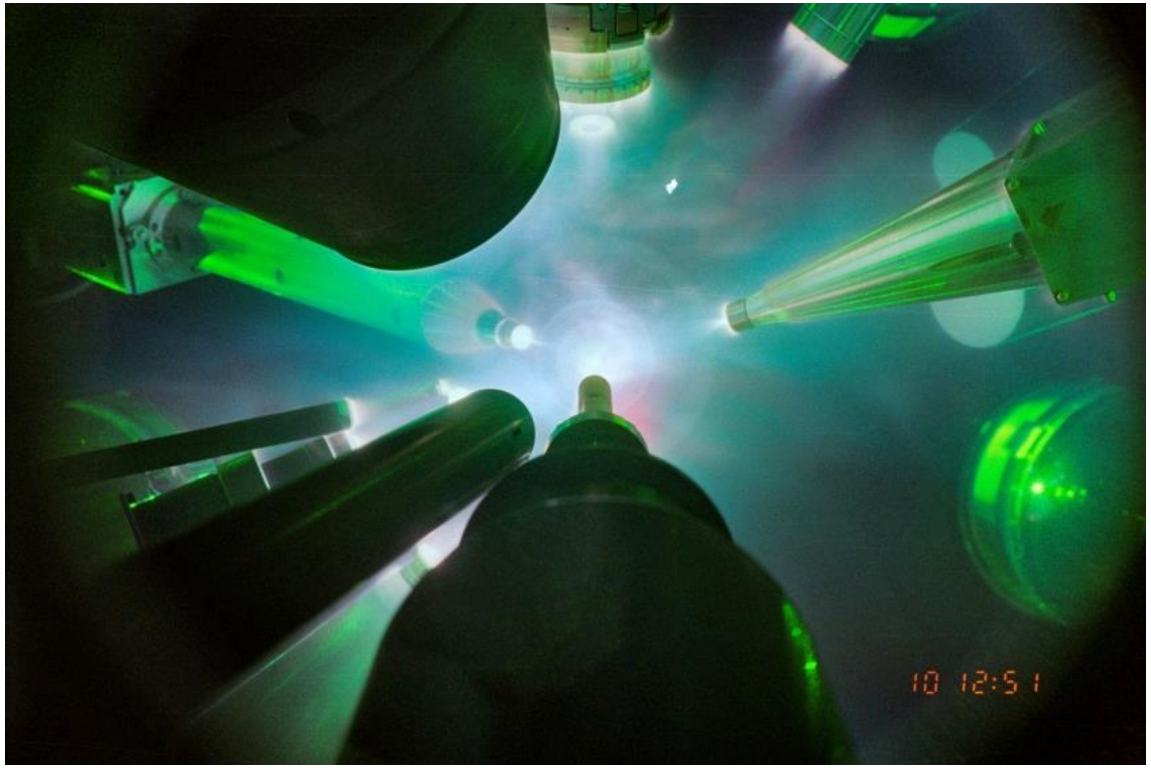
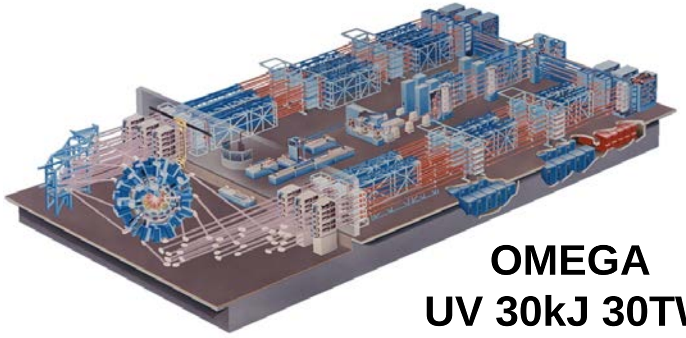
Latest results in laser-driven inertial confinement fusion

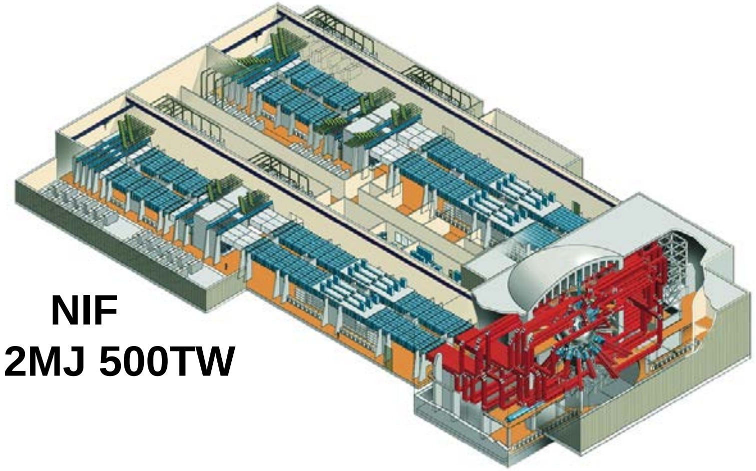


R. Betti
Dept. Mechanical Engineering and Physics & Astronomy
Chief Scientist, Laboratory for Laser Energetics
University of Rochester

Colloquium
CNR-INO and Frascati Research Center
December 17, 2021

In the US, inertial fusion via lasers is pursued through the direct and indirect drive approaches

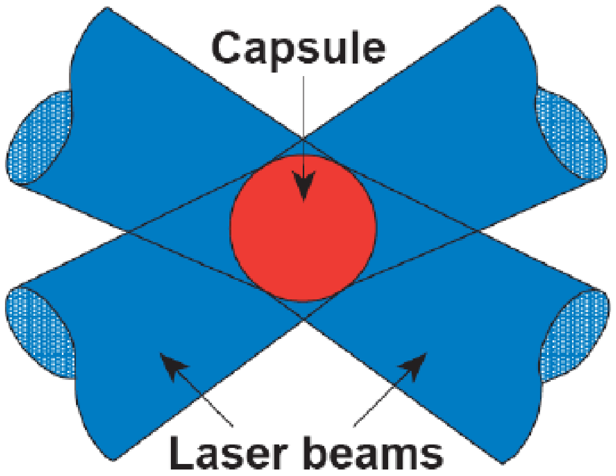




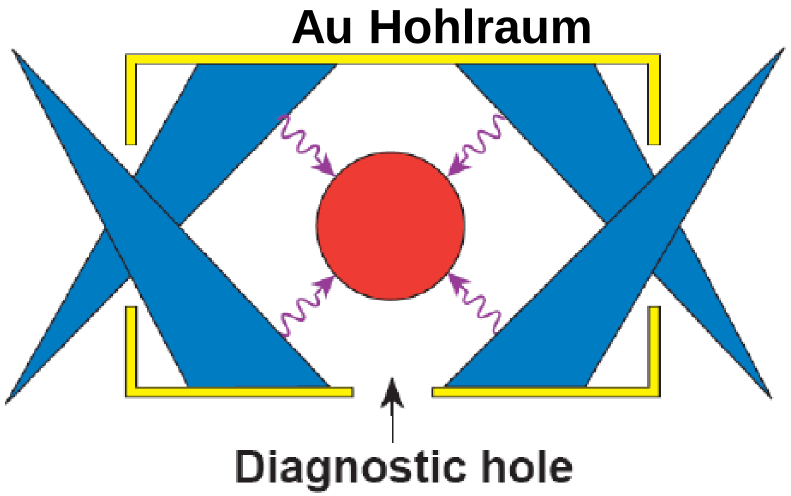
OMEGA
UV 30kJ 30TW

NIF
UV 2MJ 500TW

Direct-drive target



Indirect-drive target



Review papers/books on ICF

Atzeni & Meyer-ter-vehn
“Physics of Inertial Fusion” 2005

Lindl et al, Review of Indirect Drive
Phys. Plasmas 2004

Lindl et al, Review National Ignition
Campaign, Phys. Plasmas 2014

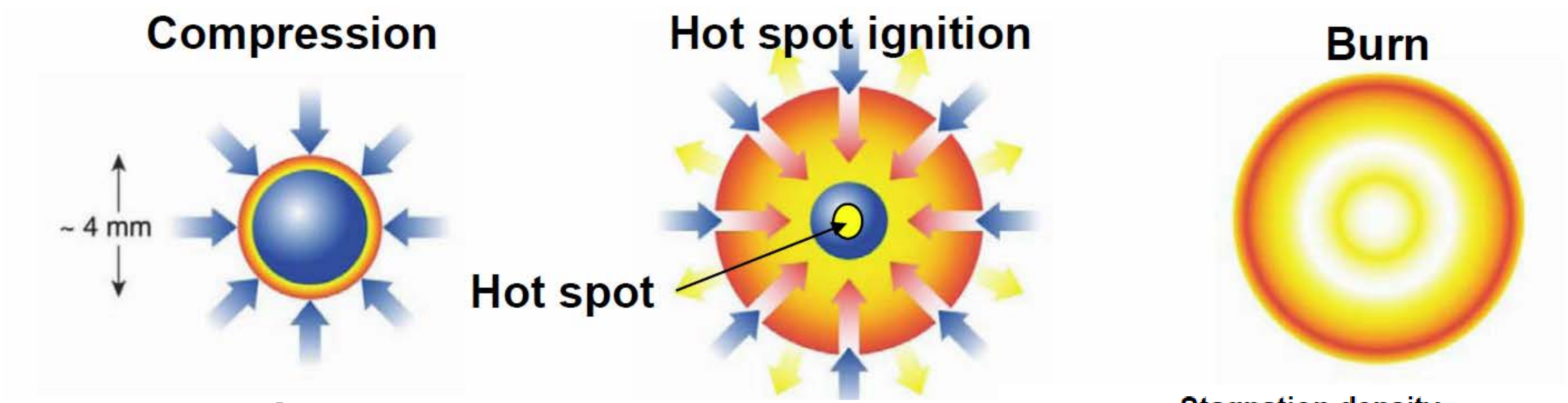
Craxton et al, Review of Direct Drive
Phys. Plasmas 2015

Betti & Hurricane, ICF via Lasers
Nature Physics, 2016

Atzeni et al, Review of Shock Ignition
Nuclear Fusion 2014

Tabak et al, Review of Fast Ignition
Phys. Plasmas 2005

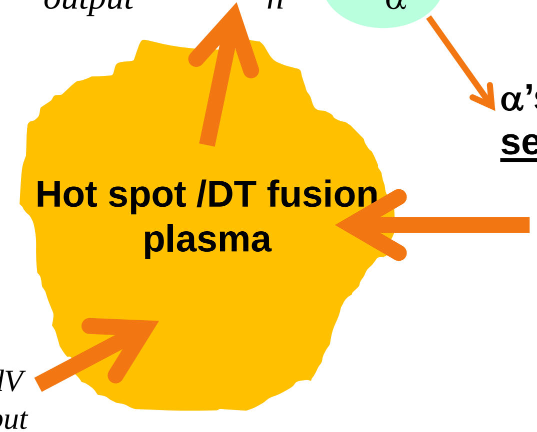
Both direct and indirect drive ICF aim to achieve the conditions for ignition and propagating thermonuclear burn

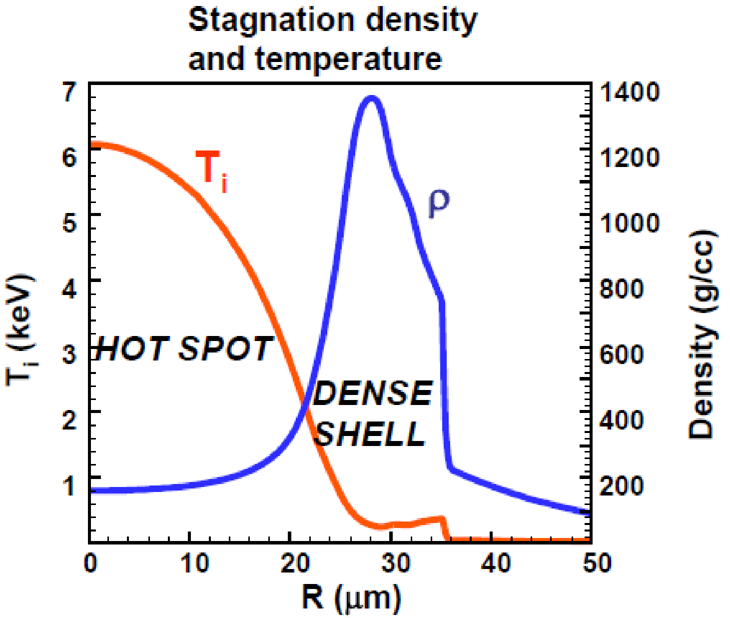


D + T → n(14.1MeV)+α(3.5MeV)

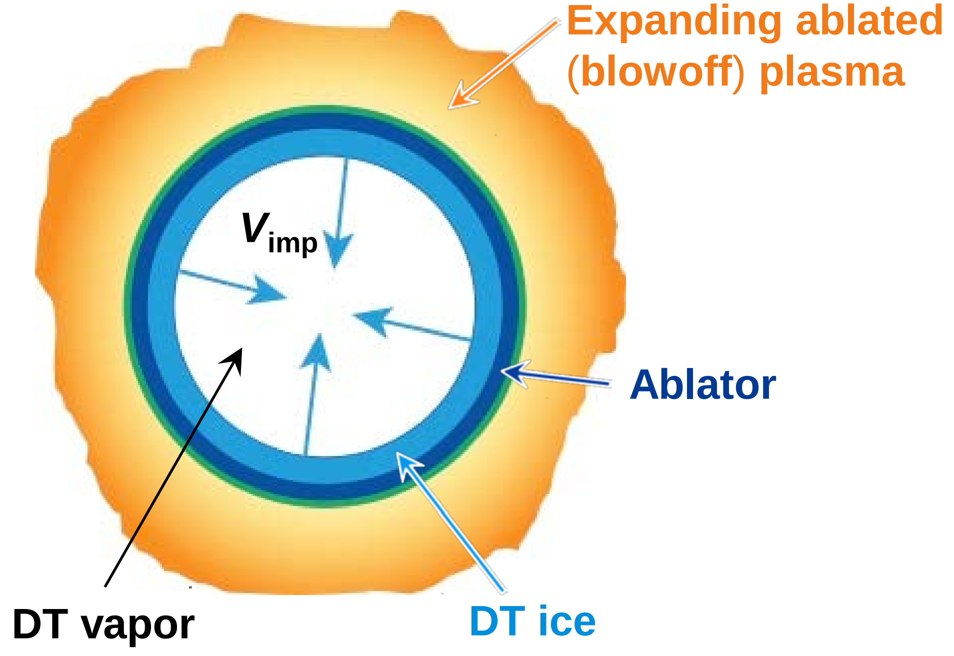
$$E_{output}^{nuclear} = E_n + E_\alpha$$

α's slow-down and <u>self-heat</u> the plasma





Driving ICF targets with lasers is a very inefficient process



Examples:

NIF Indirect Drive
Laser energy = 2 MJ
Shell final kinetic energy = 20-30 kJ
Total efficiency = 1-1.5%

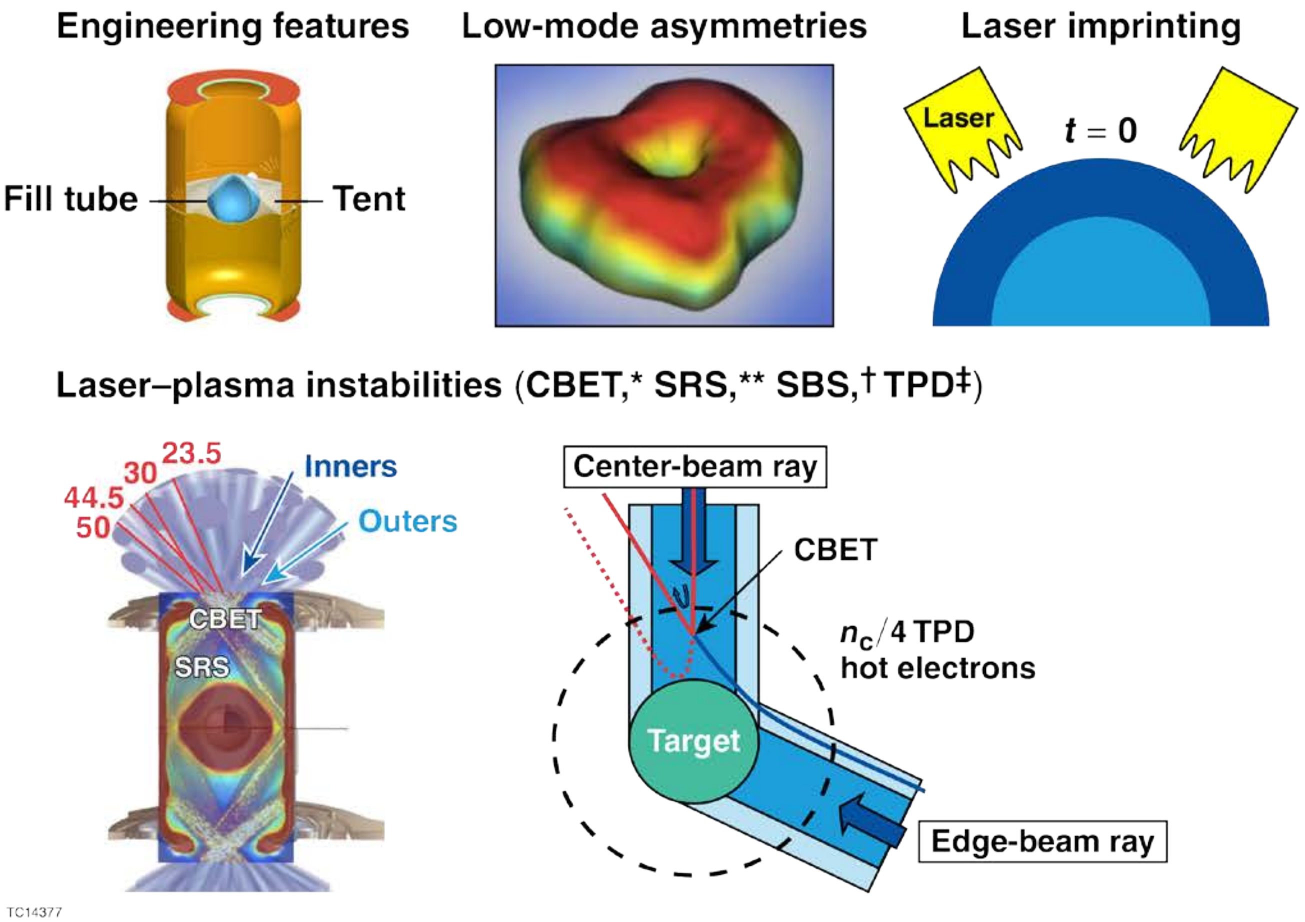
NIF Direct Drive
Laser energy = 2 MJ
Shell final kinetic energy = 80-100 kJ
Total efficiency = 4-5%

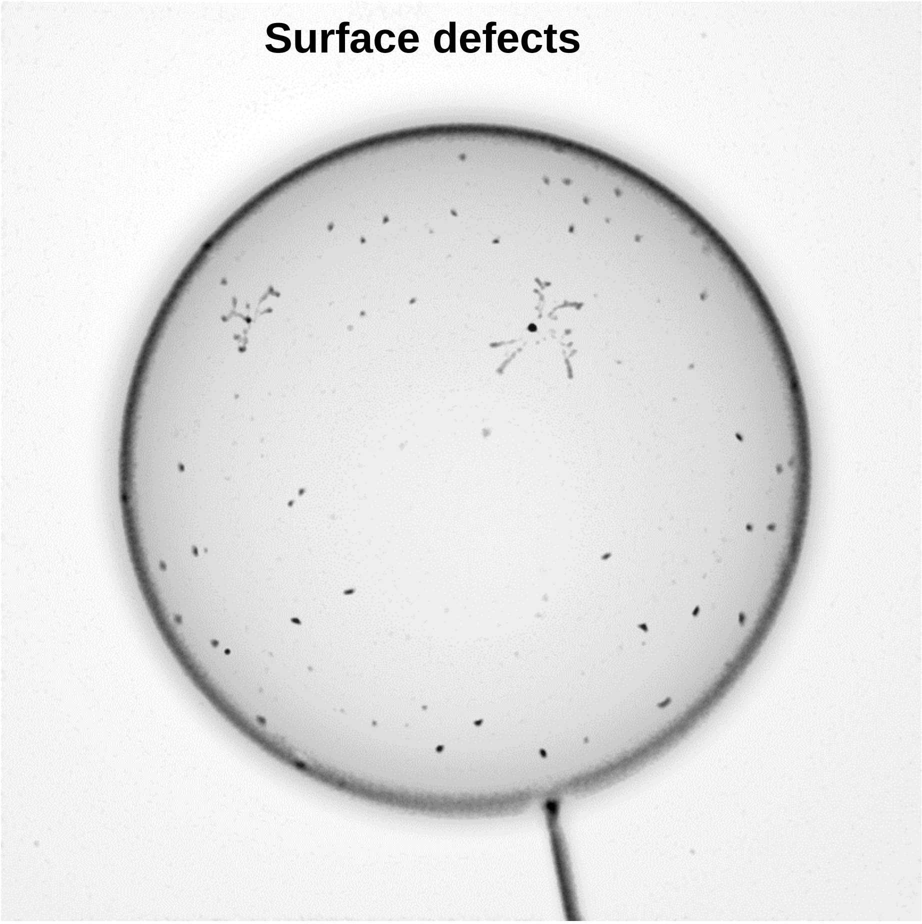
Useful kinetic energy $= \frac{1}{2} M^{\text{shell}}_{\text{unablated}} V^2_{\text{imp}}$

Only a small fraction of the driver energy is converted into useful kinetic energy of the implosion

V_{imp} = implosion velocity

Achieving ignition requires control of hydrodynamic and laser–plasma instabilities, low-mode asymmetries and the impact of engineering features





* CBET: cross-beam energy transfer
** SRS: stimulated Raman scattering

† SBS: stimulated Brillouin scattering
‡ TPD: two-plasmon decay

The different forms of the Lawson triple product are the main ignition metrics

$\dot{q}_\alpha$ **Alpha heating** **losses** **pdV work =0 at stagnation**

$$\frac{3}{2}\frac{dP}{dt}=\frac{3}{2}\frac{P^2}{24}\varepsilon_\alpha\frac{\langle\sigma v\rangle}{T^2}-\frac{3}{2}\frac{P}{\tau}-\frac{3}{2}P\frac{1}{V}\frac{dV}{dt}$$

$\dot{q}_\alpha$ **Alpha heating** **losses**

$$\frac{P^2}{24}\varepsilon_\alpha\frac{\langle\sigma v\rangle}{T^2}>\frac{P}{\tau}$$

Lawson criterion

$$\chi\equiv\frac{P\tau}{[P\tau]_{ign}}>1$$

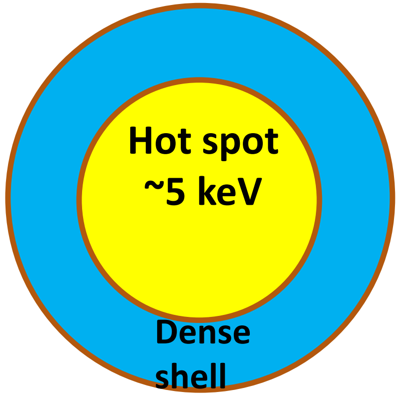
$$[P\tau]_{ign}\equiv\frac{24T^2}{\varepsilon_\alpha\langle\sigma v\rangle}$$

Different form of Lawson

$$\frac{\dot{q}_\alpha V\tau}{(3/2)PV}=\frac{E_\alpha}{E_{plasma}}\Rightarrow \text{in ICF}\Rightarrow\frac{E_\alpha/2}{E_{HotSpot}}=f_\alpha>1$$

The normalized Lawson parameter for ICF can be rewritten in terms of areal density, DT mass and neutron yields or ion temperature

$$\rho R = \int_0^\infty \rho dr$$



- **Rewrite Lawson for ICF using an imploding shell compressing a plasma rather than a static plasma:**

$$\chi = \frac{P\tau}{[P\tau]_{ign}} \approx \left\langle \rho R_{g/cm^2} \right\rangle^{0.61} \left(\frac{0.12 Yield_{16}}{M_{DTstag}^{mg}} \right)^{0.34}$$

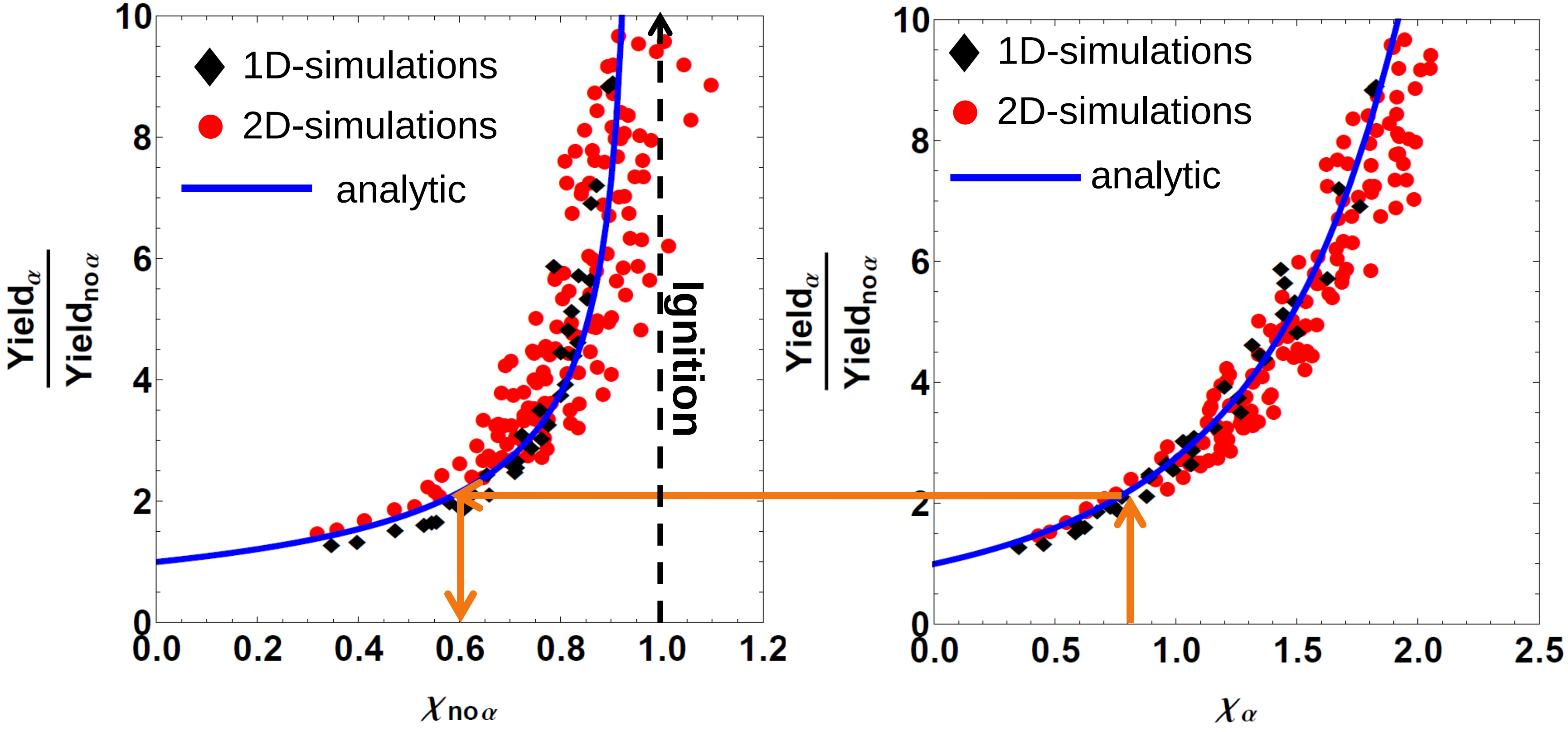
Other forms of ignition criterion using hot spot areal density and temperature**

$$(\rho R)_{HotSpot}\, T_{ion} > 0.3 \times 5 \text{ g/cm}^2 \text{ keV}$$

****Atzeni and Caruso, Nuovo Cimento 1984**
Kemp, Meyer-ter-vehn and Atzeni, PRL 2001

***R. Betti et al, PRL 2015**
A. Christopherson et al, PoP (2018 and 2019)
Lindl, PoP, 2018
Spears, PoP 2012 (ITFx)

A measure of the alpha heating level is the yield amplification from alpha heating which is strongly correlated to the no-α and with-α Lawson parameter

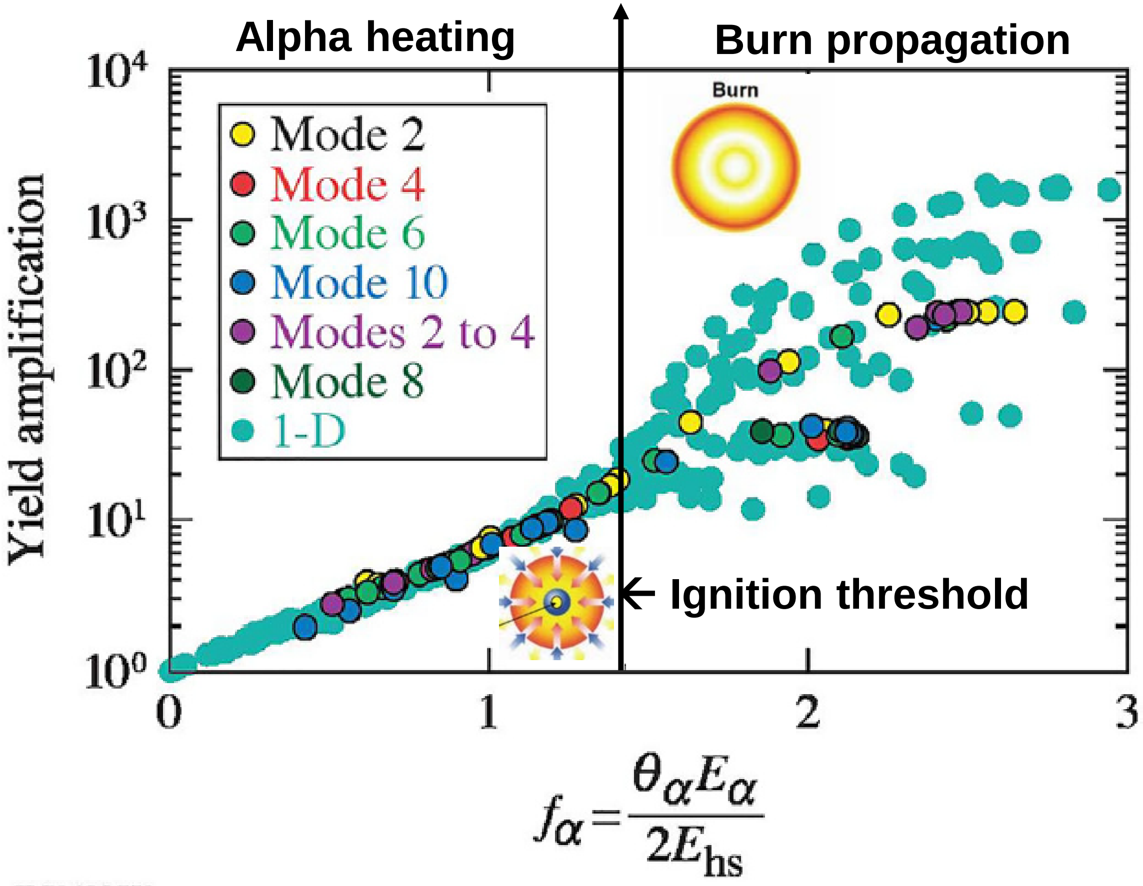


$$\chi_{no\alpha} \equiv \frac{[P\tau]_{no\alpha}}{[P\tau]^{ign}_{no\alpha}}$$

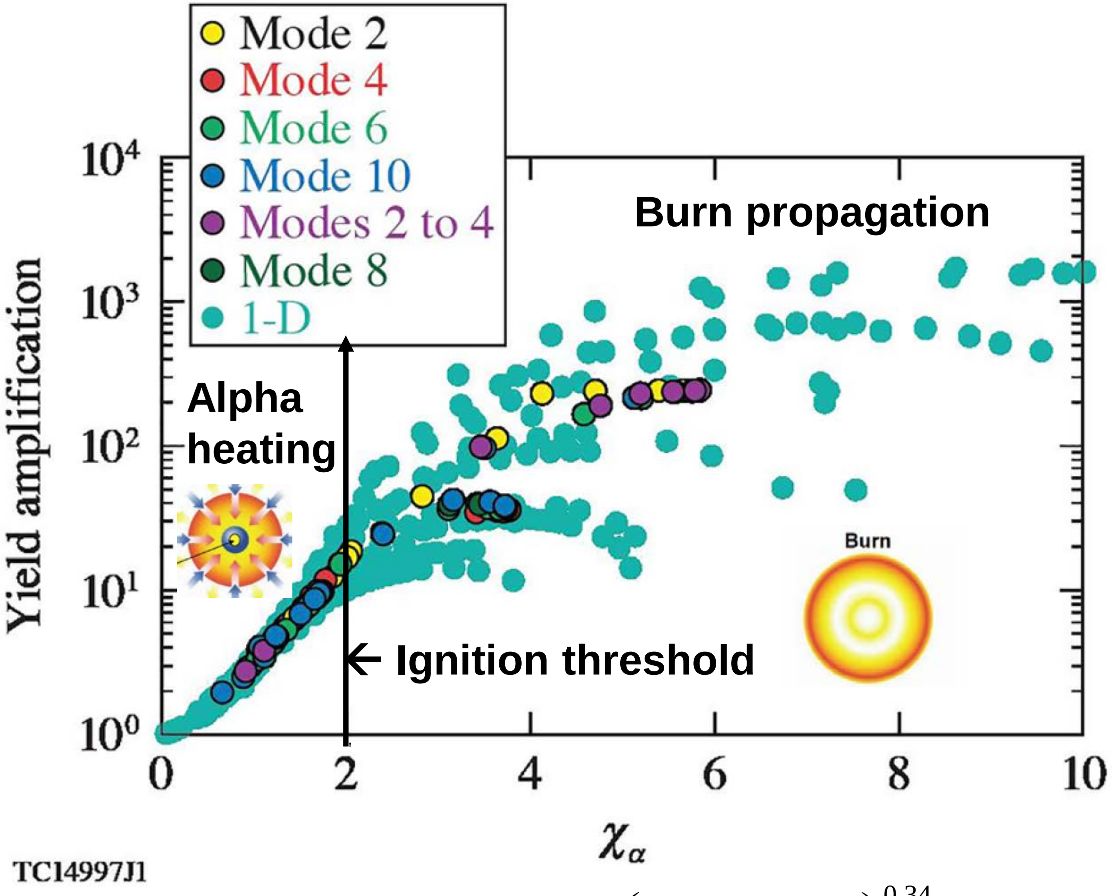
$$\chi_{\alpha} \equiv \frac{[P\tau]_{\alpha}}{[P\tau]^{ign}_{\alpha}}$$

*Betti et al, PoP 2010

Ignition is the transition from rapidly growing alpha heating within the hot spot to burn propagation in the dense shell



Ignition→ $f_\alpha > 1.4$



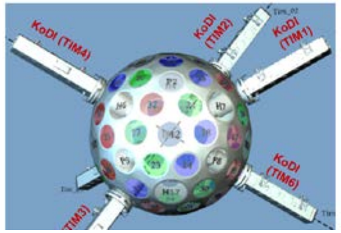
Ignition→ $\chi_\alpha = \left\langle \rho R_{g/cm^2} \right\rangle^{0.61} \left(\frac{0.12 Yield_{16}}{M^{mg}_{DTstag}} \right)^{0.34} > 2$

Critical ignition-relevant properties are inferred through nuclear and x-ray diagnostics

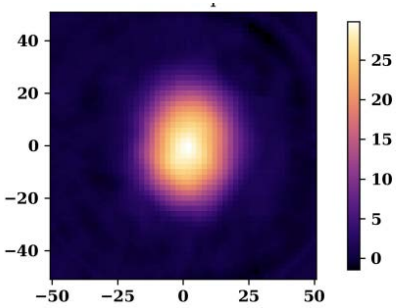
Inference of the core pressure

NTOF
+
Activation

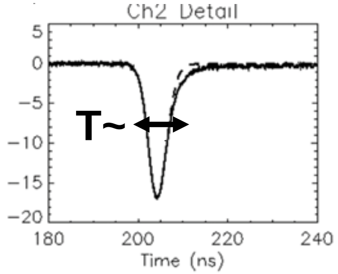
$$Yield \sim n^2 \langle \sigma v \rangle V\tau \sim \mathrm{P}^2 \frac{\langle \sigma v \rangle}{T^2} V\tau$$



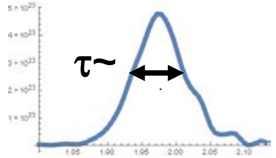
x ray + neutron images



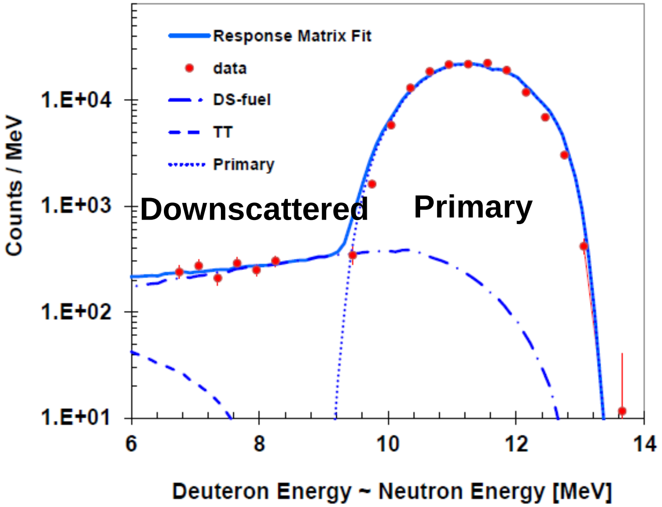
NTOF
Brisk

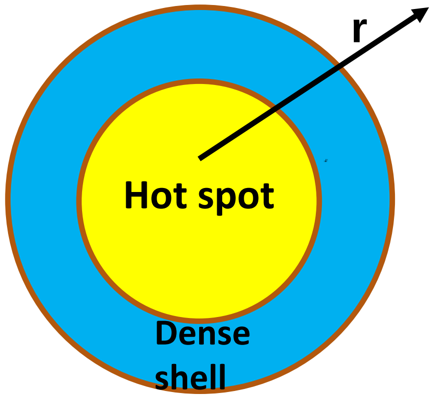


Neutron+γ-ray+x-ray
temporal diagnostic



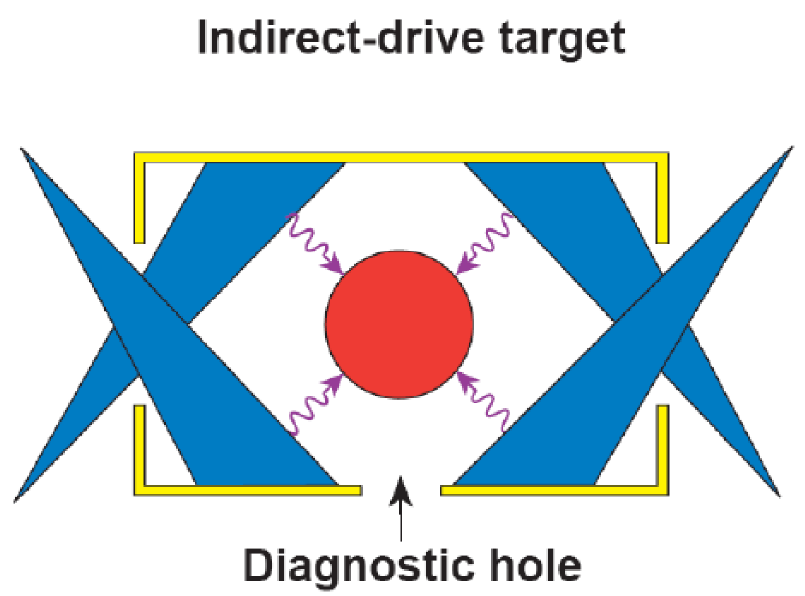
Inference of the areal density



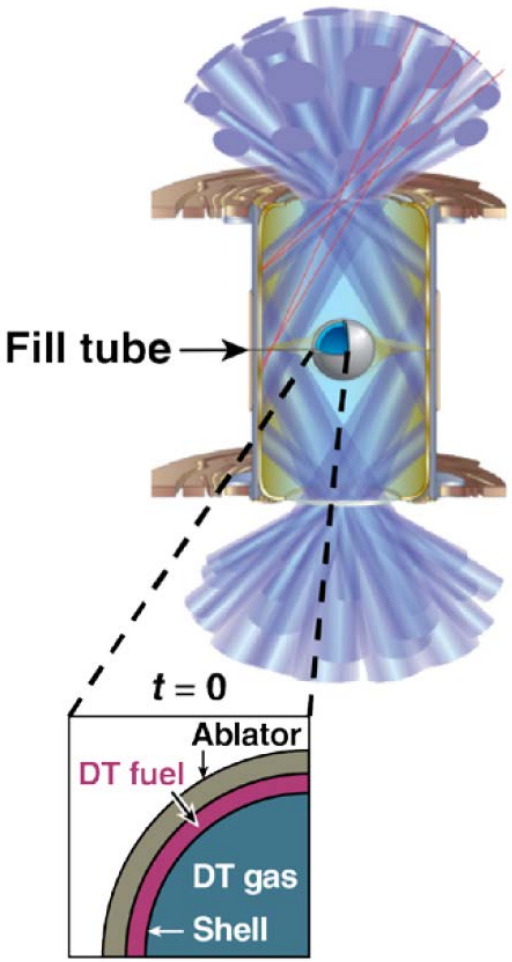


$$\rho R = \int_0^\infty \rho dr \sim DSR = \frac{\text{Downscattered}}{\text{Primary}}$$

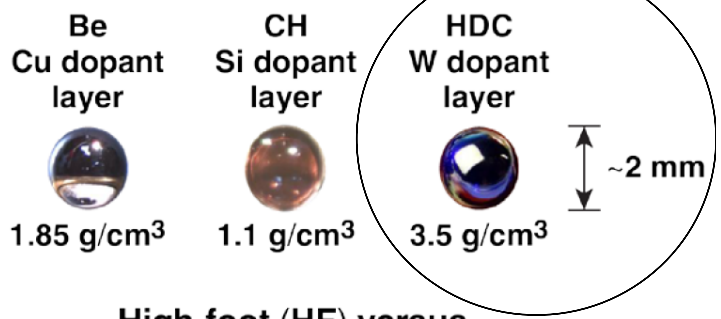
Laser indirect drive on NIF



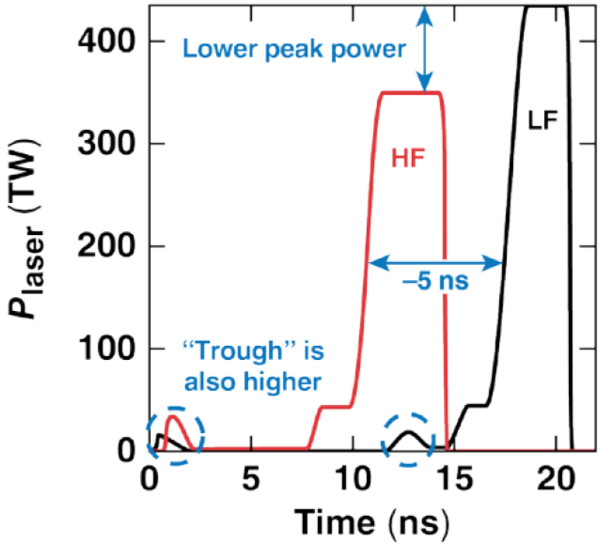
Current LLNL high performance targets use HDC ablators with optimized target specifications and laser pulse shapes (Hybrid-E)



NIF indirect drive

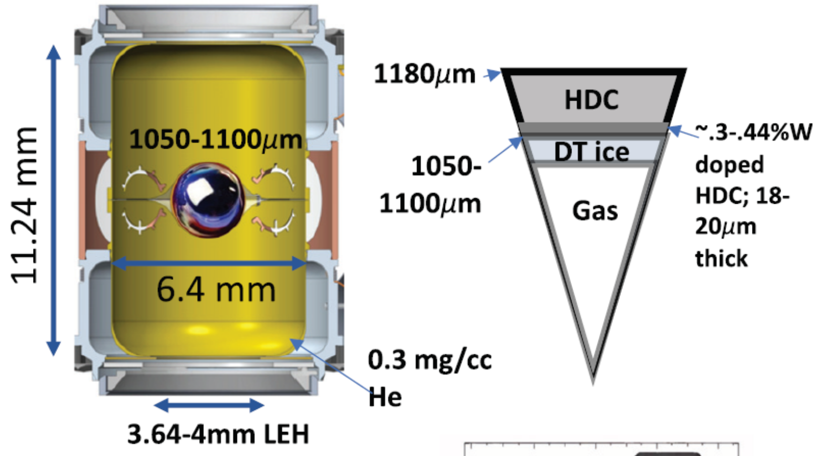


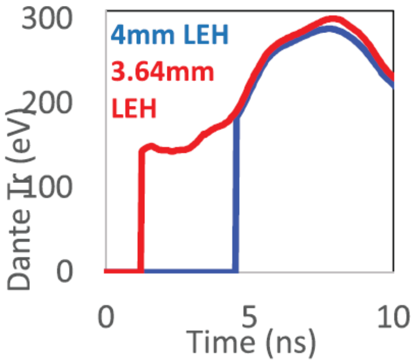
High-foot (HF) versus Low-foot (LF) pulse shapes

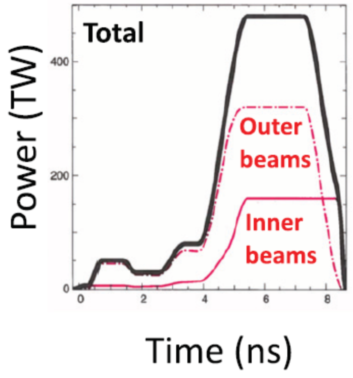


*

Hybrid-E targets & pulse shapes





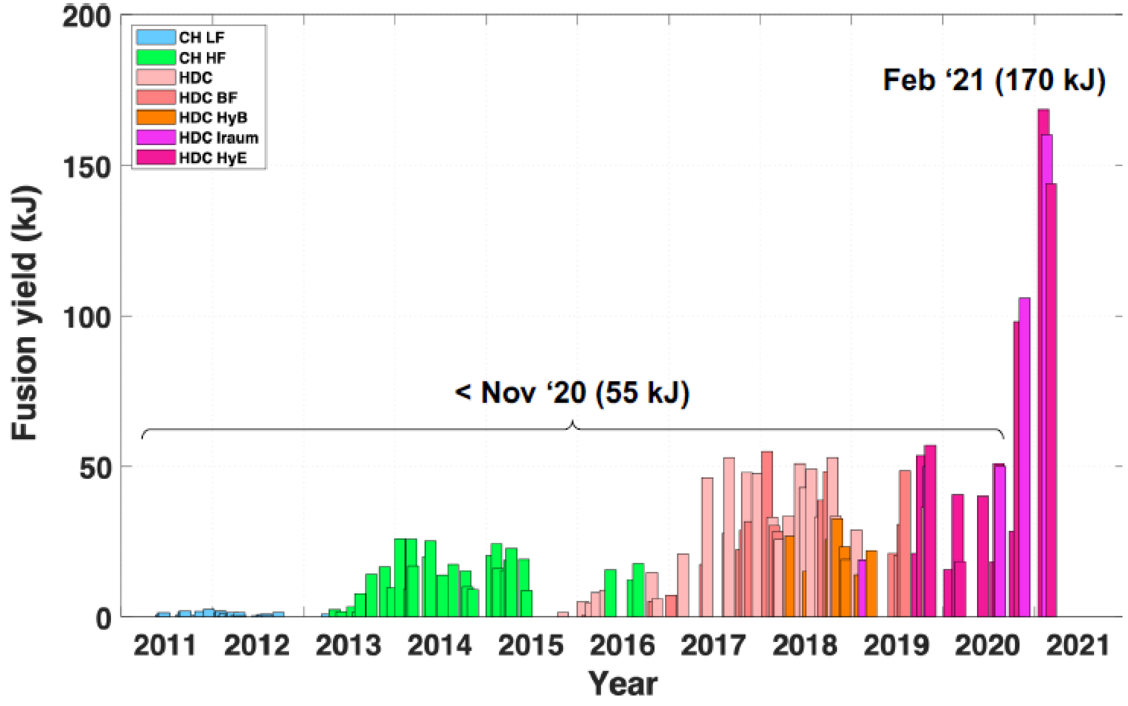


Kritcher et al, Phys. Plasmas (2021)
Zylstra et al, PRL (2020)

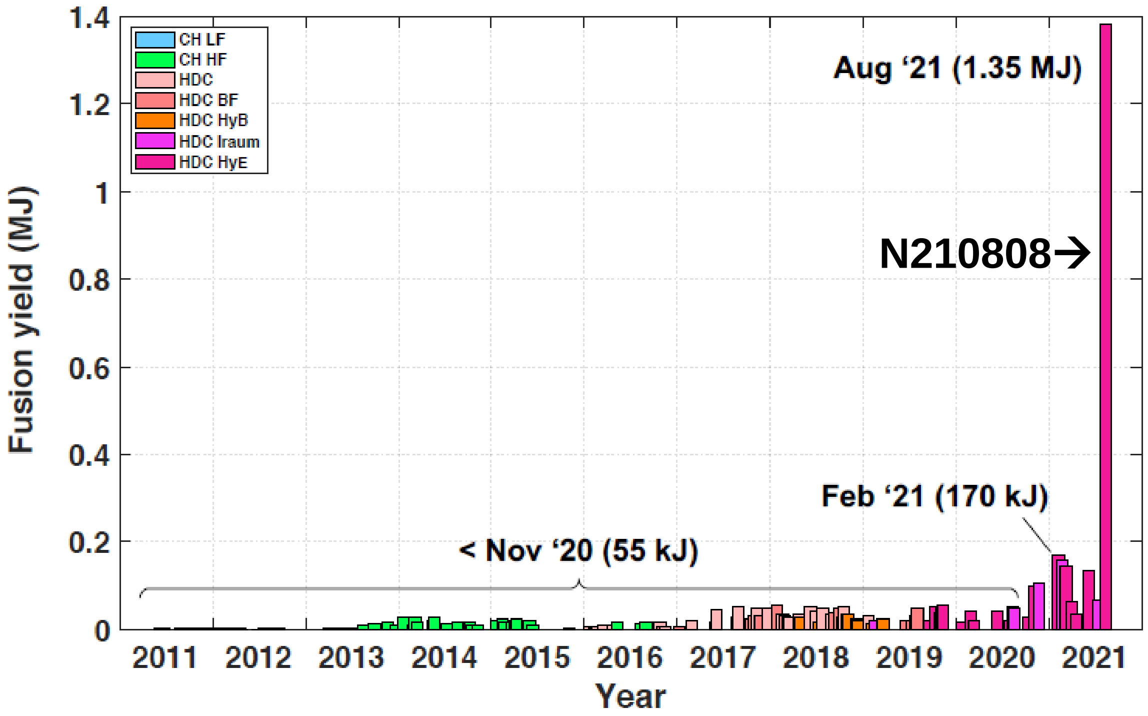
*Pulse shapes used in CH target
Hurricane et al, Nature 2014

In terms of fusion yield, shot N210808 stands out as both qualitatively and quantitatively different from previous high performance implosions

Up to Feb 2021

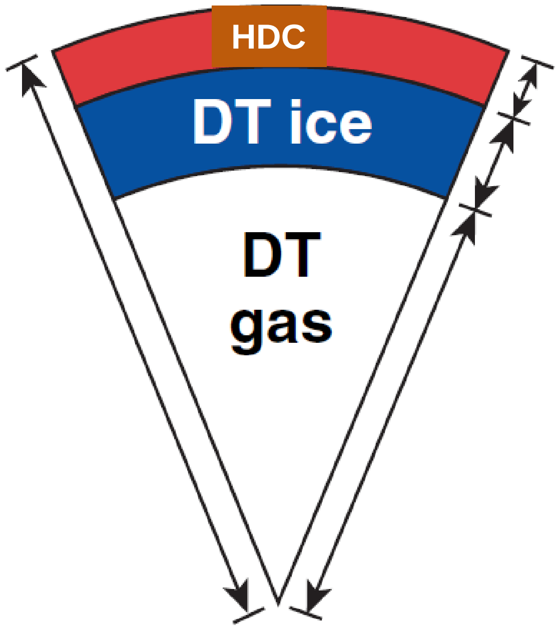


Up to Aug 2021

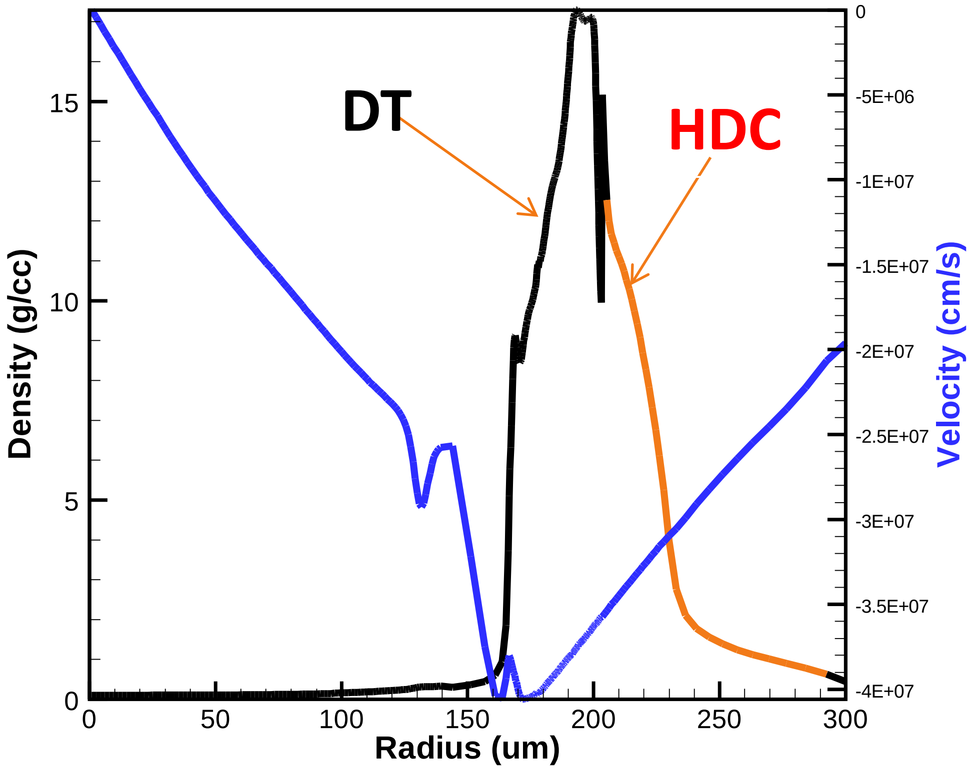


(from P. Patel, APS-DPP 2021, available for download from meeting website)

An implosion with similar characteristics to shot N210808 can be reconstructed using 1D rad-hydro code LILAC and publicly disseminated data*



Density and velocity at time of peak velocity from reconstruction



DT fuel peak implosion velocity ~ 390km/s
DT mass = 210ug
Remaining ablator mass HDC ~200ug
Total kinetic energy ~ 25-30 kJ

- **From LLNL talks at APS-DPP meeting Callahan, Hurricane, Zystra, Kritcher, Patel et al**

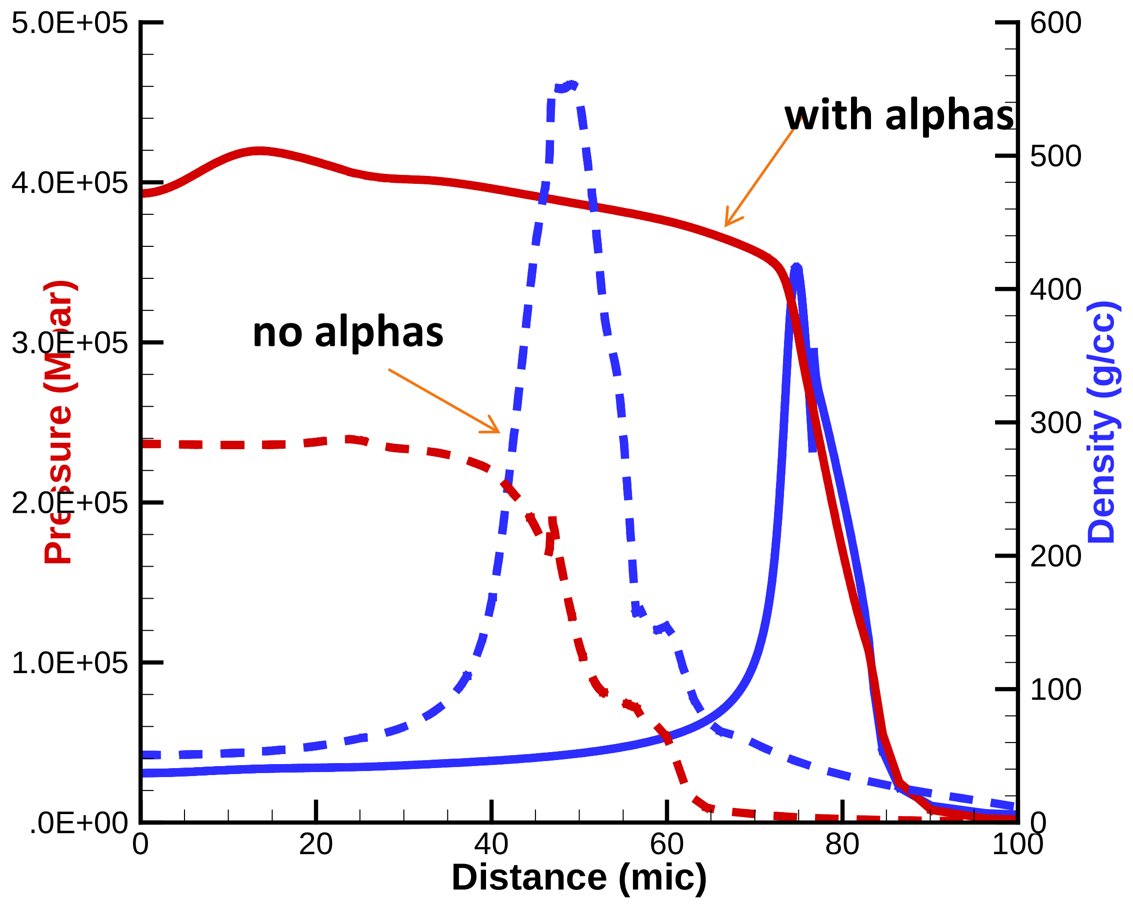
Comparison with the measured/inferred core conditions indicates the simulated implosion is a good surrogate

	Measured*	Simulated
Neutron Yield	4.9×10^{17}	4.9×10^{17}
Implosion Velocity (km/s)	390	382
T_{ion} (DT/DD) (keV)	9.8/8.2	8.6/8.3
Total Areal Density (g/cm^2)	0.57	0.55
Hot spot radius (μm)	77	73
Burn width (ps)	89	92
DT mass (μg)	210	210

* From LLNL talks at APS-DPP meeting

Hot spot pressure is approximately doubled by alpha heating.
Hot spot size about doubled by alpha heating indicating propagating burn.

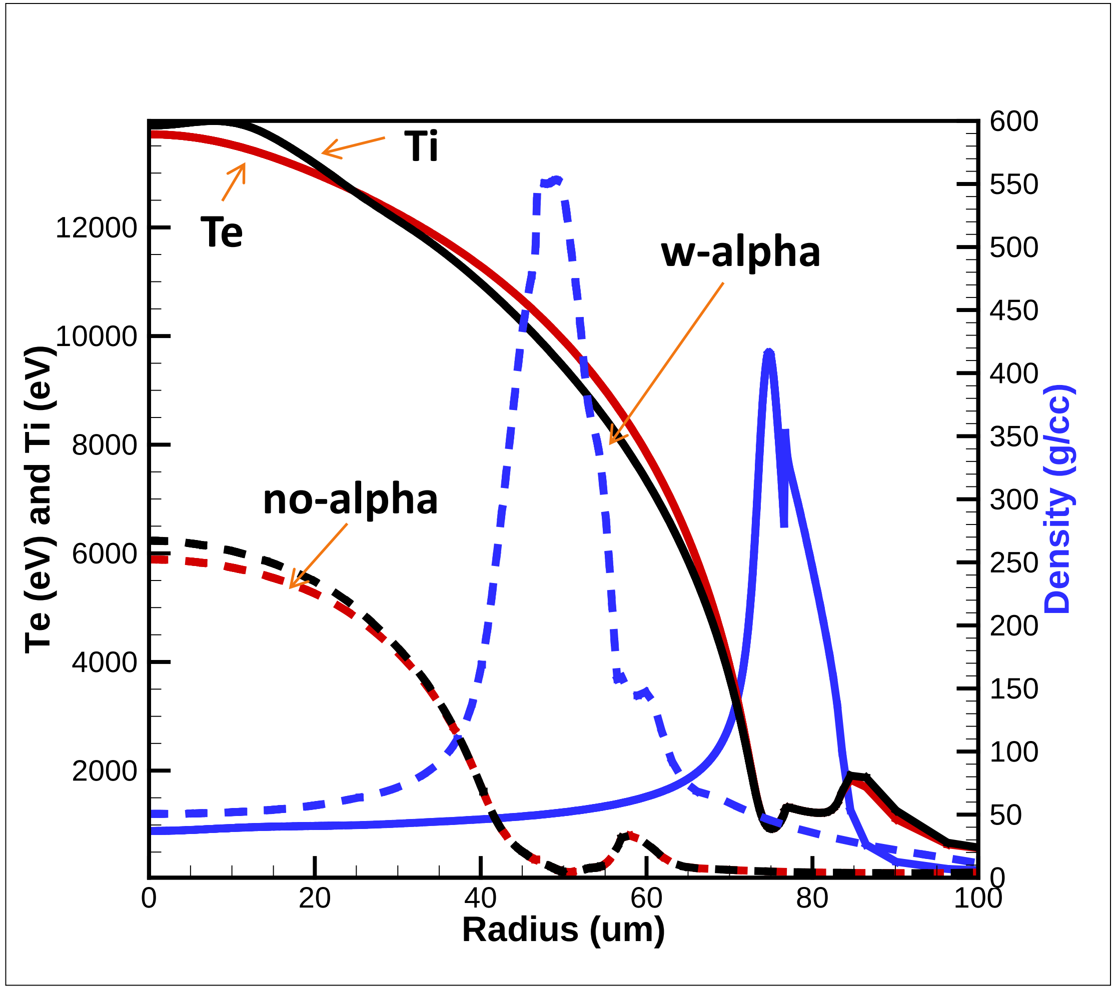
Hot spot pressure and density (no-alphas and with-alphas)



Pressure at peak burn no-alphas: 256Gbar
Pressure at peak burn with-alphas: 454Gbar

$R_{17\%}$ xray with-alphas=73um
$R_{17\%}$ xray no-alphas=38um
$R_{17\%}$ xray measured: 77um

Te and Ti are approximately doubled by alpha heating. Doubling of temperature is another definition of ignition

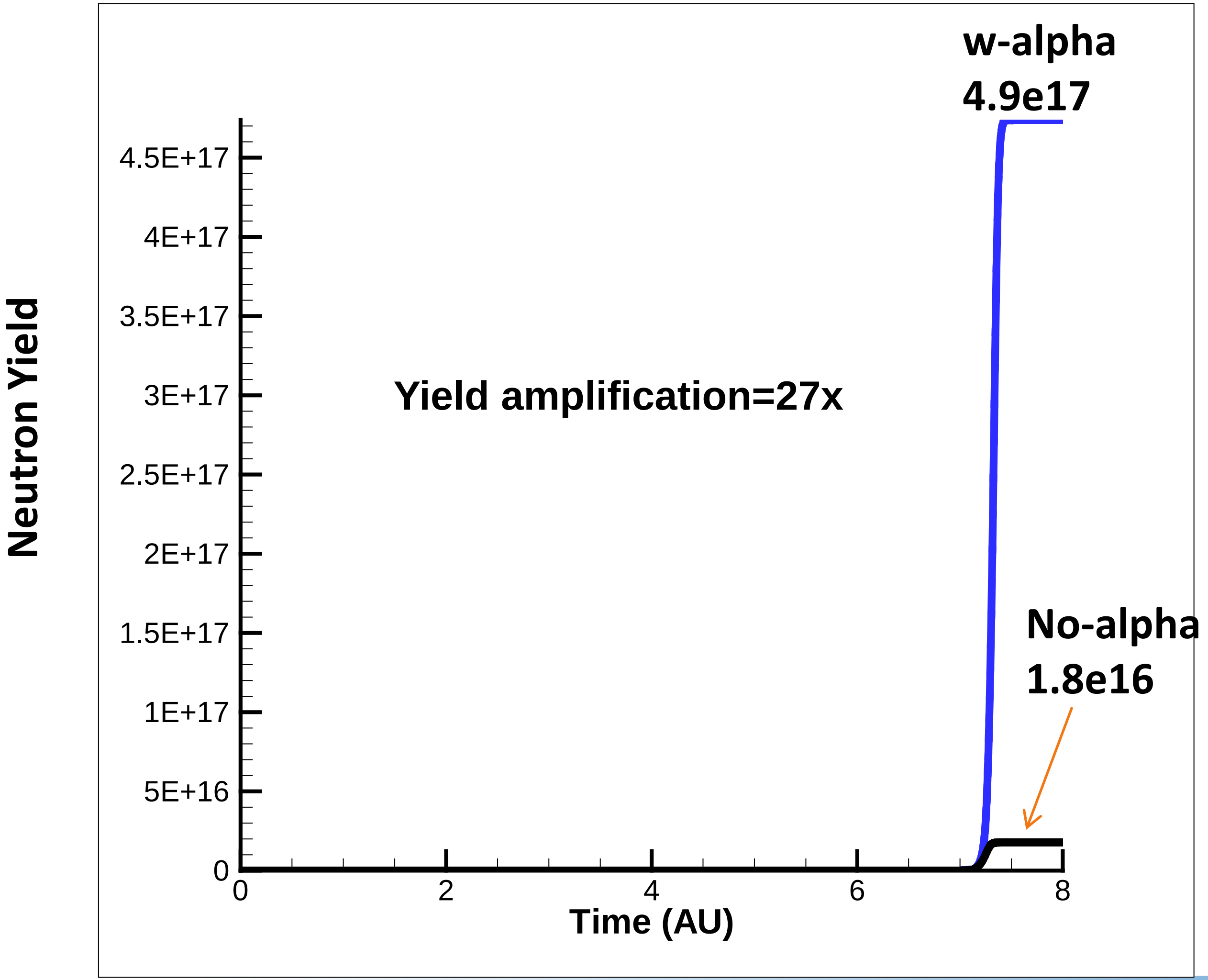


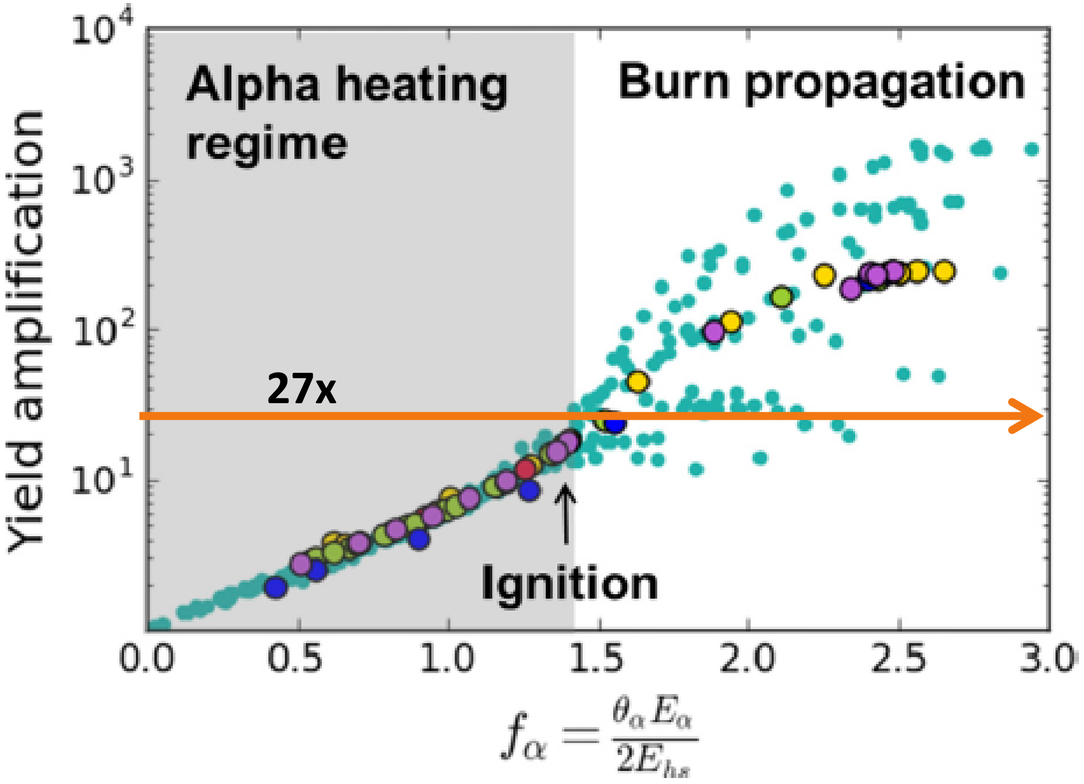
Ti (DT) no-alpha=4.6 keV

Ti (DT) with-alpha=8.6 keV

Ti measured = 9.8 keV

The reconstructed yield amplification from alpha heating is ~ 27x consistent with an ignited hot spot





A. Christopherson et al PRE 2019

All the ignition metrics based on the normalized Lawson parameter point to core conditions at or exceeding the ignition threshold*

Without accounting for HDC mass and ρR
Use: Y=4.9e17, ρR_DT=0.57g/cm2 and M_DT_total=0.214mg
χ_α =2.72 (ignition for χ_α>2)

Accounting for (simulated) HDC mass and ρR
Use: Y=4.9e17, ρR_tot=0.57+0.21=0.78g/cm2, Total Mass=0.4mg
χ_α =2.67 (ignition for χ_α>2)

Using hot spot size from x-rays (77um)
f_α =1.4 (ignition for f_α>1.4)

Using hot spot size from neutron imaging (54um)
f_α =2.2 (ignition for f_α>1.4)

* This is my personal opinion

Simple energetics also points to ignition in shot N210808 with a fusion yield consistent with a burnup fraction from the measured areal density and T_{ion}

UR LLE

Simple energetics

Total kinetic energy ~ 25-30 kJ
Fuel kinetic energy ~ 16-20 kJ
pdV work on hot spot ~ 8-10 kJ

Alpha energy ~ 274 kJ
Fusion energy ~ 1370 kJ

Fusion Energy ~150x hot spot energy
Alpha Energy ~ 30x hot spot energy

Difficult to explain without the thermonuclear instability taking place!

Assume propagating burn*

Simplified form of burn-up fraction: θ

T~10keV

0.57g/cm2

$$\theta(\xi) \approx \frac{\xi}{4+\xi} \qquad \xi \equiv \frac{n_i(0)\langle\sigma v\rangle R_0}{2C_s} = \frac{\langle\sigma v\rangle}{(m_D+m_T)C_s}\rho(0)R_0$$

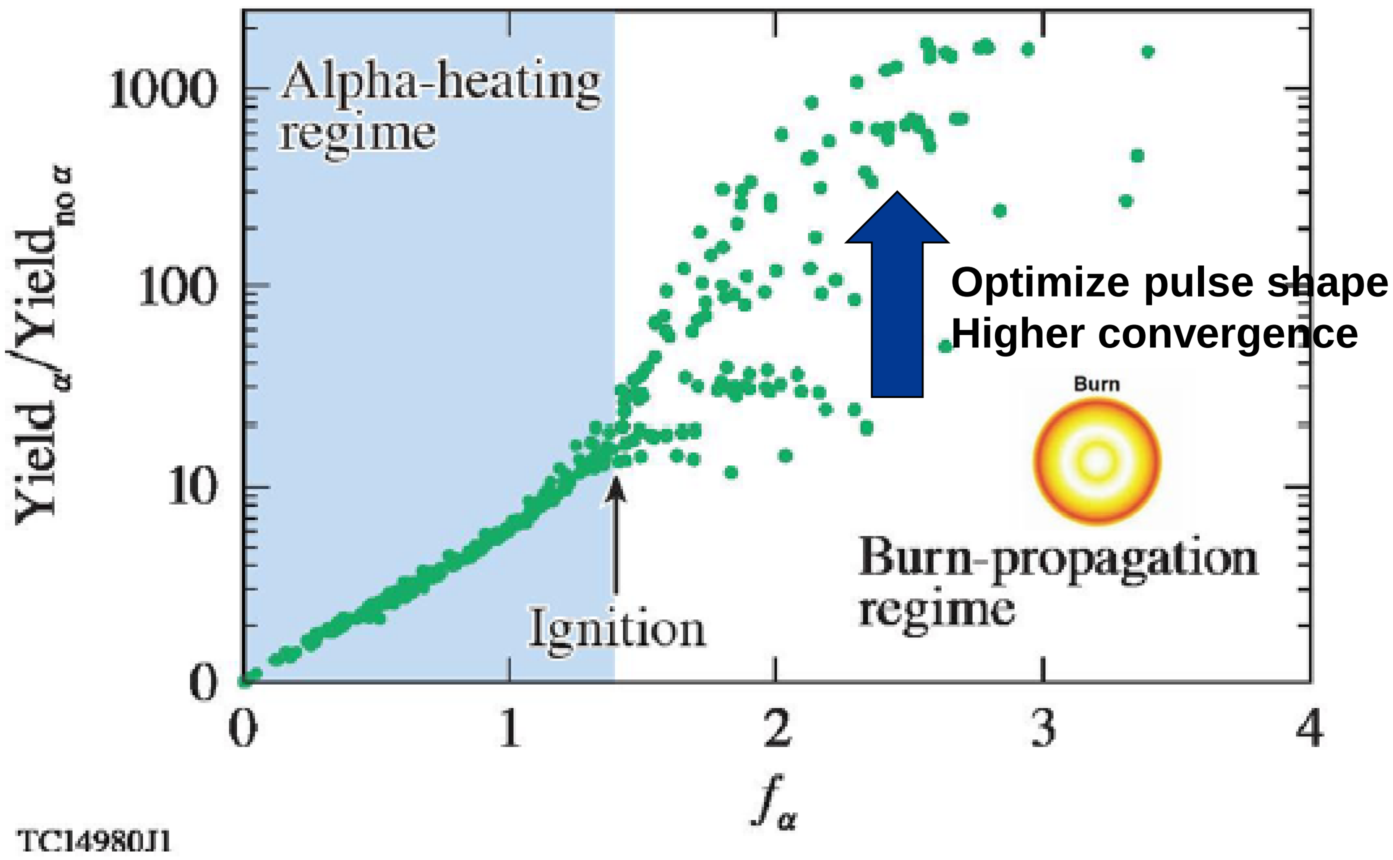
$$\xi = 0.084 \qquad \theta(\xi) \approx 0.021$$

$$E_f = \frac{\varepsilon_f \theta M_{DT}}{m_D + m_T} \approx 1.5MJ$$

← **from burnup fraction**
← **Consistent with measured yield**

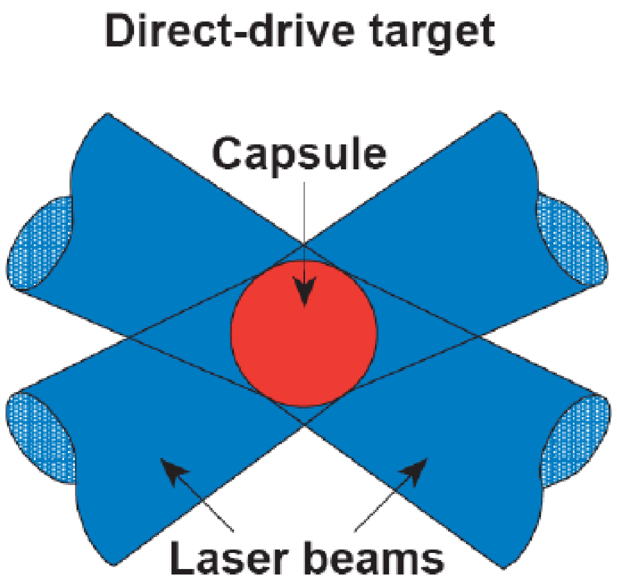
- Atzeni and Meyer-ter-Vehn, "The physics of inertial fusion", Oxford Science Pub
- Betti, ICF lectures, http://www2.me.rochester.edu/courses/ME533/

Next steps for indirect drive on NIF: repeat, optimize pulse shape, lower adiabat, higher convergence, higher areal densities, higher burnup fractions, higher yields

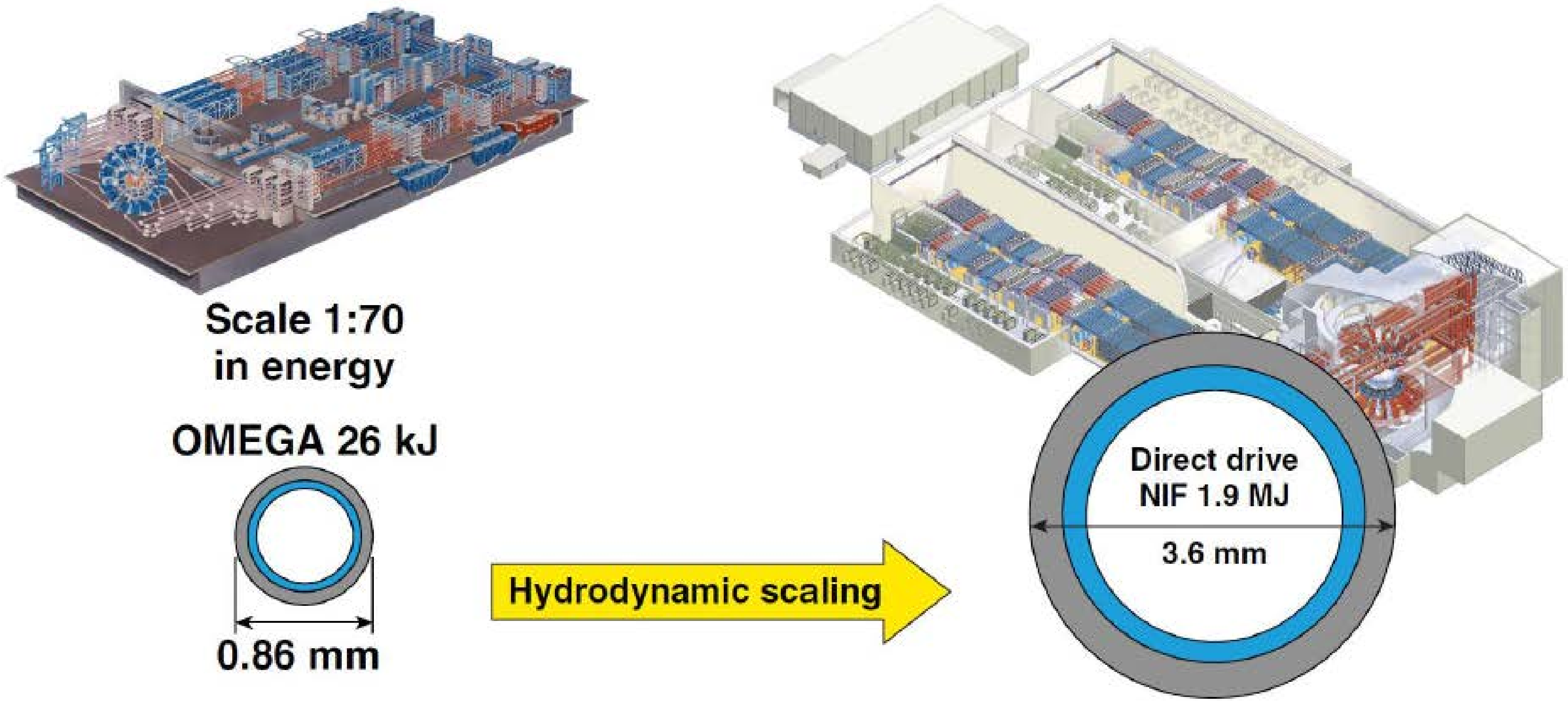


What is the highest yield from indirect drive on current NIF?

Laser Direct Drive on OMEGA



OMEGA experiments are not at ignition scale. An additional complication is the extrapolation of OMEGA results to ignition-relevant NIF energies



R. Nora *et al.*, Phys. Plasmas 21, 056316 (2014);
R. Nora, Ph.D. thesis, University of Rochester, 2015.

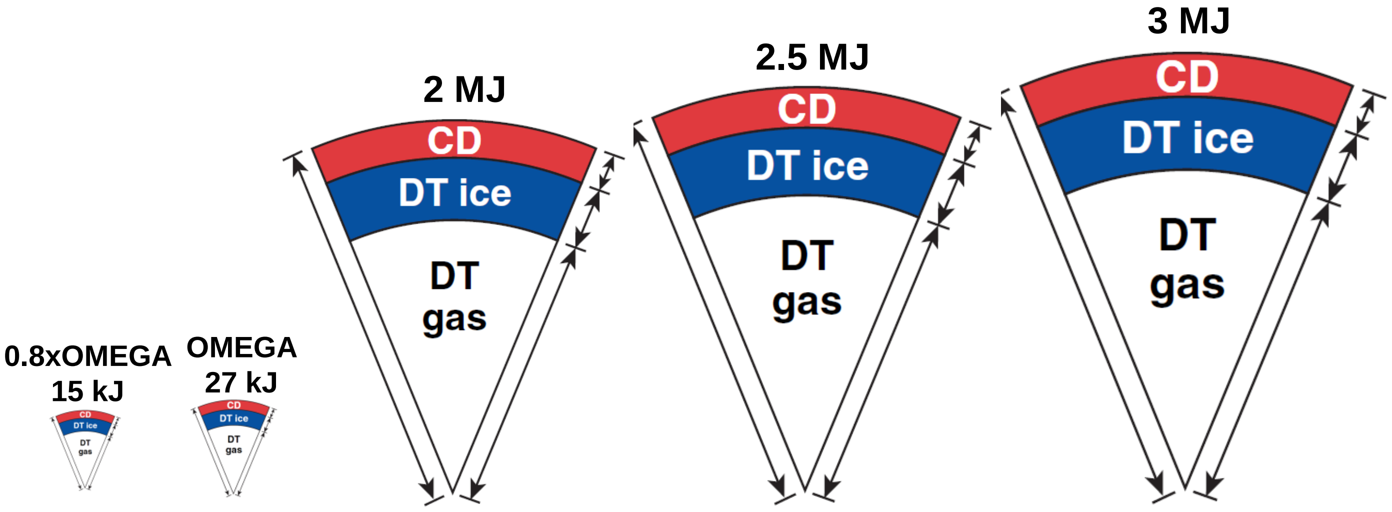
TC13889I

The goal of OMEGA DT cryo campaign is to demonstrate hydro-equivalent ignition at 2MJ of symmetric drive

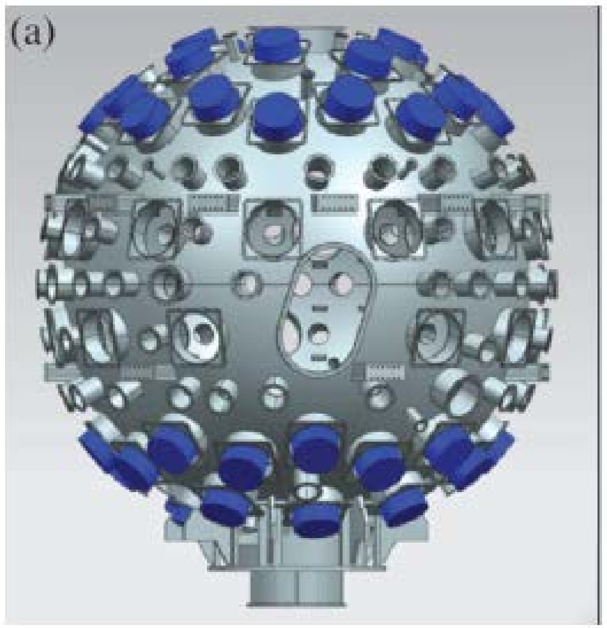
Hydrodynamic scaling does not include important physics such as laser-plasma interactions and the NIF polar geometry

V_{imp} =constant, Pressure=constant, α=constant

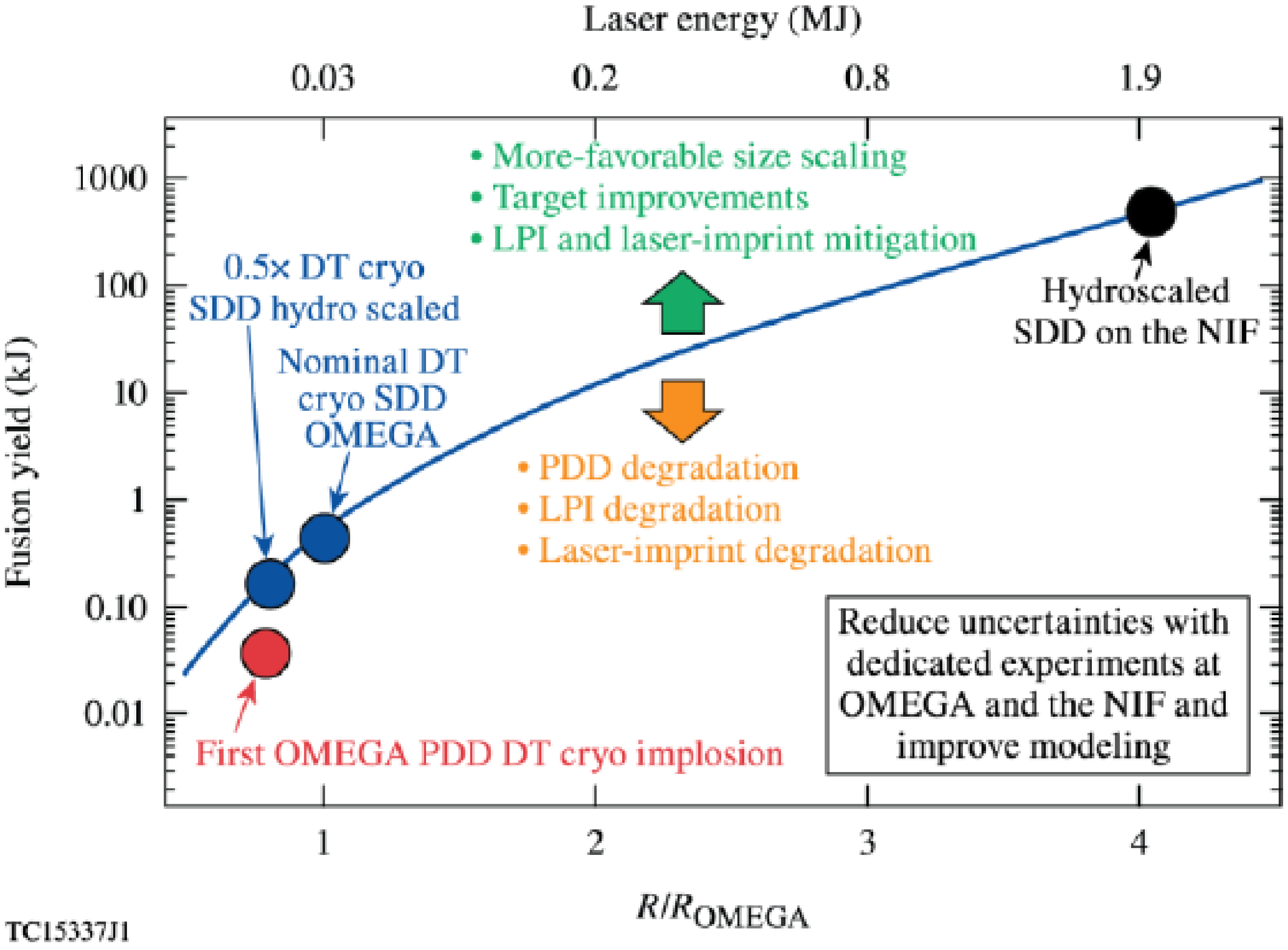
$E_{Laser} \sim R^3$ $Power_{Laser} \sim R^2$ Mass ~ R^3



NIF beam port configuration



Hydrodynamic scaling is insufficient for a reliable extrapolation from OMEGA to NIF. A direct drive experimental campaign is under way on NIF



Current NIF configuration is not optimal for direct drive:

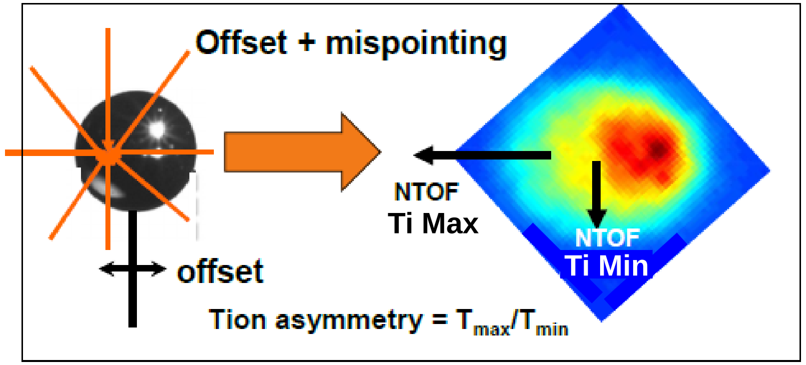
Polar beam configuration

Not enough laser smoothing

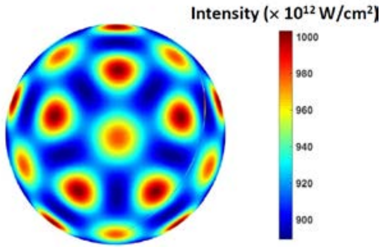
Inadequate phase plates (beam shape)

Direct drive experiments on NIF study laser-plasma instabilities and laser-target energy coupling

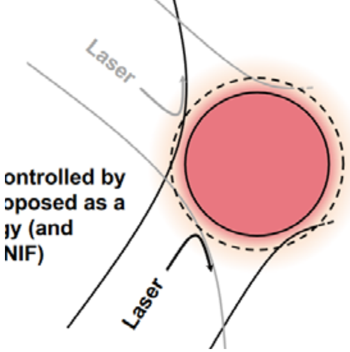
Many factors impact the performance of direct-drive implosions on OMEGA



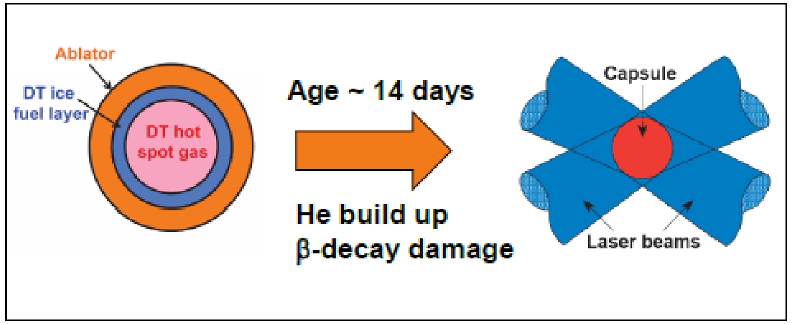
Illumination asymmetry



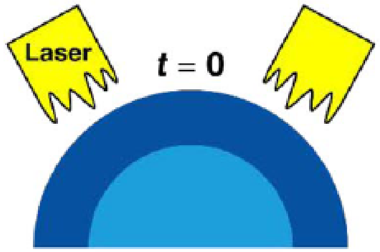
Cross-beam Energy Transfer



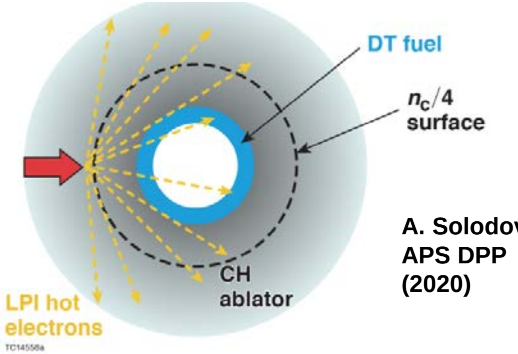
D. Turnbull, APS DPP (2019)



Laser imprinting



Two-plasmon Decay



A. Solodov, APS DPP (2020)

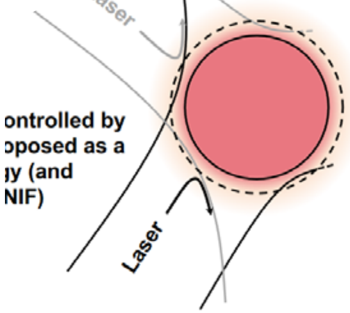
Degradation mechanisms affecting the fusion yield of OMEGA implosions have been quantified through statistical mapping to the experimental data

Yield degradation → $$\text{YOC=Yield-Over-Clean}=\frac{\text{Yield (measured)}}{\text{Yield (1D codes)}}$$

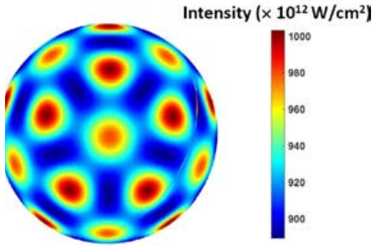
CBET/1D physics? | **Beam mode** | **Short wavelengths** | ℓ=1 | **T-decay**

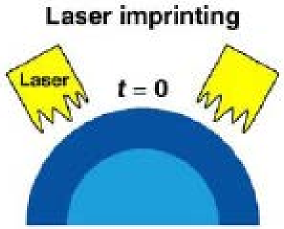
$$YOC\sim\left(\frac{Rb}{Rt}\right)^{b_1} e^{-(b_2+b_3\alpha+b_4CR)\sigma_{rms}^{b_5}}\left(\frac{\alpha_F^{b_6}}{IFAR}\right)^{b_7,b_8} Max\left[\left(\frac{T_{max}}{b_9T_{min}}\right),1\right]^{b_{10}} YOC_{He3}^{b_{11}}YOC_{res}$$

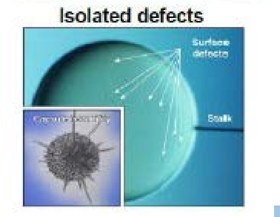
1D coupling (corrections)



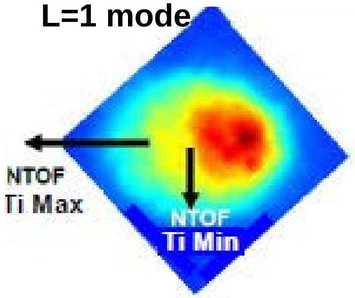
Beam mode

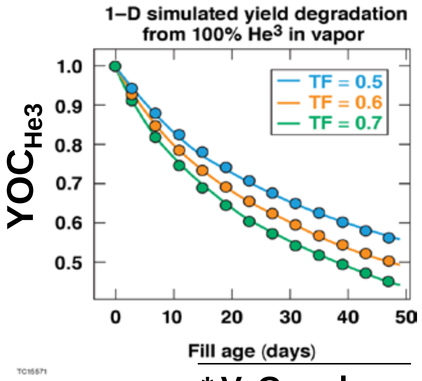






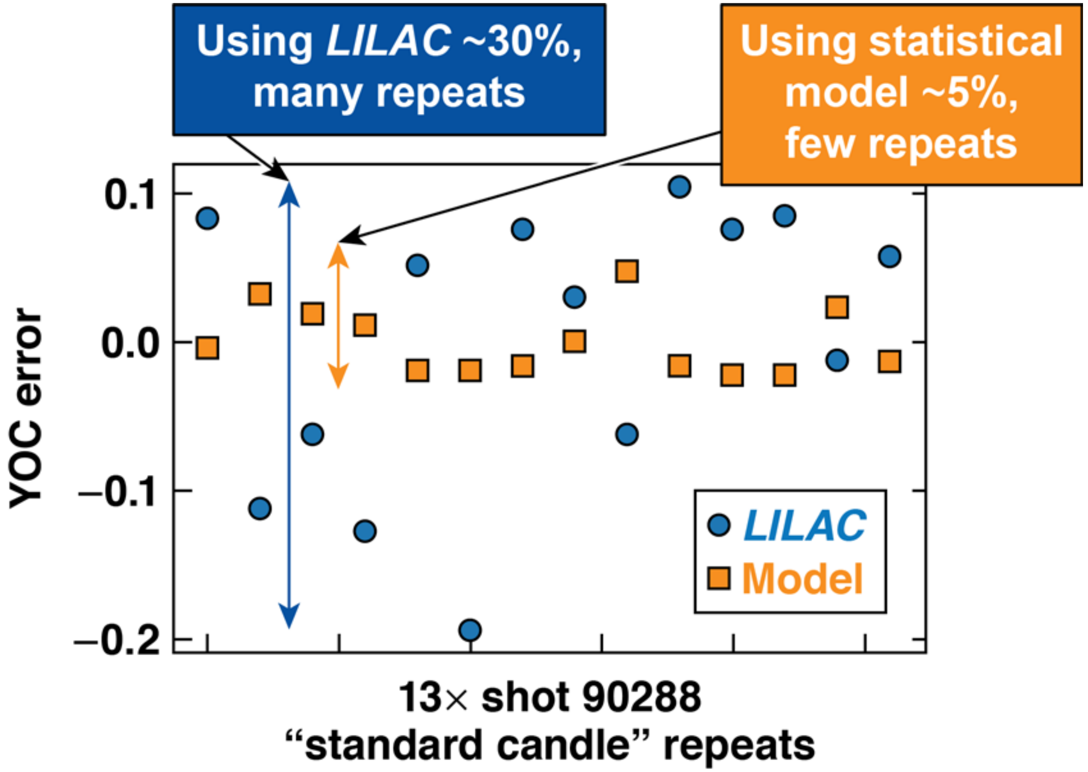
L=1 mode



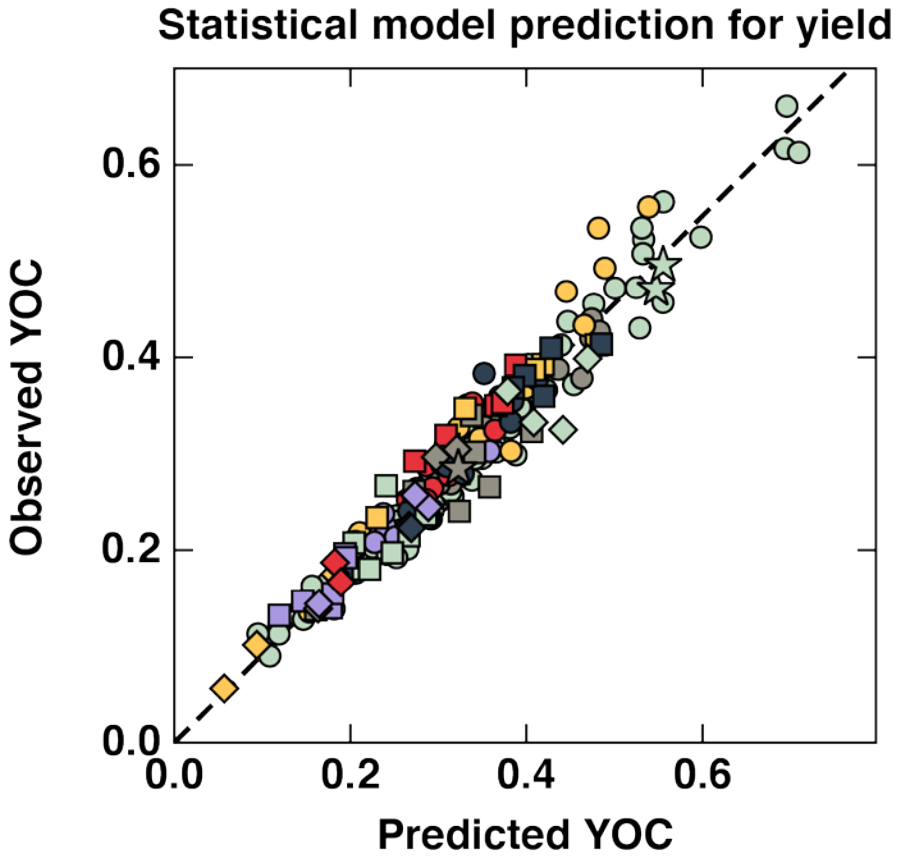


*** V. Gopalaswamy, Nature 565, 581–586 (2019)**
**** A. Lees, Phys. Rev. Lett.127, 105001 (2021)**

Predictive statistical models of the neutron yield are extremely accurate and speed up validation of new designs

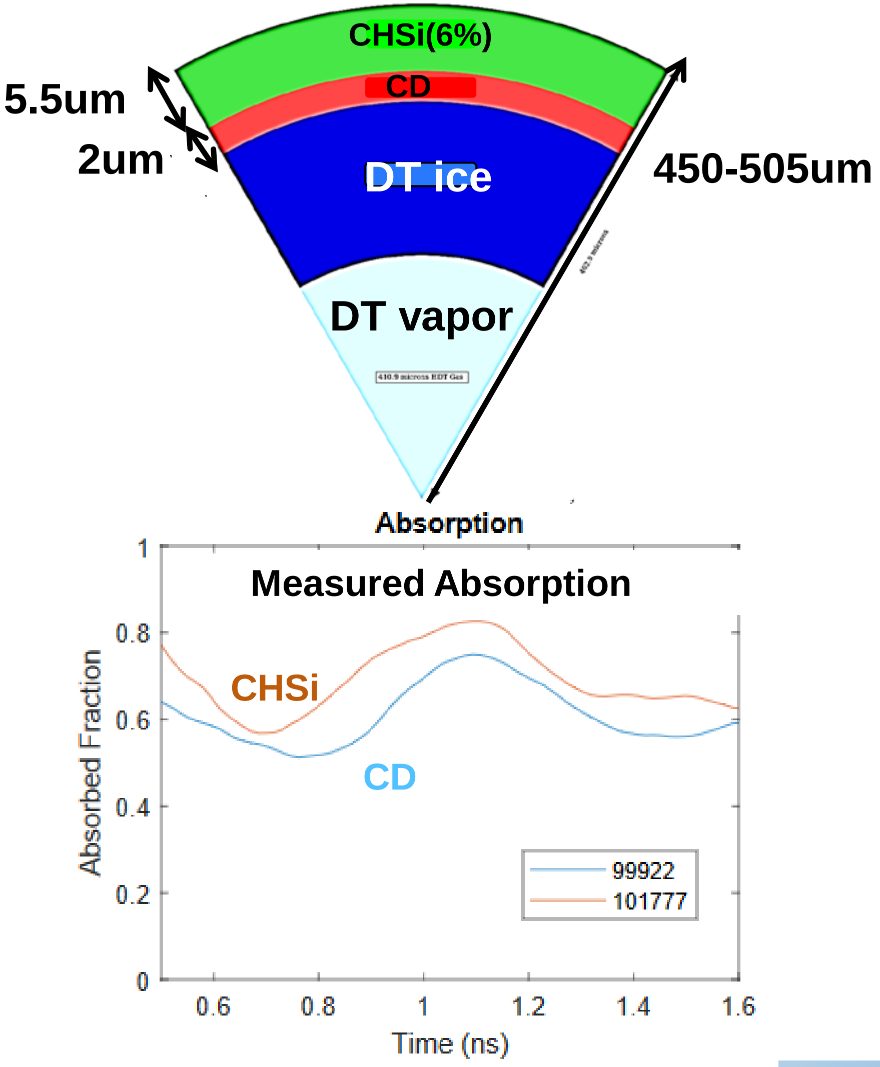


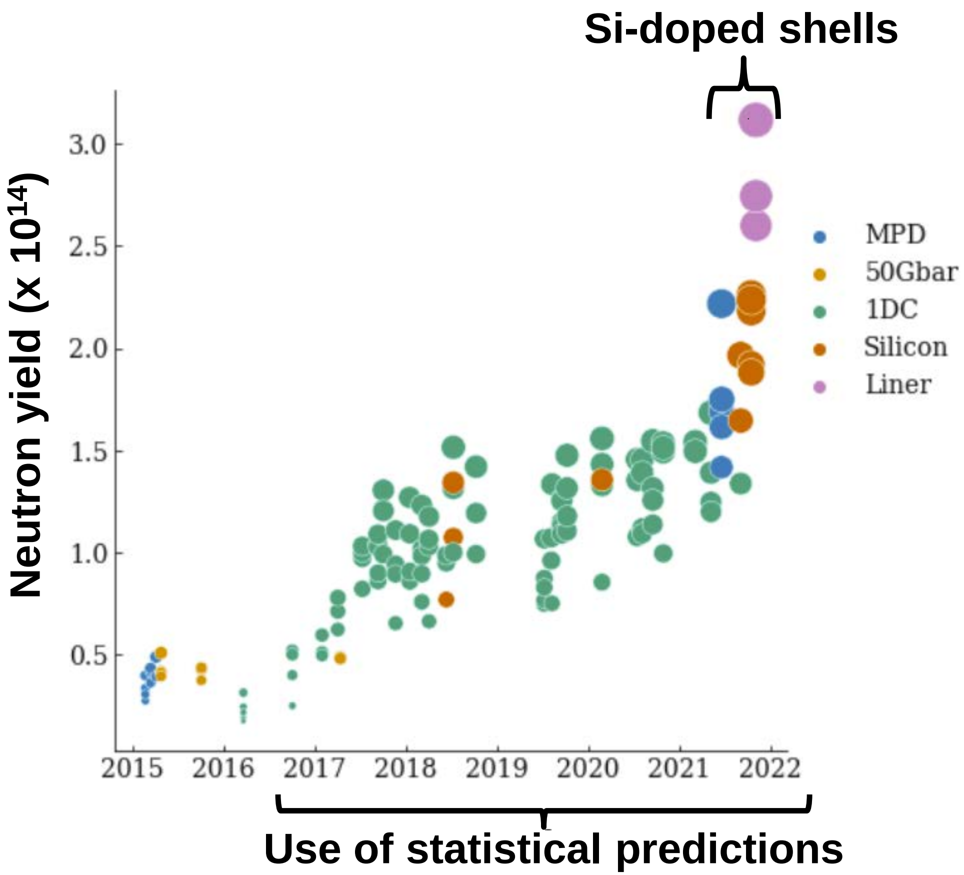
TC15878b



TC15878

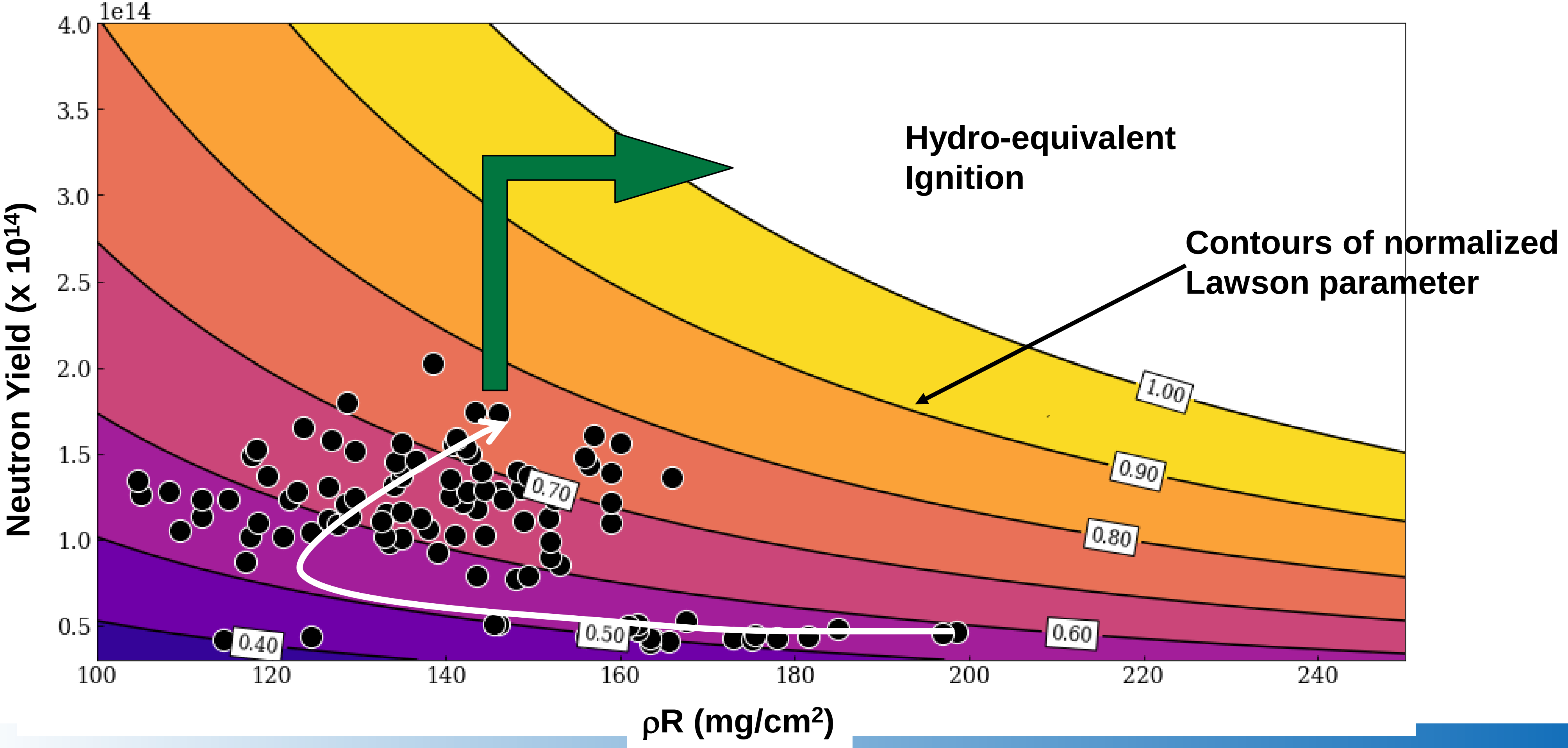
Statistical predictions are used to optimize target specs and laser pulse shapes leading to higher fusion yields



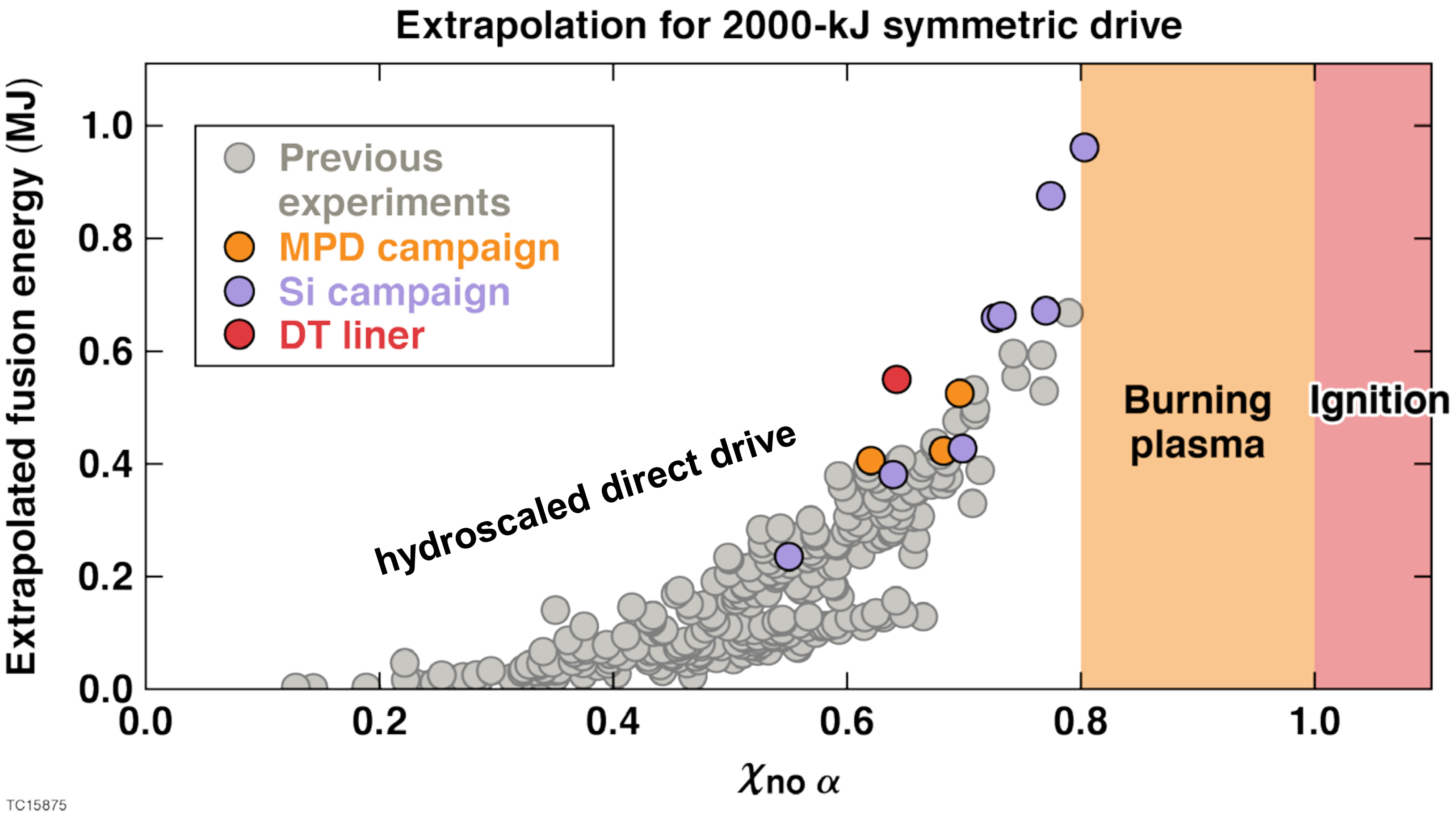


The path to hydro-equivalent ignition on OMEGA requires only a modest increase in both yields and areal densities

Contours of χ_{noa} extrapolated to 2MJ of symmetric drive



Current OMEGA best performing implosions extrapolate to a fusion yield of ~1 MJ at 2 MJ of laser energy and symmetric illumination



Normalized Lawson triple product (noα)

Significant progress has been made in improving implosion performance in both direct and indirect drive ICF

- The path to ignition requires optimization of yields and areal densities

- Indirect drive on NIF has achieved conditions that can be interpreted as thermonuclear ignition

- [ ] Fusion energy output ~ 1.3-1.4 MJ
- [ ] Yield amplification from alpha heating ~ 27x
- [ ] Fusion yield ~ 150x hot spot energy
- [ ] Alpha energy ~ 30x hot spot energy
- [ ] Doubling of temperature from alpha heating

- Direct drive on OMEGA has achieved conditions that hydro-scale to ~1 MJ yield at 2 MJ of symmetric illumination and 80% of the Lawson triple product required for ignition