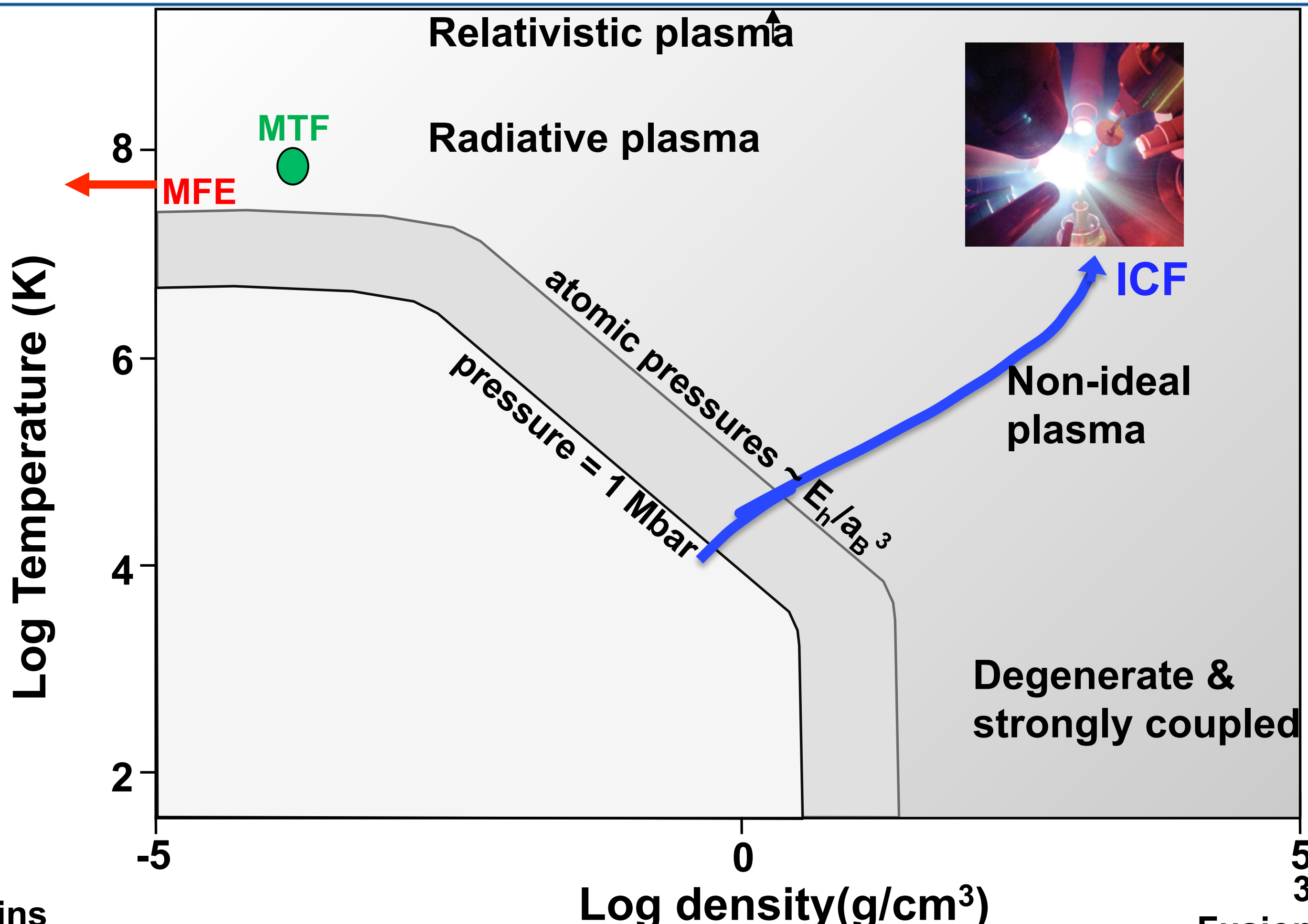
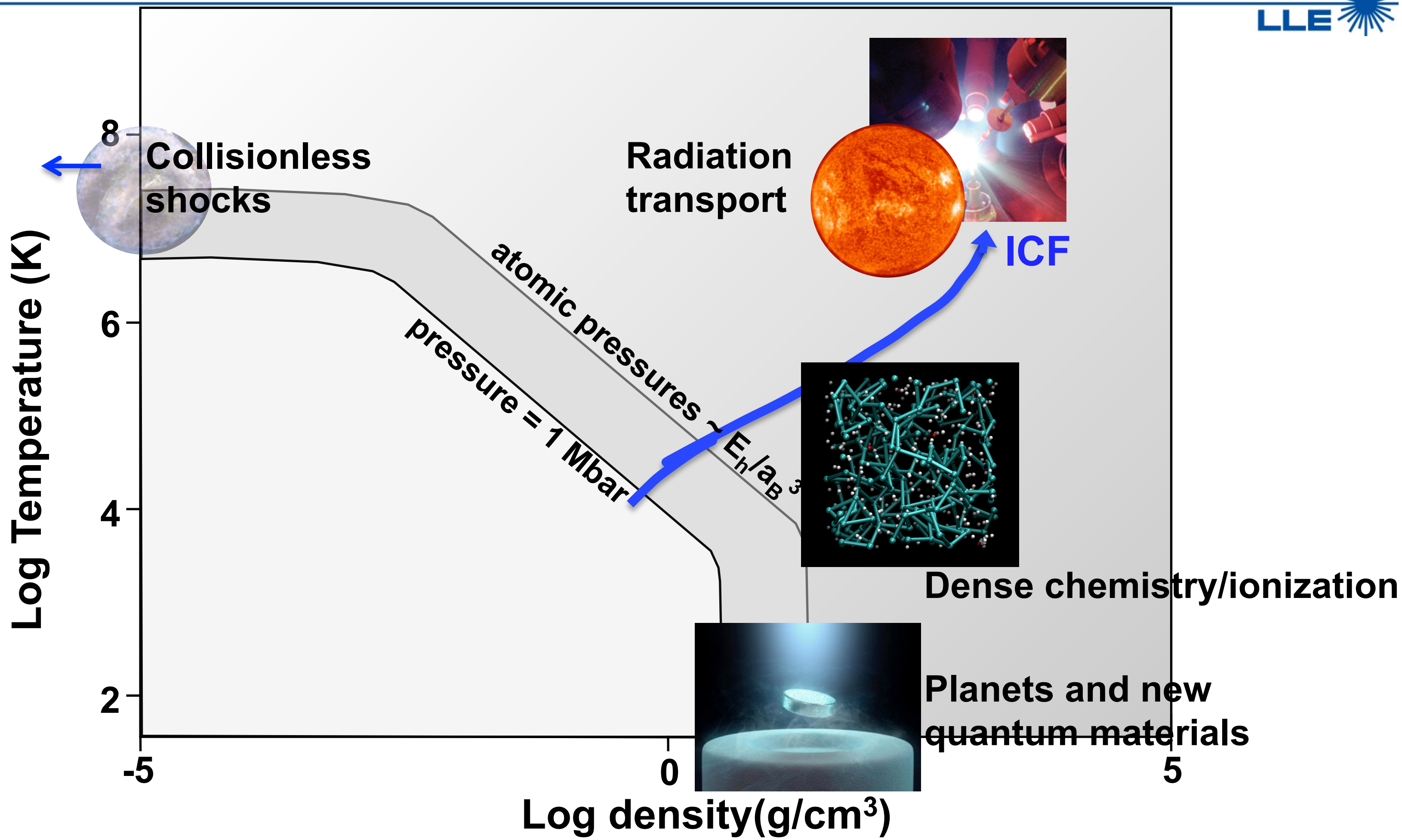
High Energy Density (HED) Microphysics: Progress and Plans



G. W. Collins
University of Rochester
Laboratory for Laser Energetics

38th Annual Meeting
Fusion Power Associates
Washington, DC
6-7 December 2017

High Energy Density (HED) Microphysics: Progress and Plans



Outline: HED microphysics plays a key role in understanding and controlling fusion

- Define what I mean by underlying HED science (microphysics)
  & it's importance to ICF

- A few examples of the brave new world of HEDP
  - EOS Example (beyond Thomas Fermi)
  - Transport

- Building a roadmap to tomorrows physical understanding of controlled thermonuclear fusion

How do we strategically enable next-generation microphysics, to help guide our way towards controlled fusion

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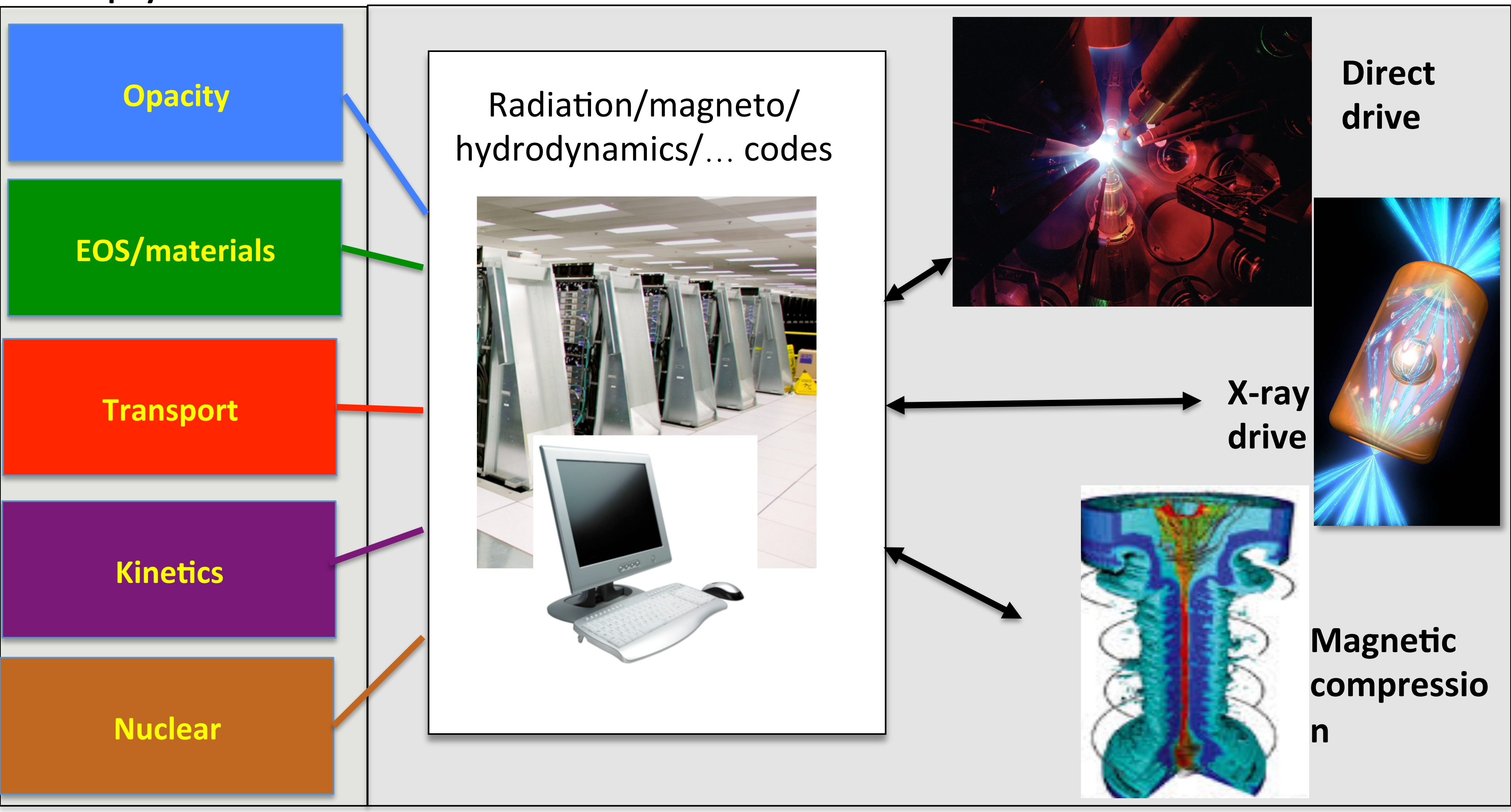
Microphysical models are important for all fusion ignition schemes

Microphysics models



Typically when microphysics models are inadequate we end up with ad-hoc corrections

Each energy compression step in ICF design requires fundamental HEDP models

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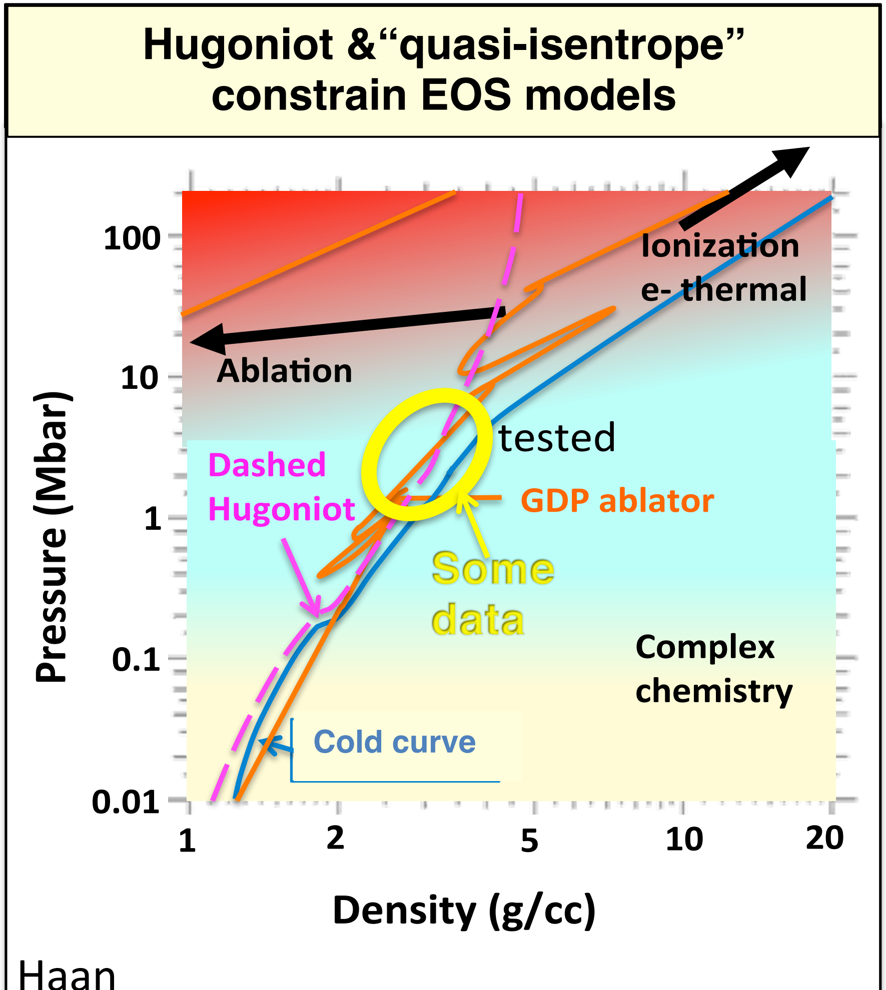
Indirect drive		Direct drive
Laser Energy = 1.6 MJ		Laser Energy
	Laser-Plasma physics	
X-ray Energy = 1.3 MJ		
Radiation transport		e^- transport
Energy to capsule =150 kJ Set adiabat		Energy to capsule =800 kJ Set adiabat
	Dense Matter Physics	
Fuel K.E. = 12 KJ, Shell K.E. ~ 20 KJ		Fuel K.E. = 48 KJ, Shell K.E. ~ 80 KJ
	Transport, “hydro”	
Hot spot = 10KJ		Hot spot = 40KJ
	Fusion burning plasma	
Burn propagation		Burn propagation

EOS of the ablator and fuel impact predictions of capsule stability and implosion efficiency

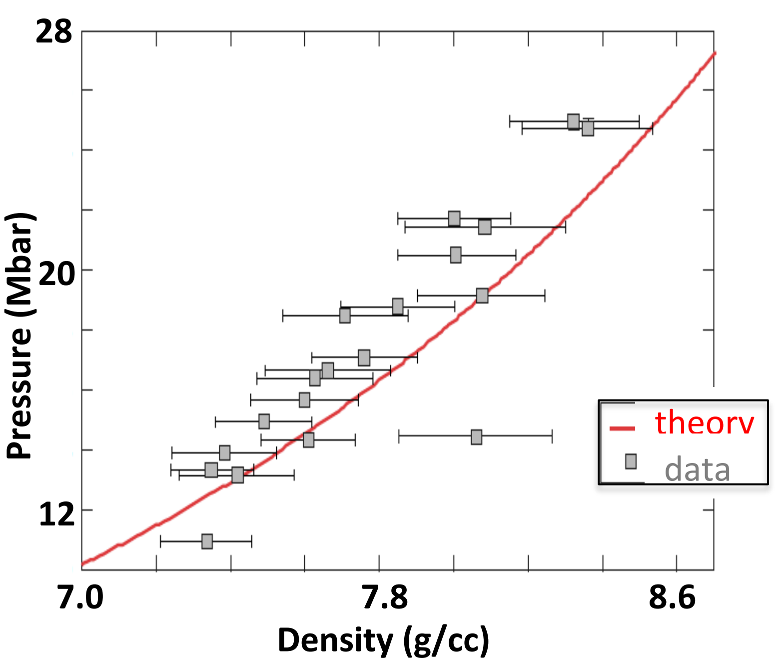


Benchmark experiment platforms

- Billion atmosphere EOS platform
- Million atmosphere shocks
- Precompressed and ramp compression

Surprises exist at even modest pressures, e.g. Recent diamond Hugoniot data

Current models to not match low density carbon data



Work from UR student Michelle Gregor who now works at LLNL

The high Γ and Cv (not shown) suggest a complex chemistry in this dense plasma

Surprises exist at even modest pressures, e.g. Recent diamond Hugoniot data

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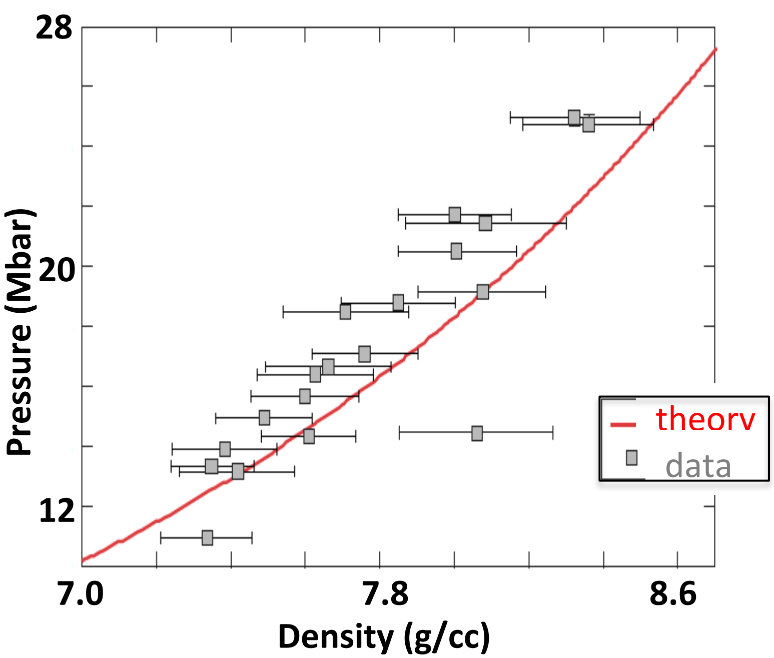
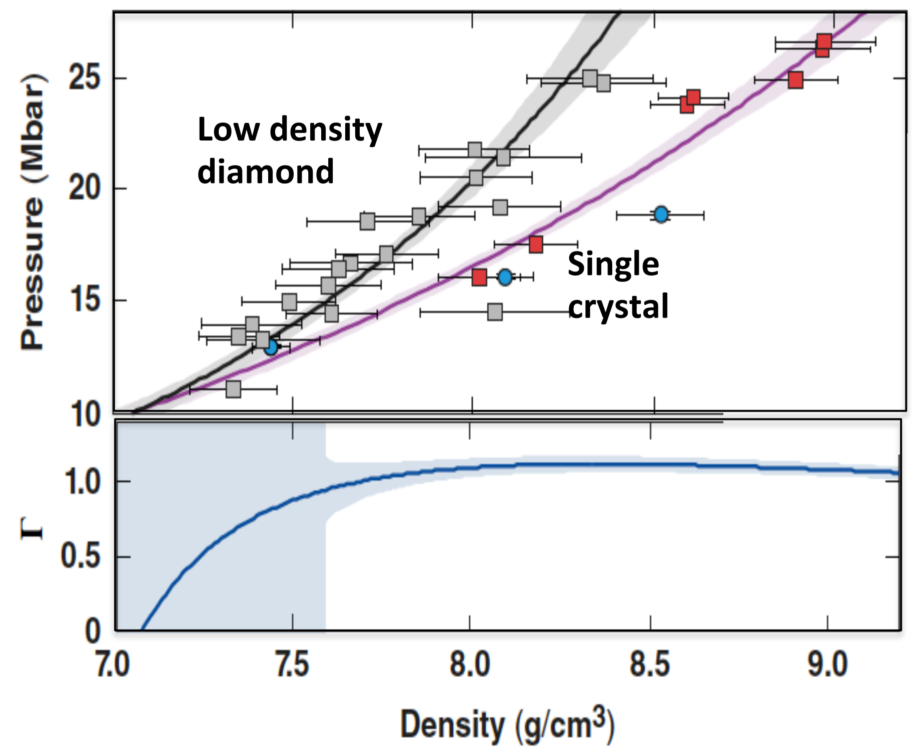
Current models to not match low density carbon data



Data (points) match a simple gruneisen model (lines)

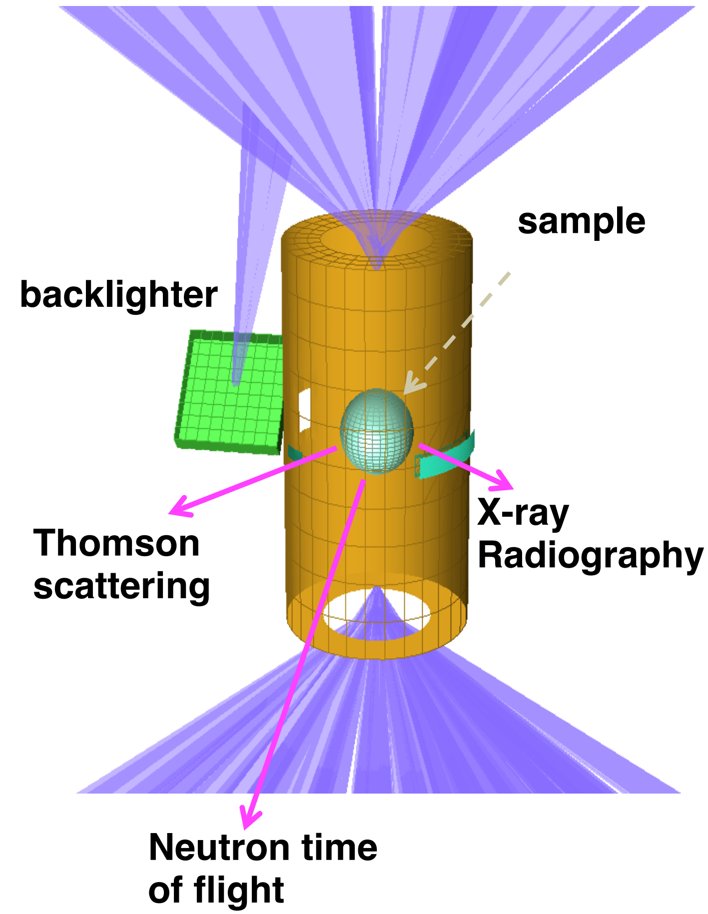


Work from UR student Michelle Gregor who now works at LLNL

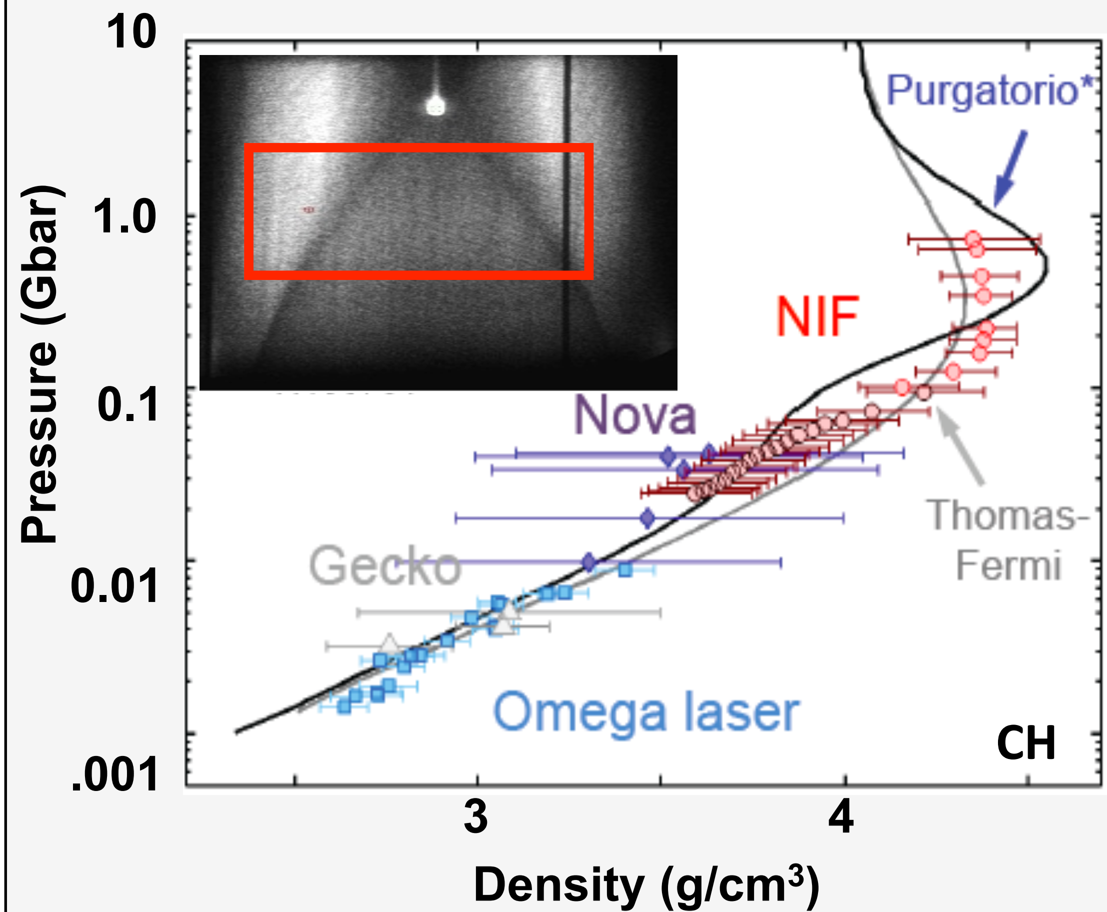
The high Γ and Cv (not shown) suggest a complex chemistry in this dense plasma

Convergent shock waves are used to explore to Gigabar pressures where core e⁻-shells are ionized

CH Gigabar Equation of State experiment



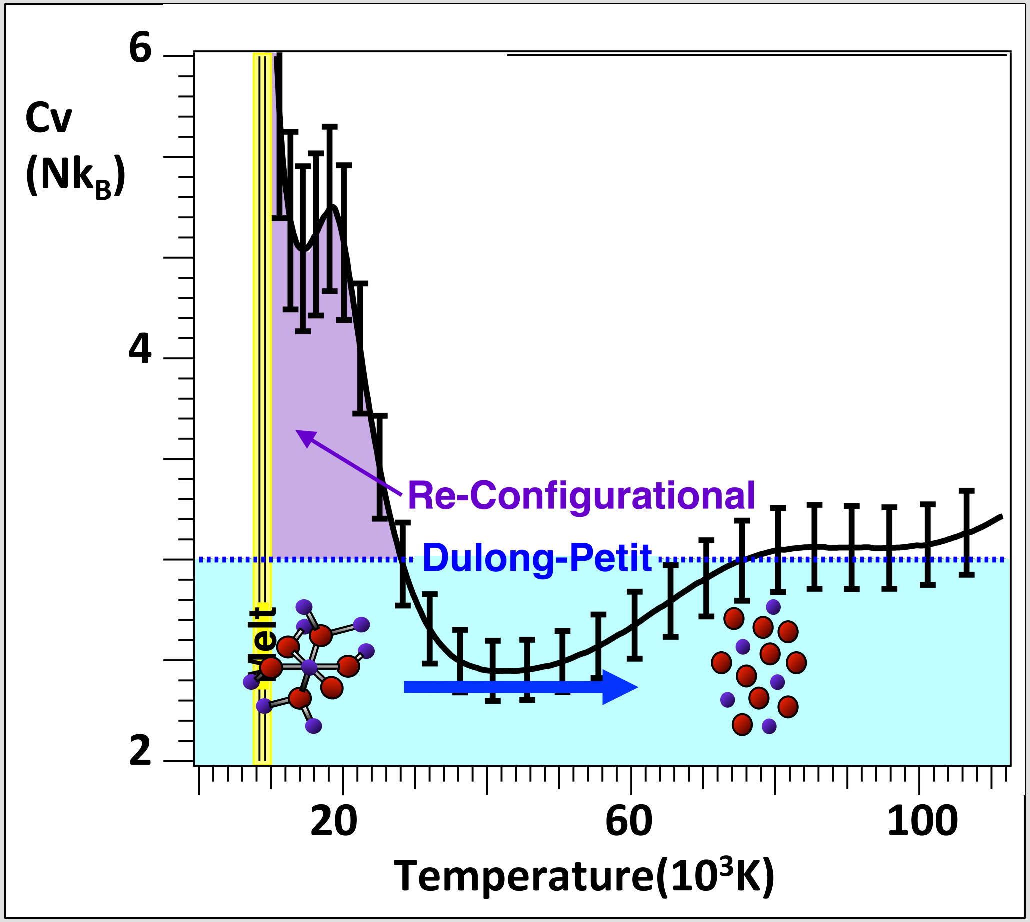
Convergent shock radiography data reveal ionization effects compression less than



Bachman, Swift, Doeppner, Kritcher, et al. LLNL

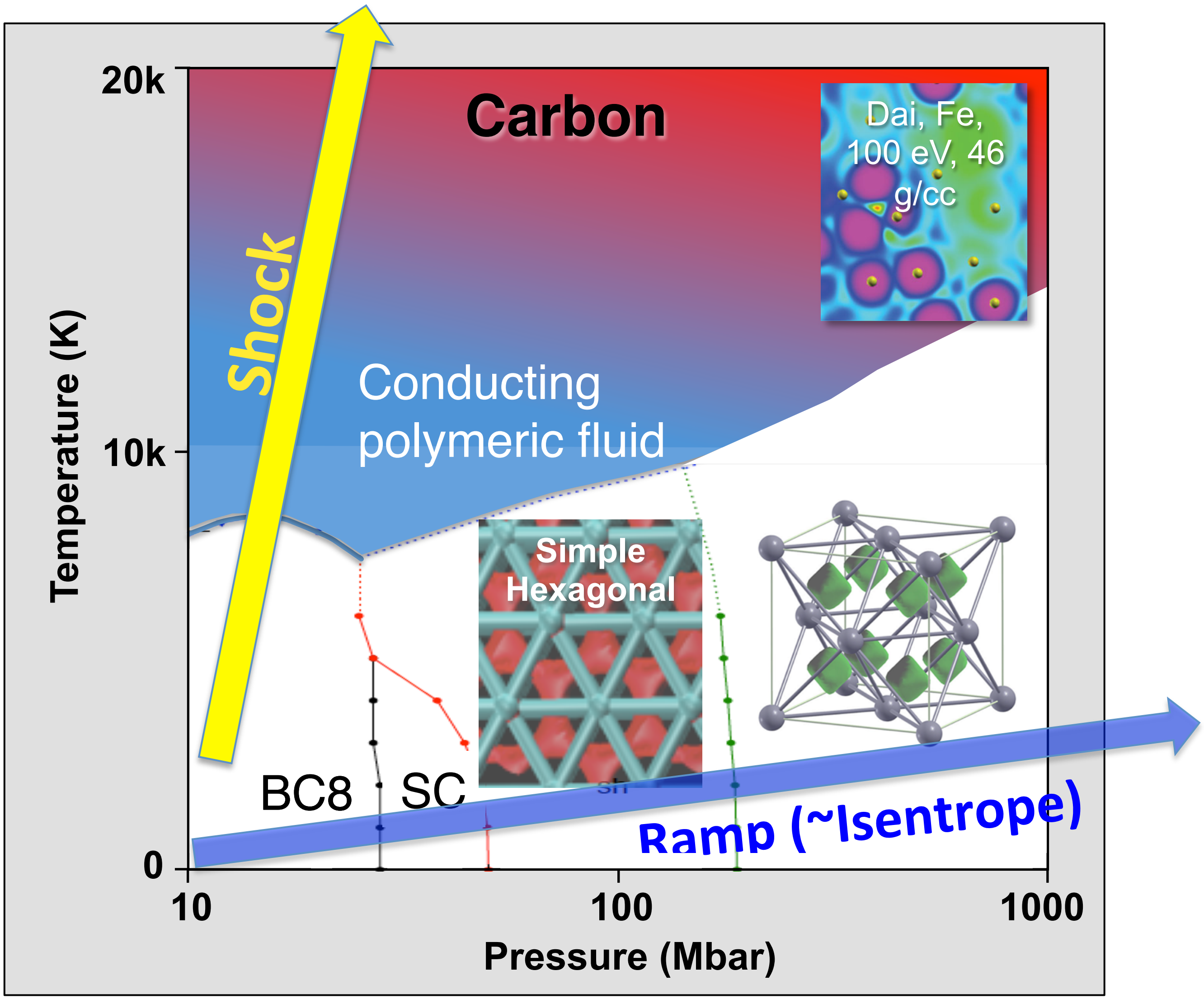
Combining shock Hugoniot and pyrometery data reveals WDM as a complex chemistry phase

Very high heat capacity suggests complex chemistry phase



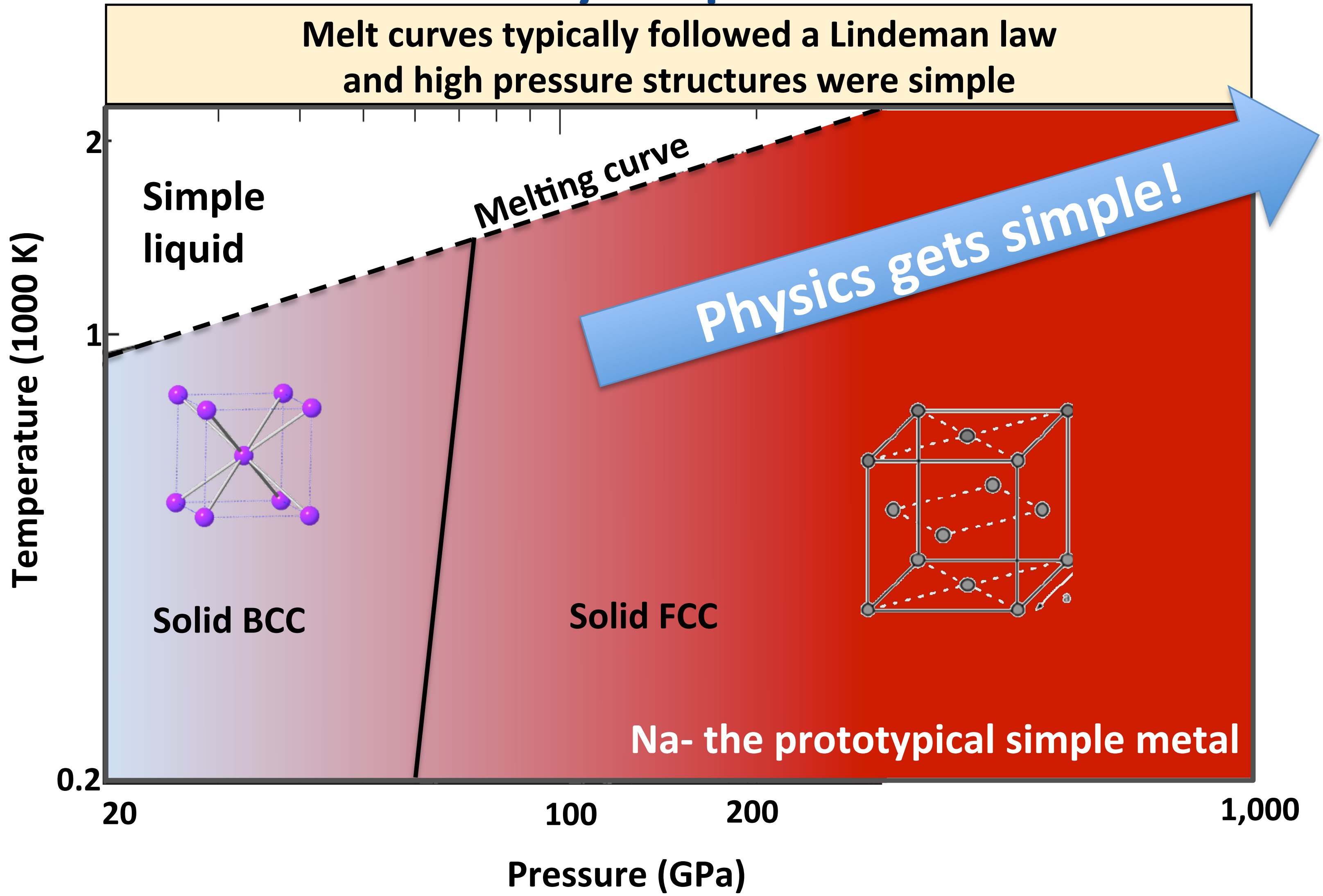
Eggert 2008

At still higher densities, calculations are predicting still more exotic behavior



Canales, PRL, (2012)
Hamel et al, 2014

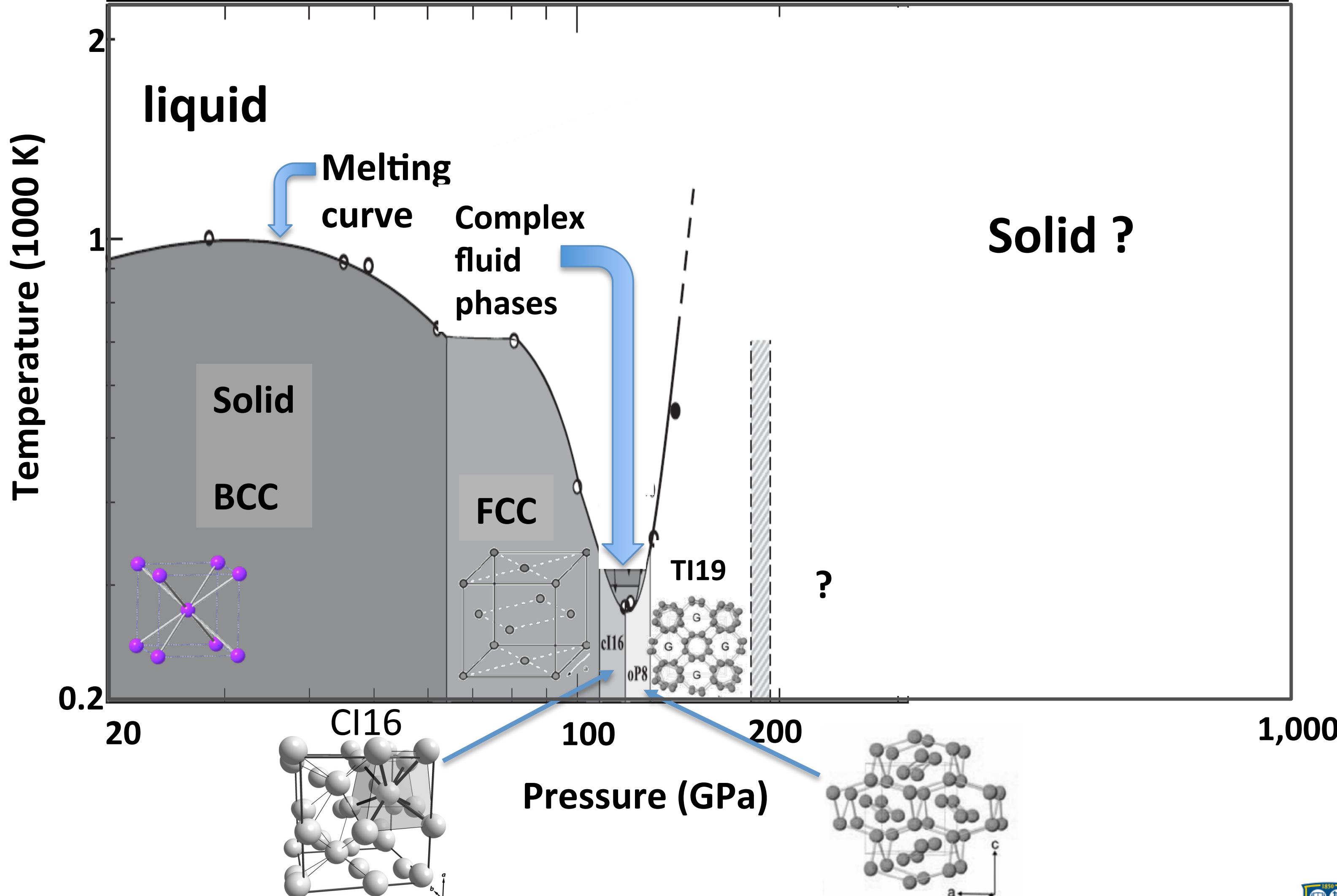
Just a few years ago, ultra-high pressure phase diagrams for materials were very simple



* M. Marques *et al.*, PHYSICAL REVIEW B 83, 184106 (2011)

However, a few recent observations and calculations suggest a very different behavior

There is increasing structural complexity and an opening of the electronic band gap with increasing pressure



* M. Marques *et al.*, PHYSICAL REVIEW B 83, 184106 (2011)

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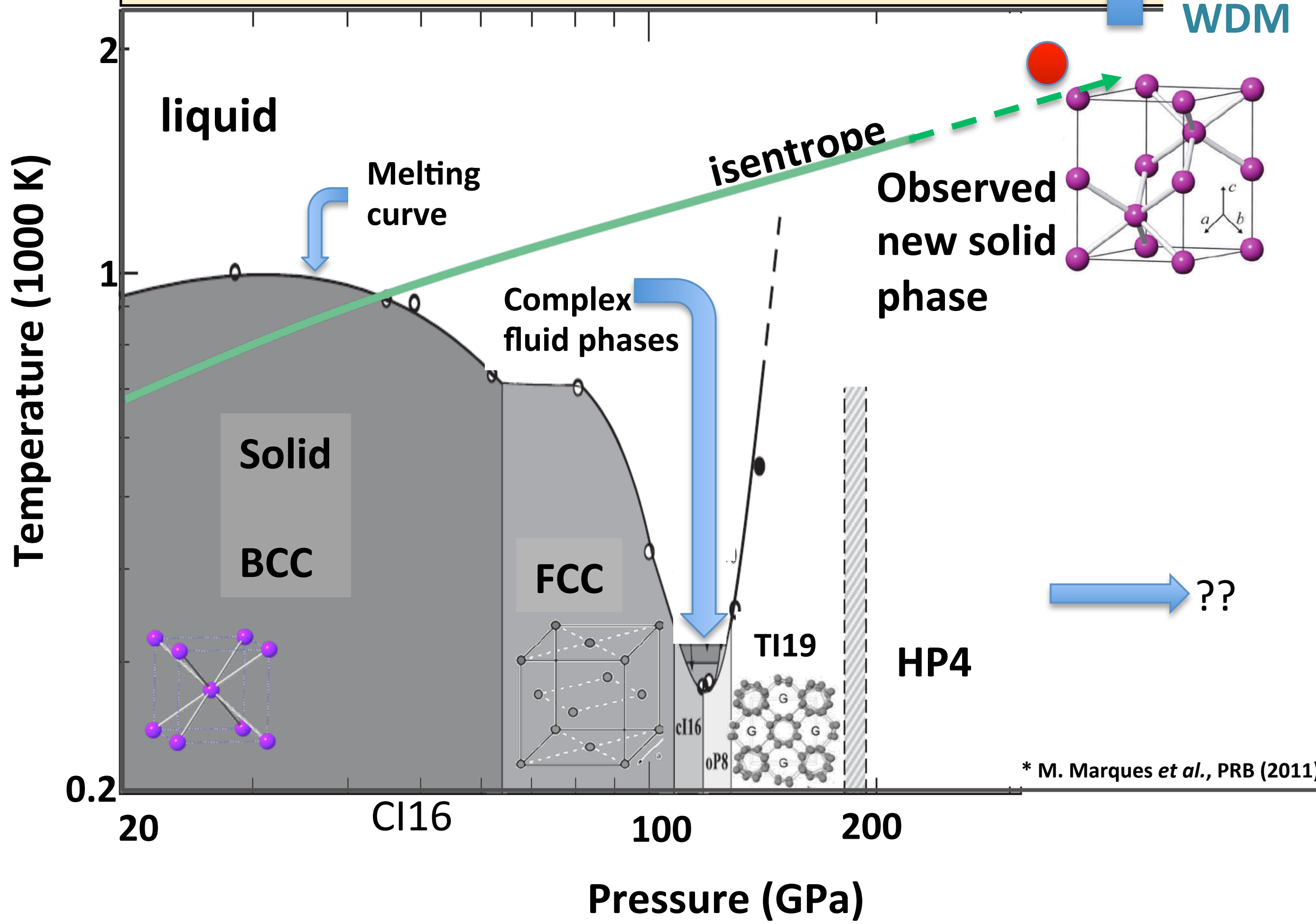
Ramp compression + diffraction reveals Na is an "electride" in the solid-&-likely a Warm Dense Matter insulator

We collected structural and EOS data for Na to more then 3 Mbar



Optical diagnostics show Na is less conducting, perhaps insulating in the warm dense matter regime between 3 and 5 Mbar

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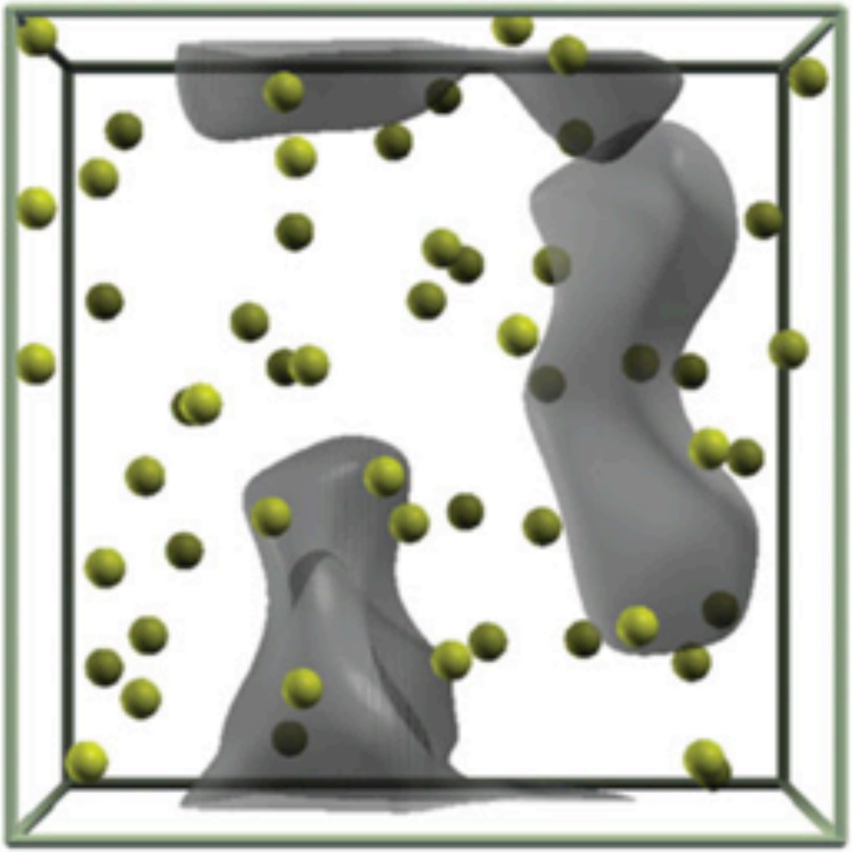
Is there an analogous electride fluid or dense-plasma phase?

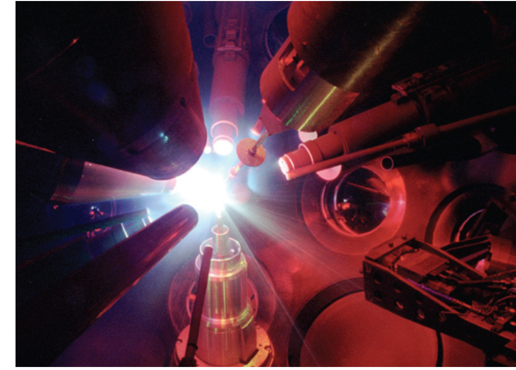
- At 158 Mbar and 0K Fe is predicted to form an FCC electride phase.
- At similar densities but in the warm dense matter phase, electron clumping in the plasma phase is predicted

Fe at 100 eV, 48.23 g/cc

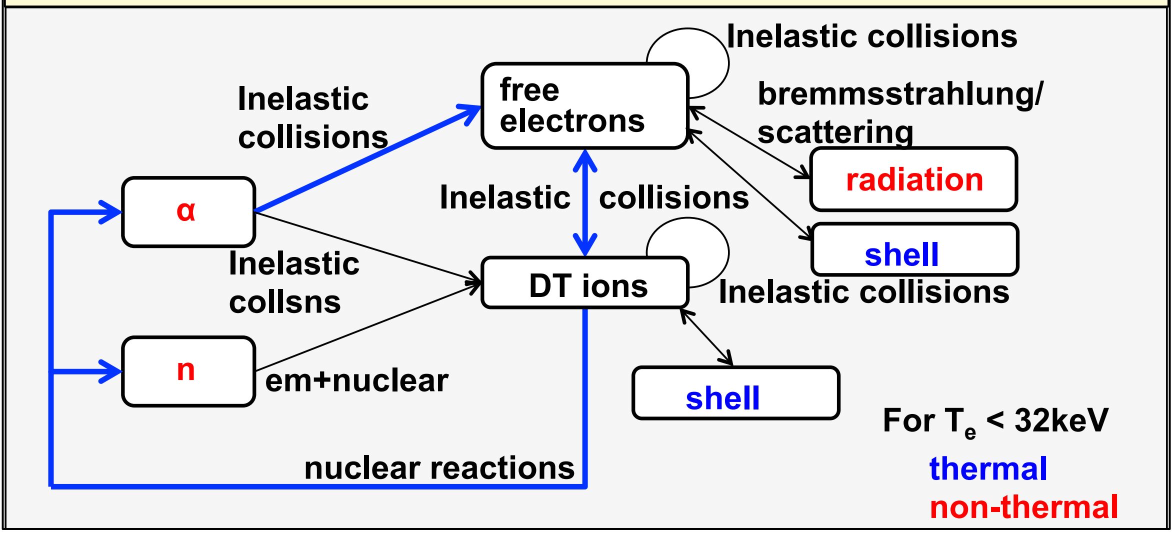


Dai, et al. 2012

Transport quantities are important at all stages of implosions



All time constants for energy production and transport at stagnation are comparable



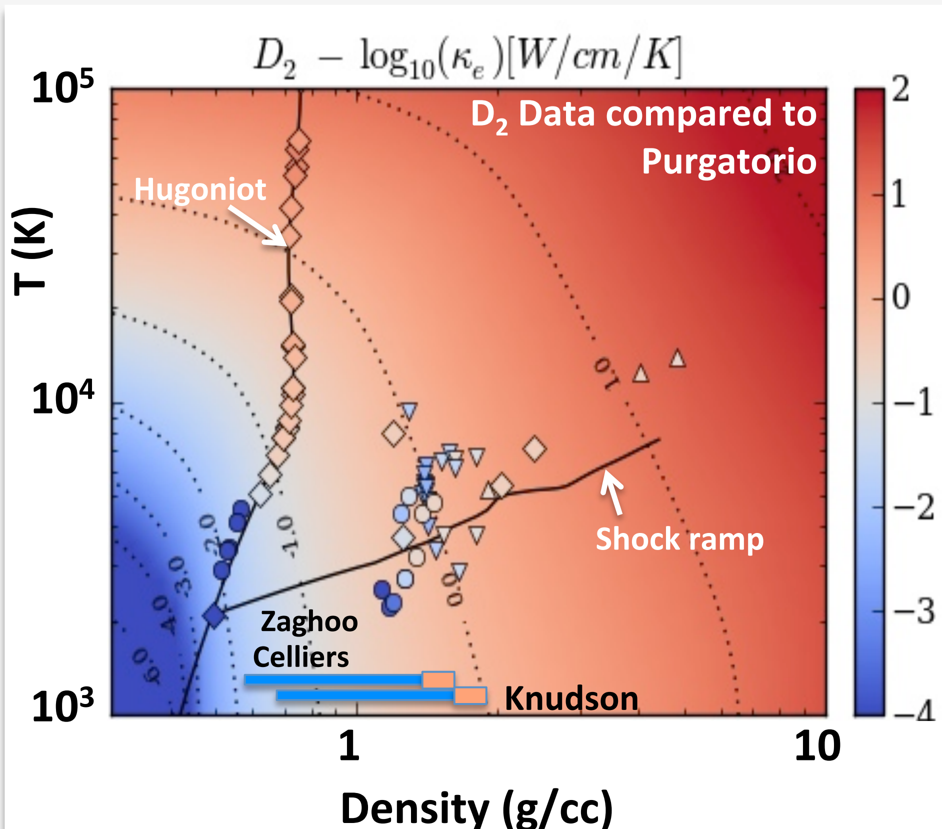
Natural timescales in ICF hotspots

$\tau_{e\text{-}ion}$ ~2 ps
τ_{Brems} ~20 ps
$\tau_{stopping}$ ~30 ps
$\tau_{Reaction}$ ~40 ps
τ_{hydro} ~50-100+ ps
$\tau_{electron\ conduction}$ ~20 ps
$\tau_{ion\text{-}conduction}$ ~ depends

Let's consider just thermal conduction (local)

Even in the few Mbar regime, there are many surprises and discoveries

Conductivity data at high densities do not agree with models



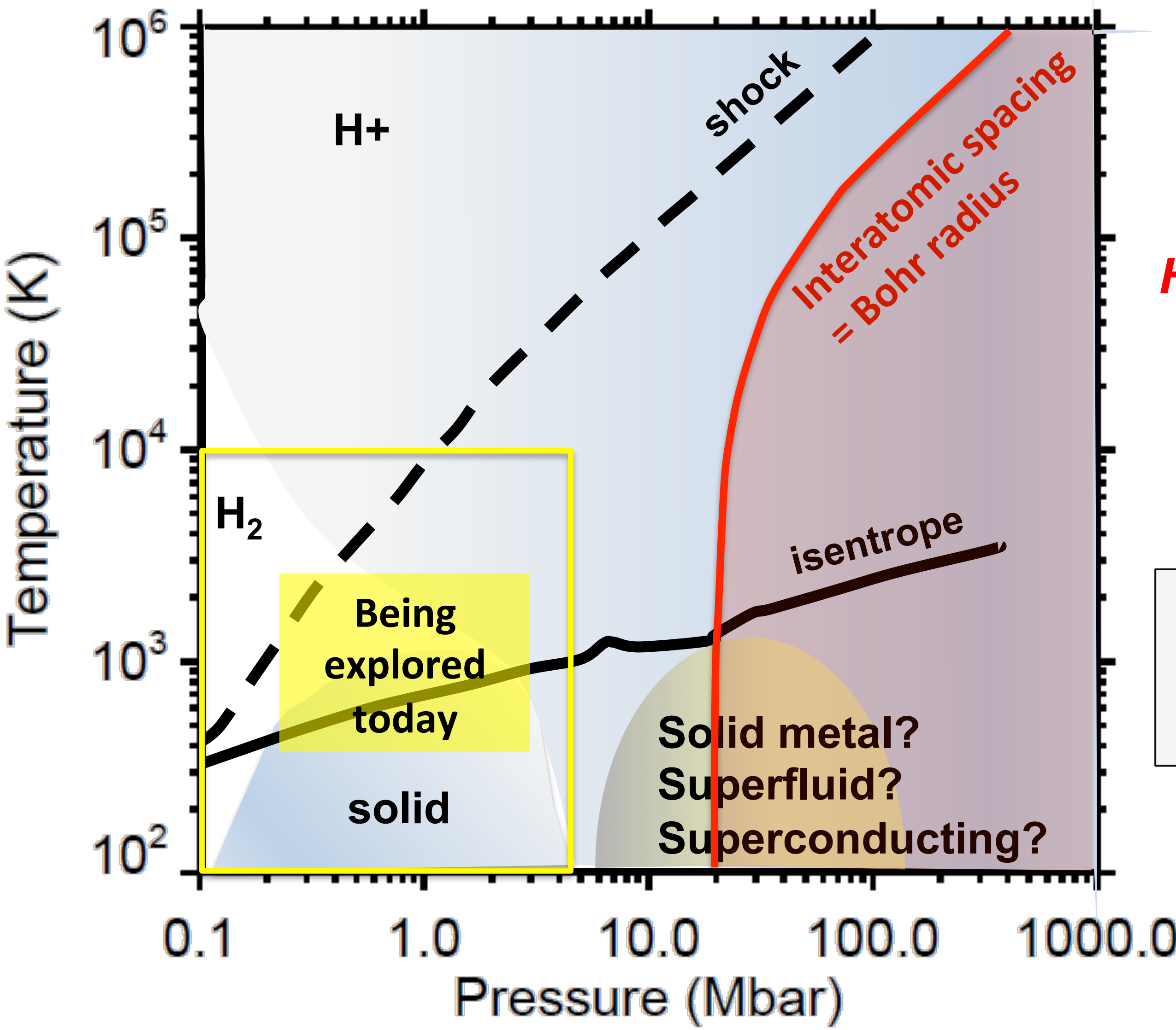
- Z experiments (Knudson, Science 2015) measured metal insulator transition at ~ 1000 K and 3 Mbar,
- diamond cell data (Zaghoo, PRB 2016) and NIF data (Celliers, 2017) suggest this occurs at ~1.4 Mbar
- Models disagree from data almost everywhere
- 30% differences in thermal conductivities at 10^5 K and 10 g/cc effect ICF stability

Experimental data:
Nellis1992, ○ Nellis1999, ○
Celliers2000, ◇ Fortov2003, △
Ternovoi2009, ▽

Theory from Sterne et al.

Rygg, NLUF with Berkeley ◇

We have only explored a small fraction of the phase diagram needed for ignition

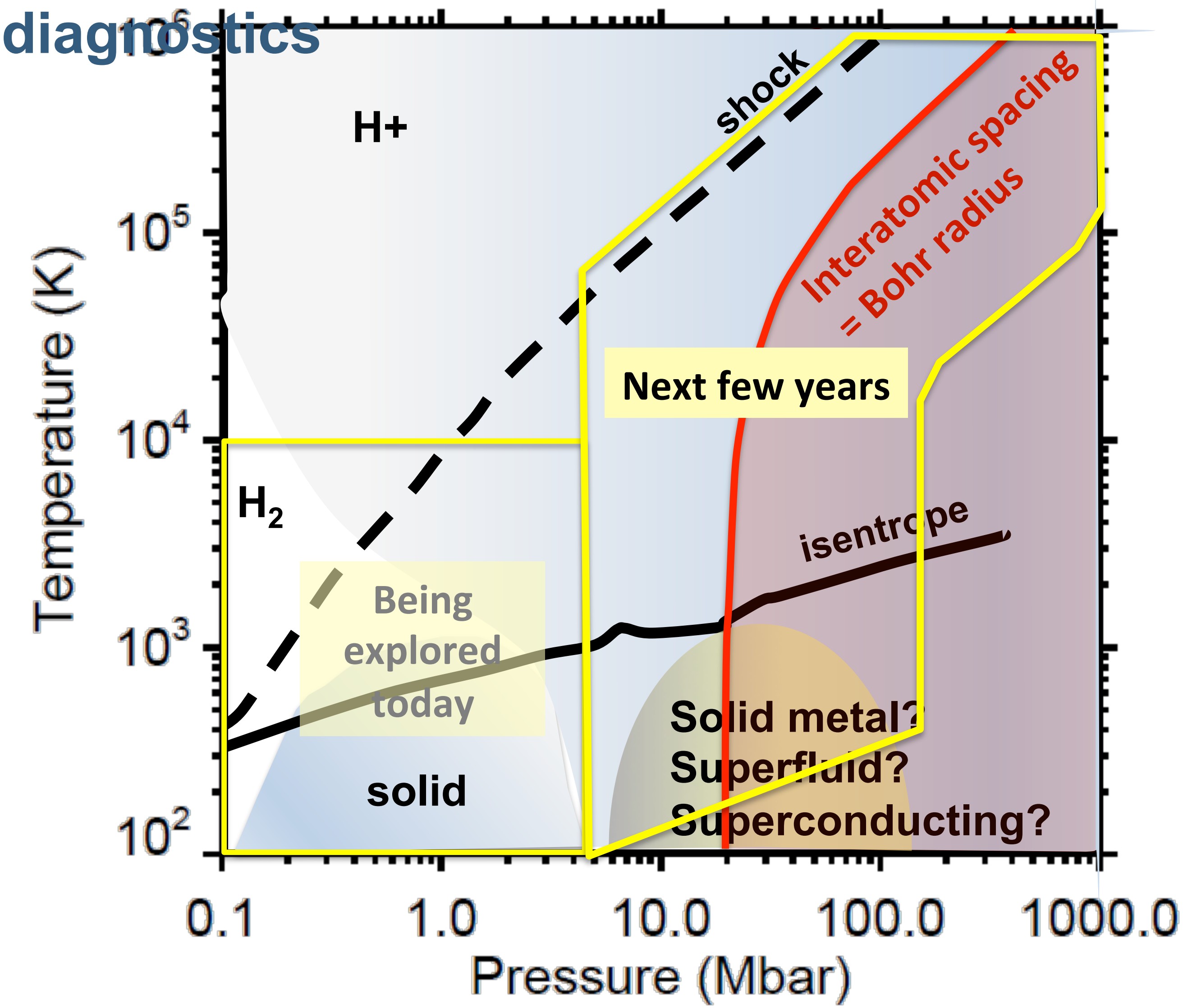


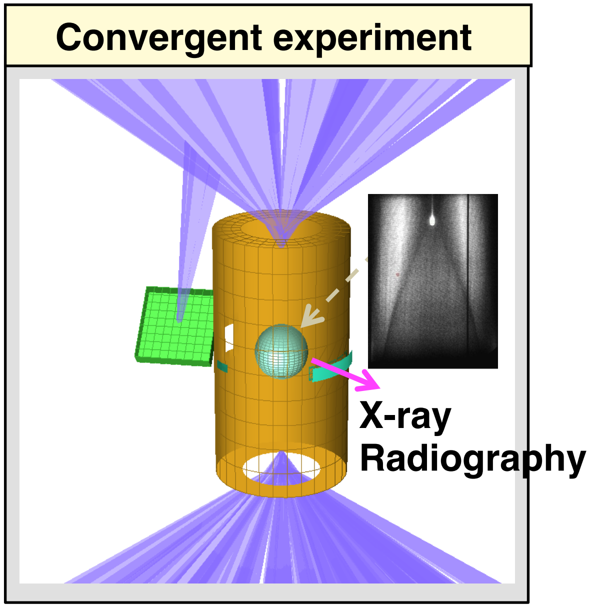
Superconducting Superfluid Hydrogen > 5 Mbar?

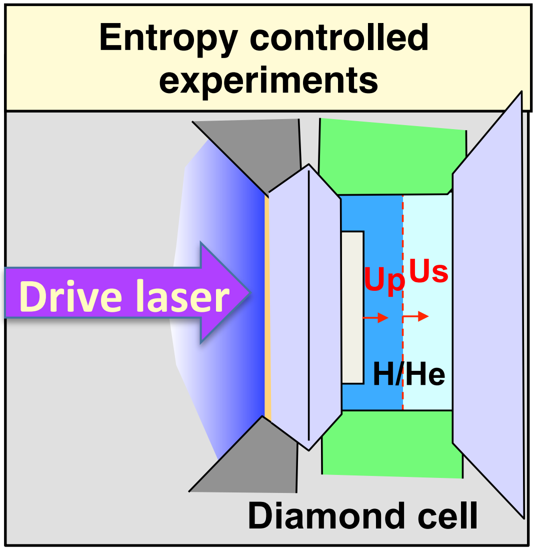
>20 publications on this last year!

Still, these conditions are very far from those needed for ICF

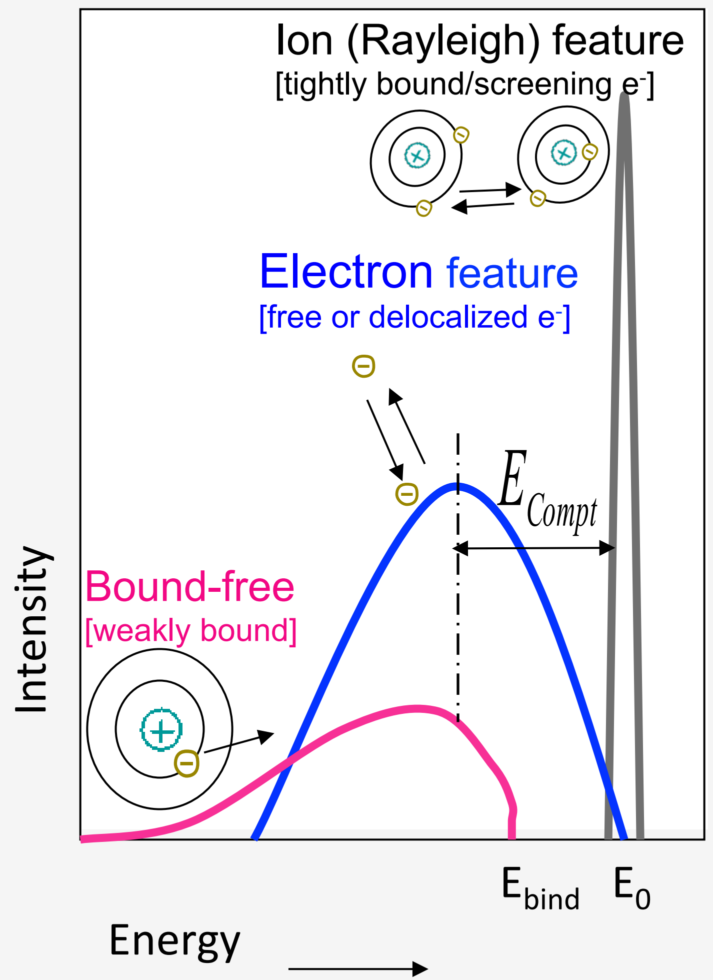
In the next few years we will be extending into the many 10's Mbar range with new diagnostics







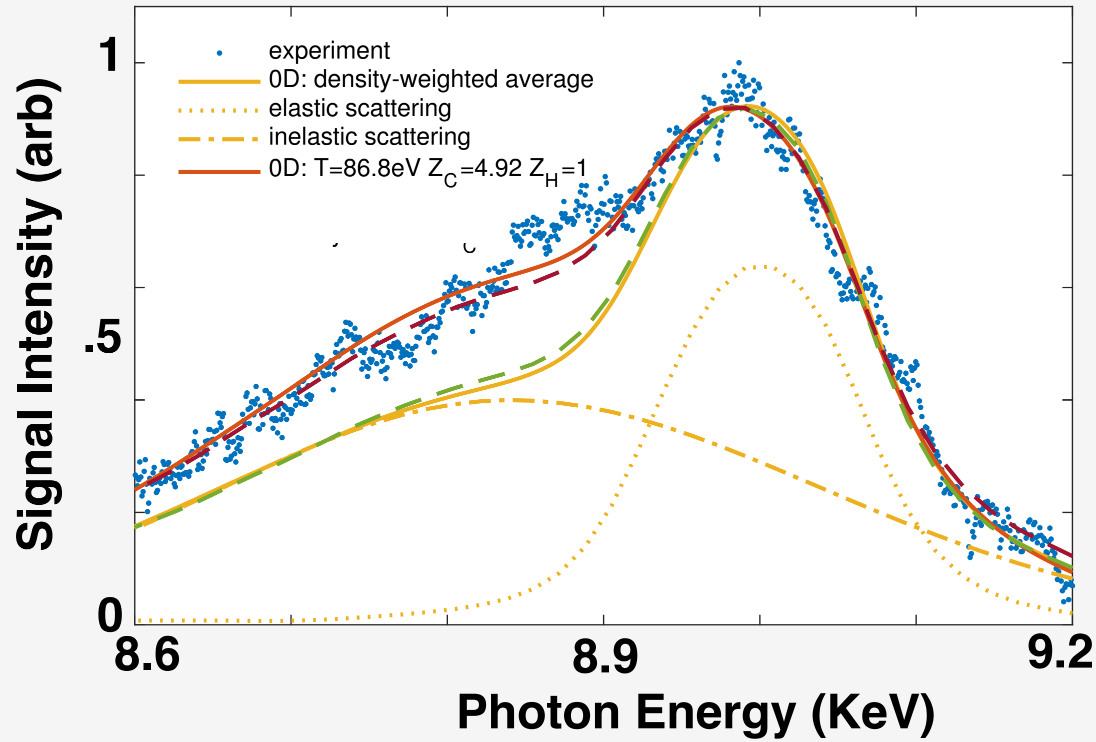
Thomson scattering suggests a 20% different ionization in the warm dense matter regime than predicted by models



Schematic Scattering spectrum

The average ionization comes from comparing the elastic and inelastic scattering

~200 Mbar, ~4.5 g/cc



Nature Comm. 2016

D. Kraus, T. Doeppner, Roger Falcone et al.

NNSA has enabled a number of workshops to help define regions of greatest uncertainty in our physical models

Report on the 2016 Laser-Plasma Interaction Workshop

D. H. Froula[1], M. Glinsky[2], P. Michel[3], J. Myatt[1,4], J. Weaver[5], L. Yin[6]

Workshop on Stopping Powers (2016)

S. Hansen

The Kinetic Physics in ICF workshop: findings and paths forward (April, 2016)

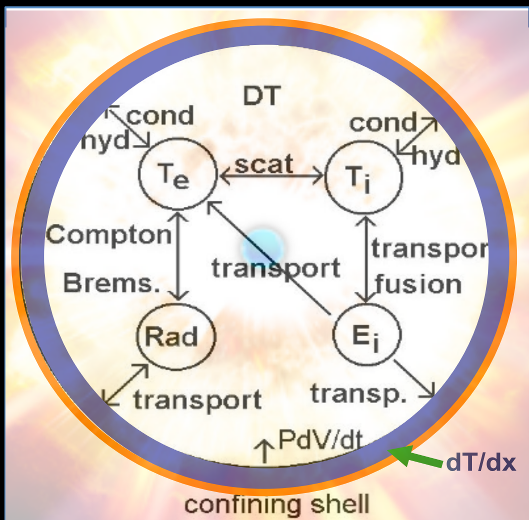
Hans G. Rinderknecht[1,*], P.A. Amendt[1], S.C. Wilks[1], and G. Collins[2]

The First DOE/NNSA Equation-of-State (EOS) (5/31-6/2/2017)

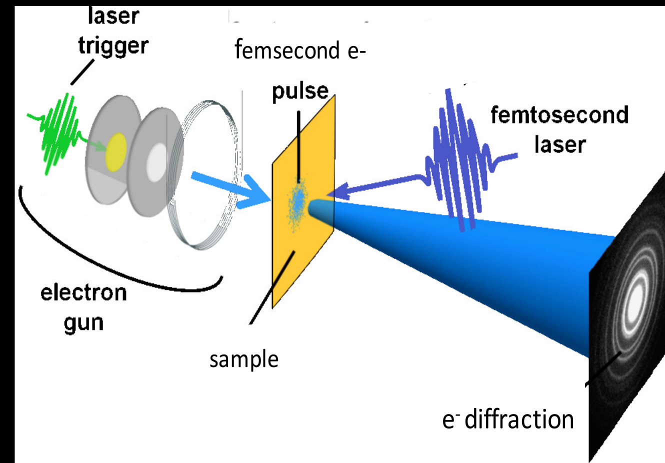
Suxing Hu, Jim Gaffney, G. Collins

We're launching a new generation of HEDS fundamental research to help improve our predictive capability for fusion

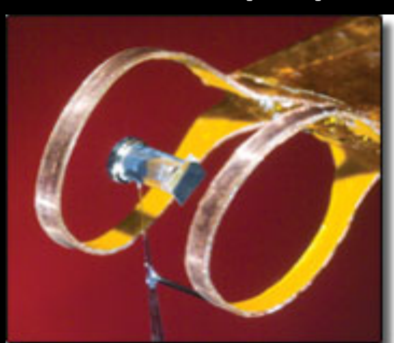
Accurate measurements & descriptions of HED matter



Transformational diagnostics



Advanced ways to control HEDP properties



Building new HEDP curriculum

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Thanks to a large team of scientist working on several different aspects regarding the microphysics of thermonuclear fusion

T. Boehly, R. Rygg, M. Zaghoo, D. Polsin, X. Gong, B. Henderson, J.J.Ruby, L. Crandel, M. Huff, G. Tabak, R. Saha, A. Chin, S. Hu

University of Rochester and LLE

B. Bachmann, M. Millot, Rick Kraus, J.H. Eggert , D. Braun, R.F. Smith J.A. Hawreliak, A. Lazicki, F. Coppari, D. Fratanduono, D. Hicks, D. Swift, P. Celliers, S. Hamel, A. Fernandez, M. Gregor, S. Haan, T. Doeppner, A. Kritcher, H. Rinderknecht, G. Zimmerman, L. Bennedict, P. Sterne, J. Gaffney, Y. Ping

Lawrence Livermore Laboratory

F. Beg

University of California, San Diego

P. Loubeyre, S. Brygoo

Commissariat a l'Energie Atomique

R. Jeanloz, R. Falcone

University of California, Berkeley

Natalia Dubrovinskaia, Leonid Dubrovinsky

Bayreuth University, Germany

T. Duffy, J. Wang

Princeton University

M. McMahon

University of Edinburgh

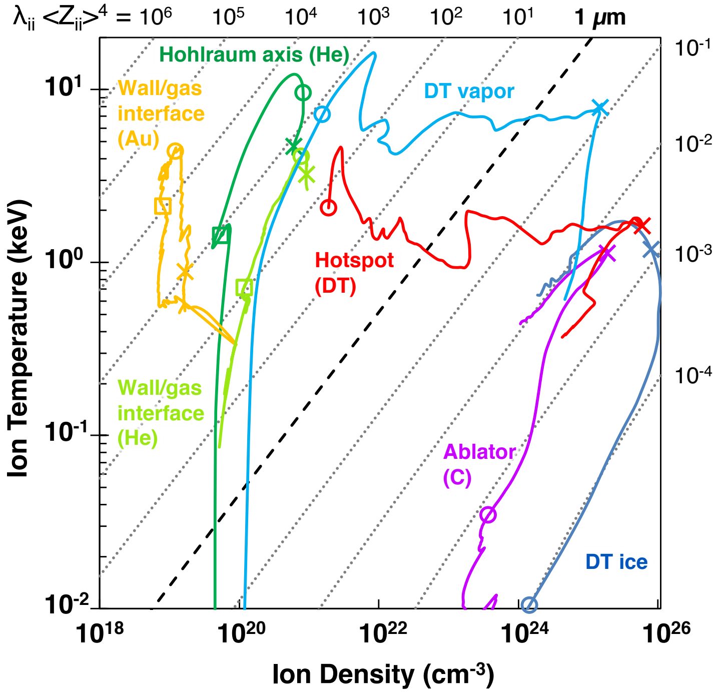
G. Gregori, J. Wark

Oxford University

backups

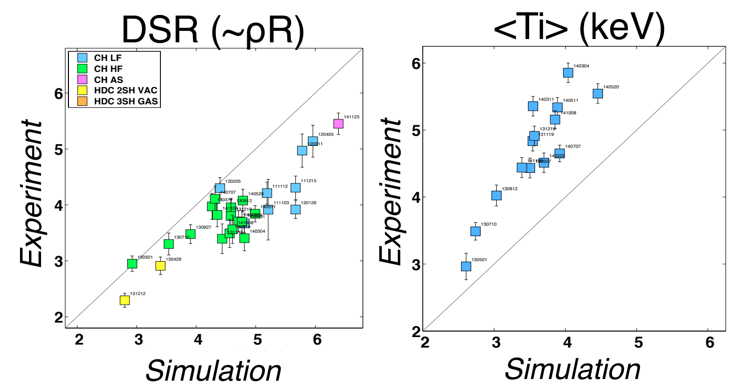
Progress is being made understanding the impact of kinetic physics in ICF. The workshop identified…

…Regions likely to be influenced or dominated by kinetic physics:



- ***LEH:*** LPI & hot electrons
- ***Hohlraum:*** multi-species; EM fields; return-current instability
- ***Ablator/DT interface:*** mix; melting; shock breakout
- ***Fuel Assembly:*** species separation, multi-Ti, frictional heating; shock-front formation; EM fields

…Anomalies in NIF data, potentially caused by kinetic physics:



Low-mode drive asymmetry, "Missing" energy, ρR & <Ti> prediction, <Ti> ratio prediction, yield ratio prediction.

…Paths Forward:

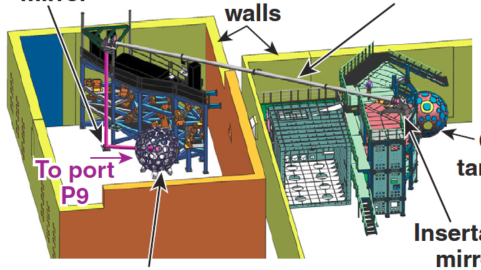
1. Benchmark high-fidelity physics simulations (*multicomponent hydro, multi-fluid, VFP, and hybrid-PIC*) ***toward full ICF simulations.***
2. Perform **integrated scaling experiments** sensitive to kinetic physics.

Workshop summary available at: https://lasers.llnl.gov/nif-workshops/kinetic-physics-workshop-2016

LLE hosted a national laser-plasma interactions workshop with over 50 scientists to help organize and defined the future of the field

- A more-complete understanding of laser-plasma instabilities will fill our knowledge gaps and lead to an expanded design space for ICF
- The LPI community has been integral in the success of the ICF Program from the early days—demonstrating innovation at critical times
- The interplay between hydrodynamics and LPI (at both micro and macroscopic levels) requires focused studies that isolate the LPI physics—small scale facilities play a critical role
- Computational tools have matured to a stage to help understand advanced laser conditioning (e.g., wavelength effects) on LPI—use LPI tools to define new laser schemes for mitigation

Tunable Omega Port 9 Capability
($\Delta\lambda$=3.5 nm in the UV)



LPI experiments are scheduled for next month using the TOP9—this is ~12 months after the LPI Workshop's proposal

The First DOE/NNSA Equation-of-State (EOS) Workshop has been held at the Laboratory for Laser Energetics (LLE) University of Rochester (5/31-6/2/2017)

The importance of EOS to the ICF/HED community:

- ➢EOS is needed to close hydro-equation
- ➢EOS determines ρ/T profile of shock compressed materials in ICF/HED-expts
- ➢EOS model/experiment discrepancies need to reconcile
- ➢EOS model comparisons are needed for informing the ICF/HED community

Summary of findings from the EOS Workshop:

- ❑ Large discrepancies in EOS models were identified in the warm-dense matter regime of 1-10 eV temperatures for ICF-relevant materials
- ❑ High-pressure EOS experiments (50-Mbar to ~Gbar) are needed at maximum compression (where EOS models differ significantly)
- ❑ The physics validity in various EOS models were explicitly discussed
- ❑ Off-Hugoniot EOS data (including releasing) are needed for constraining models
- ❑ A review article on EOS understanding is under drafting by the community