Probing planetary interiors: Shock compression of water to 700 GPa and 3.8 g/cc, and recent high precision Hugoniot measurements of deuterium

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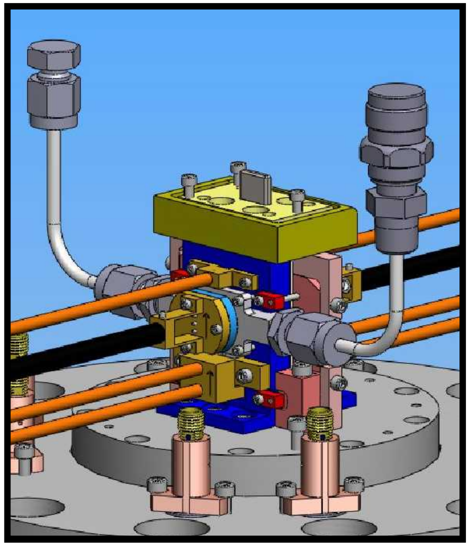

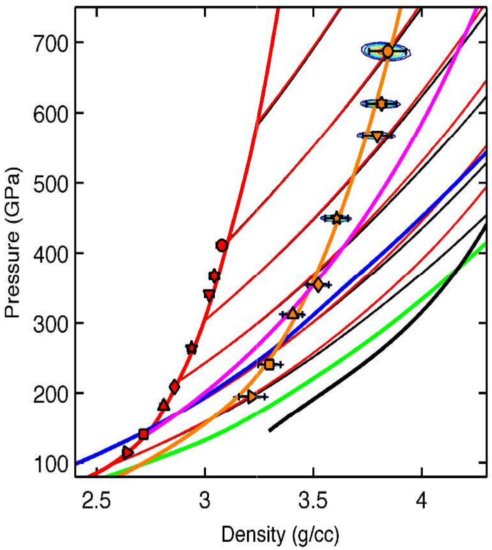

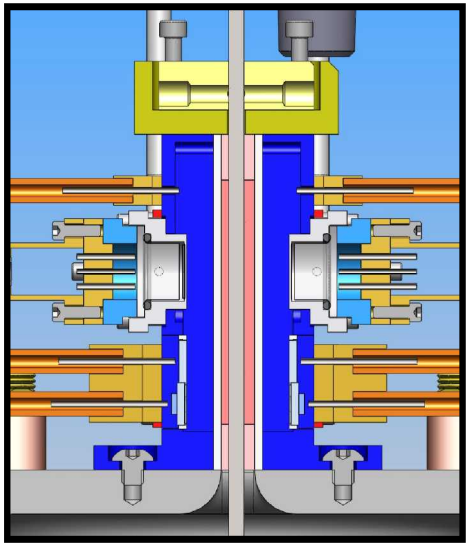

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  - Planetary modeling
- Ray Lemke
  - Flyer plate design and MHD simulations
- Jean-Paul Davis, Devon Dalton, Ken Struve, Mark Savage, Keith LeChien, Brian Stoltzfus, Dave Hinshelwood
  - Bertha model, pulse shaping
- Charlie Meyer, Devon Dalton, Dustin Romero, Anthony Romero, entire Z crew…
  - Experiment support

Ktech CORP.

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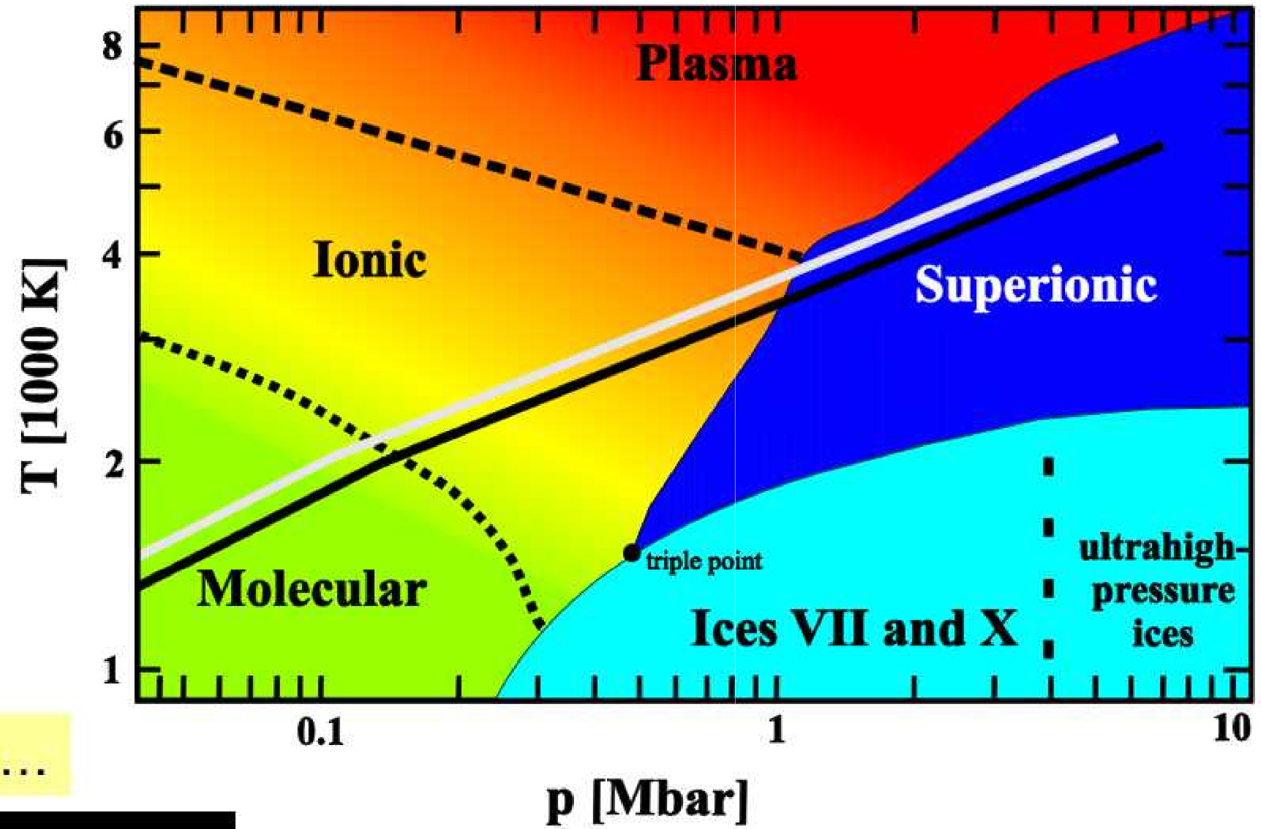
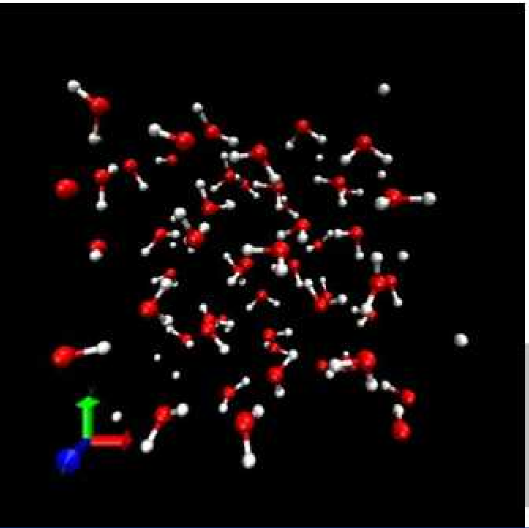
Water phase diagram at ultra-high pressures



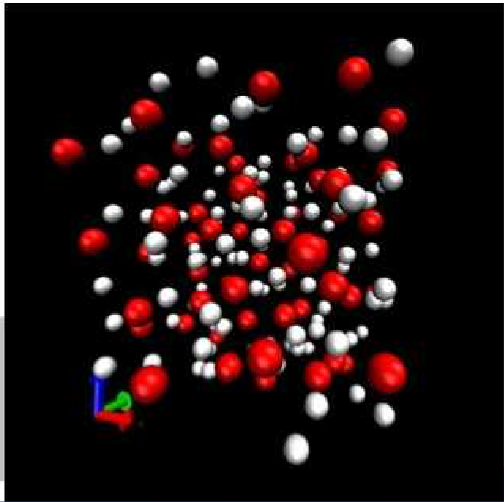
Relevant for the interiors of Neptune (black) and Uranus (white)

From R. Redmer Univ. of Rostock

Normal ice…



… and superionic water at 7 g/cm^3 and 6000 K

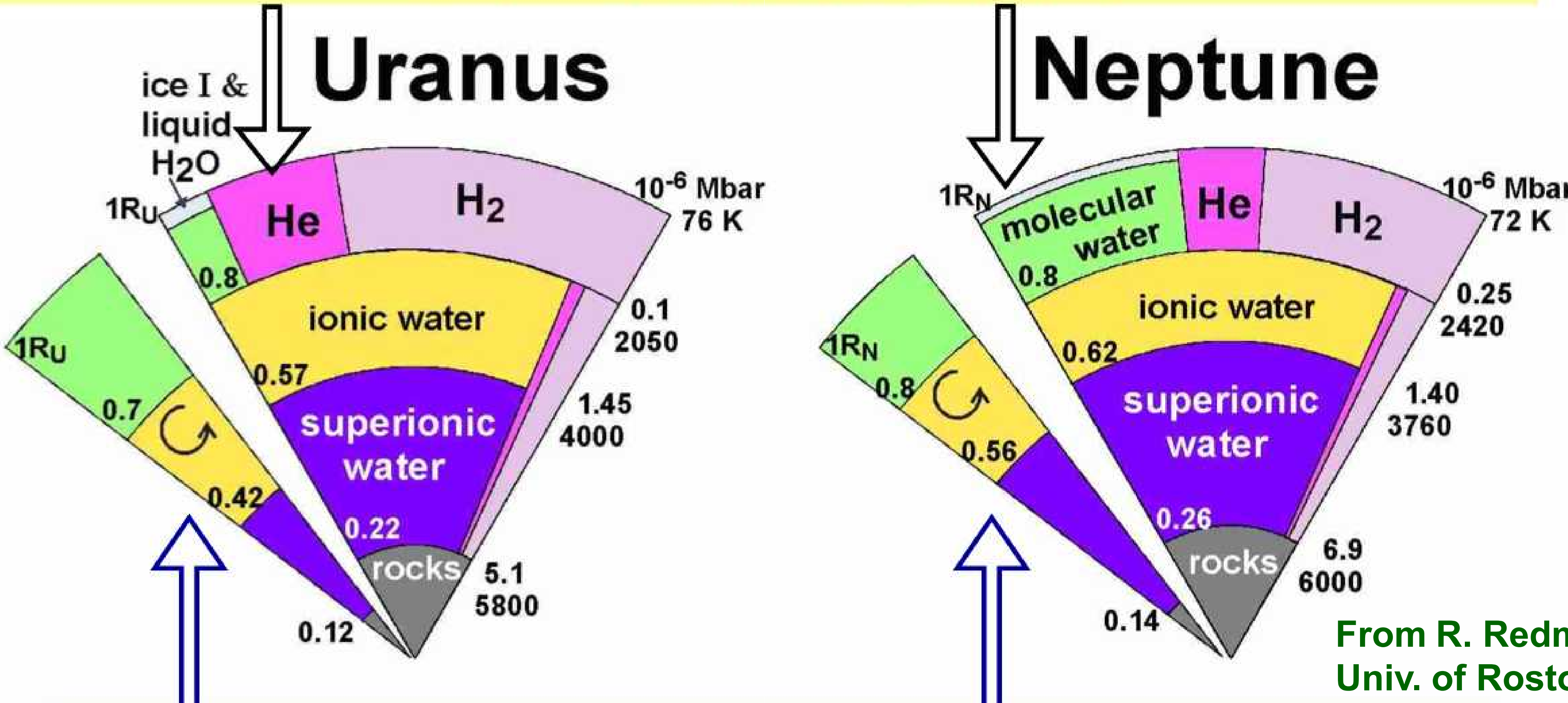


EOS and phase diagram:
M. French et al., PRB **79**, 054107 (2009),
Transport properties (diffusion, conductivity):
M. French et al., PRB **82**, 174108 (2010)

see also C. Cavazzoni et al., Science **283**, 44 (1999),
T.R. Mattsson, M.P. Desjarlais, PRL **97**, 017801 (2006),
E. Schwegler et al., PNAS **105**, 14779 (2008)

Interior of Neptune and Uranus

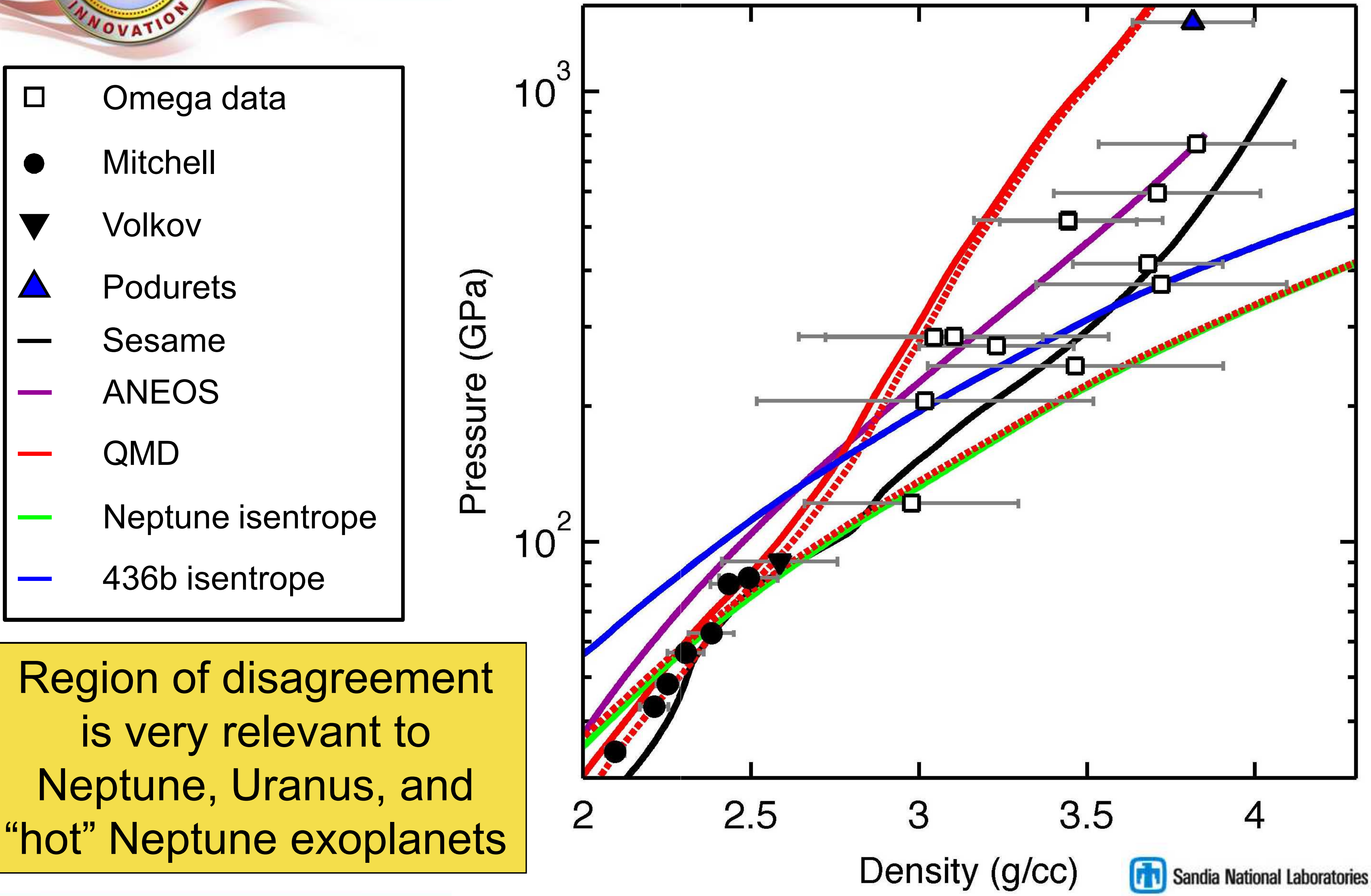
Our **interior models** reproduce the gravity data based on the EOS and the phase diagram of H_2O and H, He:
J.J. Fortney, N. Nettelmann, Space Sci. Rev. **152**, 423 (2009),
R. Redmer et al., Icarus **211**, 798 (2011)



From R. Redmer
Univ. of Rostock

Independent **dynamo models** reproduce the non-dipolar and non-axisymmetric magnetic fields of N and U by assuming a rather thin conducting shell (yellow) and a central region (magenta) that is stable against convection but of similar conductivity (here: superionic!):
S. Stanley and J. Bloxham, Nature **428**, 151 (2004).

The QMD results are in disagreement with previous data and widely used EOS models



Region of disagreement is very relevant to Neptune, Uranus, and “hot” Neptune exoplanets

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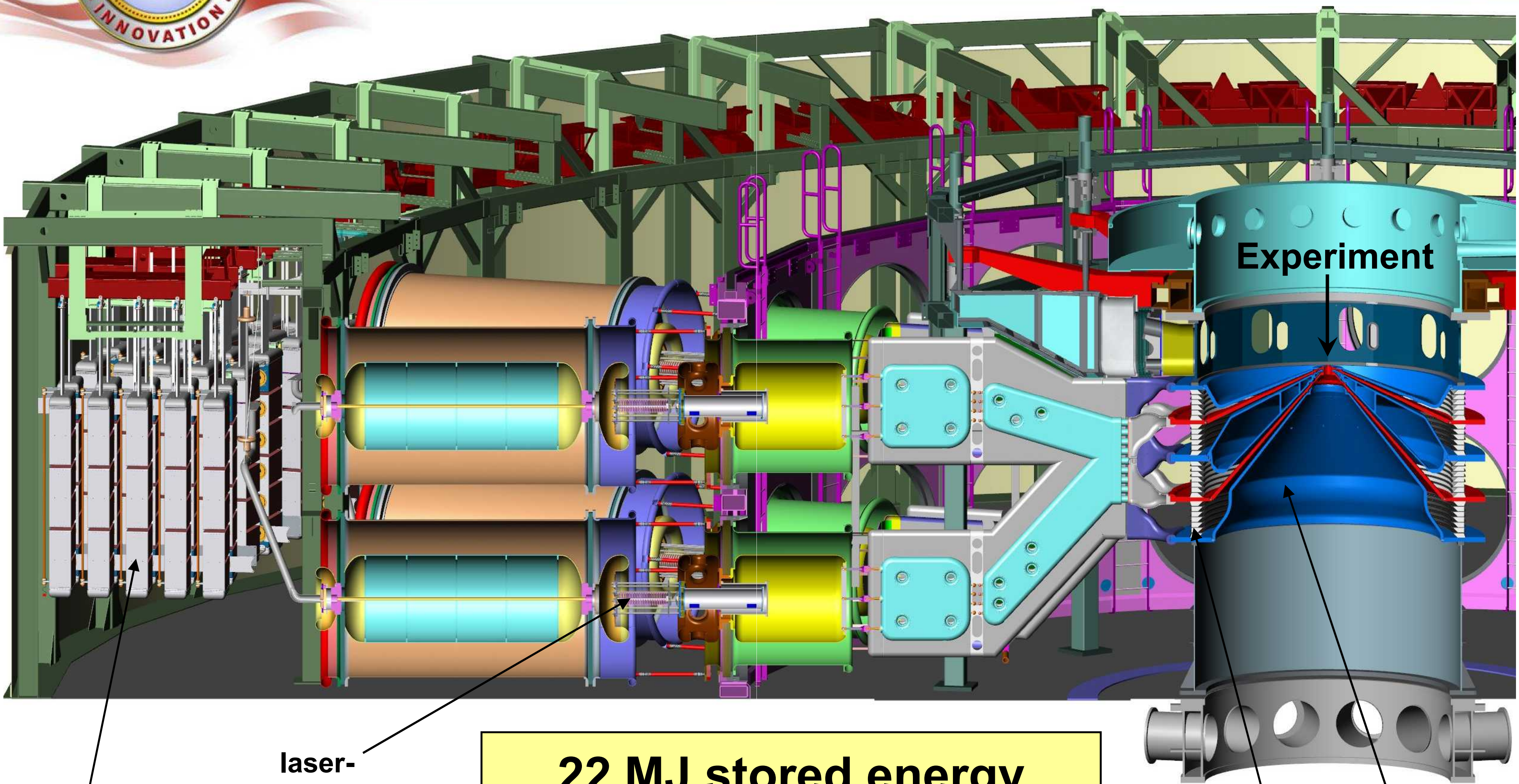
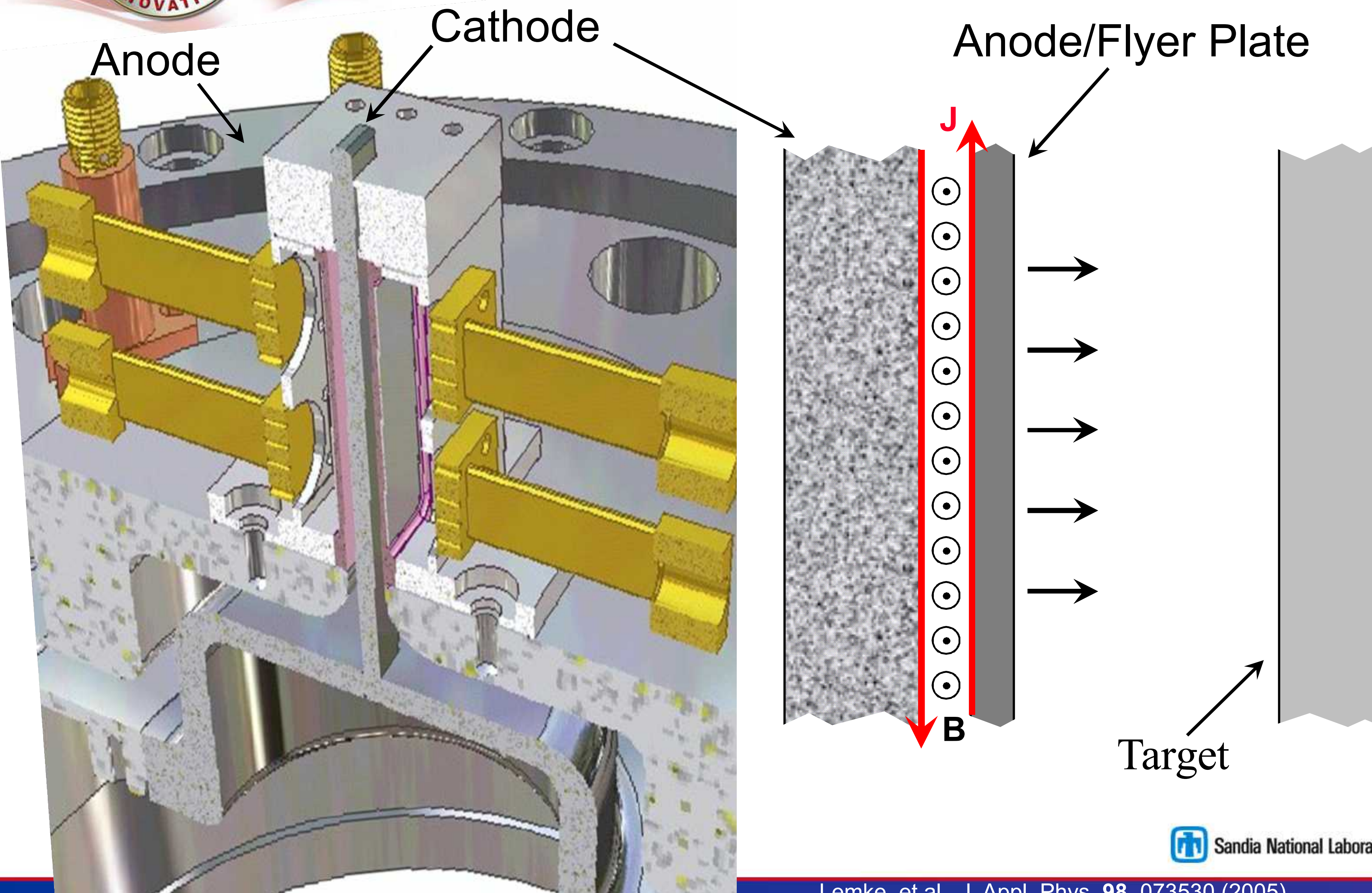
The Sandia Z Machine

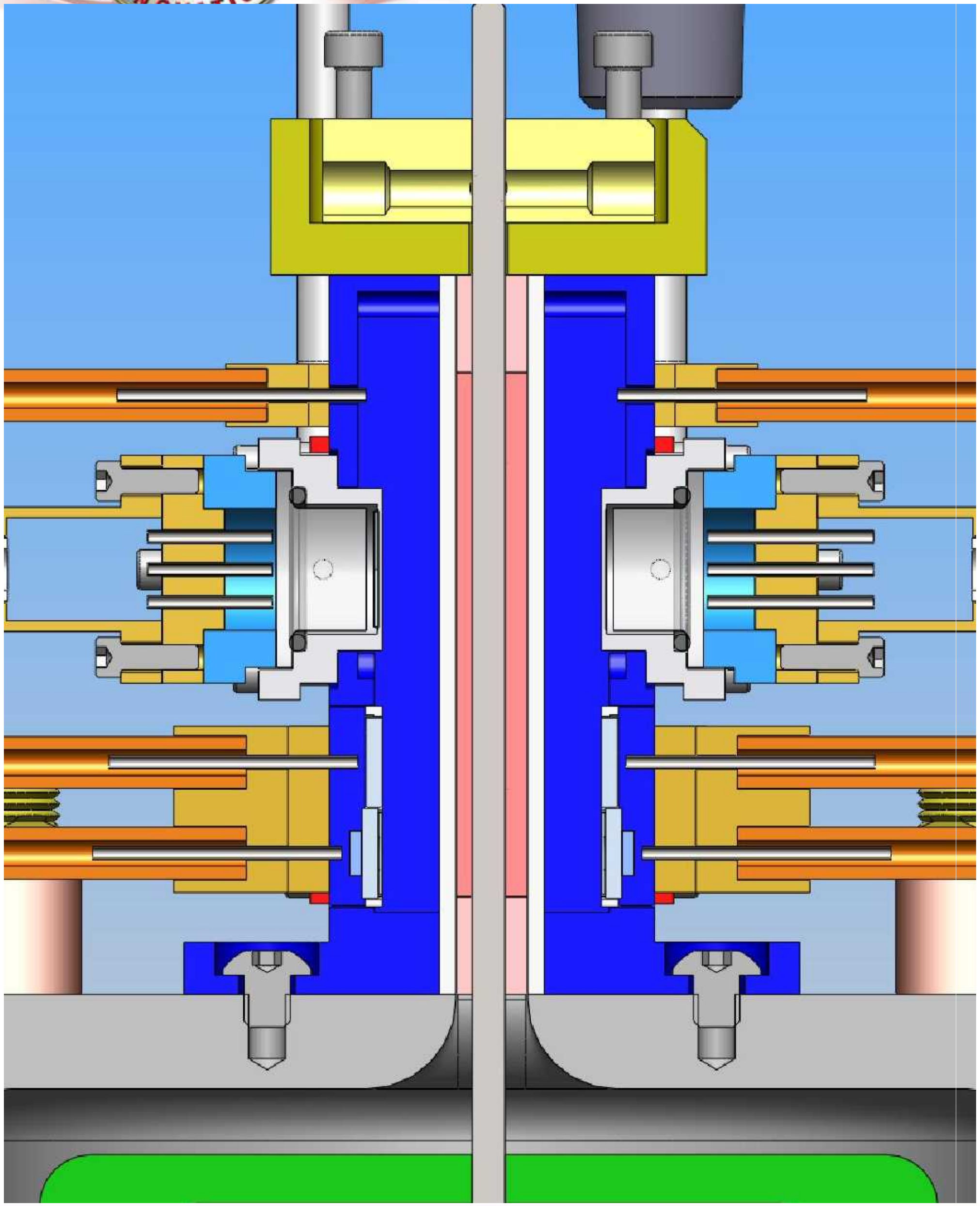


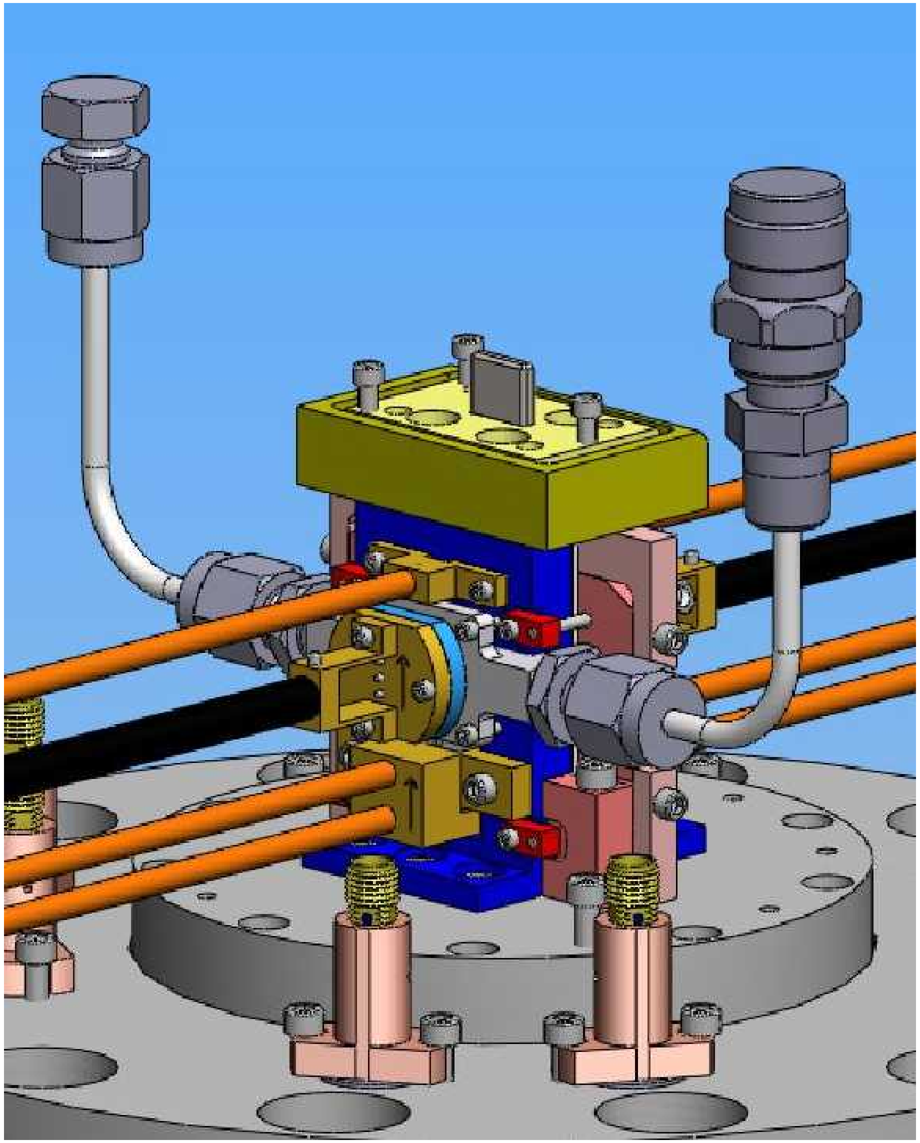
22 MJ stored energy
~25 MA peak current
~200-600 ns rise time

With proper pulse shape and design the anode can be launched as an effective high-velocity flyer plate



Experimental configuration





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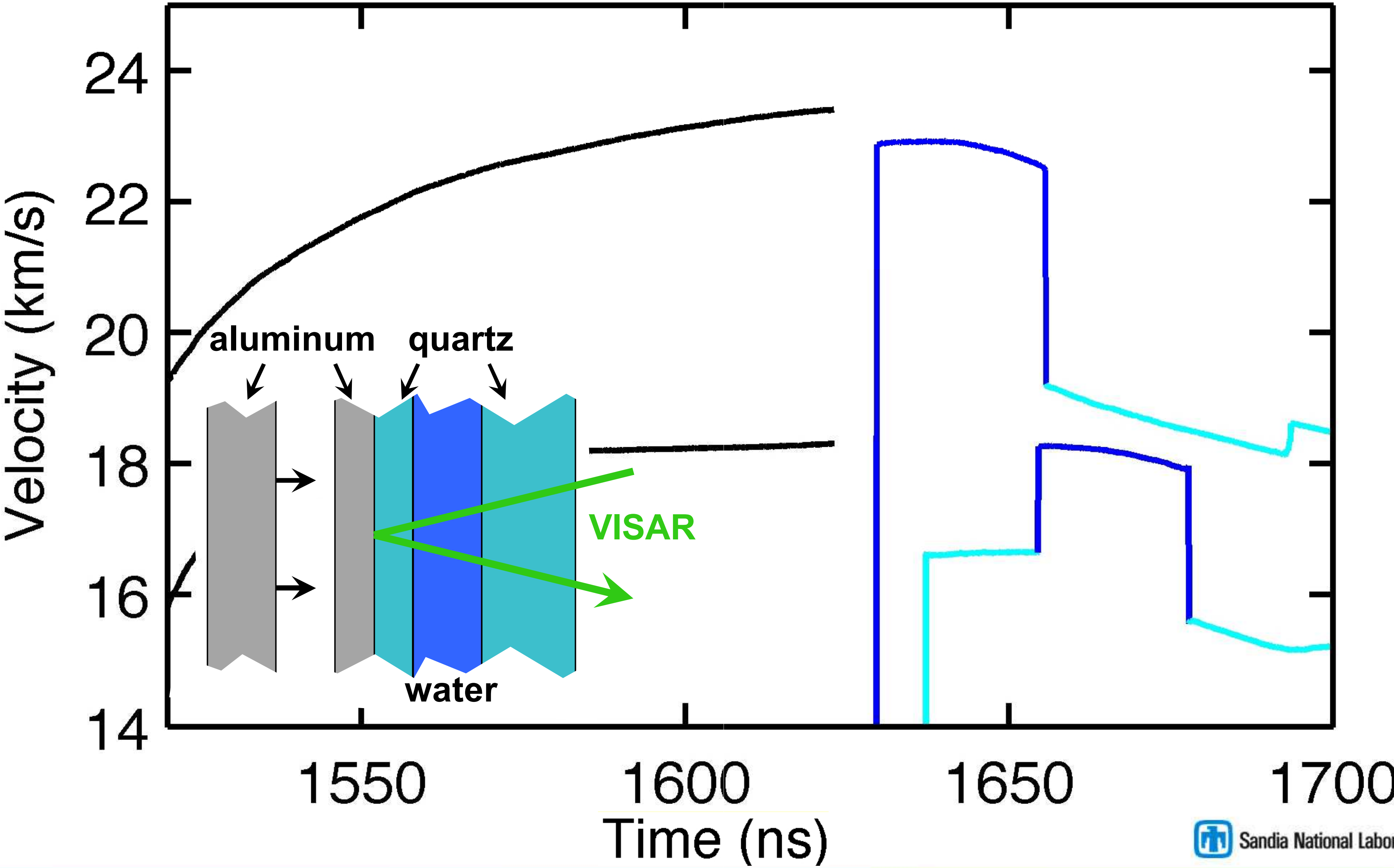
VISAR was used to obtain precise flyer velocities and shock velocities in the water and quartz



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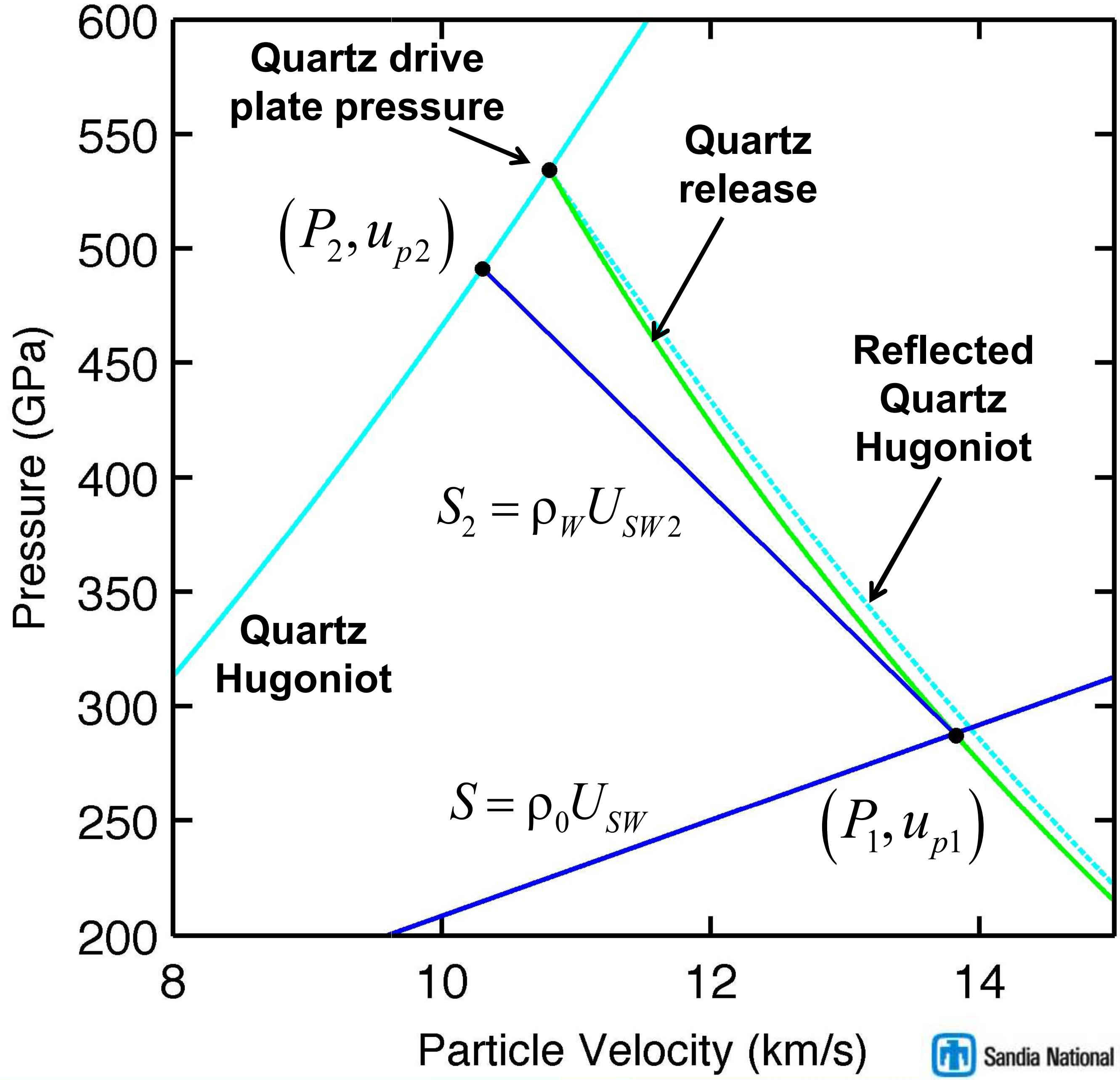
The shock states in the water are determined by impedance matching with quartz and aluminum

Precision of the results is determined by the precision of the velocity measurements

Accuracy of the results depend upon both the Hugoniot of quartz as well as the release response in the several Mbar regime



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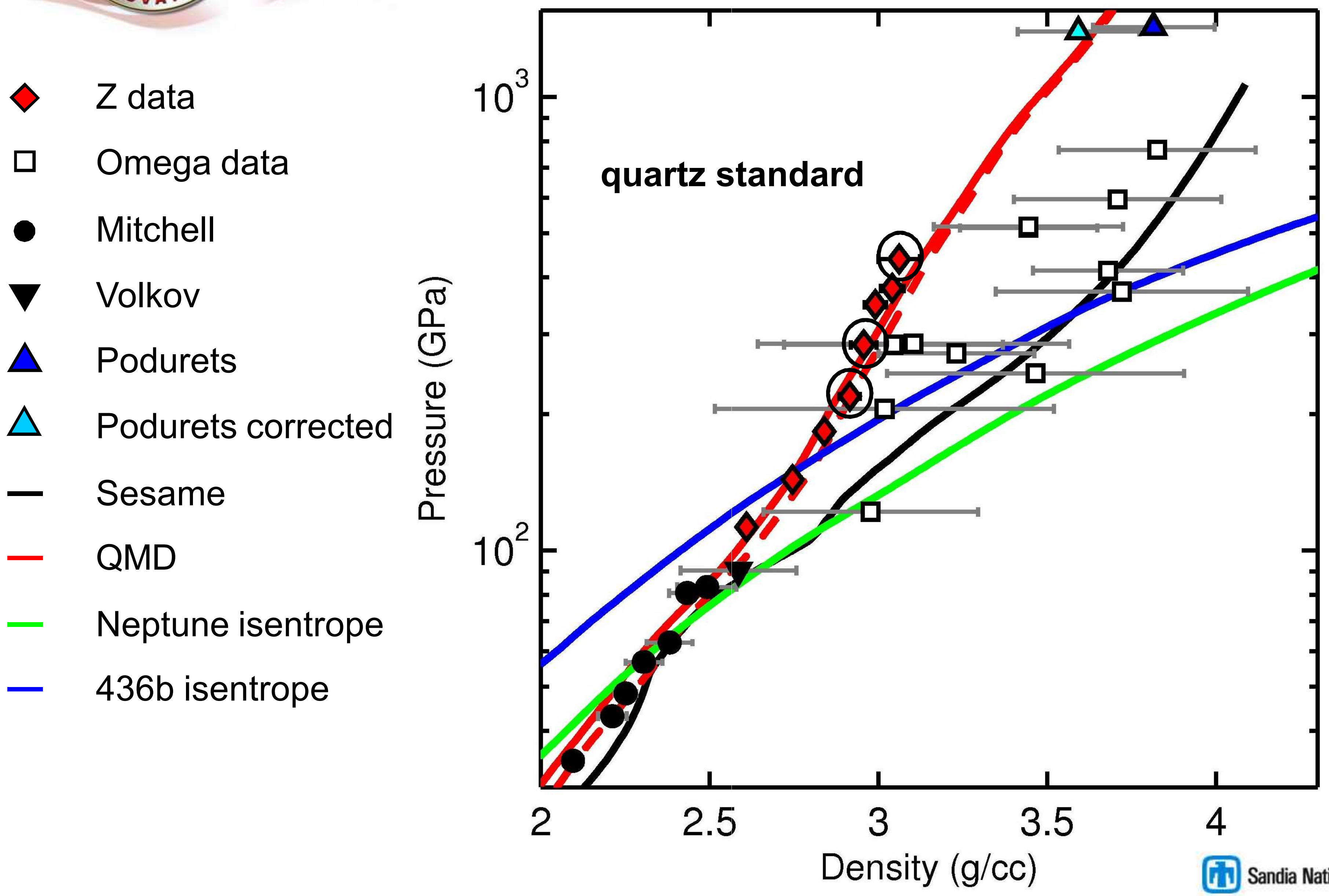
Knudson et al., PRL **108**, 091102 (2012)

Excellent agreement found between experiment and recent QMD calculations



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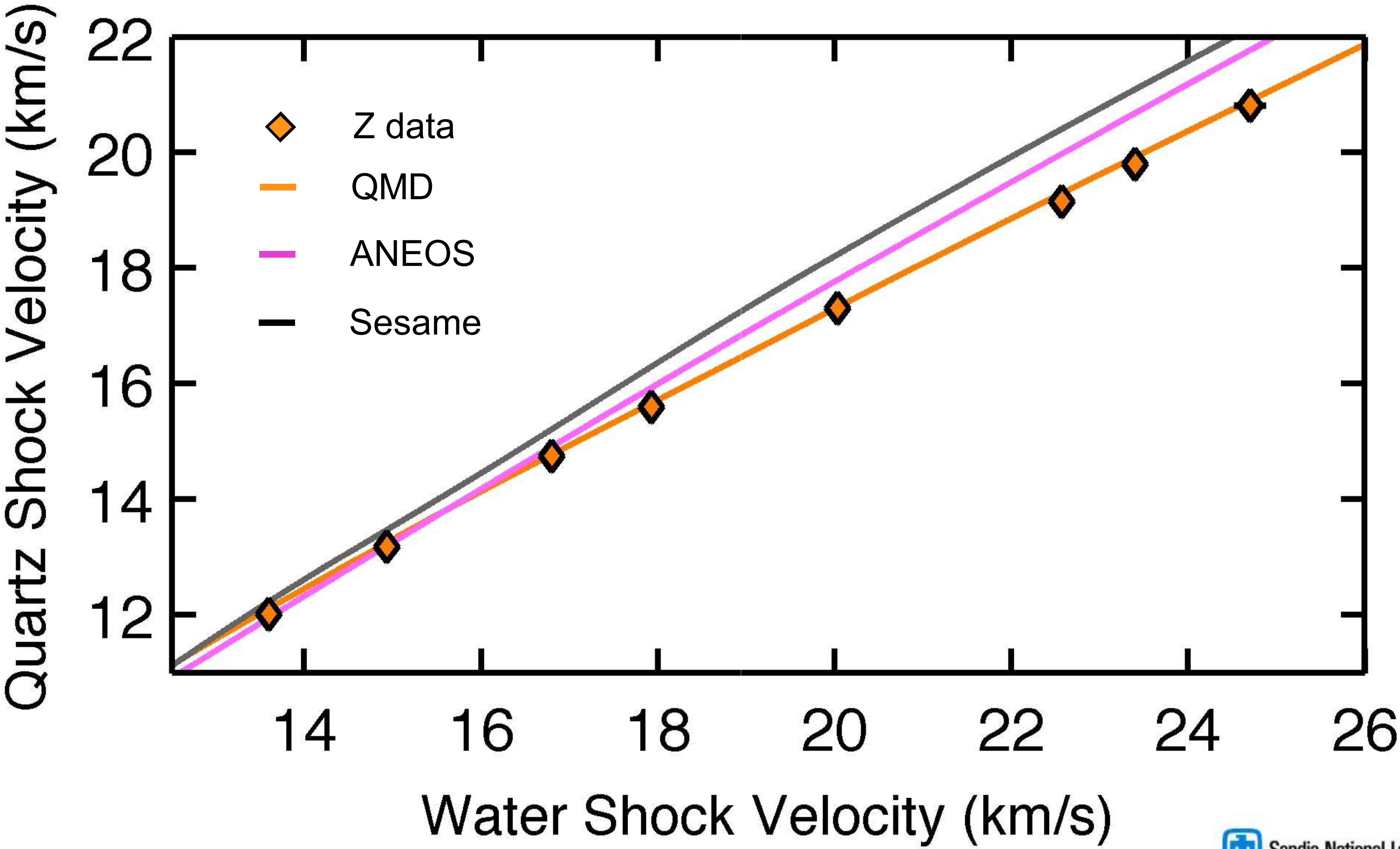
Direct comparison with observables clearly favors the QMD re-shock in this regime



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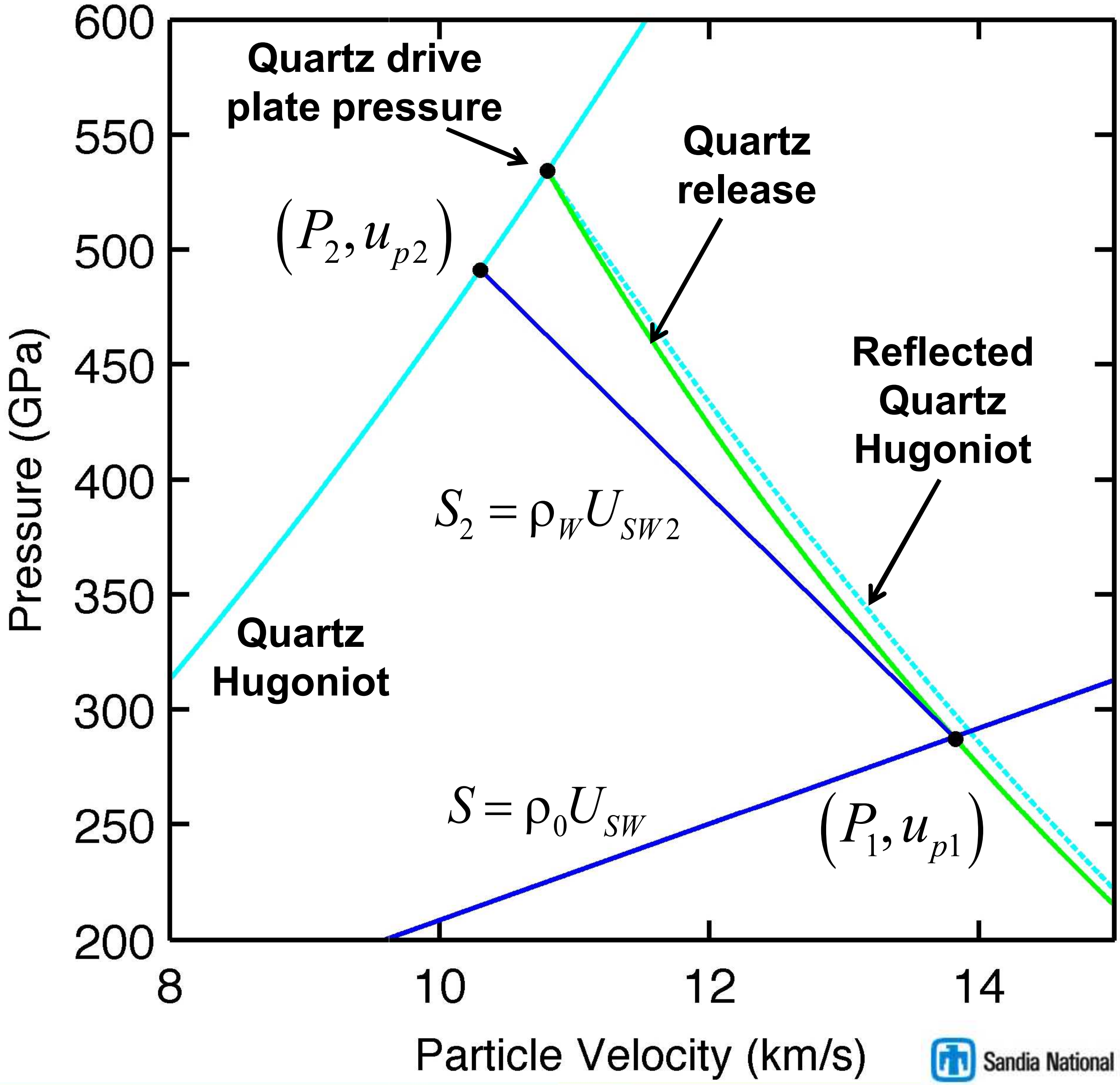
Knudson et al., PRL **108**, 091102 (2012)

The re-shock states could also be determined by impedance matching with quartz

The re-shock state depends upon the initial shocked state and the quartz Hugoniot

Uncertainties in the re-shock state can be propagated through a Monte Carlo method that accounts for all random and systematic uncertainties in measurements and standards



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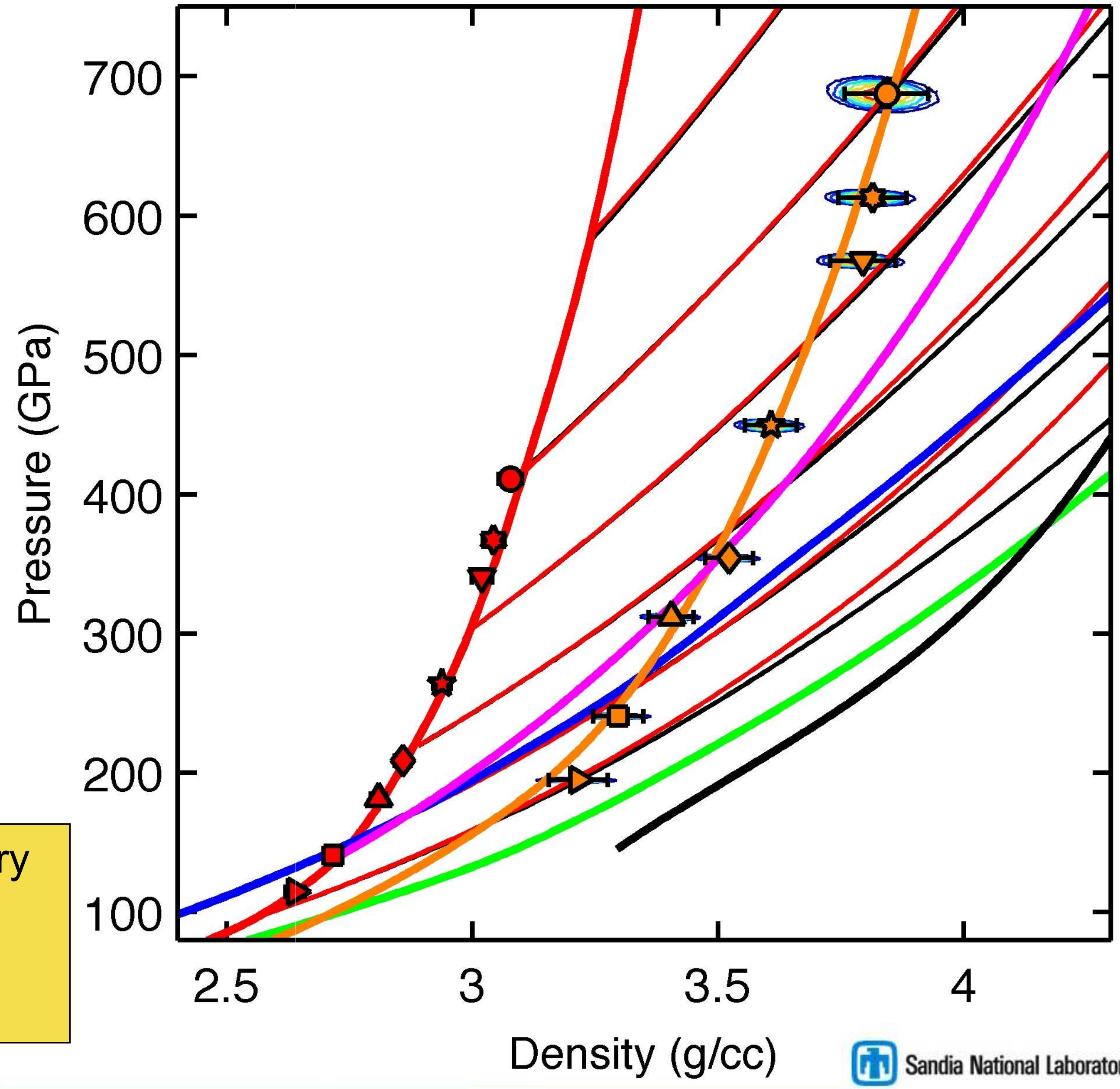
Knudson et al., PRL **108**, 091102 (2012)

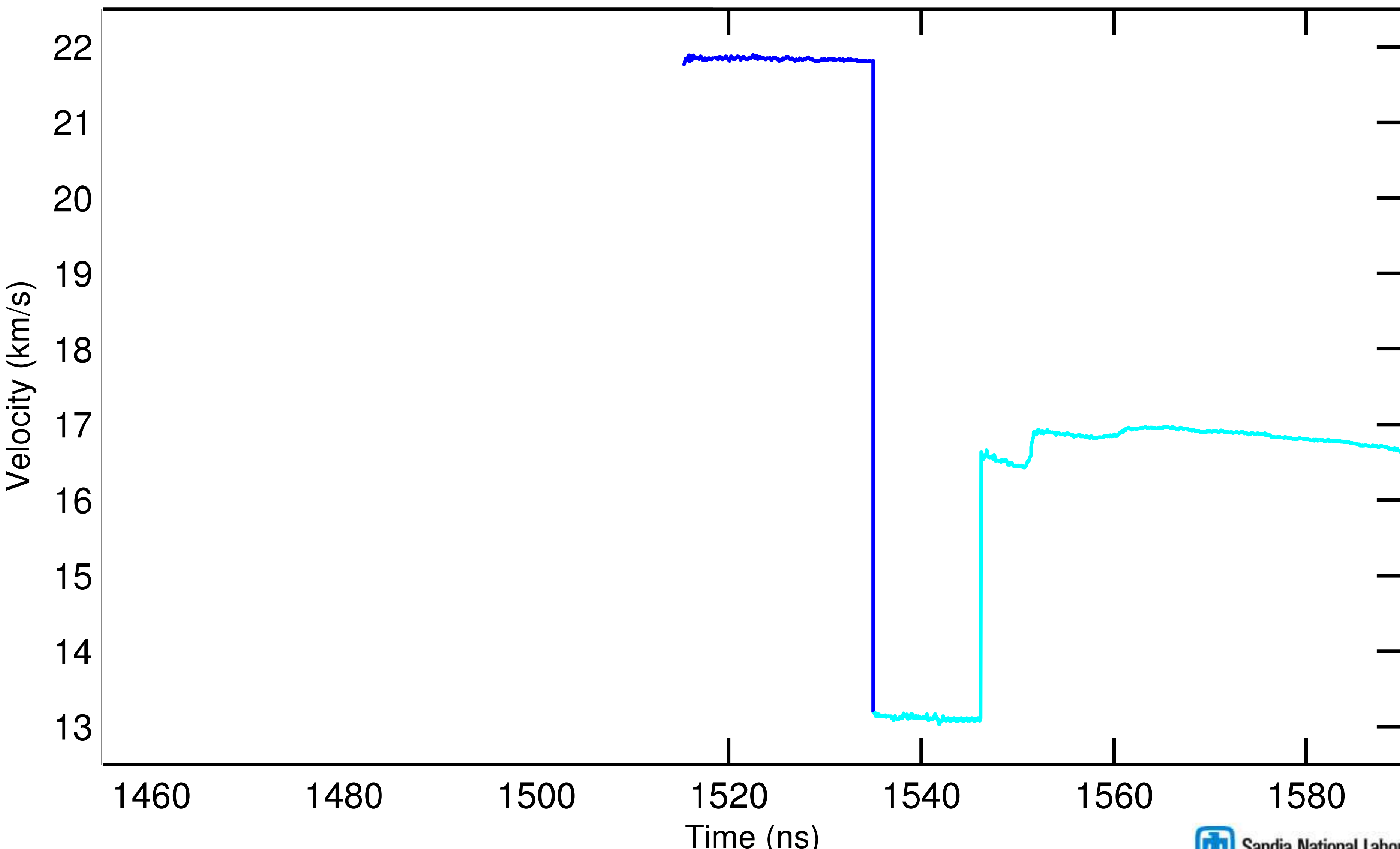
The locus of re-shock states agrees well with QMD – validates isentropes at planetary conditions

- Z data first shock
- Z data re-shock
- QMD Hugoniots
- QMD isentropes
- QMD re-shock locus
- ANEOS re-shock locus
- Sesame re-shock locus
- Neptune isentrope
- 436b isentrope



The re-shock states are very close to isentropic at the densities probed in the re-shock experiments

VISAR was used to obtain precise flyer velocities and shock velocities in the D_2 and quartz



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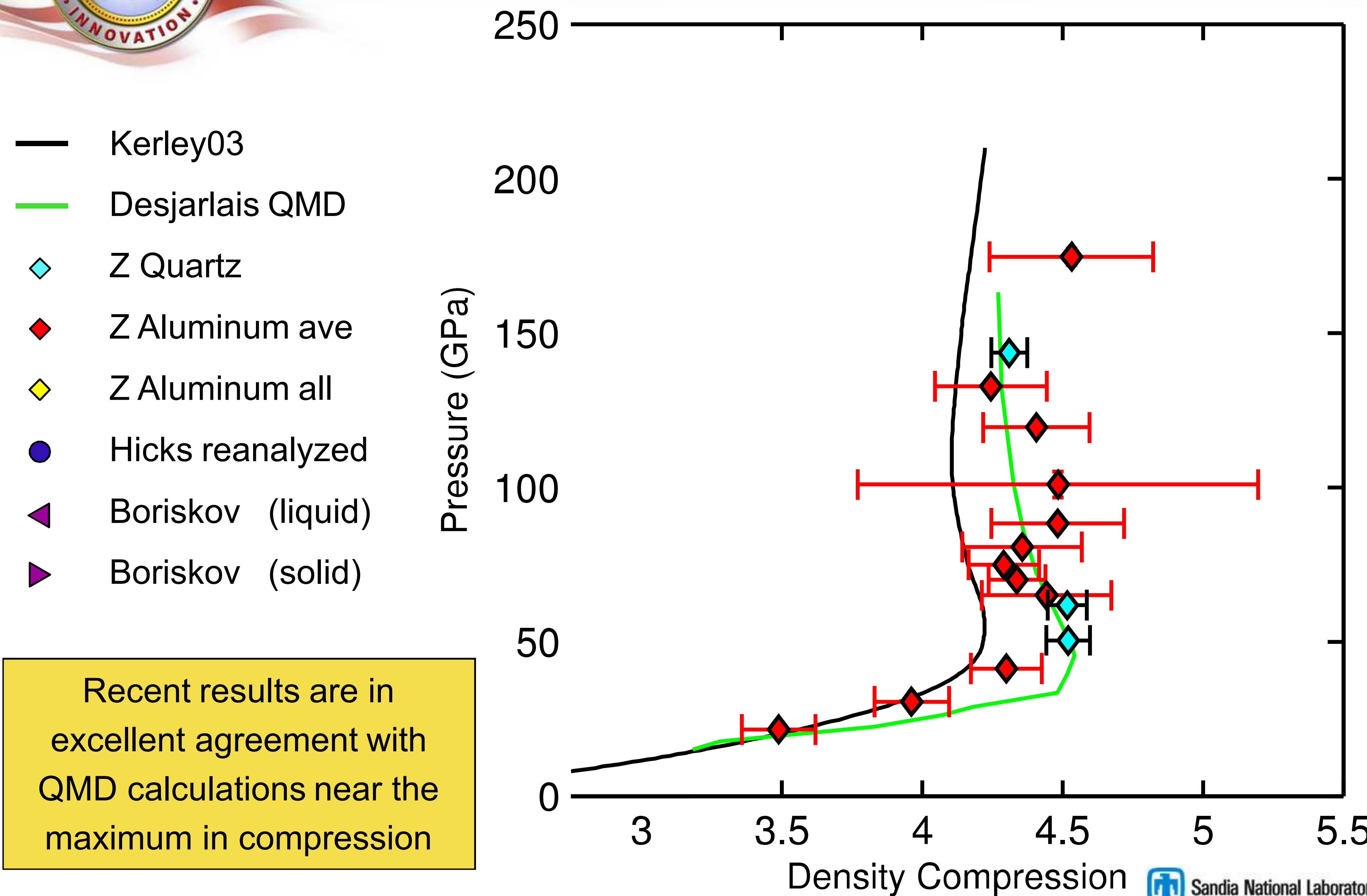
Recent results show significant improvement in precision with respect to previous data



Recent results are in excellent agreement with QMD calculations near the maximum in compression

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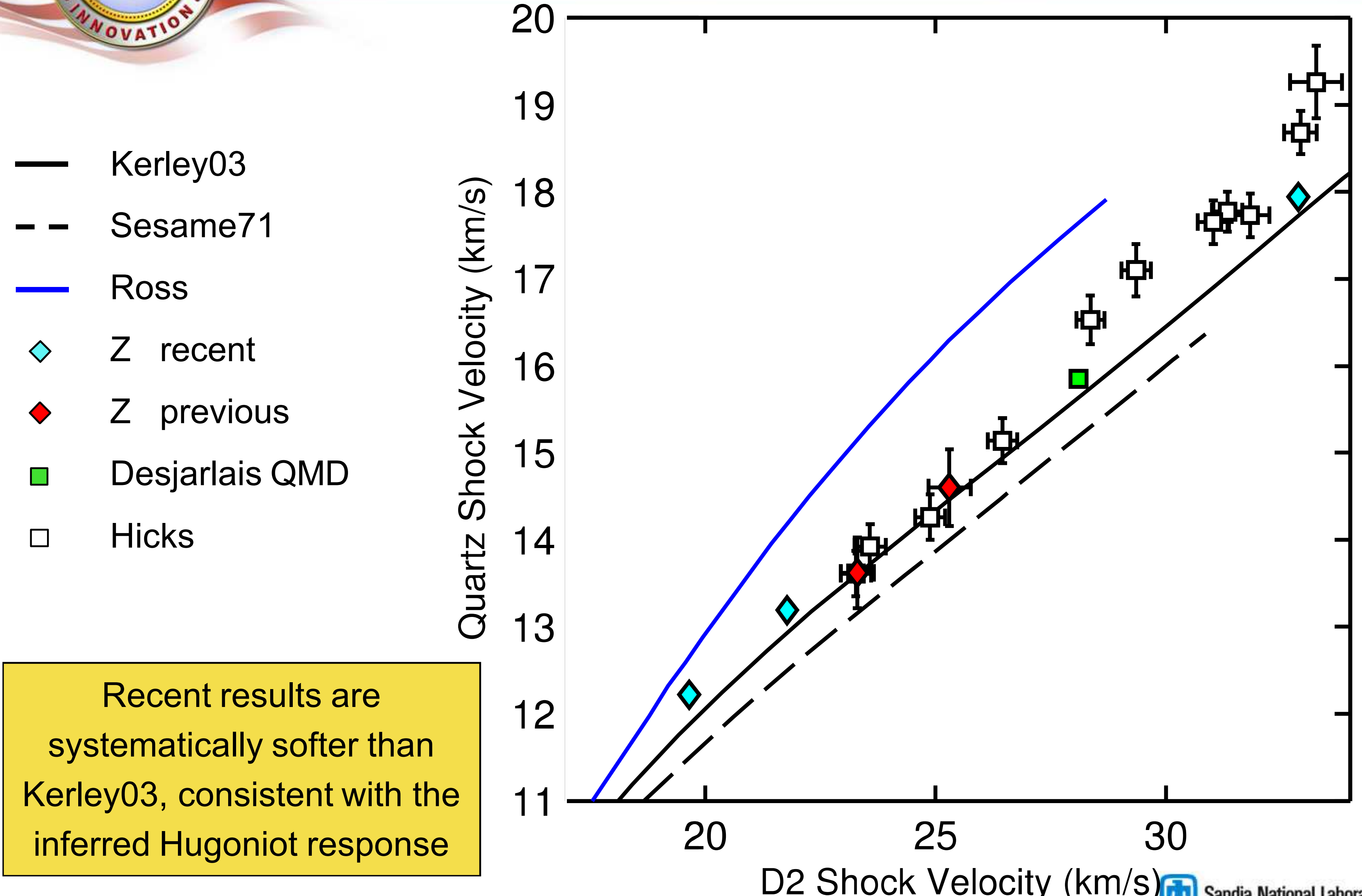
These results also significantly improve precision of the quartz re-shock measurement



Recent results are systematically softer than Kerley03, consistent with the inferred Hugoniot response

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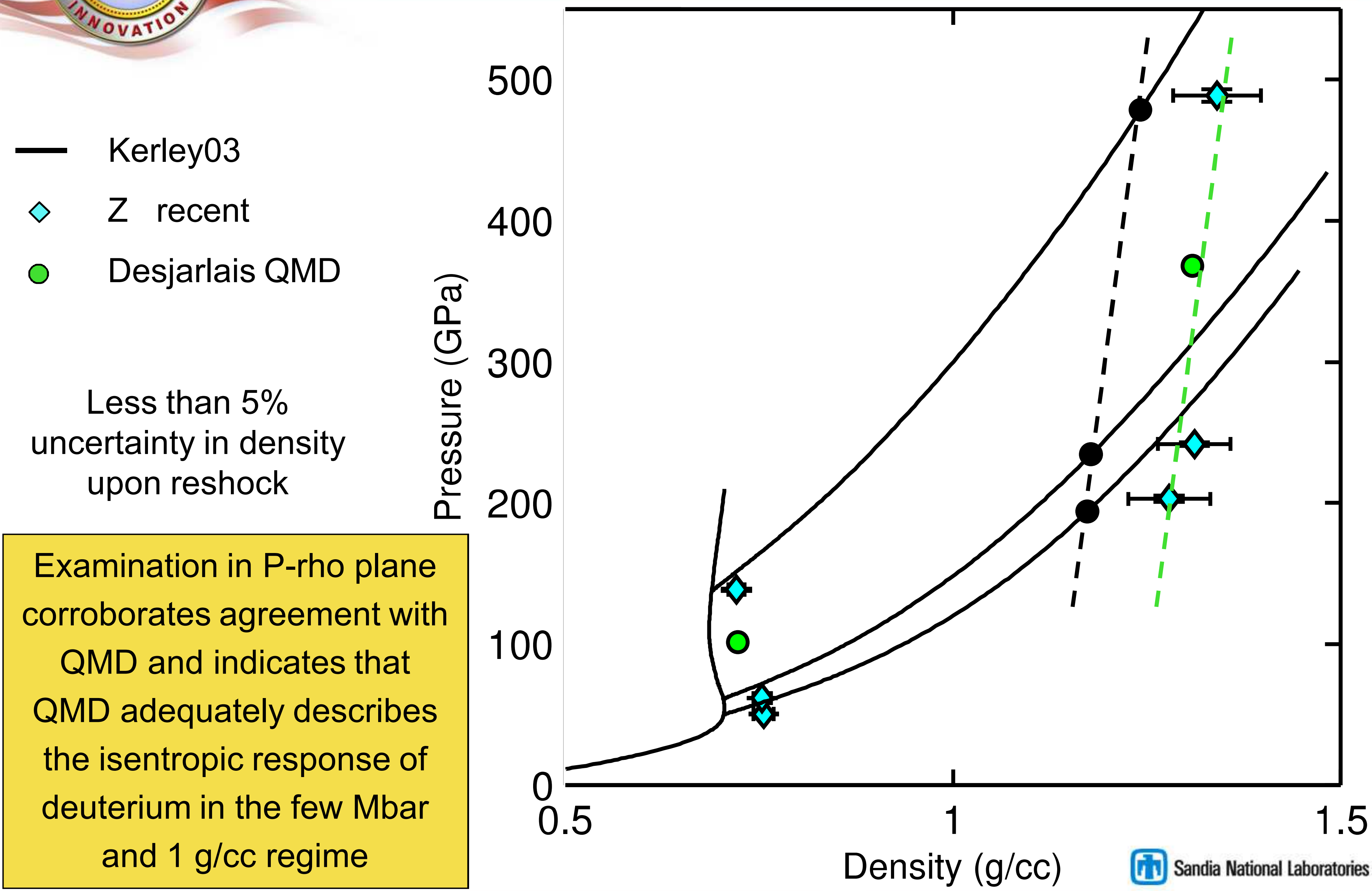
Re-shock provides a stringent constraint on the isentropic response of D_2 in this regime



Less than 5% uncertainty in density upon reshock

Examination in P-rho plane corroborates agreement with QMD and indicates that QMD adequately describes the isentropic response of deuterium in the few Mbar and 1 g/cc regime

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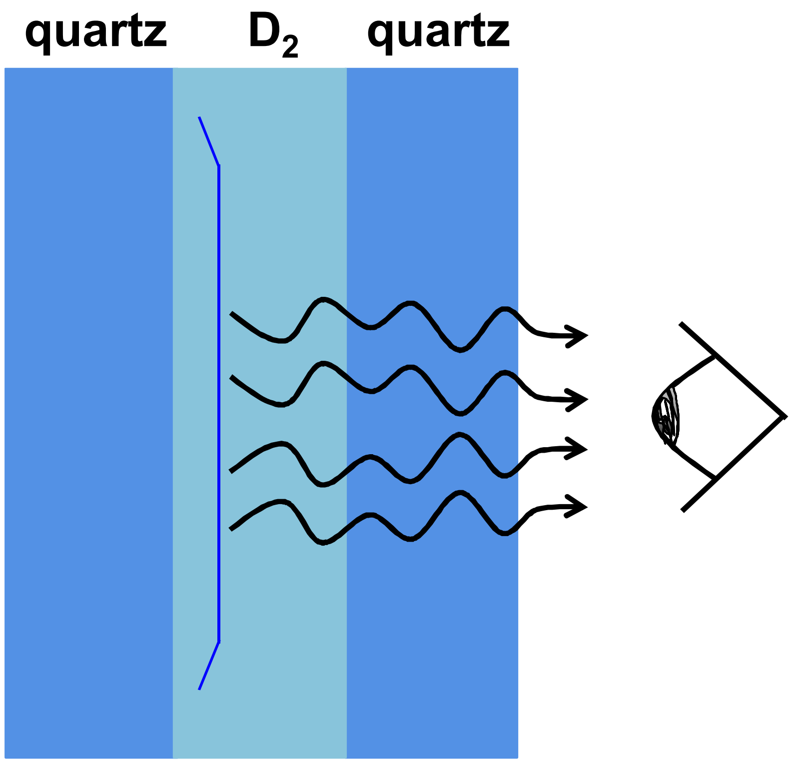
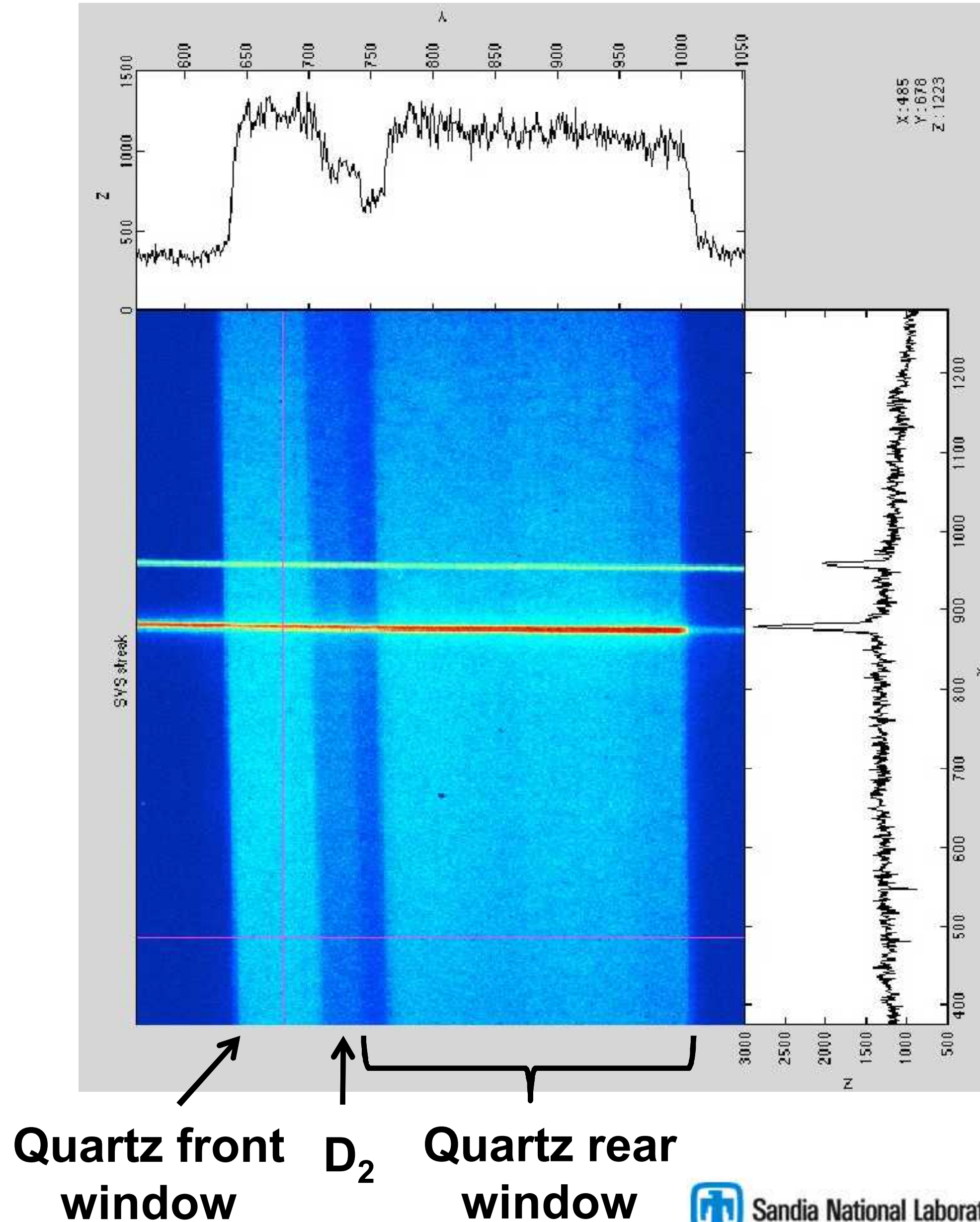
Visible emission dispersed in wavelength and time to infer temperature along the Hugoniot



Quartz emission used both as a relative calibration and to correct for effect of reflections at quartz/sample interfaces



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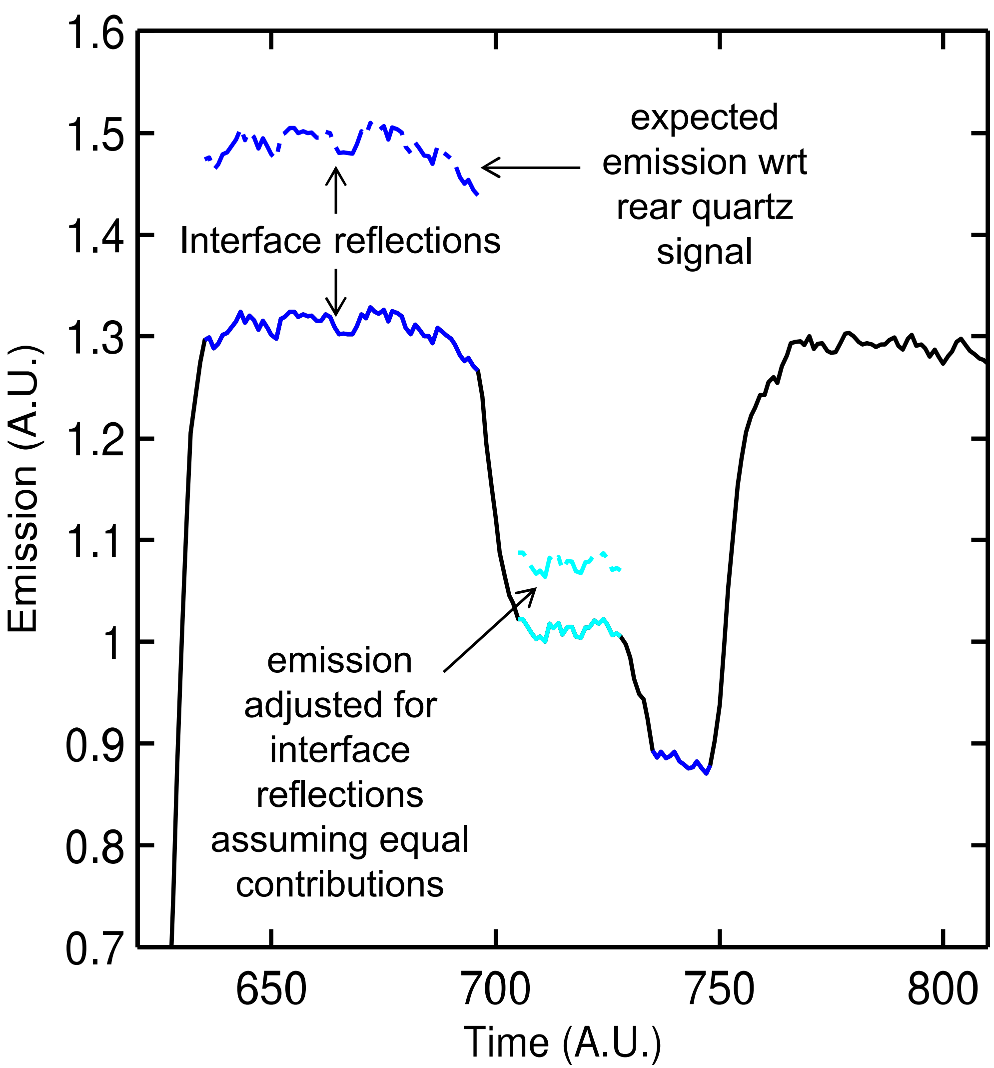
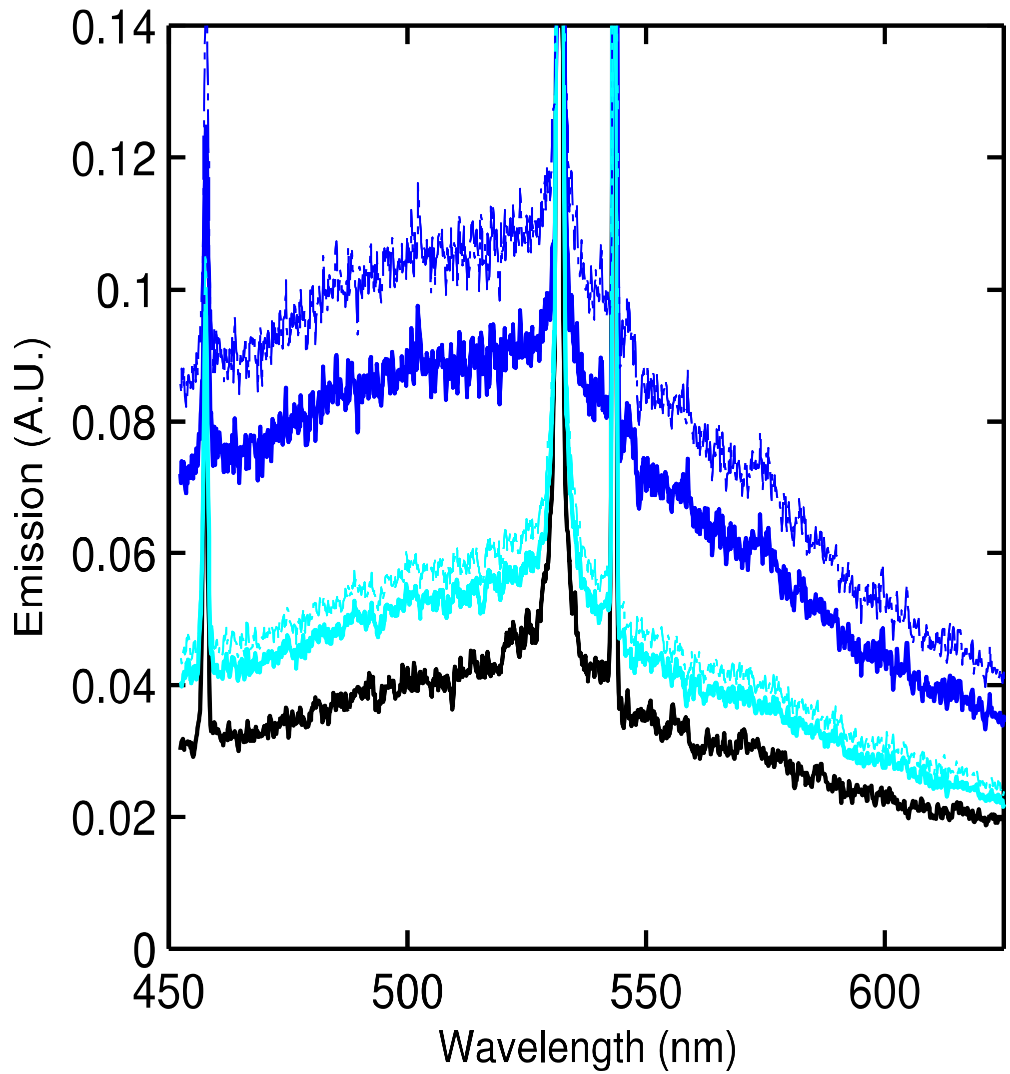
Quartz emission on either side of the D_2 is used as a relative calibration to account for interfaces





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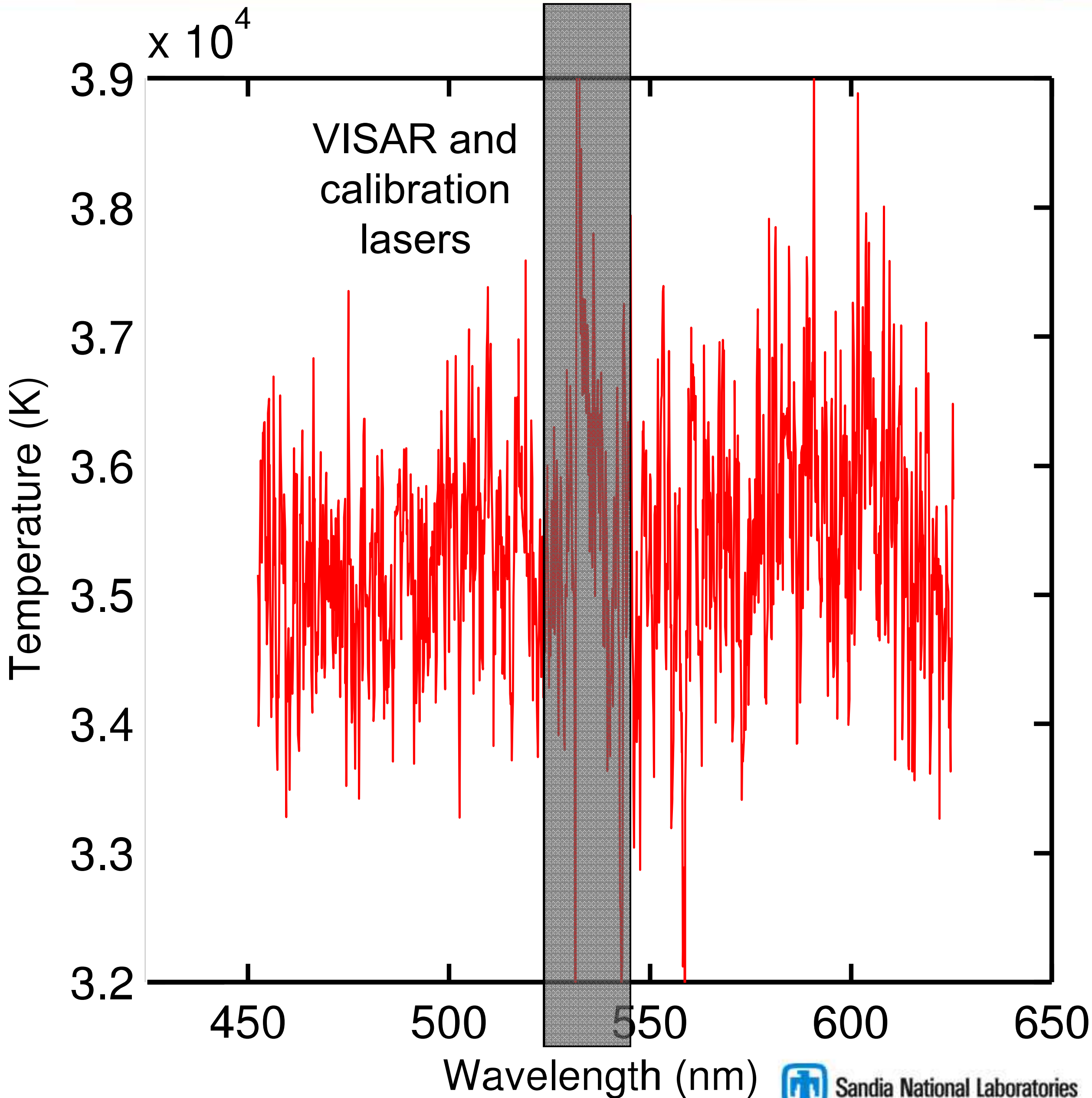
Calculation is done at each wavelength over a few hundred nm wavelength range

Emissivity for quartz and deuterium are determined from QMD calculations and are wavelength dependent

Wavelength independent response suggests that the method used to correct for reflections at the interfaces is reasonable

Technique was recently employed with data from LiD which further corroborate the method



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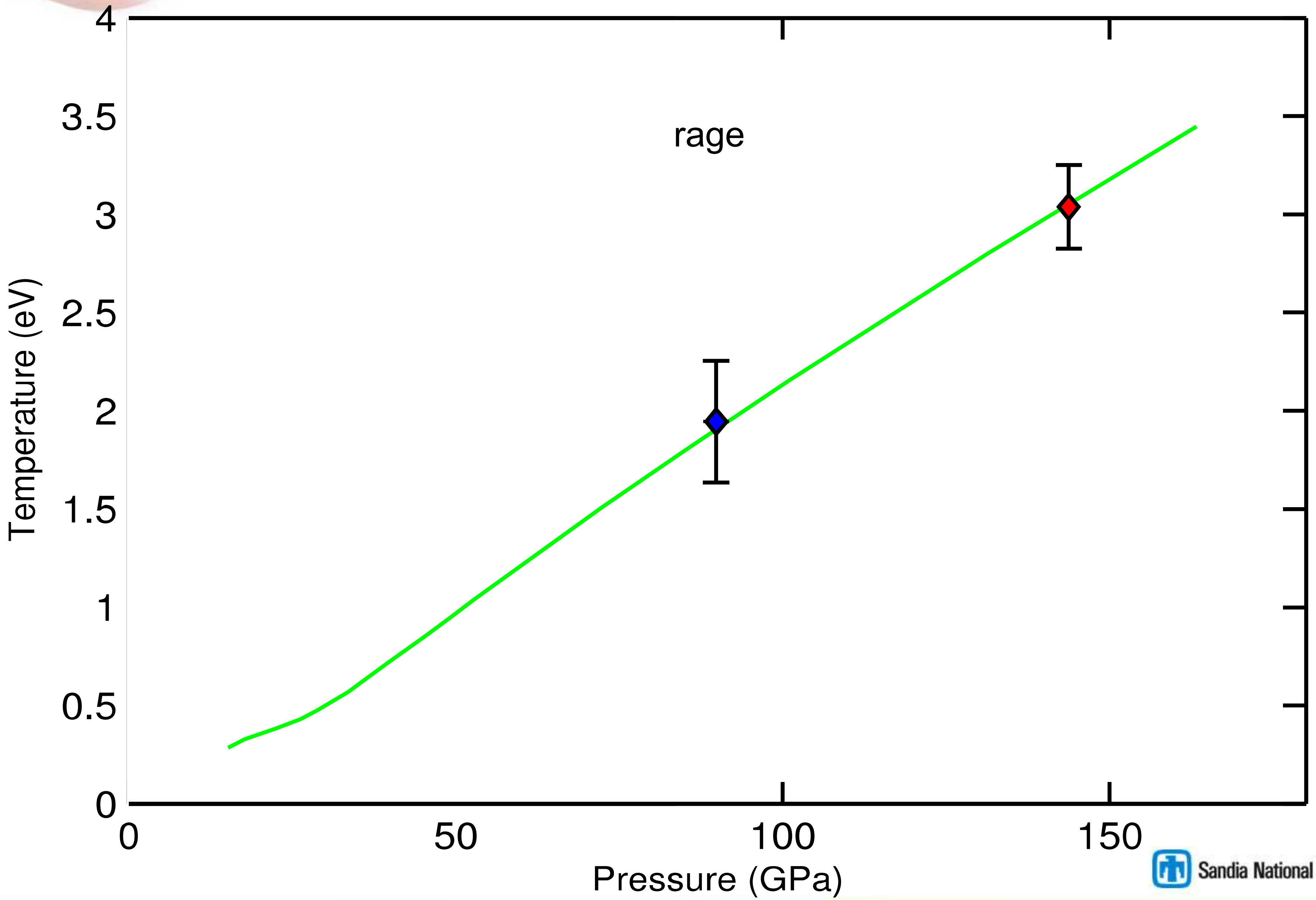
Temperature measurements are in very good agreement with QMD and previous data



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Conclusions

- Hugoniot and re-shock experiments have been performed on water over the range of 100-700 GPa
  - In particular, the re-shock measurements allow for the probing of the isentropic response of water at planetary conditions
- All experimental observables from the water experiments suggest the QMD calculations of water are accurate at conditions relevant to planetary interiors
  - Advocate that this water model be used as the standard for modeling Neptune, Uranus, and "hot Neptune" exoplanets
- Recent Hugoniot and re-shock experiments on deuterium have been performed near peak compression and well above dissociation
  - Significant improvement in precision that provides stringent constraint on the Hugoniot and isentropic response of deuterium in the few Mbar and 1 g/cc regime

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