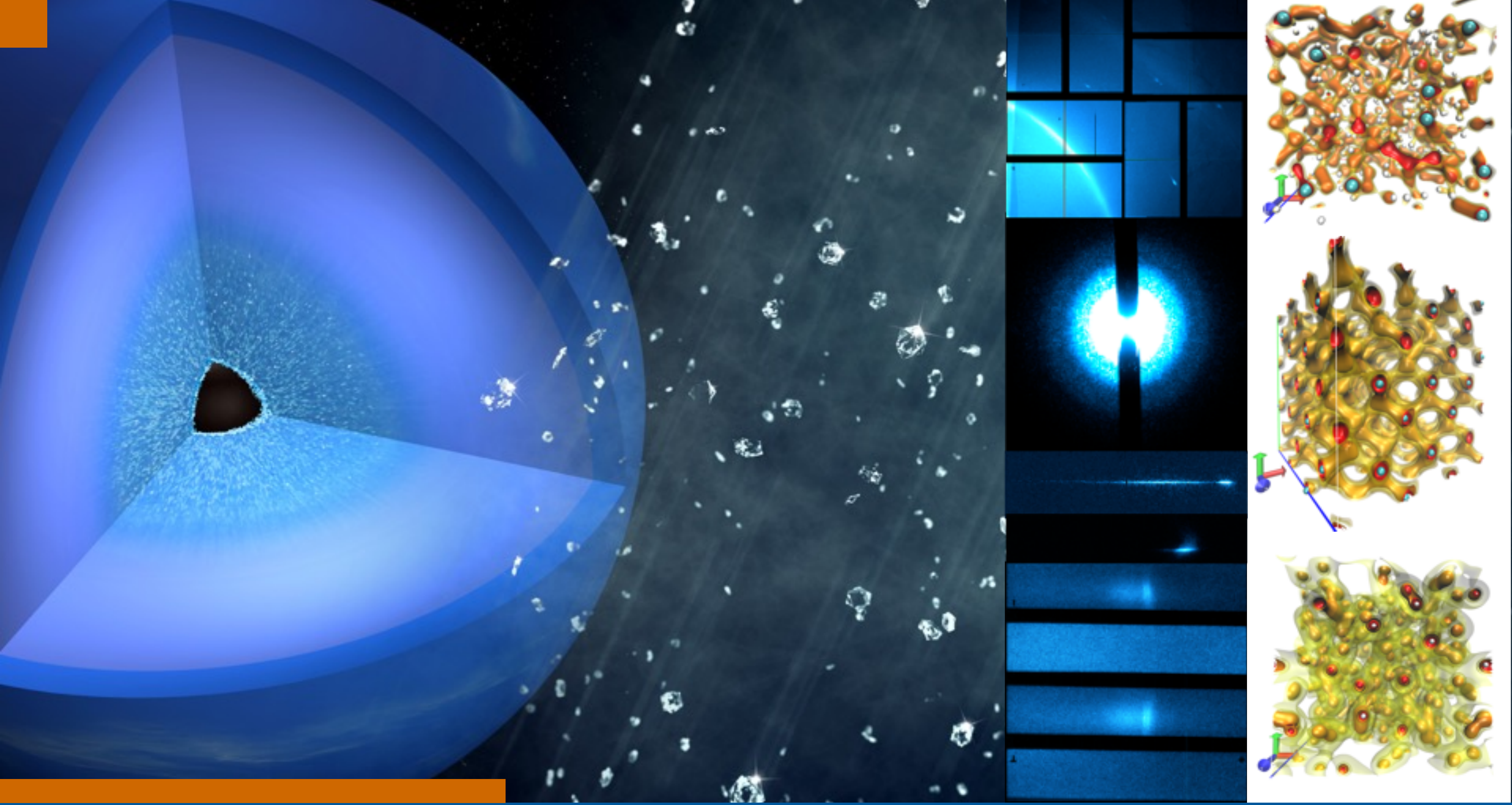

Formation of diamonds in laser-compressed hydrocarbons at planetary interior conditions

Dominik Kraus

TECHNISCHE UNIVERSITÄT DRESDEN
IFMP Institut für Festkörper- und Materialphysik

HZDR
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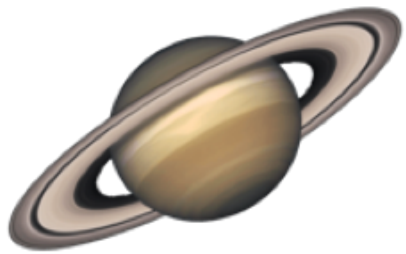
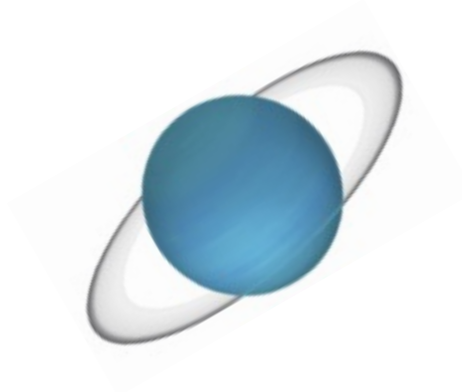
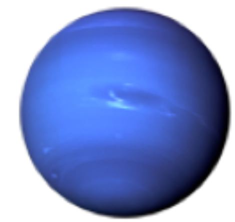
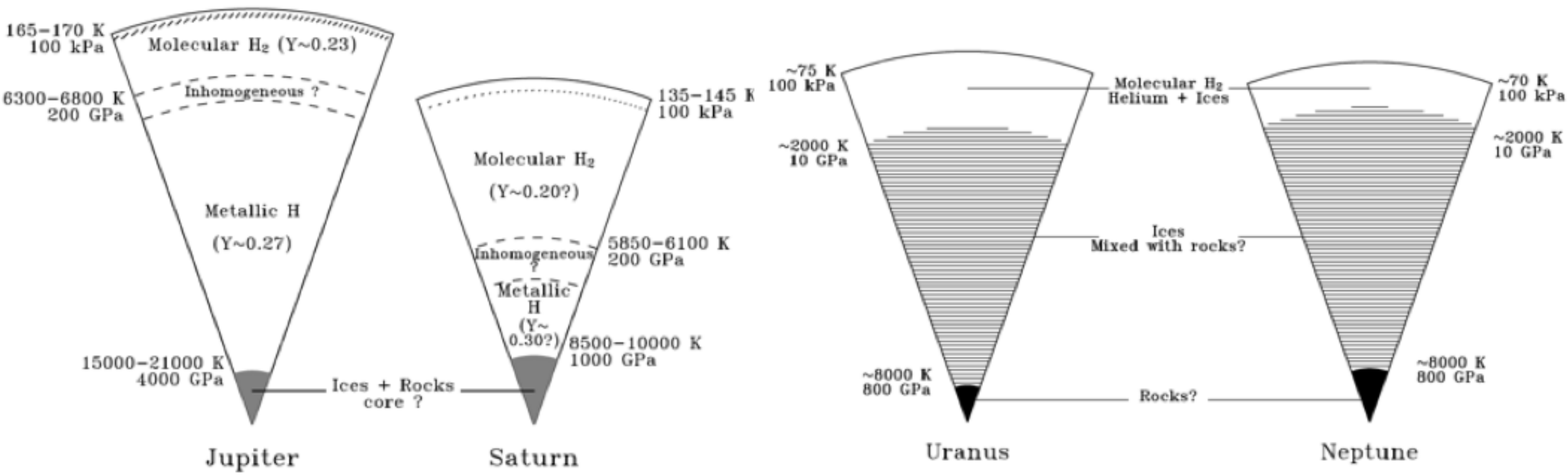
Giant Planets

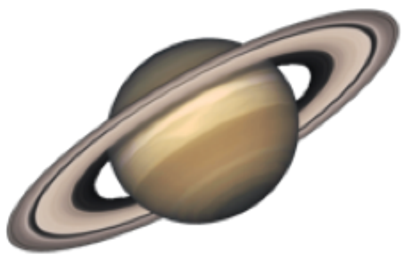





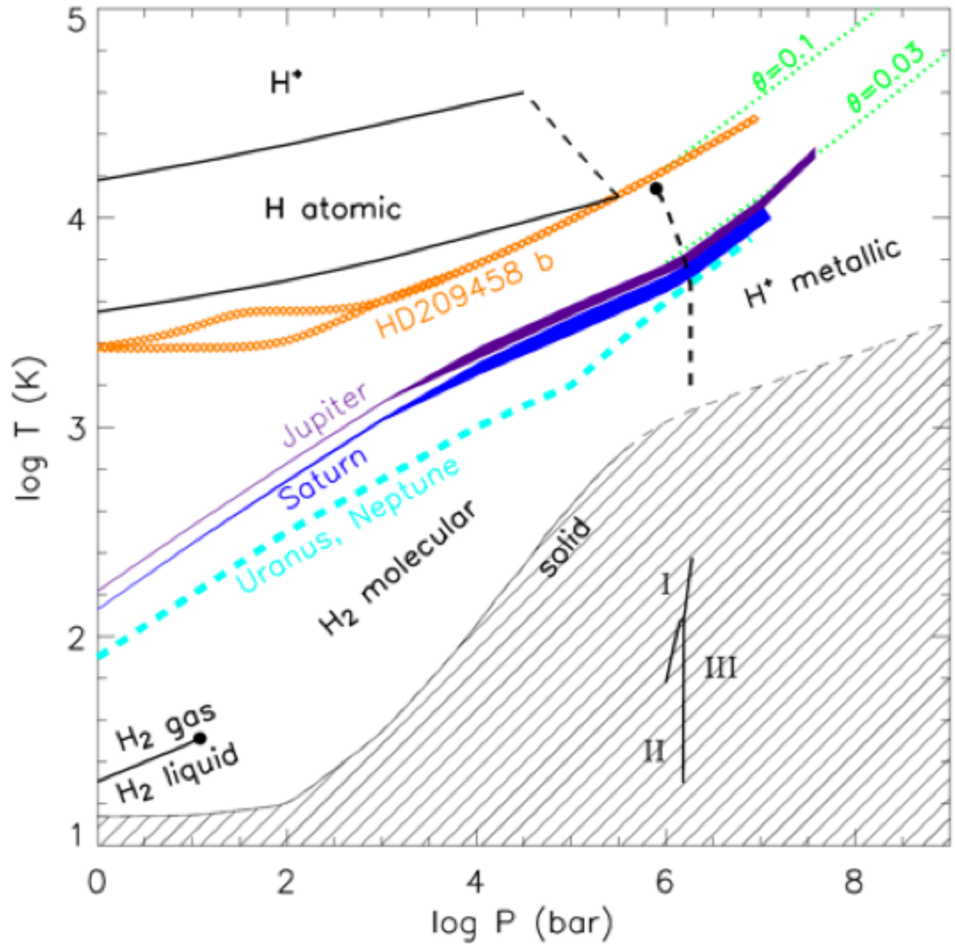


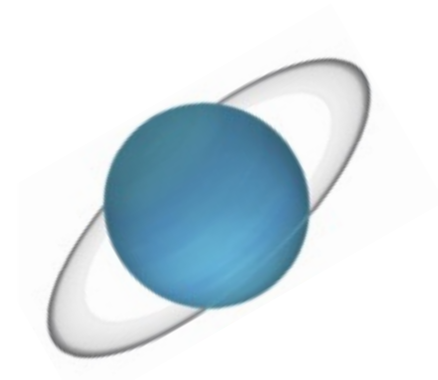
T. Guillot, Science 286, 72 (1999)
T. Guillot, & D. Gautier, Treatise Geophys. 10, 439–464 (2007)

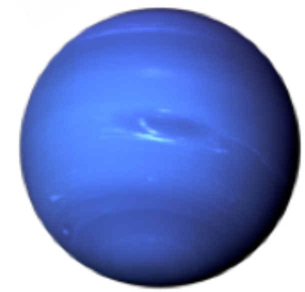
Giant Planets – Hydrogen phase diagram

100 GPa = 1 Mbar









T. Guillot, Science 286, 72 (1999)
T. Guillot, & D. Gautier, Treatise Geophys. 10, 439–464 (2007)

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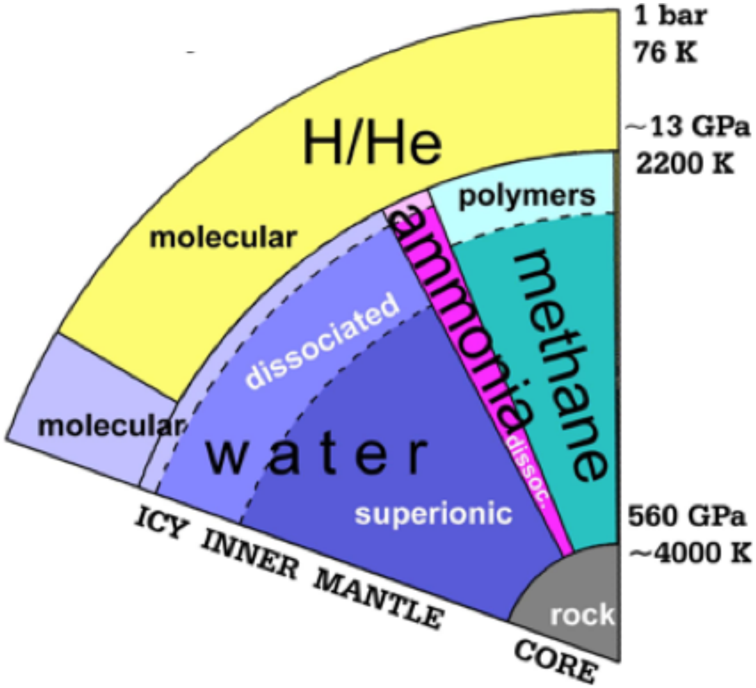
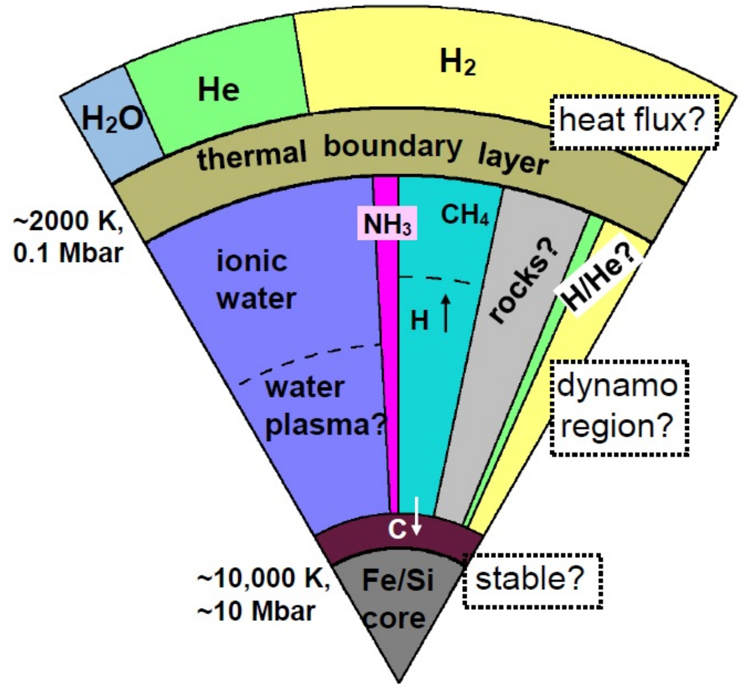
Models of the icy giant planets

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?

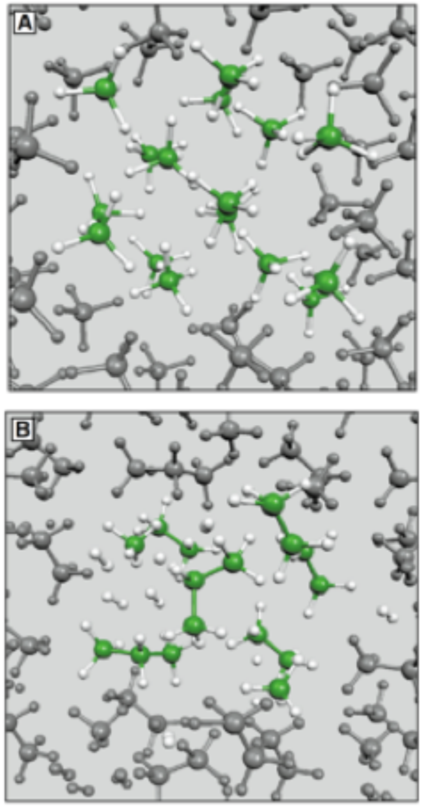
MARVIN ROSS

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

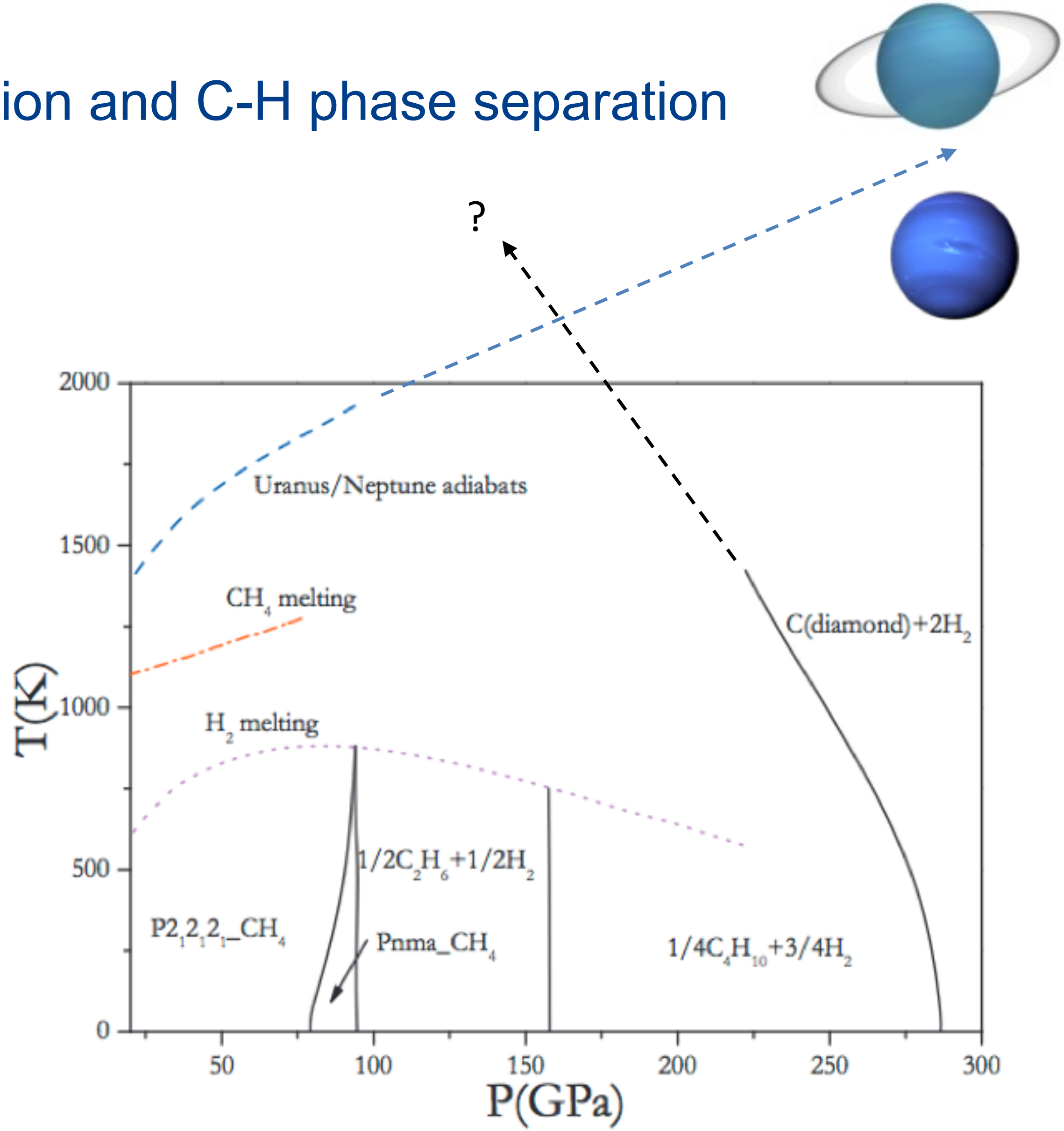
letters to nature

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

Simulations: Polymerization and C-H phase separation in methane

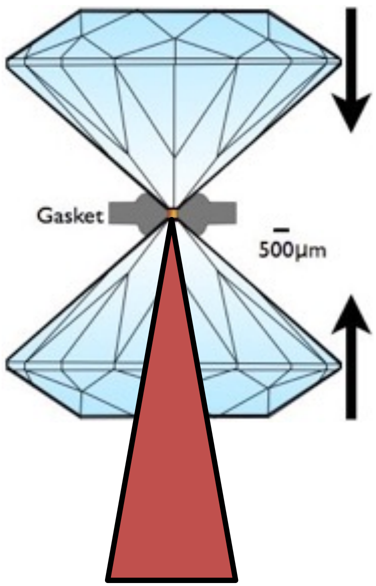


F. Ancilotto et al., Science 275, 1288 (1997)



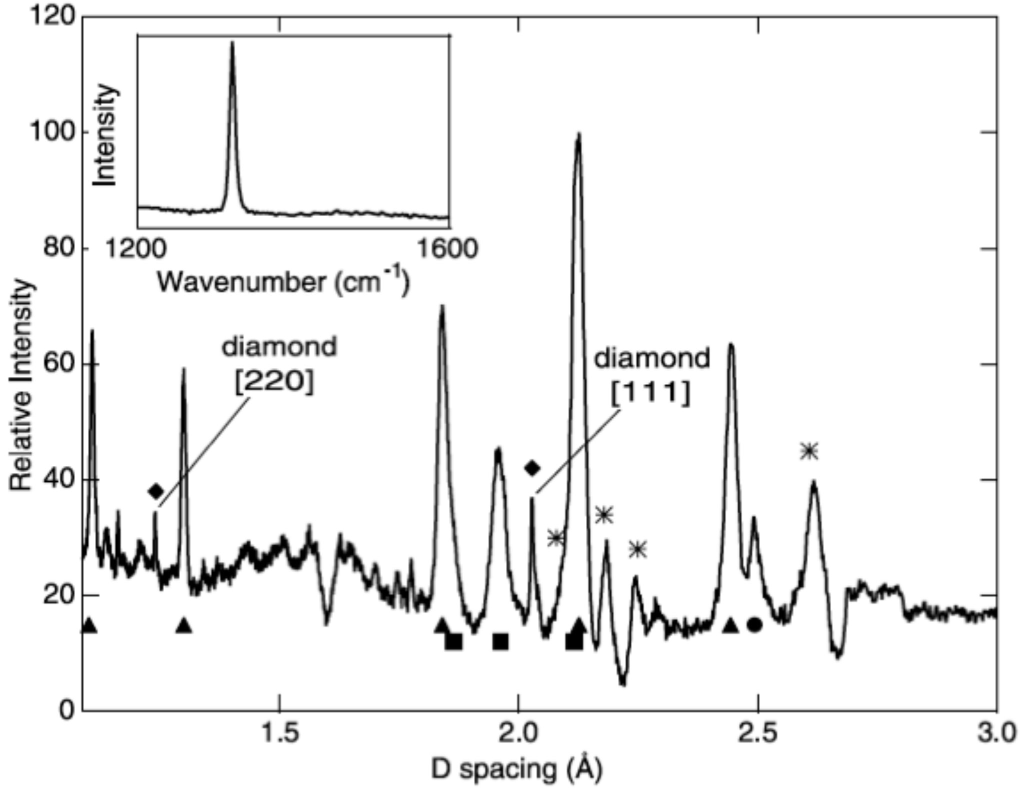
G. Gao et al., J. Chem. Phys. 133, 144508 (2010)

Compressed and heated methane



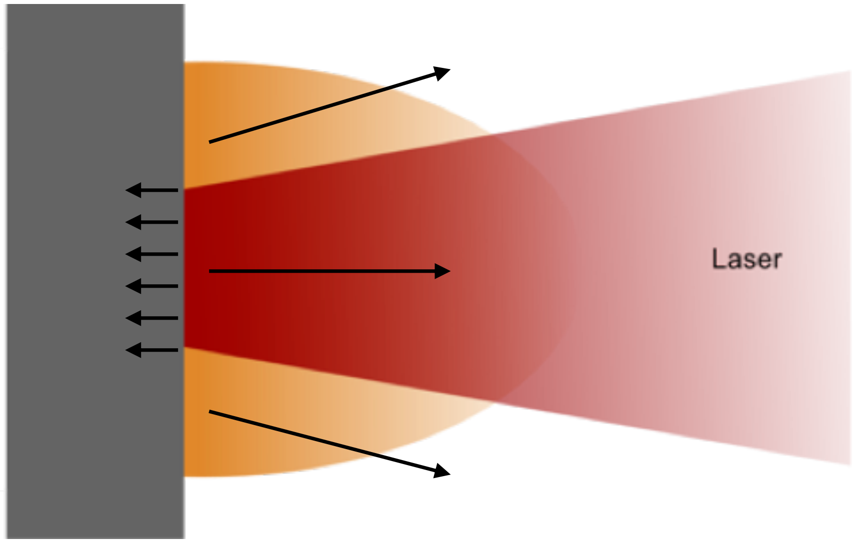
heating laser

CH_4 recovered from DAC at 20 GPa and 2000 K



L. R. Benedetti et al., Science 286, 100 (1999)

Laser-driven shock waves



Intensity ~10^{13} W/cm^2 (wavelength 527 nm):

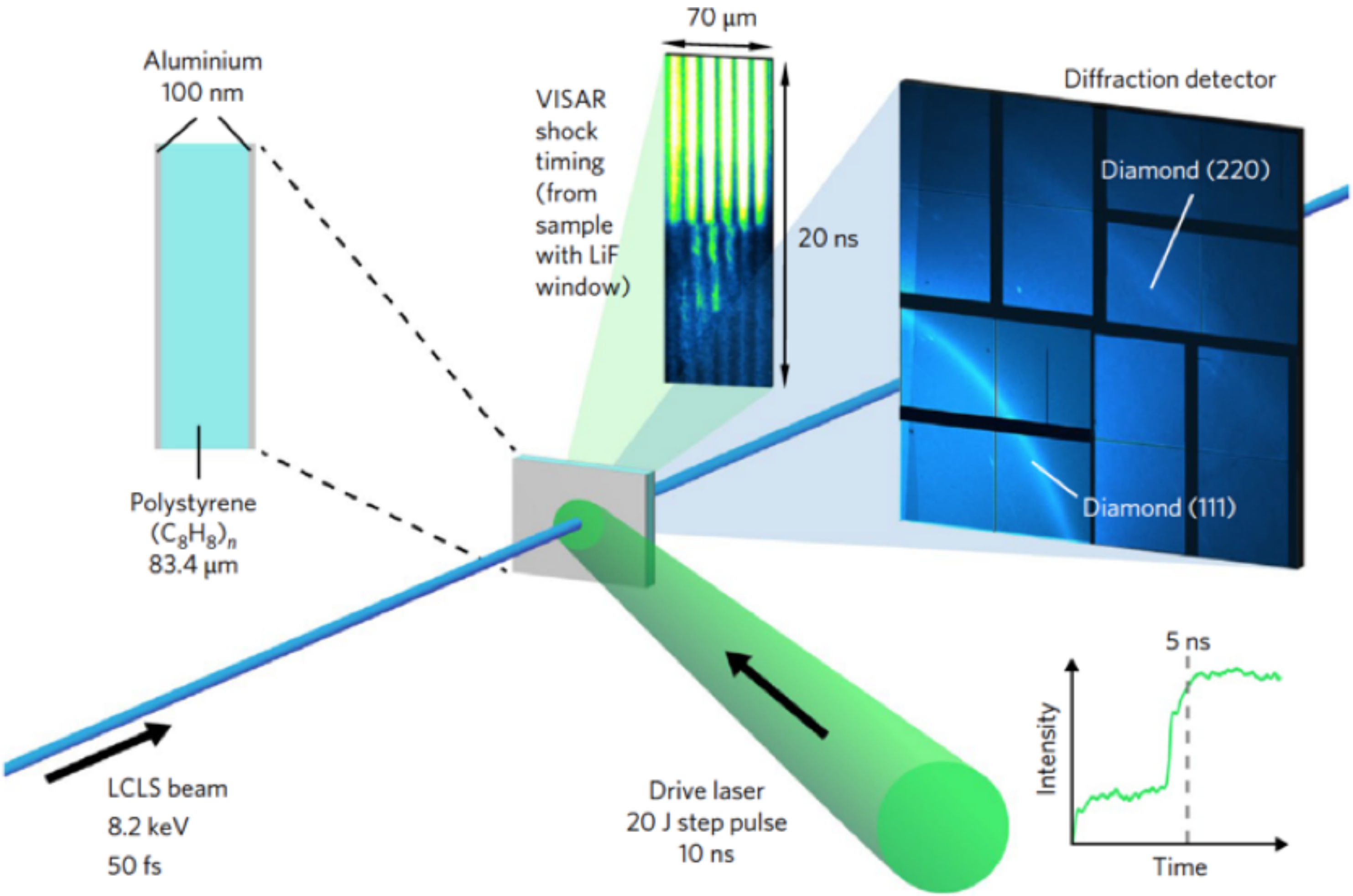
Ablation pressure:
P ~ 150 GPa = 1.5x10^6 bar

→ shock wave

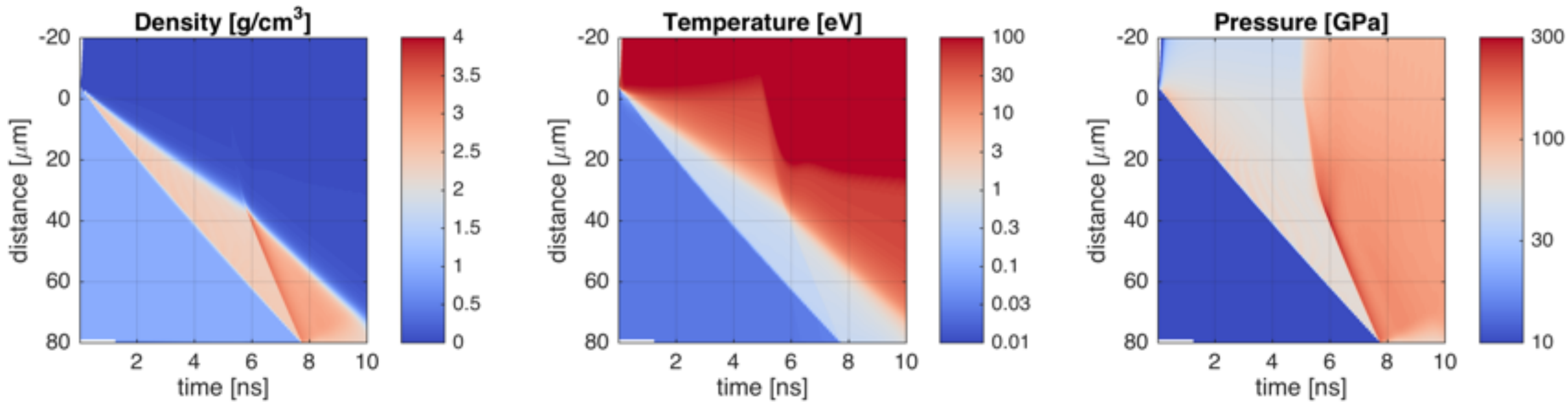
→ Entropy and temperature increase due to compression wave

→ Multiple shocks: lower entropy and temperature increase compared to single shock to same pressure!

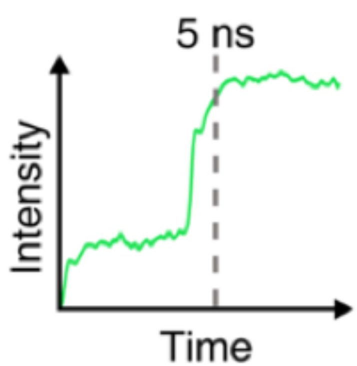
LCLS experiments on CH phase separation



LCLS experiment on CH phase separation



Pulse shape

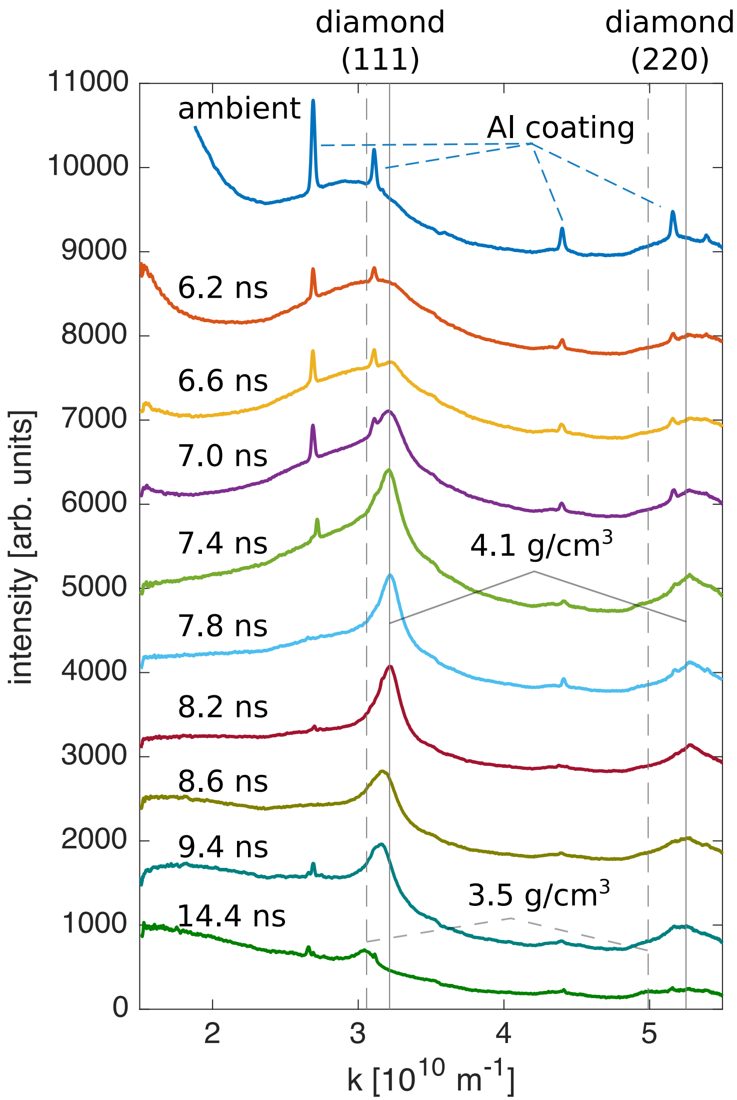


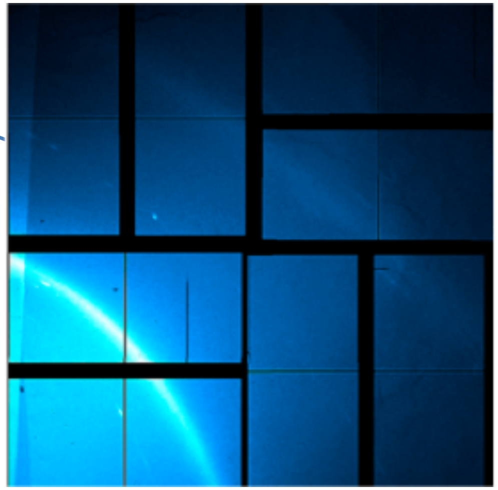
83 µm polystyrene:

1st shock: 60 GPa, 4000 K

2nd shock: 150 GPa, 5000 K

LCLS experiment on CH phase separation

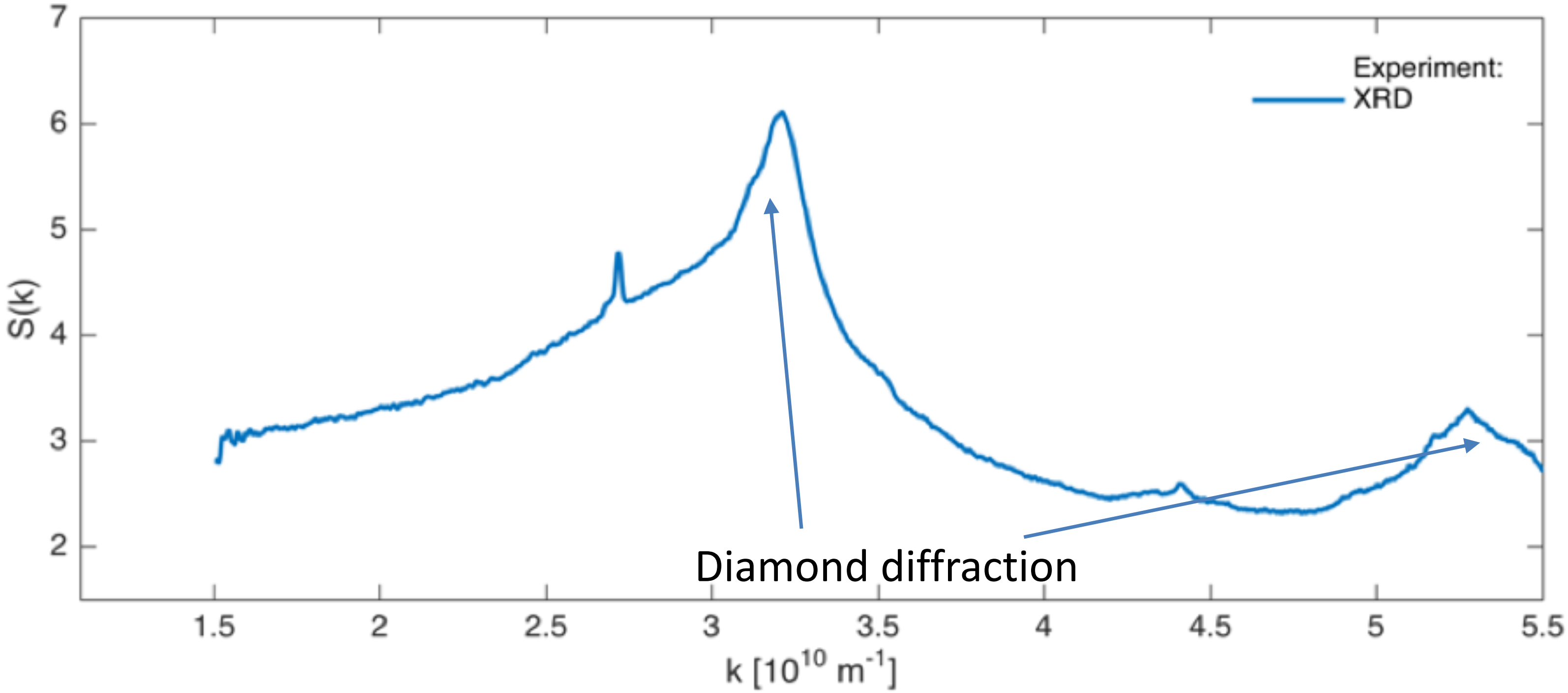




D. Kraus et al., Nature Astronomy 1, 606-611 (2017)

X-ray diffraction + spectrally resolved X-ray scattering

$$S(k) = W_{el}(k) + W_{bound-free}(k) + W_{free-free}(k)$$



Diamond diffraction intensity (scaled to Al): ~40% of carbon atoms are in diamond lattice.

Member of the Helmholtz Association
Dominik Kraus | Institute of Radiation Physics | www.hzdr.de

X-ray diffraction + spectrally resolved X-ray scattering

$$S(k) = W_{el}(k) + W_{bound-free}(k) + W_{free-free}(k)$$

Unpublished data

Diamond diffraction intensity (scaled to Al): ~40% of carbon atoms are in diamond lattice.

CH liquid diffraction intensity: <100% of sample volume consists of CH liquid.
(would need to be >100 % for CH_2 and CH_3 to fit data)

X-ray diffraction + spectrally resolved X-ray scattering

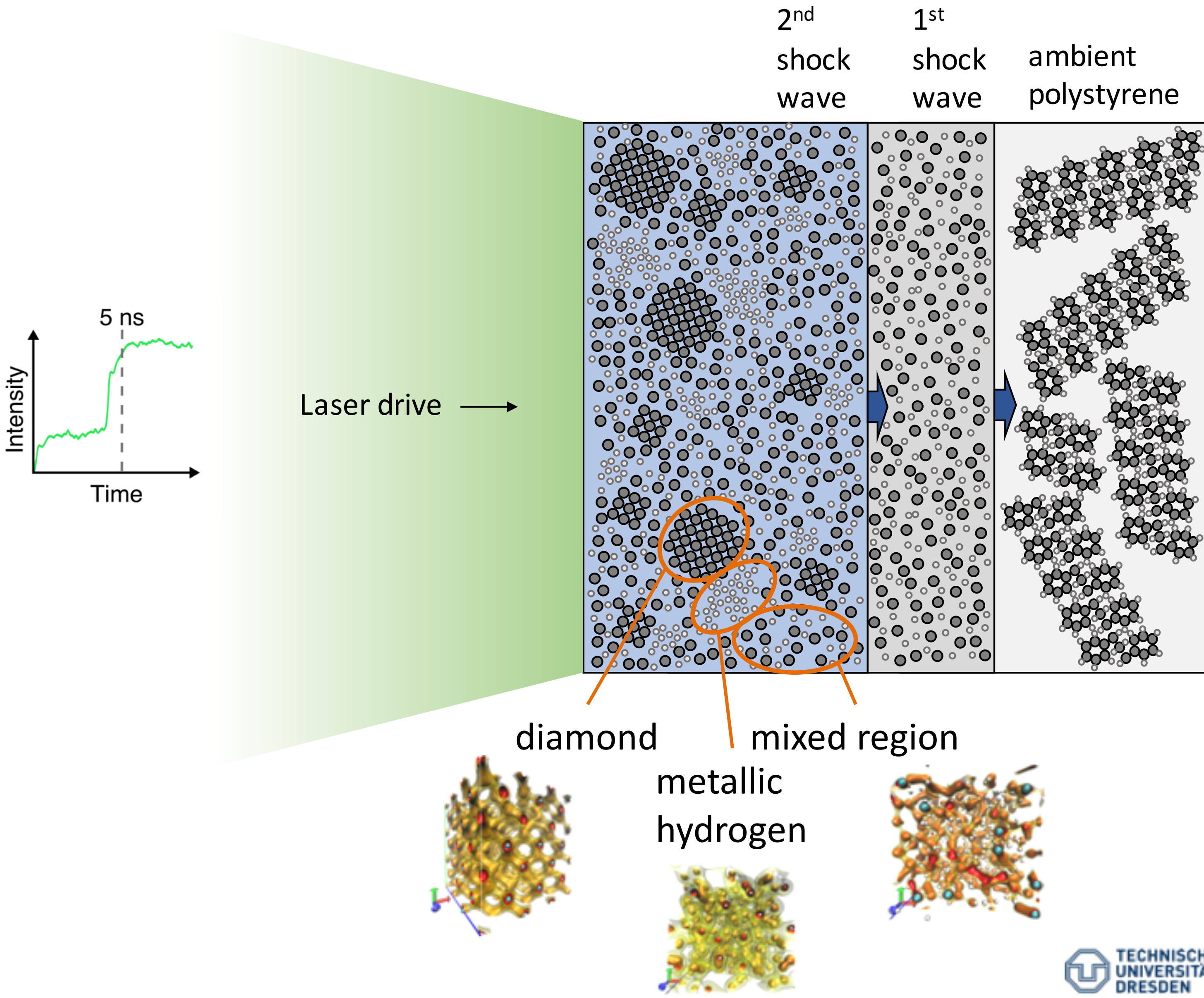
$$S(k) = W_{el}(k) + W_{bound-free}(k) + W_{free-free}(k)$$

Unpublished data

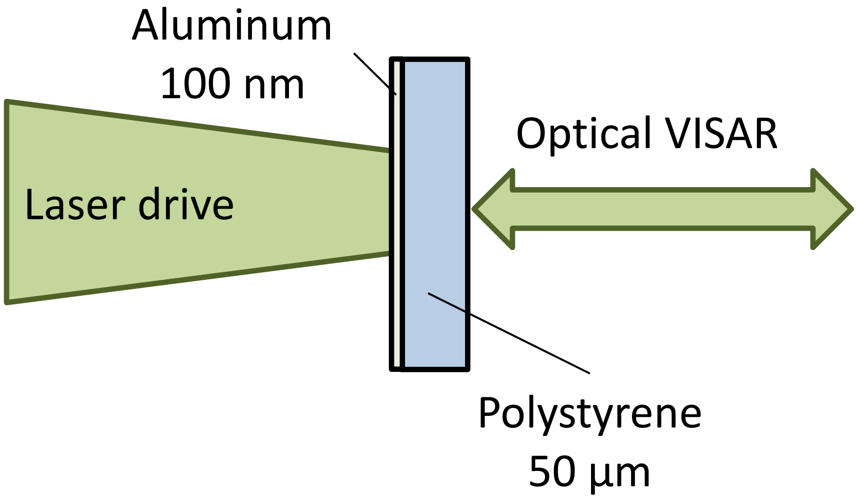
Diamond diffraction intensity (scaled to Al): ~40% of carbon atoms are in diamond lattice.

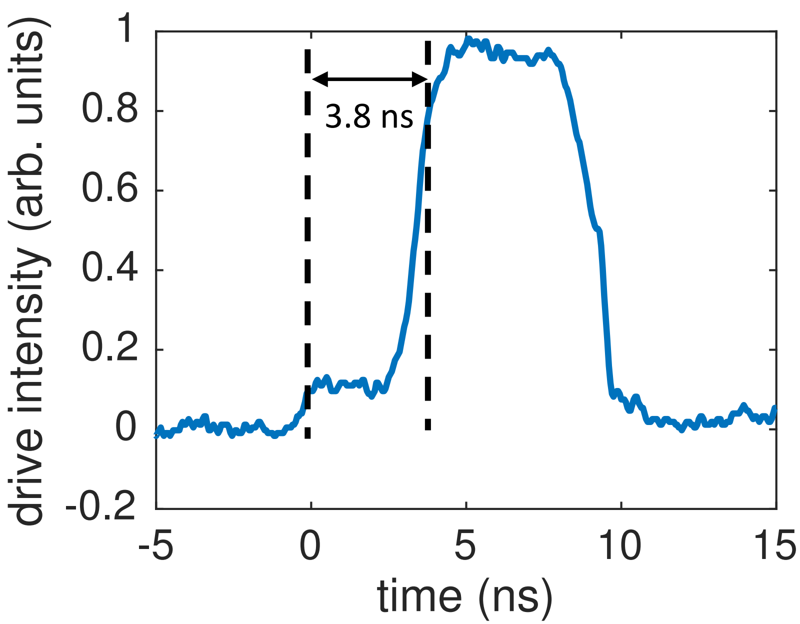
CH liquid diffraction intensity (scaled to XRTS): <100% of sample volume consists of CH liquid. (would need to be >100 % for CH_2 and CH_3 to fit data)

Microscopic picture



VISAR data for step pulse from 50 µm polystyrene



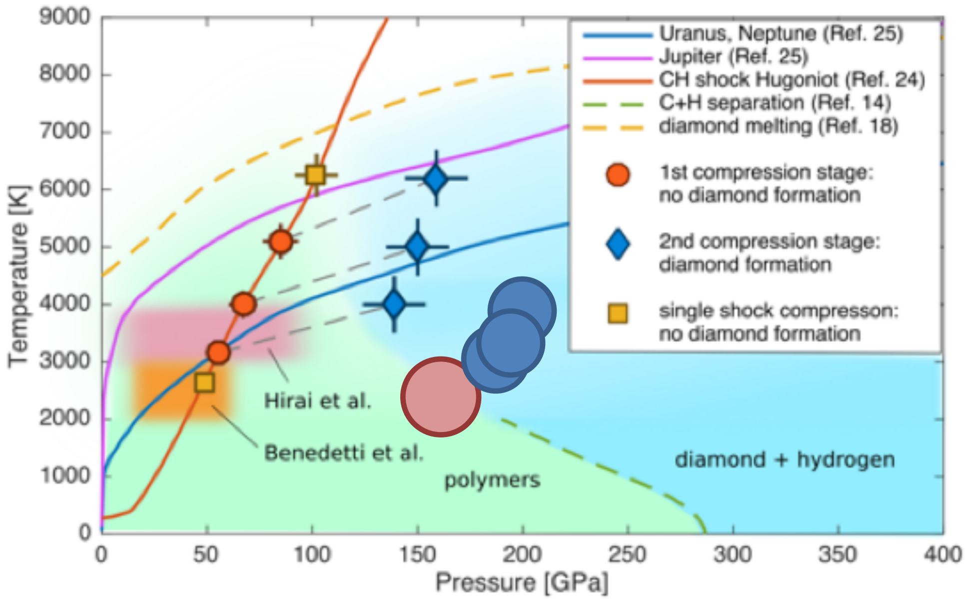


Unpublished data

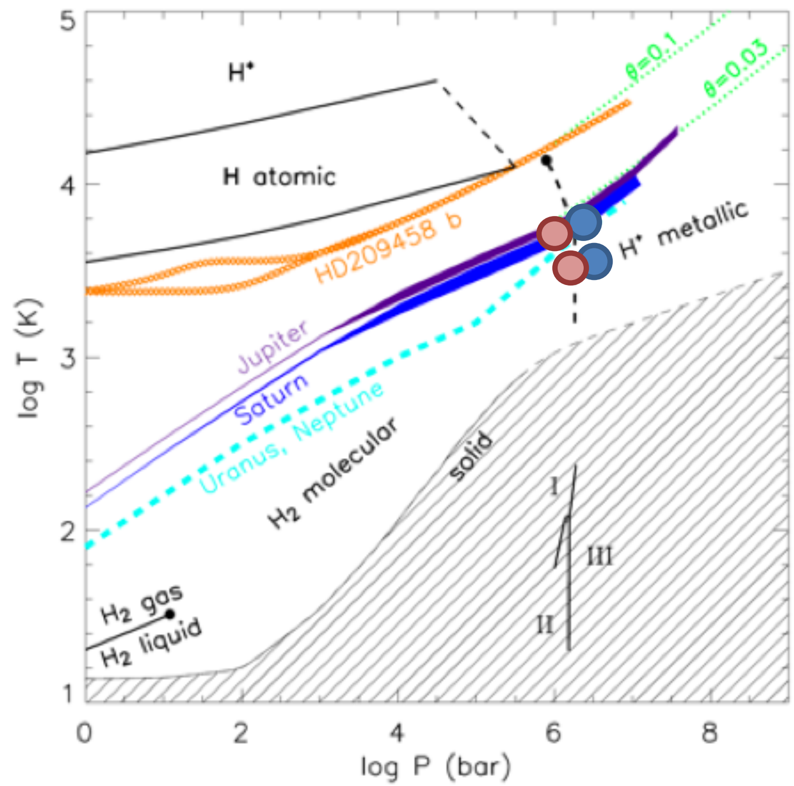
time

X-ray diffraction at 5.3 ns

Approximate locations in phase diagram from simulations



D. Kraus et al., Nature Astronomy 1, 606-611 (2017)



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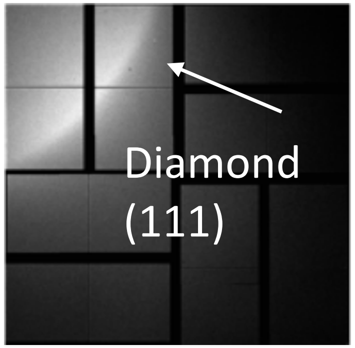
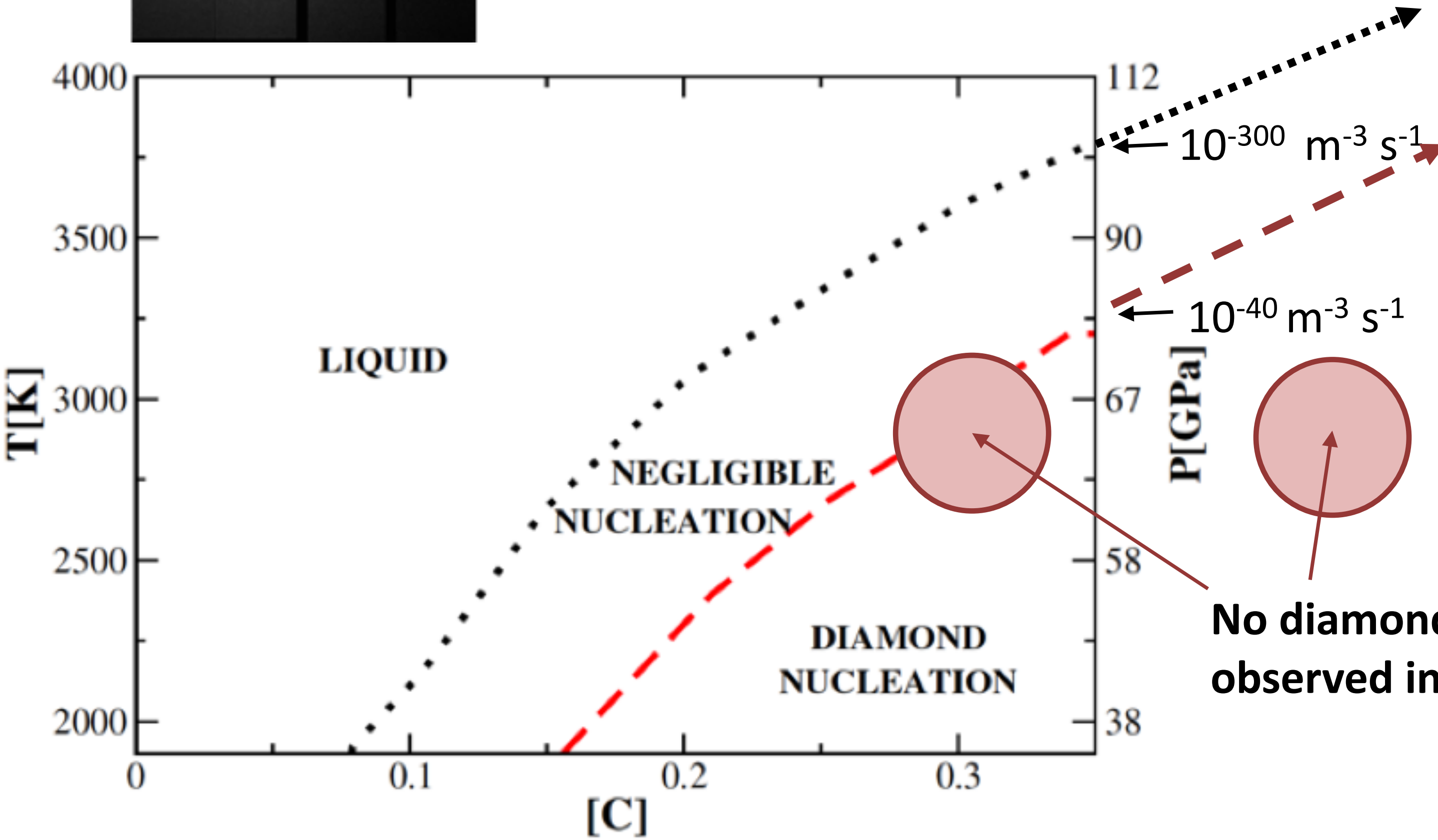
Diamond nucleation rates from hydrocarbons



Measurements:
~10^{30} m^{-3} s^{-1}

Starting with PMMA $C_5H_8O_2$

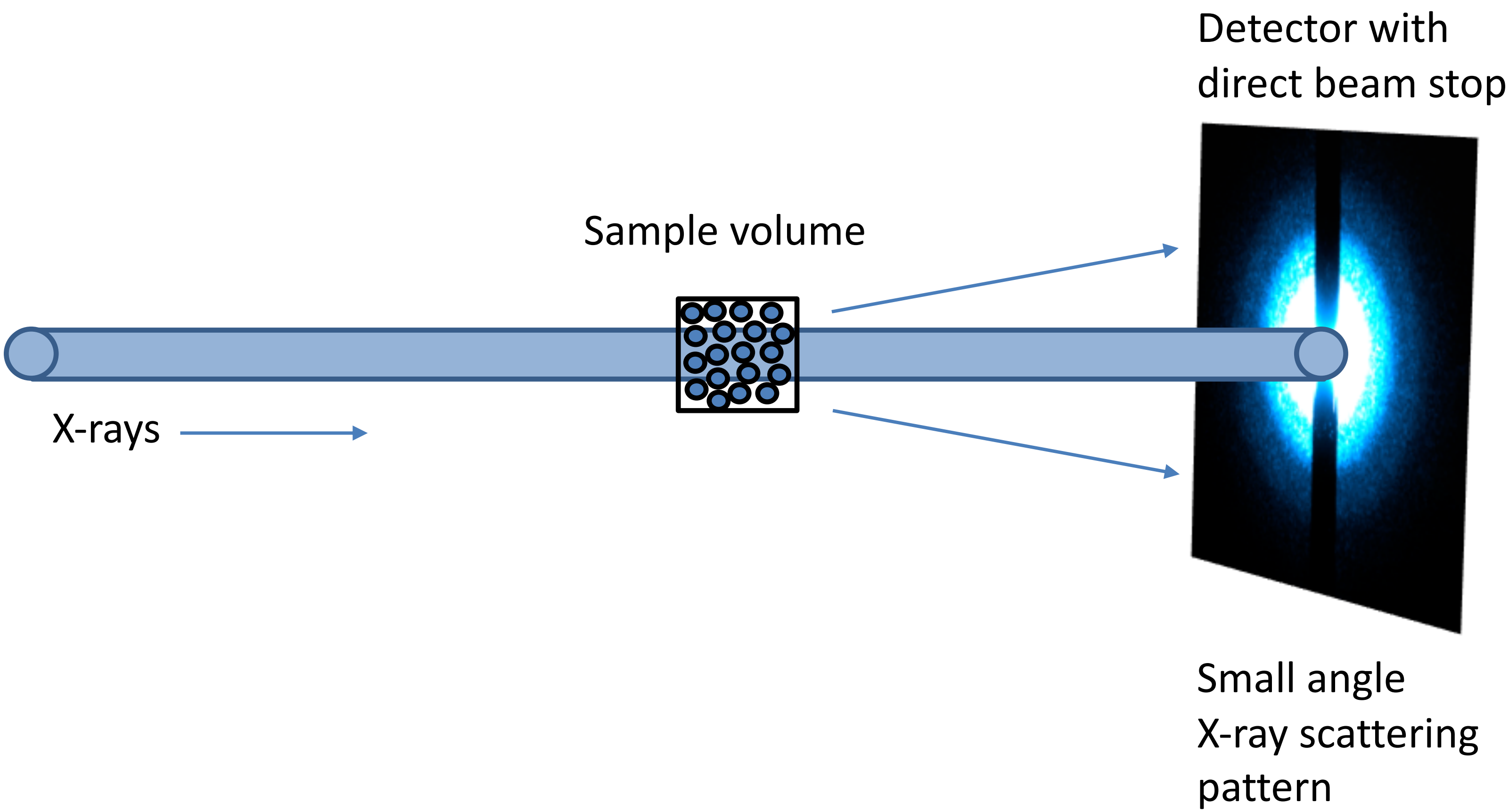
Starting with polystyrene CH



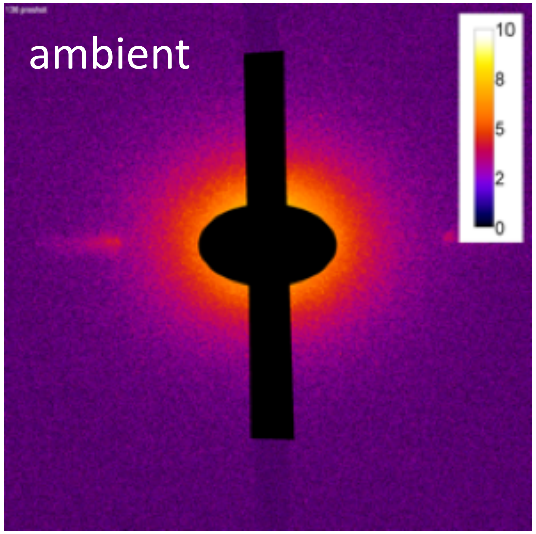
No diamond formation observed in experiment

L. Ghiringhelli et al, PRL 99, 055702 (2007)

Using SAXS to infer diamond size



Using Small Angle X-ray Scattering (SAXS) to infer diamond size



Unpublished data

Unpublished data

Unpublished data

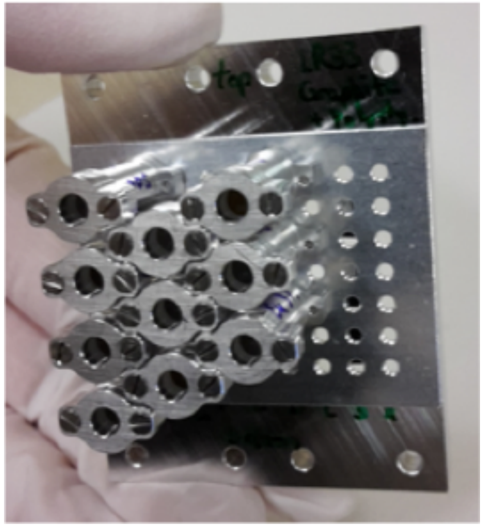
Using Small Angle X-ray Scattering (SAXS) to infer diamond size

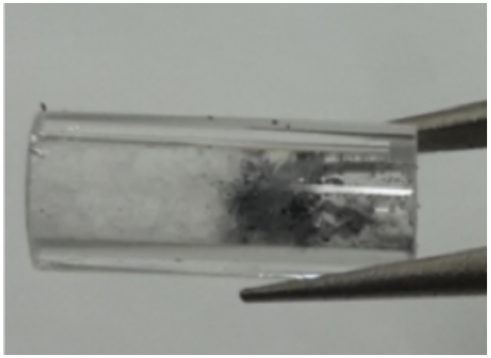
Unpublished data

Unpublished data

Diffraction: lower limit via Scherrer formula: **diamond diameter > 4nm** consistent with SAXS

Recovery target tests





Unpublished data

Summary

X-ray Free Electron Lasers in combination with high-energy lasers:
Unprecedented possibilities for studying chemical processes inside giant planets.

Example: Diamond precipitation inside ice giants

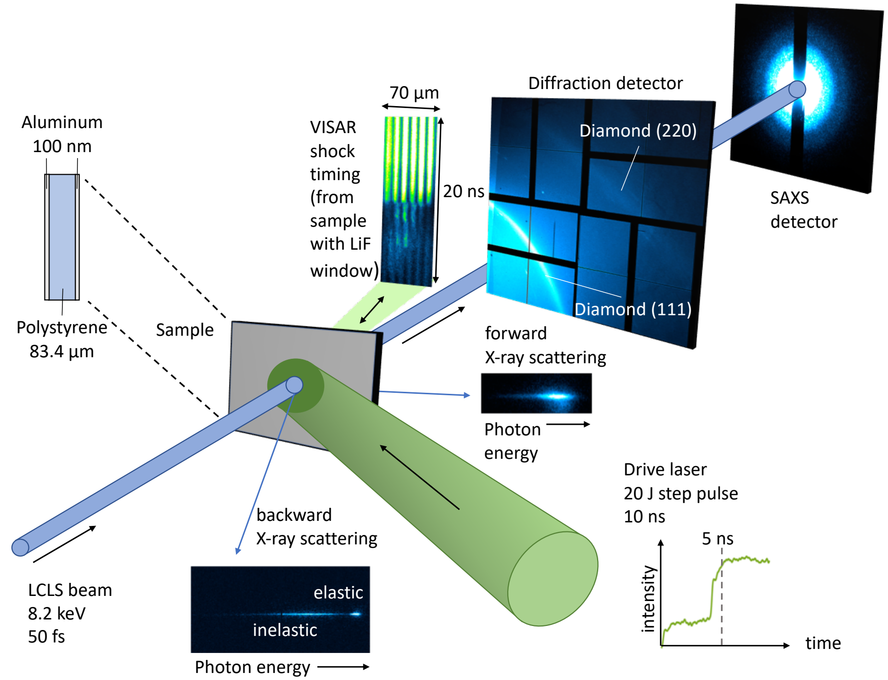
Combining various X-ray diagnostics in one experiment is extremely powerful!

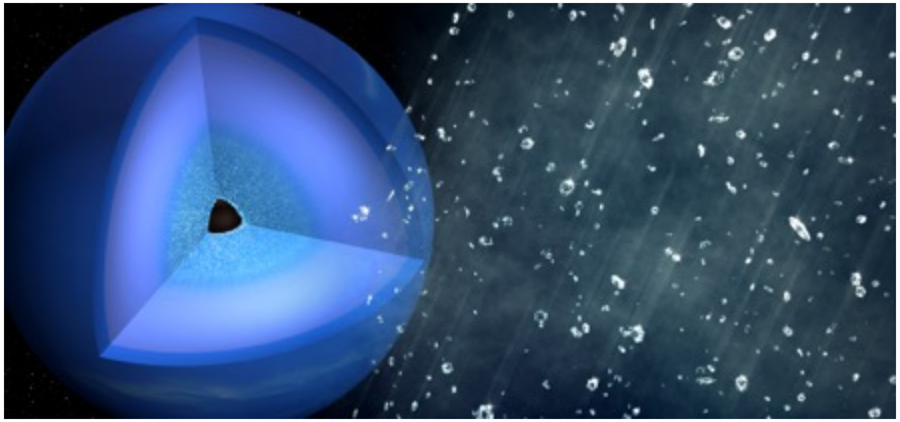
Just the beginning of studies like this!
→ e.g. HED / HIBEF at XFEL.EU

HiBEF

www.hibef.eu

European XFEL





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Collaboration LL58

D.Kraus, J. Vorberger, A. Pak, N. J. Hartley, N. Alexander, L. B Fletcher, S. Frydrych, E. Galtier, E. J. Gamboa, D. O. Gericke, S. H. Glenzer, E. Granados, M. MacDonald, A. J. MacKinnon, E. E. McBride, I. Nam, P. Neumayer, M. Roth, A. M. Saunders, P. Sun, T. van Driel, T. Döppner, R. W. Falcone

Collaboration LP34

D. Kraus, N. J. Hartley, A. K. Schuster, K. Rohatsch, I. Prencipe, M. Rödel, A. Laso, A. Pelka, T. E. Cowan, A. Ravasio, S. Frydrych, T. Döppner, H. J. Lee, E. E. McBride, S. Brown, P. A. Heiman, D. O. Gericke E. Cunningham, P. Sun, M. Schörner, E. J. Gamboa, R. Redmer, S. H. Glenzer, A. E. Saunders, M. M. MacDonald, R. W. Falcone, S. J. Demaio-Turner, A. Zettl, M. Schölmerich, J. Vorberger

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Lawrence Livermore National Laboratory

Berkeley UNIVERSITY OF CALIFORNIA

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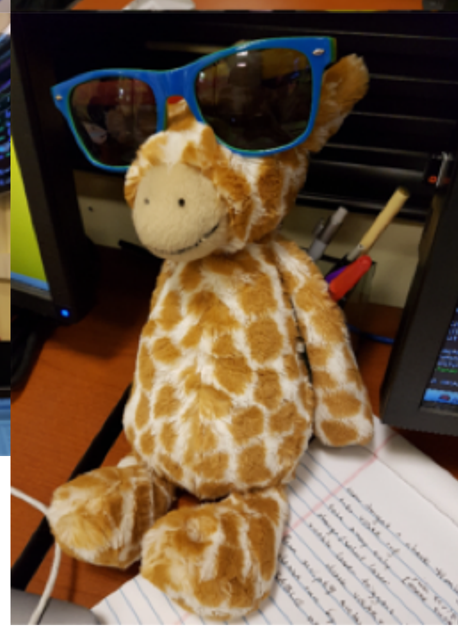
UNIVERSITÄT ROSTOCK gegründet 1419

THE UNIVERSITY OF WARWICK

European XFEL



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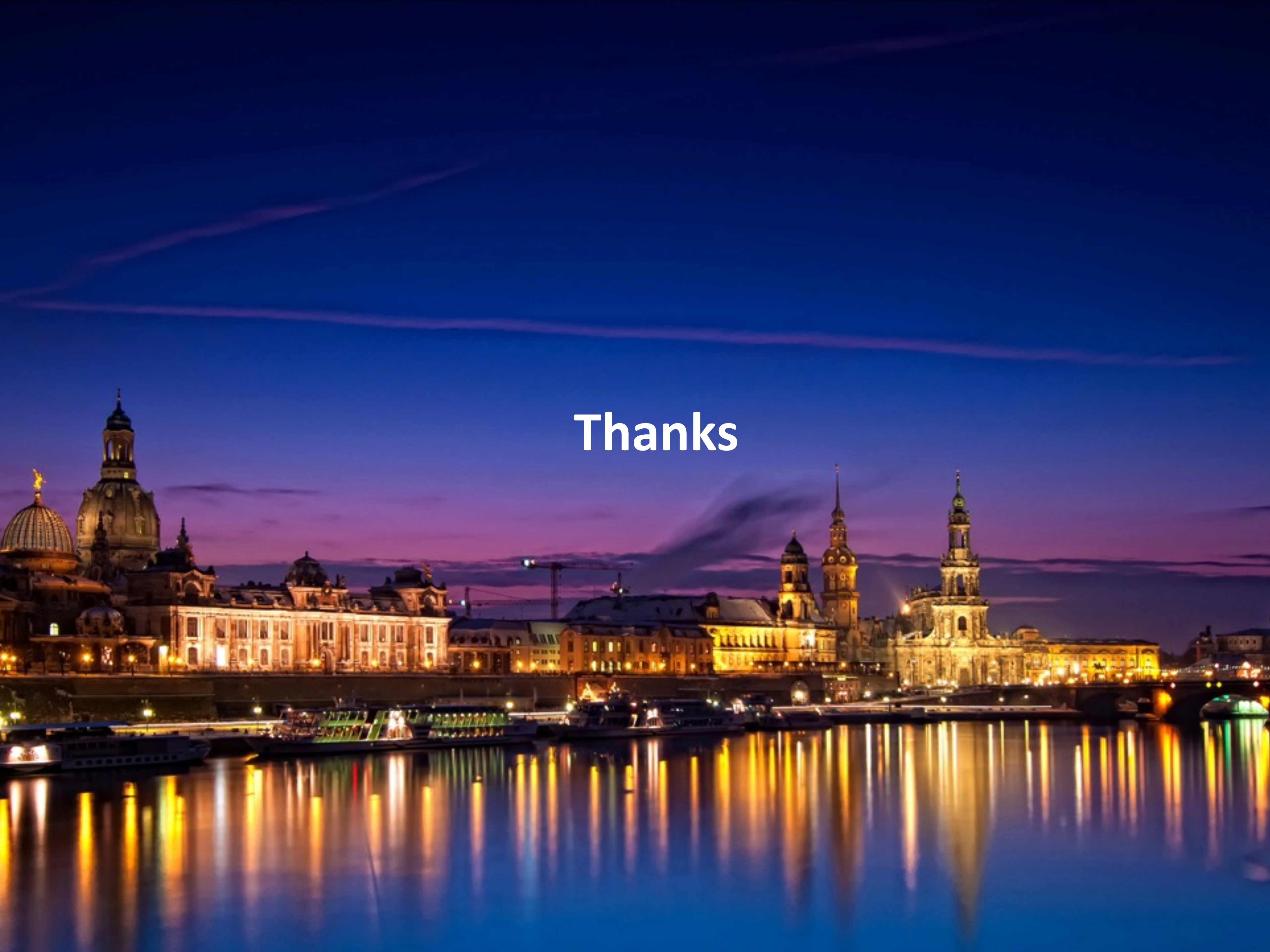
Thanks