Visualizing the transformation of matter in extreme conditions

Siegfried H. Glenzer (SLAC)

June 8th, 2017

Presentation to:

Lawrence Livermore National Laboratory

HED Physics Seminar

Outline

- Introduction
  - What is High Energy Density Physics?
  - Why the answer matters and some insights
- The Axes of the Extremes
- New Discovery Science experiments
  - Insights from the Linac Coherent Light Source
  - Investigate the physics of brown dwarfs on NIF
- Conclusions and Outlook

This presentation includes contributions from a large collaboration

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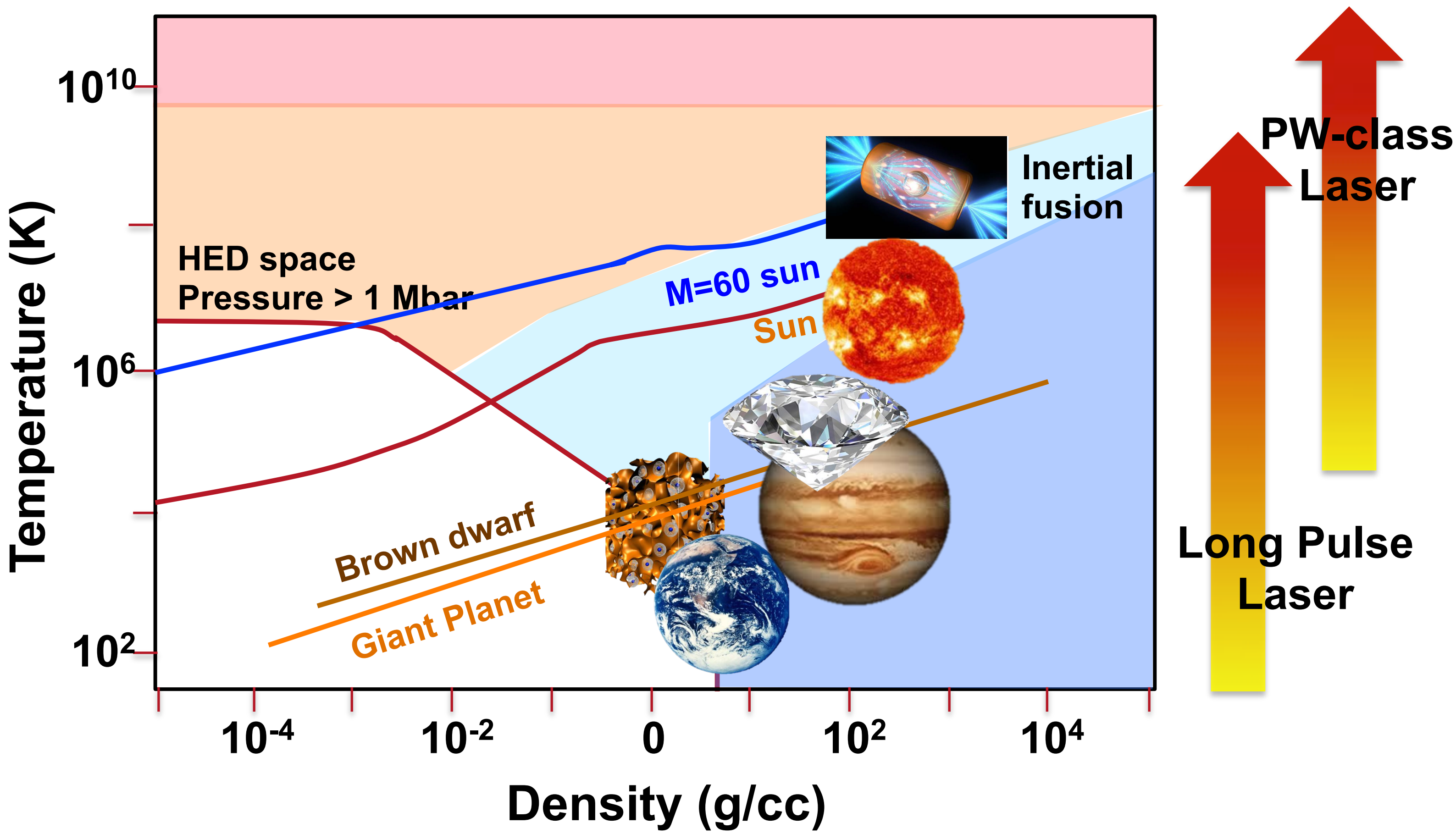
- **LCLS, USA**
  E. Gamboa, H.J. Lee, D. Milathianaki, L. Fletcher
- **UC Berkeley /LBNL, USA**
  R.W. Falcone (PI),
  D. Kraus*, M. MacDonald, A. Saunders
  *now with HZDR Dresden
- **LLNL, USA**
  T. Doeppner, A. Kritcher, B. Bachmann, D. Swift, J. Hawreliak, J. Gaffney, S. Hamel, L. Benedict, A. Pak, C. Weber, P. Sterne, C. Mauche, J. Nilson, P. Celliers, O. Landen, G. Collins, A. Jenei, L. Divol
- **University of Warwick, UK**
  D. Gericke, R. Baggott
- **Univ. of Rostock, Germany**
  R. Redmer (PI), B. Witte, P. Sperling, R. Bredow
- **Sandia Nat'l Lab**
  S. Hansen
- **Polymath**
  B. Afeyan
- **GSI, Germany**
  P. Neumayer (PI)
  B. Borm
- **AWE, UK**
  D. Chapman,
  S. Rothman
- **LANL, USA**
  A. Yi, J. Kline
- **XFEL/DESY,**
  C. Fortmann,
  S. Toleikis

The High Energy Density Science discovery space



A majority of interested scientists/students find it difficult to connect with this picture

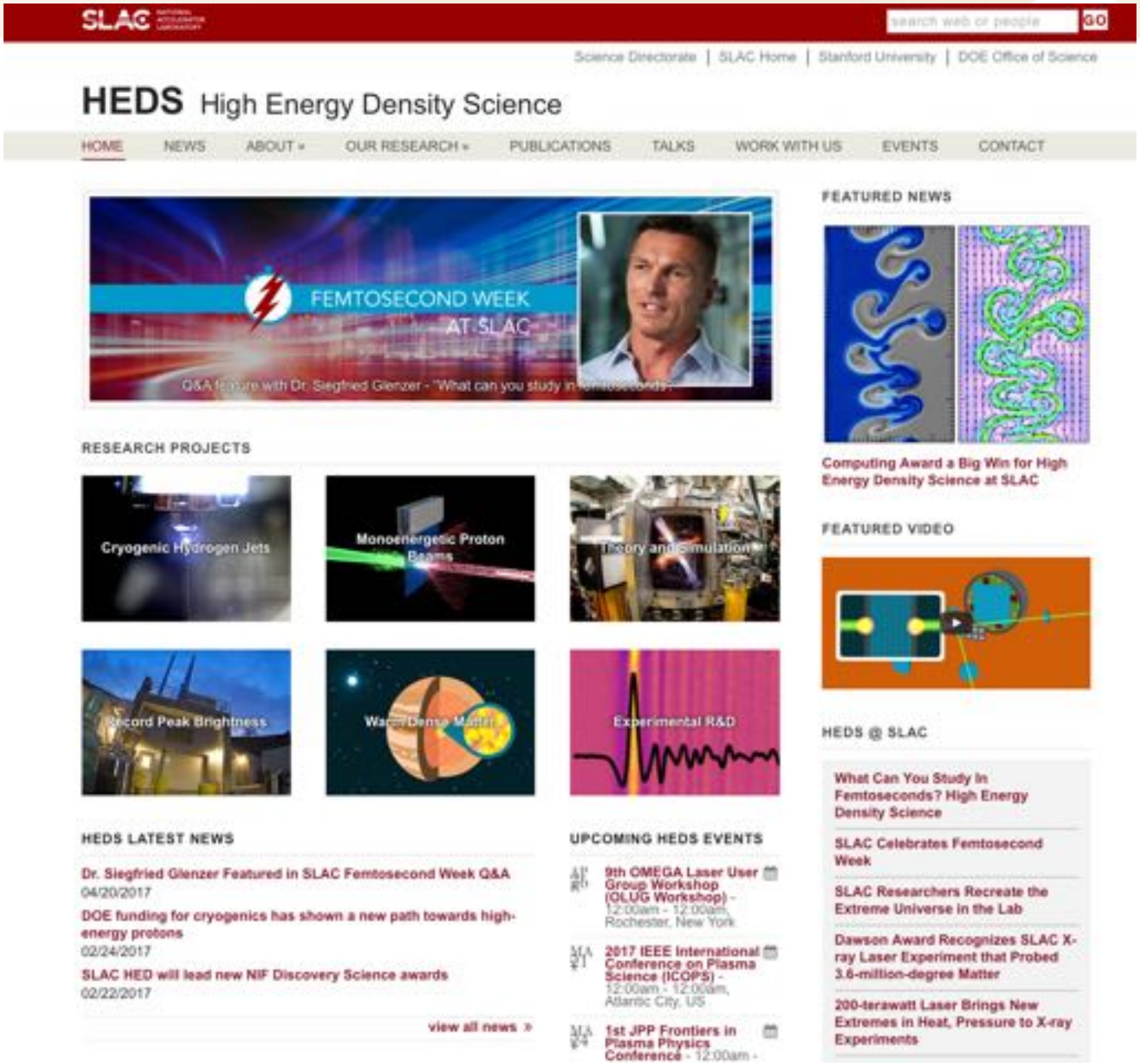
A new definition…

- The Generation, Study and Control of Self-Organization, Far From Equilibrium, through the Action of Intense Fields

- That is the mission of HEDP to demonstrate and make possible. The study of states far from equilibrium finding nonlinear self-organized stability

Bedros Afeyan, 2017

We defined a new program that pushes the extremes;
- became a major attraction to students and postdocs



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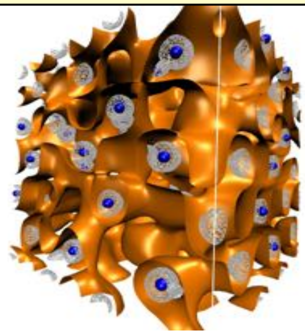
The Axes of the Extremes

Structure of Warm Dense Matter

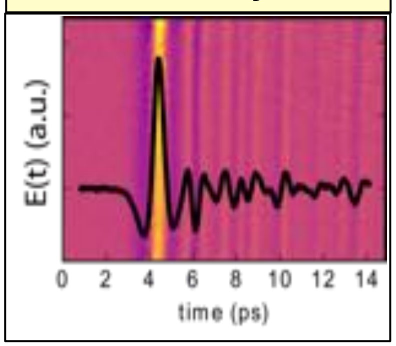


Diamond formation under compression

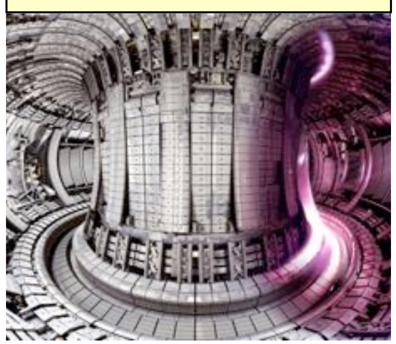
Properties of Hydrogen

Non-equilibrium Water ultrafast heating

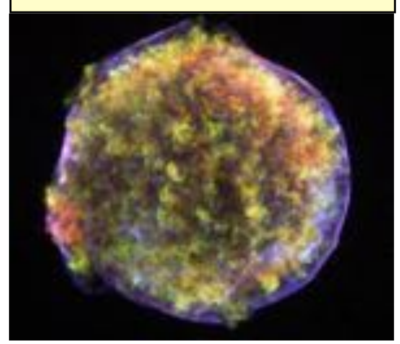
From THz, VUV to hard X-rays



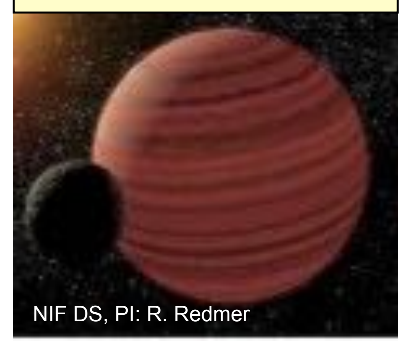
Materials under extreme Radiation



Origin of Cosmic Rays Extreme B fields

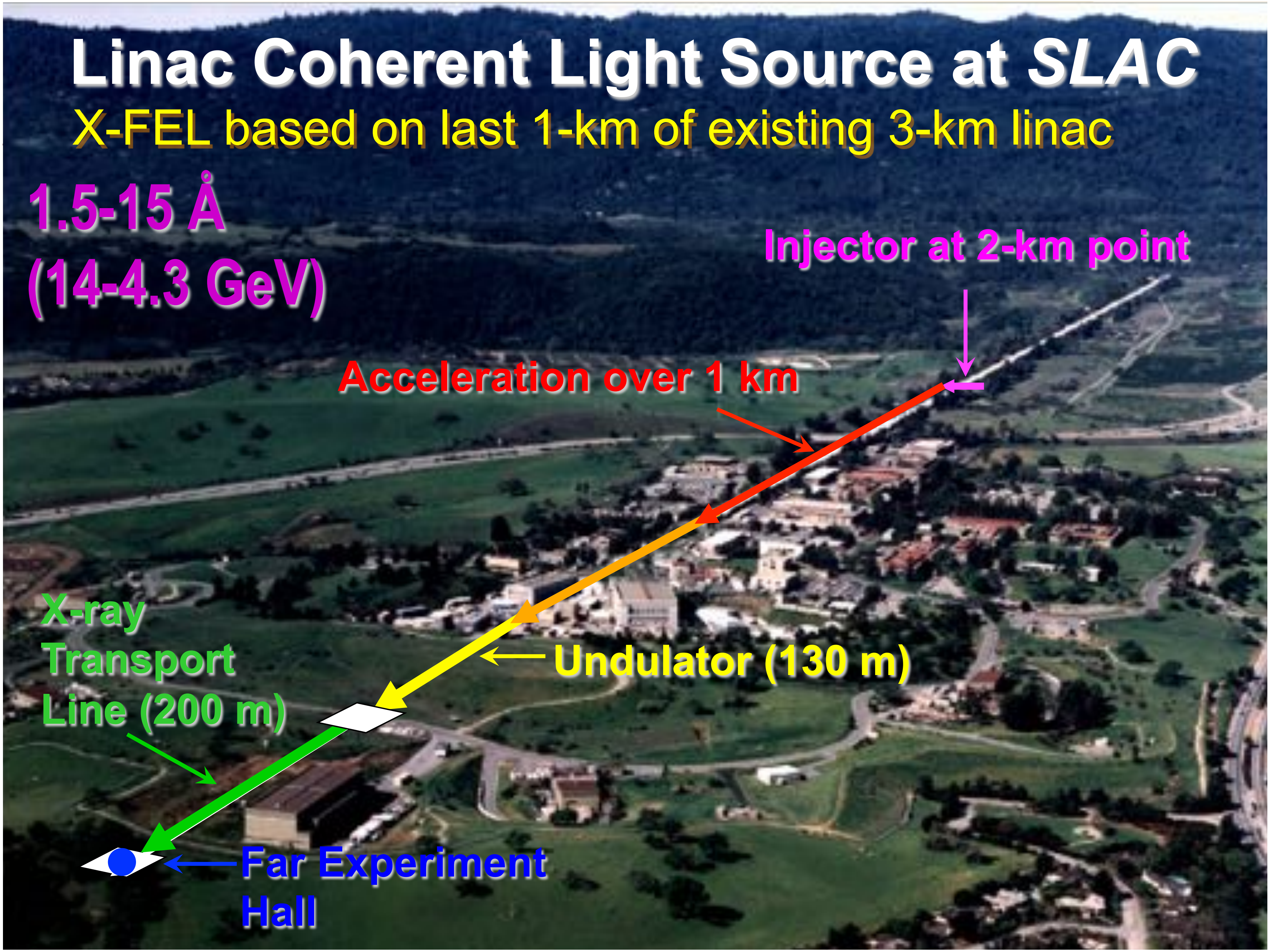


Physics of Brown Dwarfs

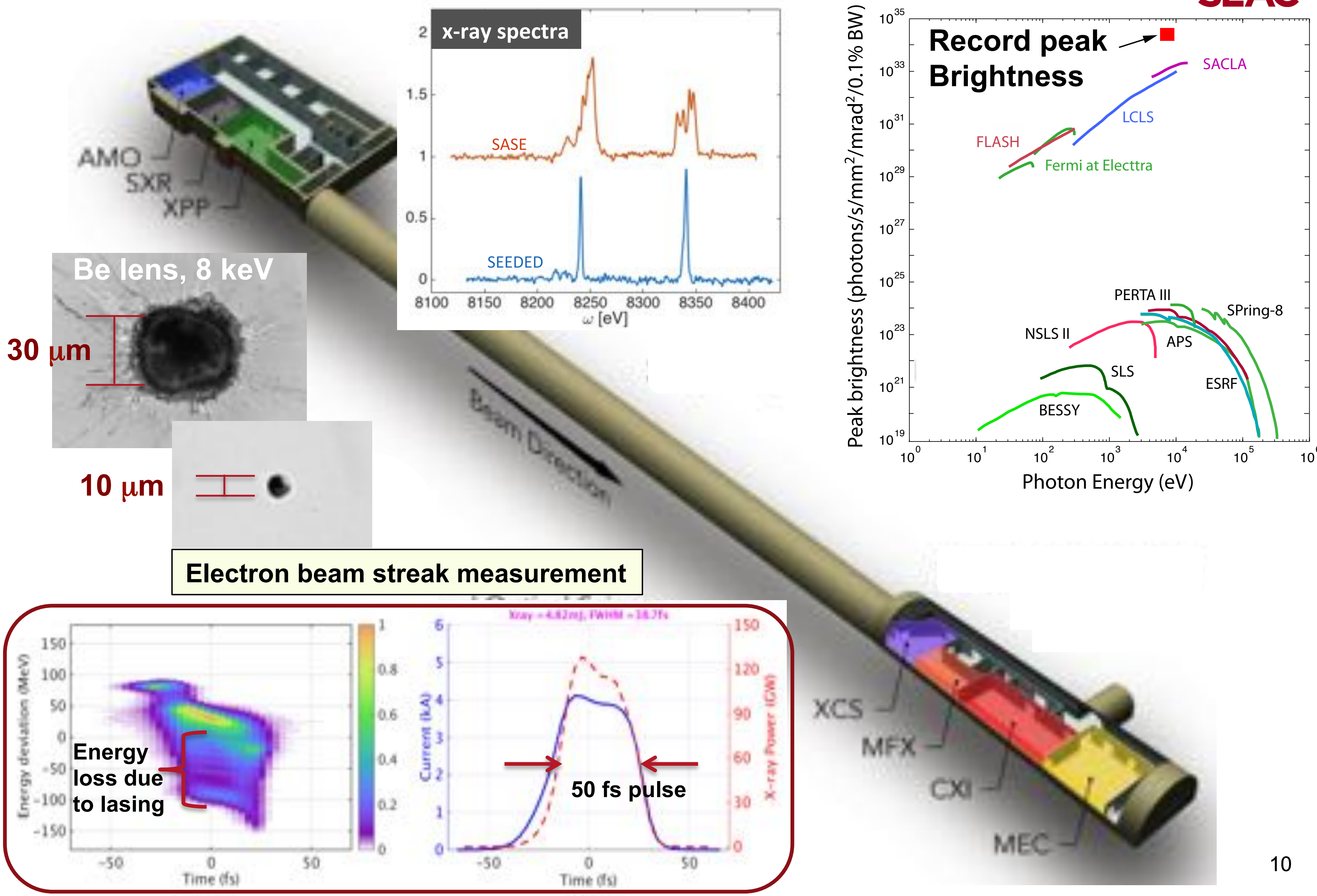


Linac Coherent Light Source at *SLAC*

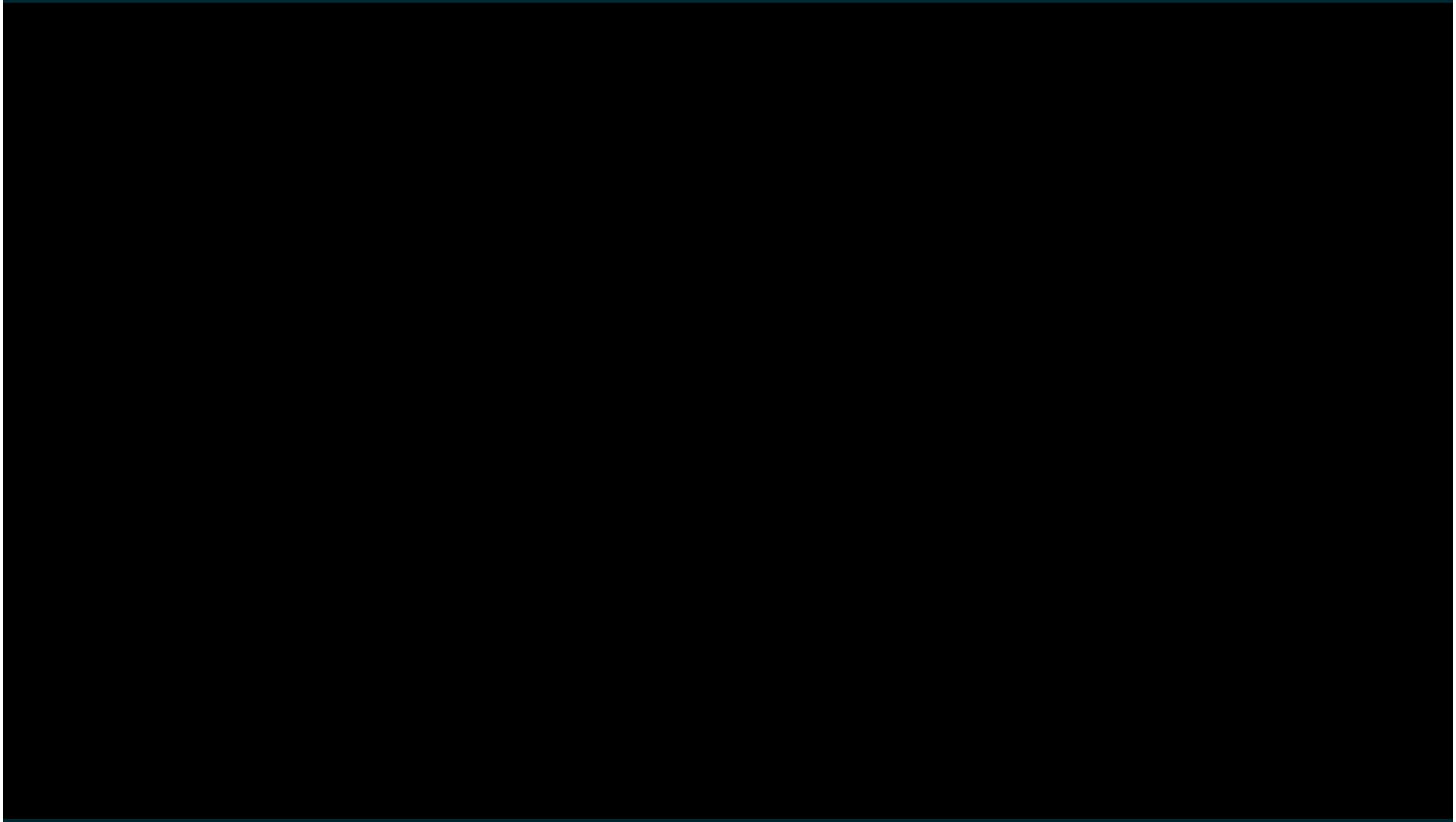
X-FEL based on last 1-km of existing 3-km linac



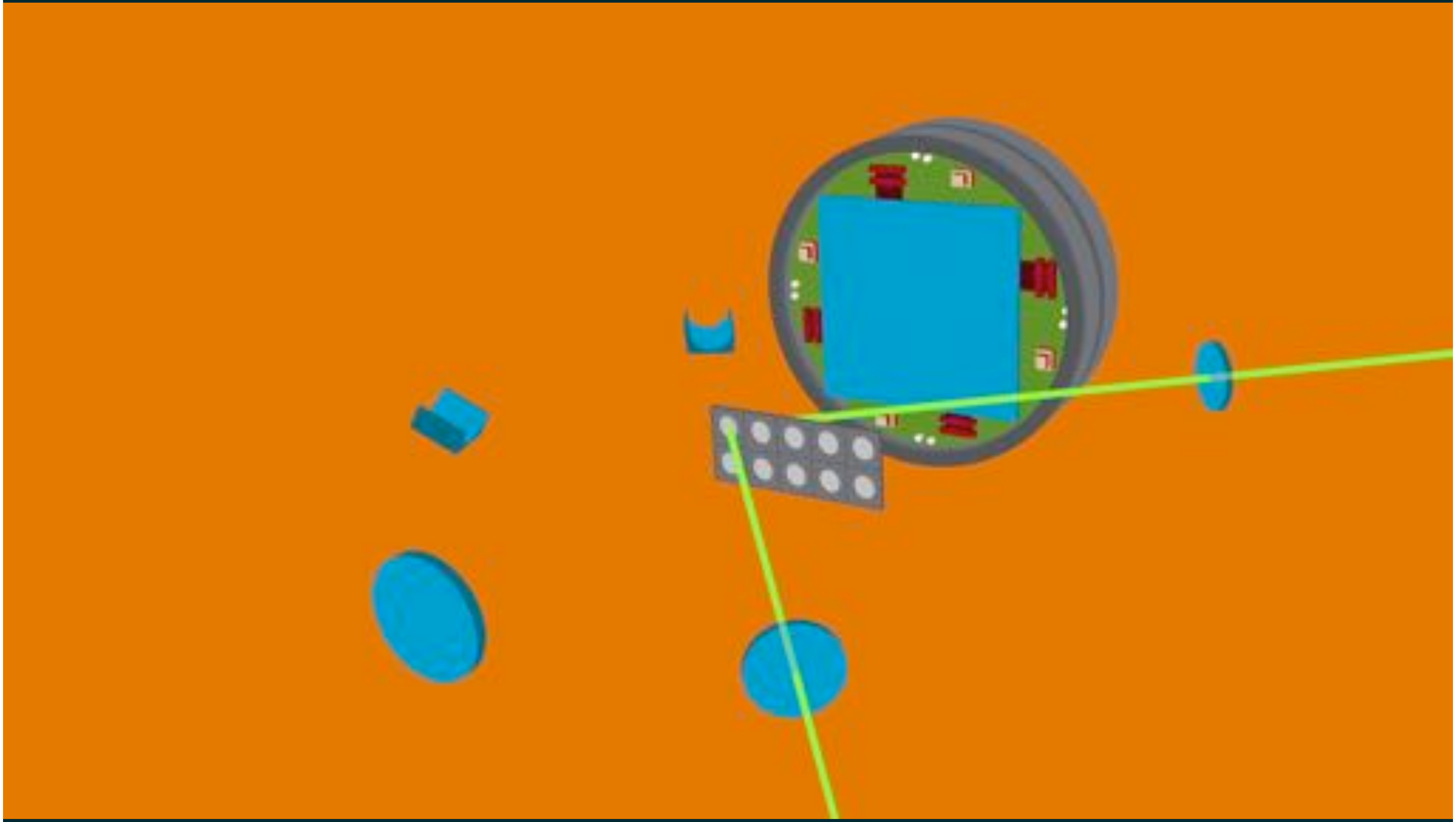
LCLS is an instrument to access extreme conditions



Matter in Extreme Conditions (MEC)

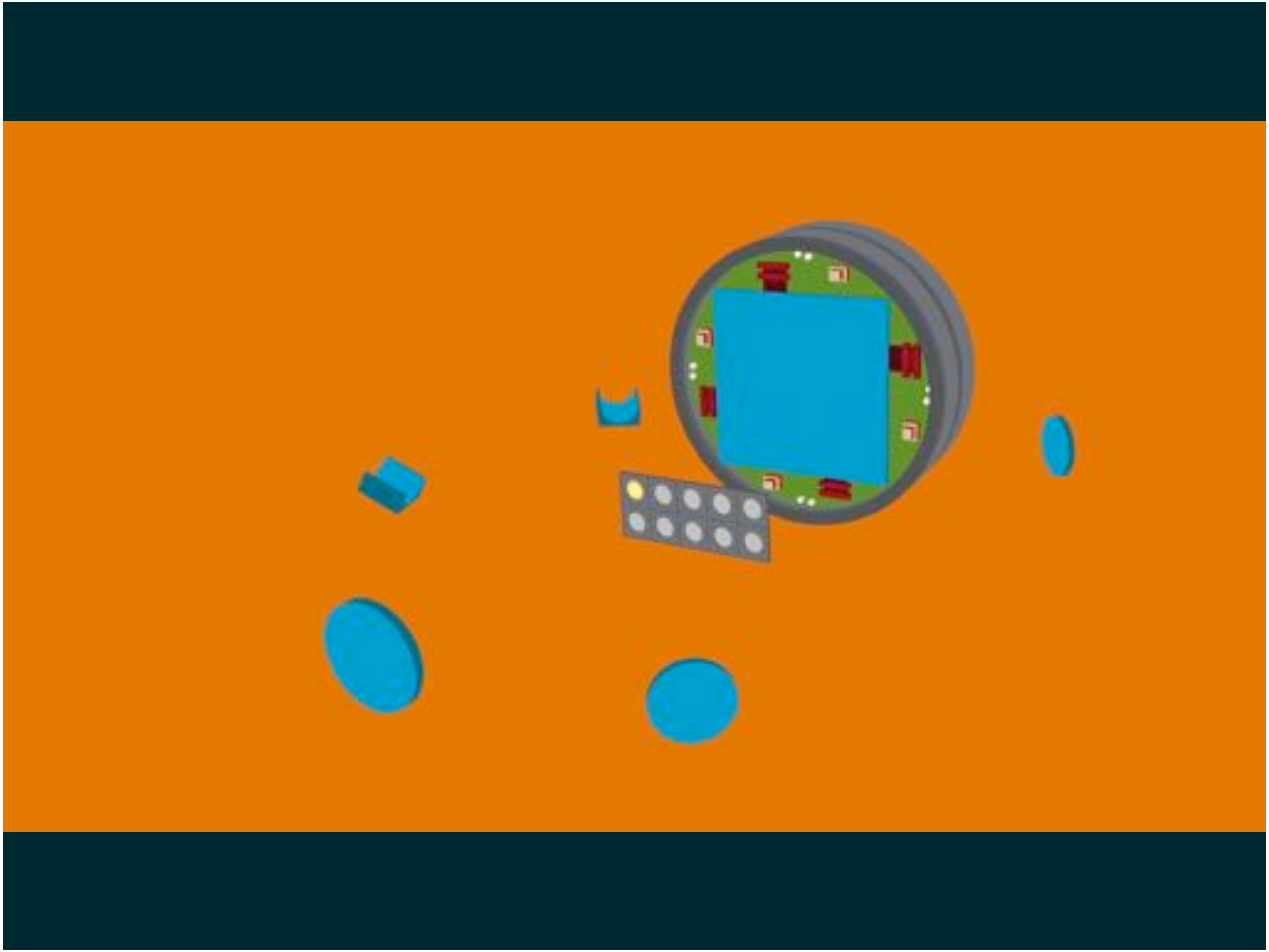


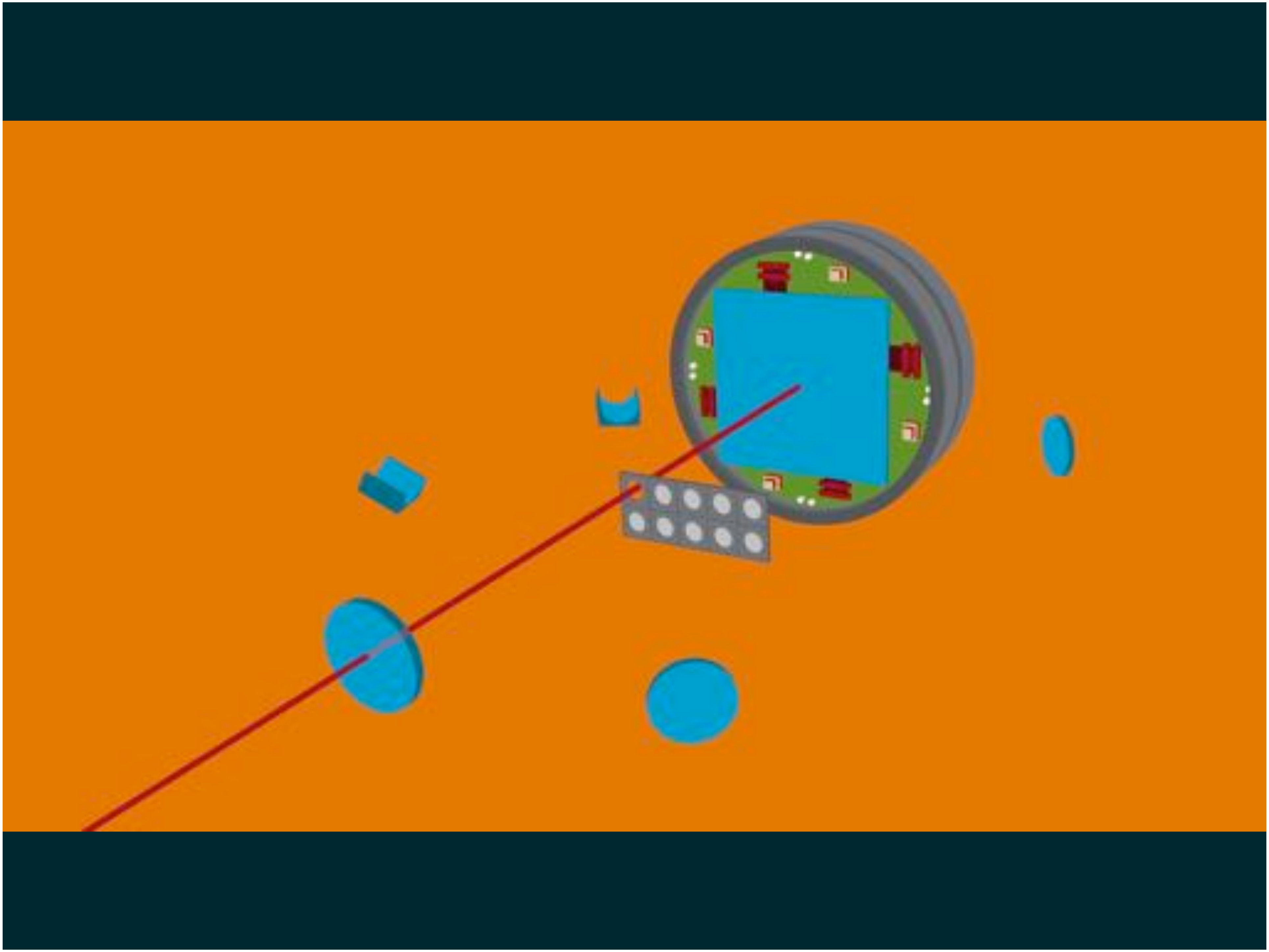
Shaped nanosecond glass laser

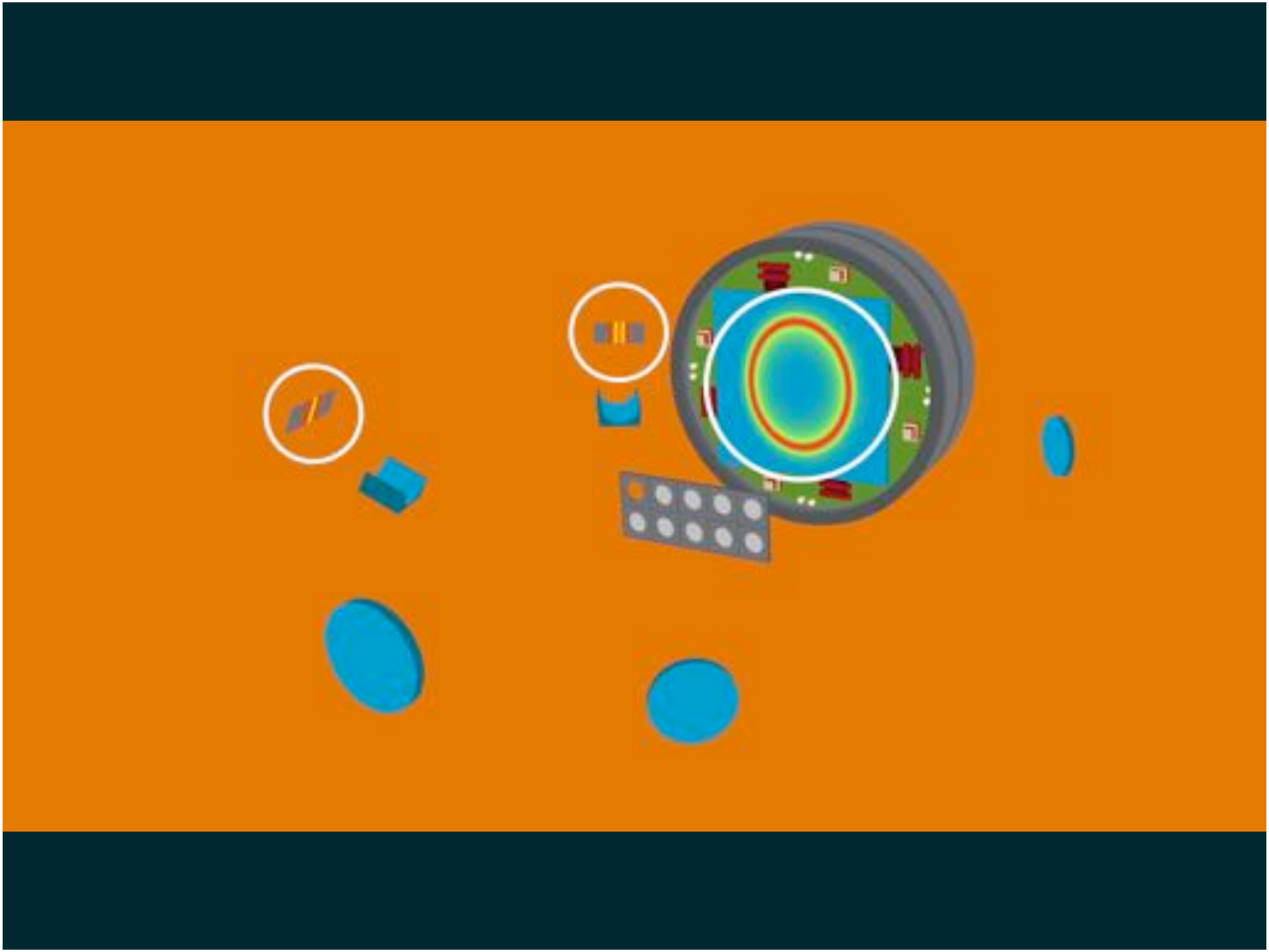


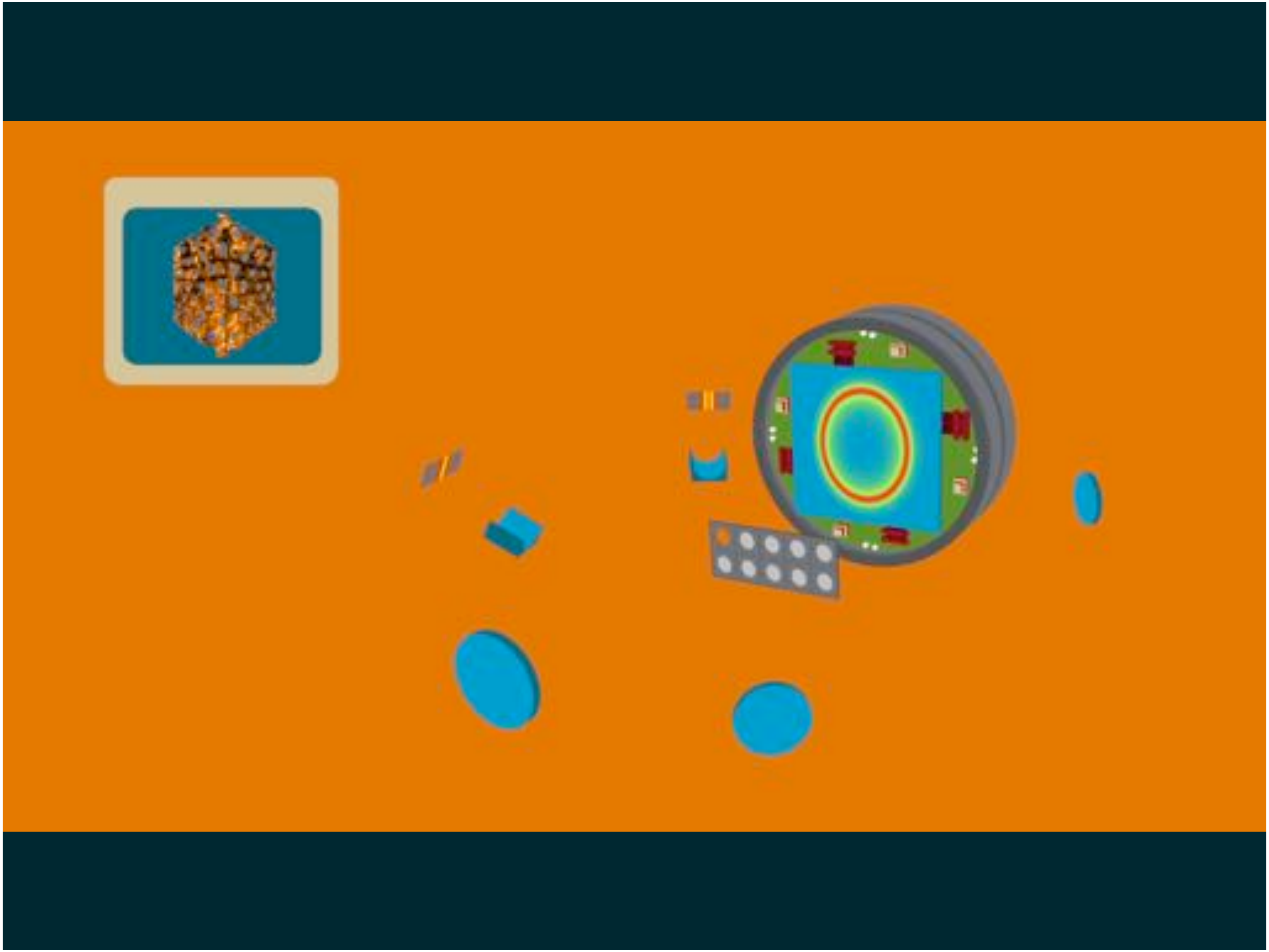
Newton's third law:

Action = Reaction

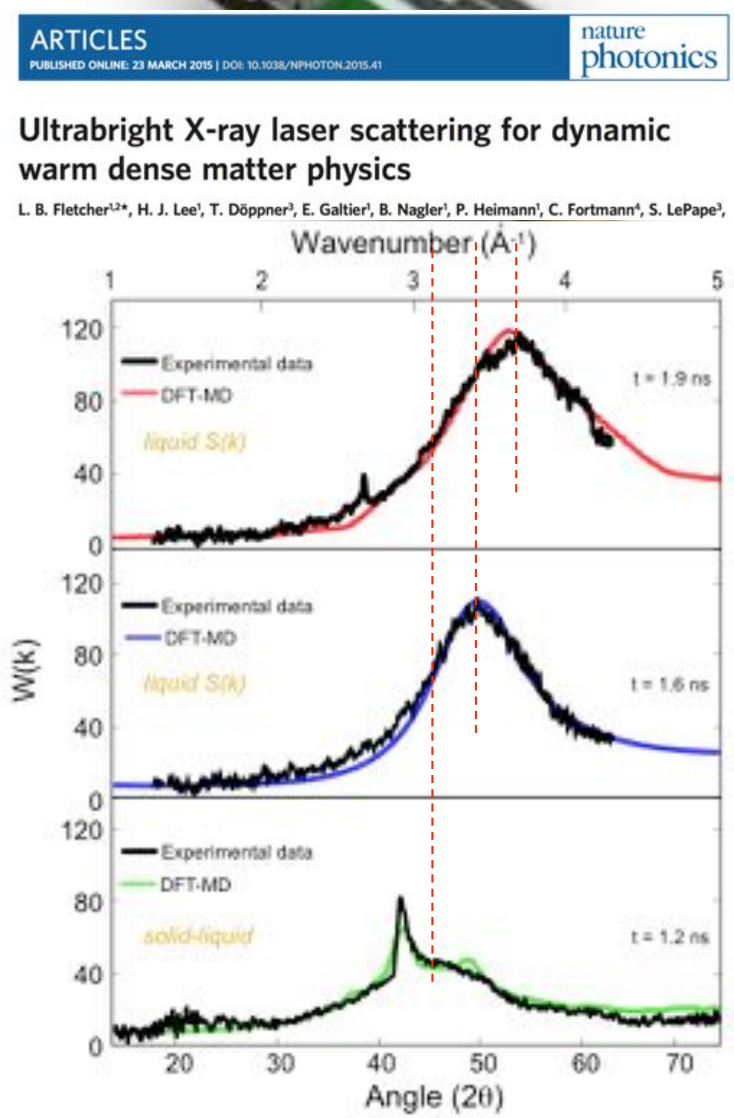


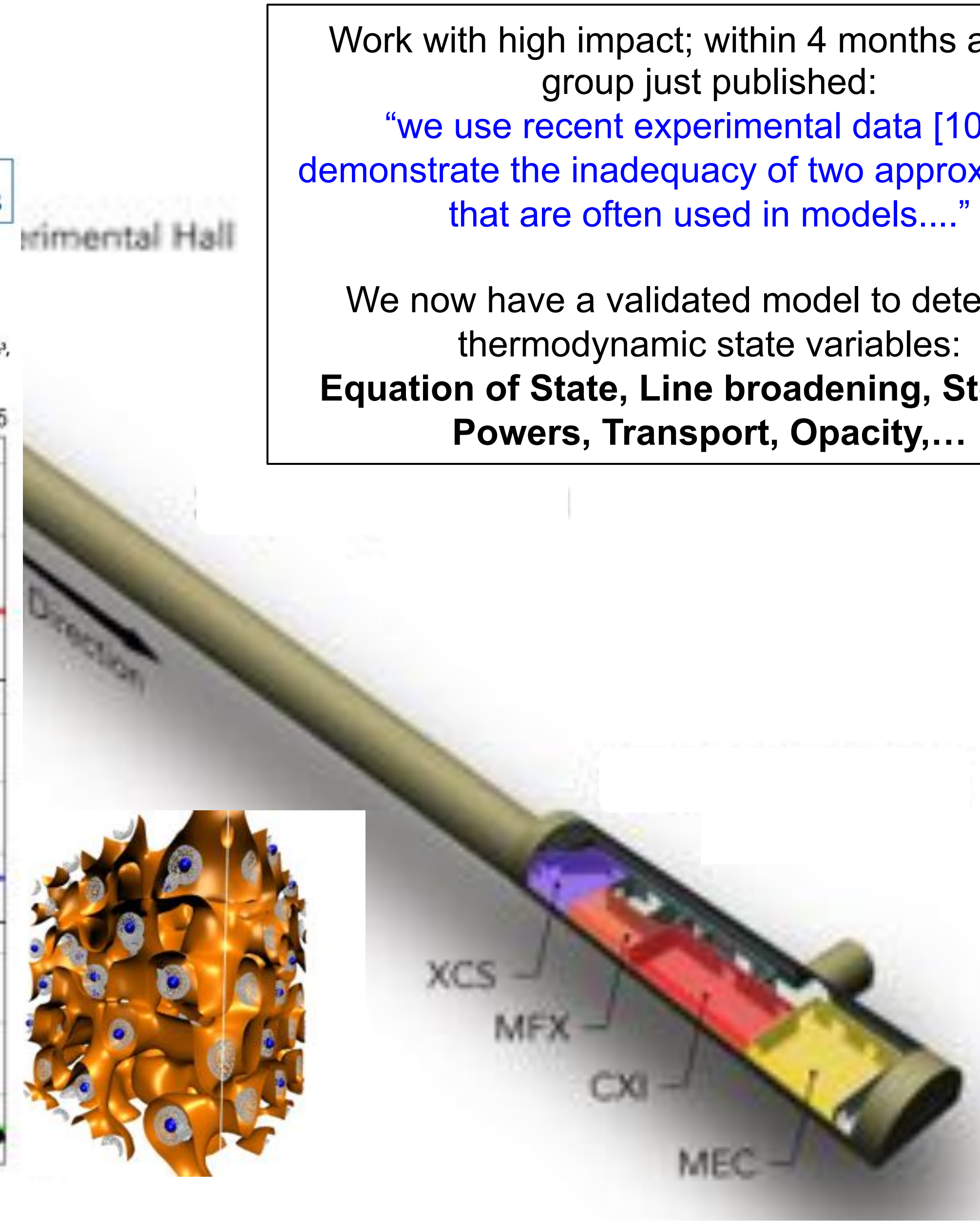






Record peak brightness experiments have validated DFT simulations of warm dense matter





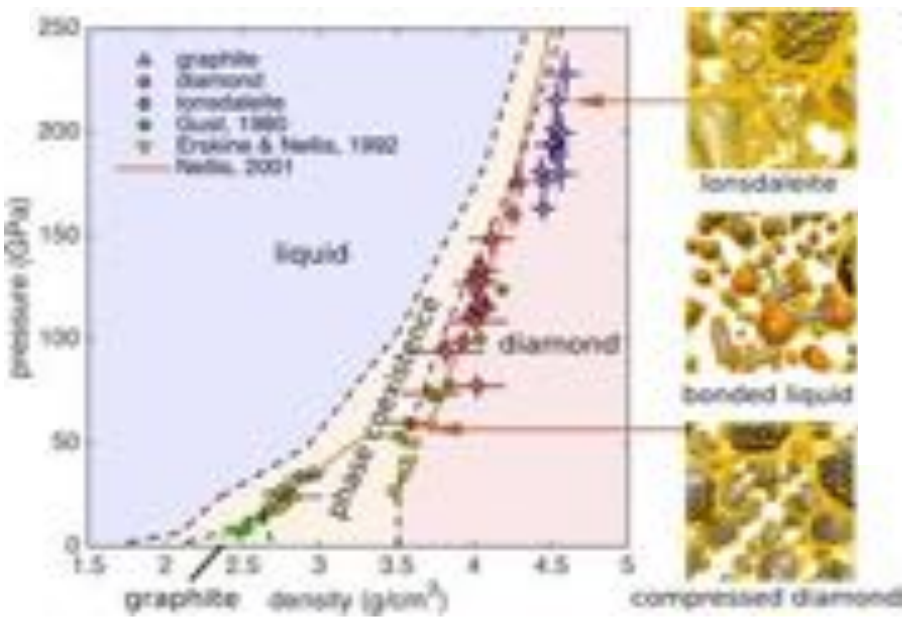
Work with high impact; within 4 months another group just published:
"we use recent experimental data [10] to demonstrate the inadequacy of two approximations that are often used in models...."

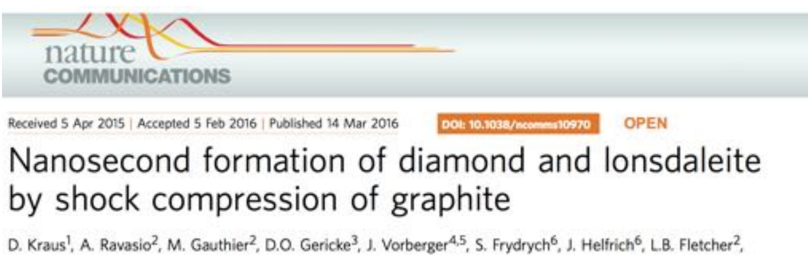
We now have a validated model to determine thermodynamic state variables:
Equation of State, Line broadening, Stopping Powers, Transport, Opacity,…

Dynamic compression experiments have resolved diamond formation and possibly provide strength

Ultra-bright LCLS x-rays have observed lonsdaleite, ie hexagonal diamond

Experiments on the diamond Hugoniot indicate elastic plastic waves




nature COMMUNICATIONS

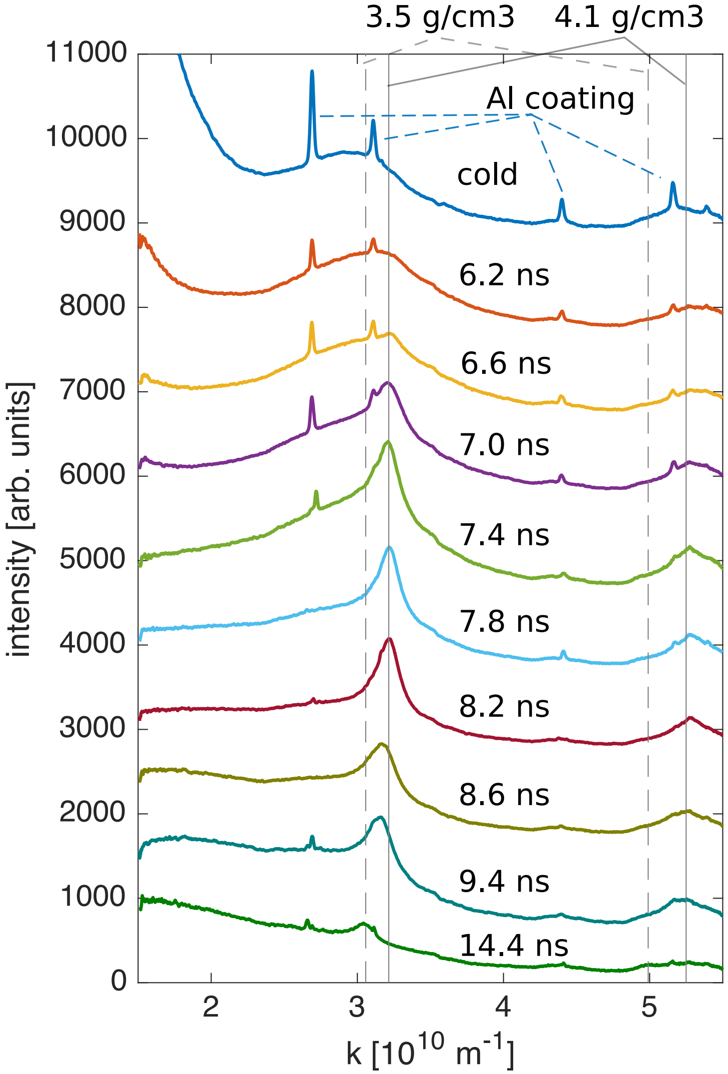
Received 5 Apr 2015 | Accepted 5 Feb 2016 | Published 14 Mar 2016 DOI: 10.1038/ncomms10970 OPEN

Nanosecond formation of diamond and lonsdaleite by shock compression of graphite

D. Kraus[1], A. Ravasio[2], M. Gauthier[2], D.O. Gericke[3], J. Vorberger[4,5], S. Frydrych[6], J. Helfrich[6], L.B. Fletcher[2],

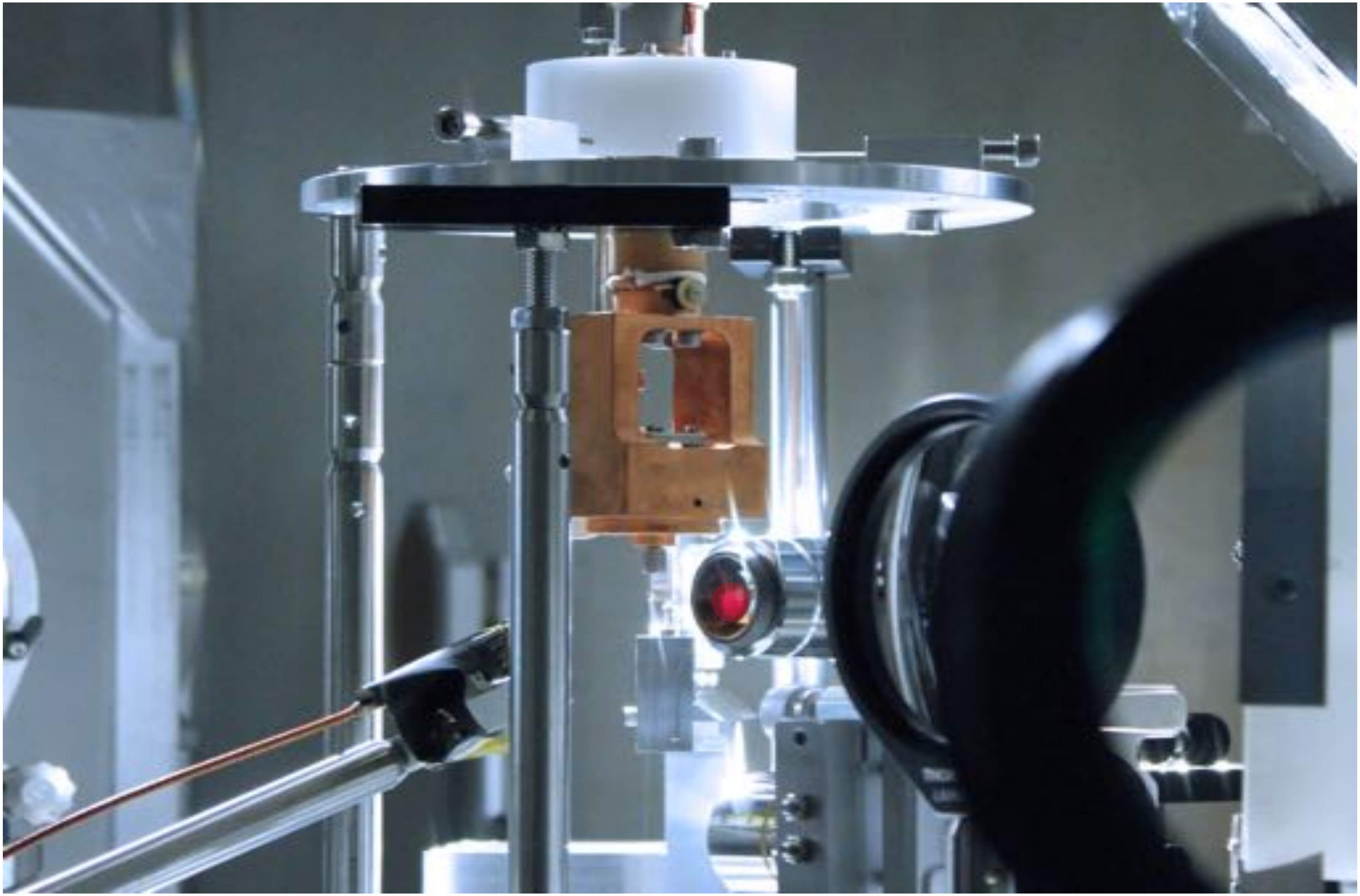
A big surprise: nano-diamonds form by compressing plastic (CH) foils

Observation of strong diamond diffraction at 200 GPa



- **Important for planetary models and understanding of kinetics in dynamic compression**

We have developed cryogenic jets for 120 Hz experiments



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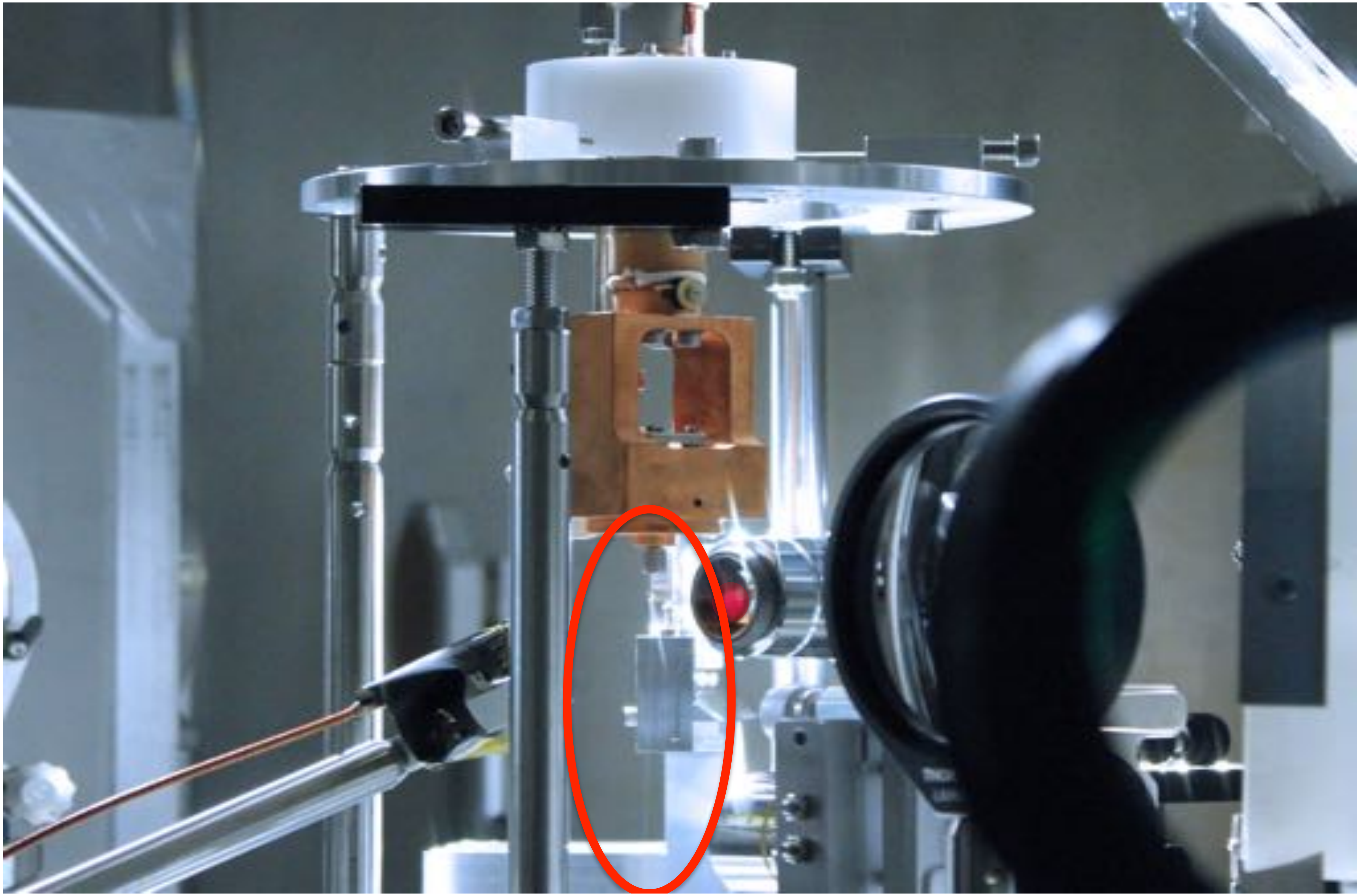
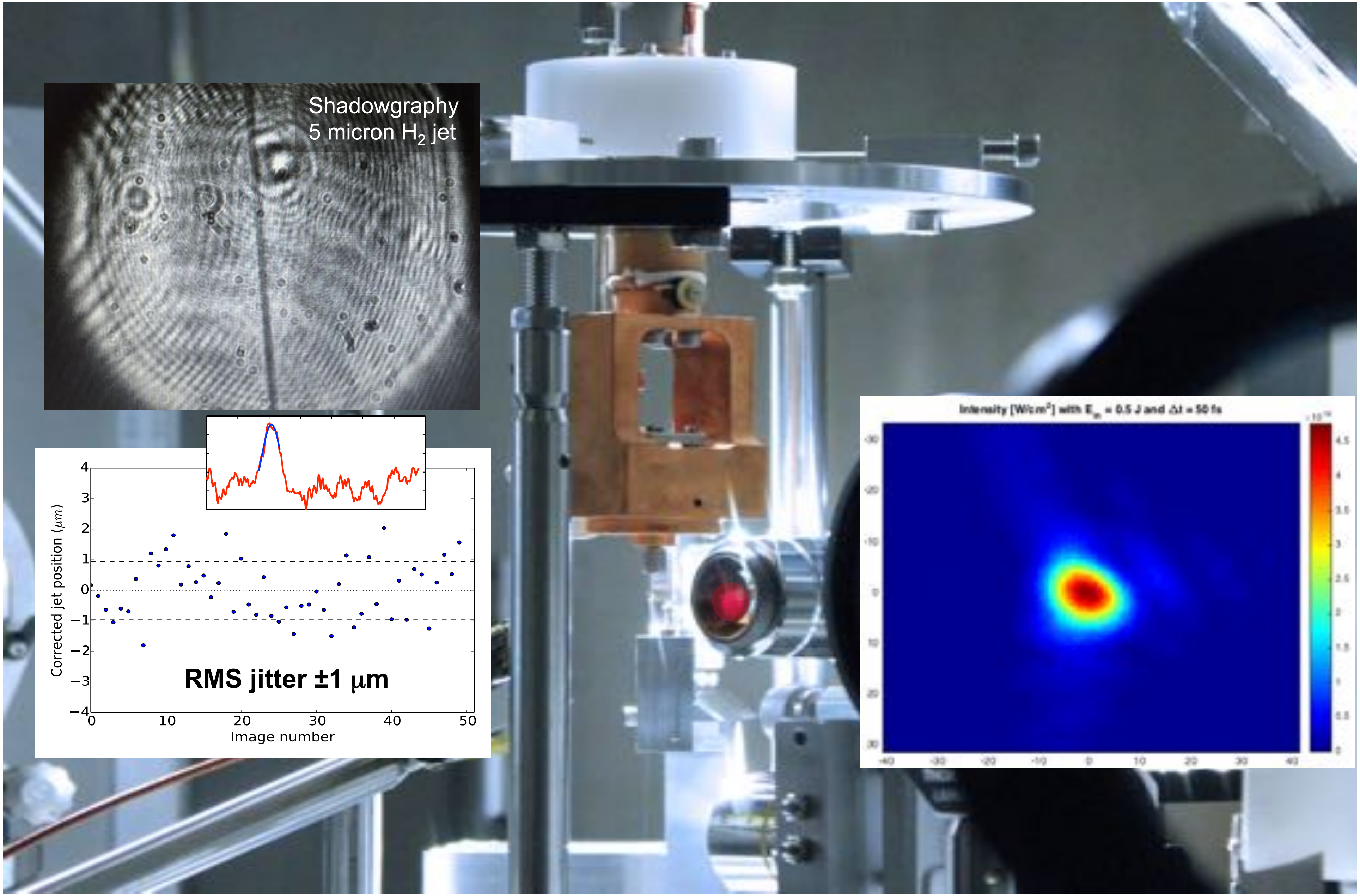


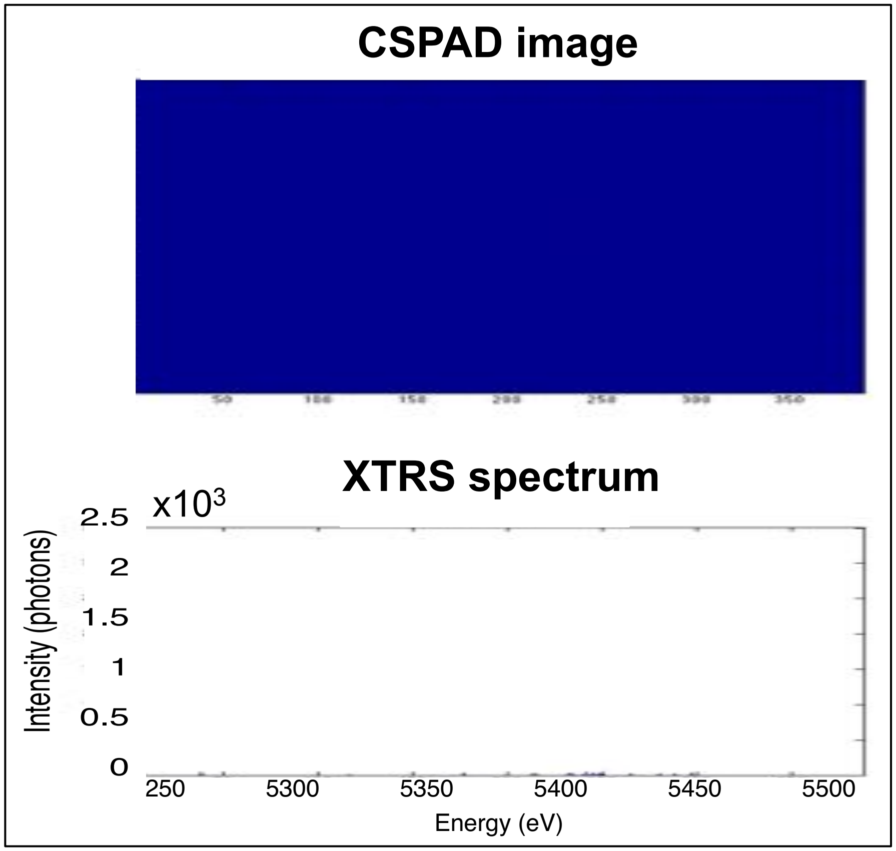

You see with your eyes:
1/10th the diameter of a human hair
Jet: 5 μm
Human hair: ~50 μm

Super-cooled hydrogen icicle

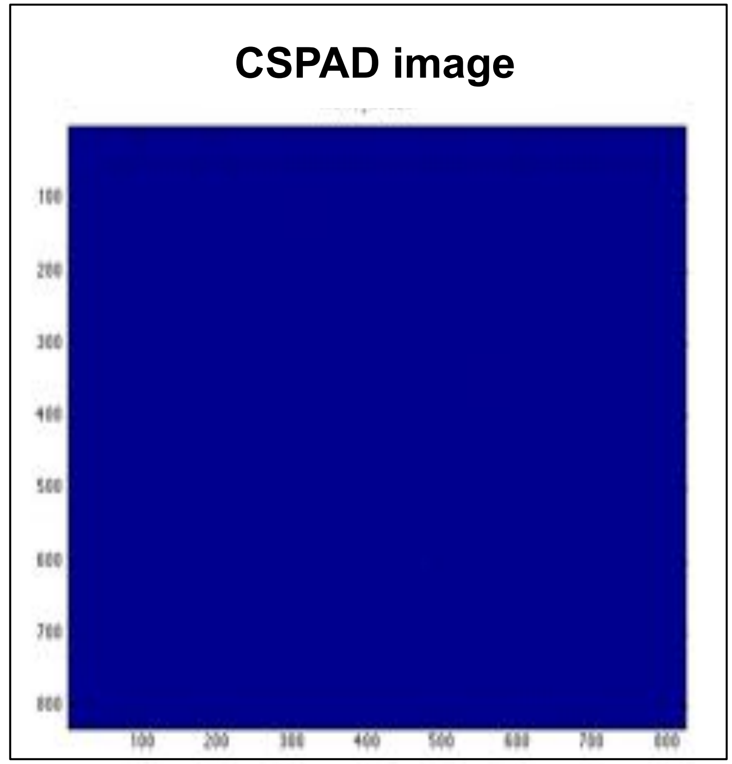


X-ray scattering at 120 Hz

Inelastic single photon x-ray detection (170^0) @ 120 Hz

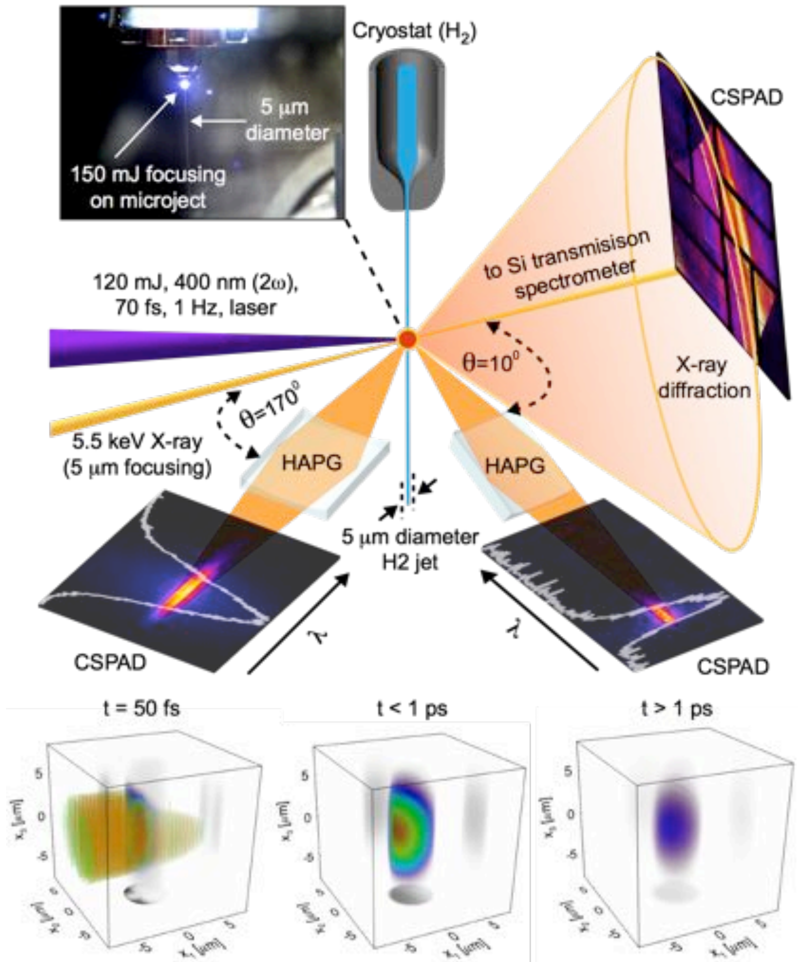


Single crystal x-ray diffraction (30^0-55^0) @ 120 Hz



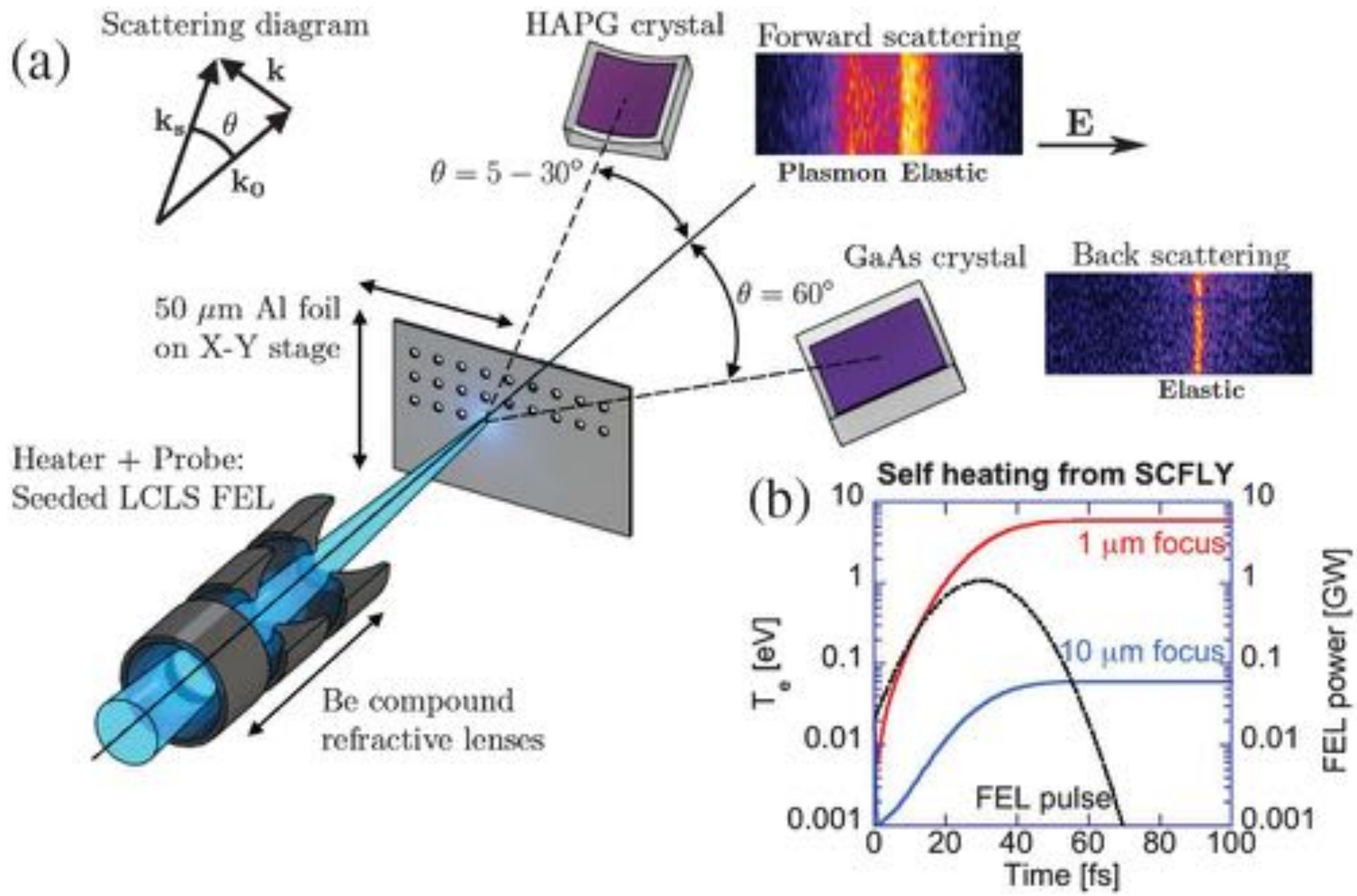
	500 shots	5,000 shots
120 Hz	4 seconds	40 seconds
5 Hz	2 minutes	17 minutes

The experiments show that quantum kinetic theories are needed to explain equilibration time



Recent Theories which include electron degeneracy and coupling with collective ion modes (Vorberger '10, Daligaud '16) agree with experiment

New discovery science experiments on NIF are motivated by LCLS self-heating experiments



LCLS:

$\Delta E/E = 25\text{x}10^{-4}$

E_{ph} = 7.98 keV

t_{FWHM} = 25 fs

E = 0.1 mJ

d_{FWHM} = 1-10 μm

P. Sperling et al., Phys. Rev. Lett. **115**, 115001 (2015).

LCLS experiments show nonlinear damping; well-established BMA can not predict the width

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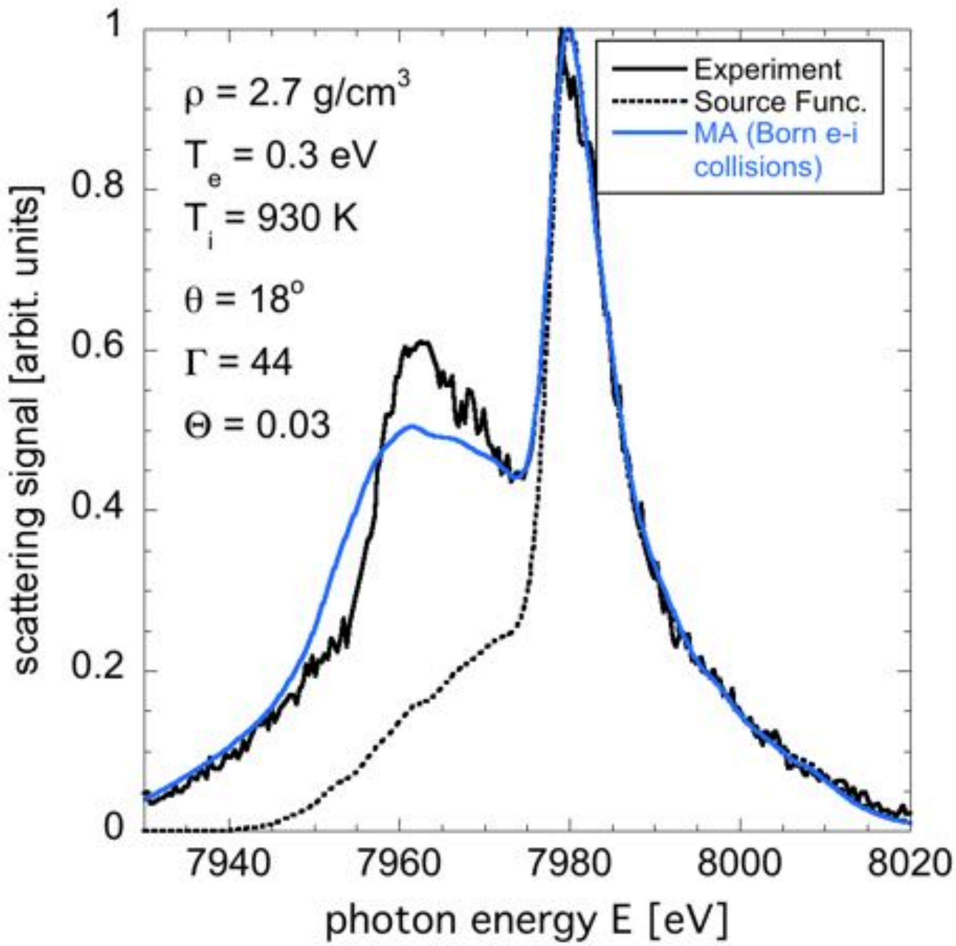
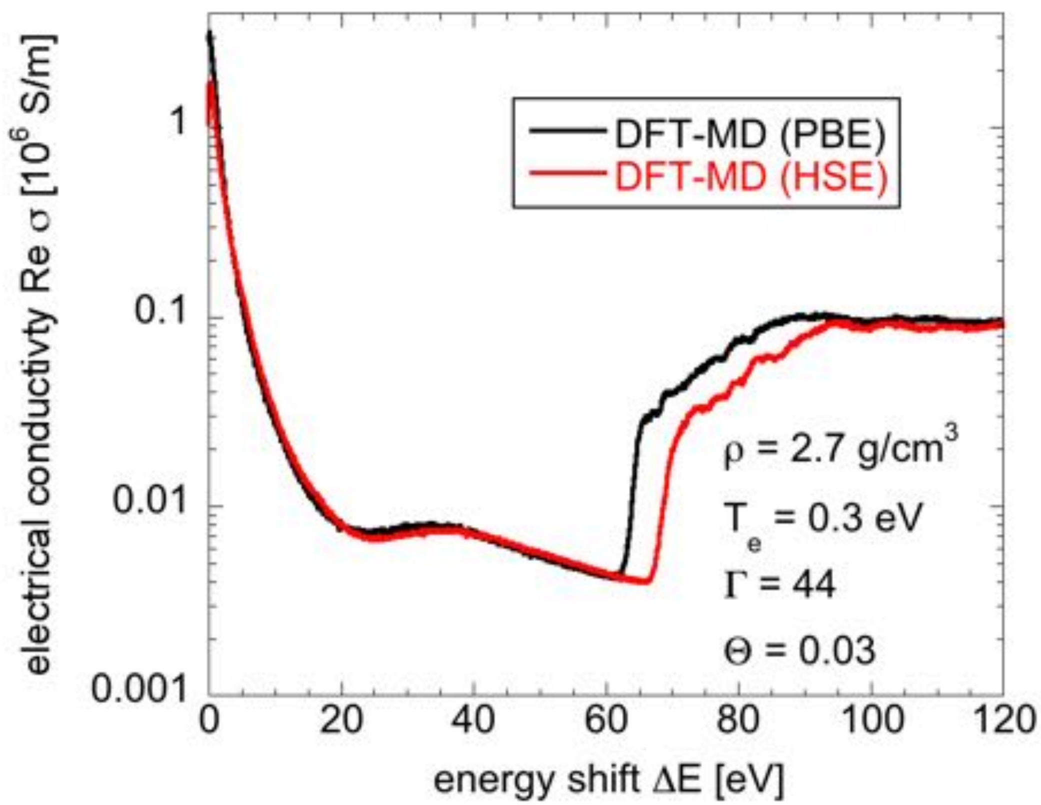


- **Experimental plasmon width is too narrow**
- **Dispersion appears to be matched**
- **Previous studies have shown agreement with both shift and width**
- **Temperature from detailed balance**

We have applied DFT-MD simulations to further analyze this effect

DFT-MD results are sensitive to the choice of the exchange functional

Conductivity calculated from Kubo-Greenwood formula



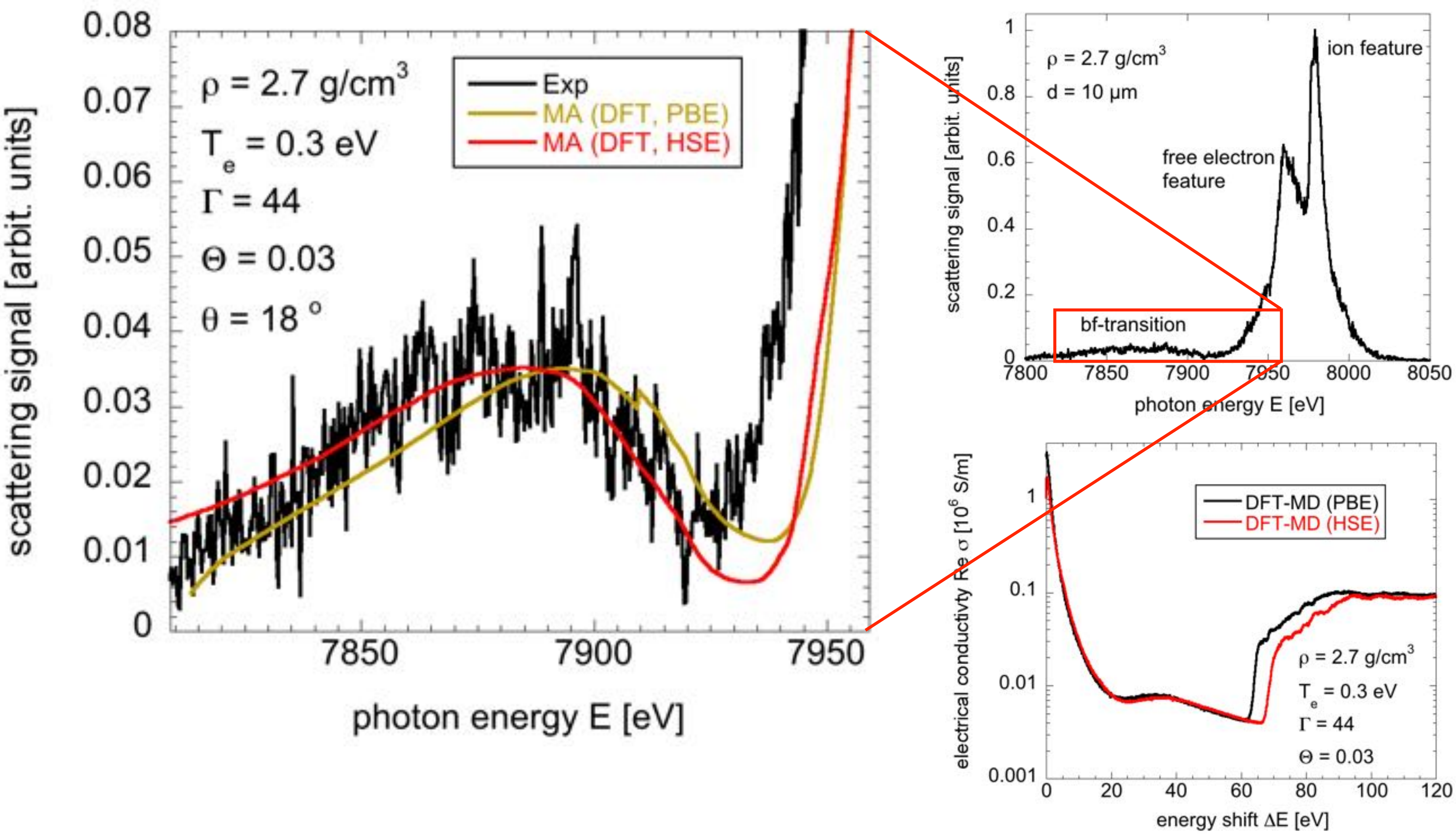
Conductivity show different effects:

- **Electron collisions**
- **Excitations of conduction band electrons**
- **Excitations of bound electrons**

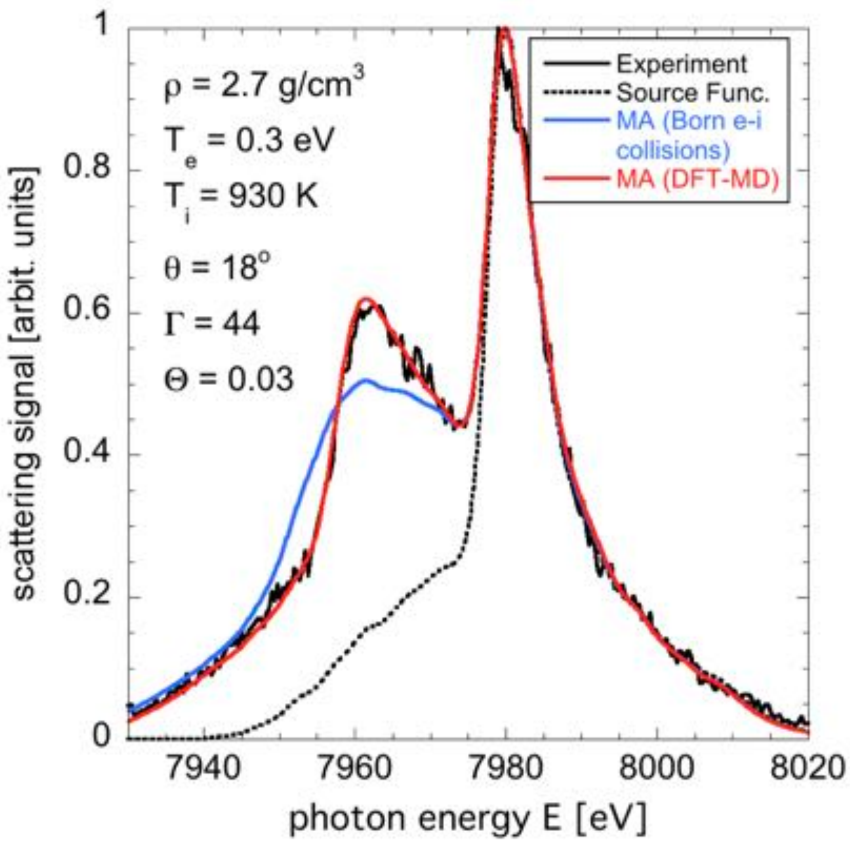
Difference between PBE and HSE functional:

- **dc conductivity (ΔE->0)**
- **ionization edge position**

The HSE functional reproduces experimental data



Nonlinear plasmon damping is due to electron excitations: effect opposite to what we predict for NIF



Extraction of collision frequency $\nu(\omega)$:

$$\mathrm{Re}\,\varepsilon(\omega) = 1 - \frac{1}{\varepsilon_0\omega}\mathrm{Im}\,\sigma(\omega)$$

$$\mathrm{Im}\,\varepsilon(\omega) = \frac{1}{\varepsilon_0\omega}\mathrm{Re}\,\sigma(\omega)$$

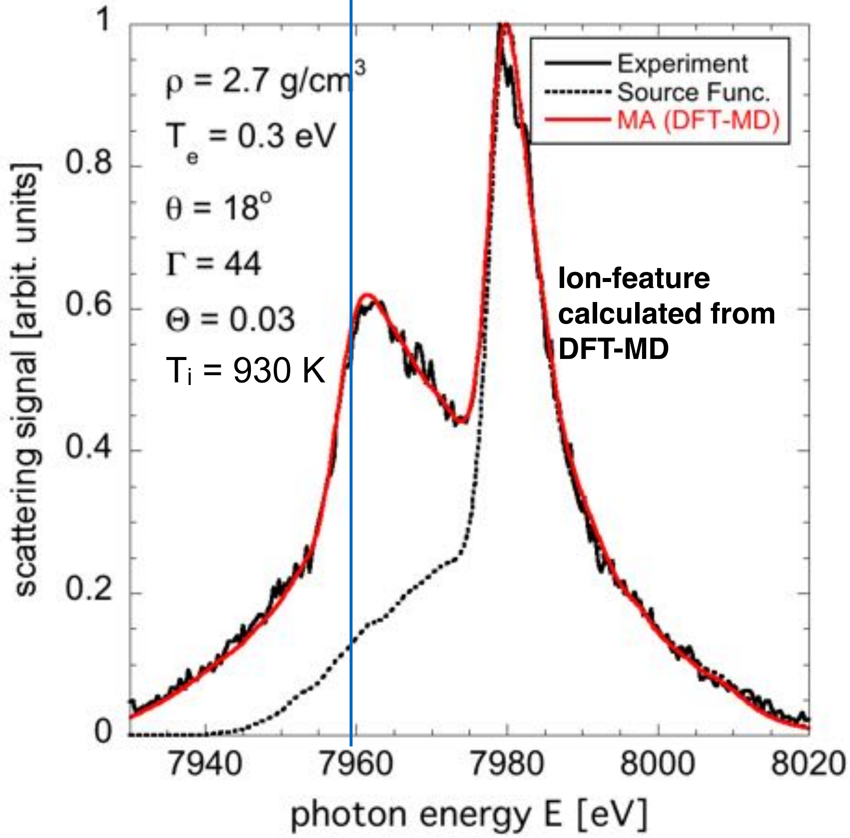
$$\varepsilon^{\mathrm{DFT}}(\omega,\nu(\omega)) = \varepsilon^{\mathrm{M}}(\omega,\nu(\omega))$$

- **additional damping by electron excitations (ΔE > 20 eV) not described by analytical models**

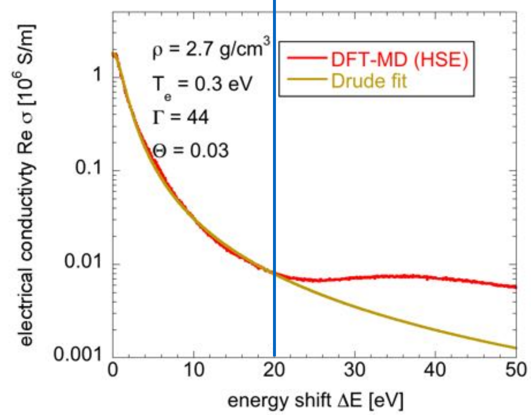
Analysis beyond the Chihara approximation shows nonlinear damping
2010 Fields Medal topic

Nonlinear plasmon damping is due to electron excitations: effect opposite to what we predict for NIF

conduction band electron excitation | Drude-like behavior



Drude-like behavior | conduction band electron excitation



- **Demonstration of non-Drude conductivity at solid density WDM**
- **Previous studies have shown non-Drude behavior in expanding plasmas**

PRL **118,** 225001 (2017) PHYSICAL REVIEW LETTERS week ending 2 JUNE 2017

Warm Dense Matter Demonstrating Non-Drude Conductivity from Observations of Nonlinear Plasmon Damping

B. B. L. Witte,[1,2] L. B. Fletcher,[1] E. Galtier,[1] E. Gamboa,[1] H. J. Lee,[1] U. Zastrau,[3]

We can well reproduce nonlinear plasmon damping; dispersion is well described by BMA

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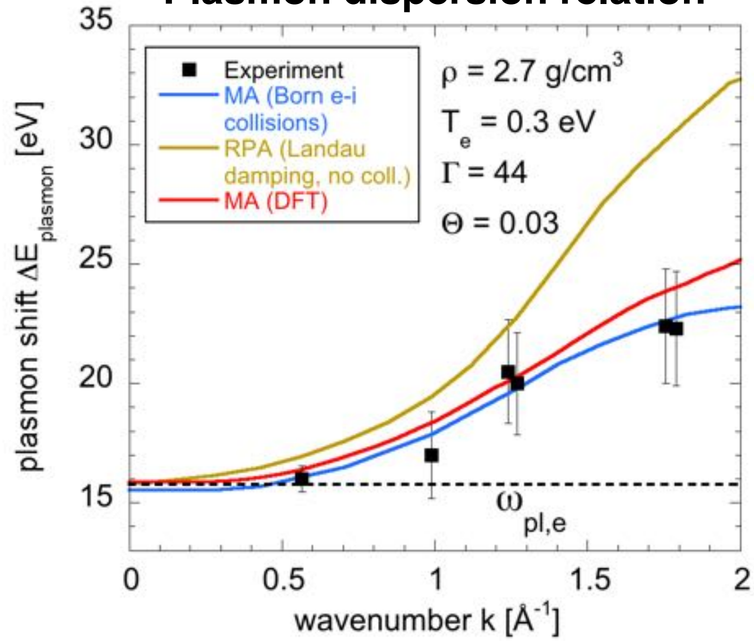
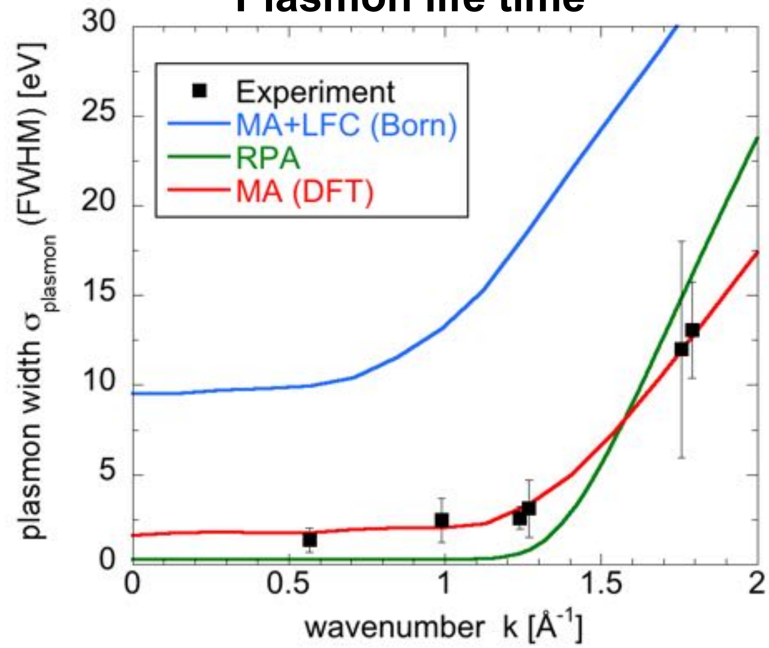
Plasmon dispersion relation



experiment agrees with simulation (DFT) and model (Born)

Plasmon life time



Standard theories fail at Plasmon damping

Creating and measuring the conditions of brown dwarfs

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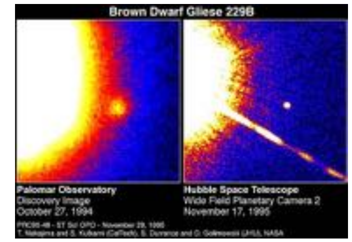
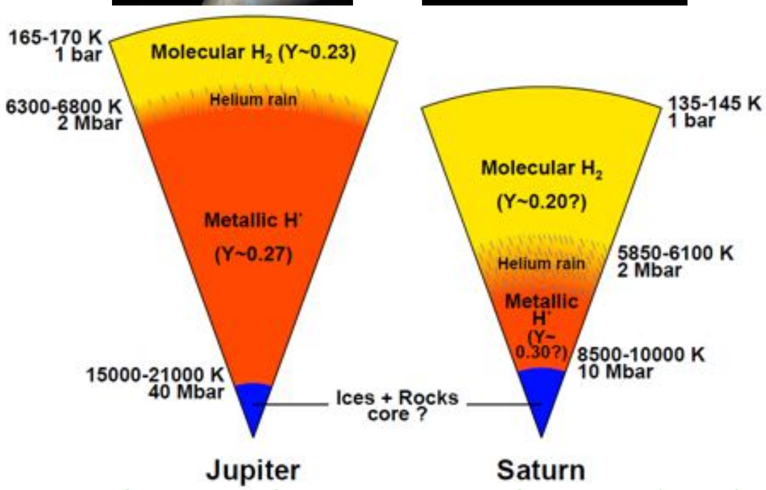


Gliese 229 B
1995, 18.8 ly
M1 + T6 (50 AU)

Giant planets in the Solar System:

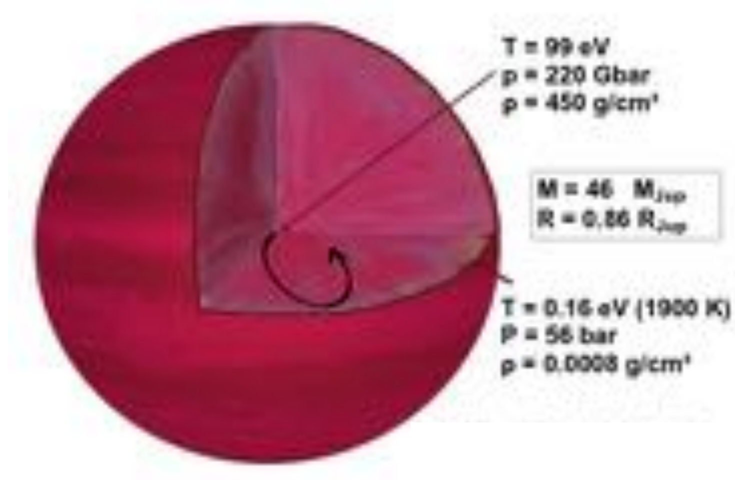
- Layered structure? Size of the core? He rain?
- Interior – evolution – dynamo
- Juno & Cassini missions



T. Guillot, D. Gautier, Treatise Geophys. (2014)

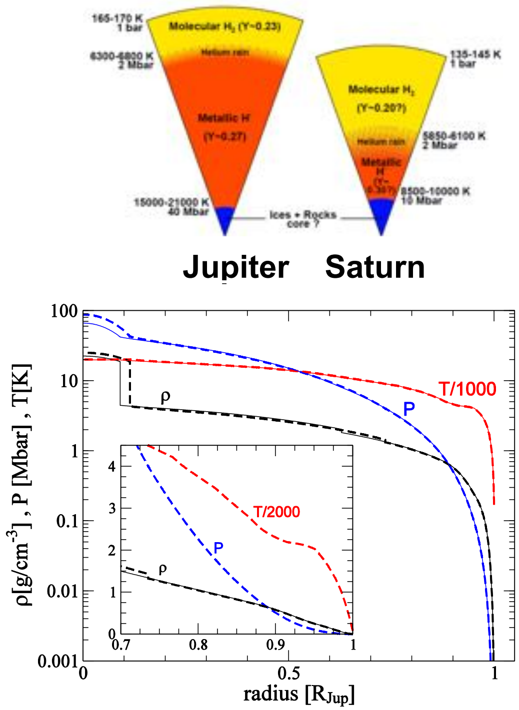
Brown Dwarfs:

- Jupiter-sized
- 13 $M_{Jupiter}$ < M < 75 $M_{Jupiter}$
- Degenerate matter
- Interior – evolution – dynamo
- Fully convective layer (?)

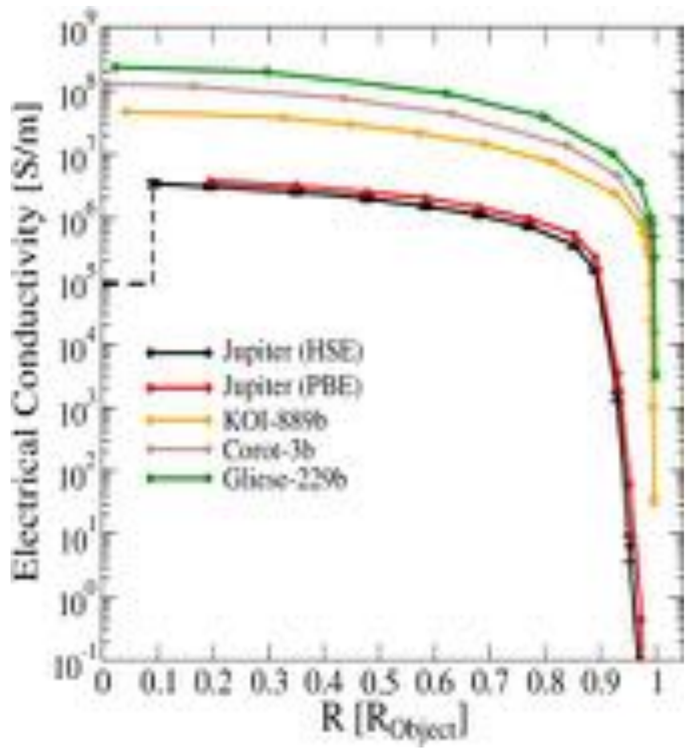


A. Becker et al., ApJS **215**, 21 (2014)

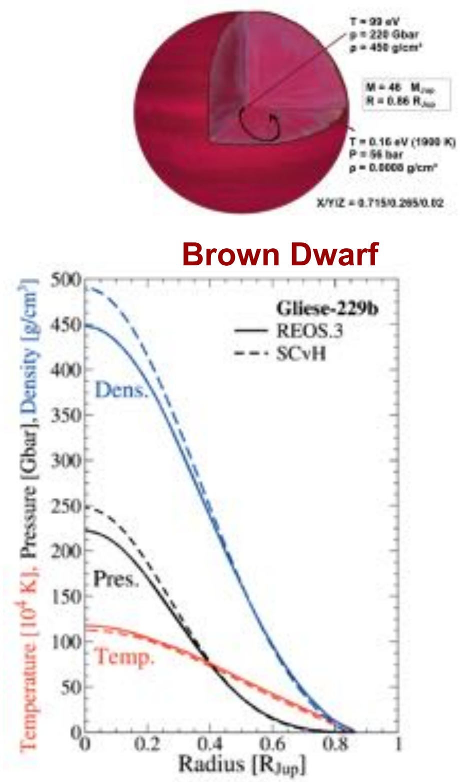
Creating and measuring the conditions of brown dwarfs



M. French et al., ApJS 202, 5 (2012)



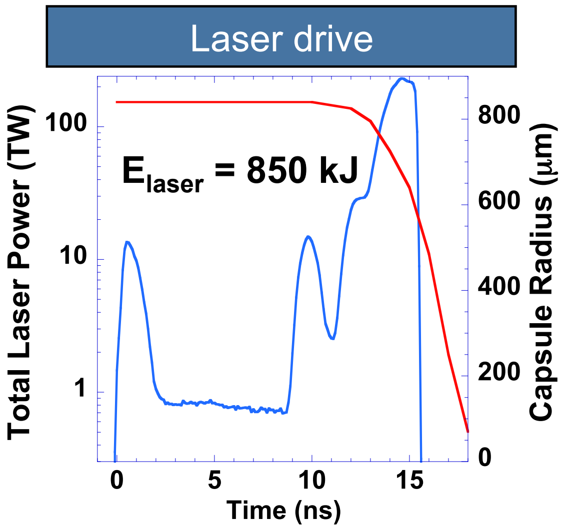
A. Becker et al. (2016)

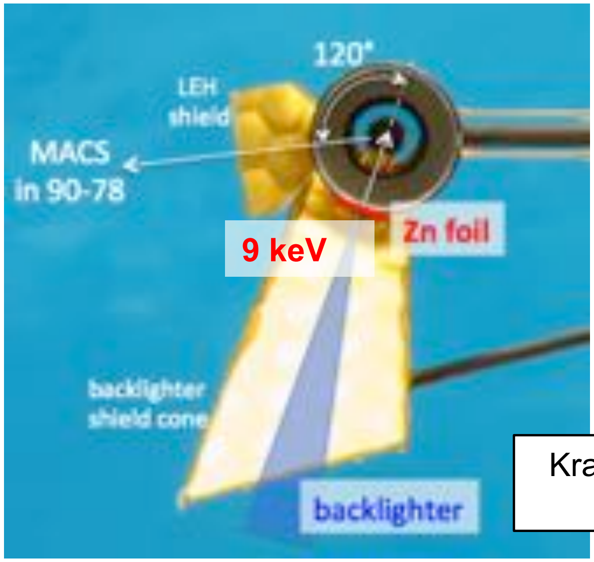


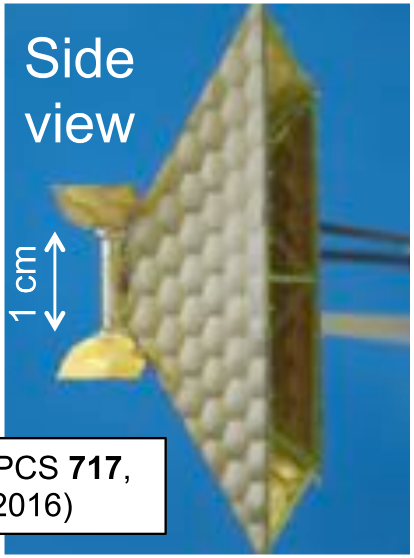
A. Becker et al., ApJS **215**, 21 (2014)

Probe extreme states of matter as deep inside brown dwarfs: tens of eV and tens of g/cm^3

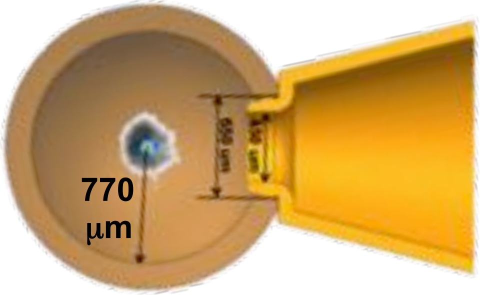
X-ray Thomson scattering has been developed as part of the NIF discovery science program





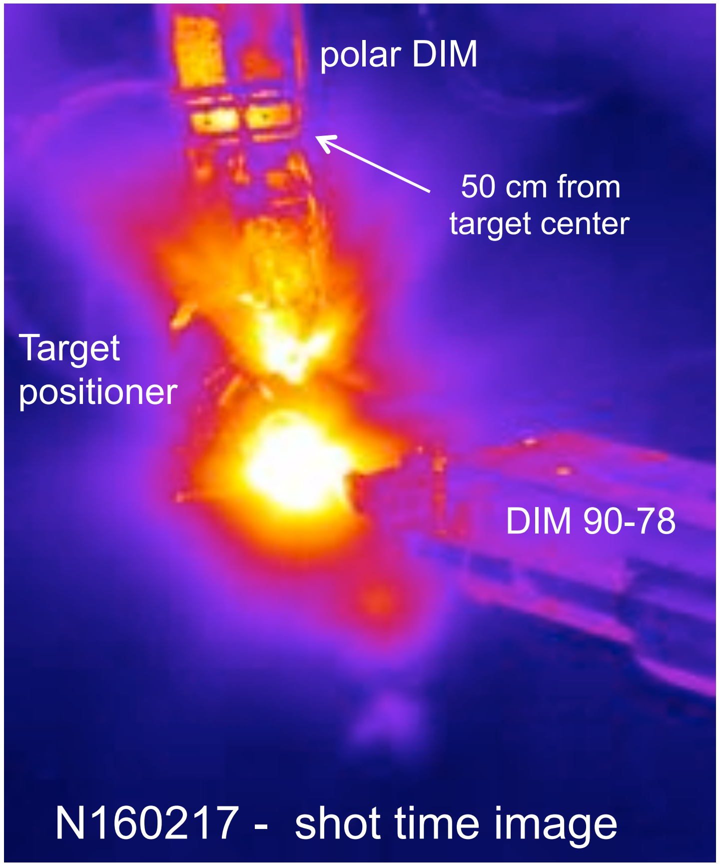


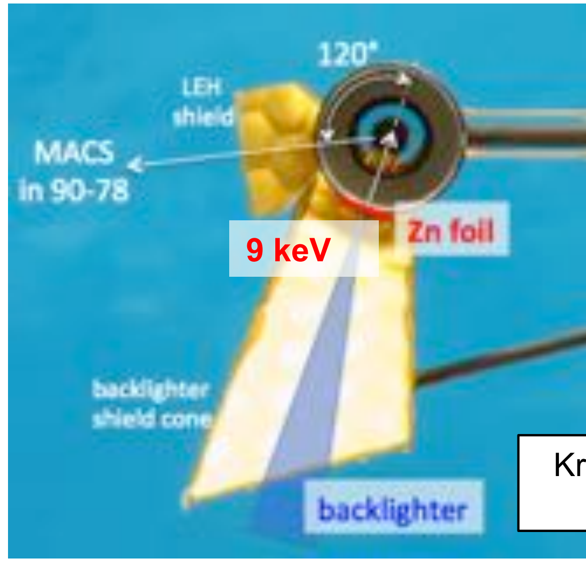
Kraus et al. JPCS **717**, 012067 (2016)

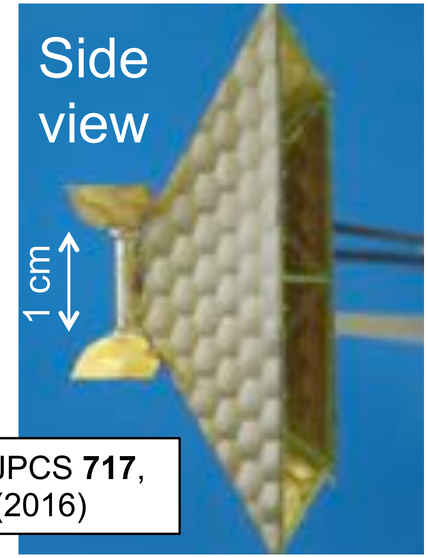


NIF X-ray scattering experiments have been demonstrated on CH and Be shell implosions, NIF PI T. Döppner

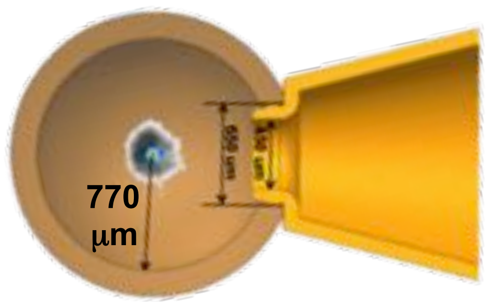
X-ray Thomson scattering has been developed as part of the NIF discovery science program







Kraus et al. JPCS **717**, 012067 (2016)



NIF X-ray scattering experiments have been demonstrated on CH and Be shell implosions, NIF PI T. Döppner

X-ray Thomson scattering has been developed as part of the NIF discovery science program

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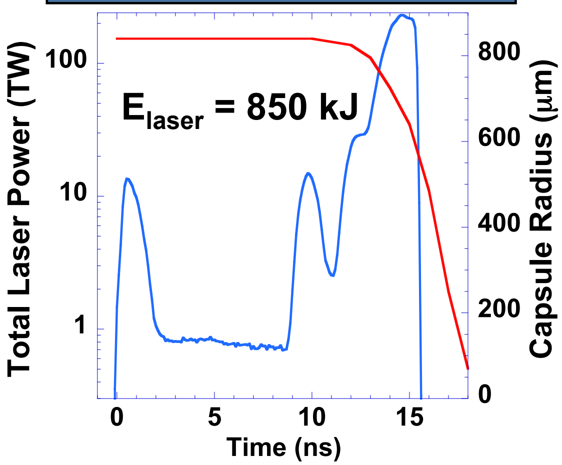
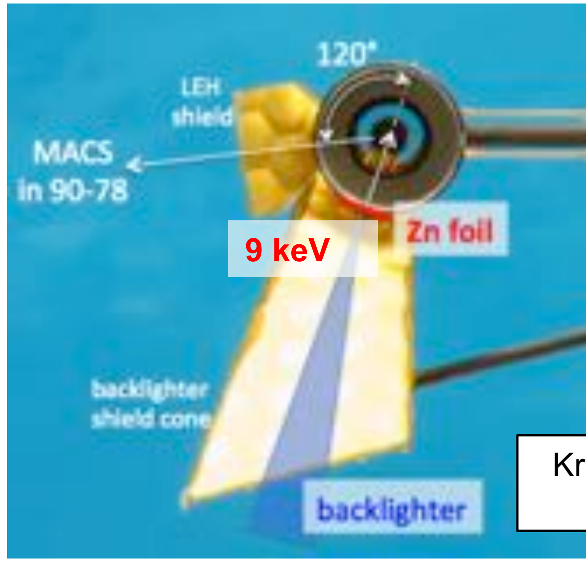
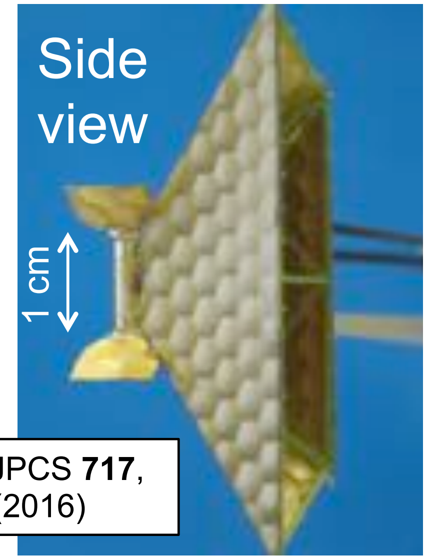
Laser drive

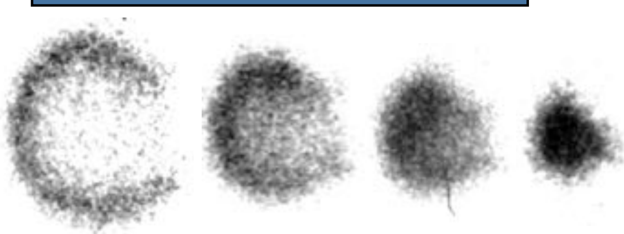


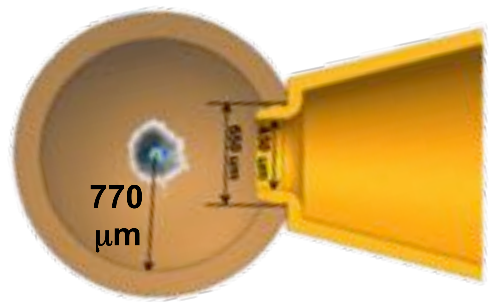




Kraus et al. JPCS **717**, 012067 (2016)

X-ray radiography





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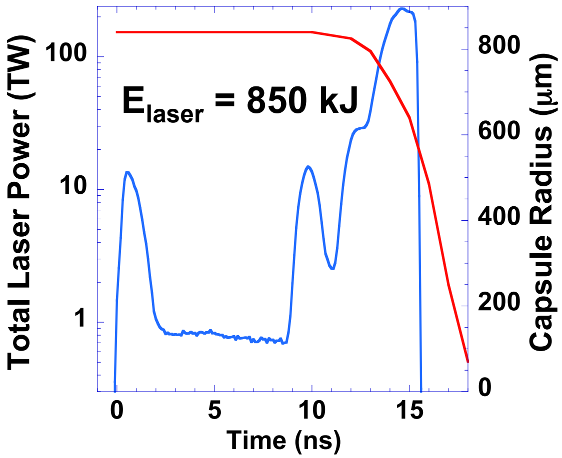
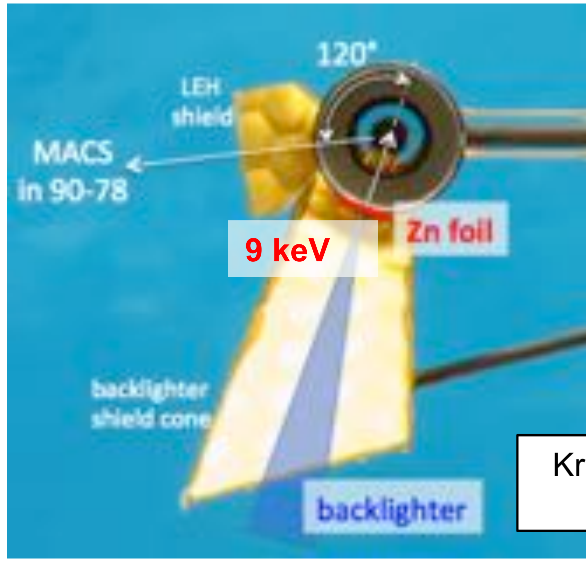
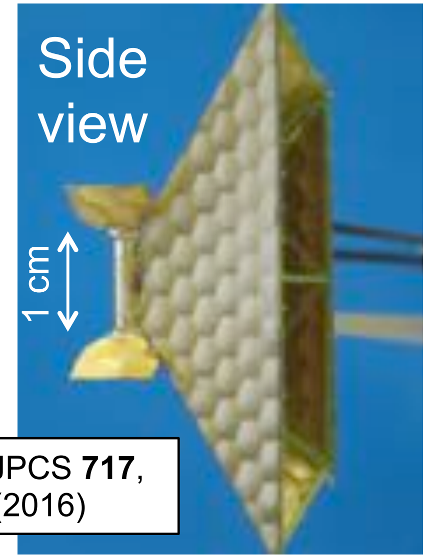
X-ray Thomson scattering has been developed as part of the NIF discovery science program

Laser drive

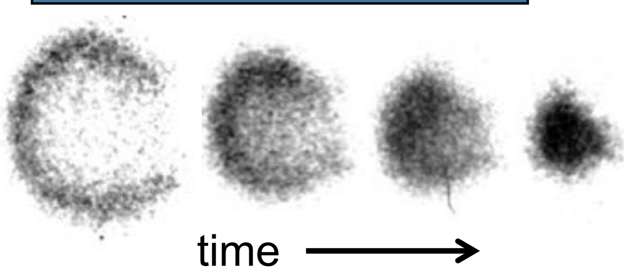


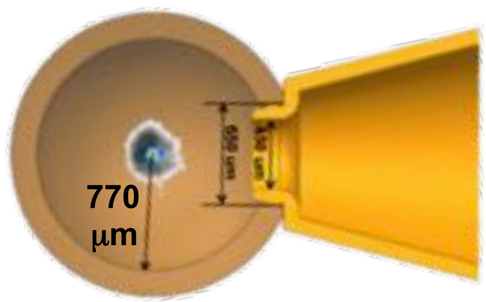


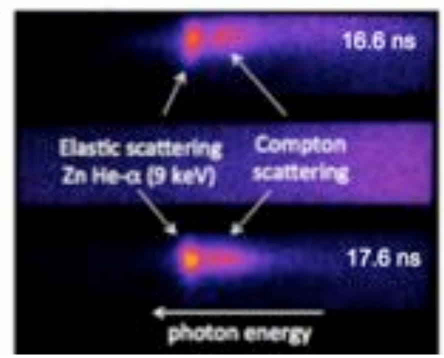


Kraus et al. JPCS **717**, 012067 (2016)

X-ray radiography







NIF X-ray scattering experiments have been demonstrated on CH and Be shell implosions, NIF PI T. Döppner

XRTS data in the Compton regime show 50 g/cc

Compton width: sensitive to ρ
Reduced elastic scatter at highest ρ

MUZE **(S. Hansen) shows reduction of atomic scattering and structure factor**

Compton width is a robust indicator of ρ demonstrating conditions such as those found in brown dwarfs

DFT-MD simulations for NIF brown dwarf experiments predict DOS – EOS – sigma – XRTS spectrum

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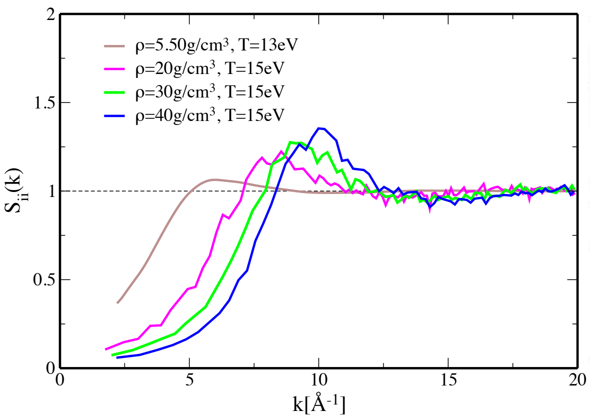
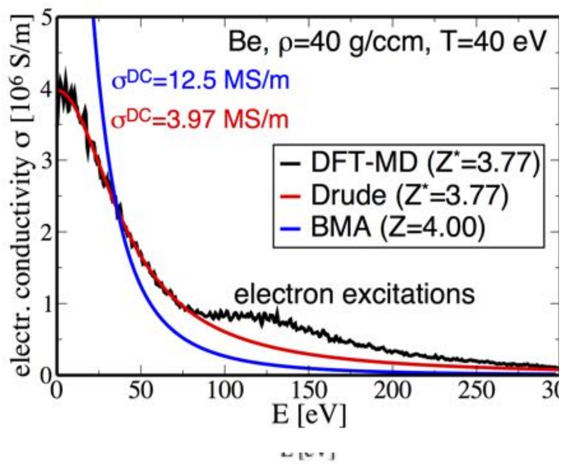
Be as promising test case at NIF





Structure Factor:

- Peak shift as expected
- Important for conductivity

Electrical Conductivity:

- Drude fit yields Z*=3.77
- Electron excitations occur above 80eV (non-Drude)
- Born-Mermin predictions are invalid

XRTS plasmon feature:

- Electron excitations change shape and width of plasmon
- Plasmon damping and dispersion yields dynamic relaxation time and electrical conductivity

Our predictions for the plasmon scattering spectrum shows significant departures from standard theories

Outline

- Introduction
  - What is High Energy Density Physics?
  - Why the answer matters and some insights
- The Axes of the Extremes
- New Discovery Science experiments
  - Insights from the Linac Coherent Light Source
  - Investigate the physics of brown dwarfs on NIF
- Conclusions and Outlook

Rapid progress in the development of Cryogenic Jets has resulted in high-energy proton/deuteron beams

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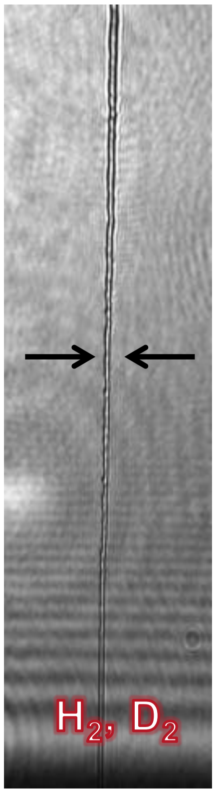
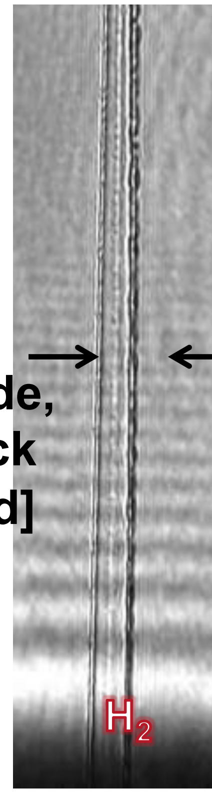
Cylindrical H2 Jet

2-20 μm diameter



Flat H2 Jet

30 μm wide,
1 μm thick
[patented]



Droplet H2 Jet

5 μm radius

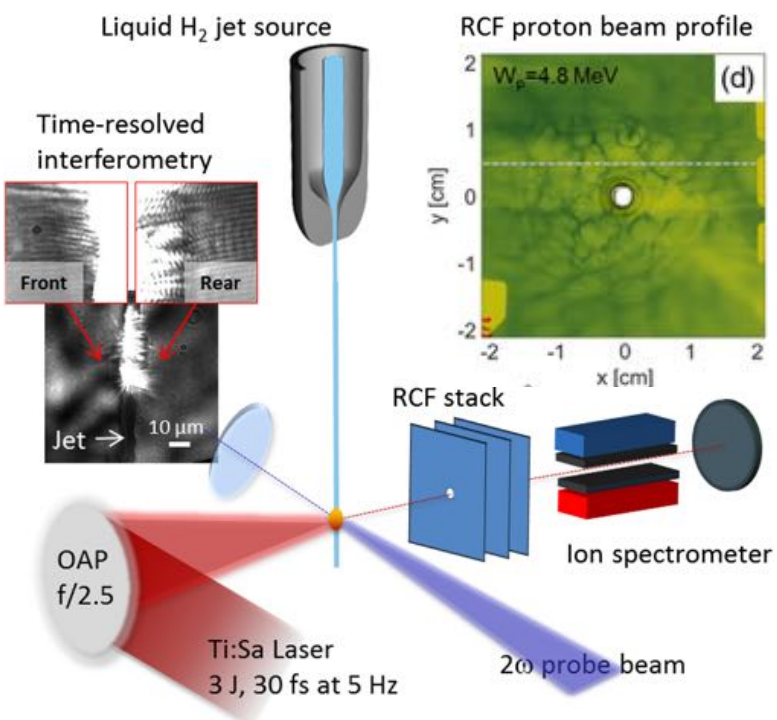
Cryogenic jets are an excellent tool for HED physics studies

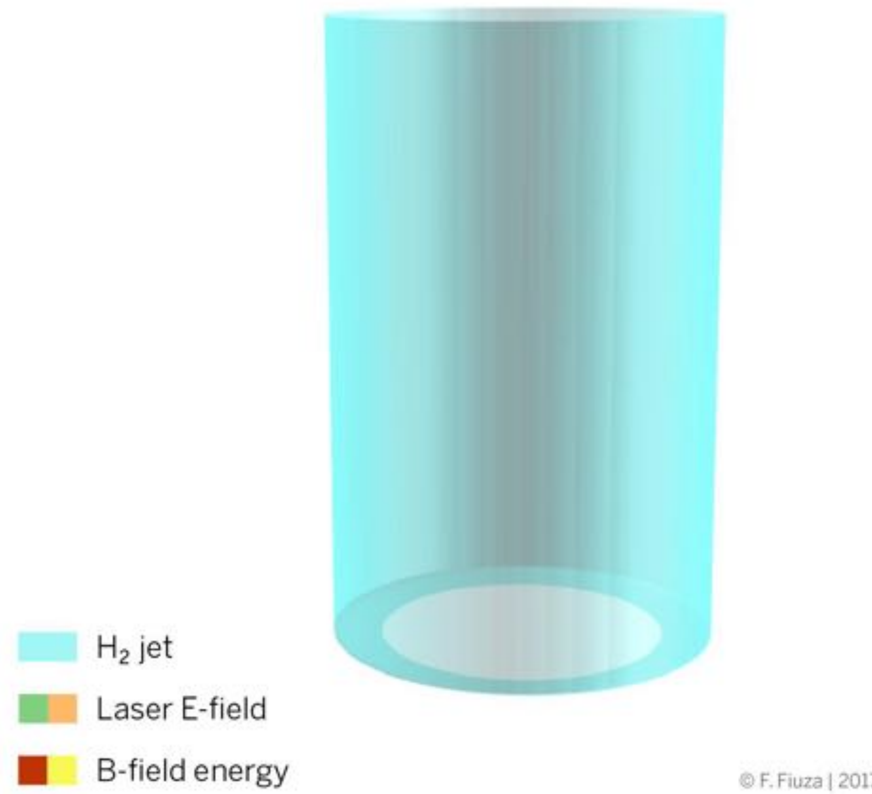
Experiments on cryogenic hydrogen jets have observed the generation of 100 MG Weibel B-fields

PRL 118, 194801 (2017) PHYSICAL REVIEW LETTERS week ending 12 MAY 2017

Relativistic Electron Streaming Instabilities Modulate Proton Beams Accelerated in Laser-Plasma Interactions

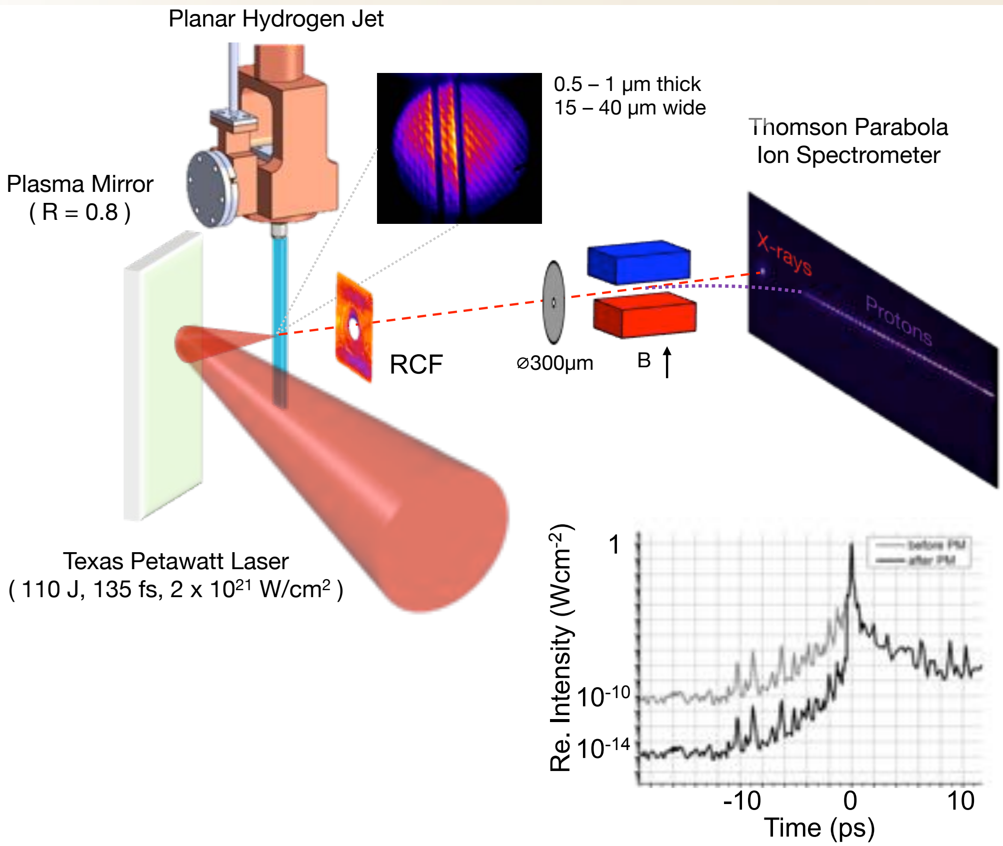
S. Göde,[1,2] C. Rödel,[1,3] K. Zeil,[4] R. Mishra,[1] M. Gauthier,[1] F.-E. Brack,[4,6] T. Kluge,[4] M. J. MacDonald,[1,5]



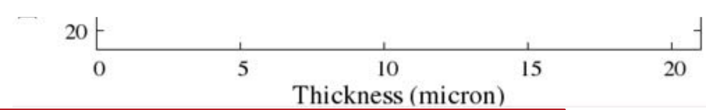


Modulated laser-accelerated proton beams probe the Weibel instability, not RT

Experiments with cryogenic hydrogen have observed record 80 MeV protons at Texas PetaWatt



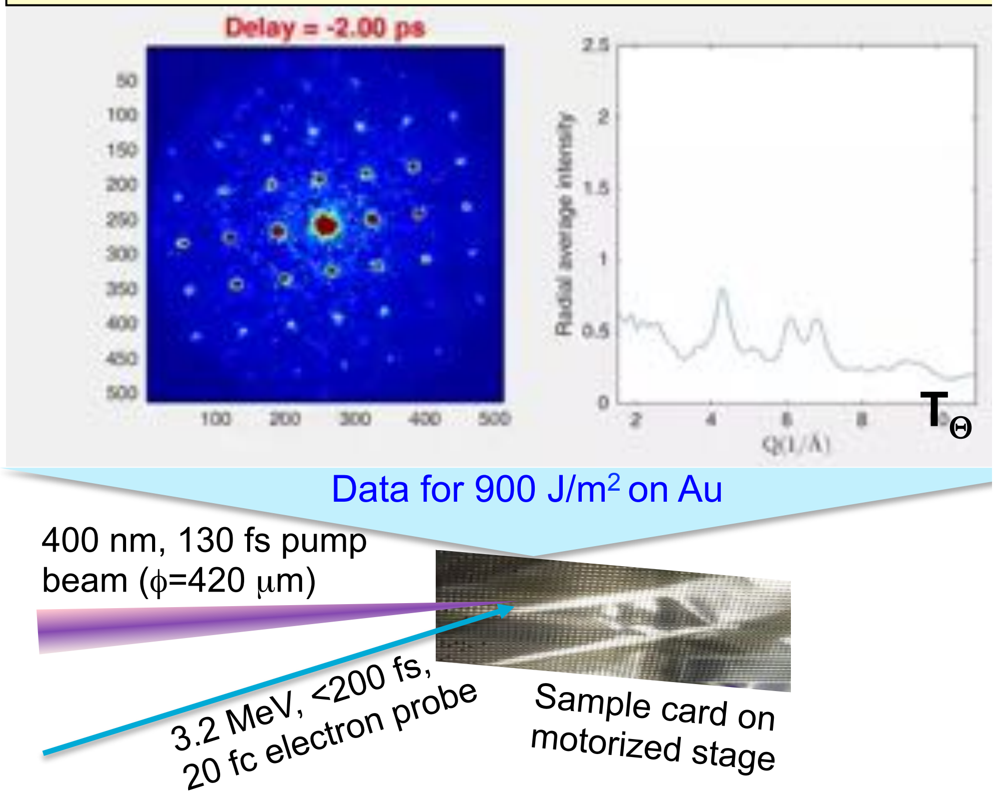
- Optimization of target thickness
- Further improve contrast (2 plasma mirrors)
- Increase shot rate



Setting the stage for fusion plasma diagnostics and novel accelerators

Applying our LCLS techniques to visualize the ultrafast transformation of matter to warm dense matter

Observation of Debye-Waller effect and formation of W



Precision experiments provide melting data on atomic scales to test modeling

Phonon softening prevails over phonon hardening in the observed three melting regimes in warm dense gold

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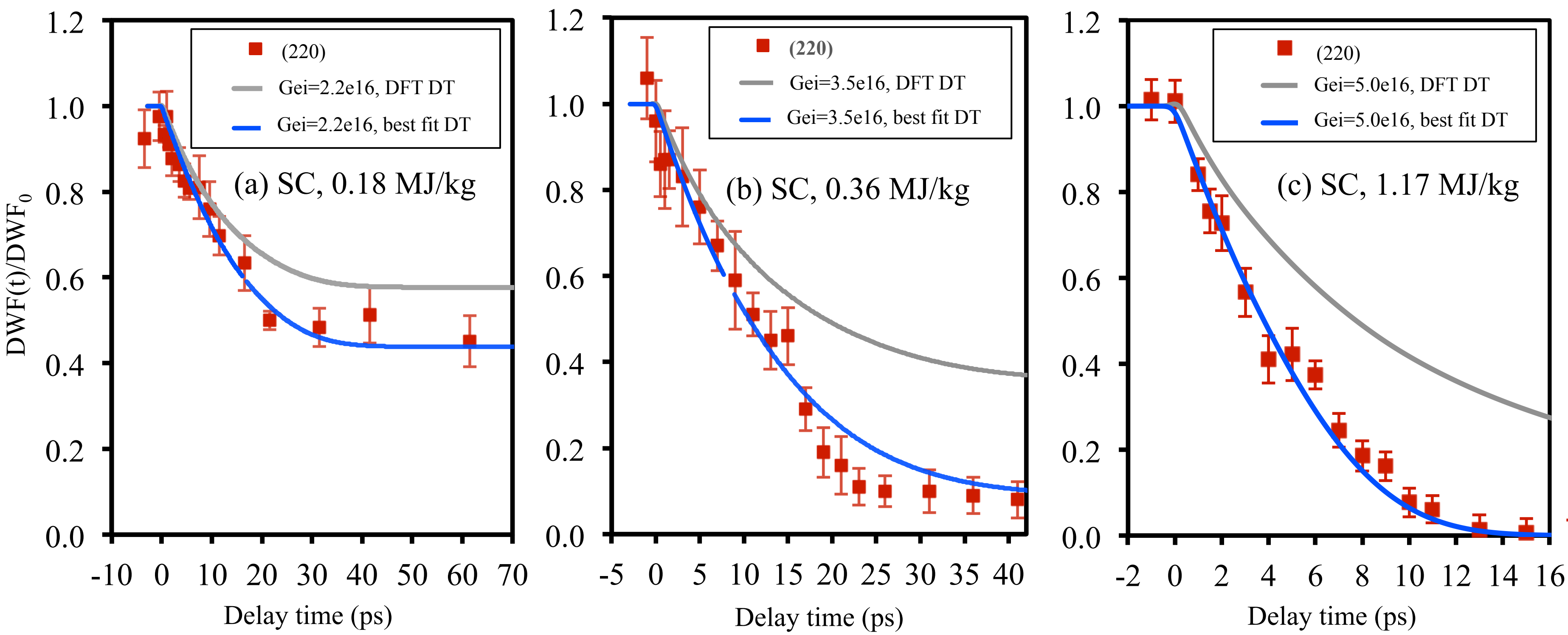
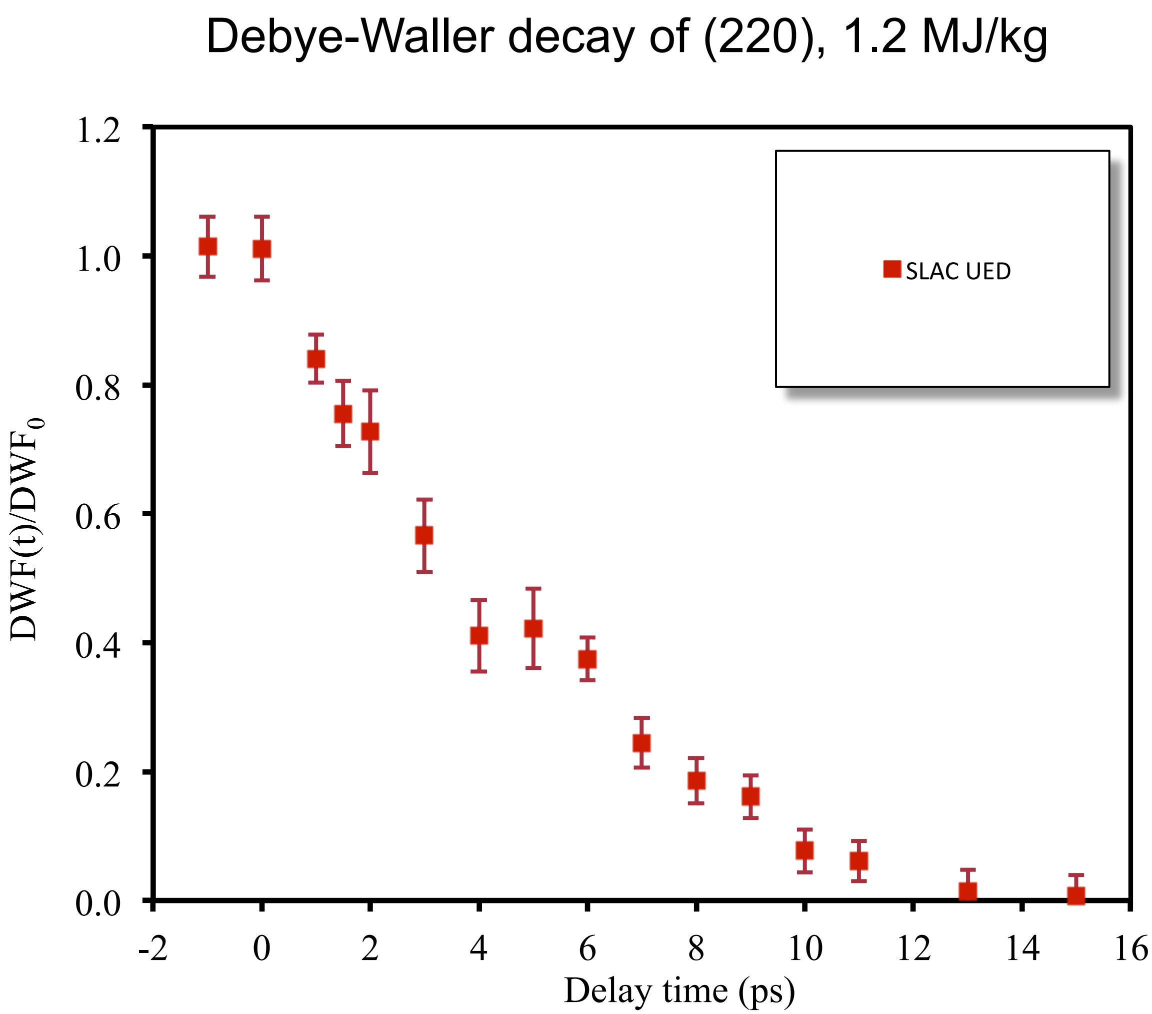
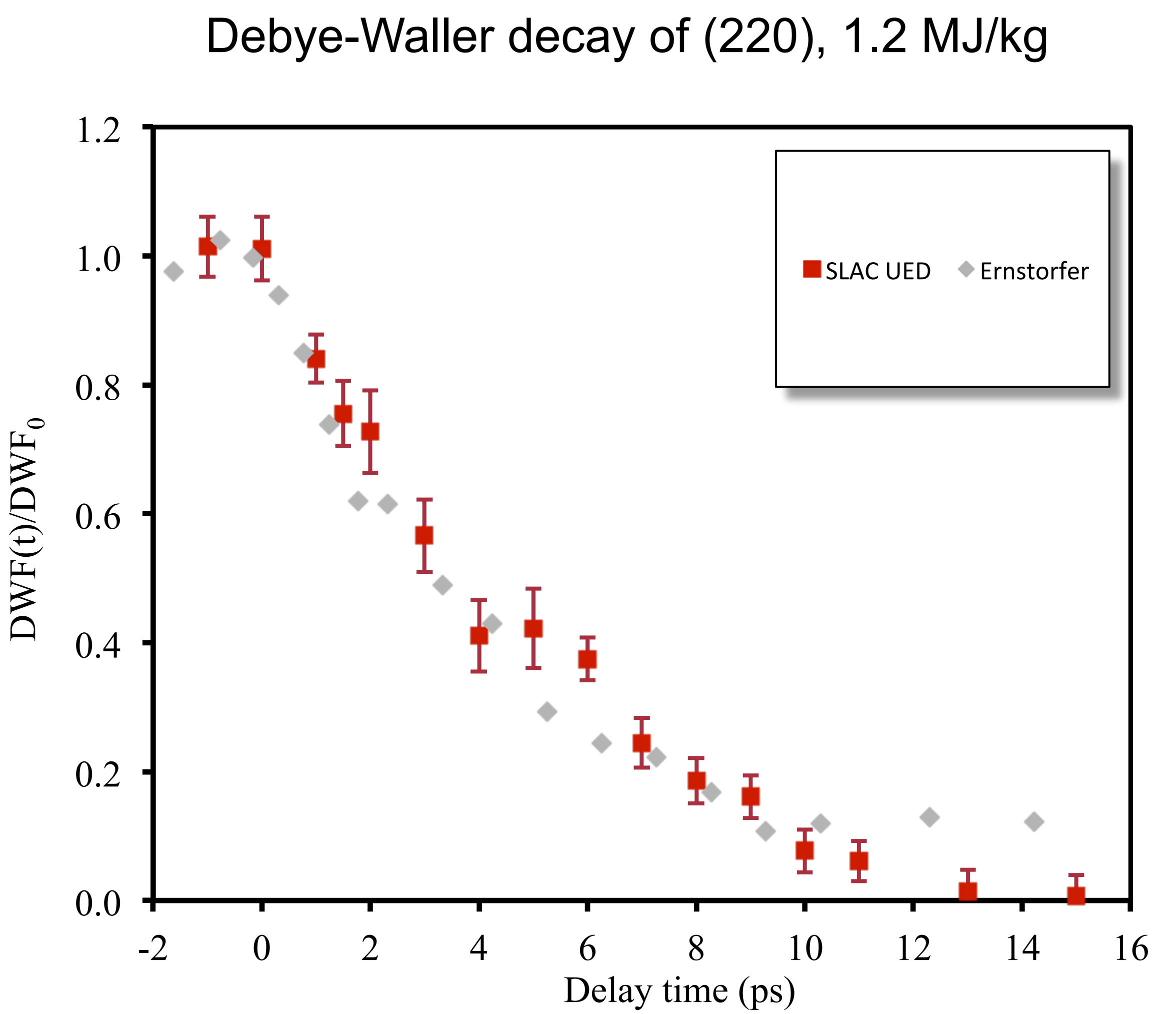


Our data for various energy densities can be fit with one simple constrain

Comparison with Ernstorfer's published data

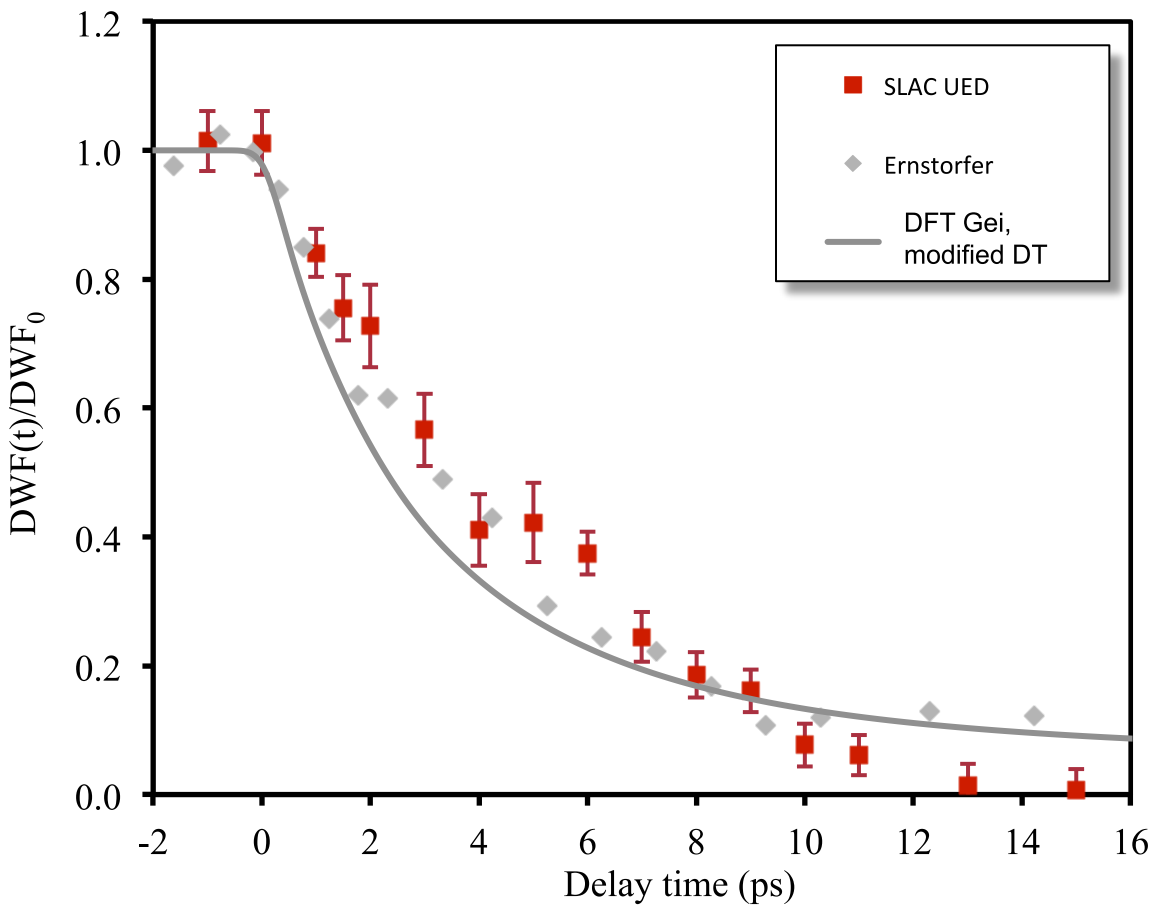


Comparison with Ernstorfer's published data



Comparison with Ernstorfer's published data

Debye-Waller decay of (220), 1.2 MJ/kg



Comparison with Ernstorfer's published data

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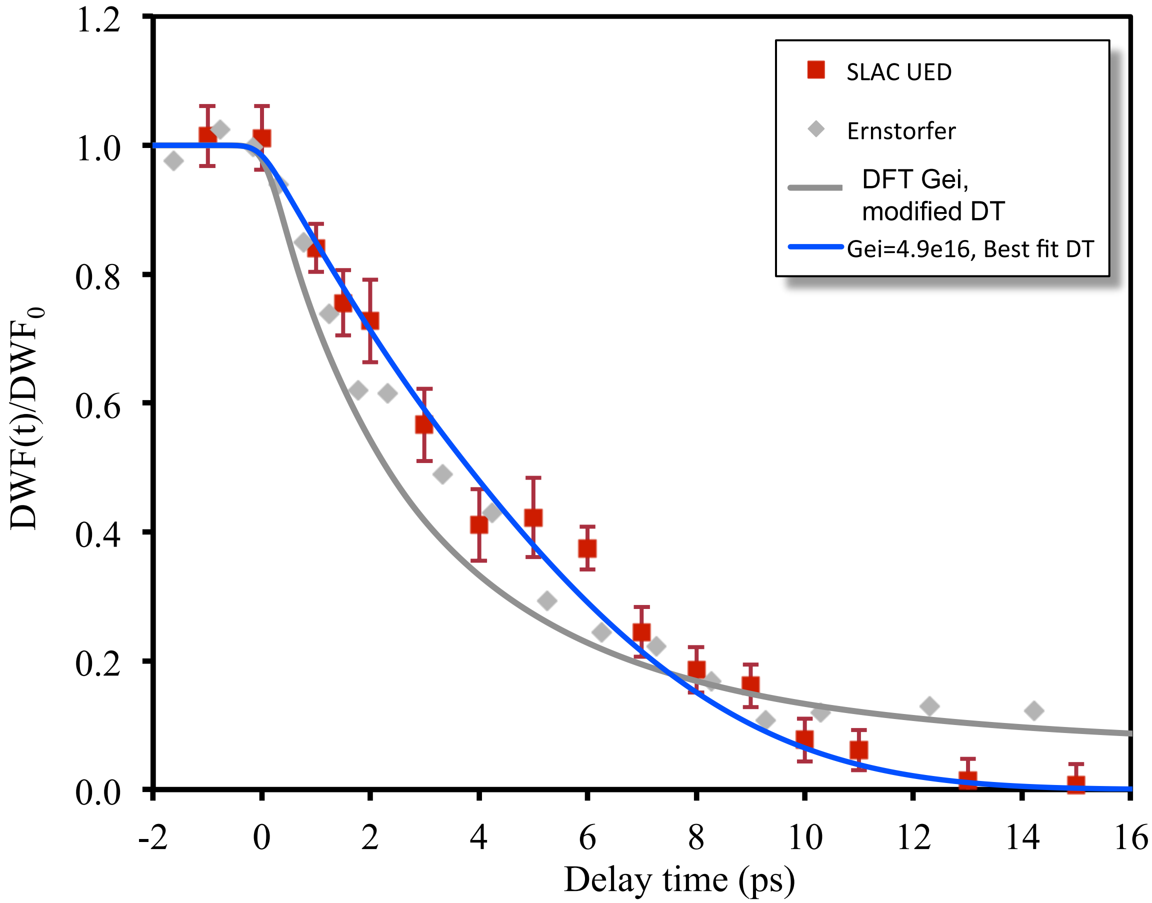
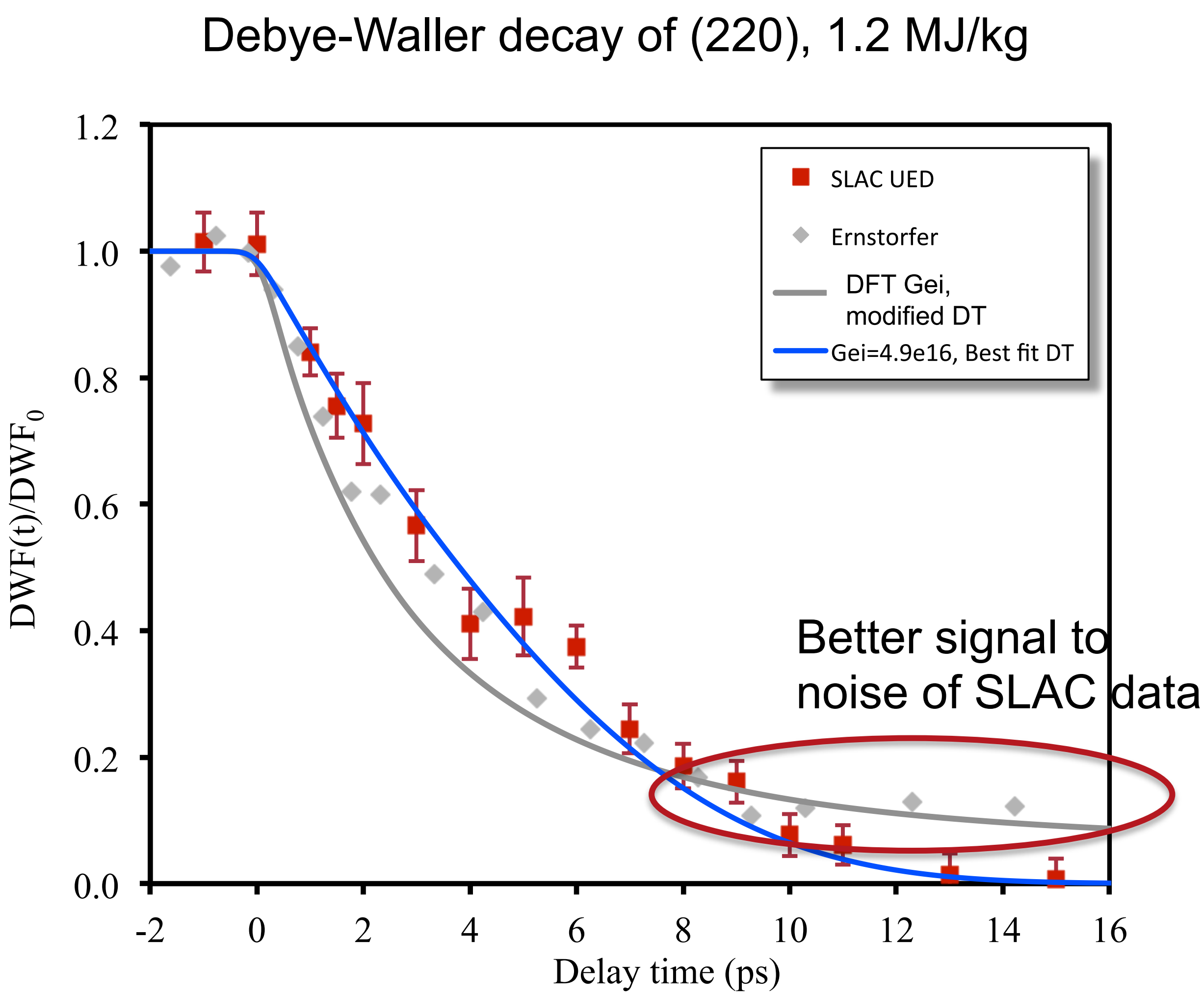
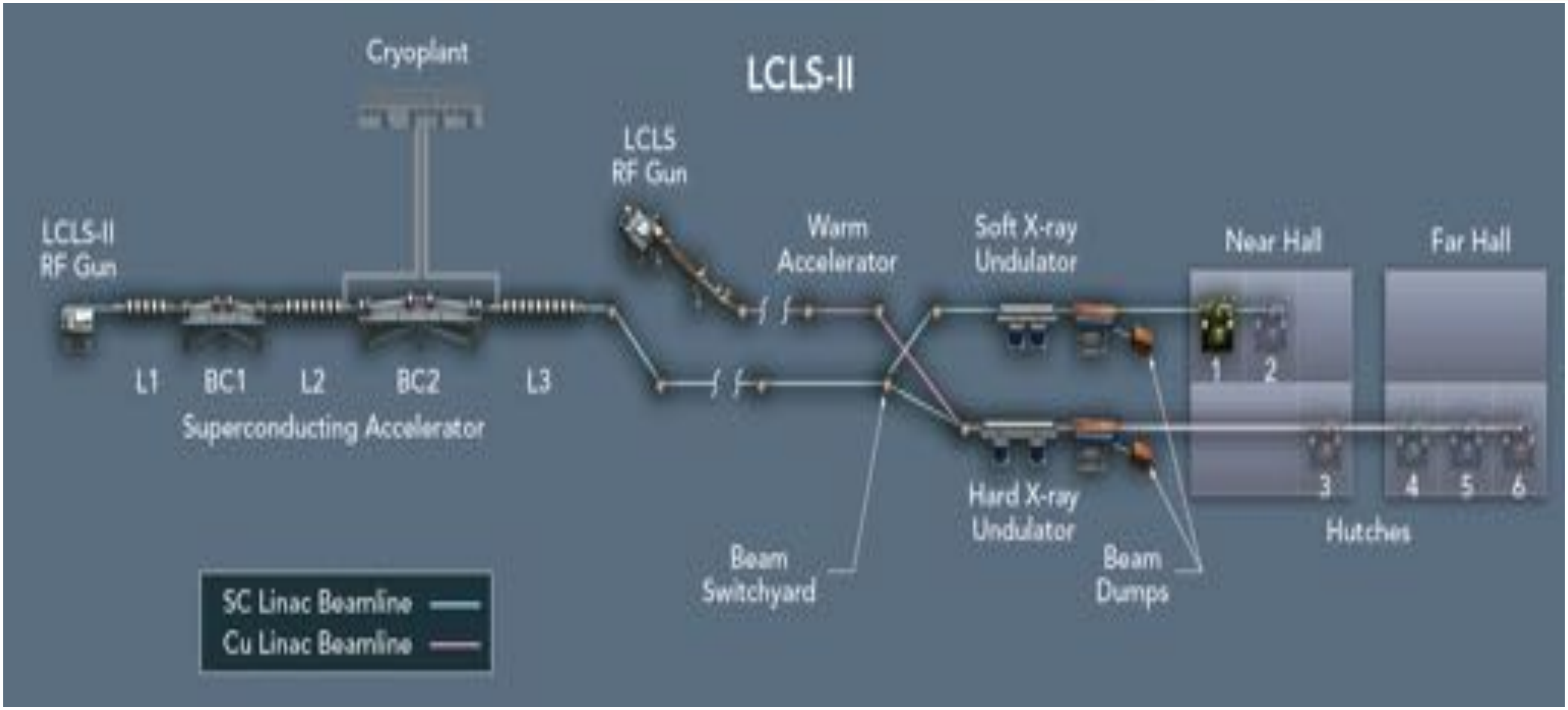
Debye-Waller decay of (220), 1.2 MJ/kg



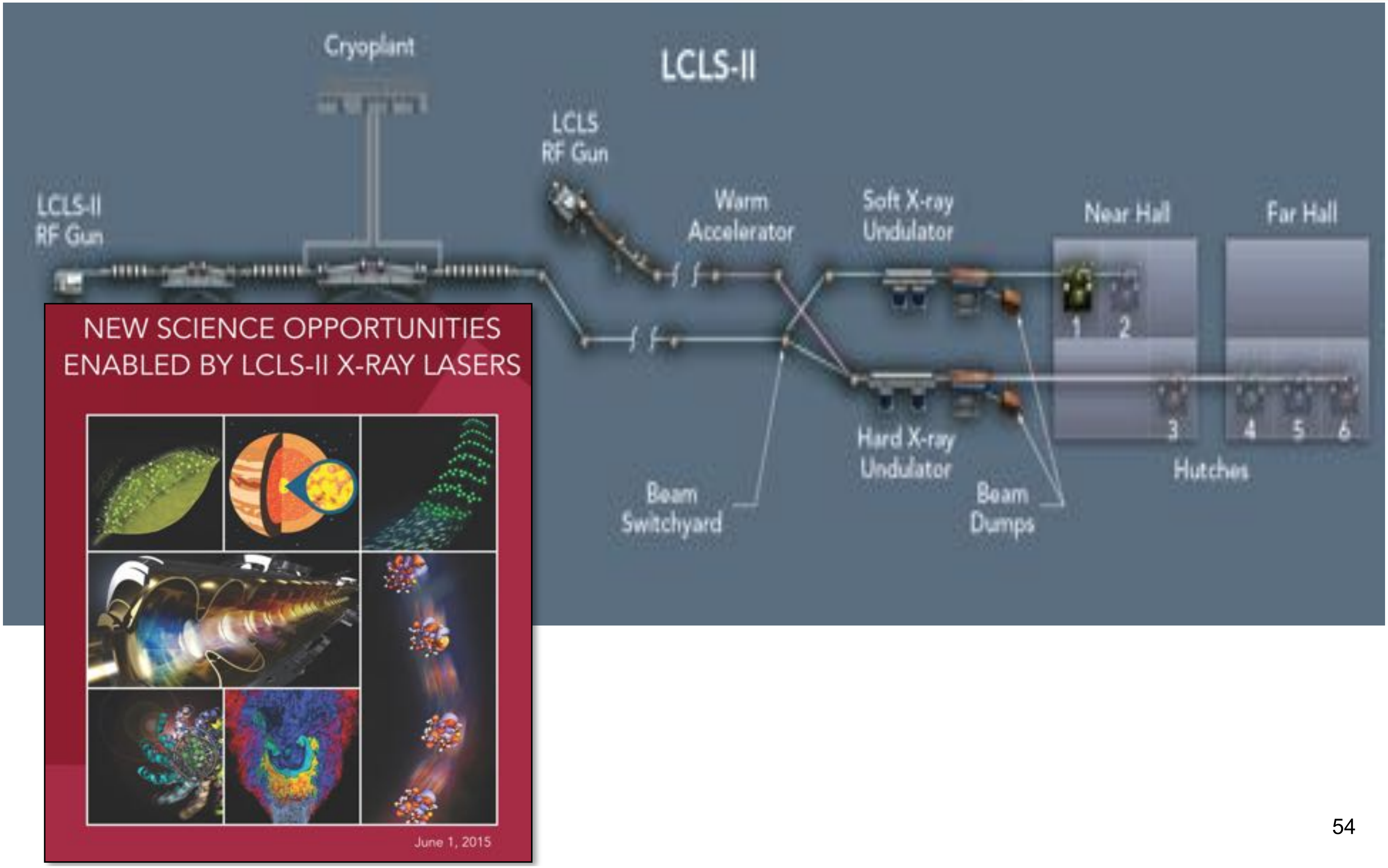
Comparison with Ernstorfer's published data



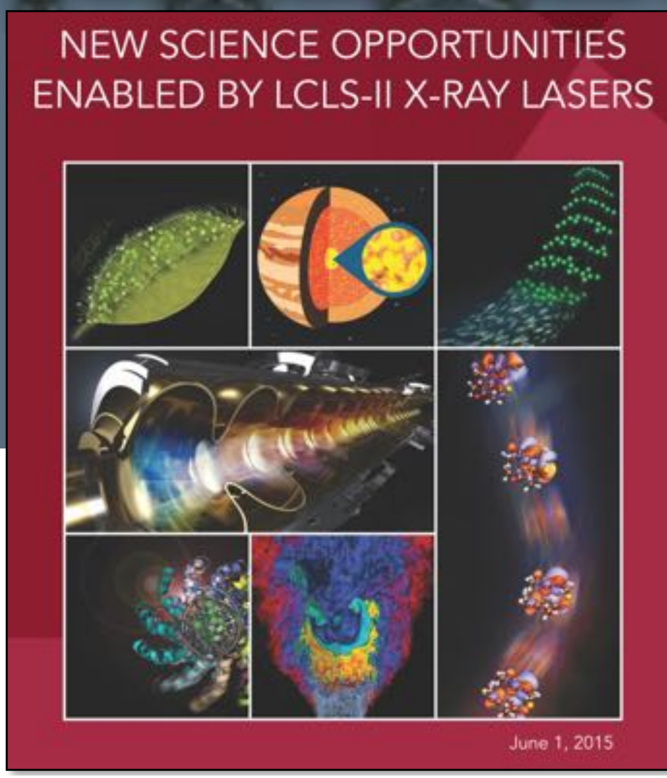
LCLS-II will greatly enhance x-ray capabilities for HED research



LCLS-II will greatly enhance x-ray capabilities for HED research



LCLS-II will greatly enhance x-ray capabilities for HED research



New LCLS-II capabilities

- Higher photon energy (0.25- 25 keV)
- Higher energy per pulse (> 4 mJ)
- 20 fs synchronization [optical-x-ray; x-ray-x-ray]
- 2 color pulses
  - $E_1 - E_2 = 0 - 500$ eV
  - 0- 200 fs; N* 330 ps
- Pulse Trains
  - 8 pulses
  - $\Delta X < 20\ \mu m$
- Variable bandwidth
  - $10^{-4} - 2\%$
- Attosecond Pulses
  - 0.5fs

SLAC HED is bringing the HED community to MEC and LCLS


Thank you!