LLNL-CONF-443151

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Reaching for the Stars: Dynamic Extreme-Compression Experiments

J. H. Eggert

July 19, 2010

COMPRES: #2010 Annual Meeting
Stevenson, WA, United States
June 22, 2010 through June 25, 2010

Reaching for the Stars: Dynamic Extreme-Compression Experiments

COMPRES
2010 Annual Meeting

Skamania Lodge
Stevenson, WA

June 23, 2010

Jon Eggert

Acknowlegments: Ray Smith, Ryan Rygg, Jim Hawreliak, Dylan Spaulding, Peter Celliers, David Bradley, Dave Braun, Gilbert Collins, Tom Duffy, Raymond Jeanloz, Stuart McWilliams, Tom Boehly, Dayne Fratanduano, . . .

Prepared by LLNL under Contract DE-AC52-07NA27344.

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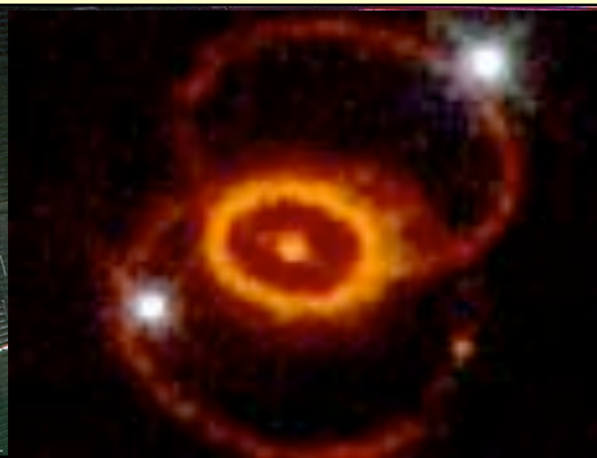
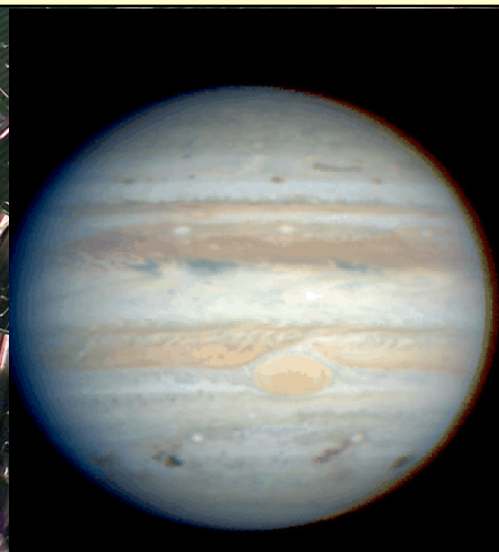
The National Ignition Facility (NIF) will access unprecedented energy densities

NIF will create ≥10^{33} neutrons per cm^2 per second, equivalent to a supernova

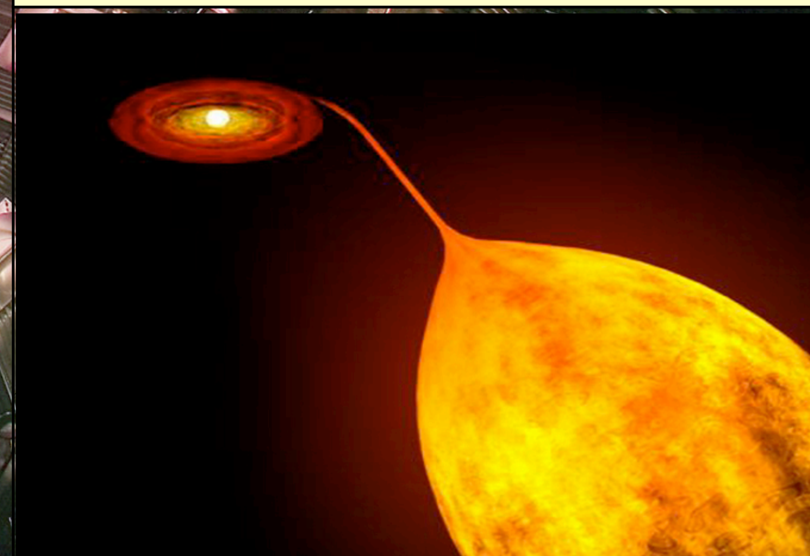


NIF will create thermal plasmas at the conditions of stellar interiors

NIF generates pressures found at the center of Jupiter



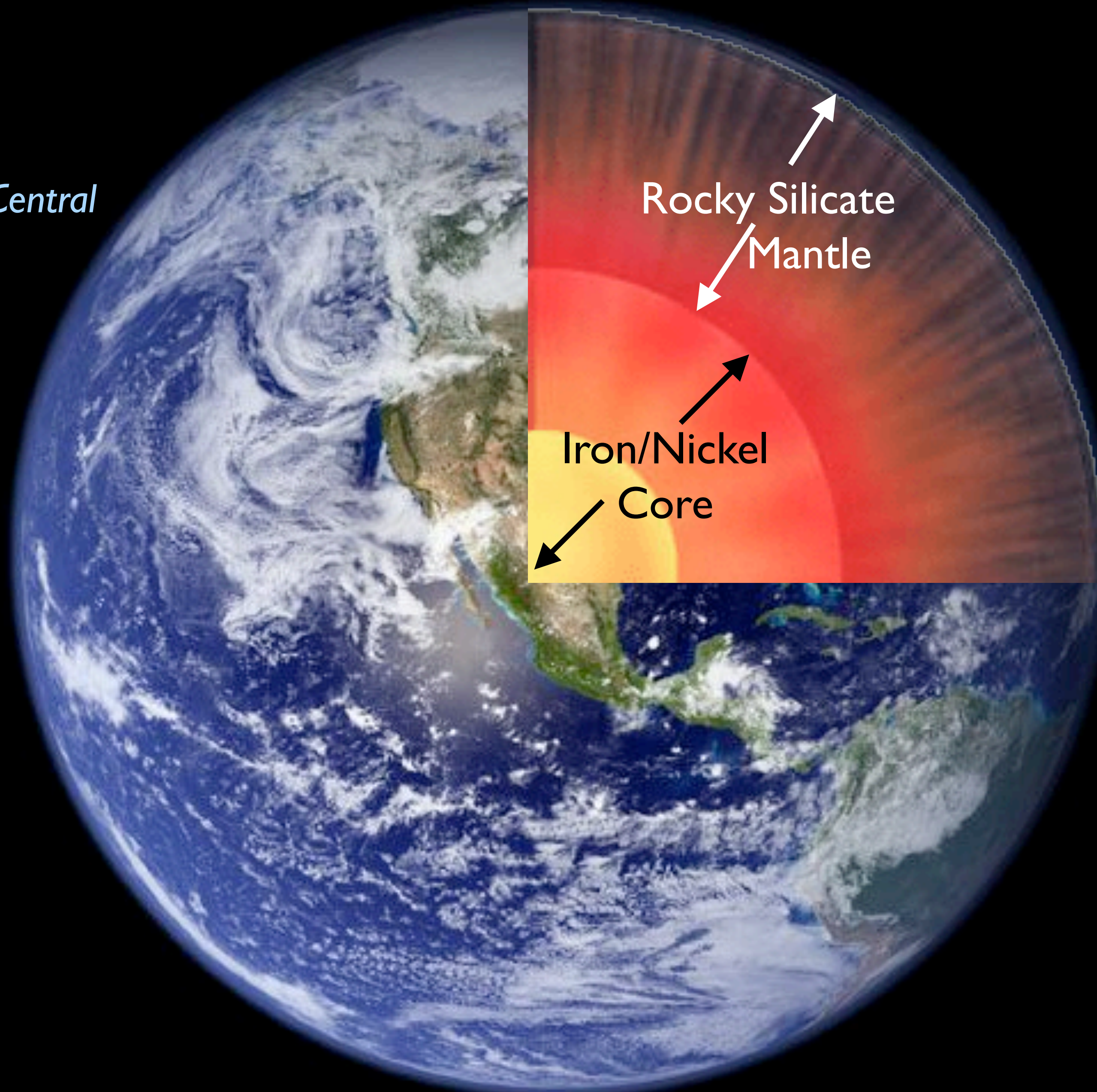
NIF will produce enough x-ray flux to simulate conditions in an accretion disk



NIF-0506-12157
22EIM/sb

Matter at very extreme conditions is common in the universe

Central Pressure: 3.6 Mbar *Central Temperature:* 6000 K



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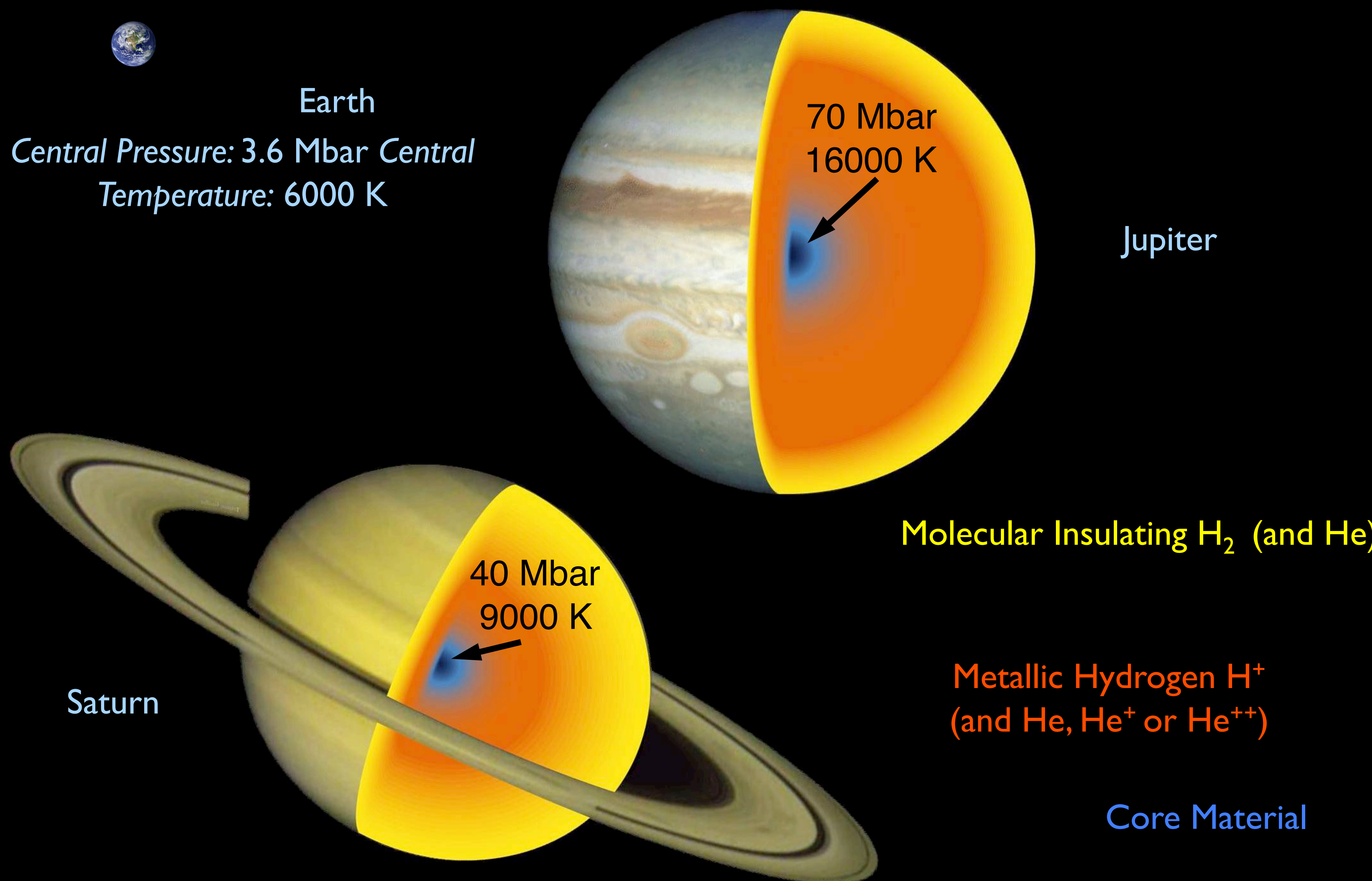
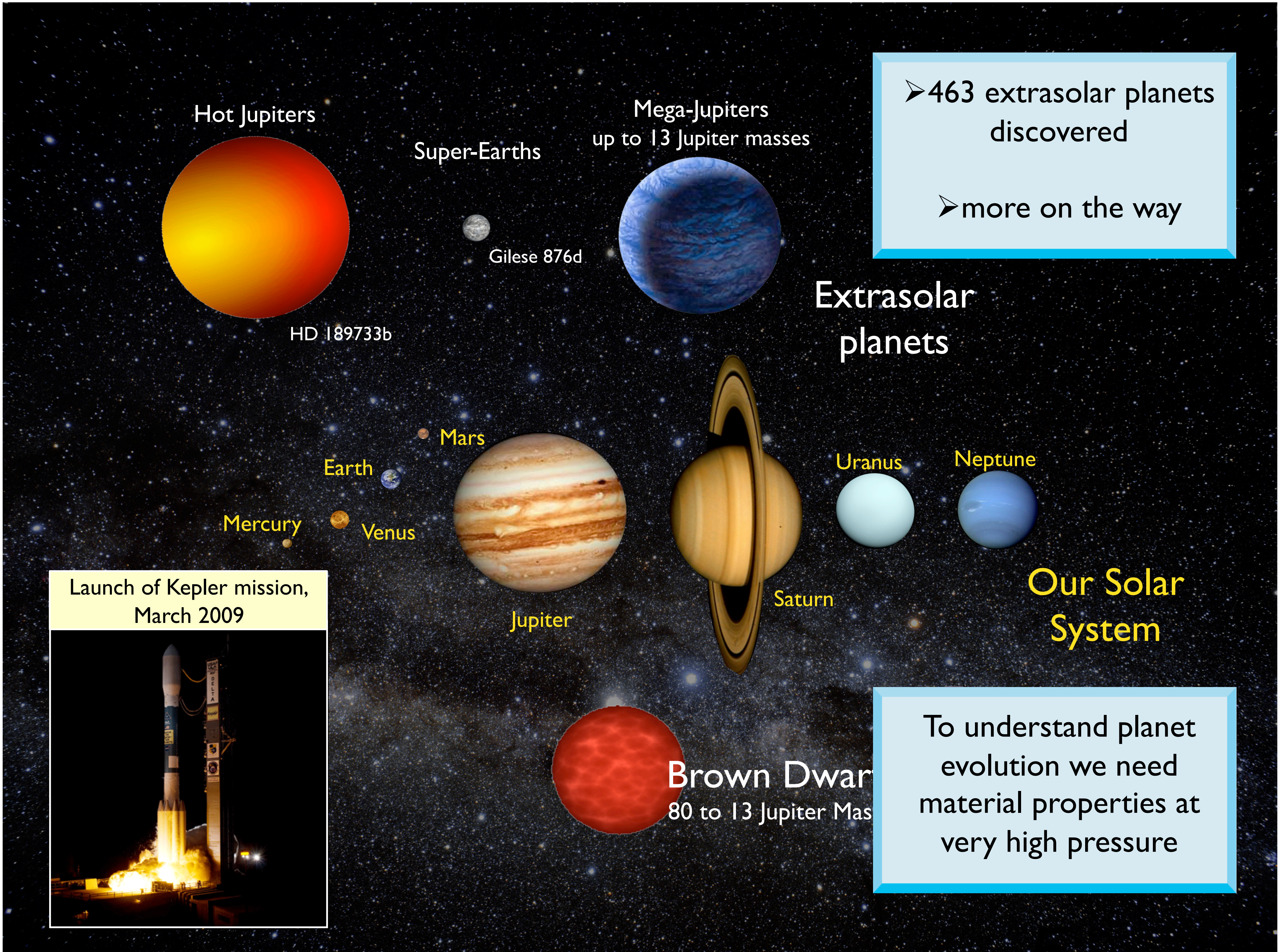
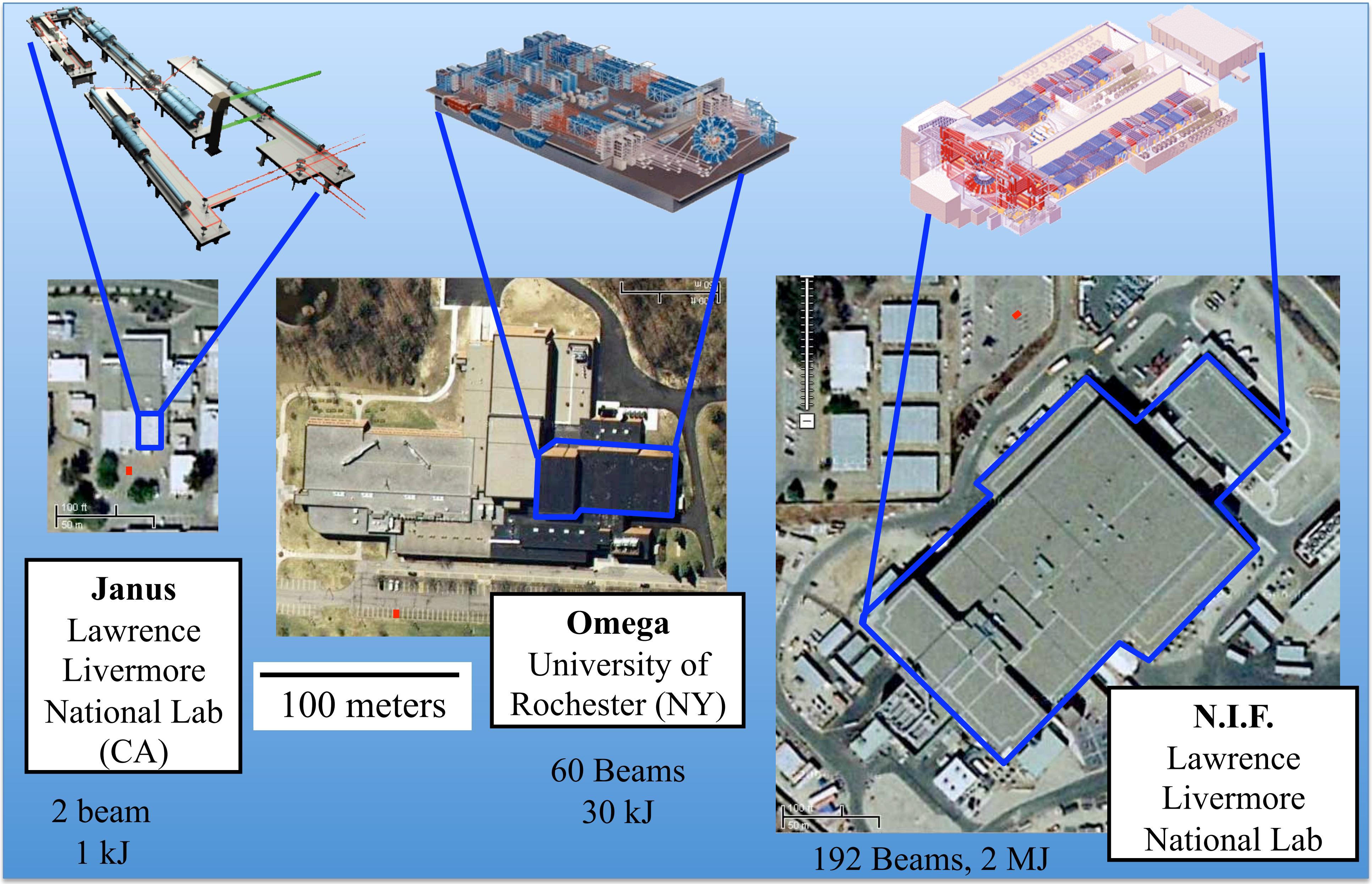



Hot Jupiters
HD 189733b
Super-Earths
Gilese 876d
Mega-Jupiters
up to 13 Jupiter masses
➢463 extrasolar planets discovered
➢more on the way
Extrasolar planets
Mars
Earth
Mercury
Venus
Jupiter
Saturn
Uranus
Neptune
Our Solar System
Launch of Kepler mission, March 2009
Brown Dwar
80 to 13 Jupiter Mas
To understand planet evolution we need material properties at very high pressure

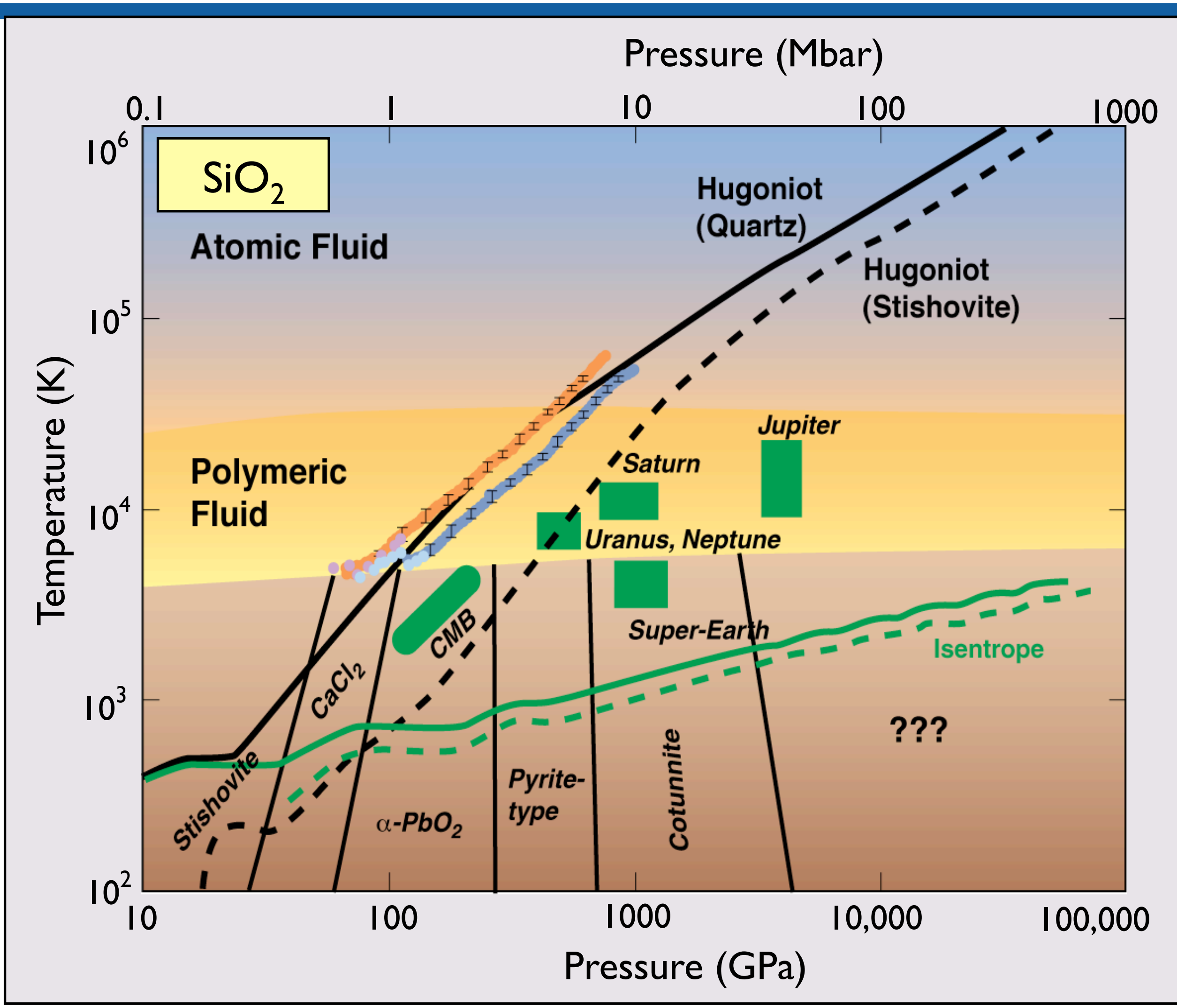
Outline

- ***Approaching Solids at TPa Pressures***
- Introduction
- Ramp-Compression EOS
  - Cold Sample
  - Absolute Stress-Strain
- X-ray Diffraction
  - Far Above Shock Melting on Hugoniot
  - Still Solid
- Optical Measurements
  - Refractive Index and Transparent Window to 800 GPa

Laser Facilities

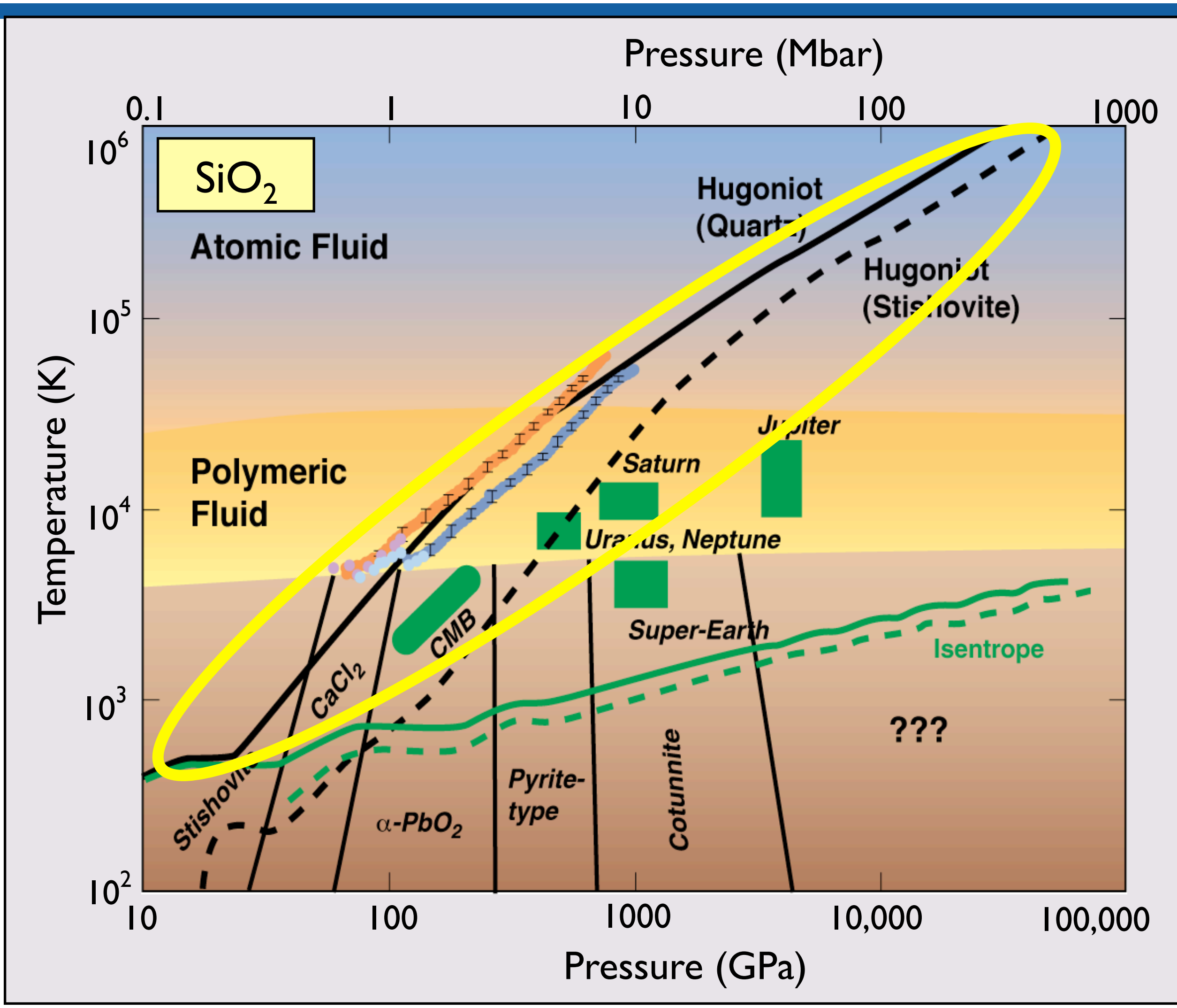


Dynamic compression is used to explore how matter behaves at extreme conditions



Hicks, 2006

Shocks generate very high temperatures



Hicks, 2006

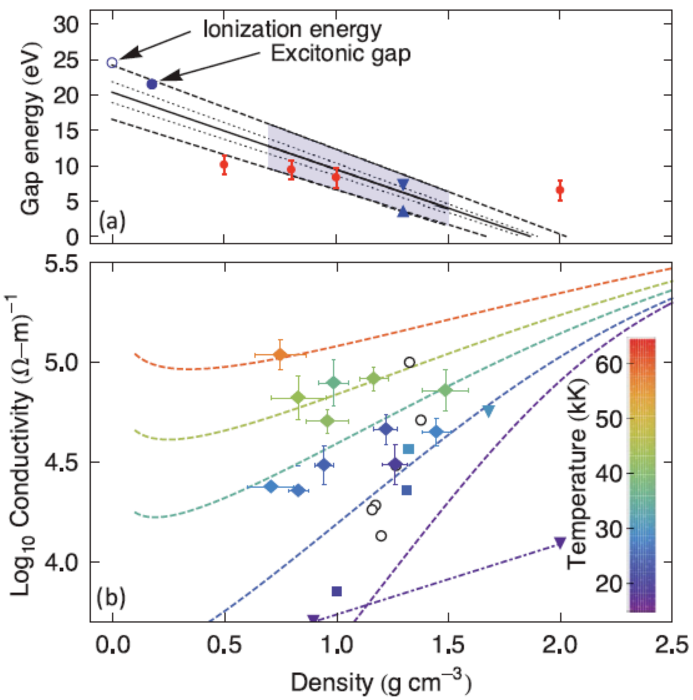
Shocks

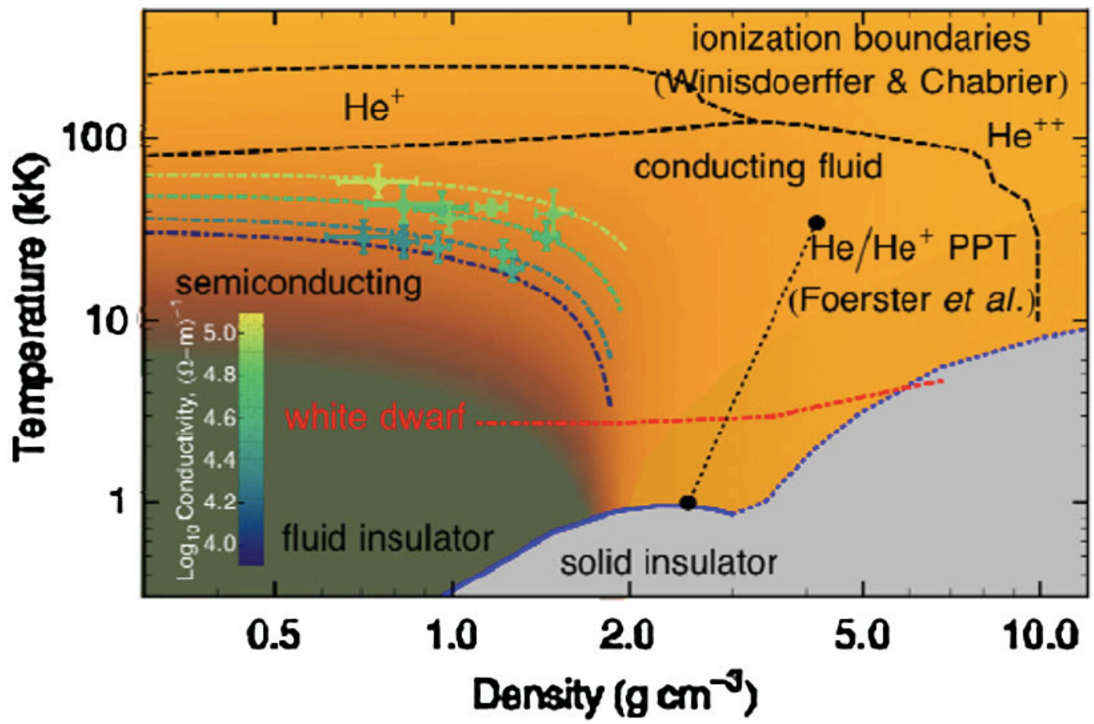
Bullet

PRL 104, 184503 (2010) PHYSICAL REVIEW LETTERS week ending 7 MAY 2010

Insulator-to-Conducting Transition in Dense Fluid Helium

P. M. Celliers,[1] P. Loubeyre,[2] J. H. Eggert,[1] S. Brygoo,[2] R. S. McWilliams,[3,5] D. G. Hicks,[1] T. R. Boehly,[4] R. Jeanloz,[5] and G. W. Collins[1]



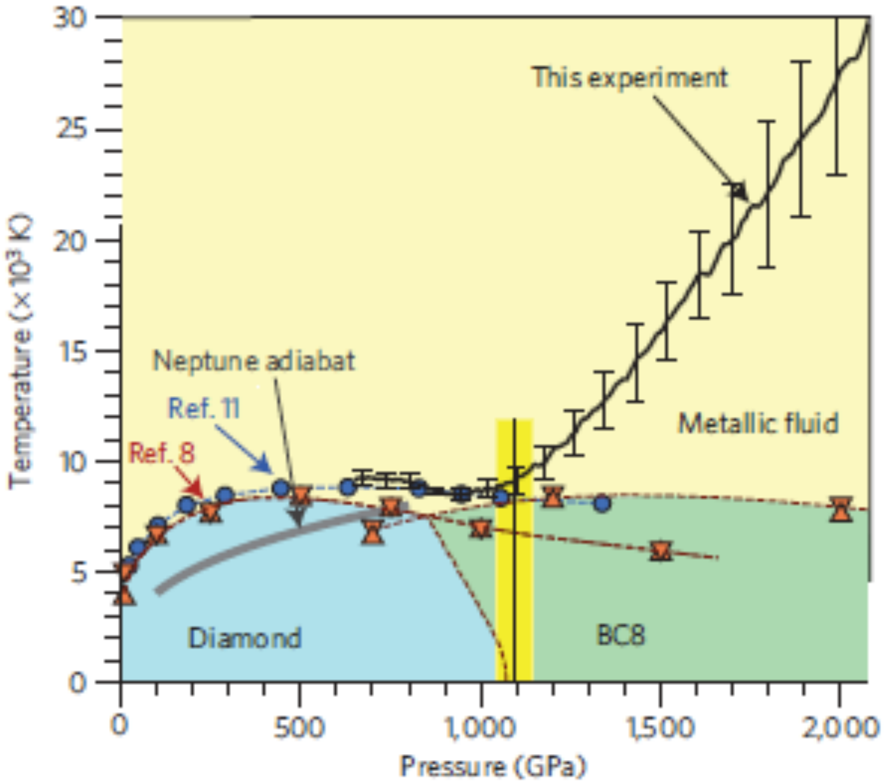


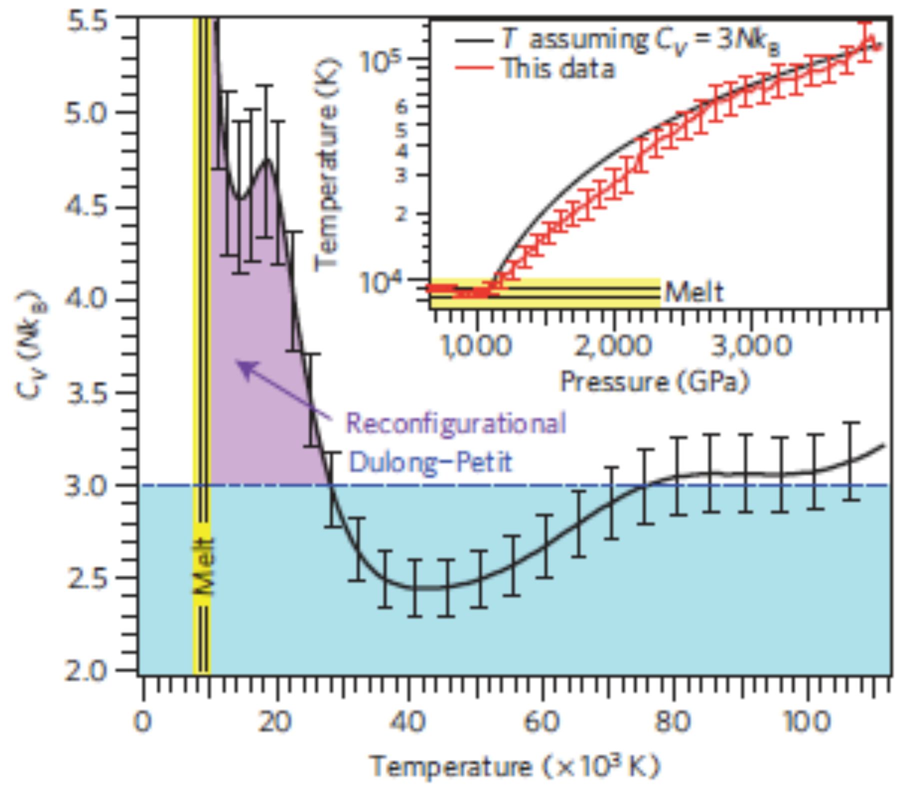
LETTERS
PUBLISHED ONLINE: 8 NOVEMBER 2009 | DOI:10.1038/NPHYS1438

nature physics

Melting temperature of diamond at ultrahigh pressure

J. H. Eggert[1]*, D. G. Hicks[1], P. M. Celliers[1], D. K. Bradley[1], R. S. McWilliams[1,2], R. Jeanloz[2], J. E. Miller[3], T. R. Boehly[3] and G. W. Collins[1]



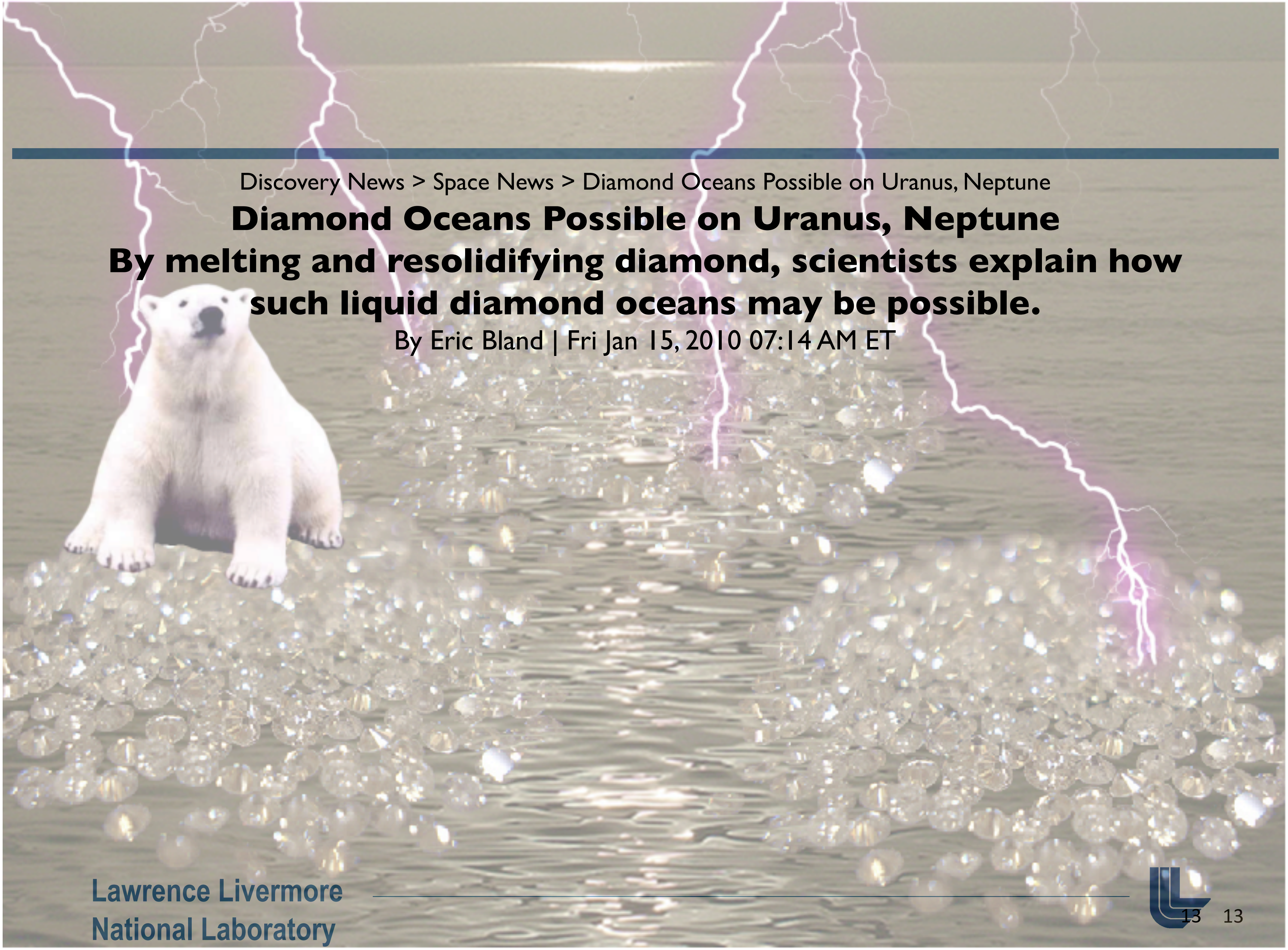


Discovery News > Space News > Diamond Oceans Possible on Uranus, Neptune

Diamond Oceans Possible on Uranus, Neptune

By melting and resolidifying diamond, scientists explain how such liquid diamond oceans may be possible.

By Eric Bland | Fri Jan 15, 2010 07:14 AM ET



Discovery News > Space News > Diamond Oceans Possible on Uranus, Neptune

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By Eric Bland | Fri Jan 15, 2010 07:14 AM ET

Oceans of diamond possible on Uranus and Neptune

DR EMILY BALDWIN, ASTRONOMY NOW

Posted: 21 January 2010

'Oceans of diamonds' on Uranus and Neptune

Telegraph.co.uk


Uzayda Elmas Okyanusları Var
Yeni bir araştırmaya göre Uranüs ve Neptün
olabilir.
Bilim insanları yeni bir
üzerinde 'elmas
e elmas okyanusları
Uranüs ve Neptün gezegenleri
eğini ortaya koydu.
Diamond
By melting and resolidifying
such liquid
may be pos
07:14 AM ET
Planètes au cœur de diamant
CIEL & ESPACE
Tähdet ja avaruus
POHJOISMAIDEN SUURIN TÄHTITIEDELEHTI
Laboratoriossa rakentui hyppysellinen Neptunuksen sisustaa
Jääjättiläisten sisuksissa timanttikin sulaa
Neptune
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יהלומים בחדשות > חדשות היהלומים > בעולם
חדשות היהלומים
מחקר: סבירות גבוהה להימצאות יהלומים בנפטון
בעולם / 11:16 ,19.01.10
Lawrence
National Lab
15 15


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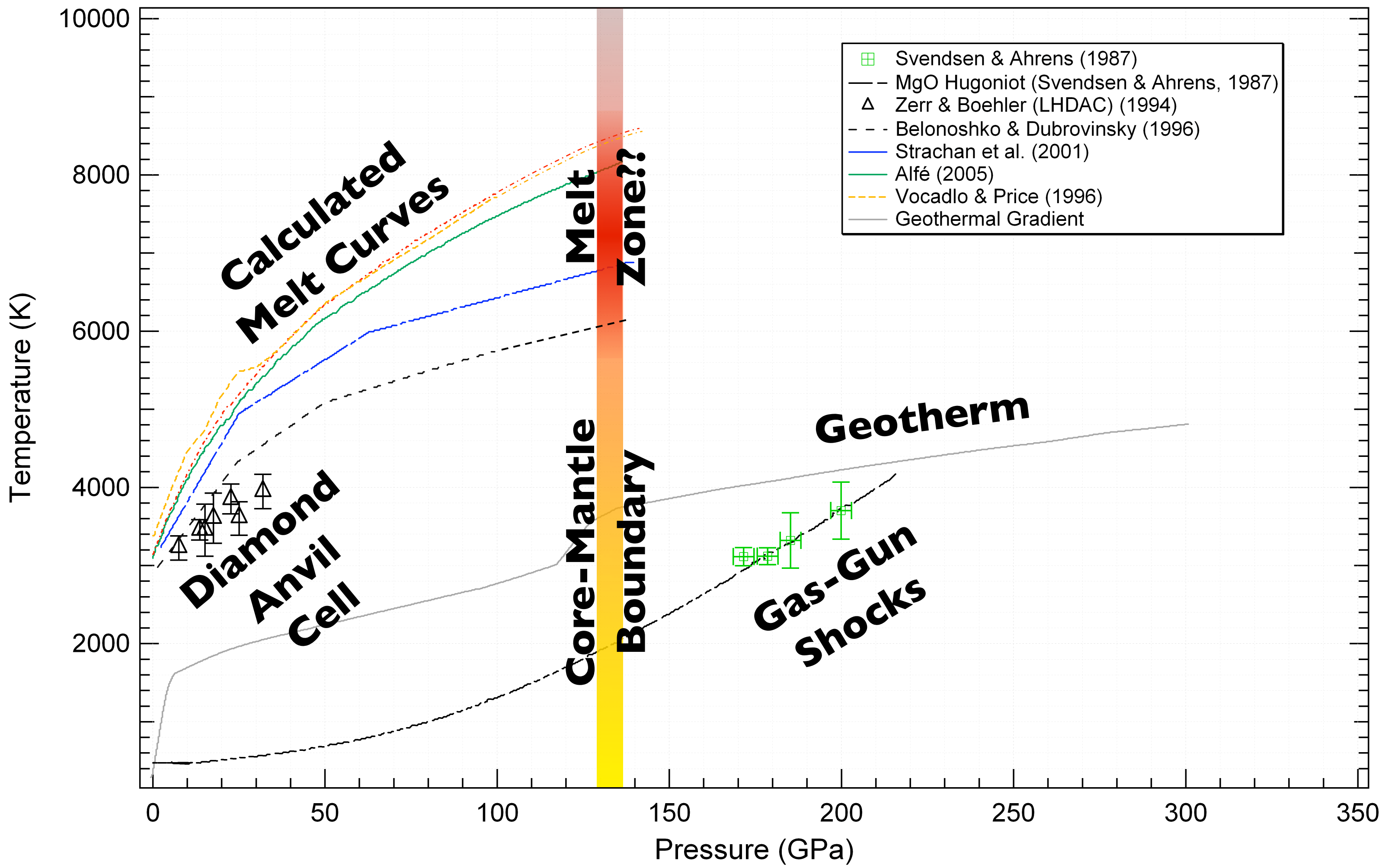
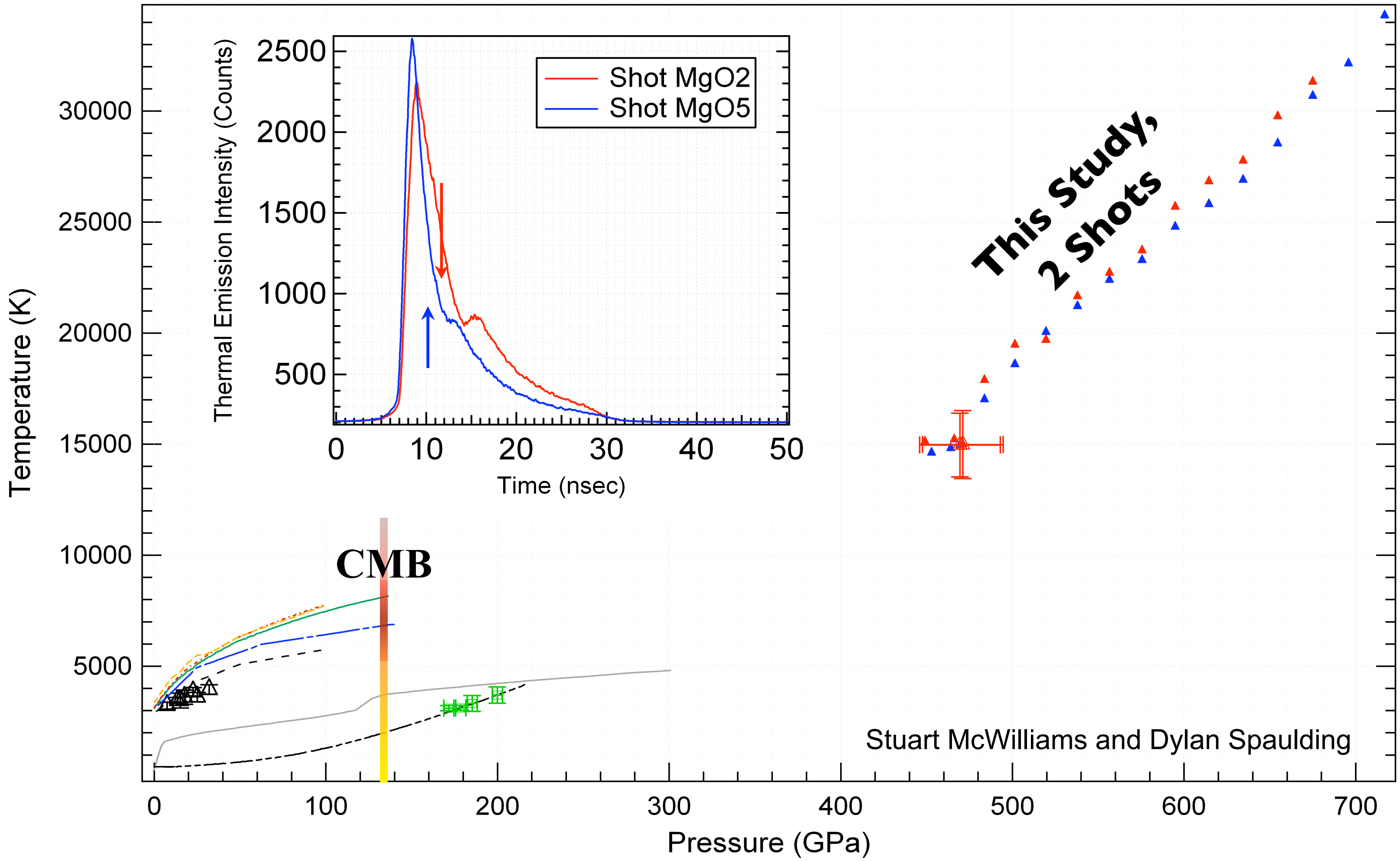
cœur de diamant
Diamond
By melting and resolidifying
such liquid
may be pos
Science Finally Serves Purpose,
Discovers Oceans of Diamonds
By Michael Jordan January 22, 2010
Laboratorio
rakentui hyppy
Neptunuksen sisusta
Jääjättiläisten sisuksissa timanttikin sulaa
.co.uk
חדשות היהלומים
יהלומים בחדשות
מחקר: סבירות גבוהה להימצאות יהלומים
בעולם / 11:16 ,19.01.10
Lawrence
National Lab

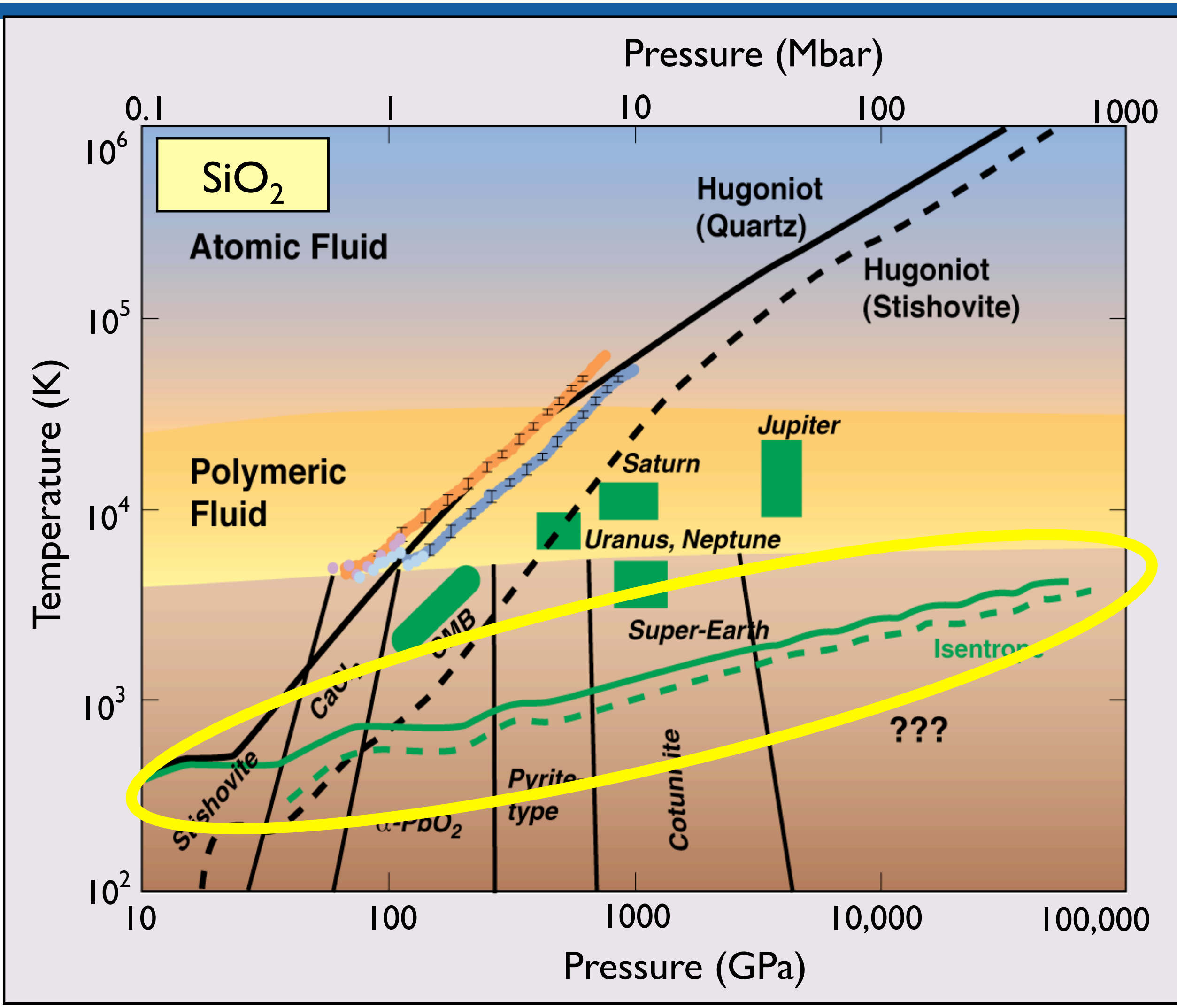
Constraining High-Pressure Melting of MgO



Constraining High-Pressure Melting of MgO

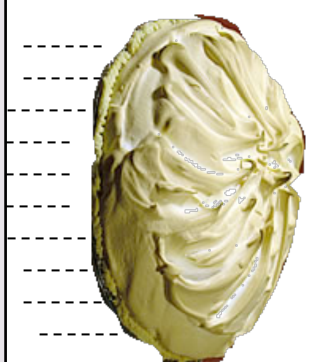


Ramp compression can lower the temperature dramatically



Ramps

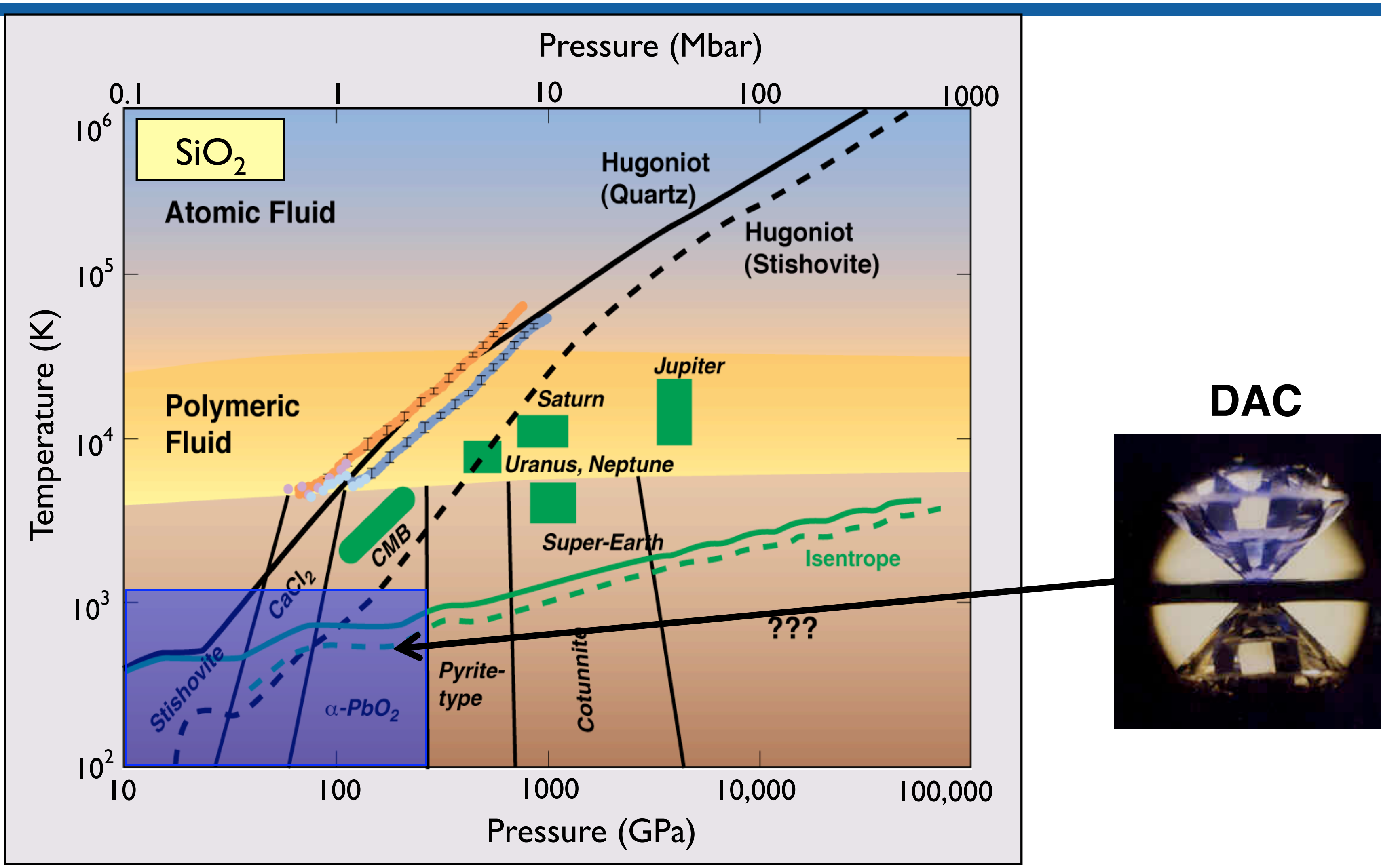
Cream pie



Sample

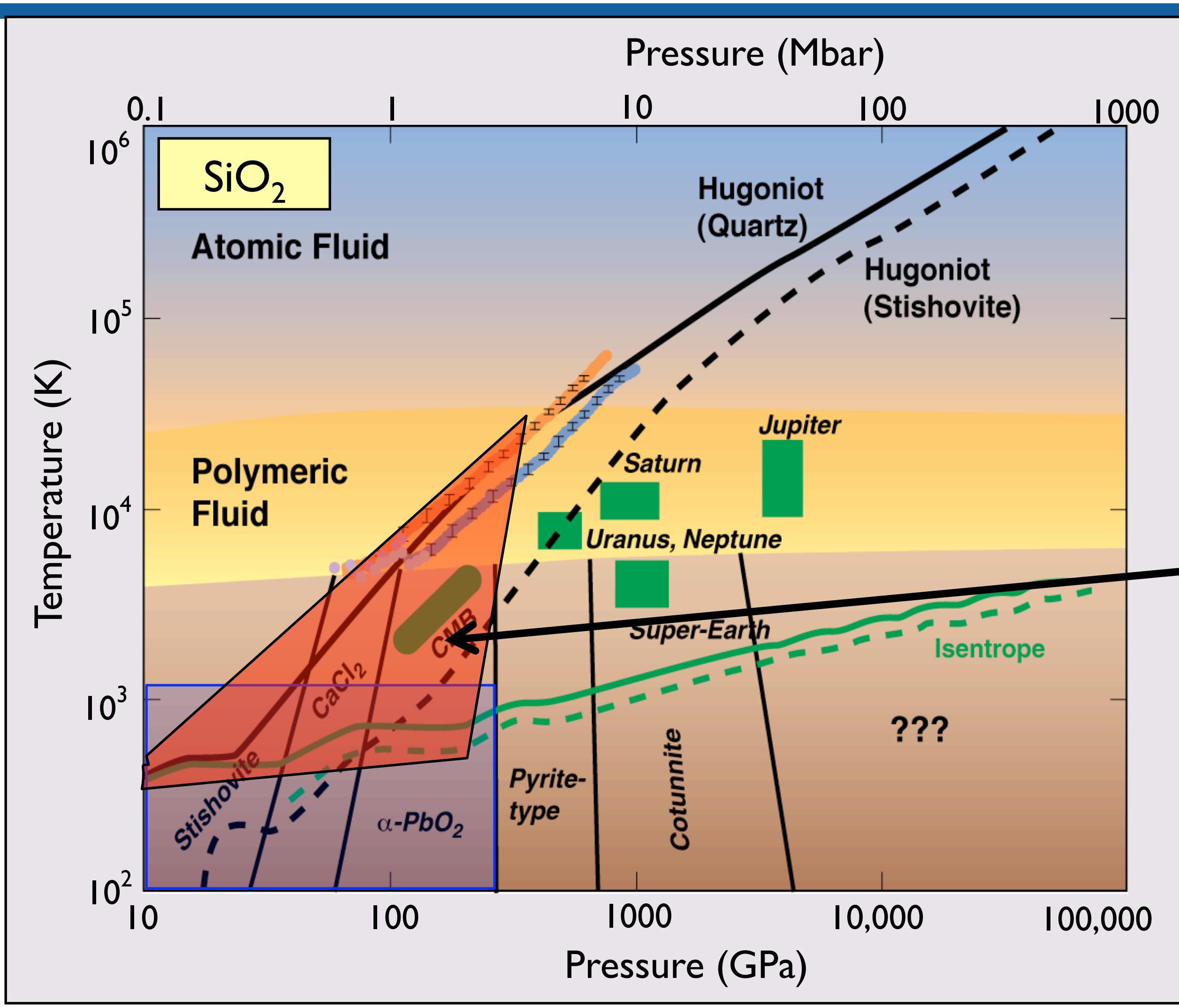
Hicks, 2006

What pressures-temperatures can you achieve with different ramp-compression drivers?

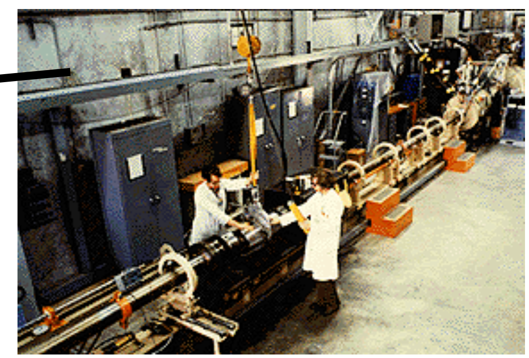


Hicks, 2006

What pressures-temperatures can you achieve with different ramp-compression drivers?



Guns



Hicks, 2006

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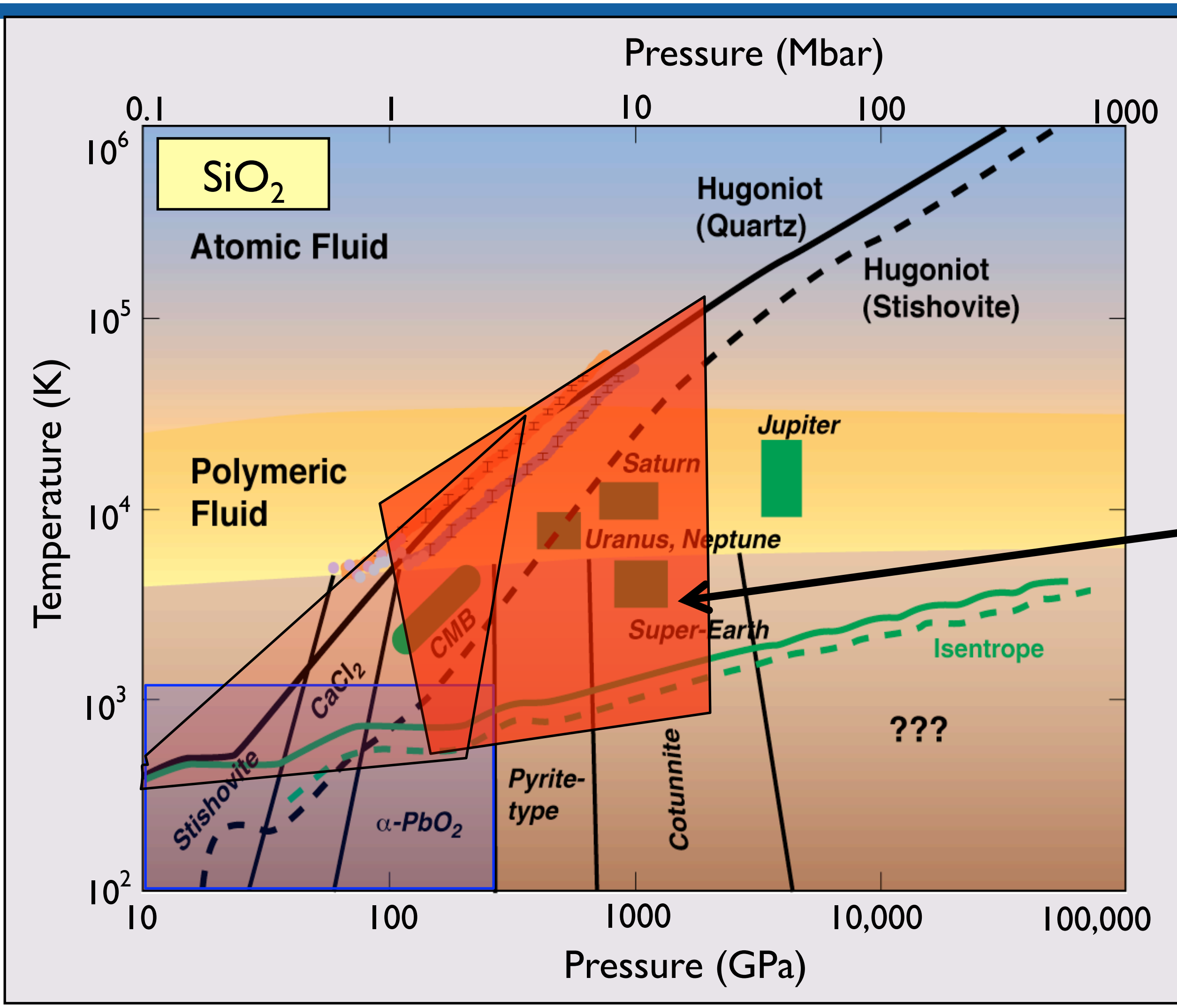
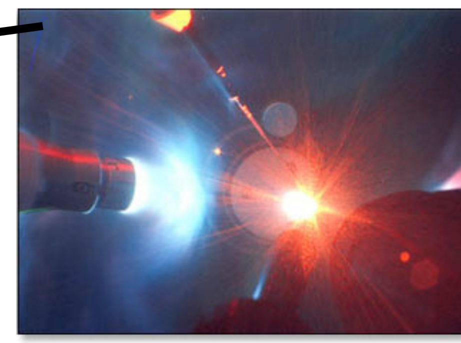


KiloJoule class laser or Z Machine



Hicks, 2006

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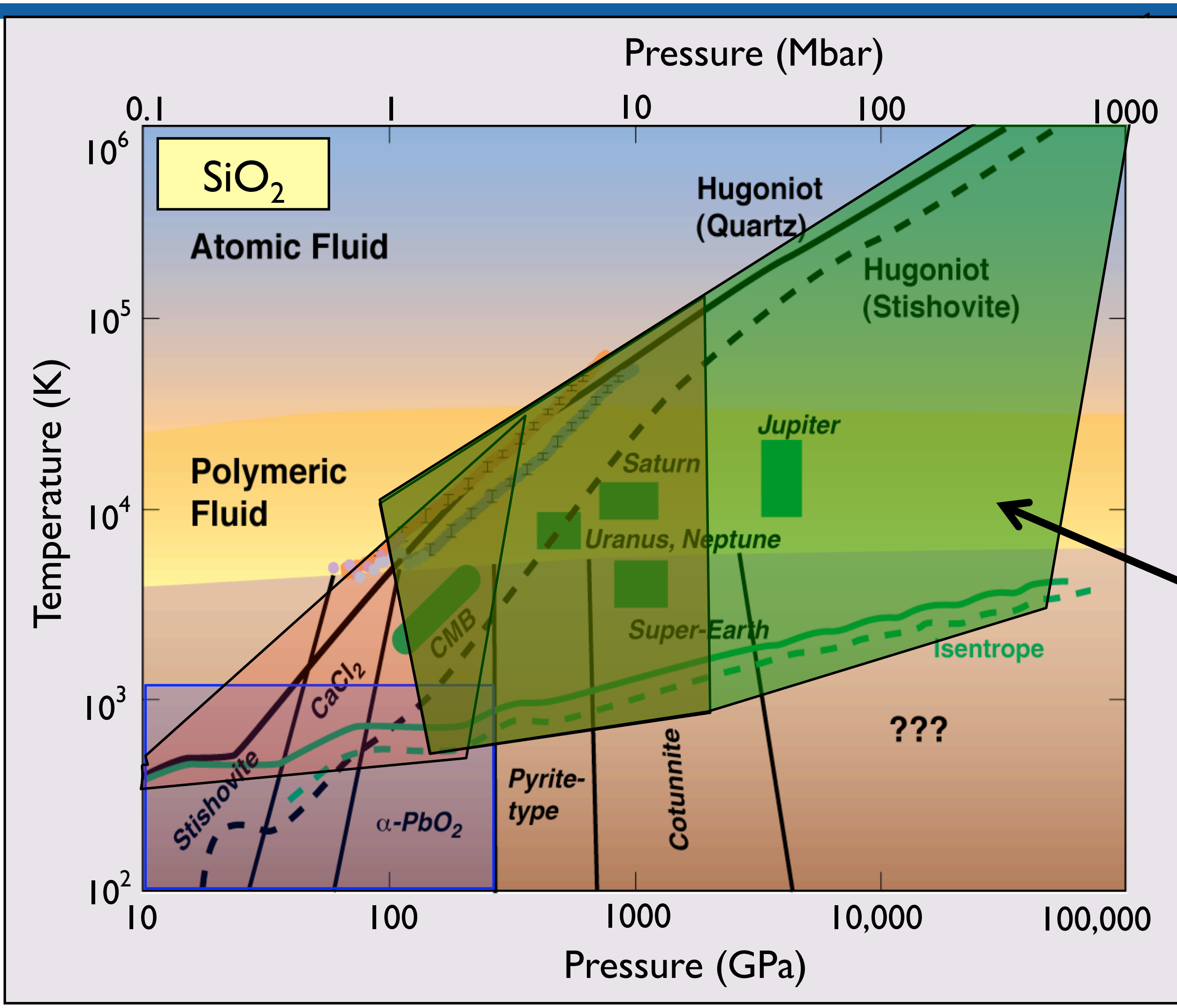
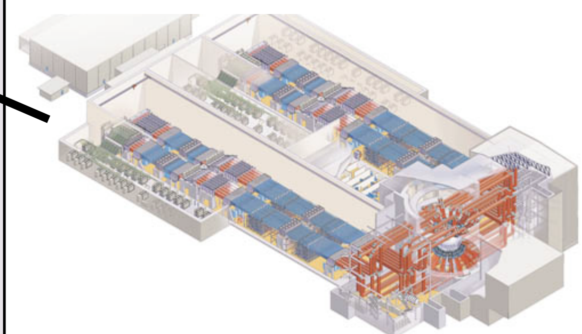


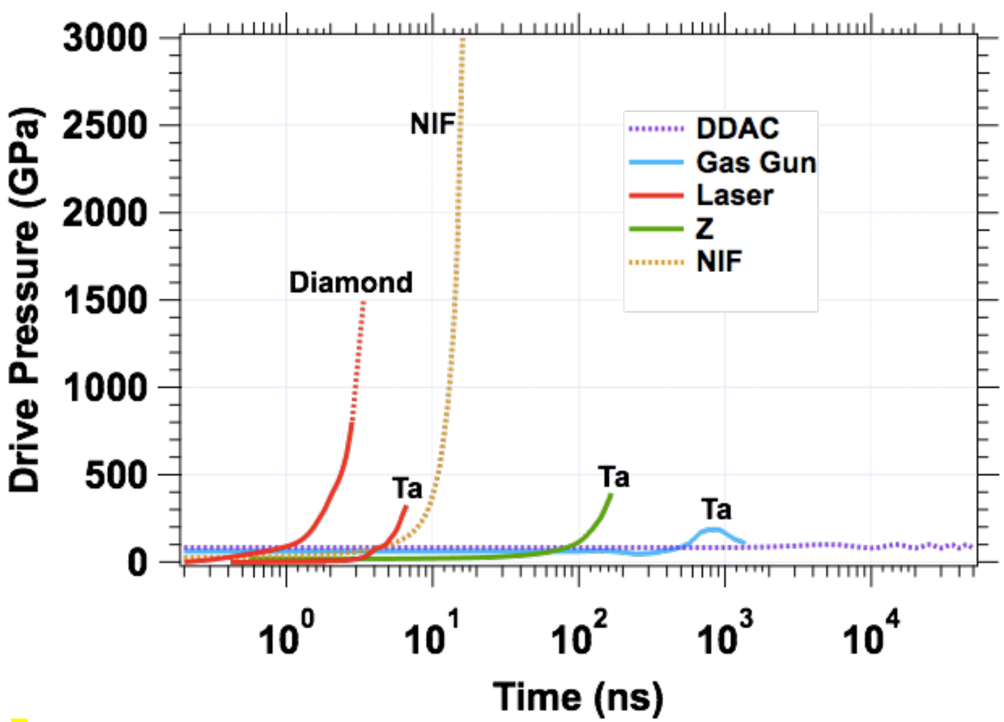
Hicks, 2006

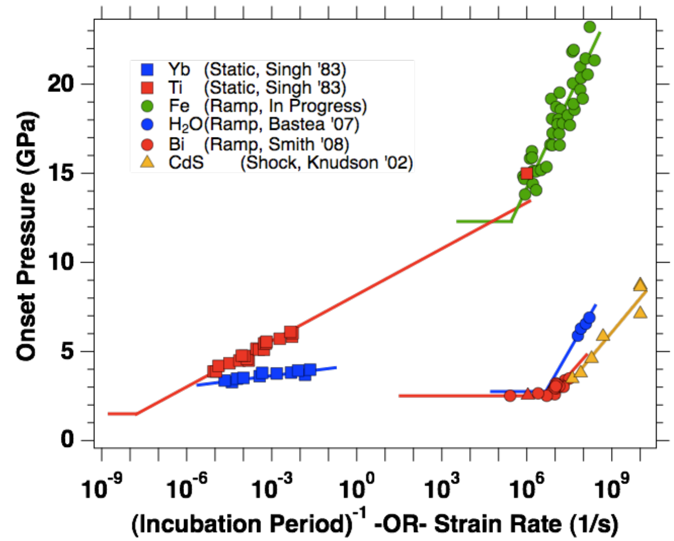
NIF

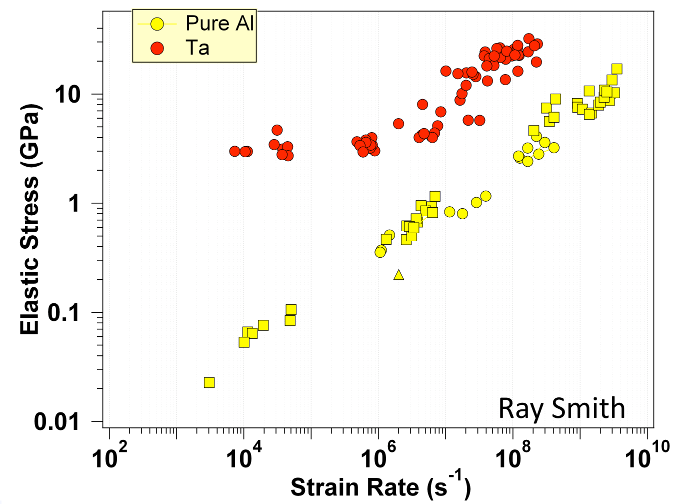


Strain rates vary by orders of magnitude

- Dynamic DAC (DDAC)
- Gas Gun (GDI)
- Pulsed-Power (Z)
- Laser: Shaped Ablation



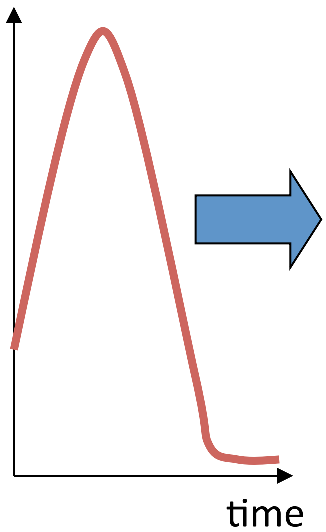


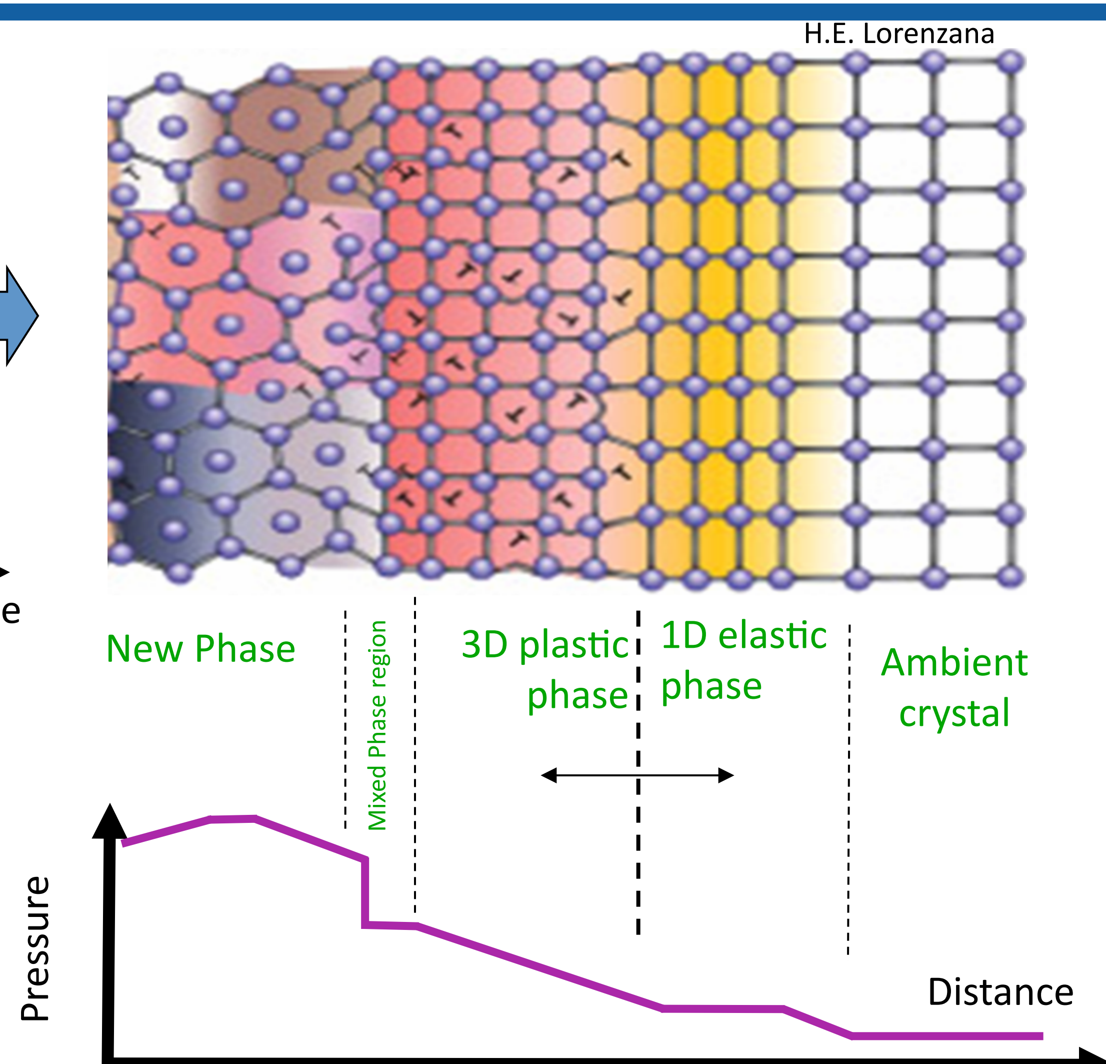


Material properties can change significantly under ramp compression

1

Applied Ramp Pressure

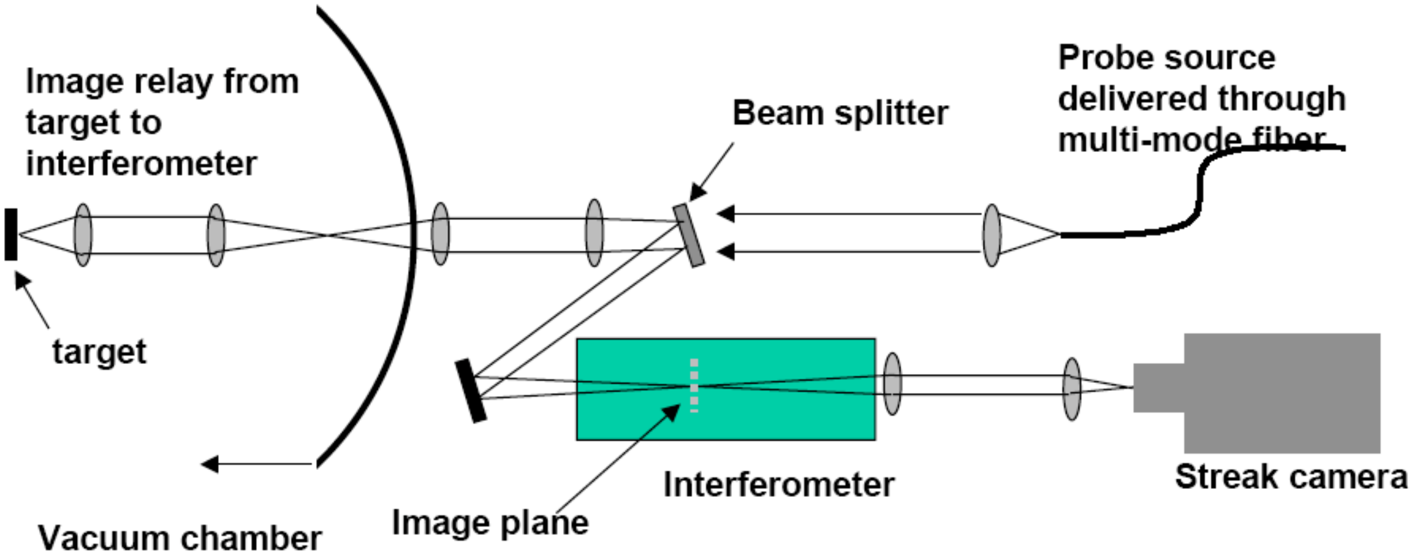


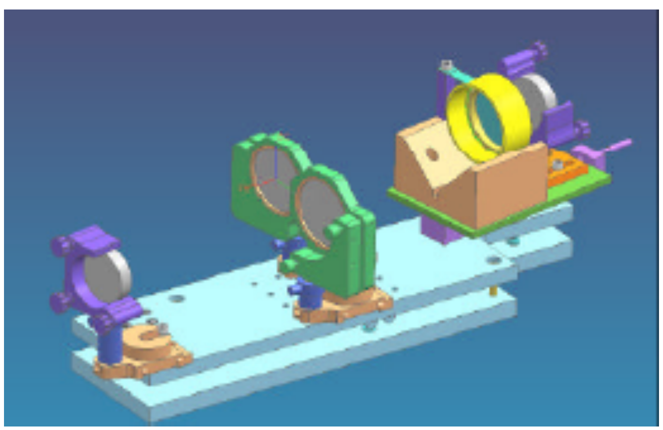


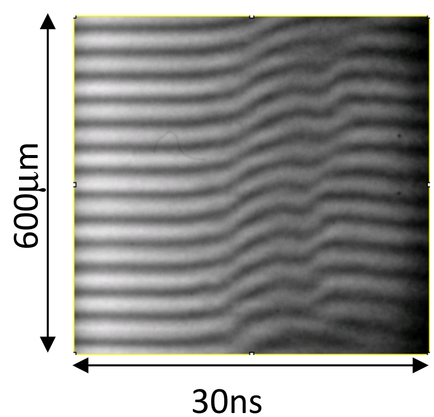
2

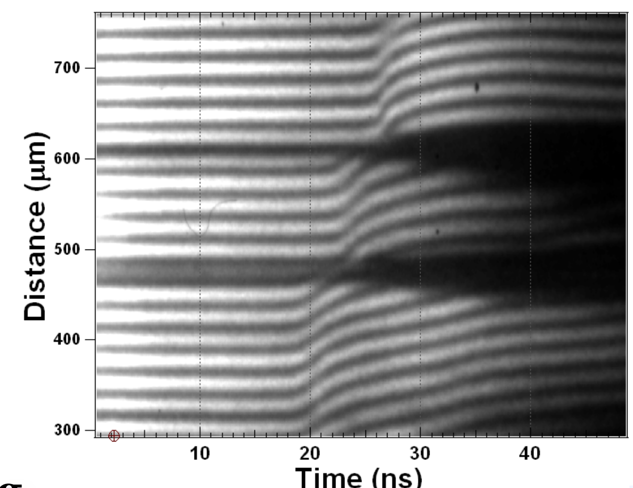
Transmitted profile modified by material properties

VISAR—Velocity Interferometer System for Any Reflector







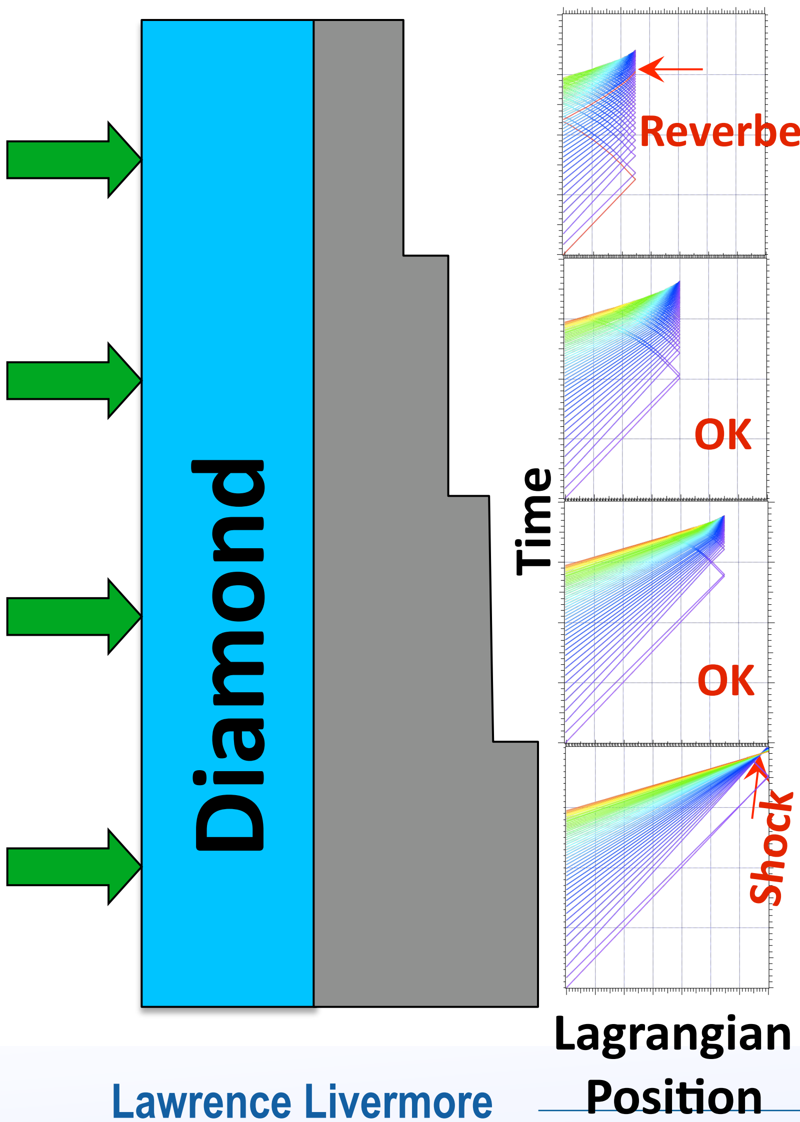


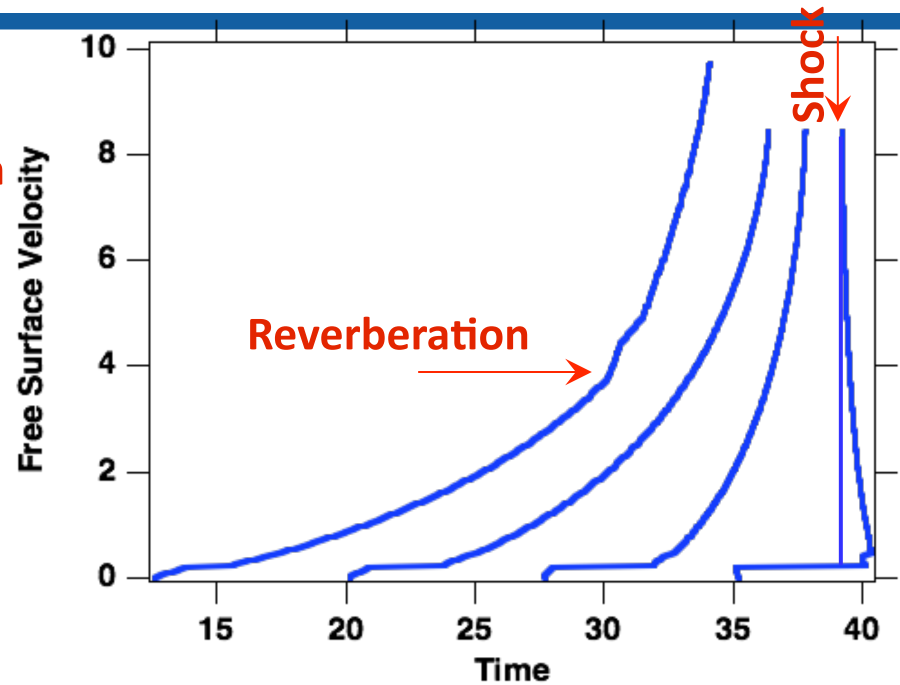
Velocity, Reflectivity, Timing

Absolute Stress Density by Ramp Compression

- **Ramp-Compression EOS on Diamond to 800 GPa**
- **Ramp-Compression EOS on Tantalum to 320 GPa**
- **Estimates of Temperature due to P-V and Plastic-Work Heating.**

Ramp-Wave EOS --Design Requirements--



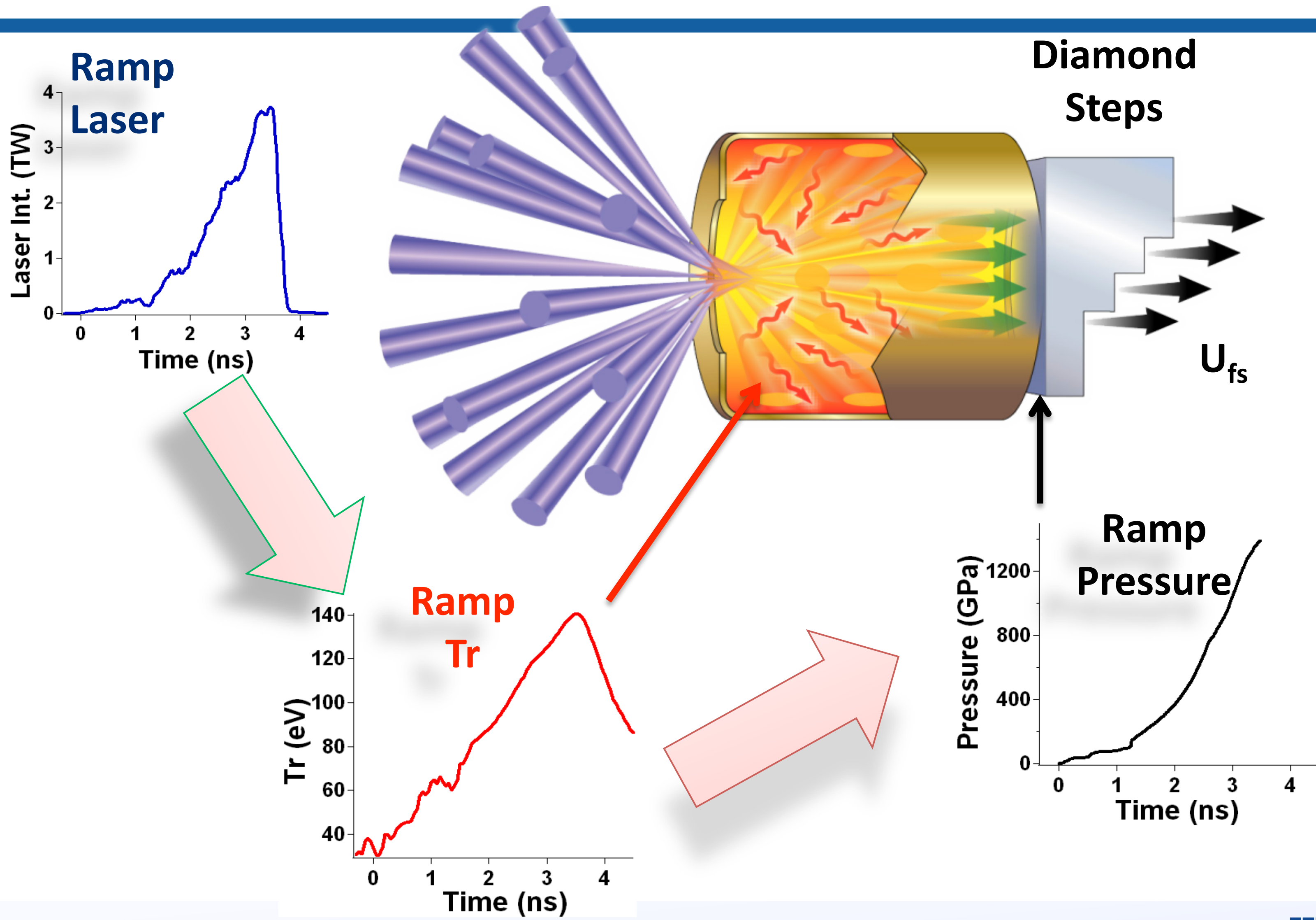


No reverberation

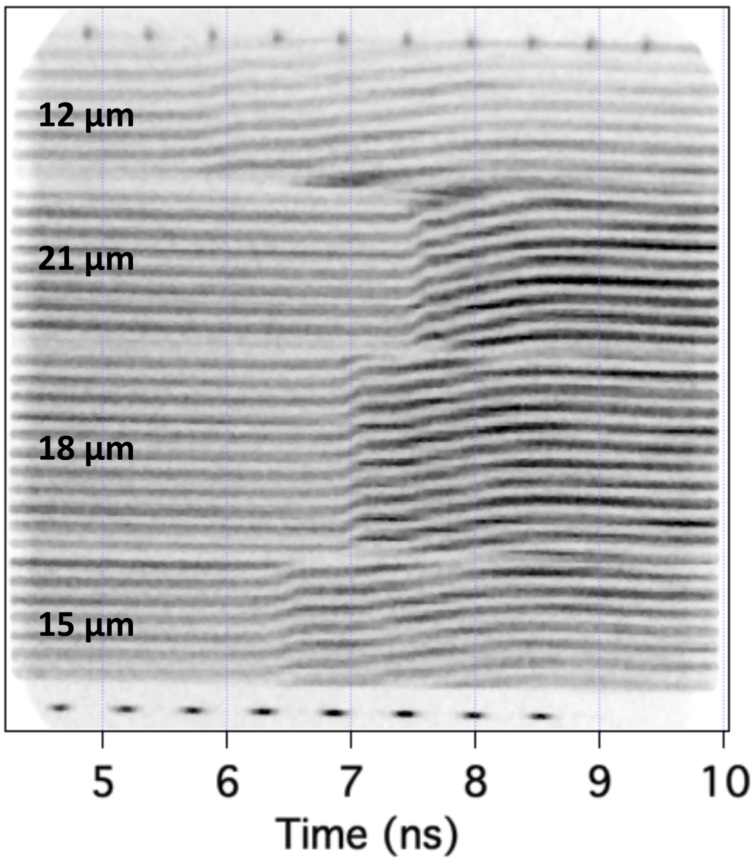
--and--

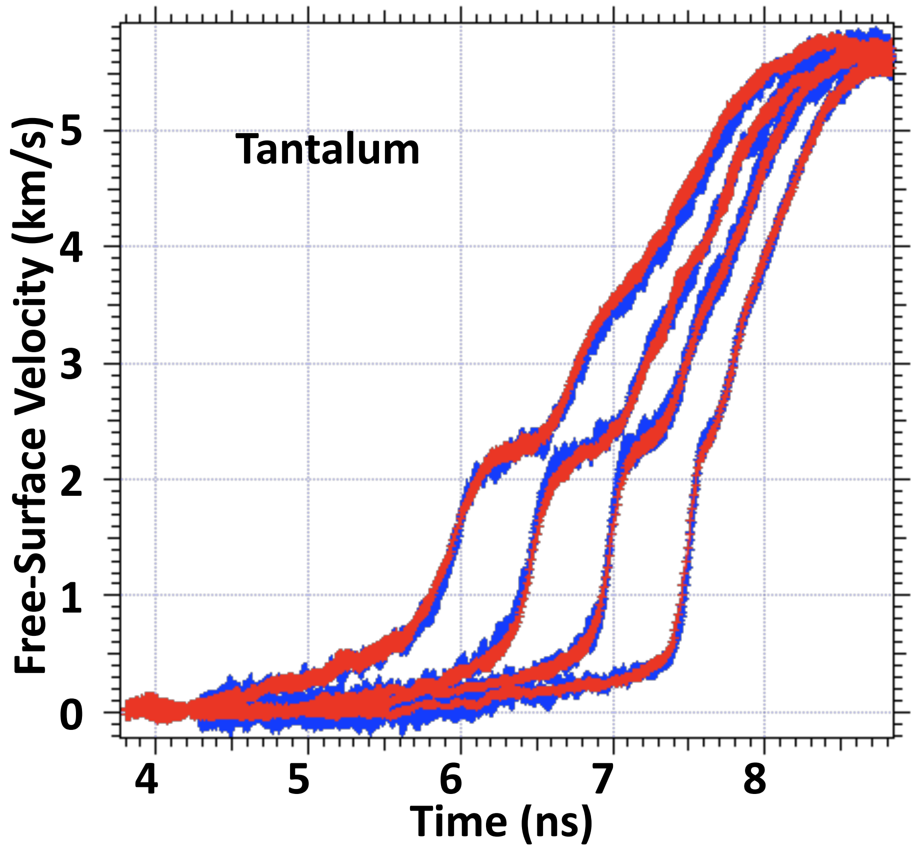
No Shock.

We ramp compressed diamond to 1500 GPa

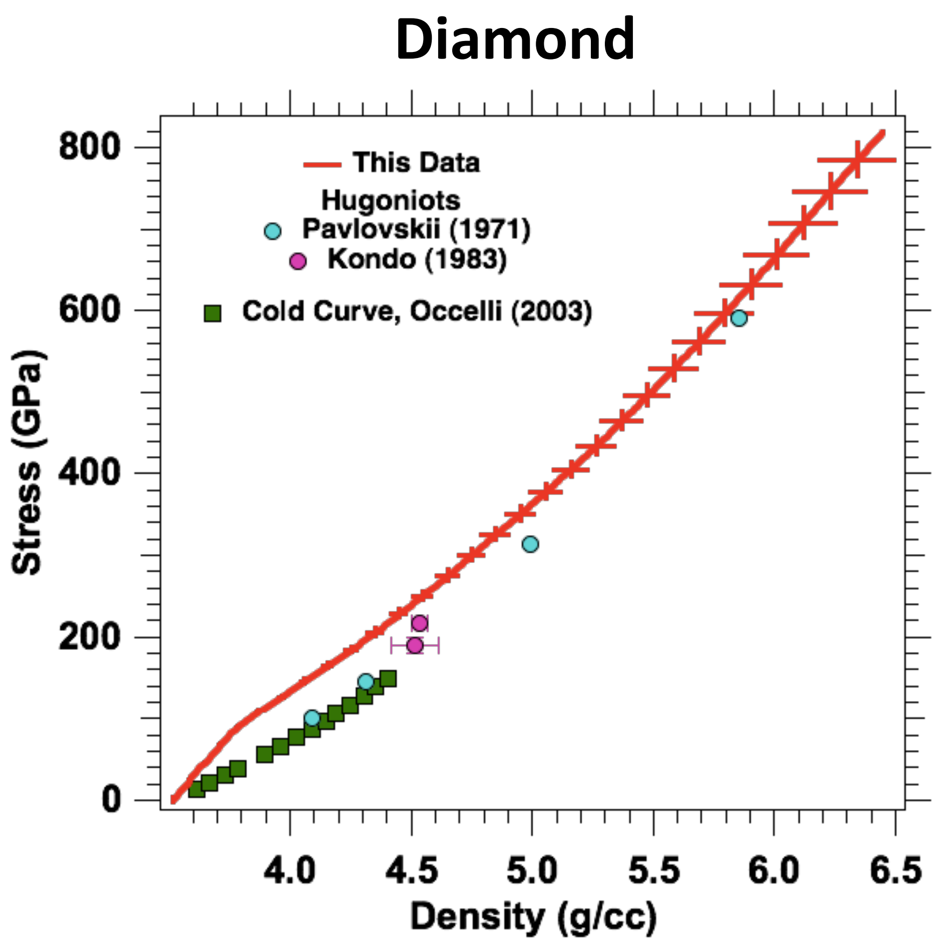


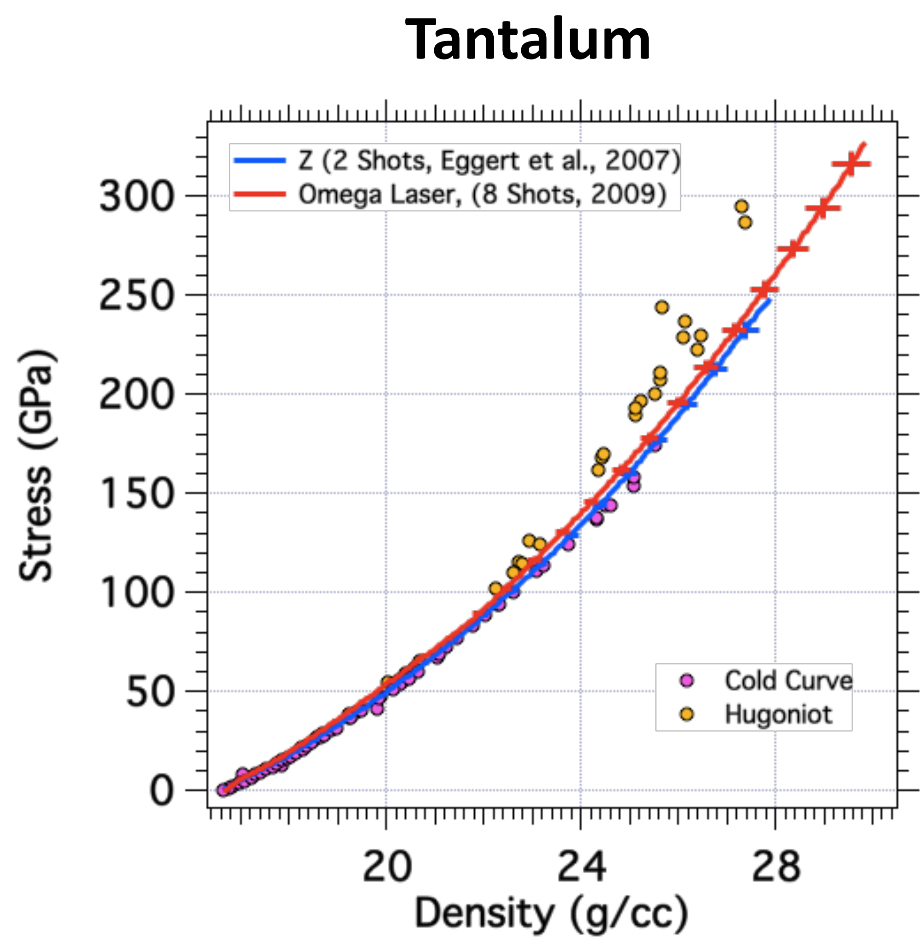
VISAR Wave Profiles– Omega Shot 54777





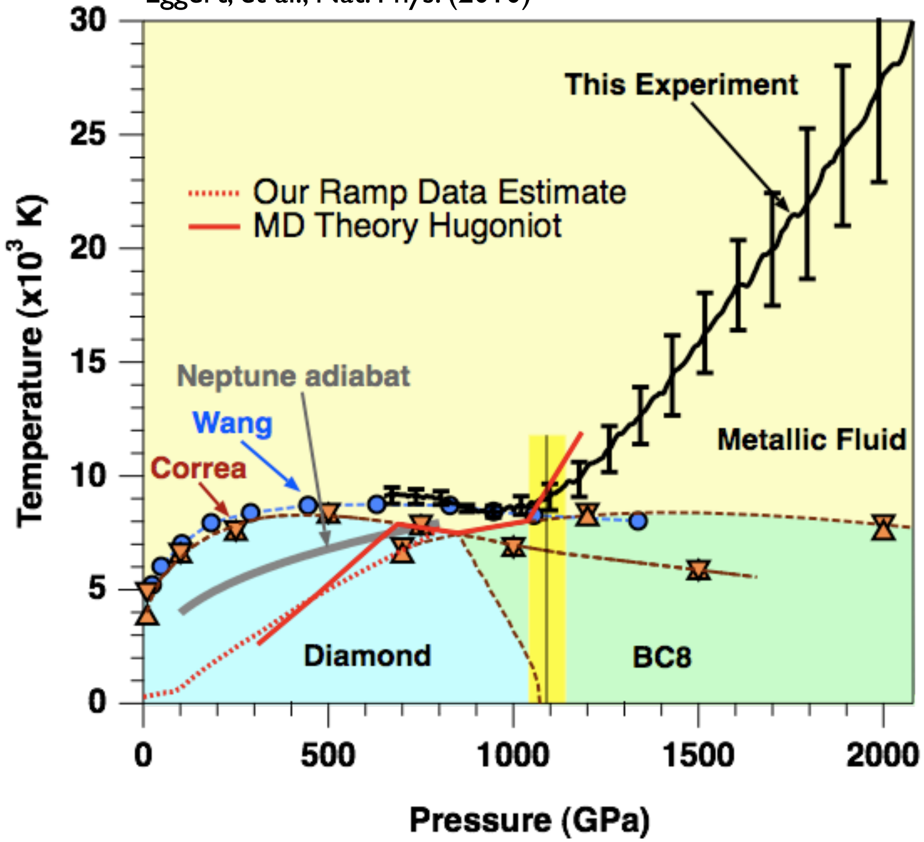
EOS Measurements

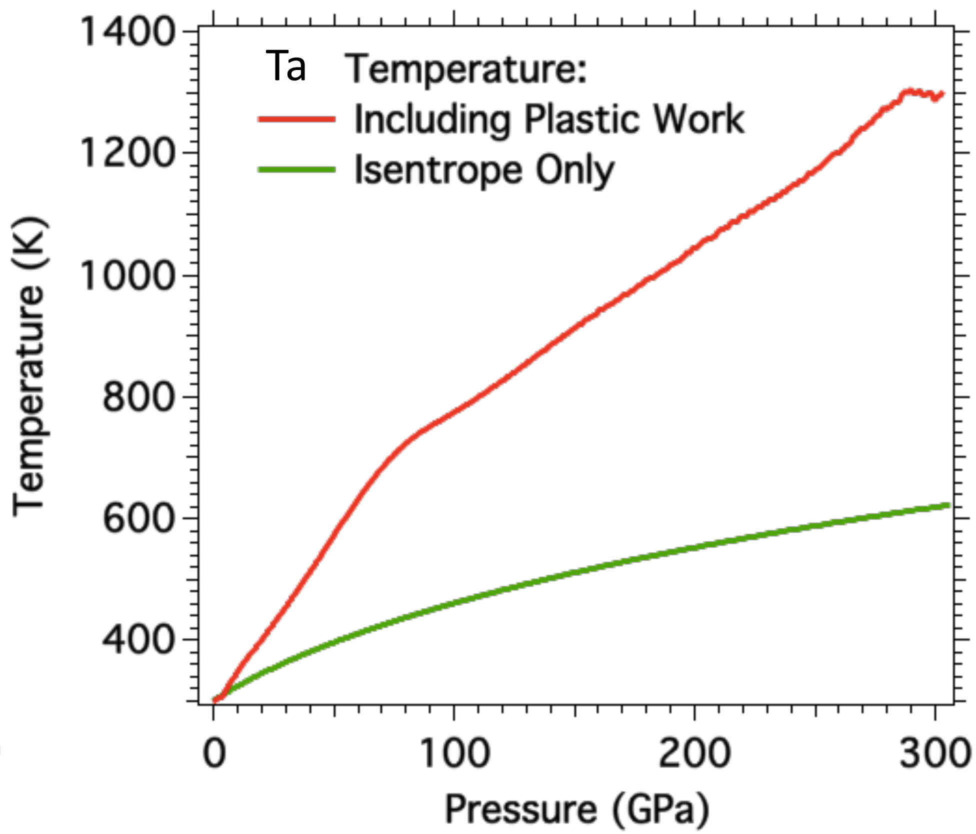




We Estimate the Temperature due to P-V and Plastic-Work Heating

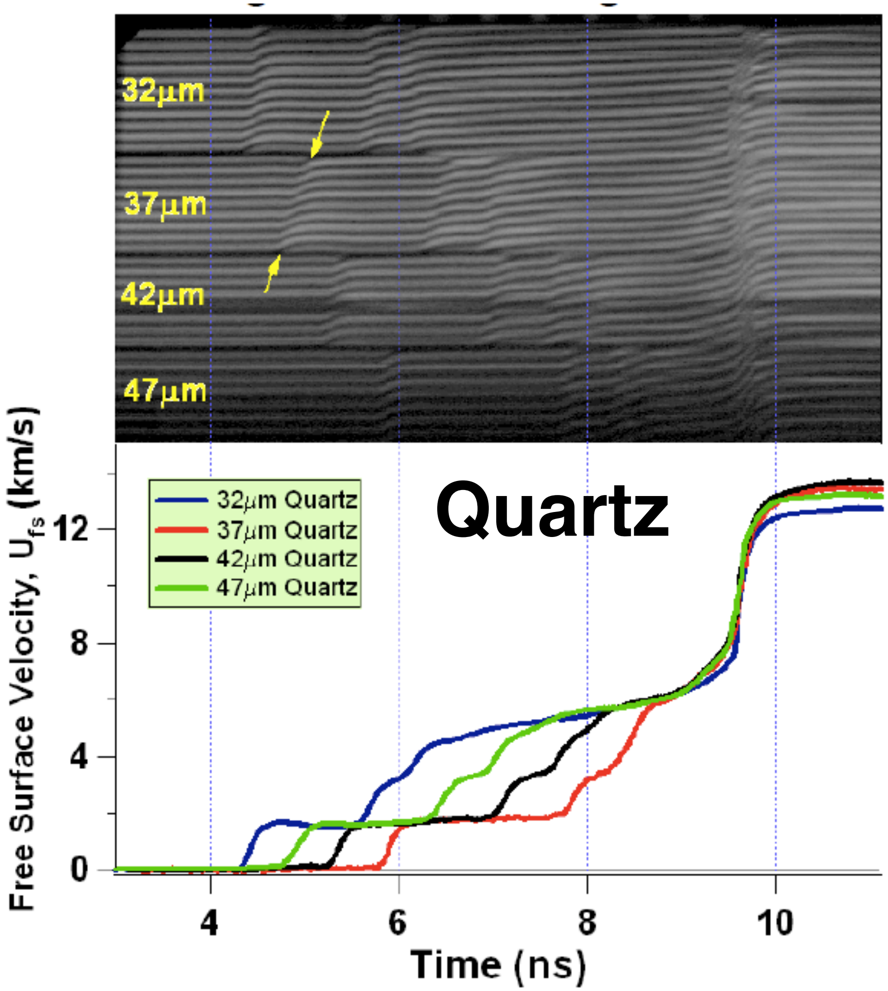
Eggert, et al., Nat. Phys. (2010)

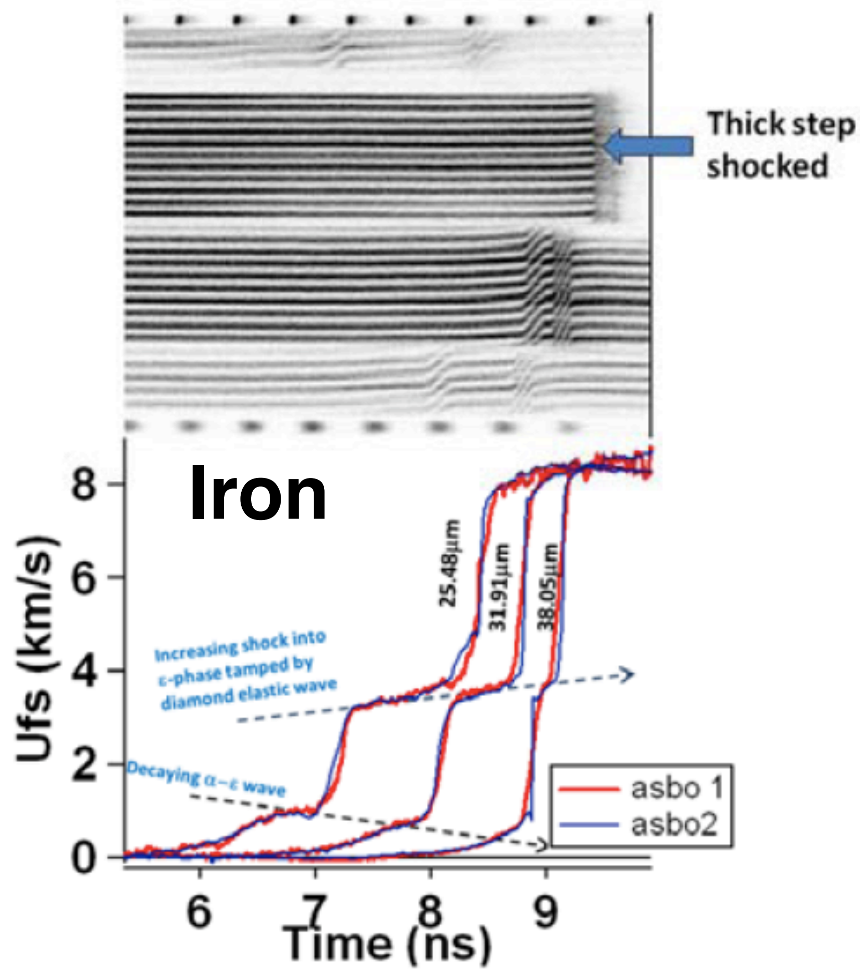




Assuming Dulong-Petite limit for specific heat. Iterative approach used to correct strength for thermal pressure.

We are beginning to measure ramp EOS beyond phase transitions (In collaboration with Tom Duffy)





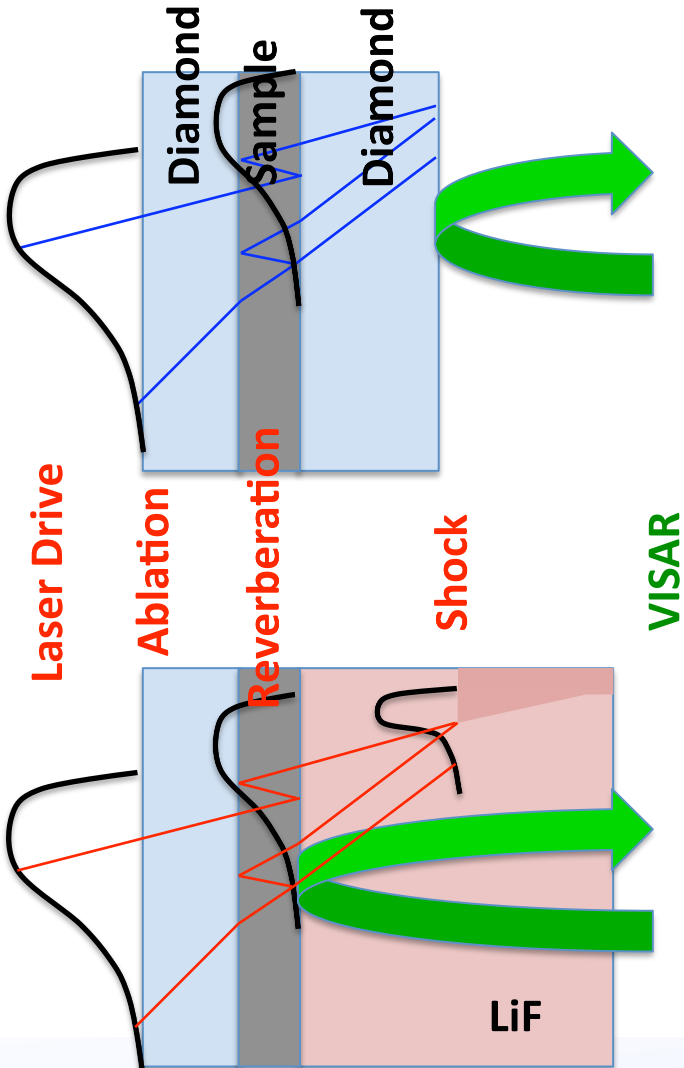
Phase transitions cause shocks and very strange response in quartz

DACs in the '80s ⟺ Laser Compression in the 00's

DACs	Lasers
Ruby Calibration (Pressure, Temperature)	Quartz Calibration (Pressure, Temperature, Reflectivity)
Raman and Visible Spectroscopy	VISAR
X-ray Diffraction (energy dispersive)	X-ray Diffraction (angle dispersive)

- **The last 20 years have seen fantastic advances in DAC techniques, measurements, and diagnostics.**
- **Our challenge is to make similar progress in the next 20 years on laser-compression experiments.**

Sandwich Ramp-Compression



the LiF or Diamond interfacial pressure is the same as in sample

If we know the EOS of LiF or Diamond we can find the Pressure in the sample using the VISAR diagnostic

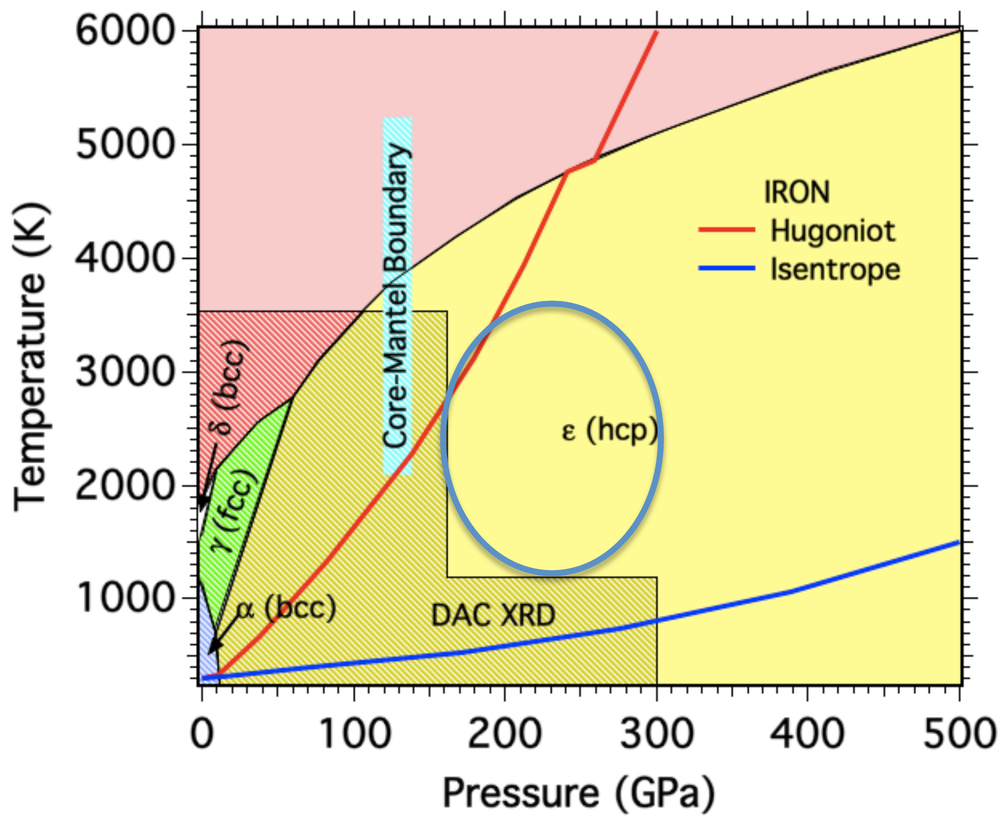
Using this target design, we believe we can ramp compress samples to ~30 Mbar, Hold the state for several ns, Determine the pressure, and Make a measurement.

XRD, XAFS, XANES, Reflectivity, ... Temperature remains the most important parameter that we do not know how to measure.

X-Ray Diffraction

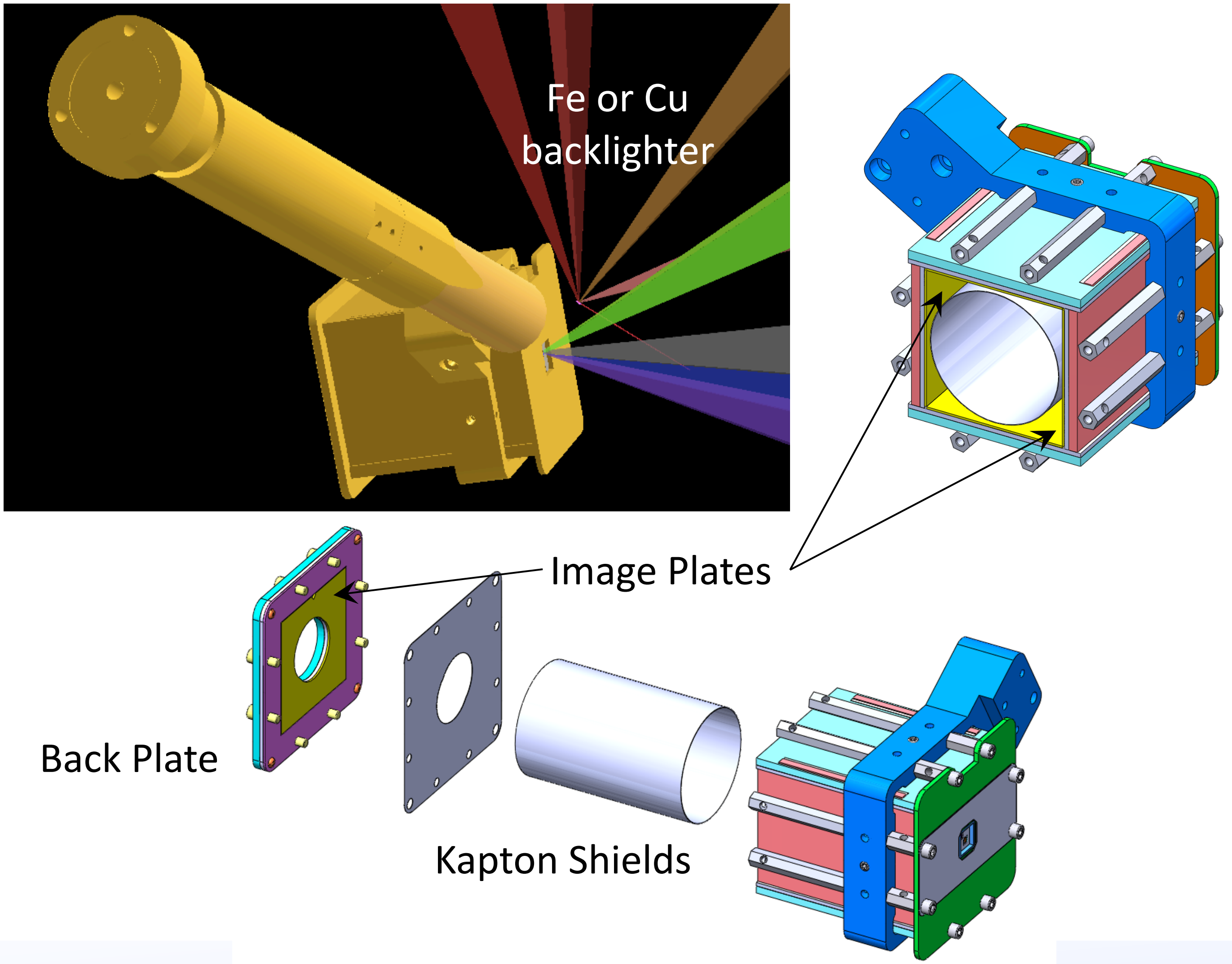
- **Diffraction -- Most direct way to determine crystal structure**
- **Laser Drive -- Ideal for X-ray diagnostics**
- **Ramp Compression -- limits shock heating, very high pressures in solid phase.**

Iron Phase Diagram

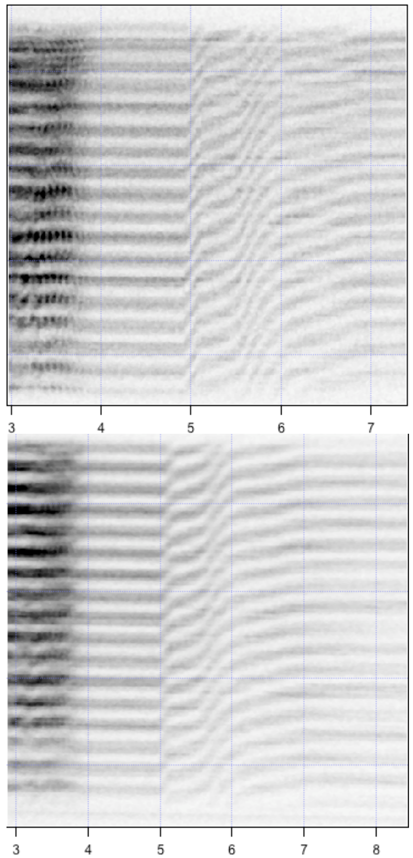


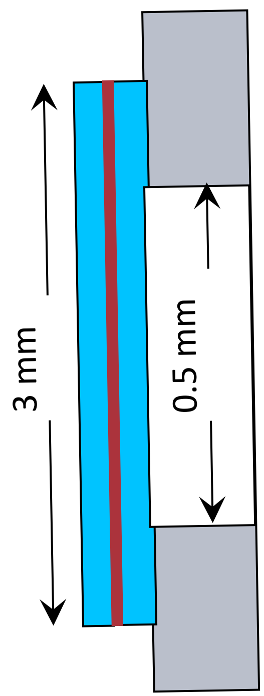
- **Diffraction above the shock melting pressure?**

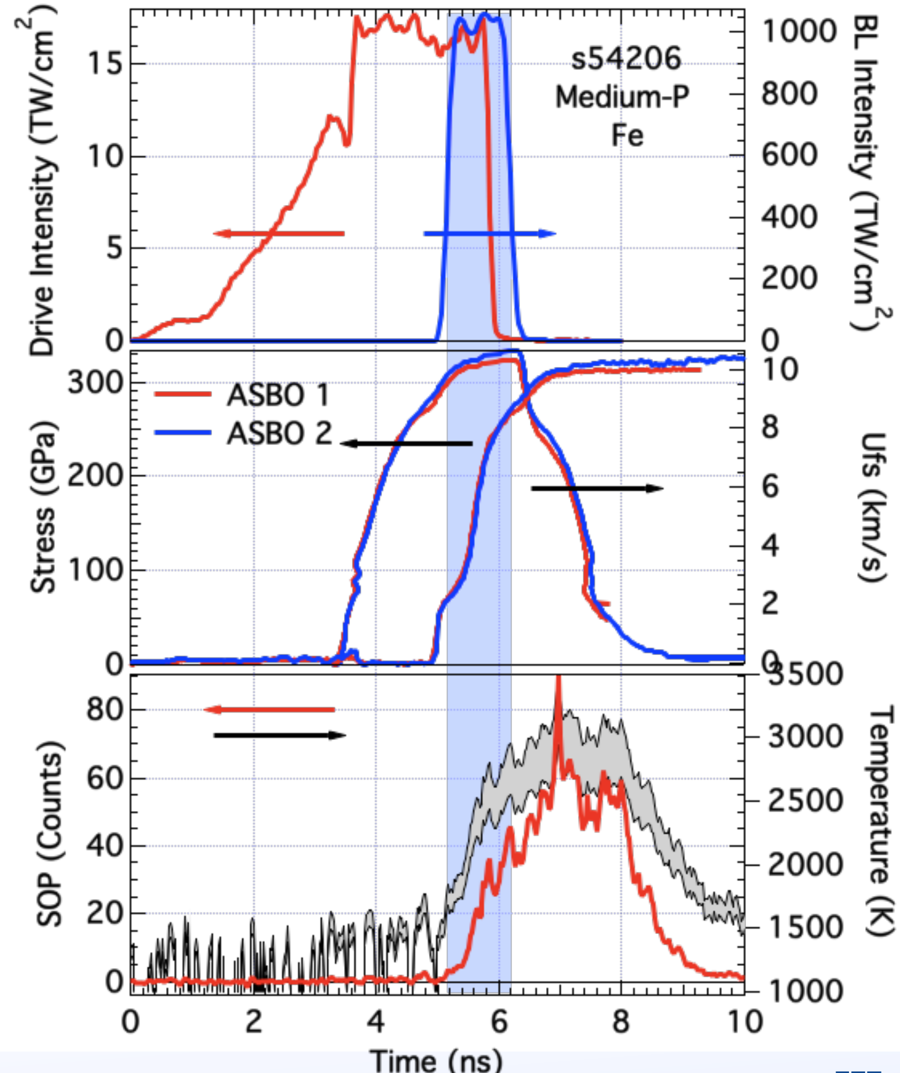
X-Ray Diffraction at Omega Laser



s54206, Fe X-ray Diffraction



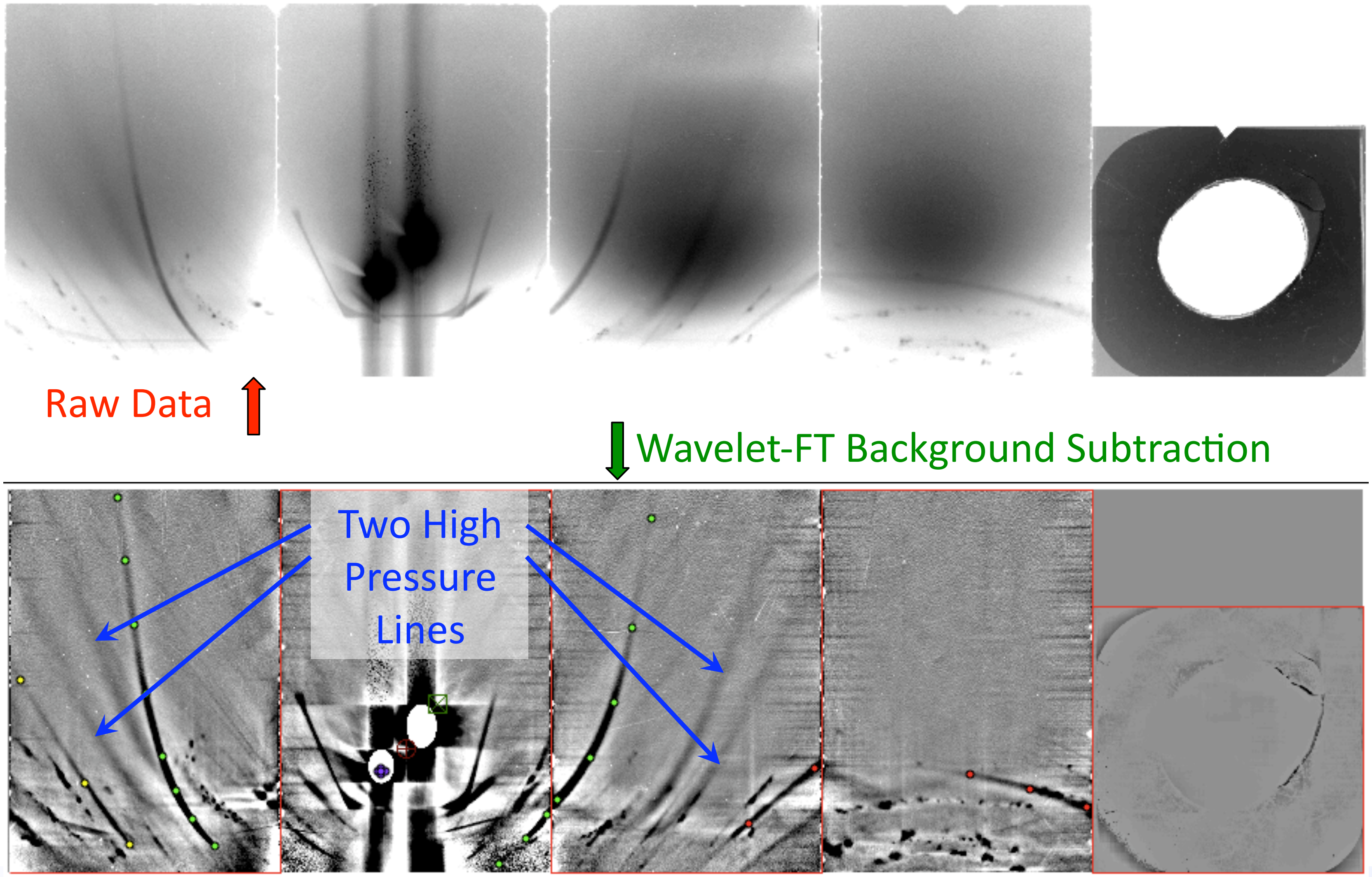




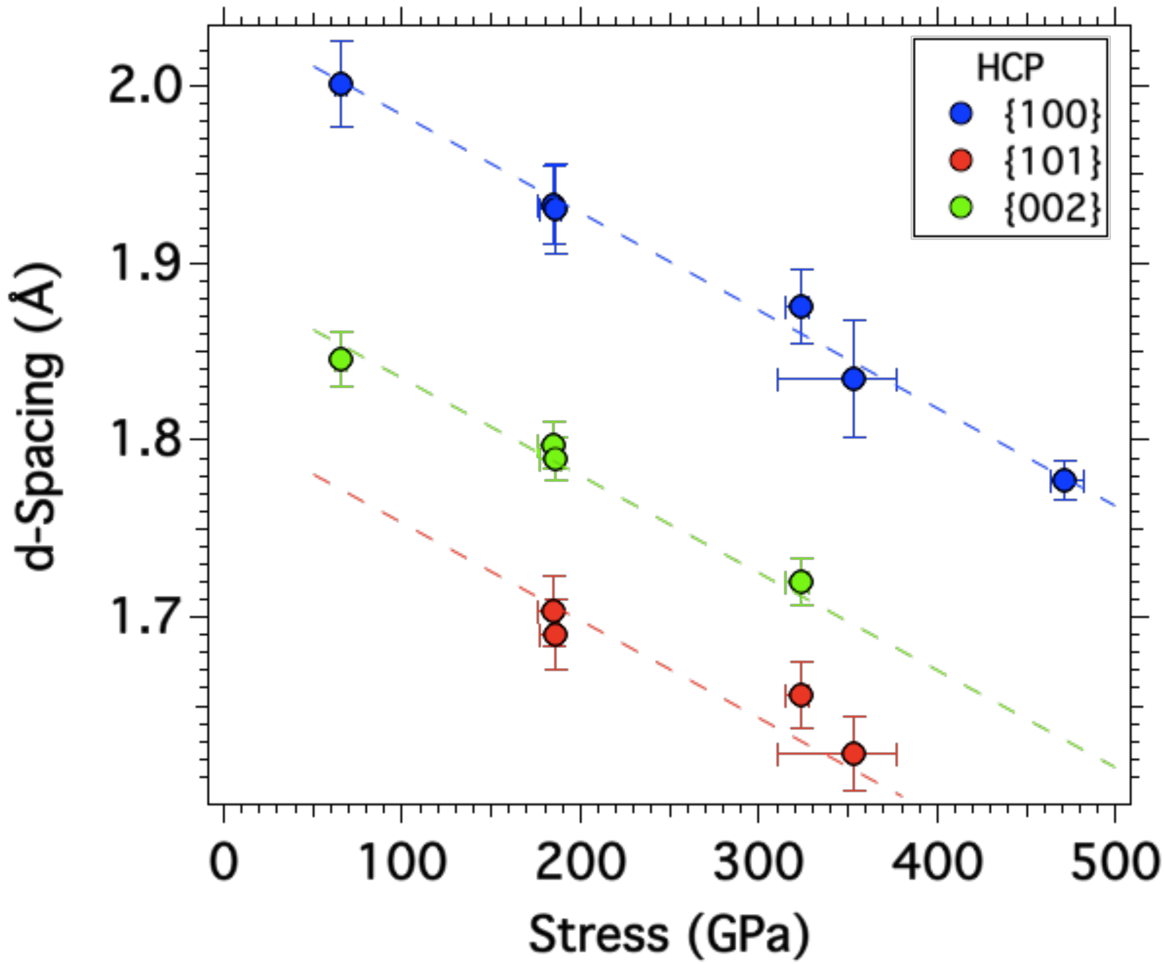
Strain rate is very high, ~10^8 s^{-1}.
Looks like temperature is low.
What does diffraction look like?

Shot 54206, Fe X-ray Diffraction

$$P = 324^{+9}_{-15}\ \text{GPa}$$

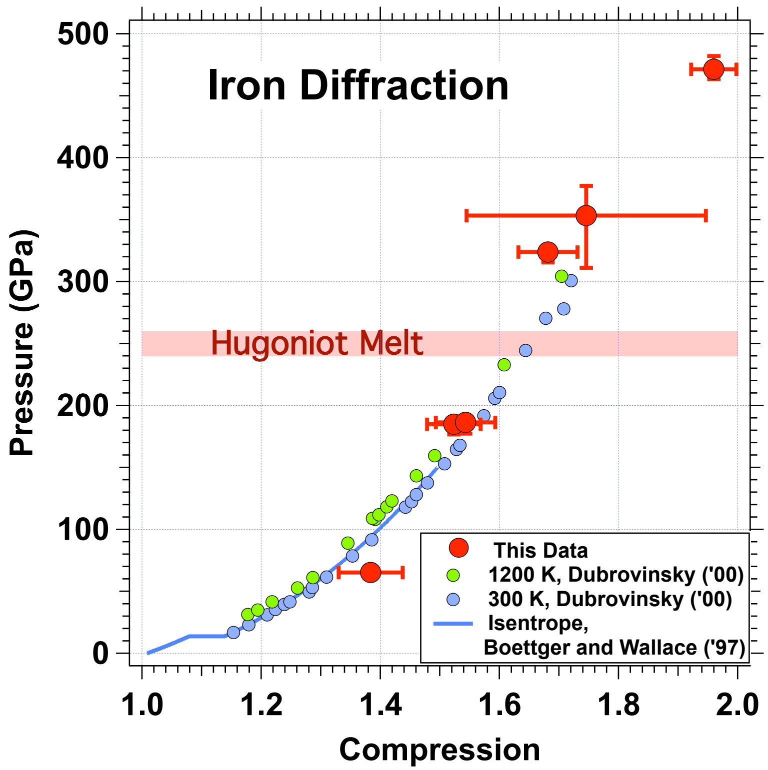


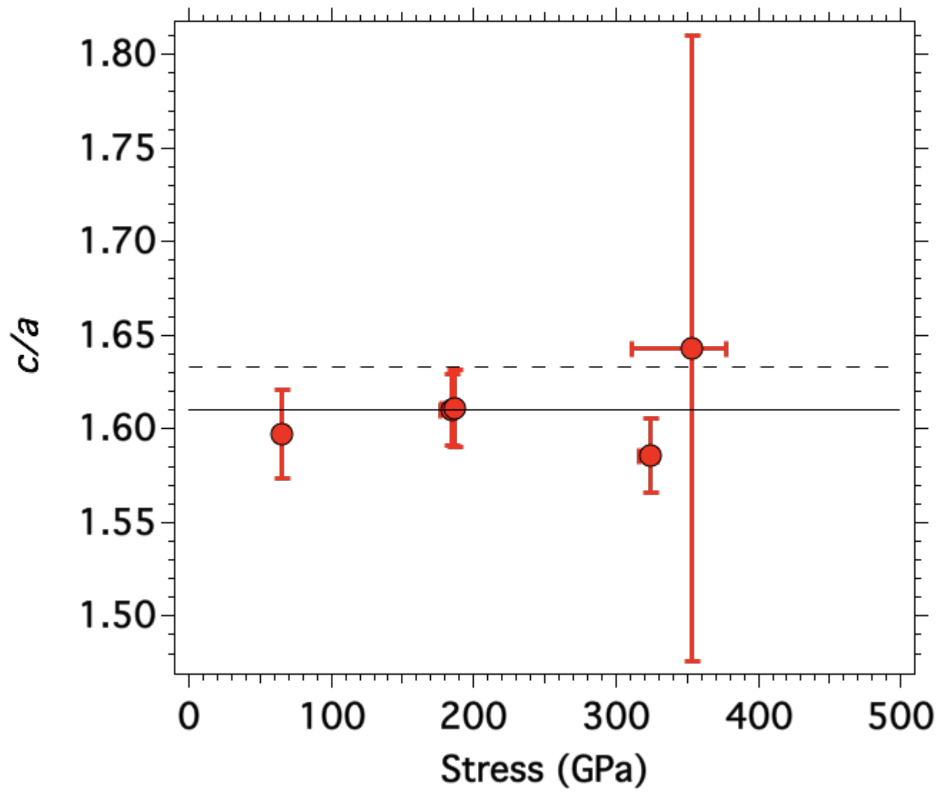
We see 2 strong, 1 weak reflections.



We will assume a structure and fit.

Results and Comparison





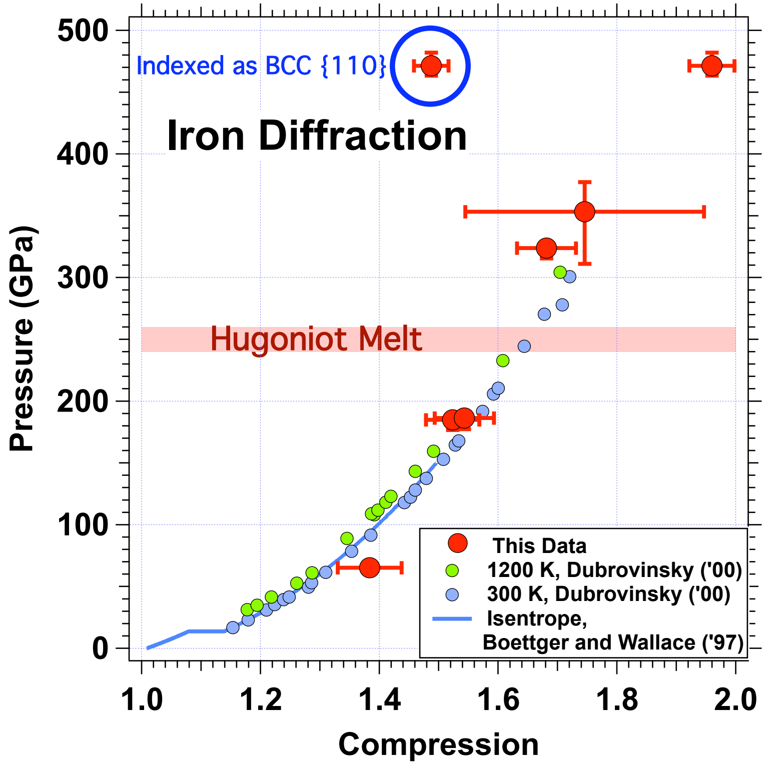
Diffraction on solid Fe to 472 GPa

•Highest pressure X-ray diffraction ever.

•Far above Hugoniot melt (~250 GPa).

•Structure appears to be HCP with c/a~1.61.

Results and Comparison



At 470 GPa we have only 1 diffraction line. If it is indexed as BCC {110}, then the compression is inconsistent with other data and DAC.

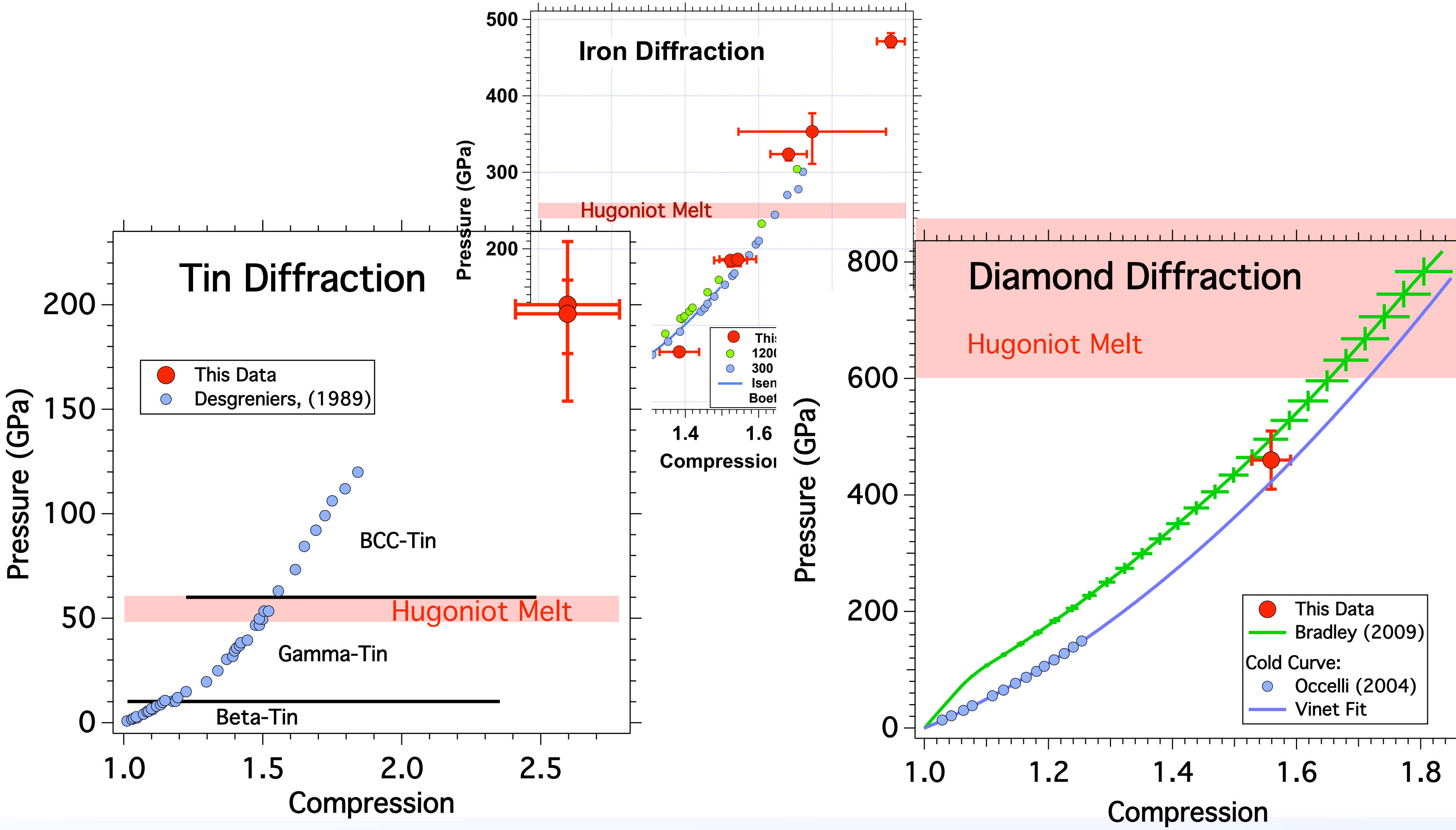
Diffraction on solid Fe to 472 GPa

•Highest pressure X-ray diffraction ever.

•Far above Hugoniot melt (~250 GPa).

•Structure appears to be HCP with c/a~1.61.

We have also measured Tin and Diamond



Optical Experiments

- **Need a transparent window—previously limited to <1.6 Mbar.**

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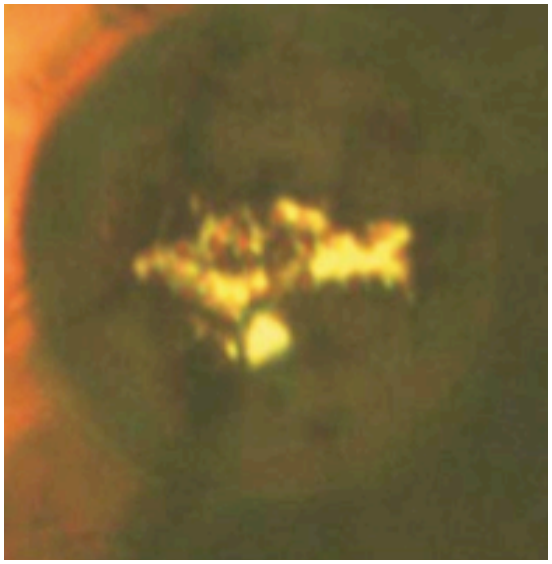


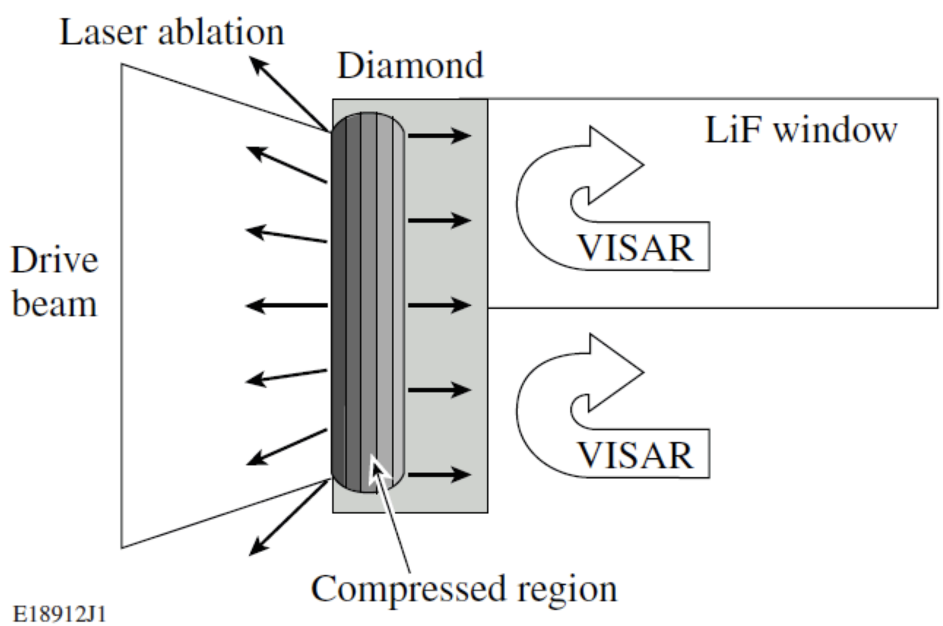
At 2 Mbar sodium is transparent
Ma, *et al*. Nature, 458, 07786 (2009).

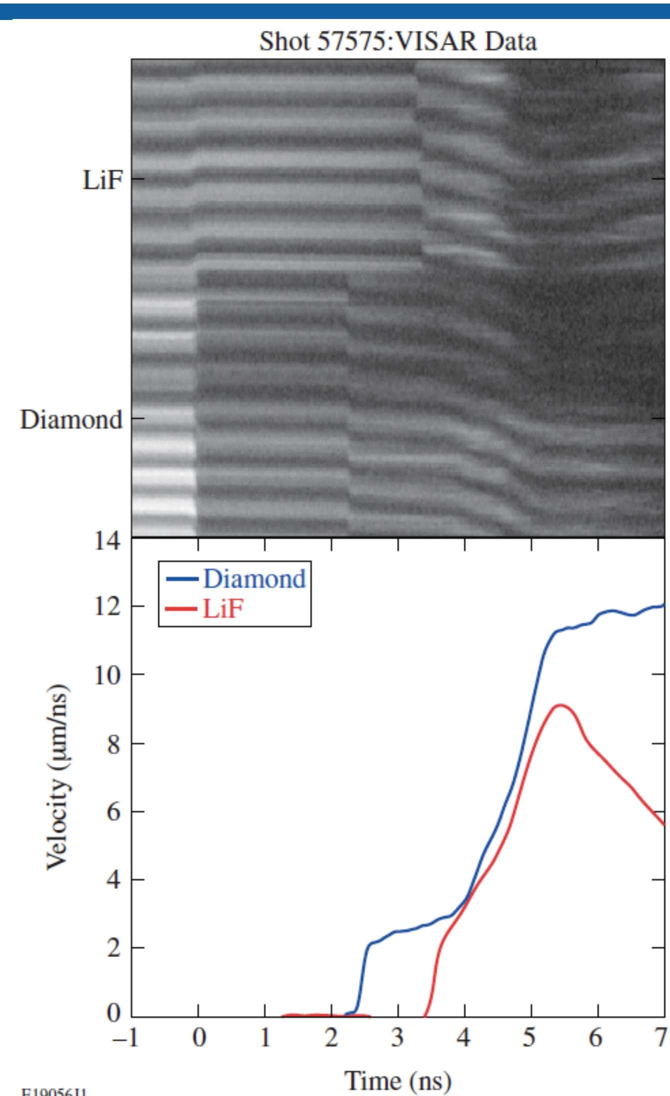
- **"Comparison of theory and experiment is one of the touchstones of *ab initio* electronic structure research"** –Richard M. Martin (2004).

- **". . . what the present results most assuredly demonstrate is the importance of pressure in revealing the limitations of previously hallowed models of solids and their associated electronic behaviour"** –Neil Ashcroft (2009).

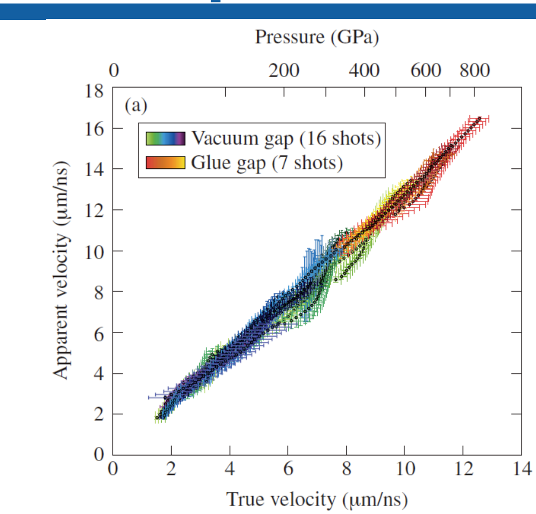
Until what pressure is sodium transparent? What other metals behave similarly?

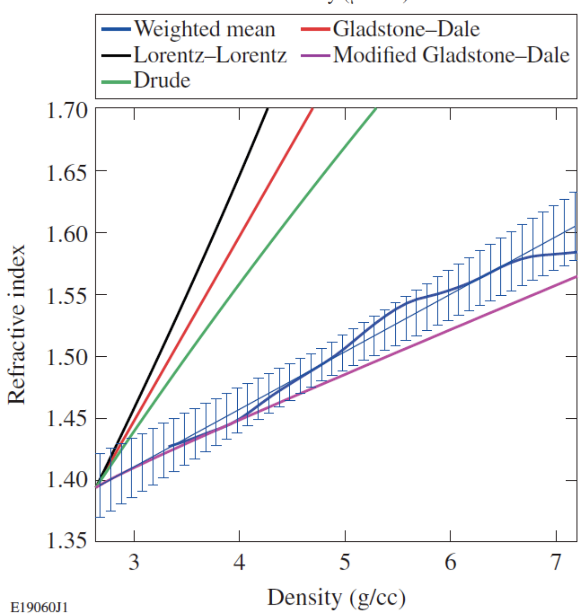
LiF remains transparent to 800 GPa under ramp compression





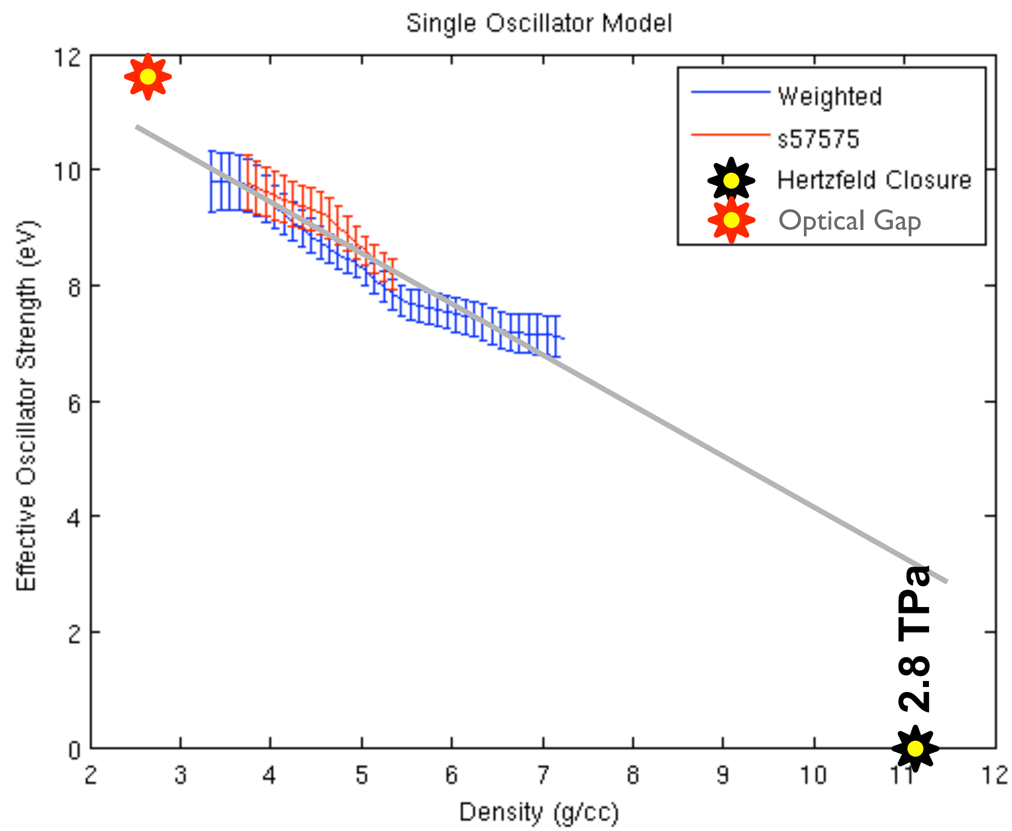
LiF remains transparent to 800 GPa under ramp compression





$$\left.\frac{dU_A}{dU_T}\right|_{U_T} = \left.\left(n - \rho\frac{dn}{d\rho}\right)\right|_{U_T}$$

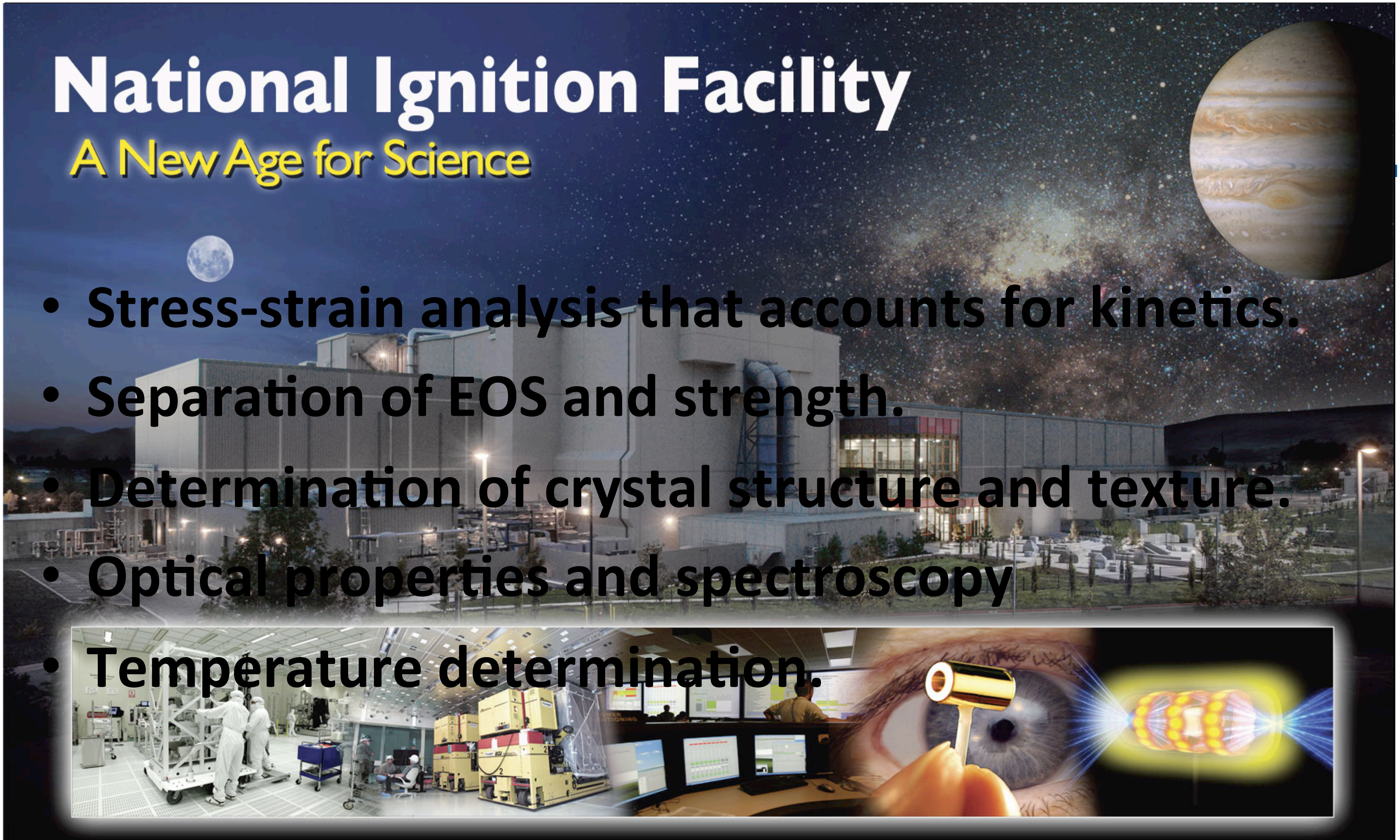
$$n^2 - 1 = \frac{E_d E_o}{E_0^2 - \hbar^2\omega^2}$$



48

Future Directions

- Stress-strain analysis that accounts for kinetics.
- Separation of EOS and strength.
- Determination of crystal structure and texture.
- Optical properties and spectroscopy
- Temperature determination.



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- **On to the NIF!!!**