Creating, Diagnosing, and Controlling High Energy Density Matter with the National Ignition Facility

University of Michigan

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National Ignition Facility Director
Thanks to the NIF team

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Lawrence Livermore National Laboratory

It's an exciting time in the field of High Energy Density Science and on the National Ignition Facility

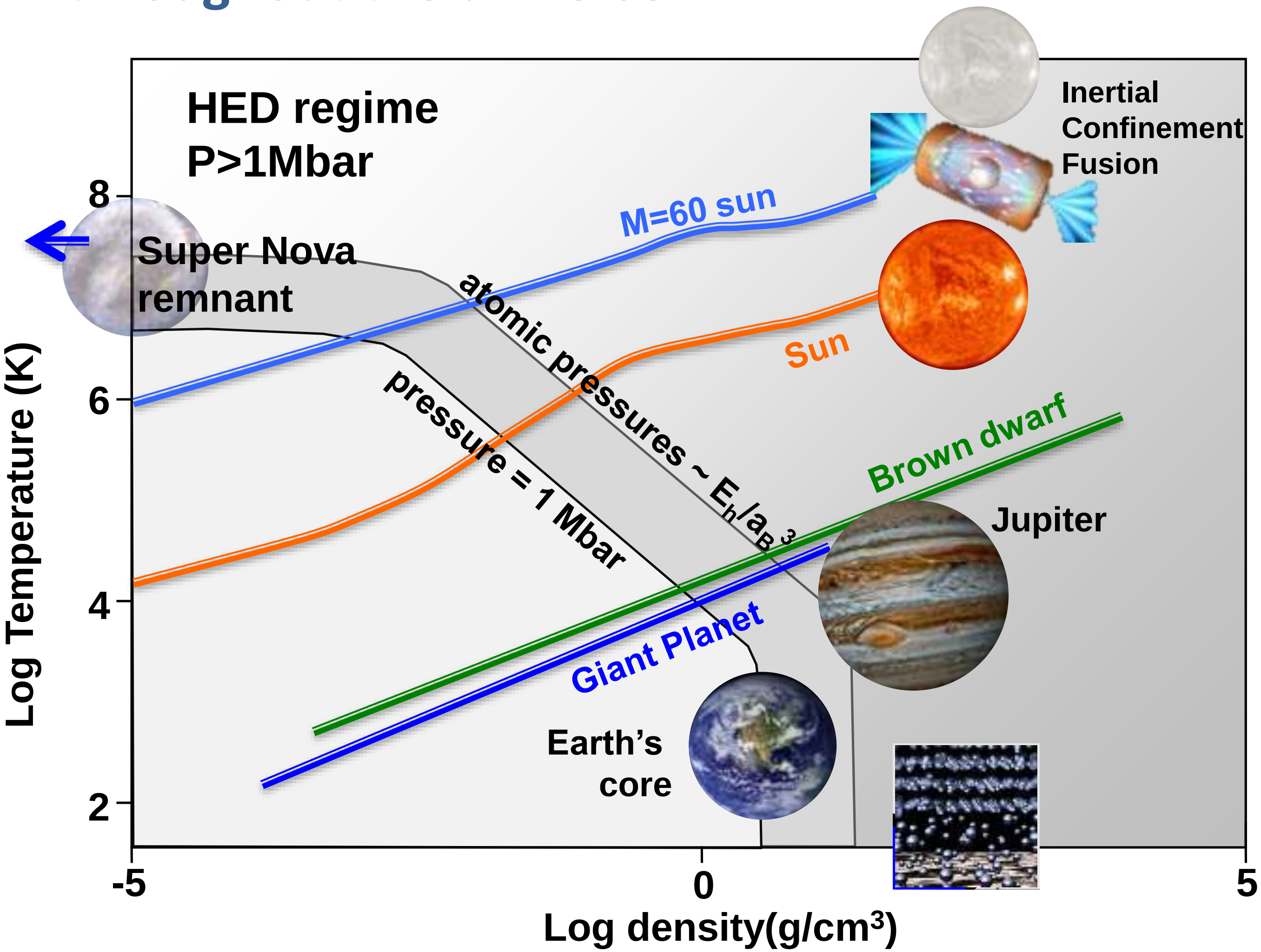
- Matter at high energy densities is ubiquitous in the Universe. There is a lot to understand about matter in these conditions.
- Experimental facilities to create and study matter in these extreme conditions have been developed and enhanced over the past decade, including the National Ignition Facility, the world's most energetic laser.
- On NIF we are performing ~ 2 experiments per day studying some of the most fundamental questions facing the field of high energy density science
- Achieving inertial confinement fusion ignition in the Laboratory is a grand scientific challenge. Progress is being made on understanding and improving inertial confinement fusion target performance, driven by new measurements. We remain committed to the exciting goal of obtaining fusion ignition in the laboratory

What is high energy density (HED) matter?

- **Pressure (Pascals, bars) is equivalent to Energy Density (J/m^3)**
  - **1 Mbar = 10^6 atm = 10^{11} Pascals = 10^{11} J/m^3**
- **HED threshold is pressures >1 Mbar, which exceeds the internal energy density of molecules/atoms (solids become compressible, etc.)**

Object	Pressure (Mbar)
Atmosphere at sea level	1e-6
High pressure gas cylinder	1e-4
TNT	0.1
Internal energy of H atom	1.0
Pressure at the center of the Earth	3.5
Pressure at the center of Jupiter	30+
Center of the sun	$2.5*10^5$

Matter in High Energy Density (HED) conditions is found throughout the universe



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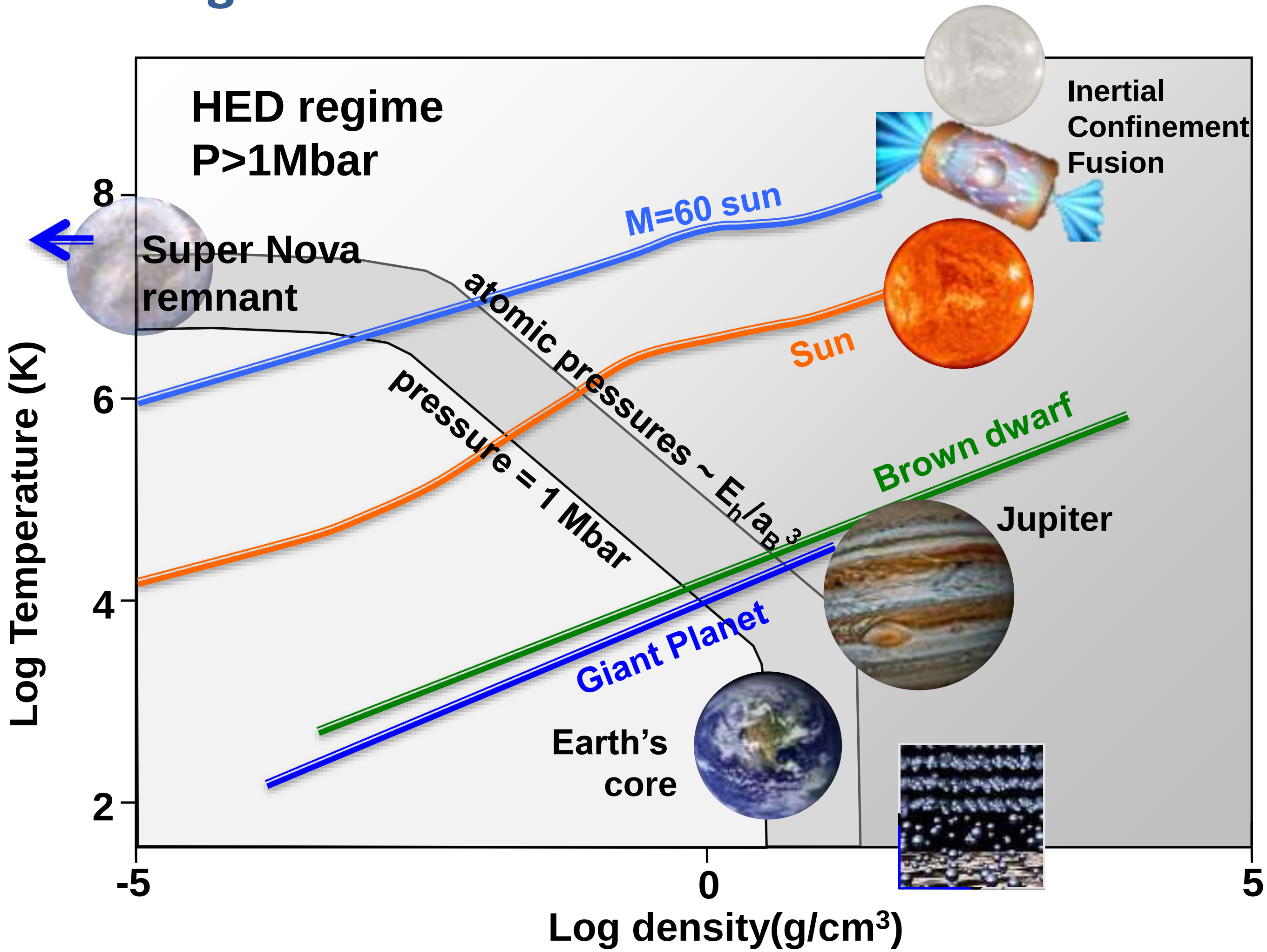


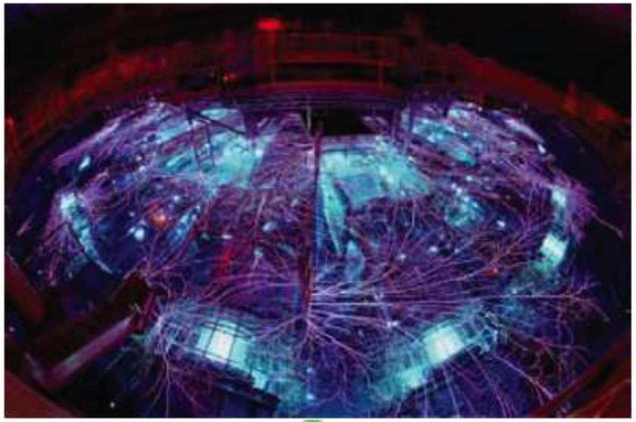
Important to understand:
Equation of State
Phase
Strength
Conductivity
Opacity
Ionization
Transport
Kinetics
Chemistry
…

For the first time in history we can produce and accurately characterize the states and processes over this broad range of conditions

The National Ignition Facility(NIF) is one of 3 major high energy density science facilities in the US

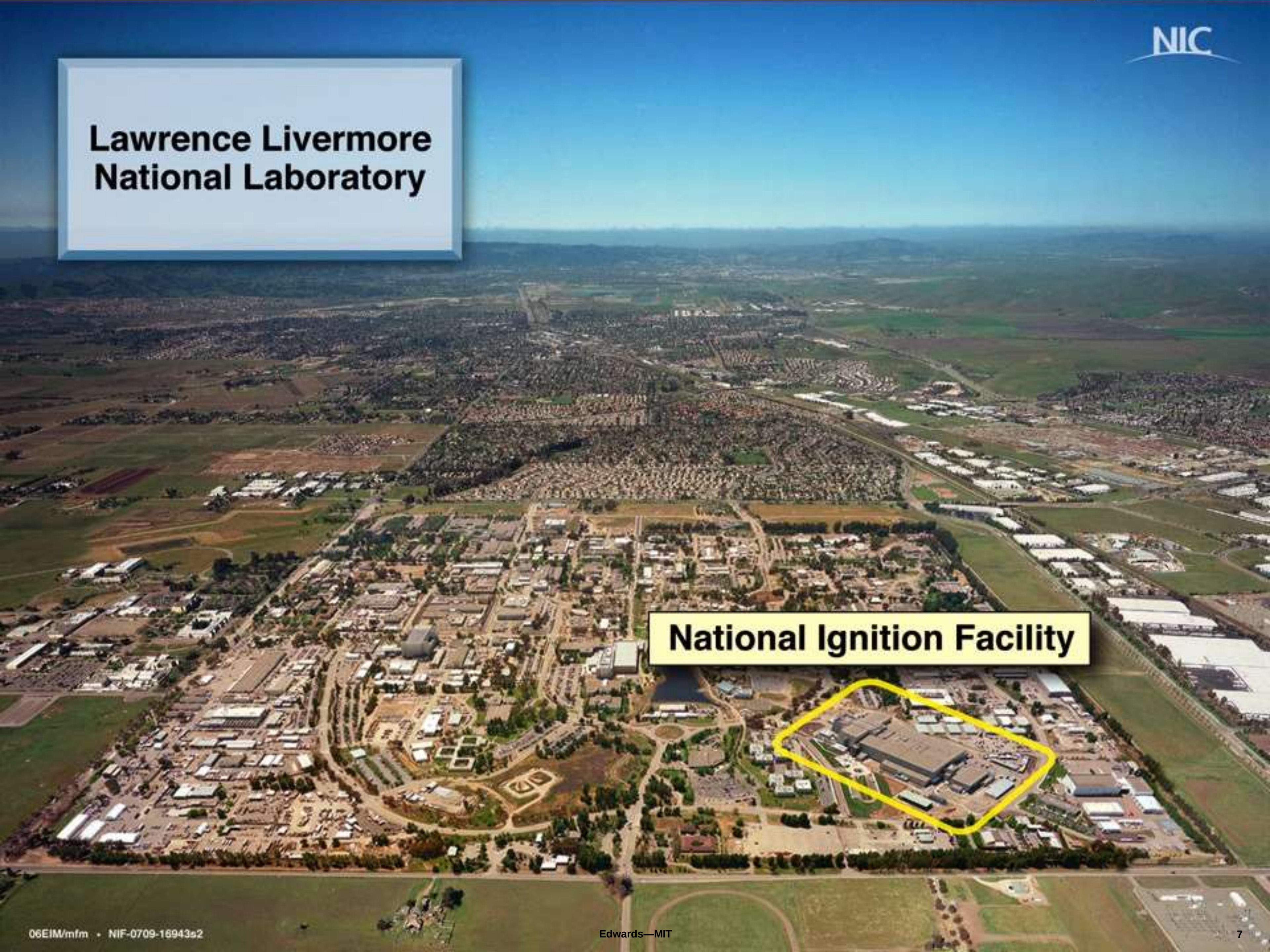
Omega and Omega EP Laser Facilities

Z Pulsed Power Facility



National Ignition Facility

NIF, Omega, and Z are supported by the National Nuclear Security Administration as a key part of the Stockpile Stewardship Program, which has the goal of maintaining a safe, secure, and effective US nuclear deterrent without further underground nuclear testing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National Ignition Facility
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The National Ignition Facility is the world's most energetic, high power laser and was designed to enable precision studies of the behavior of matter in the High Energy Density (HED) state.


Cardinal
GOLDEN BEARS
Bruins
Stanford
CALIFORNIA
UCLA

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

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


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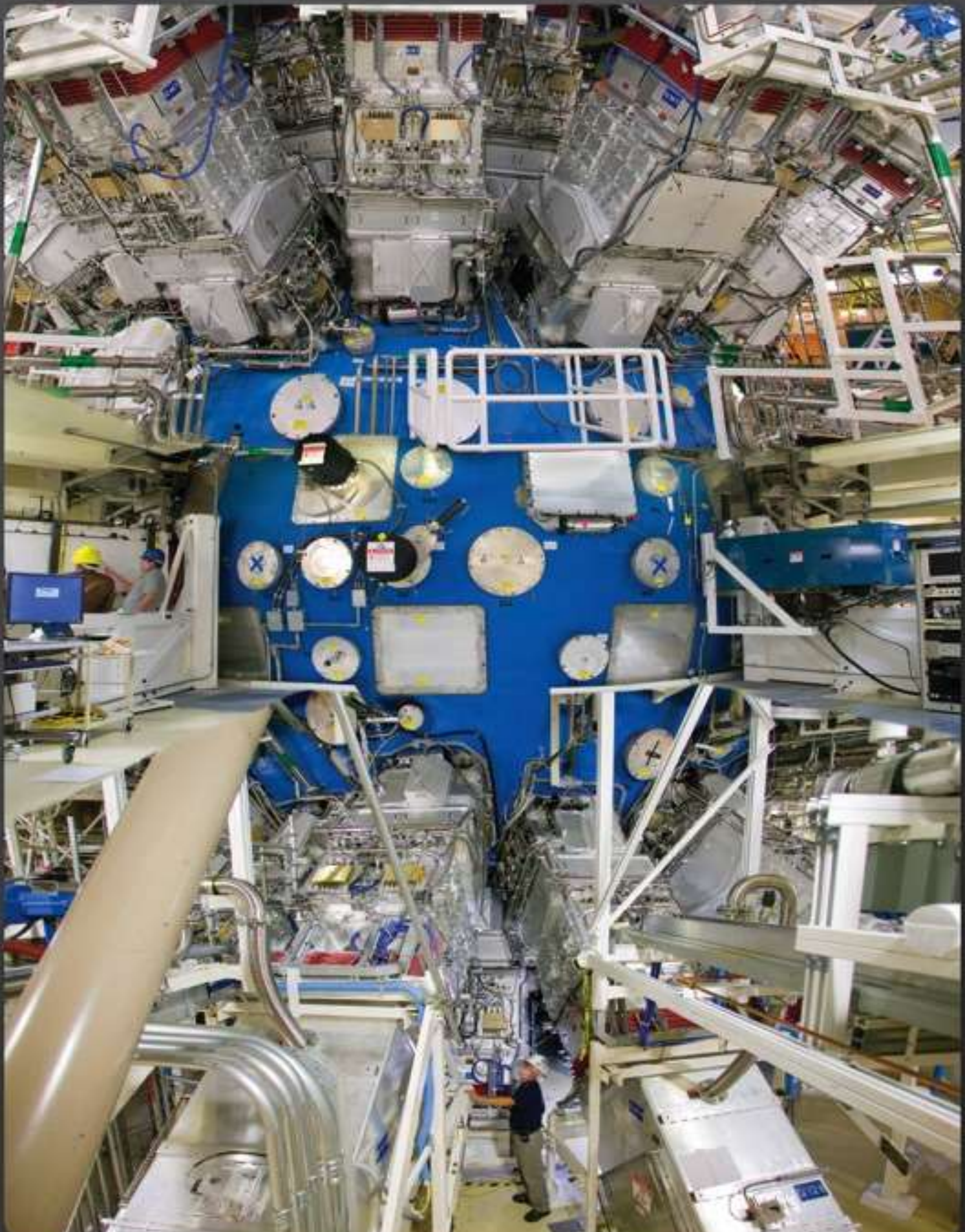
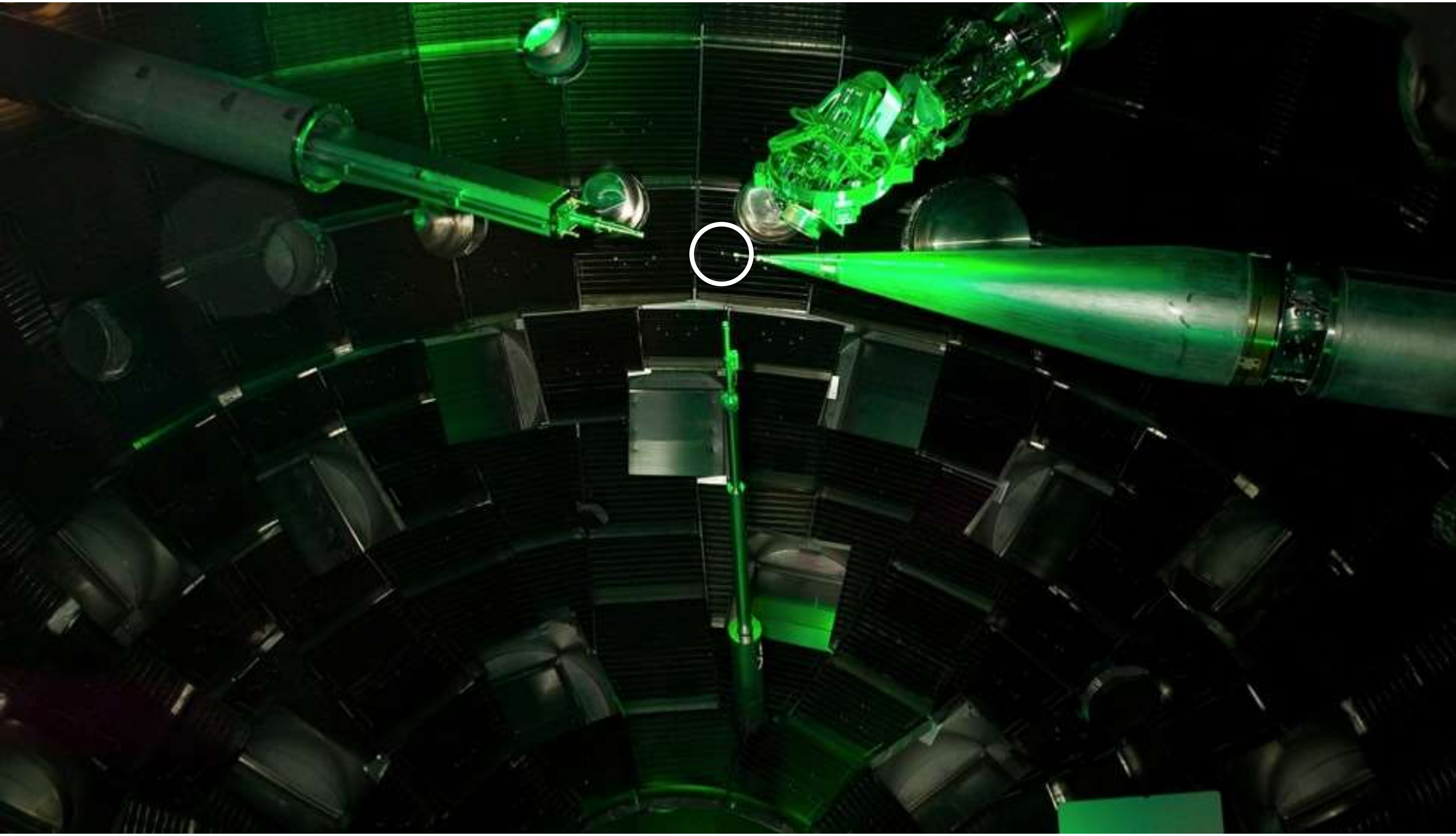


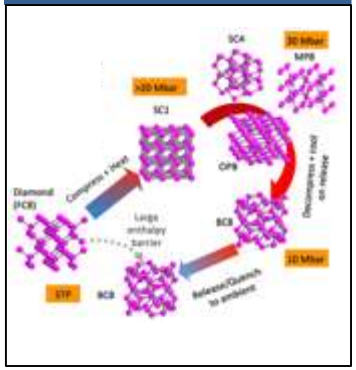
The ~cm scale target is inserted to the center of NIF's 10 m target chamber



Over 80 diagnostics

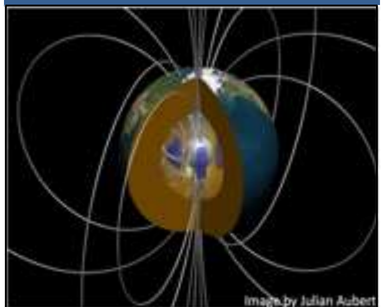
NIF allocates a small fraction of the facility's time to "Discovery Science"

Metastability of dynamically compressed C



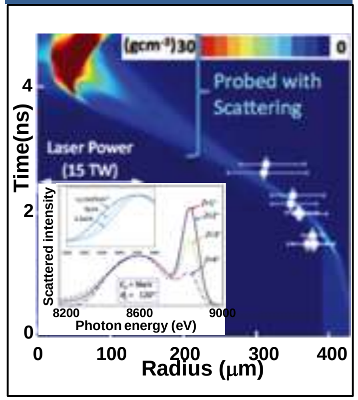
Wark (Oxford)

Iron melt curve, magnetospheres, and habitable Super Earths



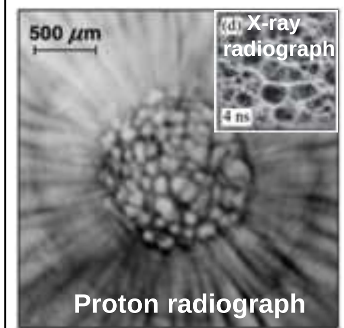
Hemley (CIW), Stewart (UCD)

Pressure ionization at extreme densities



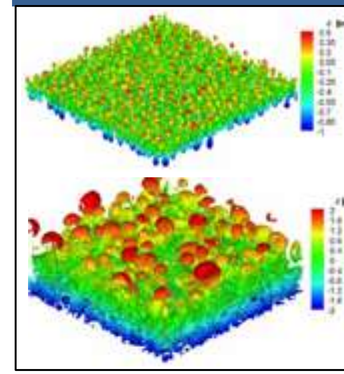
Neumayer(GSI), Falcone(UCB)

Direct-drive hydrodynamics



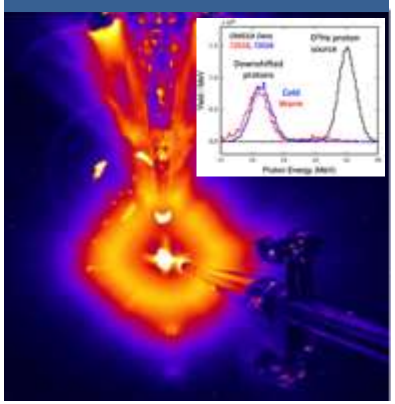
Casner(CEA),

Asymptotic self-similar instabilities



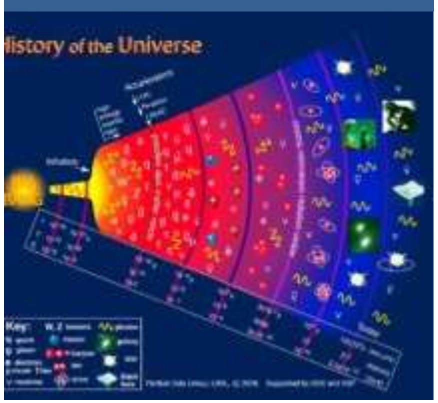
Shvarts(Israel), Drake(Mich)

Charged particle stopping powers



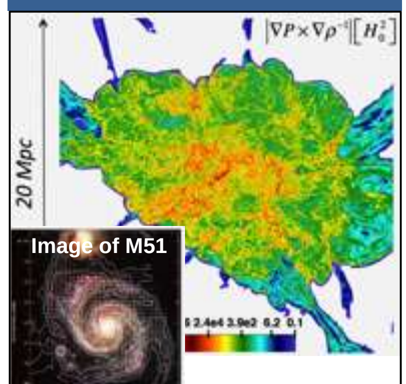
Zylstra (LANL), C.K.Li (MIT)

Stellar and Big Bang nucleosynthesis



Gatu-Johnson (MIT)

Turbulent dynamo B field amplification



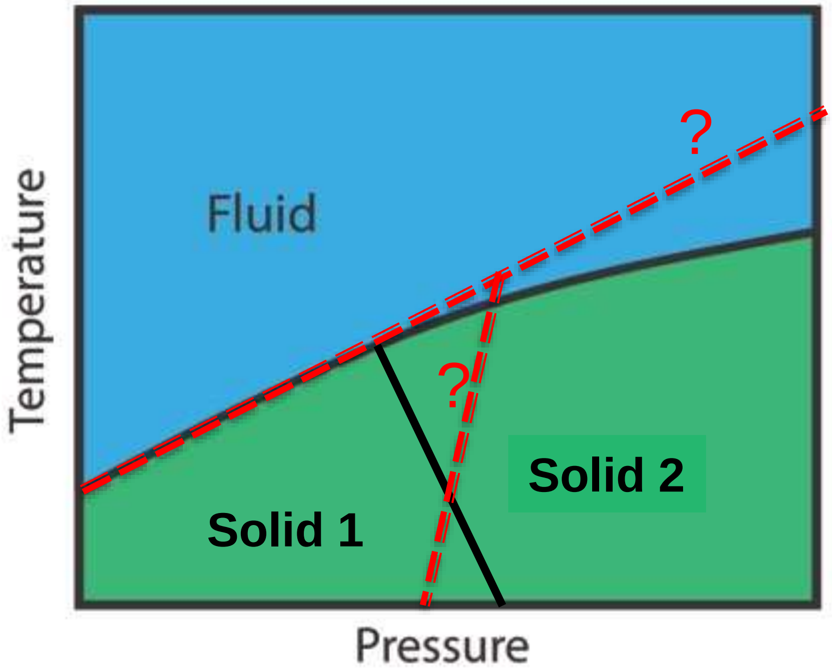
Gregori (Oxford), Lamb (Chicago)

Collisionless astrophysical shocks

Sakawa(Osaka), Spitkovsky(Princeton)

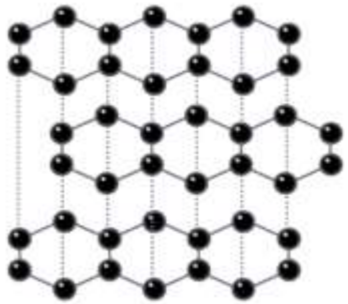
A material's atomic structure (or phase) can change abruptly as its temperature and/or pressure is varied

Phase Diagram



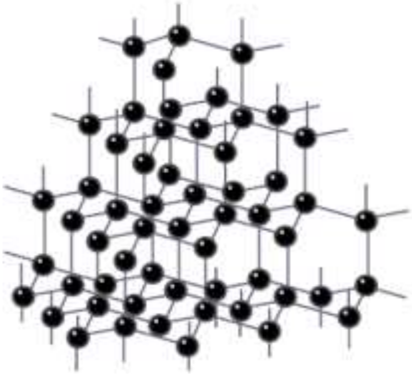
Graphite (Solid 1)

Atomic Structure



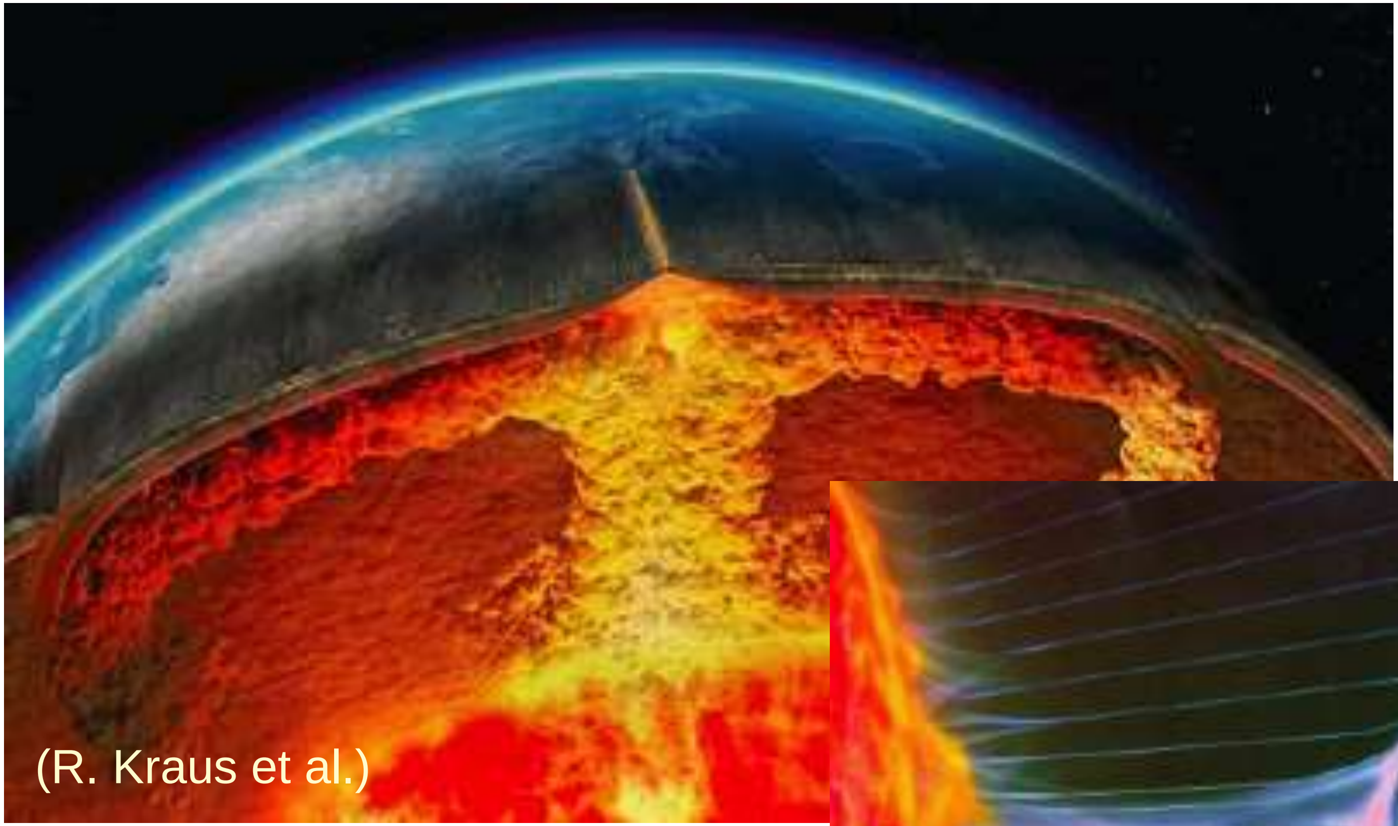
Diamond (Solid 2)

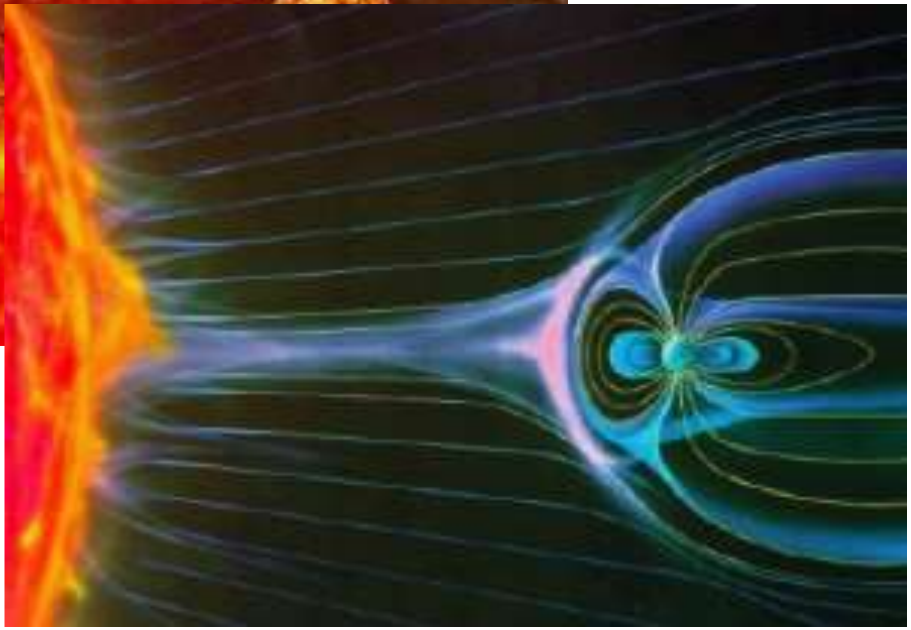
Atomic Structure



Graphite (pencil lead) turns into diamond when squeezed to high pressure

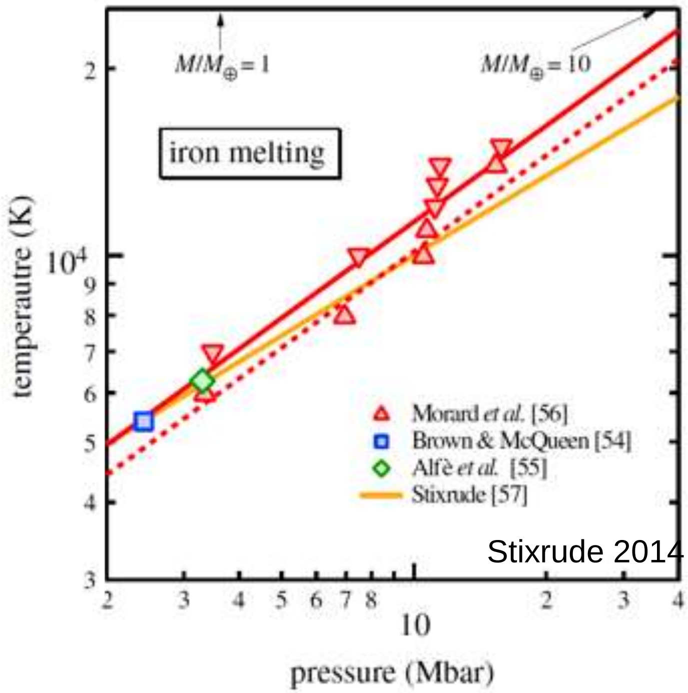
Material properties at high pressure play a key role in the evolution of habitable planets: protective magnetosphere, plate tectonics..

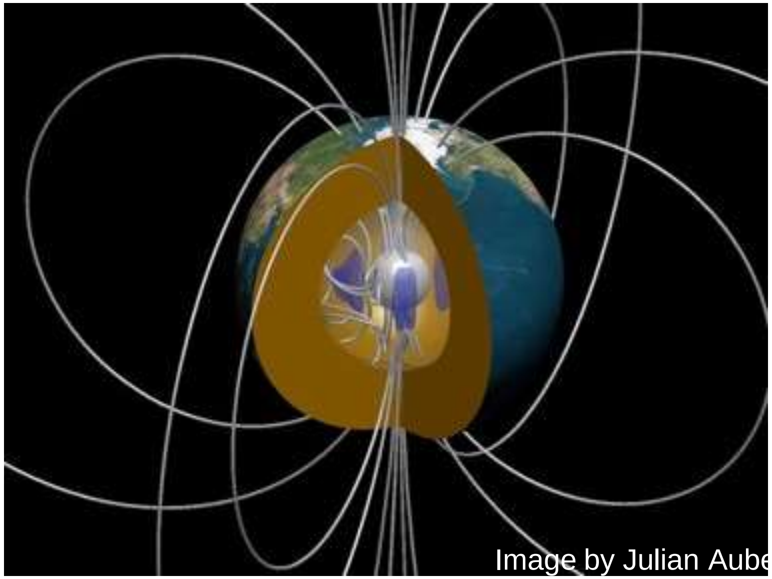




Solidification of the core plays a major role in the evolution of habitable planets

- Convection driven by solidification of the inner core can generate a magnetosphere, which protects the surface from charged particles



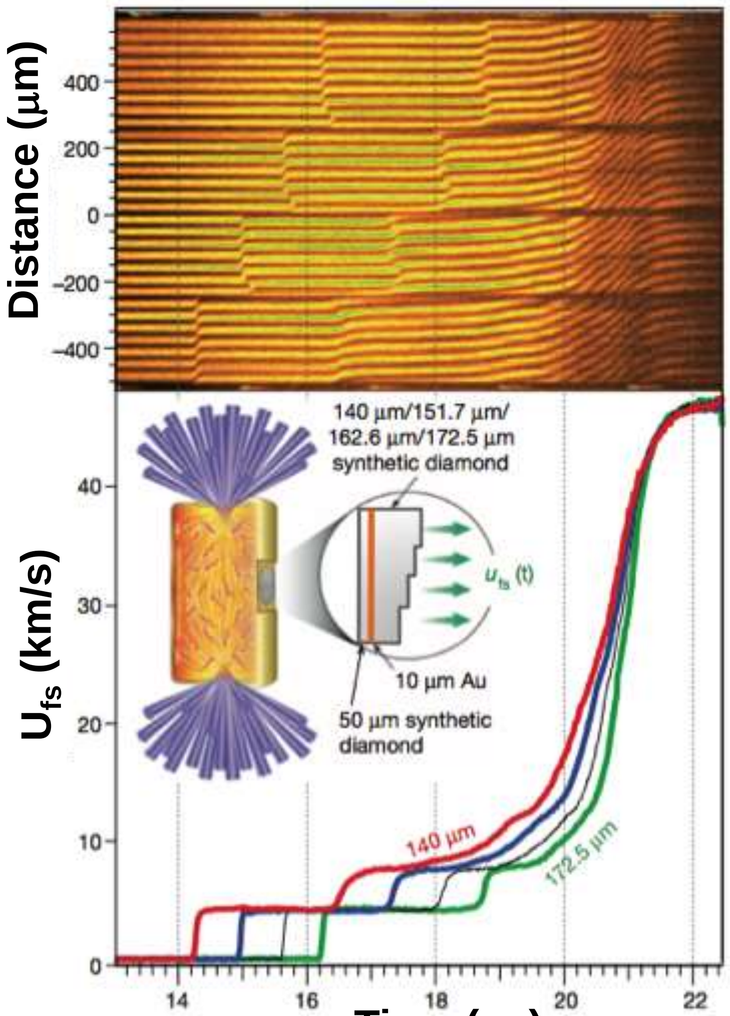


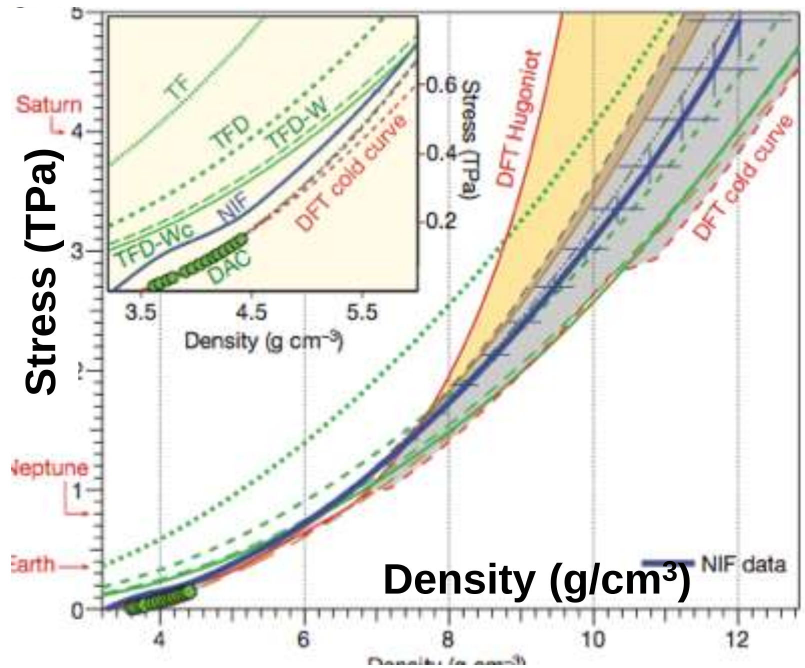
Our goal is to determine the types of exoplanets that can have a solidifying inner core, and therefore generate a protective magnetosphere.

Our goal is to determine the melting curve of iron from 5-20 Mbar.

[Courtesy of Rick Kraus (LLNL)]

The Carbon - Iron EOS team from Princeton, UCB, and LLNL carried out ramp compression of diamond (carbon) to five terapascals (50 Mbar)

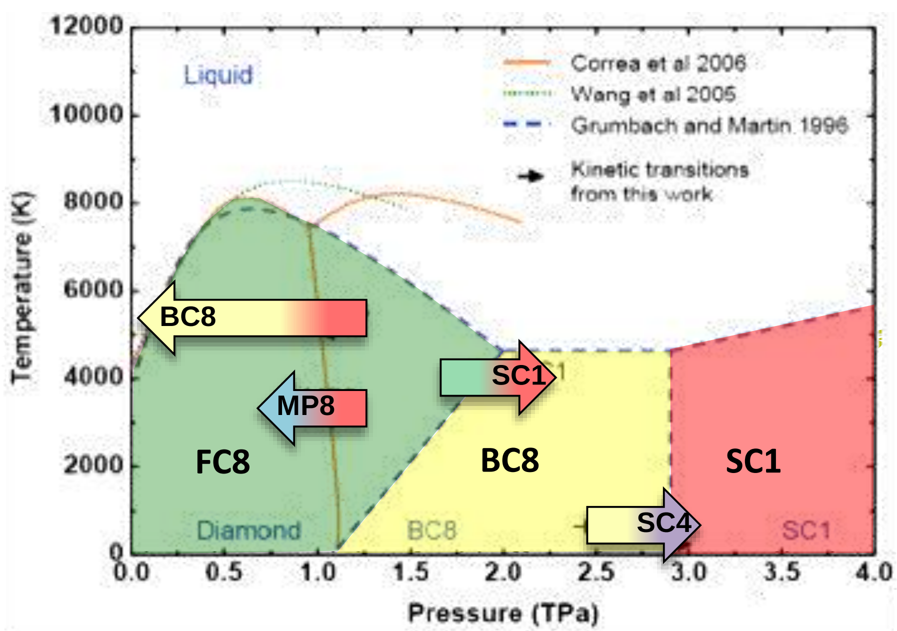




[“Ramp compression of diamond to five terapascals ,” R. F. Smith, J. H. Eggert, R. Jeanloz, T. S. Duffy, D. G. Braun, J. R. Patterson, R. E. Rudd, J. Biener, A. E. Lazicki, A. V. Hamza, J. Wang, T. Braun, L. X. Benedict, P. M. Celliers, and G. W. Collins, Nature 511, 330 (2014)]

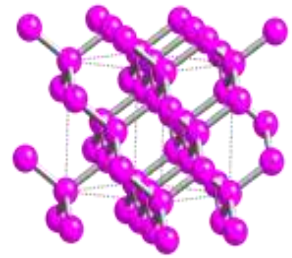
Multiple stable and metastable high-pressure phases predicted for diamond, and path for dynamic recovery at ambient conditions

Carbon Phase Space

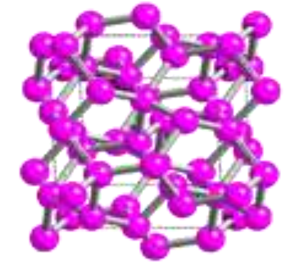


Sun, Klug, and Martonak, JCP 2009

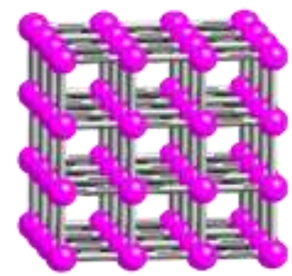
FC8 diamond



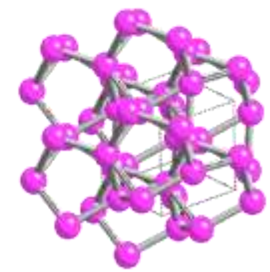
BC8 (1 TPa)



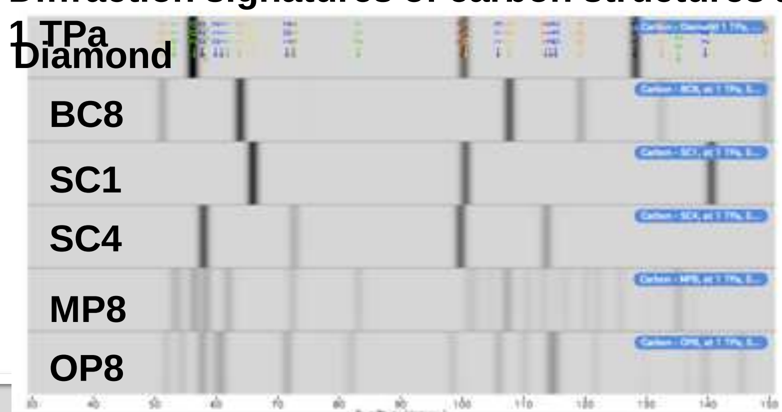
SC1 (3 TPa)



SC4 (metastable)



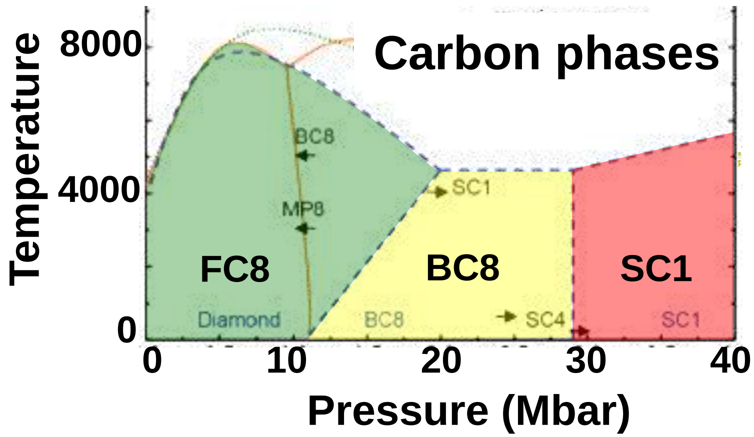
Diffraction signatures of carbon structures at 1 TPa

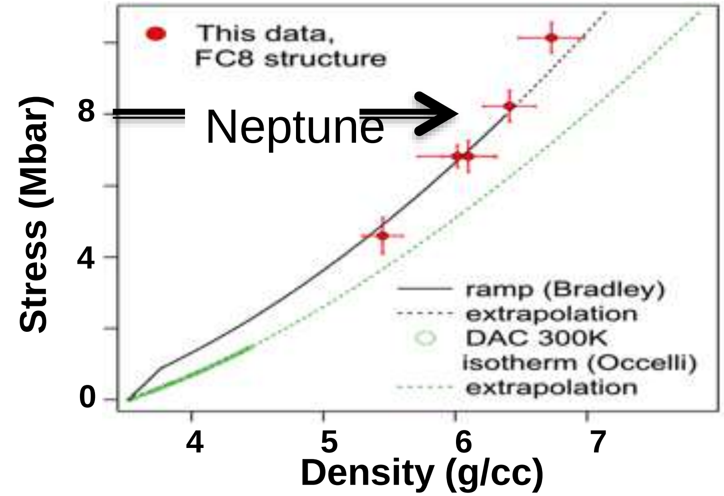


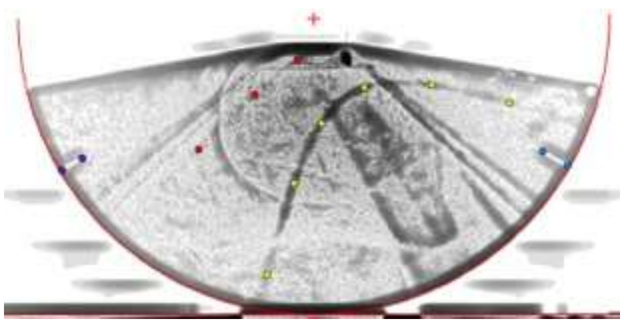
Possible path to new high-strength material, *Metastable BC8 carbon*!

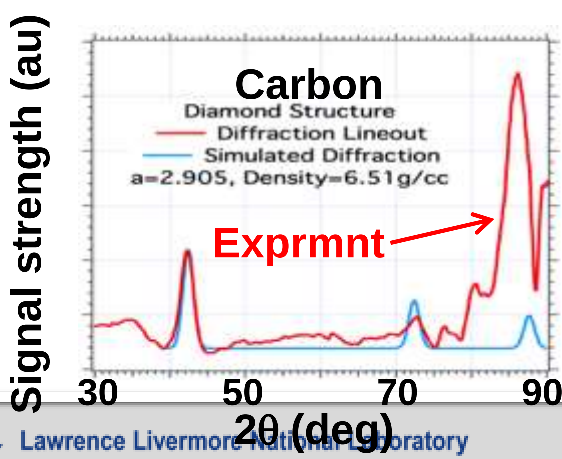
[Courtesy of Amy Lazicki Jenei (LLNL)]

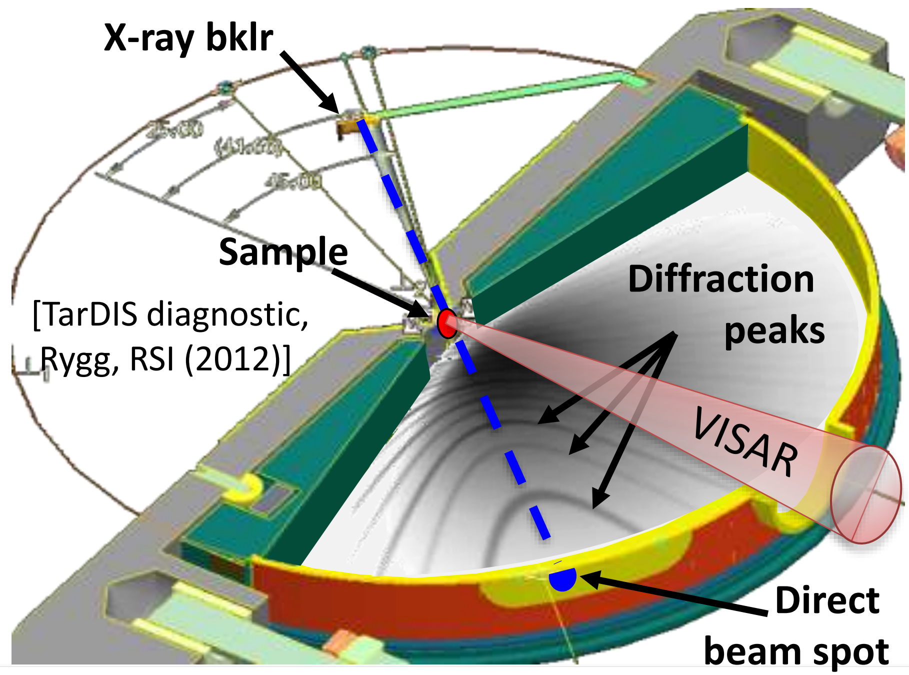
We are measuring the crystal structure of ramp-compressed carbon up to peak pressures of ~15 Mbar on NIF







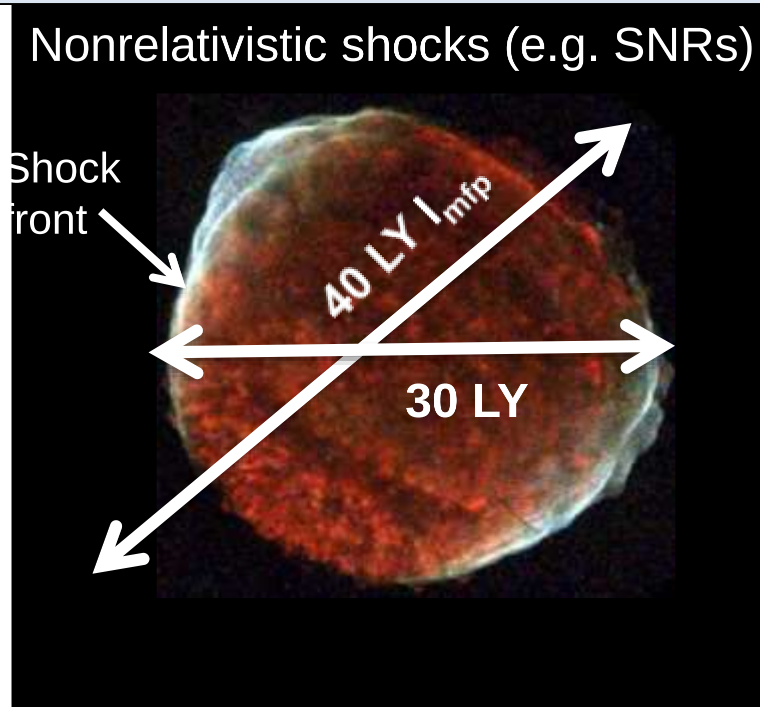




[Courtesy of Amy Lazicki Jenei; and see Jon Eggert]

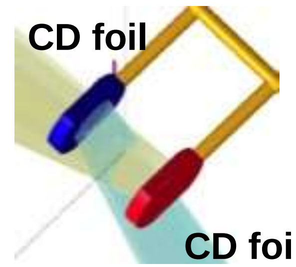
The collisionless shock collaboration on NIF shows how large, diverse collaborations can arise to work on these fascinating problems

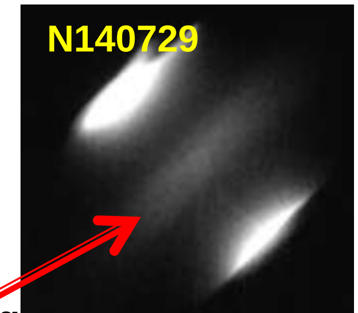
Collisionless shocks are ubiquitous in universe; Weibel instabilities can generate magnetic fields to form these shocks



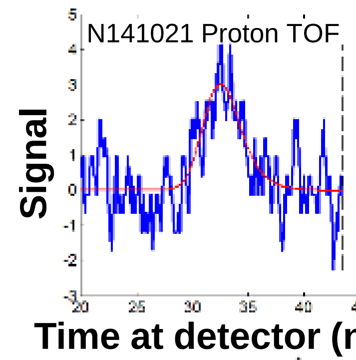
[Courtesy of Hye-Sook Park, Y. Sakawa (2015); C.M. Huntington, Nat. Phys. (2015)]

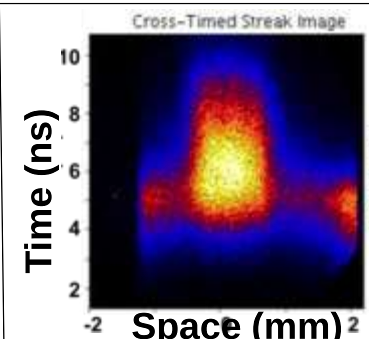
Experiments with CD-CD targets observed x-rays, neutrons and protons from the central shock-forming region





X-ray brightening from self-emission of hot plasmas





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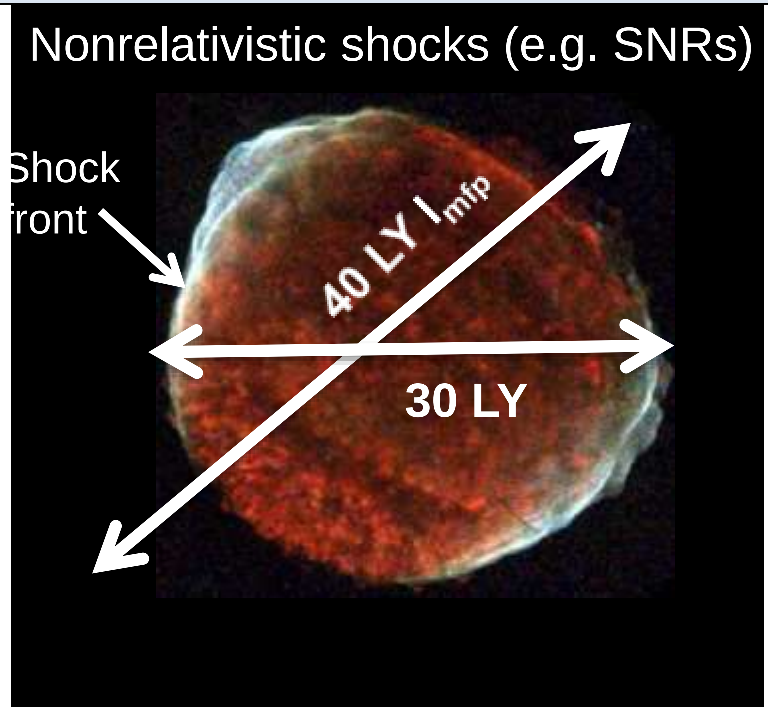

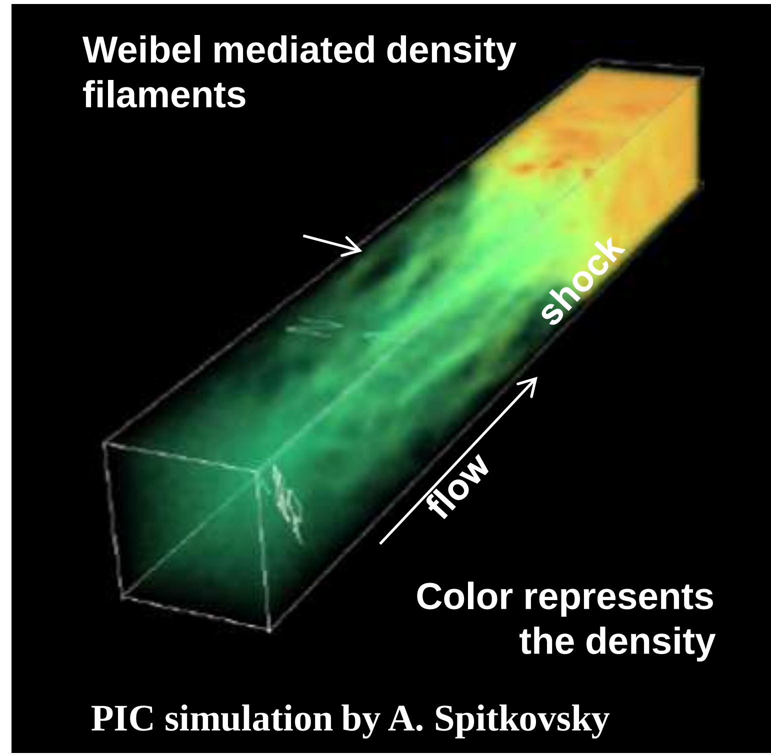

[Courtesy of Hye-Sook Park, Y. Sakawa (2015);
C.M. Huntington, Nat. Phys. (2015)]

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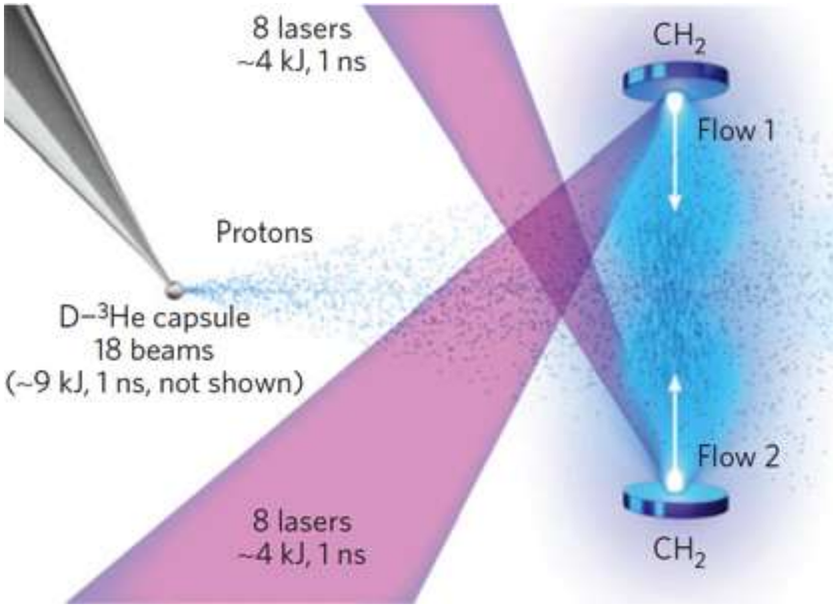
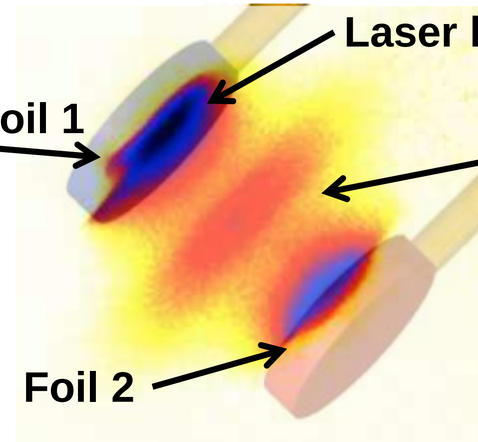
The NIF astrophysical collisionless shock experiment is seeing the beginning stages of shock formation



(Self generated) X-ray imaging



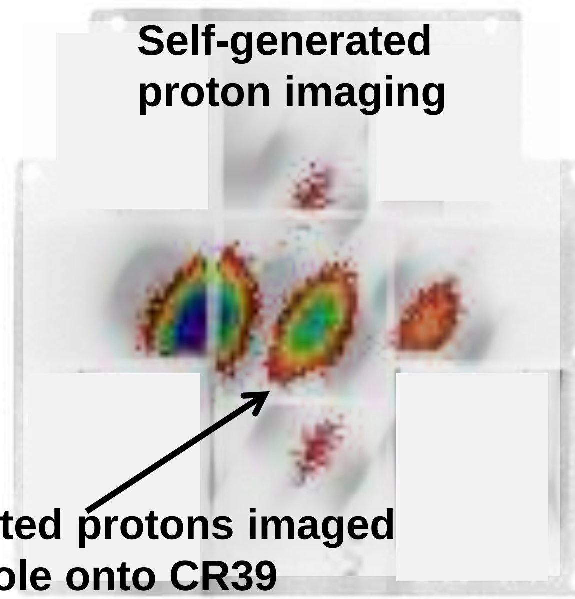
Laser hitting the target

Foil 1

X-ray brightening from self-emission of hot plasmas

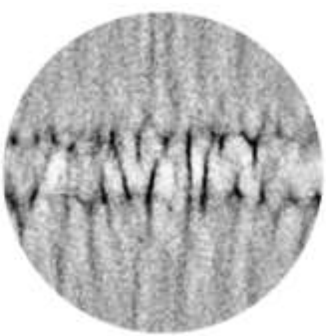
Foil 2

Self-generated proton imaging



Self-generated protons imaged with a pinhole onto CR39

PIC simul. of Weibel interactions

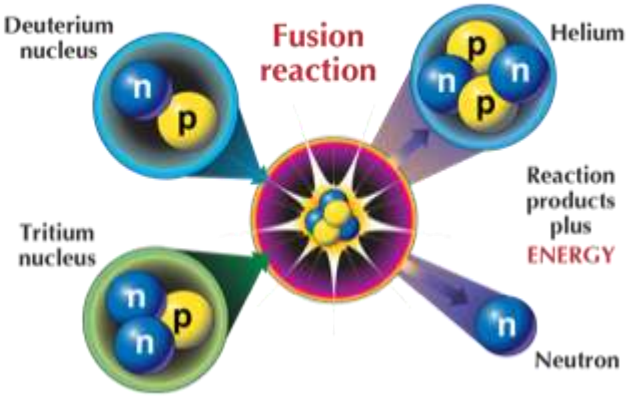


Omega exprmnt

[Huntington, Nature Phys. (2015)]

[Courtesy of Hye-Sook Park, Youichi Sakawa and Steve Ross]

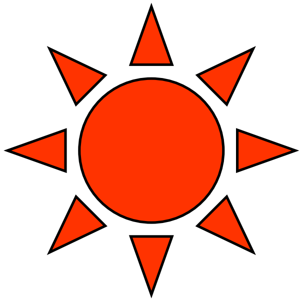
Like many areas of plasma physics, we not only want to understand nature, we want to control it



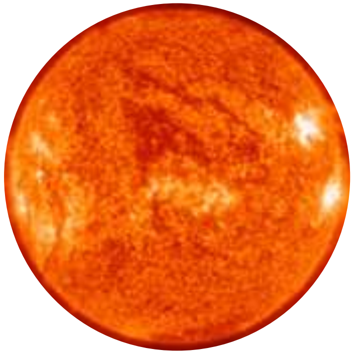
Can we assemble a mass of Deuterium and Tritium to high enough densities and temperatures that significant fusion takes place before the plasma falls apart?

Can the inertia of the assembled mass provide the confinement needed for fusion ignition?

Can we create a fusion yield comparable to the laser energy we invested in creating the DT plasma?



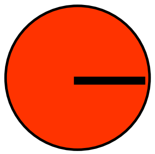
Inertial Confinement Fusion (ICF)



Gravitational Confinement

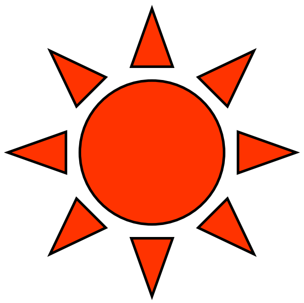
Magnetic Confinement Fusion

Under extreme conditions a mass of DT can undergo significant thermonuclear fusion before falling apart



ρ, R, T

$$\tau_{disassembly} \sim \frac{R}{c_s} \sim \frac{R}{\sqrt{T}}$$



$$\tau_{burn} \sim \frac{1}{n_i\langle\sigma v\rangle} \sim \frac{1}{\rho\langle\sigma v\rangle}$$

- The fractional burn up of the DT (for small burn up) is:

$$f_{burn} \approx \frac{\tau_{disassembly}}{\tau_{burn}} \sim \rho R \frac{\langle\sigma v\rangle}{\sqrt{T}}$$

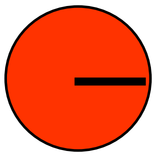
- At sufficiently high ρR and T the fractional burn up becomes significant and the energy deposited by alpha particles heats the fuel further leading to a runaway reaction (“ignition”)

- Typical conditions are:

$$\rho R \approx 0.4\,\mathrm{g/cm^2}$$

$$T \approx 5\,\mathrm{keV}$$

For hot spot ignition in the laboratory fusion fuel must be brought to a pressure of a few hundred billion atmospheres



ρ, R, T

For ignition conditions: $\left\{ \begin{array}{l} \rho R \approx 0.4\,\mathrm{g/cm^2} \\ T \approx 5\,\mathrm{keV} \end{array} \right\}$

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

$E_{NIF} \sim 15\,\mathrm{kJ} \Rightarrow P \sim 400\,\mathrm{GBar}$ $\quad R \sim 30\,\mu\mathrm{m} \Rightarrow$ and $\rho \sim 130\, g/cm^3$

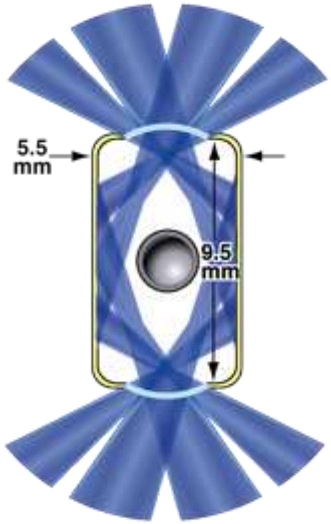
$$\tau_{conf} \sim \frac{R}{c_s} \sim 30\, ps$$

High velocity implosions can achieve these conditions

Note for magnetic confinement fusion ignition $\quad \tau_{conf} \sim$ few seconds $\quad P \sim$ few Bars $\quad \rho \sim$ few $10^{-10}\, g/cm^3$

High velocity, thin shell implosions are the most common approach to reach these conditions

Indirect Drive (X-ray)



In either direct or indirect drive, peak drive pressures are of order ~ 50-150 MBars

We need to get pressures to > 1000X that for ignition!

Spherical implosions enable us to store energy in the fusion fuel in the form of kinetic energy, which is converted to pressure at stagnation

$$P_{stag} \sim \alpha \rho_{stag}^{5/3} \qquad \alpha \rho_{stag}^{2/3} \sim \mathrm{v}^2 \Rightarrow P_{stag} \sim \mathrm{v}^5 / \alpha^{3/2}$$

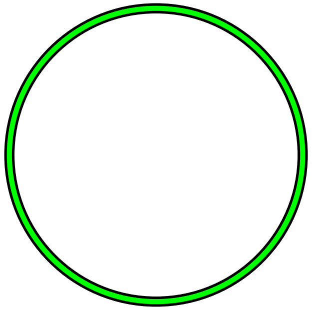
$$\alpha \equiv P / P_{Fermi}$$

Direct Drive (Laser)

Thin shell implosions can reach the 200-400 km/sec needed for ICF

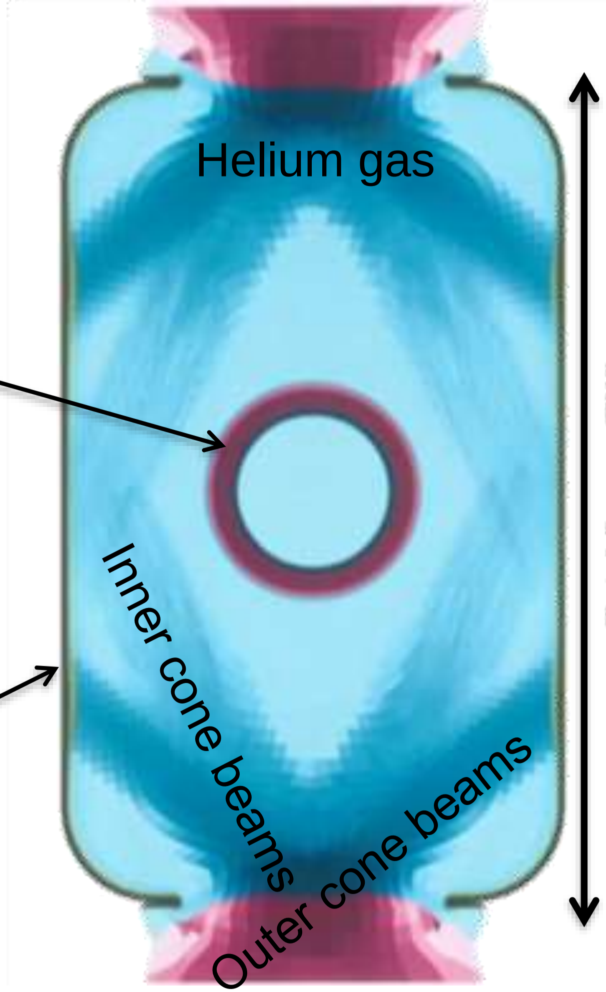
$$\int P_{drive} \mathrm{dV} = \frac{1}{2} m \mathrm{v}^2 \qquad m \sim 4\pi R^2 \rho \delta R$$

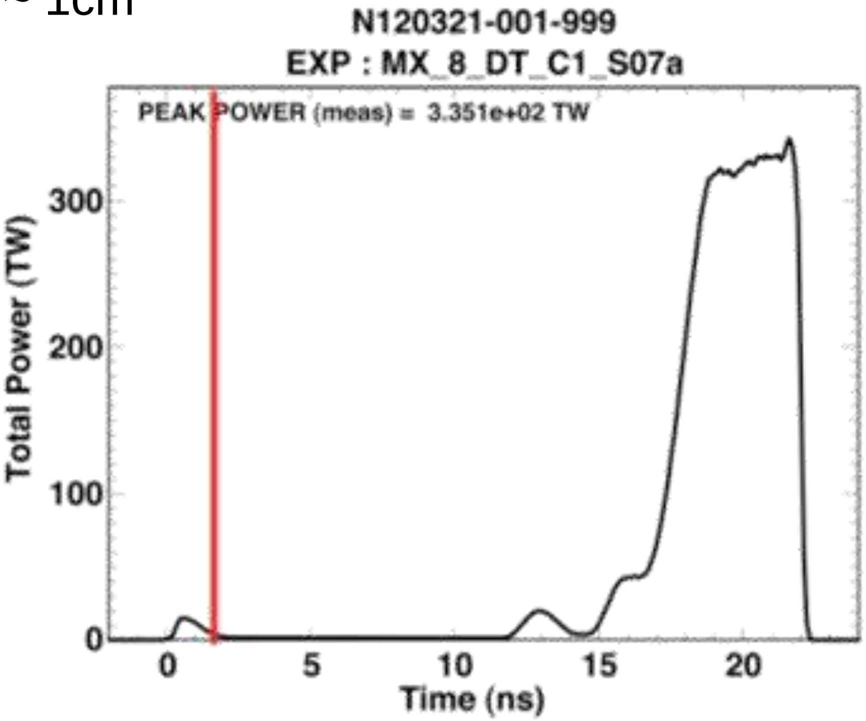
$$P_{drive} R^3 \sim R^2 \rho \delta R \, \mathrm{v}^2 \Rightarrow \mathrm{v}^2 \sim \frac{P_{drive}}{\rho} \frac{R}{\delta R}$$

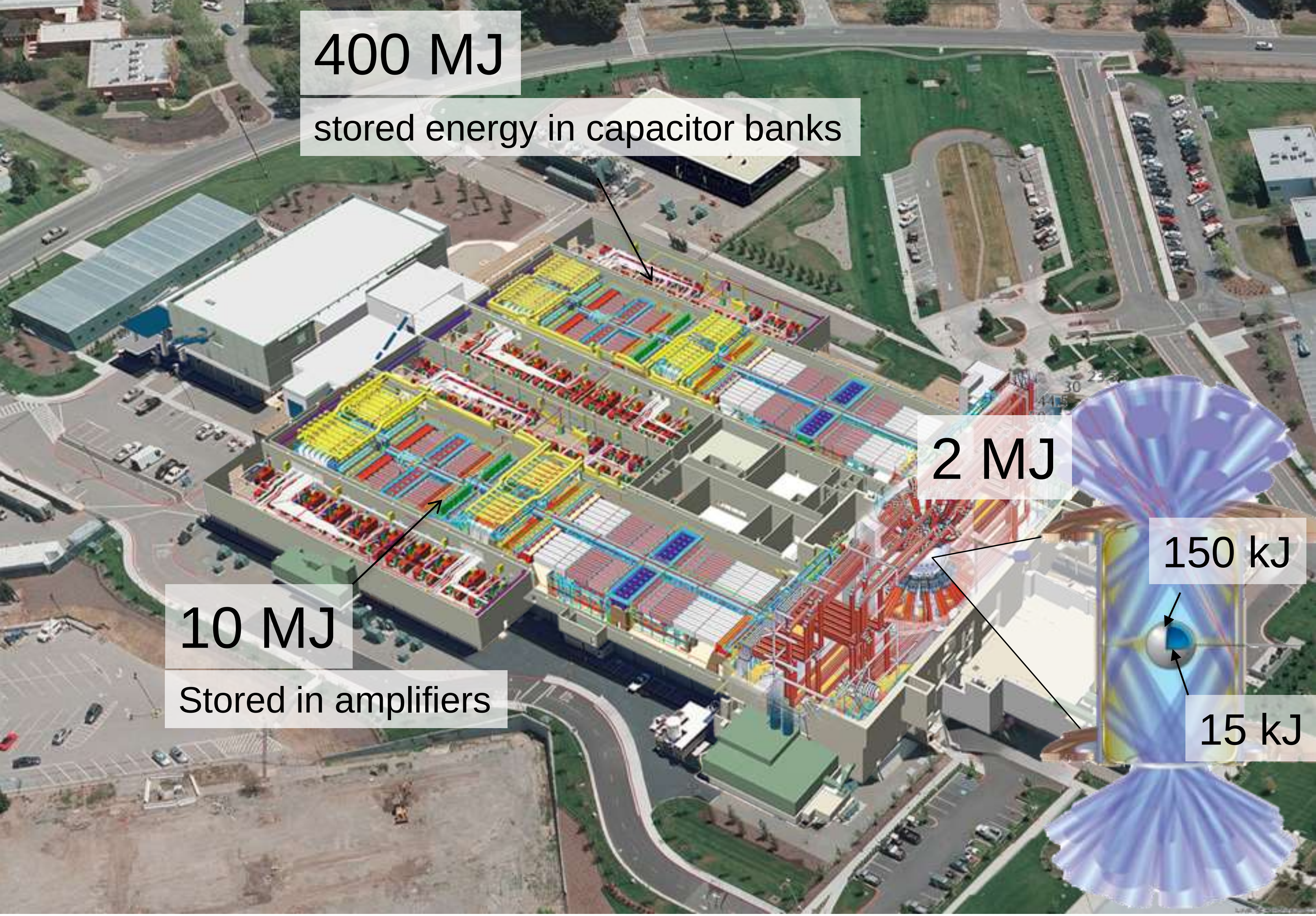


A fundamental and open question is how efficiently do implosions stagnate in nature

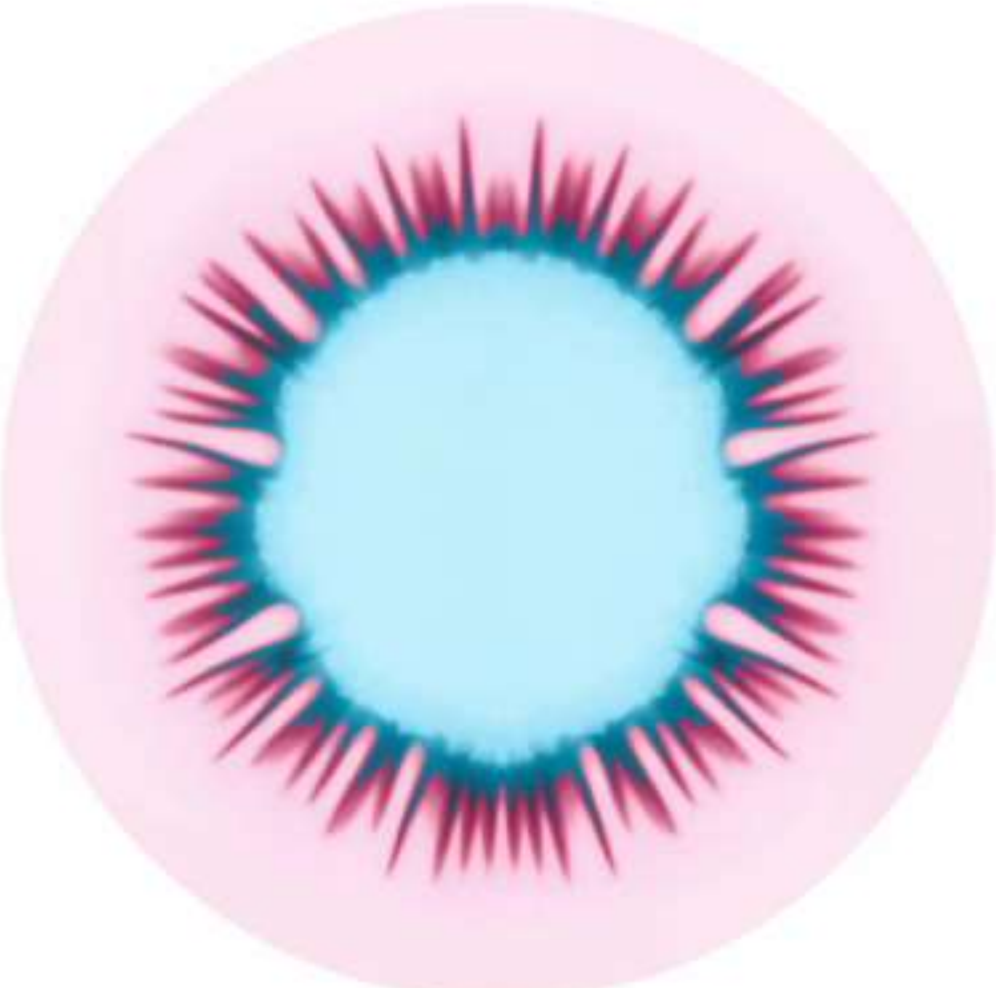
The primary ICF approach on NIF uses the lasers to indirectly drive the capsule implosion (Laser Power-> X-ray Power)



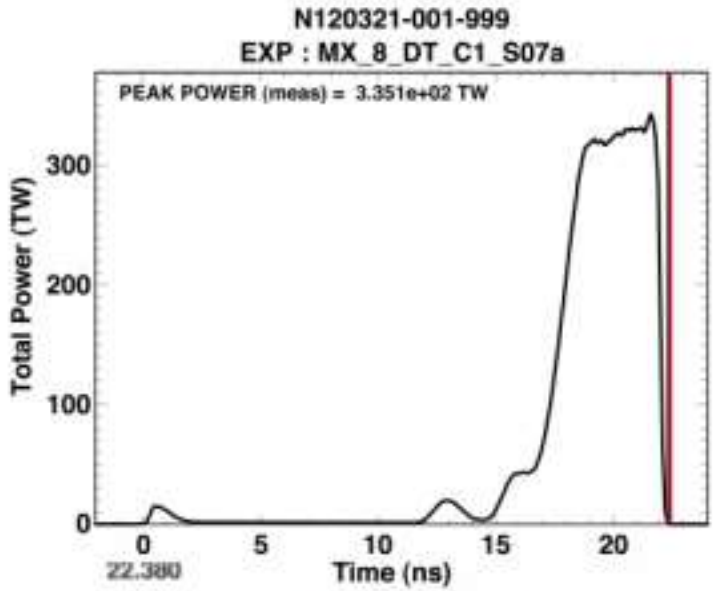


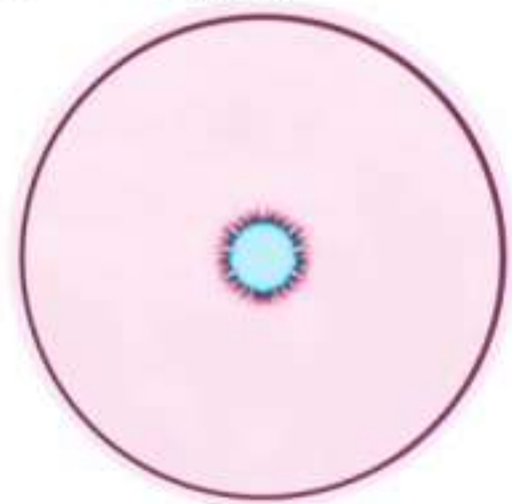

400 MJ
stored energy in capacitor banks
2 MJ
10 MJ
Stored in amplifiers
150 kJ
15 kJ

Detailed simulations show the susceptibility of the capsule to hydrodynamic instabilities

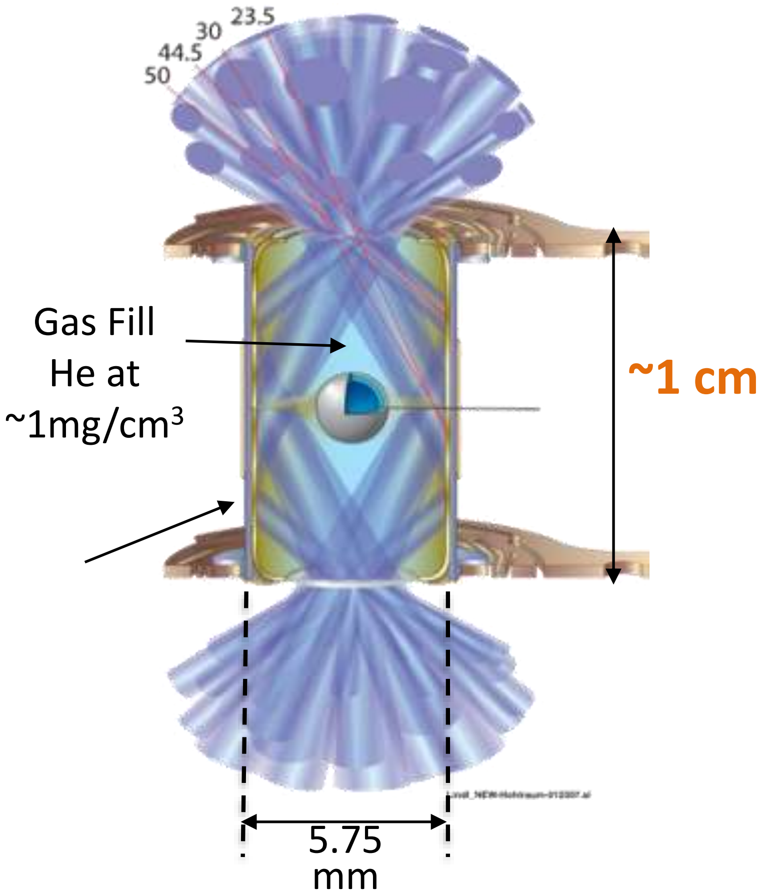


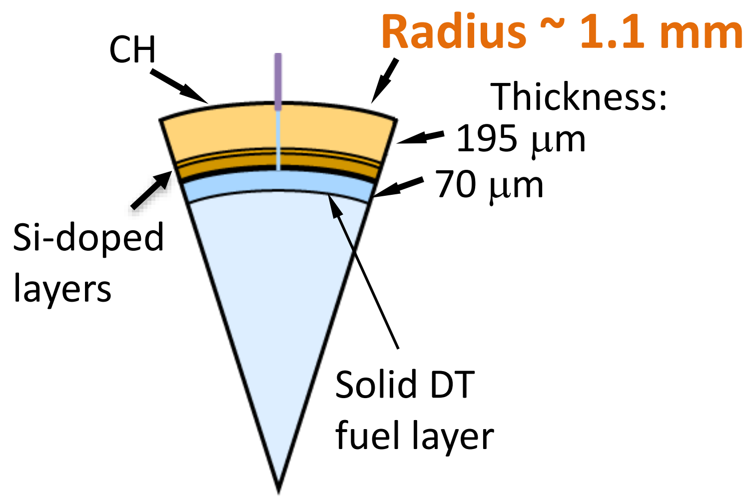
VGLayoutHoSm.mov



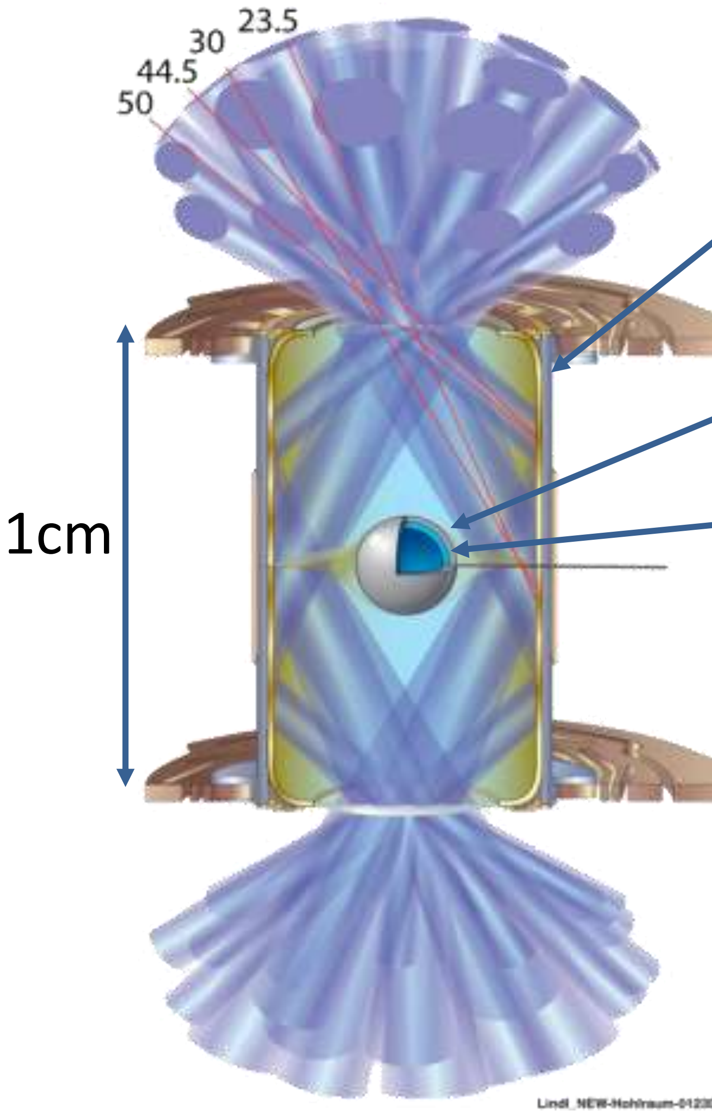


Each new experiment requires a detailed specification of the configuration, there is a large parameter space





There is a large parameter space that can be explored



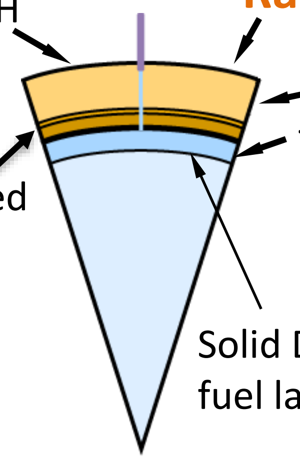
Hohlraum
- Fill
- Wall
- Shape

Capsule

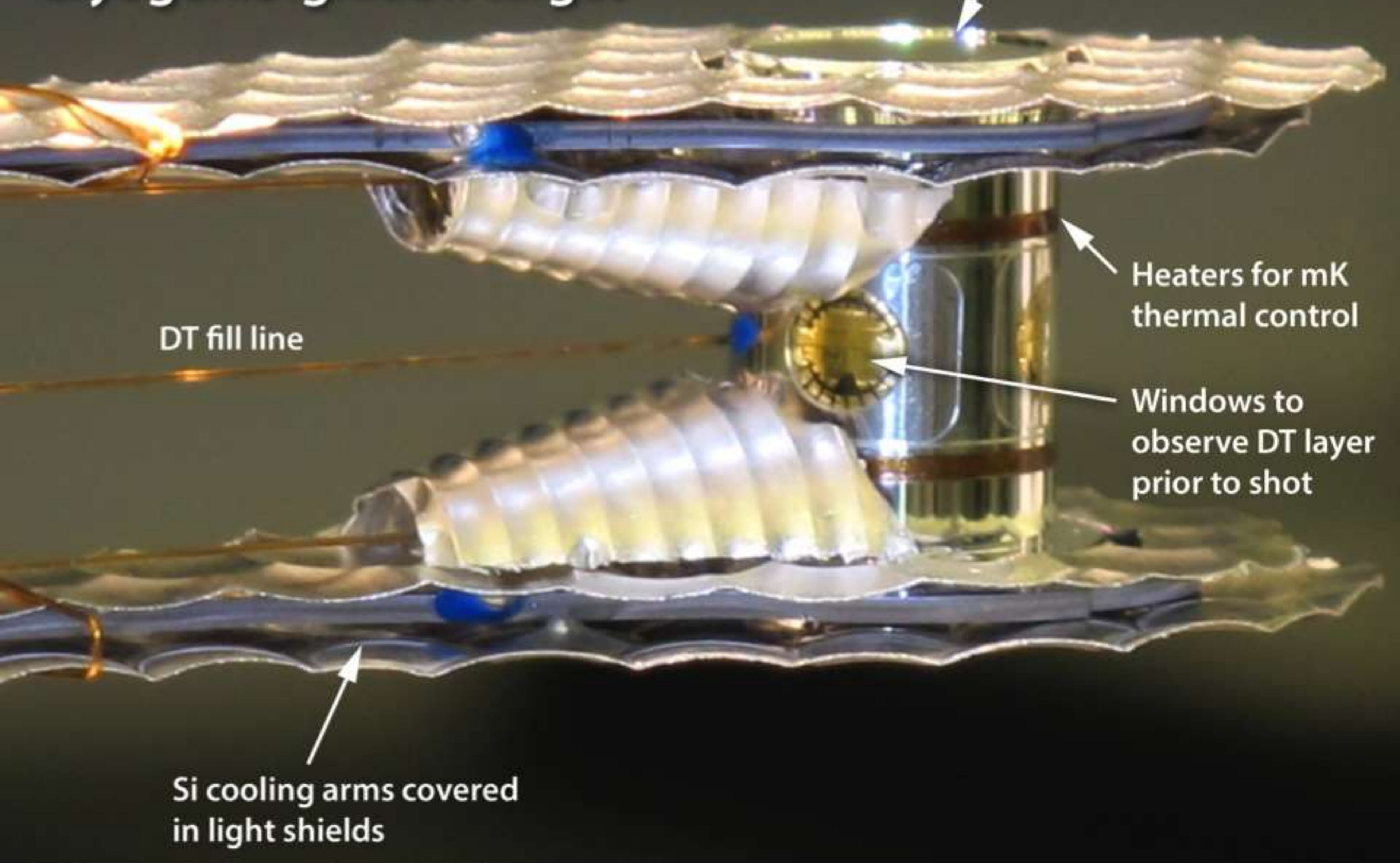
DT fuel

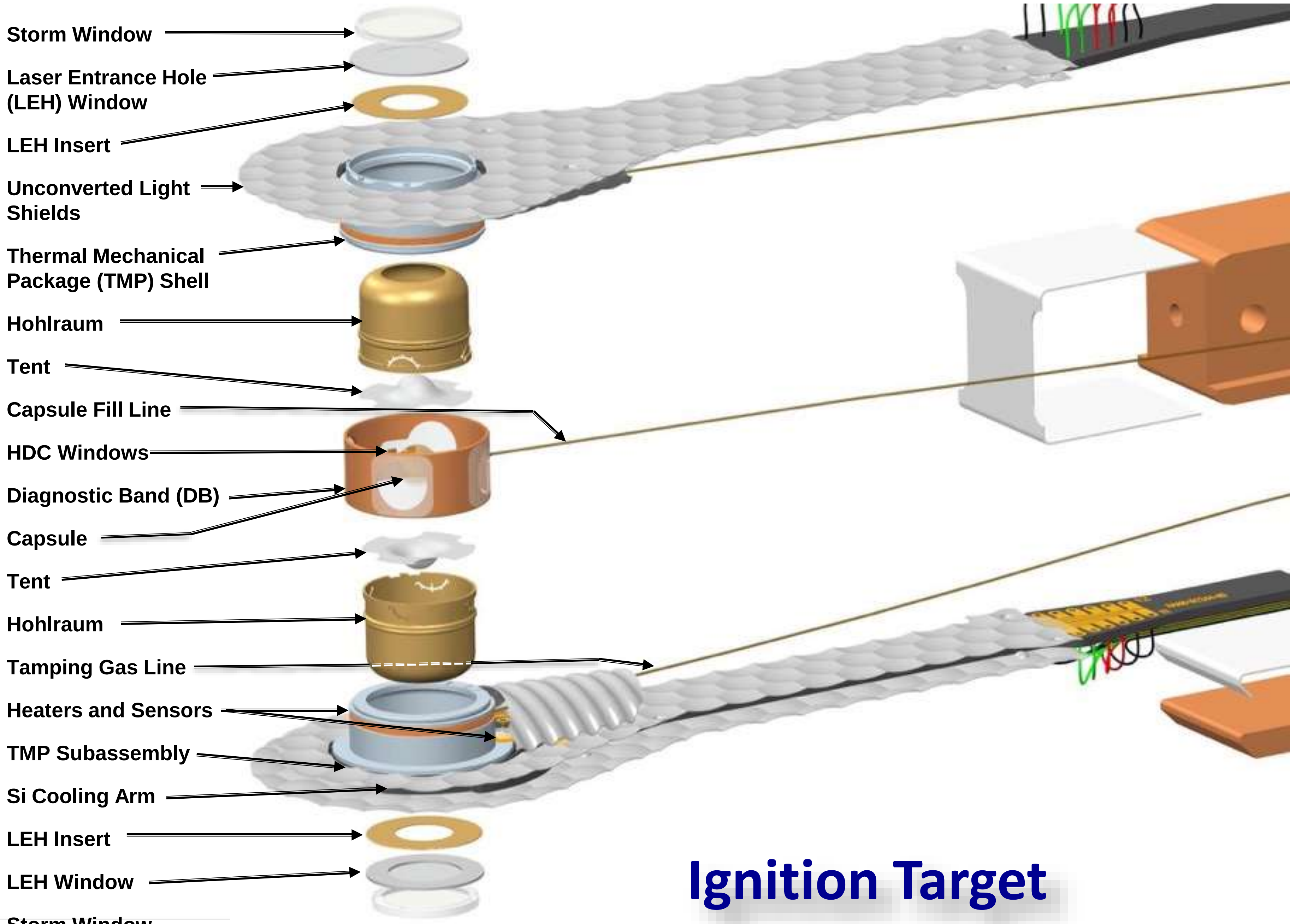
CH	Beryllium	Diamond
(1.1 g/cc)	(1.85 g/cc)	(3.5 g/cc)

Radius ~ 1.1 mm



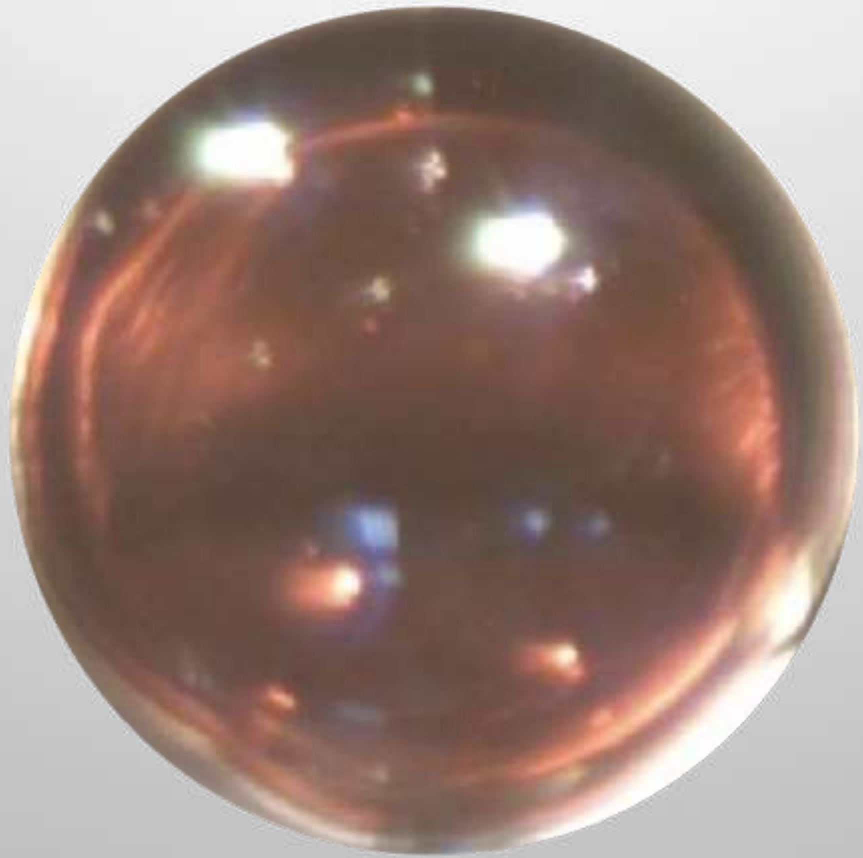
Cryogenic Ignition target

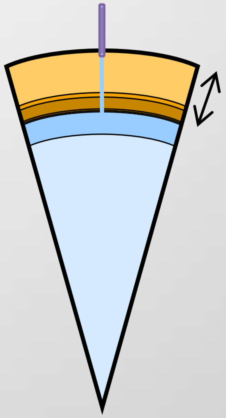




Ignition Target

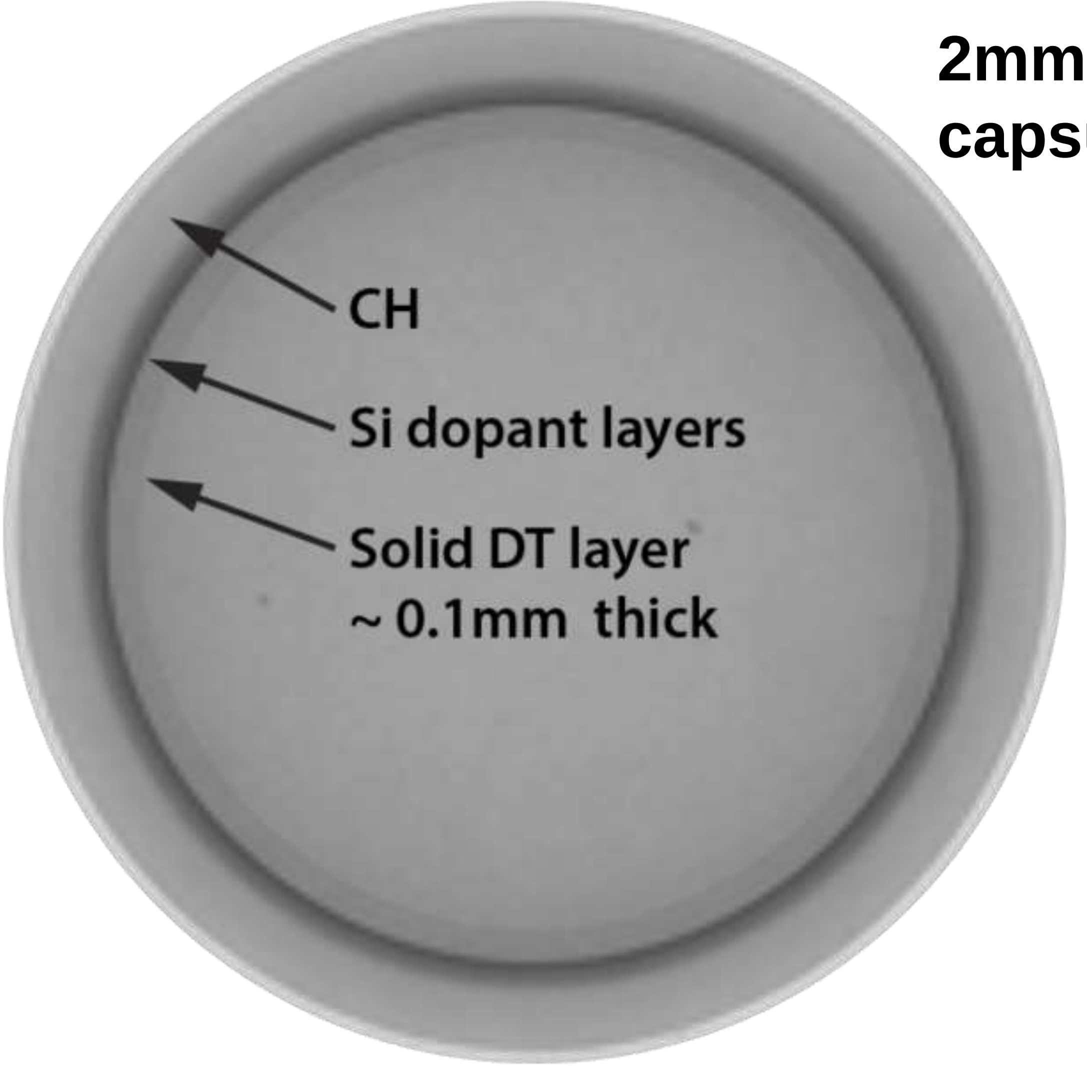
Plastic Ignition Capsule





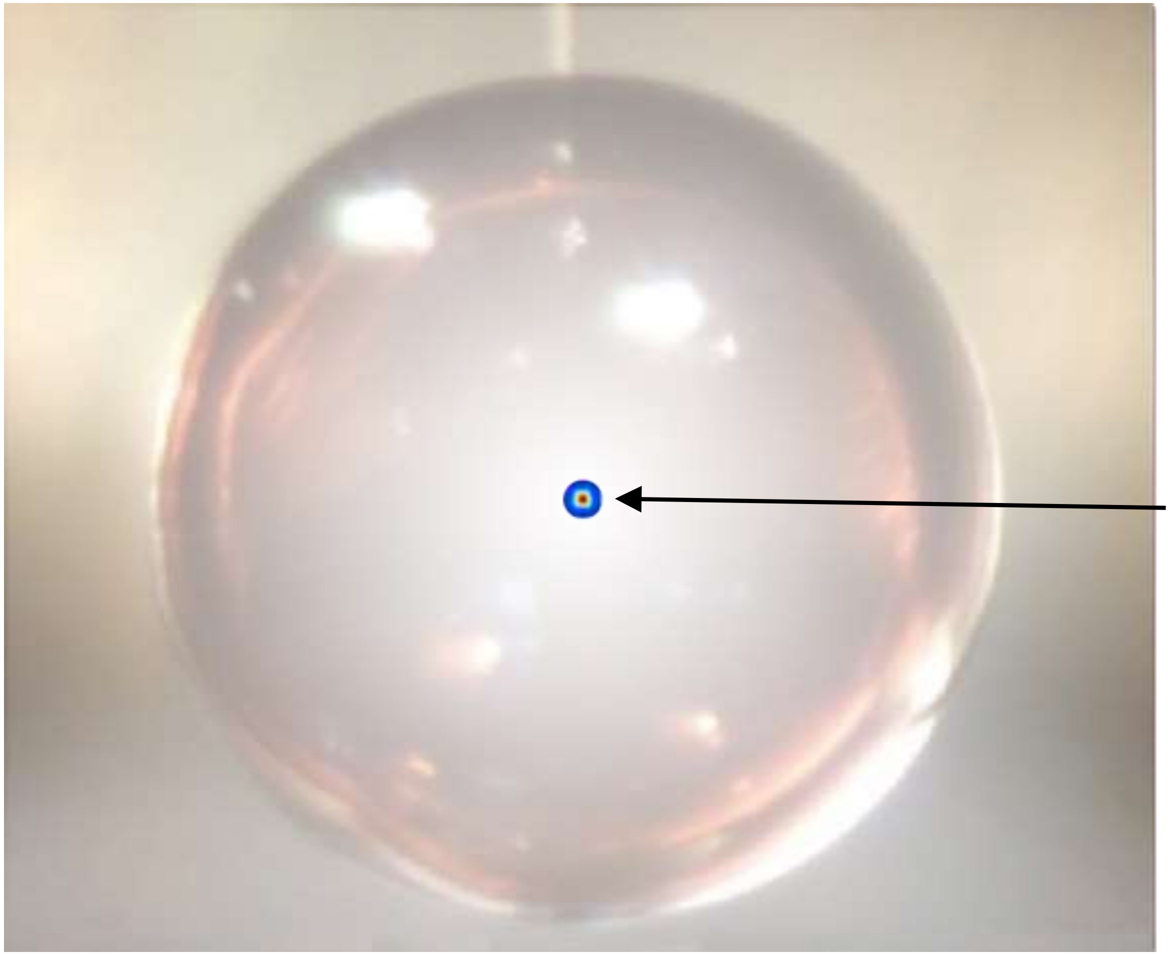
~2 mm diameter

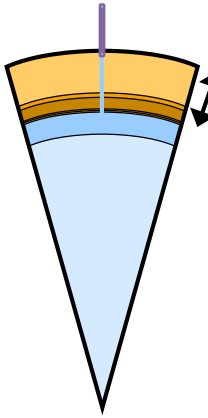
X-ray picture of capsule taken down axis of the hohlraum just before a shot



2mm diameter capsule

The "hot spot" of the capsule implosion has a diameter ~35X smaller than the initial capsule diameter

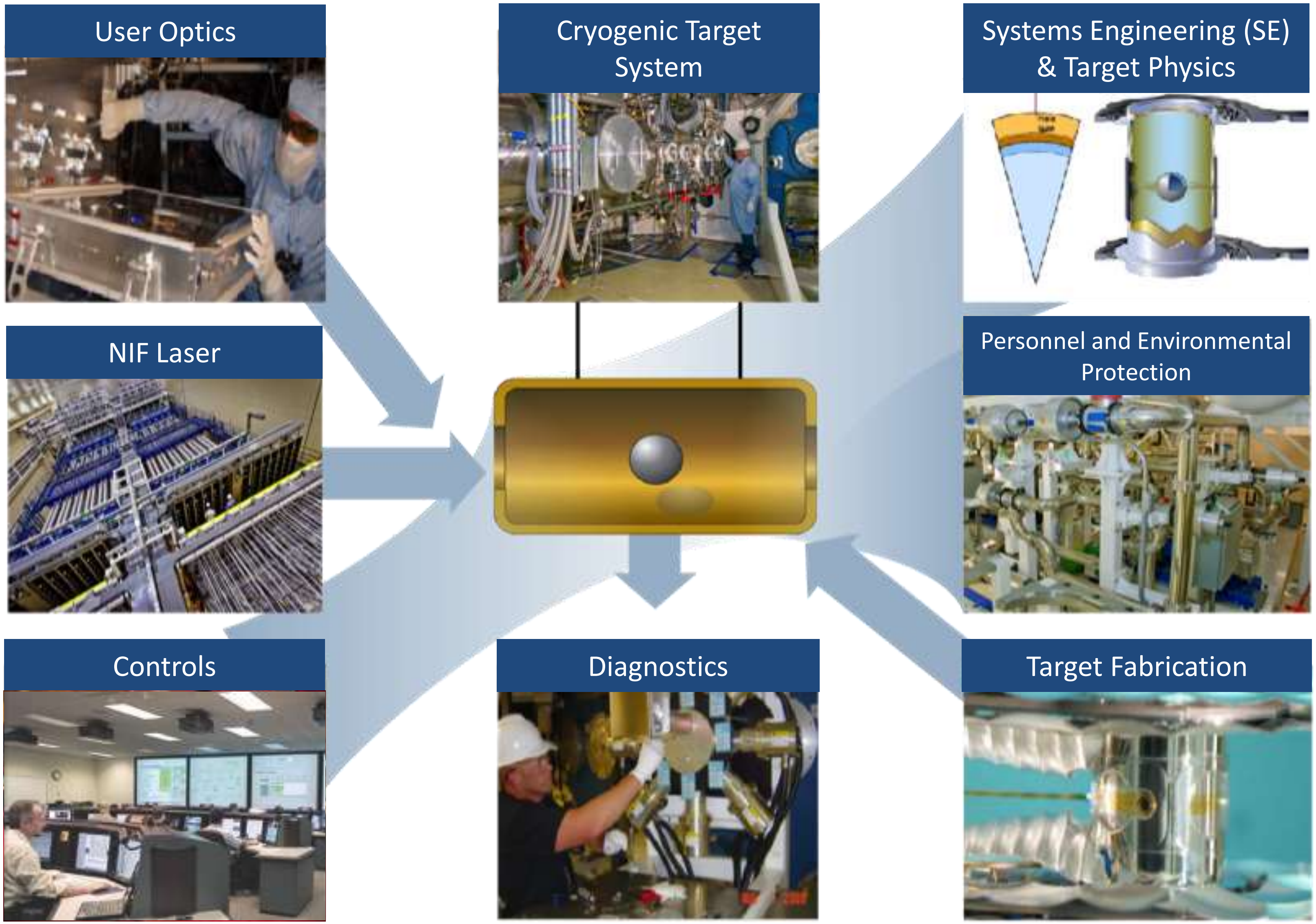




DT emission at Bang Time (less than 100 µm)

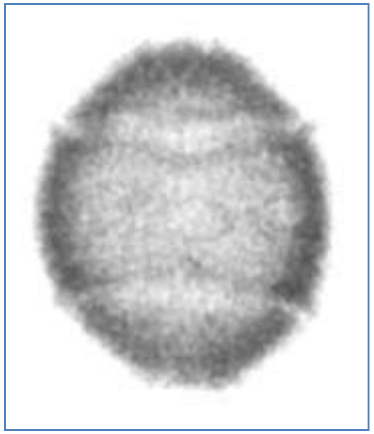
~2 mm diameter

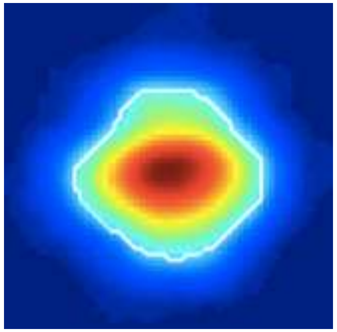
The extreme conditions needed for fusion ignition drive requirements for all the systems on NIF



We are making progress in controlling inertial confinement fusion implosions

2012/13

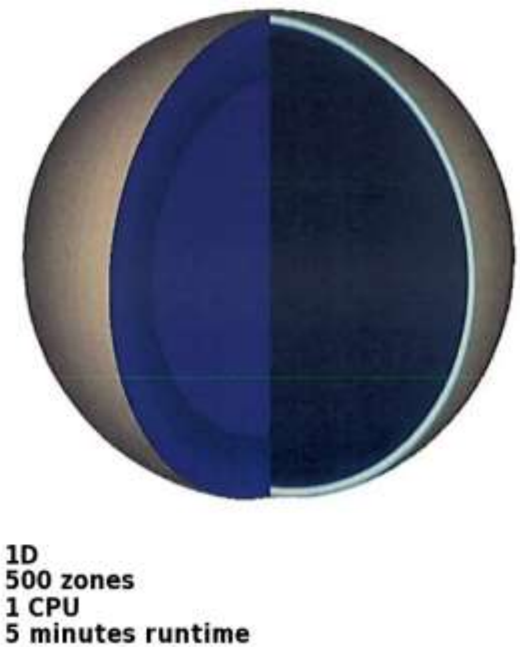




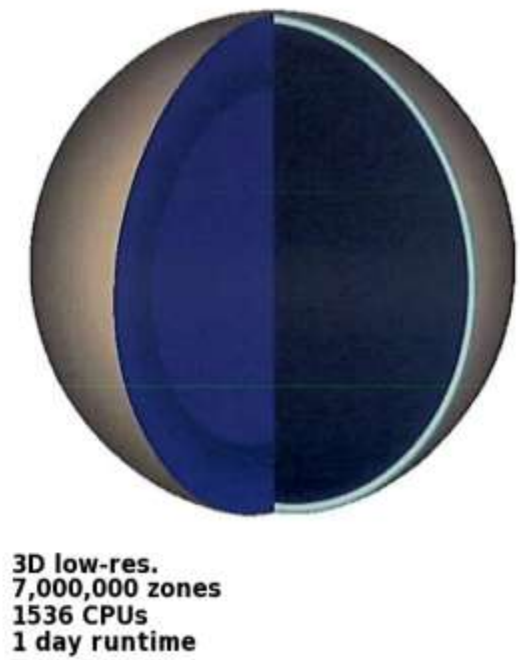
Yield ~ 2 kJ
Pressure ~ 150 GB
(7e14 DT neutrons)

Initial experiments on NIF were strongly affected by implosion asymmetries and perturbations

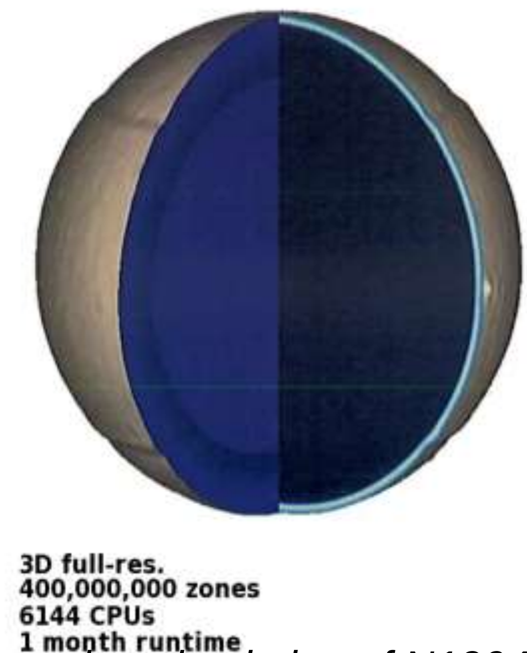
1D



3D, including low modes



3D, including all perturbations

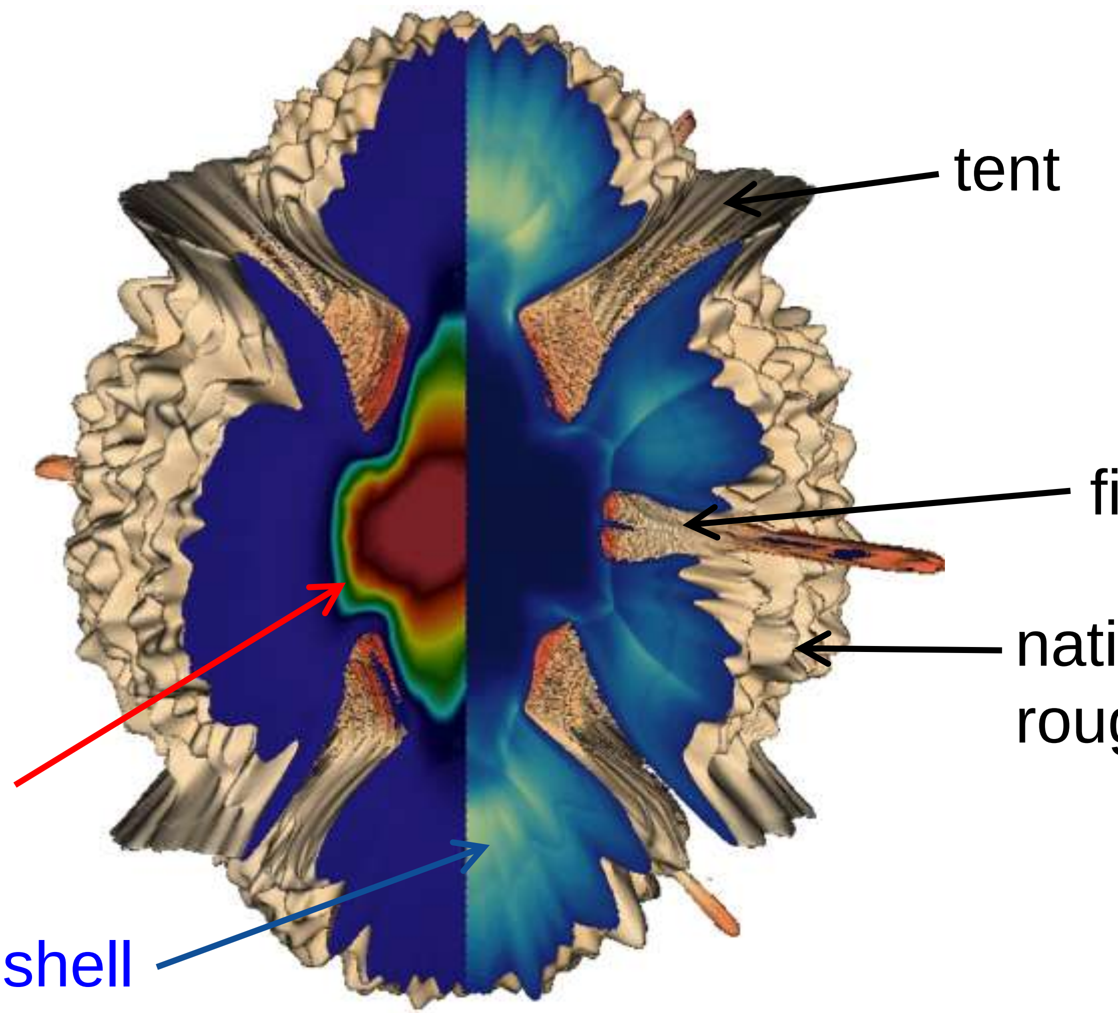


Post-shot simulation of N120405
D. Clark et al.

Simulations provide critical insight. A grand challenge is to diagnose these implosions and constrain modeling in these extreme conditions

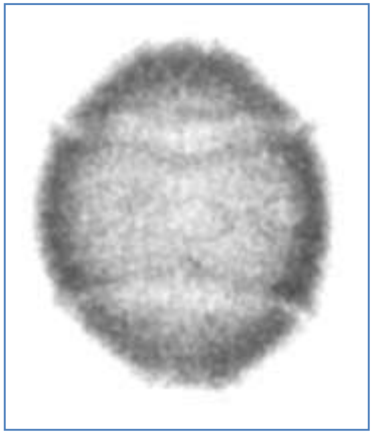
D. Clark –
3D Simulation of low foot N120405

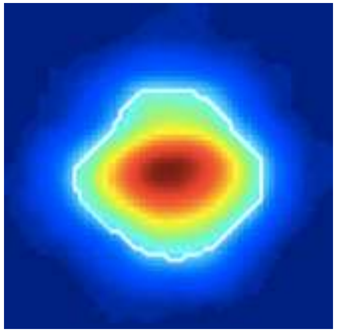
C. Weber –
Postprocessed movie



We are making progress in controlling inertial confinement fusion implosions

2012/13

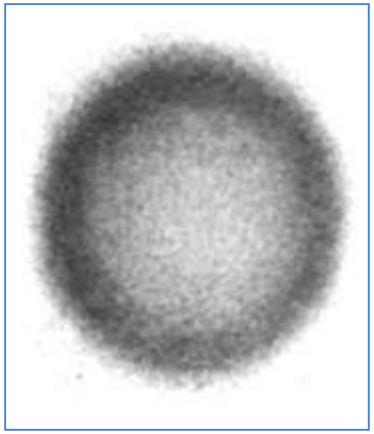


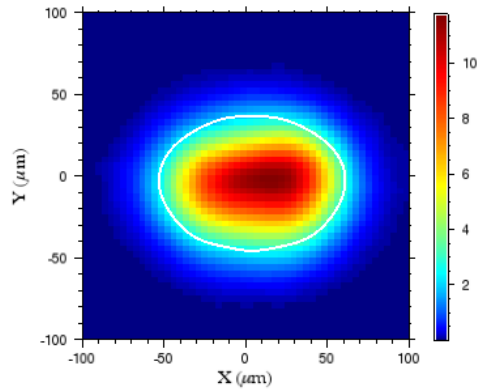


Yield ~ 2 kJ
Pressure ~ 150 GB
(7e14 DT neutrons)

Better hydro

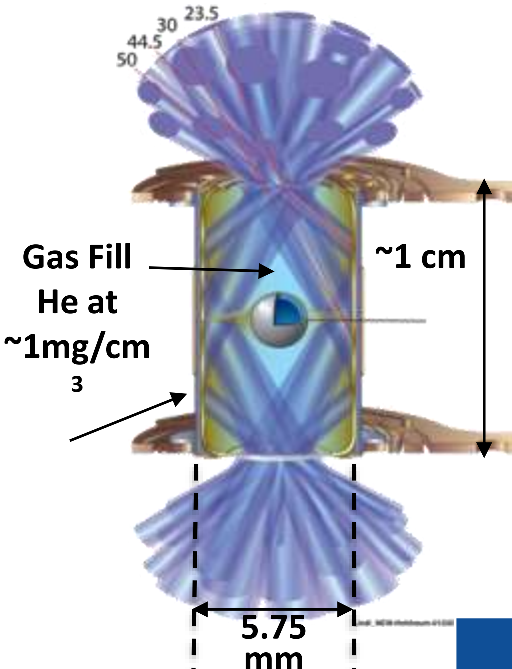
2014/15

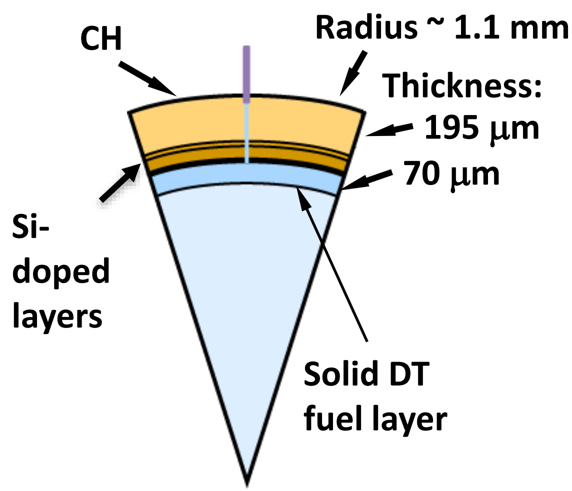


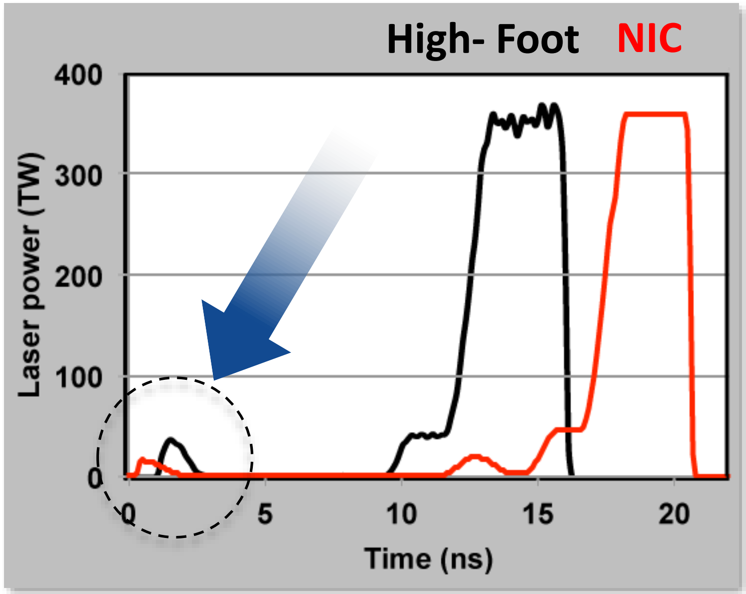


Yield ~ 27 kJ
Pressure ~ 250 GB
(9 e15 DT neutrons)

The "High-foot"* is a pulse-shape modification designed to reduce hydrodynamic instability



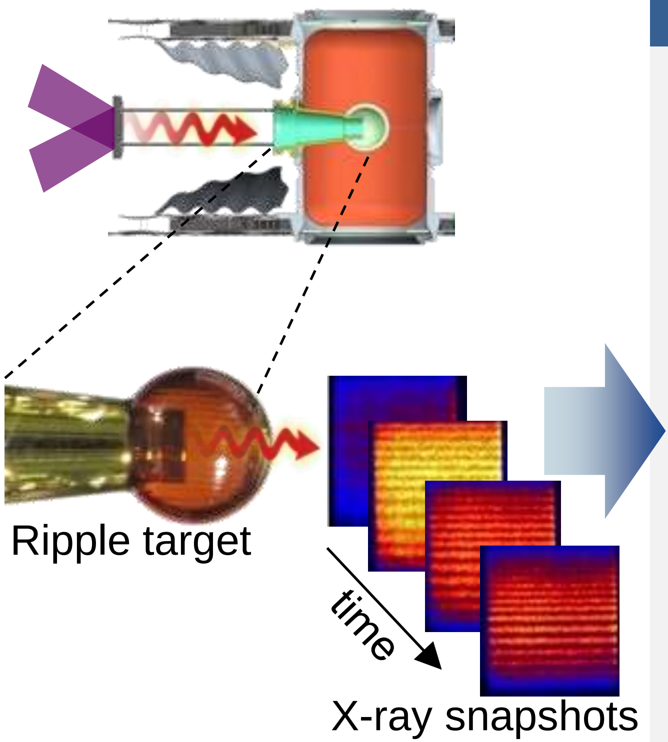


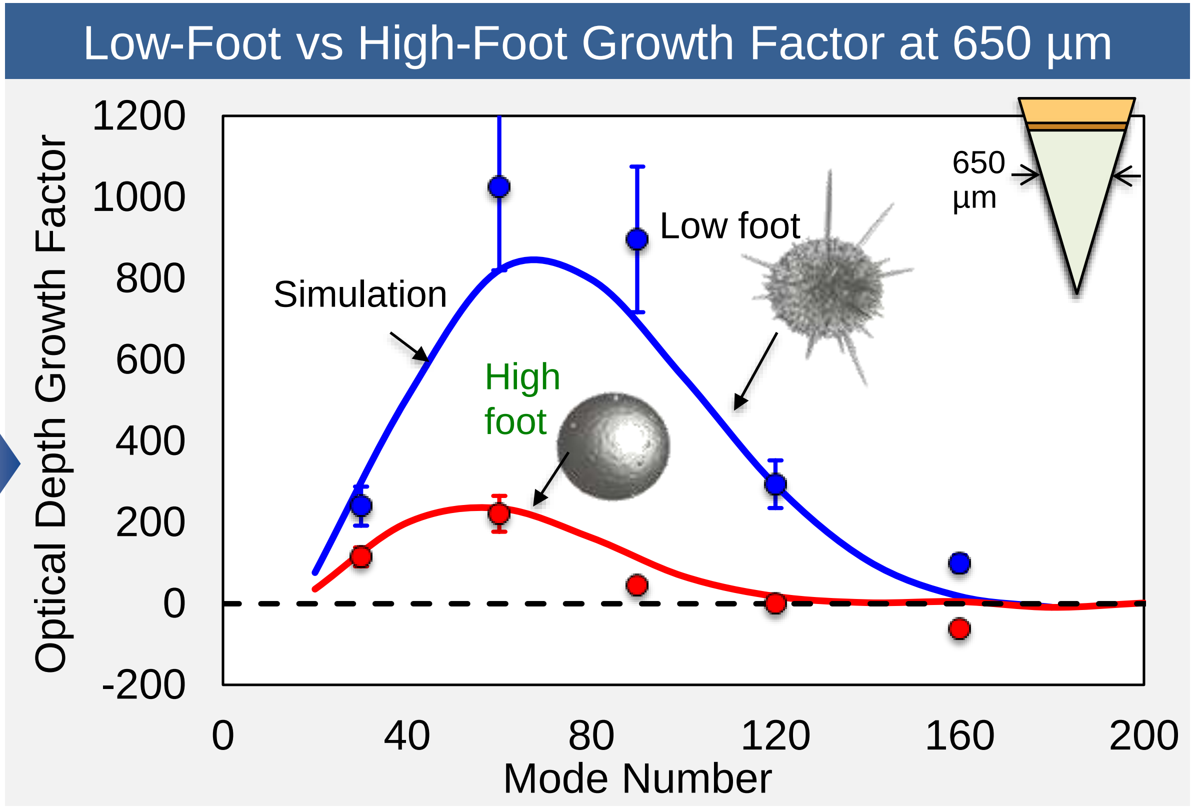


	NIC Low-foot	High-foot
Adiabat (a measure of entropy)	~1.5	**Increased to:** ~2.5
In-flight aspect ratio, (IFAR)	~20	**Reduced to:** ~10
Convergence	~45	**Reduced to:** ~30

*Dittrich et al., *PRL*, ***112***, 055002 (2014); Park et al., *PRL*, ***112***, 055001 (2014); Hurricane et al., *Nature*, ***506***, 343 (2014); Hurricane et al., Phys. Plasmas, Vol. **21**, No. 5 (2014)

Raising the foot reduces the growth rate of hydrodynamic instabilities

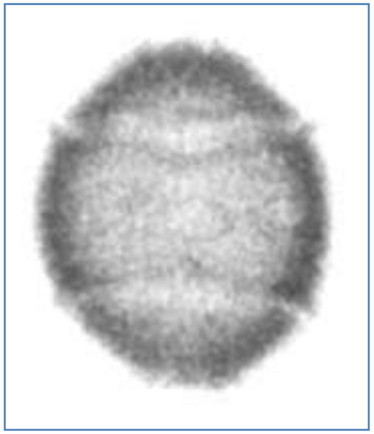


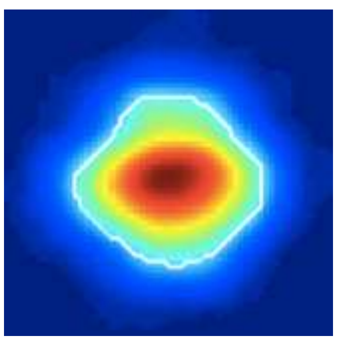


Raman, Peterson, Smalyuk, Robey

We are making progress in controlling inertial confinement fusion implosions

2012/13

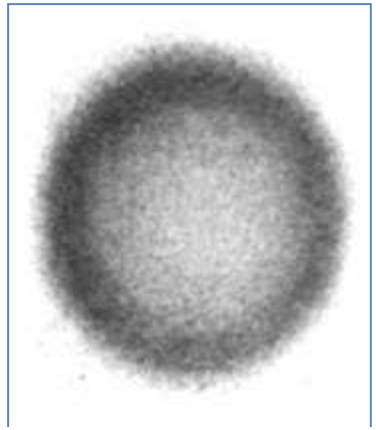


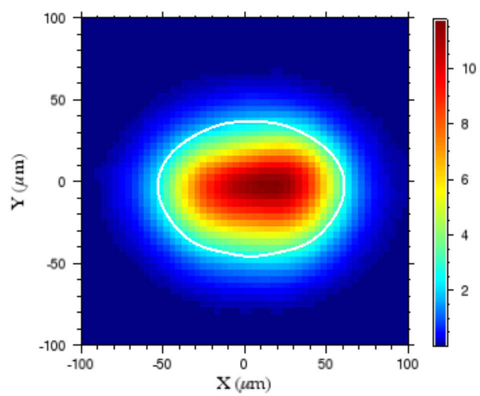


Yield ~ 2 kJ
Pressure ~ 150 GB
(7e14 DT neutrons)

Better hydro

2014/15

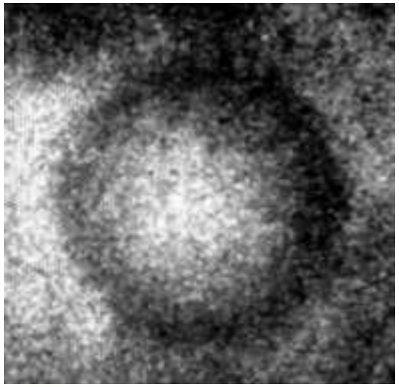


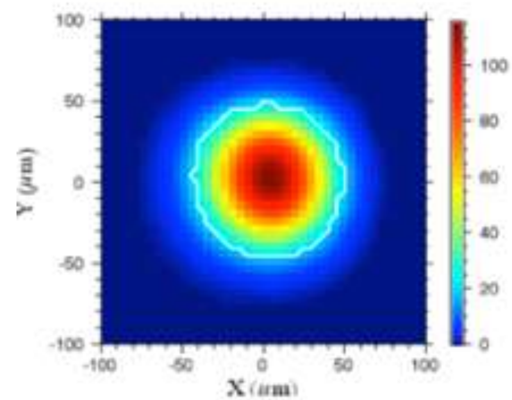


Yield ~ 27 kJ
Pressure ~ 250 GB
(9 e15 DT neutrons)

Better LPI, symmetry
Reduce fill tube

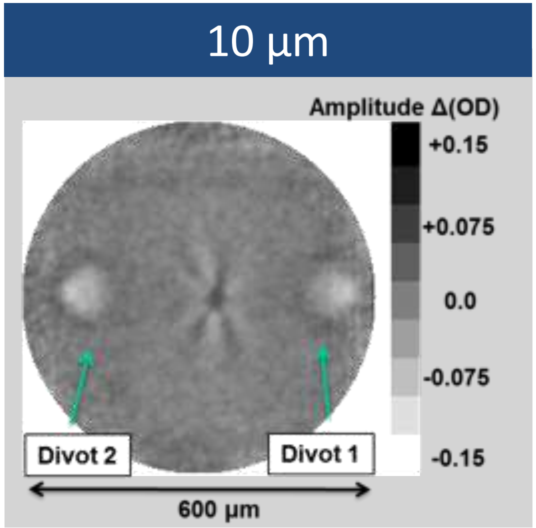
2016/17

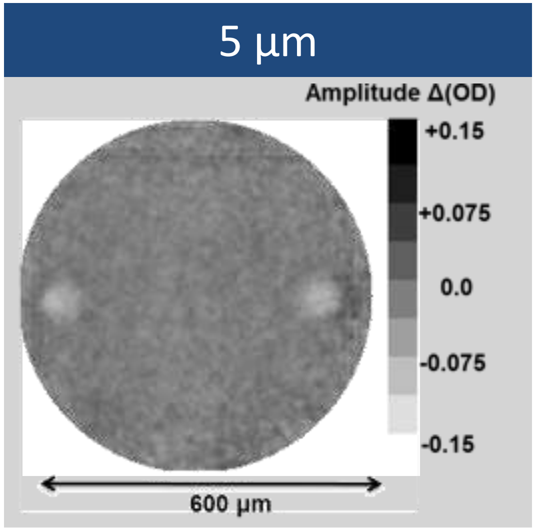


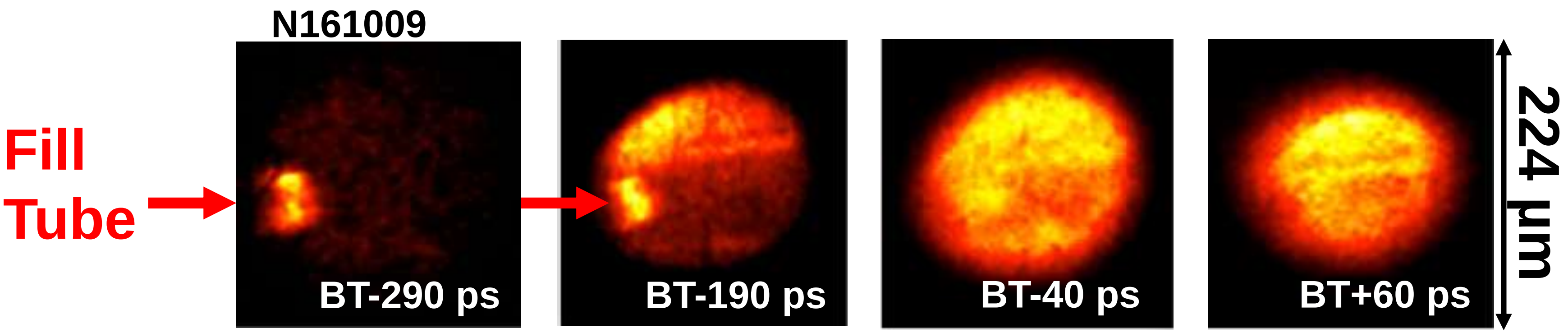


Yield ~ 57 kJ
Pressure ~ 350 GB
(2 e16 DT neutrons)

Measurements have highlighted that the perturbation from the fill tube is bigger than expected

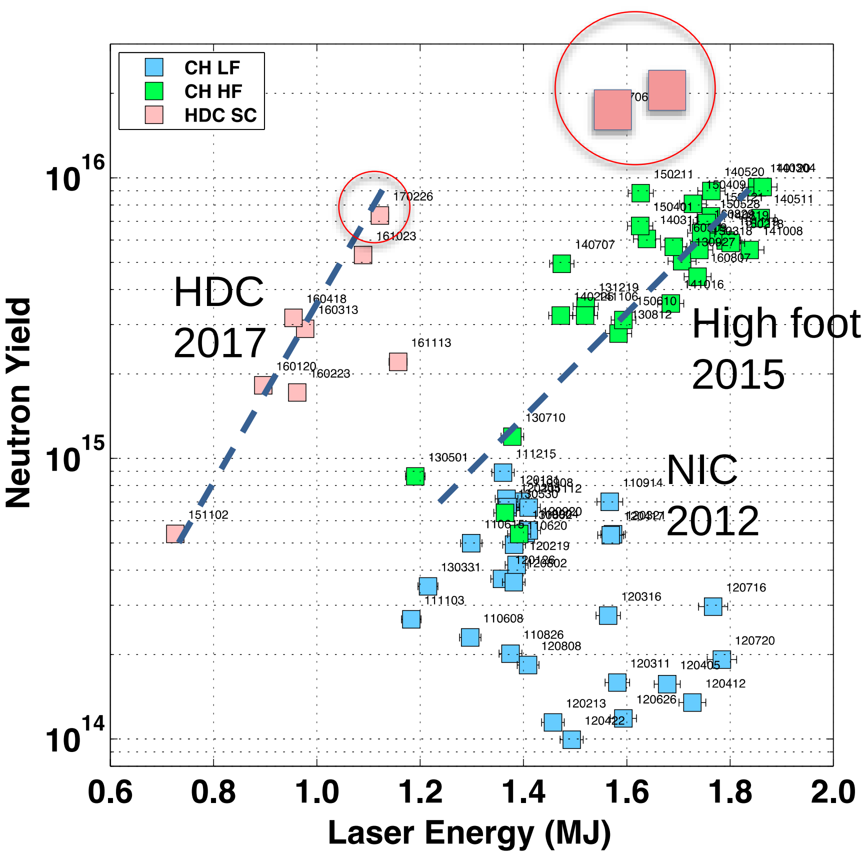


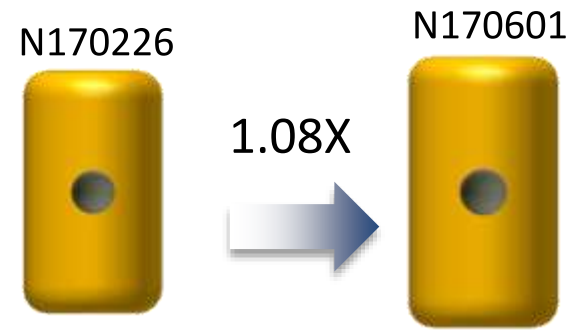




MacPhee, et al, Pickworth, et al.

Earlier this year we reached a new pressure (and yield!) record





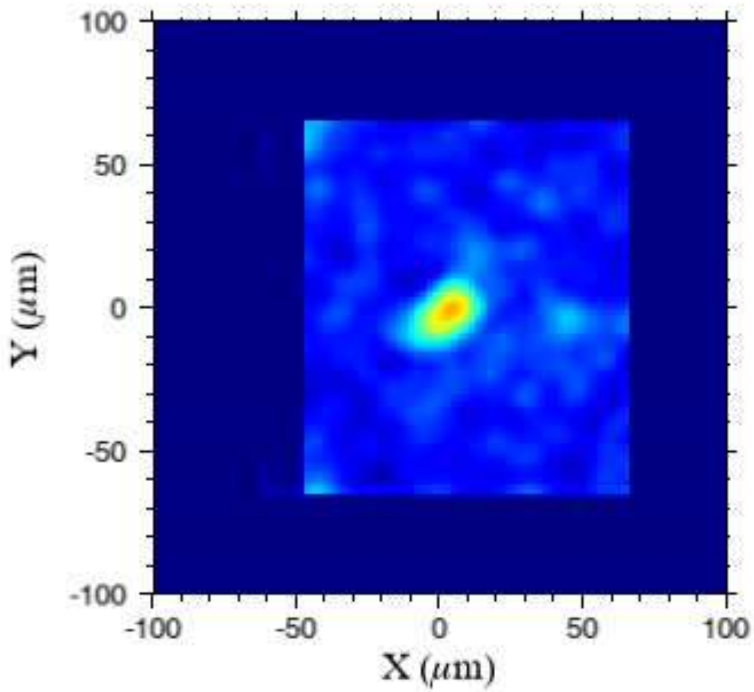
N170601 - preliminary	
E_{laser} (MJ)	1.57
P_{laser} (TW)	465
Y_{total} (#)	1.7×10^{16}
T_{Brysk} (keV)	4.7
ρR_{fuel}(g/cm^2)	0.64
ρR_{hs}(g/cm^2)	0.22-0.24
P_{stag} (Gbar)	250-300
$Y_{\alpha}/Y_{no-\alpha}$	~2.5
velocity (km/s)	~380

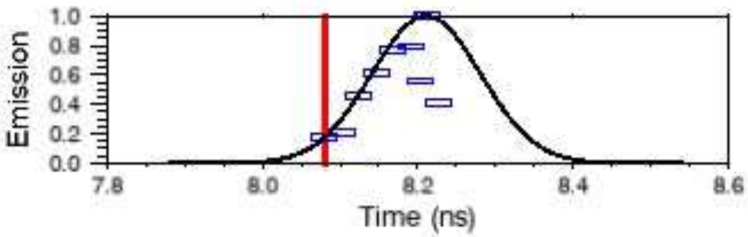
Y~47kJ, 57 kJ versus 27kJ previous record

New diagnostics capture the dynamics on a 10x faster time scale than was previously possible

DIXI recorded an x-ray movie of implosion

X-ray movie of the Implosion

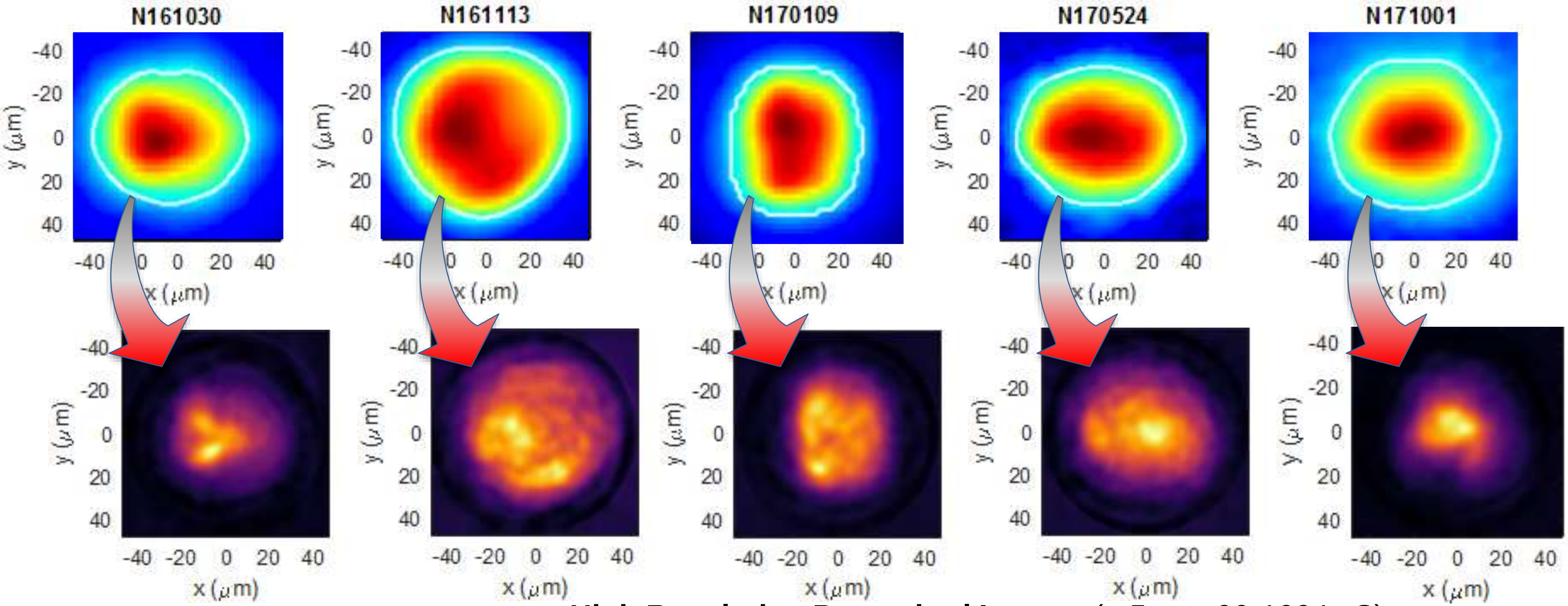




Diagnosing 3-D morphology with high spatial and temporal resolution in combination with the burn history is critical for all approaches

New diagnostics, like penumbral imaging, are giving new insights into implosion performance

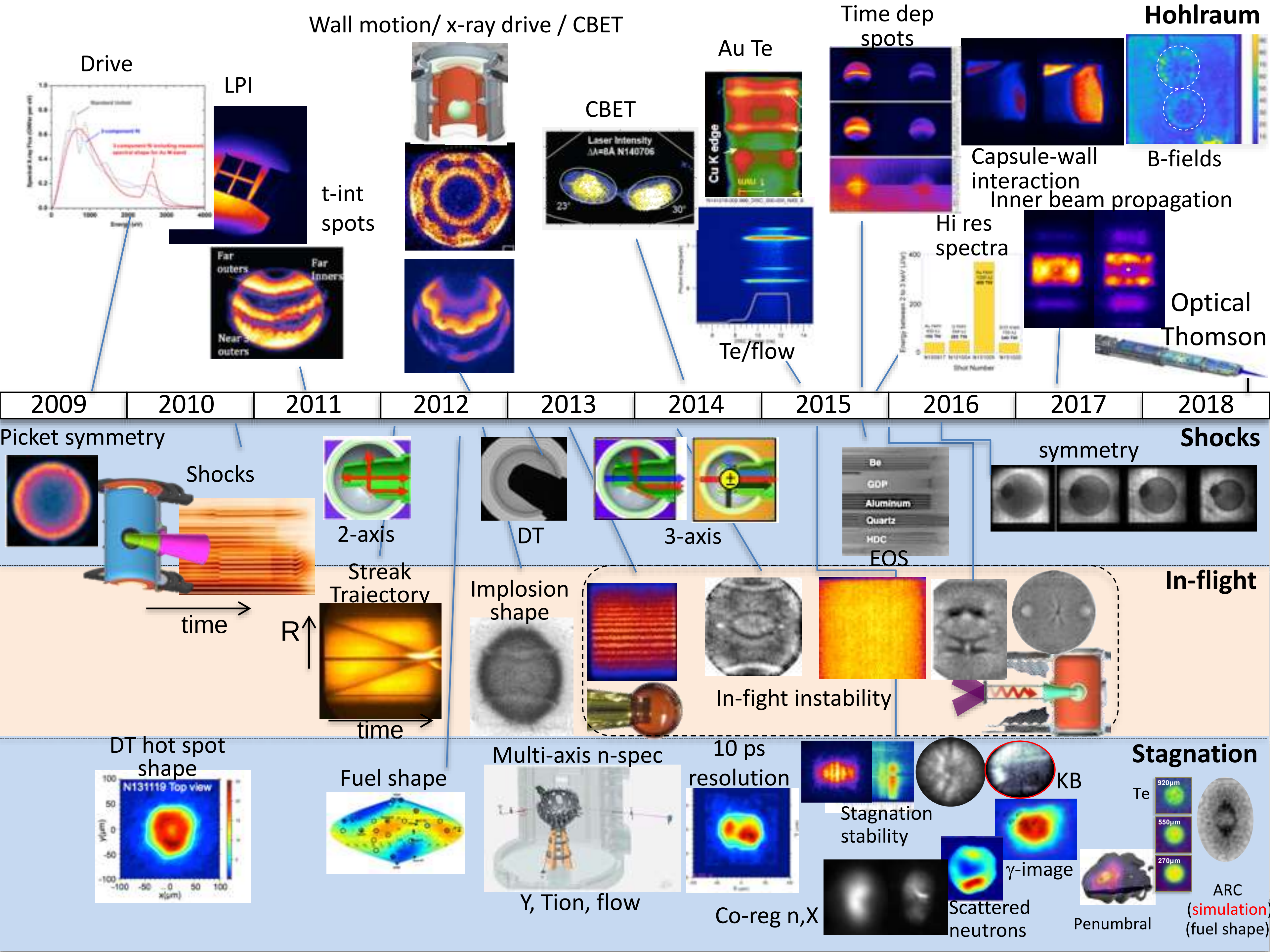
Low Resolution Pinhole Images (standard pinhole res. ~ 14 μm, 90-78 LoS)



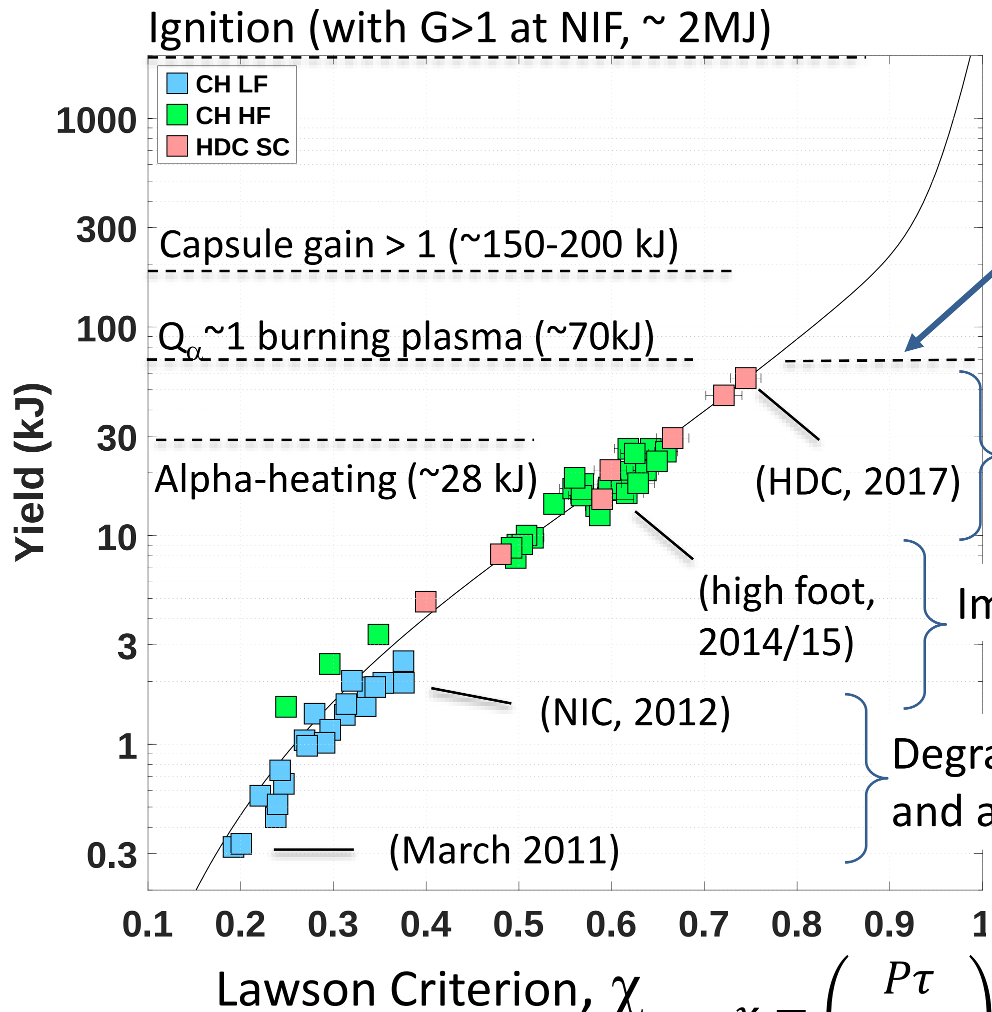
High Resolution Penumbral Images (~ 5 μm, 90-100 LoS)

Bachmann et al.

4


Hohlraum
Drive
LPI
t-int
spots
Wall motion/ x-ray drive / CBET
CBET
Au Te
Time dep
spots
Capsule-wall
interaction
B-fields
Inner beam propagation
Hi res
spectra
Optical
Thomson
Te/flow
Far outers
Far Inners
Near outers
Laser Intensity
Cu K edge
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Shocks
Picket symmetry
Shocks
symmetry
2-axis
DT
3-axis
Be
GDP
Aluminum
Quartz
HDC
EOS
time
In-flight
Streak
Trajectory
R
time
Implosion
shape
In-fight instability
Stagnation
DT hot spot
shape
N131119 Top view
Fuel shape
Multi-axis n-spec
10 ps
resolution
Y, Tion, flow
Co-reg n,X
Stagnation
stability
KB
Te
920µm
550µm
270µm
γ-image
Scattered
neutrons
Penumbral
ARC
(simulation)
(fuel shape)

NIF's goal is to achieve fusion energy out = laser energy in
We are making steady progress



**"Burning plasma": energy deposited in DT hot spot by alpha particles exceeds compressional work*

Improved hydro stability, LPI and hohlraum drive symmetry

Improved hydro stability

Degraded by hydro instability, LPI and asymmetry

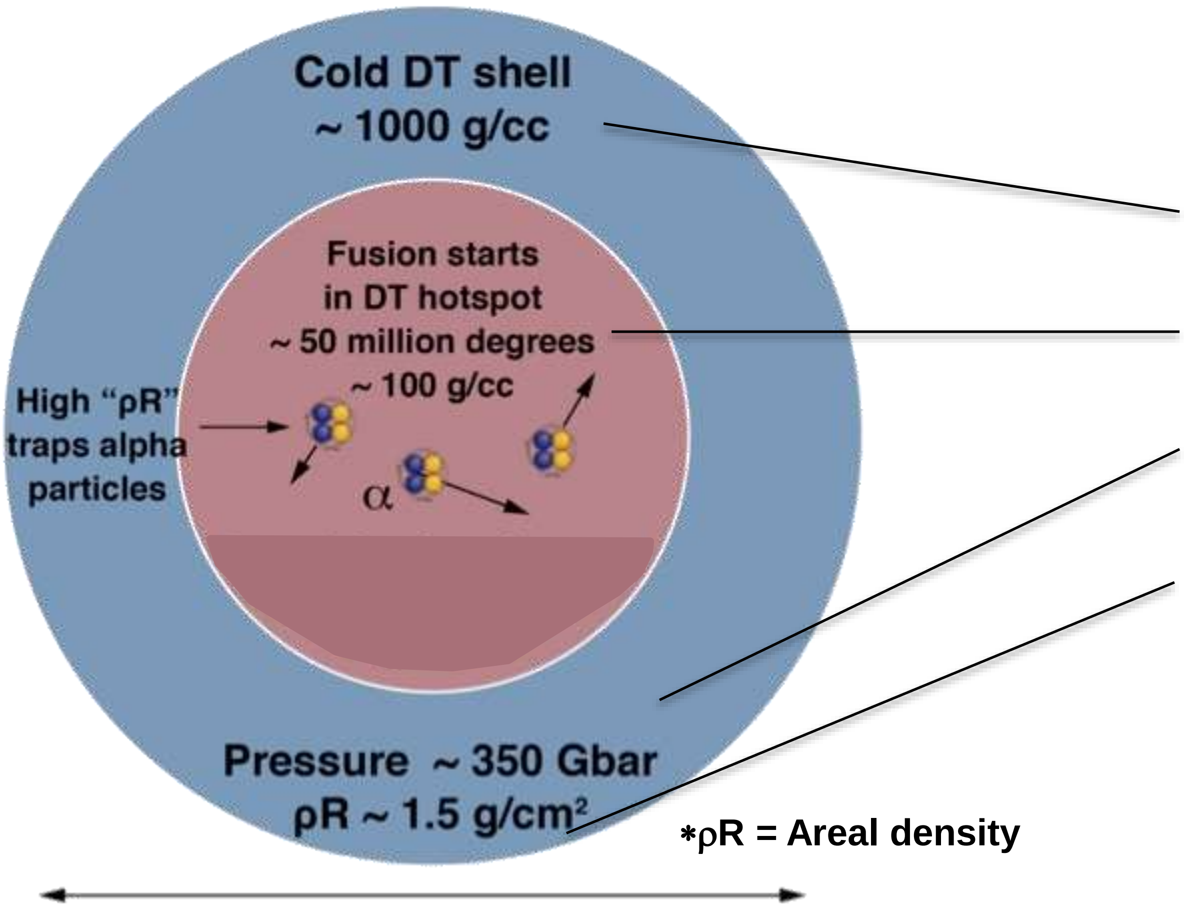
Betti R. et al., PRL **104**, 135002, (2010).

$$\chi = \left(\frac{P\tau}{P\tau_{IGN}}\right)$$

*Betti R. et al., PRL **114**, 255003, (2015).

NIF pressures are close to those needed for ignition according to simulations

Deuterium-Tritium (DT) fuel



*ρR = Areal density

~ 0.1 mm

Best performance
on single shot

~ 57kJ

~ 500 g/cc

~ 80 g/cc, ~5 keV

~ 360 Gbar

~ 0.75 g/cm ^{2}

We are always looking for great people!

- Looking for well qualified scientists and engineers in HED Science, Diagnostics, Lasers, Pulsed Power, Optics, Target Fabrication, …
- Postings and applications at:
  - https://careers-llnl.ttcportals.com/jobs/search
- Laser-plasma interactions, optical diagnostics and measurements, implosions and stagnation (hydrodynamics, x-rays and nuclear), materials and radiation effects
- Radiation physics and spectroscopy, dynamic material properties, X-ray diagnostics and measurement science
- Laser systems engineering, optical design, pulsed power science and engineering

- Please email me: herrmann9@llnl.gov if you have any questions

It's an exciting time in the field of High Energy Density Science and on the National Ignition Facility

- Matter at high energy densities is ubiquitous in the Universe. There is a lot to understand about matter in these conditions.
- Experimental facilities to create and study matter in these extreme conditions have been developed and enhanced over the past decade, including the National Ignition Facility, the world's most energetic laser.
- On NIF we are performing ~ 2 experiments per day studying some of the most fundamental questions facing the field of high energy density science
- Achieving inertial confinement fusion ignition in the Laboratory is a grand scientific challenge. Progress is being made on understanding and improving inertial confinement fusion target performance, driven by new measurements. We remain committed to the exciting goal of obtaining fusion ignition in the laboratory