Progress in the U.S. Inertial Confinement Fusion Program

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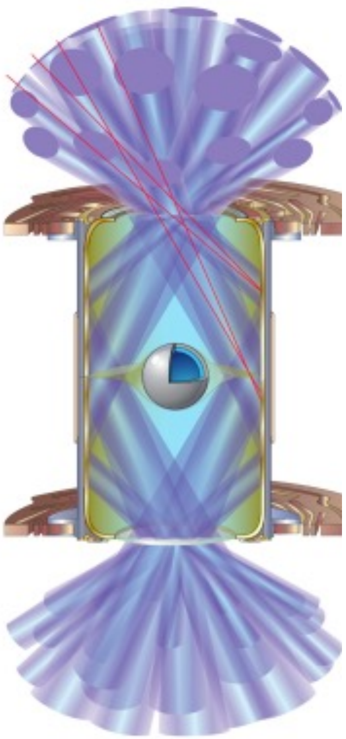
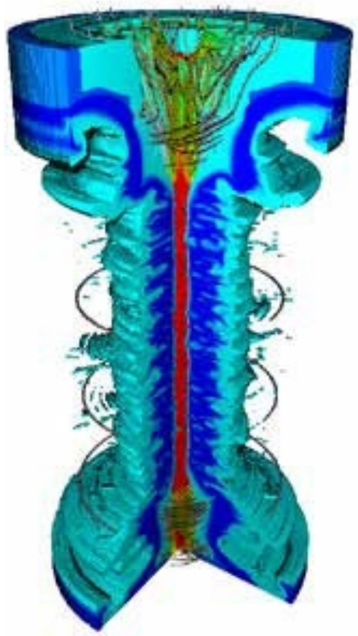
In the US there are three major approaches to achieving ignition and high yield through inertial fusion

Laser indirect-drive

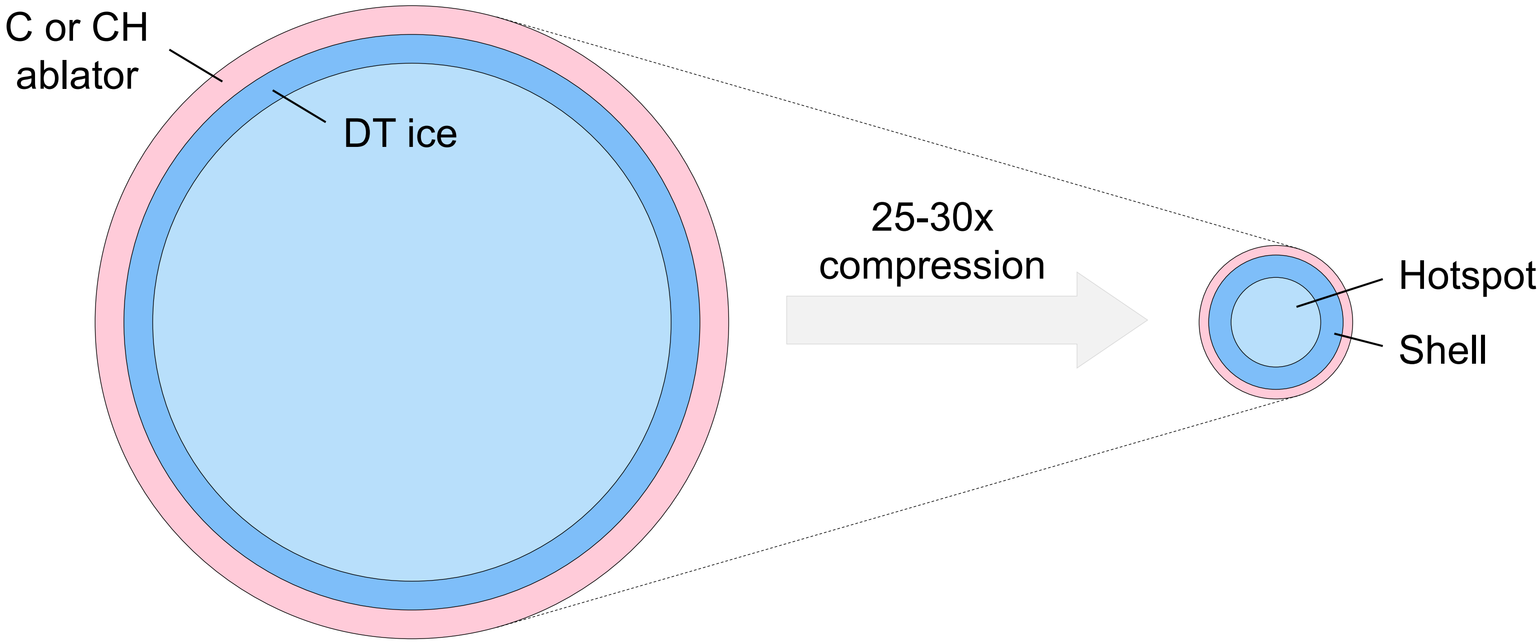


Laser direct-drive

Magnetic direct-drive

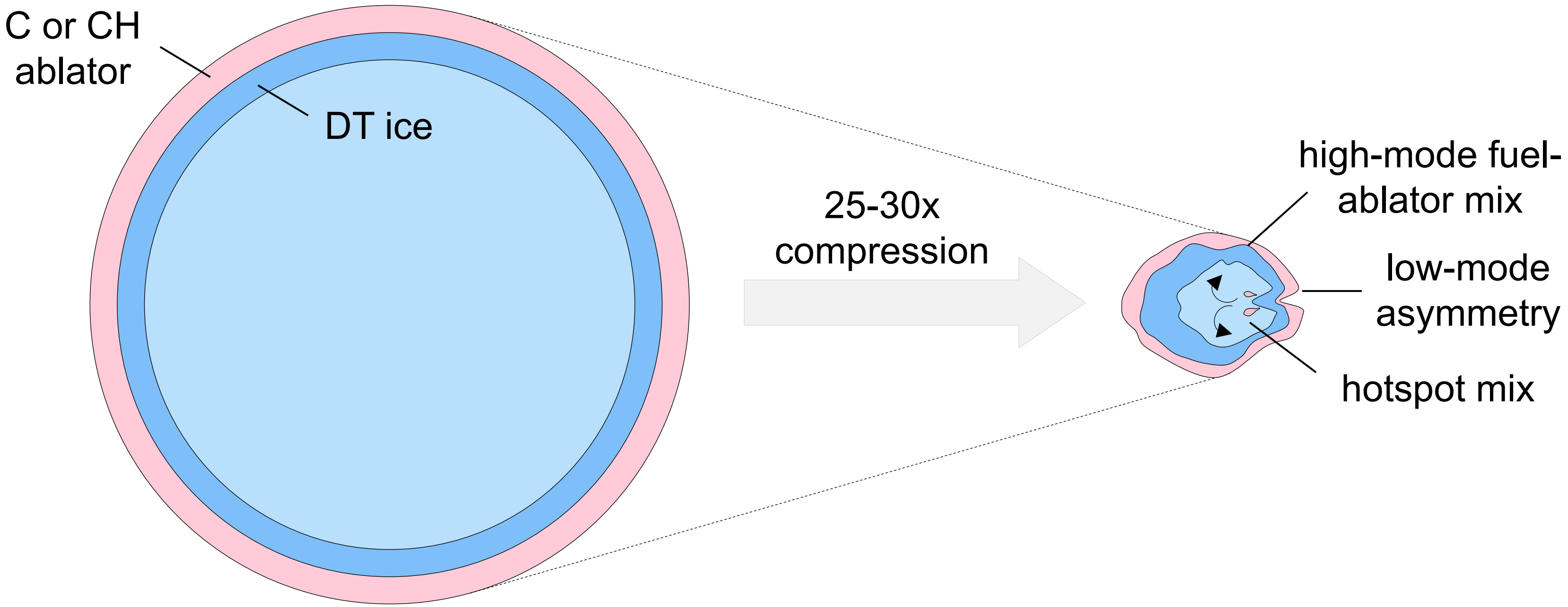


In x-ray and laser-drive we use spherical compression to achieve the densities and temperatures needed for ignition



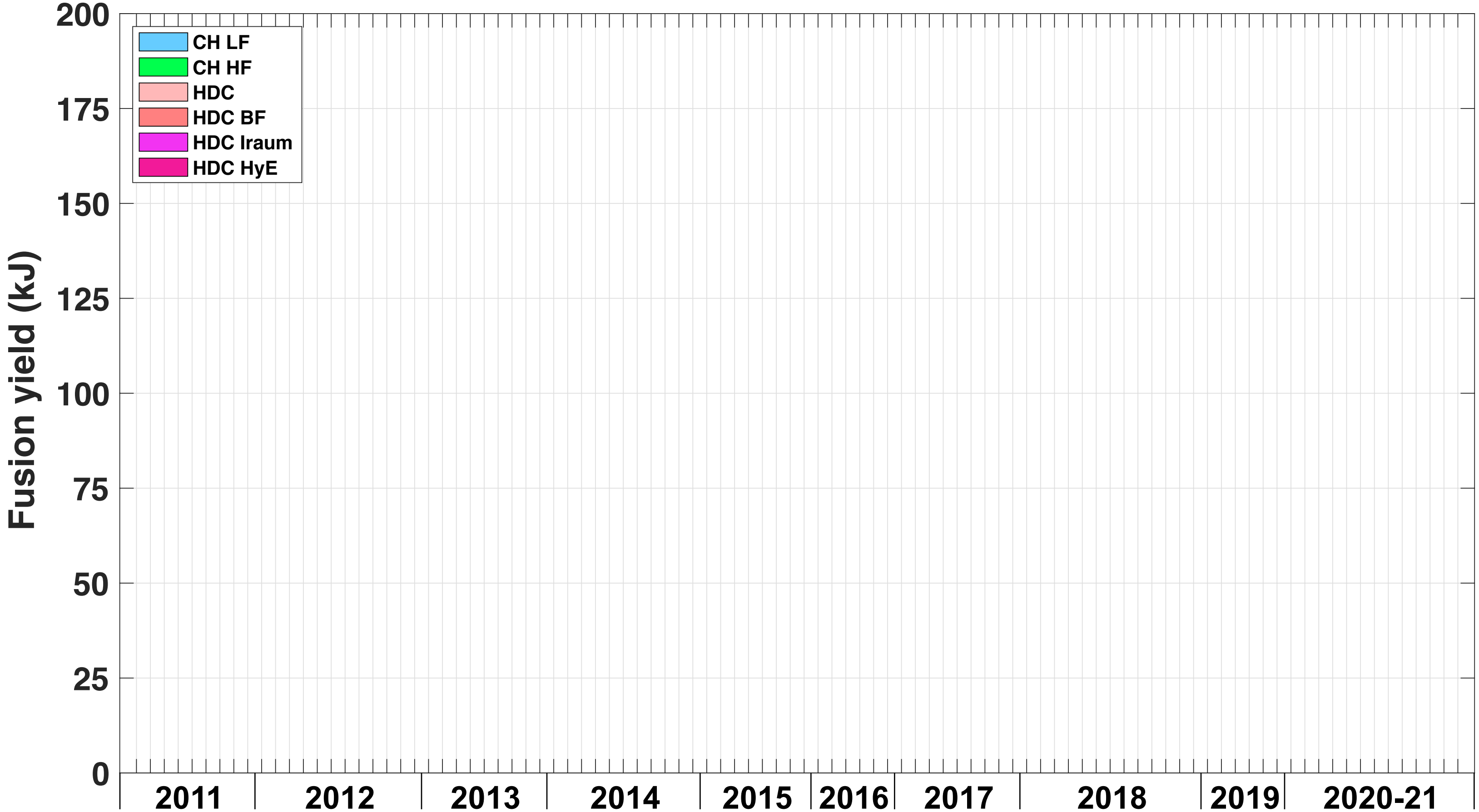
Kinetic energy of the imploding shell converted to internal energy on stagnation

In practice a variety of 3D effects can degrade the efficiency of the implosion from the ideal 1D



- High-mode mix reduces compressibility of the DT shell
- Low-mode asymmetry reduces the efficiency of converting shell kinetic energy to internal energy
- Ablator mix in hotspot increases radiation losses

Progress in ignition experiments on the NIF



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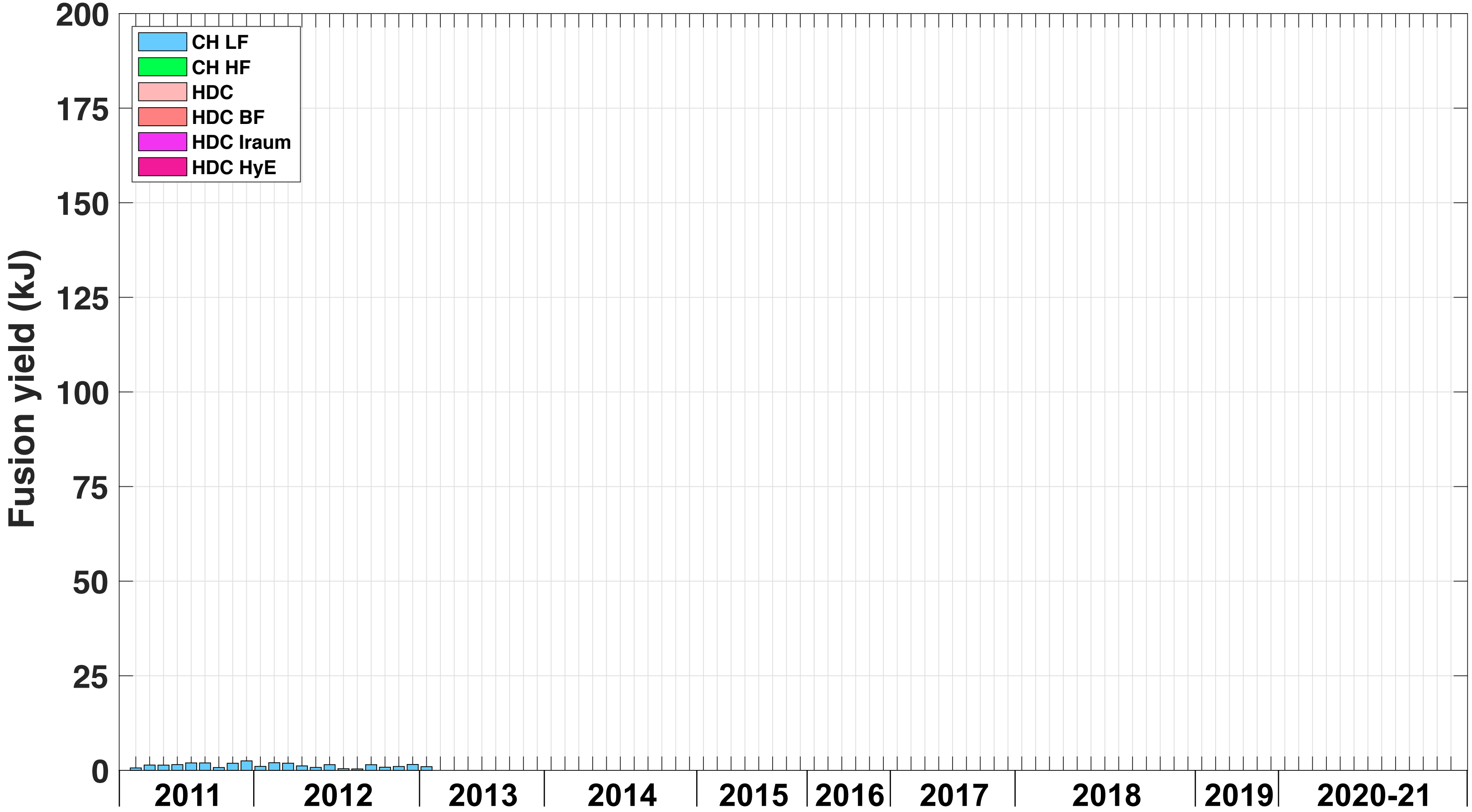

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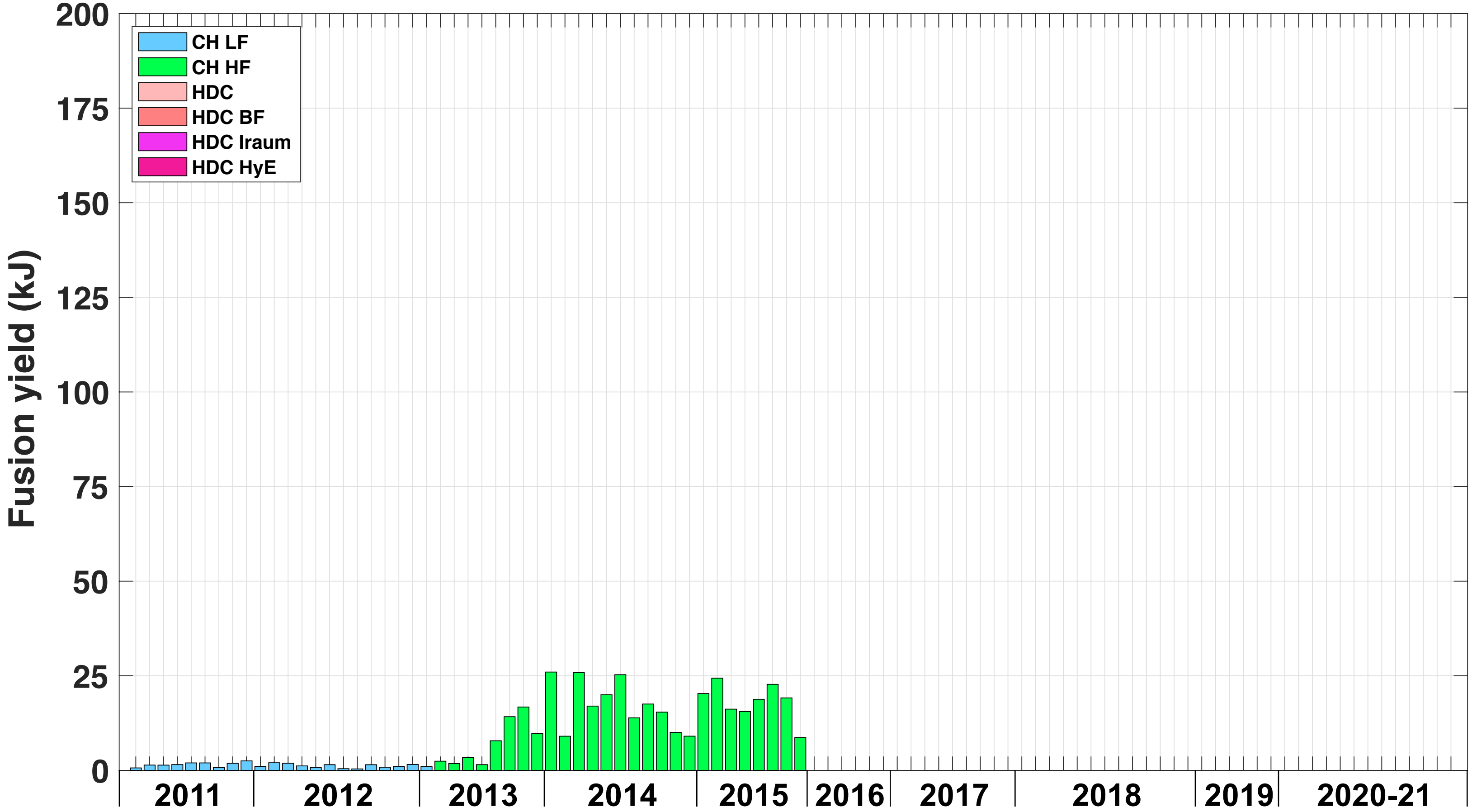

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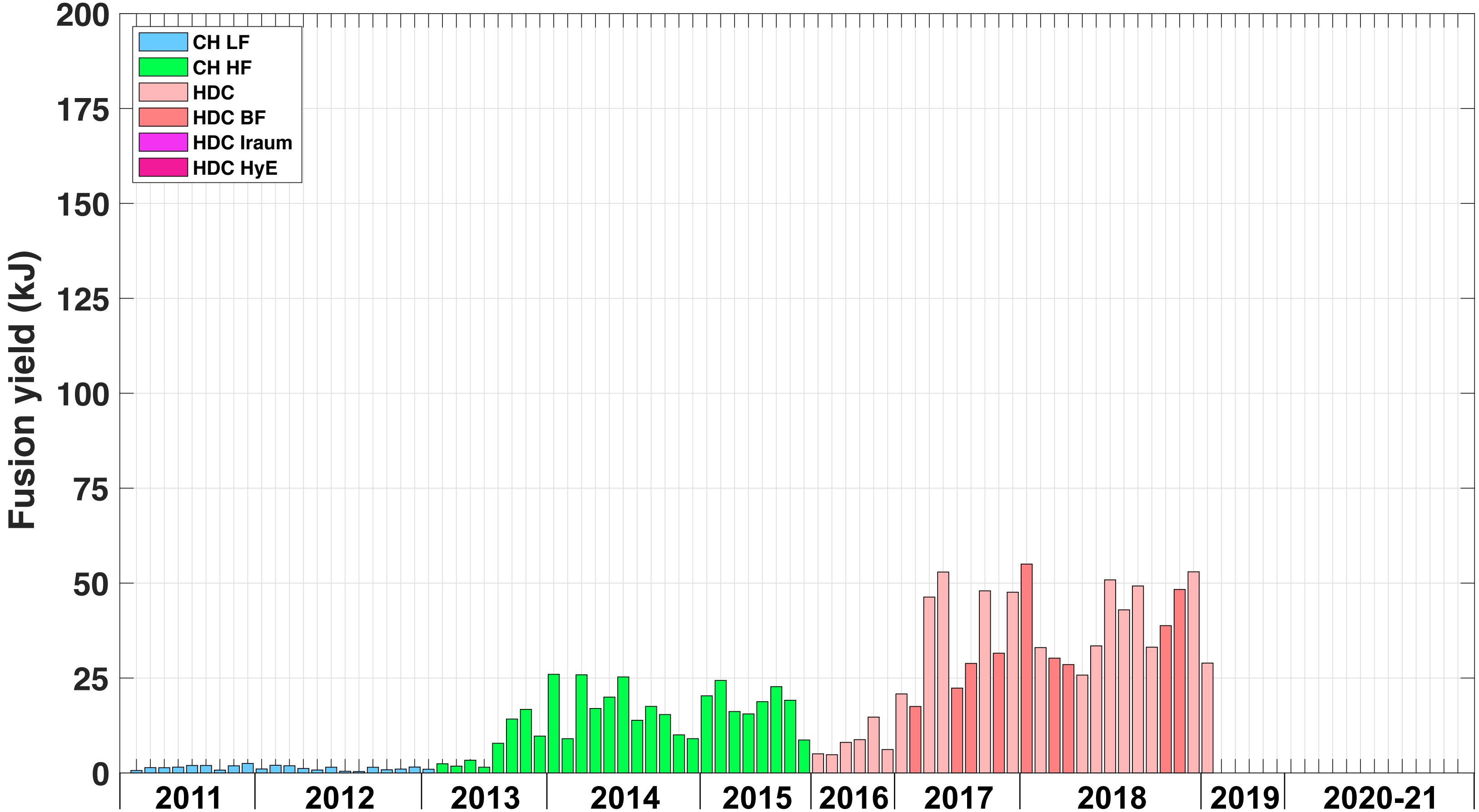

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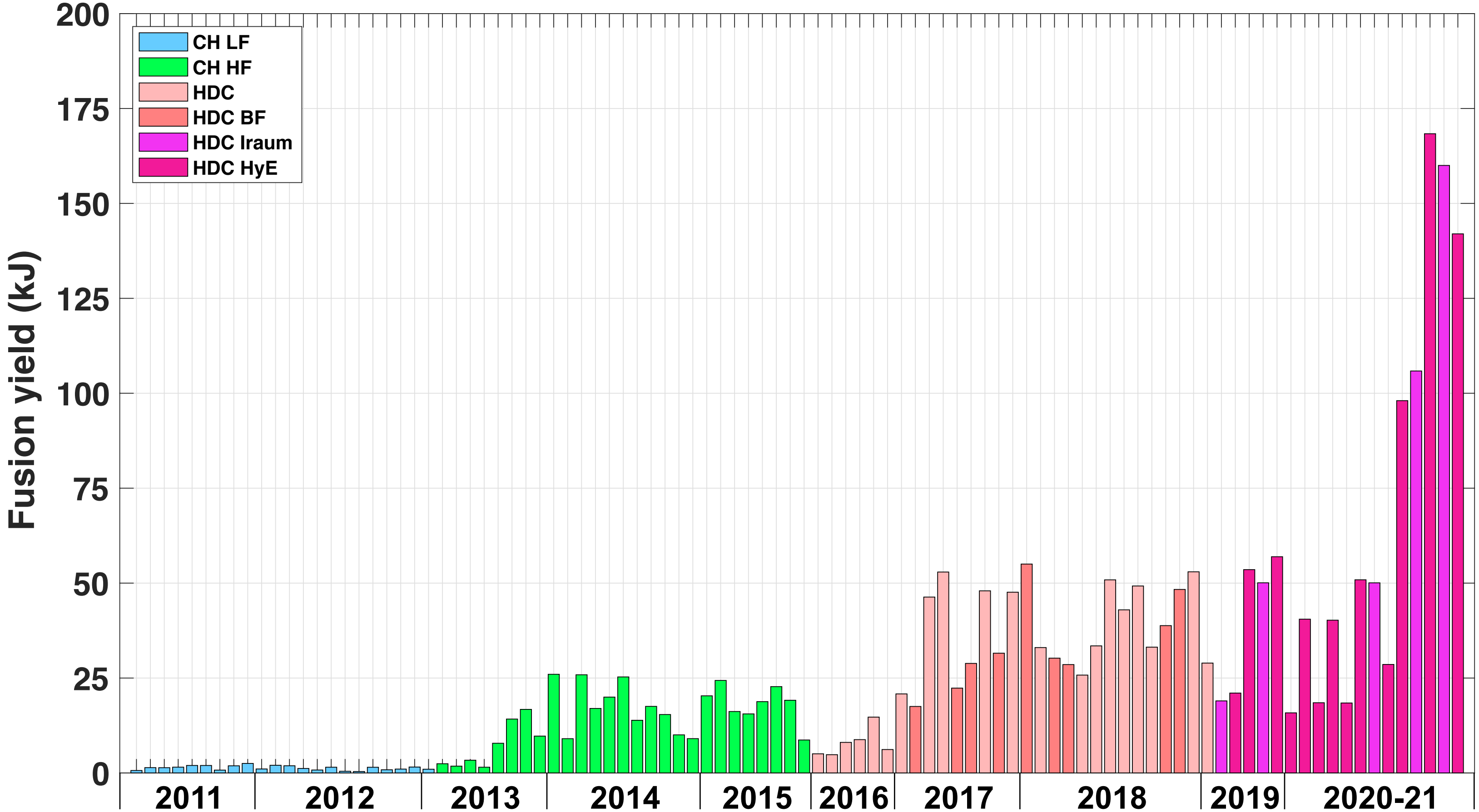
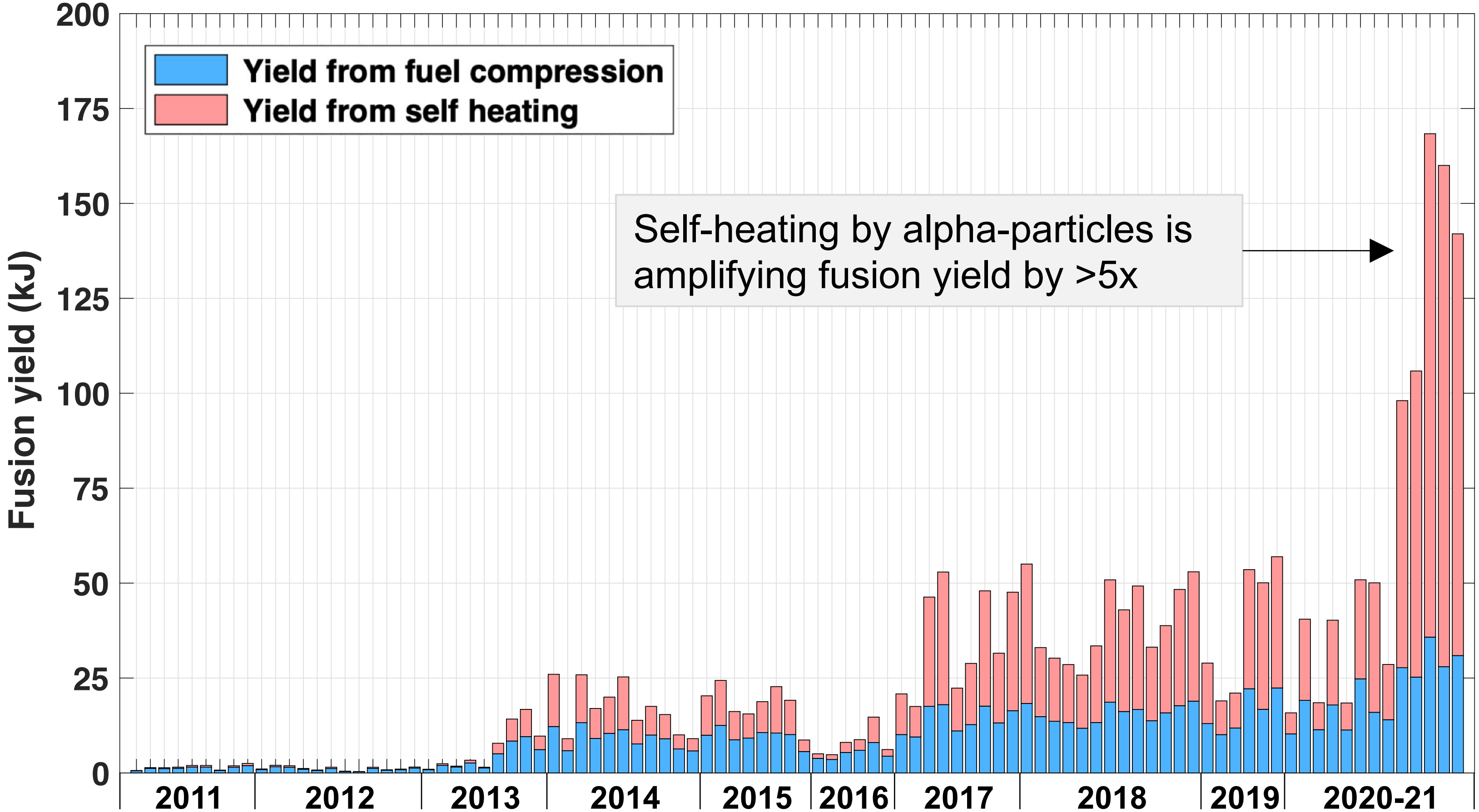


Progress in ignition experiments on the NIF



We can examine proximity to ignition in terms of a Generalized Lawson Criterion (GLC)

Alpha particle heating rate > hotspot energy loss rate

$$\varepsilon_\alpha \, dY_n/dt > \tfrac{3}{2} PV/\tau$$

$$dY_n/dt = \tfrac{1}{4} n^2 \langle \sigma v \rangle_{DT} V$$

$$\Rightarrow \quad P\tau \frac{\langle \sigma v \rangle_{DT}}{T^2} \varepsilon_\alpha / 24 > 1$$

$$\Rightarrow \quad P\tau S(T) \varepsilon_\alpha / 24 > 1$$

$$S(T) = \frac{\langle \sigma v \rangle_{DT}}{T^2}$$

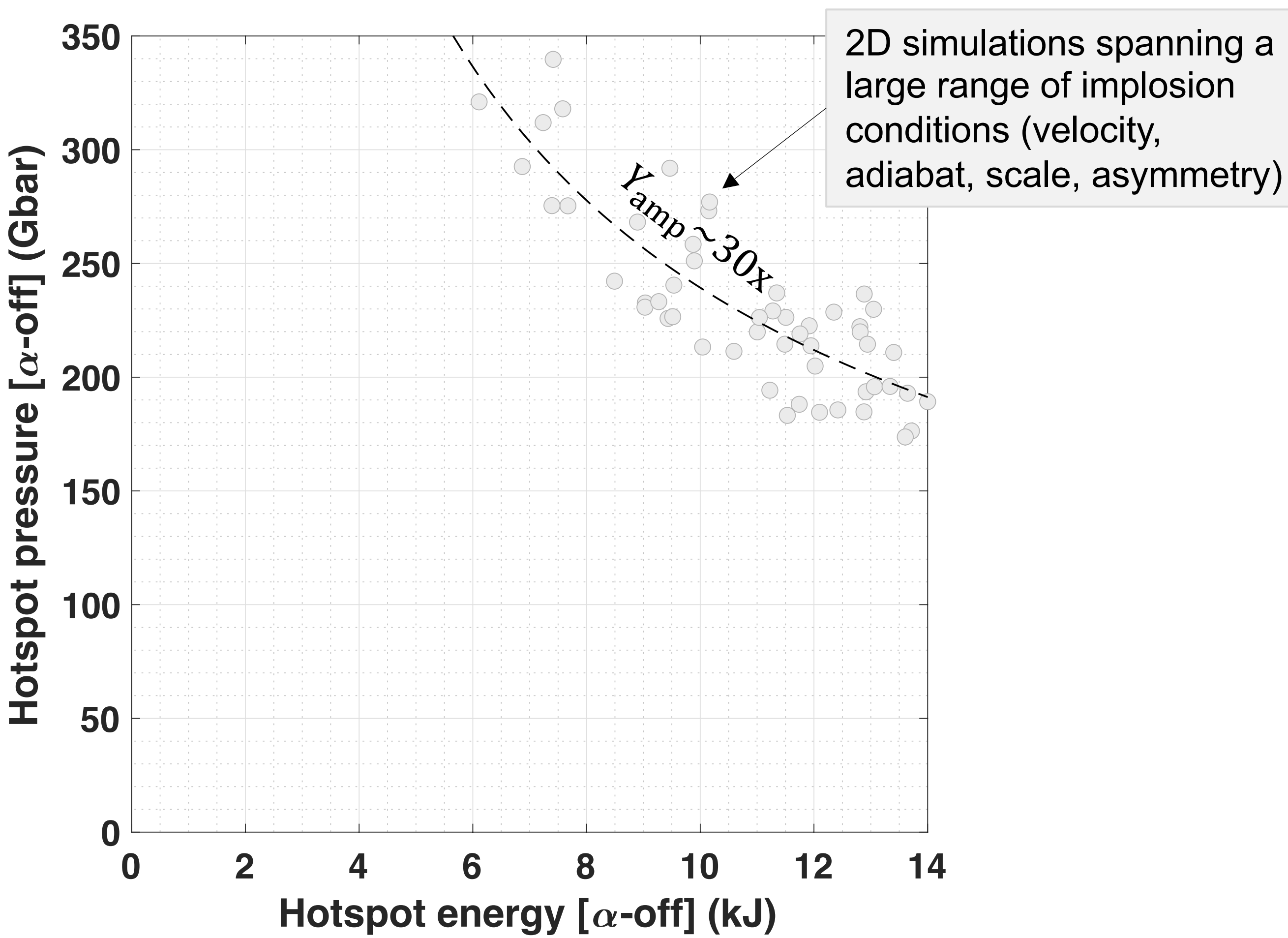
$$GLC \equiv \frac{P\tau}{P\tau_{\mathrm{ign}}}$$

$$P\tau_{\mathrm{ign}}(T) = \frac{24}{\varepsilon_\alpha S(T)}$$

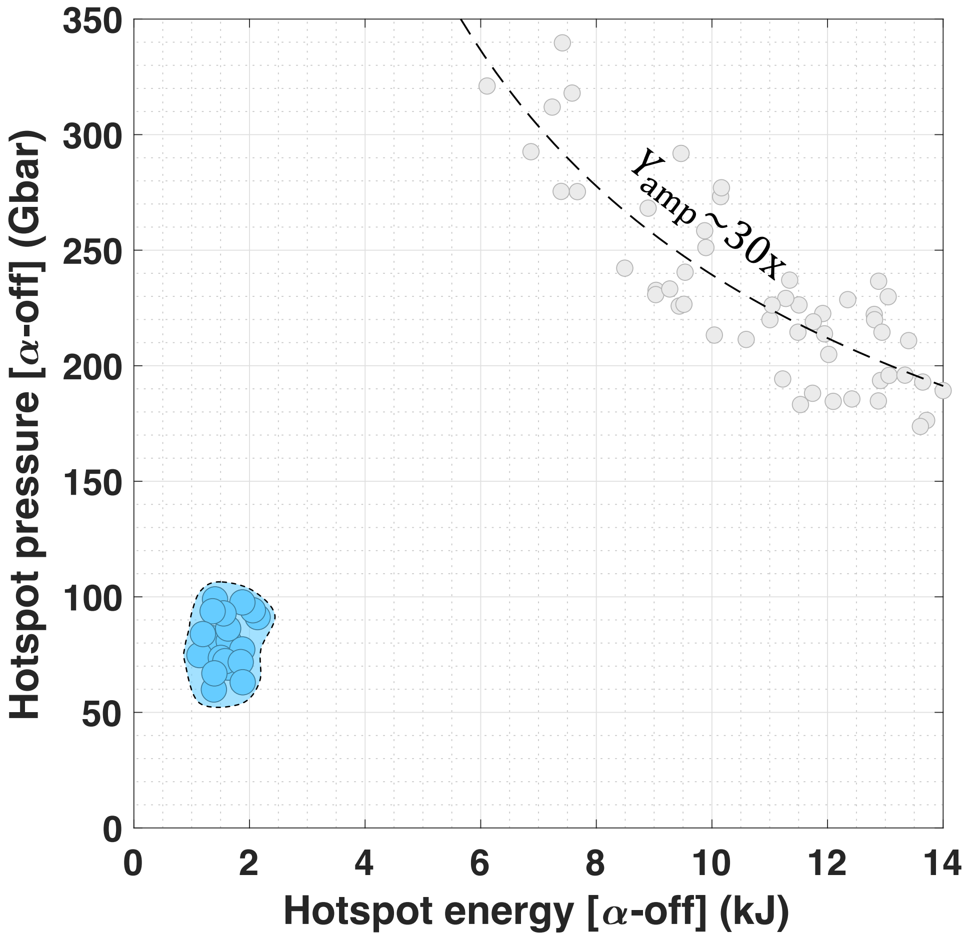
A convenient form of $P\tau$ is $(P\tau)^3 \propto P^3 R^3 \propto P_{hs}^2 E_{hs}$

R. Betti, Phys. Plasmas **17**, 058102 (2010)

Ignition boundary (Y_{amp}~30x) is quite well defined in hotspot pressure-energy space



Title and text and more text



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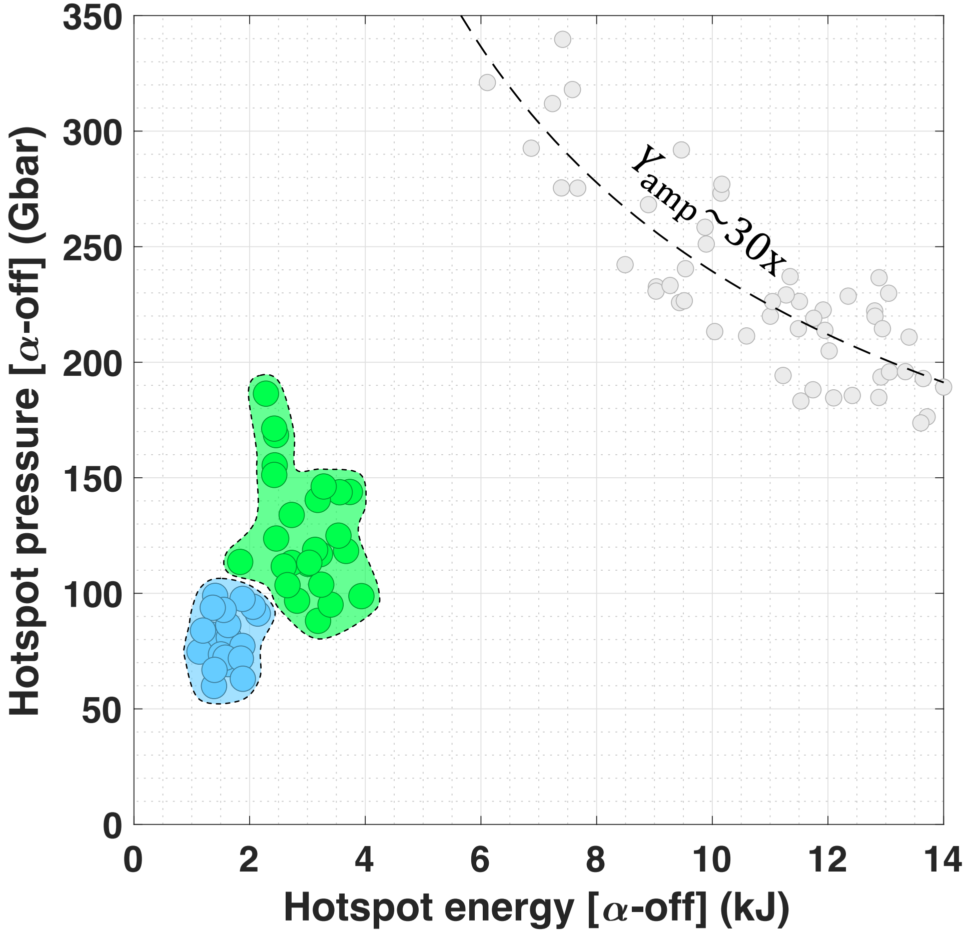

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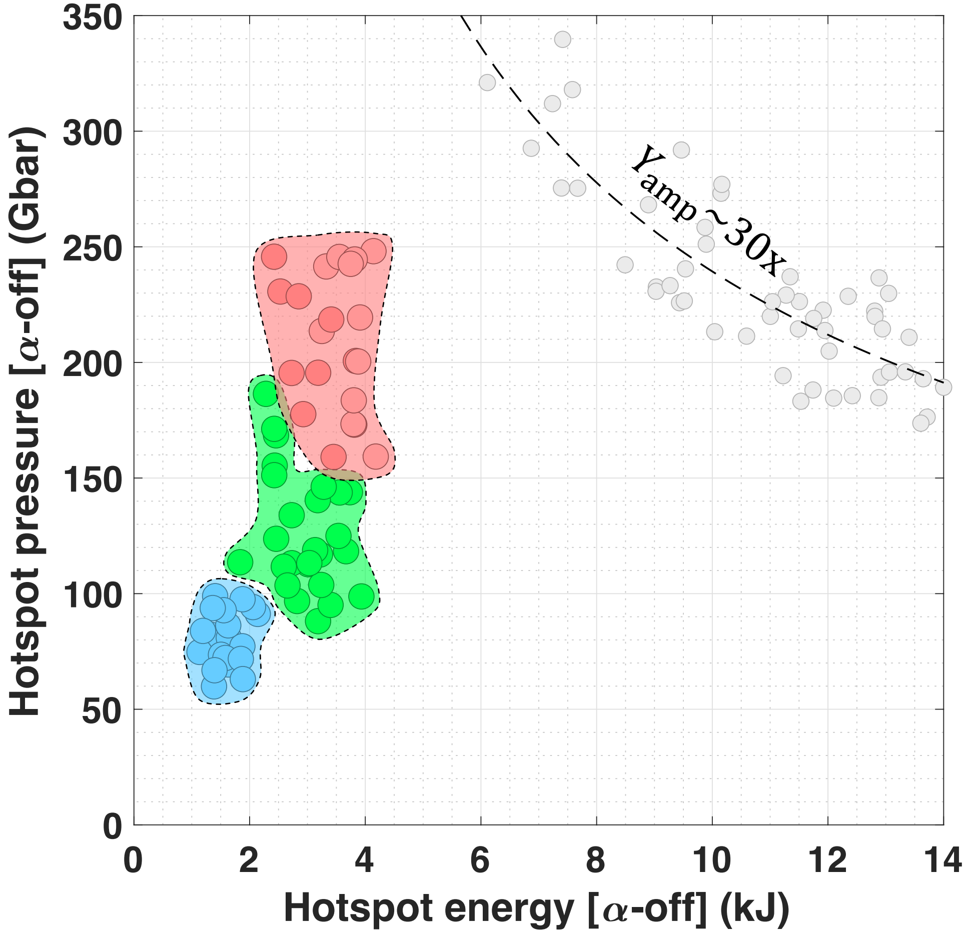

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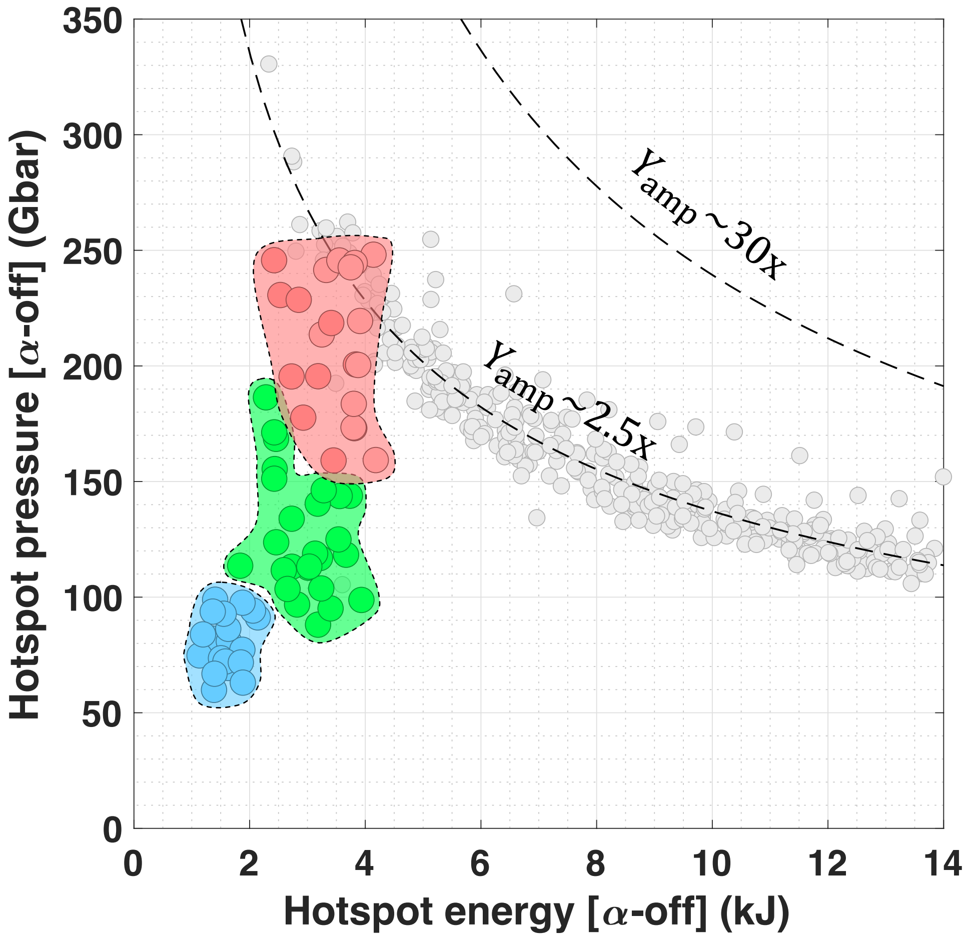

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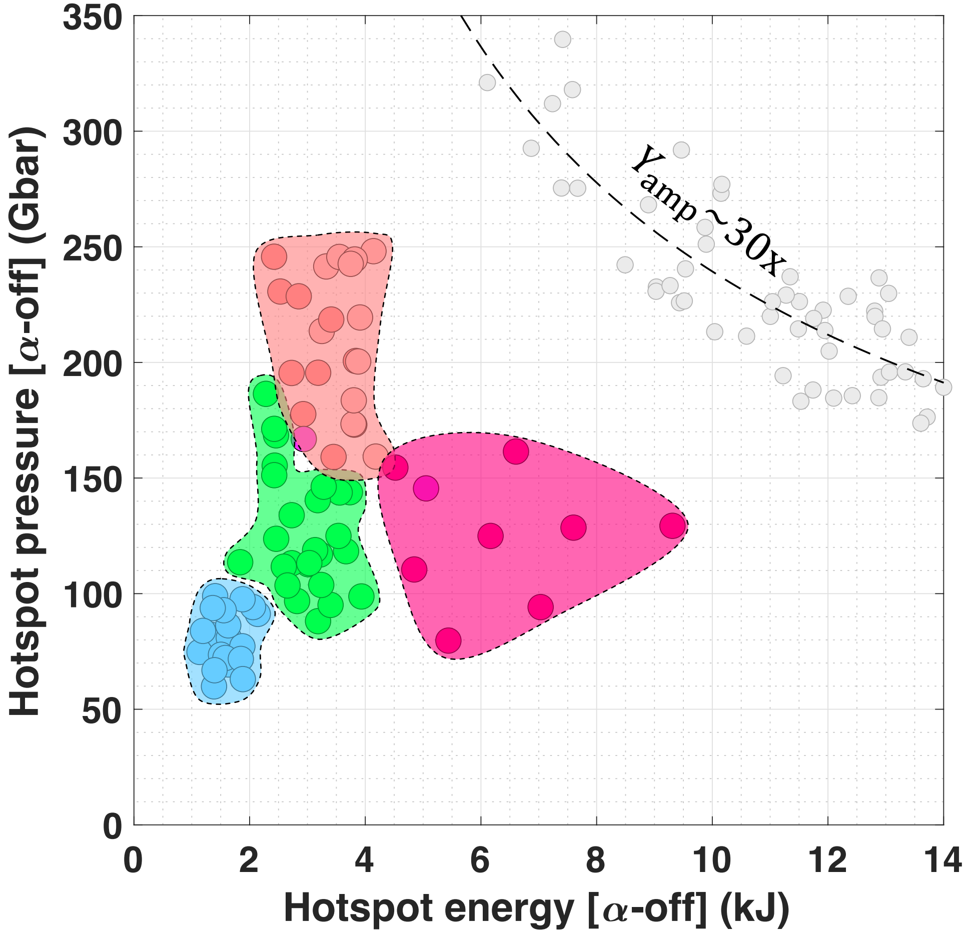

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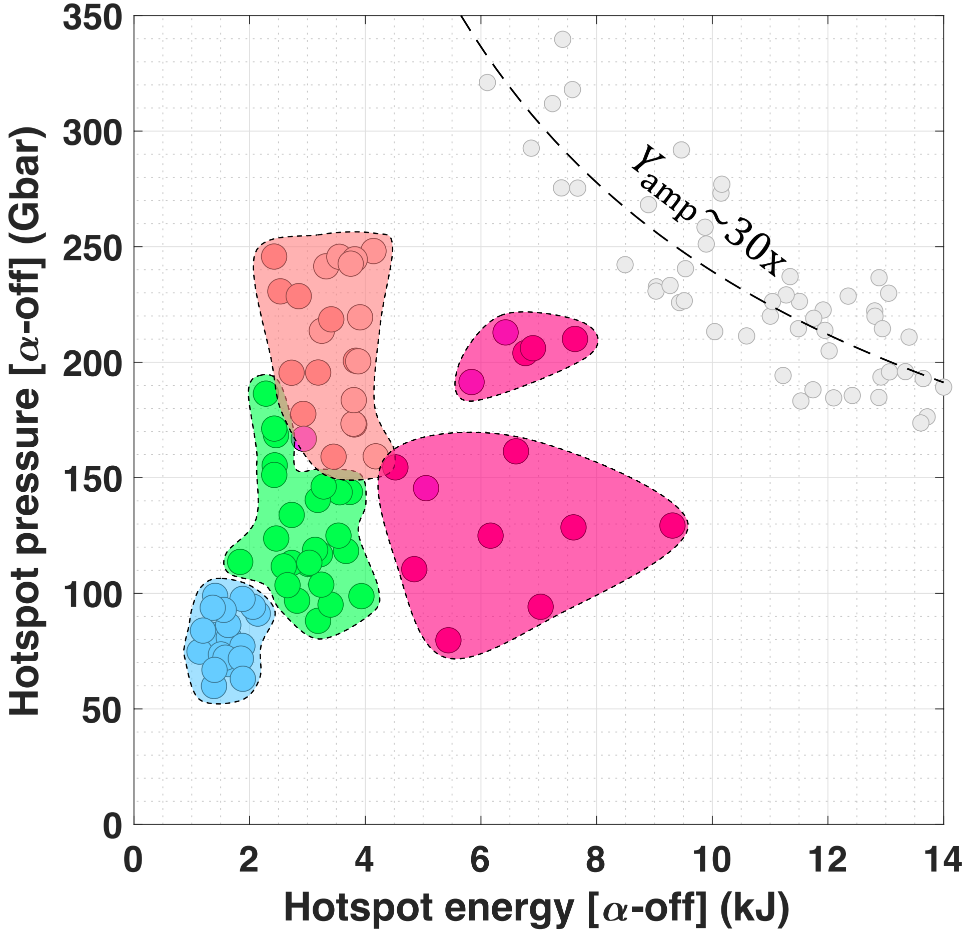

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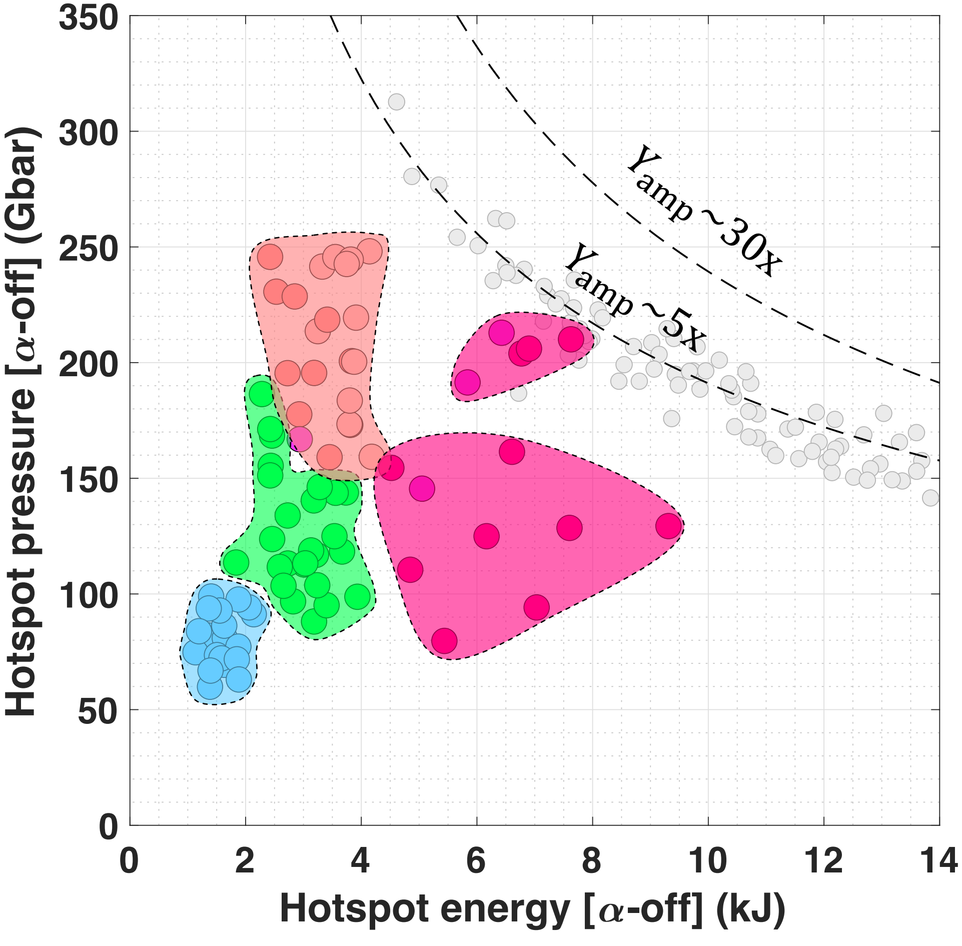

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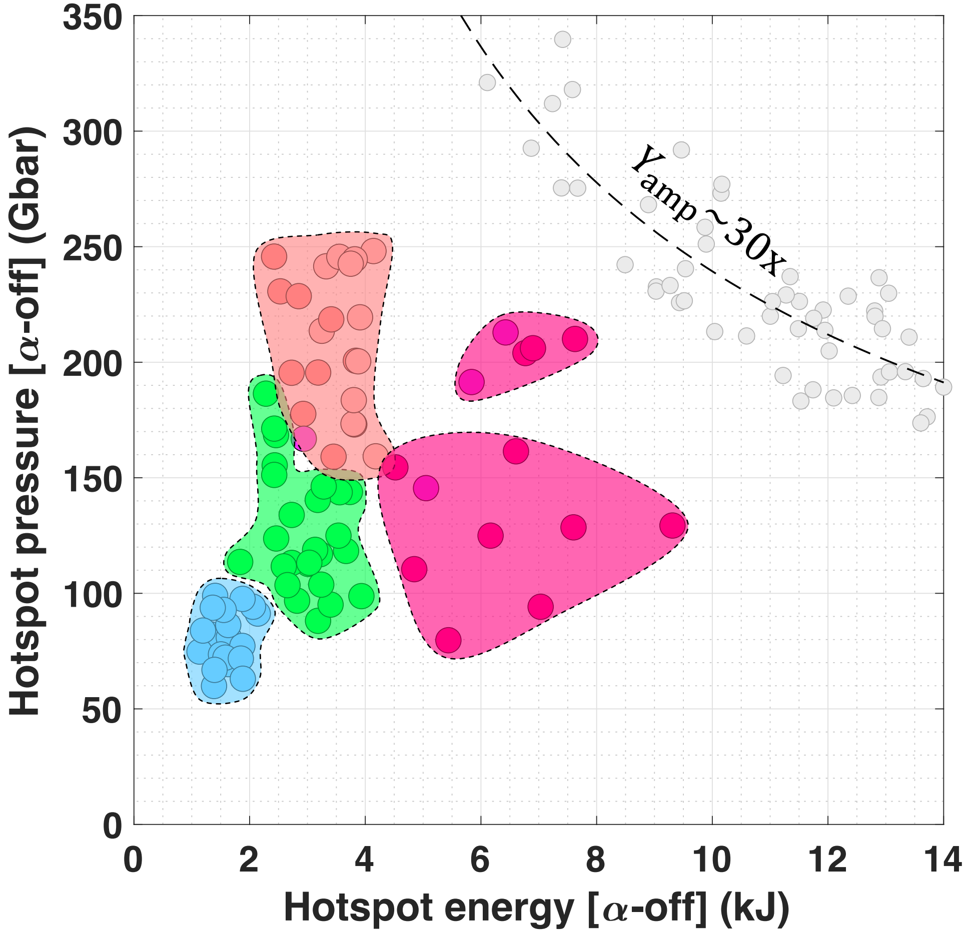
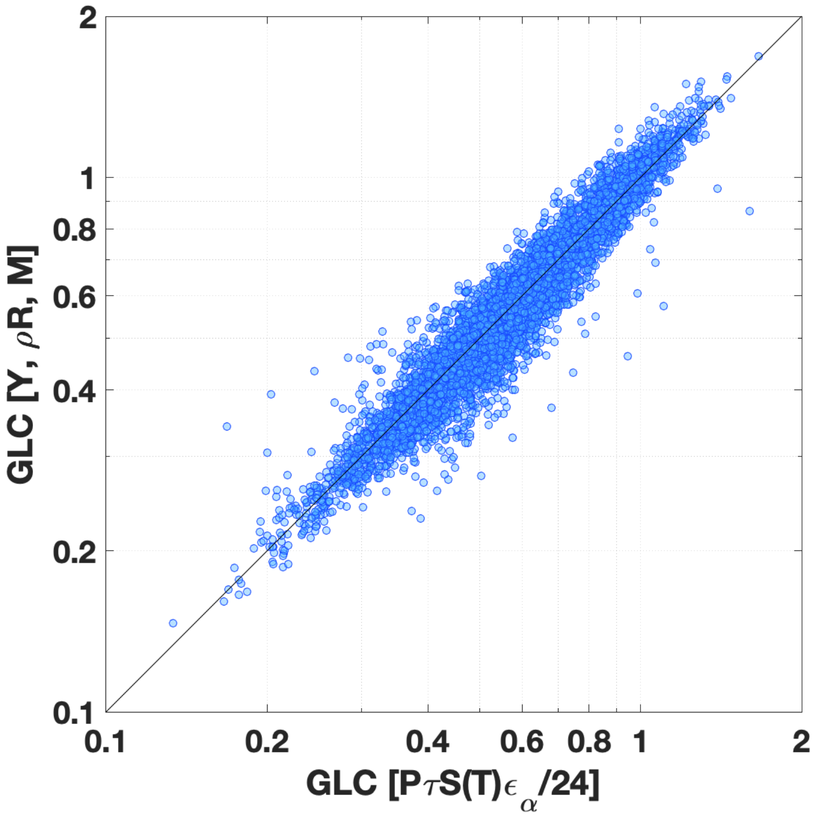


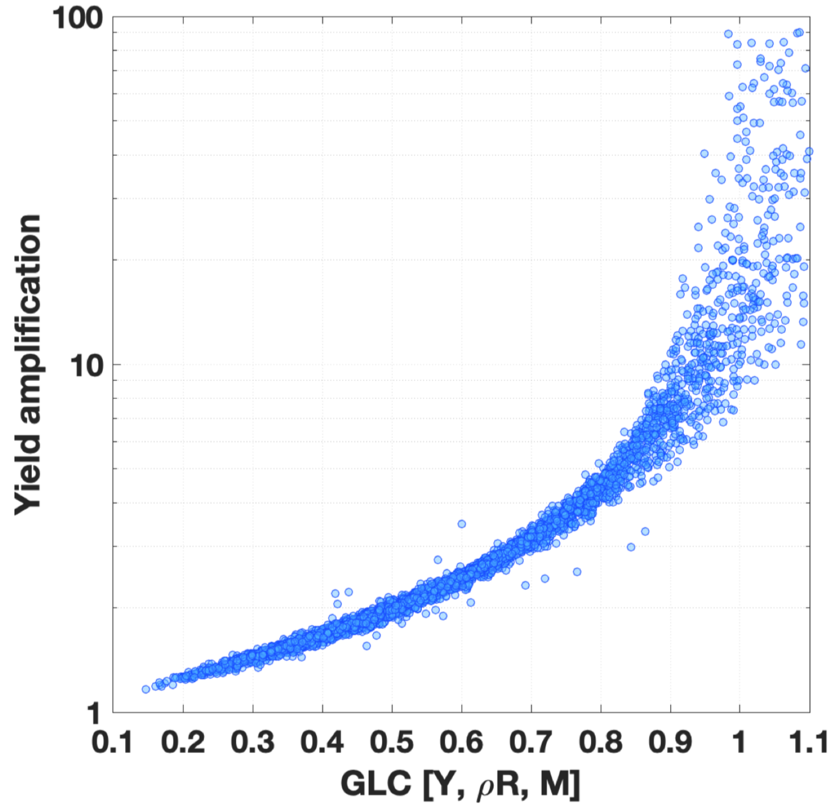
Hotspot pressure [α-off] (Gbar)
Hotspot energy [α-off] (kJ)
Y_{amp}~30x
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14

For a more accurate assessment of proximity we can recast the GLC in terms of measureable quantities

$$P\tau/P\tau_{\text{ign}} \approx 1.67\text{E}{-7}\; Y_{1315}^{0.5}(\rho R)_{\text{tot}}^{0.96}/M_{\text{DT}}^{0.5}$$

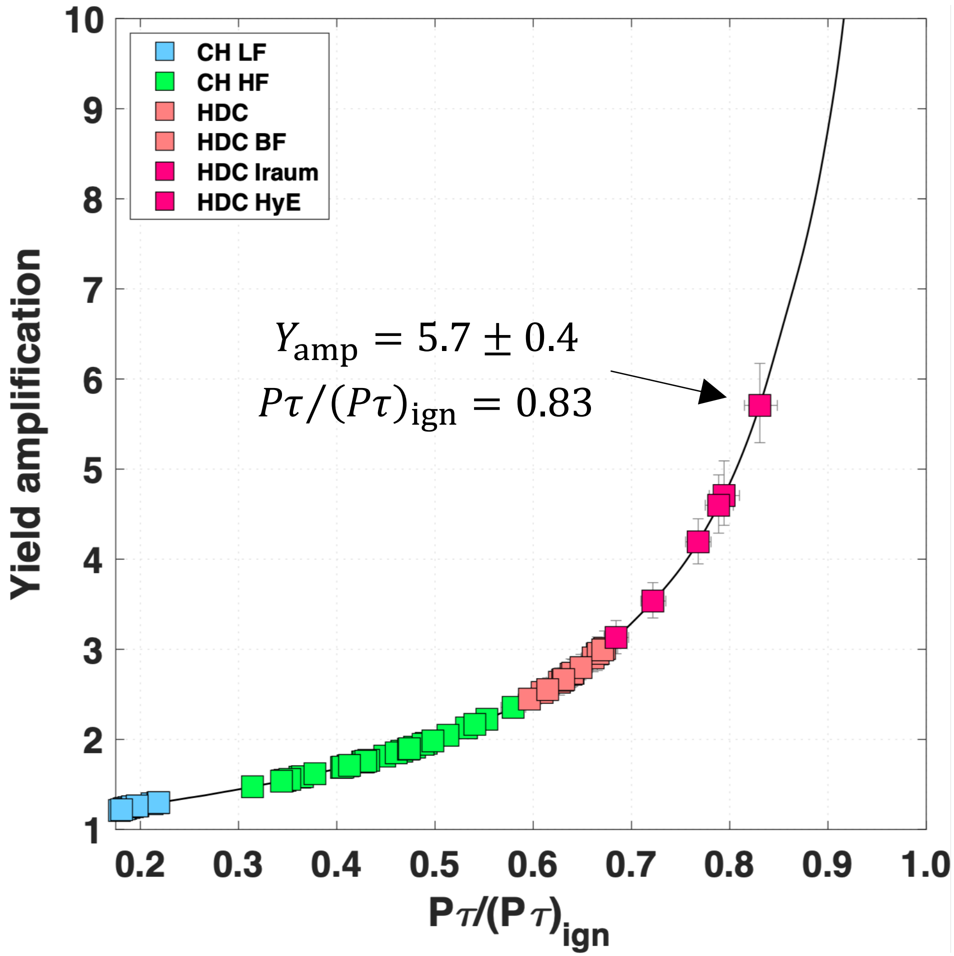


$$Y_{\text{amp}} = f(\text{GLC})$$

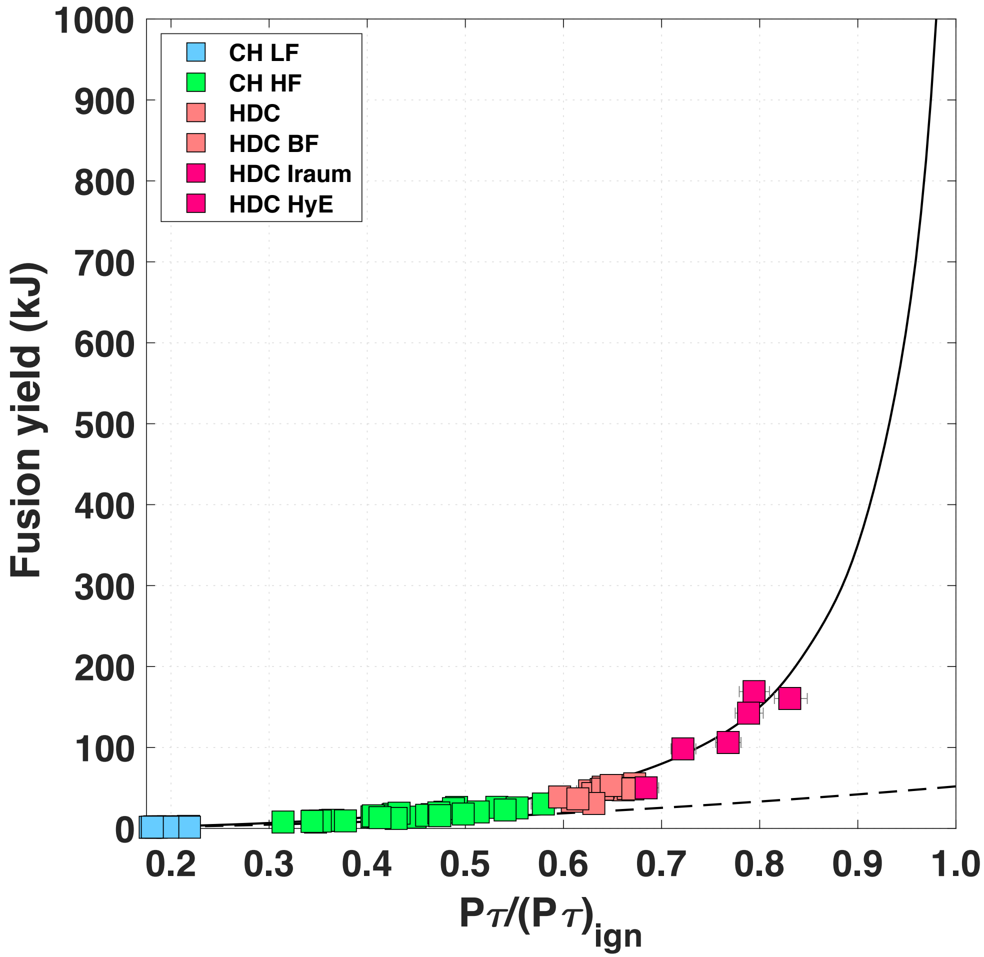


J. D. Lindl, Phys. Plasmas **25,** 122704 (2018)
P. K. Patel, Phys. Plasmas **27,** 050901 (2020)

GLC and Yield amplification



Yield



CH LF
CH HF
HDC
HDC BF
HDC Iraum
HDC HyE
Fusion yield (kJ)
1000
900
800
700
600
500
400
300
200
100
0
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
$P\tau/(P\tau)_{ign}$

The current implosions still suffer from some significant degradation mechanisms

- In 1D the implosions are predicted to ignite (~1 MJ yields)
- Experimental data show that implosion performance is being affected by at least 3 major factors: (i) asymmetry, (ii) hotspot mix, and (iii) reduced compression

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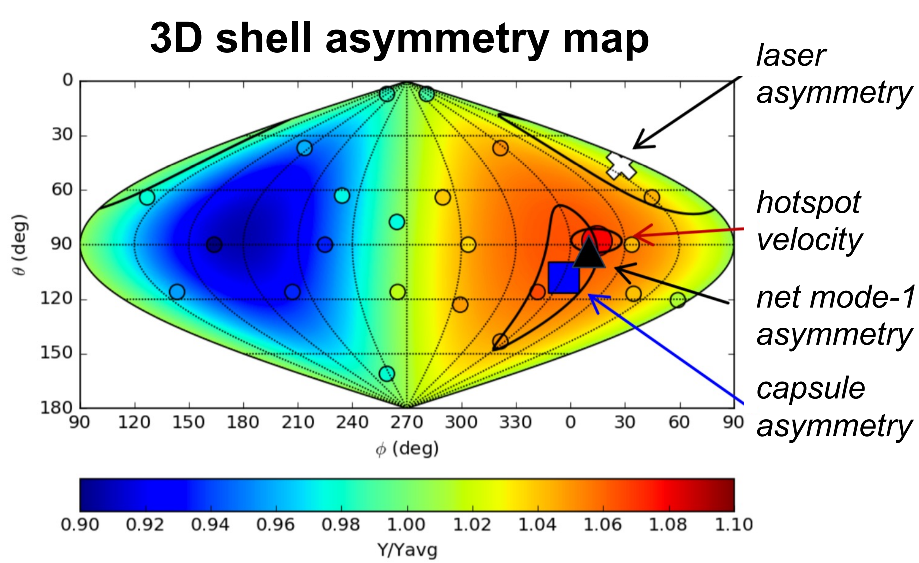

Degradation mechanism

- Two independent diagnostics have revealed a mode-1 asymmetry at stagnation which varies shot-to-shot
- We've discovered the two biggest sources: <1% variations in radiation flux due to laser power imbalance, and <1% variations in capsule thickness

Mitigation

- Improvements in laser power balance, and improved metrology of capsule thickness variations

D T. Casey, PRL **126,** 025002 (2021)
H. G. Rinderknecht, PRL **124,** 145002 (2020)

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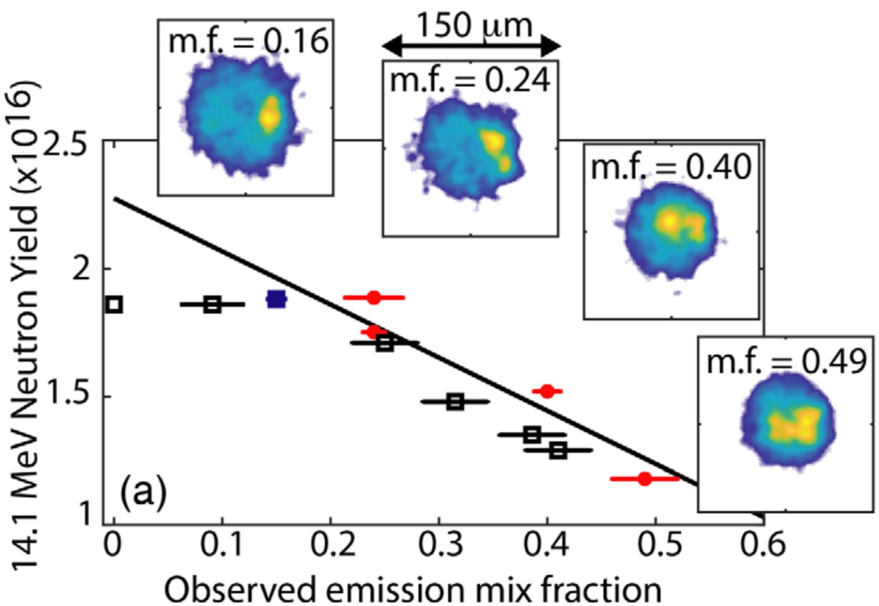

Degradation mechanism

- Hotspot mix can be seeded by engineering features, such as the capsule fill-tube, or tent support, or by capsule imperfections
- Observed as bright features in x-ray imaging,and through spectroscopy

Mitigation

- Narrow fill-tubes, alternate capsule supports, higher quality capsules

A. Pak, PRL 124, 145001 (2020)

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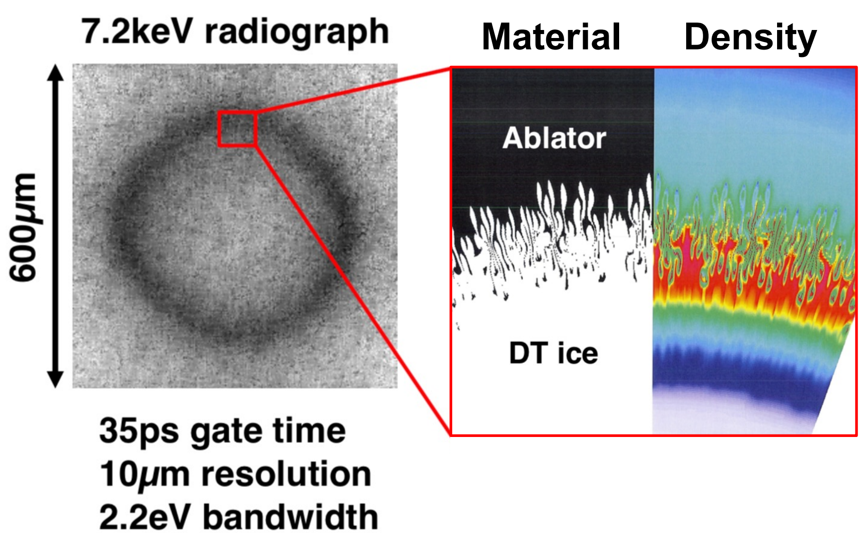


Degradation mechanism

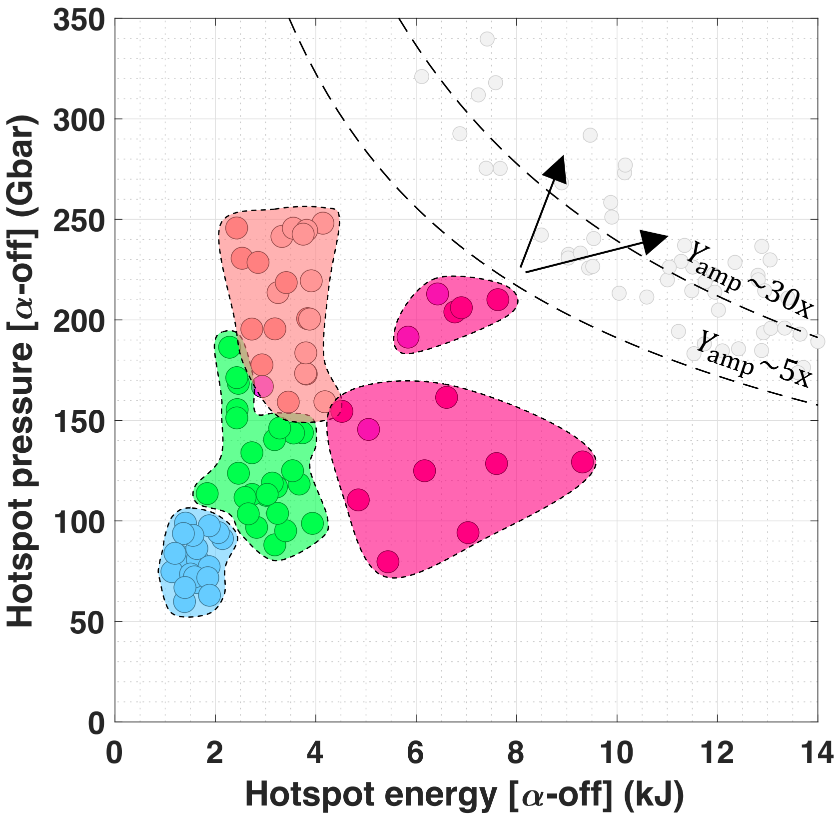
- Measured fuel areal densities are consistently 10-25% lower than simulation predictions
- A leading hypothesis is high-mode mix at the fuel-ablator interface, supported by recent experiments

Mitigation

- Modified capsule designs with more stable fuel-ablator interface

G. Hall, C. Weber (APS DPP 2020)
D. S. Clark, Phys. Plasmas **26,** 050601 (2019)

There are several path forwards for closing the gap to the ignition boundary



Improving implosion quality (pressure)

- Reducing low-mode asymmetry
- Reducing ablator mix in hotspot
- Increasing compression ratio
- Reducing 3D perturbations may enable driving implosions at higher velocity, increasing 1D margin

Increasing implosion scale (energy)

- Increase capsule size with fixed NIF laser energy through more efficient hohlraum designs
- Increase capsule and hohlraum size with additional NIF laser energy (exploring up to 2.6 MJ)

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