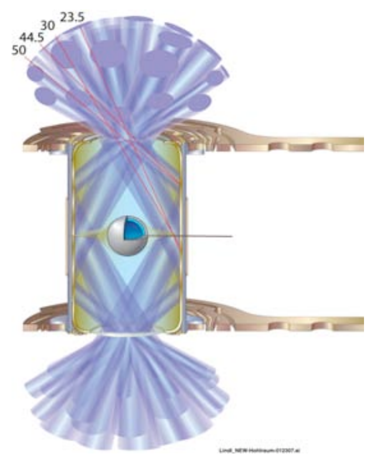
Basics of Inertial Confinement Fusion

AAAS Annual Meeting

14-18 February - Boston



John Lindl
NIF and Photon Science Directorate Chief Scientist
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Fusion Represents an Inexhaustible Energy Supply for Mankind

- Fusion fuels deuterium (D) and tritium (T) are hydrogen isotopes

- 3/4 oz. of heavy water has the same energy content as 13,000 gallons of oil for D-D reaction, or 32,000 gallons of oil for D-T reaction

- Tritium is made from
  $n + Li \Rightarrow T + He$

- Lithium is plentiful both in the earth's crust and oceans

Outline

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- The challenge of Inertial Confinement Fusion
- Development of the science basis for ignition on the Nova and Omega laser
- Final steps on the path to ignition - the National Ignition Campaign (NIC)
- Opportunities for the future on NIF

Fusion can be accomplished in three different ways

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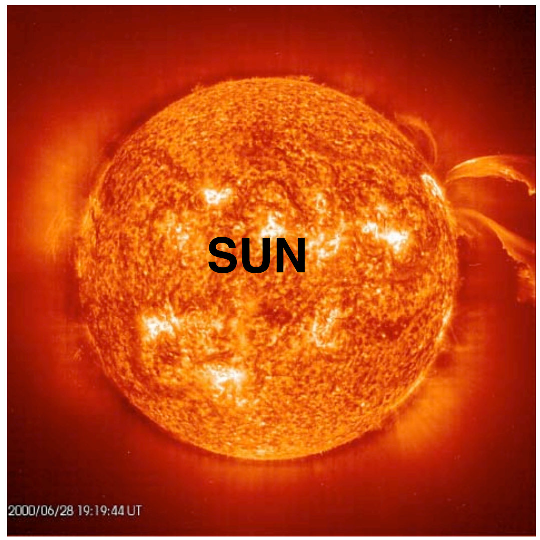
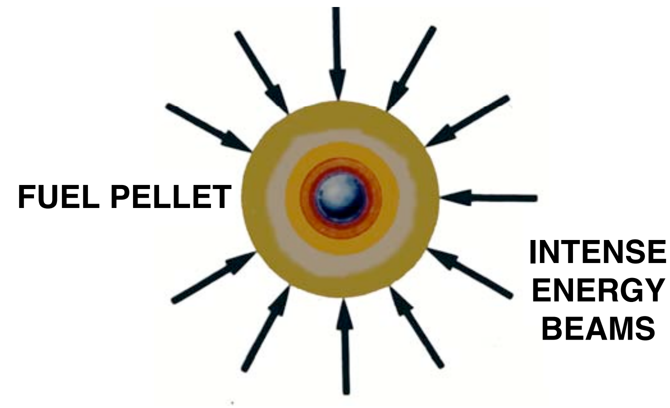
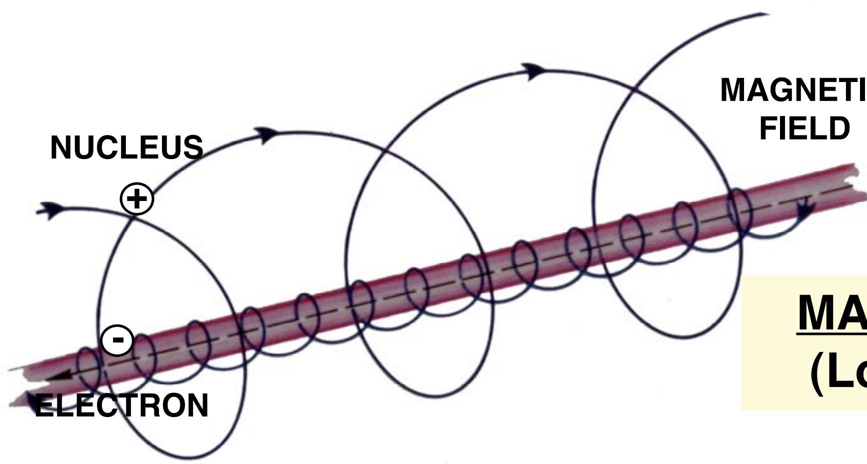
GRAVITATIONAL CONFINEMENT
(High density for billions of years)





INERTIAL CONFINEMENT
(High density for less than a billionth of a second)



MAGNETIC CONFINEMENT
(Low density for seconds)

The extreme conditions required for inertial fusion ignition are found only in stellar interiors and nuclear weapon tests

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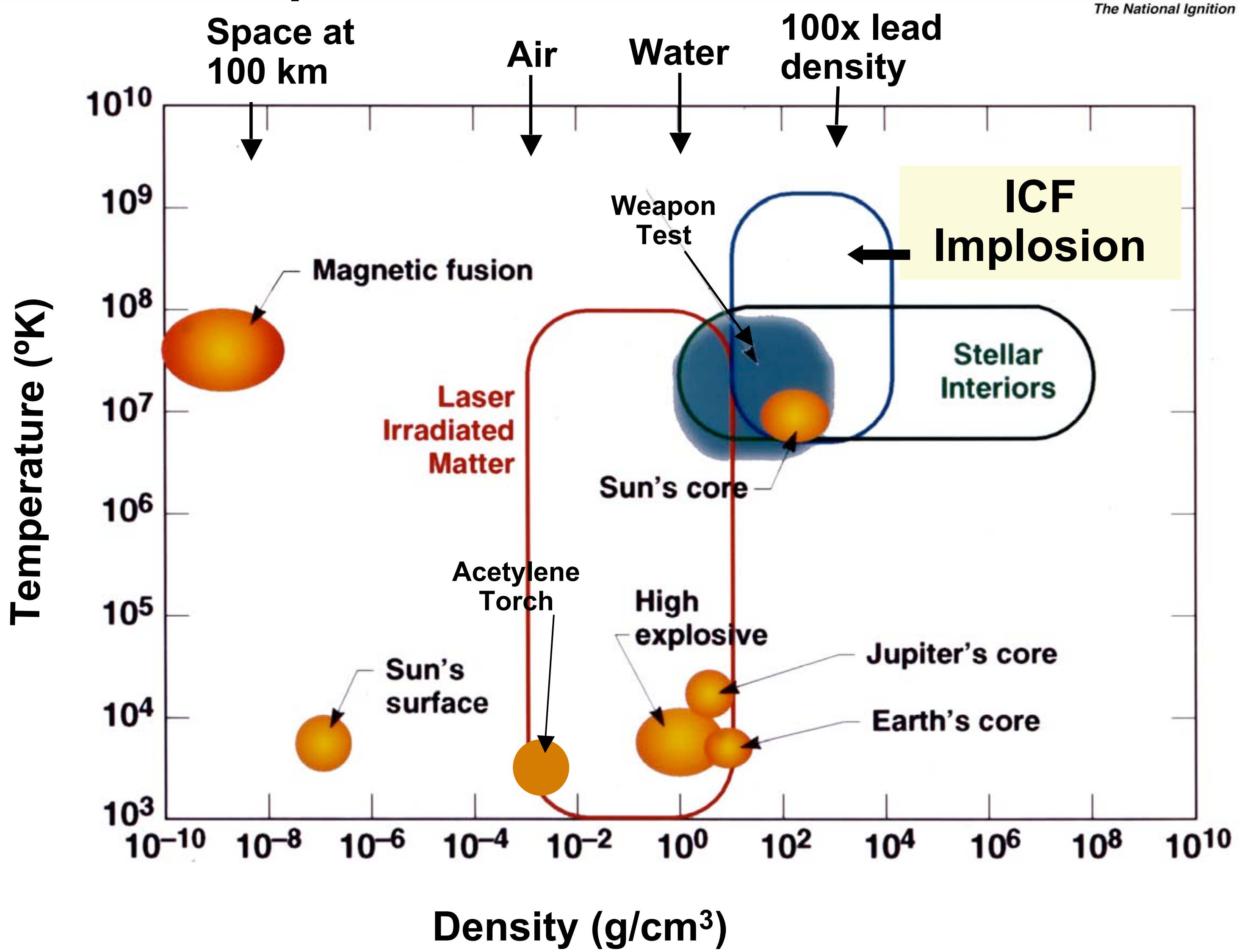

There are two principal approaches to compression in Inertial Confinement Fusion

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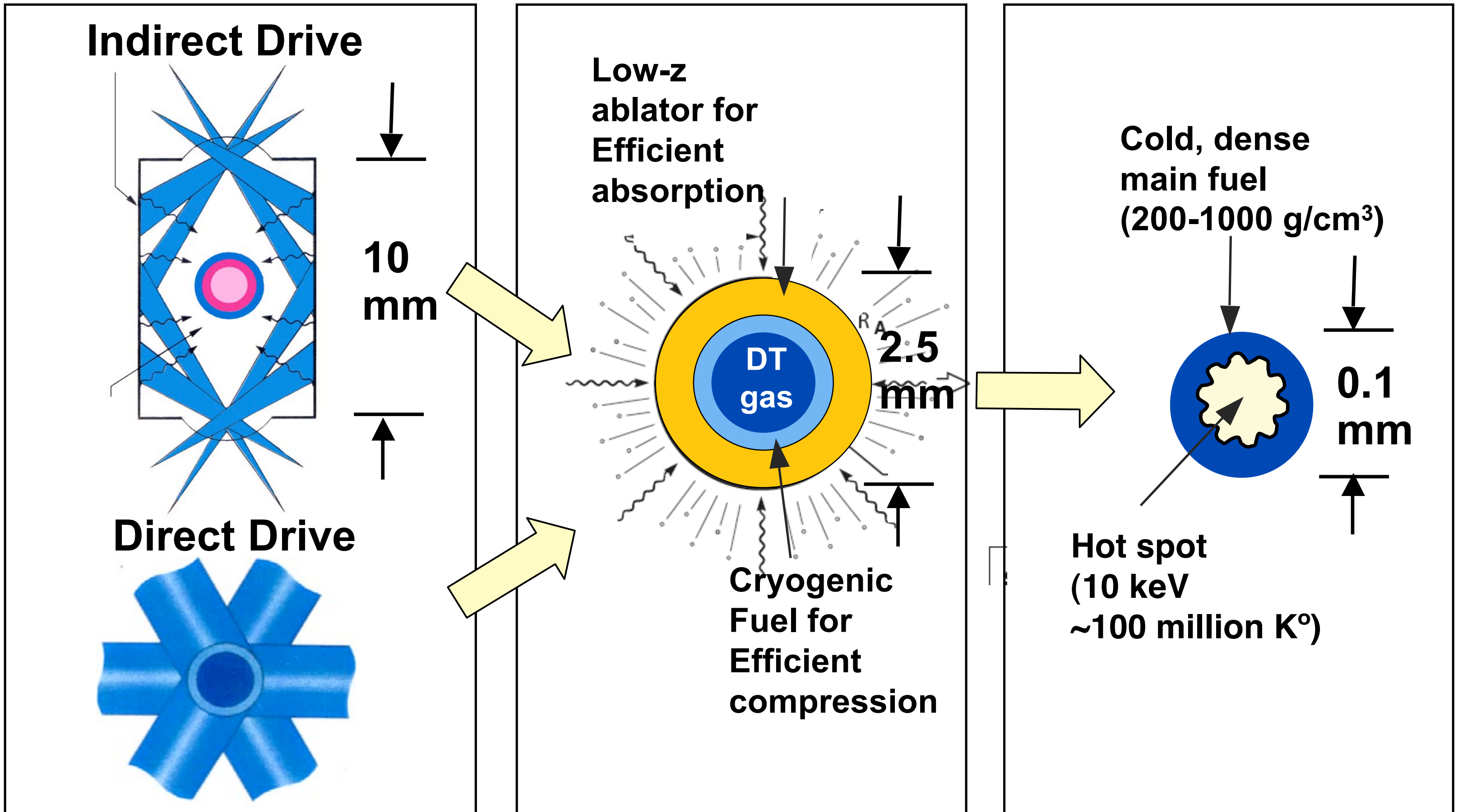

Rocket-like implosion achieves velocities of nearly 1 million MPH

Spherical collapse produces high temperatures and densities

The scale of ICF ignition experiments is determined by the limits to compression

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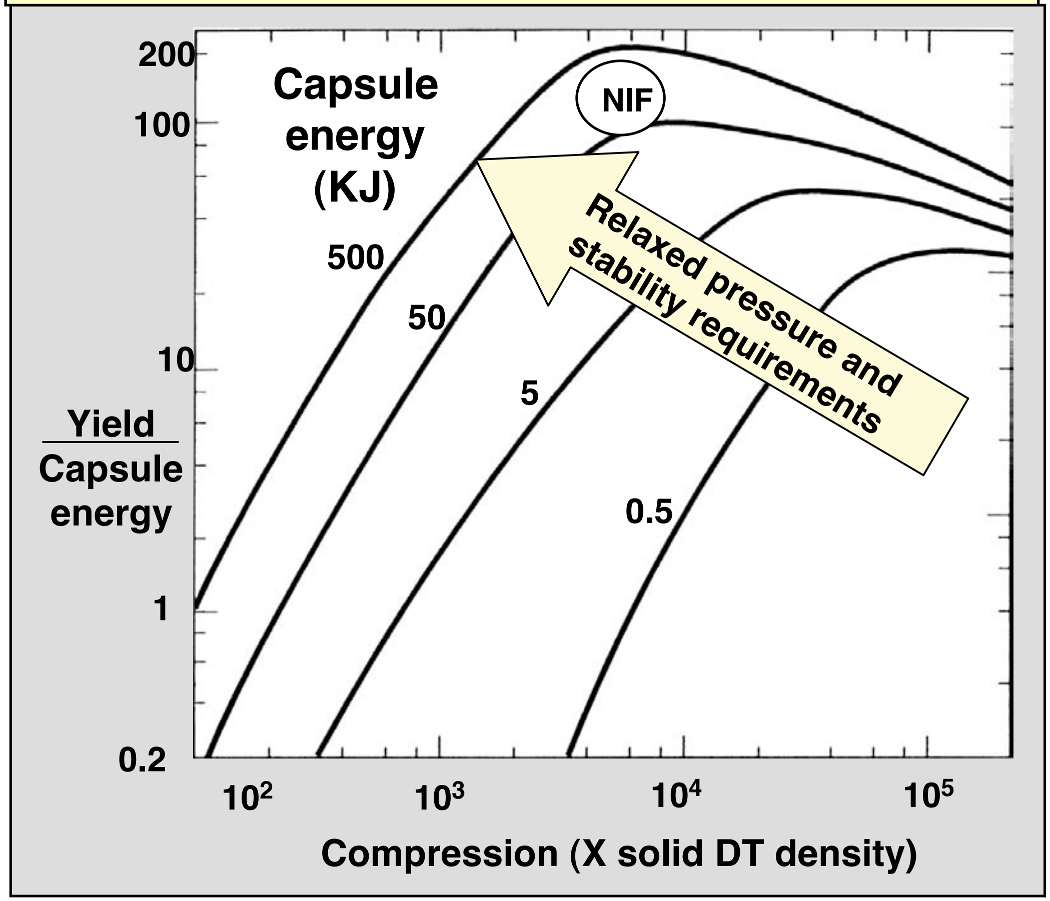
Capsule Energy Gain Plotted vs Compression



- Constraints on x-ray drive and hydrodynamic instabilities limit implosion velocities to

$$V_{imp} < 400 \text{ kilometers/sec}$$

(~900,000 MPH)

and this limits the maximum compression

4000X solid DT density is ~100X the density of lead or ~10 times the density of the center of the Sun

X-rays enhance implosion symmetry and reduce hydrodynamic instability at a cost in efficiency

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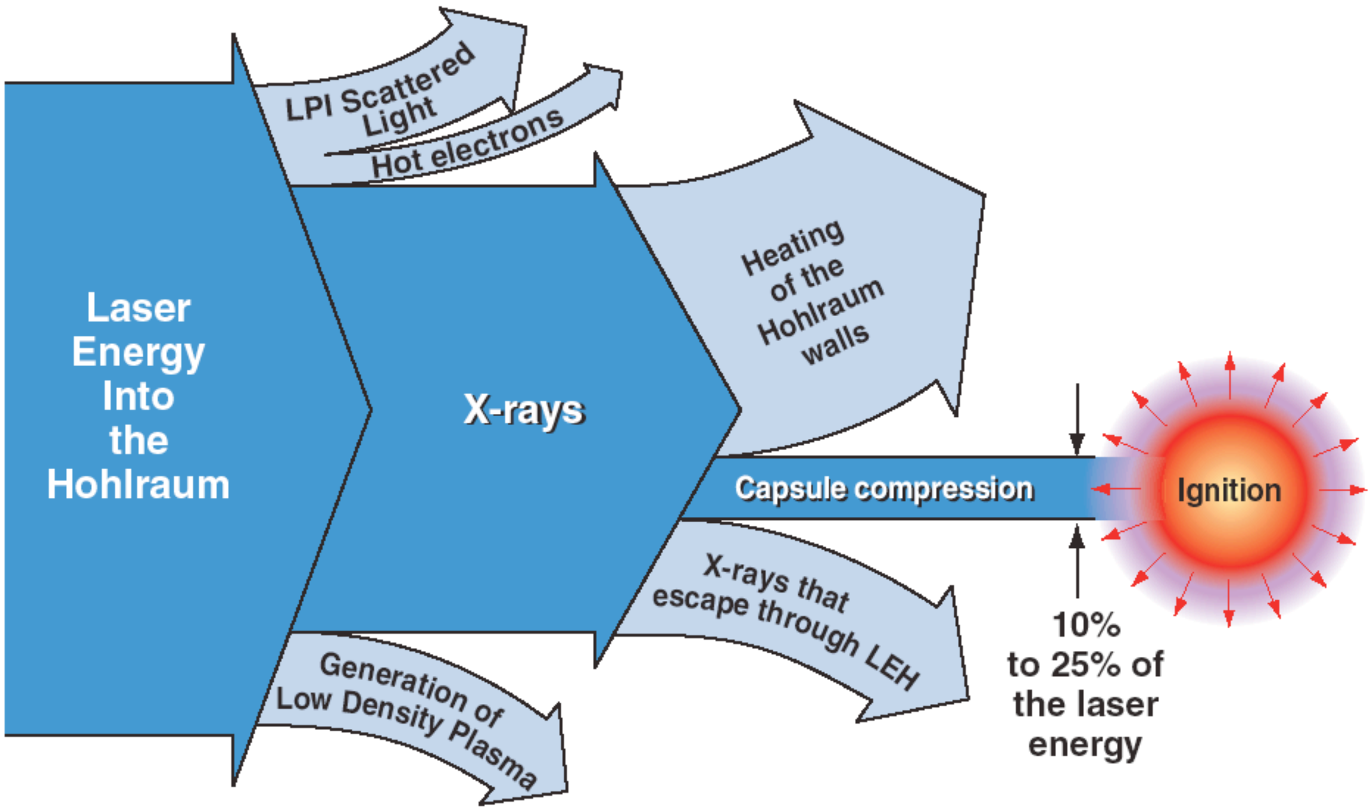

Fast Ignition is an approach to ICF which decouples compression from ignition

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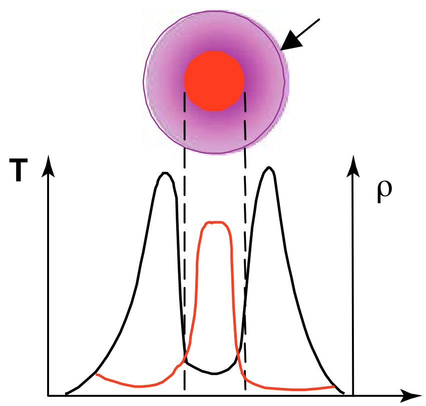
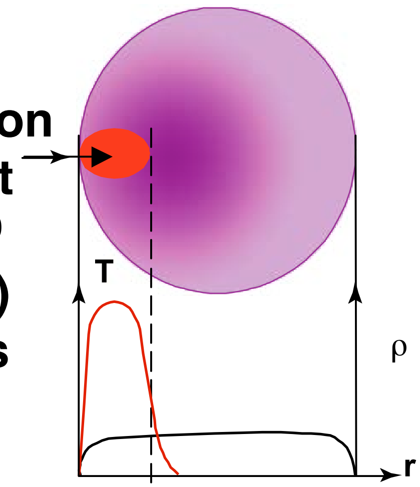
Hot Spot ICF	Fast Ignition
($I \sim 10^{15}$ w/cm^2) (1-10 ns pulse)	Fast injection of heat ($I \sim 10^{20}$ w/cm^2) (~10ps pulse)





- Central hot spot ignition relies on precise control of implosion symmetry and hydrodynamic instability

- Fast ignition will require significant advances in the understanding of charged particle production and transport at ultra-high intensity

Why do we believe that ignition will work on NIF?

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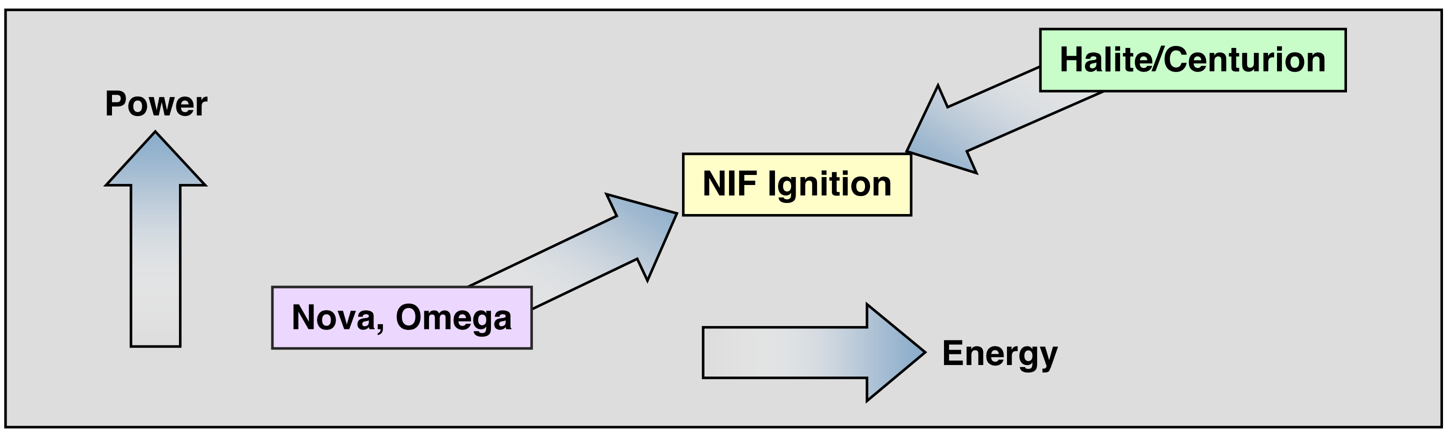
- Over 3 decades of experiments on Nova, Omega and other facilities have provided an extensive data base to develop confidence in the numerical codes
- Benchmarked numerical simulations with radiation-hydrodynamics codes provide a first principles description of x-ray target performance (Laser-plasma interactions are treated separately with codes which are now becoming predictive for NIF-relevant plasmas)
- "The Halite/Centurion experiments using nuclear explosives have demonstrated excellent performance, putting to rest fundamental questions about the basic feasibility to achieve high gain" - from 1990 NRC review of ICF



From 1984 to 1999, the 10 beam, 30 kJ, 0.35 μm Nova laser was the central facility for indirect drive ICF

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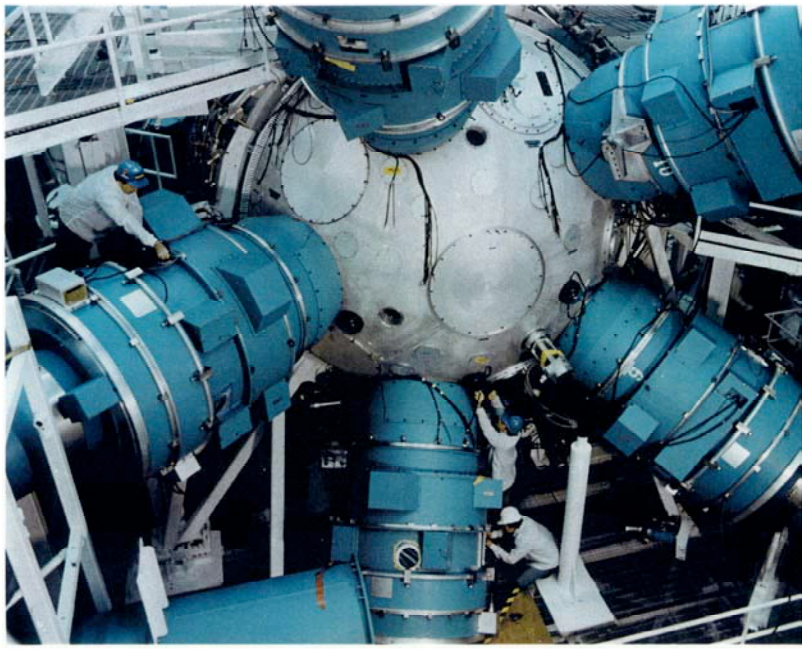
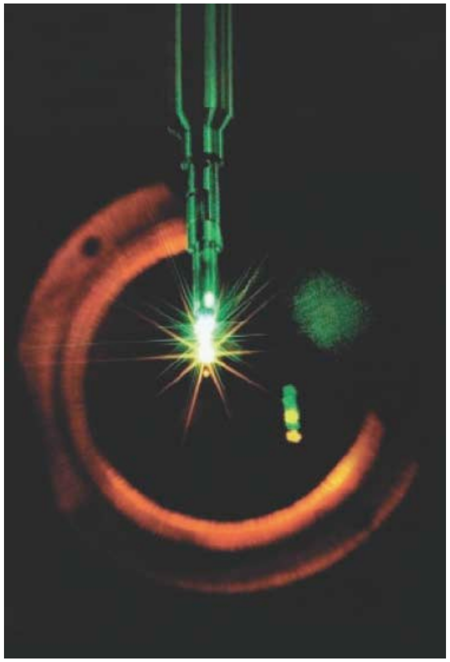
Nova Target Chamber



Implosion Experiment



Advances in laser performance, precision diagnostics, and advanced modeling tools combined to establish the requirements for Ignition.

The Nova ignition physics program utilized targets which were scaled to test key issues

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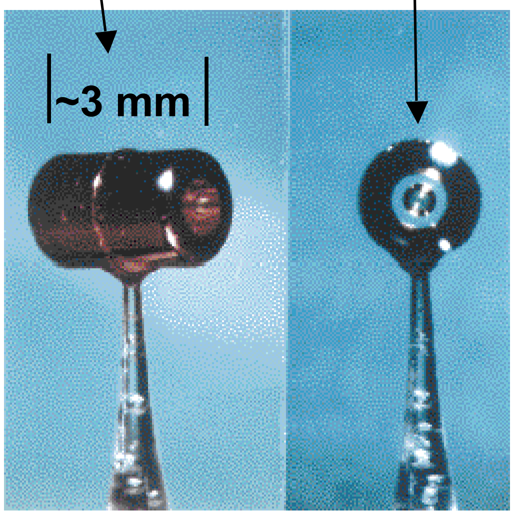
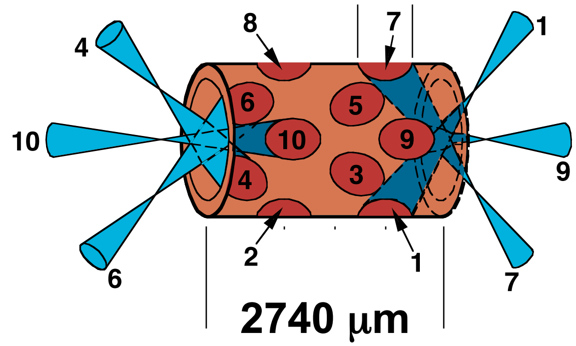
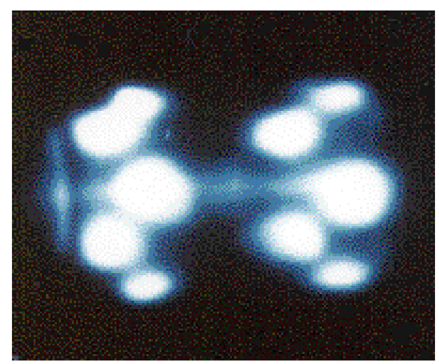
Gold Hohlraum

CH capsule
~0.5 mm diameter





X-ray image of laser spots inside hohlraum



Advanced diagnostics have been central to measuring the phenomena critical to understanding NIF

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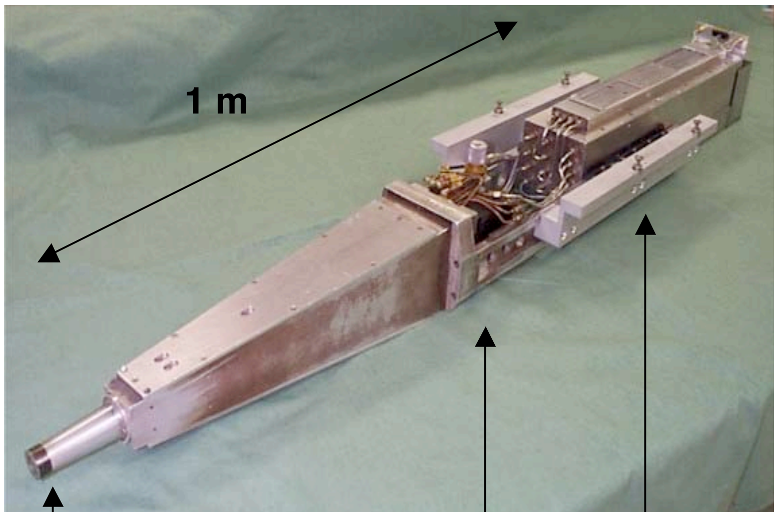
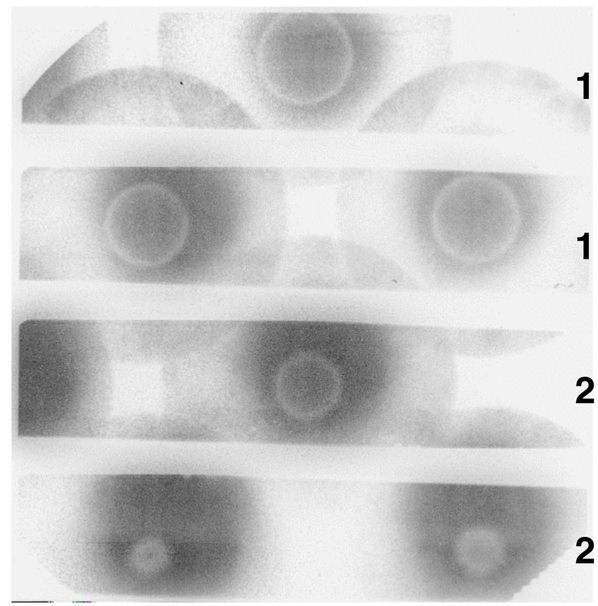
Gated micro-channel plate (MCP) x-ray imager



Sequence of x-ray backlit images of imploding capsule



MCP gated imagers were operated between 100 eV and 10 keV with 5-50 μm, and 30-300 ps resolution

Compression of an ICF capsule requires exceptionally uniform drive pressure

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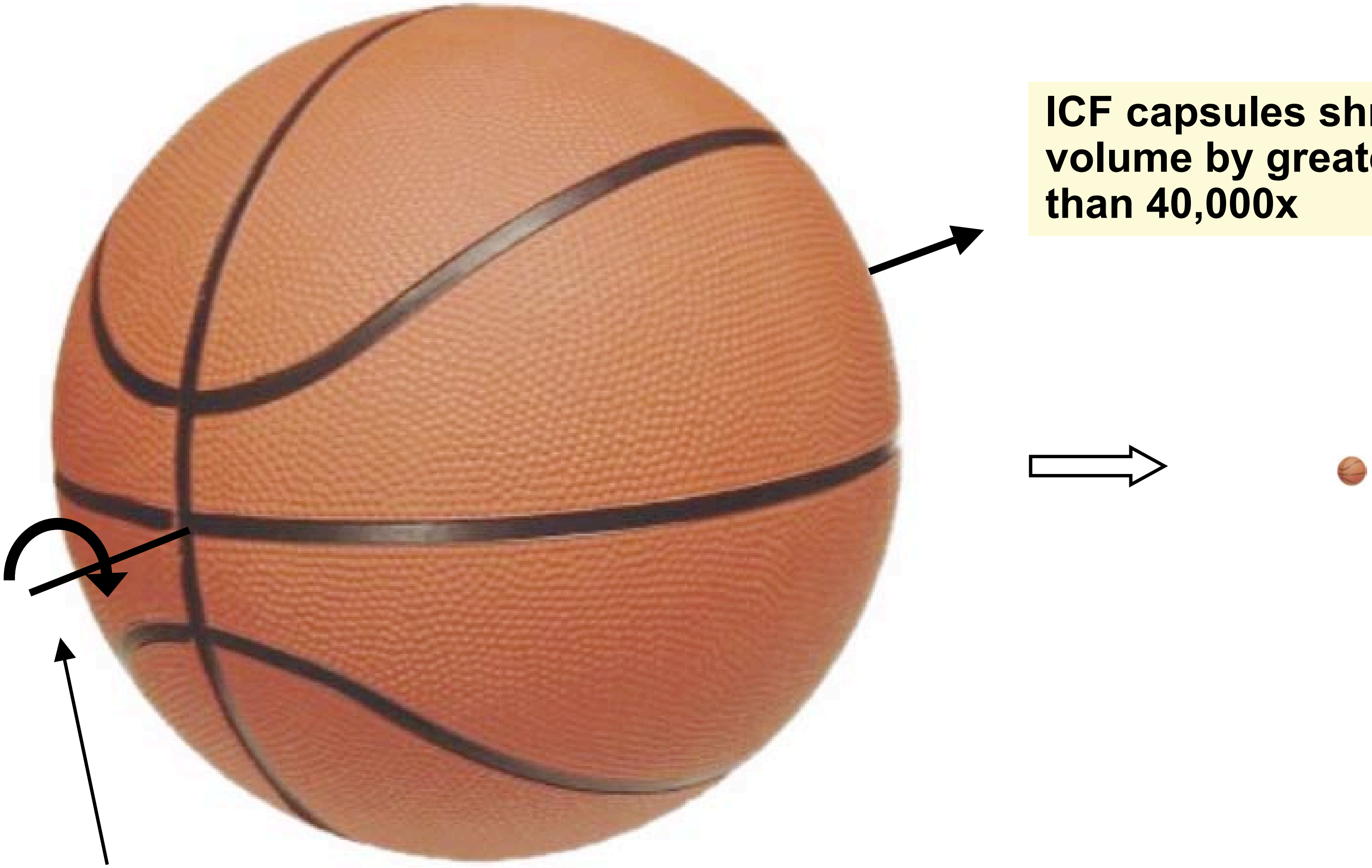
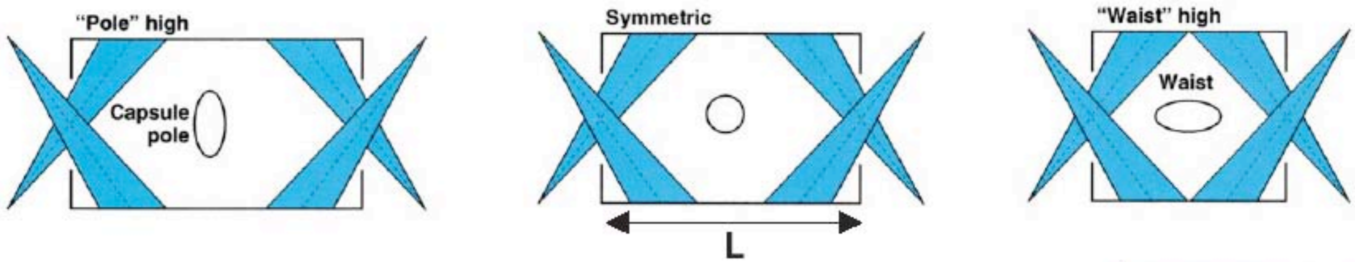
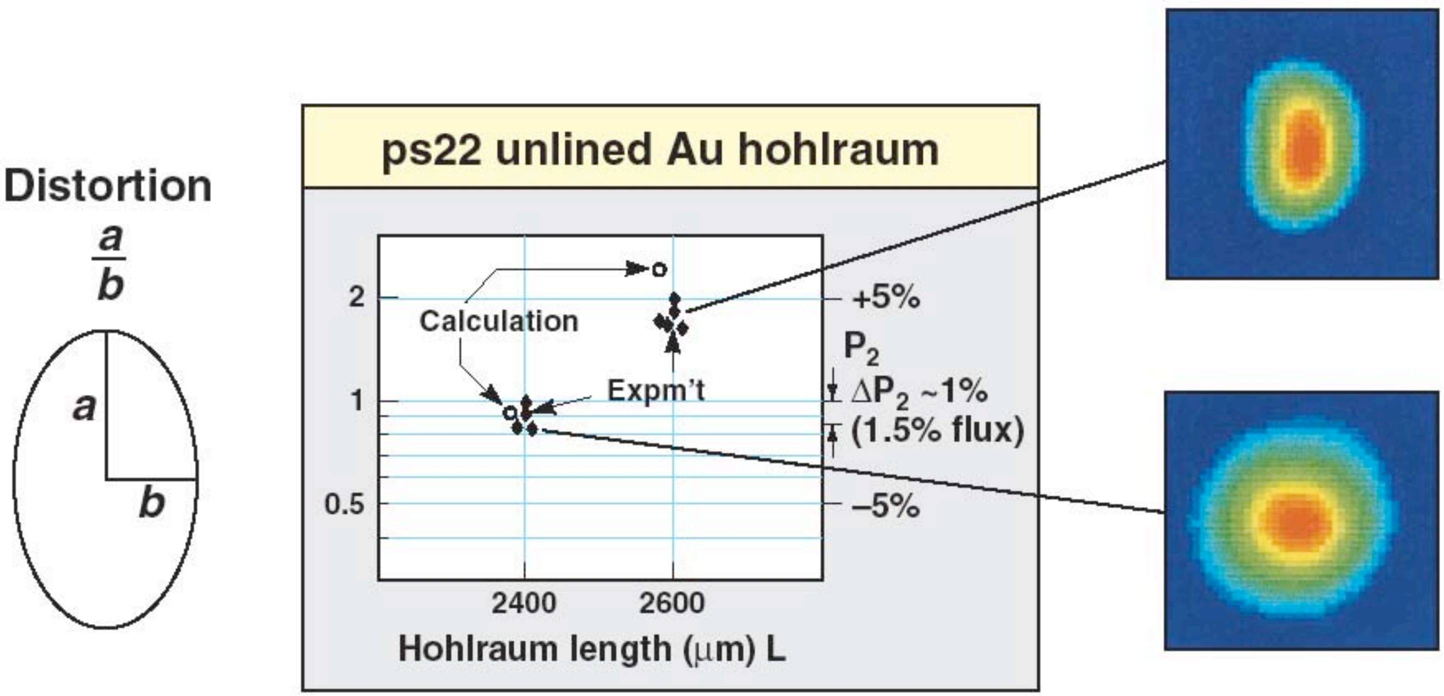


ICF capsules shrink in volume by greater than 40,000x

Hohlraum axis: NIF hohlraums irradiate ignition capsules with symmetry similar to that of a basketball

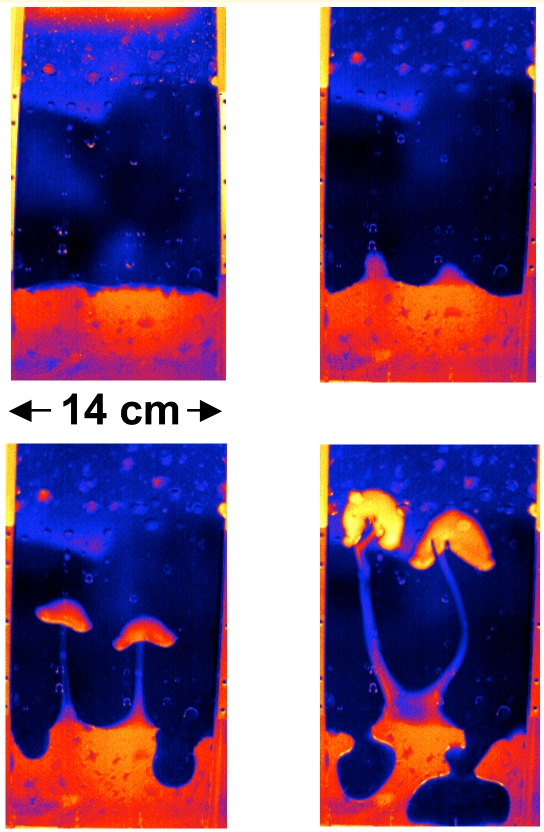
On Nova and Omega, we demonstrated control of symmetry by varying the hohlraum length





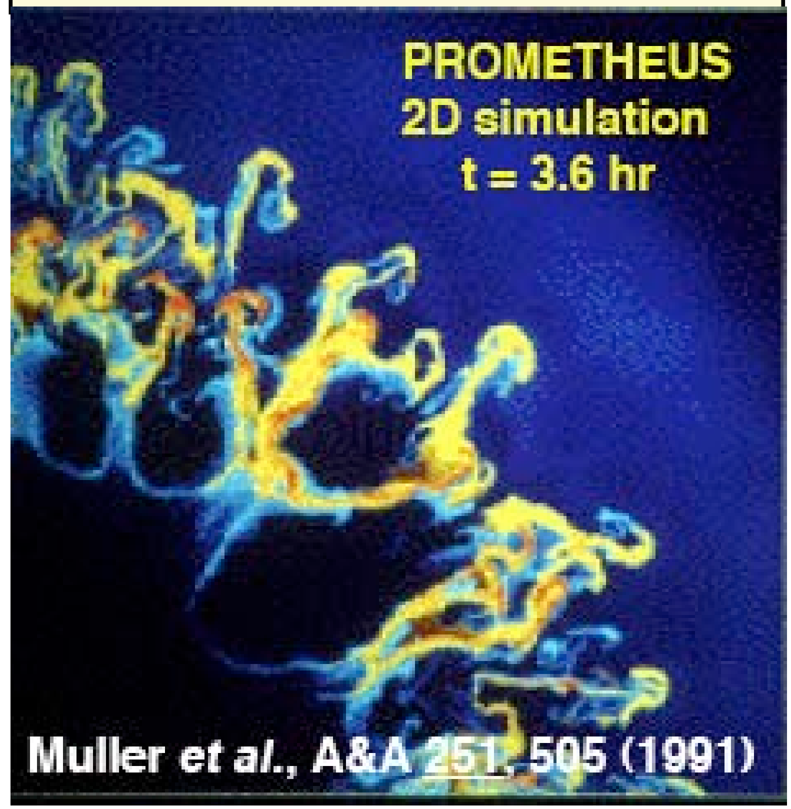
The Rayleigh-Taylor instability occurs when a heavy fluid "sits on top of" a light fluid

Water (blue) on mineral oil (red)
(images at 1 second intervals)



A similar situation occurs in ICF implosions

…and in astrophysical situations such as an expanding supernova



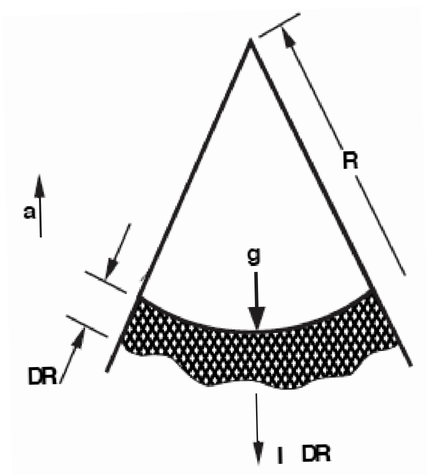
Observations from supernova SN1987A suggest strong mixing of the radiative core into the outer envelope

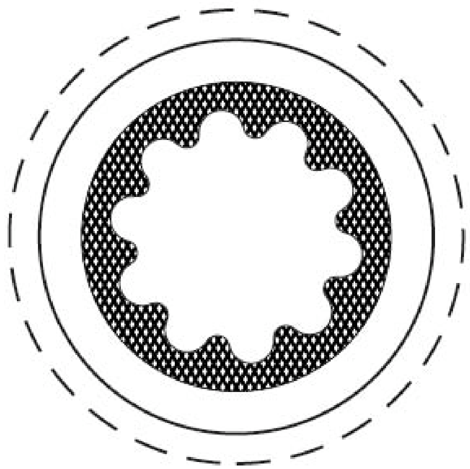
ICF Implosions are hydrodynamically unstable

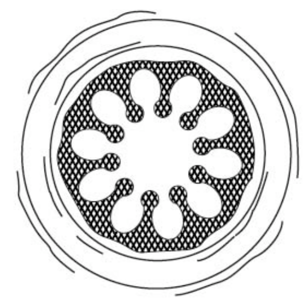
The largest growth of perturbations occurs mainly on the outer surface during acceleration

Feed through and initial roughness seeds inner surface Perturbations

Inner surface seeds grow on deceleration







Can be tested in planar experiments

The measured growth of ablative hydrodynamic instabilities in ICF agrees with numerical models

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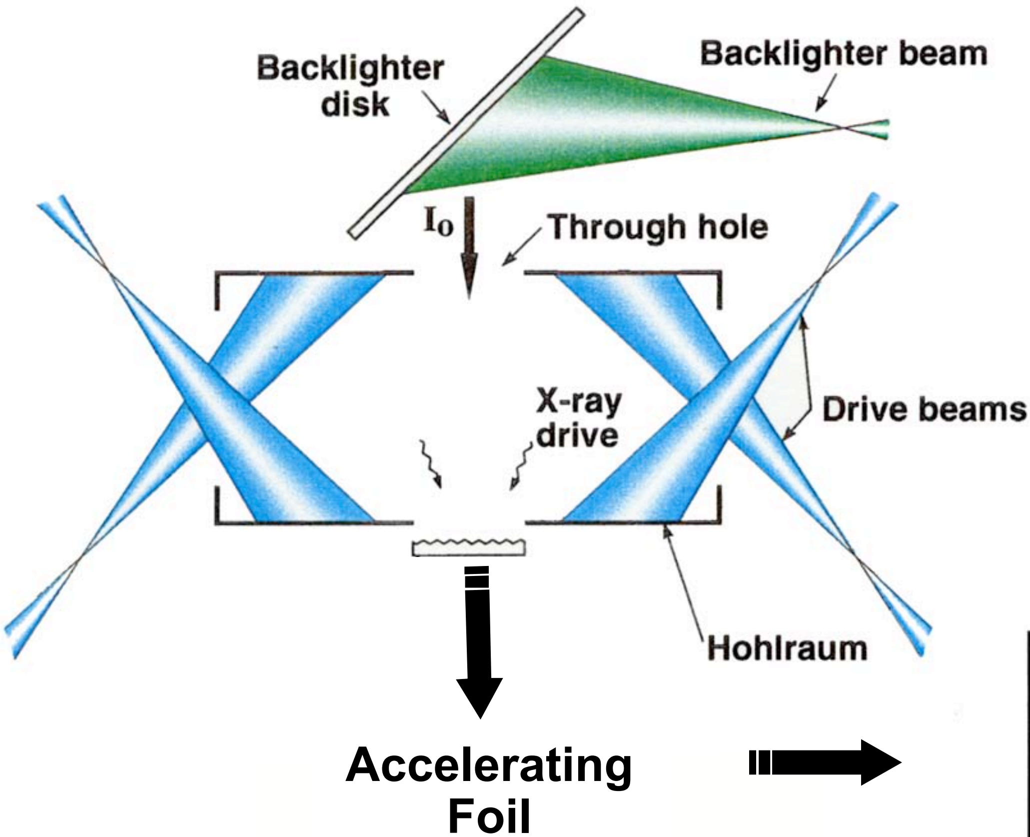

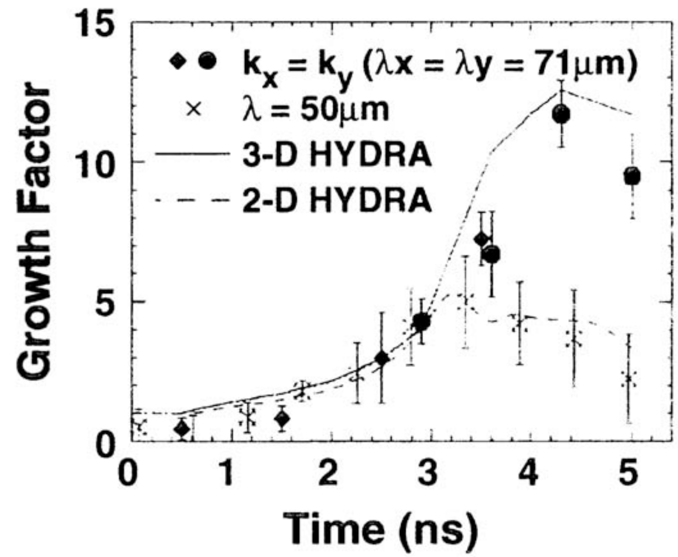

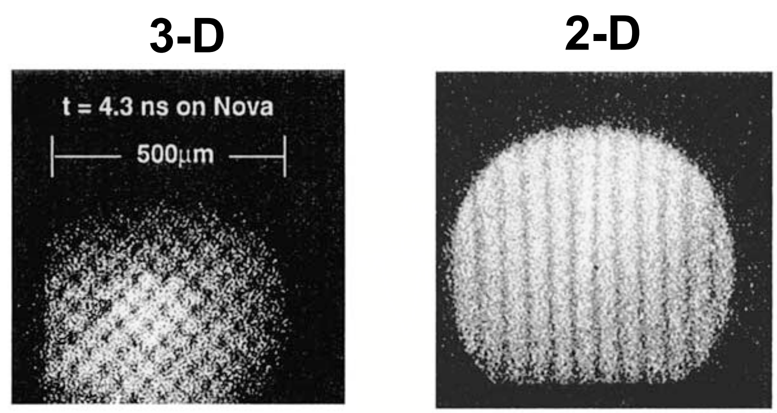

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We have validated our ability to model hohlraum temperatures in a broad range of experiments

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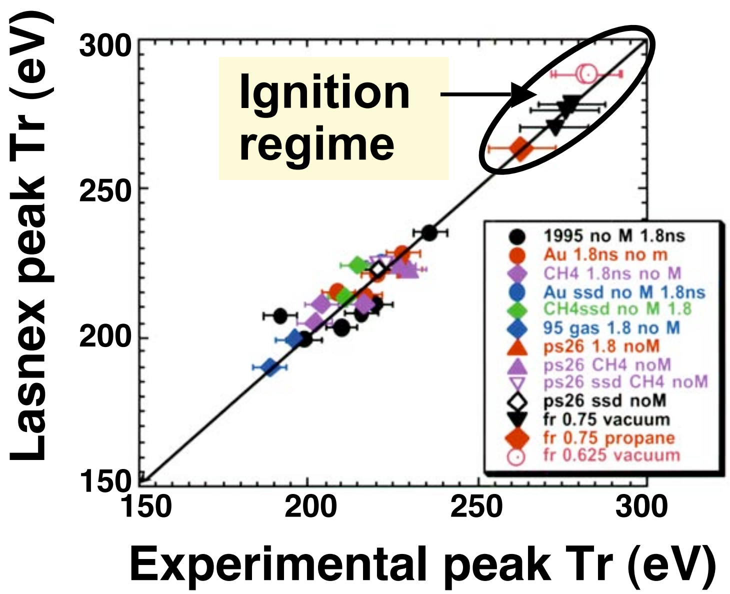
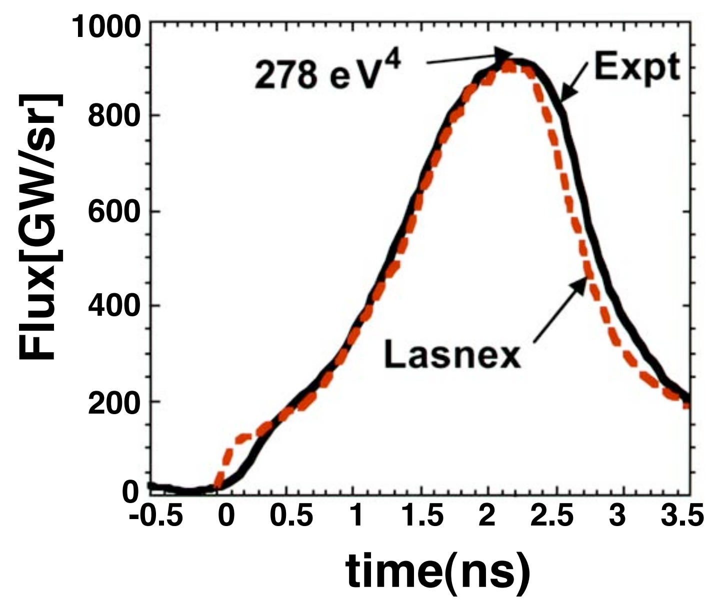
Scaling of peak drive temperature



X-ray flux versus time (from the hohlraum laser entrance hole)



Parametric Laser plasma instabilities (LPI) limit the achievable hohlraum temperatures

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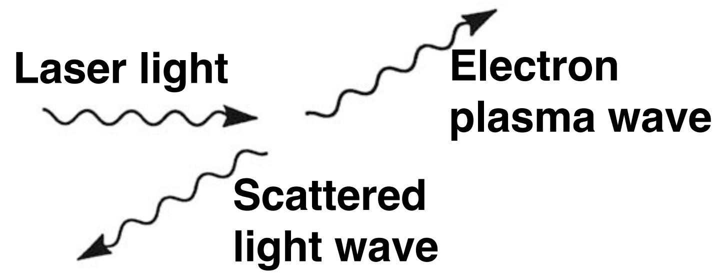
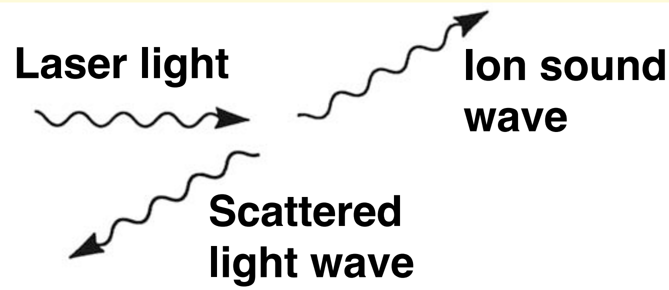
A child's swing is a simple parametric amplifier

Scattered light reduces hohlraum absorption (efficiency issue) and changes its location (symmetry issues)

- **Stimulated Raman Scattering (SRS)**



- **Stimulated Brillouin Scattering (SBS)**



Ignition target optimization must balance LPI effects, laser performance impacts, and capsule robustness

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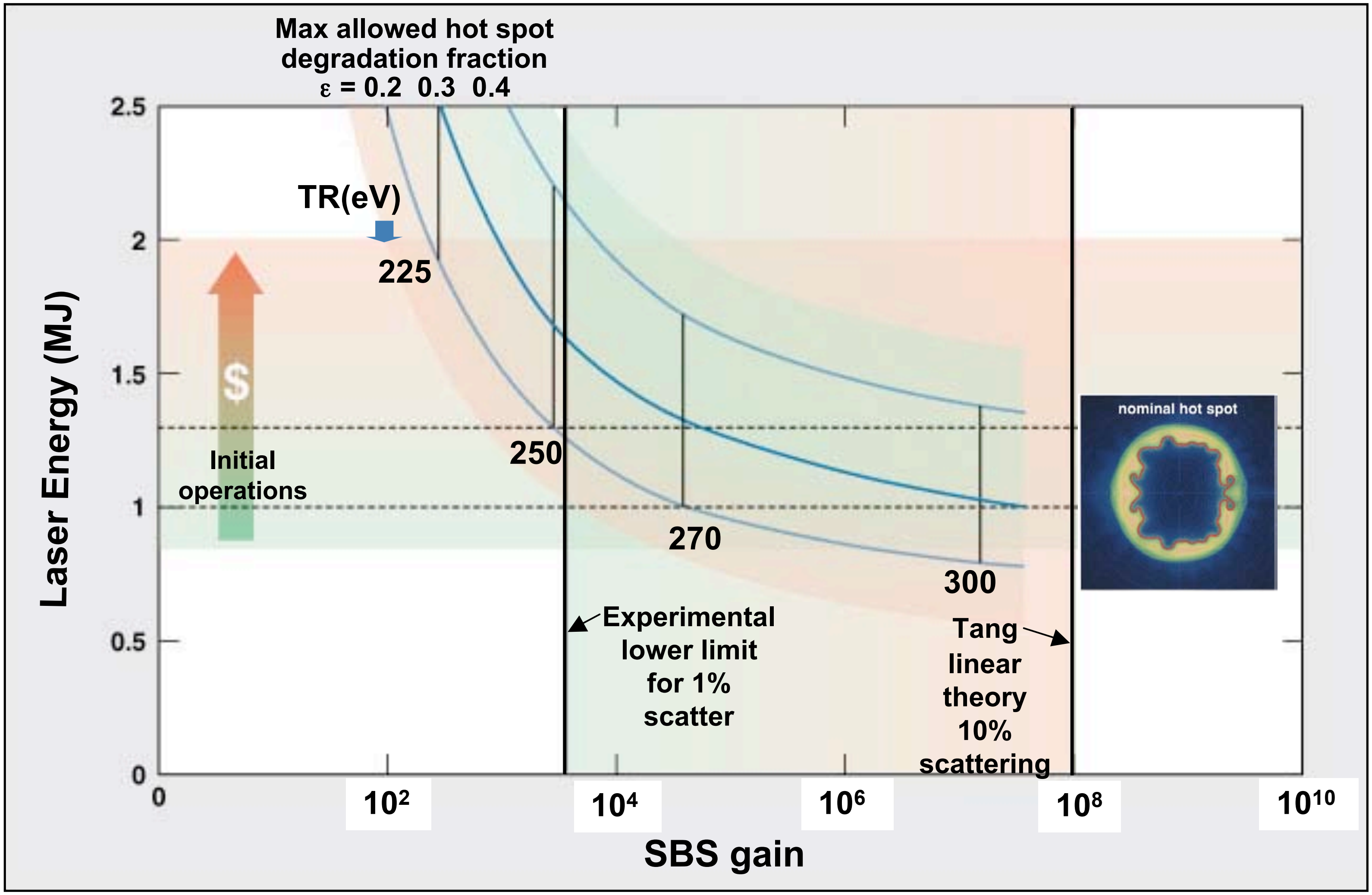

Ignition point design optimization must balance LPI effects, laser performance impacts, and capsule robustness

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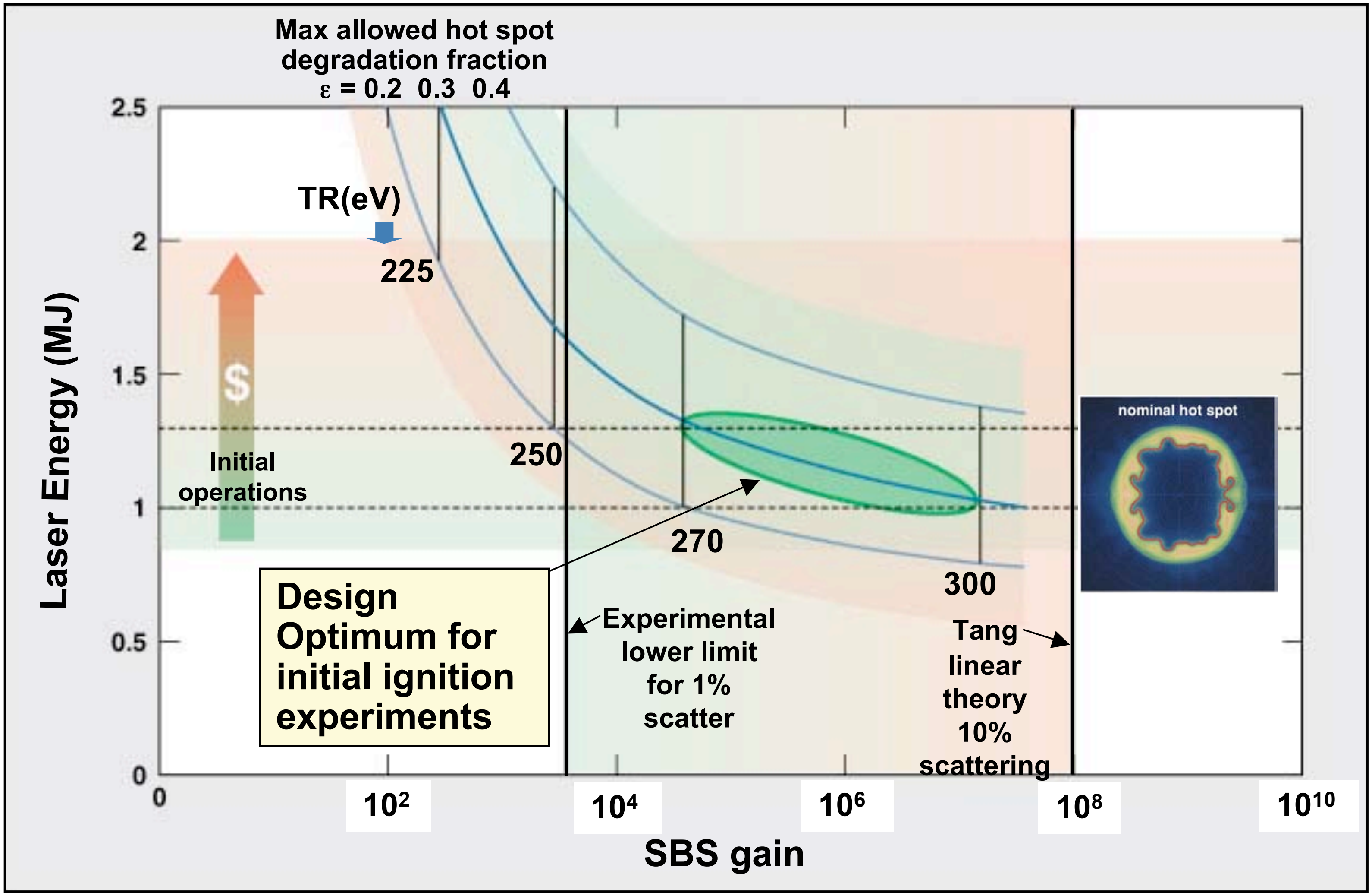

The NIF point design has a graded-doped, beryllium capsule in a hohlraum driven at 285 eV

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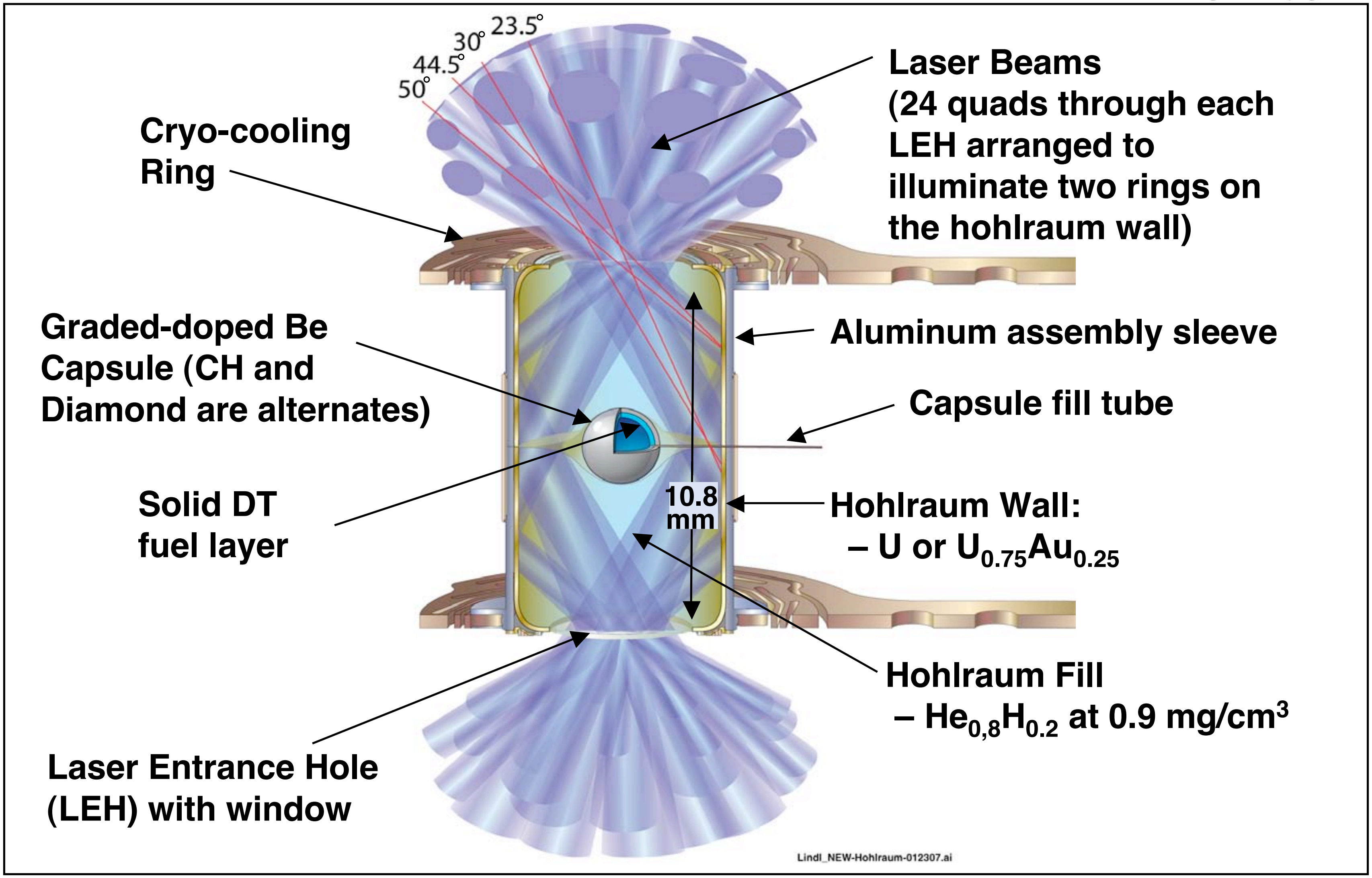

Precision targets being developed for the NIF meet the ignition target requirements

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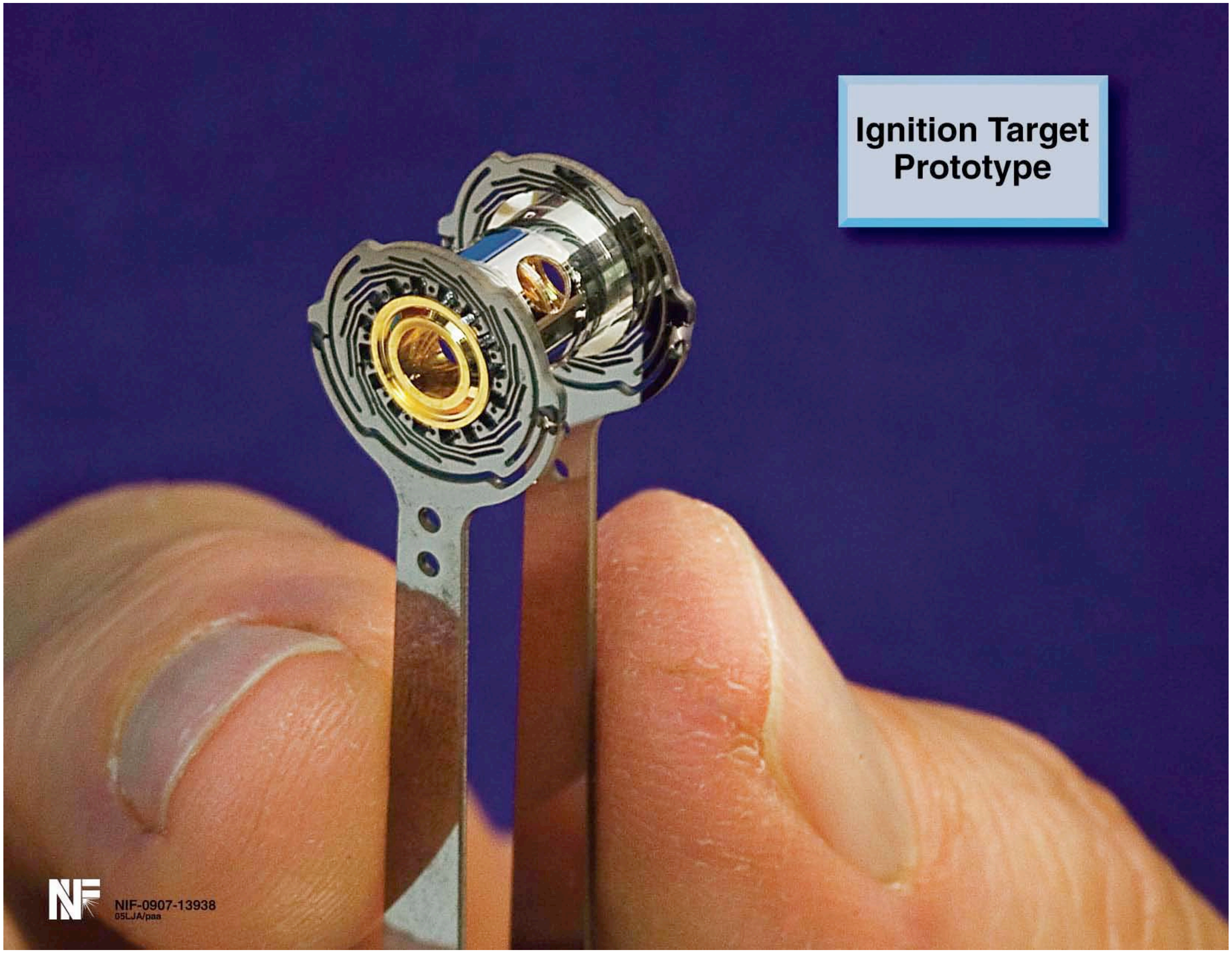

Extensive 2D and 3D calculations are a central part of our strategy

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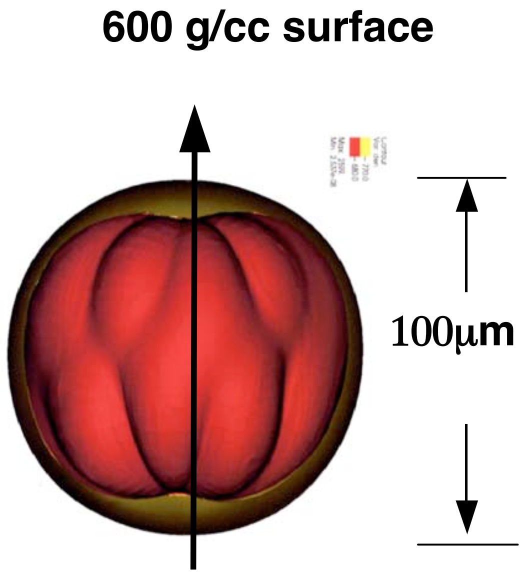
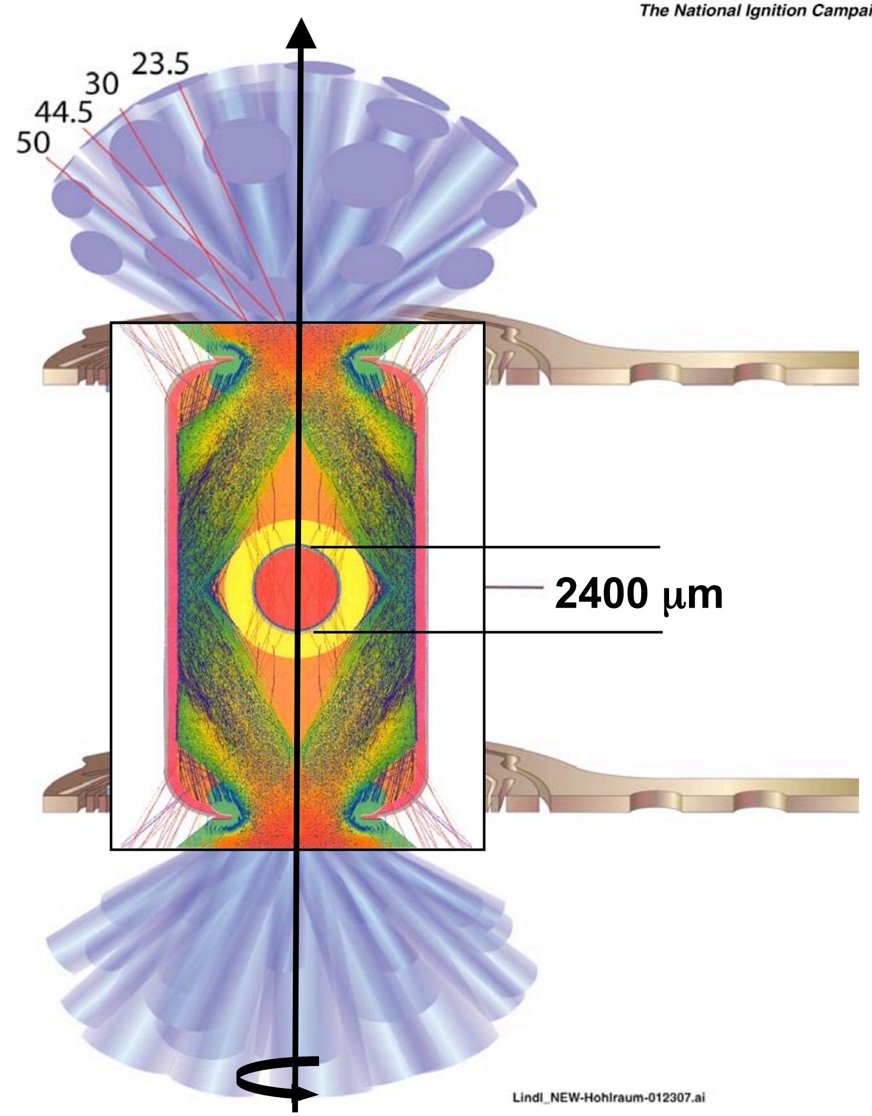
Fuel region at ignition time



Results of 3D Hydra Code calculation



The National Ignition Campaign is focused on preparing for the first ignition experiments in 2010

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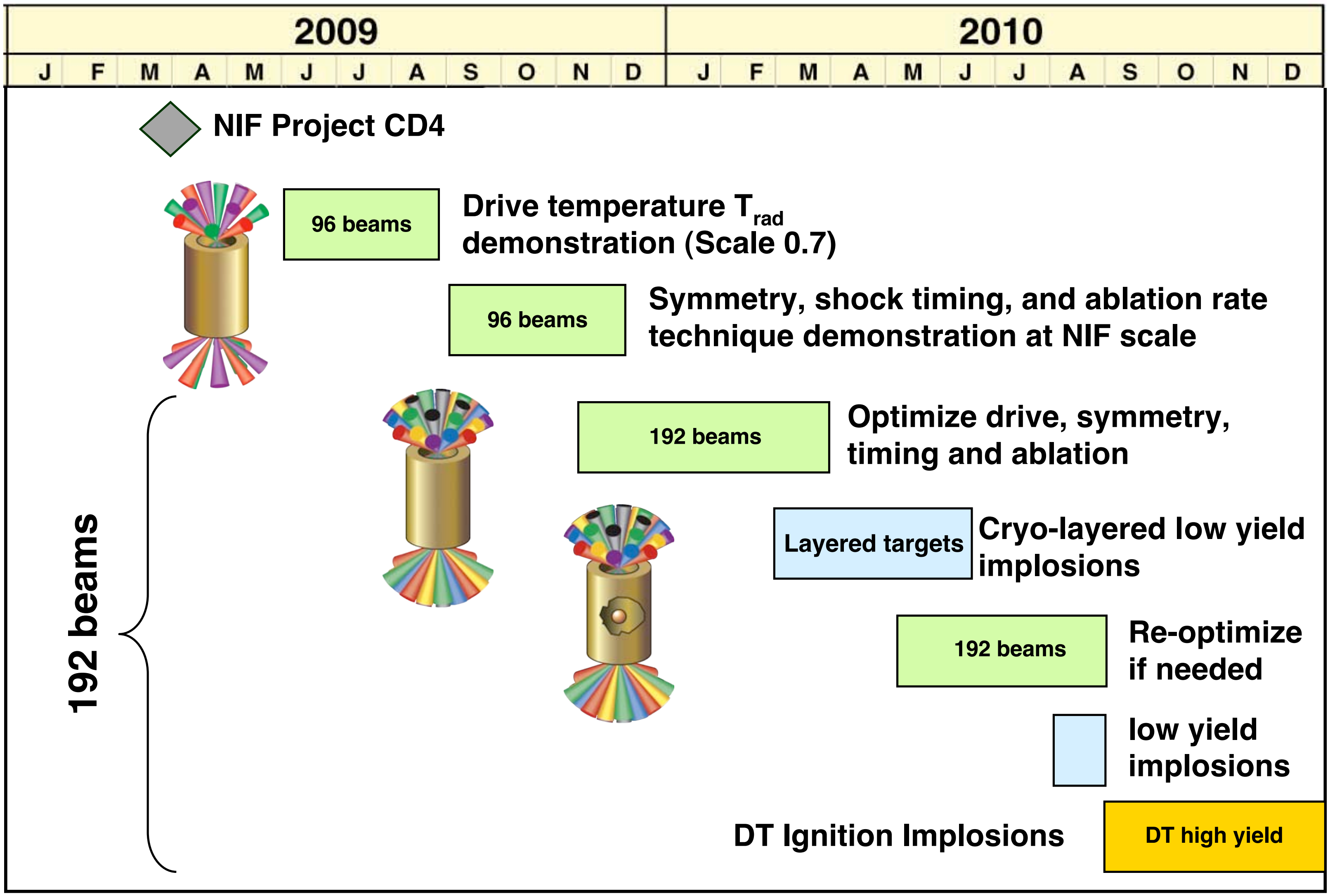

Initial ignition experiments in 2010-2011 only begin to explore NIF's potential

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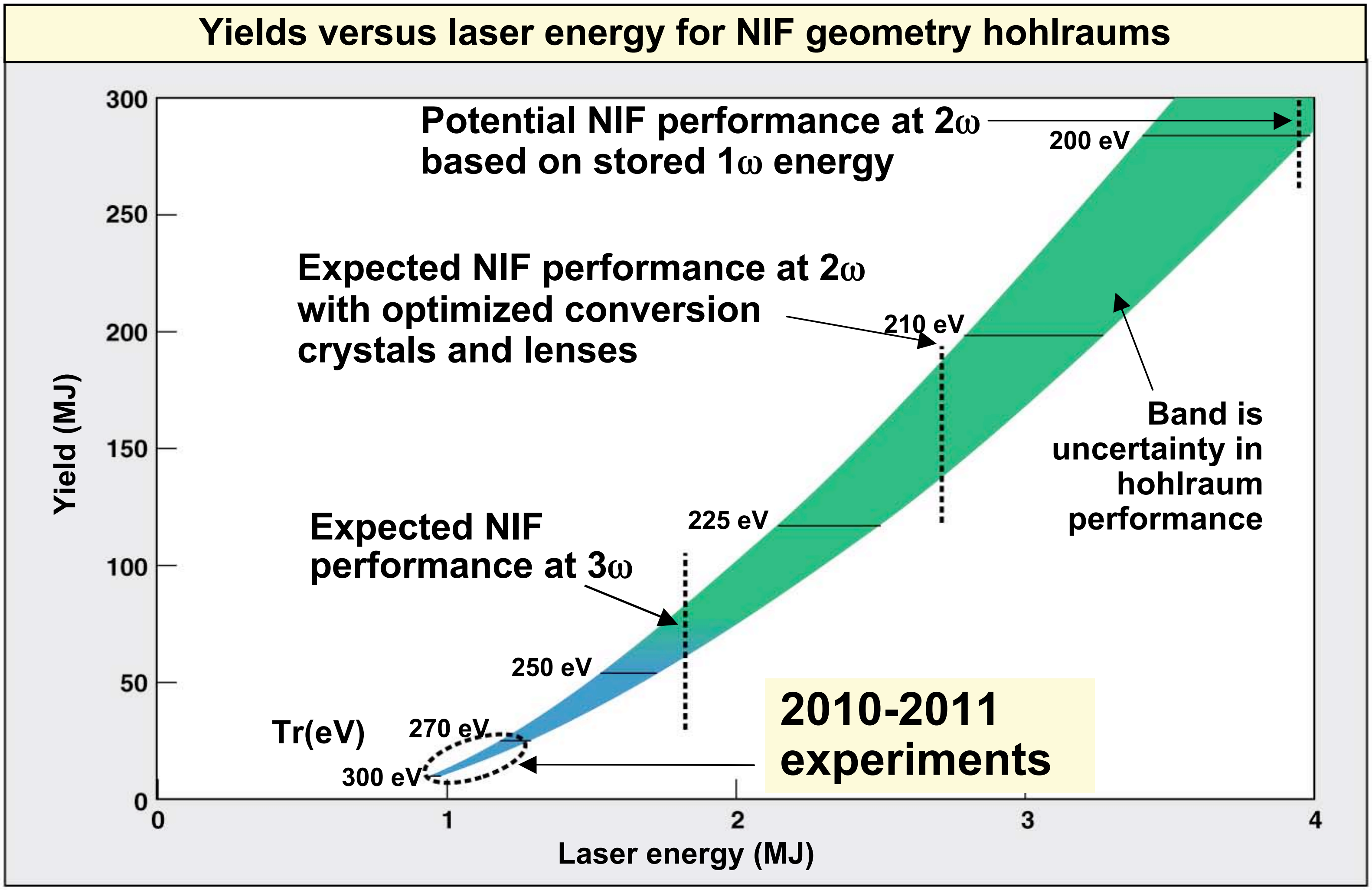

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NIF can explore direct drive or fast ignition as alternate approaches to ignition

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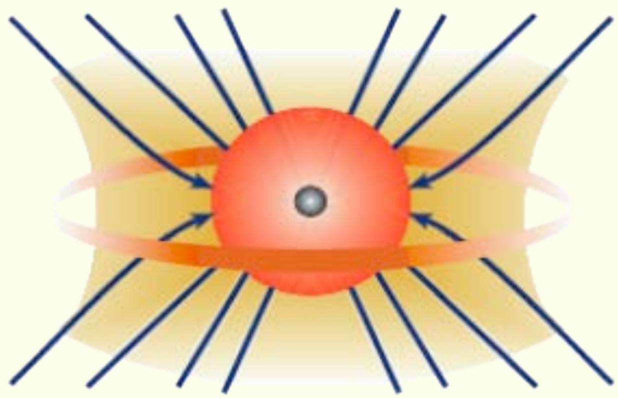
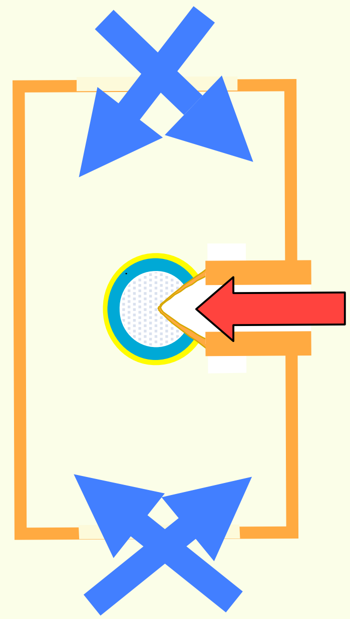
Polar Direct Drive



- Direct Drive in the Indirect Drive Geometry
- Higher coupling efficiency than indirect drive
- Beam smoothing and implosion symmetry are major challenges

Fast Ignition



- Separate compression and ignition
- Potentially highest gain
- Short pulse physics is major issue

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The physics of inertial fusion shares much in common with a wide variety of astrophysical phenomena

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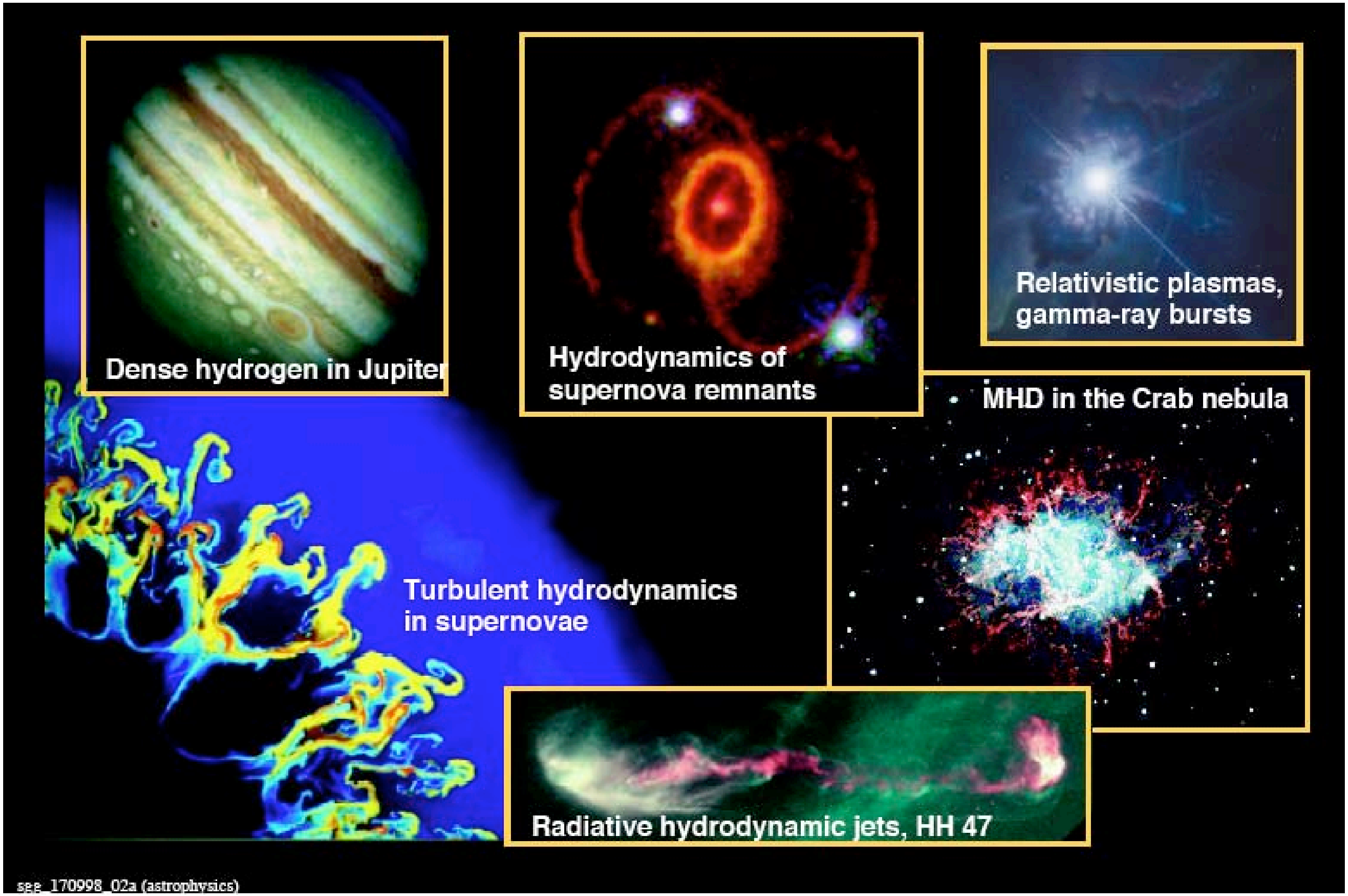

The NIF ignition experiments will be the culmination of five decades of development which started with the invention of the laser in 1960

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- Dramatic advances in computations, lasers, diagnostics, and target fabrication over the past 3 decades have laid the groundwork for NIF and the National Ignition Campaign (NIC)
- We are designing precision experimental campaigns for hohlraum driven implosions, which will take 100-200 shots leading up to the first ignition attempts in 2010
- Targets near 1 MJ of laser energy have a credible chance for ignition in early NIF operations

Ignition is a grand challenge undertaking. It is likely to take a few years to achieve the required level of precision and understanding of the physics and technology needed for success.

- The initial ignition experiments only scratch the surface of NIF's potential

NIC

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