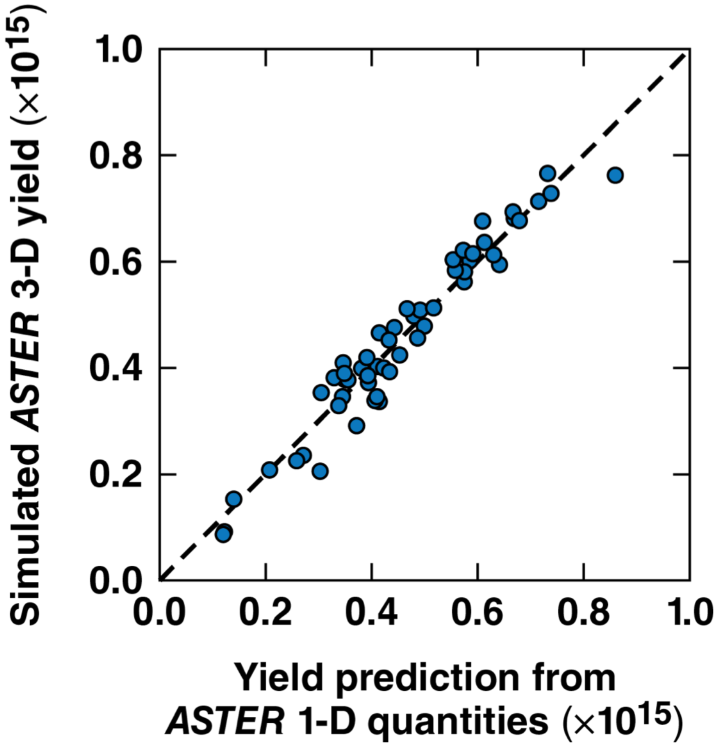
Improved Predictive Models and Further Progress in the Cryogenic Optimization Campaign on OMEGA



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Summary

Statistical models have been developed to simultaneously predict the yield, ρR, hot-spot radius, and ion temperature of cryogenic implosions on OMEGA

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- A synthetic database was developed to validate the statistical mapping methods in 3-D
- It is shown that the simulated 3-D yield can be predicted using simulated 1-D parameters if 3-D asymmetries are systematic
- A minimum 1-D yield was derived to assess the degradation in experimental yield caused by 3-D effects (2$\times$ degradation resulting from 3-D effects is inferred for OMEGA experiments)

Collaborators

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If experiments are systematically perturbed, it is possible to construct a predictive model from 1-D hydrocodes

Systematic perturbation seeds (constant)

Inputs not accounted for in simulations

Random perturbation seeds (negligible if experiments repeat)

$$O^{\text{exp}} = F_{\text{exp}}\Big[\underbrace{F_{\text{sim}}^{-1}\big(O_{\text{1-D}}^{\text{sim}}\big), I_{\text{other}}}, S_{\text{3-D}}^{\text{sys}}, S_{\text{3-D}}^{\text{ran}}\Big]$$

$$\boxed{O^{\text{exp}} \approx F_{\text{map}}\big[O_{\text{1-D}}^{\text{sim}}, I_{\text{other}}\big]}$$

Predict experiment from 1-D simulation

The stagnation effect of $S_{\text{3-D}}^{\text{sys}}$ can only be a function of $O_{\text{1-D}}^{\text{sim}}$ and I_{other}, and can be folded into F_{map}

*V. Gopalaswamy *et al.*, *Tripled yield in direct-drive laser fusion through statistical modelling*, Nature 565, 581–586 (2019).

The mapping model can be expanded with a set of basis functions with free parameters determined from data

$$O^{\mathrm{exp}} \approx F_{\mathrm{map}}\left[O^{\mathrm{sim}}_{1-\mathrm{D}}, I^{\mathrm{other}}\right]$$

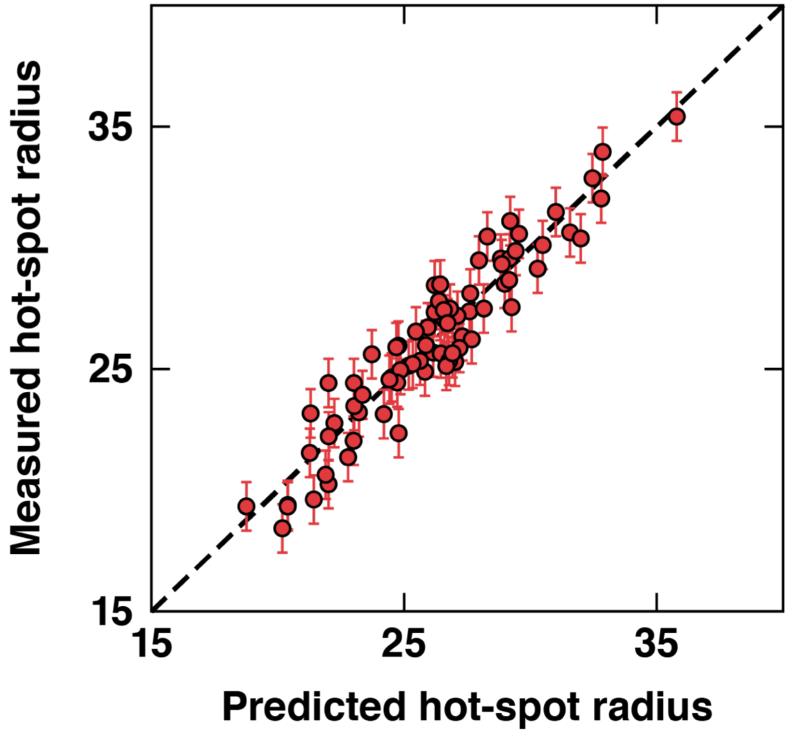
Power laws as basis function

$$F_{\mathrm{map}}\left[O^{\mathrm{sim}}_{1-\mathrm{D}}\right] = a_0 \prod \left(O^{\mathrm{sim}}_{\mathrm{i}}\right)^{a_{\mathrm{i}}} \prod \left(I^{\mathrm{other}}_{\mathrm{i}}\right)^{b_{\mathrm{i}}}$$

Free parameters a_{i}, b_{i} to be determined from data

$$O^{\mathrm{exp}} \approx a_0 \prod \left(O^{\mathrm{sim}}_{\mathrm{i}}\right)^{a_{\mathrm{i}}} \prod \left(I^{\mathrm{other}}_{\mathrm{i}}\right)^{b_{\mathrm{i}}}$$

Free parameters can be determined by χ^2 minimization, Bayesian inference, etc.



$$R_{\mathrm{exp}} = 0.4\,\tau^{-0.06}\langle\rho R\rangle^{-0.5}\left(\frac{\mathrm{IFAR}}{\mathrm{IFAR}}\right)^{-0.44} t_{\mathrm{rel}}^{-2.7} t_{\mathrm{coast}}^{-2} R_0^{1.3}$$

The choice of basis function and regression variables are up to the physicist.

$\overline{\text{IFAR}}$: in-flight aspect ratio

The accuracy of predictive models depends on the ability to predict 3-D effects from 1-D simulated quantities

Consider systematically perturbed 3-D implosions with "perfect" 1-D simulations

$$O_{\mathrm{exp}}^{3-\mathrm{D}} = F_{\mathrm{exp}}\left[F_{\mathrm{sim}}^{-1}\left(O_{\mathrm{sim}}^{1-\mathrm{D}}\right), S_{3-\mathrm{D}}^{\mathrm{sys}}, 0\right] = F_{\mathrm{map}}\left[O_{\mathrm{sim}}^{1-\mathrm{D}}, S_{3-\mathrm{D}}^{\mathrm{sys}}\right]$$

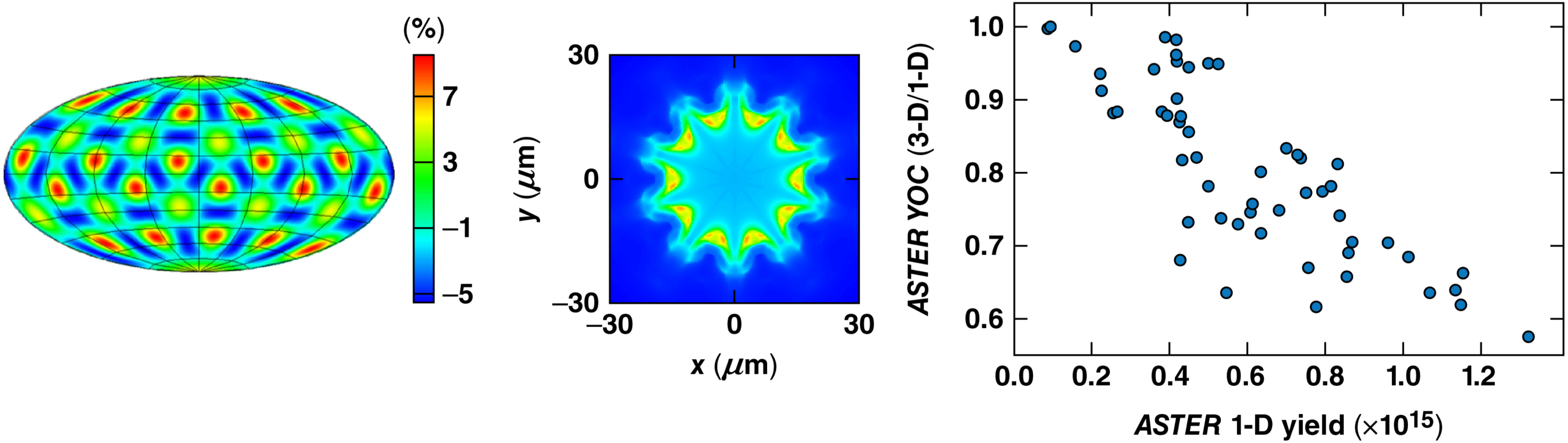
F_{map} is an identity function if $S_{3-\mathrm{D}}^{\mathrm{sys}} = 0$

Use synthetic datasets as a stand-in for the experiment (3-D simulations) and simulation (1-D simulations)

$$O_{3-\mathrm{D}} = F_{3-\mathrm{D}}\left[F_{1-\mathrm{D}}^{-1}\left(O_{1-\mathrm{D}}\right), S_{3-\mathrm{D}}^{\mathrm{sys}}, 0\right] = F_{\mathrm{map}}\left[O_{1-\mathrm{D}}, S_{3-\mathrm{D}}^{\mathrm{sys}}\right]$$

A 3-D synthetic database of distorted implosions is generated using ASTER3D*

Severe beam-geometry perturbations were imposed using small (SG5-650) phase plates.

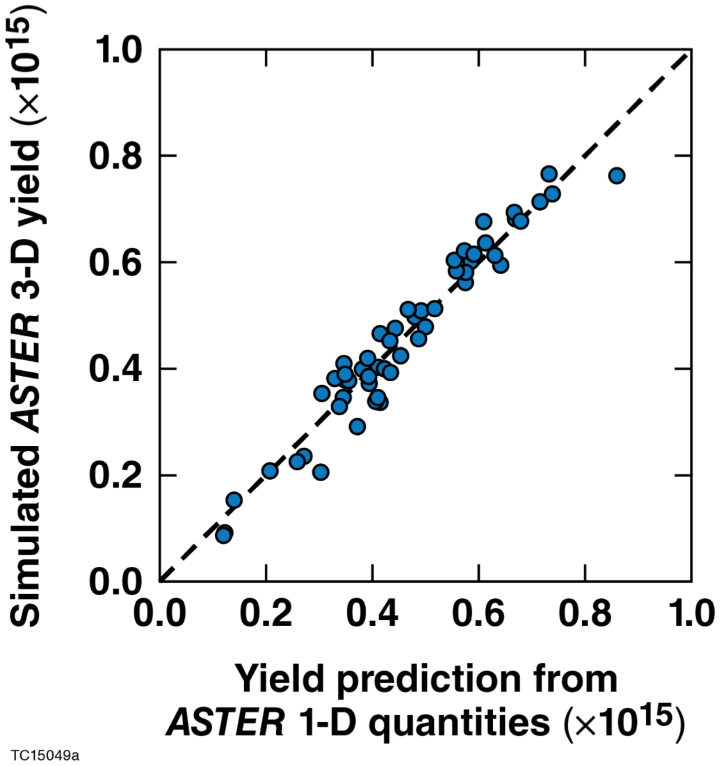


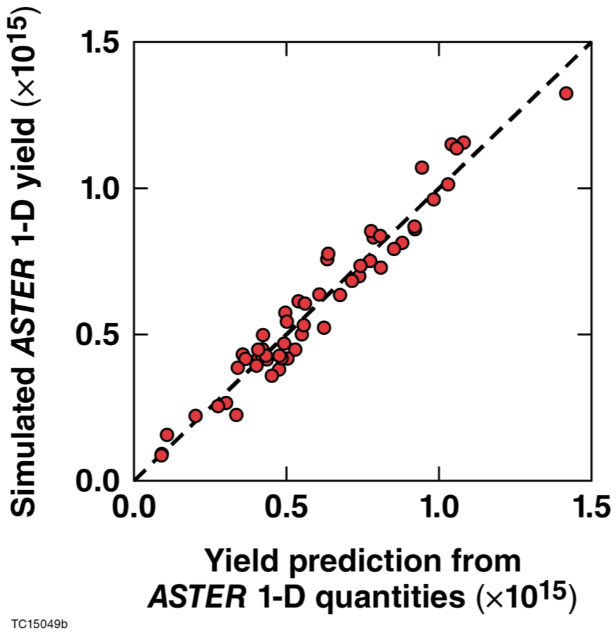
TC15048A

Simulations were run using *ASTER with no radiation transport or CBET.**

*I. V. Igumenshchev *et al.*, Phys. Plasmas 23, 052702 (2016).
CBET: cross-beam energy transfer

The statistical model is able to account for systematic port-geometry illumination asymmetries





$$Y_{ASTER\ 3-\mathrm{D}} \propto \rho R_{ASTER\ 1-\mathrm{D}} v^{4}_{ASTER\ 1-\mathrm{D}}$$

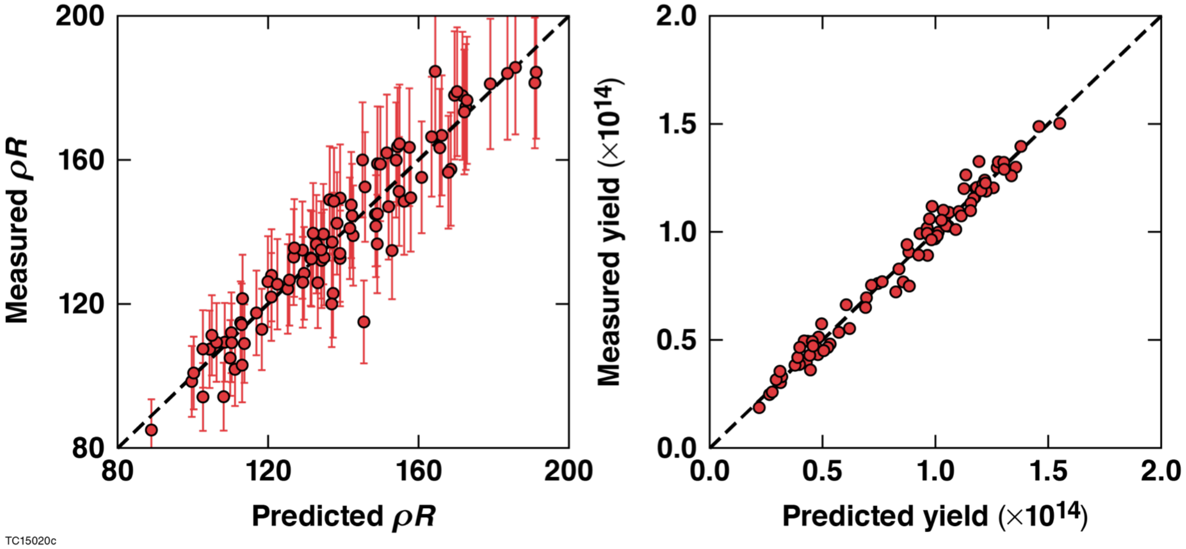
$$Y_{ASTER\ 1-\mathrm{D}} \propto \rho R^{1.5}_{ASTER\ 1-\mathrm{D}} v^{5.5}_{ASTER\ 1-\mathrm{D}}$$

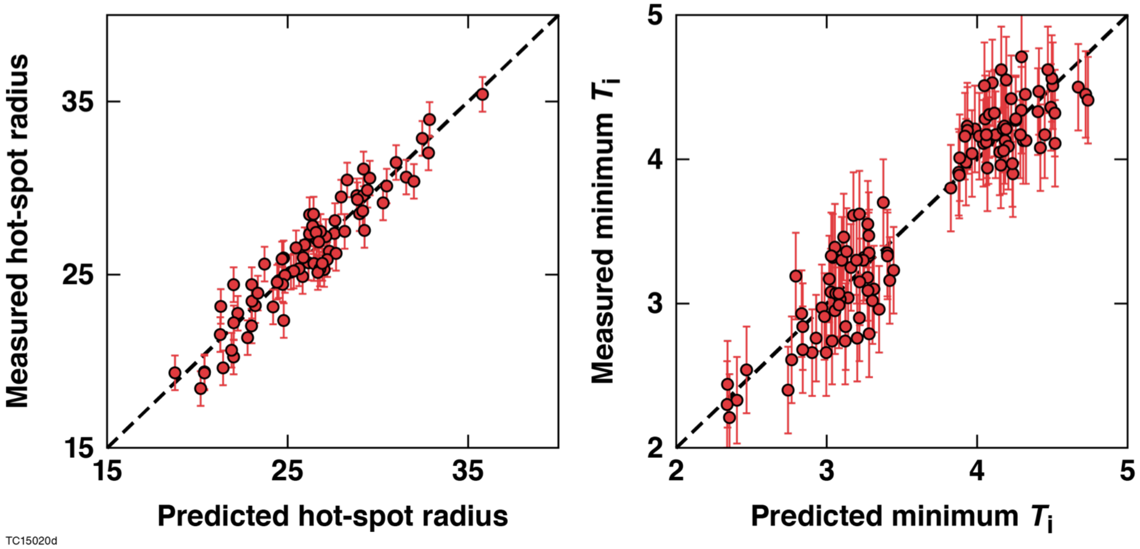
$$Y_{\mathrm{exp}} \propto \rho R^{0.3}_{LILAC} v^{4}_{LILAC}$$

Asymmetries lead to a weaker yield dependence on velocity and ρR as observed in experiments.

A predictive model for experimental OMEGA yields, ρR, T_i, and hot-spot radius has been developed

T_i predictions are the most inaccurate because of flows along the different nTOF LOS.





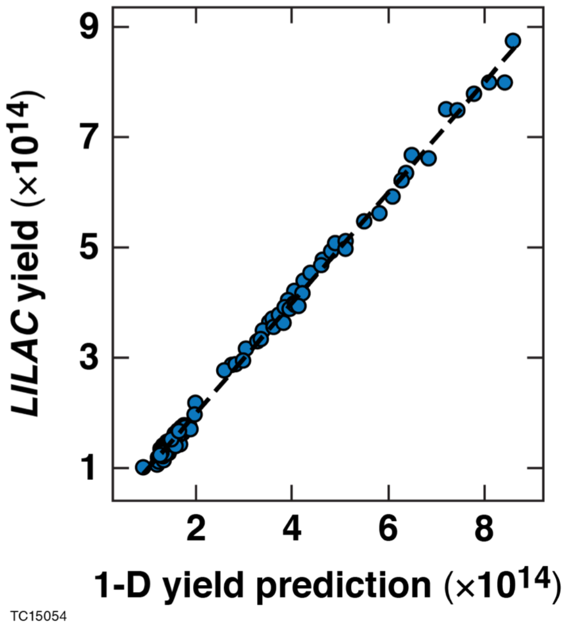
Consistent predictions lead to increased confidence in designs.

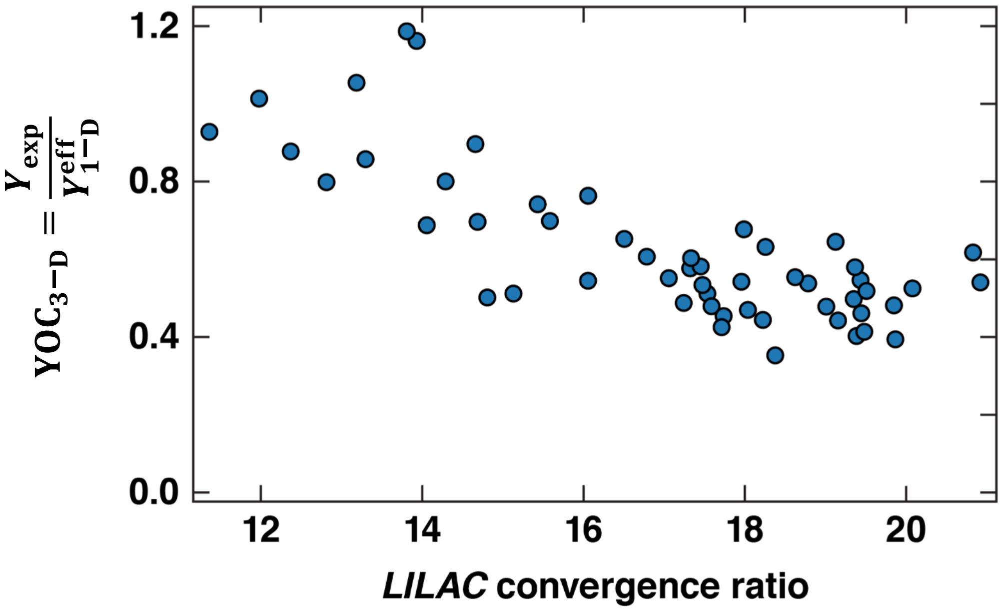
nTOF: neutron time of flight
LOS: line of sight

The yields of the best-performing implosions appear to be degraded by at least 2× with respect to 1-D

$Y^{\text{eff}}_{1-\text{D}}$ is the yield expected from a sphere of plasma with burn volume V_{hs}, thermal temperature T_{i}, and areal density ρR_{n}.

$$Y^{\text{eff}}_{1-\text{D}} \approx 2.3 \times 10^{14} \left(\frac{V_{\text{hs}}^{\mu\text{m}^3}}{6.5 \times 10^4}\right)^{0.63} \left(\frac{T_{\text{i}}^{\text{keV}}}{4}\right)^{3.8} \left(\frac{\rho R_{\text{n}}^{\text{mg/cm}^2}}{200}\right)^{1.7}$$



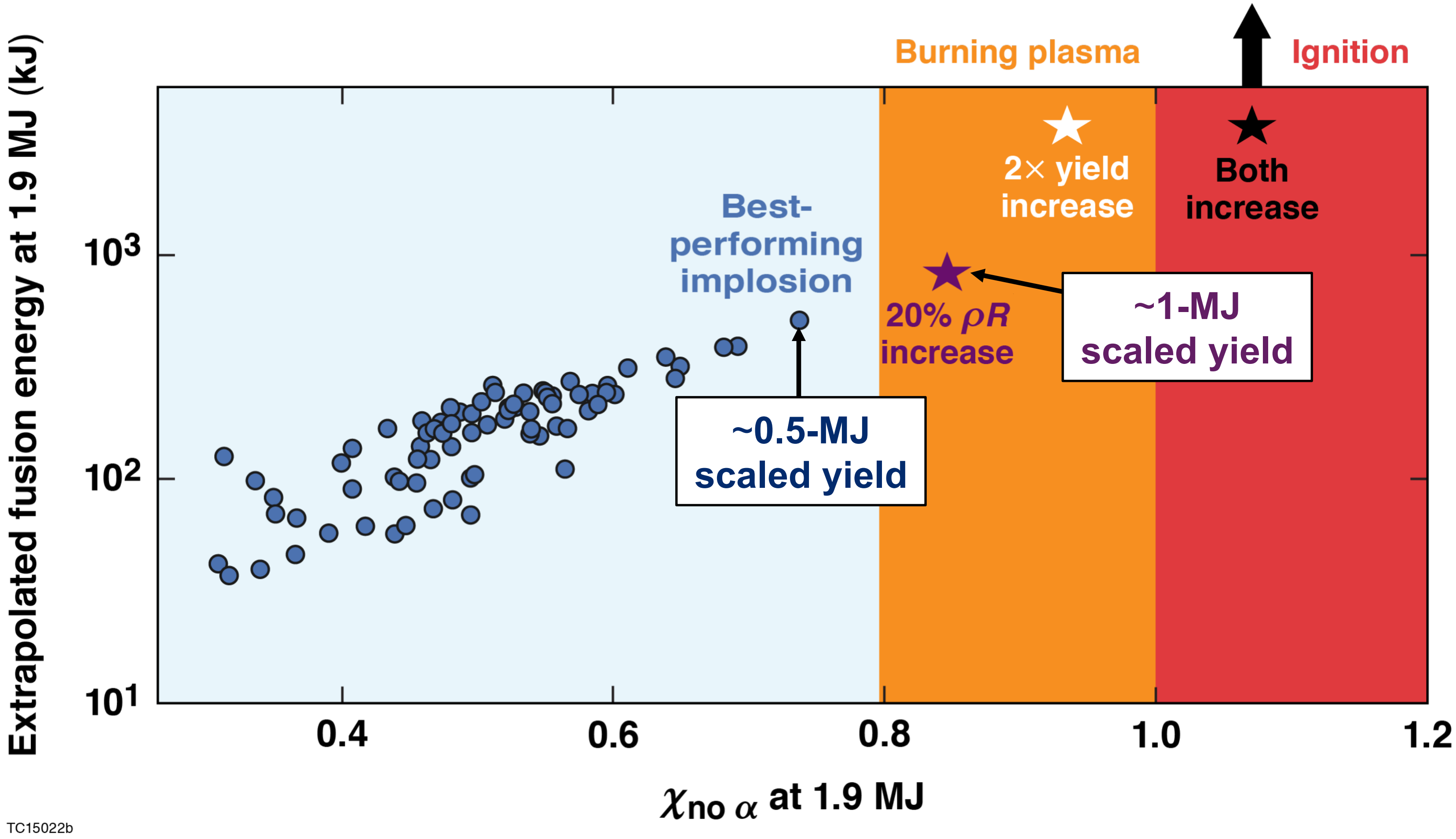


An ~2× drop in yield should be explained by 3-D effects, consistent with D. Patel's analysis.*

*D. Patel *et al.*, BO5.00007, this conference.

YOC: yield-over-clean

The possibility of hydroscaled megajoule yields for symmetric direct drive on the NIF exists with modest performance improvements in current OMEGA implosions



A. Christopherson, UI2.00001, this conference (invited).
NIF: National Ignition Facility

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