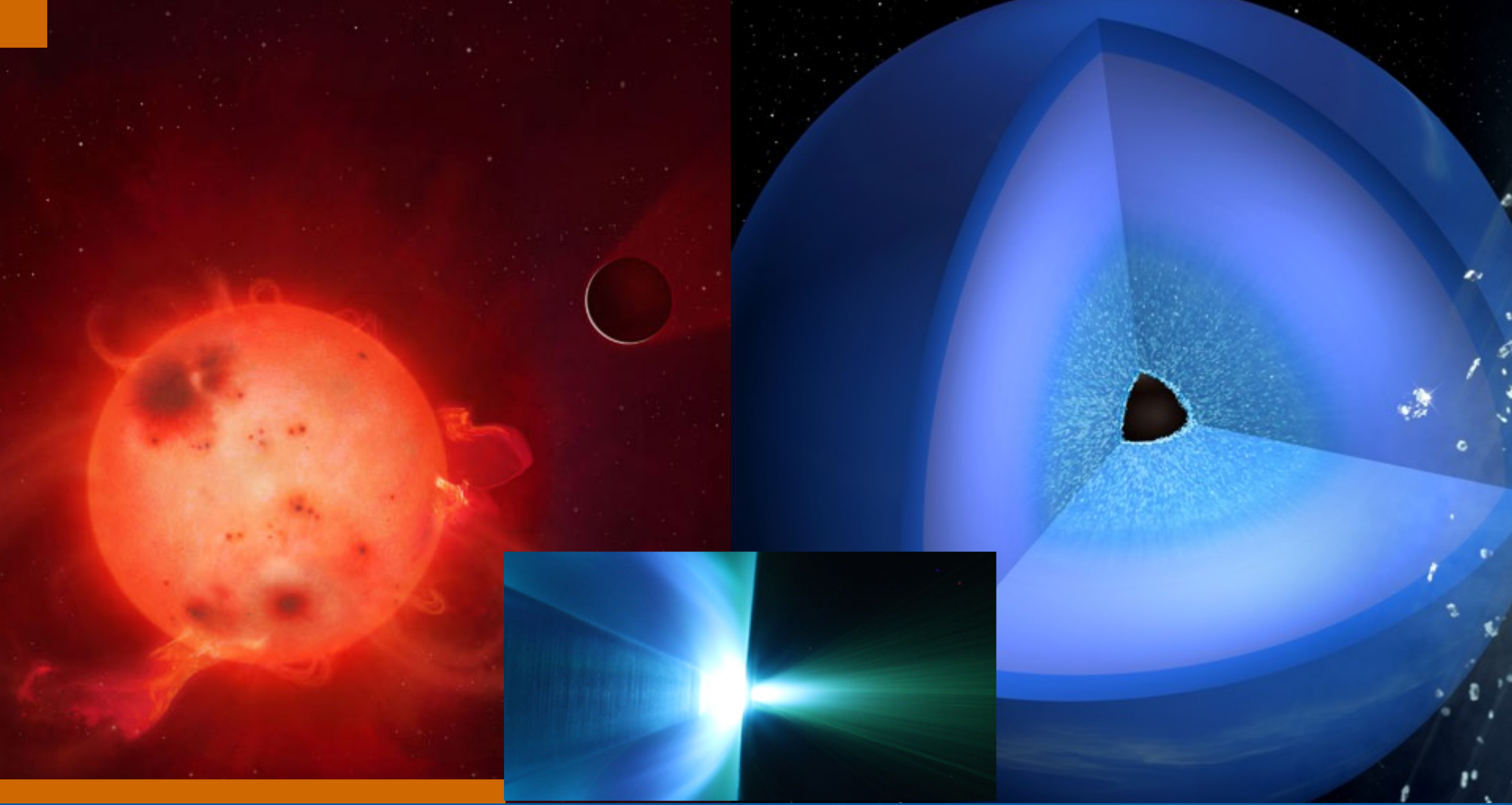


Warm Dense Matter: From Giant Planets and Stars to Nanoparticles

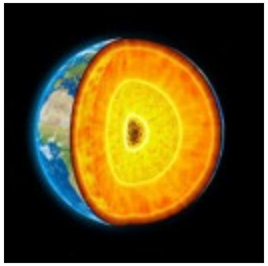
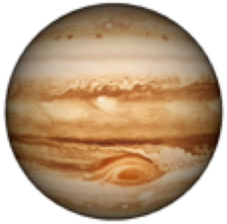
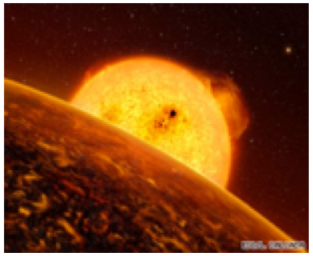
Dominik Kraus

Warm Dense Matter

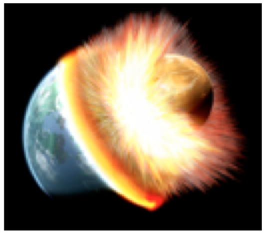
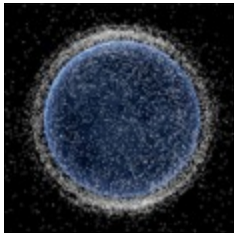
transition regime
solid state $\Longleftrightarrow$ hot dense plasma

properties:
- 0.1 – 10 times solid state density
- temperature: ~5000 K up to ~10^6 K
- pressure: ~1 GPa up to ~10 TPa
- partially ionized
- partially degenerate $n_e \lambda_{th}^3 \approx 1$
- strongly coupled ions
- $k_B T \sim \frac{e^2}{4\pi\varepsilon_0}\frac{1}{\langle d \rangle} \sim E_F \sim E_{bond} \sim$ eV

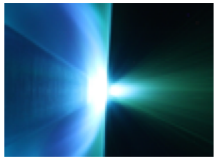
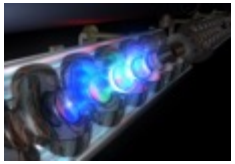
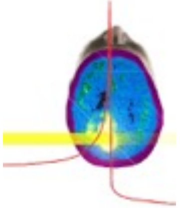
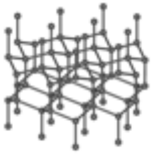
Planets / Brown Dwarfs / Stars

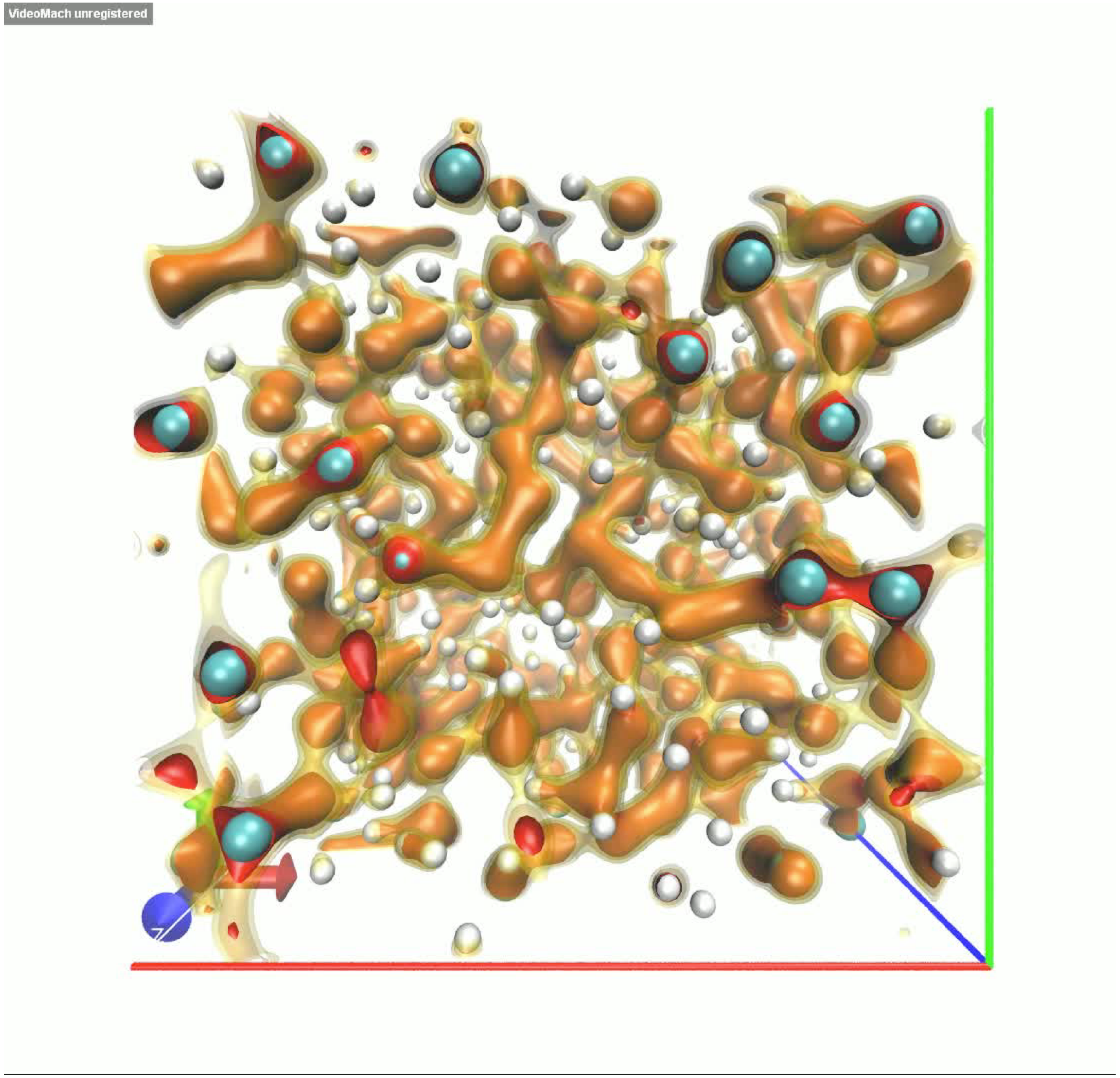
Impacts

Technology applications

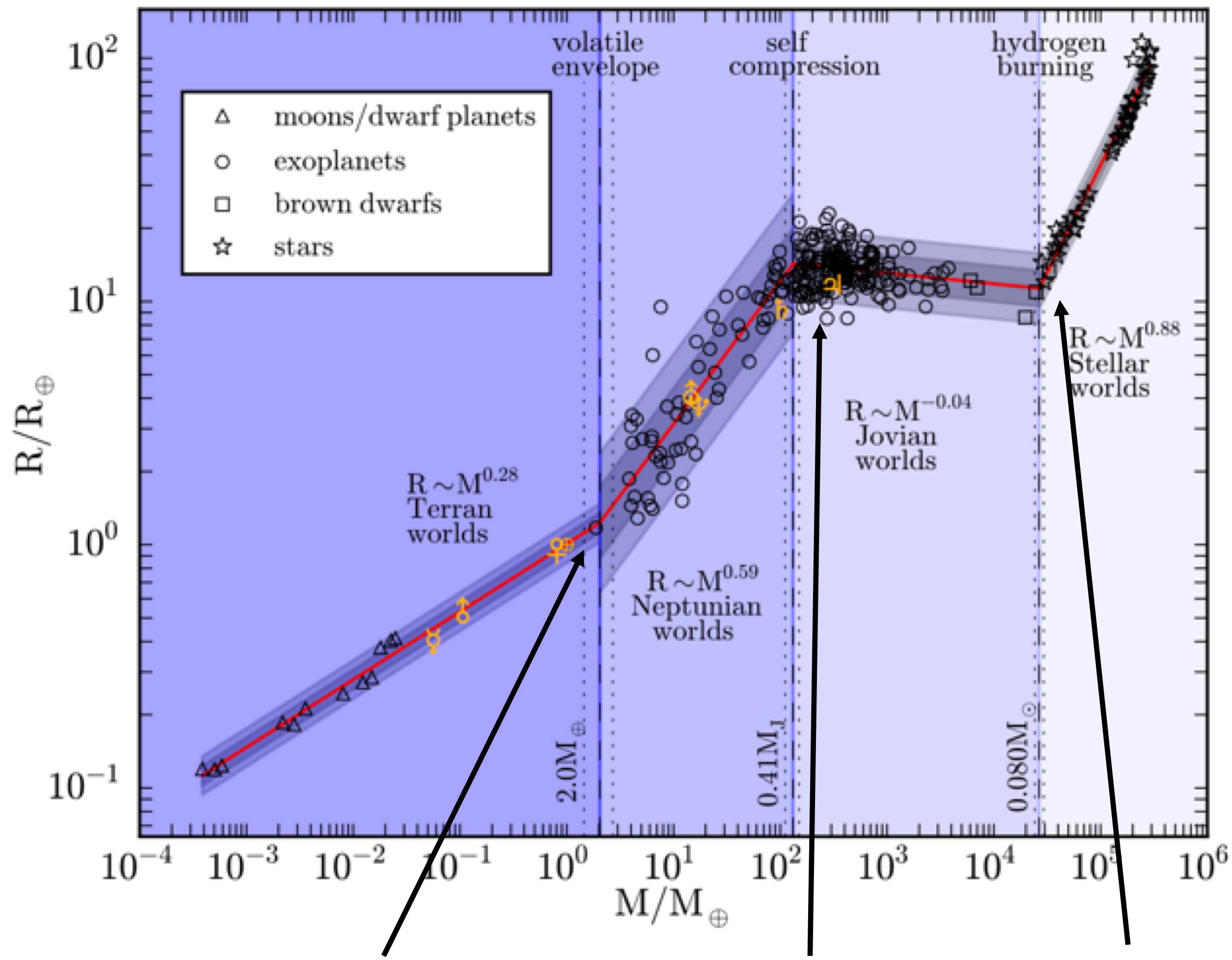





Warm Dense Matter



J. Vorberger

Mass-radius relation: planets and stars



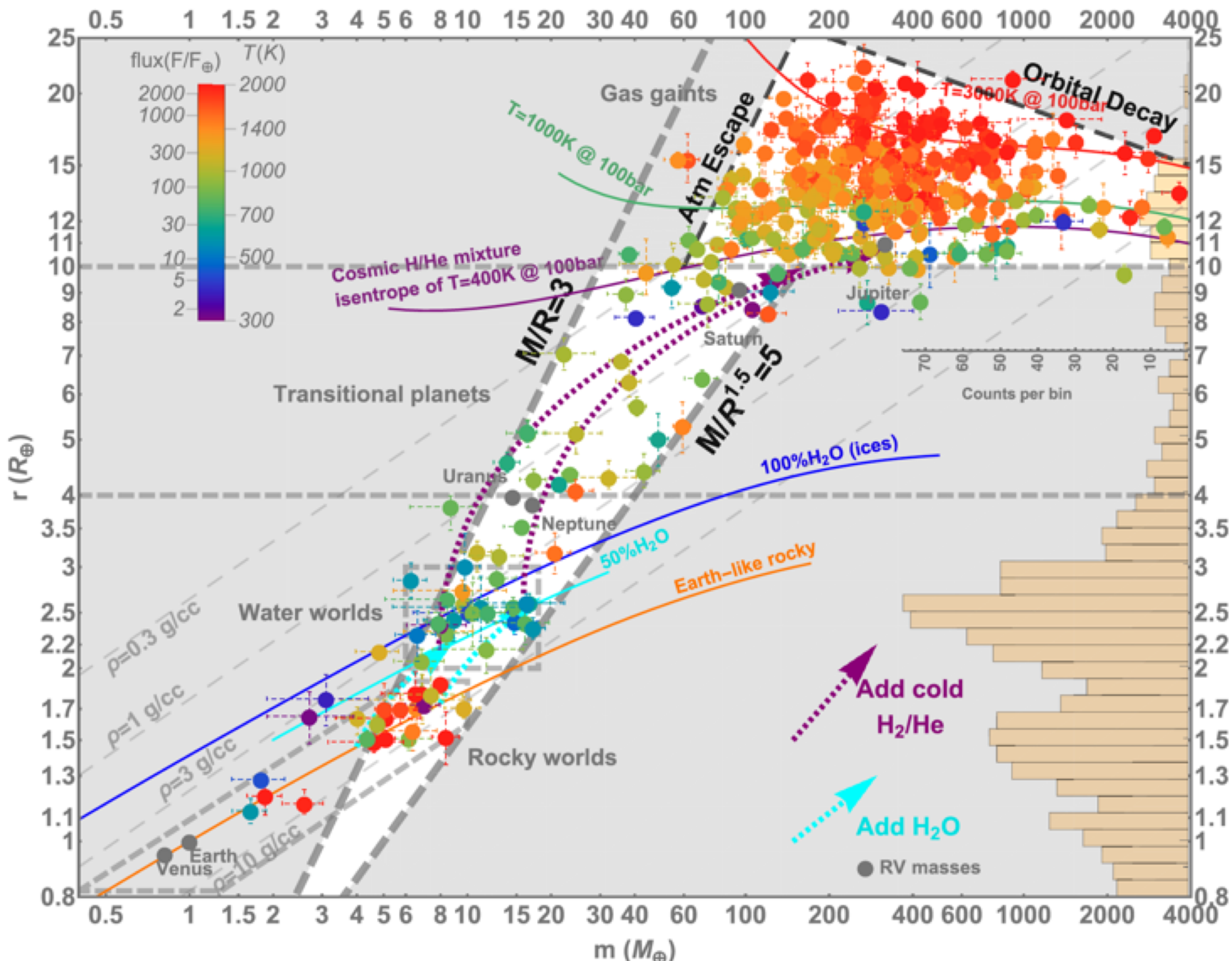
few 100 GPa
few 1000 K

few TPa
few 10,000 K

few PPa
few 1,000,000 K

J. Chen and D. Kipping, ApJ 834, 17 (2017)

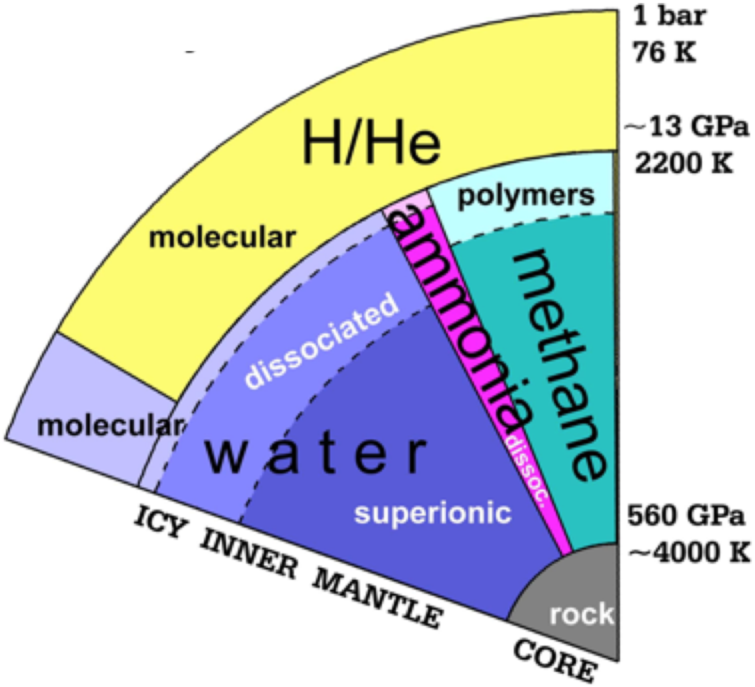
Large abundance of "icy planets"



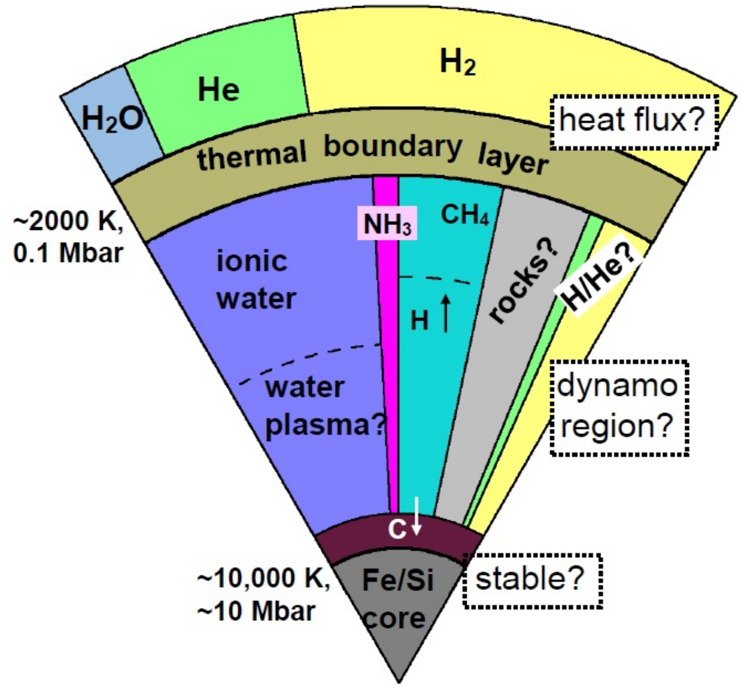
L. Zeng et al., PNAS 116, 9723-9728 (2019)

Models of the icy giant planets

100 GPa = 1 Mbar



M. Bethkenhagen et al., Astrophys. J. 848, 67 (2017)



N. Nettelmann et al., Icarus 275, 107–116 (2016)

The ice layer in Uranus and Neptune—diamonds in the sky?

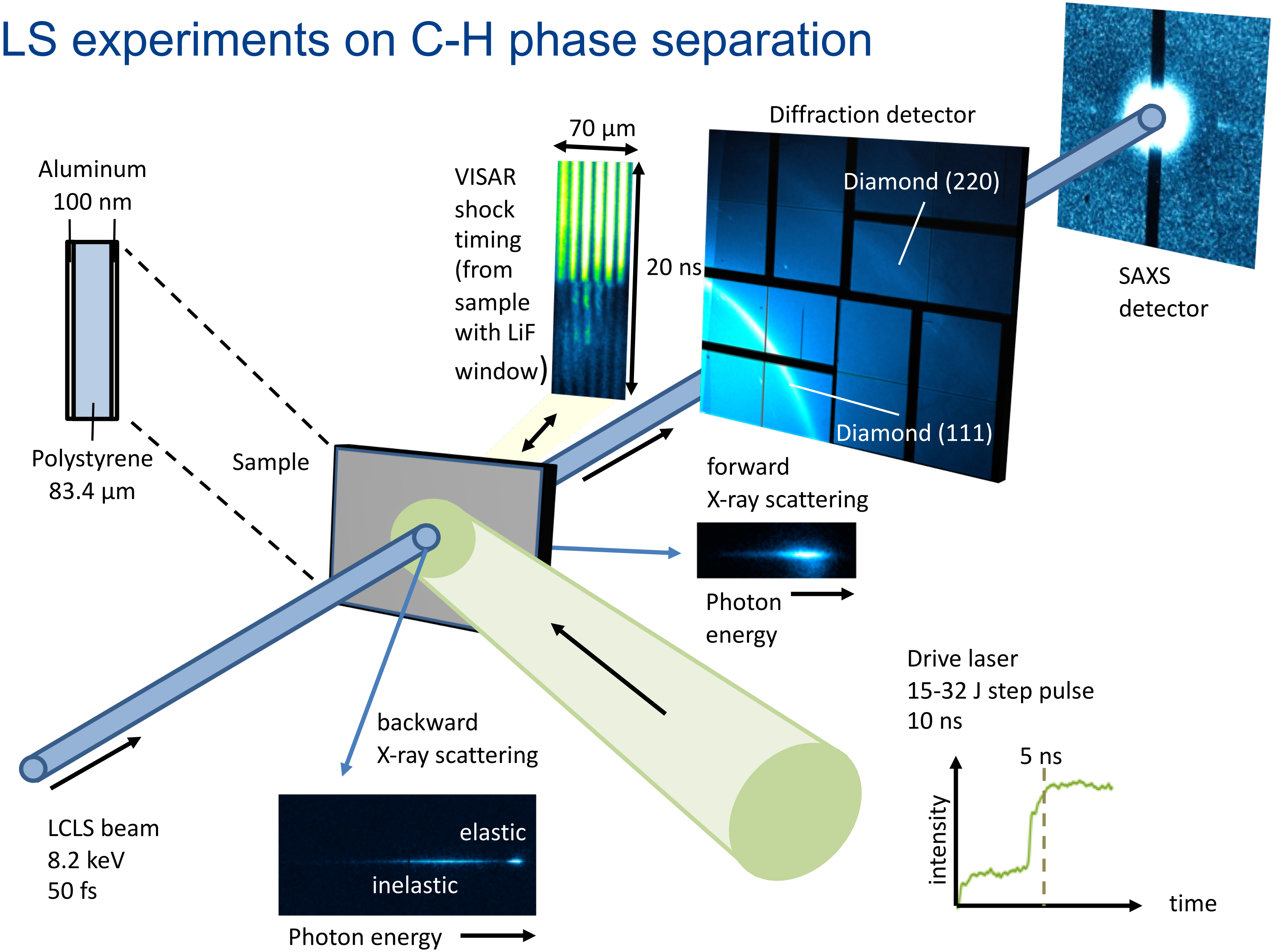
MARVIN ROSS

University of California, Lawrence Livermore National Laboratory, Livermore, California 94550, USA

letters to nature

Nature **292**, 435 - 436 (30 July 1981); doi:10.1038/292435a0

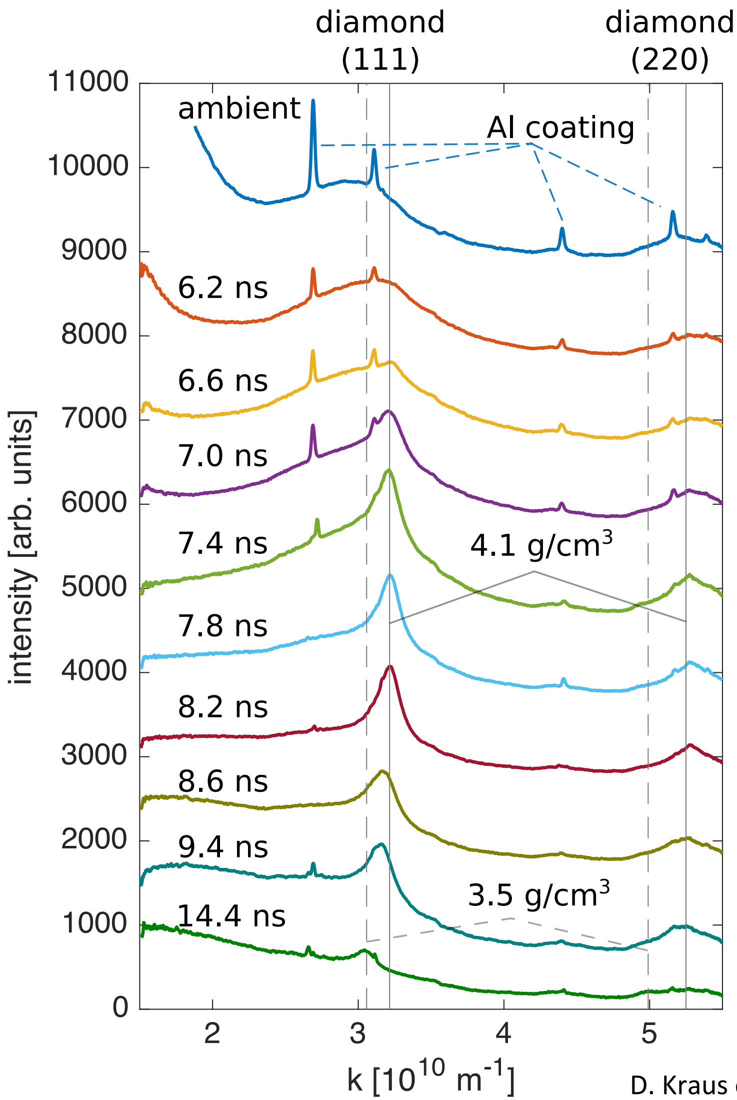
LCLS experiments on C-H phase separation



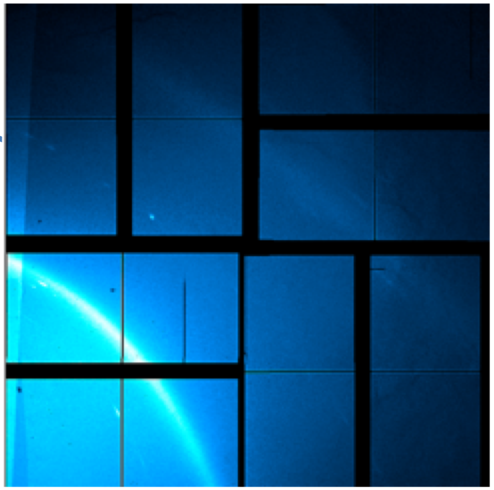
D. Kraus et al., Nature Astronomy 1, 606-611 (2017)
N. J. Hartley et al., Phys. Rev. Lett. 245501 (2018)
D. Kraus et al., Phys. Plasmas 25, 056313 (2018)
N. J. Hartley et al., Scientific Reports 18, 18044 (2019)

Dominik Kraus | Institute of Radiation Physics | www.hzdr.de

LCLS experiment on CH phase separation



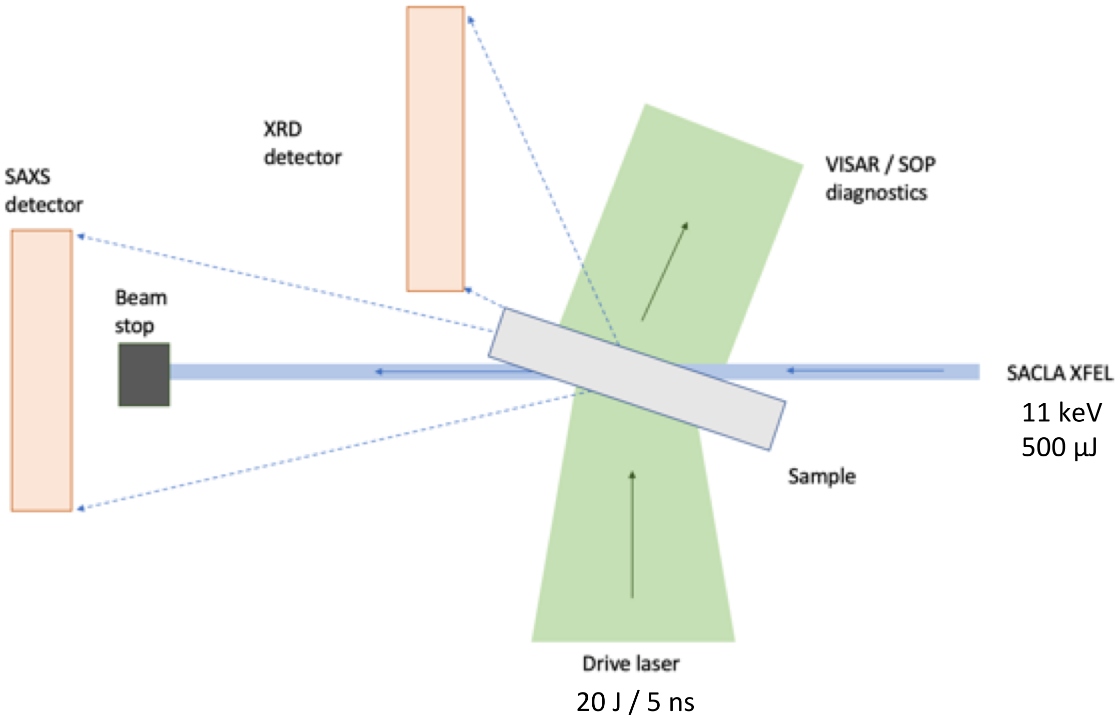
ambient



driven

D. Kraus et al., Nature Astronomy 1, 606-611 (2017)
D. Kraus et al., Phys. Plasmas 25, 056313 (2018)

Different types of plastics at SACLA



SAXS

unpublished data

Polystyrene

unpublished data

PET

unpublished data

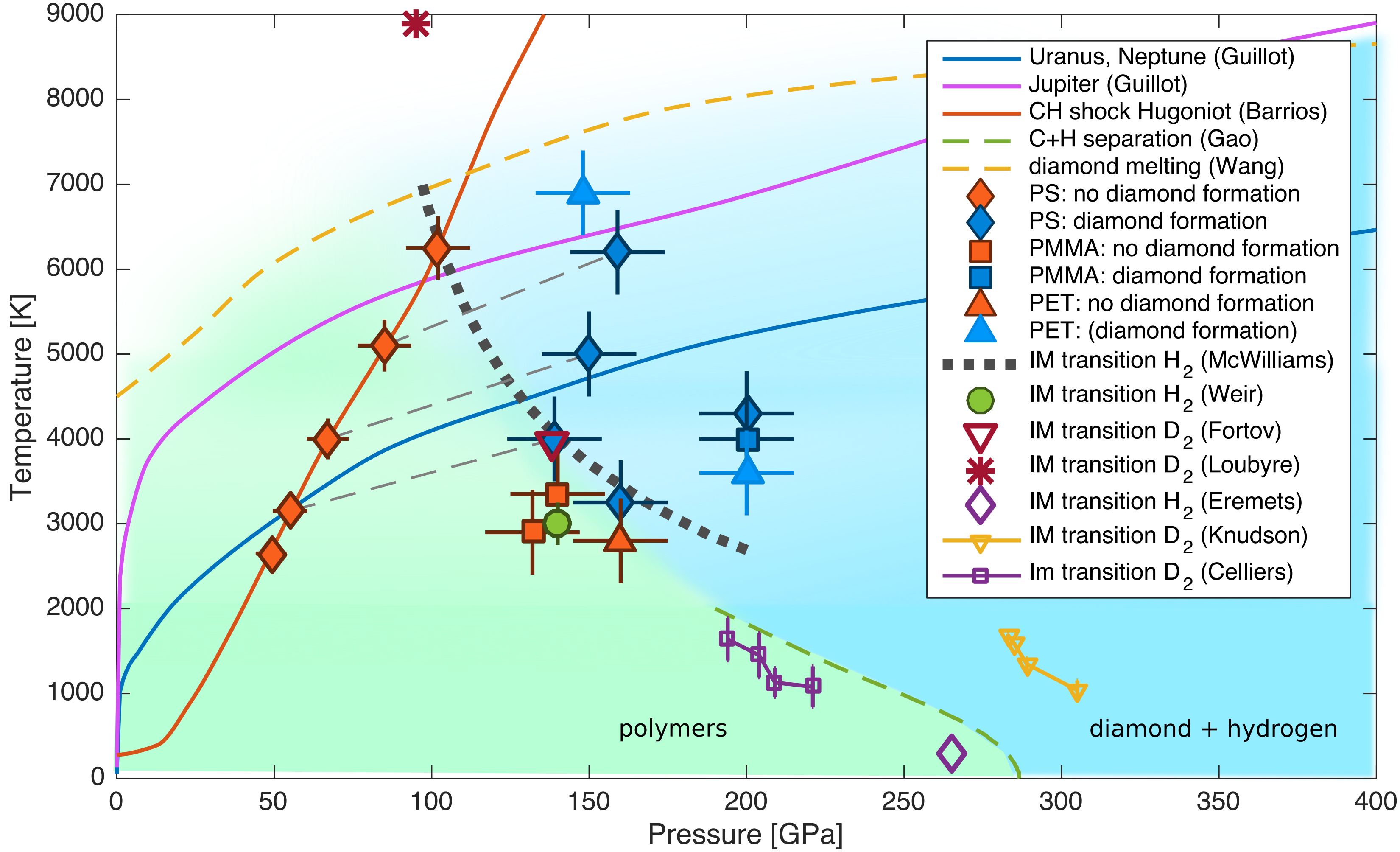
PMMA

unpublished data

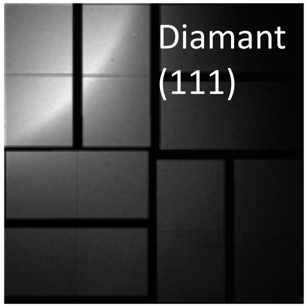
Polyethylene

unpublished data

Carbon-hydrogen demixing and hydrogen metallization

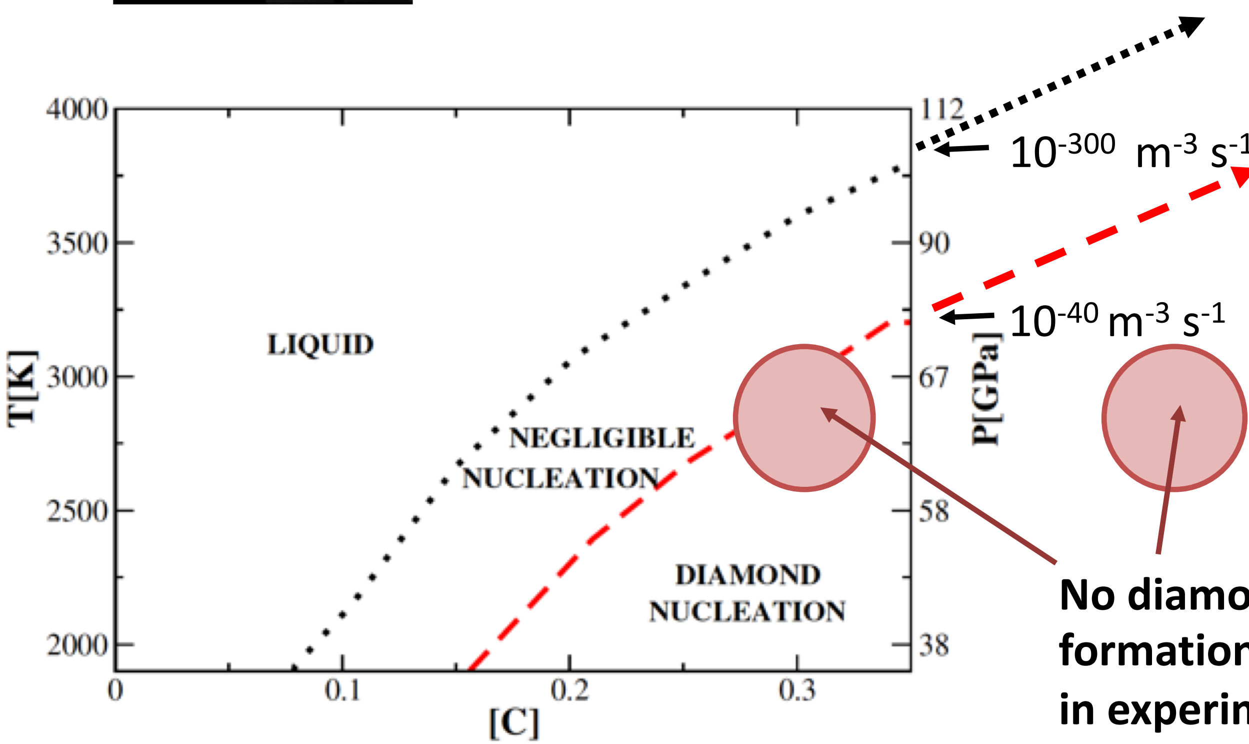


Diamond nucleation rates



PMMA $C_5H_8O_2$

measurements:
~10^{32} m^{-3} s^{-1}

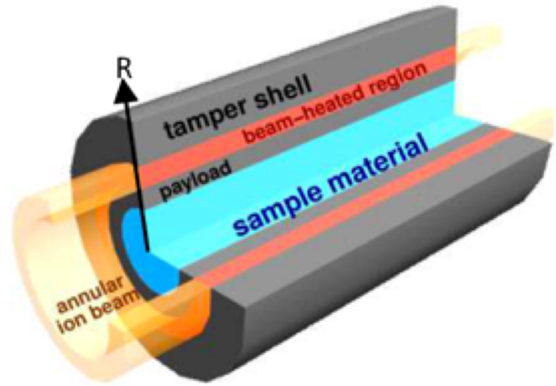


No diamond formation observed in experiment

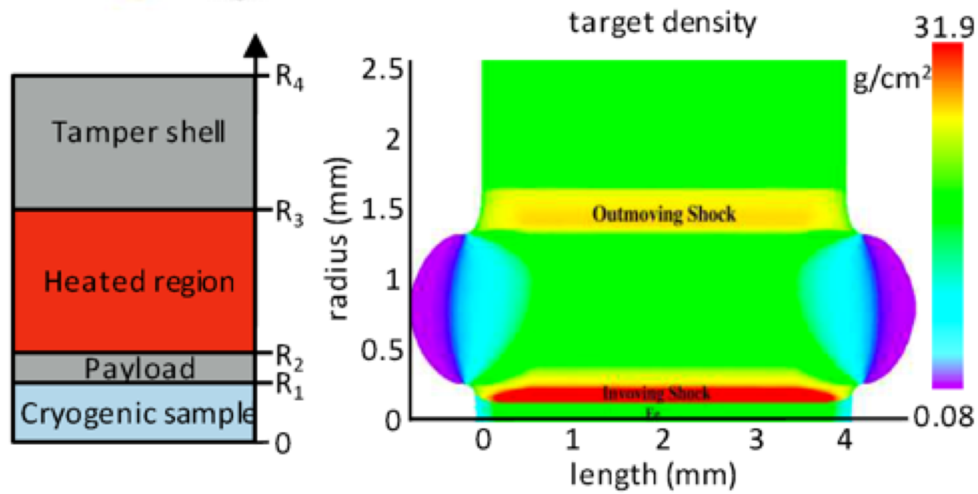
L. Ghiringhelli et al, Phys. Rev. Lett. **99**, 055702 (2007)
A. K. Schuster et al., submitted

Future experiments at FAIR
10-100 times longer timescales + larger sample volumes

FAIR



LAPLAS



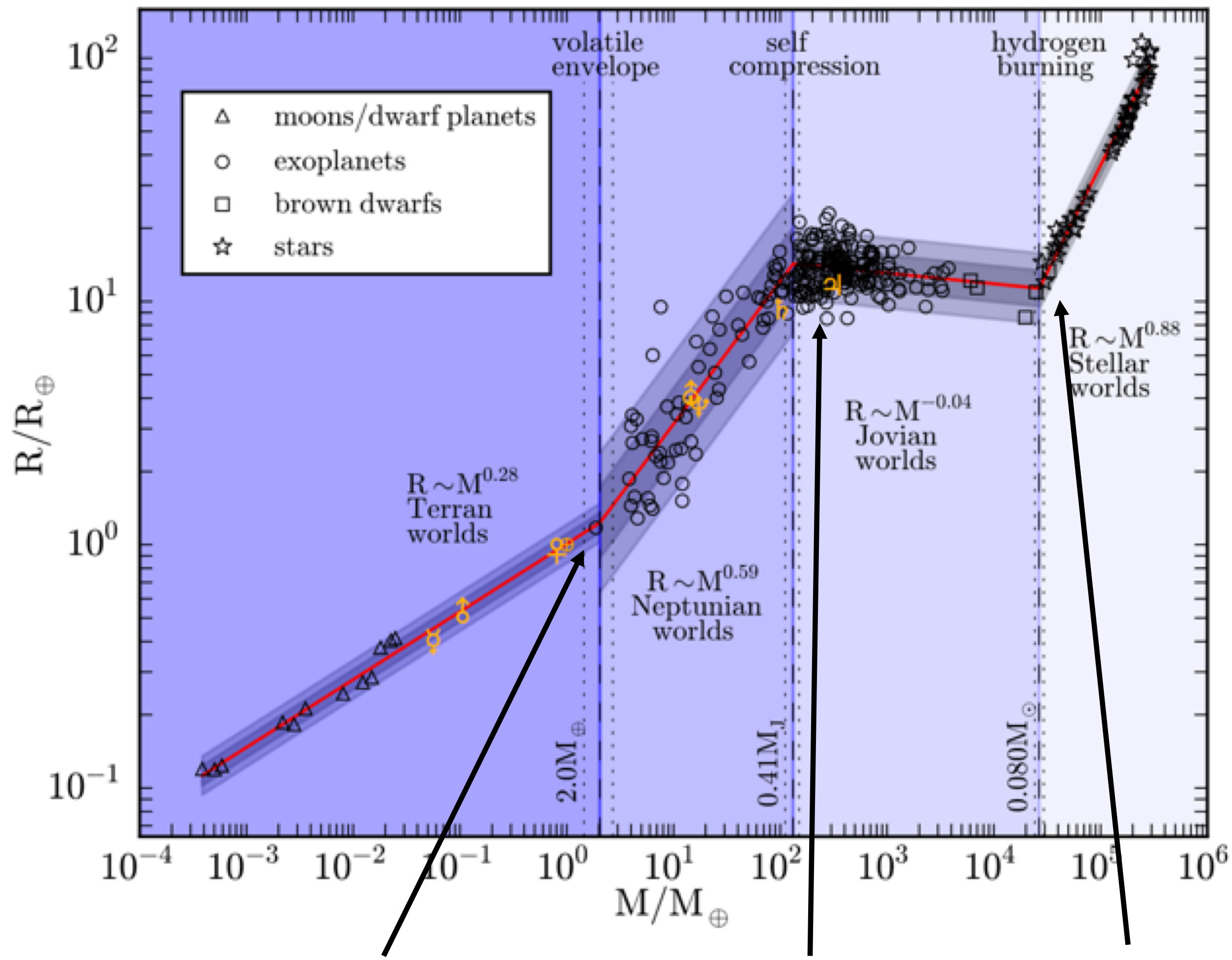
K. Schoenberg et al., submitted

Recovery of nanodiamonds

unpublished data

A. K. Schuster et al., in preparation

Mass-radius relation: planets and stars

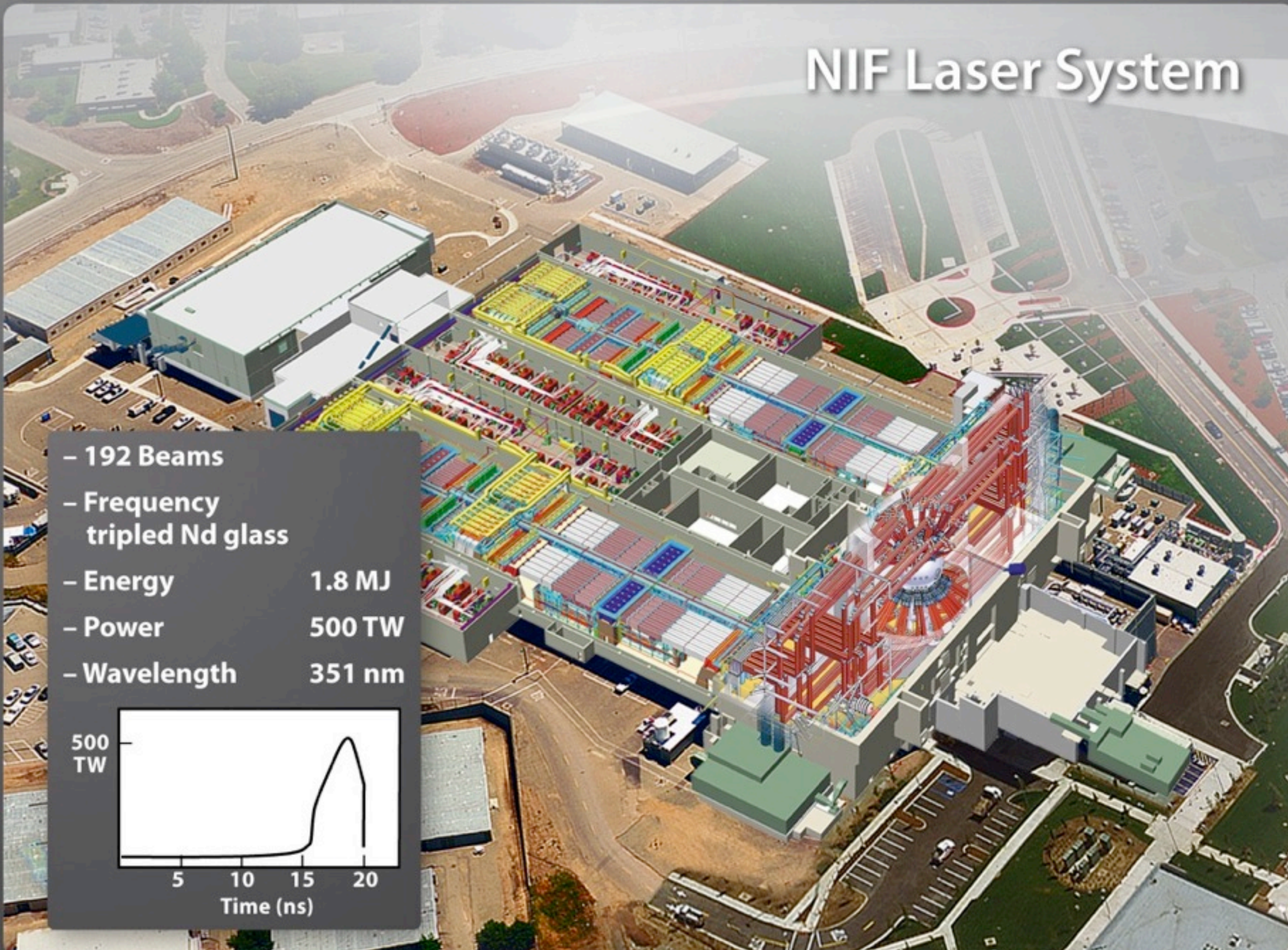


J. Chen and D. Kipping, ApJ 834, 17 (2017)

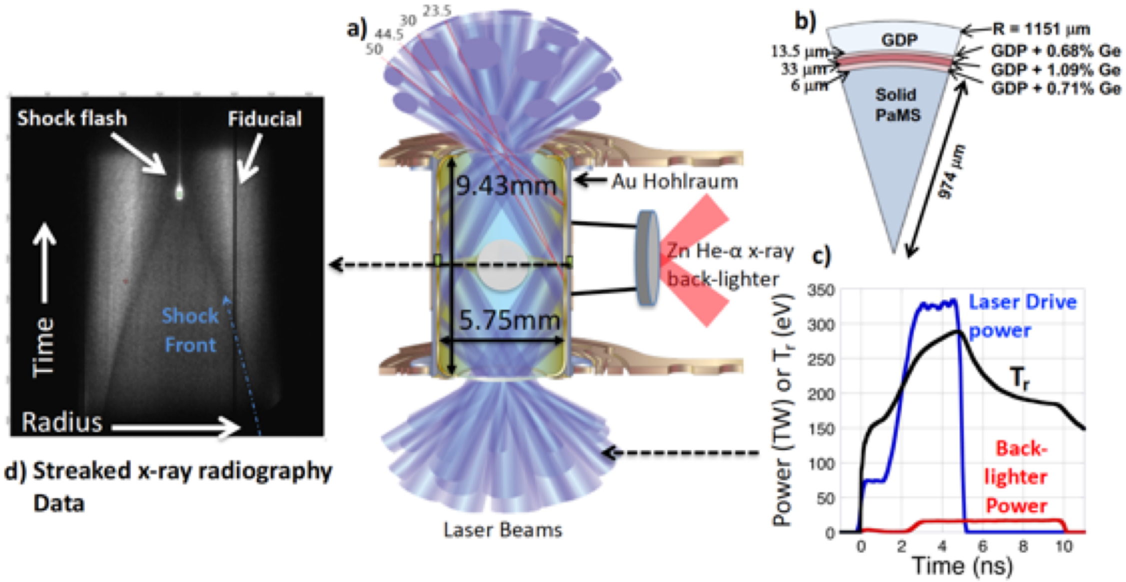
few 100 GPa
few 1000 K

few TPa
few 10,000 K

few PPa
few 1,000,000 K


NIF Laser System
– 192 Beams
– Frequency tripled Nd glass
– Energy 1.8 MJ
– Power 500 TW
– Wavelength 351 nm
500 TW
5
10
15
20
Time (ns)

Approaching Equation of State measurements at Gbar pressures at the NIF

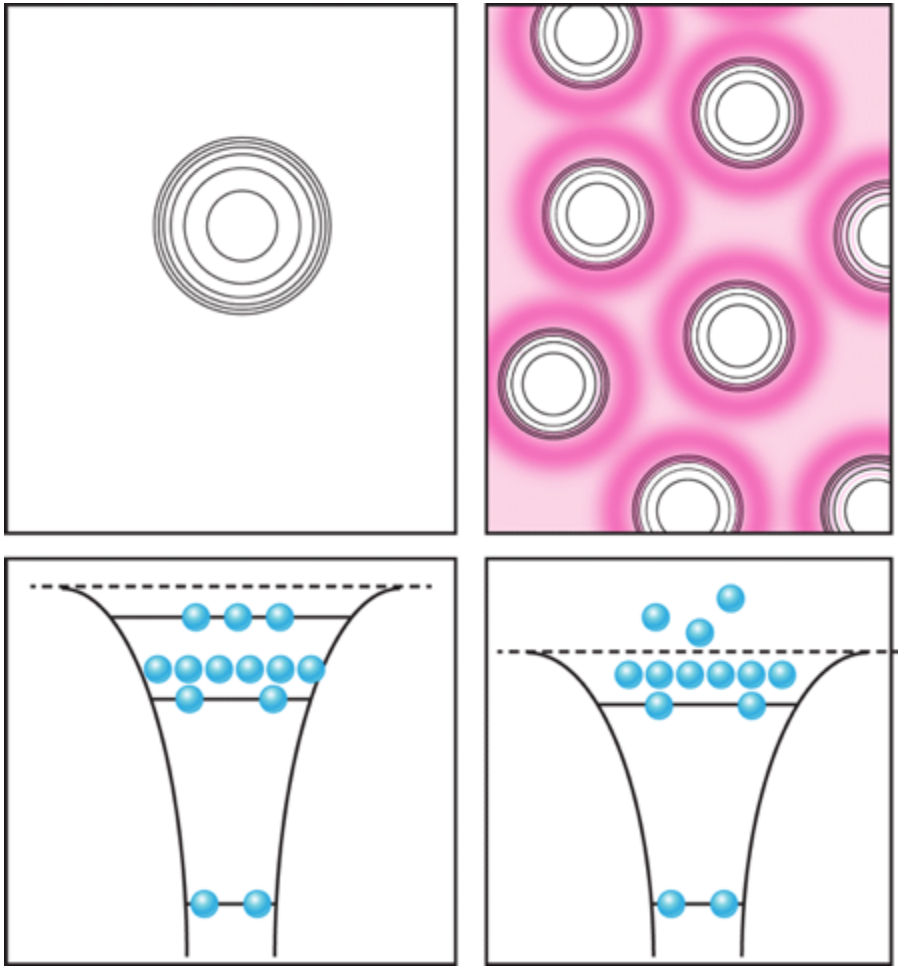


unpublished data

Benchmark for equation-of-state models for the carbon envelopes of White Dwarfs

T. Döppner et al., Phys. Rev. Lett. 121, 025001 (2018)
A. L. Kritcher et al., Nature (in review)

Ionization Potential Depression



Viewpoint: Extreme X Rays Probe Extreme Matter
D. Umstadter, Physics. **5**, 88 (2012)

Selected for a Viewpoint in *Physics*
PRL **109,** 065002 (2012) PHYSICAL REVIEW LETTERS week ending 10 AUGUST 2012

Direct Measurements of the Ionization Potential Depression in a Dense Plasma

O. Ciricosta,[1] S. M. Vinko,[1] H.-K. Chung,[2] B.-I. Cho,[3] C. R. D. Brown,[4] T. Burian,[5] J. Chalupský,[5] K. Engelhorn,[3] R. W. Falcone,[3,6] C. Graves,[7] V. Hájková,[5] A. Higginbotham,[1] L. Juha,[5] J. Krzywinski,[7] H. J. Lee,[7] M. Messerschmidt,[7] C. D. Murphy,[1] Y. Ping,[8] D. S. Rackstraw,[1] A. Scherz,[7] W. Schlotter,[7] S. Toleikis,[9] J. J. Turner,[7] L. Vysin,[5] T. Wang,[7] B. Wu,[7] U. Zastrau,[10] D. Zhu,[7] R. W. Lee,[7] P. Heimann,[3] B. Nagler,[7] and J. S. Wark[1,*]

[1]*Department of Physics, Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom*
[2]*Atomic and Molecular Data Unit, Nuclear Data Section, IAEA, P.O. Box 100, A-1400, Vienna, Austria*
[3]*Lawrence Berkeley National Laboratory, 1 Cyclotron Road, California 94720, USA*
[4]*Plasma Physics Department, AWE Aldermaston, Reading, United Kingdom*
[5]*Institute of Physics ASCR, Na Slovance 2, 18221 Prague 8, Czech Republic*
[6]*Department of Physics, University of California, Berkeley, California 94720, USA*
[7]*SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, California 94025, USA*
[8]*Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, California 94550, USA*
[9]*Deutsches-Elektronensynchrotron DESY, Notkestrasse 85, 22603 Hamburg, Germany*
[10]*IOQ, Friedrich-Schiller-Universität Jena, Max-Wien-Platz 1, 07743 Jena, Germany*
(Received 30 March 2012; published 6 August 2012)

PRL **110,** 265003 (2013) PHYSICAL REVIEW LETTERS week ending 28 JUNE 2013

Observations of the Effect of Ionization-Potential Depression in Hot Dense Plasma

D. J. Hoarty,[1] P. Allan,[1] S. F. James,[1] C. R. D. Brown,[1] L. M. R. Hobbs,[1] M. P. Hill,[1] J. W. O. Harris,[1] J. Morton,[1] M. G. Brookes,[1] R. Shepherd,[2] J. Dunn,[2] H. Chen,[2] E. Von Marley,[2] P. Beiersdorfer,[2] H. K. Chung,[3] R. W. Lee,[4] G. Brown,[3] and J. Emig[3]

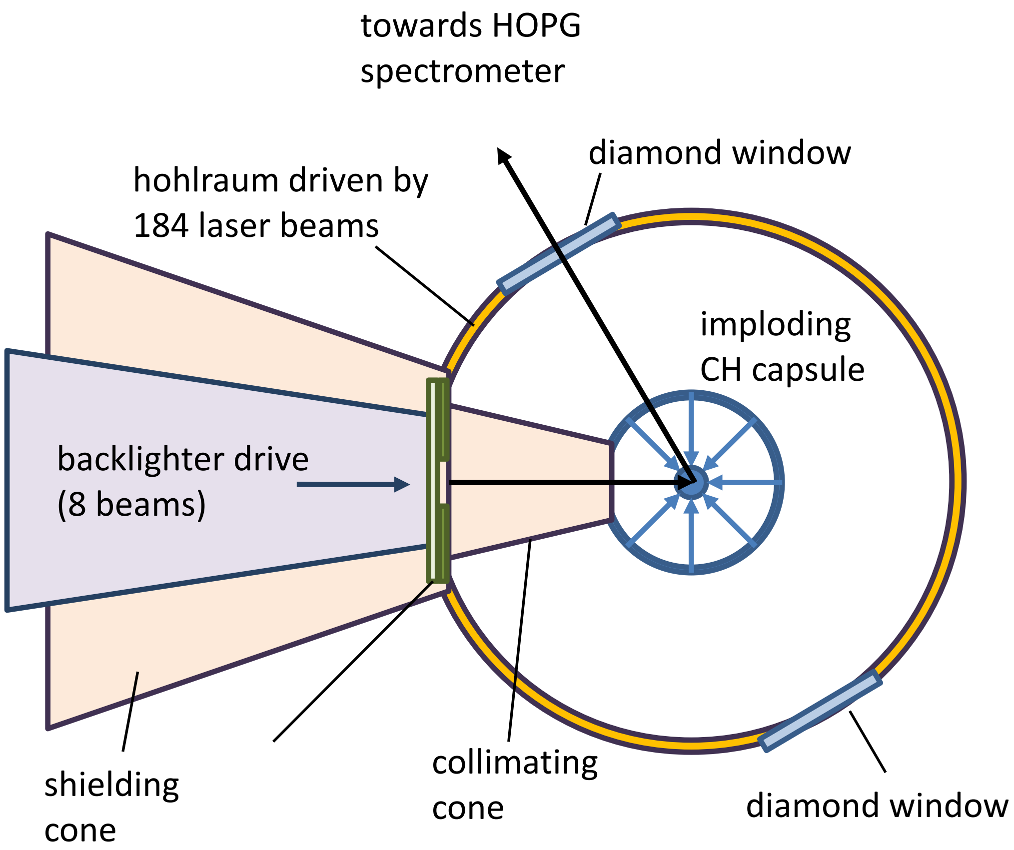
[1]*Directorate of Research and Applied Science, AWE plc, Reading RG7 4PR, United Kingdom*
[2]*Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, California 94550, USA*
[3]*Nuclear Data Section, Division of Physical and Chemical Sciences, International Atomic Energy Agency, P. O. Box 100, A-1400 Vienna, Austria*
[4]*Institute for Material Dynamics at Extreme Conditions, University of California, Berkeley, California 94720, USA*
(Received 28 January 2013; published 26 June 2013)

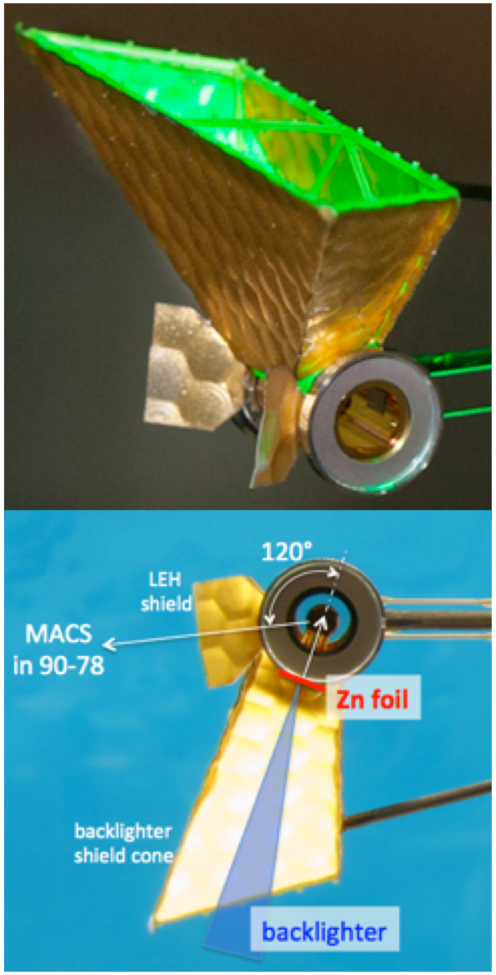
A plea for a reexamination of ionization potential depression measurements

Carlos A. Iglesias

Lawrence Livermore National Laboratories, P.O. Box 808, Livermore, CA 94550, USA

X-ray scattering platform at NIF

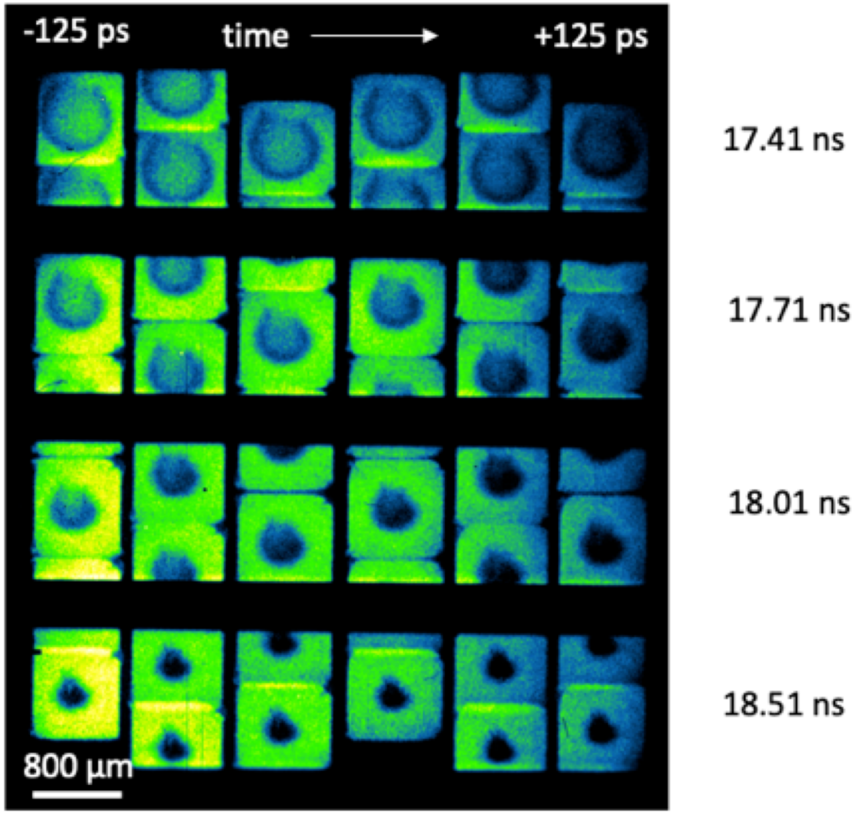




D. Kraus et al., JPCS 717, 012067 (2016)
K. J. Boehm et al., Fusion Sci. Tech. 70, 324 (2016)
T. Doeppner et al., JPCS 500, 192019 (2014)

X-ray scattering from imploding C-H capsules

In-flight radiography



D. Kraus et al., Phys. Rev. E **94**, 011202(R) (2016)
D. Kraus et al., in preparation
T. Doeppner et al., in preparation

X-ray scattering measurements

unpublished data

Decrease in elastic scattering:
-> increasing ionization

Broadening of inelastic scattering:
-> extreme densities (degenerate plasma)

Fit results

unpublished data

unpublished data

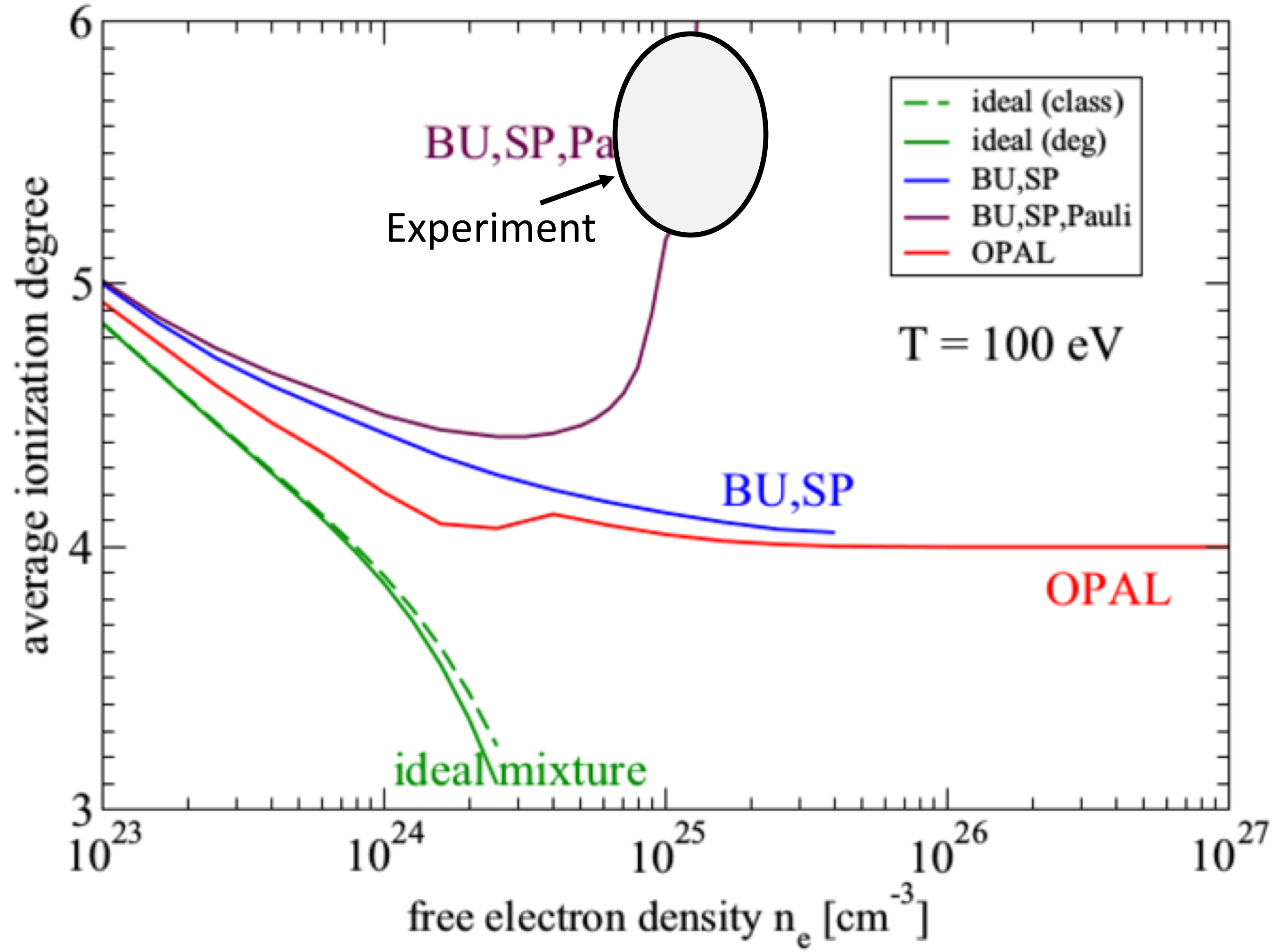
Experiments started 2014
Last shot of campaign:
Last week!

Compression by 30x,
n_e ~10^{25} cm^{-3}
Pressure ~2 Gbar
Temperature ~150 eV

Carbon ionization Z_C ~ 5.9
FLYCHK+Stewart-Pyatt
Model : Z_C ~ 4.5

D. Kraus et al., Phys. Rev. E **94**, 011202(R) (2016)
D. Kraus et al., in preparation
T. Doeppner et al., in preparation

Many-body quantum effects on IPD: analytic treatment

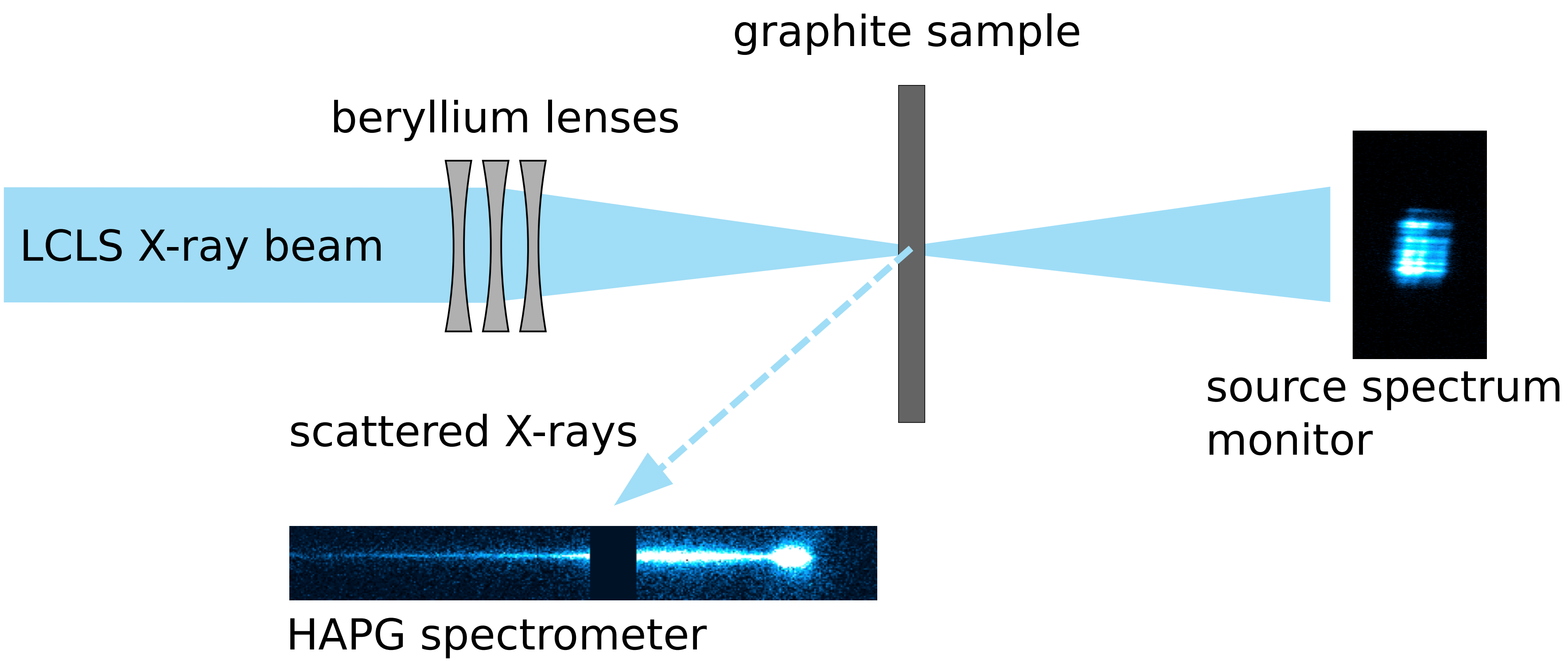


G. Röpke et al., Phys. Rev. E 99, 033201 (2019)

Many-body quantum effects on IPD: DFT-MD

M. Bethkenhagen et al., in preparation

How can XFELs help
-> isochoric heating and precise scattering measurements

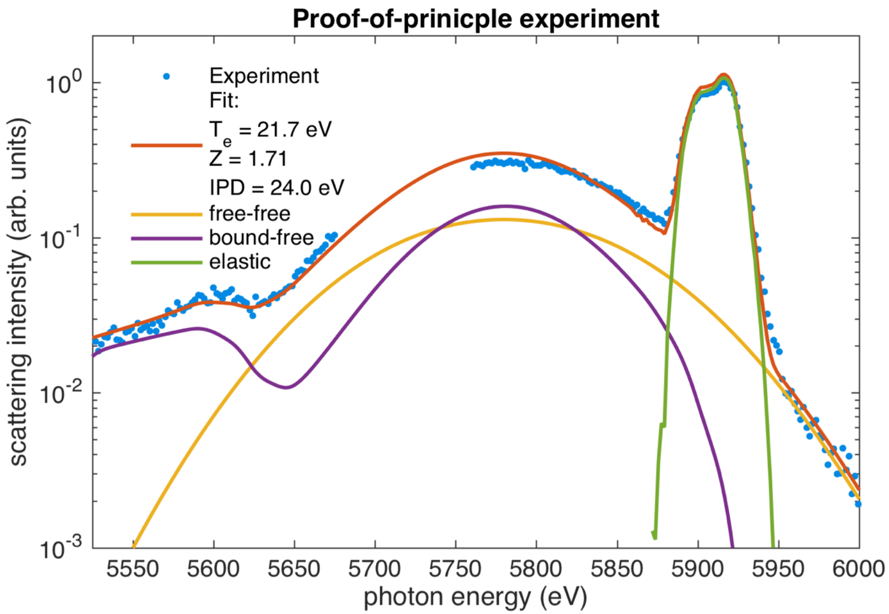


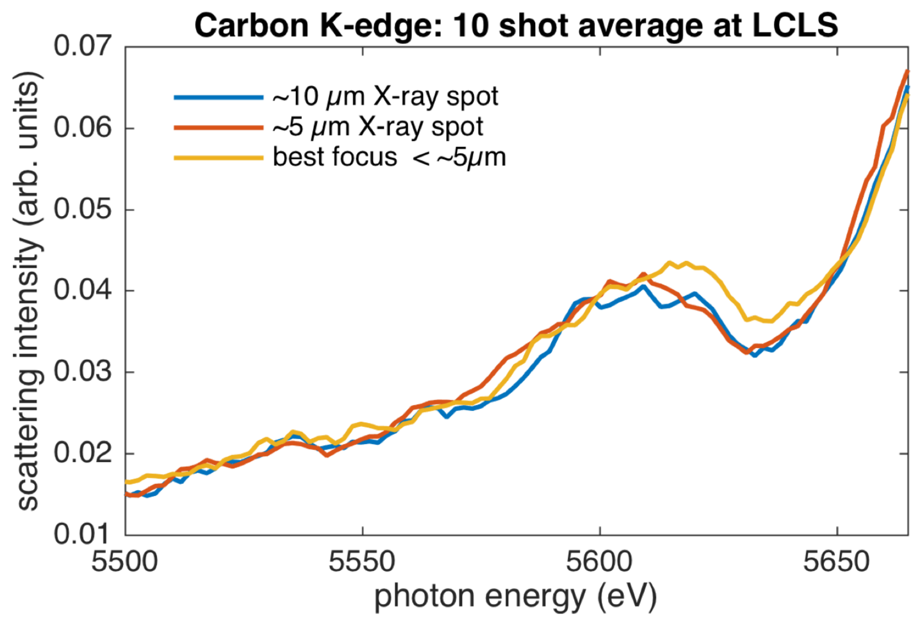
D. Kraus et al., PPCF **61**, 014015 (2019)

Proof-of-Principle Experiment at LCLS

D. Kraus et al., PPCF **61**, 014015 (2019)

Was done just for a few minutes "parasitically" during another experiment

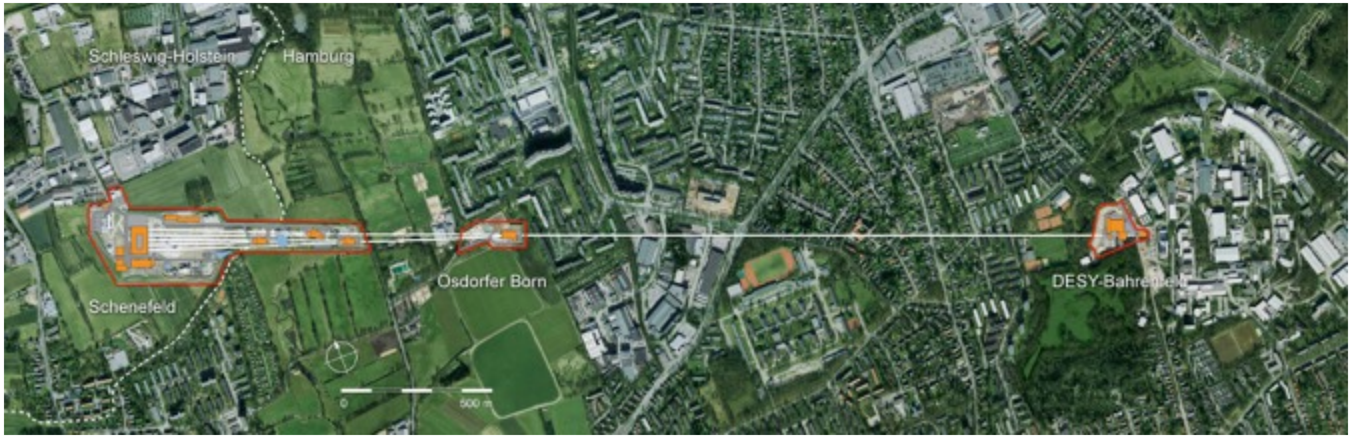


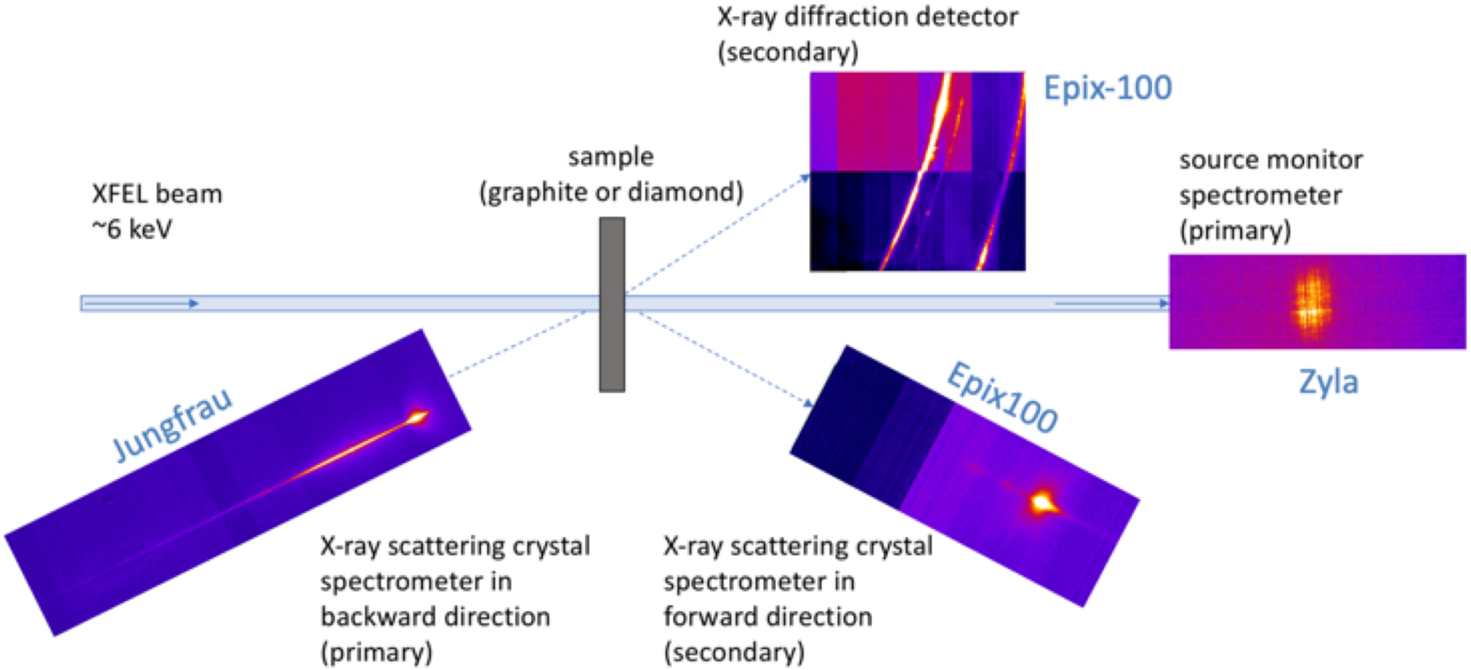


Graphite sample, 10-shot average,
5.9 keV, few mJ pulse energy, scattering angle 160 deg.

Can resolve K-shell bound-free and some effect due to focusing
-> edge is slightly shifted to higher energies for best focus

Experiment at HED instrument of European XFEL





High-quality spectra obtained at European XFEL

unpublished data

European XFEL

Next beamtime: April 2020

unpublished data

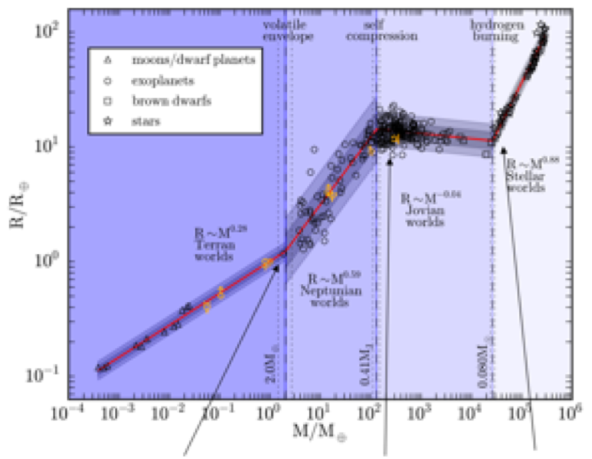
- Demonstrated capabilities to precisely characterize ionization potential depression in Warm Dense Matter
- X-ray Raman Spectroscopy: very promising diagnostics for low-Z WDM

K. Voigt et al., in preparation

Summary

LCLS

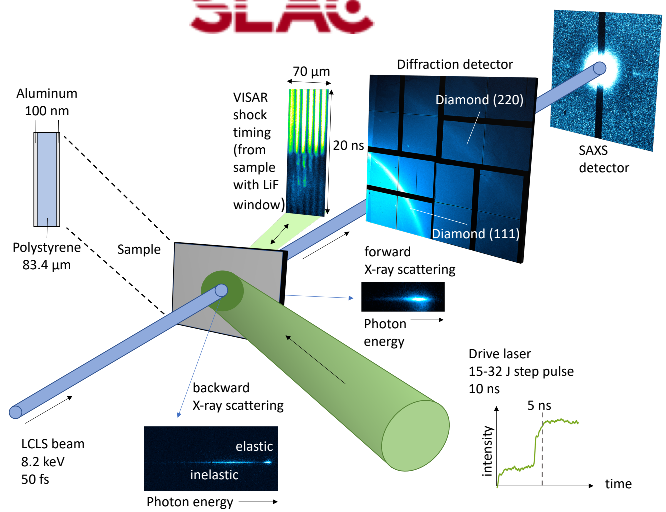
SLAC

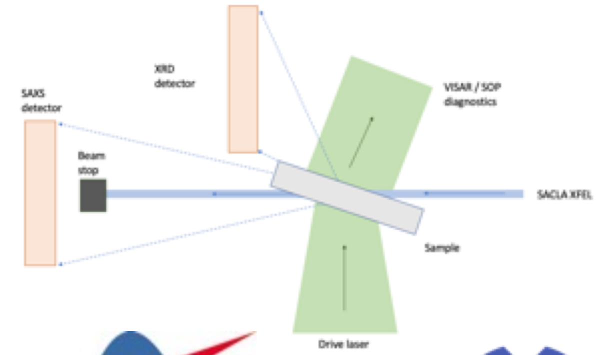


few 100 GPa few 1000 K

few TPa few 10,000 K

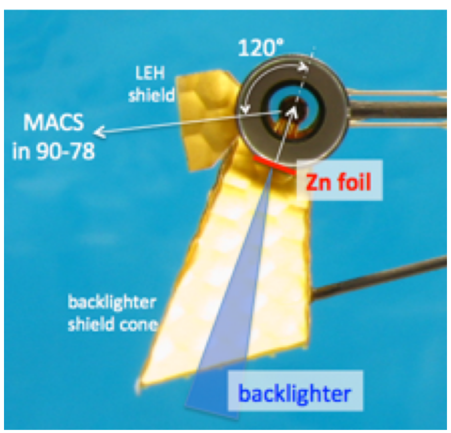
few PPa few 1,000,000

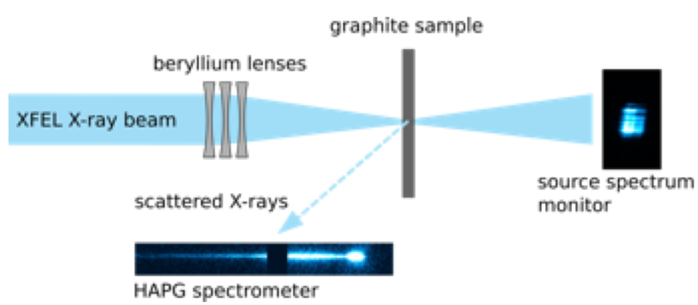




SACLA

OSAKA UNIVERSITY





FAIR

NIF National Ignition Facility

European XFEL

HiBEF

Thanks!