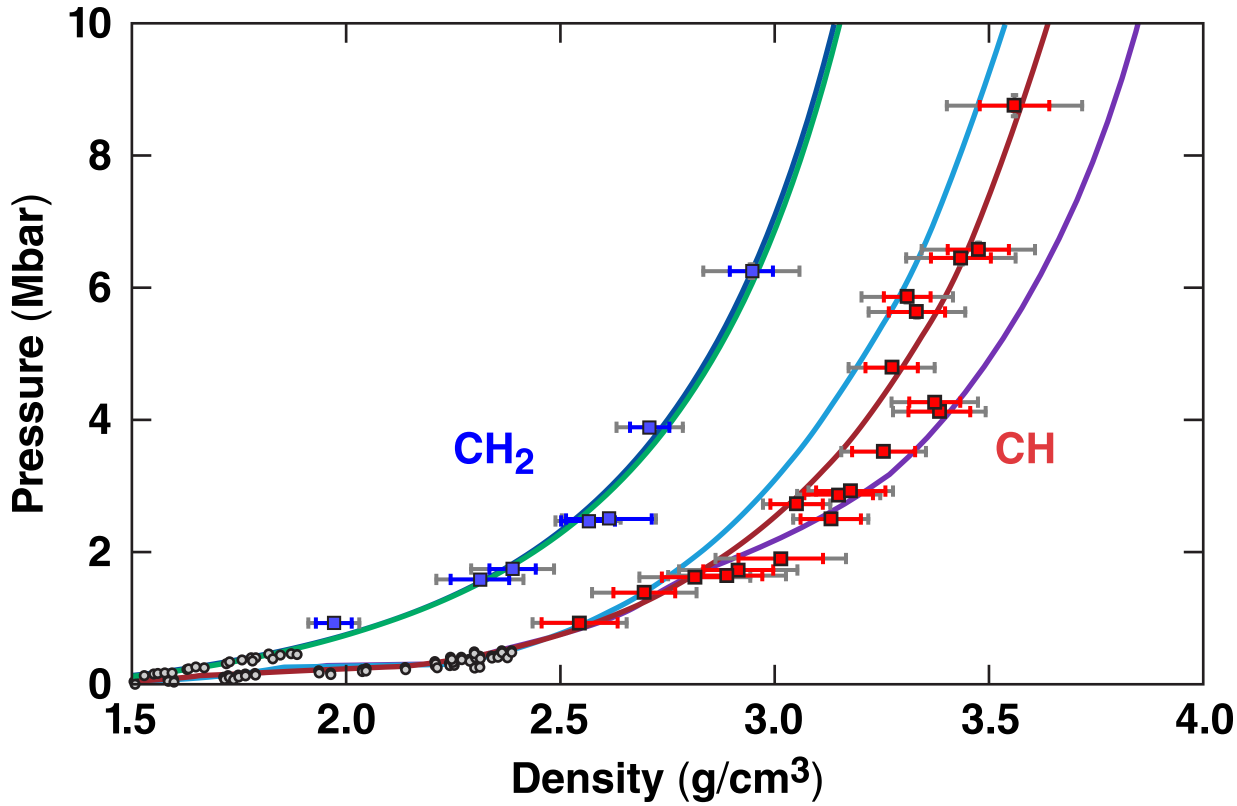
High-Precision Measurements of the Equation of State of Polymers at 1 to 10 Mbar



M. A. Barrios
University of Rochester
Laboratory for Laser Energetics

51st Annual Meeting of the
American Physical Society
Division of Plasma Physics
Atlanta, GA
2–6 November 2009

Summary

Precision equation-of-state (EOS) measurements are obtained on various polymers at 1 to 10 Mbar

- Precise knowledge of ablator EOS is required for ICF target designs
  - some NIF target designs use Ge-doped GDP
- Laser-driven shock waves produce EOS data using the impedance-matching (IM) method
- CH data allows for model discrimination, favoring *SESAME* 7592
  - mild softening is not accounted for between 2 to 4 Mbar
  - single- and double-shock results display similar behavior
- Stoichiometry effects between CH and CH_2 are well-predicted by models
- EOS data for NIF ablator material was acquired

Outline

I. Motivation

II. Precision EOS measurements

III. Experiments

- A. Single shock, principal Hugoniot measurements
  - i. Polystyrene (CH)
  - ii. Polypropylene (CH_2)

  C:H ratio

  - iii. GDP ($CH_{1.3}O_{0.023}$)
  - iv. 0.6at% Ge-doped GDP

  NIF ablators
- B. Double shock, off Hugoniot measurements
  - i. Polystyrene (CH)

Collaborators

D. E. Fratanduono

T. R. Boehly

D. D. Meyerhofer

University of Rochester
Laboratory for Laser Energetics

D. G. Hicks

P. M. Celliers

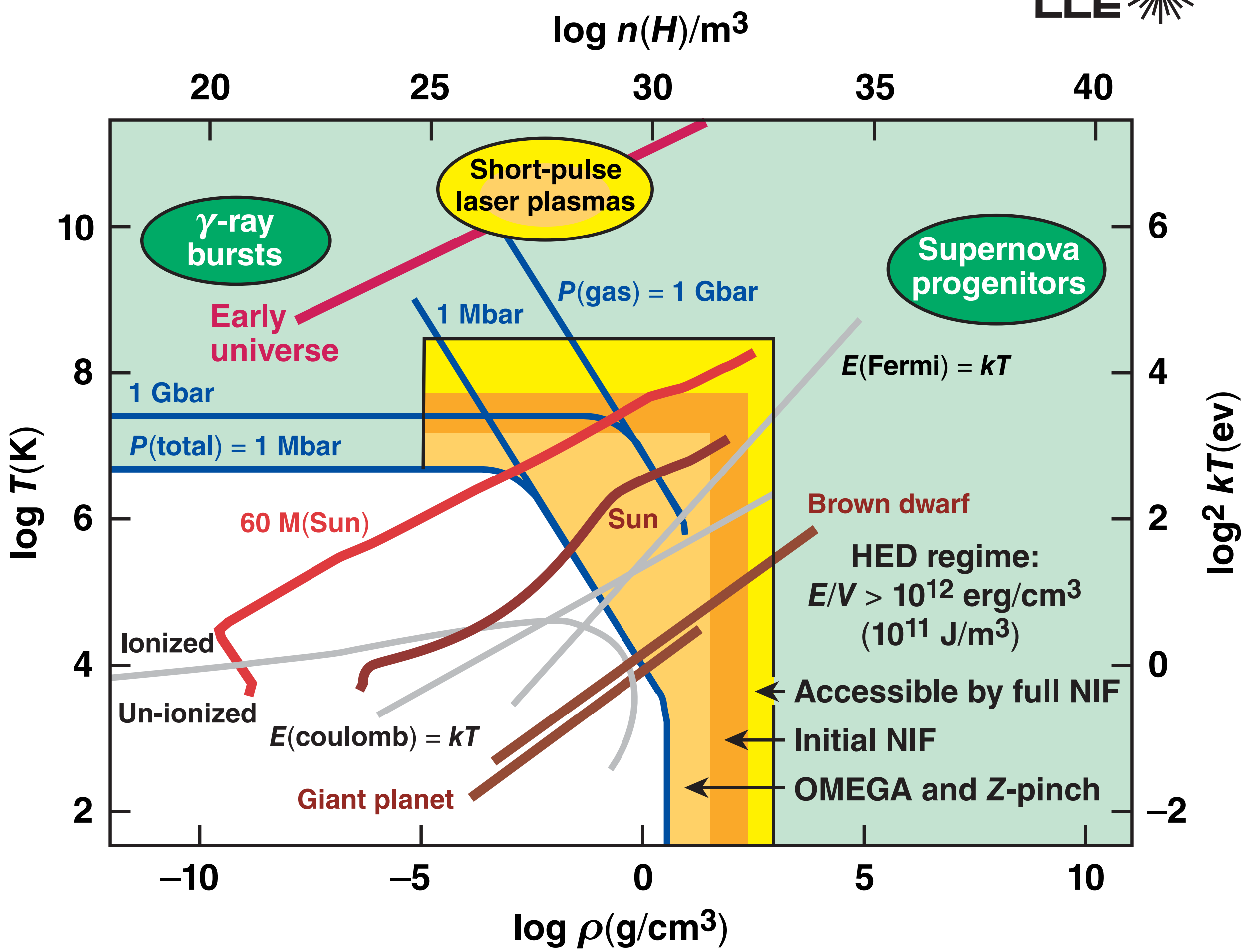
J. Eggert

Lawrence Livermore National Laboratory

Motivation

High-pressure EOS data are required to understand high-energy-density (HED) physics

- Reliable EOS data is important to dense plasma theory, where radiation hydrodynamic codes are used.
- Need material EOS over wide density and temperature ranges.
- Existing data covers a small fraction of these ranges.

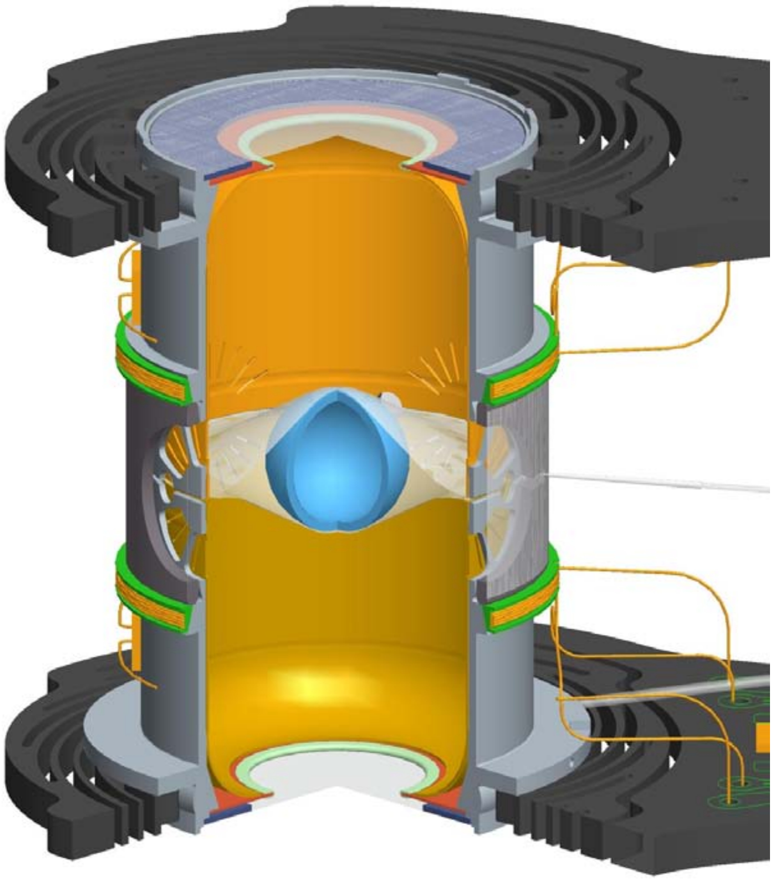


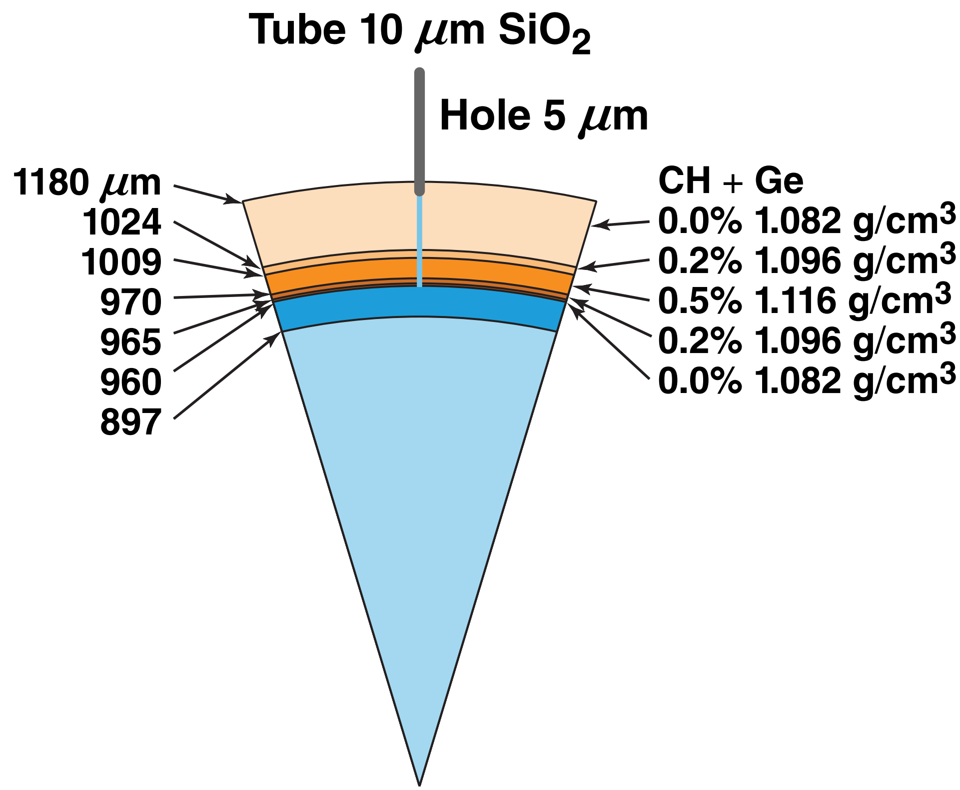
EOS measurements above 1 Mbar are used to benchmark models.

National Research Council (U.S.) Committee on High Energy Density Plasma Physics, *Frontiers in High Energy Density Physics: The X-Games of Contemporary Science* (National Academies Press, Washington, DC, 2003).

E18342

Some NIF ignition target designs use Ge-doped plastic ablators—high-pressure EOS measurements are needed



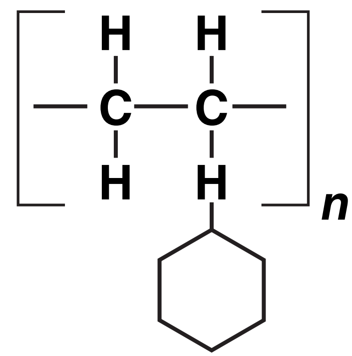


S.W. Haan, IFSA 2009.

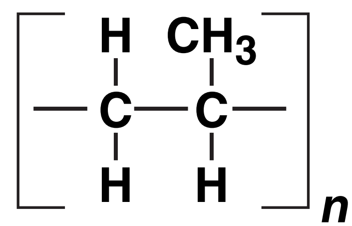
Hydrocarbons are common ablator materials for ICF fuel pellets

- Ablator material properties are essential to the design and simulation of ICF targets
- By varying C to H ratio, the effect of stoichiometry on high-pressure behavior can be investigated

	Formula
Polystyrene	CH
Polypropylene	CH_2
Glow discharge polymer (GDP)	$CH_{1.3}O_{0.023}$
Ge-doped GDP	$CH_{1.3}O_{0.023} + Ge_{at\%\ 0.6}$



CH

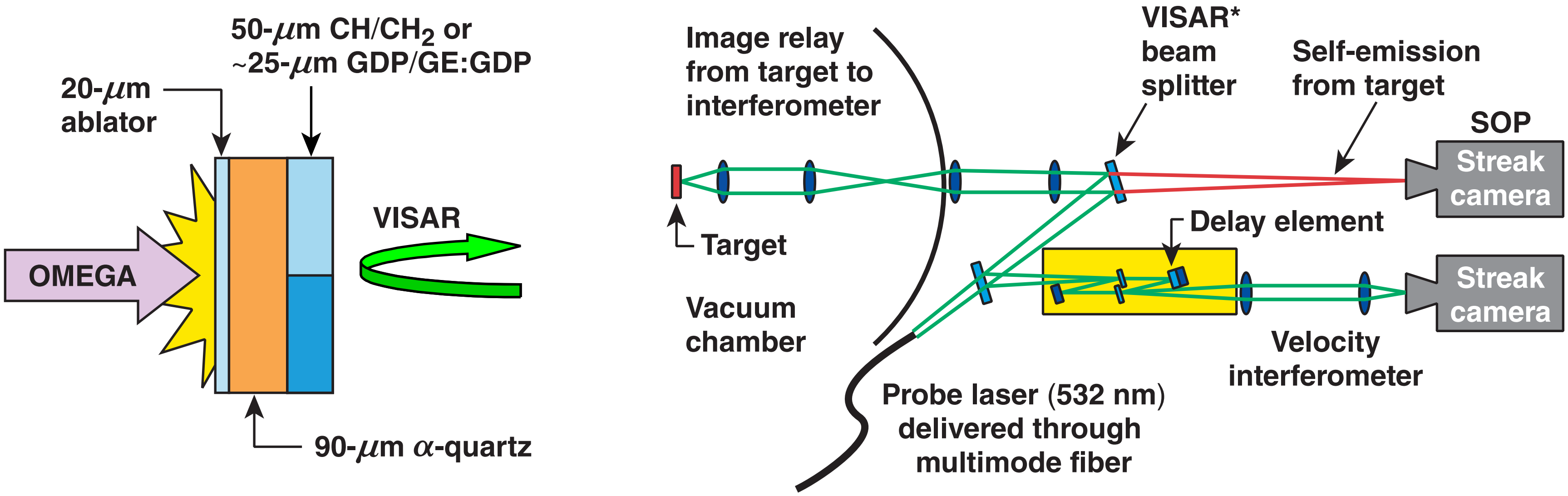


CH_2

EOS measurements on CH_x will provide benchmark behavior on hydrocarbon polymers under extreme P, ρ conditions.

OMEGA Experiments

Polymer EOS experiments were performed using laser-driven shock waves on OMEGA



- Experiments used laser energies between 200 to 1130 J delivered in a nominally 2-ns square pulse.
- Average laser irradiances on target were 0.3 to 1.1 $\times$ 10^{14} W/cm^2

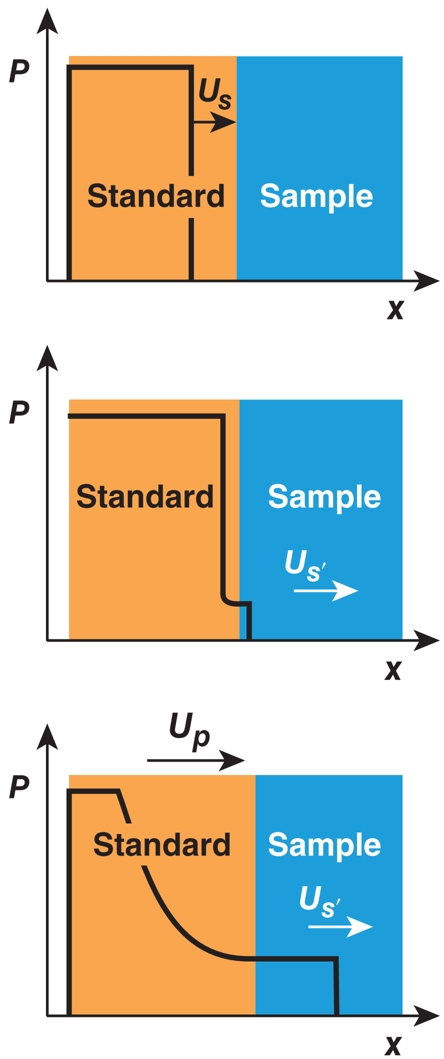
VISAR* has time resolution of <30 ps and shock-velocity precision of ~1%.

E18346

*Velocity Interferometer System for any Reflector

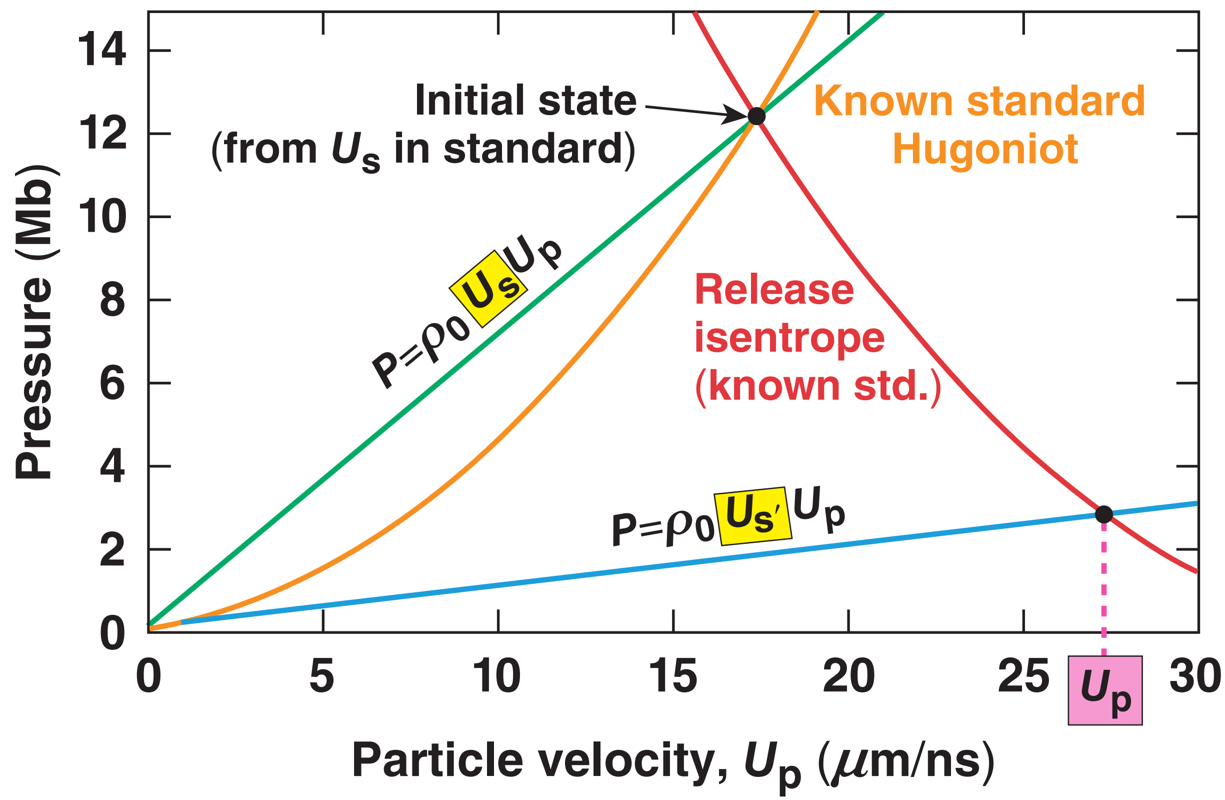
Impedance Matching $U_s = F(U_p)$

EOS data are obtained from the impedance-matching technique



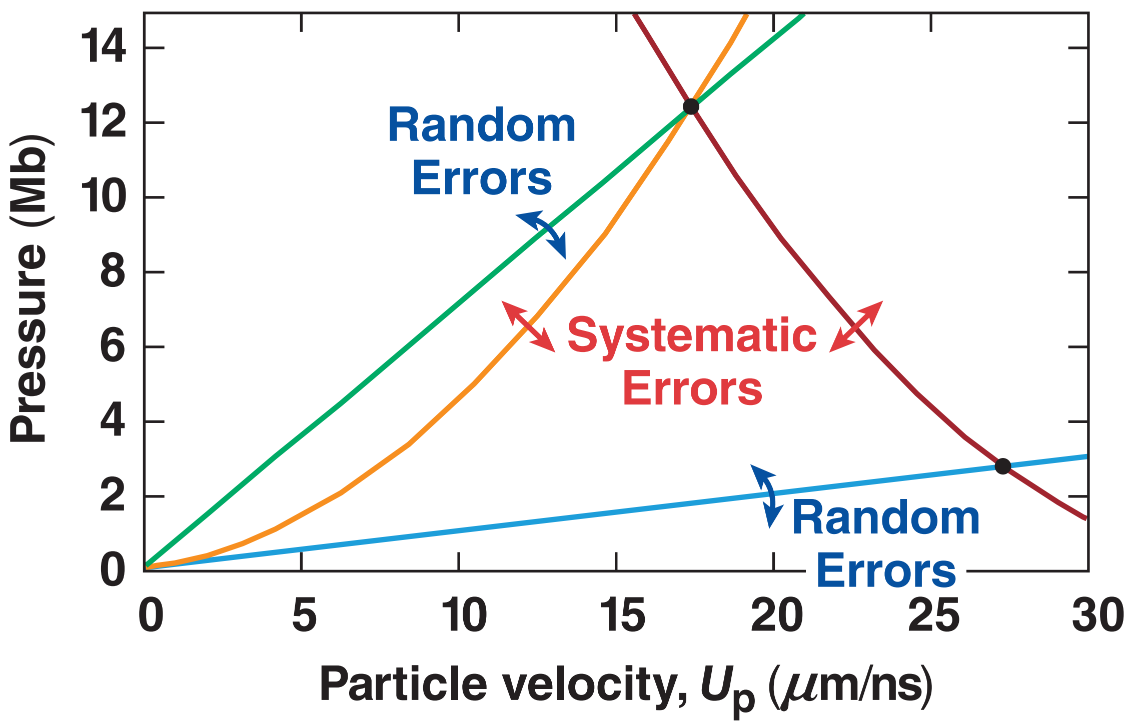
Rankine–Hugoniot Equations

$$\rho_0 U_s = \rho_1 (U_s - U_p)$$
$$P_1 - P_0 = \rho_0 U_s U_p$$



E17323b

Experimental errors must be minimized and systematic errors understood for precision EOS measurements



- Measurement accuracy depends on knowledge of standard.
- Most impedence-matching (IM) studies quote only random errors.
- Cannot propagate systematic errors using theoretical EOS.

- Random errors

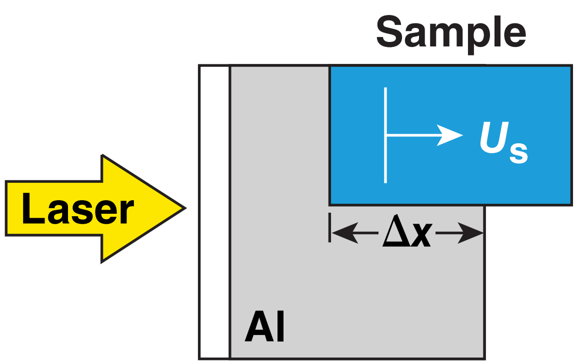
$$\frac{\delta\rho}{\rho} \propto (\eta - 1) \times \frac{\delta U_s}{U_s}, \quad \text{where } \eta = \frac{\rho}{\rho_0};$$

$$\eta \simeq 4 - 6 \rightarrow \frac{\delta\rho}{\rho} \propto (3-5) \times \frac{\delta U_s}{U_s}$$

E13920d

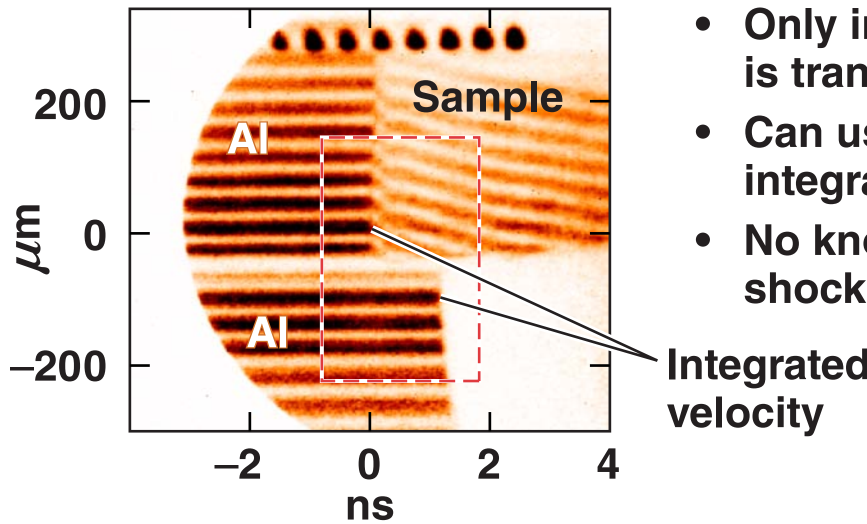
Random Errors

Higher precision is obtained with a transparent standard compared to an opaque standard

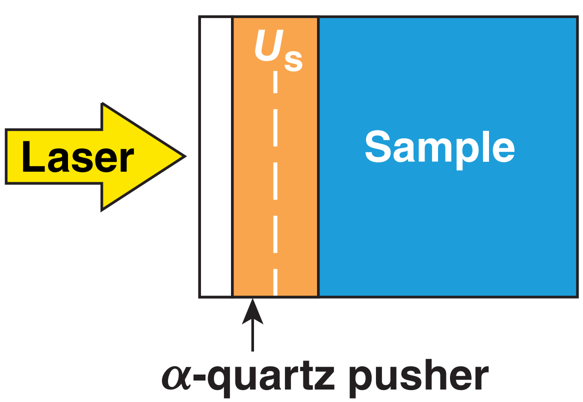


U_s is inferred from transit times

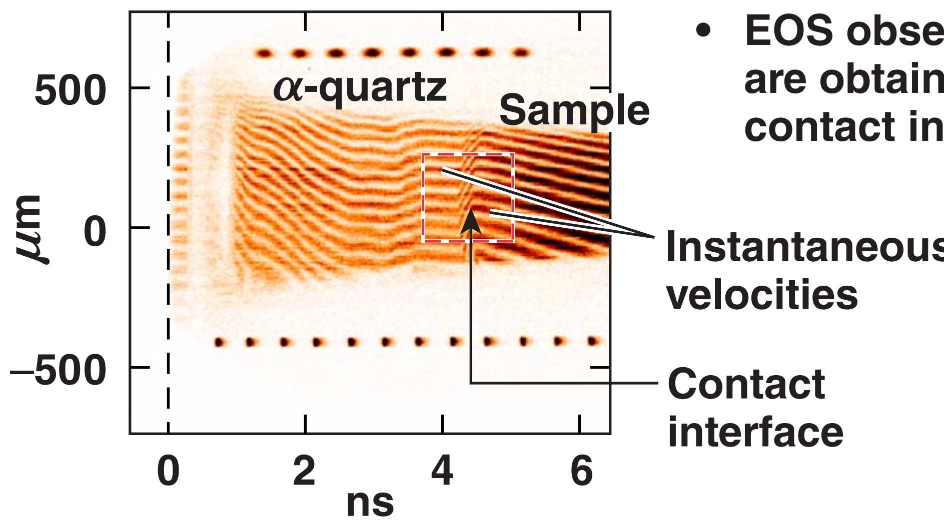
VISAR-1 shot 29425



- Only information is transit time
- Can use only integrated shock
- No knowledge of shock stability



VISAR-1 shot 52118

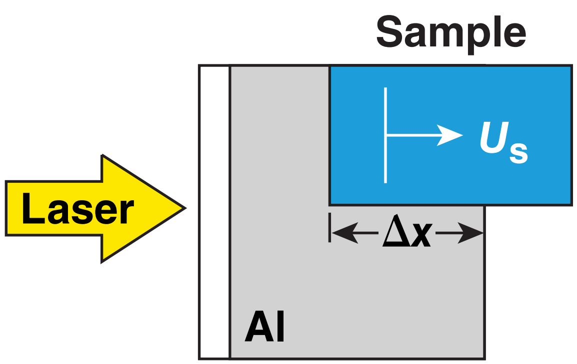


- EOS observables are obtained at the contact interface

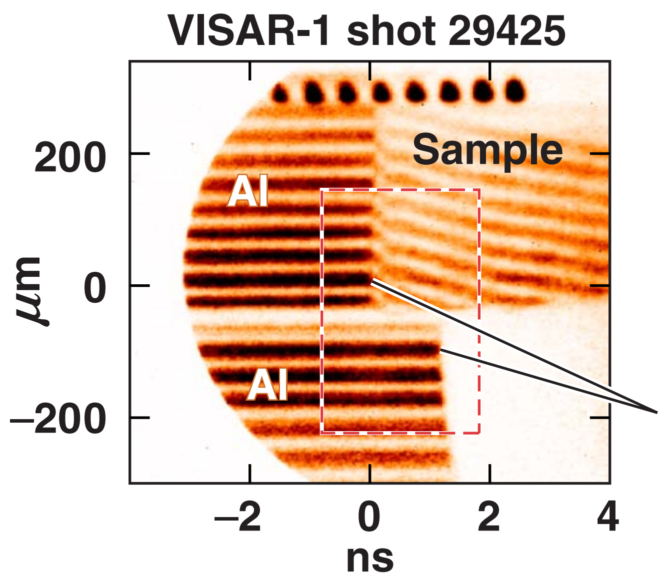
E17324b

Random Errors

Higher precision is obtained with a transparent standard compared to an opaque standard

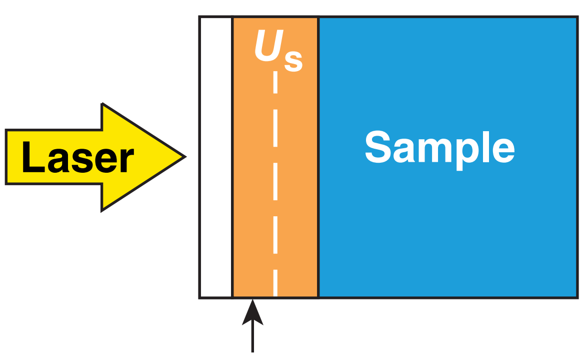


U_s is inferred from transit times

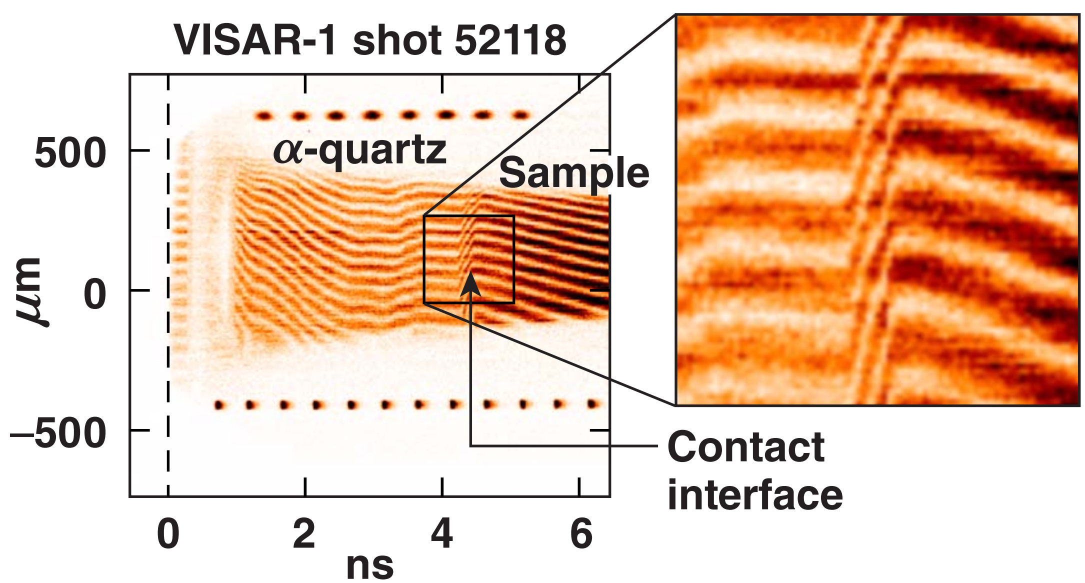


Integrated velocity

- Only information is transit time
- Can use only integrated shock
- No knowledge of shock stability



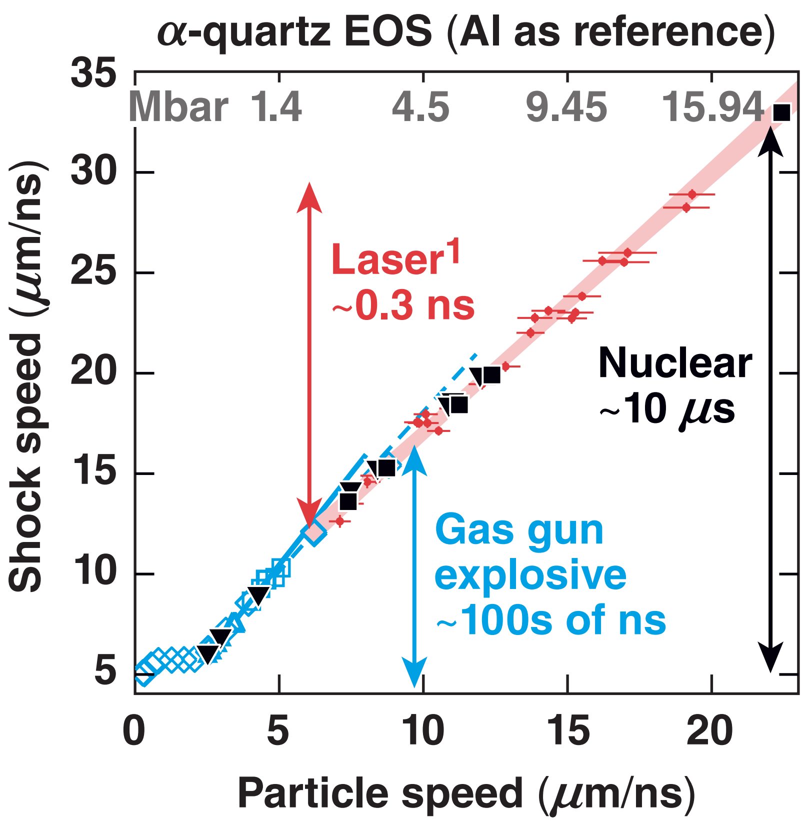
α-quartz pusher

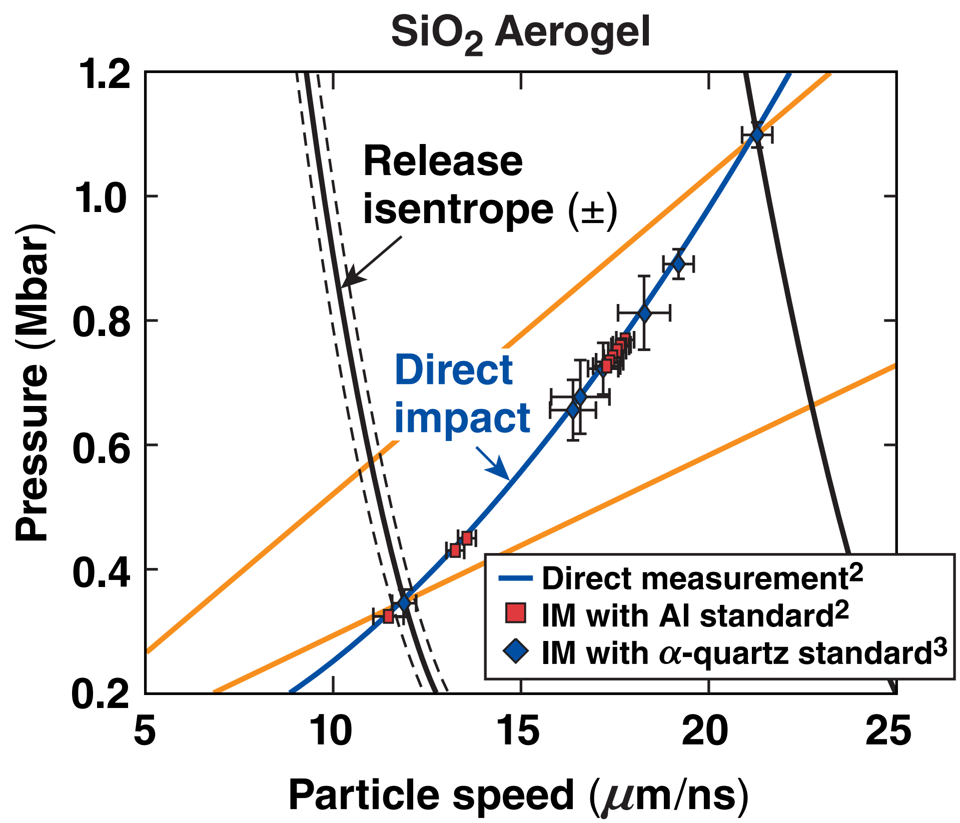


E17324b

Systematic Errors

α-quartz has been validated as an EOS standard





[1] D. G. Hicks *et al*., Phys. Plasmas 12, 082702 (2005).

[2] M. D. Knudson *et al*., J. Appl. Phys. 97, 073514 (2005).

[3] T. R. Boehly *et al*., in *Shock Compression of Condensed Matter–2007*, Vol. 955, p 19–22.

E17325b

Systematic Errors

α-quartz's release isentrope is approximated using the Mie-Grüneisen EOS

- Γ describes pressure differences between equal volume states on the Principal Hugoniot

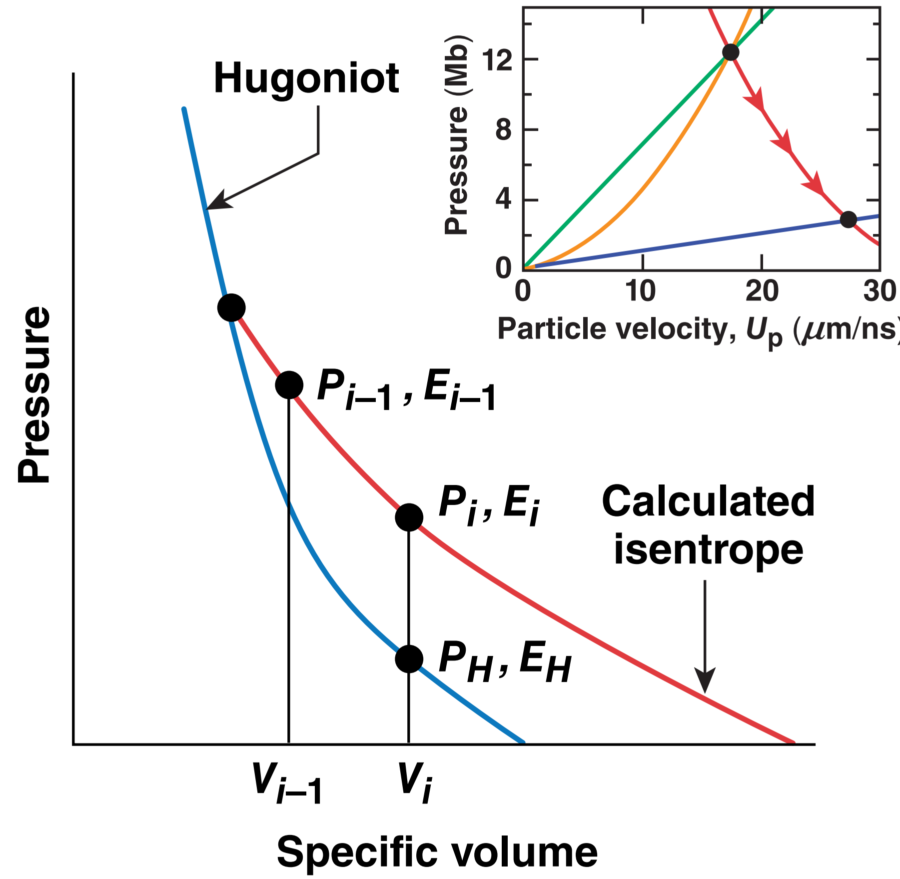
$$\Gamma = V\left(\frac{dP}{dE}\right)_V$$

- Combining the above with the first law of thermodynamics,

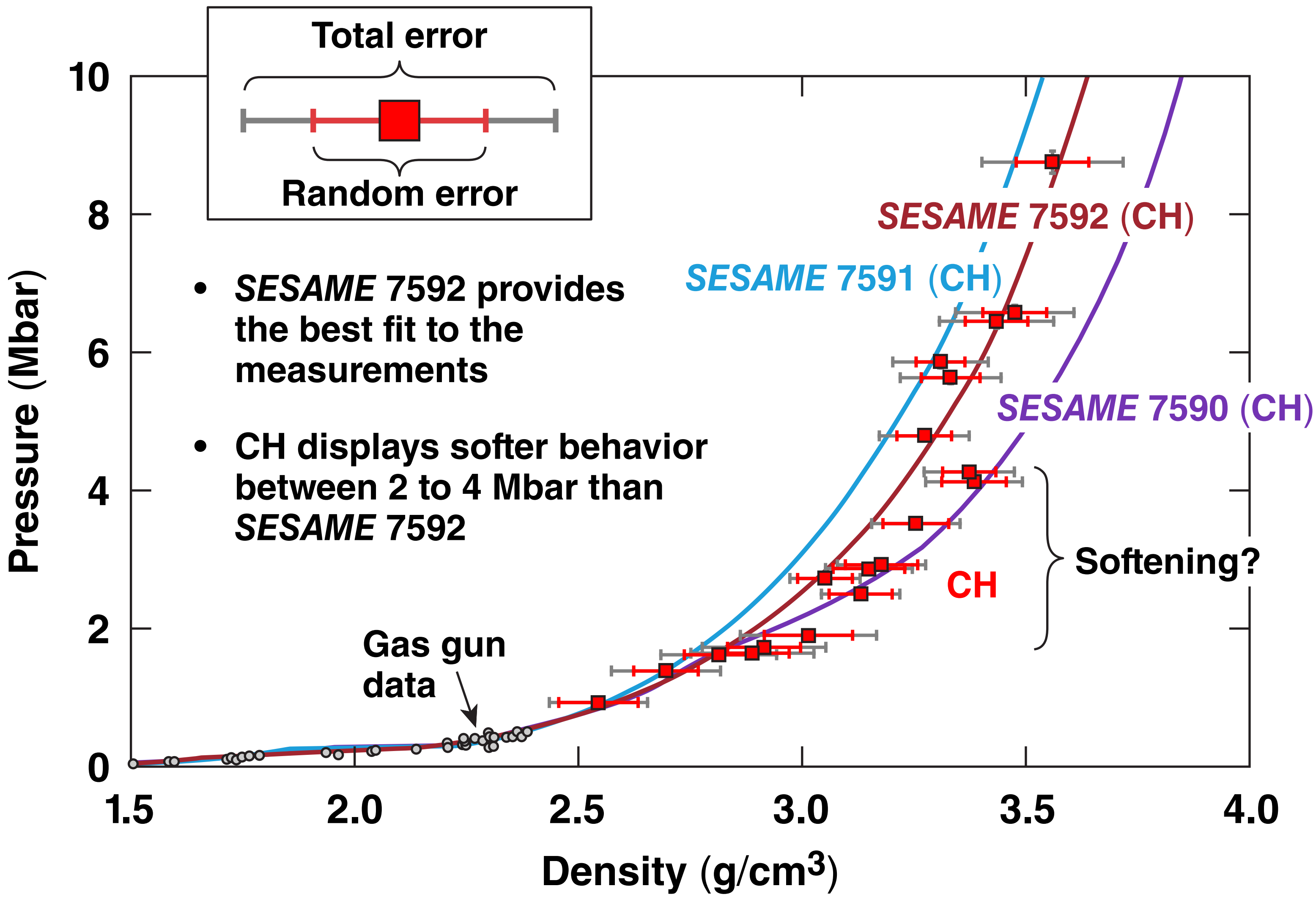
$$dE = TdS - PdV$$

  with $dS = 0$, leads to a recursion relation describing a loci of isentropes in the P–V plane

- Based on models, Γ is assumed to be constant in the high-pressure fluid regime, with value $\Gamma = 0.64 \pm 0.11$



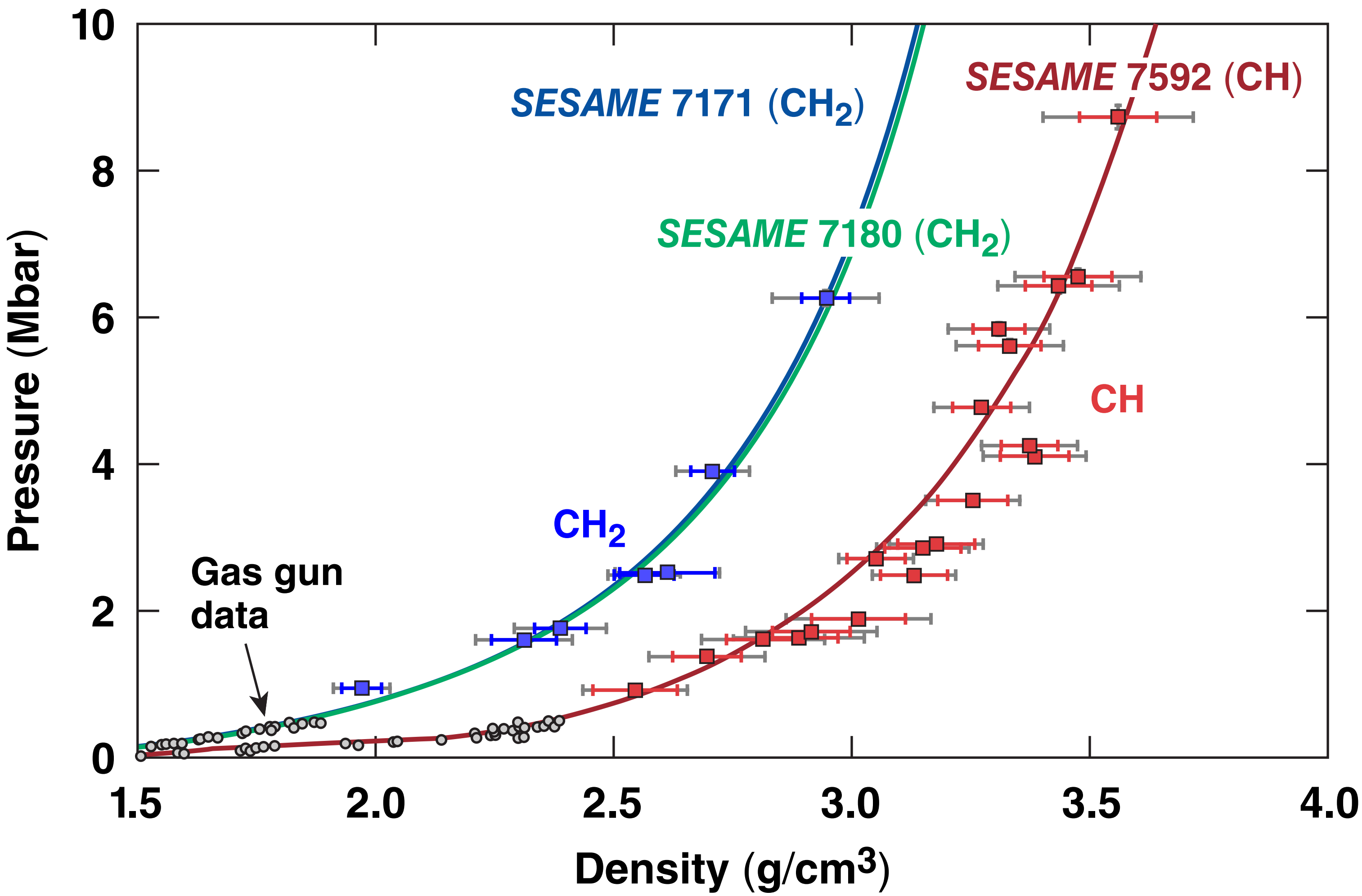
Precision EOS data tightly constrain polystyrene (CH) EOS models



- *SESAME* 7592 provides the best fit to the measurements
- CH displays softer behavior between 2 to 4 Mbar than *SESAME* 7592

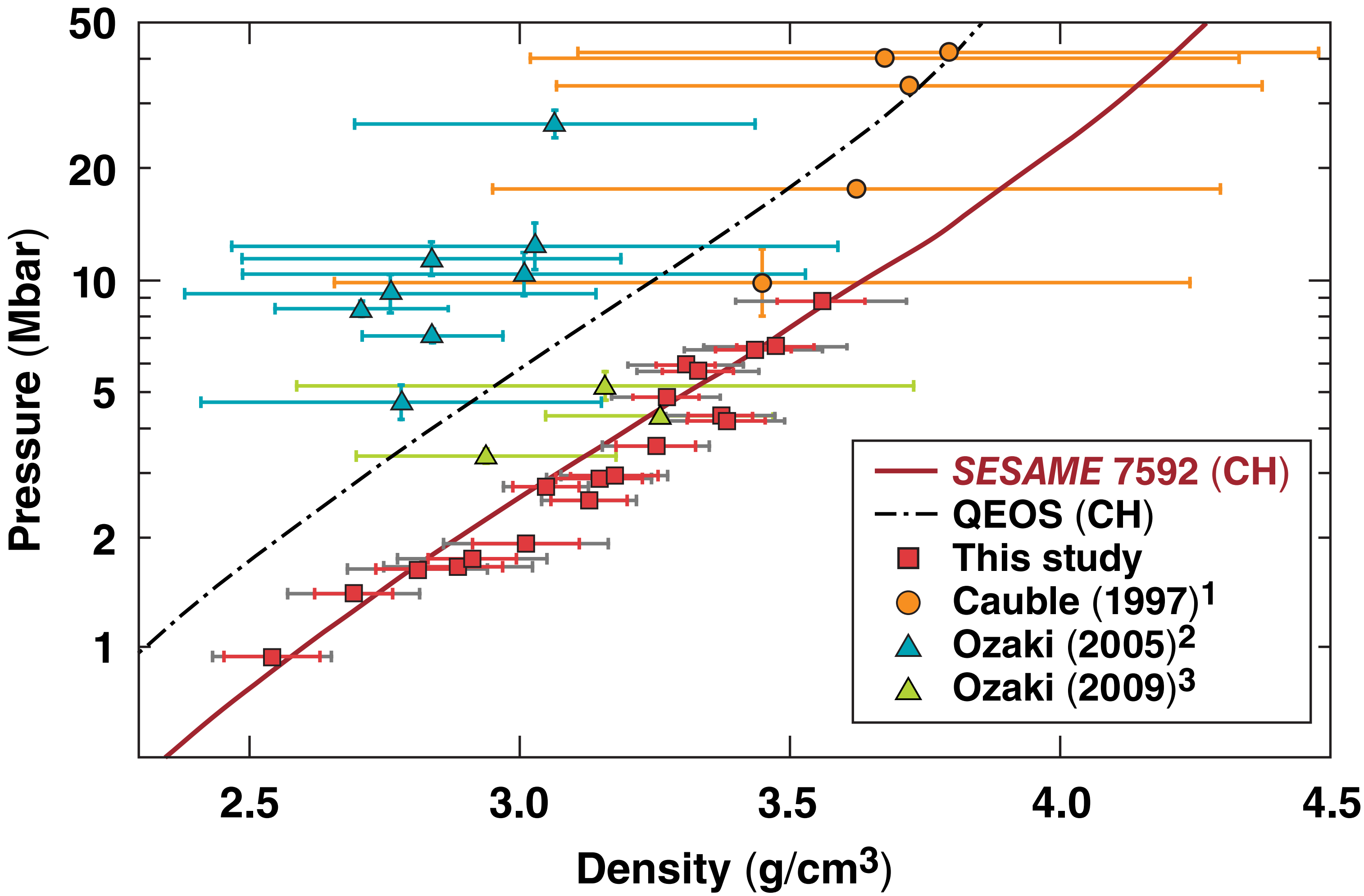
E18347

The dependence on the C:H ratio is well-predicted by models



E18348

The polystyrene results have higher precision than previous studies

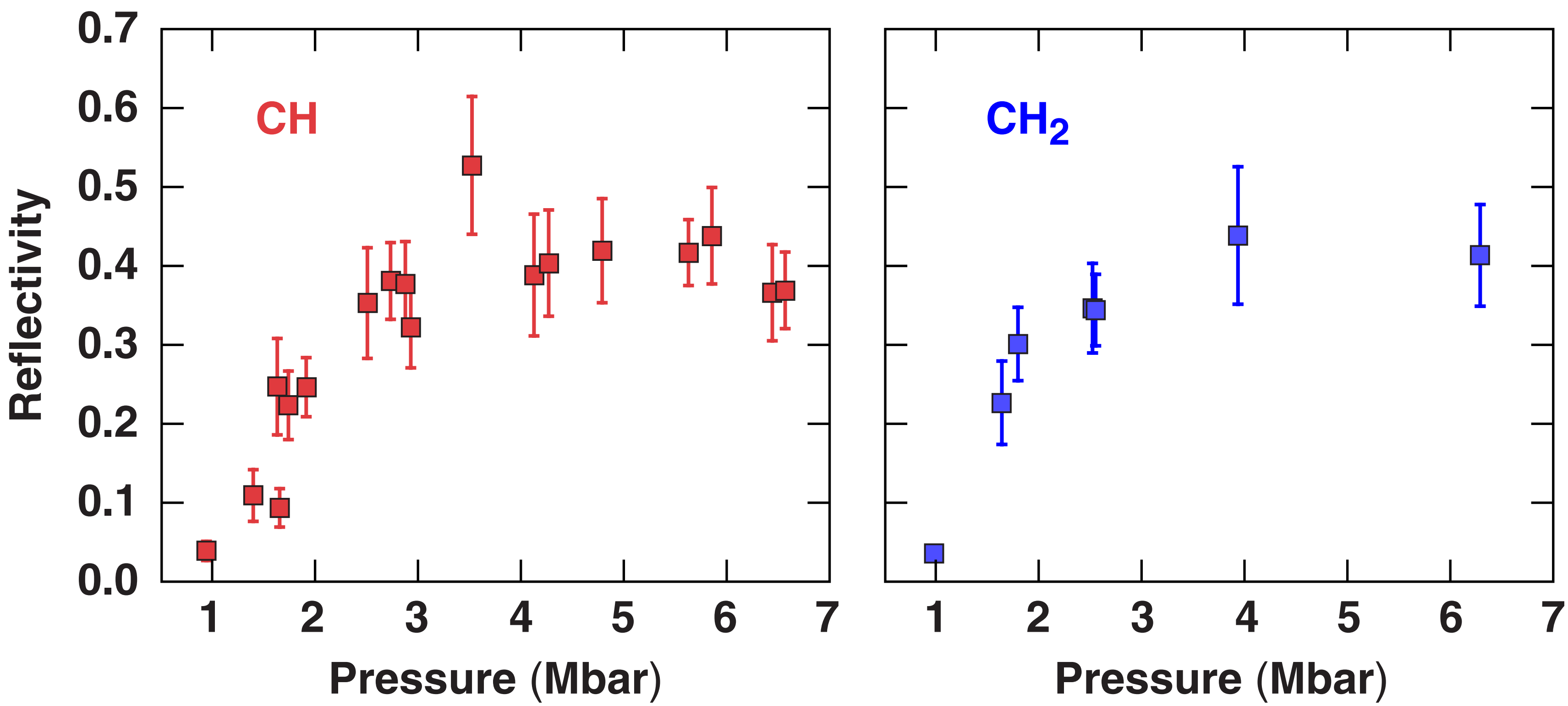


[1]R. Cauble *et al.*, Phys. Plasmas 4, 1857 (1997).
[2]N. Ozaki *et al.*, Phys. Plasmas 12, 124503 (2005).
[3]N. Ozaki *et al.*, Phys. Plasmas 16, 062702 (2009).

E18350

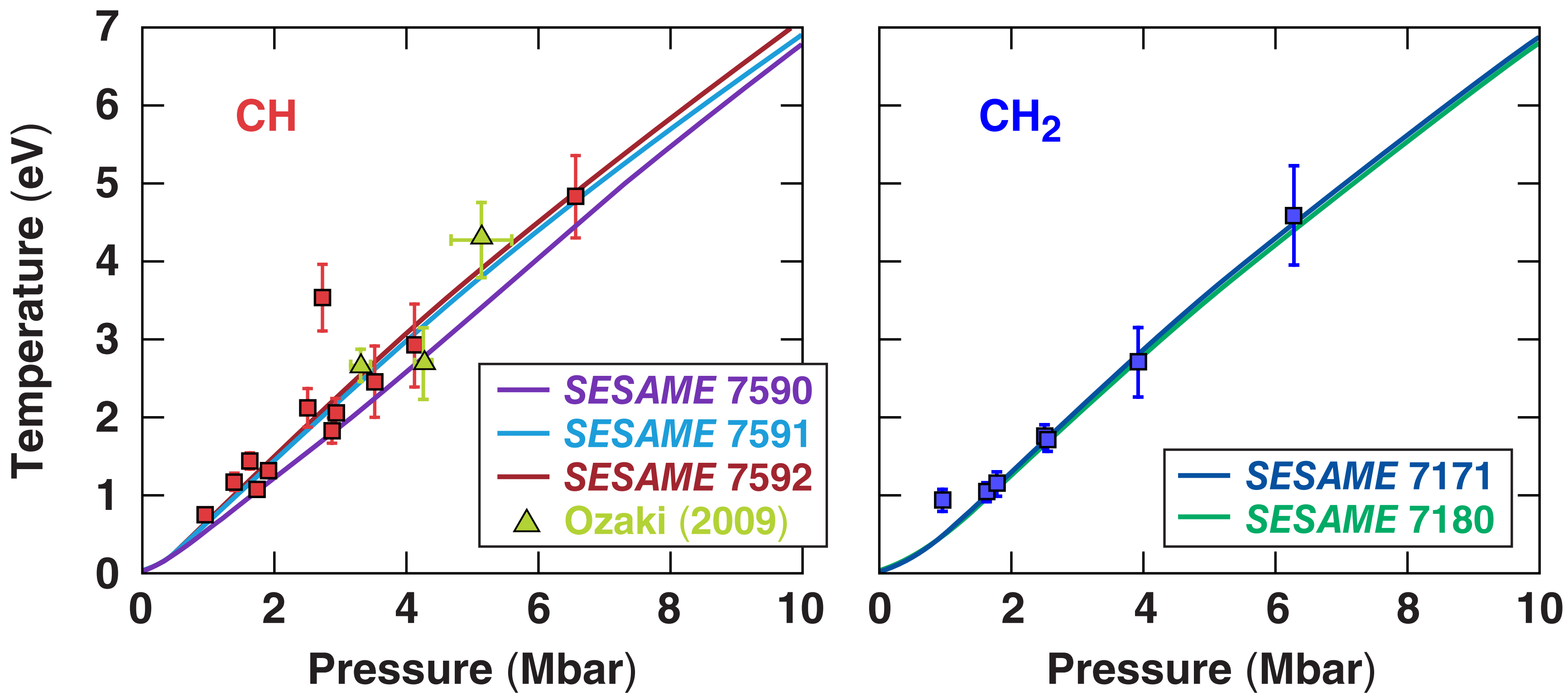
Shocked CH and CH_2 become reflective at 1 to 2 Mbar

- Reflectivity measurements are needed for temperature calculations



Expected behavior of dielectrics undergoing insulator-conductor transition.

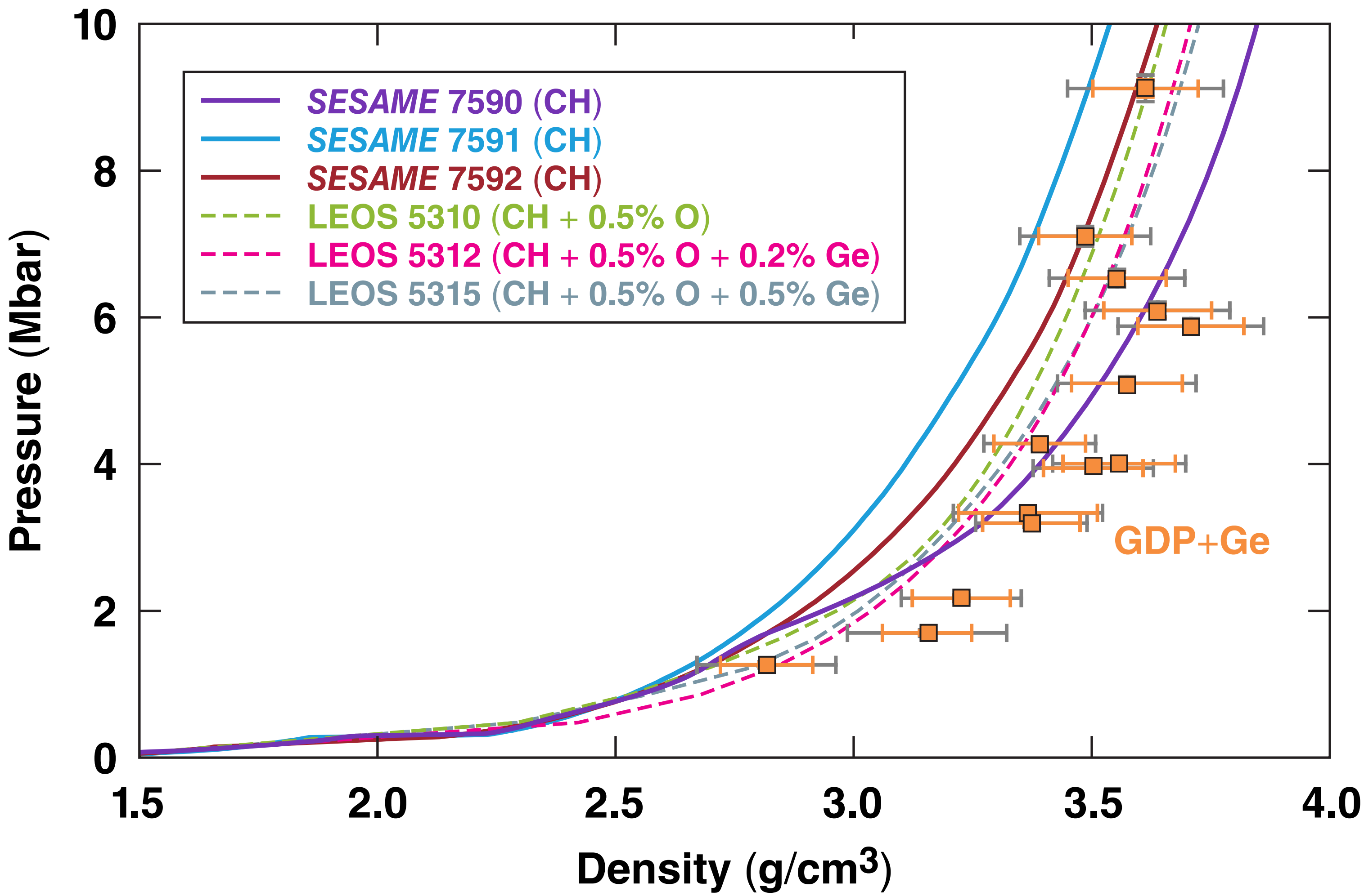
The measured brightness temperatures are consistent with models; but differences among models are too small to be discerned



This provides a complete EOS of CH and CH_2.

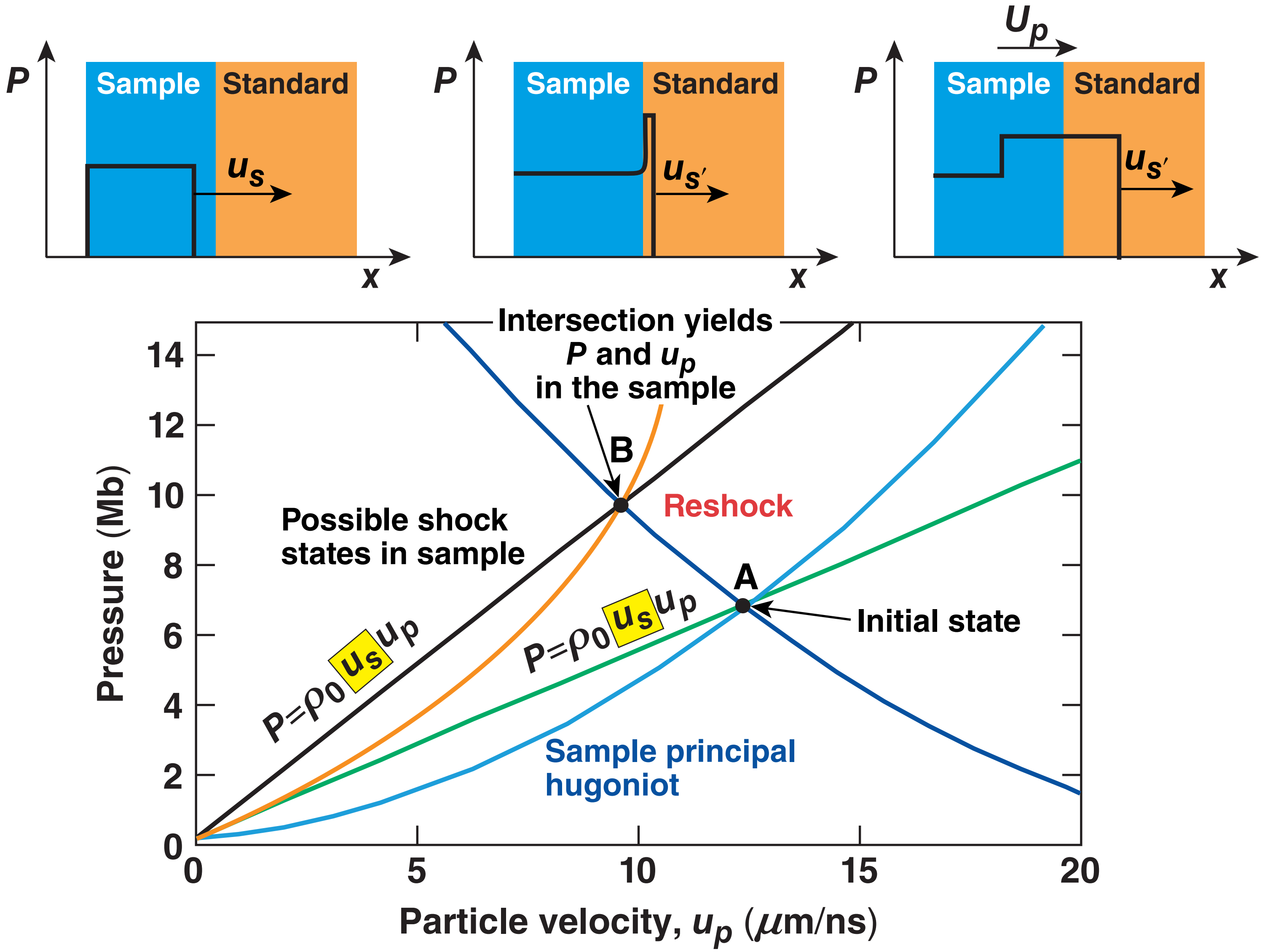
E18384

Preliminary data on Ge-doped GDP displays softer behavior than most models



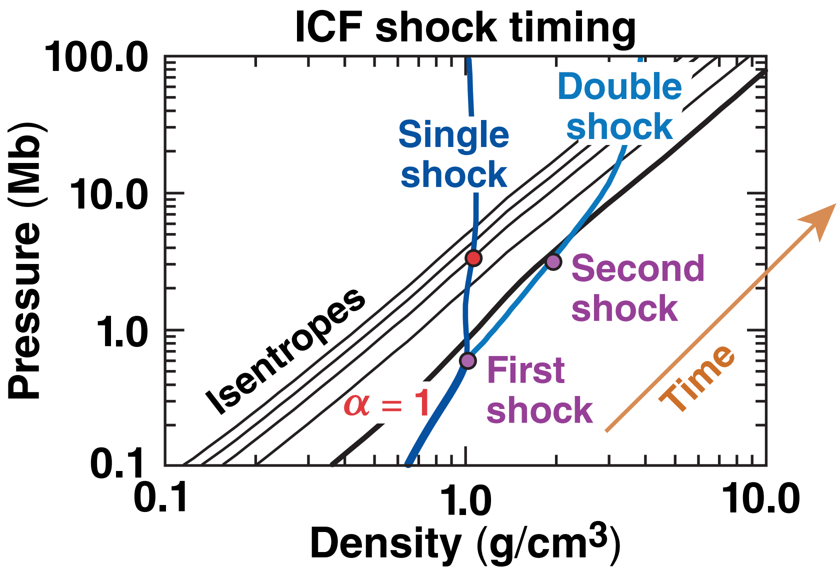
Double Shock

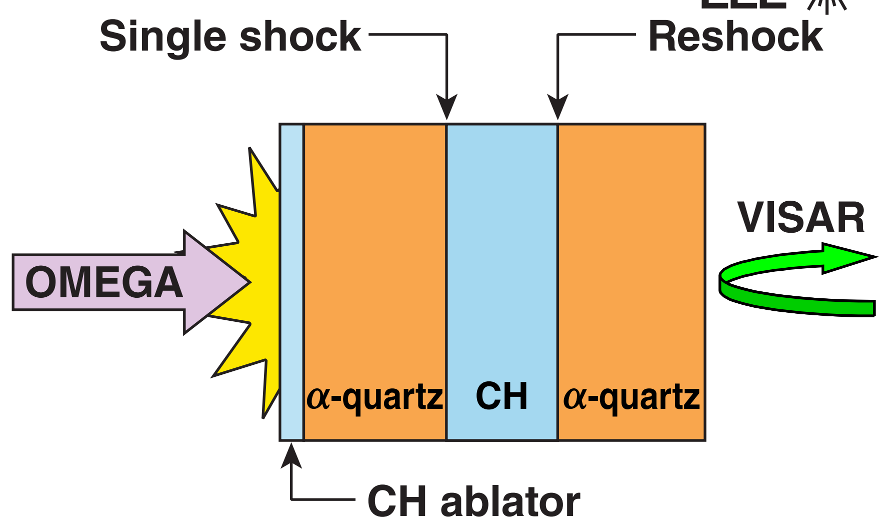
Shock transit into a higher impedance material results in a reflected shock

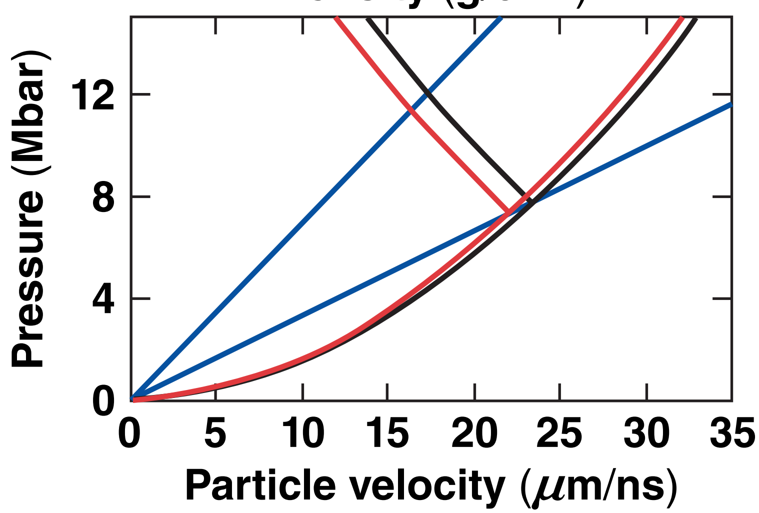


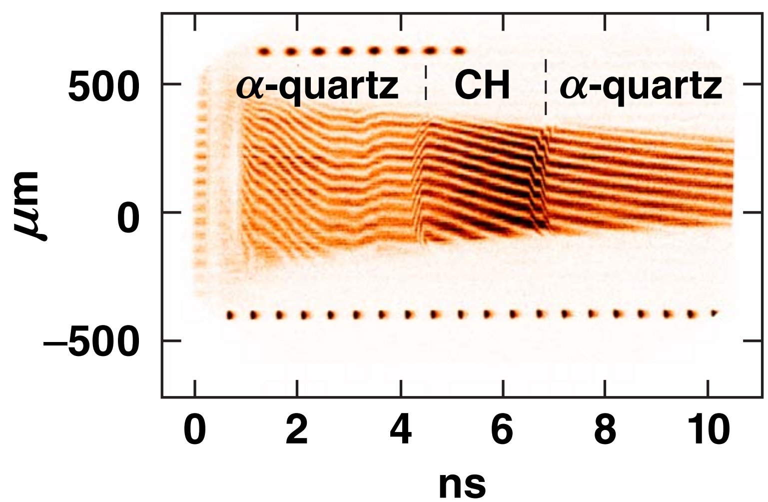
E17079a

Reflected shocks are used to create double shock states in CH





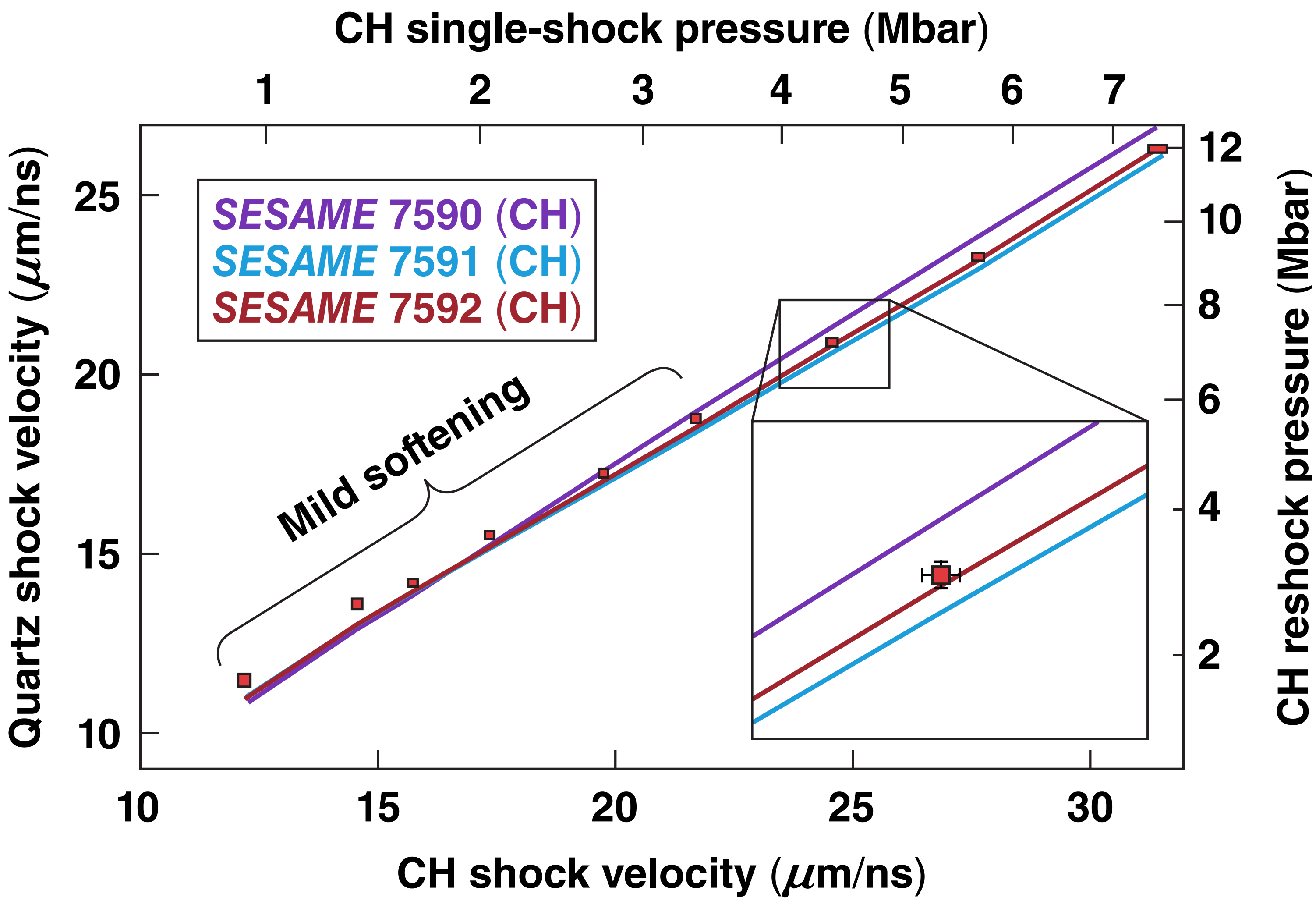




Small differences in models are amplified using reshock to move off the Hugoniot.

E18057a

Polystyrene (CH) double-shock data are in agreement with single-shock results



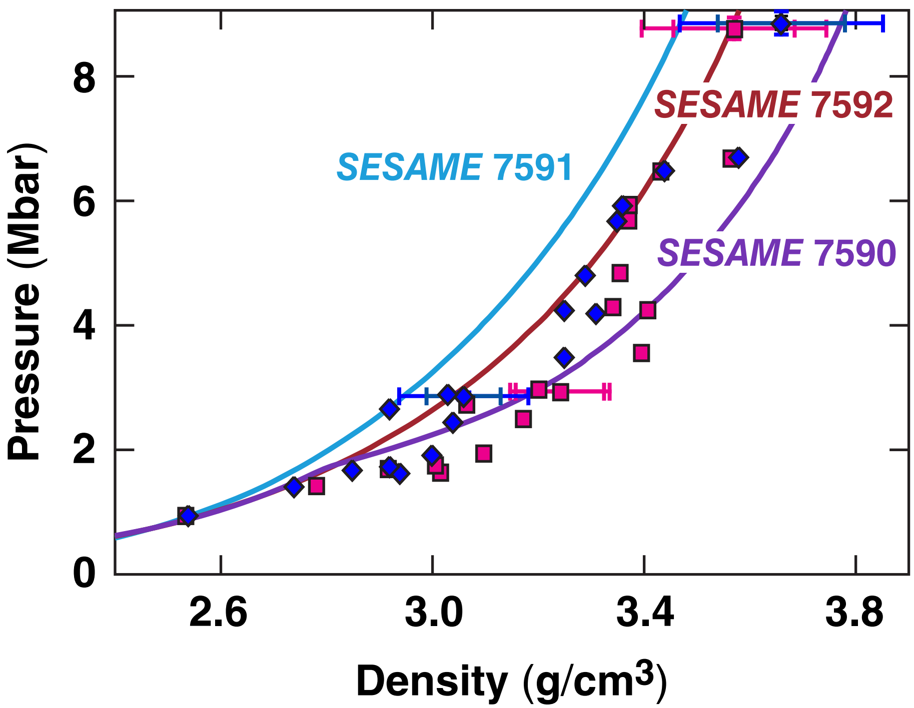
E18352

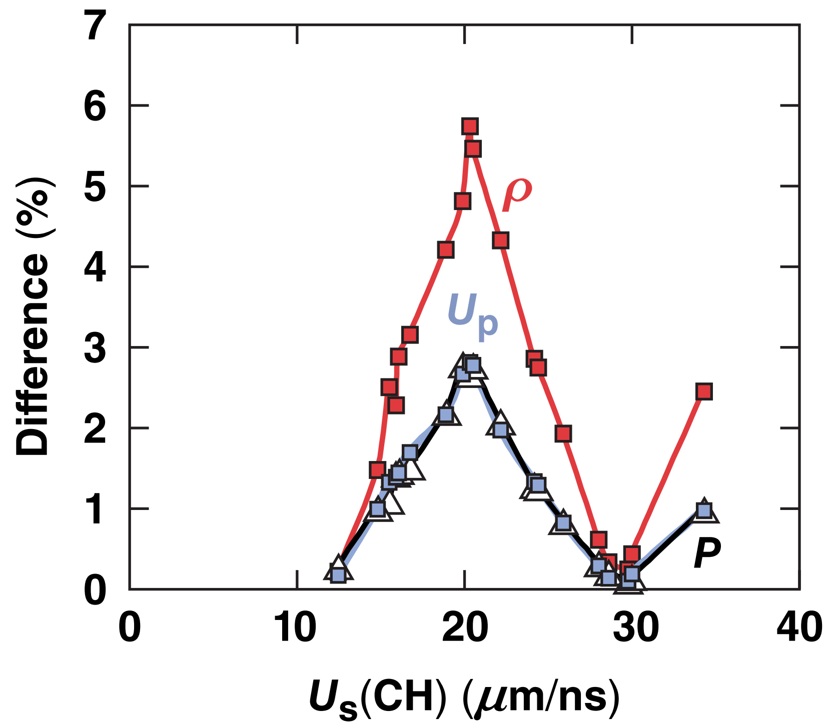
Summary/Conclusions

Precision equation-of-state (EOS) measurements are obtained on various polymers at 1 to 10 Mbar

- Precise knowledge of ablator EOS is required for ICF target designs
  - some NIF target designs use Ge-doped GDP
- Laser-driven shock waves produce EOS data using the impedance-matching (IM) method
- CH data allows for model discrimination, favoring *SESAME* 7592
  - mild softening is not accounted for between 2 to 4 Mbar
  - single- and double-shock results display similar behavior
- Stoichiometry effects between CH and CH_2 are well-predicted by models
- EOS data for NIF ablator material was acquired

Inclusion of a softer α-quartz EOS produces ~0.2% to 6.0% difference in polystyrene density values





E18353