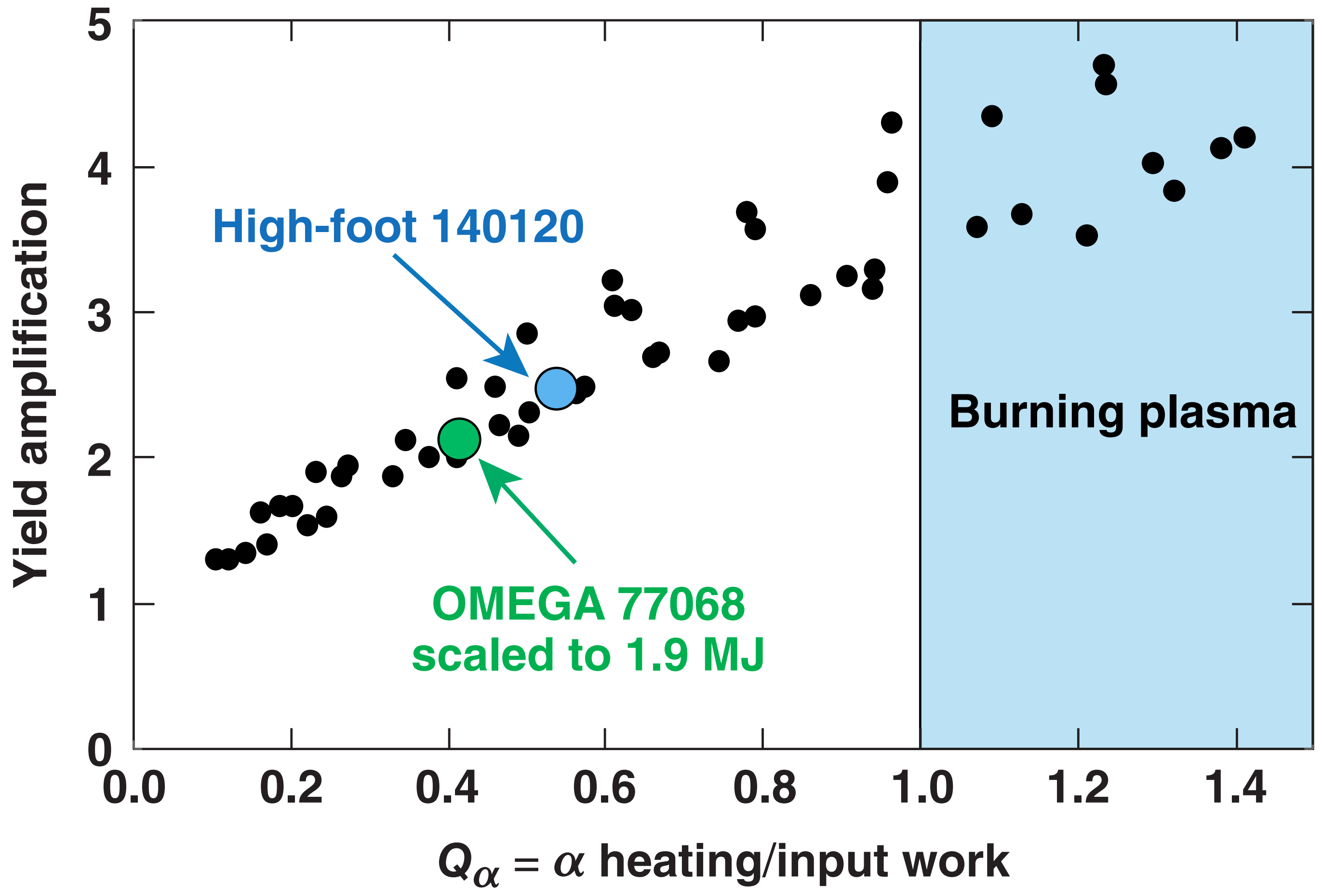
Alpha Heating and Burning Plasmas in Inertial Confinement Fusion



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Summary

The onset of the burning-plasma regime can be identified through experimental observables related to the yield amplification from α heating

- The fundamental parameter characterizing burning plasmas is $Q_\alpha = \alpha$ heating / PdV work
- Current high-foot (HF)* implosions at the National Ignition Facility (NIF) have achieved $Q_\alpha^{hs} \approx 0.5$ to 0.6 with a yield amplification, caused by α heating, of about 2.3× at 1.9-MJ laser energy
- For a high-foot-like* target, the onset of the burning-plasma regime in the hot spot $(Q_\alpha^{hs} = 1)$ requires ~50 kJ of fusion energy
- Hydro-equivalent** extrapolations of direct-drive OMEGA implosions to 1.9-MJ symmetric illumination indicate performance similar to indirect drive with a yield amplification of about 2× and over 100 kJ of fusion energy

*O. A. Hurricane *et al*., Nature 506, 343 (2014).
**R. Nora *et al.*, Phys. Plasmas 21, 056316 (2014).

TC12264a

Collaborators

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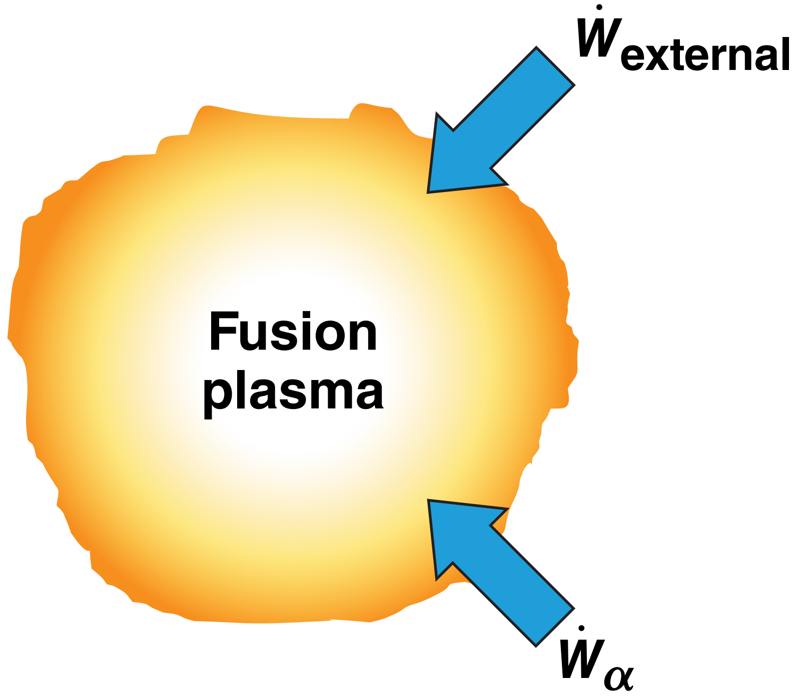
Outline

- Defining burning plasmas and α heating
- Inferring burning plasma regimes in inertial confinement fusion (ICF)
- α heating in indirect drive on the NIF
- Extrapolation of OMEGA implosions to symmetric direct drive on the NIF

In a burning plasma, α heating is the dominant power input to the fusion plasma



$$Q_{\alpha} \equiv \frac{\dot{W}_{\alpha}}{\dot{W}_{\text{ext}}}$$

Burning plasmas
$Q_{\alpha} > 1$

Steady-state energy balance with power input

External input → $$\dot{W}_{\text{ext}} + C_{\alpha} P^2 V = \frac{3}{2} \frac{P}{\tau} V$$ ← Energy losses

$\dot{W}_{\alpha} = \alpha$ heating for $\langle \sigma v \rangle \sim T^2$

J. P. Freidberg, *Plasma Physics and Fusion Energy* (Cambridge University Press, Cambridge, England, 2007).

TC12284b

The yield amplification caused by α heating depends exclusively on Q_α

Pressure with α from the power balance

$$\dot{W}_{ext}(1+Q_\alpha) = \frac{3/2\ PV}{\tau_{ICF}} \qquad \tau_{ICF} \sim \frac{1}{\sqrt{P}} \qquad P_\alpha \sim \left[\frac{\dot{W}_{ext}}{V}(1+Q_\alpha)\right]^{2/3}$$

Pressure without α from the power balance

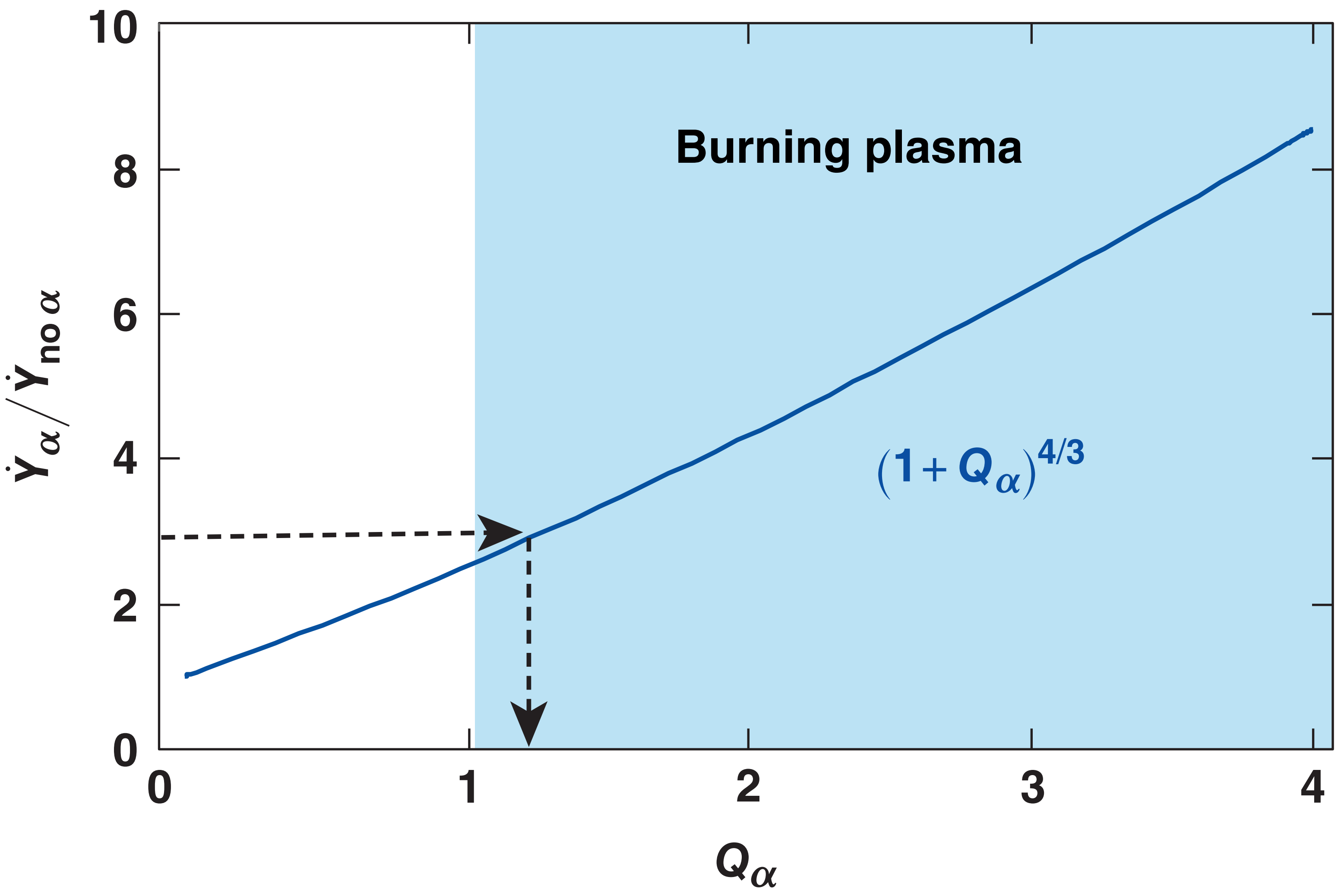
$$P_{no\ \alpha} \sim \left(\frac{\dot{W}_{ext}}{V}\right)^{2/3}$$

Yield amplification is a unique function of Q_α

$$\frac{\dot{Y}_\alpha}{\dot{Y}_{no\ \alpha}} = \left(\frac{P_\alpha}{P_{no\ \alpha}}\right)^2 = (1+Q_\alpha)^{4/3}$$

TC12286b

If the yield amplification Y_{amp} is known, Q_α is determined from the Y_{amp}–Q_α plot



TC12591

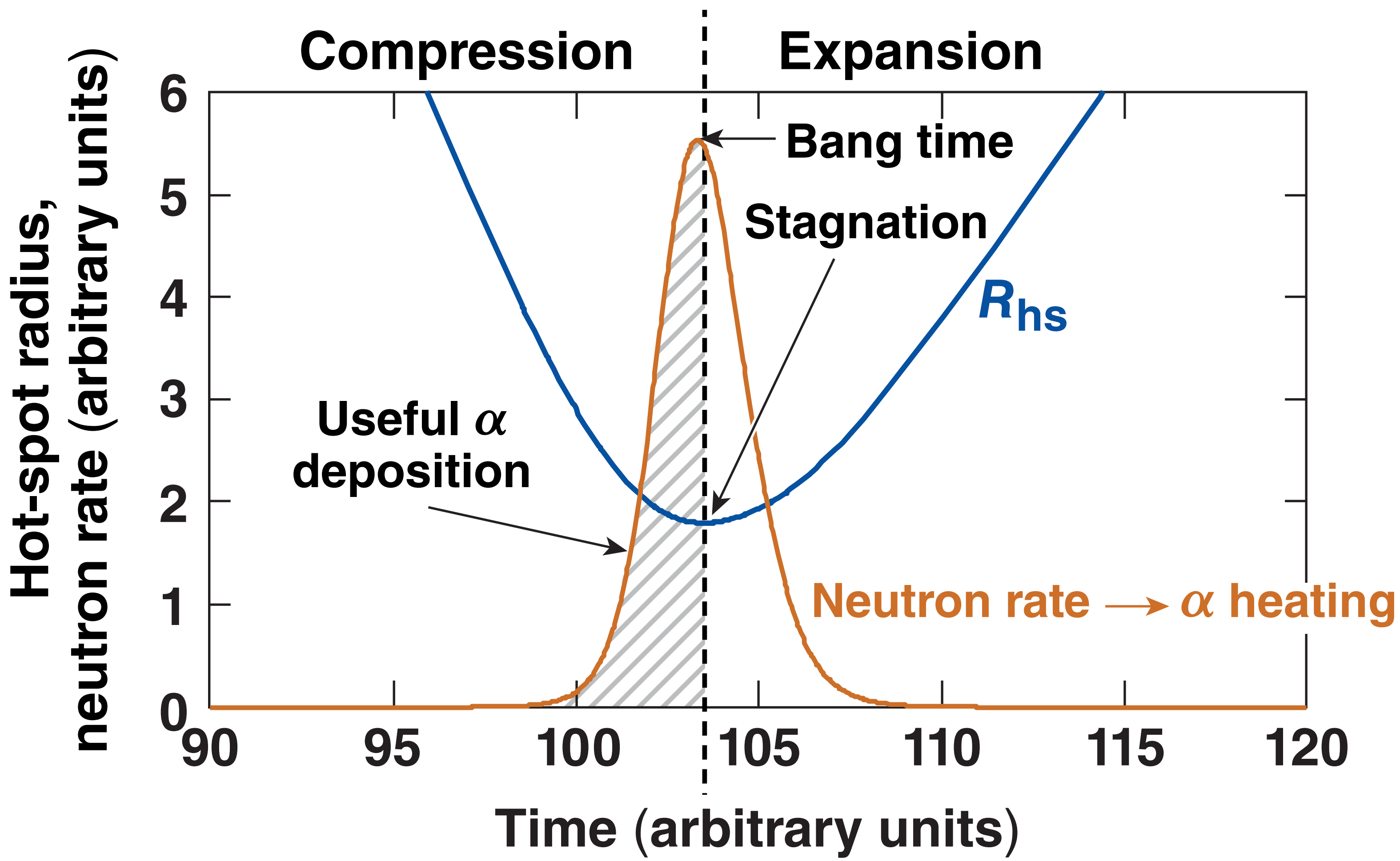
The definition of Q_α is modified to capture the transient character of ICF implosions

Steady state: $$Q_\alpha = \frac{\dot{W}_\alpha}{\dot{W}_{ext}}$$

ICF definition: $$Q_\alpha^{hs} = \frac{\dfrac{E_\alpha}{2\tau_E}}{\dfrac{PdV_{hs}}{\tau_E}} = \frac{\frac{1}{2}E_\alpha}{PdV_{hs}}$$

- PdV_{hs} = input energy delivered to the hot spot caused by compression
- τ_E = ICF energy confinement time
- E_α = total α energy produced

Only the α energy deposition during hot-spot compression should be included when determining Q_α

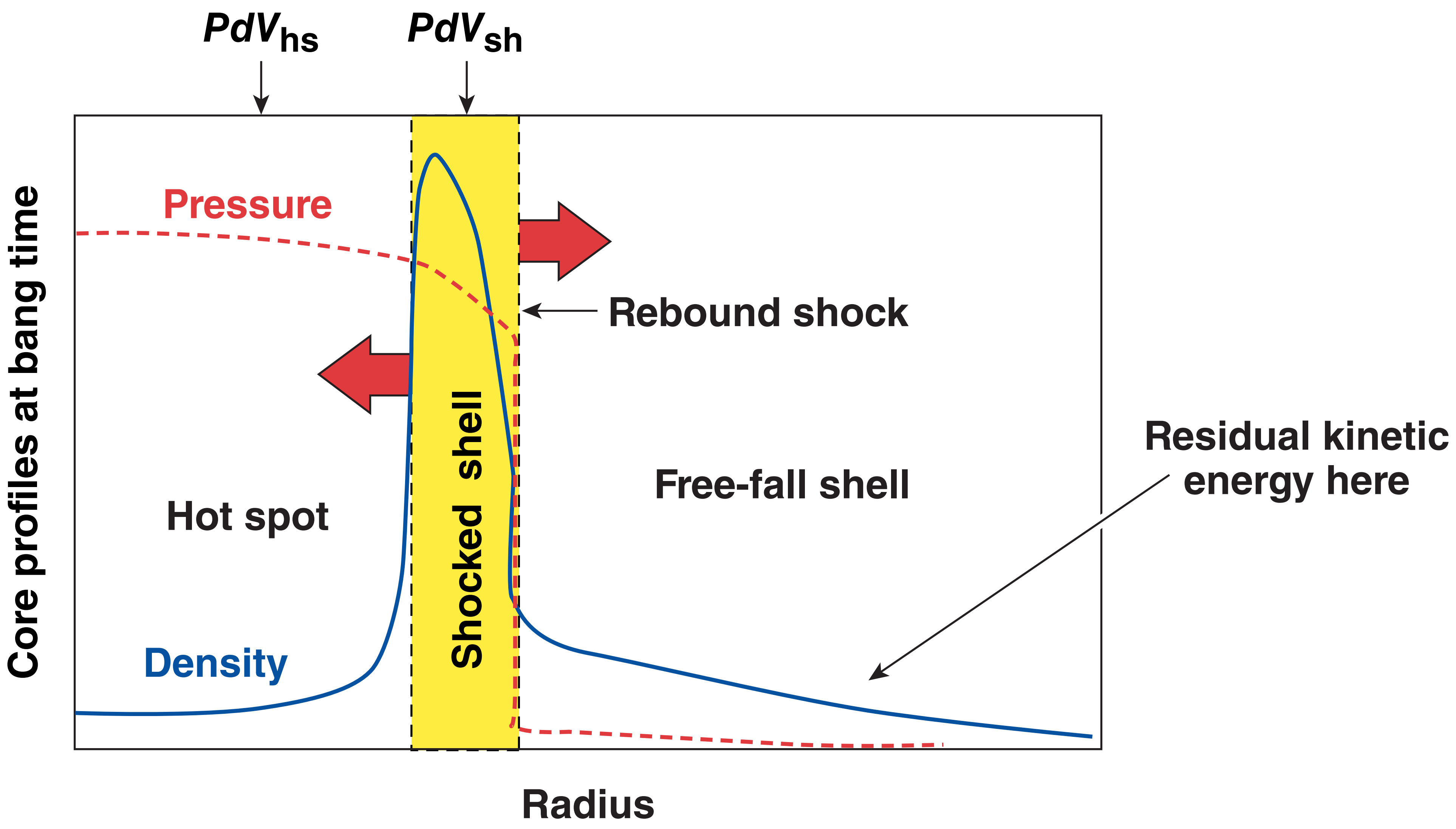


$$Q_\alpha^{hs} = \frac{1/2\, E_\alpha}{PdV_{hs}}$$

Hot spot Q_α

TC12288a

In ICF the input energy is distributed between the hot spot and the shell



TC12290a

Two burning-plasma regimes are identified:
α heating exceeds *PdV* work to the hot spot
α heating exceeds *PdV* to hot spot + shell

Hot spot Q_α

$$Q_\alpha^{hs} = \frac{\frac{1}{2} E_\alpha}{\left| PdV_{hs} \right|}$$

- First burning-plasma regime

$$Q_\alpha^{hs} \geq 1$$

Total Q_α

$$Q_\alpha^{tot} = \frac{\frac{1}{2} E_\alpha}{\left| PdV_{hs} \right| + \left| PdV_{sh} \right|}$$

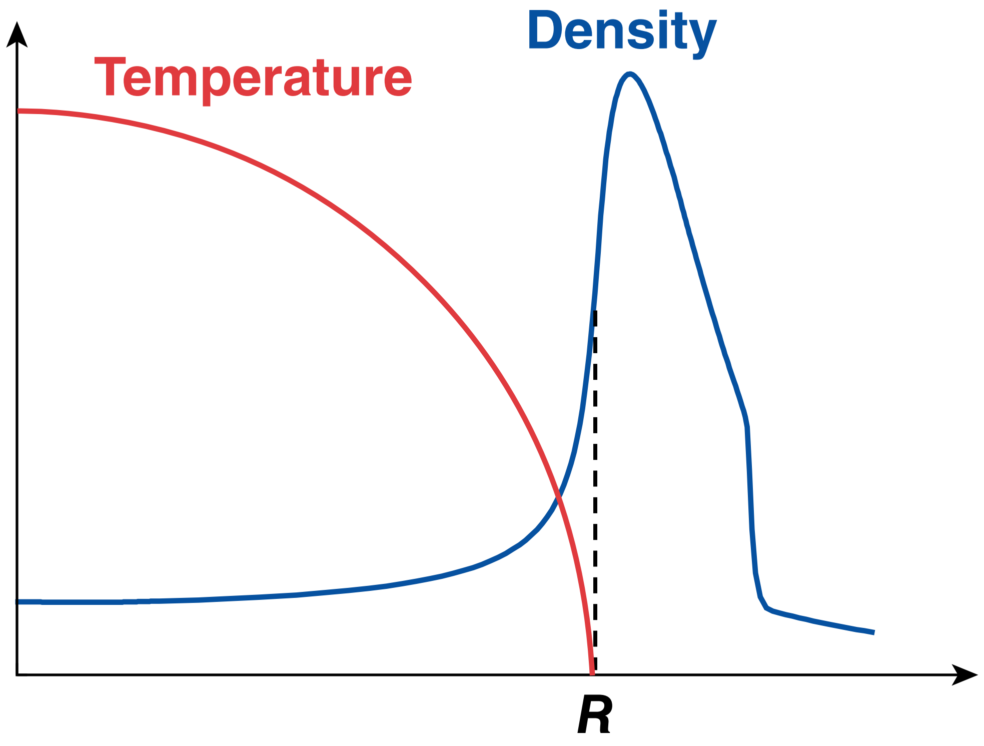
- Second burning-plasma regime

$$Q_\alpha^{tot} \geq 1$$

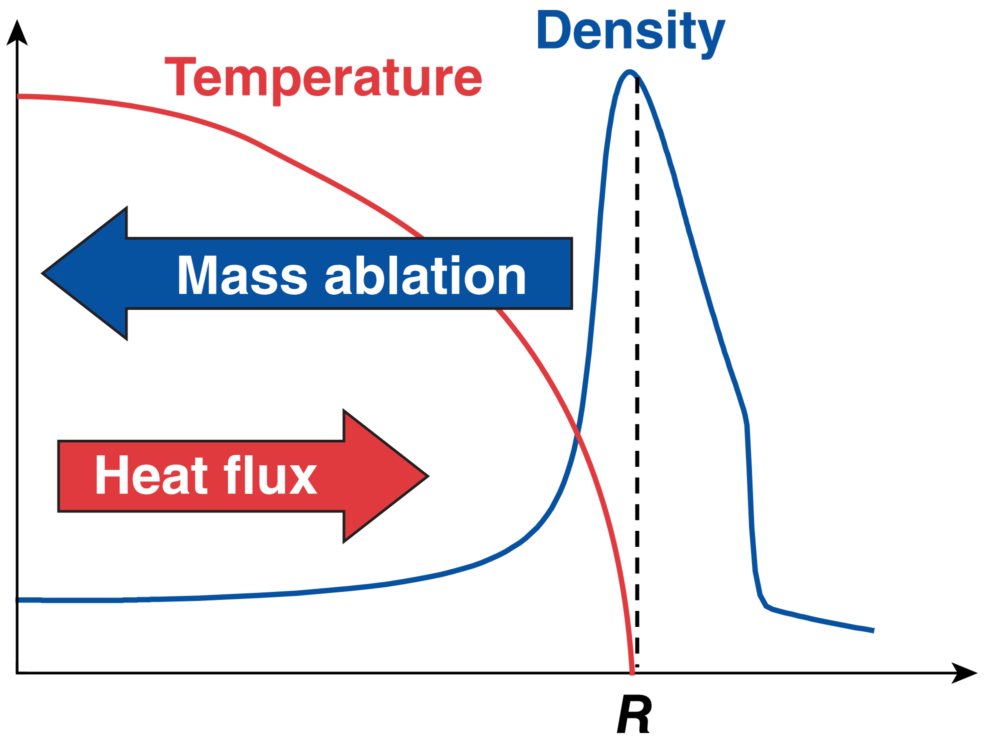
TC12289b

In simulations the *PdV* work is calculated by considering a fixed mass enclosed by the hot-spot volume at peak neutron production

- Hot-spot mass defined at peak neutron-production time



- Hot-spot mass traced back in time before peak neutron production



$$M_{hs}(t) = \int_0^{R(t)} 4\pi r^2 \rho dr = \text{constant} = \text{hot-spot mass at bang time}$$

TC12593

The *PdV* work delivered to the hot spot can be exactly calculated in 1-D

Hot-spot *PdV* work up to stagnation: $PdV_{hs} = \int_0^{t_{stag}} 4\pi P R^2 \dot{R} dt$

Valid in the presence of ablation driven by heat conduction, α heating, and radiation for a Lagrangian mass

$$M_{hs}(t) = \int_0^{R(t)} 4\pi r^2 \rho dr = \text{constant} = \text{hot-spot mass at bang time}$$

TC12594

In experiments and multidimensional simulations, the bang-time *PdV* work can be estimated from the hot-spot energy balance

Hot-spot energy balance at bang time

$$\frac{3}{2}PV \approx PdV_{hs} + \frac{E_{\alpha}}{2} - \frac{E_{rad}}{2}$$

- $\frac{3}{2}PV$: **Hot-spot internal energy**
- PdV_{hs}: ***PdV* work done on hot spot up to bang time**
- $\frac{E_{\alpha}}{2}$: **α heating**
- $\frac{E_{rad}}{2}$: **Radiation losses**

TC12595

Experimental observables are used to infer hot-spot energy, α energy, and radiation losses

Hot-spot energy from burnwidth, neutron yield, T_i, and self-emission

$$Y_N \approx \frac{P^2}{16}\frac{\langle \sigma v \rangle}{T^2} V_{hs}\tau \quad \Rightarrow \quad \frac{3}{2}PV \approx \sqrt{\frac{36 Y_N T^2 V_{hs}}{\langle \sigma v \rangle \tau}}$$

τ : from neutron or x-ray burnwidth
T : from neutron time of flight
V_{hs} : from size of x-ray self-emission image

α energy from neutron yield

$$E_\alpha = (3.5\ \text{MeV})\, Y_N$$

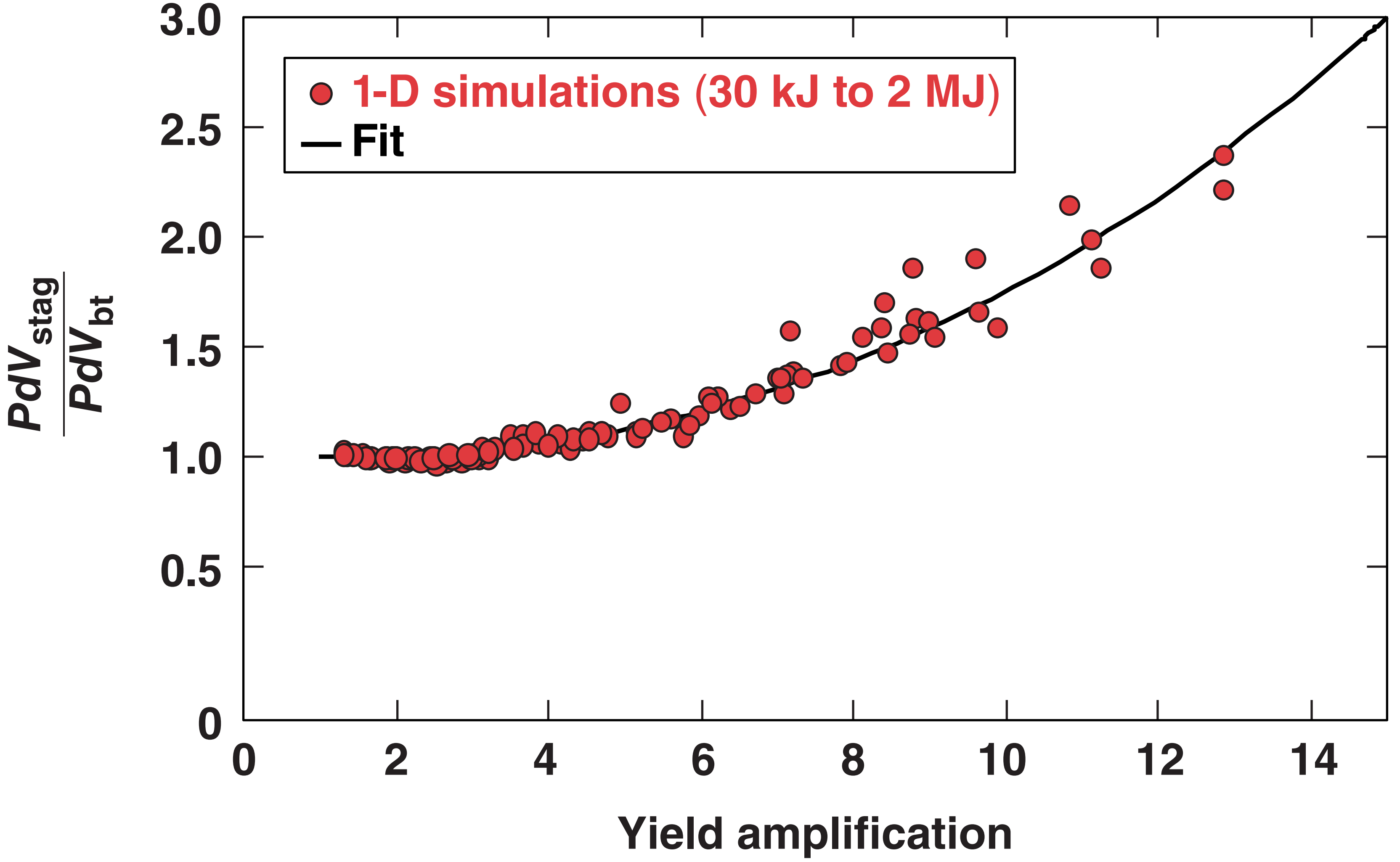
Radiation losses from α energy and temperature

$$E_{rad} \approx E_\alpha \cdot \left(\frac{3.8\ \text{keV}}{T_i}\right)^{2.8}$$

C. Cerjan, P. T. Springer, and S. M. Sepke, Phys. Plasmas 20, 056319 (2013).

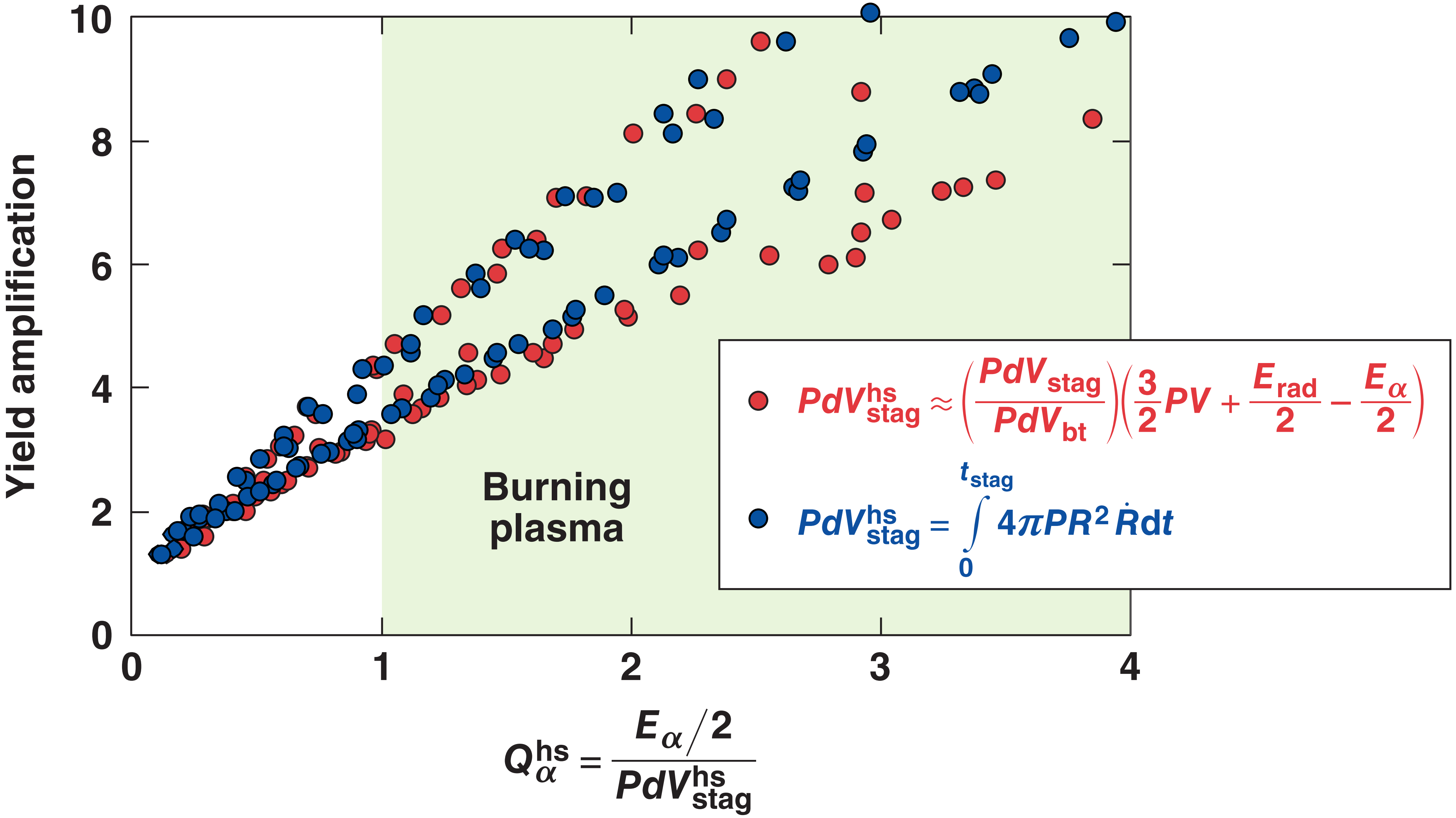
TC12596

The bang-time *PdV* is less than the stagnation *PdV* because of the rapid expansion of the hot spot at large-yield amplifications



TC12642

The yield amplification from simulations (30-kJ to 2-MJ energy) using both ways of calculating *PdV* is strongly correlated with Q_α



TC12597a

The physics of the hot-spot formation and shell deceleration depends on three dimensionless parameters

$$\chi_\alpha \equiv \frac{P\tau}{24\,T^2/\varepsilon_\alpha\langle\sigma v\rangle} = \frac{E_\alpha}{E_{hs}}$$ Lawson parameter (α heating)

$$\beta_{rad} \equiv \frac{E_{rad}}{E_{hs}}$$ Radiation losses

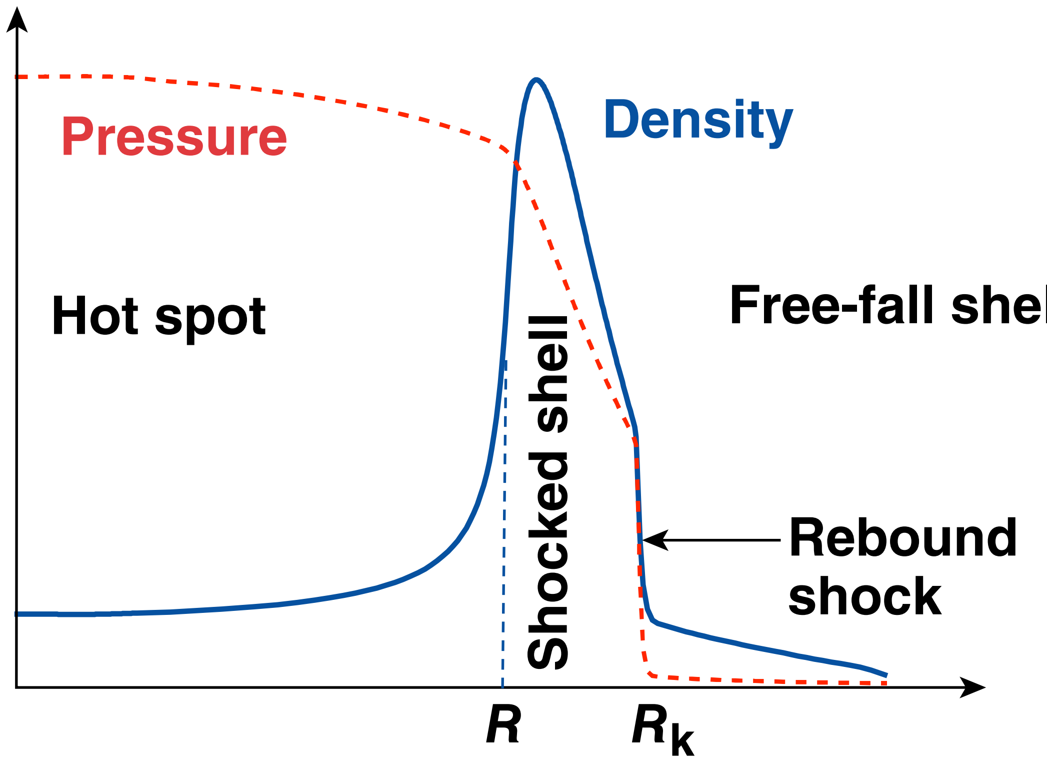
$$A_{sh}^{dec} = \frac{R_{hs}(t_{dec})}{\Delta(t_{dec})}$$ Aspect ratio at beginning of deceleration

$$\text{Mach} \equiv \frac{V_i}{C_s^{hs}}$$ Shell Mach number

P. Y. Chang *et al.*, Phys. Rev. Lett. 104, 135002 (2010);
R. Betti *et al.*, Phys. Plasmas 17, 058102 (2010);
J. Lindl *et al.*, Phys. Plasmas 21, 129902(E) (2014).

The second burning-plasma regime requires calculating the total *PdV* to the hot spot and shell

$$Q_\alpha^{tot} = \frac{0.5\,E_\alpha}{PdV_{hs} + PdV_{sh}}$$

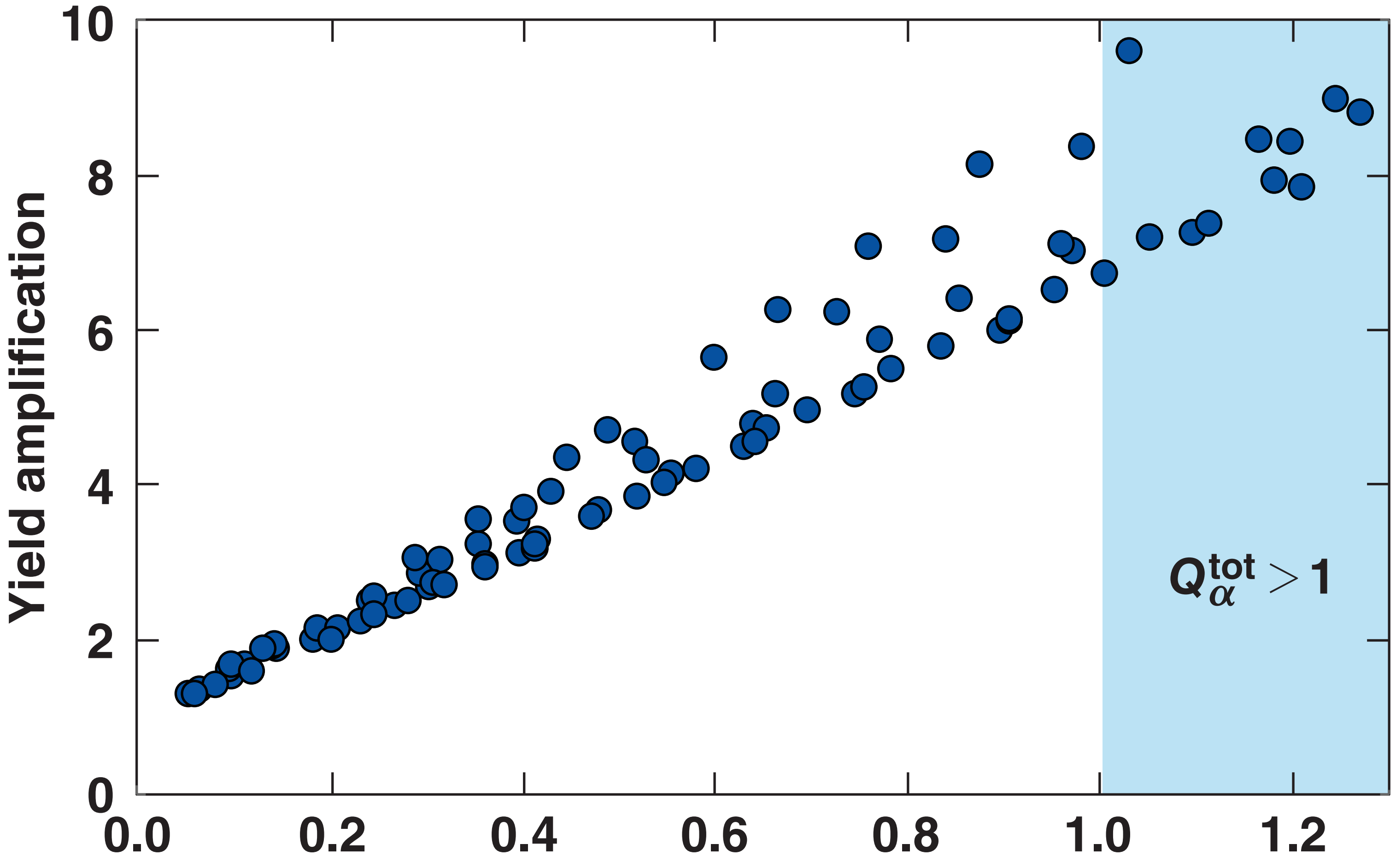


Valid in 3-D

$$\text{Total } PdV \text{ work} = PdV_{hs} + PdV_{sh} = -\int_0^{t_{bang}} 4\pi P R_k^2 \dot{R}_k\, dt = KE_{max} - KE_{bt}$$

TC12598

The yield amplification from simulations (30-kJ to 2-MJ energy) is strongly correlated with Q_α^{tot}



$$Q_\alpha^{tot} = \frac{0.5\, E_\alpha}{KE_{max} - KE_{bt}}$$

TC12599a

The yield amplification is mostly a function of the measurable Lawson parameter χ_α

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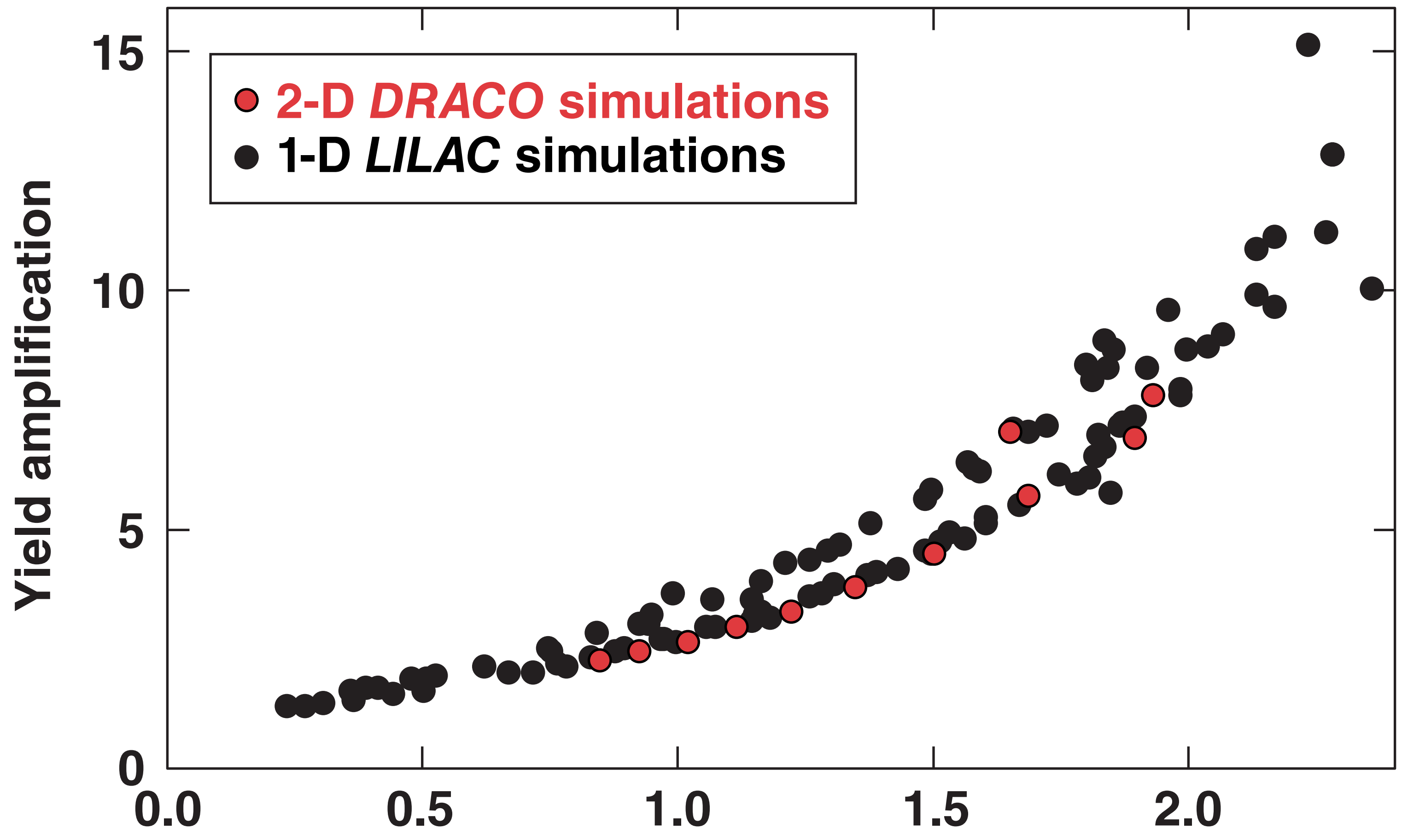


$$\chi_\alpha = \frac{E_\alpha}{E_{hs}}$$

TC12601

J. Lindl *et al.*, Phys. Plasmas 21, 129902(E) (2014).

In the indirect-drive high-foot shot 140120, α heating caused a yield amplification of about 2.3×

$\langle P \rangle \approx 170$ Gbar

$\langle T \rangle \approx 5$ keV

$R_{hs} \approx 35\ \mu m$

$\tau_{burn} \approx 161$ ps

$E_{hs} \approx 4.6$ kJ

$E_{\alpha} \approx 5.2$ kJ

$E_{fusion} \approx 26$ kJ

$$\chi_{\alpha} = \frac{E_{\alpha}}{E_{hs}} \approx 1.1$$

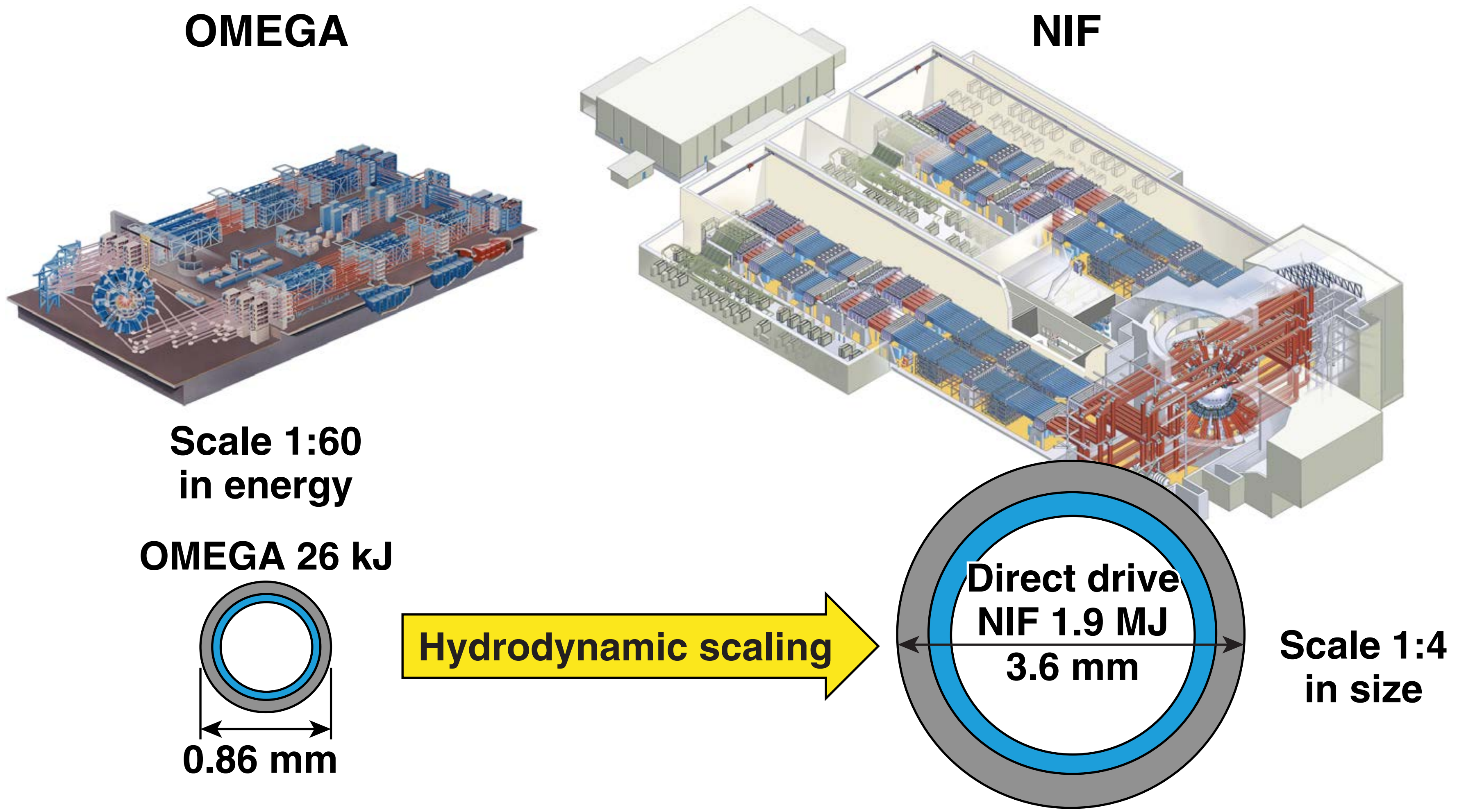
$$\frac{Y_{\alpha}}{Y_{no\ \alpha}} \approx 2.3$$

$$Q_{\alpha}^{hs} \approx 0.55$$

P. K. Patel, Lawrence Livermore National Laboratory, private communication (2014);
T. Döppner *et al*., Phys. Rev. Lett. 115, 055001 (2015).

TC12298a

Hydrodynamic equivalence provides a tool to scale the performance of OMEGA direct-drive implosions to NIF energies for symmetric illumination



Hydrodynamic scaling does *not* account for differences in laser–plasma interactions between OMEGA and the NIF.

TC12300a

Three-dimensional theory by R. Nora *et al*., Phys. Plasmas 21, 056316 (2014).

The hydrodynamic scaling leads to equal pressures at stagnation

- In-flight scaling: $V_{imp} \sim$ const $\alpha \sim$ const RT * growth factors $\sim$ const

  $R \sim E_L^{1/3}$ $P_L \sim E_L^{2/3}$ $\tau_{pulse} \sim E_L^{1/3}$

In the absence of α heating:

- Stagnation scaling: $P \sim$ const $T \sim R^{0.2}$ $V_{hs} \sim R^3$

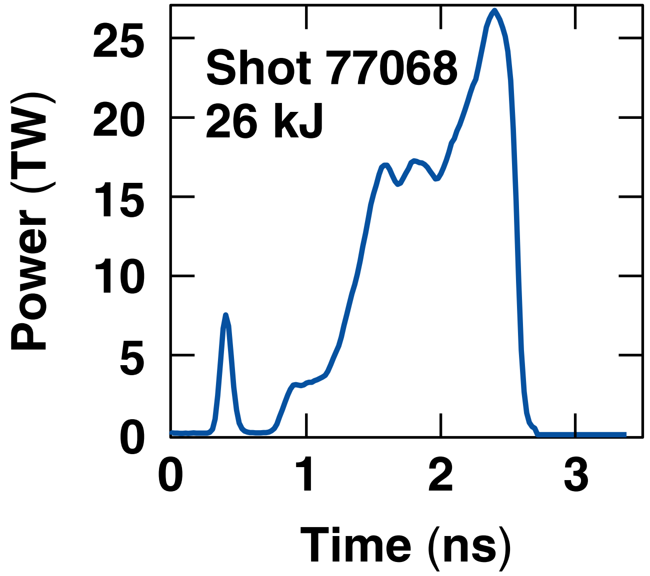
  $\tau_{burn} \sim R$ $\rho R_{tot} \sim R$

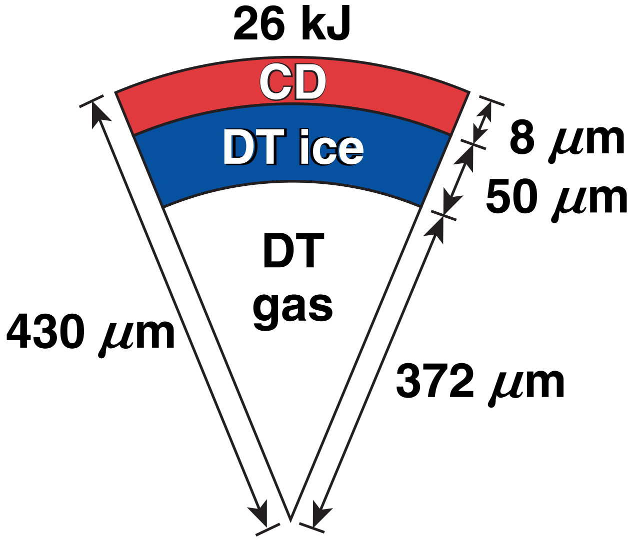
From 26 kJ to 1.9 MJ → P is the same; R, τ_{burn}, ρR are up 4×, and T is up 30%.

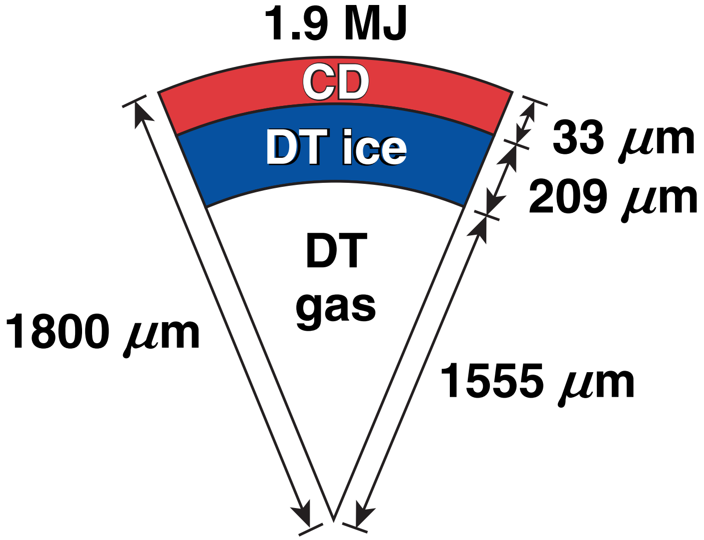
TC10975c

*RT = Rayleigh–Taylor

The best-performing OMEGA implosion is readily scaled up to NIF energies



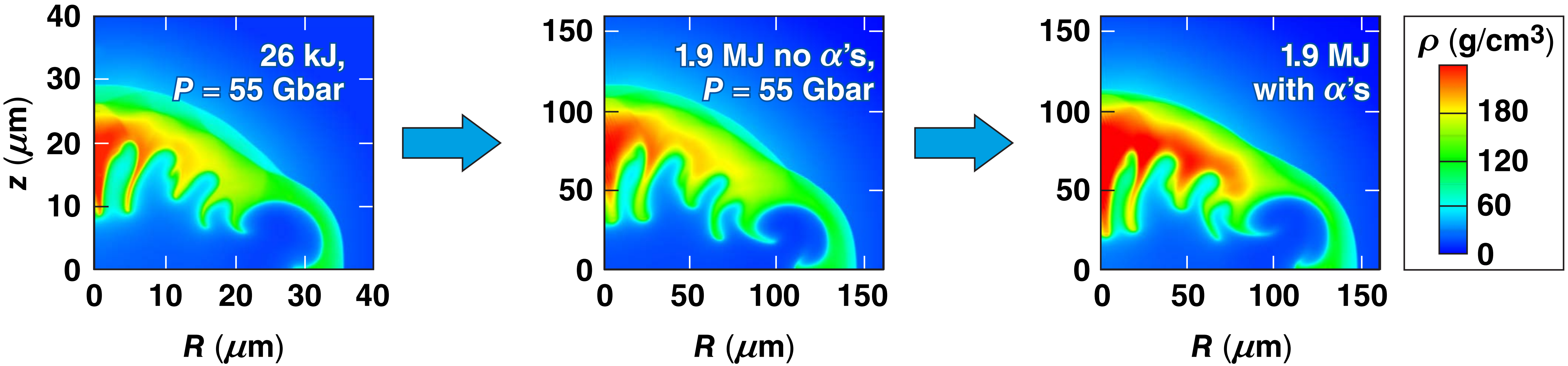




Observable	Experiment	1-D simulation
Yield	5.3×10^{13}	1.7×10^{14}
P (Gbar)	56 (±7)	97
T_i (keV)	3.6 (±0.3)	3.82
R_{hs} (μm)	22 (±1)	22
Burnwidth (ps)	66 (±10)	61
ρR (g/cm^2)	0.198 (±0.018)	0.211

A multimode ice perturbation is used to degrade the target performance to reproduce the OMEGA experiment; the same perturbation is applied to the 1.9-MJ target

Density at bang time



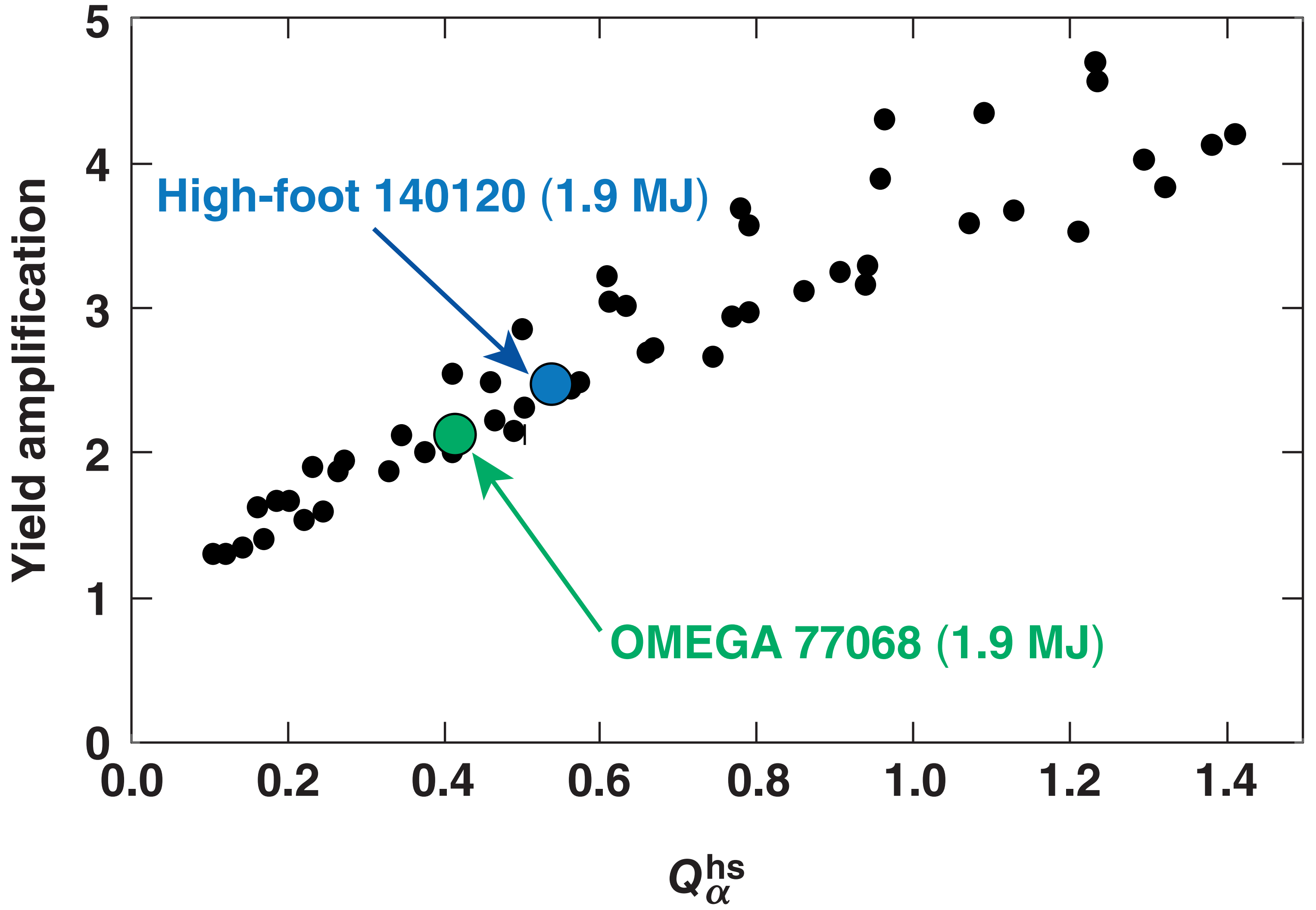
Yield with α's = 125 kJ
Yield no α's = 63 kJ

$$\frac{Y_{\alpha}^{1.9\,\text{MJ}}}{Y_{\text{no}\,\alpha}^{1.9\,\text{MJ}}} \approx 2$$

A. Bose *et al*., GO5.00004, this conference;
K. M. Woo *et al*., GO5.00003, this conference.

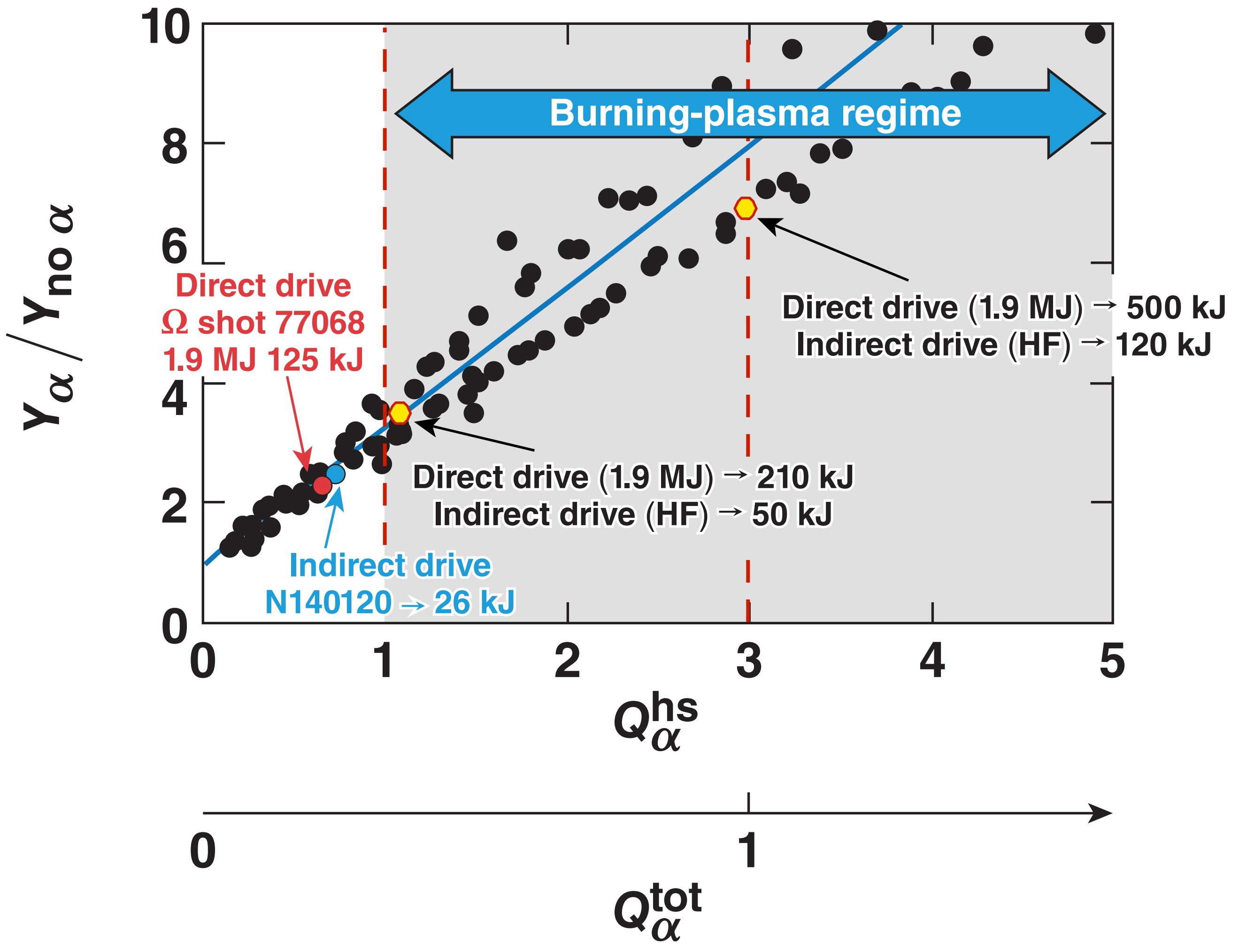
TC12590

OMEGA shot 77068 scaled up to 1.9 MJ achieves a yield enhancement of $\approx 2\times$ and $Q_\alpha \approx 0.4$



TC12602

Access to the burning-plasma regime requires about 50 kJ of HF targets in indirect drive and about 200 kJ of fusion energy for direct drive



Both direct and indirect drive must double the yield amplification to access the burning-plasma regime.

TC12302c

Summary/Conclusions

The onset of the burning-plasma regime can be identified through experimental observables related to the yield amplification from α heating

- The fundamental parameter characterizing burning plasmas is $Q_\alpha = \alpha$ heating / PdV work
- Current high-foot (HF)* implosions at the National Ignition Facility (NIF) have achieved $Q_\alpha^{hs} \approx 0.5$ to 0.6 with a yield amplification, caused by α heating, of about 2.3× at 1.9-MJ laser energy
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*O. A. Hurricane *et al.*, Nature 506, 343 (2014).
**R. Nora *et al.*, Phys. Plasmas 21, 056316 (2014).

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