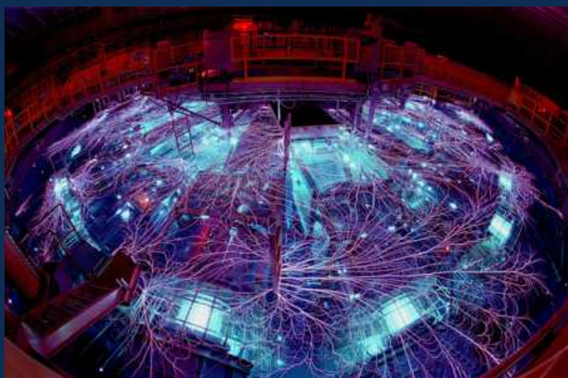
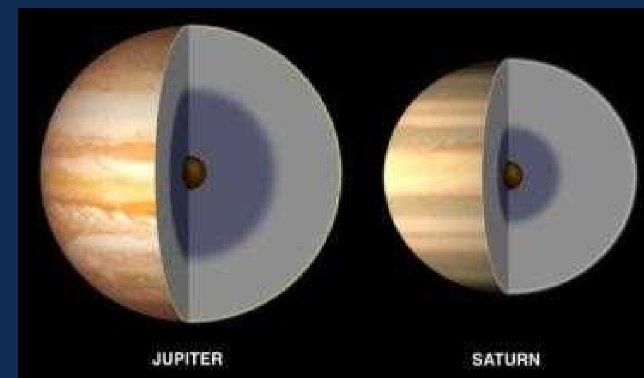
SAND2016-4605C

Exceptional service in the national interest

Sandia National Laboratories





Direct observation of an abrupt insulator-to-metal transition in dense liquid deuterium

Marcus D. Knudson

mdknuds@sandia.gov

Dynamic Material Properties Group
Sandia National Laboratories
Albuquerque, NM

Institute for Shock Physics
Washington State University
Pullman, WA

Universität Rostock, Institut für Physik

U.S. Department of Energy — NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Acknowledgements

Experiment Design/Analysis

Marcus Knudson

Ray Lemke

Kyle Cochrane

Devon Dalton

Dustin Romero

Diagnostics

Charlie Meyer

Jeff Gluth

Devon Dalton

Anthony Romero

Dave Bliss

Alan Carlson

QMD Calculations

Mike Desjarlais

Andreas Becker

Winfried Lorenzen

Ronald Redmer

Planetary Modeling

Nadine Nettelmann

Andreas Becker

Ronald Redmer

Pulse Shaping

Ray Lemke

Jean-Paul Davis

Mark Savage

Ken Struve

Keith LeChien

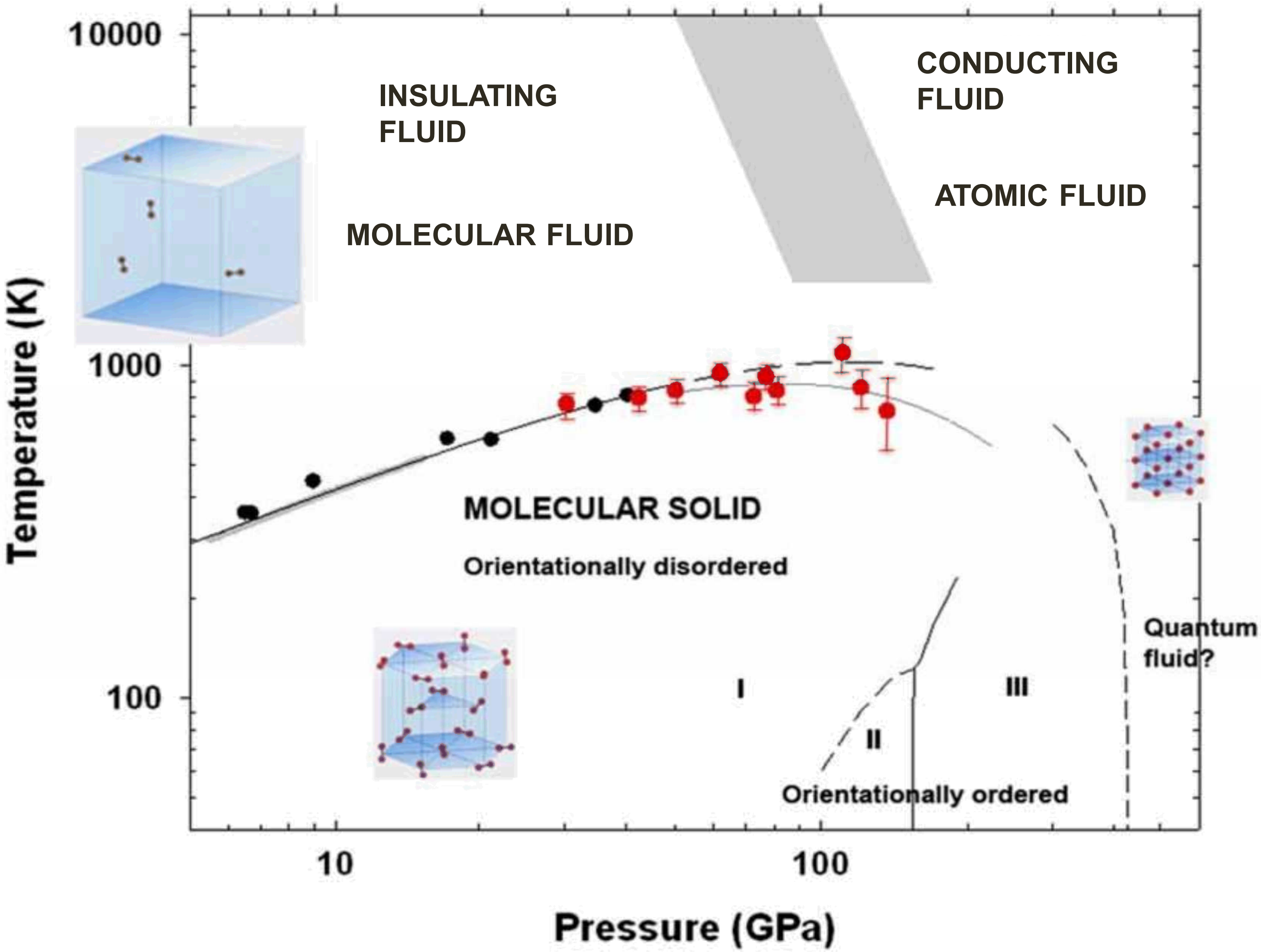
Brian Stoltzfus

Dave Hinshelwood

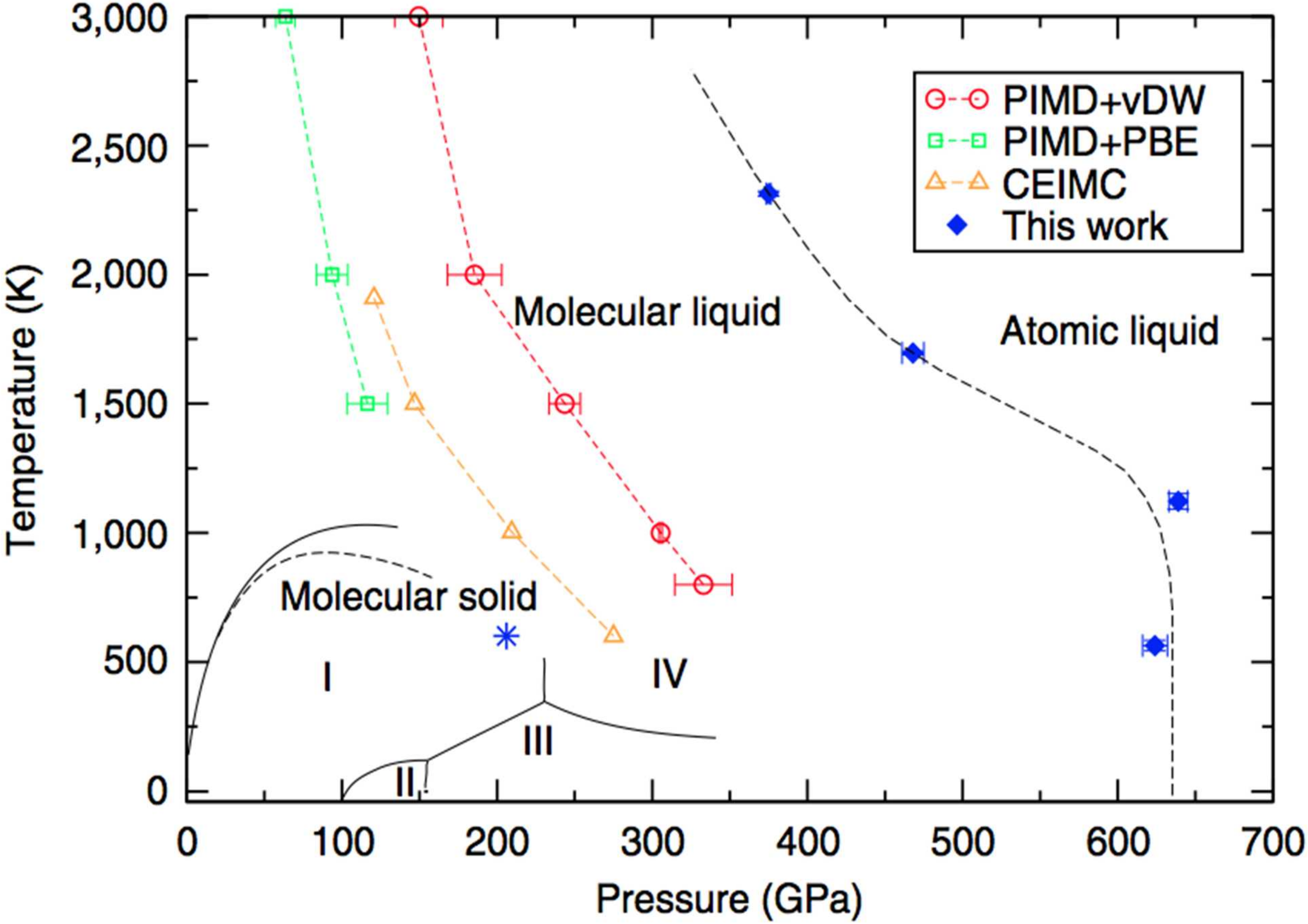
Entire Z crew

University of Rostock

Hydrogen at high pressures – the known phase diagram so far

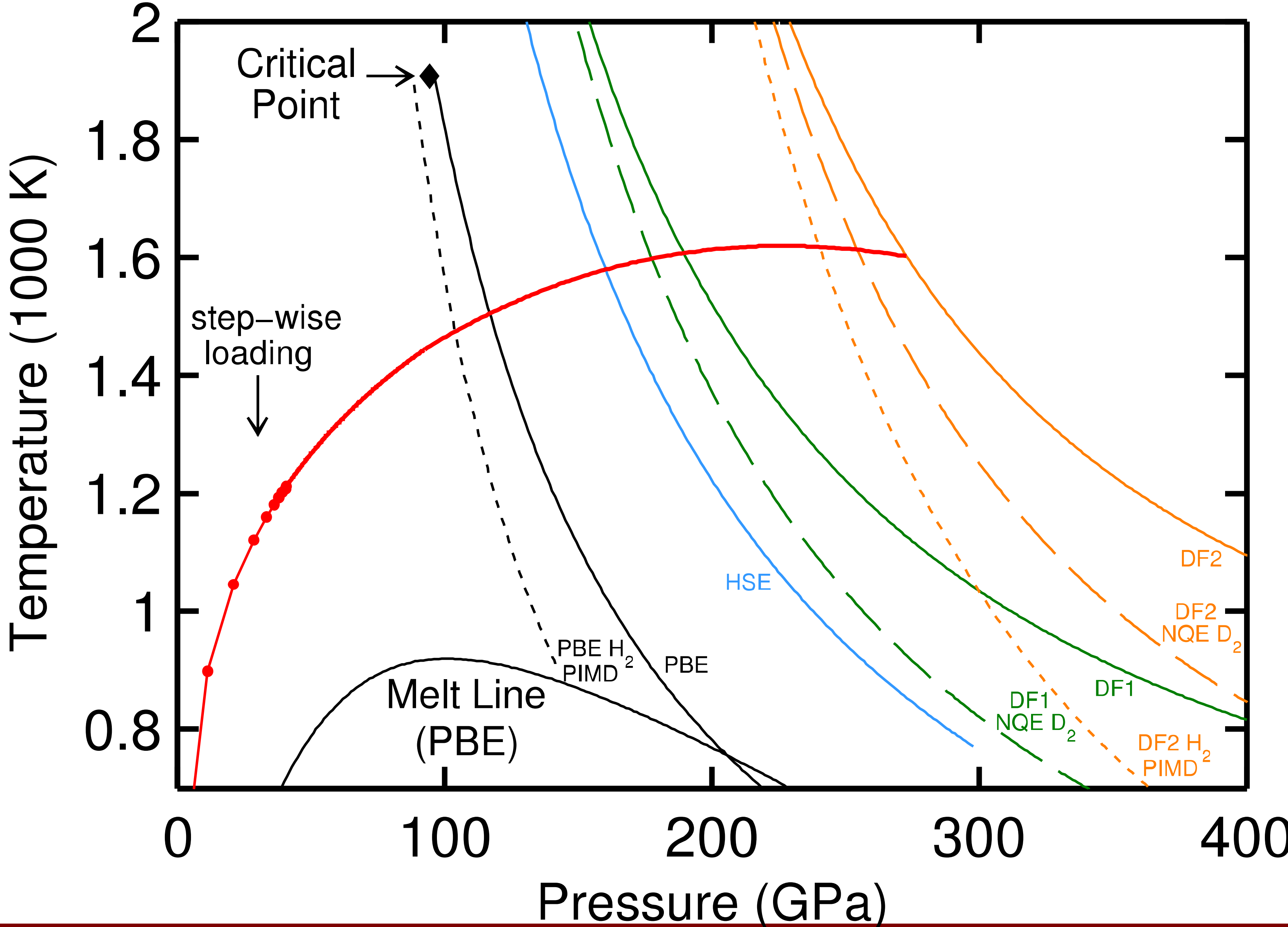


Recent predictions of the LL-IMT in hydrogen

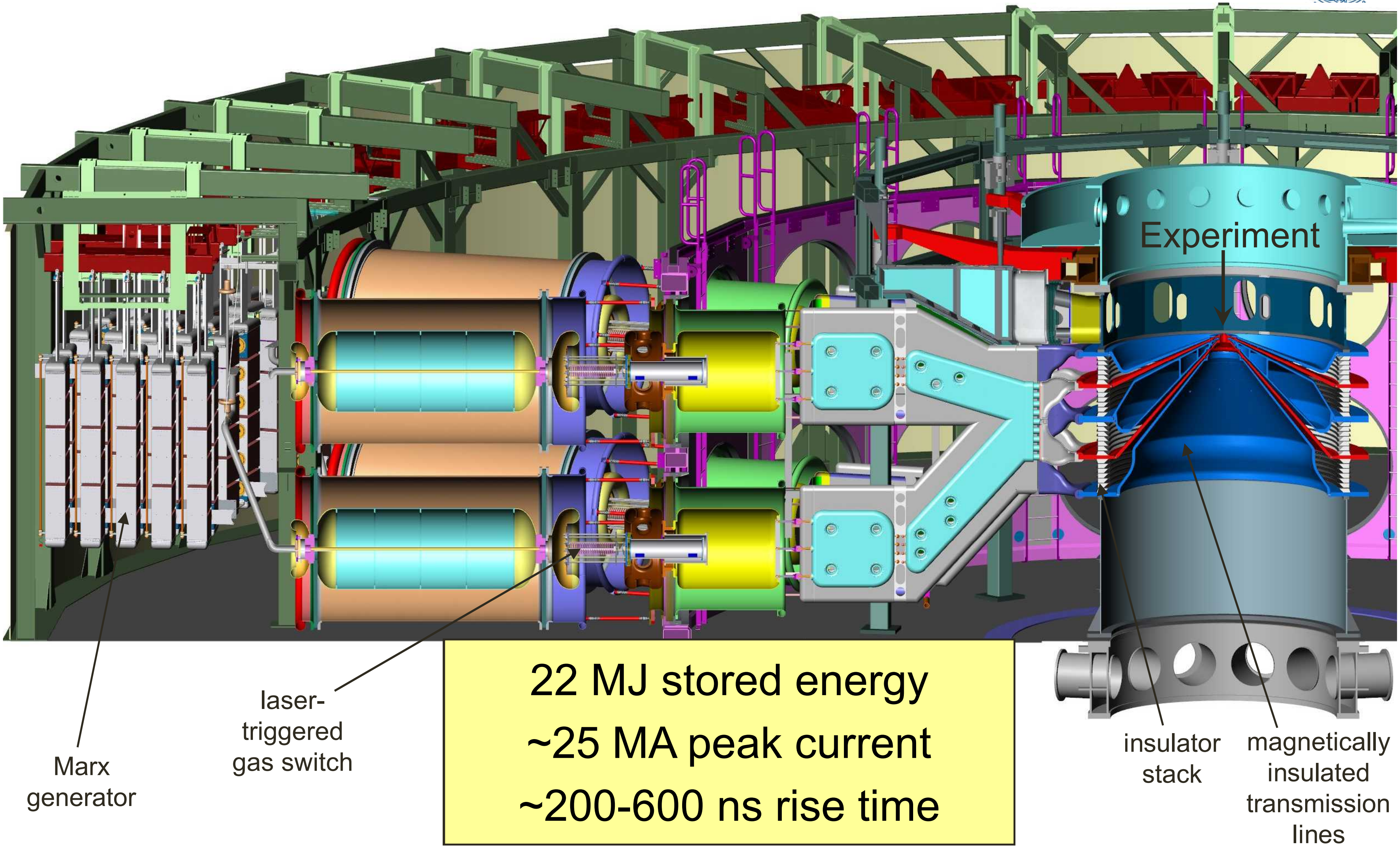


...atter (2014)

Proposed Experiment: Shock - Ramp

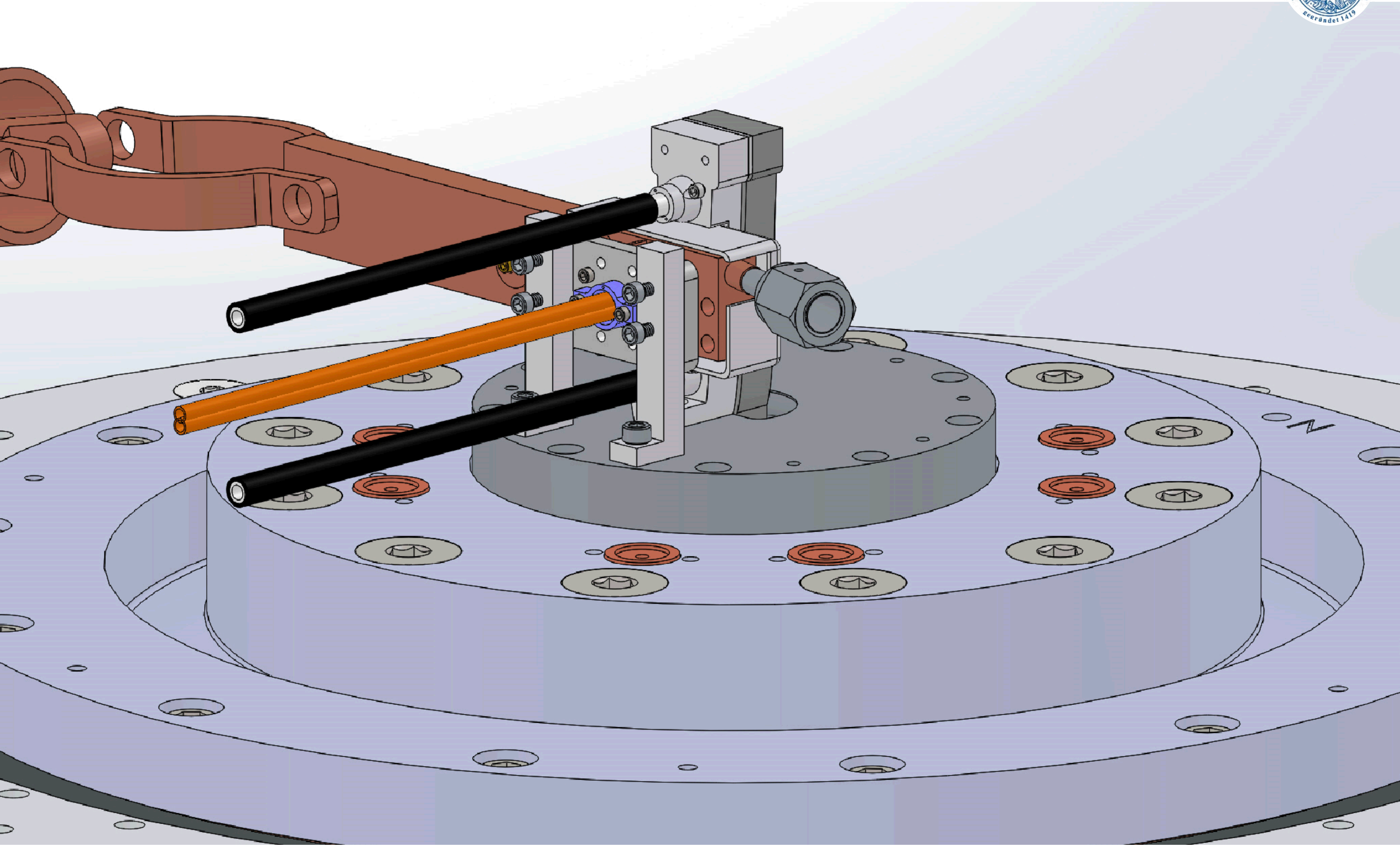


Sandia Z Machine

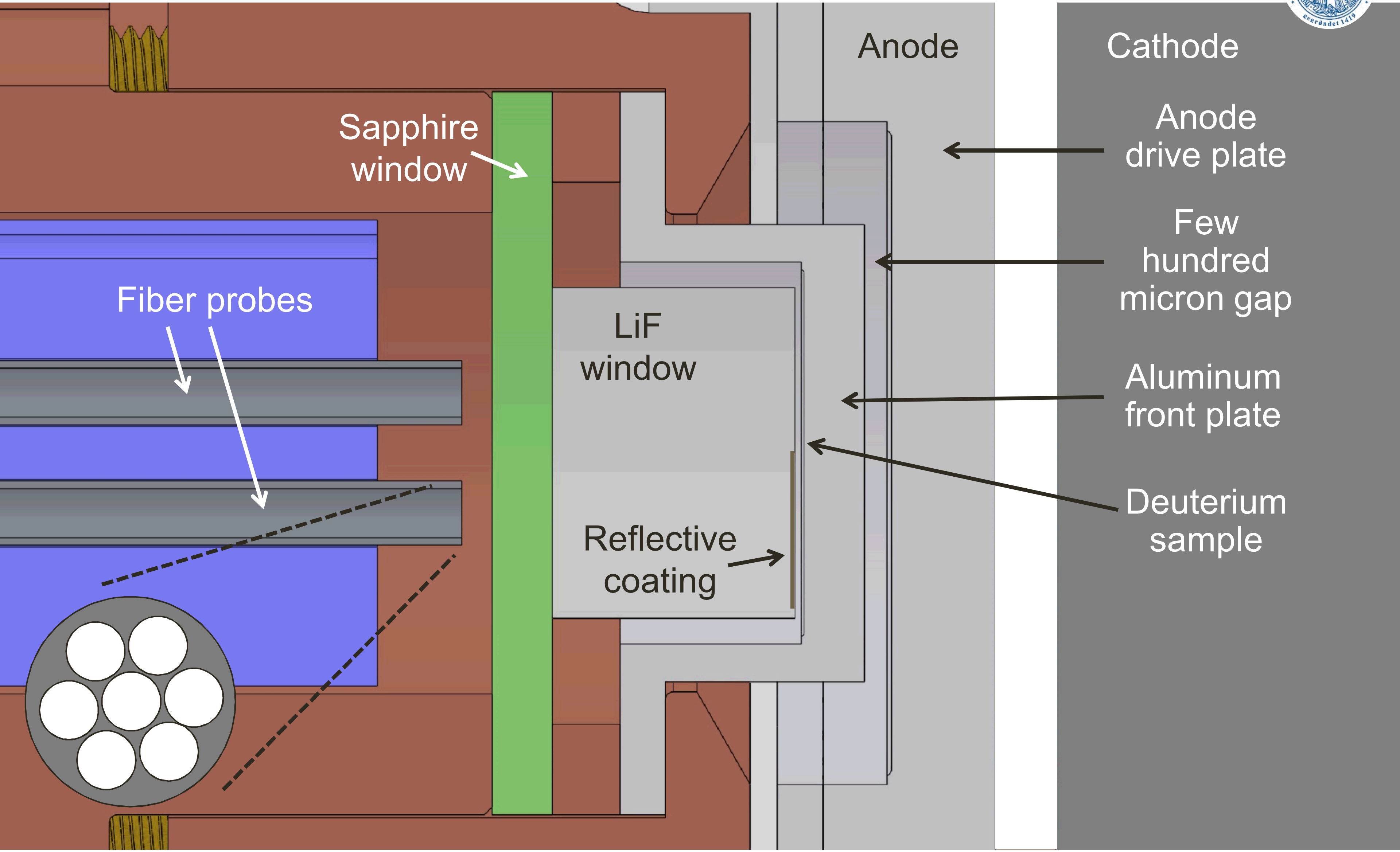


22 MJ stored energy
~25 MA peak current
~200-600 ns rise time

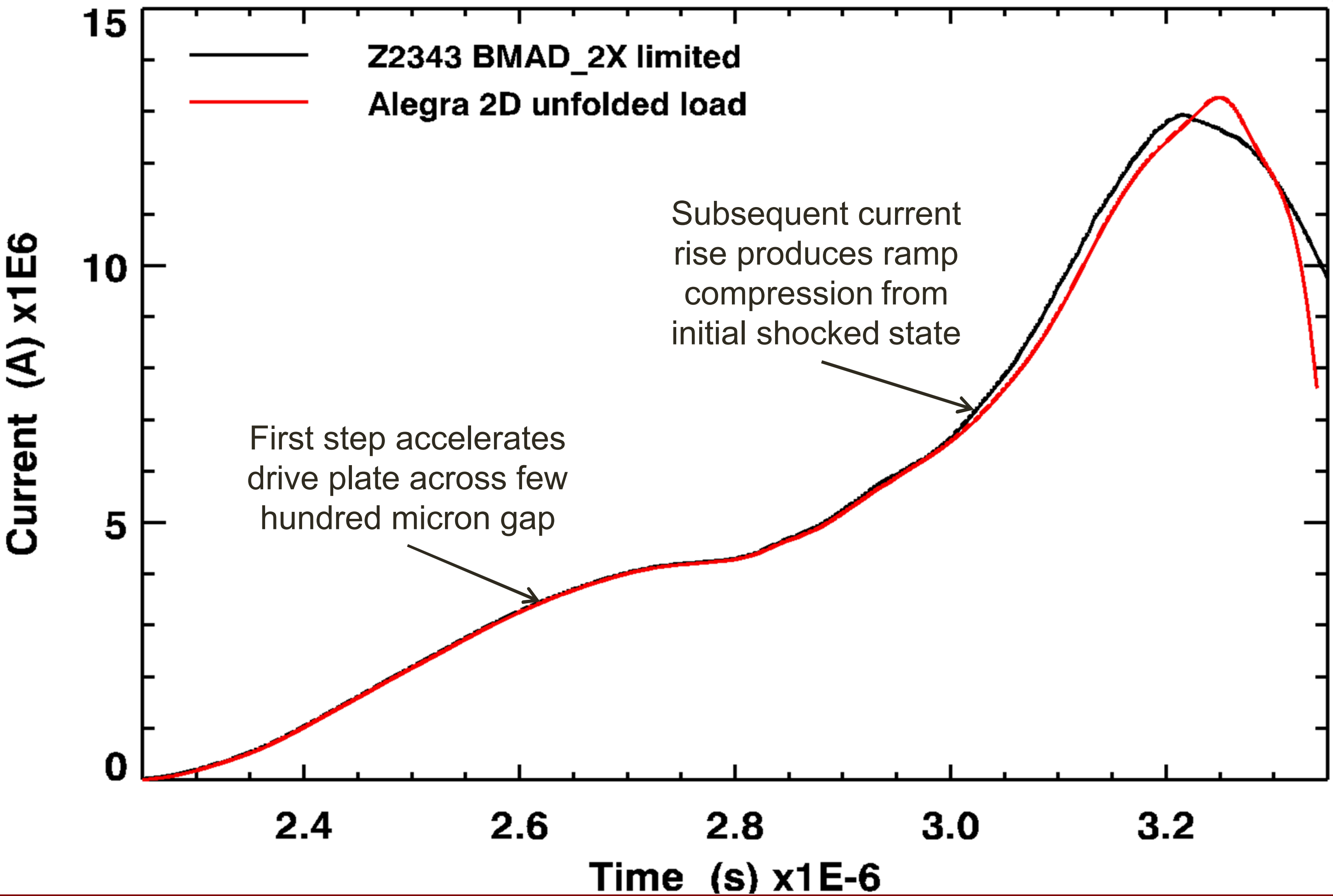
Stripline experimental configuration



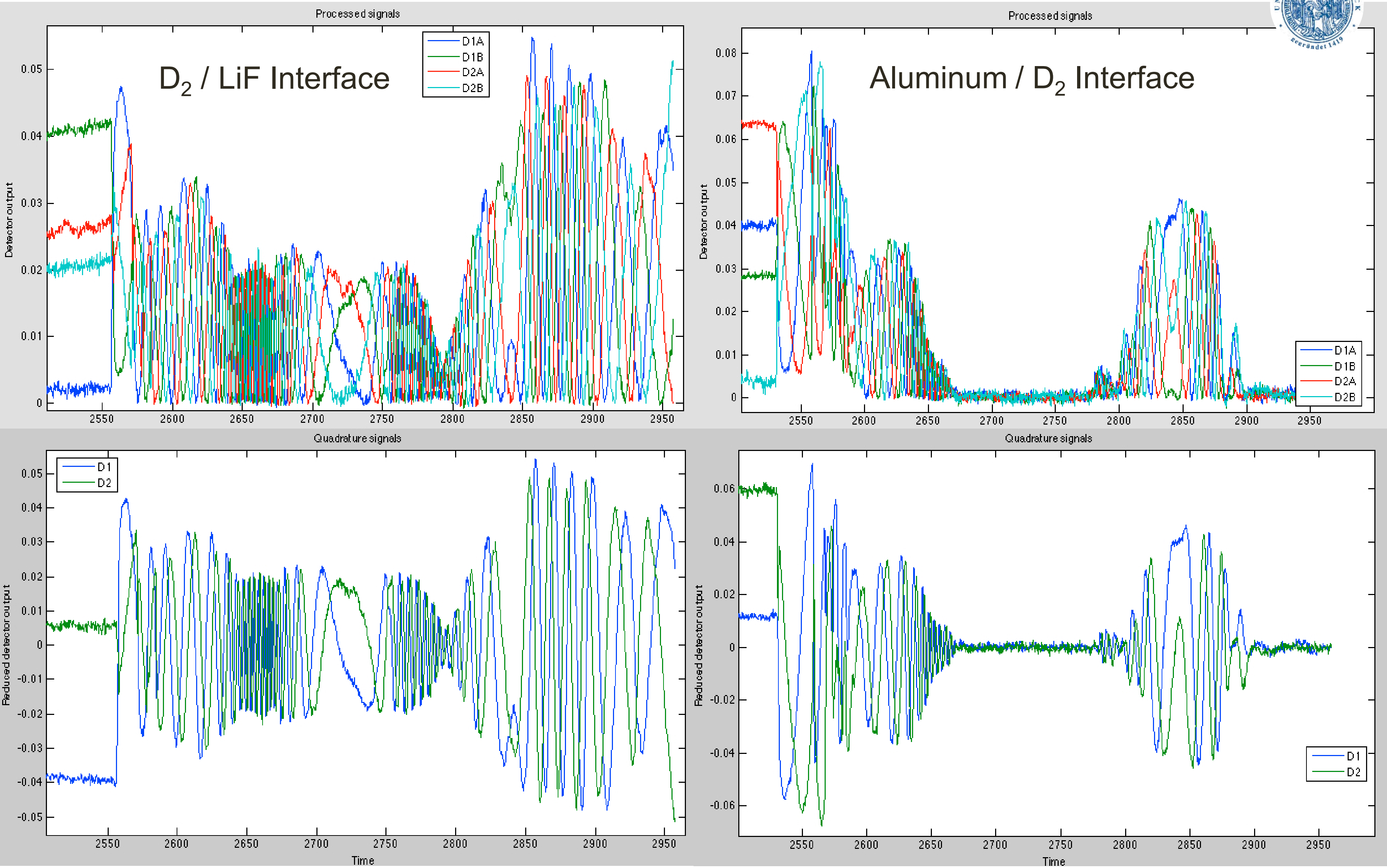
Experimental configuration



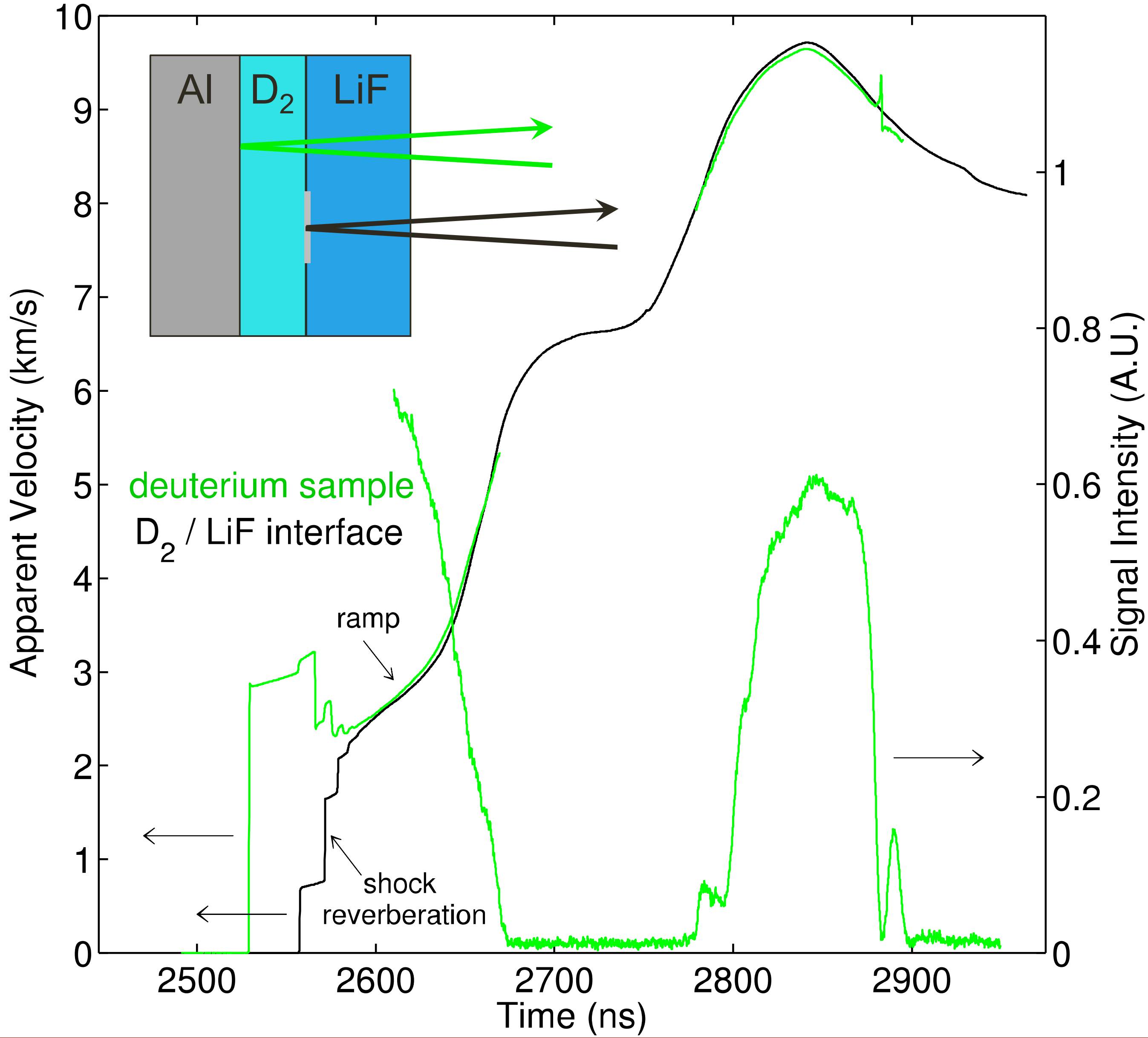
Two-step pulse shape provides shock-ramp profile



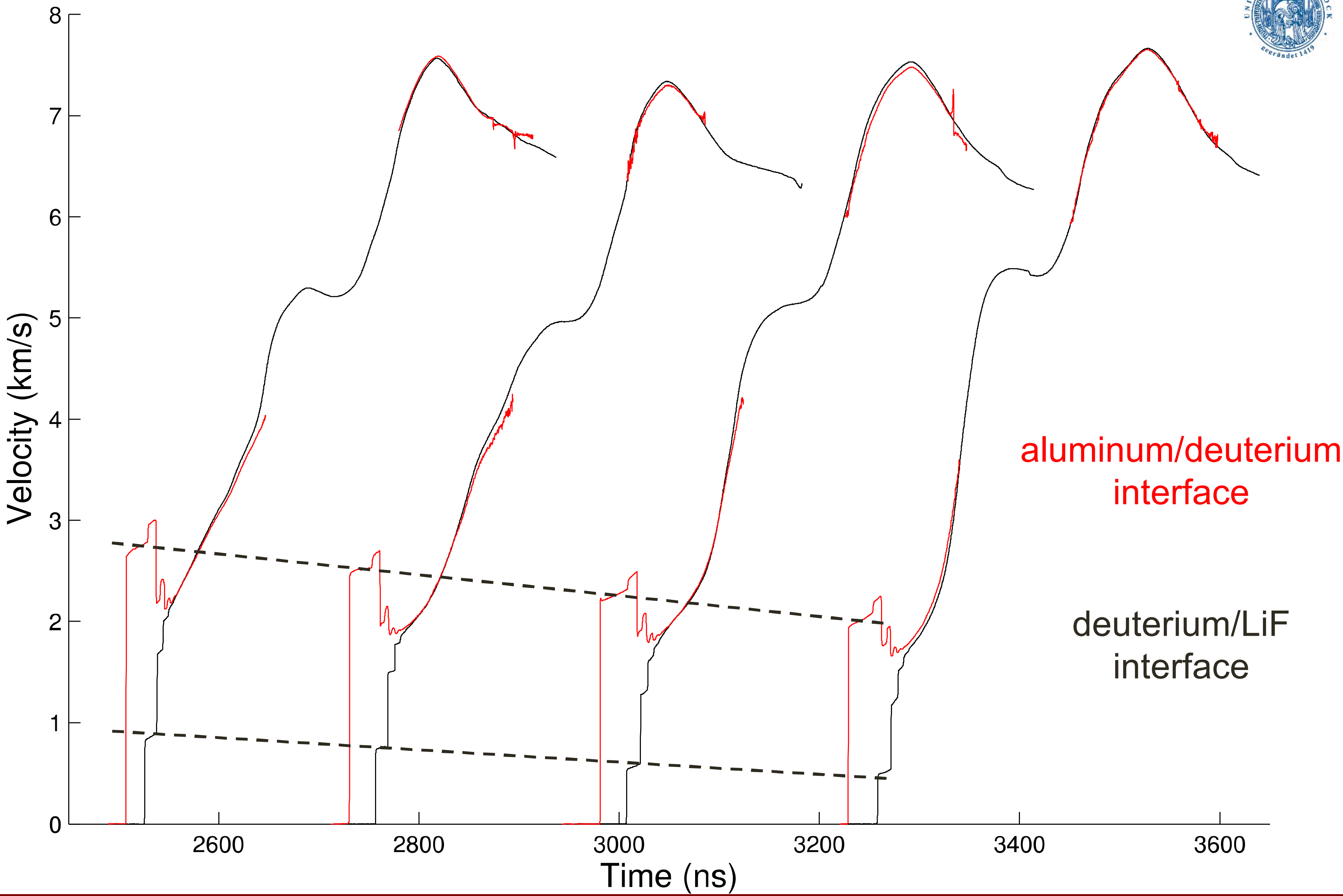
Processed VISAR signals



Measured observables in deuterium



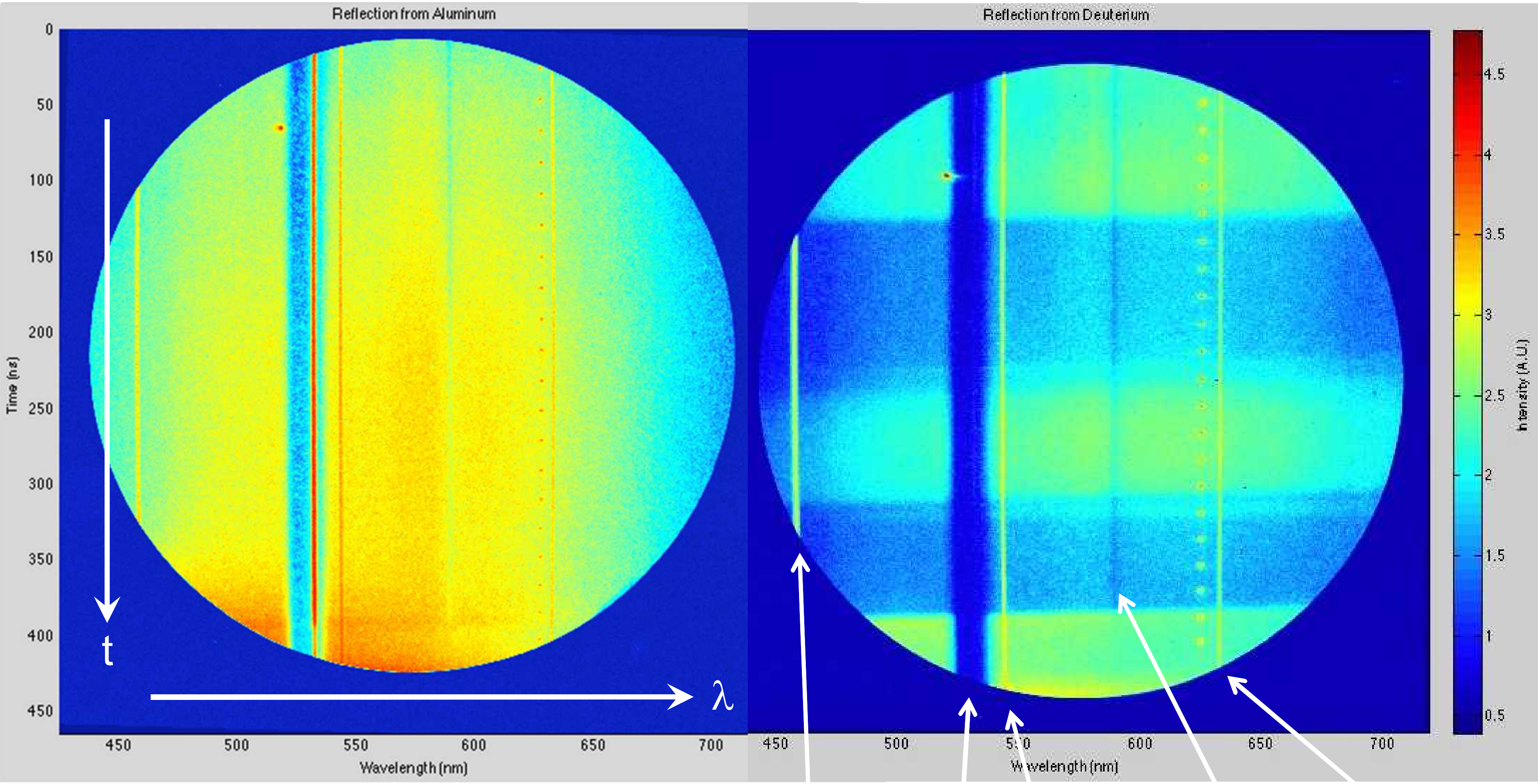
Stripline experimental profiles



SVS system provides data to infer reflectivity

Reflection from aluminum coating

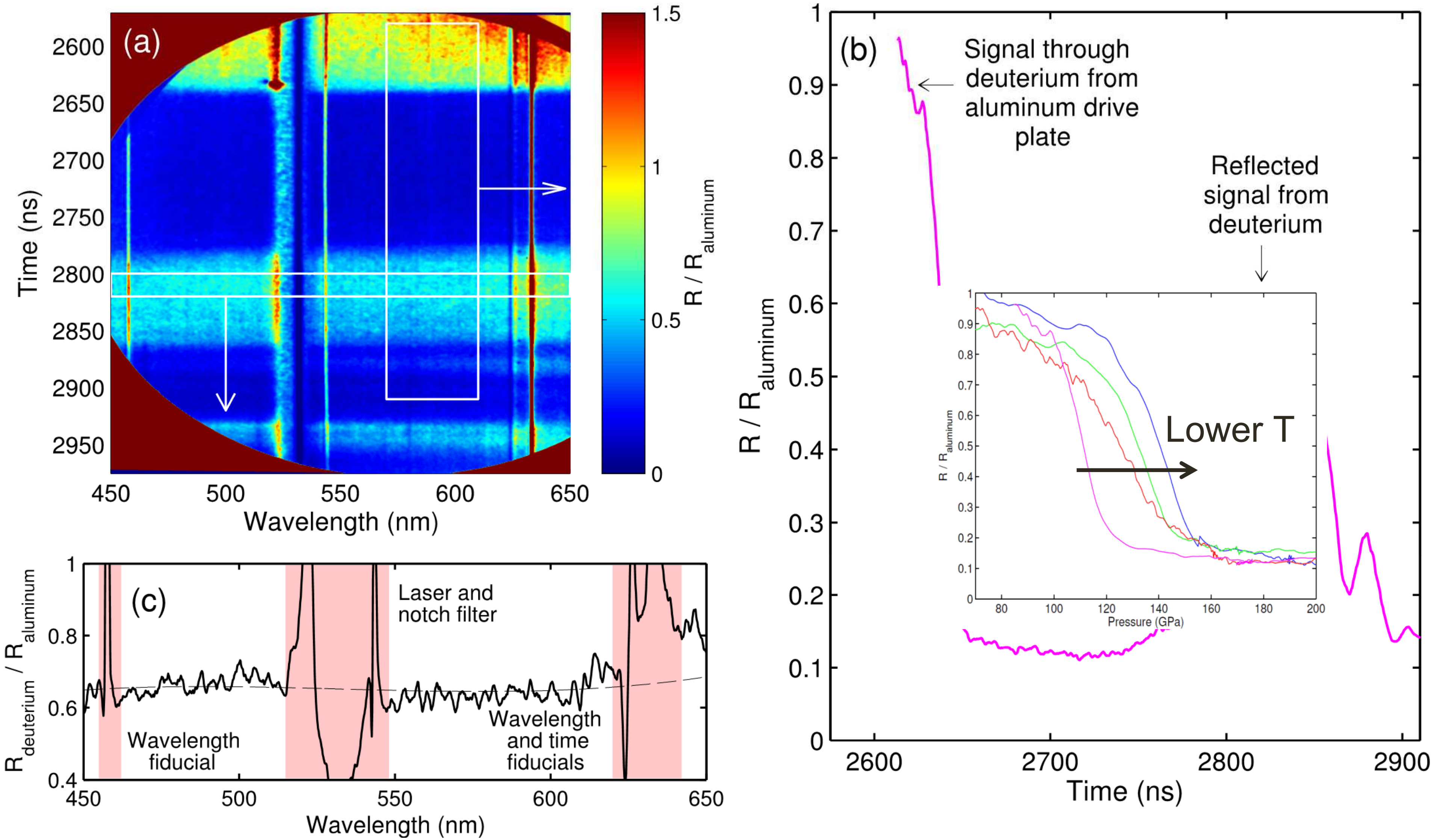
Reflection from deuterium



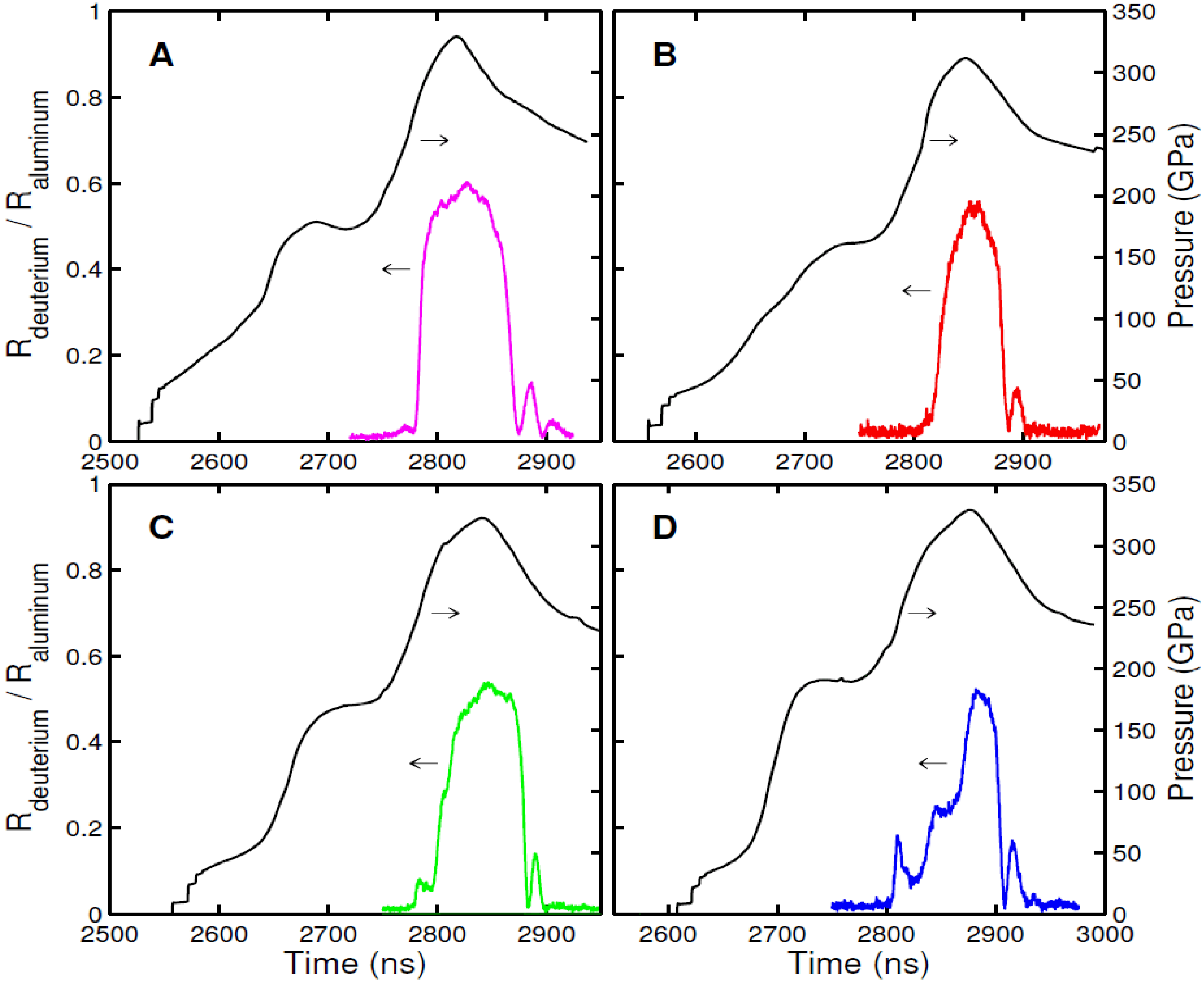
Wavelength range ~450-700 nm

457.9 nm   532 / 543.5 nm   589.3 nm   633 nm

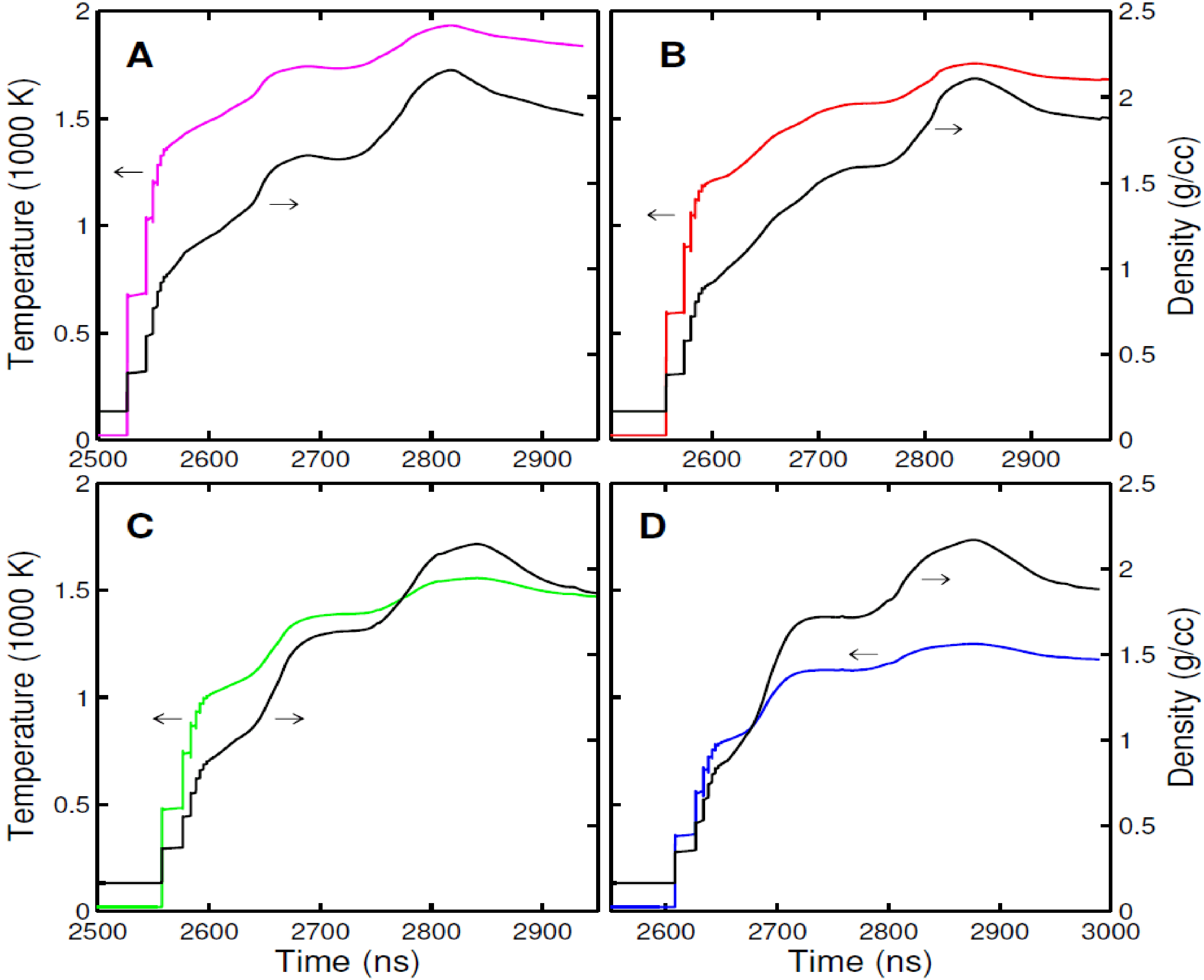
SVS system provides data to infer reflectivity



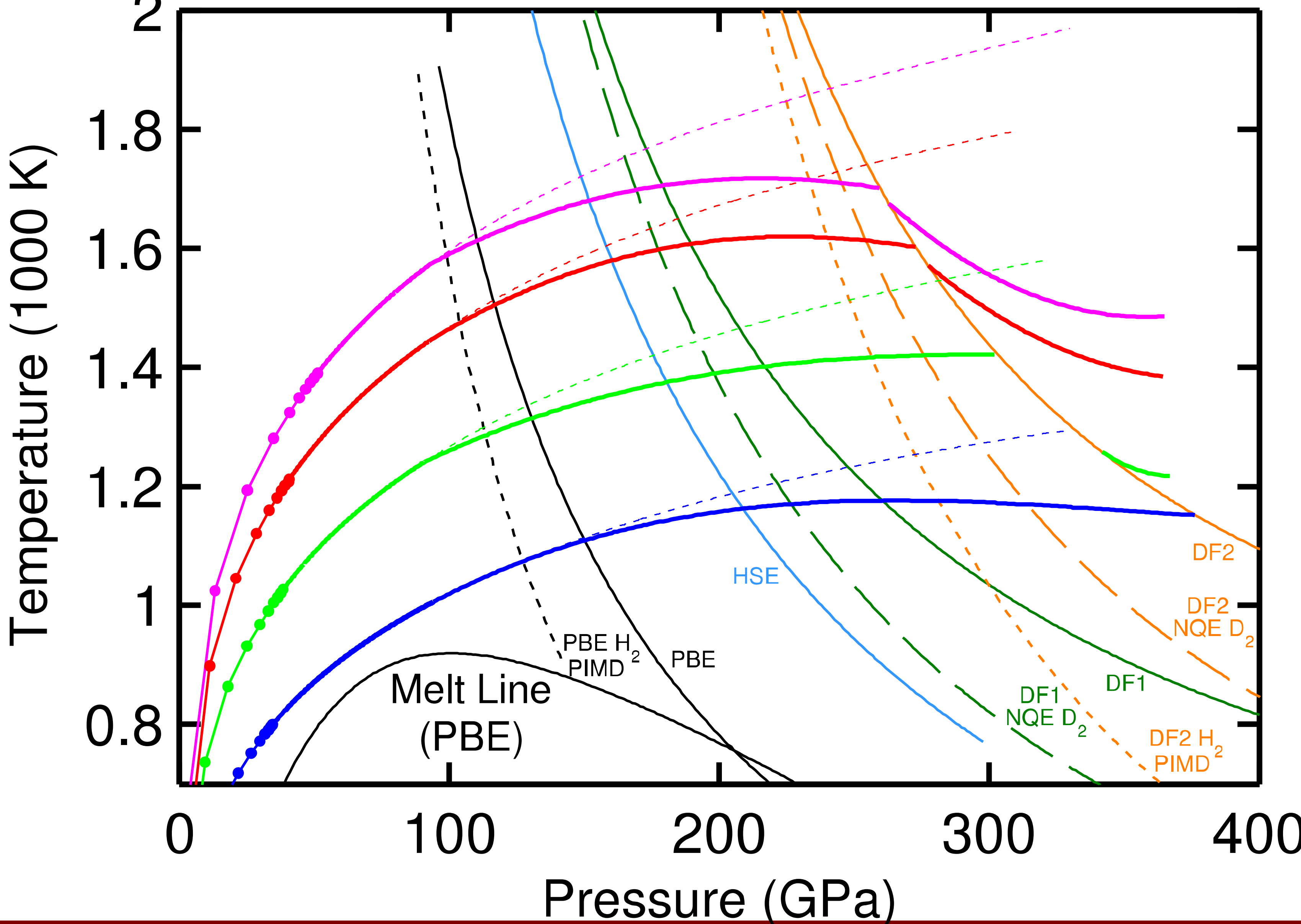
P(t) obtained from v(t) and LiF EOS



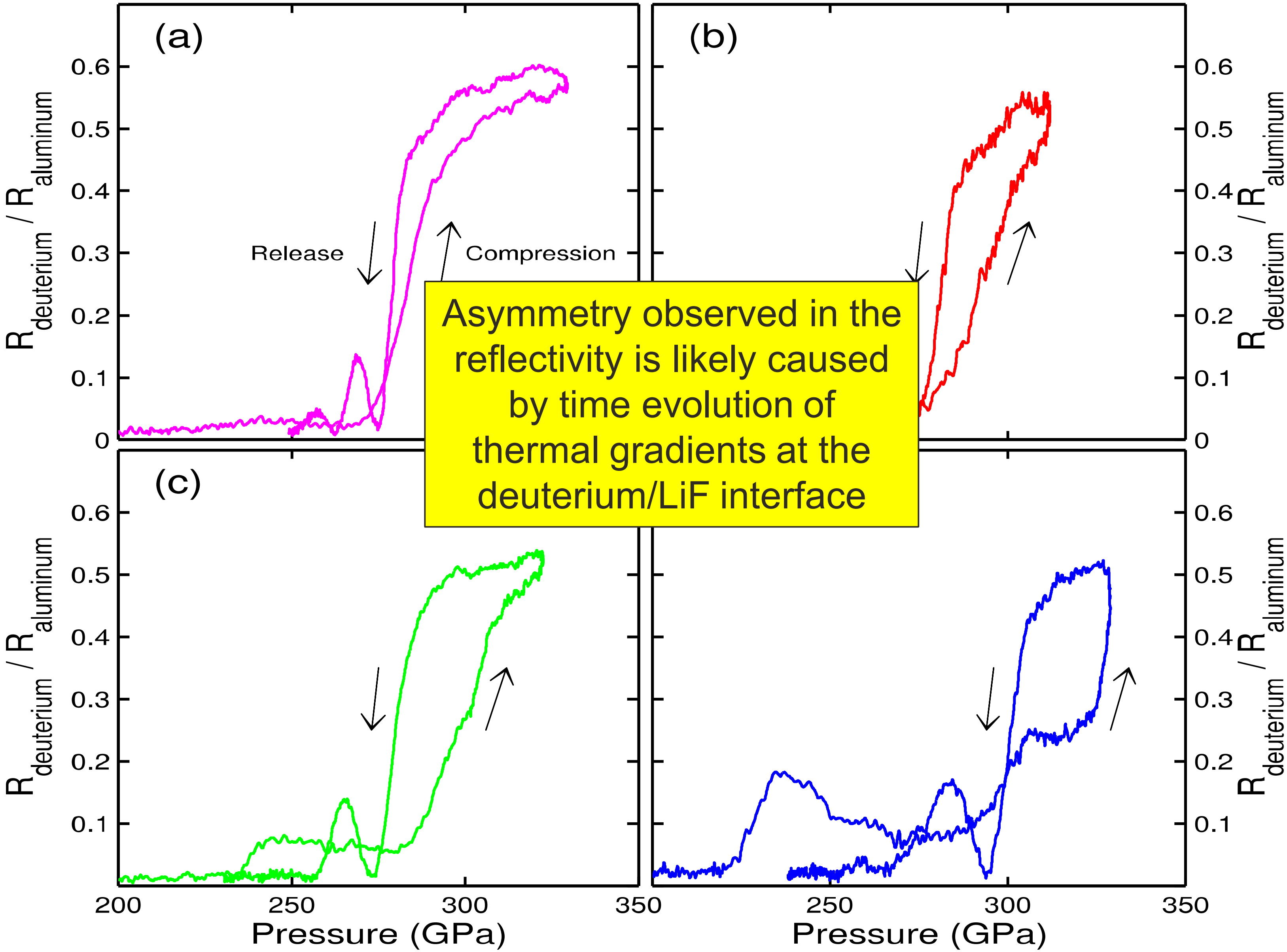
T(t) and ρ(t) obtained from D_2 EOS (Kerley03)



Experimental PT Paths

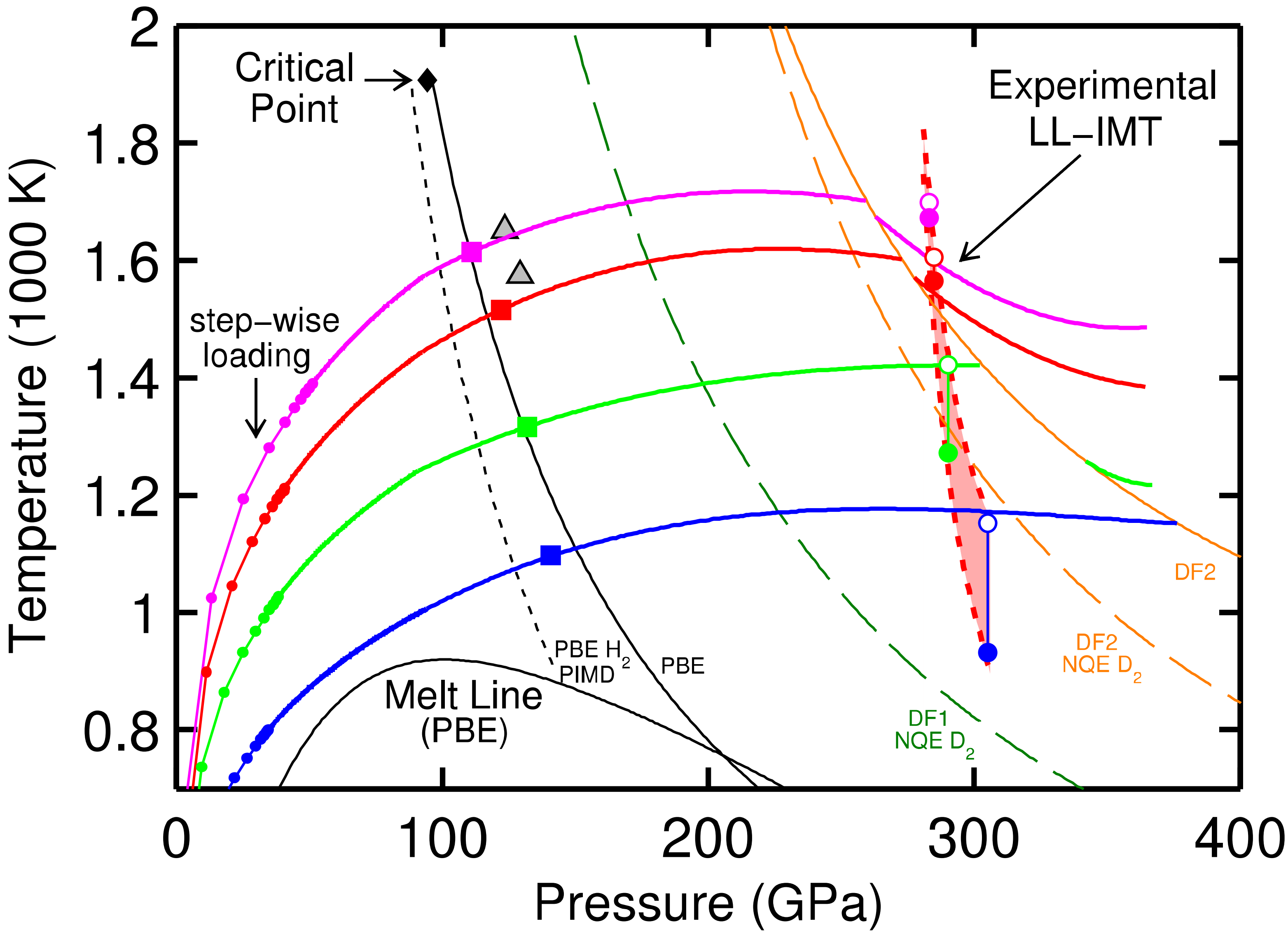


Reflectivity signals mapped to pressure

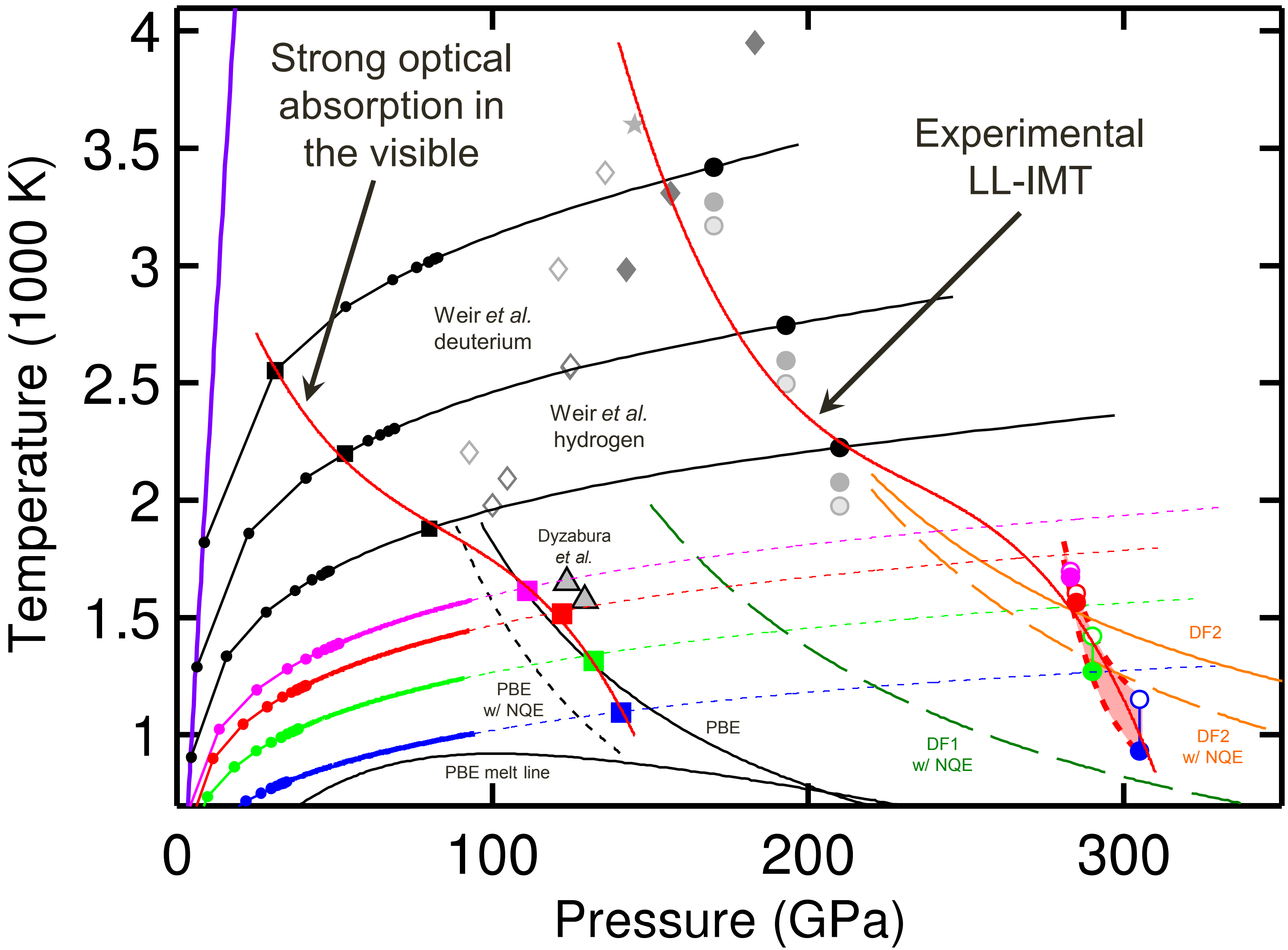


Asymmetry observed in the reflectivity is likely caused by time evolution of thermal gradients at the deuterium/LiF interface

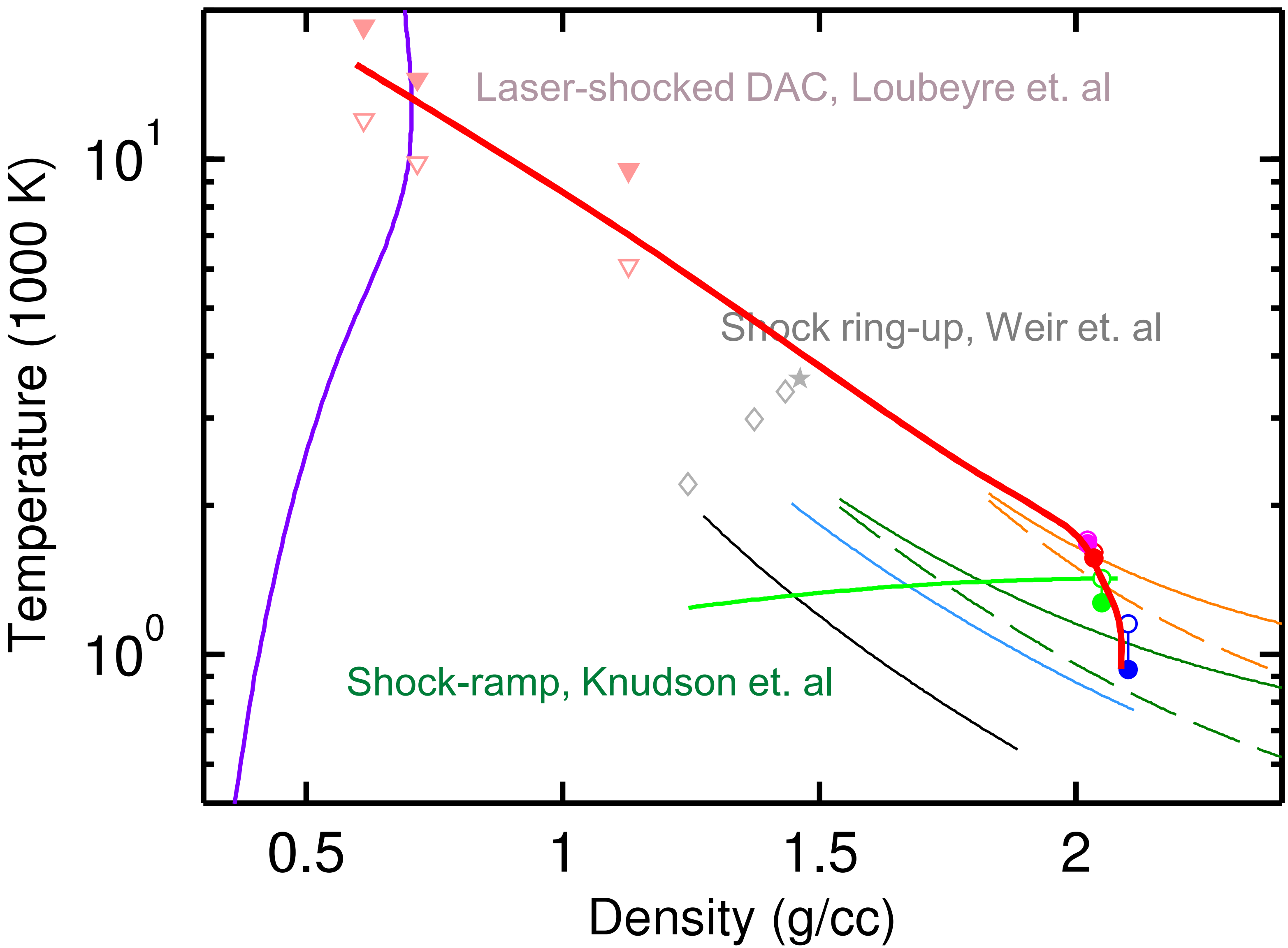
Location of the LL-IMT in deuterium



Location of the LL-IMT in deuterium



Extended P-ρ diagram for deuterium



Conclusions

- Shock-ramp technique enables experimental access to the region of phase space where the liquid-liquid, insulator-metal transition (LL-IMT) has been proposed for hydrogen
  - Temperature of the adiabat controlled by magnitude of initial shock
  - P(t) in the experiments determined from the LiF equation on state
- Experiments above ~250 GPa show clear evidence of metallization of deuterium
  - Very abrupt increase in reflectivity to ~40-50%
  - Pressure state well above numerous first principles predictions
  - Indications suggest that the transition is first order
- Relative insensitivity to T suggests this is a ρ-driven transition
  - ρ at the transition is inferred to be ~2-2.1 g/cc in deuterium

Acknowledgements

Experiment Design/Analysis

Marcus Knudson
Ray Lemke
Kyle Cochrane
Devon Dalton
Dustin Romero

Diagnostics

Charlie Meyer
Jeff Gluth
Devon Dalton
Anthony Romero
Dave Bliss
Alan Carlson

QMD Calculations

Mike Desjarlais
Andreas Becker
Winfried Lorenzen
Ronald Redmer

Planetary Modeling

Nadine Nettelmann
Andreas Becker
Ronald Redmer

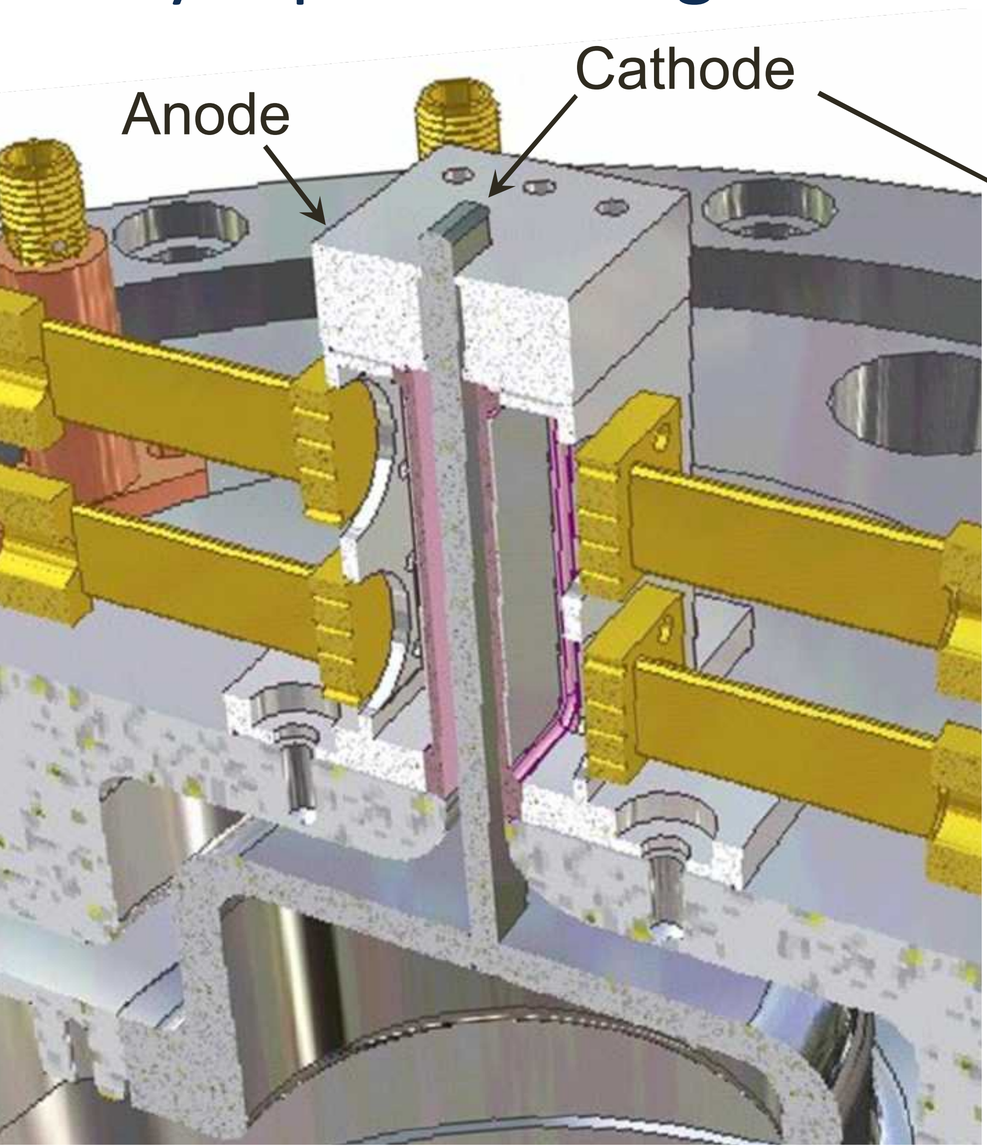
Pulse Shaping

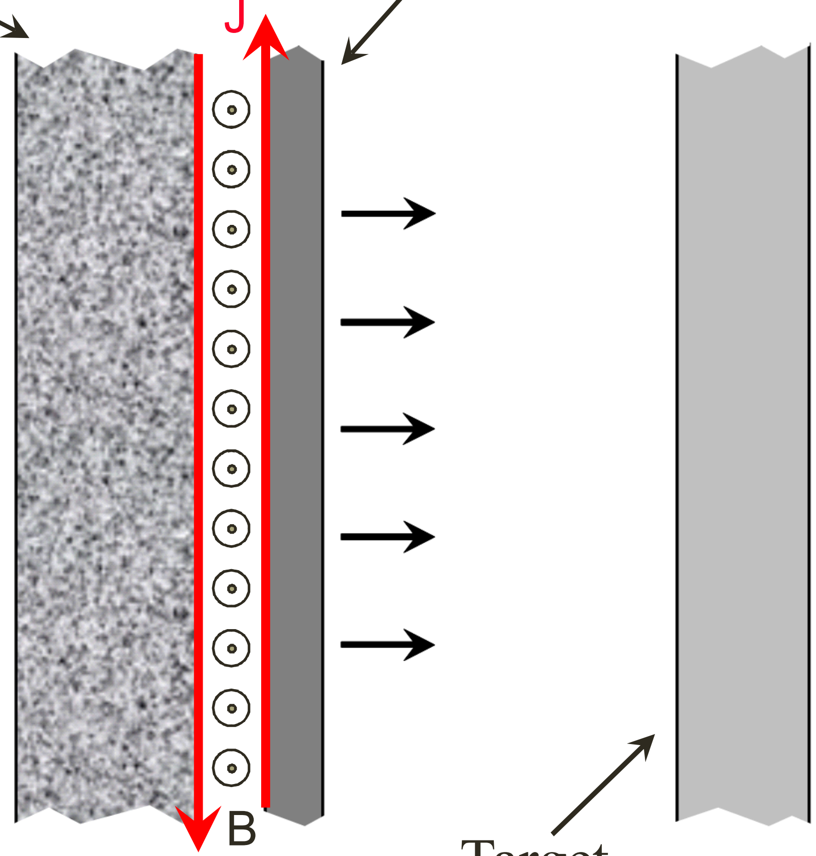
Ray Lemke
Jean-Paul Davis
Mark Savage
Ken Struve
Keith LeChien
Brian Stoltzfus
Dave Hinshelwood

Entire Z crew

University of Rostock

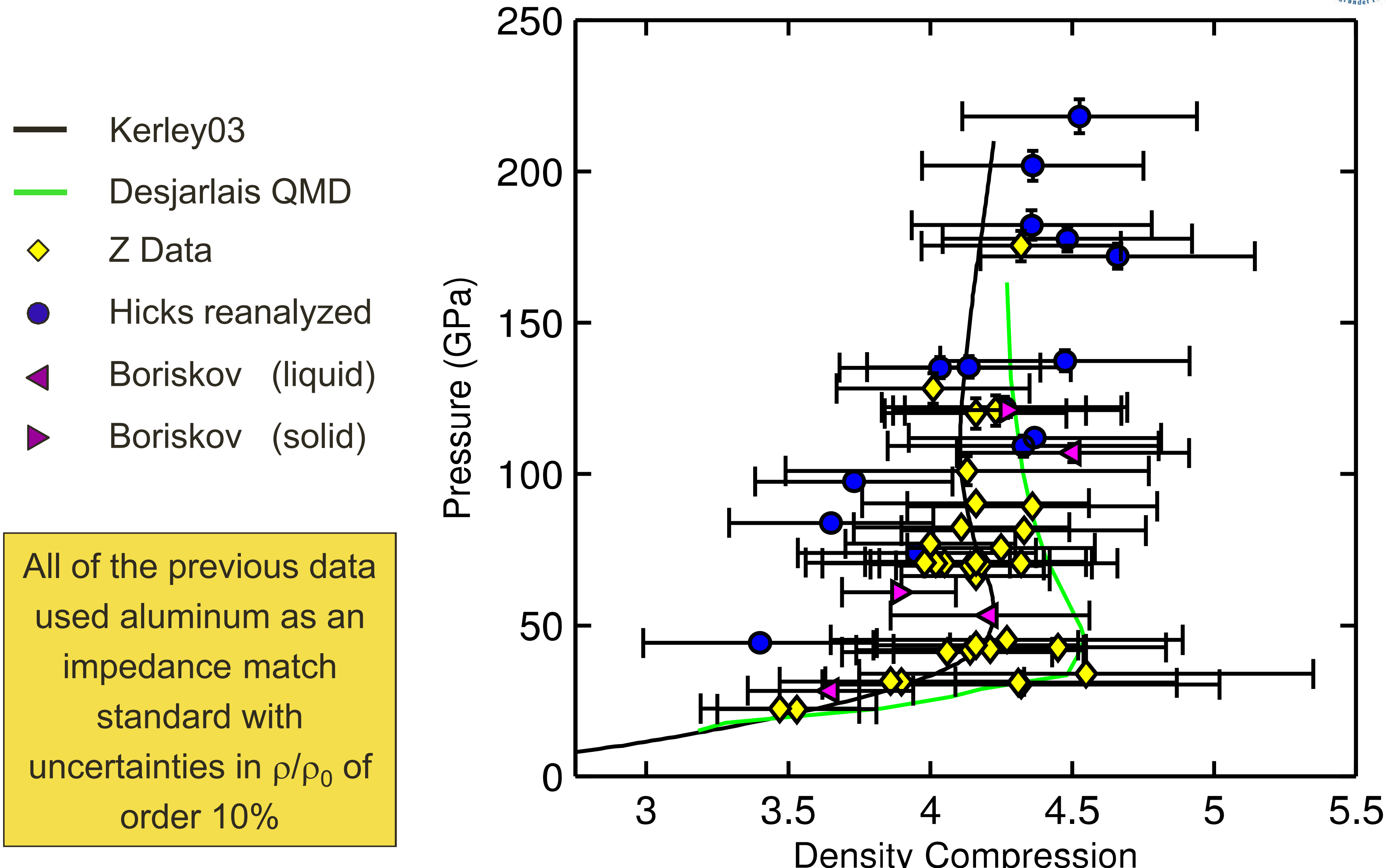
Magnetic pressure can also be used to launch flyer plates to high velocity





Lemke et al., J. Appl. Phys. 98, 073530 (2005)

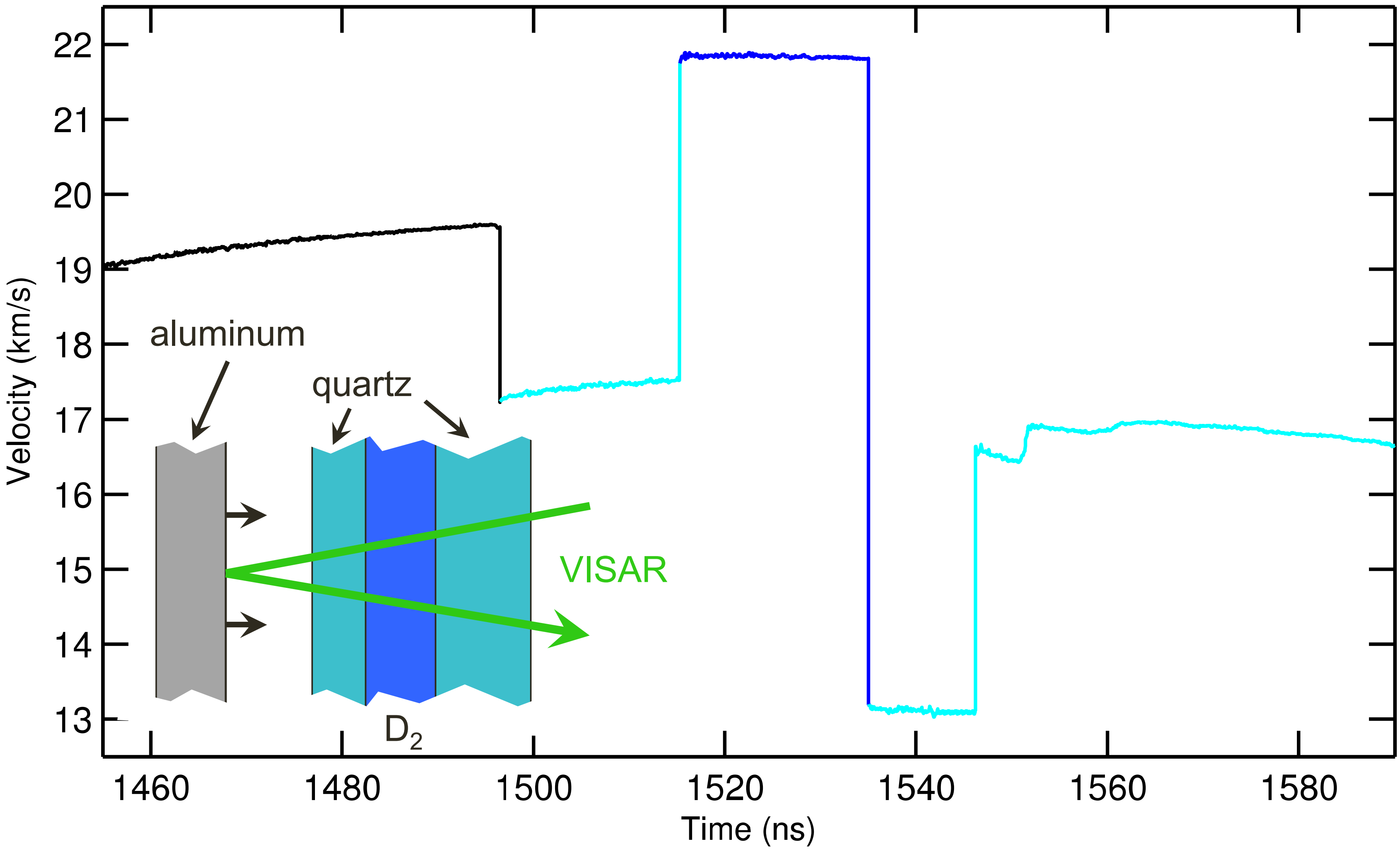
Previous Hugoniot data for deuterium has relatively large uncertainty and scatter



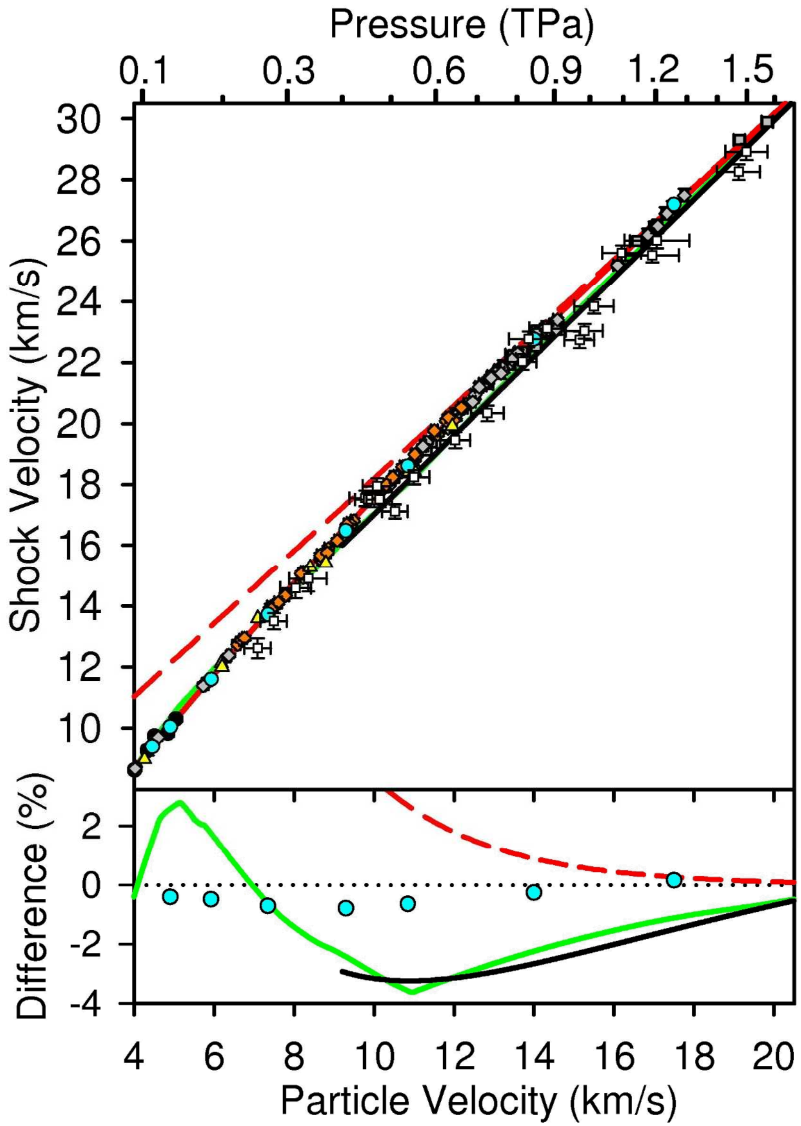
All of the previous data used aluminum as an impedance match standard with uncertainties in ρ/ρ_0 of order 10%

Boriskov et al., PRB 71, 092104 (2005) Knudson et al., PRB 69, 144209 (2004) Hicks et al., PRB 79, 014112 (2009)

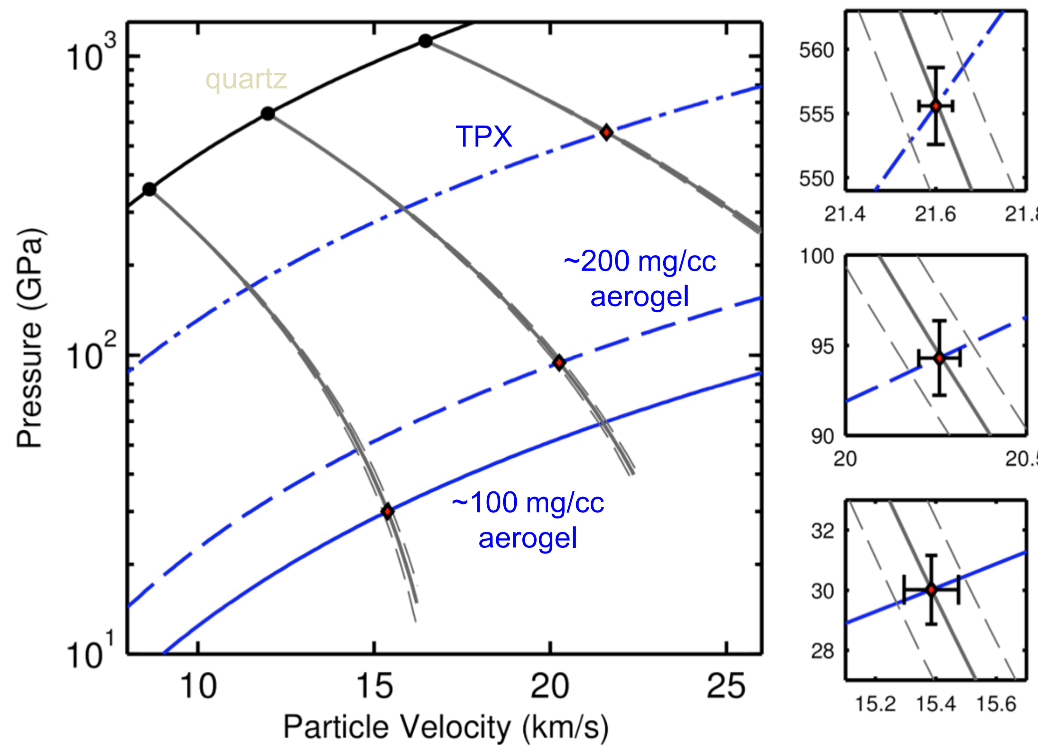
VISAR was used to obtain precise flyer plate and shock velocities in the D_2 and quartz



Quartz Hugoniot and release has been extensively studied in the multi-Mbar regime



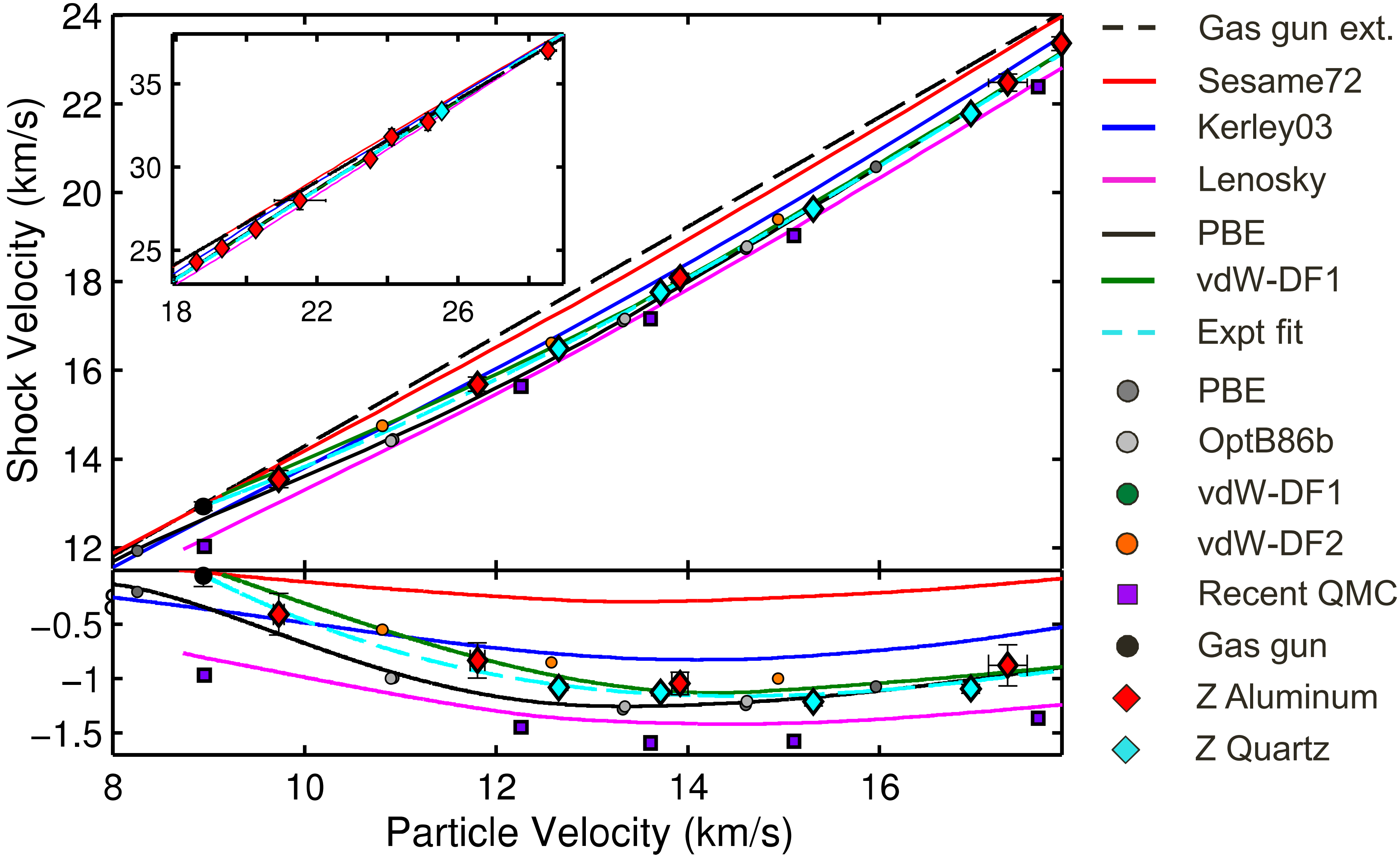
- Nearly 300 Hugoniot points for quartz have been obtained between 1 and 15 Mbar
- A release model was developed using release measurements obtained from TPX, and both ~200 mg/cc and ~100 mg/cc aerogel



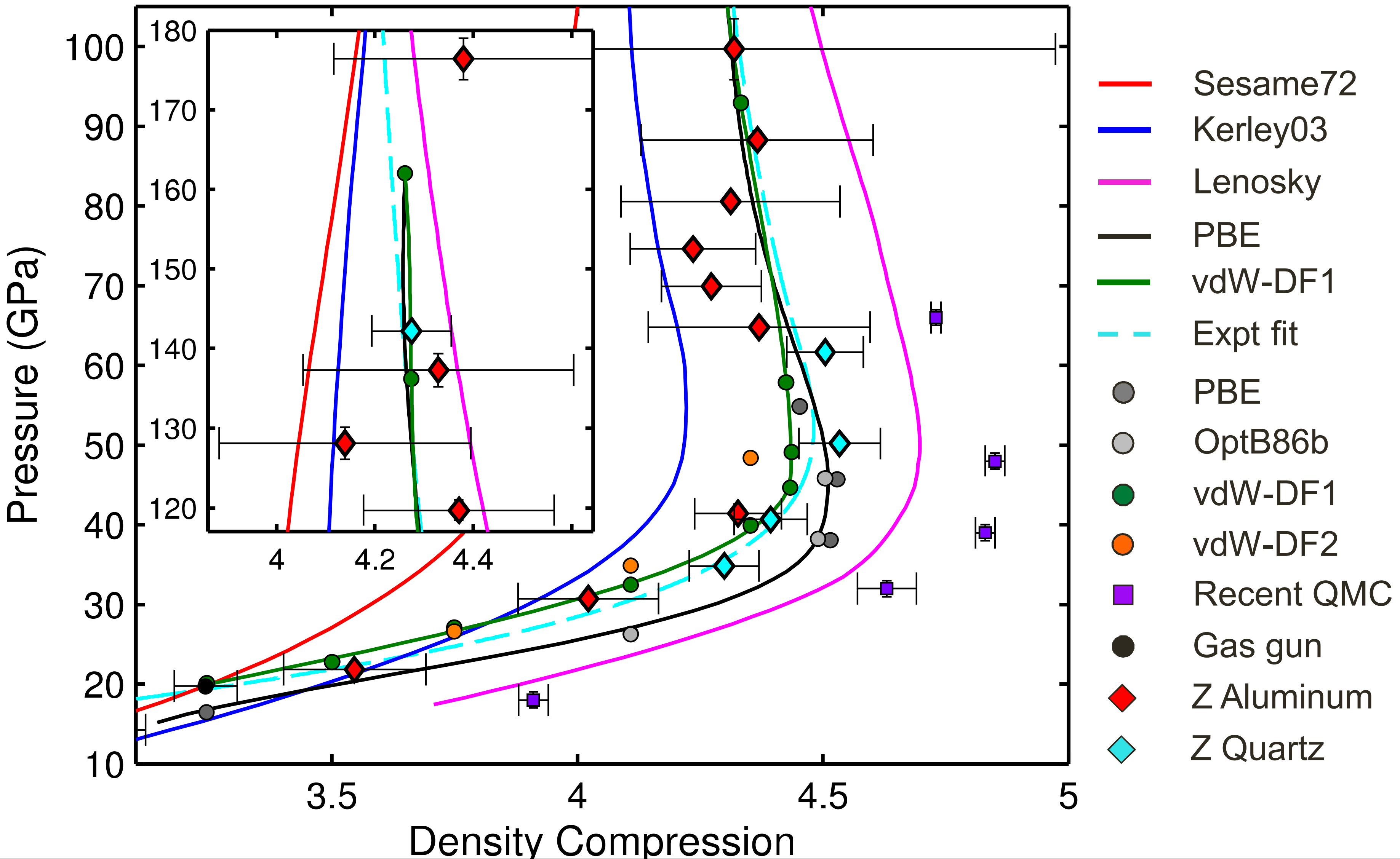
 Knudson and Desjarlais, PRL 103, 225501 (2009)

Knudson and Desjarlais, PRB 88, 184107 (2013)

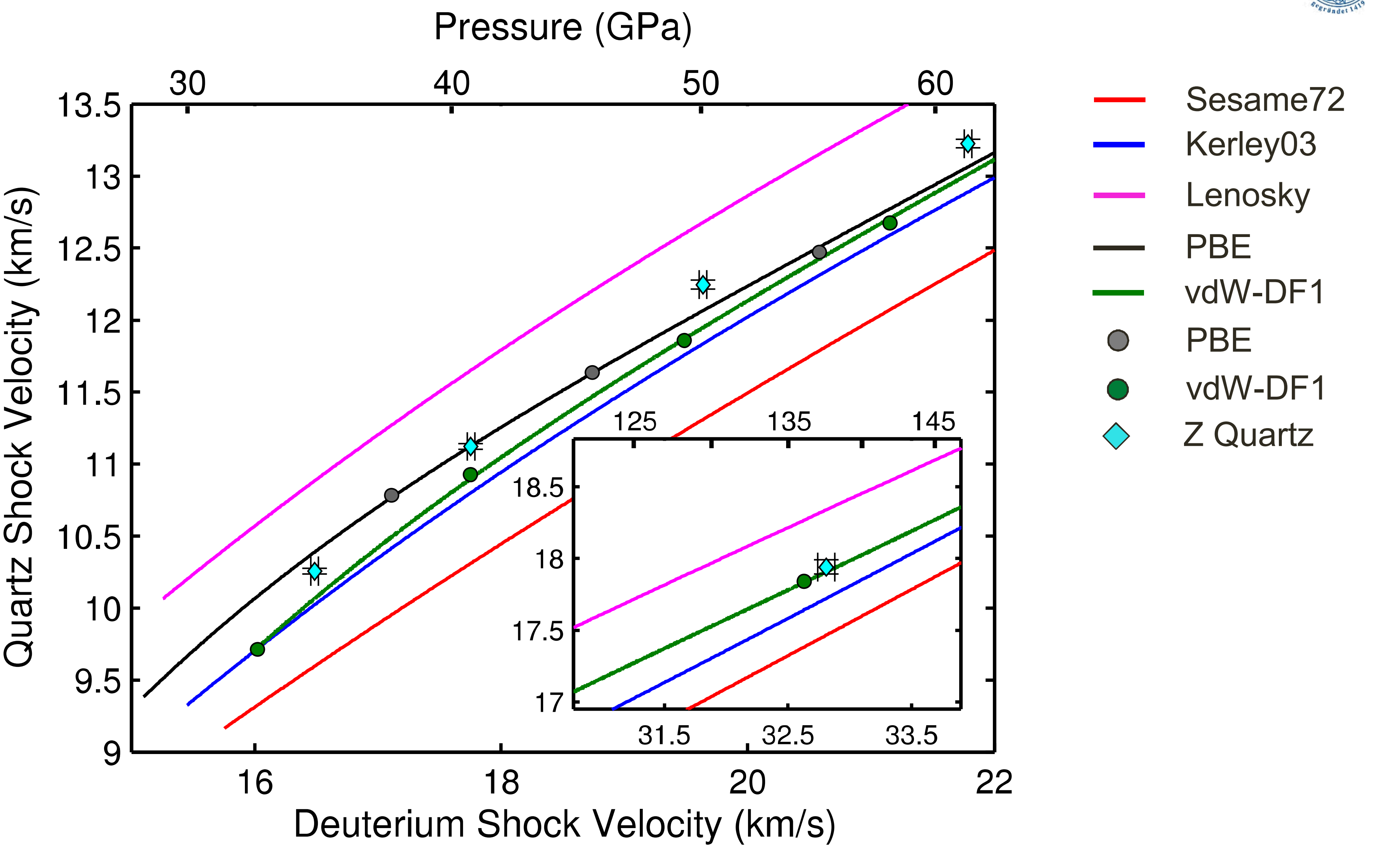
Recent results show significant improvement in precision with respect to previous data



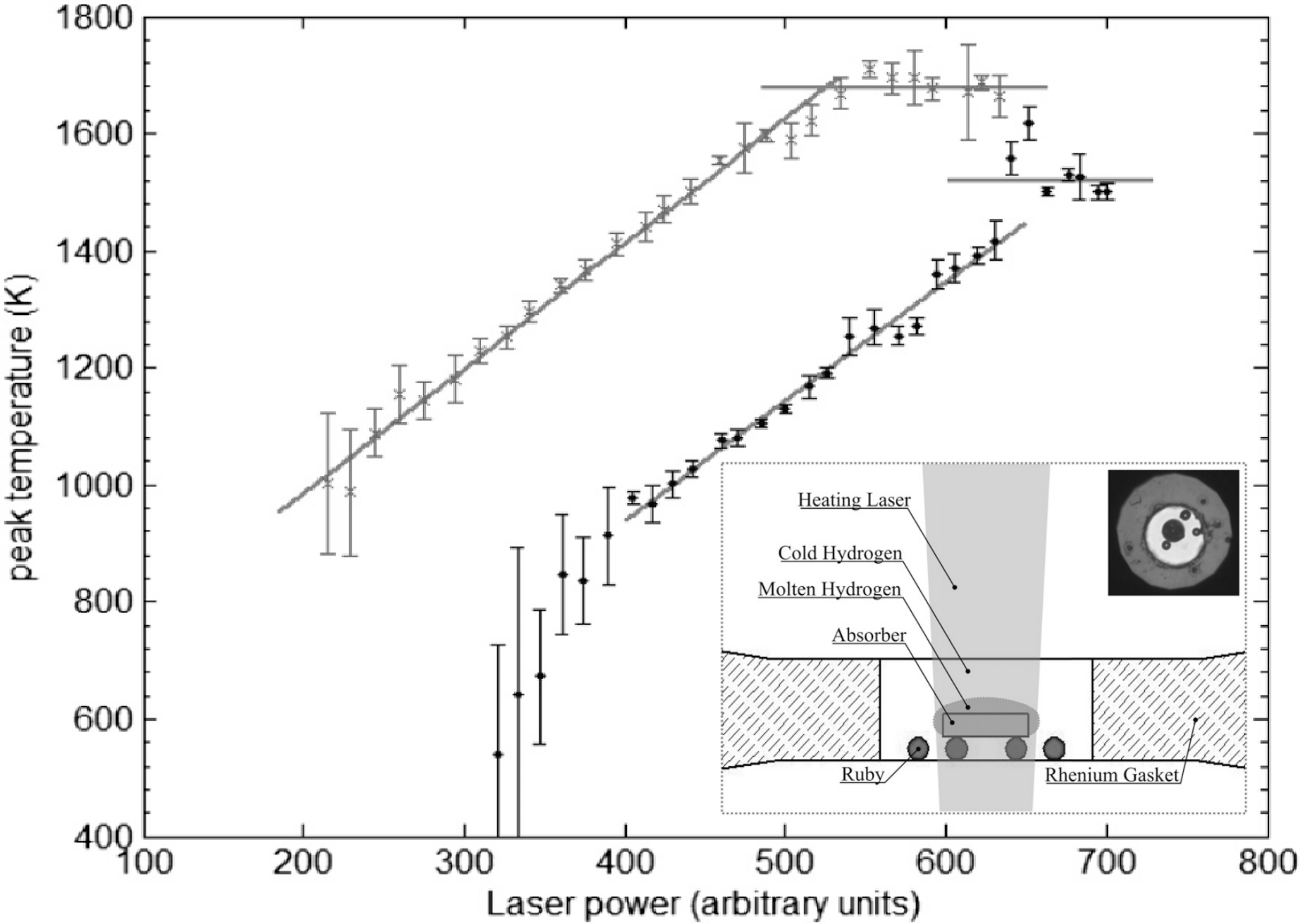
Recent results show significant improvement in precision with respect to previous data



Conclusions from Principal Hugoniot experiments are corroborated by reshock measurements

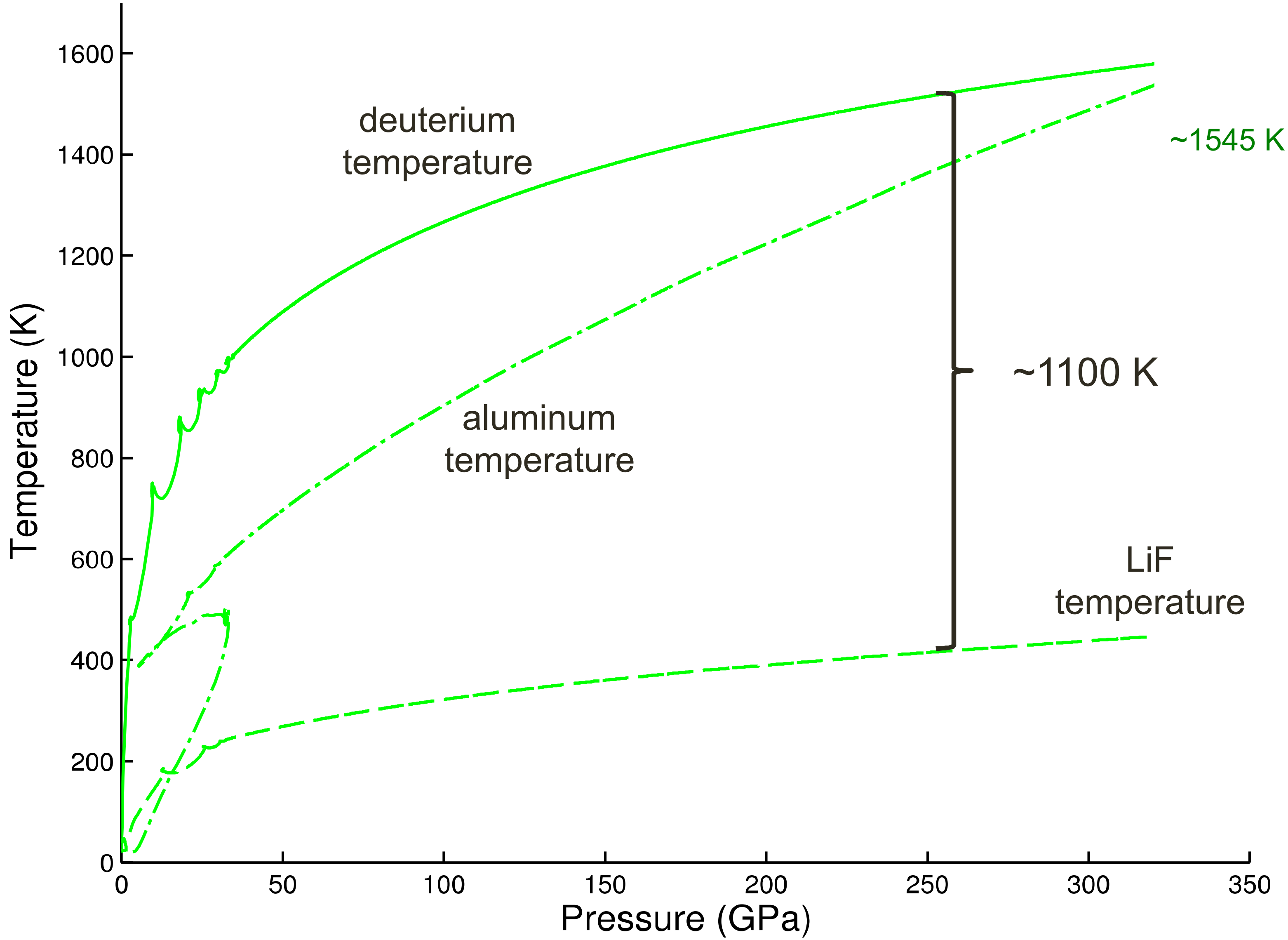


Dzyabura experiment

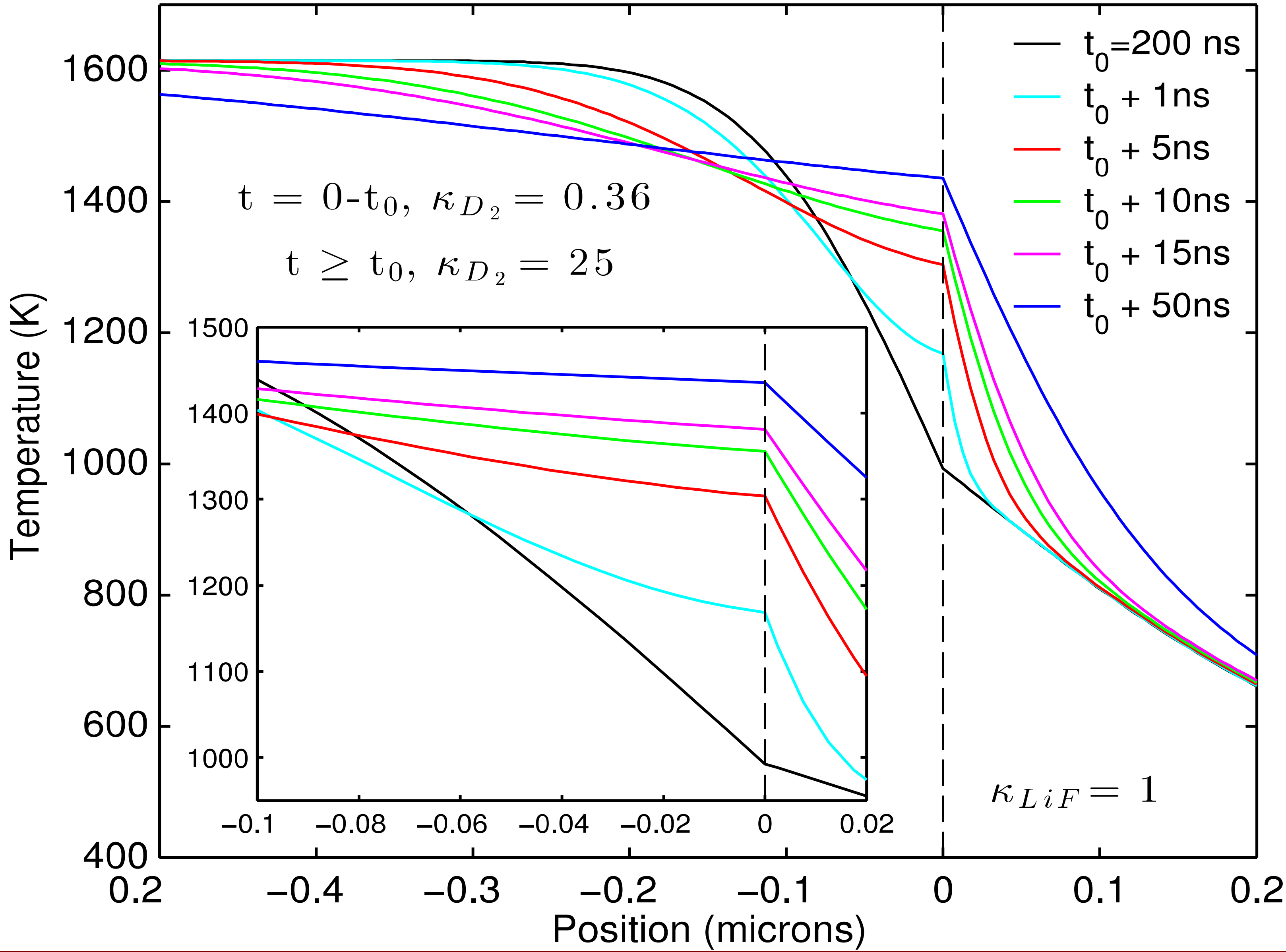


V. Dzyabura, et al. Proc. Natl. Acad. Sci. U.S.A. 110, 8040 (2013)

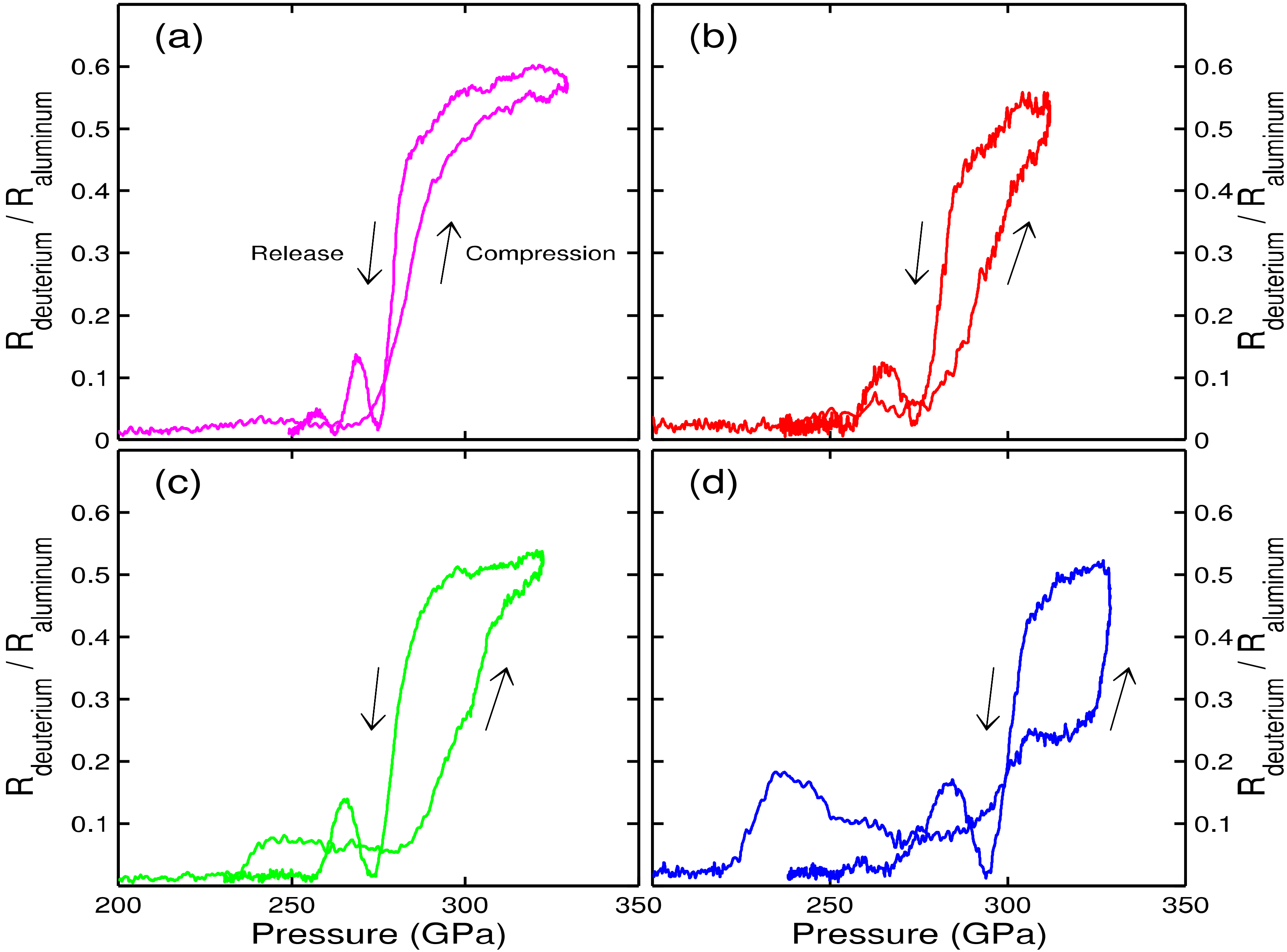
There is a significant temperature difference at the deuterium/LiF interface



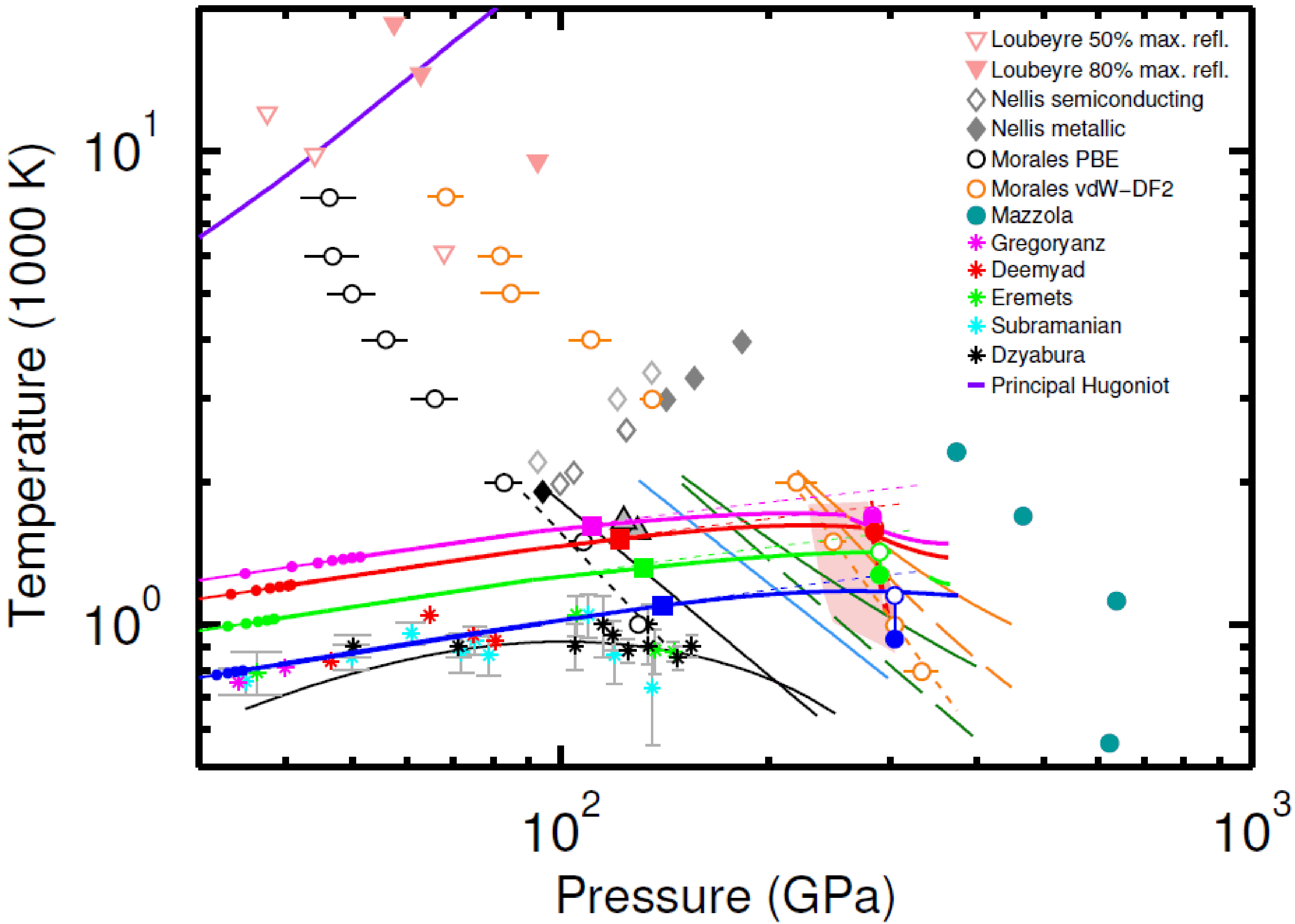
Thermal conduction simulations



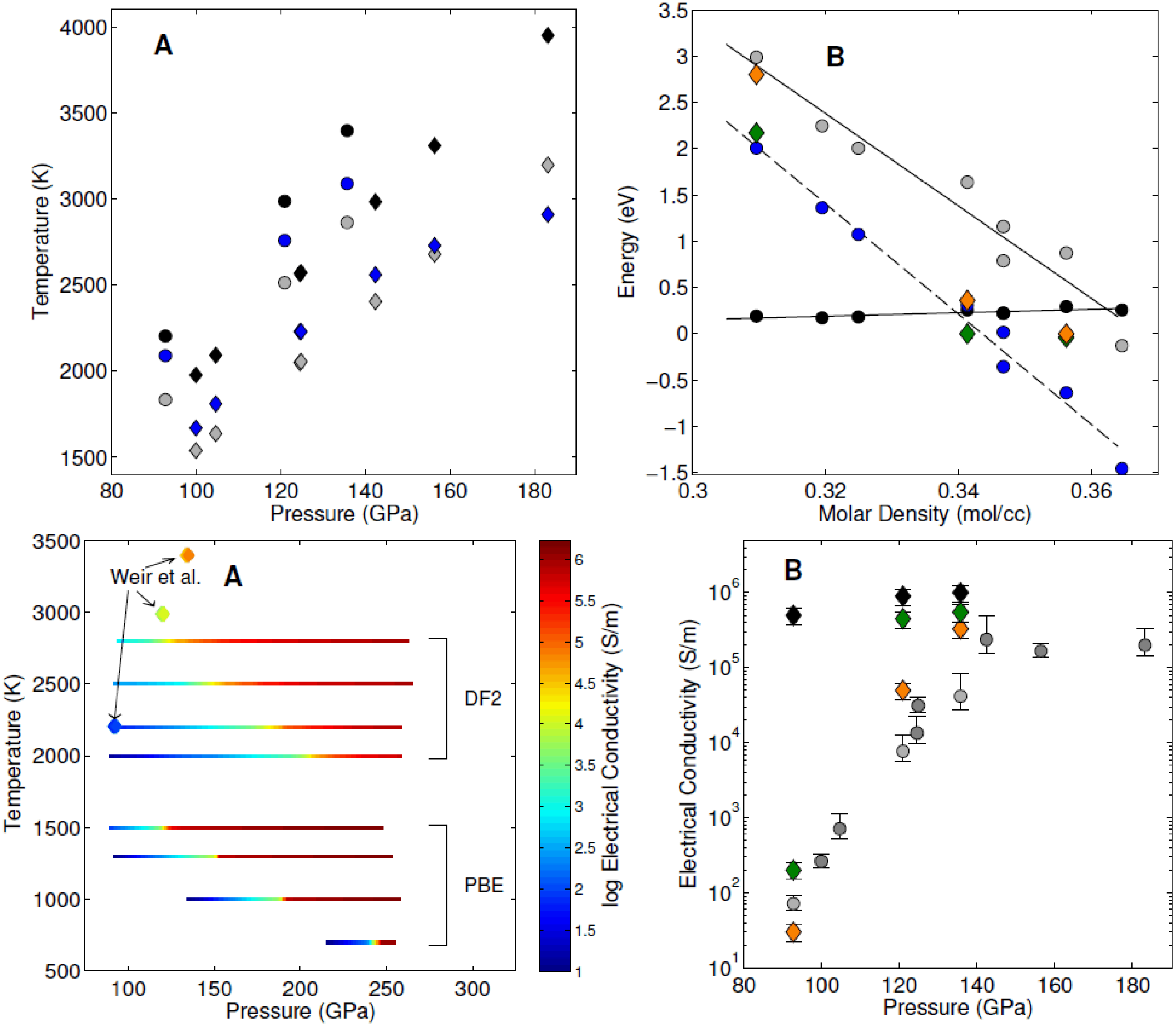
Reflectivity signals mapped to pressure



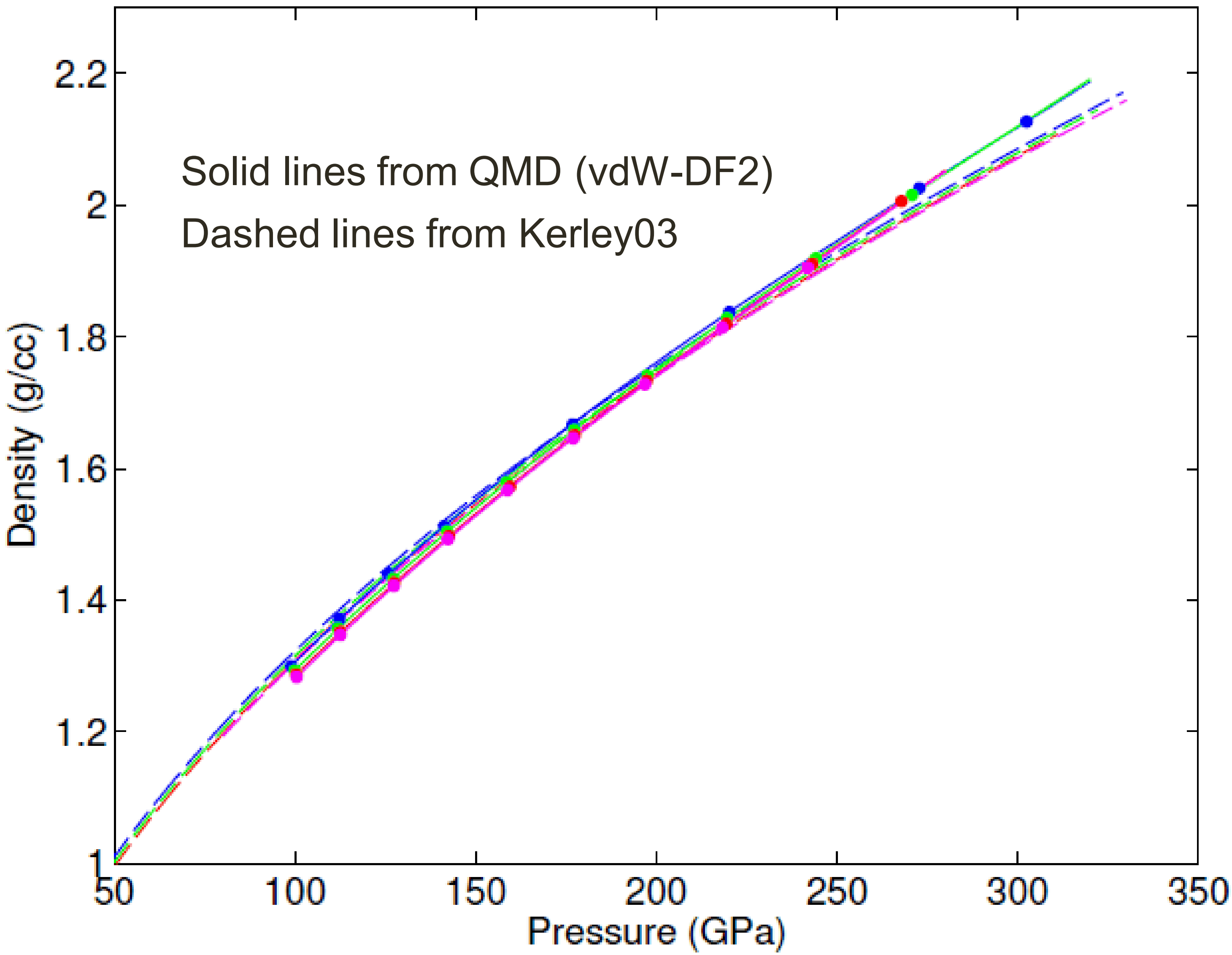
Extended P-T diagram for hydrogen



Reanalysis of Weir et al data

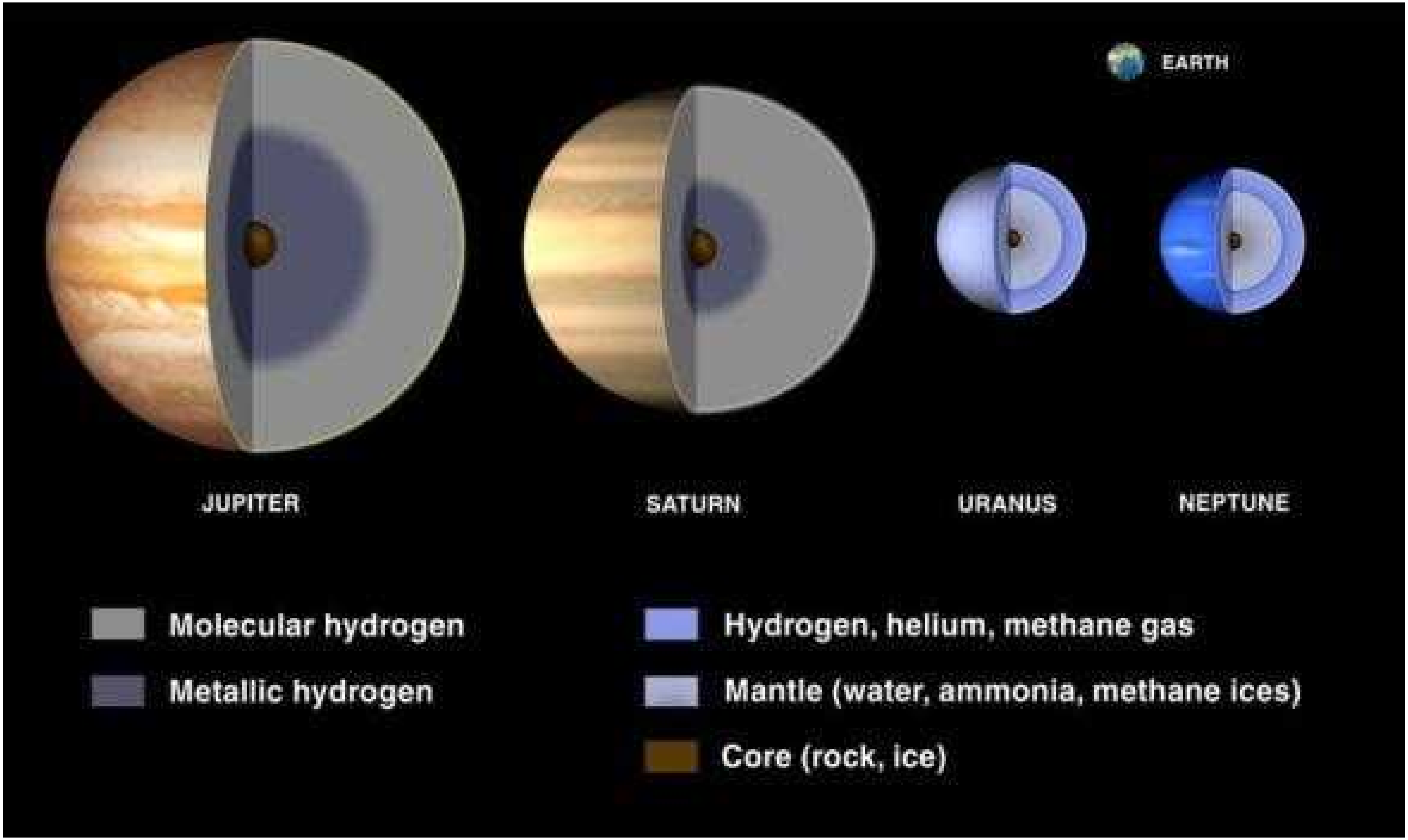


P(ρ) relatively insensitive to EOS model

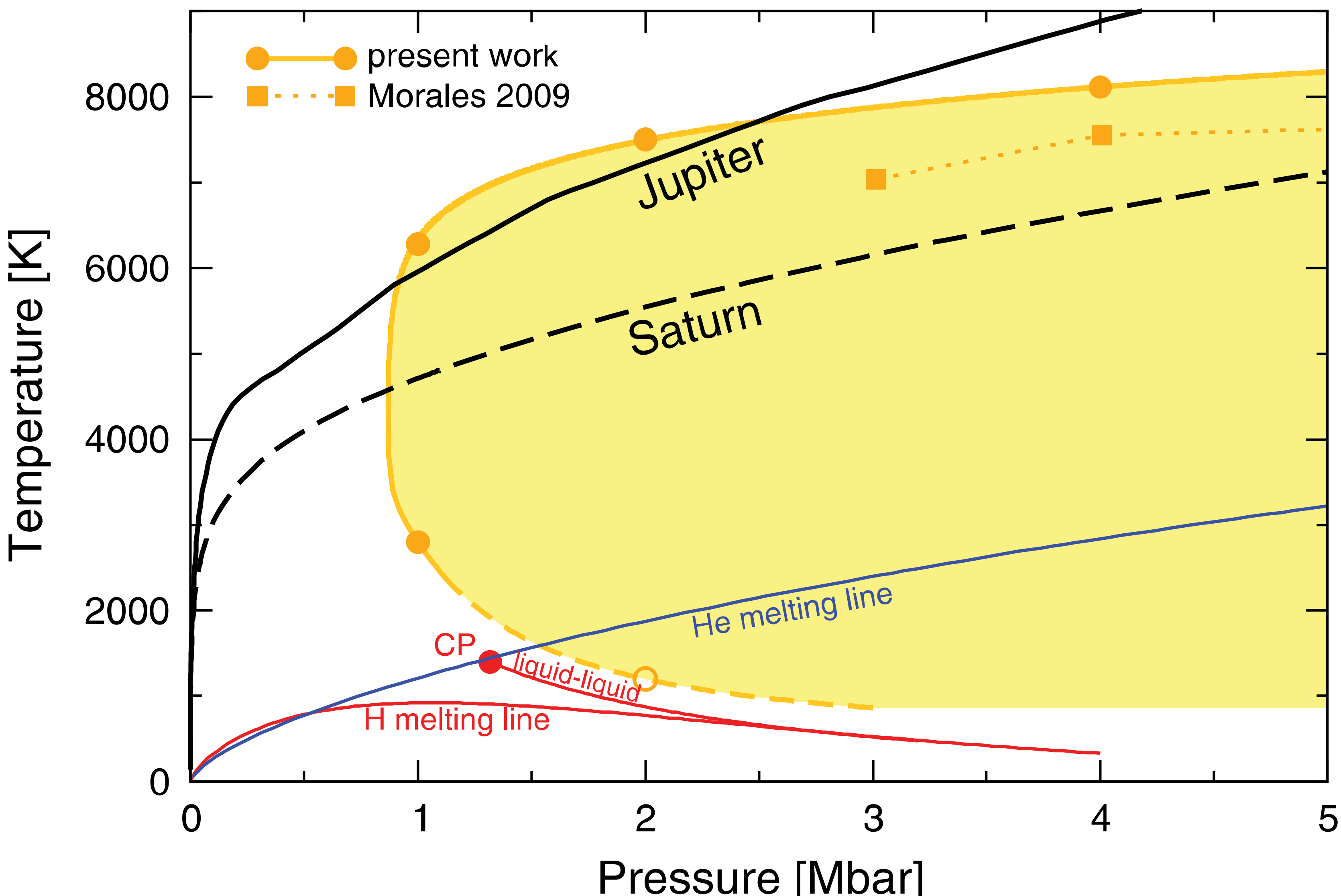


Giant planets in the Solar system

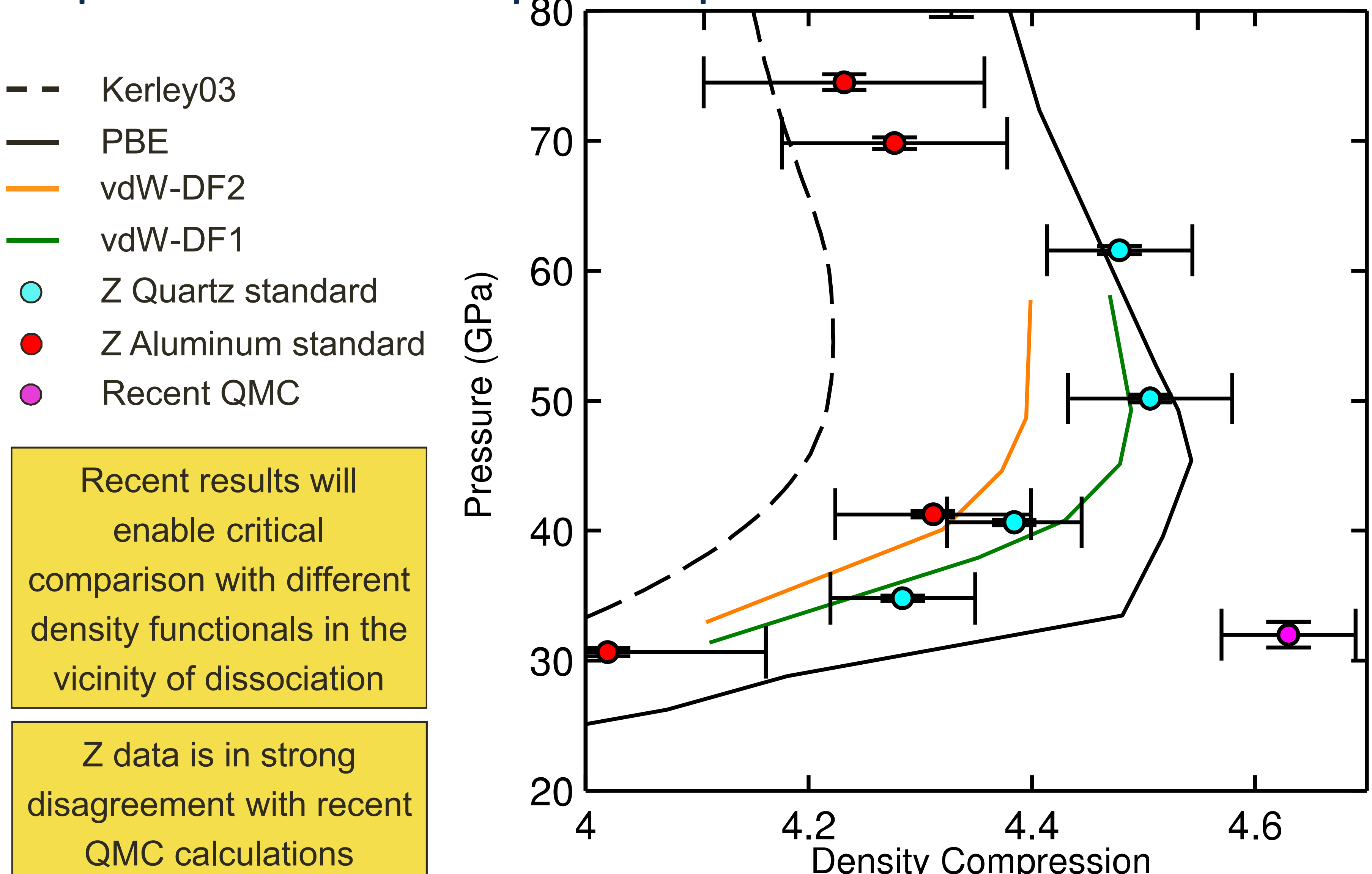
Interior composed of the lightest elements H & He, hydrides NH_3, OH_2, CH_4 (ices) and small amounts of heavier elements (cores)



H-He de-mixing appears to be precipitated at low T and P by metallization in hydrogen



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



Recent results will enable critical comparison with different density functionals in the vicinity of dissociation

Z data is in strong disagreement with recent QMC calculations

Tubman et al., PRL 115, 045301 (2015) Knudson et al., PRB 69, 144209 (2004) Desjarlais, PRB 68, 064204 (2003)