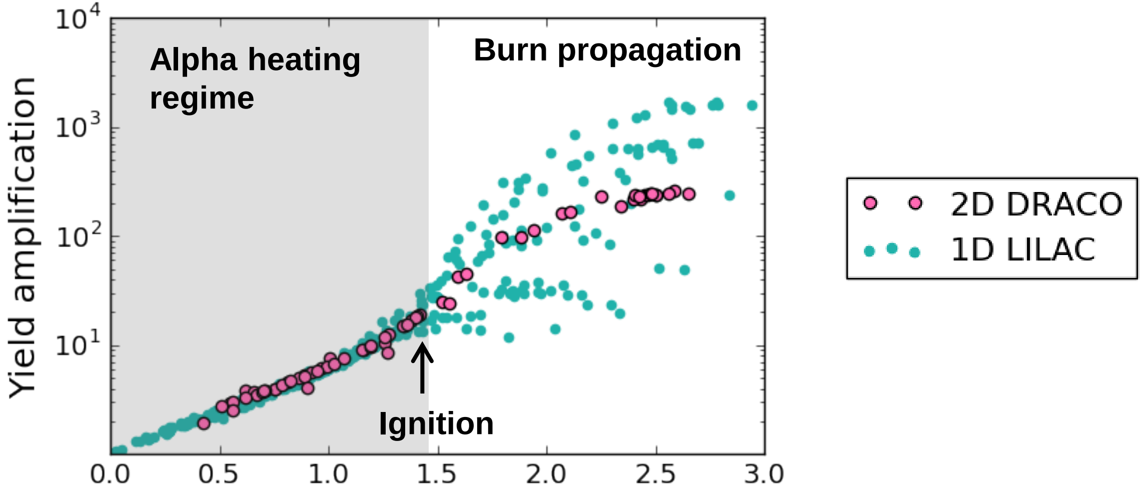
Thermonuclear Ignition and the Onset of Propagating Burn in Inertial Fusion



$$f_\alpha = \frac{\text{Alpha energy absorbed in hot spot}}{\text{Hot spot internal energy}}$$

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Summary

A new ignition criterion identifies the transition from alpha heating to burn propagation and is valid in multi-dimensions

- In the alpha heating regime, 1D simulations show that the yield enhancement due to alpha heating varies as a unique function of the parameter f_α until the transition to burn propagation
- Ignition is this transition point which occurs at $f_\alpha \approx 1.4$ and yield amplifications of 15-25x.
- This definition of ignition is valid in multi-dimensions when the fraction of absorbed alpha particles is correctly accounted for in the definition of f_α
- For implosions typical of the indirect drive campaign on the NIF*, the fusion yield required for ignition varies between 0.5-1.5 MJ depending on areal density and DT mass

*National Ignition Facility

Collaborators

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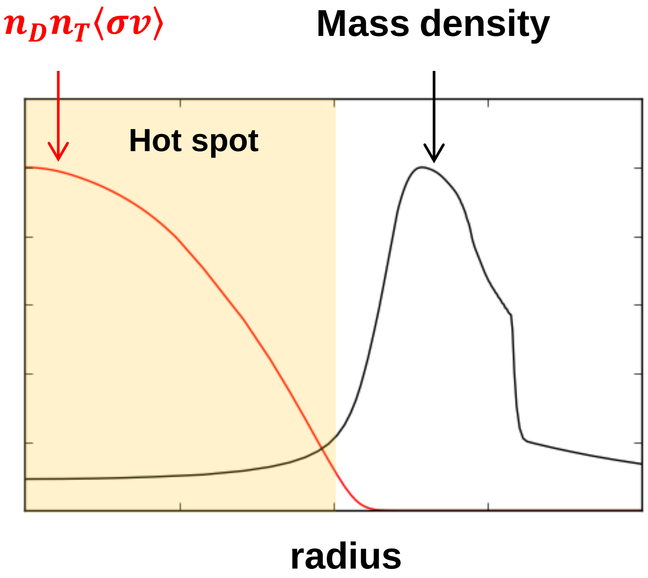
In ICF implosions, alpha heating levels can be characterized by comparing the alpha energy deposited into the hot spot to the hot spot energy*

$$\boxed{f_\alpha = \frac{\frac{1}{2}\theta_\alpha E_\alpha}{E_{hs}}}$$



$E_{hs} = \frac{3}{2}PV_{HS} =$ Hot spot internal energy

$E_\alpha = \varepsilon_\alpha\, Yield =$ total alpha energy

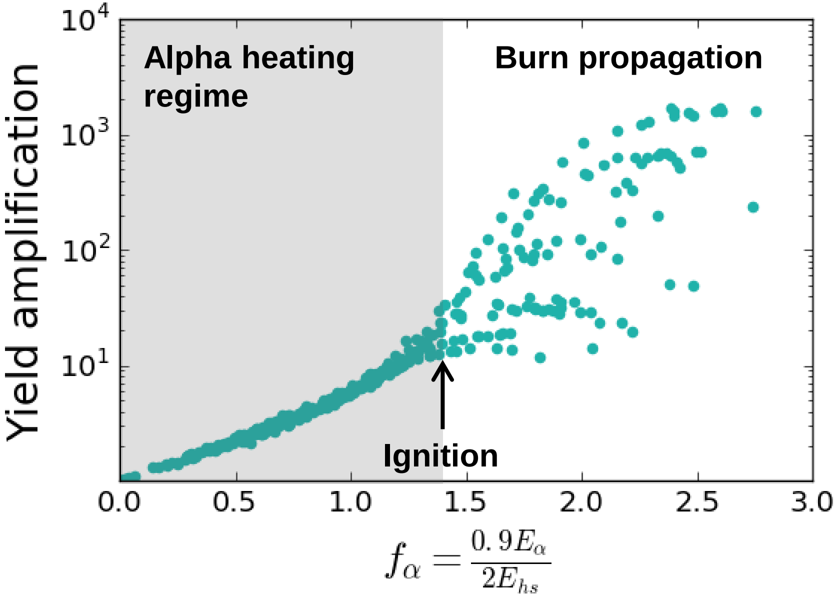
$\varepsilon_\alpha = 3.5\ MeV =$ alpha birth energy

$\theta_\alpha =$ absorbed alpha fraction (≈ 0.9 in 1D and doesn't vary much)

$V_{HS} =$ hot spot volume (17% neutron contour)

*A. Christopherson et al, Phys. Plasmas 25, 072704 (2018).

Ignition in ICF plasmas can be identified as the transition from hot-spot alpha heating to burn propagation in the shell occurring at $f_\alpha \approx 1.4$



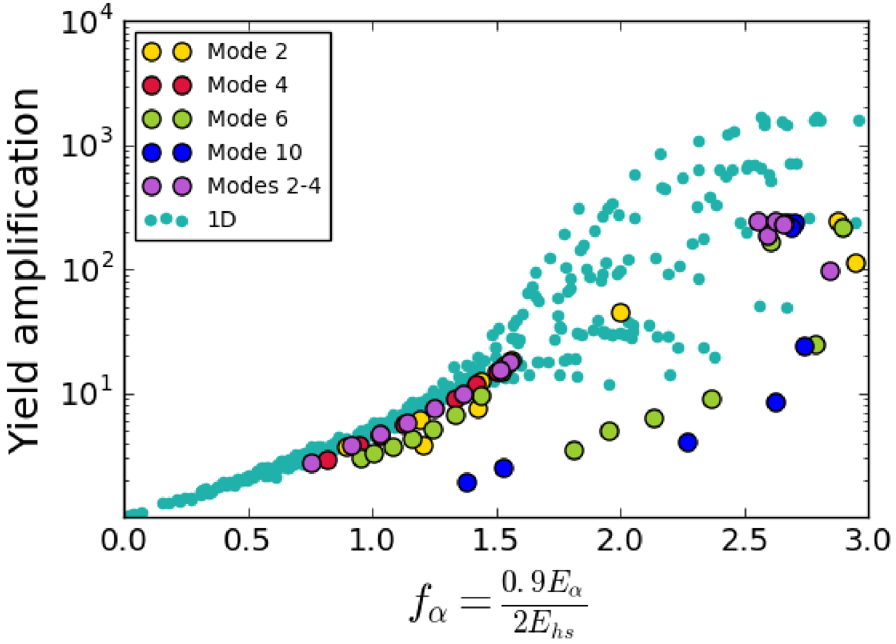
1D LILAC simulation database

$\alpha \sim 1-6$

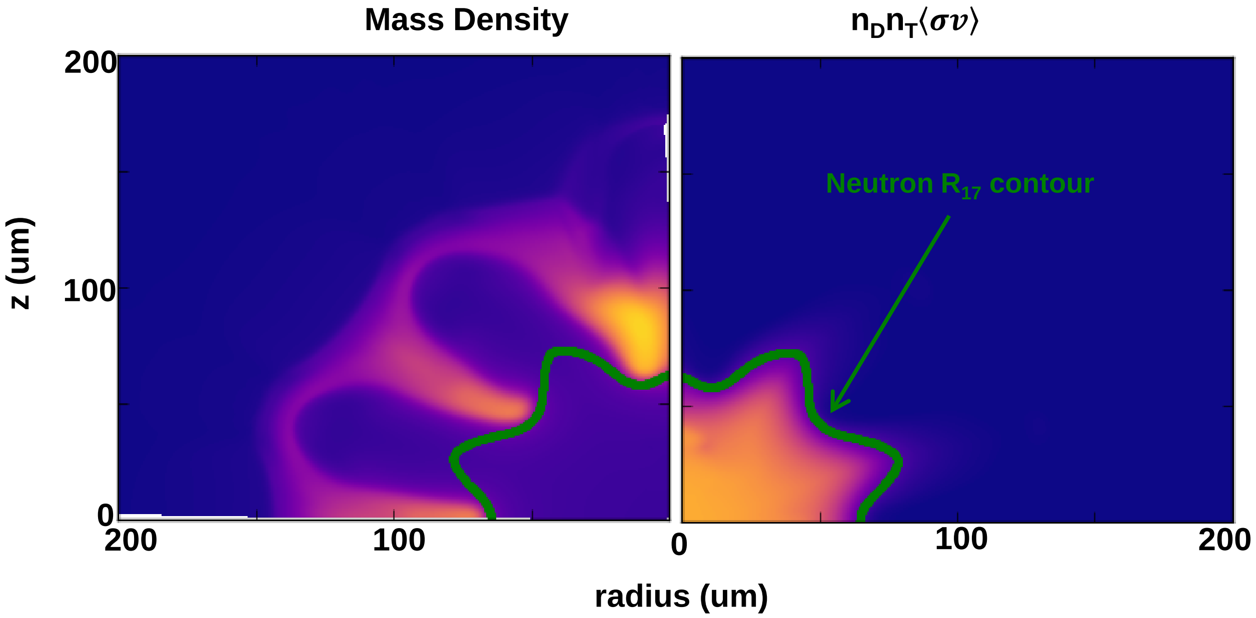
$V_i \sim 200-600\,\frac{km}{s}$

$E_L \sim 30kJ\ -10MJ$

2D perturbed DRACO simulations do not follow the 1D yield amplification curve



The leading hypothesis for the discrepancy observed in perturbed implosions is that the alphas from the neutron producing region are deposited into the bubbles

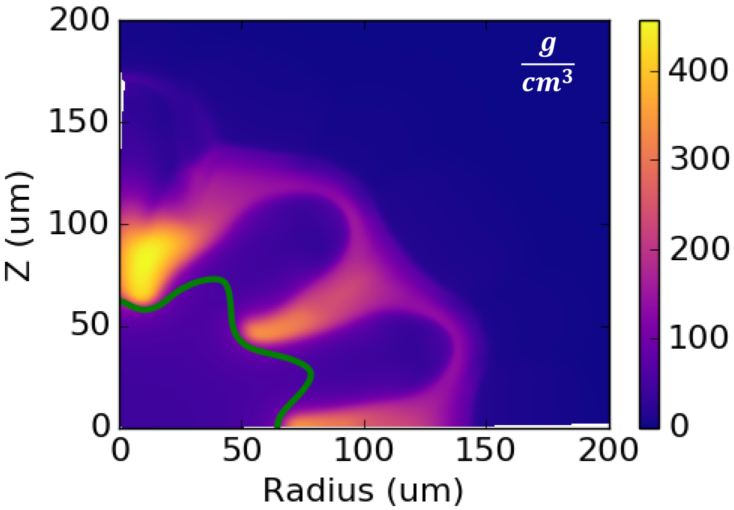


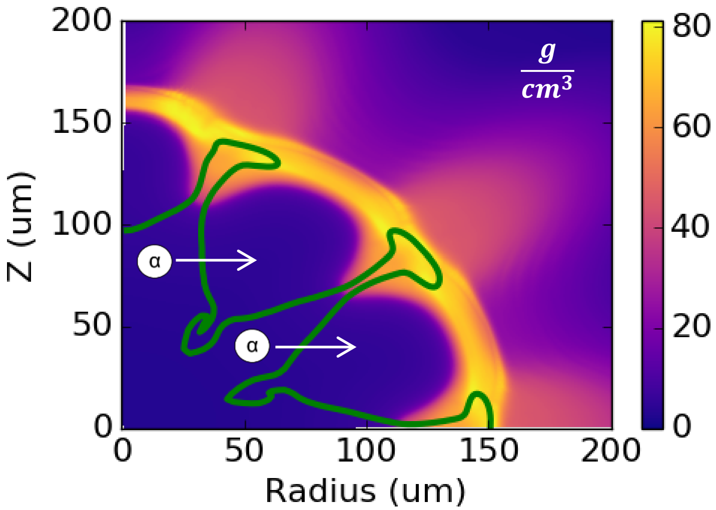
Mode 10,
Yield amplification = 12
Yield over clean = 0.5

The alpha deposition into a distorted mass can be determined exactly by calculating the Lagrangian trajectories of points along the hot spot boundary.

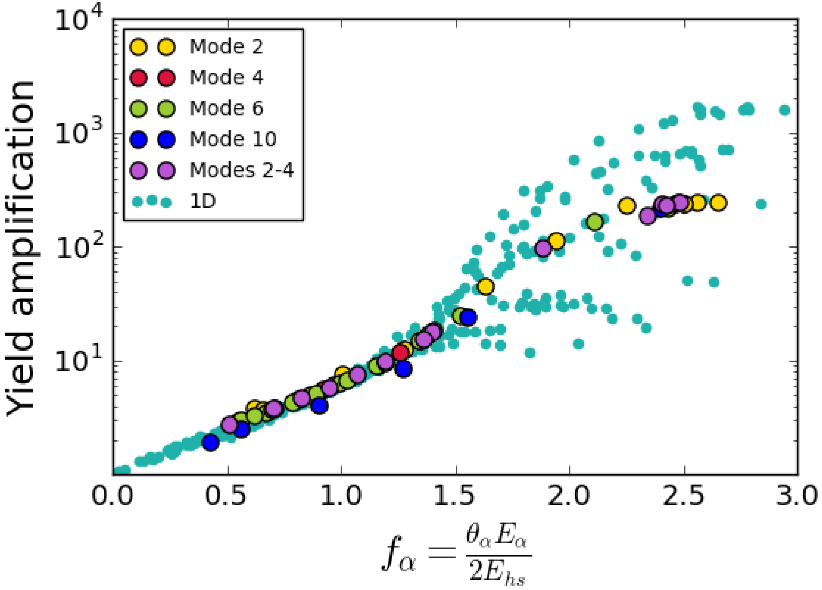
Hot spot boundary at bang time

Hot spot boundary before alpha production (defined by solving $d\vec{r}/dt = \vec{u}$ for all hot spot boundary points back in time)





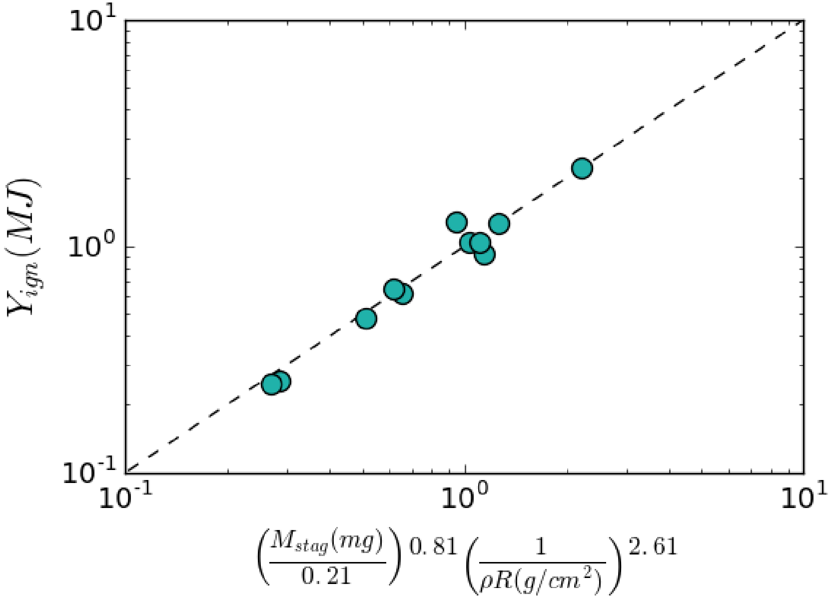
2D perturbed yield amplification curves follow the same 1D behavior when the fraction of absorbed alpha particles is taken into account in the definition of f_α



$$\theta_\alpha \equiv \frac{\text{Alpha energy absorbed in hot spot}}{\text{Total alpha energy absorbed in domain}}$$

We conclude that yield amplification=20 is a valid definition of ignition even in the presence of asymmetries

The required fusion yield required for ignition is derived for a yield amplification of 20



$$Y_{ign} \approx Y_{amp} Y_{no\ \alpha} = 20 Y_{no\ \alpha}$$

$$\chi_{no\alpha} \sim (\rho R)^{0.61} \left(\frac{Y_{no\ \alpha}}{M_{stag}}\right)^{0.34}$$ ~1 at ignition

$$Y_{no\ \alpha} \sim \chi_{no\alpha}^{3} \frac{M_{stag}}{\rho R^{1.8}}$$

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- Ignition is this transition point which occurs at $f_\alpha \approx 1.4$ and yield amplifications of 15-25x.
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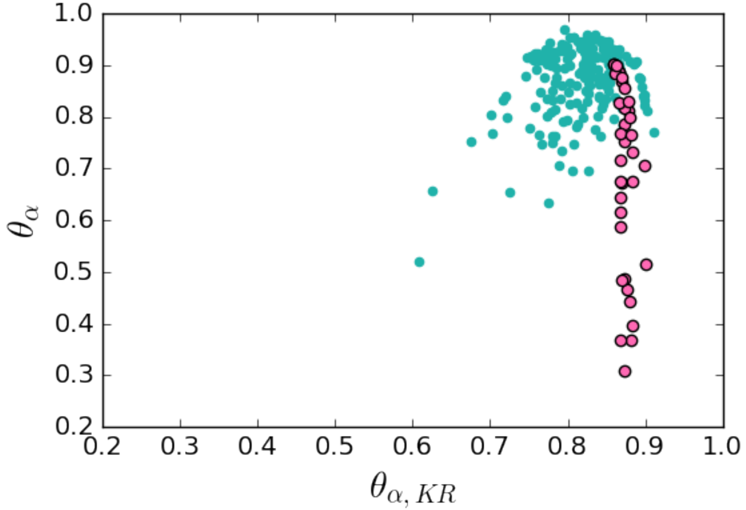
Extra slides

The fraction of absorbed alphas in the hot spot is less than what would be determined from the well used Krokhin and Rozanov formula*



Alpha range** $\rho\lambda = \dfrac{0.25\,T^{5/4}}{1{+}0.0082\,T^{5/4}}$

$$\theta_{\alpha,KR} \approx 1 - \frac{1}{4}\frac{\rho\lambda}{\rho R_{hs}}$$

***O. N. Krokhin and V. B. Rozanov, Sov. J. Quantum Electron. 2, 393 (1973).**

**** G.S. Fraley, E.J. Linnebur, R.J. Mason, and R.L. Morse, Physics of Fluids 17, 474 (1974).**

The fraction of alpha particles deposited into the hot spot can be calculated exactly from simulations by tracking the lagrangian hot spot mass

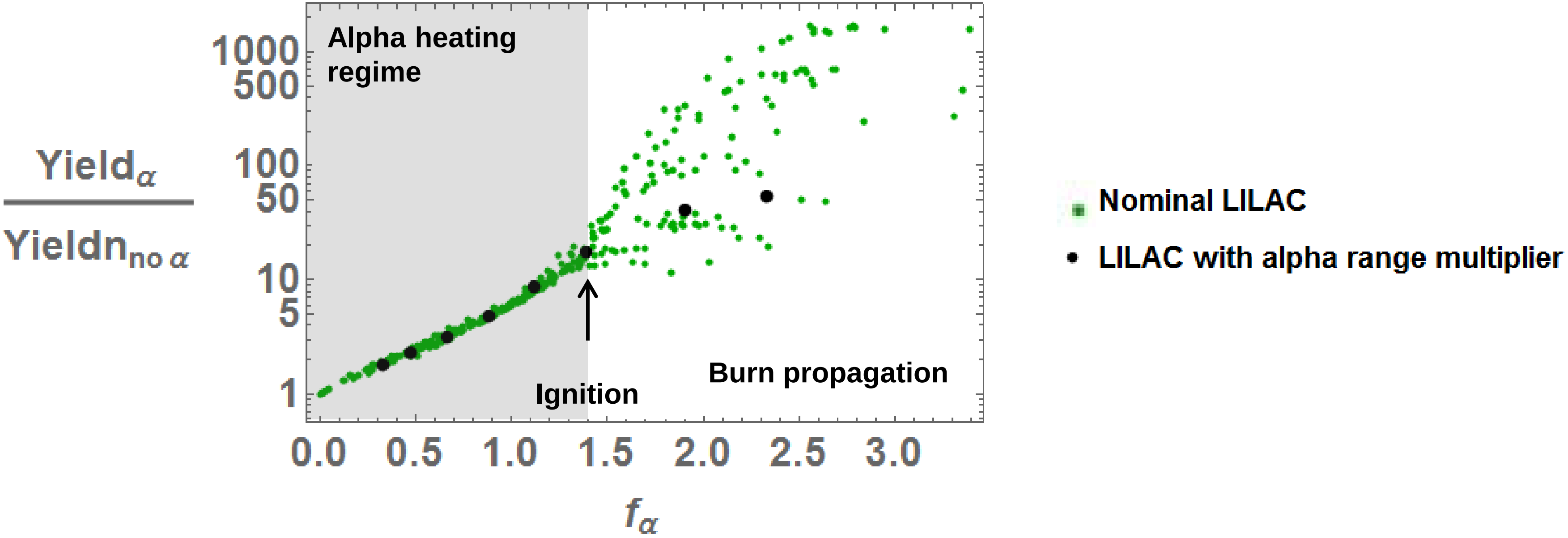
$$w_{\alpha,deposited} = alpha\ energy\ deposited\ per\ unit\ volume\ and\ time$$

$$E_{\alpha,absorbed,tot} = \int_0^{t_{bang}} \int w_{\alpha,deposited}\, dV\, dt$$

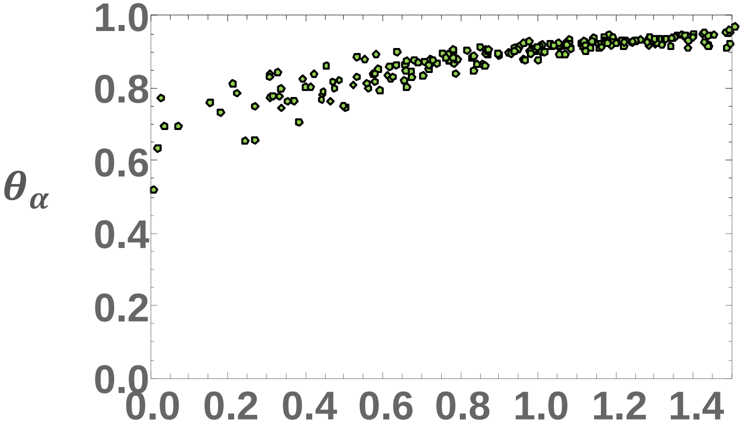
$$E_{\alpha,absorbed,hs} = \int_0^{t_{bang}} \int w_{\alpha,deposited}\, dV_{hs}\, dt$$

$$\boxed{\theta_\alpha \equiv \frac{E_{\alpha,absorbed,hs}}{E_{\alpha,absorbed,tot}}}$$

The ignition curve is not affect by differences in alpha transport when the alpha range is multiplied by two in the simulations.



The fraction of alpha particles absorbed in the hot spot θ_α doesn't vary significantly among 1D implosions

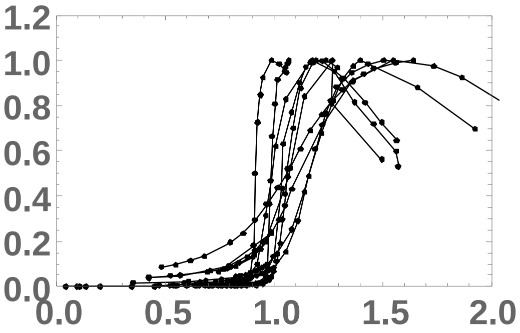


$$f_\alpha = \frac{1}{2}\frac{E_\alpha}{E_{hs}}$$

$$\theta_\alpha \equiv \frac{Alphas\ absorbed\ in\ hot\ spot\ before\ bang\ time}{Alphas\ absorbed\ everywhere\ before\ bang\ time}$$

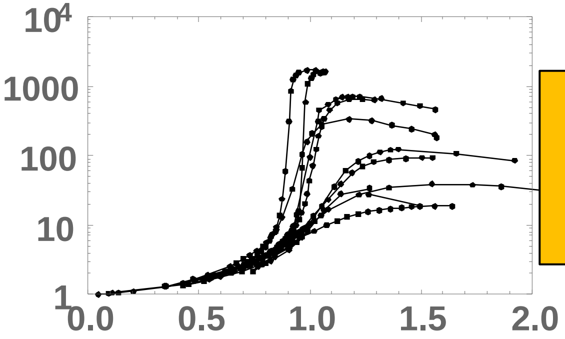
Ignition has traditionally been defined as $\chi_{no\ \alpha} = 1$ which predicts when the implosion has reached one-half of its maximum gain

$$\frac{Y_{amp}}{Max[Y_{amp}]}$$



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

$$Y_{amp}$$



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

LILAC simulations
$\alpha \sim 1 - 6$
$V_i \sim 200 - 600 \frac{km}{s}$
$E_L \sim 30kJ\ - 10MJ)$

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