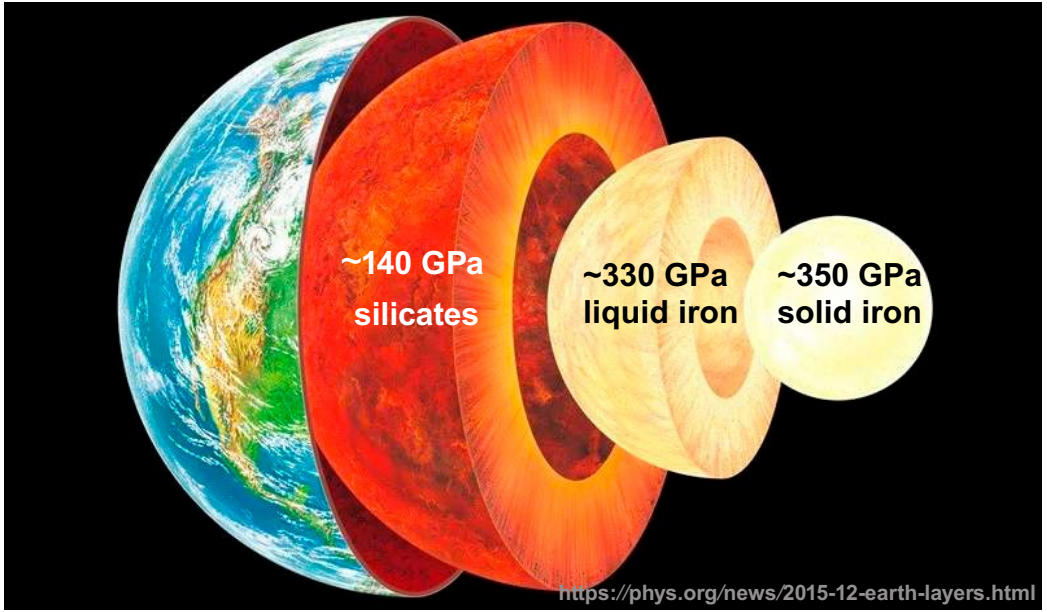
Measurements of Sound Speed in Iron Shock-Compressed to ~1 TPa



M. Huff
University of Rochester
Laboratory for Laser Energetics

60th Annual Meeting of the American Physical Society Division of Plasma Physics
Portland, OR
5–9 October 2018

The sound speed in shock-compressed iron was measured using arrival times of pressure perturbations

- At high pressure, the sound speed provides information about thermodynamic derivatives ($c_s^2 = \left.\frac{dP}{d\rho}\right|_s$) of the equation of state, which are relevant to core formation and dynamo physics.
- The bulk sound speed is calculated with the Nonsteady Waves method* from transit times of pressure perturbations in shocked materials.
- Iron shocked to 927 GPa has a sound speed of ~14.7$\pm$1.5 km/s.
- These pressures are similar to those in the interior of a 2.5-$M_\oplus$ planet.

*D. E. Fratanduono, et al., J. Appl. Phys. 116, 033517 (2014).

Collaborators

J. R. Rygg, G. W. Collins, T. R. Boehly, M. Zaghoo, D. N. Polsin, B. J. Henderson, and L. E. Crandall

University of Rochester

Laboratory for Laser Energetics

D. E. Fratanduono, M. Millot, R. F. Smith, J. H. Eggert, P. M. Celliers, and M. C. Gregor

Lawrence Livermore National Laboratory

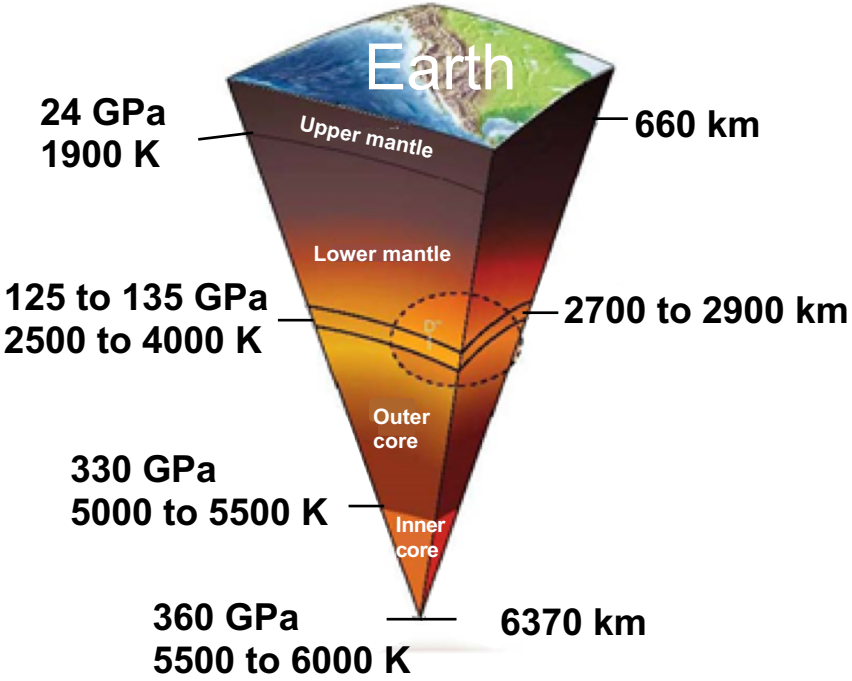
C.A. McCoy

Sandia National Laboratories

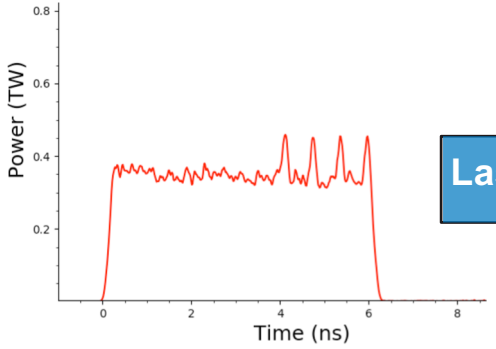
Sound velocity in metals at extreme pressures provides information about core conditions in Super-Earth planets

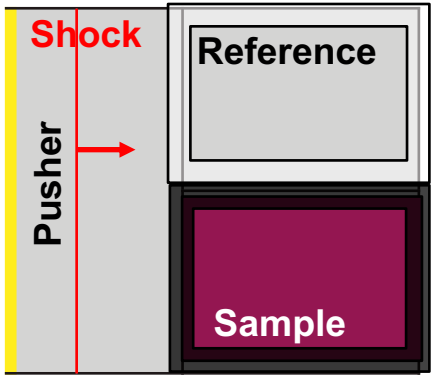
- Pressures and temperatures up to ~1.6 TPa are expected in large, rocky exoplanets at 10 $M_{\oplus}$

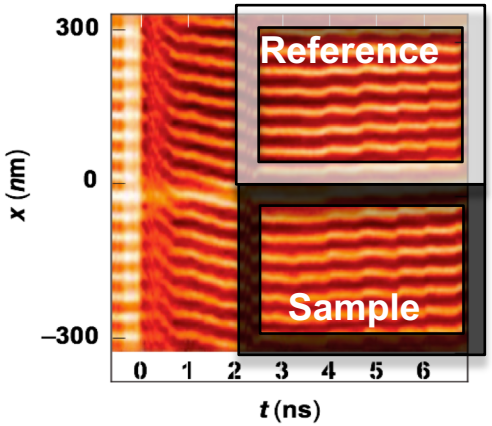
- Constraints on iron sound speed can help interpret seismological data and determine core boundaries

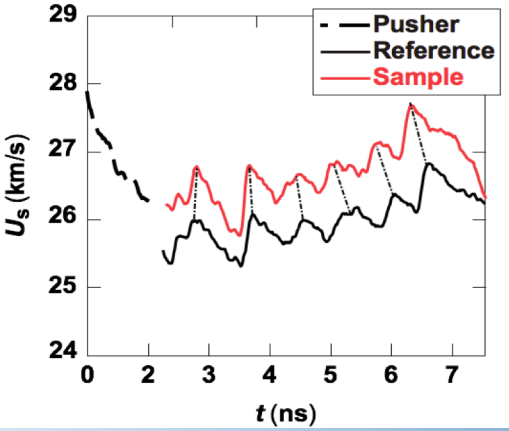


Modulations in the laser drive applied uniformly across a sample and reference are used to infer relative sound speed in the shocked samples





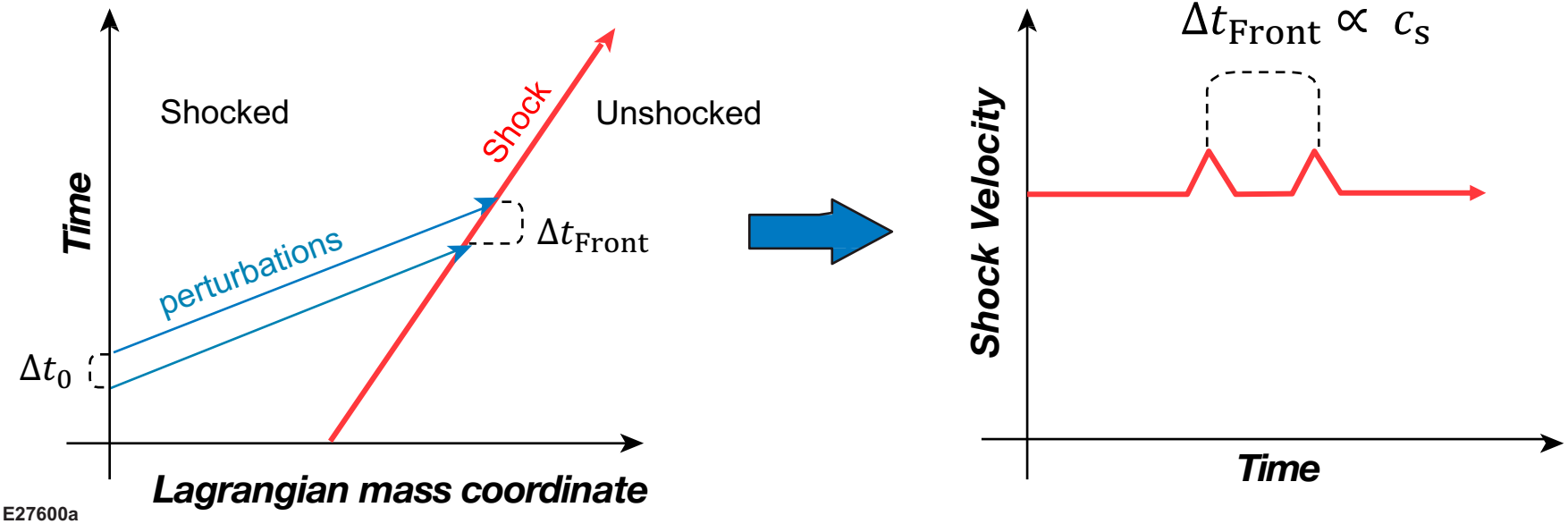




- Transit times are proportional to sound speed
- Referenced to quartz**

*Velocity interferometry system for any reflector
**C.A. McCoy *et al.*, J. Appl. Phys. 120, 235901 (2016).

Perturbations in drive pressure travel at the local sound velocity to catch up with the shock front



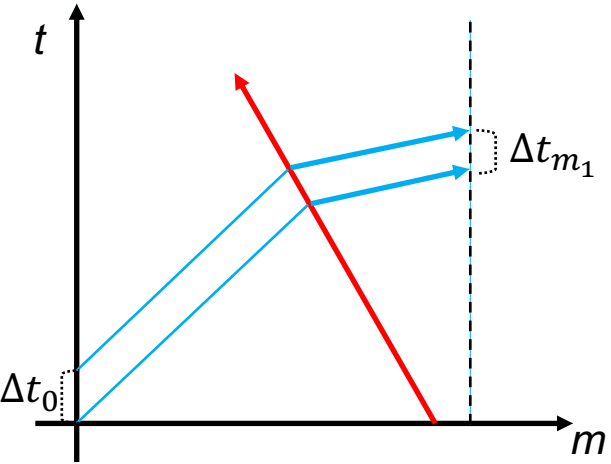
E27600a

Transmission coefficients for temporal and amplitude changes can be calculated for perturbations traversing regions of various states

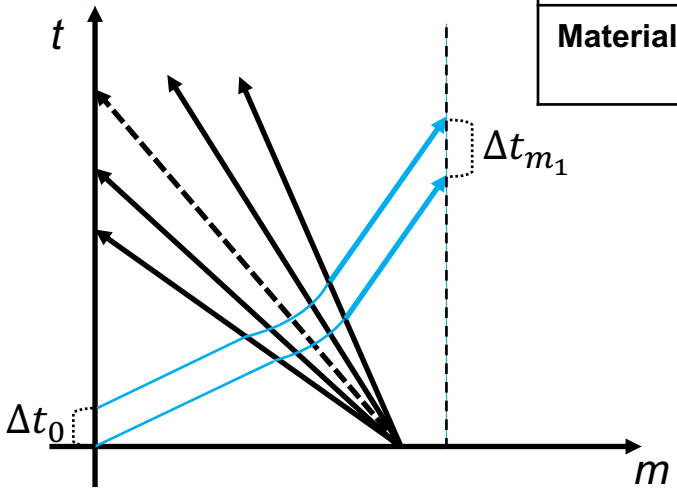
- Sound-speed calculations depend on only the temporal coefficients
- Coefficients depend on the Mach number of the two regions

Receding shock	$\frac{\Delta t_{\text{Front}}}{\Delta t_0} = \frac{1}{1 - M_1}$
Counter-propagating shock	$\frac{\Delta t_{m1}}{\Delta t_0} = \frac{1 + M_1}{1 - M_0}$
Rarefaction	$\frac{\Delta t_{m1}}{\Delta t_0} = \frac{1 + M_1}{1 - M_0}$
Material interface	$\frac{\Delta t_{m_1}}{\Delta t_0} = 1$

Counter-propagating Shock



Rarefaction



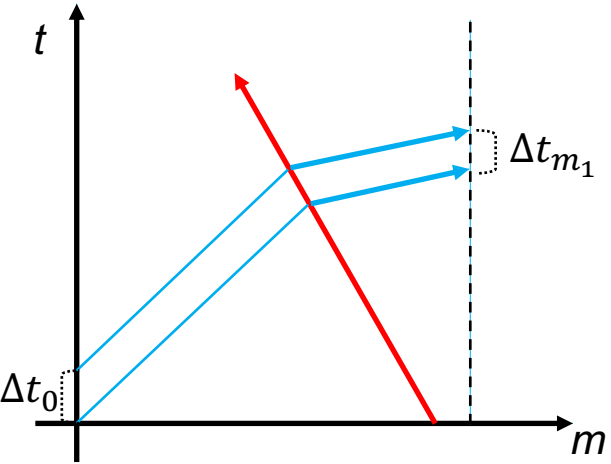
$$M_n = \frac{P_n}{u_n \rho_n c_{s,n}}$$

Transmission coefficients for temporal and amplitude changes can be calculated for perturbations traversing regions of various states

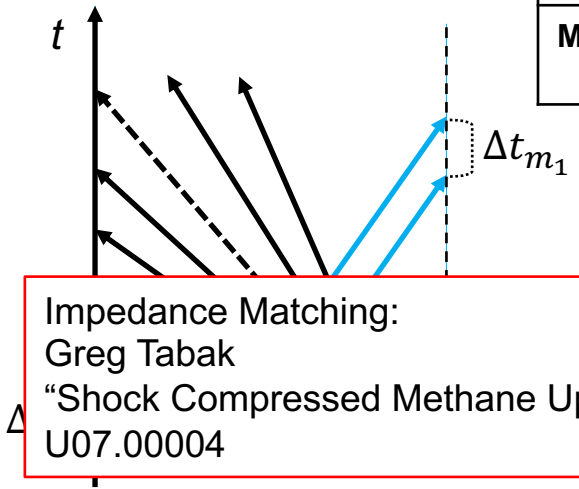
- Sound-speed calculations depend on only the temporal coefficients
- Coefficients depend on the Mach number of the two regions

Receding shock	$\frac{\Delta t_{\mathrm{Front}}}{\Delta t_0} = \frac{1}{1 - M_1}$
Counter-propagating shock	$\frac{\Delta t_{m1}}{\Delta t_0} = \frac{1 + M_1}{1 - M_0}$
Rarefaction	$\frac{\Delta t_{m1}}{\Delta t_0} = \frac{1 + M_1}{1 - M_0}$
Material interface	$\frac{\Delta t_{m_1}}{\Delta t_0} = 1$

Counter-propagating Shock



Rarefaction



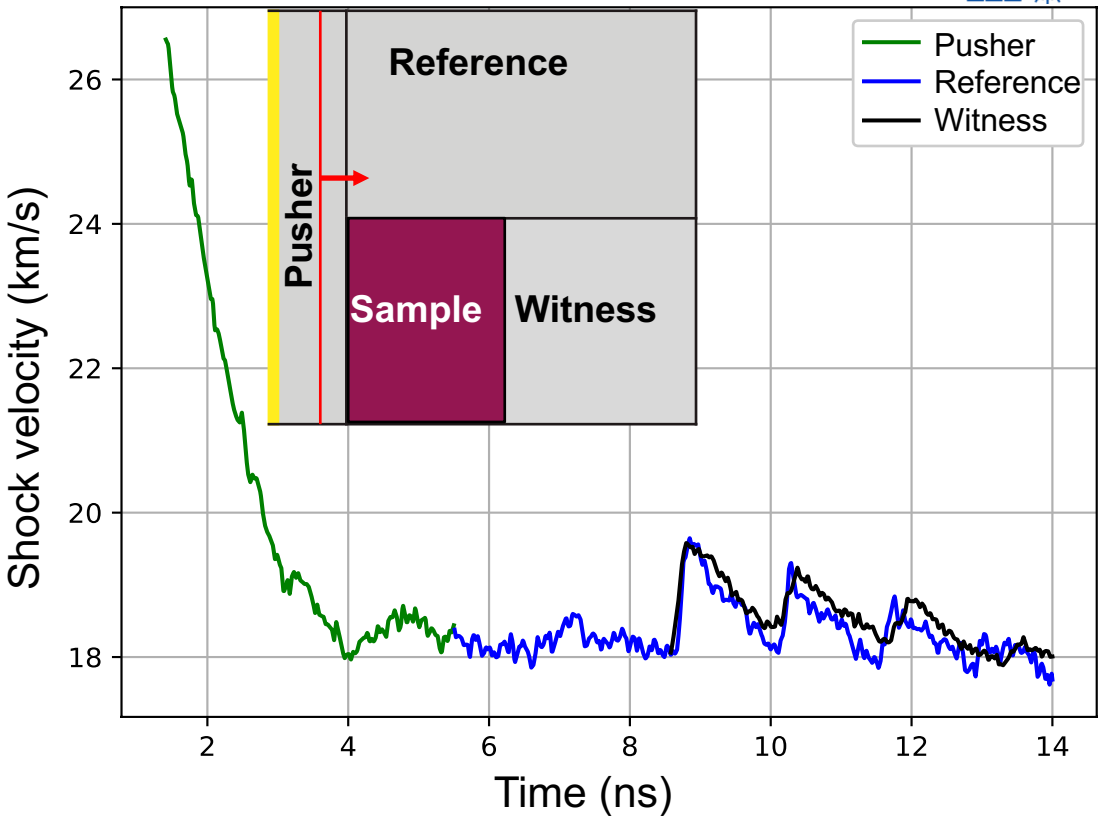
Impedance Matching:
Greg Tabak
"Shock Compressed Methane Up to 400 GPa"
U07.00004

$$M_n = \frac{P_n}{u_n \rho_n c_{s,n}}$$

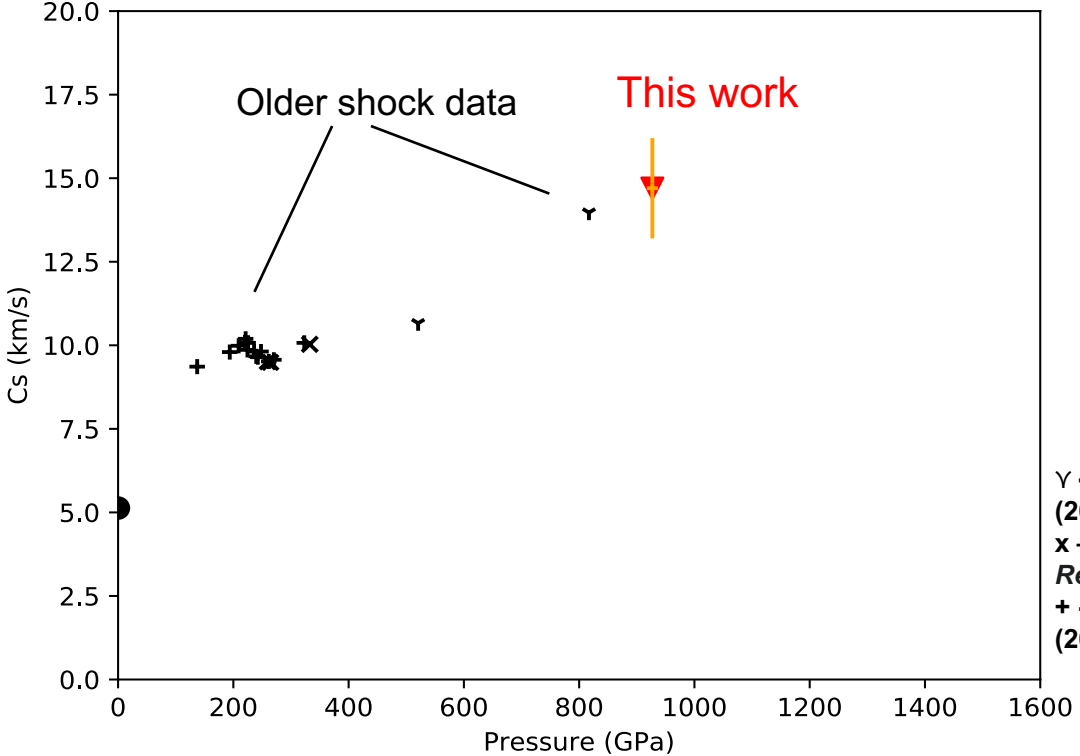
Since iron is opaque, the perturbations must be observed AFTER they have traversed the iron sample

- **A quartz witness on the rear of the iron provides a measurement of perturbations that transited the iron**

- **At ~1 TPa, there are only minor differences in arrival times; therefore iron and quartz must have similar sound speeds**

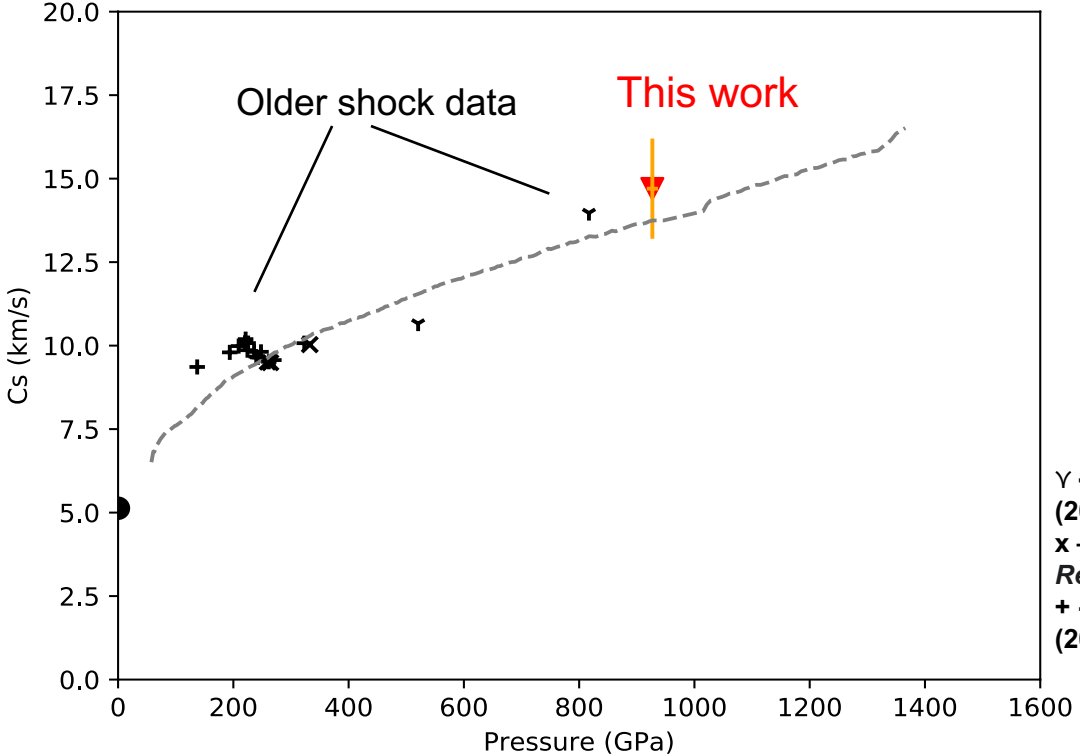


The sound speed was measured in shock-compressed iron to 927 GPa, comparable to the pressure of a 2.5-$M_{\oplus}$ planet



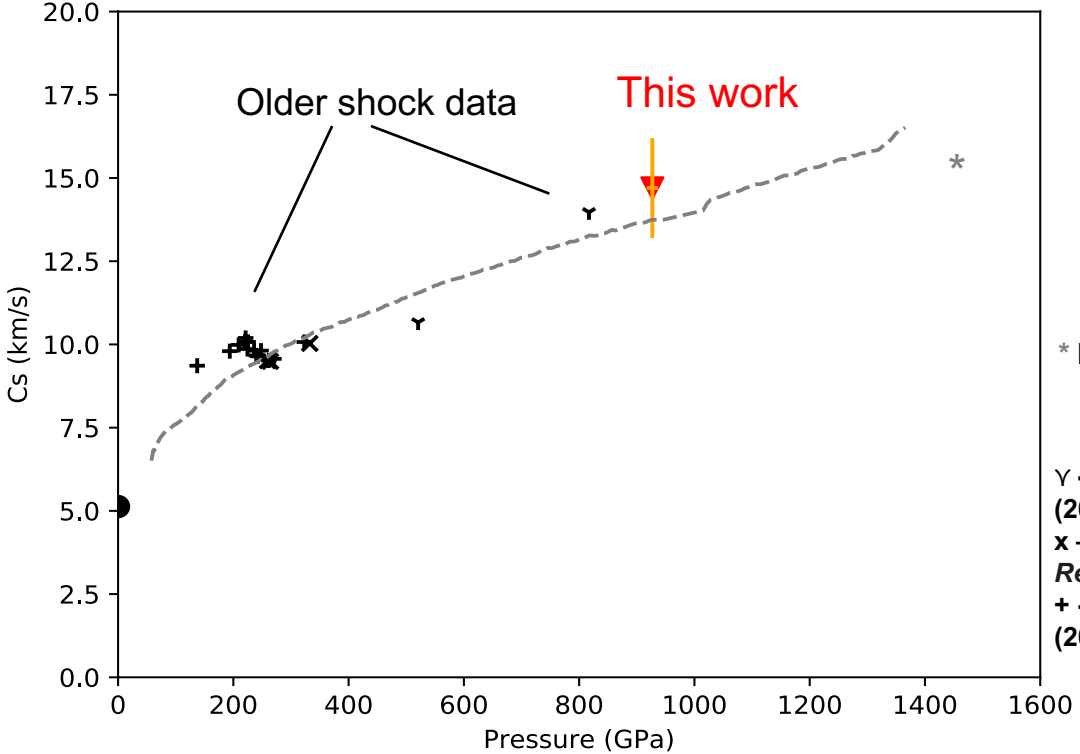
ϒ - J. H. Nguyen and N. C. Holmes, *Nature* 427,339 (2004).
x – J. M. Brown and R. G. McQueen, *J. Geophys. Res.*, 91(B7), 7485–7494 (1986).
+ - Sakaiya,et al, *Earth Planet. Sci. Lett.* 392, 80-85, (2014).

The sound speed was measured in shock-compressed iron to 927 GPa, comparable to the pressure of a 2.5-$M_{\oplus}$ planet



ϒ - J. H. Nguyen and N. C. Holmes, *Nature* 427,339 (2004).
x – J. M. Brown and R. G. McQueen, *J. Geophys. Res.*, 91(B7), 7485–7494 (1986).
+ - Sakaiya,et al, *Earth Planet. Sci. Lett.* 392, 80-85, (2014).

The sound speed was measured in shock-compressed iron to 927 GPa, comparable to the pressure of a 2.5-$M_\oplus$ planet



* R. F. Smith, et al., *Nature*, 2, 452–458, (2018)

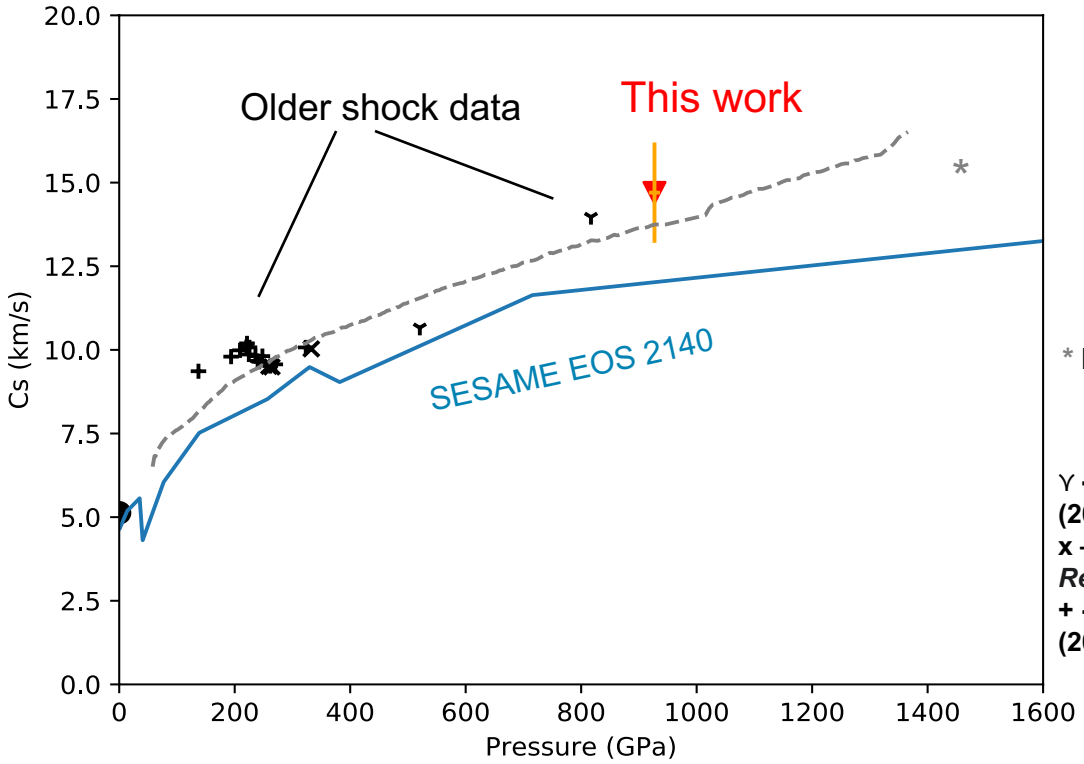
$$(C_E^H)^2 = V^2\left[\left(\frac{\delta P}{\delta V}\right)_H\left[(V_0 - V)\frac{\gamma}{2V} - 1\right] + \frac{P\gamma}{2V}\right]$$

ϒ - J. H. Nguyen and N. C. Holmes, *Nature* 427,339 (2004).

x – J. M. Brown and R. G. McQueen, *J. Geophys. Res.*, 91(B7), 7485–7494 (1986).

\+ - Sakaiya,et al, *Earth Planet. Sci. Lett.* 392, 80-85, (2014).

The sound speed was measured in shock-compressed iron to 927 GPa, comparable to the pressure of a 2.5-$M_{\oplus}$ planet



* R. F. Smith, et al., *Nature*, 2, 452–458, (2018)

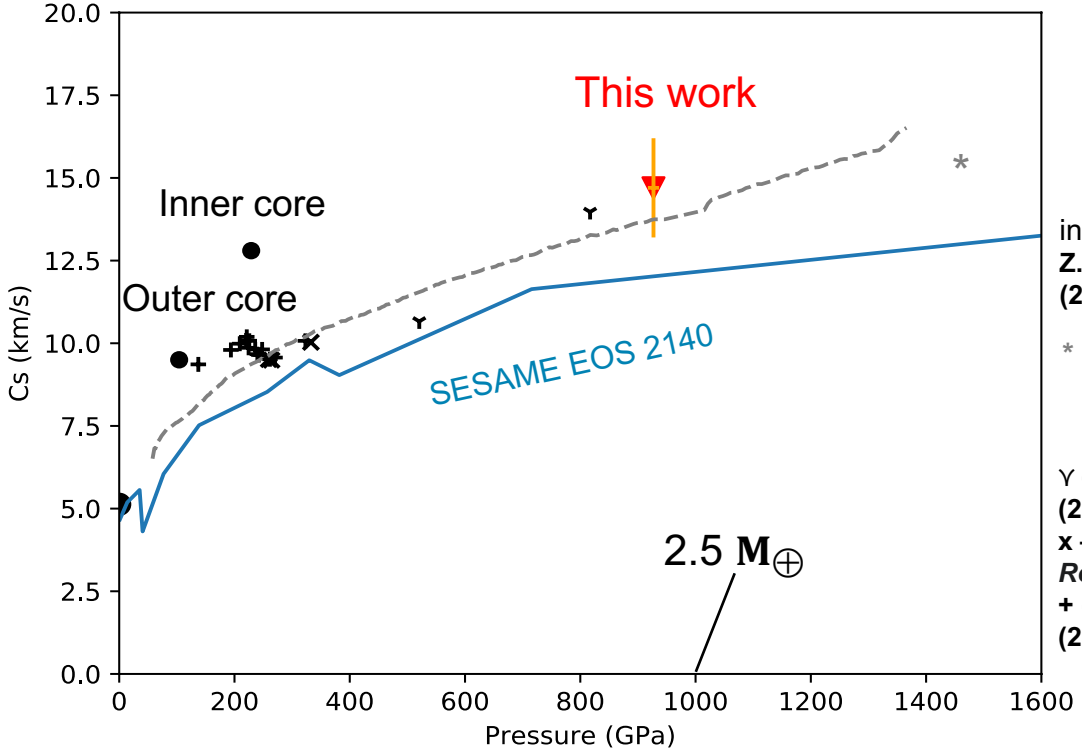
$$(C_E^H)^2 = V^2\left[\left(\frac{\delta P}{\delta V}\right)_H\left[(V_0 - V)\frac{\gamma}{2V} - 1\right] + \frac{P\gamma}{2V}\right]$$

ϒ - J. H. Nguyen and N. C. Holmes, *Nature* 427,339 (2004).

x – J. M. Brown and R. G. McQueen, *J. Geophys. Res.*, 91(B7), 7485–7494 (1986).

\+ - Sakaiya,et al, *Earth Planet. Sci. Lett.* 392, 80-85, (2014).

The sound speed was measured in shock-compressed iron to 927 GPa, comparable to the pressure of a 2.5-$M_\oplus$ planet



inner and outer core data from
Z. Mao, et al., *PNAS,* vol. 109 (26), 10329, (2012)

* **R. F. Smith, et al., *Nature*, 2, 452–458, (2018)**

$$(C_E^H)^2 = V^2\left[\left(\frac{\delta P}{\delta V}\right)_H\left[(V_0 - V)\frac{\gamma}{2V} - 1\right] + \frac{P\gamma}{2V}\right]$$

ϒ **- J. H. Nguyen and N. C. Holmes, *Nature* 427,339 (2004).**
x – J. M. Brown and R. G. McQueen, *J. Geophys. Res.*, 91(B7), 7485–7494 (1986).
+ - Sakaiya,et al, *Earth Planet. Sci. Lett.* 392, 80-85, (2014).

The sound speed in shock-compressed iron was measured using arrival times of pressure perturbations

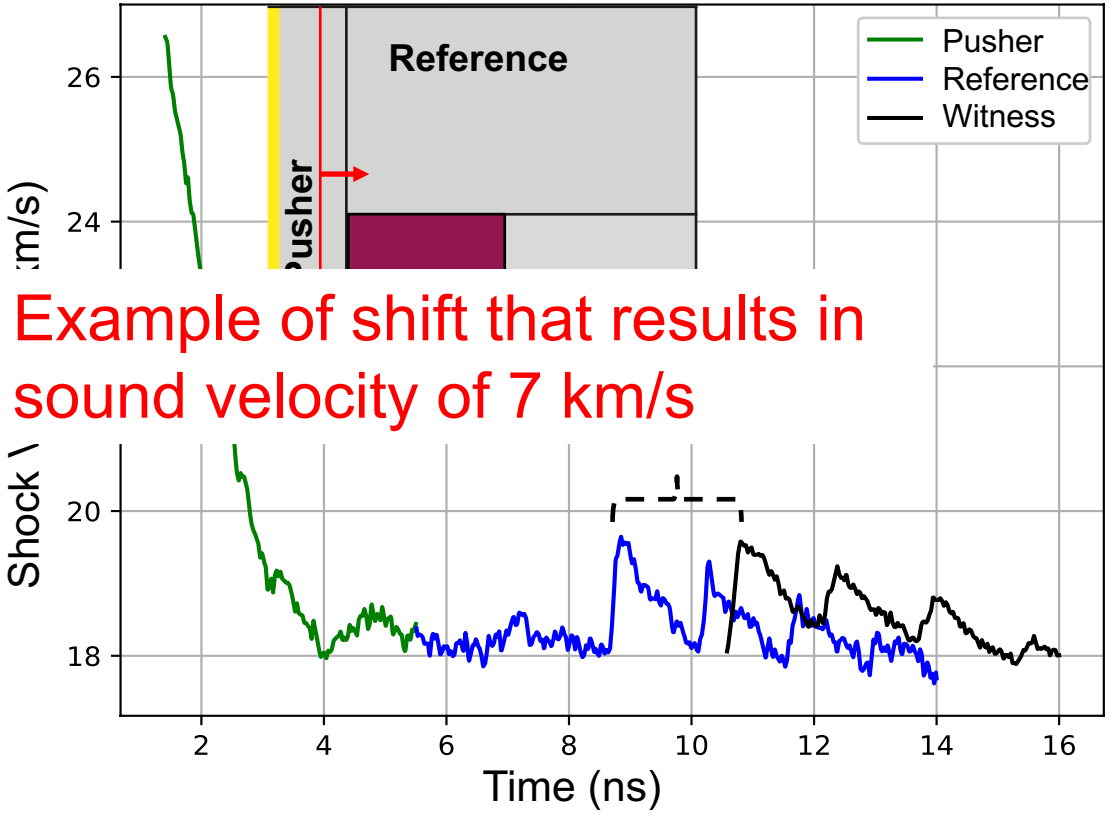
- At high pressure, the sound speed provides information about thermodynamic derivatives ($c_s^2 = \left.\frac{dP}{d\rho}\right|_s$) of the equation of state, which are relevant to core formation and dynamo physics.
- The bulk sound speed is calculated with the Nonsteady Waves method* from transit times of pressure perturbations in shocked materials.
- Iron shocked to 927 GPa has a sound speed of ~14.7$\pm$1.5 km/s.
- These pressures are similar to those in the interior of a 2.5-$M_\oplus$ planet.

*D. E. Fratanduono, et al., J. Appl. Phys. 116, 033517 (2014).

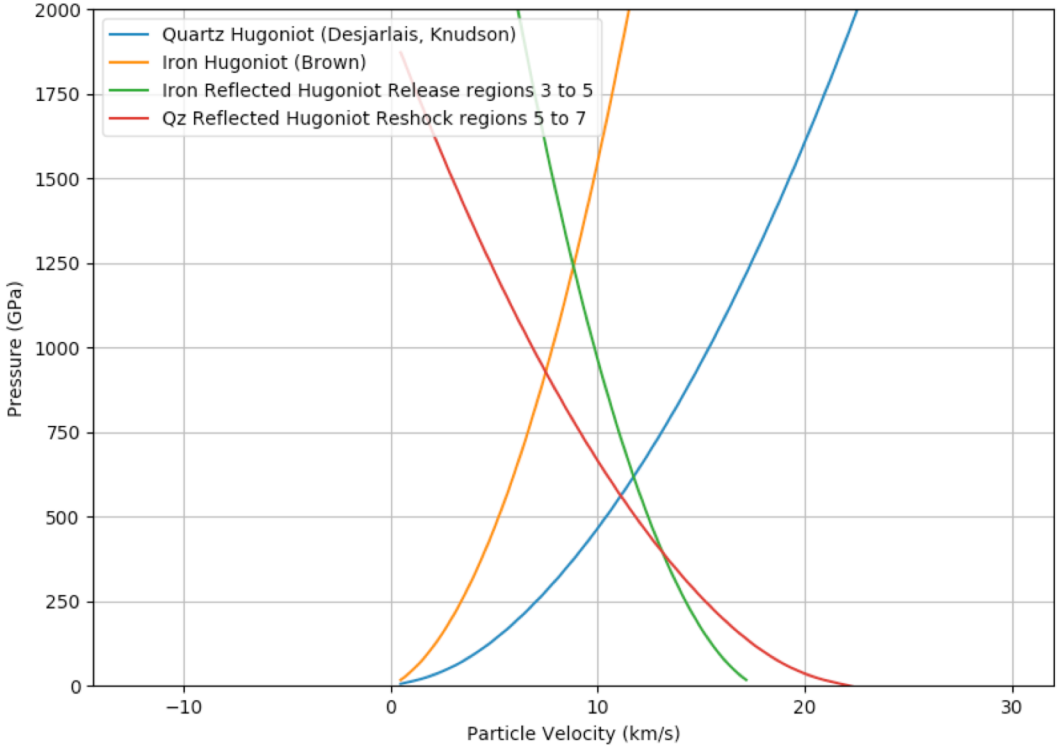
Since iron is opaque, the perturbations must be observed AFTER they have traversed the iron sample

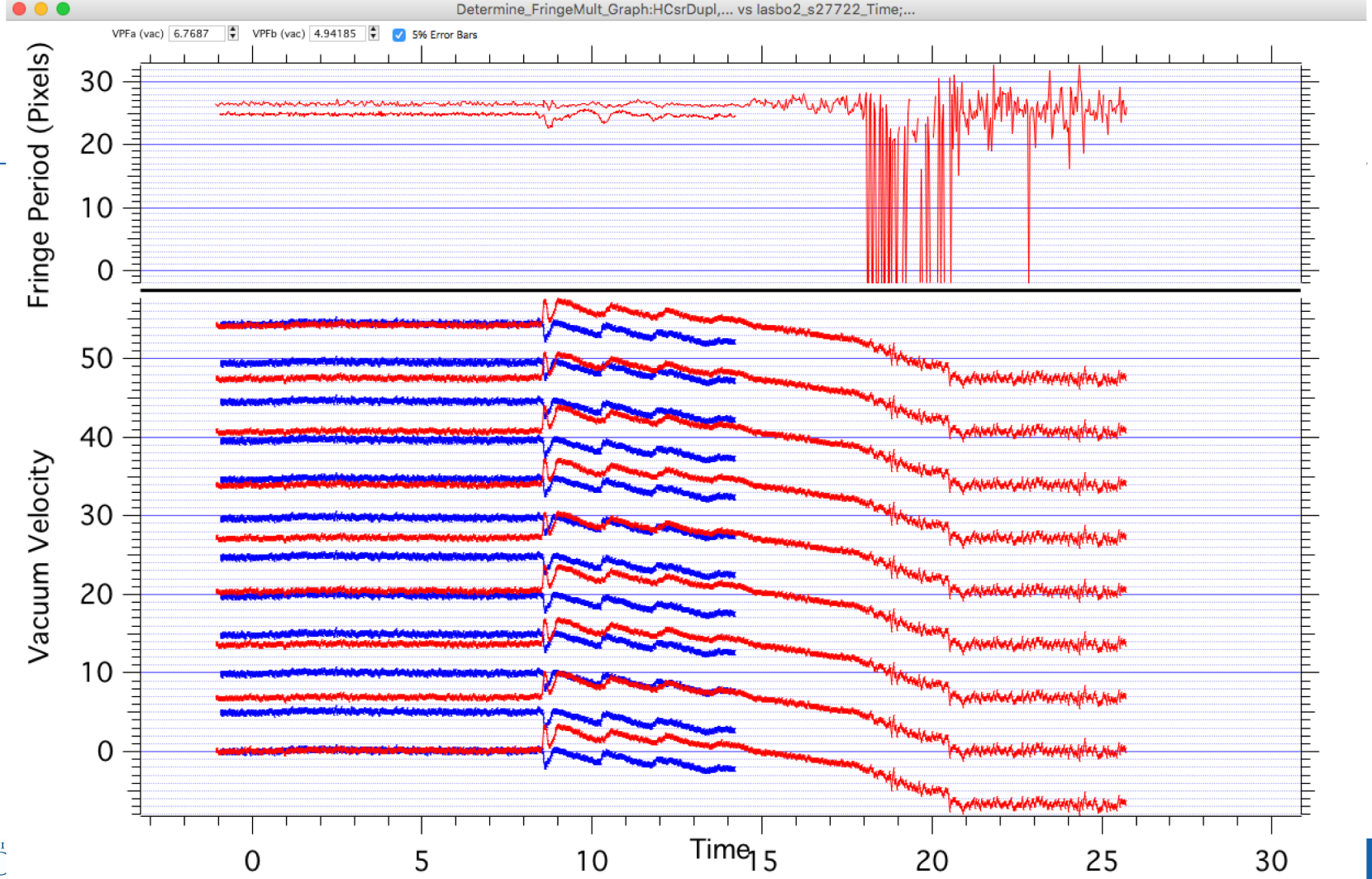
- **A quartz witness on the rear of the iron provides a measurement of perturbations that transited the iron**

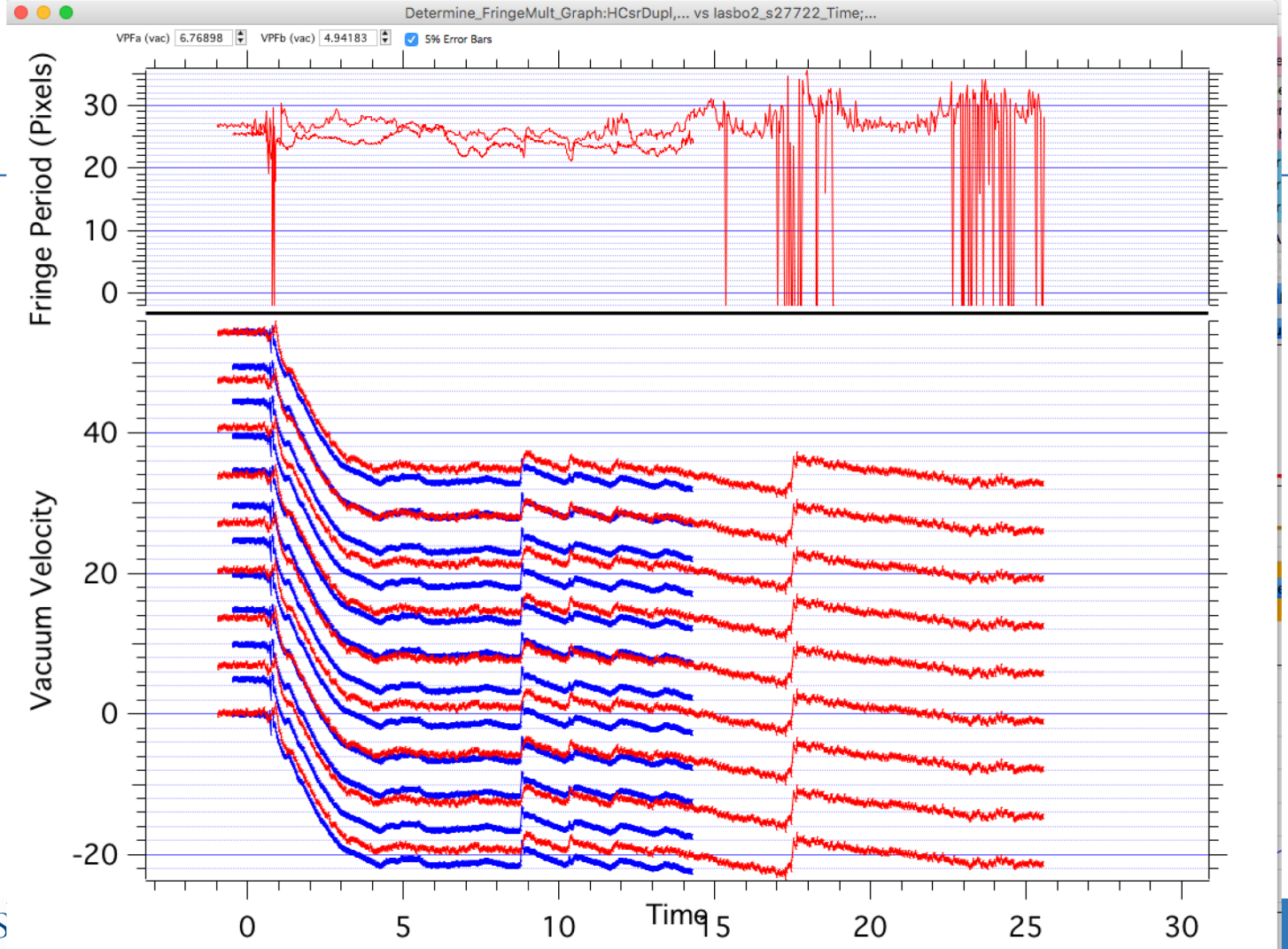
- **At ~1 TPa, there are only minor differences in arrival times; therefore iron and quartz must have similar sound speeds**



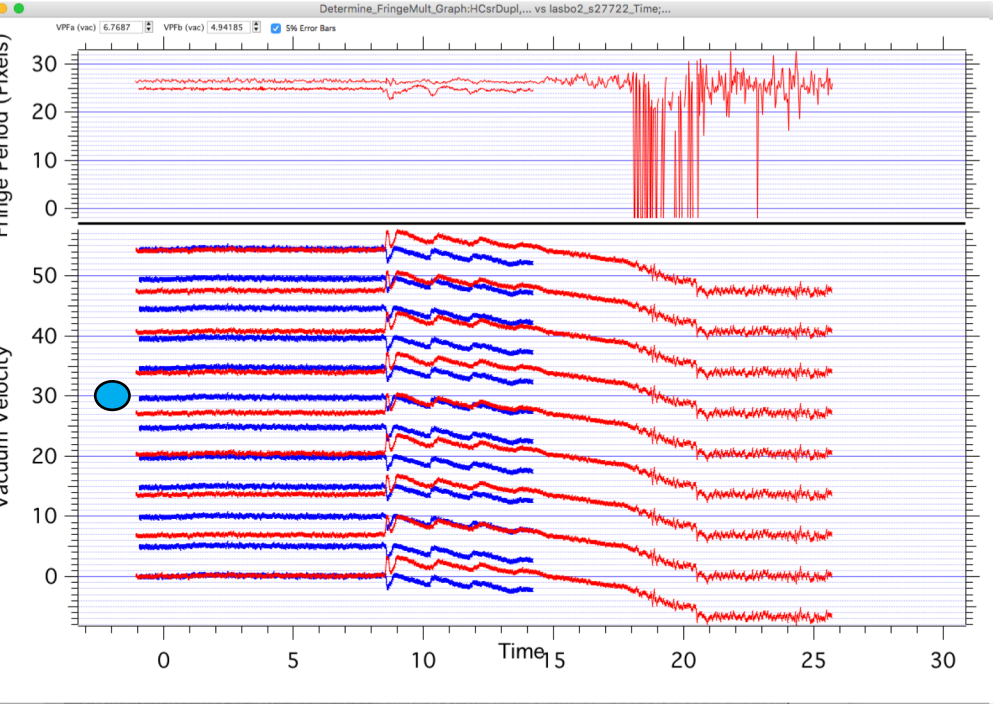
Backup Slides

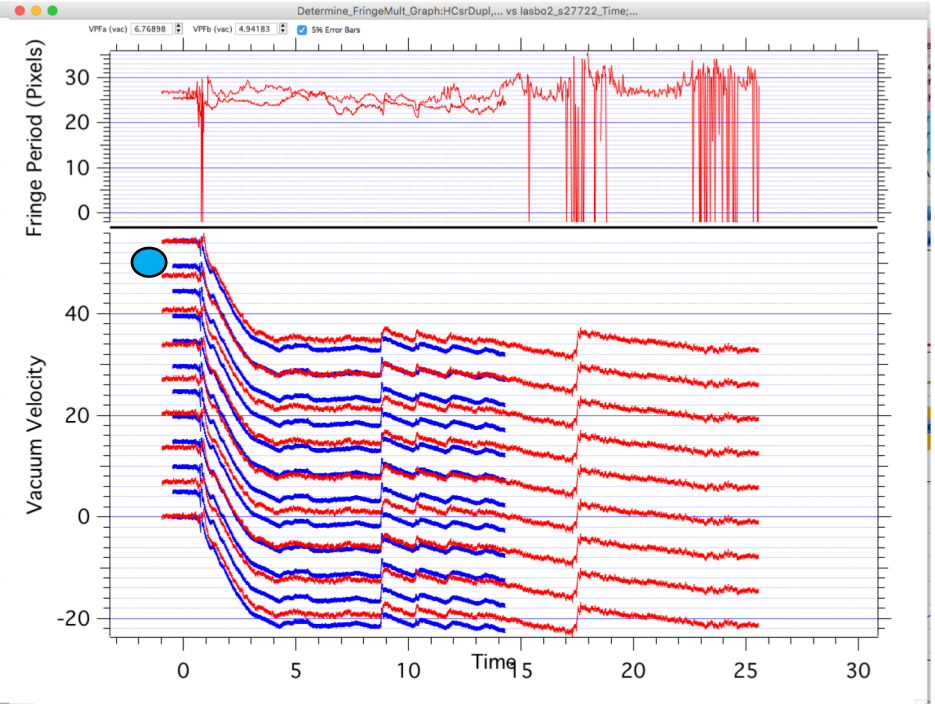



Determine_FringeMult_Graph:HCsrDupl,... vs lasbo2_s27722_Time;...
VPFa (vac) 6.7687
VPFb (vac) 4.94185
5% Error Bars
Fringe Period (Pixels)
30
20
10
0
Vacuum Velocity
50
40
30
20
10
0
0
5
10
Time
15
20
25
30


Determine_FringeMult_Graph:HCsrDupl,... vs Iasbo2_s27722_Time;...
VPFa (vac) 6.76898
VPFb (vac) 4.94183
5% Error Bars
Fringe Period (Pixels)
30
20
10
0
Vacuum Velocity
40
20
0
-20
0
5
10
15
20
25
30
Time

Problems with IGOR/VISAR: Choices of velocities don't match with Transit time/Impedance matching (see next page)





Transit times/Impedance Matching

- Transit time in quartz pusher: 4.7335 ns Thickness: 99.7 microns

  Avg Shock Velocity: 21.06 km/s

- Transit time in Iron: 3.184 ns Thickness: 50.1 microns

  Avg Shock Velocity 15.64 km/s

Transit time in Qz anvil: ASBO 1 only: 12.02 ns

Avg Shock Velocity: 16.91 km/s

- Can't do transit time in witness because ASBO cuts off the end/breakout
- Tried to analyze one where I added shock breakouts, didn't work because I got 12.19 km/s from Qz pusher… got this from starting velocity of 27.45 km/s that decays to 8.12 km/s where the quartz pusher ends, then divided by index of refraction of Qz: 1.4585
- Tried to see what velocity the Qz anvil would have based on the iron transit time velocity, got: 17.5 km/s