Laboratory equation of state measurements of the carbon envelopes of white dwarf stars

HEDS seminar

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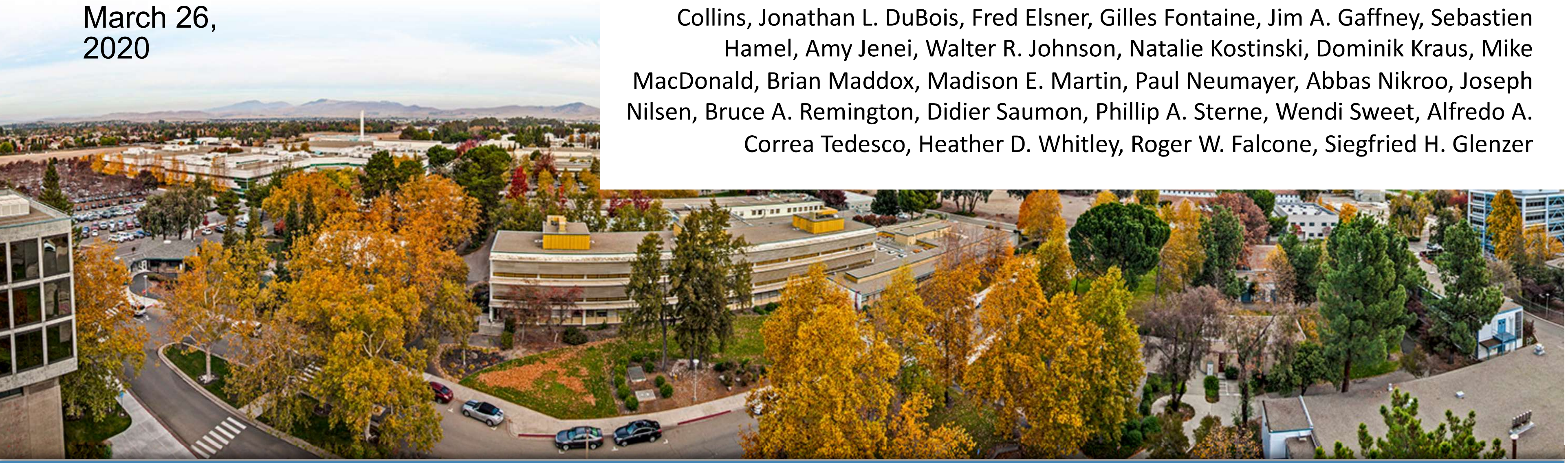
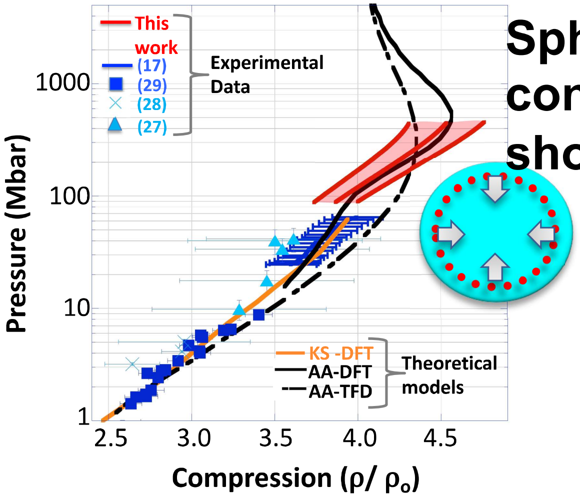


LLNL-PRES-816072

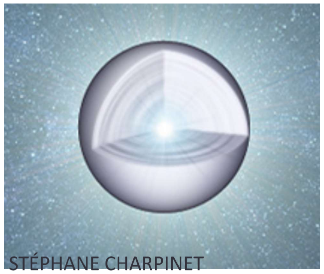
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

We have measured the EOS of matter to the highest pressures ever achieved in the laboratory



Spherically converging shock waves


STÉPHANE CHARPINET

Accessed conditions in envelopes of white dwarf stars

- We measure the Hugoniot of hydrocarbon, up to 450 Mbar
- The observed maximum compressibility is consistent with theoretical models that include detailed electronic structure and an increase in compressibility due to ionization of the inner core orbitals of carbon
- Here we directly probe the weakest link in constitutive physics of white dwarf modeling

This work was recently accepted to Nature

This effort was part of a large international collaboration and made possible through the fundamental science program at NIF

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NIF Beam-time awarded by fundamental science program

White dwarf stars provide important tests of stellar physics models; EOS models at these extreme conditions are largely untested

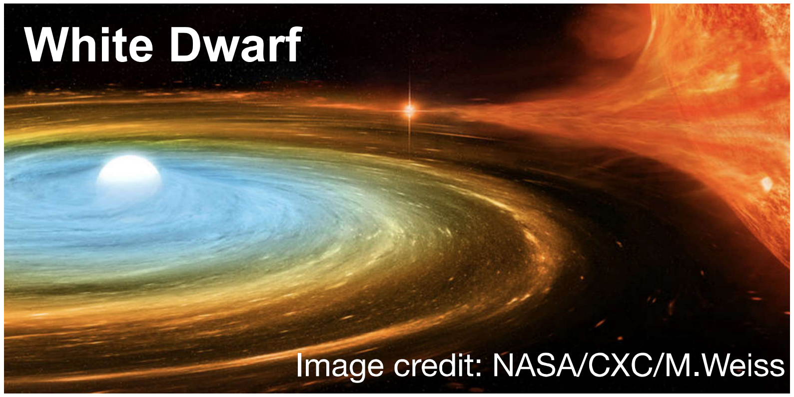
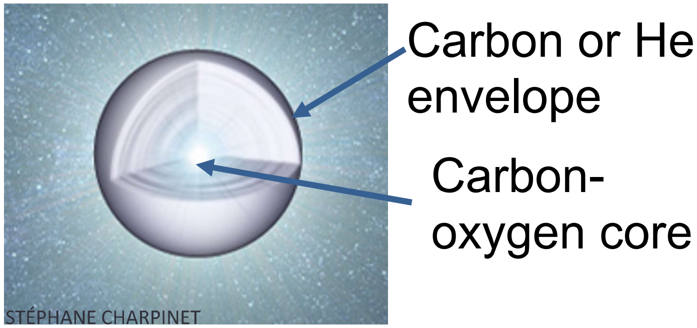


Image credit: NASA/CXC/M.Weiss



STÉPHANE CHARPINET

- White dwarfs represent the final state of evolution for the most stars
- Some WDs pulsate, modeling of these stringent tests of the outcome of the late stages of stellar evolution
- White dwarf cores are highly degenerate C/O (>million g/cc) surrounded by a lower density high temperature envelope (100s Mbar-Gbar)
- Theory is largely untested at these conditions

Here we measure the equation of state at conditions relevant for the carbon envelopes of white dwarf stars

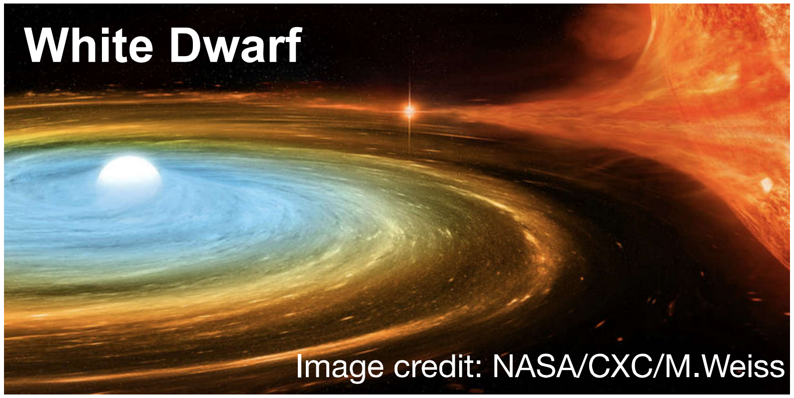
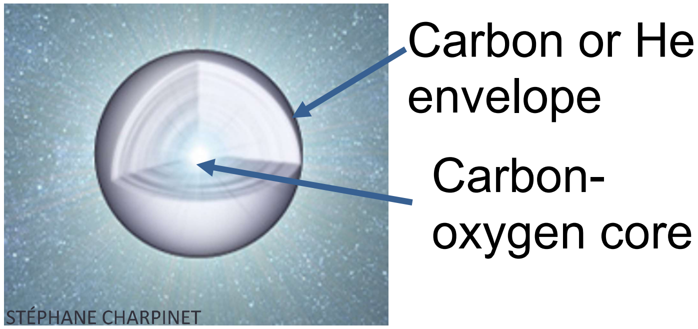
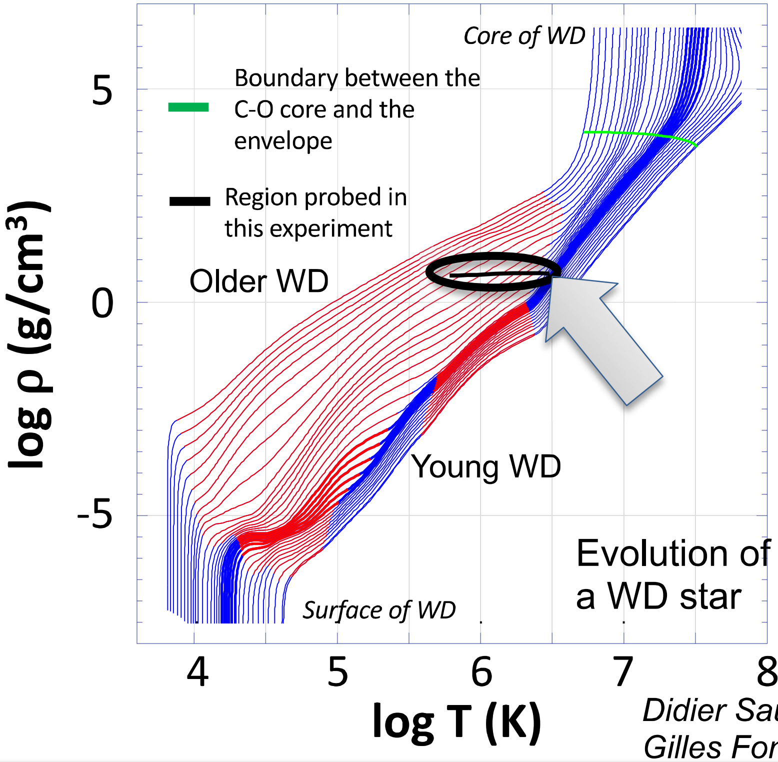


Image credit: NASA/CXC/M.Weiss

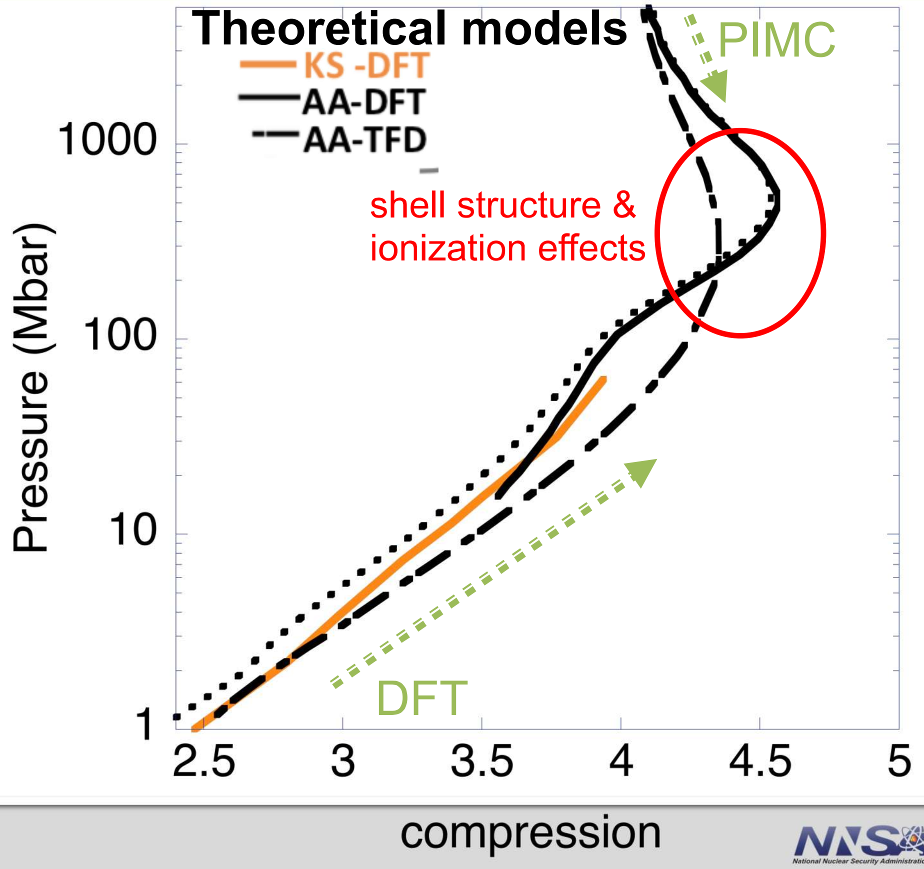




Didier Saumon and Gilles Fontaine

Benchmarking Hugoniot models at 100s Mbar-Gbar pressures is important as the EOS can be sensitive to electronic structure

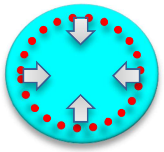
- Pressure and temperature ionization may affect the compressibility, No first principles method available in this regime.



Previous polystyrene experiments in planar geometry have have been limited to pressures of <100 Mbar

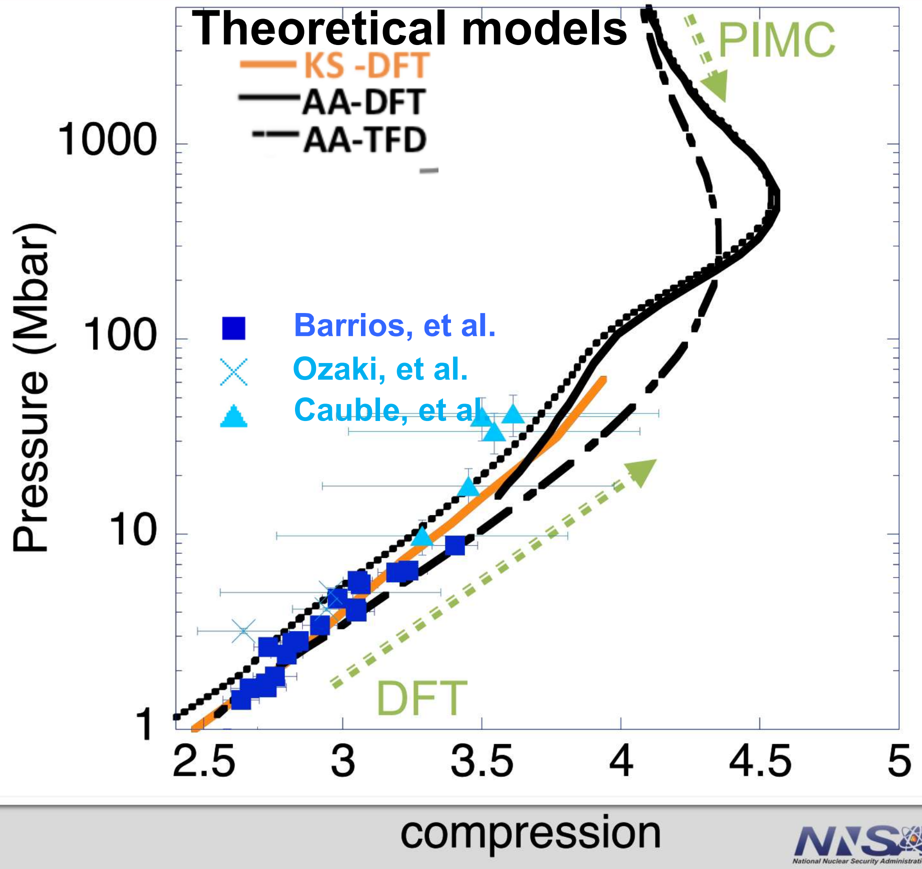
- We use spherically converging shock waves to reach high pressures >100 Mbar

$$\frac{P}{P_0} \sim r^{-1}$$



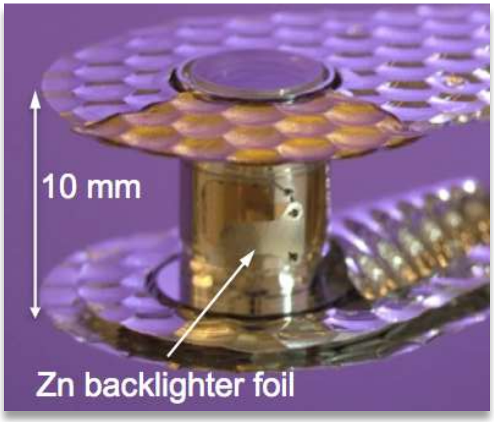
Spherical

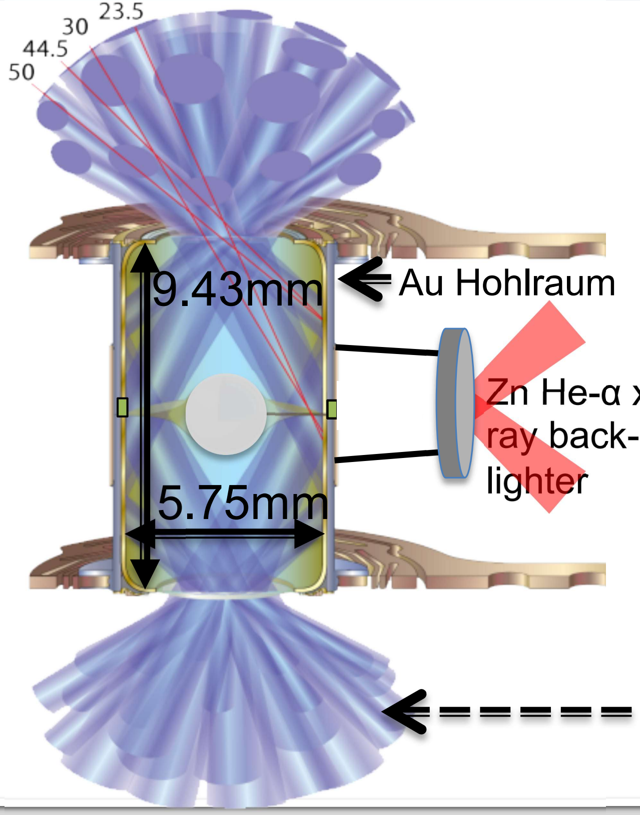
- We can access a range of locus points in one shot



We use 1.1 MJ of laser light to create a near 300 eV hohlraum at NIF for the spherical shock generation

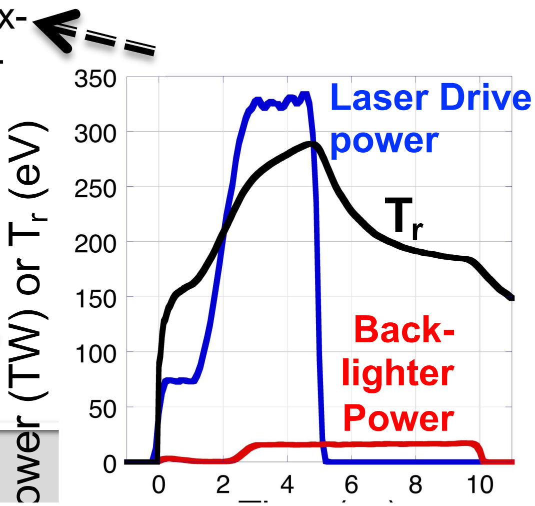
Target





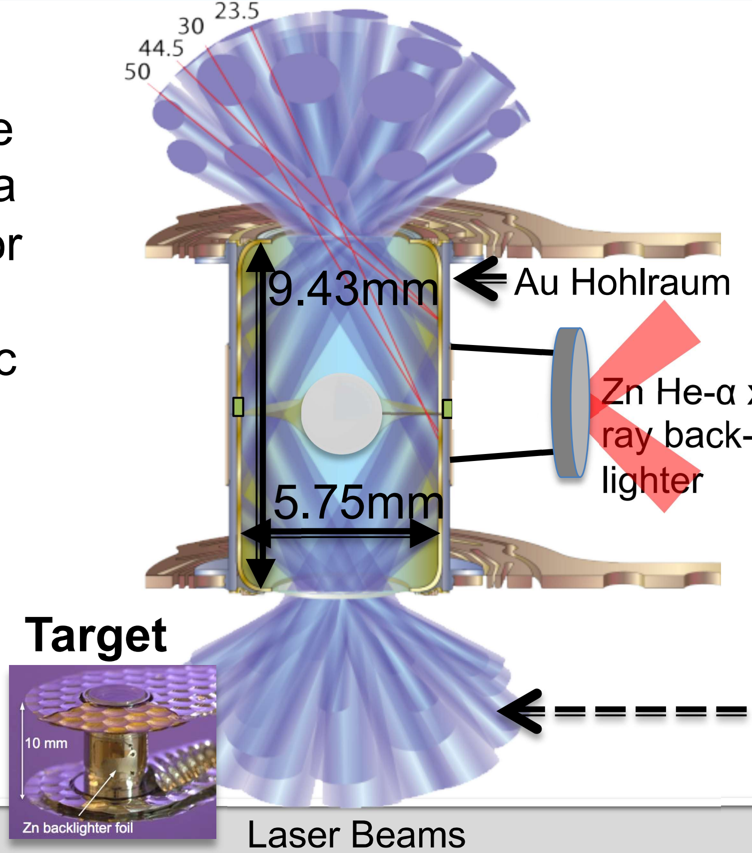
Laser Beams

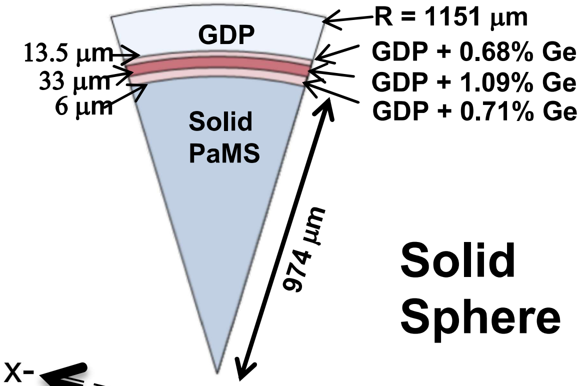
- 16 NIF used to create a 9 keV x-ray backlighter

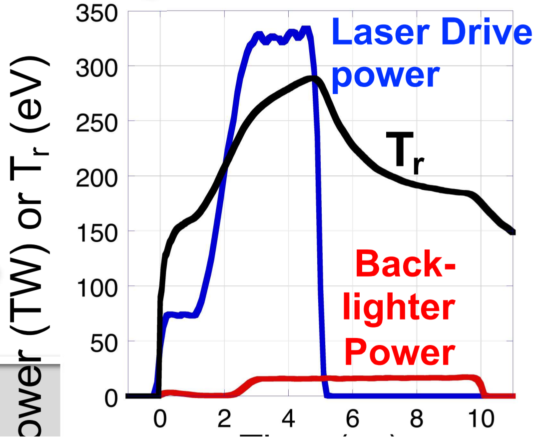


The target at the center of the hohlraum was a solid sphere of polycarbon enabling spherically converging shock waves

- The solid sphere is covered with a doped ablator for preheat shield and radiographic marker layer

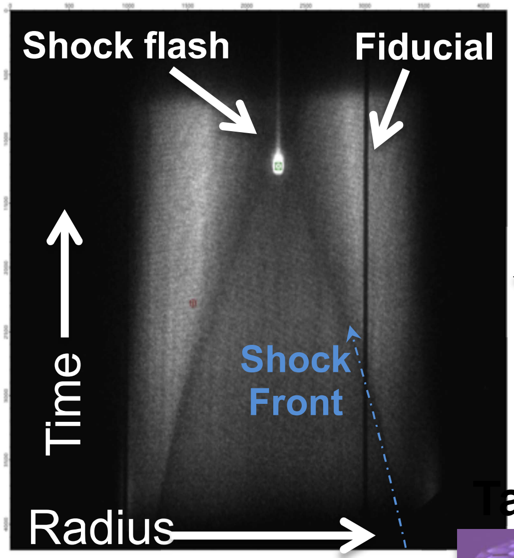


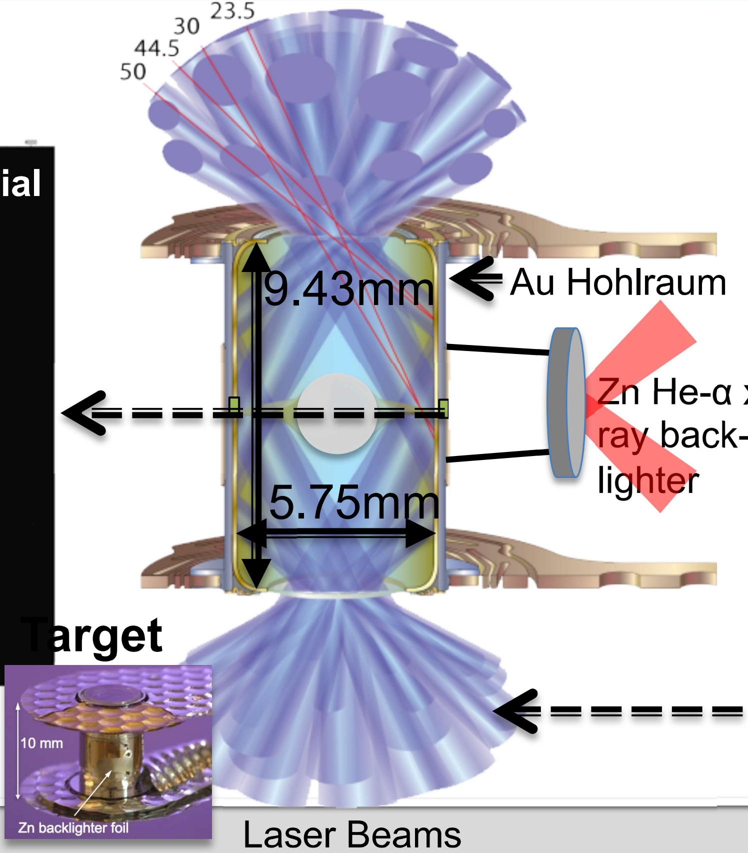


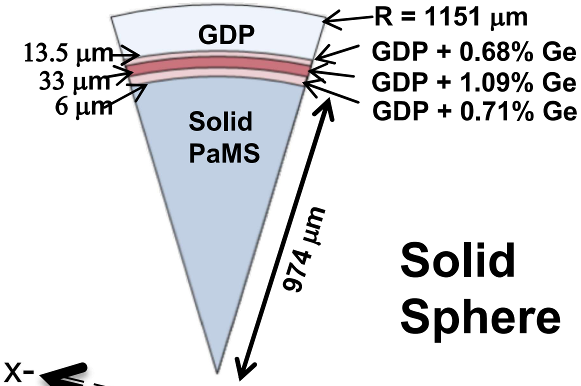


We measure the spherically converging shock traveling through the solid sphere using streaked x-ray radiography

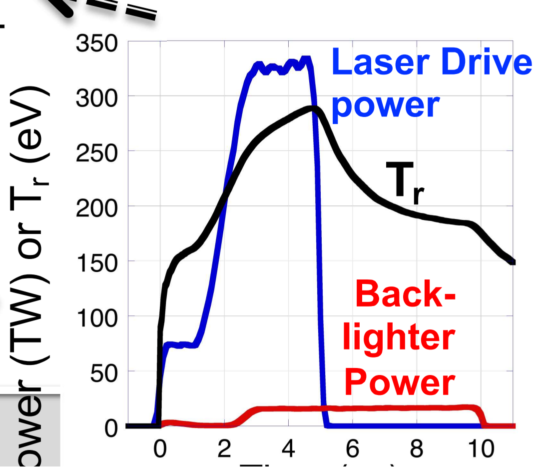
Streaked x-ray radiography Data



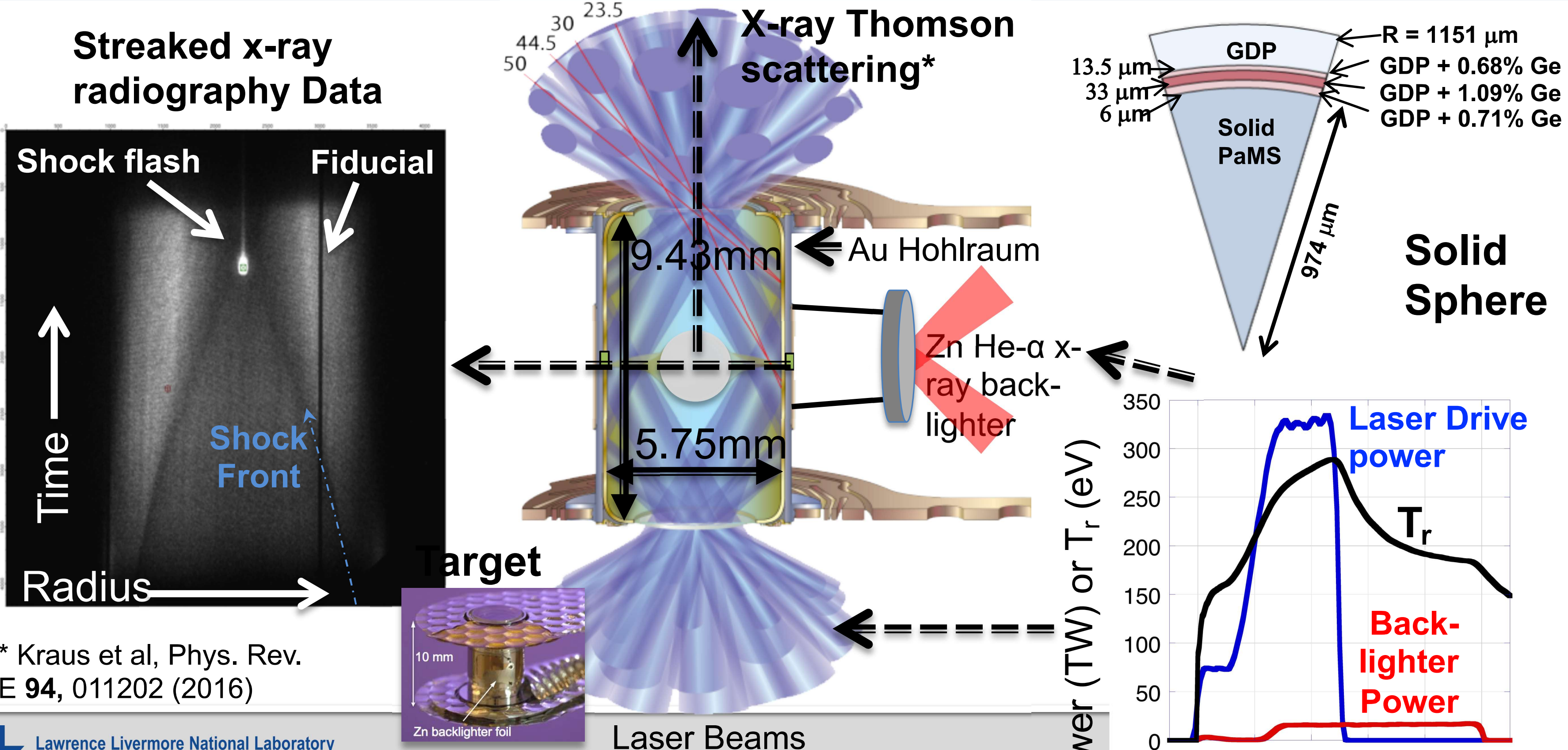




Solid Sphere

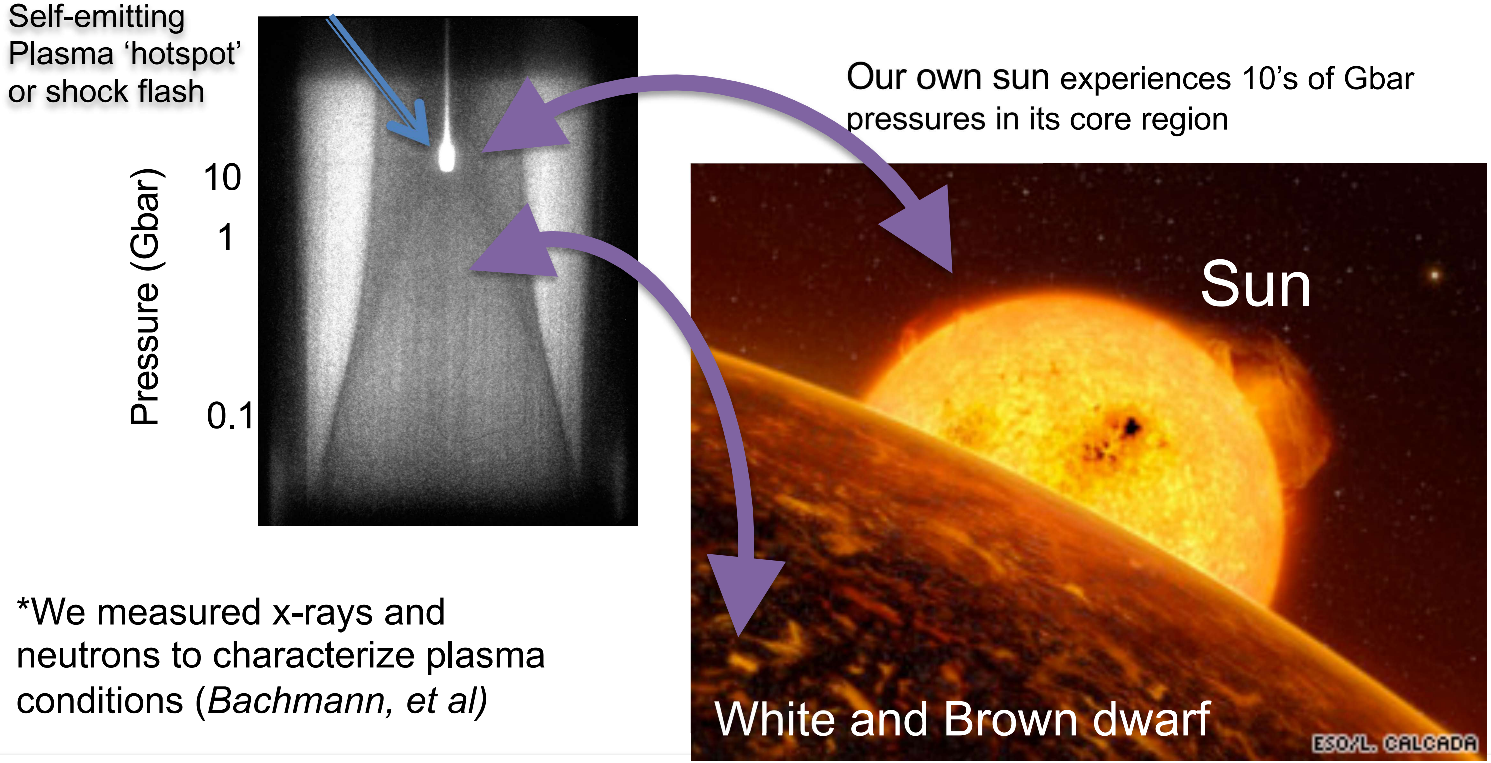


We also fielded x-ray Thomson scattering in the pole to measure electron temperature/ionization of the bulk shocked material



* Kraus et al, Phys. Rev. E **94,** 011202 (2016)

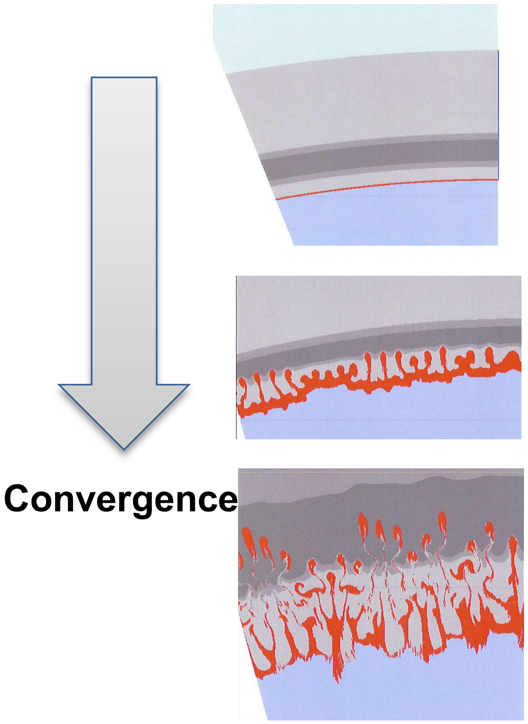
Gbar platform at NIF can create conditions from planets and failed stars (> 1 Gbar) towards the center of our sun (100 Gbar)*



Our own sun experiences 10's of Gbar pressures in its core region

*We measured x-rays and neutrons to characterize plasma conditions (*Bachmann, et al*)

Shocked solid spheres are more hydro-dynamically stable than imploding capsules



Capsule implosions

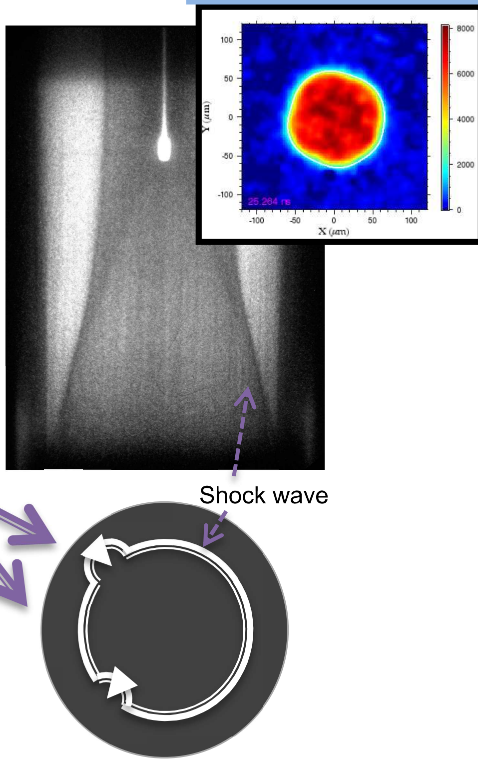
Capsule implosions are prone to hydrodynamic instabilities at each interface

Solid sphere

Converging shockwaves are self-symmetrizing

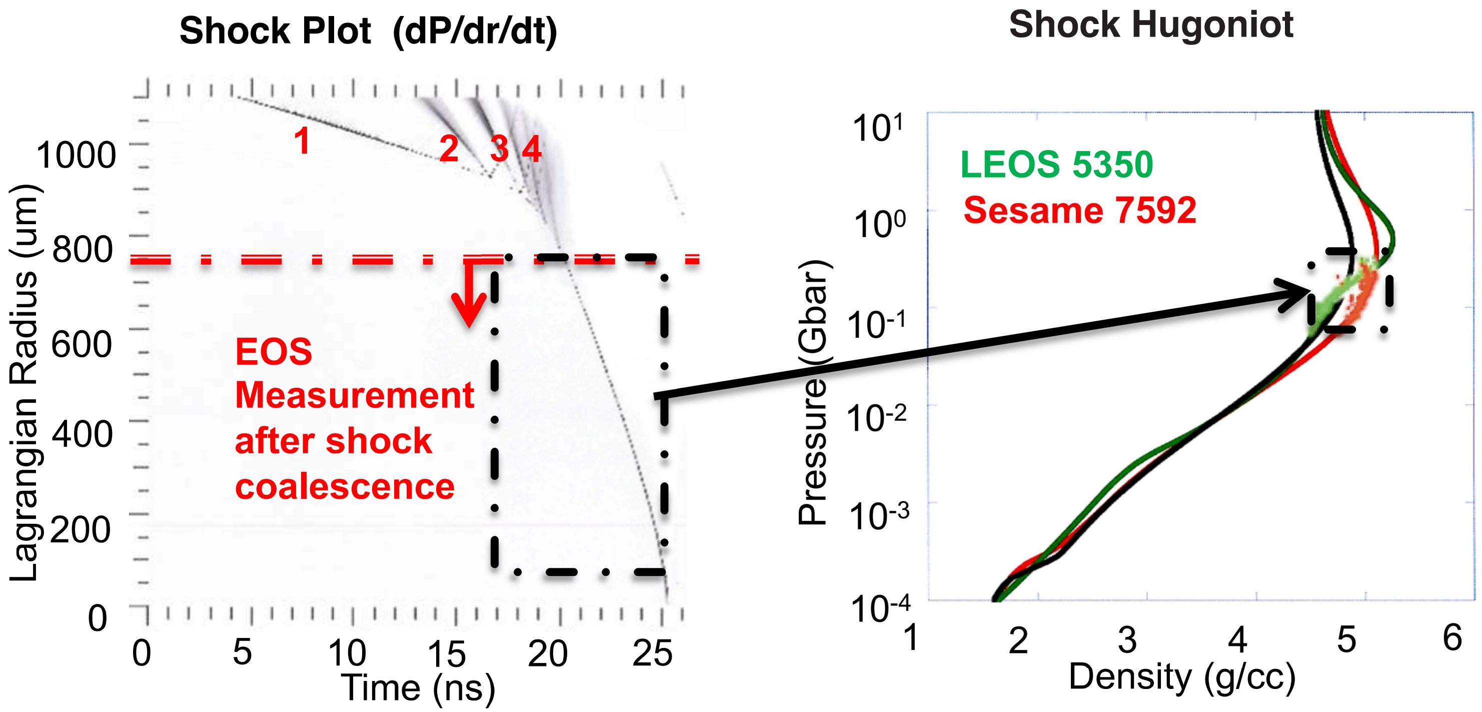
- The shock wave keeps ‘forgetting’ about past conditions,undergoing damped oscillation

Self emission from shock



The measured shock coming in and final shock flash are also very symmetric and has

We measure the shock Hugoniot after multiple shocks* from the laser pulse coalesce into one strong shock



Shock Plot (dP/dr/dt)

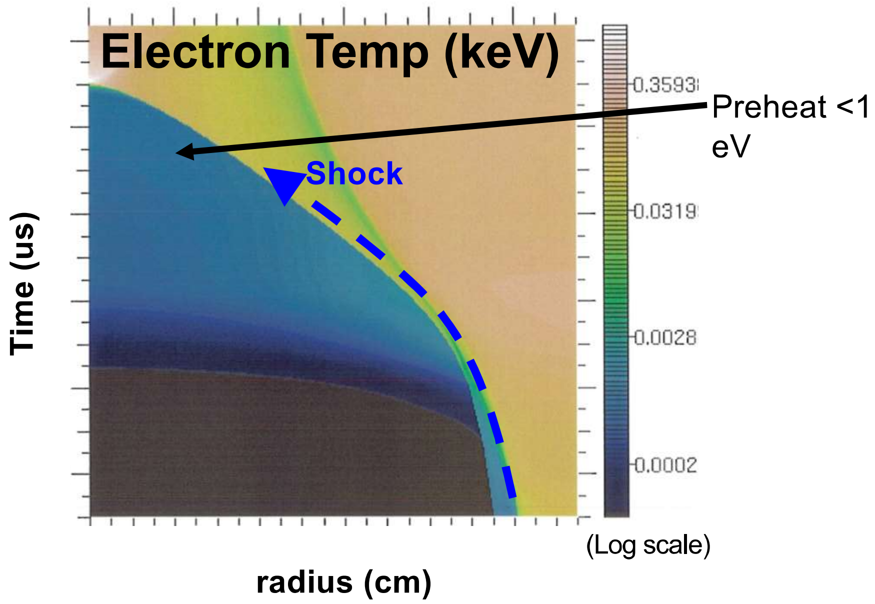
Shock Hugoniot

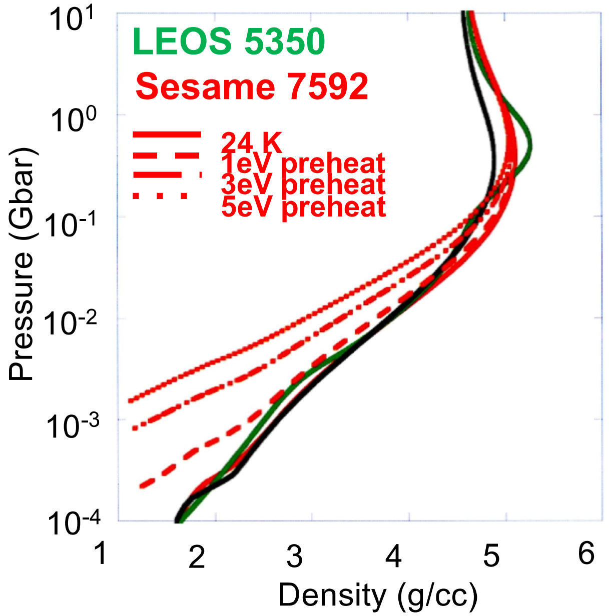
*example from 4 shock Gbar experiment

Radiation Hydrodynamic simulations follow input shock Hugoniot after coalescence

The doped ablator and solid sphere provides a shield against preheat from the hohlraum x-rays of the sample material

Hydra Simulations w/5x measured M-band

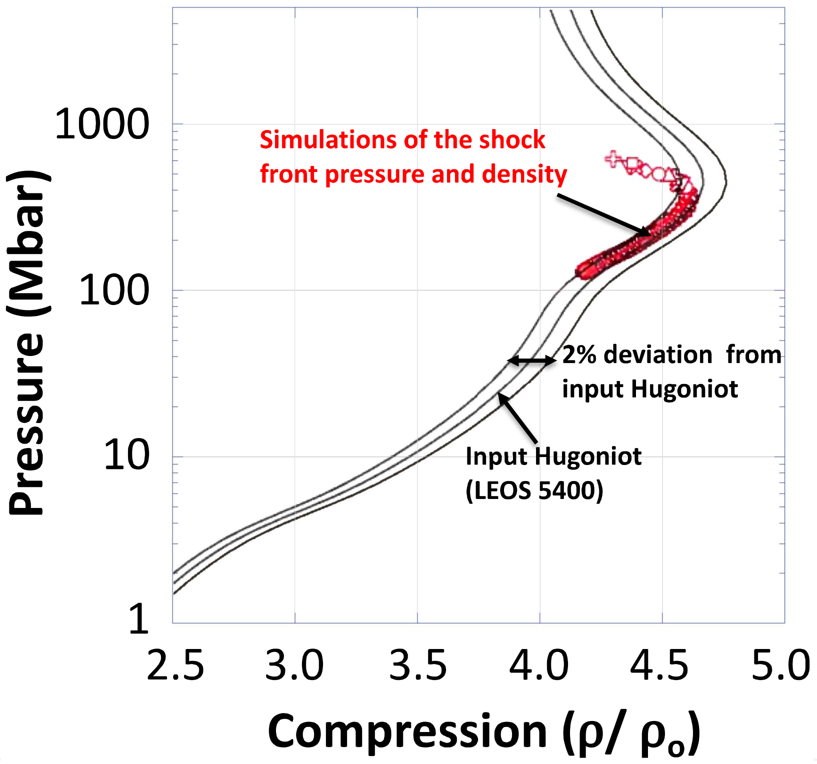




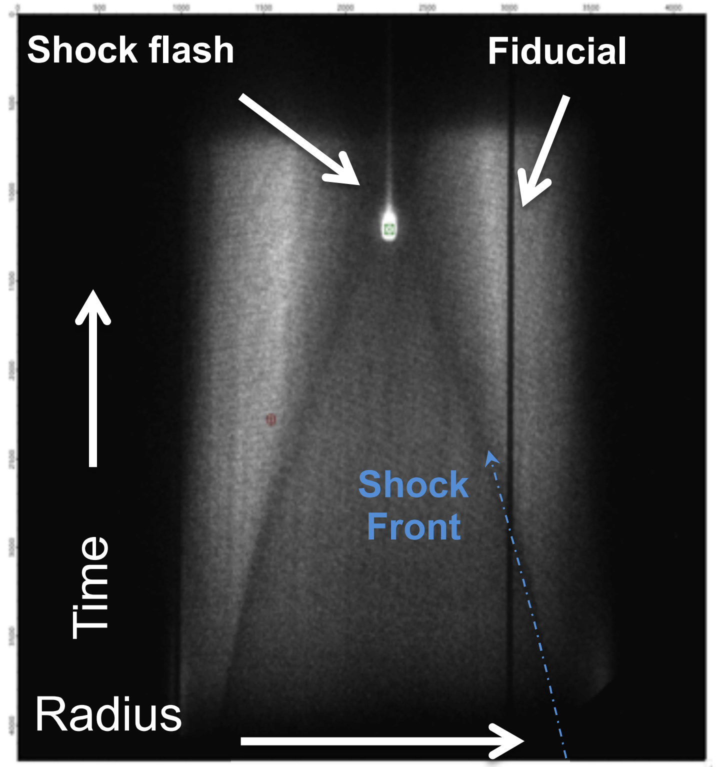
Preheat from the gold Hohlraum is predicted to be <2% effect on Hugoniot at low end of pressure range
At higher pressures bulk preheat at this level is insignificant

Later in time radiative preheat from the converving shock front can cause Hugoniot to roll over (density at shock front lower)

- We estimate this onset using radiation-hydrodynamic simulations (~450Mbar)
- We measure the shock front up to ~720 Mbar w
- Could further mine data at higher pressures, currently cut off at 450 Mbar



The density and pressure at the shock front are measured/inferred using streaked x-ray radiography



Rankine-Hugoniot Relations

Measured *from radiograph*

Measure Shock Speed *D*:

$$D^2 = v_0^2 \frac{p - p_0}{v_0 - v}$$

Measure ρ from the Transmitted photons

Measure Mass Density (unfolded from transmission*):

$$v = \frac{1}{\rho} = \text{Specific volume}$$

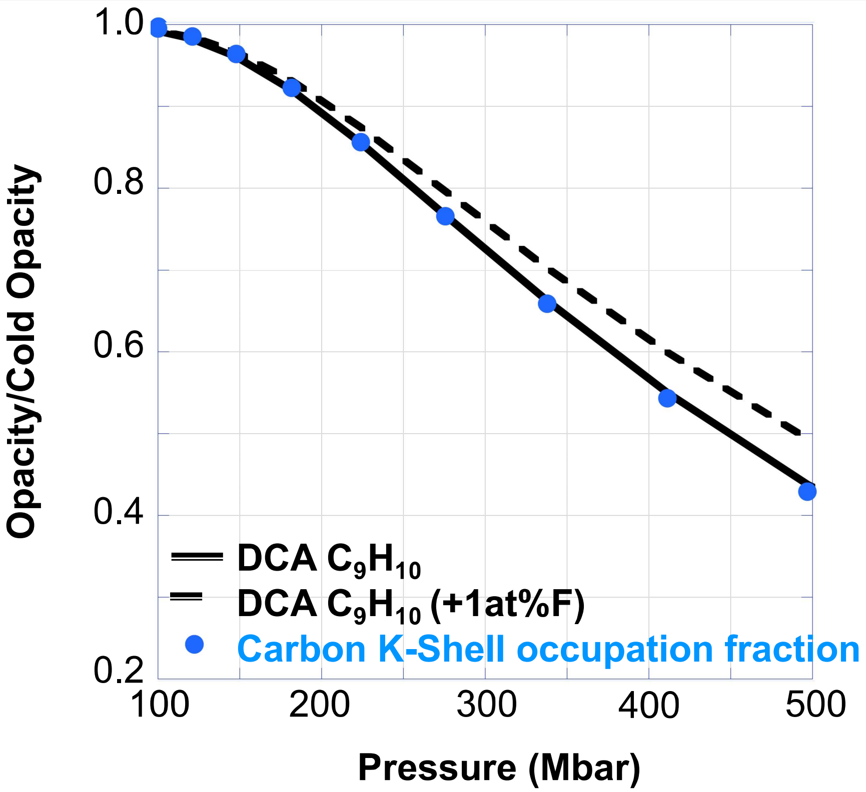
Use these to determine *P*

Infer Pressure :

$$p = p_0 + \frac{D^2}{v_0^2}(v_0 - v)$$

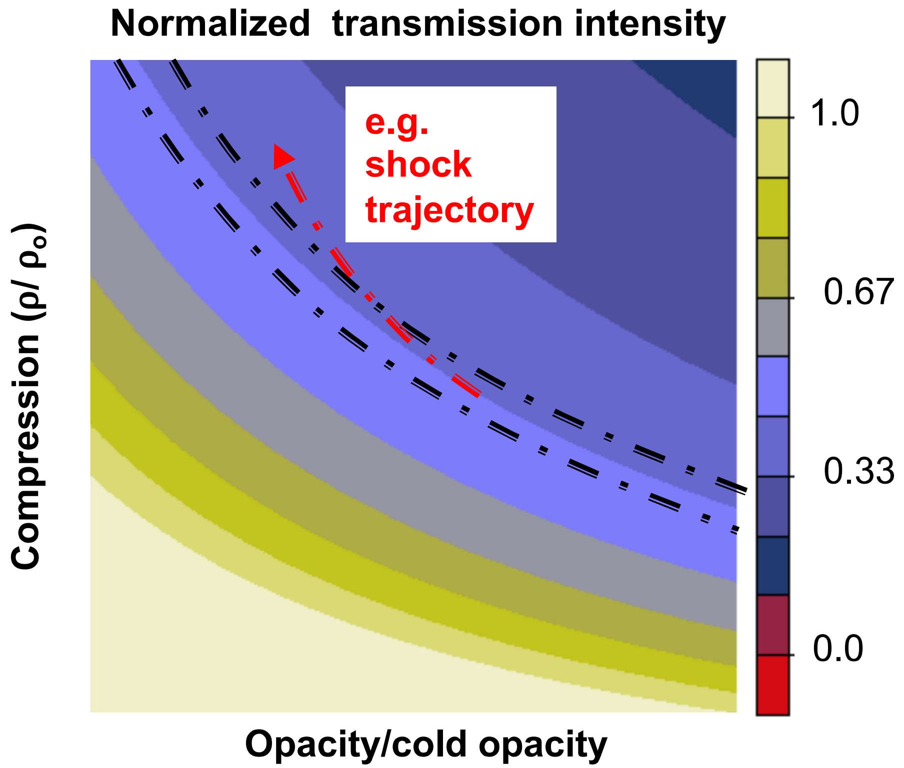
- → **With *P* and *ρ* we determine the Hugoniot**
- → **These are absolute EOS measurements that do not rely on a standard material**

The transmission radiograph is dependent on the material density *and* opacity



- Opacity deviates from cold opacity at high pressures due to shell ionization
- At pressures of 100 Mbar calculations show reduced opacity
- We simultaneously extract the density and opacity from the radiograph using a marker layer (basic concept next few slides)

For a given measured transmission intensity there is a range of compressions and opacities that can be inferred



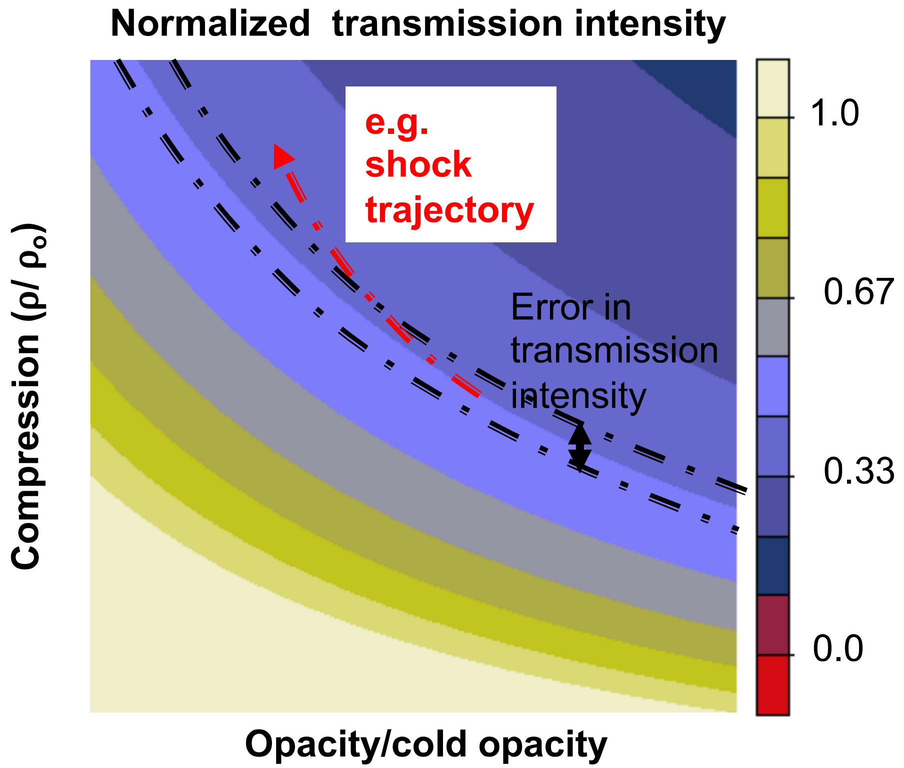
- As the shock converges the compression and opacity at the shock front moves through this plot

Attenuation

$$\frac{dI}{dl} = -I\mu\rho \qquad \mu\text{: opacity.}$$

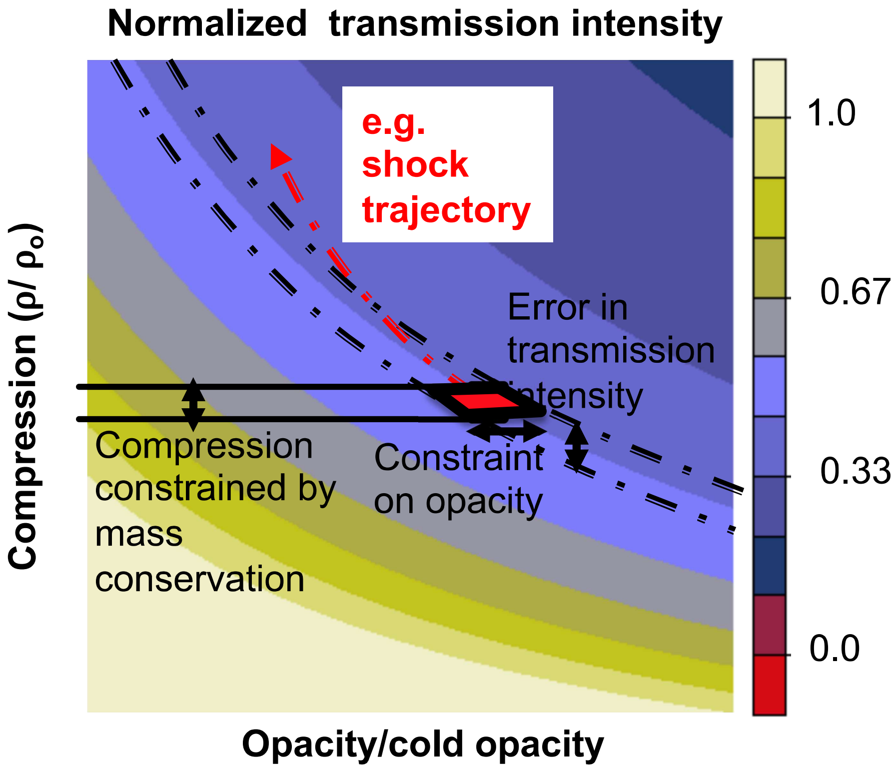
$$I = I_0 e^{-\mu\rho l}$$

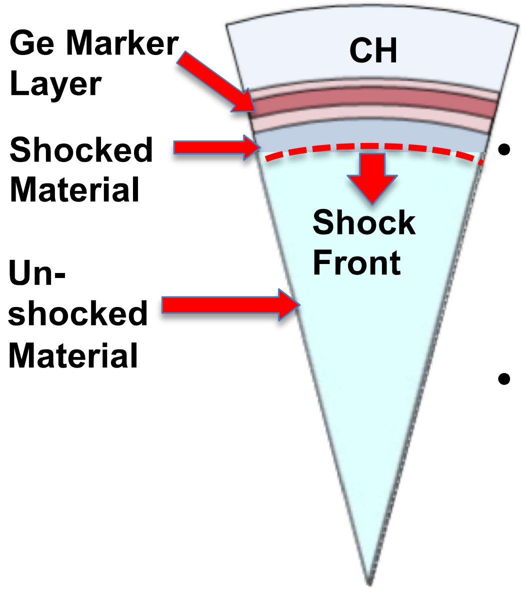
For a given measured transmission intensity there is a range of compressions and opacities that can be inferred



- As the shock converges the compression and opacity at the shock front moves through this plot
- There is also a range due to uncertainty in transmission measurement
- Transmission is measured as a function of time and radius

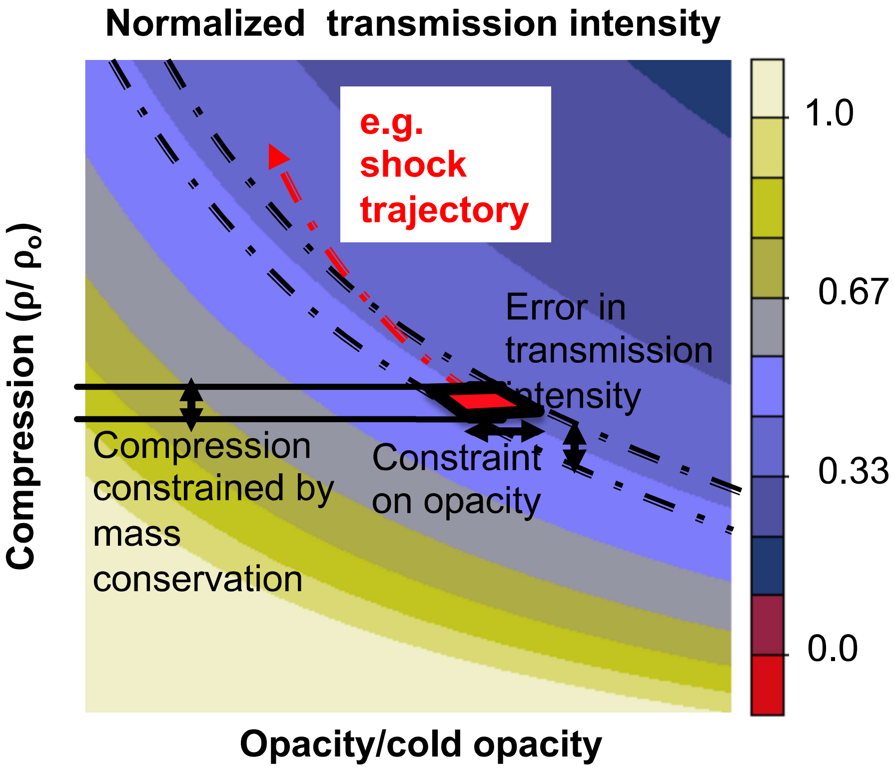
Radially resolved measurements enable determining the mass and volume of the shocked region using radiographic marker layer

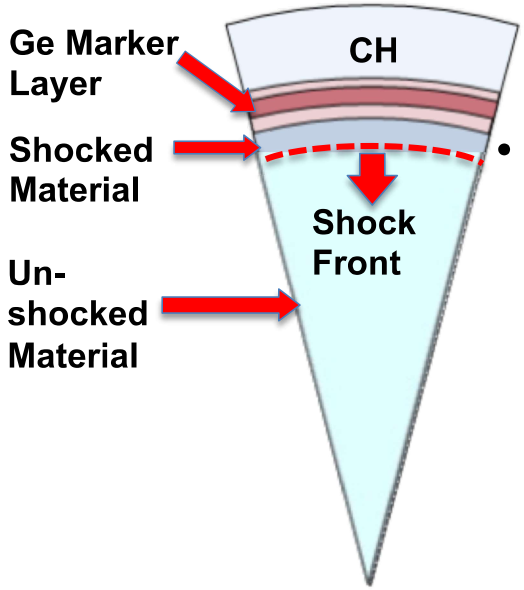




- In the shocked region, mass and volume is known
- This constrains opacity

Temporally resolved measurements further constrain density and opacity

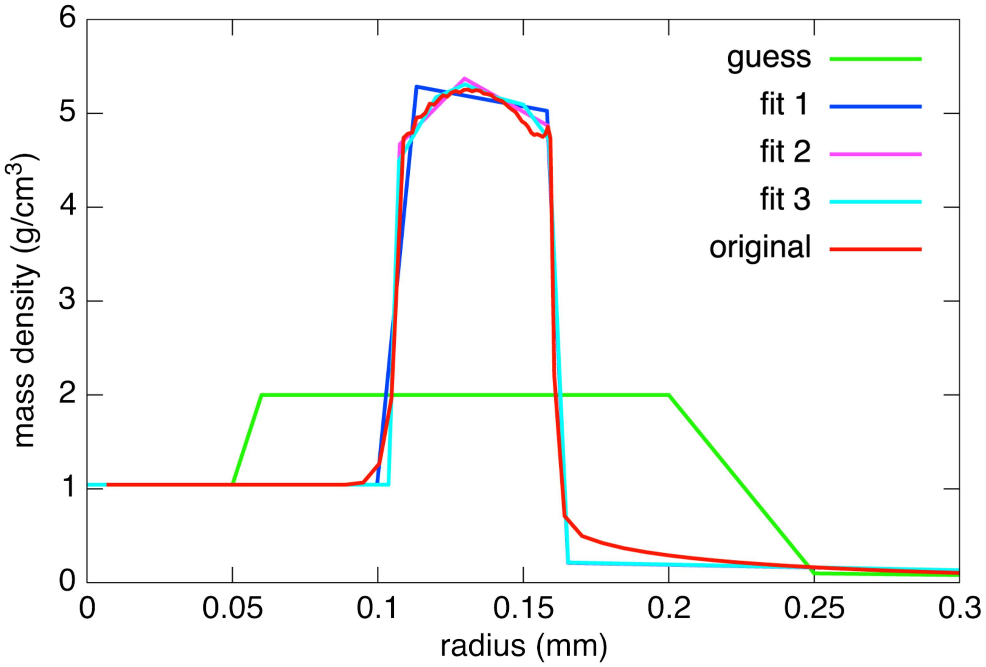




- Can only have smoothly varying opacity, no discontinuities

Radial profile matching further constrains the mass density and opacity due to known density ahead of the shock front

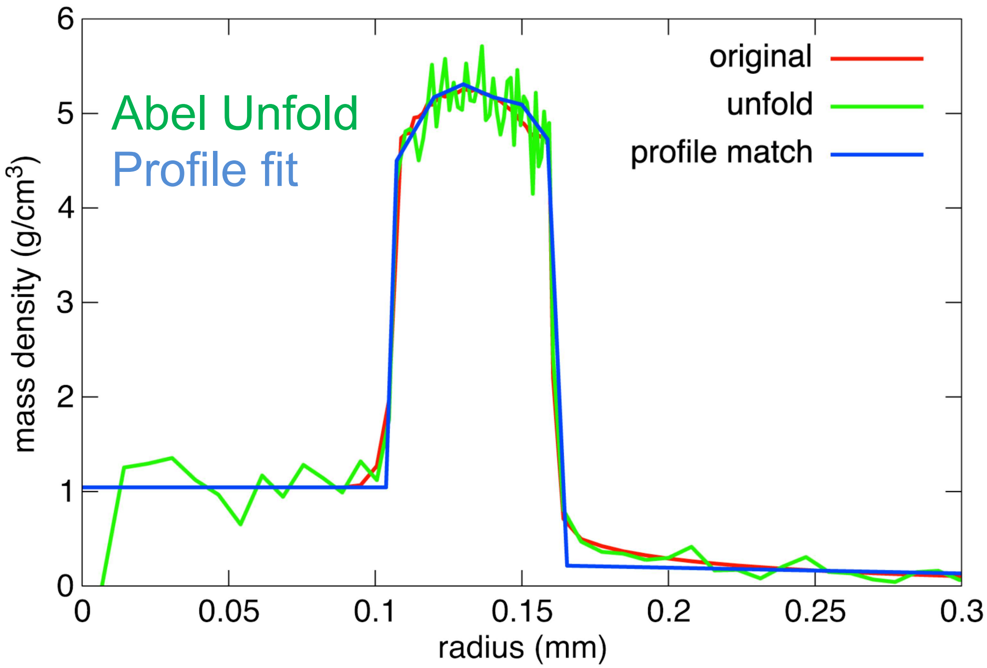
- Use a density profile with adjustable parameters (e.g. nodes) and constraints
- Simulate radiograph
- Adjust parameters for best fit
- Refine
- Solid target gives fiducial in-front of shock for profile matching (fit shock jump more accurately)



D. Swift

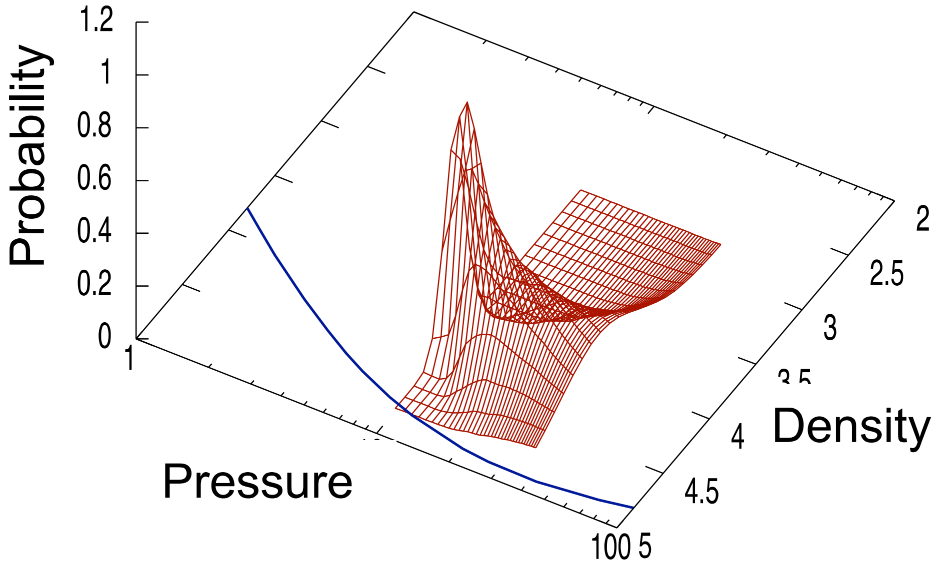
Compared to an Abel unfold profile matching is less noisy and better fits the input value

- Use a density profile with adjustable parameters (e.g. nodes) and constraints
- Simulate radiograph
- Adjust parameters for best fit
- Refine
- Solid target gives fiducial in-front of shock for profile matching (fit shock jump more accurately)



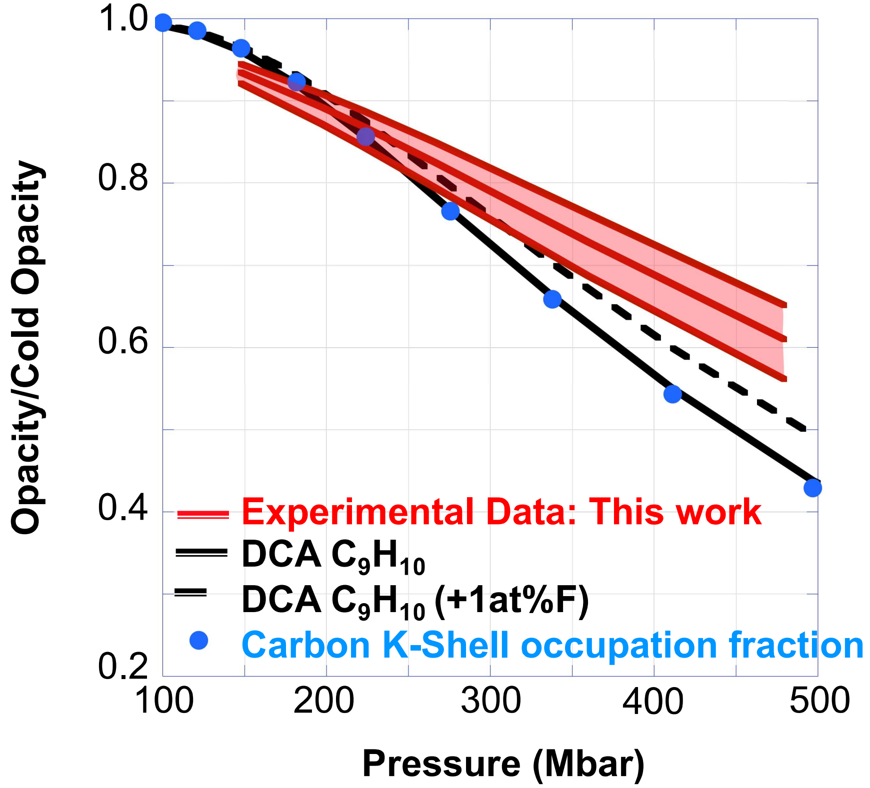
D. Swift

The best-fit to the radiograph gives a probability distribution over the entire radiograph for pressure and density



- Space-time profiles are fit simultaneously
- Uncertainty contours are taken as 1-sigma of probability distribution
- Now the results…

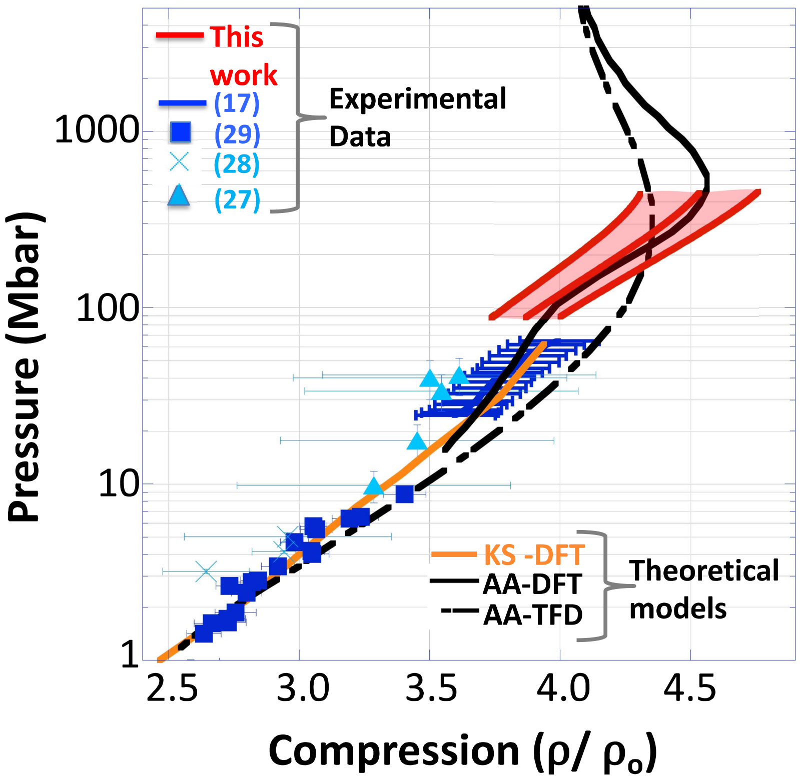
We measured a reduction in opacity at high pressures → significant ionization of the carbon inner shell



- Measured opacities are consistent with the modeling at pressures up to ~300 Mbar and slightly higher than theory at higher pressures.

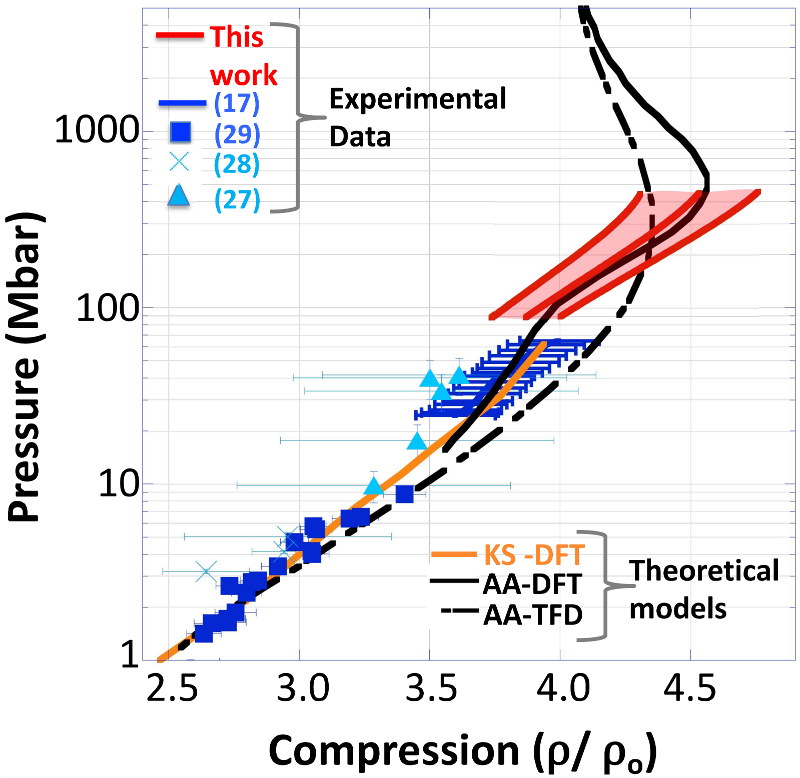
- The measured drop in opacity consistent with ~63% occupation at 450Mbar of Carbon K-shell.

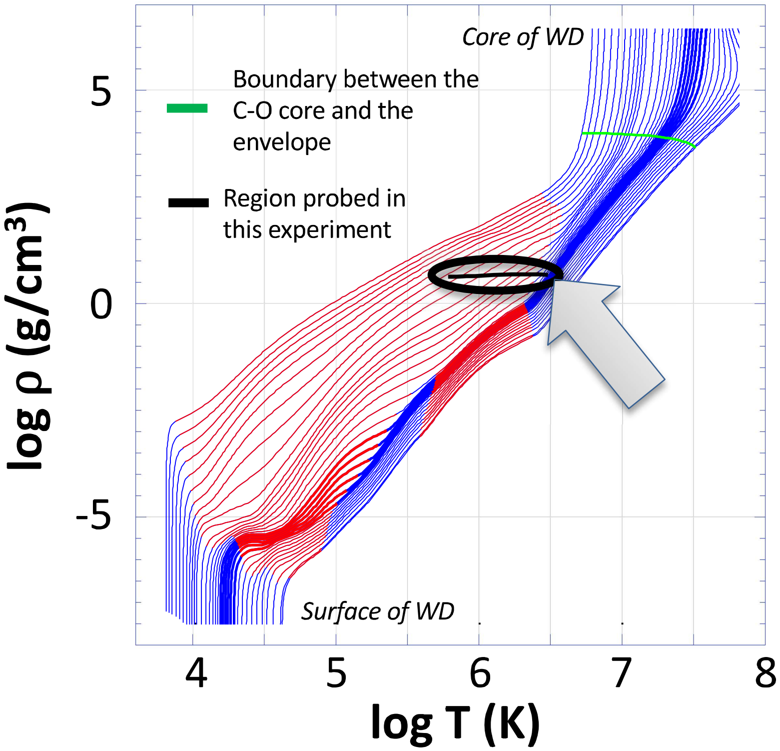
We measured the CH Hugoniot (Pressure vs density) from 100-450 Mbar which showed features related to electronic structure



Data agrees with equations of state models that include the electronic shell structure (e.g.AA-DFT) which show a sharper bend in the Hugoniot and higher maximum compression than models that lack electronic shells (e.g. AA-TFD)

This pressure range along the Hugoniot corresponds to the conditions in the envelope of white dwarf stars



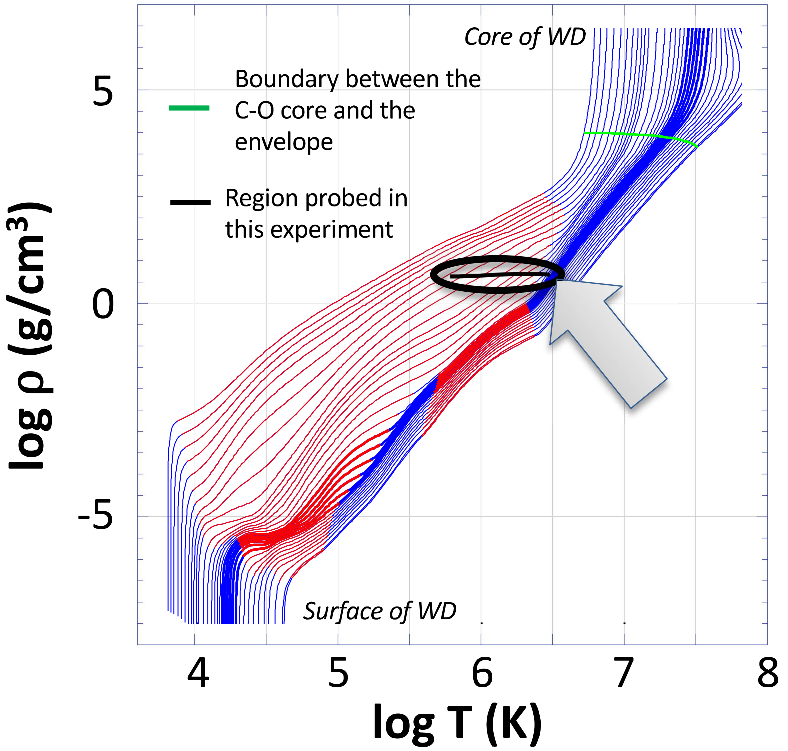


We probe deep in the convection zone which is the “weakest link” for constitutive physics of white dwarfs

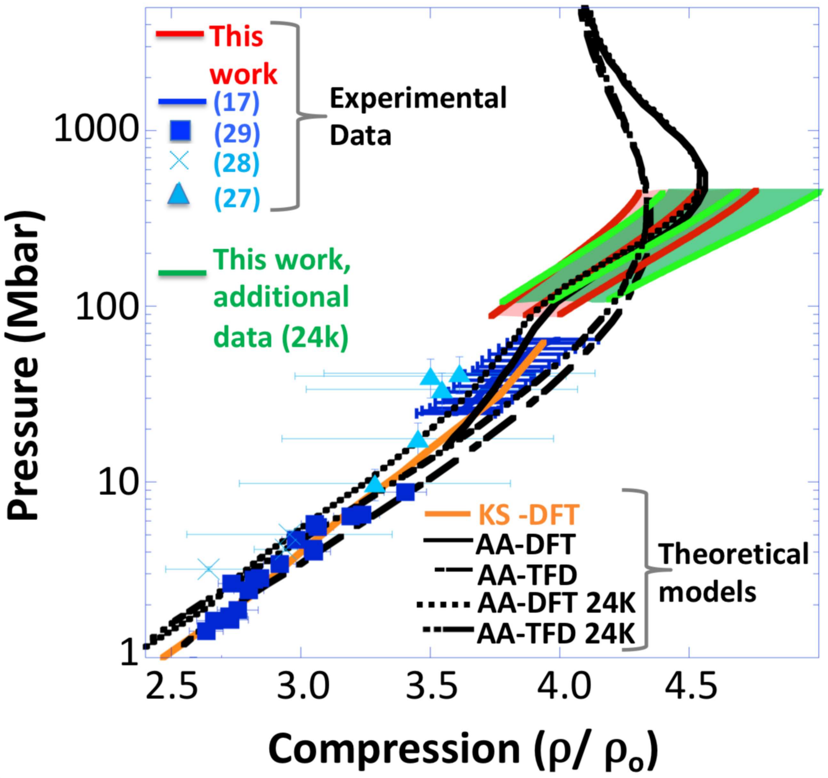
- EOS of WD envelopes are partially ionized, partially degenerate, non-ideal plasmas; called the “weakest link” in WD constitutive physics modeling --*Fontaine*

- Region most responsible for driving unstable pulsation modes and where models show the greatest variability

- Constraining EOS models here results in more accurate models of hot DQ stars (interior structures, pulsation properties, spectral evolution, and their complex origin)

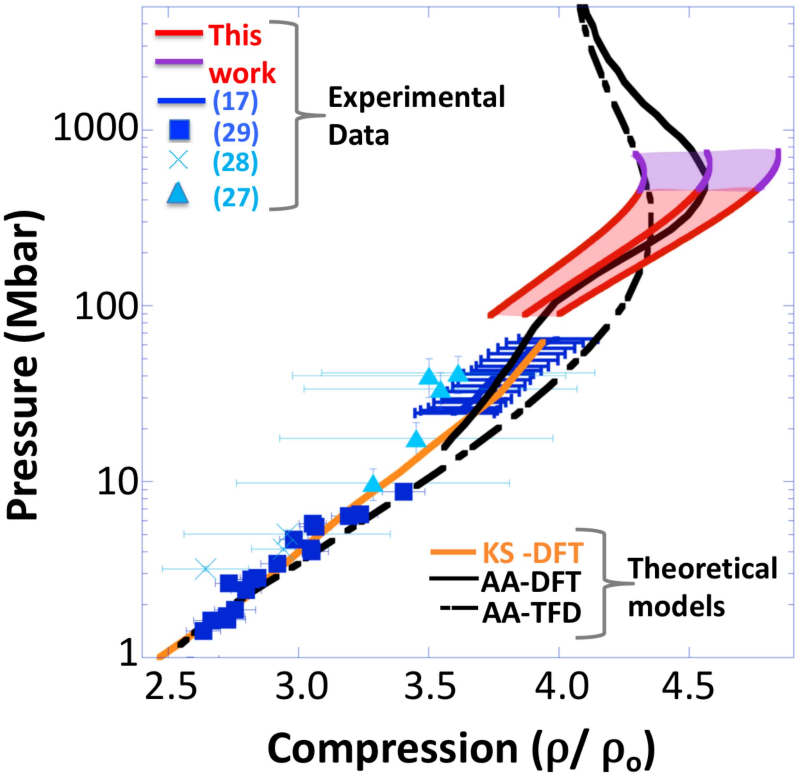


A repeat experiment at cryogenic temperatures was also in agreement



- Same target material
- Different laser pulse shape and hohlraum gave same results (looking after shock coalescence)
- Error bars are larger due to fewer number of backlighter beams on this shot

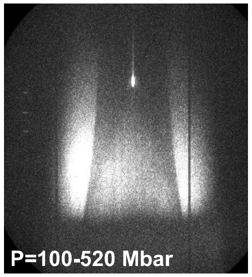
The streak record extends to higher pressures but additional analysis is needed to account for radiation from the shock front



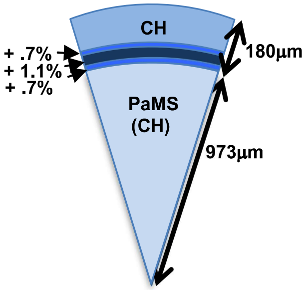
- Radiation from shock front calculated to preheat material ahead of shock at these pressures
- Data does not show significant “roll over” to lower density
- We can test experimentally by reaching higher pressure at larger radii

We obtained high quality data for 3 materials, over a range of pressures, in two different ICF relevant hohlraums

CH



E_L=1.3 MJ
Gas filled (cryo)



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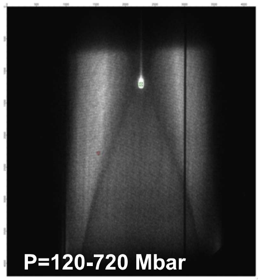
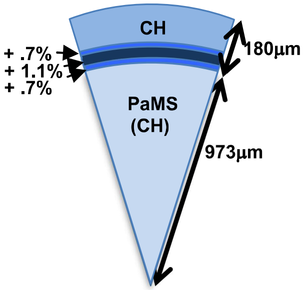


E_L=1.1 MJ
Near Vacuum (RT)



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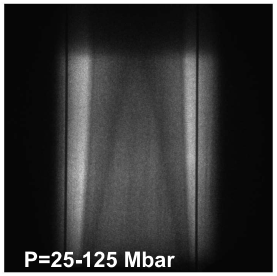
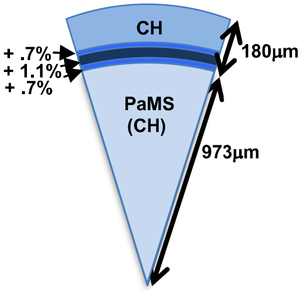
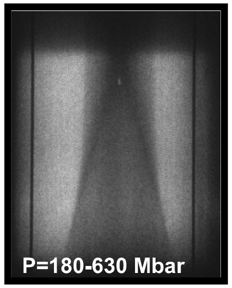


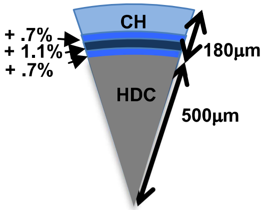
E_L=0.3 MJ
Near Vacuum (RT)



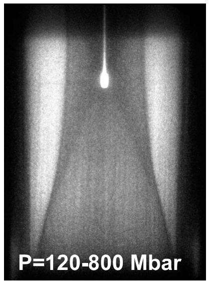
HDC



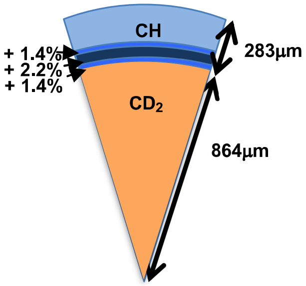
E_L=0.8 MJ
Near Vacuum (RT)



CD_2

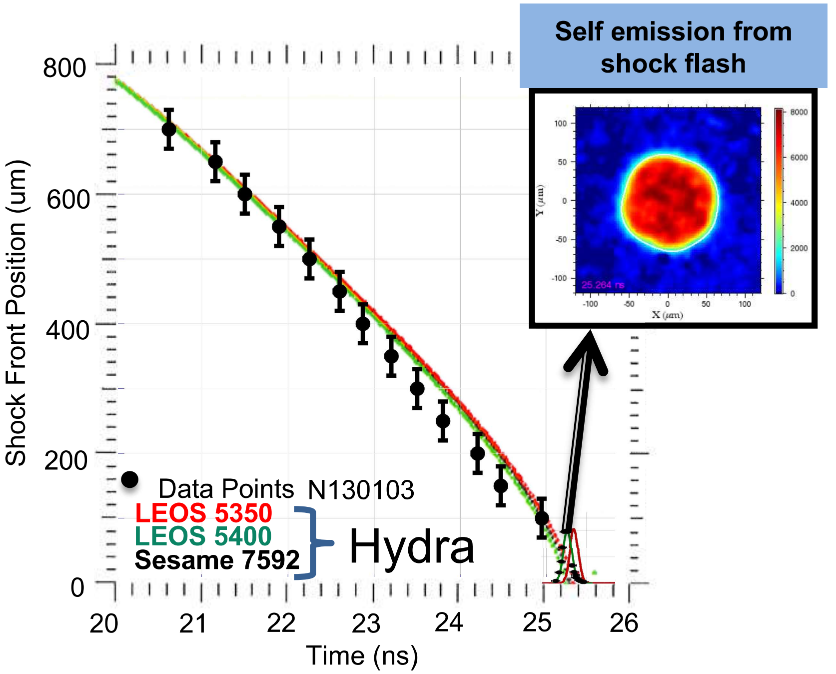


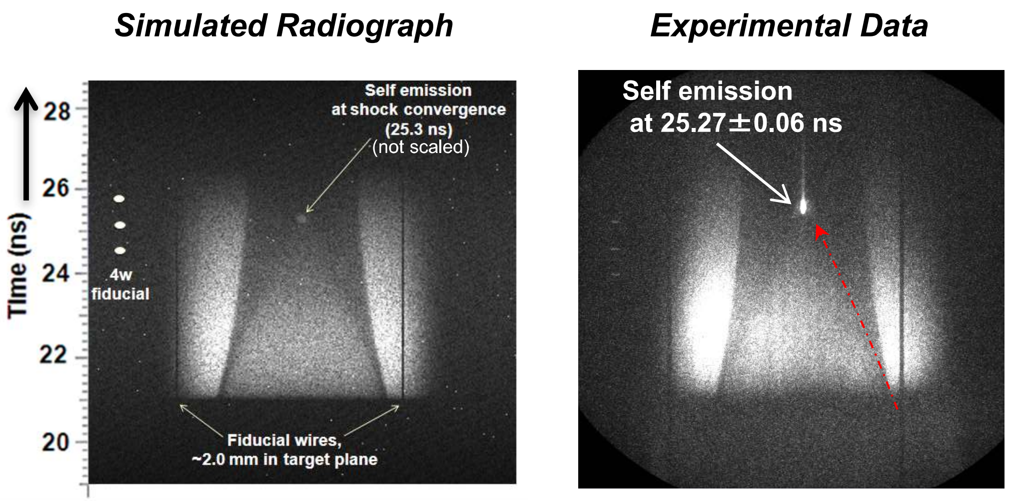
E_L=1.1 MJ
Near Vacuum(RT)



More data obtained since this campaign by the program, stay tuned for future publications…

The data also provides tests of radiation hydrodynamic modeling of integrated NIF experiments (hohlraum and capsules)



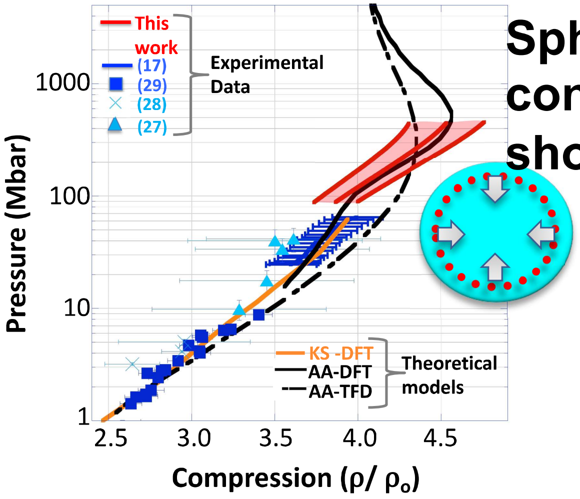

Simulated Radiograph

Experimental Data

e.g. Cryogenic CH experiment (N130103)

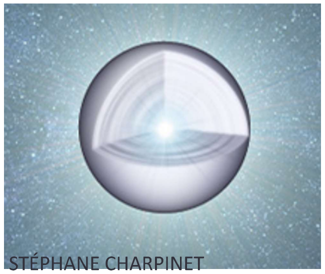
Radiation hydrodynamic calculations using HYDRA used to design the experiment show a good match to data

We have measured the EOS of matter to the highest pressures ever achieved in the laboratory



Spherically converging shock waves

Accessed conditions in envelopes of white dwarf stars


STÉPHANE CHARPINET

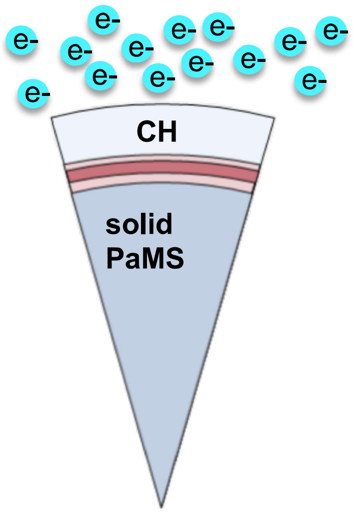
- We measure the Hugoniot of hydrocarbon, up to 450 Mbar
- The observed maximum compressibility is consistent with theoretical models that include detailed electronic structure and an increase in compressibility due to ionization of the inner core orbitals of carbon
- Here we directly probe the weakest link in constitutive physics of white dwarf modeling

This work was recently accepted to Nature

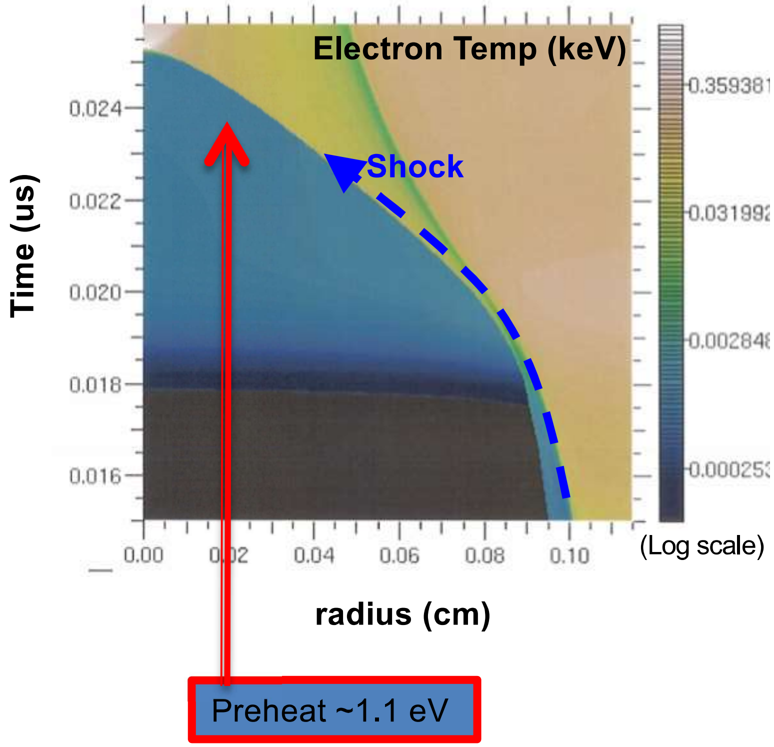
Lawrence Livermore
National Laboratory

The hot electron preheat is estimated to be ~1 eV estimated from measured hard x-ray emission (*FFLEX)*

Hot electron source applied to capsule only simulations



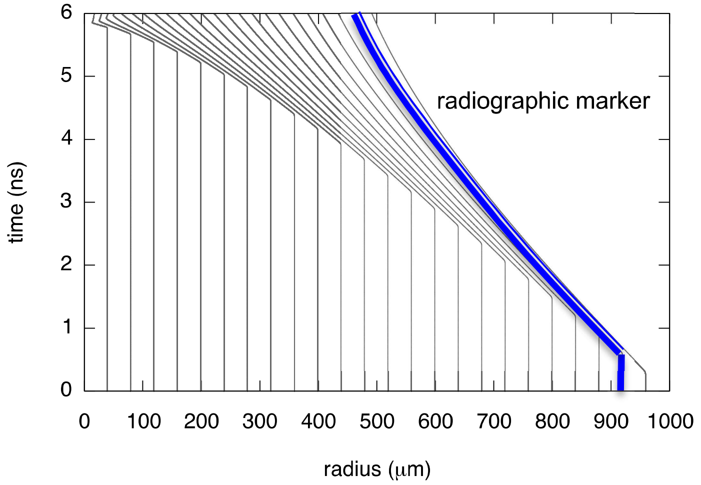
Used a tuned source w/ similar pulse shape *(H. Robey*) w/more hot electrons (FFLEX, TI)

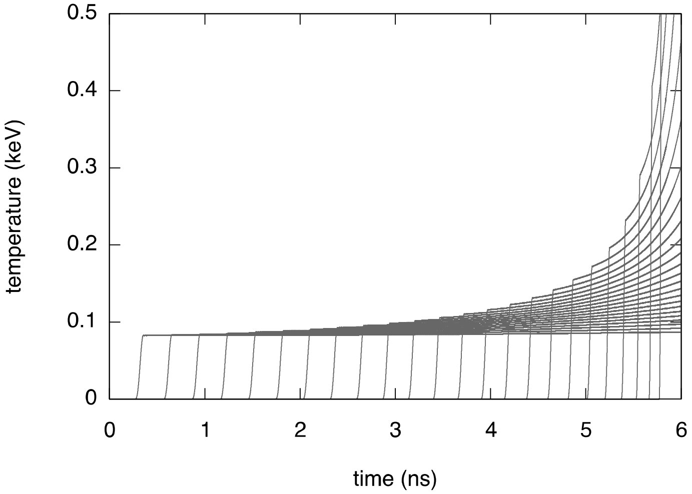


Preheat ~1.1 eV

Opacity change: dominated by shock heating

Need to assume opacity of compressed material remains known at later times.
Temperature is dominated by initial shock heating.
Assume this sets opacity; could correct using a model.





If opacity *only* changes on shocking,
obtain from change in apparent mass:

$$\mu_0 \frac{dm}{dt} = 4\pi r_s^2 \rho_0 D(\mu_s - \mu_0) \Leftrightarrow \mu_s = \mu_0 \left(1 + \frac{dm/dt}{4\pi r_s^2 \rho_0 D}\right)$$

Auspices Statement

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC.