# Present understanding of ignition and Gain using indirect-drive inertial confinement fusion target designs on the U.S. National Ignition Facility

Omar A. Hurricane, Chief Scientist, ICF Indirect-Drive Collaboration

NIF/JLF Users Group

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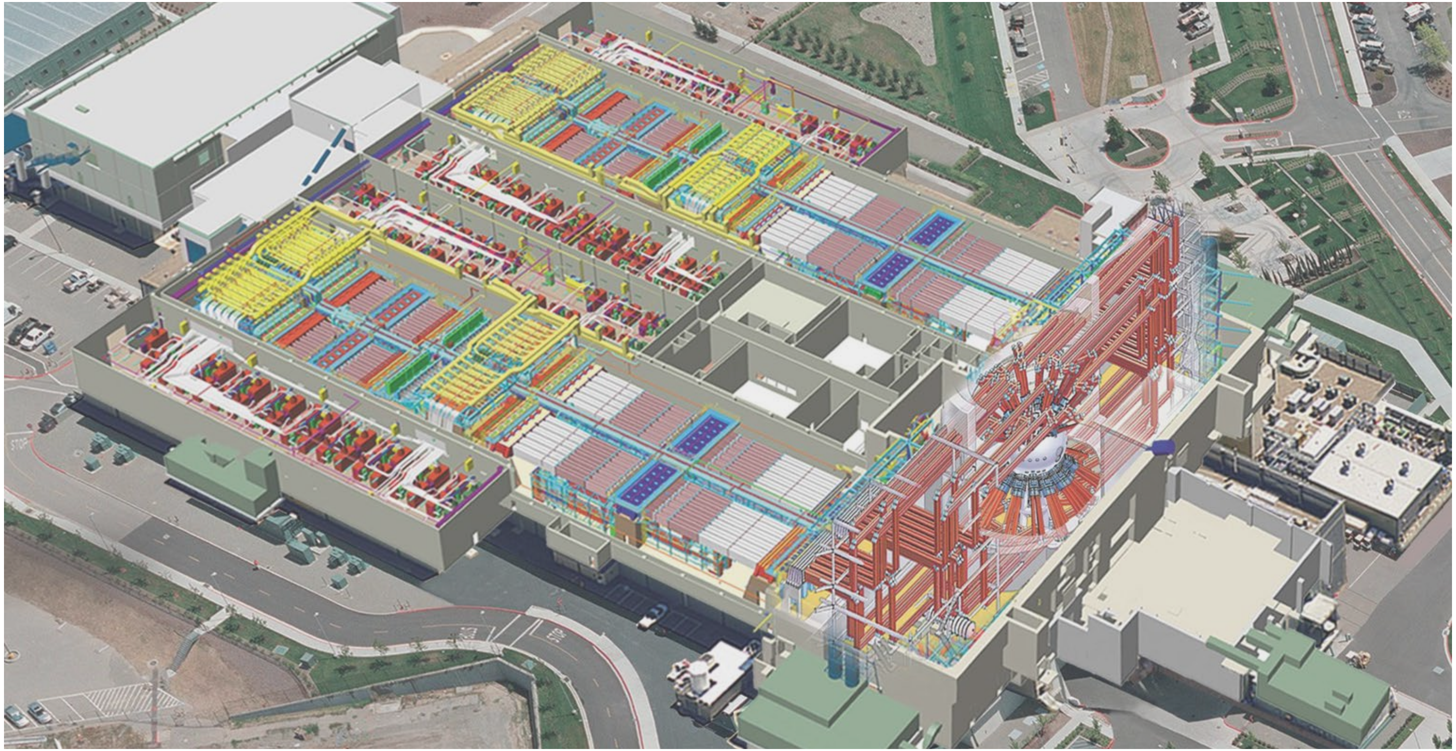
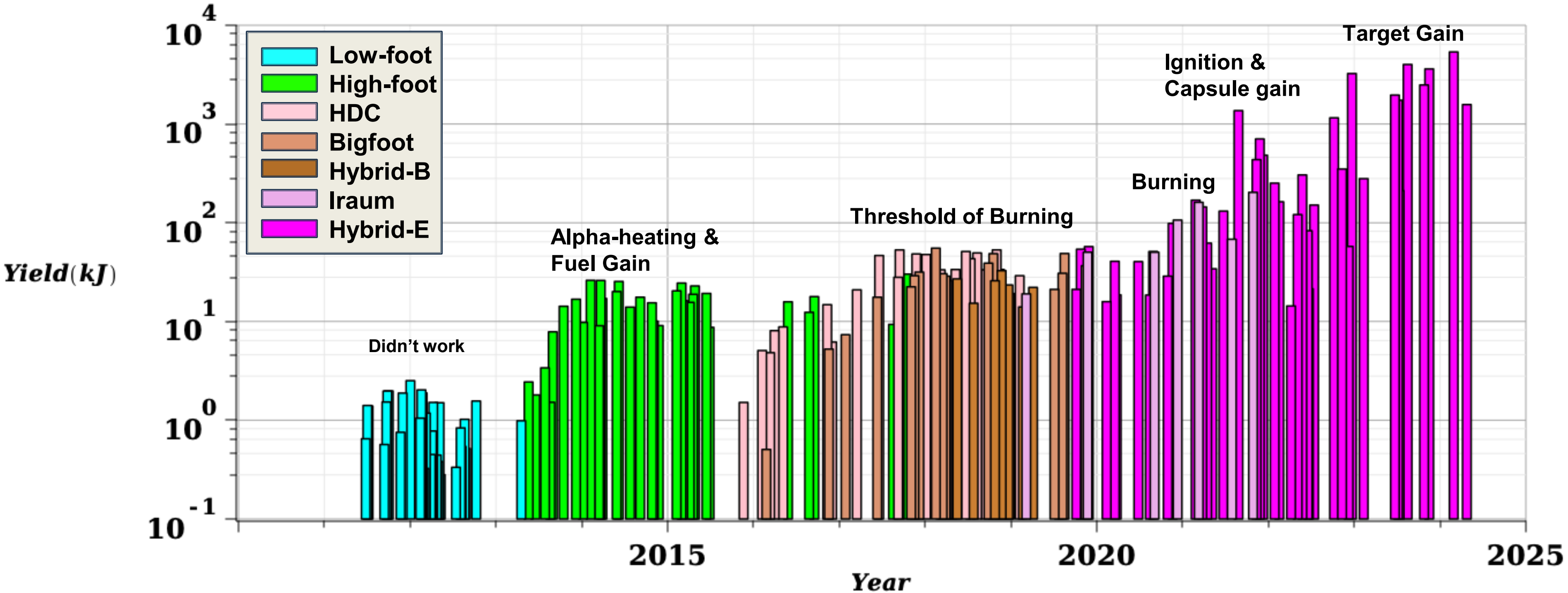
# The National Ignition Facility (NIF) is the first laboratory fusion fusion facility in the World to demonstrate fusion “ignition”



- Size of 3 football fields
- 327 MJ of stored electrical energy
- 2.2 MJ of 351 nm (“blue”) light directed into the target chamber
- 20 years to design and build
- 10 years of experiments to get ignition

Original vision due to Nuckolls, et al., Nature 1972

# We have an "existence proof" that ignition in the laboratory is possible, but getting ignition has been extremely difficult



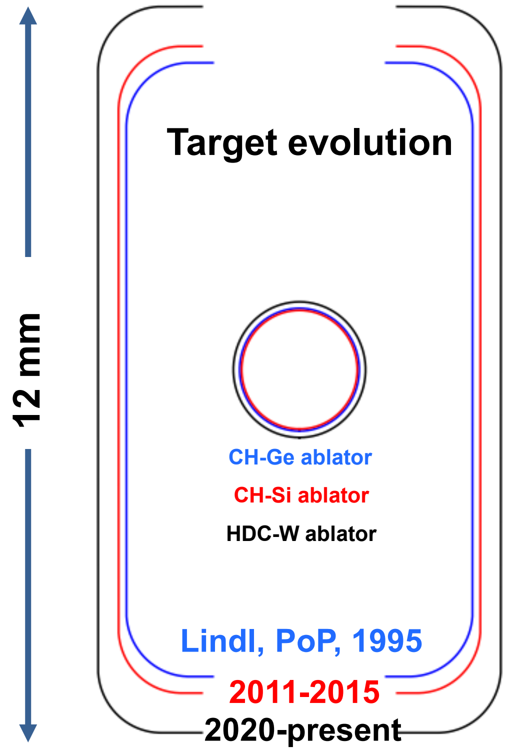

Diagnostics + simulation infrastructure + target production + laser operations

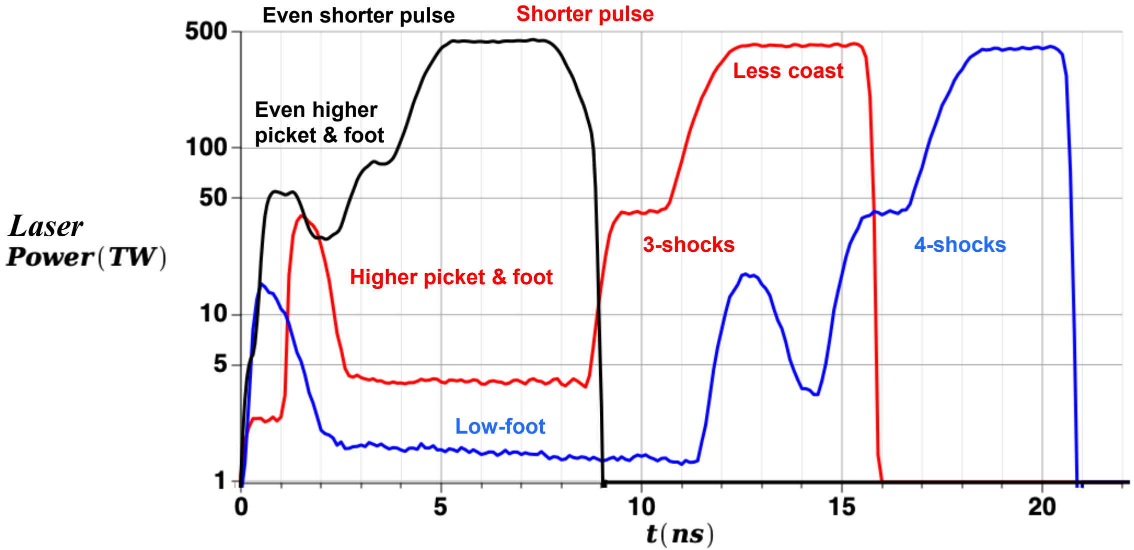
Ablation-front RT control + reduced coast-time

LPI control + increased velocity + improved symmetry

Increased capsule mass + improved symmetry control + improved capsule quality

# Today's target design* on the NIF was built upon a 10+ year *evolutionary exploration* of how to manage all the technical challenges




**Qualitative Design: Unchanged**

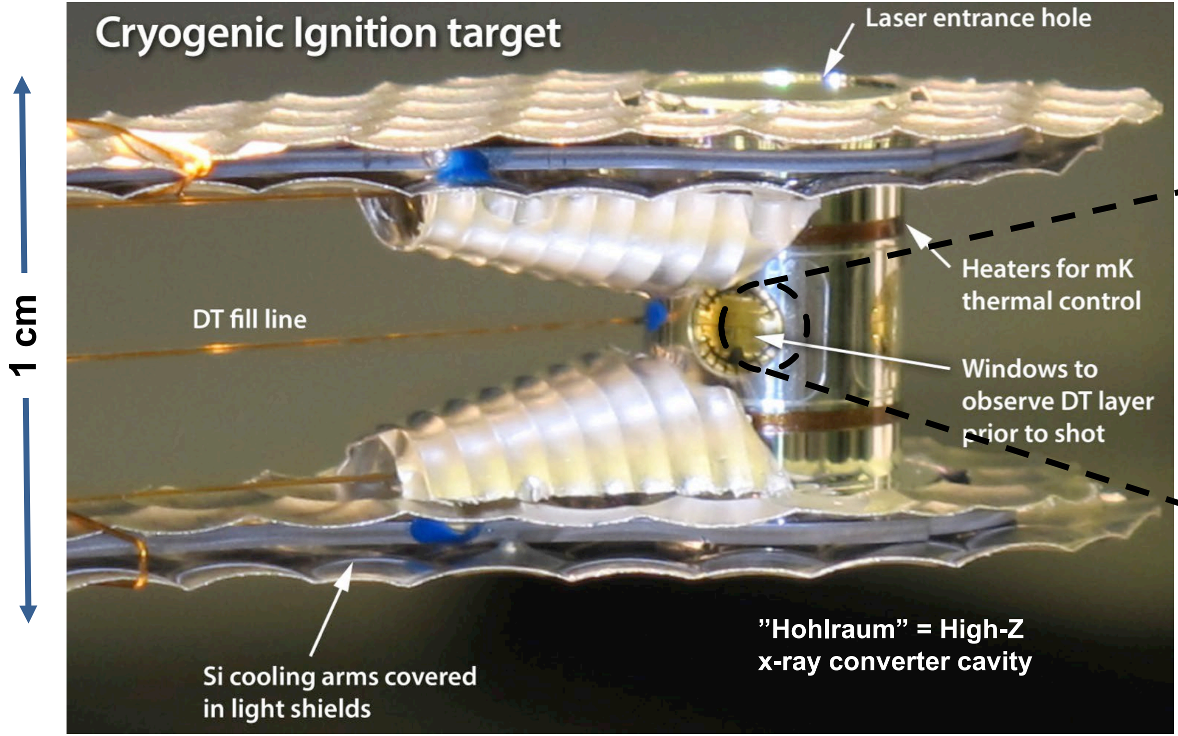
**Strategy: High energy gain → Just get something to ignite, even if barely**

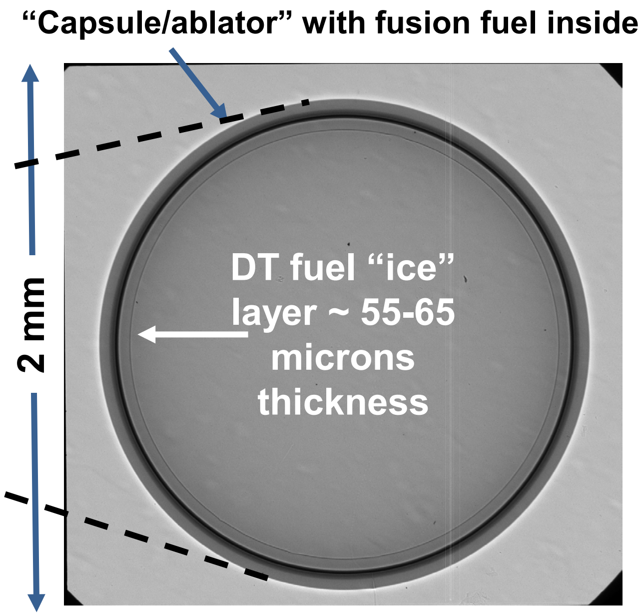
**Tactics: Many detailed changes – extraordinary sensitivity to "small" changes**



*Kritcher et al., PRE, 2022 & 24

# Inertial confinement fusion uses highly engineered “targets” that are complicated, fragile, and (because of reality) imperfect



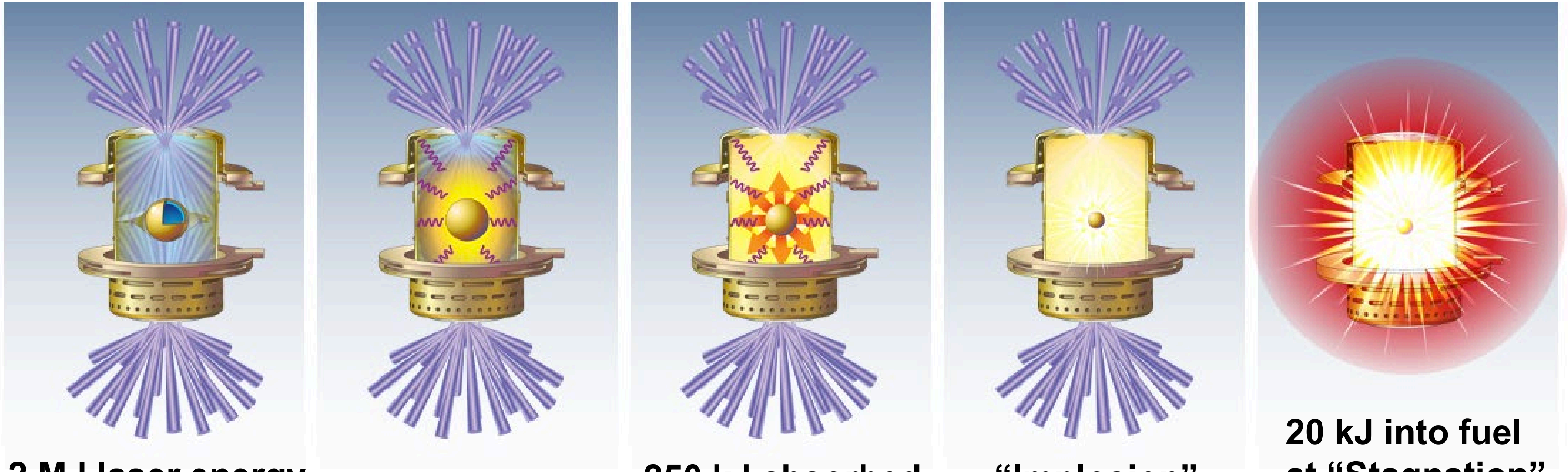

Ablator materials: high-density carbon (HDC), glow-discharge polymer plastic (GDP or CH), Beryllium, $B_4C$, etc.



e.g. T. Braun, et al., Nuclear Fusion, 2022

# Indirect drive inertial confinement fusion (ICF) uses x-rays to ablate and accelerate a capsule of fusion fuel to extreme velocity

| Lasers deposit energy into hohlraum | A bath of x-rays is created as the hohlraum heats | The capsule surface ablates at ~150 Mbar | Capsule accelerates inwards doing *pdV* work | Kinetic energy is converted into internal energy |
|---|---|---|---|---|



2 MJ laser energy

250 kJ absorbed

"Implosion"

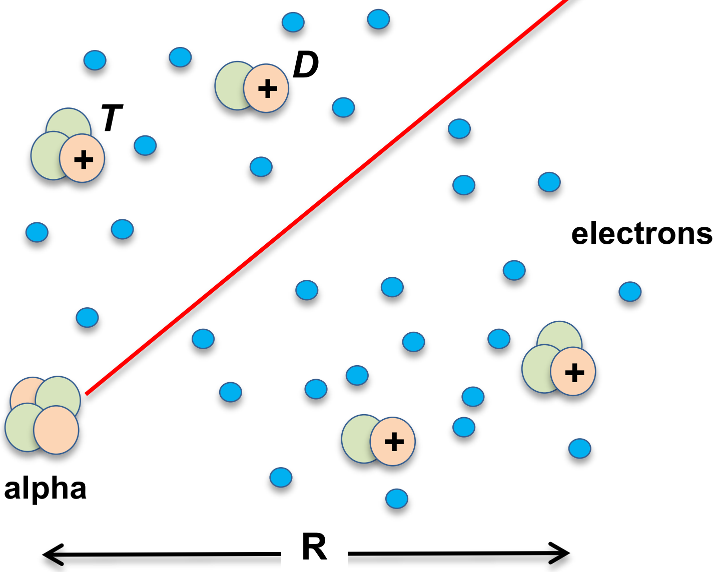
20 kJ into fuel at "Stagnation"

**Energy is sacrificed to amplify pressure in the fusion fuel, $pR^5 \sim constant$**

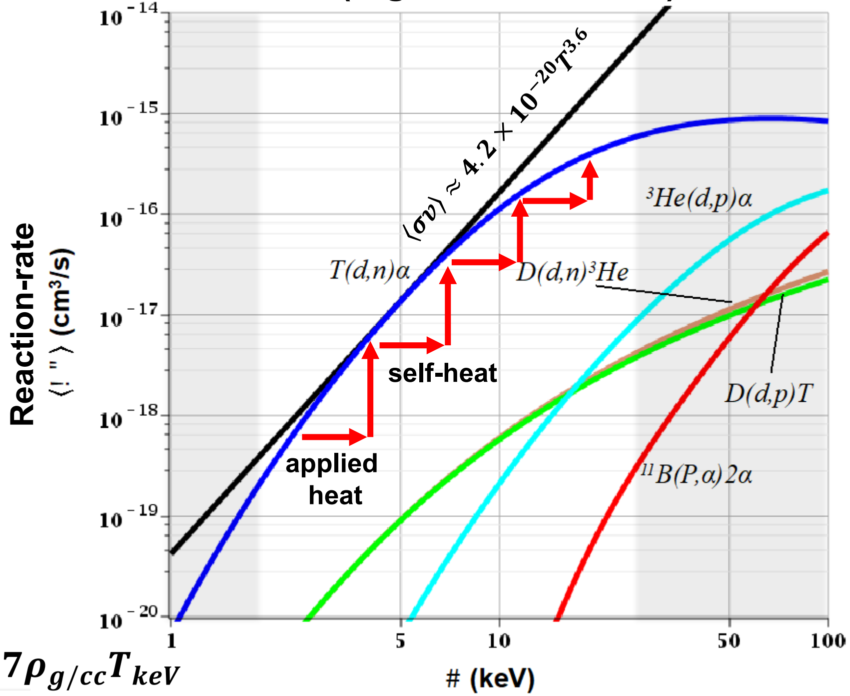
# As the alpha's deposit energy inside the plasma *thermonuclear instability* ("ignition") can occur if $\rho RT$ is large enough for long enough

$$D + T \rightarrow n\,(14.1\,MeV) + \alpha\,(3.5\,\text{MeV})$$

**High ρR**
**(high chance of thermalization)**




**High *T***
**(high reaction-rate)**

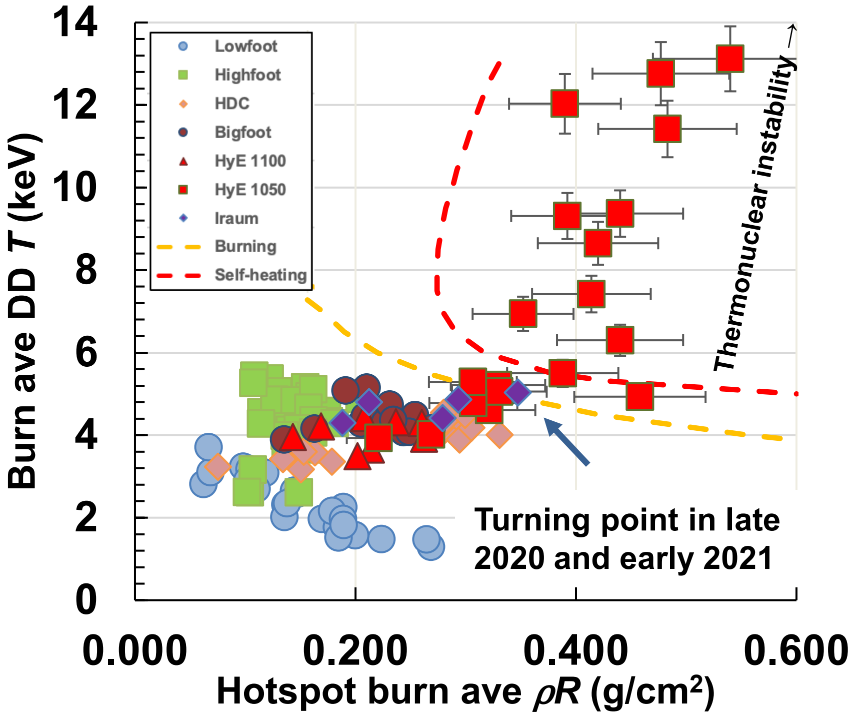



$$P_{DT}(Gbar) \sim 0.77 \rho_{g/cc} T_{keV}$$



1st evidence of self-heating: Hurricane, et al., Nature, 2014

# Obtaining the thermodynamic conditions for fusion ignition was exceeding difficult, but the theoretical threshold was where we expected it to be




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

**Example α-stopping:**

**$T$ ~ 10 keV (~110,000,000 Kelvin)**
**$\rho R$ ~ 0.4 g/cm$^2$**

**~ 70% of alpha's deposit energy in hot plasma**

"Once a burning plasma was achieved, ignition wasn't a question of *if* but *when*." *R. Betti, Nature 2022*

# Early ignition experiments on the NIF tried for ultra-high compression, but we had to back-off to get things working

## NIF DT experiments fuel gain vs. fuel areal density

Fusion yield/energy into the DT

From Hurricane, et al., Plasma Physics and Controlled Fsion. Phys, 2024

Present

Simulations

2021

2020

2014

Experiments

2011

← Consistent Inconsistent →

**Change of strategy:**

**Instead of going straight for high yield and high gain, back-off and find a regime where simulations and data start to better agree.**

**Then move forward by solving problems in steps.**

**“Basecamp strategy”**



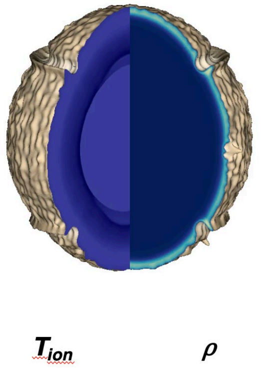
**We still don’t understand all the reasons for the discrepancy**

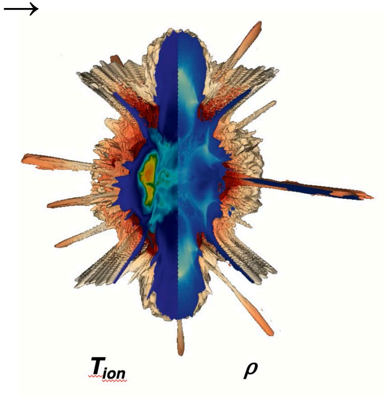
# Implosions can be nonlinear *problem-amplifiers*, amplifying the hydrodynamic perturbations of defects and asymmetry

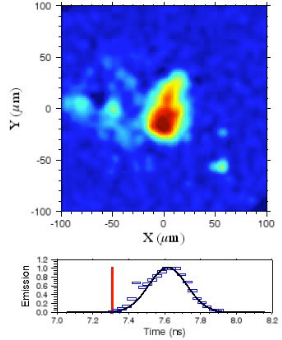
Time →

**Instability & defects:**

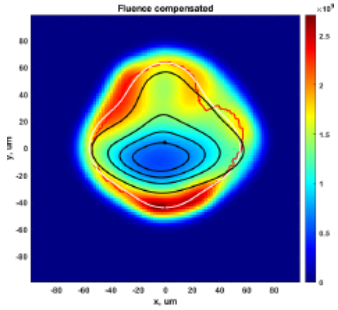
e.g. D. Clark *et al.*, Phys. Plasmas 23, 056302 (2016)



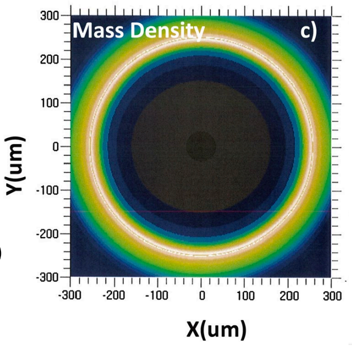



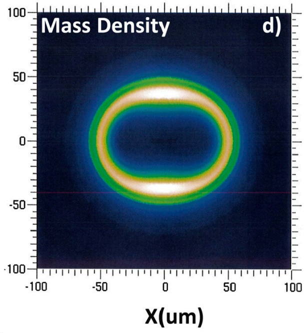

FC Downscatter Data (N210307):




**Asymmetry:**

e.g. A. Kritcher *et al.*, Phys. Plasmas 21, 042708 (2014)

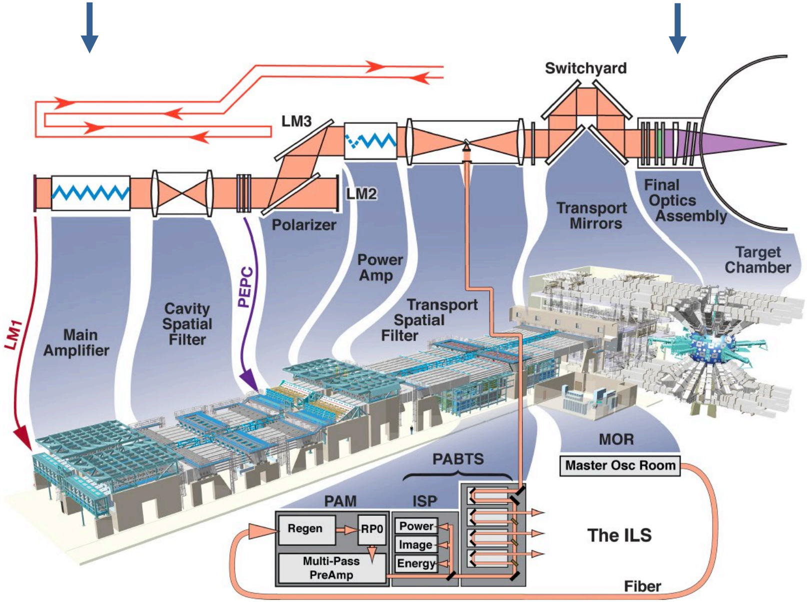





**Both problems effectively "cost" us energy**

# In the future, the NIF will extend* the present 2.2 MJ laser energy capability, at 351 nm, to 2.6+ MJ for use with larger targets




M. L. Spaeth, et al, Fusion Science & Technology, 69, 25-145, 2016

*J. M. Di Nicola, Nuclear Fusion, 59, 032004, 2019

# Remarkable that we can now talk about burning plasmas, ignition, and scientific breakeven ($G_{target} > 1$) in the past-tense!

- *Maximizing energy delivery to the DT fuel without pressure loss* has been key
  - Asymmetry costs *energy*
  - Instability and mixing costs *energy*
  - Long coast-time costs *power*
- "Ignition" is where we expected it in terms of plasma conditions, but engineering control (of laser and targets) was/is extremely challenging and more laser energy than expected was needed
- While "scientific breakeven" was obtained on December 5, 2022, the NIF laser facility consumed $\sim 100 \times$ more energy (327 MJ) than was created with DT fusion
- Future work involves extending the laser energy delivery capability of the NIF to drive larger scale targets to higher yields and to try and solve some of the outstanding mysteries we've encountered over the past 12 years of work

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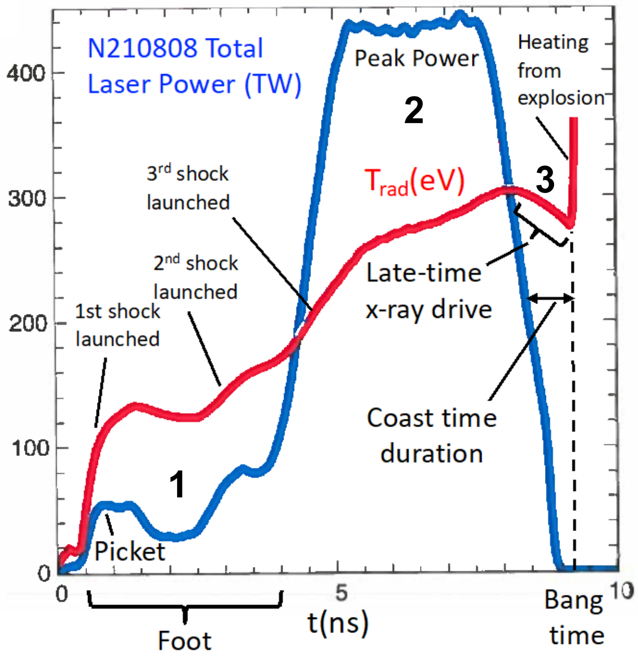
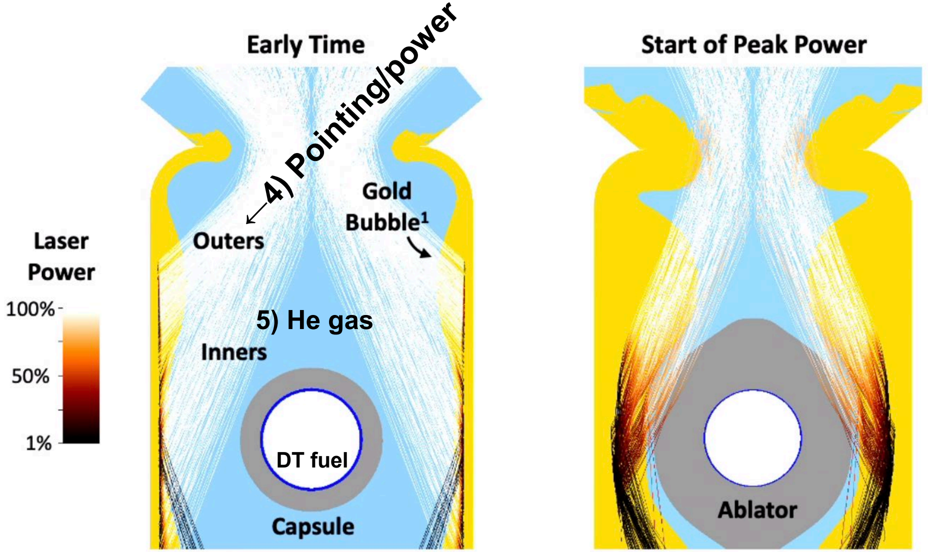
# The NIF laser in combination with an x-ray driven target creates an implosion that compresses and heats the fusion fuel




Ablation pressure: $p_{abl} \sim T_{rad}^{2.5-3.5}$

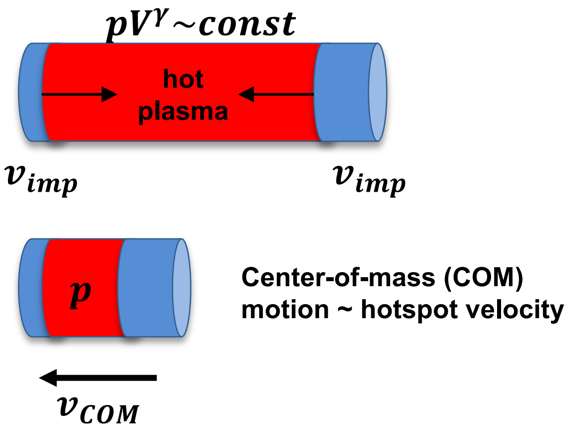
1) Stability & entropy ("adiabat")
2) Peak velocity
3) Coast-time (mechanical power)

4) Laser pointing and "cone" power (symmetry)
5) Helium gas-fill (resists plasma ingress)

# Implosion symmetry control is important, because it wastes shell KE, that could have heated & compressed the fusion fuel

## Asymmetric implosion abstracted to pistons

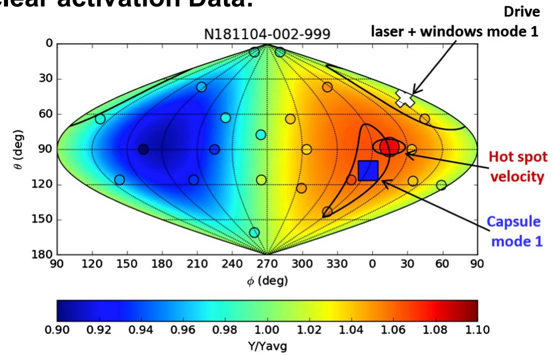
**Mode-1 classical mechanics model**



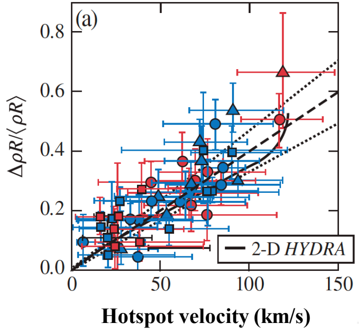

## Unrecoverable KE due to COM motion:

$$f^2 \equiv \left(\frac{\rho\delta R_{max} - \rho\delta R_{min}}{\rho\delta R_{max} + \rho\delta R_{min}}\right)^2 = \frac{v_{com}^2}{v_{imp}^2} = nRKE$$

**Nuclear activation Data:**




**Nuclear time-of-flight (NToF) Data:**

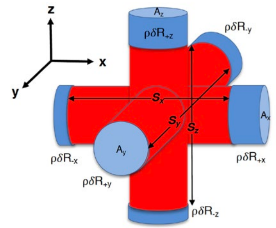





Hurricane, et al, PoP, 2020; Rinderknecht, et al., PRL, 2020; Casey, et al, PRL, 2021; MacGowan, et al, HEDP, 2022; Mode-1 Tion asymmetry work by Spears, et al, PoP, 2014; Schlossberg, et al, PRL, 2021

# 3D geometry reflects energy efficiency, and one finds the key measure is the weighted harmonic mean of shell $\rho\delta R$

**3D abstraction:**



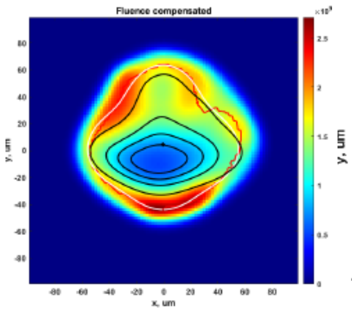

**Newton's laws →**

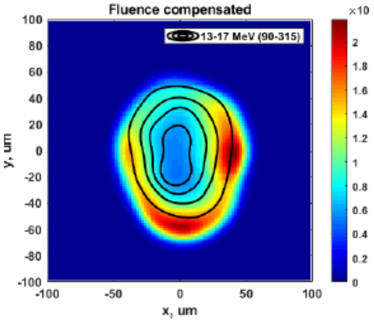
$$f^2 = 1 - \frac{\left\langle \frac{1}{\rho\delta R} \right\rangle^{-1}}{\langle \rho\delta R \rangle}$$

**Weighted harmonic mean of shell areal density**

**where** $\langle \blacksquare \rangle = \frac{\int \blacksquare dA}{\int dA}$ **and the hotspot surface area weighting is *dA***

**FC Downscatter Data (N210307):**




**FC Downscatter Data (N201101):**

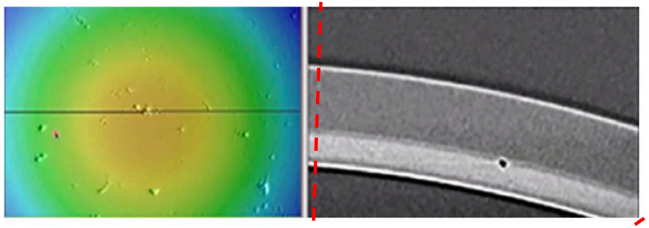
**Thin regions reduce implosion efficiency**



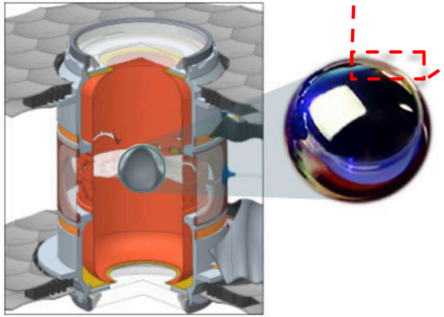
* Area Weighted Harmonic Mean (WHM): Hurricane, et al, PoP, 2022; Woo and Betti, PoP, 2021

# Defects in targets can have a significant energetics consequence and can be a limiting factor for ignition and energy gain

## Capsule defects seed instability and mixing

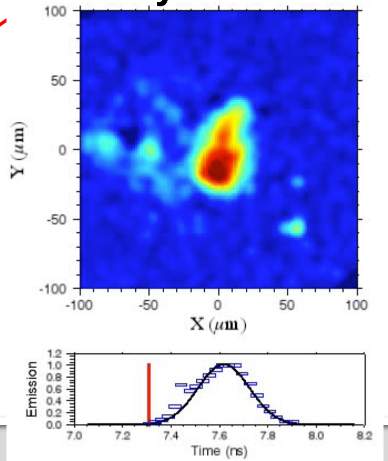


*(Left) Confocal microscope image showing pits on the capsule surface. (Right) Tomographic image showing an internal void.*

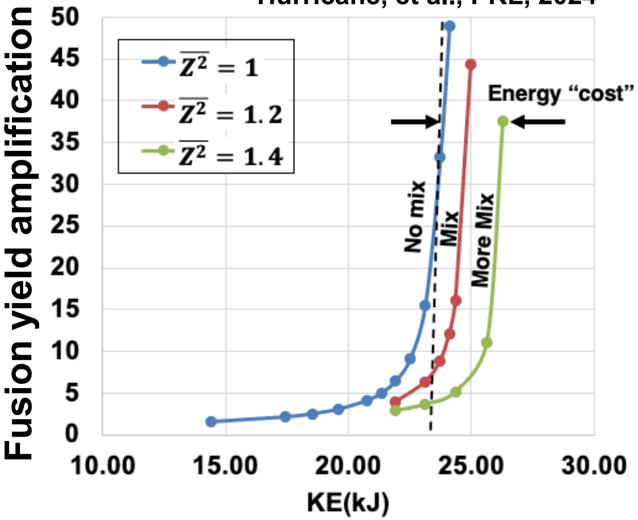


Braun, et al., Nuclear Fusion, 63, 2022

**X-ray emission**




Hurricane, et al., PRL, 2024



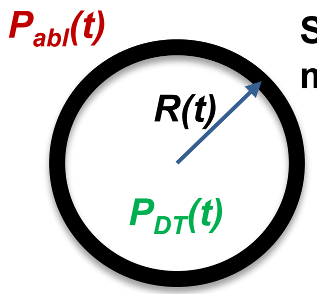

**Ignition threshold moves to higher energy:**

$$KE_{mix} \approx KE_{no-mix}\overline{Z^2}^{0.3}$$

Data: Divol, et al., PoP, 2024
Fill-tube: Pak, et al, PRL, 2020

# ICF implosions are mechanical systems that act as nonlinear power and pressure amplifiers, as kinetic energy converts to internal energy

**Ablation pressure**

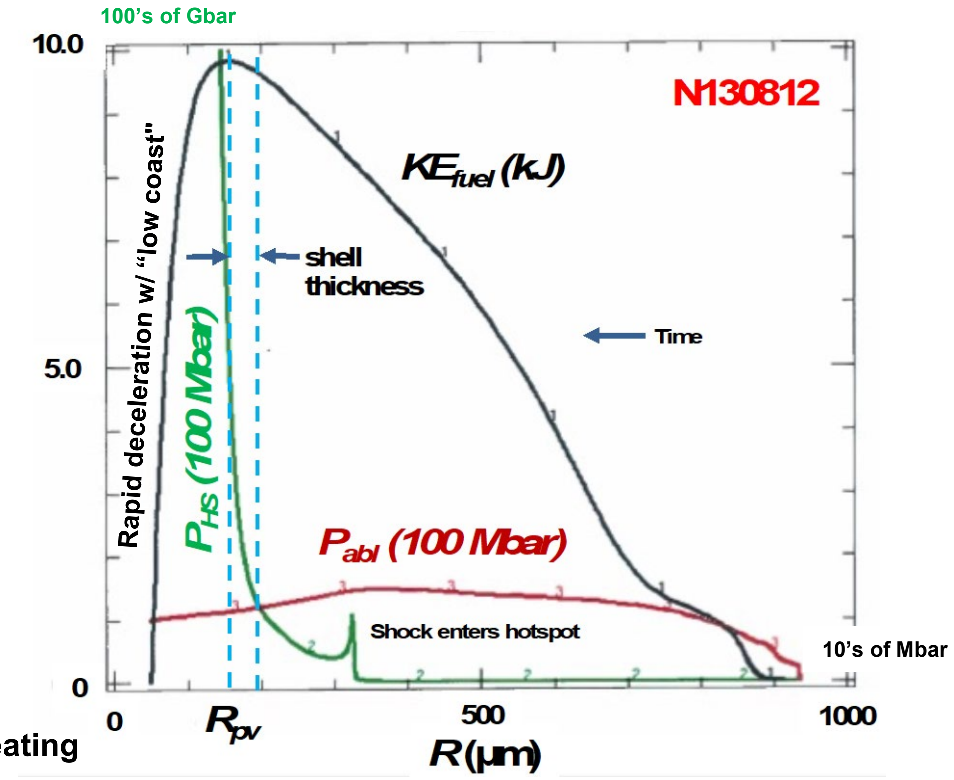



**Shell (fuel + ablator) mass, $m_{sh}$**

**Thermodynamics:** $P_{DT} \approx P_{pv} \left(\frac{R_{pv}}{R}\right)^5 e^{P_{DT}\tau H(T,\bar{Z})}$

**amplification from convergence**

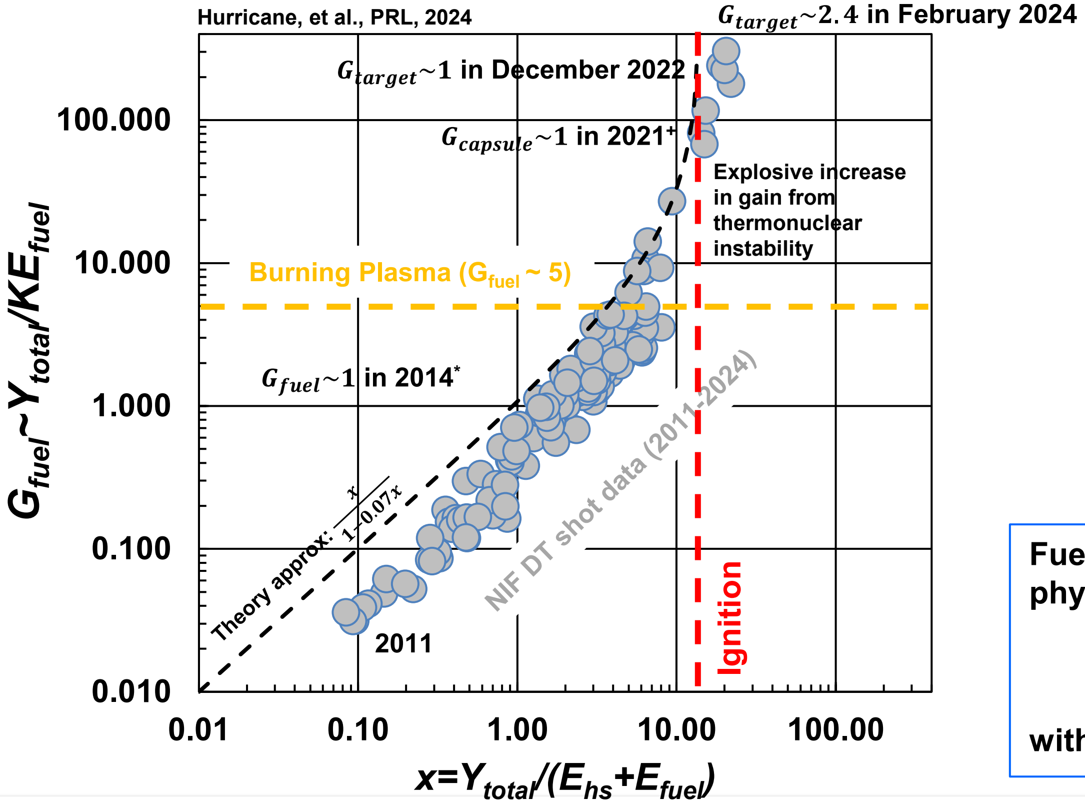
**implicit exponential amplification from alpha-heating**

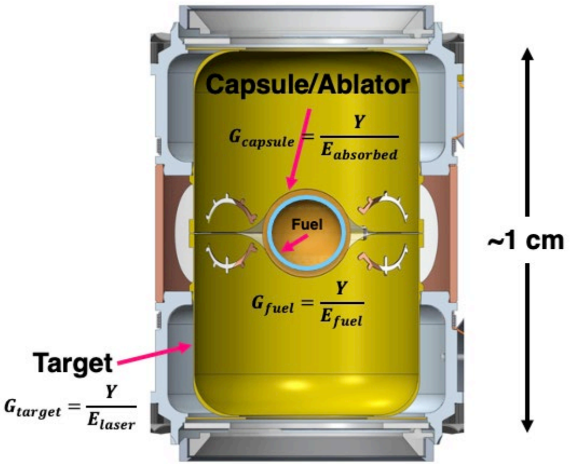



**Peak DT fuel KE ~ 20-25 kJ @ $R_{pv}$ ~ 150-200 microns in today's designs**

# Three energy "gain" (energy out/energy in) milestones have been achieved over that same decade of work

Hurricane, et al., PRL, 2024




**Fuel energy gain, $G_{fuel}$, is directly connected to the physics of the fusion plasma (Lawson Parameter)**

$$\frac{Y_{\rm total}}{E_{\rm hs}} = \frac{5\int_0^\tau mQ_\alpha dt}{c_{\rm DT} mT} \approx 4.6\times 10^{26} p_{\rm hs}\tau \frac{\langle\sigma v\rangle(T_{\rm hs})}{T_{\rm hs}^2},$$

**with pressure in Gbar, T in keV, and $\tau$ in s**

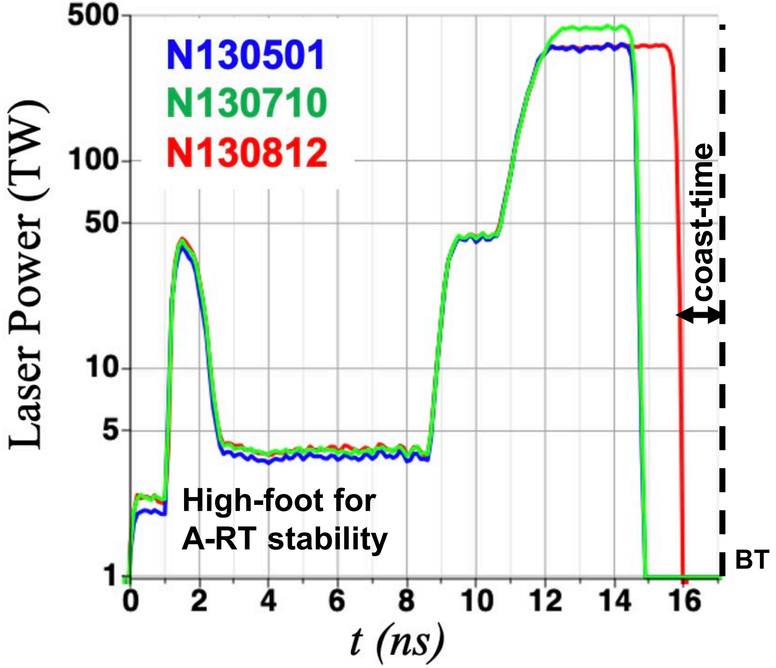


*Hurricane, et al., Nature, 2014

+Abu-Shawareb, et al. (Indirect Drive ICF Collaboration), PRL, 2022; Kritcher et al., PRE, 2022; Zylstra, et al., PRE, 2022

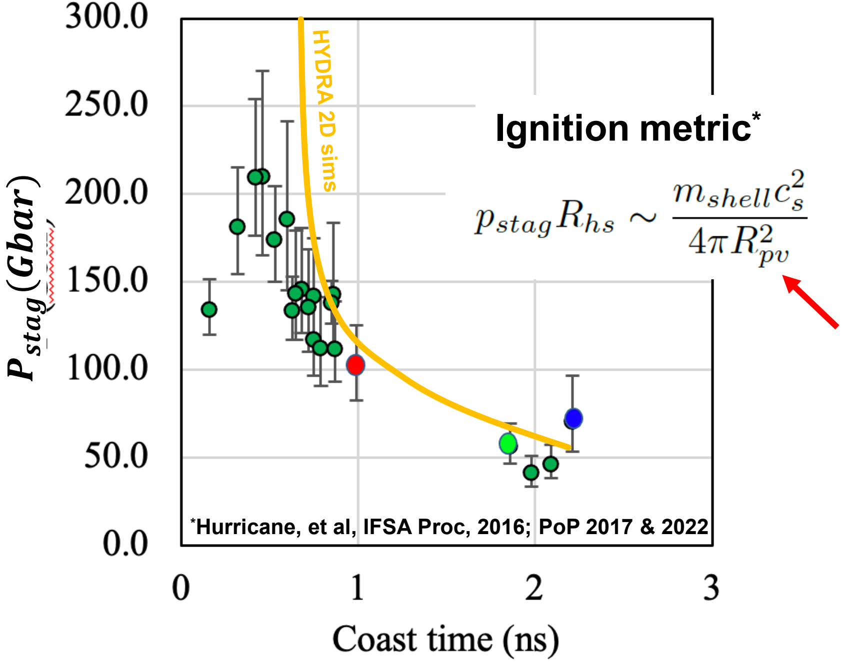
# Even at the cost of peak power (at fixed energy), a longer duration of peak power ("lower coast time") is beneficial

**Which is better: Adding energy with more power or more duration?**




Dittrich et al., PRL, 2014; Park et al., PRL, 2014; Hurricane, et al., Nature, 2014

**Experimental observation**



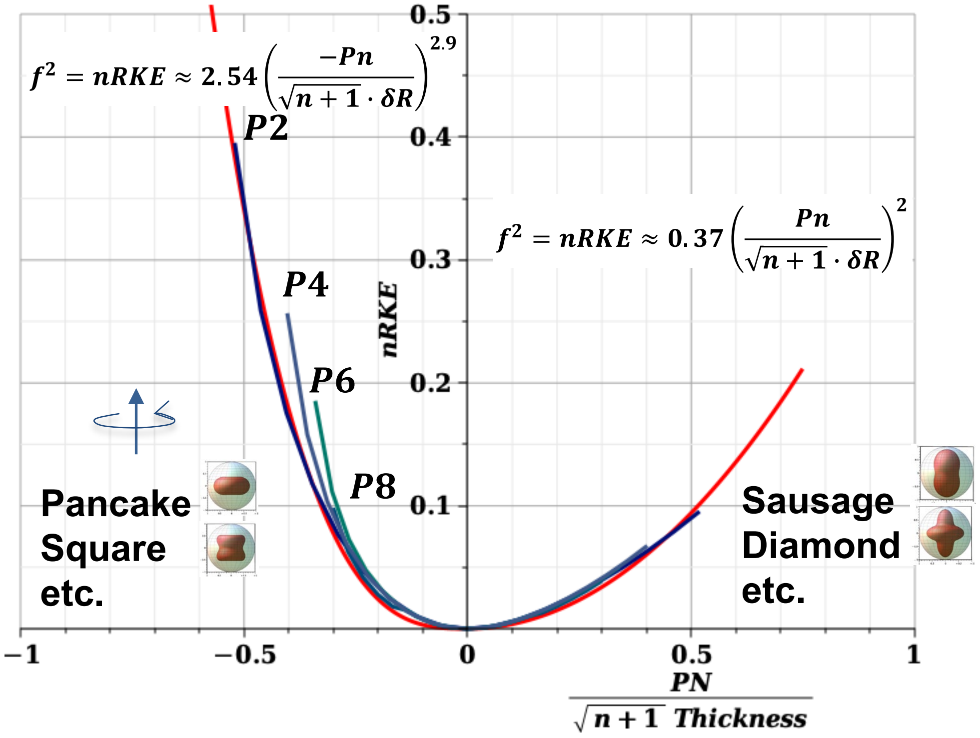

**Optimal coast-time << hohlraum cooling time**



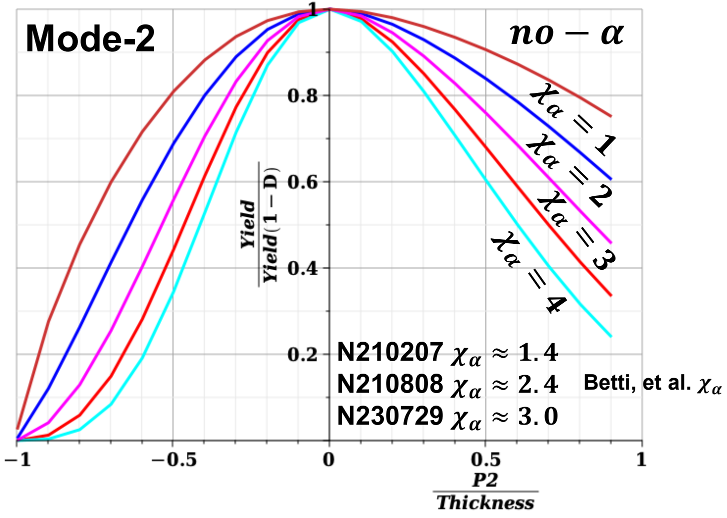
**Effect on $\rho R$ was previously noted: Zylstra, PoP (2014); Landen, PoP, (2012)**

# Quantitatively, asymmetry sensitivity is *reduced* by shell thickness and *amplified* by alpha-particle self-heating

**Even modes:**




**Asymmetry yield degradation is amplified by alpha-heating:**




Asymmetry and shape observed in data: e.g. J. Ralph, et al, *Nat. Comm.*, (2024) 15:2975

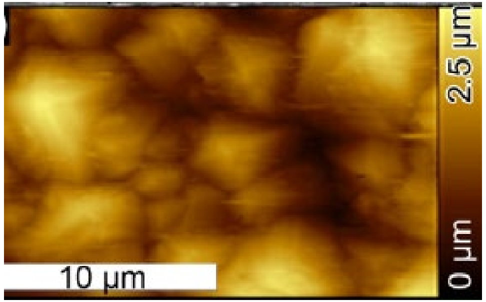


$\delta R = thickness\ \&\ Pn\ is\ P_n(cos\theta)\ mode\ amplitude$

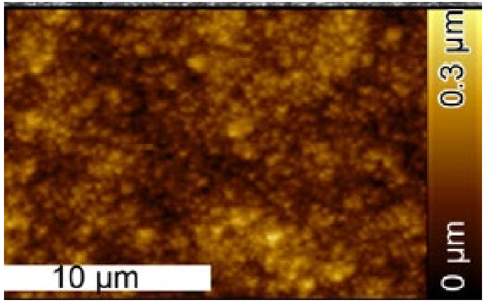
# Without a long-pulse driver capability, advanced light source facilities are likely limited to exploring target issues <10 Mbar

## Ablator structure

### Micro-crystalline



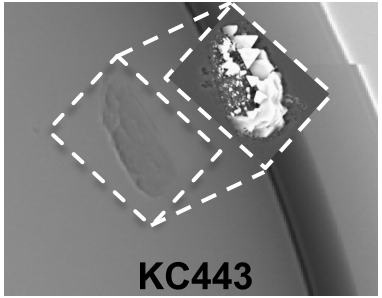

### Nano-crystalline




[C. Dawedeit et al. Diamond & Related Materials 40 75–81 (2013)]

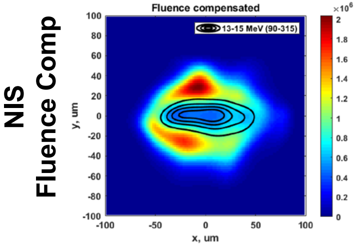
## Defects

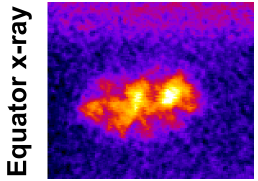
### Inner surface defect

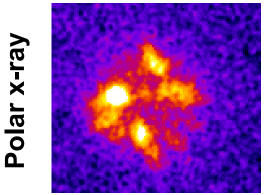



**N181203**

**KC468-01**



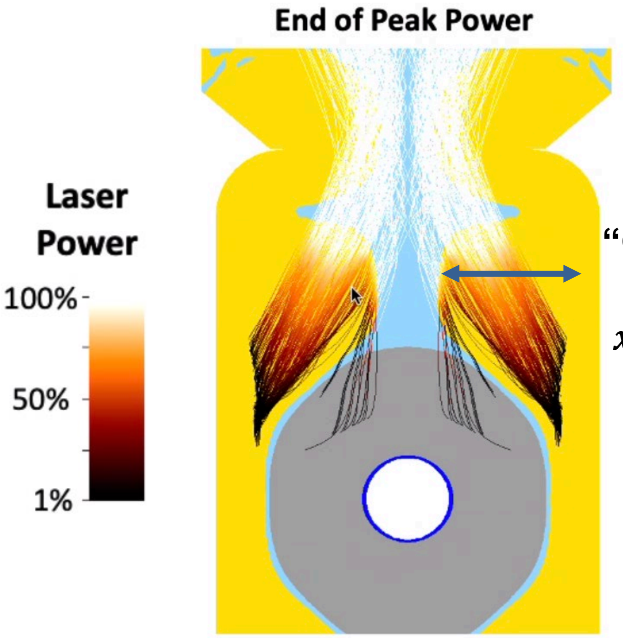






*Braun, et al., Nuclear Fusion, 63, 2022; Zylstra, et al., Phys. Plasmas, 2020; Hohenberger, et al, PoP, 2020

**S. Ali et al, Physics of Plasmas 25, 092708 (2018)

# Significantly improved understanding of the levers controlling IDD implosion symmetry obtained by 2018

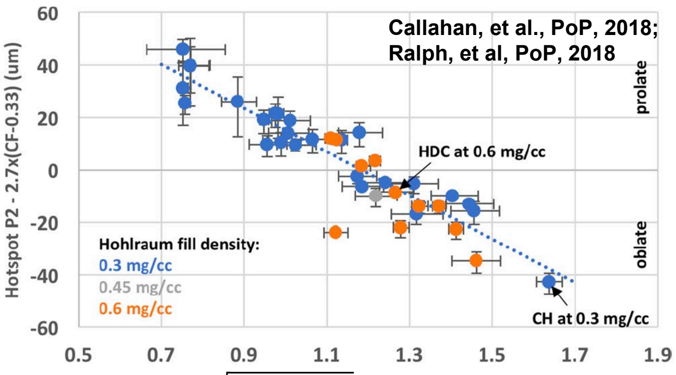



*Bubble blocks inner propagation*

**Legendre mode-2 ("P2") empirical scaling:**

**"Gold bubble" ingress:**

$$x_{bubble} \sim \sqrt{\frac{E_{picket}}{\rho_{gas}}}\, t_{laser}$$




$$\sqrt{\frac{E_{picket}}{A_{outer}\rho_{gas}}\frac{t_{laser}}{R_{hohl}}\frac{r_{cap}}{R_{hohl}}}$$

$\Delta\lambda = 0\text{Å}$ $\Delta\lambda = 1\text{Å}$

A. L. Kritcher, et al *Phys. Rev. E* 98, 053206 (2018);
L. Pickworth, et al, PoP (2020)