# Lessons from fusion ignition and the implications for fusion energy science and engineering

CWFEST

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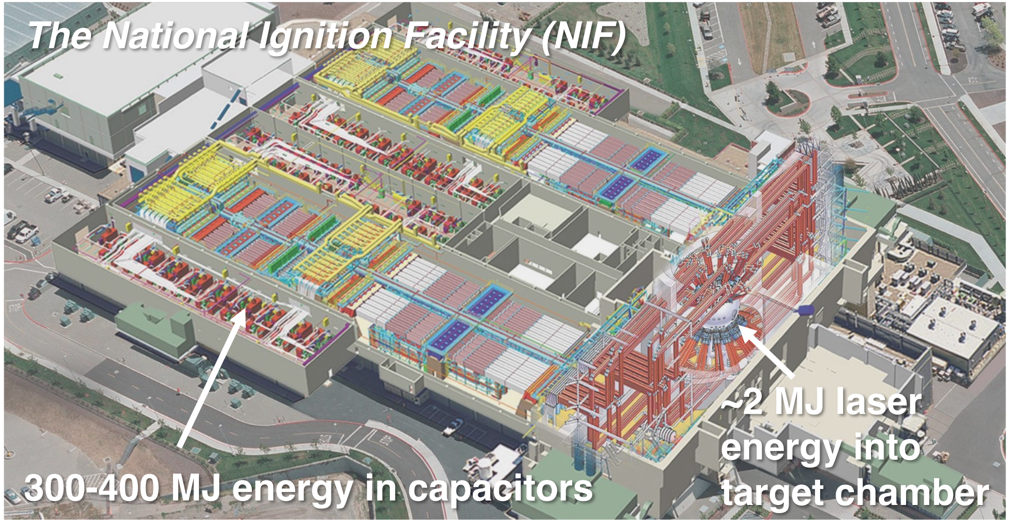
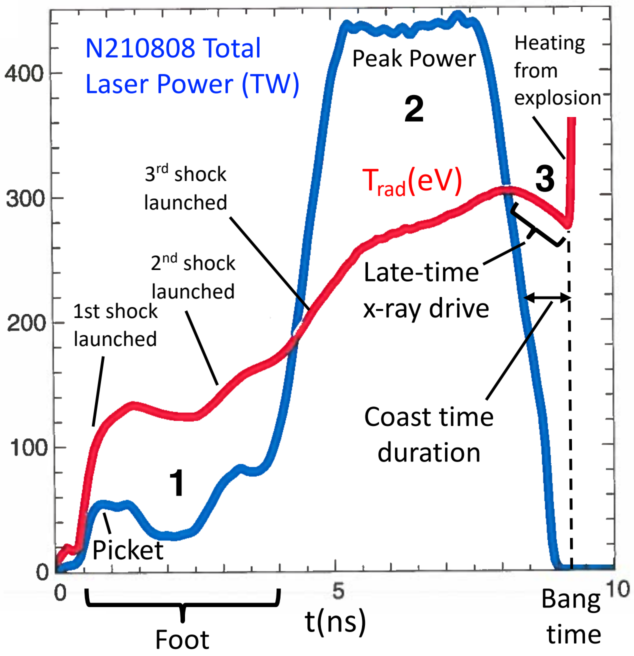
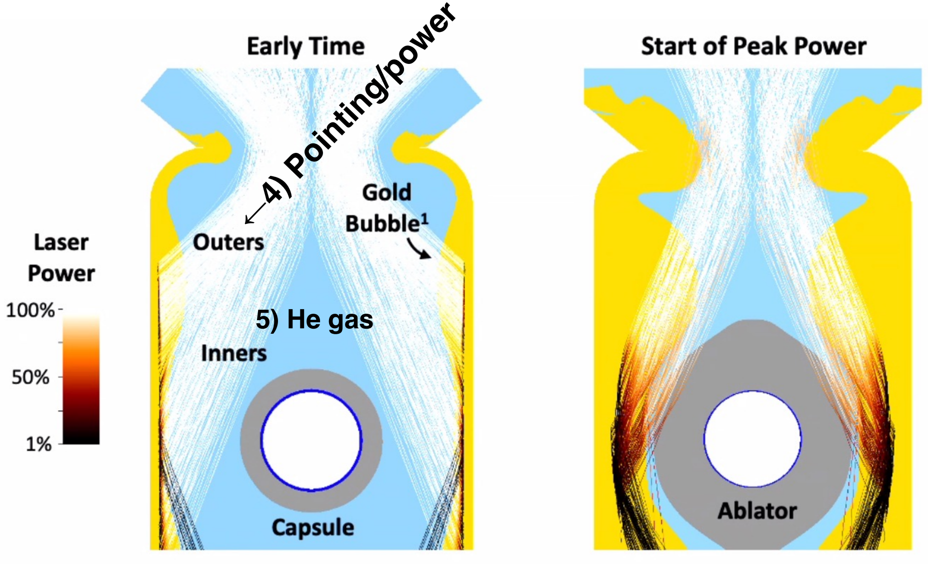
# We have an "existence proof" that ignition in the laboratory is possible, but getting ignition has been extremely difficult

- "Ignition," defined as the tipping-point of thermodynamic instability, obtained on August 8, 2021
- "Scientific Breakeven," i.e. "Target Gain > 1" obtained on Dec. 4, 2022 and bested on July 29, 2023
- "Net energy gain," i.e. "Engineering Gain > 1" not yet demonstrated
- Lessons learned:
  - Stability control, symmetry control, and high compression all more difficult than originally envisioned
  - More sensitivity to target quality and laser delivery than originally envisioned
  - Higher energy has been more useful than high peak power



# In indirect-drive, the hohlraum, capsule ablator, and laser-pulse integrate together to control the implosion



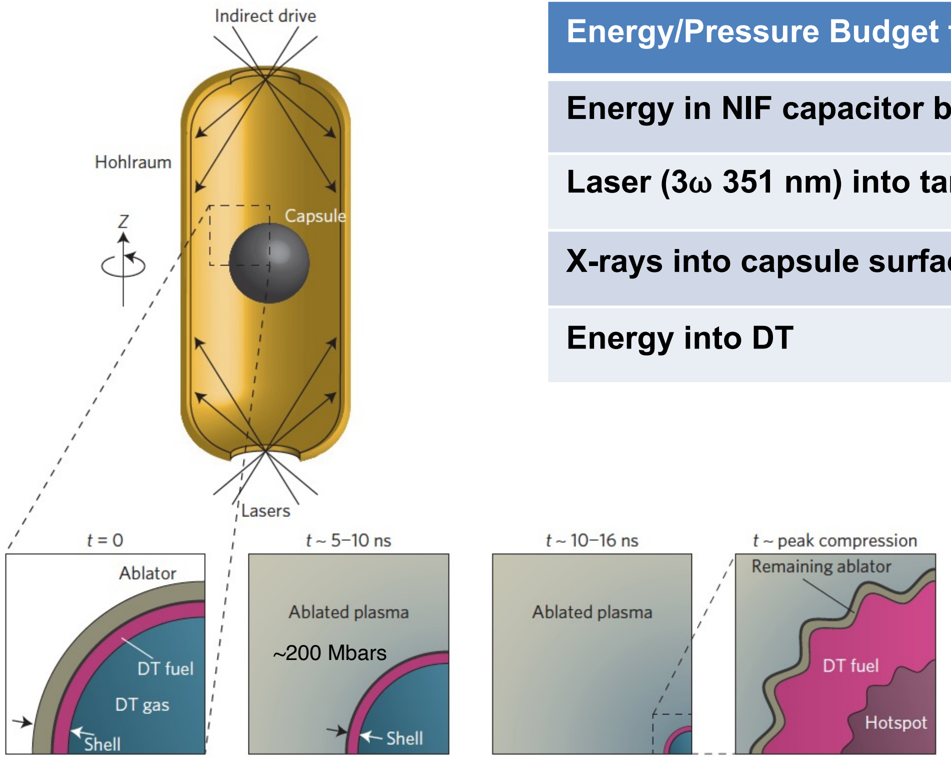




**Ablation pressure:** $p_{abl} \sim T_{rad}^{2.5-3.5}$

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)**
6) **Target (fuel, capsule, hohlraum) geometry**

# Indirect drive is energy inefficient, but we are trading energy for *energy density* since implosions act like "pressure amplifiers"



Betti & Hurricane, Nature Phys. (2016)

~400 Gbars

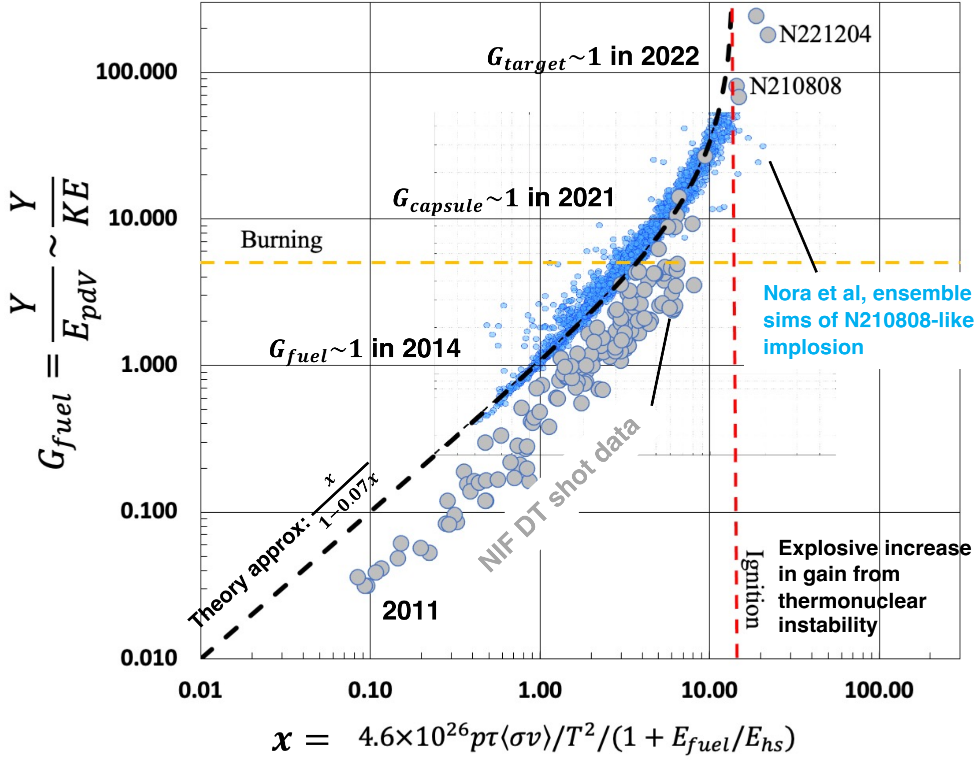
| Energy/Pressure Budget for NIF | Energy | Pressure | Gain Term |
|---|---|---|---|
| Energy in NIF capacitor banks | 300-400 MJ | n/a | $G_{engineering}$ |
| Laser (3ω 351 nm) into target | 1-1.9 MJ | n/a | $G_{target}$ |
| X-rays into capsule surface | 150-250 kJ | 100-200 Mbar | $G_{capsule}$ |
| Energy into DT | 10-20 kJ | 100-550 Gbar | $G_{fuel}$ |

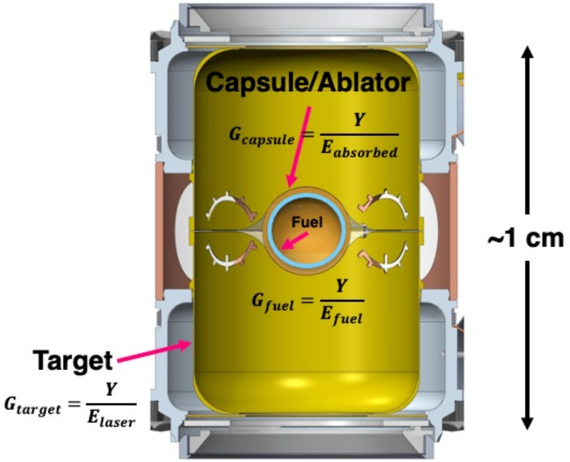
**The dramatic loss in energy at different stages of ICF operation leads to several different definitions of Gain:**

- $G_{engineering}$ = fusion yield / facility energy
- $G_{target}$ = fusion yield / laser energy
- $G_{capsule}$ = fusion yield / capsule absorbed energy
- $G_{fuel}$ = fusion yield / energy delivered to DT

# After a decade of problem solving, for the first time in the laboratory ignition and scientific breakeven have been achieved

Hurricane, et al, PRL, submitted 2023



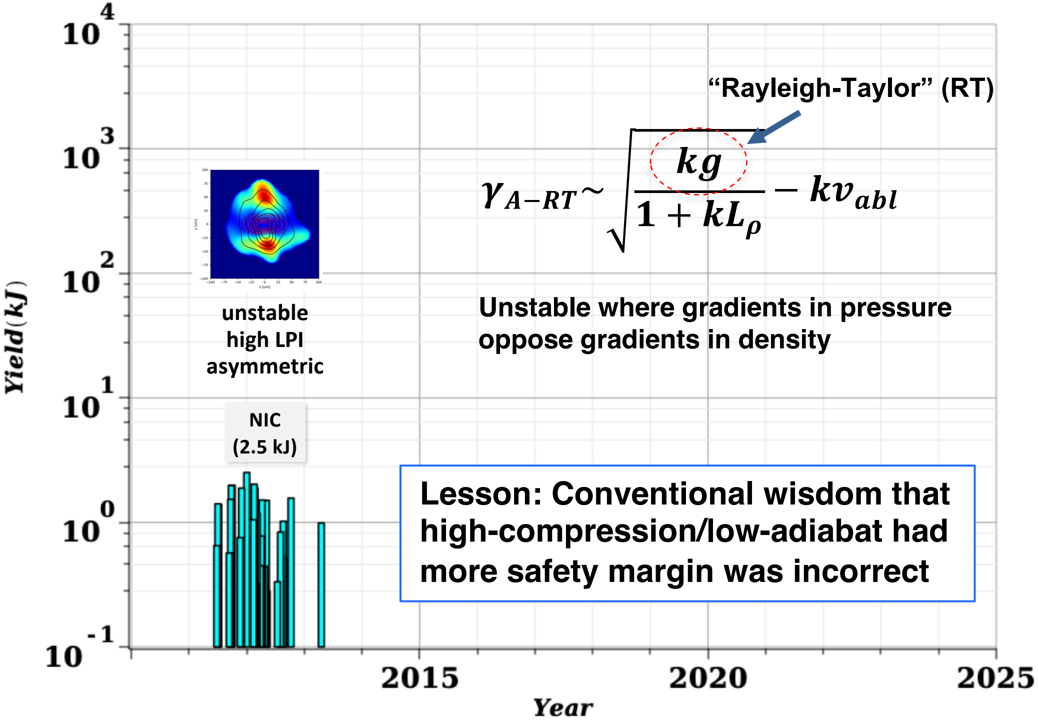

**Progress in "Gain" by incremental improvements in a Lawson-like product of DT**

$p$ = plasma pressure
$T$ = thermal temperature
$\tau$ = confinement time



$G_{target} > 1$ is not "net energy gain," because of facility energy consumption

# 2010-12: Plastic ablator "Low-foot" implosions were designed to be high compression and yield ( > 1 MJ), but underperformed*

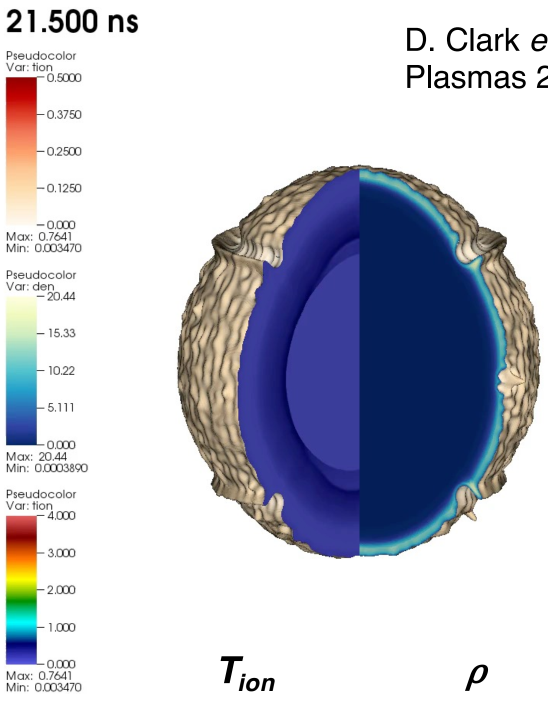



"Rayleigh-Taylor" (RT)

$$\gamma_{A-RT} \sim \sqrt{\frac{kg}{1+kL_\rho}} - kv_{abl}$$

**Unstable where gradients in pressure oppose gradients in density**

**Lesson: Conventional wisdom that high-compression/low-adiabat had more safety margin was incorrect**

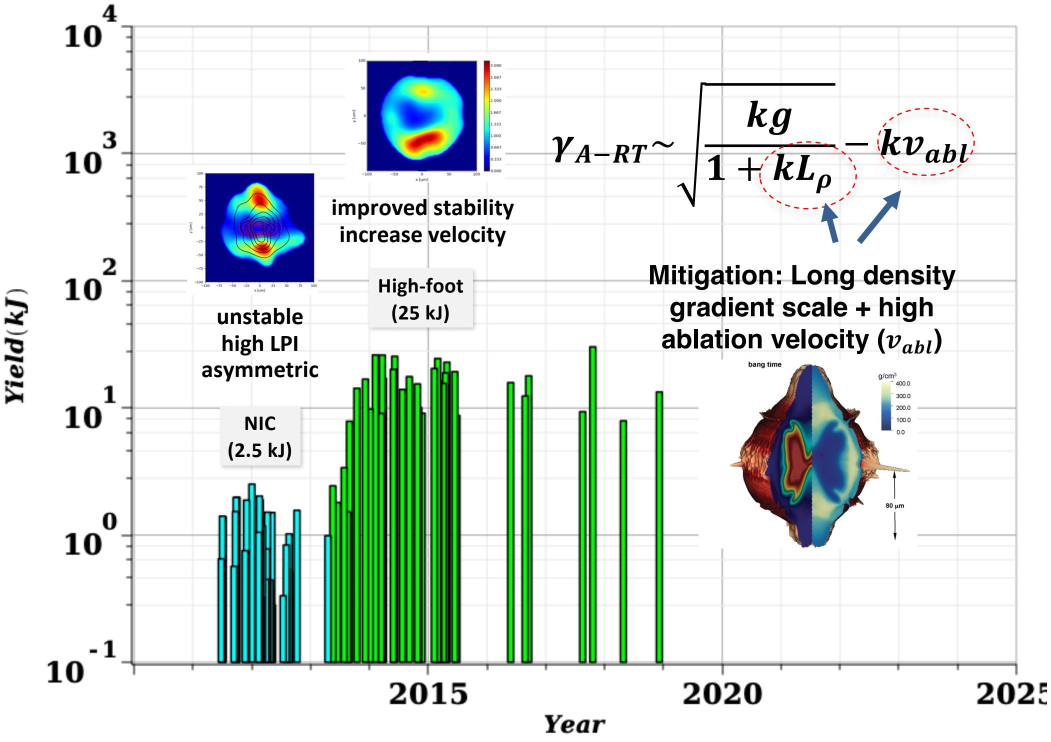


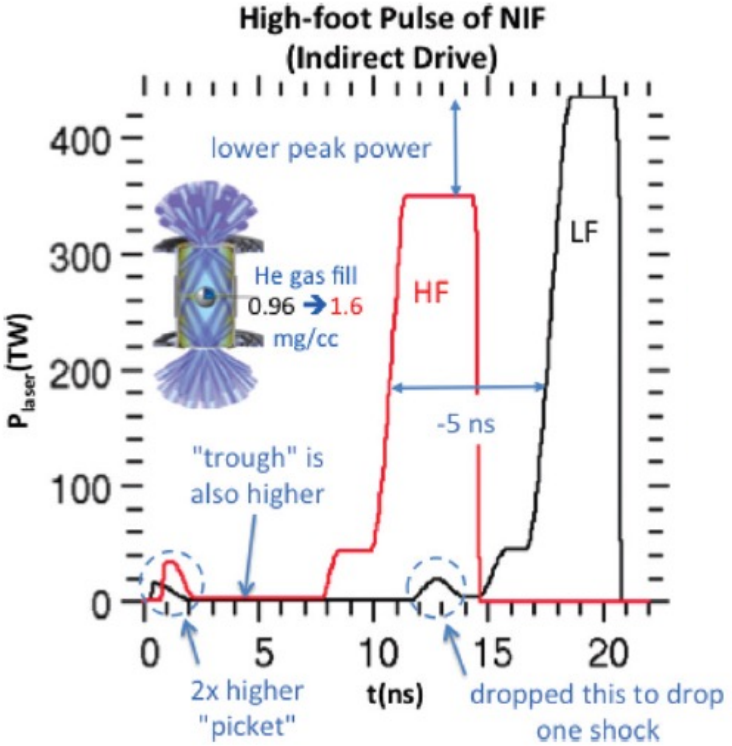

D. Clark *et al.*, Phys. Plasmas 23, 056302 (2016)



*Edwards, et al, PoP, 2013; Ma, et al., PoP, 2013; Regan et al, PRL, 2013; Lindl, et al., PoP, 2014; Clark, et al, PoP, 2016

# 2013-2015: High-foot implosions tested if better controlling hydrodynamic instability would improve performance

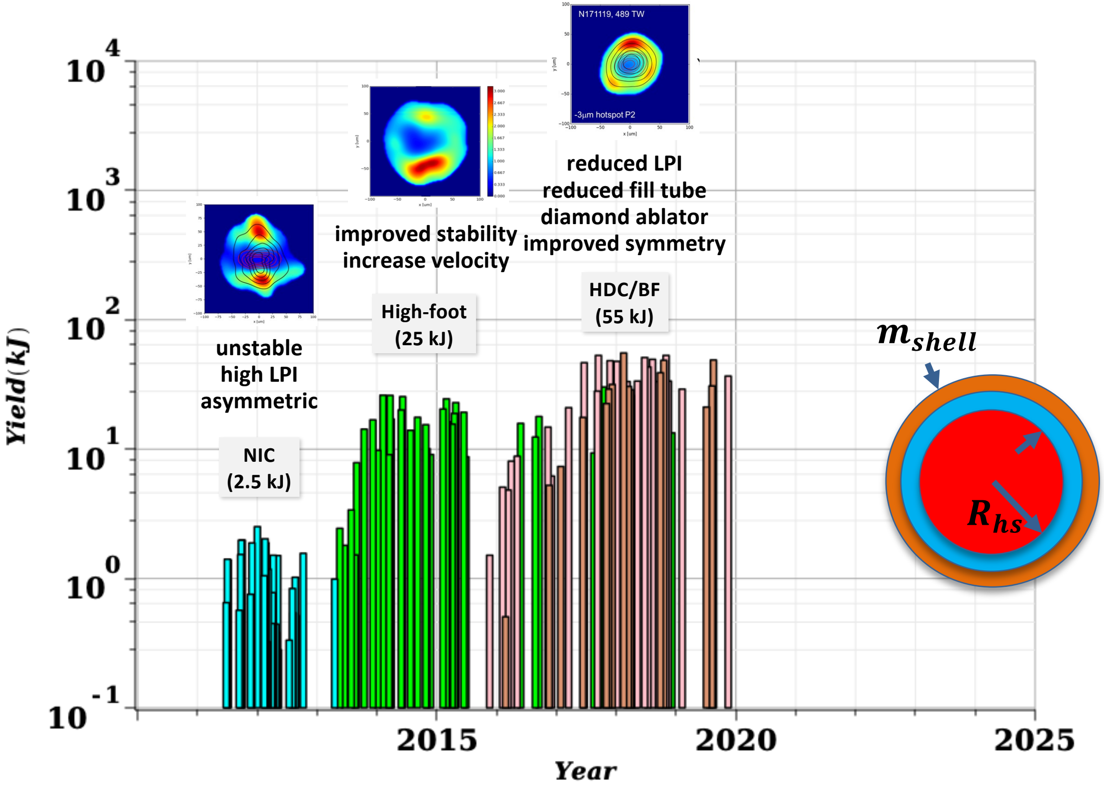


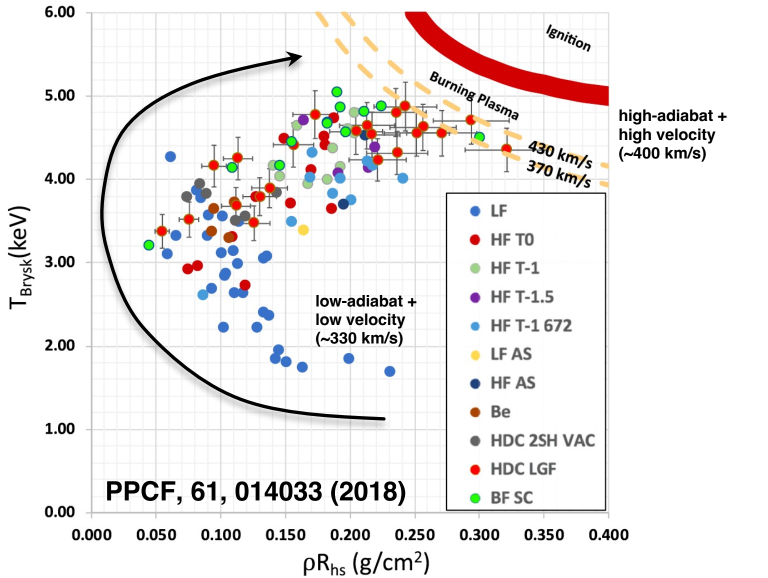



Hinkel, et al. PPCF, 2013; Dittrich, et al. PRL, 2014; Park, et al., PRL, 2014; Hurricane, et al., Nature, 2014; Callahan, et al., PoP, 2015; Ma et al., PRL, 2015; Döppner, PRL, 2015

# 2015-2018: 2x higher yield achieved using high density carbon ablators (instead of plastic) and low helium gas-fill hohlraums




## Implosions seemed "stuck" at T ~ 5 keV




**Need more hotspot** $\rho RT \sim PR \sim \frac{m_{shell} v_{imp}^2}{R_{hs}^2}$



Divol, et al, PoP, 2017; LePape, et al, PRL, 2018; Berzak-Hopkins, et al, PPCF, 2018; Casey, et al, PoP, 2018; Baker, et al, PRL, 2018; Thomas, et al., PoP, 2020

# Felt that $v_{imp}$ and $R_{hs}$ were already near limits due to hydro-instability, so only design knob left was to increase $m_{shell}$

**But if we increase $m_{shell}$ without increasing energy coupling, we reduce $v_{imp}$ and convergence**

### High Yield Big Radius Implosion Design* (HYBRID)

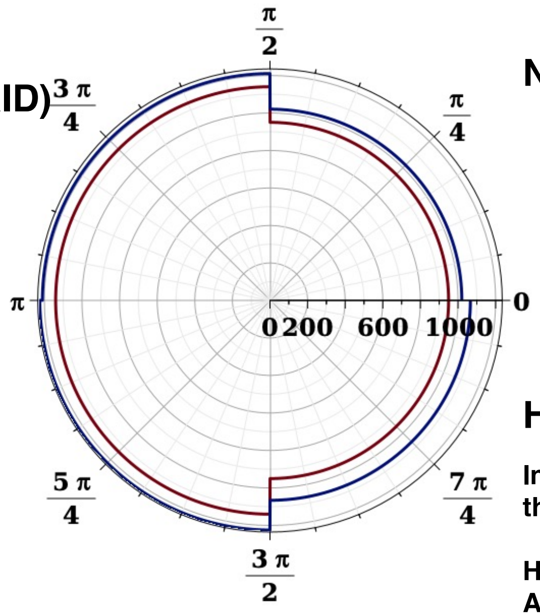
Radius increased
Thickness ~ same to start
Thicker later w/ more coupling

Slightly increased A-RT risk

### Hydroscale (e.g. Iraum+)

Radius and Thickness increase in the same proportion

Risk with new hohlraum, but low A-RT risk




### Nominal capsule geometry

### HotThick

Inner (or outer) radius ~same, but thickness increased

Hot hohlraum (risky) for ~same velocity but A-RT stability much better

**All need symmetry control otherwise the energy delivered to the hotspot is diminished**

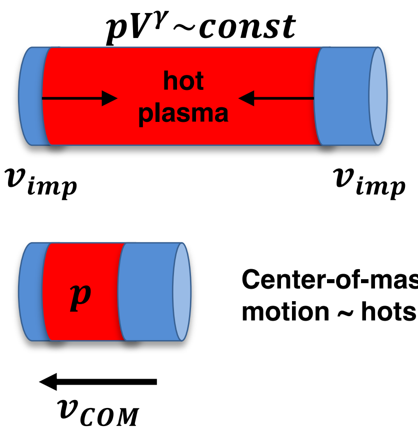


* Hurricane, et al, PPCF, 2018/2019 & Hurricane, et al, PoP, 2019; +Robey, et al, PoP, 2018

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

## Asymmetric implosion abstracted to pistons

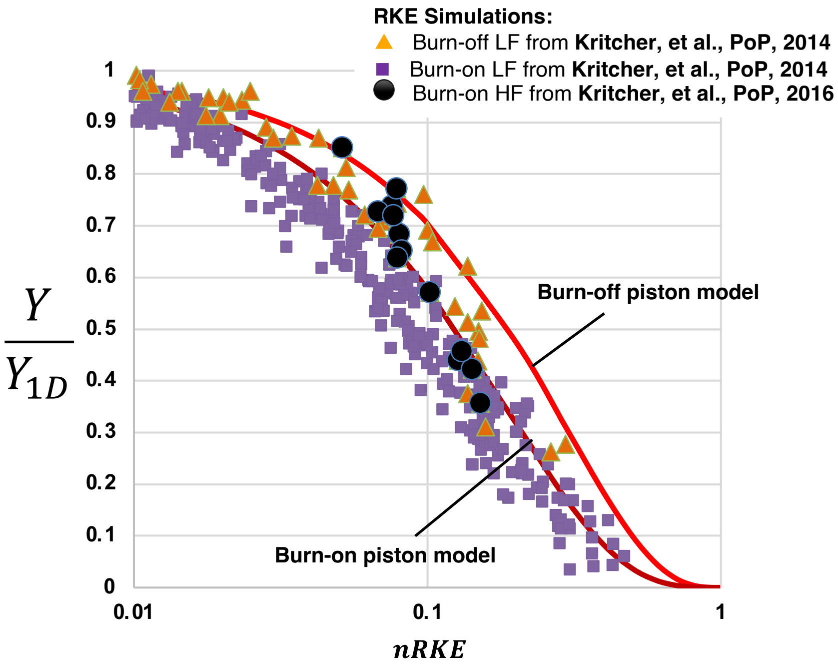
**Mode-1 classical mechanics model**




**Center-of-mass (COM) motion ~ hotspot velocity**

$$nRKE = \frac{v_{com}^2}{v_{imp}^2} = \frac{\rho R_{max} - \rho R_{min}}{\rho R_{max} + \rho R_{min}} \xrightarrow{3D^*} \frac{\left\langle \frac{1}{\rho R} \right\rangle^{-1}}{\langle \rho R \rangle}$$

$$\frac{Y_{no-burn}}{Y_{1D}} = (1 - nRKE)^a \text{ with } \langle \sigma v \rangle \sim T^a$$



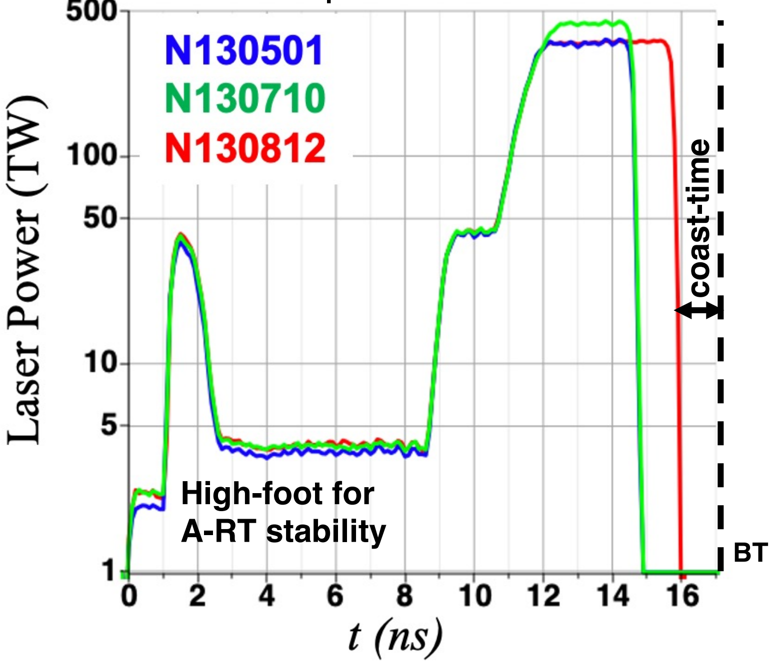

* Area Weighted Harmonic Mean (WHM): Hurricane, et al, PoP, 2022; Woo and Betti, PoP, 2021



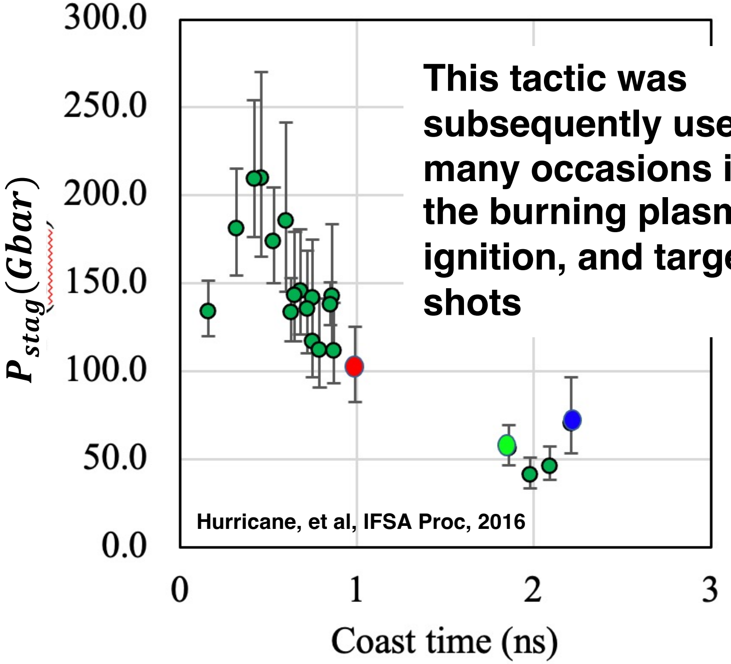
Hurricane, et al, PoP, 2020; Rinderknecht, et al., PRL, 2020; Casey, et al, PRL, 2021; MacGowan, et al, HEDP, 2022; Mode-1 Tion asymmetry work by Spears, et al, PoP, 2014; Schlossberg, et al, PRL, 2021

# We need to maintain short "coast-times" in order to minimize the implosion deceleration time, maximizing hotspot pressure & power

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




**Experimental observation**

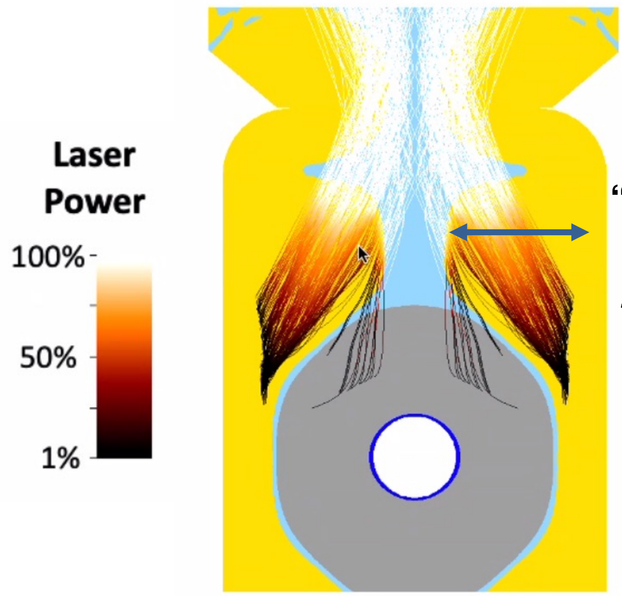



This tactic was subsequently used on many occasions including the burning plasma, ignition, and target gain > 1 shots

Optimal coast-time << hohlraum cooling time

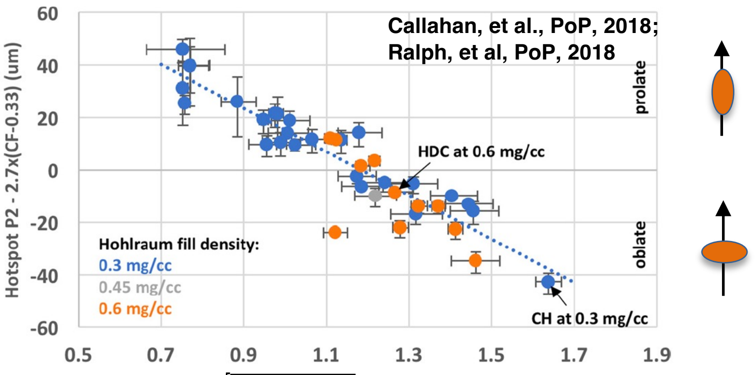
Hurricane, et al, PoP, 2017; Hurricane, et al, PoP, 2022
Effect on $\rho R$ was previously noted: Zylstra, PoP (2014); Landen, PoP, (2012)

# Significantly improved understanding of the levers controlling laser indirect drive implosion symmetry obtained by 2018




*Bubble blocks inner propagation*

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




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

**"Gold bubble" ingress:**

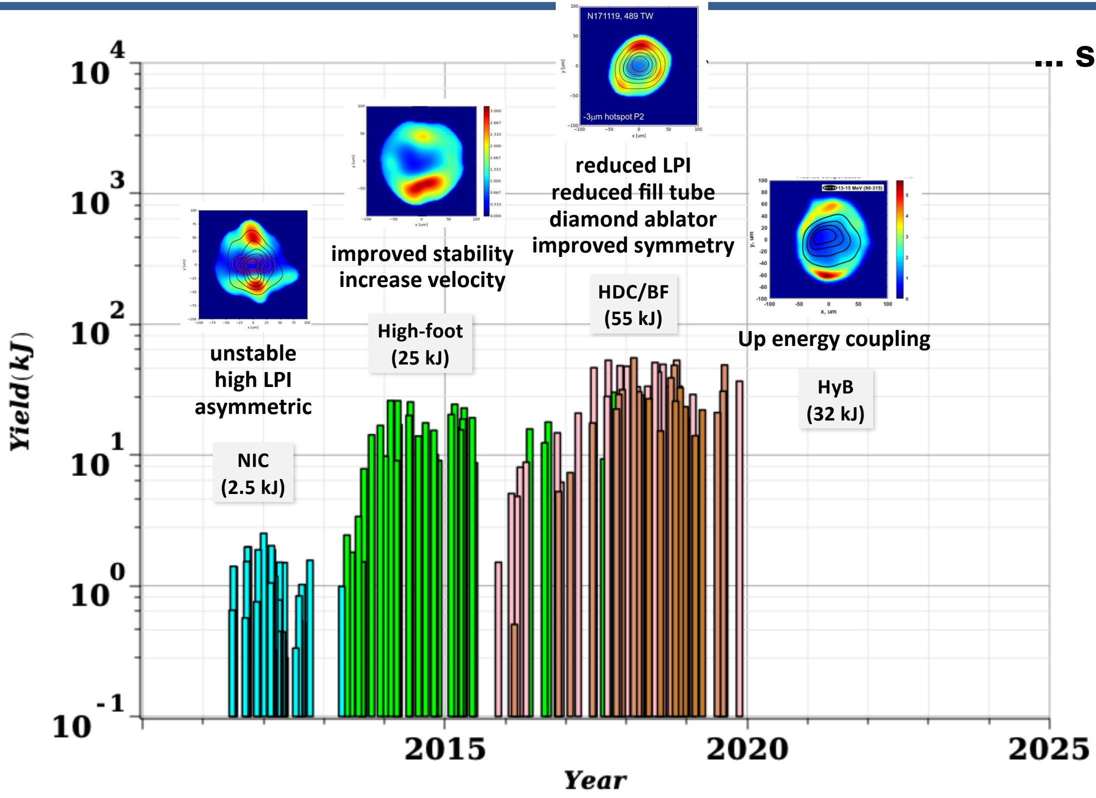
$$x_{bubble} \sim \sqrt{\frac{E_{picket}}{\rho_{gas}}}\, t_{laser}$$

**Cross-beam energy transfer (CBET) with low gas-fill:**

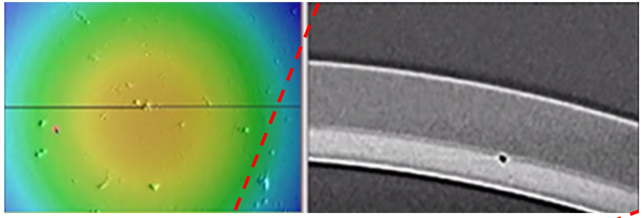
$\Delta\lambda = 0\text{Å}$ $\Delta\lambda = 1\text{Å}$

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

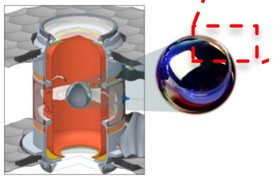
# 2018-2020: With a better understanding of the levers on capsule and hohlraum control, we scaled up capsule radius, but ...

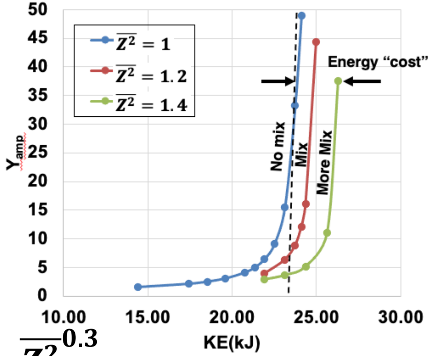



## ... surprised by capsule defects that cost energy



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





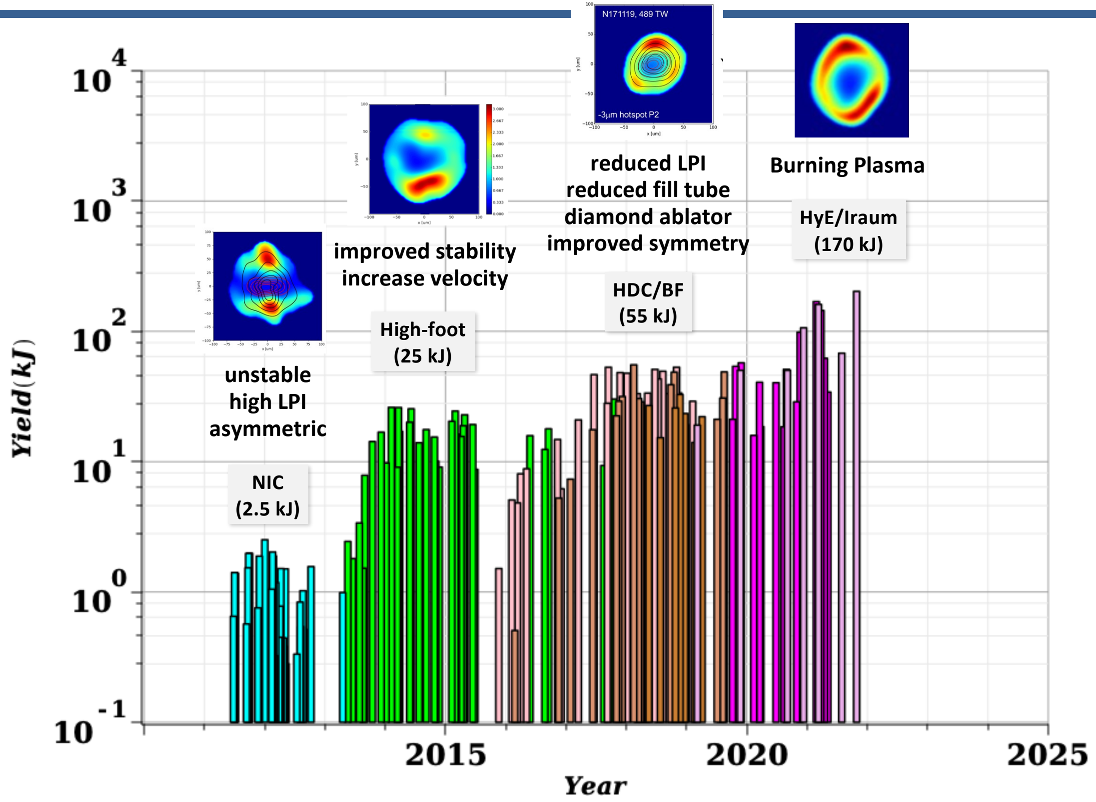

Ignition threshold moves to higher energy:

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

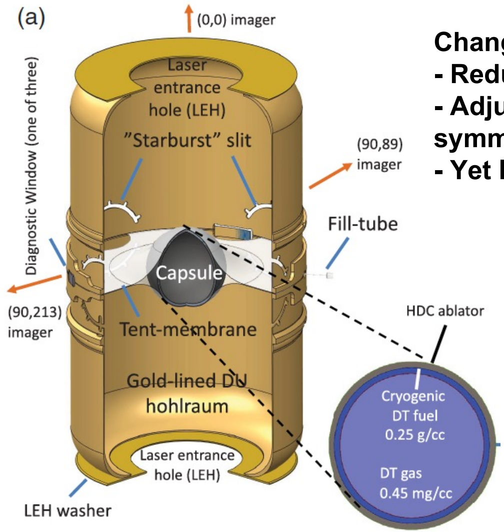


Braun, et al., Nuclear Fusion, 63, 2022; Zylstra, et al., Phys. Plasmas, 2020 (Hybrid-B)

# In 2019, both Hybrid-E and Iraum were renewed attempts at larger capsules, 1.9 MJ NIF, and different hohlraum tactics



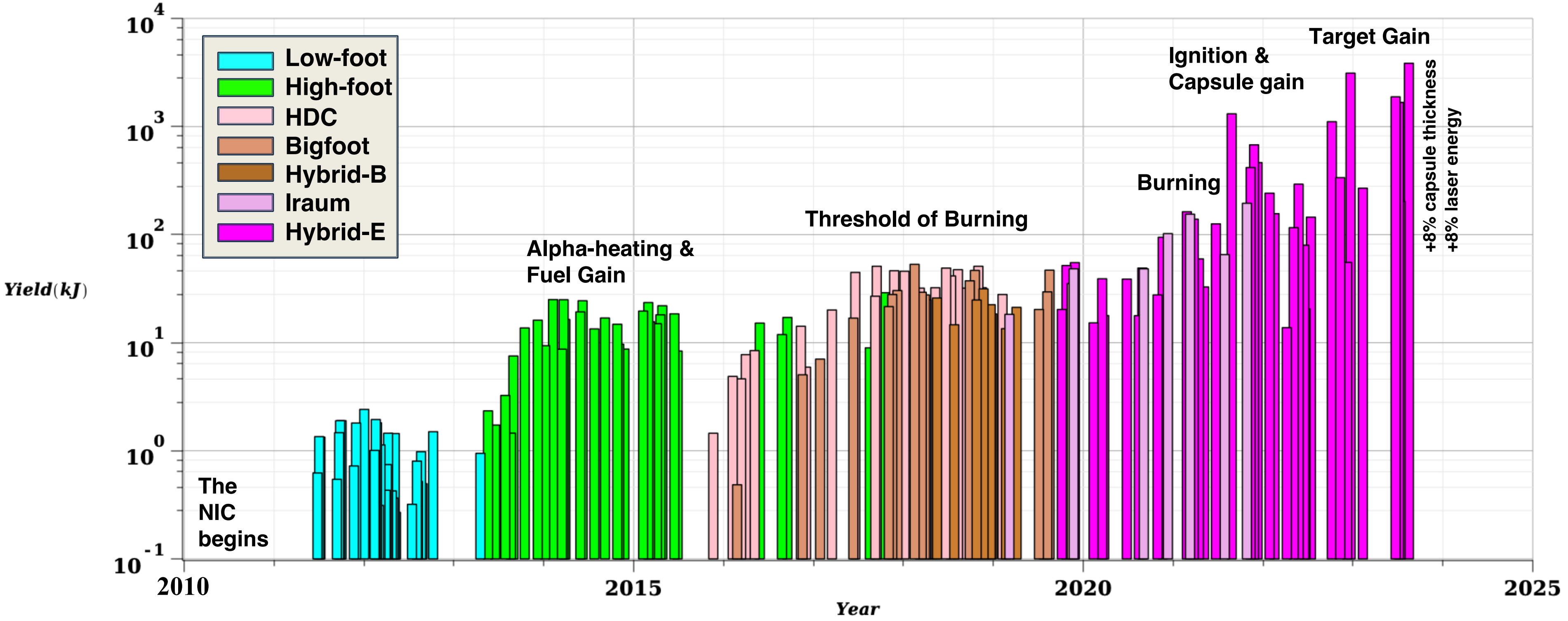

**"Once a burning plasma was achieved, ignition was not a matter of if but when"**
**- Betti, Nature, 2022**




**Changes:**
- **Reduced LEH size**
- **Adjustments to symmetry control**
- **Yet lower coast-time**

**Both worked and obtained a burning plasma (e.g. Betti, et al, PRL, 2015)**
**Zylstra, et al., Nature (2022); Kritcher et al, Nature Phys. (2022); Ross, et al, arXiv (2022)**

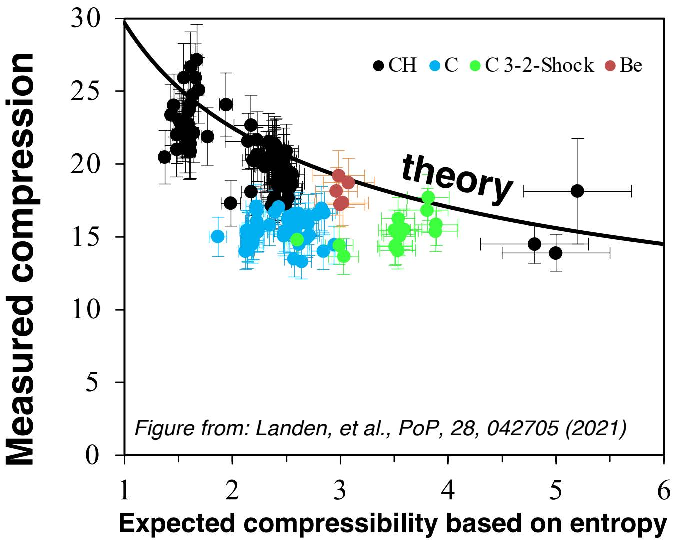
# 12 years of experimental effort to obtain fusion ignition (on 8/8/21) and target energy gain (on 12/4/22) by problem-solving in *steps*

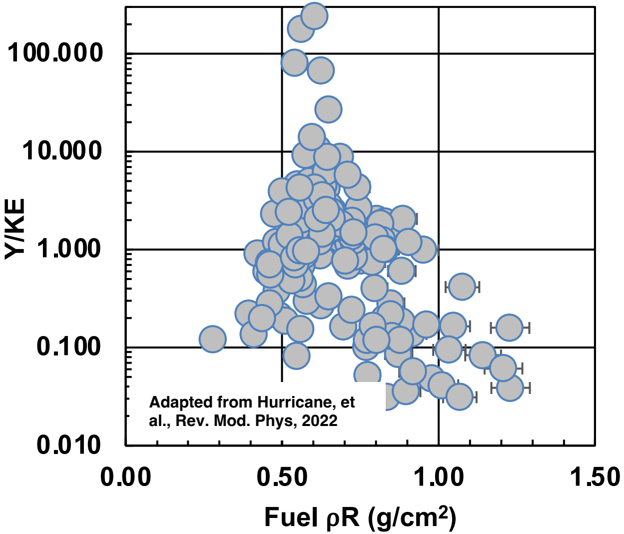





Abu-Shawareb, et al (Indirect Drive ICF Collaboration), PRL, 2021; Kritcher, et al, PRE, 2021; Zylstra, et al, PRE, 2021

# Outstanding problem: materials appear stiffer than models expected and higher compression is needed for increased burn efficiency




**Fraction of DT fuel burned:**

$$\phi \approx \frac{\rho R_{hs}}{\rho R_{hs} + 7}$$

Fraley, et al., Phys. Fluids, 17, 1974

**Record so far ~ 5%**

**~33% usually assumed for IFE purposes**

**Leading hypothesis for problem is (still) hydro-instability**



**The end of the beginning…there is more work to do!**

# We have an “existence proof” of fusion ignition and scientific breakeven (i.e. target gain >1) but practical challenges exist

- Low adiabat designs have yet to work as desired
  - Leading hypothesis is instability control at the fuel-ablator interface
  - Forces us to work at high adiabat which implies lower potential gain
- High implosion velocity and low coast (extended duration of late-time x-ray drive) are very effective, if the implosion is not compromised by other degradations
  - More energy to target is highly desirable in order to “pay” for symmetry and mix energy “costs”
- Symmetry control has been very hard to manage
  - Symmetry of the shell (fuel + remaining ablator) areal density is the driving physical factor
  - Favors shorter laser pulses, low hohlraum gas fill (for LPI), and larger case-to-capsule ratio hohlraums
    - Opposite of what you want for IFE!
- Hydro instability and mix are manageable to a degree, but are still a limiting factor
- Engineering control (of laser and targets) is extremely challenging
- Keep in mind 1 kWh (kilowatt-hour) = 3.6 MJ and average US household energy use is 30 kWh per day, so a long way to go for practical fusion energy