

An LLNL and National Ignition Facility perspective

National Academy of Sciences

Committee on the Decadal Assessment of Plasma Physics

Mark Herrmann
NIF Director

Thanks to the NIF team and Rip Collins, Rulon Linford, Bruce Remington

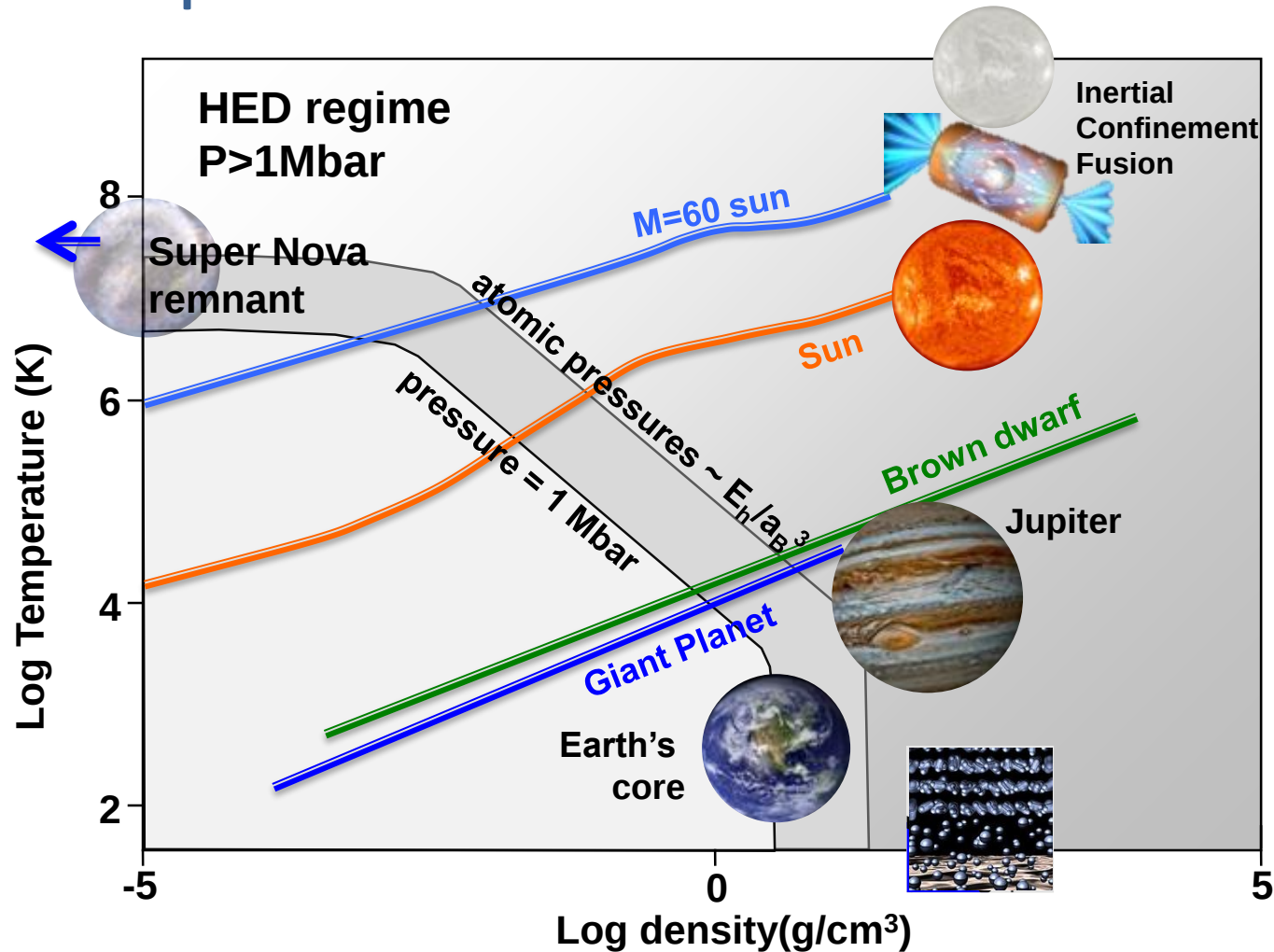
January 11, 2019



It's an exciting time for high energy density science and plasma physics!

- Amazing capabilities have been developed over the past decade to perform fascinating science on the boundary of what is possible.
- Plasma physicists/HED scientist are exploiting these capabilities and delivering fabulous science. The work is being well received by the broader scientific community.
- “Discovery Science” allocations play an important role in enabling innovation and addressing the most fundamental questions facing our field
- We are just scratching the surface of the many scientific grand challenges that can be addressed by our community
- Pursuit of fusion ignition is a tremendous scientific and engineering challenge, which drives innovation

Most of the matter in the universe is far from Standard Temperature and Pressure!

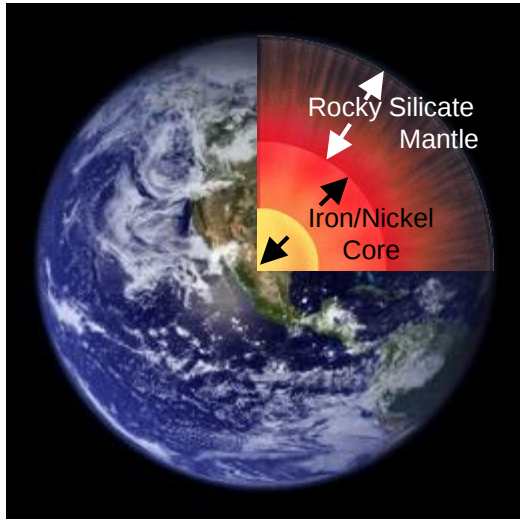


1 Mbar = $10^6 \text{ atm} =$
100 Gpa = 10^{11} Pascals
= 10^{11} J/m^3

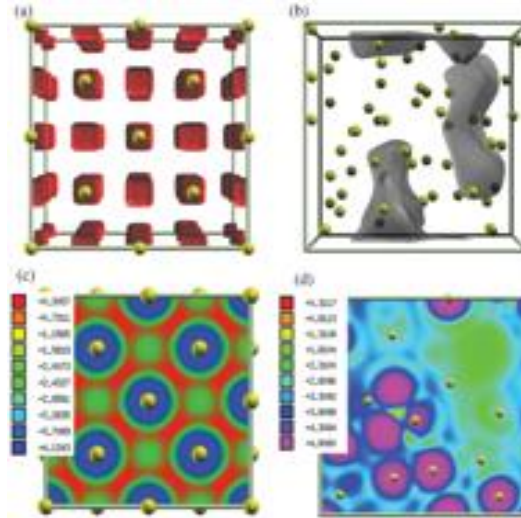
New experimental tools and new diagnostics enable us to produce and accurately characterize the states and processes over this broad range of conditions

We have more reasons than ever to understand matter at extreme conditions

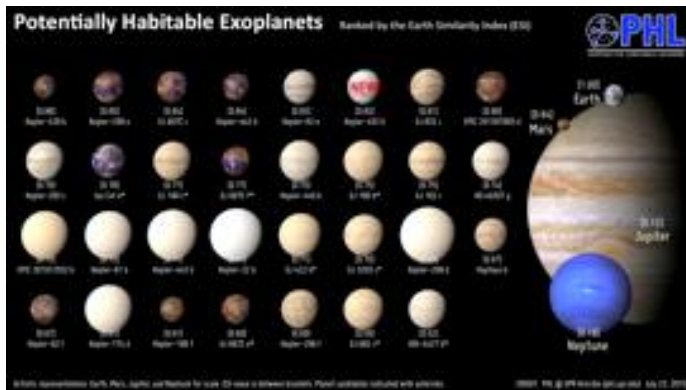
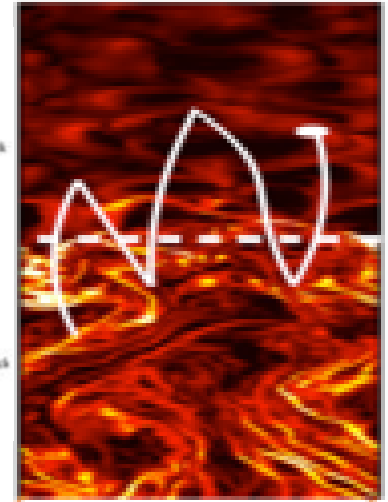
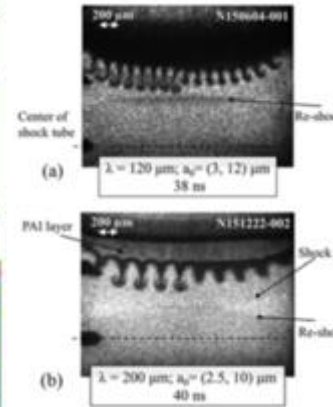
Planetary Science



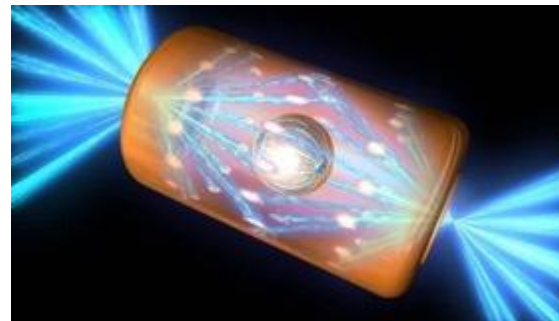
New Materials?



Radiation Hydrodynamics Plasma Astrophysics



Exoplanets



Laboratory Fusion

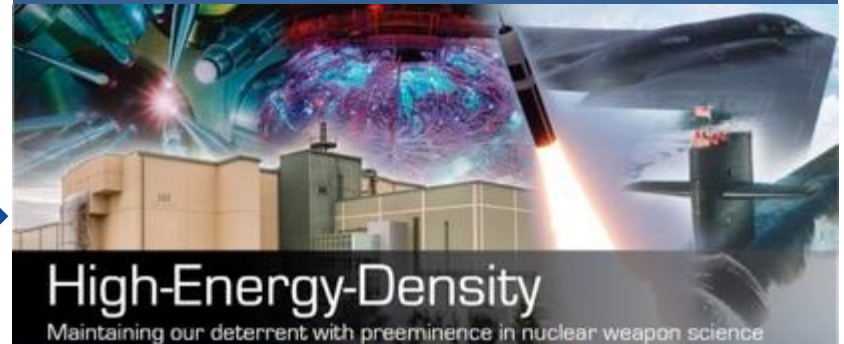


Stockpile Stewardship

Stockpile Stewardship Program: Maintain safe, secure, effective US nuclear deterrent without further underground nuclear testing



Science Based Stockpile Stewardship



1945

1992

2018

2032

Increasing role of S&T as we move further away from the nuclear testing era

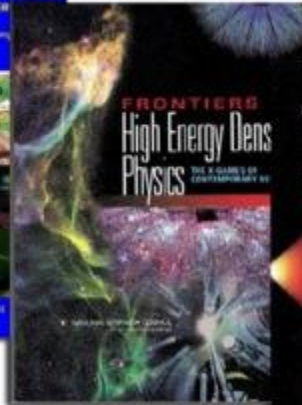
A number of studies of high energy density science were performed in the “2000’s”

2002



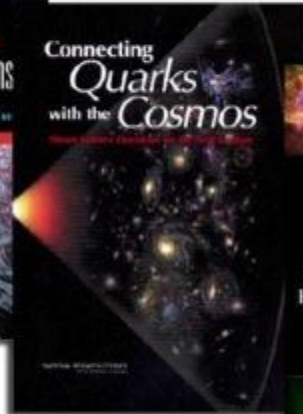
BES,
OFES
2011

2003



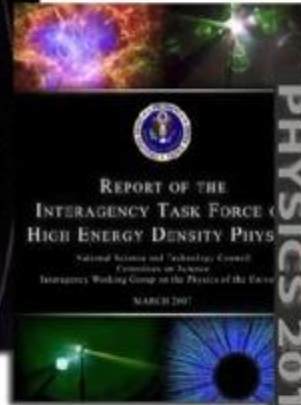
National
Academy

2003



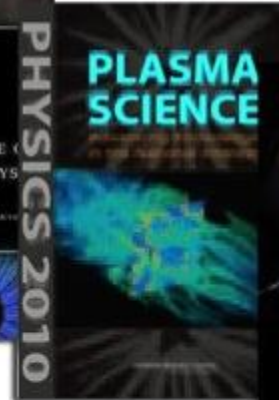
National
Academy

2007



Office of
the
President

2007



National
Research
Council

2010



DOE

2010



Decadal
survey in
Astronomy &
Astrophysics

DOE & NNSA

Lawrence Livermore National Laboratory

Option:UCRL#



A number of studies of high energy density science were performed in the “2000’s”

2002



BES,
OFES

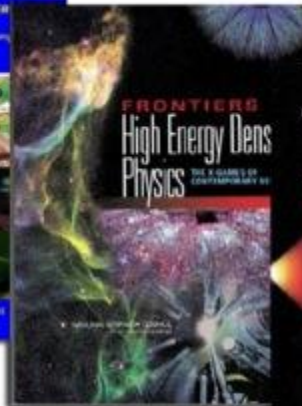
2011



DOE & NNSA

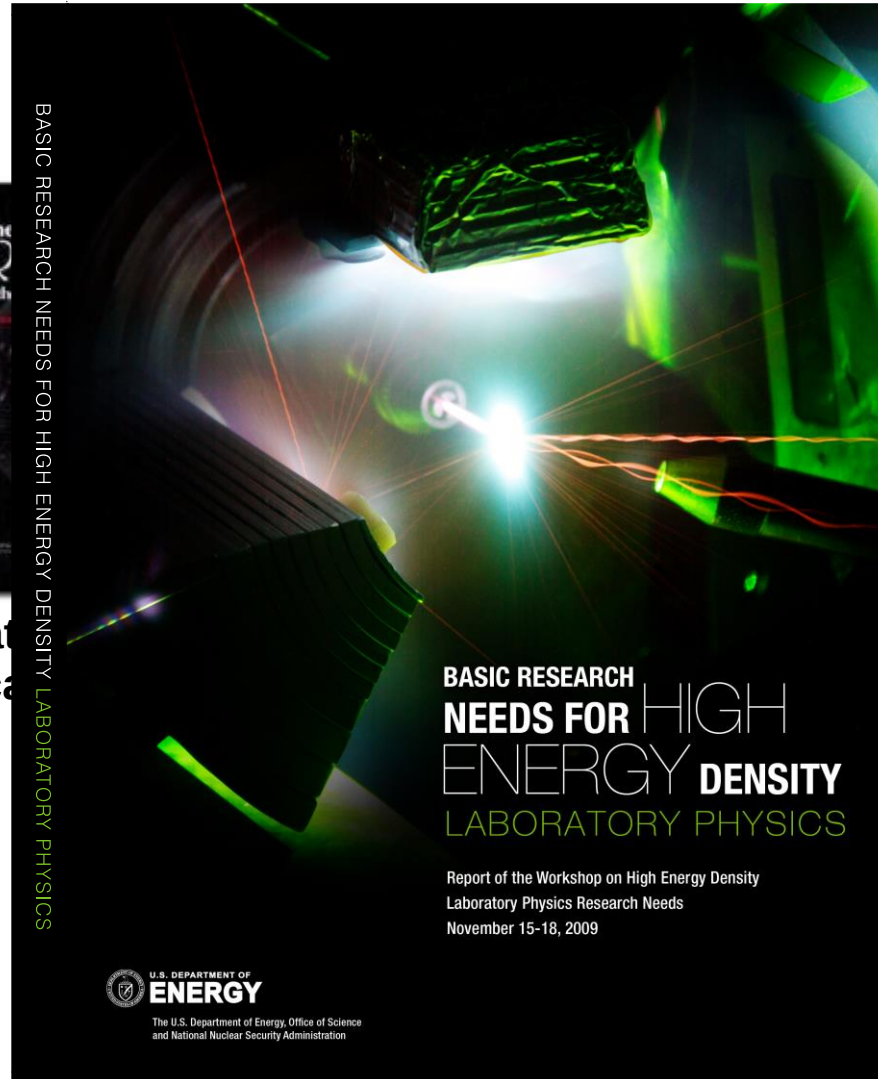
Lawrence Livermore National Laboratory

2003



National
Academy

BASIC RESEARCH NEEDS FOR HIGH ENERGY DENSITY LABORATORY PHYSICS



2010

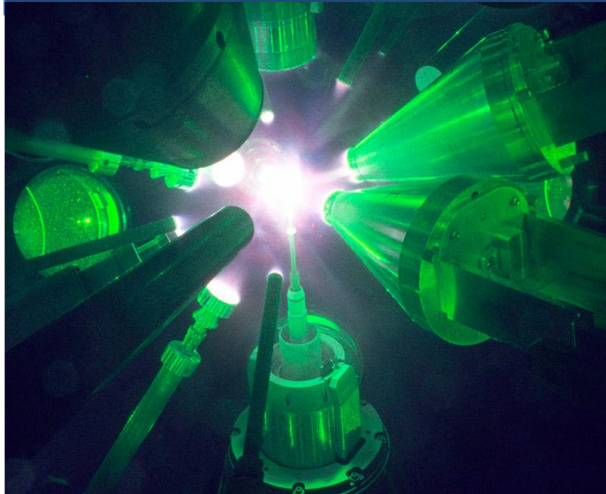


Decadal
survey in
Astronomy &
Astrophysics

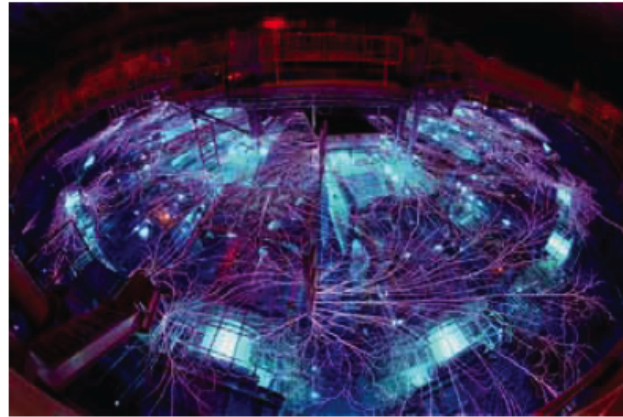
It is time for another BRN for HEDLP

At the same time, significant construction and upgrades were being performed on world class capabilities for creating and studying high energy density science

**Omega and Omega EP
Laser Facilities**



ZR Pulsed Power Facility



**National Ignition
Facility**



These investments all came online in the 2007-2009 timeframe, continuing US clear world leadership in this field

LCLS

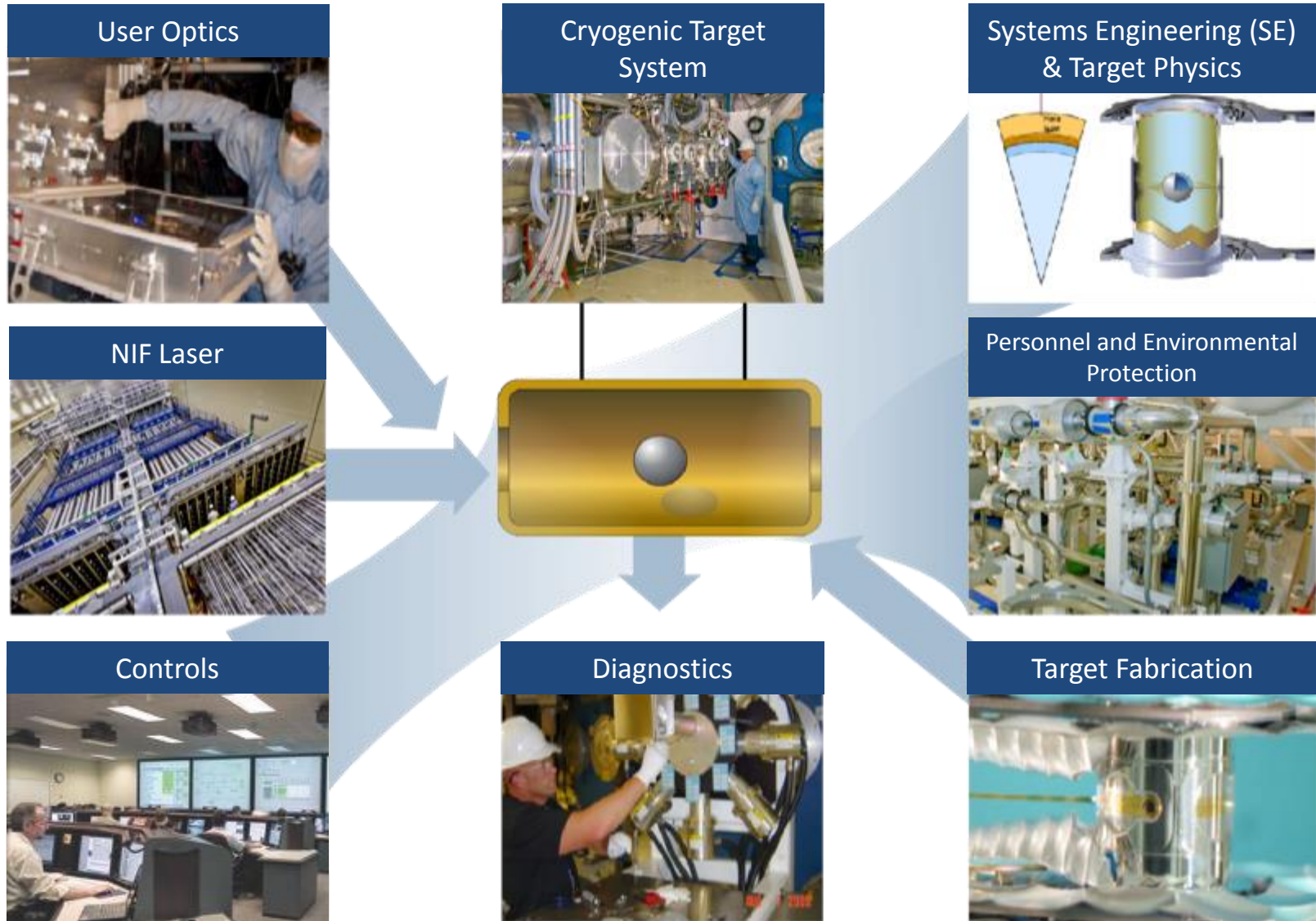


NIF concentrates 192 laser beams (~10 kJ each at 351 nm) into a few mm³ in a few nanoseconds

Matter temperature	$>10^8$ K
Radiation temperature	$>3.5 \times 10^6$ K
Densities	$>10^2$ g/cm ³
Pressures	$>10^{11}$ atm



The challenges of building, maintaining, and improving NIF require world leading innovation in a number of areas



HED scientists are exploiting these capabilities to push the scientific boundaries



nature
geoscience

LETTERS

PUBLISHED ONLINE: 2 MARCH 2015 | DOI: 10.1038/NNGEO2369

Impact vaporization of planetesimal cores in the late stages of planet formation

Richard G. Kraus^{1,2*}, Seth Root³, Raymond W. Lemke⁴, Sarah T. Stewart^{1,5}, Stein B. Jacobsen¹ and Thomas R. Mattsson⁶



ARTICLE

Received 6 May 2014 | Accepted 2 Jan 2015 | Published 4 Feb 2015

DOI: 10.1038/ncomms7190

A laboratory study of asymmetric magnetic reconnection in strongly driven plasmas

M.J. Rosenberg¹, C.K. Li¹, W. Fox², I. Igumenshchev³, F.H. Séguin¹, R.P.J. Town⁴, J.A. Frenje¹, C. Stoeckl³, V. Glebov³ & R.D. Petrasso¹

LETTER

doi:10.1038/nature14048

A higher-than-predicted measurement of iron opacity at solar interior temperatures

J. E. Bailey¹, T. Nagayama¹, G. P. Loisel¹, G. A. Rochau¹, C. Blancard², J. Colgan³, Ph. Cosse², G. Faussurier², C. J. Fontes³, F. Gillieron², I. Golovkin⁴, S. B. Hansen¹, C. A. Iglesias⁵, D. P. Kilcrease², J. J. MacFarlane⁴, R. C. Mancini², S. N. Nahar², C. Orban², J.-C. Pain², A. K. Pradhan⁷, M. Sherrill¹ & B. G. Wilson²

nature
physics

LETTERS

PUBLISHED ONLINE: 19 JANUARY 2015 | DOI: 10.1038/NPHYS3178

Observation of magnetic field generation via the Weibel instability in interpenetrating plasma flows

C. M. Huntington^{1*}, F. Fiuza¹, J. S. Ross¹, A. B. Zystra², R. P. Drake³, D. H. Froula⁴, G. Gregori⁵, N. L. Kugland⁶, C. C. Kuranz³, M. C. Levy¹, C. K. Li², J. Meinecke⁵, T. Morita⁷, R. Petrasso², C. Plechaty¹, B. A. Remington¹, D. D. Ryutov¹, Y. Sakawa⁷, A. Spitkovsky⁸, H. Takabe⁷ and H.-S. Park¹



Direct observation of an abrupt insulator-to-metal transition in dense liquid deuterium

M. D. Knudson *et al.*

Science **348**, 1455 (2015);

DOI: 10.1126/science.aaa7471

ARTICLES

PUBLISHED ONLINE: 23 MARCH 2015 | DOI: 10.1038/NPHOTON201541

nature
photonics

Ultrabright X-ray laser scattering for dynamic warm dense matter physics

L. B. Fletcher^{1,2*}, H. J. Lee¹, T. Döppner³, E. Galtier¹, B. Nagler¹, P. Heimann¹, C. Fortmann⁴, S. LePape³, T. Ma³, M. Millot^{2,3}, A. Pak³, D. Turnbull¹, D. A. Chapman^{5,6}, D. O. Gericke⁶, J. Vorberger⁷, T. White⁸, G. Gregori⁹, M. Wei⁹, B. Barbel², R. W. Falcone², C.-C. Kao¹, H. Nuhn¹, J. Welch¹, U. Zastrau^{1,10}, P. Neumayer¹, J. B. Hastings¹ and S. H. Glenzer^{1*}

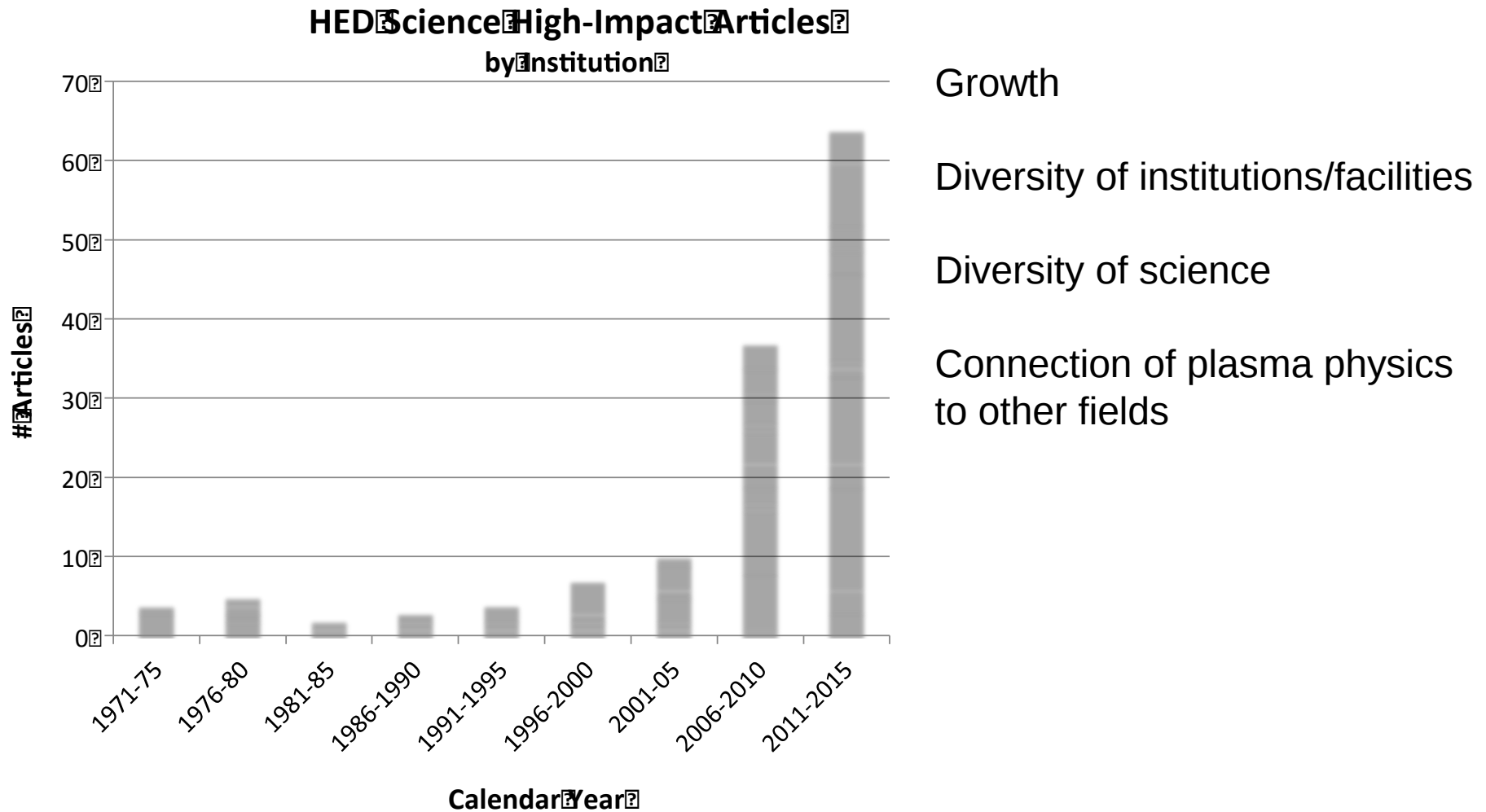


Lawrence Livermore National Laboratory

P1959268.ppt – M. Herrmann – MAC – November 05, 2015

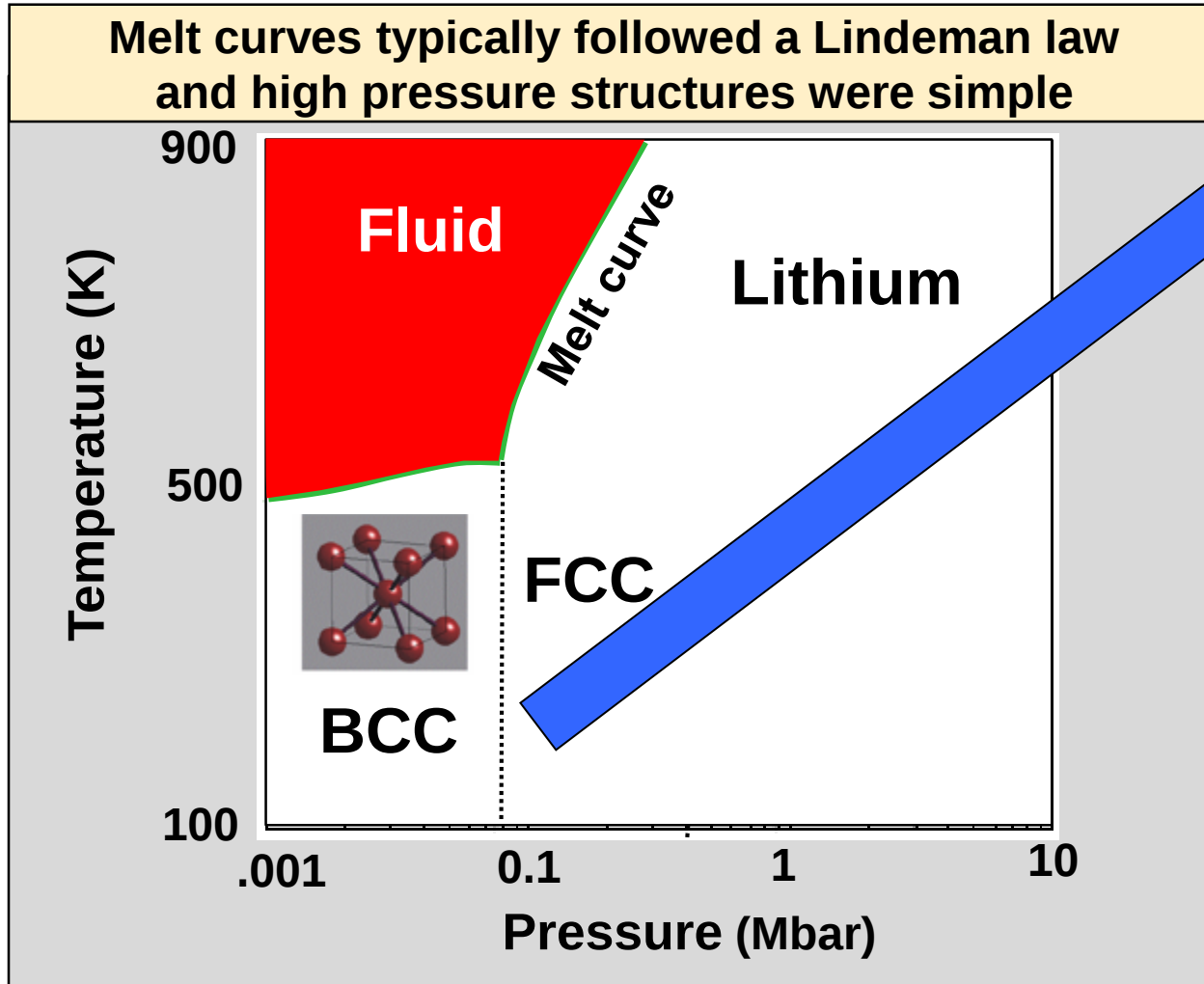


The HED Science community is delivering on the promise that was identified in the 2000's



Impact factor > 10, e.g. Nature, Science, etc., does not include PRL's
(Courtesy of Rulon Lindford)

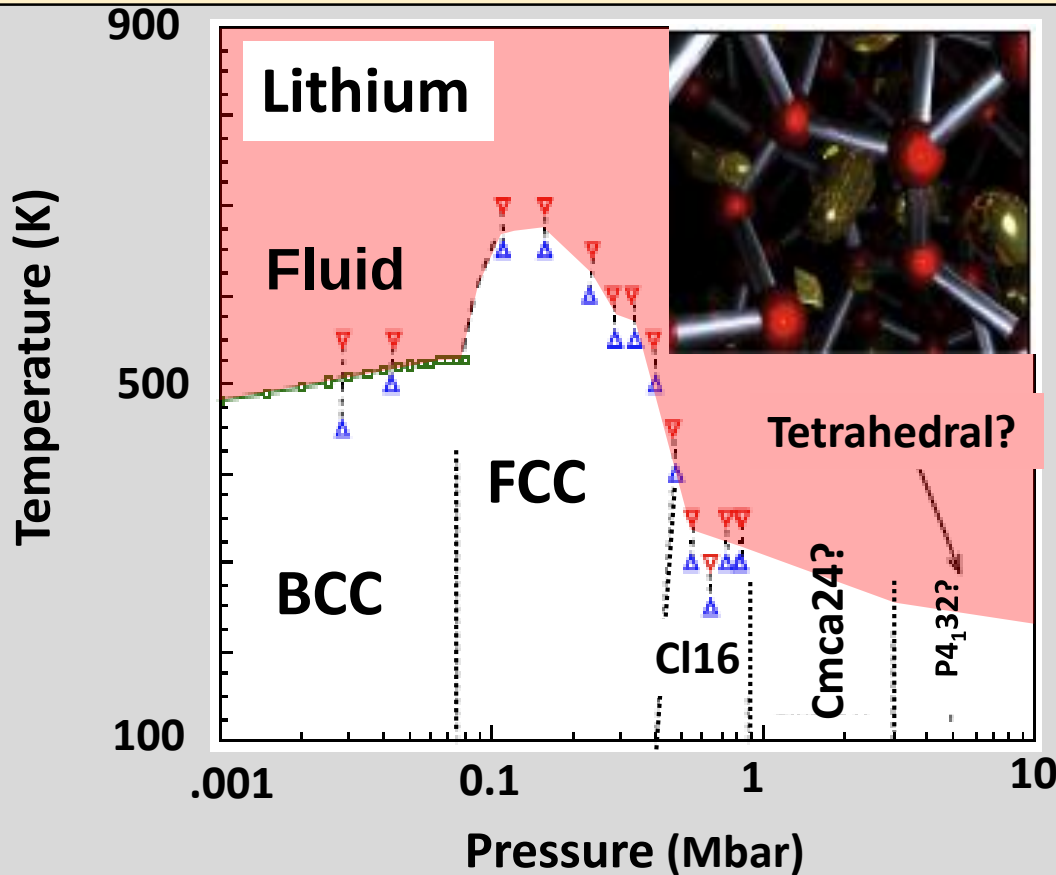
Just a few years ago, ultra-high pressure phase diagrams for materials were very simple



**Physics
Gets
Simple!**

As we study this regime in more detail, complexity emerges

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

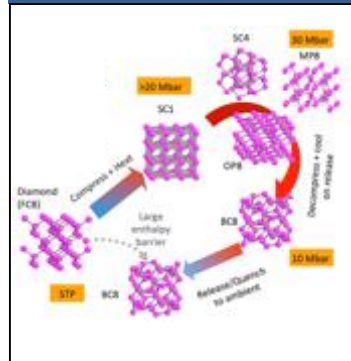


- Many materials exhibit this complexity
- Extends beyond phase to affect all basic properties

Neaton and Ashcroft, Marqués, Hanfland et al, Syassen, K, Gregoryanz, E., J. Raty et al)

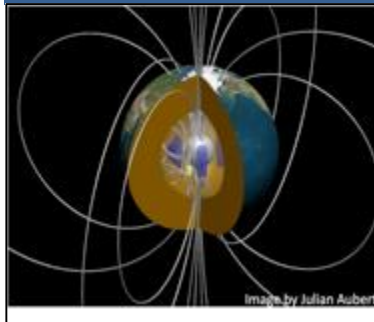
NIF's allocates a small fraction of its time to "Discovery Science". Most recent call for proposals was ~5x oversubscribed.

Metastability of dynamically compressed C



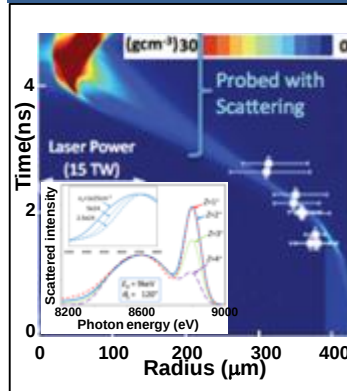
Wark (Oxford)

Iron melt curve, magnetospheres, and habitable Super Earths



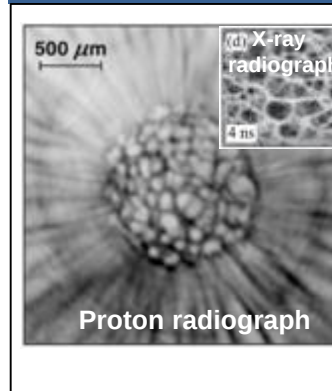
Hemley (CIW), Stewart (UCD)

Pressure ionization at extreme densities



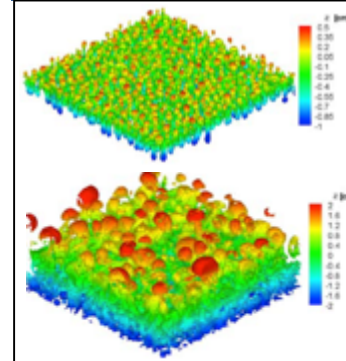
Neumayer(GSI), Falcone(UCB)

Direct-drive hydrodynamics



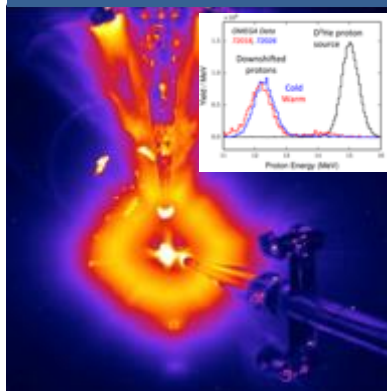
Casner(CEA),

Asymptotic self-similar instabilities



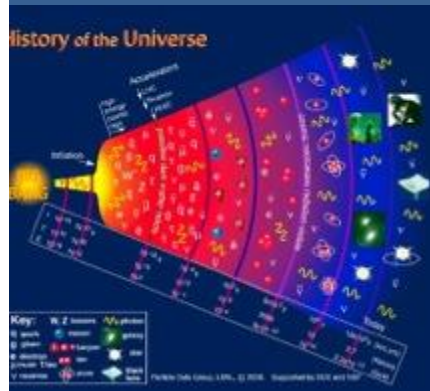
Shvarts(Israel), Drake(Mich)

Charged particle stopping powers



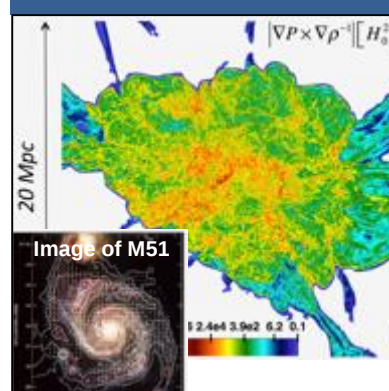
Zylstra (LANL), C.K.Li (MIT)

Stellar and Big Bang nucleosynthesis



Gatu-Johnson (MIT)

Turbulent dynamo B field amplification



Gregori (Oxford), Lamb (Chicago)

Collisionless astrophysical shocks



Sakawa(Osaka), Spitkovsky(Princeton)

The Discovery Science program is generating high impact scientific results

Selected 2018 Publications

Science
AAAS

HIGH-PRESSURE PHYSICS

Insulator-metal transition in dense fluid deuterium

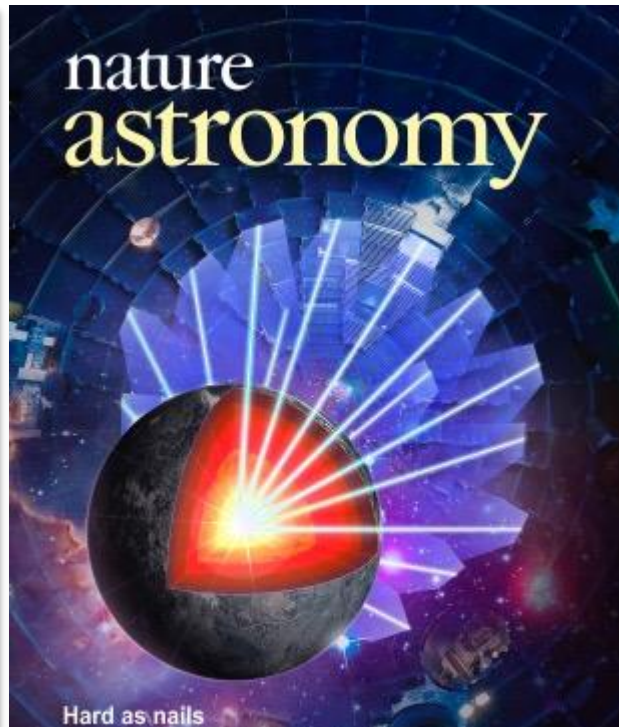
Peter M. Celliers¹, Marius Millot¹, Stephanie Brygoo², R. Stewart McWilliams³, Dayne E. Fratanduono¹, J. Ryan Ryga^{1,4}, Alexander F. Goncharov¹, Paul Loubeyre⁵, Jon H. Eggert¹, J. Luc Peterson¹, Nathan B. Meezan¹, Sebastien Le Pape¹, Gilbert W. Collins^{1,4}, Raymond Jeanloz⁶, Russell J. Hemley⁷

The New York Times Science

CLIMATE | SPACE & COSMOS | HEALTH | TECHNOLOGY | SCIENTIFIC | OUT THERE



Settling Arguments About Hydrogen With 168 Giant Lasers



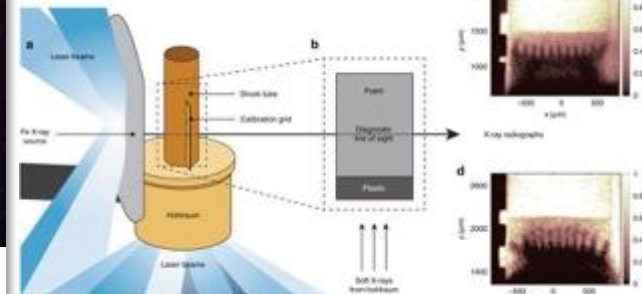
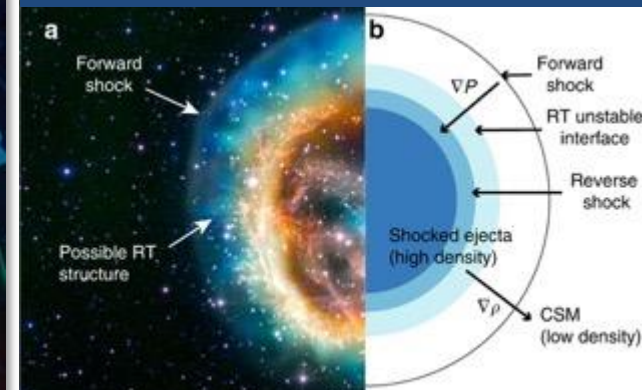
Equation of state of iron under core conditions of large rocky exoplanets

Raymond F. Smith¹, Dayne E. Fratanduono², David G. Braun³, Thomas S. Duffy⁴, June K. Wicks⁵, Peter M. Celliers¹, Suzanne J. Ali¹, Amalia Fernandez-Pafella¹, Richard G. Kraus¹, Damian C. Swift¹, Gilbert W. Collins¹ & Jon H. Eggert¹

Nature Astronomy 2, 452–458 (2018)
doi:10.1038/s41550-018-0437-9
Download Citation

Received: 02 November 2017
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Published: 15 April 2018

Nature Communications



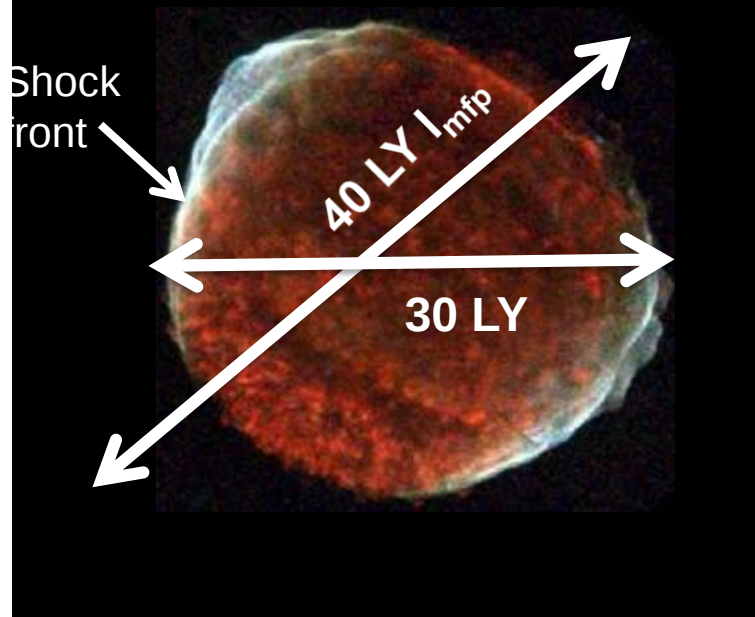
How high energy fluxes may affect Rayleigh-Taylor instability growth in young supernova remnants

C.C. Kuram¹, H.-S. Park², C.M. Huntington², A.R. Miles², B.A. Remington², T. Plewa³, M.R. Tranter¹, H.F. Robey², D. Shvarts^{4,5}, A. Shimony^{4,5}, K. Ramani², S. MacLaren², W.C. Wan^{1,4}, F.W. Doss¹, J. Kline⁶, K.A. Filippo⁶, G. Malamud^{1,5}, T.A. Handy⁷, S. Prishvety², C.M. Kraus², S.R. Klein², E.C. Harding⁸, R. Wallace², M. J. Grosskopf⁹, D.C. Marion¹, D. Kalantar², E. Giraldez² & R.P. Drake¹

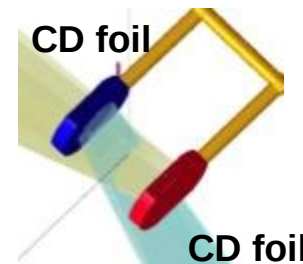
The collisionless shock collaboration on NIF shows how large, diverse collaborations can arise to work on these fascinating problems

Collisionless shocks are ubiquitous in universe; Weibel instabilities can generate magnetic fields to form these shocks

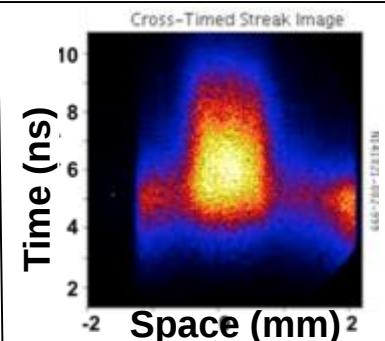
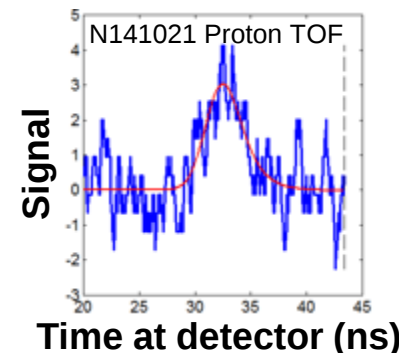
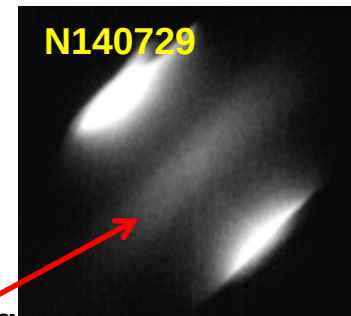
Nonrelativistic shocks (e.g. SNRs)



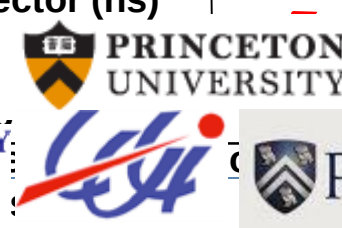
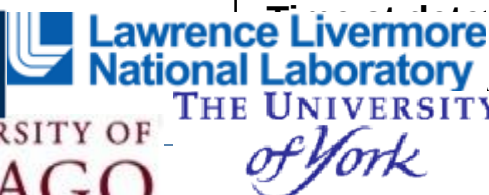
Experiments with CD-CD targets observed x-rays, neutrons and protons from the central shock-forming region



X-ray brightening from self-emission of hot plasmas



[Courtesy of Hye-Sook Park (2015);
C.M. Huntington, Nat. Phys. (2015)
S. Ross, Phys. Rev. Lett. (2017).]



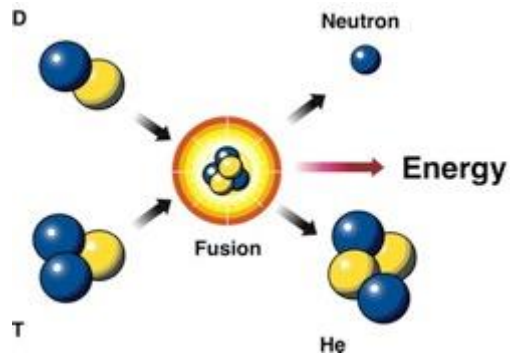
x-ray streak

Providing a small percentage of NIF, Z, and Omega time to the academic community provides significant benefits to the nation

- Engages world-leading scientists with Lab scientists
- Innovation
 - Many new ideas that benefit SSP have come from outsiders
 - Ensures we are aware of what is possible to avoid technological surprise
- Academic pipeline
 - Helps create cadre of academic scientists who do research in HEDP, essential for pipeline
 - Students of world leading scientists recruited to Lab
 - High profile science attracts staff to Lab
- Staff engagement
 - Enables LLNL staff to continue to publish and develop in their field, a major component of retaining world-class scientists in the SSP
 - Enables LLNL staff to engage with outside scientists and students
- High profile publications
 - Provides peer review of techniques and methods that are also applied to SSP
 - Attracts high quality scientists to the Lab
 - Provide a visible manifestation of the
 - credibility of our deterrent
 - (not possible with classified work)
- A broader constituency of users for the NIF
- A richer national scientific enterprise



Like many areas of science, we not only want to understand nature, we want to control it



For ignition conditions:

$$\left\{ \begin{array}{l} r R \gg 0.4 \text{ g/cm}^2 \\ T \gg 5 \text{ keV} \end{array} \right\}$$

$$E_{HS} \propto m_{HS} T_{HS} \propto r_{HS} R_{HS}^3 T_{HS} \propto \frac{(r_{HS} R_{HS})^3 T_{HS}^3}{P_{HS}^2}$$

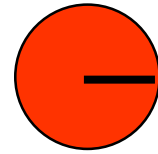
$$E_{\text{NIF}} \sim 15 \text{ kJ} \quad P \sim 400 \text{ GBar} \quad R \sim 30 \text{ mm} \quad \text{and} \quad r \sim 130 \text{ g/cm}^3$$

$$t_{\text{conf}} \sim \frac{R}{c_s} \sim 30 \text{ ps}$$

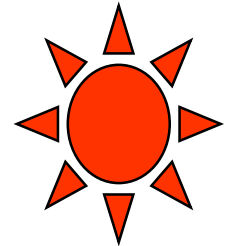
High velocity implosions can achieve these conditions

Note for magnetic confinement fusion ignition

$$\tau_{\text{conf}} \sim \text{few seconds} \quad P \sim \text{few Bars} \quad r \sim \text{few } 10^{-10} \text{ g/cm}^3$$

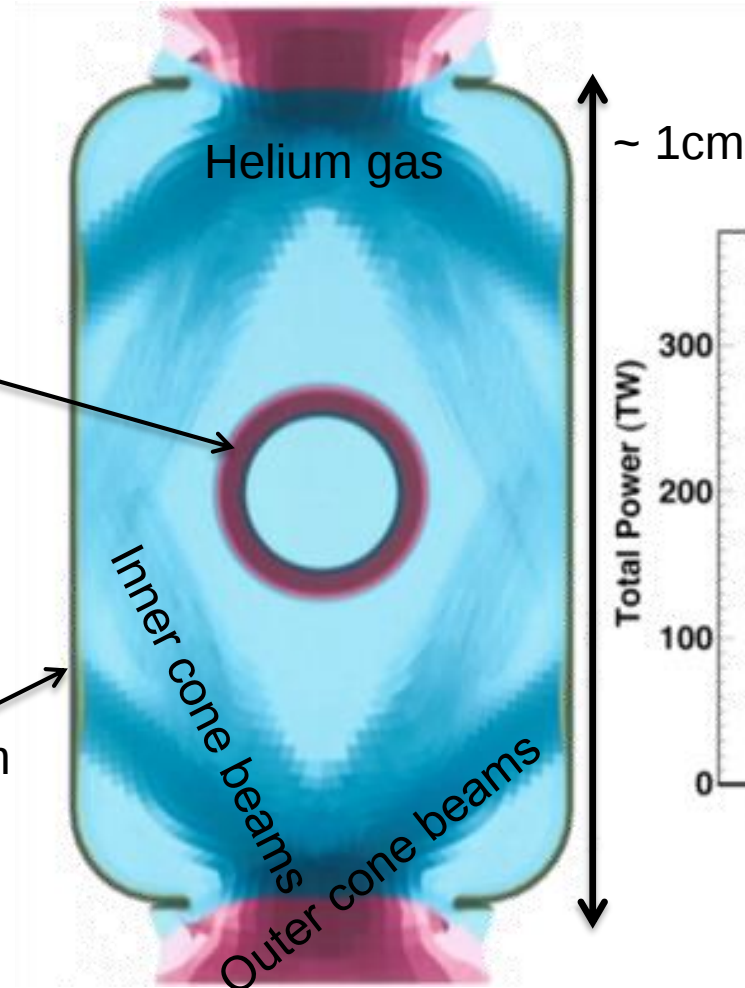


ρ, R, T

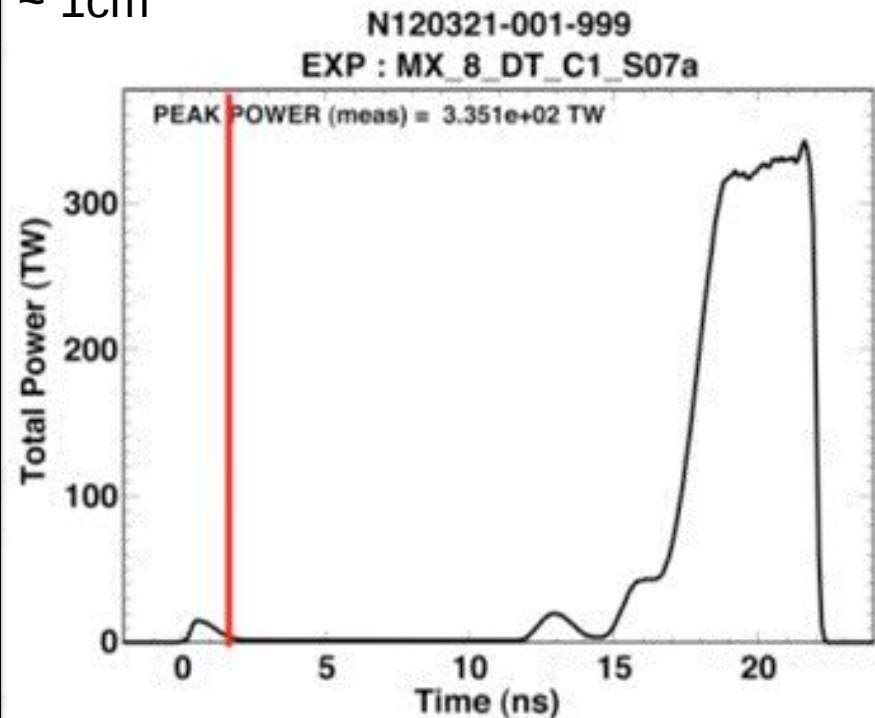


The primary ICF approach on NIF uses the lasers to indirectly drive the capsule implosion (Laser Power $\rightarrow$ X-ray Power)

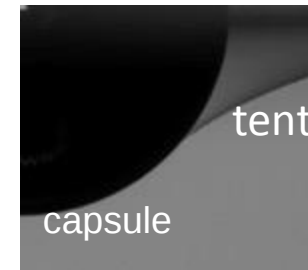
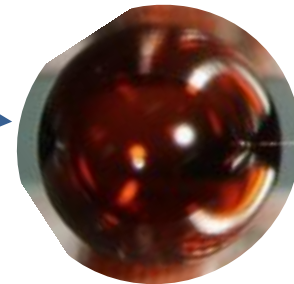
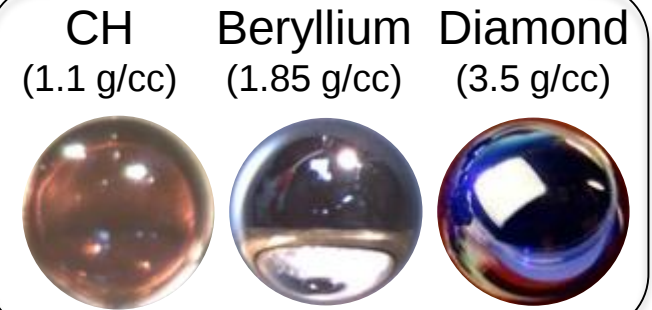
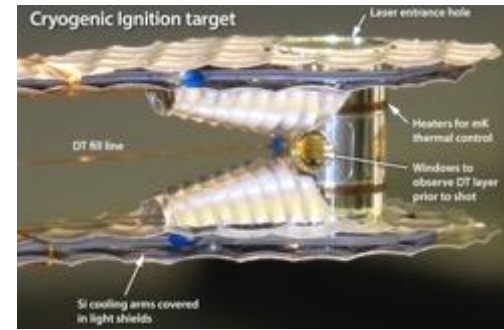
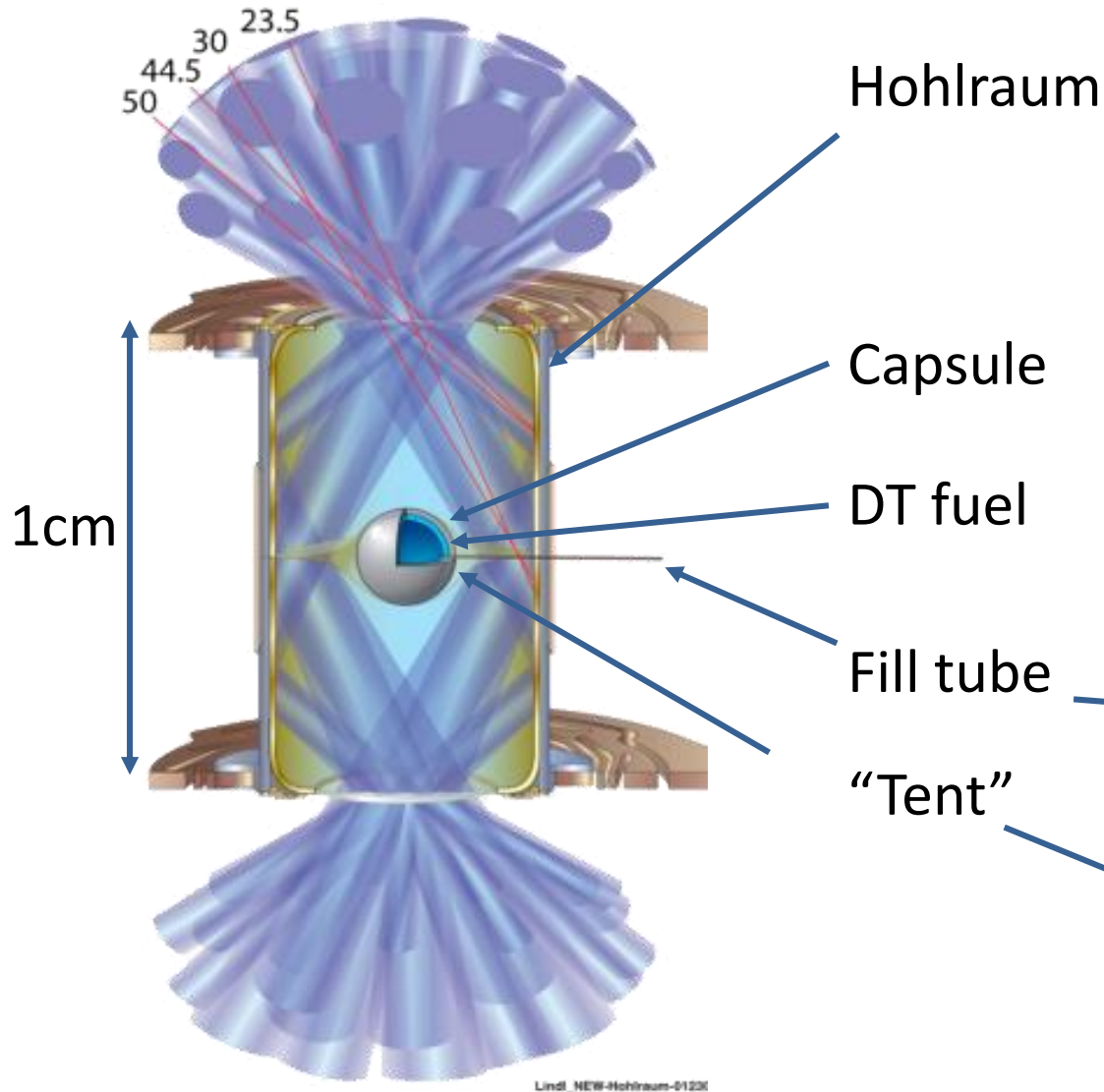
Laser entrance hole (LEH)



Laser "Pulse-shape"

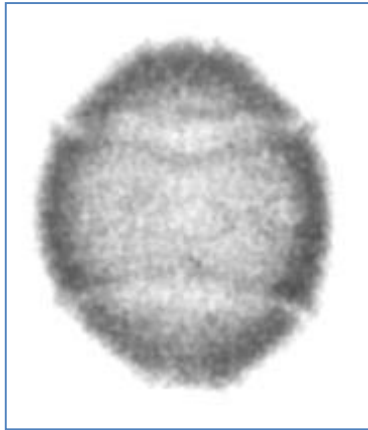


We are navigating the large parameter space available for ignition



We are making progress in controlling inertial confinement fusion implosions

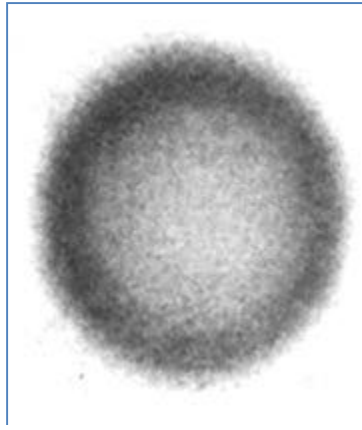
2012/13



Better
hydro



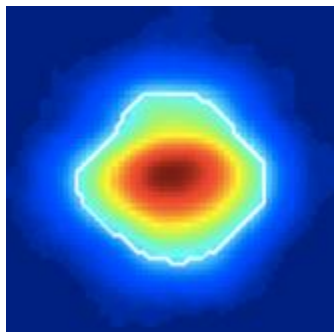
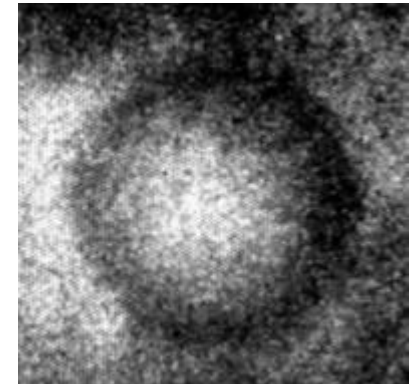
2014/15



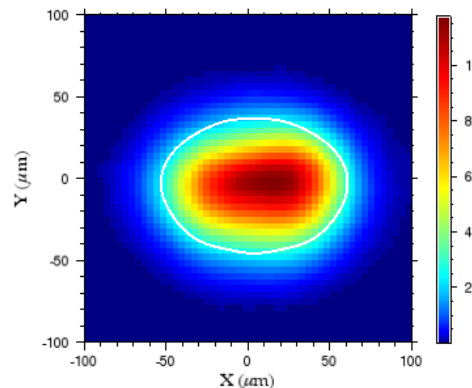
Better LPI,
symmetry
Reduce fill
tube



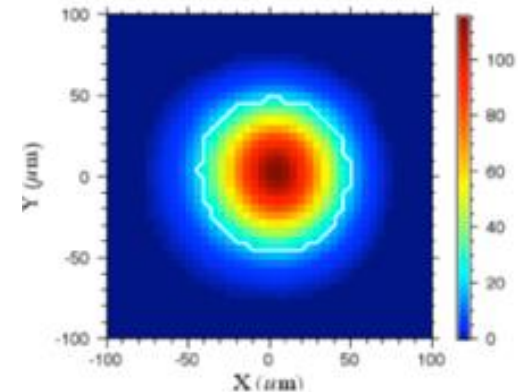
2017/18



Yield ~ 2 kJ
Pressure ~ 150 GB
(7e14 DT neutrons)



Yield ~ 27 kJ
Pressure ~ 250 GB
(9 e15 DT neutrons)



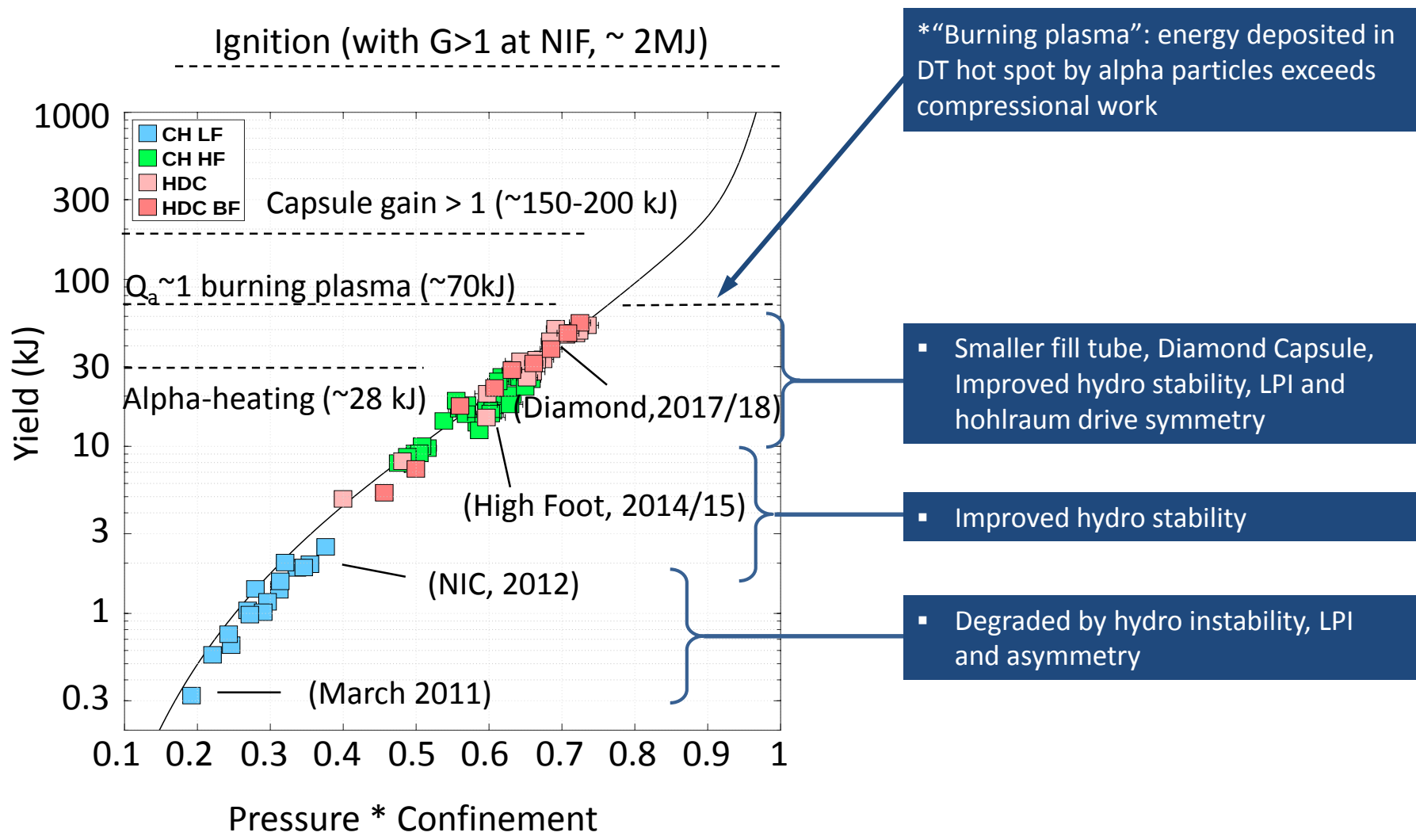
Yield ~ 55 kJ
Pressure ~ 350 GB
(2 e16 DT neutrons)

Post the National Ignition Campaign NNSA began an effort to develop transformative diagnostic capabilities, which is enabling new measurements

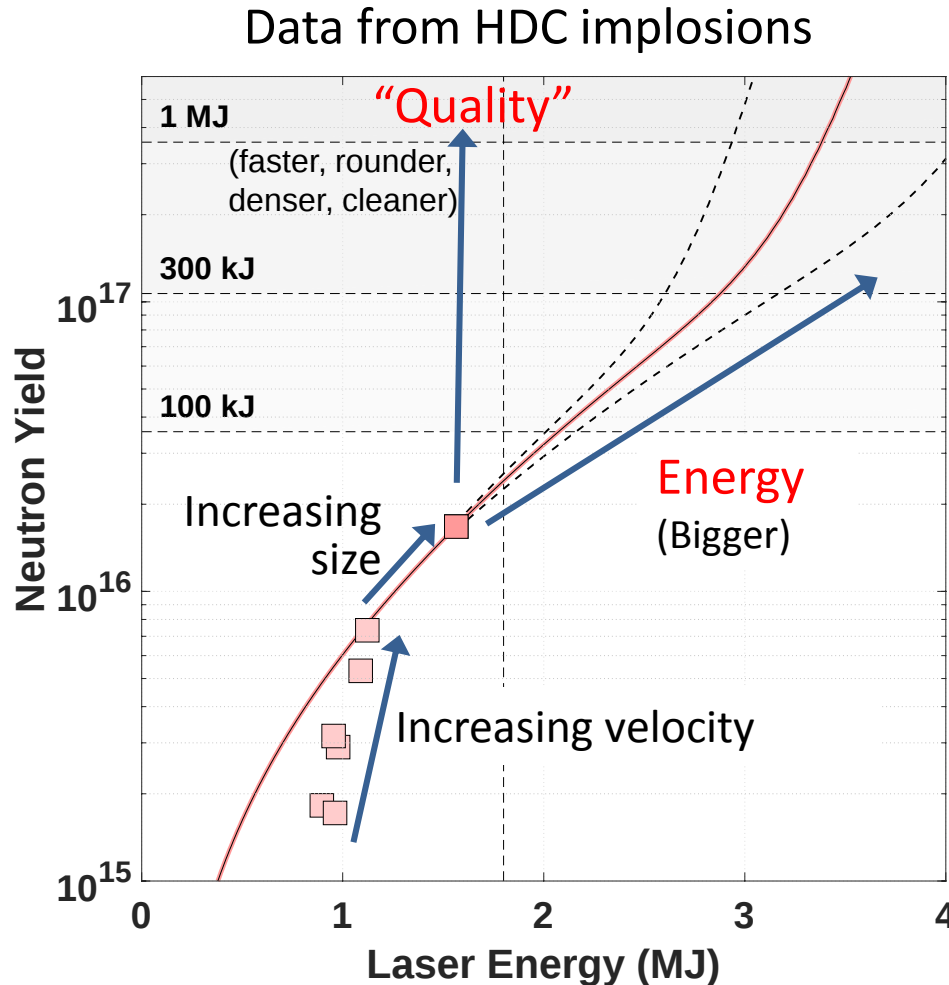
Transformative diagnostic	Institutions	New capability-program
Single LOS imaging (h-CMOS, dilation)	SNL,GA, LLNL,LLE, AWE	Many measurements on one shot for all missions. Short gating capability for implosions measure shape change during the stagnation process.
Optical Thomson Scattering (OTS)	LLE, LLNL, LANL, NRL	Hohlraum ne, Te, Ti, Z-All: Radiation channel flow: discovery science
3D n/gamma imaging (NIS)	LANL, LLNL	3D shape of burn
Gamma spectroscopy (GCD)	LANL, AWE, GA,LLNL	Burn duration, mix
Time resolved n spectrum (MRS-t)	MIT LLNL, GA, LLE	Alpha heating diagnostic - burn
Hi Res. X-ray spect. (HiRes)	LLNL,LLE,PPPL, NSTec, SNL	T warm compressed hi Z-strength: density of burning plasmas
Hard x-ray imaging (Wolter)	SNL, LLNL	Higher areal density backlighting for strength, complex hydro. Time & space resolved T of burning plasmas.
Time resolved diffraction TARDIS-t	SNL, LLNL	Material phase change versus time for strength & discovery science

NIF's goal is to achieve fusion energy out = laser energy in

We are making steady progress



Path forward is to work on improving implosions while also exploring scaling to higher energy



- Scientific understanding aided by new measurements leading to quality improvements:

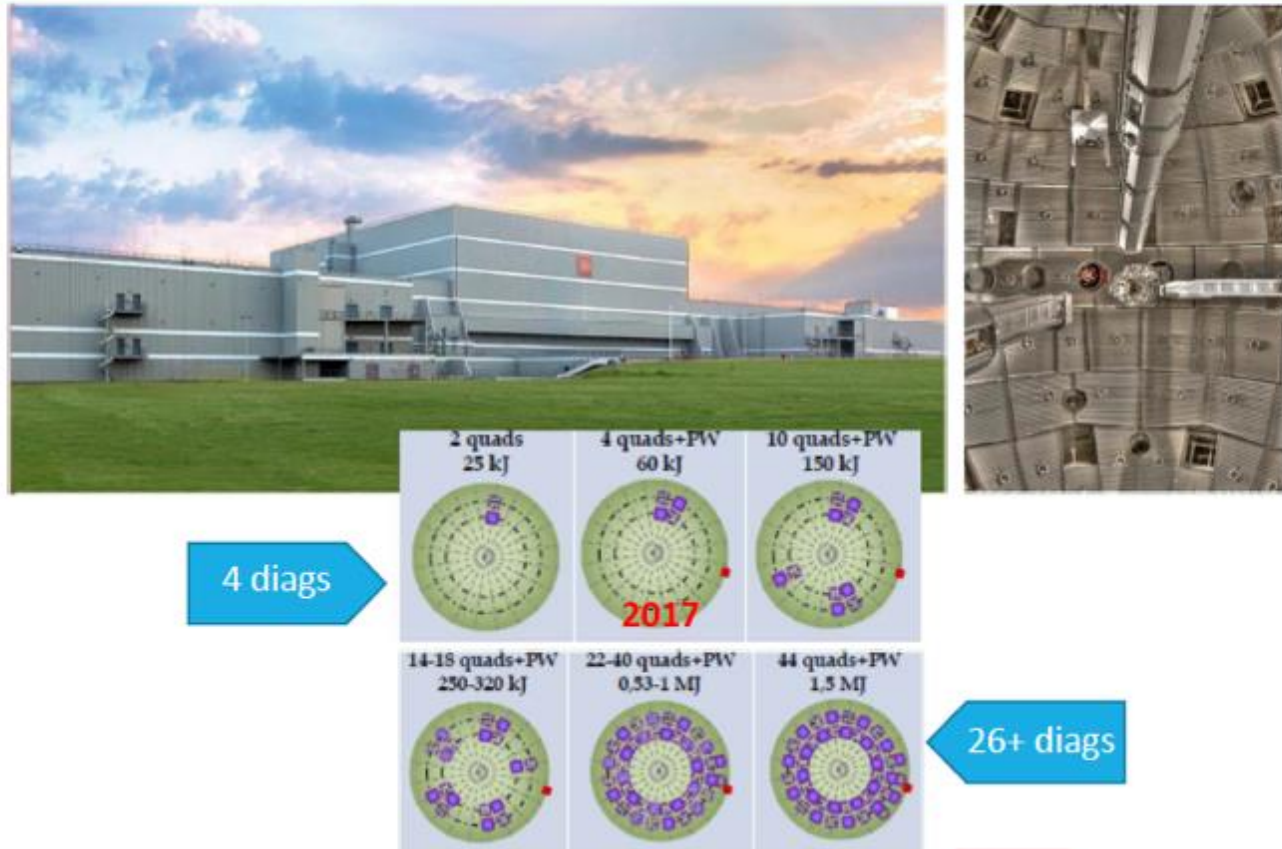
- Improved understanding of hohlraums and time dependent symmetry
- Optimization of design (Higher coupling efficiency)
- Improved understanding of implosion dynamics, instability growth, and degradations
- Reduced engineering features (fill tubes, tent)
- Improved capsule fabrication
- Higher laser power and energy
- Innovative and alternate designs (e.g. magnetized targets, double shells, ...)

The next decade will be a pivotal time for inertial confinement fusion and inertial fusion energy research

- NIF, Z, and Omega will continue to deliver high energy density (HED) data needed for the Stockpile Stewardship program while advancing our fundamental understanding of HED science
- The achievement of inertial confinement fusion ignition in the Laboratory and eventually high yield will continue to be a significant goal of the Stockpile Stewardship Program
 - Steady progress is being made on understanding and improving inertial confinement fusion target performance on NIF (as well as Z and Omega)
 - New diagnostics and simulations are providing critical insights that will lead to further progress and may motivate facility upgrades
 - New HED investments by the nation will be needed. By the end of the 2020's we will have achieved ignition or have an ignition facility under construction
- Worldwide effort in ICF and HED will grow significantly over this time frame
- Continued advances in important related technologies will make leveraging these technologies for IFE research an attractive path

Laser Megajoule, in France, has performed its first experiments and will be ramping up the number of beams over the next few years

LMJ ramps up power gradually, allowing a robust roadmap towards ignition

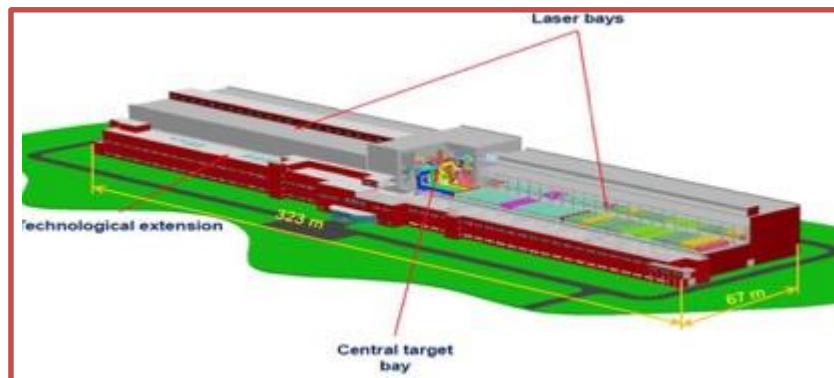


- Plan has 40 beams coming on line in 2019 eventually 176

Both Russia and China are investing significantly in the area of lasers for high energy density physics

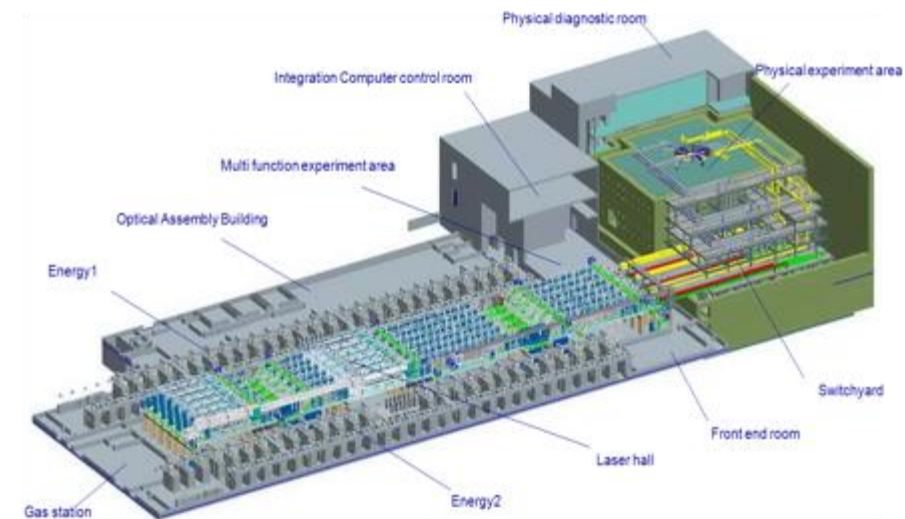
UFL-2M

- 192 beams, 2.8 MJ (1.5x NIF energy)
- Construction underway



Shenguang III (180 kJ) is now operating

- 48 beams arranged in polar configuration
- 80 diagnostics
- World's second most energetic laser
- Discussion of bigger facility taking place



The recently passed Department of Energy Research and Innovation act calls for research into IFE

NAS 2013 Study “An Assessment of the Prospects for Inertial Fusion Energy”* had a number of conclusions and recommendations including:

- “The appropriate time for the establishment of a national, coordinated, broad-based inertial fusion energy program within DOE would be when ignition is achieved”.
- Nevertheless the committee also concluded: “The potential benefits of energy from inertial confinement fusion ... also provide a compelling rationale for including inertial fusion energy R&D as part of the long-term R&D portfolio for U.S. energy.”

A modest IFE program in the US would leverage significant investments:

- World leading capabilities in ICF research (including NIF, Omega, and Z) funded by NNSA
- Advances in rep-rated lasers and pulsed power drivers, advanced manufacturing, new materials, machine learning, ...

The Department of Energy Research and Innovation Act (H.R. 589):

INERTIAL FUSION ENERGY RESEARCH AND DEVELOPMENT.—The Director shall support research and development activities for inertial fusion for energy applications.

**An Assessment of the Prospects for Inertial Fusion Energy*, Committee on the Prospects for Inertial Confinement Fusion Energy Systems, NRC (National Academies Press, Washington, D.C., 2013).

Intermediate scale facilities play a critical role in the health of High Energy Density Science. LLNL operates the Jupiter Laser Facility as a flexible, hands on user facility for training, innovation, and exploration

Laser Bay

Two 1-kJ ns beams
(presently 0.7kJ)

or

One 300-J ps beam +
One 1-kJ ns beam

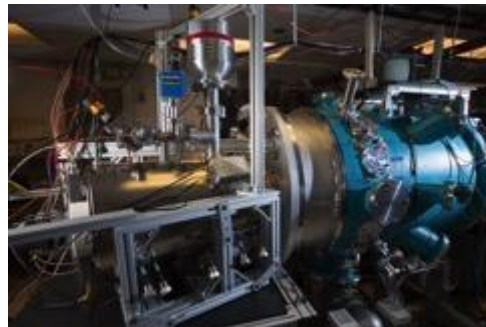


Janus



Titan

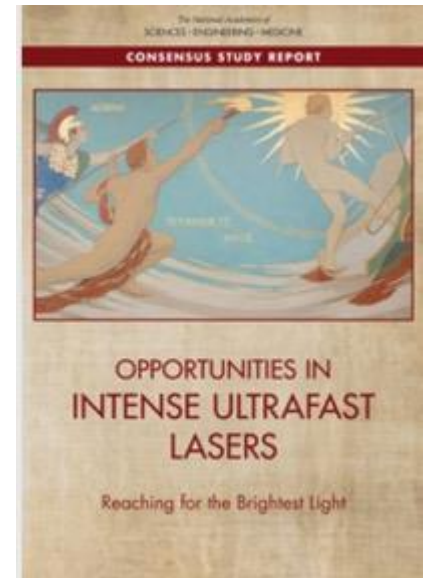
One or two beams
0.5 ps – 2 ns
Up to 7 J



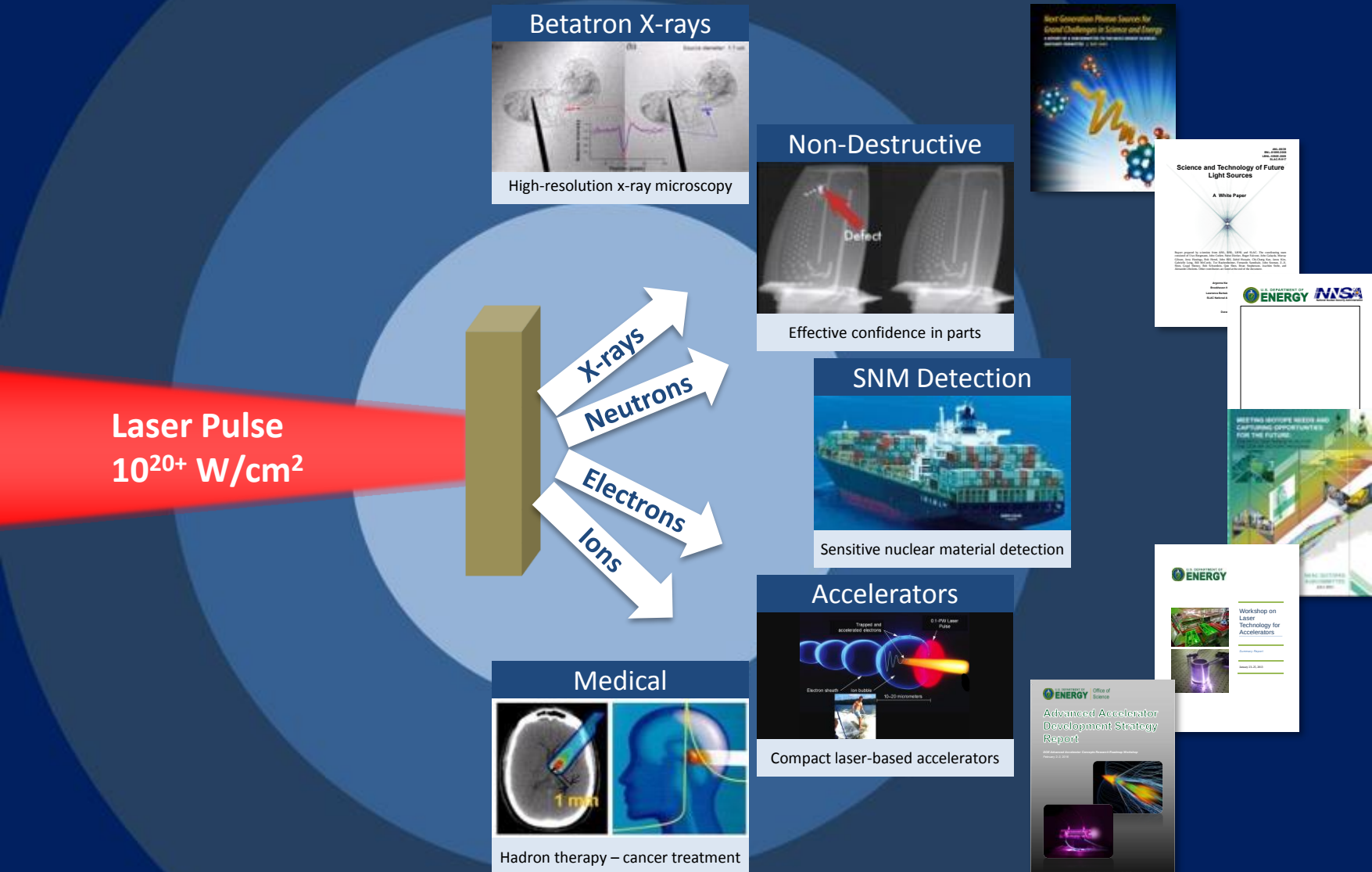
COMET

National Academy of Sciences: “U.S. Has Lost Its Dominance in Highly Intense, Ultrafast Laser Technology to Europe and Asia”

- 2017 National Academy of Sciences report “Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light”
 - surveyed and took a snapshot of high-intensity science research and related technology, the impact of applications, and the status of US technical capabilities
 - considered whether a national strategy exists for stewarding high-intensity laser science and technology
 - reported conclusions and recommendations constituting a roadmap for action
- NAS report conclusions:
 1. High-intensity lasers enable a large and important body of science.
 2. Intense ultrafast lasers have broad applicability.
 3. A large and talented US technical community exists, but it is fragmented.
 4. No cross-agency stewardship exists in the United States
 5. The US originally led innovation and applications, but Europe and Asia now dominate through coordinated research and infrastructure programs.
 6. Co-location with existing infrastructure is essential and a key advantage over the ELI concept in Europe
 7. Academia/Laboratory/Industry cooperation is necessary to retain and renew the talent base.



High-average Power, High-Intensity Lasers are poised to have far reaching impact on science, industry, and society



My two cents:

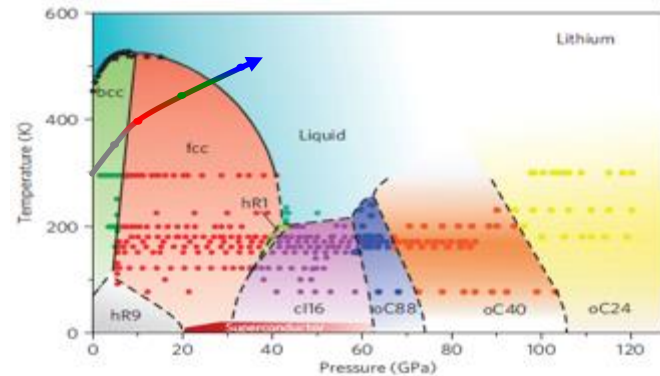
- Inclusive vision of plasma physics
- Utilization of NNSA facilities for plasma physics has tremendous payoffs for science and for national security
- A new Basic Research Needs Workshop for High Energy Density Laboratory Plasmas is needed
- While fusion is hard, pursuit of it is essential for our field and the nation
- Improving diagnostics are an essential part of making scientific progress
- The nation should have a modest inertial fusion energy program, to be cognizant of technology advances and their implications
- Intermediate scale facilities play an essential role in the ecosystem, and yet support for them is at risk
- US leadership in HEDP will shrink. We need deliberate investment to avoid falling far behind in some areas

Backup



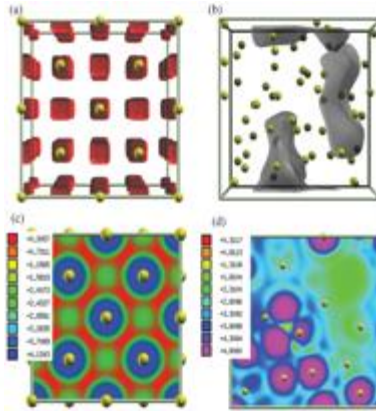
There are many exciting scientific directions for future HED research (Materials)

Phase Diagram of Li



Guillaume, et al. , Nature Physics, 2011

“Electrides”



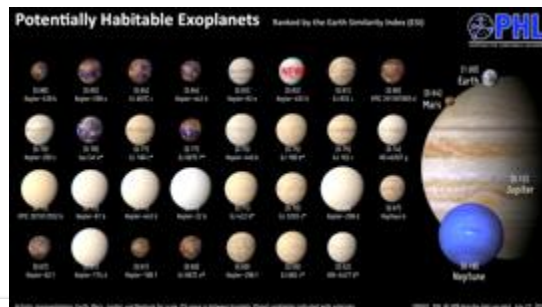
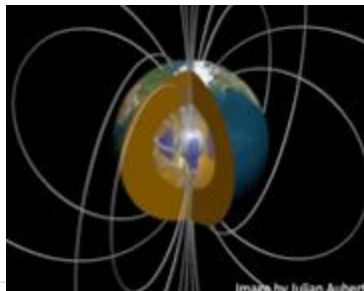
Dai, et al. PRL 109, 175701 (2012)

- Shedding light on materials behavior at high pressures, addressing fascinating complexity in quantum behavior of solids under compression. Could there be new metastable material forms that can be generated only under HED conditions?

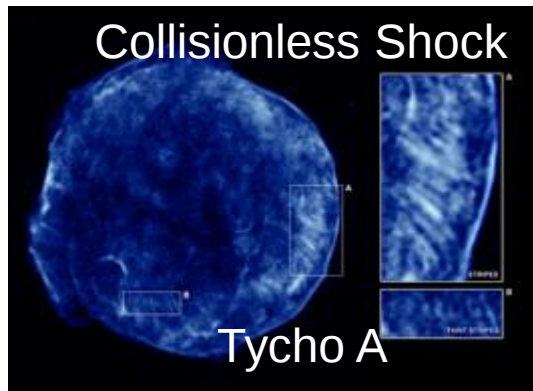


Juno Mission

- Helping (via measurements of material properties) address fundamental questions regarding planetary structure, supporting both solar system planetary missions and exo-planet research. Can we help provide constraints on which exoplanets may have magnetic fields, potentially enabling life?



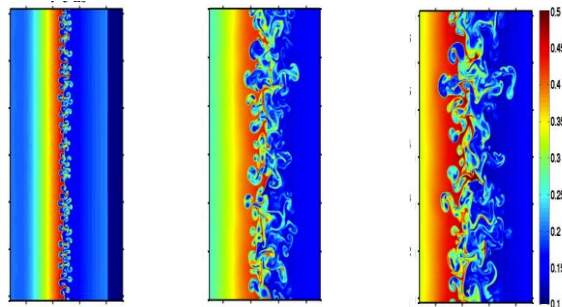
There are many exciting scientific directions for future HED research (Plasma Astrophysics and Radiation Hydrodynamics)



- Creating and diagnosing in the laboratory plasmas that can help explain ubiquitous processes in the universe, like collisionless shocks, particle acceleration/generation of cosmic rays, generation and amplification magnetic fields.



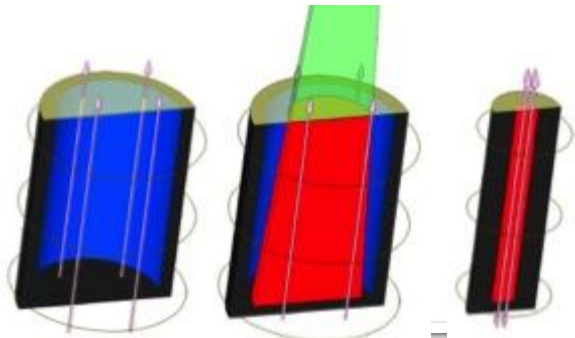
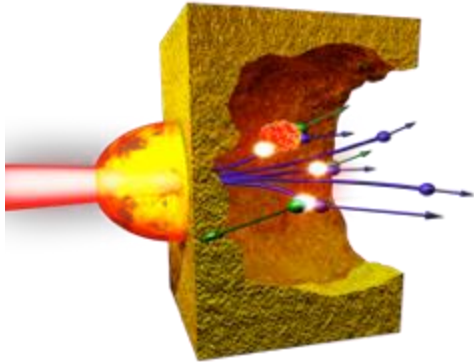
- Generating and explaining jets that are extraordinarily collimated and appear in many astrophysical situations



*2D
bubble
merger
simulations (G.
Malamud
2014)*

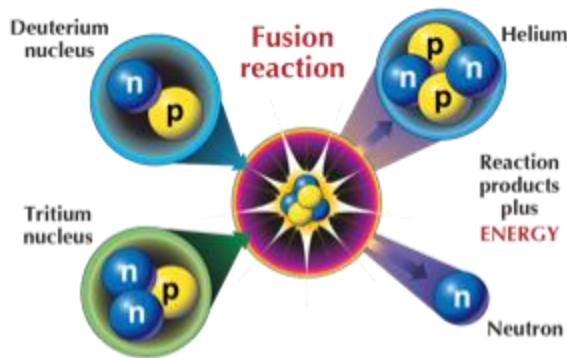
- Illuminating fundamental issues in the evolution of nonlinear HED flows and the transition to turbulence.

There are many exciting scientific directions for future HED research (High intensity laser matter interactions and magnetic fields)

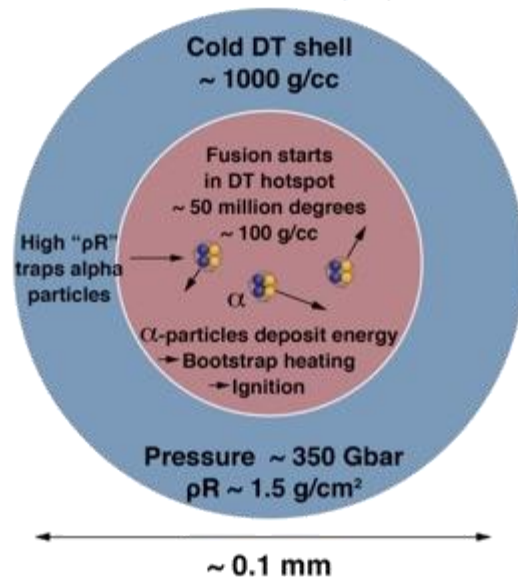


- Creating and understanding well behaved high intensity laser heated plasmas that have sufficient control for the application at hand and that enable applications beyond what is currently possible
- Exploring the limits of high intensity laser science, the unique sources that can be created, and generating new plasmas such as dense electron positron pair plasmas
- Studying the effect of magnetic fields on the plasma astrophysics and radiation hydrodynamics. Exploring the limits of what field can be produced in the laboratory.
- Assessing whether or not magnetic fields can significantly reduce the pressure needed for ignition

Ignition is a grand scientific challenge and a critical enabling capability for HED science



Deuterium-Tritium (DT) fuel



- Creating, controlling, and diagnosing matter at the energy densities needed for ignition in the laboratory is a daunting challenge.
- Our goal on NIF is to achieve ignition or understand the science well enough to answer the question of what capability would be needed to achieve it
- Achieving/Understanding what is required for ignition provides the most stringent constraints on our entire field. In doing so it pushes diagnostics, codes, drivers, optics, targets, capabilities and operations
- There is lots of room for innovation in the quest for ignition, including alternate approaches and new ideas!
- If achieved, ignition will open a whole new window into the HED science that can be performed in the laboratory, and may pave the way for even more extreme capabilities in the future