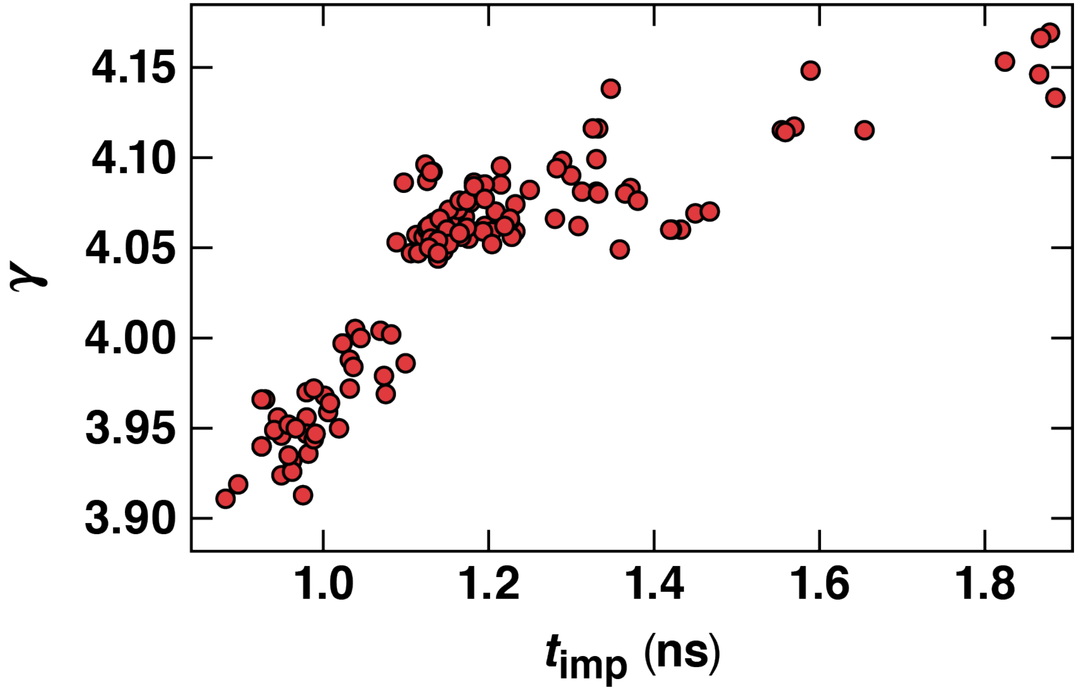
Hydrodynamic Scaling Relations for OMEGA Cryogenic Implosions



Scaling exponent

$$Y_{NIF} = Y_{OMEGA} \times 4^{\gamma}$$

$$t_{imp} = R/V_{imp}$$

D. Patel
University of Rochester
Laboratory for Laser Energetics

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Summary

Hydrodynamic scaling of OMEGA cryogenic implosions to NIF* scale was studied using 1-D radiation-hydrodynamic simulations

- **Data from an ensemble of simulations generated using the 1-D radiation-hydrodynamic code *LILAC*** indicates that the no-alpha hydrodynamic yield scaling depends on OMEGA implosion time**
- **This additional dependence arises because of non-scaling physics of electron–ion energy equilibration**
- **Simulations using 2-D radiation-hydrodynamic code *DEC2D*† show that an intermediate mode $(l = 12)$ grows faster (hence greater yield degradation) on NIF scale compared to Omega because of non-scaling physics of thermal conduction**

* NIF: National Ignition Facility
** J. Delettrez *et al.*, Phys. Rev. A 36, 3926 (1987).
† K. M. Woo *et al.*, Bull. Am. Phys. Soc. 59, BAPS.2014.DPP.UP8.87 (2014).

Collaborators

R. Betti, K. M. Woo, V. Gopalaswamy, and J. C. Carrol

University of Rochester
Laboratory for Laser Energetics

A. Bose

Massachusetts Institute of Technology

A simple analytical model is generally used to hydrodynamically extrapolate OMEGA yield to NIF scale

UR LLE

$$Y_{\text{no }\alpha} \sim n^2 \langle \sigma v \rangle V\tau \sim P^2 \frac{\langle \sigma v \rangle}{T^2} V\tau$$

for $\langle T_{\text{i}} \rangle$ in 4 to 5 keV range $\frac{\langle \sigma v \rangle}{T^2} \sim T$

$$Y_{\text{no }\alpha} \sim P^2 T V \tau$$

For hydrodynamic scaling, P is conserved, $V \sim S^3, \tau \sim S$ ⟶ Pure hydro scaling (all physics scales) $Y_{\text{no }\alpha} \sim S^3 S \sim S^4 \rightarrow Y_{\text{NIF}} \sim 256 \times Y_{\text{OMEGA}}$

Thermal conduction does not hydro scale $\rightarrow T_{\text{NIF}} \neq T_{\text{OMEGA}}$

Assuming $T_{\text{i}} \sim T_{\text{e}}$ and neglecting radiation losses $T \sim S^{2/7}$

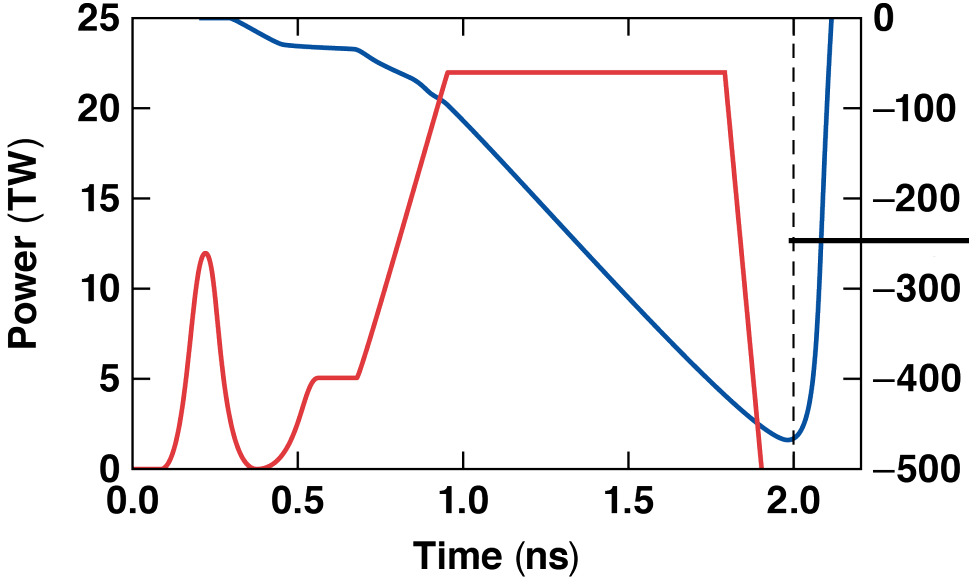
$$Y_{\text{no }\alpha} \sim S^{2/7} S^3 S \sim S^{4.28} \rightarrow Y_{\text{NIF}} \sim 390 \times Y_{\text{OMEGA}}$$

Analytical models show a hydrodynamic scaling exponent of ~4.3 because of the non-scaling physics of thermal conduction.

The 1-D radiation hydrodynamic code *LILAC* was used to simulate only the deceleration phase of scaled implosions to obtain hydrodynamic scaling relations

$\eta = \frac{E_{KE}}{E_L} = \text{constant}$ **Target:** $OD \sim S$, $\Delta_{sh} \sim S$

Laser: $E_L \sim S^3$, $P_L \sim S^2$, $t_L \sim S$ **Dynamics:** α, V_{imp}, $\text{IFAR} = \text{constant}$



TC15533

Extract r, ρ, u, P, T … at max V_{imp} → $r \rightarrow 4 \times r$ (28 kJ → 1.9 MJ) → Input to *LILAC* to simulate the deceleration phase

Simulations covered a large parameter space, with 800 < OD (μm) < 1060, 2.5 < α < 8, and 230 < V_{imp} (km/s) < 540.

IFAR: in-flight aspect ratio

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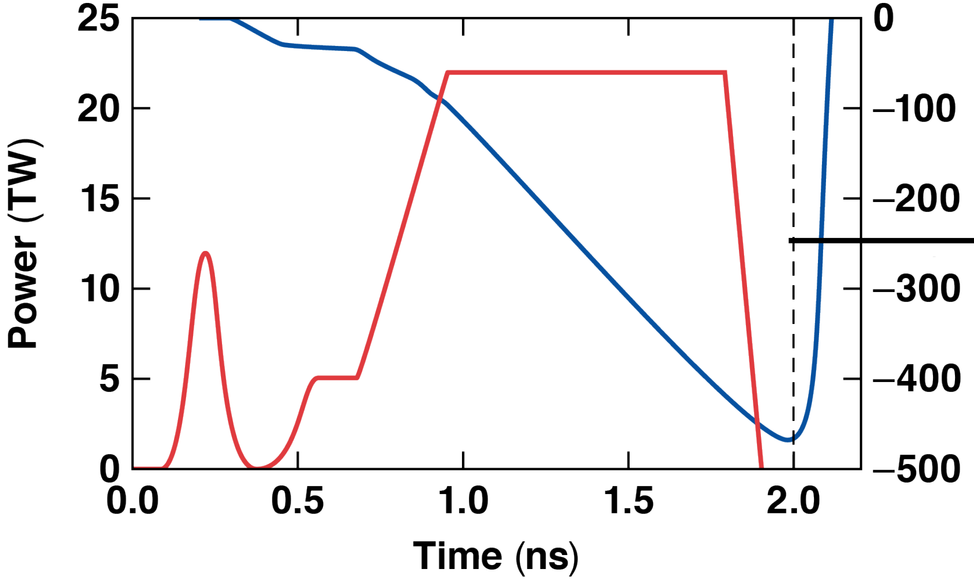
OMEGA-scale *LILAC* simulation



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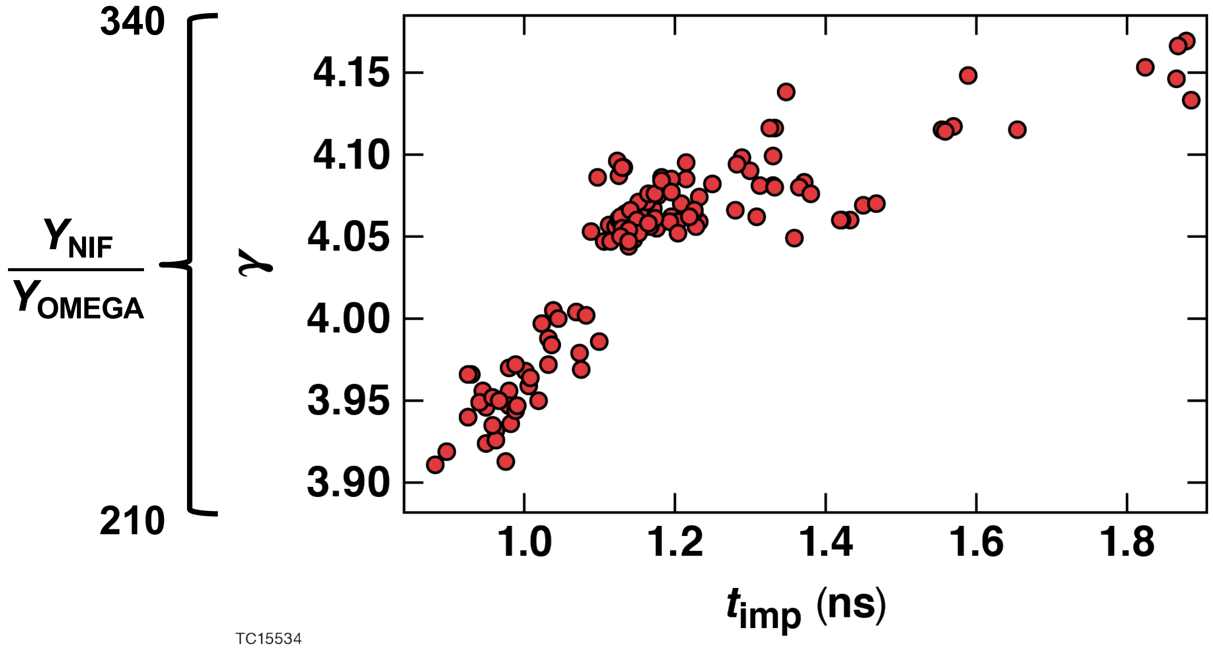
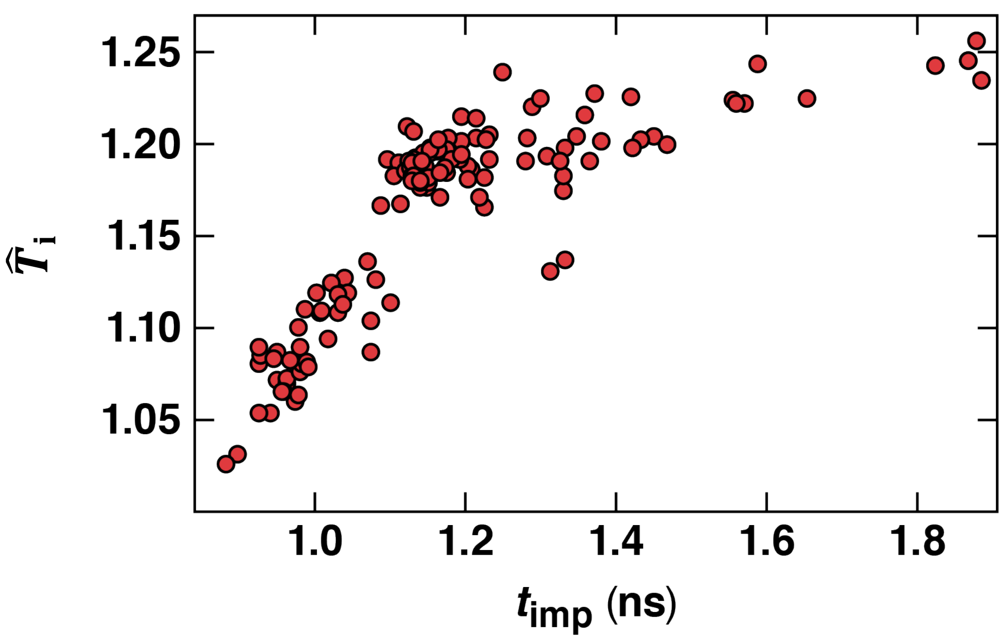
IFAR: in-flight aspect ratio

Simulations indicate that no-alpha yield scaling has an additional dependence on implosion time t_{imp}

$$Y_{NIF} = Y_{OMEGA} \times 4^{\gamma}$$

$$\hat{T} = \frac{\langle T \rangle_{n_{NIF}}}{\langle T \rangle_{n_{OMEGA}}}$$

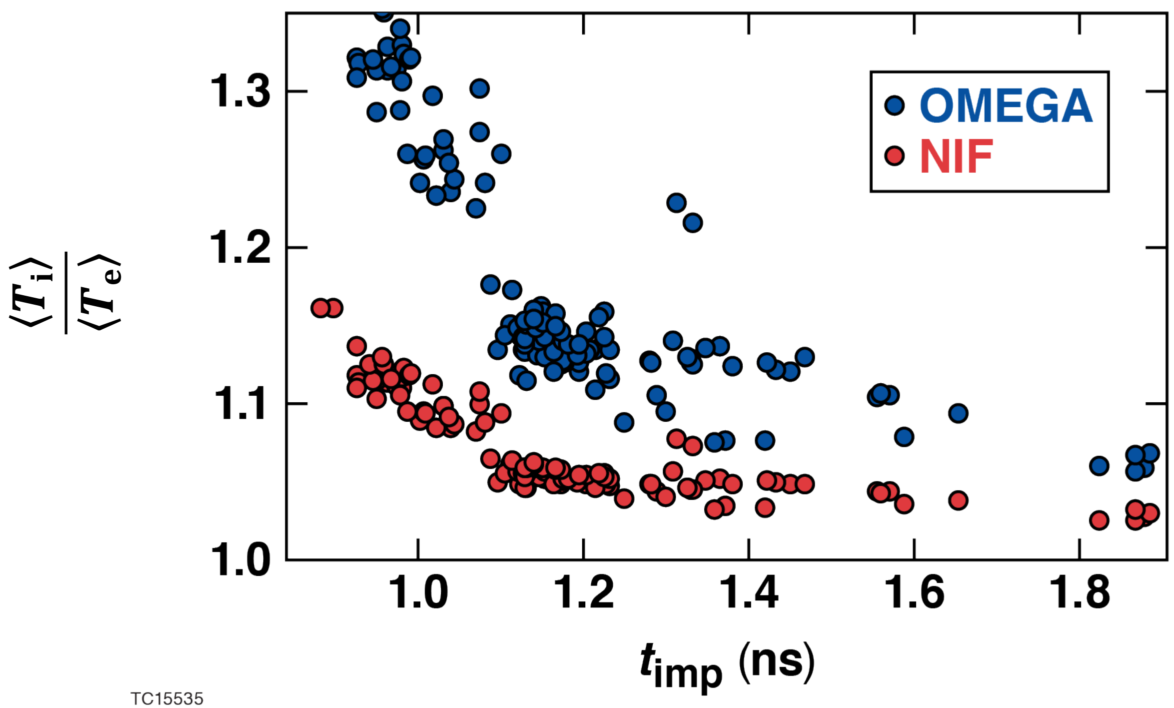




$t_{imp} = R/V_{imp}$ R = OMEGA outer diameter (μm) V_{imp} = implosion velocity (μm/ns)

The primary cause for yield scaling's t_{imp} dependance is the variation in ion temperature scaling with implosion time.

The dependence of T_{ion} scaling on t_{imp} is a result of the non-scaling physics of electron–ion energy equilibration



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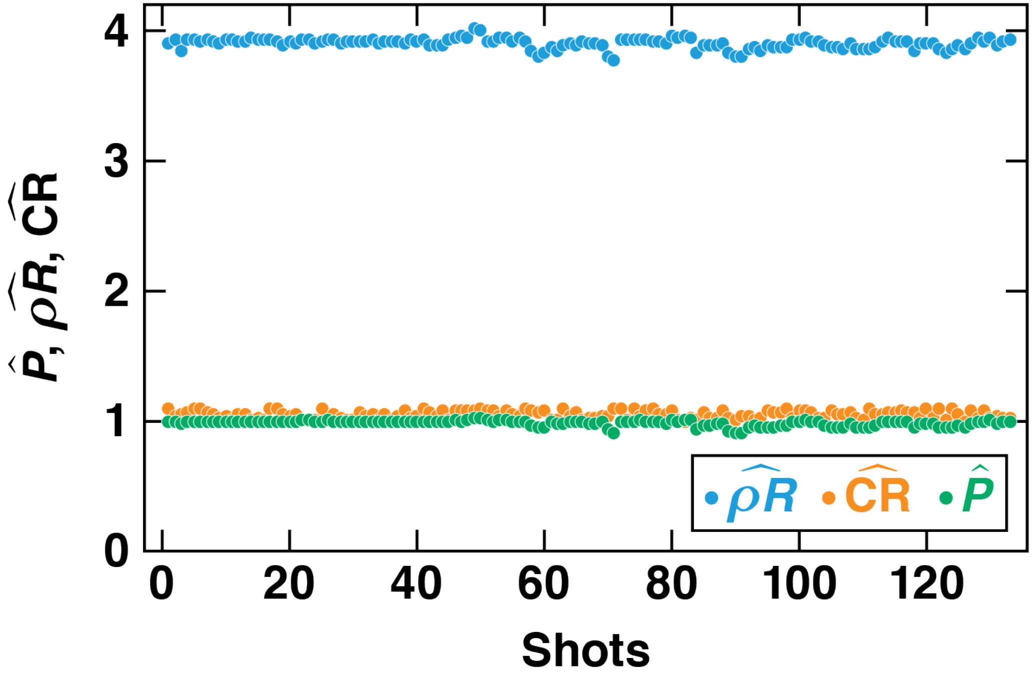
$\tau_{eq} = e - i\ equilibration\ rate$

$\tau_{eq}^{NIF} \sim \tau_{eq}^{Omega}$

$t_{imp}^{NIF} \sim 4 \times t_{imp}^{Omega}$

Scaled NIF implosions have more time for ions to lose energy to electrons; therefore, T_i and, consequently yield scaling, vary as a functions of implosion time.

Shell compression, inner convergence, and total pressure scale as expected



TC15536

$$\widehat{P} = \frac{\langle P_e + P_i \rangle_{n_{NIF}}}{\langle P_e + P_i \rangle_{n_{OMEGA}}}$$

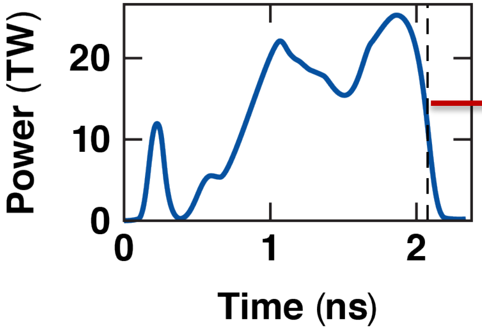
$$\widehat{\rho R} = \frac{\langle \rho R \rangle_{n_{NIF}}}{\langle \rho R \rangle_{n_{OMEGA}}}$$

$$\widehat{CR}^1 = \frac{\langle CR \rangle_{n_{NIF}}}{\langle CR \rangle_{n_{OMEGA}}}$$

Areal density scales with size, while total pressure and inner convergence are conserved.

[1] CR: convergence ratio

The radiation-hydrodynamic code *DEC2D* was used to simulate the effects of degradation mechanisms on no-alpha yield scaling with size

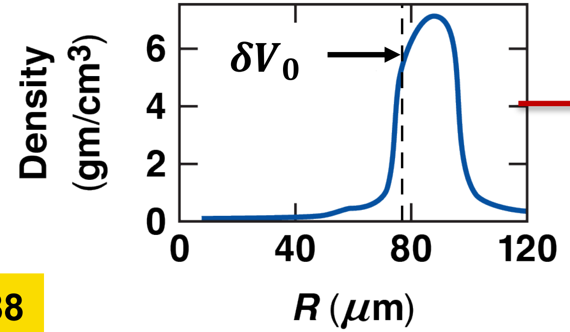


TC15537

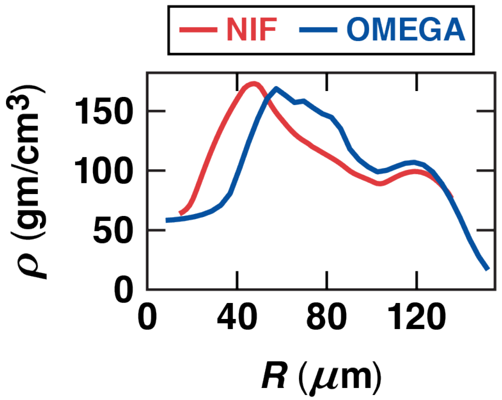
LILAC
ρ, u, P, T
profiles at
maximum V_{imp}

+

Shot 90288



DEC2D



Density profile through RT spike for l = 12 simulations

	Clean	Mode l = 2	Mode l = 12	Mode l = 12 (no thermal conditions)
Yield scaling exponent	4	4.02	3.91	3.98
YOC_{NIF}/YOC_{OMEGA}	N/A	1.01	0.82	1

*The RT instability for l ~ 12 in scaled NIF implosions experiences lower ablative stabilization (higher growth rates) because ablation velocity does not scale hydrodynamically; instead, $V_{abl} \sim R^{-0.5}$.

*A. Bose *et. al.*, Phys. Plasmas. 22. 072702 (2015).
YOC: yield over clean
RT: Rayleigh–Taylor

Summary/Conclusions

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Backup

Simulations with faster (100×) equilibration rates and without radiation were performed and results compared with simple analytical no-α scaling formulas

$$Y_{no-\alpha} \sim n^2 < \sigma v > V\tau \sim P^2 \frac{<\sigma v>}{T^2} V\tau$$

For $< T_i >$ in 4-5 keV range $\frac{<\sigma v>}{T^2} \sim \mathrm{T}$

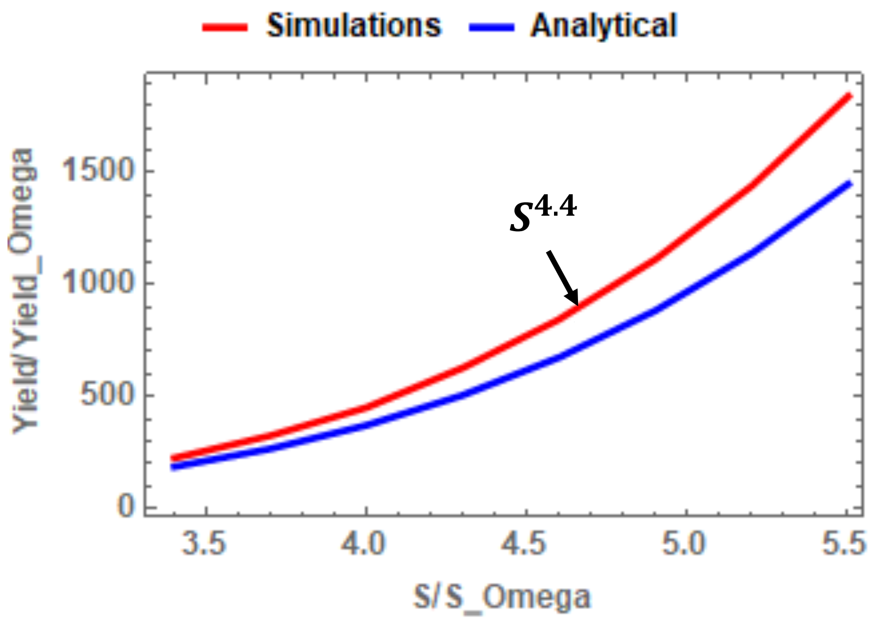
$$Y_{no-\alpha} \sim P^2 T V \tau$$

For hydrodynamic scaling P is conserved $V \sim S^3, \tau \sim S$

thermal conduction does not hydro-scale

Assuming T_i/T_e scales and neglecting radiation losses $T \sim S^{2/7}$

$$Y_{no-\alpha} \sim S^{2/7} S^3 S \sim S^{4.28}$$



Simulations suggest a faster 1-D no-α yield scaling compared to analytical scaling relations.