UCRL-PRES-233984

Scaled HED Laboratory Astrophysics

Presentation to the
Nuclear Astrophysics Conference
August 27, 2007
The Martinelli Conference Center
Livermore, CA

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Lawrence Livermore National Laboratory

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under Contract No. W-7405-ENG-48.

The NRC CPU organized the physics of the universe around 11 fundamental questions in their Q2C report

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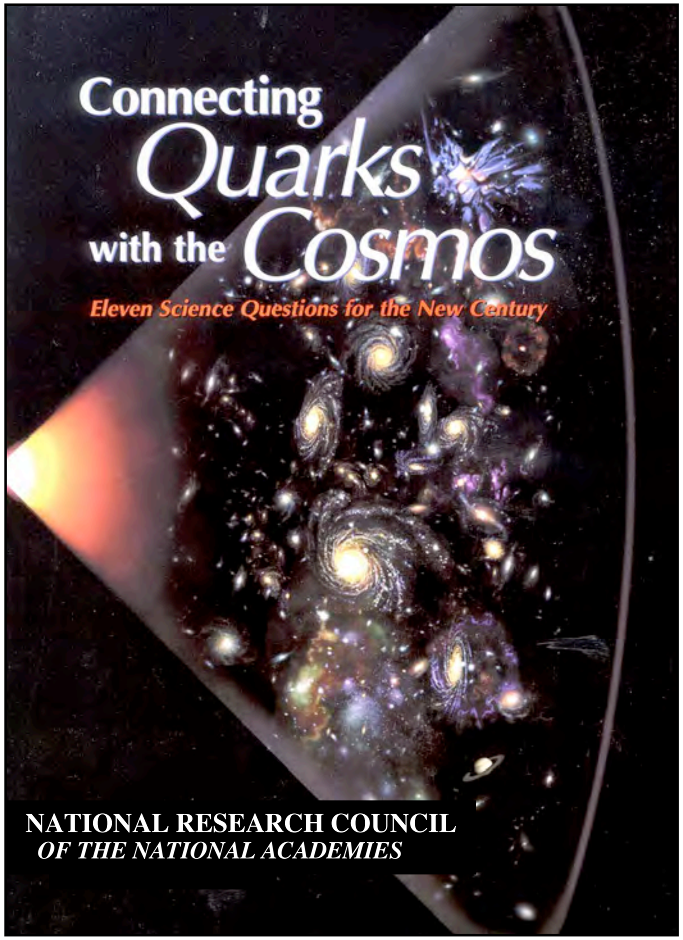
"Q2C" report, Michael Turner *et al.*



[http://www.nap.edu/]

Eleven science questions for the new century:

2. What is the nature of dark energy?
— Type 1A SNe (burn, hydro, rad flow, EOS, opacities)

4. Did Einstein have the last word on gravity?
— Accreting black holes (photoionized plasmas, spectroscopy)

6. How do cosmic accelerators work?
— Cosmic rays (strong field physics, nonlinear plasma waves)

8. Are there new states of matter at extreme HED?
— Neutron star interior (photoionized plasmas, spectroscopy, EOS)

10. How were the elements made and ejected?
— Core-collapse SNe (reactions off excited states, turbulent hydro, rad flow)

Excerpt from the conclusions:

- **HEDP can provide crucial experiments to help interpret astrophysical observations**

The NRC Committee on the Physics of the Universe has presented a science vision for the new century

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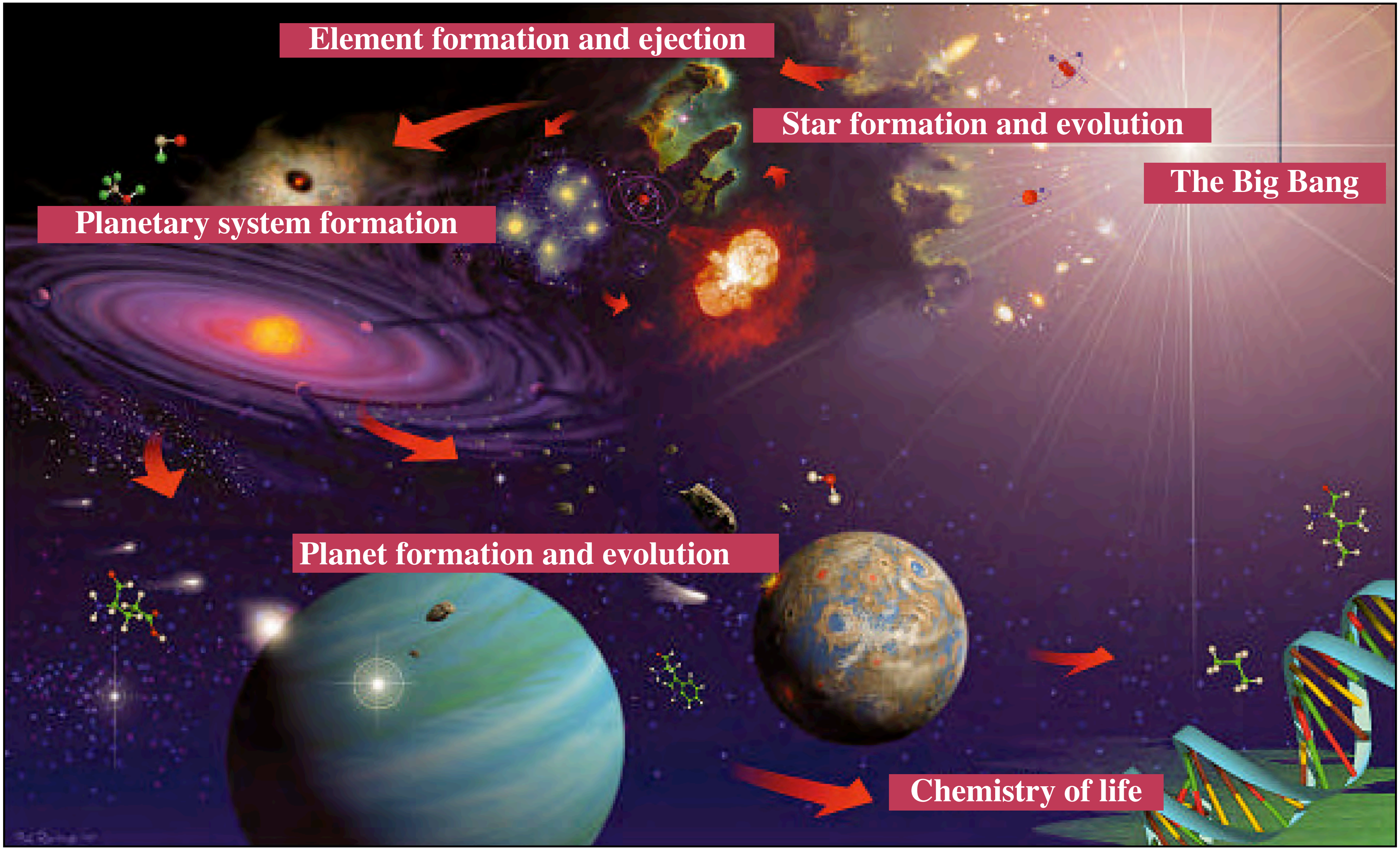
Frontiers of research at the intersection of physics and astronomy



[Fig. 1.1.1, Q2C Report, Michael Turner et al., National Academies Press (2003); <http://www.nap.edu/>]

The NRC committee on HEDP issued the "X-Games" report detailing this new cross-cutting area of physics

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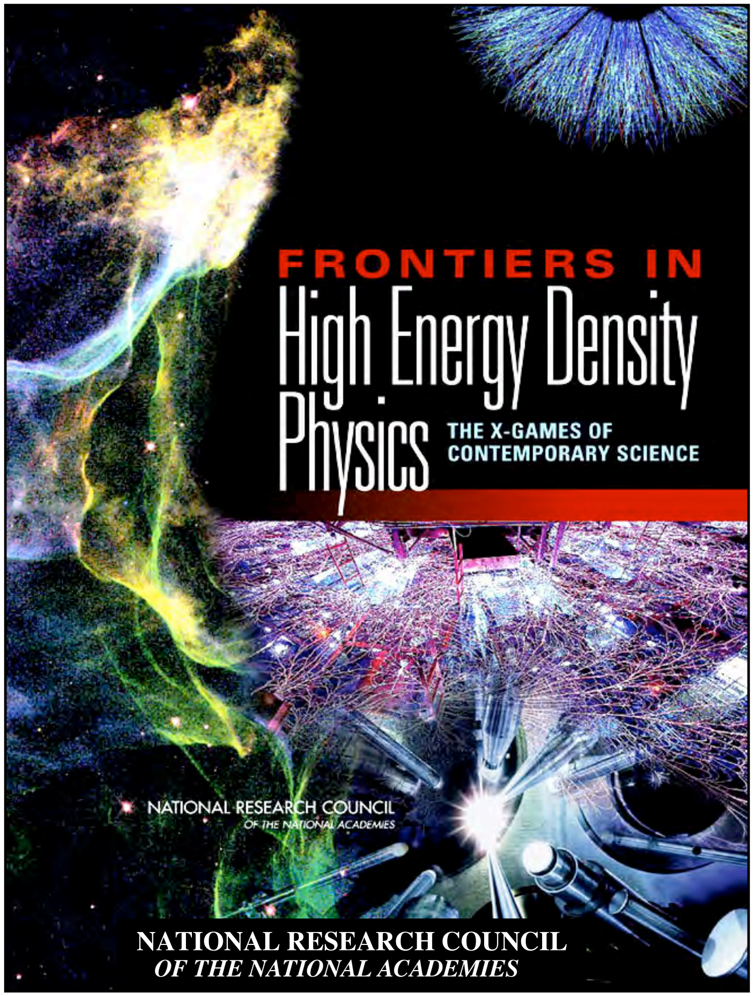
"X-Games" report, Ron Davidson *et al.*



[http://www.nap.edu/]

- **Frontier research opportunities in:**
  - **plasma physics**
  - **laser and particle beam physics**
  - **condensed matter and materials science**
  - **nuclear physics**
  - **atomic and molecular physics**
  - **fluid dynamics**
  - **magnetohydrodynamics**
  - **astrophysics**

Excerpt from the conclusions:

- **HEDP provides unique opportunities in basic, applied, interdisciplinary, and integrated research of the highest intellectual caliber**

High power lasers and magnetic pinch facilities allow matter to be studied under unique HED conditions relevant to astrophysics

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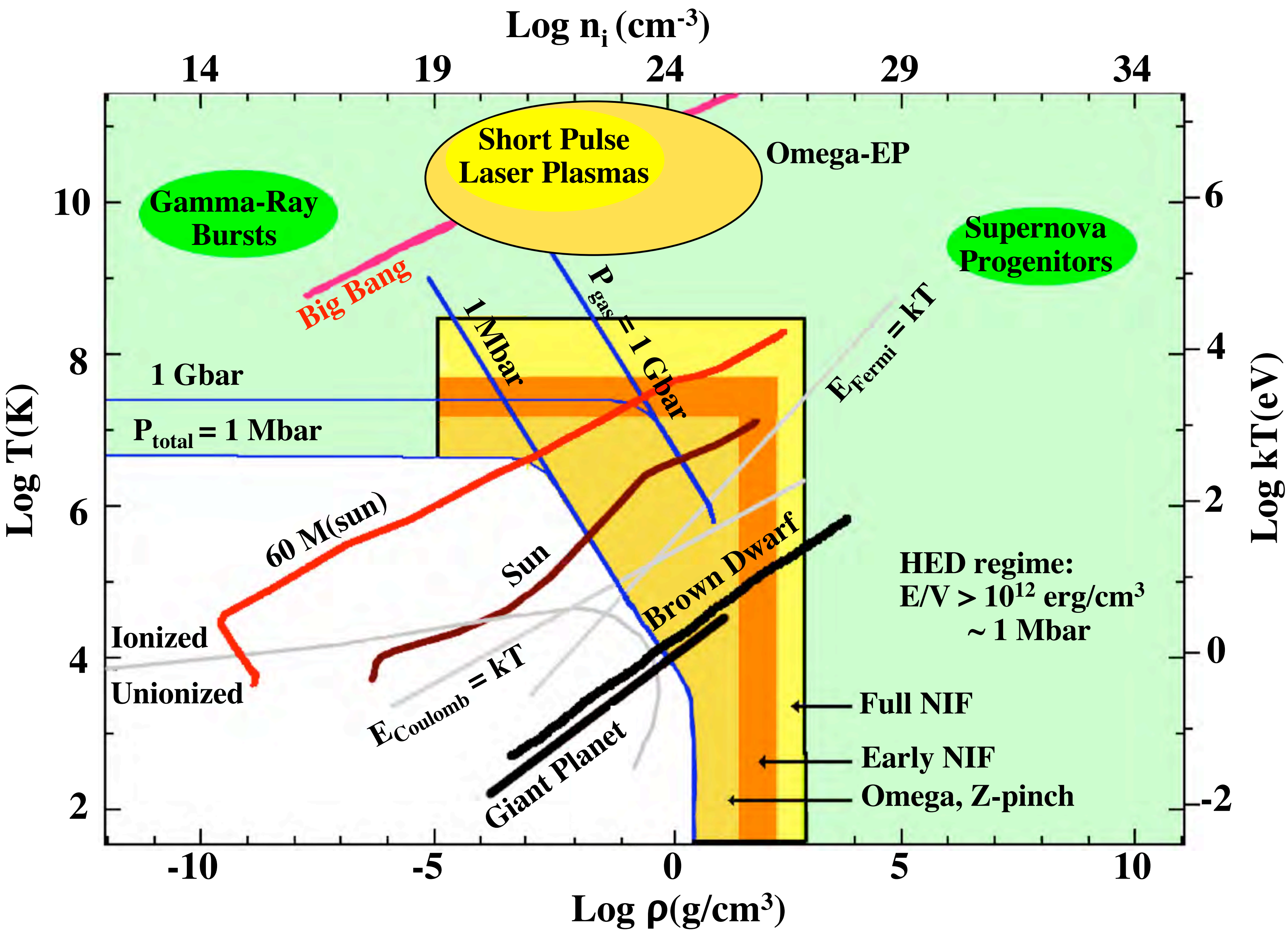

[Fig. 1.1, X-Games Report, Ron Davidson et al., National Academies Press (2003); <http://www.nap.edu/>]

There are extended regimes of astrophysical interest, uniquely accessible on HED facilities

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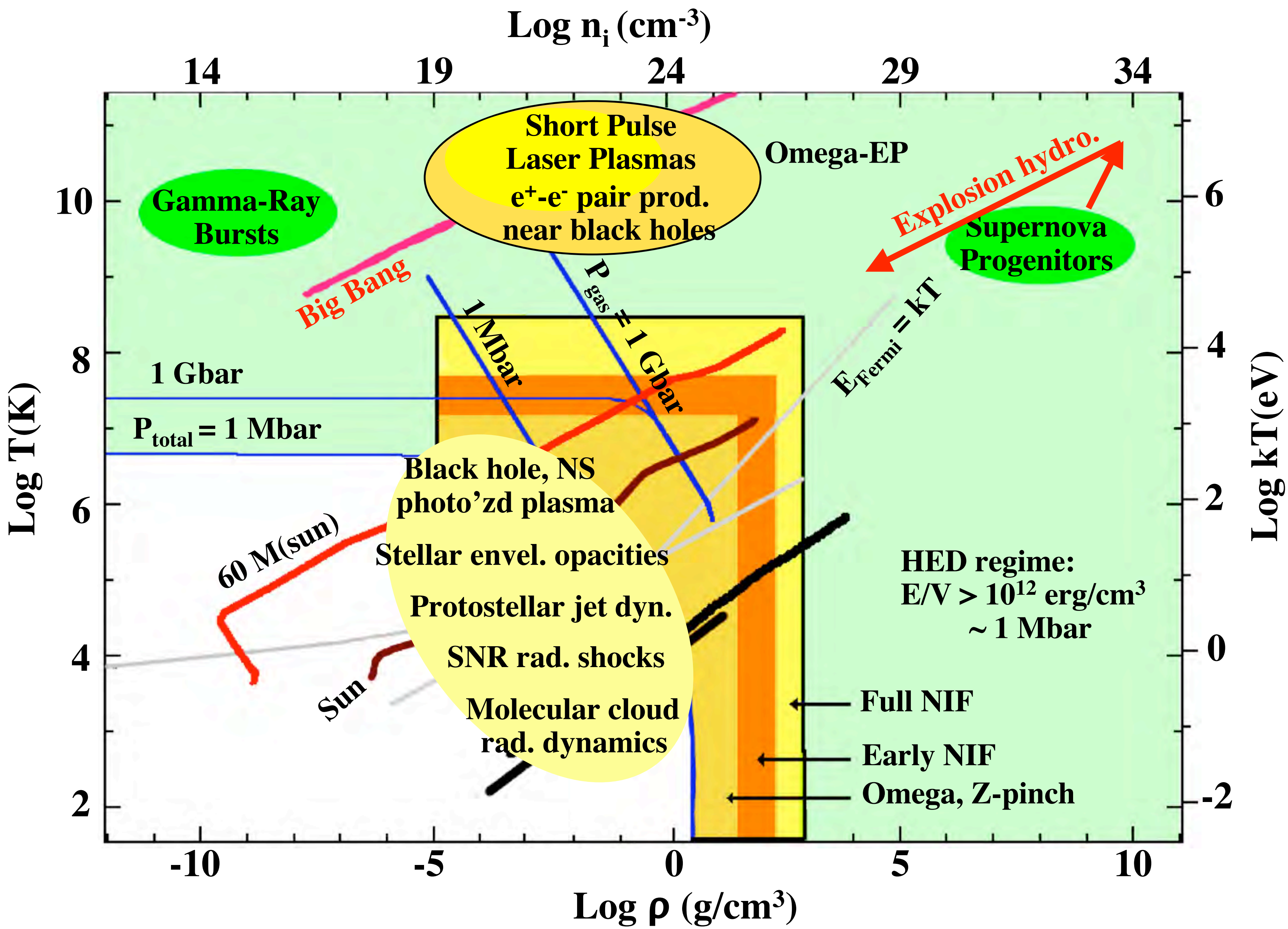

[Fig. 1.1, X-Games Report, Ron Davidson et al., National Academies Press (2003); <http://www.nap.edu/>]

What are HED experimental facilities?

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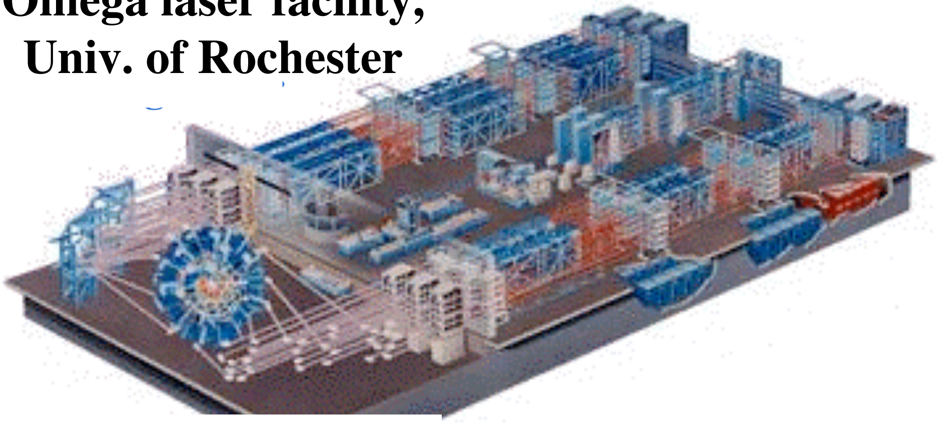
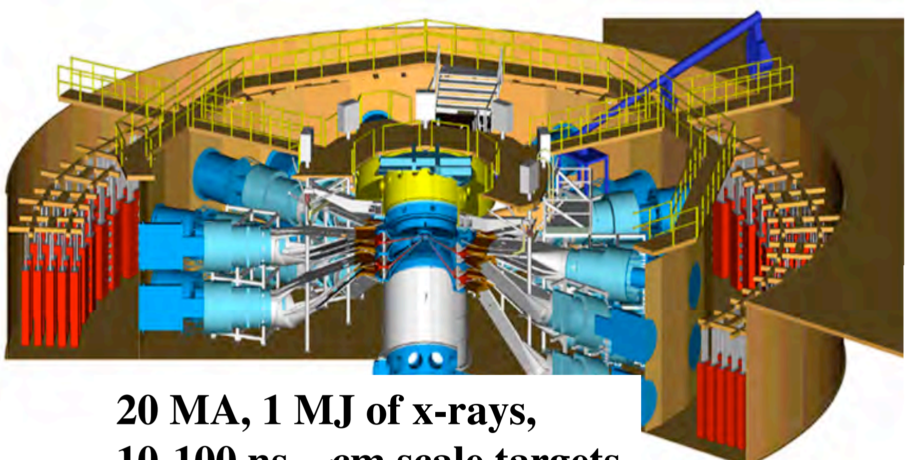
HED facilities deliver:
$E/V \geq 10^{12}$ erg/cm^3 or $P \geq 1$ Mbar
over spatial scales $L \geq 1$ mm

Omega laser facility, Univ. of Rochester



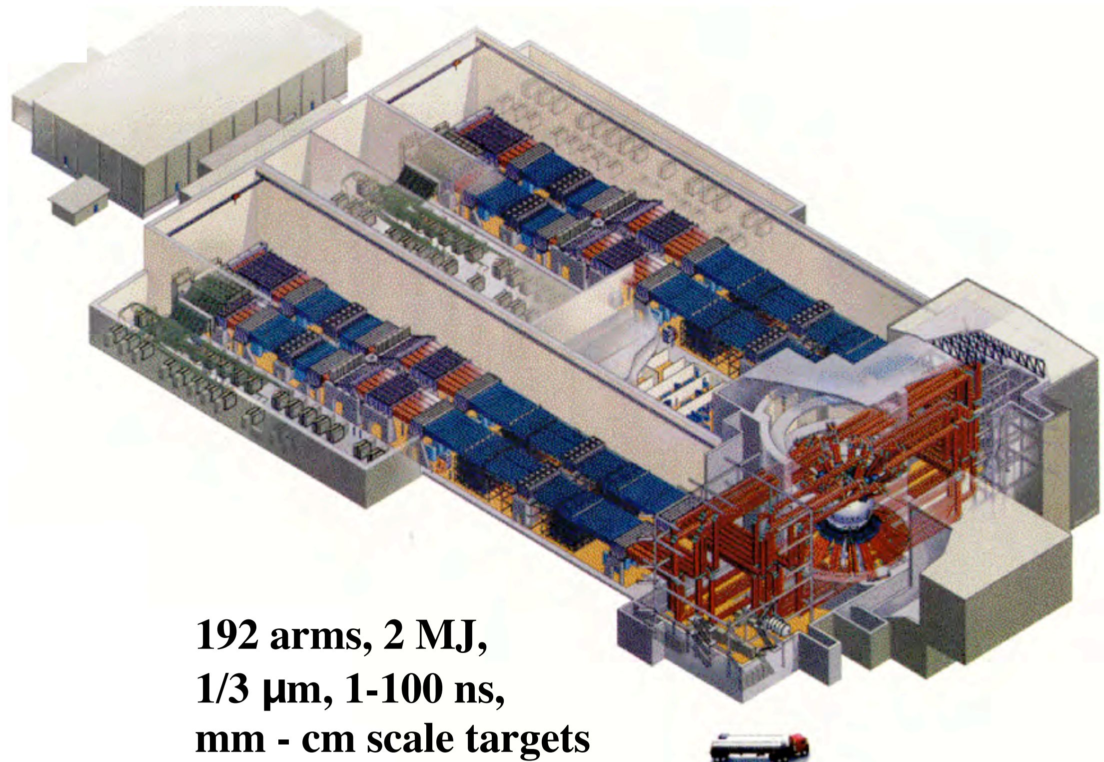
60 arms, 30 kJ,
1/3 µm, 1-10 ns,
~mm scale targets
($E/V \sim 10^{14}$ erg/cm^3)

Z (magnetic pinch) facility, SNLA



20 MA, 1 MJ of x-rays,
10-100 ns, ~cm scale targets
($E/V \sim 10^{13}$ erg/cm^3)

The National Ignition Facility (NIF) at LLNL



192 arms, 2 MJ,
1/3 µm, 1-100 ns,
mm - cm scale targets
($E/V \sim 10^{13}$ - 10^{16} erg/cm^3)

Typical experiments on HED facilities, such as lasers, can generate high pressures for brief intervals

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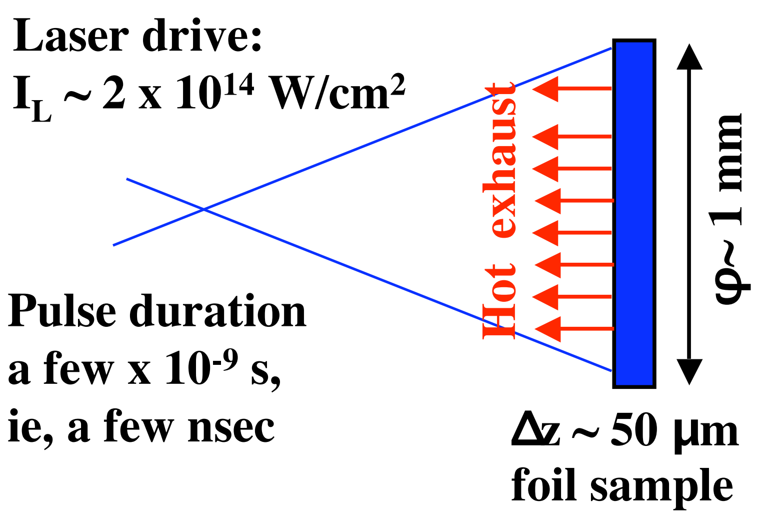
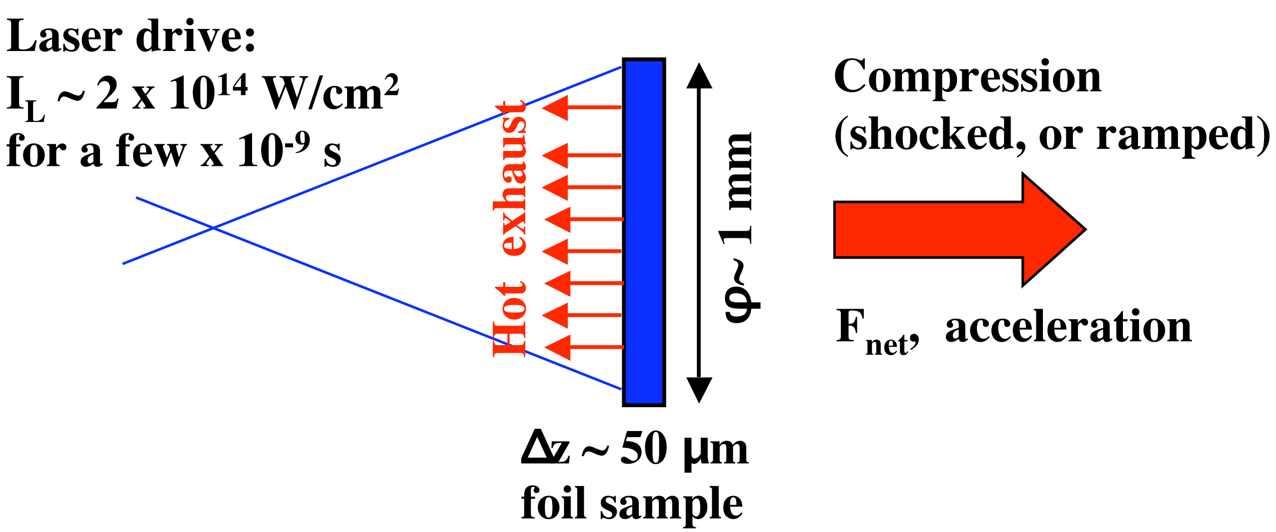


$$P(\text{Mbar}) \approx 40\left[\frac{I_{15}}{\lambda_{(\mu m)}}\right]^{2/3} = 40\left[\frac{0.2}{1/3\ \mu m}\right]^{2/3} \approx 30\text{ Mbar} = 30 \times 10^{12}\text{ dyne/cm}^2 = 3\text{ TPa}$$

[Lindl, *Inertial Confinement Fusion* (Springer, 1998); and Phys. Plasmas 2, 3933 (1995)]

These high pressures can generate very high compressions or accelerations for brief intervals



$$P(\text{Mbar}) \approx 40\left[\frac{I_{15}}{\lambda_{(\mu m)}}\right]^{2/3} = 40\left[\frac{0.2}{1/3\ \mu m}\right]^{2/3} \approx 30\ \text{Mbar} = 30 \times 10^{12}\ \text{dyne/cm}^2 = 3\ \text{TPa}$$

- Newton's 2nd law, $P = \rho \cdot \Delta z \cdot g$, gives $g = 6 \times 10^{15}$ cm/s^2 = 60 µm/ns^2 ~ $(10^{12} - 10^{13})\, g_0$, yielding very high accelerations over a few nsec

[Lindl, *Inertial Confinement Fusion* (Springer, 1998); and Phys. Plasmas 2, 3933 (1995)]

Typical experiments on high energy lasers use multiple beams to both generate the high pressure conditions and diagnose the response in-flight

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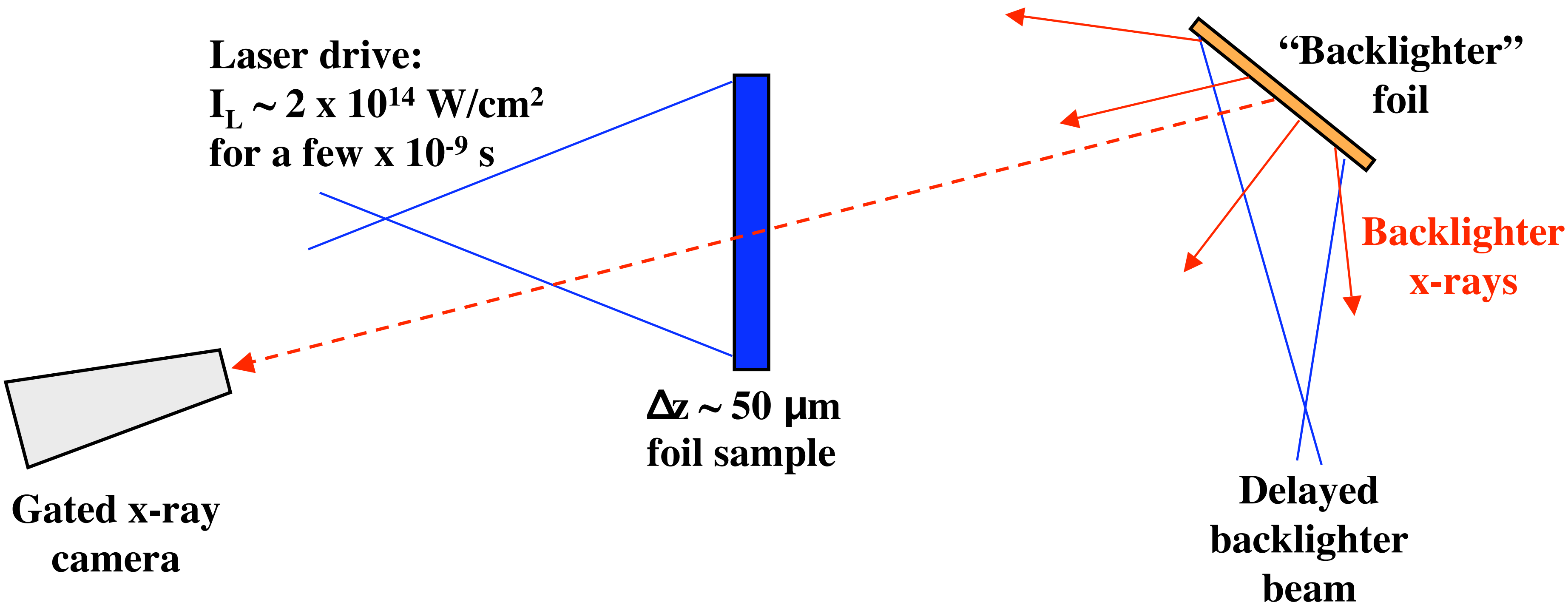

$$P(\text{Mbar}) \approx 40\left[\frac{I_{15}}{\lambda_{(\mu m)}}\right]^{2/3} = 40\left[\frac{0.2}{1/3\ \mu m}\right]^{2/3} \approx 30\ \text{Mbar} = 30 \times 10^{12}\ \text{dyne/cm}^2 = 3\ \text{TPa}$$

- Newton's 2nd law, $P = \rho \cdot \Delta z \cdot g$, then gives $g = 6 \times 10^{15}$ cm/s^2 = 60 µm/ns^2 ~ $10^{13} g_0$, yielding high accelerations over a few nsec

- A typical diagnostic technique is to use separate, delayed laser beams to drive an x-ray backlighter for radiography or absorption spectroscopy

Lasers can also generate a thermal radiation environment for heating or driving samples

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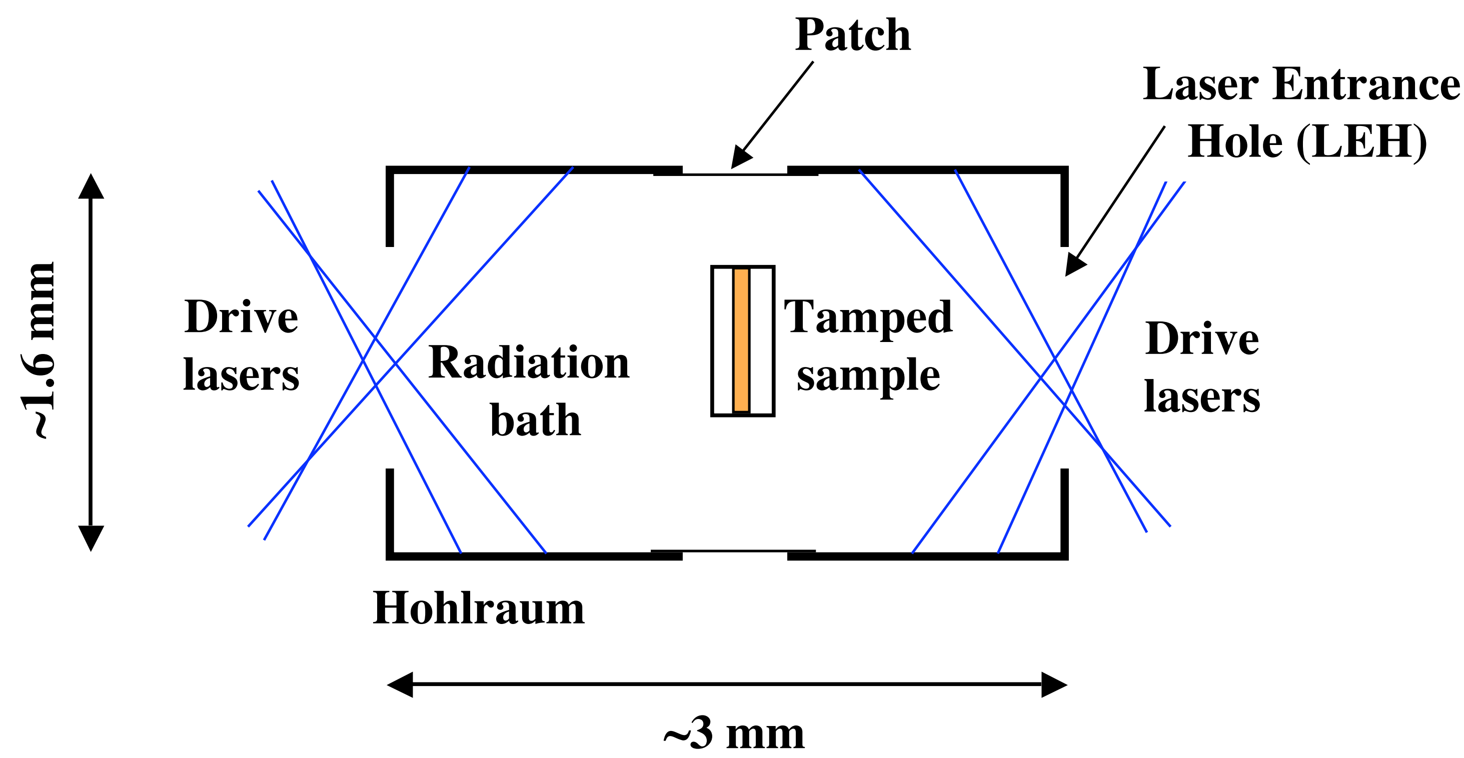
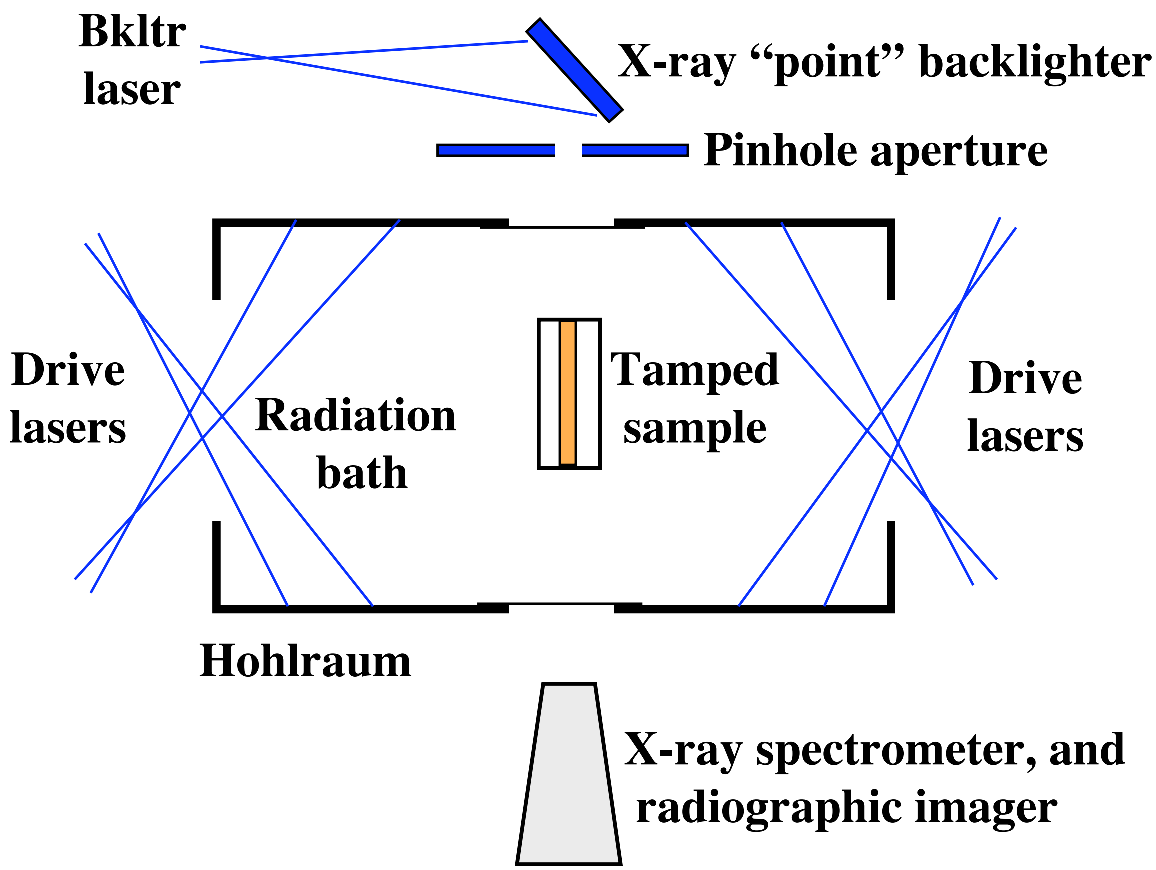


$$\eta E_{Laser}(kJ) = 4.4 A_{wall}(cm^2) T_r^{3.3}(heV) + 6.25 A_{holes}(cm^2) T_r^4(heV)$$

- **Typical drive of E_L = 20 kJ in 1 ns gives $T_r \sim 2.1$ heV = 210 eV, assuming a 75% LEH and an x-ray conversion efficiency of $\eta \sim 0.6$**

[Lindl, *Inertial Confinement Fusion* (Springer, 1998); and Phys. Plasmas 2, 3933 (1995)]

Opacity measurements are one example of experiments that use such a radiation bath to heat a sample, then spectrally diagnose its transmission



$$\eta E_{Laser} = 4.4 A_{wall} T_r^{3.3} + 6.25 A_{holes} T_r^4$$

- **Typical drive of E_L = 20 kJ in 1 ns gives $T_r \sim$ 2.1 heV = 210 eV, assuming a 75% LEH and an x-ray conversion efficiency of $\eta \sim 0.6$**
- **Diagnose density, temperature, and spectral transmission to measure opacity**

Key questions in stellar explosions, planetary interiors, and multi-hit nuclear reactions can be investigated

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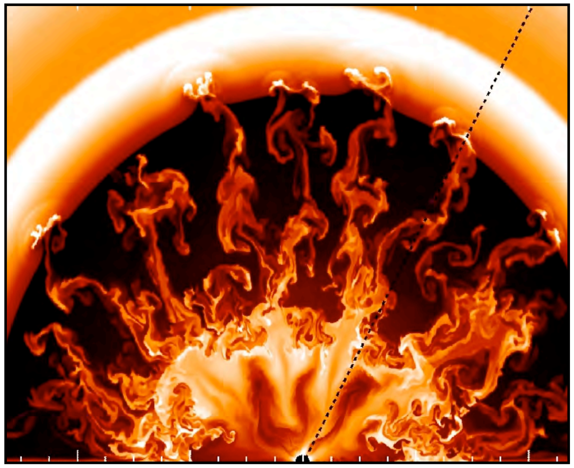
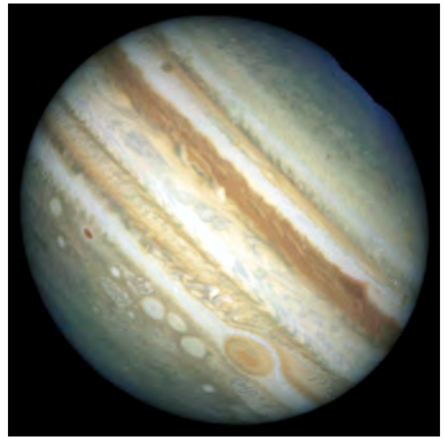
Stellar death, SNe

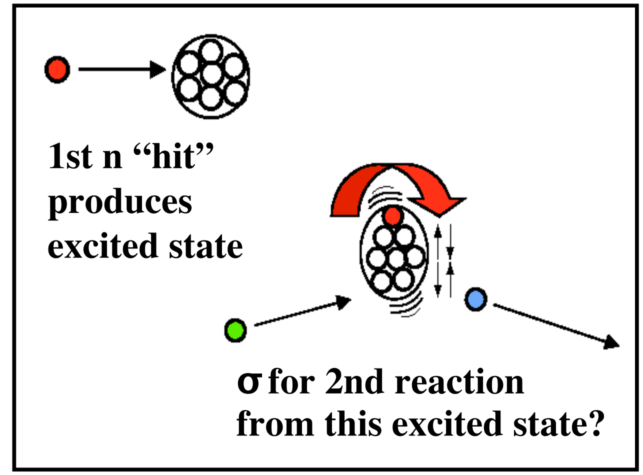


[Kifonidis (2003; 2006)]

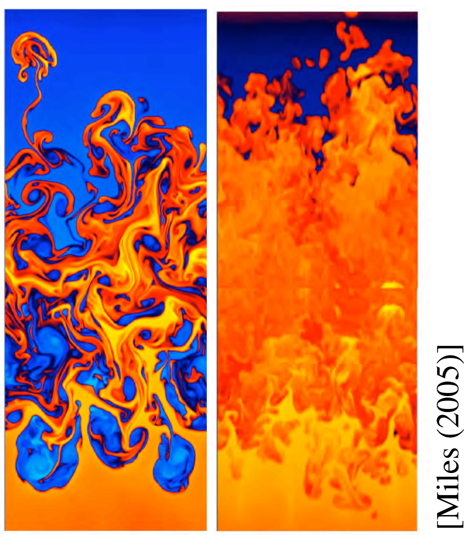
Jupiter



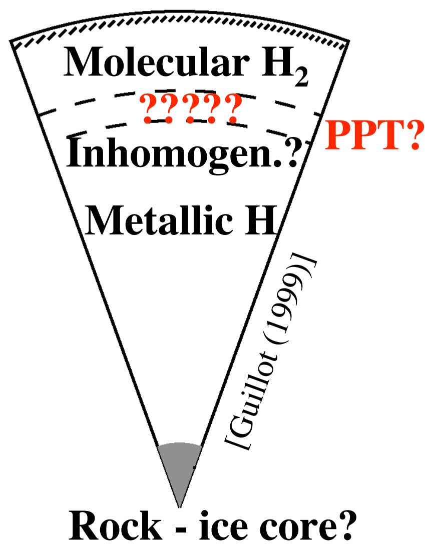
Nuclear physics off excited states



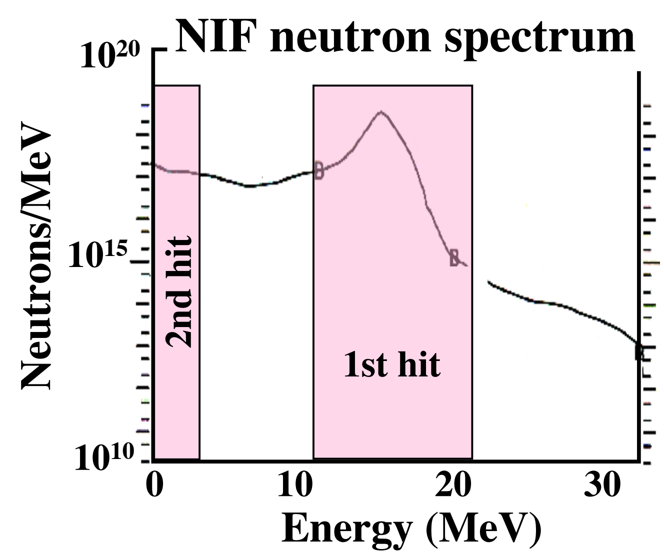
[Courtesy S. Libby (2005)]



[Carolyn Kuranz, Mon. 3:45 pm; Casey Meakin, Wed. 8:45 am]



[Raymond Jeanloz, Mon. 1:45 pm]



[Lee Bernstein, Tues., 2:00 pm; Steve Libby, Tues., 3:30 pm]

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

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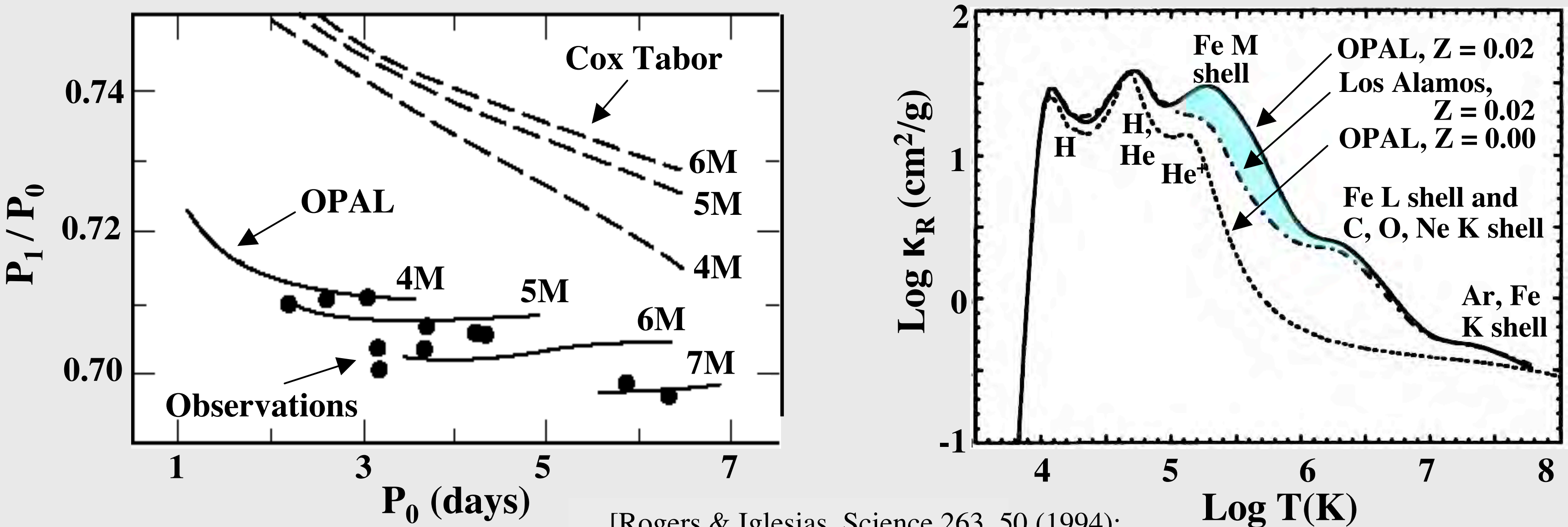

[Rogers & Iglesias, Science 263, 50 (1994); Da Silva et al., PRL 69, 438 (1992)]

[Steve Libby, Tues. 3:30 pm]

- **The original simulations of Cepheids predicted pulsation periods longer than observed**

- **The measured opacities of Fe under relevant conditions were larger than calculated:**

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

- **New OPAL simulations of the opacity of Fe reproduced the data**

- **This allowed Cepheid Variable pulsations to be correctly modeled**

Extreme materials science and hypervelocity impact studies define a new frontier of condensed matter science

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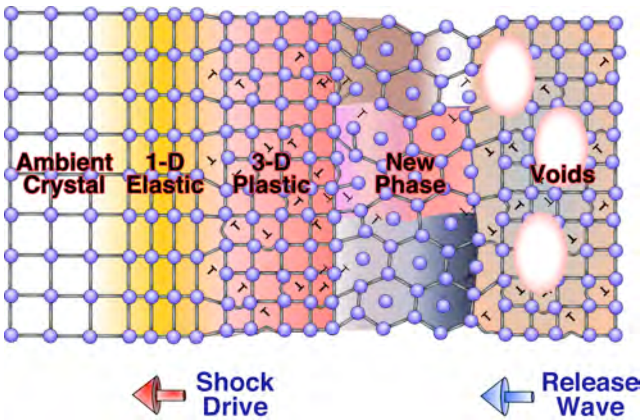
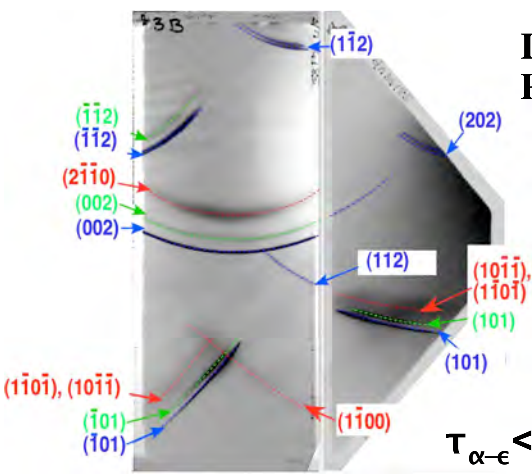
Lattice Dynamics



Dynamic Diffraction Lattice Msmt

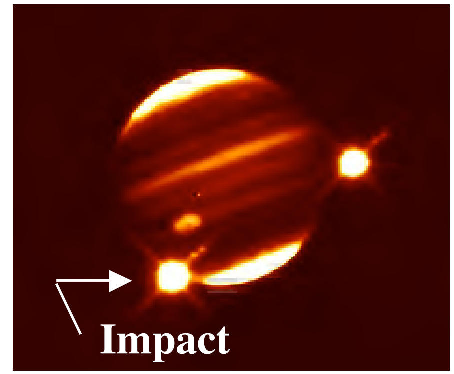


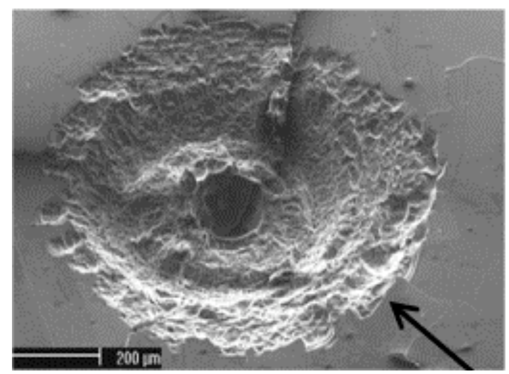
Iron,
P_{shk} ~20 GPa

$\tau_{\alpha-\epsilon}$ < ~1 ns

[D.H. Kalantar et al., PRL 95 ,075502 (2005)]

Shoemaker-Levy impact into Jupiter, July 1994,
v_{impact}~ 60 km/s, diam ~ 1-2 km, ρ ~ 0.5 g/cm^3,
M ~ 10^{15} g, $E_{released}$~10^{28} erg ~ 0.25 million Mton





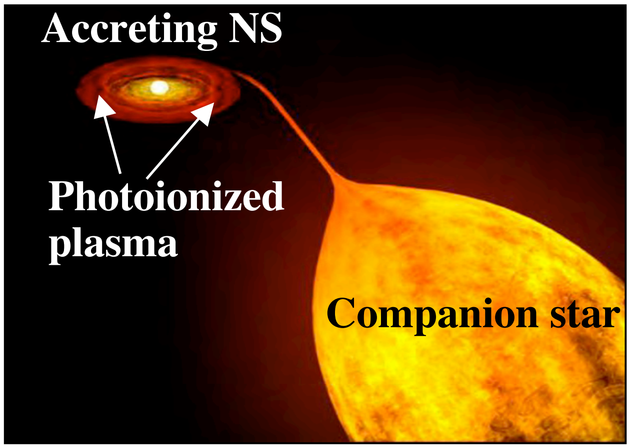
Micro-crater damage on Hubble solar cell

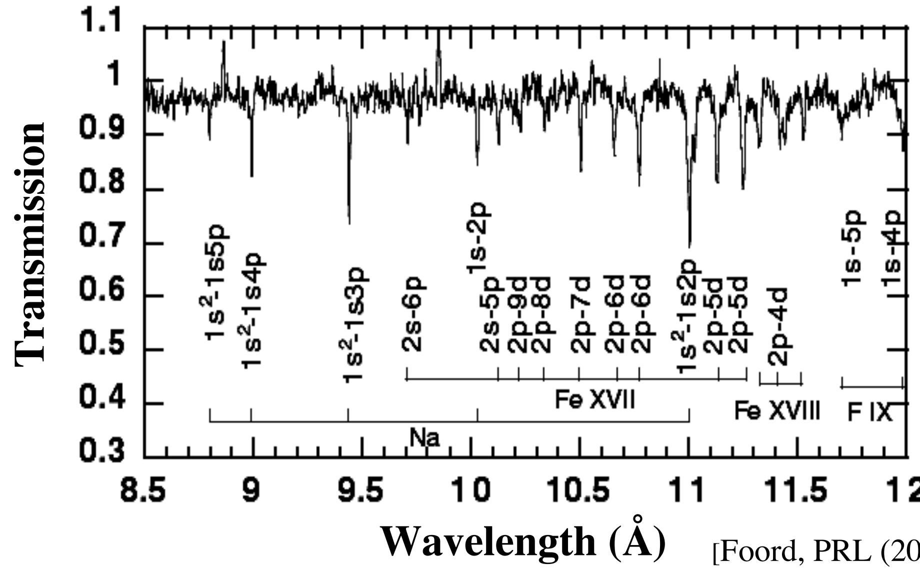
[G.A. Graham et al., MAPS. 41, 159 (2006)]

- **Extreme materials science and hypervelocity impact experiments possible on ZR and NIF**
- **Micro-impactors accelerated to velocities of 50-100 km/s should be possible**
- **New impactor physics is accessed: ionization, ablation, radiation, micro- or nano-scales**

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

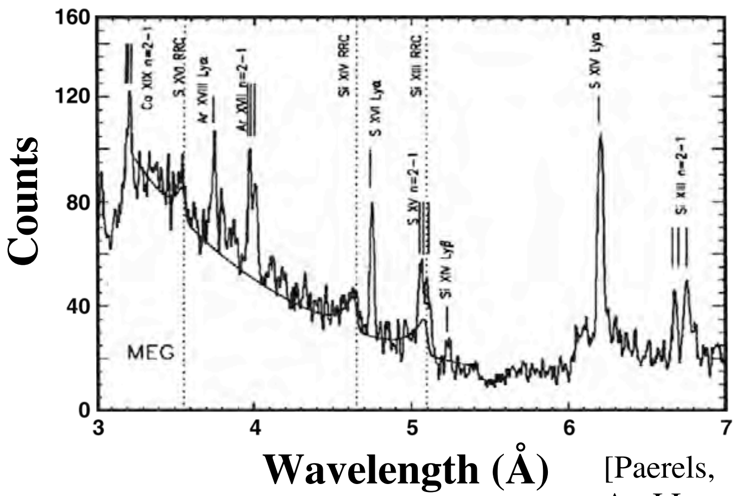
- Understanding rad. dominated photoionized plasmas essential for interpreting these data





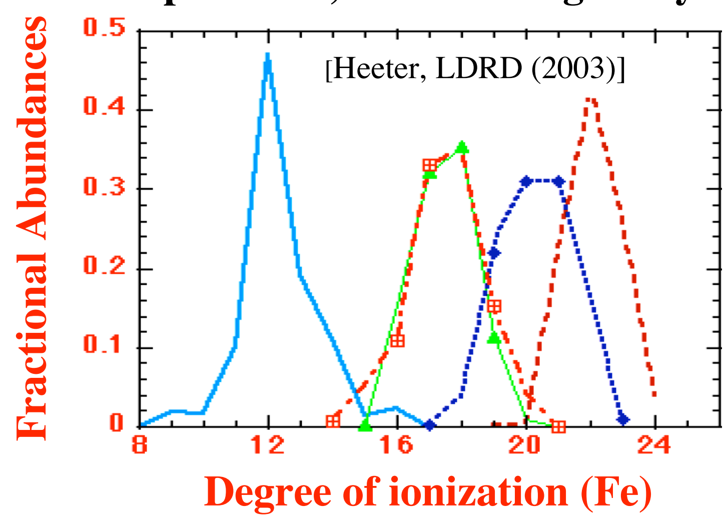
[Foord, PRL (2004)]

Chandra Spectrum of Cyg X-3 X-ray Binary



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

Prior to experiment, models disagree by ~2x



- Scaled experiments of photoionized plasmas are possible on NIF and ZR

Accreting neutron stars and black holes offer spectral signatures of the dynamics as matter spirals inward

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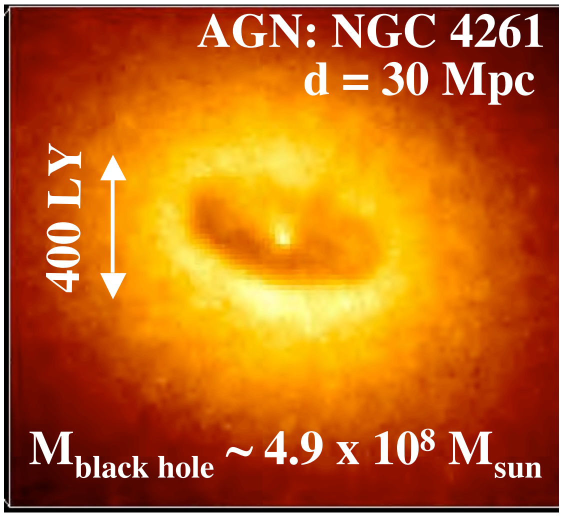
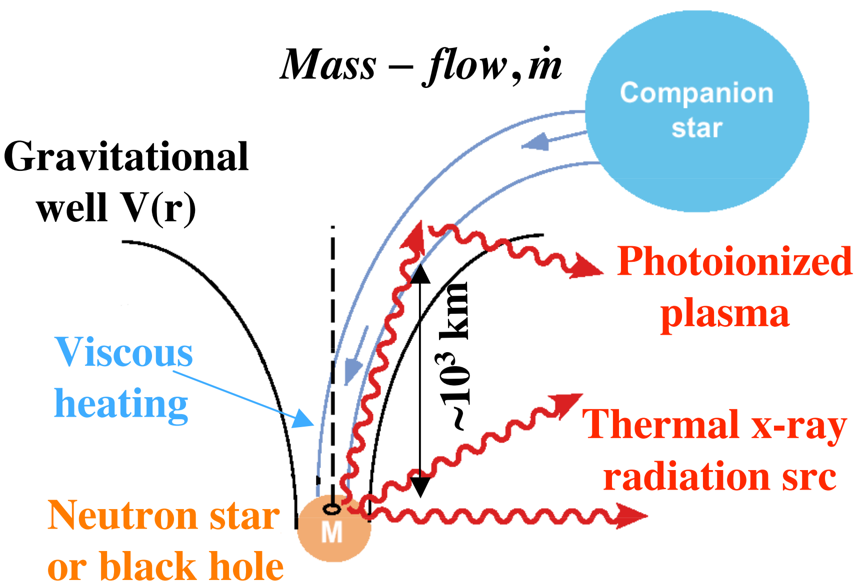
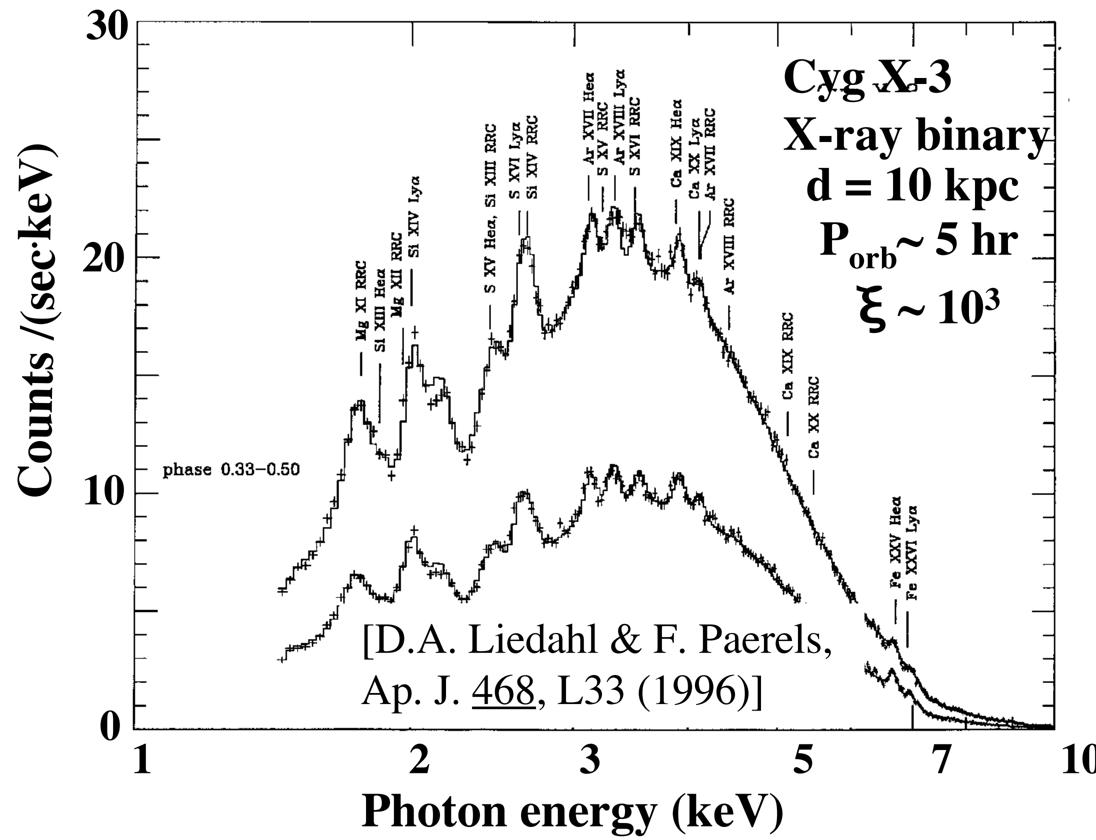


[Ferrarese *et al.*, Ap. J. 470, 444 (1996)]



[R. Heeter *et al.*, RSI 71,4092 (2000); M.E. Foord et al., PRL 93, 055002 (2004)]

- Analysis and interpretation require accurate photoionization models
- Photoionization parameter ξ = Łnr^2 characterizes the regime
- Astrophysical regimes: $\xi = 10^2$-10^3



HED experiments on Z have demonstrated radiation-dominated photoionized plasmas

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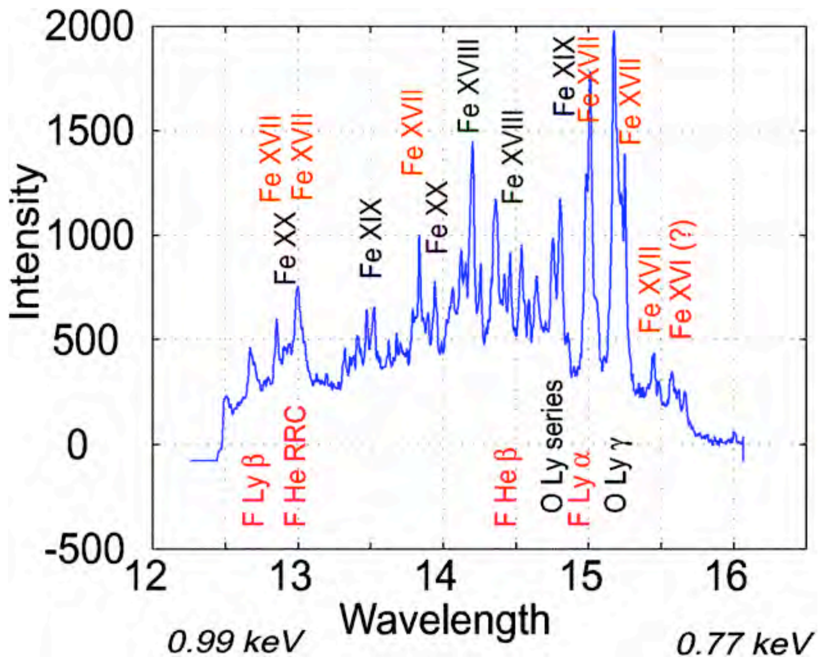
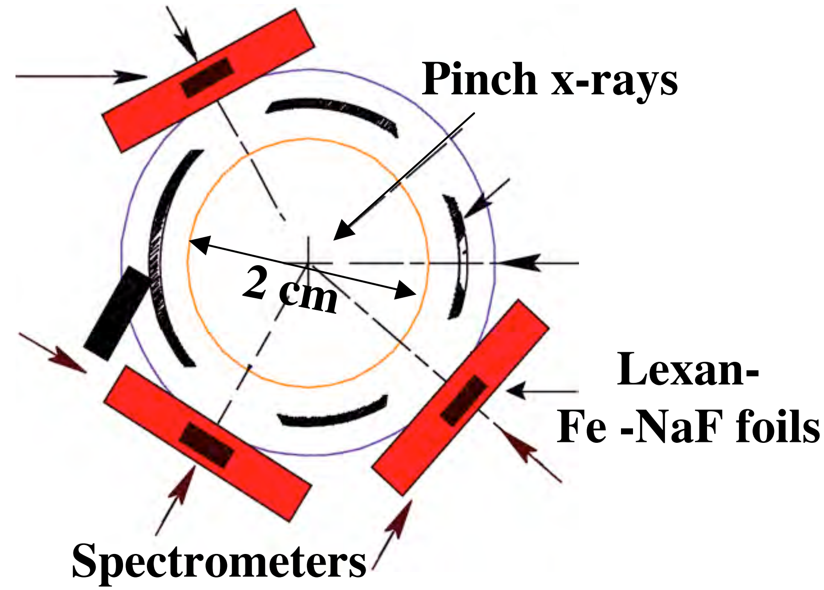
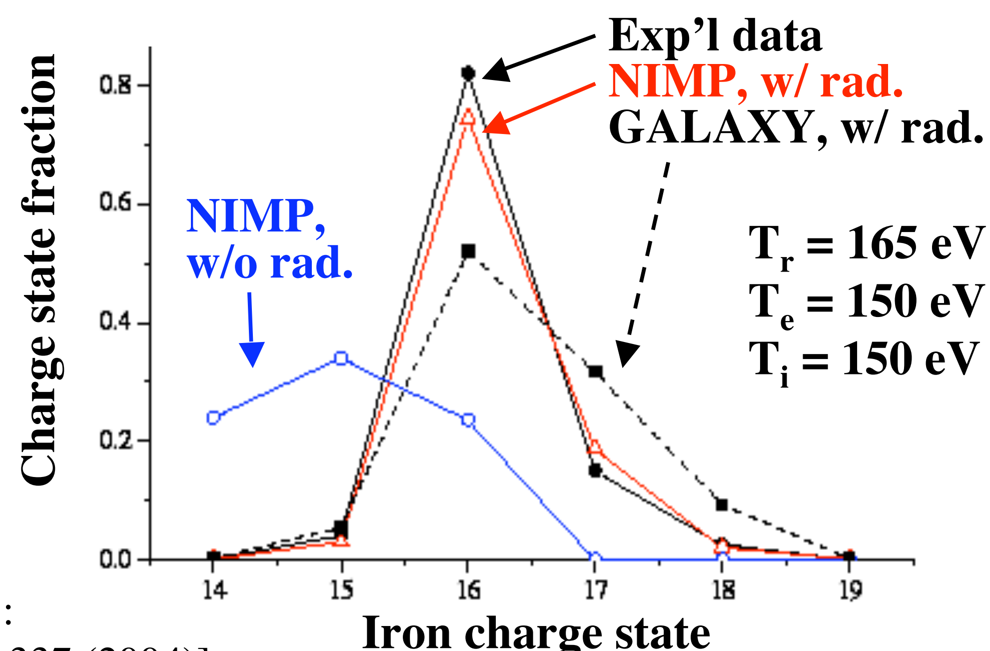


T_e ~30 eV,
T_r ~180 eV,
n_e ~1.5×10^{19}cm^{-3},
ξ ~ 47



[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
- NIF will allow the astrophys. relevant regimes of ξ ~ 10^2 - 10^3 to be accessed

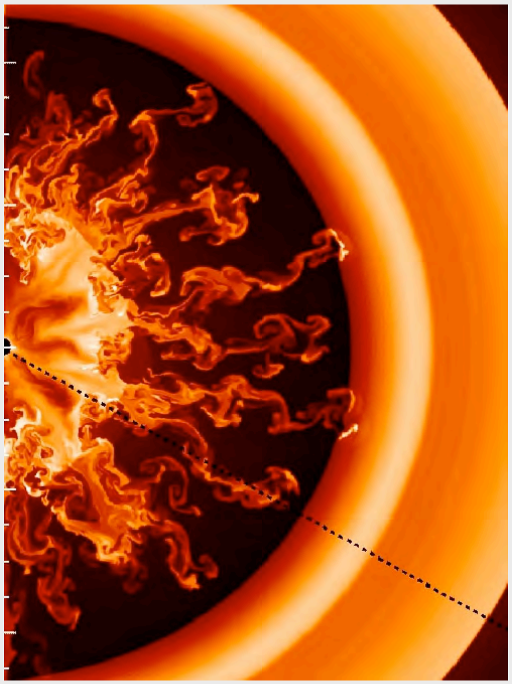


[S. Rose et al., J. Phys. B: At. Mol. Opt. Phys. 37, L337 (2004)]

As an example, three university teams are starting to prepare for NIF shots in unique regimes of HED physics

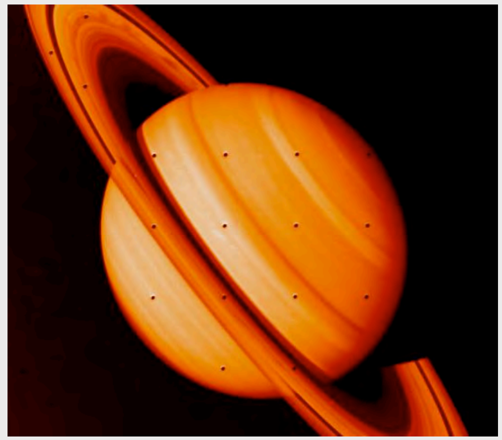
Getting started:

Astrophysics - hydrodynamics



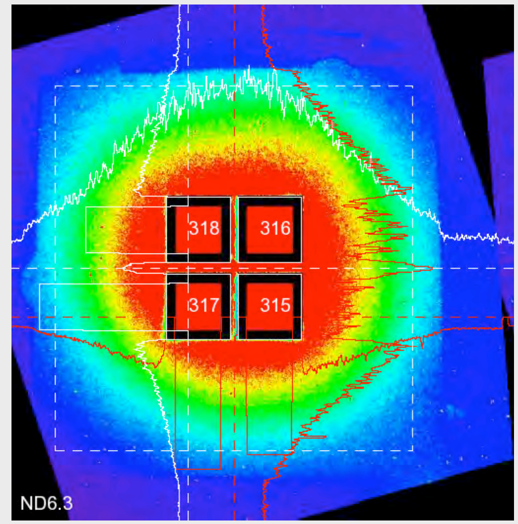
Paul Drake, PI, U. of Mich.,
Carolyn Kuranz, U. of Mich.,
David Arnett, U. of Arizona,
Adam Frank, U. of Rochester,
Tomek Plewa, U. of Chicago,
Casey Meakin, U. of Chicago,
Todd Ditmire, U. Texas-Austin
LLNL hydrodynamics team

Planetary physics - EOS



Raymond Jeanloz, PI,
UC Berkeley
Thomas Duffy, Princeton U.
Russell Hemley, Carnegie Inst.
Yogendra Gupta, Wash. State U.
Paul Loubeyre, U. Pierre &
Marie Curie, and CEA
LLNL EOS team

Nonlinear optical physics - LPI



Christoph Niemann, PI
UCLA NIF Professor
Chan Joshi, UCLA
Warren Mori, UCLA
Bedros Afeyan, Polymath
David Montgomery, LANL
Andrew Schmitt, NRL
LLNL LPI team

An HEDP community is emerging, enhancing the scientific interest and creating increased access to the facilities

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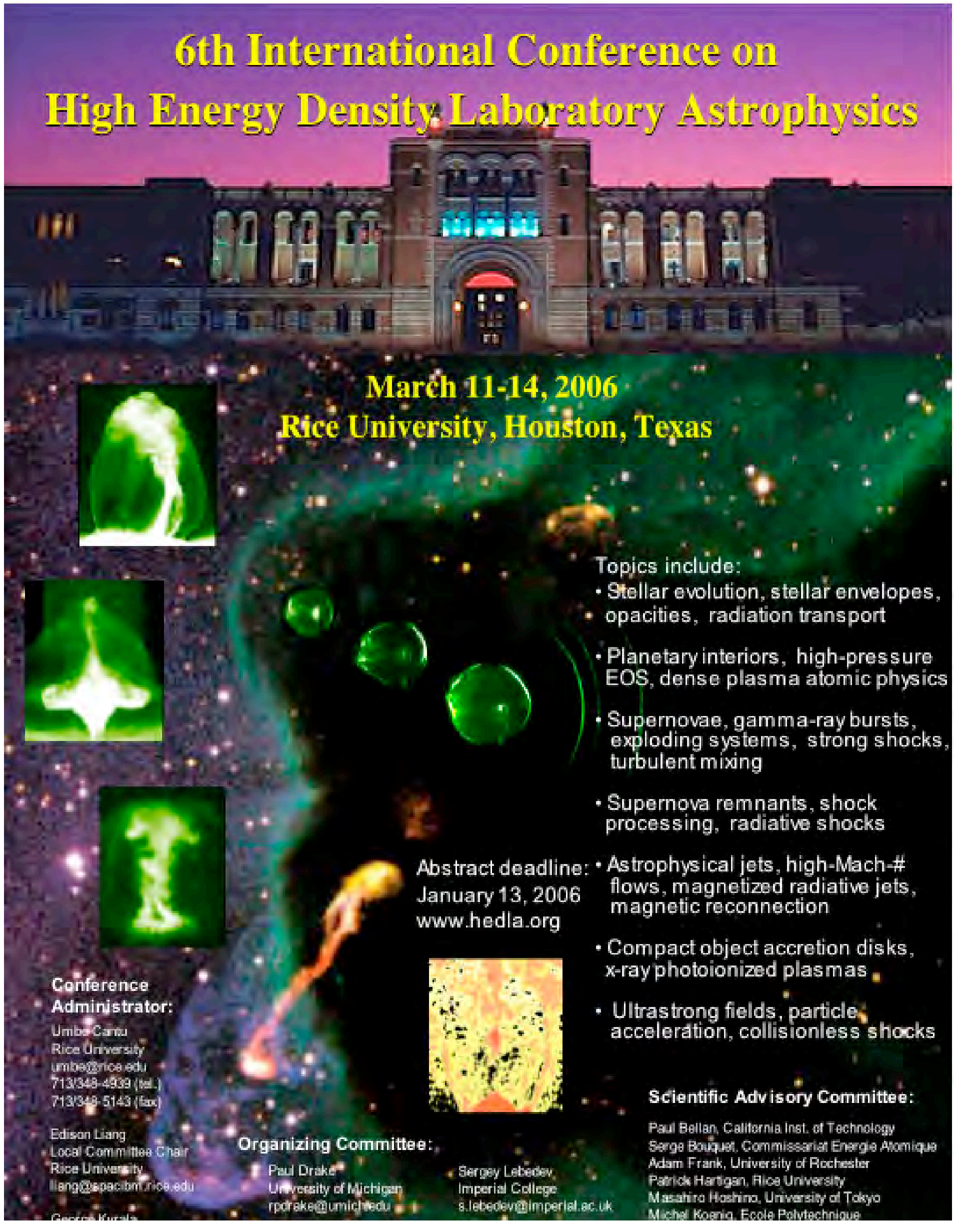
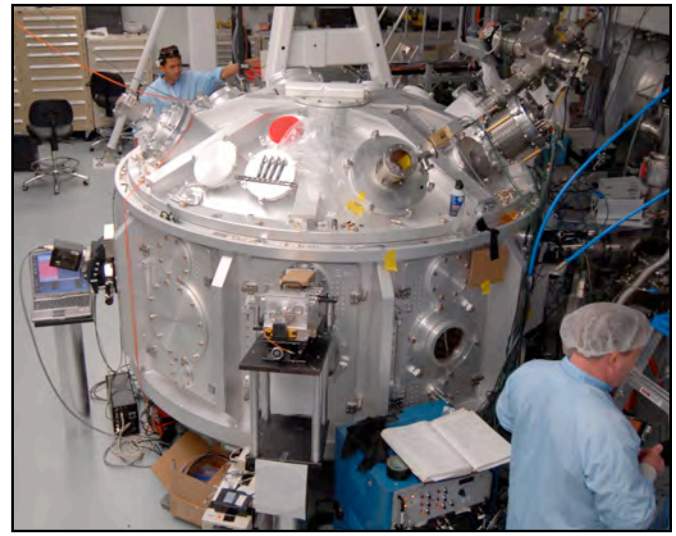
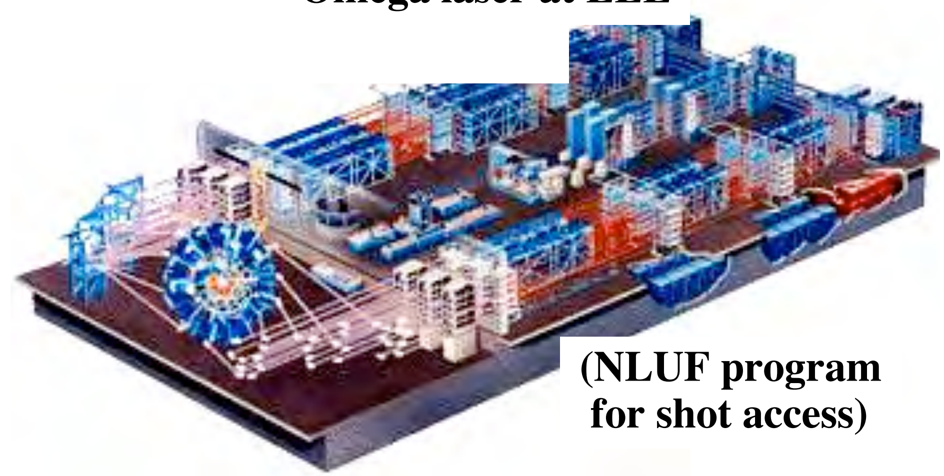


Titan laser at LLNL



(New HED intermed.-scale user facil.)

Omega laser at LLE



(NLUF program for shot access)

• **HEDLA/HEDP-08 will be April 11-15, 2008, with the April-APS, in St. Louis, MO**

HED laboratory astrophysics allows unique, scaled testing of models of some of the most extreme conditions in the universe

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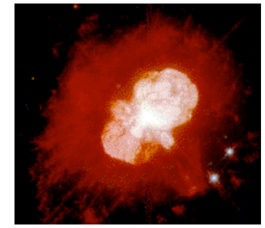
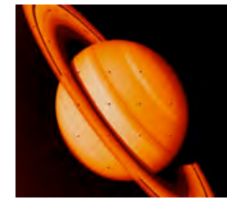
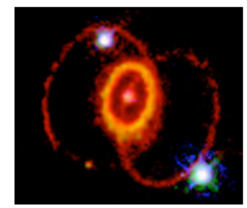


- **Stellar evolution: opacities (eg., Fe) relevant to stellar envelopes; Cepheid variables; sellar evolution models; OPAL opacities**



- **Planetary interiors: EOS of relevant materials (H_2, H-He, H_20, Fe) under relevant conditions; planetary structure - and planetary formation - models sensitive to these EOS data**



- **Core-collapse supernovae: scaled hydrodynamics demonstrated; turbulent hydrodynamics within reach; aspects of the "standard model" being tested**

- **Supernova remnants: scaled tests of shock processing of the ISM; scalable radiative shocks within reach**

- **Protostellar jets: relevant high-M-# hydrodynamic jets; scalable radiative jets, radiative MHD jets; collimation quite robust in strongly cooled jets**

- **Black hole/neutron star accretion disks: scaled photoionized plasmas within reach**

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


National Ignition Facility