High Energy Density Physics: A brief introduction

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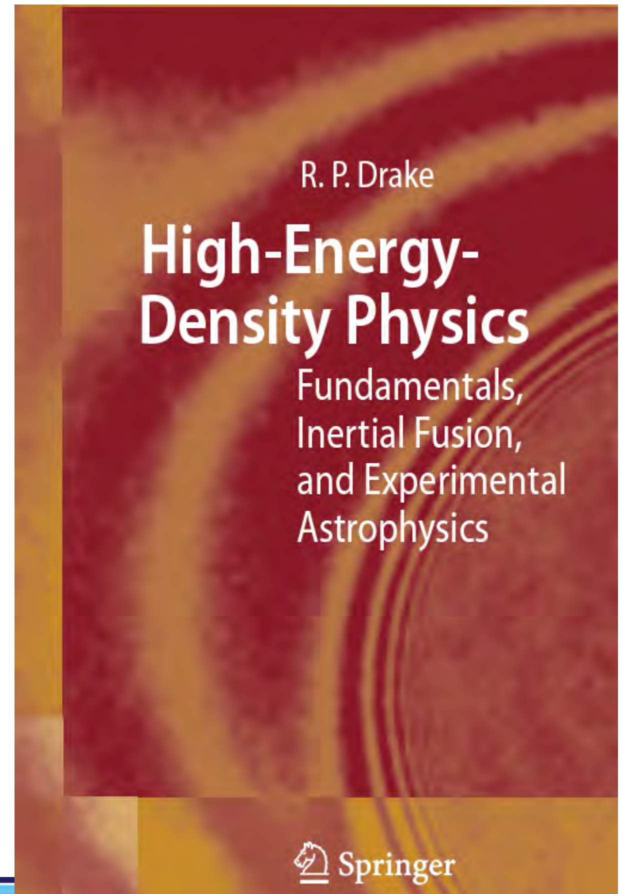
Perspectives on plasma physics and HEDP

- The mid-20th-Century approach to plasma physics, as seen in most textbooks, was simple
  - Many particles per Debye sphere often as the definition of "plasma"
  - Quasineutral
  - Only hydrogen
  - Spatially uniform
  - Maxwellian distributions
  - Deviations from spatial uniformity or Maxwellians drive instabilities
- 21st Century plasma physics breaks these and other assumptions
  - An era of creation and control of systems that deviate strongly from the simple cases
  - High-energy-density plasmas are very much a case in point

My goal is to give you some introduction to elements of HED Physics that matter for experiments you may develop

- **Features and connections of HEDP**
- **Key physical elements of HEDP systems**
- **A few new wrinkles beyond things discussed in my book:**



MICHIGAN

CRASH

Precursors to high-energy-density physics

- **First half 20th Century: Stellar structure**
  - **Eddington, Chandrasekhar, Schwarzschild, among others**

- **Mid-20th Century: Nuclear weapons**
  - **Oppenheimer, Sakharov, Teller, Bethe, Fermi, others**
    - **Compressible metals!**
  - **Zel'dovich and Raizer 1966**
    - **Physics of Shock Waves and High Temperature Phenomena**

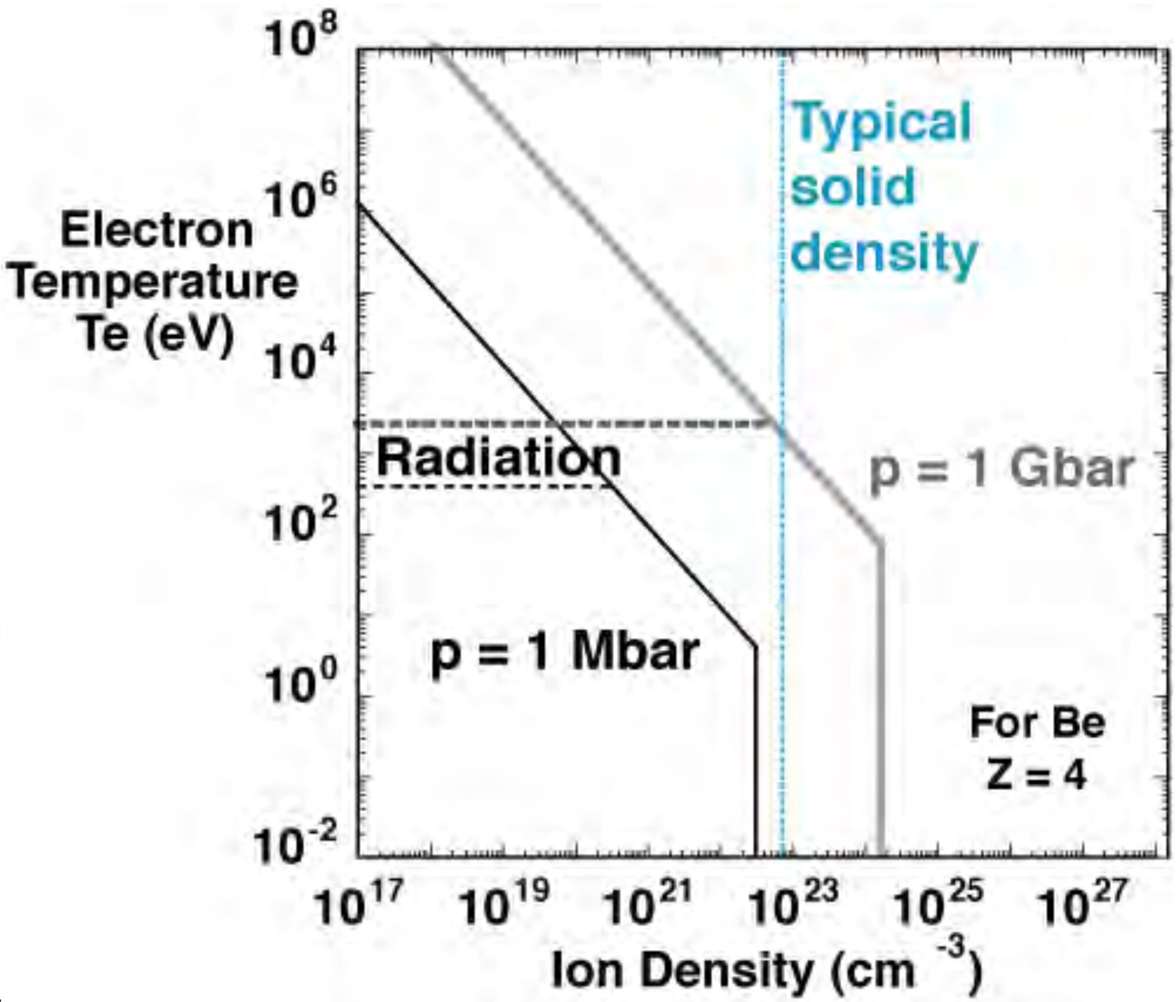
- **Post Mid-20th Century (1960-1980): Inertial fusion origins**
  - **Nuckolls, Basov, Emmett, others**

- **I date HEDP as a discipline from about 1979**
  - **Complex quantitative *physics* experiments became feasible**
  - **The first user facility program (NLUF) began in 1979**

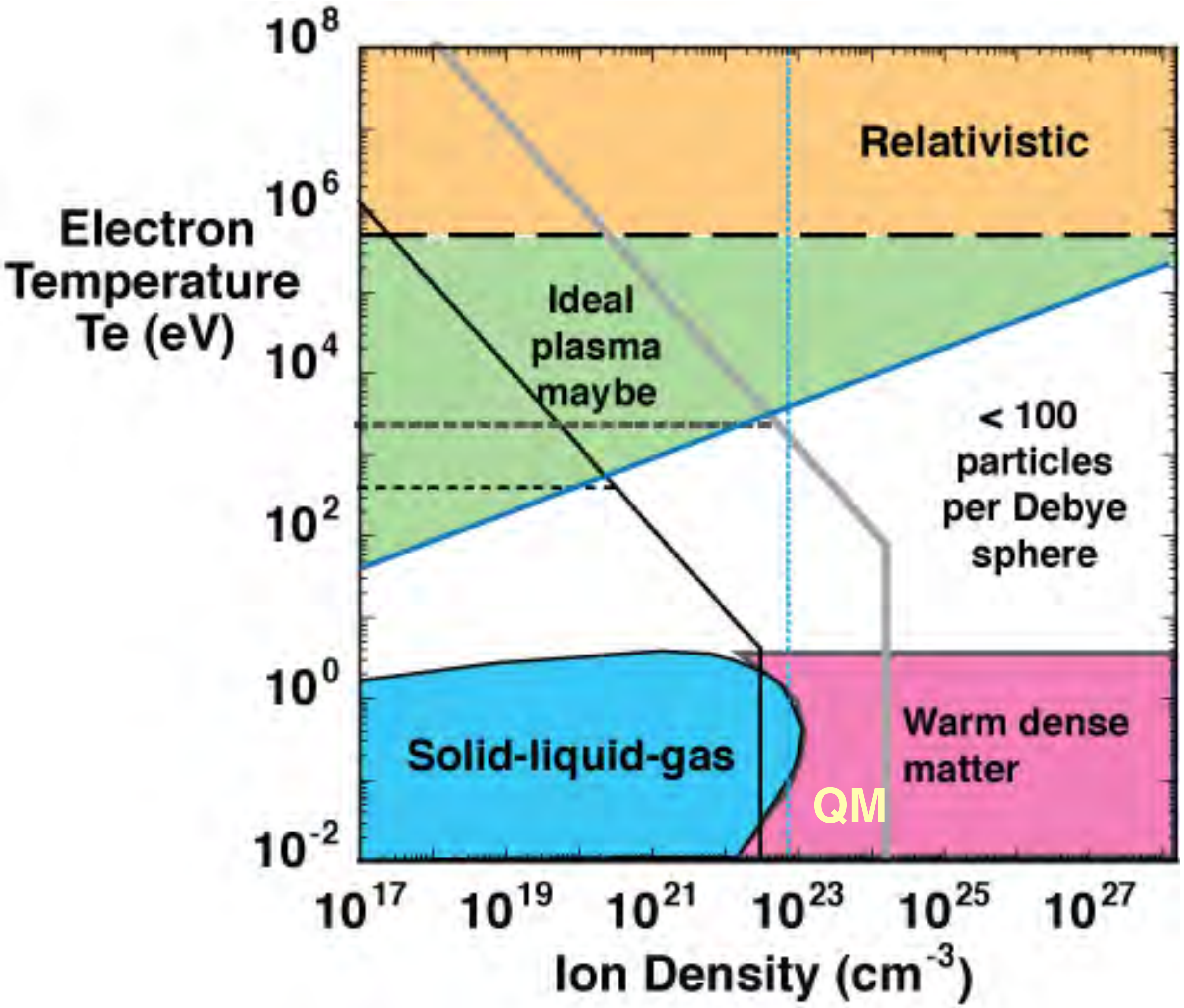
Image credit NNSA Nevada Site Office

We will use this plot to see aspects of high-energy-density physics (HEDP)

- HEDP parameters
- Physics connections
- Astrophysics connections
- Plasma physics connections
  - Particles per Debye sphere
  - Pressure and Fermi degeneracy
  - Strong coupling



Physics connections within and beyond HEDP



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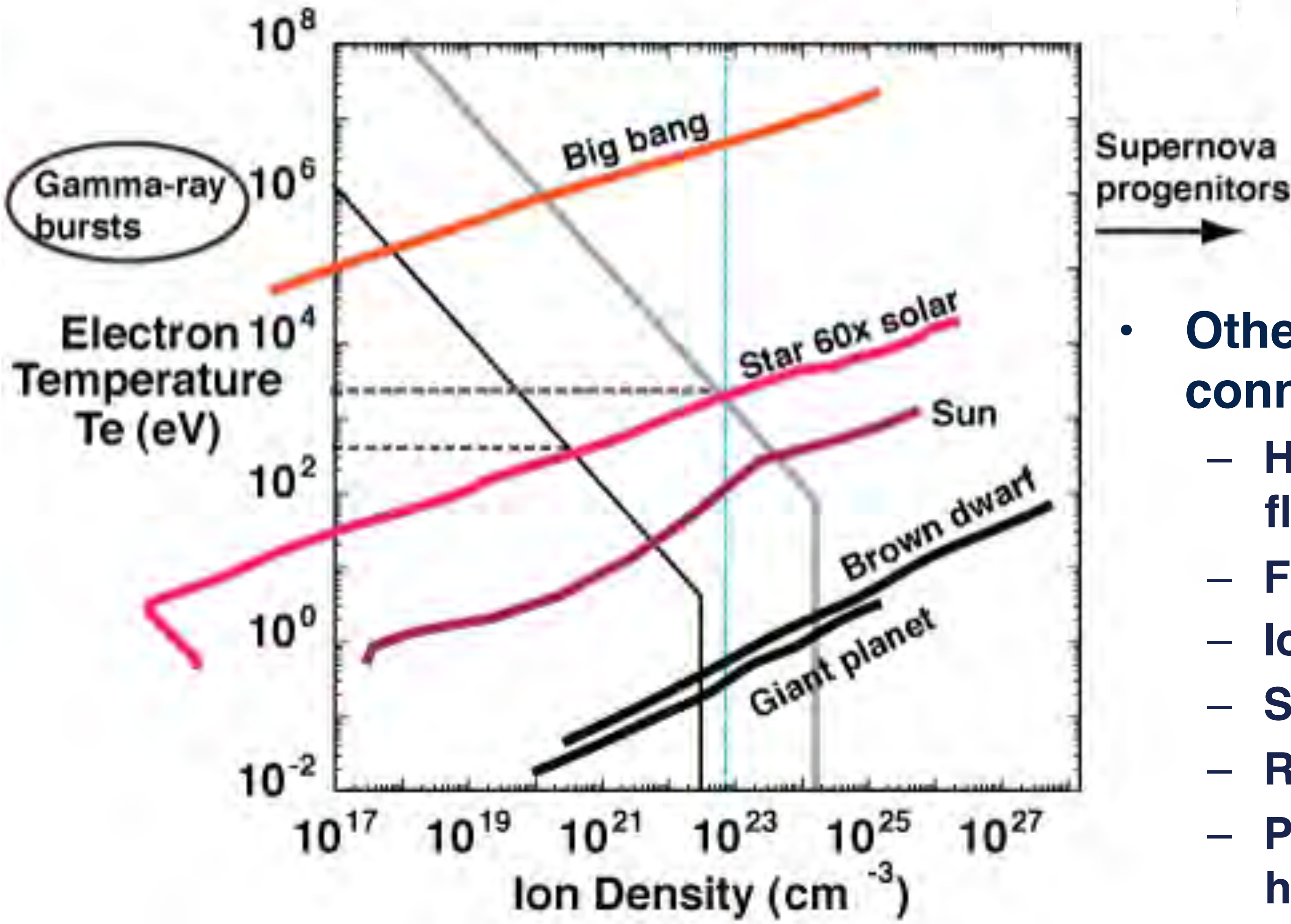
Quark-gluon plasmas

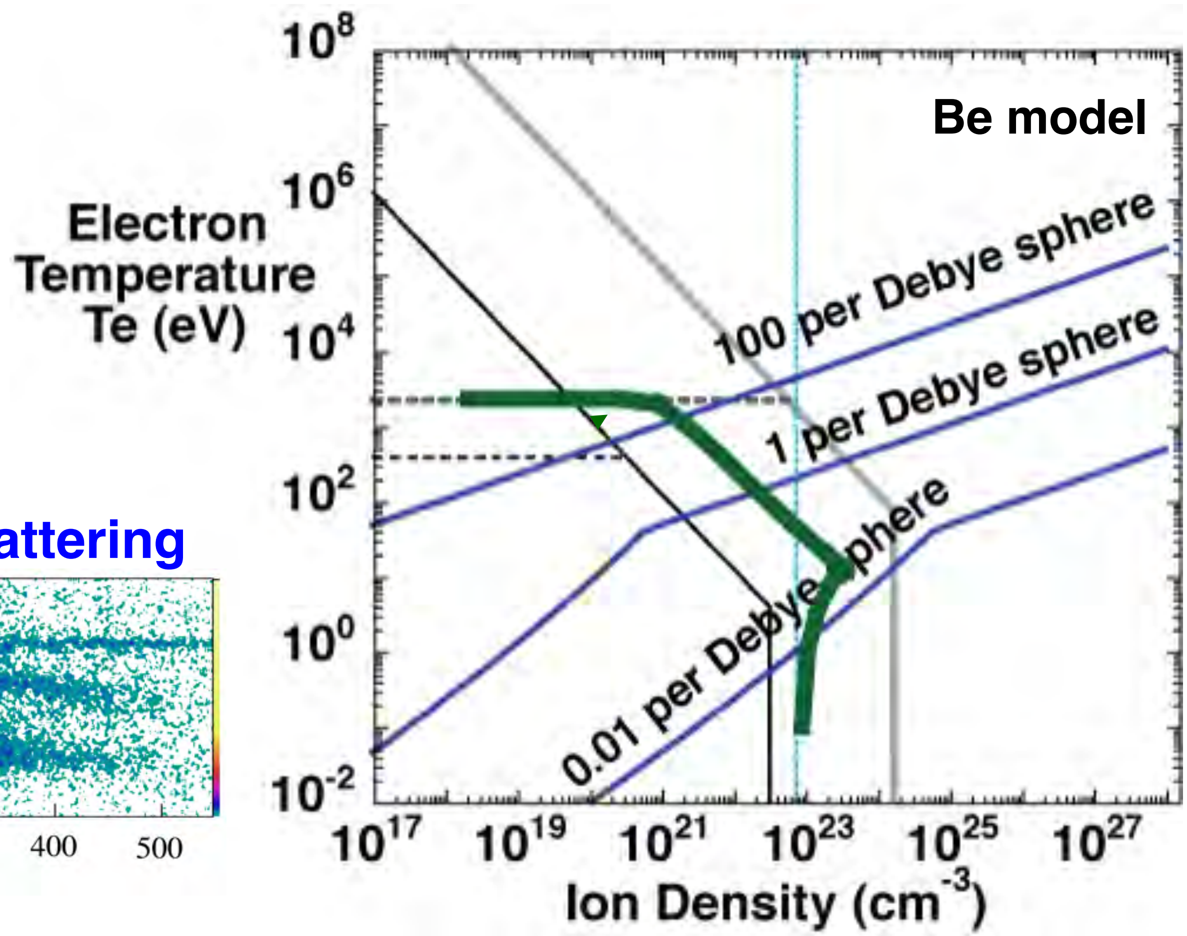
Astrophysics connections with HEDP



- **Other elements of this connection**
  - **High Mach number flows**
  - **Fast shocks**
  - **Ionizing**
  - **Strong B fields**
  - **Radiation matters**
  - **Plasma hydrodynamics**

Curves credit NRC report on HEDP

HEDP systems often have few particles per Debye sphere



UV Thomson scattering

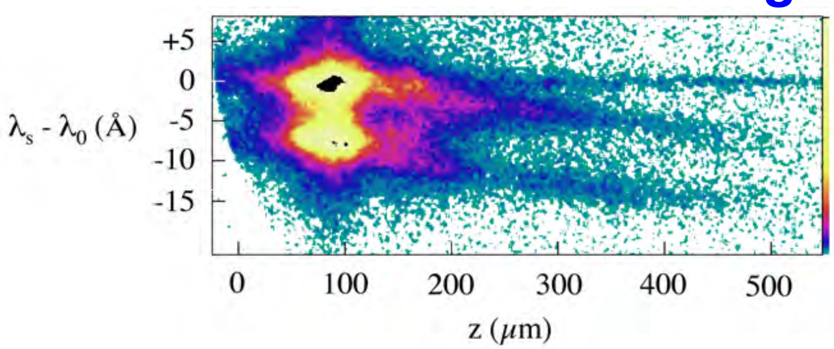
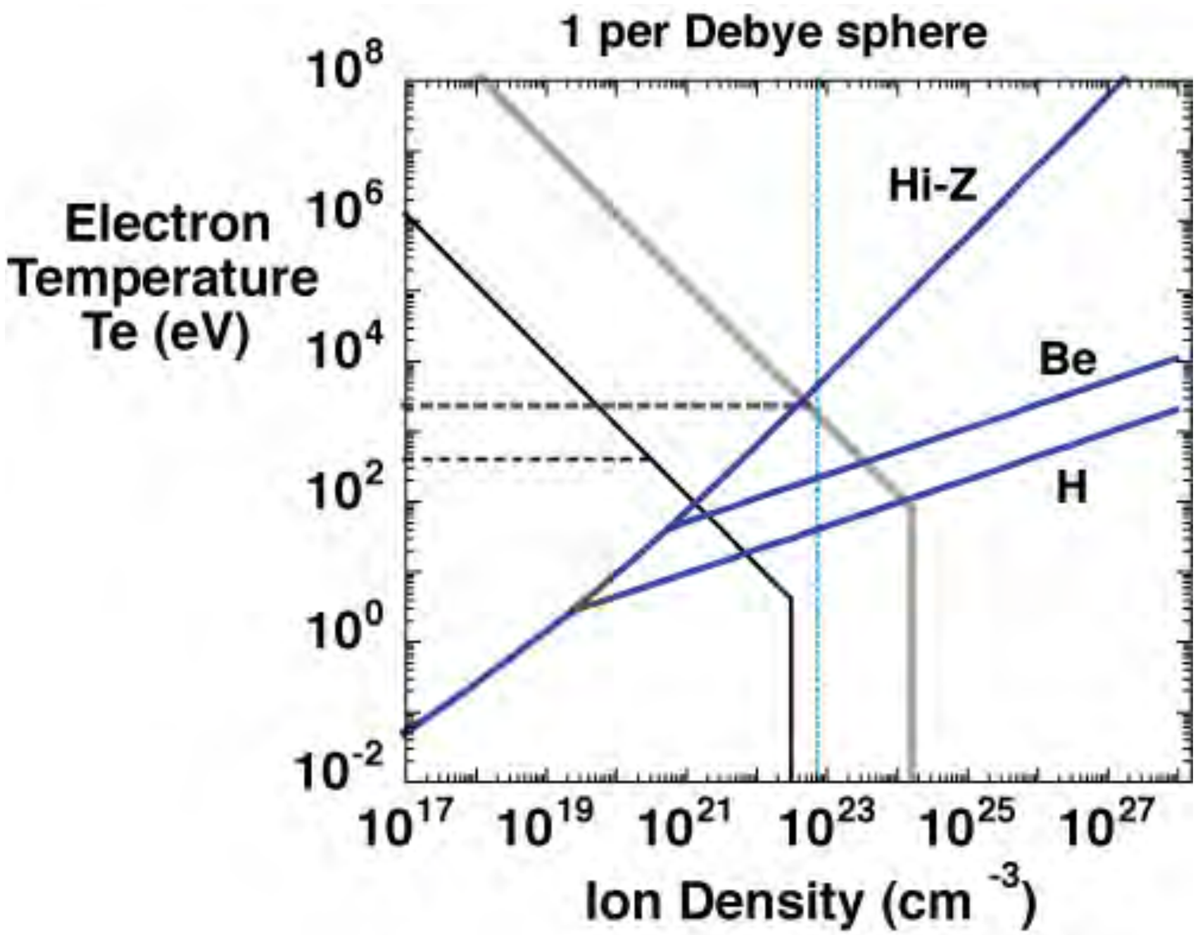
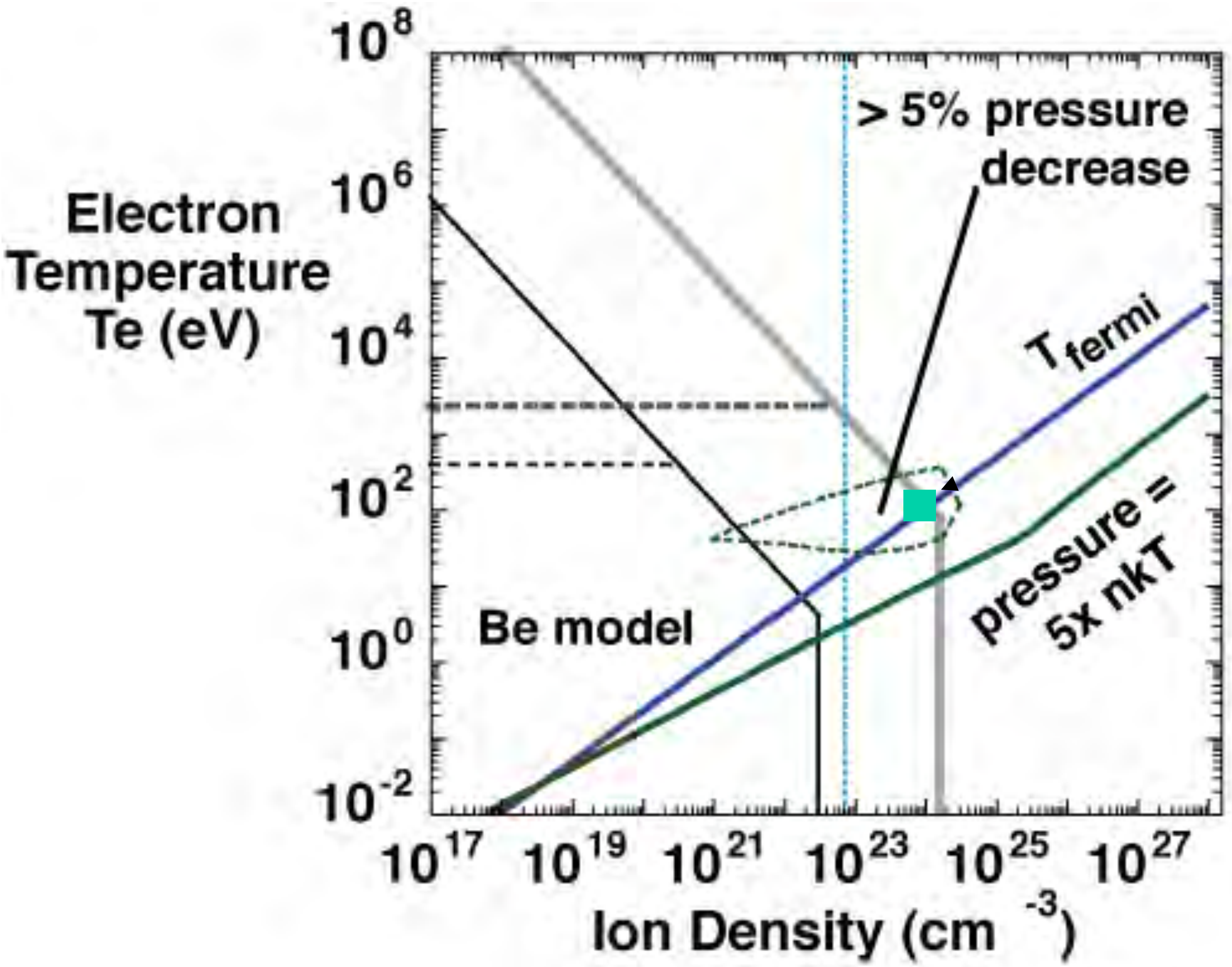


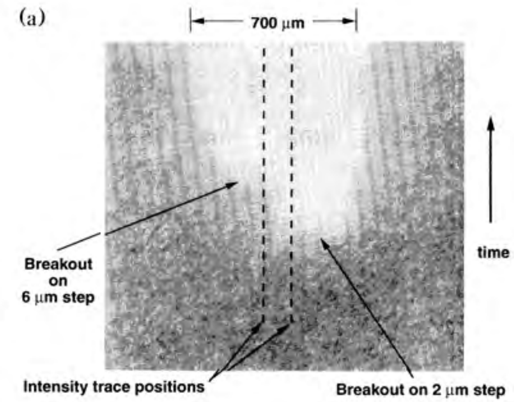
Image credit David Montgomery

Regime boundaries move as materials change



The pressure often is not nkT

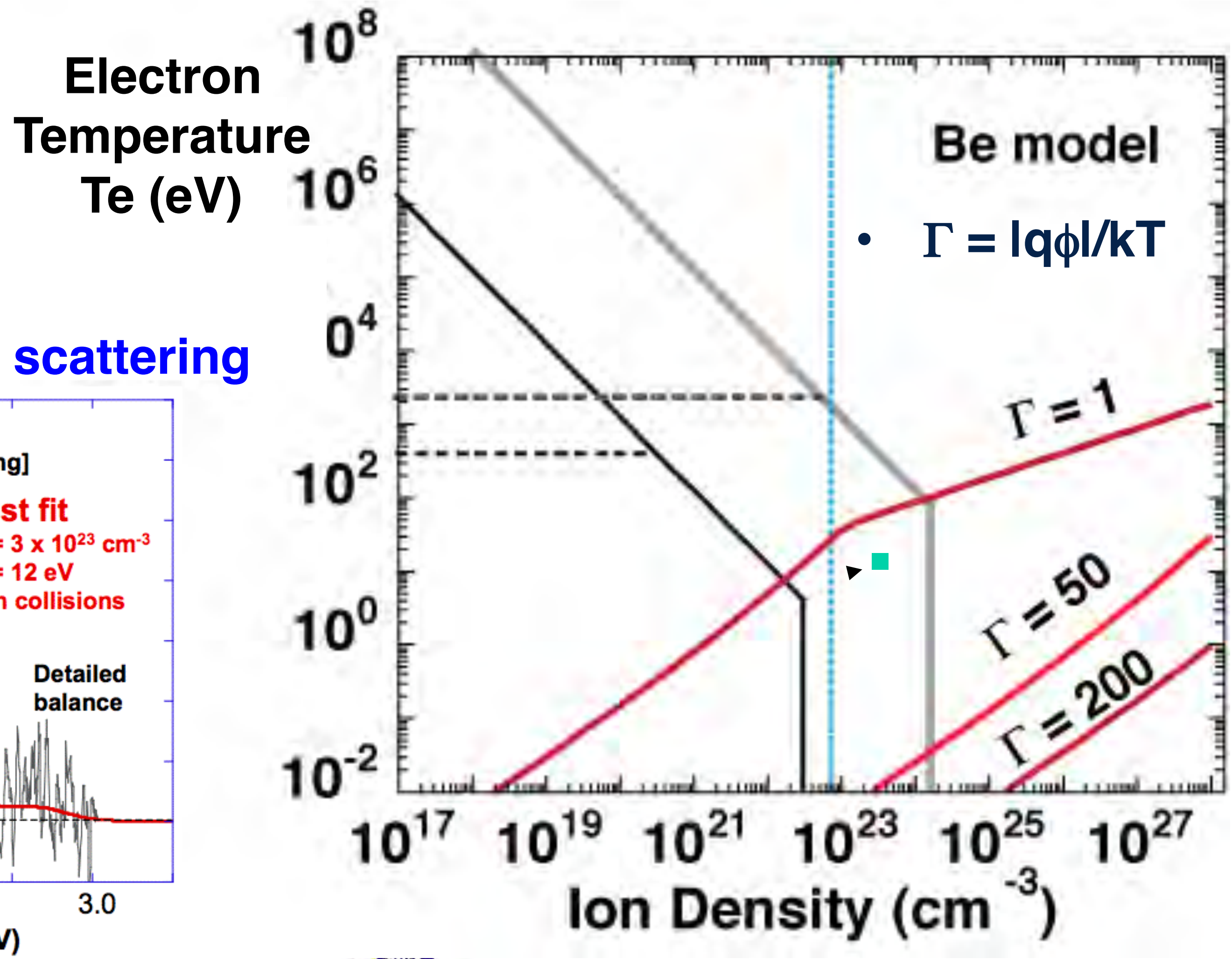




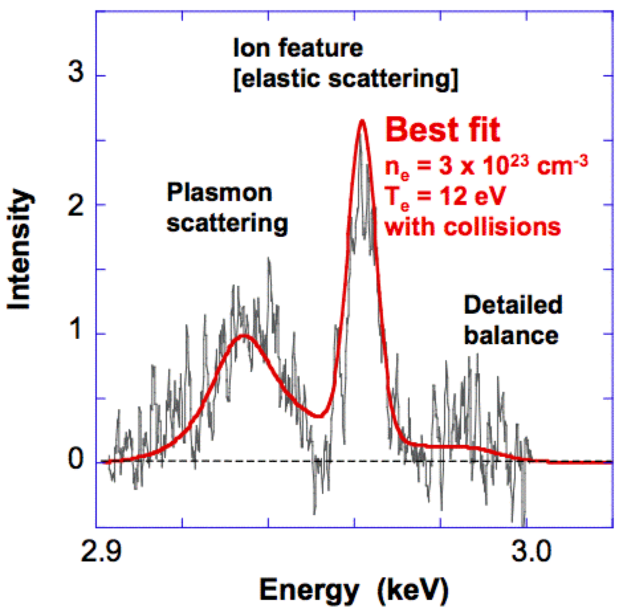
~ Gbar shock in Al

Data from Cauble et al, PRL 1991

HEDP plasmas can be very strongly coupled



X-ray Thomson scattering



Data from Glenzer & Redmer, RMP 2008

The problems of simulating and of producing these plasmas reveals some of the important physical issues

- Equations from a typical rad-hydro code
  - To see some of the physics issues
- Equations of state and related issues
- Heat conduction
- Hydrodynamic phenomena
- Radiative effects

CRASH like any Radhydro Code must solve conservation equations with source terms

$$\frac{\partial}{\partial t}\left\{\begin{array}{c}\rho\\ \rho\mathbf{u}\\ \mathcal{E}+\frac{1}{2}\rho\mathbf{u}\cdot\mathbf{u}\\ \mathcal{E}_e\end{array}\right\}+\nabla\cdot\left\{\begin{array}{c}\rho\mathbf{u}\\ \rho\mathbf{u}\mathbf{u}+p\mathbf{I}\\ \mathbf{u}\left(\frac{1}{2}\rho\mathbf{u}\cdot\mathbf{u}+\mathcal{E}+p\right)\\ \mathbf{u}\mathcal{E}_e\end{array}\right\}=\mathbf{S}$$

$$\mathbf{S}=\left\{\begin{array}{c}0\\ -\mathbf{S}_{rm}\\ \nabla\cdot C_e\nabla T_e-S_{re}+S_L\\ -p_e\nabla\cdot\mathrm{u}+\nabla\cdot C_e\nabla T_e+\frac{\rho k_B(T_i-T_e)}{M_pA\tau_{ei}}-(S_{re}-\mathbf{S}_{rm}\cdot\mathbf{u})+S_L\end{array}\right\}$$

laser energy deposition

radiation/electron momentum exchange

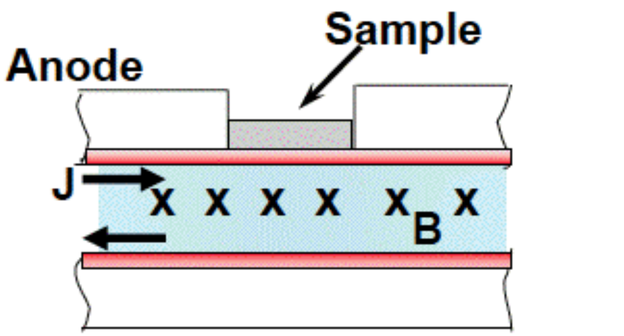
electron heat conduction

Compression work

collisional exchange

radiation/electron energy exchange

One gets at equation of state by measuring effects during uniform changes of pressure

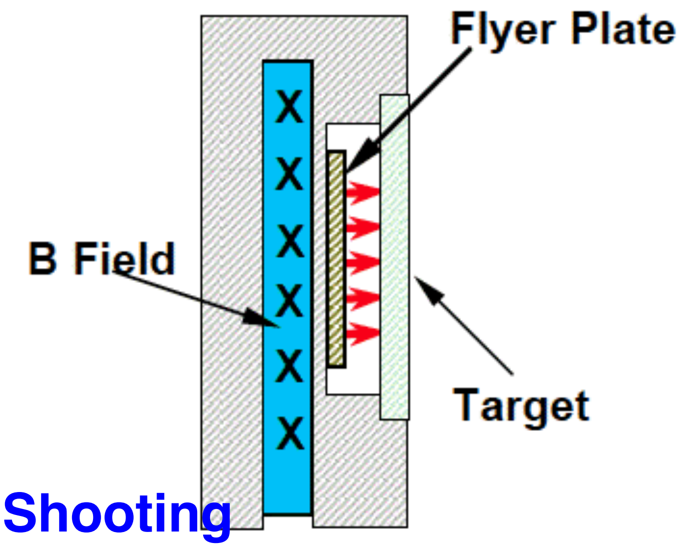


Squeezing

Isentropic Compression Experiments (ICE)*

Magnetically produced Isentropic Compression Experiments (ICE) provide measurement of continuous compression curves
- previously unavailable at Mbar pressures
- presently capable of ~4 Mbar

* Developed with LLNL



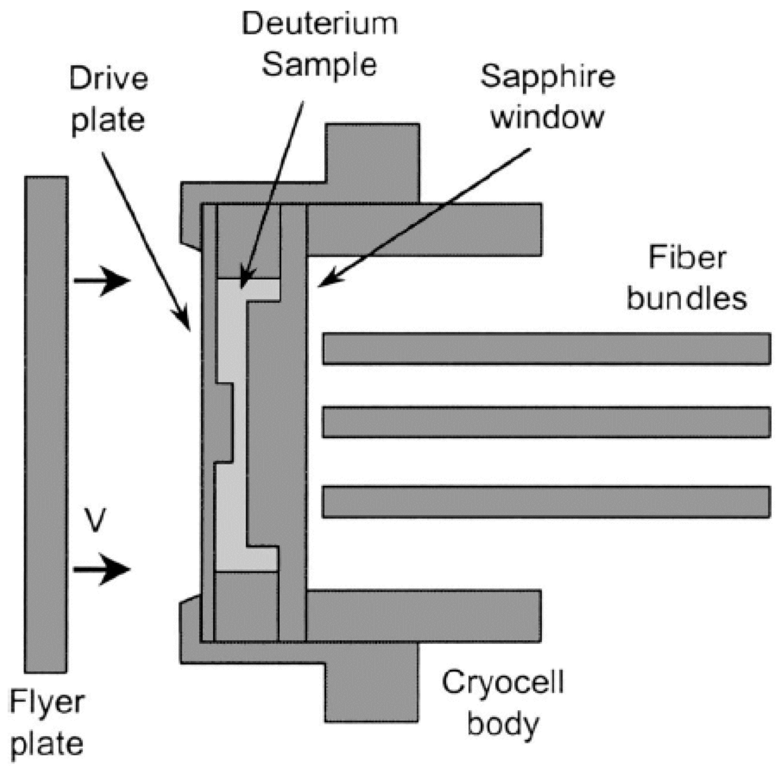
Shooting

Magnetically launched flyer plates

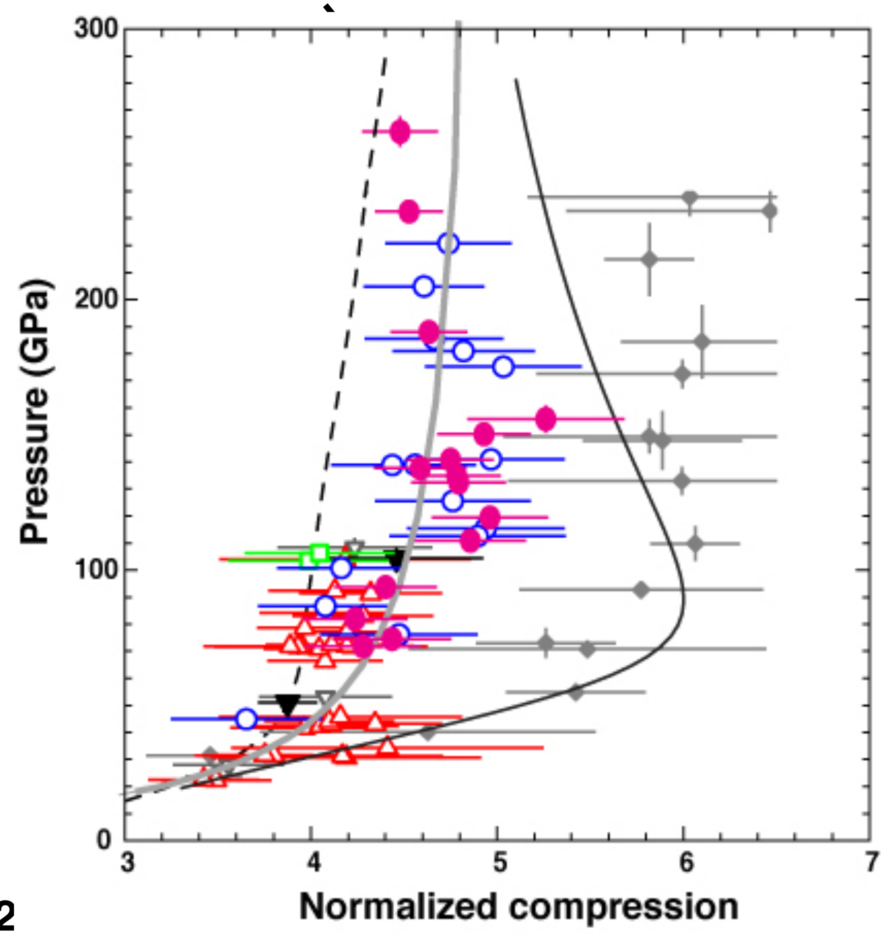
Magnetically driven flyer plates for shock Hugoniot experiments at velocities to ~ 33 km/s
- exceeds gas gun velocities by ~ 4X and pressures by ~ 4-5X with comparable accuracy
- Presently capable of ~ 20 Mbar

Slide credit: Keith Matzen

Flyer plate experiments with lasers and pulsed power uncovered new D_2 EOS features

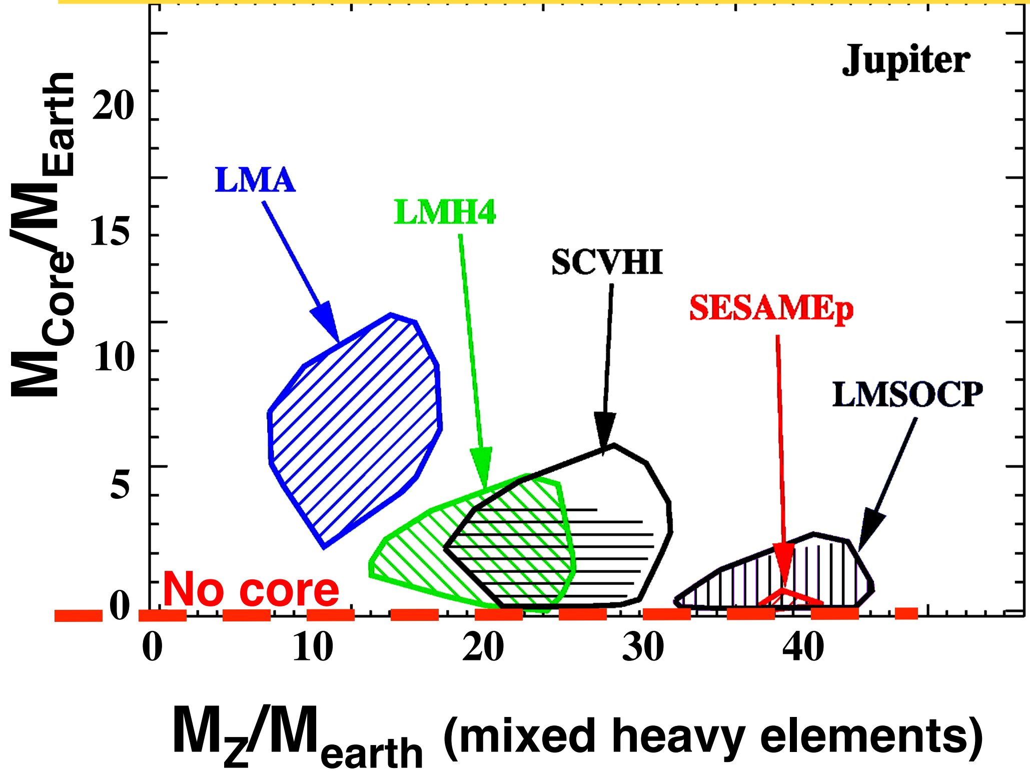


Data from many experiments



D. Hicks, et al., PHYS. REV. B 79, 014112

The different EOS models for hydrogen directly impact whether Jupiter is predicted to have a central dense core or not



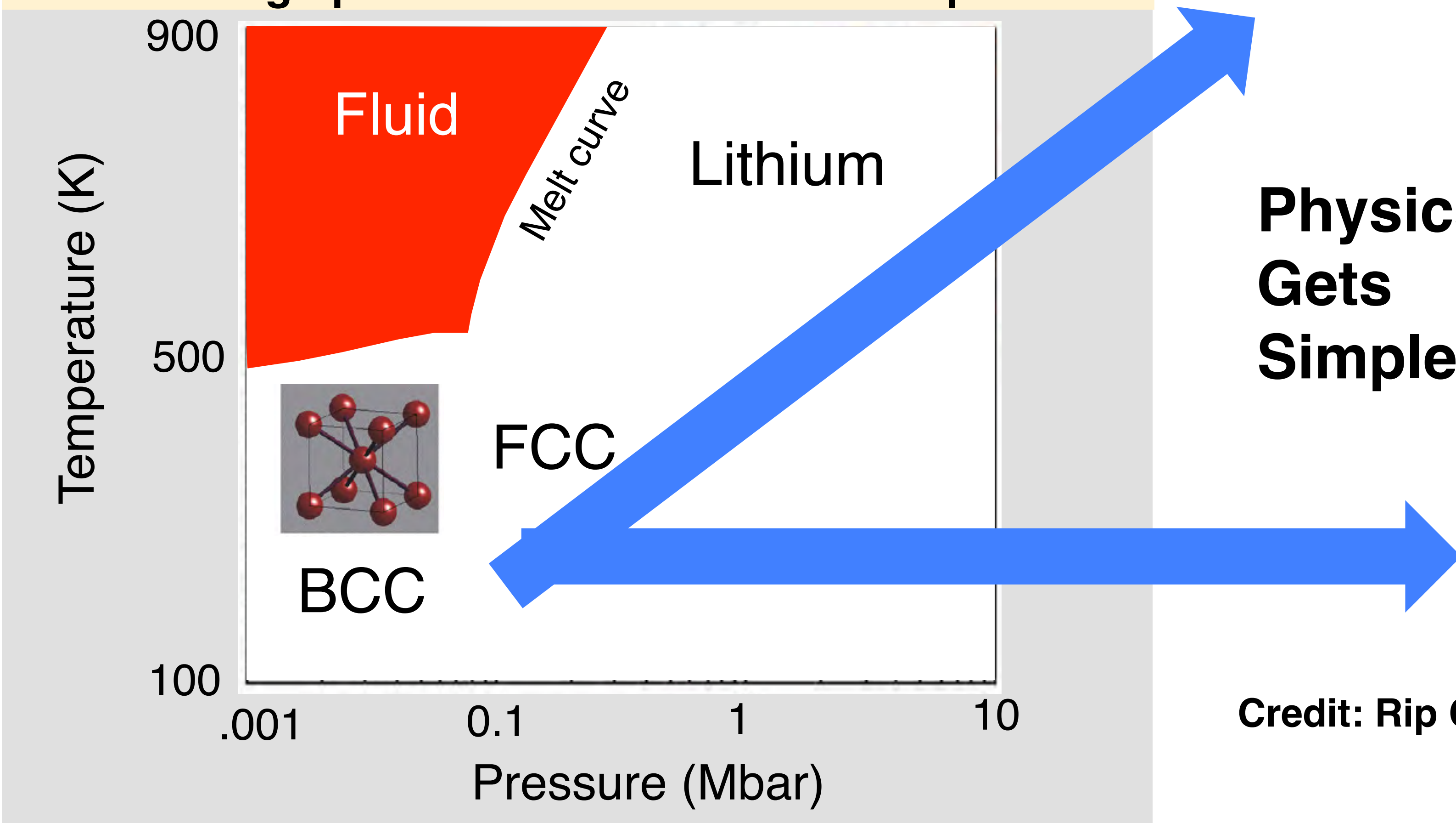
- **Outlines show range of models matching Jupiter's properties within 2σ of observed**
- **Cannot yet tell whether Jupiter has a core**
- **The predicted age of Jupiter is is also sensitive to the H EOS, which affects luminosity**
- **Only experiments can validate the correct model**

[D. Saumon and T. Guillot, Ap. J. 609, 1170 (2004)]

Adapted from slide by Bruce Remington

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

Melt curves typically followed a Lindeman law and high pressure structures were simple

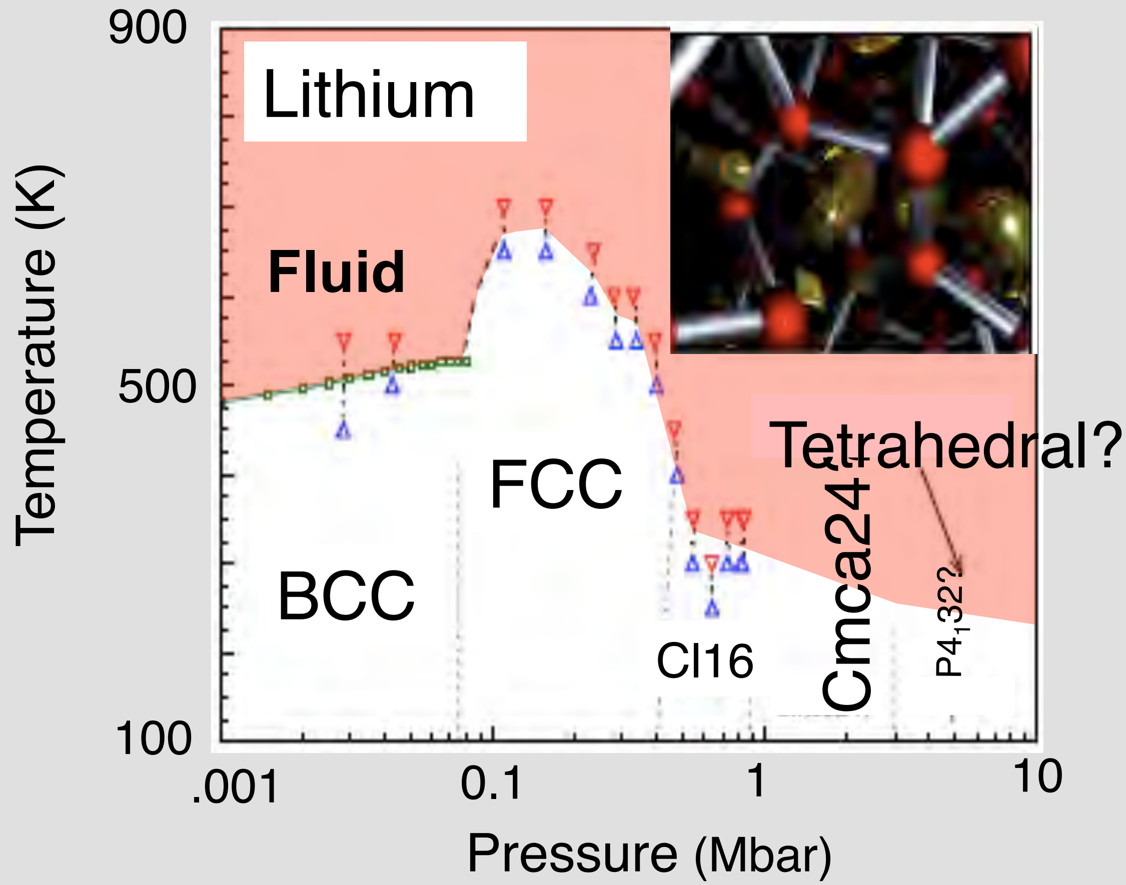


Physics Gets Simple!

Credit: Rip Collins

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

Core electrons have a profound effect on structure and melt at high pressure



Bonev, et al, PRL 2010

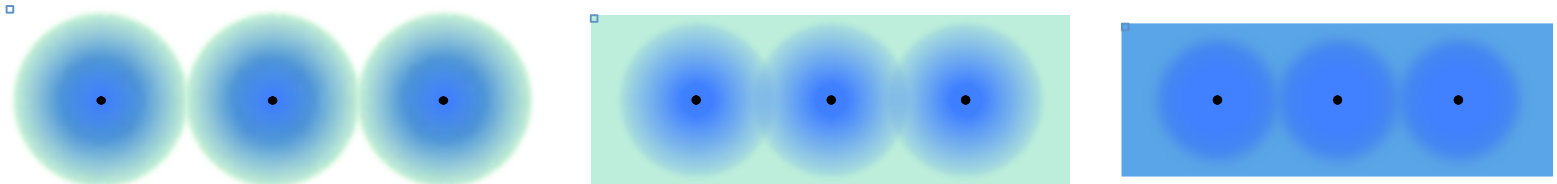
Guillaume, et al Nature Phys. (2011)

Credit: Rip Collins

Similar to the beautiful work on Na (Marqués, Neaton and Ashcroft, Hanfland et al, Syassen, K, Gregoryanz, E., J. Raty et al)

Credit: Rip Collins

Traditional View



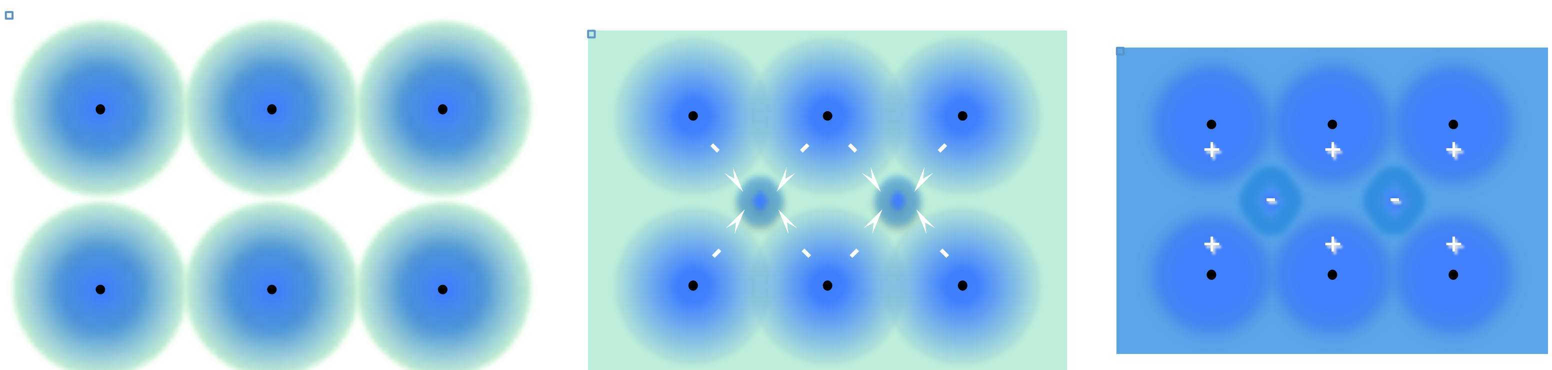
Insulator

Metal
smearing of electron orbitals

"Sea of Electrons"
Metal
TFD theory

Shaping charge density under compression →

New Understanding



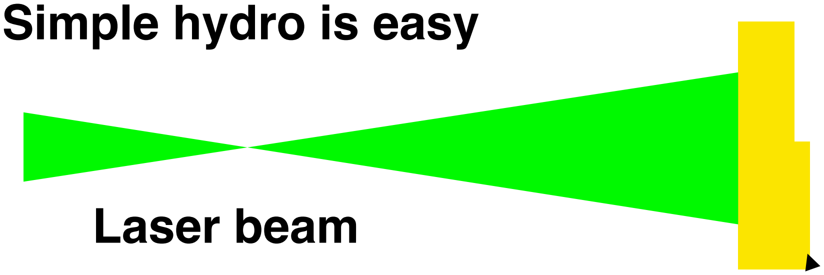
Insulator

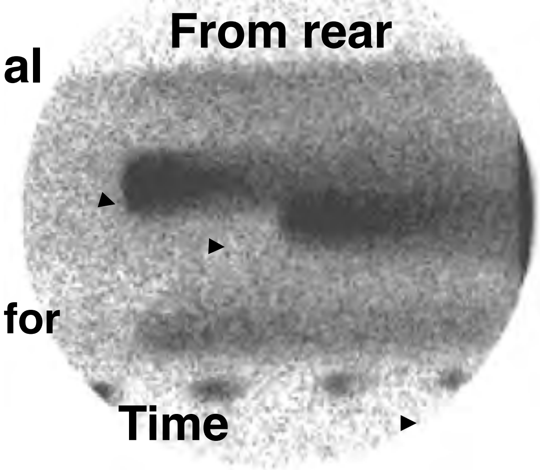
charge density accumulates between ion cores

"Ionic" Bond

Hydrodynamics produces things to study but also complicates a lot of experiments

Simple hydro is easy





Laser: 1 ns pulse (easy)
≥ 1 Joule (easy)
Irradiance ≥ 10^{13} W/cm^2
(implies spot size of 100 μm at 1 J,
1 cm at 10 kJ)

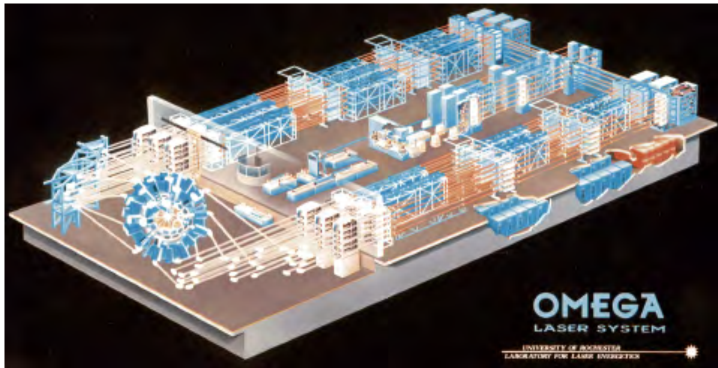
This produces a pressure ≥ 1 Mbar (10^{12} dynes/cm^2, 0.1 TP).

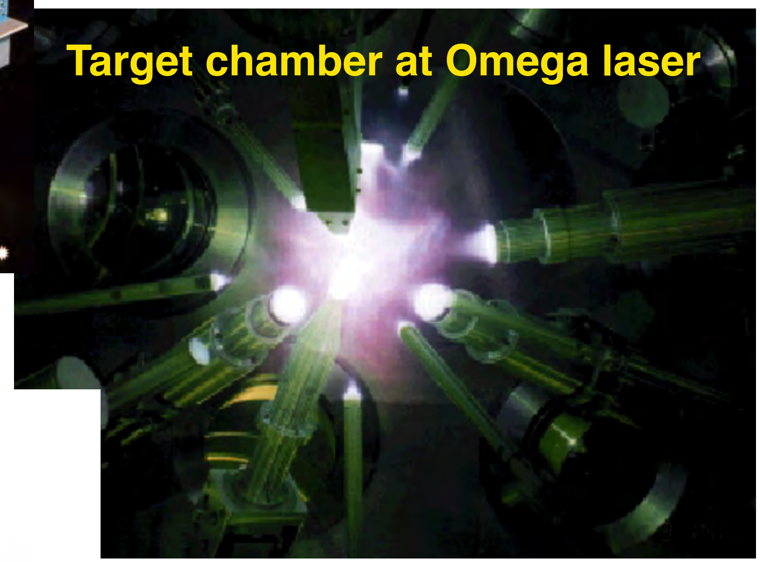
Momentum balance gives $p \sim 3.5\, I_{14}^{2/3} / \lambda_{\mu m}^{2/3}$ Mbars

This easily launches a shock.
Sustaining the shock takes more laser energy.

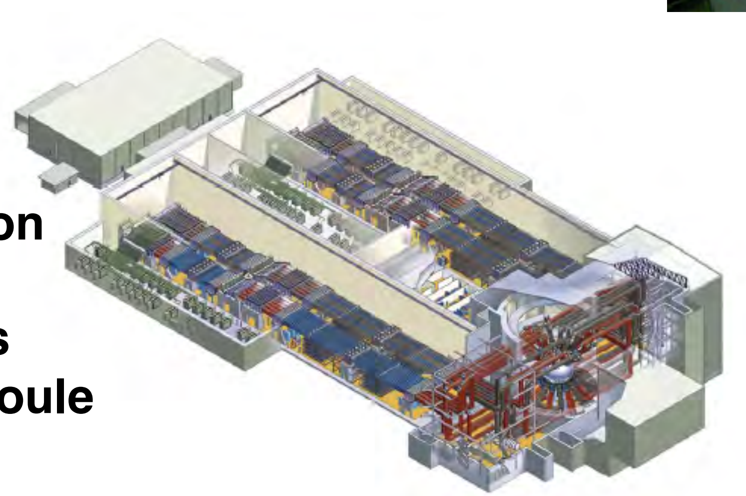
The biggest lasers can produce 100 Mbar pressures on mm^2 to cm^2 areas

Omega
60 beams
30 kJ



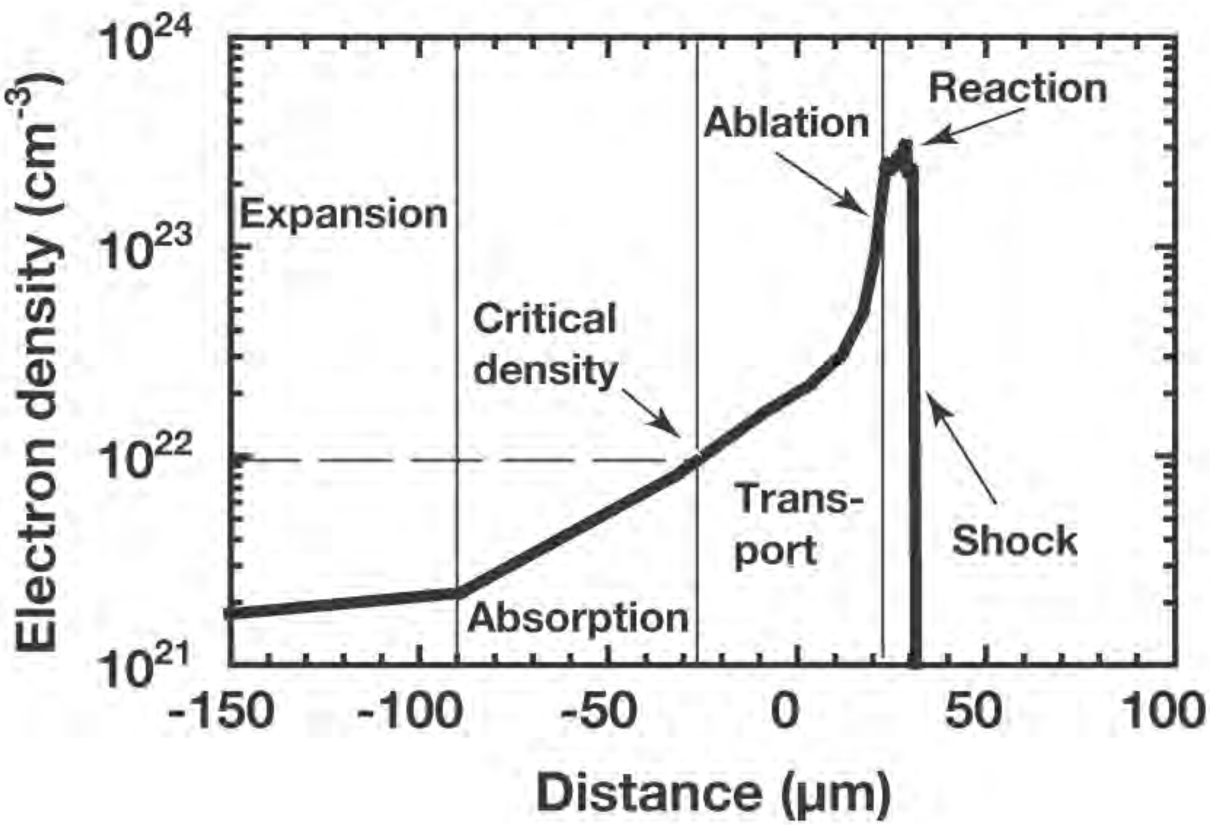


National Ignition Facility
192 beams
> 1 Megajoule



The laser creates structure at the target surface

- The laser is absorbed at less than 1% of solid density
- Heat transport is a critical element in correct modeling



From Drake, *High-Energy-Density Physics*, Springer (2006)

Ablation pressure from approximate momentum balance:

$$p \sim 3.5\ I_{14}^{2/3} / \lambda_{\mu m}^{2/3} \text{ Mbars}$$

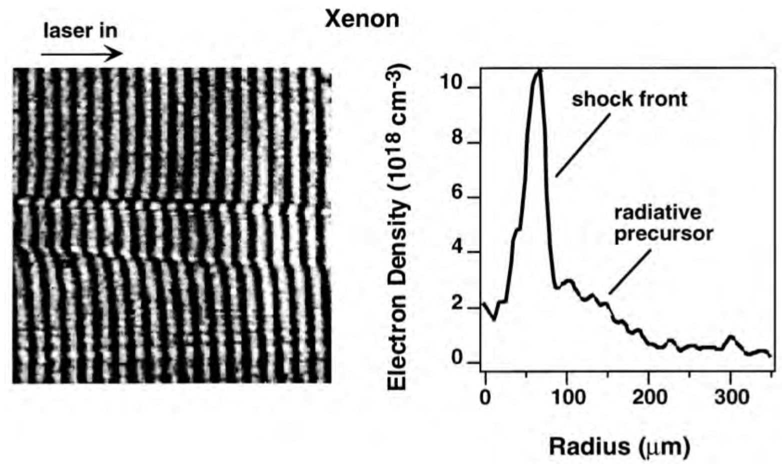
This is a bit low; better calculations replace 3.5 by 8.6

A pressure > 100 Mbars is practical

Perspectives on strong shocks in HEDP

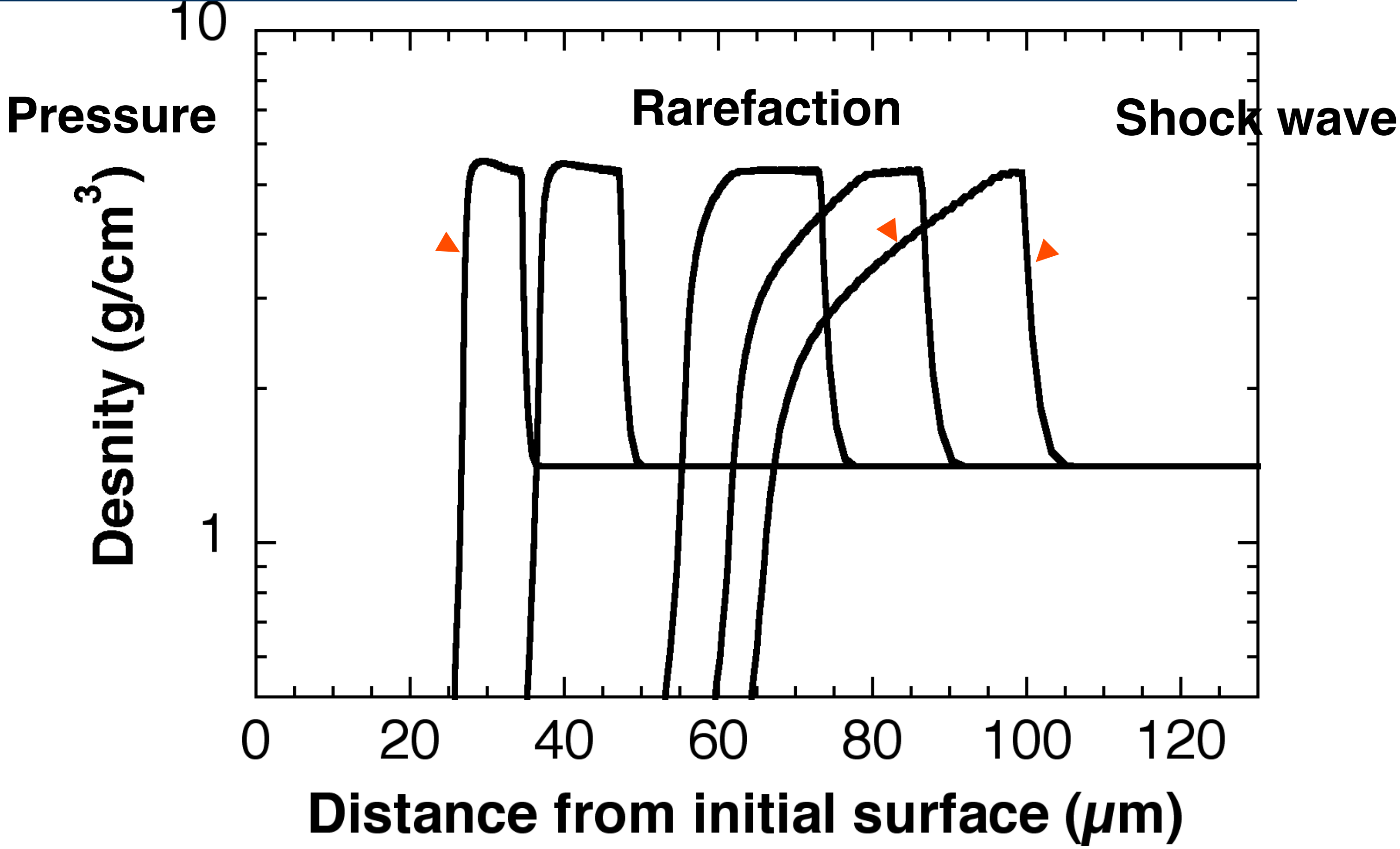
- **Many HEDP experiments involve at least one strong shock**
  - A natural consequence of depositing kJ/mm^3 in matter
- **Strong shocks are useful!**
  - In Inertial Confinement Fusion
  - For equation of state measurements
  - As sources of energy or momentum
    - Radiative shocks
    - Isentropic compression
    - Hydrodynamic processes

Shock in Xe clusters



Data from Ditmire et al. ApSS 2000

Shocks and rarefactions are the building blocks of high-energy-density systems



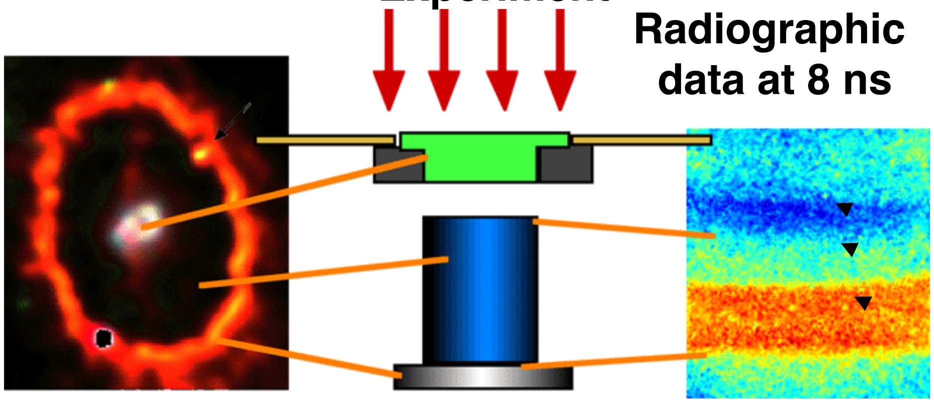
From Drake, *High-Energy-Density Physics*, Springer (2006)

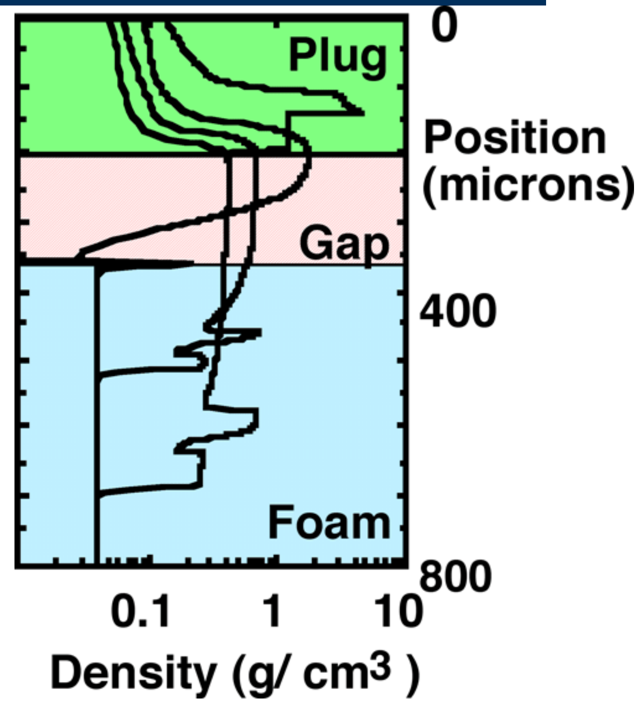
Many HEDP experiments have both shocks and rarefactions

SN 1987A

Sketch of Experiment

Radiographic data at 8 ns



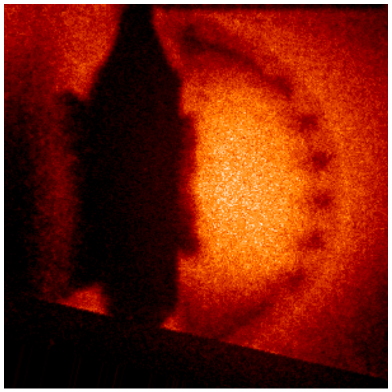


R.P. Drake, et al.
ApJ 500, L161 (1998)
Phys. Rev. Lett. 81, 2068 (1998)
Phys. Plasmas 7, 2142 (2000)

This experiment to reproduce the hydrodynamics of supernova remnants has both shocks and rarefactions

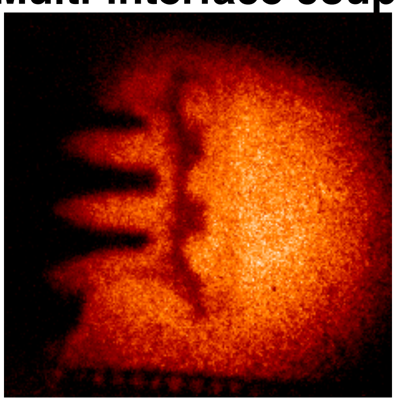
The other hydrodynamic element of HEDP systems is instabilities

Spherical divergence



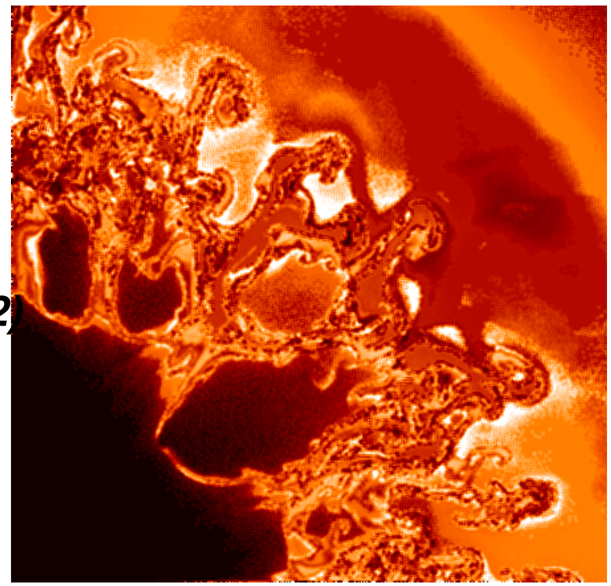
Drake et al., ApJ 564, 896 (2002)

Multi-interface coupling

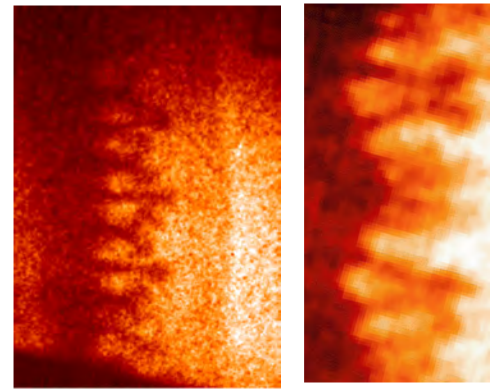


Kane et al., PRE 63, 55401 (2001)

2D simulation of SN1987A
Muller, Fryxell, and Arnett (1991)

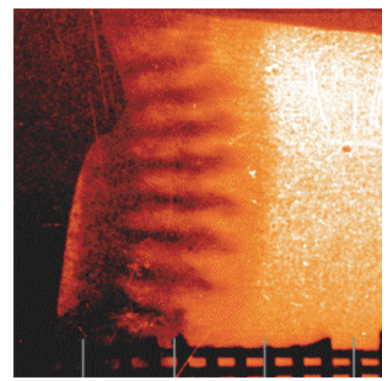


Multi-mode instability



Miles *et al.*, Phys. Plas. (2004)

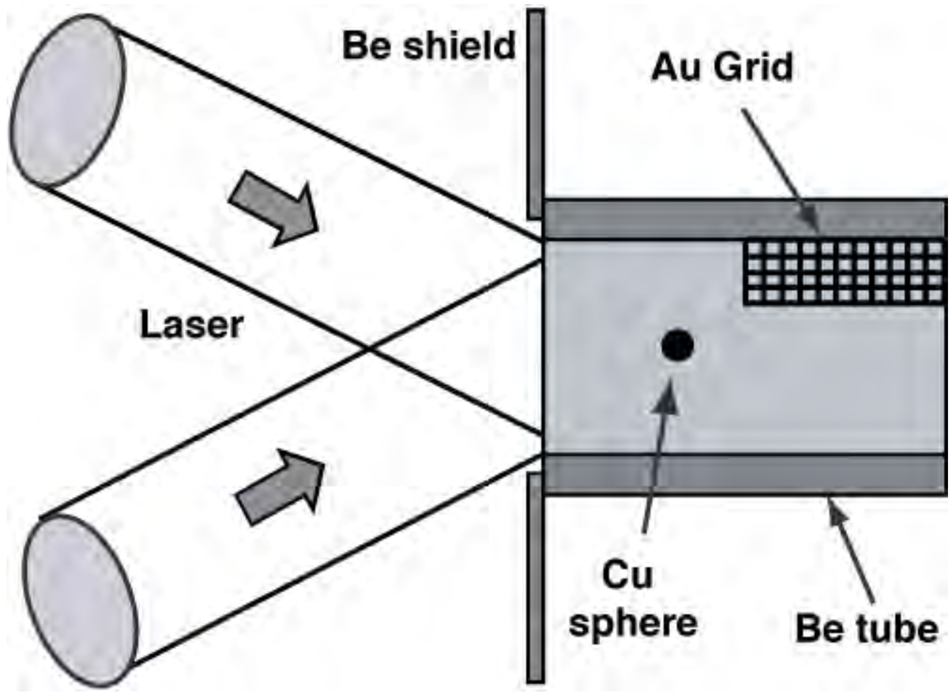
Longer-term evolution



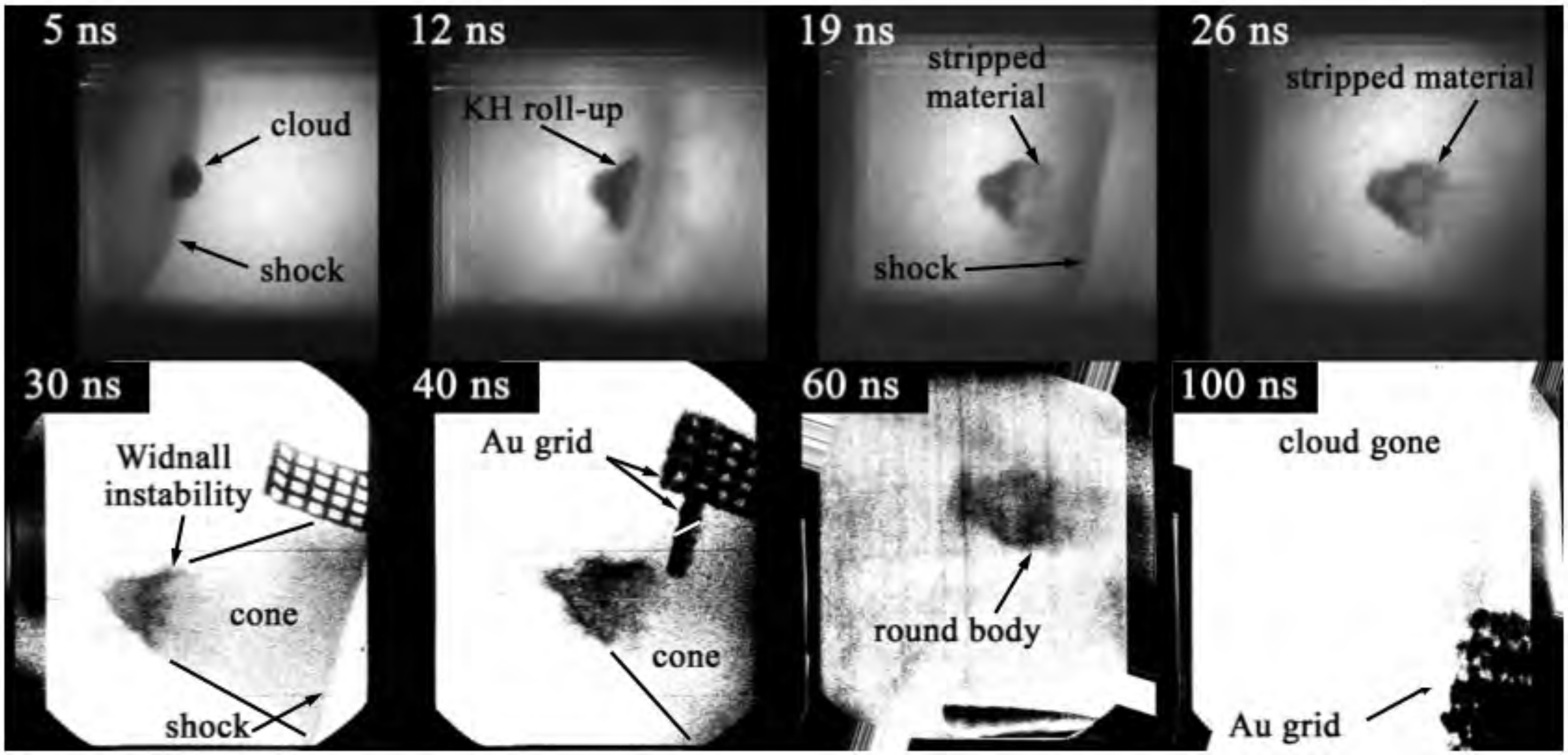
Kuranz, several papers
DiStefano, in prep

Example: shock-clump experiments

- The experiment involves destruction of a spherical clump by a blast wave
- Early experiments used Cu in plastic; recent experiments use Al in foam

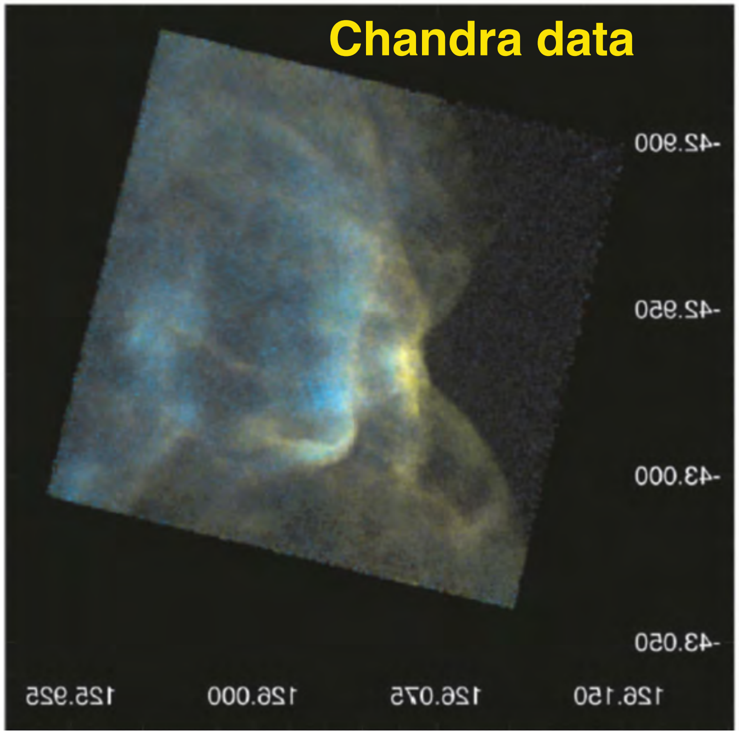


Observations of the Al/foam case continued until mass stripping had destroyed the cloud



- **Hansen et al., ApJ 2007, PoP 2007**

Destruction of clumps in post-shock flow has been a research area with impact



Well scaled experiment

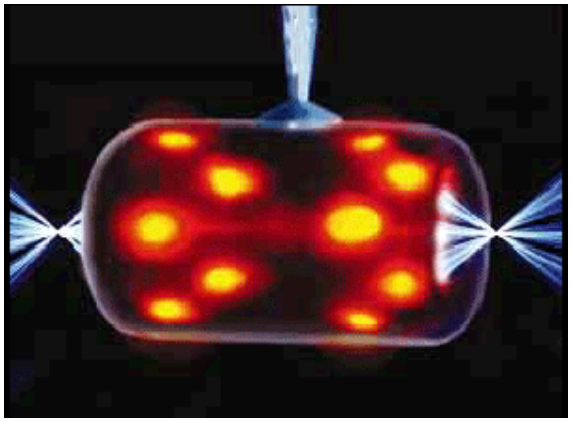
Klein et al., ApJ 2003
Robey et al., PRL 2002

- **Experimental results used to help interpret Chandra data from the Puppis A supernova remnant**
- **Well-scaled experiments have deep credibility**
- **Una Hwang et al., Astrophys. J. (2005)**

Hohlraums: radiation-hydrodynamic systems that enable rad-hydro experiments

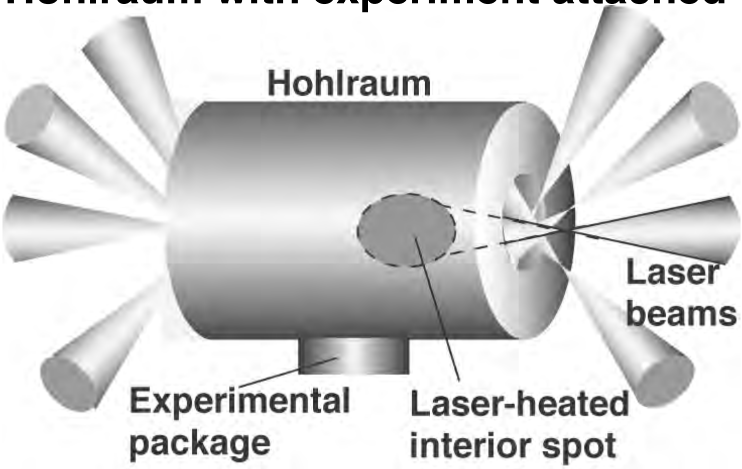
- Put energy inside a high-Z enclosure
- The vacuum radiation field stays in equilibrium with the resulting hot surface
- One gets temperatures of multi MK because the radiation wave moves slowly through the wall, penetrating few microns

Laser spots seen through thin-walled hohlraum.



Credit LLNL

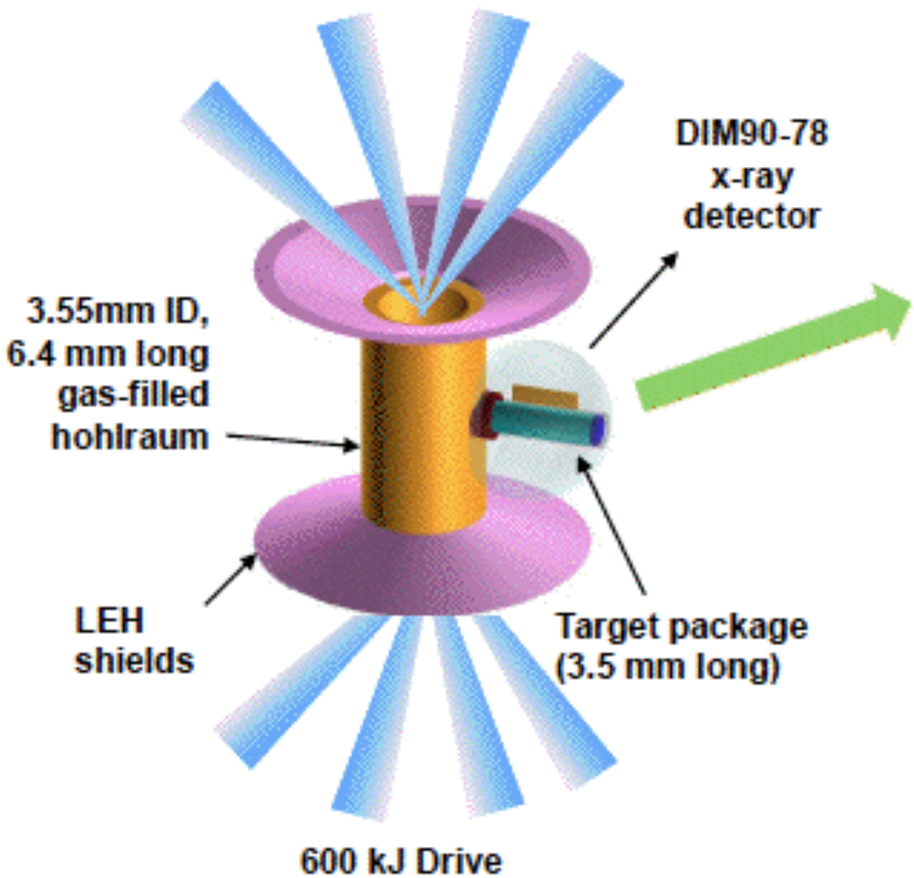
Hohlraum with experiment attached on bottom



From Drake, *High-Energy-Density Physics*, Springer (2006)

Our current experiments at the National Ignition Facility use hohlraums to create high pressure

- Inject laser energy into high-Z container
- Result is x-ray source at up to > 3 MK (> 300 eV)

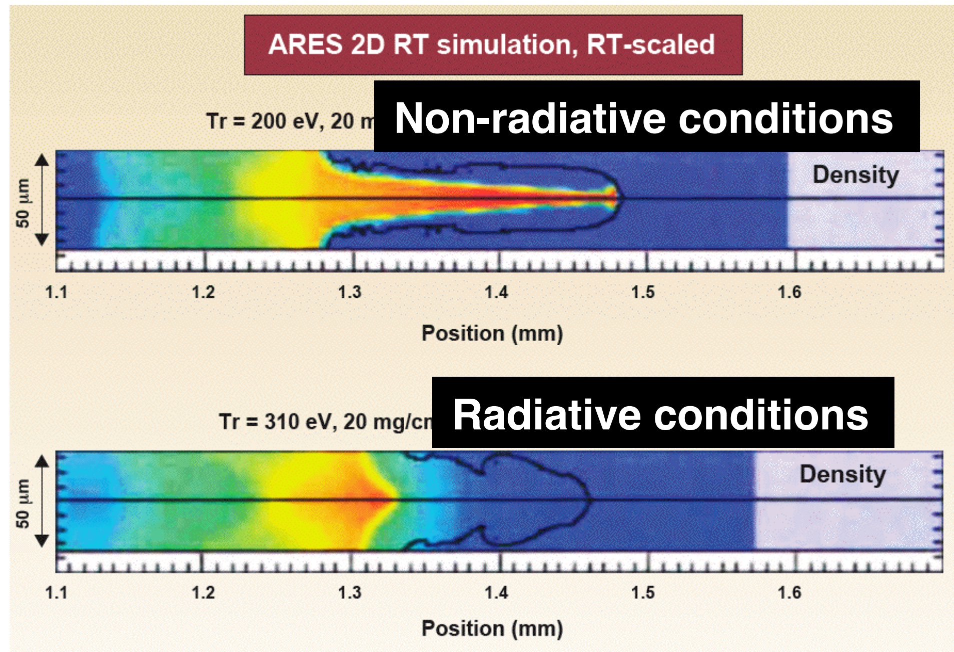


- Small NIF hohlraum shown here
  - Makes > 300 eV with < half of NIF energy
- Drive package producing hydrodynamic instability
- Can vary radiative effects in package

The hydrodynamic instability varies with how hot the shocked material becomes

- **Three shots to date for technique development needed by many programs**
  - Backlit pinhole radiography
    - Huntington RSI 2010
  - 300 eV, low-stagnation hohlraum
    - Kuranz A&SS 2011
  - Integrated test shot, Sept. 2012
    - Being analyzed

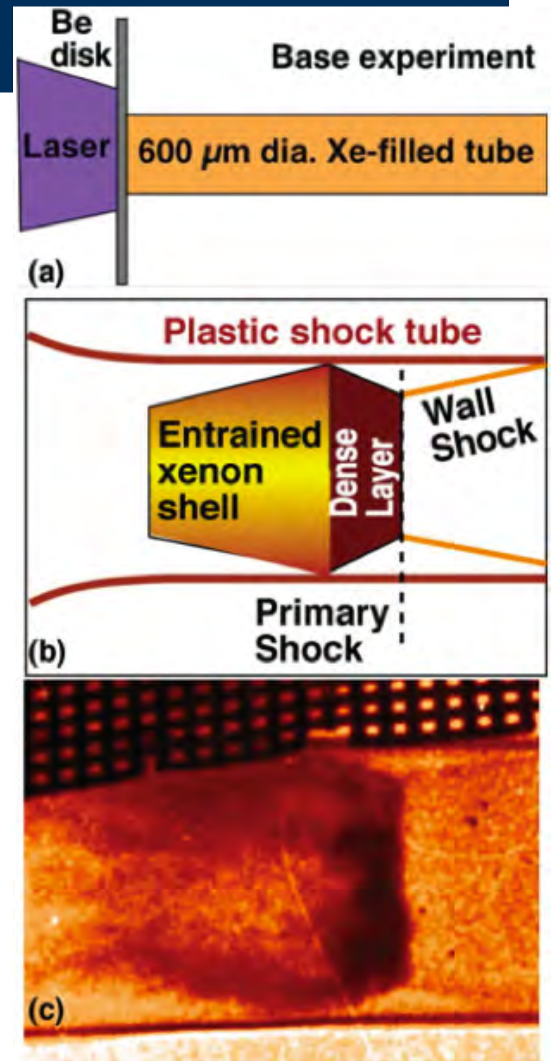
Density plots



Hotter hohlraum –> stronger drive –> radiative shock –> changed hydrodynamic instability

One can also do laser-driven radiation hydrodynamics by launching fast shocks through high-Z gas

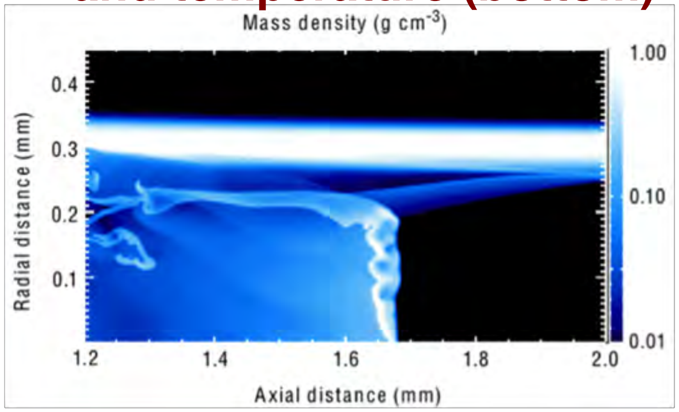
- **An example from UM**
  - Irradiate 20-μm-thick Be disk for 1 ns with 4 kJ
  - Drive shock down gas-filled tube at ~ 150 km/s
  - Use a gas of Ar, Kr, Xe
- **Result is a strongly radiative shock**
- **Several related experiments in Europe too**

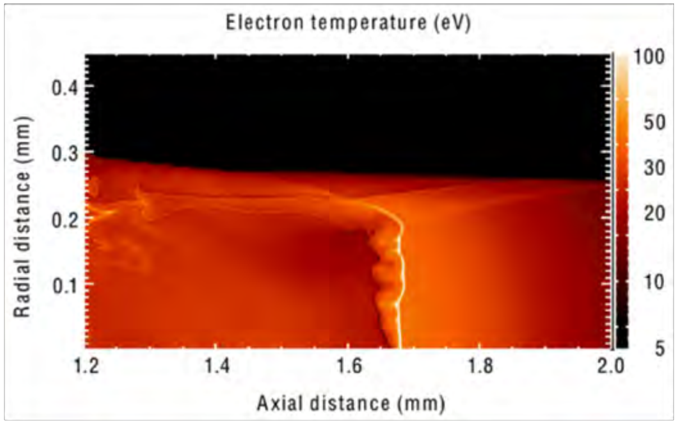


Our experimental program at UM is strongly synergistic with the CRASH Center

- **CRASH code (2D and 3D)**
  - Eulerian, high-resolution Godunov
  - Block adaptive dynamic AMR
  - Level set interfaces
  - Single fluid with Te and Ti
  - Multigroup diffusion radtran
  - Flux limited electron heat conduction
  - Laser package (3D)
- **CRASH uncertainty quantification**
  - Code run sets focused on uncertainties in physics, models and experiments
  - Statistical analysis for prediction

RZ plots of density (top) and temperature (bottom)





CRASH is funded by NNSA Advanced Scientific Computing

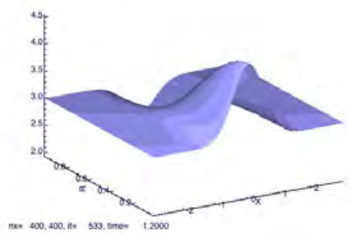
X-ray-driven radiative shocks: Simulations: Eric Myra

We extensively test our code

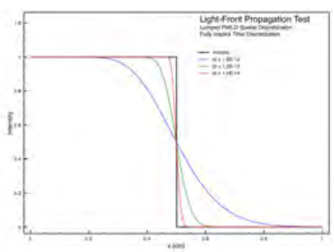
- New program units implemented with unit tests
  – Nightly execution of many unit tests for CRASH and its parent code BATSRUS
- New features implemented with verification tests
  – Daily verification & full system tests are run on a 16-core Mac.
  – > 100 tests cover all aspects of the new feature, including restart, using grid convergence studies and model-model comparison.
- Compatibility & reproducibility checked with functionality test suite
  – Nightly runs. 9 different platforms/compilers on 1 to 4 cores: tests portability
- Parallel Scaling Tests
  – Weekly scaling test on 128 and 256 cores of hera.
  – Reveals software and hardware issues, and confirms that results are independent of the number of cores.

Multiple classes of tests are in our suite

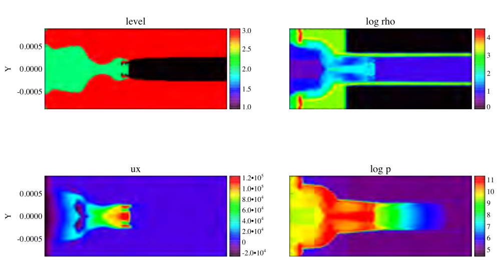
HEAT CONDUCTION



RADIATION TRANSPORT

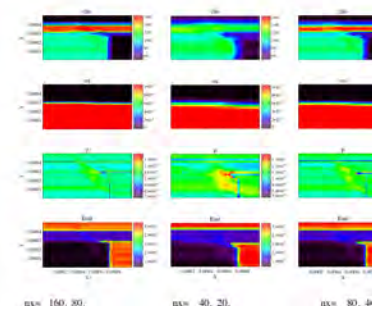


FULL SYSTEM

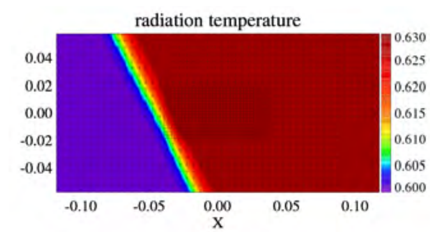


- Hydrodynamics
- Radiation transport
- Radiation hydrodynamics
- Heat conduction
- Simulated radiography
- Material properties (EOS and opacities)
- Laser package
- Unit tests
- Full-system tests

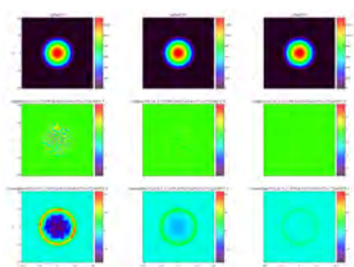
HYDRODYNAMICS



RADIATION HYDRODYNAMICS



SIMULATED RADIOGRAPHY

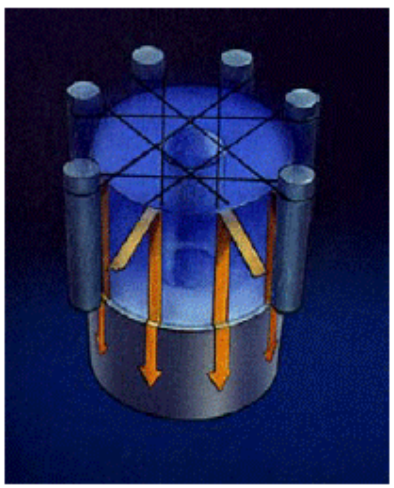


Z pinches also produce high-energy-density conditions

- Today's biggest is the Z machine at Sandia, when run as a Z pinch (~ 2 MJ of x-rays)
- Z pinches exploit the attraction between parallel currents

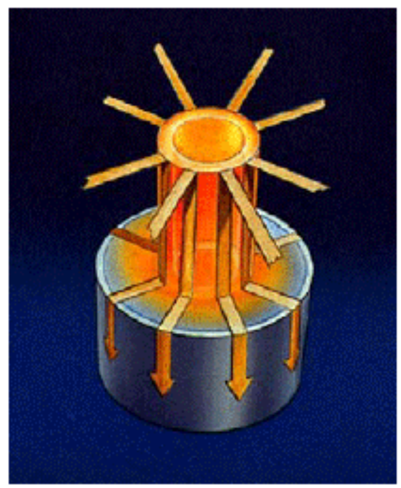
Credit:
Keith Matsen

Cylindrical wire array



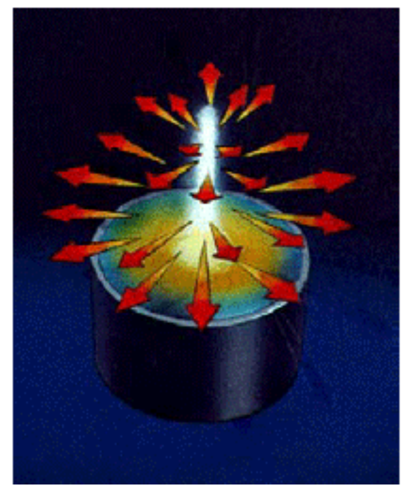
Inward J X B force

Implosion



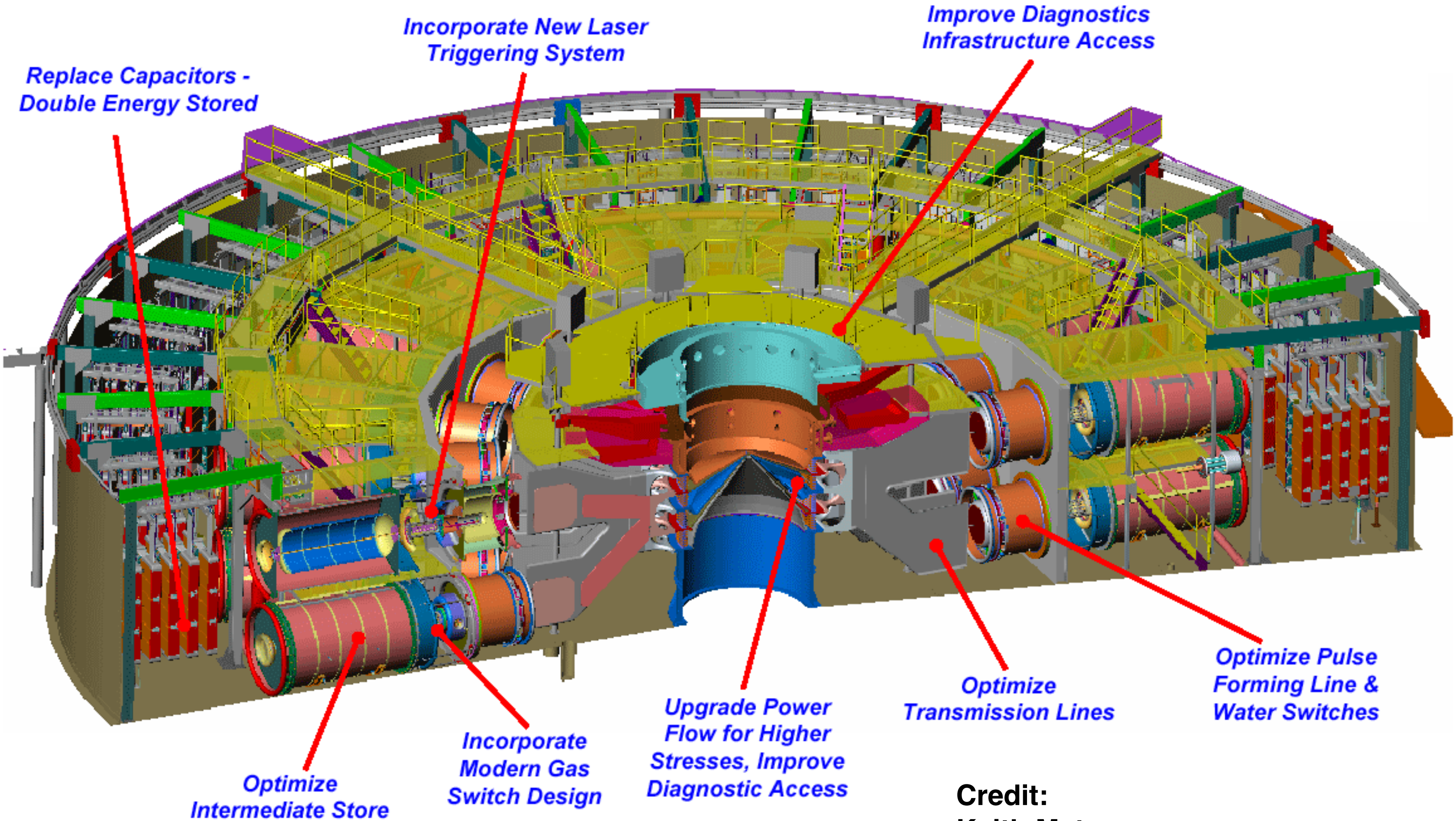
Inward acceleration

Stagnation



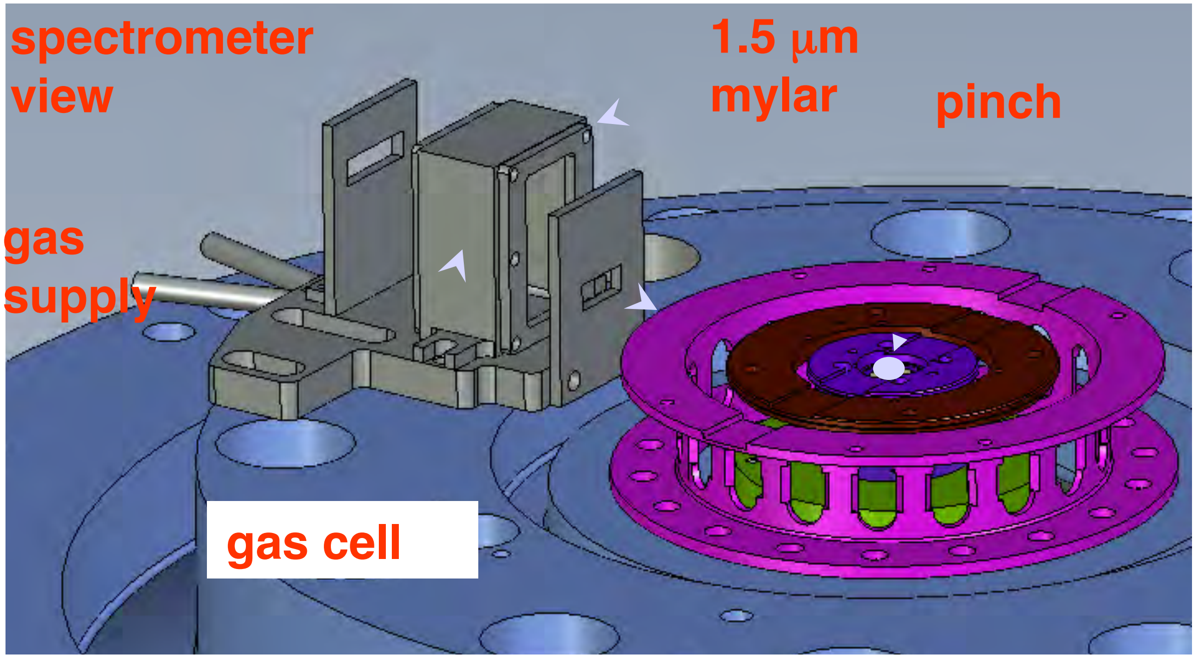
Shock heating &
Radiative cooling

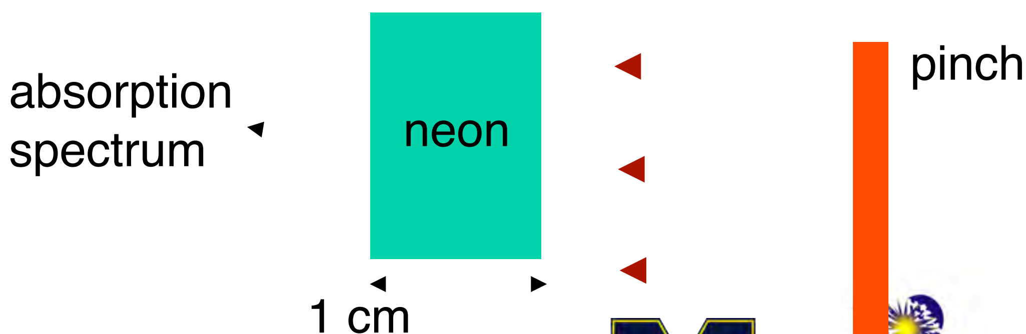
The action is at the center of a large though compact structure



Credit:
Keith Matsen

Z pinch x-rays are ideal for photoionization and opacity experiments



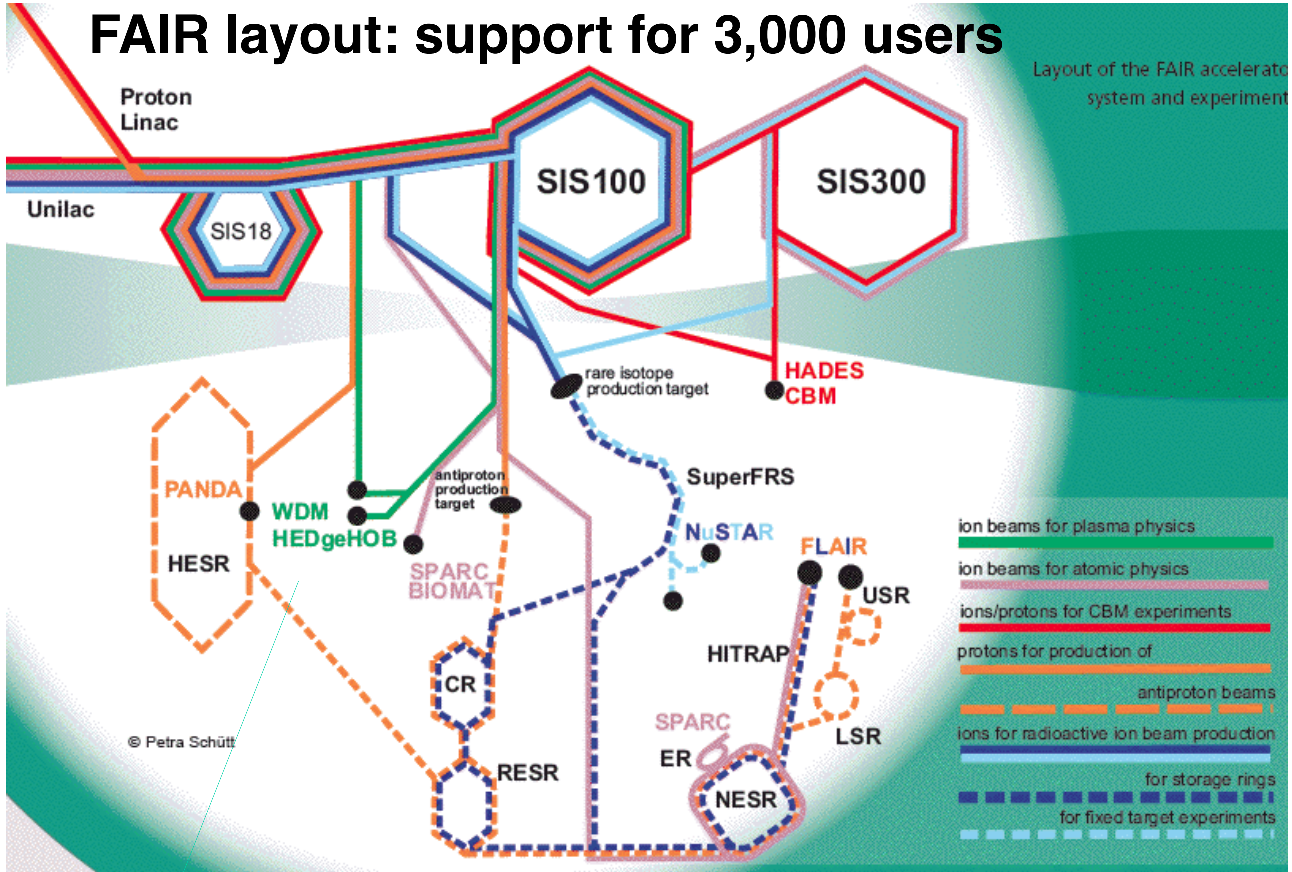


J.E. Bailey *et al.*, JQSRT 71 157 (2001).

D.H. Cohen *et al.*, RSI 74, 1962 (2003).

Heavy ion beams can also “cook” matter

- **FAIR at GSI**
  - Facility for Antiproton and Ion Research
  - 4×10^{13} 29 GeV protons in ~10 ns pulses
- **USA**
  - NDCX-II (1.5-3 MeV Li+ sub-ns beam pulse, 1-3 eV target temperature)



High Energy Density user areas

Physics that is not in the code also can matter

- Laser-plasma instabilities
- Hot electron preheat
- Actual radiation transport

Colleagues at Michigan

- **HEDP Experimental Program**
  - Grad students:
    - Visco, Doss, Huntington,
    - Krauland, DiStefano, Gamboa, Young
  - Many undergrads
  - Staff:
    - Grosskopf, Marion, Klein, Gillespie, Susalla

Dr. Carolyn Kuranz

- **Center for Radiative Shock Hydrodynamics (CRASH)**
  - Staff: Fryxell, Myra, Toth, Sokolov, van der Holst, Andronova, Torralva, Rutter
  - Grad students: Patterson, Chou, and many others
  - UM Professors: Powell, Holloway, Stout, Martin, Larsen, Roe, van Leer, Fidkowsky, Thornton, Nair, Karni, Gombosi, Johnsen
  - TAMU: Adams, Morel, McClarren, Mallick, Amato, Raushberger, Hawkins
  - Simon Frazer: Bingham

Much depends on our scientific and financial collaborators

Scientific collaborators (partial):

LLE/Rochester – *Knauer, Boehly*
LLNL – *Park, Remington, Glenzer, Fournier, Doeppner, Robey, Miles, Froula, Ryutov, others*
LANL – *Montgomery, Lanier, Workman, others*
Florida State – *Plewa*
France – *Bouquet, Koenig, Michaut, Loupias, others*
Britain -- *Lebedev*
Texas – *Wheeler*
Arizona – *Arnett, Meakin*

Financial collaborators:

Joint HEDLP program
(grant DE-FG52-04NA00064)
Predictive Science Academic Alliance Program
(grant DE-FC52-08NA28616)
National Laser User Facility
(grant DE-FG03–00SF22021)
DTRA
Los Alamos Nat. Lab.
Laboratory for Laser Energetics

Past support:
Lawrence Livermore Nat. Lab.
Naval Research Lab.

To End: Forefront fundamental areas of HEDP

- **High energy density hydrodynamics**
  - How do the distinct properties of high energy density systems alter hydrodynamic behavior?
- **Radiation-dominated dynamics and material properties**
  - What are the unique properties of radiation-dominated HED plasmas?
- **Magnetized HED dynamics**
  - How do magnetic fields form, evolve, and affect the properties of high energy density plasmas?
- **Nonlinear optics of HED plasmas**
  - How does high-intensity coherent radiation alter the behavior of high energy density plasmas?
- **Relativistic high energy density plasma physics**
  - How do plasmas with relativistic temperatures or relativistic flows behave?
- **Warm dense matter physics**
  - What are the state, transport, and dynamic properties of warm dense matter?