Experiments to probe warm dense matter conditions for planetary science

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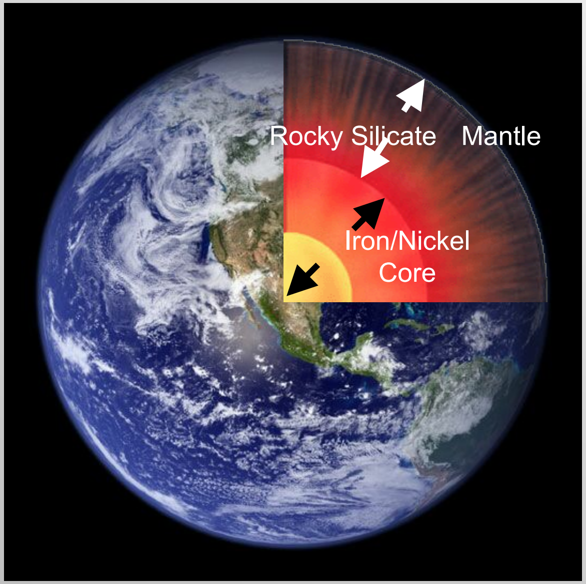
Outline

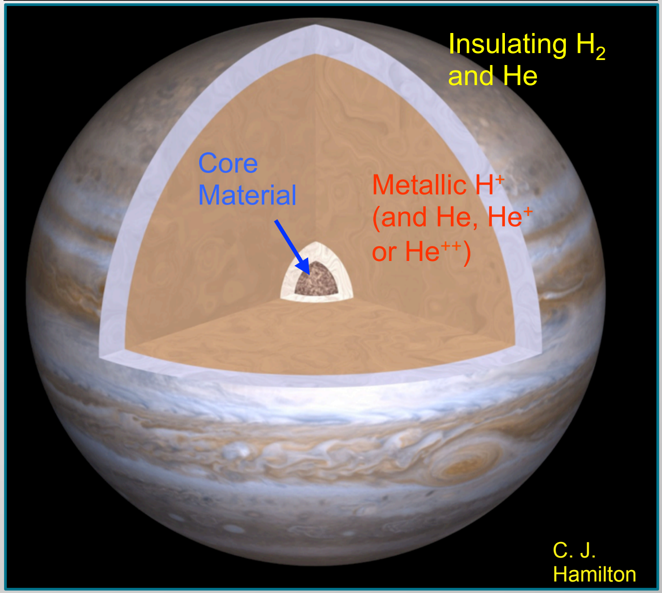
- Planetary core conditions: what and why?
- Laboratory techniques
  - Dynamic compression techniques
  - Drivers & facilities
  - Diagnostics
- Survey of recent results
- Summary

Core conditions in planets reach multi-Mbar pressures at moderate temperatures

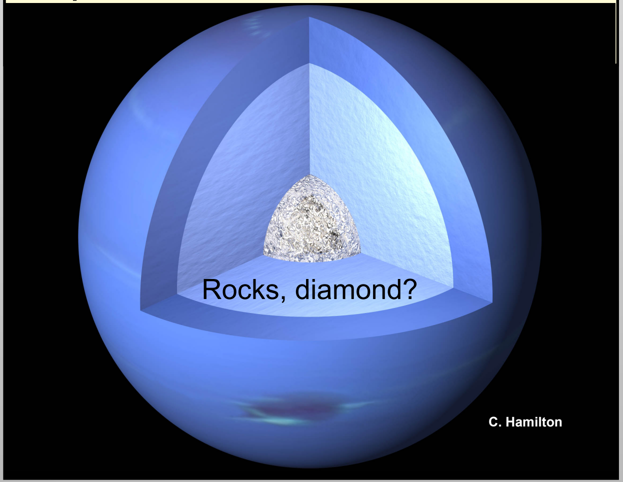
Earth: central pressures ~3.6 Mbar and temperatures ~6000 K



Jupiter: central pressures ~77 Mbar and temperatures ~16000 K

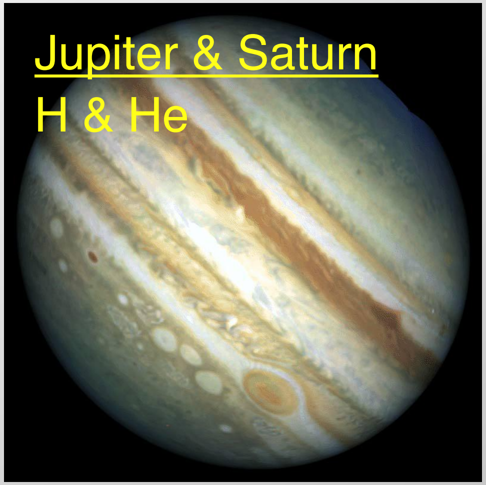


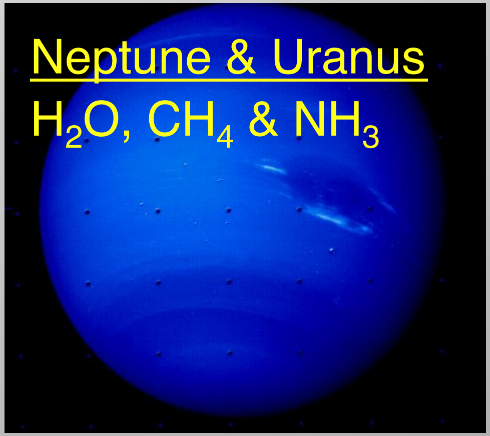
Neptune: central pressures 8 Mbar **and temperatures** ~5000 K



Understanding planetary interiors depends on theoretical models

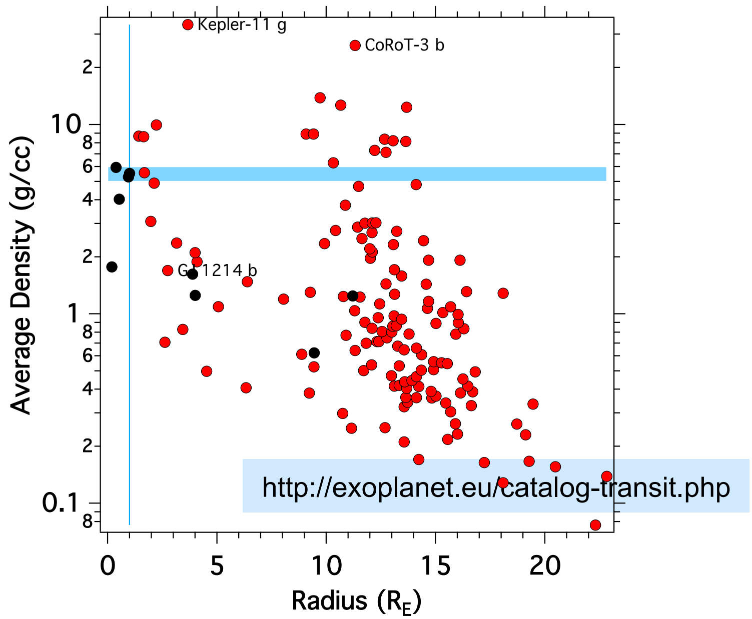
- Planetary models are constructions based on a combination of theory and observation
- A few basic parameters are known:
  - Mass, radius, luminosity, and some gravitational moments, B-field, surface composition
- Interior models depend on our knowledge of the high pressure phase diagrams of the abundant elements and their compounds (H, He, C, O, N, Mg, Si, Fe etc.)
  - Equation of state - gives density profile
  - Conductivity and metallic transitions - magnetic dynamo models
  - Phase transitions?
    - — Introduce new complications in the structure and transport mechanisms





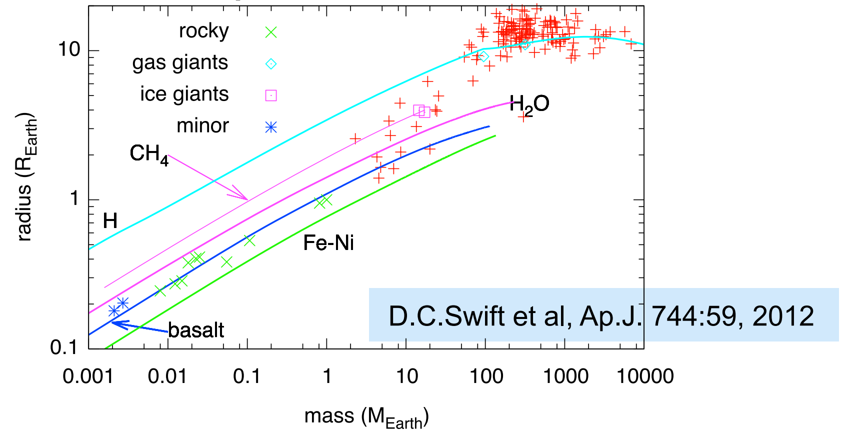
Extra-Solar Transiting Planets

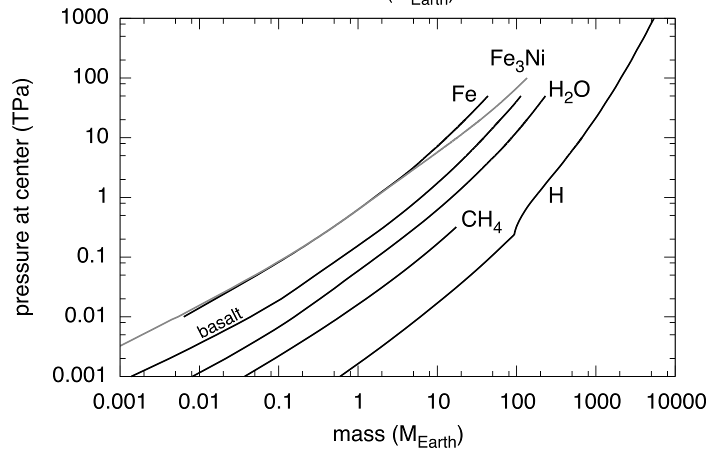
More than 500 known planets, most do not match planet evolution models



>15 exo-planets with average density larger than earth

EOS models important to infer compositions from mass-radius relationships





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Laboratory dynamic compression techniques to reach core conditions

- Shock waves
- Ramp compression techniques
- Dynamic compression facilities
- Hybrid techniques

Shock compression technique

- Rankine-Hugoniot relations (conservation laws):

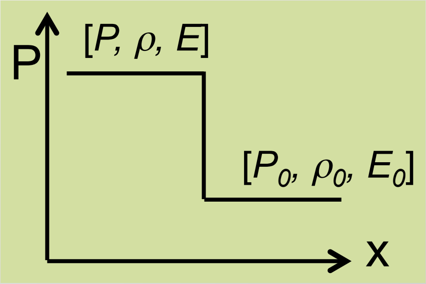
$$\frac{\rho}{\rho_0} = \frac{u_s}{u_s - u_p} \quad \text{[mass]}$$

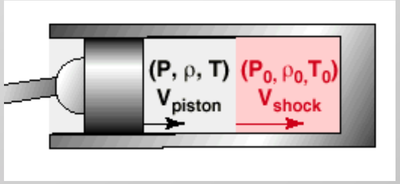
$$P - P_0 = \rho_0 u_s u_p \quad \text{[momentum]}$$

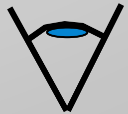
$$E - E_0 = \frac{1}{2} P\left(\frac{1}{\rho_0} - \frac{1}{\rho}\right) \quad \text{[energy]}$$

- 5 parameters (P, ρ, E, u_s, u_p) and 3 equations
  - need measure two parameters to determine the rest
  - *We measure velocities ➔ infer P, ρ, E*
  - Temperature has to be determined independently

Impulsive load



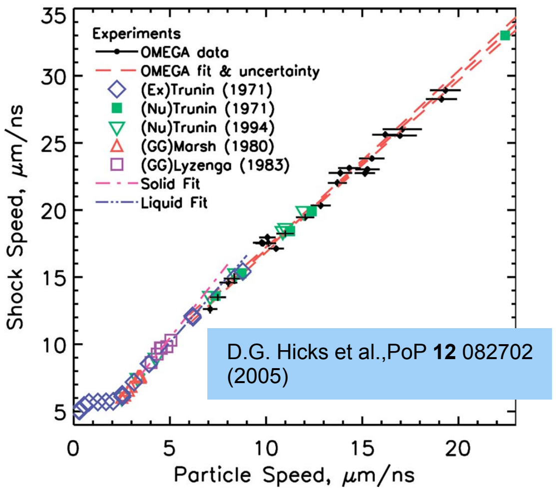




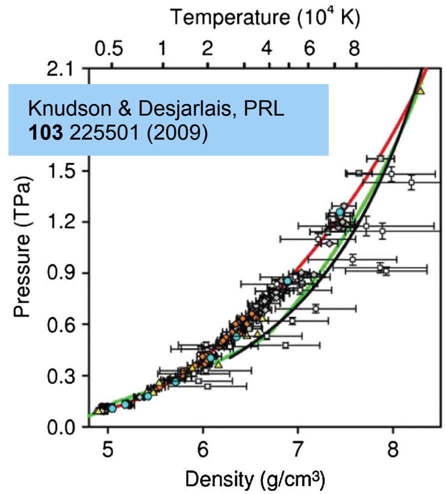
Measure u_s & u_p

Shock wave data sets

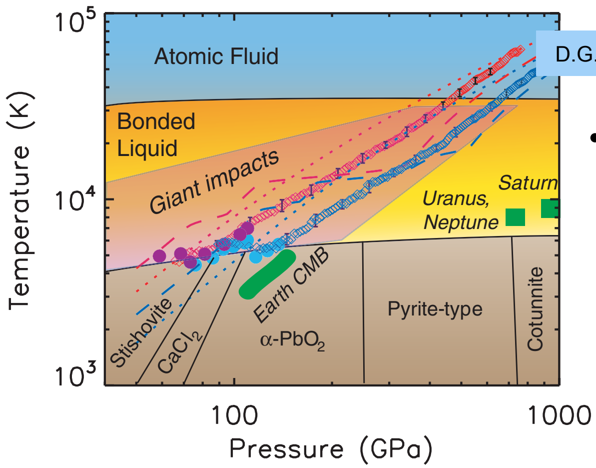
Quartz and fused silica



D.G. Hicks et al.,PoP **12** 082702 (2005)



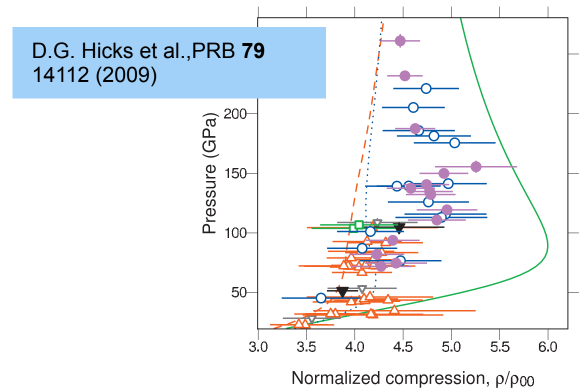
Knudson & Desjarlais, PRL **103** 225501 (2009)



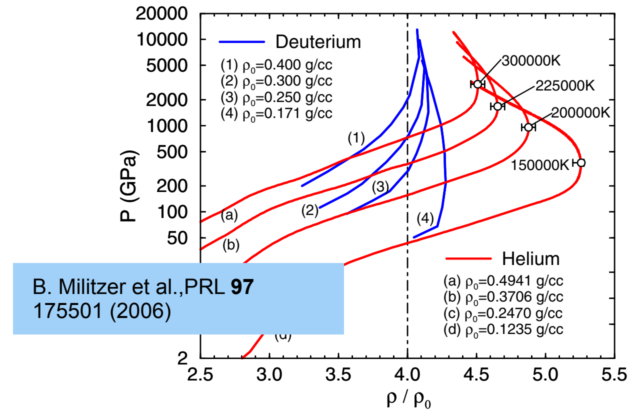
D.G. Hicks et al.,PRL **97** 025502(2006)

- Most solids melt under shock in the Mbar range, e.g. SiO2 at ~1 Mbar, Fe at ~2.5 Mbar

Deuterium & He



D.G. Hicks et al.,PRB **79** 14112 (2009)



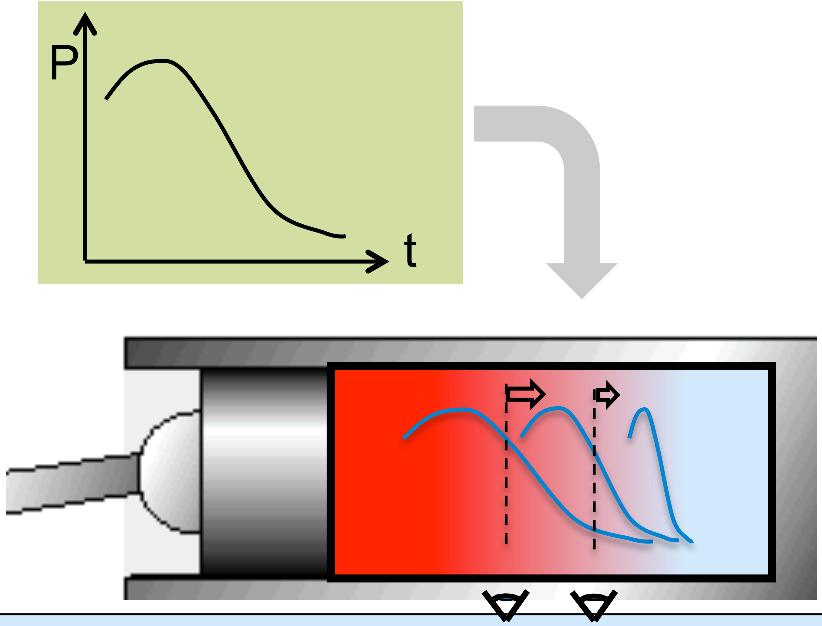
B. Militzer et al.,PRL **97** 175501 (2006)

Shock waves reach a limiting compression

Ramp compression

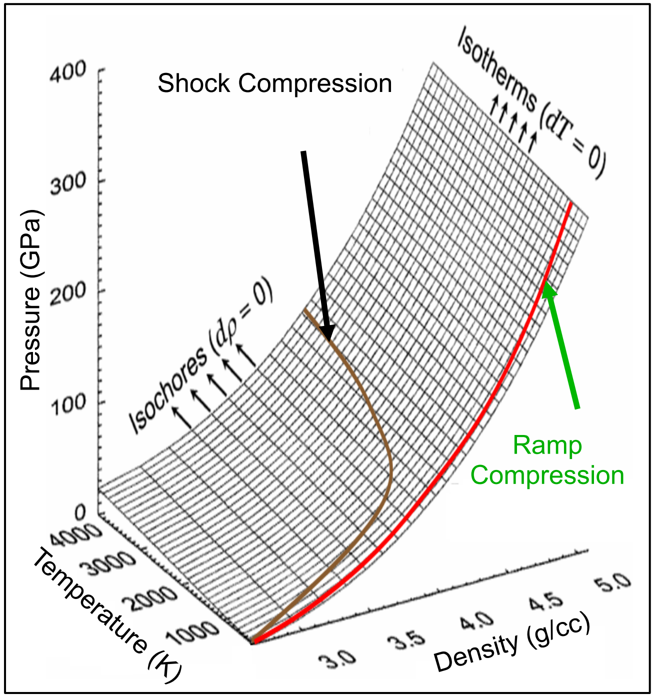
Apply a time-varying load to the sample

- Fundamental measurement ansatz: thermodynamic state is a function of the particle speed



Measure the motion of the sample material as the wave passes through

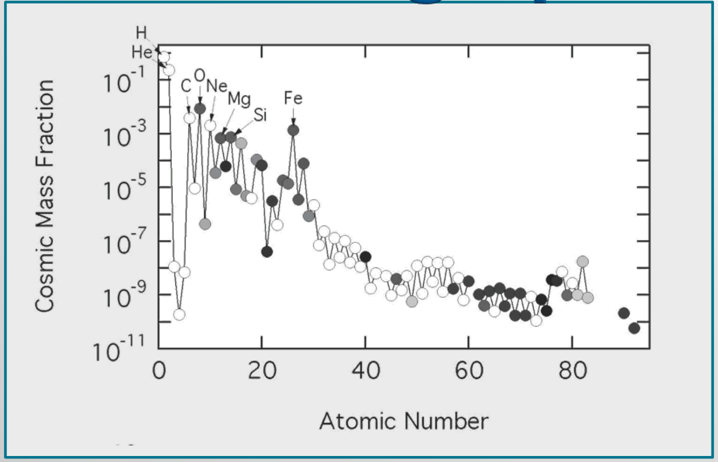
Continuous compression follows a quasi-isentropic path

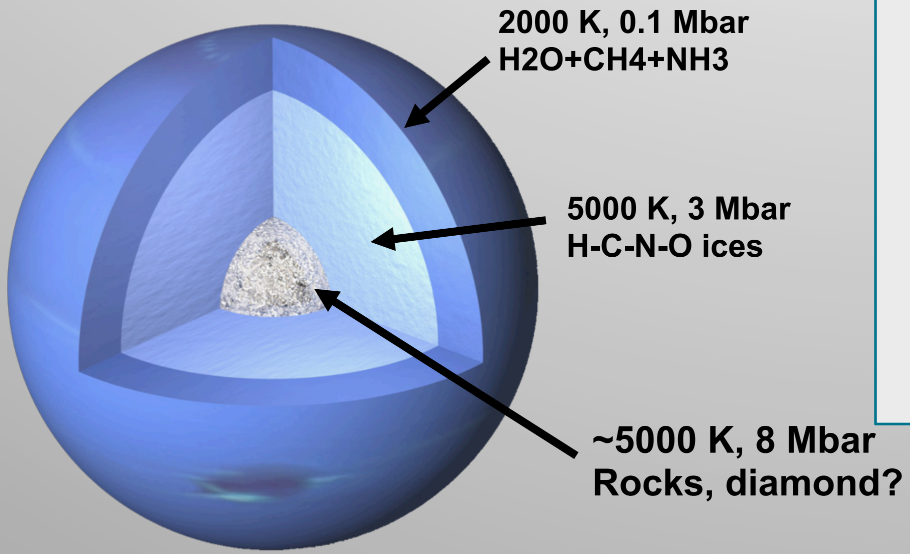


J-P. Davis (2008)

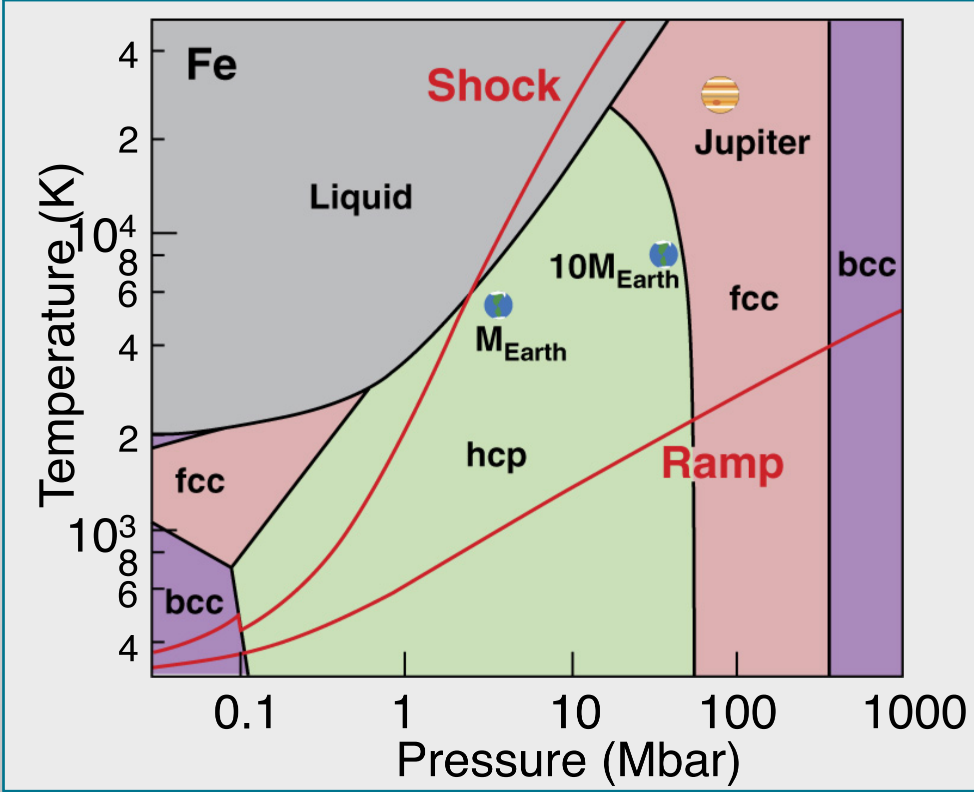
No limiting compression

Ramp compression keeps the sample solid at high pressure





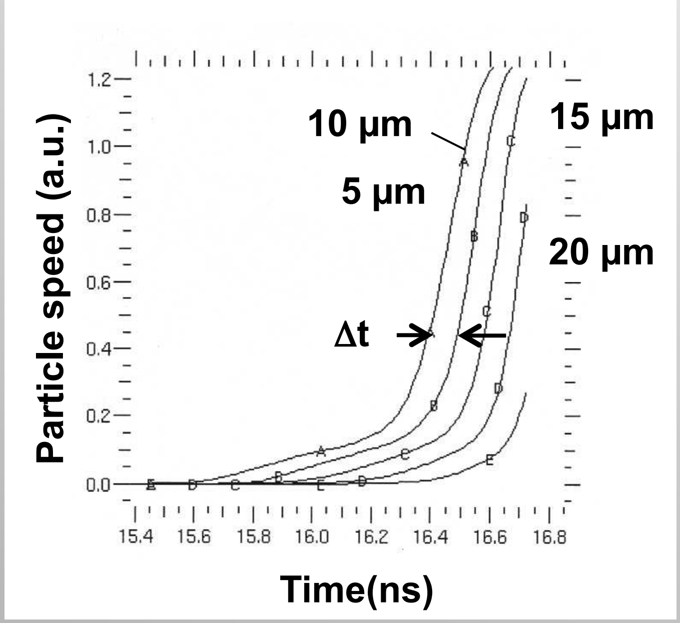
Crystal structure of Fe at extreme conditions



Stixrude, 2008

Ramp compression experiments yield quantitative EOS data

- Measure material motion at two or more positions – determine the Lagrangian sound speed
- As with shock technique: absolute EOS is inferred from wave speed measurements



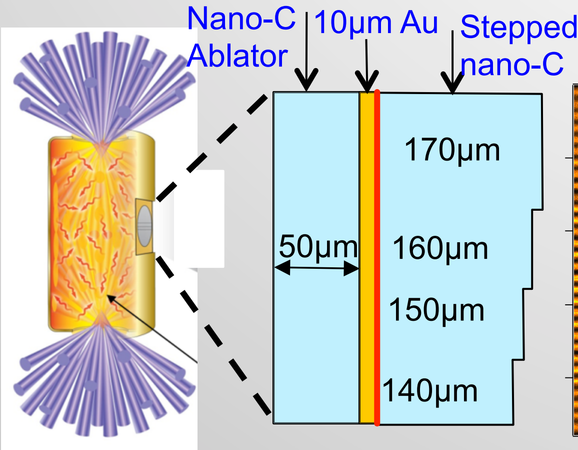
$$c_L(u_p) = \Delta x_p / \Delta t \qquad \text{[observable]}$$

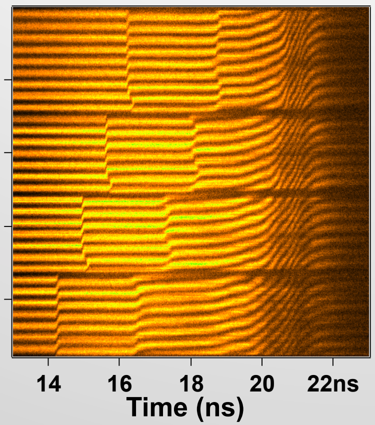
$$V(u) = V_0 \int_0^u \frac{1}{c_L(u_p)} du_p \qquad \text{[mass]}$$

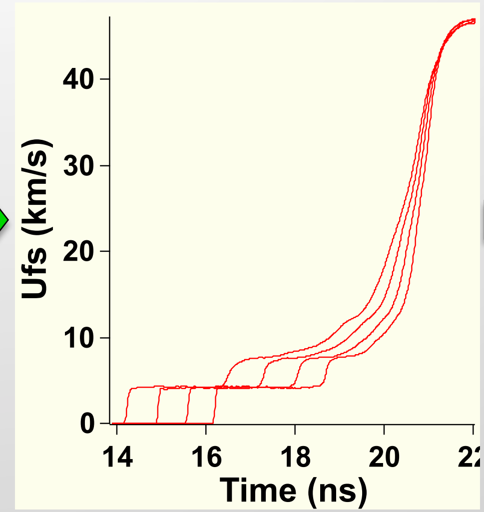
$$P(u) = P_0 + \rho_0 \int_0^u c_L(u_p) du_p \qquad \text{[momentum]}$$

$$\Rightarrow \quad P(V), \text{ and } E(V) = E_0 - \int_{V_0}^{V} P(V') dV'$$

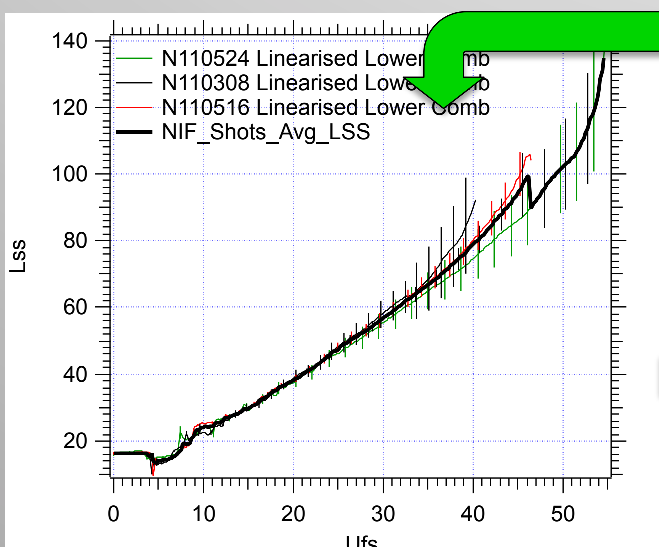
Iterative Lagrangian analysis to extract stress and density (Rothman, et al., (2005)







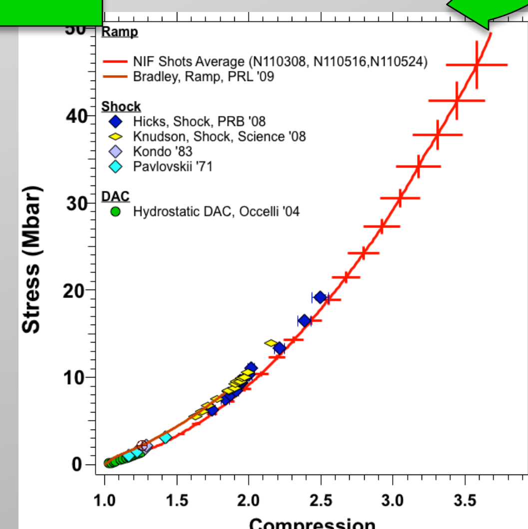
$$C_L(u) = \frac{\Delta x}{\Delta t}$$



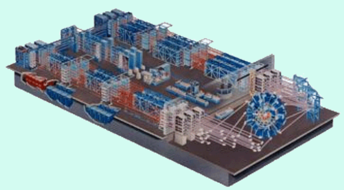
Since we measure free surface velocity, not *u* we must use an iterative correction developed by Rothman (2005)

$$\rho(u) = \rho_0 \left(1 - \int du/C_L\right)^{-1}$$

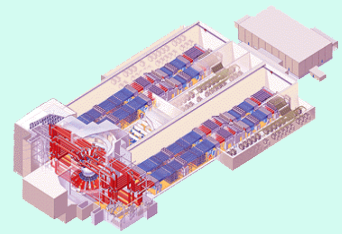
$$P_x(u) = \rho_0 \int C_L \, du$$



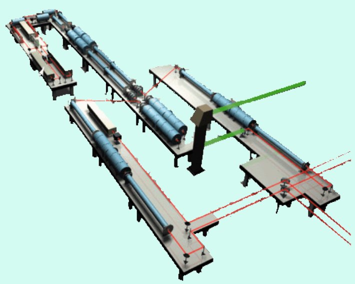
Dynamic compression facilities



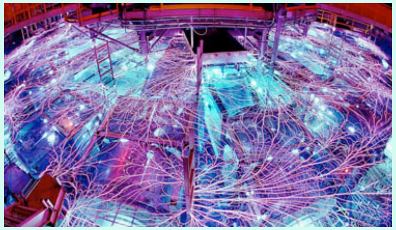
Omega
University of Rochester (NY)
60 Beams, 30 kJ



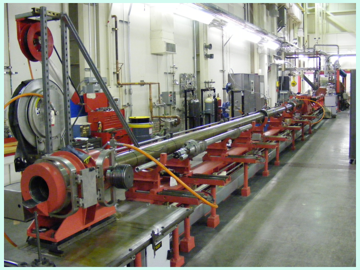
N.I.F.
Lawrence Livermore National Lab
192 beams, 1.8 MJ



Janus
Lawrence Livermore National Lab
2 beams, 1 kJ

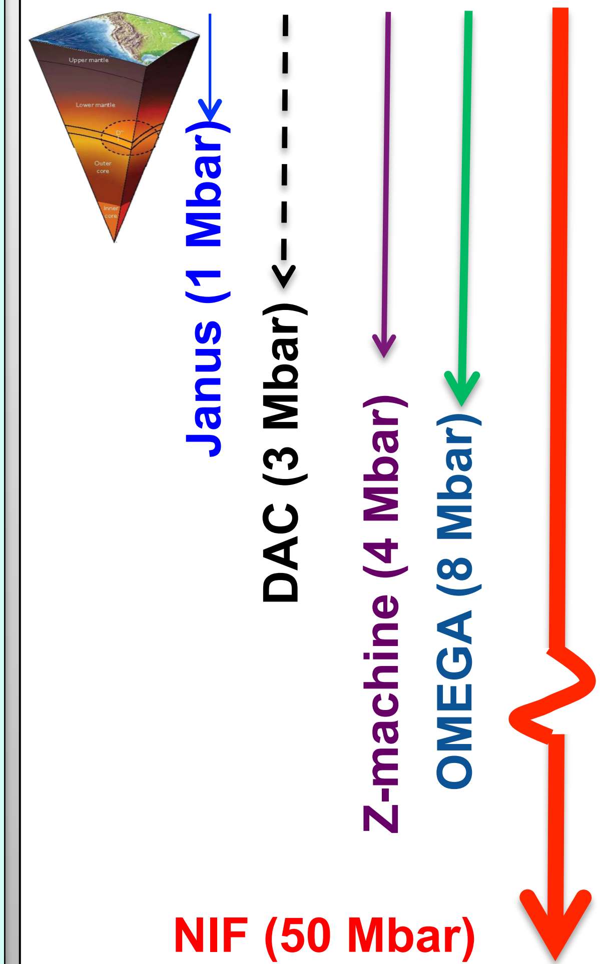


Z Machine
Sandia Labs
~20 MA, ~6 Mbar magnetic pressure
< 45 km/s flyer plates



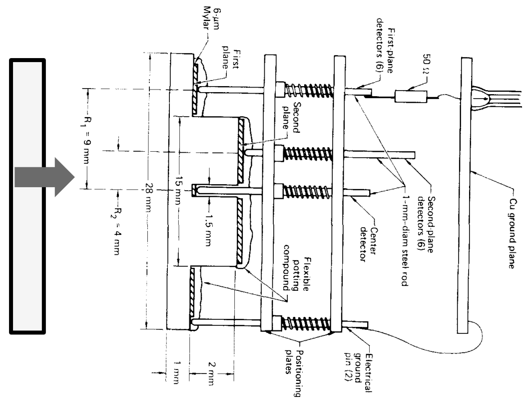
Gas guns
Various (LLNL, LANL, Sandia, WSU and others)
< 8 km/s

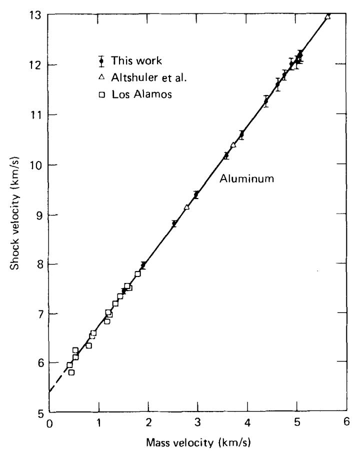
Ramp compression capability



High pressures generated by projectile impact (gas guns)

Plate impact generates strong shock

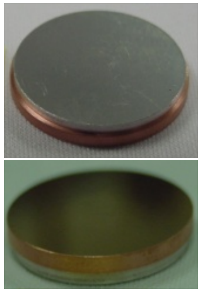


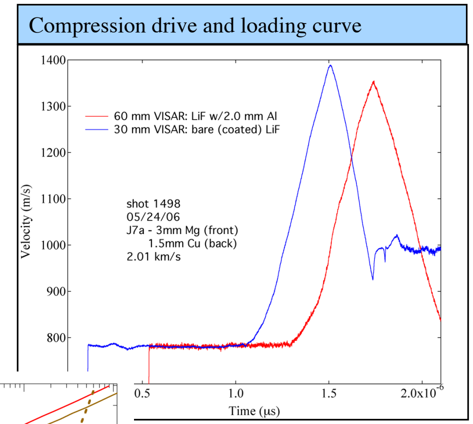


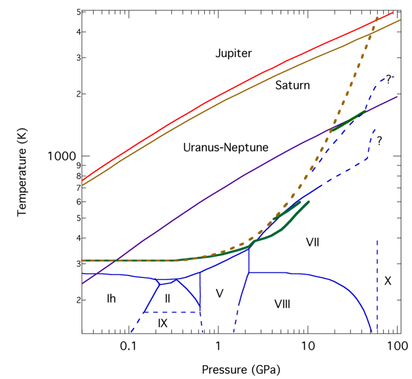
- Peak velocities: ~ 8 km/s
- Peak pressures ~4 Mbar depending on the target

Mitchell, Nellis 1970's and 1980's

Graded density impactor generates ramp compression wave





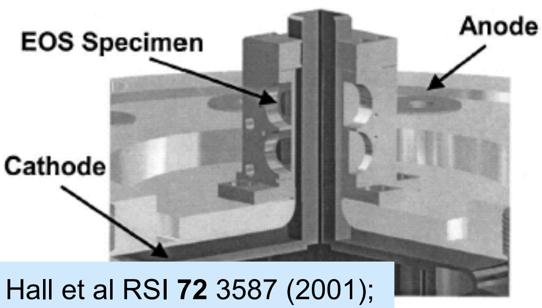


- ~ 1 μs time scale

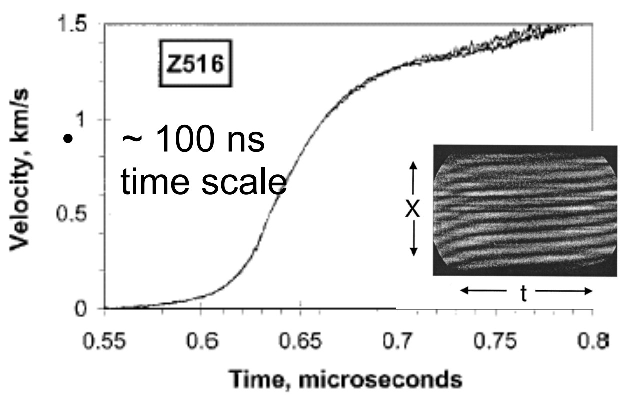
Ngyuen, Holmes, Chau (LLNL)

High pressures generated by pulsed power (Z accelerator)

Direct application of magnetic stress to the sample

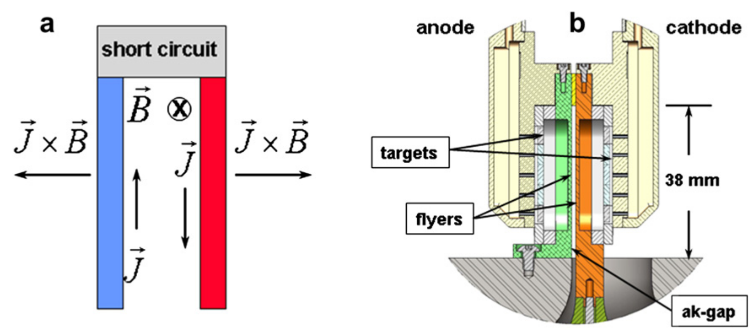


C.A. Hall et al RSI **72** 3587 (2001);
D.B. Reisman JAP **89** 1625 (2001)



Generates ramp wave

Magnetically-accelerated flyer plate



R.W. Lemke et al, IntJ.Impact Eng. **38** 480 (2011)

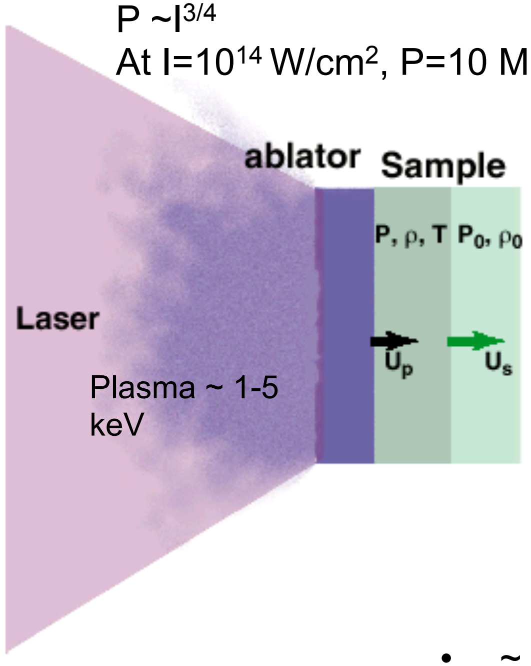
- Plate impact generates single strong shock (aka gun expts)
- Peak velocities: ~ 42 km/s (Al) ~ 22 km/s (Cu)
- Peak pressures ~30 – 40 Mbar depending on the target

Shock hugoniot applications

High pressures generated by lasers

"Direct drive": Laser ablates the surface to create rocket like compression

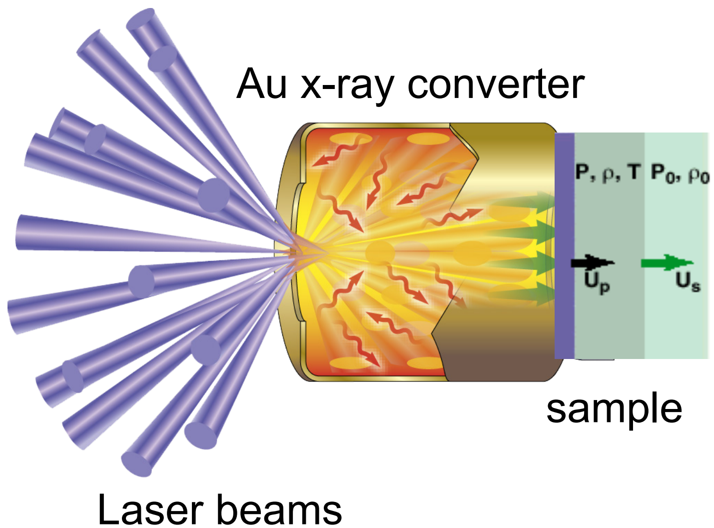
$P \sim I^{3/4}$
At $I=10^{14}$ W/cm^2, P=10 Mbar



- ~ 1 – 10 ns time scale

"Indirect drive": Laser energy converted into soft x-rays, blackbody spectrum

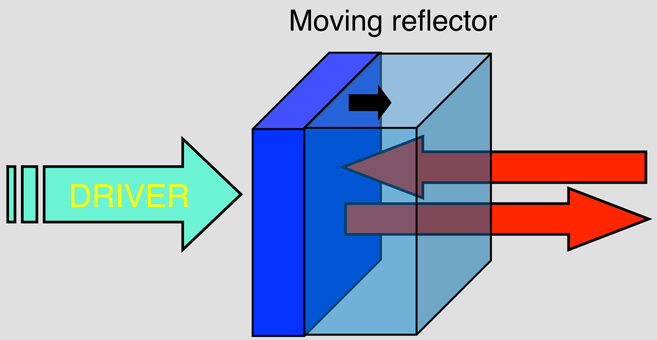
$P(\text{Mbar}) \sim 0.1T_r(\text{eV})^{3/4}$
~ 100 Mbar at 250 eV



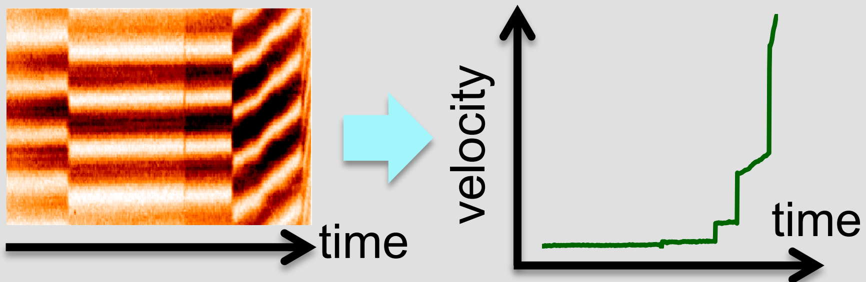
Pulse shape & target determines if compression is a shock or ramp

Basic diagnostics

Optical velocimetry

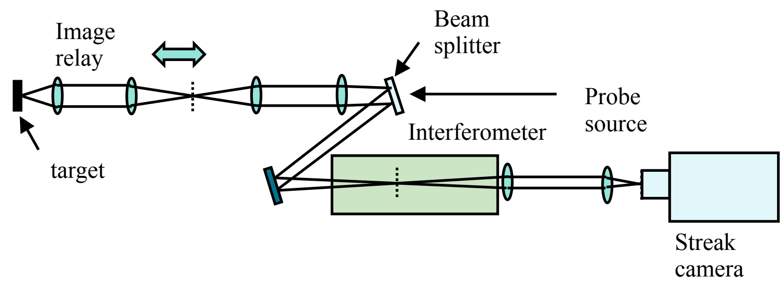


VISAR: "Velocity Interferometer System for Any Reflector"



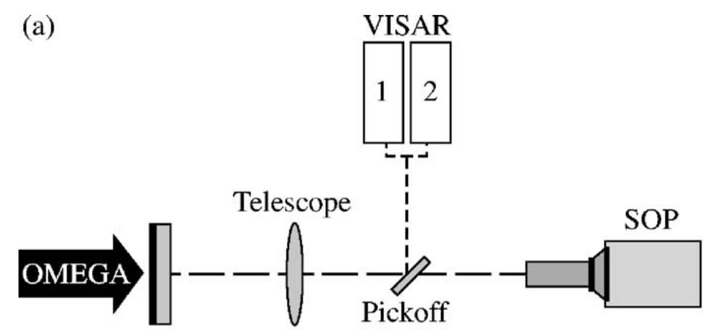
Doppler shift ⇔ fringe phase⇔ velocity

Line-imaging VISAR



P.M. Celliers et al, RSI **75** 4916 (2004)

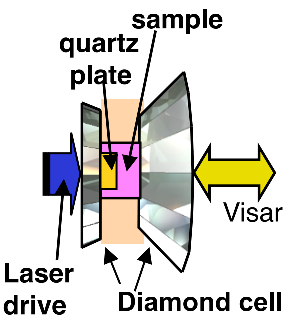
Streaked Optical Pyrometer (SOP)

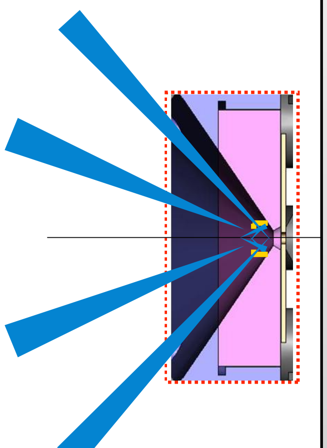


J.E. Miller, RSI **78** 034903 (2007)

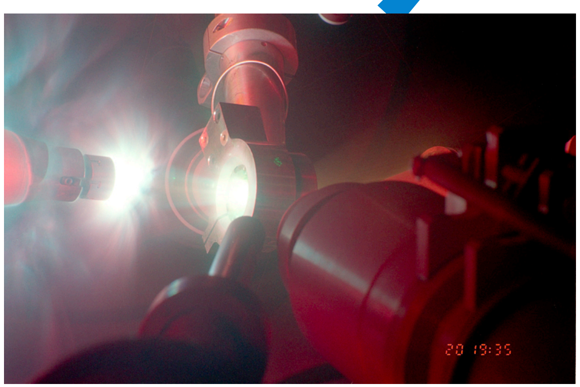
Confined geometries & hybrid variations

Laser shocks coupled into diamond anvil cells

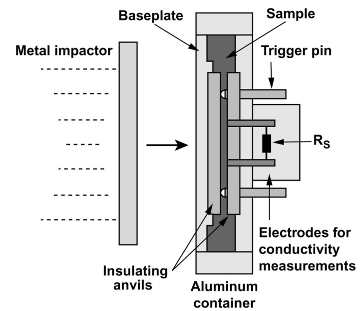




Loubeyre, Jeanloz

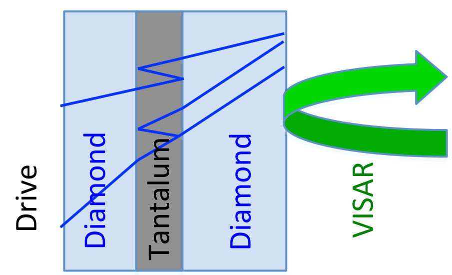


Reverberating compression schemes



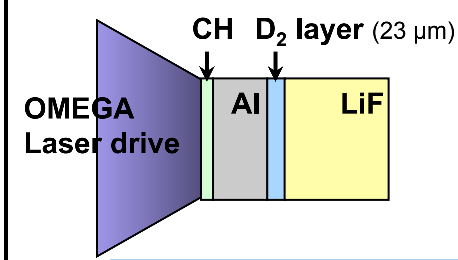
Reverberating compression of water & H_2 on LLNL gas gun

S.T. Weir et al PRL **76** 1860 (1996); R. Chau et al, J.Chem.Phys. (2001)



Eggert, Hicks, Rygg, Ping, Coppari

Samples confined between diamond plates



R. Rygg, SCCM 2011

Reverberating compression of D_2 at OMEGA

Combine with additional probe: conductivity, diffraction

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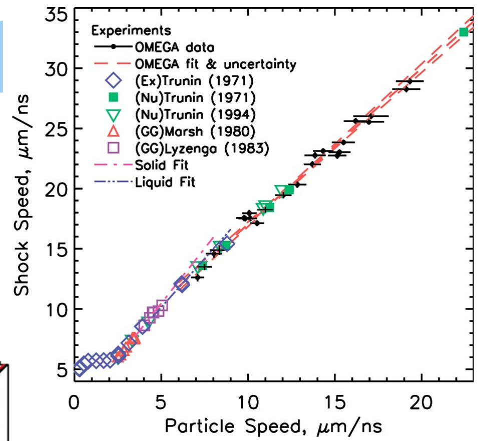
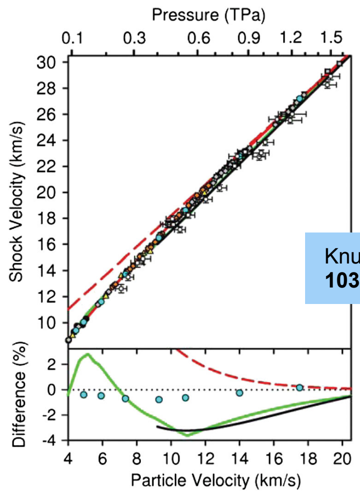
High precision EOS

Quartz hugoniot

D.G. Hicks et al.,PoP **12** 082702 (2005)



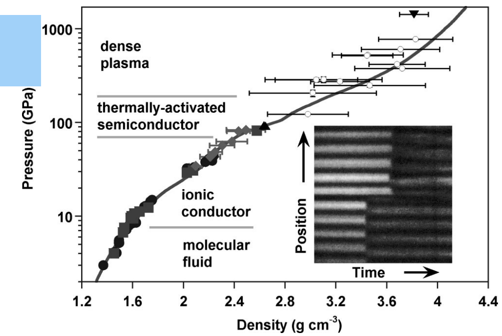


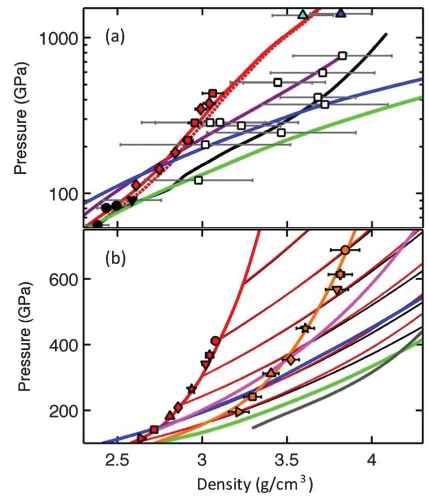
Knudson & Desjarlais, PRL **103** 225501 (2009)

Establishes quartz as an impedance-matching shock standard

Water hugoniot

P.M. Celliers et al.,PoP **11** L41 (2004)





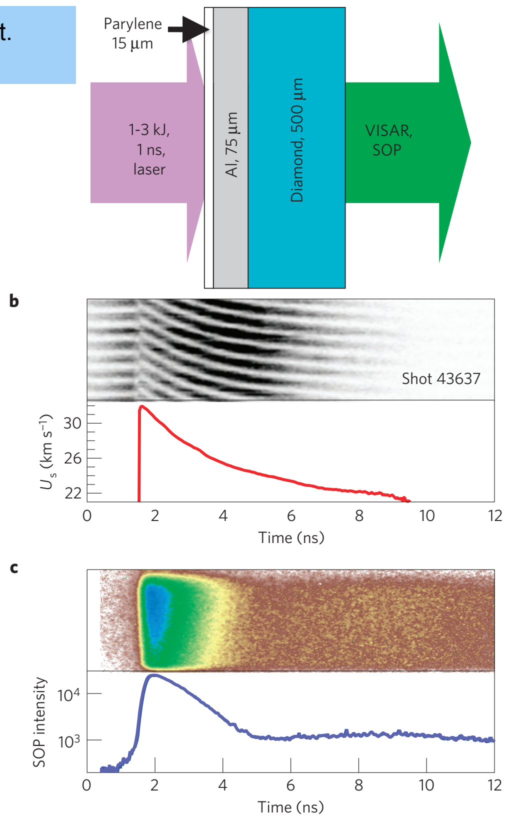
M.D. Knudson et al.,PRL **108** 091102 (2012)

Improvements in measurement accuracy

Melting of diamond on the Hugoniot

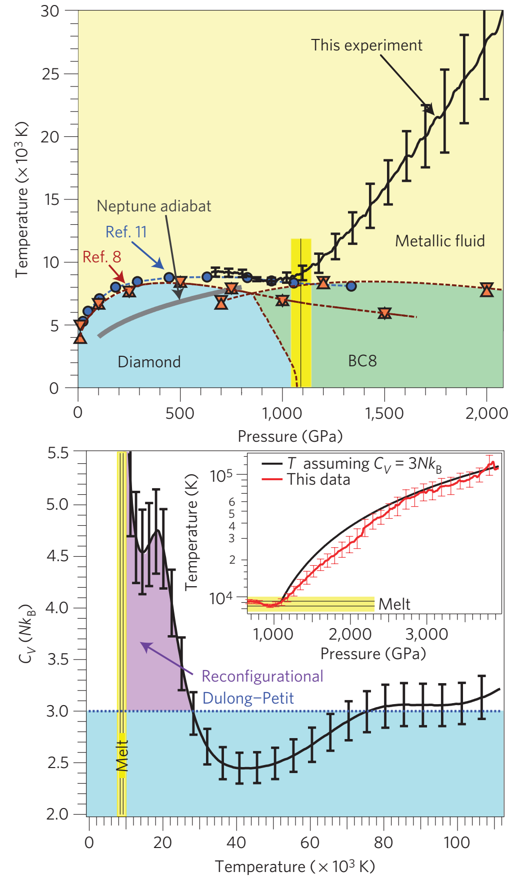
Decaying shock experiment

J.H. Eggert et al, Nat. Phys. **6** 40 (2010)



Simultaneous observation of shock velocity & thermal emission

Temperature plateau at melt

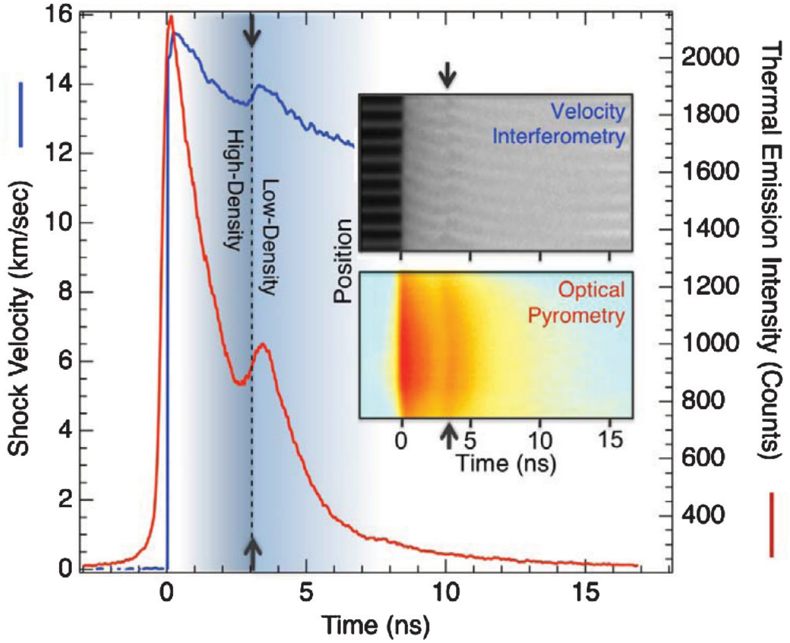


High specific heat in the melt

Phase transition in $MgSiO_3$

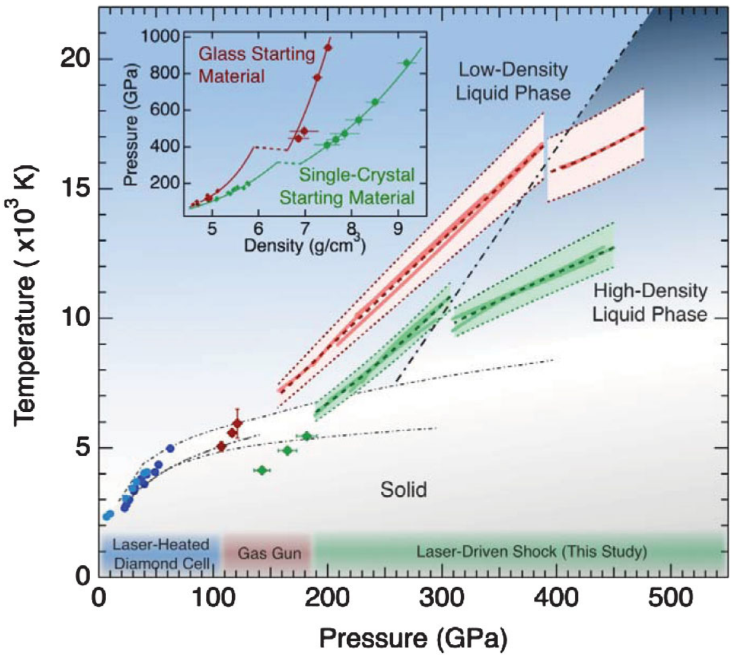
Decaying shock experiment

D.K. Spaulding et al, PRL **108** 065701 (2012)



Anomaly in velocity & emission observed

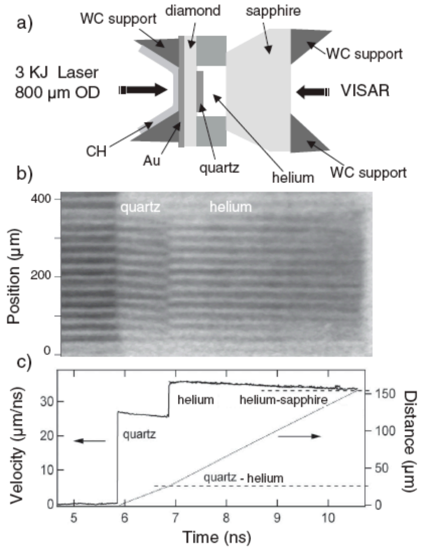
Effect is observed for both crystalline & glass initial states



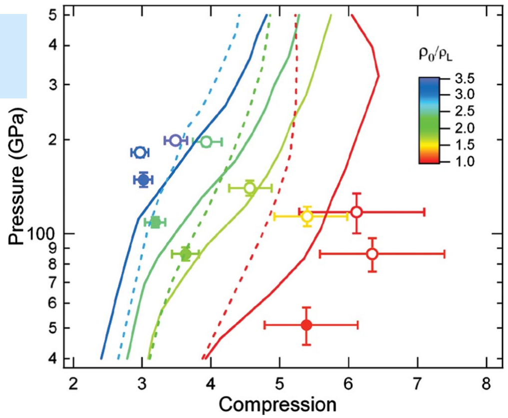
A high temperature-high pressure liquid-liquid phase transition?

Compression of He to 1.5 g cm^{-3}

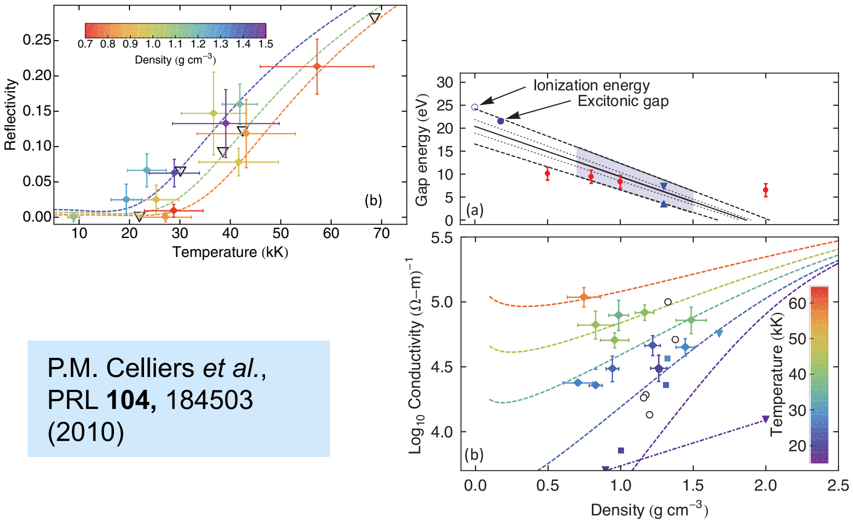
Hugoniot measurements



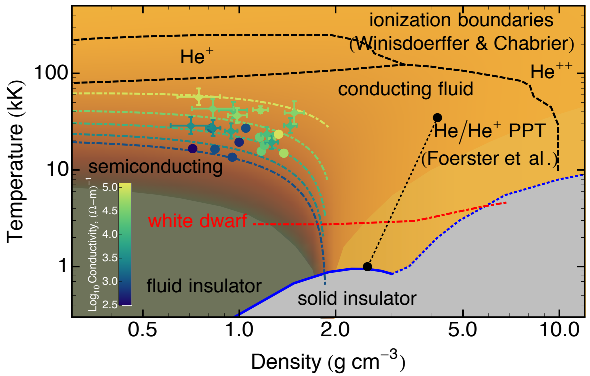
J. Eggert *et al.*, PRL **100,** 124503 (2008)



Reflectivity measurements

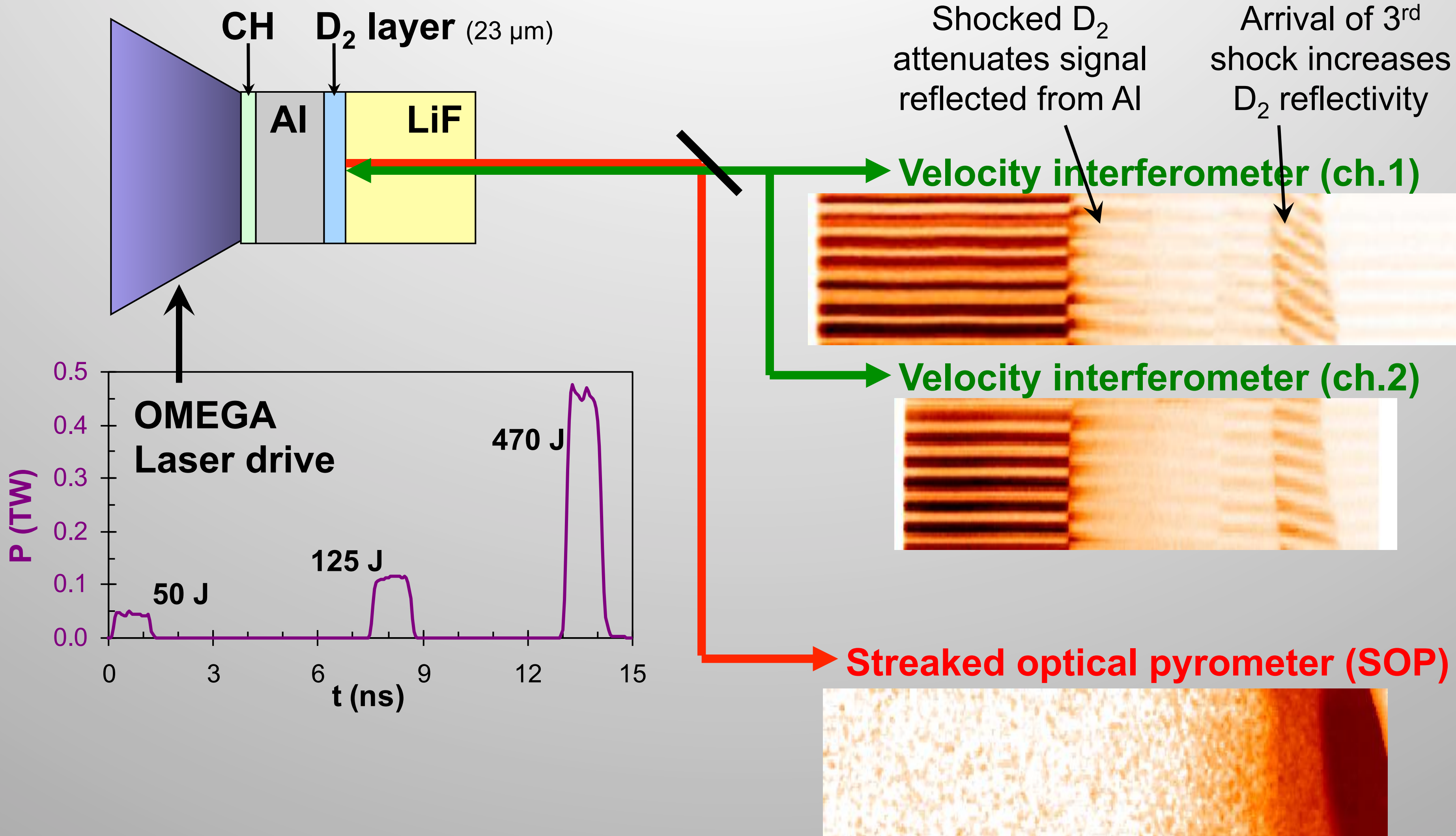


P.M. Celliers *et al.*, PRL **104,** 184503 (2010)



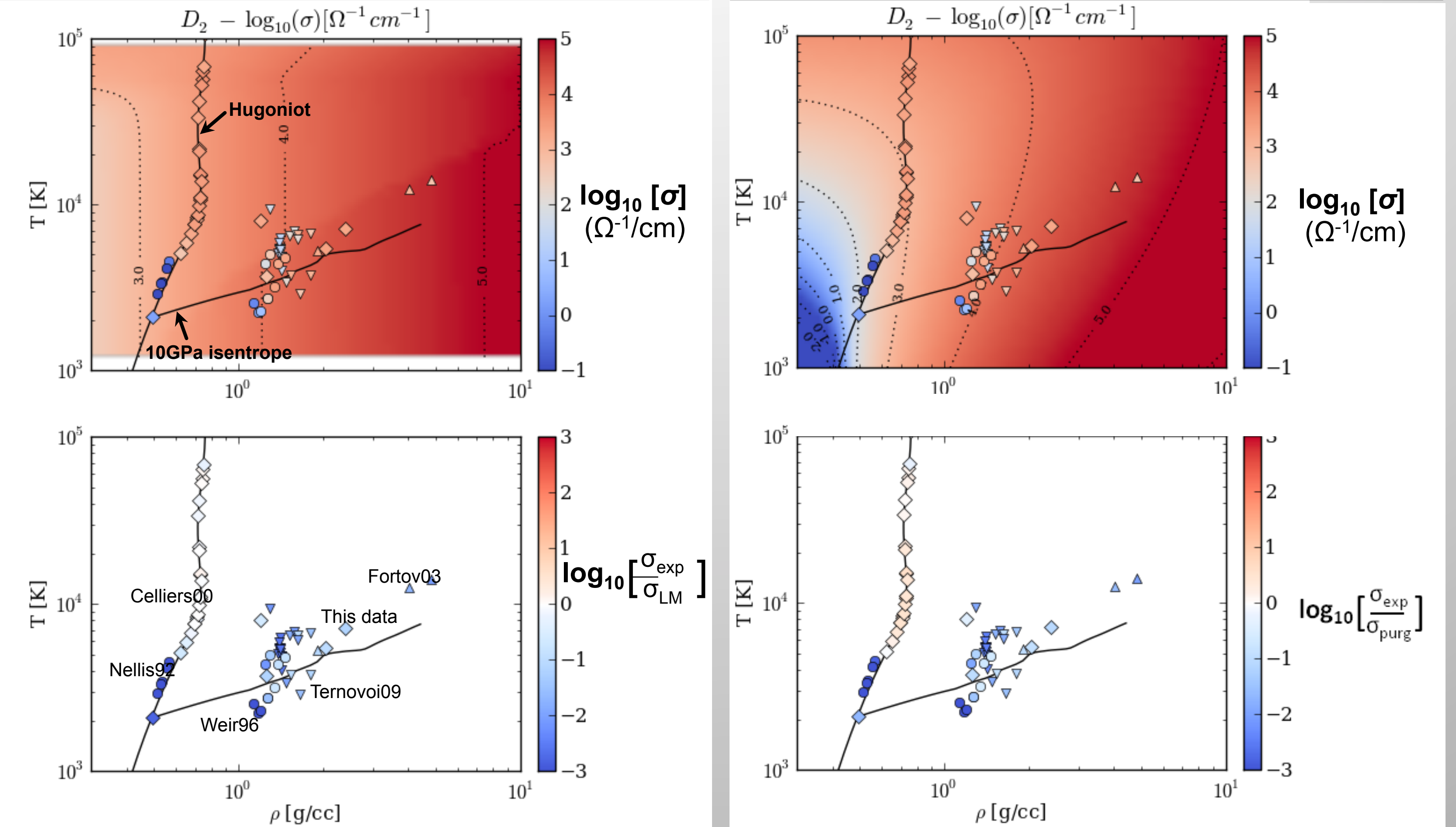
Metallization near 2 g/cm^3 – [?]

Multiple shock compression of deuterium



Electrical conductivity: theory vs experiment

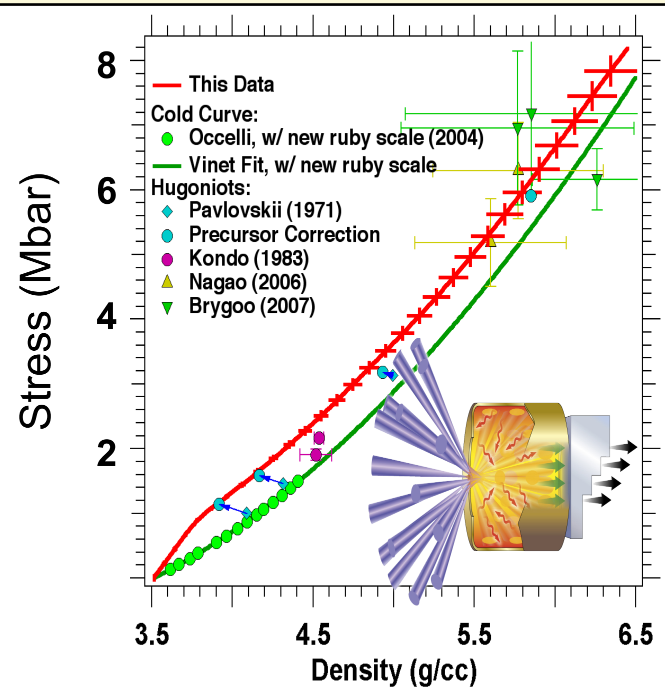
Lee-More	Purgatorio



Experimental data: ○ Nellis1992 (Hugoniot), ○ Weir1996, ◇ Celliers2000 (Hugoniot), △ Fortov2003, ▽ Ternovoi2009, ◇ This work

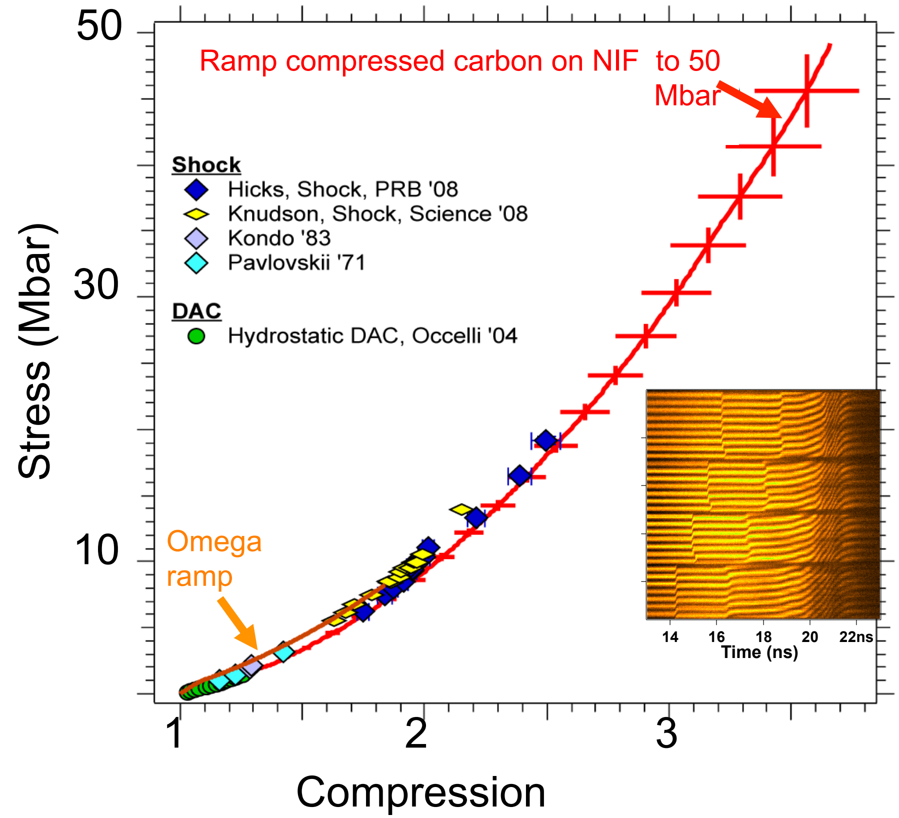
Ramp compression of diamond: 8 Mbar at OMEGA, 50 Mbar at NIF

P-ρ for up to 8 Mbar on OMEGA



D.K. Bradley *et al.*, PRL **103,** 075503(2009)

NIF achieved 17 times the maximum diamond anvil cell pressure

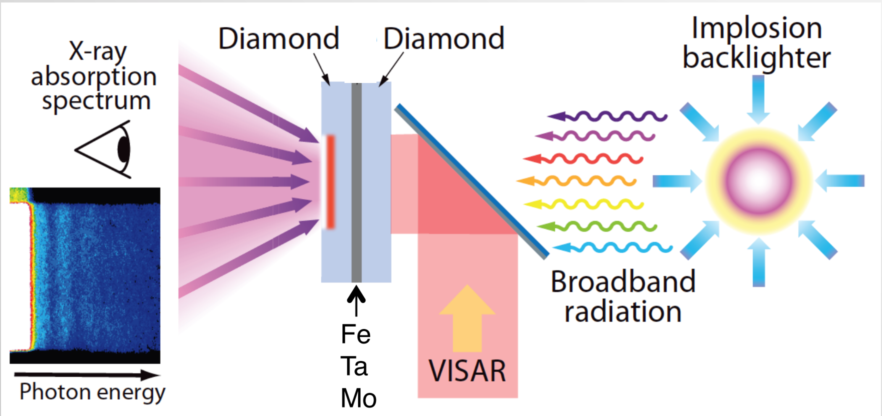


Important applications to confine reverberation samples for x-ray probing

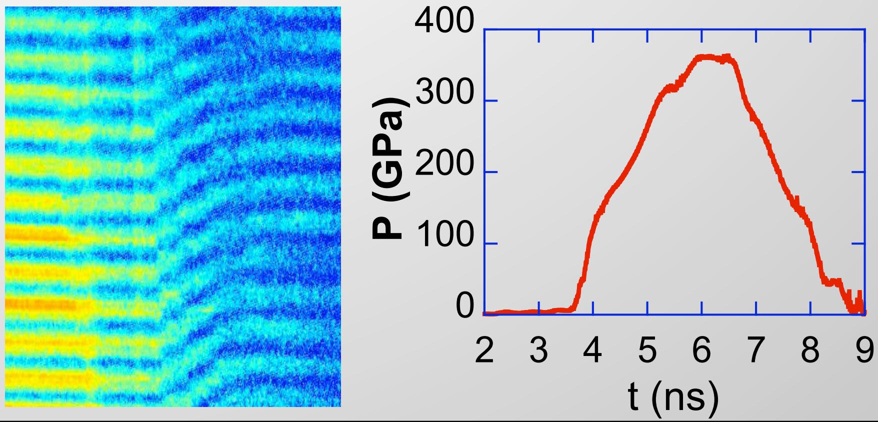
Smith, Eggert, Duffy, Wang

EXAFS on ramp-compressed Fe

Experimental setup: x-ray absorption spectroscopy with implosion backlighter

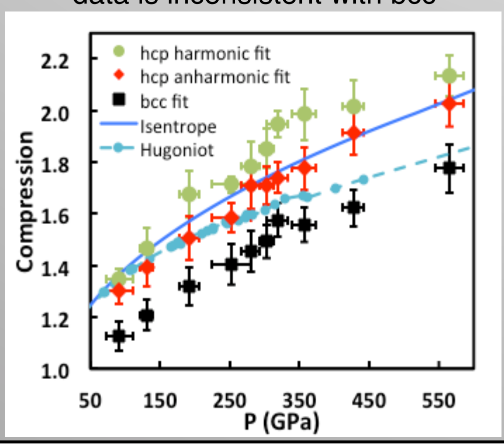


Pressure is probed by VISAR, showing quasi-ramp compression by multi-shock

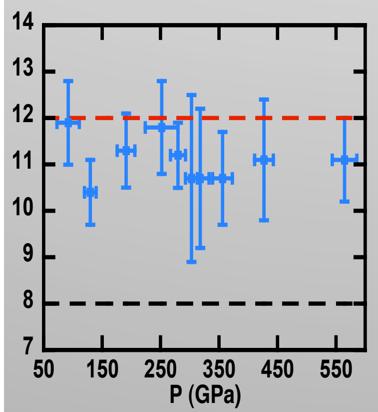


Fe is close-packed up to 560GPa, 8000K

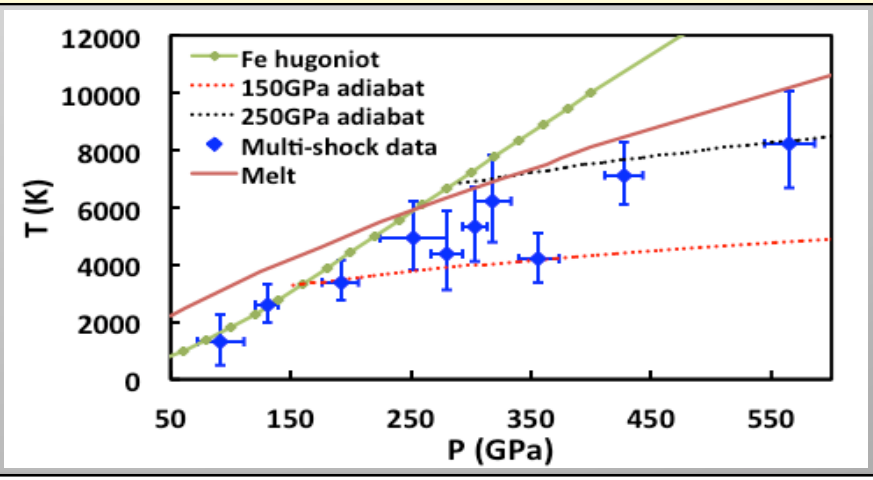
Compression vs pressure: data is inconsistent with bcc



First coordination number vs pressure

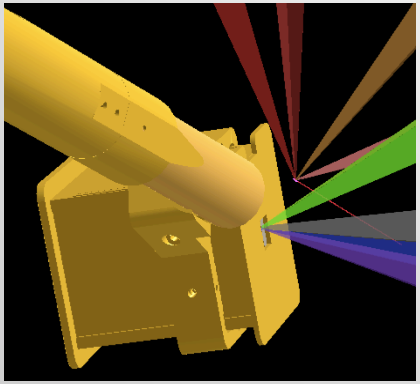


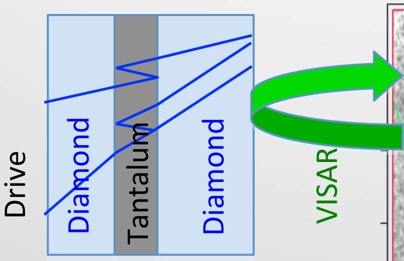
Fe EXAFS data confirm off-Hugoniot states in quasi-ramp compression



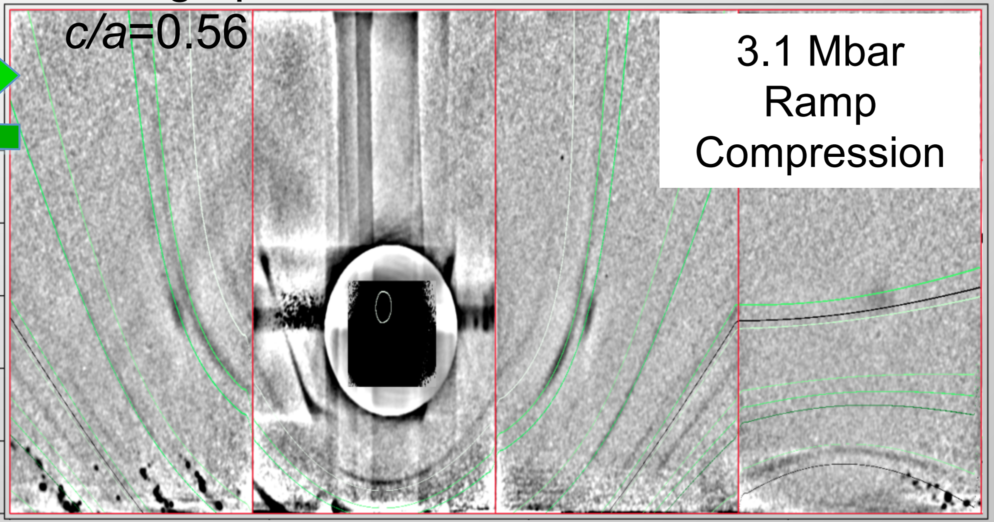
Ping, Hicks, Eggert, Rygg, Coppari

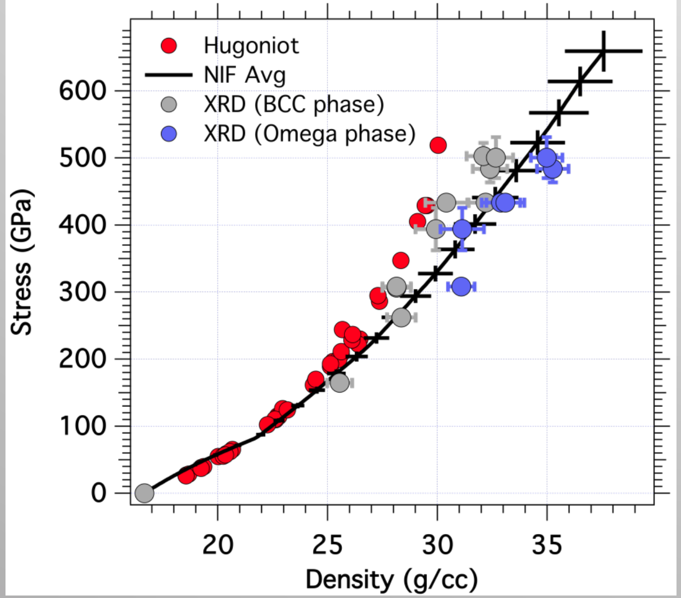
X-ray diffraction Fe, MgO & Ta

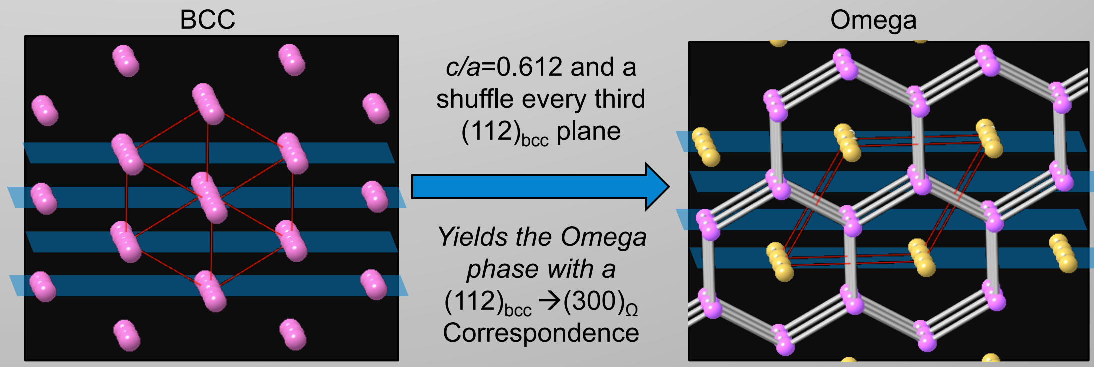




Omega phase best fit with *V*=29 cc, and *c/a*=0.56





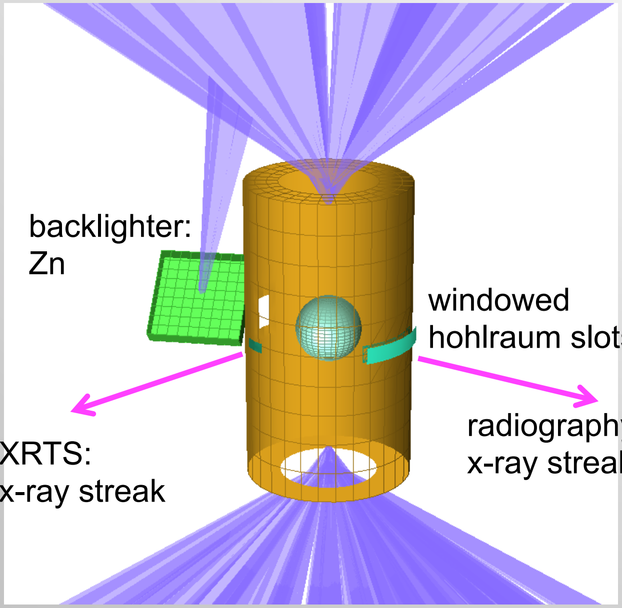


Eggert, Rygg, Coppari, Lazicki

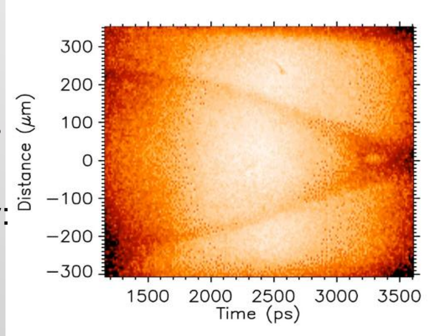
Planned on NIF

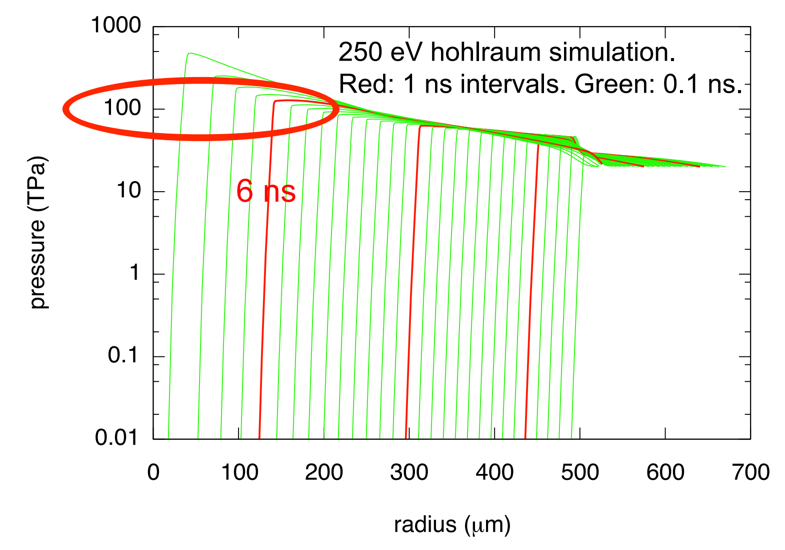
Gigabar EOS: Radiographic measurement of convergent shock

Based on NIF ignition hohlraum: spherically symmetric drive.

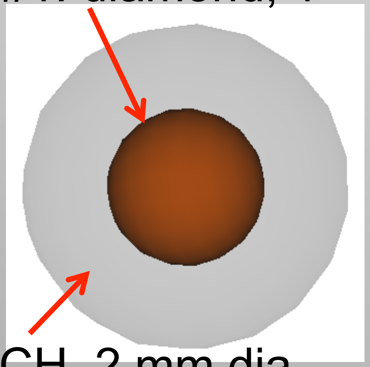


Convergence: shock pressures rise to multiple gigabars over ~100 μm

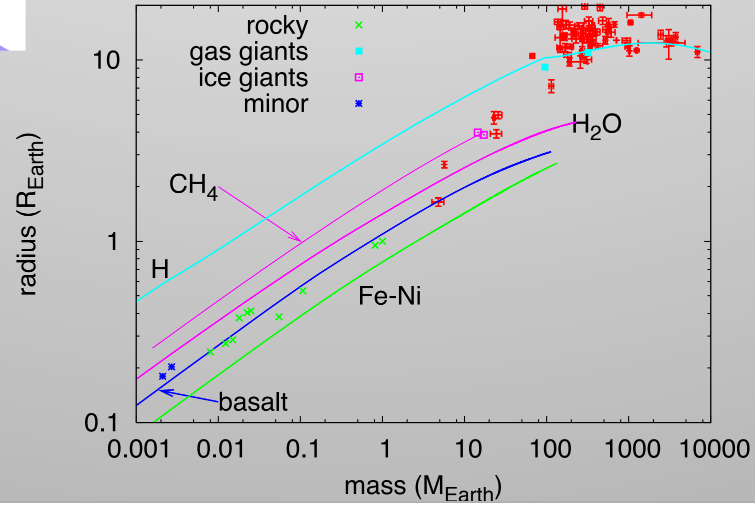




Sample #1: diamond, 1 mm dia



Ablator: CH, 2 mm dia

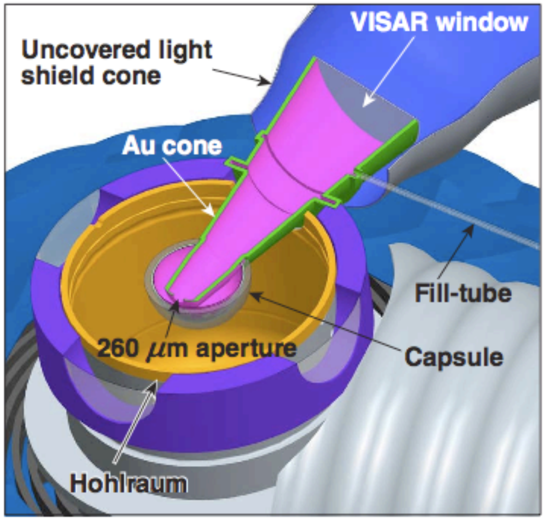


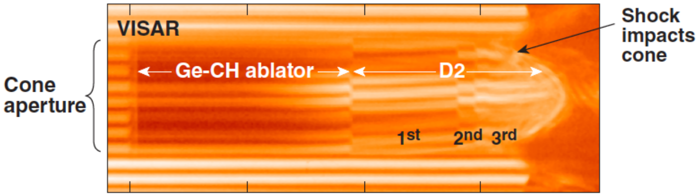
Scientific impact:

- Exoplanet structure
- Dark matter (MACHOS: brown dwarf limit).
- Highest ever EOS measurements.
- ICF designs, etc.

Hydrogen at TPa pressures

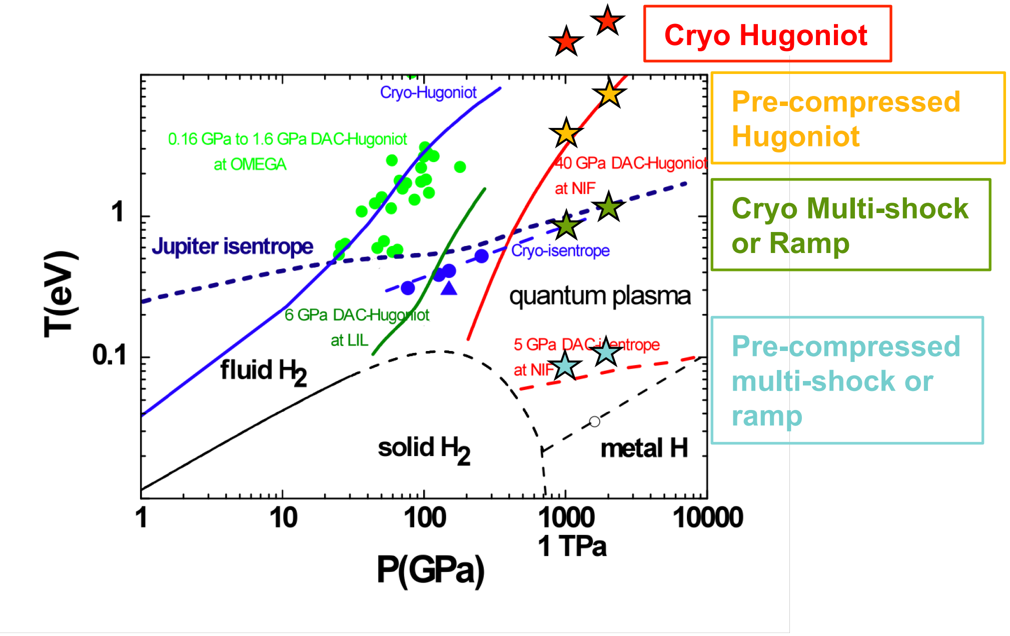
Shock compression of deuterium is routine in the ignition campaign





Shocks in D_2 up to 30 Mbar

Plans to reach dense quantum plasma states in D_2 are being developed



Hemley, Jeanloz, Loubeyre et al

Summary

- New capabilities in dynamic compression facilities like NIF, OMEGA and Z can achieve planetary core conditions
- Recent developments in compression techniques and diagnostics are enabling:
  - Creation of material states at planetary core conditions
  - High precision measurements of EOS
  - Probing of new high pressure structures and phases

Lawrence Livermore National Laboratory