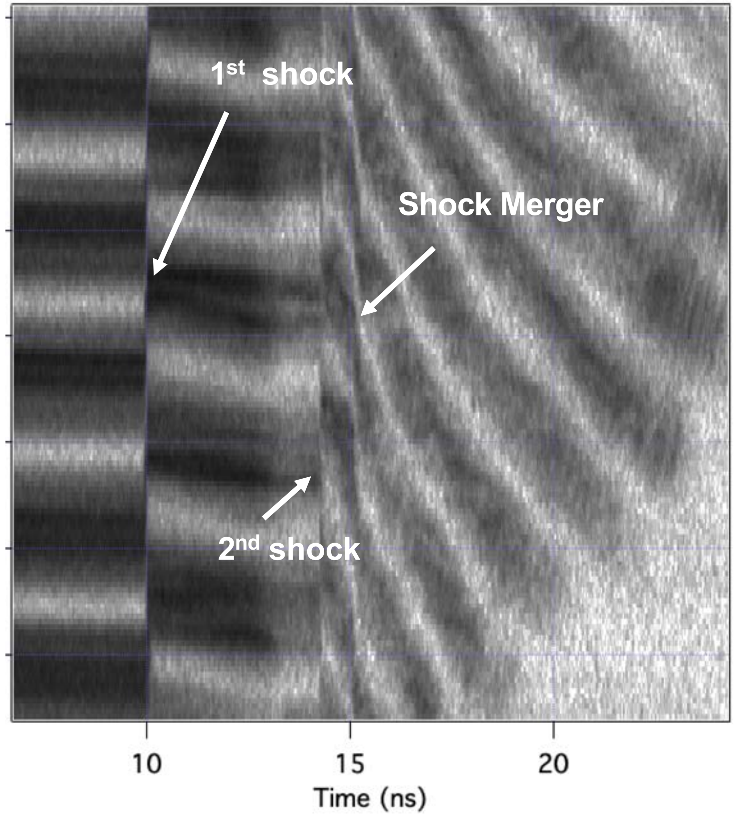
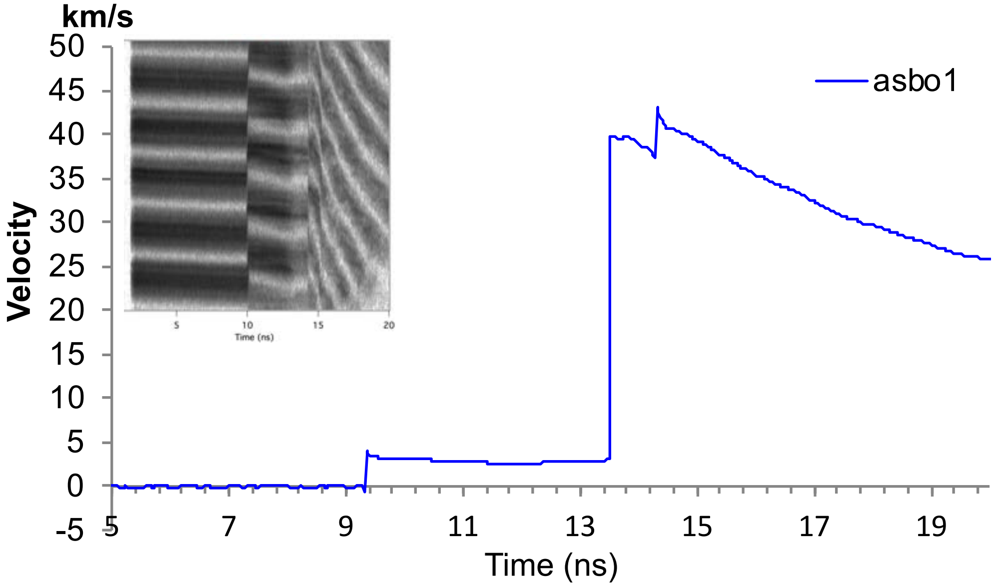
# Accessing High Density States in $D_2$ using Double Shock





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**Laboratory for Laser Energetics**


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**Pittsburgh, Pennsylvania**
**November 9, 2021**

# Double-Shock platform is able to facilitate unique access to high density states

- $D_2$ double-shock states were observed up to pressures of ~8 Mbar and densities of up to ~1.9 g/cc
- We find that these high density states probe the transition in $D_2$ from liquid metal to classical plasma
- We measure temperatures of up to ~ 7.5 eV for our double-shock states and note that they were significantly cooler than states with identical pressures on the principal Hugoniot

# Collaborators

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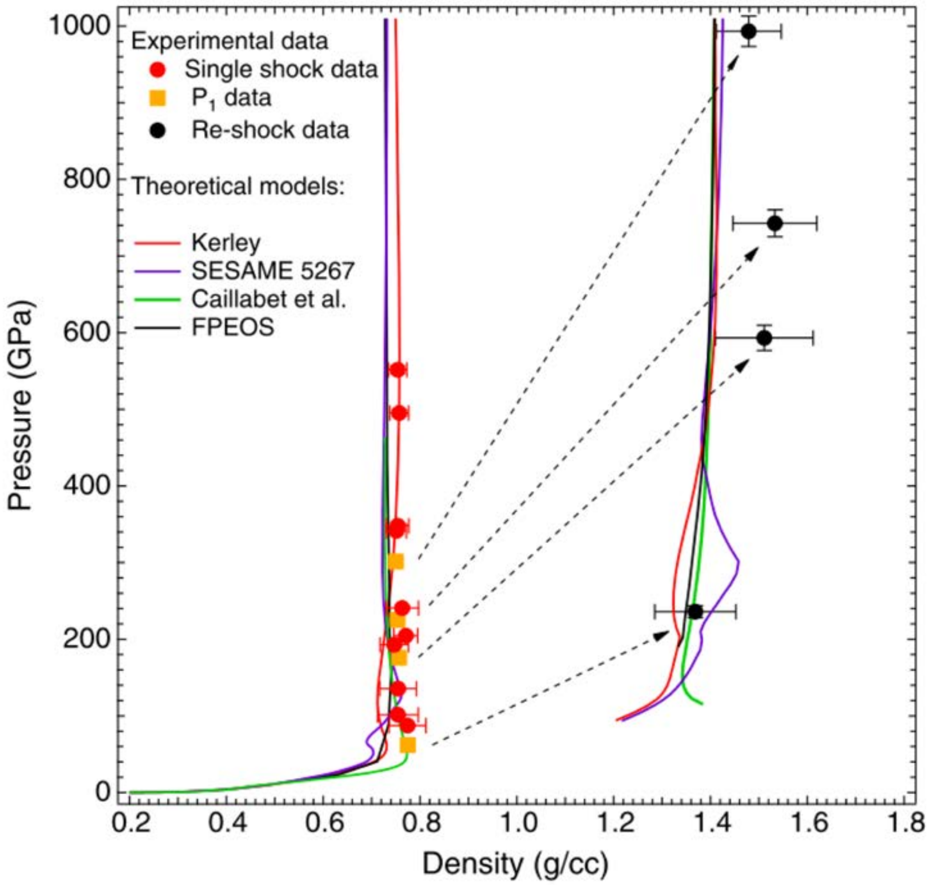
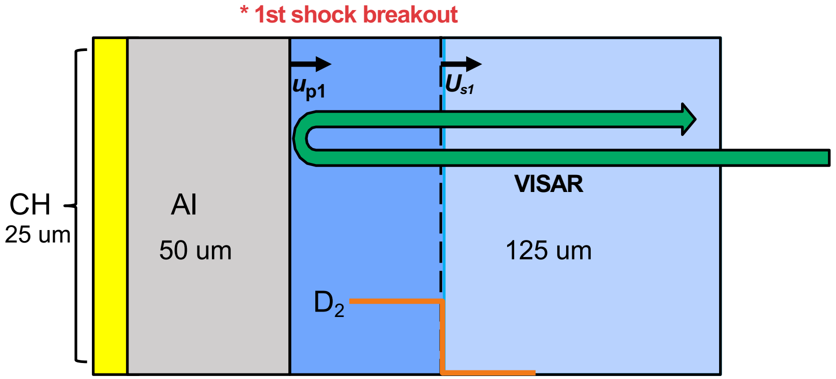
# Double-Shock compression allows us to achieve high density states

- High density behavior of hydrogen is important for models of planetary interiors and for Inertial Confinement Fusion (ICF)
- This work will inform discrepancies observed between experiment and models in high density $D_2$




A. Fernandez-Pañella et al. Phys. Rev. Lett. 122, 255702 – Published 25 June 2019

# Double-shock ($P_2$,$\rho_2$) state is determined by a self-impedance matching technique




☐ **Denotes Experimental Observable**

Conservation of Mass:

$$\frac{\rho_1}{\rho_0} = \frac{U_{s1}}{U_{s1} - \boxed{u_{p1}}}$$

Conservation of Momentum:

$$P = \rho_0 U_{s1} \boxed{u_{p1}}$$

Guargaglini et al. Phys. Plasmas 26, 042704 (2019)

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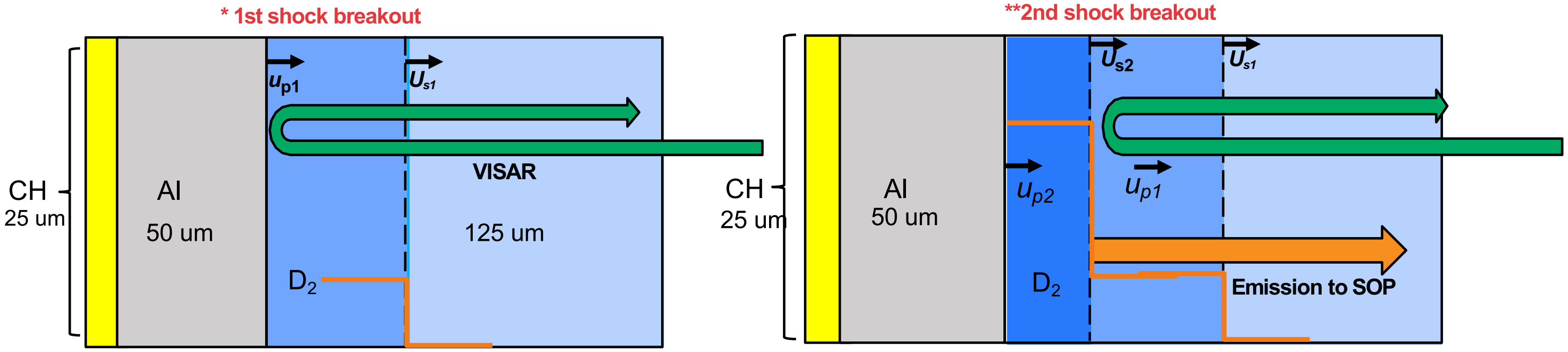


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Conservation of Mass:

$$\frac{\rho_1}{\rho_0} = \frac{U_{s1}}{U_{s1} - u_{p1}}$$

$$\frac{\rho_2}{\rho_1} = \frac{U_{s2} - u_{p1}}{U_{s2} - u_{p2}}$$

Conservation of Momentum:

$$P = \rho_0 U_{s1} u_{p1}$$

$$P(u_p) = P_1 + \rho_1 (U_{s2} - u_{p1})(u_p - u_{p1})$$

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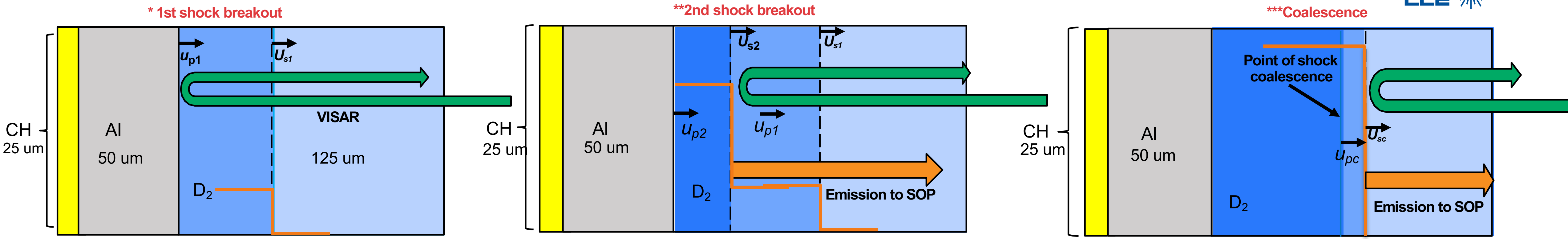


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Conservation of Mass:

$$\frac{\rho_1}{\rho_0} = \frac{U_{s1}}{U_{s1} - u_{p1}} \qquad \frac{\rho_2}{\rho_1} = \frac{U_{s2} - u_{p1}}{U_{s2} - u_{p2}} \qquad \frac{\rho_c}{\rho_0} = \frac{U_{sc}}{U_{sc} - u_{pc}}$$

Conservation of Momentum:

$$P = \rho_0 U_{s1} u_{p1} \qquad P(u_p) = P_1 + \rho_1 (U_{s2} - u_{p1})(u_p - u_{p1}) \qquad P(u_p) = \rho_0 U_{sc} u_p$$

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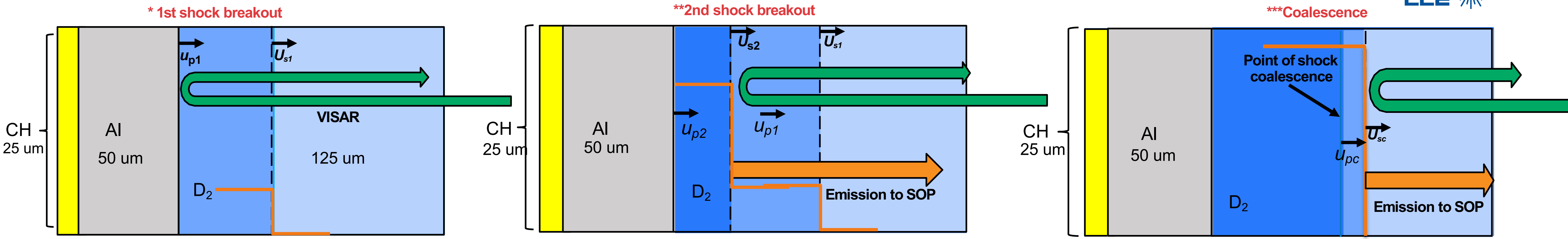
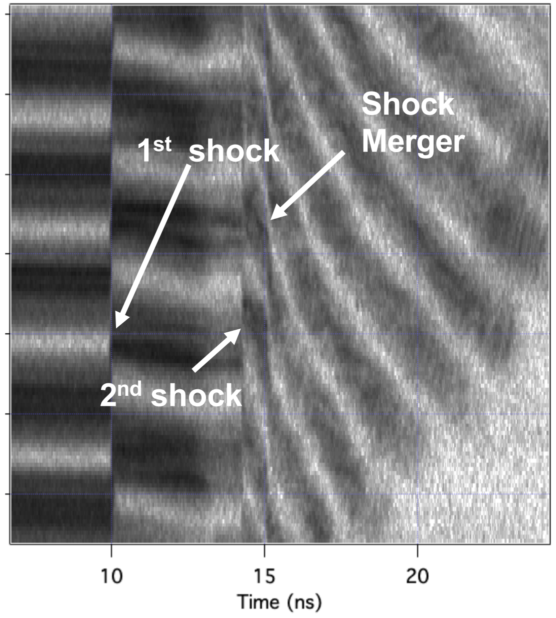
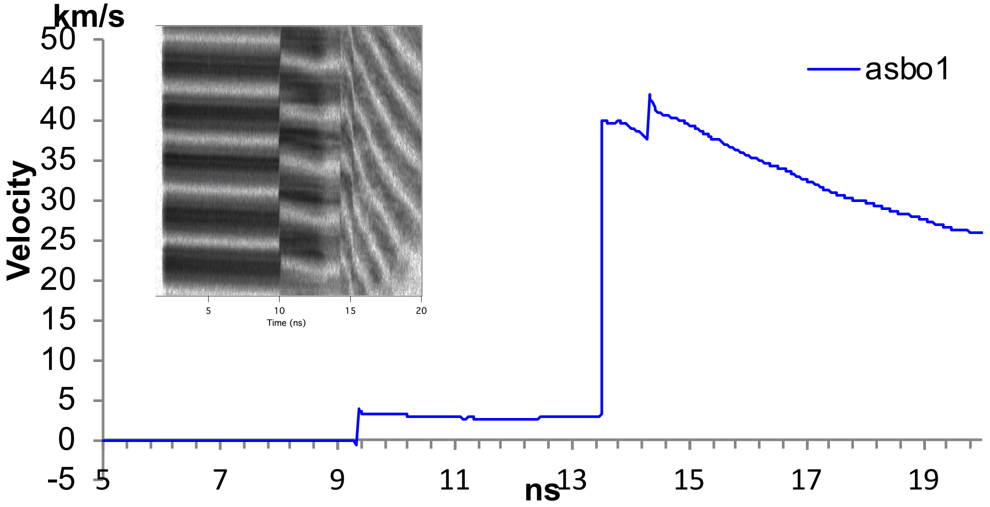
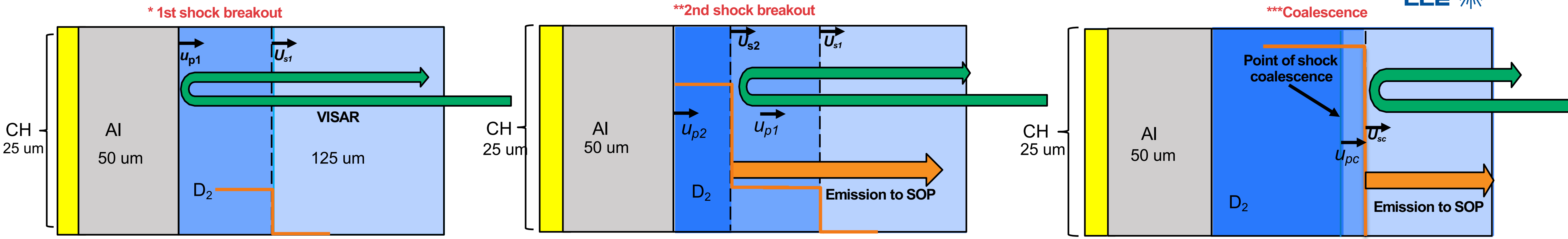
# We observe single, double, and coalesced shocks in $D_2$ with VISAR

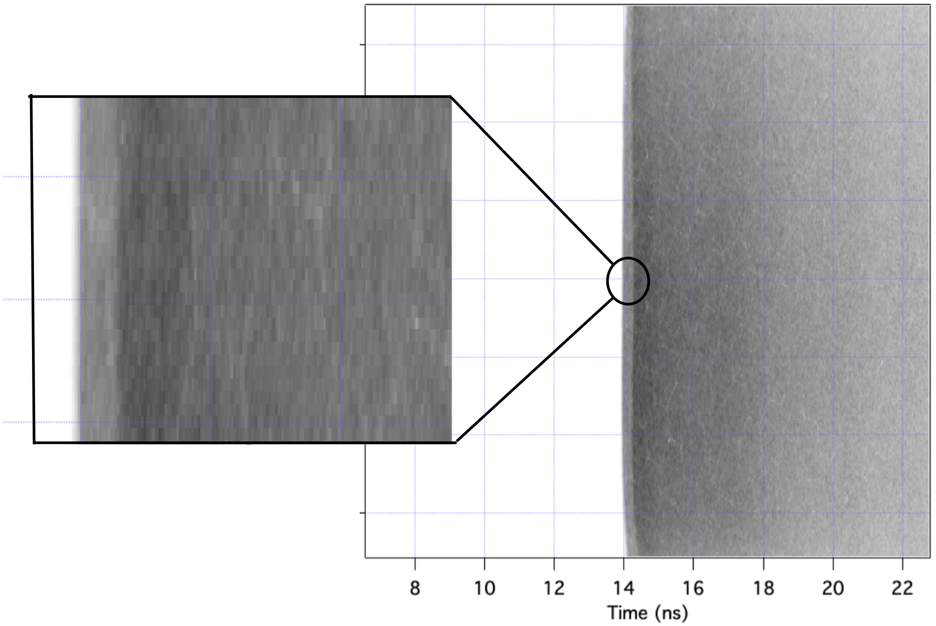


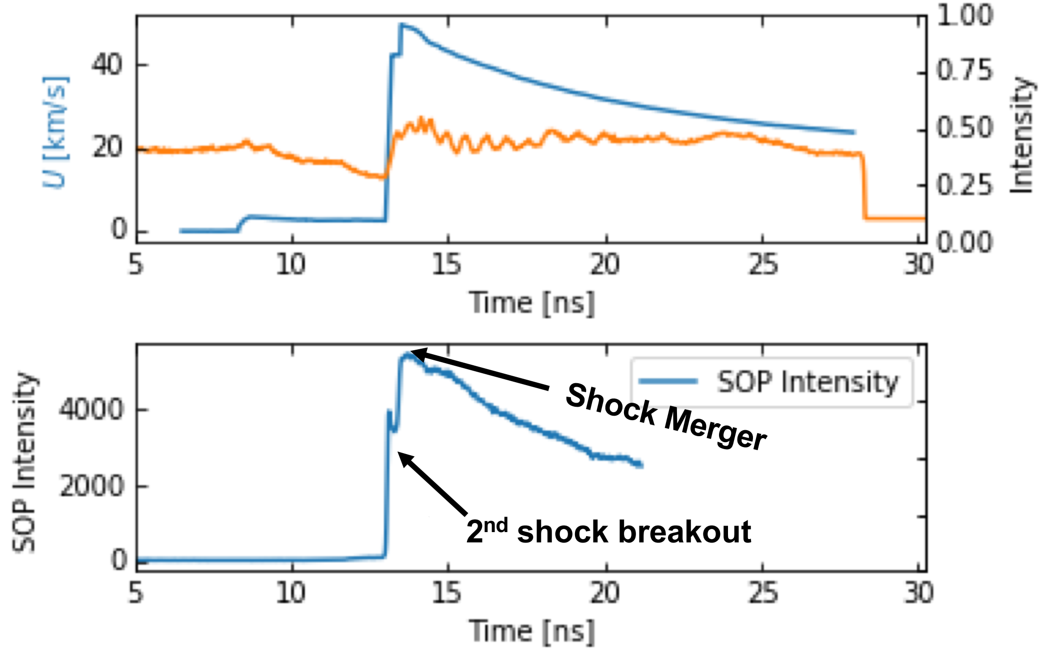



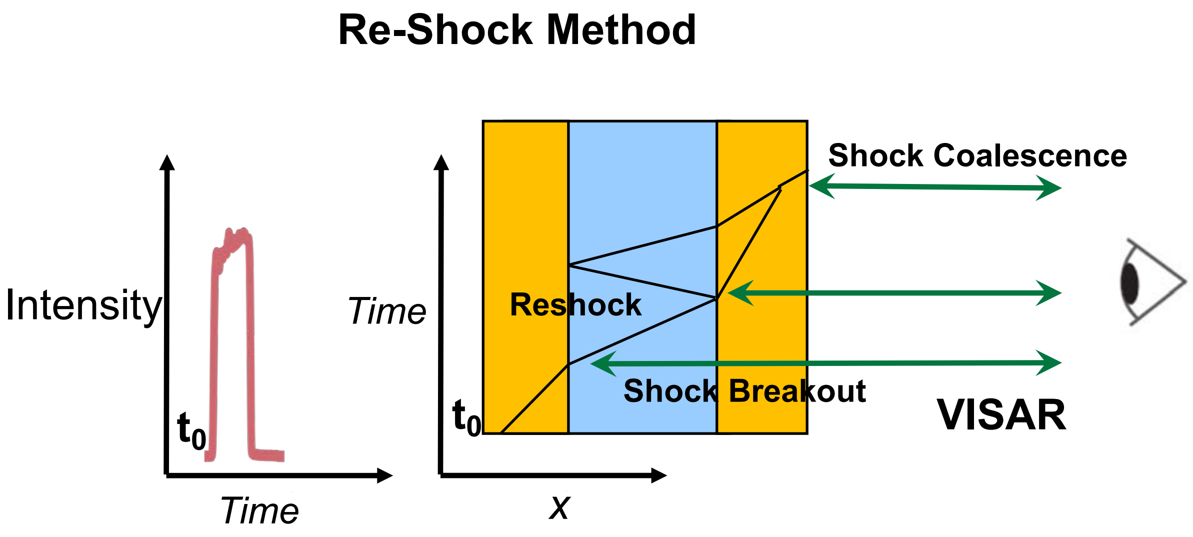
# Temperature of shock material can be measured with SOP

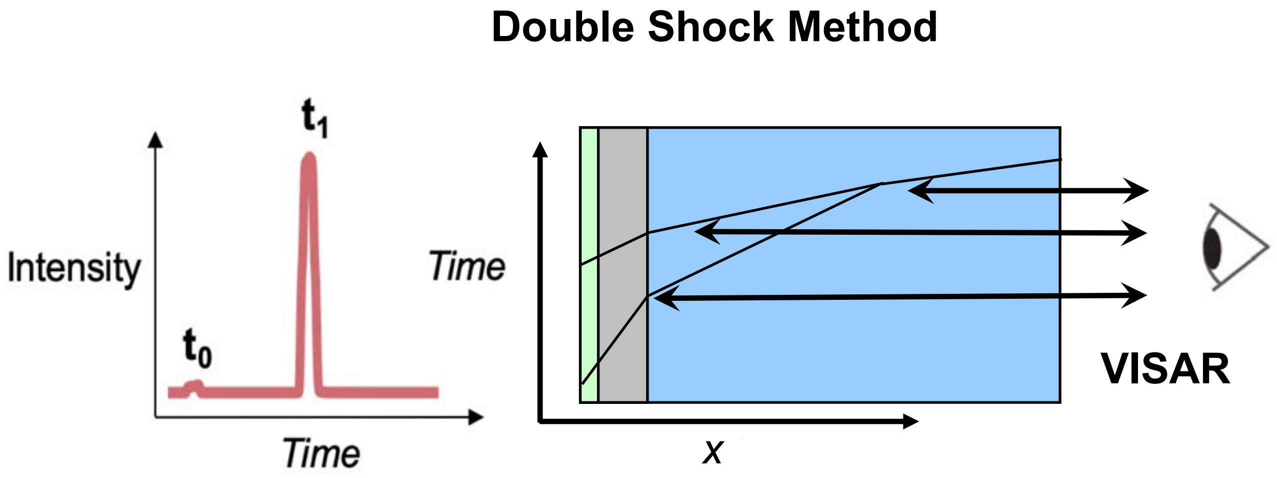


# Double-shock platform allows for Temperature and Conductivity measurement




- Anvil re-shock experiments require the sample to be sandwiched between materials with a higher resistance to shocks (*shock impedance*)
- Due to the reflectance of the shock in the quartz anvil, reflectivity and temperature could not be obtained for the $D_2$ sample using existing methods

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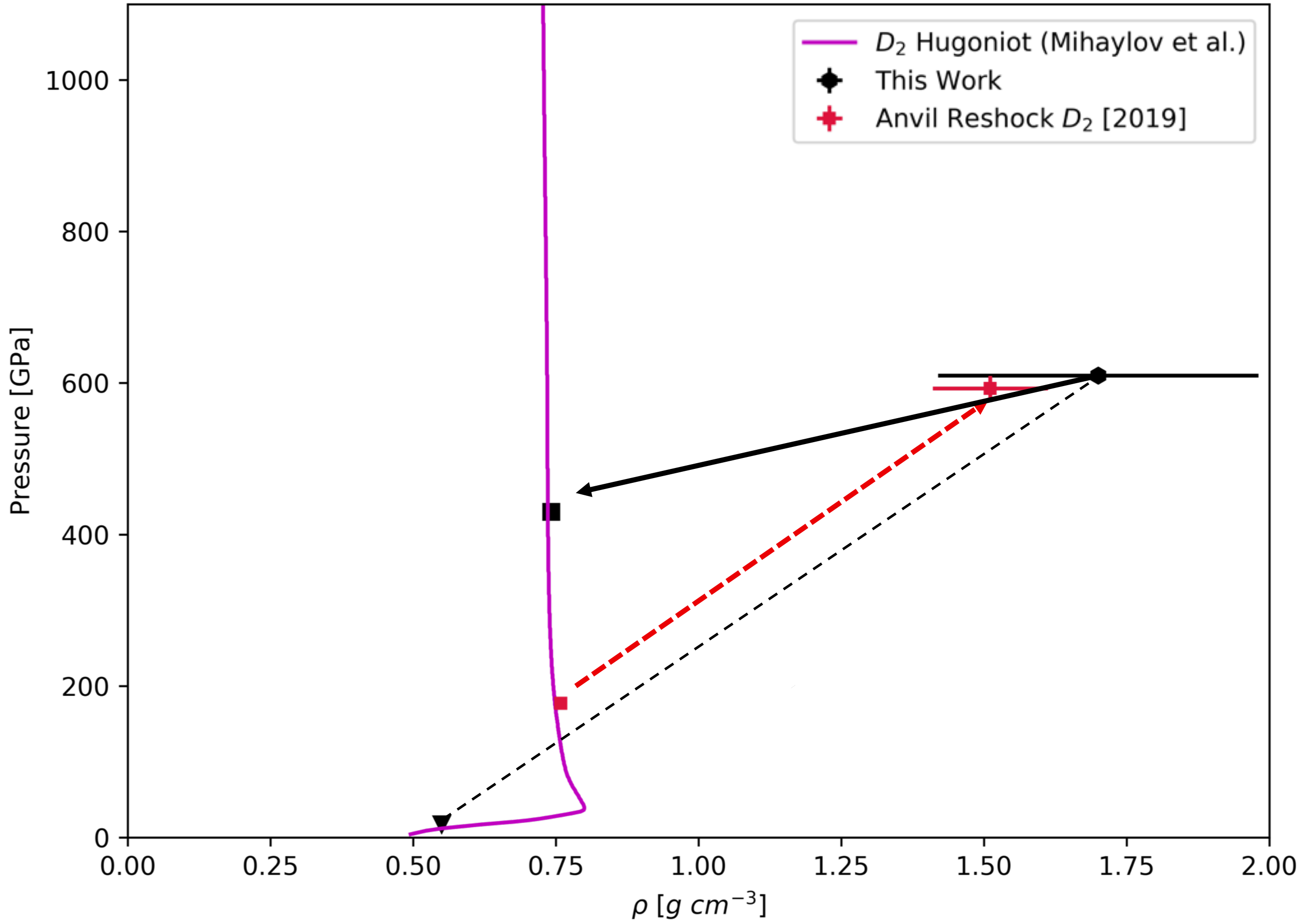
# We achieve similar pressures and densities as those obtained by $D_2$ anvil re-shock




- There is a limit on the strength of the first shock in the double shock platform

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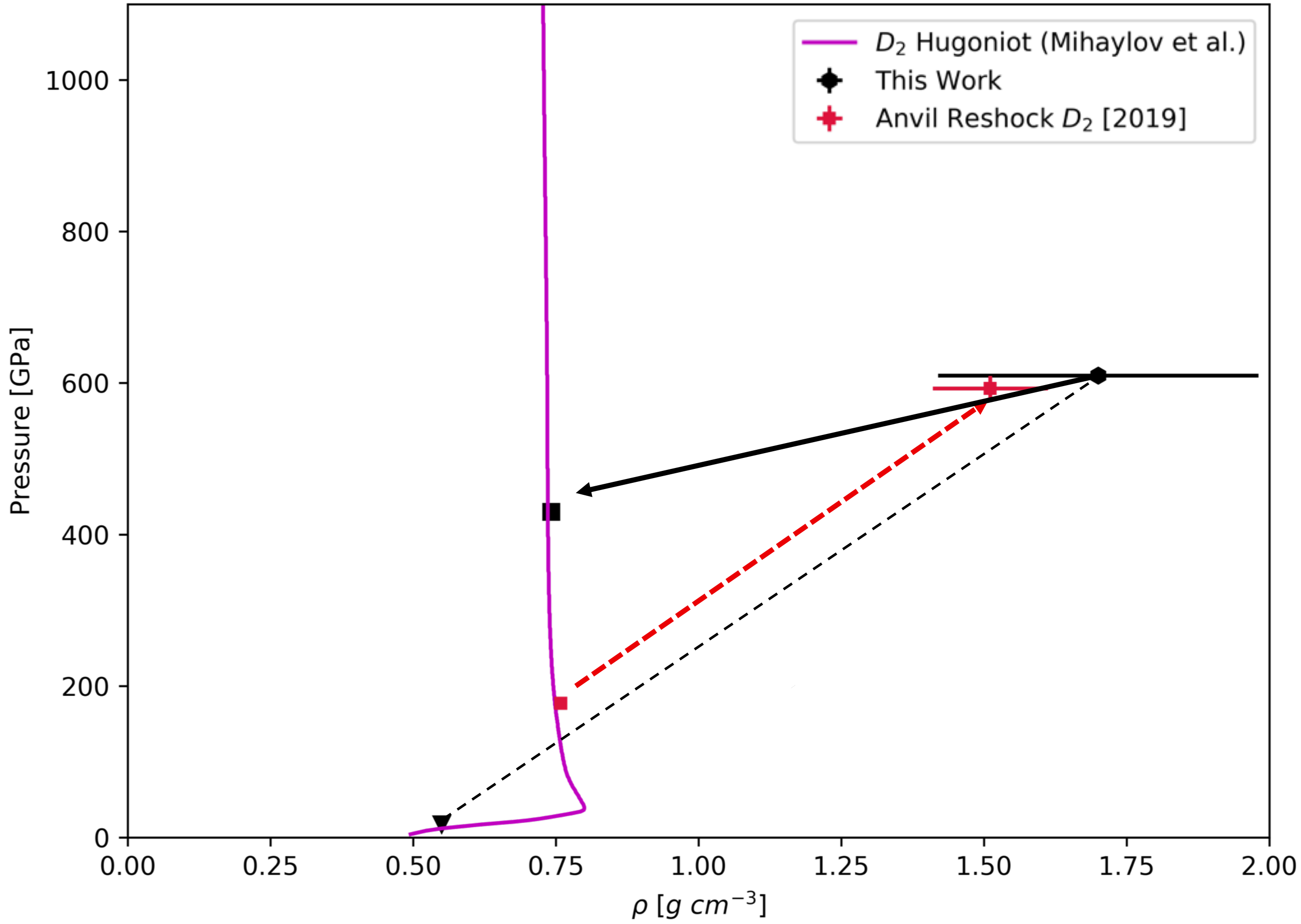


- There is a limit on the strength of the first shock in the double shock platform
- This is due to the self-impedance matching method requirement that the shock remain transparent

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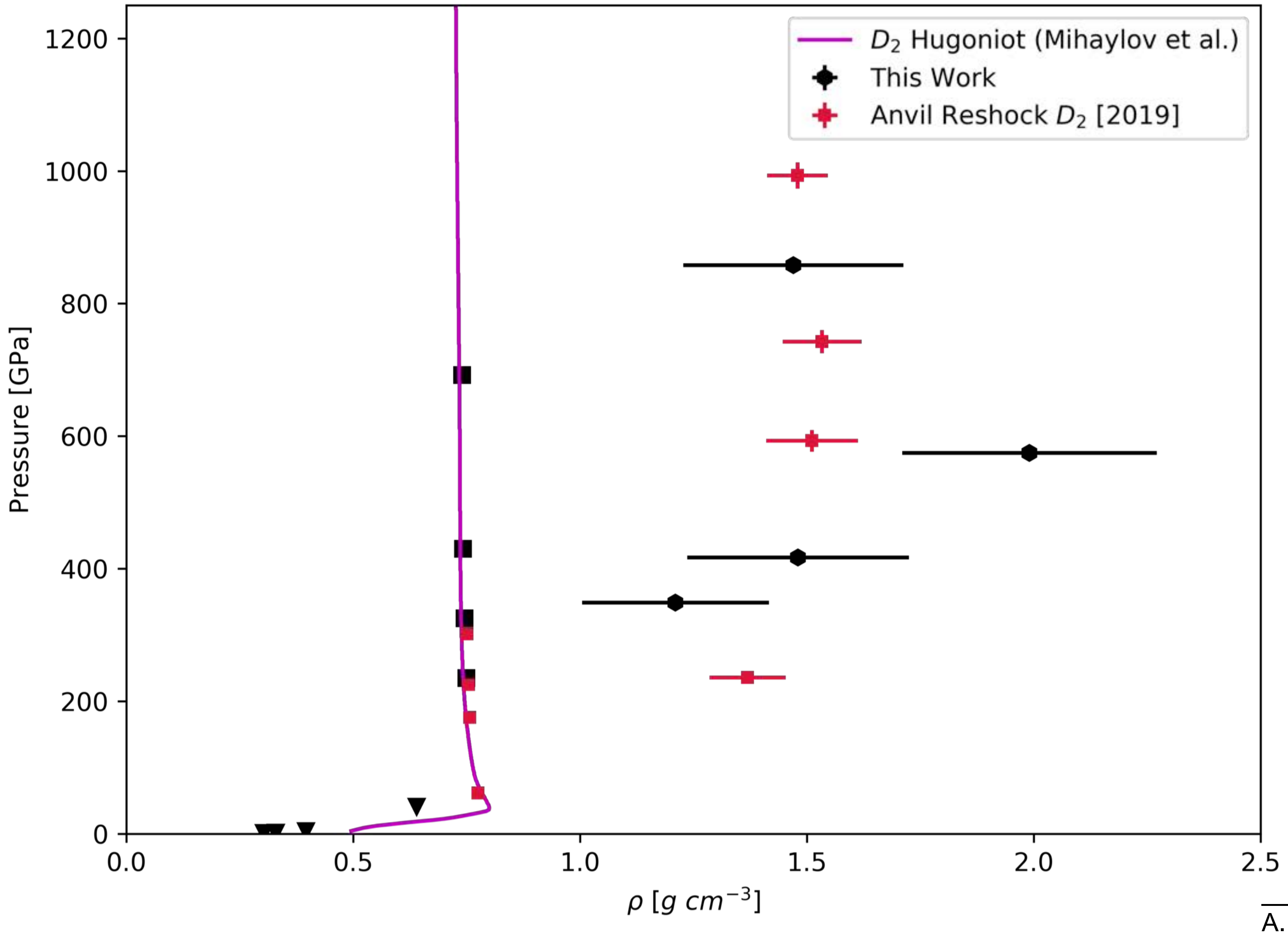


- Double shock platform allows us to "tune" the density of the off-hugoniot state with the 1st shock pressure and density

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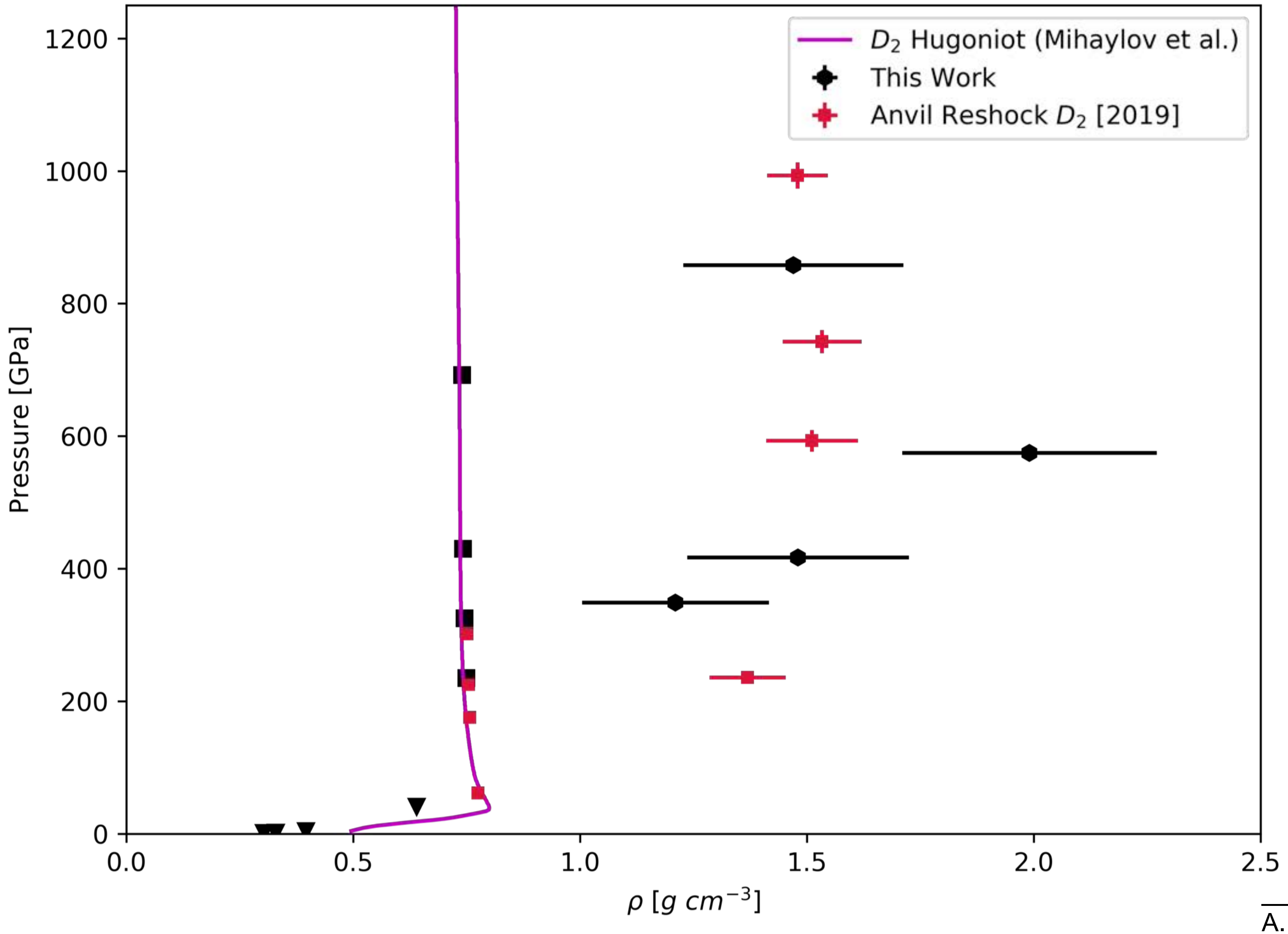


- Double shock platform allows us to "tune" the density of the off-hugoniot state with the 1st shock pressure and density
- Our data show that anvil re-shock and double shock methods are capable of obtaining similar pressures and densities of off-hugoniot states **($P_2$,$\rho_2$)

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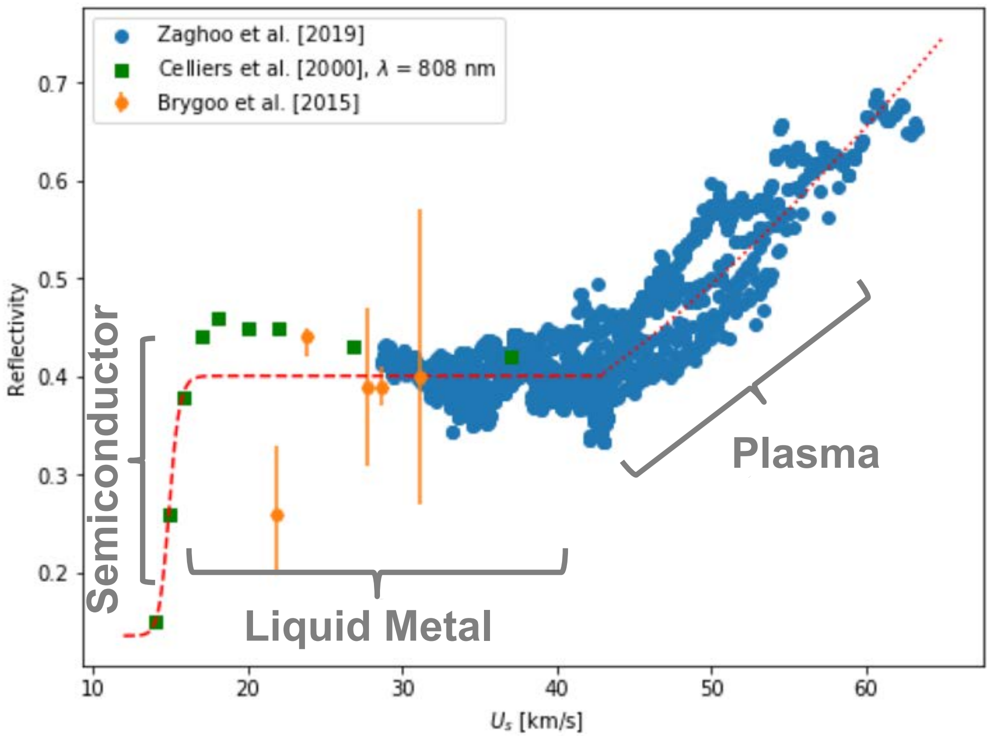
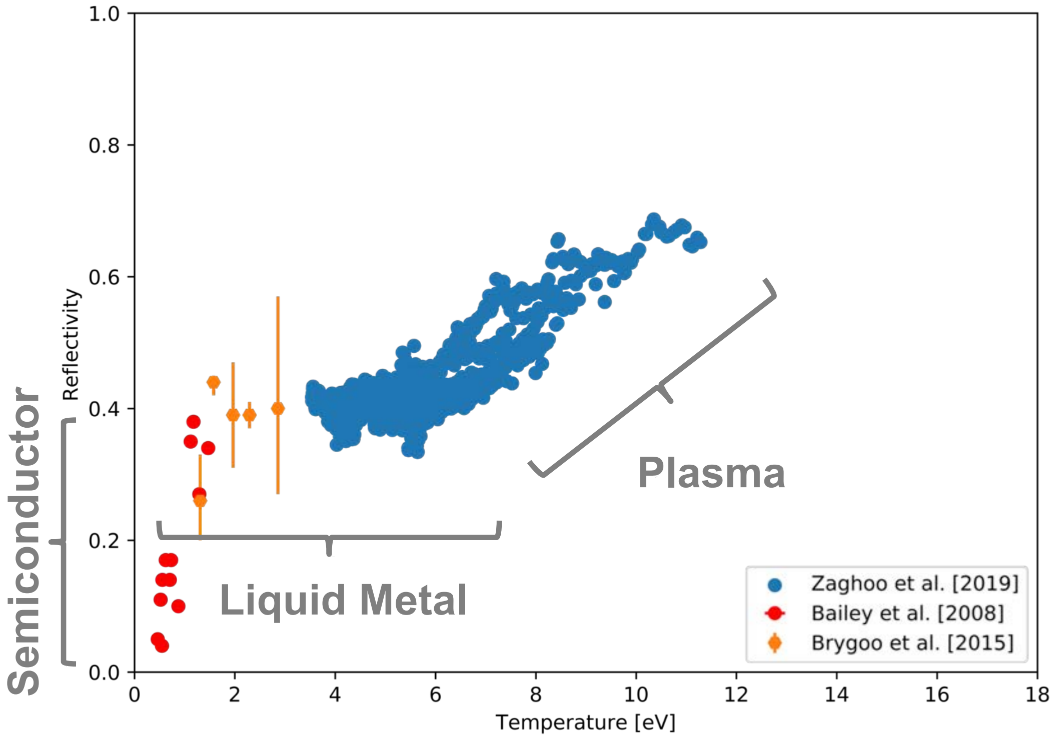
# Our data occupy a range of states in the liquid metallic and plasma regimes




- The feflectivity saturation observed on the L-$D_2$ Hugoniot between shock velocities of ~20 km/s– 40 km/s and temperatures of ~ 2 eV - 6 eV is consistent with the existence of a liquid metallic state
- A transition from liquid metal to plasma is observed at shock velocities > 40 km/s and temperatures > 6 eV

M. Zaghoo, et al. Phys. Rev. Lett. **122**, 085001 – Published 27 February 2019

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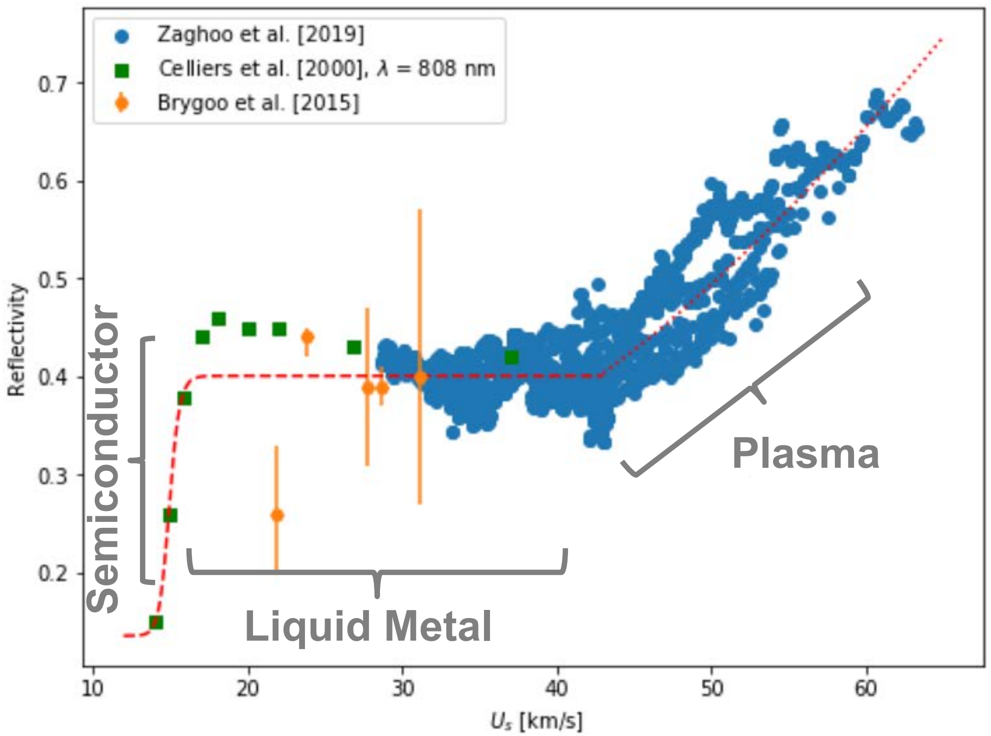


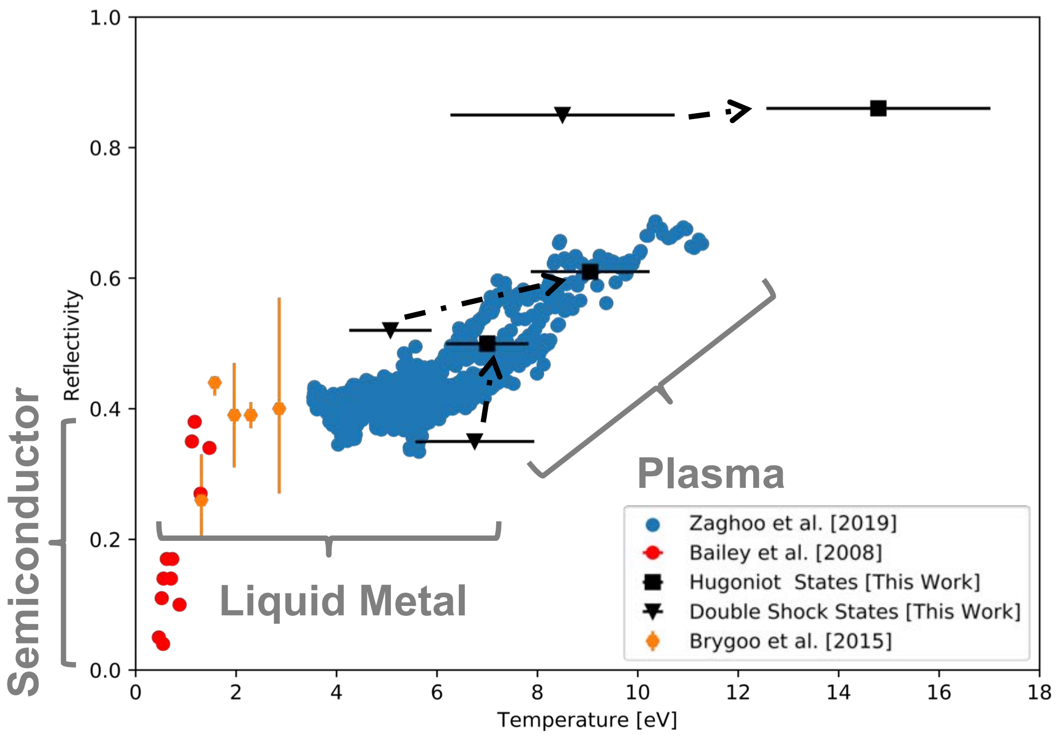


- Our preliminary data appears to overlap the transition of L-$D_2$ from a Fermi-degenerate system to a classical plasma

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