Introduction to Inertial Confinement Fusion

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June 15, 2022

2022 Introduction to Fusion Energy and Plasma Physics Course

Email freely with questions: bkraus – at – pppl.gov

PRINCETON
PLASMA PHYSICS
LABORATORY

You could be up here, too!

Autobiography:

2013: NUF internship (precursor to SULI)

…

2021: PhD in Astrophysical Sciences

2022: Giving you a SULI lecture

Plan for introducing you to ICF:

- **What** is fusion? → What is **inertial confinement**?
- **How** do we get ICF to work?
- **When** are we going to get there? How do we know?
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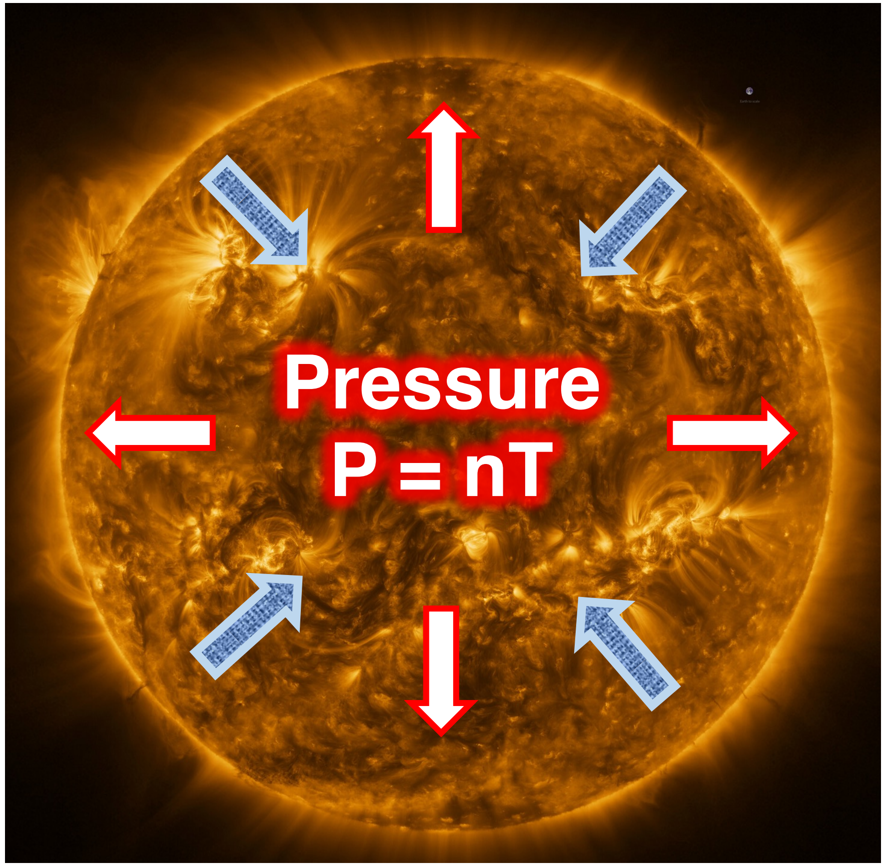
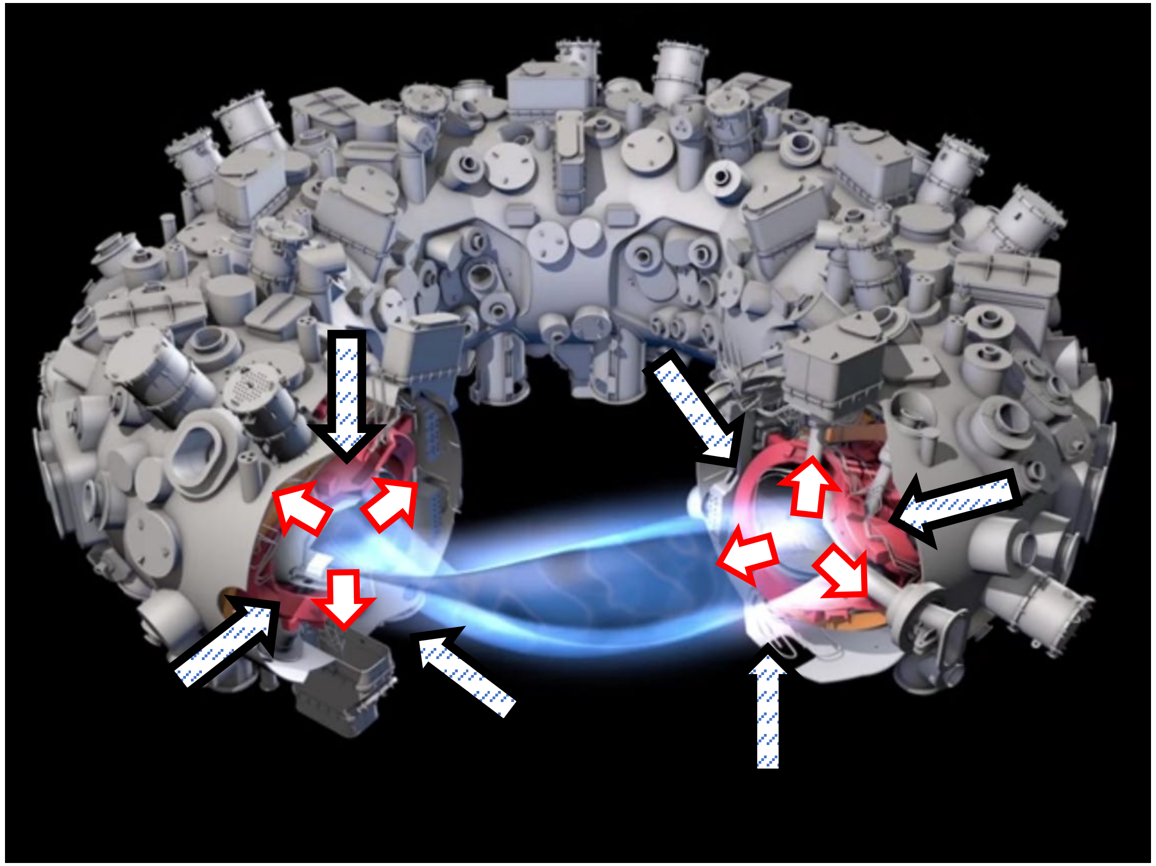
Fusion sustains by counteracting **enormous plasma pressures**

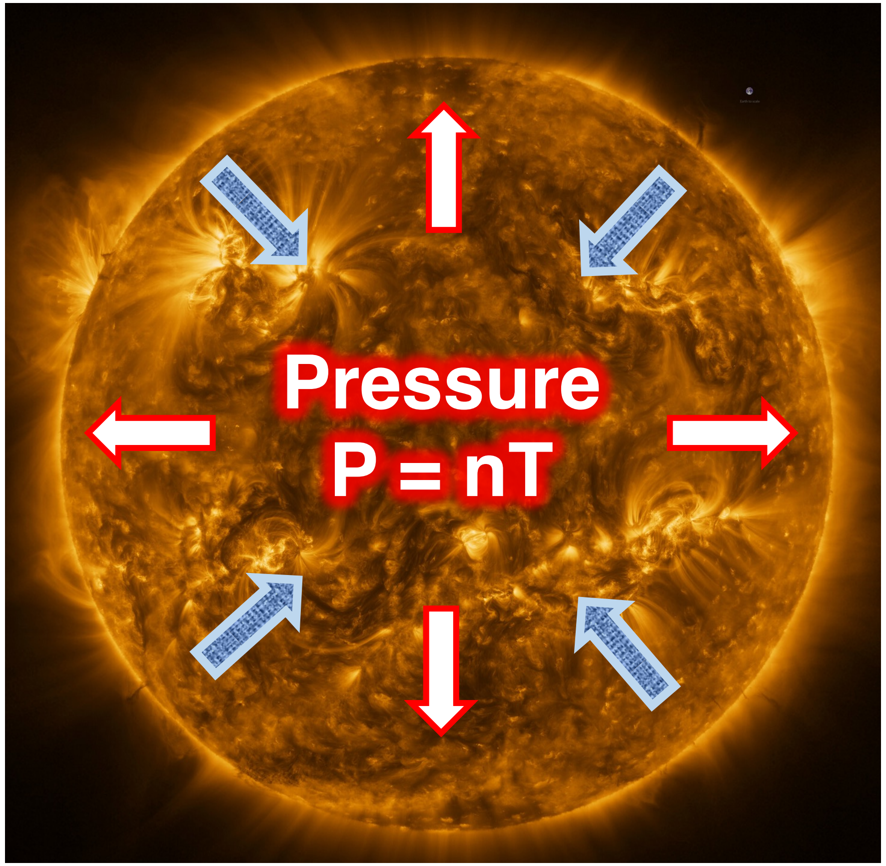


vs. Gravity

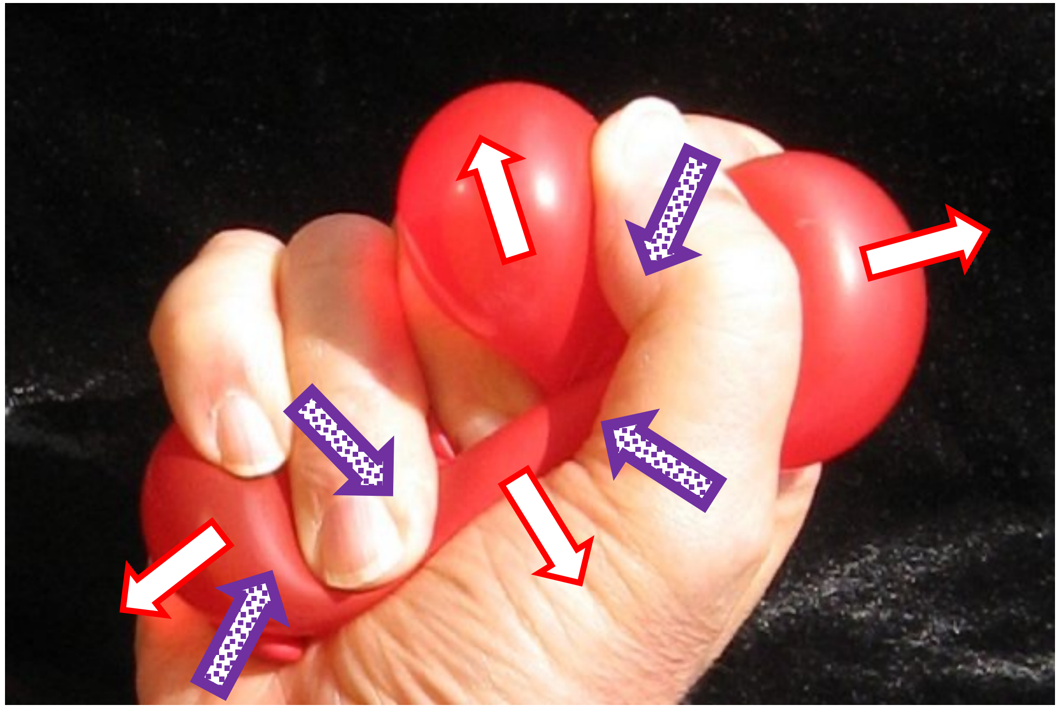


vs. Magnetic Fields

Fusion sustains by counteracting **enormous plasma pressures**

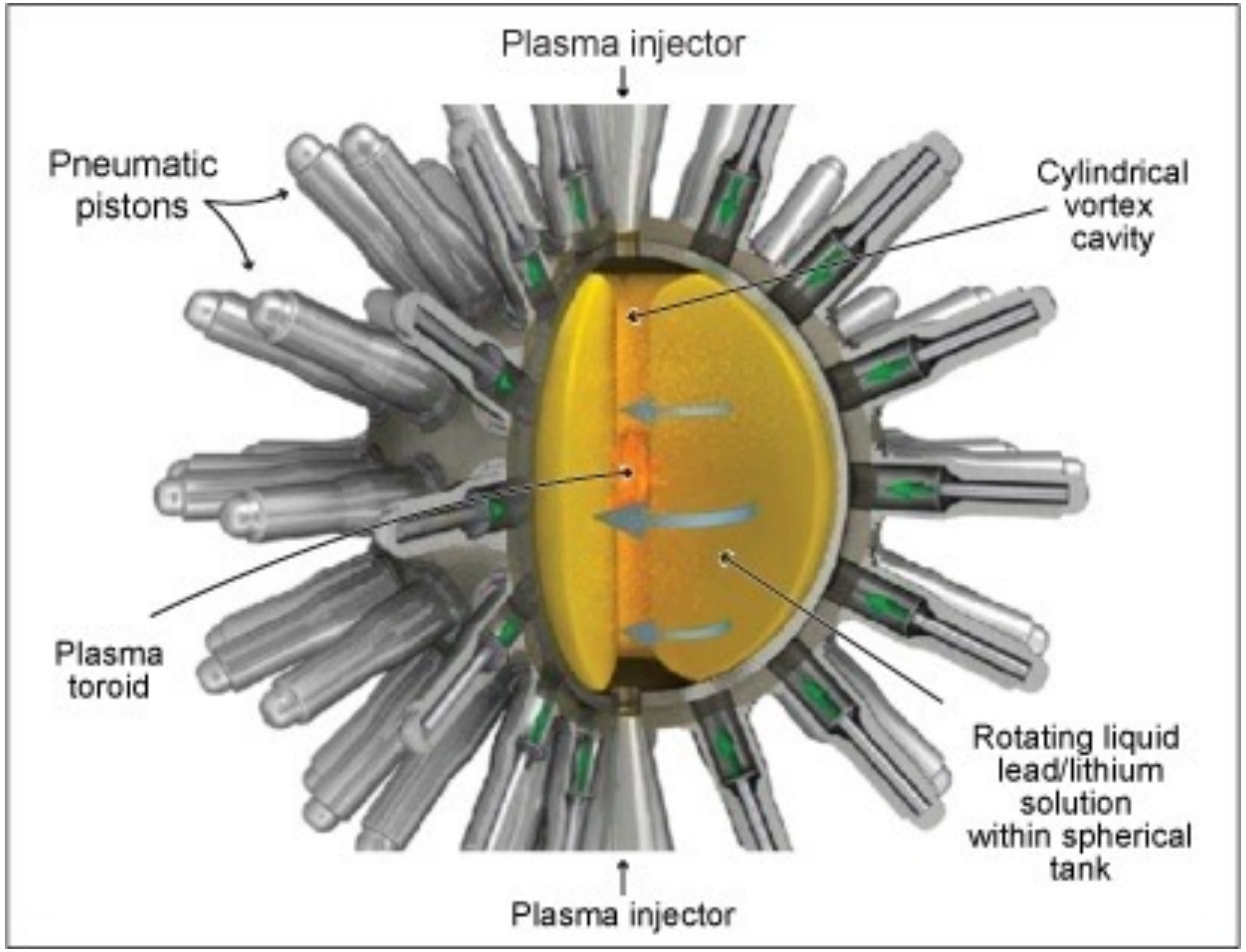


vs. Gravity



vs. Momentum, e.g., smashing

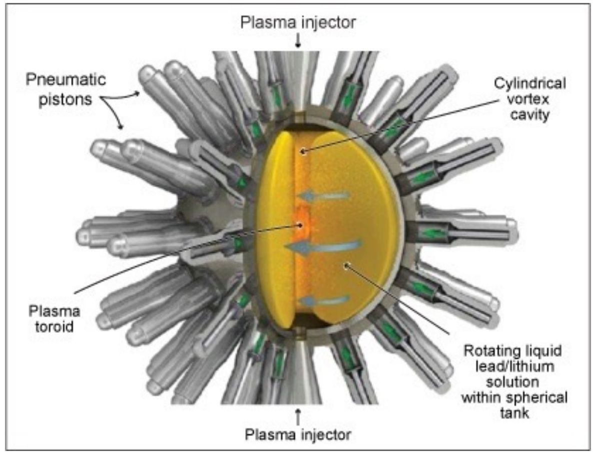
You can smash DT with many hammers



General Fusion
(private Canadian company)

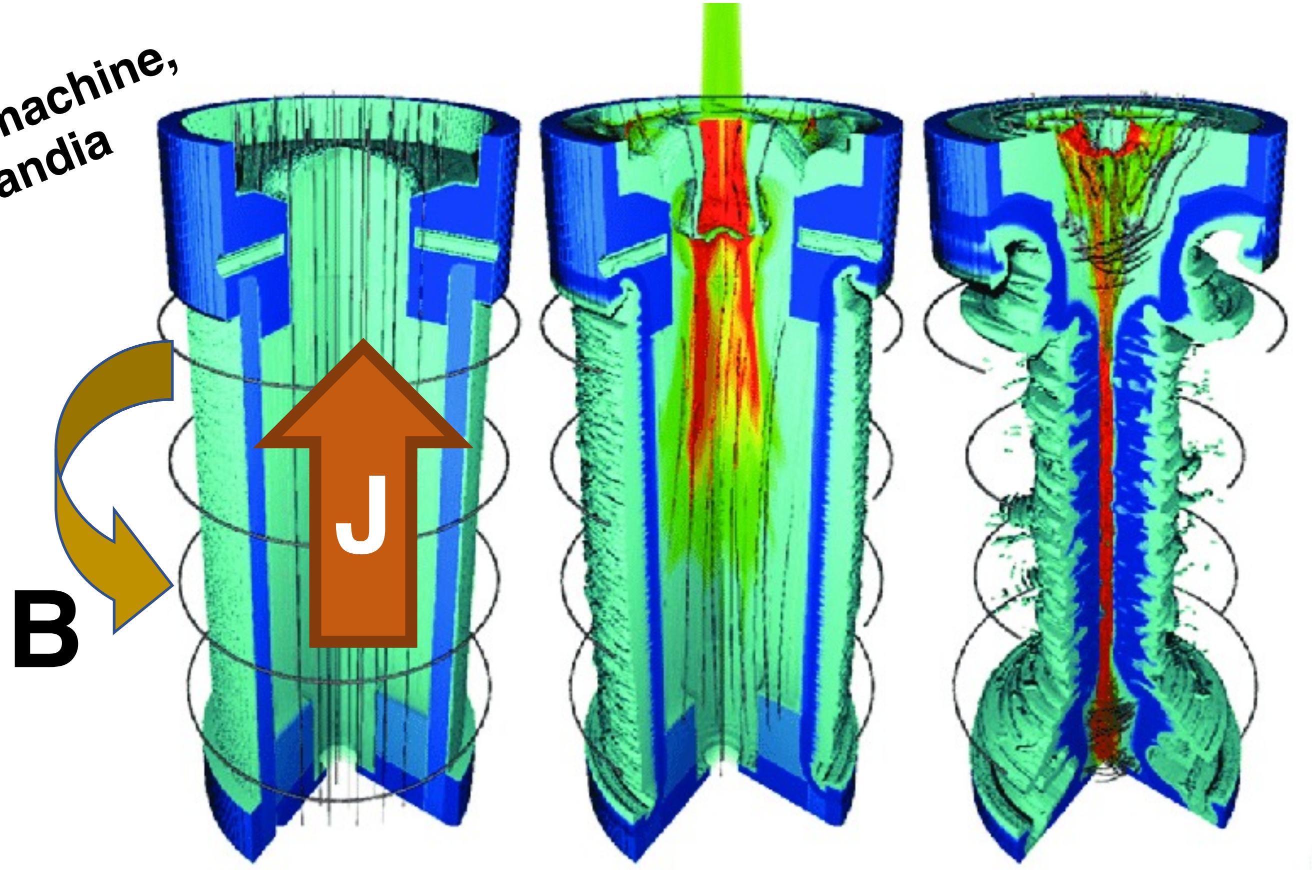
Liquid lithium sphere
imploded by pistons

You can smash DT with many hammers



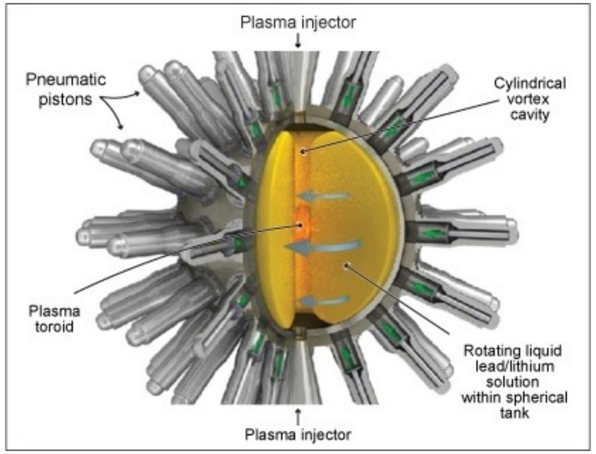
General Fusion
Imploding lithium liquid

Z machine,
Sandia

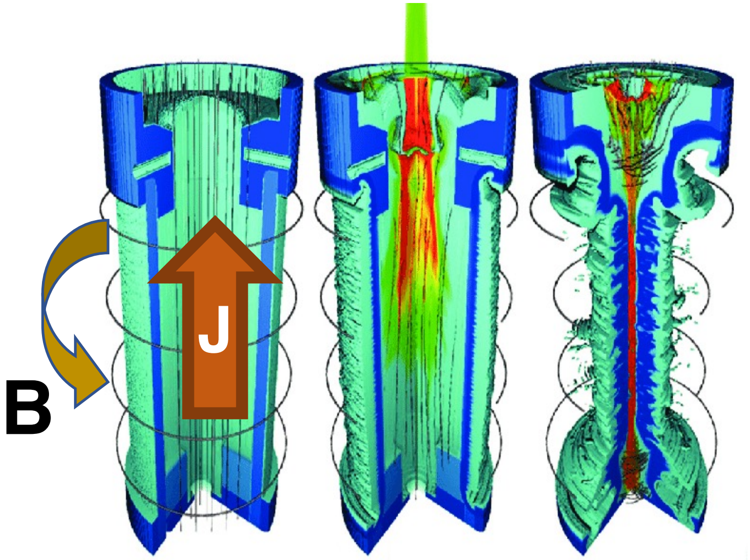


Magnetized Liner Inertial Fusion : MagLIF
Inertial confinement by pulsed power JxB force

You can smash DT with many hammers



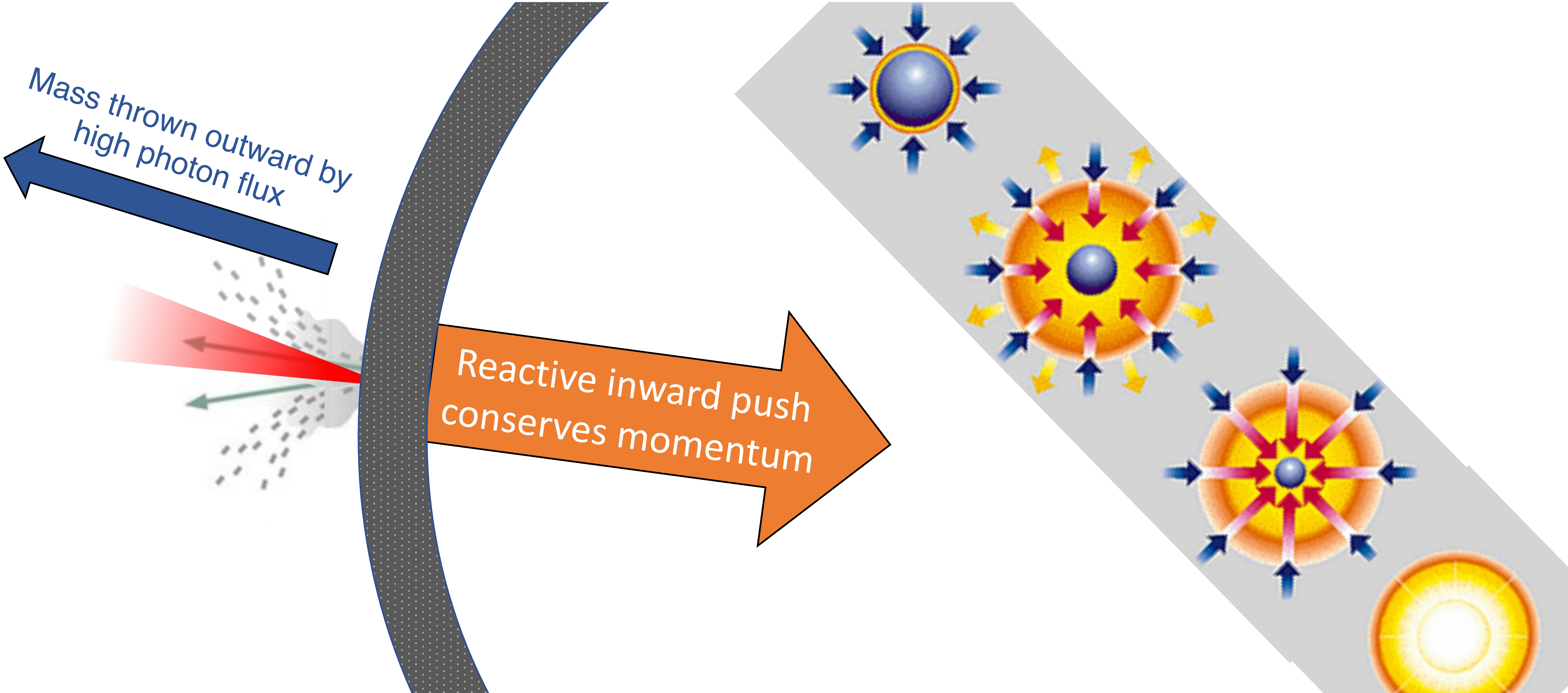
General Fusion
Imploding lithium liquid



MagLIF
Pulsed power JxB force

National Ignition Facility
Laser-driven,
spherical shell implosions

Ultimately, hammer = plasma blowoff from laser- or secondarily-driven ablation



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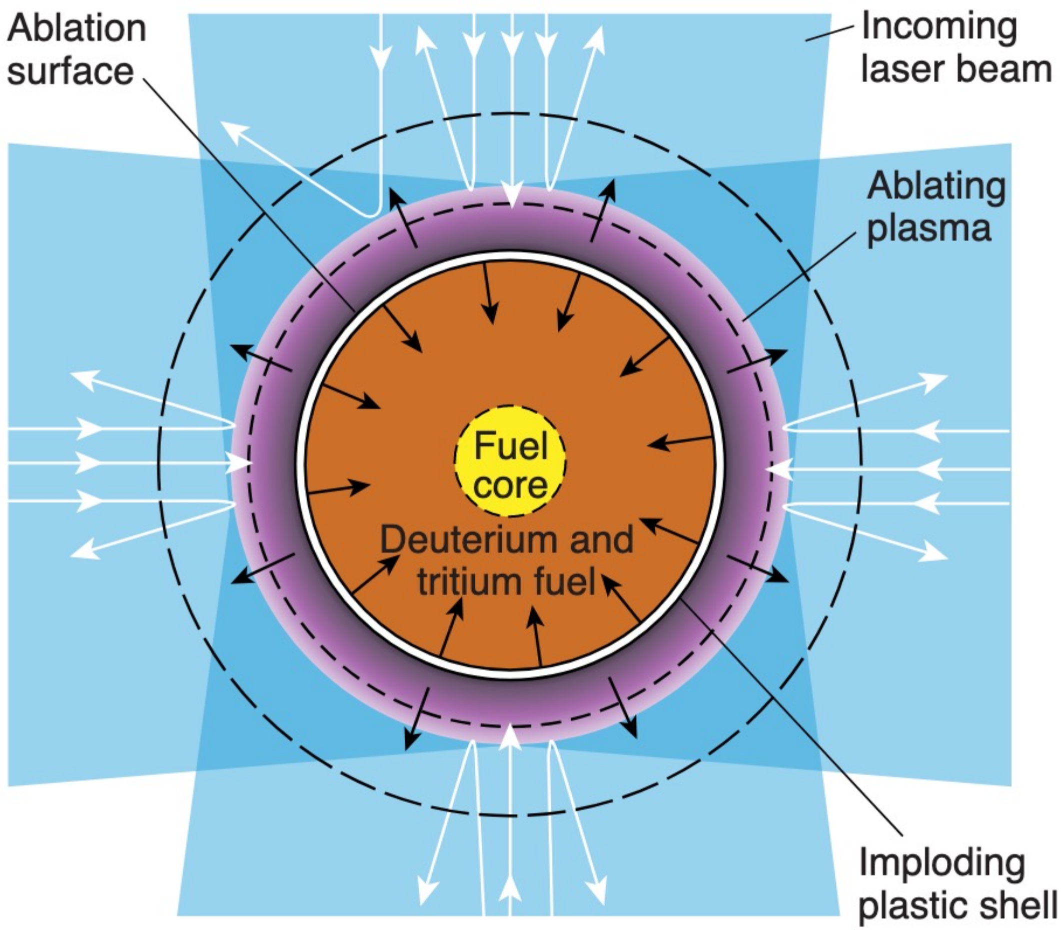
Compress a DT fuel core to hot dense conditions and ignite burn wave through ice



Timeline from capsule to *bang time*:

1. Outer shell ablates
2. Inner ice and gas compress
3. Gaseous central region (*hot spot*) ignites
4. Hot alphas and neutrons burn dense DT ice surrounding hot spot

*Textbook by Gresh, LLE 2009

Lasers need to be strong enough to produce **sustained fusion**, e.g., self-heating

System should satisfy the Lawson criterion:

$$\text{alpha-heating power} > \text{plasma power loss}$$

$$E_{\text{alpha}} \times (\text{rate of alpha production}) > \frac{\text{plasma energy}}{\text{confinement time}}$$

$$E_{\text{alpha}} \frac{dY_n}{dt} > \frac{3}{2} \frac{PV}{\tau}$$

* From PPPL Colloquium by Prav Patel, formerly LLNL

Lawson criterion for ICF can be written in terms of two variables: T_i and ρR

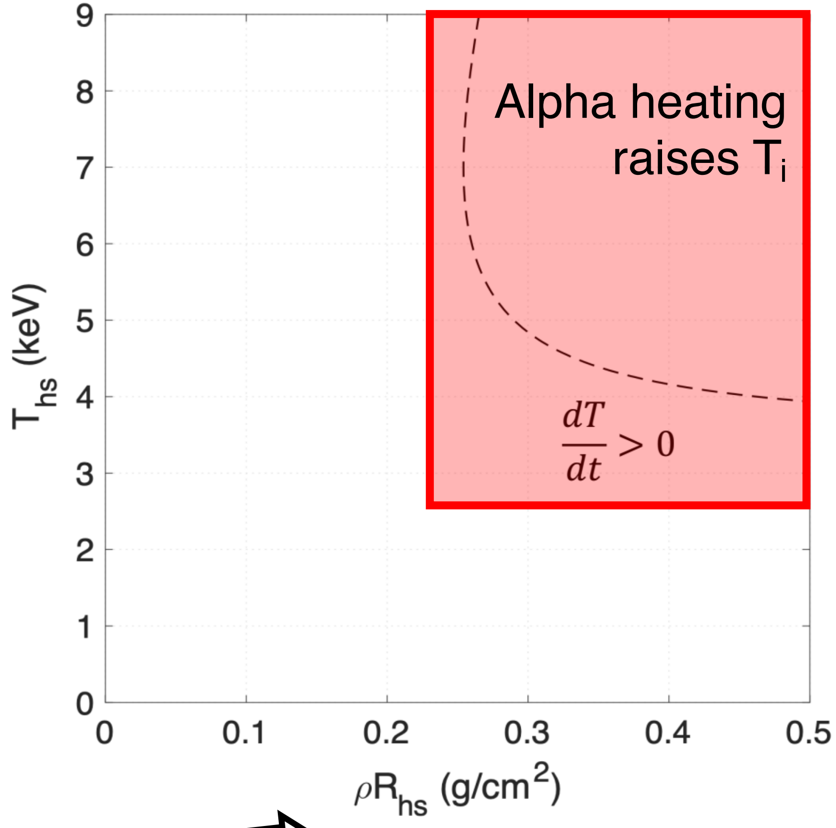
T_i : ion temperature

hotter ions → more fusion

ρR : areal density, or

mass density × radius

more material → more fusion



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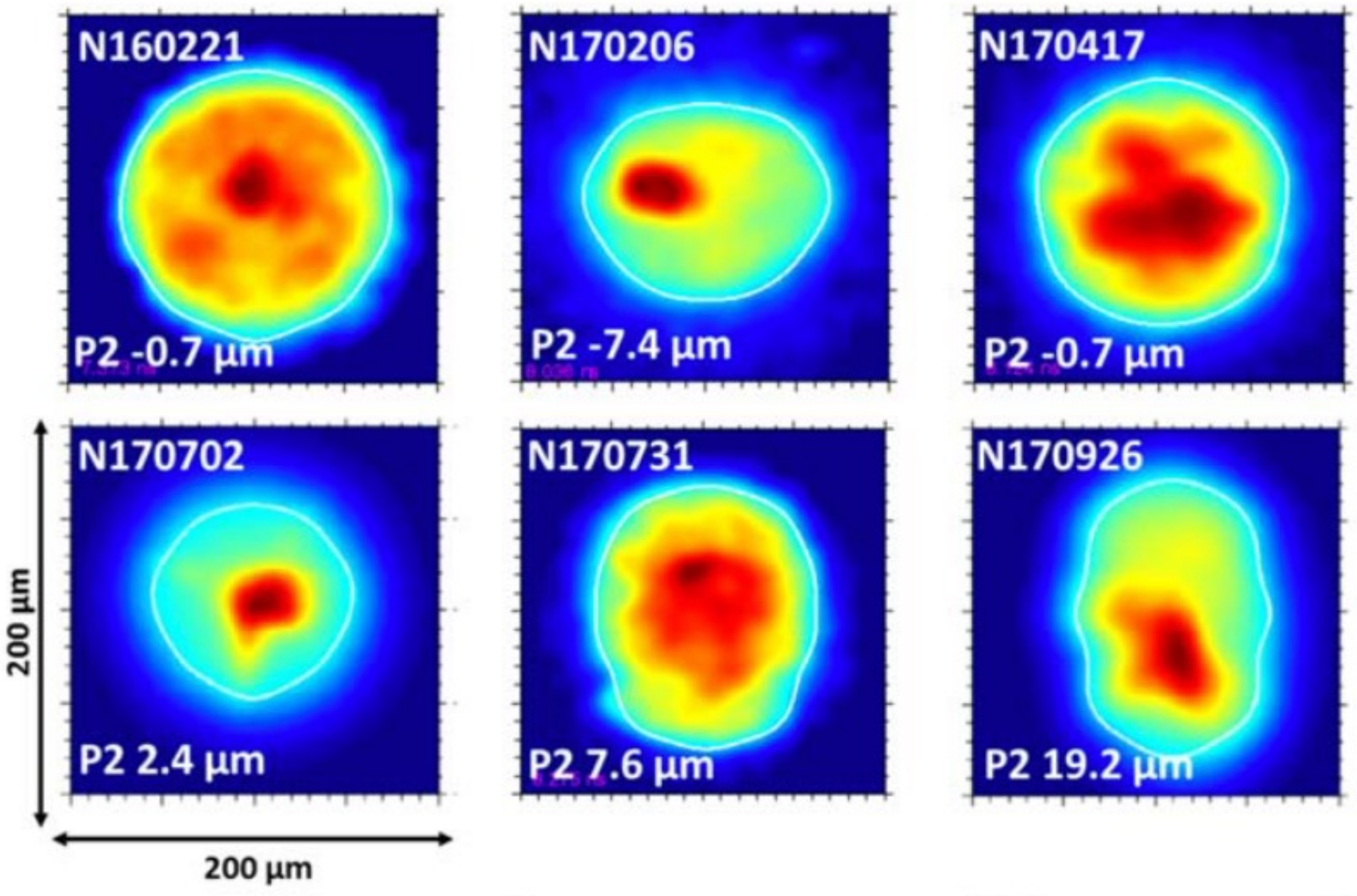
Optimizing T_i and ρR for given laser energy happens with good implosion symmetry



6 NIF shots

Equatorial x-ray images at “bang-time”

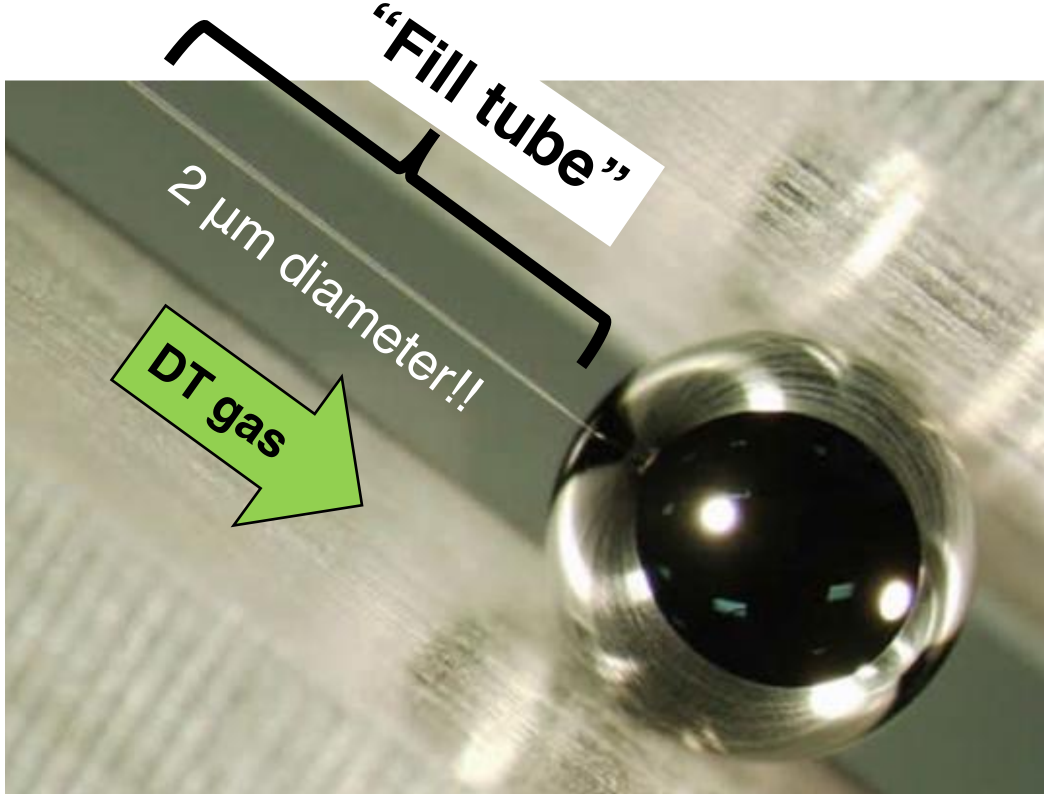
P2 indicates oval-ness

P2 = 0 → most circular

*Hopkins PPCF 2019

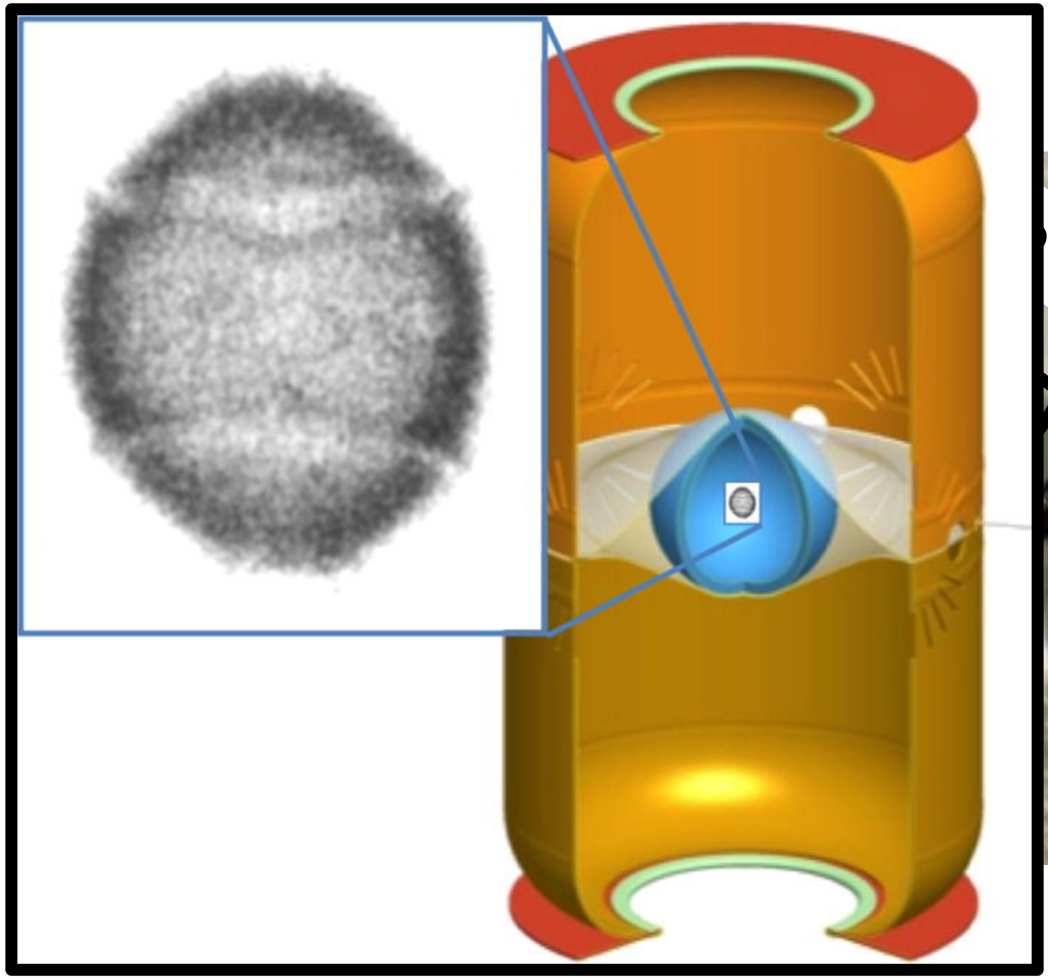
… even though ideal spherical symmetry is **impossible!**

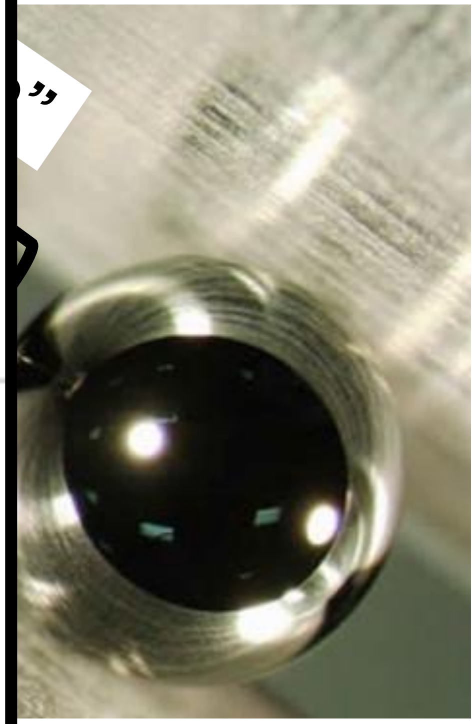
- Fill tube



… even though ideal spherical symmetry is **impossible!**

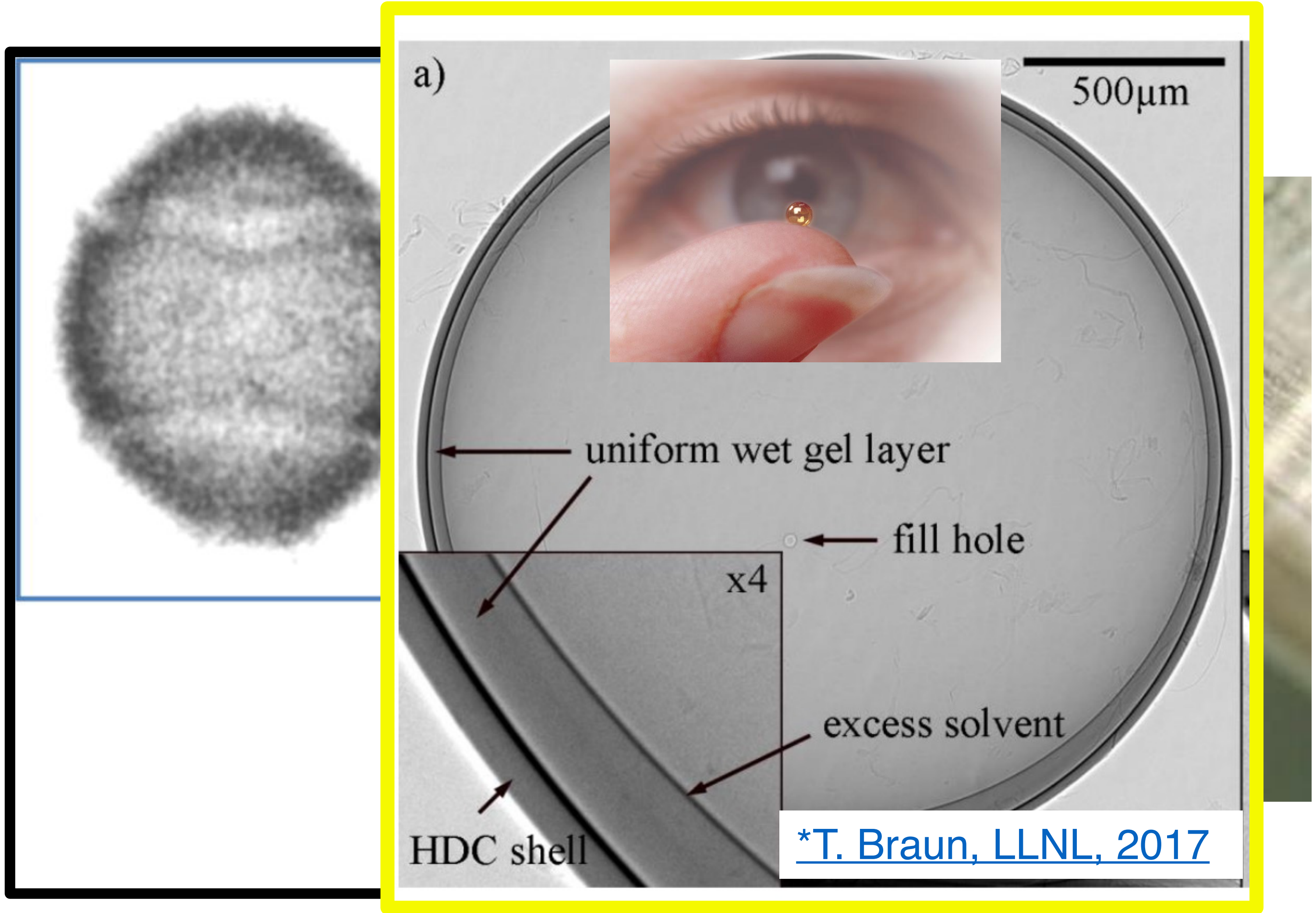
- Fill tube
- Capsule holder





… even though ideal spherical symmetry is **impossible!**

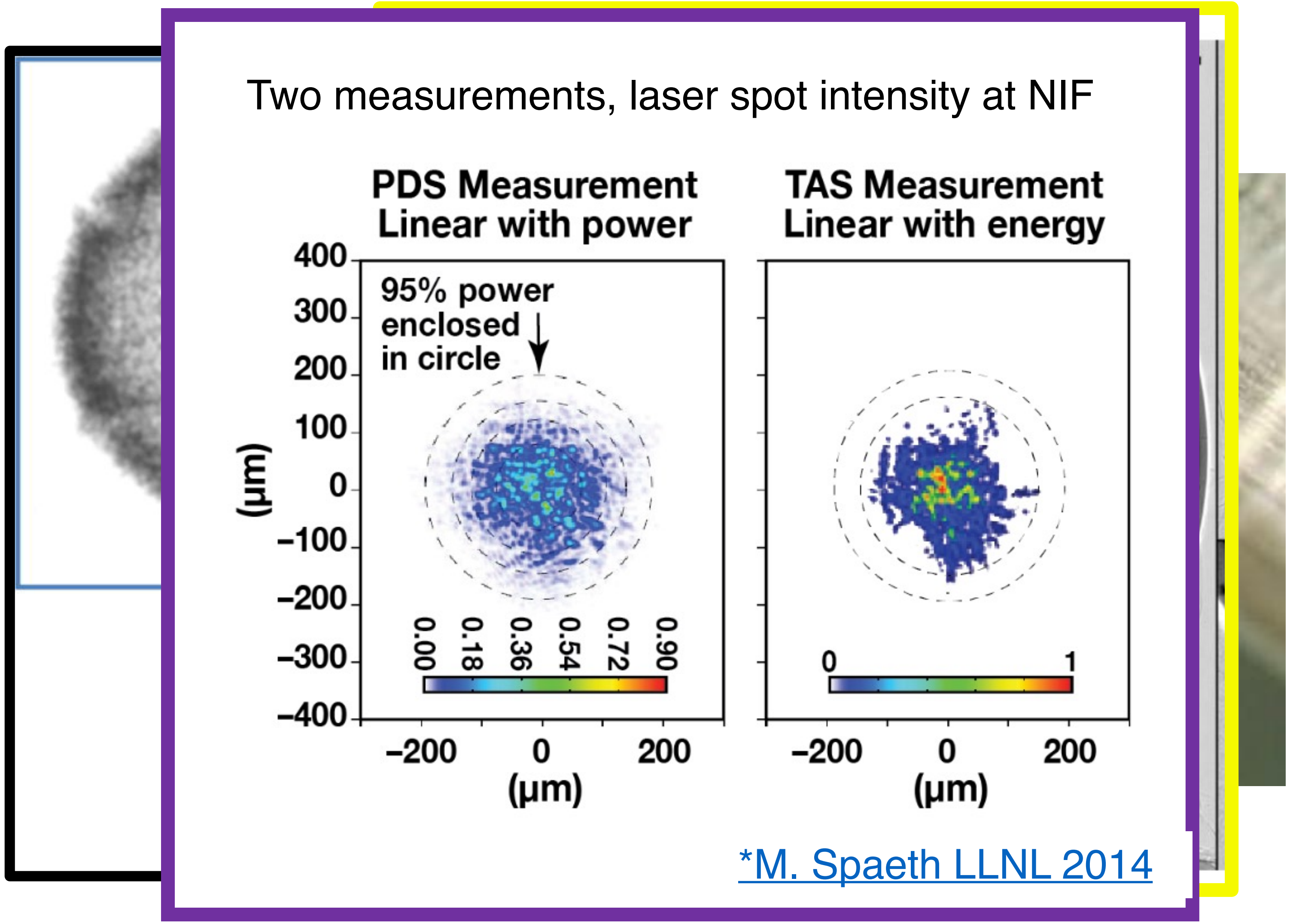
- Fill tube
- Capsule holder
- Roughness in shell



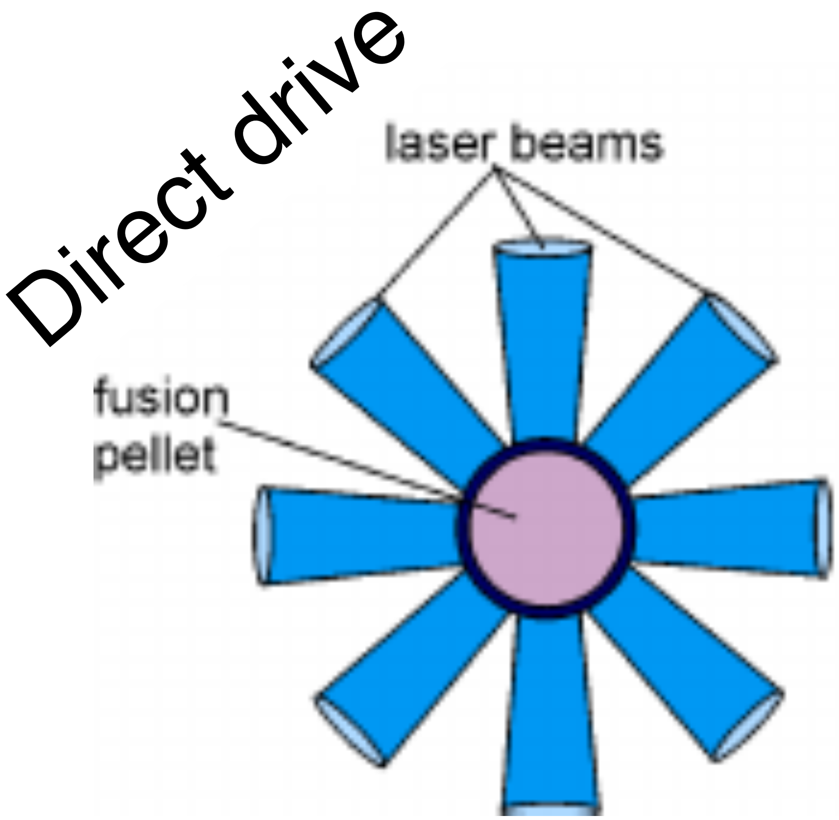
*T. Braun, LLNL, 2017

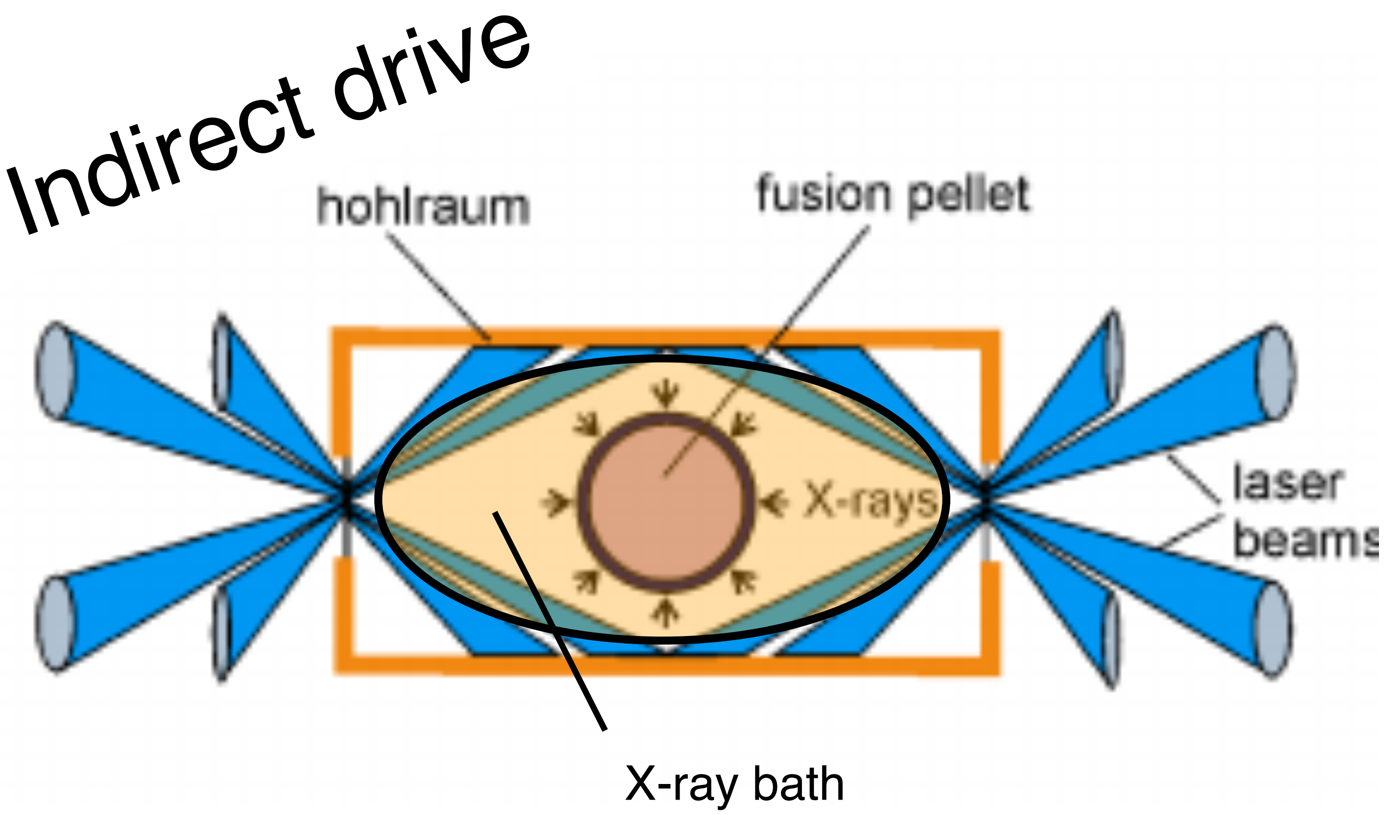
… even though ideal spherical symmetry is **impossible!**

- Fill tube
- Capsule holder
- Roughness in shell
- Non-uniform laser footprint



Different strategies for smoothing out nonuniformities: direct vs. indirect drive





*Badziak, Bulletin of Polish Acad. Sci. 2012

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When did ICF research begin? and codependence with laser technology

- **1957, Atoms for Peace:** idea of x-ray bath crushing pellet.. But how?
- **1972**: public announcement of concept-level ICF work at Lawrence Livermore
- **1980s**: Prototype beamlines at LLNL and Rochester's Lab. Laser Energetics
- **2009**: NIF, intended to demonstrate power-generating fusion, turns on
- **2021**: First convincing burn-ignited shot

1960:
Laser invented

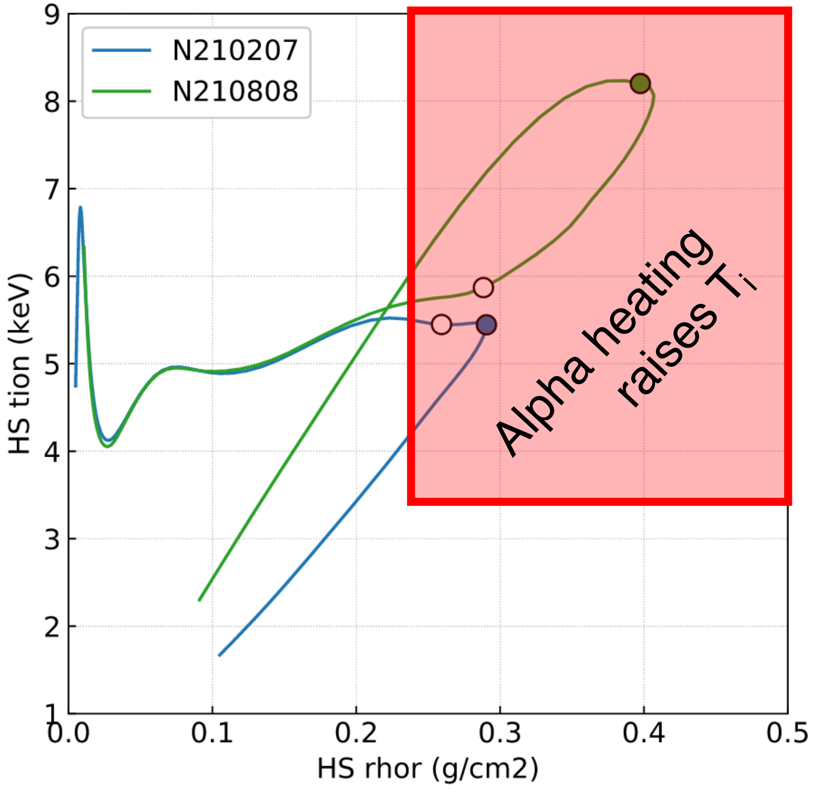
1985:
Short-pulse (ps, fs) lasers invented

2000s: better laser glass improves high-energy amplifiers

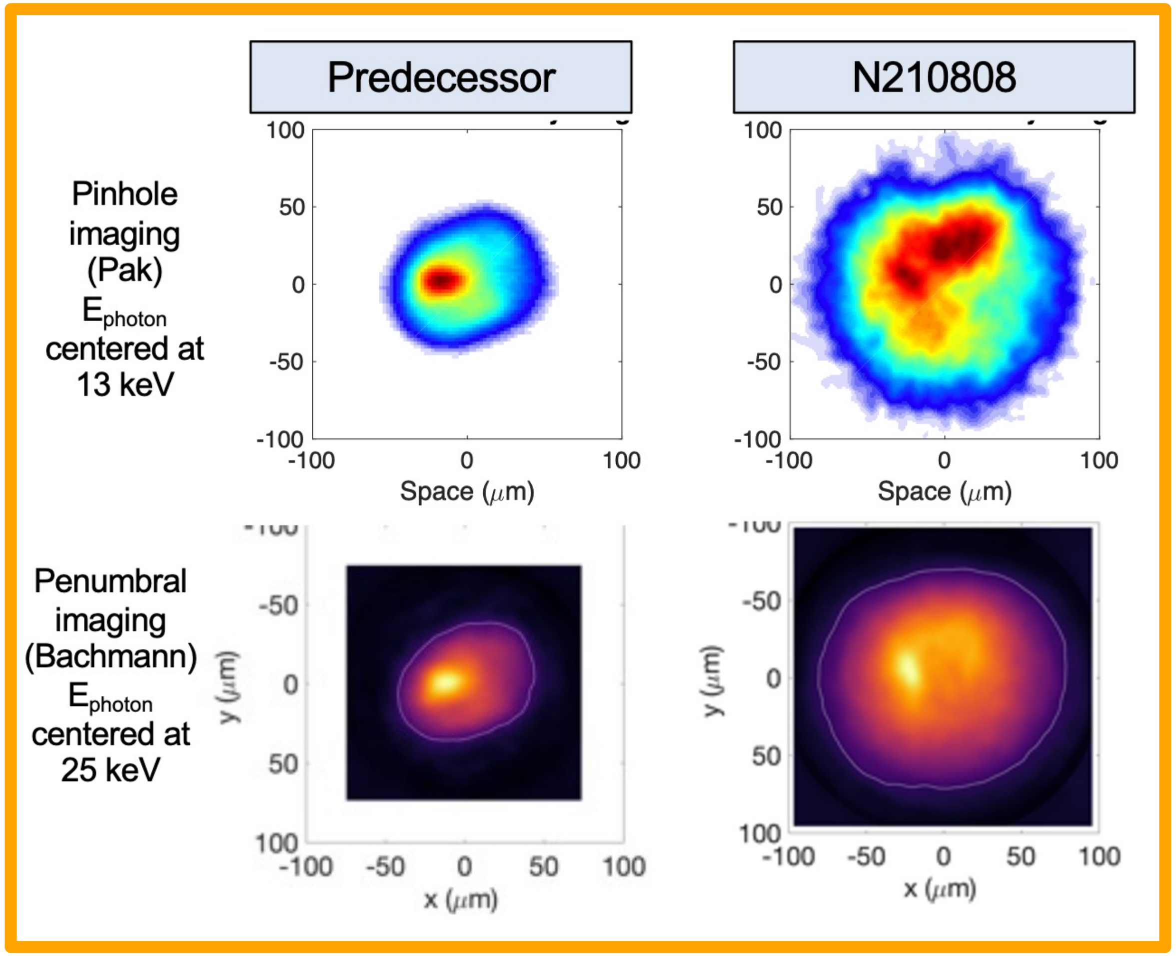
Recent: burning plasma at NIF!

X-rays

T_i



ρR

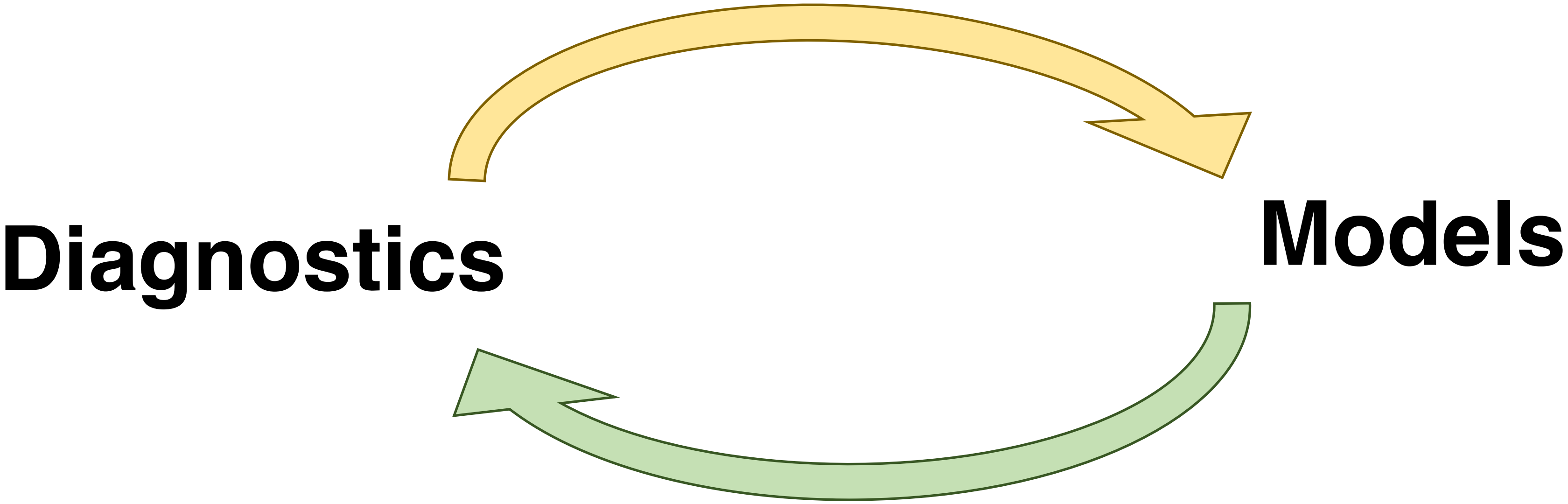


*Public talk from former NIF Director Mark Herrmann

How do we know how close we are?

Build knowledge of current capabilities and conditions

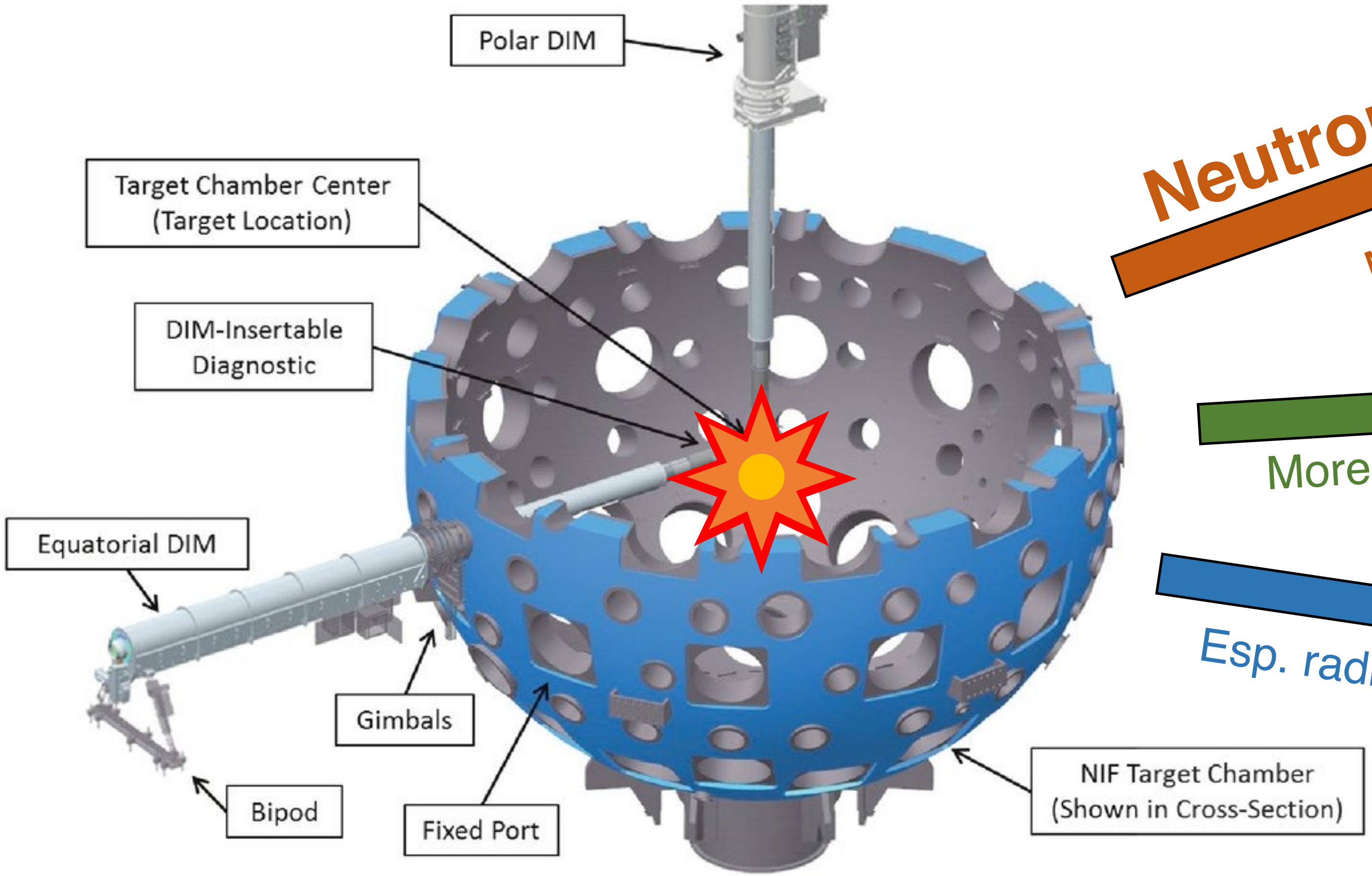
Tell models where they are wrong



Predict which experimental knobs will improve conditions

Extrapolate to future capabilities; what do we have to build to get fusion?

Diagnostic suites on ICF devices



Neutrons and fusion gammas

More with high DD or DT fusion

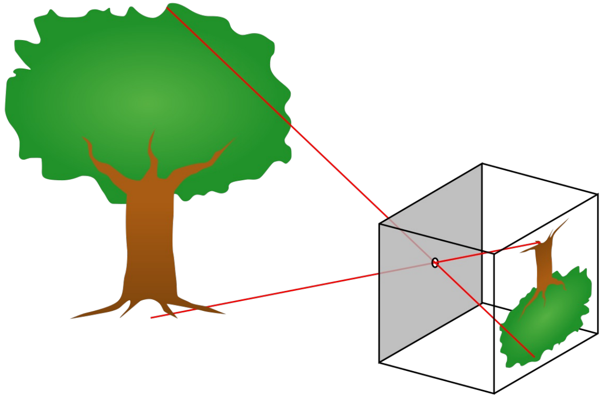
X-rays

More with hot plasma & high-Z material

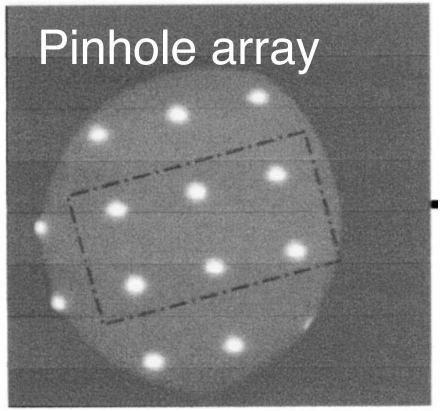
Protons

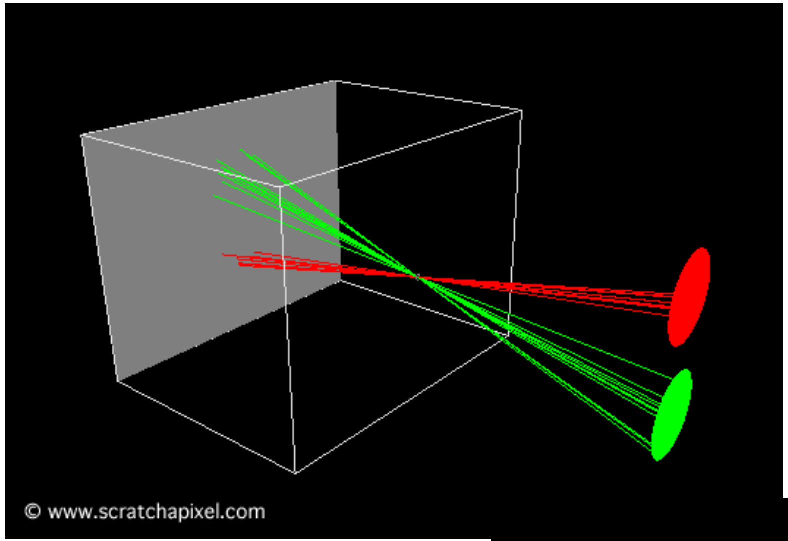
Esp. radiography, originating behind target

Simple imaging principles apply just as well to x-rays or neutrons



Principle of **pinhole** imaging



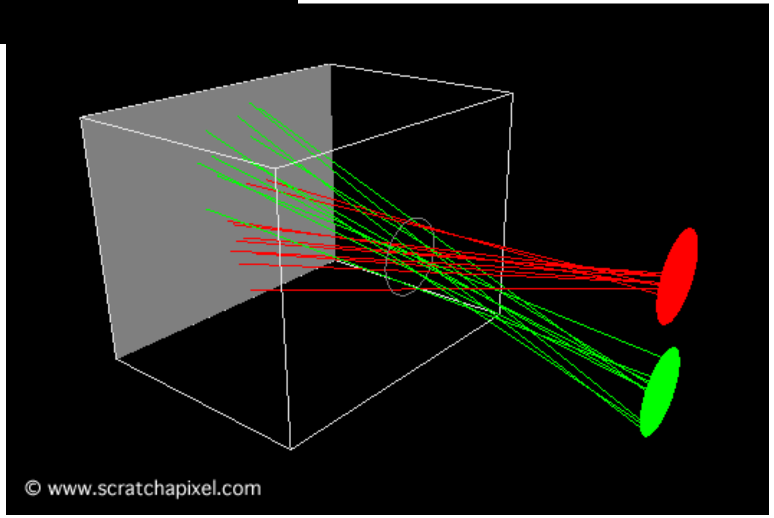


High-res
Less light

Low-res
More light

Small ⌀ ↑

Large ⌀ →

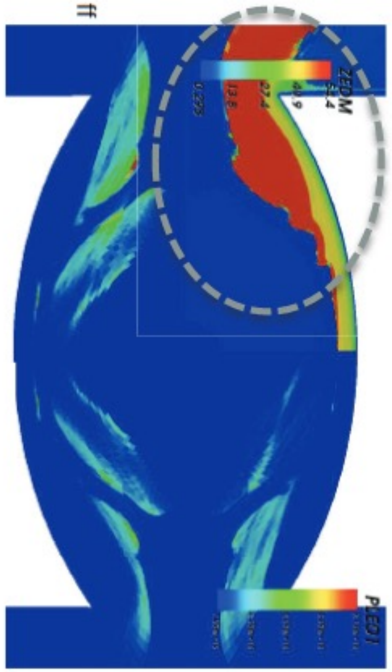


Pinhole size limits resolution

[*via scratchapixel.com](scratchapixel.com)

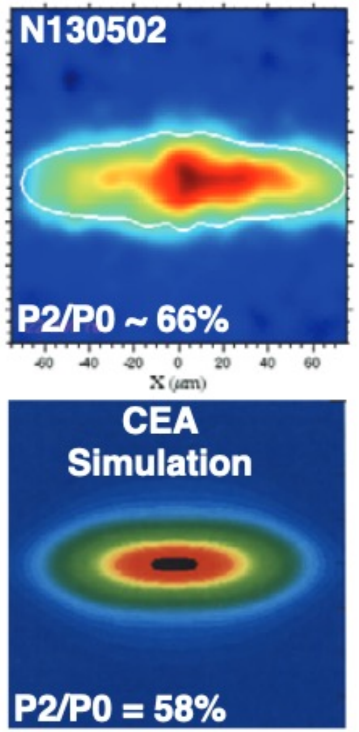
X-ray images can validate theory and indicate what affects symmetry

Au plasma from outer beams blocks inner beams in N130502

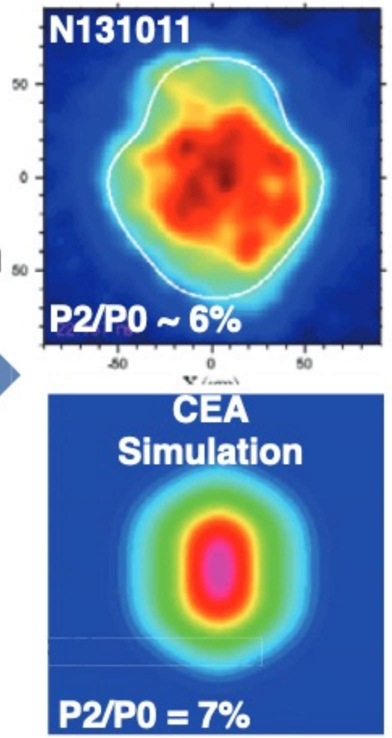


Oblate implosion

Equatorial x-ray images

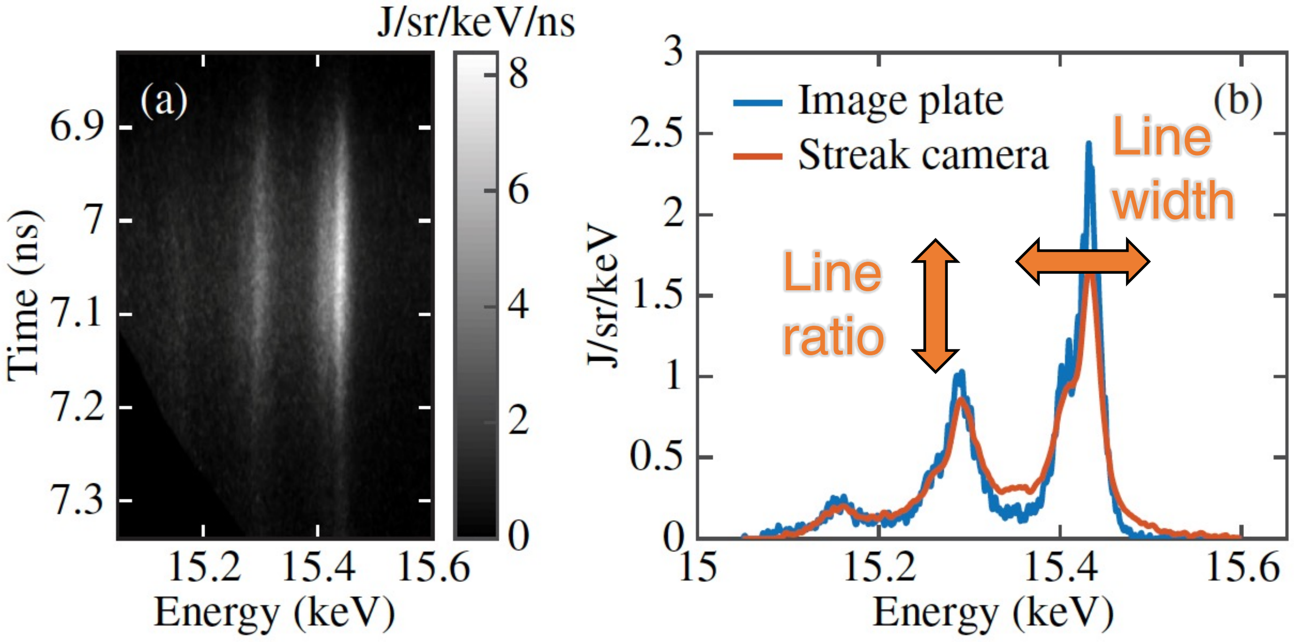


Solution: repoint outer beams 500 μm

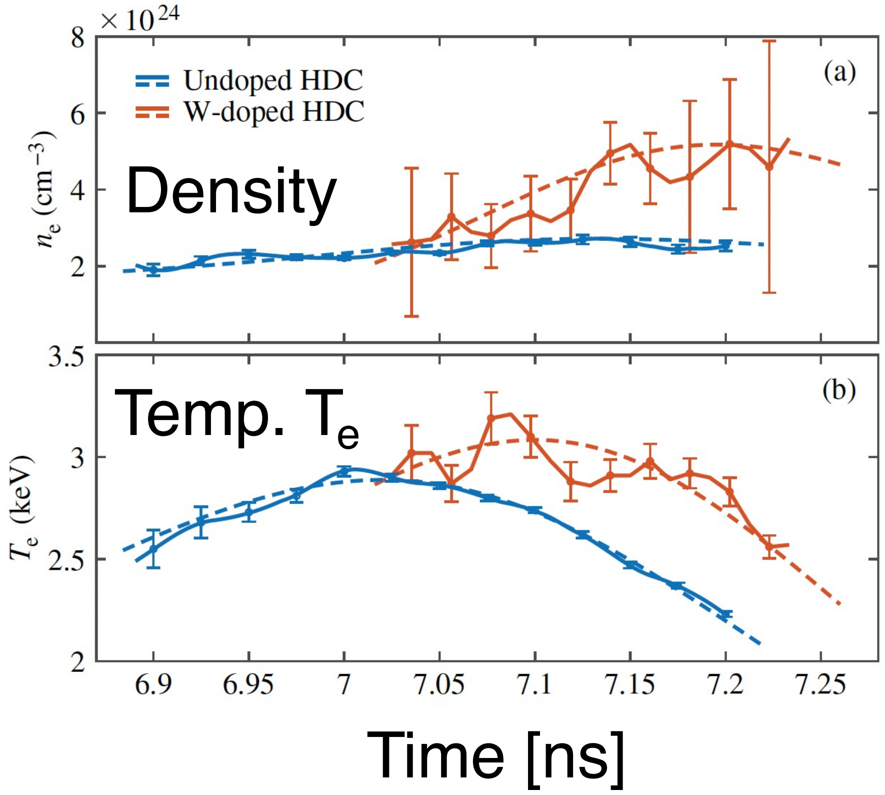


*Edwards J. Phys. Conf. 2016

X-ray spectroscopy resolves photons in energy to learn detailed plasma conditions

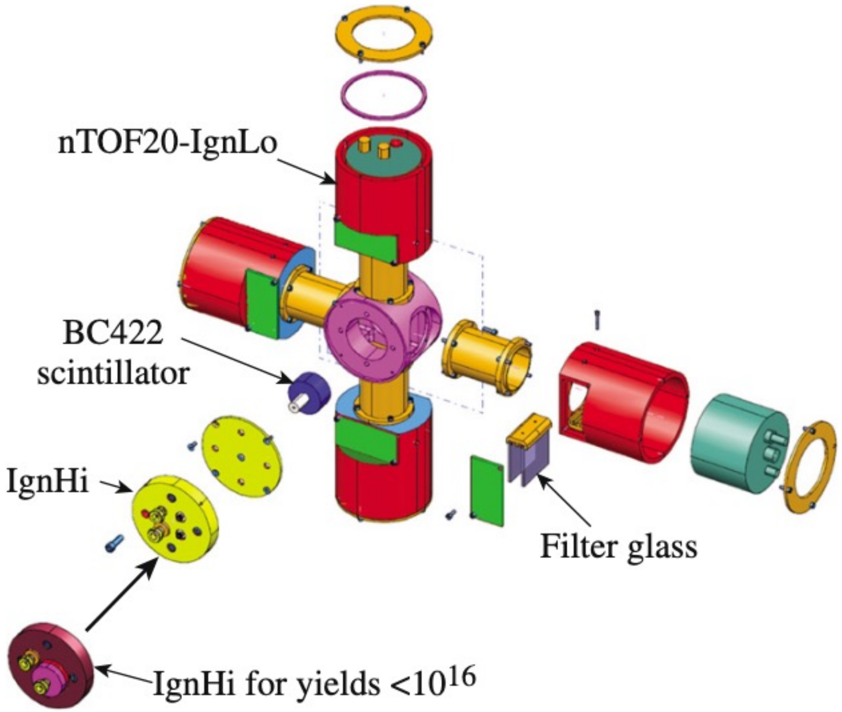


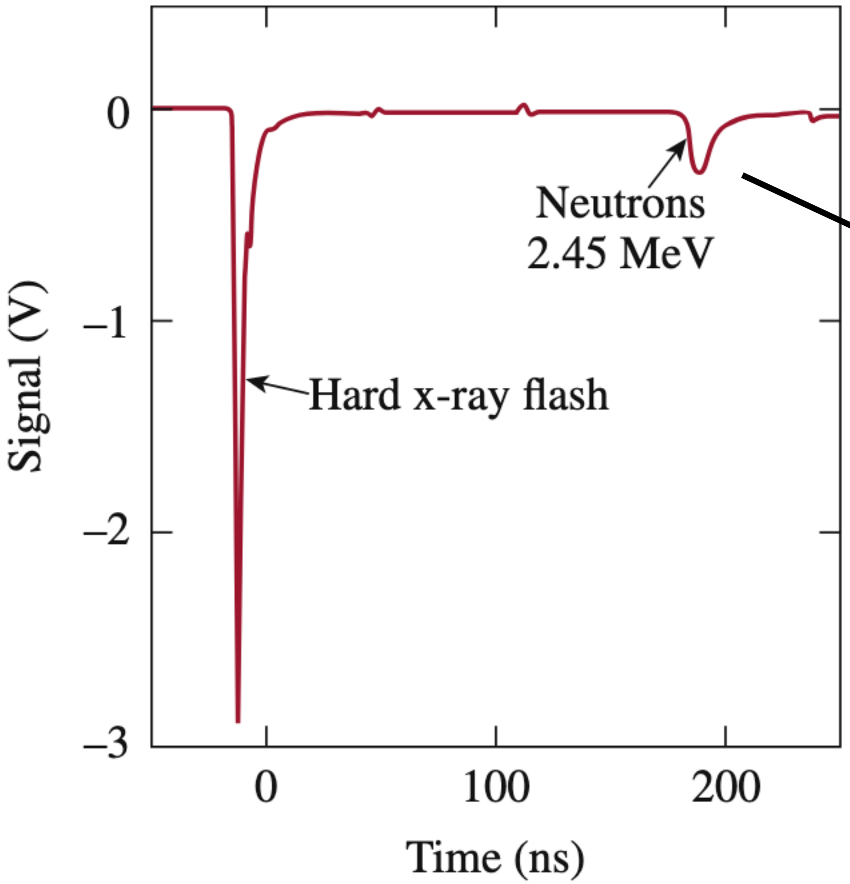
High-resolution x-ray lines from trace Kr in NIF implosion
Resolved in time!



*Gao PRL 2022

Neutron time-of-flight (nTOF) measures yield (#) and fusion-averaged T_i (width)



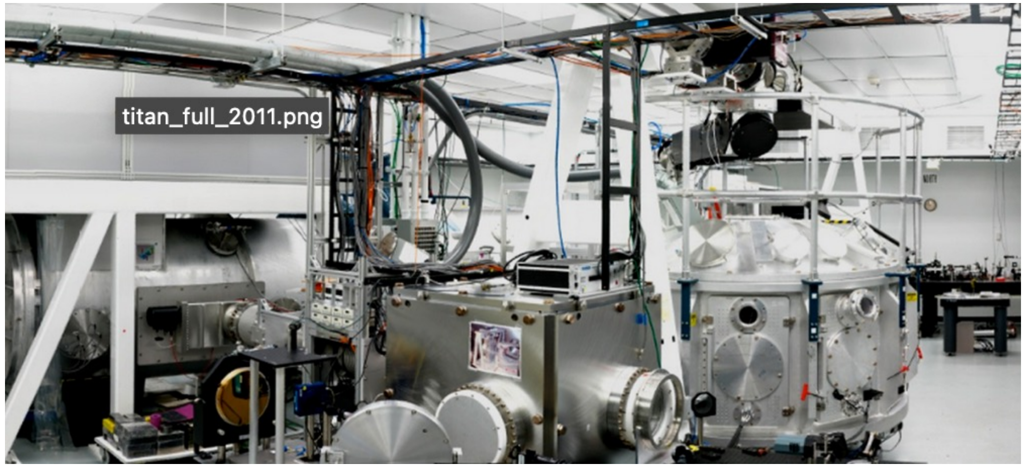


From D+D fusion reaction

*Glebov RSI 2010

Collaborations with short-pulse facilities develop diagnostics and physics for ICF

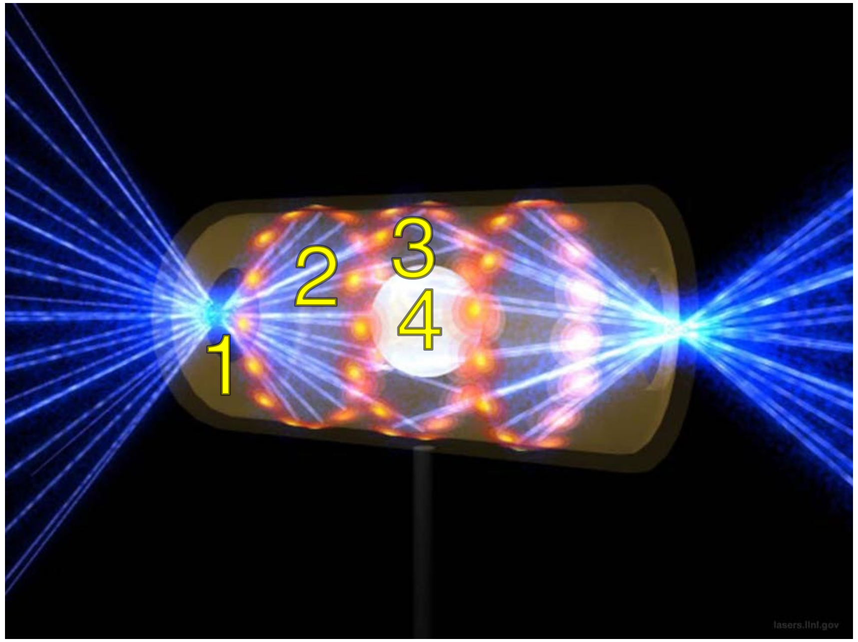
Titan laser @ Lawrence Livermore Nat'l Lab

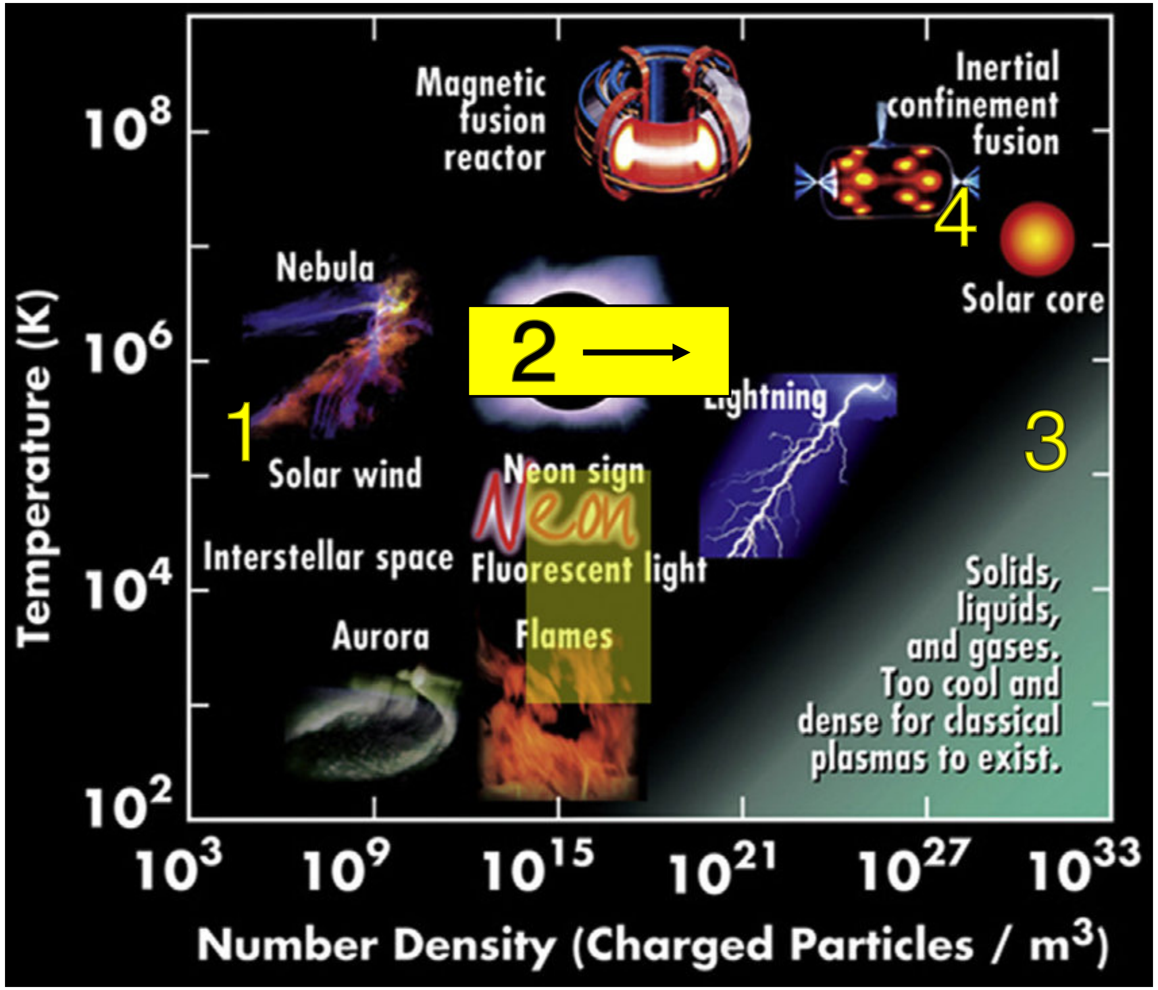


LaserNetUS

Experimental team @ Sophia Malko's proton stopping power experiment, ALEPH, Colo. State U.

Modeling, as usual, couples together many plasma regimes





1. Cross-beam instabilities, laser-plasma interactions
2. Ambient warm gold plasma
3. Ablation of shell and warm-dense ice interior
4. Hot spot with fusion-relevant conditions

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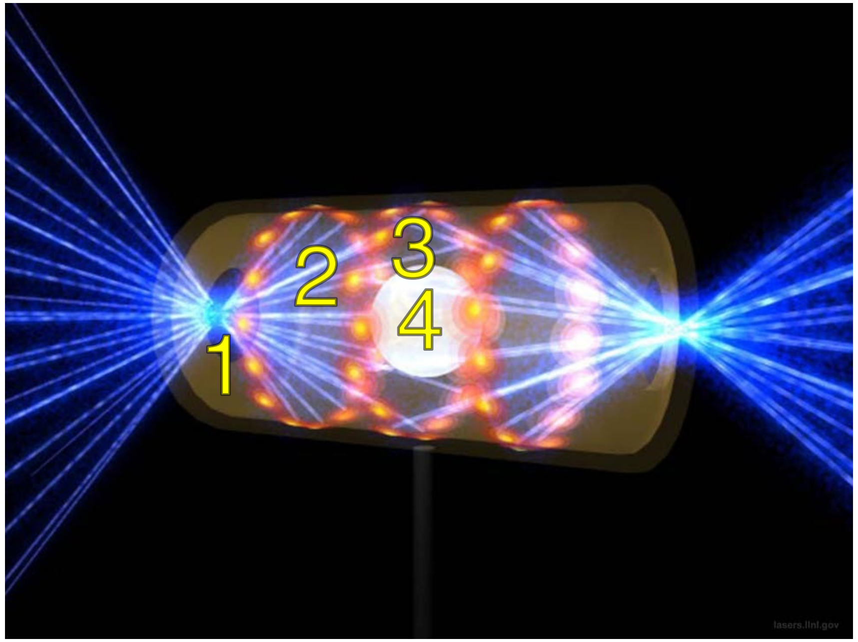
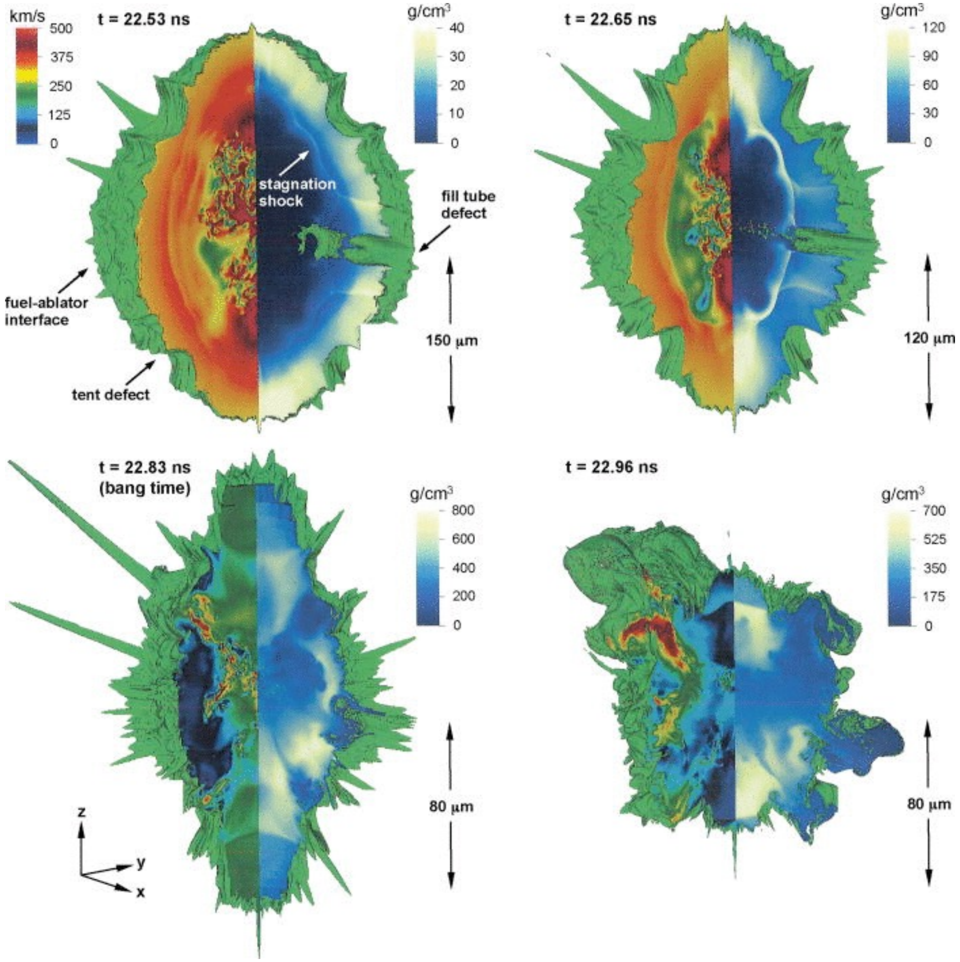


e.g., 4:



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*Clark Phys. Plasmas 2015

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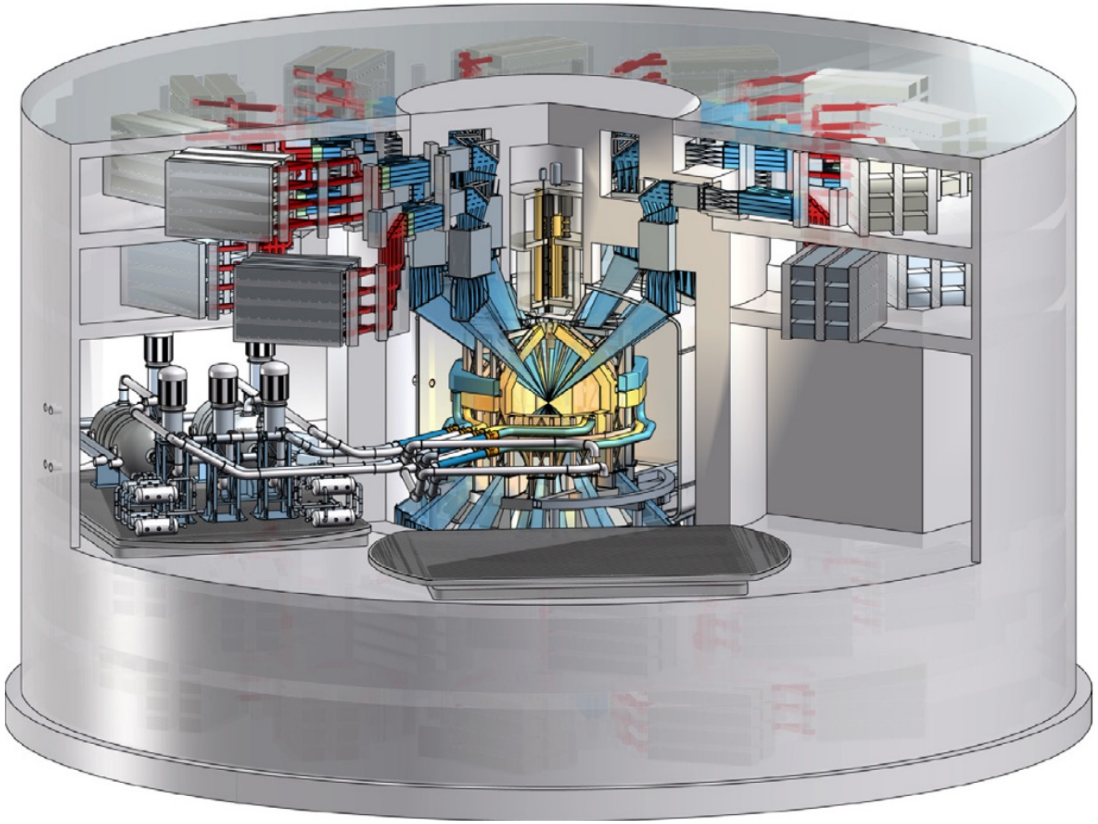
Who are the stakeholders in ICF research?

Why do they care about this program?

Obviously, ICF could be a path toward fusion for power plants and other applications



LIFE: Laser Inertial Fusion Energy

Market-entry plant: 2.2 MJ @ 8.3 Hz

First-gen commercial plants:
2.2 MJ @ 16.7 Hz

Chamber wall protected from x-rays and ions by thin Xe chamber fill

[*Meier Fusion Engineering and Design 2014]

But let’s be realistic about the challenges:

Radially pure pellet
pre-fills with DT

Pellet launched
(…inside co-launched
hohlraum???)

Lasers hit target exactly at
chamber midplane, ±5 µm?

Symmetric implosion of pellet

Hot-spot fusion pushes lucrative
burn wave through DT ice

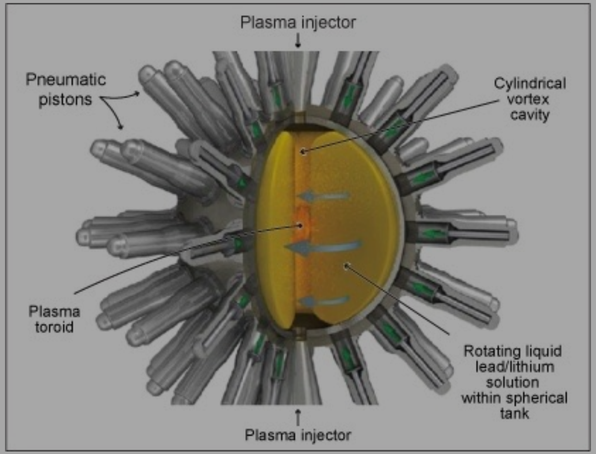
Neutrons, alphas (??) deposit
thermal energy in blanket

Power is harvested

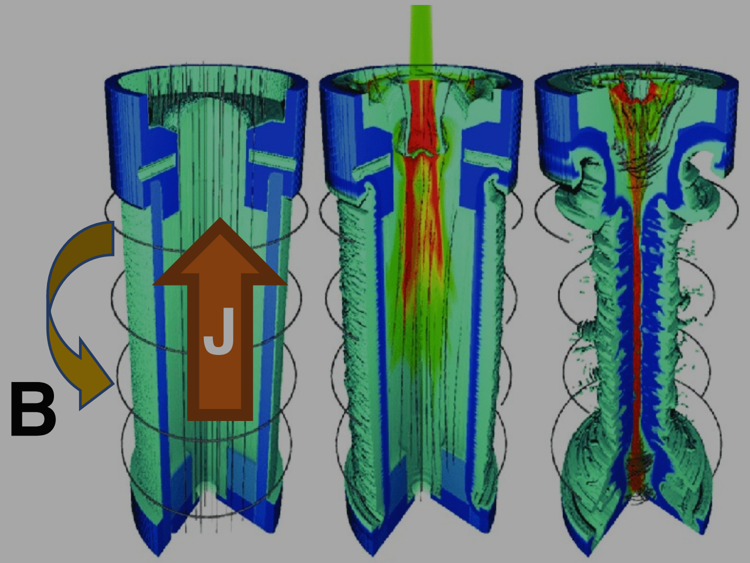
…. Wait 0.1 s?

Lasers charged to fire

So… I made a major omission saying “You can smash DT with many hammers”



General Fusion
Imploding lithium liquid



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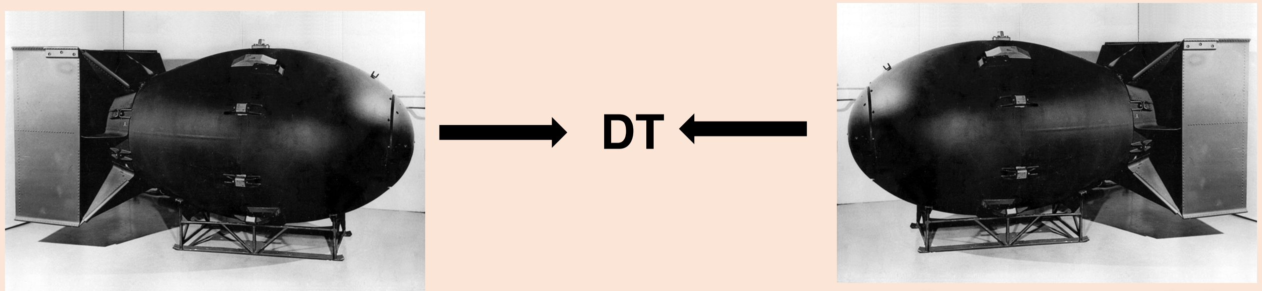
Nuclear Bombs !!!



The most powerful hammers yet engineered by mankind!

But not many bomb experiments happen these days…

1997: Clinton bans US explosions by signing Comprehensive Nuclear Test Ban Treaty

To environmentalists, peace advocates, most of humankind:

- Less research into weapons → less chance of devastating, nuclear war
- Reducing government arsenals reduces arms race pressures and need for military funding
- Stop dispersion of radioactive material into the environment

To physicists:

- Loss of an **experimental platform** for high-energy-density fusing material

(…. Of course, studying this platform directly fuels development of more efficient, powerful nuclear weapons)

But if US Dept. Defense, nuclear weapons agencies want to study high-density fusion,

"We need the strongest, most advanced nuclear arsenal on the planet"

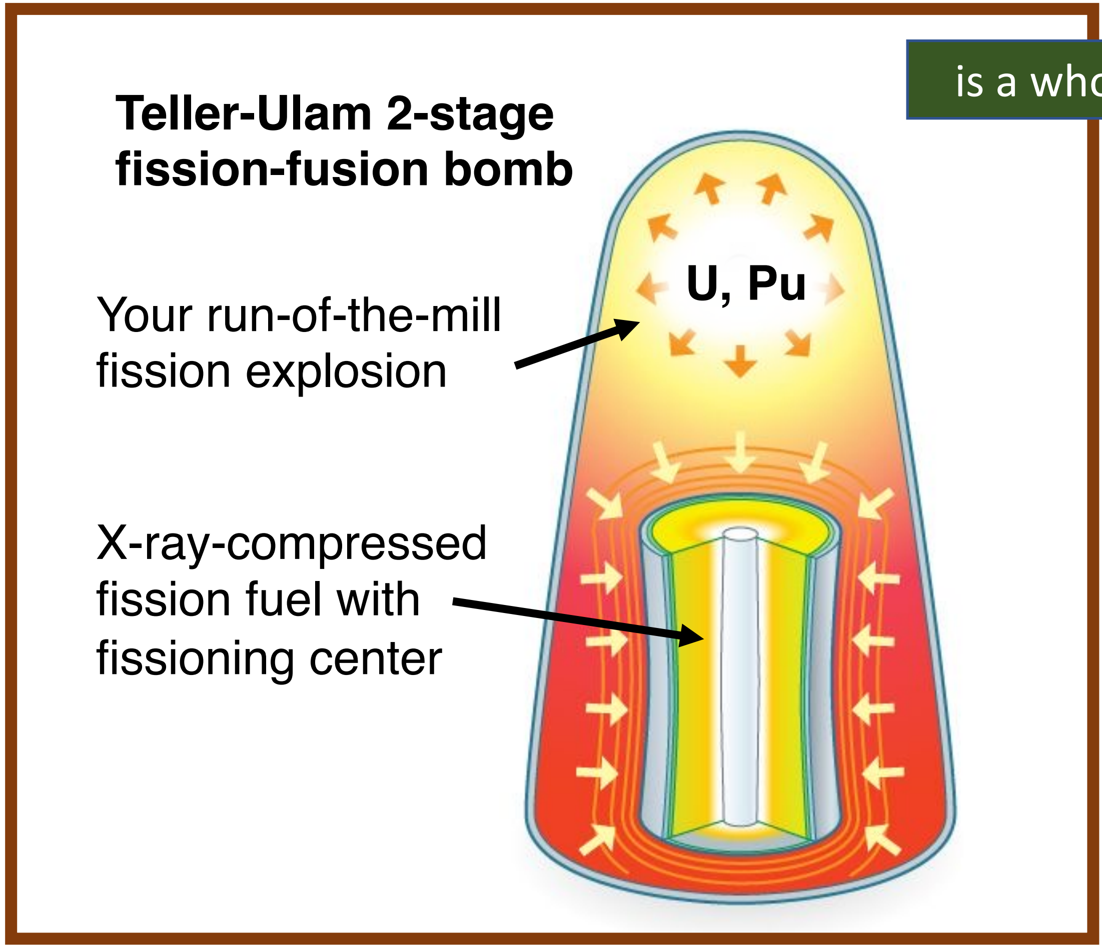
i.e., so that we can

- Assure general security of the nation
- Maintain safety (?) through mutually assured destruction
- Win arms races / not cede ground when Russia backs out of agreements
- Respond to threats from rogue nuclear states, e.g., North Korea, Iran

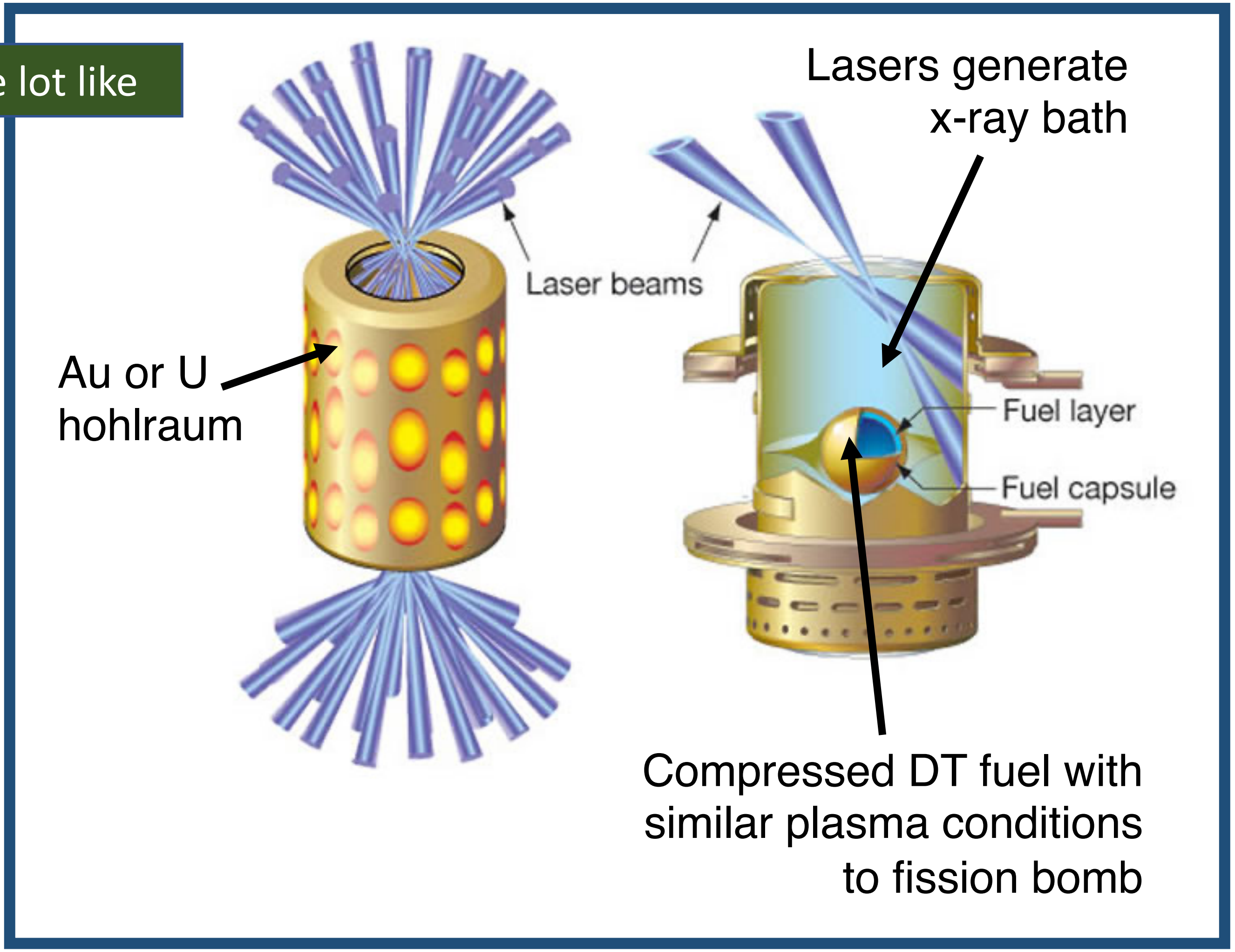
"But we can't test our newest fusion weapon designs" :(

Worry spreads: how can we maintain today's geopolitical hegemony ?? :(:(:(

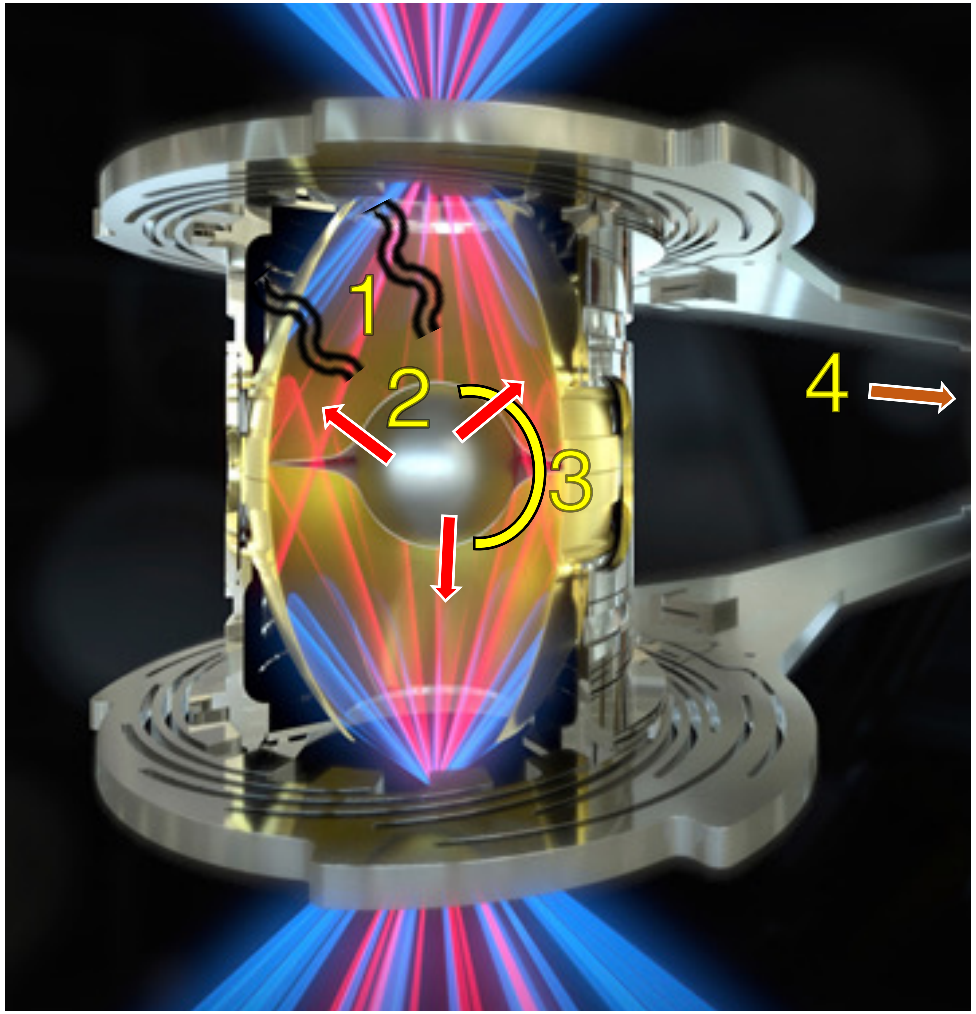
… they may benefit from compressing material in just the same way as in ICF



is a whole lot like



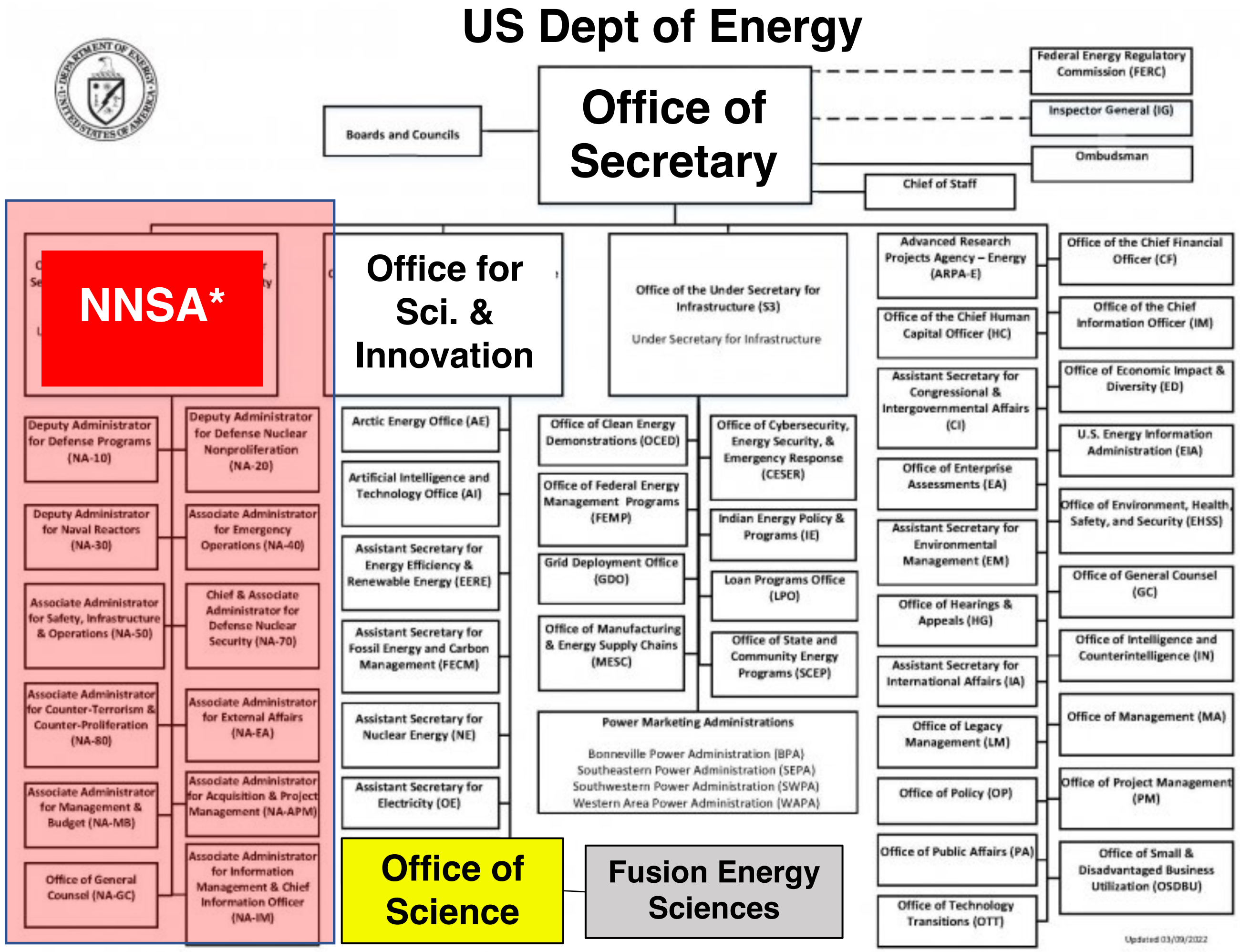
ICF diagnostics and modeling are of fundamental interest to the weapons program



Themes in common:

1. How does heat transport through dense, high-Z plasma?
2. How do alphas and neutrons slow down through solid-density DT?
3. How much axial/spherical symmetry is needed to effectively convert compression to thermal ion energy?
4. How can we engineer our devices (walls, holders, etc.) to withstand rapidfire bursts of radiation?

US Dept. of Energy (DoE) governs research around “stockpile stewardship”



***National Nuclear Security Administration**

In FY2020,

NNSA Funding
$2.4 billion: weapons R&D
$0.56 billion: inertial conf. fusion

Fusion Energy Sciences
$0.41 billion all together

Tangency to weapons programs makes high-density science inherently political

- Scientists often need information clearance
- Labs take extra care to avoid leaks and protect information
- ***Some*** information **will not be publishable** without omission of crucial elements
- For work on the highest-level programmatic ICF research in the U.S., citizenship is almost essential

(same in France, China, etc., for their respective programs)

Of course, there are many legitimate and powerful reasons to do these experiments!

Conditions of planetary interiors

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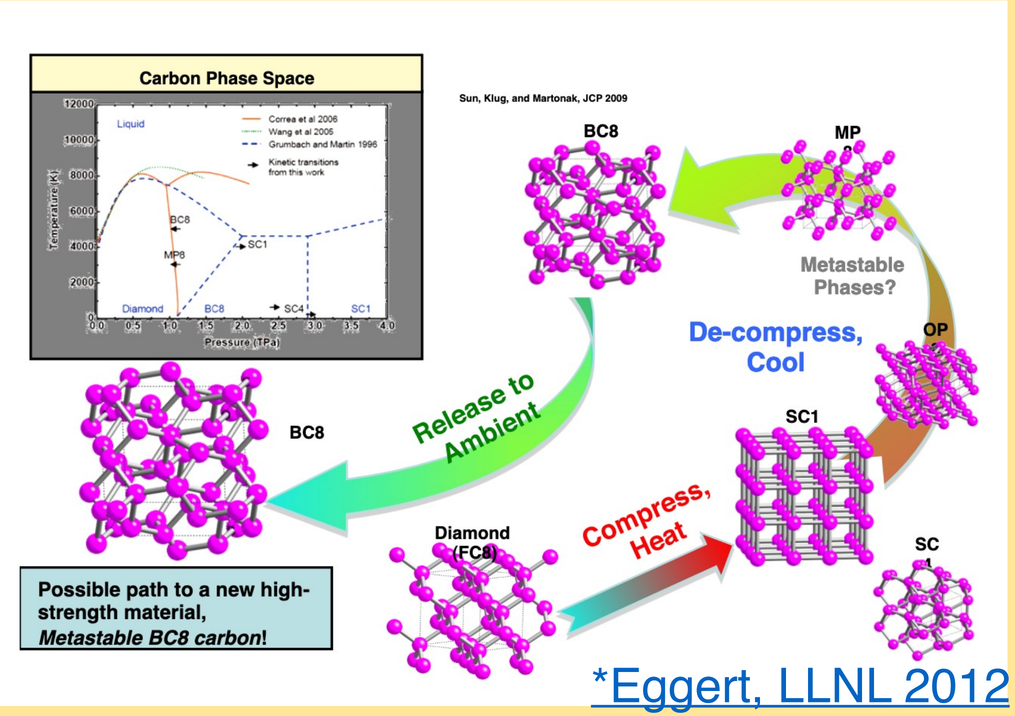
Conditions of planetary interiors

Condensed matter studies of materials at high pressures and densities



*Eggert, LLNL 2012

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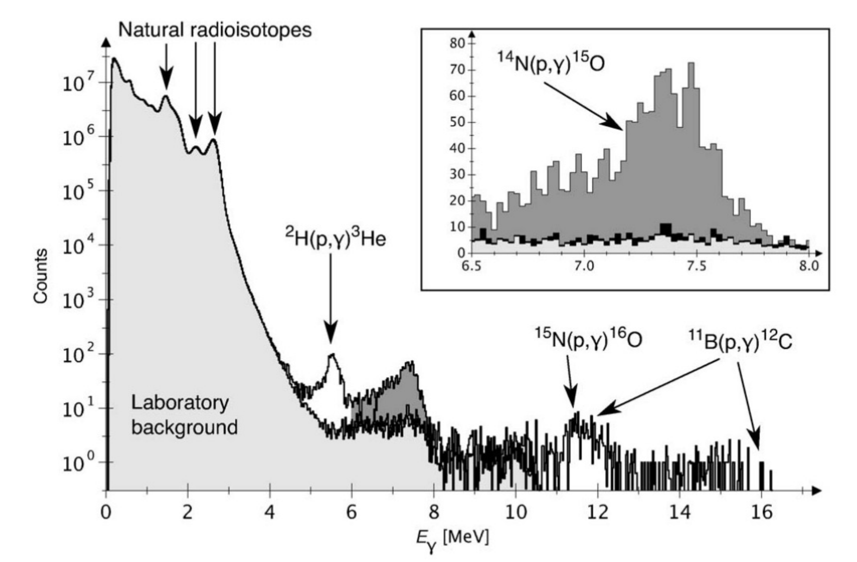
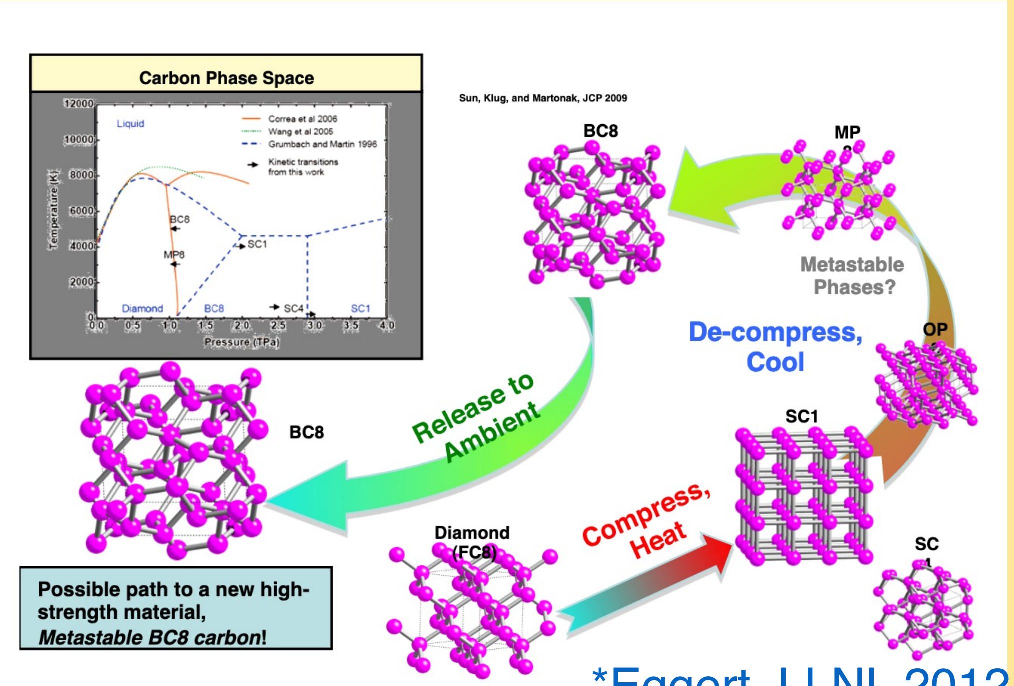
Conditions of planetary interiors

Opacity and nuclear cross section measurements relevant to the solar lifetime



[*Lemut, Phys. Lett. B 2006]

Condensed matter studies of materials at high pressures and densities



[*Eggert, LLNL 2012]

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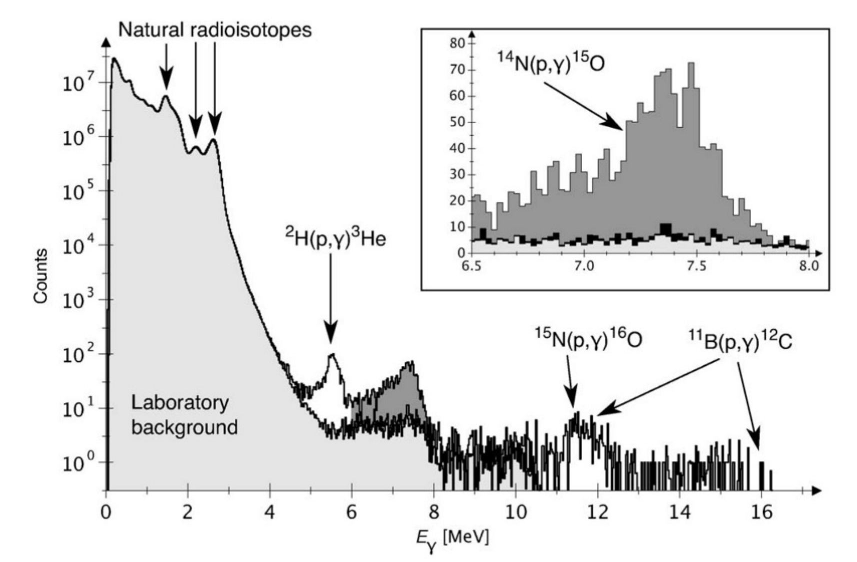

*Lemut, Phys. L... 2006

Test theories of highly coupled quantum fluids

The DFT program produces the Kohn-Sham orbitals ψ_i and associated eigenenergies ε_i, from which we determine both the electrical and thermal conduction properties from a Chester-Tellung-Kubo-Greenwood formulation[12] by calculating various frequency-dependent Onsager kinetic coefficients L_{nm} using the basic form[11,13]

$$L_{nm}(\omega) = (-1)^{n+m}\frac{2\pi e^2 h^2}{\Omega m^2}\sum_{i,j}(\varepsilon_i-\mu)^{n-1}(\varepsilon_i-\mu)^{m-1} \times F_{ij}(\omega)|D_ij|^2\delta(\varepsilon_j-\varepsilon_i-h\omega),$$

*Hanson Phys. Plasmas 2011

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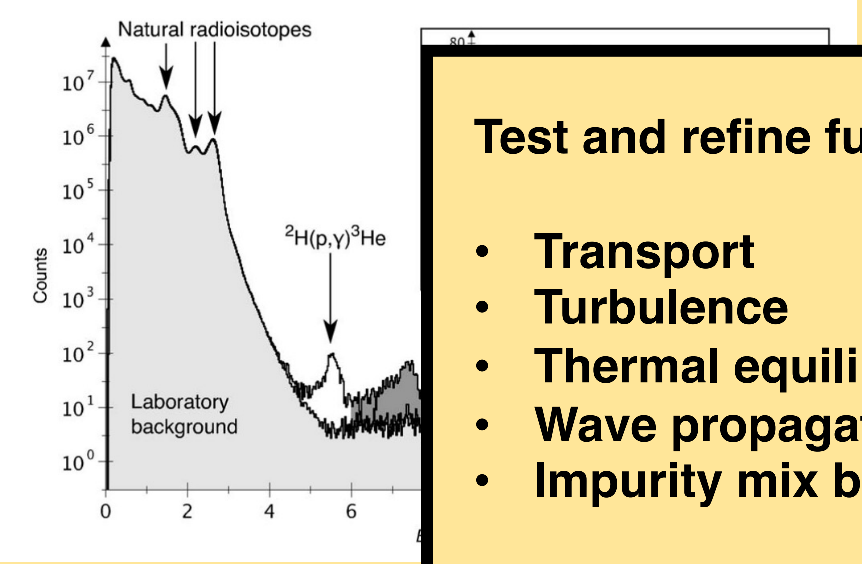

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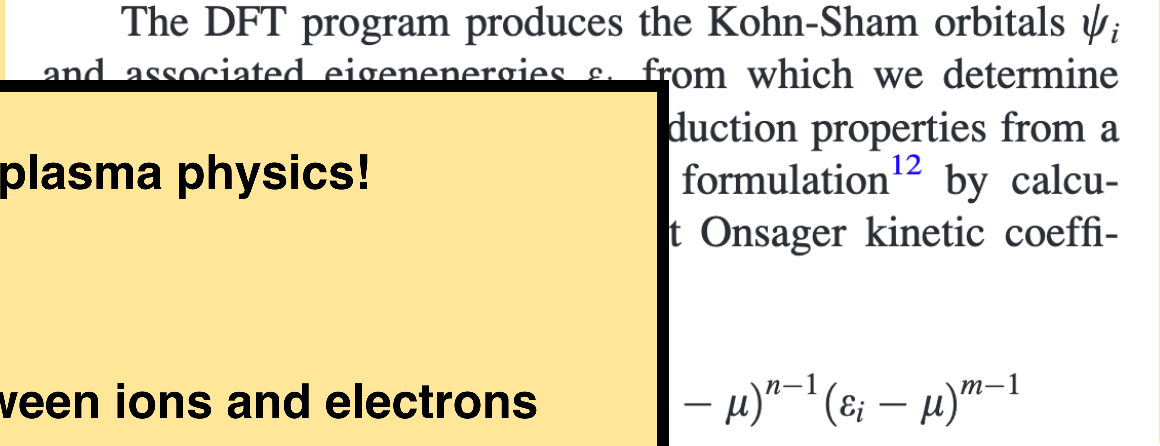
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$$-\mu)^{n-1}(\varepsilon_i - \mu)^{m-1}$$

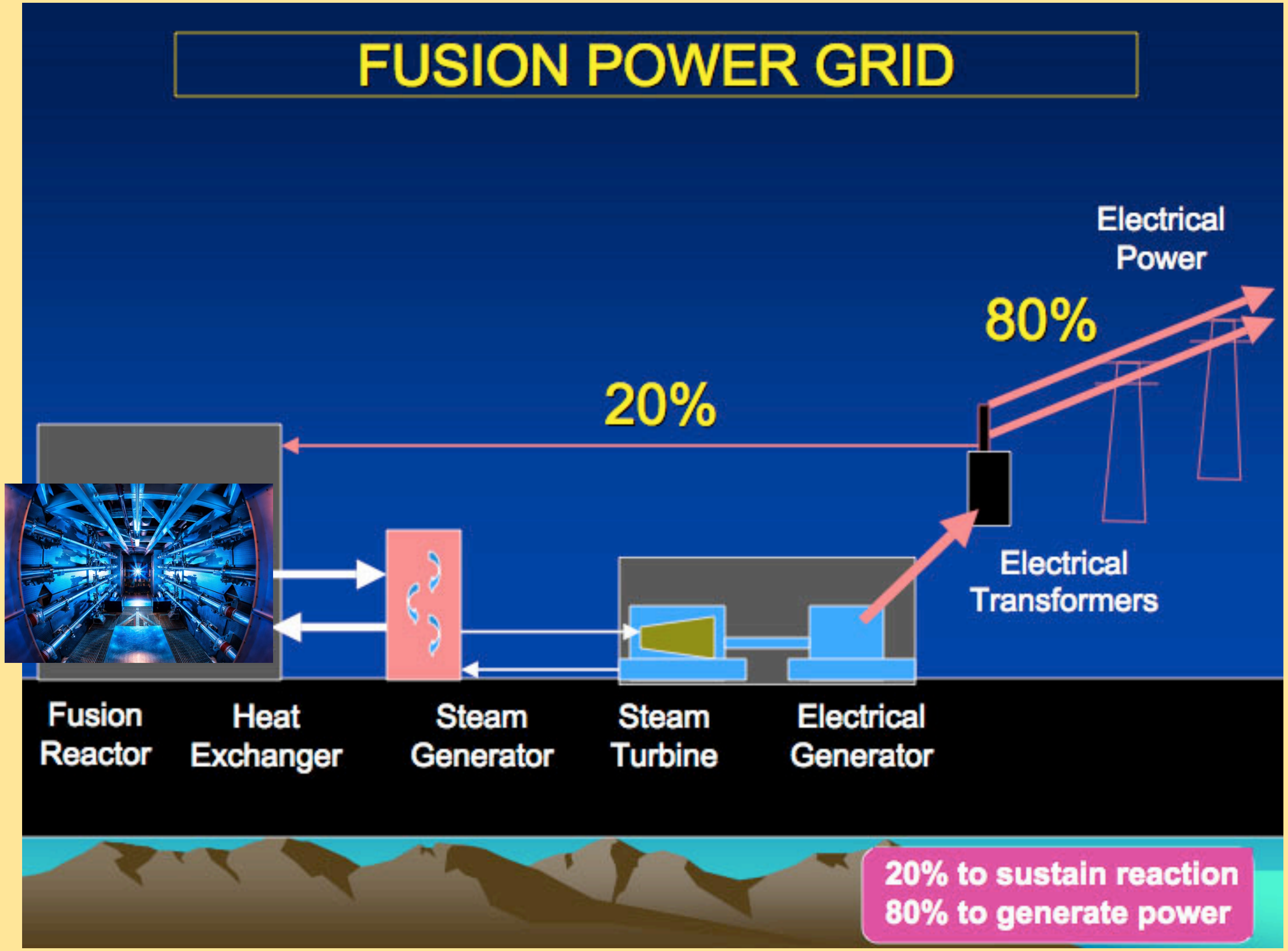
$$-\hbar\omega),$$

[*Hanson Phys. Plasmas 2011](#)

Test and refine fundamental plasma physics!

- **Transport**
- **Turbulence**
- **Thermal equilibration between ions and electrons**
- **Wave propagation**
- **Impurity mix between boundary regions**

Of course, there are many legitimate and powerful reasons to do these experiments!



And, obviously, for the prospect of boundless fusion power!

Many scientists & external players are gaining confidence: ICF could generate net power

LIVESCIENCE

Fusion experiment breaks record, 10 quadrillion watts of power

By Tom Metcalfe published August 18, 2021

Nature

Burning plasma achieved in inertial fusion

In the impulsive case of inertial confinement fusion (ICF), Qα can be stated either as a power during burn, or as an

Jan 26, 2022

the business of photonics

optics.org

Ex-pro baseball star Alex Rodriguez takes part in $15M funding round for startup Focused Energy.

- Lasers are getting more efficient
- Success is exponential: ignited DT fuel ignites deeper into ice
- As with all other methods of confinement, one more generation of investment (e.g., beyond NIF) may be necessary to show real, power-relevant ICF

Speaking of engineering challenges, i.e., doing the impossible…

Radially pure pellet pre-fills with DT

Pellet launched (…inside co-launched hohlraum???)

Lasers charged to fire

…. Wait 0.1 s?

Lasers hit target exactly at chamber midplane, ±5 μm?

Power is harvested

Symmetric implosion of pellet

Neutrons, alphas (??) deposit thermal energy in blanket

Hot-spot fusion pushes lucrative burn wave through DT ice

EUV lithography with laser-ionized Sn droplets

Melted tin droplet enters chamber

Laser hits droplet to make plasma

Plasma emits 13.5 nm line emission

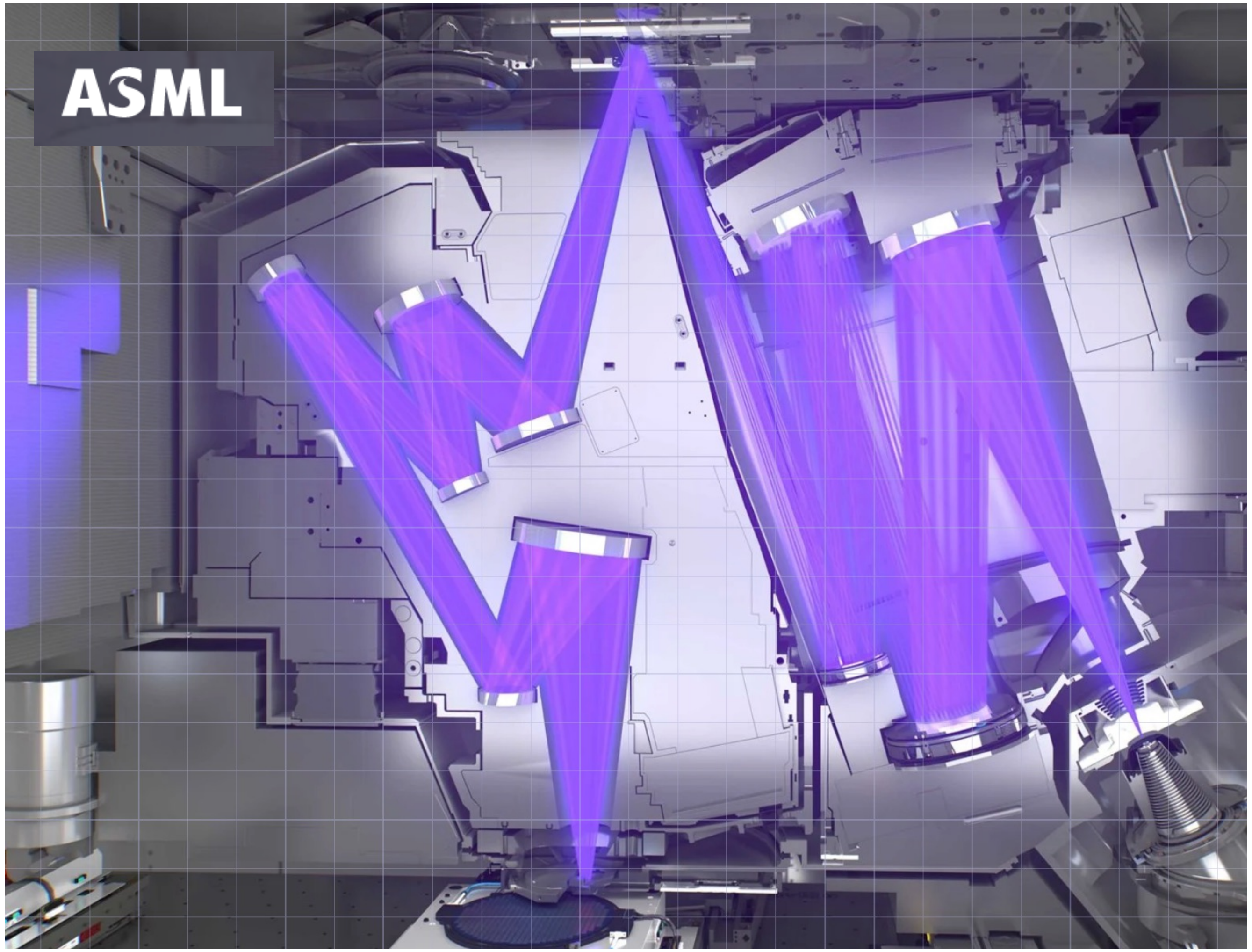
Line emission is collected by many inefficient mirrors …

… and focused onto a microchip!

50 kHz repetition rate

\$200-\$400 million each x 140 sold so far
(28 billion ~ 47 years of US fusion funding)

Commercialized thanks to \$\$\$\$ in the electronics industry



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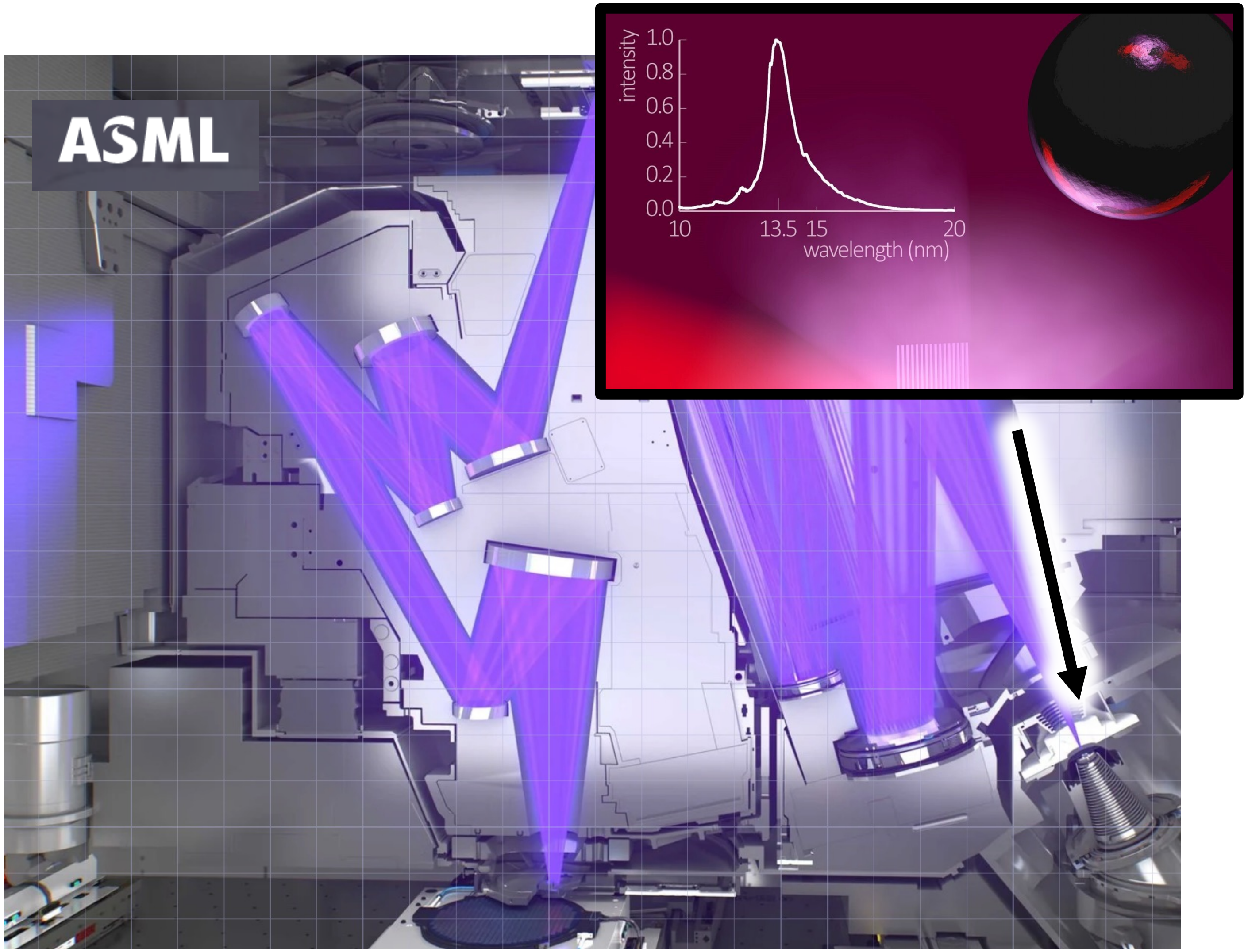

* Torretti, Nature Comm. 2020

Summary, or
Q's you may be able to answer now

- **What** is fusion? → What is **inertial confinement**?
- **How** do we get ICF to work?
- **When** are we going to get there? How do we know?
- **Who** is supporting ICF research and **why**?

Please reach out if you like: bkraus – at – pppl.gov