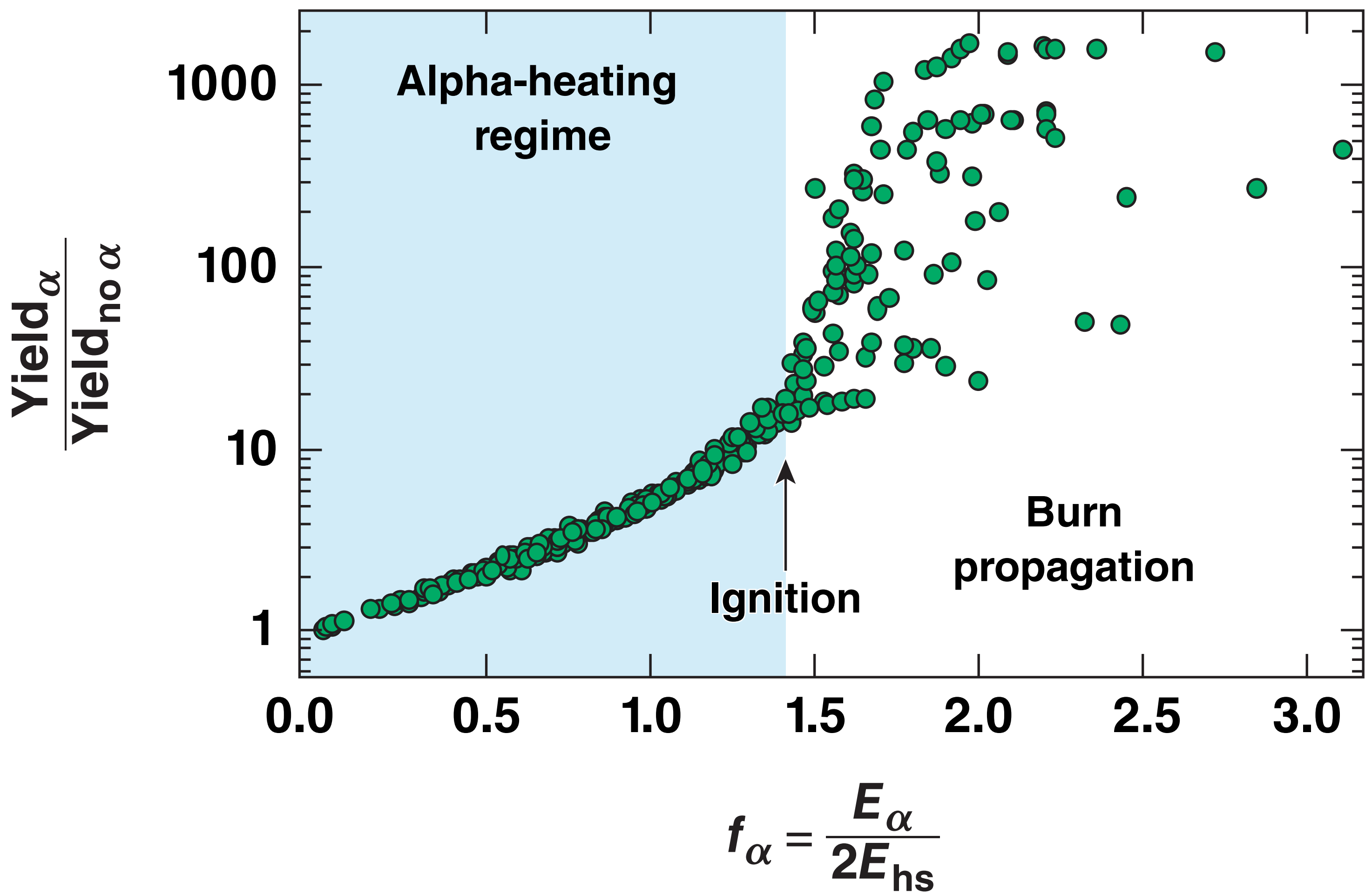
Definition of Ignition in Inertial Confinement Fusion



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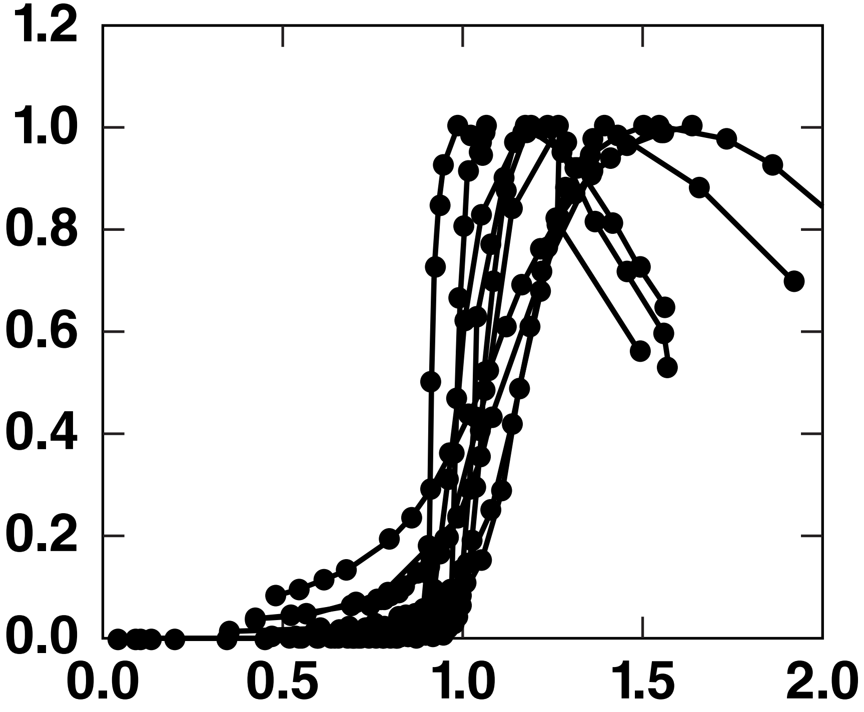
Summary

Hot-spot ignition is defined as the point when the peak in fusion production moves from the hot spot to the shell

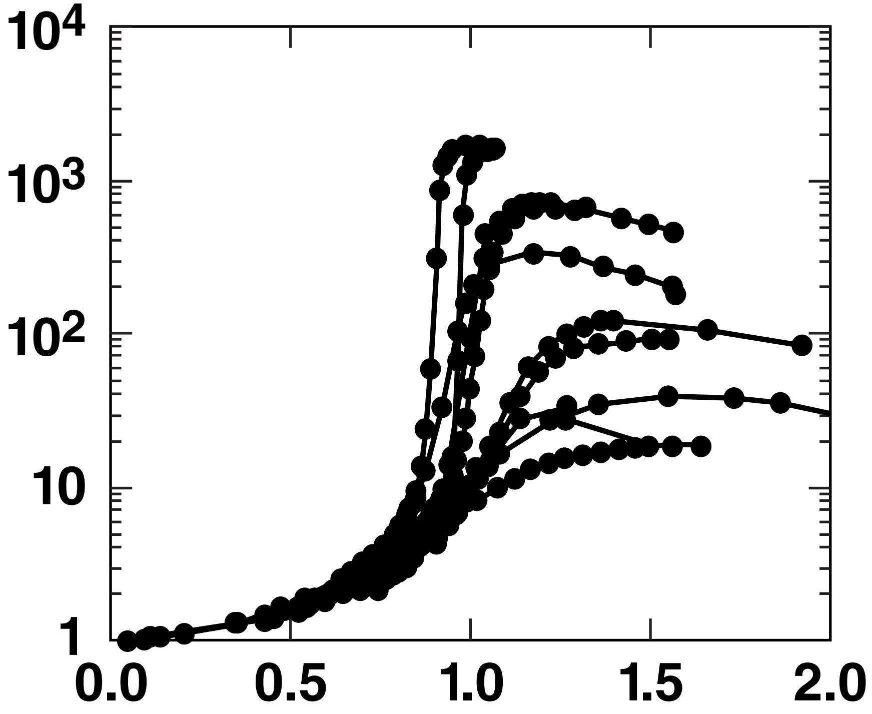
- Hot-spot ignition is commonly viewed as the precursor of the burn propagation in the dense shell
- A clear transition between the hot-spot alpha-heating regime and burn-wave propagation in the shell is identified from the experimentally measureable parameter metric $f_\alpha \equiv 0.5\, E_\alpha/E_{hs}$
- We show that ignition is defined as the hot-spot alpha-heating transition to burn propagation; it occurs at $f_\alpha \sim 1.4$, corresponding to yield amplification of ~15 and temperature amplification of ~2

Ignition has been previously defined as Gain = 1 (which is not a physics definition) or $\chi_{\text{no}\ \alpha} = 1$ (which requires no-alpha parameters)



$$\frac{\text{Yield}_\alpha}{\text{Yield}_{\text{no}\ \alpha}} \Big/ \text{Max}\left(\frac{\text{Yield}_\alpha}{\text{Yield}_{\text{no}\ \alpha}}\right)$$

$$\chi_{\text{no}\ \alpha} = \left(\frac{\rho R}{\text{g/cm}^2}\right)^{0.61}\left(\frac{0.12\,Y_{16}}{M_{\text{stag(mg)}}}\right)^{0.34}$$



$$\text{Yield}_\alpha / \text{Yield}_{\text{no}\ \alpha}$$

$$\chi_{\text{no}\ \alpha} = \left(\frac{\rho R}{\text{g/cm}^2}\right)^{0.61}\left(\frac{0.12\,Y_{16}}{M_{\text{stag(mg)}}}\right)^{0.34}$$

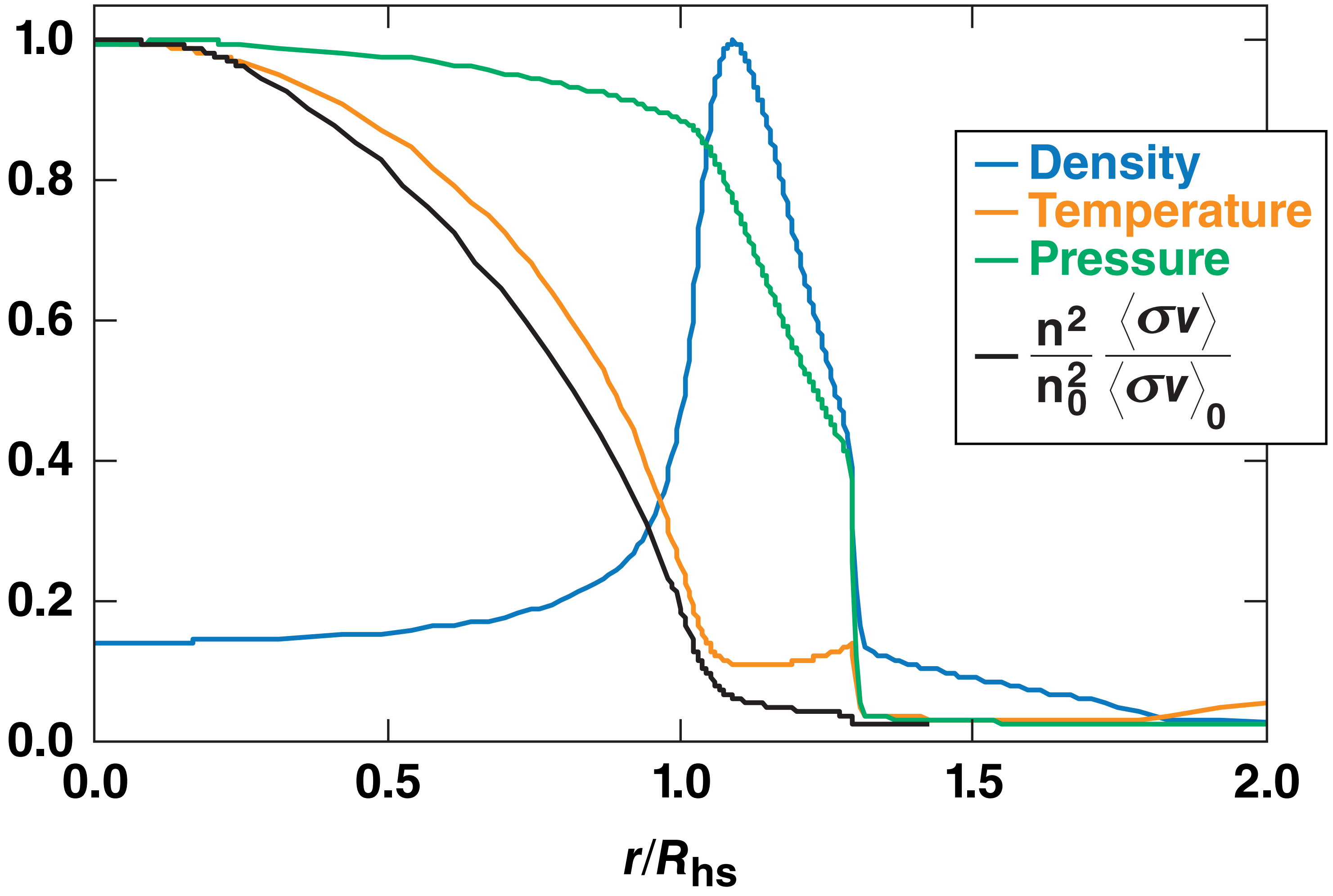
LILAC simulations
α ~ 1 to 4
V_{imp} ~ 200 to 600 km/s
E_L ~ 30 kJ to 10 MJ

The ignition cliff predicted by $\chi_{\text{no}\ \alpha} = 1$ cannot be directly measured and it does not distinguish between the physics of hot-spot ignition and burn propagation in the surrounding dense shell.

Progress toward ignition can be described by comparing the alpha energy deposited in the hot spot to the hot-spot energy at bang time

$$f_\alpha = \frac{1/2\, E_\alpha}{E_{hs}}$$

- E_{hs} = hot-spot internal energy
- $E_\alpha = \varepsilon_\alpha$ yield total alpha energy
- ε_α = 3.5 MeV = alpha birth energy



TC13914

The alpha-heating metric f_α can be related to $p_0\tau/(p_0\tau)_{ign}$ evaluated in the center of the hot spot, where $(p_0\tau)_{ign} = 24\, T_0^2/\varepsilon_\alpha\langle\sigma v\rangle(T_0)$

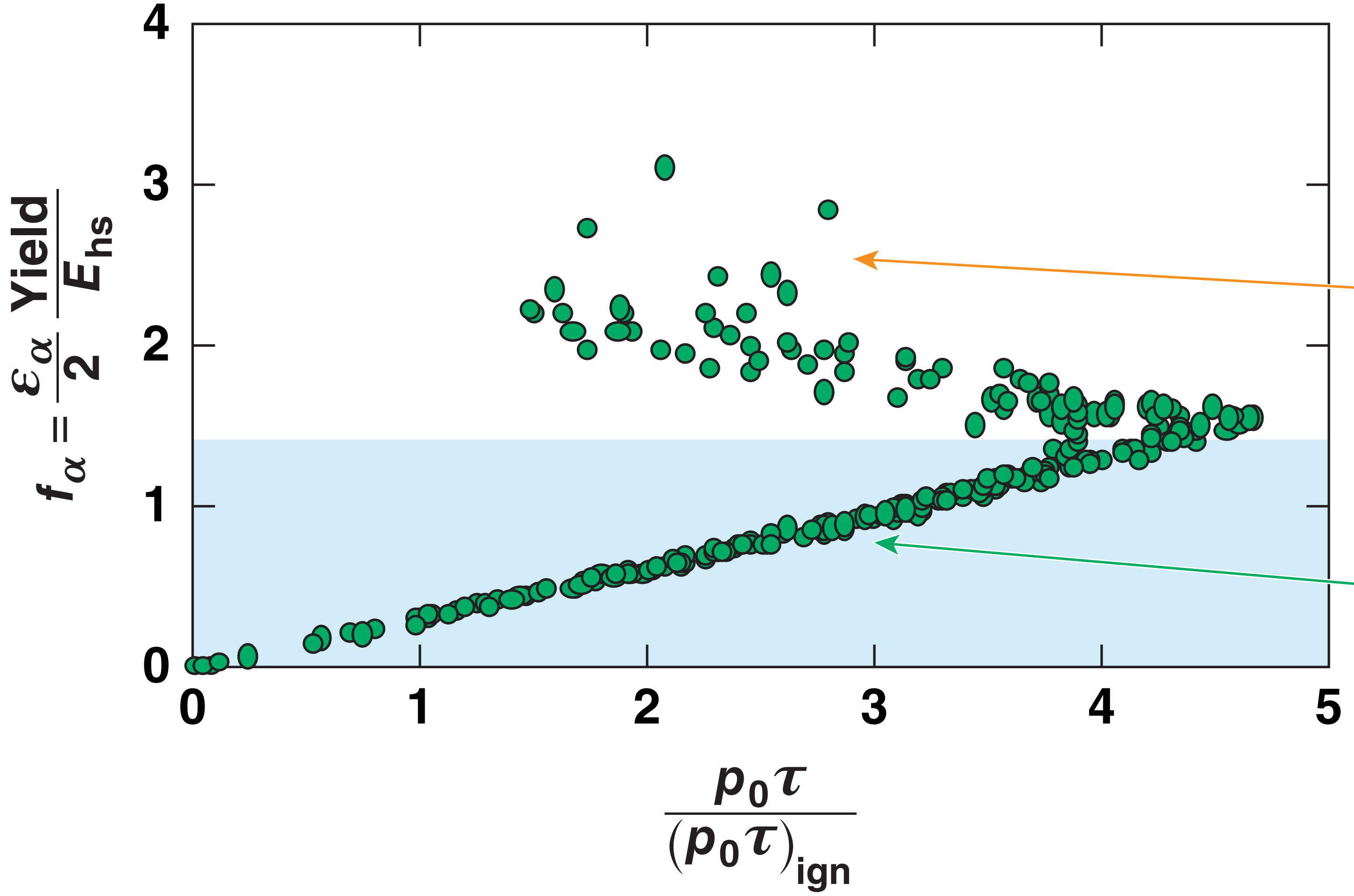
$$f_\alpha \simeq \frac{1}{2}\frac{\varepsilon_\alpha \tau \int_0^\infty p^2/16T^2 \langle\sigma v\rangle 4\pi r^2\, dr}{3/2\int_0^{R_{hs}} p4\pi r^2\, dr} = \frac{1}{2}\frac{p_0\tau}{(p_0\tau)_{ign}}\mu$$

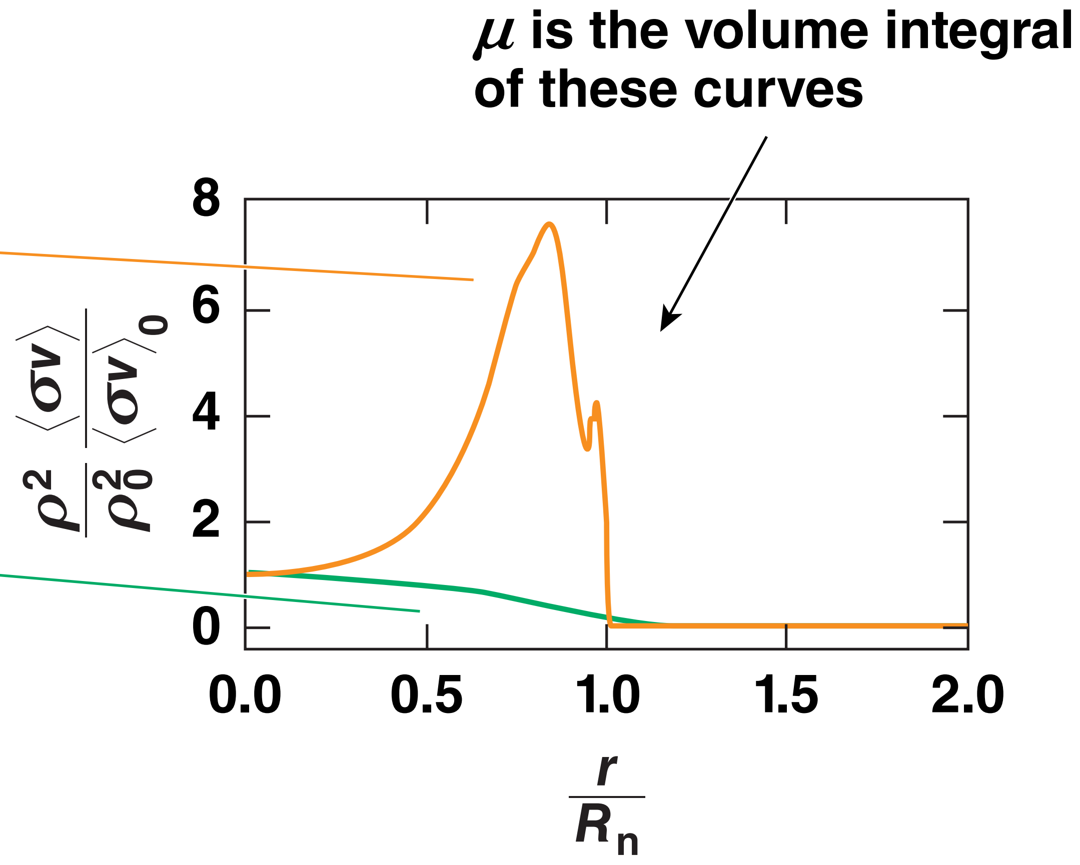
- μ is a dimensionless factor that accounts for spatial profiles in the hot spot since the alpha production rate is not constant in space

$$\mu = \frac{T_0^2}{p_0^2\langle\sigma v\rangle(T_0)R_{hs}^3}\int_0^\infty 3\frac{p^2}{T^2}\langle\sigma v\rangle r^2\, dr$$

TC13915

Using neutron R_{17} as the definition of hot-spot radius, 1-D *LILAC* simulations show a tight correlation between f_α and the Lawson parameter until $f_\alpha \sim 1.4$



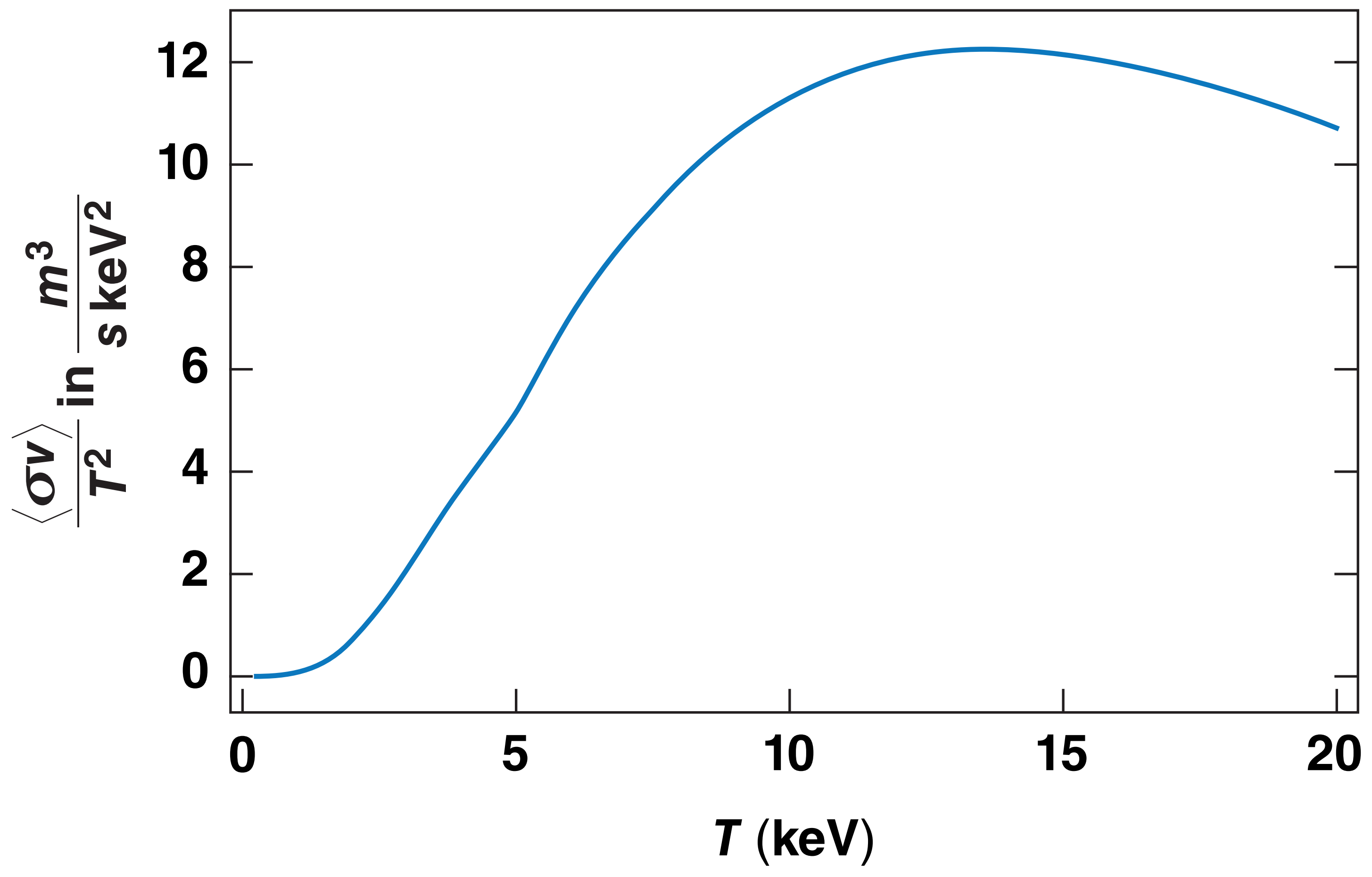


Near $f_\alpha \sim 1.4$, the factor representing spatial distribution of alpha production in the hot spot changes significantly.

TC13916

The scaling of reactivity with temperature causes the difference in the alpha-production profile μ

$$\frac{\text{Alpha production rate}}{\text{Volume}} \sim p^2 \frac{\langle \sigma v \rangle (T)}{T^2}$$



In an isobaric hot spot, when $T_0 > 14$ keV, the peak in neutron production moves away from the center and toward the shell inner surface.

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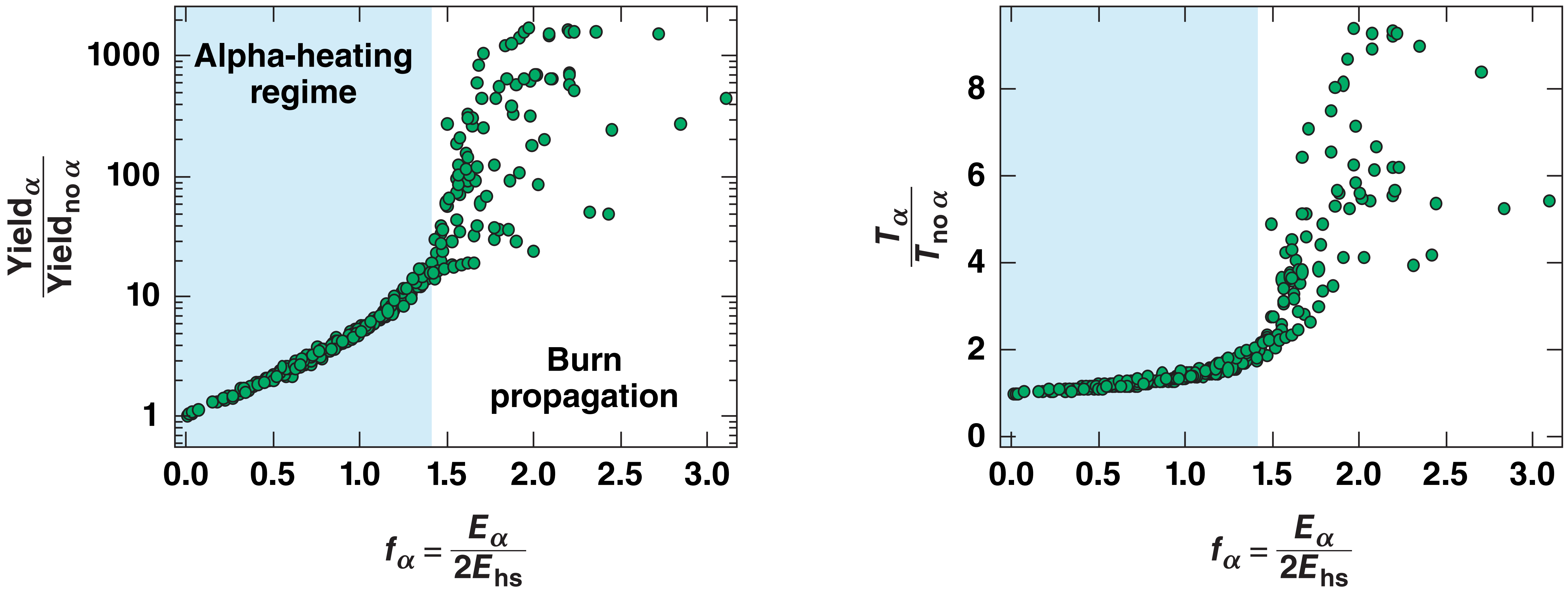
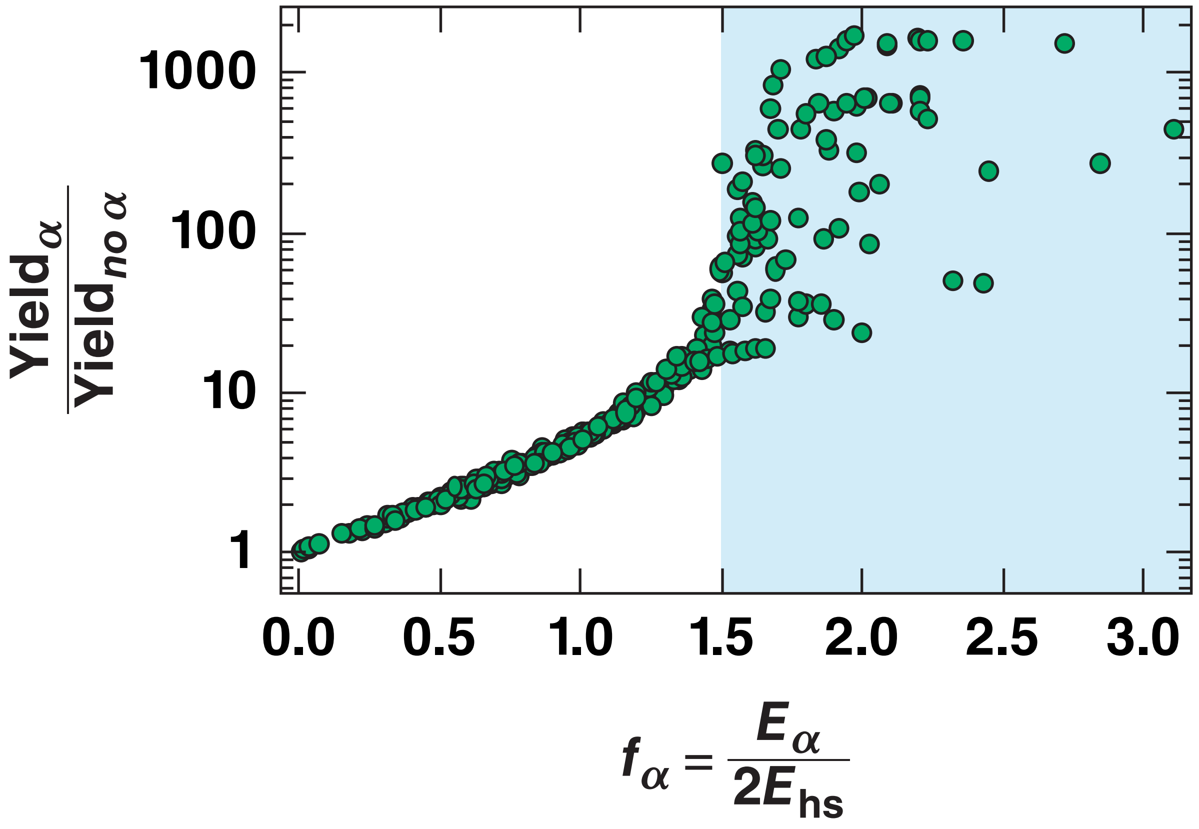
The yield and temperature amplifications caused by alpha heating are unique functions of f_α until a critical point after which the shell burnup fraction determines the maximum obtainable fusion yield

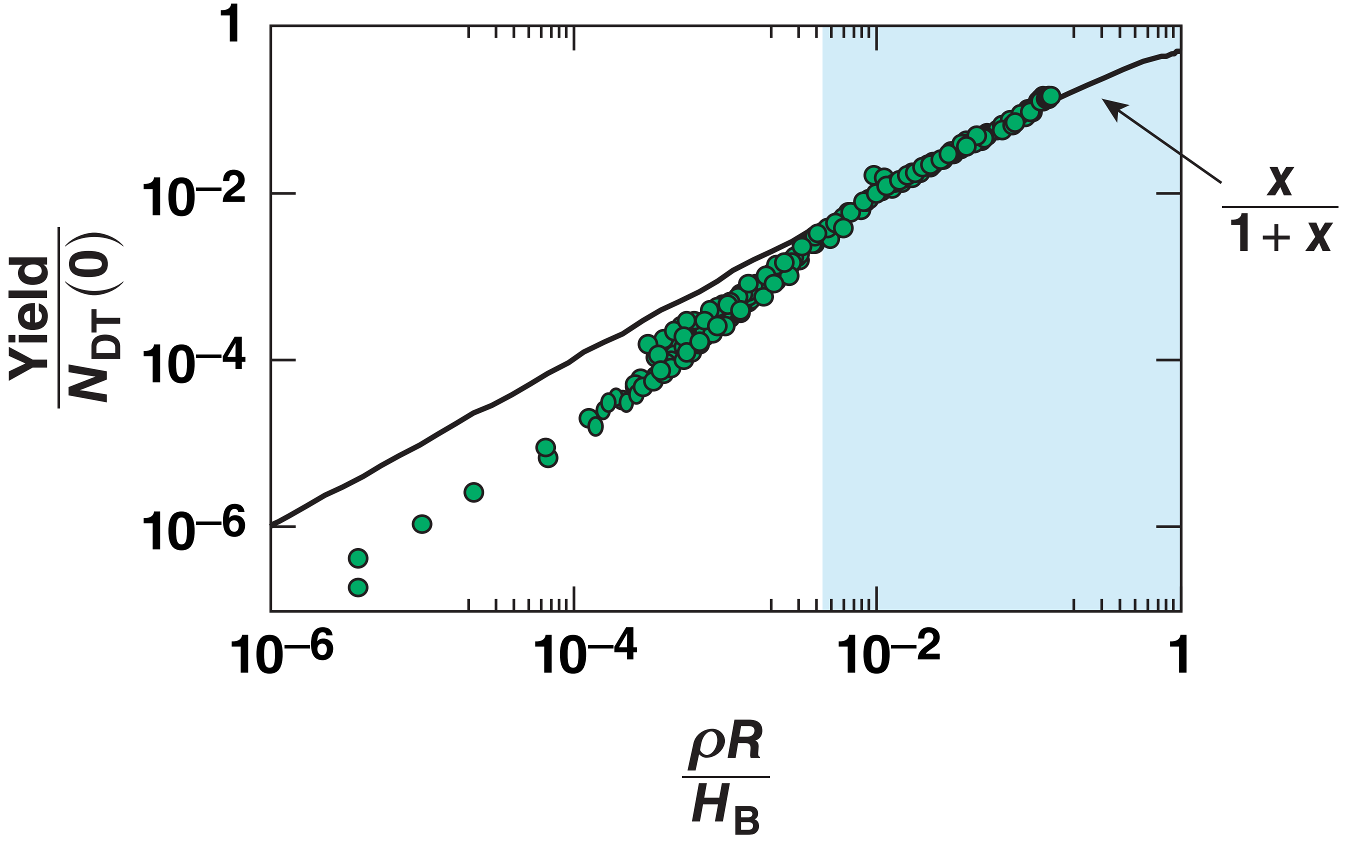


TC13918

After the ignition point, the yield is determined by the burnup fraction, similar to a decompressing burning sphere with an initially constant temperature and density

$$\frac{\text{Yield}}{N_{DT}(0)} = \frac{\rho R}{\rho R + H_B} \qquad H_B \sim \sqrt{T} / \langle \sigma v \rangle$$

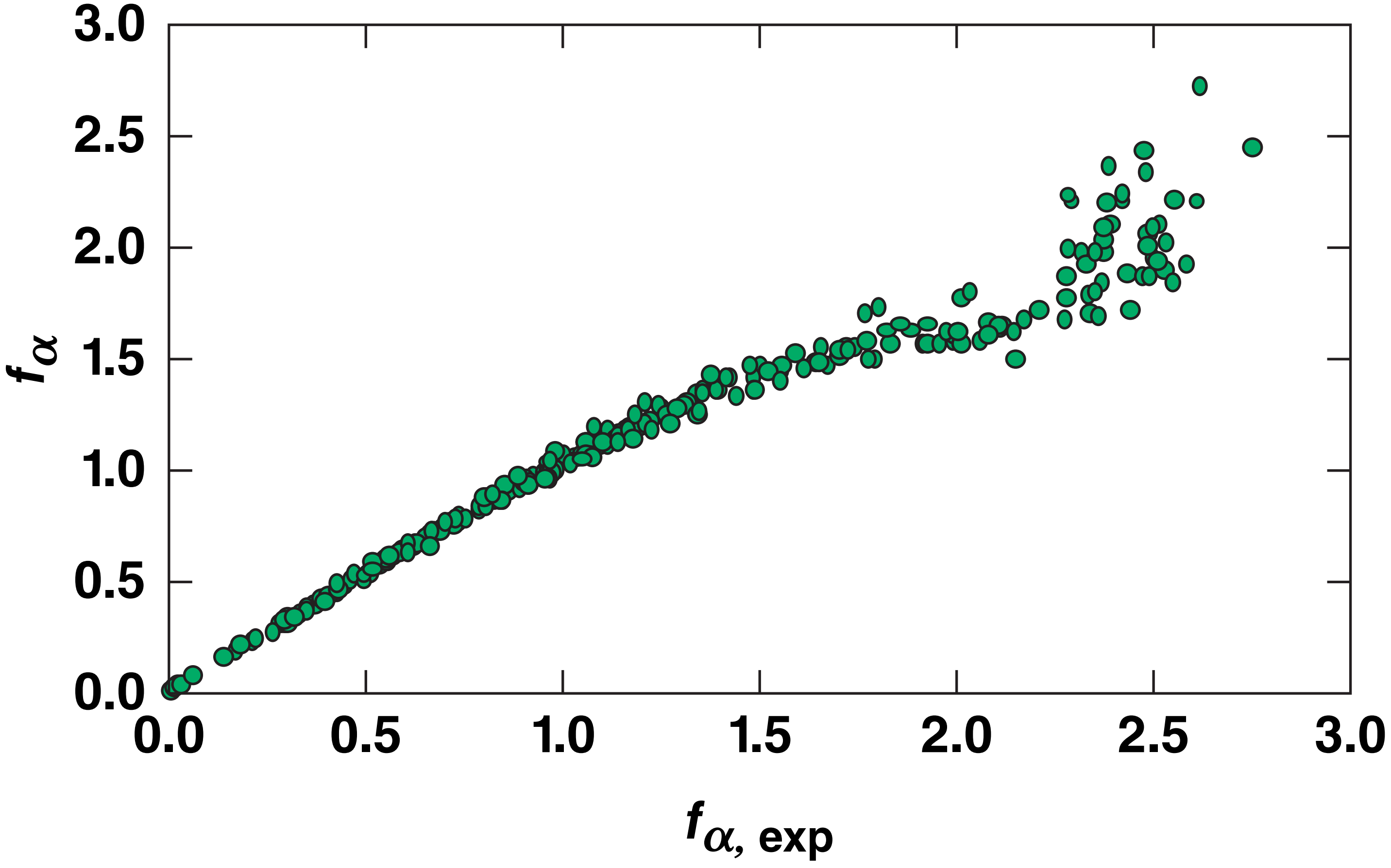




S. Atzeni and J. Meyer-ter-Vehn, *The Physics of Inertial Fusion: Beam Plasma Interaction, Hydrodynamics, Hot Dense Matter*, 1st ed., International Series of Monographs on Physics, Vol. 125 (Oxford University Press, Oxford, 2004).

TC13919

f_α can be approximately inferred from experimental observables with reasonable accuracy for $f_\alpha < 1.5$



$$\langle p \rangle \approx \sqrt{\frac{16\,Y\,T_i^2}{\tau V_{hs} \langle \sigma v \rangle (T_i)}}$$

$$f_{\alpha,\,exp} = \frac{0.5\varepsilon_\alpha Y}{1.5 \langle p \rangle V_{hs}}$$

TC13920

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

Summary/Conclusions

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- A clear transition between the hot-spot alpha-heating regime and burn-wave propagation in the shell is identified from the experimentally measureable parameter metric $f_{\alpha} \equiv 0.5\ E_{\alpha}/E_{\text{hs}}$
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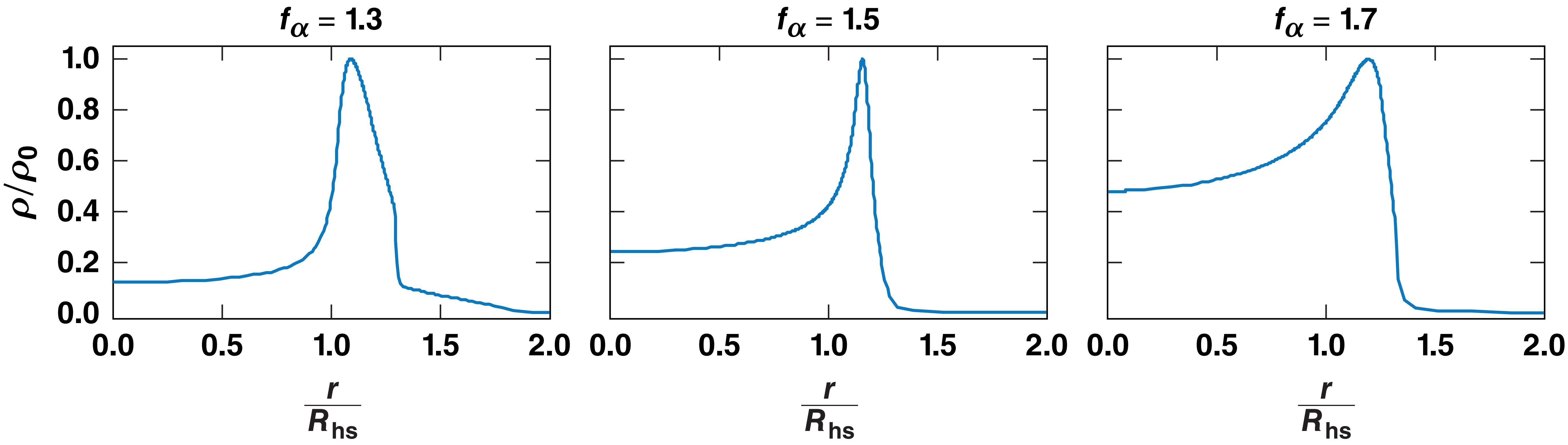
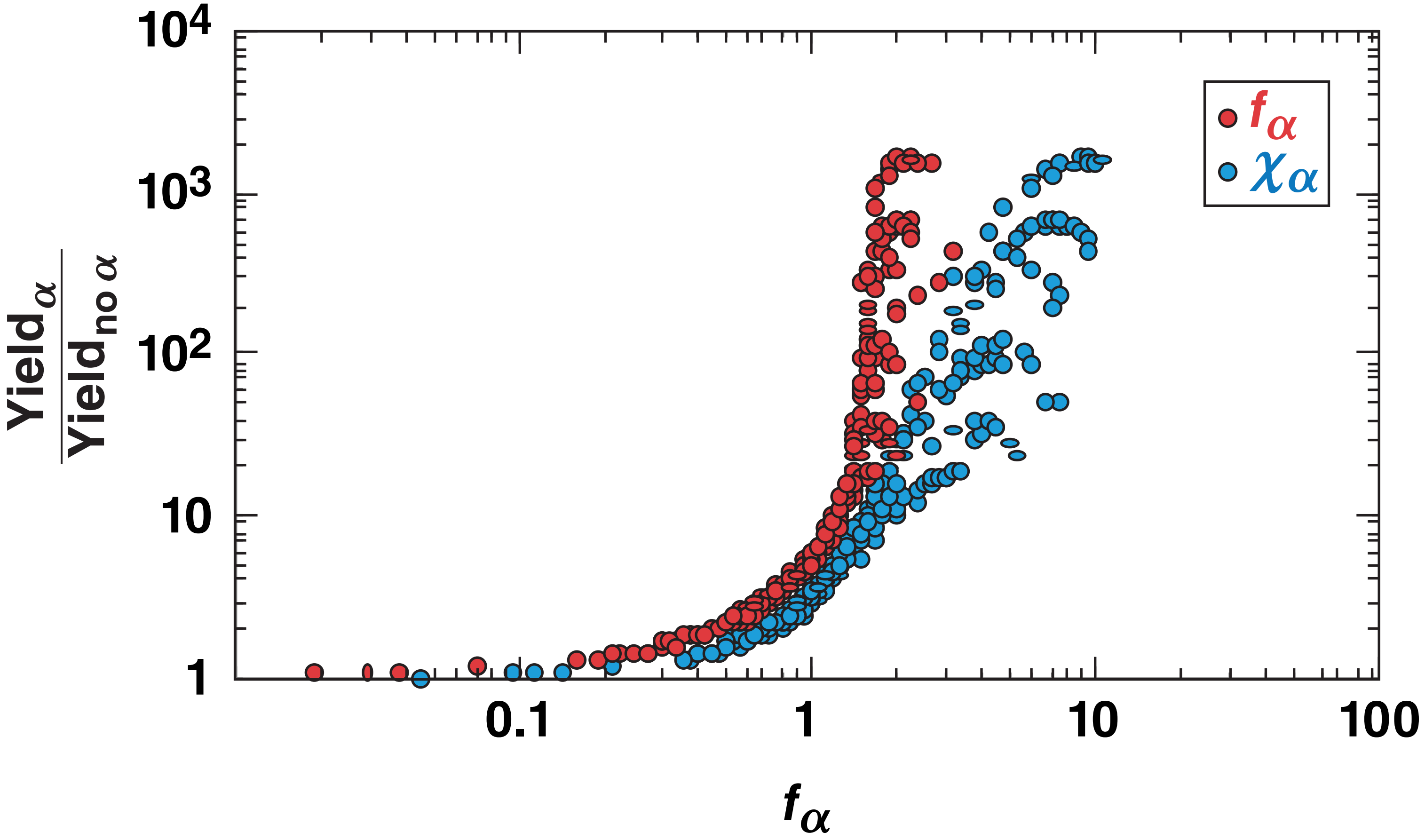
The ignition point is associated with a large increase in the hot-spot mass



The yield amplification exhibits a tighter correlation with f_α compared to χ_α



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