To ignition and beyond!

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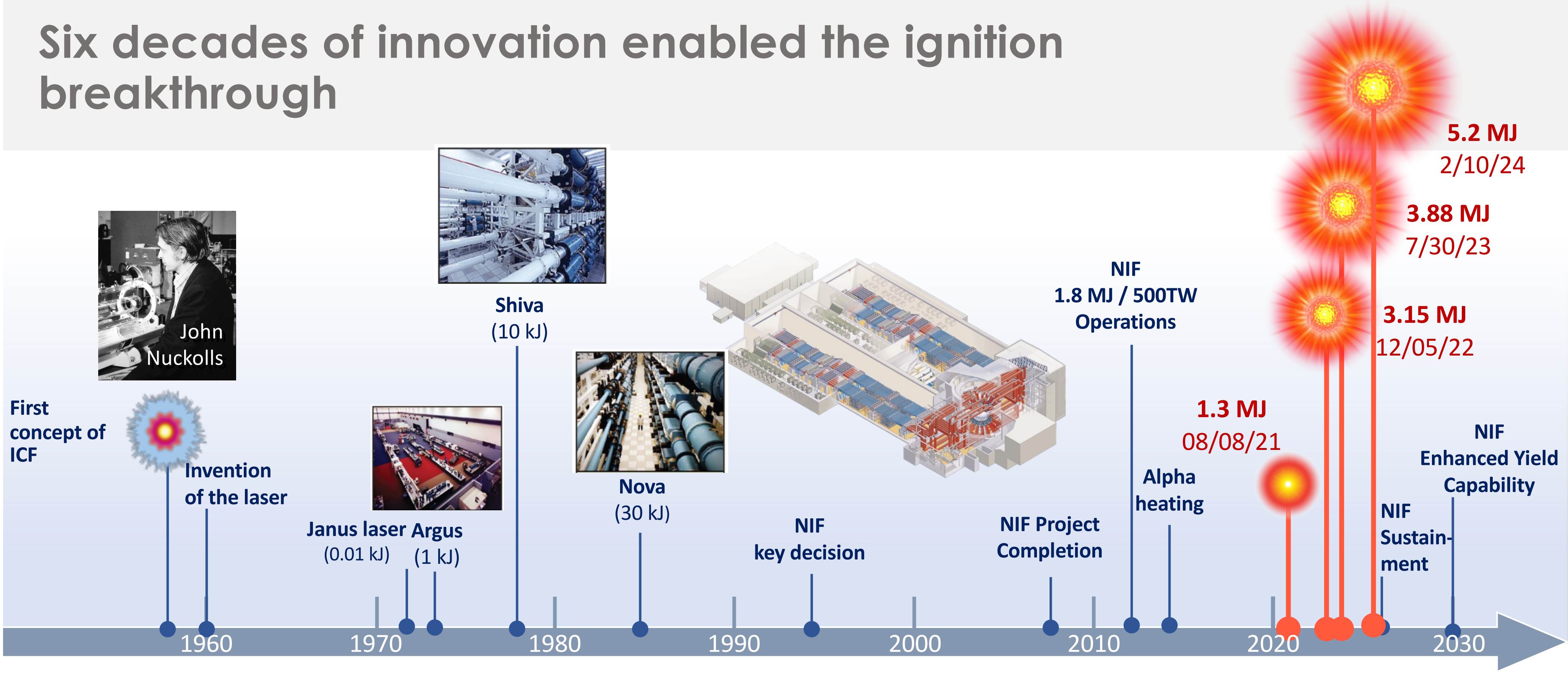
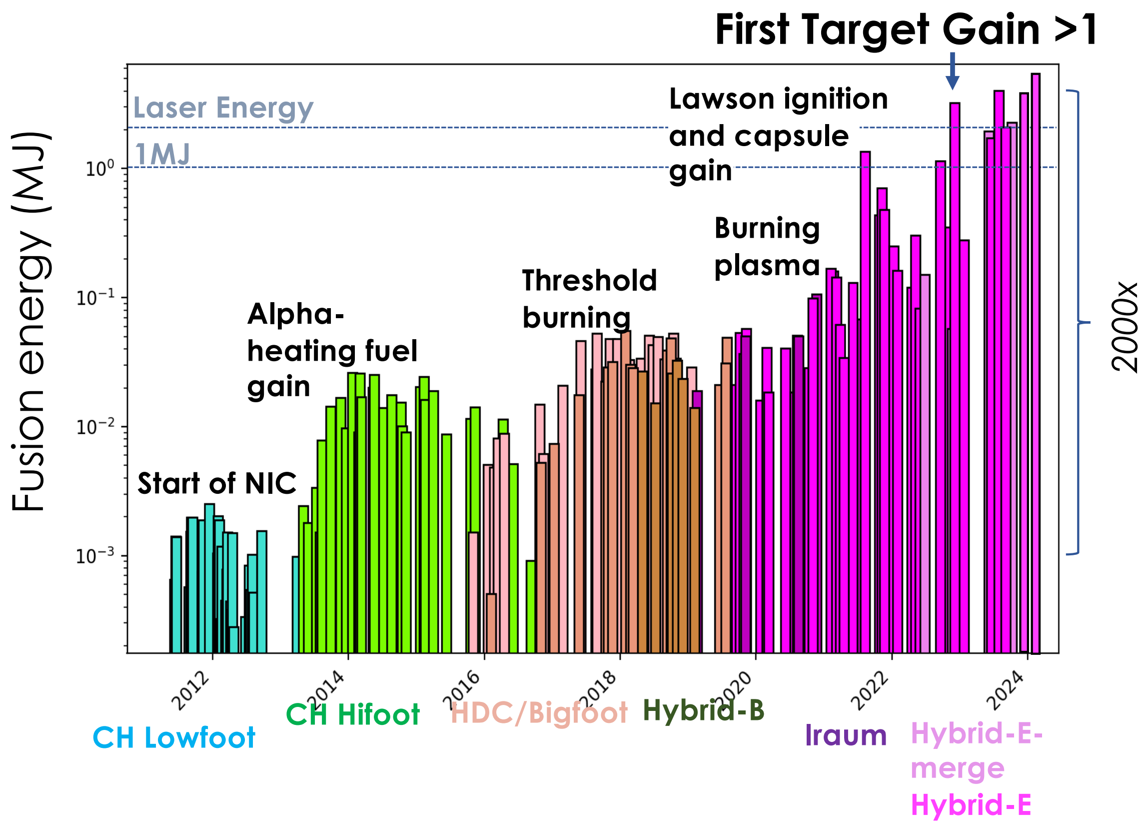
Six decades of innovation enabled the ignition breakthrough



It has been and continues to be an amazing journey!

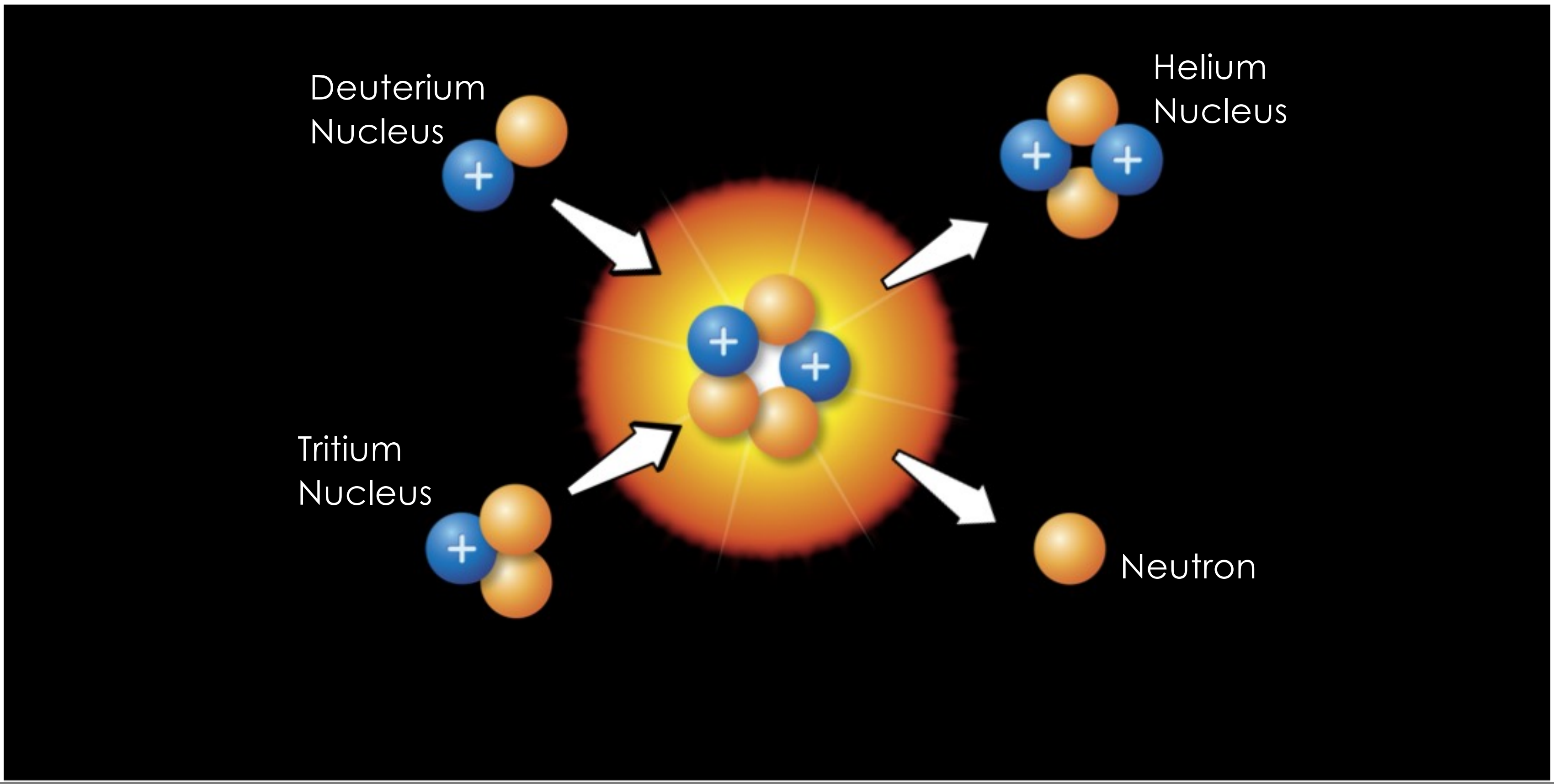
We have achieved and exceeded all definitions of ignition: more energy out than laser energy delivered to the target

- December 5, 2022: (*target gain >1*) NIF exceeded ignition by all metrics
- February 10, 2024: *(> 5 MJ, target gain > 2.3)* laser energy increase to 2.2 MJ + capsule ablator thickness increase
- Target gain now demonstrated a number of times now at NIF
- Indirect drive approach
- We have entered a new era!

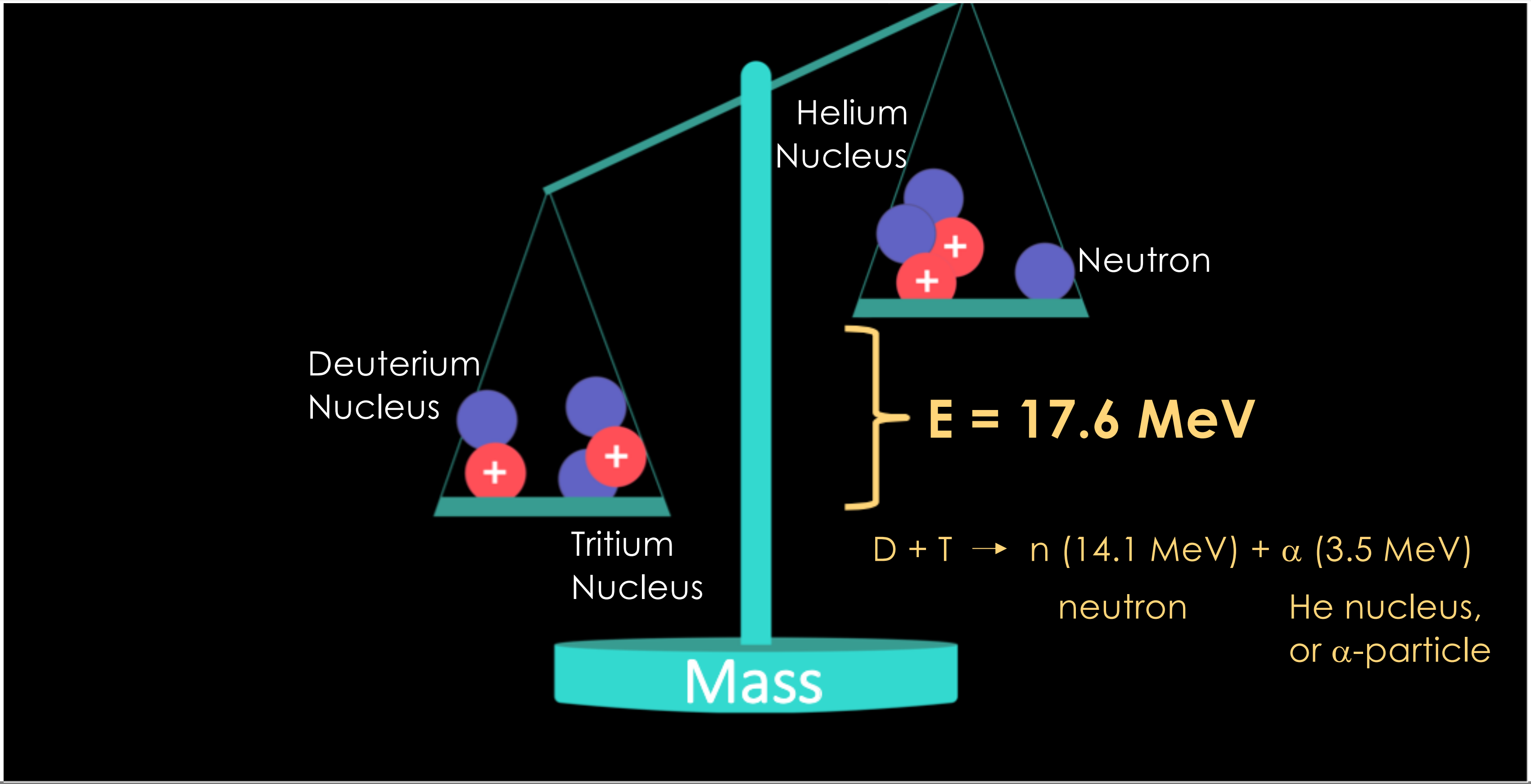


NIF collaboration, PRL, 129, 075001 (2022); K**ritcher, et al.**, PRE, 106, 025201 (2022); **Zylstra, et al.**, PRE, 106, 025202 (2022);
NIF collaboration, PRL, (2024); K**ritcher, et al.**, PRE, (2024); **Pak, Zylstra, et al.**, PRE, (2024), **Hurricane, et al.**, PRL, (2024);

Fusion occurs when two light nuclei combine



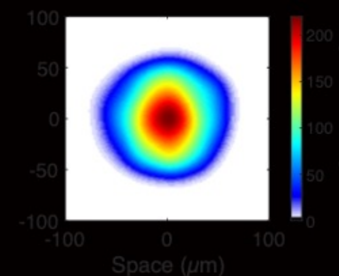
The total mass of the products after fusing is less and energy is released



Fusion fuel is pressurized to high temperature and density

Gravitational confinement sustains fusion

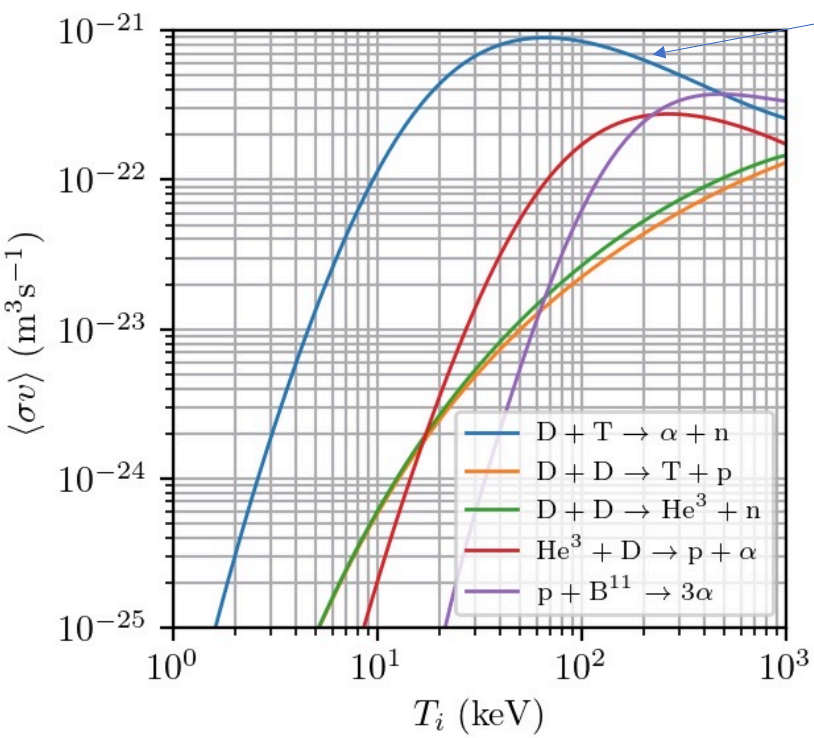
Inertial Confinement fusion (ICF) experiment



Like compressing a basket ball down to the size of a pea

- Temperature > 5x center of the Sun
- Pressure > 2x center of the Sun
- But for just 90 trillionths of a second!

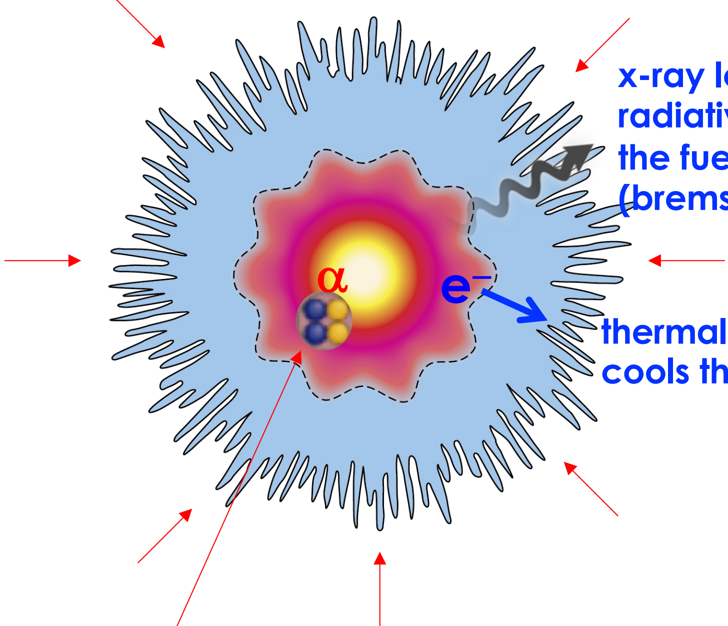
For ignition, fusion fuel is heated and compressed to the point where α-heating occurs

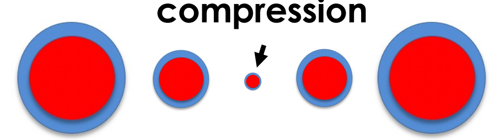


D + T → n (14.1 MeV) + α (3.5 MeV)

- α-heating: heating from stopping α-particles in DT
  - – α's deposit energy, heat up DT
  - – reaction rate increases
  - – more reactions
  - – more heating

PdV work and α-heating provide implosion energy – but these must overcome losses to achieve ignition





Heat balance:

$$c_{DT}\frac{dT}{dt} = f_\alpha P_\alpha - f_B P_B - P_e - \frac{1}{m} p \frac{dV}{dt}$$

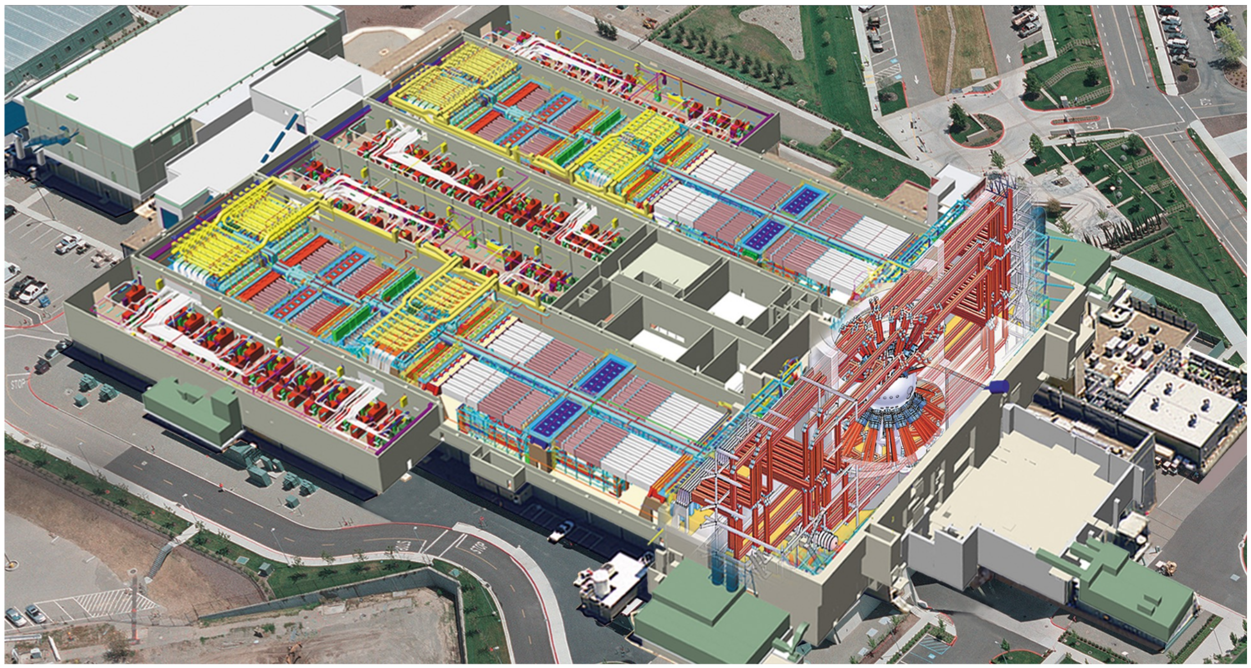
ignition when these terms dominate $\frac{dT}{dt} \sim T^{3.6}$

balancing these two terms: T_{min} ~ 4.3 keV ⟹ a fast implosion (> 320 km/s)

heats on implosion
cools on explosion

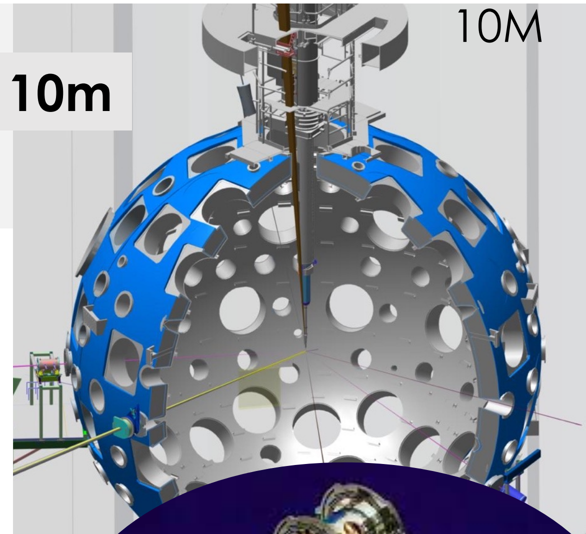
We use the world's most energetic laser to drive the fusion process

We use the world’s most energetic laser to drive the fusion process



300 MJ of electrical energy in capacitor banks in a facility the size of 3 football fields

Up to 2.2 MJ of laser energy of blue light delivered to target ~1.2 cm in length and 0.64 cm in diameter

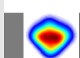


scale ~ 10m

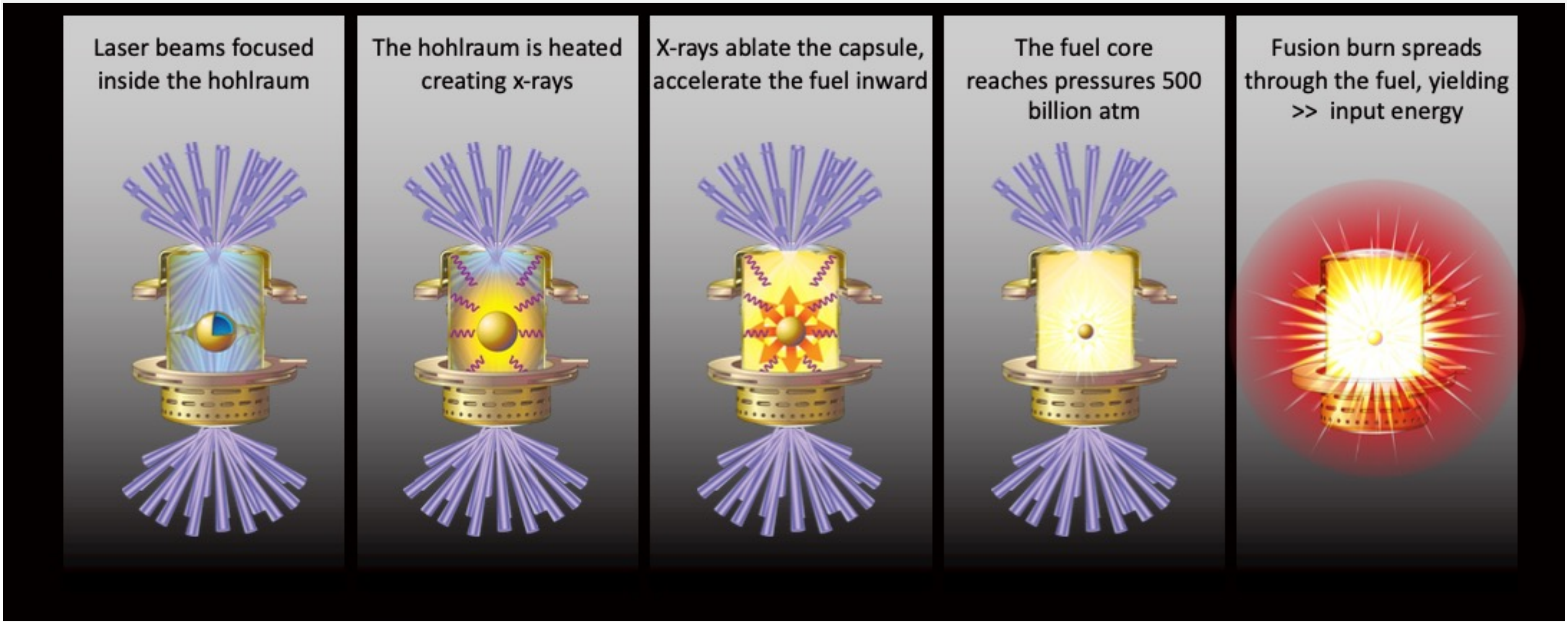
scale ~ 1cm

scale ~ 2mm

scale ~ human hair

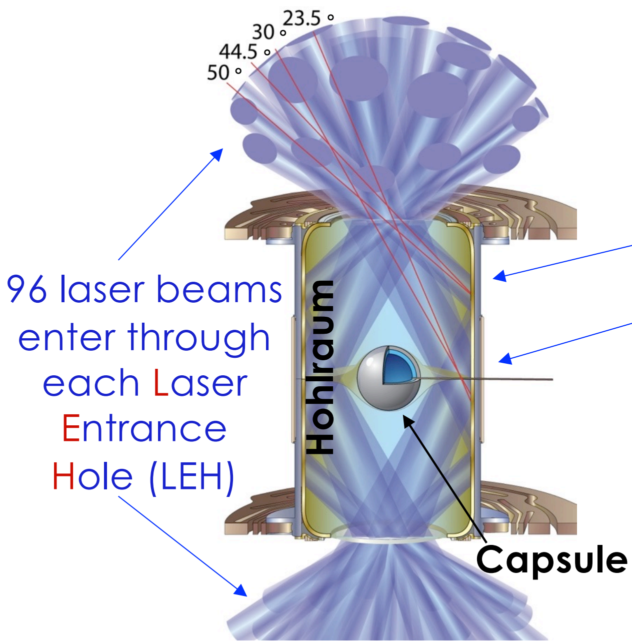


Our approach uses x-rays created by the laser to compress and heat the fuel to ignition conditions



NIF provides up to ~~1.8~~ ~~1.9~~ ~~2.05~~ 2.2 MJ of laser energy to drive inertially confined implosions

- Indirect drive: laser energy couples to hohlraum and converts to x-rays



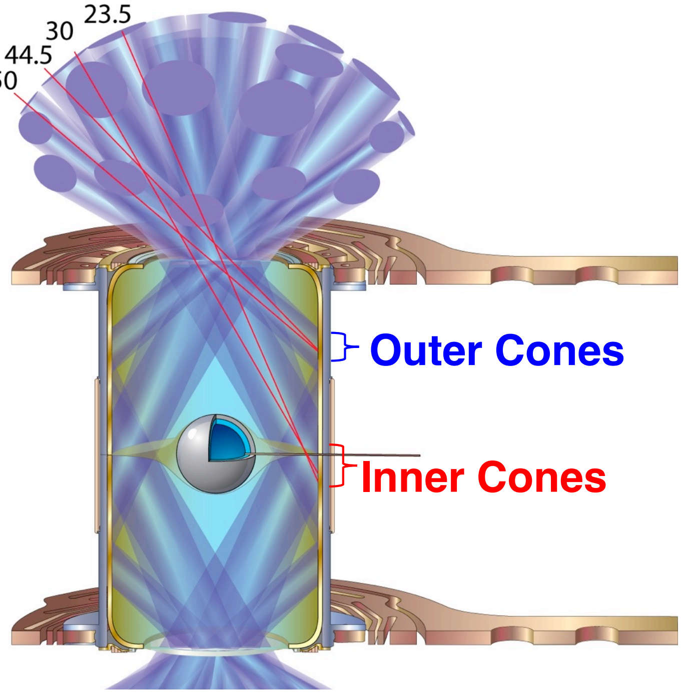
- 4 cones of laser beams deliver energy at the wall in different locations
  - 44.5°/50° (outer) beams closer to LEH
  - 23.5°/30° (inner) beams near mid-plane

- laser beams propagate through hohlraum (LEH window, gas fill, ablator) to hohlraum wall

  - *laser-plasma interactions (LPI) can limit how much energy reaches the wall*

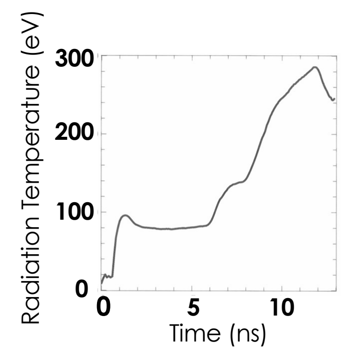
  - *LPI also can produce hot electrons that pre-heat the capsule ablator and fuel*

The "hohlraum" produces the radiation environment that implodes the capsule (indirect drive)

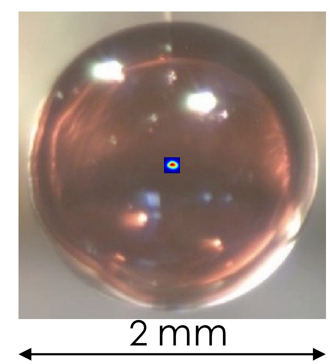


Hohlraum wall composed of Au-lined DU
– laser deposits energy in Au
– DU enhances peak drive

- ***"Hot":*** hohlraum creates a radiation 'oven' that heats the capsule
  - backscatter generated by LPI reduces drive

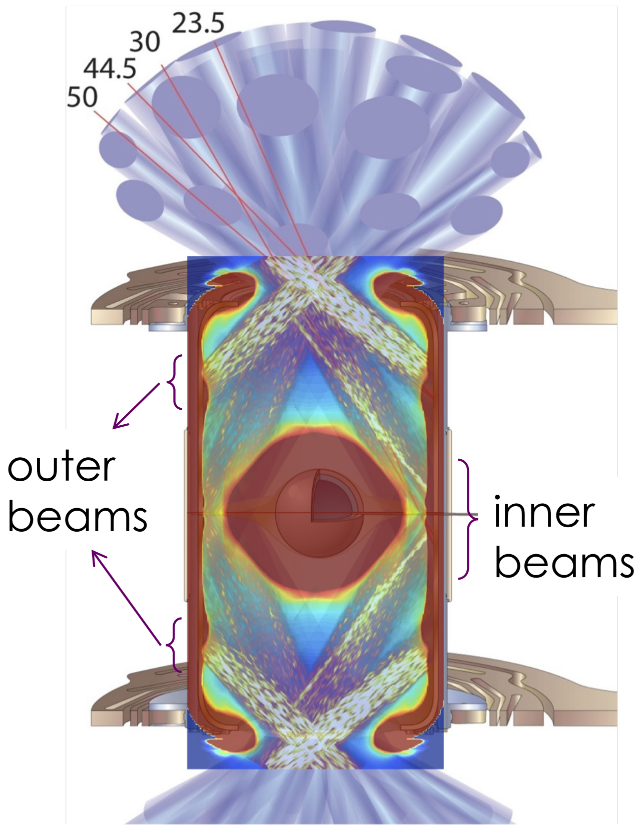


- ***"Round":*** hohlraum provides symmetric irradiation for a round implosion
  - low mode radiation symmetry is a stringent requirement (LPI can help here!)

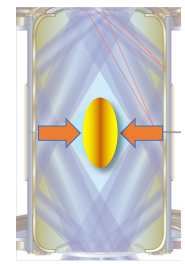


"Round"

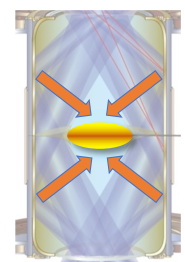
Low mode radiation symmetry is established by the hohlraum geometry



- too much energy on inner beams => **prolate** implosion (**+P2**)



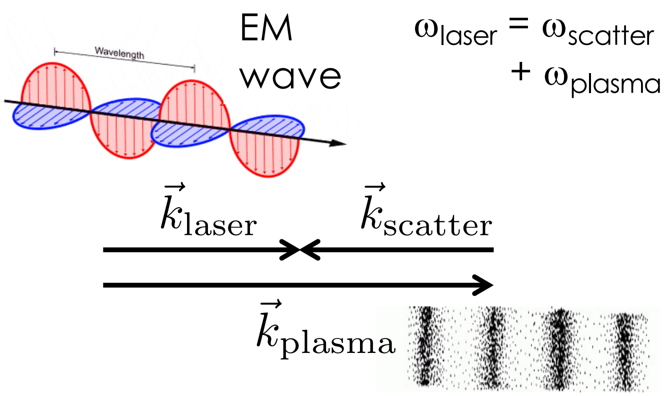
- too much energy on outer beams => **oblate** implosion (**–P2**)



"Hot"

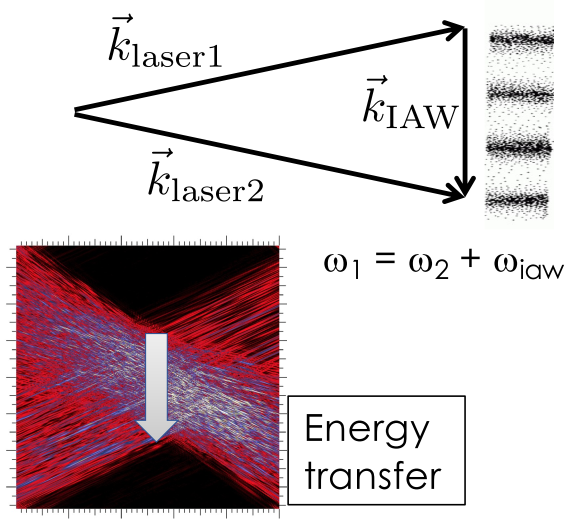
Laser-plasma interactions (LPI) can scatter/redirect laser light and generate hot electrons...

Backward stimulated laser scatter (reduces drive)



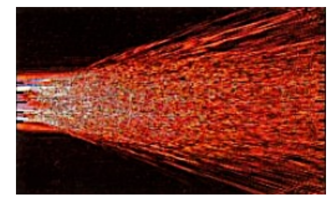
- Stimulated scattering reduces target coupling + impacts symmetry
- SBS: optics damage risk
- SRS: hot electron source (unwanted target preheat)

Cross-beam energy transfer (CBET) (impacts symmetry)



- CBET is driven by:
  - Plasma flows
  - Imposed wave length detuning ($\Delta\lambda$) to correct implosion symmetry

And more...



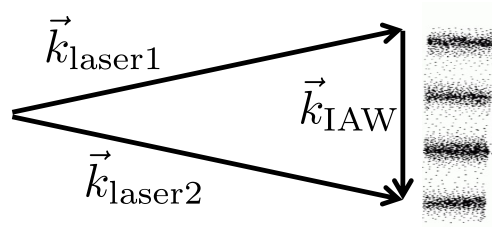
- Filamentation decollimates the laser
- Forward SBS decollimates the laser and can modify CBET (introduces additional $\Delta\lambda$)
- Two-plasmon decay produces hot electrons

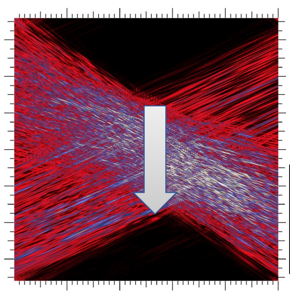
"Round"

… but LPI is also a powerful symmetry tool!

+

Crossed beam energy transfer (CBET)

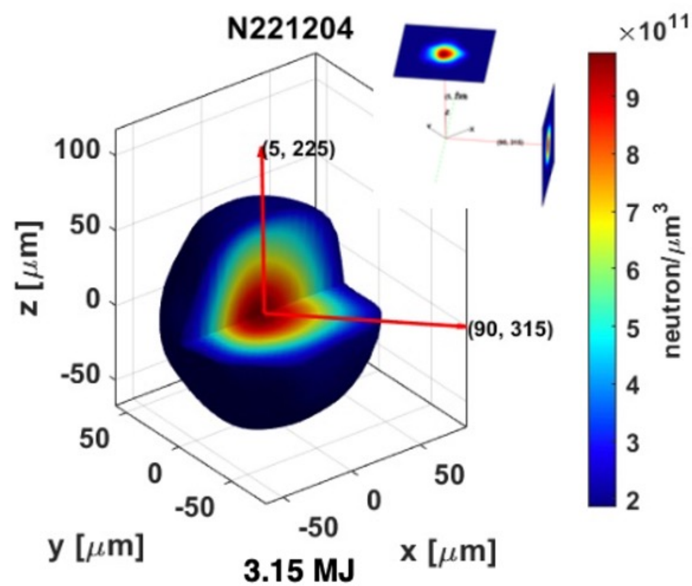




$\omega_1 = \omega_2 + \omega_{iaw}$

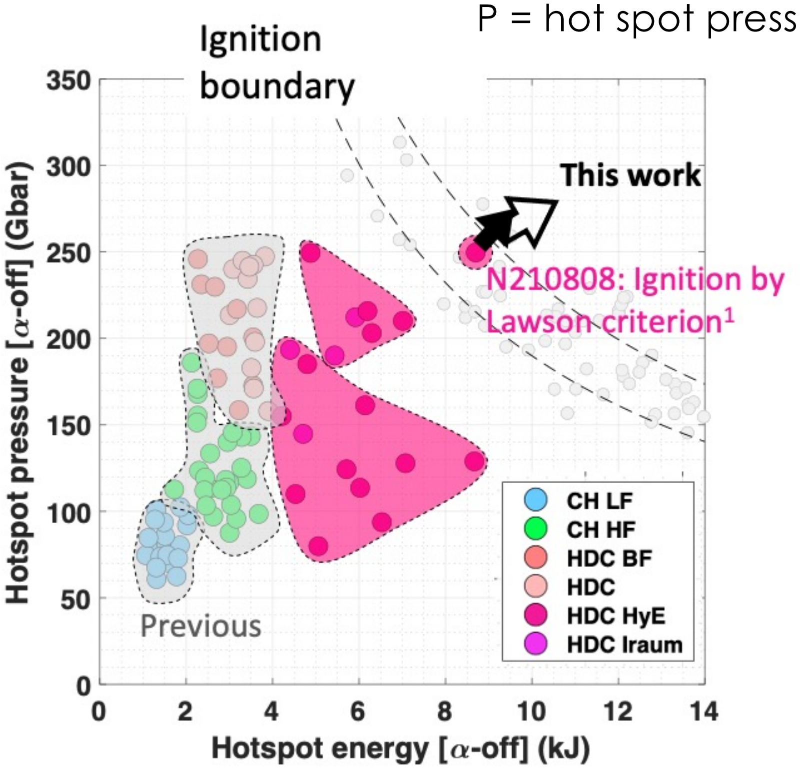
- CBET is driven by:
  - Plasma flows
  - Imposed wavelength detuning ($\Delta\lambda$) to correct implosion symmetry

=



Design changes resulted in an increase in a key ignition metric by 25%

E = hot spot internal energy
P = hot spot pressure



- Newer designs*: > 4% of DT fuel burnt up
- First shot (N210808) was more sensitive to:
  - low mode asymmetry
  - radiative losses from ablator mixing into hot spot
  - design changes provide for "margin" against realistic fielding challenges
- Thicker ablators increase confinement
- Thicker ablators are also better for stability
- This makes the fuel more "clean"

*A. L. Kritcher

So why did it take so long to achieve ignition?

- ***HED/ICF science entails physics at multiple spatial and temporal scales***
  - still not computationally tractable to directly simulate all of the “sub-grid” physics
  - reduced model descriptions are developed to attempt to include this physics

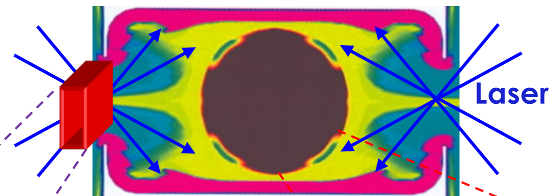
- ***Over the last several decades reduced models of “sub-grid” physics have improved***
  - many of these models are still not accurate enough
  - a priority of the ICF program is defining and executing focused experiments at NIF to improve our predictive capability

- ***To address these shortcomings:***
  - designs/simulations are “calibrated” to match observables
  - perturbative changes as a campaign proceeds, but large enough so that new results fall outside experimental error bars
  - new and improved diagnostics

The design challenge: incorporate the correct physics at all relevant spatial and temporal scales

macroscale

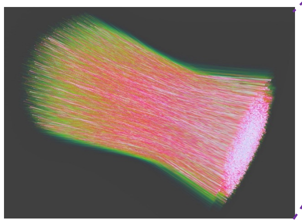
- **Gross hydrodynamic length and time scales are set by target size [O(mm)] and laser pulse length [O(ns)]**



⇒ environment -- plasma parameters and scale lengths

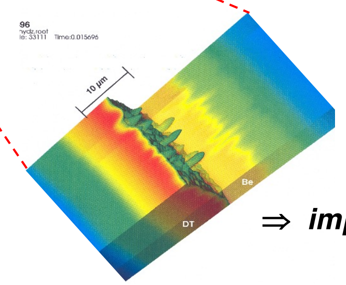
Simulations cannot incorporate all of the necessary physics

mesoscale



⇒ beam propagation

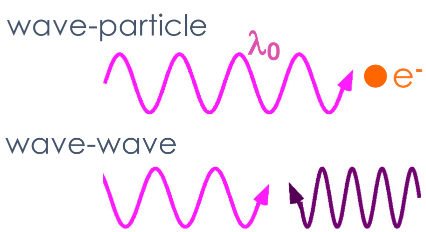
- **evolves on:**
  μm length scales
  ps time scales

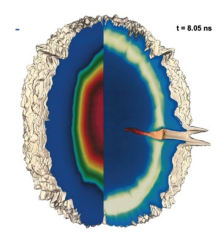


⇒ implosion stability

microscale

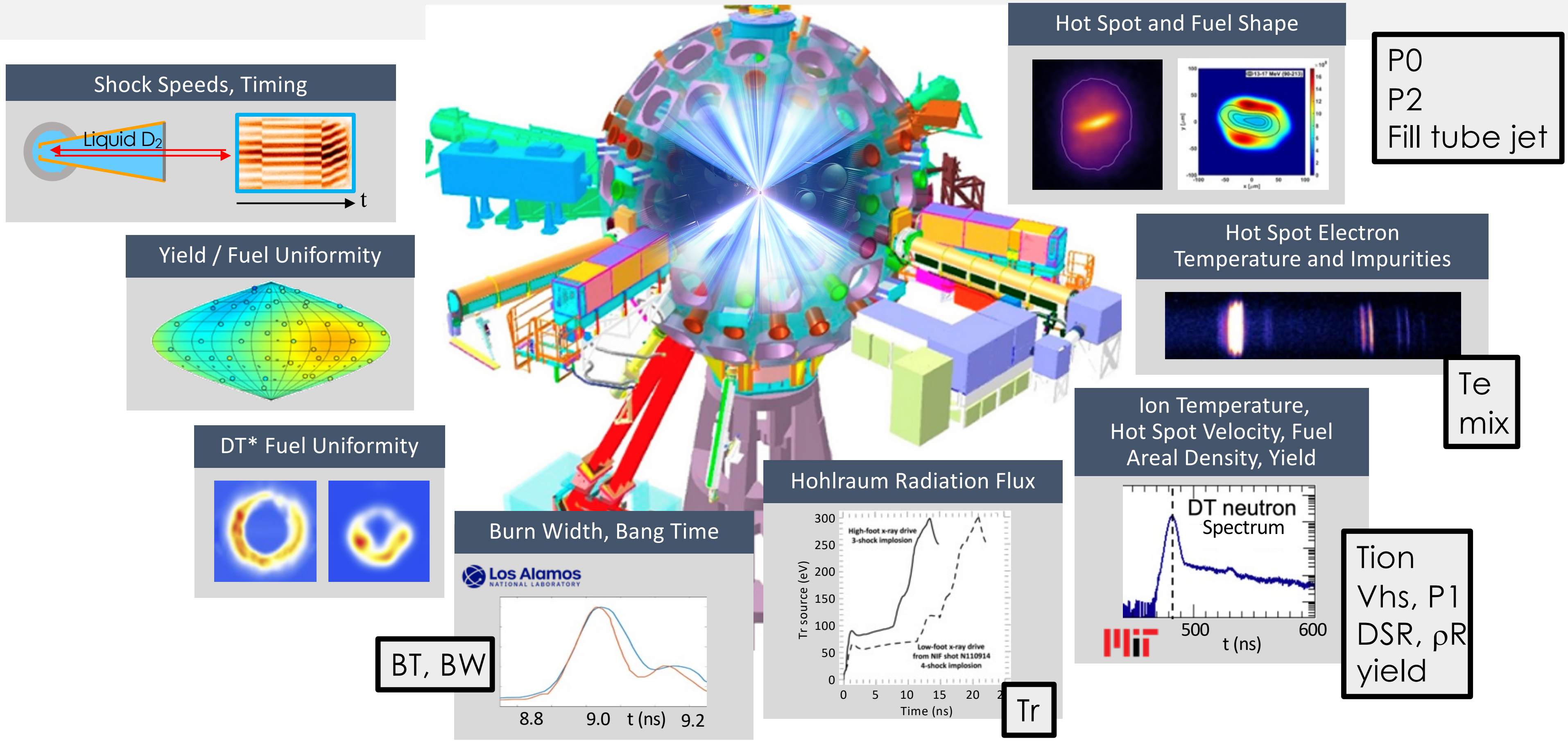
- **Detailed processes of beam propagation occur on "light" spatial and temporal scales**
  ⇒ kinetic effects





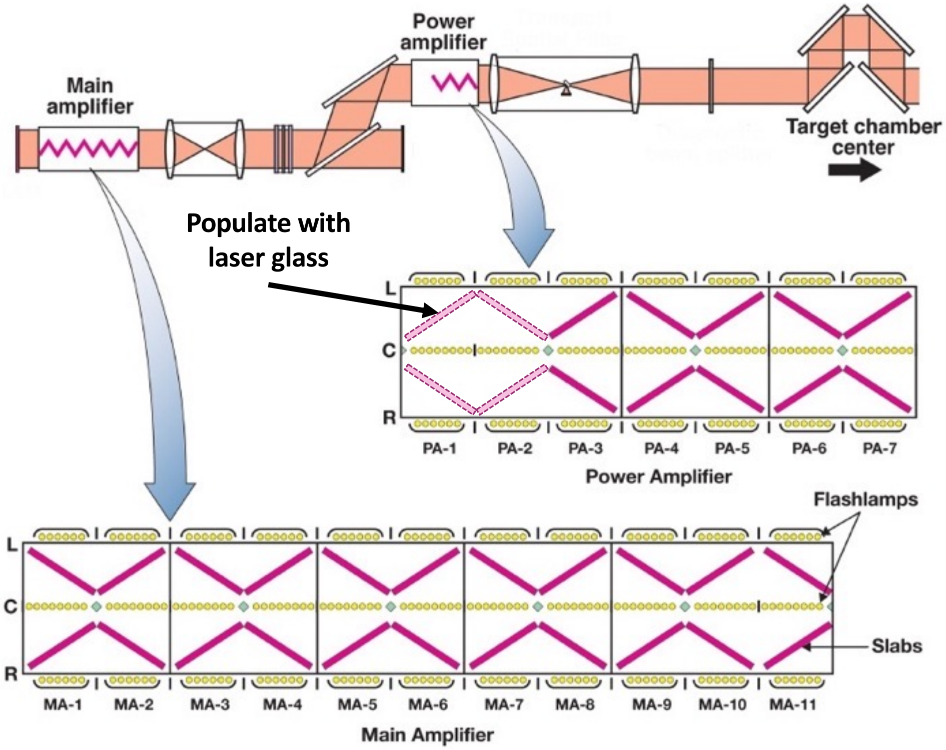
- **Engineering features such as the fill tube, tent, crystallinity, … require calibration to direct numerical simulations**

Success when diagnostic data is coupled to simulation!



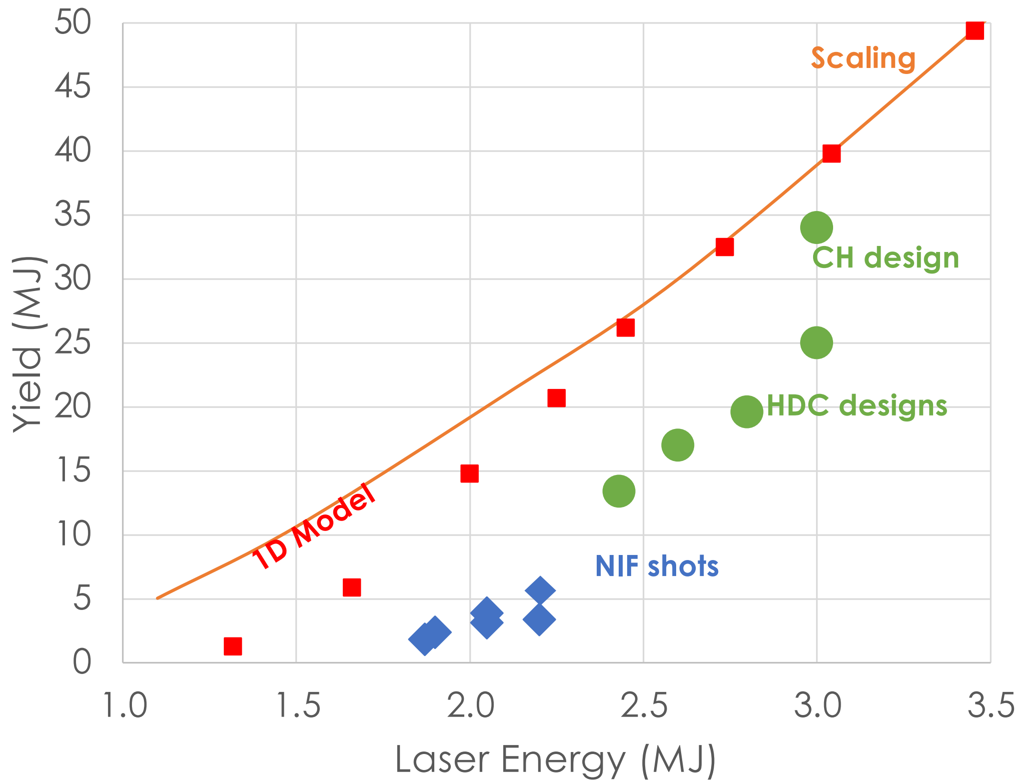
We are developing a proposal to upgrade the NIF termed the Enhanced Yield Capability (EYC)

- Add amplifier glass to increase energy by 40%
- Existing vendor base & proven technologies
- Direct and repetitive project
- Does not require facility down time



NIF can deliver even higher energy (2.6-3.0 MJ) with just modest modifications

We have identified design options that generate yields between 20-40 MJ at 3 MJ laser energy



- Yield depends on the implosion adiabat, hohlraum-to-capsule efficiency and implosion quality
- These designs assume similar implosion parameters demonstrated on current NIF scaled to higher energy/power
- We plan to execute experiments to expand our demonstrated space, e.g.
  - Higher efficiency hohlraums
  - Higher efficiency ablators
  - Lower adiabat implosions

The main physics design risks are laser-plasma instabilities (LPI), symmetry control and incorporating applications

Laser-plasma instabilities (LPI)

- For current shots LPI is predominantly stimulated Brillouin scattering (SBS) with 1-3% energy loss
- Analyses suggest we are close to threshold, where an increase in power or scale length may lead to increased losses

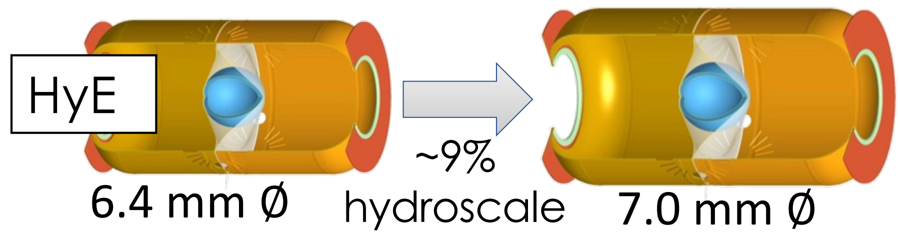
Symmetry control

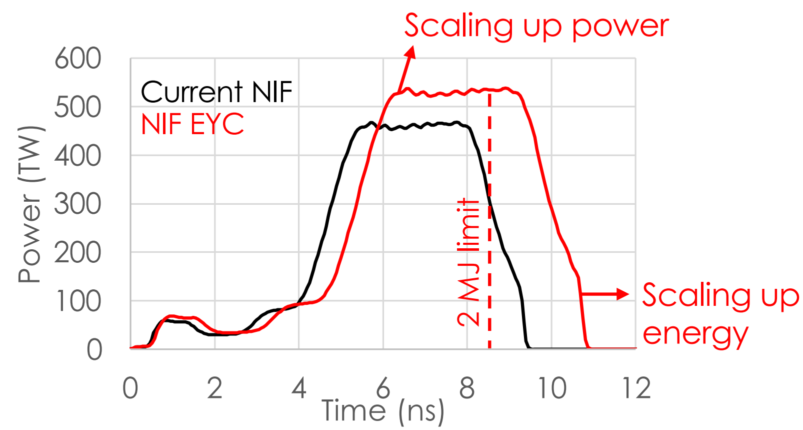
- Developed and implementing a multi-year plan to address hypotheses to improve our hohlraum modeling capabilities
- Longer pulses are more challenging for symmetry; Will address in scaled integrated shots

Incorporating applications

- Some identified applications require backlighter pulses
- Target modifications to support applications

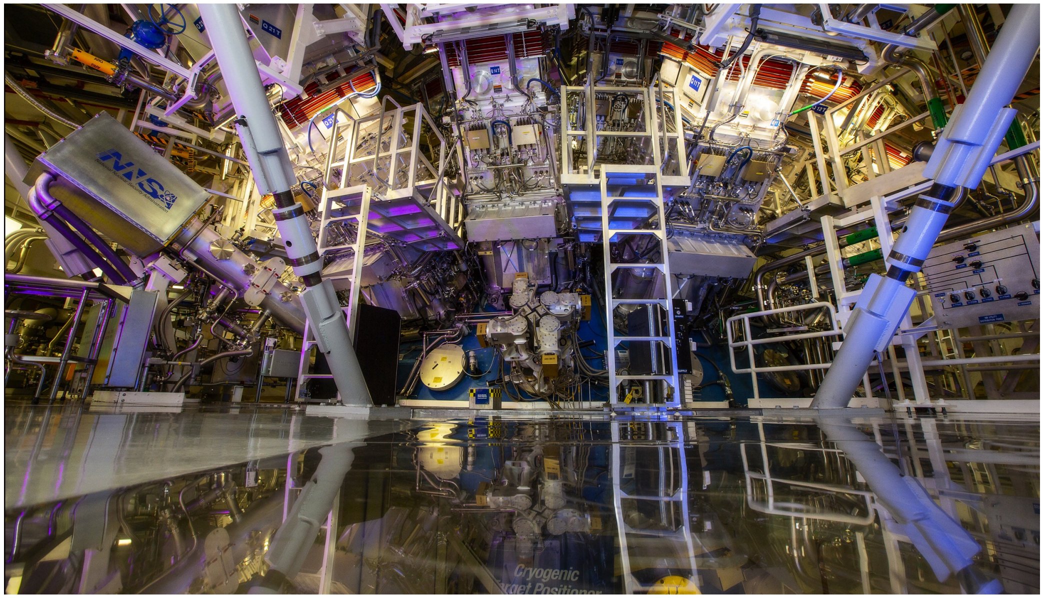
FY24 LPI Testing*





We have a long way to go – but we have taken a very important step forward

- How large of a gain can we achieve at NIF?
- Higher gain designs
- More NIF energy
- Improved predictive capability informed by focused experiments



Making the impossible possible:
powered by NIF and an international collaboration

How NIF works

How NIF works

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