Discovery Science on the National Ignition Facility

Presented to the ICTP-IAEA College on Advanced Plasma Physics

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NIF

LLNL-PRES-648407

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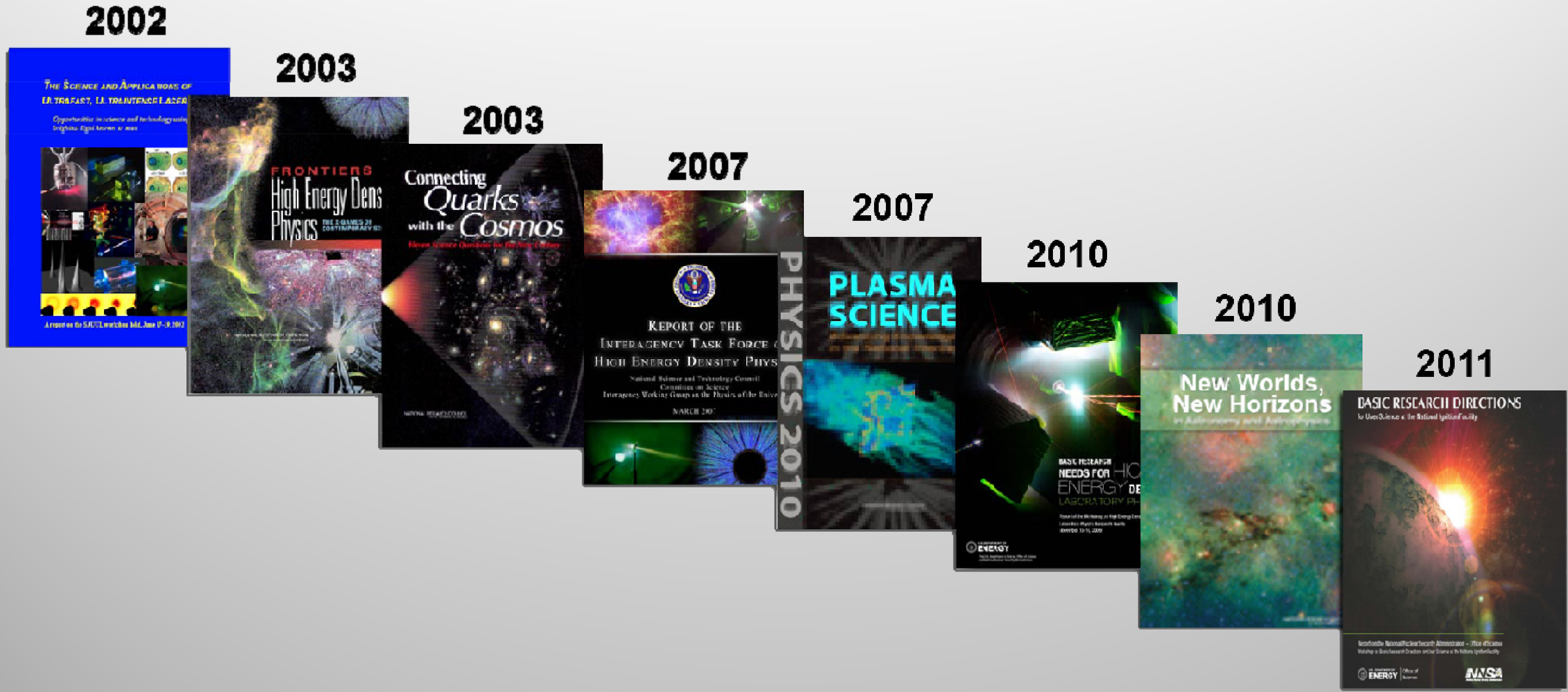
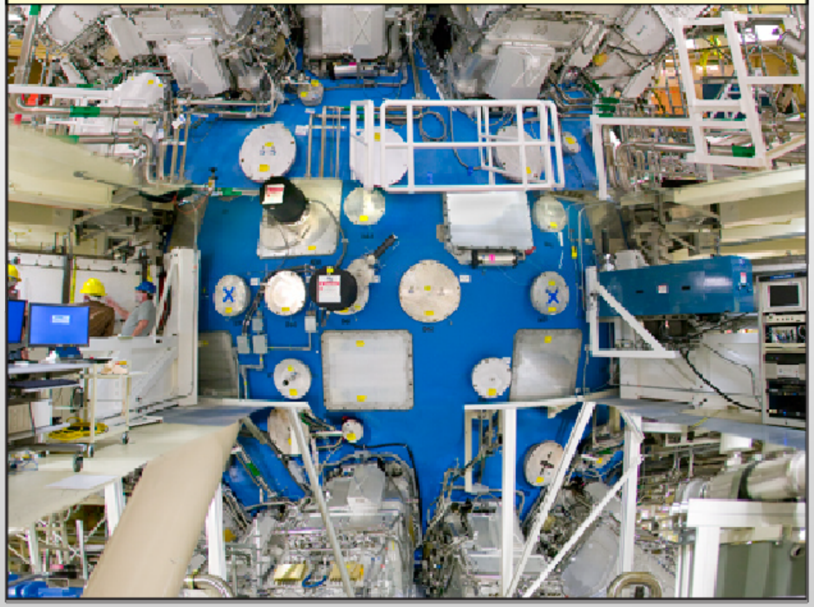
Scientific opportunities in HED science are well documented



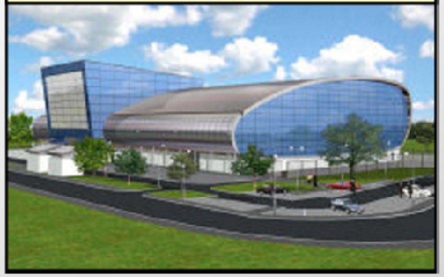
HED science is rapidly expanding worldwide

China - SG-III

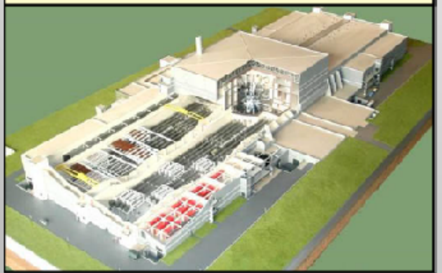
USA - NIF Laser



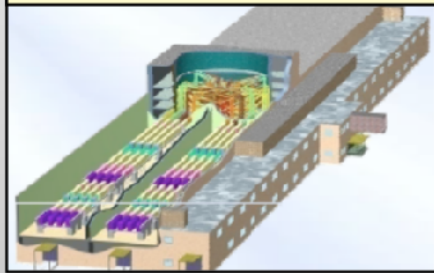
UK - ORION



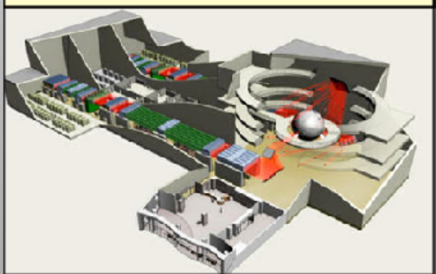
France - LMJ



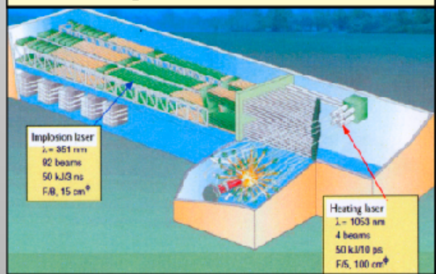
Russia - UFL-2M



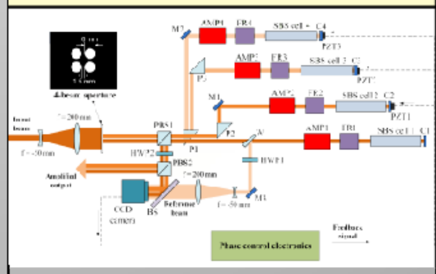
EU - HiPER



Japan - FIREX



Korea

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NIF missions

Ensuring National Security

Advancing Frontier Science

Enabling Clean Energy

Building Future Generations of HED Scientists

Fundamental science on NIF was addressed most recently in a 2011 NNSA/Office of Science report

Summary of Workshop Priority Research Directions

Panels	Priority Research Directions
1. Laboratory Astrophysics	1.1 Simulating Astrochemistry: The Origins and Evolution of Interstellar Dust and Prebiotic Molecules
	1.2 Explanation for the Ubiquity and Properties of Cosmic Magnetic Fields and the Origin of Cosmic Rays
	1.3 Radiative Hydrodynamics of Stellar Birth and Explosive Stellar Death
	1.4 Atomic Physics of Ionized Plasmas
2. Nuclear Physics	2.1 Stellar and Big Bang Nucleosynthesis in Plasma Environments
	2.2 Formation of the Heavy Elements and Role of Reactions on Excited Nuclear States
	2.3 Atomic Physics of Ionized Plasmas
3. Materials at Extremes and Planetary Physics	3.1 Quantum Matter to Star Matter
	3.2 Elements at Atomic Pressures
	3.3 Kilovolt Chemistry
	3.4 Pathways to Extreme States
	3.5 Exploring Planets at NIF
4. Beams and Plasma Physics	4.1 Formation of and Particle Acceleration in Collisionless Shocks
	4.2 Active Control of the Flow of Radiation and Particles in HEDP
	4.3 Ultraintense Beam Generation and Transport in HED Plasma
	4.4 Complex Plasma States in Extreme Laser Fields

The same NIF capabilities that are being used in the quest for ignition can also be used for basic science

- Densities of ~ 10^3 g/cm3
- Neutron densities as high as 10^{26}
- Relatively large areas at pressures greater than 10^{11} atm
- Relatively large volumes of matter having temperatures exceeding 10^8K
- Relatively large volumes of matter having radiation temperatures exceeding 10^6 K

Workshop summary

Only three places in the Universe have produced extremes close to such conditions: the Big Bang, when the Universe was born in a primordial fireball; the interiors of stars and planets; and thermonuclear weapons.

Nothing within orders of magnitude of the neutron densities that will be produced in NIF has been available for laboratory experiments until now.

The capabilities of NIF and related smaller high-energy-density research facilities are ushering in a new era of investigative opportunities that will have a transformative impact in many fields.

These include planetary and space physics; radiation transport and hydrodynamics; nuclear astrophysics; the science of ultradense materials and materials damage; many areas of plasma physics; laser-plasma interactions, ultraintense light sources, and nonlinear optical physics; novel radiation sources; and other topical areas involving the interplay of electromagnetic, statistical, quantum, and relativistic physics.

From relativistic phenomena to ~ 1 eV condensed matter physics- NIF allows a wide range of experiments

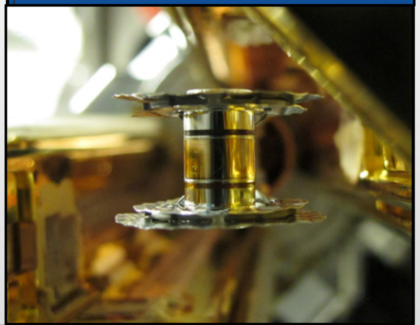
Laser

Wide variety of pulse shapes, w/ few percent reproducibility and precision (1.855 MJ/533 TW exceeds specs)

Diagnostics

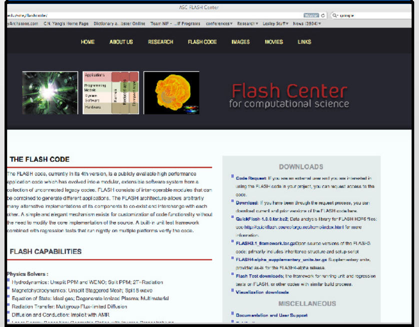
Photon and particle diagnostics w/ high spatial, temporal, spectral resolution

Targets



Spherical, planar, machined perturbations, exotic materials,..

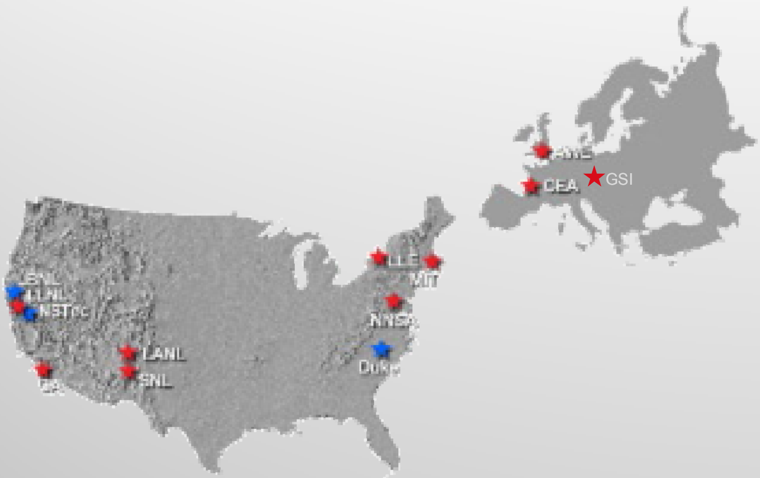
Simulation



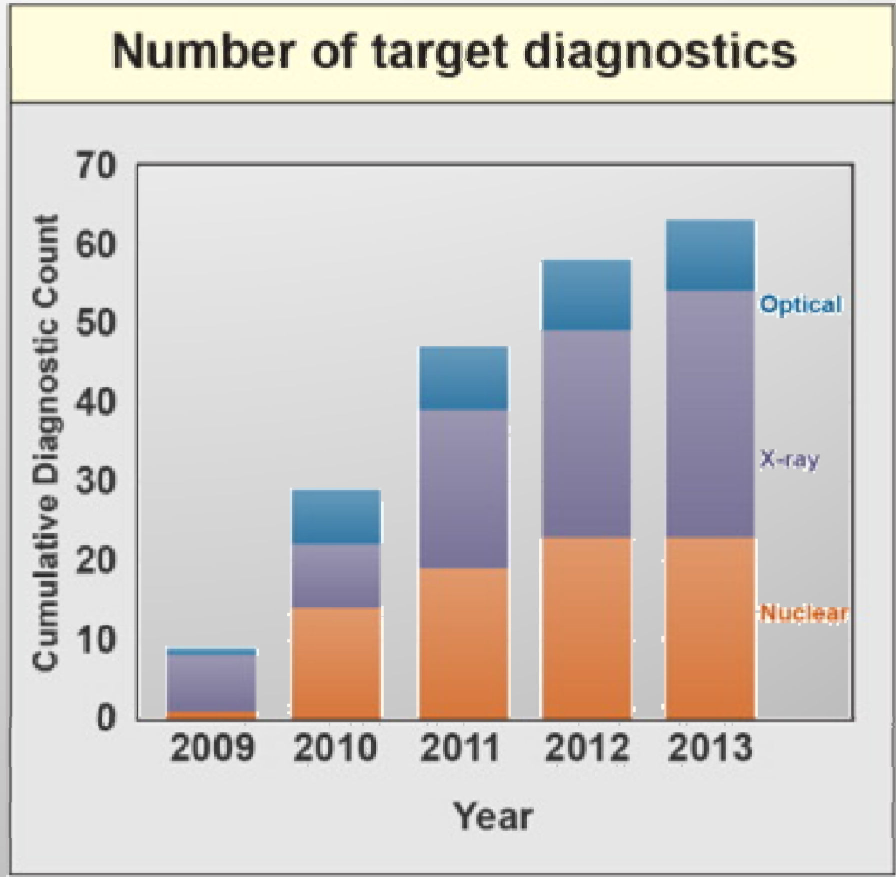
Experimental design via target and laser simulation tools

NIF will also bring an unprecedented new capability- the ability to study burning plasma physics

63 target diagnostics enable cutting edge science on the NIF

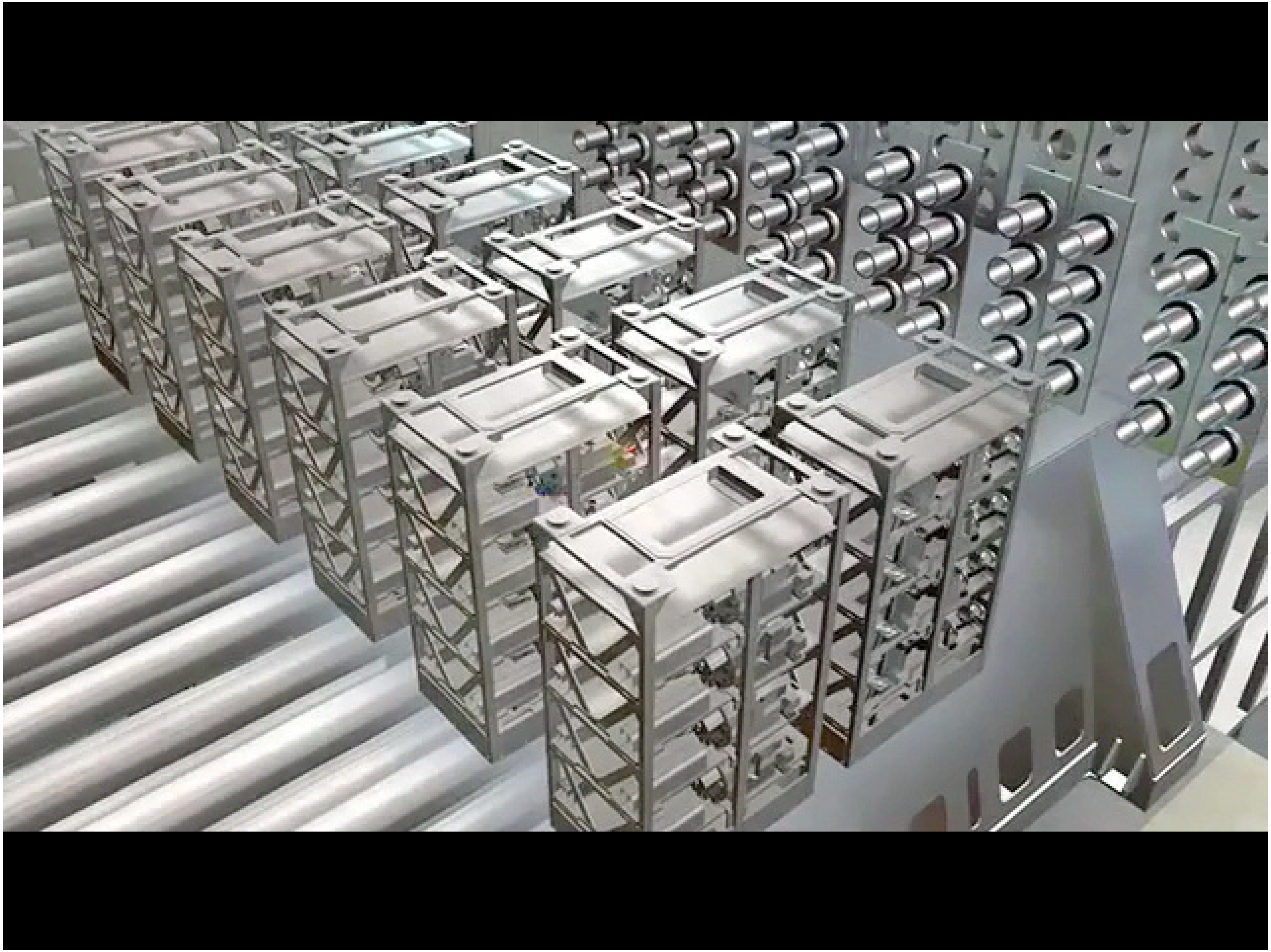


- LLNL
- LANL
- LLE
- NSTec
- U of M
- LBNL
- AWE
- MIT
- CEA
- Duke
- SNL
- GSI

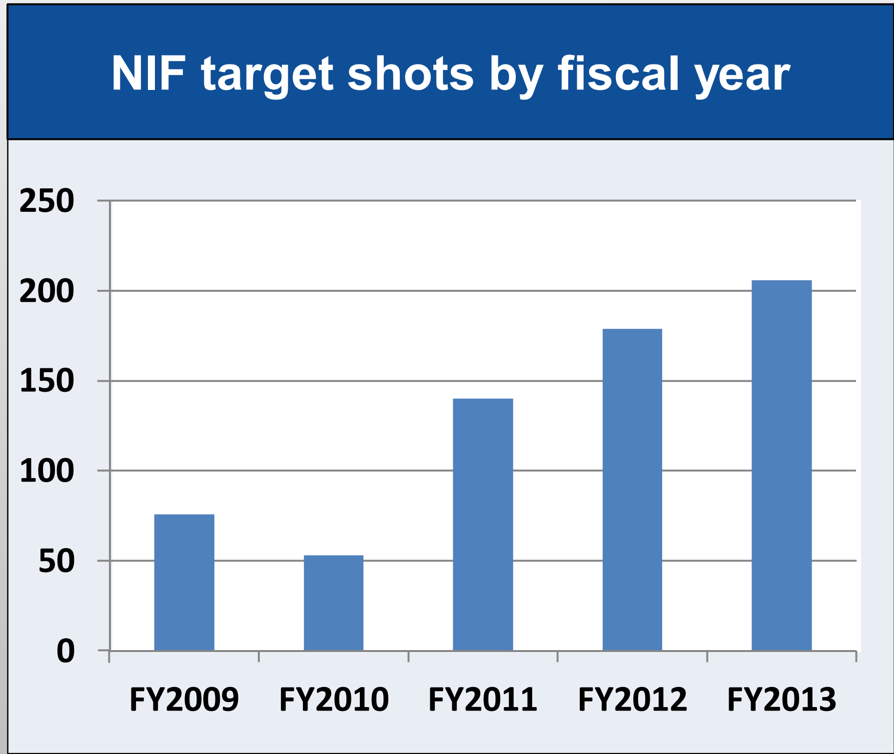


Diagnostics are an effective means of enabling collaboration on NIF — the MIT Magnetic Recoil Spectrometer (MRS) is an important example

Advanced Radiographic Capability (ARC)



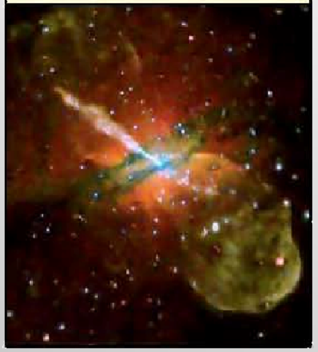
NIF target shot rate has steadily increased



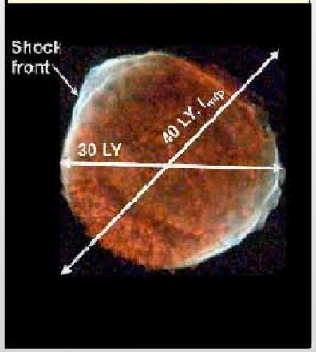
Working to increase the number of days devoted to discovery science to 15 to 17 shot days/yr

A wide variety of fundamental science experiments are underway or being planned

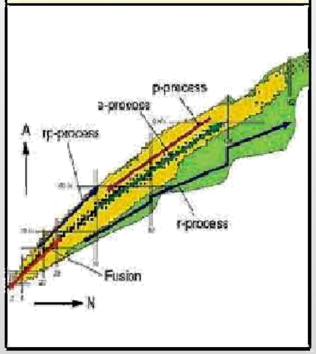
Pair plasma



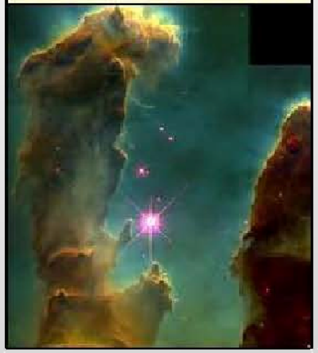
Collisionless shocks



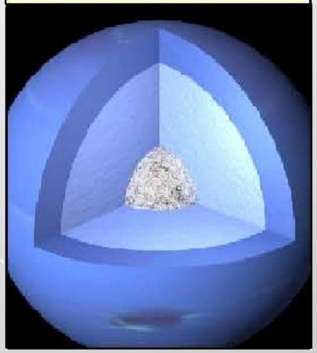
Low energy neutron spectra



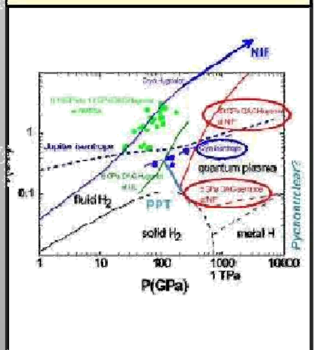
RT - instability/Eagle



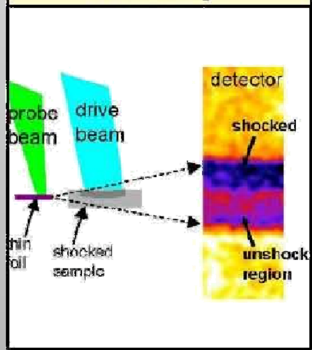
Compressed diamond structure



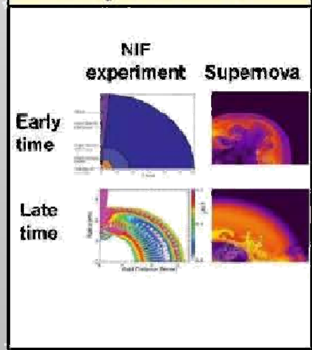
H at Tpa pressure



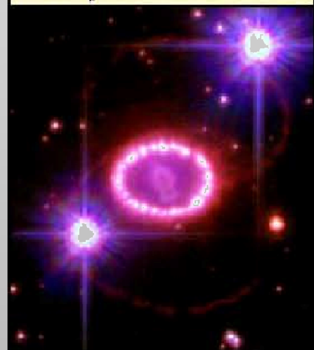
Matter at high density



Diverging supernovae



Radiative supernova RT

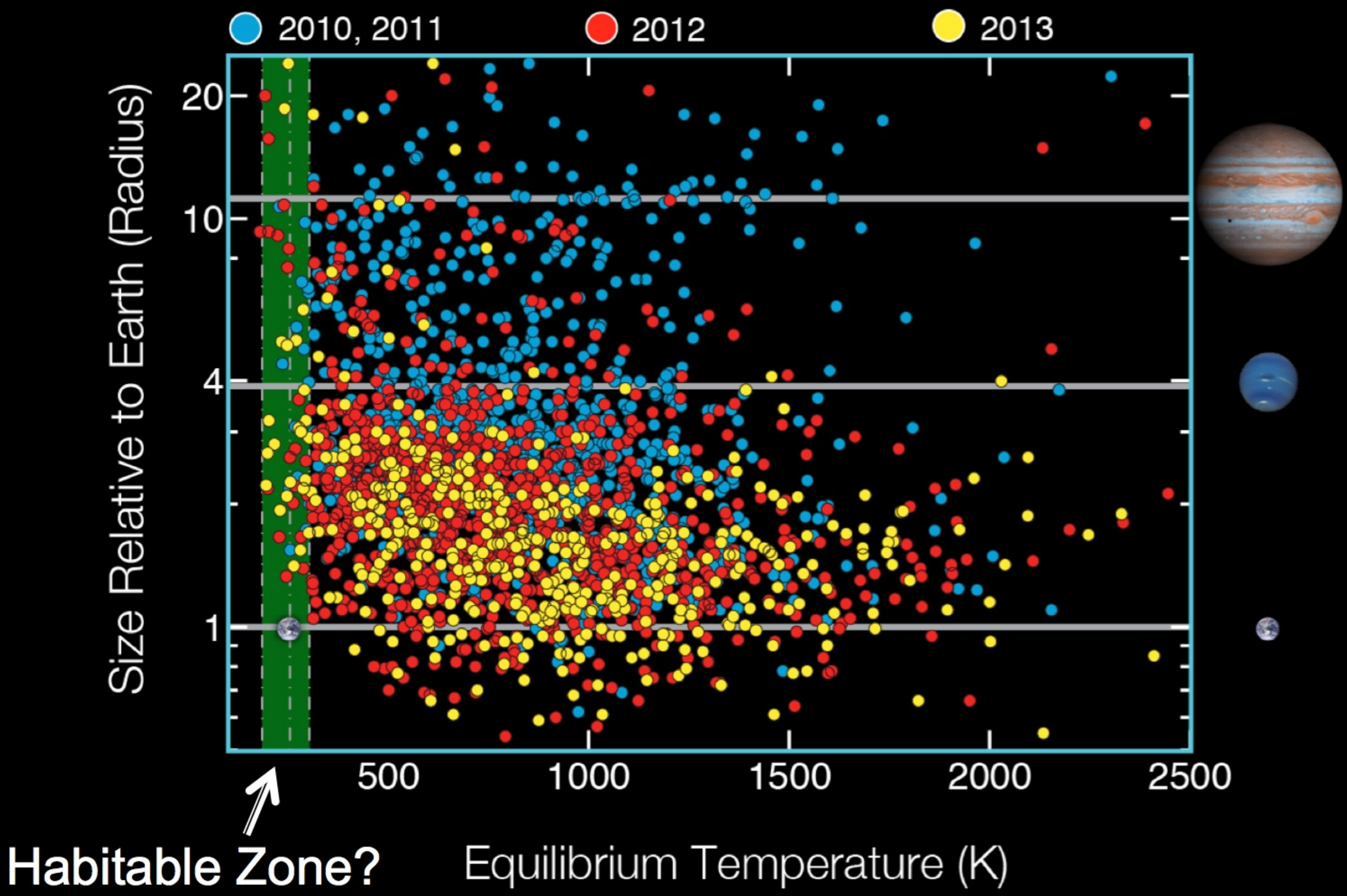


C/Fe EOS

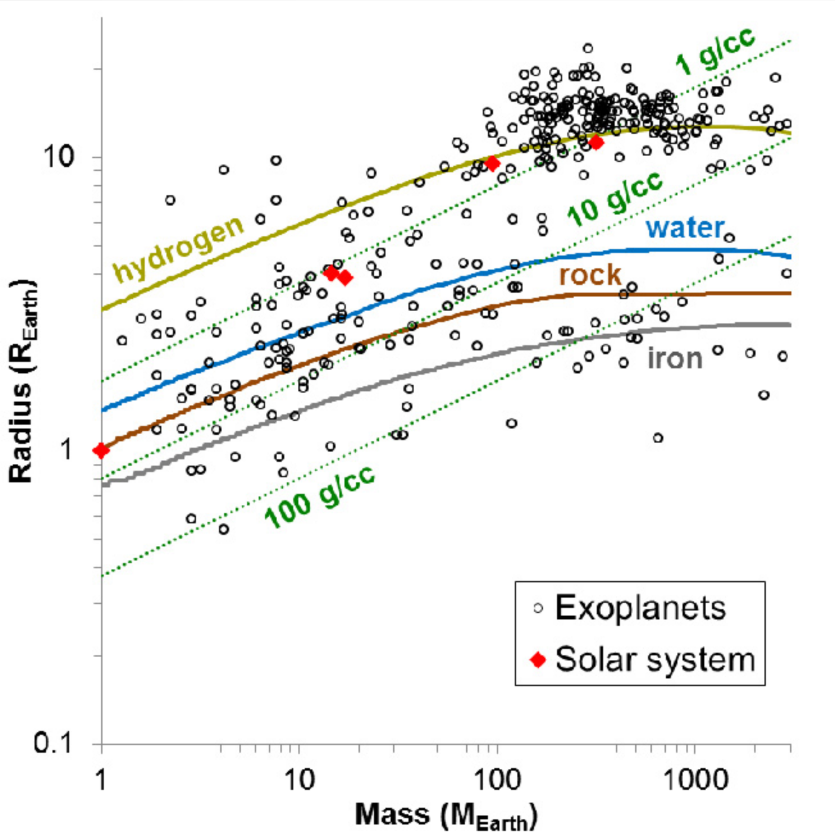
NIF discovery science experiments (through June 2, 2014)

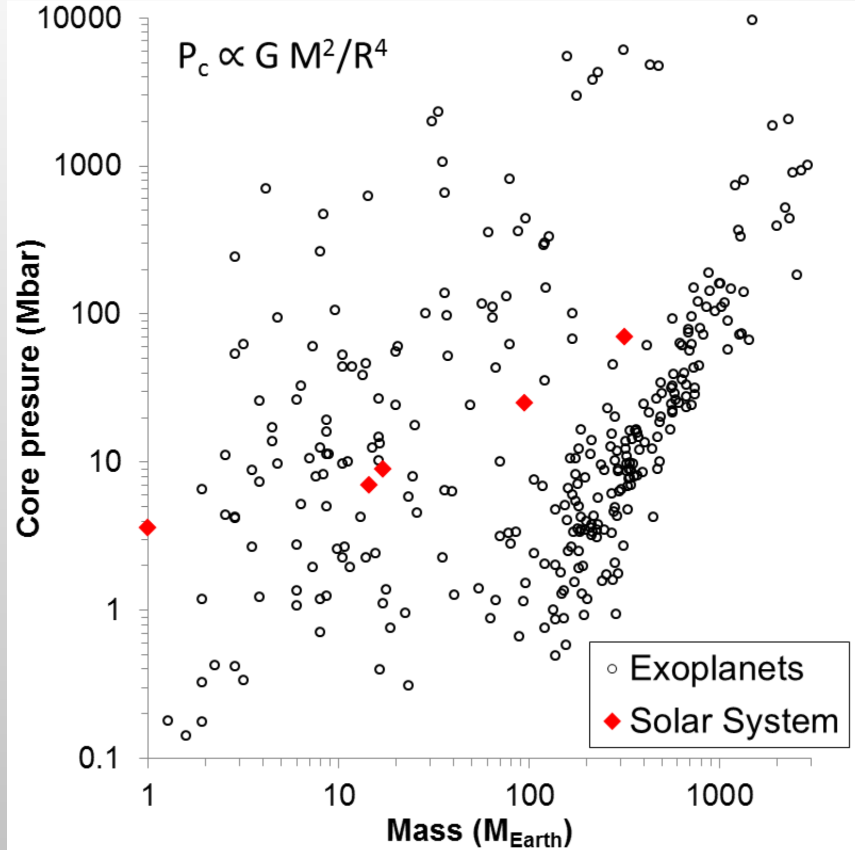
Title	PI	PI Institution	FY2009	FY2010	FY2011	FY2012	FY2013	FY2014	Total shots
Carbon and Iron Equation of State	T. Duffy/R. Jeanloz	Princeton/ UC Berkeley			4	3	2		9
Rad-SNRT	C. Kuranz	Univ. of Michigan	2	1		1			4
Novel phases of compressed diamond	J. Wark/ J. Eggert	Oxford/LLNL					1		1
Nucleosynthesis and the s-process	L. Bernstein	LLNL	Completed via ~ 60 "ride-along" shots						
Rayleigh-Taylor instability and astrophysical implications (merged proposal)	A. Casner/ V. Smalyuk J. Kane	CEA LLNL					1	3	4
Matter at ultra-high densities (merged proposal)	P. Neumayer R.Falcone	GSI UC Berkeley					3	2	5
Hydrogen and methane at ultra-high pressures (merged proposal)	R. Jeanloz R. Hemley	UC Berkeley Carnegie Institution of Washington							
Diverging Supernova hydrodynamics	T. Plewa	Florida State Univ.							
Astrophysical collisionless shocks (merged proposal)	Y. Sakawa G. Gregori	Osaka University Univ. of Oxford							
Relativistic pair plasmas	H. Chen	LLNL							
Total shots			2	1	4	4	7	5	23

The planetary science community needs guidance on which are habitable!



Exoplanet core states reach extreme pressures

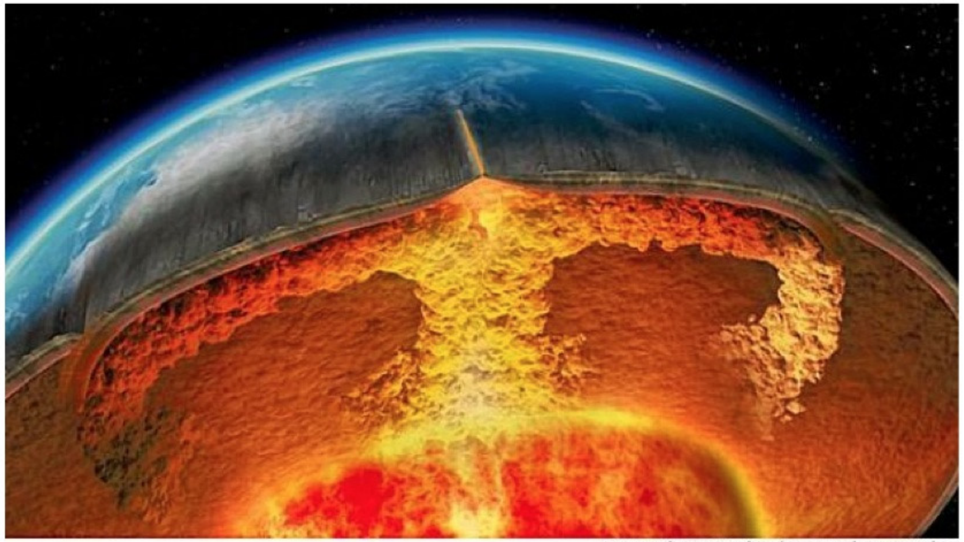




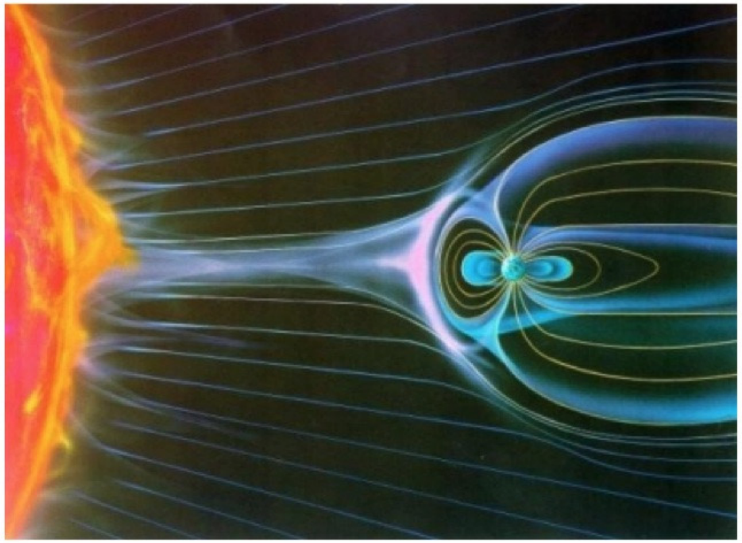
Experimental data on planetary materials is a critical component in the development of planetary structure and evolution models

The planetary science community needs more information about how planets solidify

- Solidification plays a major role in the evolution of habitable planets
  - Plate tectonics that stabilizes the atmosphere
  - Protective Magnetosphere
- Planetary materials are not pure elements
  (e.g. Mg_2SiO_4 compounds and Fe-Ni-Si alloys)

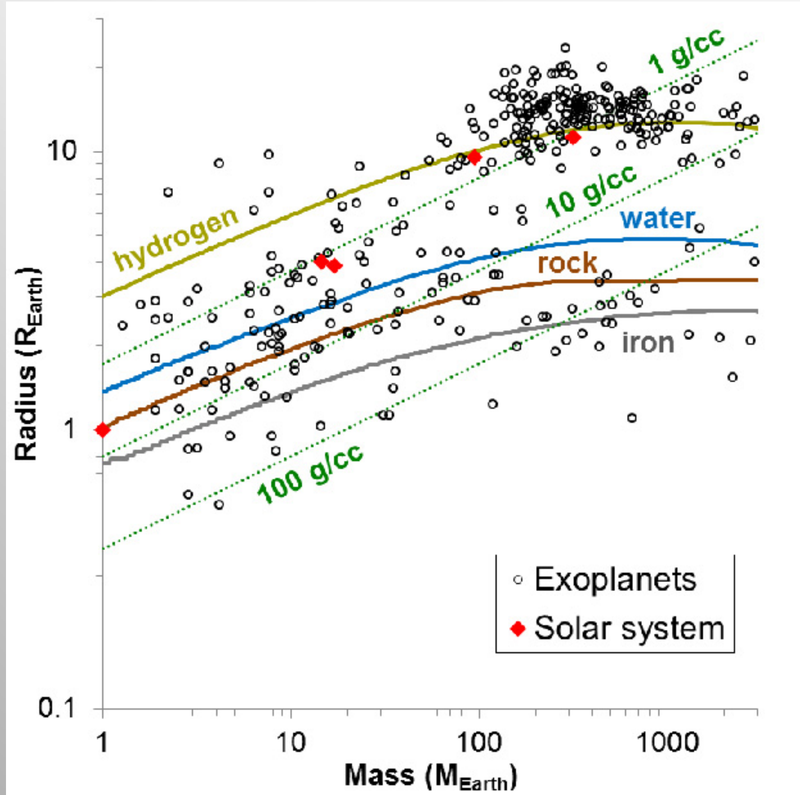


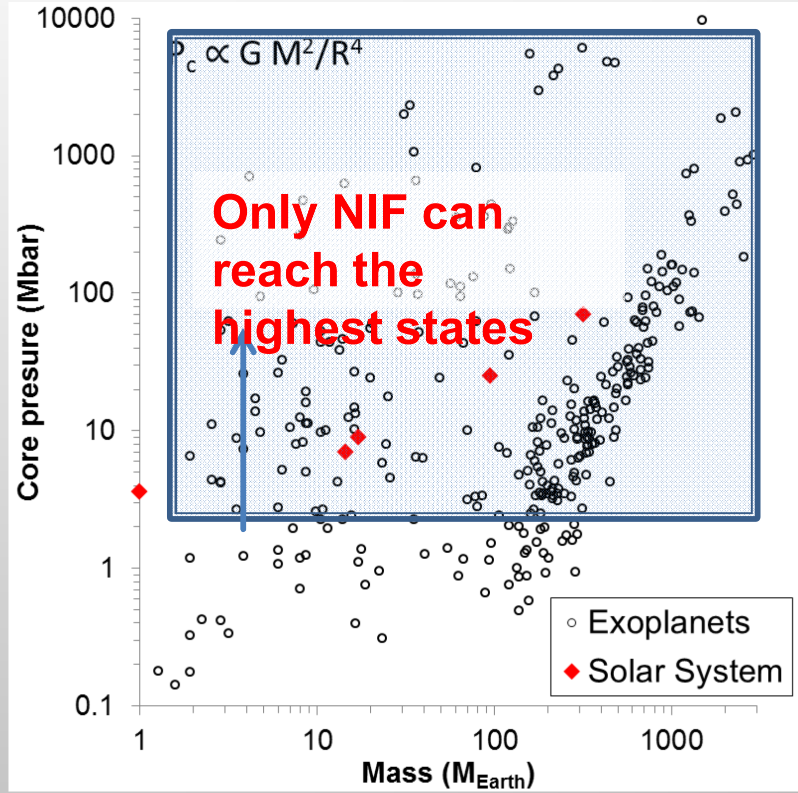
National Geographic / National Geographic



“We do not need to know the equation of state of planetary materials to a few percent accuracy, the future of planetary high pressure research is in multi-component materials and their chemistry at high pressure.”
Dave Stevenson, Caltech Professor

Only NIF can measure the highest pressure states



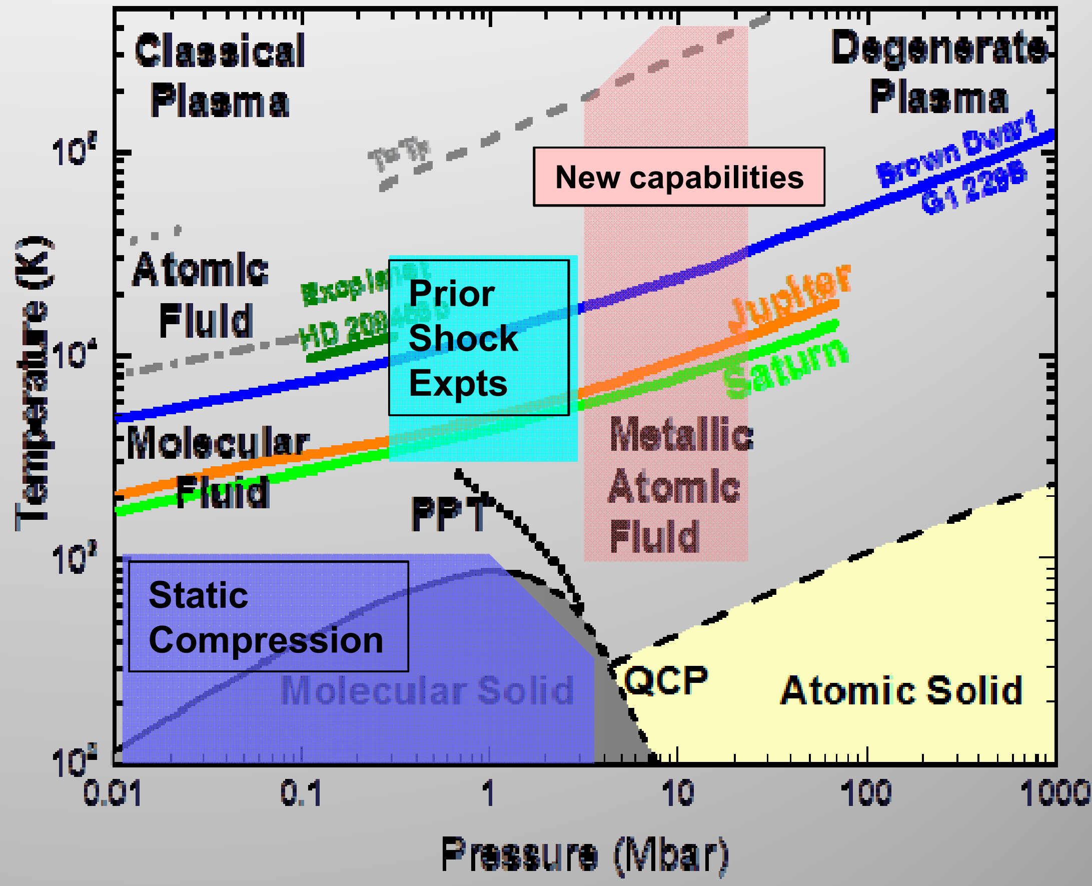


Experimental data on planetary materials is a critical component in the development of planetary structure and evolution models

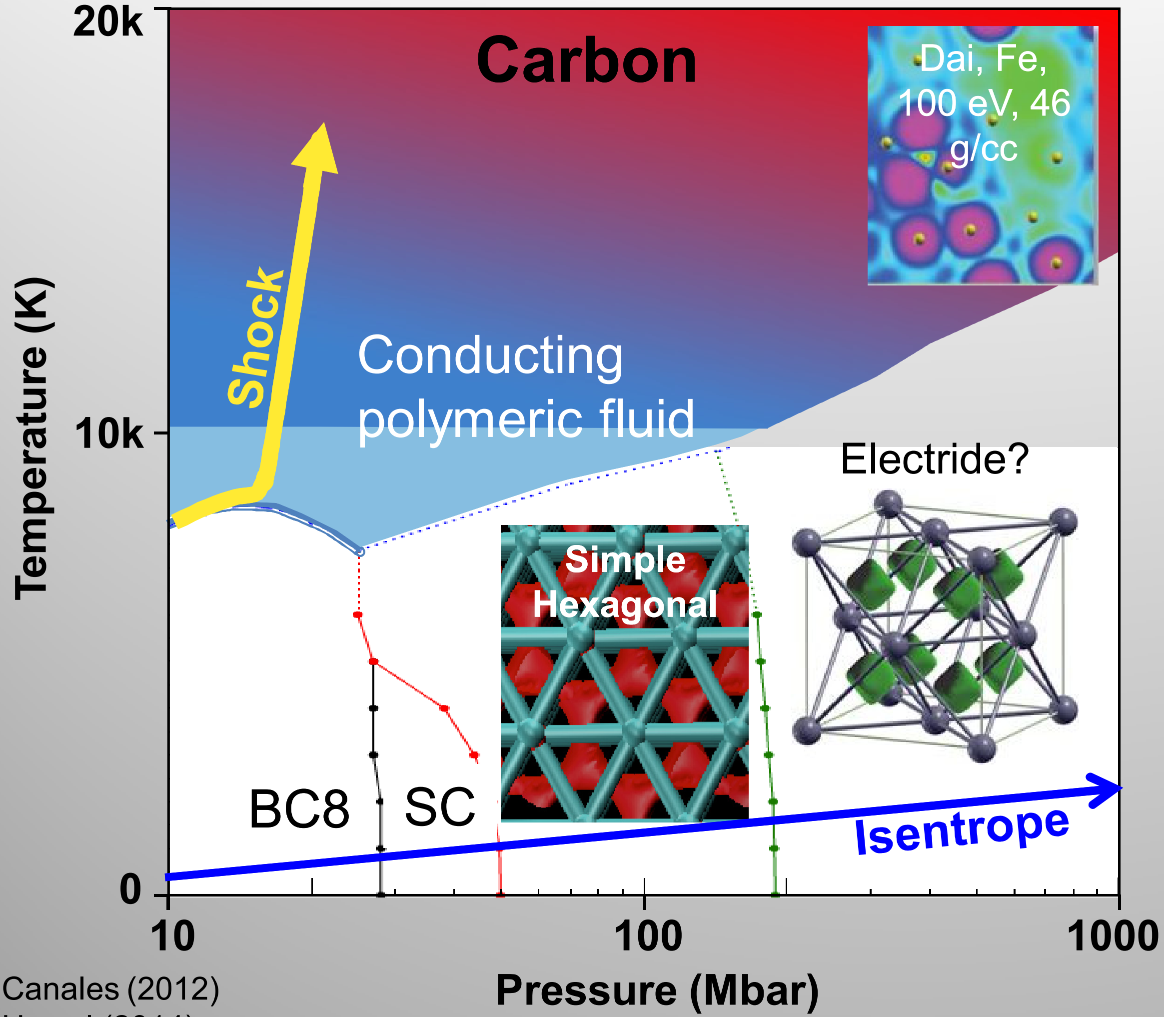
Previous H_2 EOS experiments are limited to < 3Mbar

- Previous H_2 equation-of-state measurements are limited to <3 Mbar
  - Static compression at low temperatures
  - Shock compression at moderate temperature
- New capabilities at NIF
  - FY15 will start with cryo shock to 10 and 20 Mbar
  - Submitted LOIs will explore PPT and metallic atomic fluid at similar pressures but lower temperature

Hydrogen phase diagram



It appears that many materials may adopt complex structures in high pressure solid and fluid phases



Canales (2012)
Hamel (2014)

- We now have the capability to ramp-compress materials to these extreme states, and measure stress, density, and structure

- High-presssure electride phases in Li, Na were a surprise… what other surprises await us at atomic pressures?

Broader Impact

- NIF discovery science campaigns are on the forefront of experimental planetary science
- First four shots on the rampEOS campaign measured EOS of diamond to 50 Mbar,
- Enabling the national (and international) community to field first-rate science at the NIF will increase the broader interest in HEDP, and lure excellent scientists to the field and the lab

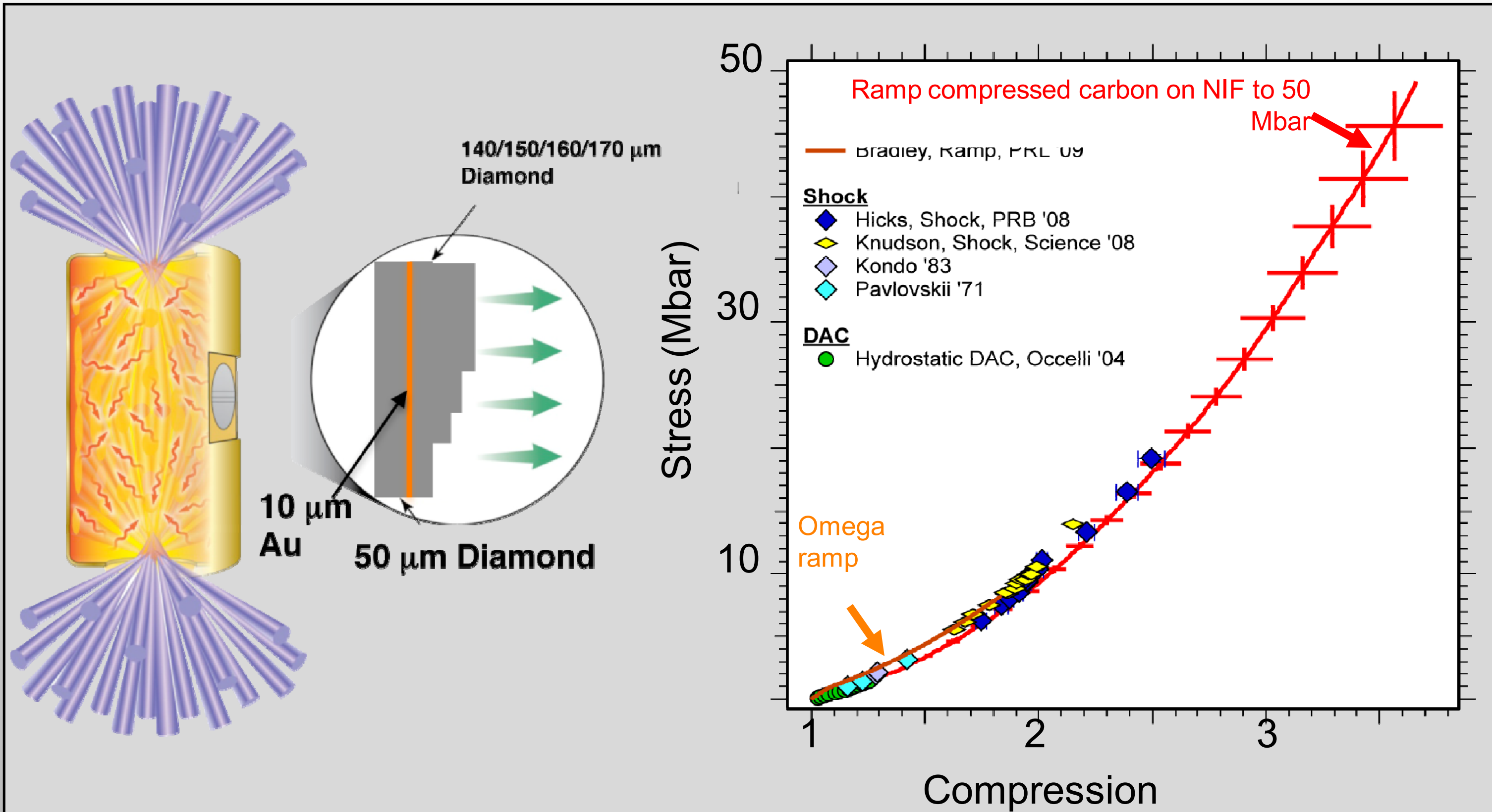
The pressures we consider approach the atomic unit of pressure

Date	Atomic unit		Discoverer	Capability/implication
1880				
1900	Energy	$E_h = m_e e^4 / \hbar^2 = 27.2eV$	Rydberg	spectroscopy =>quantum mechanics
	Mass	$m_e = 9.11 \bullet 10^{-31} kg$	Thomson	mass spectrometry
1920	Charge	$e = 1.6 \bullet 10^{-19} C$	Millikan	oil drop =>atoms are divisible
	Length	$a_0 = \hbar^2 / m_e e^2 = .0529nm$	Bragg	diffraction =>crystal structure
1940				
1960				
1980	Time	$t = \hbar / E_h = 27 \bullet 10^{-18}$	Krausz	attosecond spectroscopy =>observe electron bonding
2000–2020	Pressure	$P = E_h / a_0^3 = 294 Mbar$	NIF	Fundamental change in matter from KeV chemistry to macro-quantized states

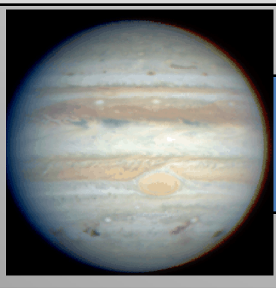
D. Hicks

The atomic unit of pressure is the pressure required to “seriously disrupt the shell structure of atoms” (Bukowinski,1994)

NIF has been used to “shocklessly” compress carbon to 50 Mbar

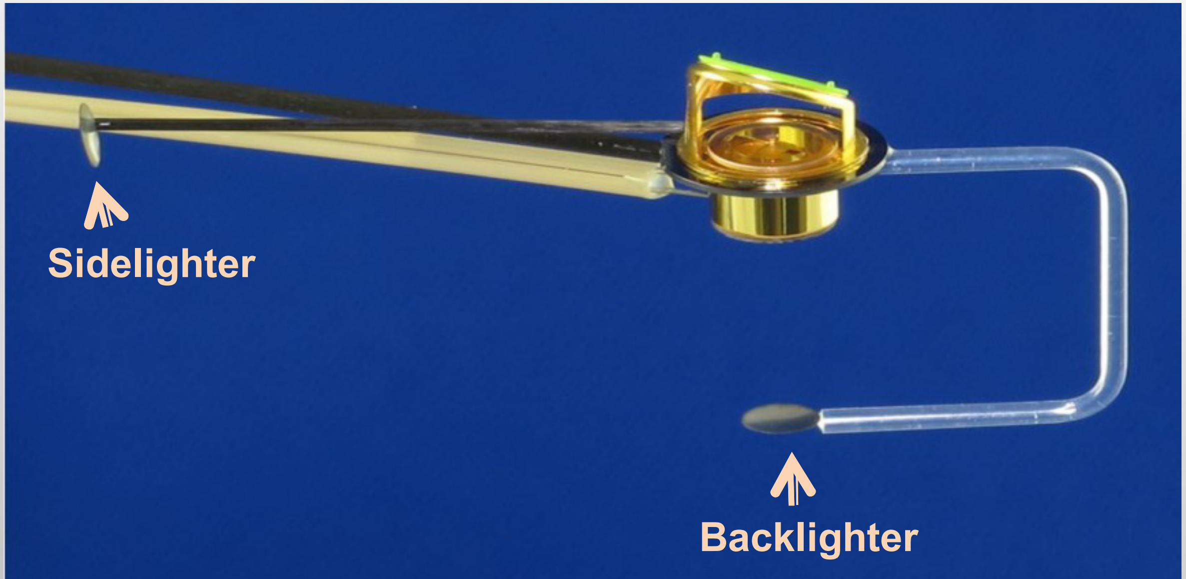


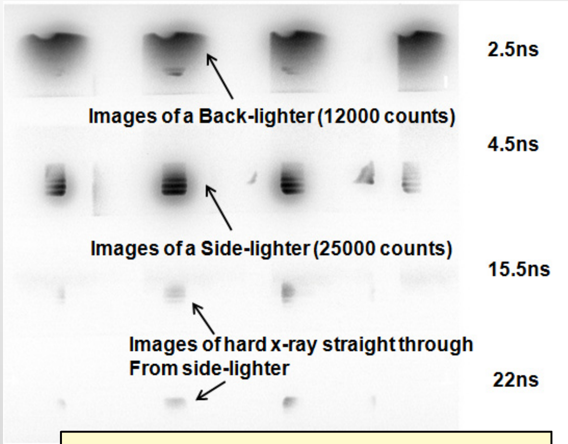
R.F. Smith, J.H. Eggert, D.G. Braun, J.R. Patterson-1, R.E. Rudd, R. Jeanloz, T.S. Duffy, J. Biener, A.E.Lazicki, A.V. Hamza, J. Wang, T. Braun, L.X. Benedict, P.M. Celliers, G.W. Collins



NIF can now recreate the most extreme planetary core states in the solar system

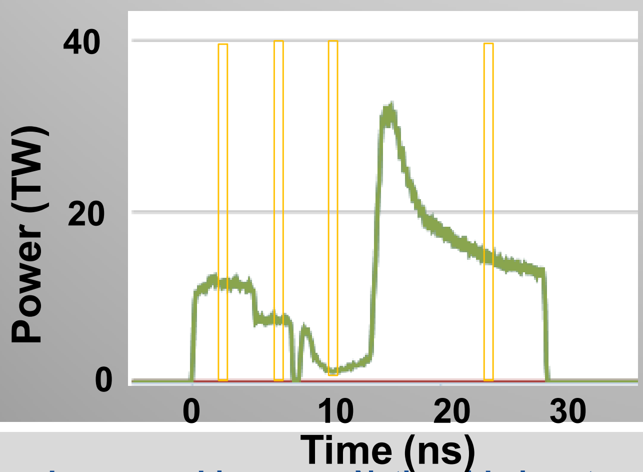
The CEA/LLNL Ablative Rayleigh-Taylor collaboration has conducted two shots in 2013 (March 2013 data shown)

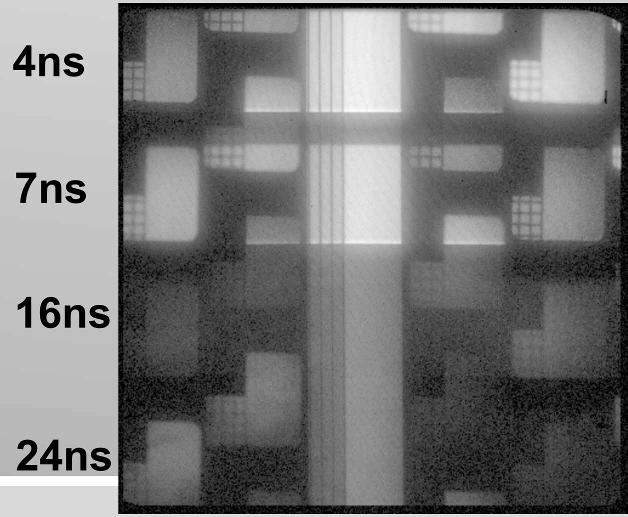




GXD on the 90-78 measured hohl bakground

Laser setting

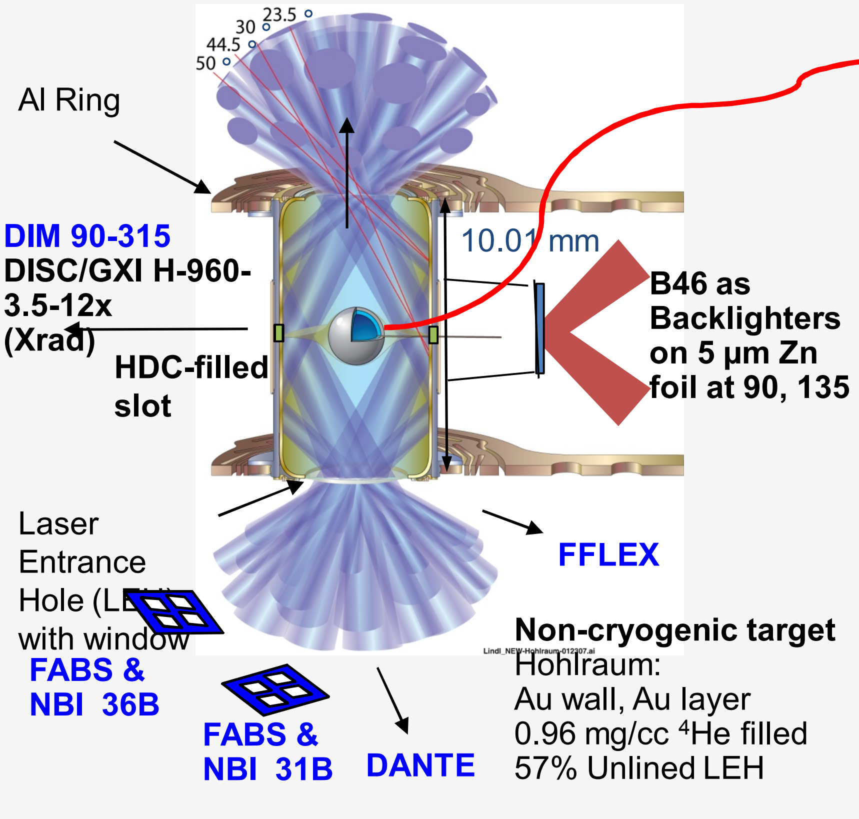




GXD on the polar dim obtained high-quality data

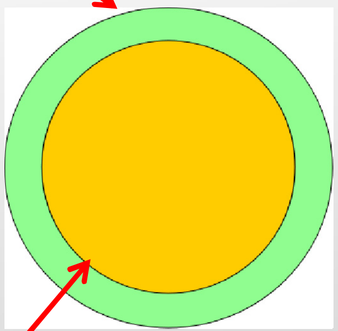
The NIF GBar collaboration (UC Berkeley-LLNL) is exploring EOS and material properties at P~ 1 GBar

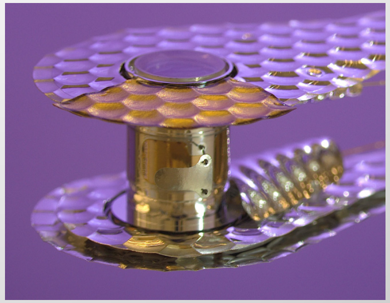
Schematic of x-ray scattering and radiography from spherically driven targets, Side View



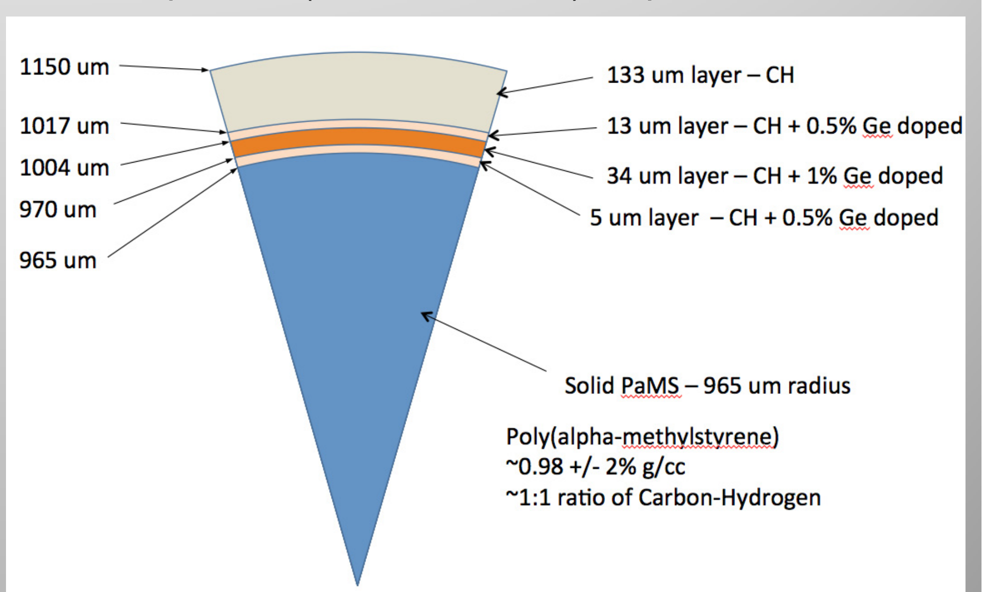
MACS to be fielded on upcoming experiments

Ignition ablator



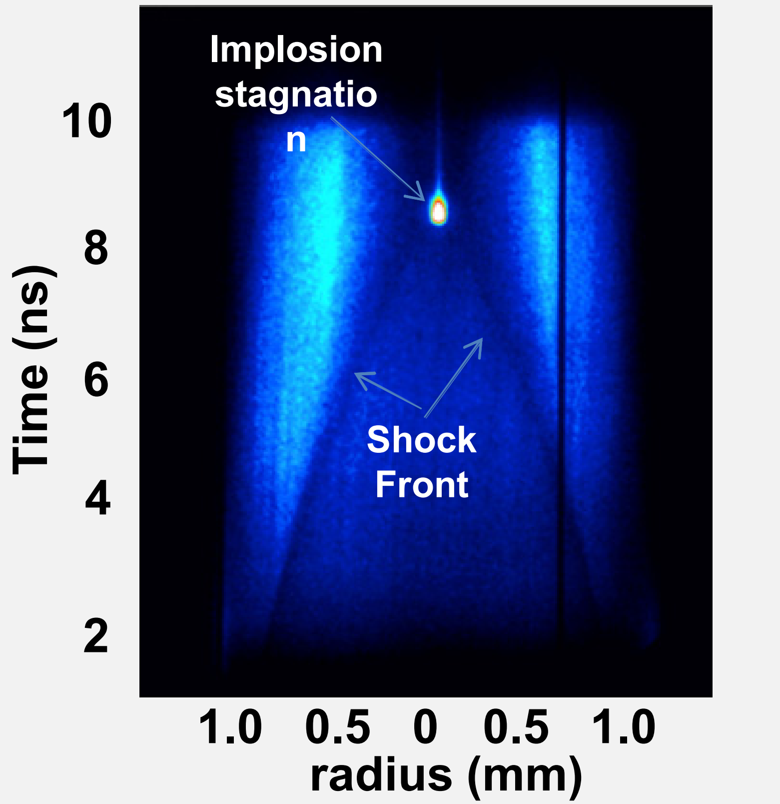


Sample: CH (PAMS: mandrel), doped

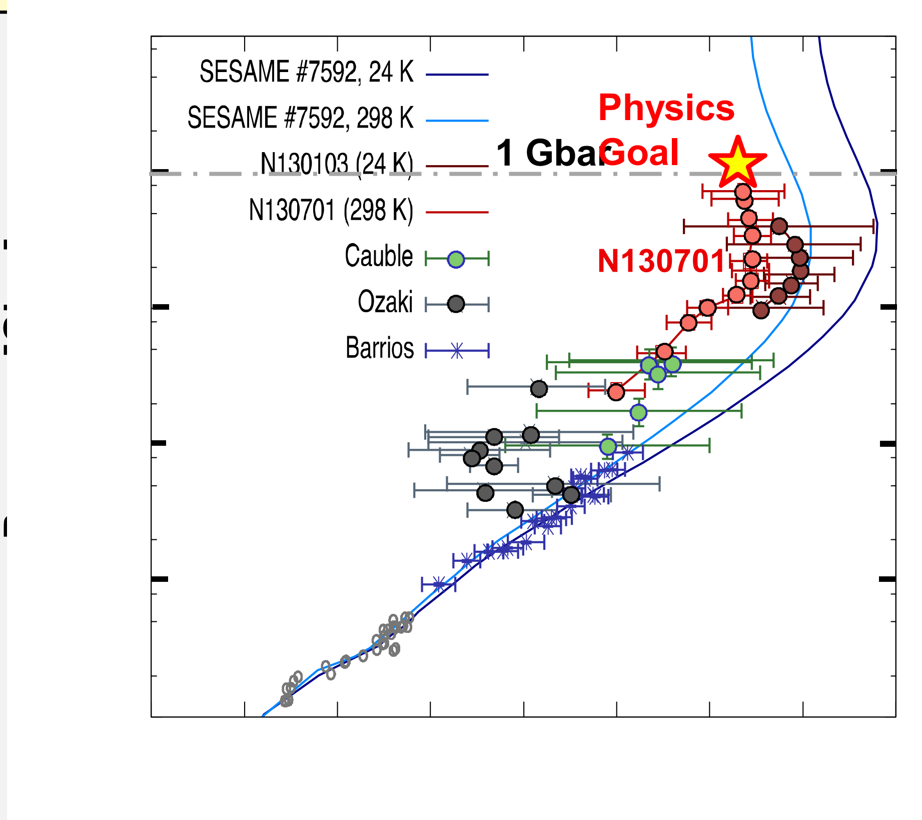


UC Berkeley and LLNL researchers are measuring equation of state in the Gbar pressure regime via NIF implosions of solid plastic capsules

Streak record from July 1, 2013 NIF implosion experiment



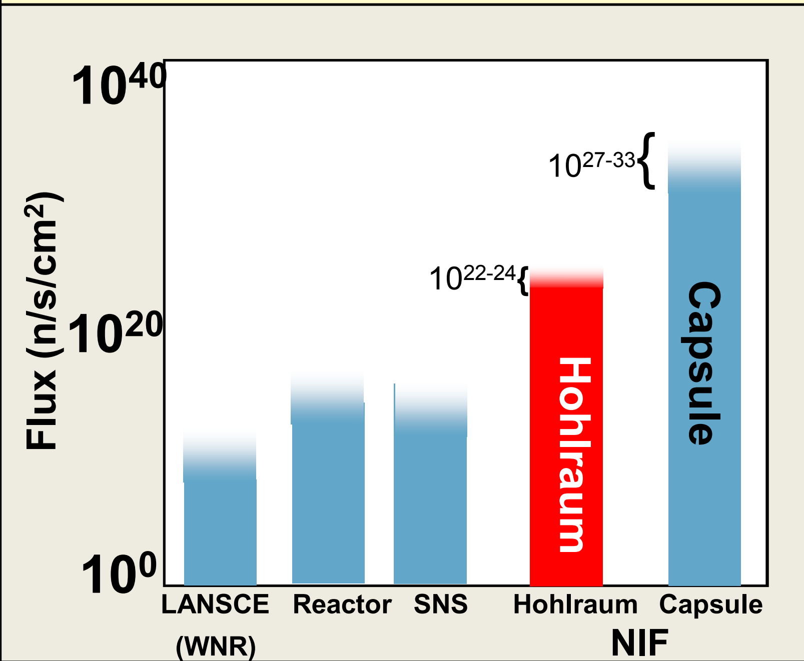
Absolute shock Hugoniot measurements of plastic equation of state

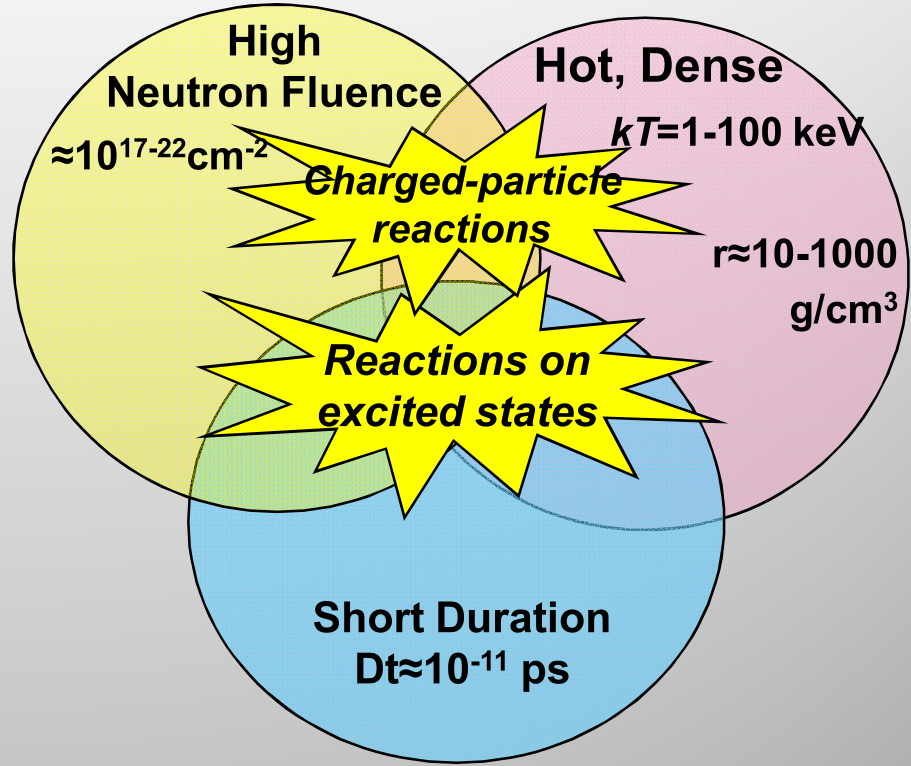


On N130701 we obtained absolute shock Hugoniot measurements for CH up to 720 Mbar, increased from 450 Mbar on N130103

The high e, γ and n-flux in a NIF capsule might allow us to explore reactions on short-lived nuclear states

Neutron flux in NIF imploded capsules is comparable to supernovae

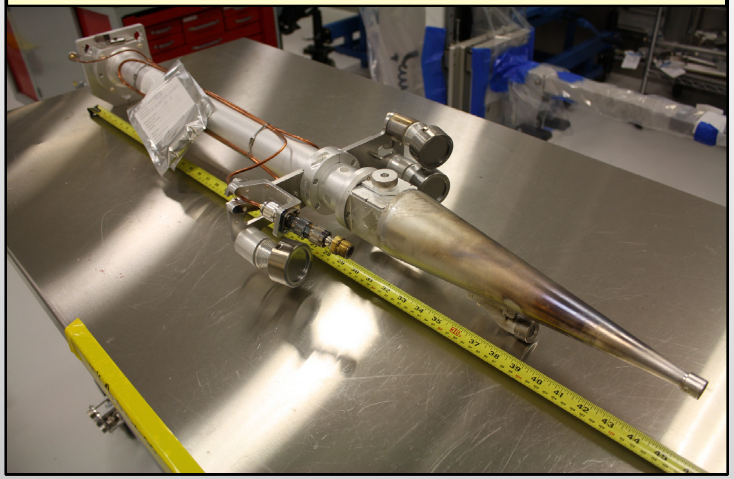




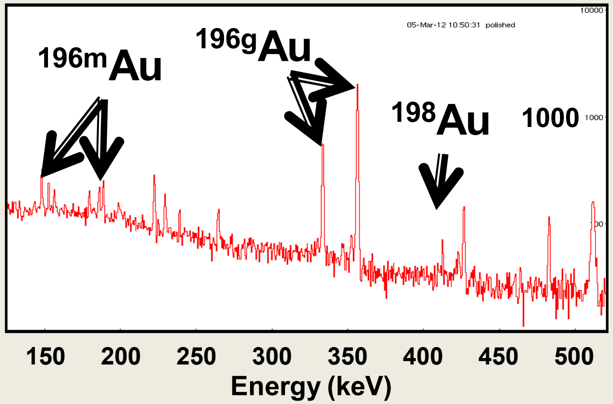
The NIF nuclear diagnostic team has obtained data from 58 "ride-along" experiments

Production of low energy neutrons in ICF implosions is important for nuclear cross sections for astrophysics and ICF ρR_{fuel} diagnostics

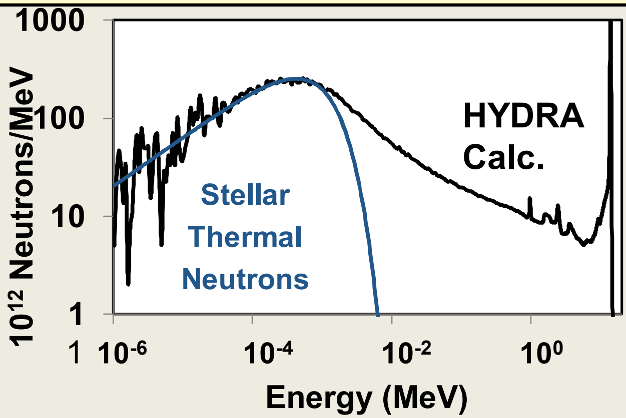
Four collectors mounted on a DIM



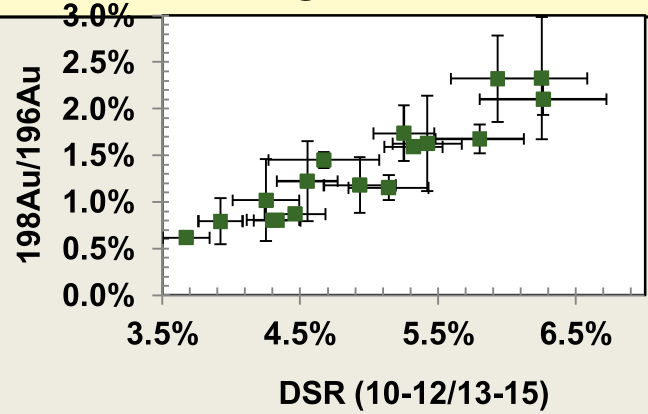
^{198}Au produced by downscattered neutrons-γs counted in B151



Inferred low-energy neutron spectrum similar to that of stars

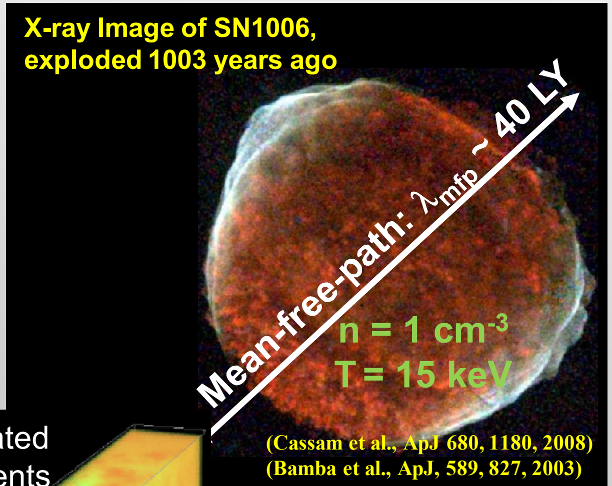


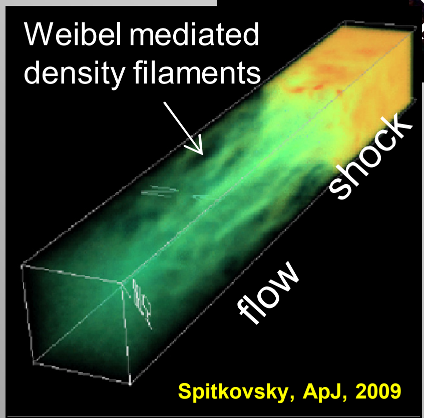
^{198}Au/^{196}Au is also a ρR_{fuel} diagnostic



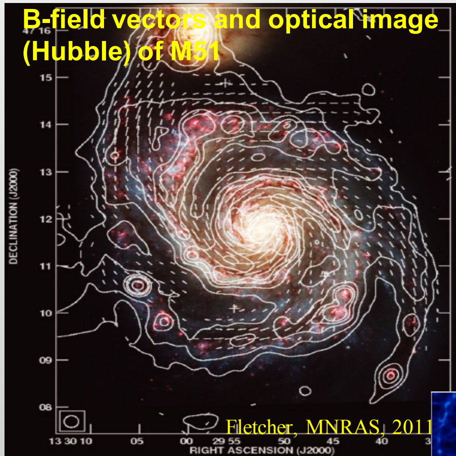
High velocity plasma flows are ubiquitous in astrophysics and are believed to be responsible for seed magnetic fields and their amplification

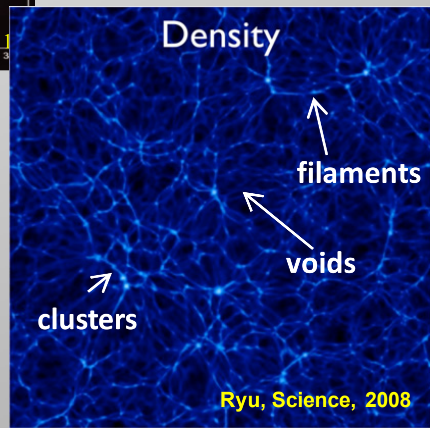
Generate magnetic fields:
Weibel is a possible mechanism





Amplify magnetic fields:
Turbulence dynamo is a possible mechanism



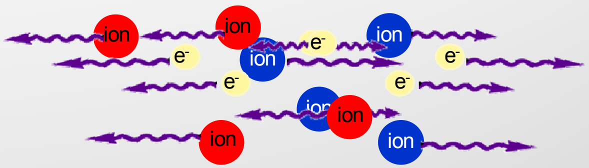


Laser driven experiments can study microphysics of high Mach number plasma flow interactions and collisionless shock formation under controlled conditions

Laser experiments can create conditions that are scalable to astrophysical phenomena, a Weibel mediated collisionless shocks is an example

Collisionless plasma flows

Coulomb mean free path is large

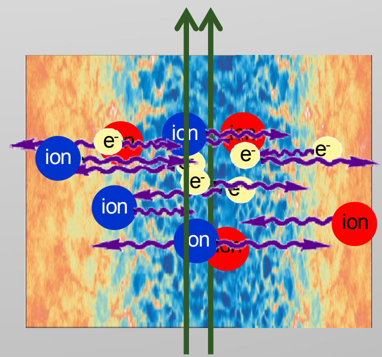


Ions pass through without creating a shock

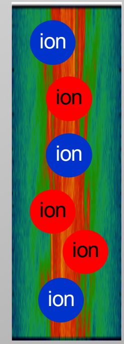
Clean interpenetration

Collisionless shock forming plasma flows

Weibel filamentation

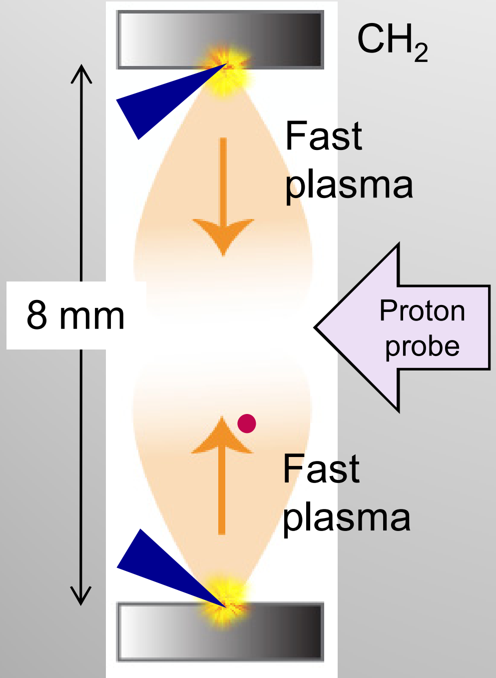


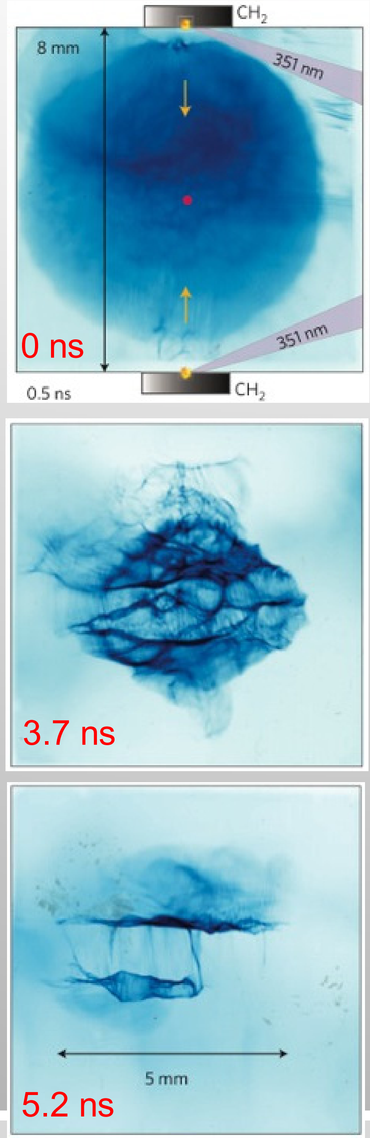
Collisionless shock forms

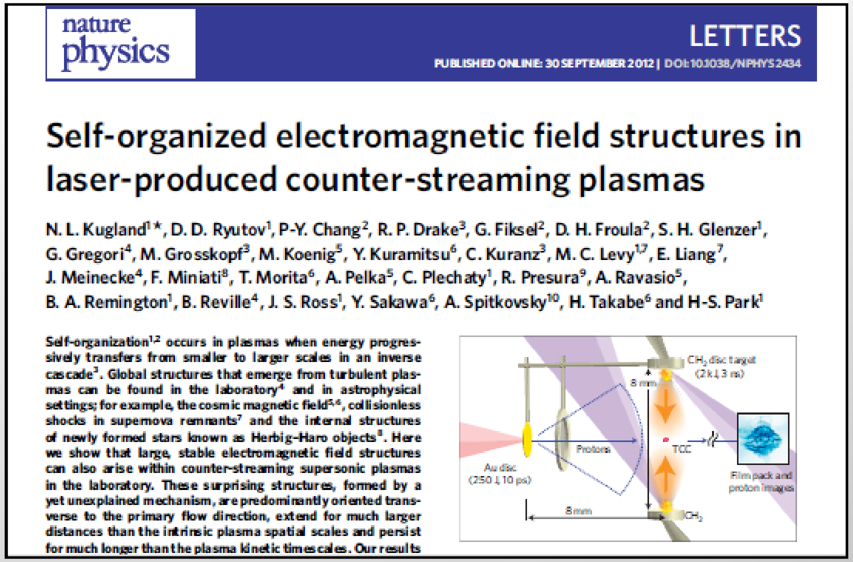


- Anisotropy in velocity forms plasma instabilities (Weibel filamentation)
- Current filamentation generates localized magnetic field
- Magnetic fields exert the Lorenz force F=q (vxB), on ions
- The ion trajectories in the interpenetrating flows are sufficiently interrupted (localized) that a shock is formed

NIF collisionless shock experiment under development builds on results from Omega/EP showing unexpected self-organizing stable field structures







nature physics | LETTERS
PUBLISHED ONLINE: 30 SEPTEMBER 2012 | DOI: 10.1038/NPHYS2434

Self-organized electromagnetic field structures in laser-produced counter-streaming plasmas

N. L. Kugland[1]*, D. D. Ryutov[1], P-Y. Chang[2], R. P. Drake[3], G. Fiksel[2], D. H. Froula[2], S. H. Glenzer[1], G. Gregori[4], M. Grosskopf[3], M. Koenig[5], Y. Kuramitsu[6], C. Kuranz[3], M. C. Levy[1,7], E. Liang[7], J. Meinecke[4], F. Miniati[8], T. Morita[6], A. Pelka[5], C. Plechaty[1], R. Presura[9], A. Ravasio[5], B. A. Remington[1], B. Reville[4], J. S. Ross[1], Y. Sakawa[6], A. Spitkovsky[10], H. Takabe[6] and H-S. Park[1]

Self-organization[1,2] occurs in plasmas when energy progressively transfers from smaller to larger scales in an inverse cascade[3]. Global structures that emerge from turbulent plasmas can be found in the laboratory[4] and in astrophysical settings; for example, the cosmic magnetic field[5,6], collisionless shocks in supernova remnants[7] and the internal structures of newly formed stars known as Herbig–Haro objects[8]. Here we show that large, stable electromagnetic field structures can also arise within counter-streaming supersonic plasmas in the laboratory. These surprising structures, formed by a yet unexplained mechanism, are predominantly oriented transverse to the primary flow direction, extend for much larger distances than the intrinsic plasma spatial scales and persist for much longer than the plasma kinetic timescales. Our results

Kugland et al., Nature Physics, 2012

- **We have obtained visual evidence that small-scale plasma processes make macroscopic field structures (self-organization) (N. Kugland et al, Nature Physics, 2012)**
- **Magnetic field advection may explain this phenomenon (D. Ryutov et al., PoP, 2013)**

The NIF ignition program also provides opportunities for scientific collaboration

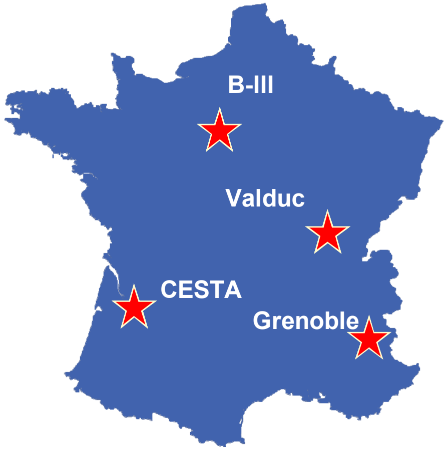
We welcome and encourage the broader scientific community to engage in the ignition science program

LLNL collaborates with the UK and France via long-standing government-to-government agreements

UK

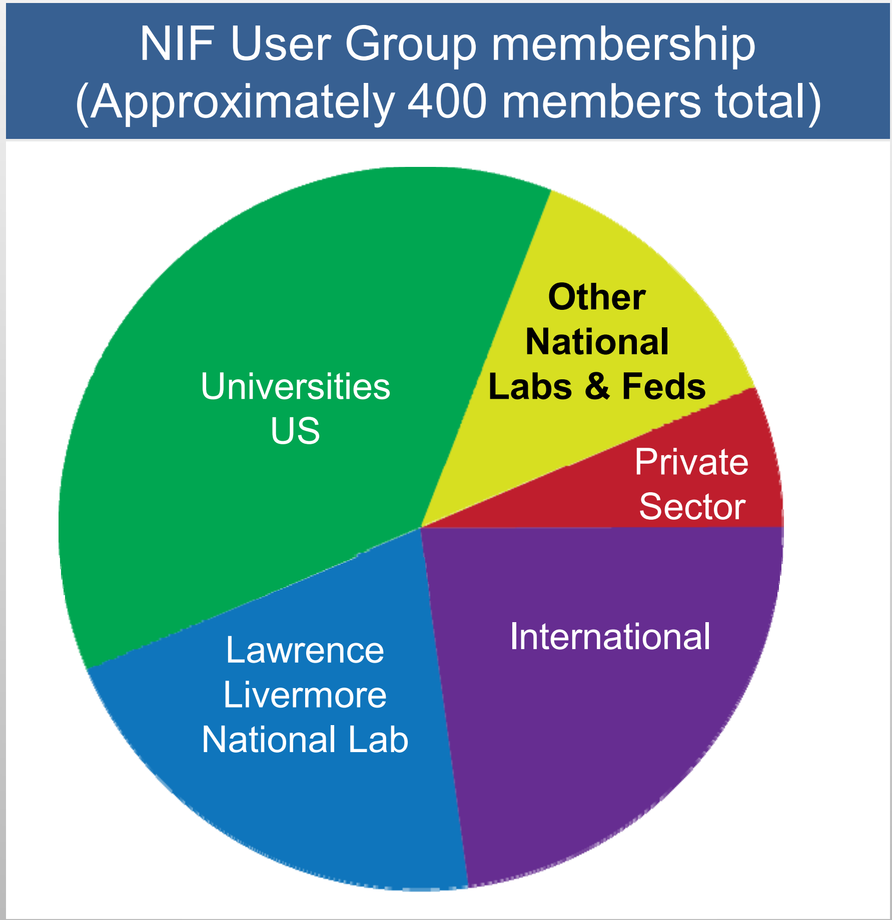
US-UK 1958 agreement: HED science on NIF, IFE, laser technology, other areas

France



DOE-CEA laser, computing, and fundamental science agreements

Overview of NIF and JLF user group membership



Elements of NIF as a user facility

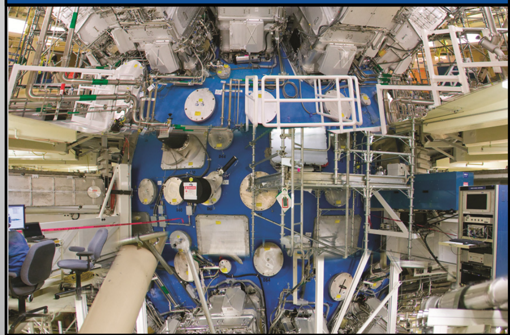
Facility management and governance

Proposal submission, evaluation, award

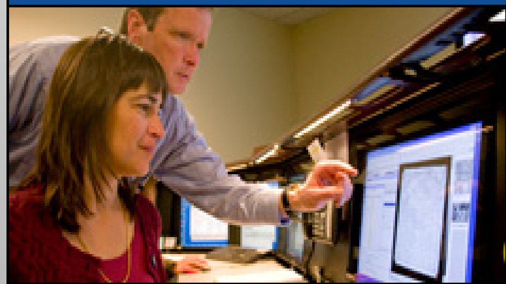
Site access, office space, computer access

User infrastructure (data access,…)

Experimental planning and execution



Data analysis and post-experiment support



The process for allocation of NIF facility time is described in the NIF Governance Plan

LLNL-AR-416565
NIF-0115829-AA

National Ignition Facility Governance Plan

NIF
National Ignition Facility

Version 0
September 28, 2012

Lawrence Livermore National Laboratory

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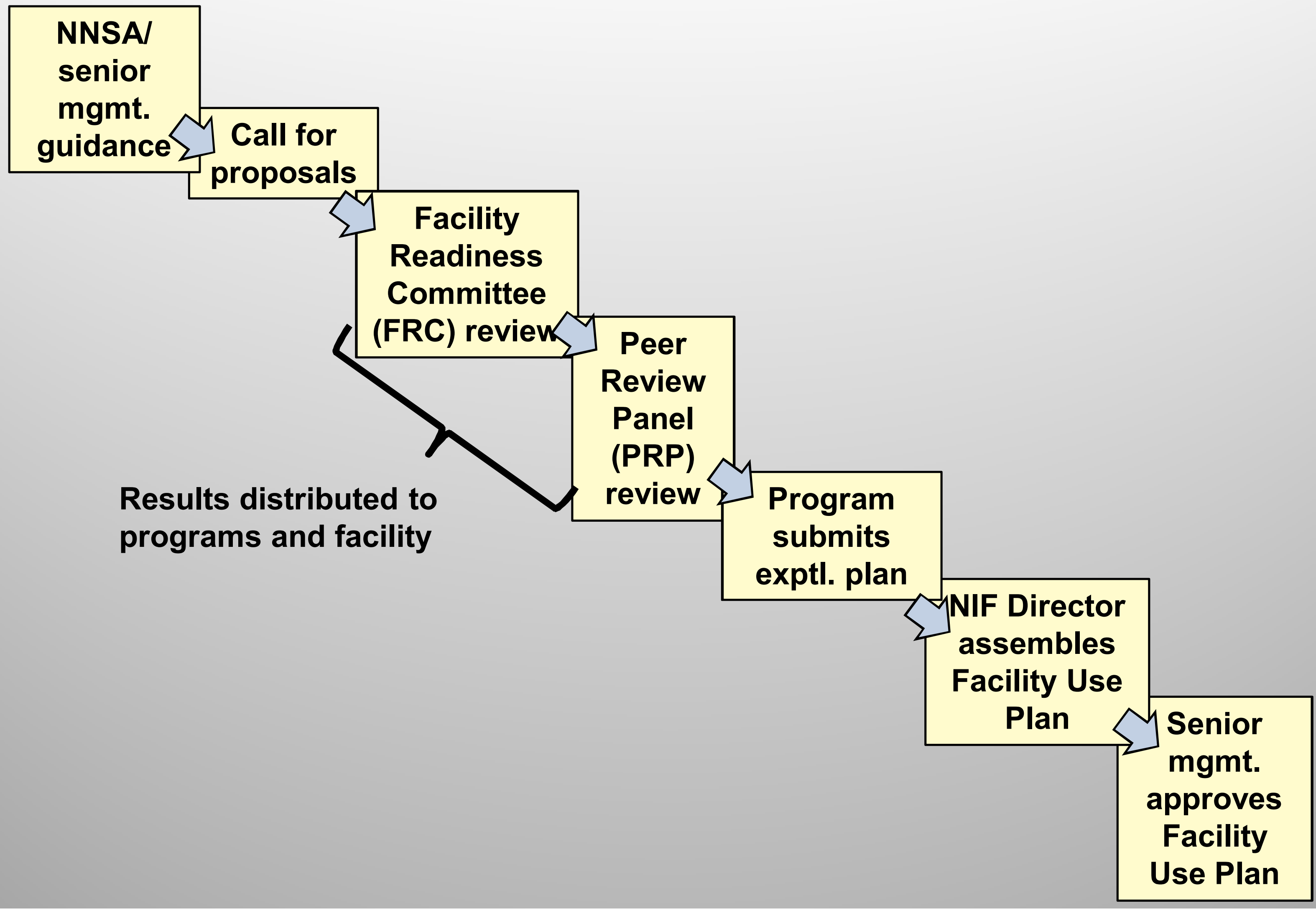
NIF governance process includes facility and technical peer reviews

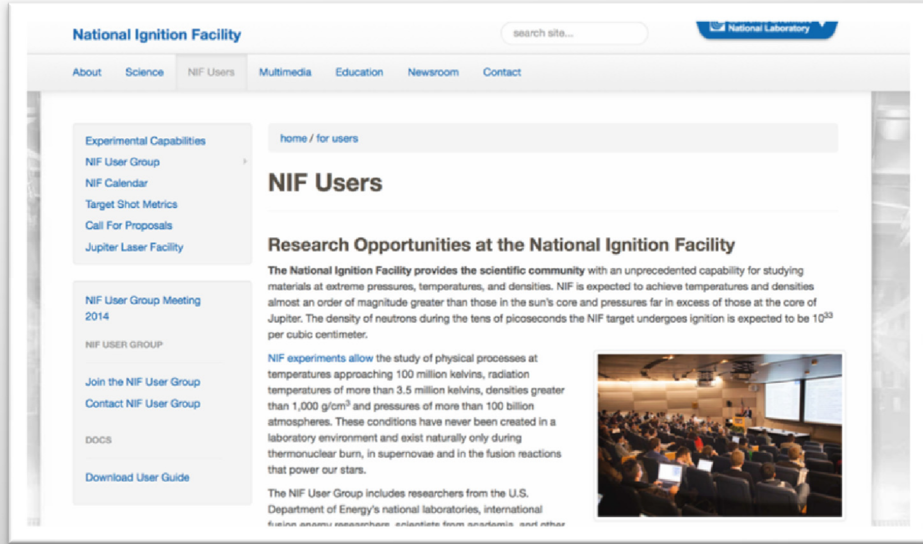


2014 NIF/Jupiter User Group meeting had ~ 200 attendees, including 55 student/postdoc attendees supported by NNSA and the DOE Office of Science

External User Resources

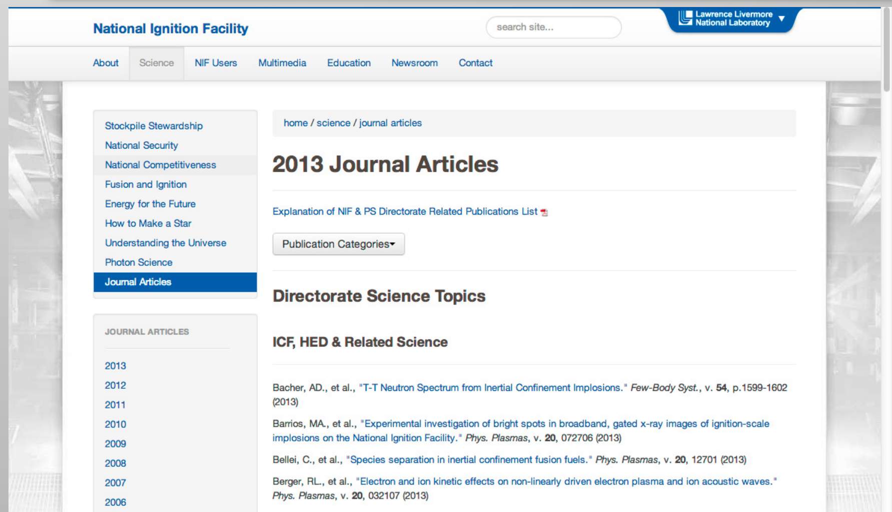
User website: https://lasers.llnl.gov/for-users

- NIF Calendar
- Target Metrics
- Annual User Group Meeting
- User Guide
- Call for Discovery Science Proposals issued May, 2014 with awards being issued in December, 2014



Journal Articles:

- https://lasers.llnl.gov/science/journal-articles



- Inquiries for User Office
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