Achieving target gain 1.5 in fusion experiments at the NIF

PPPL Summer Seminar Series

A. Kritcher for the HYBRID-E and ICF teams

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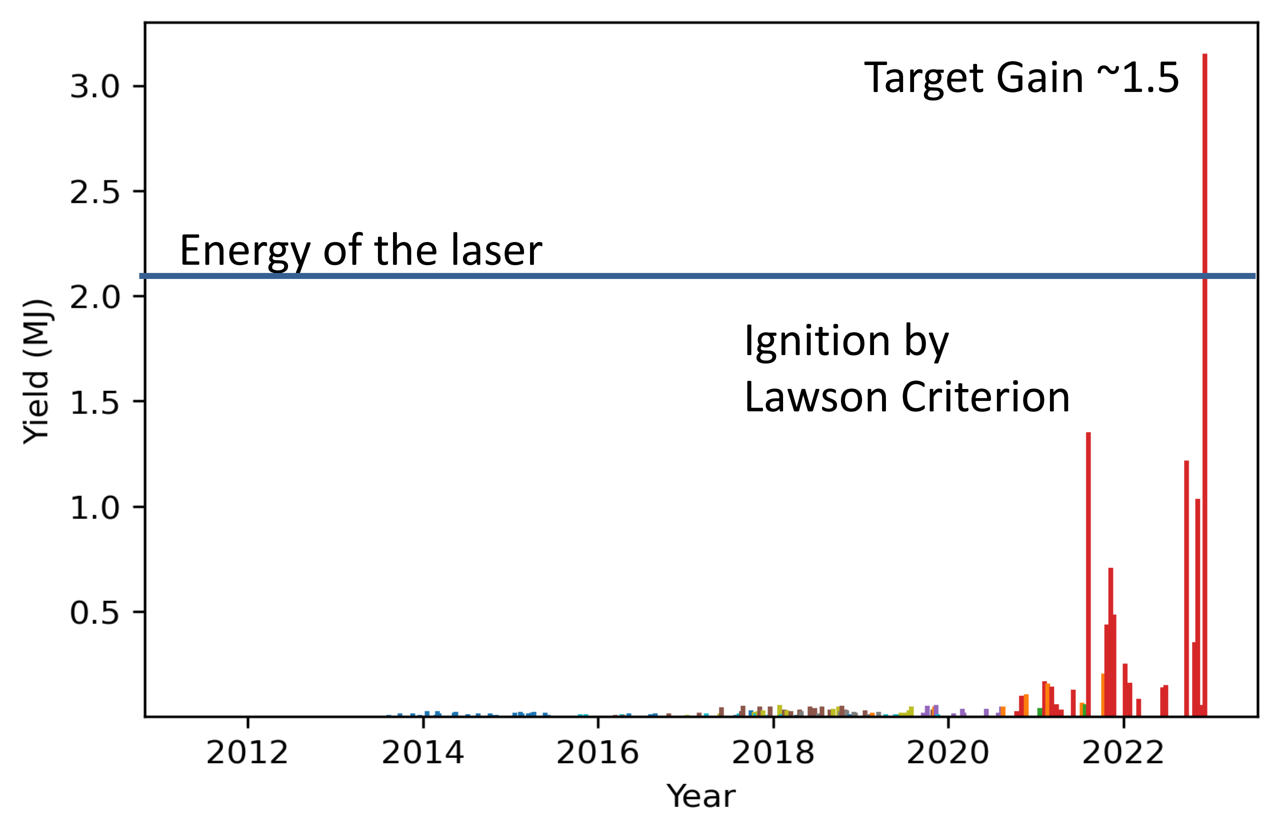
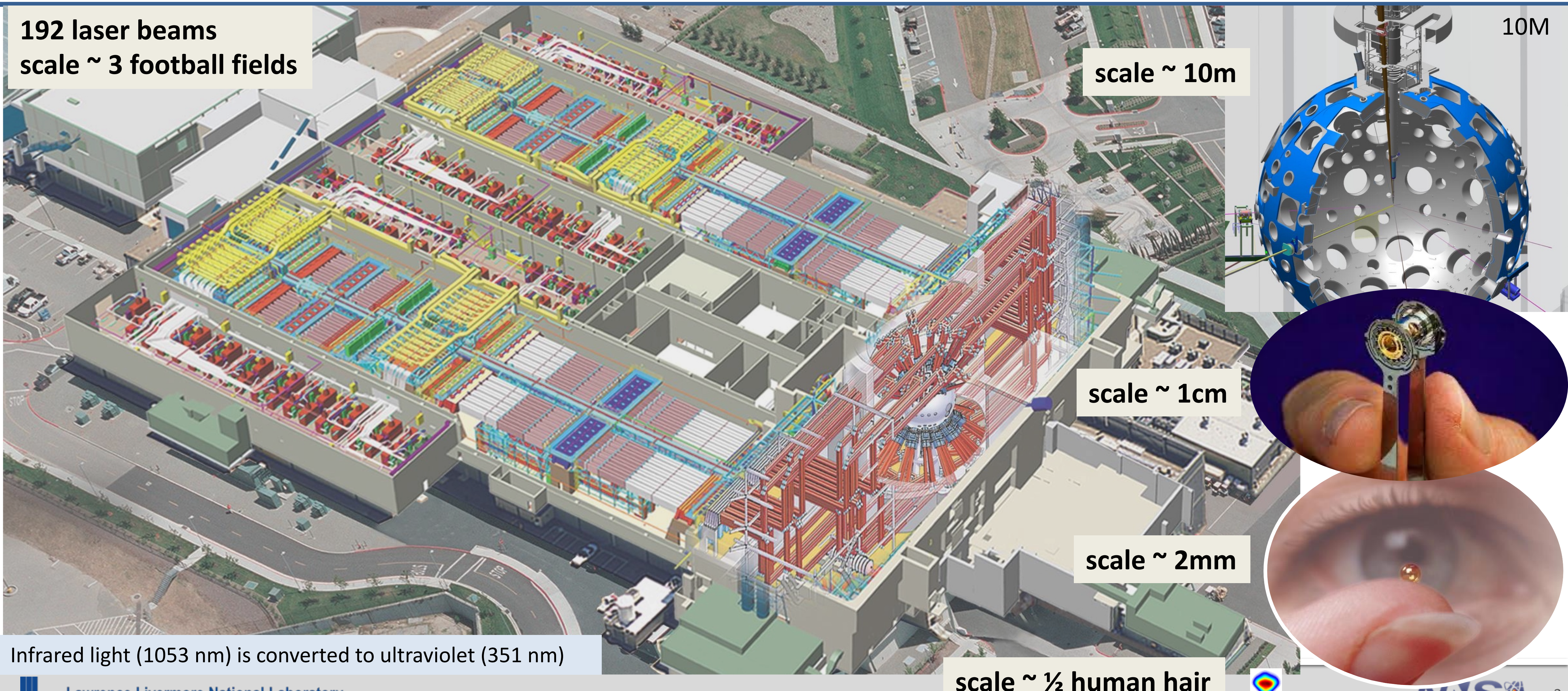
Dec 5th 2022 marks a significant advance in ICF research; shows there is nothing fundamentally limiting gain >1 in a controlled laboratory experiment



- Dec 5th 2022:
  - **>30 quadrillion watts!! (90 trillionths of a second)**
  - **Pressure > 2x center of the sun**
  - **Temperature >5x center of the sun (>100million deg)**
  - **Now meets all definitions for ignition on the NIF**
  - **Fusion energy >3.1MJ; Laser energy on target 2.05 MJ; Wall plug energy >300-400MJ**

First time Fusion yield > energy on target – still long way to go!

Experiments performed at the National Ignition Facility, world's most energetic laser, enables the creation and study of "micro-fusion" explosions



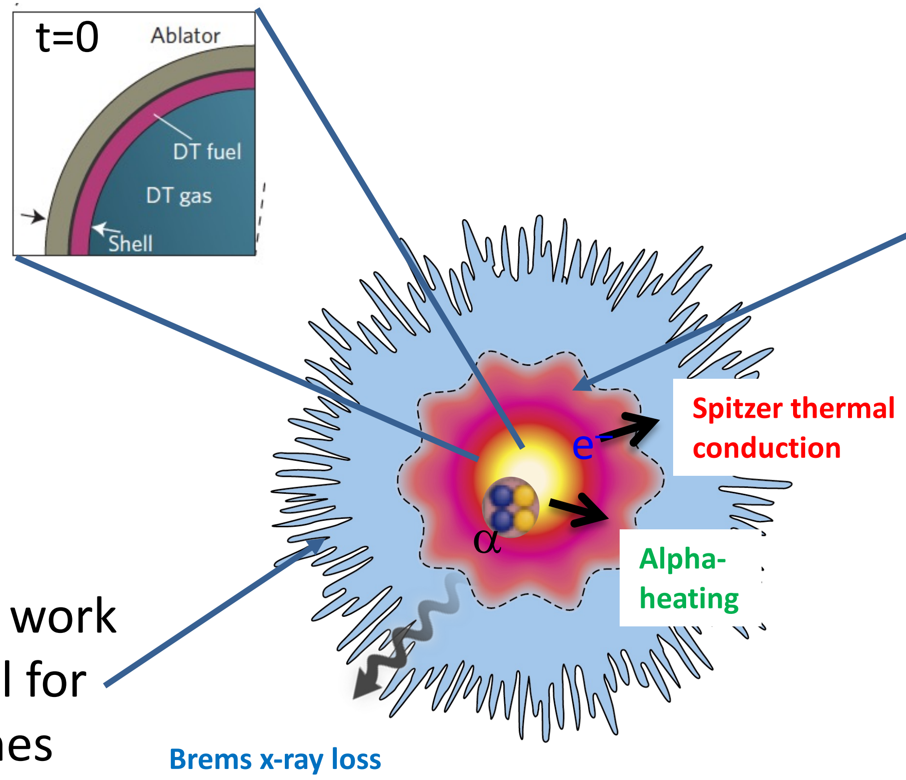
Infrared light (1053 nm) is converted to ultraviolet (351 nm)

To reach fusion ignition and gain in ICF experiments requires heating and compressing DT fuel to extreme conditions, for a duration of time (Lawson)

Fusion Reaction:

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

~5 keV (10s million degrees) to overcome Coulomb barrier!

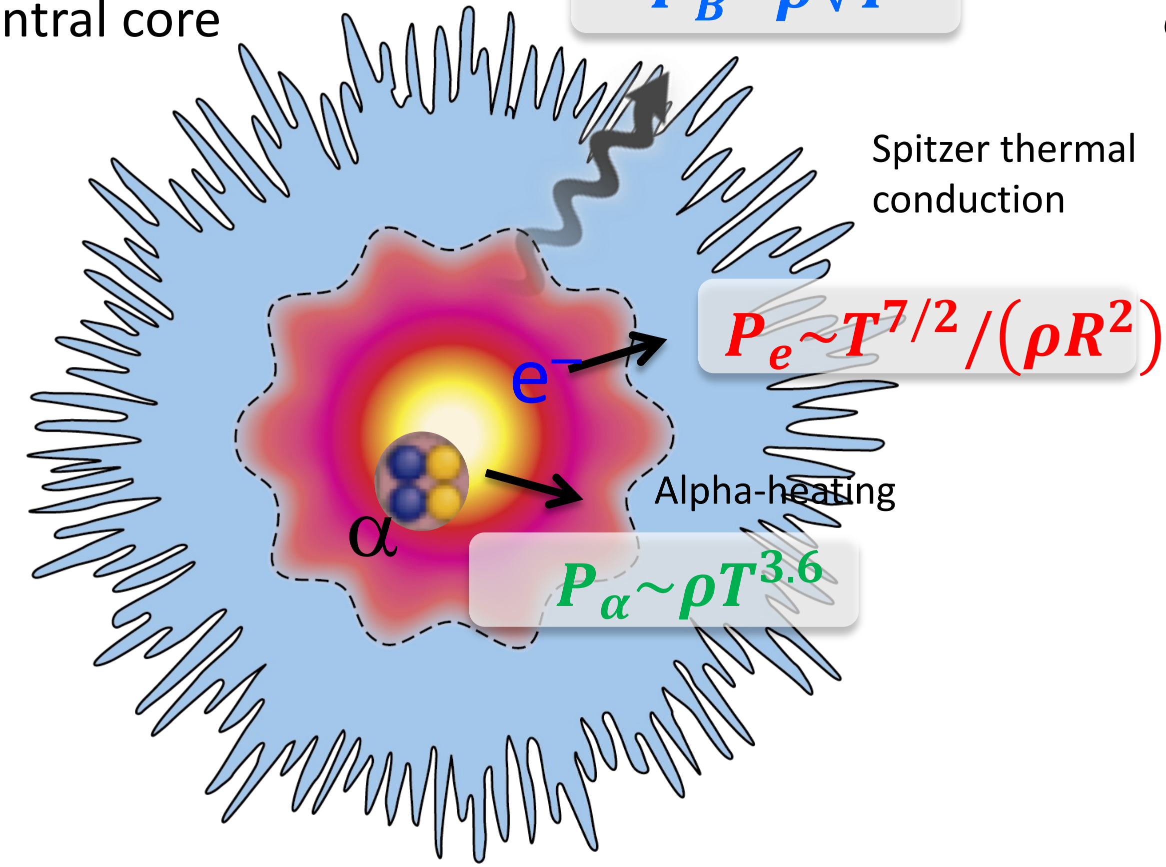


- Compress and heat a central "hot spot" containing a fraction of the fuel with a fuel piston
- Absorb α for extra "self heating"
- Core temperature rises significantly → rapid fusion gain through the cooler dense fuel
- Competing with losses

"Cold" dense DT fuel – work on hot spot, tamps fuel for longer confinement times

[1] O. A. Hurricane et al. Phys. Plasmas **26**, 052704 (2019)

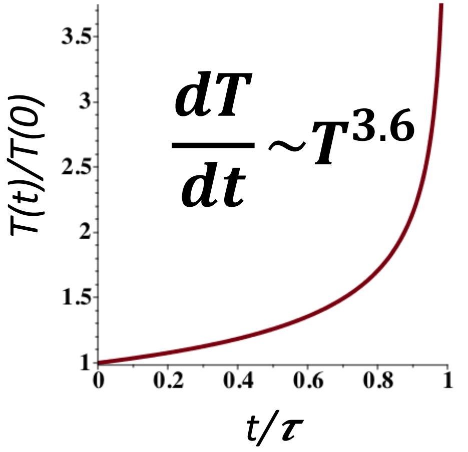
Ignition occurs when α-heating > all energy losses for a duration of time



Time dependent heat balance (power/mass):

$$c_{DT}\frac{dT}{dt} = \underbrace{f_\alpha P_\alpha}_{\text{self-heating}} - \underbrace{f_B P_B - P_e - \frac{1}{m} p \frac{dV}{dt}}_{\text{Losses}} \longleftarrow \text{Work}$$

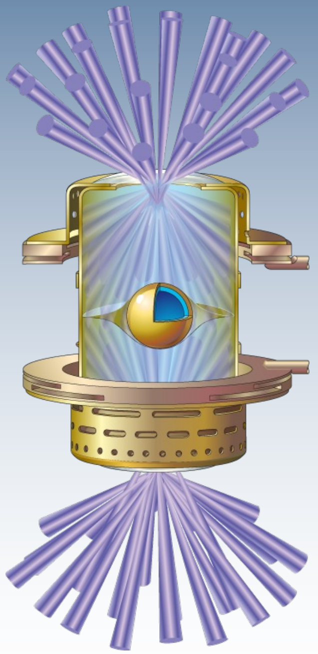
Ignition is a thermonuclear instability, as self heating dominates temperature rises rapidly



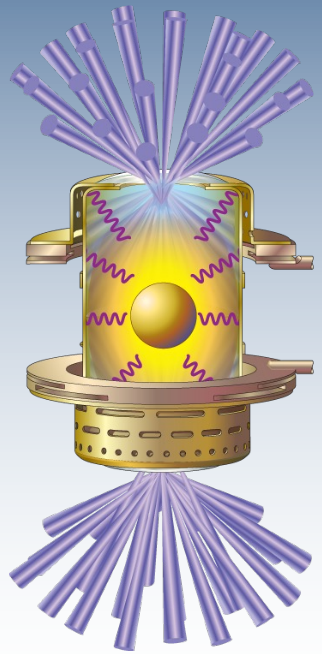
$\tau \sim 10's\ of\ picoseconds$

Laser Indirect drive inertial confinement fusion uses a laser-driven hohlraum to create the x-rays that drive the implosion

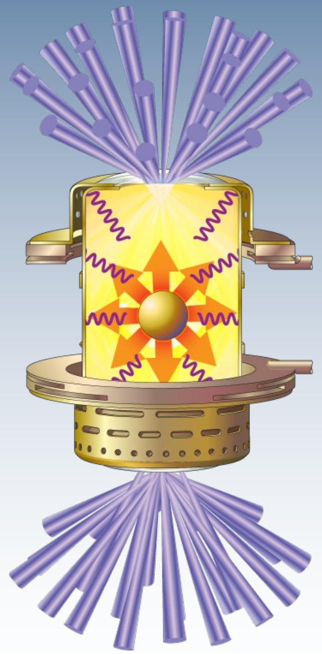
Laser beams focused inside the hohlraum



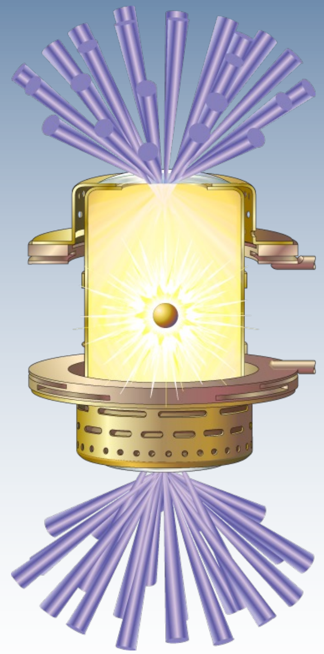
The hohlraum is heated creating x-rays



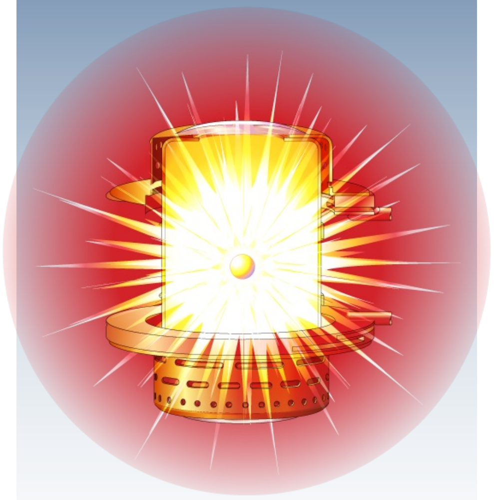
X-rays ablate the capsule, accelerate the fuel inward



The fuel core reaches pressures 500 billion atm

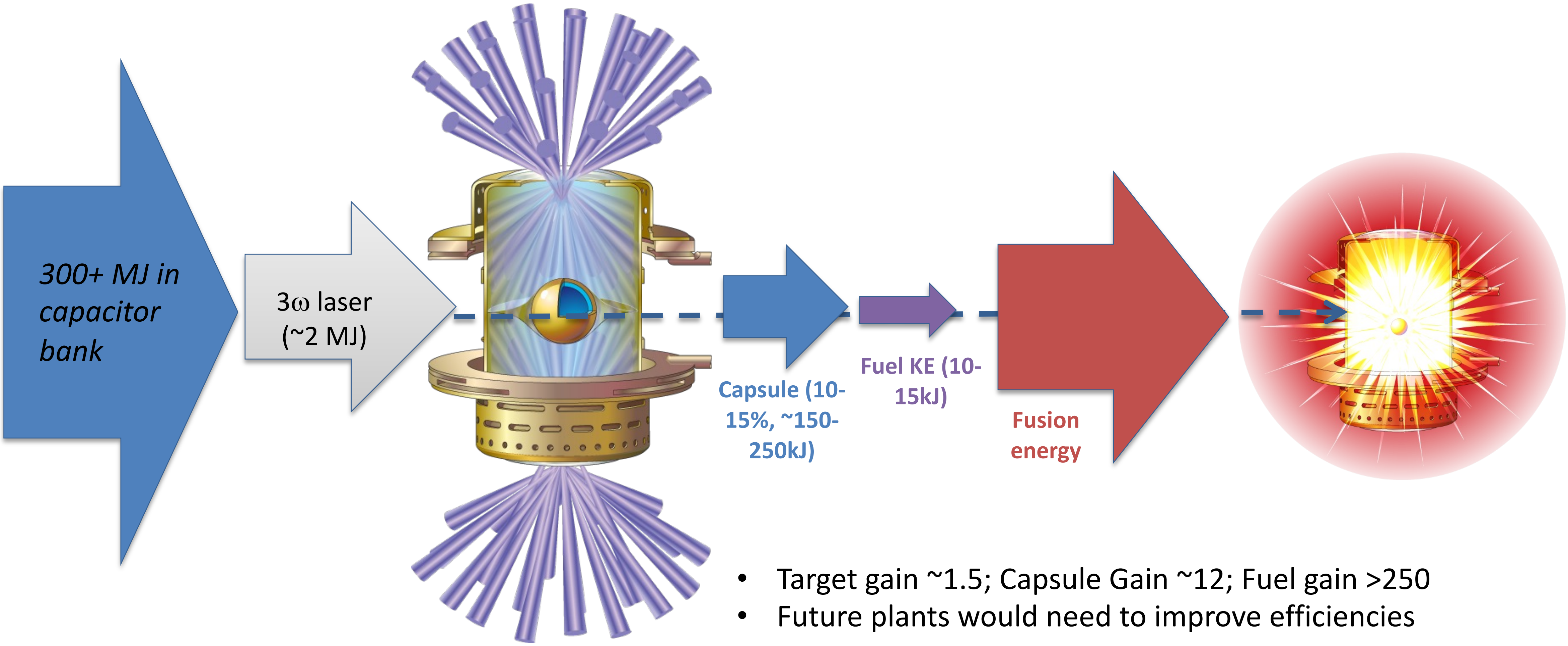


Fusion burn spreads through the fuel, yielding >> input energy



Achieving the conditions for ignition demands precise control of design, laser, and target parameters

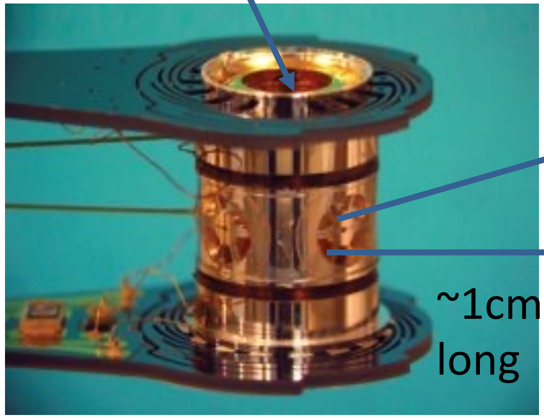
Only a small fraction of the laser energy on target is coupled to the implosion, making this so challenging



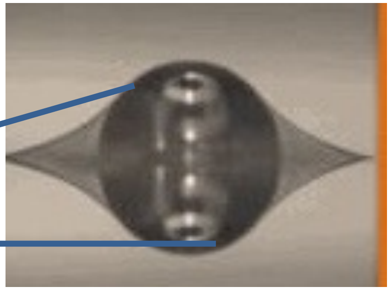
- Target gain ~1.5; Capsule Gain ~12; Fuel gain >250
- Future plants would need to improve efficiencies

The targets are engineering marvels

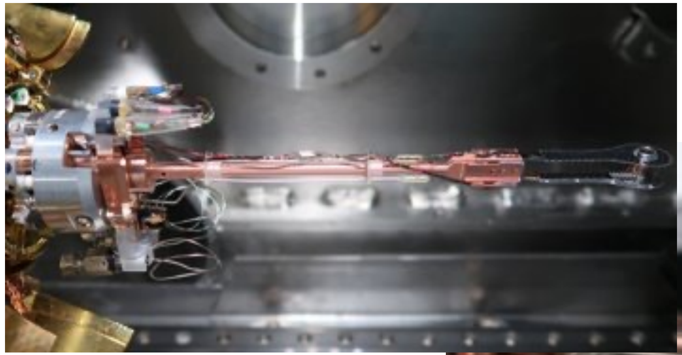
LEH



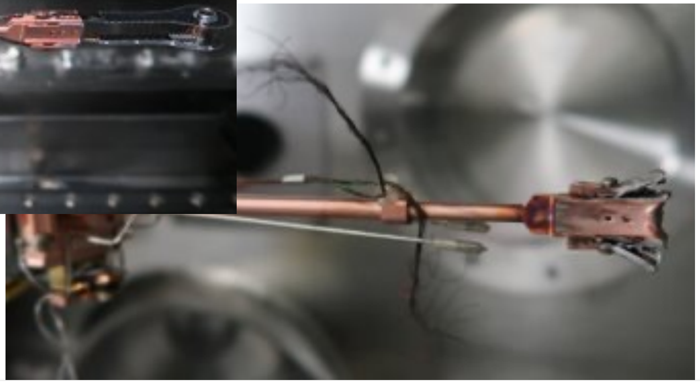
10s of nm tent

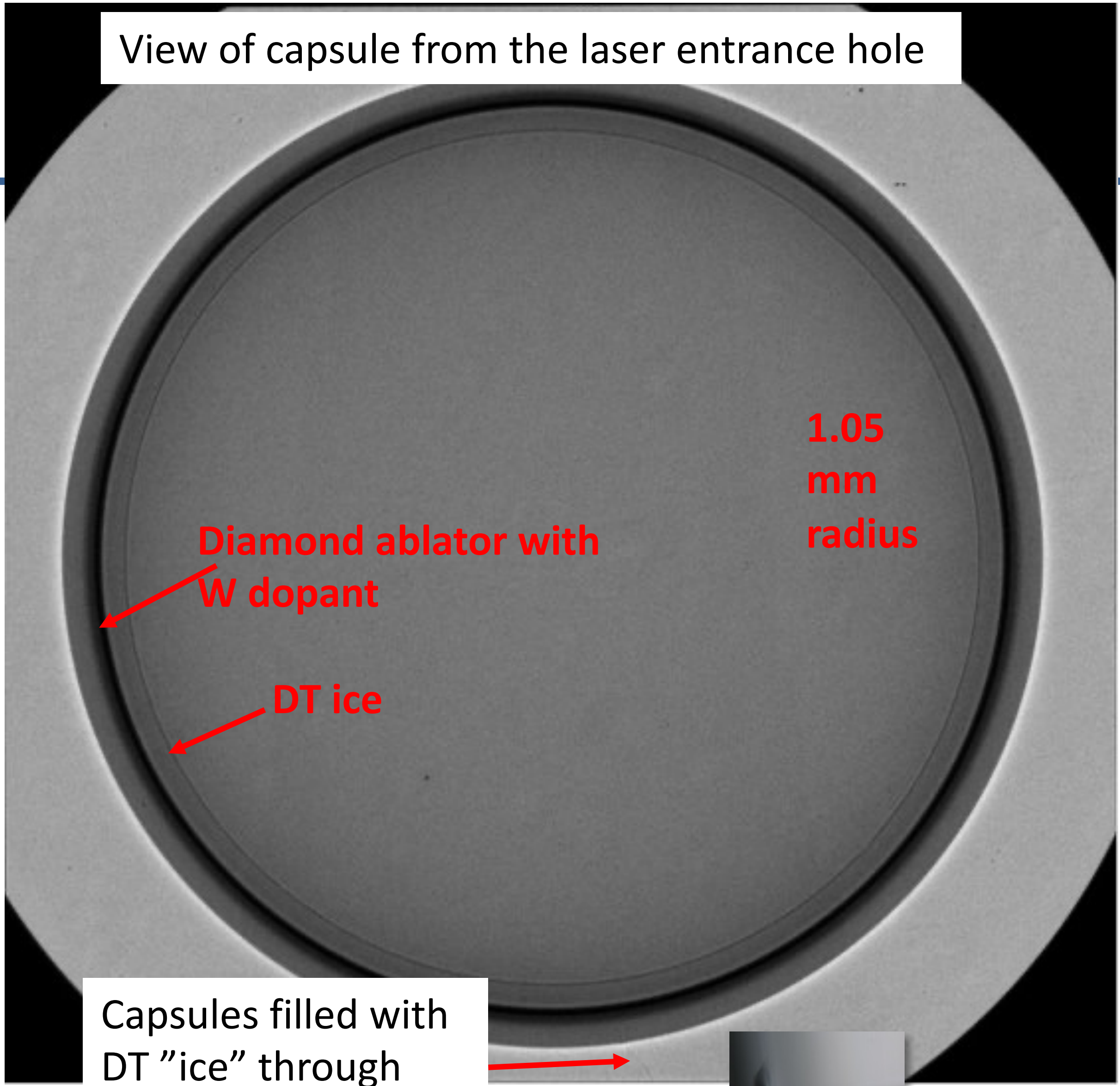


Before



After



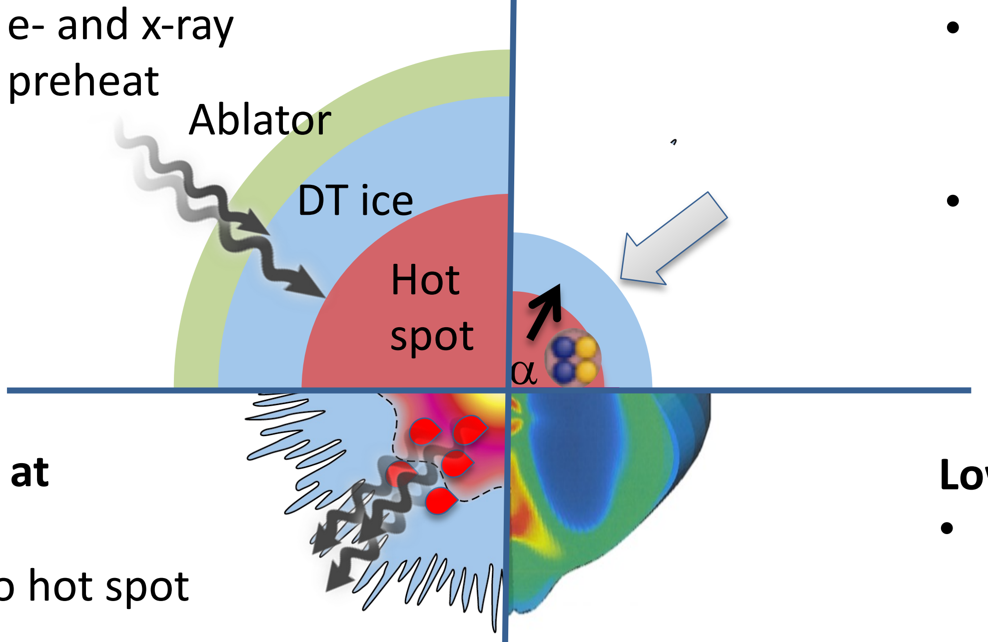


Capsules filled with DT ”ice” through mini- fill tube

Many design parameters need to be considered simultaneously to achieve these conditions

Adiabat (low entropy):
- High ρR for trapping alphas
- Increase confinement time

Velocity and ablation pressure:
- Convert kinetic energy of imploding shell to hot spot internal energy
- High late-time ablation pressure



Hydrodynamic Stability (mix at interfaces & seeds)
- Reduce energy coupling to hot spot
- Creates thin spots
- High Z mix reduces temperature

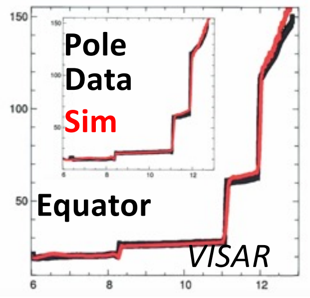
Low mode asymmetries:
- Reduce coupling of fuel KE to hot spot, creates thin spots

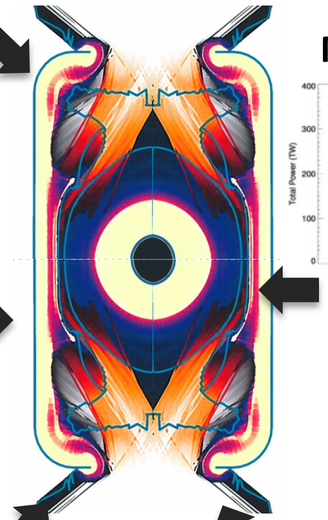
What's best for the implosion is usually difficult for the hohlraum

We use radiation-hydrodynamic simulations that are benchmarked to data to design ICF experiments

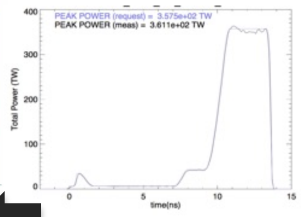
Target metrology

Shock measurements

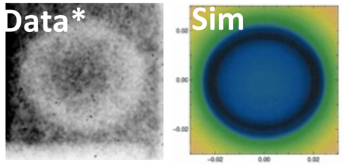




Measured laser

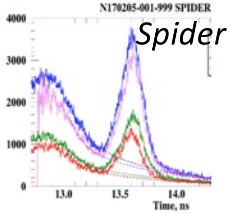


Shell Radiography

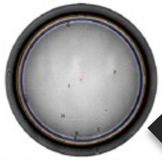


2D ConA

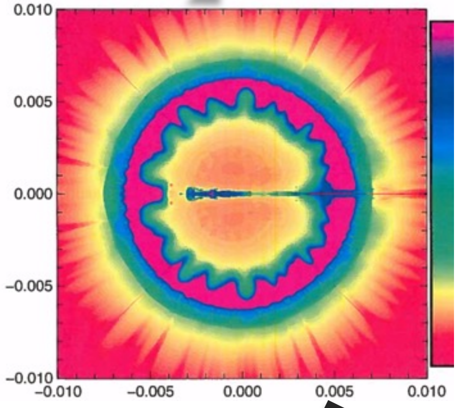
Bang time

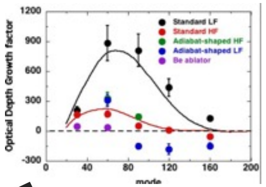


Radiation drive



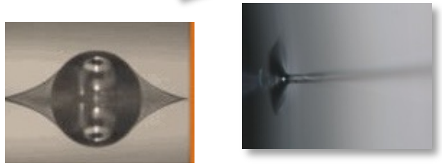
Surface roughness



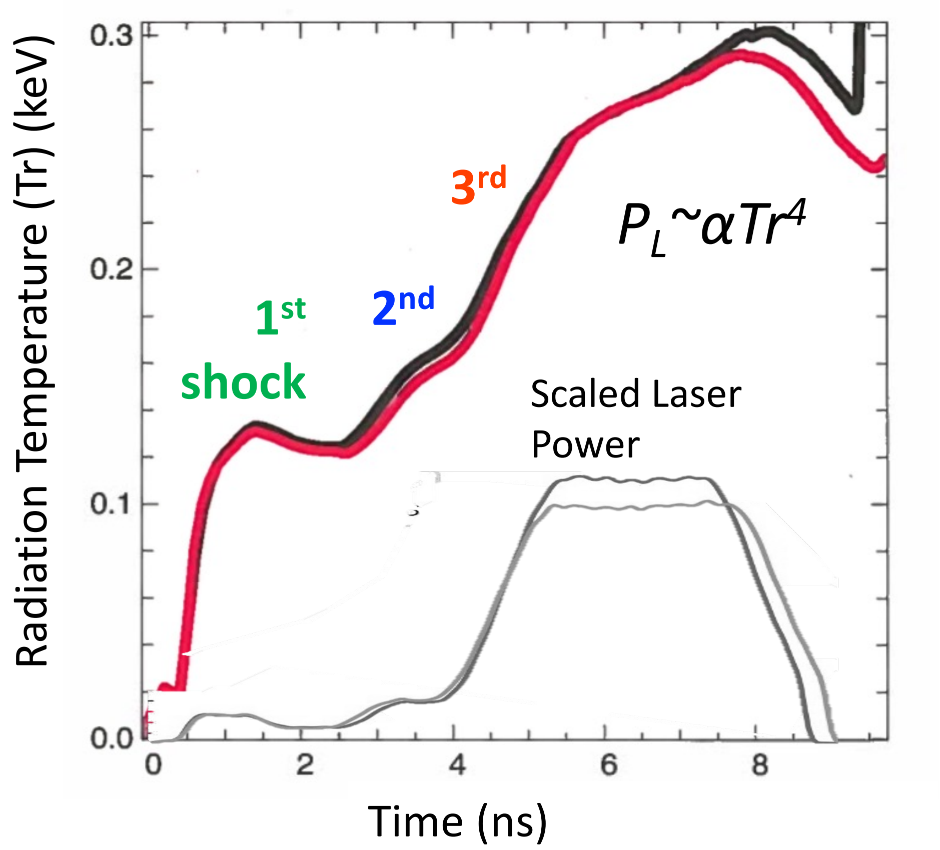


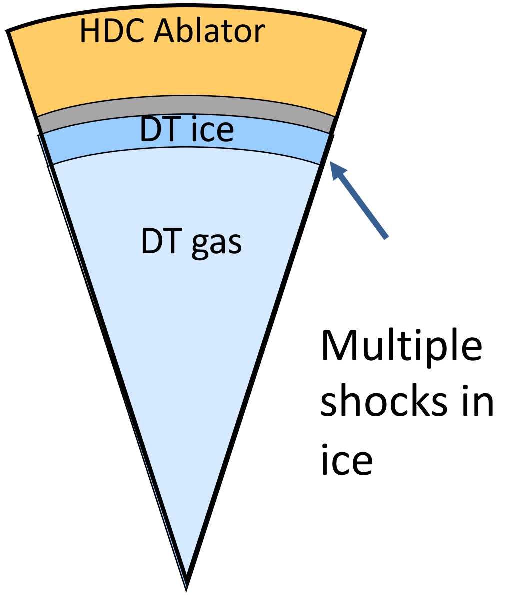
Ablation front and interface growth

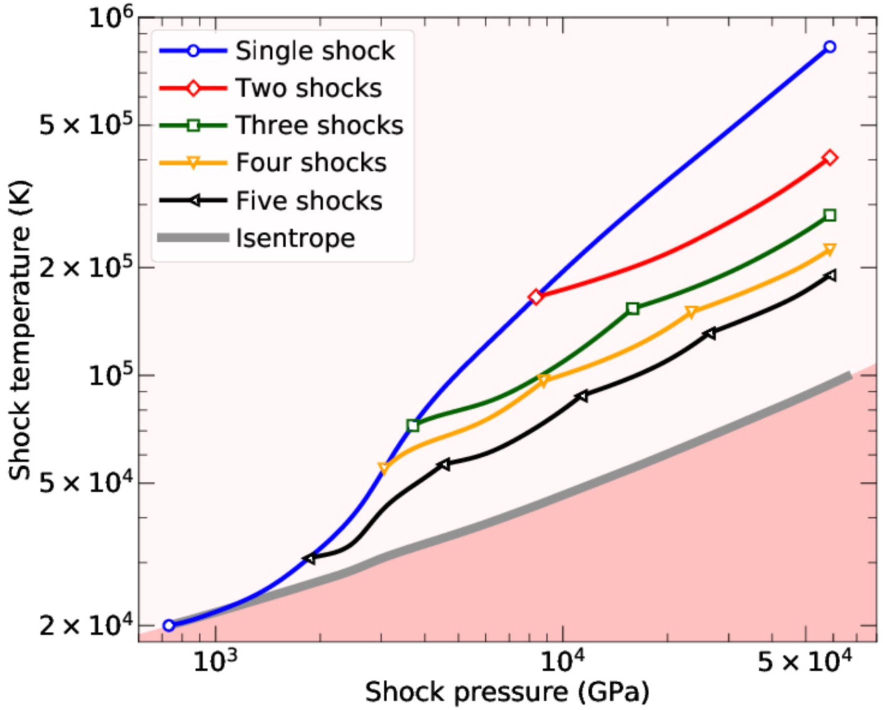
Surrogate model for tent & fill tube



We compress the DT piston on a lower entropy (adiabat) using steps in the radiation temperature launching multiple coalescing shocks



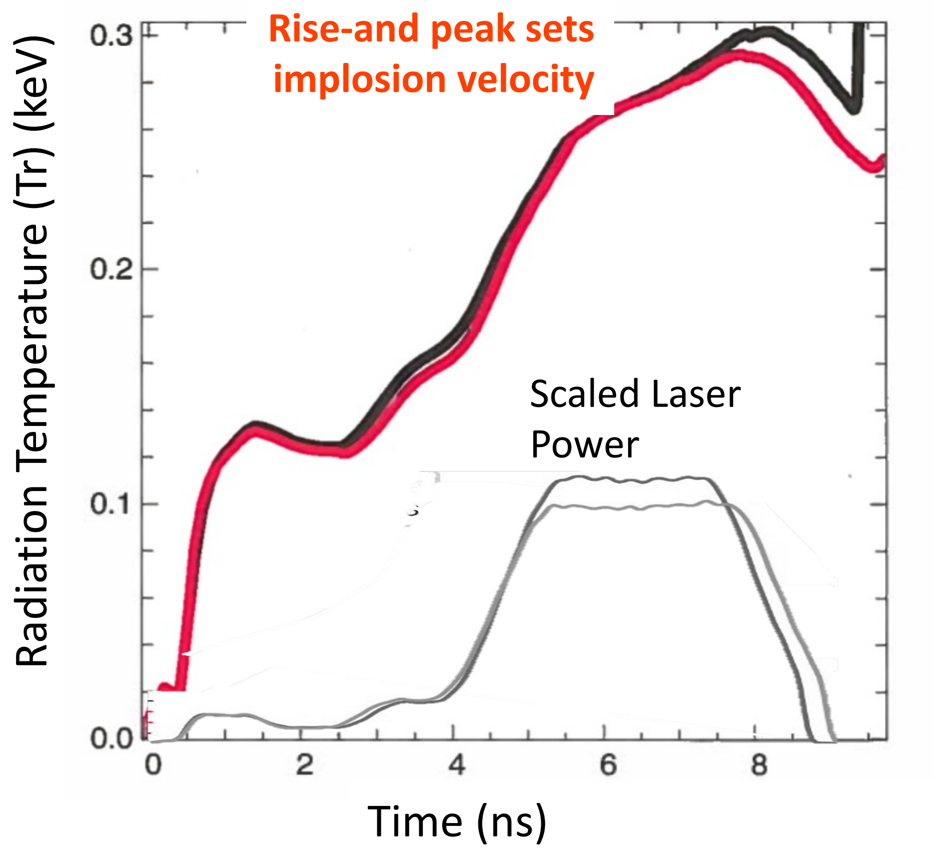




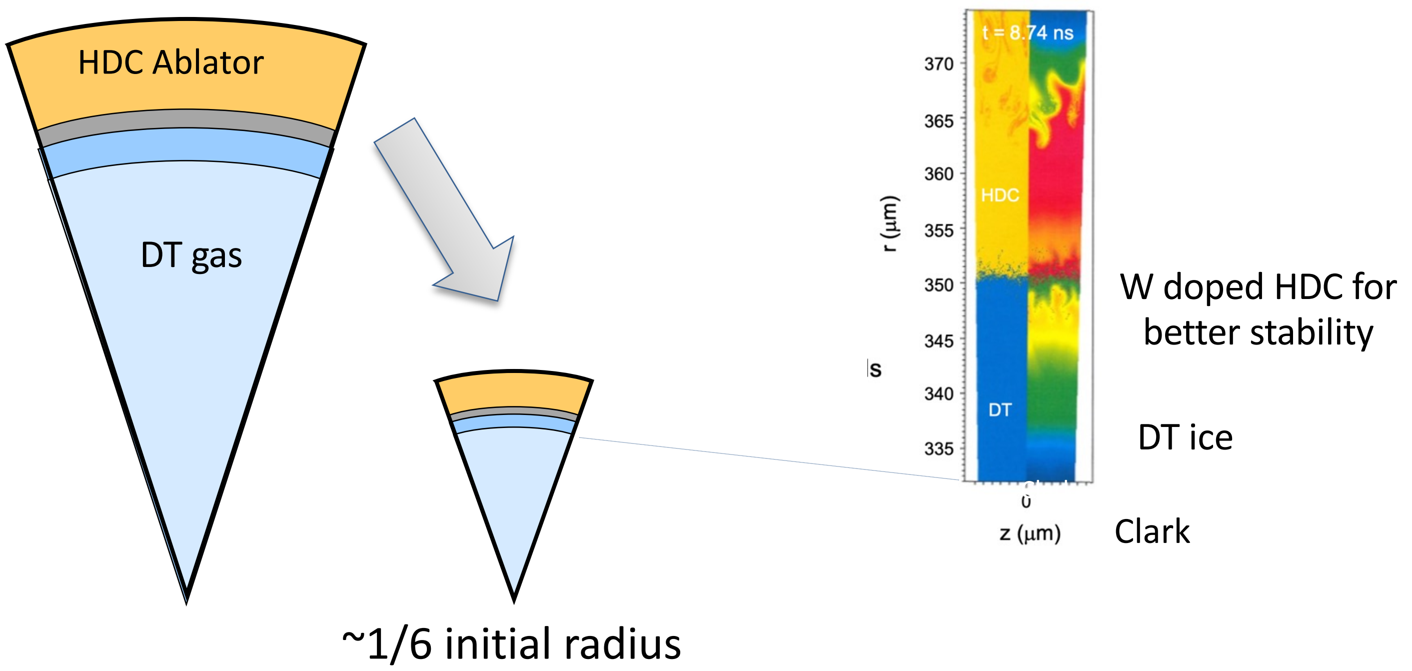
González-Cataldo, Felipe & Soubiran, François & Militzer, Burkhard. (2020).

We measure the leading shock from multiple angles within the shell to calibrate our radiation drive

The fuel is accelerated to extreme velocities ~400 km/s to do work on the hot spot with the "peak" – w/convergence: 100s Mbar in the DT shell and ablator



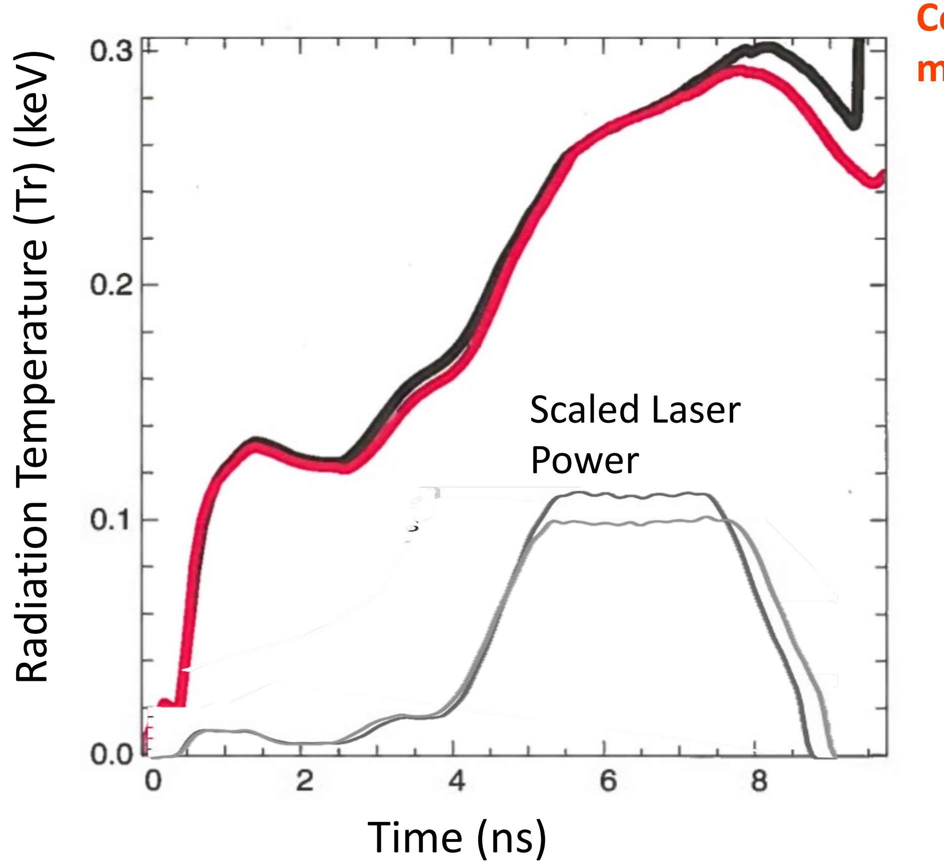
Light fluid pushing on heavy fluid!



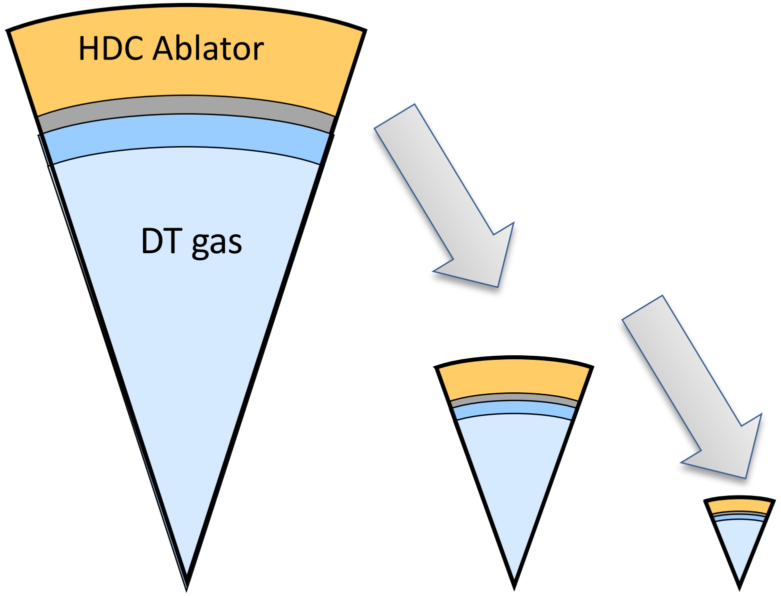
Compressed DT and HDC: 20 g/cc and 10s of eV

- Rely on models to balance high implosion velocity, instability growth at the ablation front, and growth between the fuel and ablator
- Models largely untested (non ideal plasma and Fermi-degenerate strongly coupled plasmas), understanding is sensitive to EOS/conductivity

The end of the peak is important for maintaining pressure and coupling more energy – At peak compression the DT reaches hundreds of Gbar



Coasting time important for maintaining hot spot pressure



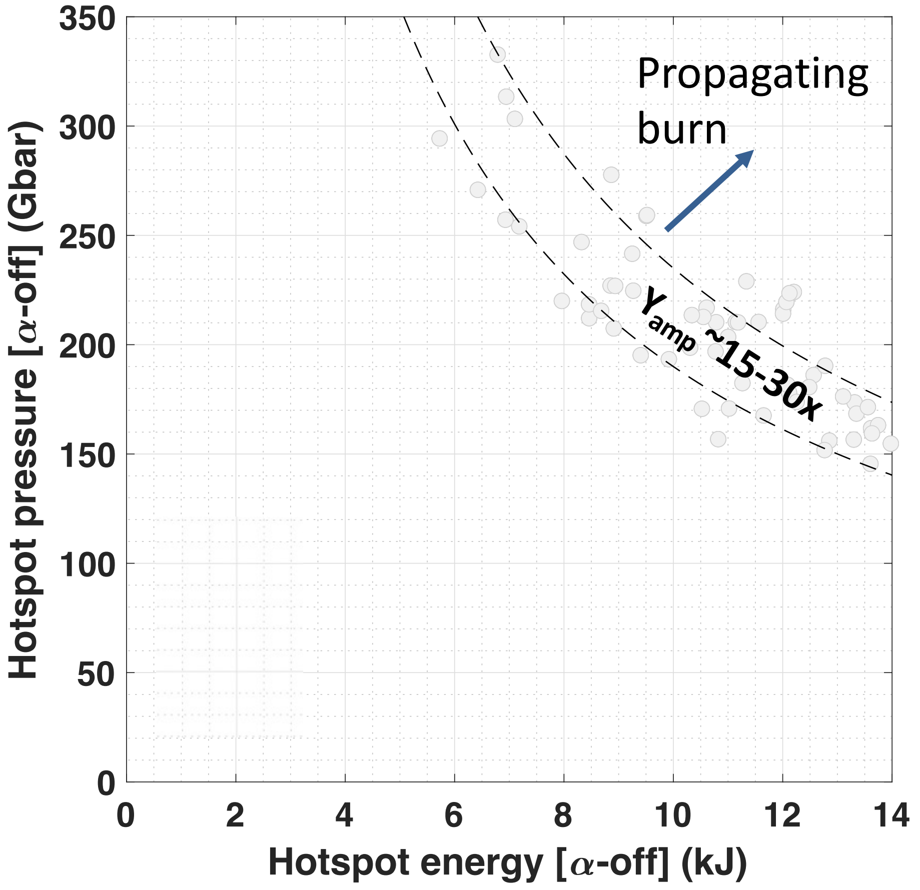
- Core:
  - >500 Gbar
  - 50-100 g/cc
  - > 10 keV
- Compressed shell
  - 400 Gbar
  - ~450 g/cc
  - ~1.5 keV

- Conditions well into HED regime, fermi-degenerate and strongly coupled in the shell, weakly coupled hot spot plasma

The program has advanced our physics designs, understanding and technology to improve performance

- *$E_{HS}P_{HS}^2$ [Patel[1]] related to ITFX*
  - Take alpha heating out
  - Y_{amp} 15-30 (yield amplification from self-heating) for onset of propagating burn[2-3]
  - Boundary is uncertain

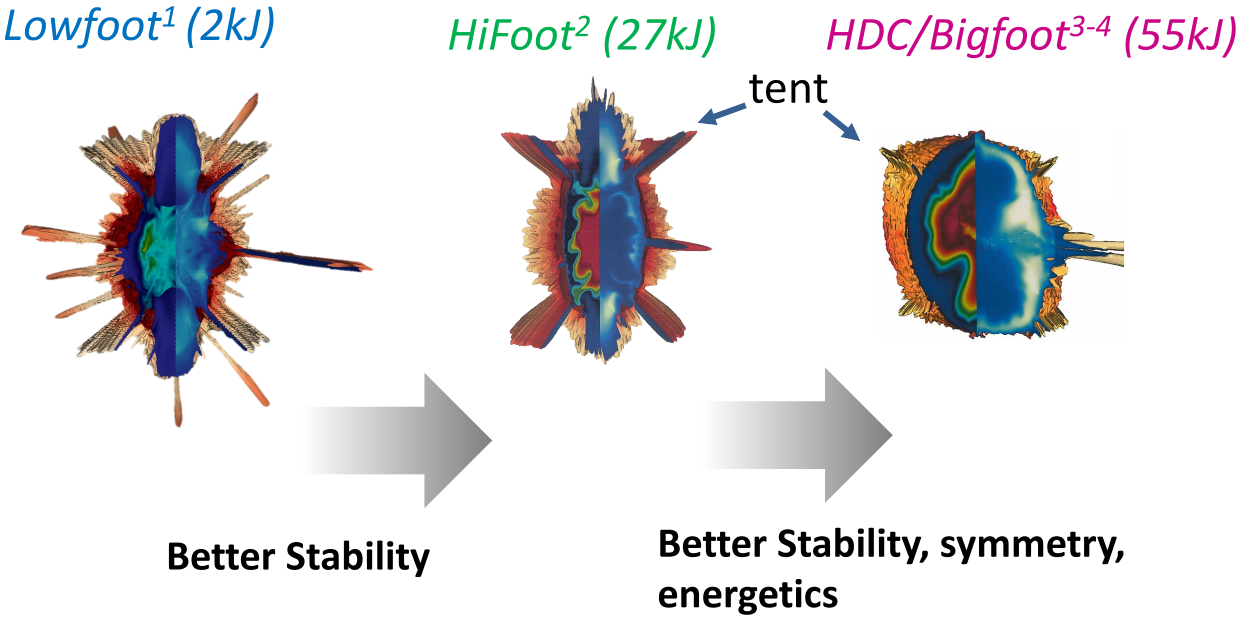
Ignition figure of merit $\sim (\rho R)^3 T^3 \sim E_{HS} P_{HS}^2$

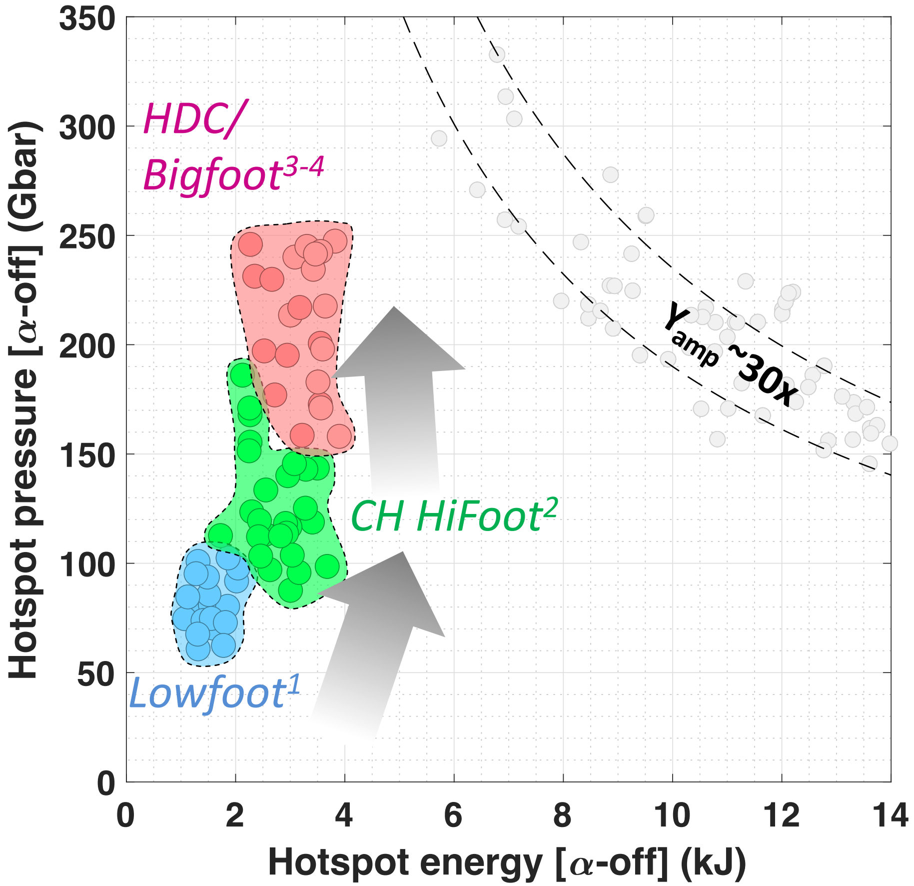


1: P. Patel, Phys. Plasmas 27, 050901 (2020)
2:A. R. Christopherson, et al, PHYSICAL REVIEW E **99**, 021201(R) (2019)
3: J. D. Lindl, et al, POP, 25, 122704 (2018)

Each color represents new understanding that led to the next improvement – moving toward the ignition boundary

Previous platforms made stability, symmetry, energetics advances to increase hot spot pressure but energy was too low





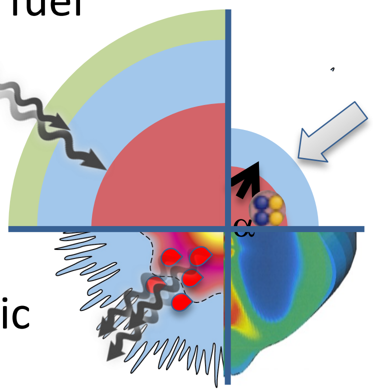
1: J. Lindl, et al, PHYSICS OF PLASMAS 21, 020501 (2014)
2: T. Dittrich, et al Phys. Rev. Lett. 112, 055002; 2: O. Hurricane, et al, Nature 506,343 (2014);
3: S. Le Pape et al., PRL 120, 245003 (2018); L.B. Hopkins et al., PPCF 61, 014023 (2018)
4: D.T. Casey et al., PoP 25, 056308 (2018); K.L. Baker et al., PRE 102, 023210 (2020)

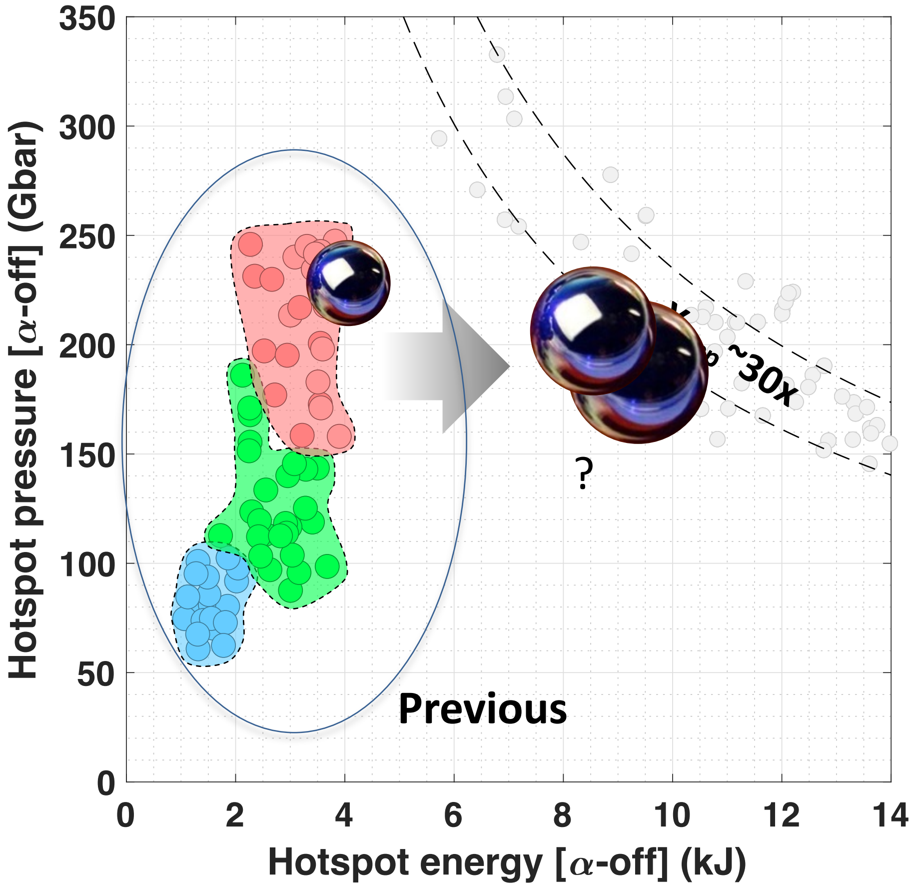
Hurricane, et al: EPS I1.201

Would need bigger capsule, but no more laser energy and same pressure – major challenge

Previous designs maxed out in laser power & energy, HYBRID[1] Challenge to make the capsule bigger! But keep similar pressure

Balance other aspects for maintaining pressure

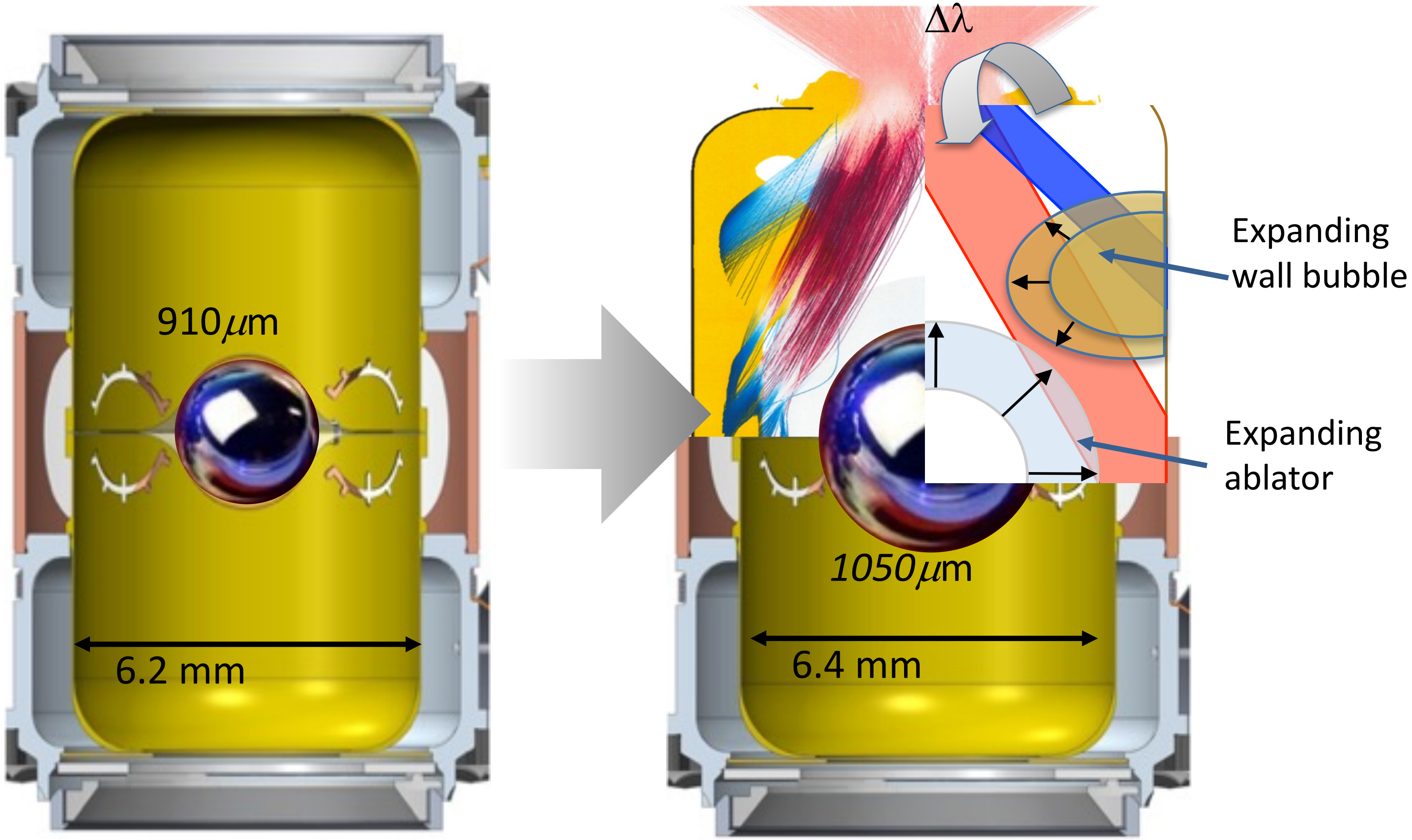




[1] *Hurricane, et al,PPCF 61, 014033 (2019); PoP 26, 052704 (2019)*

More difficult with larger scale and no addnl. laser energy, terms trade-off each other and with Hohlraum, tested two scales

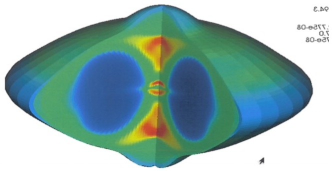
HYBRID-E[1-2] used higher efficiency hohlraums to maintain velocity for larger targets with fixed laser energy– more difficult for symmetry



(not drawn to scale)

Much bigger capsule in to slightly larger hohlraum…

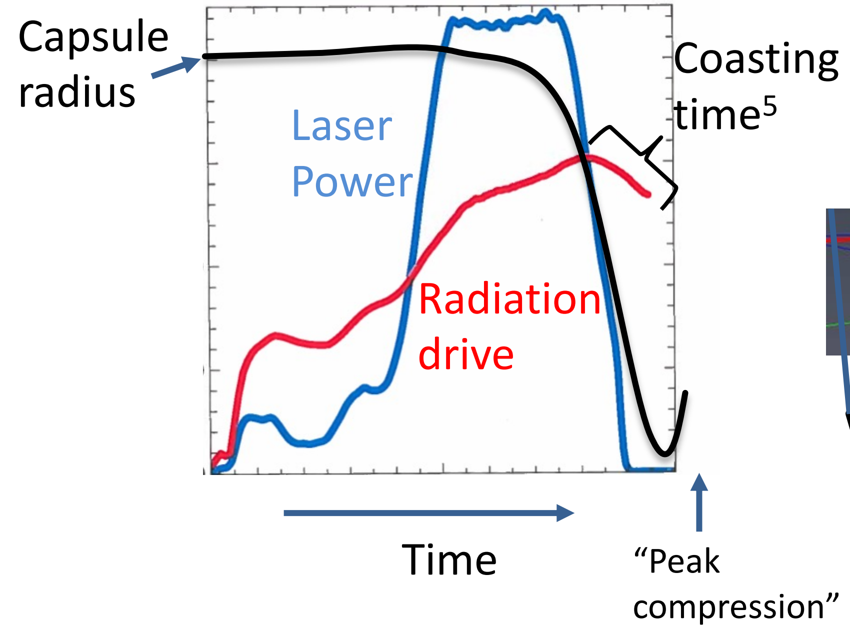
- Difficult to model use data-driven models[5] (D. Callahan) and cross beam energy transfer in low gas fill hohlraums[6]



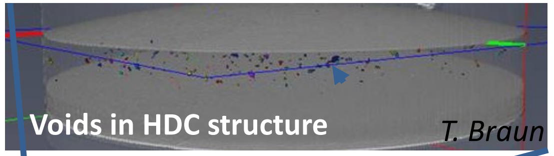
Compressed fuel with asymmetries

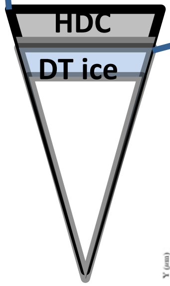
1: A.B. Zylstra et al., PRL 126, 025001 (2021);
2: A.L. Kritcher et al., PoP 28, 072706 (2021)
3: S. Le Pape et al., PRL 120, 245003 (2018); L.B. Hopkins et al., PPCF 61, 014023 (2018)
4: D.T. Casey et al., PoP 25, 056308 (2018); K.L. Baker et al., PRE 102, 023210 (2020)
5: D.A. Callahan et al., PoP 25, 056305 (2018); J. Ralph, et al., PoP, 25, 082701 (2018)
6: A. L. Kritcher, et al *Phys. Rev. E* **98**, 053206 (2018) , L. Pickworth, et al, PoP (2020)

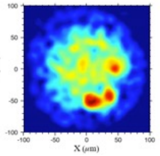
Initial tests increased energy significantly but suffered in pressure, slightly smaller capsules by 50 microns recovered pressure

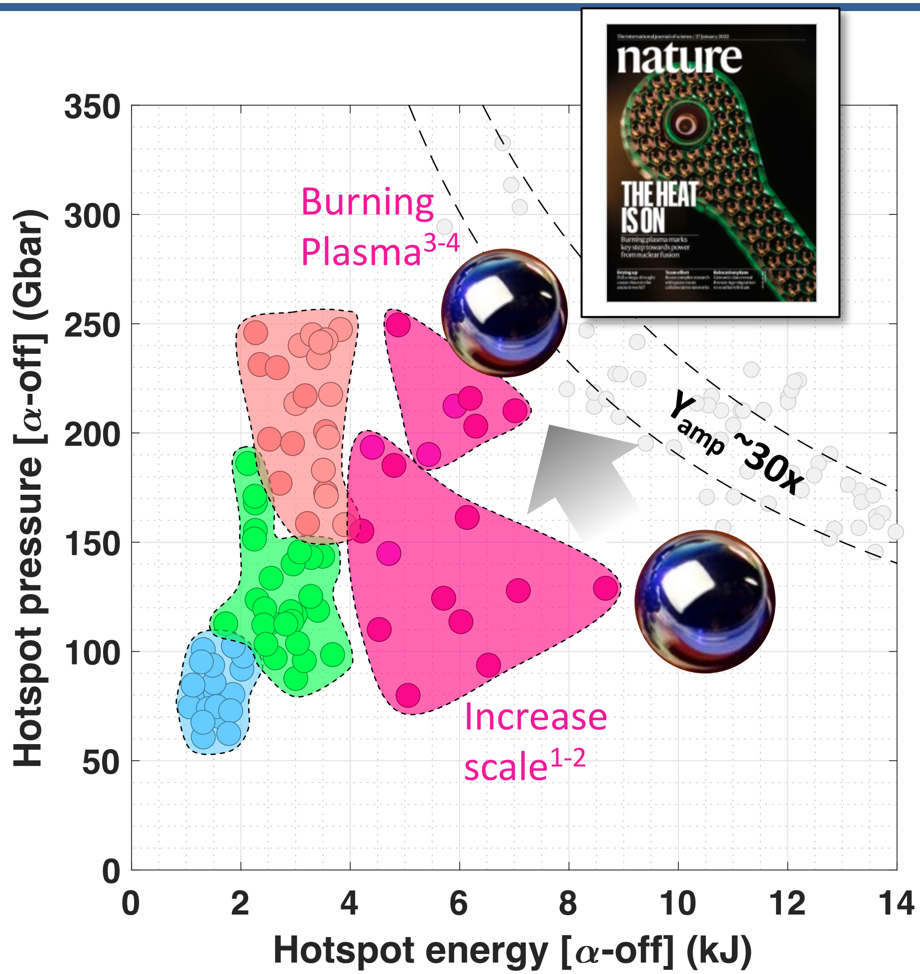


-> Reduced coast
-> Better capsules







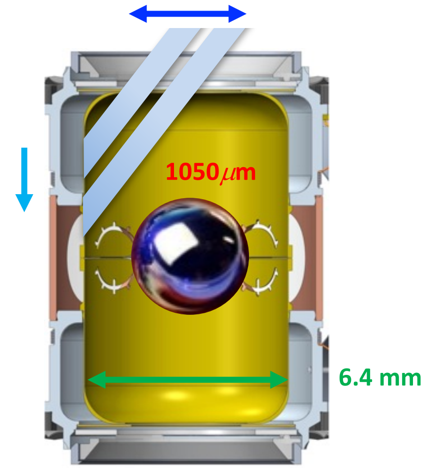


Simulations suggested coast was still sub-optimal, motivating test of yet lower coast

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: Zylstra Zylstra, et al., Nature, 601, 542 (2022);
4: Kritcher, et al., Nature Phys. 18, 251 (2022);
5: *O. Hurricane et al., PoP 24, 092706 (2017); O. Hurricane et al., PoP 27, 062704 (2020)*

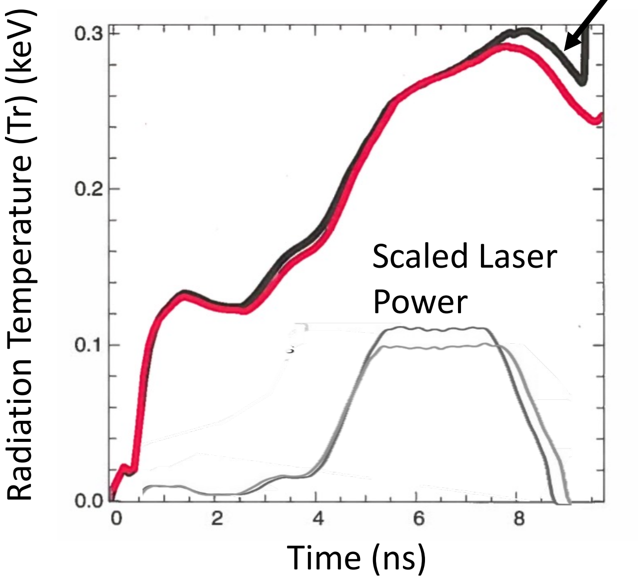
To reduce coast[3] we had to make the hohlraum even more efficient – Resulted in Aug 8th 1.35 MJ shot

Smaller LEH[5-6]

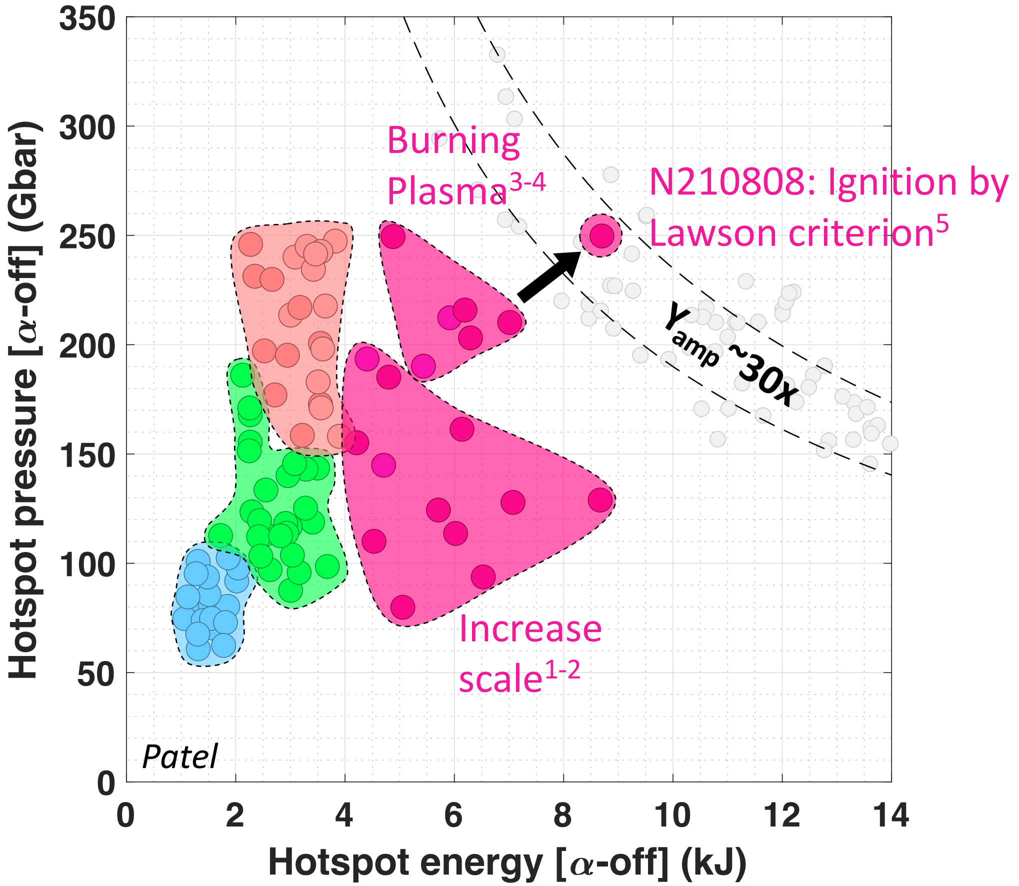


-> Reduced coast[7]

Late-time ablation pressure increased



-> Improved design stability
-> Better ablator quality



1: O. Hurricane et al, APS-DPP, PO7.00001 (2017); PPCF 61, 014033 (2019); PoP 26, 052704 (2019)
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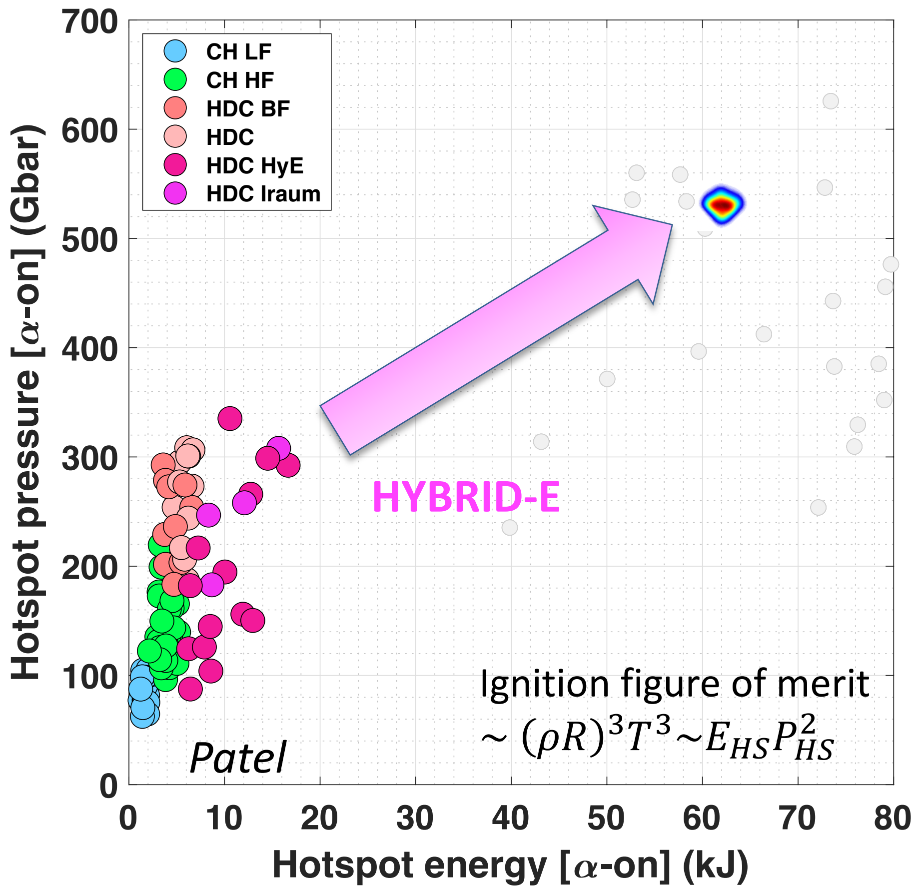
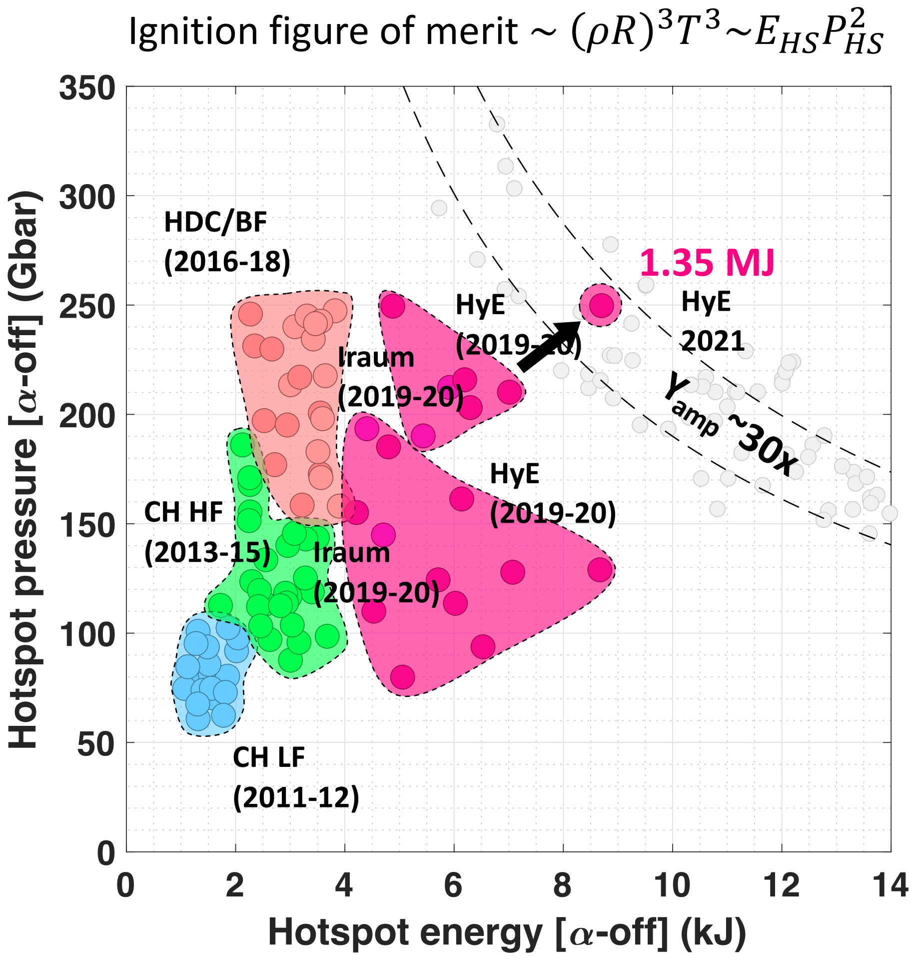
3: Zylstra Zylstra, et al., Nature, 601, 542 (2022);
4: Kritcher, et al., Nature Phys. 18, 251 (2022);
5: Kritcher, et al., PRE, 106, 025201 (2022); Zylstra, et al., PRE, 106, 025202 (2022); NIF collaboration, PRL, 129, 075001 (2022)
6: J. Ralph, T Woods, A Kritcher, et al., "Hohlraum Scans Project", (2020)
7: Hurricane, Kritcher, Callahan, et a.l, PoP, 24, 092706, 2017

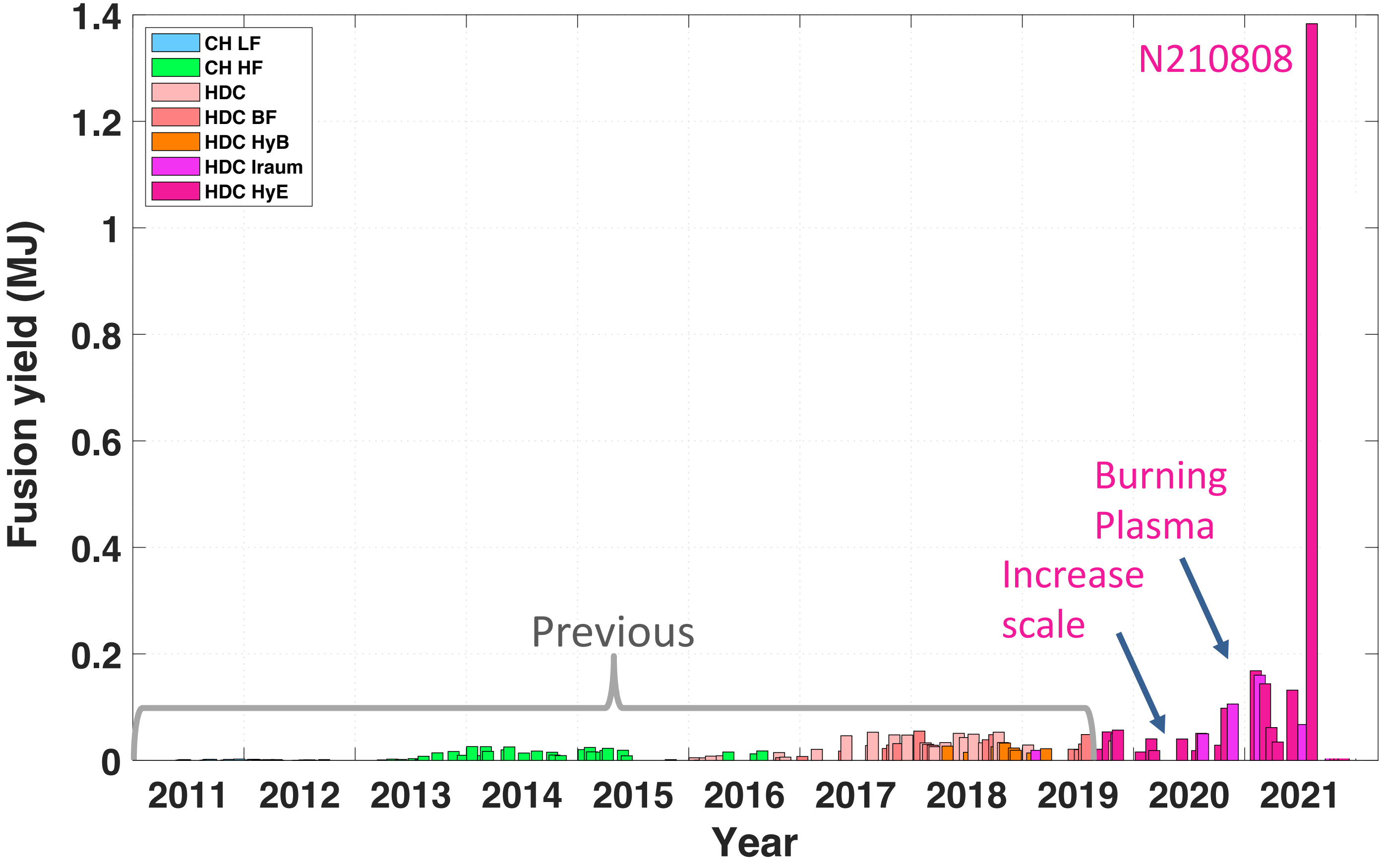
In the ignition regime small changes in “no-alpha” space can lead to large changes in real “alpha-on” space



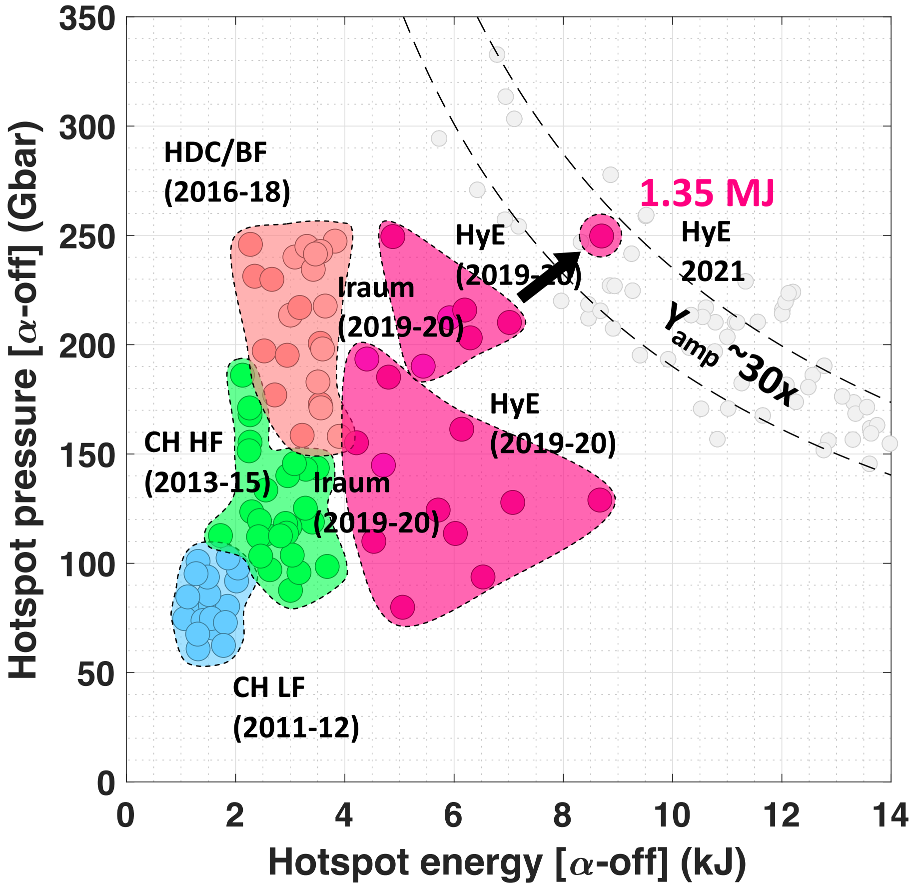


Much higher pressure and energy with small changes to input conditions indicates new regime

These improvements in hot spot energy density led to fusion energy yields exceeding MJ; more rapid progress



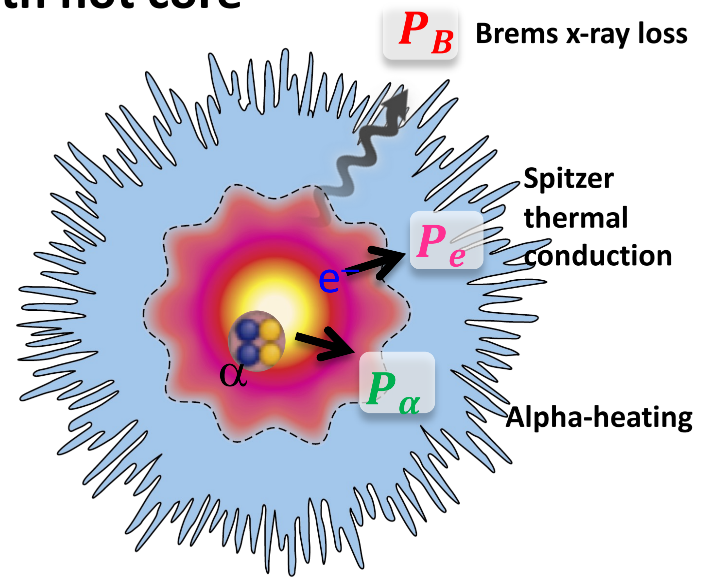
Ignition figure of merit $\sim (\rho R)^3 T^3 \sim E_{HS} P_{HS}^2$



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: Zylstra Zylstra, et al., Nature, 601, 542 (2022);
4: Kritcher, et al., Nature Phys. 18, 251 (2022);
5: Kritcher, et al., PRE, 106, 025201 (2022); Zylstra, et al., PRE, 106, 025202 (2022); NIF collaboration, PRL, 129, 075001 (2022)

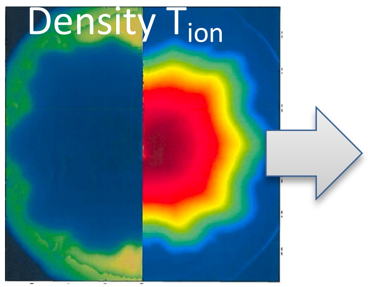
This experiment satisfied Lawson criterion for ignition, $self$-heating > input heating and all energy losses for a duration of time

Compressed fuel with hot core

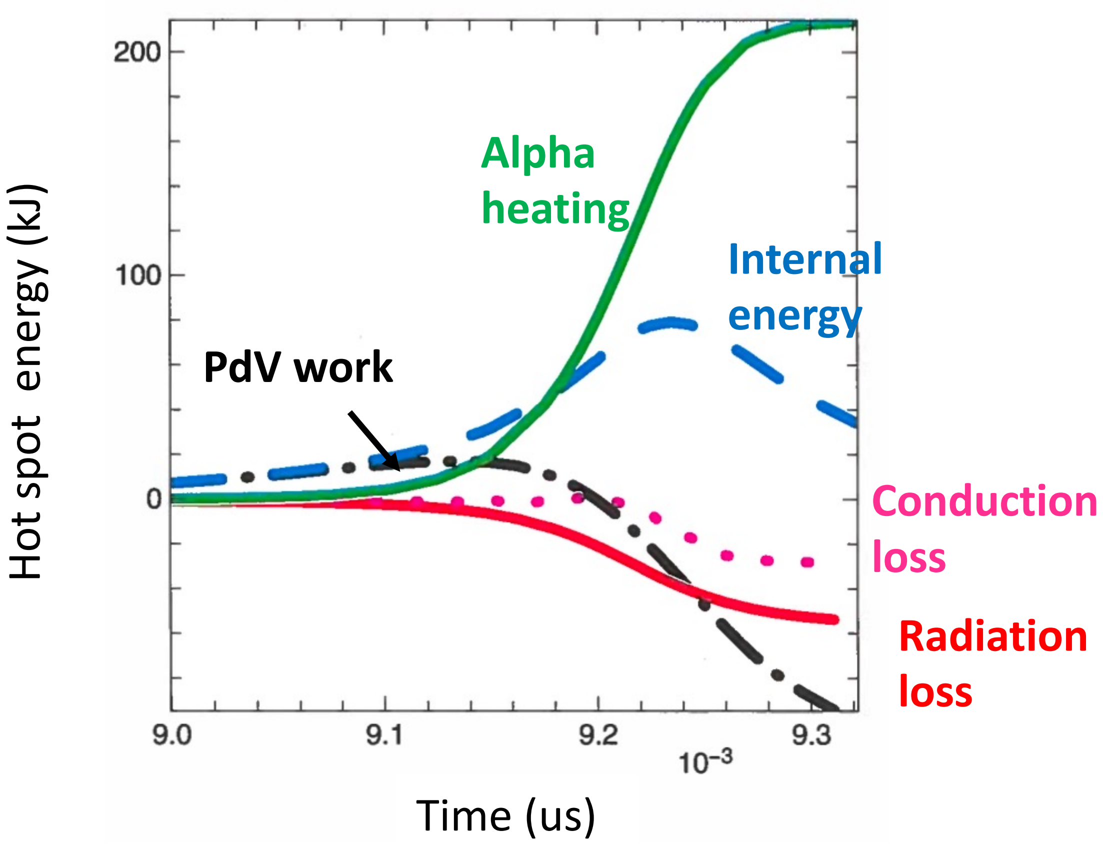


[1]O. A. Hurricane et al. Phys. Plasmas **26**, 052704 (2019)

HYDRA simulations



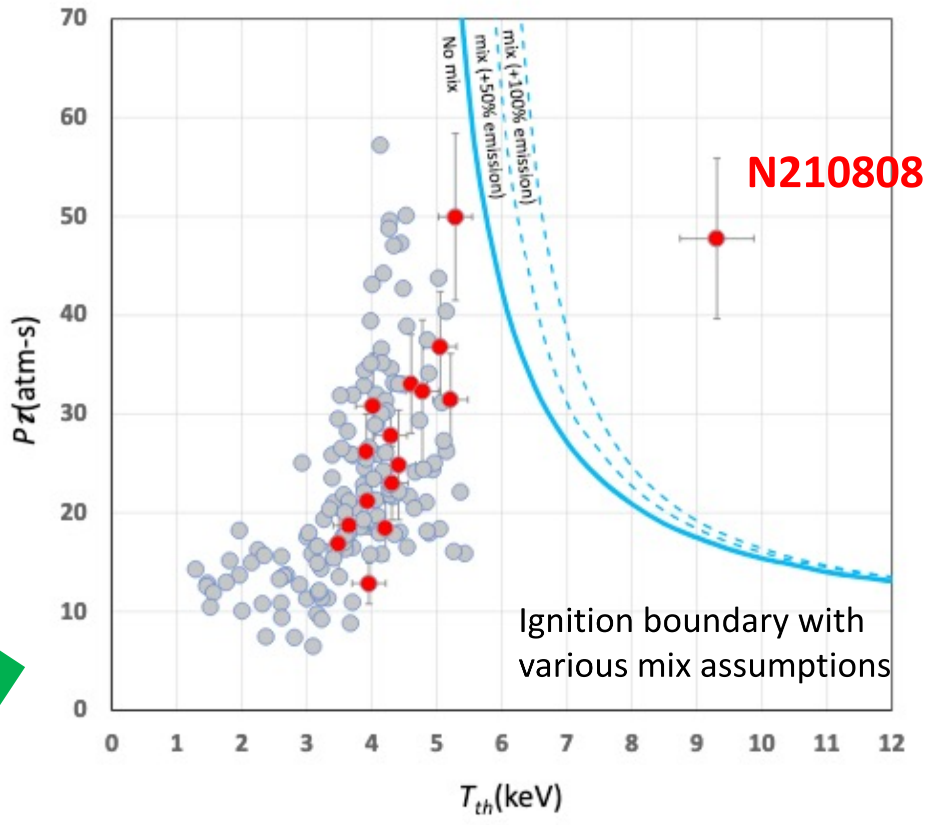
Matches measured hot spot quantities



This continuing increase in the fusion rate upon hot spot expansion was also observed directly

N210808 passed several published metrics of ignition that use measured or inferred quantities to determining if self-heating > losses

A Lawson-like criterion for ignition where self-heating dominates over all energy losses



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

Met other metrics for ignition (LC and yield amplification)

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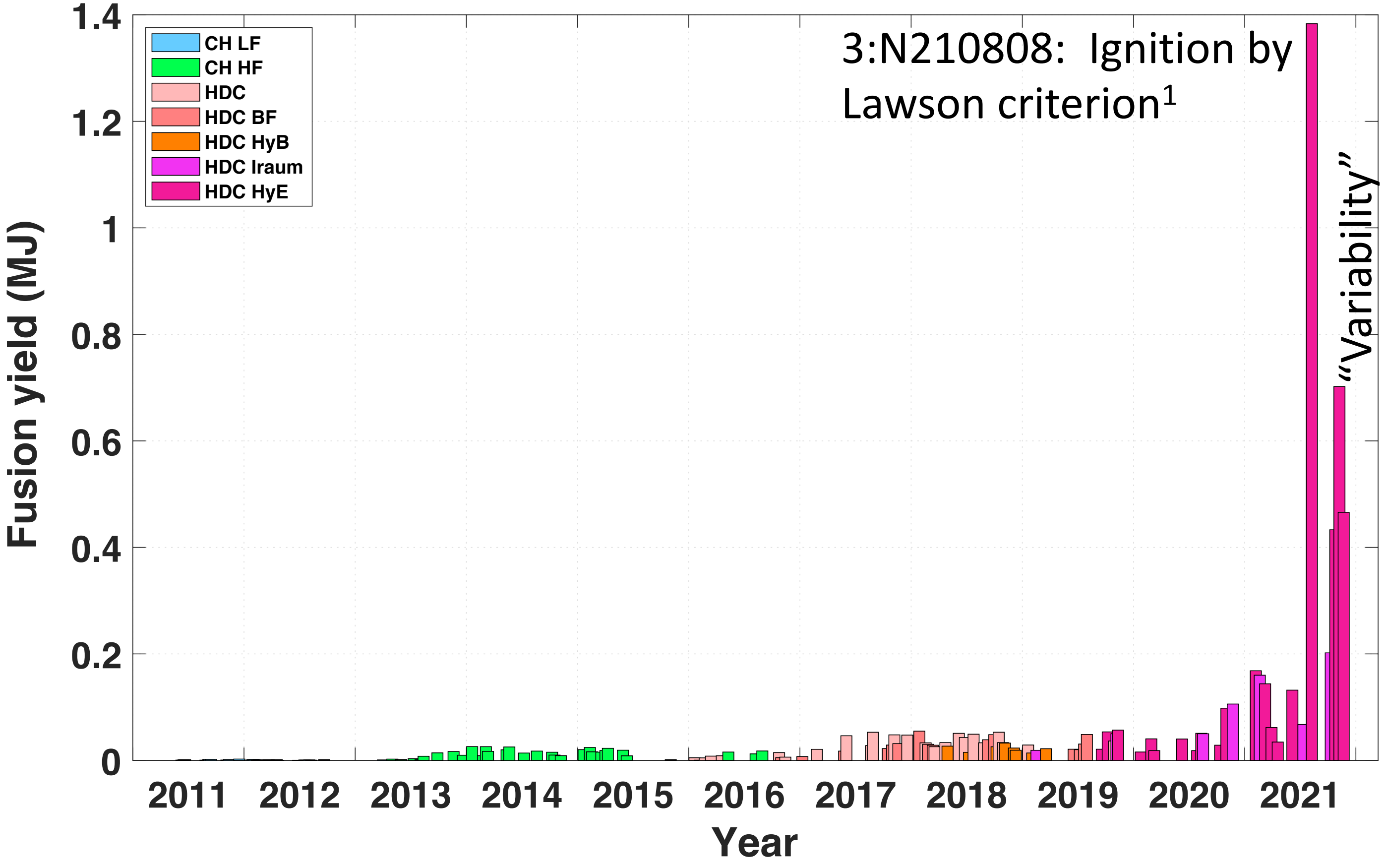
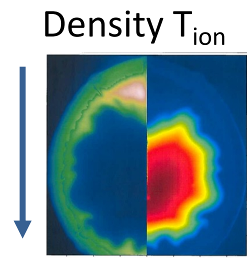
- A. R. Christopherson, R. Betti, S. Miller, B. V. Gopalaswamy, O. M. Mannion, D. Cao, Phys Plasmas, 27, 052708 (2020)
- B. K. Spears, M. J. Edwards, S. Hatchett, et al. Phys Plasmas, 21, 042702 (2014)
- P. K. Patel, P. T. Springer, C. R. Weber et al Phys Plasmas

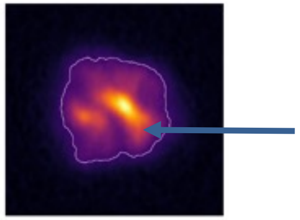
NAS definition

Follow on "variability" attempts suffered from worse fielding conditions which robbed the hot spot of internal energy or pressure



Low modes reduce piston efficiency





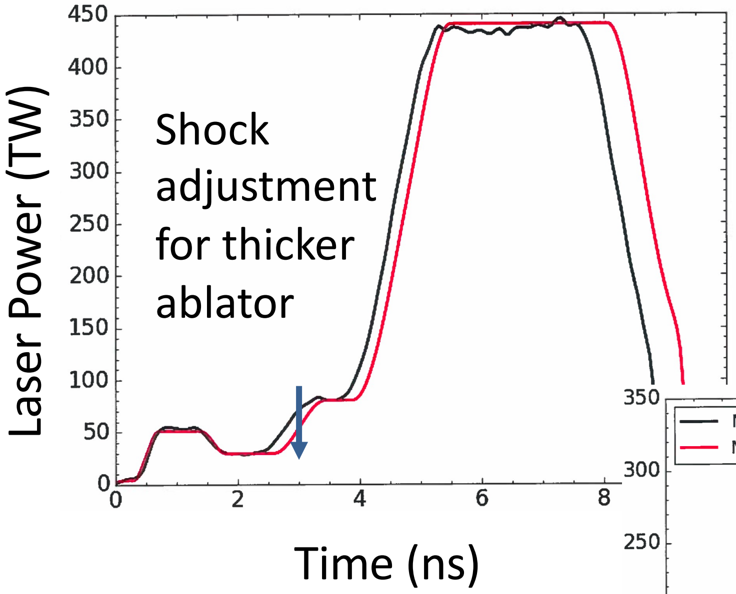
Bachmann

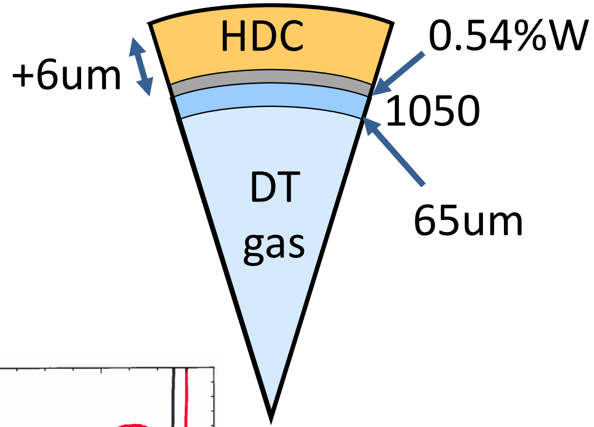
Ablator mixing into the hot spot

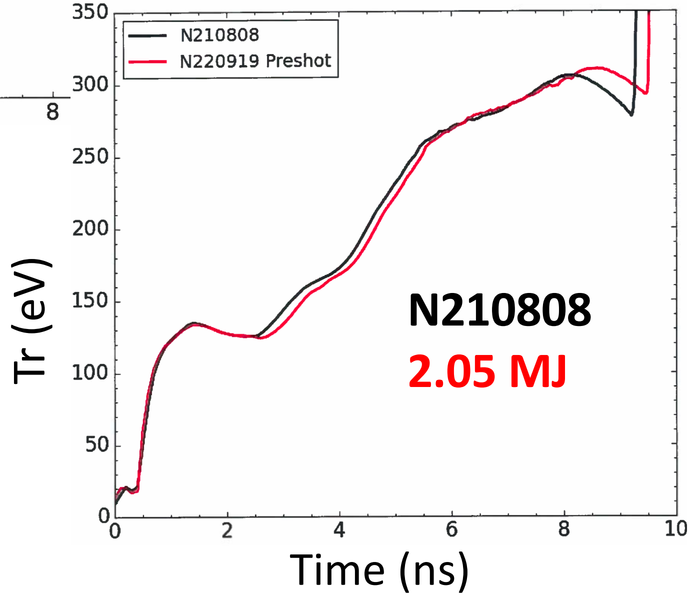
The higher-energy thicker ablator work is designed to increase margin to these fielding challenges

[1]Kritcher, et al., PRE, 106, 025201 (2022); Zylstra, et al., PRE, 106, 025202 (2022); NIF collaboration, PRL, 129, 075001 (2022)

The higher-energy thicker campaign uses an extended pulse* to increase late-time Tr and drive thicker HDC ablators







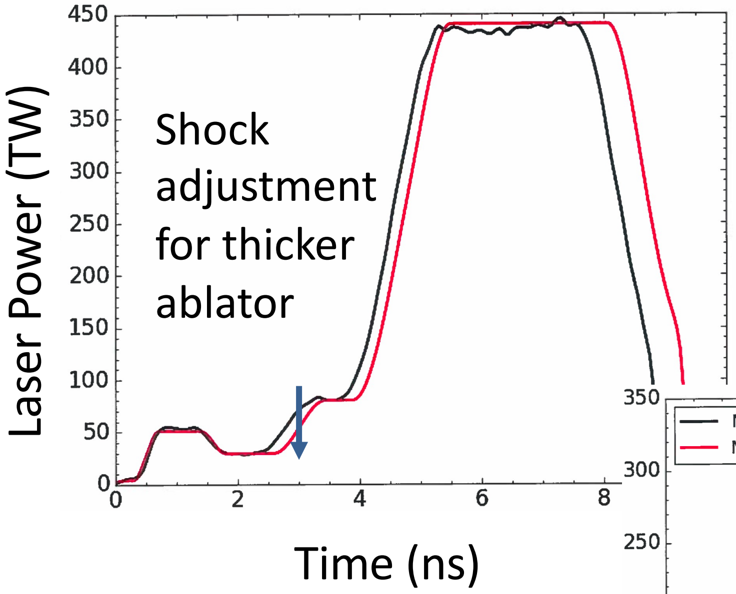
* Current laser capiability; Initial thickness chosen for fixed power

Enabled by laser upgrades!
- JM Di Nicola Photonics West Feb. 2023
- JM Di Nicola, et al, Proceedings Volume 11666, High Power Lasers for Fusion Research VI; 1166604 (2021)
- J.M. Di Nicola *et al* 2019 *Nucl. Fusion* **59** 032004

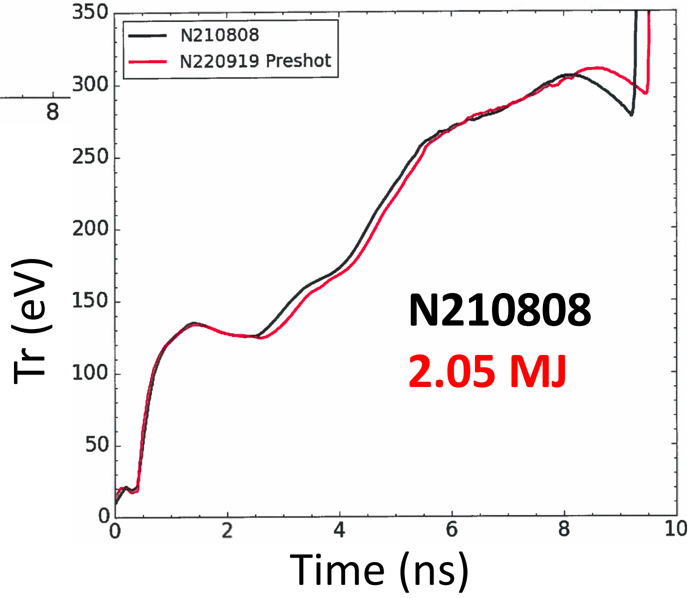
Next 480TW, 2.2 MJ, better velocity & ”coast” vs N210808 with +10-12um HDC

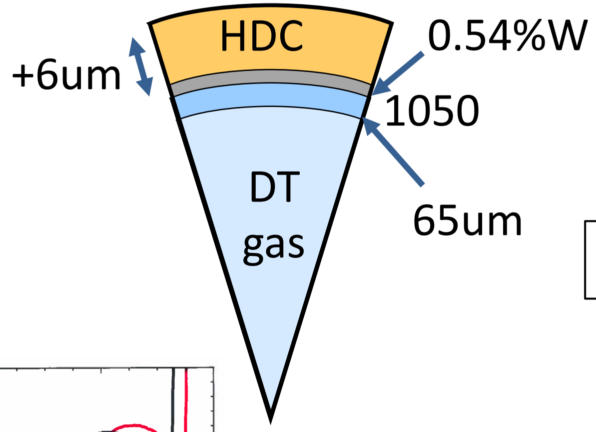
Ref. C. Young et al High Radiation Temperature Hohlraum for ICF Implosions, APS DPP, 2020.
A. Kritcher, et al, Physics of Plasmas **27**, 052710 (2020) (HybridB design up to 2.05 MJ)

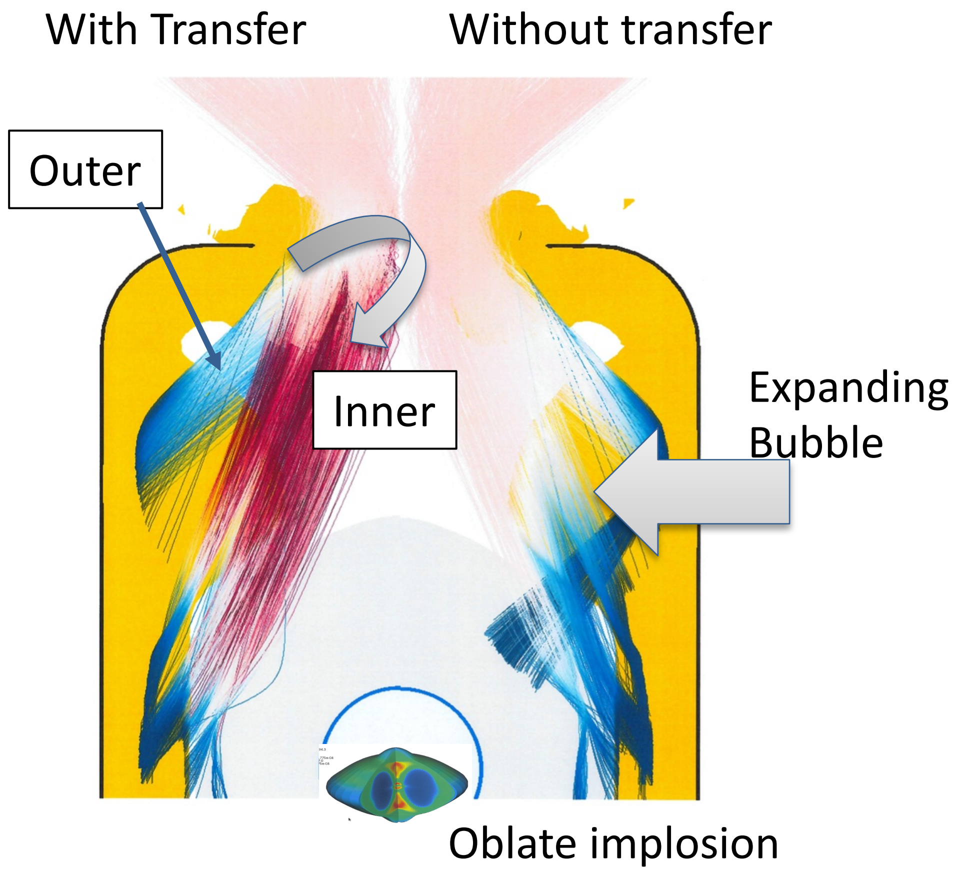
The longer pulse results in more plasma filling of the hohlraum; symmetry was controlled by transferring more energy between beams



* Current laser capability; Initial thickness chosen for fixed power



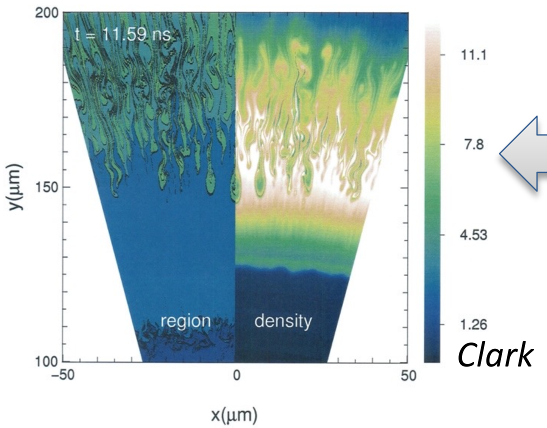




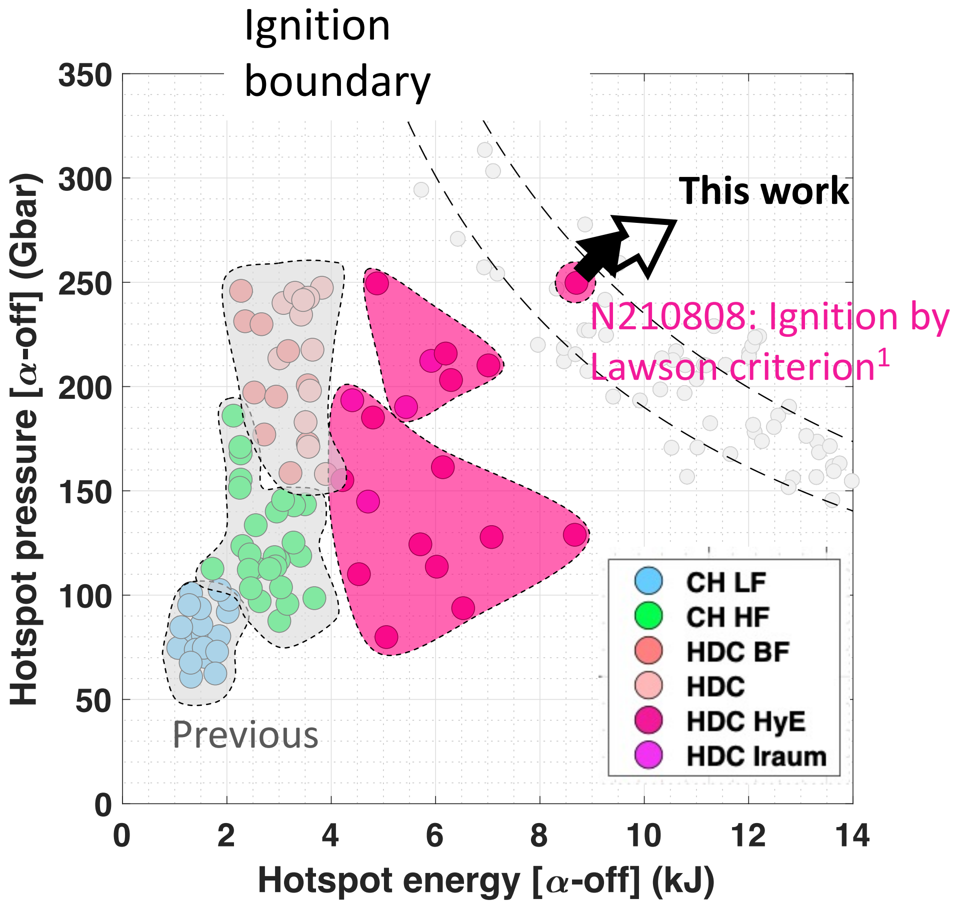
- The laser wavelengths are detuned to create a plasma grating and transfer energy toward the center of the hohlraum
- Early time powers adjusted for same effective inner drive after transfer

Increase in energy density provides more margin for perturbations that reduce hot spot energy to still “ignite” the plasma

- Increased confinement
  - higher fuel+ablator ρR ~ Fusion Yield
- Better for stability– “cleaner fuel”

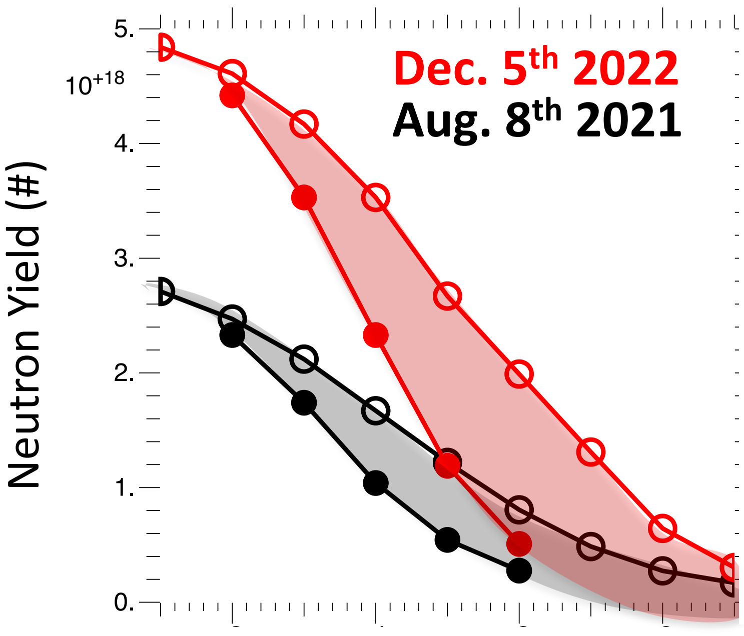


Mixing between capsule and DT ice

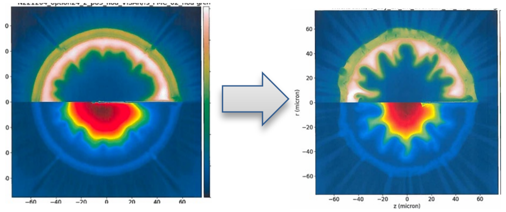


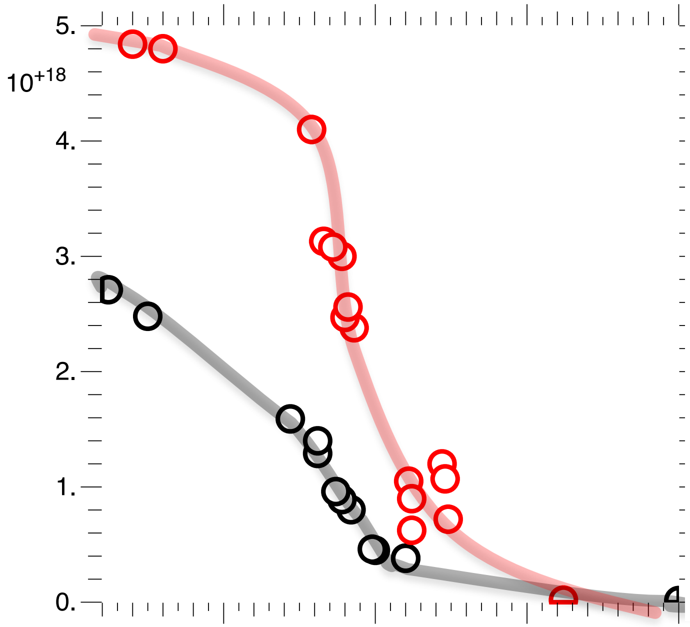
1: Kritcher, et al., PRE, 106, 025201 (2022); Zylstra, et al., PRE, 106, 025202 (2022); NIF collaboration, PRL, 129, 075001 (2022)

With the extra margin we can tolerate more perturbations and still reach MJ yields – higher yields for the same perturbation

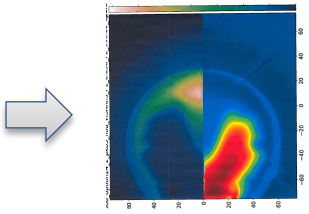


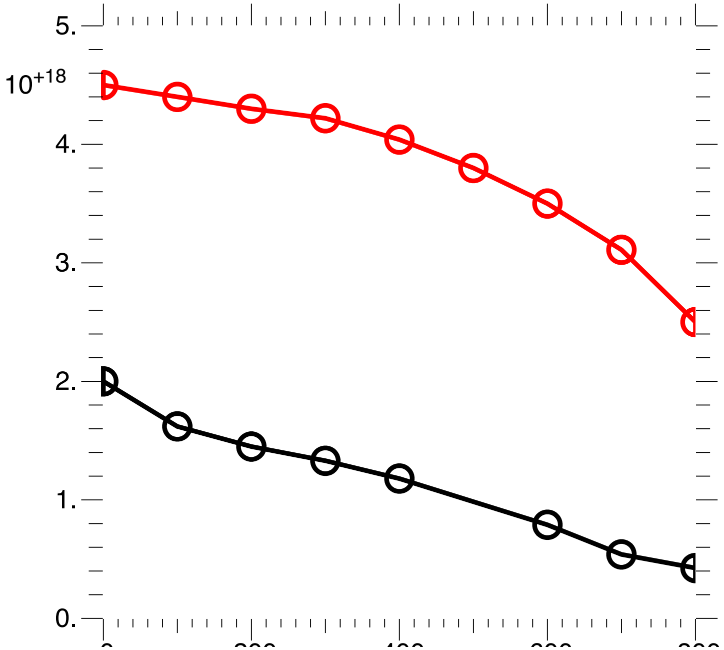
Worse stability or capsule quality



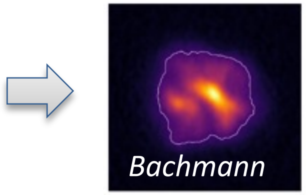


Increased low mode asymmetry

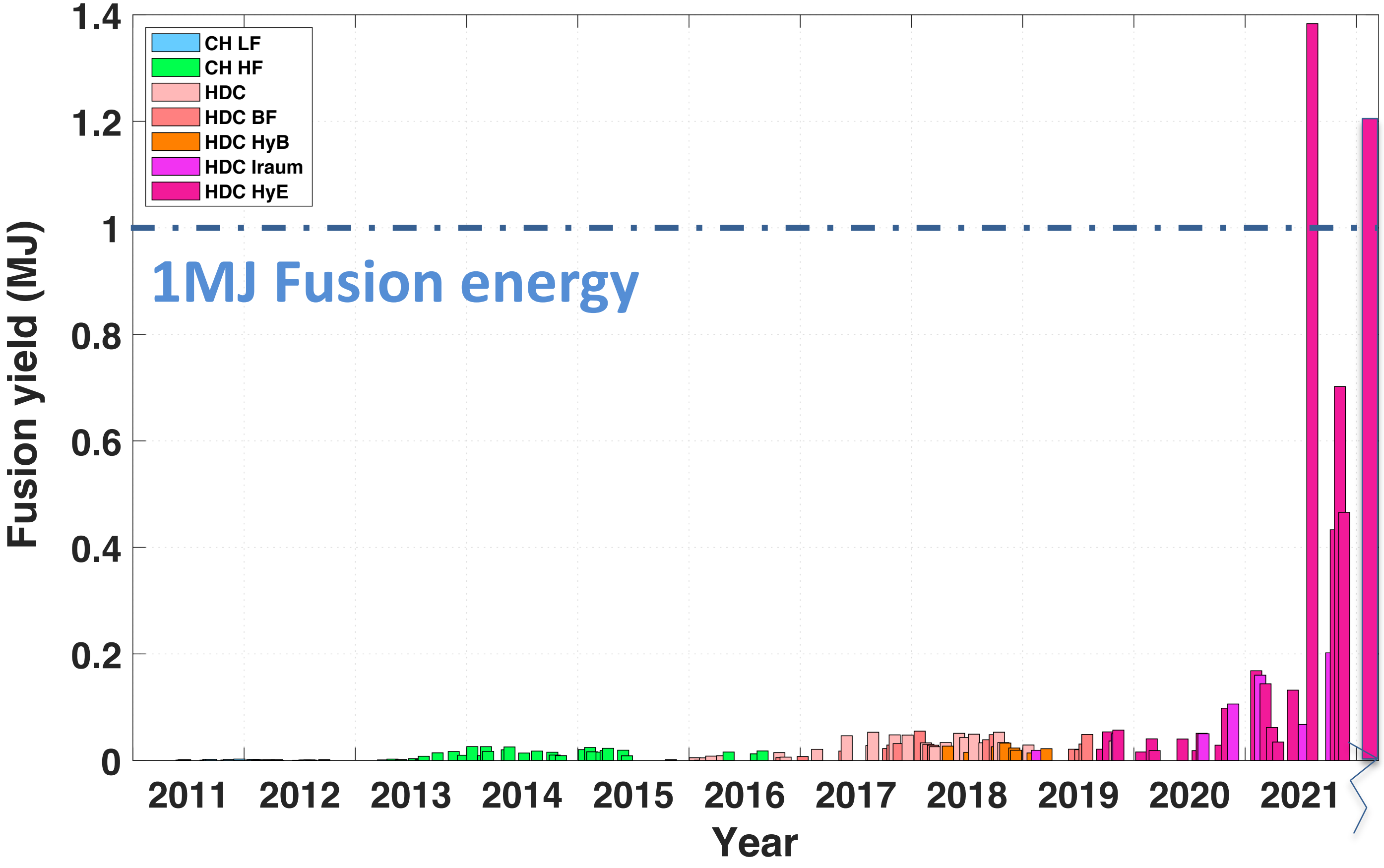


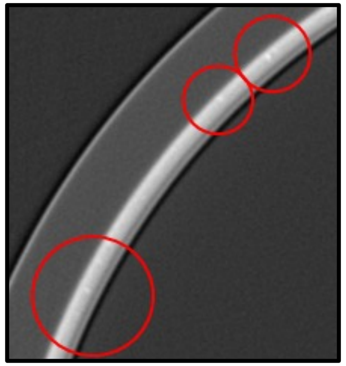


Ablator mix into the hot spot (ng)



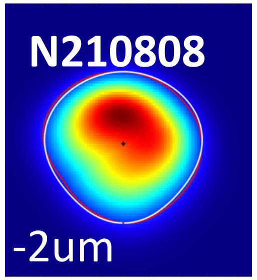
First attempt N220919 was comparable to N210808 with worse conditions indicating more margin for achieving >MJ with non-perfect conditions

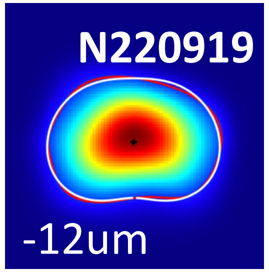




Diamond capsule

- >20X more high Z inclusions – can impact compression or reduce clean ice fraction

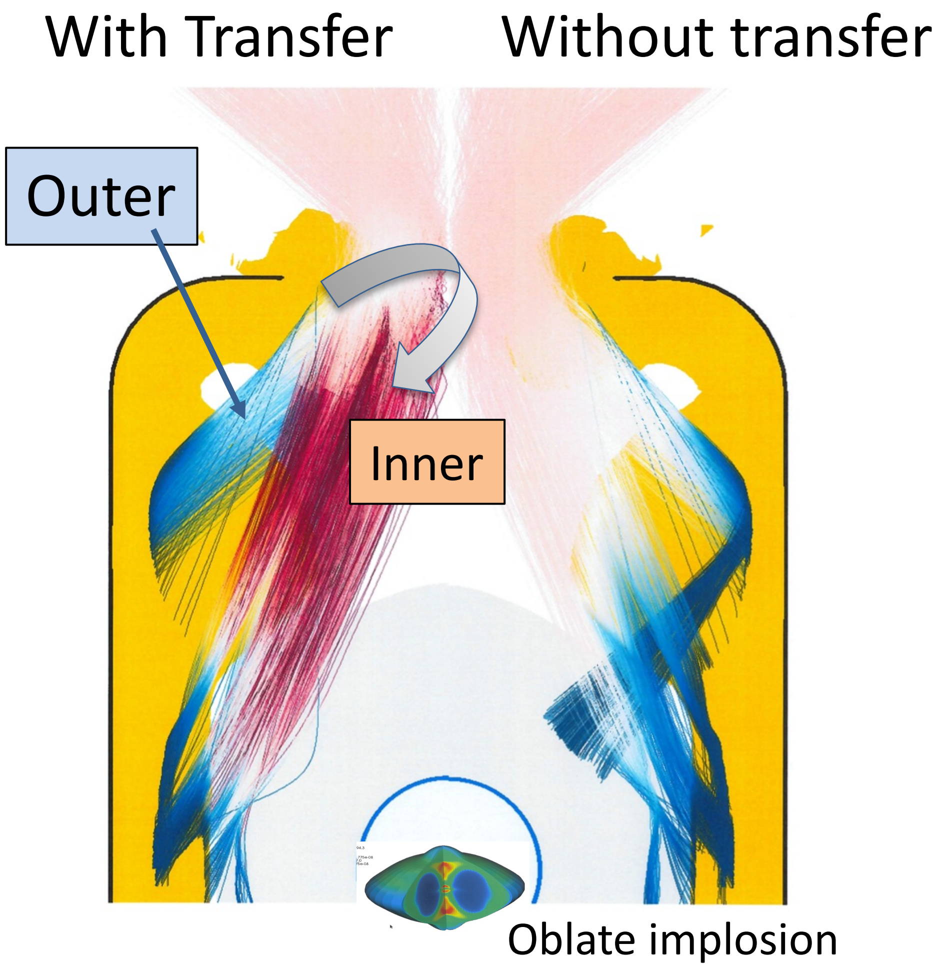


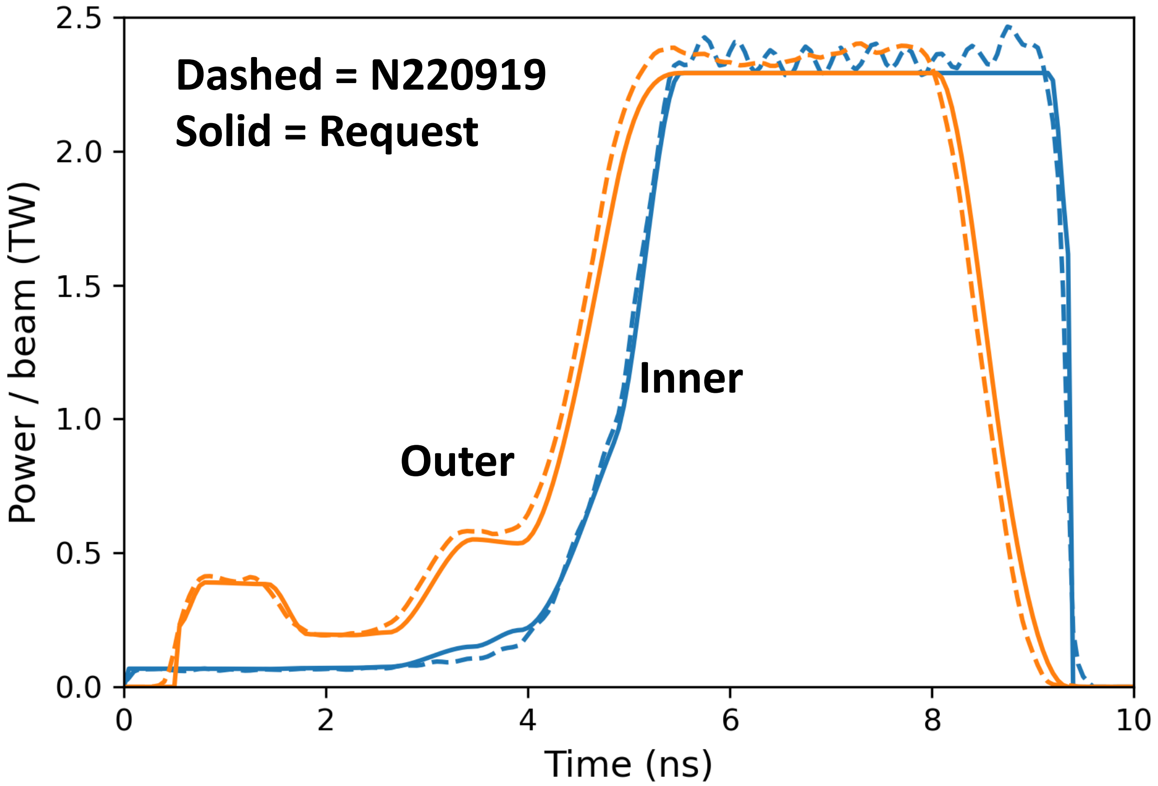


Noah Birge

A large portion of the yield degradation vs expectation for N220919 can be explained with these known degradations using radiation hydrodynamic simulations

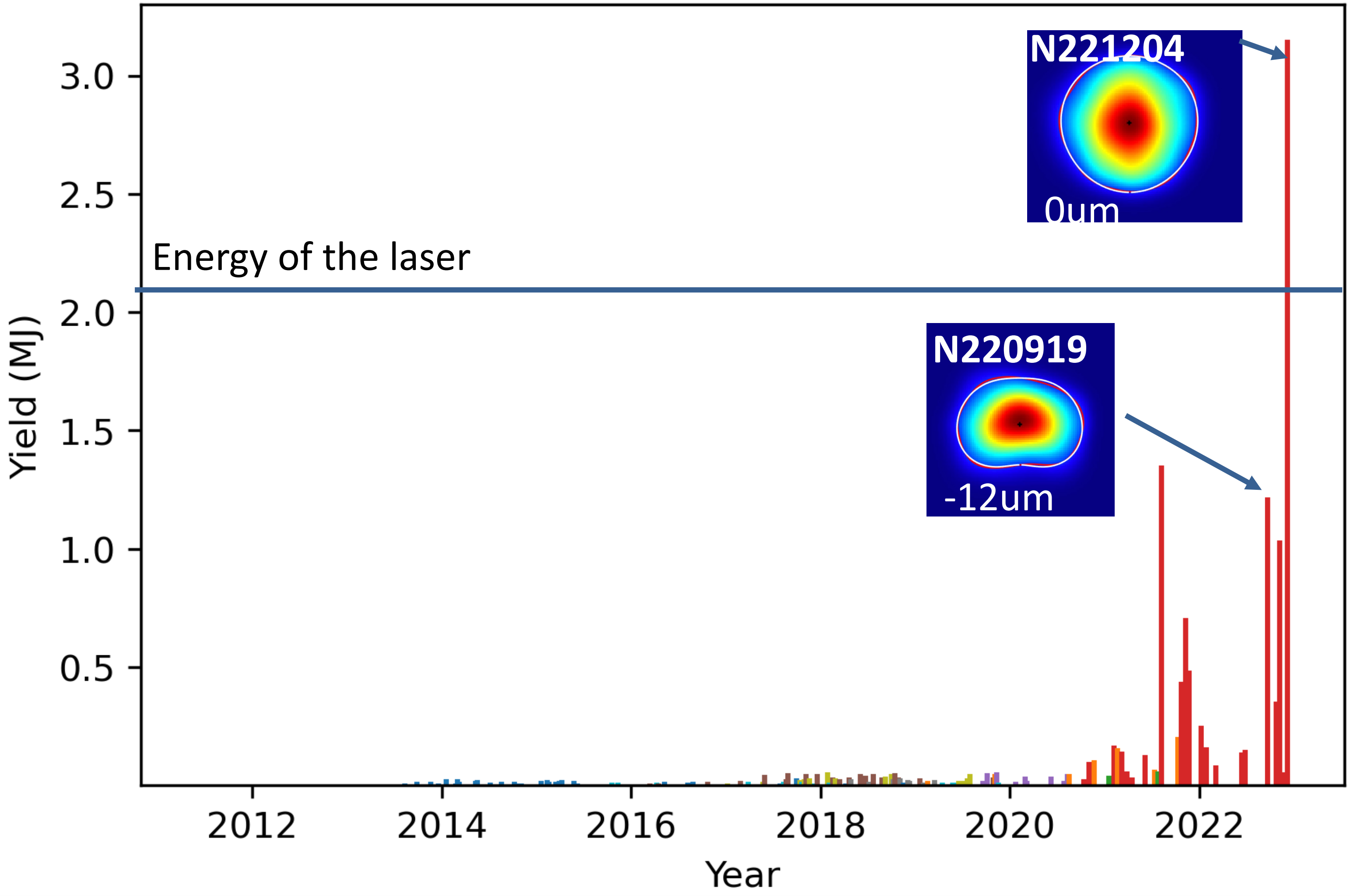
To fix the shape, the amount of transfer of energy between beams was increased by wavelength detuning the lasers





This changes the symmetry in the early part of the radiation drive so new power balances are chosen

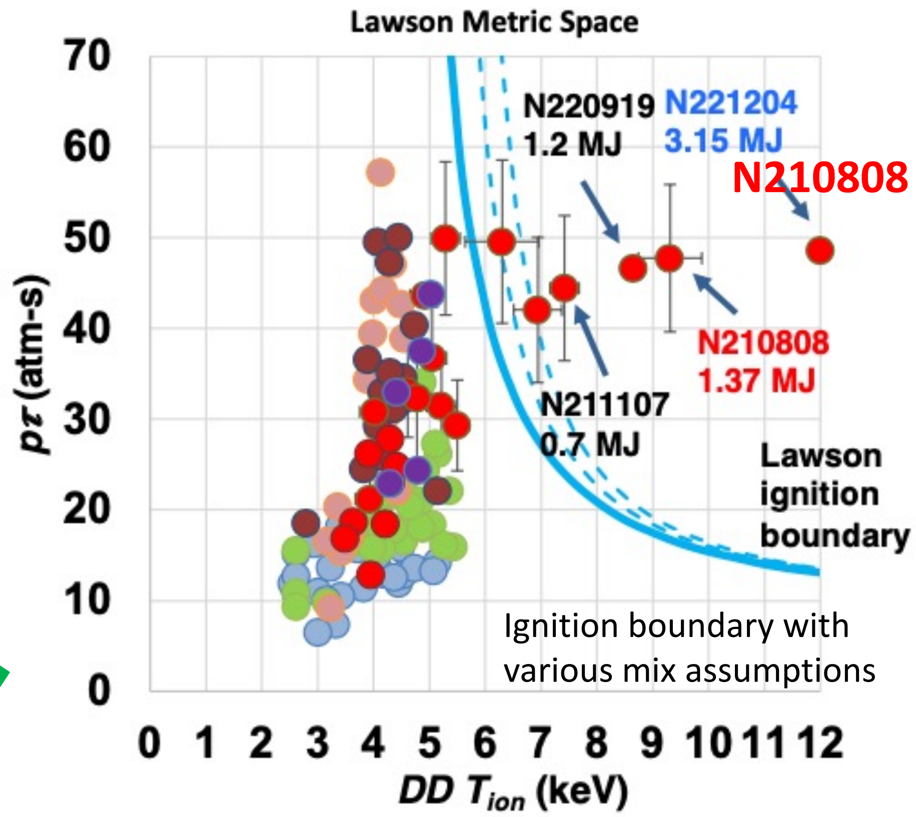
The symmetry adjustment resulted in a more spherical implosion on N220214



- The improvement in symmetry resulted in an increase in performance of ~2.5 x vs N220919 and target gain of >1.5
- Now meets all definitions for ignition (Lawson and NAS definition for NIF)

N210808 passed several published metrics of ignition but not the NAS definition, now N221204 passed all metrics

A Lawson-like criterion for ignition where self-heating dominates over all energy losses



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

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- 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

NAS definition: fusion energy exceeding laser energy on target

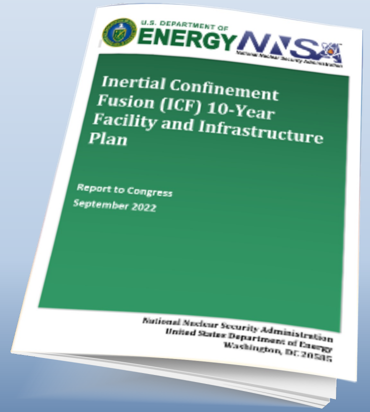
We use measured or inferred quantities to determining if the Lawson criterion was met (self heating overcoming losses for a duration of time

Next Steps: Explore high-yield, high-gain regime

NIF has not yet reached its full potential

Yield	Few MJ	10s of MJ	100+ MJ??
	2023	**2023–2028**	**2030–2040**
	Routine MJ-yield operations and ignition	Long-term Sustainment; Increase Energy and Power	Explore high-yield, high-gain regime
Laser Energy	2.2 MJ	2.6-3 MJ	

Long-term Sustainment



Increase Energy and Power

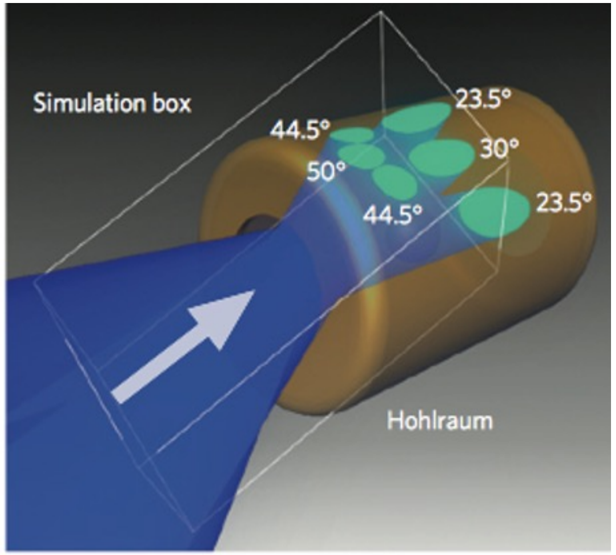
NATIONAL IGNITION FACILITY

Careers.llnl.gov

Lawrence Livermore National Laboratory

Cross-beam energy transfer moves energy between beams in an intentional way by changing the laser wavelength

- Pondermotive pressure from interreference pattern of overlapping beams creates plasma density perturbation
- Modifying relative laser wavelengths changes the frequency of this perturbation
- A resulting refractive index modulation acts as a bragg scatter which can redirect incoming laser light from one beam to another
- Max when den fluc ~ IAW resonance condition in the flowing plasma



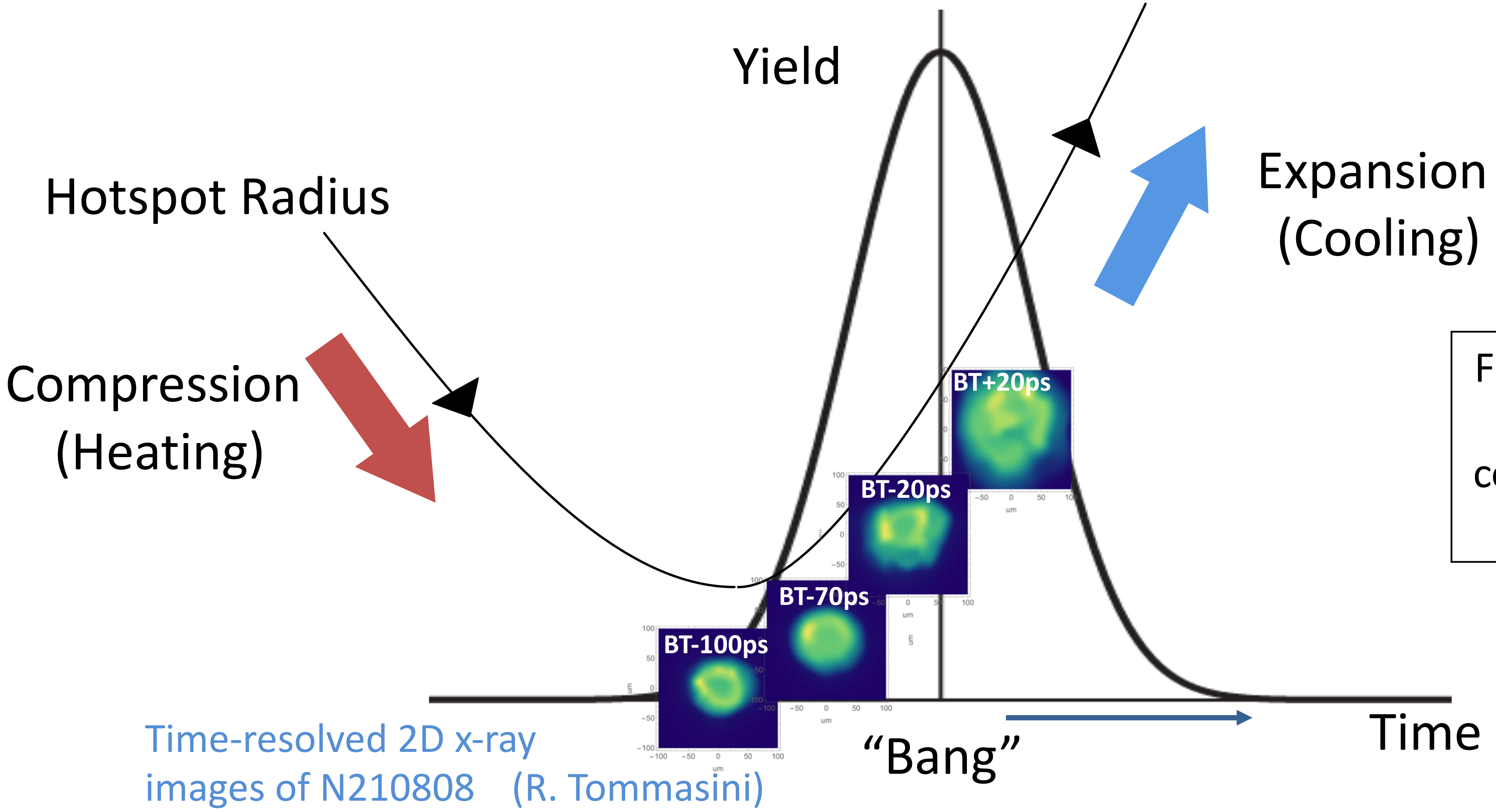
"Bad" LPI can reduce HR efficiency

SBS: laser scatters off self-generated ion acoustic waves (iaws)

SRS: laser scatters off self-generated electron plasma waves (epws)

Moody, Michelle, Hinkel et al

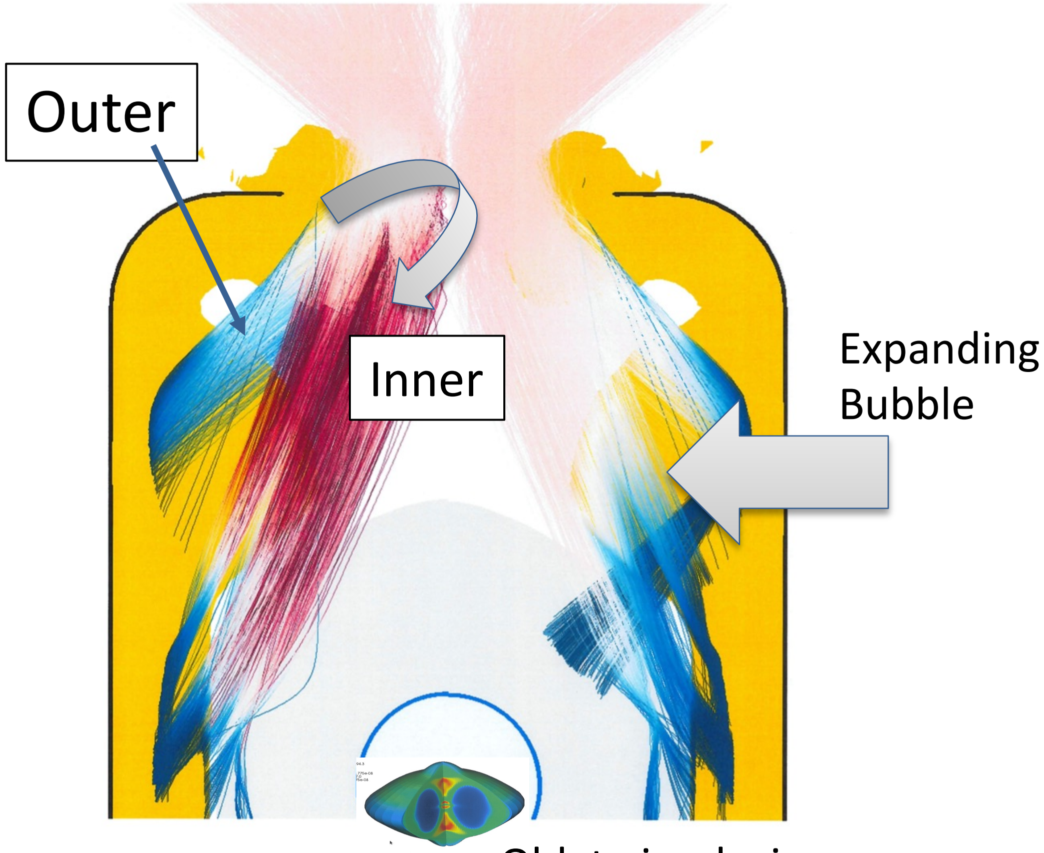
This continuing increase in the fusion rate upon hot spot expansion was observed directly

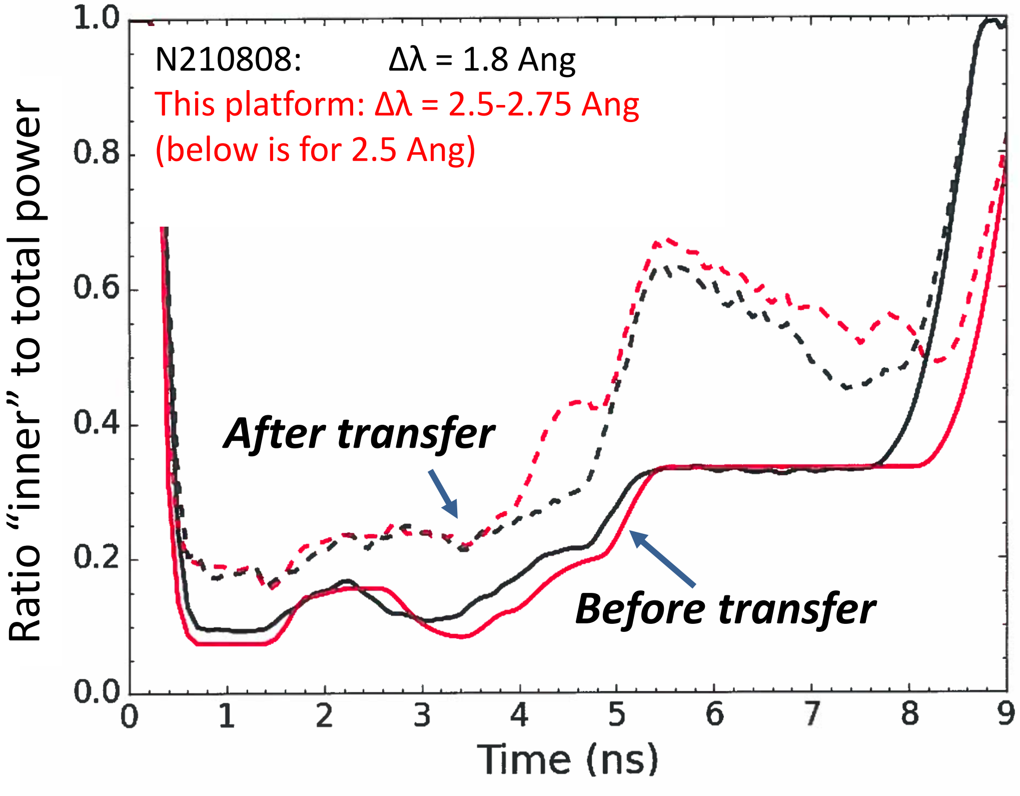


Fusion rate is so high that the core plasma continues to get hotter as it's exploding

Fusion yield increasing during the explosion phase indicates that alpha-heating exceeds all energy losses

The longer pulse results in more plasma filling of the hohlraum; symmetry was controlled by transferring more energy between beams

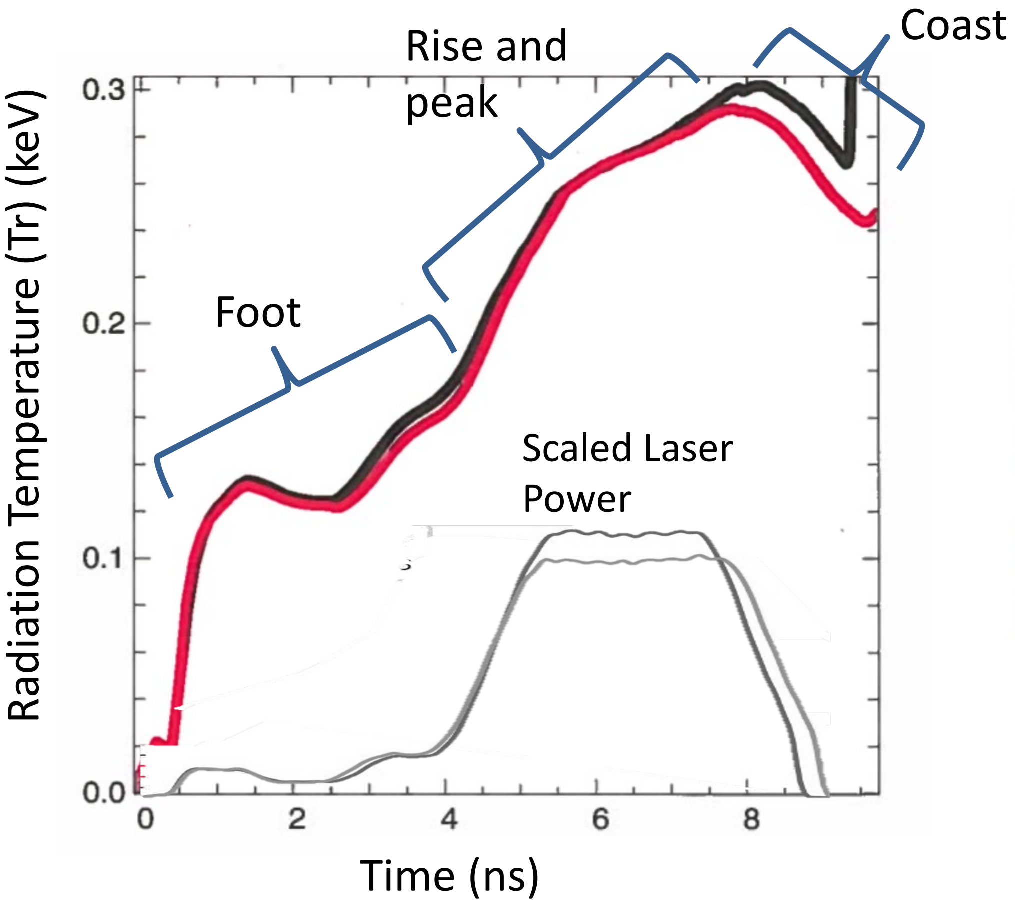


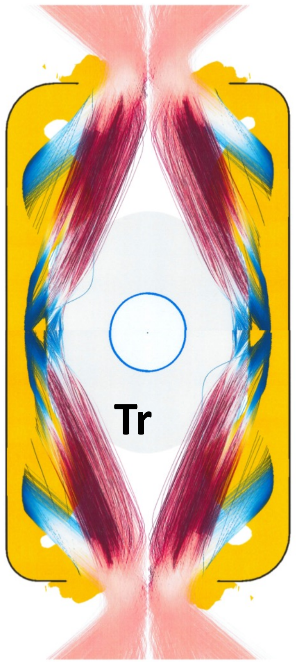


Early time powers adjusted for same effective inner drive after transfer

The laser wavelengths are detuned to create a plasma grating and transfer energy toward the center of the hohlraum

Precise control and design of the laser power and target conditions is required to reach ignition





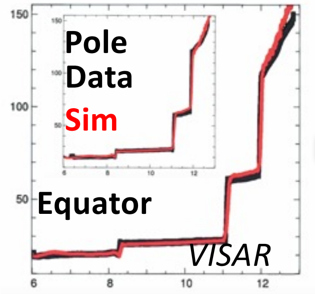
1. Foot – controls stability and majority of fuel entropy (adiabat, α_{if})
2. Peak Power – implosion velocity
3. Coast period – efficiency of KE conversion into DT internal energy, higher pressure

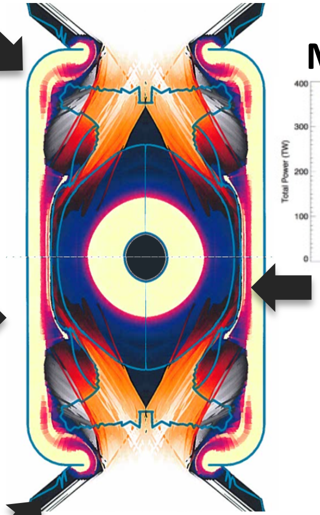
What's best for the implosion is usually worse for the hohlraum

Simulations use the as-shot conditions and models that are benchmarked against experimental data in a two step process

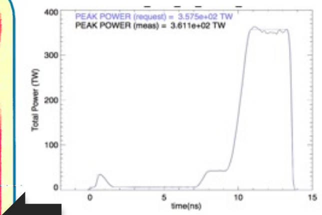
Target metrology

Shock measurements

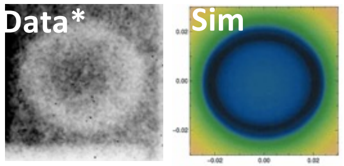




Measured laser

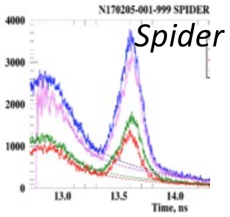


Shell Radiography

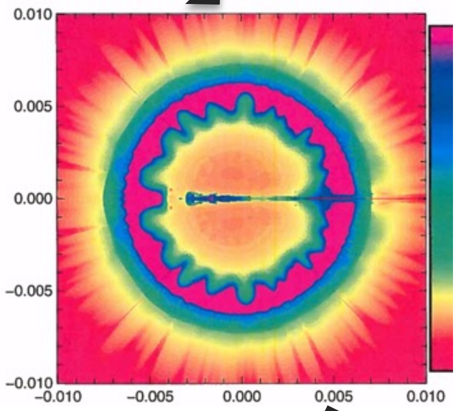


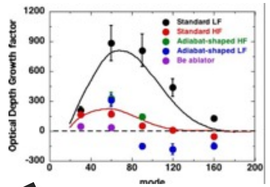
2D ConA

Bang time



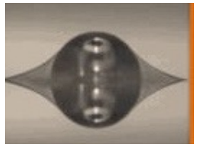
Surface roughness





Ablation front and interface growth

Surrogate model for tent & fill tube



Model energetics, shock timing, time-dependent symmetry, pass to Capsule simulations

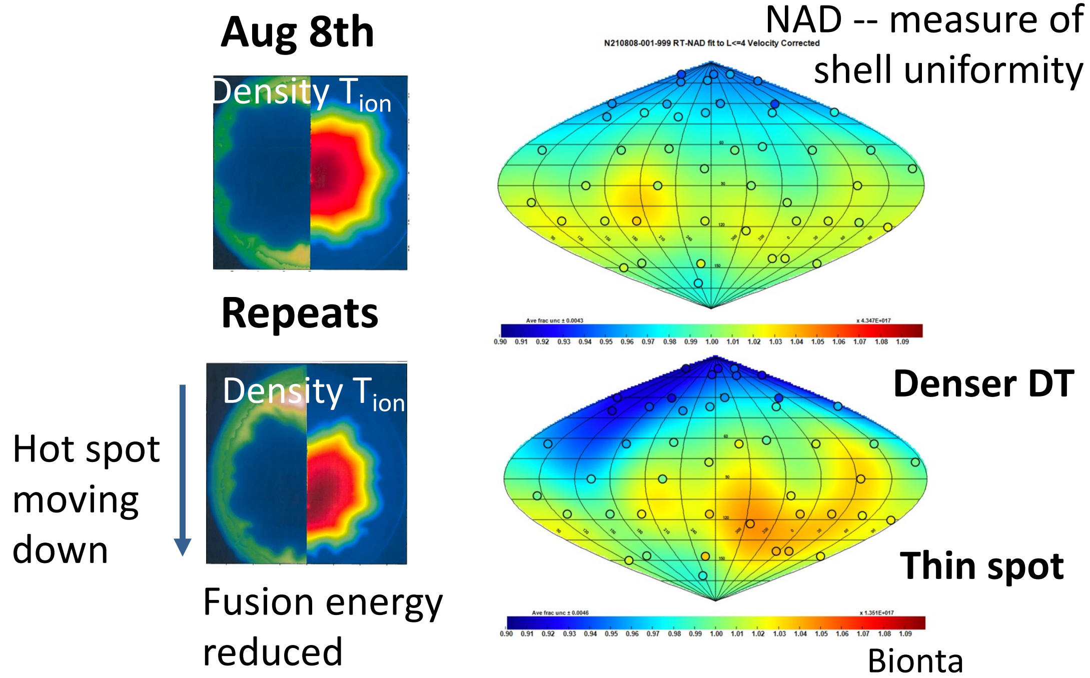
Model stability, impact of engineering features ; need to adjust shock timing to match HR and P2 to match shape

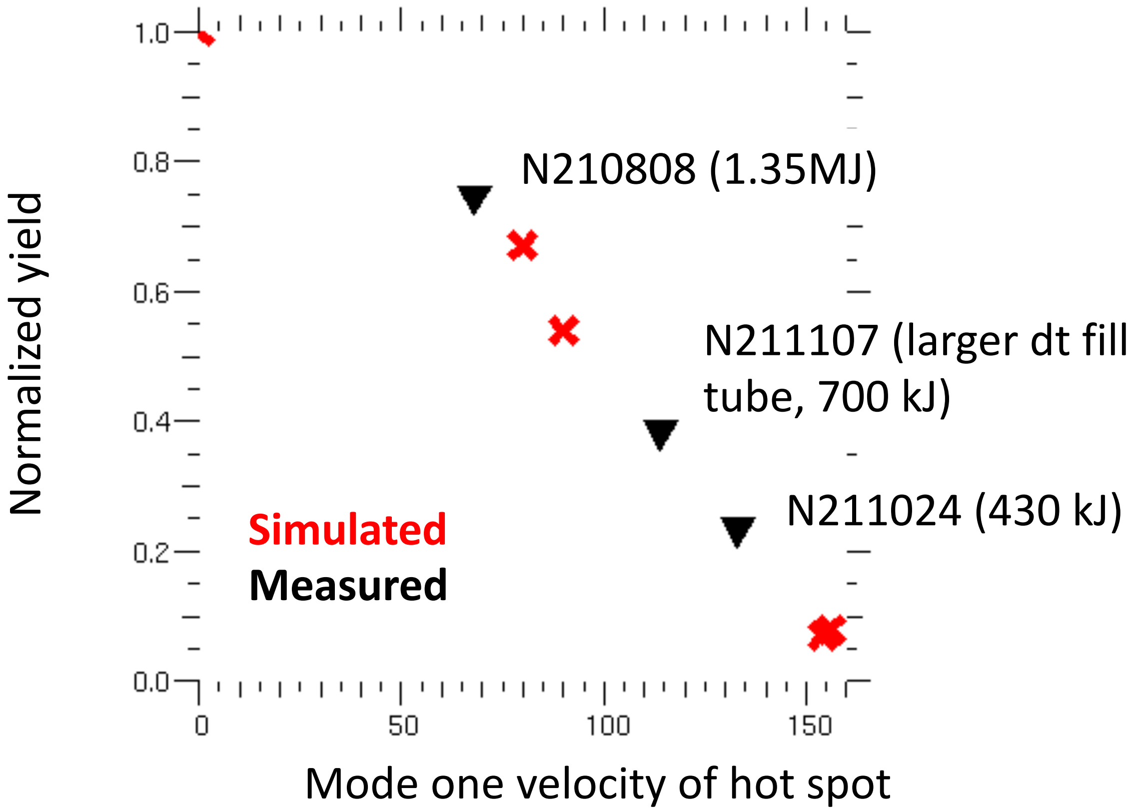
Often conflated, the terms "burning plasma," "ignition," and "gain" all mean something physically different

- **Burning plasma***
  - ICF: Self-heating energy exceeds external "pdV work" to heat and compress the DT
  - MFE: Self-heating energy exceeds external heating of the DT
- **Ignition (i.e. Lawson Criterion)**
  - Self-heating power exceeds all DT plasma power losses
    - Losses are radiative, electron heat conduction, negative pdV work
  - Results in thermodynamic instability (explosive increase in T, Y, etc).
- **Target Gain**
  - Fusion yield exceeds laser energy into target
  - 1997 NAS committee used this as "ignition" in a report & the U.S. DOE adopted this definition

Follow experiments gave capsule gain >1 but reduced performance due to a large unintentional odd mode asymmetry

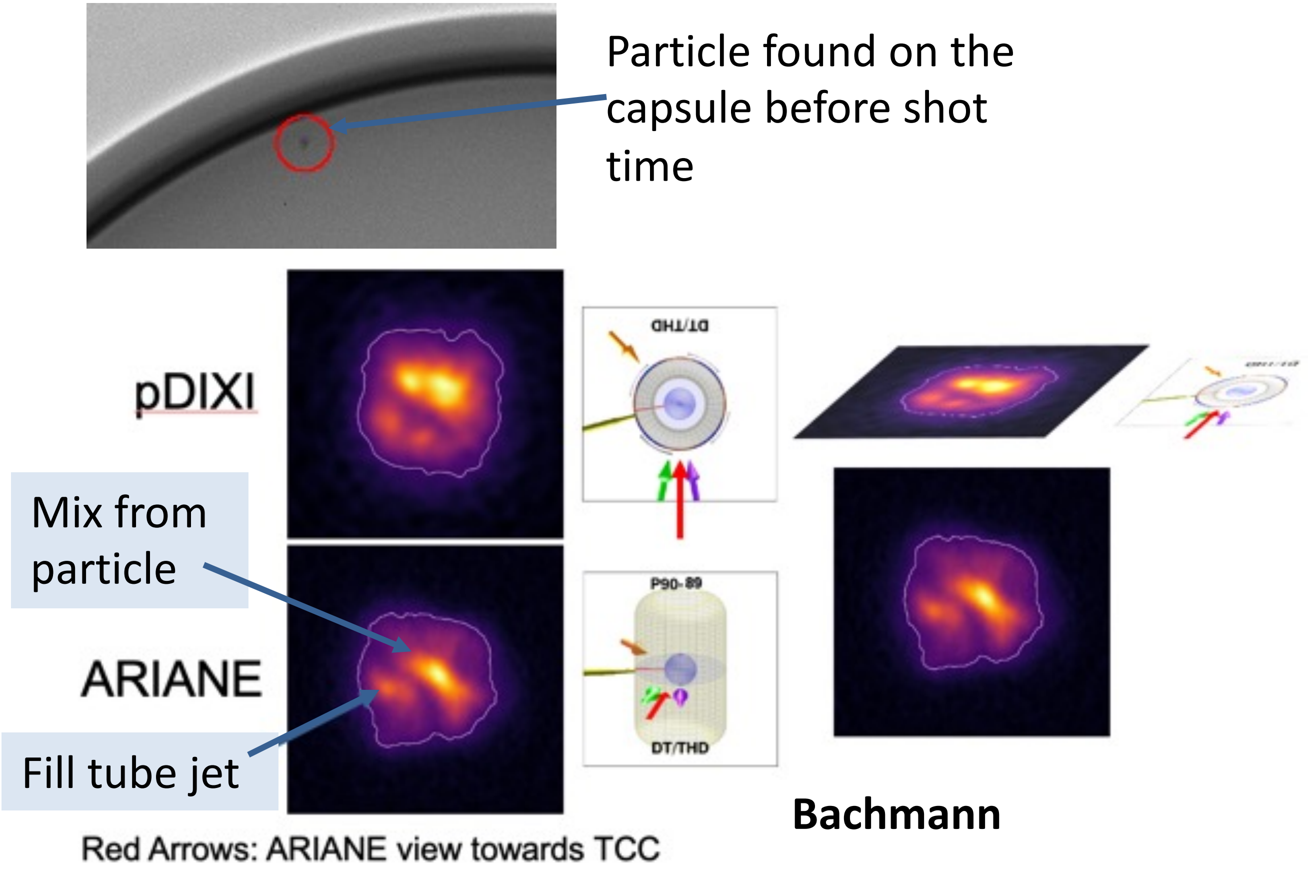
Measured shell non-uniformity and moving hot spot

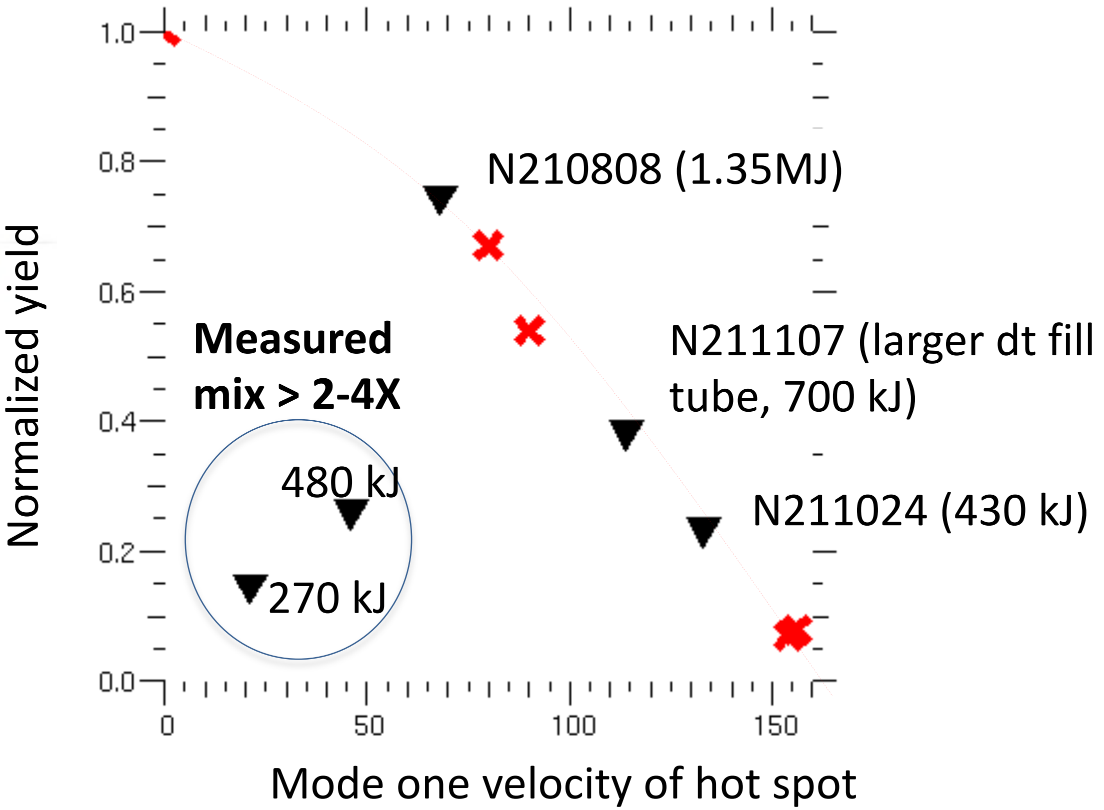




Simulations the mode one account for most of the degradation – origin explained for most "repeat" attempts

We got “better” on mode one for latest repeats but mix due to additional particles on the capsule at t=0 impacted performance



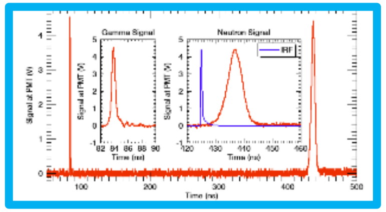


- This yield reduction from mixing is consistent with simulations and related to worse observed capsule quality
- Even with large mixing and mode one, variability experiments and N210808 are highest 5 yielding shots on NIF

Diagnostics are essential in our understanding of where we are –and what problems need fixing – significant improvement over time

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

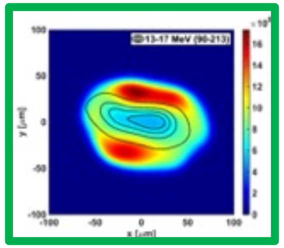
- Neutron Time of Flight (nToF)'s and MRS

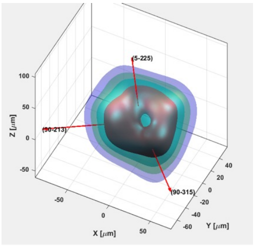


DT Neutron yield

- Zirconium/Copper Nuclear activation

Hot spot and Fuel Shape

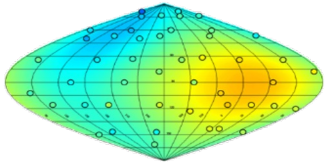


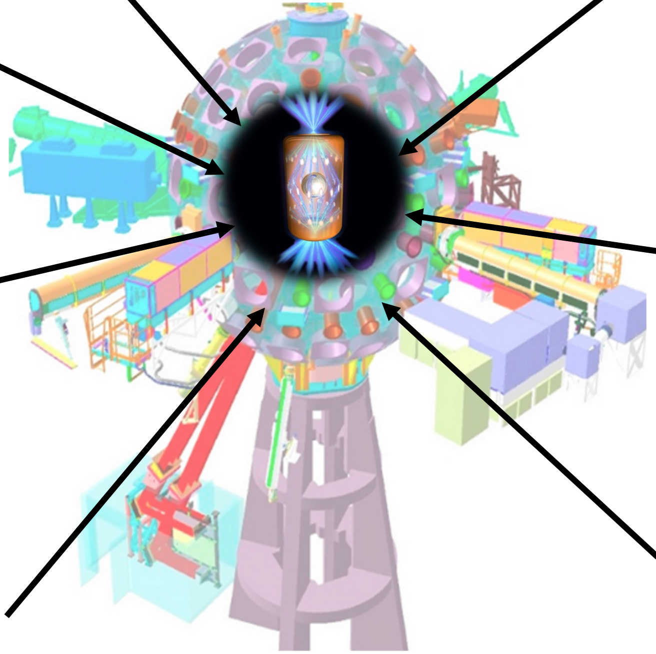


- Neutron imaging (2D 3D)

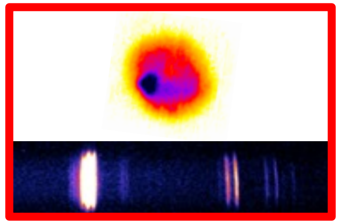
DT Yield Map /Fuel uniformity

- Nuclear Activation diagnostics





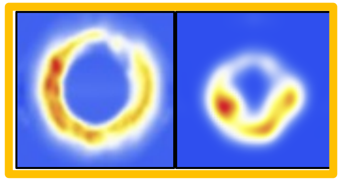
Measure mixing of material into the hot spot



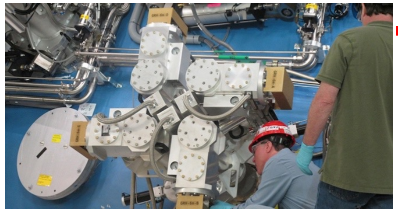
- X-ray imaging and spectroscopy

DT Fuel uniformity

- Compton Radiography



Neutron Burn-width, "Bang time"



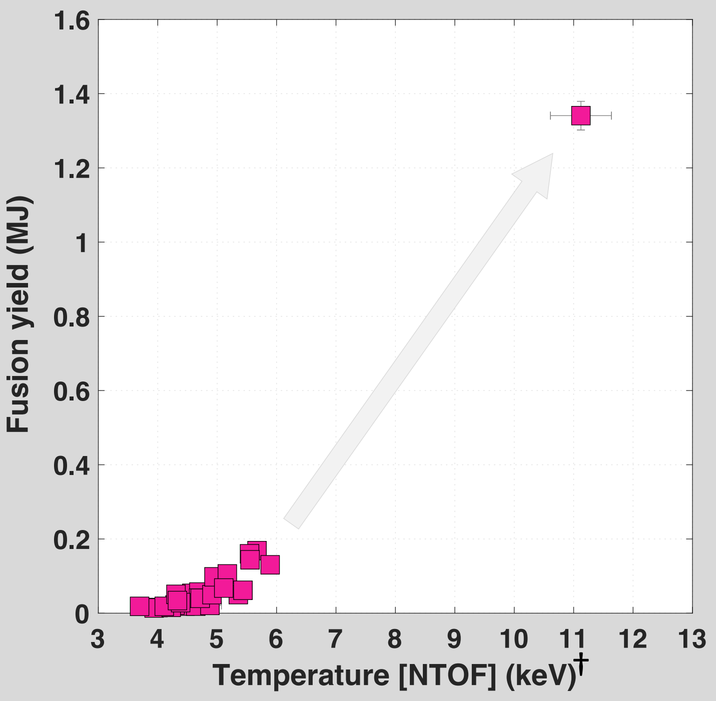
- Gamma Spectroscopy

Gamma Reaction History Diagnostic

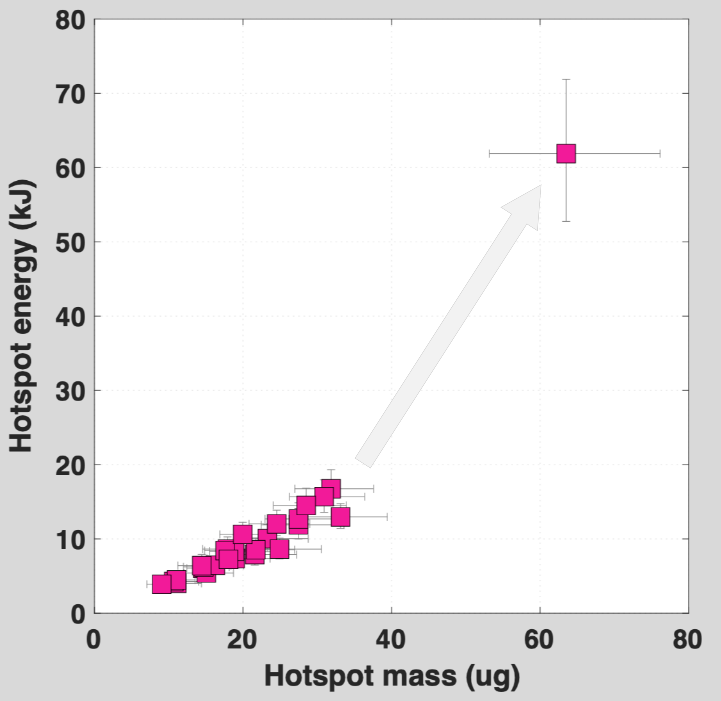
This is the best diagnosed HED plasma on the planet – Developed by entire community over decades!

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

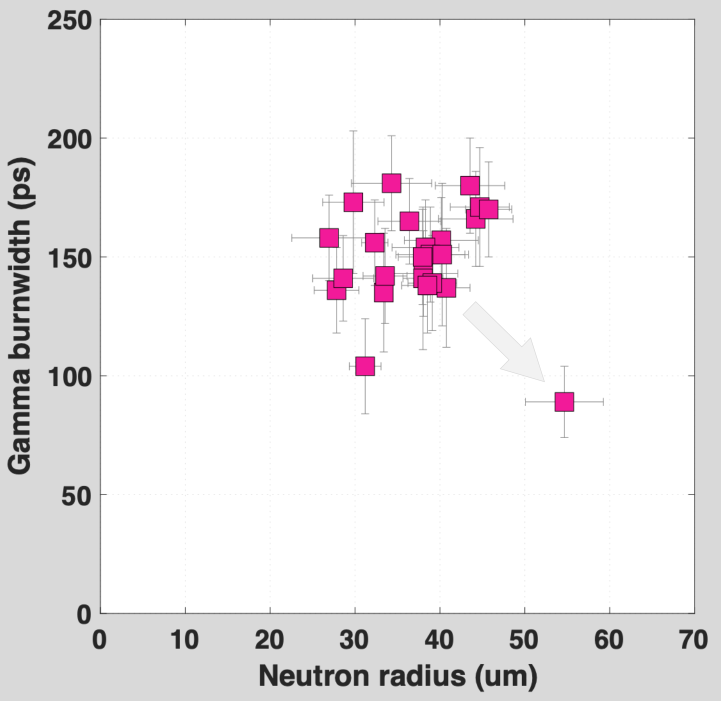
Yield and Temperature



Inferred Hotspot Mass and Energy



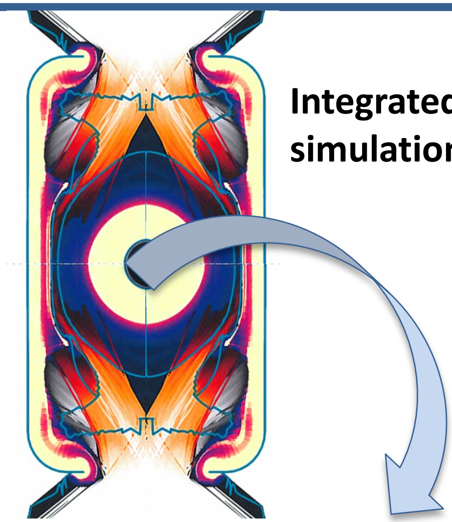
Hotspot Size and Burnwidth



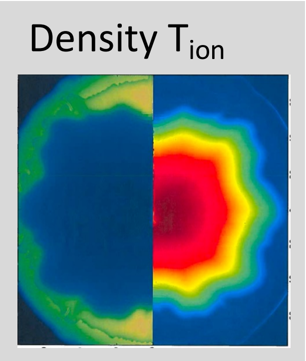
These are all signatures of a hotspot undergoing rapid self-heating

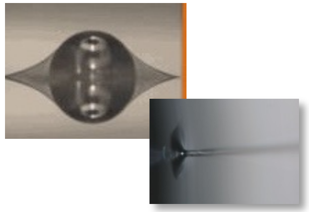
†NTOF (neutron-time-of-flight) diagnostic measures Doppler broadening of the neutron peak, which is mostly from the thermal temperature but includes contributions from fluid flow

Simulations get close in matching most performance metrics in 2D

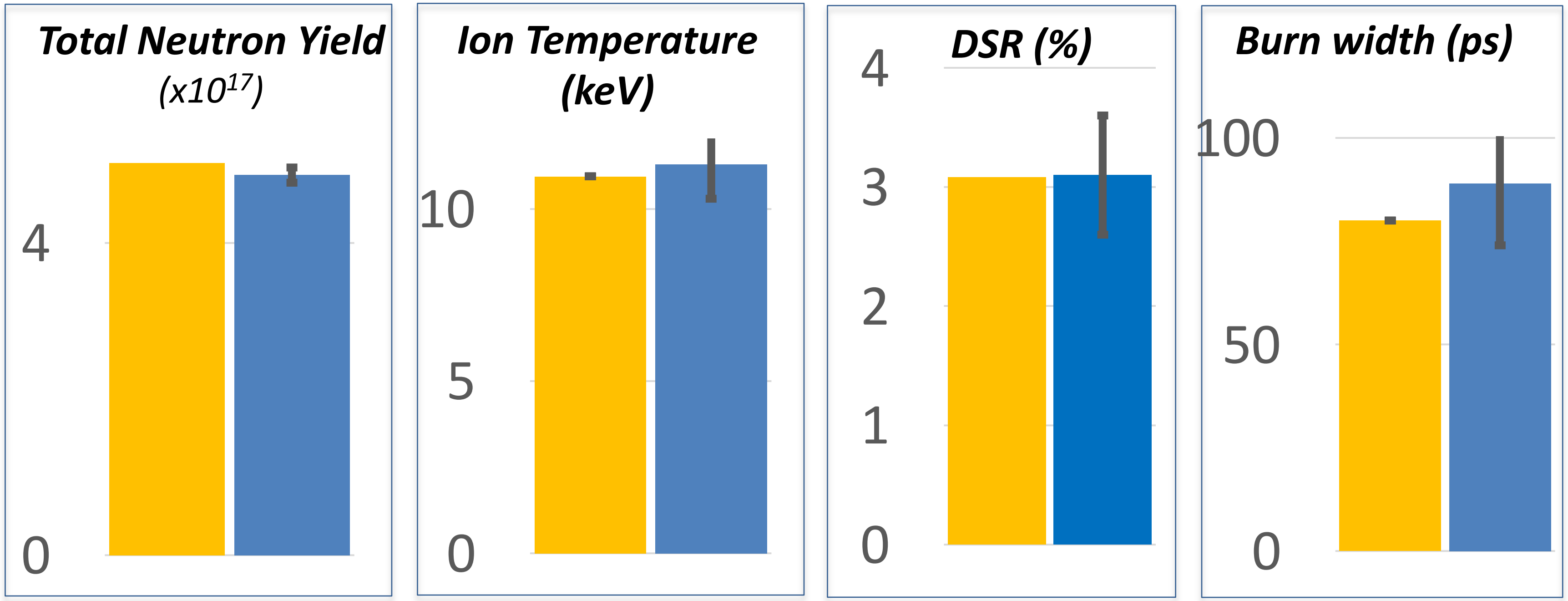


Integrated HYDRA simulations





Higher resolution capsule simulations



- Postshot sims account for as shot conditions

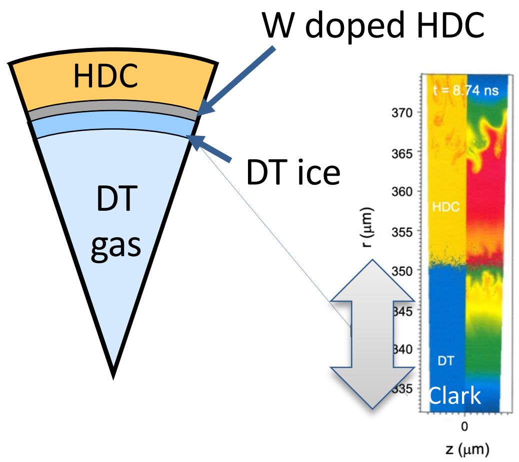
Use these simulations to calculate the heat balance equation for the hot spot

HYBRID-E increased capsule size to increase capsule energy – pressure dropped, capsule quality degraded, mix

910µm -> 1100µm capsule

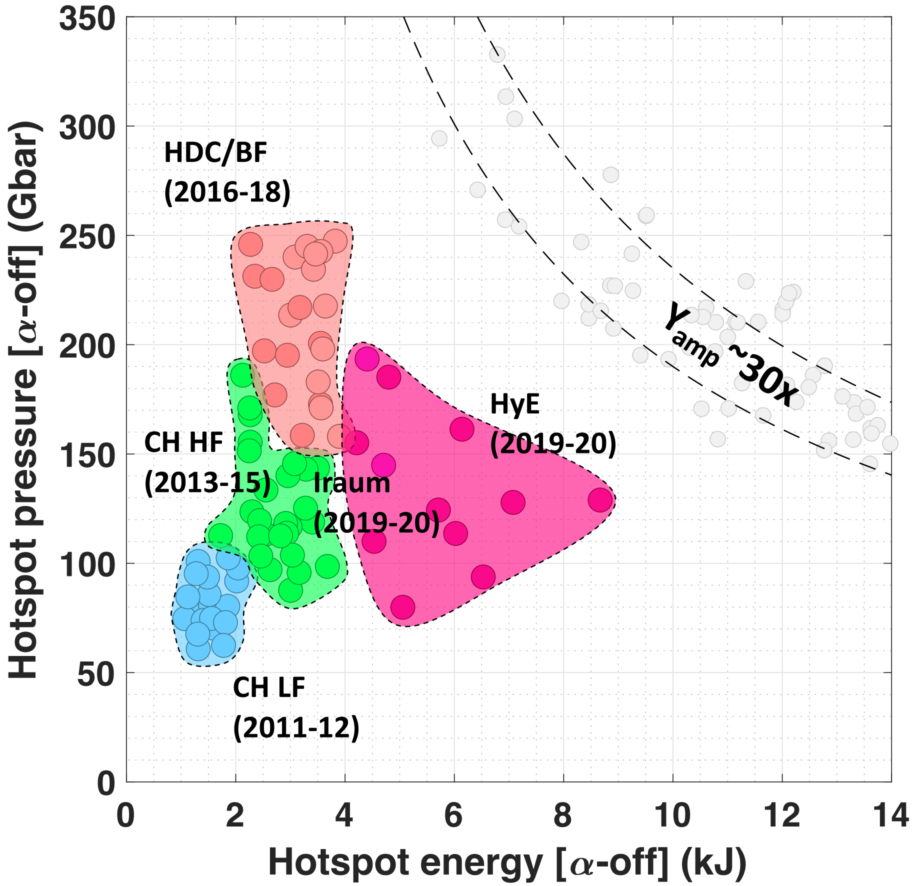
-> More coupled energy via reduced CCR (+maintain shape & velocity)
-> Longer coast
-> Capsule pits, voids
-> Mix
-> Lower pressure

Capsules and ice not hydro-scaled



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

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

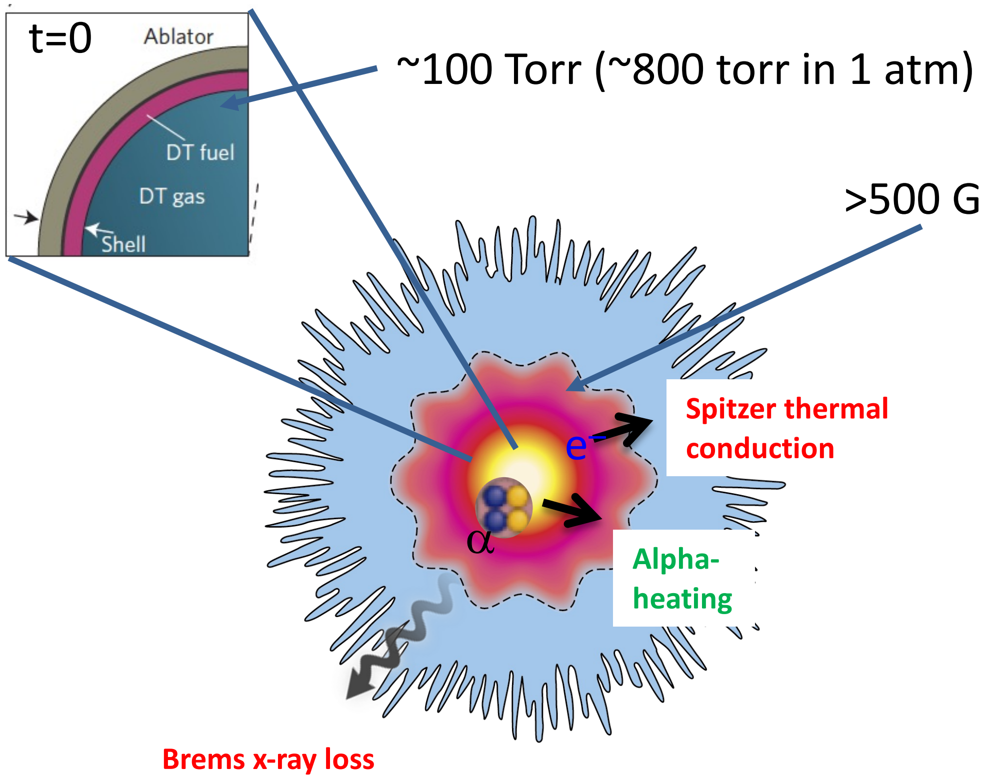


Recovering pressure (and temperature) would require lower coast and less mix

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

To reach fusion ignition and burn requires heating and compressing DT fuel to extreme conditions, for a duration of time (Lawson)

- Burn up-
  - 1.8% fuel burn up
  - 1.9% ice
  - 70MJ if all burned (20 realistic)
- Tion =9 keV (DD)
- HS = 89 g/cc
- rHS=~51um
- PHS=550-600Gbar
- EHS=~52kJ
- PdV=~20kJ
- ~190 kJ into HS from alphas
- Areal density ~1gm/cmm^2
- Rhor HS ~.44 g/cm^2
- Mass HS~60ug



E_fusion ~ <sigmav> vol_hs *tau* *n_hs/vol^2*

p_hs~ n_hs/vol

*P_hs ~p_hs * Tion;*

[1]O. A. Hurricane et al. Phys. Plasmas **26**, 052704 (2019)

The hohlraum is about 6.5 mm in diameter, 11 mm long. The Capsule had an inner radius of 1050 microns and was 76 um thick.

Suprathermal ion distribution in burning plasmas at the National Ignition Facility (NIF) (Viso) Ed Hartouni

- Viso is isotropic velocity
- Changing relationship between viso and Tion with yield could indicate departure from single temperature Maxwellian plasma behavior
- Could be due to kinetic effects
- Burning plasma with interpenetration of fuel and hot spot could create these conditions (Hurricane)