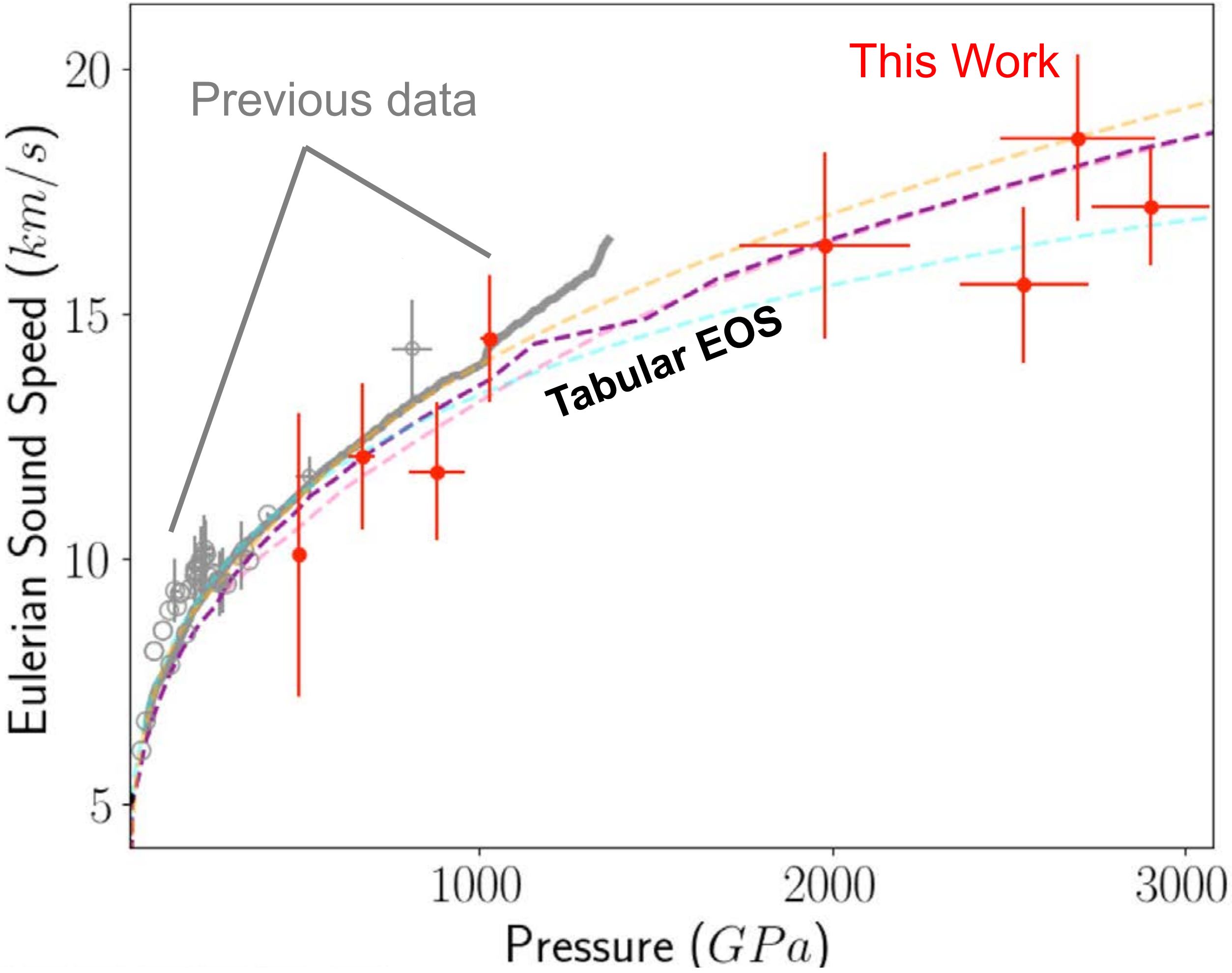
Measurements of Sound Speed in Iron Shock-Compressed to ~3000 GPa



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Division of Plasma Physics
Pittsburgh, PA
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We investigate the Gruneisen parameter and melt curve of iron using measurements of sound speed in shock-compressed iron

- Our data show that sound speed is primarily dependent on density.
- Our inferred melt curve suggests that solid, not liquid, iron exists in the core of super-Earths up to 12 times the Earth's mass
- We use a basic approximation of a giant impact event to estimate melt pressure in planets with iron cores.

Collaborators

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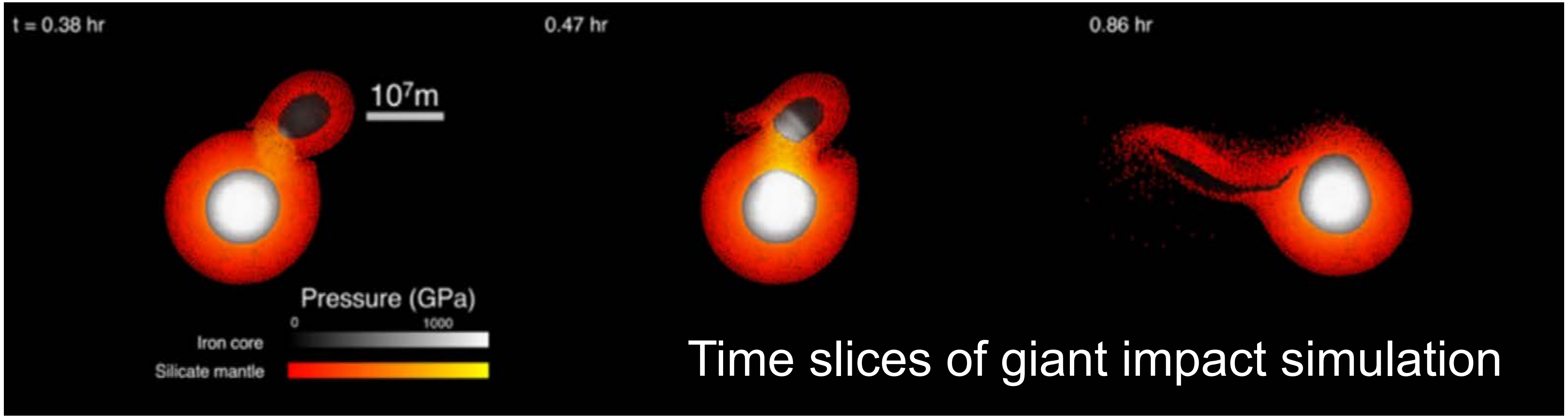
Predictions for giant impact events and terrestrial core conditions rely on accurate measurements of the iron sound speed and Gruneisen parameter

- **We use a Mie-Gruneisen equation of state to approximate a giant impact of planets with iron cores; more sophisticated models also exist.**
- **A melt curve can be constructed from our Gruneisen measurements, which at high pressures is relevant to rocky super-Earth cores.**

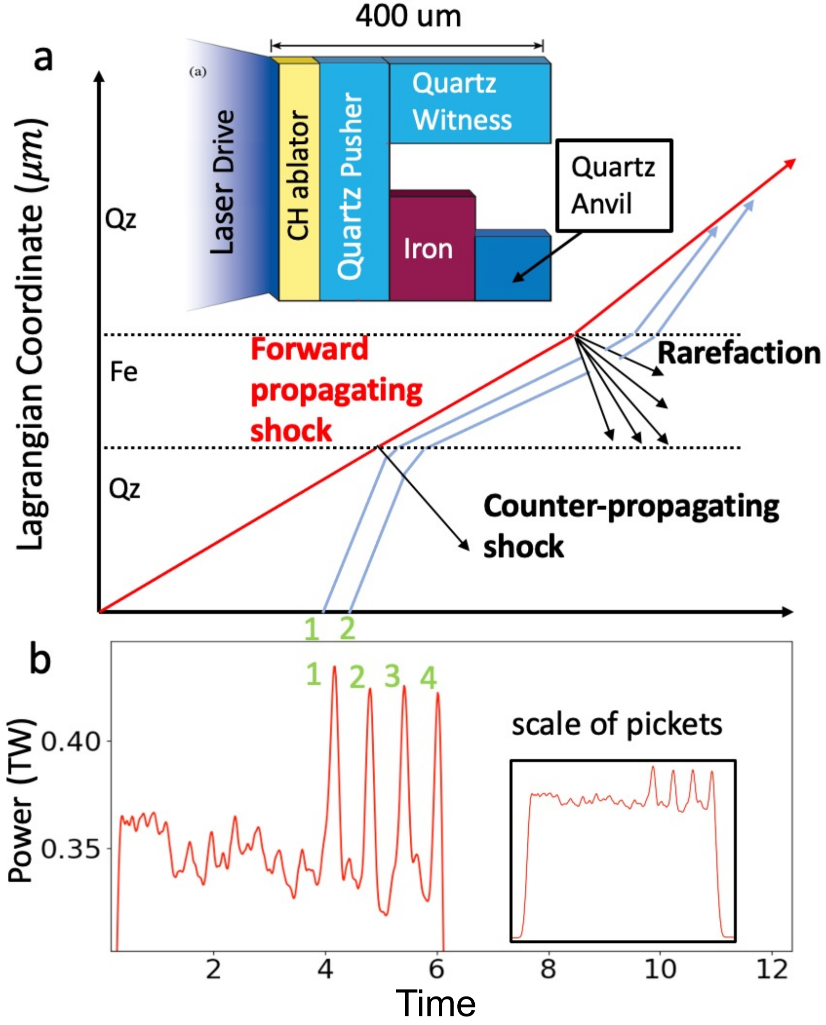


Time slices of giant impact simulation

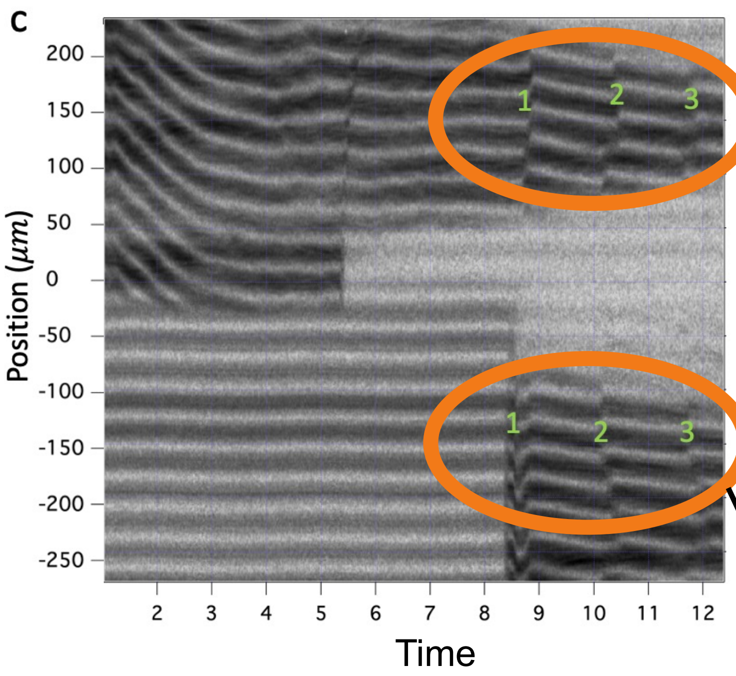
M. Nakajima, et al.

Arrival time of modulations in the laser drive depends on the iron sound speed

Experimental Design

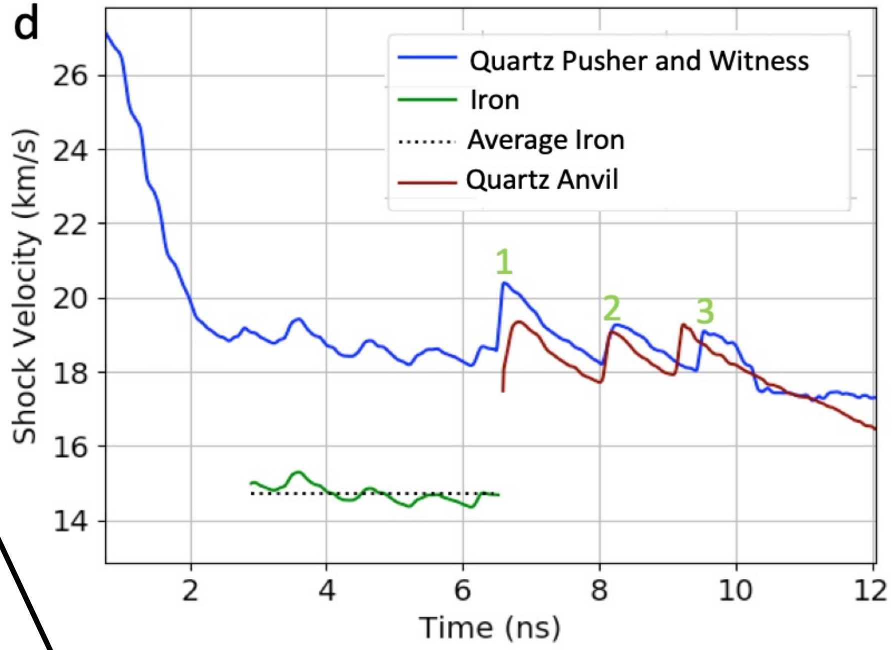


Raw VISAR



Arrival of pickets on quartz side

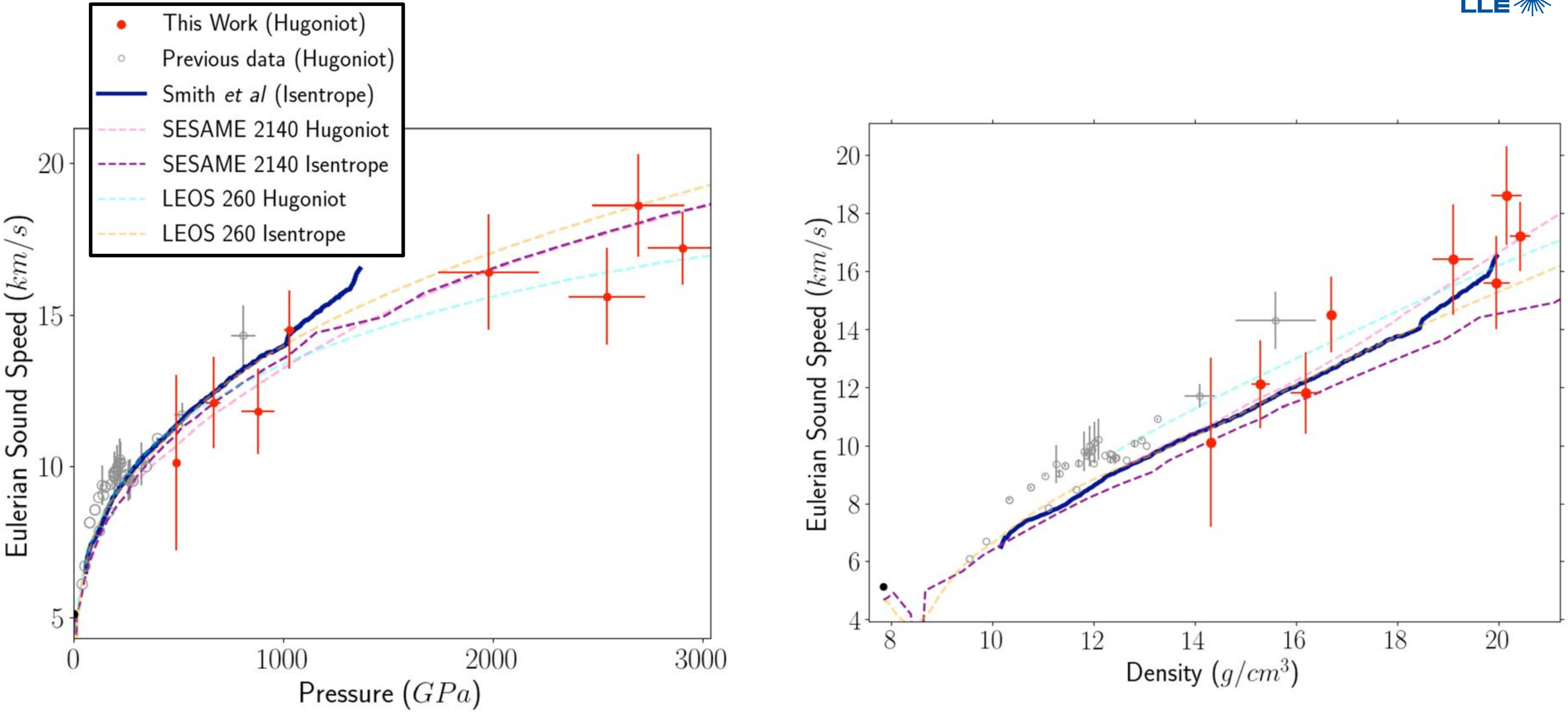
Analyzed VISAR



Arrival of pickets on iron side

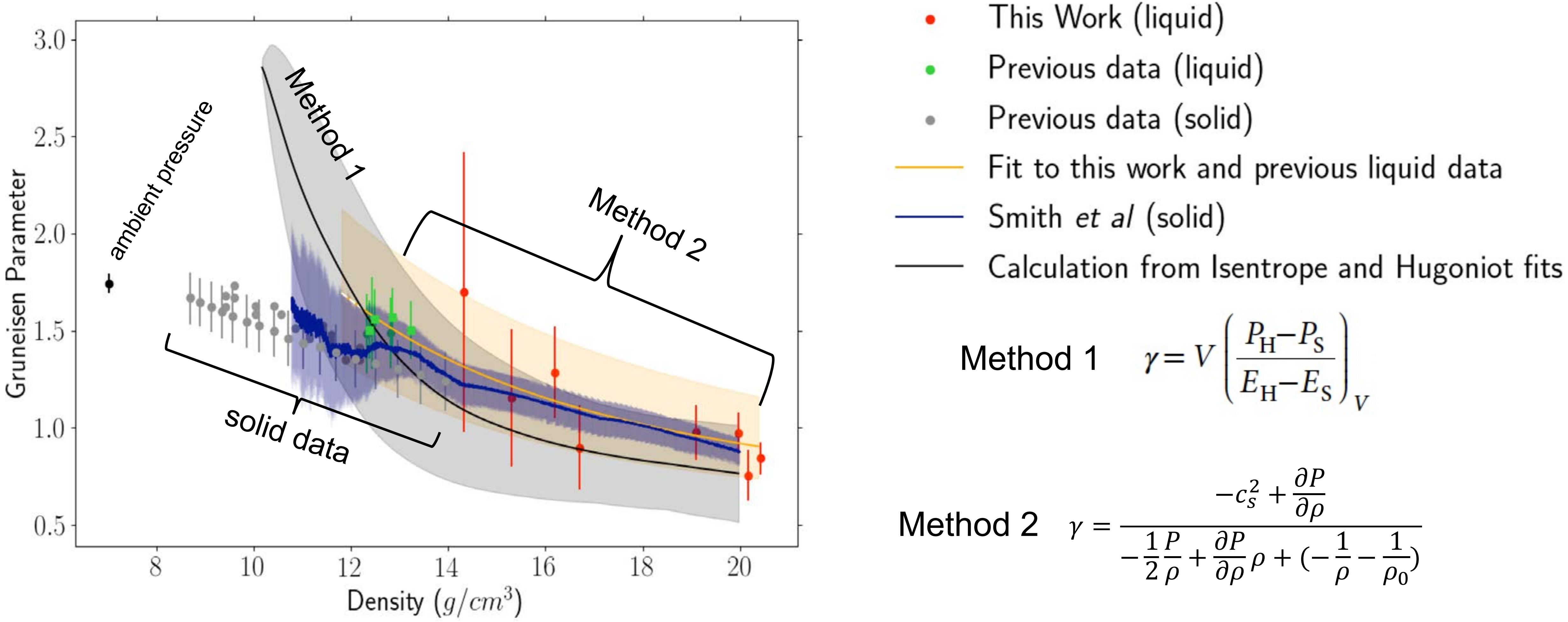
VISAR: Velocity Interferometer System for Any Reflector

Sound speed primarily depends on density



* Smith, R., 2018. *Nature Astronomy*, 2(6), pp.452-458.

We obtain the Gruneisen parameter using the measured sound speed and Hugoniot data

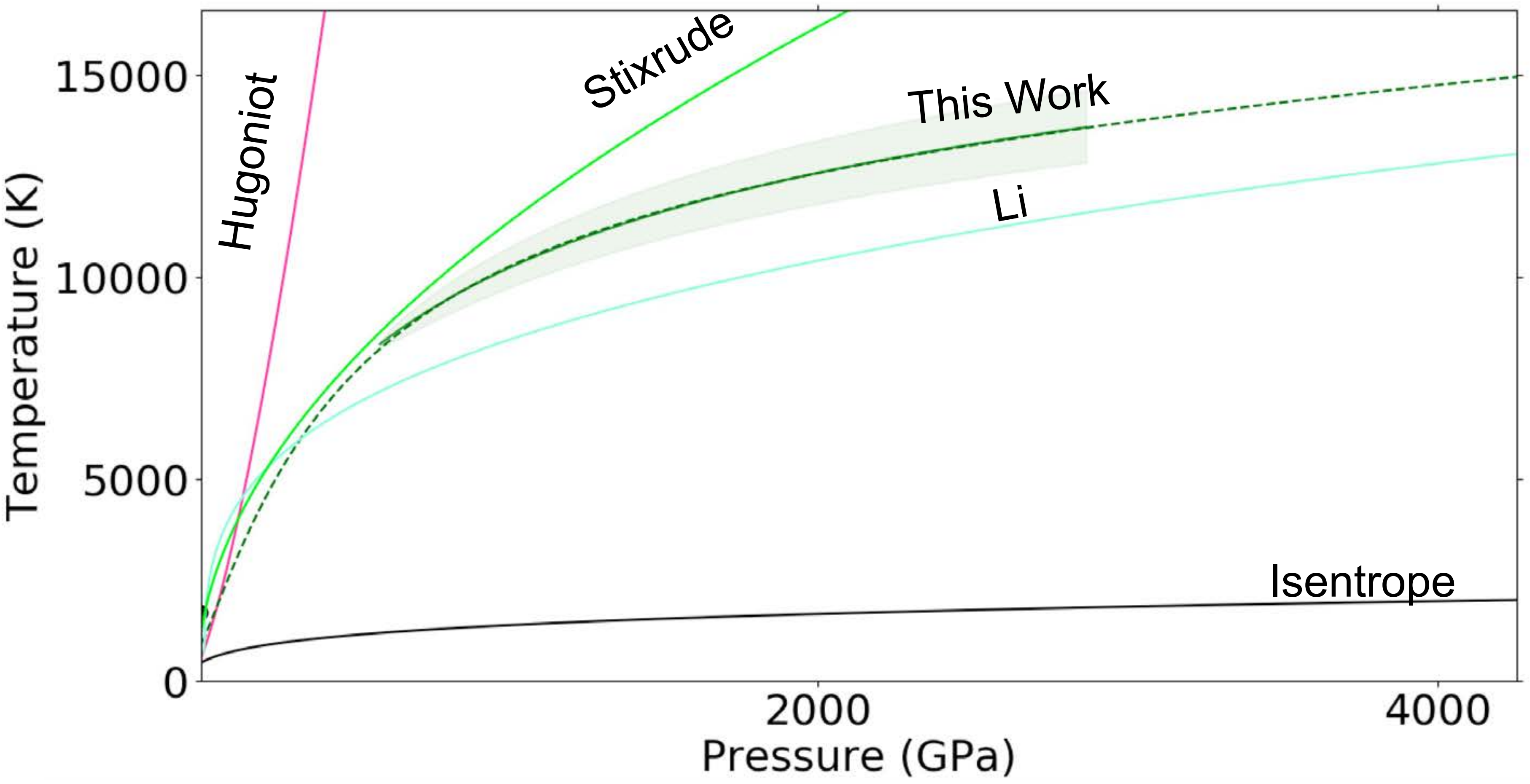


Method 1 $\gamma = V\left(\frac{P_H - P_S}{E_H - E_S}\right)_V$

Method 2 $\gamma = \frac{-c_s^2 + \frac{\partial P}{\partial \rho}}{-\frac{1}{2}\frac{P}{\rho} + \frac{\partial P}{\partial \rho}\rho + (-\frac{1}{\rho} - \frac{1}{\rho_0})}$

Smith, R., 2018. *Nature Astronomy*, 2(6), pp.452-458.

Using the Gruneisen parameter, we can estimate a melt curve for iron.



Lindemann Relation

$$\frac{\mathrm{d}\ln T_m}{\mathrm{d}P} = \frac{2(\gamma - \frac{1}{3})}{K}$$

Simon-Glatzel fit

$$T_m = T_{ref}\left(\frac{P - P_{ref}}{a} + 1\right)^b$$

J. Li, Geo. Res. Lett. 47(15) (2020)
L. Stixrude, Phil. Trans. R. Soc. A, 372 (2014)

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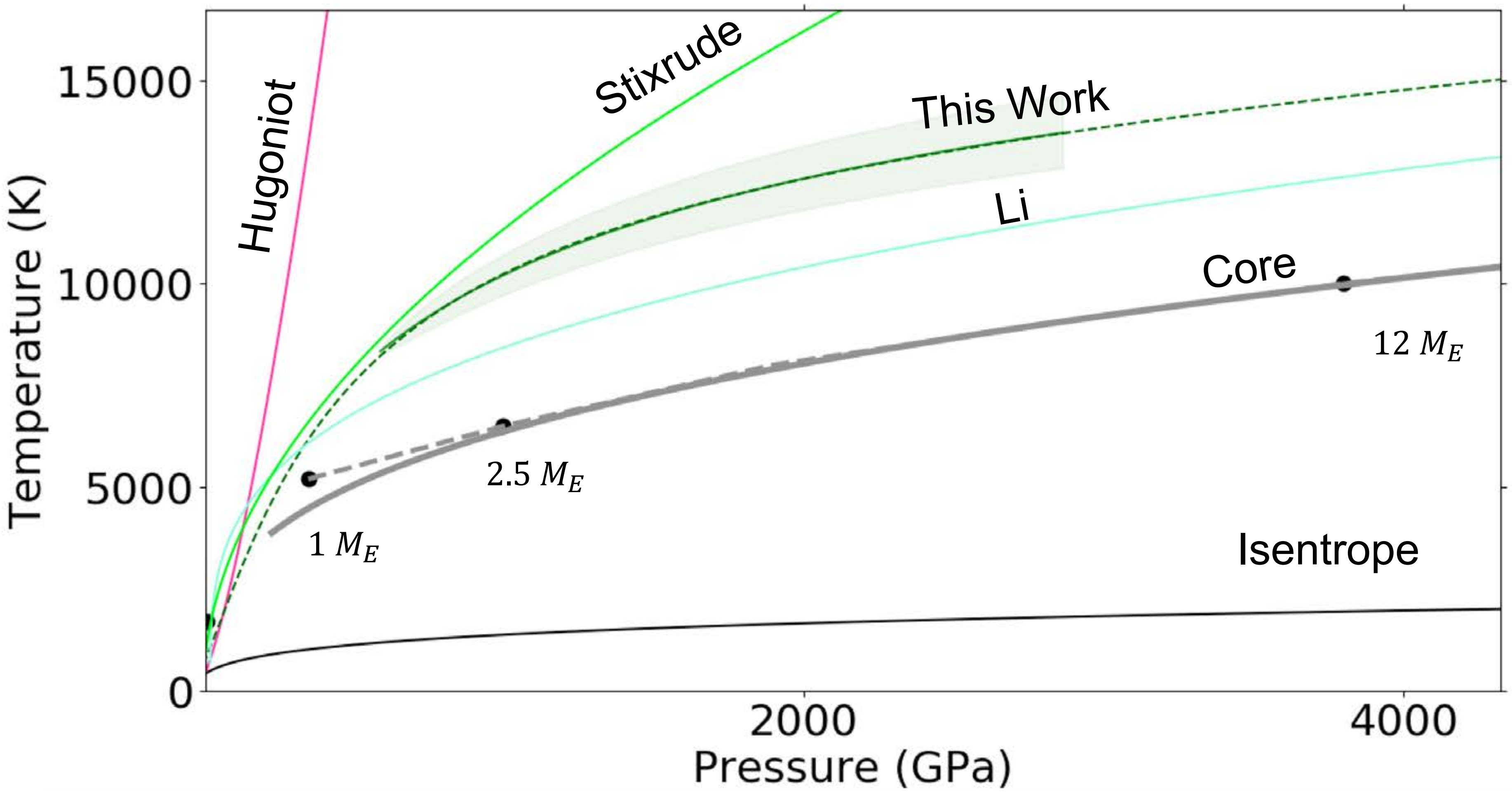

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Core pressure of rocky super-Earth 7.5 times M_E: ~2800 GPa

J. Li, Geo. Res. Lett. 47(15) (2020)
R. Kraus, Submitted (2021)
F. Wagner, Astronomy & Astrophysics, 541, p.A103 (2012).

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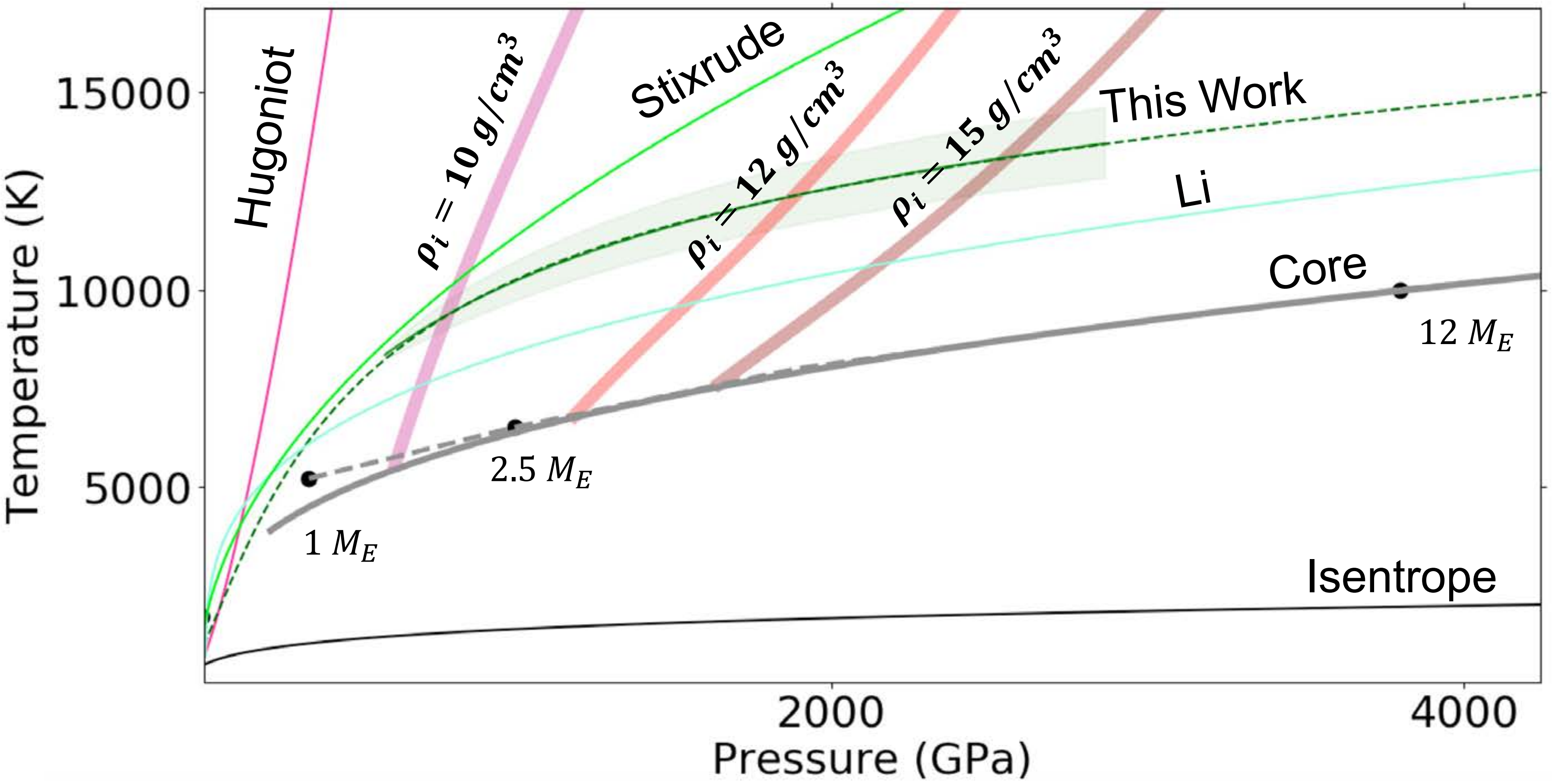

Precompressed Hugoniots are launched from the core densities of super-Earths calculated by Wagner, *et al*, using a Mie-Gruneisen equation of state.

J. Li, Geo. Res. Lett. 47(15) (2020)
F. Wagner, Astronomy & Astrophysics, 541, p.A103 (2012).

Summary

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- Our data show that sound speed is primarily dependent on density.

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Thank you for your time

Please email any comments or questions to mhuf@lle.rochester.edu, I will be happy to respond.

Backup Slides

Lindemann Law

melt temperature?

$$\frac{\mathrm{d}\ln T_m}{\mathrm{d}P} = \frac{2(\gamma - \frac{1}{3})}{K}$$

$$v = \sqrt{\frac{\text{elastic property}}{\text{inertial property}}} = \sqrt{\frac{B}{\rho}} \quad \text{where} \quad \begin{array}{l} B = \text{bulk modulus} \\ \rho = \text{density} \end{array}$$

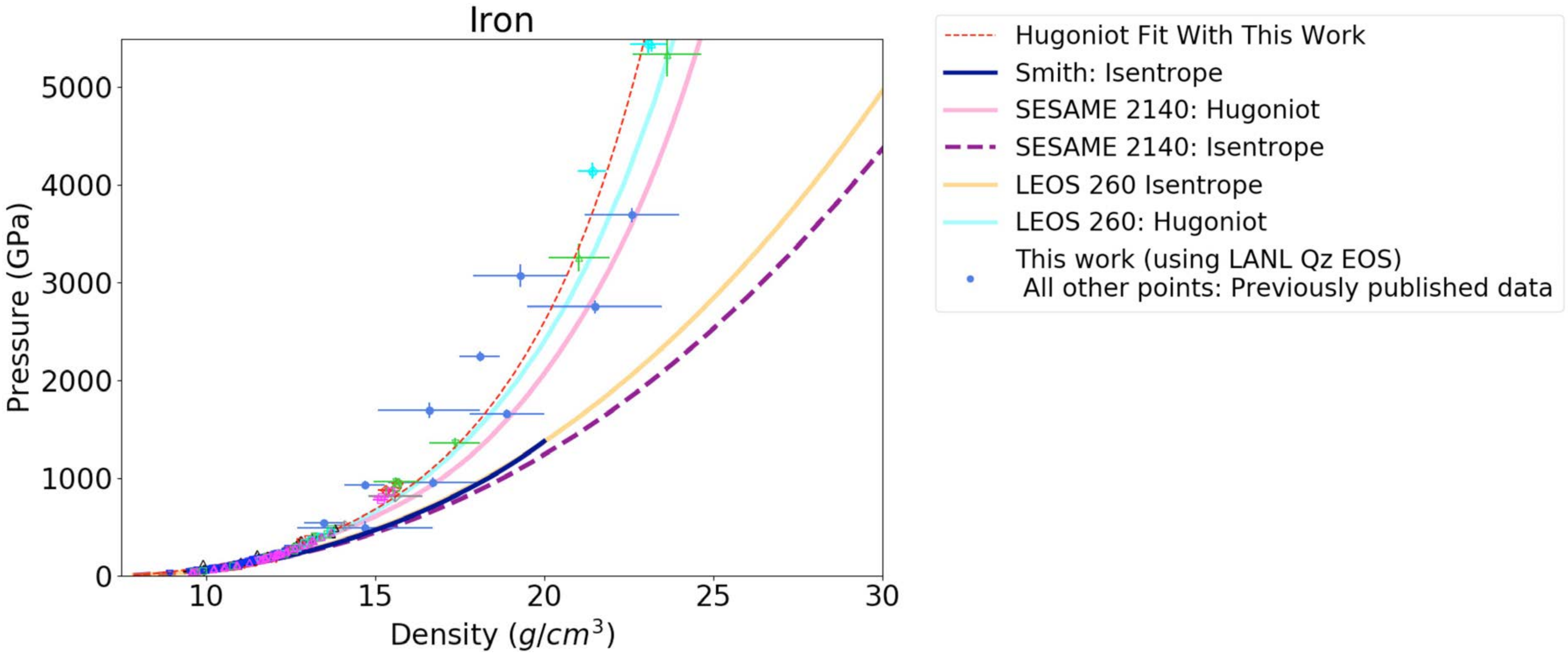
Bulk modulus

$$\frac{\mathrm{d}\ln T_m}{\mathrm{d}\ln V} = -2\left(\gamma - \frac{1}{3}\right)$$

Let $z = \log x$, i.e. $x = \exp(z)$, and $y = y(x)$ be a smooth and nonzero enough function of x; then

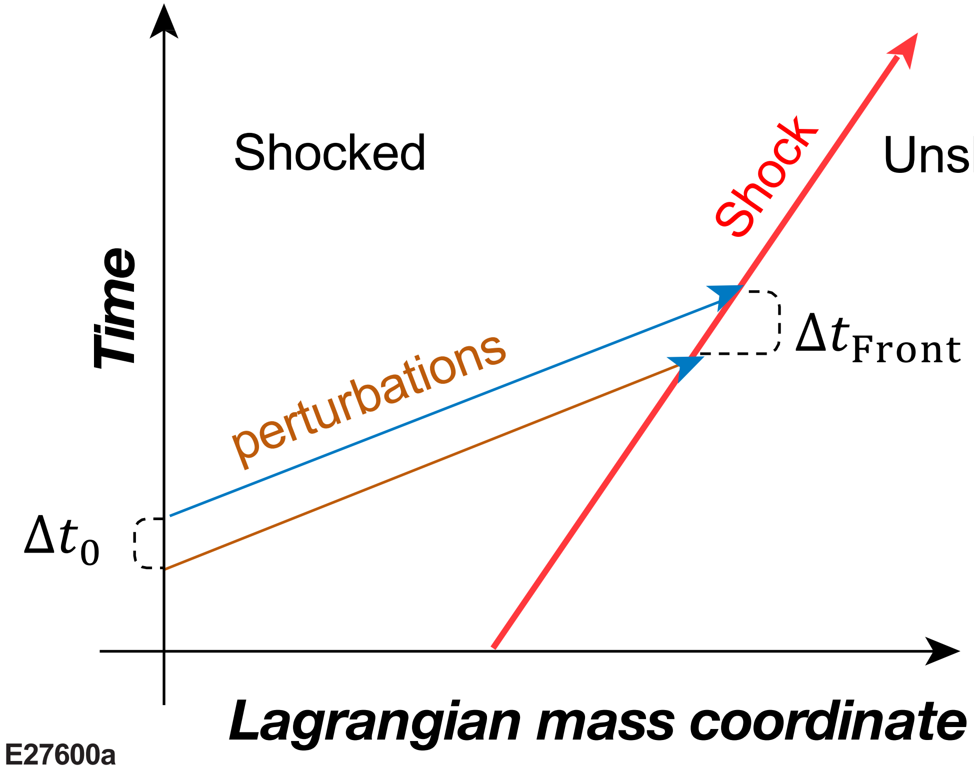
$$\frac{d \log y(z)}{dz} = \frac{1}{y(z)} y'(z) = \frac{1}{y(z)} y'(x(z)) x'(z) = \frac{dy}{dx}\frac{x}{y}$$

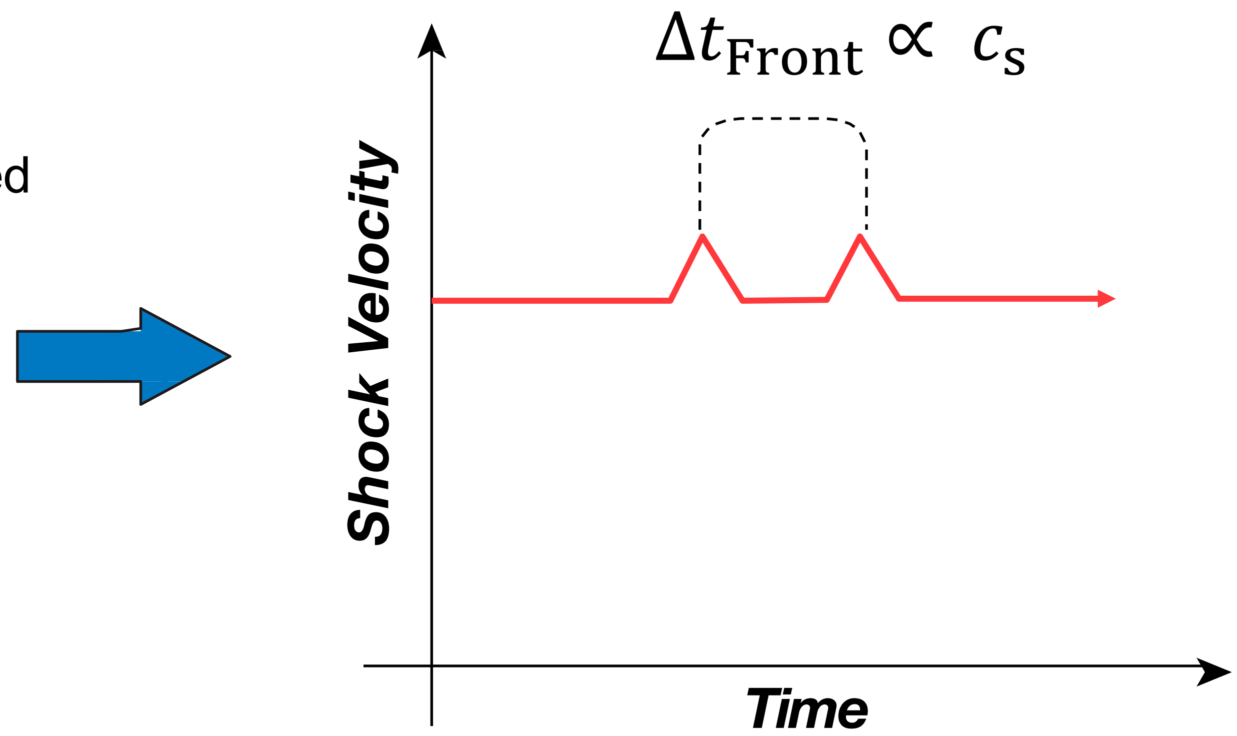
where we use the chain rule twice.


Iron
Pressure (GPa)
Density (g/cm^3)
0
1000
2000
3000
4000
5000
10
15
20
25
30
Hugoniot Fit With This Work
Smith: Isentrope
SESAME 2140: Hugoniot
SESAME 2140: Isentrope
LEOS 260 Isentrope
LEOS 260: Hugoniot
This work (using LANL Qz EOS)
All other points: Previously published data

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

UR LLE



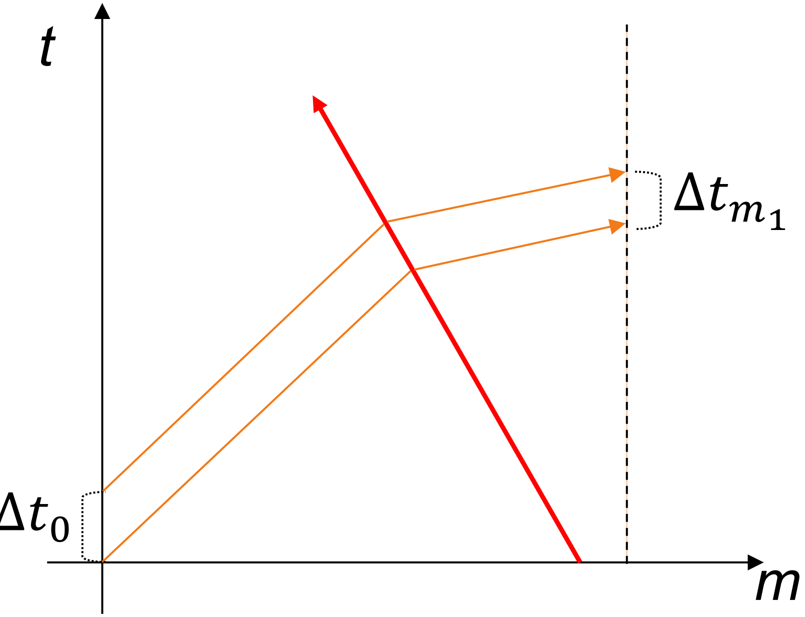


Transmission coefficients for temporal and amplitude changes can be calculated for perturbations traversing regions of various states

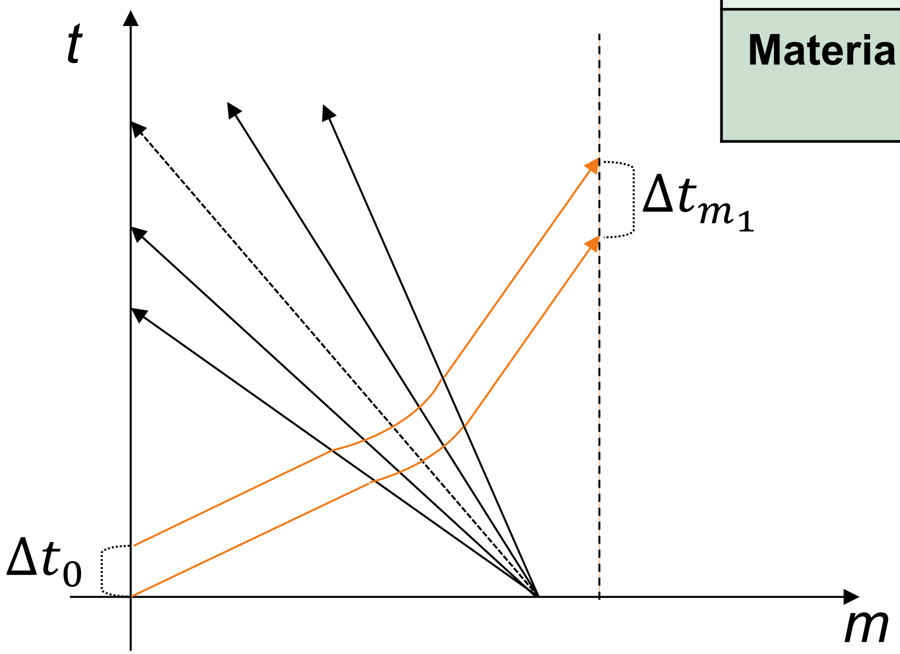
- Sound-speed calculations depend on only the temporal coefficients
- Coefficients depend on the Mach number of the two regions

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

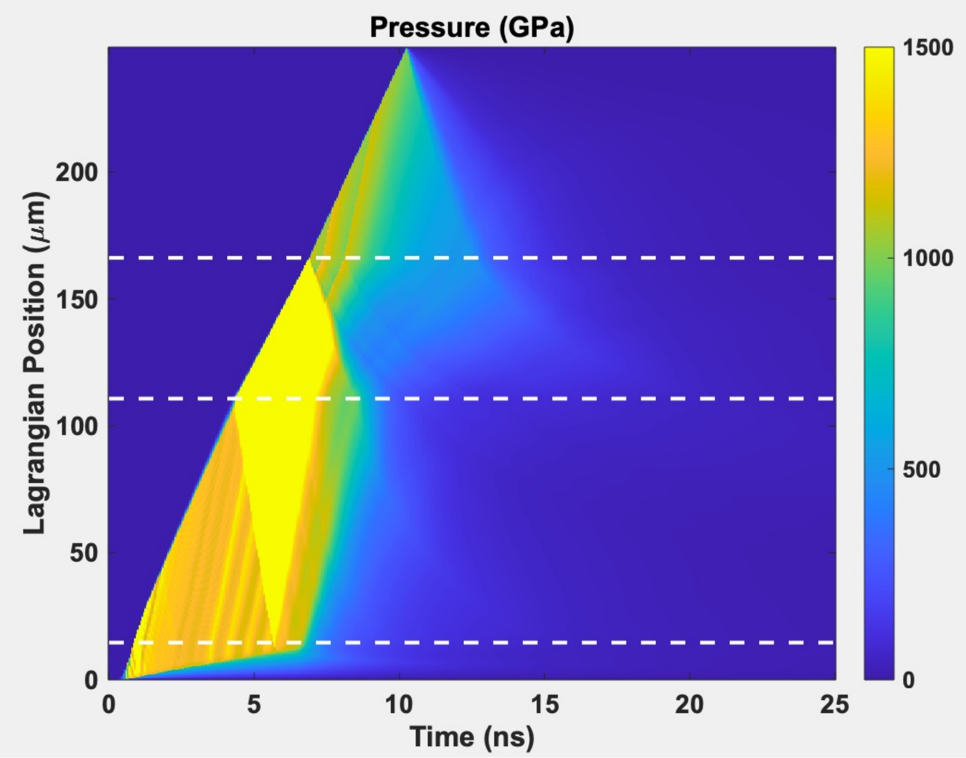


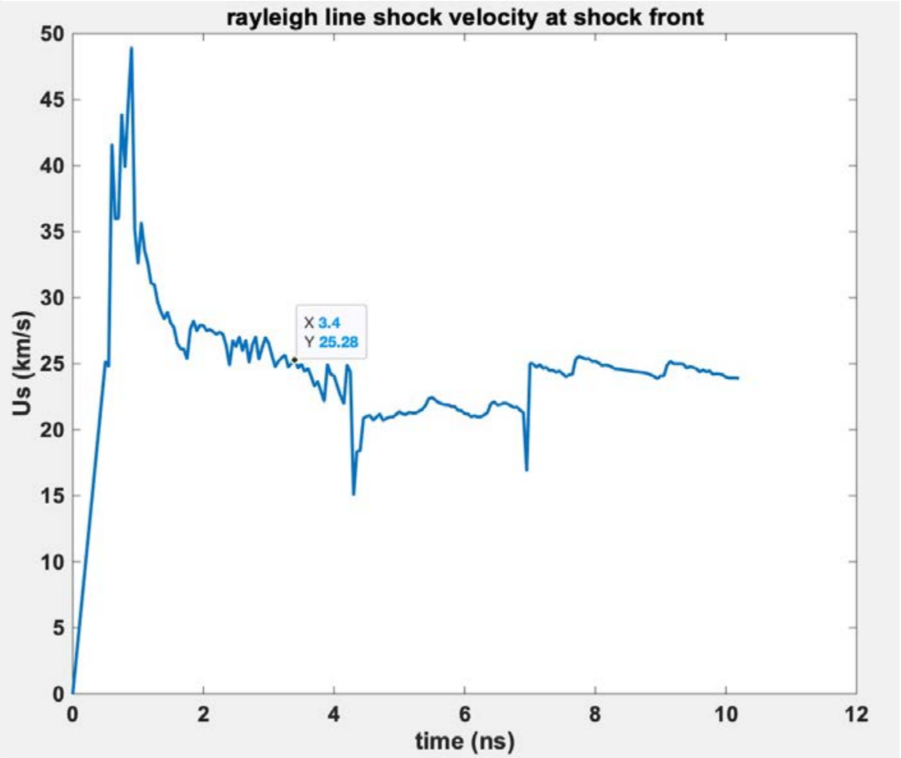
Mach number

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

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

HYADES simulations validate the Nonsteady Waves technique to extract sound speed



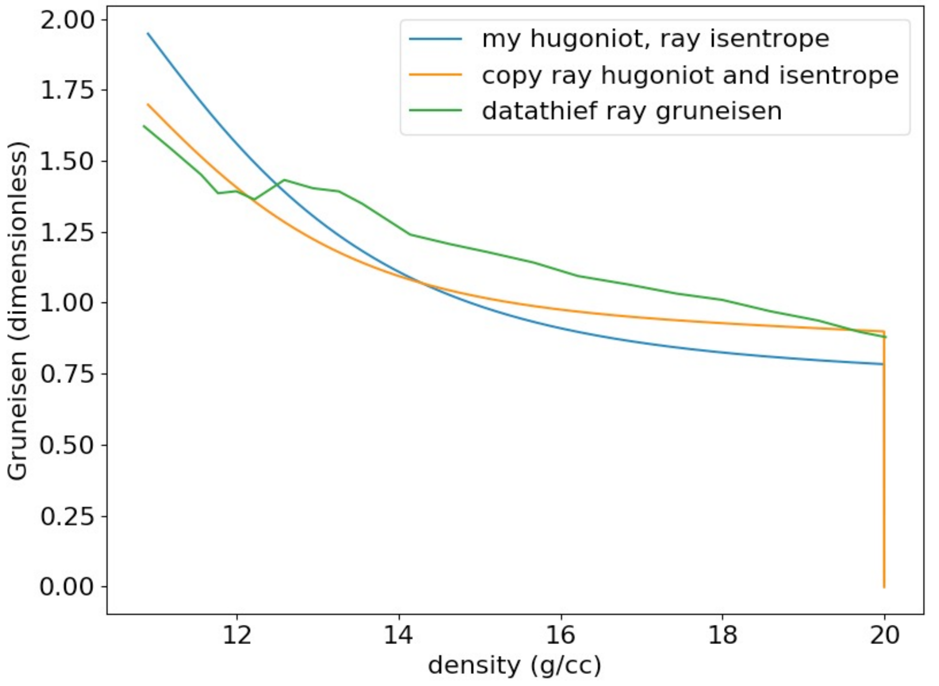


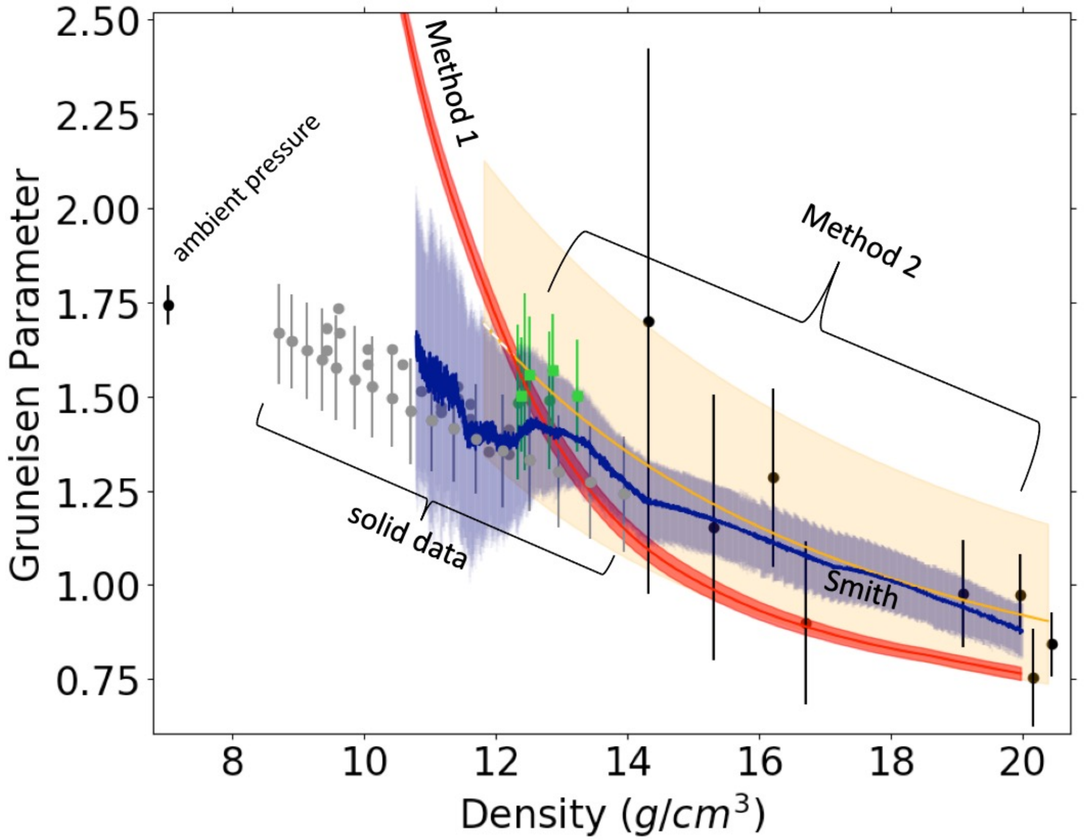
- A 1d hydrocode provides a simulated shock velocity
- Analysis using the Nonsteady Waves method recovers the sound speed along the Hugoniot

Why don't my Method 1 gruneisen parameter and Ray's line up?

1. My slope of Hugoniot

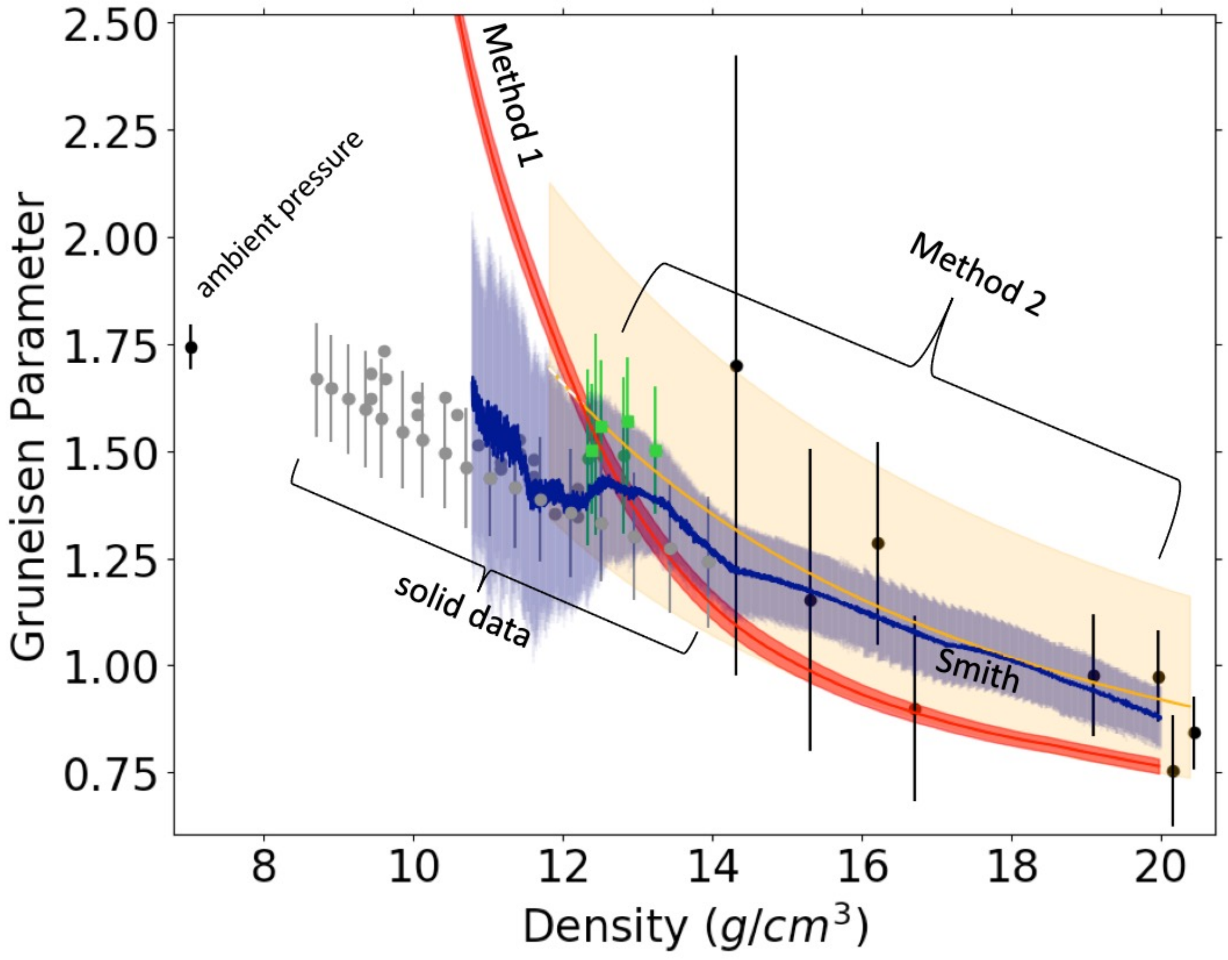
2. Using a Vinet fit instead of actual stress-density curve for Isentrope





Regions of validity

Murphy data is x ray spectroscopy on static DAC
Dubrovinsky is laser heated synchrotron x ray spectroscopy
brown mcqueen is gas gun with method 2 relying on sound speed measurement (only liquid shown here)



Method 1 cutoff: existence of ray's isentrope
method 2 cutoff to fit: existence of liquid sound speed data (specifies must be above melt)