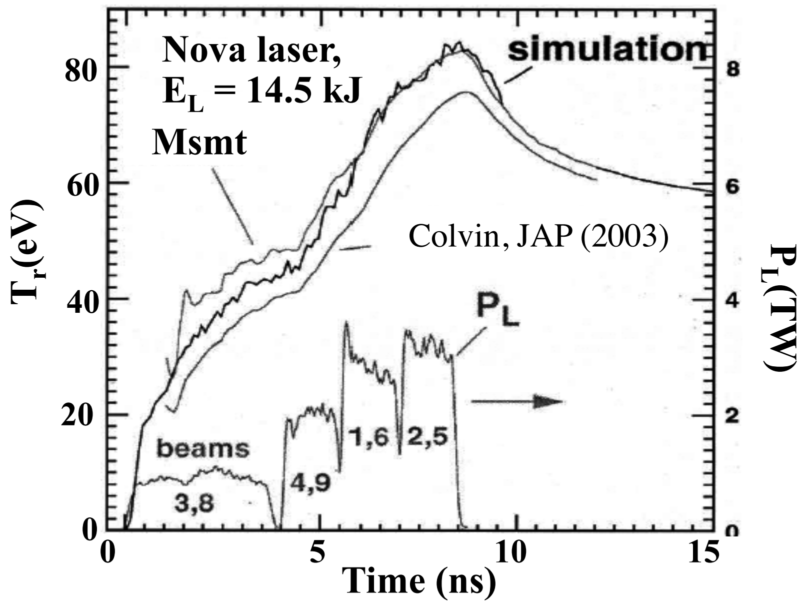
## Nova laser data

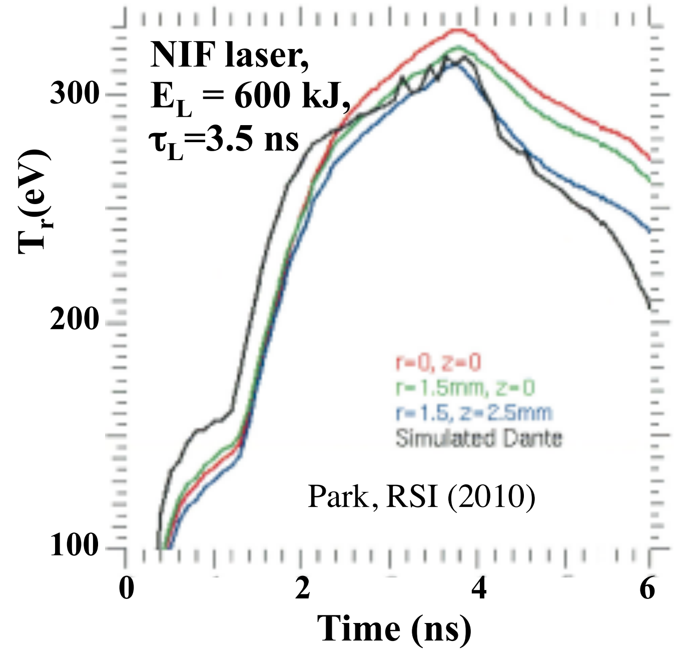


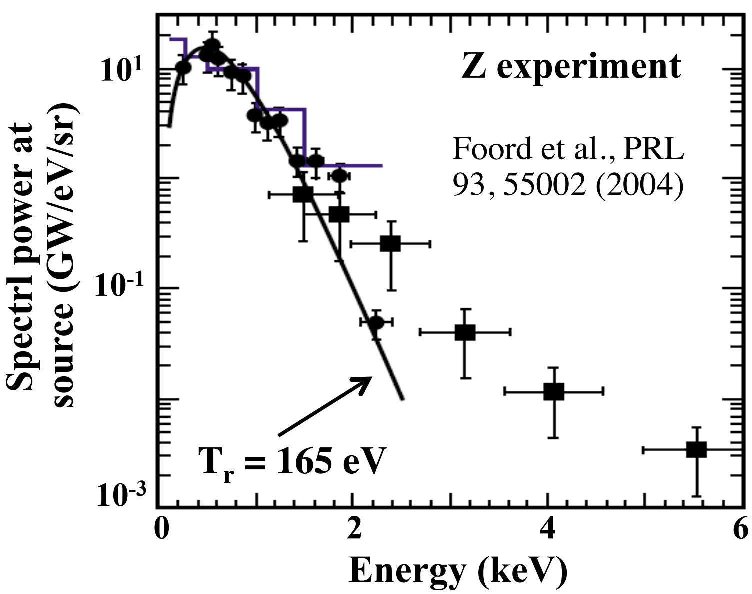

[B.A. Remington et al., Phys. Fluids B 5, 2589 (1993)]

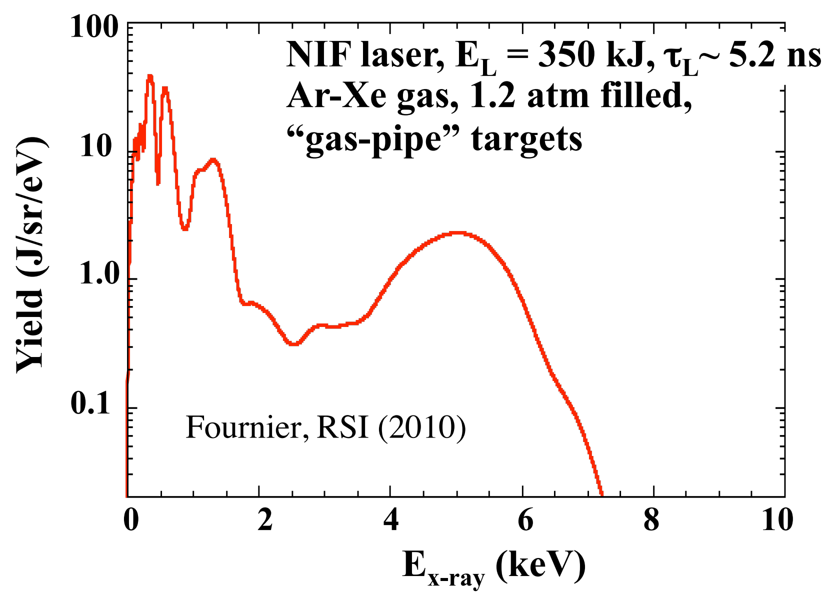


# Calibrated radiation sources could be used for exoplanet radiation-atmosphere, and/or GRB x-ray flux induced dust fragmentation studies



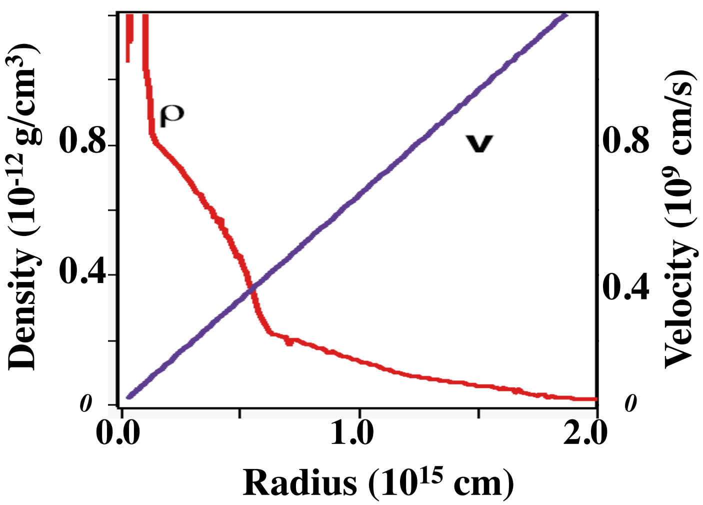
## Static radiation flow experiments have been developed. Radiation flow experiments through an expanding atmosphere have been designed.

- **Static rad-flow experiments access both diffusive and non-diffusive regimes**

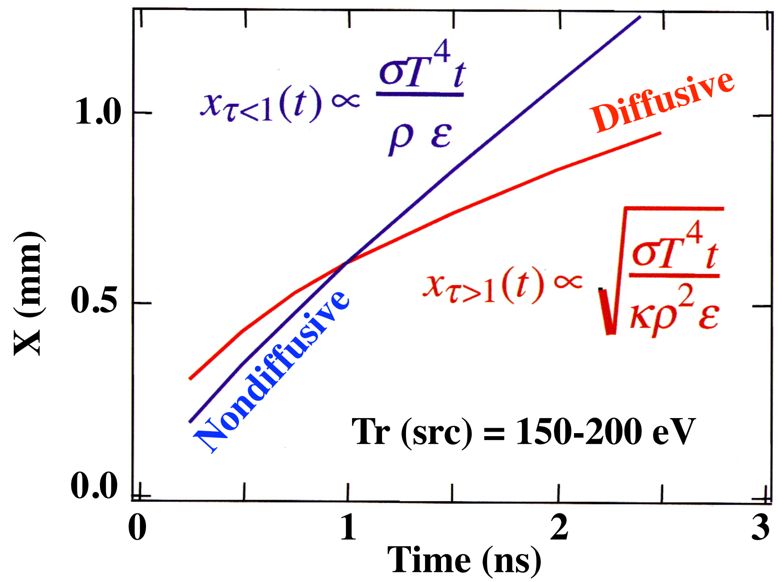
C.A. Back et al., Phys. Plasmas 7, 2126 (2000)

$$\frac{\text{radiative energy flux}}{\text{material energy flux}} = \frac{\sigma T^4}{\varepsilon \rho c_s} >> 1$$

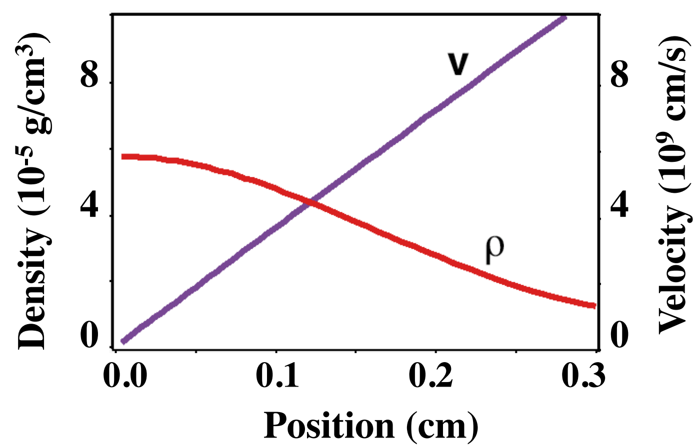
- **SNe require expanding atmospheres**
- **Relevant experiments possible on Z**




**Static atmosphere on Omega**



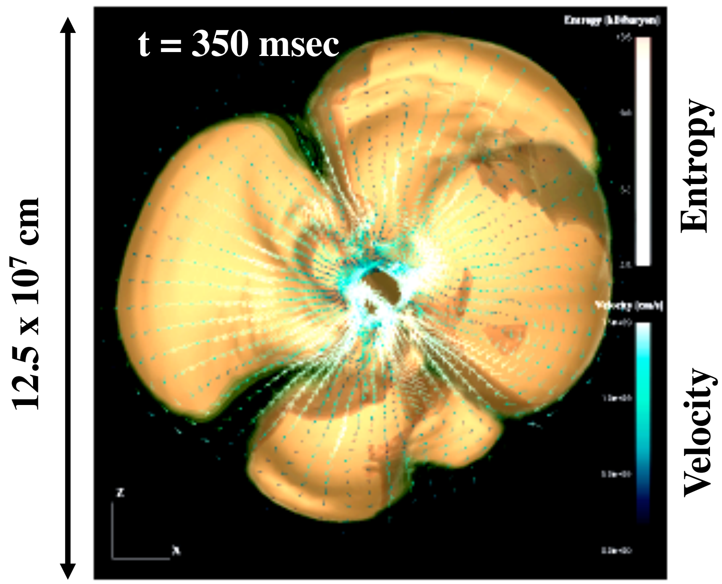

**Expanding atmos. design for NIF(?)**




*Tina_rad_flow.ppt*

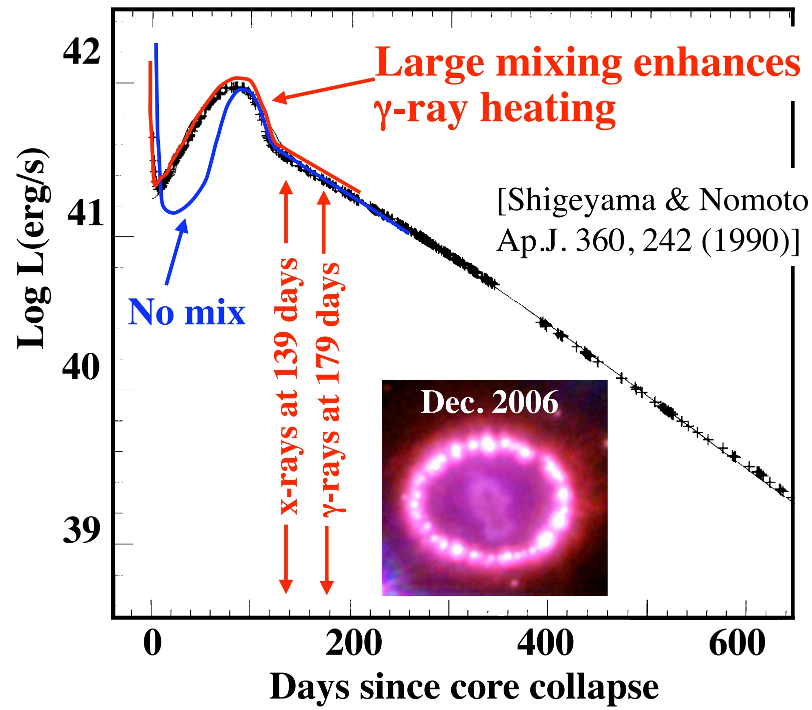
## Understanding supernovae requires understanding neutrino- and radiation-hydrodynamics in turbulent flows with large gradients

### Spherical Accretion Shock Instability (SASI) model




[Iwakami and Ohnishi, ApJ 678, 1207 (2008)]

### SN1987A luminosity (light curve) measurements did not match simulations



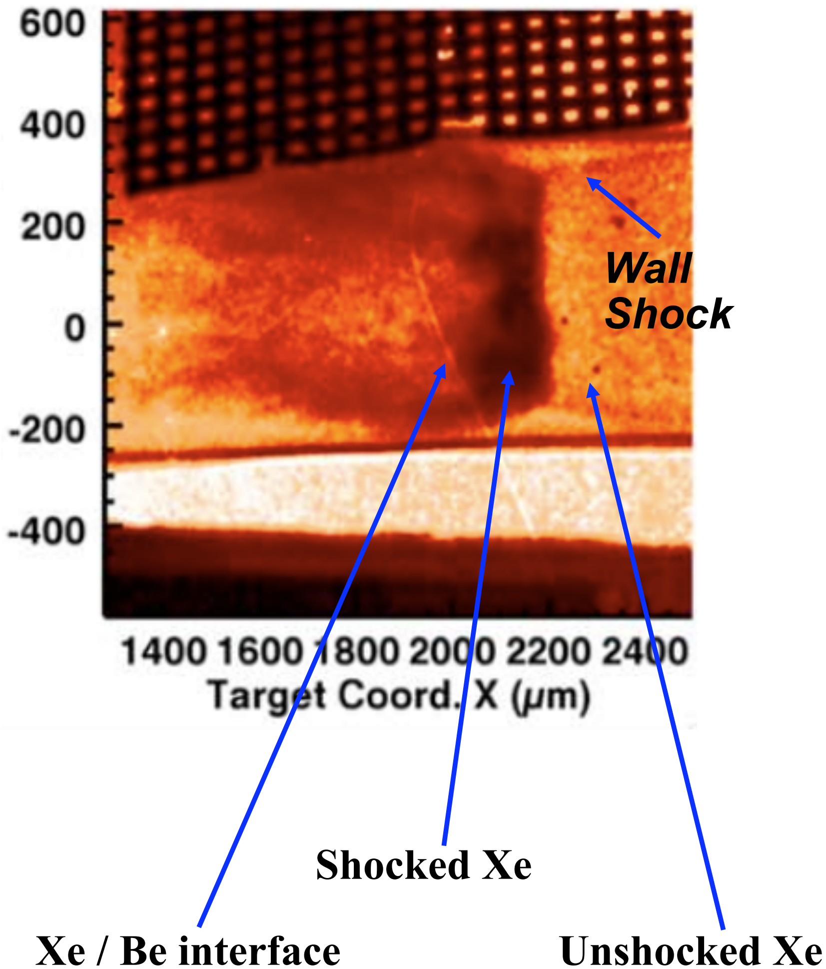

[D. Arnett, *Supernovae* (Princeton Univ. Press, 1996)]

- **Core-collapse launched shock stalls**
- **Neutrino heating + SASI refresh shock**
- **Explosion restarted**

- **Uncertainties in our understanding:**
  - **Turbulent mixing; its affect on core inversion**
  - **Deep nonlinear, 3D multimode coupling**
  - **Jet induced turbulent mix**
  - **Low mode asymmetry induced turbulent mix**
  - **Turbulent mass stripping off RT spikes**

# Radiative shock experiments have been developed on Omega that illustrate unique shock dynamics

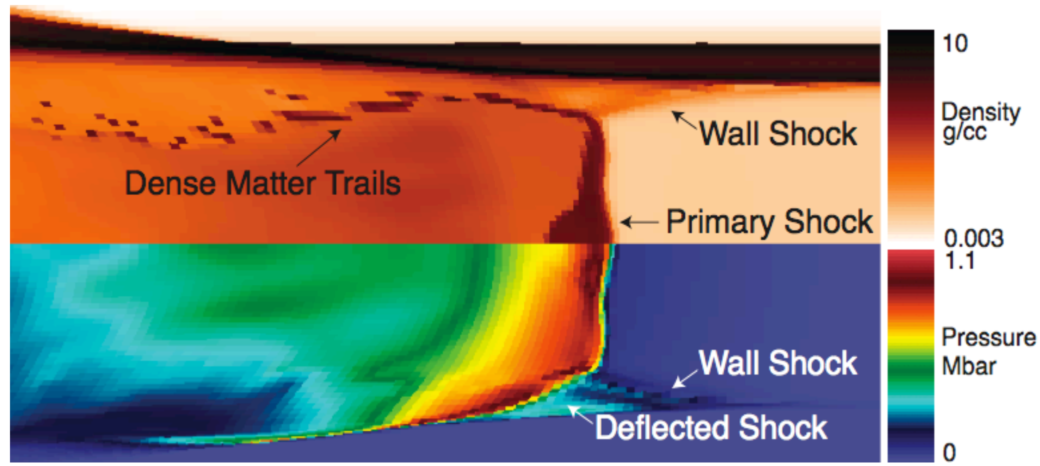
**Omega data**




**Point projection, 5.2 keV (V-He$_\alpha$), 200 ps bkltr**

[F. Doss et al., PoP 16, 112705 (2009) ]

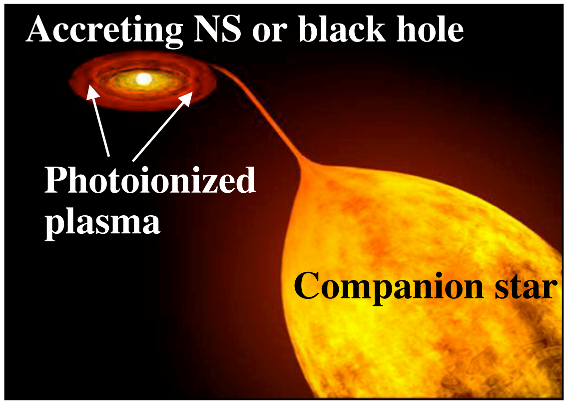
**HYDRA simulation**

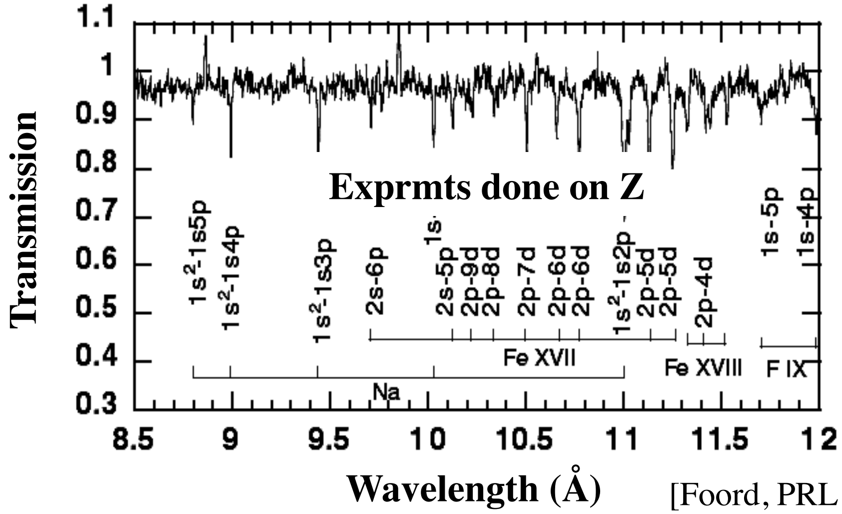



| Shot Number | Precursor Mach Number | Unheated Gas Mach Number |
|---|---|---|
| 52661 | 3.00 | 589 |
| 52663 | 2.93 | 576 |
| 52664* | 2.73 | 537 |
| 52665 | 3.12 | 613 |
| 52667 | 2.92 | 574 |
| 52668 | 3.37 | 662 |
| 52669 | 3.06 | 602 |
| 52670 | 3.01 | 592 |
| 52671 | 3.25 | 639 |

# Accreting neutron stars and black holes are observed by their x-ray spectral emissions

• **Understanding rad. dominated photoionized plasmas essential for interpreting these data**

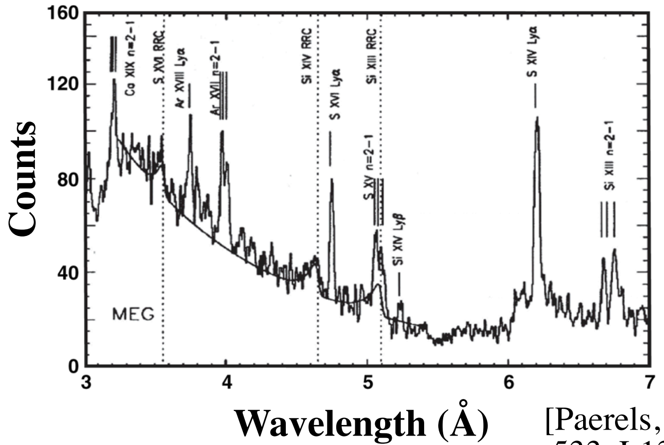



[Foord, PRL 93, 55002 (2004)]

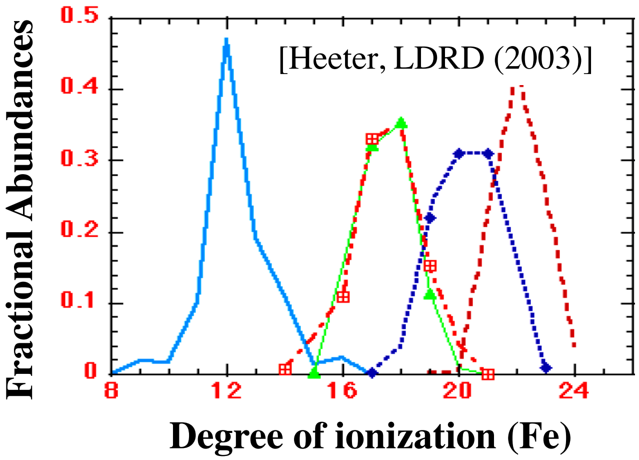
**$\xi = L/nr^2 \sim 10^2\text{-}10^3$ in relevant regimes**

**Chandra Spectrum of Cyg X-3 X-ray Binary**



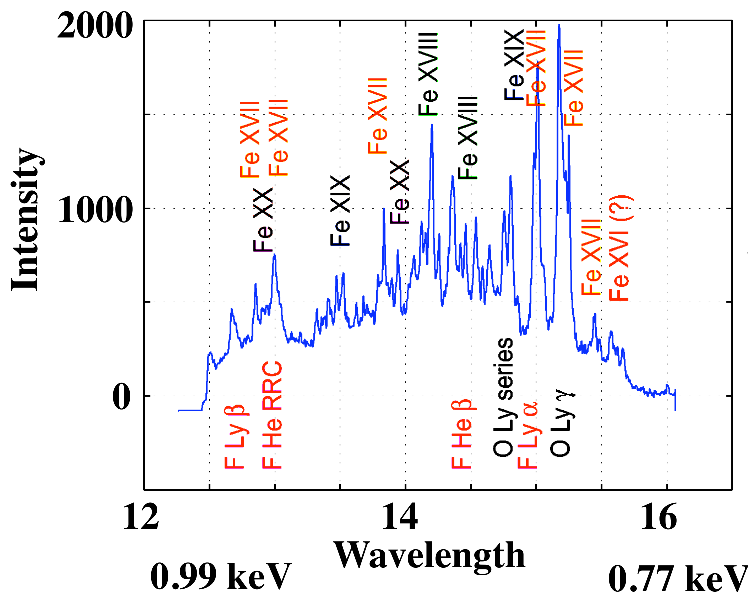

[Paerels, Ap.J.Lett. 533, L135 (2000)]

**Prior to experiment, models disagree by ~2x**

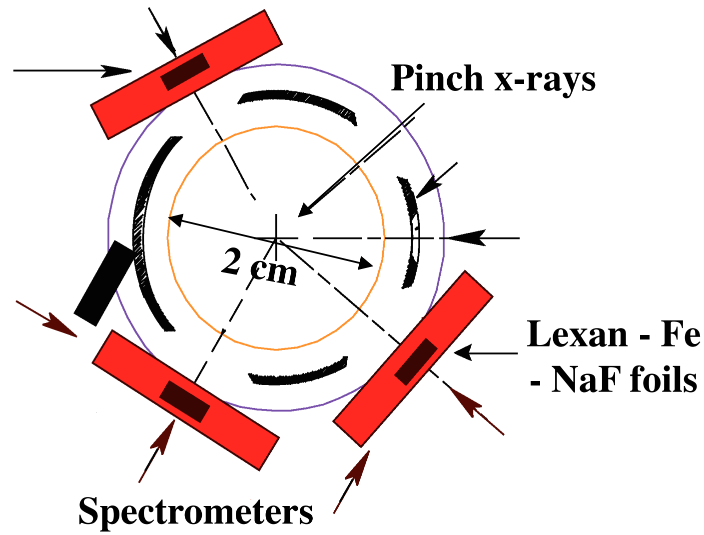



• **Models of photoionized plasmas can be tested in scaled experiments at relevant conditions**

# HED experiments on Z have demonstrated the potential for radiation-dominated photoionized plasmas

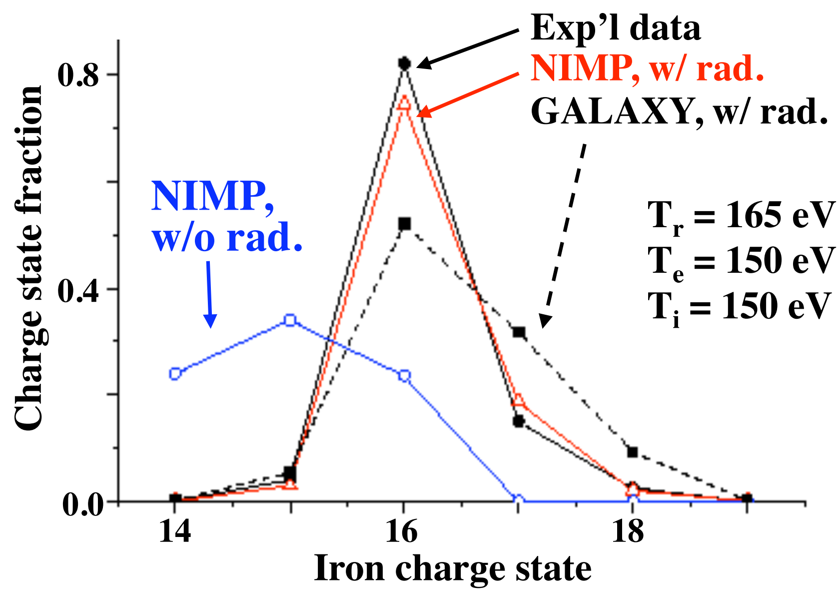



$T_e$ ~30 eV,
$T_r$ ~180 eV,
$n_e$ ~1.5x10$^{19}$cm$^{-3}$,
ξ ~ 47




[R.F. Heeter *et al.*, RSI 72, 1224 (2001)]

- **Experiments under nearly relevant conditions, ξ ~ 25, demonstrated at 'Z'**
- **Astrophysics codes disagree on <Z> by ~2x, showing the need for lab. data**




[S. Rose et al., J. Phys. B: At. Mol. Opt. Phys. 37, L337 (2004)]

# Call for proposals: fundamental science at Omega, NIF


## National Laser Users' Facility Program (NLUF)

Synopsis | Full Announcement | Application

The synopsis for this grant opportunity is detailed below, following this paragraph. This synopsis contains all of the updates to this document that have been posted as of **05/15/2008** . If updates have been made to the opportunity synopsis, update information is provided below the synopsis.

If you would like to receive notifications of changes to the grant opportunity click send me change notification emails . The only thing you need to provide for this service is your email address. No other information is requested.

*Any inconsistency between the original printed document and the disk or electronic document shall be resolved by giving precedence to the printed document.*

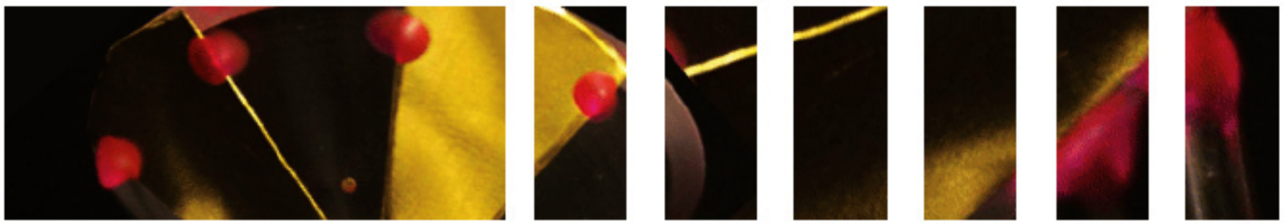
| | |
|---|---|
| Document Type: | Grants Notice |
| Funding Opportunity Number: | DE-PS52-08NA28649 |

# The 8th HEDLA will be held this March

CALIFORNIA INSTITUTE OF TECHNOLOGY

## HEDLA2010

8th International Conference on High Energy Density Laboratory Astrophysics



**March 15-18, 2010**

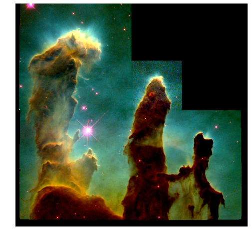
- **Home**
- **Program**
- **Register**
- **Abstract Submission**
- **Travel Information**
- **Hotel Information**
- **Organization**
- **Past Conferences**

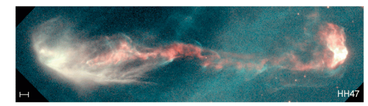
### Welcome

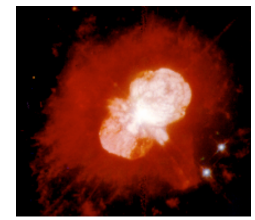
We are pleased to announce the 8th International Conference on High Energy Density Laboratory Astrophysics, to be held March 15-18, 2010 on the campus of California Institute of Technology in Pasadena, California.

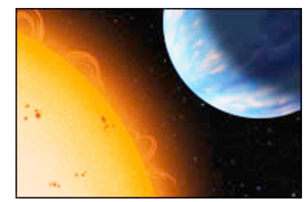
During the past decade, research teams around the world have developed astrophysics-relevant research utilizing high energy-density facilities such as intense lasers and z-pinches. Research is underway in many areas, such as compressible hydrodynamic mixing, strong shock phenomena, radiation flow, radiative shocks and jets, complex opacities, equations of state, superstrong magnetic fields, and relativistic plasmas.

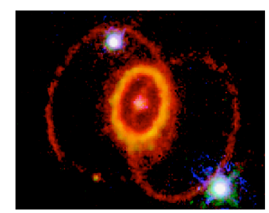
# New opportunities in HEDLA









- NIF, ZR science experiments
- High resolution spectroscopy of radiative hydrodynamic flows
- Radiation-dust interactions re. GRB after-glow curves, exoplanet atmos.
- White dwarf opacities, EOS, cooling rates
- Rad-trn in SNe-relevant expanding atmospheres (vel. grad.)
- SASI re. core-collapse SNe; neutrino “rad–transport”
- Radiative MHD systems with $Re_M > 10^3$
- Radiative hydro systems with $P_r > P_{e,i}$

## Challenges

- Multiple simultaneous diagnostics
- Multiple line-of-sight diagnostics
- Multiple time snapshots / laser or pinch shot
- Higher signal to background, higher resolution diagnostics

## Impact

- Improved diagnostics (HEDLP)
- Tighter linking, with feedback, of theory, simul., obs., exprts