How the weird and wonderful properties of magnetised laser plasmas could ignite fusion-energy research

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Overview

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1. Background
   - What is inertial confinement fusion (ICF)?
   - ICF with lasers
   - How does the National Ignition Facility (NIF), the world's highest-energy laser, work?

2. If at first you don't succeed, try, try again… ICF on the NIF
   - Initial set-back and recovery
   - Late 2020/early 2021: first burning plasma
   - August 2021: first significant self-heating
   - December 2022: ignition

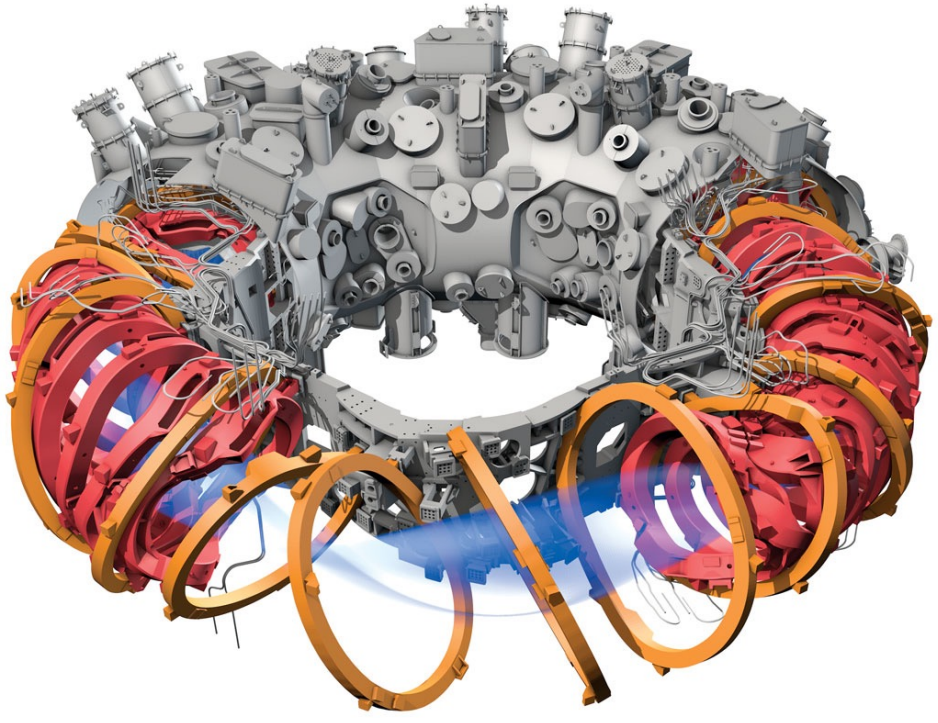
3. How do we do even better? Approaches for delivering high-gain ICF experiments in the next 5 years
   - ***Novel plasma physics: leveraging the exotic material properties of magnetised, weakly collisional plasmas***

4. Inertial fusion energy: what do we need to solve to make this work?

What is inertial confinement fusion (ICF)?

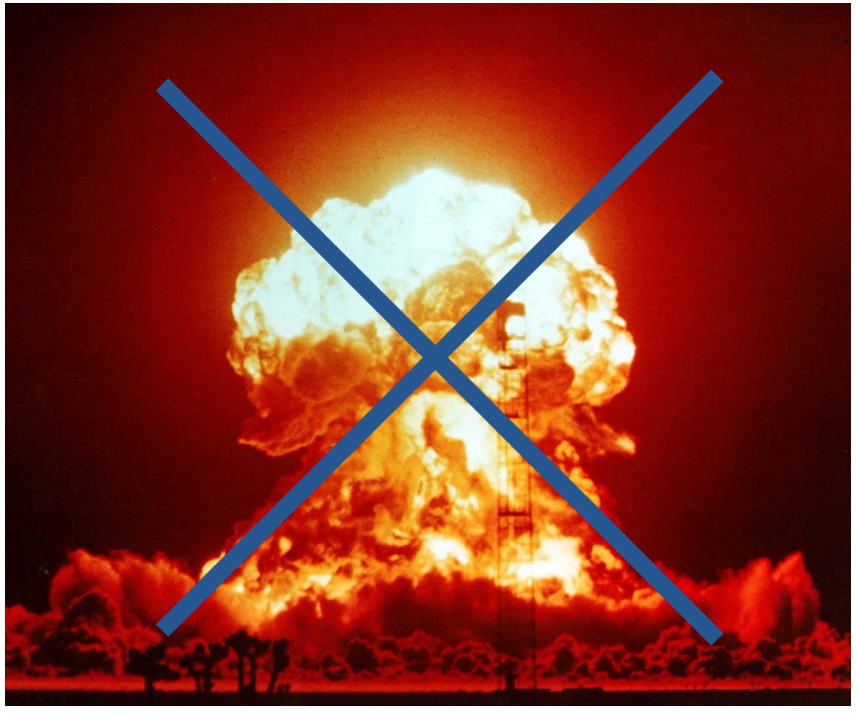
To make fusion happen, need to confine very hot plasma

Magnetic confinement fusion (MCF):
use magnetic "cage"
(tokamak/stellarator)



Credit: IPP, adapted by C. Bickel/ Science

Inertial confinement fusion (ICF):
make fusion reactions happen before
plasma has a chance to escape



Credit: NNSA

Nuclear bombs not practical… use lasers instead!

ICF with lasers

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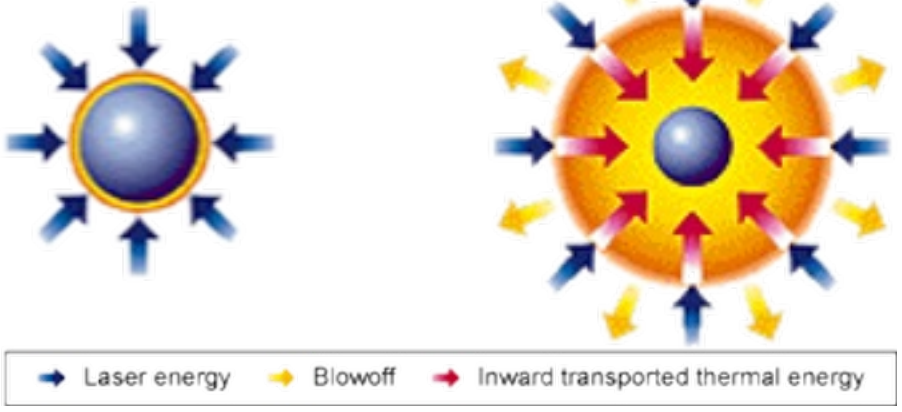
Direct-drive ICF

Atmosphere formation

Compression

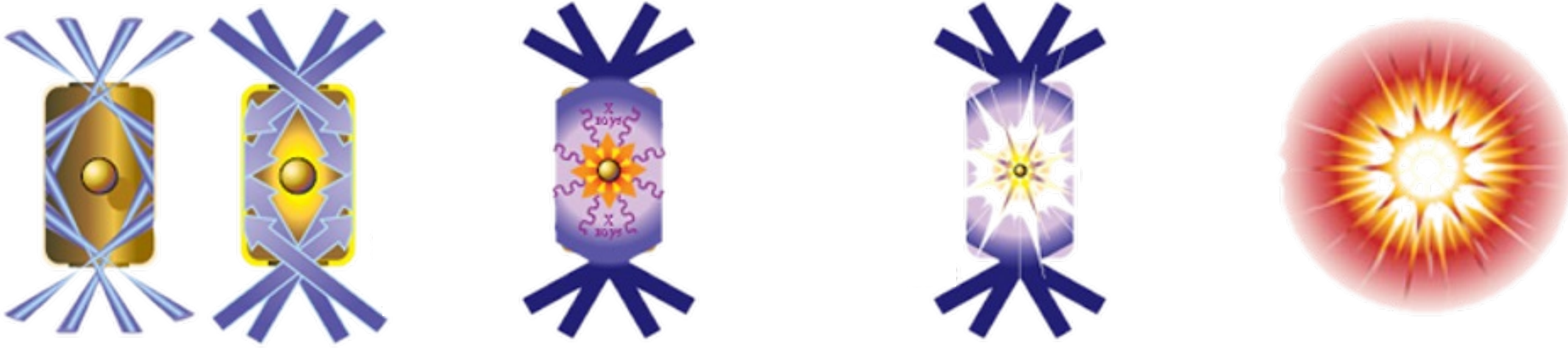
Ignition

Burn



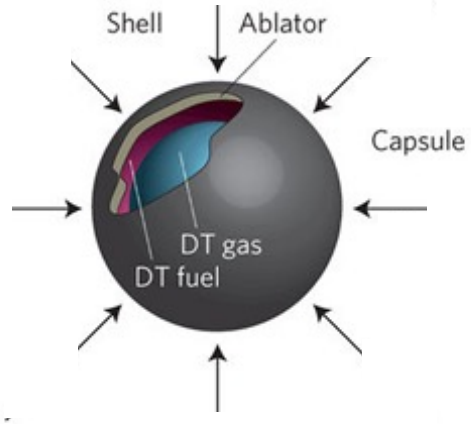
Credit: UK IFE Consortium

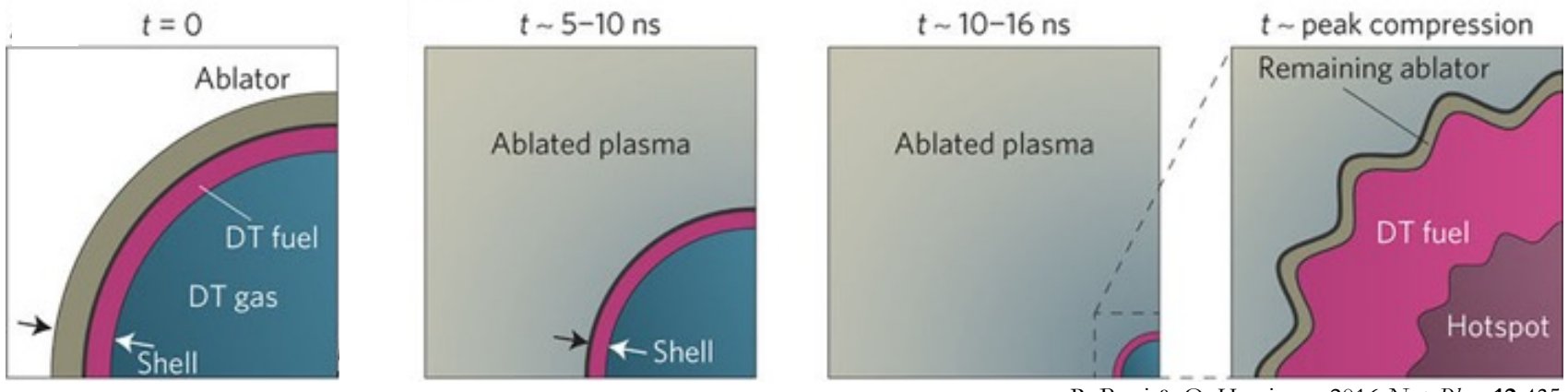
Indirect-drive ICF



Credit: UK IFE Consortium

Laser ICF capsules





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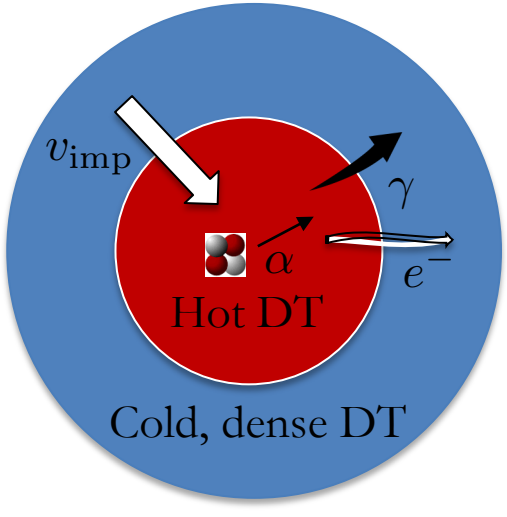


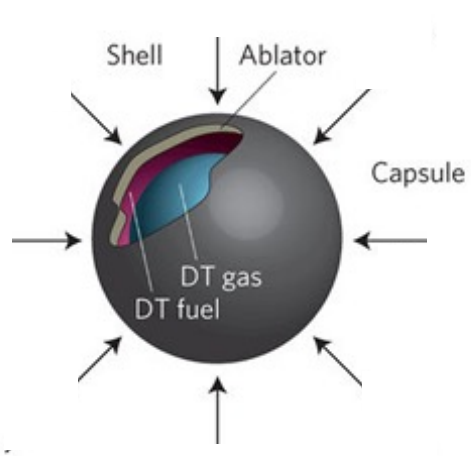
Heating **Cooling**

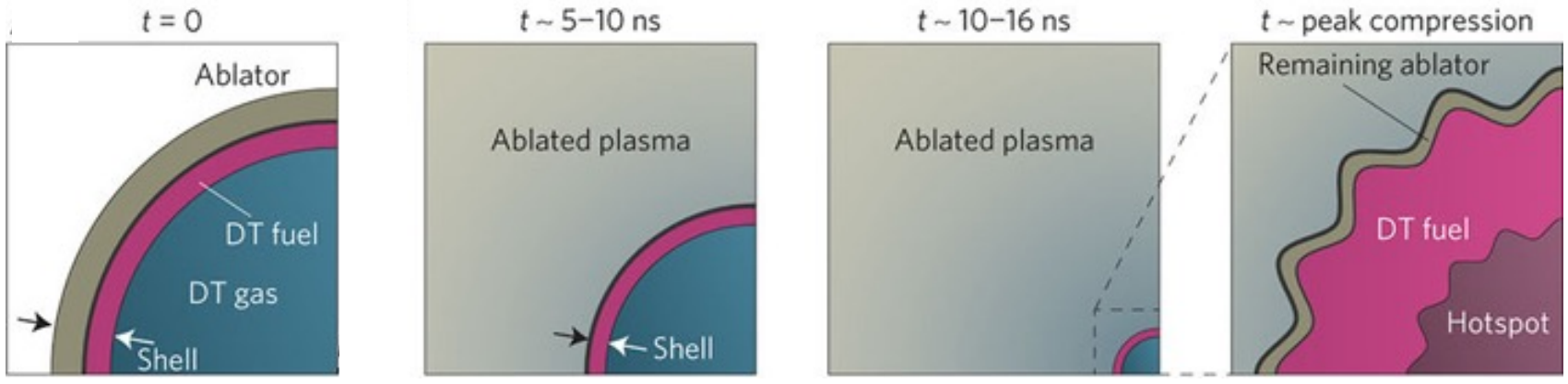
$$P_{p\,\mathrm{d}V} \sim p\frac{v_{\mathrm{imp}}}{R_{\mathrm{HS}}} \quad + \quad P_\alpha \sim n^2T^4 \quad > \quad P_{\mathrm{rad}} \sim n^2T^{1/2} \quad + \quad P_{\mathrm{e}} \sim \frac{T^{7/2}}{R_{\mathrm{HS}}^2}$$

Compression — Alpha heating — Radiation — Thermal conduction

$$\mathrm{D} + \mathrm{T} \rightarrow n(14.1\,\mathrm{MeV}) + {}^4\mathrm{He}(3.5\,\mathrm{MeV})$$

Laser ICF capsules





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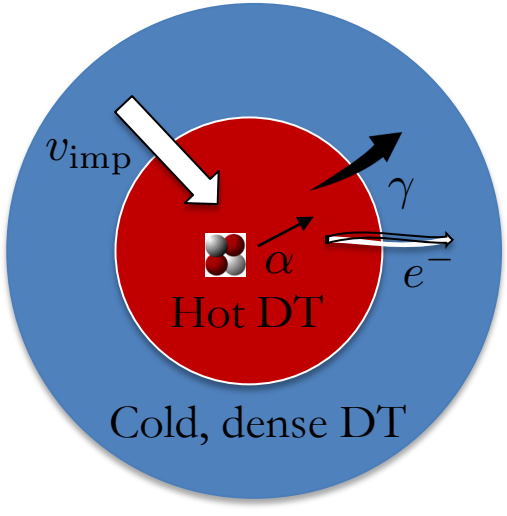
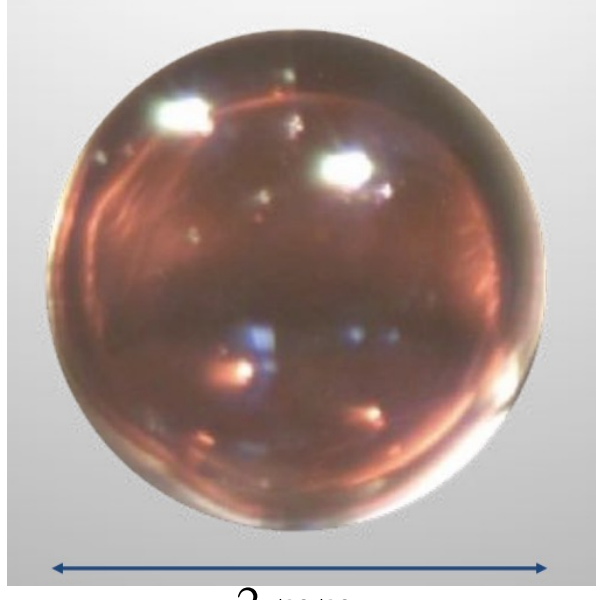
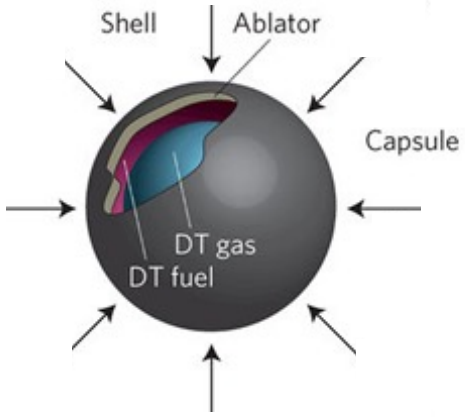


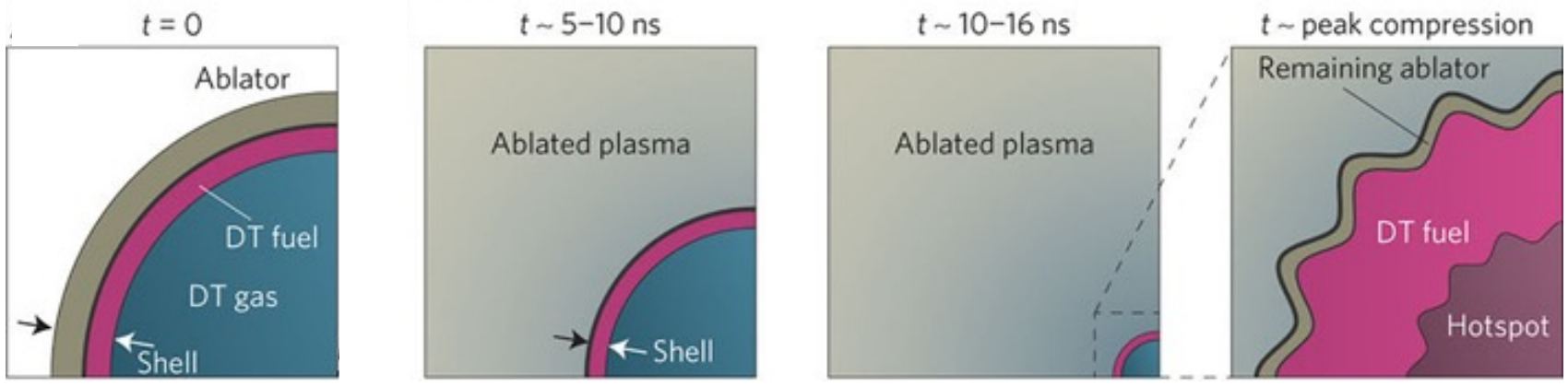


Credit: R. Town, LLNL

~2 mm

Laser ICF capsules





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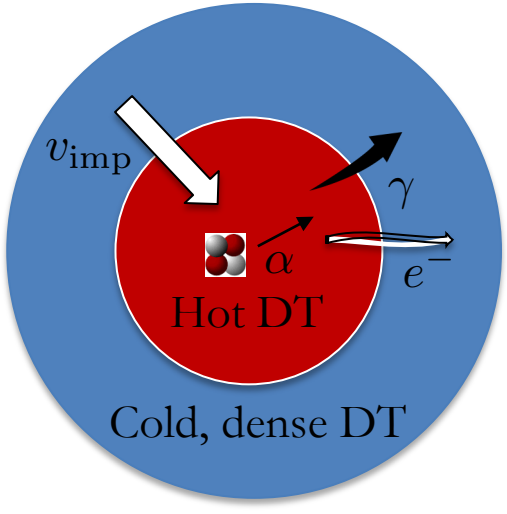
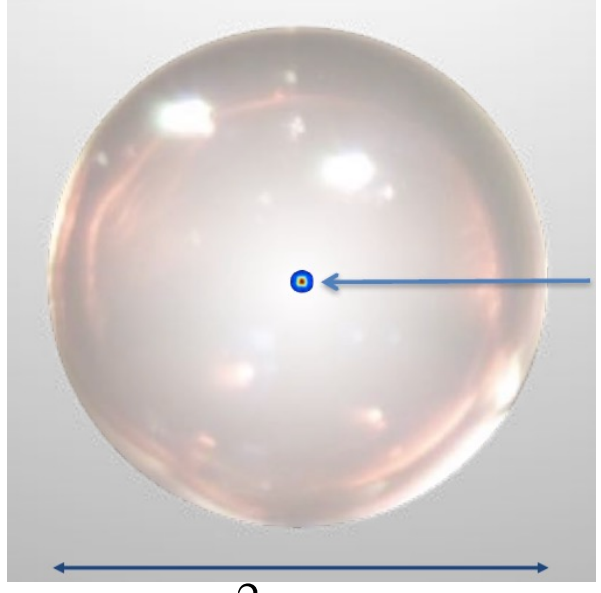




Credit: R. Town, LLNL

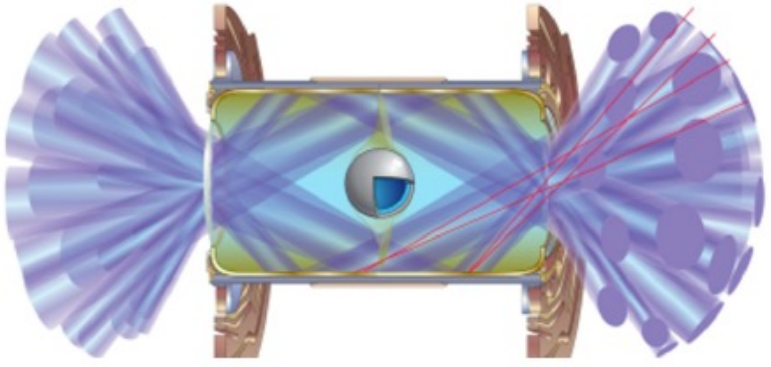
~2 mm

DT shot N120716
at bang time

Direct-drive vs. indirect drive

Indirect-drive ICF

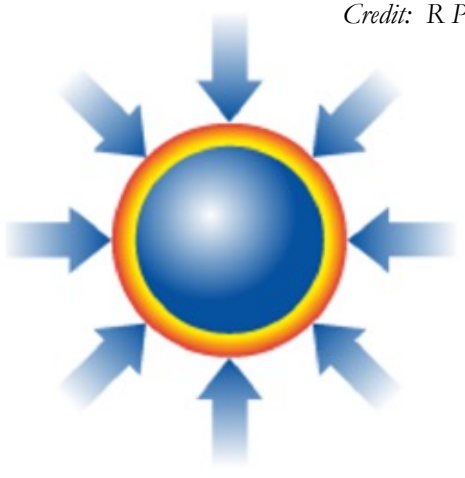
Credit: R Patel, LLNL



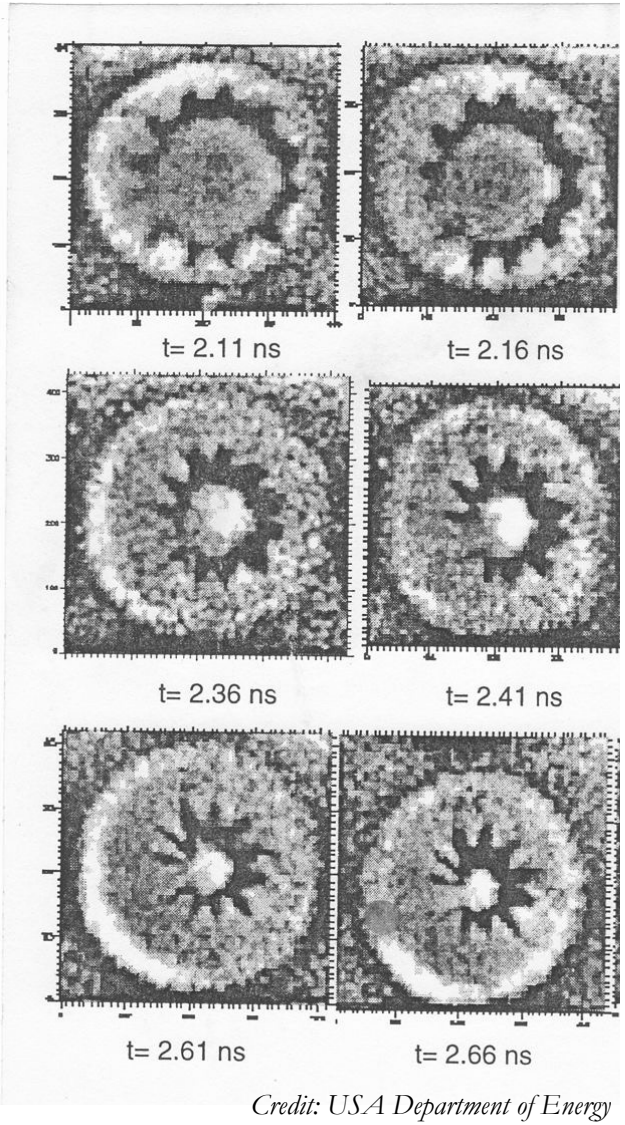
Indirect drive only couples ~10% laser energy in x-rays…

Direct-drive ICF

Credit: R Patel, LLNL

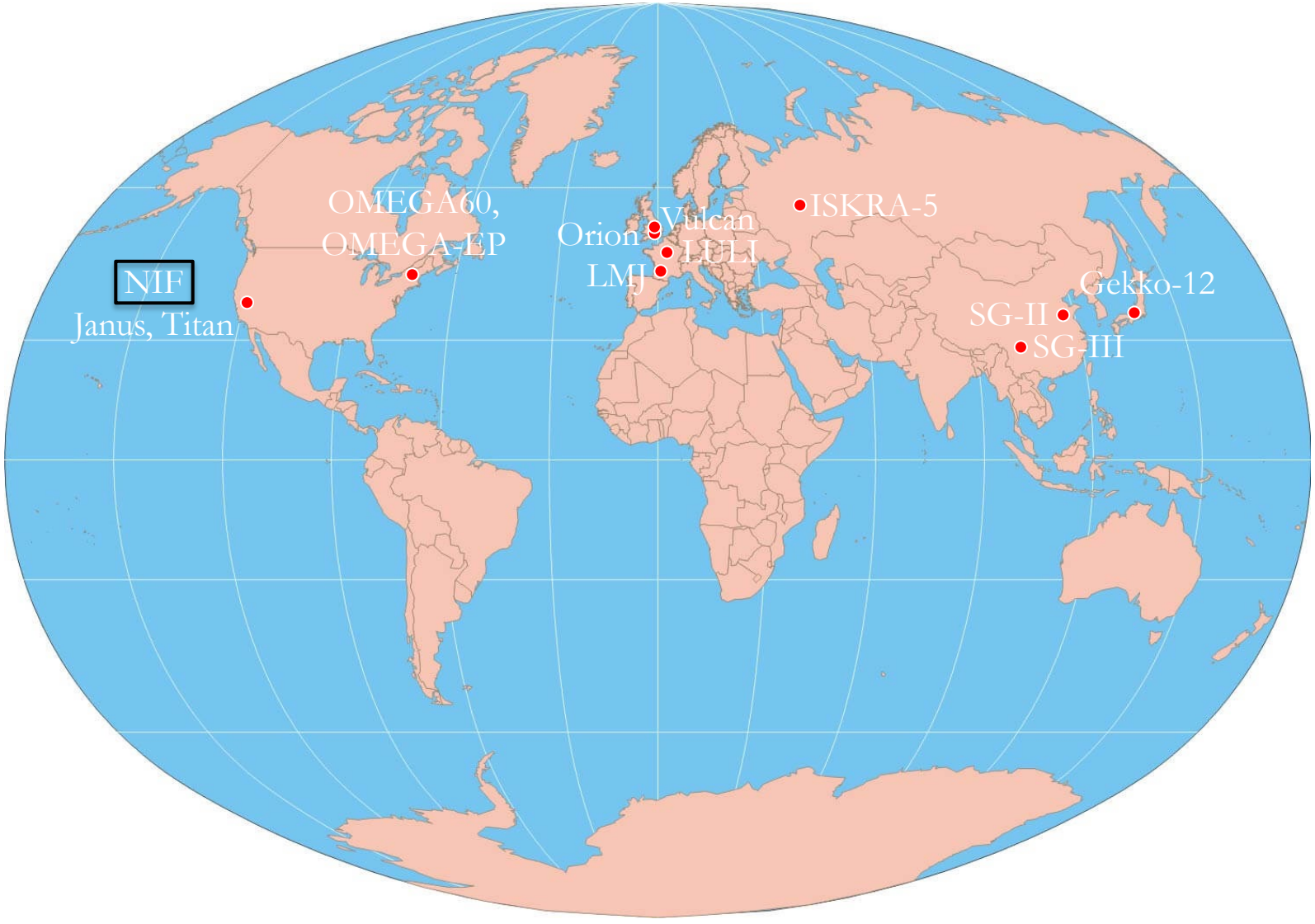


...but direct drive more prone to instabilities!

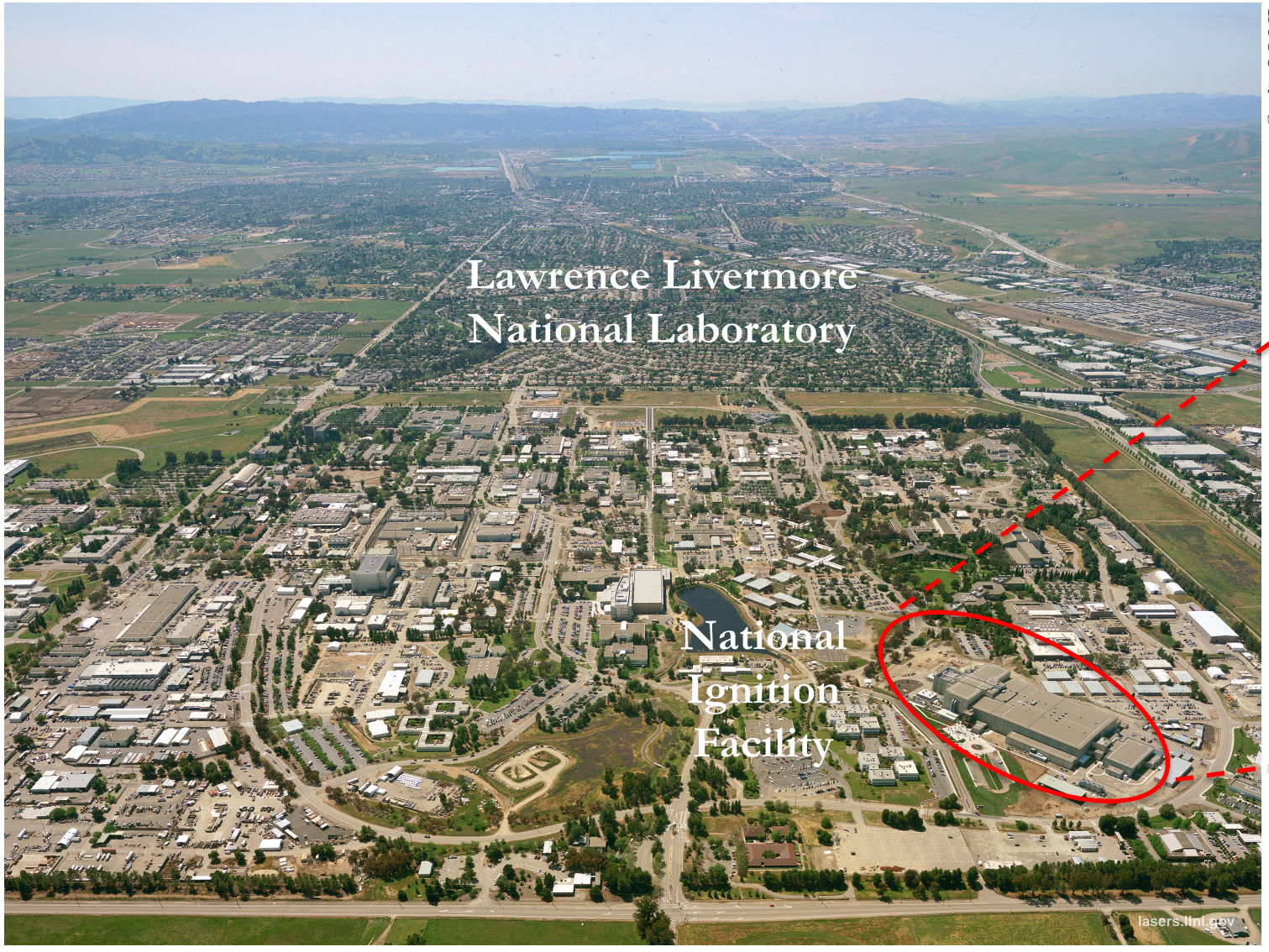


Credit: USA Department of Energy

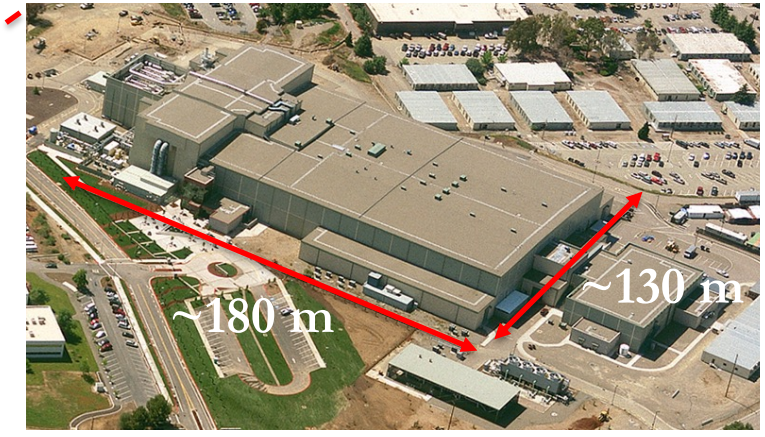
The world's highest energy lasers



The National Ignition Facility (NIF)



Credit: LLNL

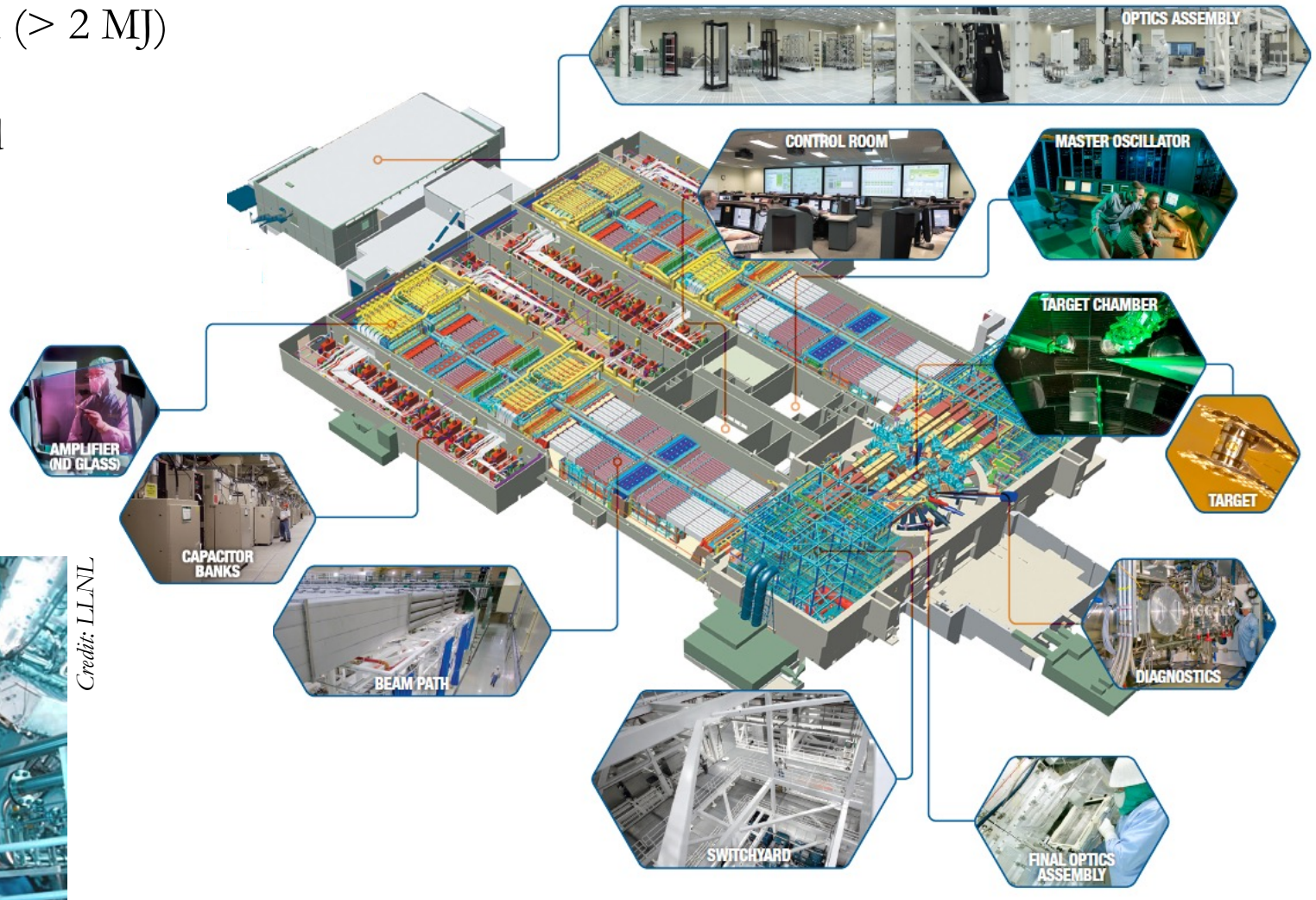


The National Ignition Facility (NIF)

1. Most energetic laser in the world (> 2 MJ)
2. Power output = US national grid
3. 192 beams converge onto ~mm^3 volume in 1 ns
4. Warp drive of the Enterprise!

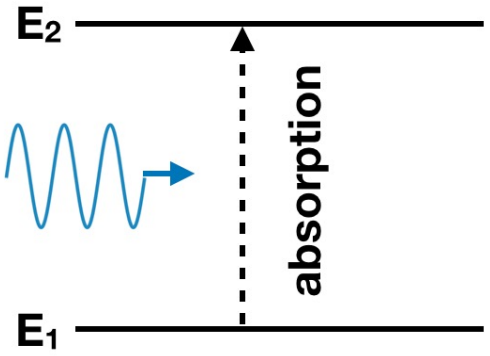
Credit: LLNL

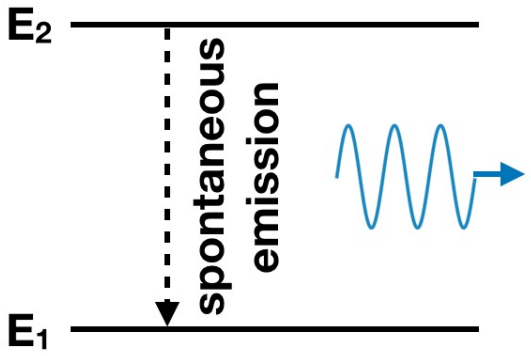
Credit: LLNL

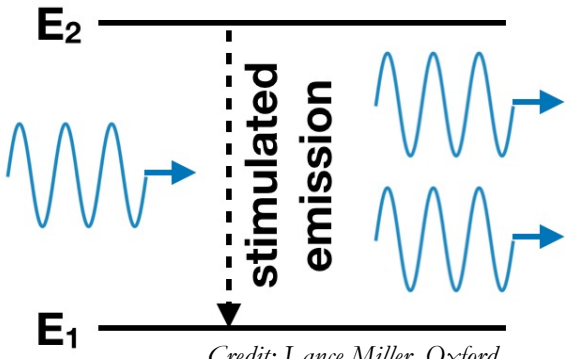


How do NIF's lasers work?

Basic principle of lasers: leveraging stimulated emission of excited atoms!



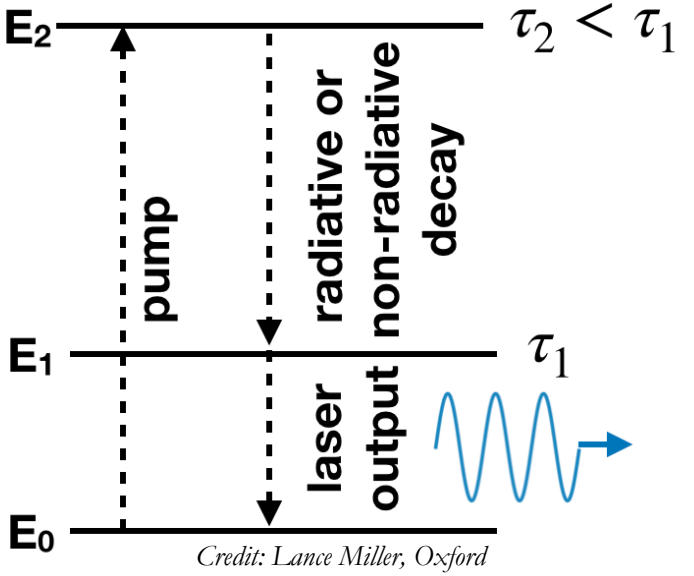




Credit: Lance Miller, Oxford

1. Population inversion: $n_2 > n_1$
2. Rate of spontaneous emission < rate of decay of lower level
3. High pumping rate/long lifetime of upper level

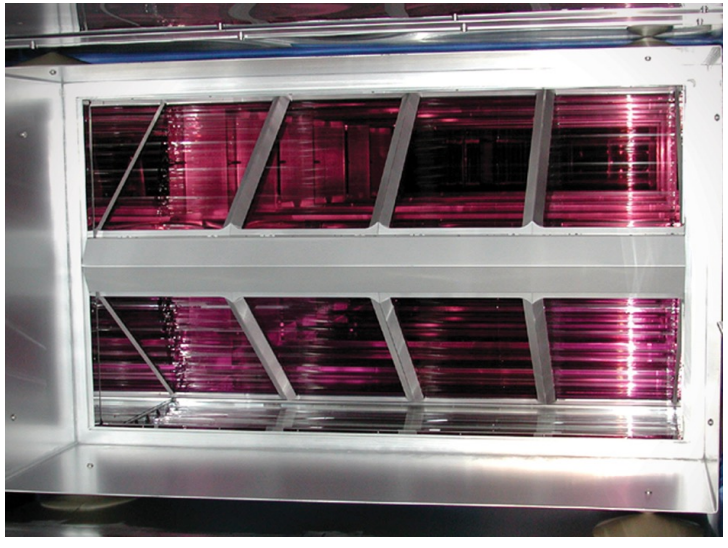
To achieve this in practice, need system (gain medium) with > 2 levels…



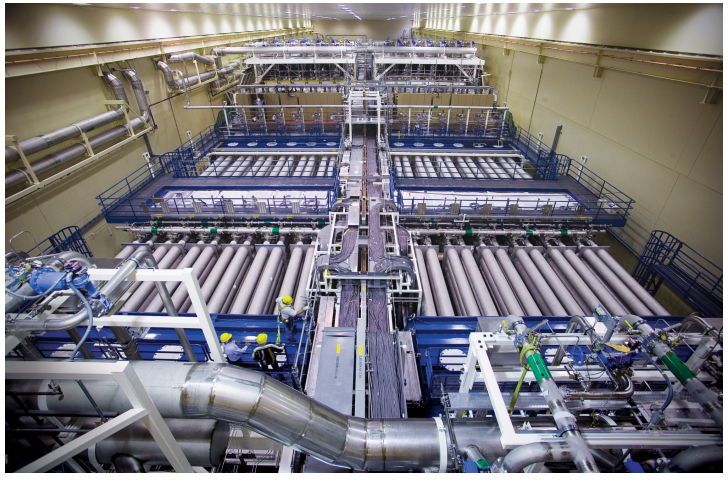
Credit: Lance Miller, Oxford

NIF's amplifiers

Gain medium on NIF: Nd-doped phosphate glass

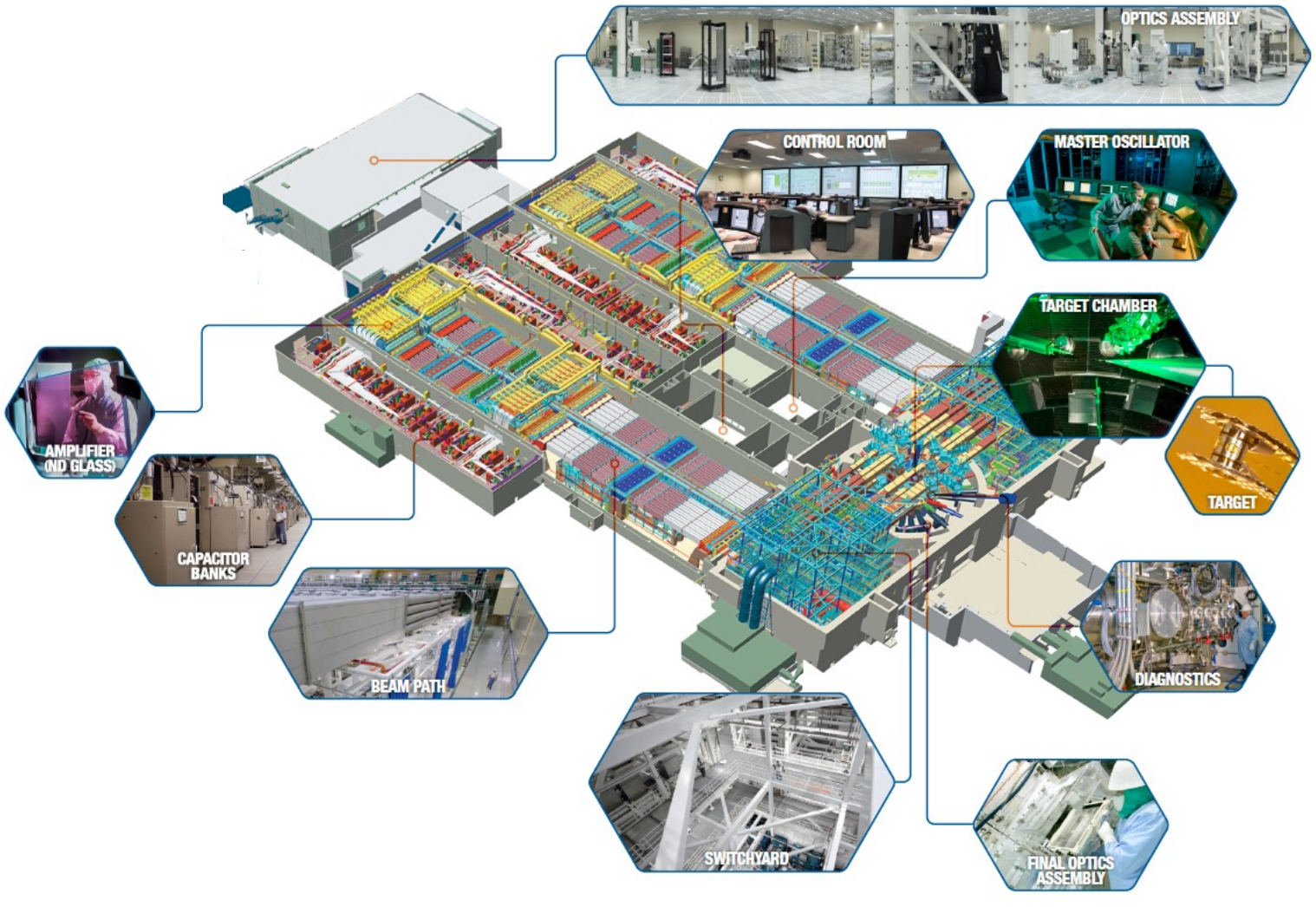


Credit: LLNL



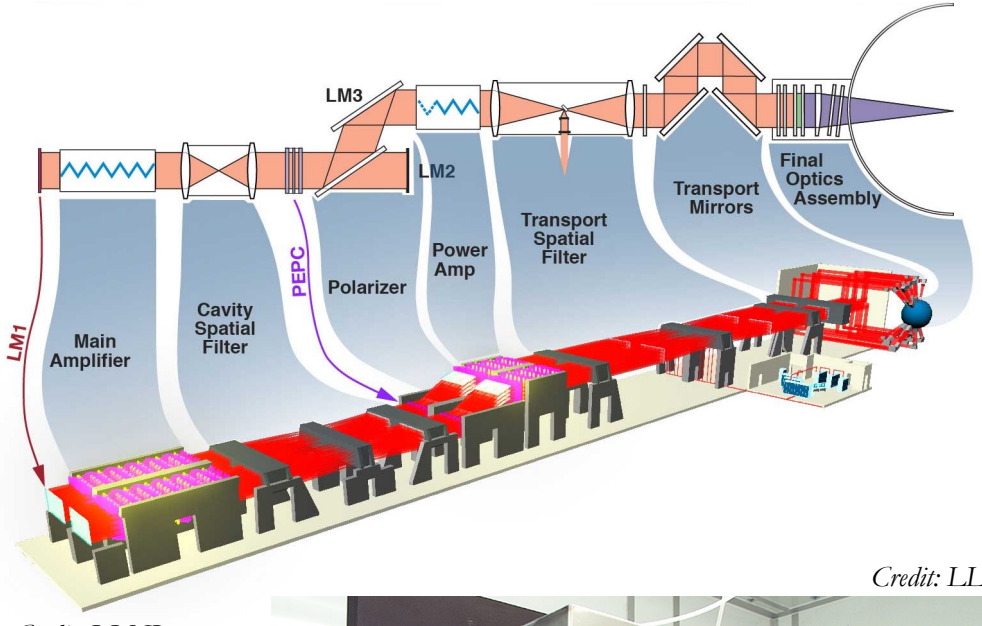
Credit: LLNL

Credit: LLNL

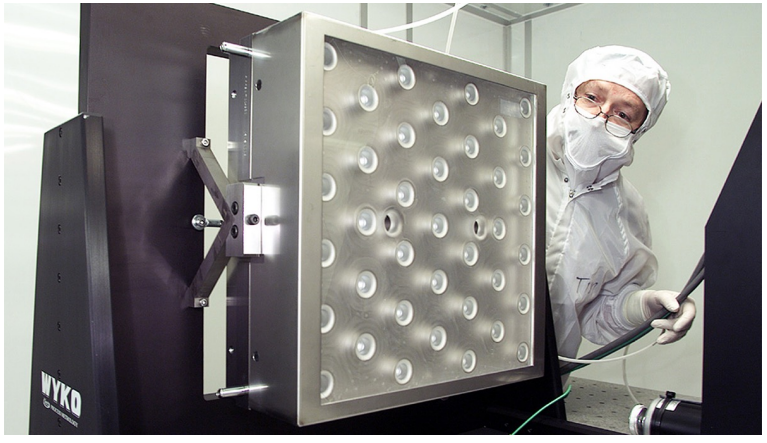


Beam transport

Post-amplification, need to fine-tune the beams…

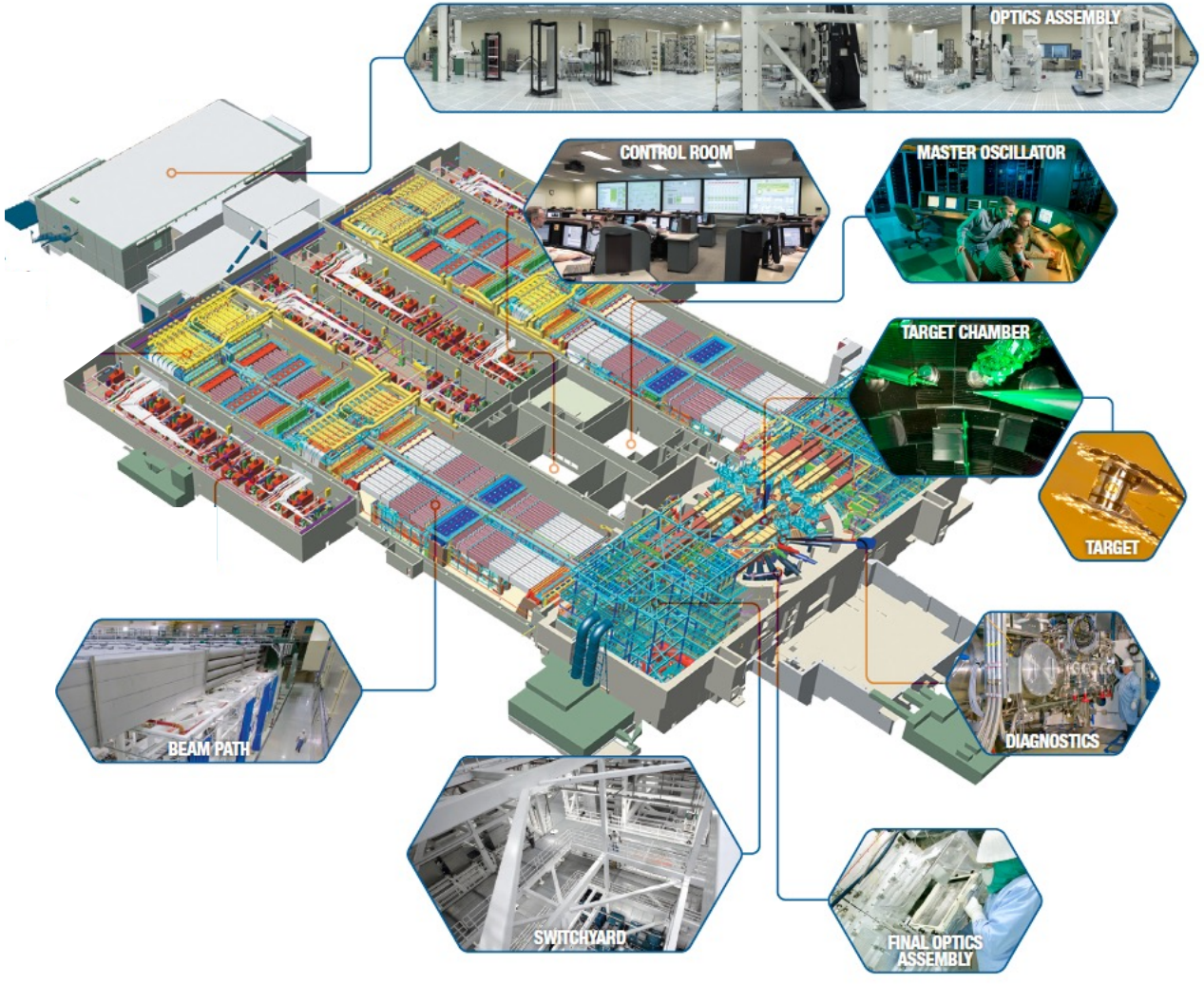


Credit: LLNL



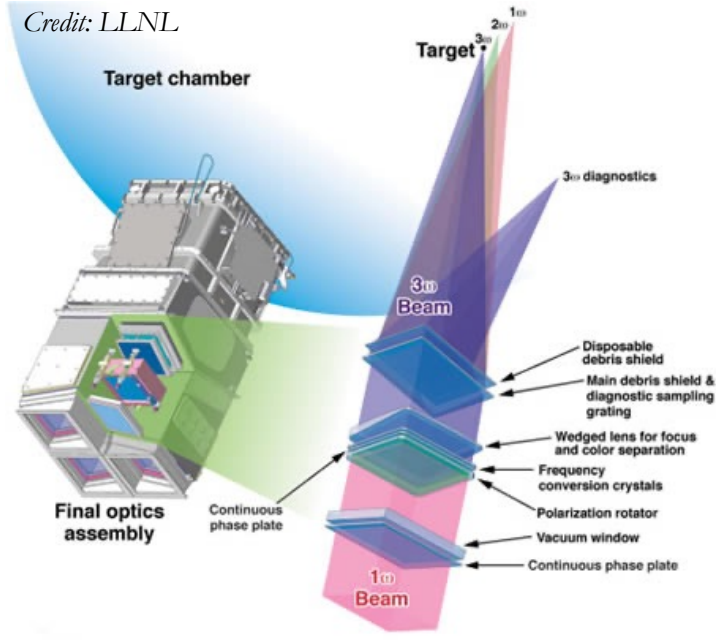
Credit: LLNL

Credit: LLNL

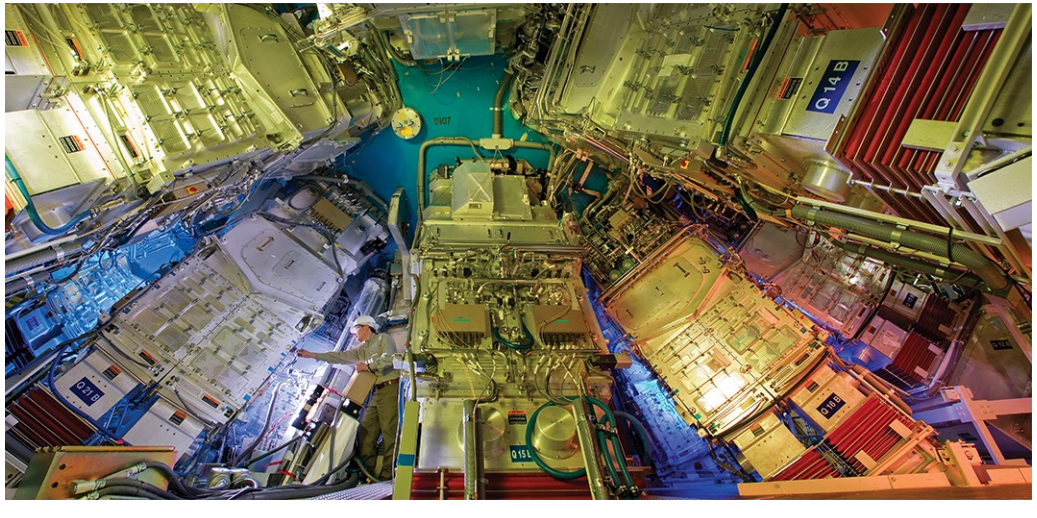


NIF's final optics

Credit: LLNL

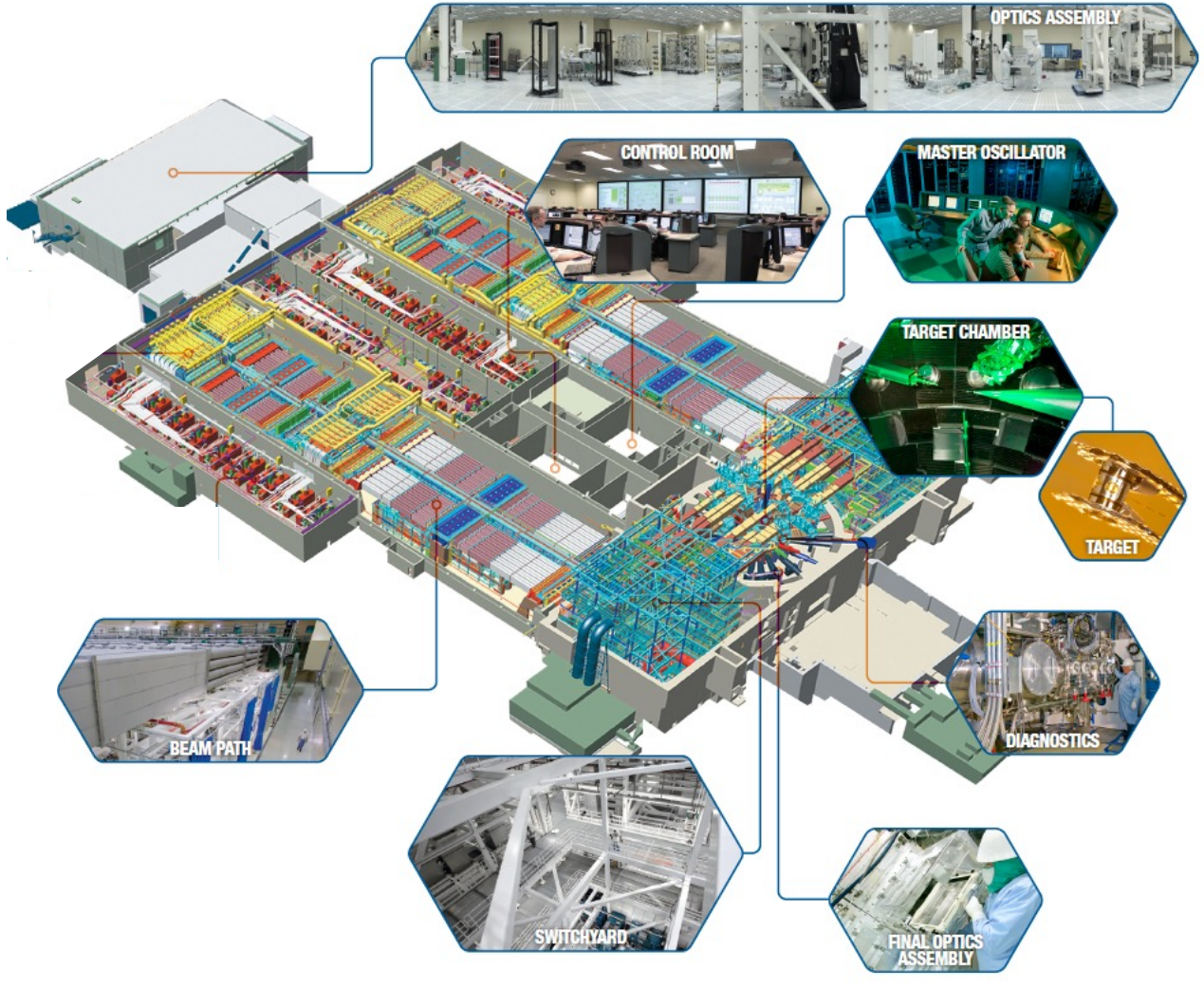


Credit: LLNL



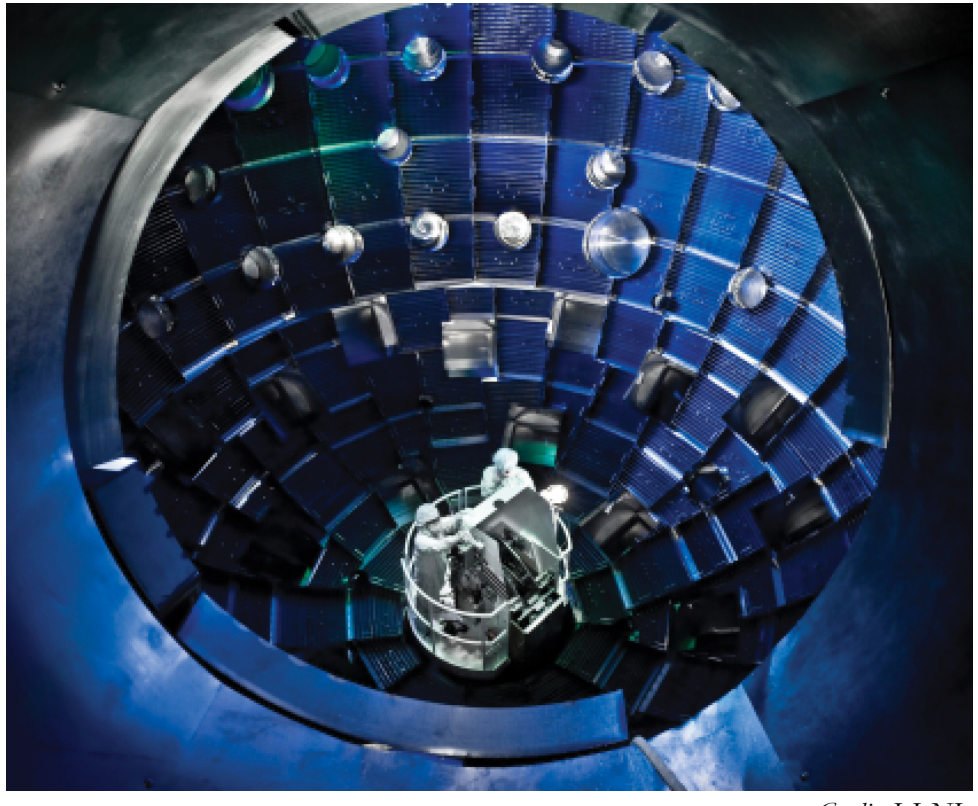
…convert them to higher-frequency light…

Credit: LLNL



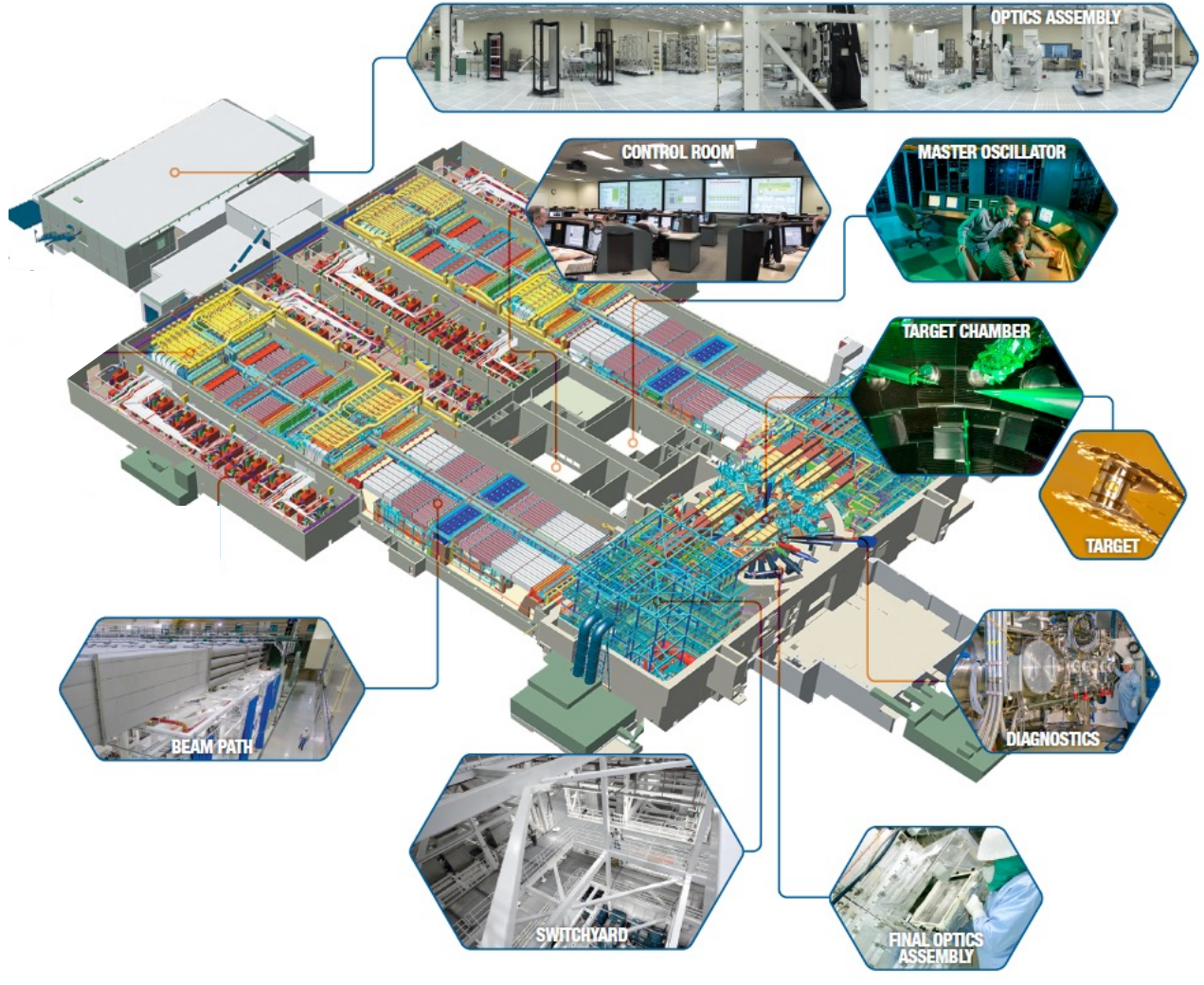
NIF's target chamber

…and then focus them into the chamber!



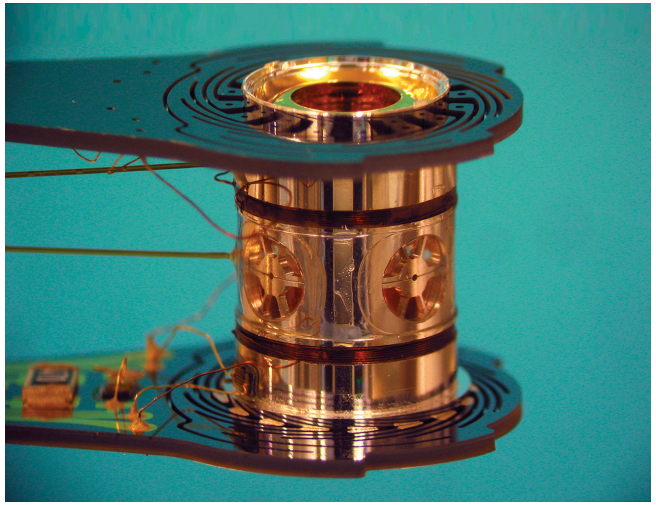
Credit: LLNL

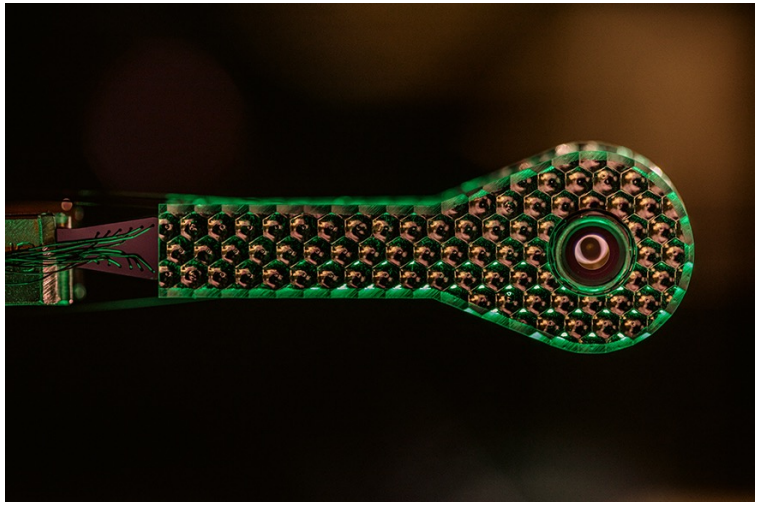
Credit: LLNL

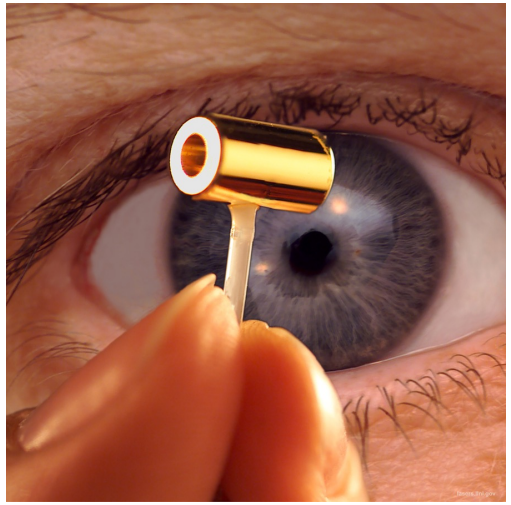


NIF indirect-drive targets

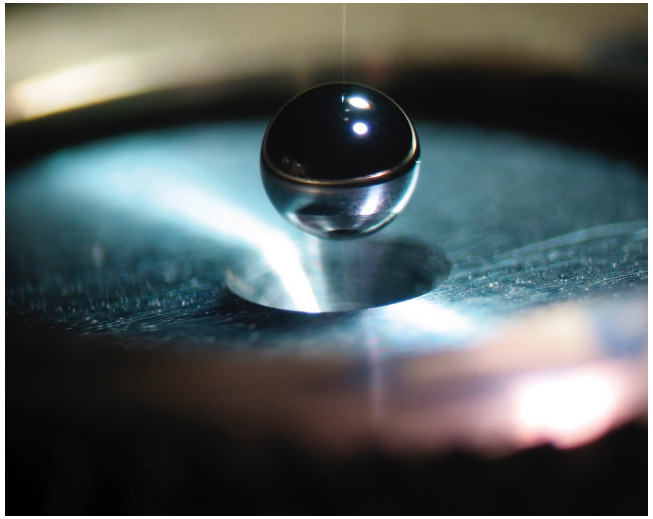
~1 cm scale hohlraums containing ~1 mm scale capsules

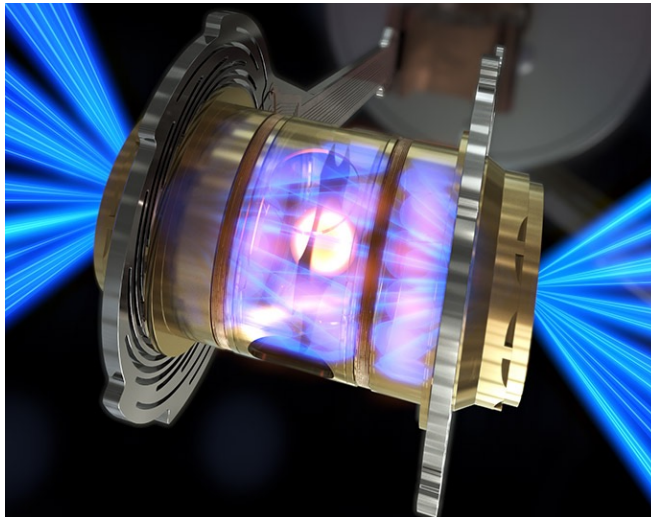


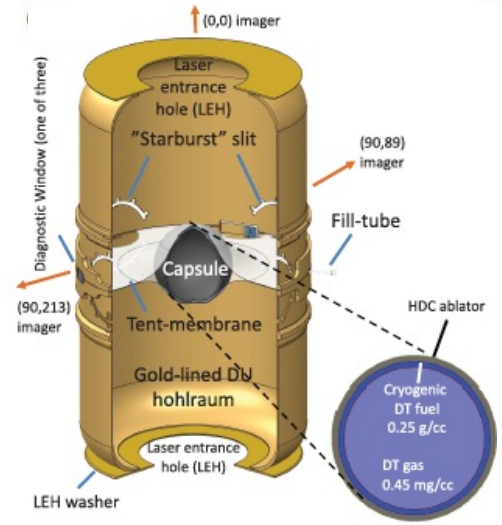




Credit for all images: LLNL







H.Abu-Shawareb *et al.* (2022), *PRL* **129** 075001

NIF's operators

All aspects of shot delivery controlled at central location by highly professional LLNL staff!

Credit: LLNL

What are the key numbers to remember for NIF?

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1. Energy stored in capacitors: ~320 MJ
2. Energy in laser beams: ~2 MJ
3. Energy in capsule-imploding x-rays: ~170 kJ

NAS definition of ***ignition***:

"Fusion energy out > Laser energy in"

"***Burning***" plasma:

"Fusion energy out > X-ray energy in"

"***Self-heating***" plasma:

"Fusion energy out ≫ X-ray energy in"

IFE needs

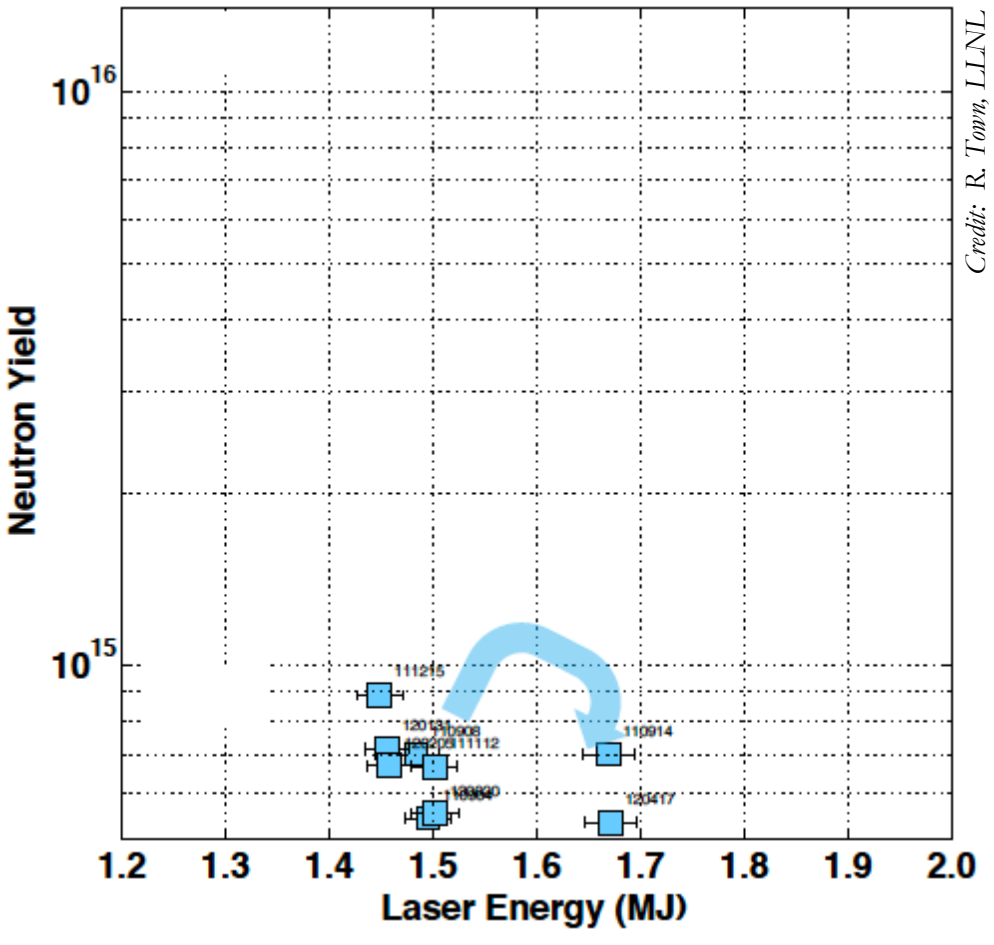
"Fusion energy out > Wall-plug energy in"

Credit: LLNL

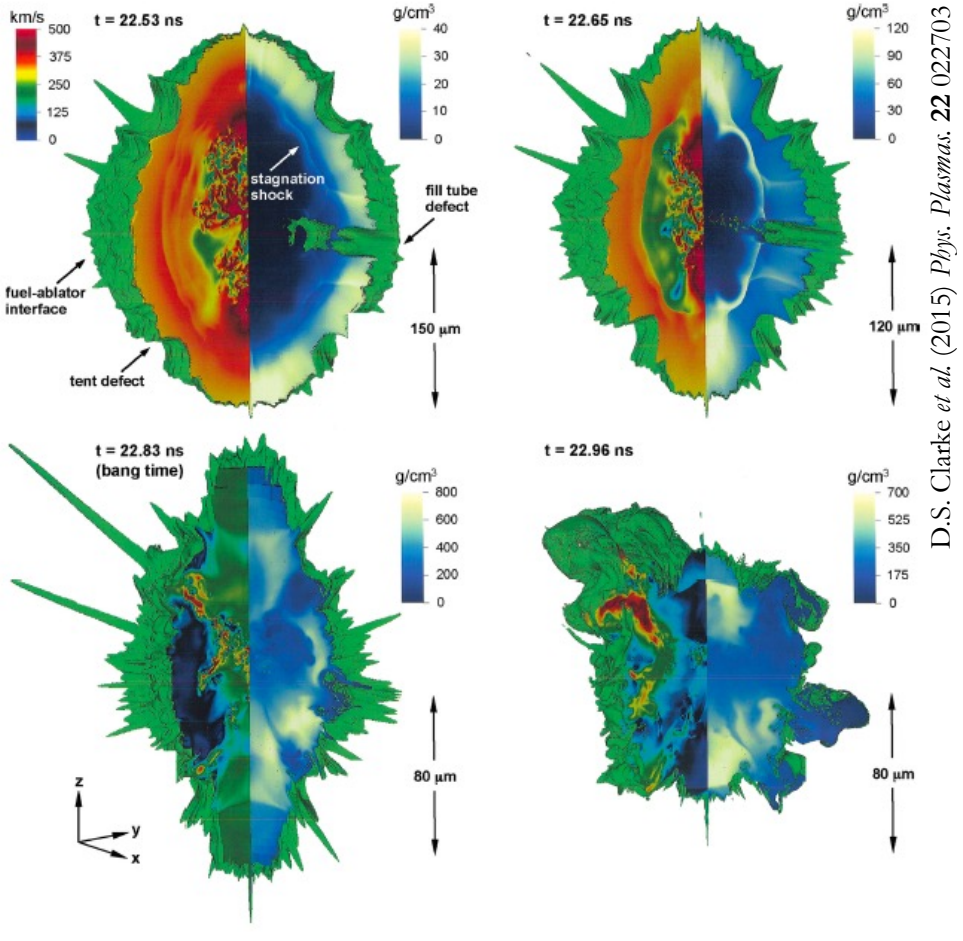
National Ignition Campaign (NIC): 2009-12

Goal of NIC: to reach ignition

Outcome of NIC: energy yields **< 3 kJ**



Credit: R. Town, LLNL



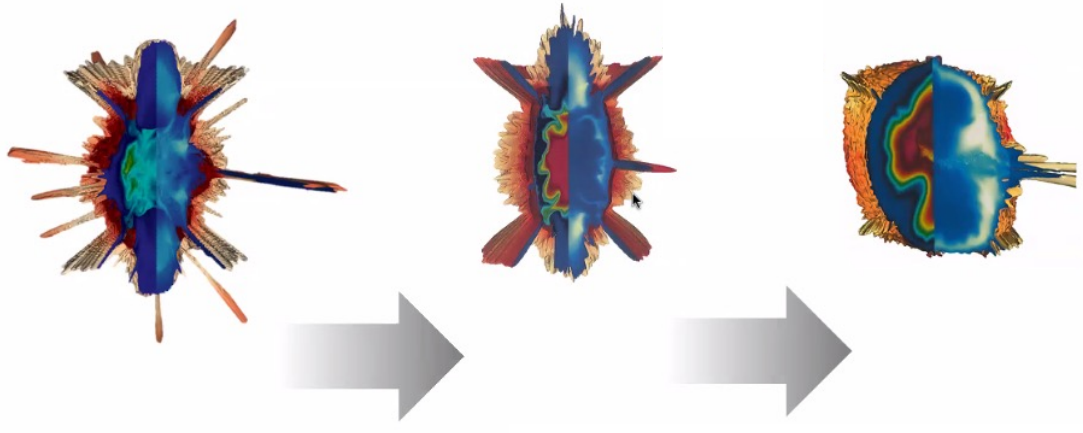
D.S. Clarke *et al.* (2015) *Phys. Plasmas.* **22** 022703

Increasing laser energy to maximum values degraded performance... Hydro instabilities responsible!

Recovering from a disappointing start…

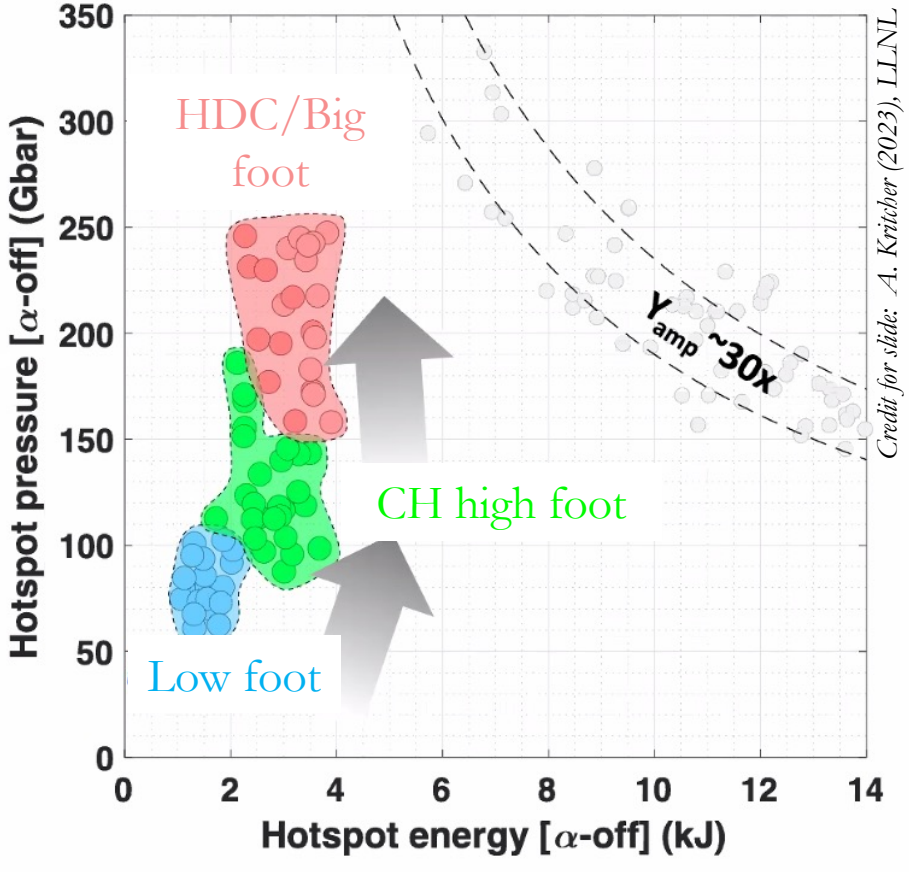
Post NIC: science-driven campaign to address known issues with implosion experiments

Low foot (2 kJ) High foot (27 kJ) HDC/Big foot (55 kJ)



Better stability

Better stability, symmetry, energetics



Credit for slide: A. Kritcher (2023), LLNL

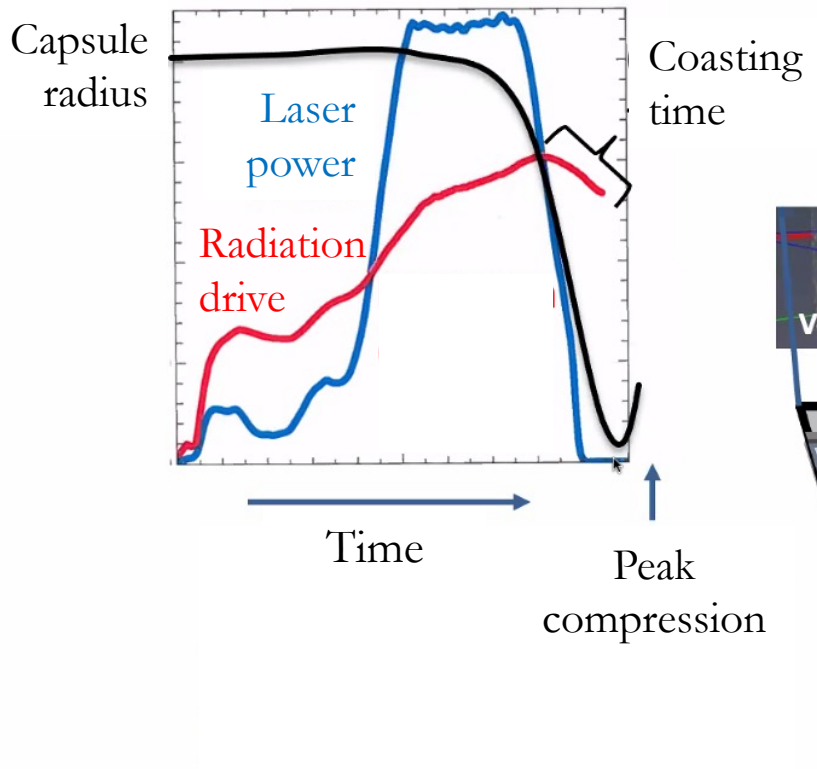
Significant progress towards higher pressures, but less improvement in energy

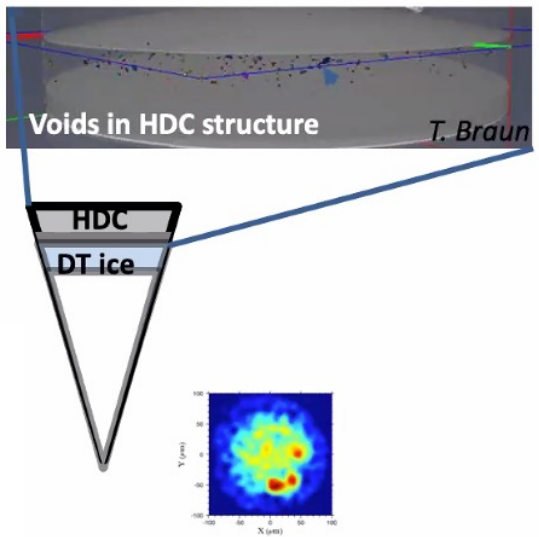
Further progress…

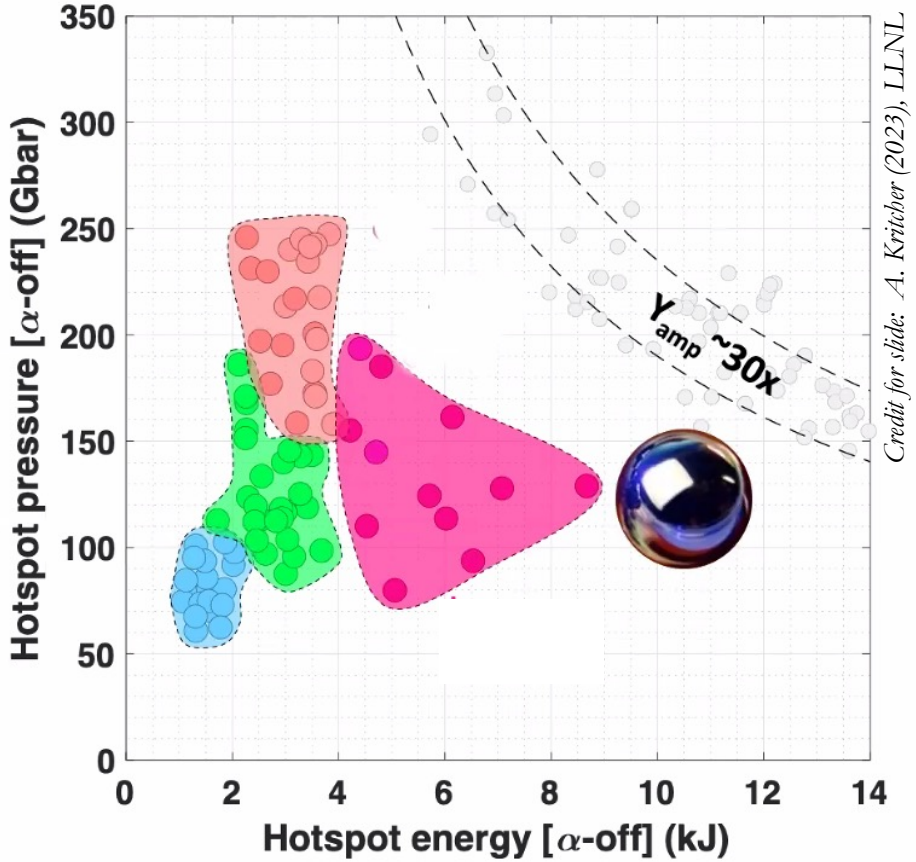
How to increase energy? Increase capsule size…?

…but initially lost hotspot pressure in doing so.

Why? Coast time too long, capsule deficiencies



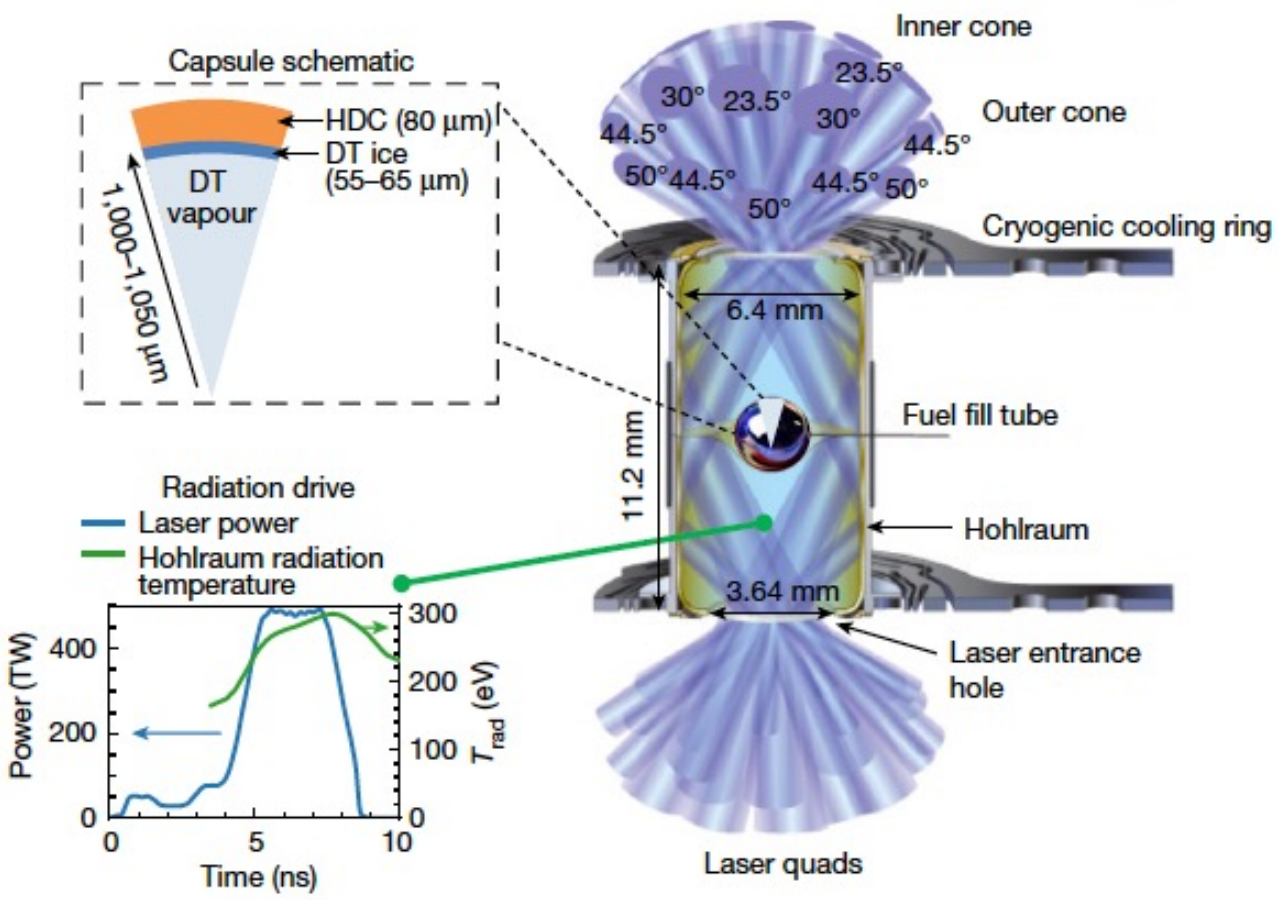




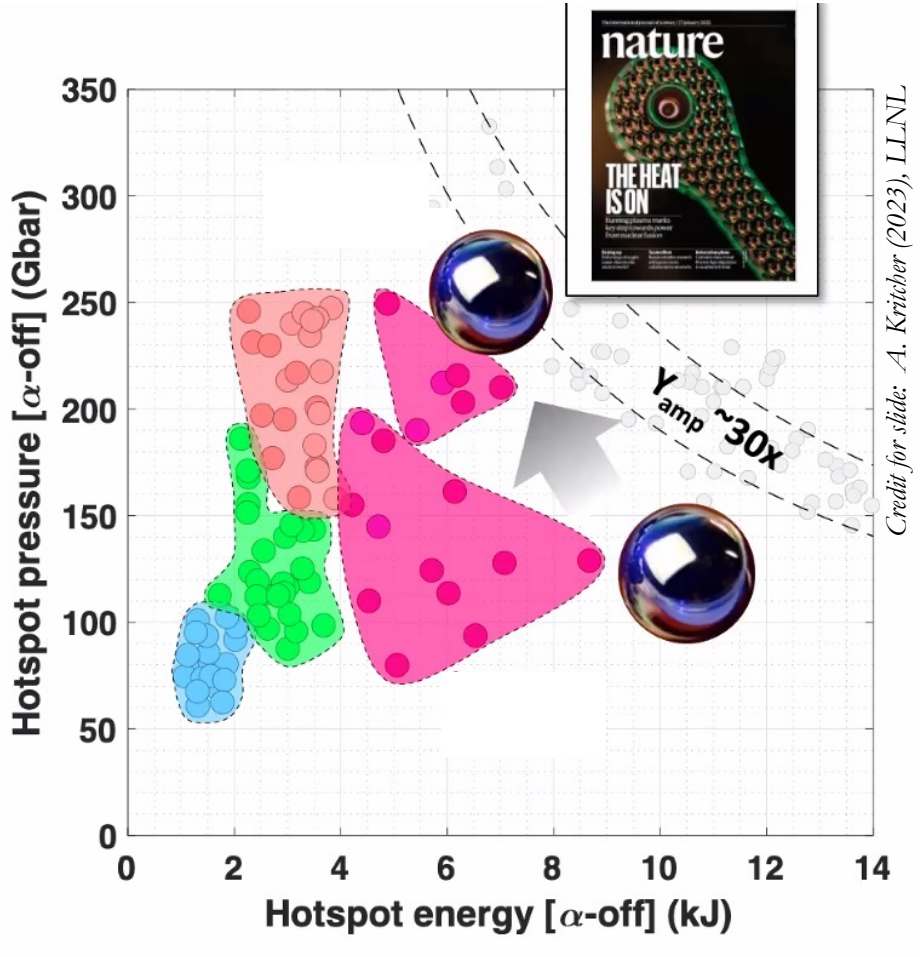
Team then improved capsules, redesigned coast…

…to make a burning plasma!

Key metric: fusion yield of 170 kJ ~ X-ray energy!



A.B. Zylstra *et al.* (2022) *Nature* **601** 542



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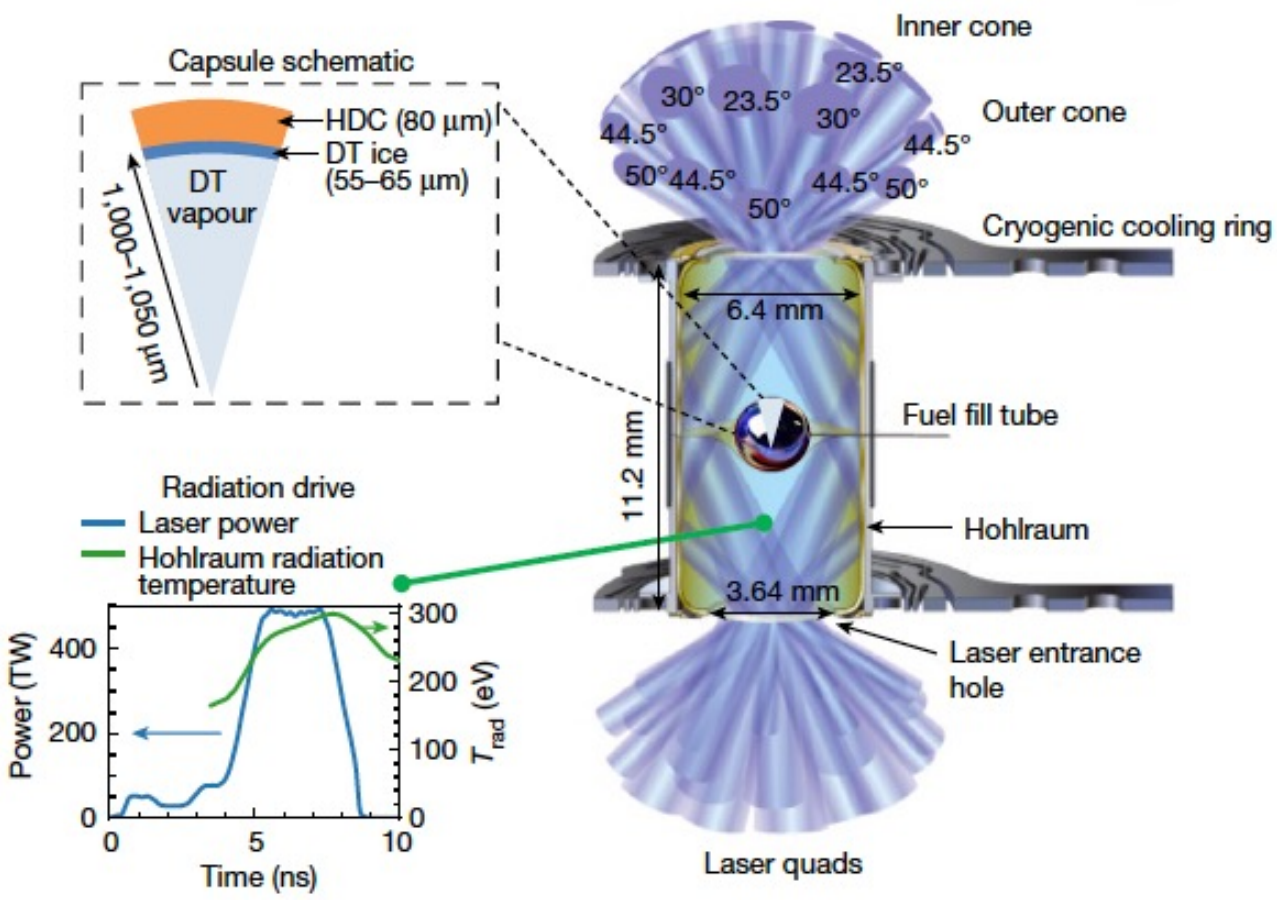
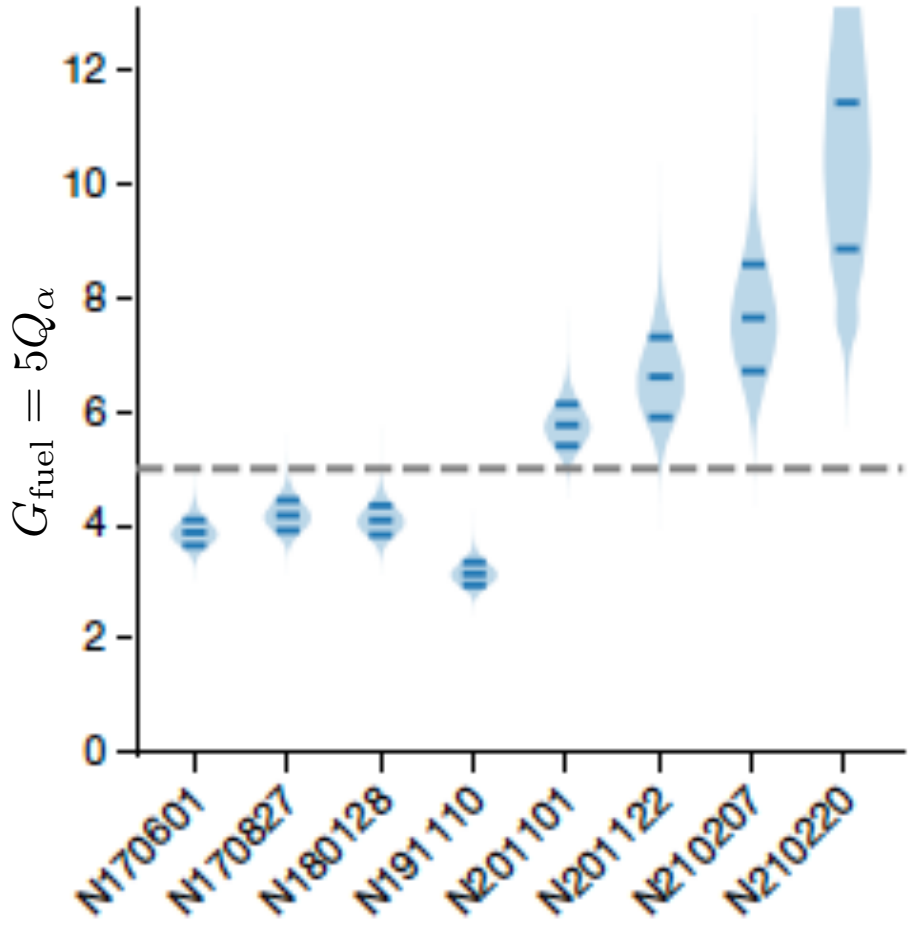


A.B. Zylstra *et al.* (2022) *Nature* **601** 542

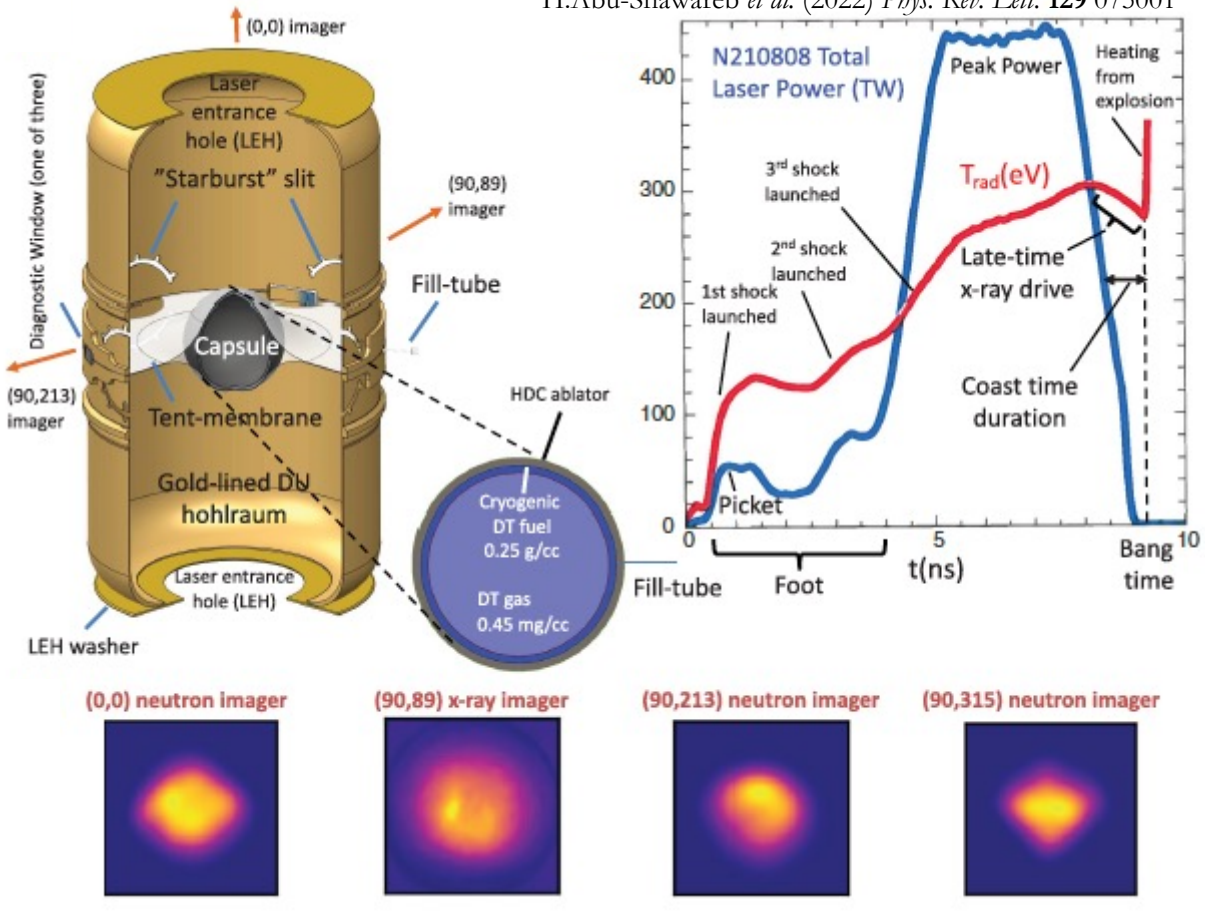


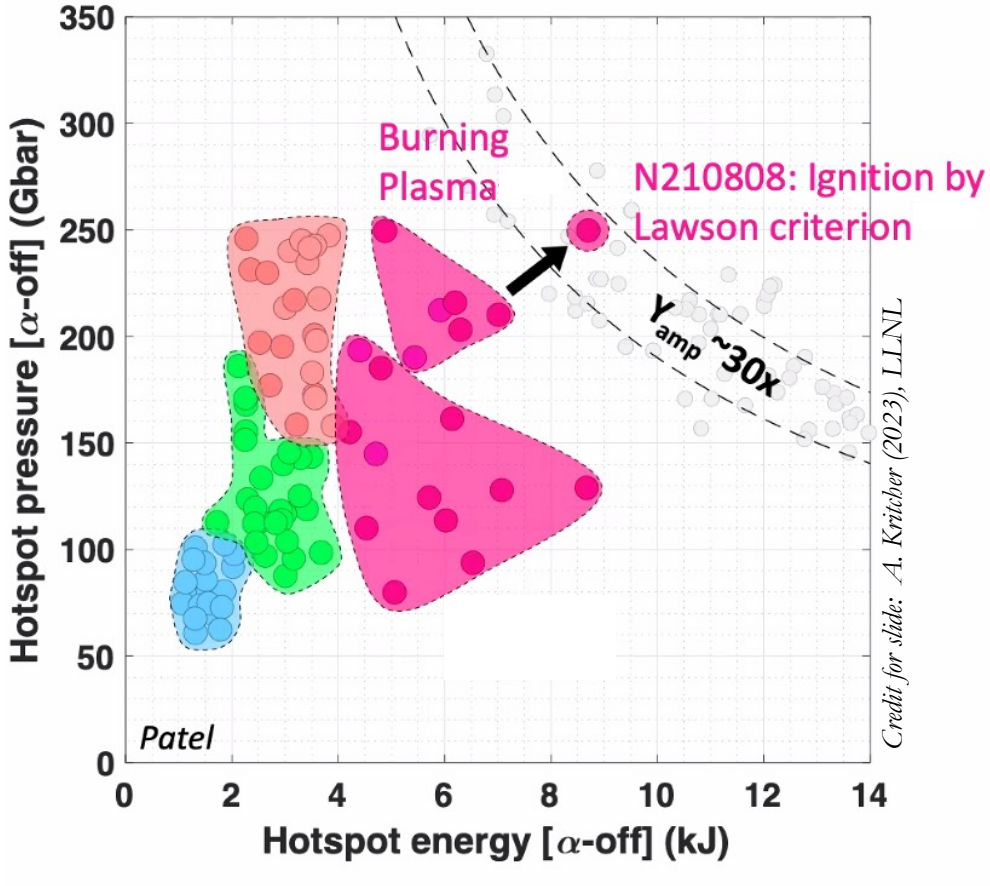
α heating of plasma ~ external heating

August 2021: significant self-heating…

Next: reduce the size of the entrance hole, reduce coast, better ablator quality…

H.Abu-Shawareb *et al.* (2022) *Phys. Rev. Lett.* **129** 075001





Fusion yield of 1.3 MJ ~ X-ray energy x8!, x0.7 of laser energy (1.9 MJ)

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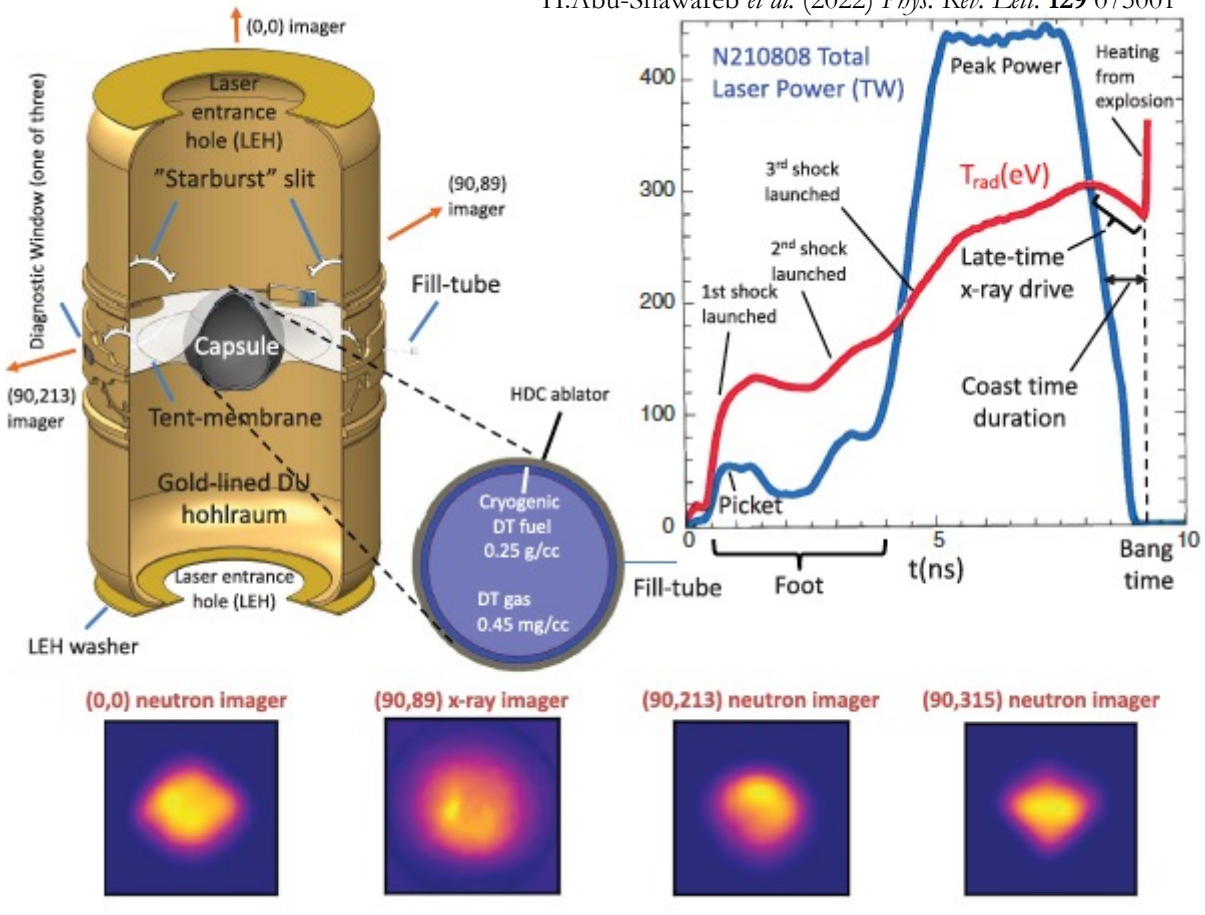

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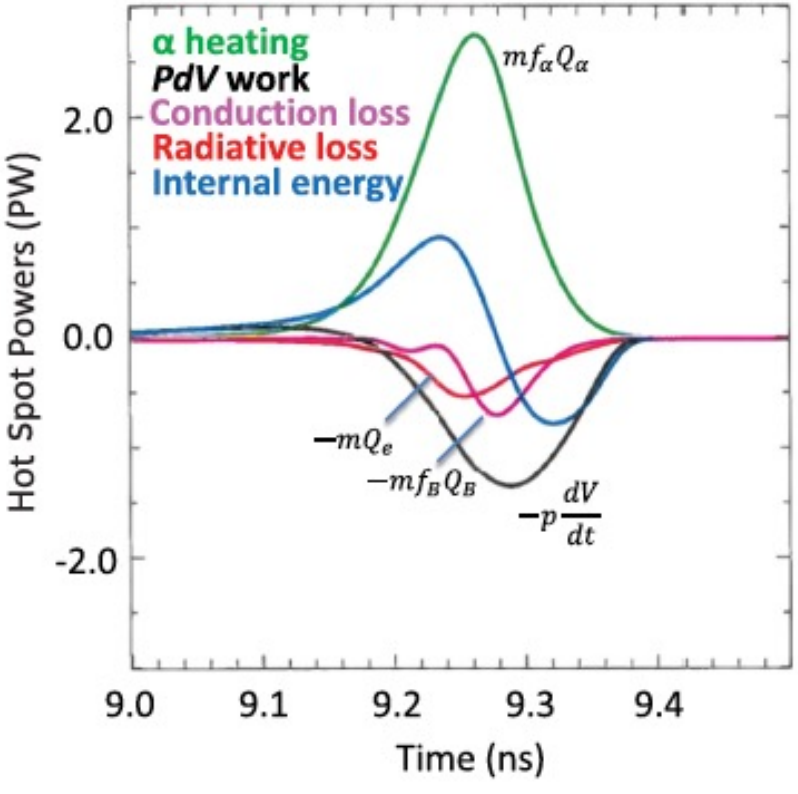
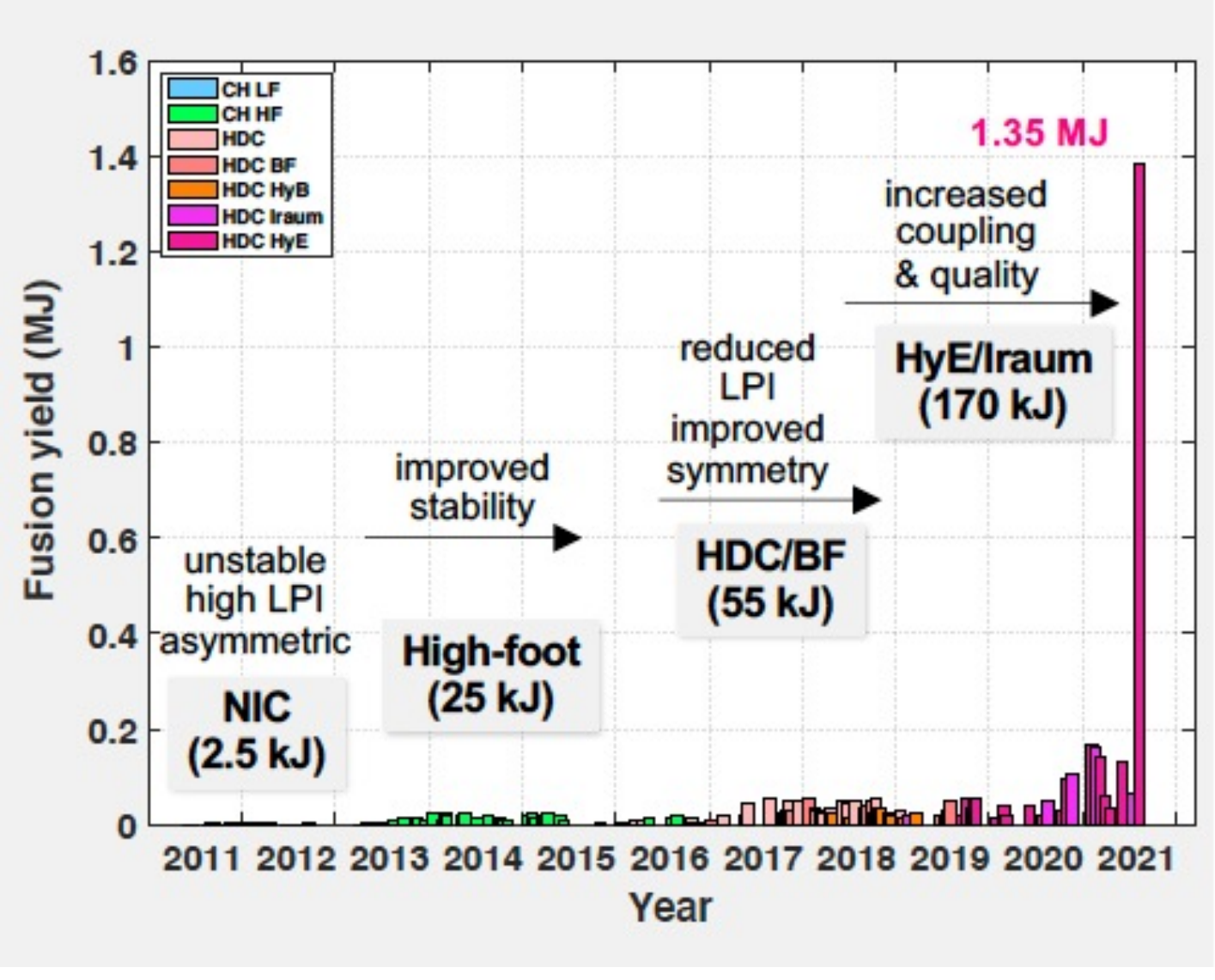


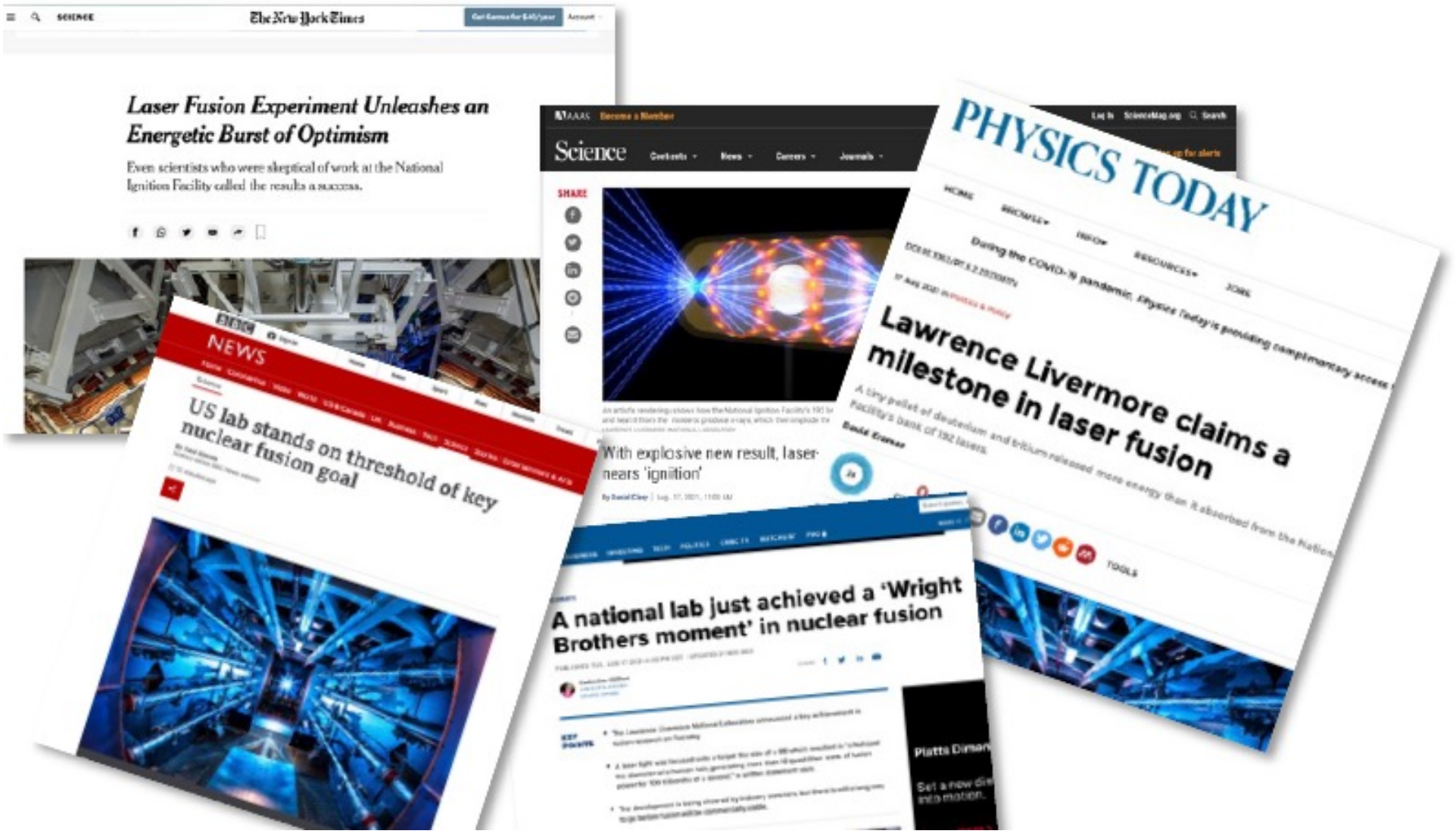
Fusion yield of 1.3 MJ ~ X-ray energy x8!, x0.7 of laser energy (1.9 MJ)

Taking stock: over 500 times improvement…



Credit for figure: T. Ma (2022), LLNL

…cue headlines!

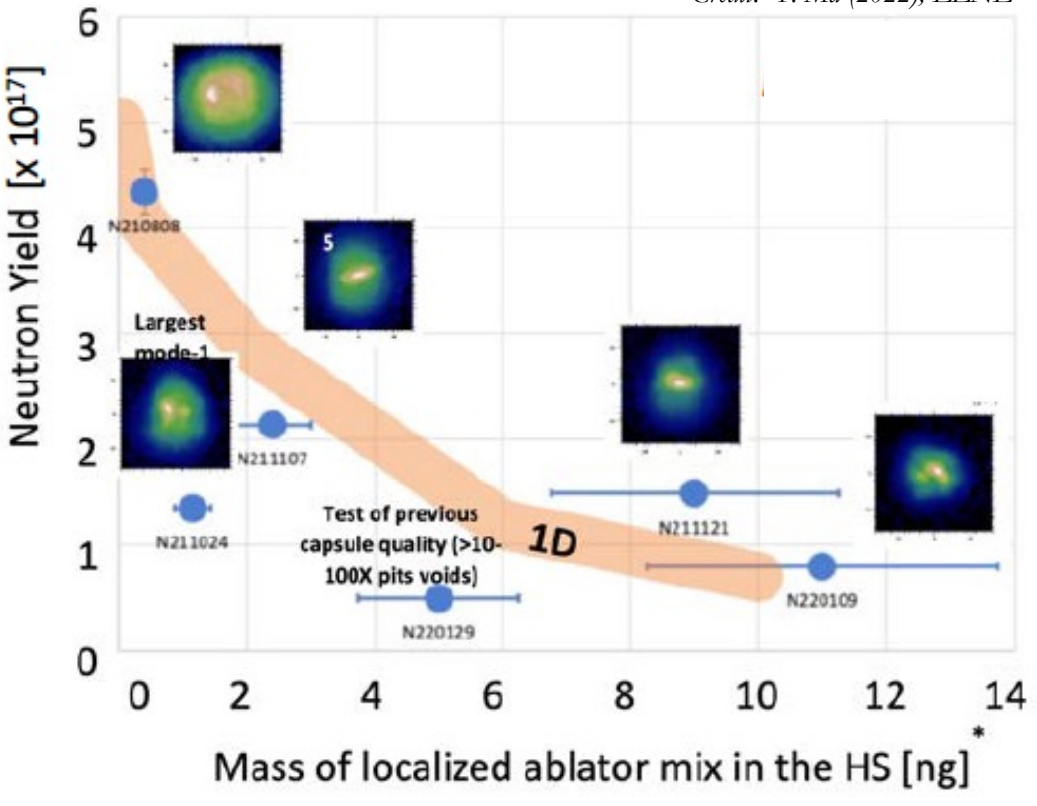


Credit for slide: T. Ma (2022), LLNL

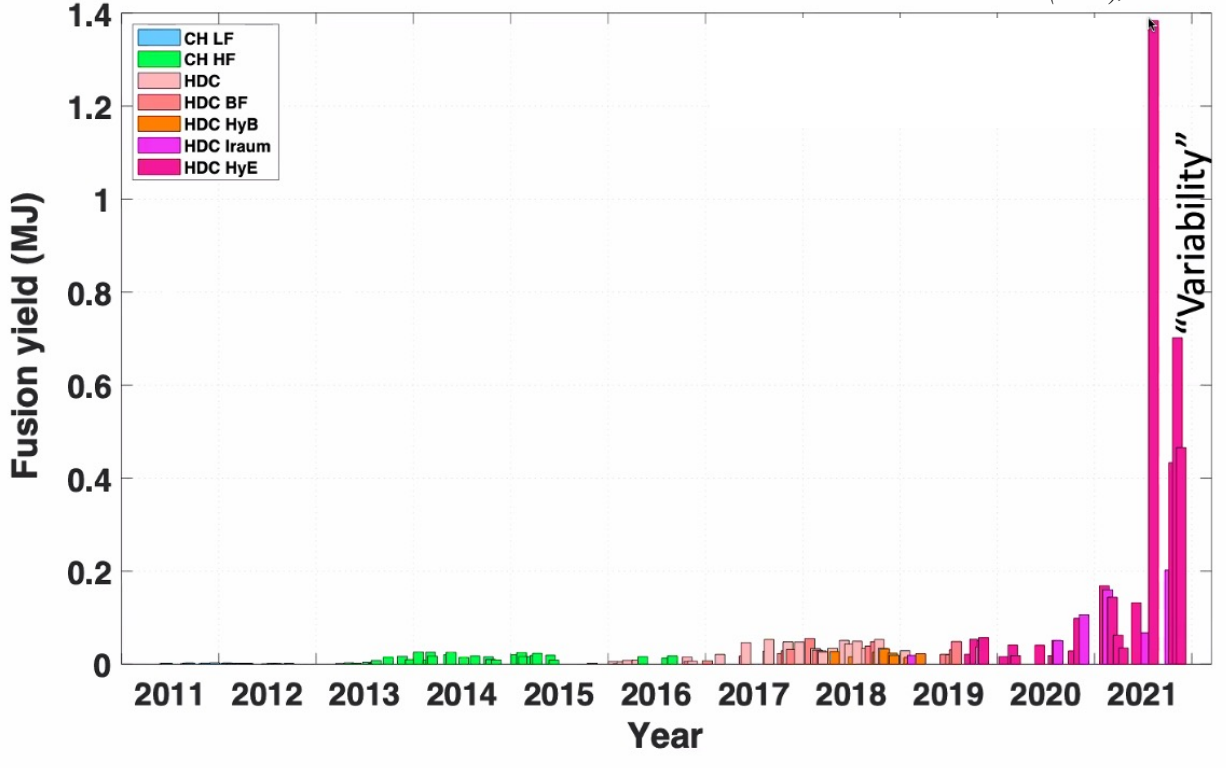
Variability post August 2021…

How repeatable was shot N210808? Initially, not very…

Credit: T. Ma (2022), LLNL



Credit: T. Ma (2022), LLNL

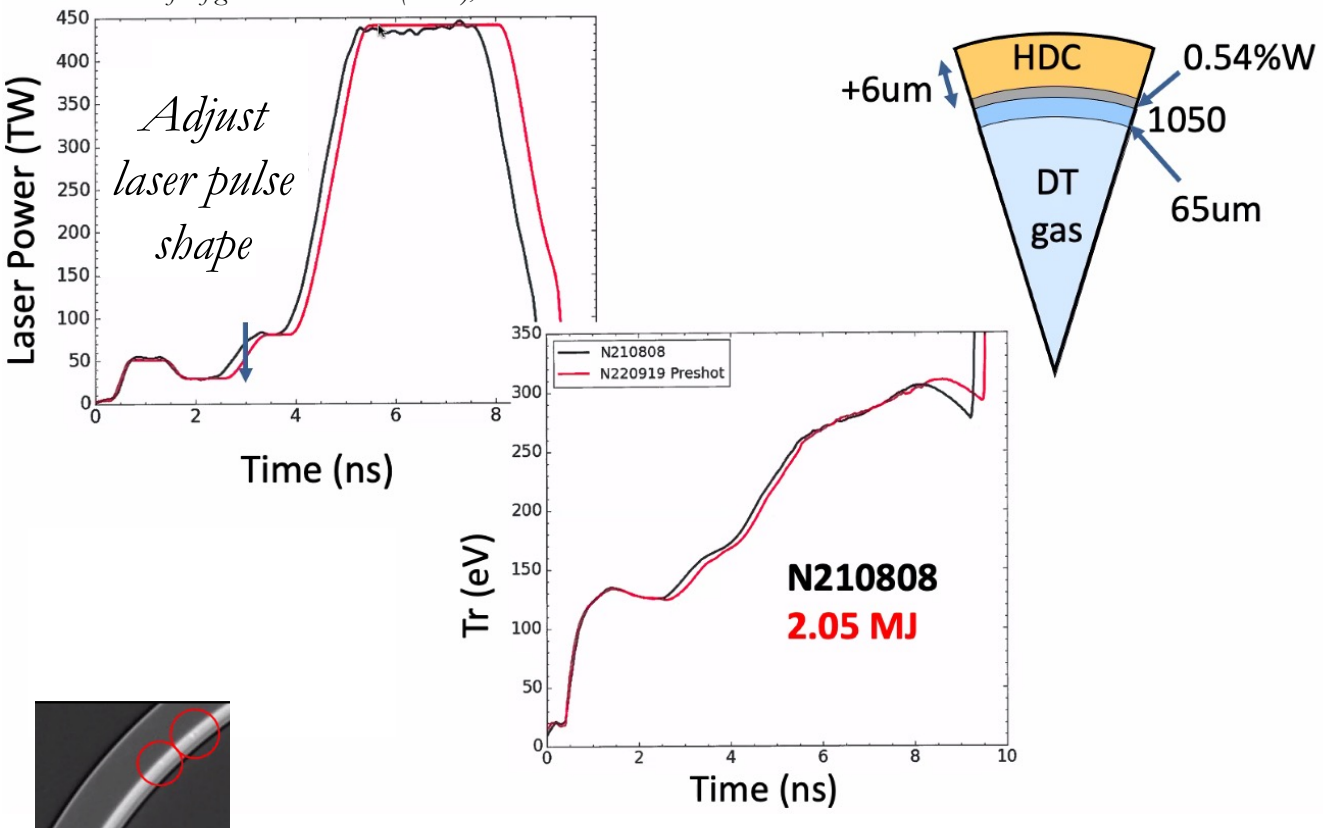


What went wrong? 1) Ablator mixing into the hot spot; 2) Low mode asymmetries; 3) Ignition cliff

Attempts to improve robustness

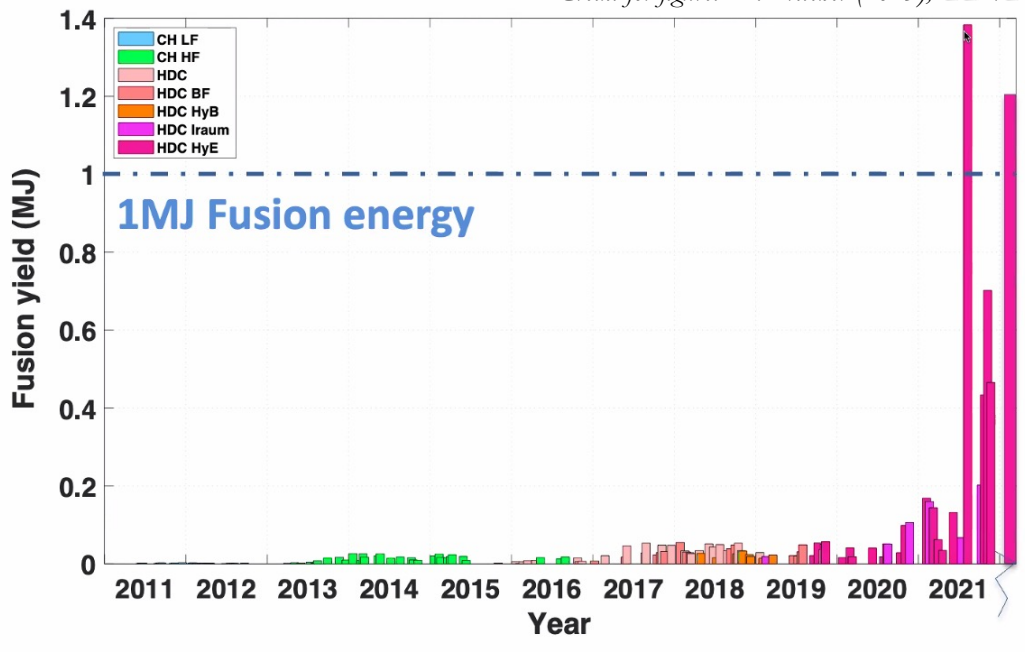
How do we overcome variability? Take advance of ignition cliff, leverage ~7% increase in laser energy

Credit for figure: A. Kritcher (2023), LLNL

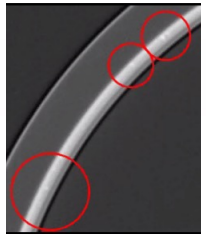


Use thicker ablator

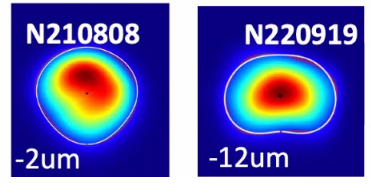
Credit for figure: A. Kritcher (2023), LLNL



Result: comparable to previous record, not better



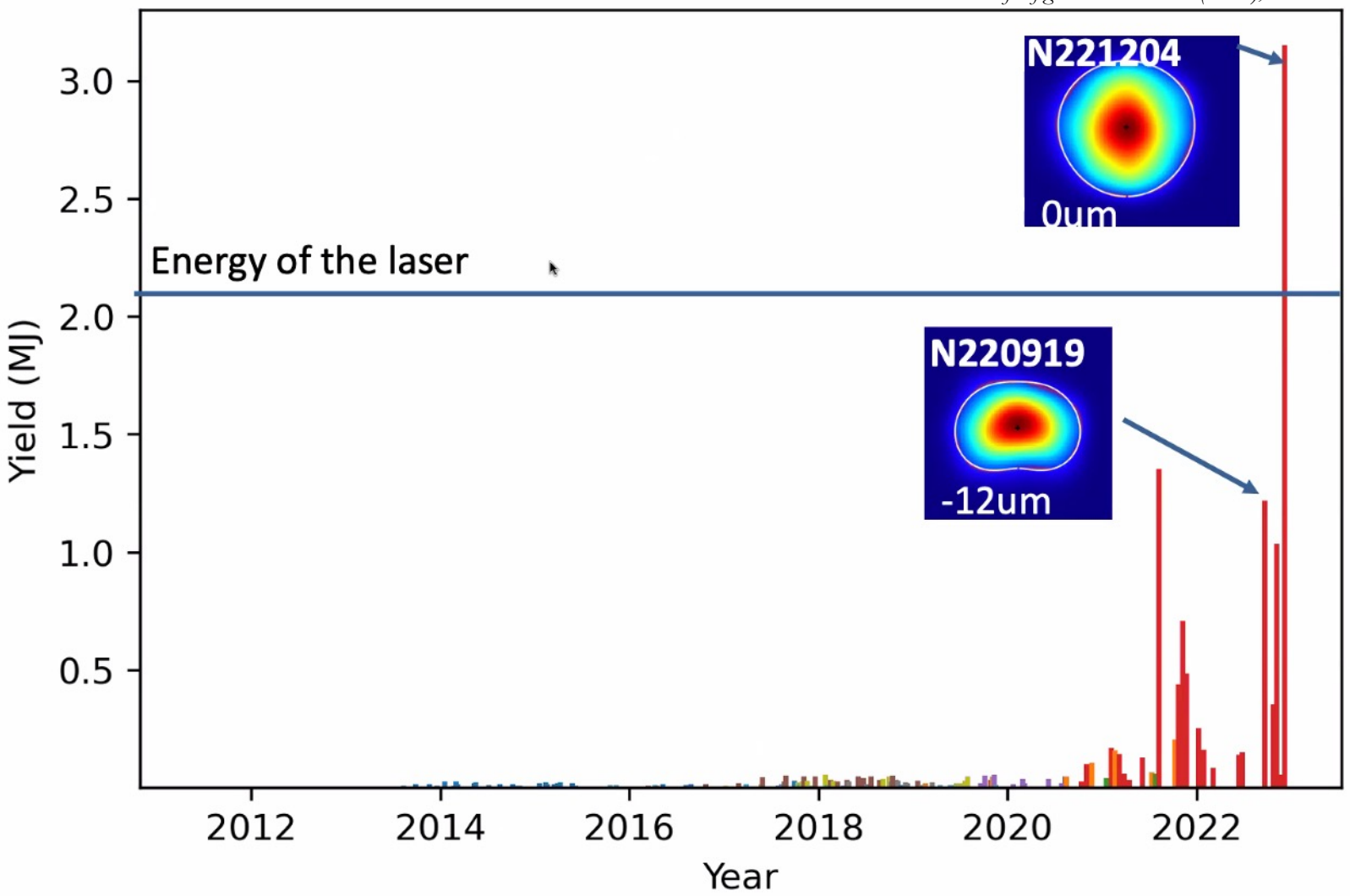
Why? 1) Capsule manufacturing issues; 2) new implosion asymmetry



And then in December 2022…

Solution: optimise laser irradiation to remove asymmetric drive!

Credit for figure: A. Kritcher (2023), LLNL



Headline results

Fusion yield of 3.15 MJ

||

~17x x-ray energy

||

~1.5x laser energy

||

Ignition!

x1,500 improvement in 10 years

Hot topic: how can we even do better?

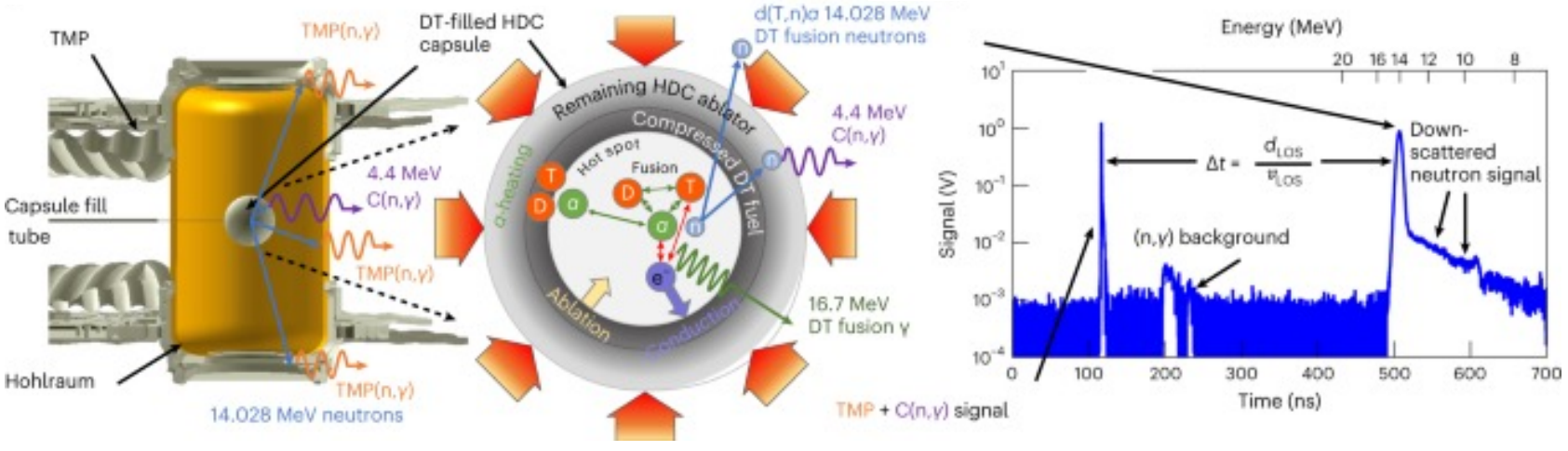
Q: how do we go from gains of ~1.5 to >40 (i.e. what's needed for power generation)?

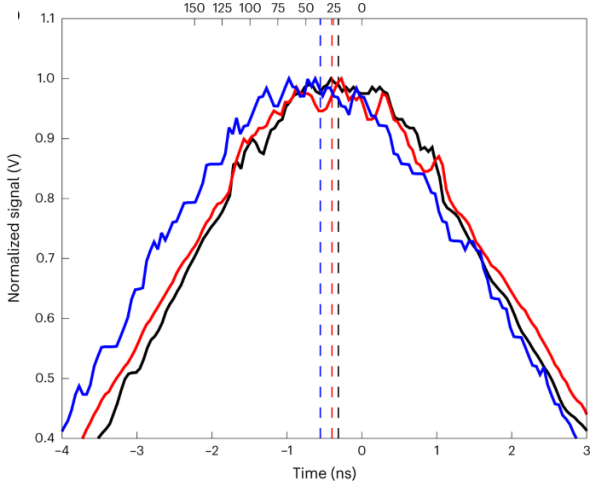
A1: Optimising the current approach:

- Improved laser to x-ray energy coupling using more efficient hohlraums
- Achieve higher compression with further pulse shape improvements
- Scale to larger capsules using further laser-energy improvements at NIF (plans to go to ~2.5-3 MJ)

A2: can we leverage plasma physics to design better capsules?

- Neutron spectra observations (E. Hartouni et al. 2022) indicate novel kinetic physics in NIF hotspots:

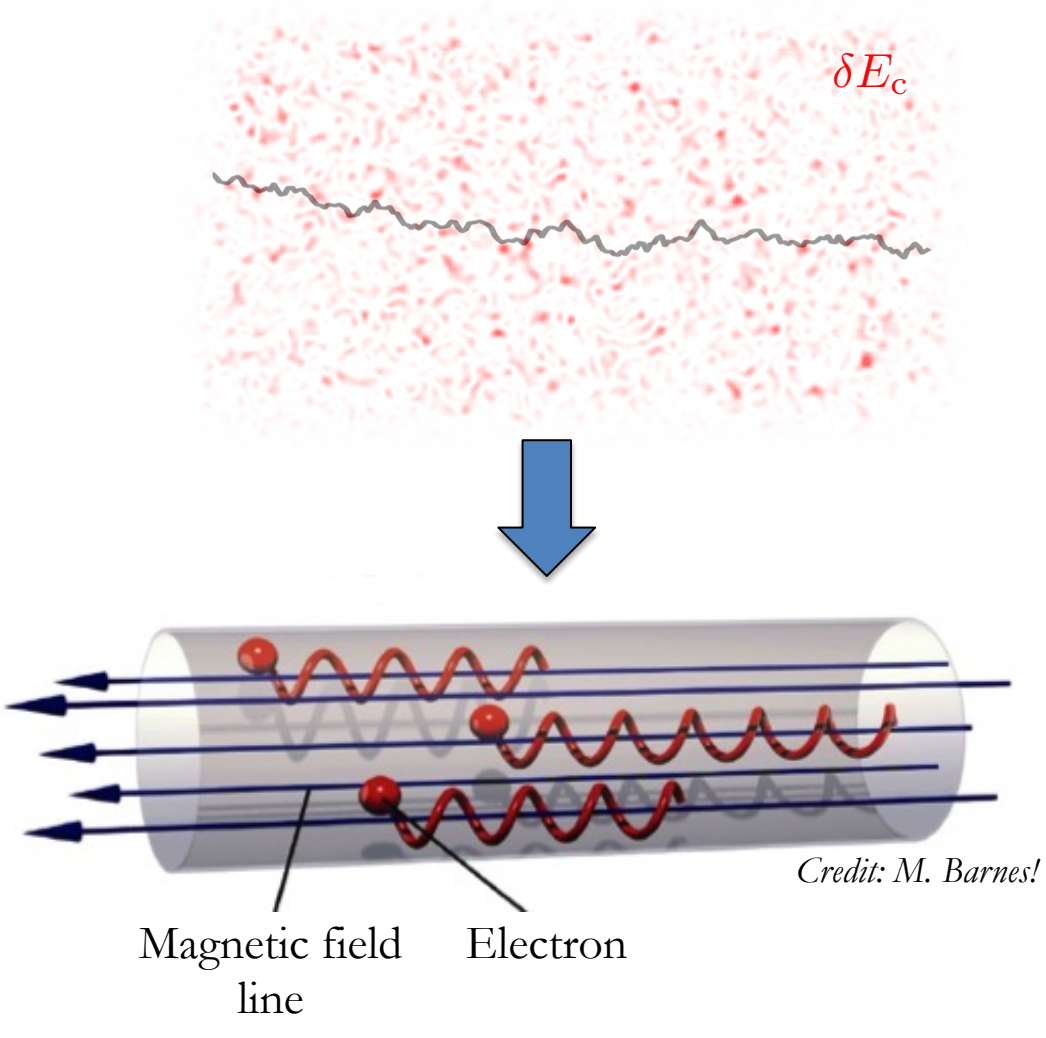


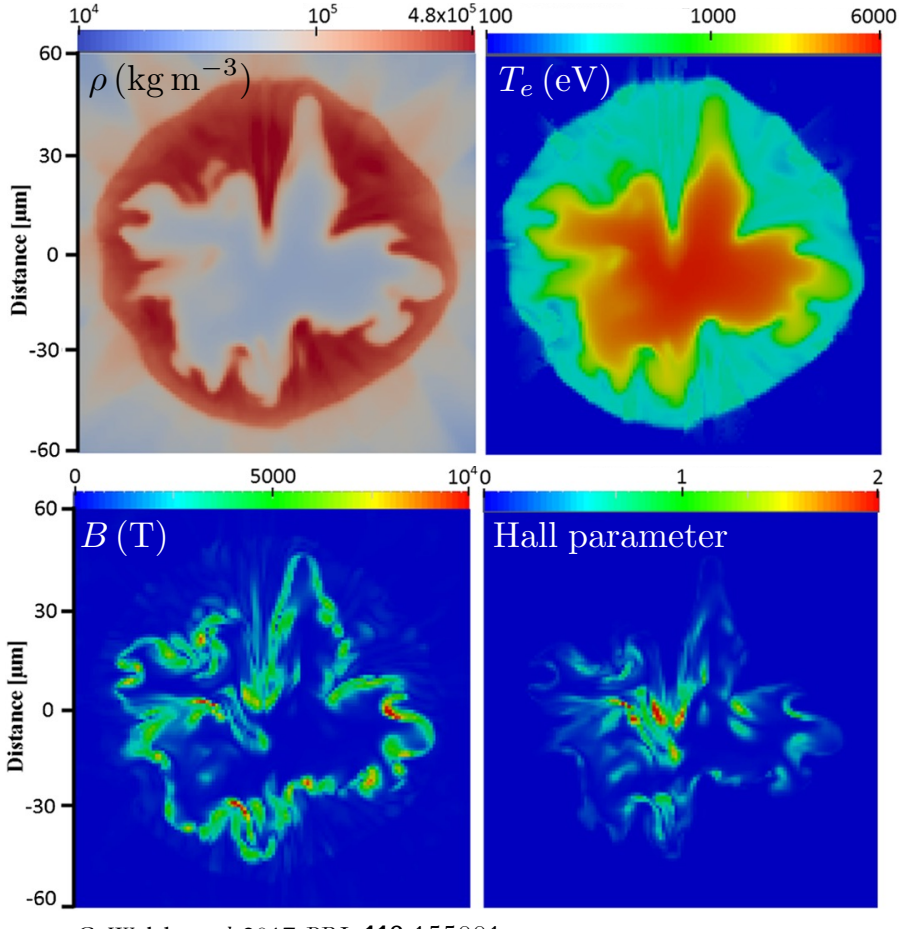


- **Magnetic fields…!**

Why do magnetic fields matter in ICF experiments?

Magnetic fields spontaneously generated in NIF ICF experiments magnetise the plasma's electrons



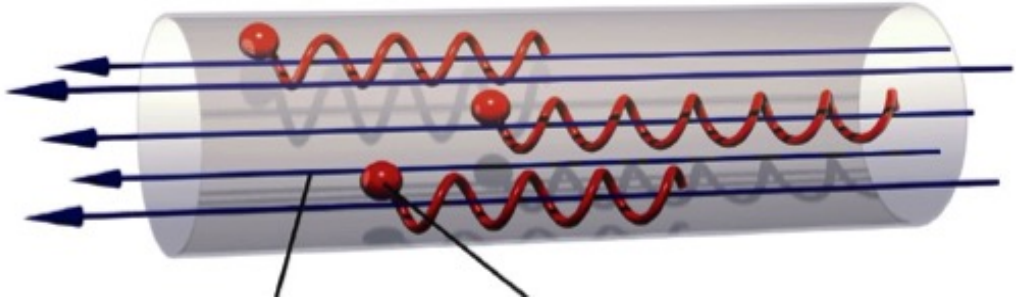


C. Walsh *et al.* 2017 *PRL* **118** 155001

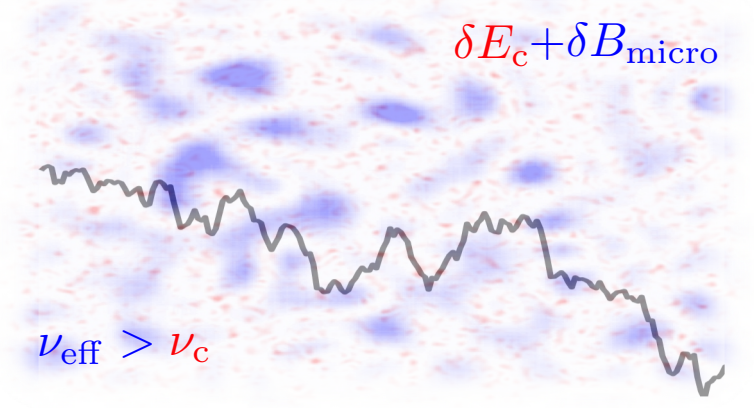
Why are these magnetic fields important?

Magnetised electrons → suppressed heat conduction…!

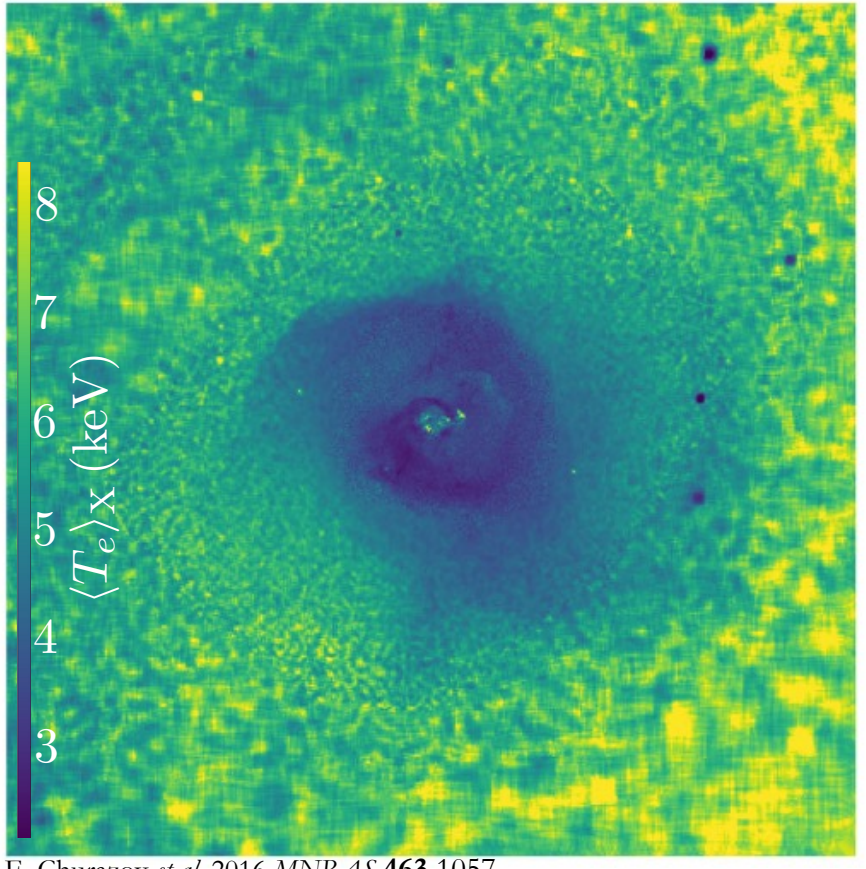
Suppressed across field lines by large scale fields …



…and along field lines by *microinstabilities*



Example: ICM of galaxy clusters

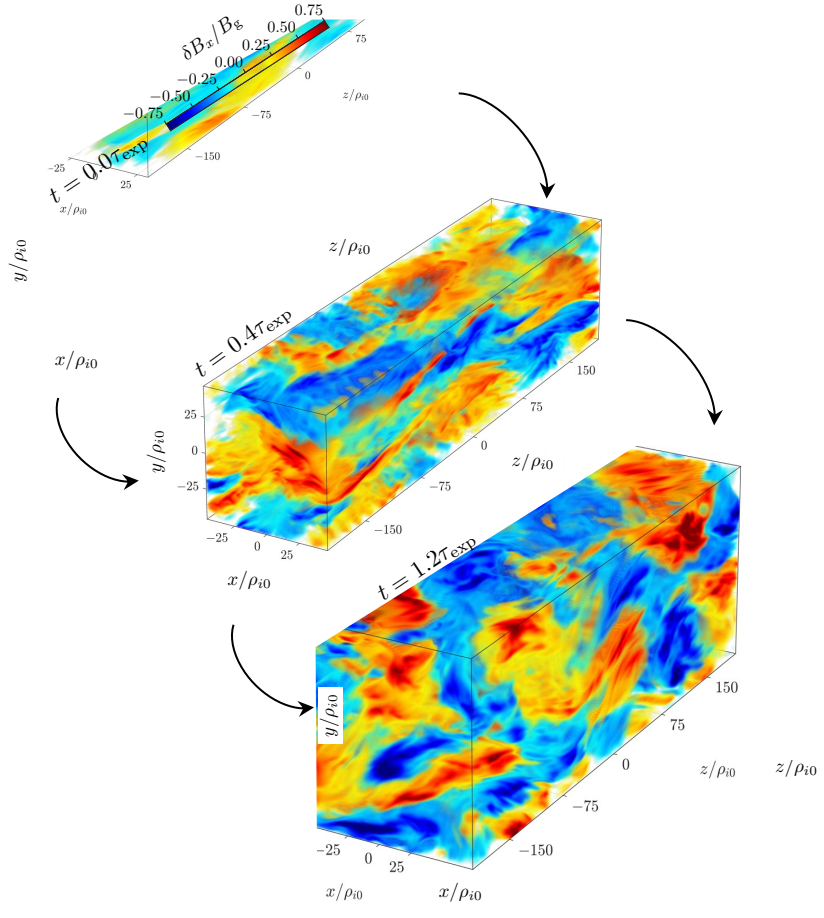


E. Churazov *et al.* 2016 *MNRAS* **463** 1057

Why investigate this possibility now?

In addition to fusion applications… perfect time for advancing our understanding of such plasmas!

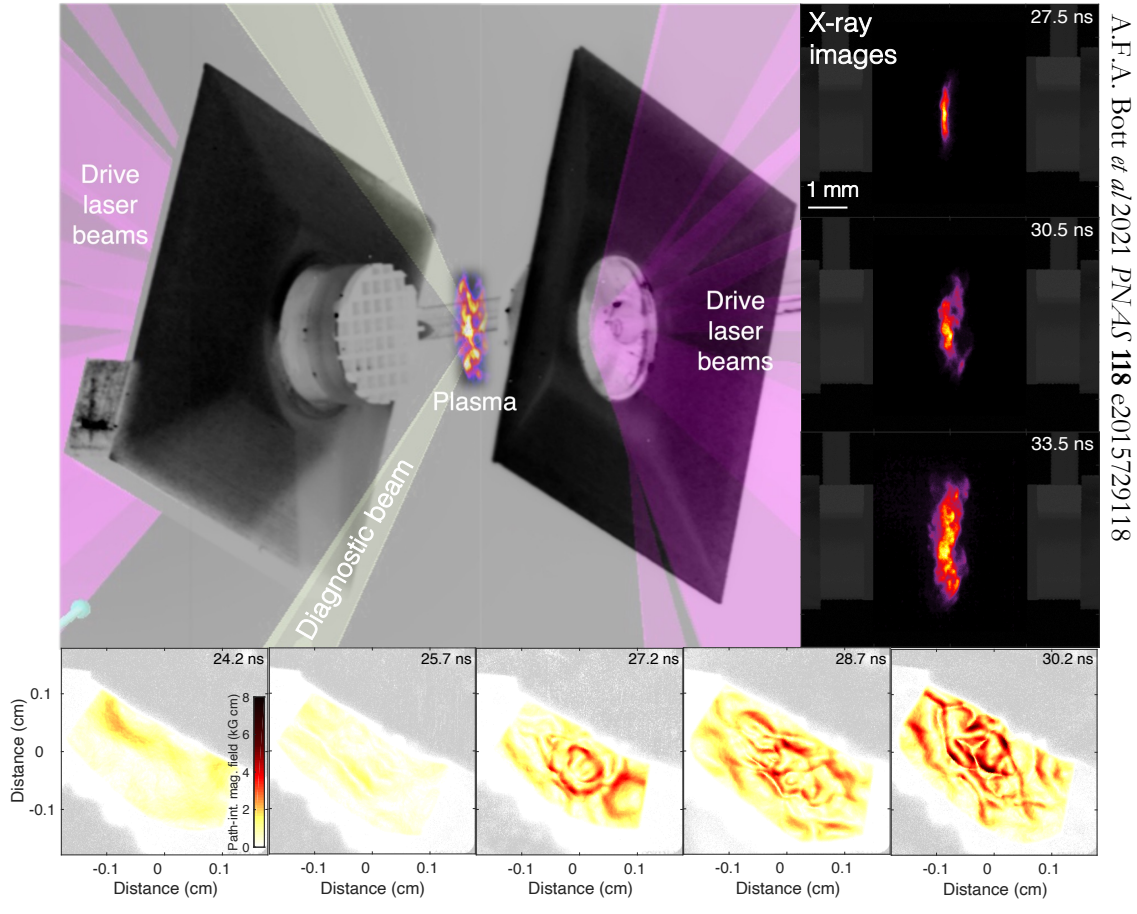
Kinetic simulations



A.F.A. Bott *et al* 2021 *ApJL* **922** L35

+

Bespoke laser-plasma experiments

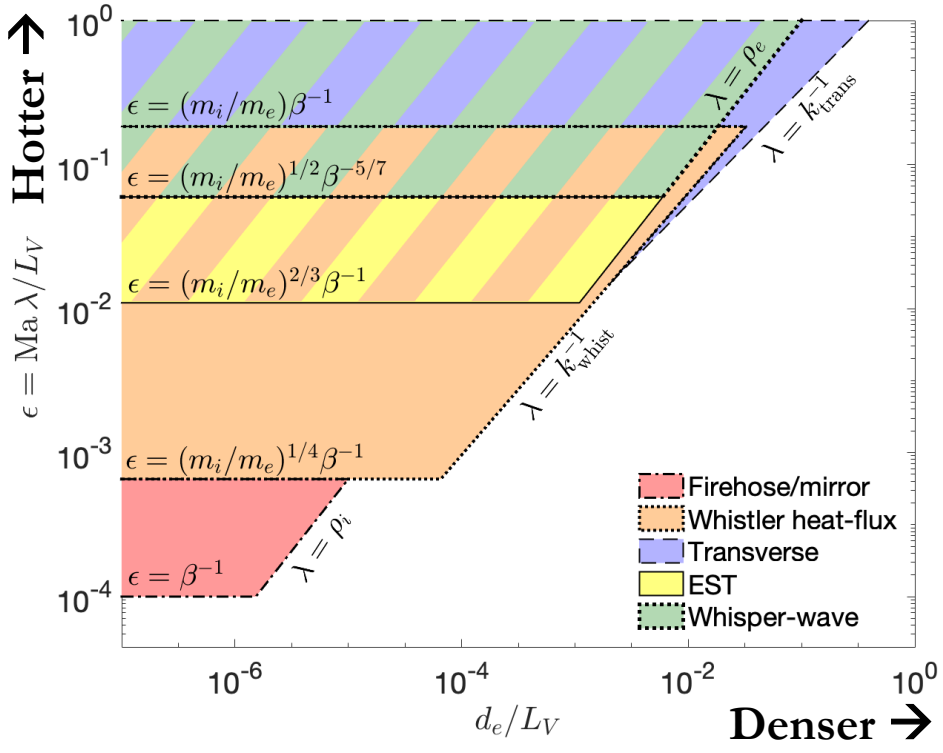


A.F.A. Bott *et al* 2021 *PNAS* **118** e2015729118

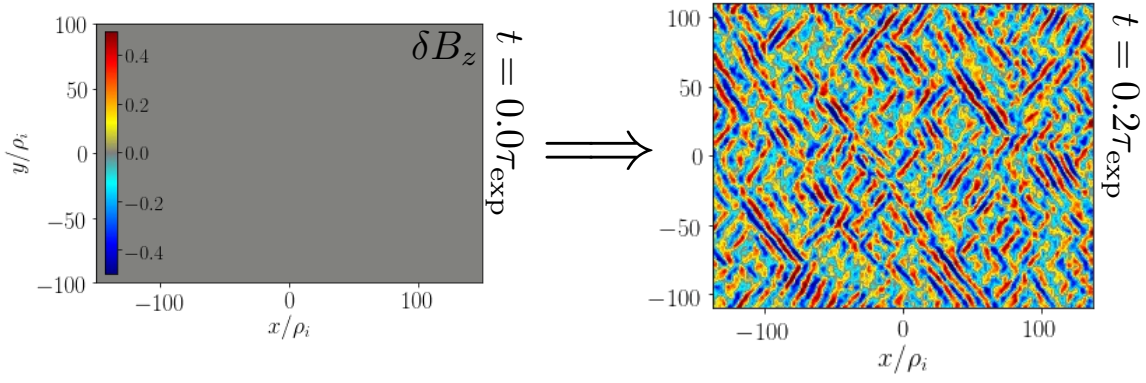
What have we done so far?

Some theoretical, numerical ***and experimental*** studies!

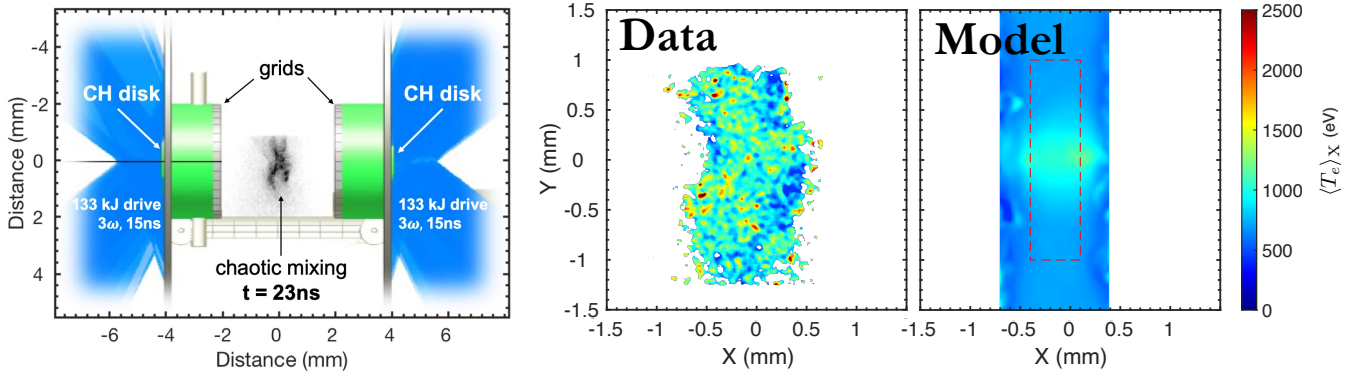
Theory: *"Kinetic stability of weakly collisional, magnetised plasmas"*



Simulations: *"The transport properties of firehose-susceptible plasmas"*

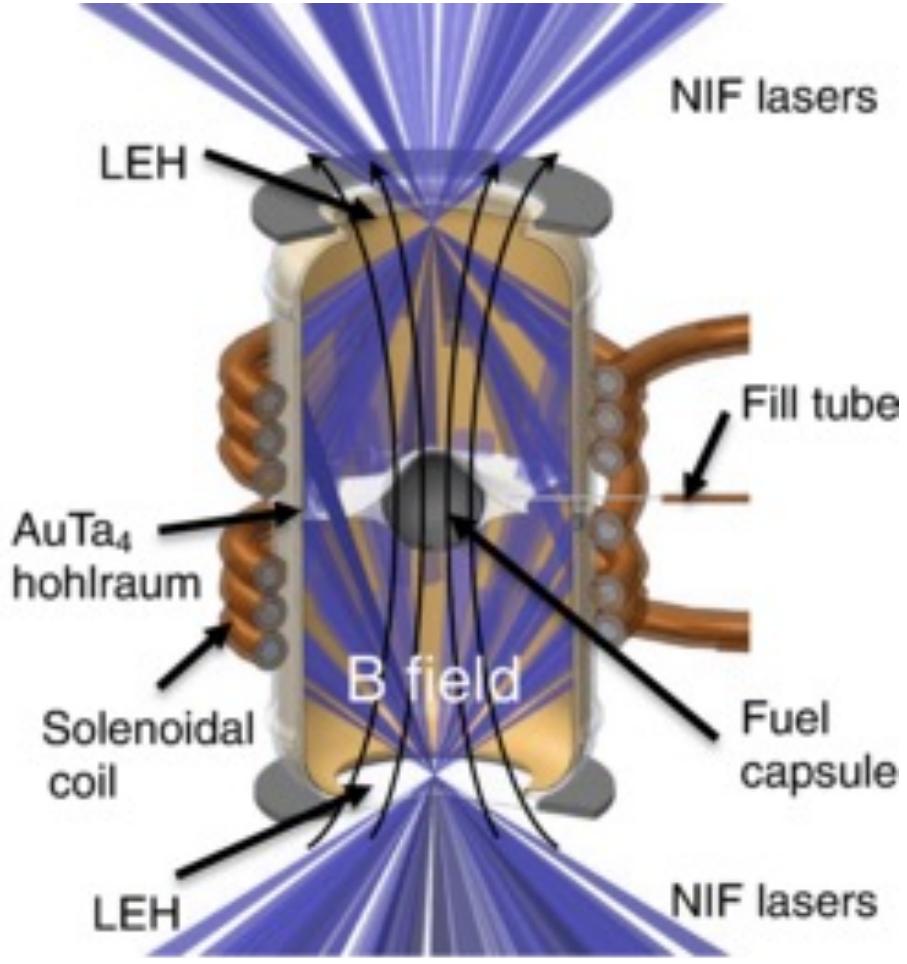


Experiments: *"Suppression of heat conduction in a laboratory replica of galaxy-cluster turbulent plasmas"* (J. Meinecke *et al* 2022 *Sci. Advances* **8** eabj6799)

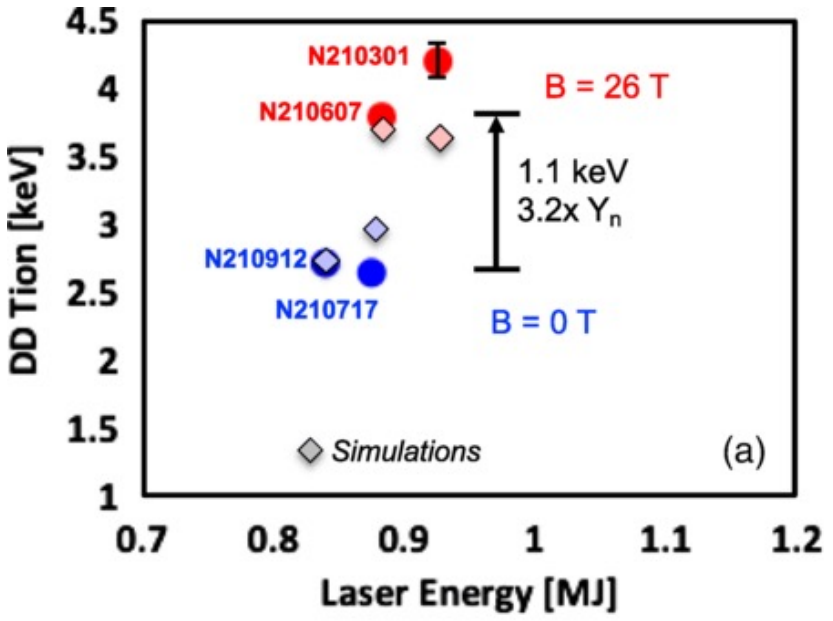


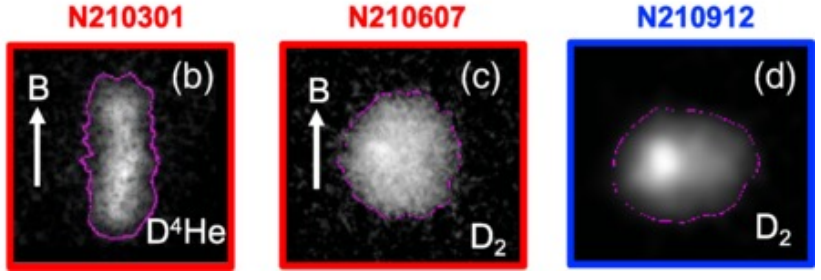
Promising first steps: Moody et al. (2022)

What about *imposing* a background field? Initial results from NIF experiments very promising



J.D. Moody *et al* 2022 *PRL* **129** 195002



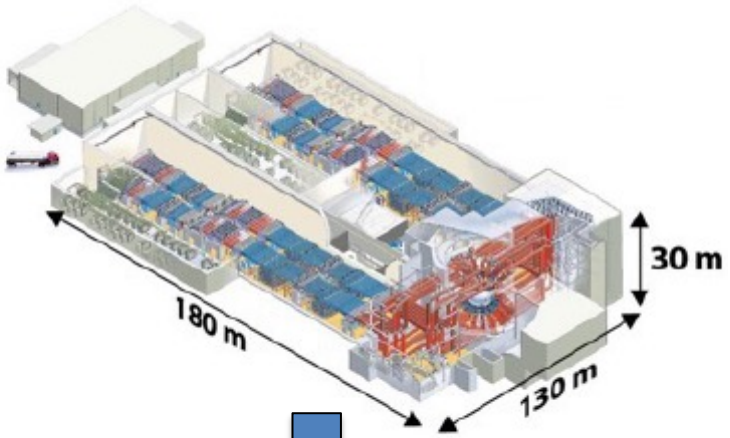


DT experiments in the next two years: *watch this space*…

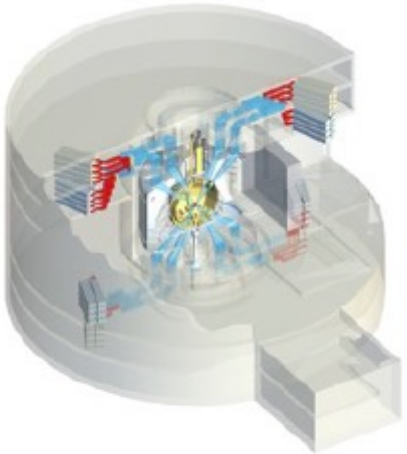
Inertial Fusion Energy (IFE)

Q: what would need to happen to make IFE a reality?

NIF



IFE power plant



Credit: T. Ma (2022), LLNL

1. High gain
2. Laser efficiency (0.6% → 15-20% wall plug efficiency)
3. High repetition shot rate
4. Simplified, economic target design
5. Material science

Thank you for listening!