High-Energy-Density Physics, with Applications to Astrophysics

Meeting of the American Physical Society
Albuquerque, New Mexico
April 20, 2002

UCRL-PRES-148023

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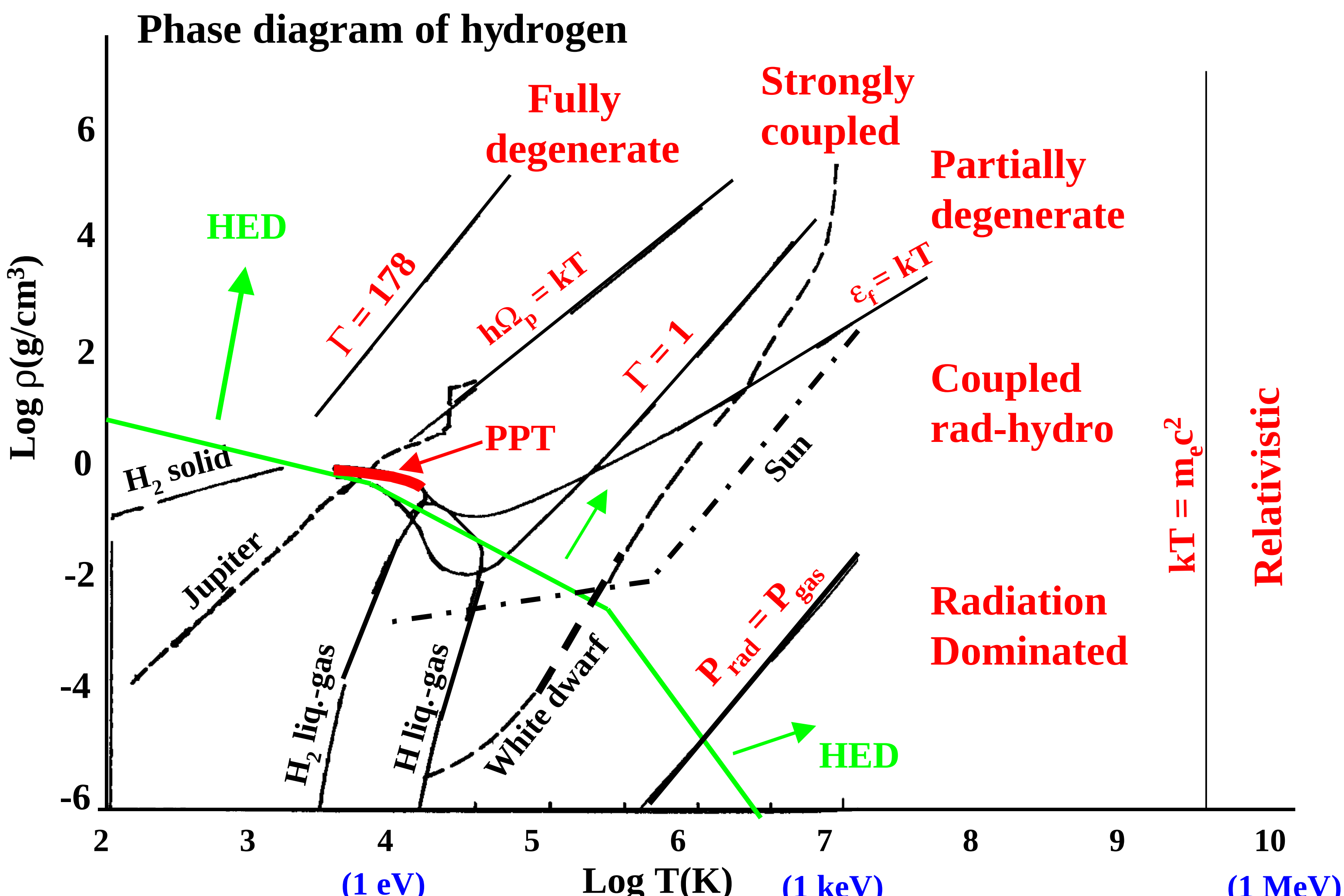
Lawrence Livermore National Laboratory

High energy density implies large Energy/Volume. The physics under these conditions is rich with subtleties.

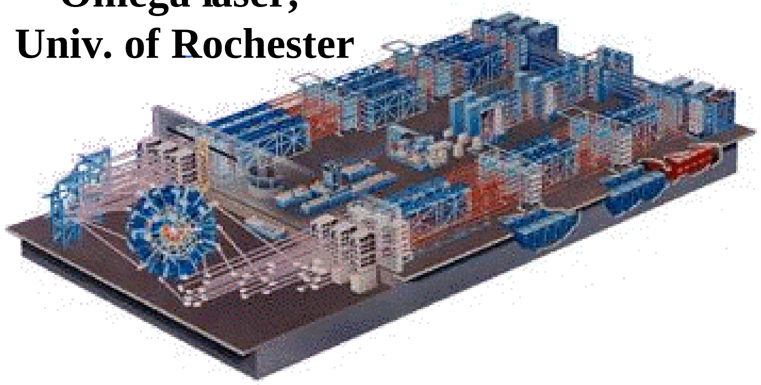


H.M. Van Horn, Science 252, 384 (1991)

- HED corresponds to $E/V > 10^{12}$ ergs/cm^3 (P > 1 Mbar)
- See Laboratory HEDPP session K7 Sunday afternoon

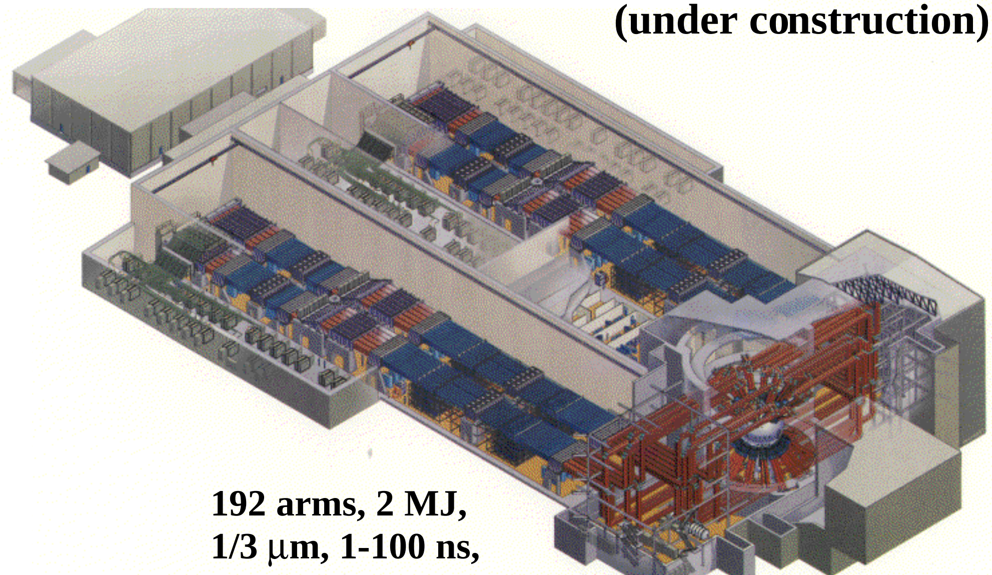
HED facilities generate large E/V over short durations. Examples are large lasers and magnetic pinch facilities.

Omega laser, Univ. of Rochester



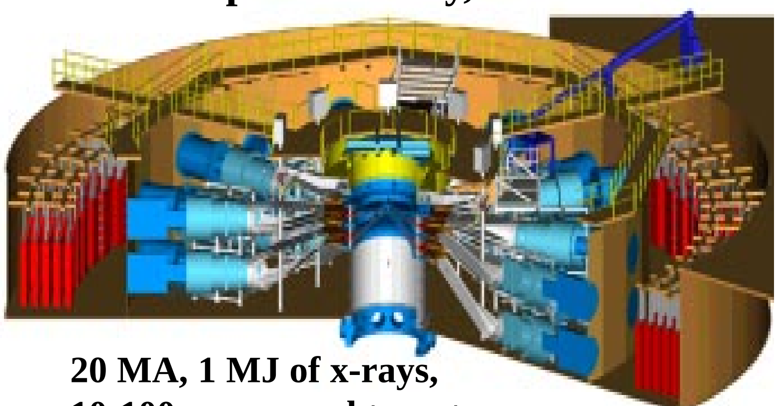
60 arms, 30 kJ,
1/3 μm, 1-10 ns,
~mm scl targets
(E/V ~ 10^{14} erg/cm^3)

The National Ignition Facility, LLNL, (under construction)



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

Z pinch facility, SNLA



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

- **See Keith Matzen talk, K7.001, Sun. afternoon in the HEDPP session**

High energy density facilities are a key ingredient towards achieving precision astrophysics

- The extreme conditions found in astrophysics can be reproduced in the laboratory only on HED facilities

- Astrophysics simulation codes can be tested under relevant conditions

- Physics models and concepts can be tested under relevant conditions

- Fundamental quantities (opacities, EOS) can be measured under relevant conditions

- Aspects of scaled dynamics can be reproduced under relevant conditions

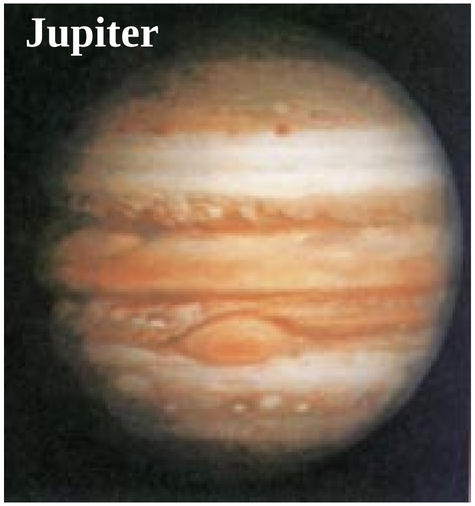
- Achieving precision astrophysics requires such HED facilities

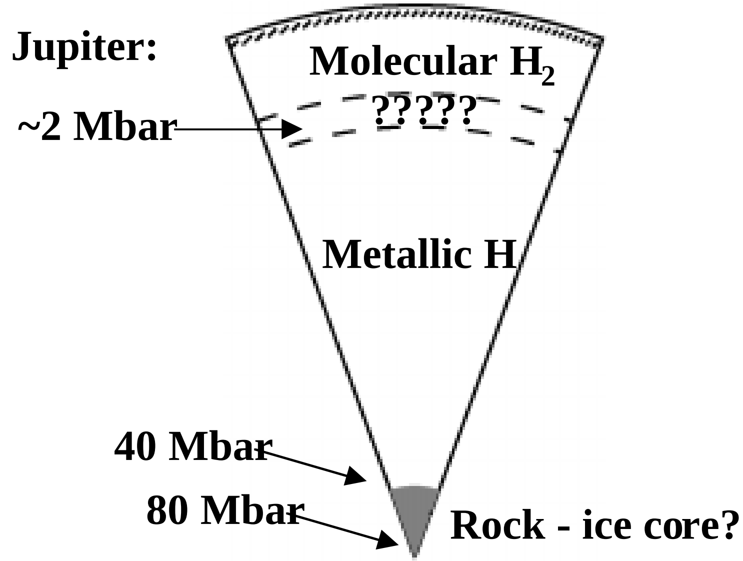
• A selection of examples will be shown, drawn from:	**Regimes:**
- planetary interiors	- degenerate plasmas
- Cepheid variable stars	- rad-hydro
- supernovae	- rad-hydro
- accreting neutron stars and black holes	- radiation-dominated
- gamma-ray bursts	- relativistic

Planetary interiors

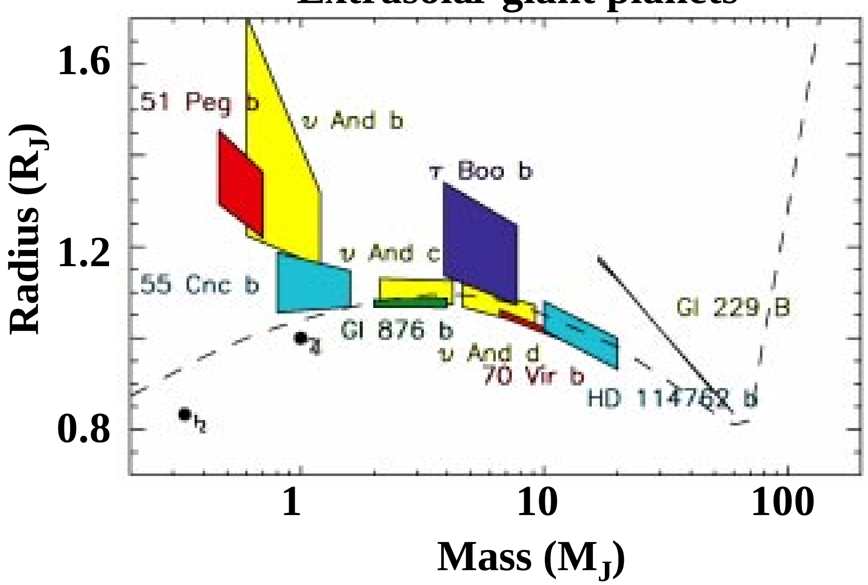
- **Can we understand planetary interiors and planetary formation mechanisms, ie, planetary birth?**
- **Regime: degenerate plasmas**

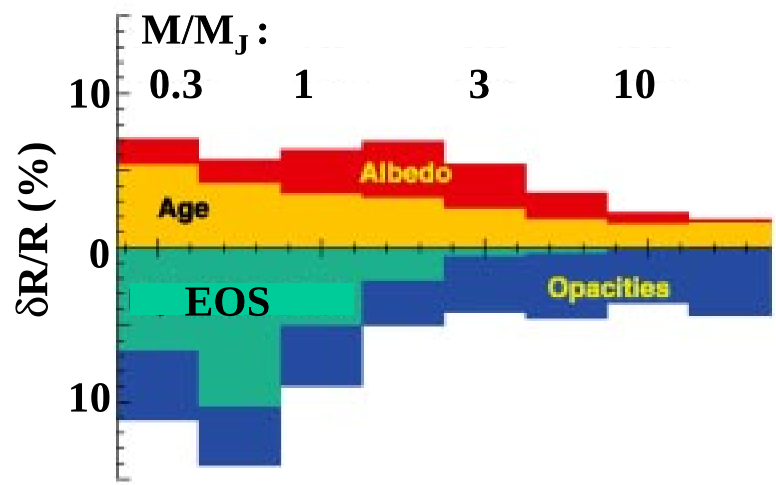
Models for planetary interiors require an accurate understanding of the EOS of dense plasma





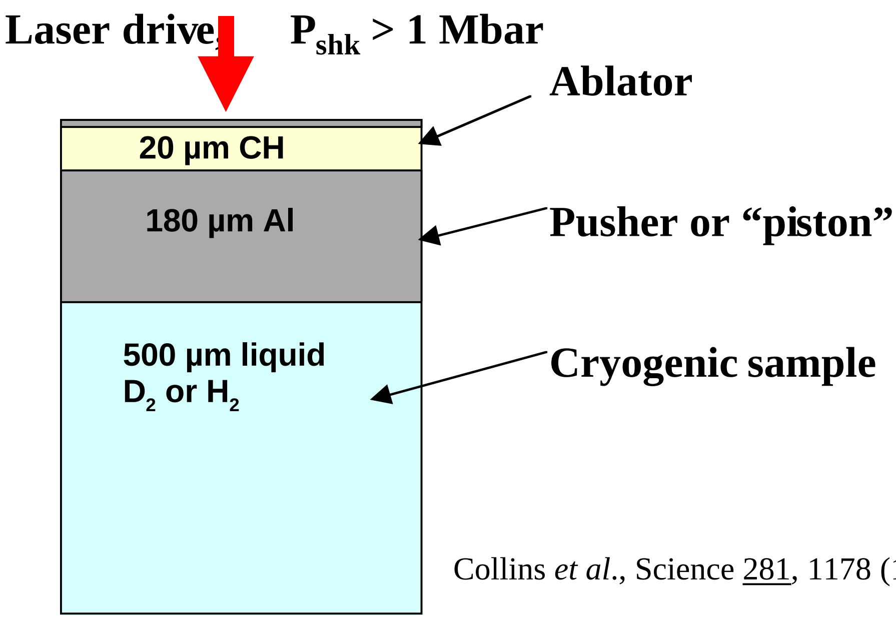
Extrasolar giant planets



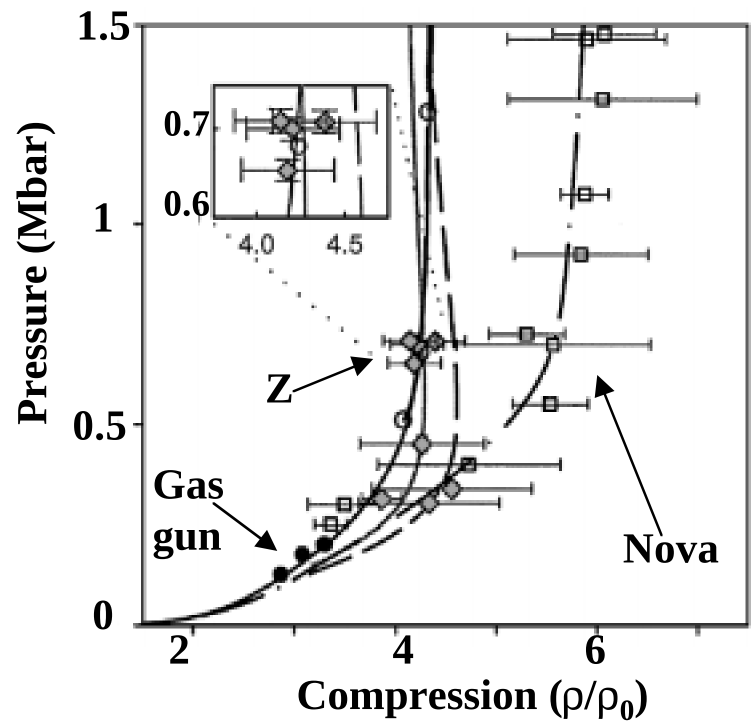


Tristan Guillot, Science 286, 72 (1999)

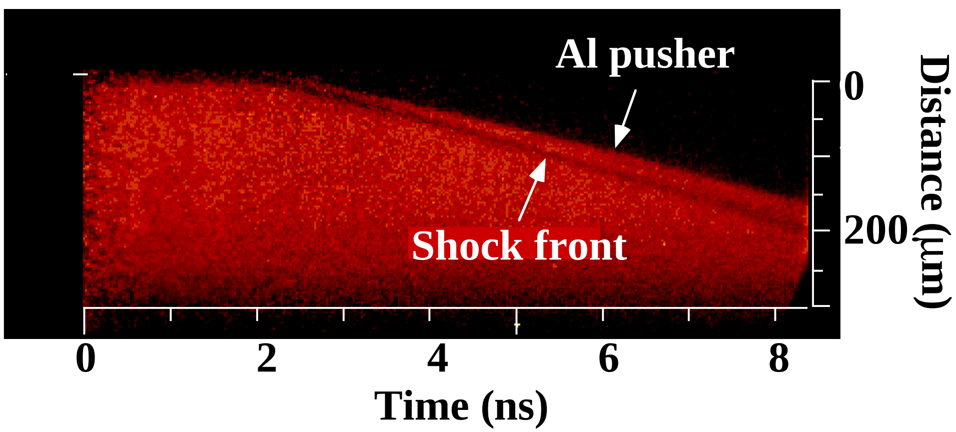
HED experiments replicate the extreme pressures of the interior of Jupiter in recent EOS msmts



Collins *et al*., Science 281, 1178 (1998)



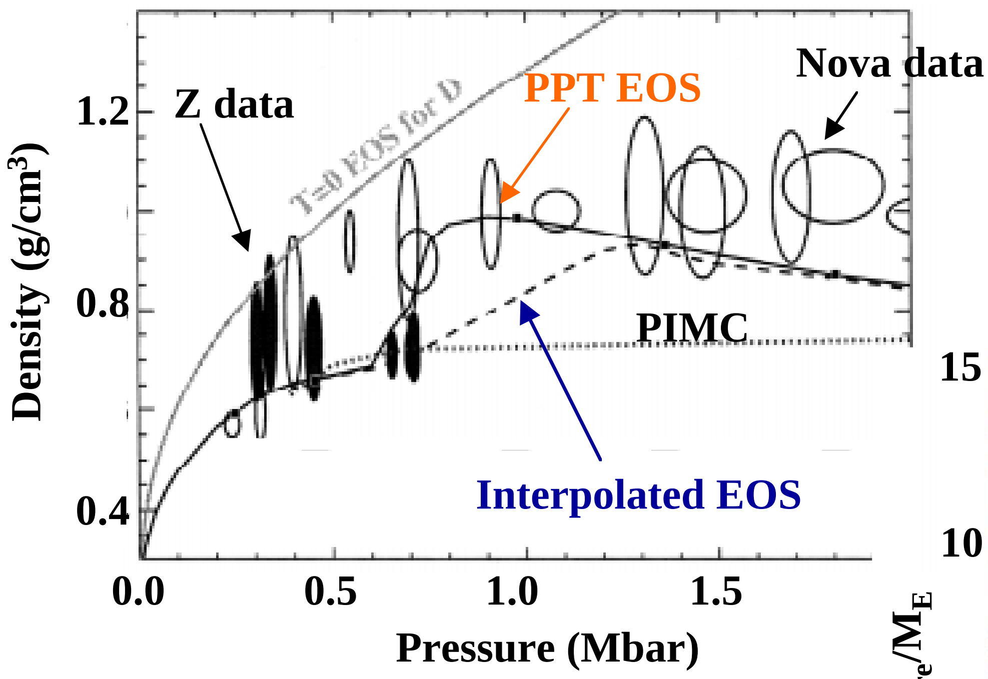
Knudson *et al*, PRL 87, 5501 (2001



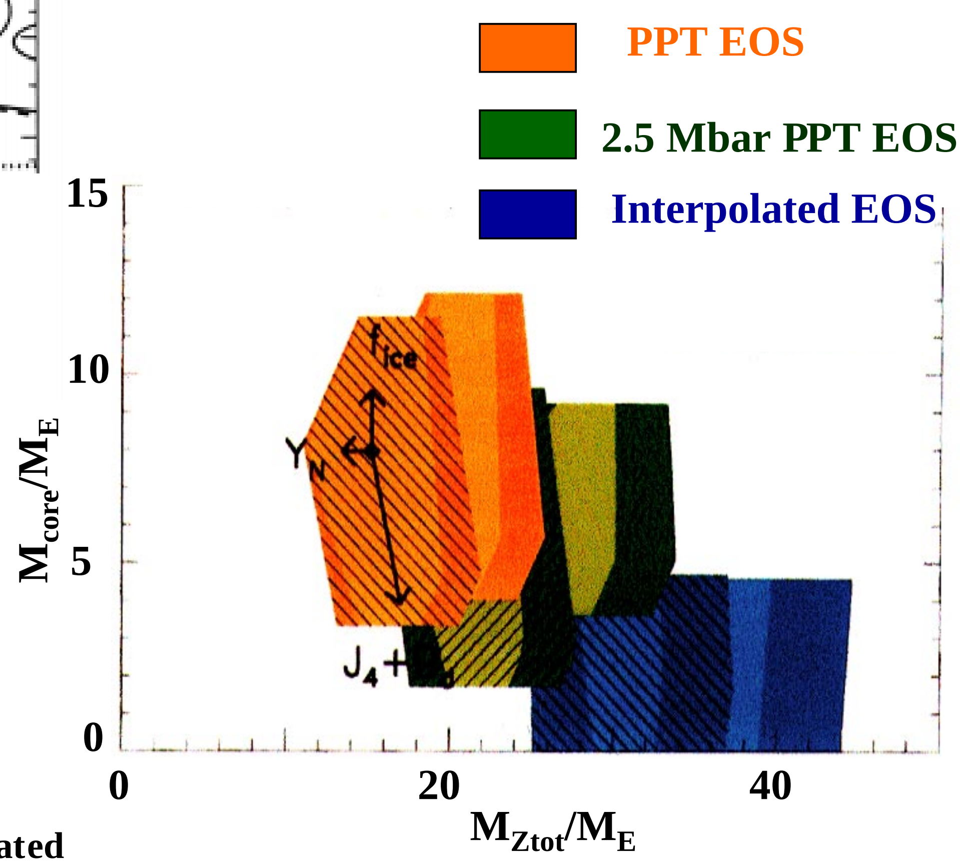
- Experiments in the most critical 0.5 - 10 Mbar regime are possible

These recent measurements of the D_2 EOS have generated enormous interest in the astrophysics community

Guillot et al., to appear in “The Interior of Jupiter” book



Guillot et al., Icarus 130, 534 (1997)



- Different planetary models are being compared to the HED data
- The implications of these models on the interior of Jupiter are significant (ie, a core or not)
- Different planetary formation models are discriminated by the existence of a central core in Jupiter

What have we learned?

- **Hydrogen EOS is much more difficult than we thought!**
- **Only additional HED experiments will resolve which planetary interior model is correct**
- **Results will affect planetary formation models**

- **See Bob Cauble talk, K7.005, Sun. afternoon**

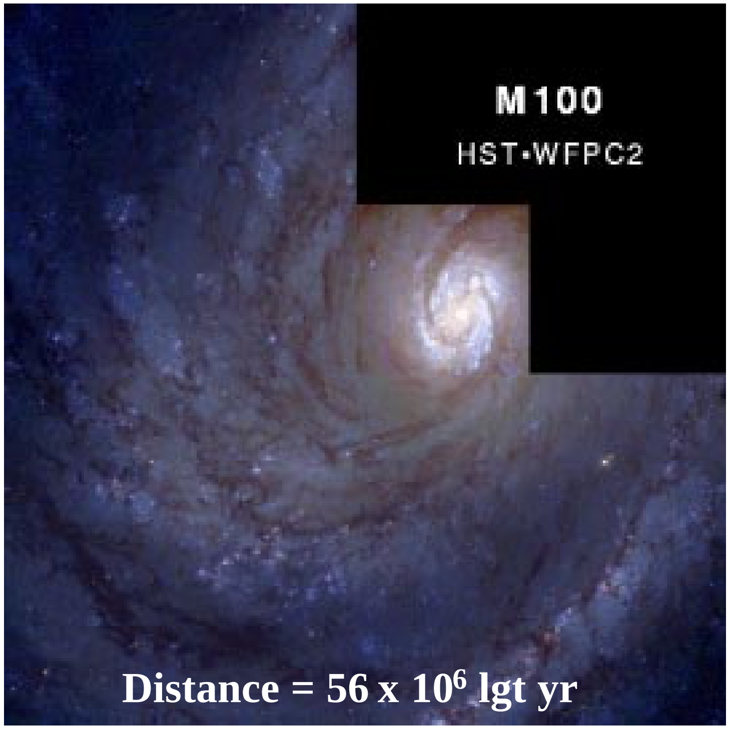
Cepheid variables

- **Can we understand Cepheid variable stars as standard candles, ie, a calibrated “yardstick of the universe”?**

- **Regime: coupled radiation hydrodynamics**

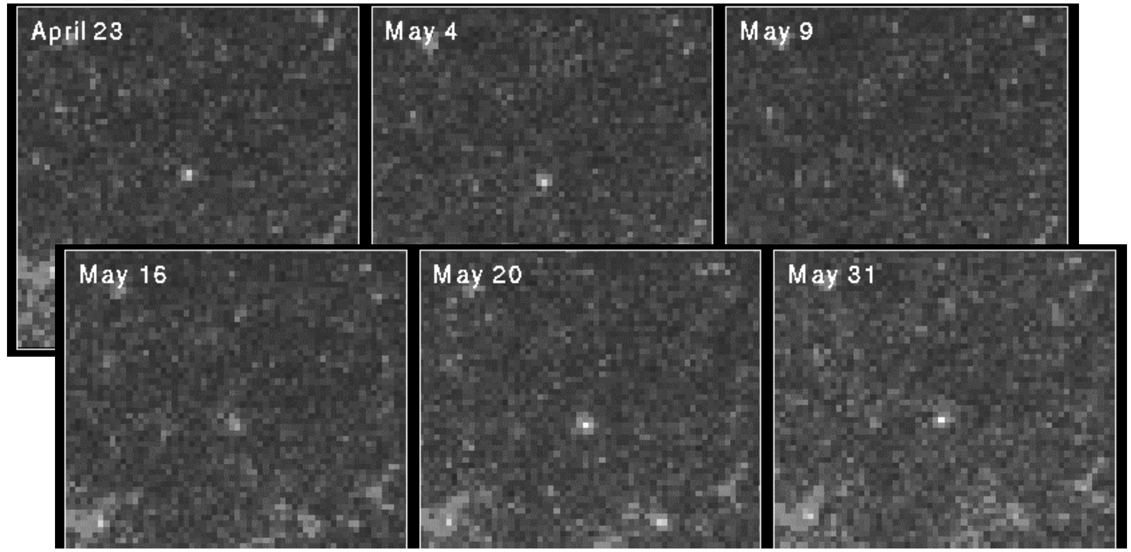
Cepheid variables are stars whose luminosities pulsate with periods of a few days to a few weeks

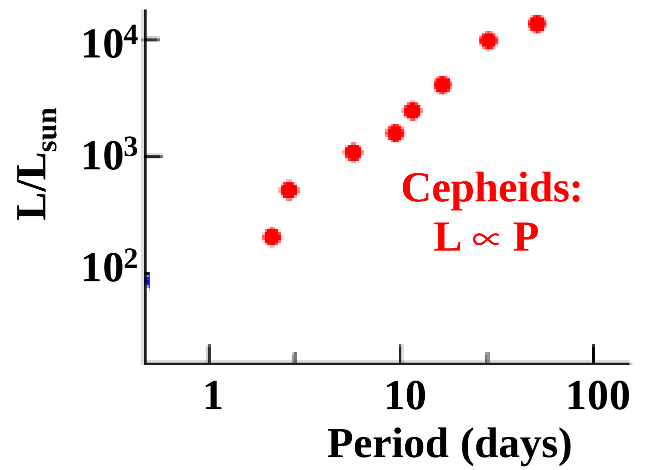
Galaxy M100



J. Trauger, JPL and NASAJ. Trauger, JPL and NASA

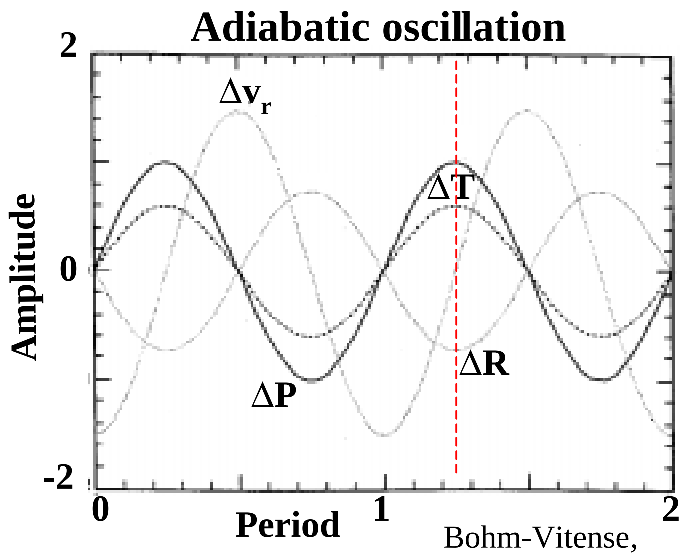
A Cepheid variable in M100, observed with HST WFPC2





- **Period ~ Size, Luminosity ~ size, hence Luminosity ~ Period**
- **Since $L \propto P$, Cepheids serve as standard candles**
- **Since $L \propto R^{-2}$, Cepheids are the most reliable distance indicator**

Why do Cepheid variables pulsate, and why are the periods of pulsation sensitive to opacity?

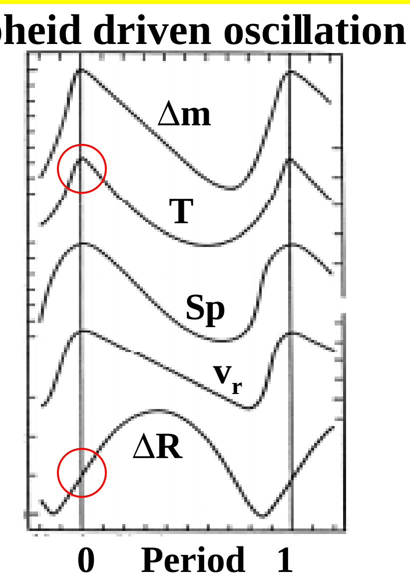


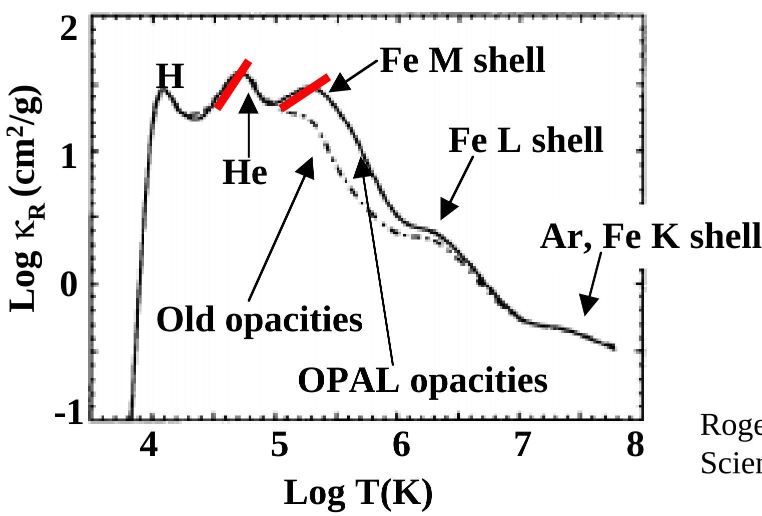
Bohm-Vitense,
Intro. Stellar Astro. (1989)

$$P \sim \frac{1}{c_s} \sim \frac{1}{\sqrt{T}} \sim \frac{1}{\kappa^{n/2}}$$

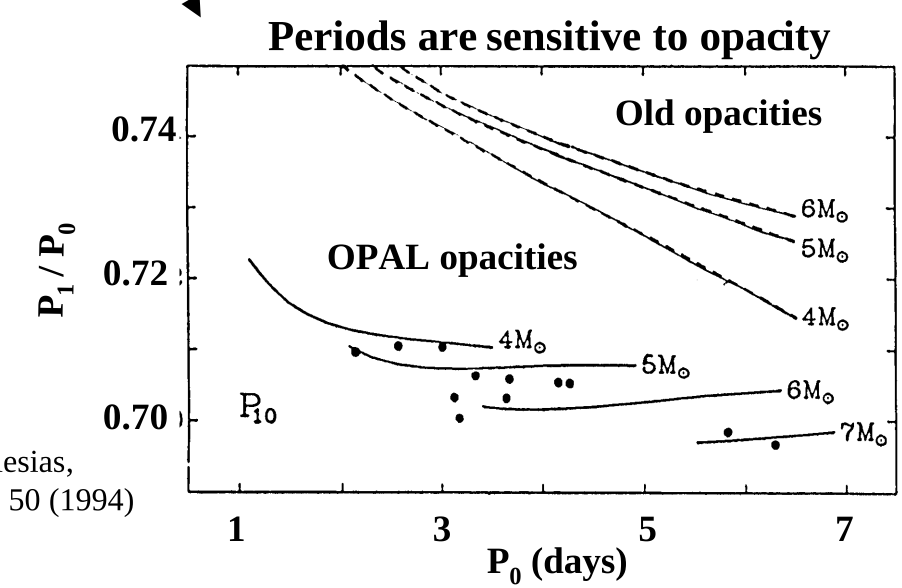
assuming $T \sim \kappa^n$

So higher opacity (κ) means shorter pulsation period, P





Rogers & Iglesias,
Science 263, 50 (1994)



- **Modeling of Cepheid oscillations requires accurate opacities**

What have we learned?

• **Correct microphysics (accurate opacities) is needed to reproduce observed macrophysics (stellar pulsation periods)**

• **Opacities of high-Z elements (eg., Fe) are very complex**

• **Direct measurements under relevant conditions can be made**

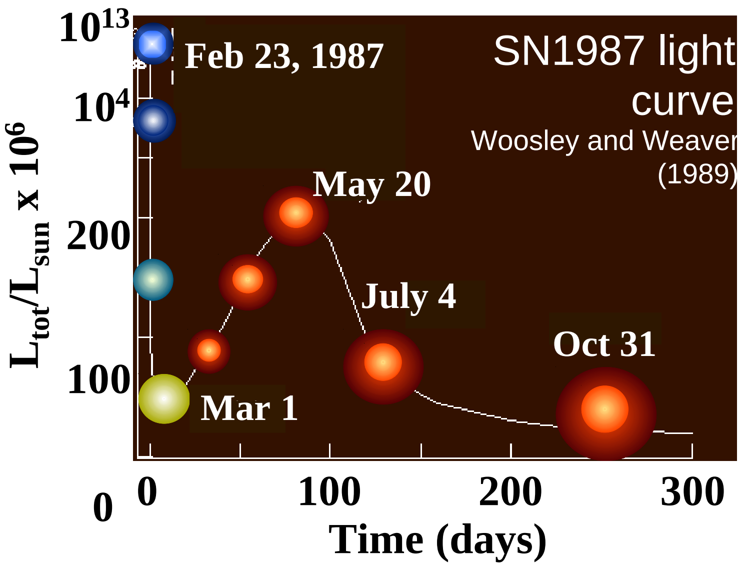
• **See Paul Springer talk, K7.003, Sun. afternoon**

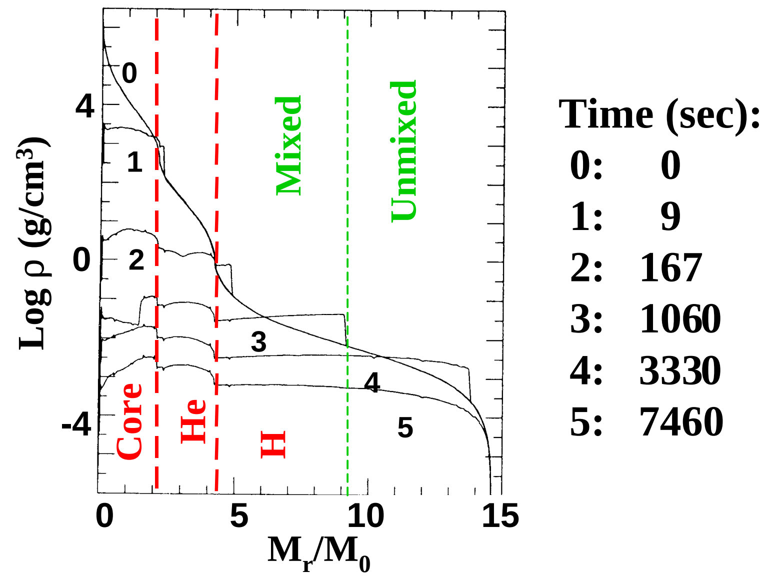
Supernovae

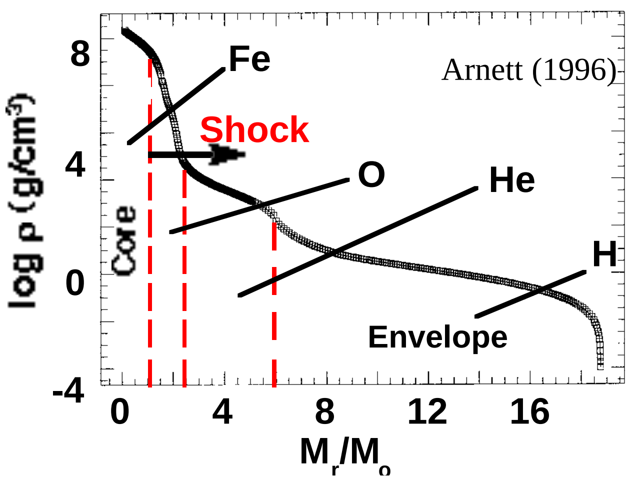
- **Can we understand supernova explosion and remnant dynamics, ie, stellar death?**

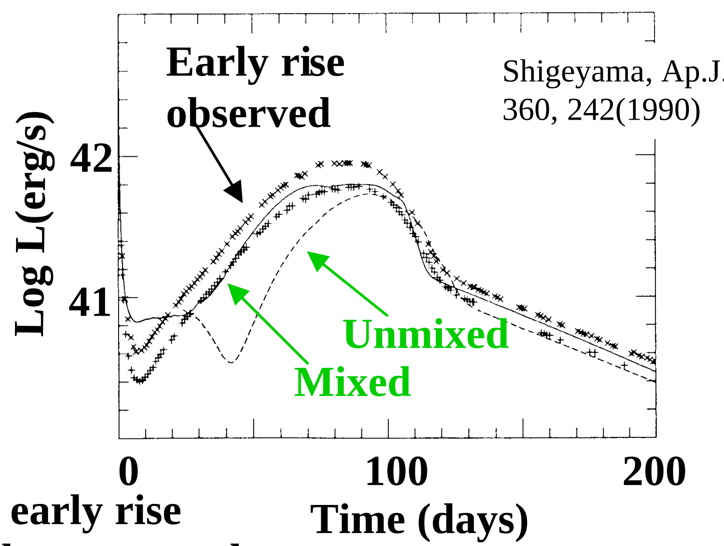
- **Regime: coupled radiation hydrodynamics**

A core-collapse supernova occurs when the Fe core of a massive star collapses







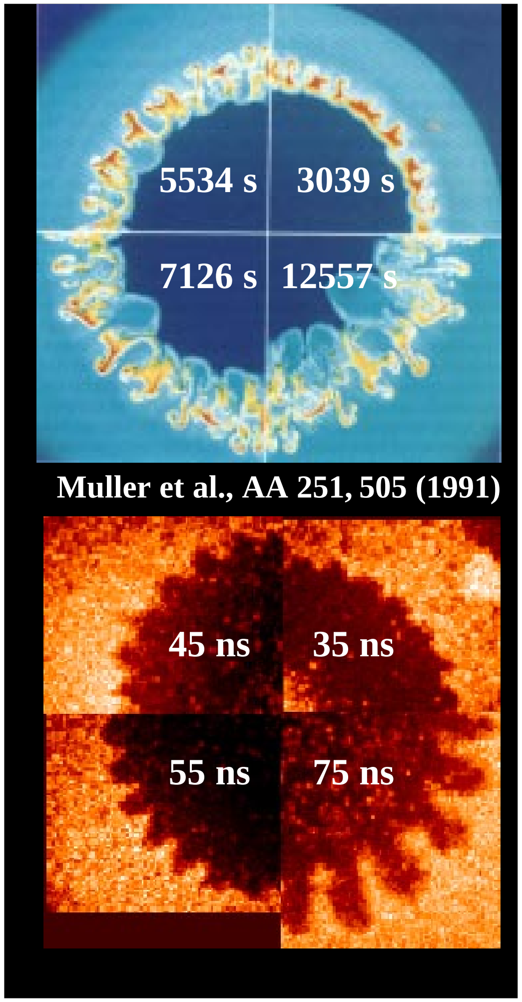


- Light curve of SN1987A was broad, with an early rise
- γ-rays from 56Co were observed 2x sooner than expected
- Strong mixing, core penetration suggested

HED experiments reproduce aspects of scaled SN explosion hydrodynamics

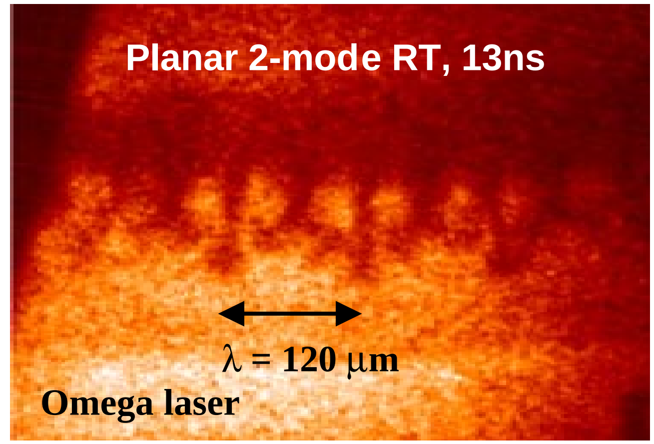
SN1987A simulation

Nova laser

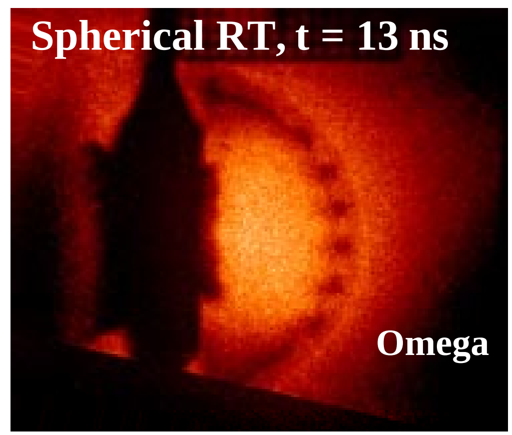


K.S. Budil, private communication (2002)

Omega laser



Robey et al., Phys. Plasmas 8, 2446 (2001)

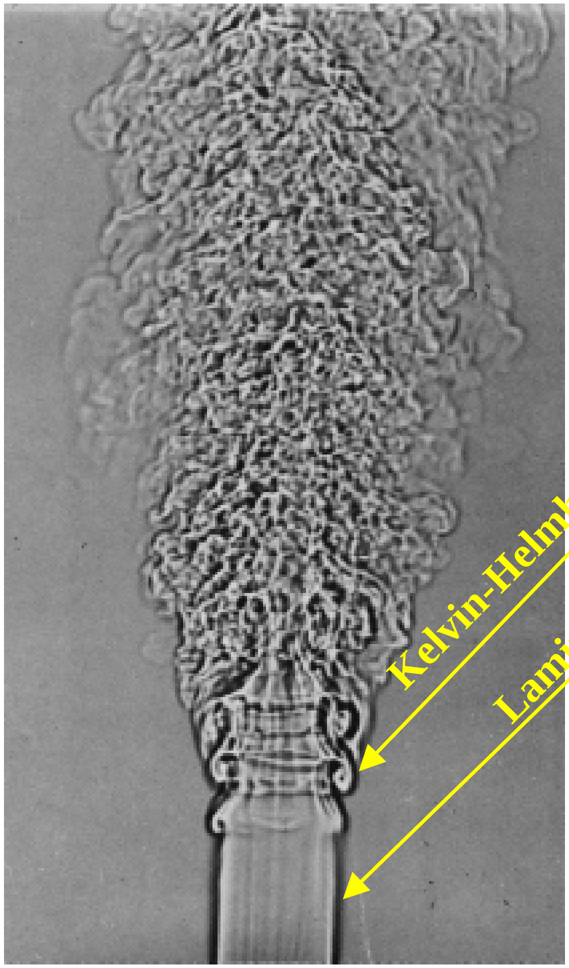


Drake et al., Ap. J. 564, 896 (2002)

- **A scale transformation of the Euler equations relates the lab experiment to the SN**

Simulations of supernova explosions show extensive material interpenetration, do not appear to be turbulent

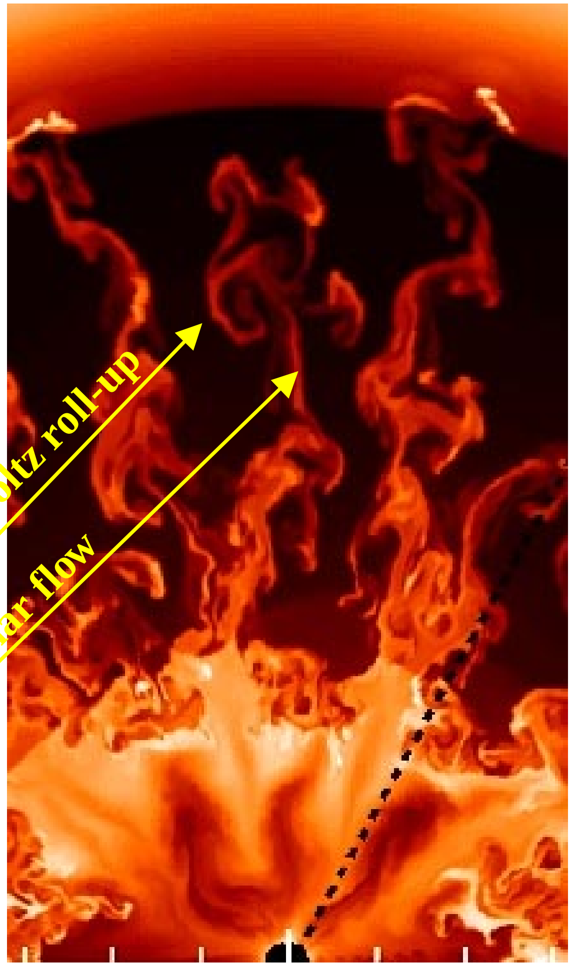
High-Re flows are turbulent



Van Dyke (1982)

Experimental image of a turbulent flow at Re = 10^4

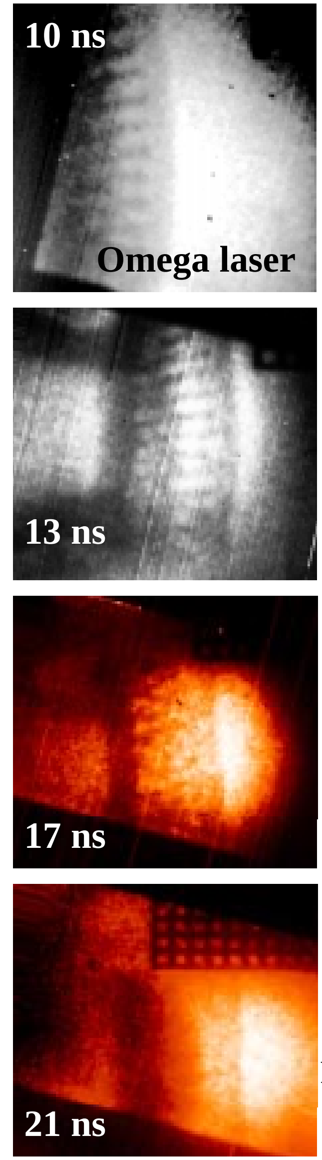
SN simulations are not



Kifonidis, Ap. J. 531, L123 (2000)

SN simulation at Re_{num}~10^3 : unstable but non-turbulent, vs. Re_{SN} ~10^{10} : fully turbulent

3D HED experiments may be



Robey (2002)

What have we learned?

- Actual SNe are high Reynolds number flows, so should be fully turbulent
- Simulations of core-collapse SNe do not transition to turbulence, whereas actual SNe must be fully turbulent
- Scaled SN experiments can bridge this gap and illustrate the impact of the transition to turbulence

- See Paul Drake talk, K7.003, Sun. afternoon

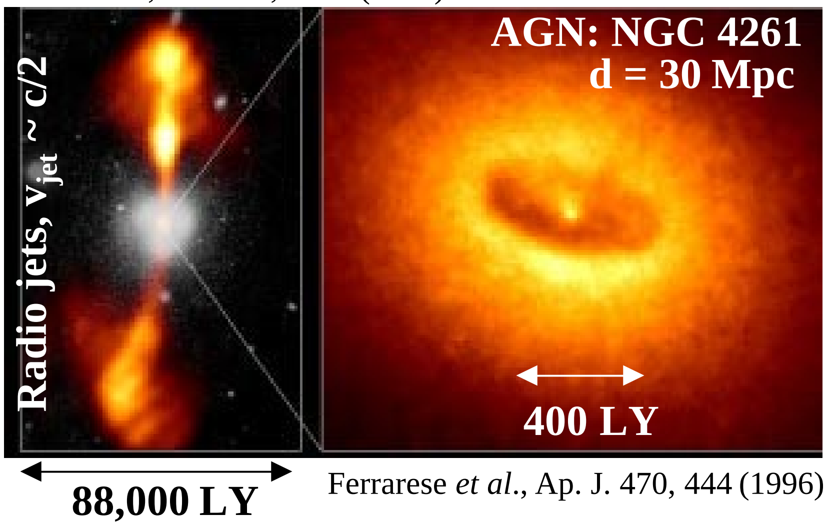
Accreting black holes and neutron stars

- **Can we understand neutron star, black hole accretion dynamics, ie, stellar post-mortem**

- **Regime: radiation-dominated plasma**

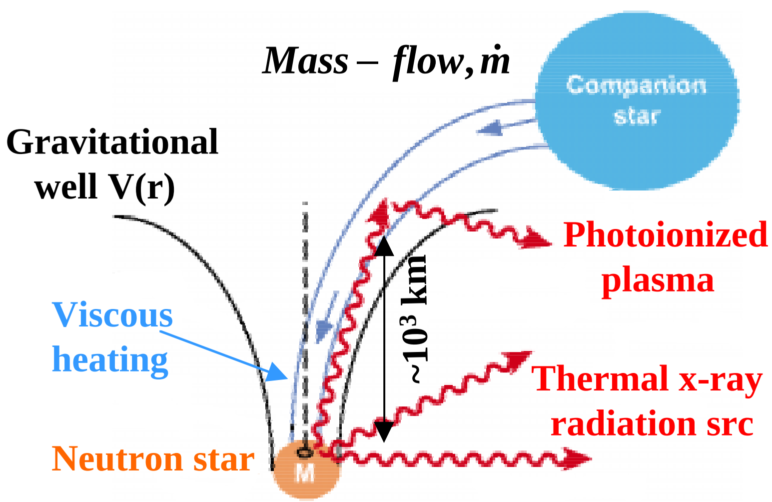
Accreting neutron stars and black holes offer spectral signatures of the dynamics as matter spirals inward

Piner *et al.*, A.J. 122, 2954 (2001)

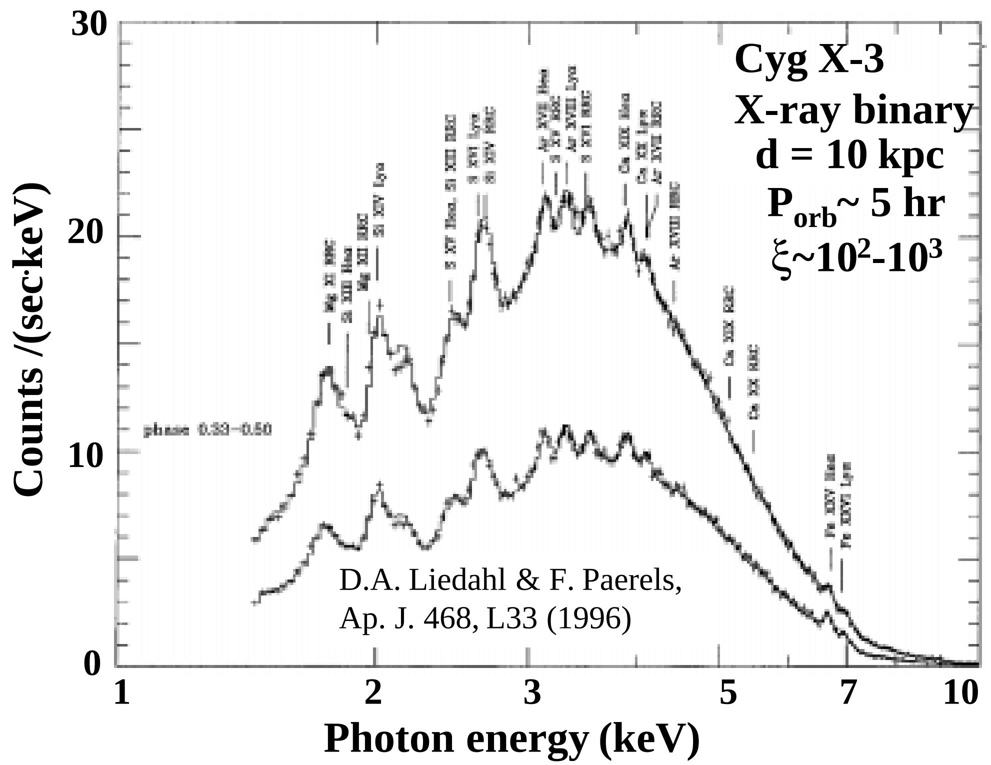


Ferrarese *et al.*, Ap. J. 470, 444 (1996)

• **Analysis and interpretation requires accurate photoionization models**



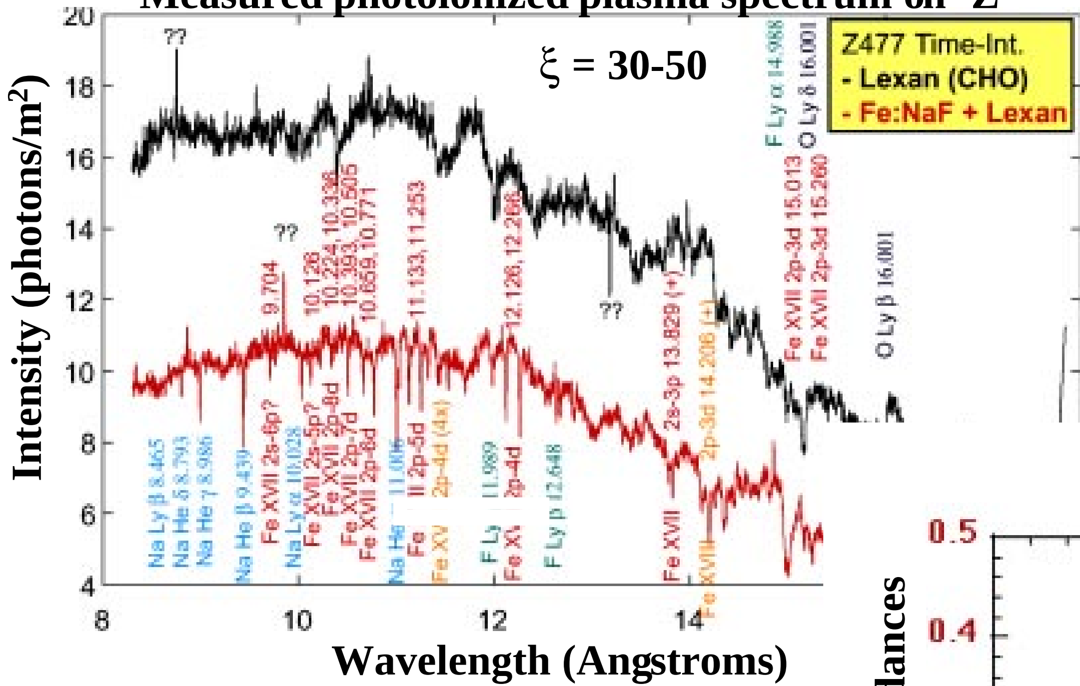
R. Heeter, private commun. (2001)



• **Photoionization parameter $\xi = L/nr^2$ characterizes the regime**

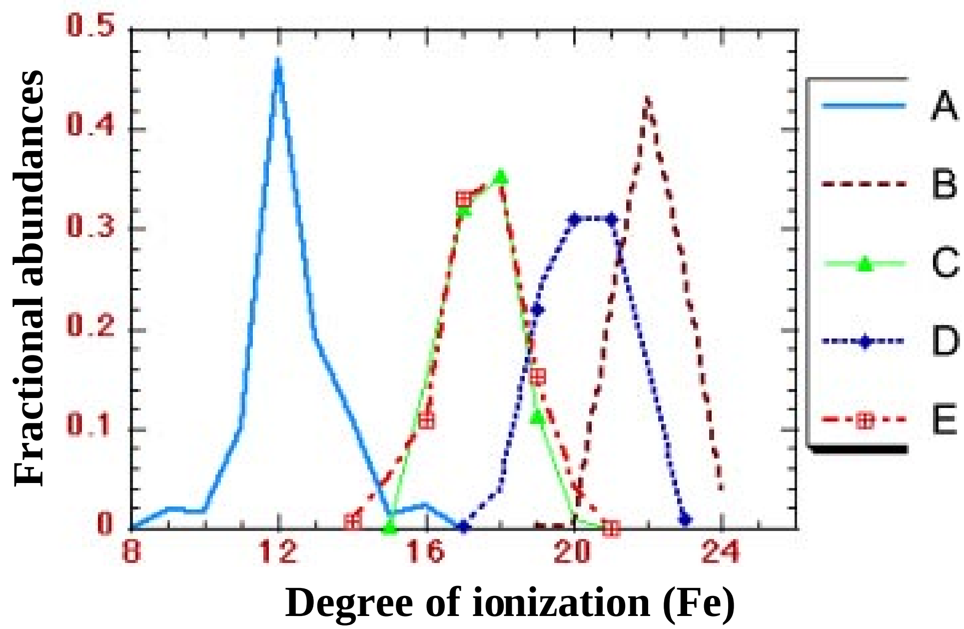
HED experiments reproduce the conditions of radiation-dominated photoionized plasmas

Measured photoionized plasma spectrum on ‘Z’



- **The photoionization parameter, $\xi = 4\pi\Gamma_{rad}/n_e$ = 50-100, establishes the relevant regime**

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



- **Experiments under relevant conditions demonstrated at the ‘Z’ facility**
- **Astrophysics codes disagree on <Z> by ~2x, showing the need for lab. data**

What have we learned?

- Current astrophysics photoionized plasma models differ by factors of 2 in <Z>
- Laboratory data is critical for calibrating these models
- Experiments under relevant conditions have been demonstrated

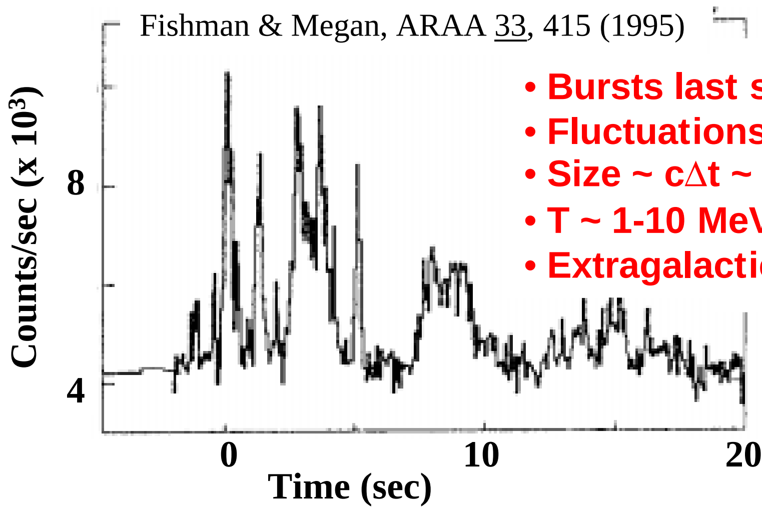
- See Paul Springer talk, K7.003, Sun. afternoon

Gamma-ray bursts

- **Can we understand gamma-ray burst explosion mechanisms and dynamics, ie, what are they?**

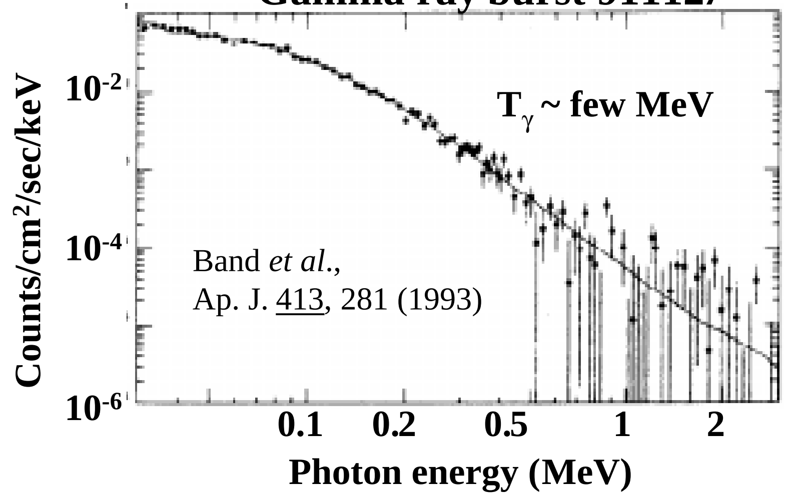
- **Regime: relativistic plasmas**

Gamma-ray bursts currently are the greatest enigma in modern astrophysics

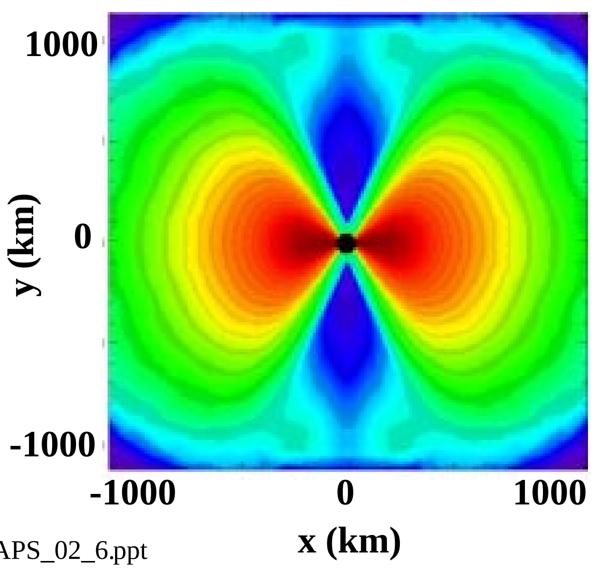


- Bursts last seconds
- Fluctuations of ~1 ms
- Size ~ $c\Delta t \sim 10^7$ cm
- T ~ 1-10 MeV
- Extragalactic

Gamma ray burst 911127



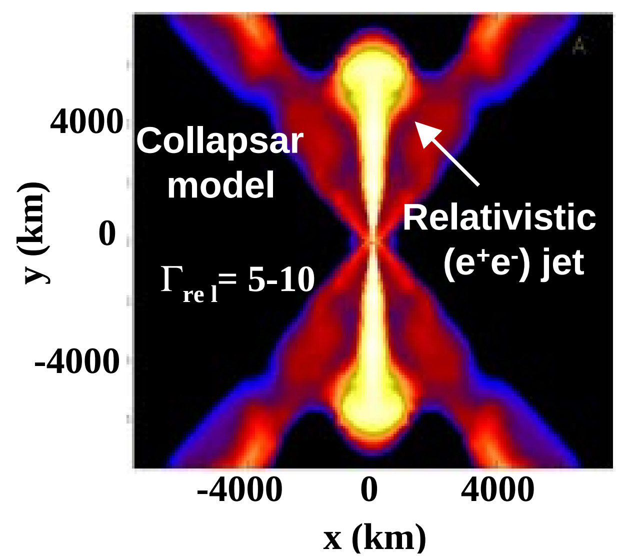
Simul'd accretion disk - black hole density structure



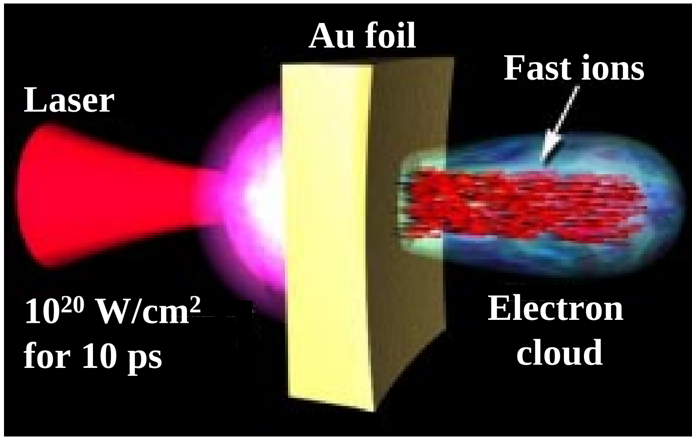
Woosley & MacFadyen, Astron. Astrophys. Suppl. Series 138, 499 (1999)

$M_i > 30M_{sun}$
Inner disk:
T ~10 MeV
$\rho \sim 10^{10}$ g/cm^3
R ~10 km
$dM/dt \sim 0.1 M_{sun}/s$
$M_{BH} \sim 5M_{sun}$

Simul'd energy density for GRB explosion

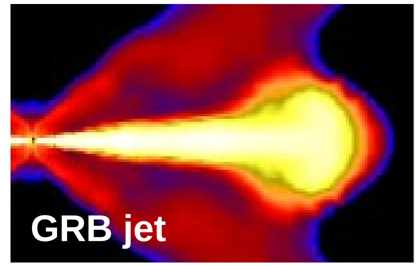


HED experiments on ultra-intense lasers access the relativistic plasma regime, relevant to aspects of GRBs

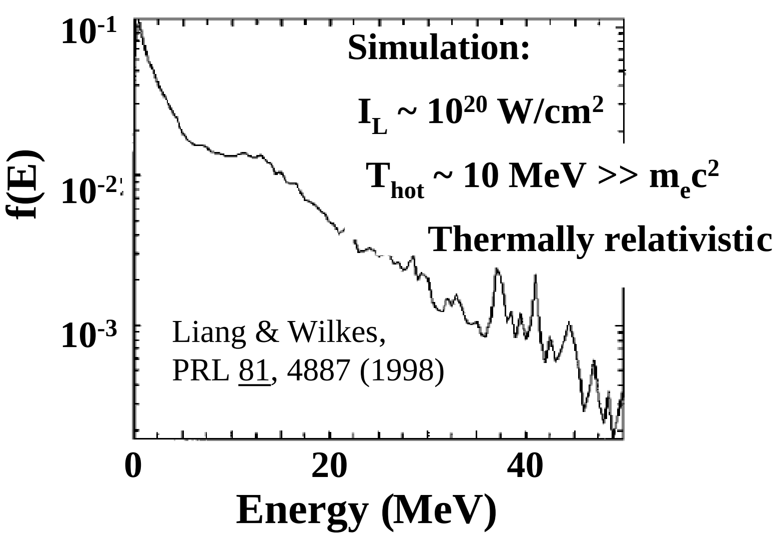


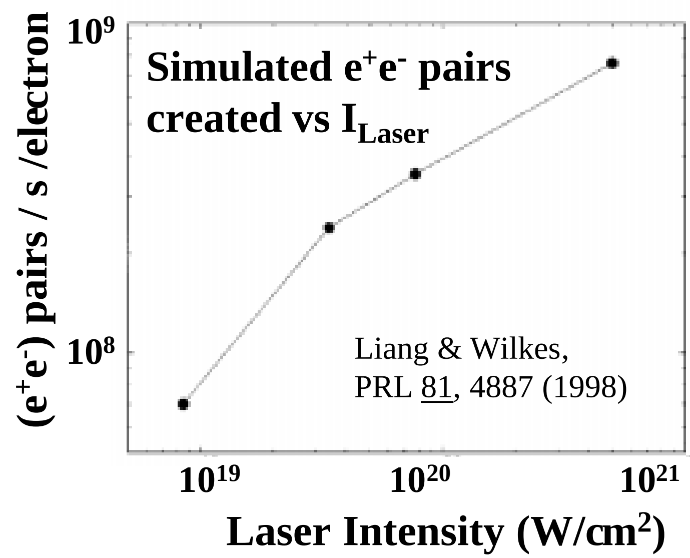
Wilks et al., Phys. Plasmas 8, 542 (2001)

Are there similarities?



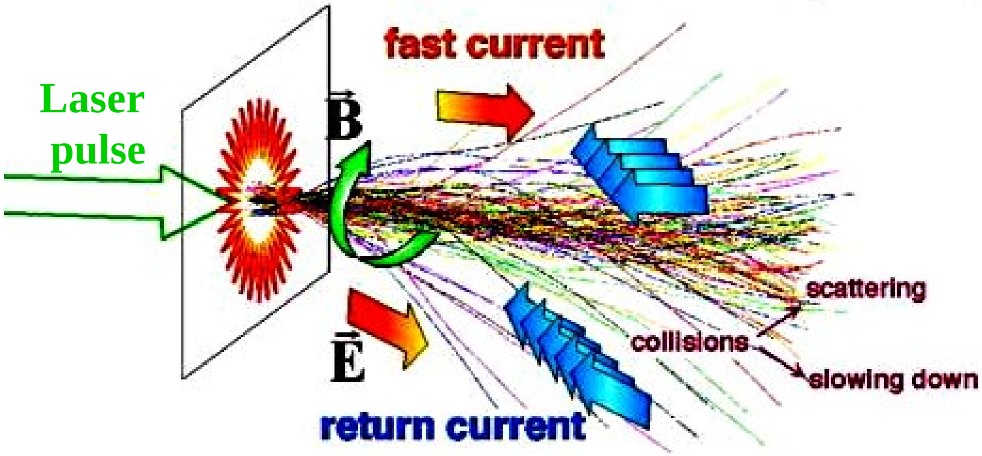
Woosley & MacFadyen, Astron. Astrophys. Suppl. Series 138, 499 (1999)



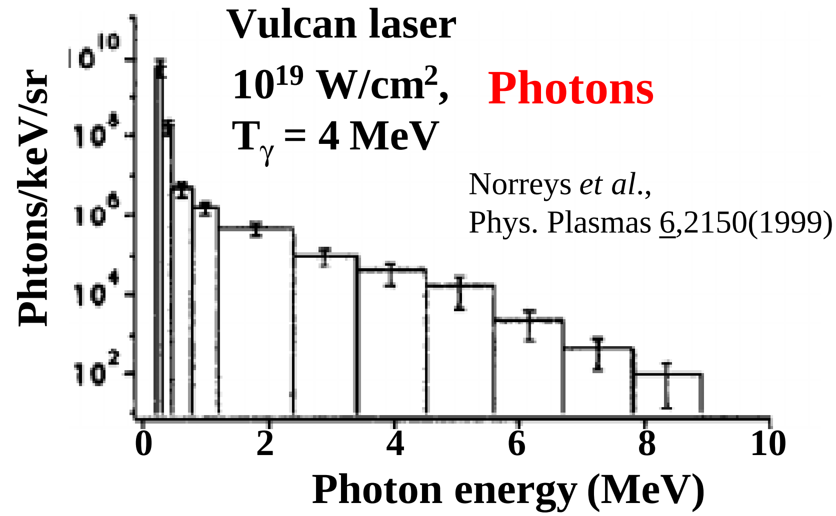


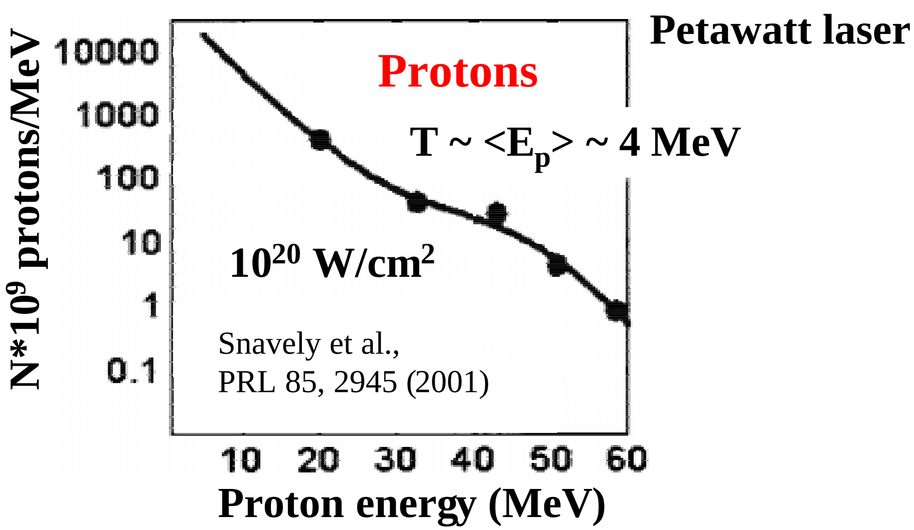
- **A measurable population of e^+e^- pairs is predicted for double-sided illumination**

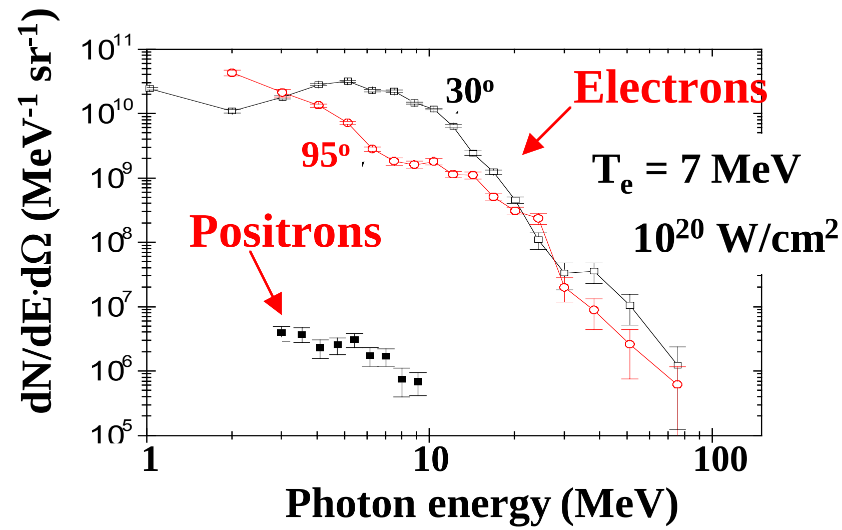
Experiments on ultra-intense lasers in the relativistic plasma regime have observed new physics phenomena



C. Toupin et al., IFSA 99 Publ. Elsevier, p. 471 (2000)







- **See Warren Mori talk K7.004 Sun. afternoon**

Cowan *et al.*, Laser & Part. Beams 17, 773 (1999)

What have we learned?

- Relativistic plasmas can be accessed experimentally
- New, unexpected physics phenomena were observed
- Dynamics of an e^+e^- (micro) fireball may be experimentally accessible
- These relativistic plasmas may have relevance to aspects of GRBs

- See Warren Mori talk, K7.004, Sun. afternoon
- See Jay Salomonson poster, N17.057, Mon. morning

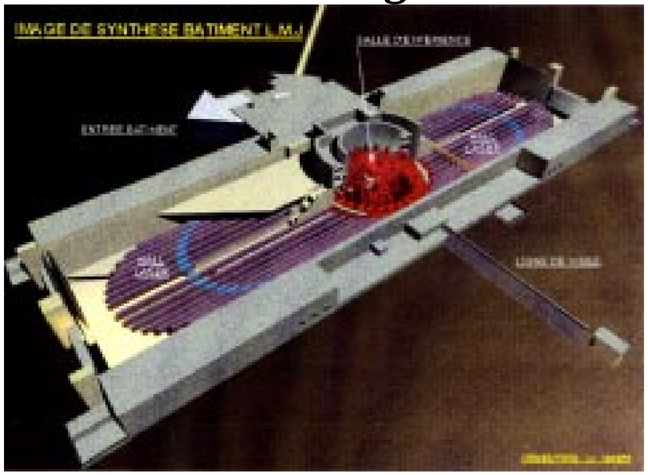
The future

The future:

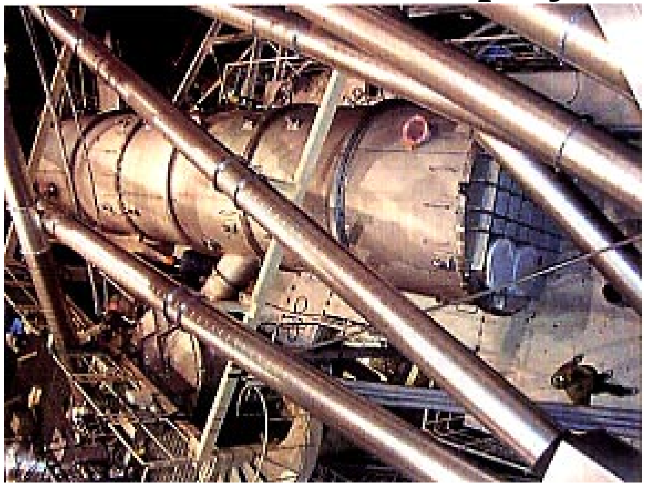
HED facilities for the next decade include the ~2 MJ NIF and LMJ lasers, the upgraded Z-R pinch facility, and several petawatt lasers

NIF construction site

LMJ design

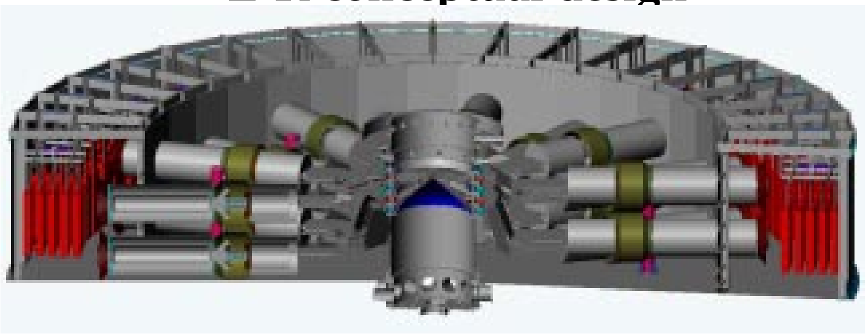


Osaka Univ. Petawatt project



Also UK, France, Germany, US

Z-R conceptual design



- **See Keith Matzen talk, K7.001, Sun. afternoon**

New facilities and new capabilities make the coming decade particularly exciting for the field of HEDP

Facilities to look forward to:

- 2-MJ NIF in U.S. + Petawatt(s?)
- 2-MJ LMJ in France
- 60-beam Omega + Petawatt
- 12-beam Gekko + Petawattt (Japan)
- 5-kJ/10-beam Vulcan + 2 x Petawatt (U.K.)
- LULI Petawatt (France)
- GSI Petawatt (Germany)
- Z-R pinch facility + Petawatt
- 60-kJ/60-beam SG-III (China)

New capabilities these will provide:

- first laboratory demonstration of thermonuclear ignition
- intense bursts of neutrons may access r-, s-, p-processes
- possible ignition physics studies of relevance to SNe-1a
- fully turbulent, hydrodynamic tests for SNe
- scaled SNe V&V testbed
- EOS at very high pressures: white dwarfs, brown dwarfs
- expansion opacity, rad-flow msmts relevant to SNe
- photoionized plasmas relevant to accretion disks, AGN
- radiative shocks relevant to SNR
- access aspects of neutron star atmospheres at ~1 keV
- relativistic plasma testbed, possible relevance to GRB
- concept for accessing Unruh radiation physics
- Gigagauss magnetic fields (n-star atmos.)
- implode rotating core
- core-kick asymmetric implosions
- solid-state properties at Jupiter core pressures
- definitive test of plasma phase transition