Frontiers for Discovery in High Energy Density Physics

Ronald C. Davidson

Professor of Astrophysical Sciences
Plasma Physics Laboratory
Princeton University

Presented to

Interagency Working Group on the Physics of the Universe

Washington, D.C.

January 20, 2006

Outline of Presentation

Provide overview of two national studies that identify research opportunities of high intellectual value in high energy density plasma science. Studies were commissioned by:

• National Academies - National Research Council (*Frontiers in High Energy Density Physics, - The X-Games of Contemporary Science* National Academies Press, 2003).

• Office of Science and Technology Policy's Interagency Working Group on the Physics of the Universe (National Task Force Report on High Energy Density Physics, July, 2004).

Conclusions

High energy density plasma science is a rapidly growing field with enormous potential for discovery in scientific and technological areas of high intellectual value.

The opportunities for graduate student training, postdoctoral research, commercial spin-offs, and interdisciplinary research are likely to increase for many decades to come.

Charge by the National Research Council:

• The study will review recent advances in the field of High Energy Density plasma phenomena, both on the laboratory scale and on the astrophysical scale.

• It will provide an assessment of the field, highlighting the scientific and research opportunities. It will develop a unifying framework for the diverse aspects of the field.

• In addition to identifying intellectual challenges, it will outline a strategy for extending the forefronts of the field through scientific experiments at various facilities where high-energy-density plasmas can be created.

• The roles of industry, national laboratories, and universities will be discussed.

Physical Processes and Areas of Research

- High Energy Density Astrophysics
- Beam- Plasma Interactions
- Free Electron Laser Interactions
- Equation of State Physics
- Theory and Advanced Computations
- Radiation-Matter Interaction
- Laser-Plasma Interactions
- Beam-Laser Interactions
- High-Current Discharges
- Physics of Highly Stripped Atoms
- Inertial Confinement Fusion
- Hydrodynamics and Shock Physics

The committee included membership from universities, national laboratories, and industry:

- **Ronald Davidson, Chair, Princeton University**
- David Arnett, University of Arizona
- Jill Dahlburg, General Atomics
- Paul Dimotakis, California Institute of Technology
- Daniel Dubin, University of California at San Diego
- Gerald Gabrielse, Harvard University
- David Hammer, Cornell University
- Thomas Katsouleas, University of Southern California
- William Kruer, Lawrence Livermore National Laboratory
- Richard Lovelace, Cornell University
- David Meyerhofer, University of Rochester
- Bruce Remington, Lawrence Livermore National Laboratory
- Robert Rosner, University of Chicago
- Andrew Sessler, Lawrence Berkeley National Laboratory
- Phillip Sprangle, Naval Research Laboratory
- Alan Todd, Advanced Energy Systems
- Jonathan Wurtele, University of California at Berkeley

Review Process and Status

The committee divided its work into three areas.

- Laboratory High Energy Density Plasmas
- Astrophysical High Energy Density Plasmas
- Laser-Plasma and Beam-Plasma Interactions

The committee solicited input from the membership of a number of professional organizations and held Town Meetings at the 2001 and 2002 American Physical Society Division of Plasma Physics meetings.

The final NRC report was published by the National Academies Press in 2003.

Follow-up study was commissioned by the Interagency Working Group on the Physics of the Universe in January, 2004.

Final report of the National Task Force on High Energy Density Physics was issued in July, 2004.

Scope of the National Research Council Study

The committee recognizes that now is a highly opportune time for the nation's scientists to develop a fundamental understanding of the physics of high energy density plasmas.

The space-based and ground-based instruments for measuring astrophysical processes under extreme conditions are unprecedented in their accuracy and detail.

In addition, a new generation of sophisticated laboratory systems ('drivers') exists or is planned that create matter under extreme high energy density conditions (exceeding 10^{11} J/m^3), permitting the detailed exploration of physical phenomena under conditions not unlike those in astrophysical systems.

Scope of the National Research Council Study – continued

High energy density experiments span a wide range of areas of physics including plasma physics, materials science and condensed matter physics, atomic and molecular physics, nuclear physics, fluid dynamics and magnetohydrodynamics, and astrophysics.

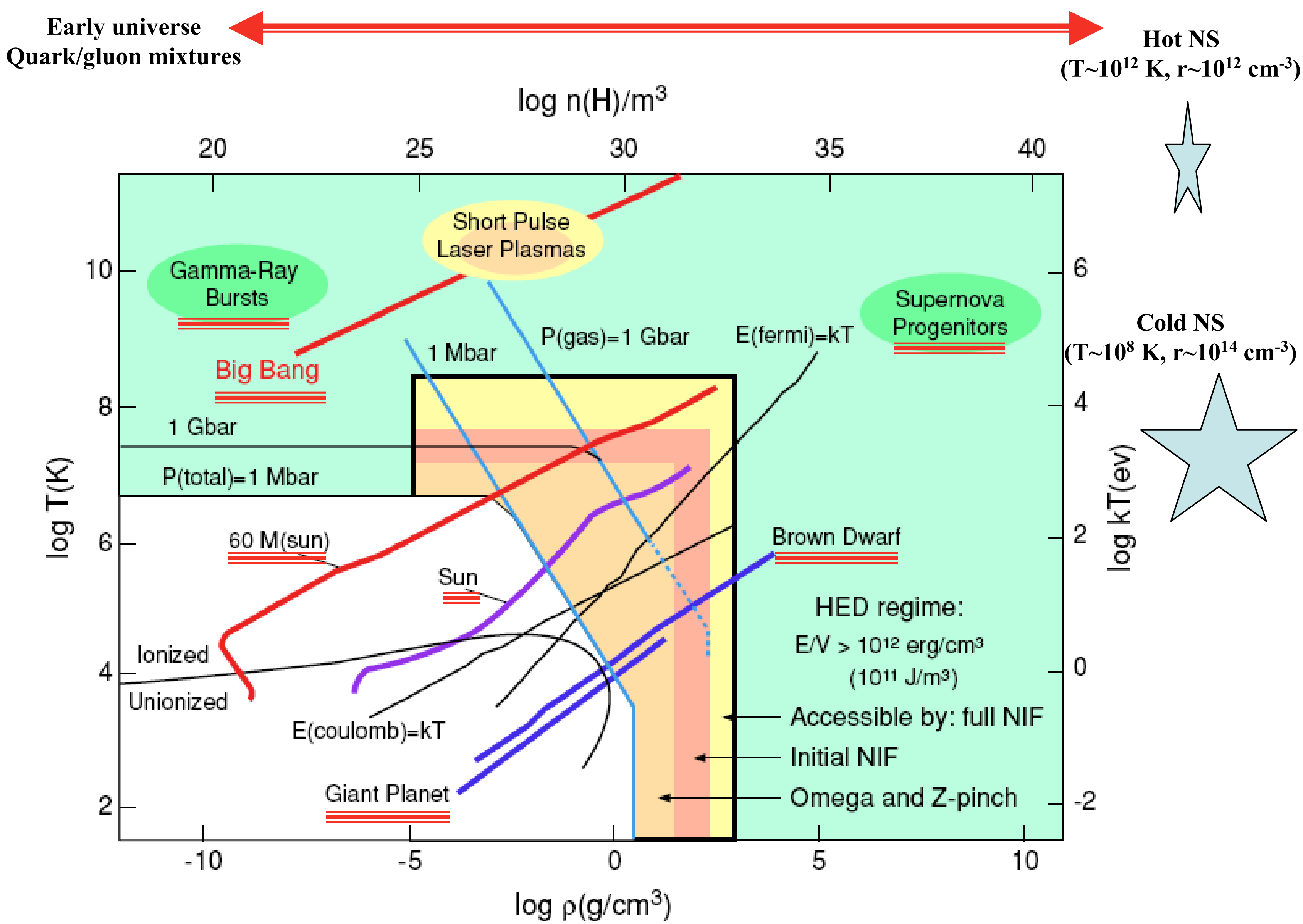
While a number of scientific areas are represented in high energy density physics, many of the techniques have grown out of ongoing research in plasma science, astrophysics, beam physics, accelerator physics, magnetic fusion, inertial confinement fusion, and nuclear weapons research.

The intellectual challenge of high energy density physics lies in the complexity and nonlinearity of the collective interaction processes.

Definition of High Energy Density

- The region of parameter space encompassed by the terminology ‘high energy density’ includes a wide variety of physical phenomena at energy densities exceeding $10^{11} J/m^3$.
- In the figure, "High-Energy-Density" conditions lie in the shaded regions, above and to the right of the pressure contour labeled "P(total)=1 Mbar".

MAP OF THE HED UNIVERSE



High Energy Density Physical Properties

High energy density systems exhibit a variety of physical properties that can be useful in characterizing such systems. Some of these are summarized below.

- Nonlinear and Collective Responses
- Full or Partial Degeneracy
- Dynamic Systems

Principal Findings

a. Attributes of high energy density.

- High energy density physics (for example, pressure conditions exceeding 1 Mbar) is a rapidly growing field, with exciting research opportunities of high intellectual challenge.

- The field spans a wide range of areas, including plasma physics, laser and particle beam physics, materials science and condensed matter physics, nuclear physics, atomic and molecular physics, fluid dynamics and magnetohydrodynamics, and astrophysics.

Principal Findings

b. The emergence of new facilities

- A new generation of sophisticated laboratory facilities and diagnostic instruments exist or are planned that create and measure properties of matter under extreme high energy density conditions.

- This permits the detailed laboratory exploration of physics phenomena under conditions of considerable interest for basic high energy density physics studies, materials research, understanding astrophysical processes, commercial applications (e.g., EUV lithography), inertial confinement fusion, and nuclear weapons research.

Principal Findings

c. The emergence of new computing capabilities

- Rapid advances in high performance computing have made possible the numerical modeling of many aspects of the complex nonlinear dynamics and collective processes characteristic of high energy density laboratory plasmas, and the extreme hydrodynamic motions that exist under astrophysical conditions.

- The first phase of advanced computations at massively parallel facilities, such as those developed under the Advanced Strategic Computing Initiative (ASCI), is reaching fruition with remarkable achievements, and there is a unique opportunity at this time to integrate theory, experiment and advanced computations to significantly advance the fundamental understanding of high energy density plasmas.

Principal Findings

d. New opportunities in understanding astrophysical processes

- The ground-based and space-based instruments for measuring astrophysical processes under extreme high energy density conditions are unprecedented in their sensitivity and detail, revealing an incredibly violent universe in continuous upheaval.

- Using the new generation of laboratory high energy density facilities, macroscopic collections of matter can be created under astrophysically relevant conditions, providing critical data and scaling laws for on hydrodynamic mixing, shock phenomena, radiation flow, complex opacities, high-Mach-number jets, equations of state, relativistic plasmas, and possibly quark-gluon plasmas characteristic of the early universe.

Principal Findings

e. National Nuclear Stewardship Administration support of university research

- The National Nuclear Security Administration has recently established a Stewardship Science Academic Alliances Program to fund research projects at universities in areas of fundamental high energy density science and technology relevant to stockpile stewardship. The National Nuclear Security Administration is to be commended for initiating this program.

- The Nation's universities represent an enormous resource for developing and testing innovative ideas in high energy density physics, and training graduate students and postdoctoral research associates—a major national resource which has heretofore been woefully underutilized.

Principal Findings

f. The need for a broad multi-agency approach to support the field

- The level of support for research on high energy density physics provided by federal agencies (e.g., National Nuclear Security Administration, the non-defense directorates in the Department of Energy, the National Science Foundation, the Department of Defense, and the National Aeronautics and Space Administration) has lagged behind the scientific imperatives and compelling research opportunities offered by this exciting field of physics.

- An important finding of this report is that the research opportunities in this cross-cutting area of physics are of the highest intellectual caliber and fully deserving of consideration of support by the leading funding agencies of the physical sciences. Agency solicitations in high energy density physics should seek to attract bright young talent to this highly interdisciplinary field.

Principal Findings

g. Upgrade opportunities at existing facilities

- Through upgrades and modifications of experimental facilities, exciting research opportunities exist to extend the frontiers of high energy density physics beyond those which are accessible with existing laboratory systems and those currently under construction.

- These opportunities range (for example) from the installation of ultra-high-intensity (petawatt) lasers on inertial confinement fusion facilities, which would create relativistic plasma conditions relevant to gamma ray bursts and neutron star atmospheres, to the installation of dedicated beamlines on high energy physics accelerator facilities for carrying out high energy density physics studies, such as the development of ultra-high-gradient acceleration concepts, and unique radiation sources ranging from the infrared to the gamma ray regimes.

Principal Findings

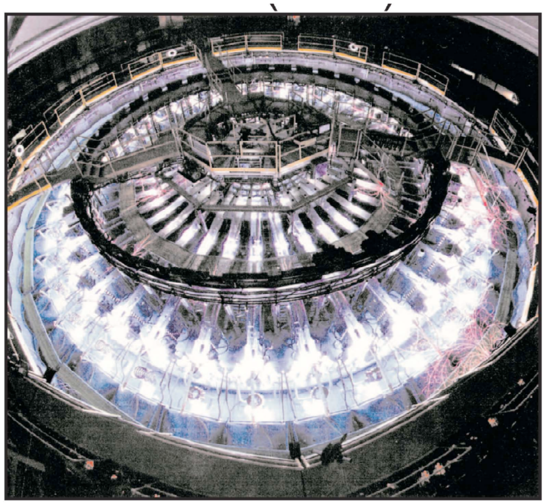
h. The role of Industry

- There are existing active partnerships and technology transfer between industry and the various universities and laboratory research facilities that are mutually beneficial. Industry is both a direct supplier of major hardware components to the field and has spun-off commercial products utilizing concepts first conceived for high energy density applications.

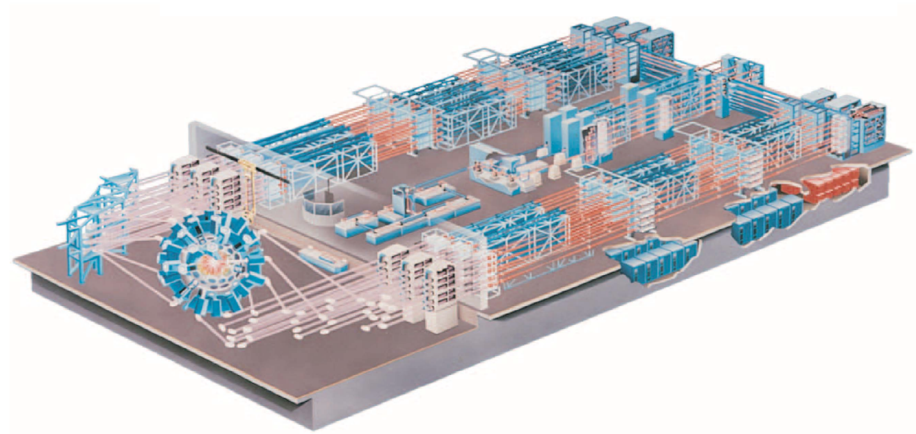
- Further, it is to be expected that industry will continue to benefit from future applications of currently evolving high energy density technology, and that high energy density researchers will benefit from industrial research and development on relevant technologies.

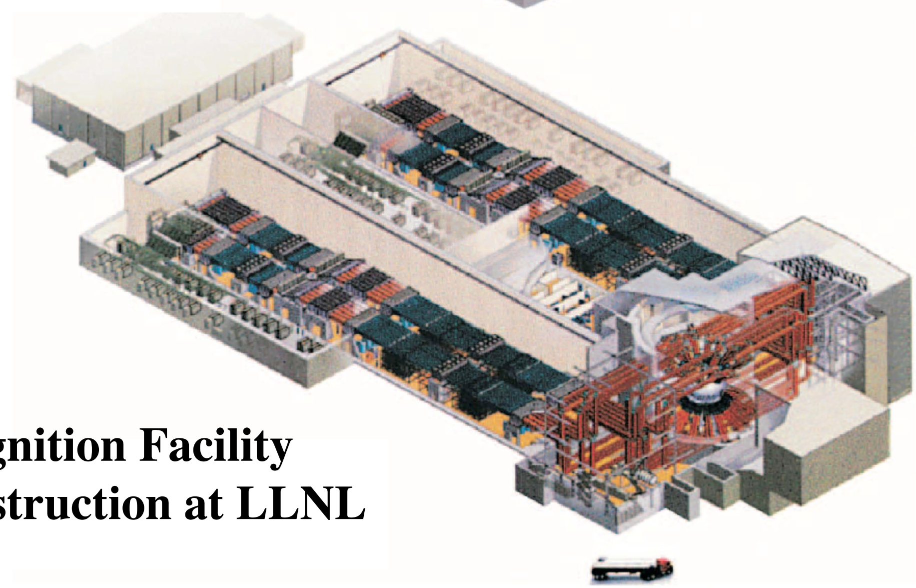
Current and future facilities open new frontiers in experimental high energy density science

20 MA SNLA Z-Facility



30-kJ OMEGA laser (UR-LLE)



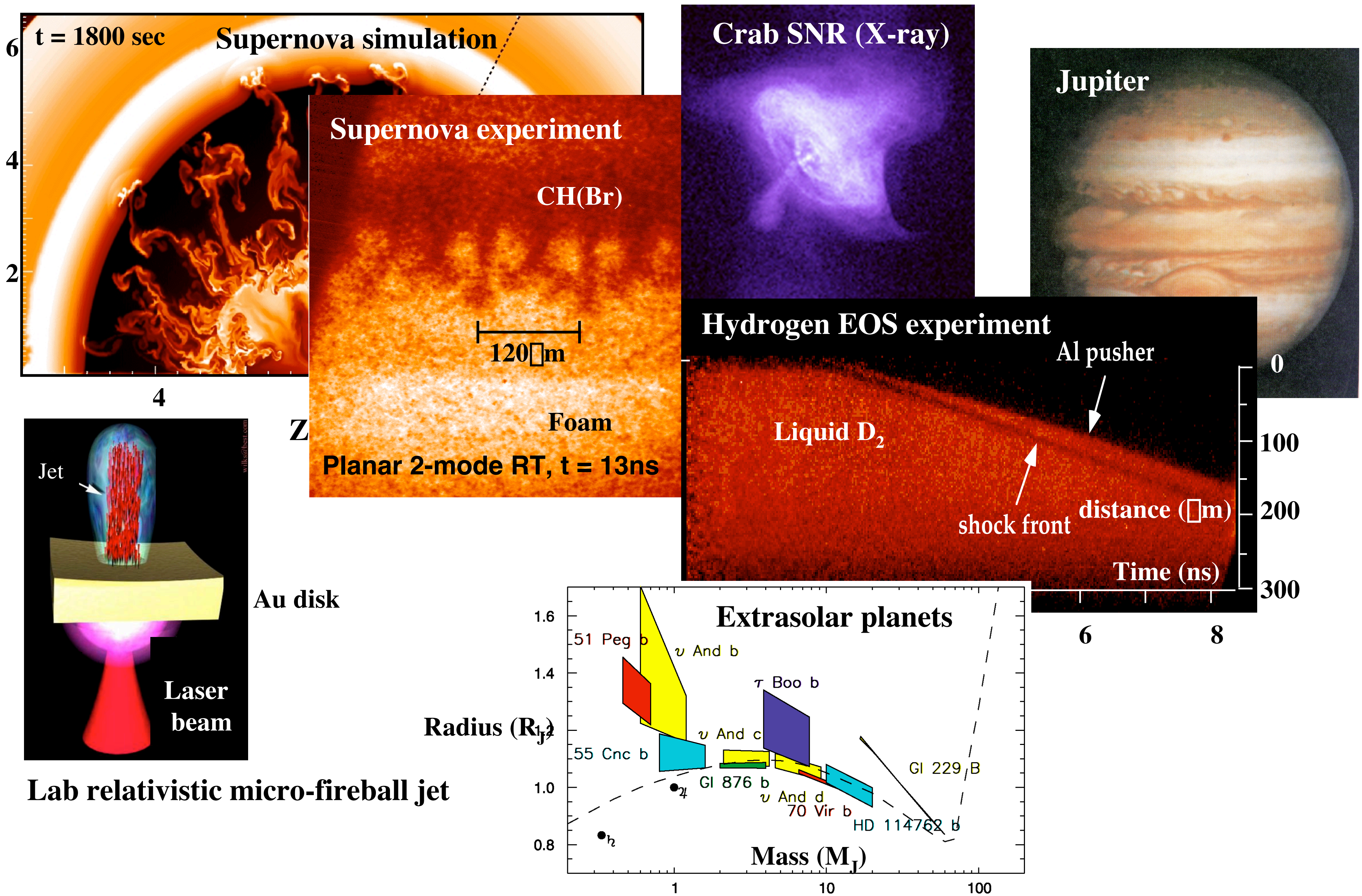


2-MJ National Ignition Facility (NIF) under construction at LLNL

Many important physics questions can be addressed in the next decade

- How does matter behave under conditions of extreme temperature, pressure, density, and electromagnetic fields?
- Can high yield thermonuclear ignition in the laboratory be used to study aspects of supernova physics and nucleosynthesis?
- Can the transition to turbulence, and the turbulent state, in high energy density systems be understood?
- What is the dynamics of strong shocks interacting with turbulent and inhomogeneous media?
- Can conditions relevant to planetary and stellar interiors, white dwarf envelopes, neutron star atmospheres, and black hole accretion disks be recreated in the laboratory on next-generation HED facilities?

High Energy Density Plasma Science and Astrophysics

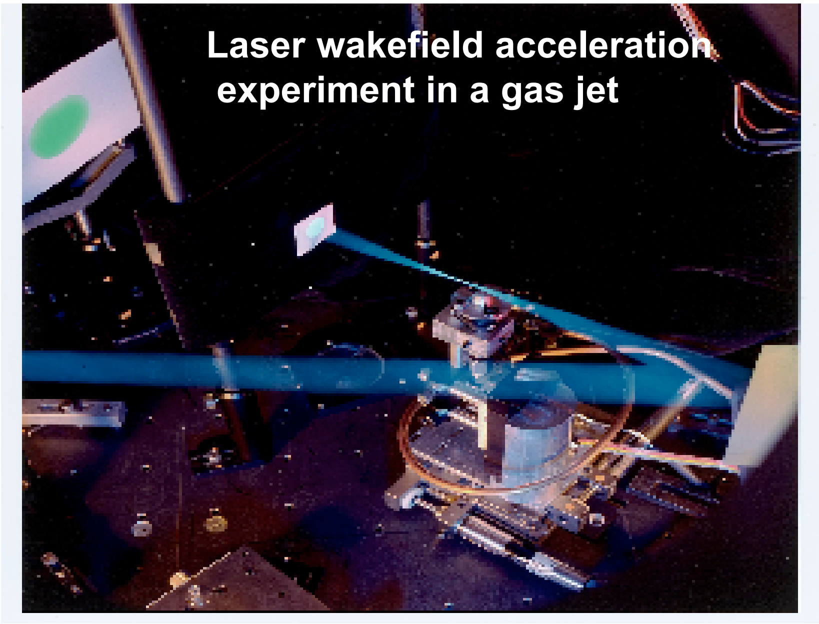


High Energy Density Plasma Science and Astrophysics

- High Energy Density Physics aims to explore and understand the physics of matter under extraordinary conditions of temperature and density, e.g., the physics of:

  - Type Ia and Type II supernovae;
  - Interiors of giant gaseous planets in the solar system and beyond;
  - Relativistic plasmas: neutron stars and gamma ray bursters; and
  - Matter in the early universe.

Facilities for Laser-Plasma and Beam-Plasma Interactions Range from Very Large to Tabletop Size



Laser-Plasma and Beam-Plasma Interactions

- Intense laser-plasma interactions, including
  - Extreme non-linear optics including multiple beamlets filamenting, braiding and scattering;
- Ultra-high gradient multi-GeV electron accelerators using plasma wakefields;
- Fast ignition; and
- Novel light sources from THz to fs X-rays.

Principal Recommendations

a. It is recommended that the National Nuclear Security Administration continue to strengthen its support for external user experiments on its major high energy density facilities, with a goal of about 15% of facility operating time dedicated to basic physics studies.

This includes the implementation of mechanisms for providing experimental run time to users, as well as providing adequate resources for operating these experiments, including target fabrication, diagnostics, etc.

Principal Recommendations

b. It is recommended that the National Nuclear Security Administration continue and expand its Stewardship Academic Alliances Program to fund research projects at universities in areas of fundamental high energy density science and technology.

Universities develop innovative concepts and train the graduate students who will become the lifeblood of the Nation's research in high energy density physics.

A significant effort should also be made by the federal government and the university community to expand the involvement of other funding agencies, such as the National Science Foundation, the National Aeronautics and Space Administration, the Department of Defense, and the non-defense directorates in the Department of Energy, in supporting research of high intellectual value in high energy density physics.

Principal Recommendations

c. A significant investment is recommended in advanced infrastructure at major high energy density facilities for the express purpose of exploring research opportunities for new high energy density physics.

This is intended to include upgrades, modifications, and additional diagnostics that enable new physics discoveries outside the mission for which the facility was built.

Joint support for such initiatives is encouraged from agencies with an interest in funding users of the facility as well as the primary program agency responsible for the facility.

Principal Recommendations

d. It is recommended that significant federal resources be devoted to supporting high energy density physics research at university-scale facilities, both experimental and computational.

Imaginative research and diagnostic development on university-scale facilities can lead to new concepts and instrumentation techniques that significantly advance our understanding of high energy density physics phenomena and in turn are implemented on state-of-the-art facilities.

Principal Recommendations

e. It is recommended that a focused national effort be implemented in support of an iterative computational-experimental integration procedure for investigating high energy density physics phenomena.

f. It is recommended that the National Nuclear Security Administration continue to develop mechanisms for allowing open scientific collaborations between academic scientists and the Department of Energy National Nuclear Security Administration laboratories and facilities, to the maximum extent possible, given national security priorities.

Principal Recommendations

g. It is recommended that federal interagency collaborations be strengthened in fostering high energy density basic science. Such program collaborations are important for fostering the basic science base, without the constraints imposed by the mission orientation of many of the Department of Energy's high energy density programs.

Conclusions of the National Research Council Study

Accomplishments of the study:

- Reviewed advances in high energy density physics on laboratory and astrophysical scales.
- Assessed the field, and highlighted scientific research opportunities.
- Developed a unifying framework for the field.
- Identified intellectual challenges.
- Outlined strategy to extend forefronts of the field.

Illustrative future challenges:

- Prioritize research opportunities.
- Clearly identify research thrusts and compelling questions of high intellectual value.
- Foster federal support for high energy density physics by multiple agencies.

TASK FORCE CHARGE AND APPROACH

In response to the January 13, 2004, charge letter from Joe Dehmer on behalf of the Interagency Working Group, the HEDP Task Force addressed the following key charge areas in order to identify the major components of a national high energy density physics program:

1. Identify the principal research thrust areas of high intellectual value that define the field of high energy density physics;

2. For each of the thrust areas, identify the primary scientific questions of high intellectual value that motivate the research;

TASK FORCE CHARGE AND APPROACH

3. Develop the compelling scientific objectives and milestones that describe what the federal investment in high energy density physics are expected to accomplish;

4. For each principal thrust area, identify the frontier research facilities and infrastructure required to make effective progress; and

5. Identify opportunities for interagency coordination in high energy density physics.

KEY BACKGROUND REFERENCES FOR TASK FORCE DELIBERATIONS

HEDP Task Force

1. *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century* (National Academies Press, 2003);

2. *Frontiers in High Energy Density Physics - The X-Games of Contemporary Science* (National Academies Press, 2003);

3. *The Science and Applications of Ultrafast, Ultraintense Lasers: Opportunities in Science and Technology Using the Brightest Light Known to Man* (Report on the SAUUL Workshop, June 17-19, 2002); and

4. Pertinent technical reviews and federal advisory committee reports.

TASK FORCE WORKING GROUPS

A - HEDP in Astrophysical Systems
Rosner (Chair), Arons, Baring, Lamb, Stone

B - Beam-Induced HEDP (RHIC, heavy ion fusion, high-intensity accelerators, etc.) Joshi (Chair), Jacak, Logan, Mellisinos, Zajc

S - HEDP in Stockpile Stewardship Facilities (Omega, Z, National Ignition Facility, etc.) Remington (Chair), Deeney, Hammer, Lee, Meyerhofer, Schneider, Silvera, Wilde

U - Ultrafast, Ultraintense Laser Science
Ditmire (Chair), DiMauro, Falcone, Hill, Mori, Murnane

THRUST AREAS IN HIGH ENERGY DENSITY ASTROPHYSICS

HEDP Task Force

Thrust Area #1 - Astrophysical phenomena

What is the nature of matter and energy observed under extraordinary conditions in highly evolved stars and in their immediate surroundings, and how do matter and energy interact in such systems to produce the most energetic transient events in the universe?

Thrust Area #2 - Fundamental physics of high energy density astrophysical phenomena

What are the fundamental material properties of matter, and what is the nature of the fundamental interactions between matter and energy, under the extreme conditions encountered in high energy density astrophysics?

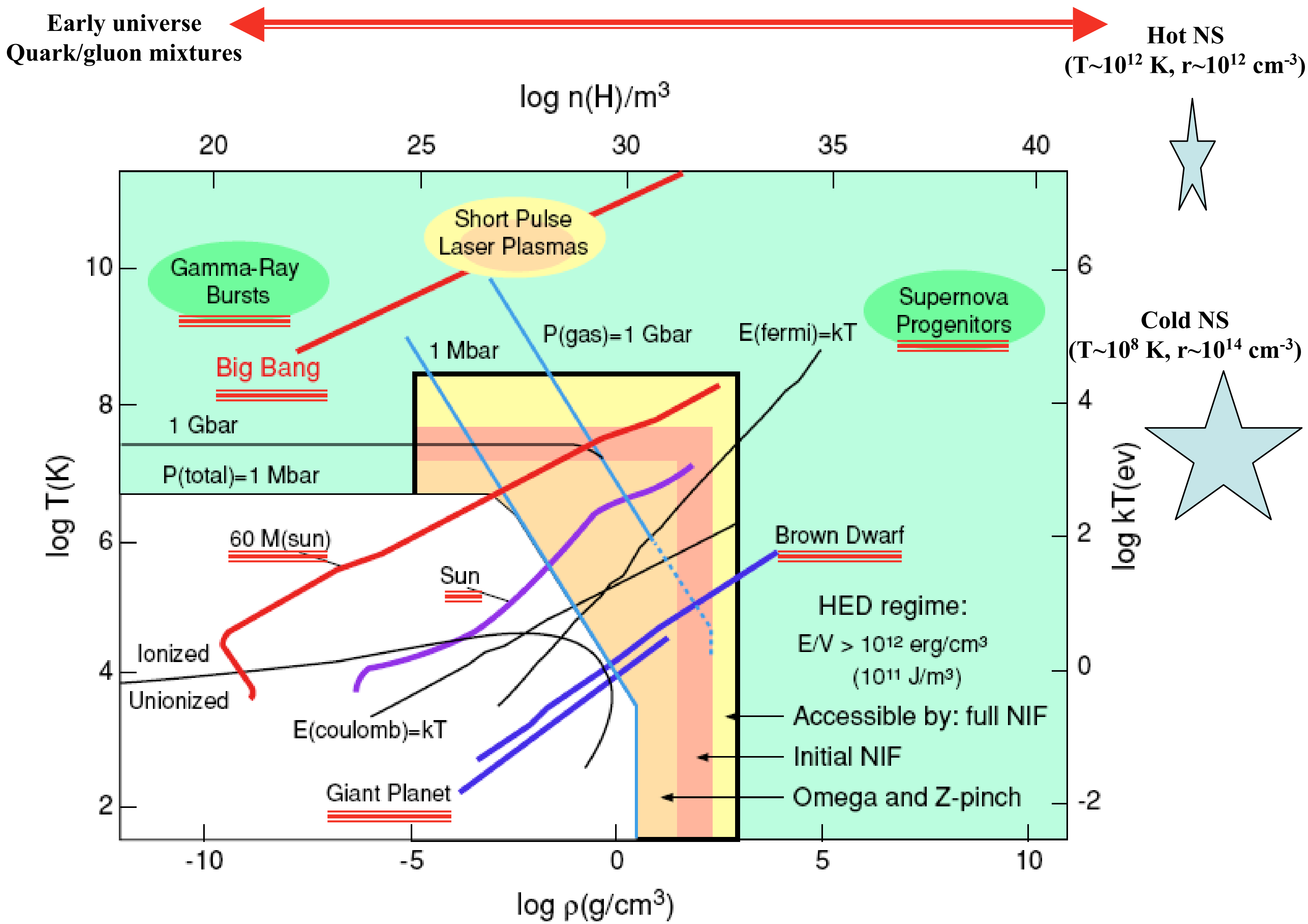
THRUST AREAS IN HIGH ENERGY DENSITY ASTROPHYSICS

HEDP Task Force

Thrust Area #3 - Laboratory astrophysics

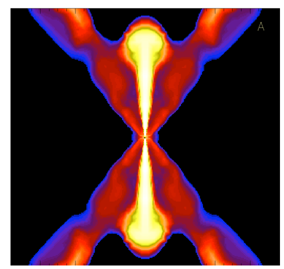
What are the limits to our ability to test astrophysical model and fundamental physics in the laboratory, and how can we use laboratory experiments to elucidate either fundamental physics or phenomenology of astrophysical systems that are as yet inaccessible to either theory or simulations?

MAP OF THE HED UNIVERSE



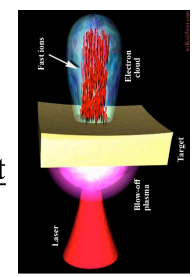
The “big questions” for HED astrophysics

- *How does matter behave under conditions of extreme temperature, pressure and density*?
  - Origin and evolution of giant planets and brown dwarfs
  - Equation-of-state, opacities, conductivity, diffusivity, viscosity, … , of stellar matter
  - Basic physics of degenerate plasmas (e.g., convection, URCA, …)
  - Nuclear burning: ignition? transition from flame to detonation?
  - Quark-gluon plasmas/the very early universe, strongly coupled plasmas
  - Ultra-high energy cosmic rays: origins? composition? propagation?
  - …
- *How does matter interact with photons and neutrinos under extreme conditions*?
  - Accreting black holes/neutron stars: disks, jets, …
  - Gamma ray bursters (GRBs)
  - Pair plasmas
  - …



GRB model (Woosley & MacFadyen 1999)

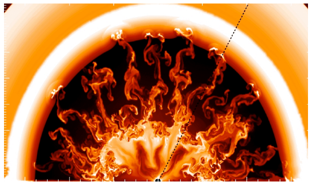
Proposed GRB experiment Liang & Wilkes 1998; Wilkes et al. 2001)

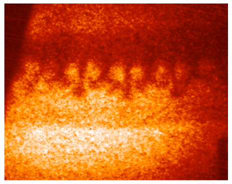


Laboratory astrophysics

- Motivating question:
  - What are the limits to our ability to test astrophysical models and fundamental physics in the laboratory; and how can we use laboratory experiments to elucidate either fundamental physics or phenomenology of astrophysical systems as yet inaccessible to either theory or simulations?
- The four key science objectives
  - Measuring material properties at high energy densities: equations of state, opacities, …
  - Building intuition for highly nonlinear astronomical phenomena, but under controlled lab conditions (with very different dimensionless parameters): radiation hydro, magnetohydrodynamics, particle acceleration, …
  - Connecting laboratory phenomena/physics directly to astrophysical phenomena/physics (viz., in asymptotic regimes for Re, Rm, …): late-time development of Type Ia and II supernovae, …
  - Validating instrumentation, diagnostics, simulation codes, … , aimed at astronomical observations/phenomena

Type II SN shock simulation (Kifonidis et al. 2000)





Type II SN shock experiment (Robey et al. 2001)

THRUST AREAS IN BEAM-INDUCED HIGH ENERGY DENSITY PHYSICS

HEDP Task Force

Thrust Area #4 - Heavy-ion-driven high energy density physics and fusion

How can heavy ion beams be compressed to the high intensities required for creating high energy density matter and fusion ignition conditions?

Thrust Area #5 - High energy density science with ultrarelativistic electron beams

How can the ultra high electric fields in a beam-driven plasma wakefield be harnessed and sufficiently controlled to accelerate and focus high-quality, high-energy beams in compact devices?

THRUST AREAS IN BEAM-INDUCED HIGH ENERGY DENSITY SCIENCE

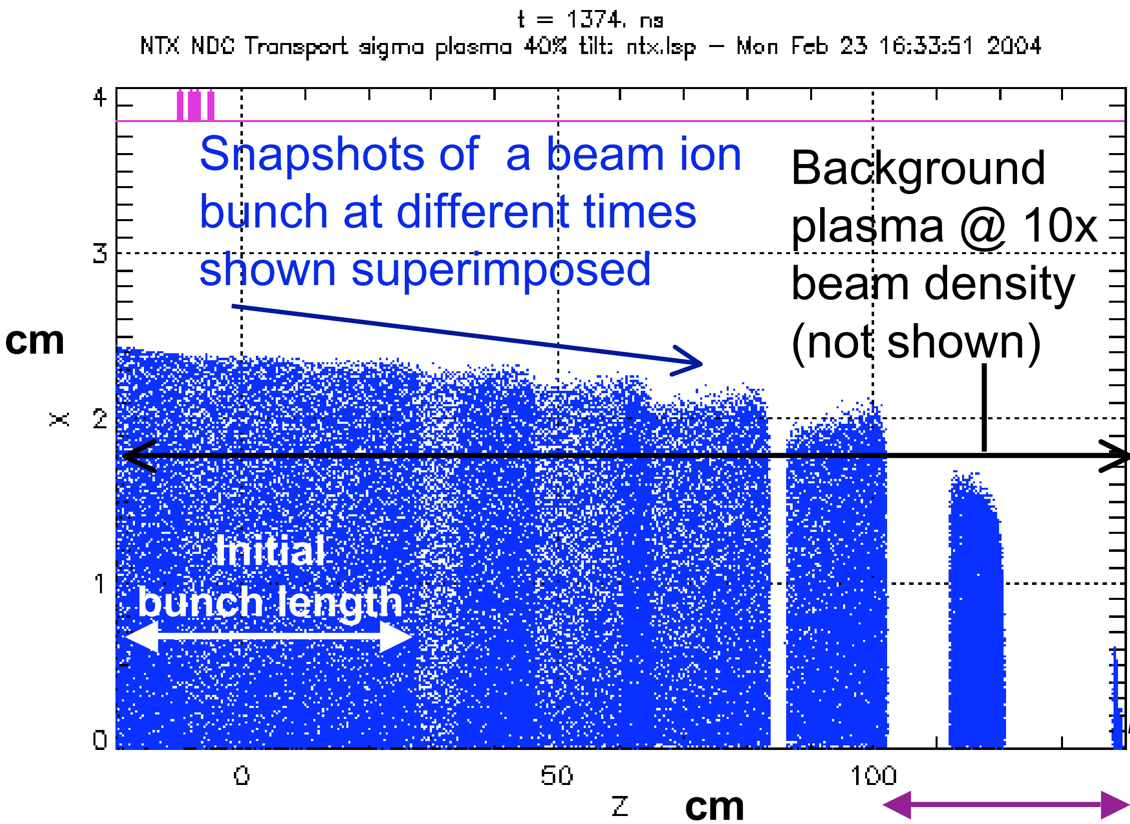
HEDP Task Force

Thrust Area #6 - Characterization of quark - gluon plasmas

What is the nature of matter at the exceedingly high density and temperature characteristic of the Early Universe?

Does the Quark Gluon plasma exhibit any of the properties of a classical plasma?

Simulations show large compressions of tailored-velocity ion beams in neutralizing background plasma



←Ramped 220-390 keV K^+ ion beam injected into a 1.4-m -long plasma column:

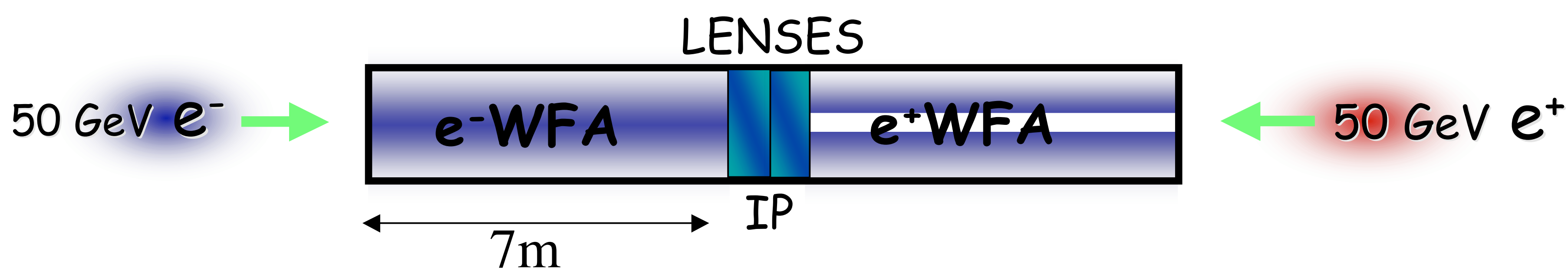
- Axial compression 120 X
- Radial compression to 1/e focal spot radius < 1 mm
- *Beam intensity on target increases by 50,000 X.*

Existing 3.9T solenoid focuses beam

- **Velocity chirp amplifies beam power analogous to frequency chirp in CPA lasers**
- **Solenoids and/or adiabatic plasma lens can focus compressed bunches *in plasma***
- **Instabilities may be controlled with $n_p >> n_b$, and B_z field (Welch, Rose, Kaganovich)**

Plasma afterburner for energy doubling

- Double the energy of the collider with short plasma sections before collision point.
- 1st half of beam excites the wake --decelerates to 0.
- 2nd half of beams rides the wake--accelerates to 2 x E_o.
- Make up for Luminosity decrease $\propto N^2/\sigma_z^2$ by halving σ in a final plasma lens.



S. Lee *et al.*, PRST-AB (2001)

Physics of Quark - Gluon Plasmas

- **Create high(est) energy density matter**
  - Similar to that existing ~1 msec after the Big Bang.
  - Can study only in the lab – relics from Big Bang inaccessible.
  - T ~ 200-400 MeV (~ 2-4 x 10^{12} K).
  - U ~ 5-15 GeV/fm^3 (~ 10^{30} J/cm^3).
  - R ~ 10 fm, t_{life} ~ 10 fm/c (~3 x 10^{-23} sec).

- **Characterize the hot, dense medium**
  - Expect quantum chromodynamic phase transition to quark gluon plasma.
  - Does medium behave as a plasma? coupling weak or strong?
  - What is the density, temperature, radiation rate, collision frequency, conductivity, opacity, Debye screening length?
  - Probes: passive (radiation) and those created in the collision.

HIGH ENERGY DENSITY THRUST AREAS IN STOCKPILLE STEWARDSHIP FACILITIES

HEDP Task Force

Thrust Area #7 - Materials properties

What are the fundamental properties of matter at extreme states of temperature and/or density?

Thrust Area #8 - Compressible dynamics

How do compressible, nonlinear flows evolve into the turbulent regime?

HIGH ENERGY DENSITY THRUST AREAS IN STOCKPILLE STEWARDSHIP FACILITIES

HEDP Task Force

Thrust Area #9 - Radiative hydrodynamics

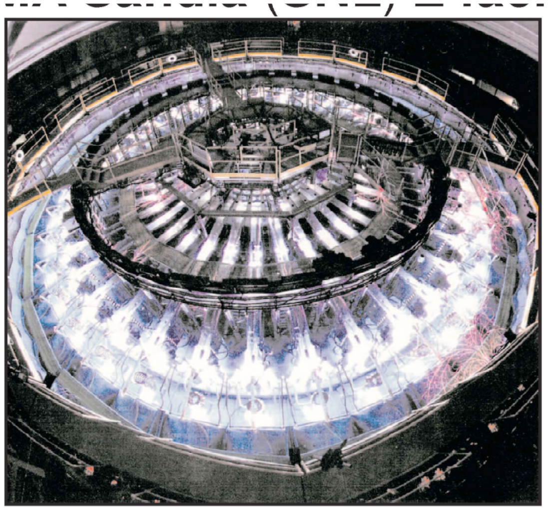
Can high energy density experiments answer enduring questions about nonlinear radiative hydrodynamics and the dynamics of powerful astrophysical phenomena?

Thrust Area #10 - Inertial confinement fusion

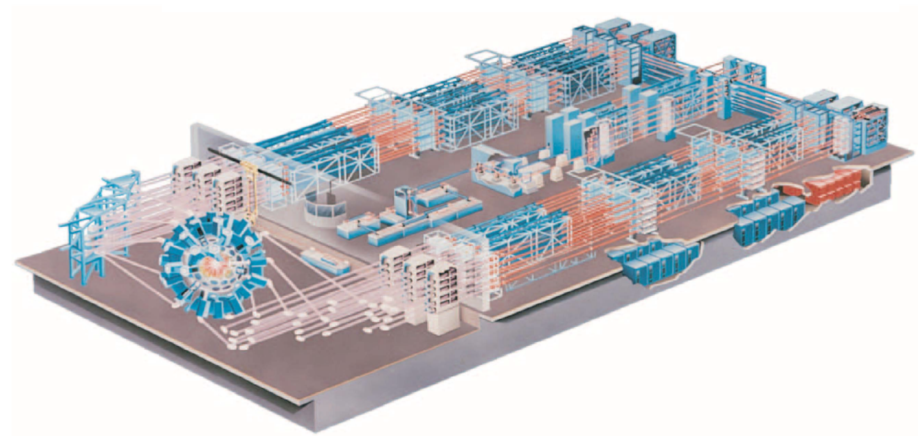
Can inertial fusion ignition be achieved in the laboratory and developed as a research tool?

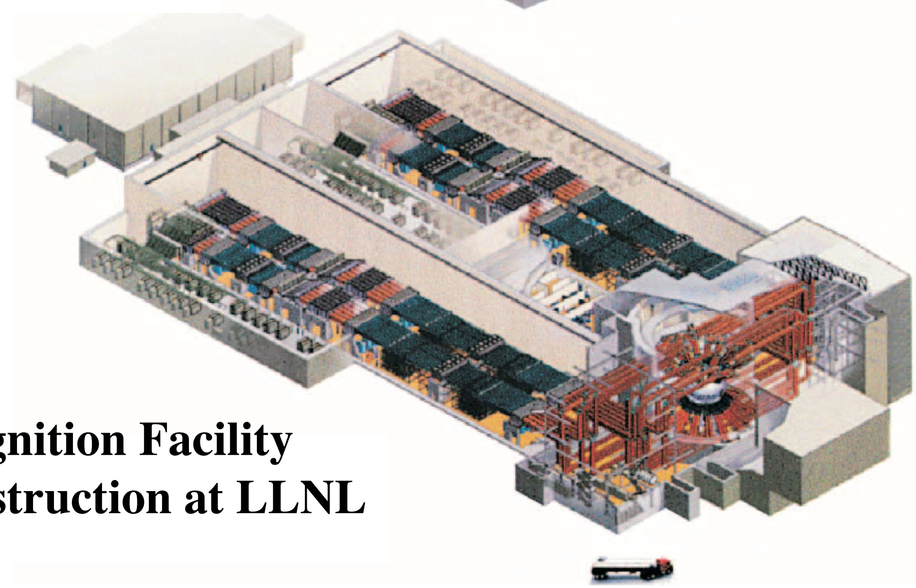
NNSA's current and future facilities are the core of its inertial confinement fusion ignition program

20 MA SNLA Z-Facility



30-kJ OMEGA laser (UR-LLE)

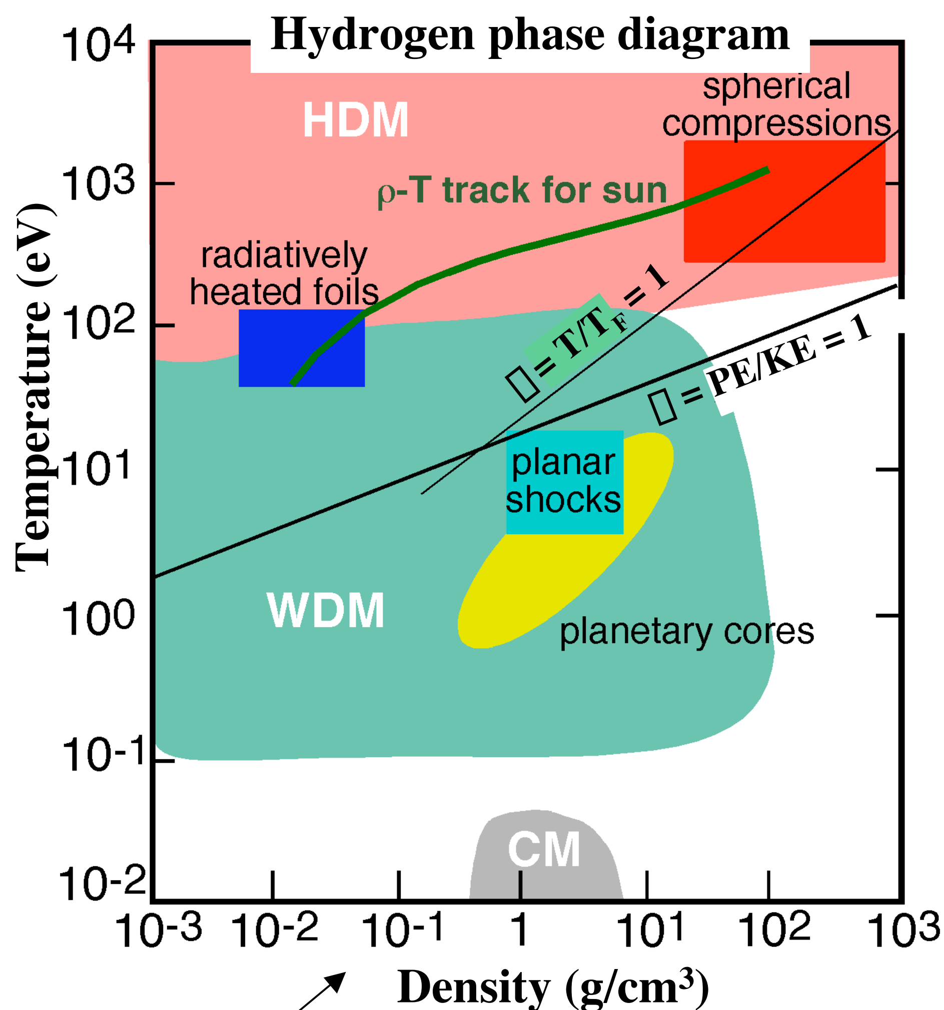




2-MJ National Ignition Facility (NIF) under construction at LLNL

The Material Properties thrust encompasses the study of fundamental properties of matter under extreme states of density and temperature

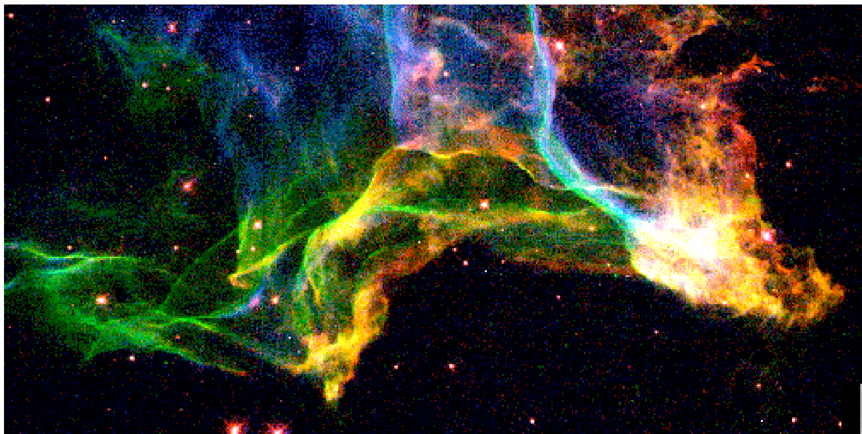
- **Material Properties describe:**
  - **- Equation of State (EOS)**
  - **- Radiative opacity**
  - **- Conductivity, viscosity, …**
  - **- Equilibration time**
- **Hot Dense Matter (HDM) occurs in:**
  - **- Stellar interiors, accretion disks**
  - **- Laser plasmas, Z-pinches**
  - **- Radiatively heated foams**
  - **- ICF capsule implosion cores**
- **Warm Dense Matter (WDM) occurs in:**
  - **- Cores of giant planets**
  - **- Strongly shocked solids**
  - **- Radiatively heated solid foils**



- **Tenuous plasma "easy": □ = PE/KE << 1;**
- **Dense plasma "difficult": □ ~ 1 and □ ~ 1**

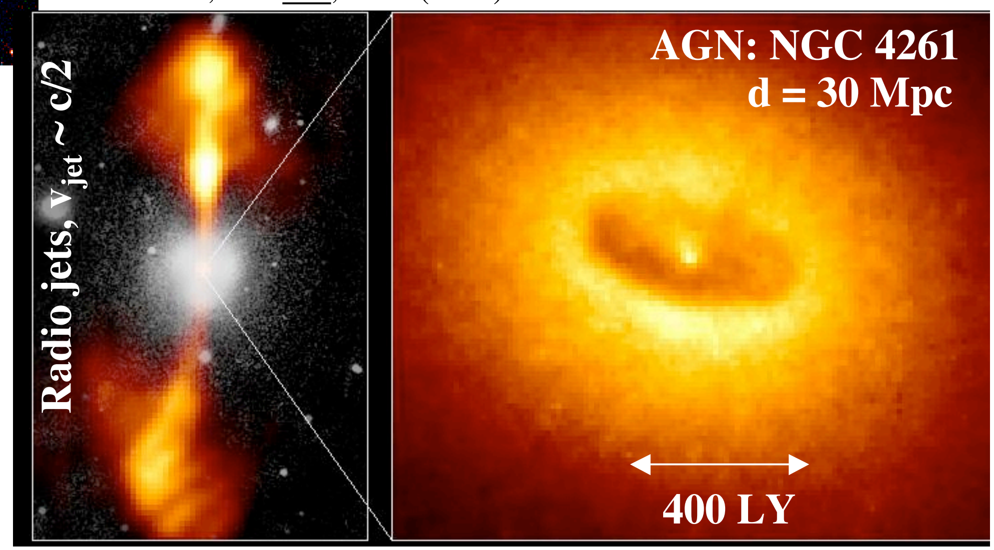
Radiative hydrodynamics abound in energetic astrophysics

Radiative shocks in the Cygnus Loop supernova remnant (SNR)



Photoionized plasmas in an accreting massive black hole

Piner *et al*., A.J. 122, 2954 (2001)



88,000 LY

Ferrarese *et al*., Ap. J. 470, 444 (1996)

- **Additional examples of radiative hydrodynamics in astrophysics:**

  - Radiatively cooled jets

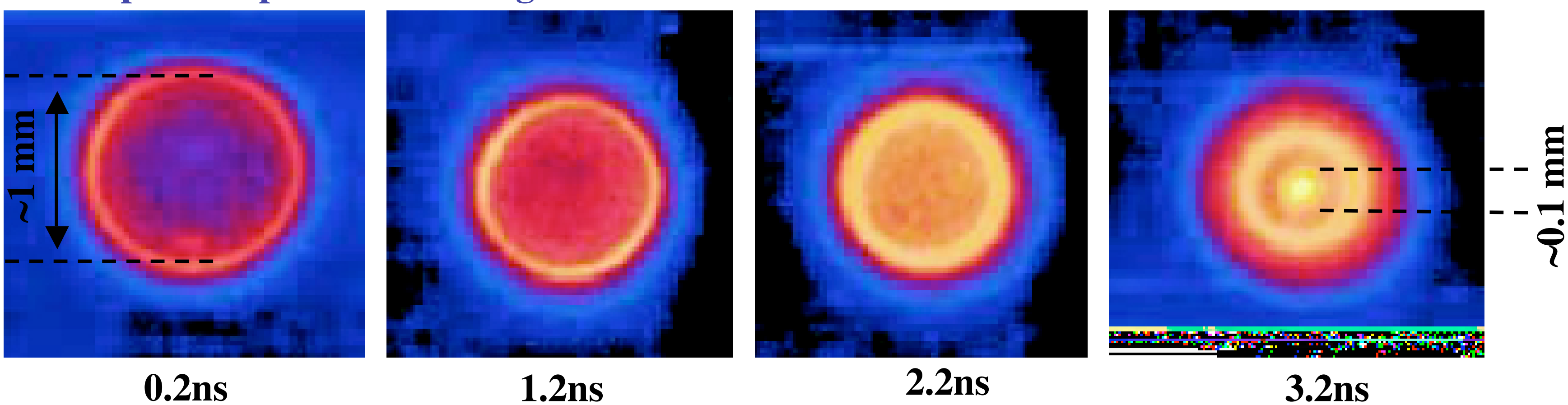
  - Radiatively driven molecular clouds

- **Our understanding of these phenomena would improve significantly if we could develop scaled radiative hydrodynamics experimental testbeds to validate modeling**

The Inertial Confinement Fusion (ICF) thrust is focused on achieving thermonuclear ignition within the decade

- The achievement of ignition and gain is a a grand challenge goal of NNSA.
- Ignition experiments will commence on the NIF laser at Livermore in about 2010.
- Supporting experiments and physics development are carried out on OMEGA (UR-LLE), Z/ZR (SNL), and smaller facilities.

ICF capsule implosion on Omega



- ICF research involves a multitude of coupled phenomena, all occurring in a few nanoseconds on sub-millimeter spatial scales
  - -Laser coupling, laser-plasma instabilities, hydrodynamic instabilities,
  - -radiation transport, electron heat transport, thermonuclear fusion reactions

Fast Ignition offers the potential to increase target gains and reduce driver energy requirements

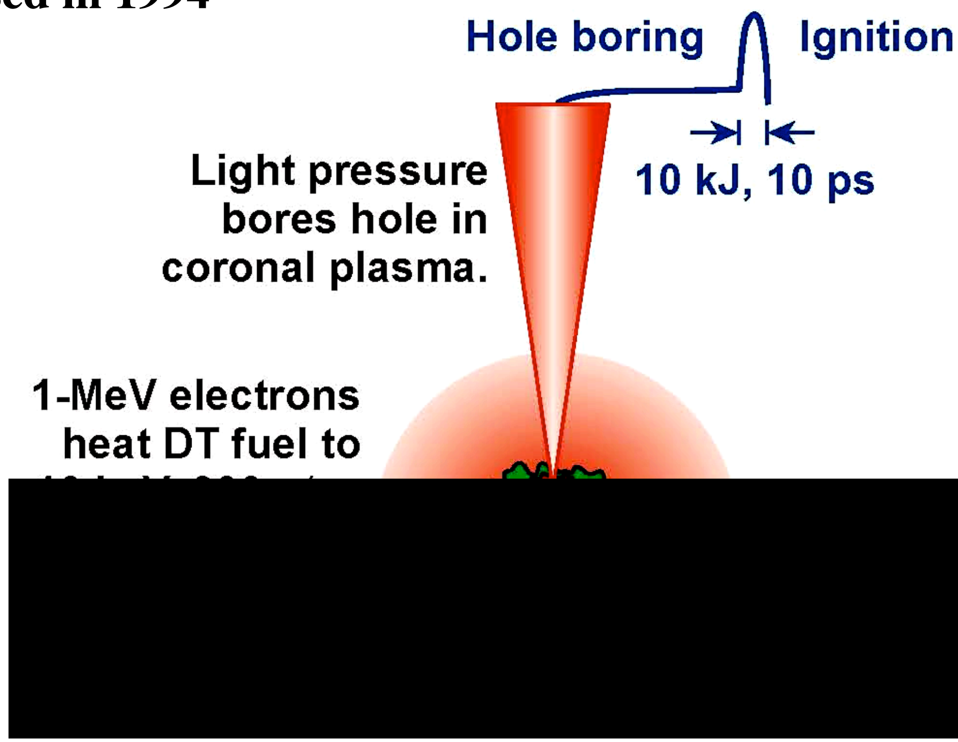
- The Fast Ignition concept was proposed in 1994

- In Fast Ignition, the compression and heating processes are separated.

- Preliminary experiments, including integrated ones in Japan, continue to increase confidence in this concept.

- All three of the large NNSA facilities are planning to add high energy petawatt capability.

- These combined facilities will address the fundamental question:



[redacted]

Will the Fast Ignition concept lead to higher target gains for the same driver energy?

THRUST AREAS IN ULTRAFAST ULTRAINTENSE LASER SCIENCE

HEDP Task Force

Thrust Area #11 - Laser excitation of many-particle systems at the relativistic extreme

How do many-body systems evolve in a light field under extreme relativistic conditions where an electron is accelerated to relativistic energies and particle production becomes possible in one optical cycle?

Thrust Area #12 - Attosecond physics

Can physical and chemical processes be controlled with light pulses created in the laboratory that possess both the intrinsic time- (attoseconds, 1 as = 10^{-18} s) and length- (x-rays, 1 Å) scales of all atomic matter?

THRUST AREAS IN ULTRAFAST ULTRAINTENSE LASER SCIENCE

HEDP Task Force

Thrust Area #13 - Ultrafast, high-peak-power x-rays

Can intense, ultra-fast x-rays become a routine tool for imaging the structure and motion of "single" complex bio-molecules that are the constituents of all living things?

Can nonlinear optics be applied as a powerful, routine probe of matter in the XUV/x-ray regime?

Thrust Area #14 - Compact high energy particle acceleration

How can ultra-intense ultra-short pulse lasers be used to develop compact GeV to TeVclass electron and or proton/ion accelerators?

THRUST AREAS IN ULTRAFAST ULTRAINTENSE LASER SCIENCE

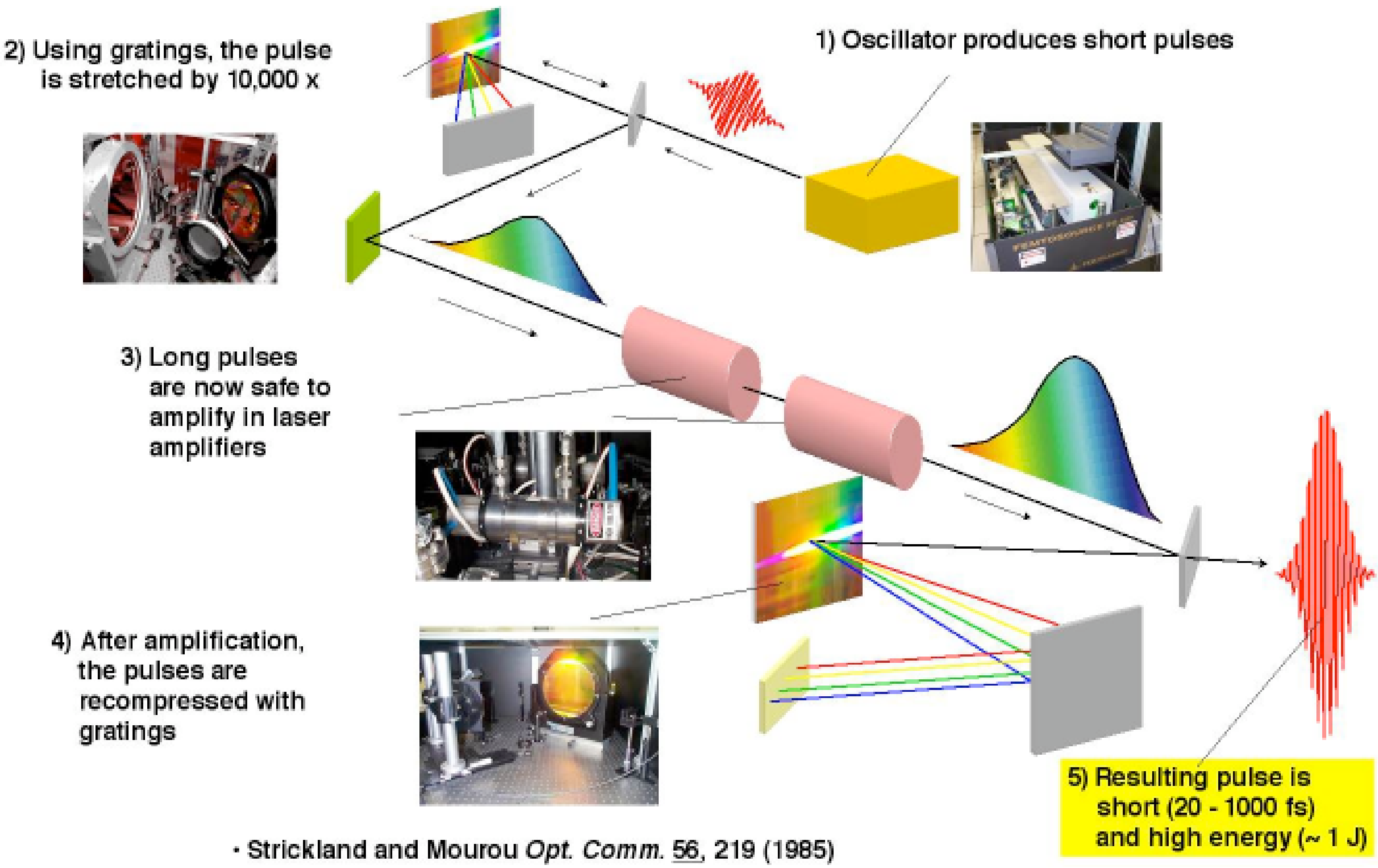
HEDP Task Force

Thrust Area #15 - Inertial fusion energy fast ignition

Is it possible to make controlled nuclear fusion useful and efficient by heating plasmas with an intense, short pulse laser?

The enabling technology for the field of ultrafast ultraintense lasers is chirped pulse amplification (CPA)

HEDP Task Force



- Strickland and Mourou *Opt. Comm.* 56, 219 (1985)

Chirped pulse amplification lasers access extremes in field strength and energy density

HEDP Task Force

Multi-TW laser focused to <10 μm
⇒
Focused light intensity of
> 10^{19} - 10^{21} W/cm^2

High Field Science

High electric fields

$E \sim 10^{10} - 10^{11}$ *V/cm*

Field strength is 10 to 100 times that of the electric field felt by an electron in a hydrogen atom

High electron quiver energy

U_{osc} = 60 *keV* - 3 *MeV*

Electron motion can become relativistic ($U_{osc} > m_e c^2$ = 512 *keV*)

High Energy Density Science

Concentrated energy

Energy density in a femtosecond pulse is 10^9 J/cm^3

Corresponds to ~ 10 keV per atom at solid density

High brightness and pressure

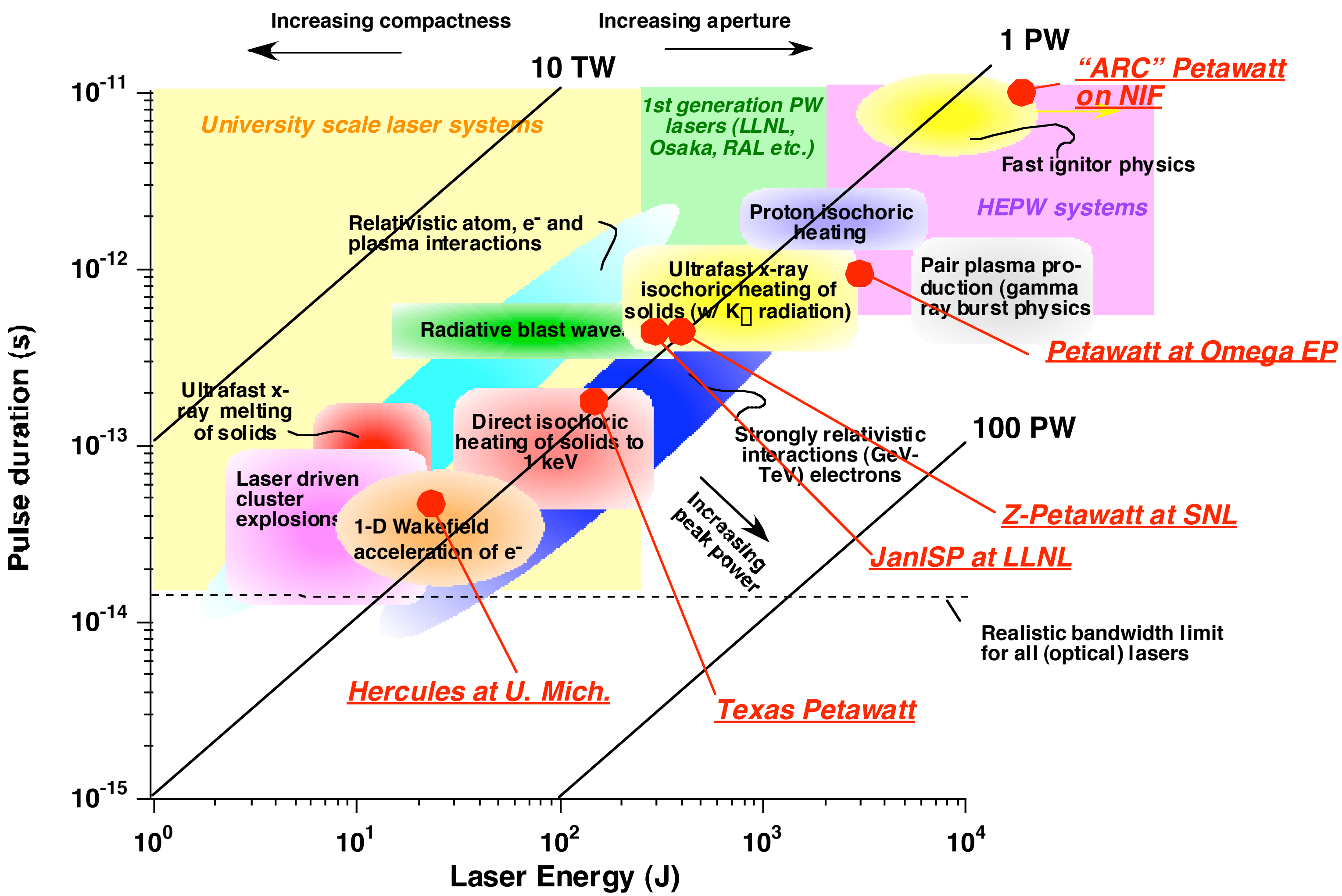
Radiance exceeds that of a 10 keV black body

Light pressure $P = I/c$ = 0.3 - 30 *Gbar*

A variety of different types of Petawatt class lasers are under development, accessing many potential applications

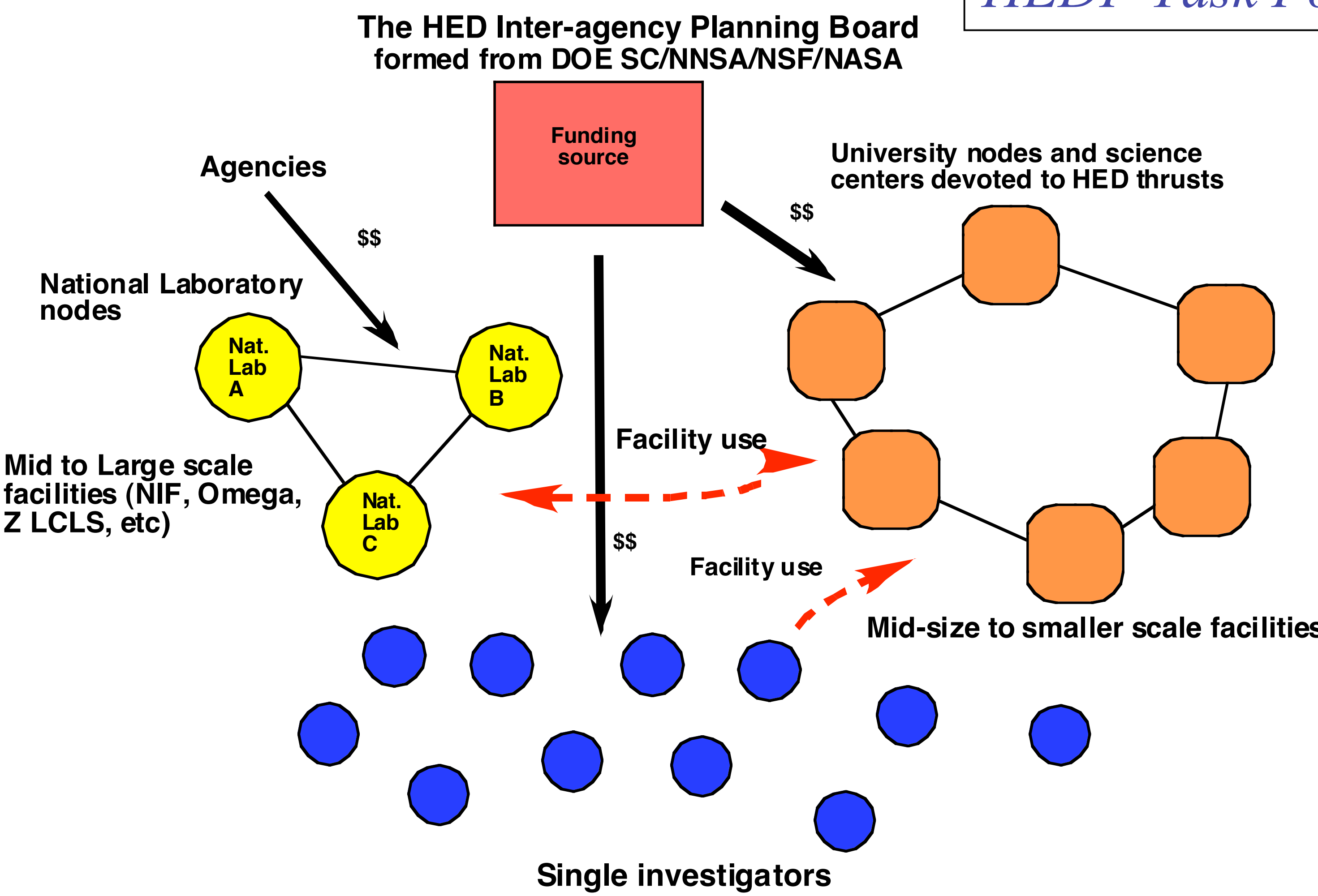
HEDP Task Force

Applications and Petawatt lasers under development in the US



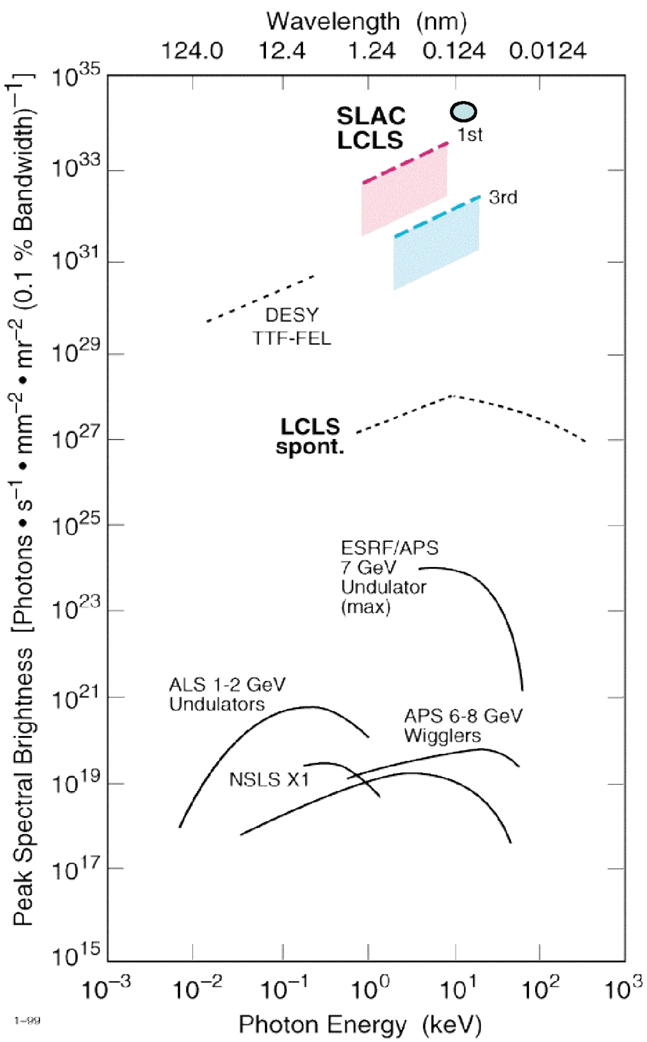
The field of High Energy Density Science could be propelled with the formation of a national network based around small, intermediate and large facilities

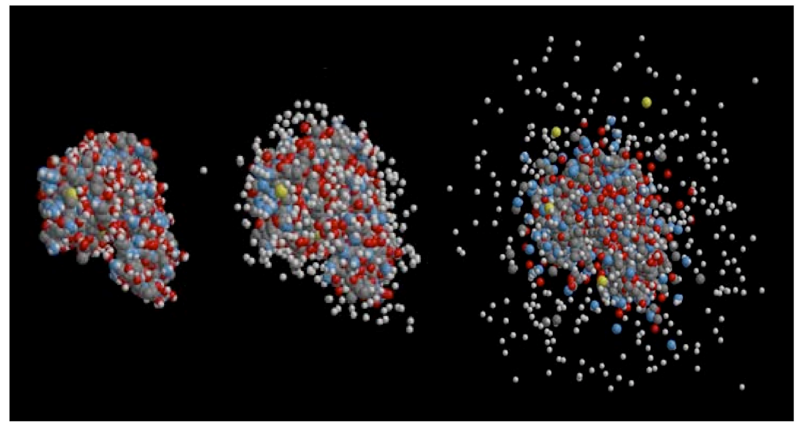
HEDP Task Force



The LINAC Coherent Light Source (LCLS) will revolutionize ultrafast x-ray science

HEDP Task Force





"potential for biomolecular imaging with femtosecond x-ray pulses"
Neutze R, Hajdu J et al., Nature 406, 752 (2000).

Baseline performance:

- 15-1.5 Angstrom
- 10 GW peak power

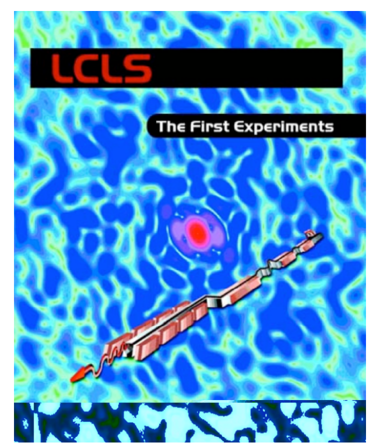
larger by 10^9 to current sources

- ultra-short, 200 fs - ???

exceeds 3rd generation by ≥ 10^3

- coherent

large degeneracy factor ≥ 10^9



CONCLUSIONS

HEDP Task Force

High energy density plasma science is a rapidly growing field with enormous potential for discovery in scientific and technological areas of high intellectual value.

The opportunities for graduate student training, postdoctoral research, commercial spin-offs, and interdisciplinary research are likely to increase for many decades to come.