Igniting, by most definitions

Achieving a ~~burning~~ plasma on the National Ignition Facility Laser

HEDS Seminar Series (reprise of APS-DPP 2021 talk)

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On behalf of the ICF program

December 16, 2021

LLNL-PRES-828821
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

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This work builds on decades of research by an incredible team across LLNL and the wider community!

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WCI WEAPONS AND COMPLEX INTEGRATION

NIF&PS

Sandia National Laboratories

DE LA RECHERCHE À L'INDUSTRIE cea

Los Alamos NATIONAL LABORATORY

Diamond Materials Advanced Diamond Technologies

UR LLE

AWE

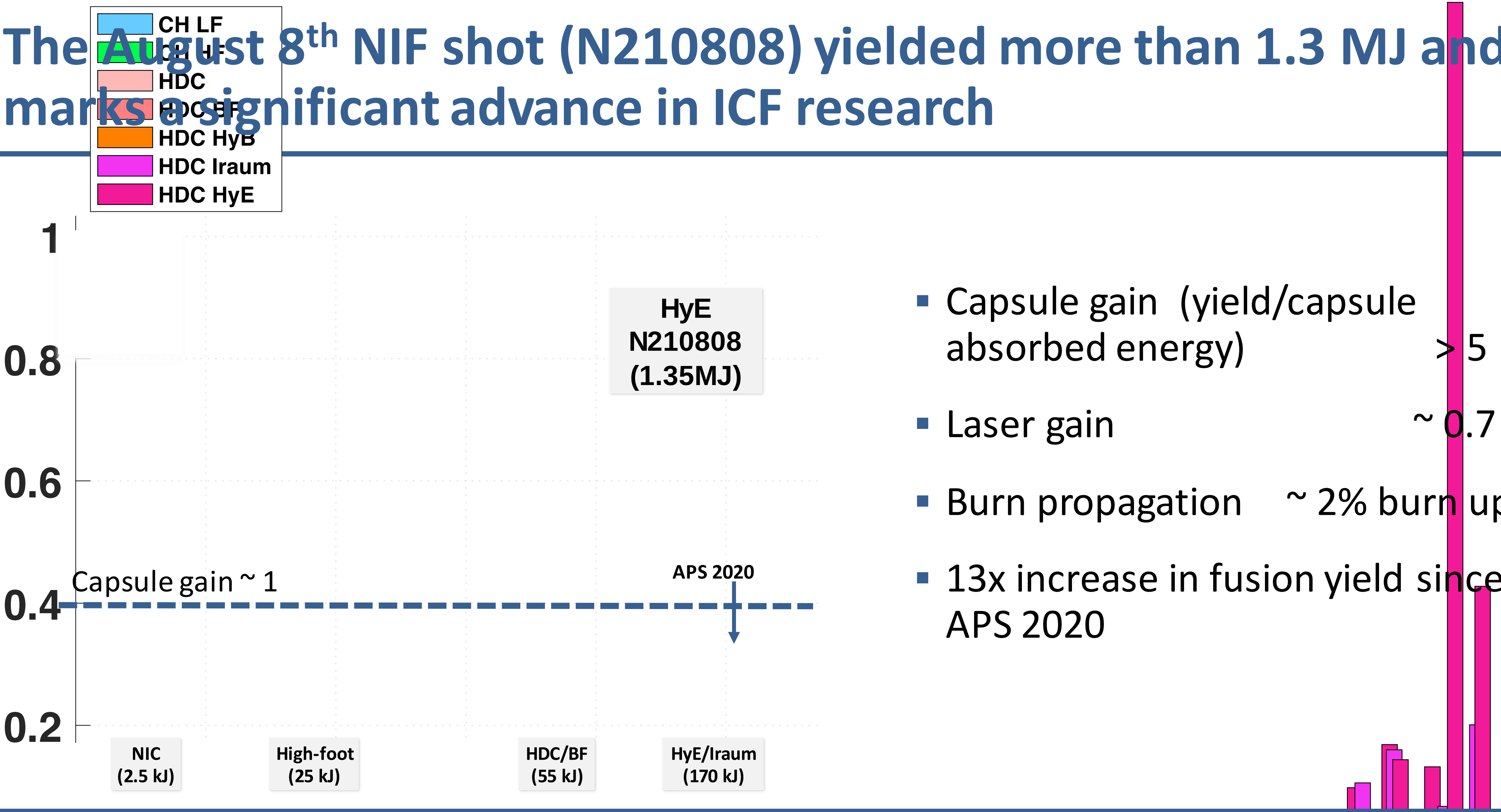
MIT | PSFC Plasma Science and Fusion Center

GENERAL ATOMICS

NNSA National Nuclear Security Administration

...and many more

The August 8th NIF shot (N210808) yielded more than 1.3 MJ and marks a significant advance in ICF research

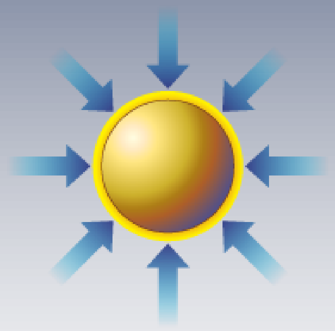


- Capsule gain (yield/capsule absorbed energy) > 5
- Laser gain ~ 0.7
- Burn propagation ~ 2% burn up
- 13x increase in fusion yield since APS 2020

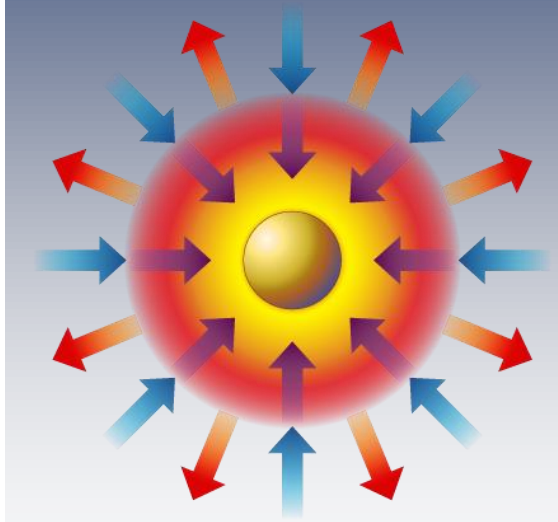
Our field is in a place that we have never been in before!

Inertial Confinement Fusion (ICF) can be achieved by using high power lasers to drive a spherical implosion

Lasers produced X-rays rapidly heat the surface of a capsule containing deuterium-tritium (DT) fuel

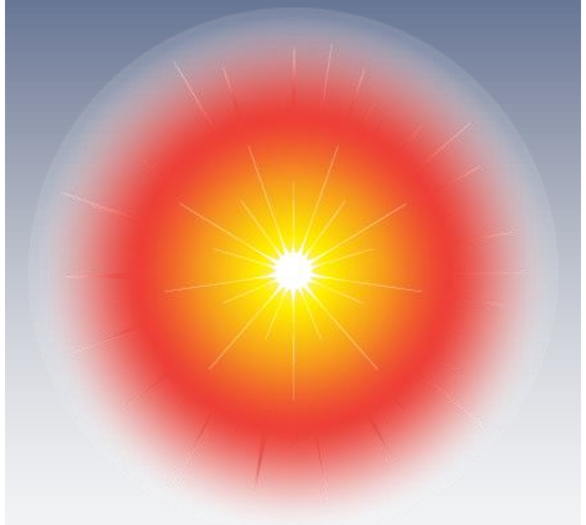


The blowoff plasma accelerates the DT fuel inwards in a rocket-like reaction



The fuel stagnates creating a hot central core, surrounded by a dense confining shell

The core ignites and fusion burn propagates into the dense shell, yielding many times the input energy



Radiation

Blowoff

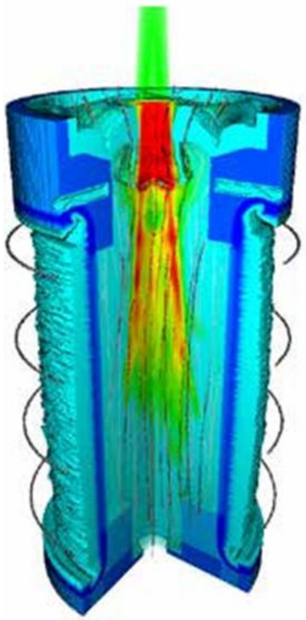
Inward Accelerated Shell

The U.S. is pursuing several complementary approaches to ignition in ICF research

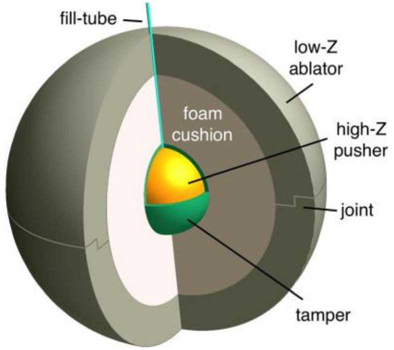
Laser indirect drive

Laser Direct Drive

Magnetic Drive



Double shells



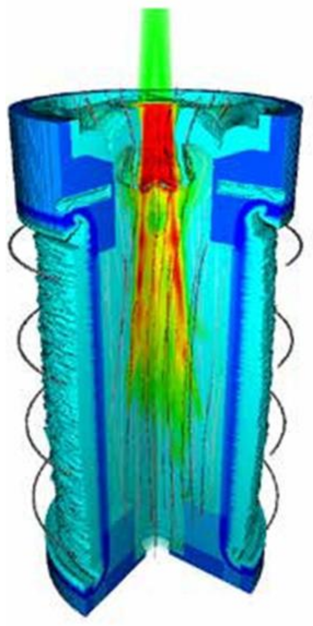
Achieving ignition in the laboratory is a Scientific Grand Challenge nearly 60 years in the making

This talk will focus on laser indirect drive

Laser indirect drive

Laser Direct Drive

Magnetic Drive



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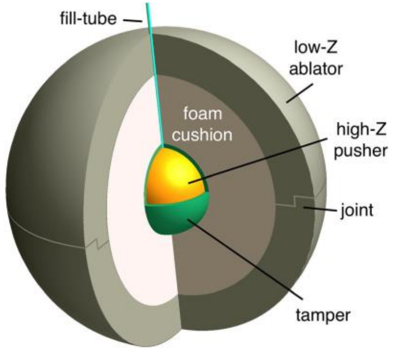


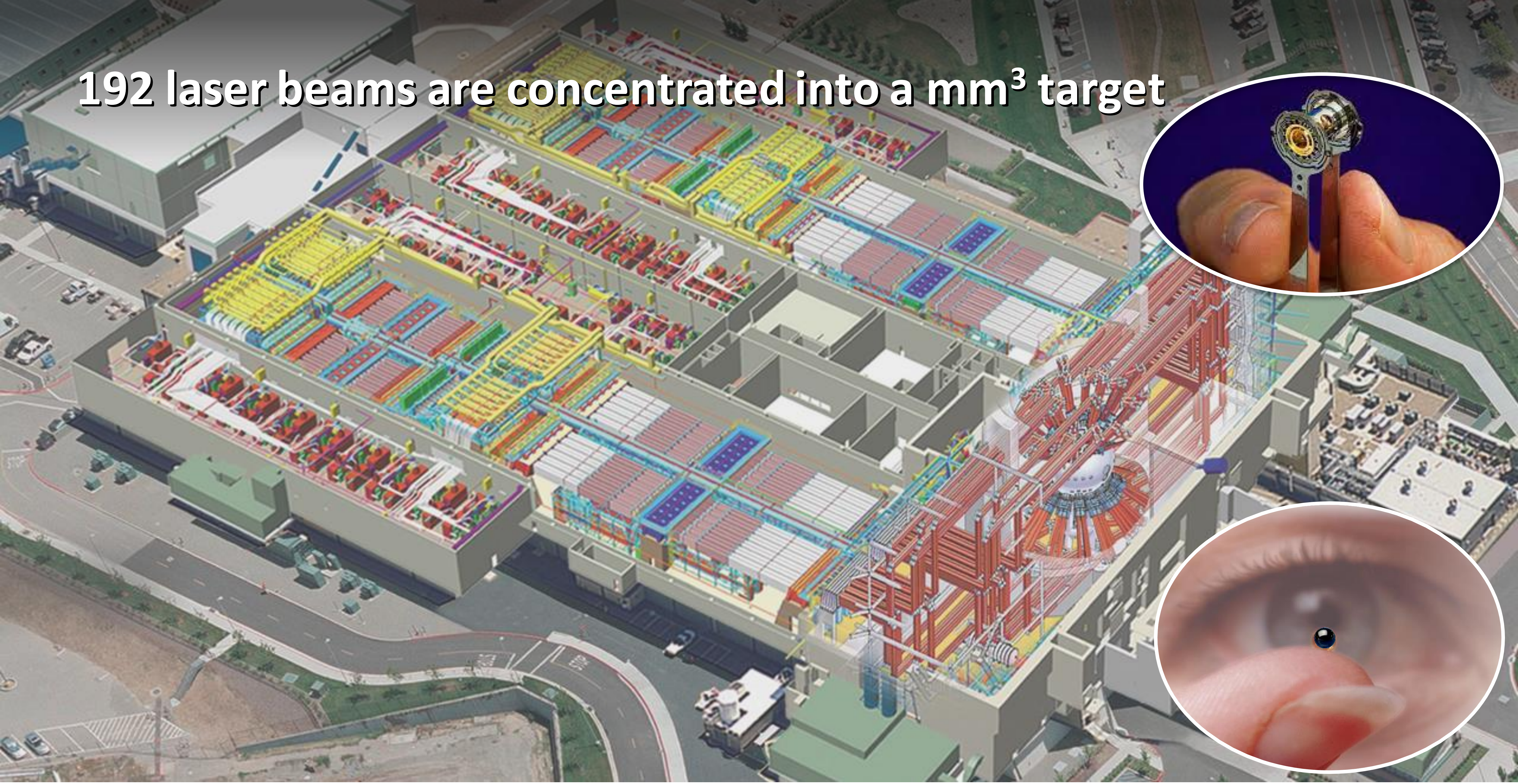
Invited sessions: BI01, KI02, QI02, WI02, ZI02

Achieving ignition in the laboratory is a Scientific Grand Challenge nearly 60 years in the making

NIF is the world's most energetic laser enabling the study of extreme conditions for Stockpile Stewardship

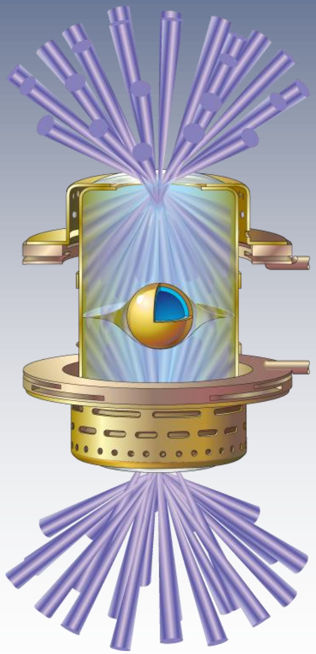
- 192 Beams, 1.9 MJ Energy, 500 TW Power
- Matter temperature $>10^8$ K
- Radiation temperature $>3.5 \times 10^6$ K
- Densities $>10^2$ g/cm^3
- Pressures $>10^{11}$ atm
- Number of Diagnostics >120

192 laser beams are concentrated into a mm^3 target

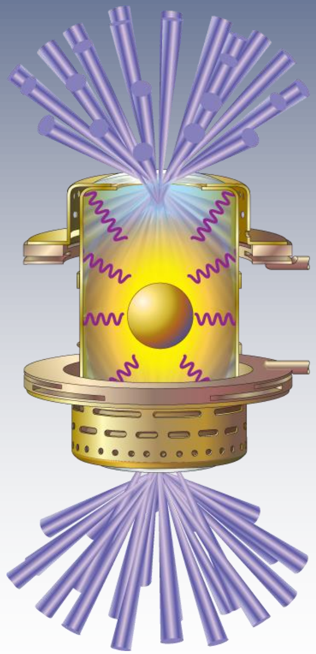


Indirect drive uses a laser driven hohlraum to compress a fuel pellet to the conditions needed for ignition

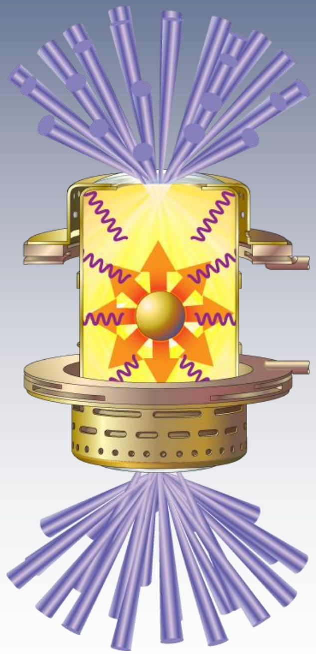
Each of the 192 laser beams are focused onto the inner wall of the hohlraum



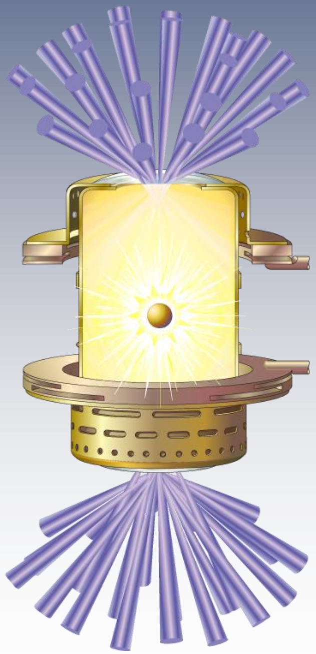
Laser beams rapidly heat the inside surface of the hohlraum creating x-rays



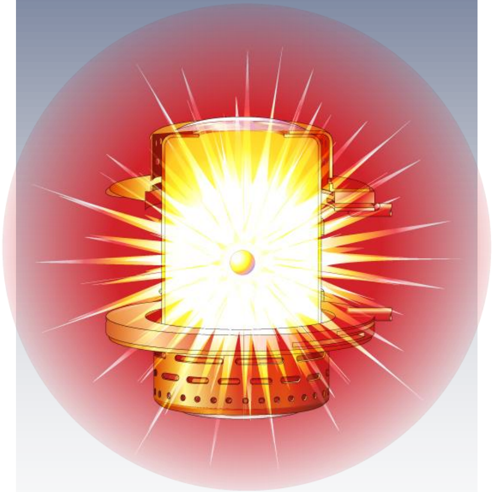
The x-rays ablate the capsule, accelerating the fuel inward to ~ 400 km/s



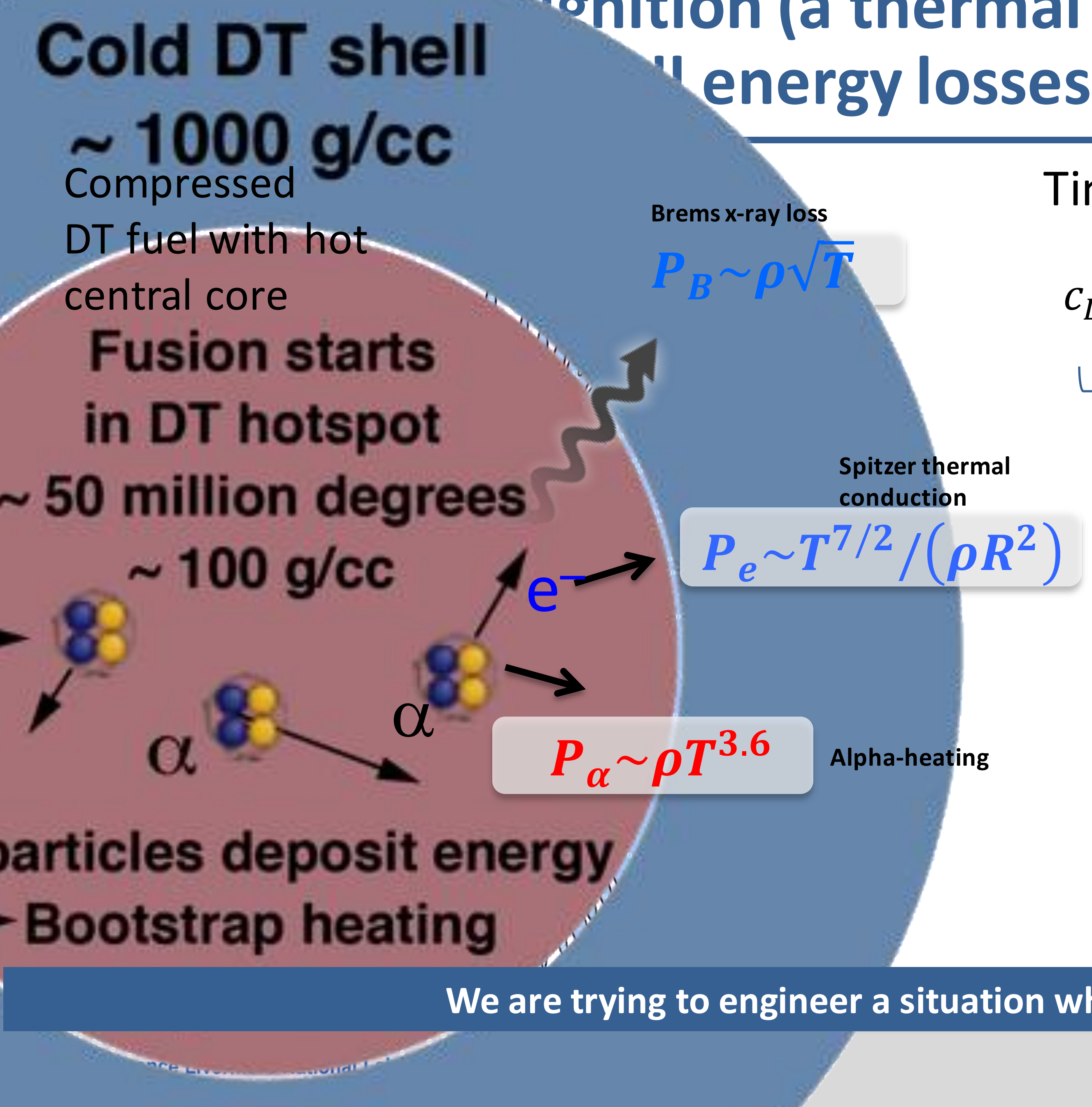
The fuel core reaches 500-1000 g/cc and ignites at temperatures >5 keV



Fusion burn spreads rapidly through the compressed fuel, yielding many times the input energy



…ignition (a thermal instability), the plasma must …ll energy losses for a duration of time

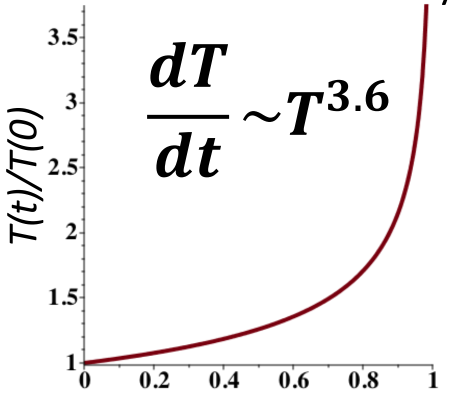


Time dependent heat balance (power/mass):

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

Ignition when these terms dominate

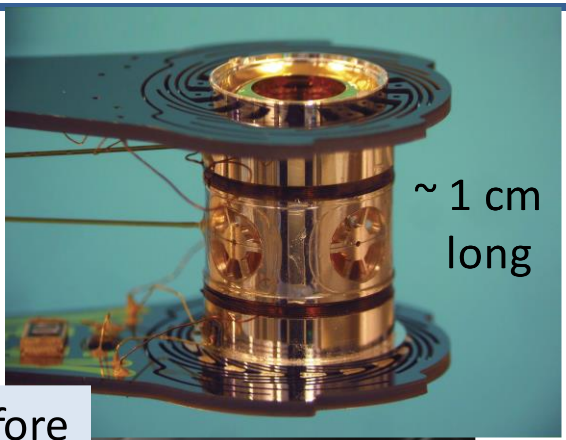
Thermonuclear instability

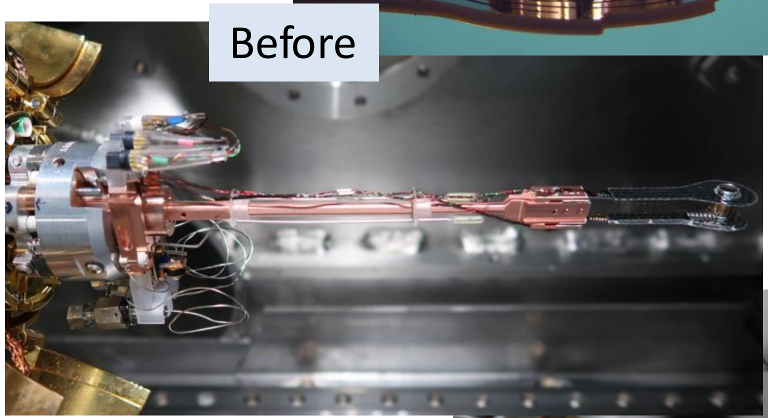


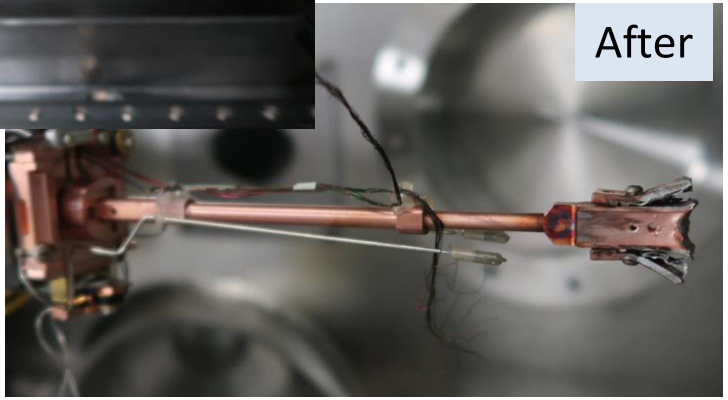
t/τ $\tau \sim 10's\ of\ picoseconds$

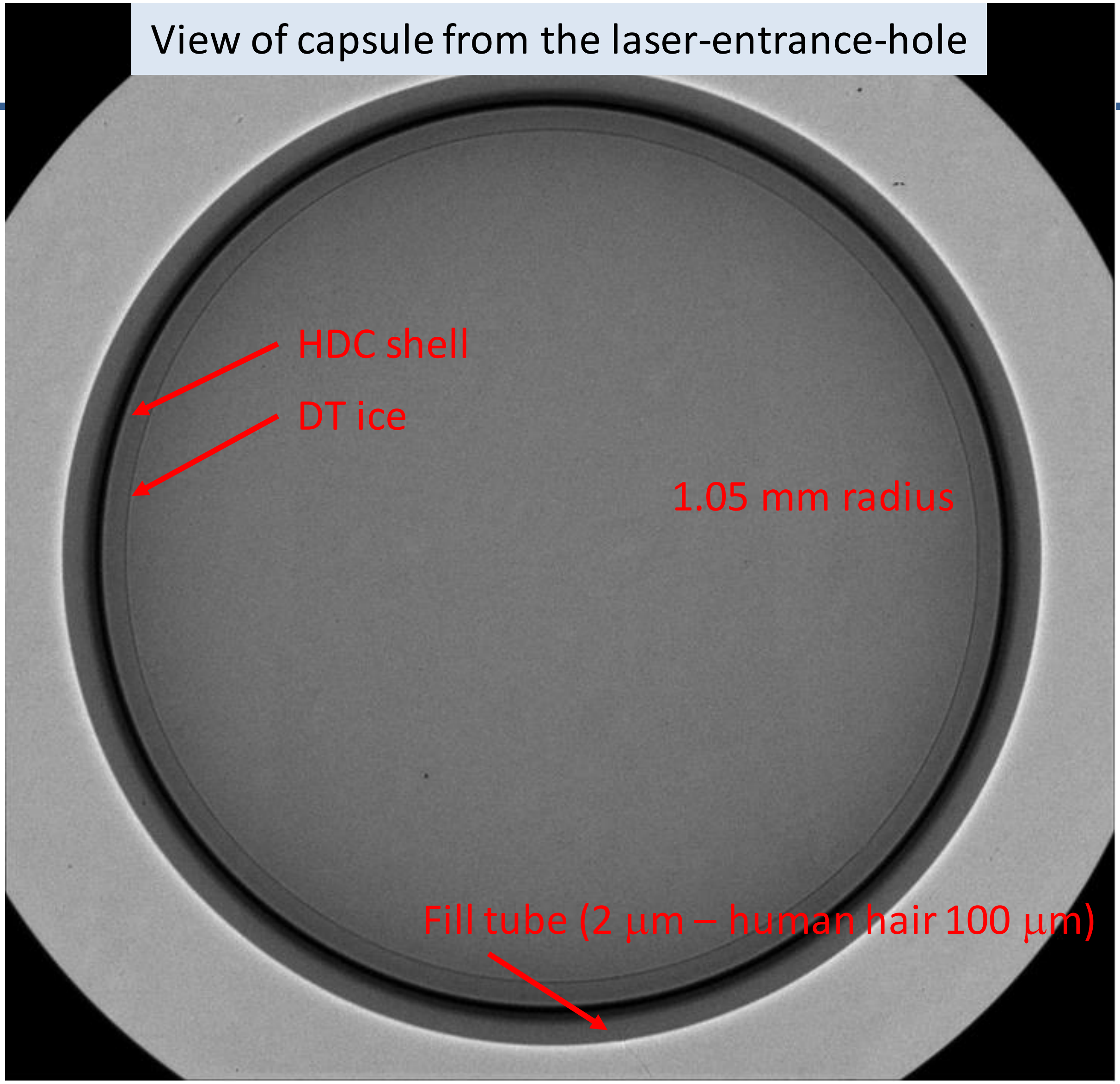
We are trying to engineer a situation where heating dominates over losses

Targets are engineering marvels

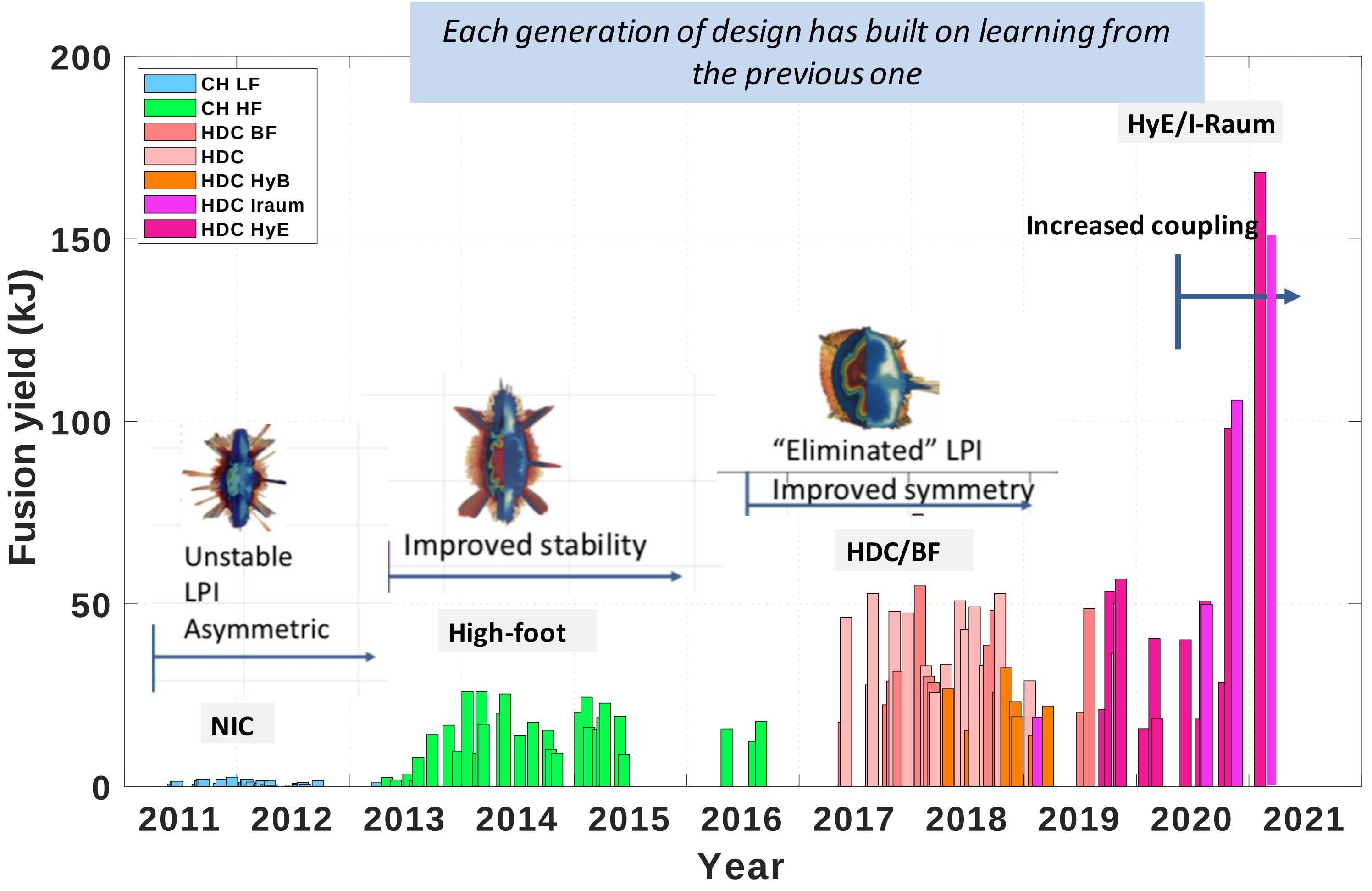


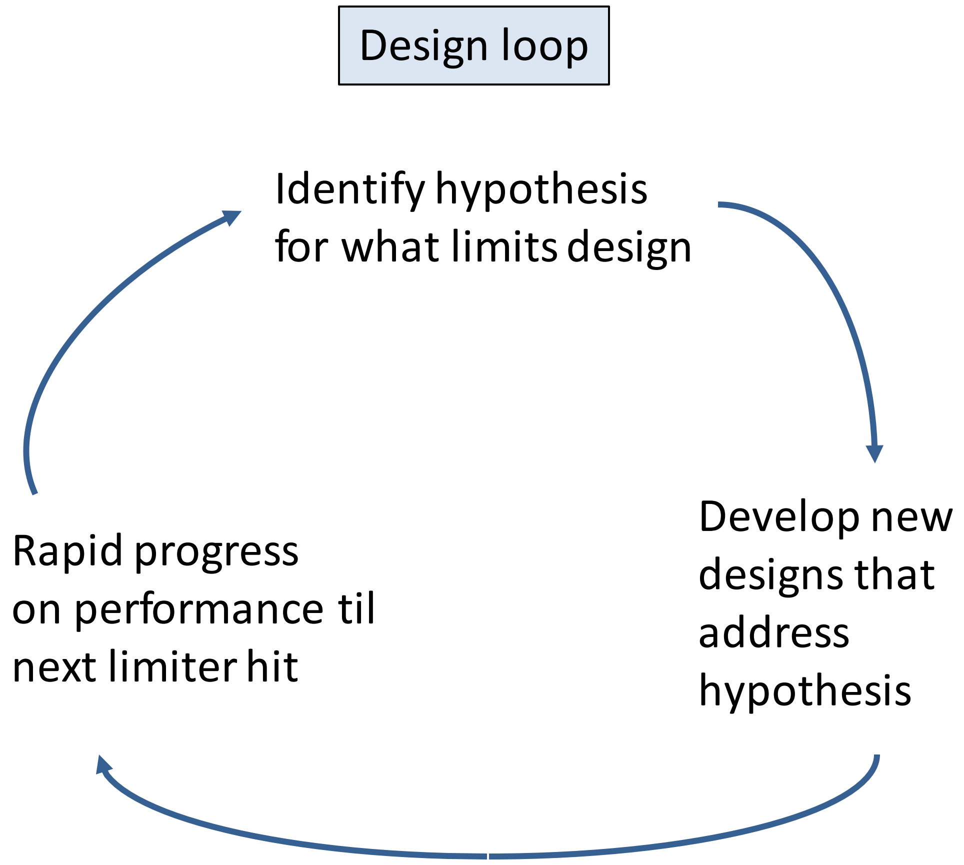






We have made progress towards ignition in steps – learning what limits the implosion and the redesigning based that learning



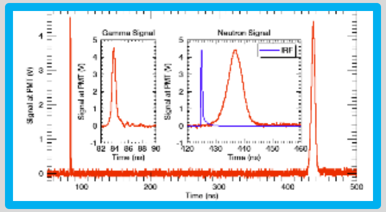


Simulations: D. Clark

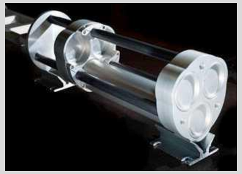
NIF diagnostics have provided key insight into our experiments and built understanding, here are some examples

DT Ion temperature, hot spot velocity, fuel density, yield

- Five Neutron Time of Flight (nToF)'s and the Magnetic Recoil Spectrometer (MRS)

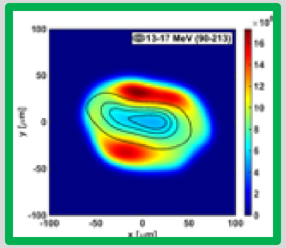


DT Neutron yield



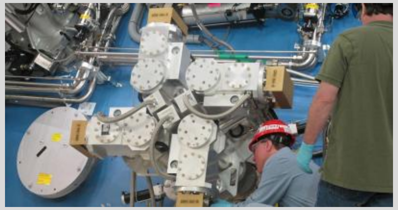
- Zirconium/Copper Nuclear activation

Hot spot and Fuel Shape from Neutron Imagers

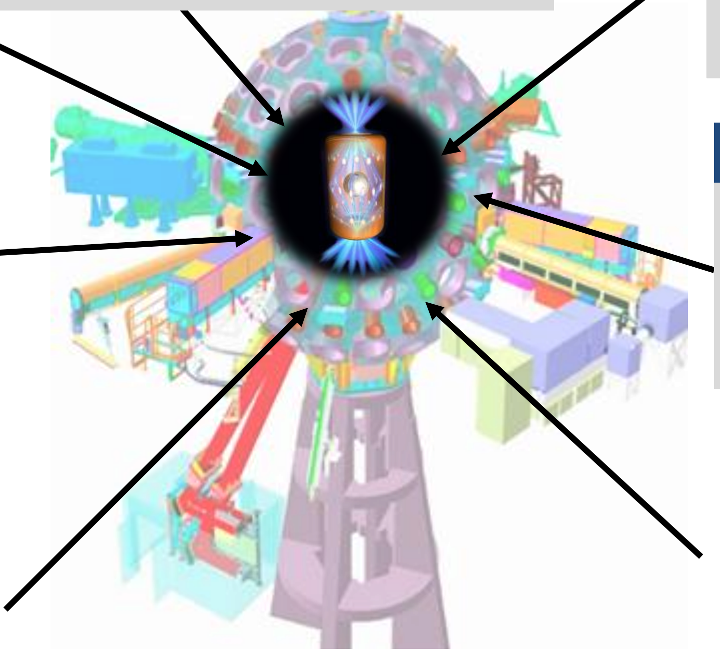


- 3 Neutron Imaging (NIS) Lines of sight for 3D reconstruction of neutron hot-spot
- 2 NIS down-scatter lines of sight for fuel shape

Burn width, Bang Time, DT neutron yield

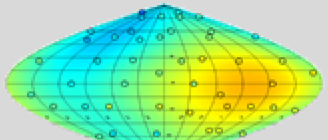


- Gamma Reaction History

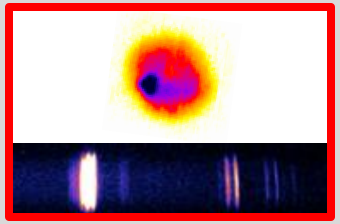


DT Yield Map /Fuel uniformity

- 48 Real-Time Nuclear Activation (NAD)'s



X-ray Imaging & Spectroscopy



- 3 x-ray imaging lines of sight
- X-ray spectroscopy to characterize material mixed into the hotspot

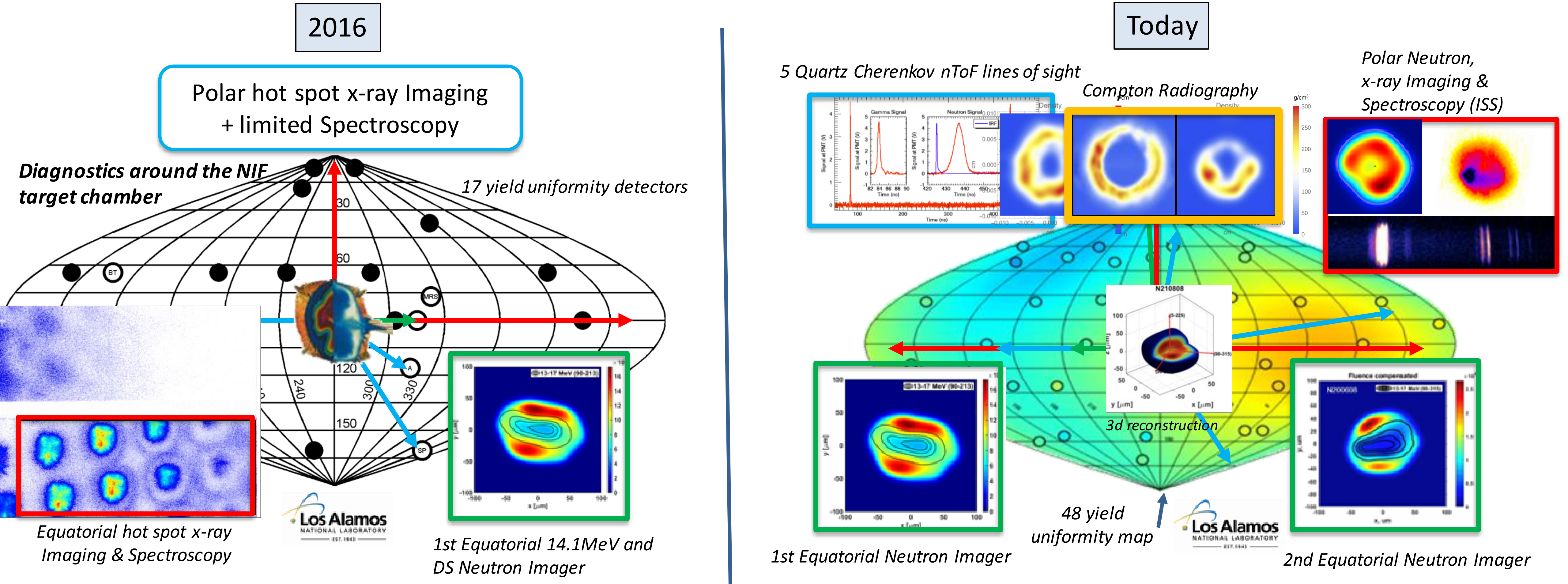
DT Fuel uniformity: Compton Radiography

- ~100keV x-rays produced by Advanced Radiography Source provide radiographs of DT fuel

See sessions GO07, ZO04, KI02

This is the best diagnosed HED plasma on the planet! -> Developed over decades by the whole HED community

Our ability to diagnose the 3D aspects of the implosion has increased significantly from 2016 to today



Improved diagnostics, theory, and simulations are key to developing our understanding

Neutron yield is a function of six parameters that we need to control to get ignition

Scaling law for yield amplification ~ 2 from theory, which guides our design choices but needs to be tested experimentally

$$Yield \sim p_{if}^{0.64}\,\frac{v_{imp}^{4.5}}{\alpha_{if}^{1.4}}\,S^{4.6}\,\delta\,(1\text{- }RKE_{norm})^{3.8}$$

- Need high velocity of the shell to produce the pdV work that heats the hotspot
- Bigger hotspot (scale) has more energy
- Need good symmetry to efficiently couple shell kinetic energy into pdV work to heat the hotspot
- Ablation pressure "inflight" by lower "coast": Need to keep pushing on the shell until late in the implosion trajectory
- Lower adiabat (entropy) is more compressible which reduces energy needed for ignition but makes implosion more sensitive
- Good stability because mix brings higher Z material into hotspot and results in radiative loss

1: *O. Hurricane et al, APS-DPP, PO7.00001 (2017); PPCF 61, 014033 (2019); PoP 26, 052704 (2019)*

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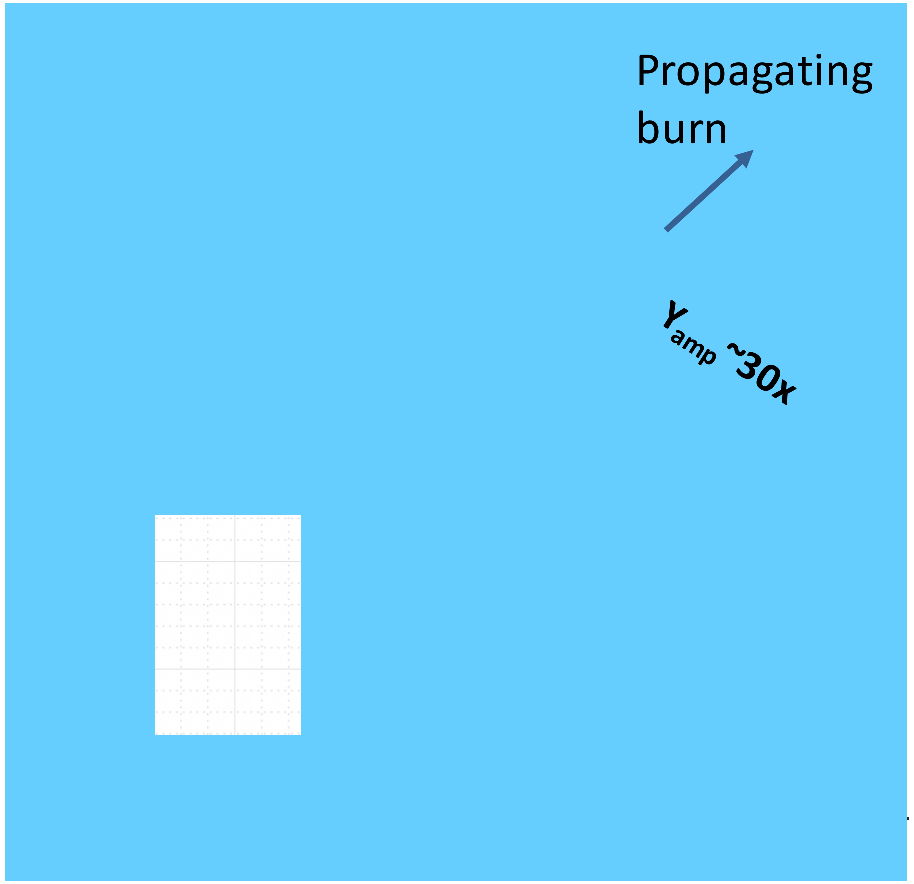
We have steadily advanced our physics understanding and the technology over the last decade to improve performance

- *$E_{HS}P_{HS}^2$ [Patel] related to ITFX and Generalized Lawson Criteria [Betti]*
  - This metric uses "no burn" quantities
    - A model is used to convert data from burn on to burn off
    - "Dudded fuel" implosions check that model (more of these expts upcoming)
  - Simulations indicate that ignition corresponds to Y_{amp} ~ 15-30x
  - Boundary is uncertain (based on simulations)

Ignition figure of merit $\sim (\rho R)^3 T^3 \sim E_{HS} P_{HS}^2$

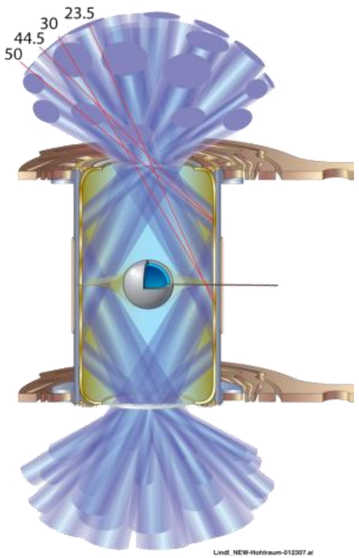


P. Patel, Phys. Plasmas 27, 050901 (2020)
R. Betti, et al, Phys. Plasmas, 17, 058102 (2010)
A. R. Christopherson, et al, PHYSICAL REVIEW E **99**, 021201(R) (2019) 4:
J. D. Lindl, et al, Phys. Plasmas, 25, 122704 (2018)

Walk through the various designs from the last several years

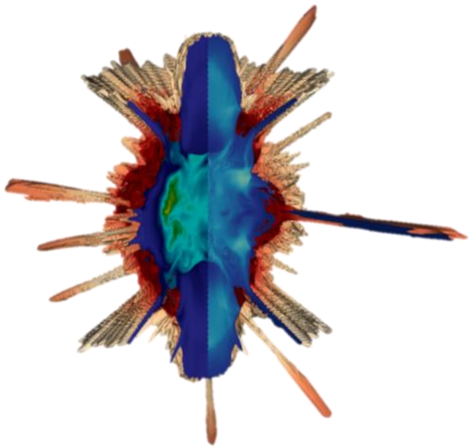
Initial designs were low adiabat, plastic capsules in high-gas filled hohlraums and had low hot spot pressure and energy

"Low foot[1]" Y = 2 kJ

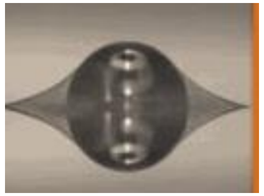


High gas filled hohlraum

Plastic capsule



Clark, et al IWPCTM, 2018



Tent

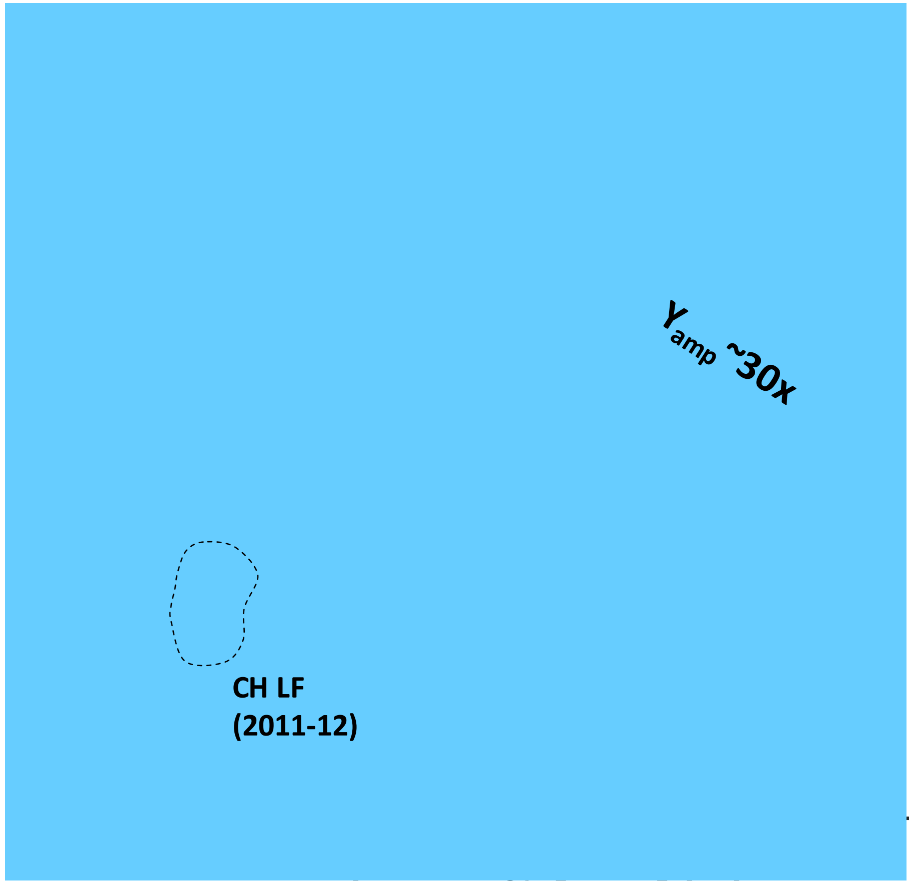
-> High LPI (reduces drive and velocity)

-> Symmetry swings

(Cross beam energy transfer)

-> Mix (tent)

Ignition figure of merit $\sim (\rho R)^3 T^3 \sim E_{HS} P_{HS}^2$



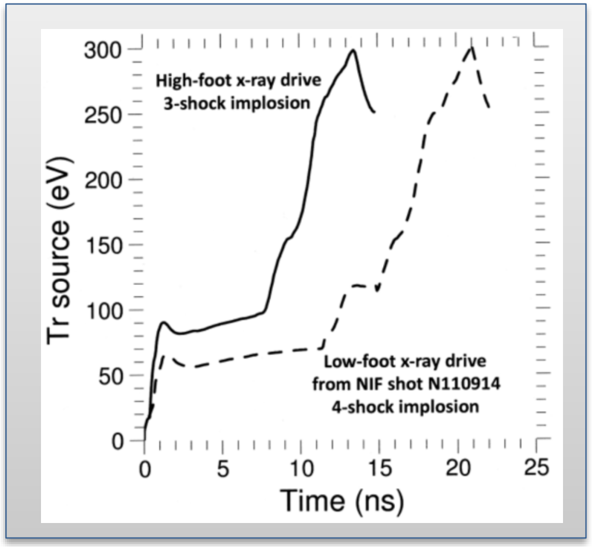
It was later found that the capsule support membrane ("tent") was a major factor disrupting the hot spot

1: J. Lindl, et al, PHYSICS OF PLASMAS 21, 020501 (2014)

The high foot design increased the adiabat to reduce capsule instability and convergence – performance improved but plateaued

"High foot[1-3]"   Y = 27 kJ

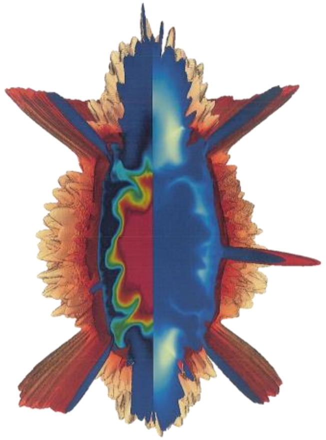
Higher adiabat[1-3]



-> Improved stability
-> Higher velocity, less mix
-> LPI and shape swings persist

High gas filled hohlraum

Plastic capsule



Clark, et al IWPCTM, 2018

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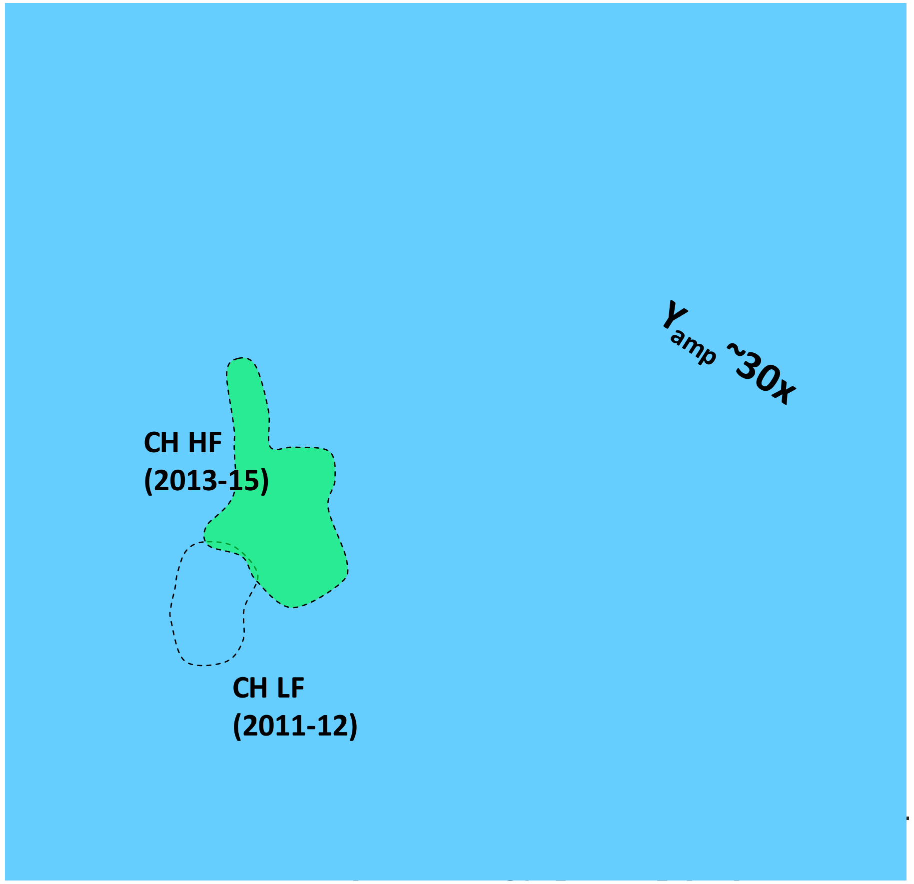


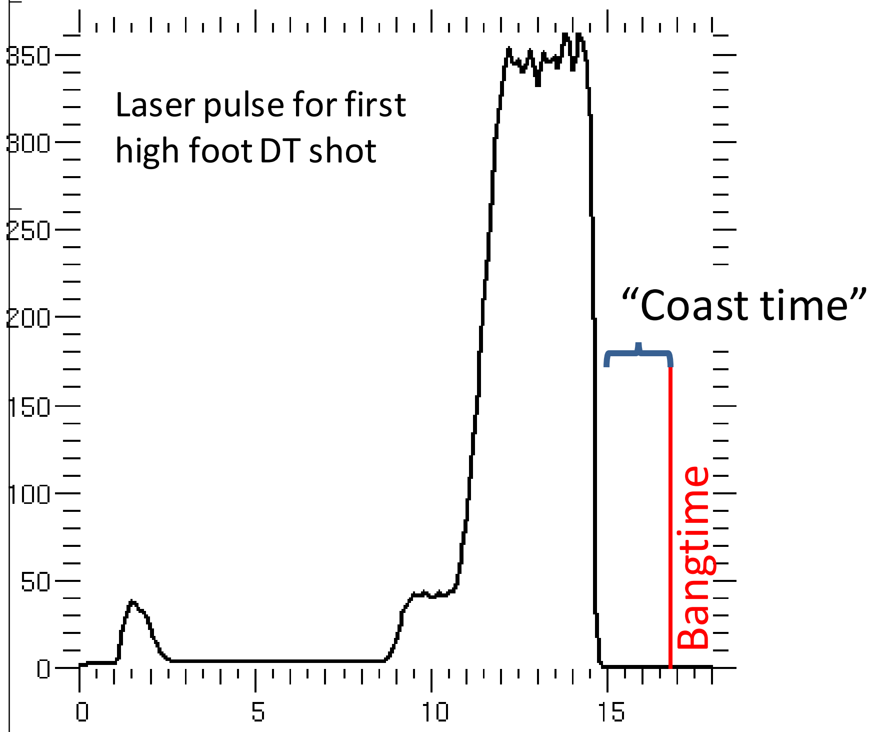
Tent caused the plateau. LPI remained a major problem -> energy losses, large symmetry swings

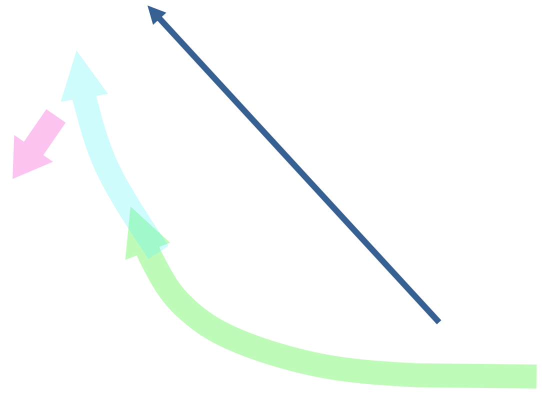
1: T. Dittrich, et al Phys. Rev. Lett. 112, 055002; 2: O. Hurricane, et al, Nature 506,343 (2014); 3: H. S. Park, et al Phys. Rev. Lett. 112, 055001

High foot showed that maintaining high ablation pressure until late in the pulse was important – control by "coast time"

"Coast time" is the time between end of the laser pulse and bangtime

Initially, we saw empirically that reducing coast time improved performance -- the longer laser pulse makes symmetry more difficult





We now have a better understanding of the impact of coast time -- see O. Hurricane's talk in the next session

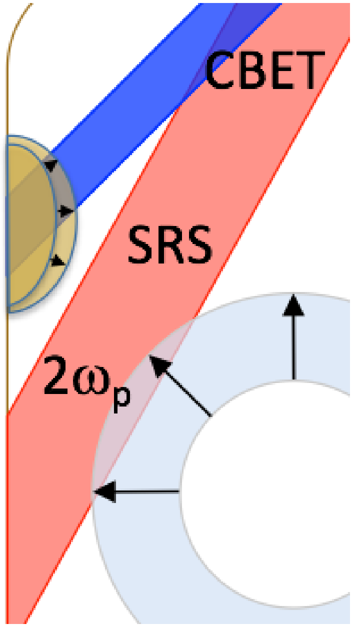
Moved to low gas-filled hohlraums to reduce laser-plasma-interactions (LPI) that had been present in high and low foot

High gas fill – LPI dominated
(~ 4-5% critical density)

Cross beam energy transfer

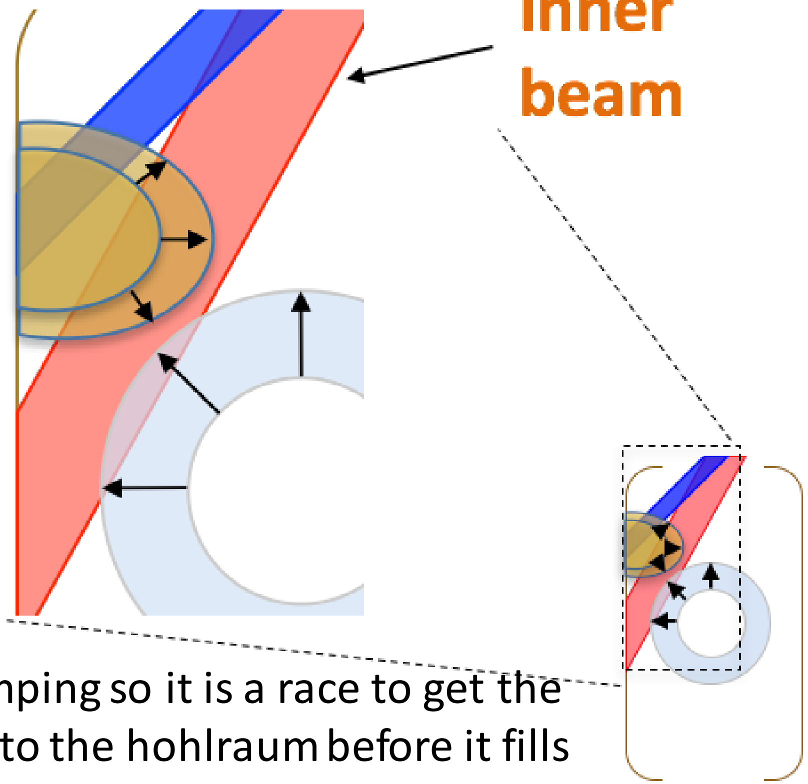
Stimulated Raman Scatter

$2\omega_p$ instability



Hohlraum fill tamps the expansion of the wall and keeps the hohlraum from filling with gold plasma but has high LPI

Low gas fill – Radiation hydrodynamics dominated
(< 2.5% critical density)



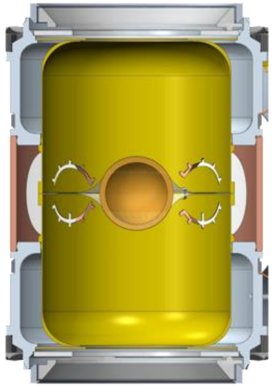
Less tamping so it is a race to get the pulse into the hohlraum before it fills with plasma

Low gasfill hohlraums are a good match to diamond (HDC) ablators because the high density leads to shorter pulses

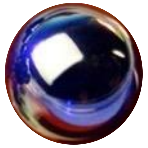
Diamond (HDC) capsules resisted the tent and used shorter laser pulses – performance improved

"HDC[1]/BigFoot[2]" Y = 55 kJ

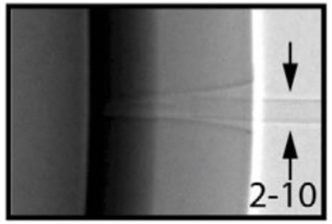
Low gas filled hohlraum



Diamond capsule



10µm -> 5µm fill tube[3]

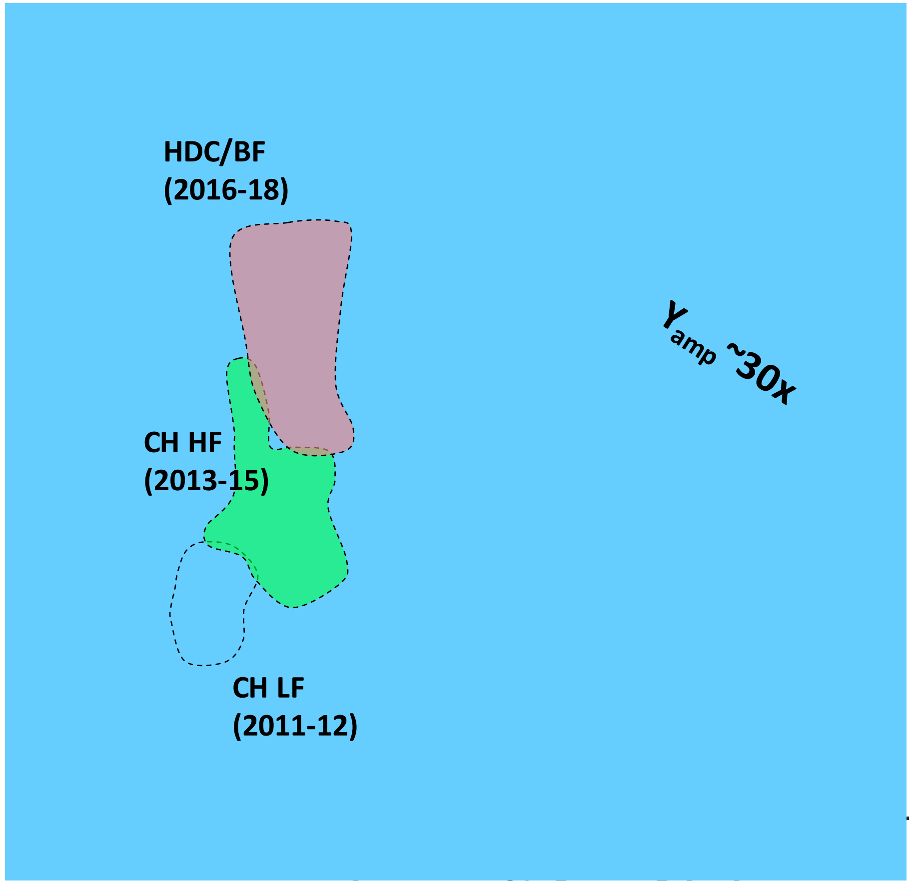


-> Reduced LPI
-> Better symmetry

-> Tent resistance
-> Higher velocity

-> Reduced mix
-> Less radiative loss

Ignition figure of merit $\sim (\rho R)^3 T^3 \sim E_{HS} P_{HS}^2$

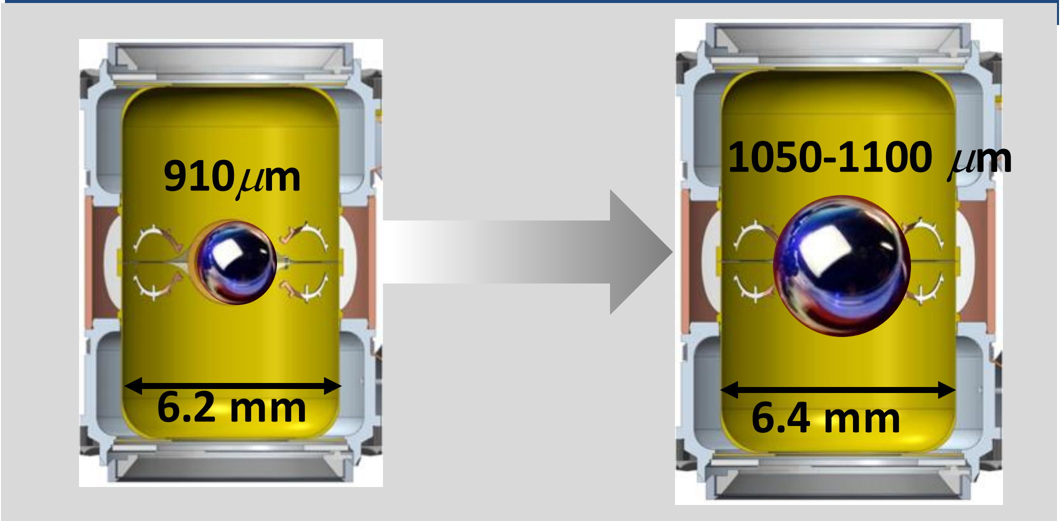


Energy still too low – need a bigger capsule, same implosion pressure, but no more laser energy – major challenge

1: S. Le Pape et al., PRL 120, 245003 (2018); L.B. Hopkins et al., PPCF 61, 014023 (2018)
2: D.T. Casey et al., PoP 25, 056308 (2018); K.L. Baker et al., PRE 102, 023210 (2020)
3: A. Pak, et al, Phys. Rev. Lett. 124, 145001

HYBRID-E Challenge: make capsule bigger! But keep similar adiabat, stability, velocity, "coast time", and *symmetry* with fixed laser energy

Much bigger capsule in to slightly larger hohlraum



***HDC* (BigFoot)**

Lead designer: L. Berzak Hopkins, C. Thomas
Lead expt: S.Le Pape, D. Casey

***HYBRID-E*[2]**

Lead designer: A. Kritcher
Lead expt: A. Zylstra

$$Y \sim p_{if}^{0.64} \frac{v_{imp}^{4.5}}{\alpha_{if}^{1.4}} S^{4.6} \delta (1 - RKE_{norm})^{3.8}$$

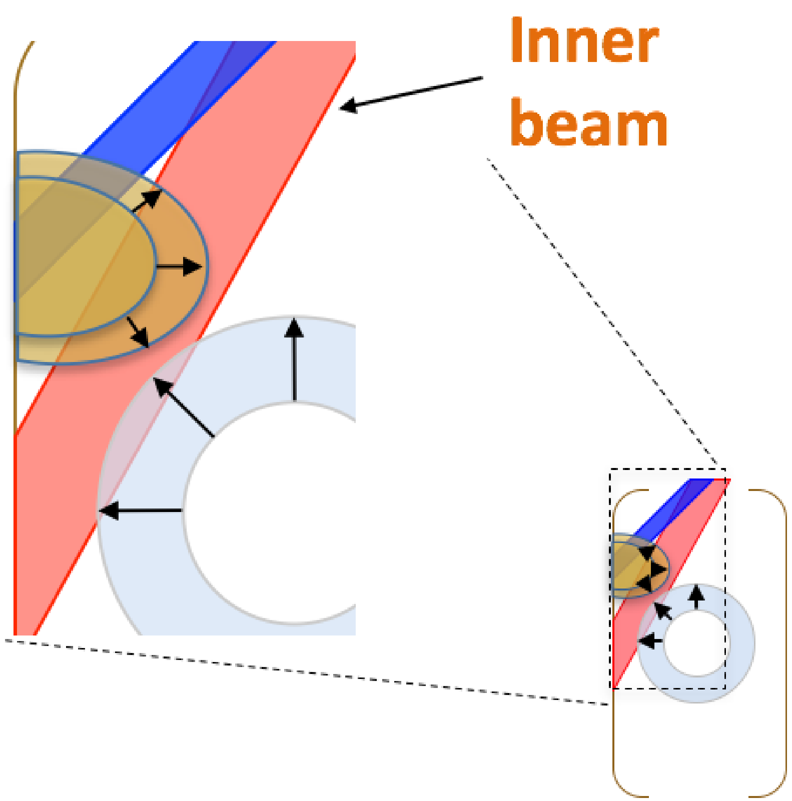
Yield; Ablation pressure "inflight" by lower "coast"; Implosion velocity; Adiabat; Scale; Symmetry; Stability

High Yield Big Radius Implosion Design (HYBRID) strategy[1]

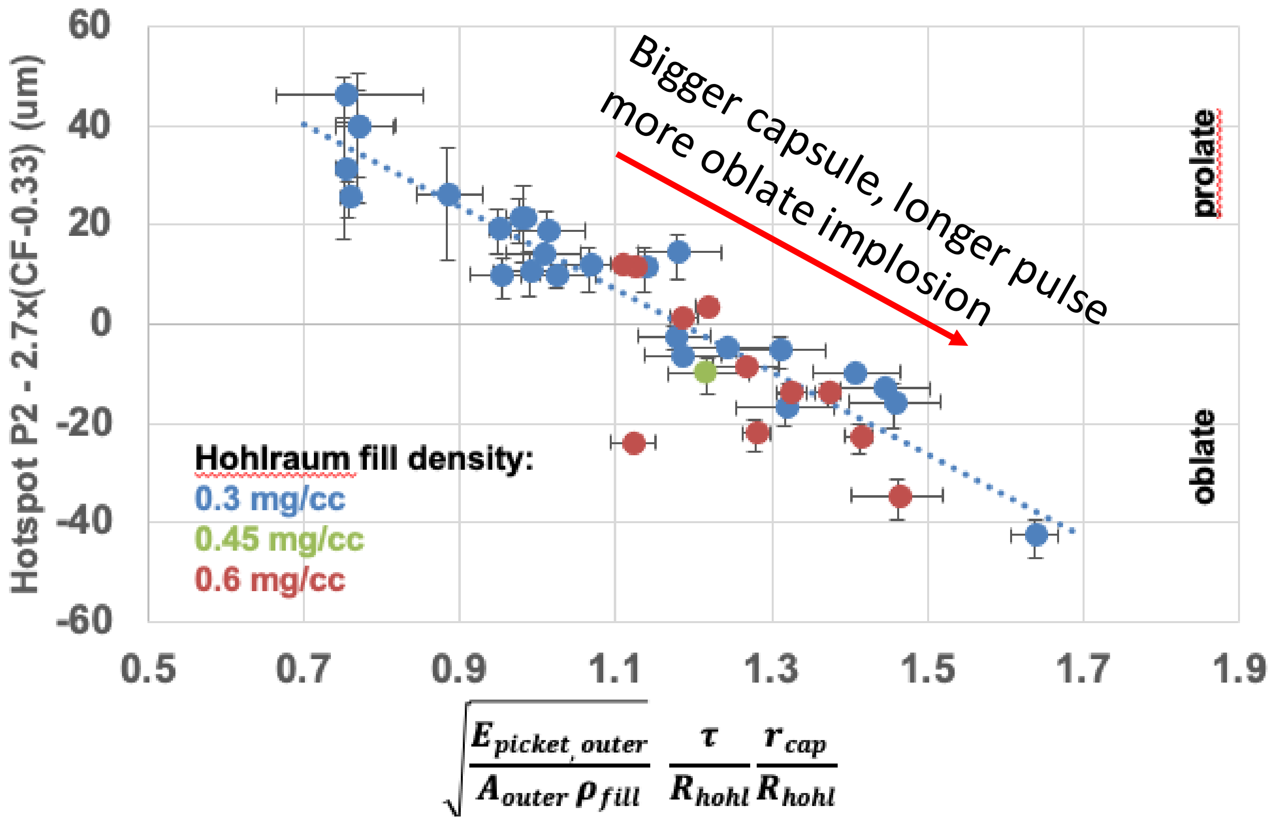
1: O. Hurricane et al, APS-DPP, PO7.00001 (2017); PPCF 61, 014033 (2019); PoP 26, 052704 (2019)
2: A.B. Zylstra et al., PRL 126, 025001 (2021); A.L. Kritcher et al., PoP 28, 072706 (2021)
3: D.A. Callahan et al., PoP 25, 056305 (2018); J. Ralph, et al., PoP, 25, 082701 (2018)
4: A. L. Kritcher, et al *Phys. Rev. E* **98**, 053206 (2018) , L. Pickworth, et al, PoP (2020)

Need to maintain a symmetric implosion with the larger capsule and low coast to effectively couple kinetic energy to the hotspot

Hohlraum symmetry dominated by the inner beams being stopped by the gold "bubble" and expanding ablator



Identified the parameters important to asymmetry in 2017/2018

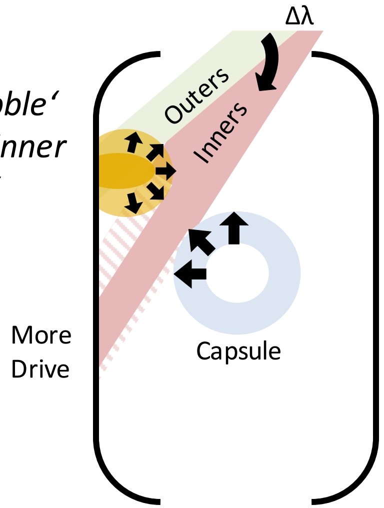


Needed some additional symmetry techniques to drive a round implosion with the larger capsule and short coast time

Developed two additional techniques for symmetry control: cross beam energy transfer and "Iraum" geometry

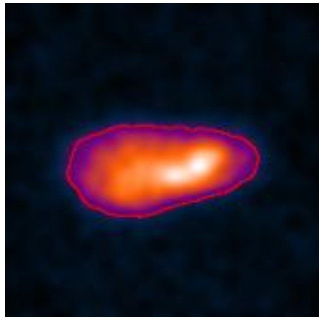
Hybrid E
Cylindrical hohlraum with cross beam energy transfer

Au 'bubble' blocks inner beams[5]

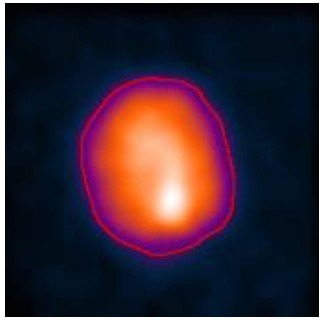


X-ray imaging

$\Delta\lambda=0$



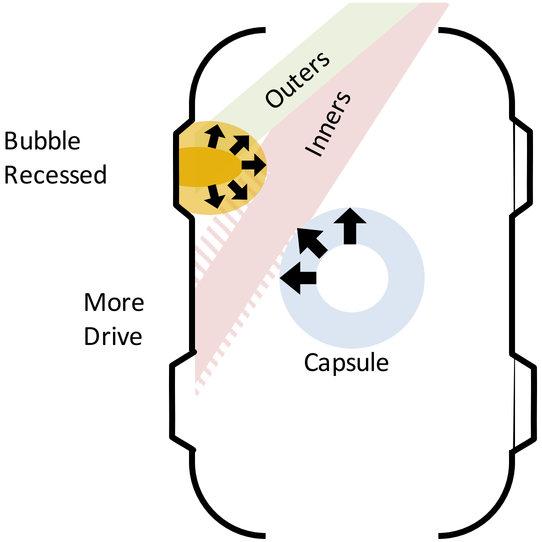
$\Delta\lambda=1A$



Detuning the outer and inner wavelengths (Δλ) transfers power from outers to inners, increasing waist drive[4]

A. Zylstra ZI02.00003
A. Kritcher GO04.00002

"Iraum"
Shaped hohlraum with cross beam energy transfer



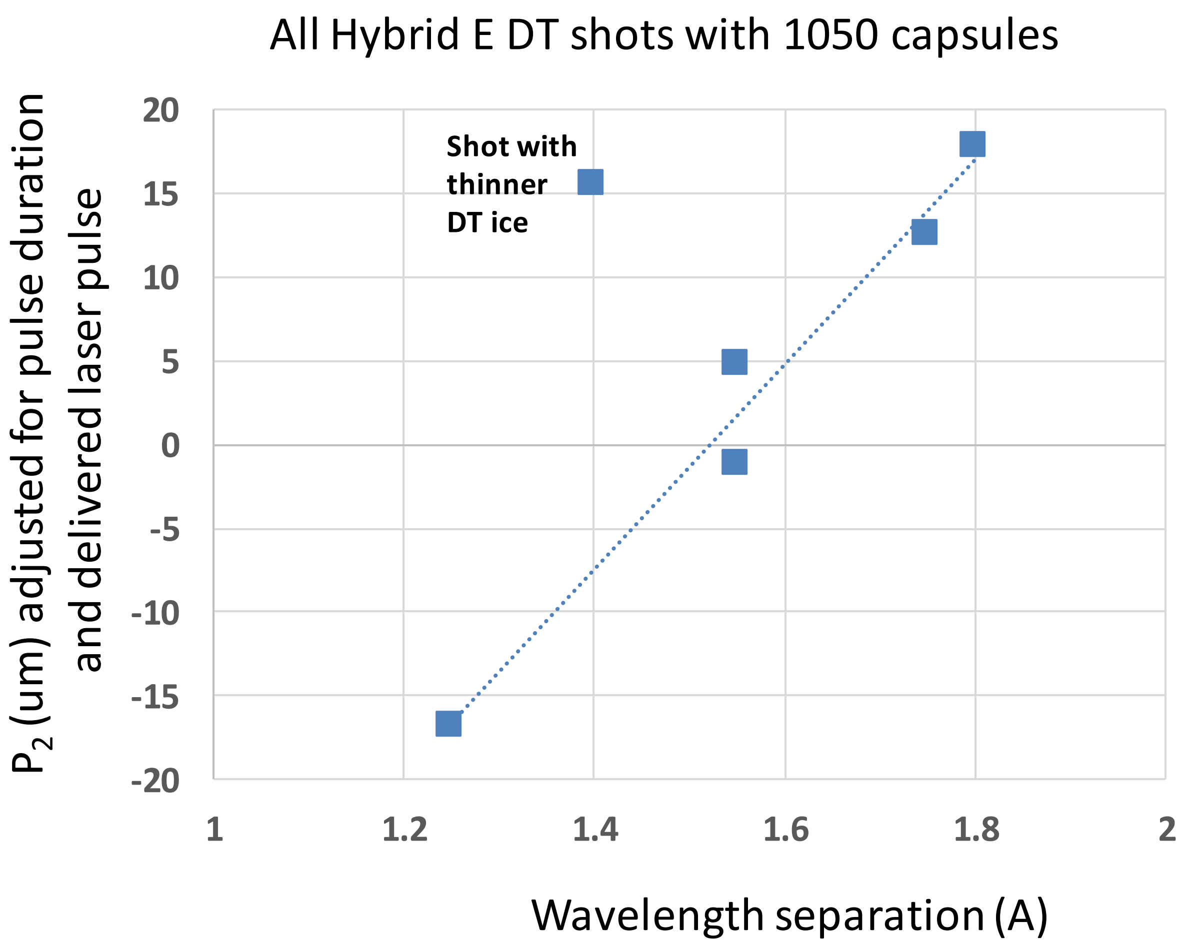
Pockets move gold bubble further away while maintaining smaller hohlraum

S. Ross BI01.00002
C. Young ZI02.00001

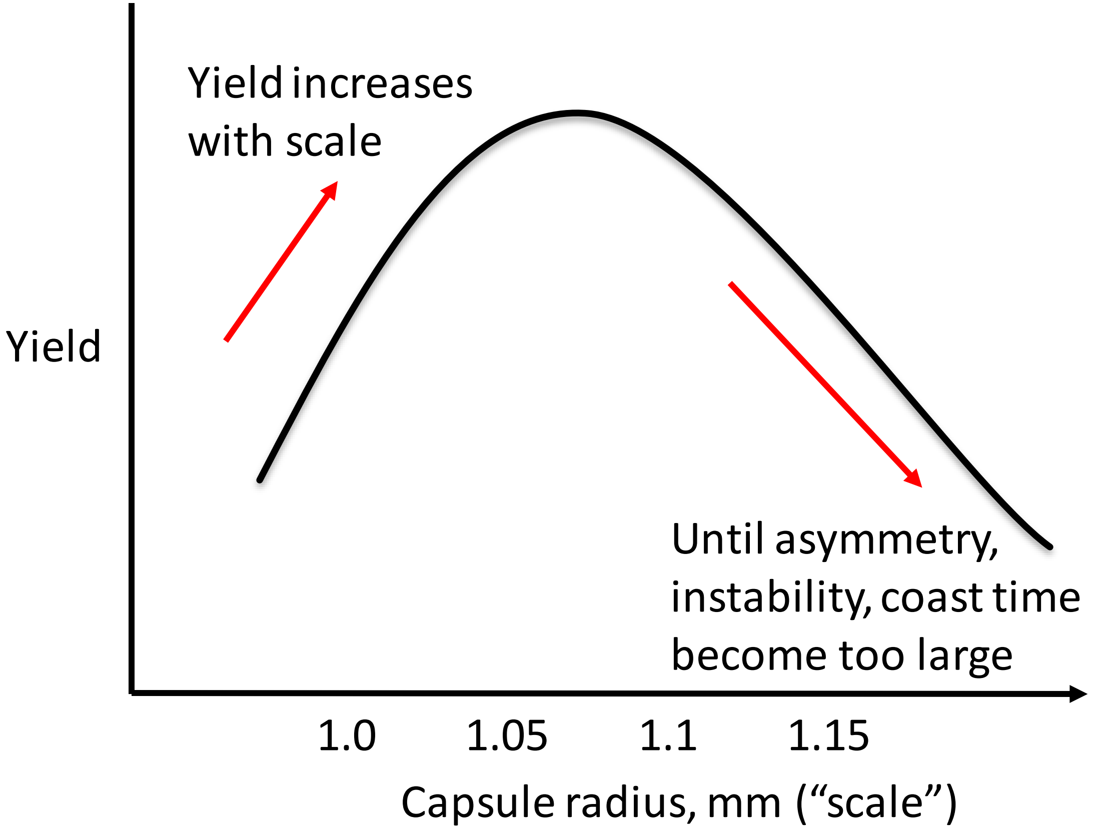
Both designs have produced a "burning plasma" in the last year!

Cross beam energy transfer (CBET) is a powerful tool for symmetry control in low gasfill hohlraums

- Low fill hohlraums -- smaller wavelength separation than high gasfill (1-2 Å vs 8-9 Å)
  - High gasfill hohlraums -- very large transfer in the foot (~ 10x). Led to swings in symmetry which were difficult to control/predict
  - Experiments show consistent scalings of P_2 with CBET but can have occasional surprises when other large changes are made (but can recover)



Because there is a tradeoff between capsule size, symmetry, and "coast time," we expected there to be an optimum capsule size



$$Y \sim p_{if}^{0.64} \frac{v_{imp}^{4.5}}{\alpha_{if}^{1.4}} S^{4.6} \, \delta \, (1 - RKE_{norm})^{3.8}$$

- Yield: Y
- Ablation pressure "inflight" by lower "coast": p_{if}
- Implosion velocity: v_{imp}
- Adiabat: α_{if}
- Scale: S
- Stability: δ
- Symmetry: $(1 - RKE_{norm})$

Plan was to use different capsule sizes and find the optimum experimentally

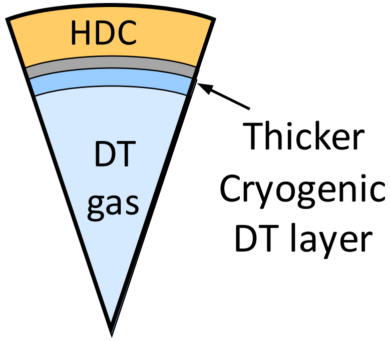
Initial HYBRID-E used the largest capsule and increased hotspot energy, but pressure dropped, capsule quality degraded, mix

“HYBRID-E[1]” 1100 μm size Y = 55 kJ

910µm -> 1100µm capsule

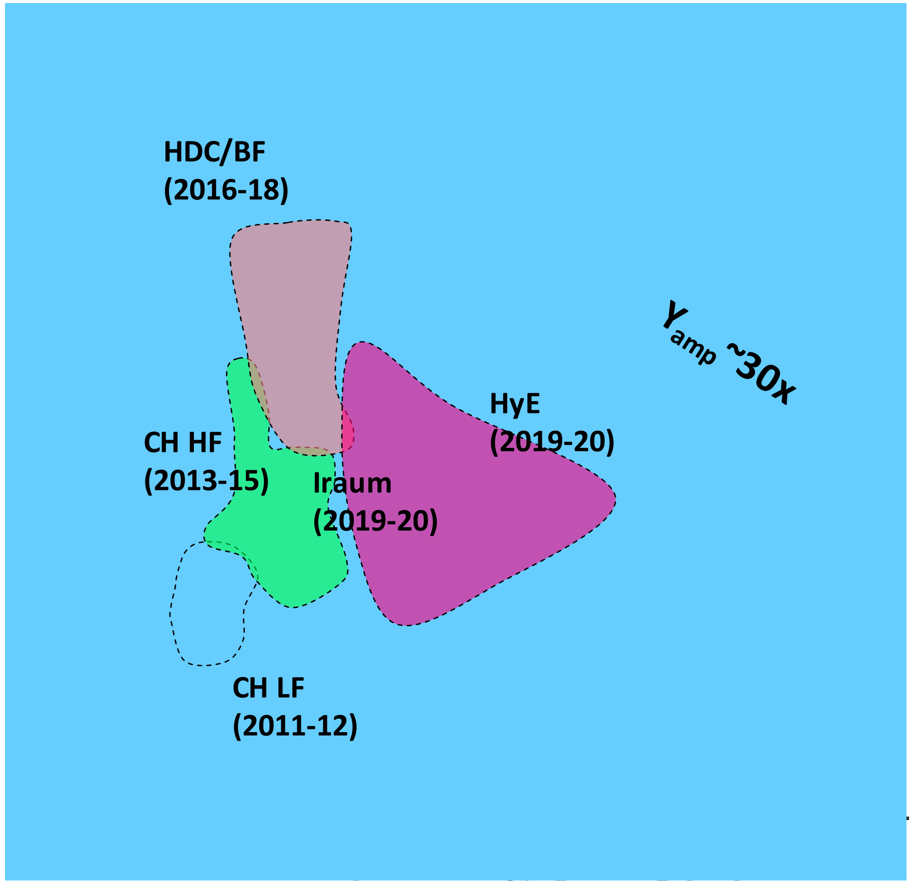
-> More coupled energy via reduced CCR (+maintain shape & velocity)
-> Longer coast
-> Capsule pits, voids
-> Mix
-> Lower pressure

Capsules and ice not hydro-scaled



-> Protection from defects
-> Better stability at low velocity but not enough

Ignition figure of merit $\sim (\rho R)^3 T^3 \sim E_{HS} P_{HS}^2$



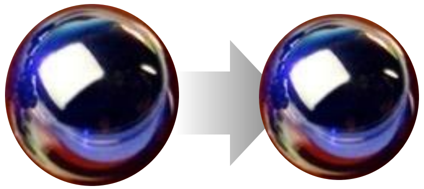
Recovering pressure (and temperature) would require lower coast and less mix

1: A.B. Zylstra et al., PRL 126, 025001 (2021); A.L. Kritcher et al., PoP 28, 072706 (2021)

Slightly smaller capsules reduced coast time, and some capsule quality improvement – performance improved markedly

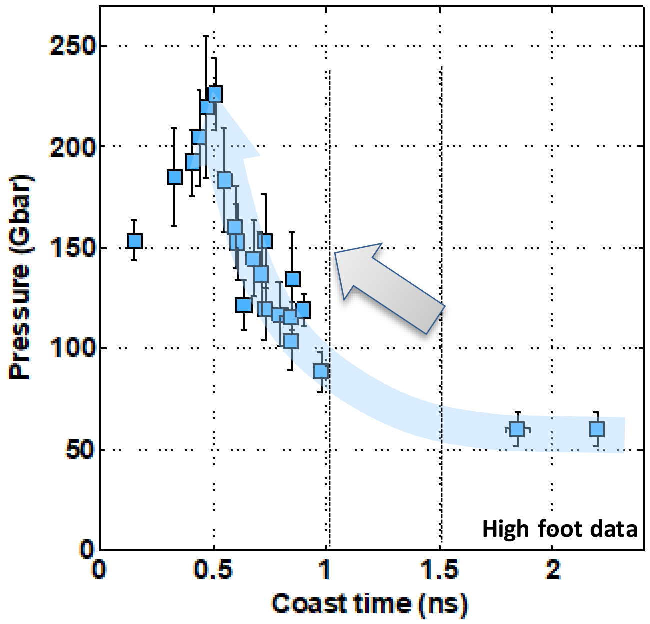
"HYBRID-E" 1050 μm size Y = 170 kJ

1100μm -> 1050μm capsule

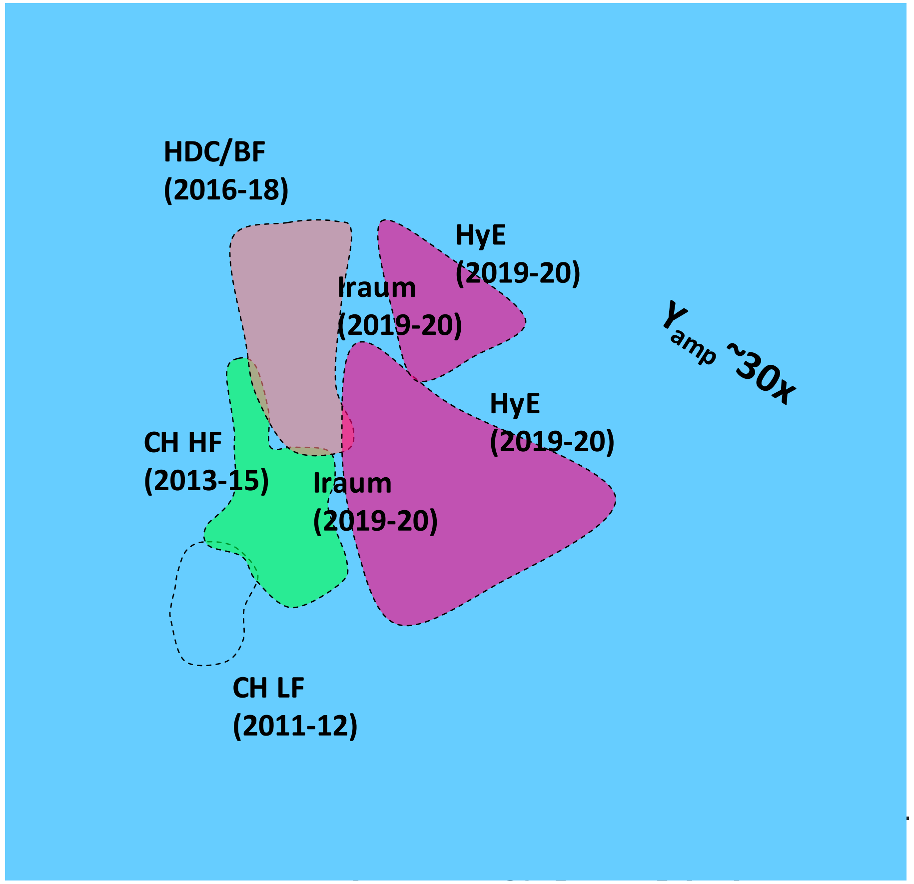


-> Reduced coast
-> Higher pressure
-> Better capsules, and higher W, less mix and higher temperature

Reduce coast time[1-2]



Ignition figure of merit $\sim (\rho R)^3 T^3 \sim E_{HS} P_{HS}^2$



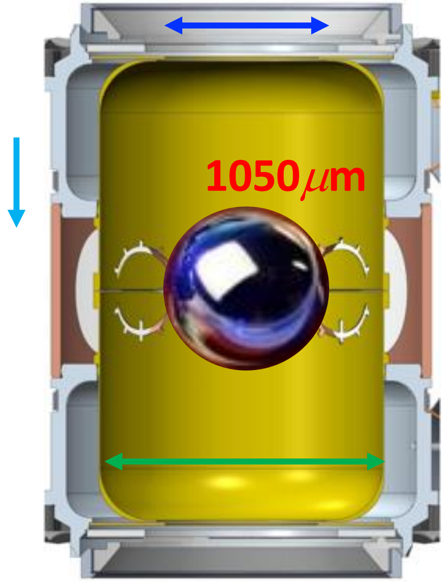
While not confirmed, analysis suggested coast was still sub-optimal, motivating test of yet lower coast

1: O. Hurricane et al., PoP 24, 092706 (2017)
2: O. Hurricane et al., PoP 27, 062704 (2020) and 2nd paper in preparation

To reduce coast time further, we had to make the hohlraum even more efficient by reducing the laser-entrance-hole size

HYBRID-E design modified with smaller LEH[3]

3.65 -> 3.1 mm LEH (27% less area)



Small CCR 2.8

- Reducing the laser-entrance-hole size reduces the radiation losses

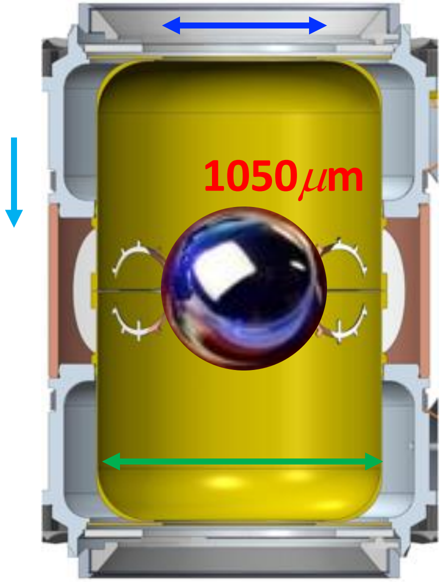
J. Ralph, GO04 Tuesday

1: O. Hurricane et al., PoP 24, 092706 (2017)
2: O. Hurricane et al., PoP 27, 062704 (2020) and 2nd paper in preparation;
3: J. Ralph, T Woods, A Kritcher, et al., "Hohlraum Scans Project", (2020)

The smaller laser-entrance-hole allows shorter coast time while maintaining implosion velocity

HYBRID-E design modified with smaller LEH[3]

3.65 -> 3.1 mm LEH (27% less area)

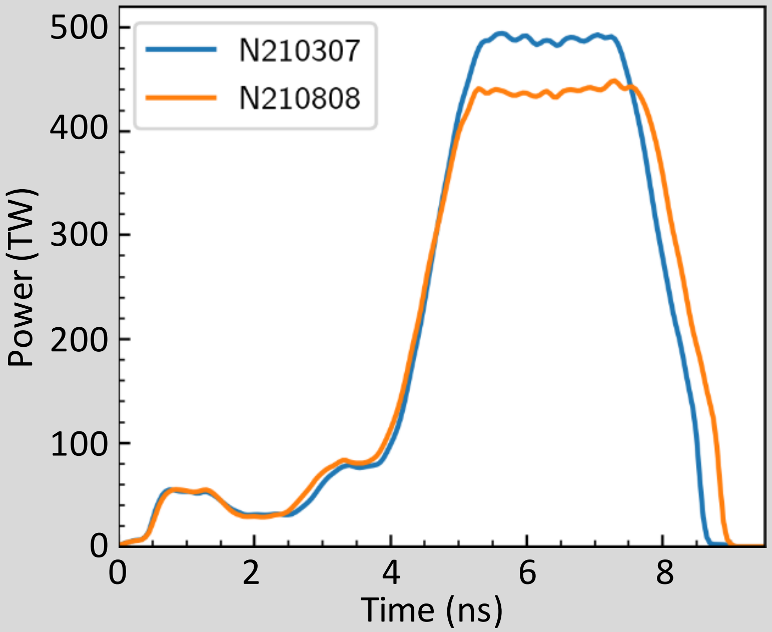


Small CCR 2.8

Used simulations and data driven models to re-tune symmetry for smaller LEH on first DT!

J. Ralph, GO04 Tuesday

Reduced radiation loss means can get same drive (Trad) with lower power



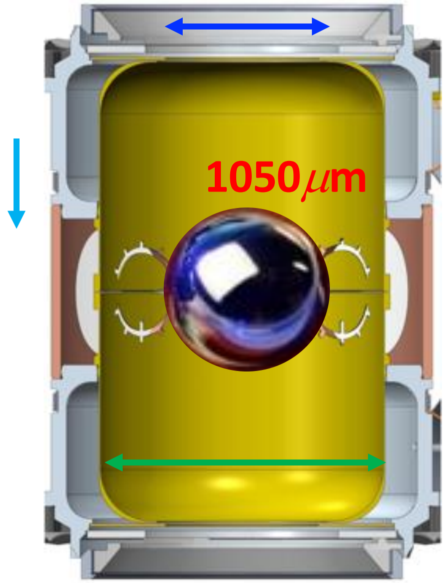
- Add the energy to the back end of the pulse to reduce coast time!

1: O. Hurricane et al., PoP 24, 092706 (2017)
2: O. Hurricane et al., PoP 27, 062704 (2020) and 2nd paper in preparation;
3: J. Ralph, T Woods, A Kritcher, et al., "Hohlraum Scans Project", (2020)

This allowed us to reduce the coast time another 350 ps – into the steep part of the curve

HYBRID-E design modified with smaller LEH[3]

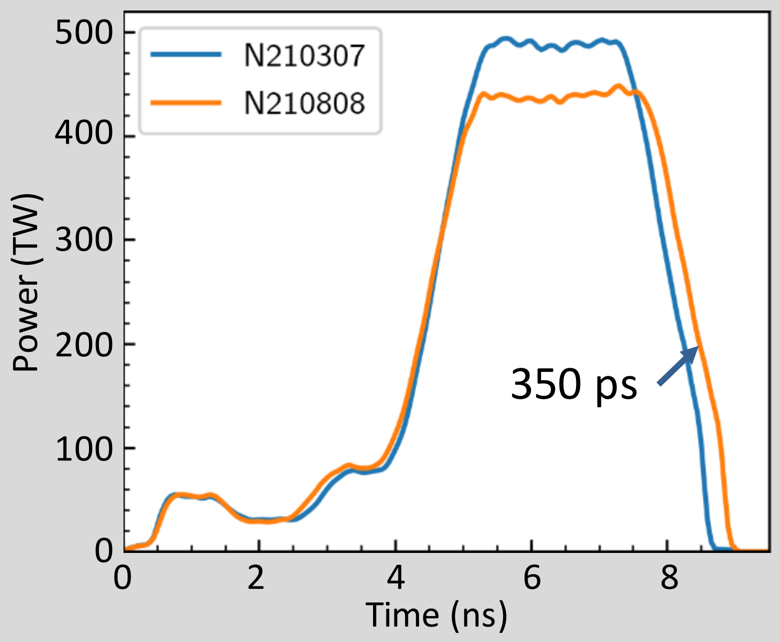
3.65 -> 3.1 mm LEH (27% less area)



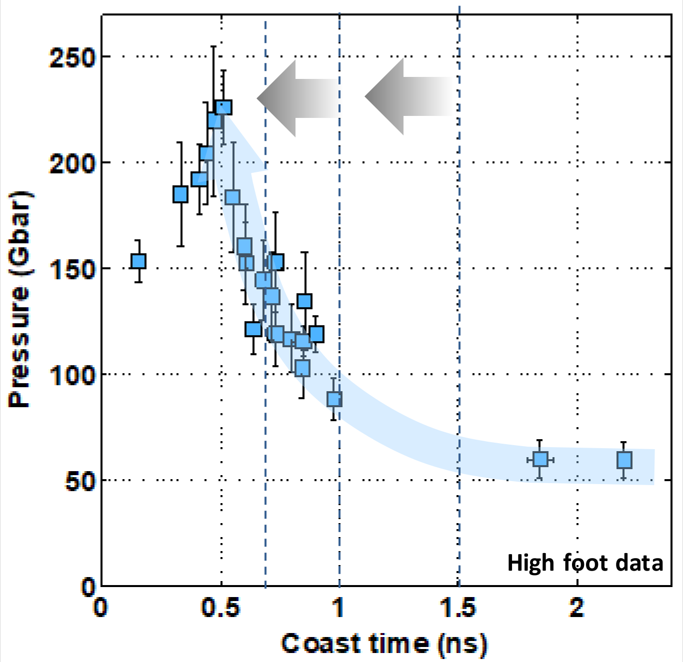
Small CCR 2.8

Used simulations and data driven models to re-tune symmetry for smaller LEH on first DT!

Reduced radiation loss means can get same drive (Trad) with lower power



Allowed us to reduce coast another 350 ps in steep part of the curve

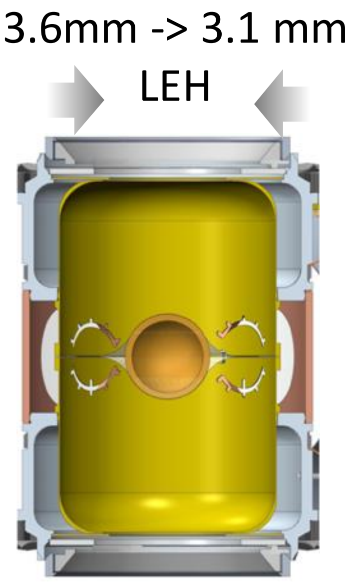


There may be room to make further improvements on this design

1: O. Hurricane et al., PoP 24, 092706 (2017)
2: O. Hurricane et al., PoP 27, 062704 (2020) and 2nd paper in preparation;
3: J. Ralph, T Woods, A Kritcher, et al., "Hohlraum Scans Project", (2020)

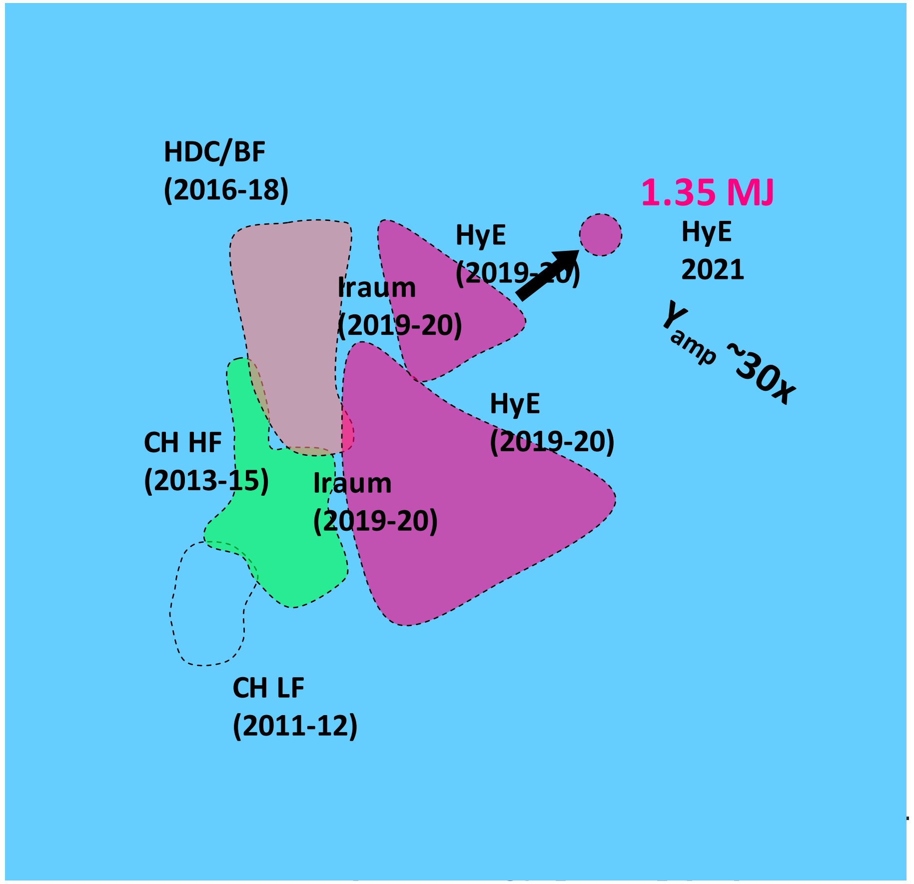
N210808 produced 1.35 MJ and the highest yield amplification of any shot to date

“HYBRID-E” Y = 1.3 MJ



-> Reduced coast
-> Higher pressure
-> Better stability

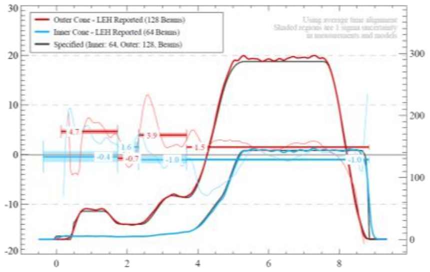
Ignition figure of merit $\sim (\rho R)^3 T^3 \sim E_{HS} P_{HS}^2$



There were also other important improvements on this shot

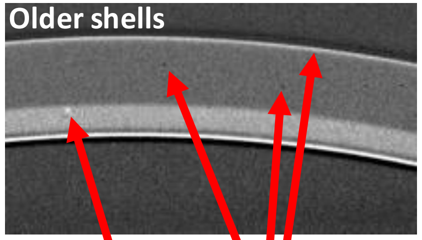
"HYBRID-E" Y = 1.3 MJ

Accumulated laser improvements



-> Precision energy delivery

Highest quality diamond capsule ever shot

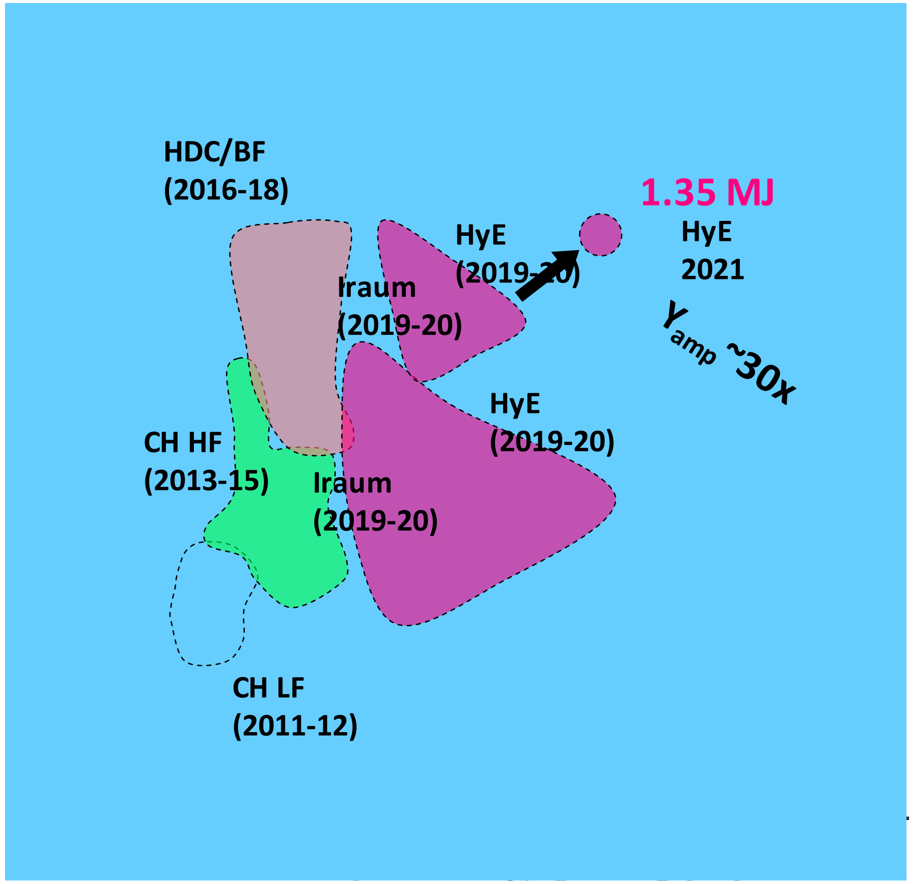


GA, Diamond Materials, LLNL

-> Less mix
-> Higher temperature

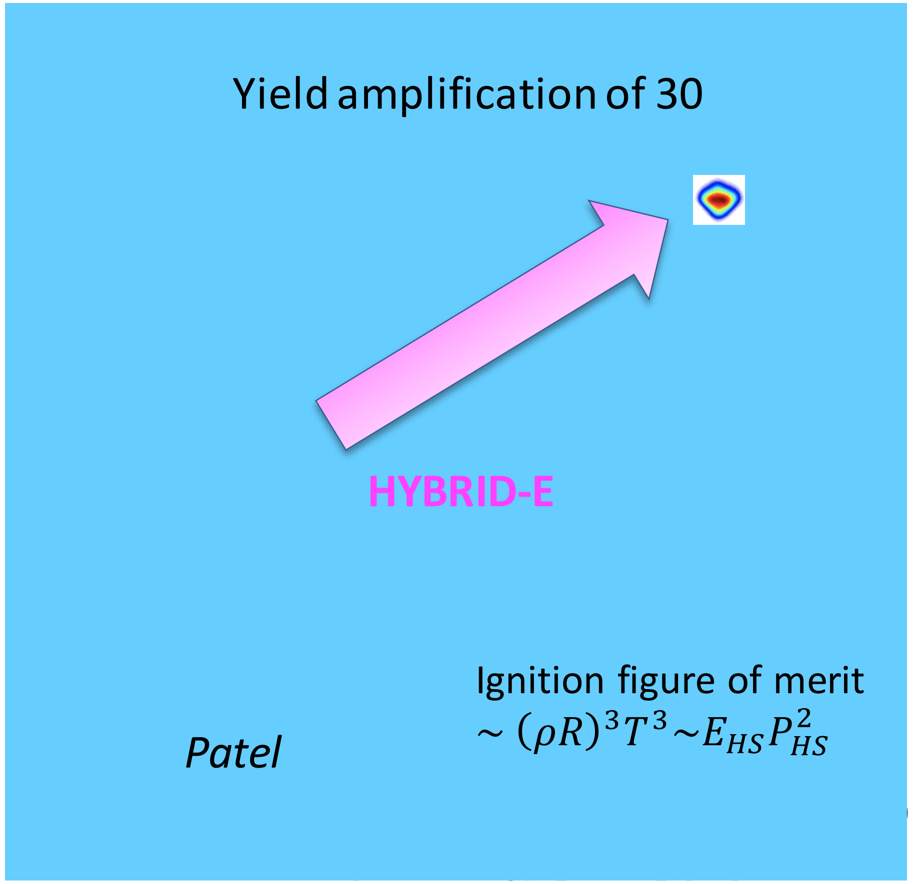
5µm -> 2µm fill tube

Ignition figure of merit ~ $(\rho R)^3 T^3 \sim E_{HS} P_{HS}^2$

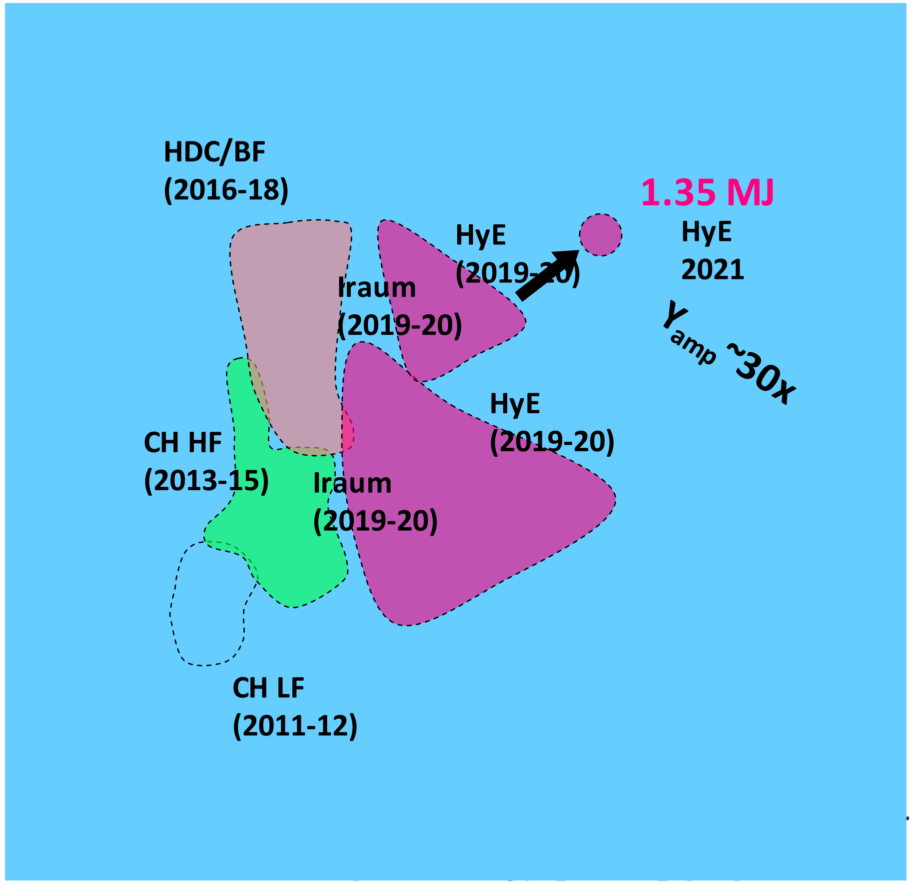


Future experiments will help understand the relative importance of each change

At the threshold of ignition, small changes in "no-alpha" space can lead to large changes in real "alpha-on" space



Ignition figure of merit $\sim (\rho R)^3 T^3 \sim E_{HS} P_{HS}^2$

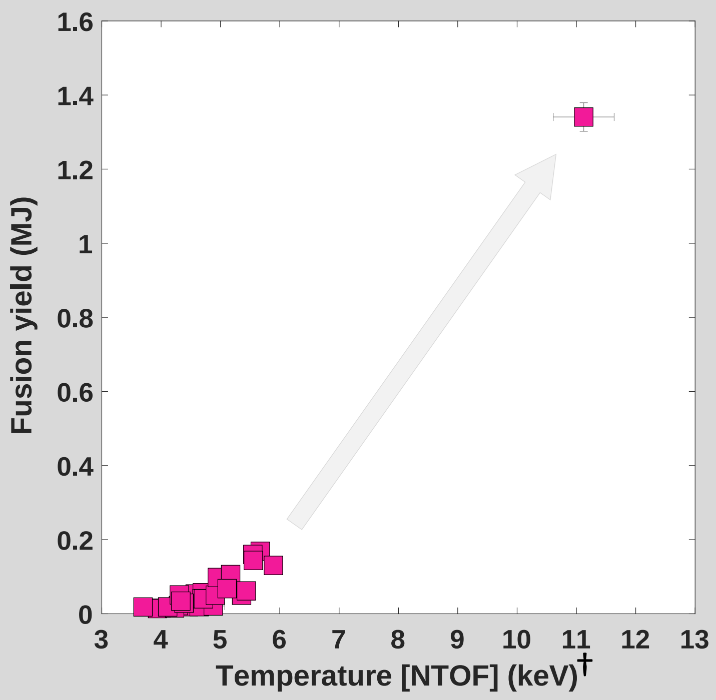


Much higher pressure and energy with small changes to input conditions indicates new regime

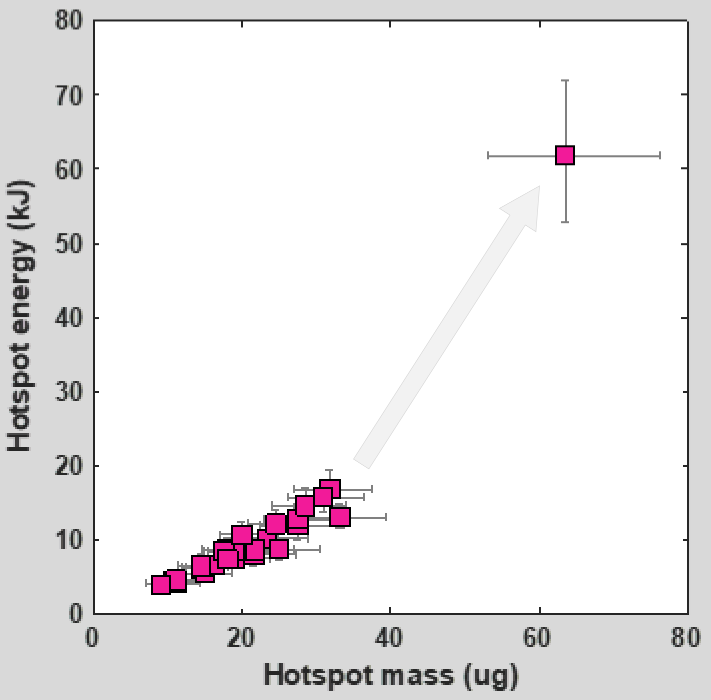
*Preliminary analysis

Many of the key experimental measurements are pointing to this implosion being in a fundamentally new regime

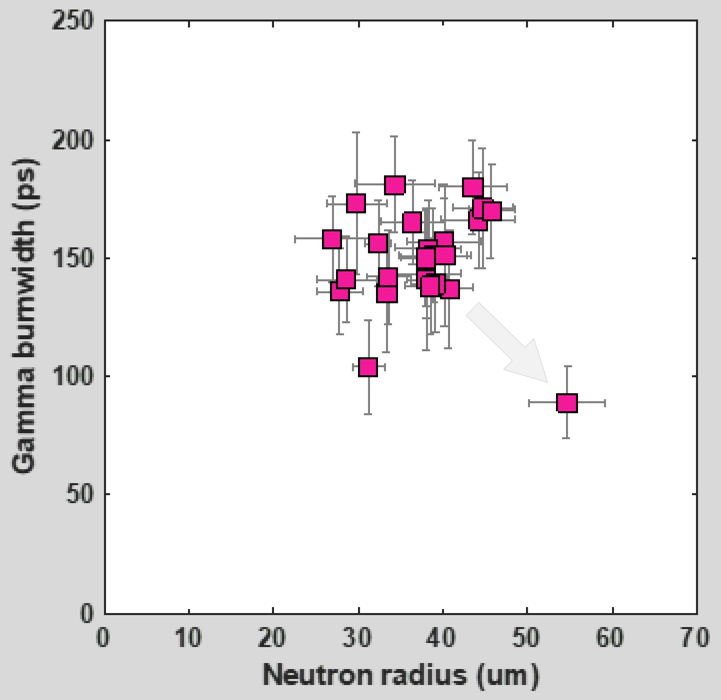
Yield and Temperature



Inferred Hotspot Mass and Energy



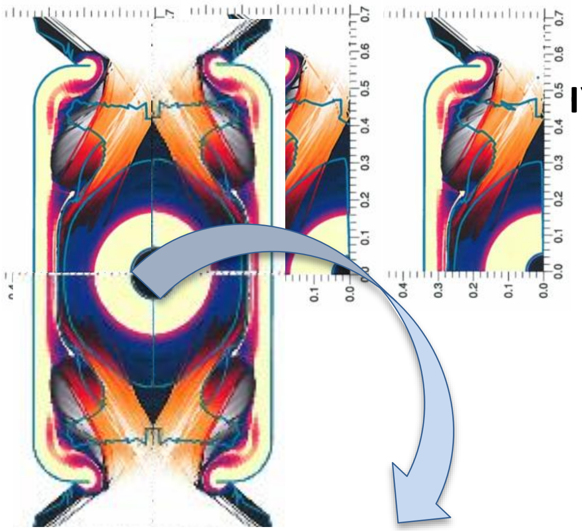
Hotspot Size and Burnwidth

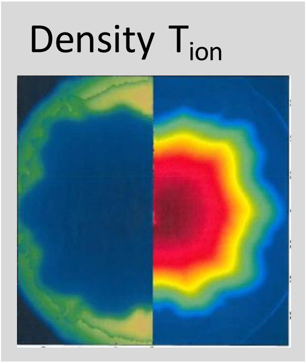


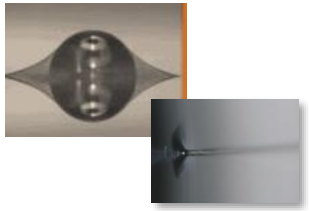
These are all signatures of a hotspot undergoing rapid self-heating and beginning to propagate burn into the surrounding dense shell

†NTOF (neutron-time-of-flight) diagnostic measures Doppler broadening of the DT neutron peak, which primarily arises from thermal temperature but does include contributions from fluid flow

2D post-shot simulations capture many of the important implosion performance metrics in this new regime for this design

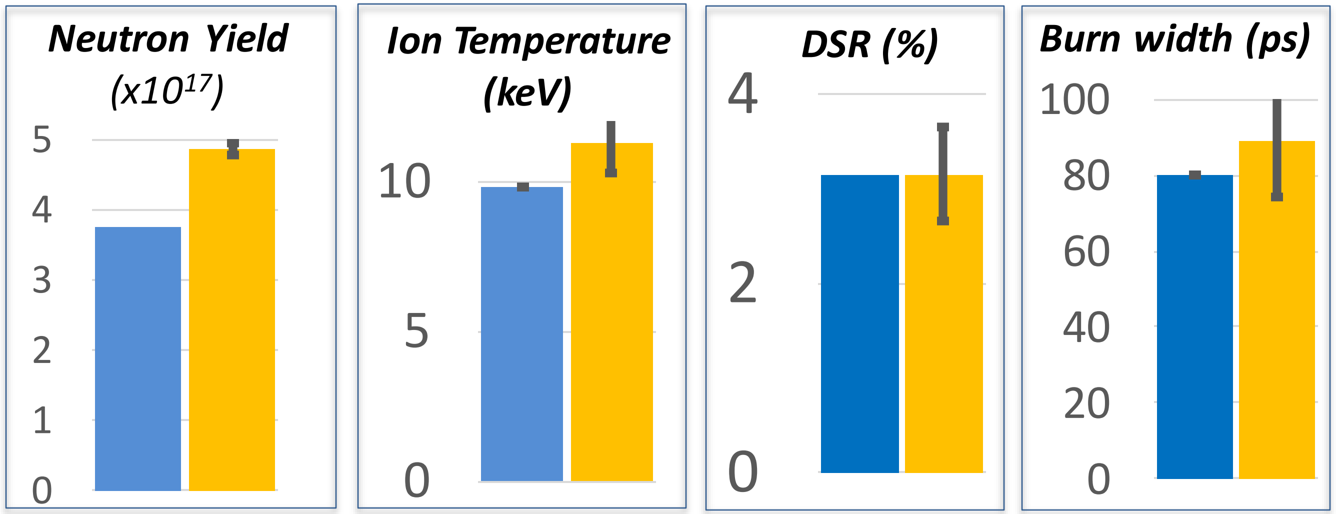






Higher resolution capsule simulations

Model for degradations is benchmarked against predecessor shots

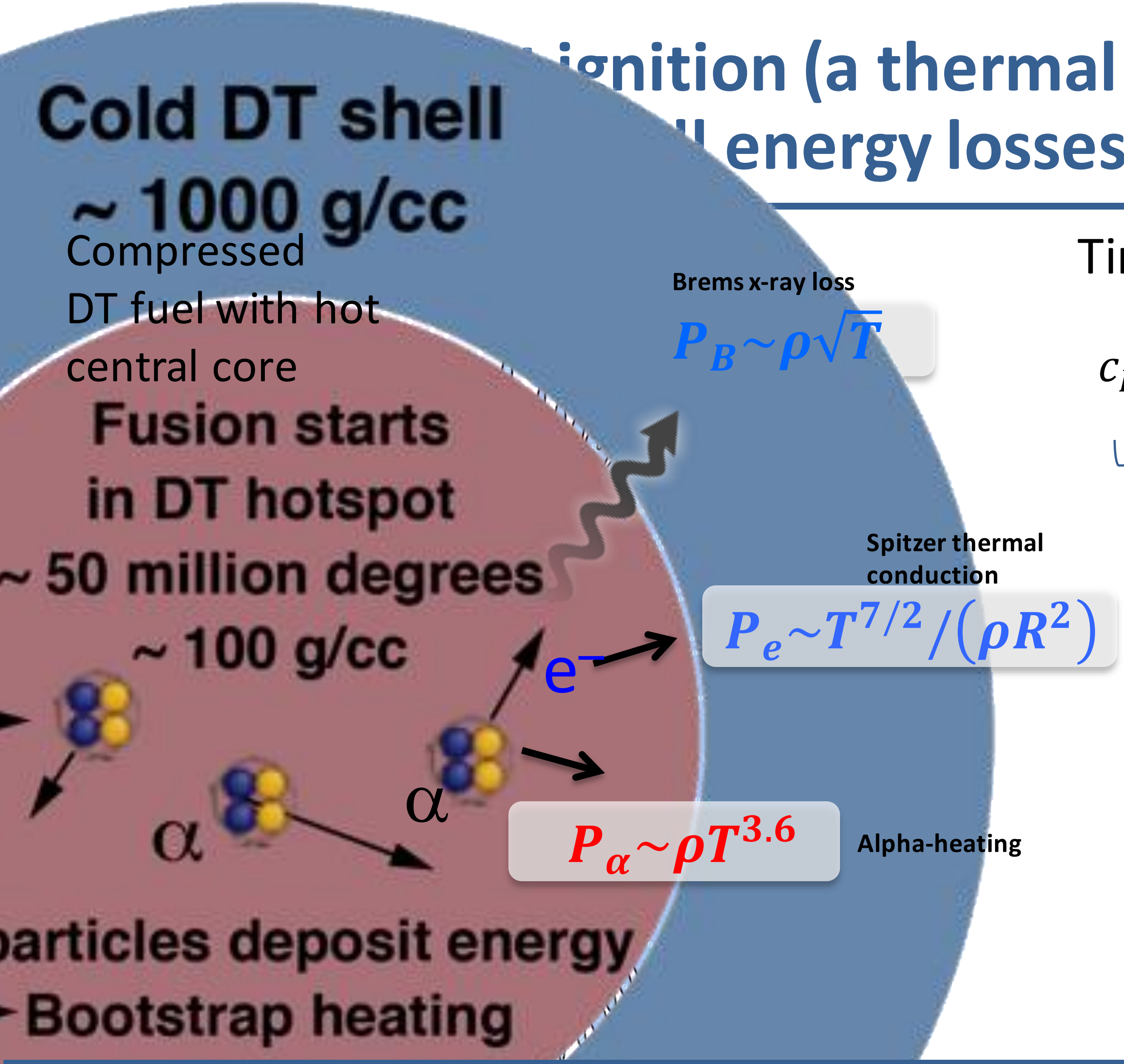


Simulated **Data**

- Consistent with high temperature, large burning hot spot
- Preshot predicted increase of 3x in neutron yield but below data (7.9x)
  - Postshot, including as delivered laser, 2 um fill tube, observed asymmetry, agrees to 20% in yield

A. Kritcher GO04.00002

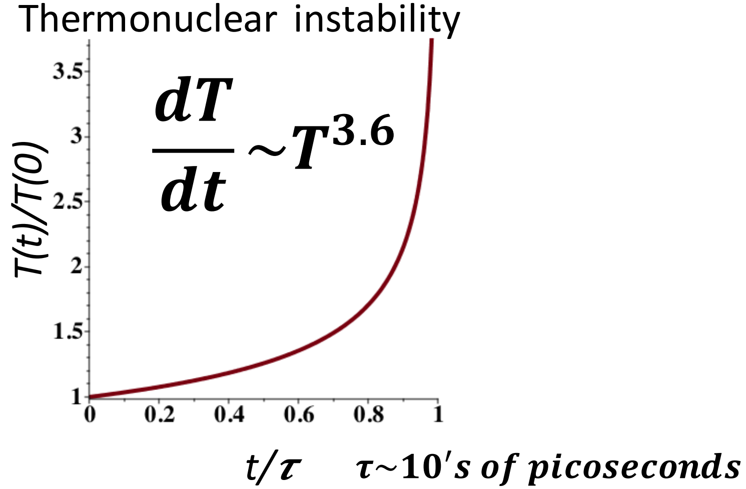
…ignition (a thermal instability), the plasma must …ll energy losses for a duration of time



Time dependent heat balance (power/mass):

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

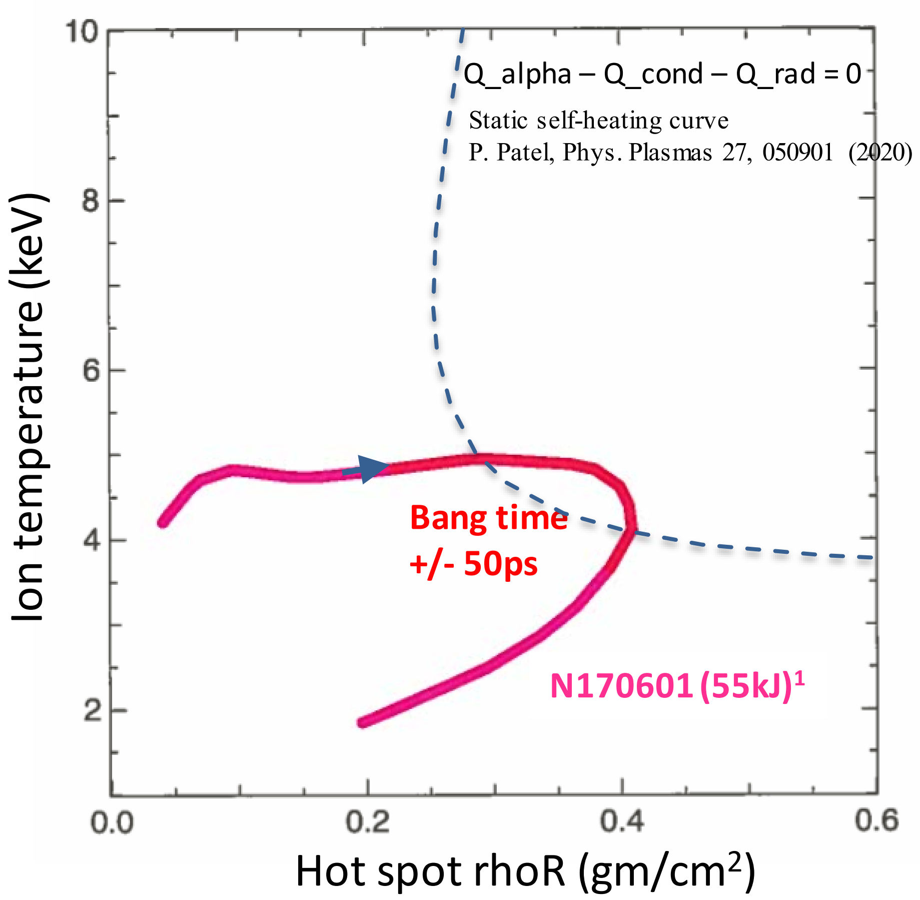
Ignition when these terms dominate



Quantities are functions of ρ, R, and T so it is interesting to look at implosions in ρR / T space

Previous 55kJ experiments had alpha-particle heating but not enough to overcome losses

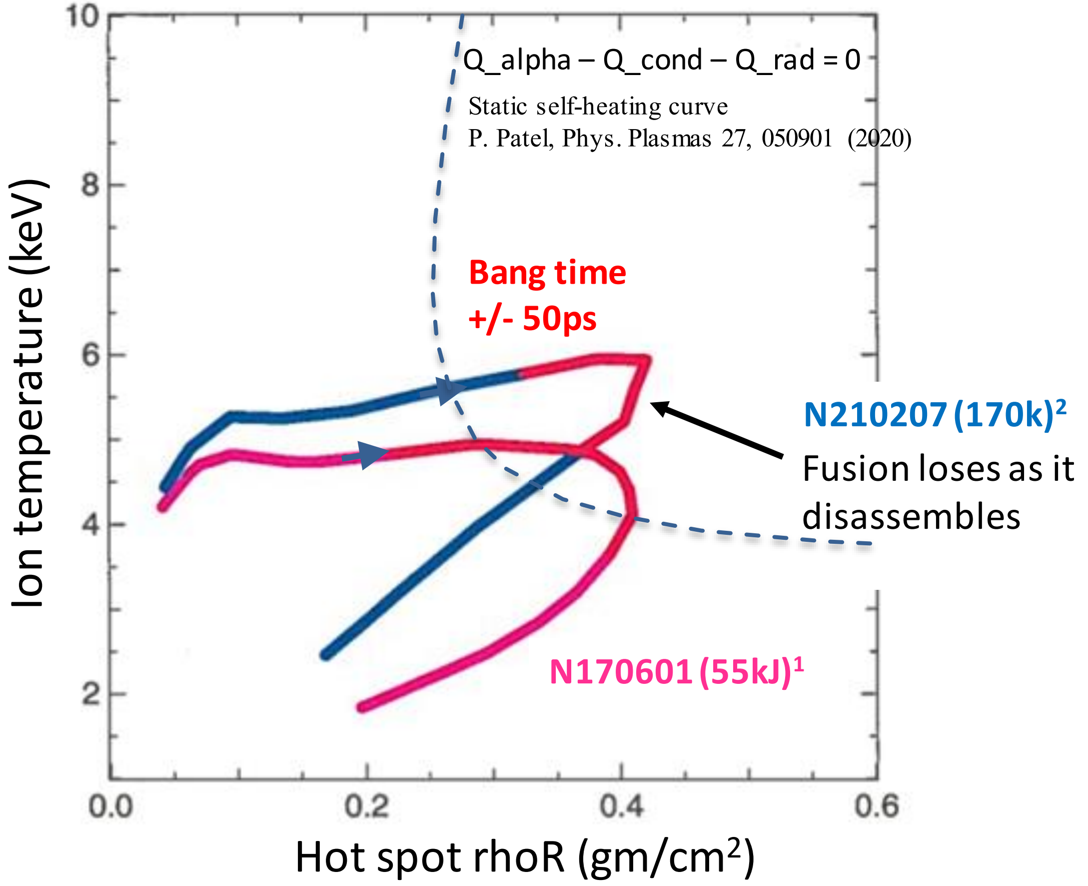
- 55kJ :
  - Alpha particle heating and hydro roughly balance radiation losses



1: Le Pape, et al, Phys. Rev. Lett. 120, 245003

170kJ shot -- alpha heating dominated implosions showed an increase in temperature but still succumb to losses

- 55kJ :
  - Alpha particle heating and hydro roughly balance radiation losses
- 170 kJ:
  - Higher initial hot spot temperature, alpha starting to win over losses but not there long enough for significant bootstrap heating

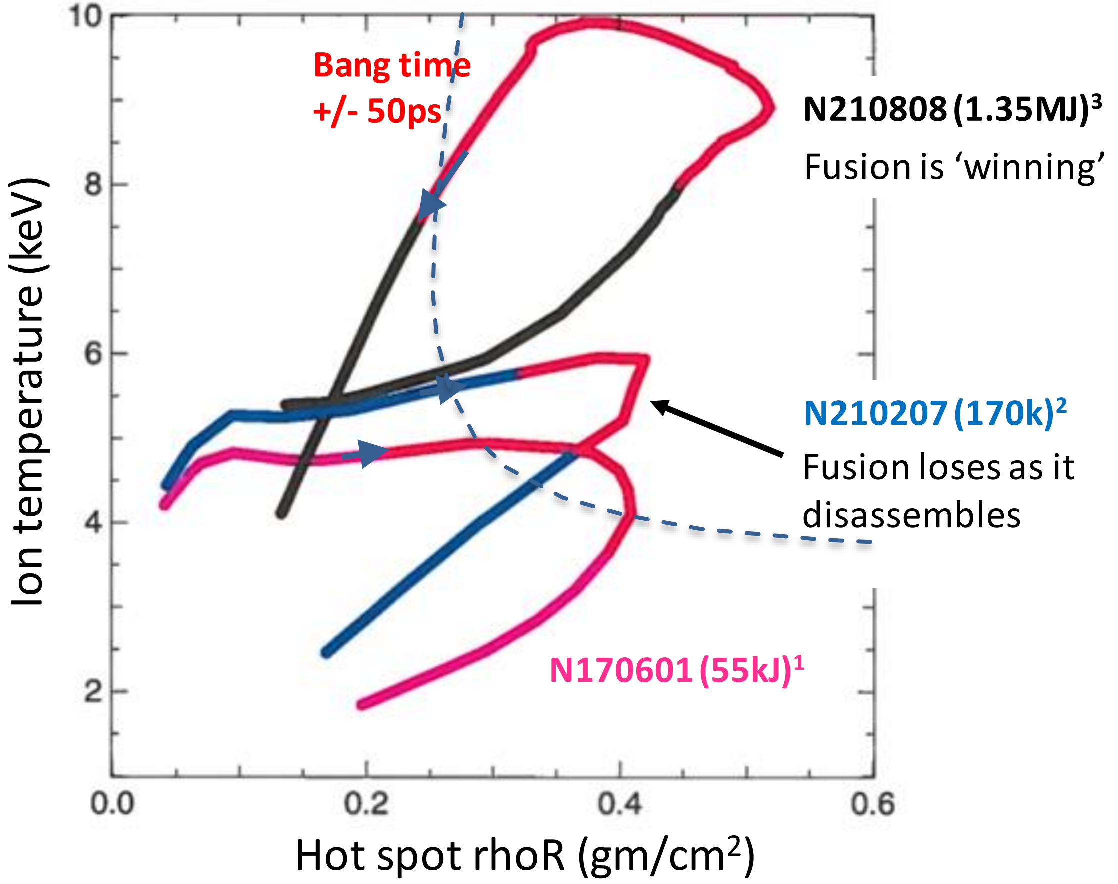


1: Le Pape, et al, Phys. Rev. Lett. 120, 245003

2: Zylstra, Hurricane, et al, in preparation; Kritcher, Young, Robey, et al, in preparation; Ross, Ralph, Zylstra et al, in preparation

N210808 shows substantial increases in calculated temperature and ρR and reversal of ρR – Tion trajectory

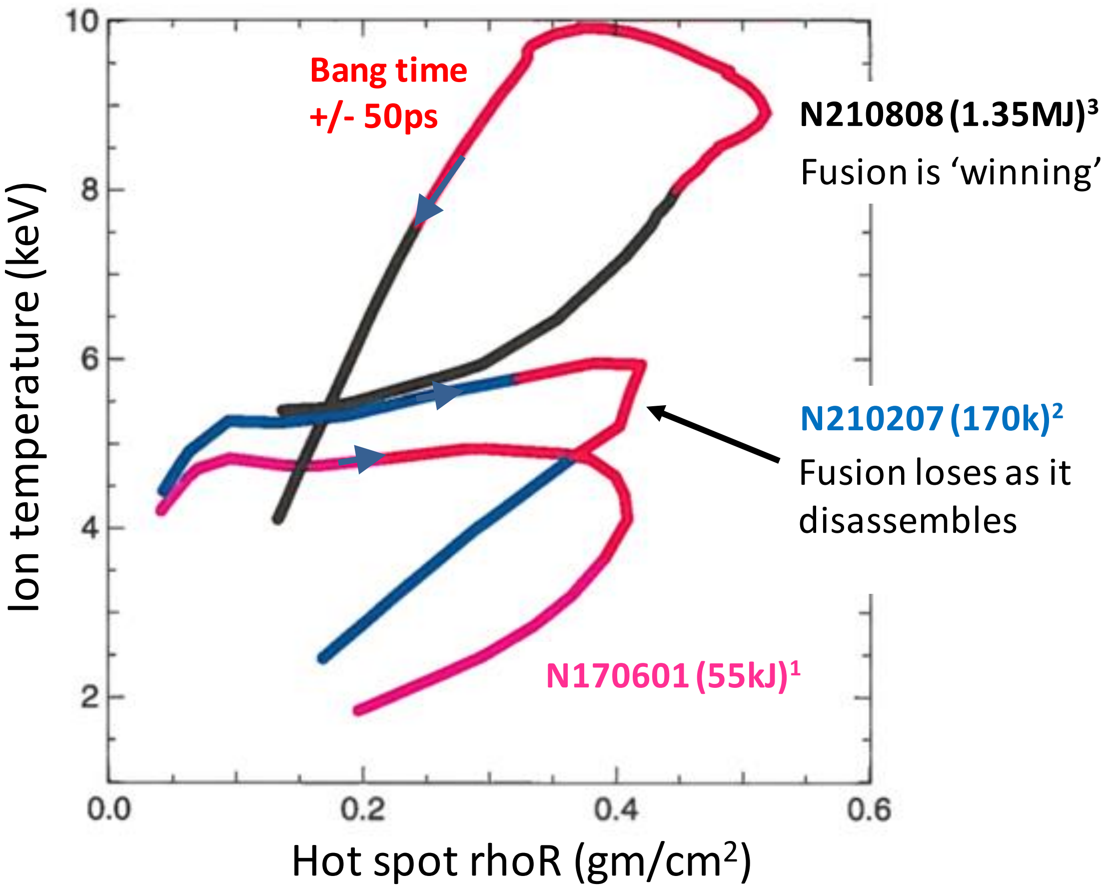
- 55kJ :
  - Alpha particle heating and hydro roughly balance radiation losses
- 170 kJ:
  - Higher initial hot spot temperature, alpha starting to win over losses but not there long enough for significant bootstrap heating
- 1.35 MJ:
  - Similar hot spot formation but better confinement due to lower coast time allows alpha heating to outweigh losses and take off



1: Le Pape, et al, Phys. Rev. Lett. 120, 245003
2: Zylstra, Hurricane, et al, in preparation; Kritcher, Young, Robey, et al, in preparation; Ross, Ralph, Zylstra et al, in preparation; 3: *in preparation*

We are now in a new regime where alpha energy is completely dominant

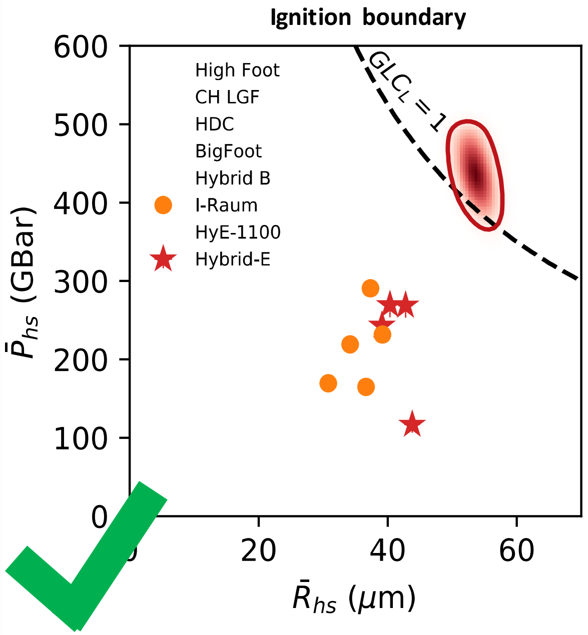
- Alpha energy >250 kJ
- PdV Work Done ~ 20 kJ
- Radiation loss ~ 60 kJ
- Total fusion energy and power: 1.35 MJ, 15 PW (quadrillion) for ~90 ps !!



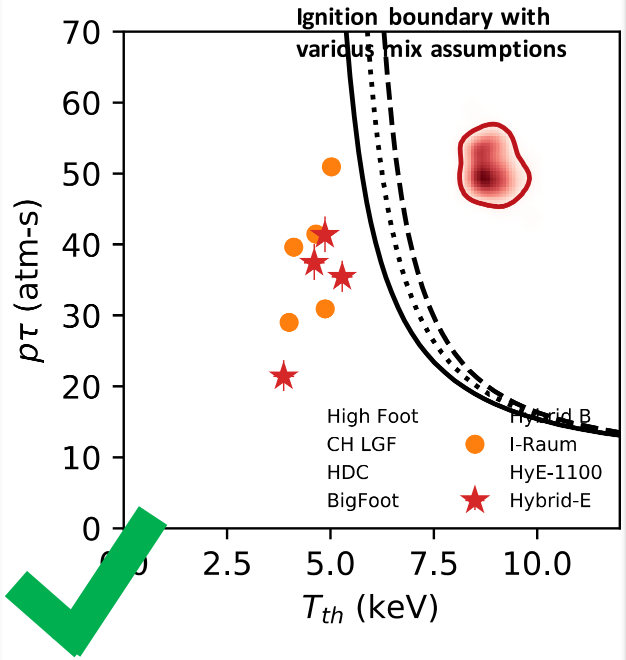
1: Le Pape, et al, Phys. Rev. Lett. 120, 245003

2: Zylstra, Hurricane, et al, in preparation; Kritcher, Young, Robey, et al, in preparation; Ross, Ralph, Zylstra et al, in preparation; 3: *in preparation*

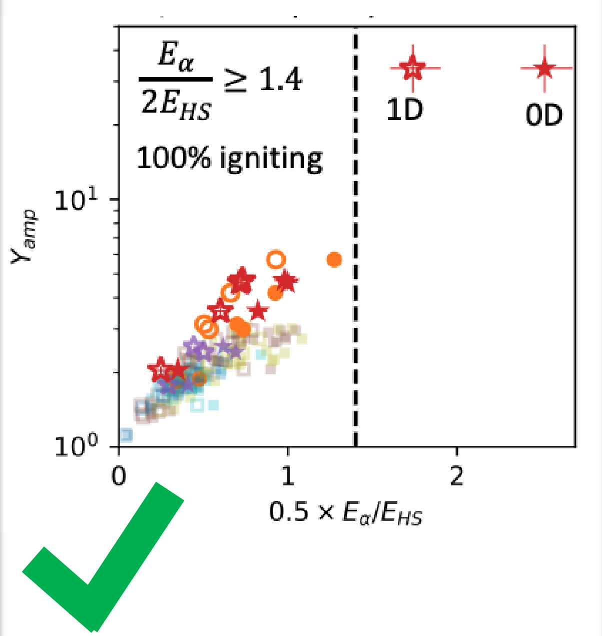
There are several published metrics for inferring ignition – we are evaluating this shot against them



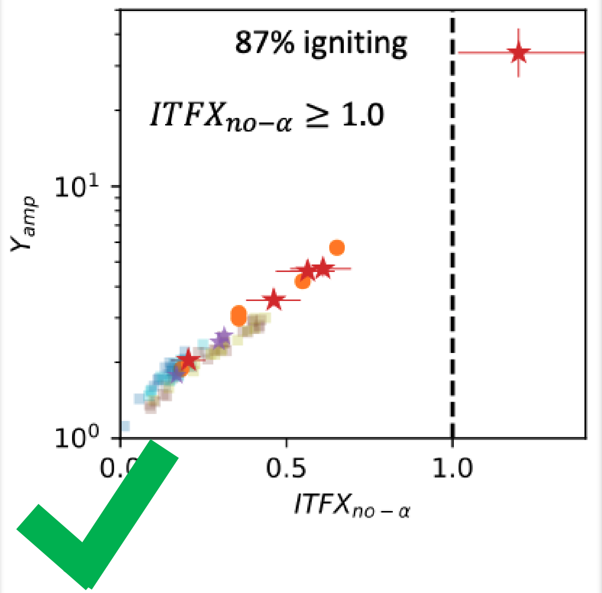
J. D. Lindl, S. W. Haan, O. L. Landen, A. R. Christopherson, R. Betti, Phys Plasmas, 25, 122704 (2018)



O. A. Hurricane, S. A. Maclaren, M. D. Rosen, J. H. Hammer, P. T. Springer, R. Betti, Phys Plasmas, 28, 022704 (2021)



A. R. Christopherson, R. Betti, S. Miller, B. V. Gopalaswamy, O. M. Mannion, D. Cao, Phys Plasmas, 27, 052708 (2020)



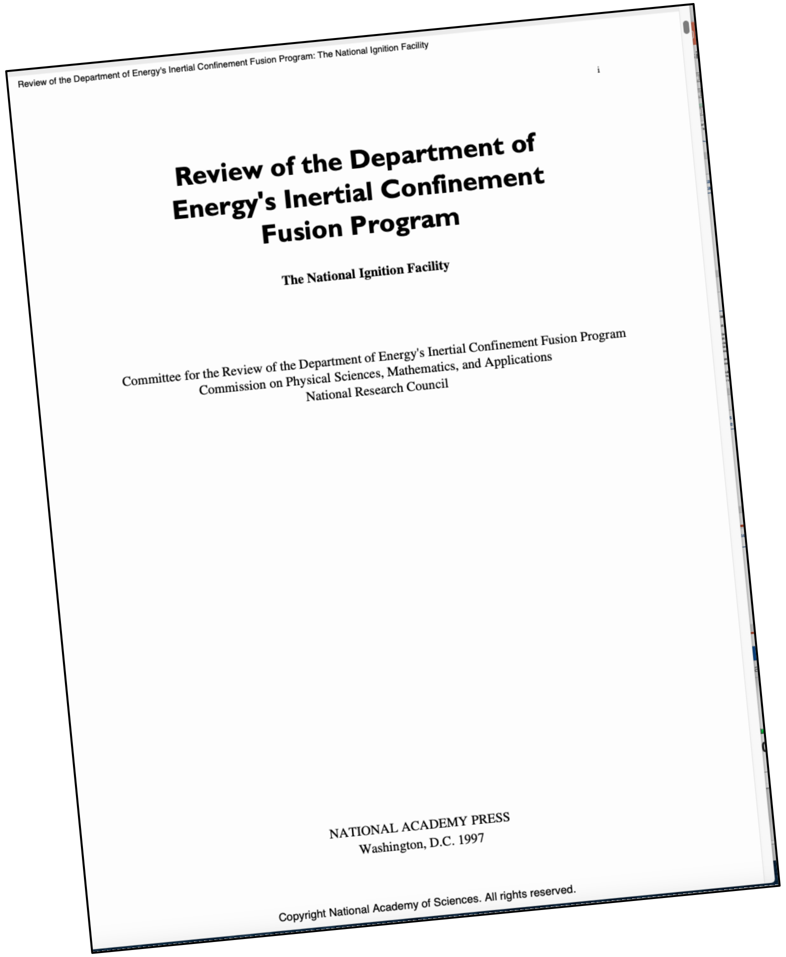
B. K. Spears, M. J. Edwards, S. Hatchett et al. Phys Plasmas, 21, 042702 (2014)

P. K. Patel, P. T. Springer, C. R. Weber et al. Phys Plasmas, 27, 050901 (2020)

See talks: A. Christopherson CO04:00005
A. Zylstra QI02.00001

Analysis: A. Zylstra

The 1997 National Academy of Science review of the ICF program defined "ignition" as "gain = 1"



Review of the Department of Energy's Inertial Confinement Fusion Program: The National Ignition Facility

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Review of the Department of Energy's Inertial Confinement Fusion Program

The National Ignition Facility

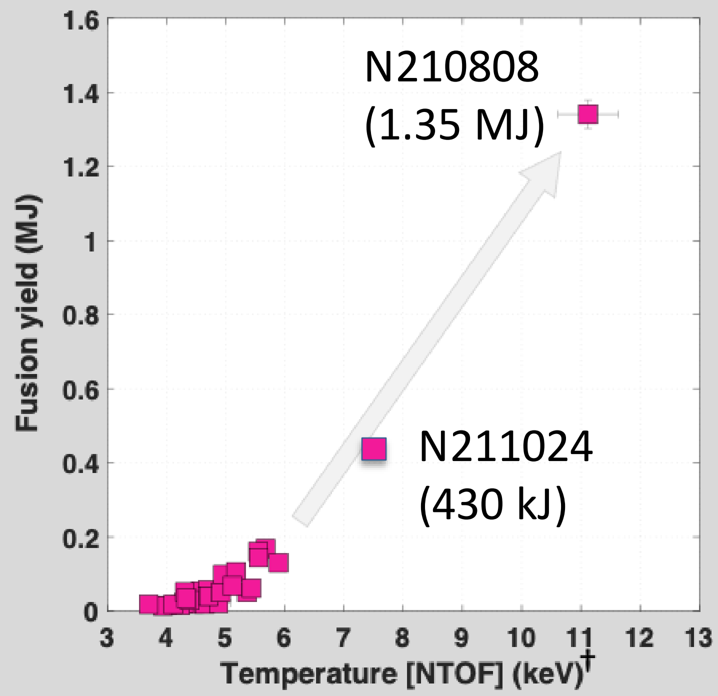
Committee for the Review of the Department of Energy's Inertial Confinement Fusion Program
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1997

- Ignition is a statement about the power balance in the hotspot of the implosion
- NAS decided to use a definition that is not about power balance but about target gain
  - Easy to evaluate
- NAS defined "ignition" as target gain=1, where fusion yield is equal to laser energy
- This shot is target gain 0.7

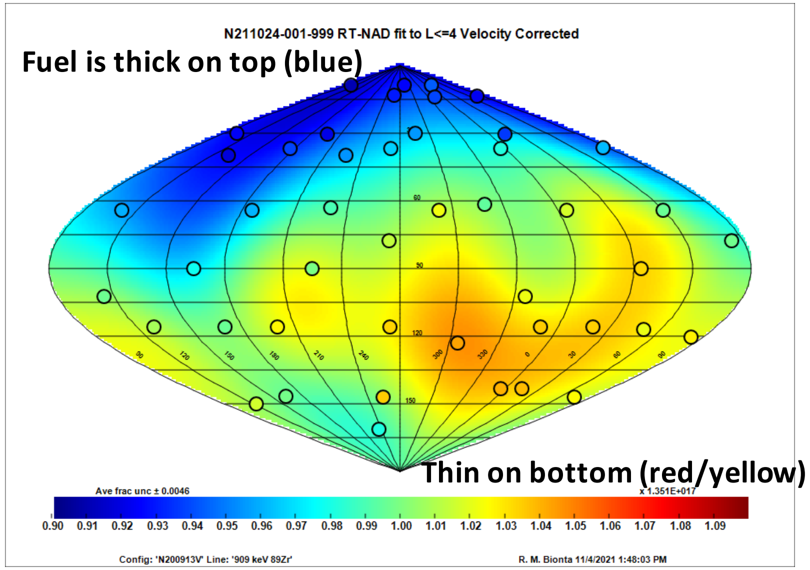
First shot to assess variability on Oct 24 gave ~ 430 kJ of yield

Yield and Temperature



- Second shot with capsule gain > 1 and yield > 1e17 neutrons!
- Data still being analyzed
- Simulations in progress
- Expect large variability near ignition cliff

Observe a large mode 1



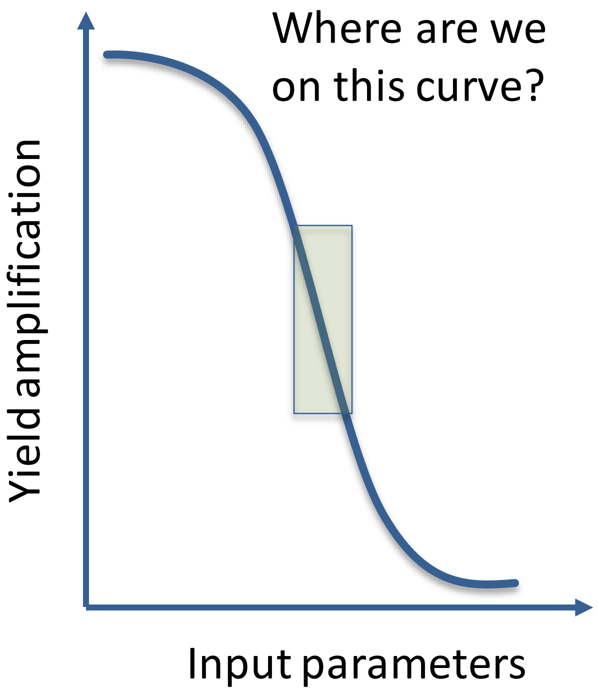
Analysis: R. Bionta

130 km/s velocity downward
(N210808 was 68 km/s)

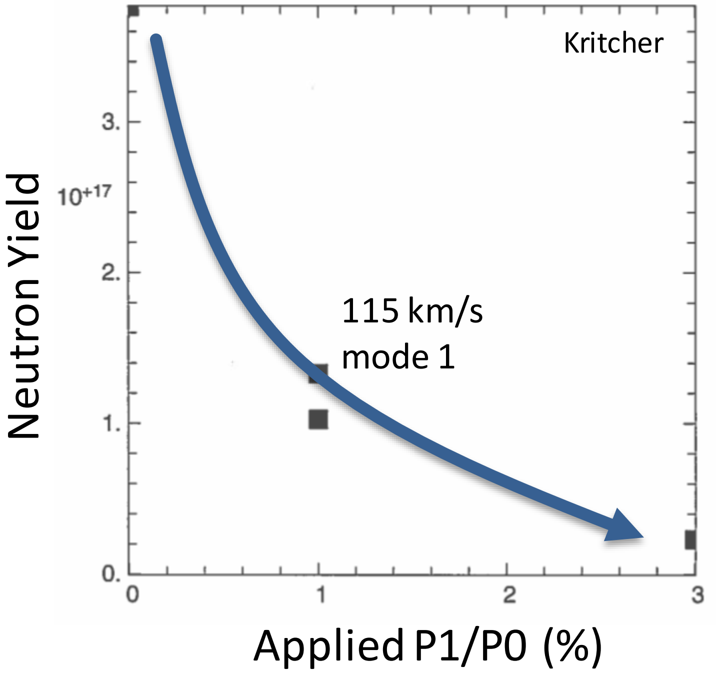
Mode 1: Schlossberg NO04.00010

Near ignition cliff, expect variability -- the designs are sensitive to input parameters and sensitivity increases with yield amplification

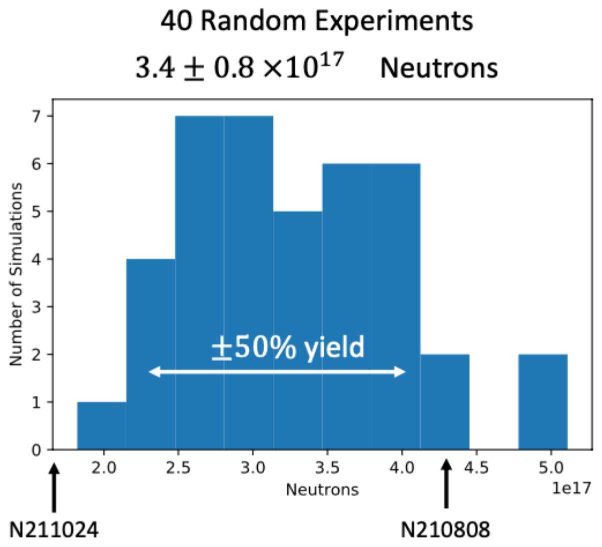
Because ignition is a threshold process we expect sensitivity to increase with higher yield amplification



Example: 2d simulations of N210808 show strong sensitivity to mode 1 (~ 2x between N210808 and repeat)

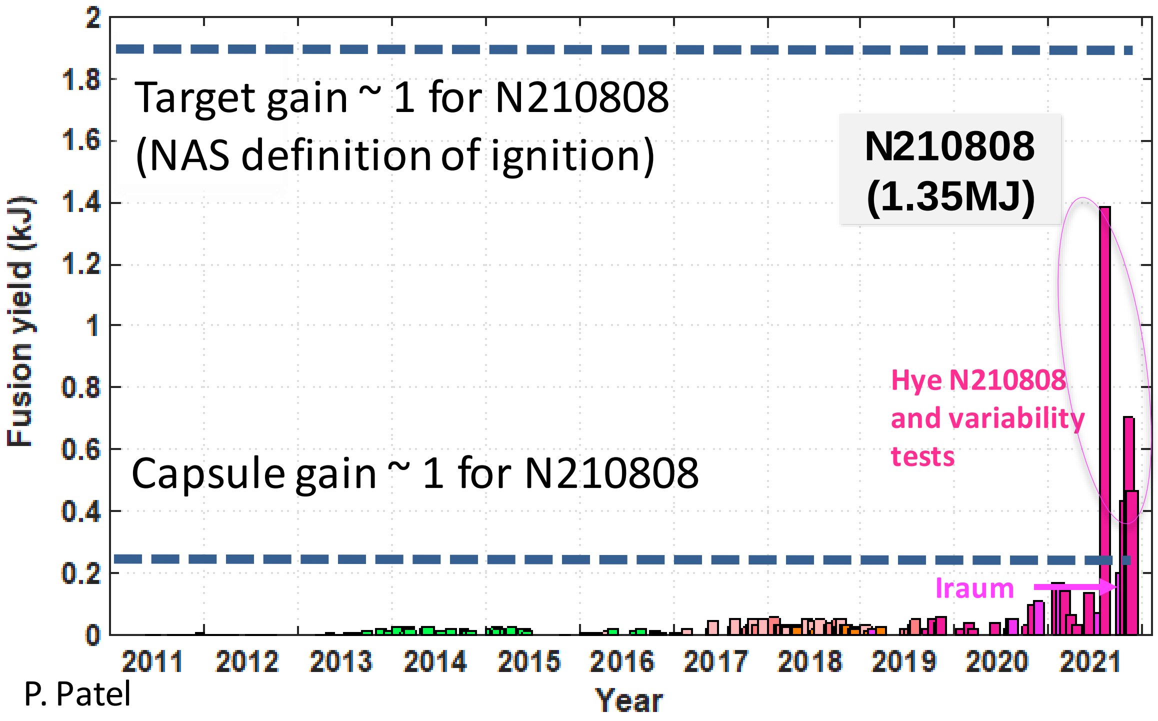


For N210808, 1d simulations show $\pm$ 25% variability in yield from laser and target variations

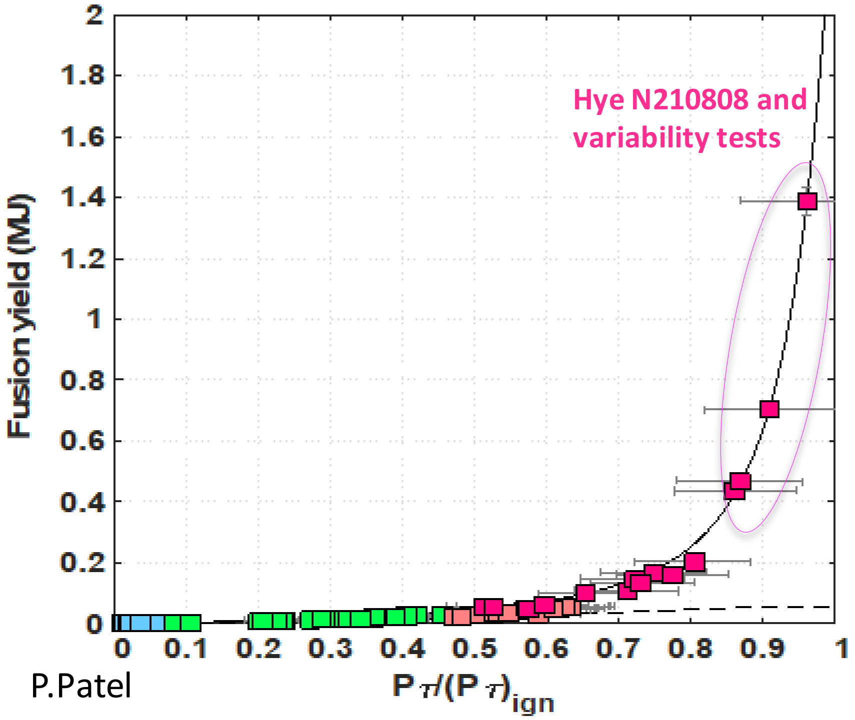


See L. Peterson TO07.00009

Three experiments testing N210808 variability have been performed: all reached >1e17 and capsule gain >2, well beyond early 2021 shots

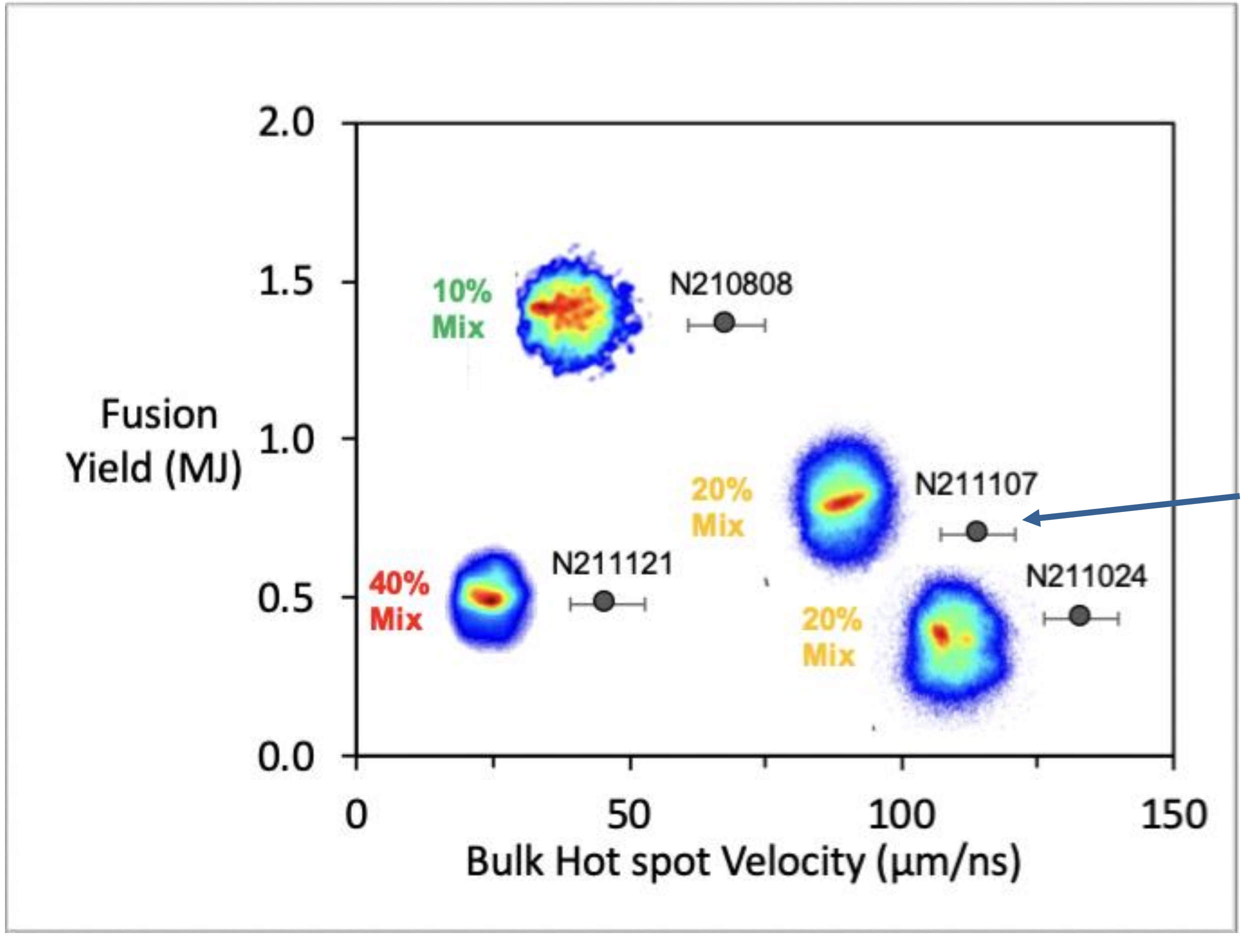


P. Patel



P.Patel

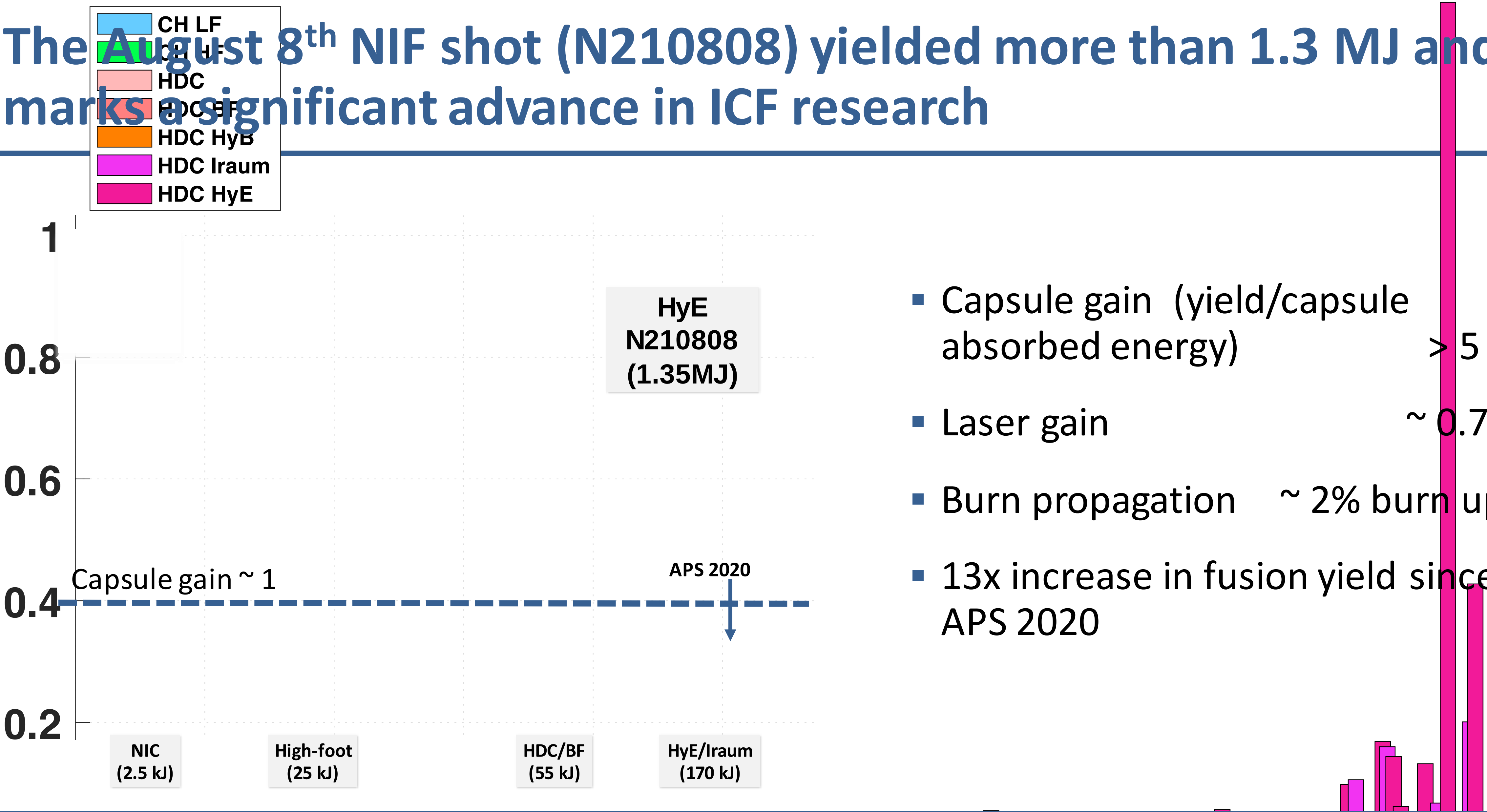
Variability mainly attributed to larger unintentional odd mode implosion asymmetry or more mix



5 um fill tube

Working on understanding and mitigating these degradations to improve robustness

The August 8th NIF shot (N210808) yielded more than 1.3 MJ and marks a significant advance in ICF research



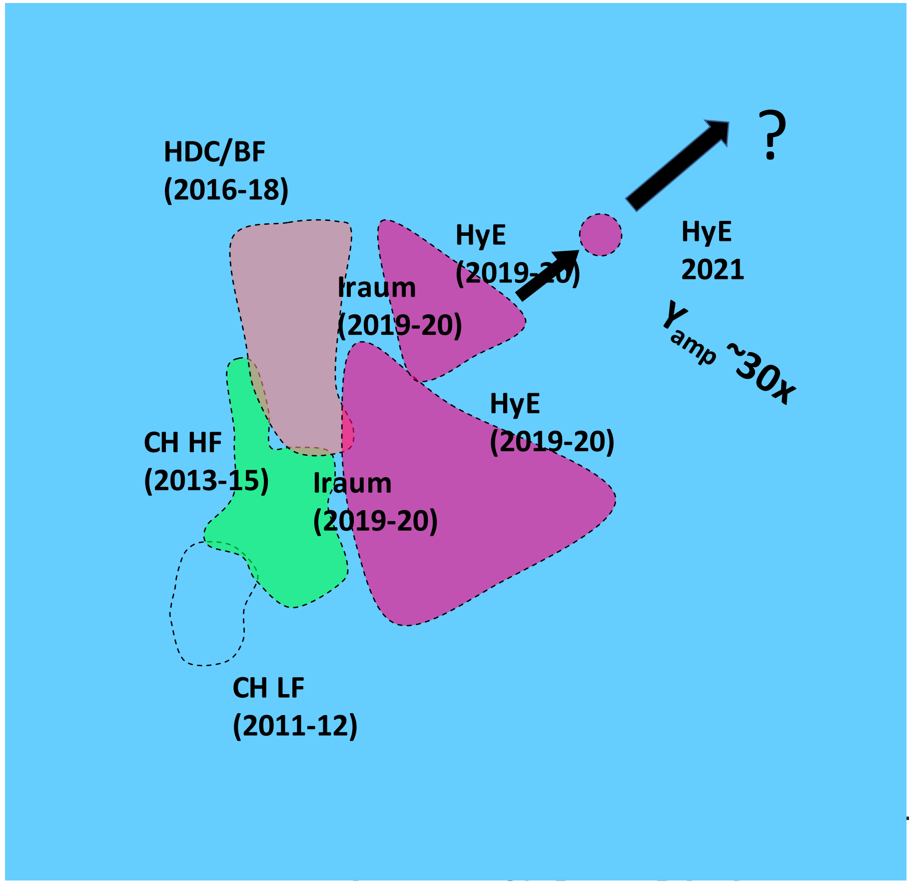
- Capsule gain (yield/capsule absorbed energy) > 5
- Laser gain ~ 0.7
- Burn propagation ~ 2% burn up
- 13x increase in fusion yield since APS 2020

We've been waiting for this since Nuckolls 1972 Nature paper!

We have made much progress in the last few years but much work remains to be done

- Understand where we are
  - Assess variability
  - Assess sensitivity to input parameters
  - "Dudded" fuel to validate models in this Y_{amp} range
- Push to higher performance
  - Higher compression
  - Higher laser energy
  - Further improvements to hohlraum
- Use the current design for science experiments
  - Output from this implosion is most powerful/energetic driver that we have for HED
- Improve our simulation capabilities

Ignition figure of merit $\sim (\rho R)^3 T^3 \sim E_{HS} P_{HS}^2$



Kritcher GO04.00002, Clark ZI02.00002, Casey CO04.00006

This is a very exciting time for our field!

“Don’t stop believing”

-- Hybrid E theme song

Lawrence Livermore National Laboratory