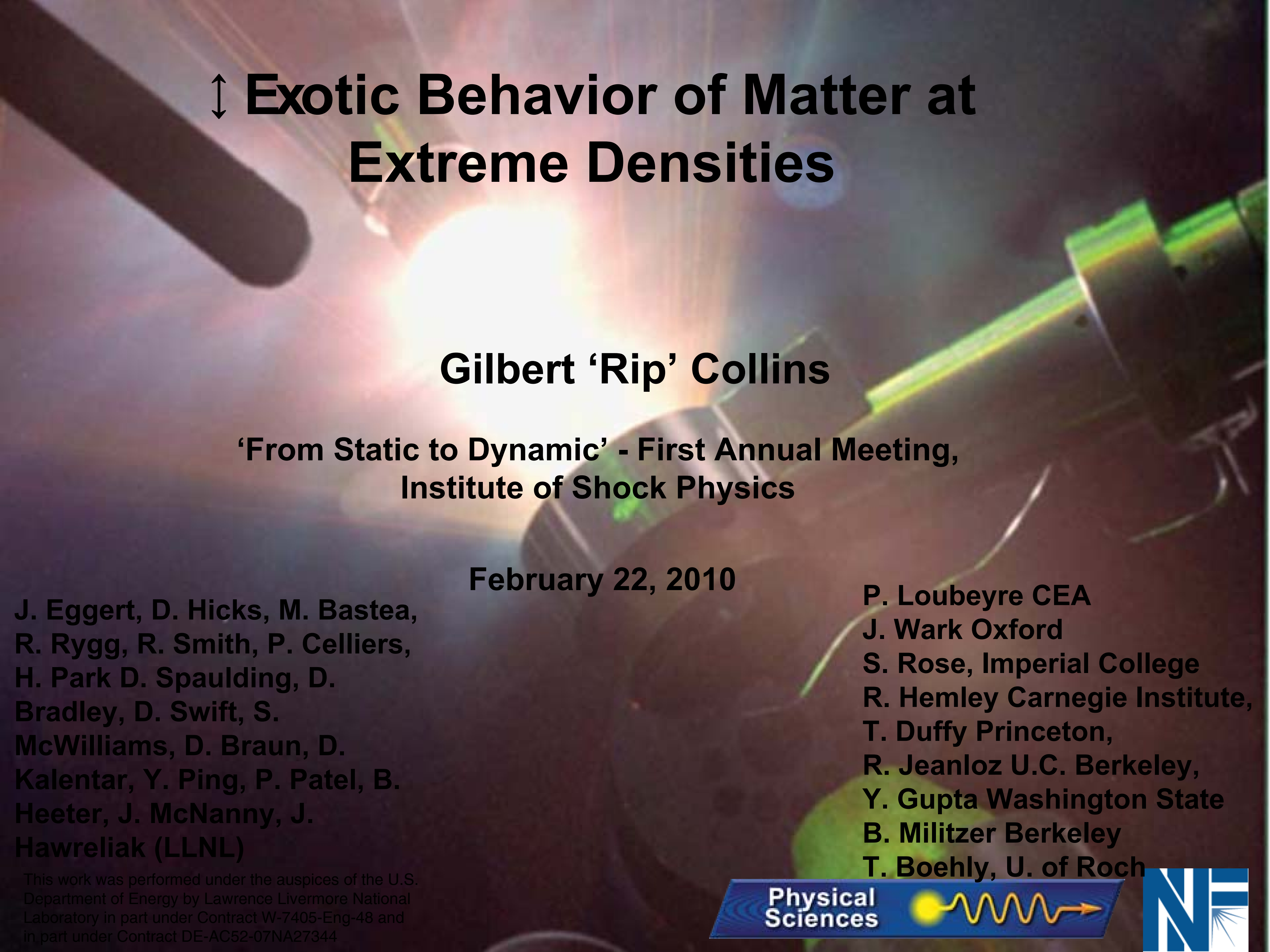


↕ Exotic Behavior of Matter at Extreme Densities

Gilbert 'Rip' Collins

'From Static to Dynamic' - First Annual Meeting,
Institute of Shock Physics

February 22, 2010

J. Eggert, D. Hicks, M. Bastea, R. Rygg, R. Smith, P. Celliers, H. Park D. Spaulding, D. Bradley, D. Swift, S. McWilliams, D. Braun, D. Kalentar, Y. Ping, P. Patel, B. Heeter, J. McNanny, J. Hawreliak (LLNL)

P. Loubeyre CEA
J. Wark Oxford
S. Rose, Imperial College
R. Hemley Carnegie Institute,
T. Duffy Princeton,
R. Jeanloz U.C. Berkeley,
Y. Gupta Washington State
B. Militzer Berkeley
T. Boehly, U. of Roch

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory in part under Contract W-7405-Eng-48 and in part under Contract DE-AC52-07NA27344

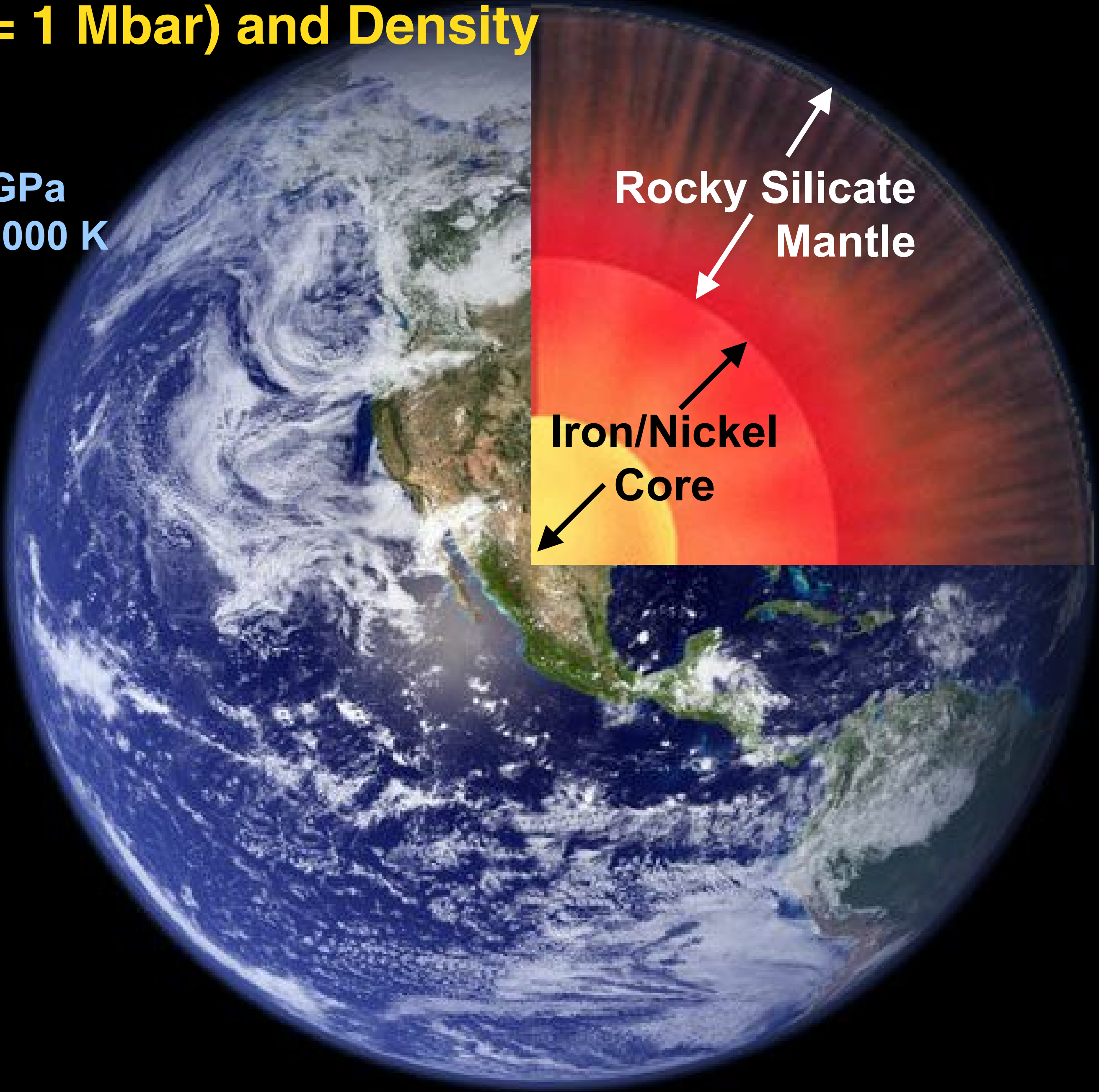
Physical Sciences

Planets contain matter at quite High Pressure (P>>100 GPa = 1 Mbar) and Density

Earth

Central Pressure: 360 GPa

Central Temperature: 6000 K



Rocky Silicate Mantle

Iron/Nickel Core

Saturn

Stewart McWilliams

Extrasolar planets

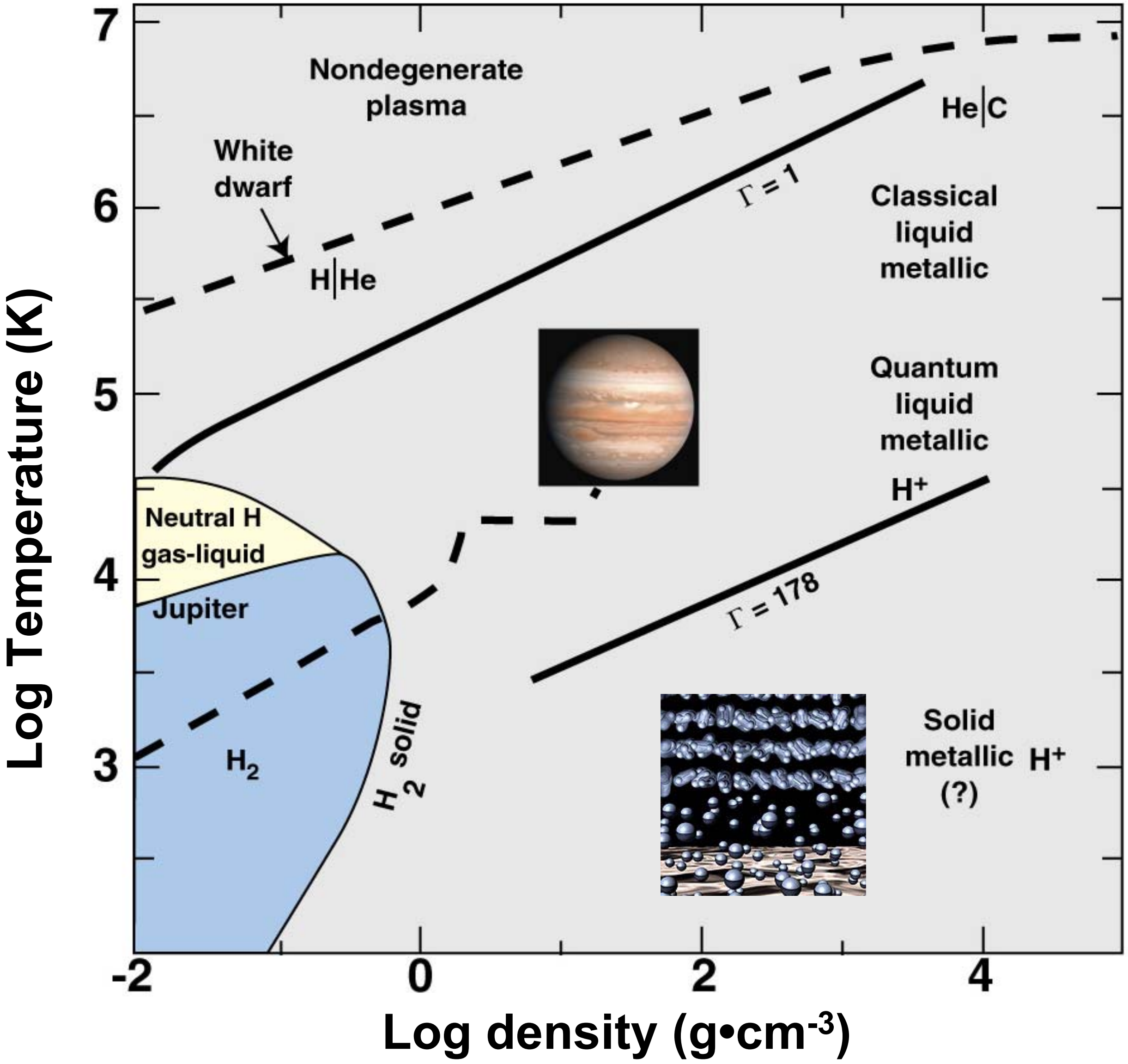
429 extrasolar planets have been discovered through January 2010, more on the way

Our Solar System

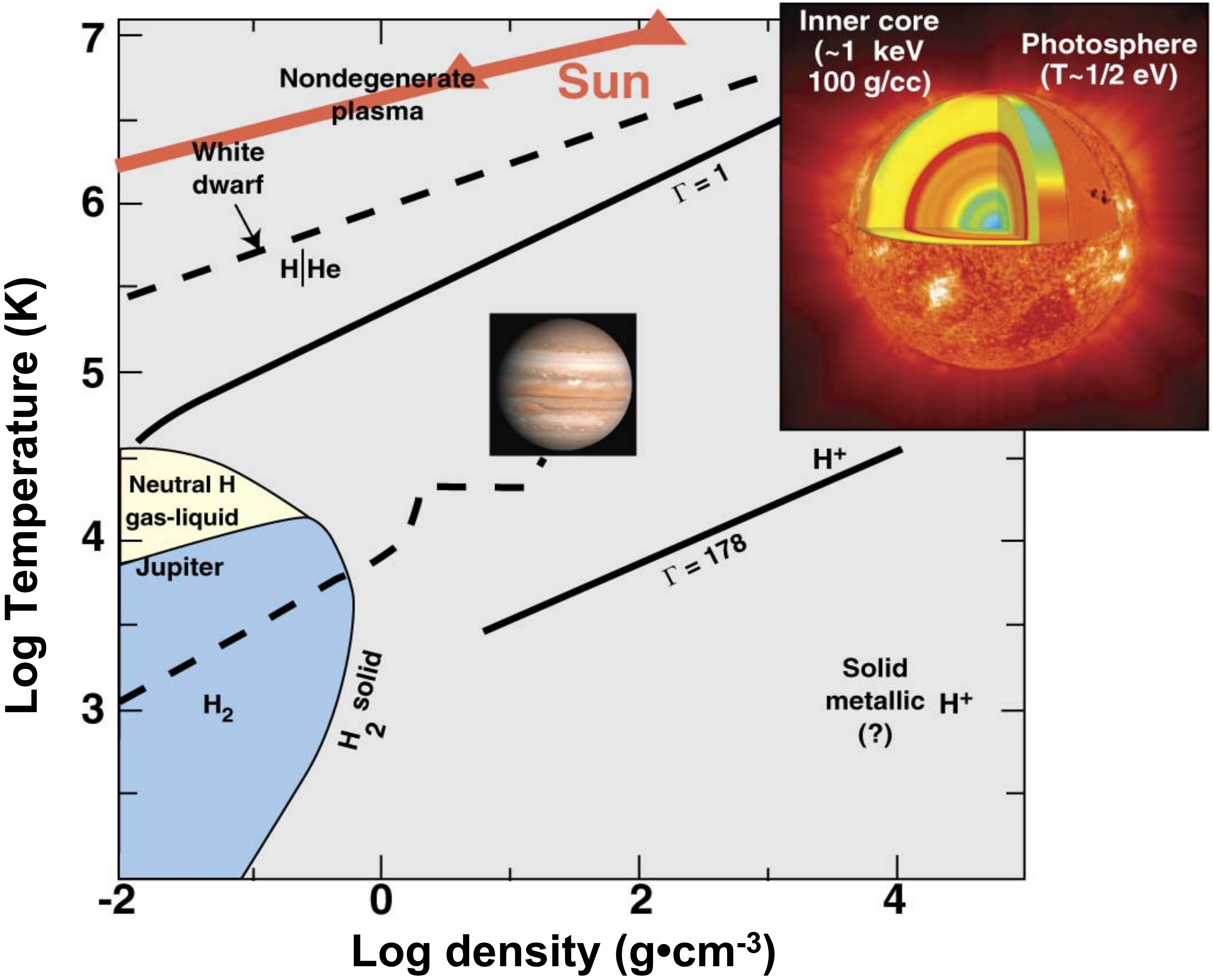
Brown Dwarfs:
80 to 13 Jupiter Masses

Launch of Kepler mission, March 2009

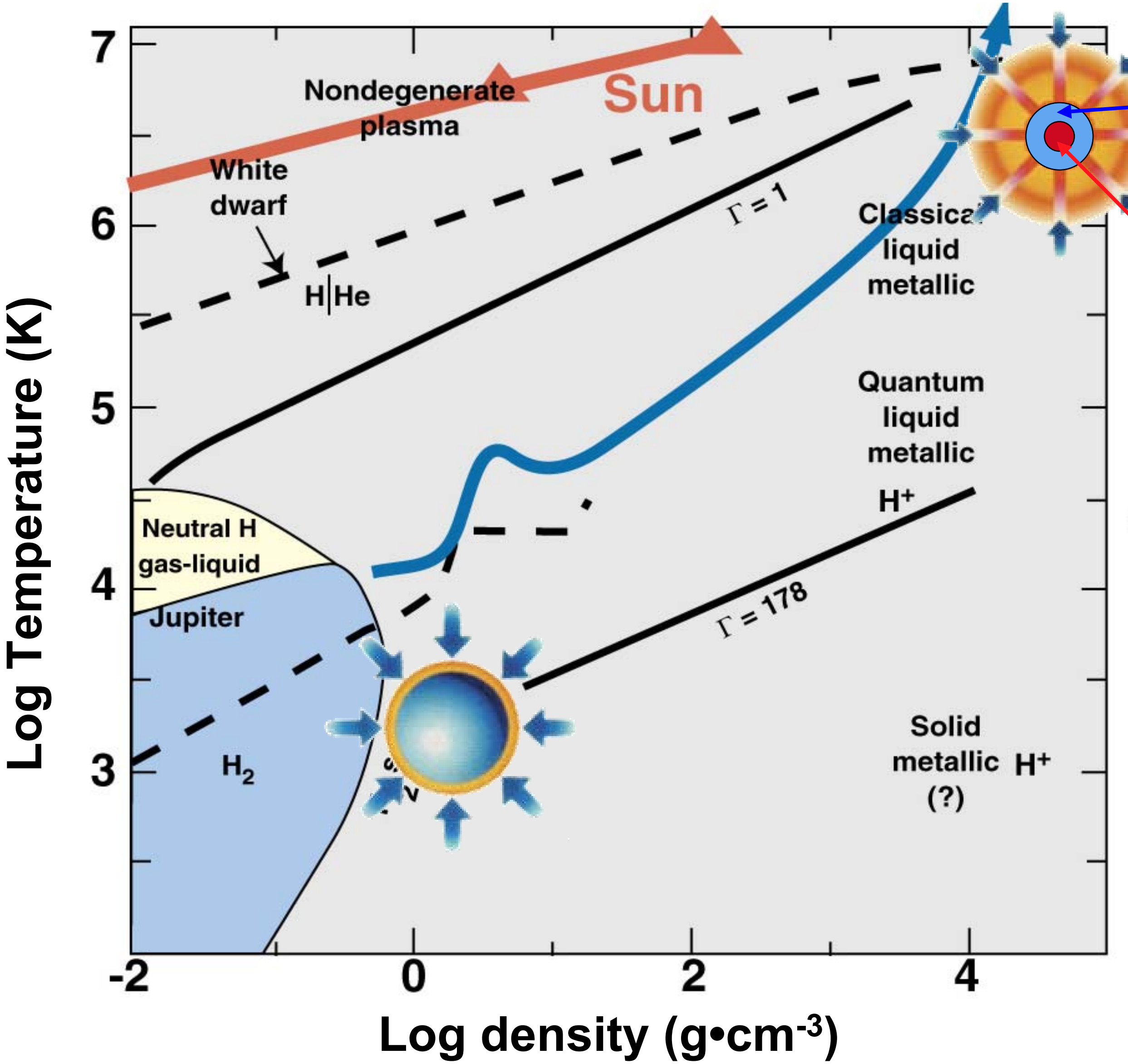
Hydrogen Phase space for high energy density science



Hydrogen Phase space for high energy density science

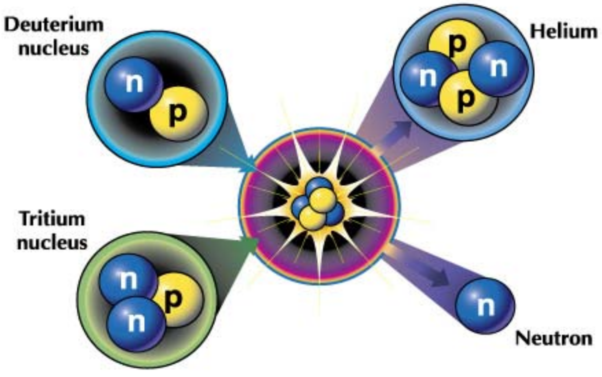


Hydrogen Phase space for high energy density science



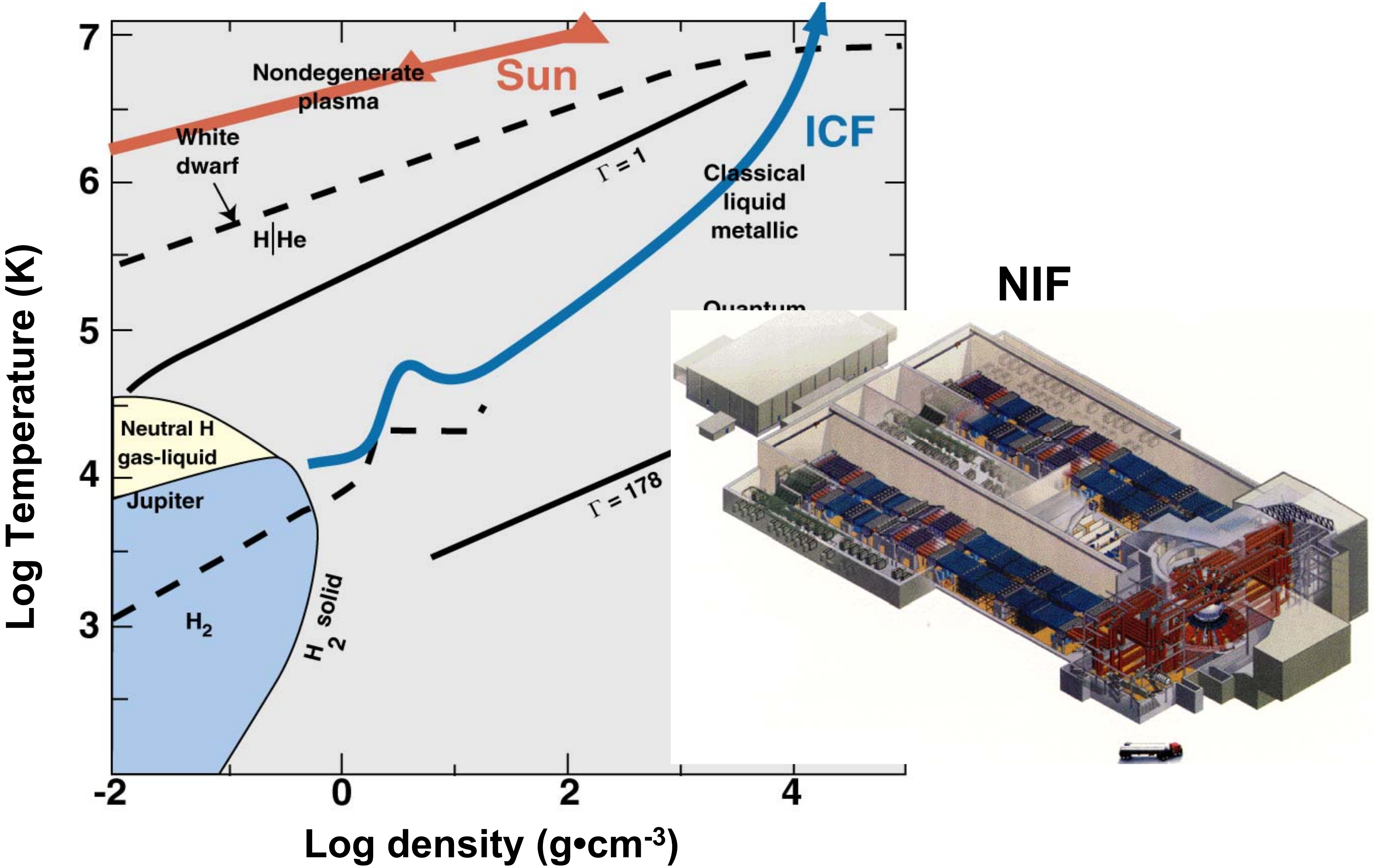
Cold fuel
1 Kg/cc

Hot spot
10^8 K



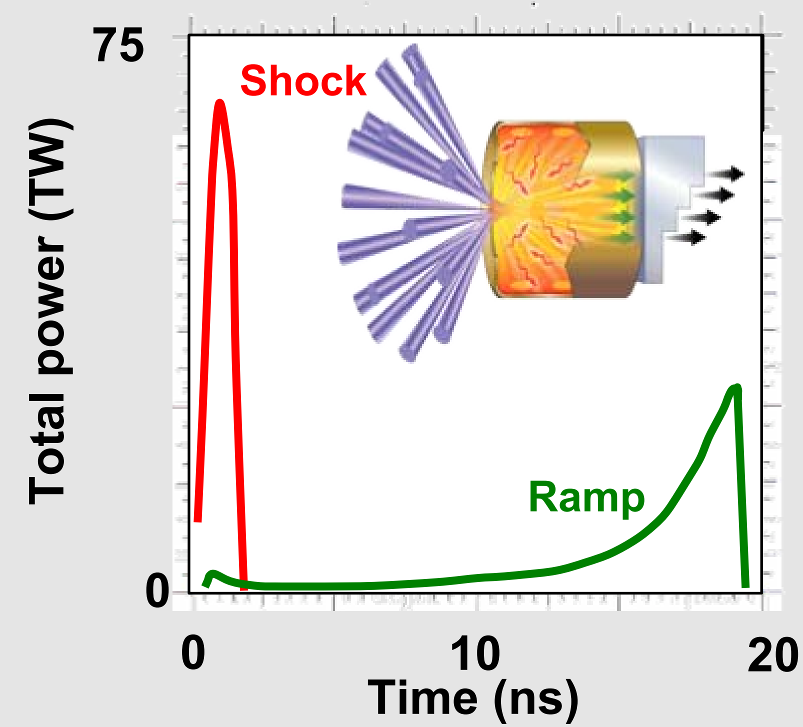
$D + T \longrightarrow \alpha + n$

Hydrogen Phase space for high energy density science

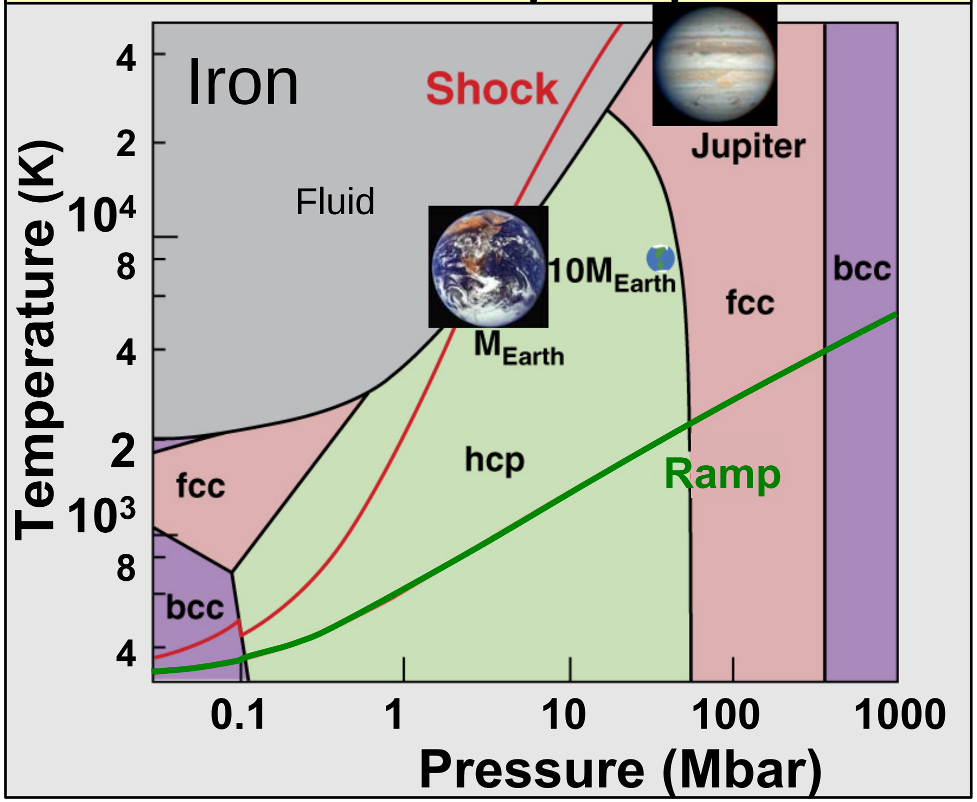


These large lasers allow us to explore very extreme pressures and densities

Pulse shape =>ultra-high pressure plasma or solid-state experiments



Soon we will study P > 1 Gbar shocks, P> 10's Mbar for Ramp compression



Stixrude, 2008

These large lasers allow us to explore very extreme pressures and densities

PROCEEDINGS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Aerial Plane Waves of Finite Amplitude

Lord Rayleigh

Proc. R. Soc. Lond. A 1910 **84**, 247-284
doi: 10.1098/rspa.1910.0075

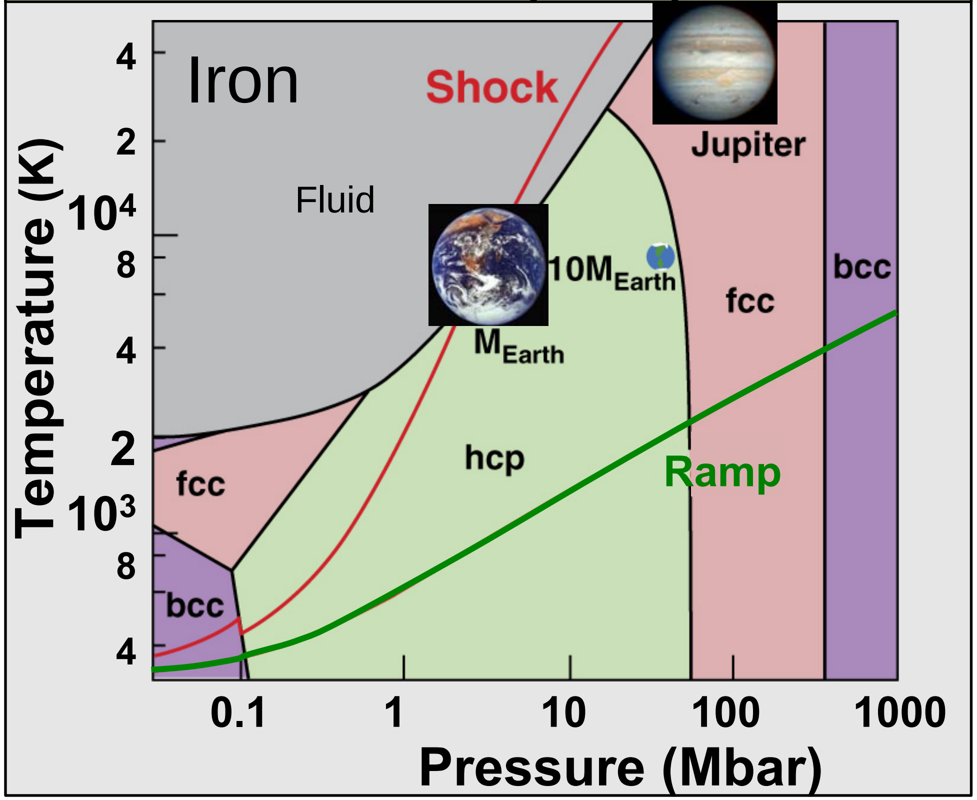
PROCEEDINGS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Conditions Necessary for Discontinuous Motion in Gases

G. I. Taylor

Proc. R. Soc. Lond. A 1910 **84**, 371-377
doi: 10.1098/rspa.1910.0081

Soon we will study P > 1 Gbar shocks, P> 10’s Mbar for Ramp compression



Stixrude, 2008

Some of the key questions in ultra-dense matter science

How does chemistry change at extreme densities?

What is the effect of core electrons on bonding?

Nature of insulator-metal transitions at high densities

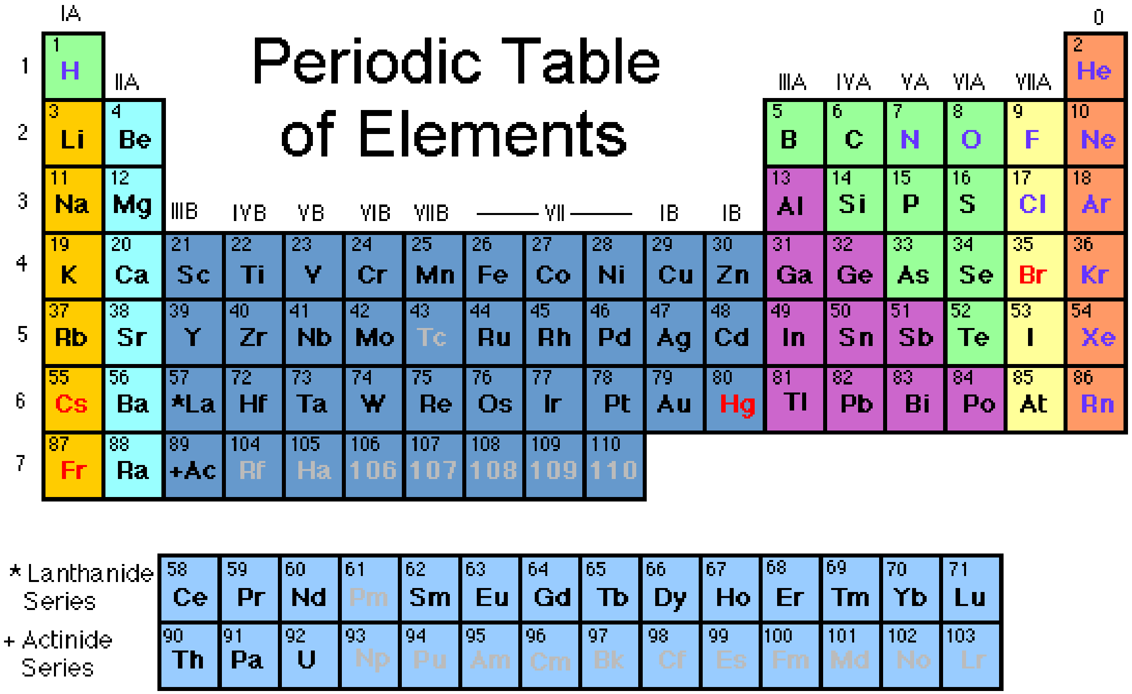
What is a solid at > 10 Mbar?

Melt, strength, phase at ultra high densities

How fast can you squish matter?

What is the nature of helium or hydrogen at the density of lead?

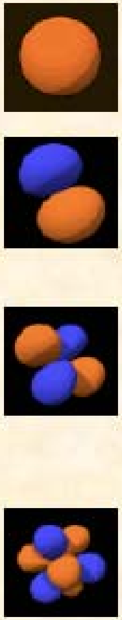
Chemistry at low pressure



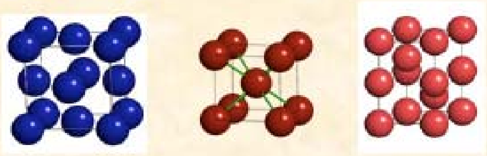
Periodic Table of Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII			IB	IB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110								

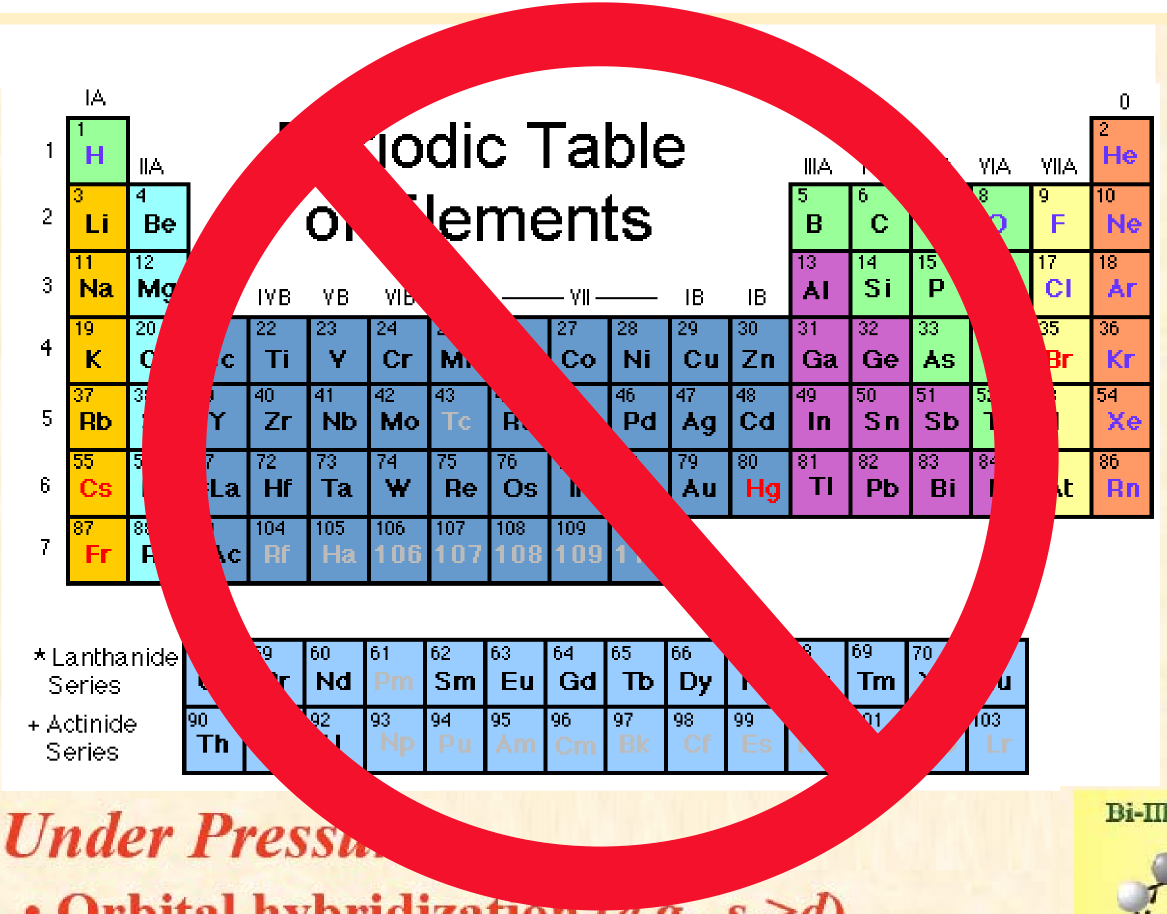
* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

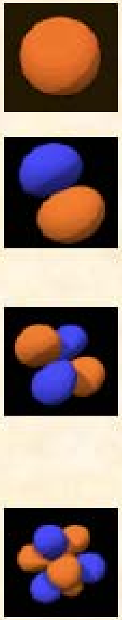


- **Filling of *s*, *p*, *d*, … orbitals**
- **Simple structures**



Chemistry at High pressure

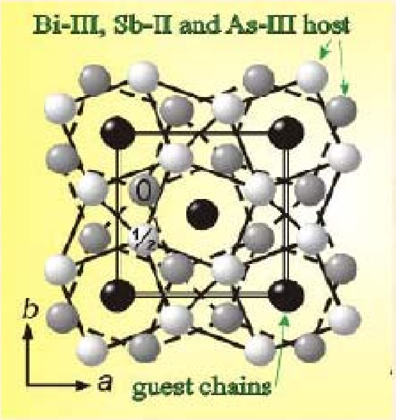




Under Pressu

- **Orbital hybridization (*e.g., s->d*)**
- **Complex structures** ⟶

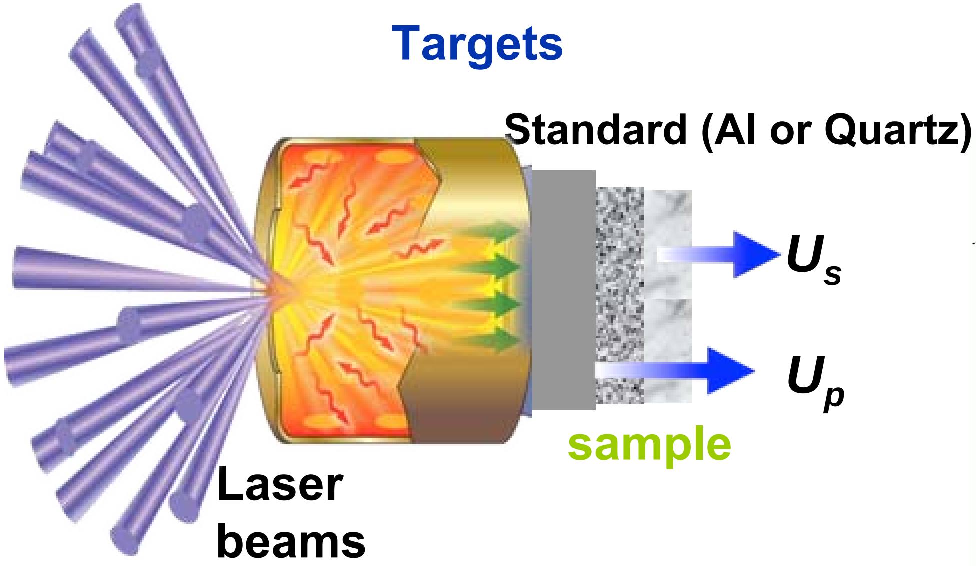
- **Effects of core orbital**



Hemley

High pressure shock conditions: determine shock and particle speed with a shock speedometer (VISAR)

Targets



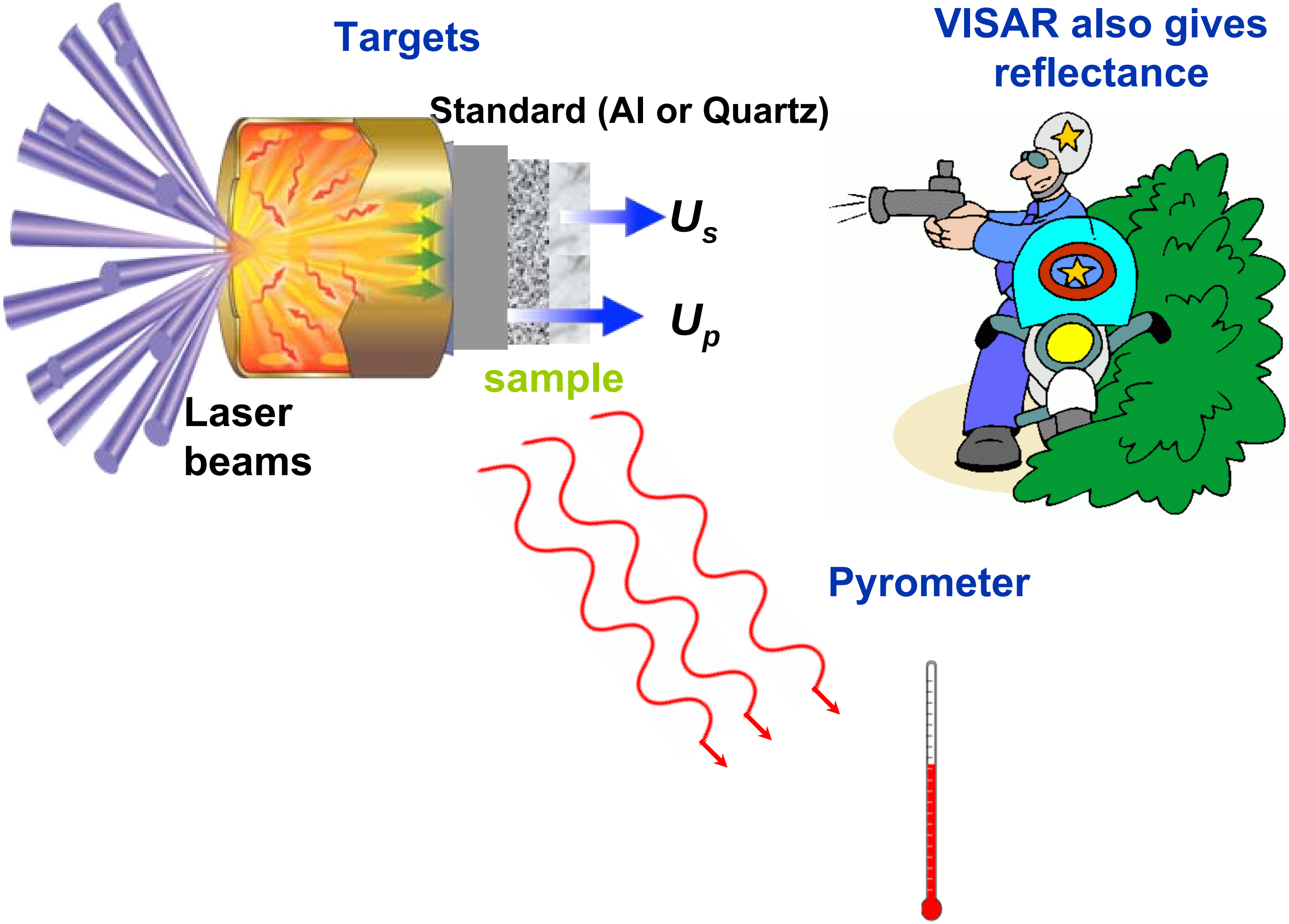
VISAR

$$\rho_o(U_s) = \rho(U_s - U_P)$$

$$P = \rho_0 U_s\, U_P$$

$$E = \frac{1}{2} P(1/\rho_o - 1/\rho)$$

Determine shock temperature with pyrometer



Targets

Standard (Al or Quartz)

U_s

U_p

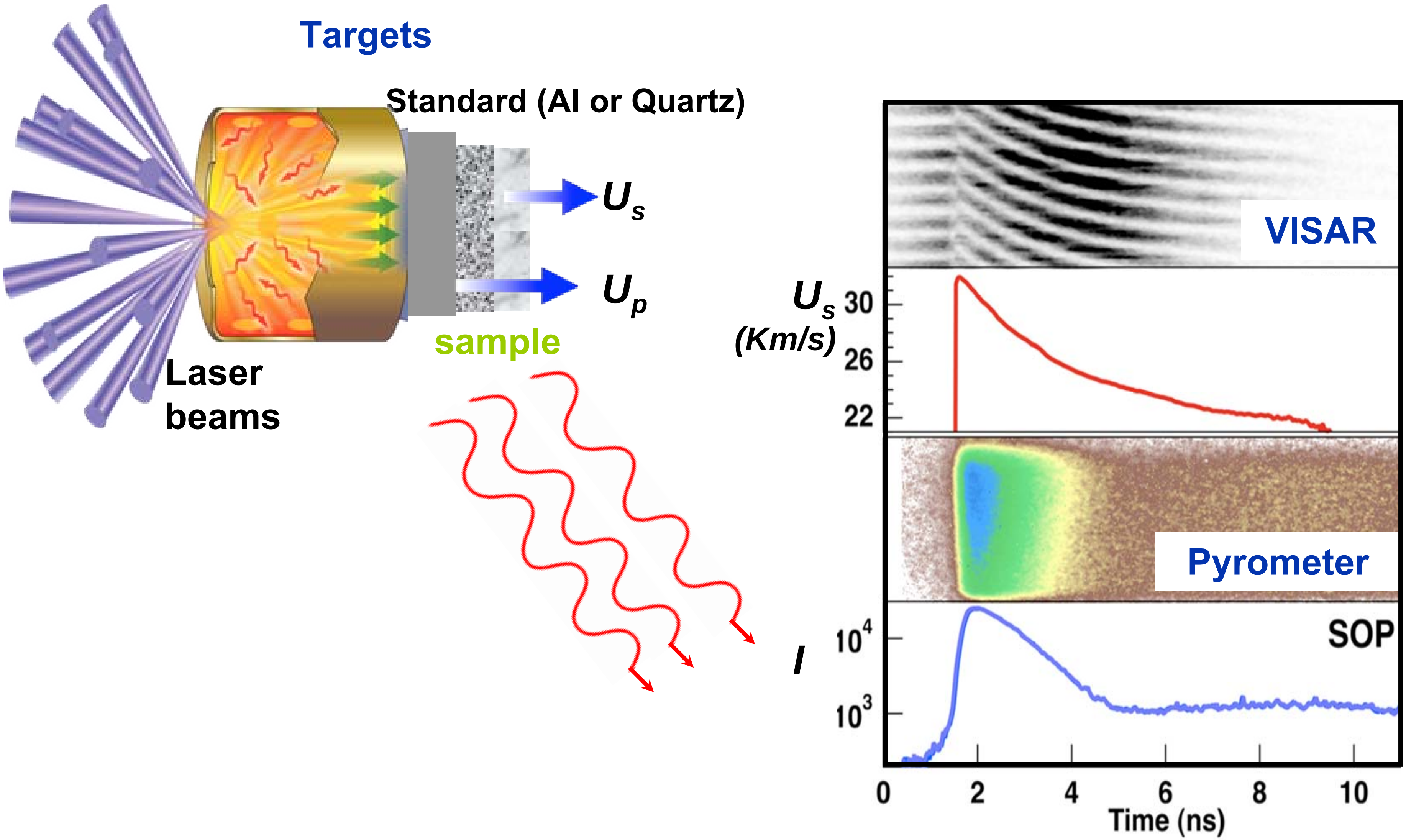
sample

Laser beams

VISAR also gives reflectance

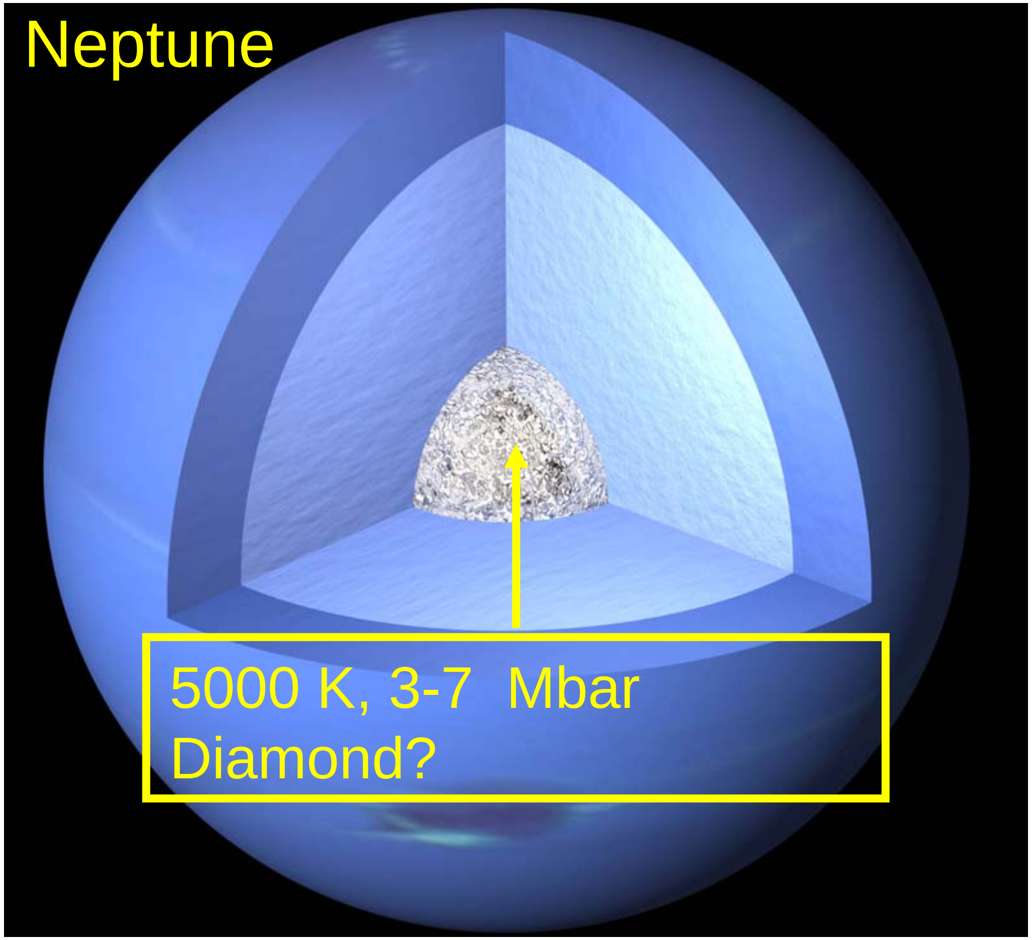
Pyrometer

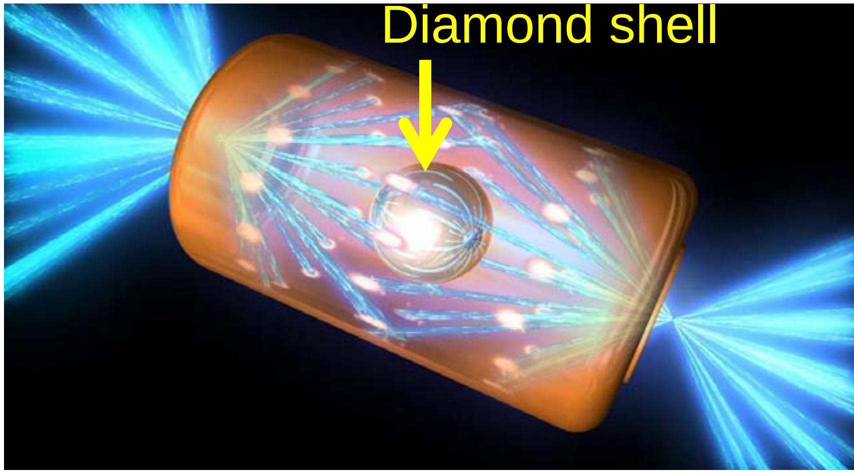
Determine shock temperature with pyrometer



Eggert Nat. Phys. 09

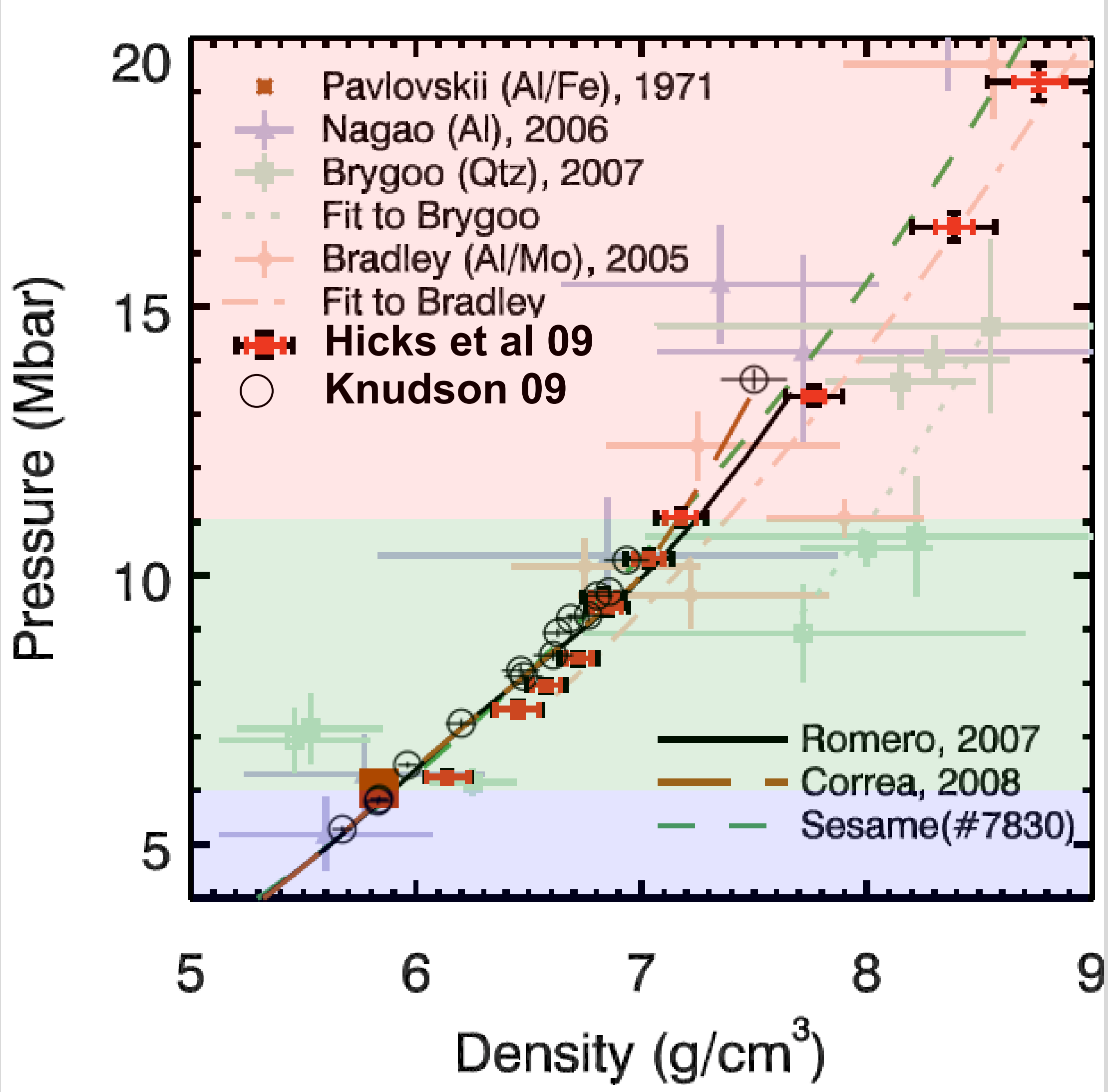
Carbon, a key constituent of Neptune and an ablator candidate for fusion, is also quite complicated at hi-P



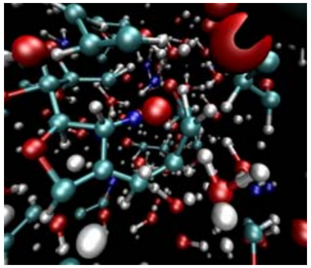


By measuring shock velocities very accurately we determine pressure and density to a few percent

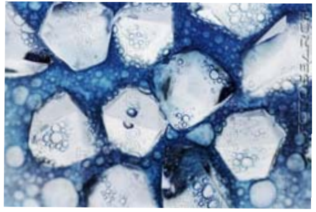
We have compressed diamond by ~ 3x



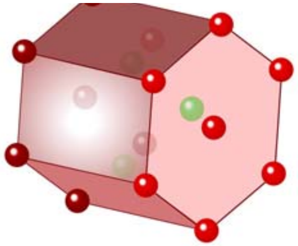
Complex fluid To plasma



Liquid-solid mix & conducting (Bradley)

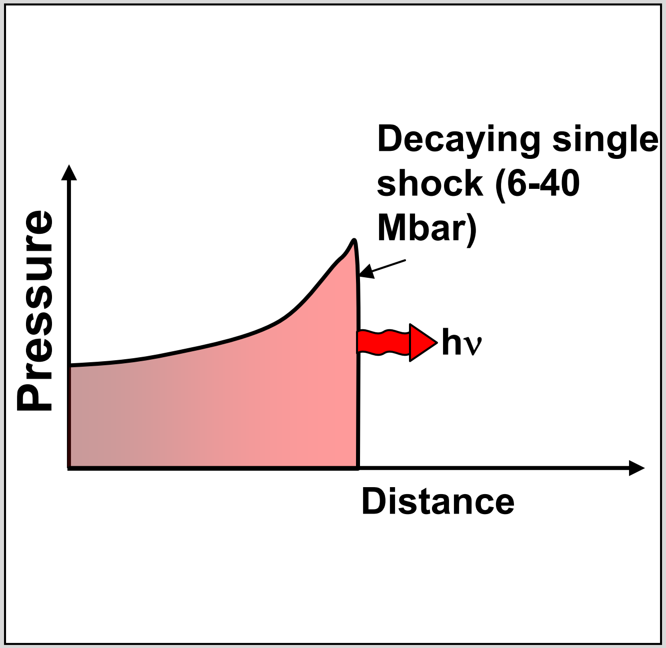


Solid insulator

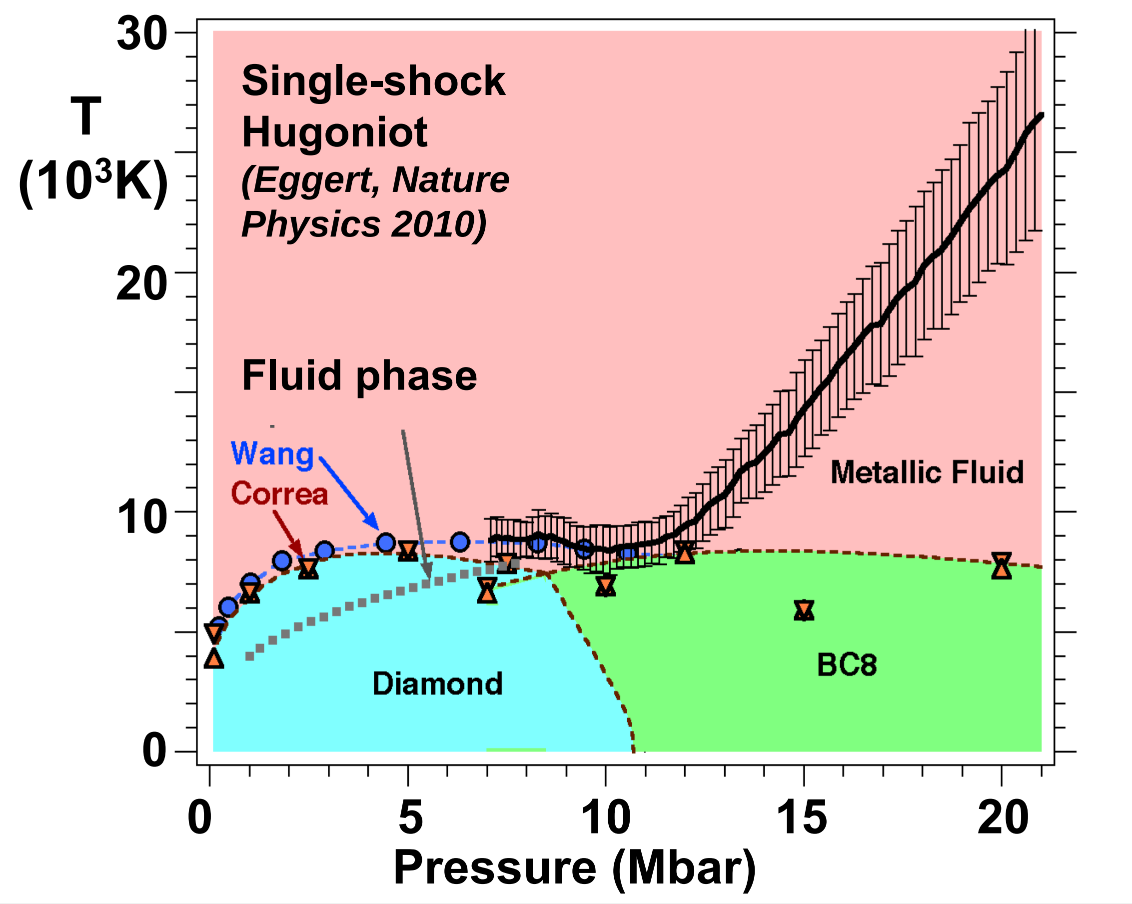


Shock temperature data show a strong signature at melt revealing the carbon melt curve from 6 to 11 Mbar

Use decaying shock to Map high P-melt curve

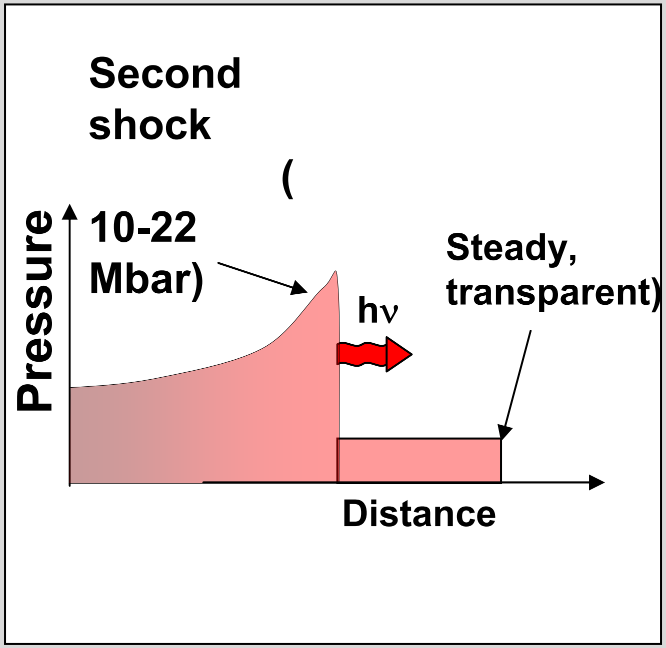


Melt curve stays nearly flat from 6-11 Mbar

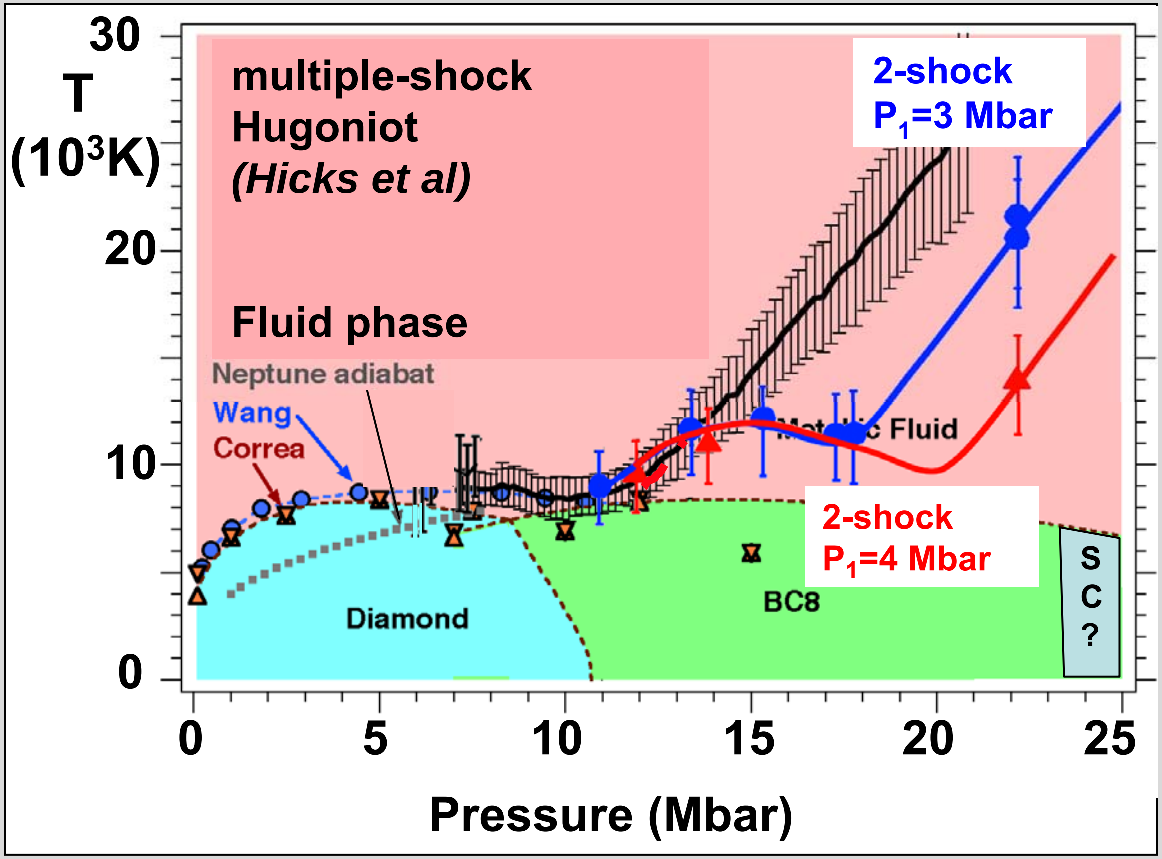


Temperature data from 2-shock compression was used to determine the melt curve of carbon to 20 Mbar

Use 2-shocks to map higher P-melt curve

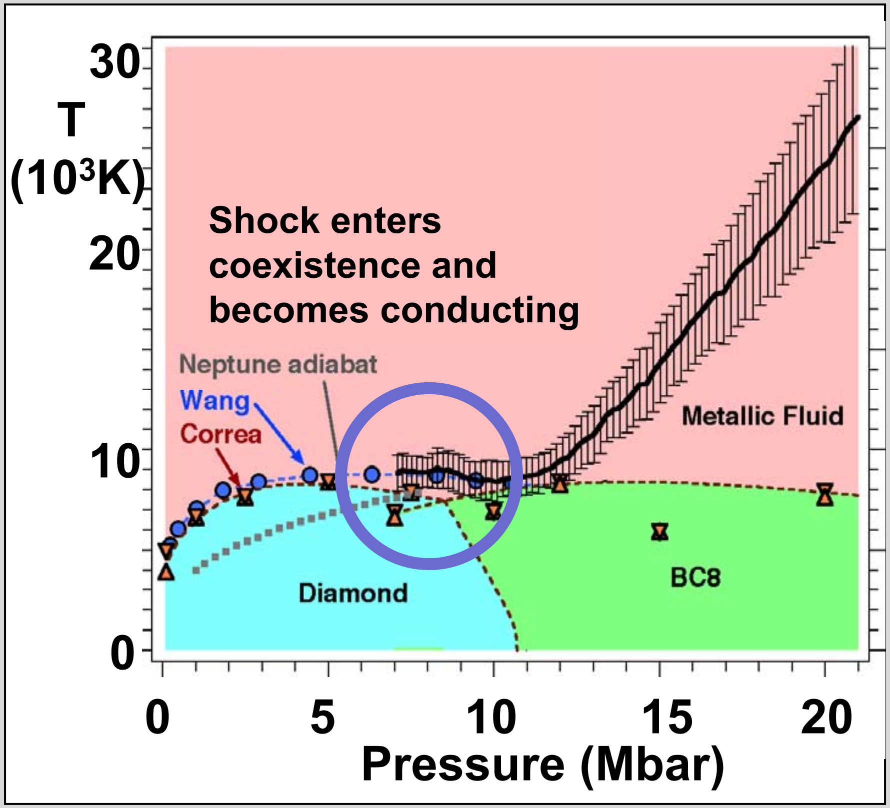


Melt curve stays nearly flat to near 20 Mbar

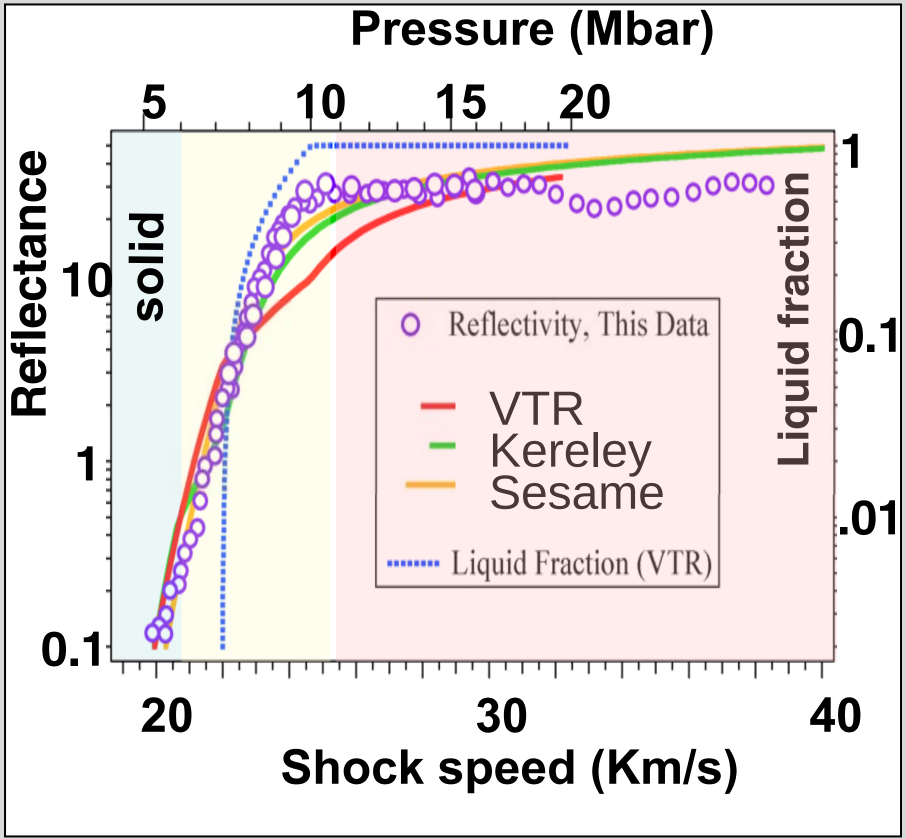


Reflectivity measurements show Carbon melts from the diamond phase to a liquid metal

Melt along 1-shock Hugoniot



Diamond melts to a liquid conductor

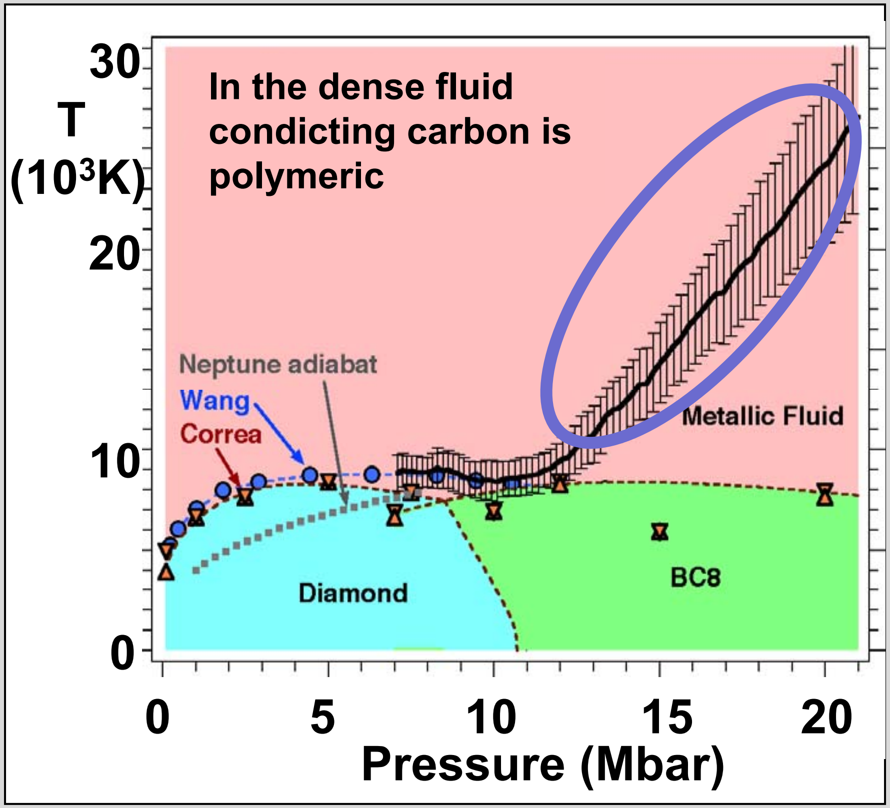


Bradley, 05

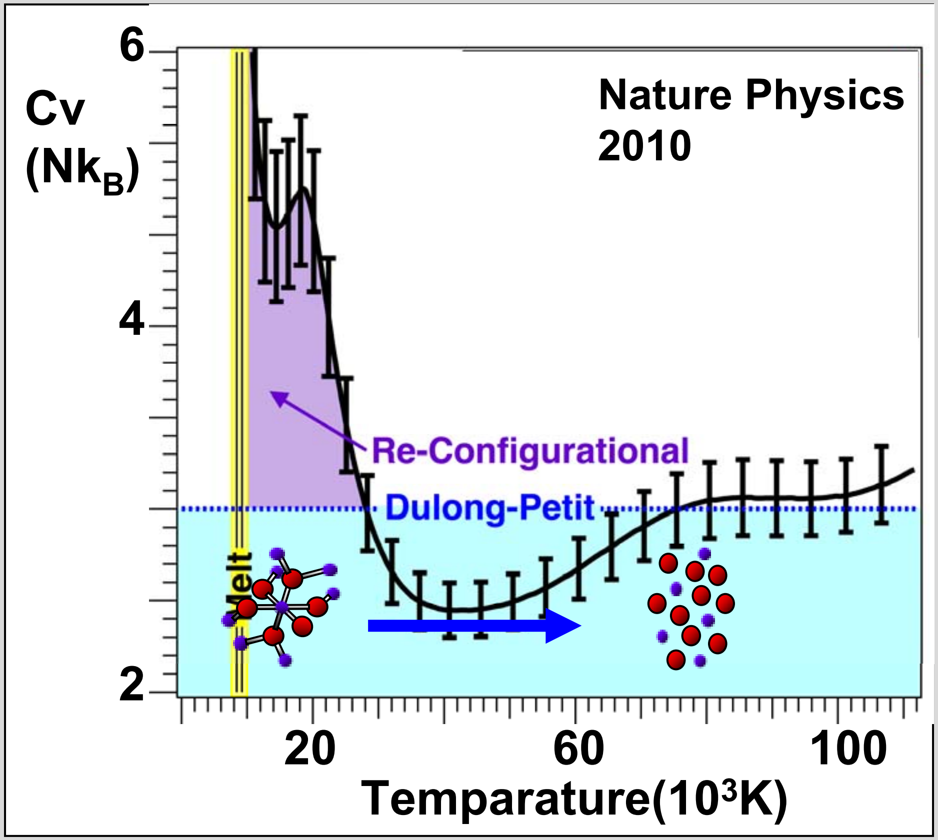
- In fact several materials become conducting upon melt (MgO, SiO2, ..) This is not what one would expect from simple condensed matter theory

Finally this carbon metallic fluid phase is also partially bonded up to 20 Mbar and 30kK

Temperature above melt



There is a significant increase in Cv just above melt suggesting complex chemistry

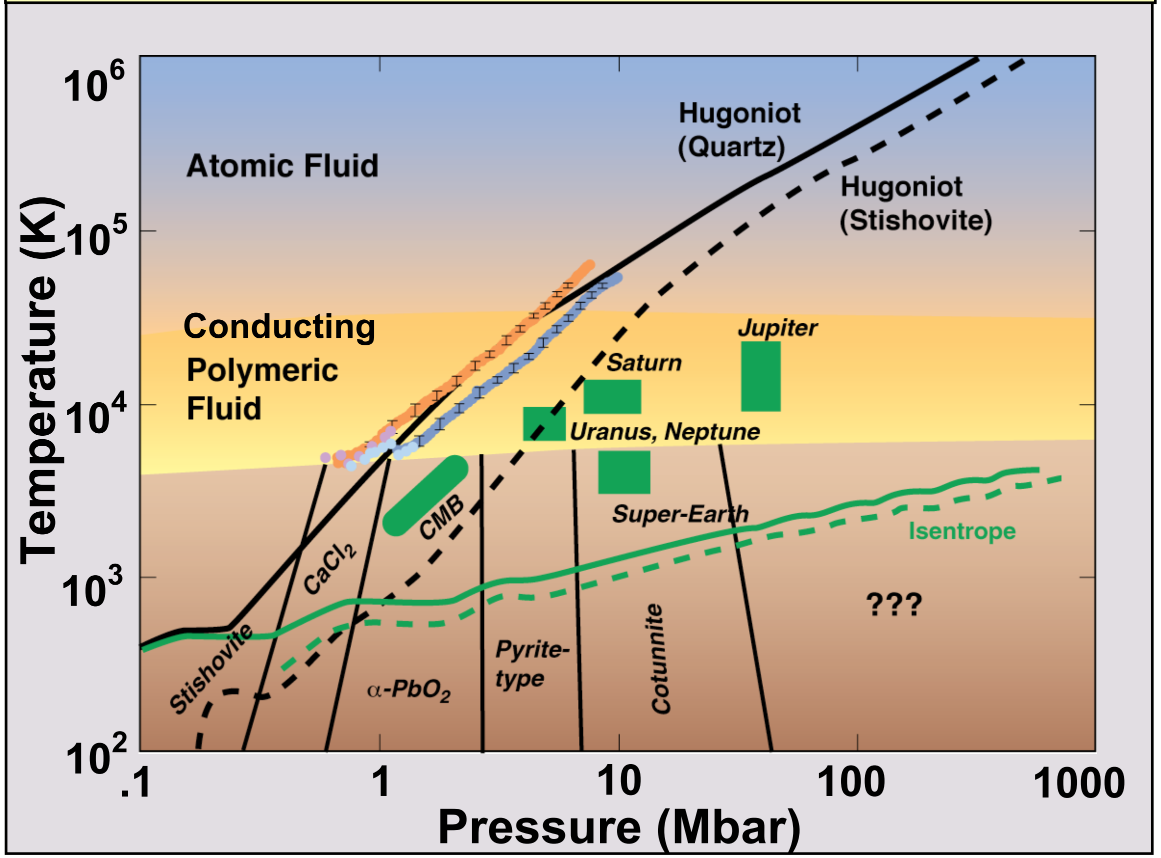


Again this is seen in many materials, MgO, $MgSiO_3$, SiO2…

This is not predicted by Ab-initio models

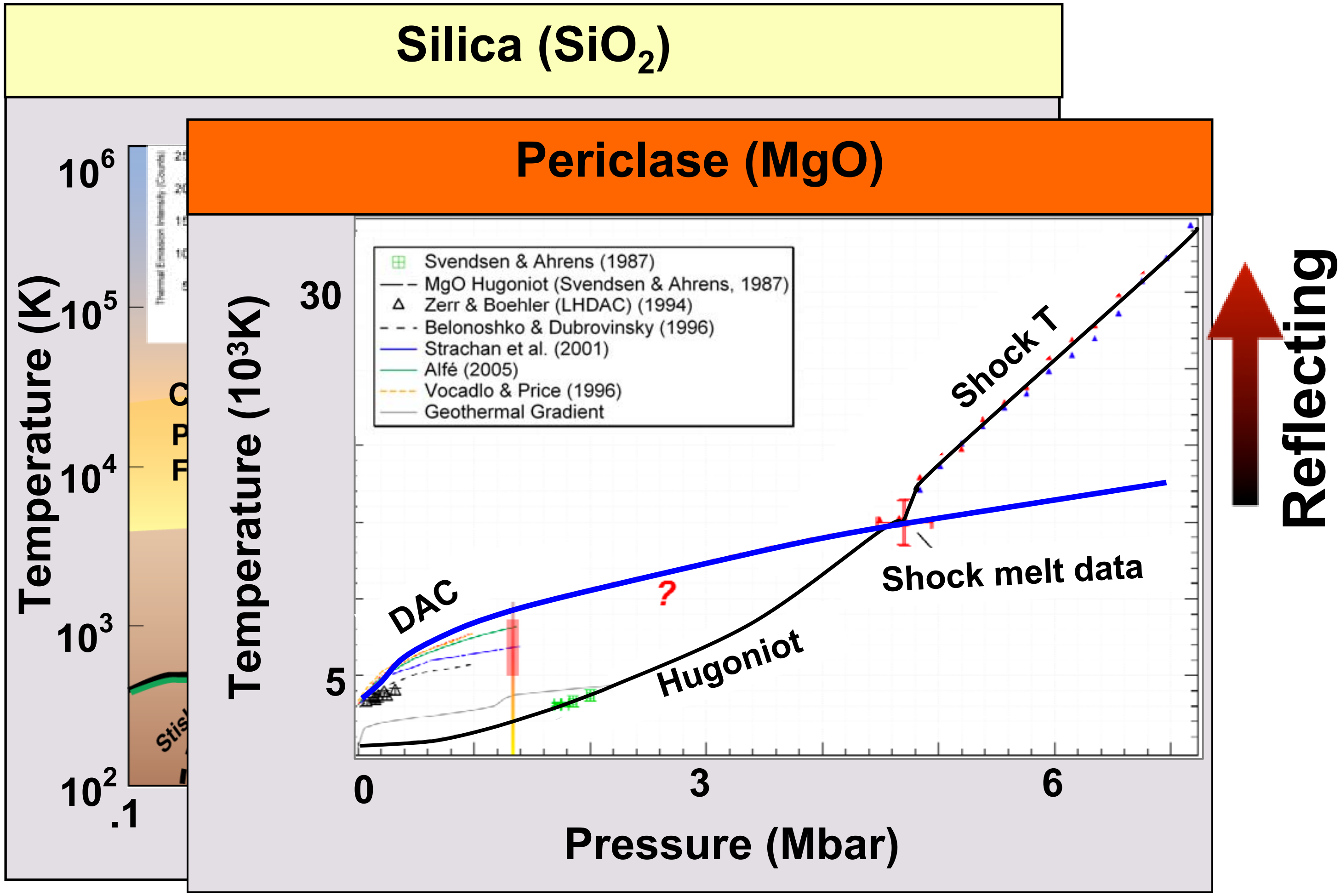
Several materials seem to become conductors and have complex chemistry just above melting

Silica (SiO_2)



Hicks PRL 07

Several materials seem to become conductors and have complex chemistry just above melting

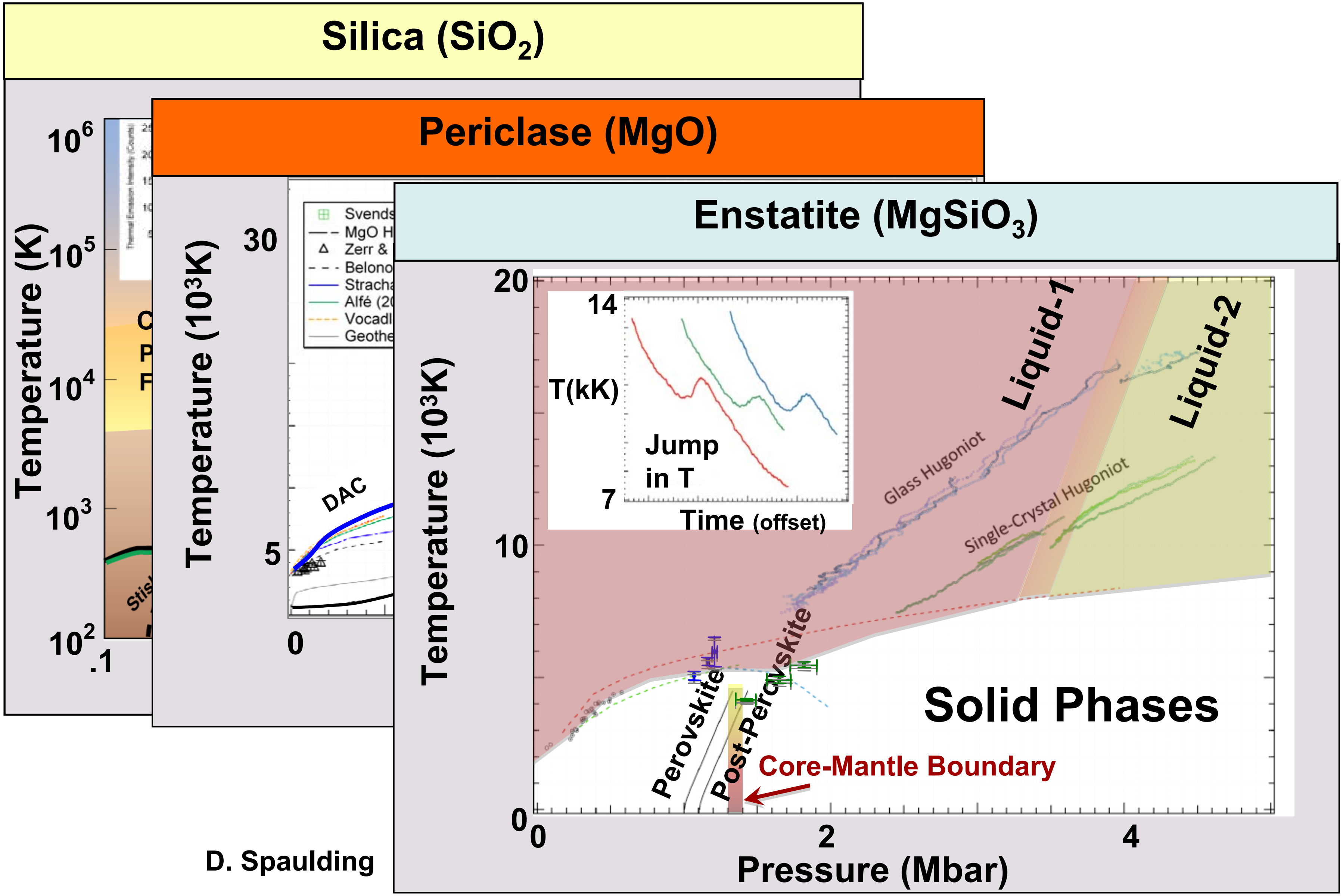


Silica (SiO_2)

Periclase (MgO)

McWilliams

Several materials seem to become conductors and have complex chemistry just above melting



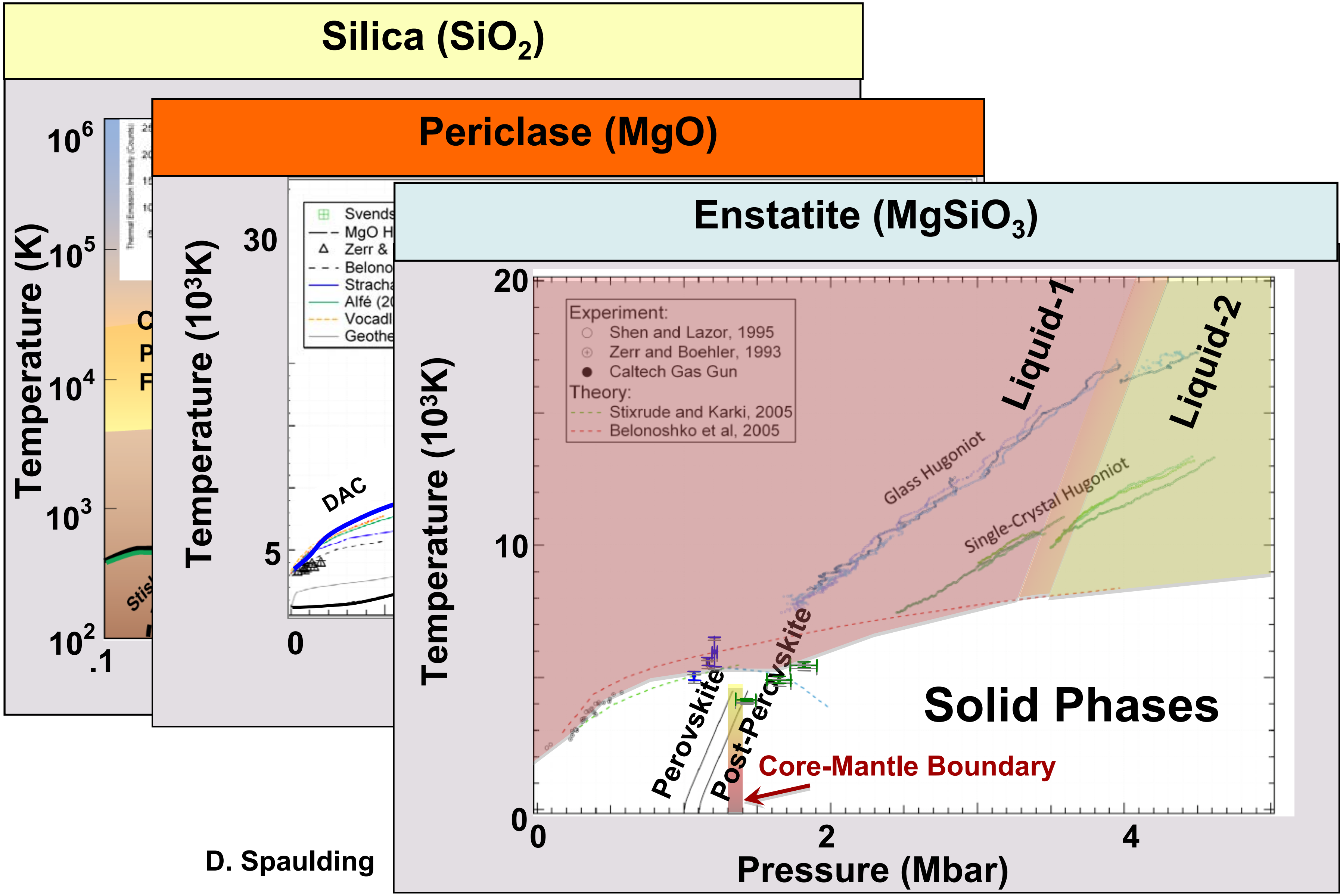
Silica (SiO_2)

Periclase (MgO)

Enstatite ($MgSiO_3$)

D. Spaulding

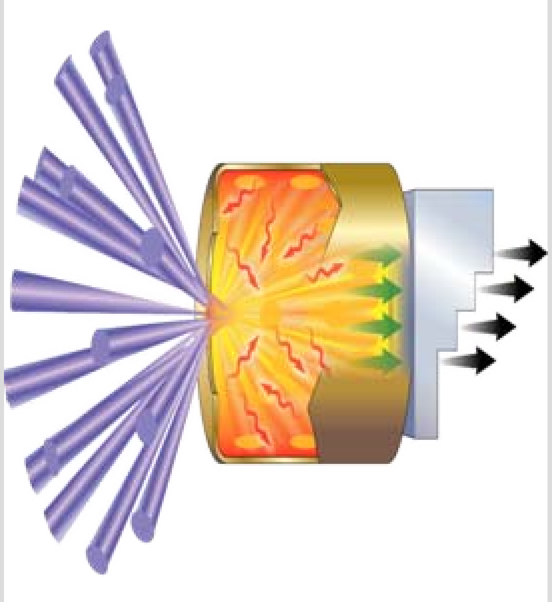
Several materials seem to become conductors and have complex chemistry just above melting



D. Spaulding

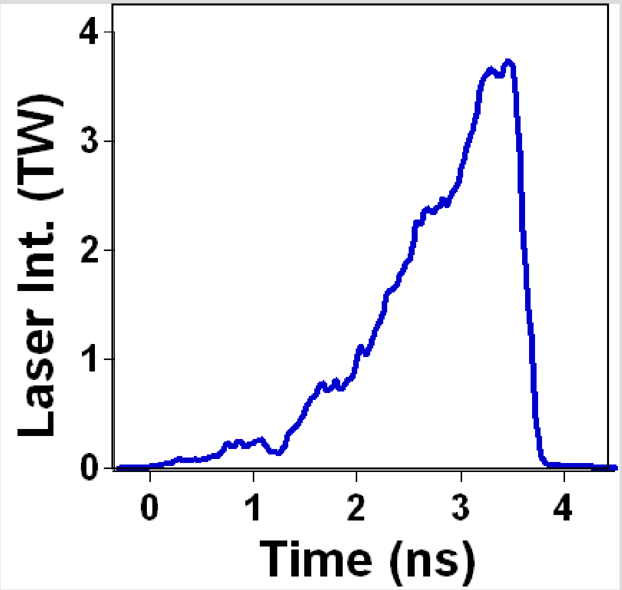
To generate colder dense states with lasers, just tune laser intensity versus time

Laser ramps use x-ray drive stepped samples



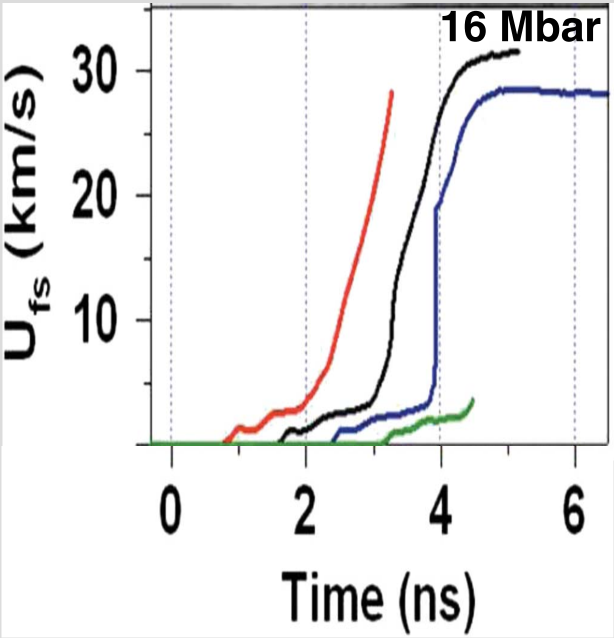
- Edwards, et al. (PRL 04)
- Smith, et al. (PRL 06)
- Bradley, et al. 08
- Eggert et al. (SCCM 07)

Ramp laser intensity to produce shockless compression



Velocity histories are used to determine P-rho

Free surface velocity vs time

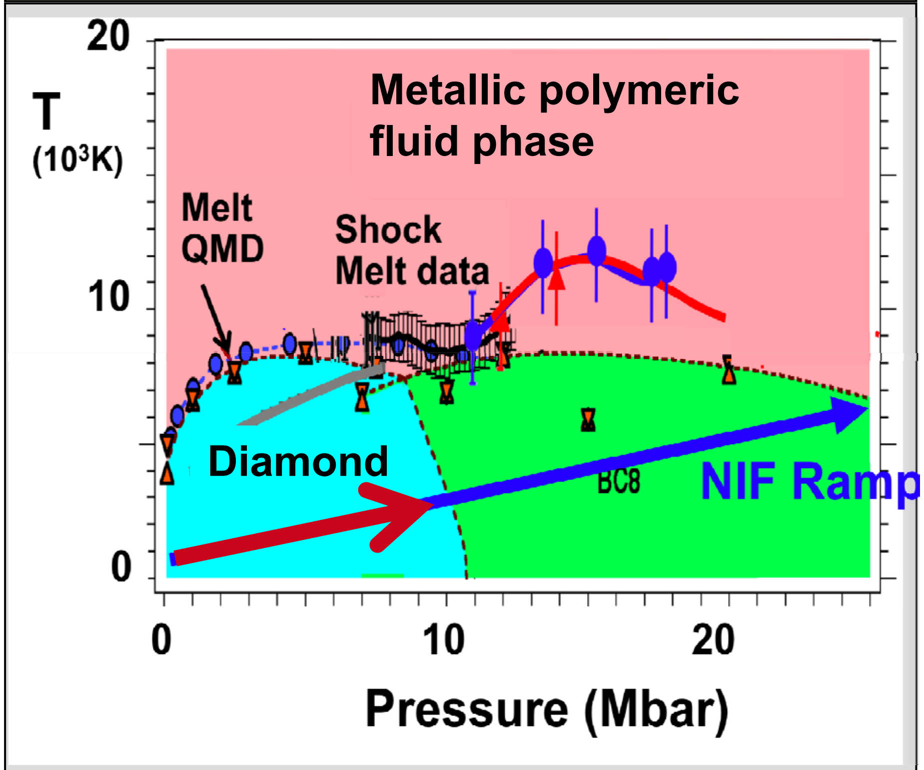


Wave-profile analysis is used to determine C_l,stress,rho (Maw,Rothman,05, Eggert 06)

R. Smith 2005

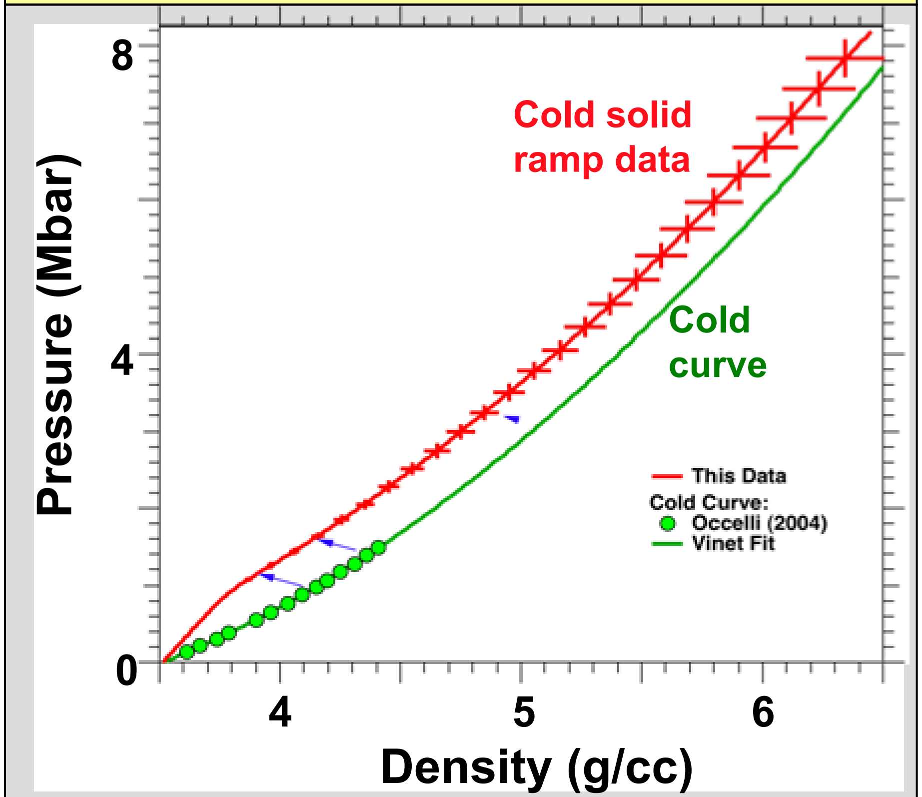
Ramp compression techniques can now explore solids at unprecedented pressures

We can now achieve solids to 10 Mbar
Next year we will make 30 Mbar solids



Eggert, Hicks

Ramp waves explore solid-state properties
Solid diamond to 8Mbar

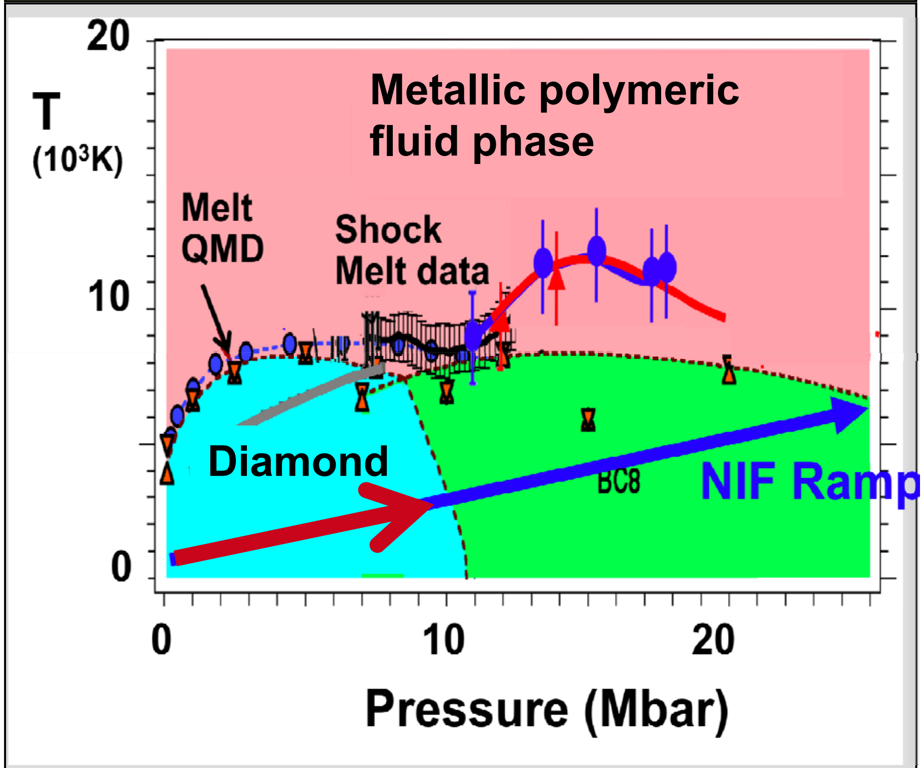


Bradley et al, PRL 08

Ramp waves have been used to explore new phases, phase transition kinetics, strength, kinetics of material deformation

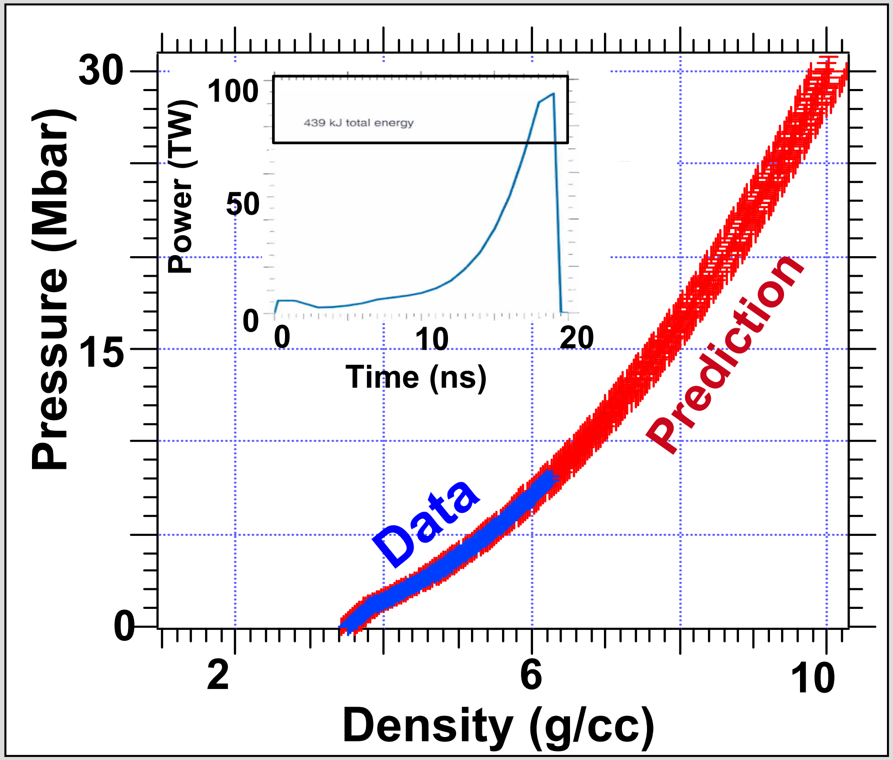
In a couple of years we will be exploring solids at 30 to 100 Mbar

We can now achieve solids to 10 Mbar
Next year we will make 30 Mbar solids



Eggert, Hicks

30 Mbar NIF design is scaled from 8 Mbar Omega experiments

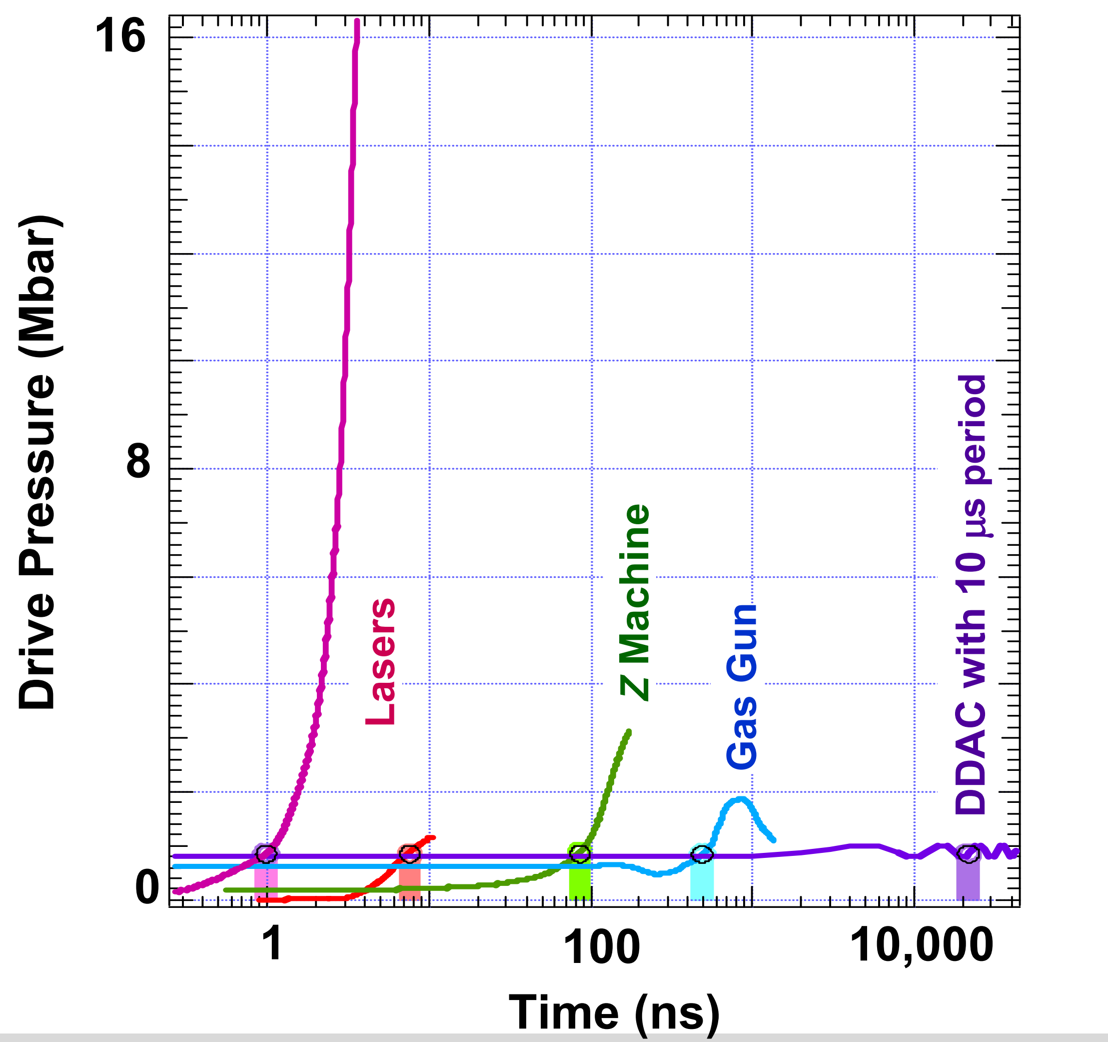


Eggert, Braun

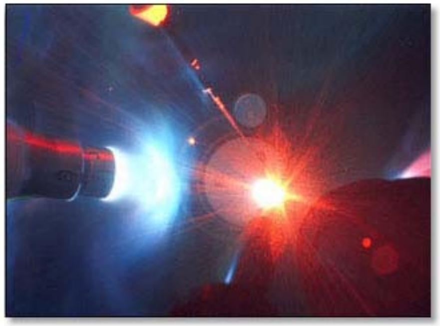
Ramp waves have been used to explore new phases, phase transition kinetics, strength, kinetics of material deformation

Combining lasers, pulse power, guns and DAC's allow us to vary ramp compression rates by more than 10^{13}

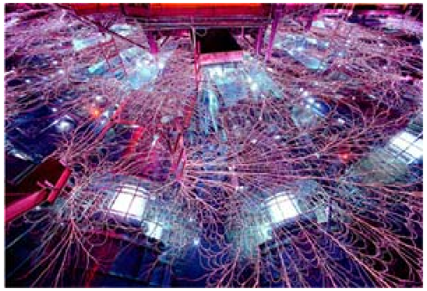
Changing compression rates over this range helps unravel deformation mechanisms



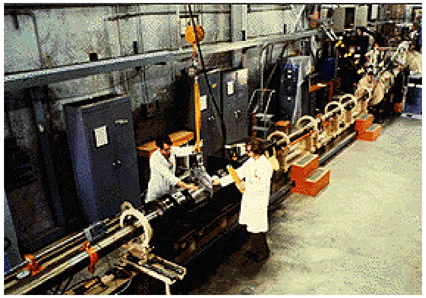
Lasers



Pulse power



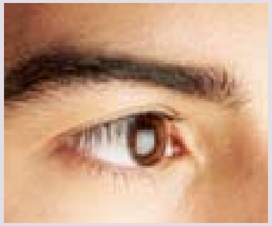
Guns

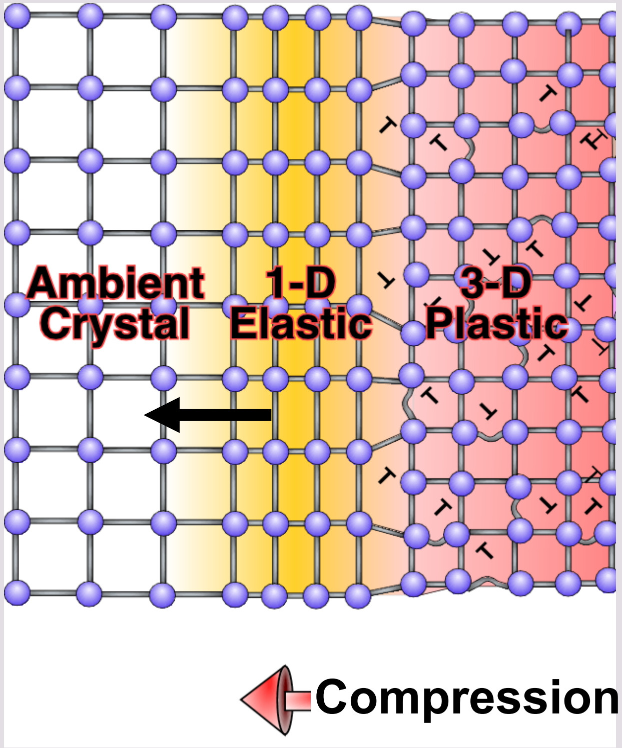


How do solids deform under dynamic compression and how fast can you squish a solid

Plastic deformation of elastic-plastic solids occurs with adequate mobile defects

Velocity meter





How do solids deform under dynamic compression and how fast can you squish a solid

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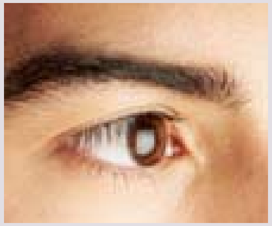
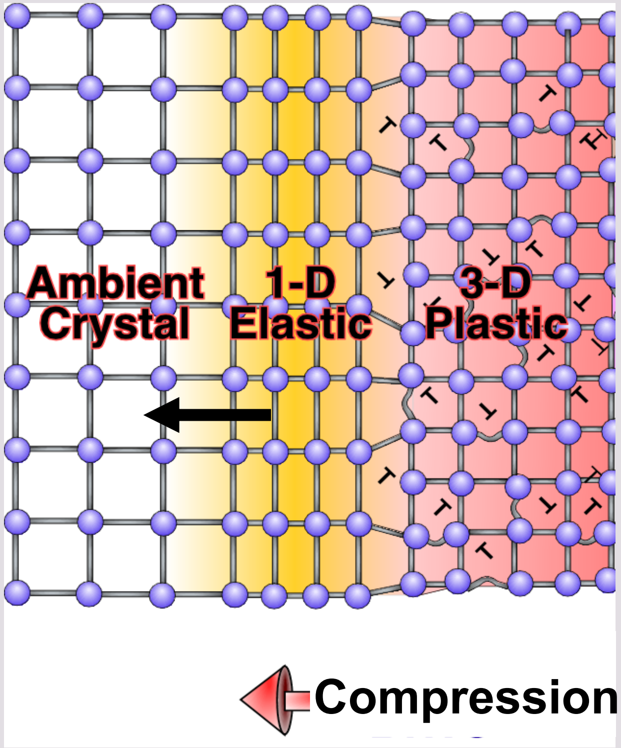
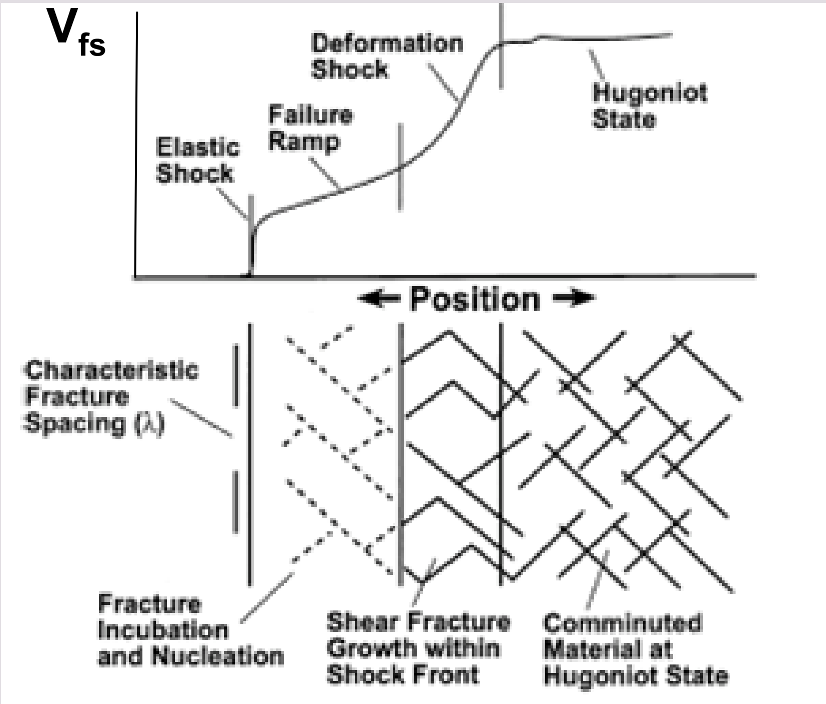




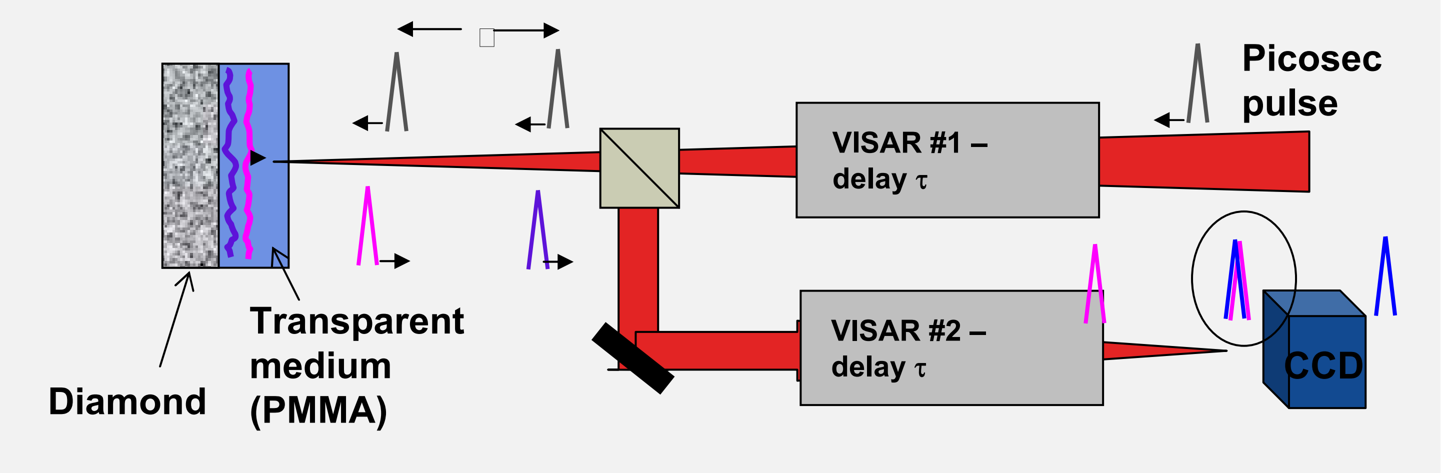
When the material is brittle, the deformation can be very different



Dennis Grady
Smith, Eggert et al.

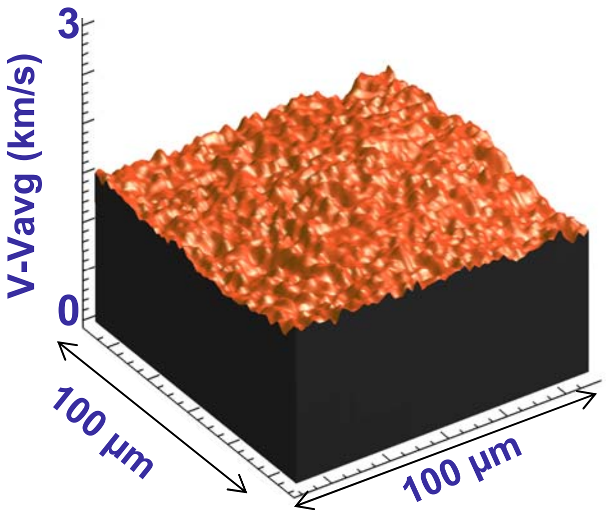
Dennis Grady

For brittle materials, there is significant shock structure up to melt



Celliers

At melt, shocks are ~ smooth
8 Mbar, 200 nm xtals



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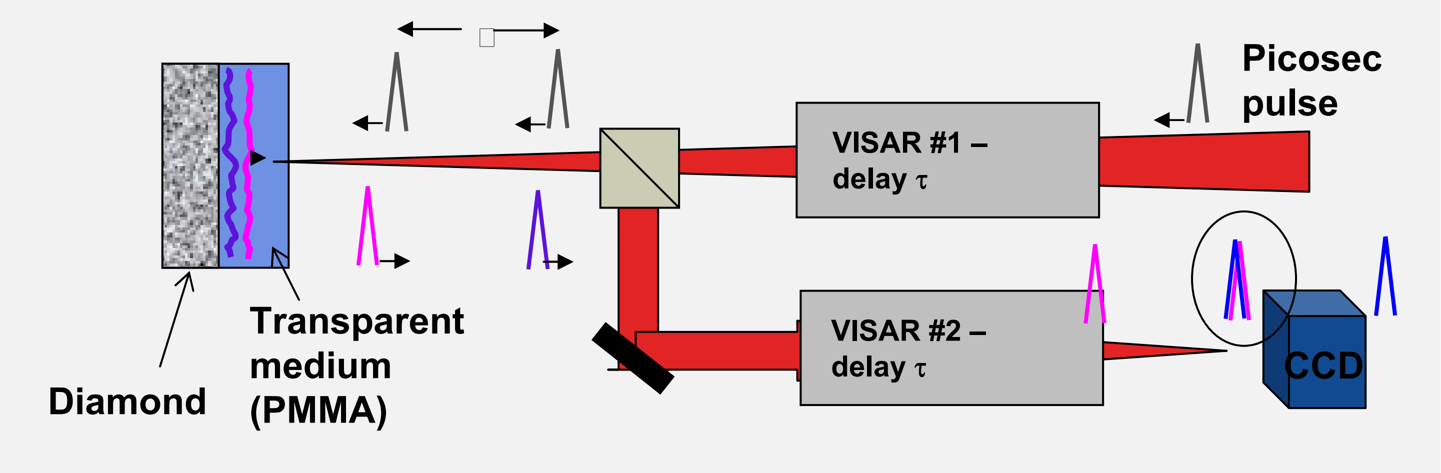

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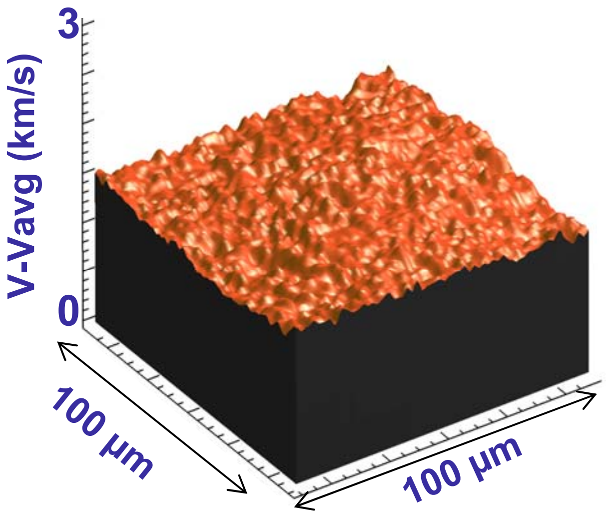
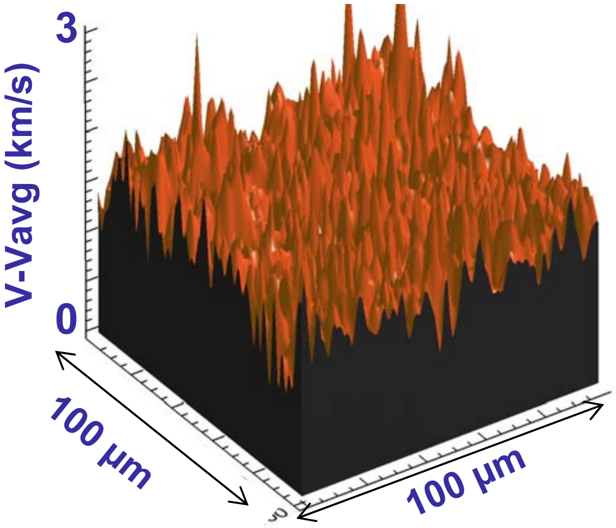
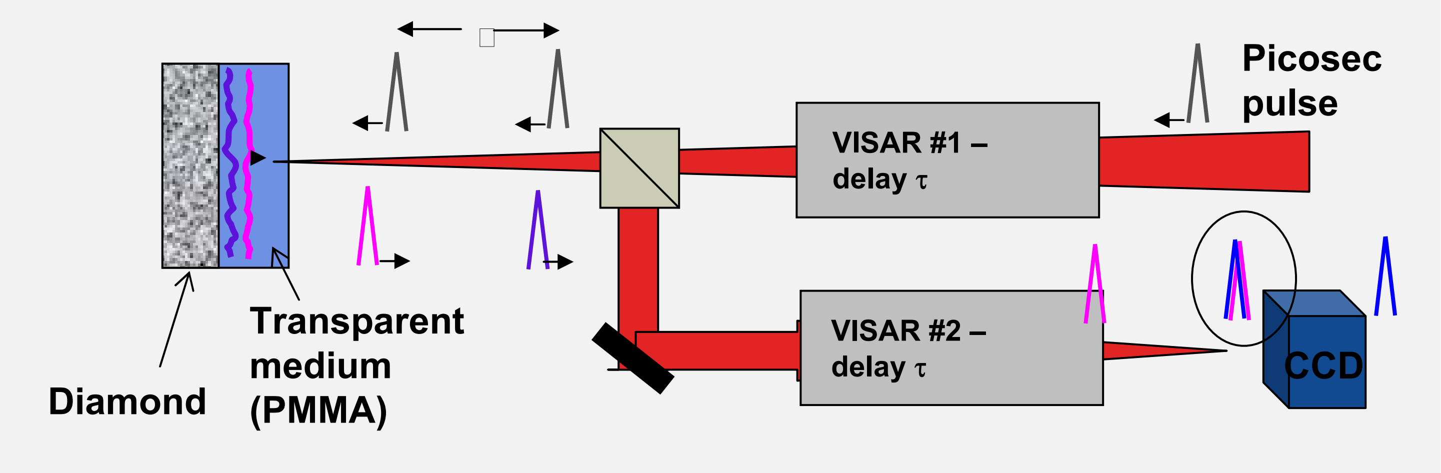


Below melt shocks have significant structure
4.5 Mbar, 200 nm xtals



For brittle materials, there is significant shock structure up to melt



Celliers

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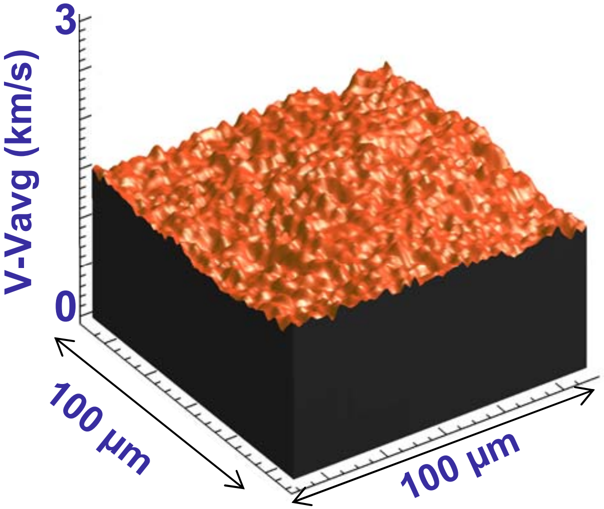

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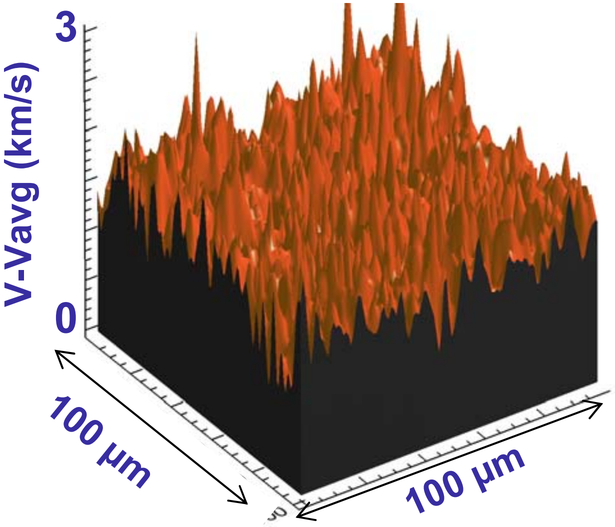
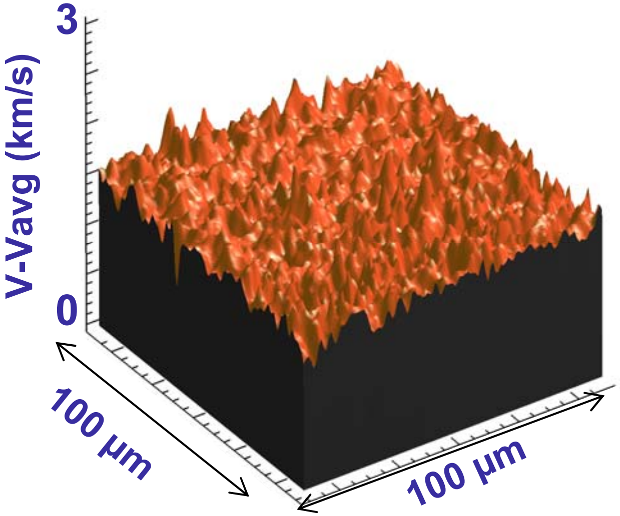
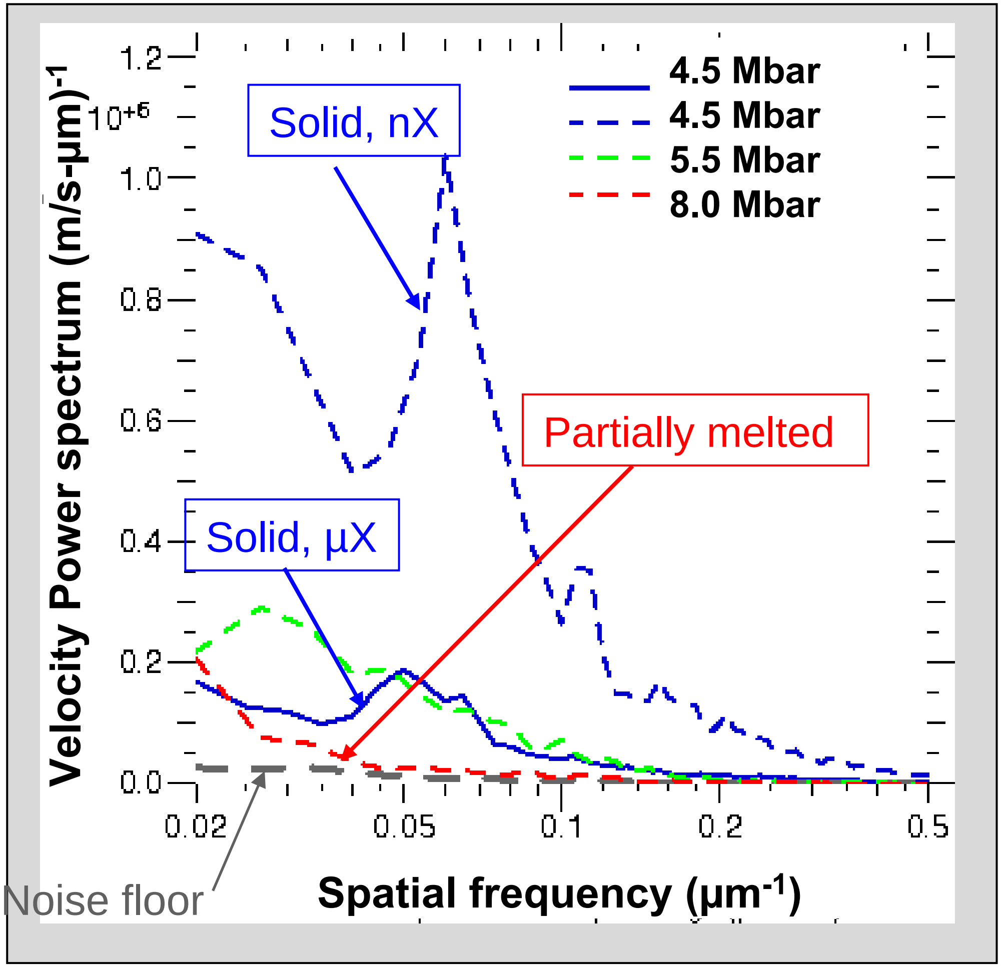


Structure depends on initial morphology,
Single or 200 µm xtals

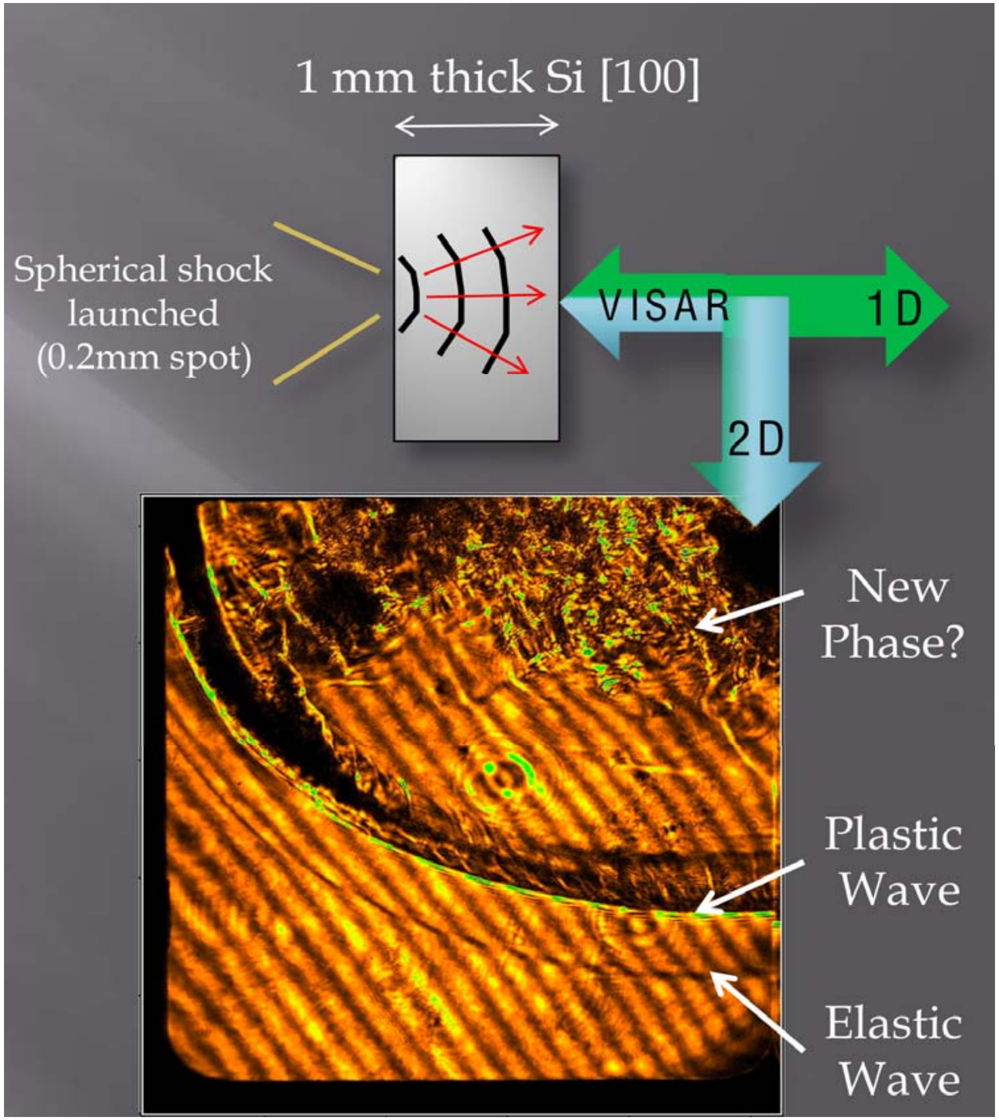


Velocity fluctuations show characteristic defect mode and scaling which will hopefully give solid viscosity

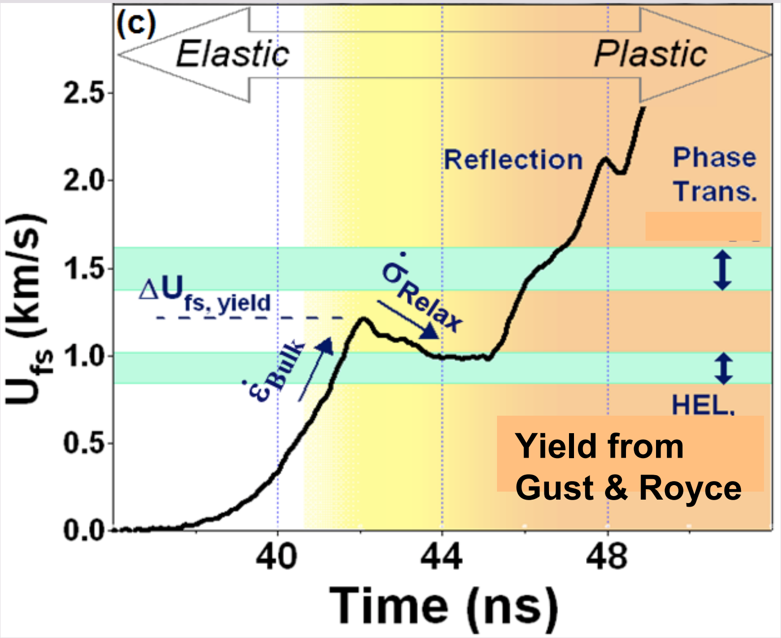
- High levels of heterogeneity in the solid phase
- Approximately 40-fold reduction in the fluctuation power near the onset of melting
- Does this suggest melt nucleation size?



For elastic-plastic solids (Si and Fe), elastic-plastic transition is smooth, but significant structure exists after a phase transition



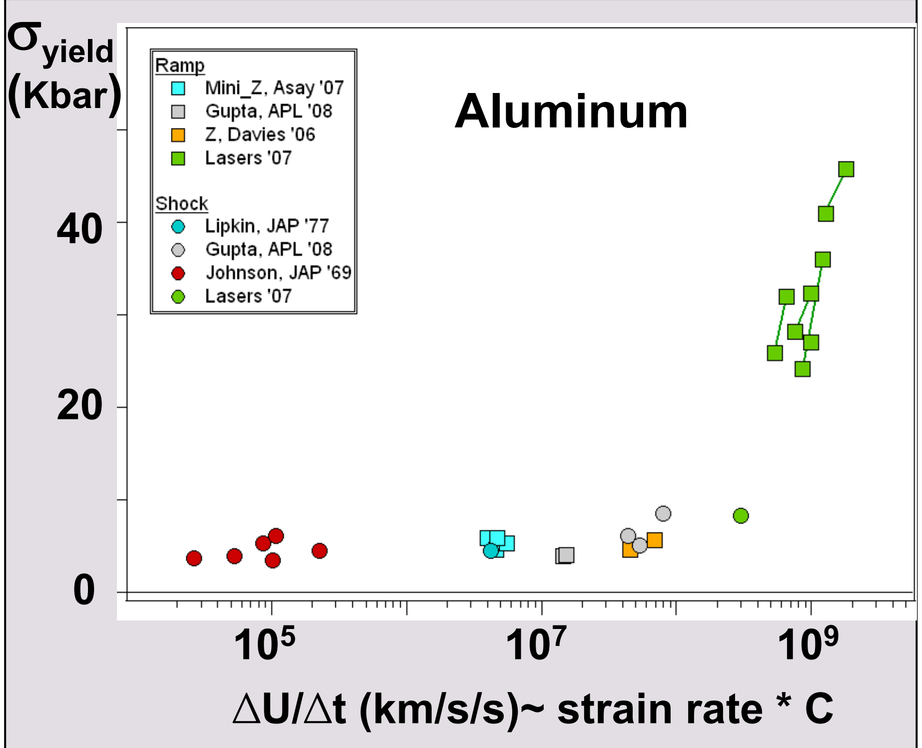
- Si is a perfect material to study since initial defect concentration is low



Smith

In general, the elastic-plastic transition increases with increasing strain rate

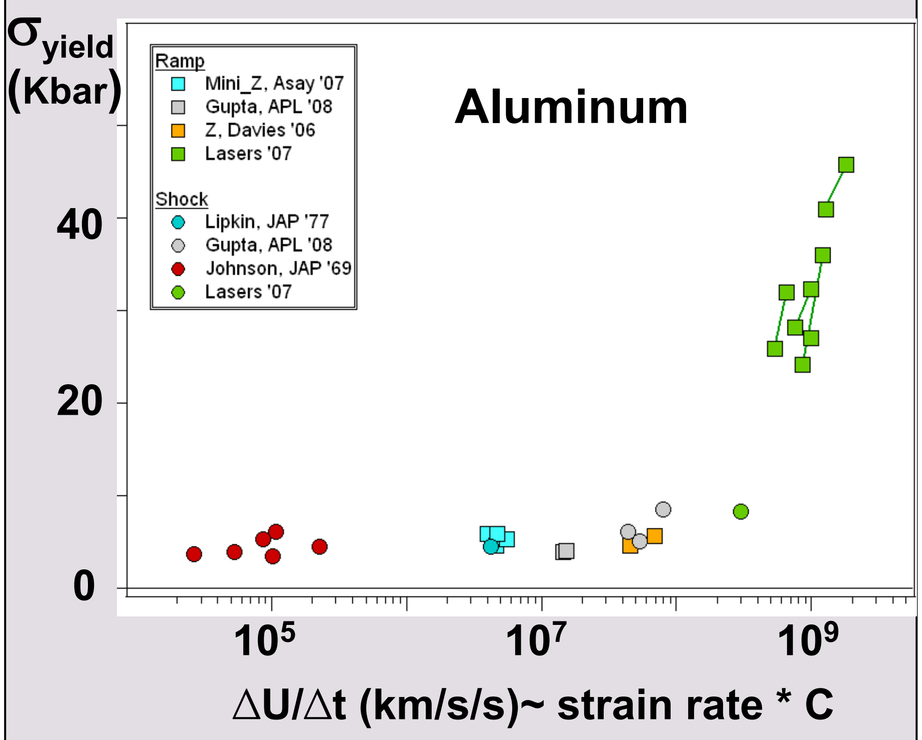
Yield stress also increases with with strain rate (decreasing thickness)



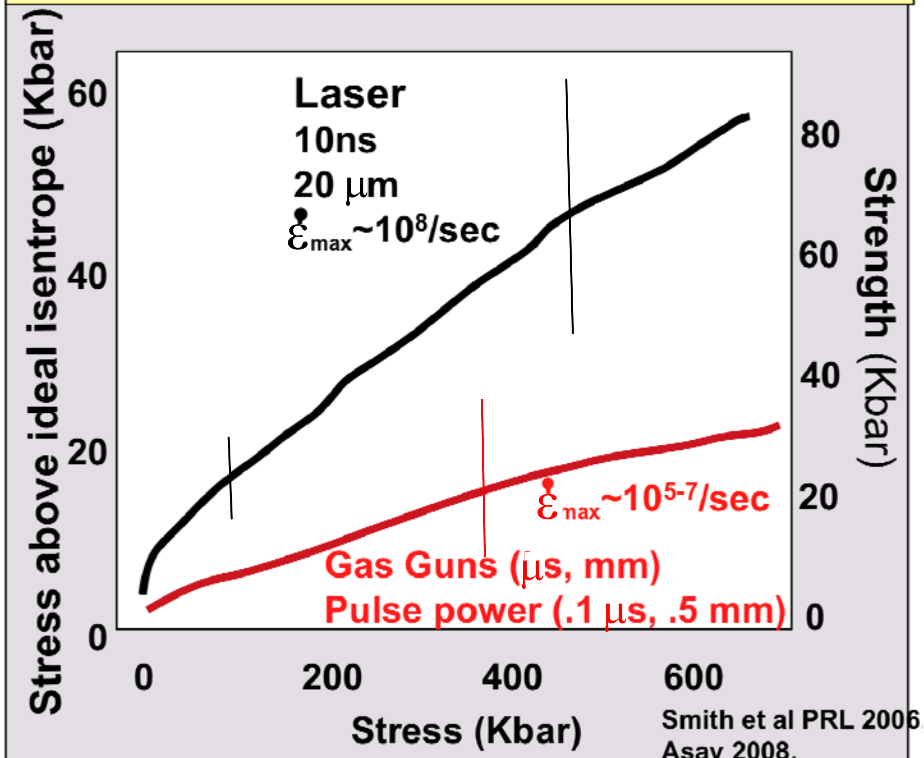
Same behavior exists for Ta, W, Fe, Si ….

The plastic flow is also strain rate dependent for several materials

Yield stress also increases with with strain rate (decreasing thickness)



Al is super stiff when compressed to a Mbar in a few ns



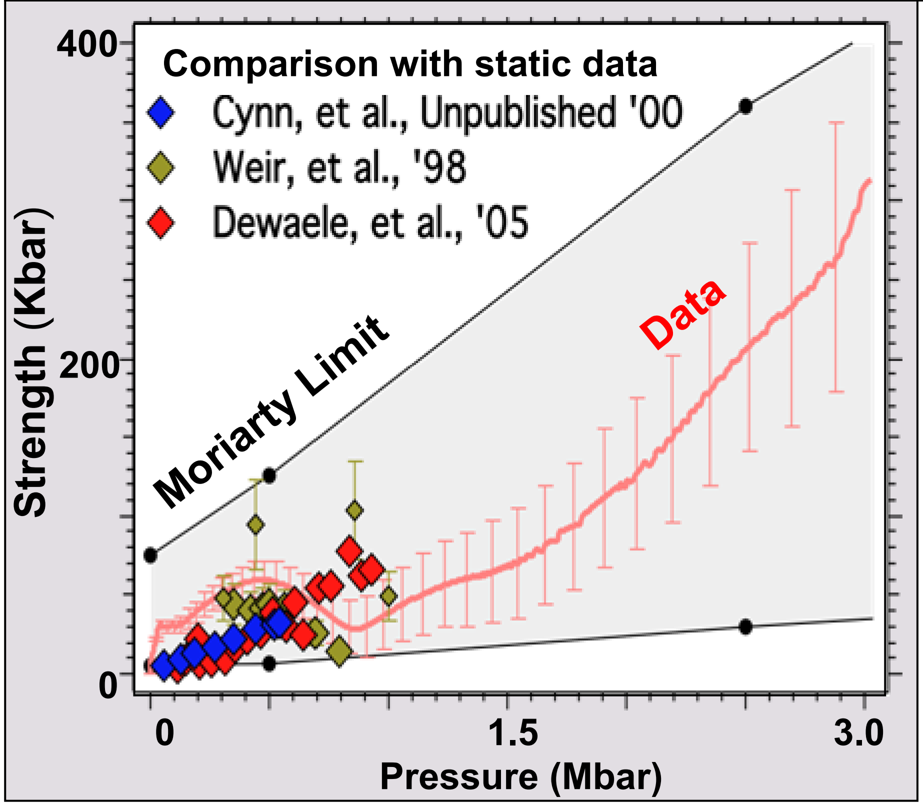
Smith et al PRL 2006
Asay 2008,
Hayes 2006

Here we equate strength with deviatoric stress $Y = \frac{3}{4}\left[\sigma(\rho) - P(\rho)\right]$

Al is in the phonon drag regime at ~ 10^8/sec strain rates

For ramp compressed Ta, we do not find rate dependence up to 10^8/sec in the plastic flow region

Ta strength is not rate dependent to 10^8/sec



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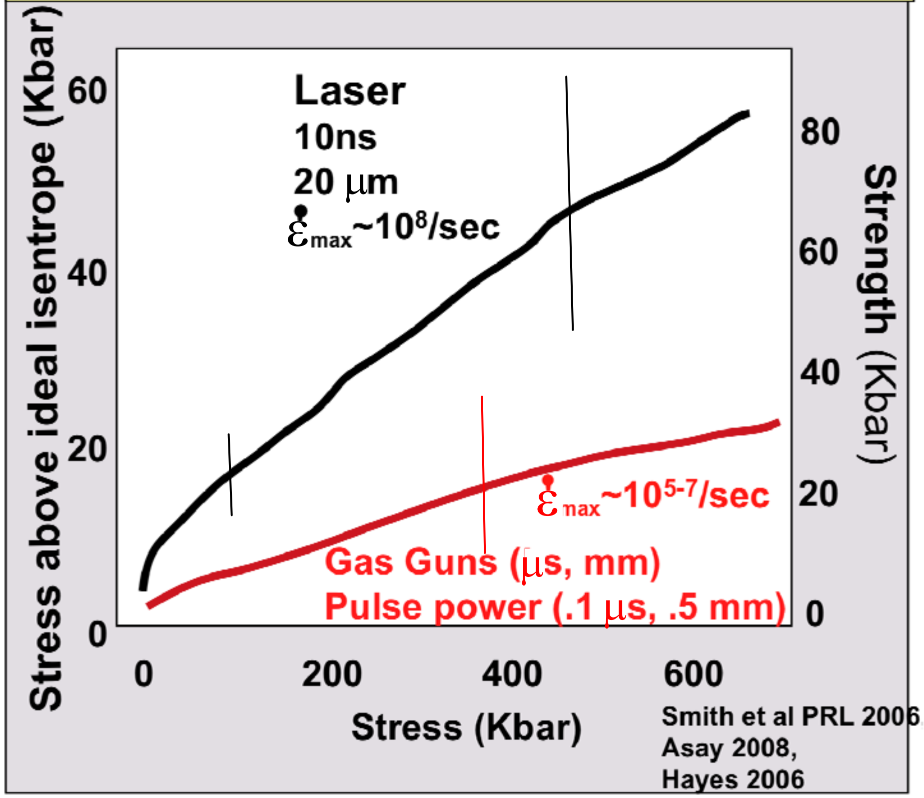


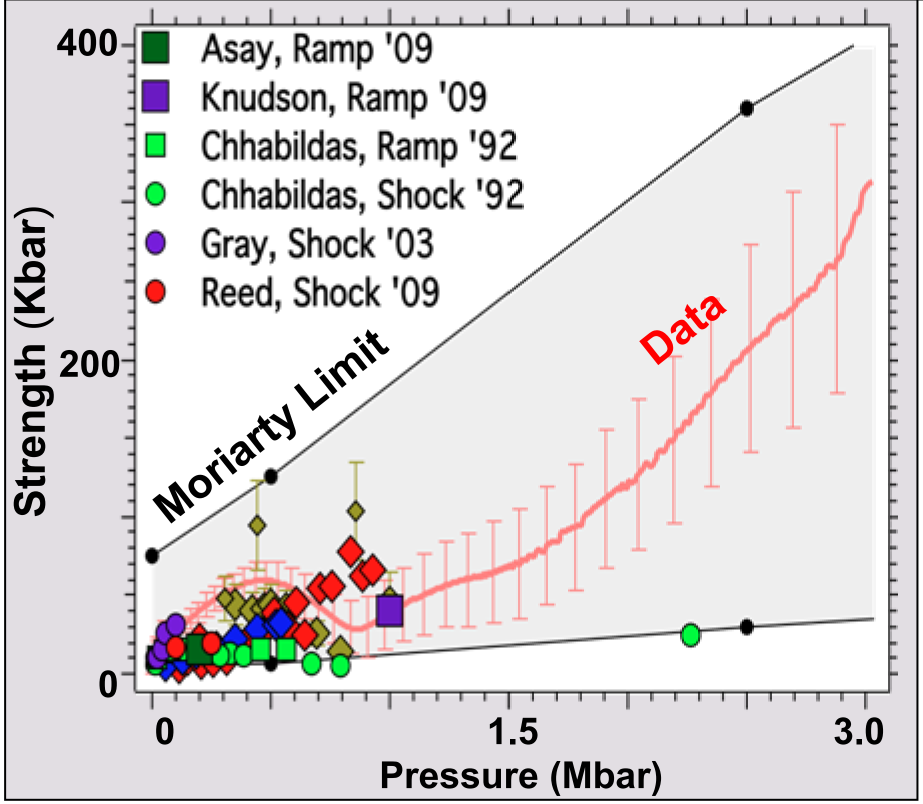
Smith et al PRL 2006
Asay 2008,
Hayes 2006

Again equate strength with deviatoric stress

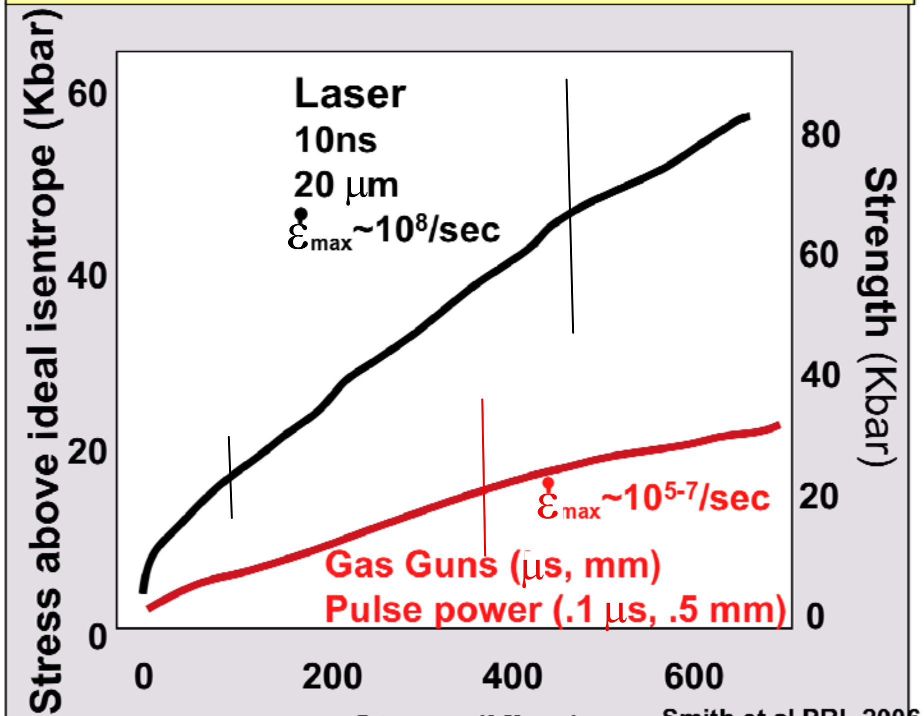
$$Y = \frac{3}{4}\left[\sigma(\rho) - P(\rho)\right]$$

For ramp compressed Ta, we do not find rate dependence up to 10^8/sec in the plastic flow region

Ta strength is not rate dependent
Comparison with static data



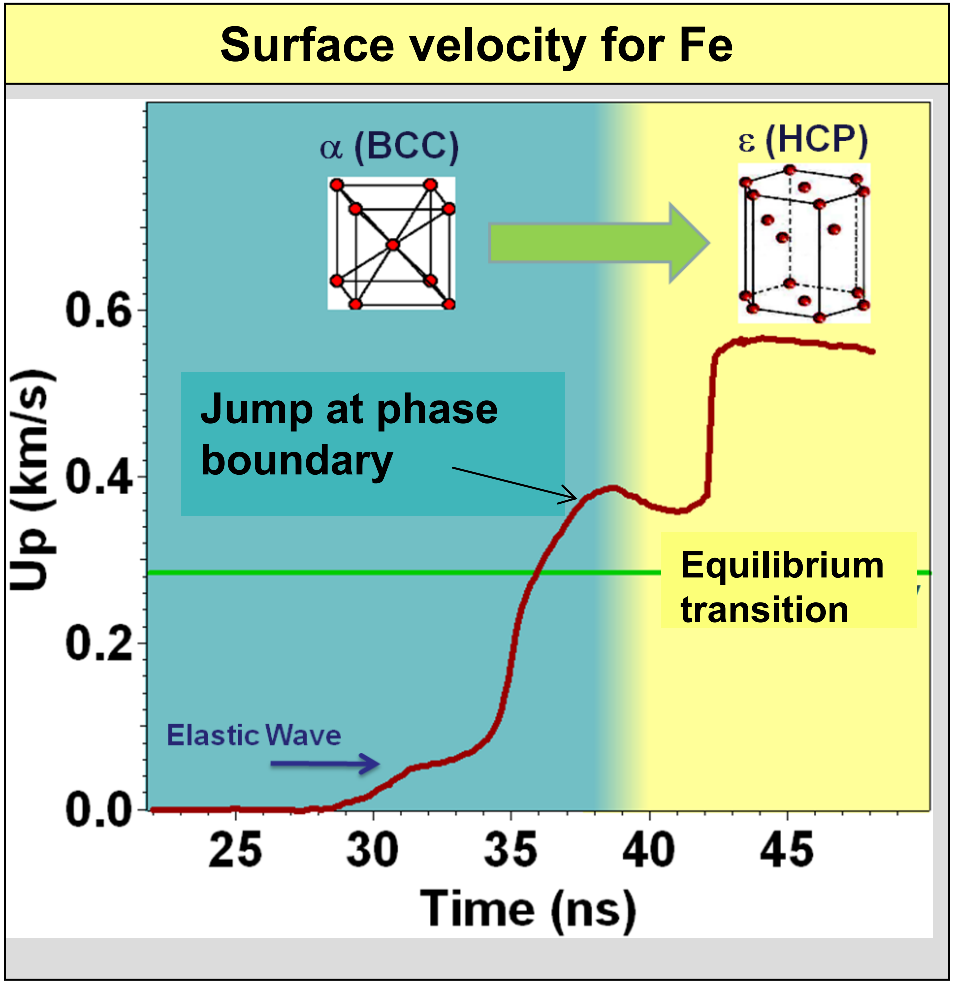
Al is super stiff when compressed to a Mbar in a few ns



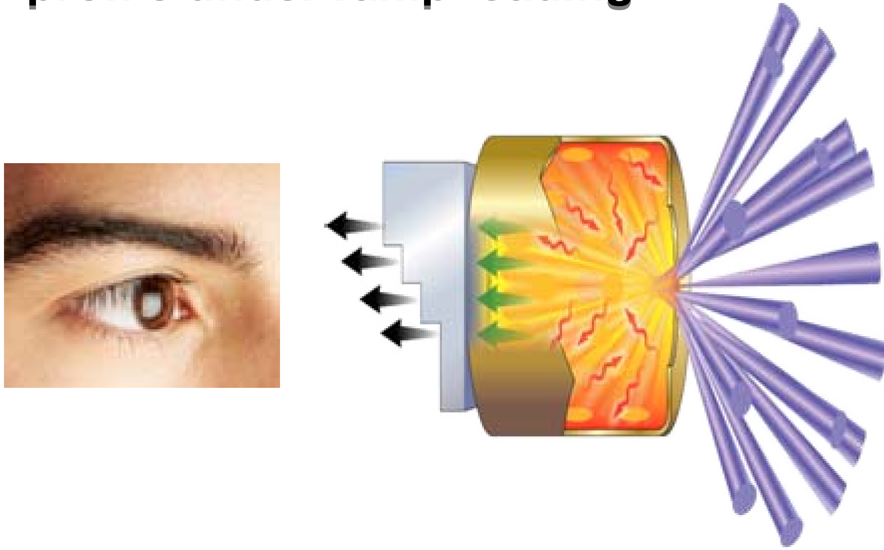
Smith et al PRL 2006,
Asay 2008,
Hayes 2006

Again equate strength with deviatoric stress $Y = \frac{3}{4}\left[\sigma(\rho) - P(\rho)\right]$

For more complicated phase diagrams how fast can you cross a phase boundary and how do we know phase?

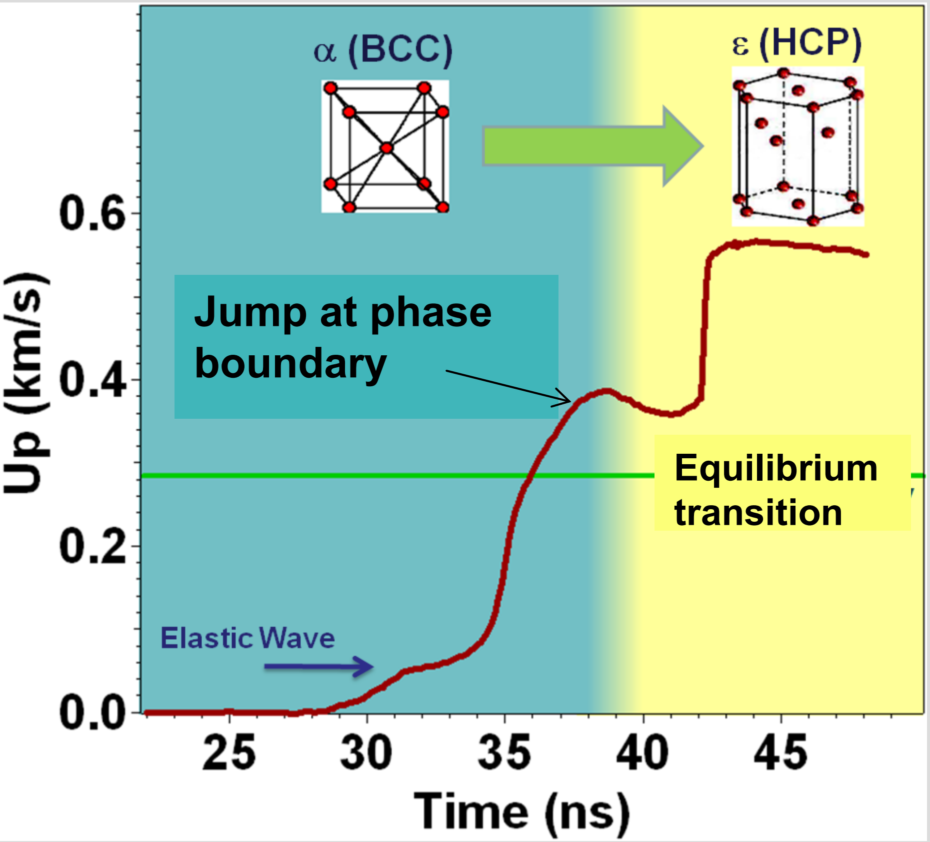


The easiest way to locate phase boundaries is to look at the wave profile under ramp loading

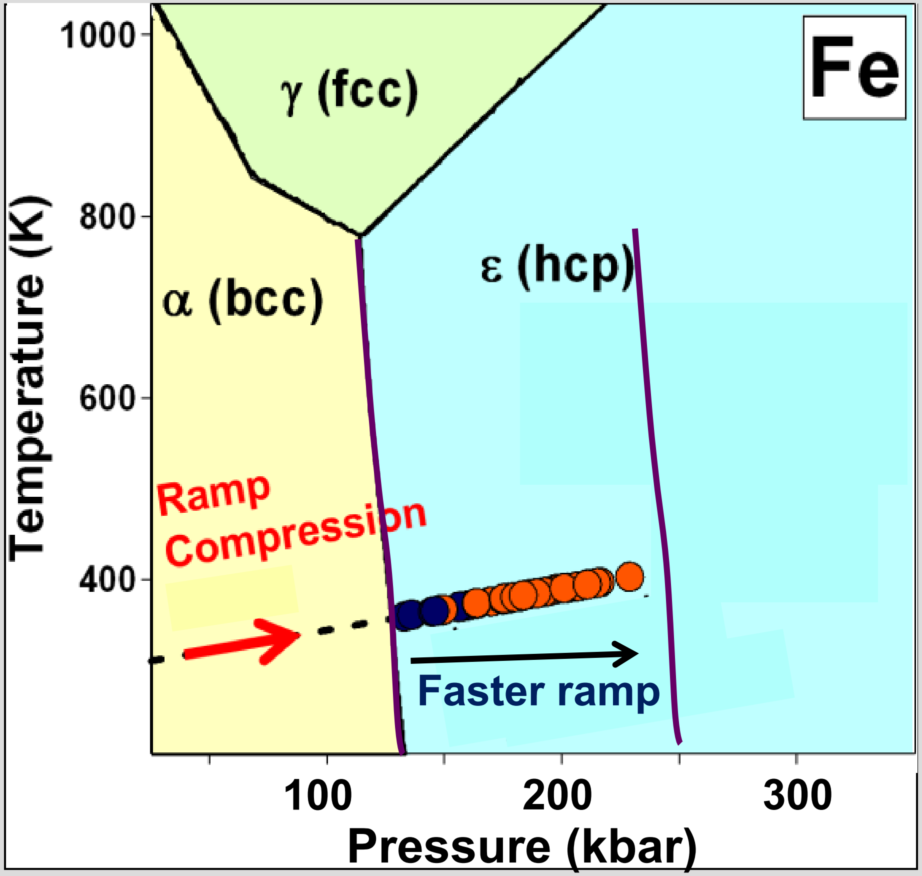


We observe large overshoot of the α–ε phase transformation in Fe

Surface velocity for Fe

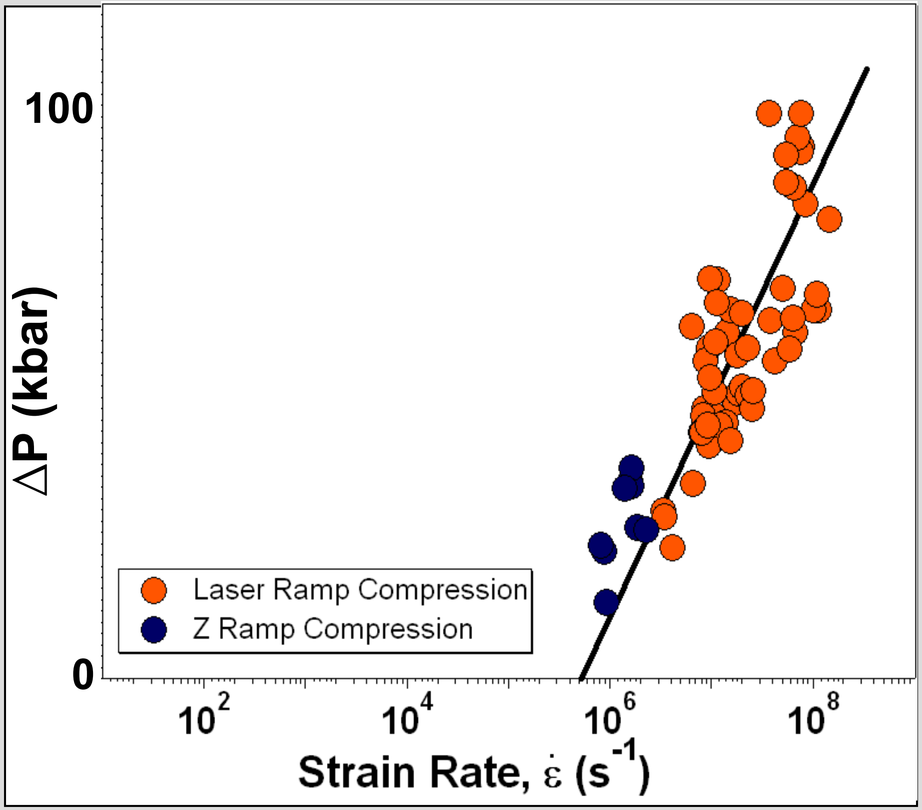


Fe phase diagram

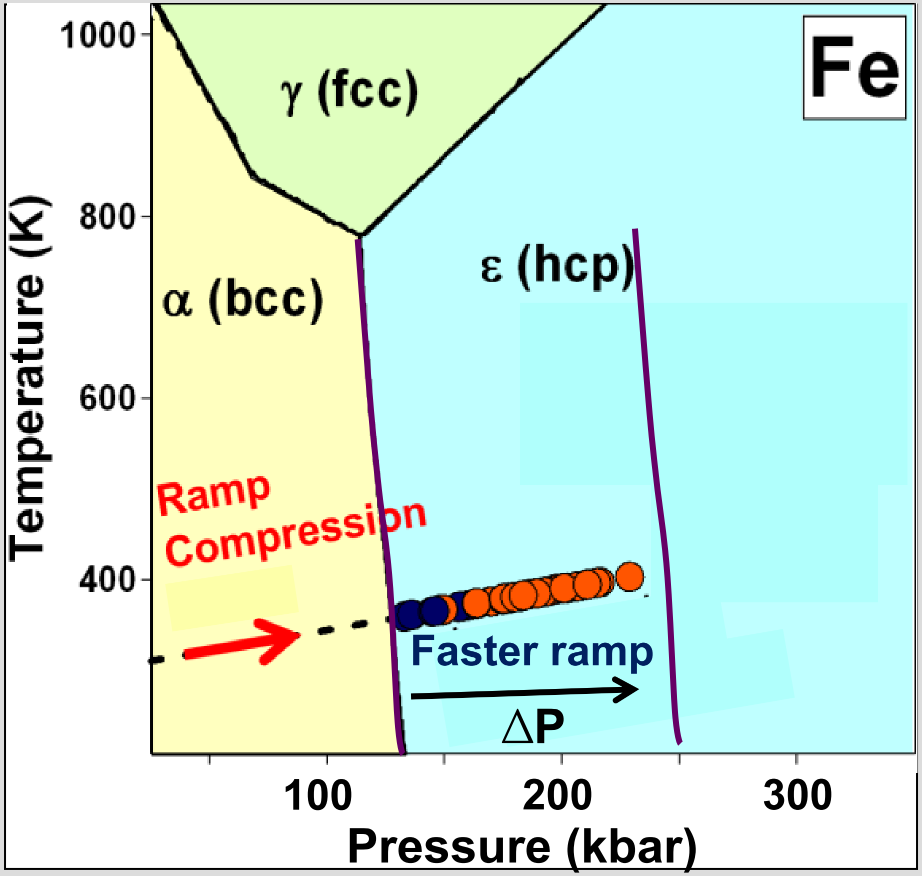


We observe large overshoot of the α–ε phase transformation in Fe

Over pressurization for transition



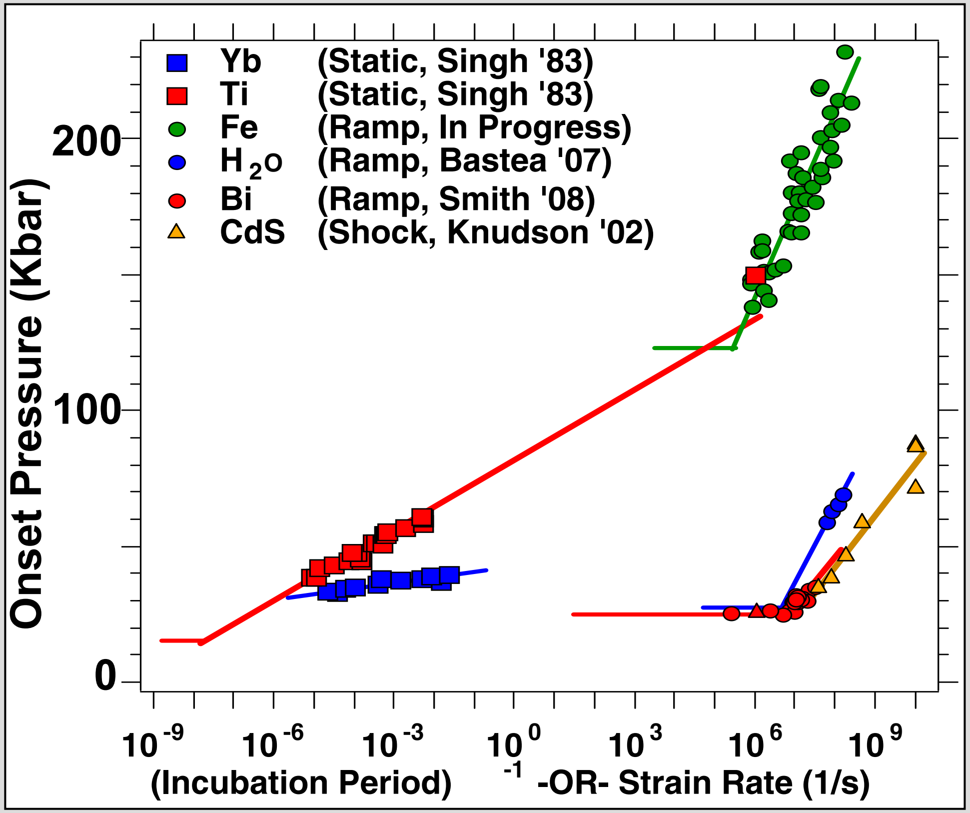
Fe phase diagram



We observe a logarithmic dependence of over-pressurization with strain rate for $\varepsilon > 5 \times 10^5\ s^{-1}$

The logarithmic increase in over-pressurization is pretty general

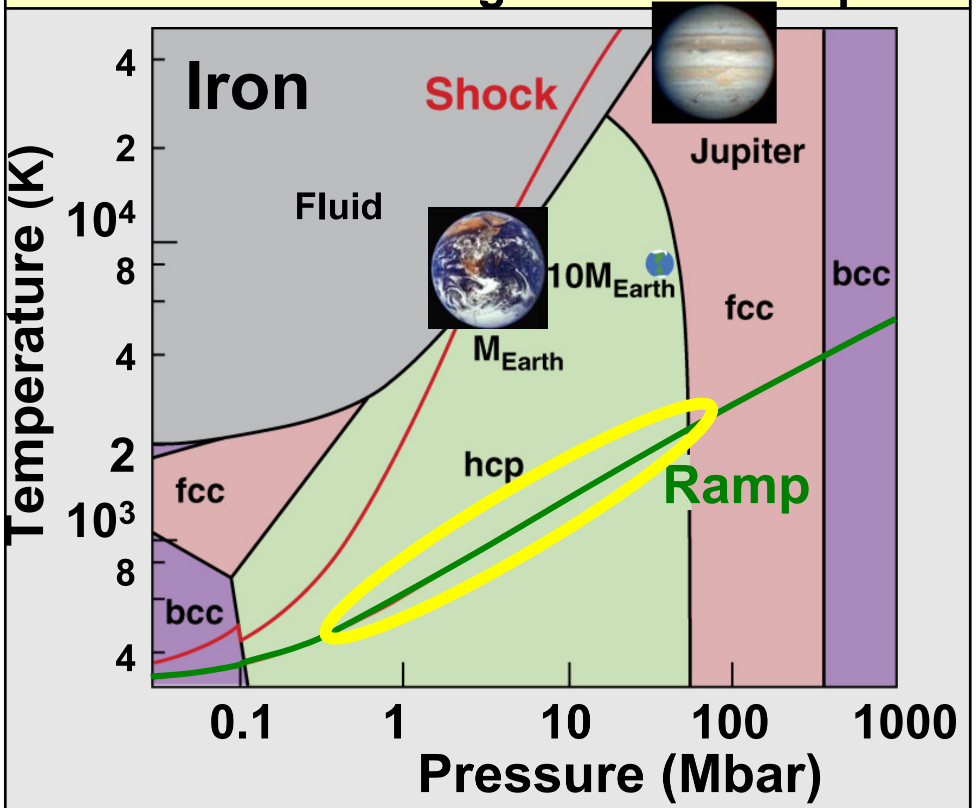
There is a significant apparent shift in phase boundaries for solid-solid, freezing, and melting



We need to determine final phase with a different technique

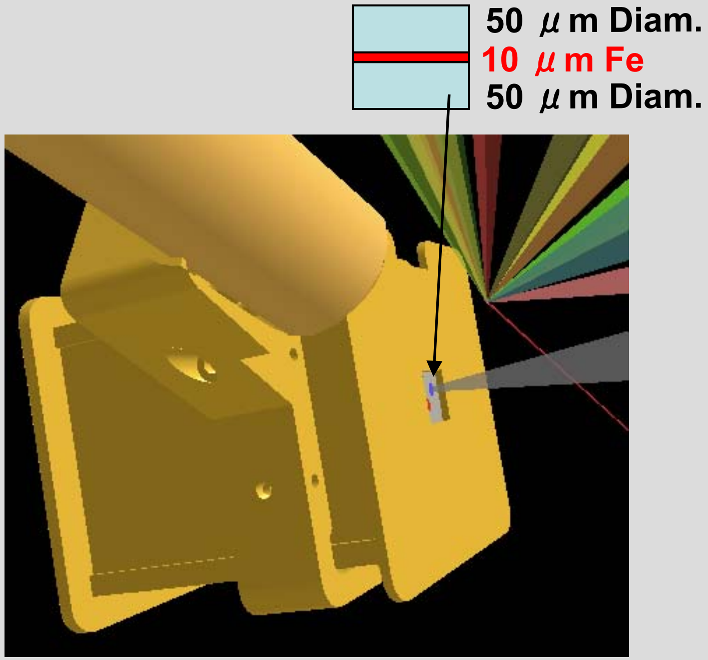
We use powder diffraction + ramp compression to explore ultra-high pressure phases

We have to be careful when crossing boundaries with large volume collapse



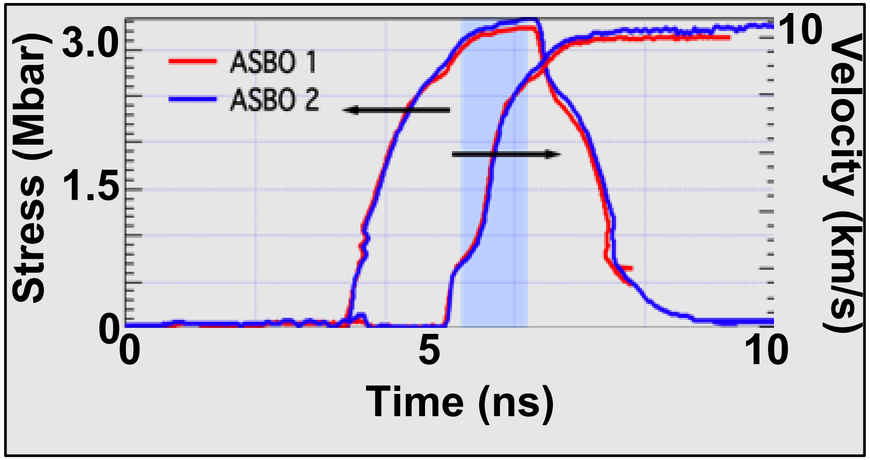
Stixrude, 08

Powder diffraction on ramp compressed samples

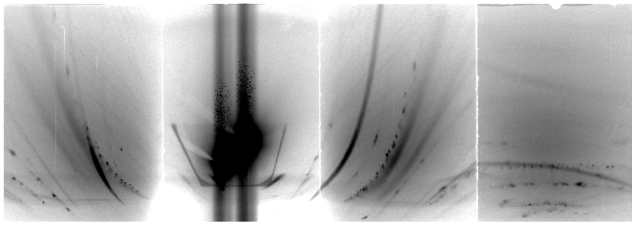


Eggert, Rygg

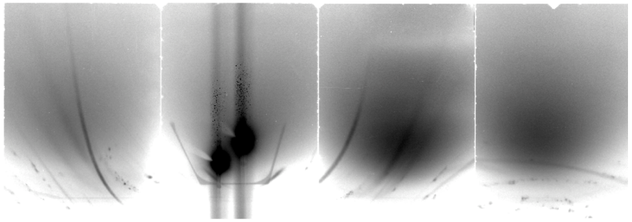
Simultaneous measurements of velocity and diffraction gives compressibility and phase



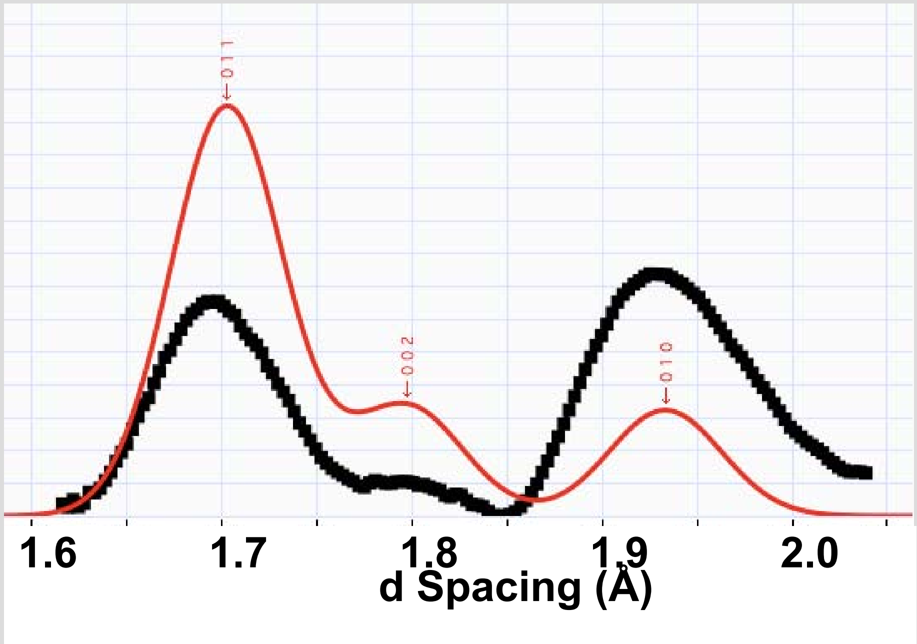
1.85 Mbar



3.24 Mbar

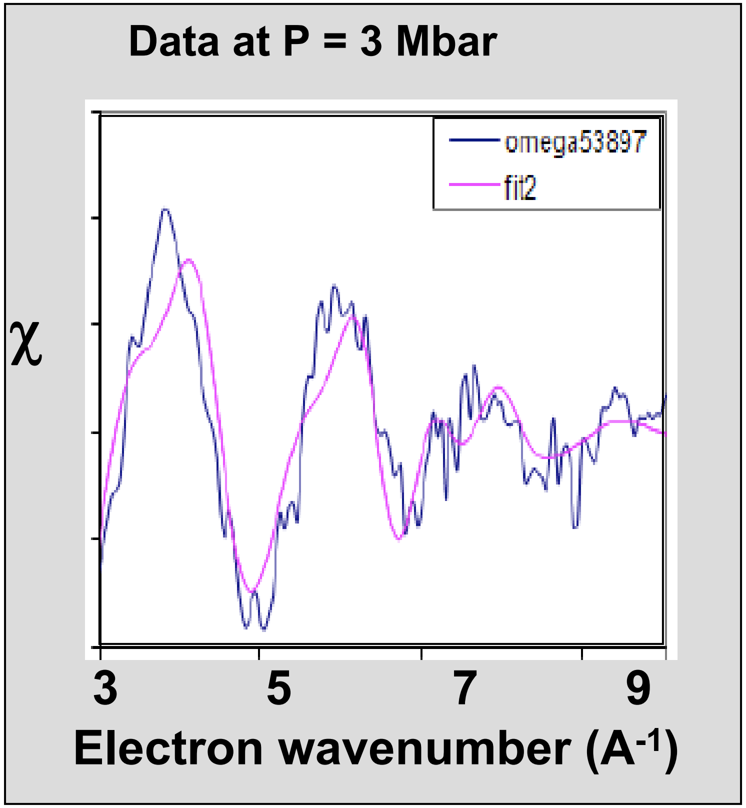


**Best Fit Assuming HCP,
c/a = 1.61 to 5 Mbar**



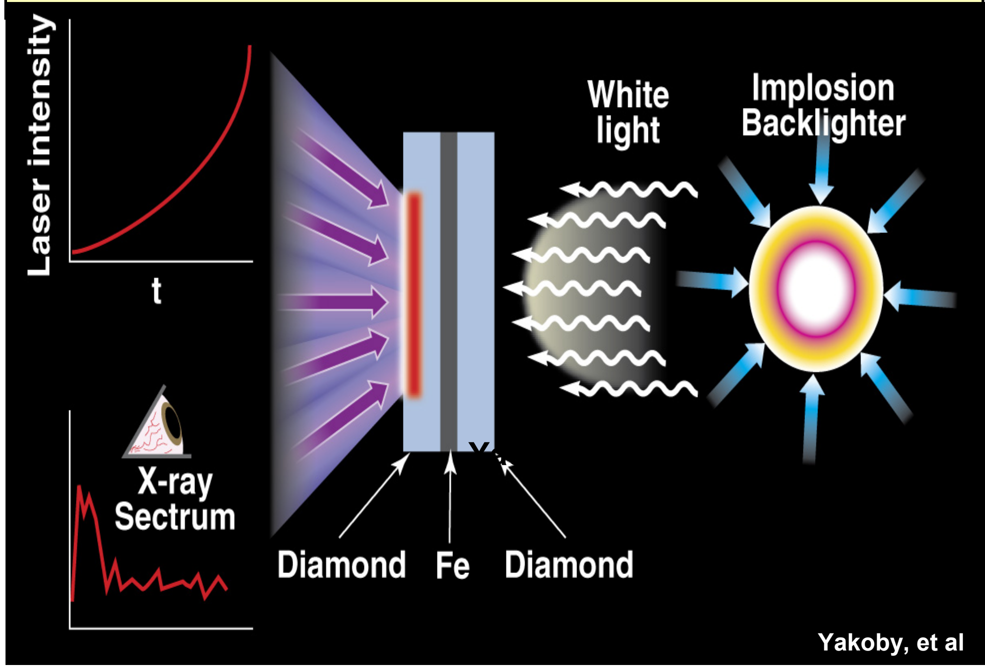
Eggert, Rygg

EXAFS data is used to determine local order, structure, temperature in a 50 ps snapshot



Data at P = 3 Mbar

X-ray Scattering/absorption shows local structure in Fe to 3 Mbar (Hicks)



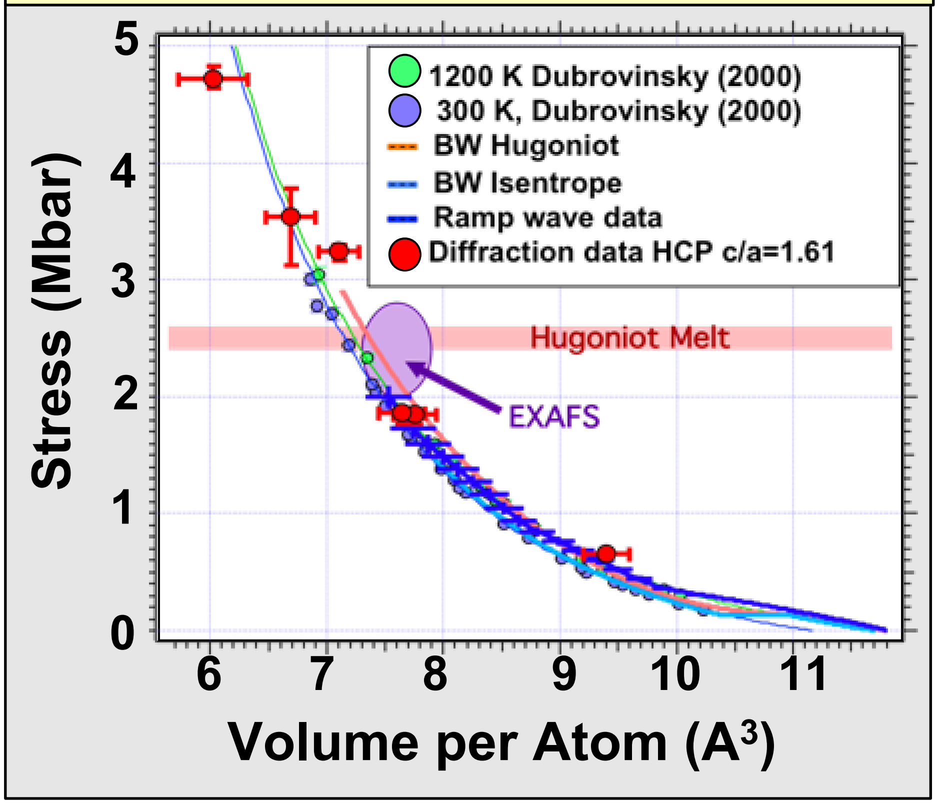
Yakoby, et al

Best fit to EXAFS data at 3 Mbar shows HCP structure, compression =1.55, T=6000 K

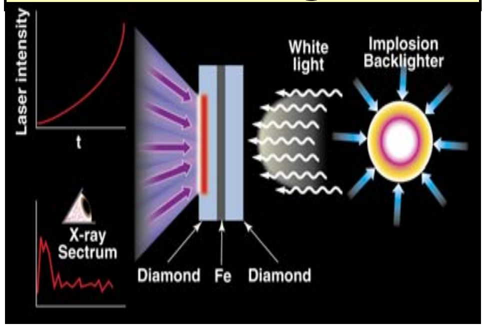
Hicks,Ping

EXAFS diffraction, and wave profile data are consistent and give P-rho-T and structure

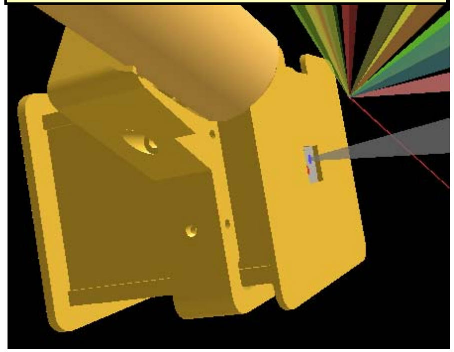
Previous isotherm data



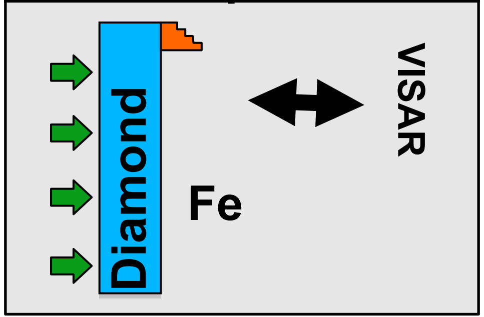
EXAFS



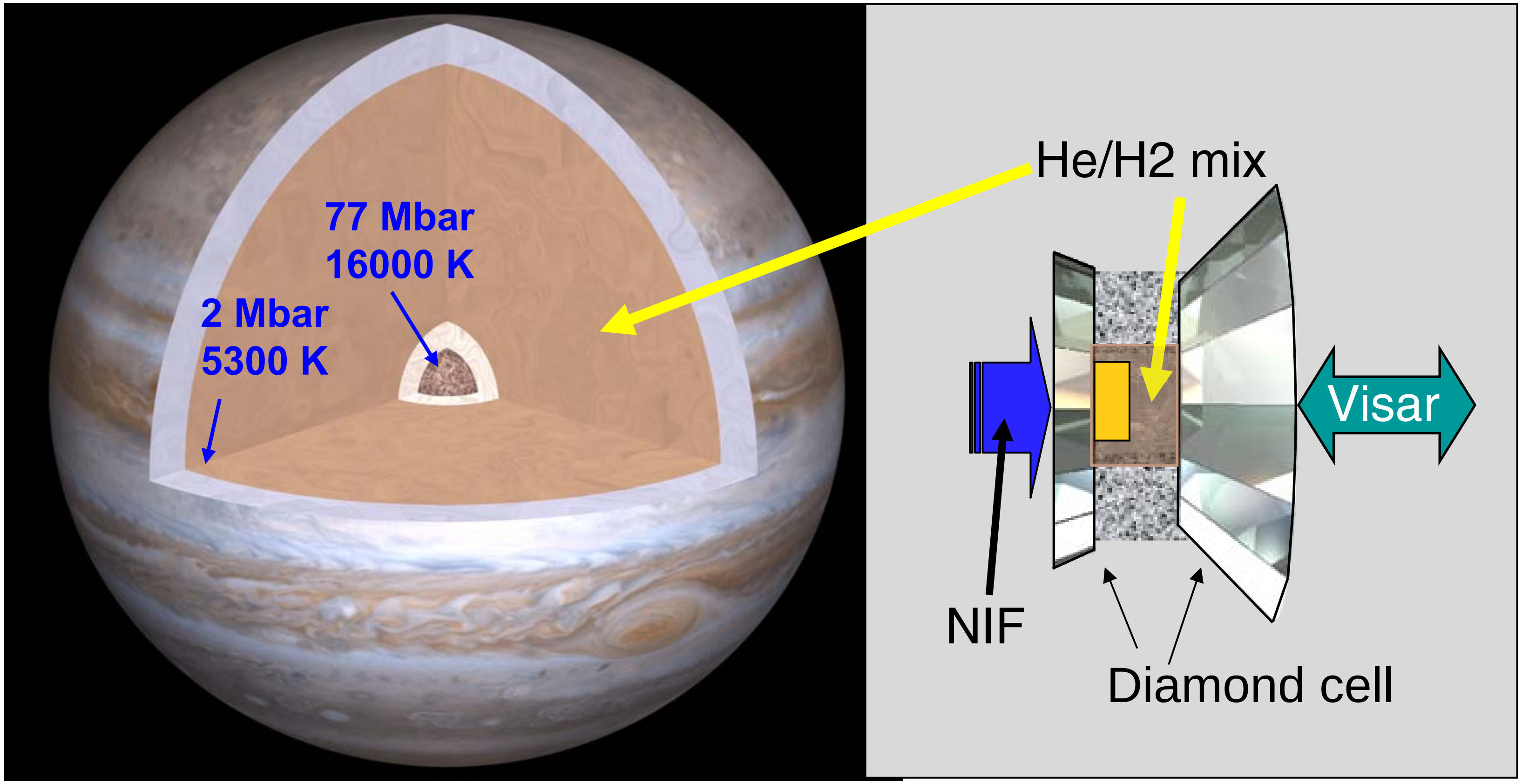
Diffraction



Wave profiles



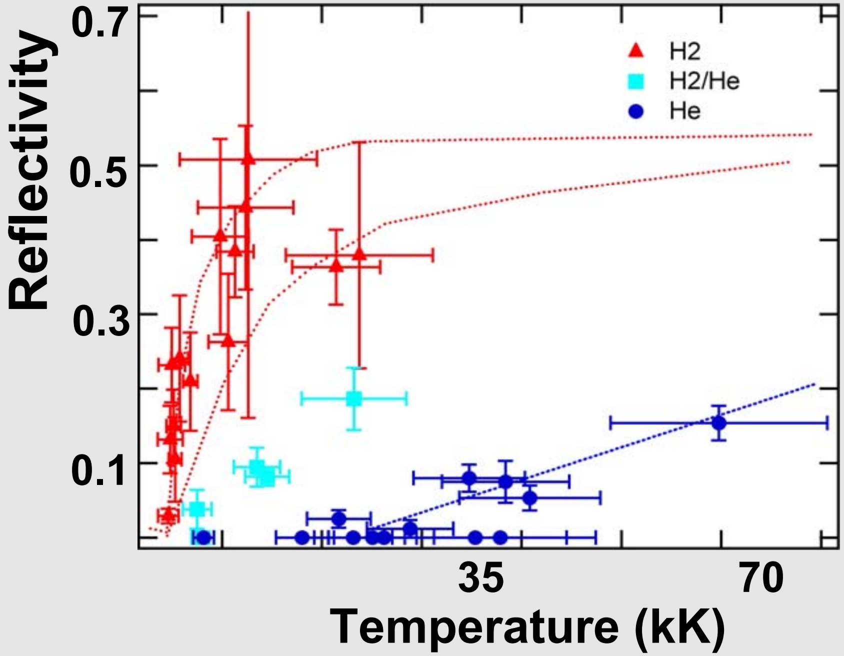
How do we study materials that are significantly more compressible, such as H and He



Use diamond cells to pre-compress H/He
Then use shocks or ramps to compress to many g/cc

He/H2 data give insight to the insulator-conductor transition of the mixture

Reflectivity and T for He/H_2 Mix is Between He and H_2

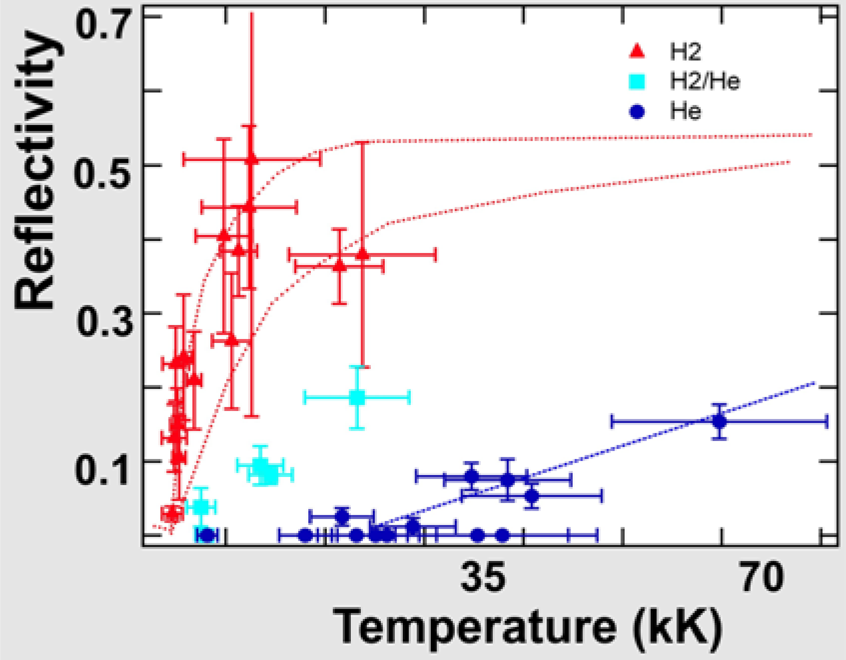


Recent data and theory suggest He/H2 likely miscible at 1 Mbar/30kK

Results comparable to Ternovoi

He/H2 data give insight to the insulator-conductor transition of the mixture

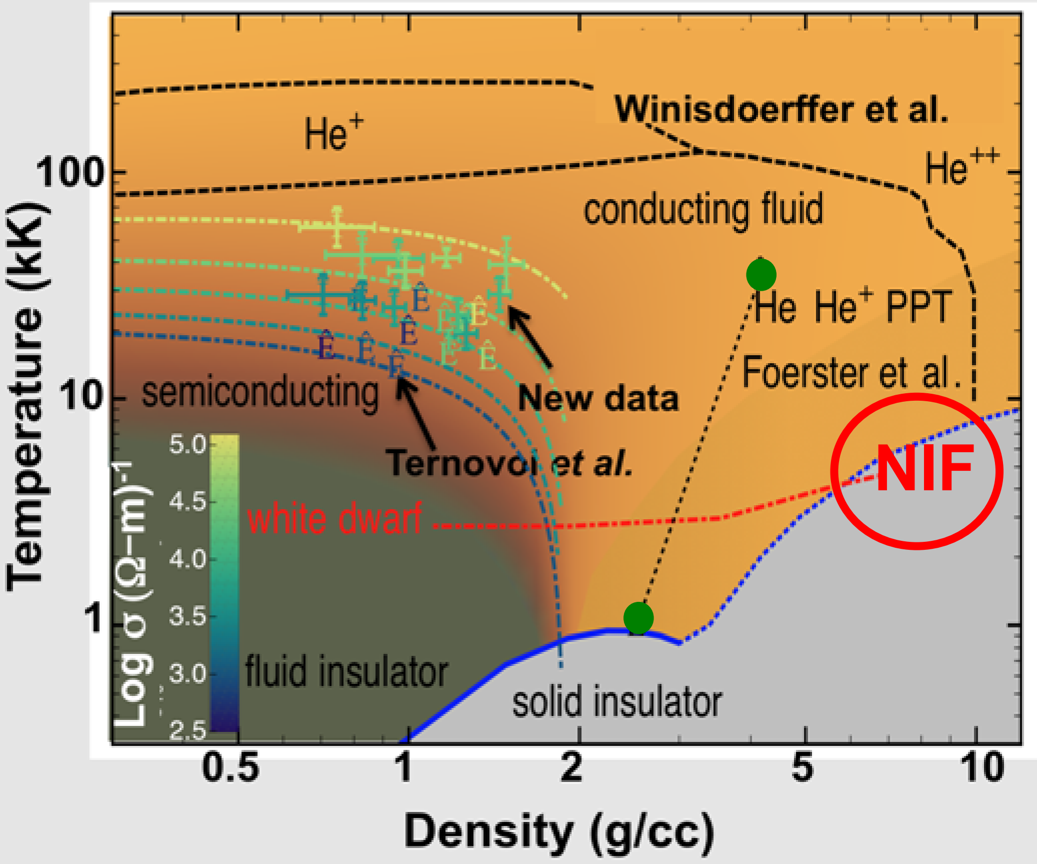
Reflectivity and T for He/H_2 Mix is Between He and H_2



Recent data and theory suggest He/H2 likely miscible at 1 Mbar/30kK

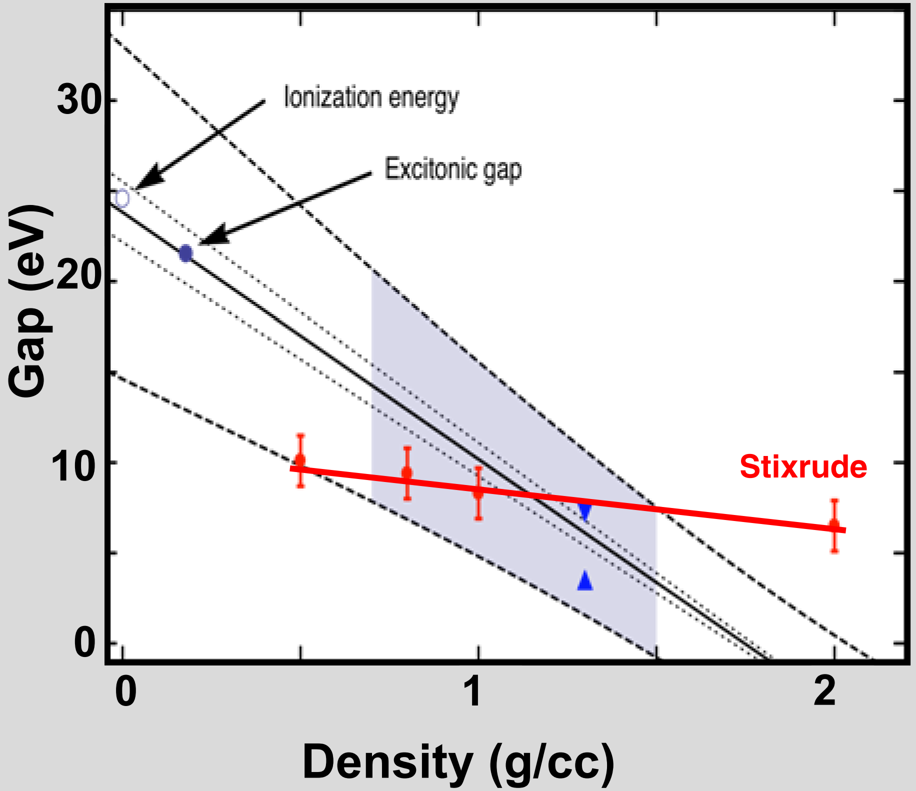
Results comparable to Ternovoi

Conductivity from Drude model fit



Reflectivity data show He becomes conducting near ~1 Mbar, and perhaps a metal at 1.8 g/cc

He bandgap closes near 1.8 g/cc



- Gap appears to have strong density dependence and not dependent on T
- LDA predicts closure at ~14g/cc
- DFT also predicts closure at significantly higher ρ

Celliers, Loubeyre, Brygoo, Eggert, et al

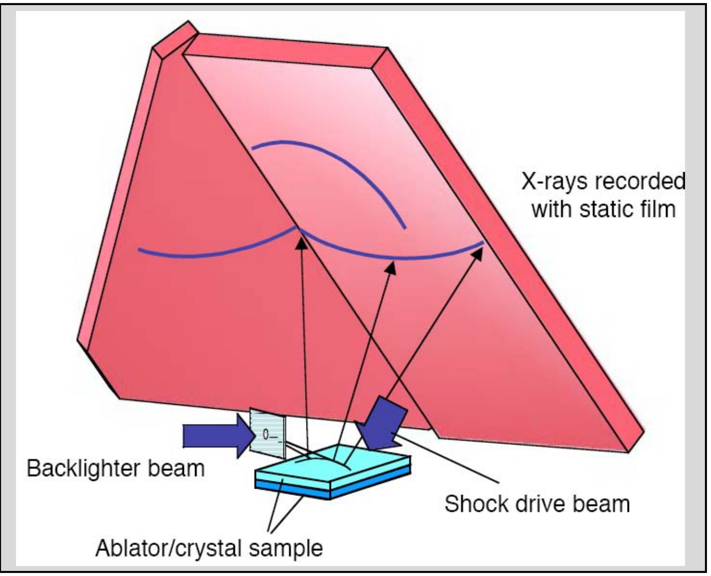
Exploring the matter at the deepest interiors of large planets is filled with surprizes

Starts Oct 2010

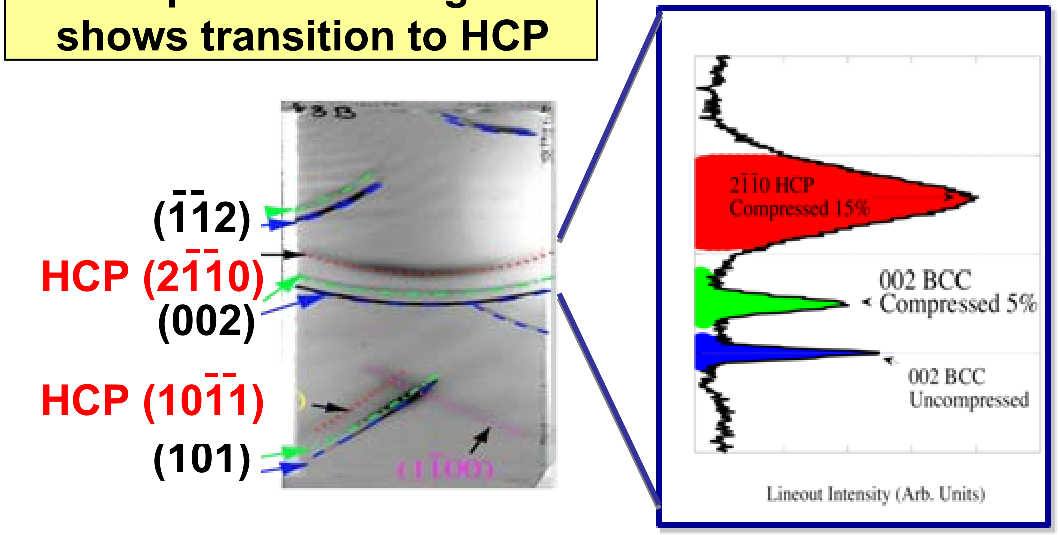
It is difficult to travel to other planets and explore the deep interior

It is a bold new era for exploring matter at extreme conditions

Initial “low pressure” dynamic diffraction on Fe used single crystals=>gave phase, pathway, morphology



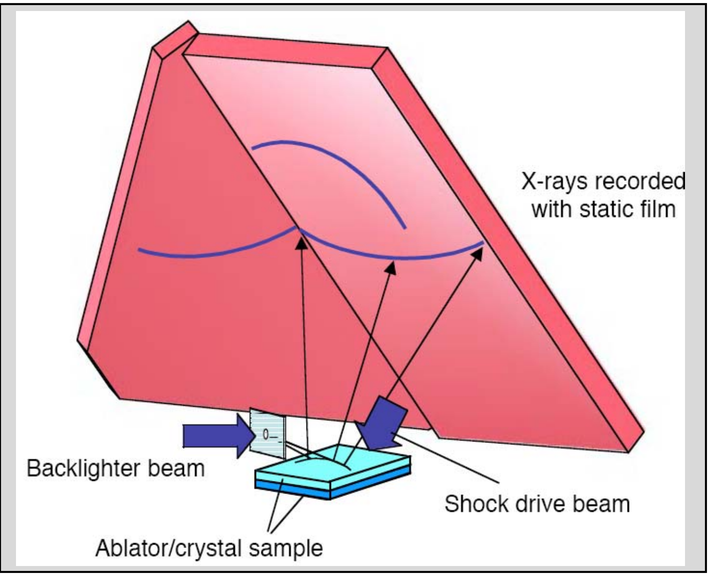
- Compression along 100 shows transition to HCP



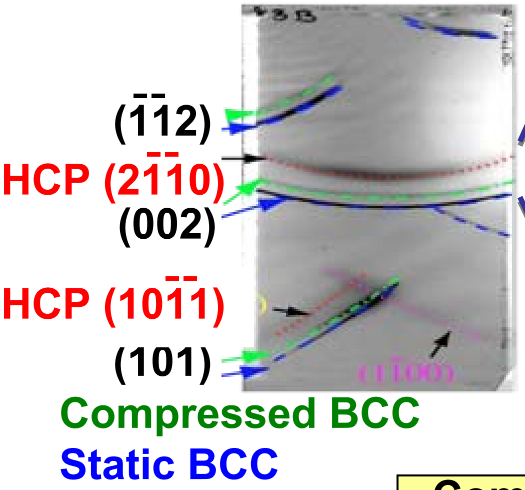
- Recall shock and ramp waves become rough after phase transition

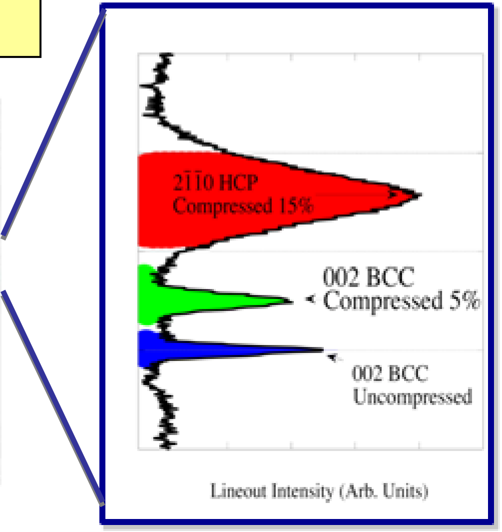
Kalantar, Wark et al., PRL 05
Hawreliak, Wark et al., PRB 06
Hawreliak, et al. PRB 08

Initial “low pressure” dynamic diffraction on Fe used single crystals=>gave phase, pathway, morphology

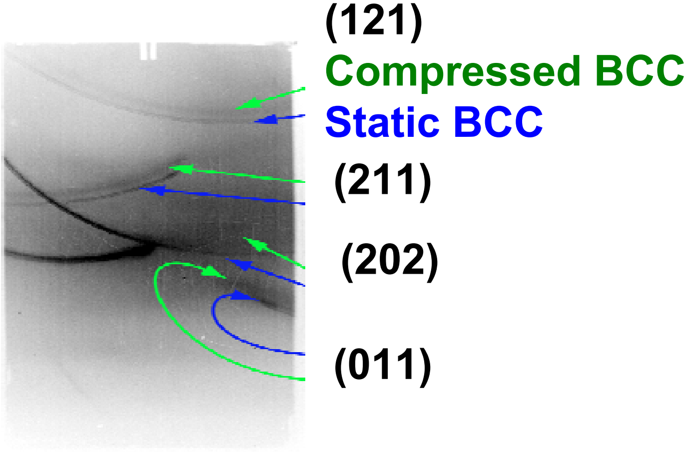


- **Compression along 100 shows transition to HCP**

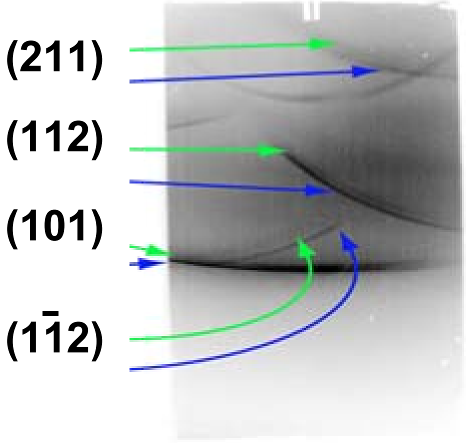




- **Compression along [111] does not show HCP lines**



- **Compression along 110 does not show HCP lines**



Kalantar, Wark et al., PRL 05
Hawreliak, Wark et al., PRB 06
Hawreliak, et al. PRB 08