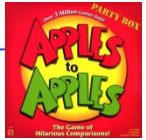
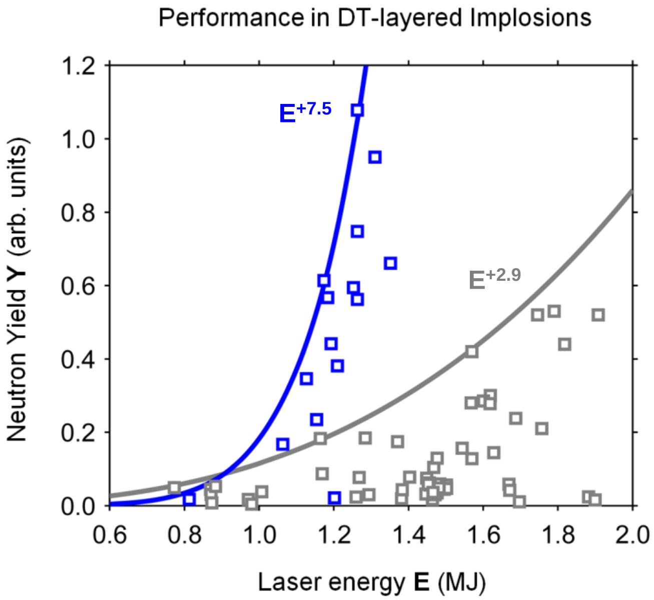
Review of BigFoot Implosion Data at NIF



BigFoot experiments
- Au hohlraum with 0.3 mg/cc fill
- DT adiabat 3 to 4
- Capsule IR 844 um**

CH, Be, and HDC experiments
- Au hohlraum with 0 to 1.6 mg/cc fill
- DT adiabat 1.5 to 2.5
- Capsule IR 900 to 1000 um



Yield quantified versus:
1. Hotspot symmetry = P_2
2. Target scale = S
3. Implosion velocity = v
4. Laser energy = E
5. DT adiabat = α
6. Shot number (reproducibility)
7. Compression = C

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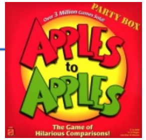
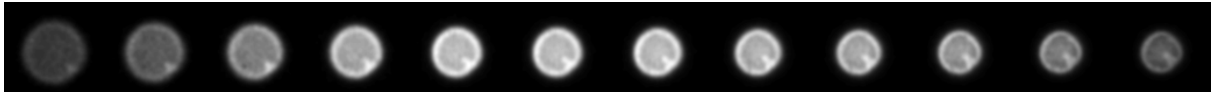
** Converted to a common scale assuming **$Y \sim S^{+4}$**

BigFoot was designed to limit hydrodynamic growth, laser-plasma instabilities, and hohlraum filling



- Minimize impacts of target quality, target alignment, laser pointing, etc.
- Maximize coupling and predictability (laser energy to target)
- Simplify interpretations of data, and physics vs reproducibility



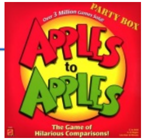
*BigFoot data (2016)***

X-ray emission ~ 10 keV *Nuclear BT* *+150 ps*

Primary goal: study implosion physics, establish understanding

** Capsule filled with Hydrogen gas, not a cryogenic DT layer

Collaborators



K. L. Baker, D. T. Casey, M. Hohenberger, A. L. Kritcher, B. K. Spears, S. F. Khan,
R. Nora, T. Woods, J. L. Milovich, R. L. Berger, D. Strozzi, D. D. Ho, D. Clark,
B. Bachmann, R. Benedetti, R. Bionta, P. M. Celliers, D. Fittinghoff, G. Grim, R. Hatarik,
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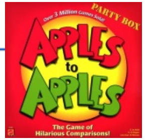
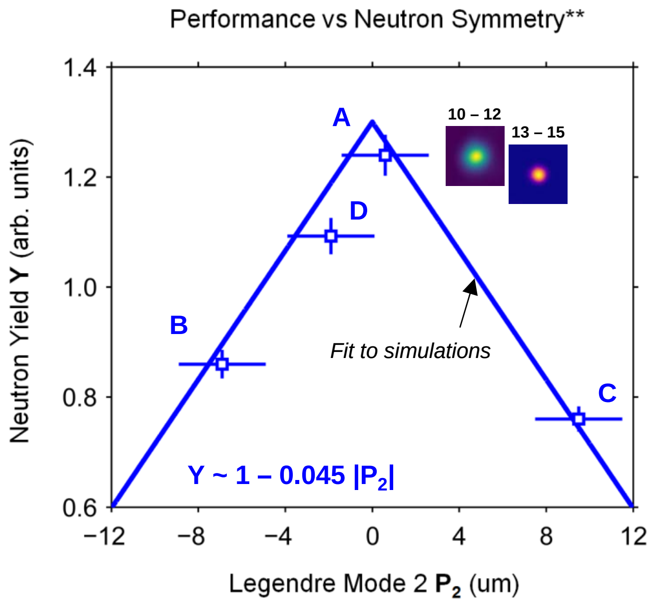
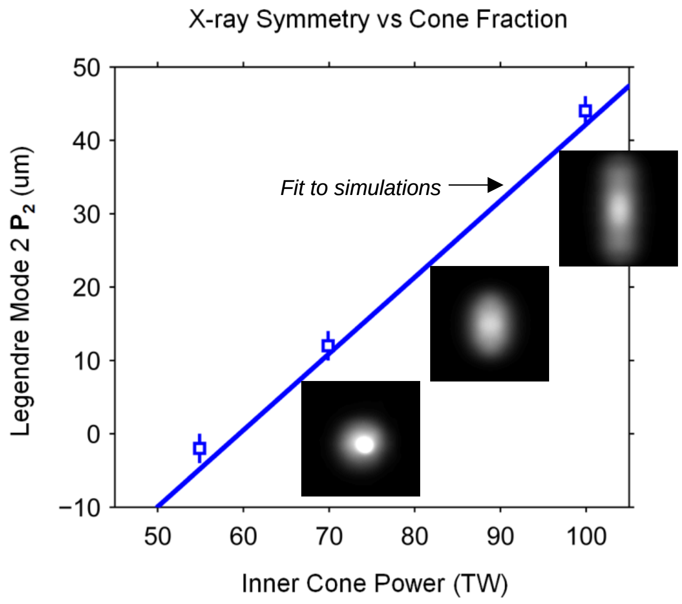
BigFoot data responds to hotspot symmetry = P_2
(though P_2 can vary, shot-to-shot)



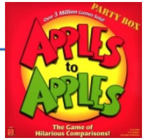




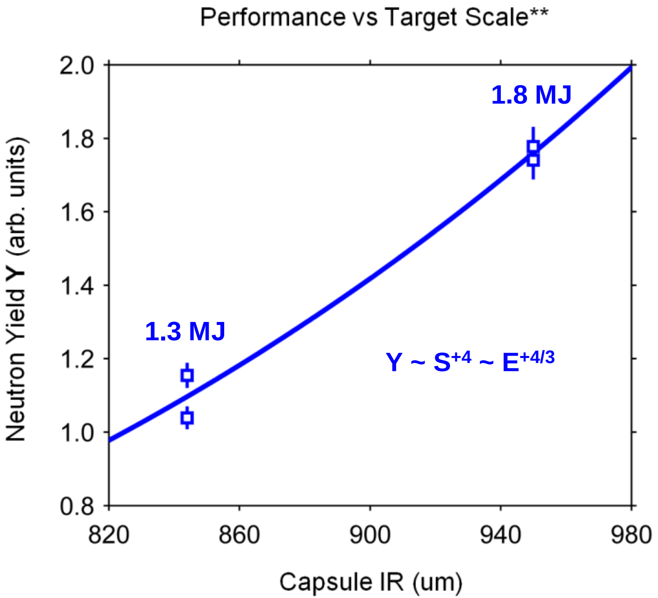
A: 180128 (highest performing experiment to-date)
B: Repeat of A after changes in the laser, target alignment system, and target fab
C: Repeat of B at 12% smaller scale
D: Repeat of C with 12% less inner cone power

** Converted to a common scale assuming **$Y \sim S^{+4}$**

Performance increases with target scale = S
(for a perfect hydro-scale: $L = S\,L_o$, $t = S\,t_o$, $P = S^2\,P_o$, $E = S^3\,E_o$)



→ $(1.125)^3$



Theory:

$Y \sim n^2\,T^{+3}\,V_{hs}\,\tau$ ← $\tau \sim R_{hs}\,T^{-0.5}$

$Y \sim nV_{hs}\;nR_{hs}\;T^{+2.5}$

$Y \sim m_{hs}\;\rho R_{hs}\;T^{+2.5}$

$Y \sim S^{+4}\;T^{+2.5}$

Neglects small changes in self-heating, tau(S), and T(S); approx consistent with data.

Hohlraum and capsule physics similar for factor of 1.5 in energy

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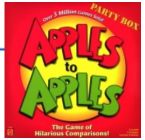
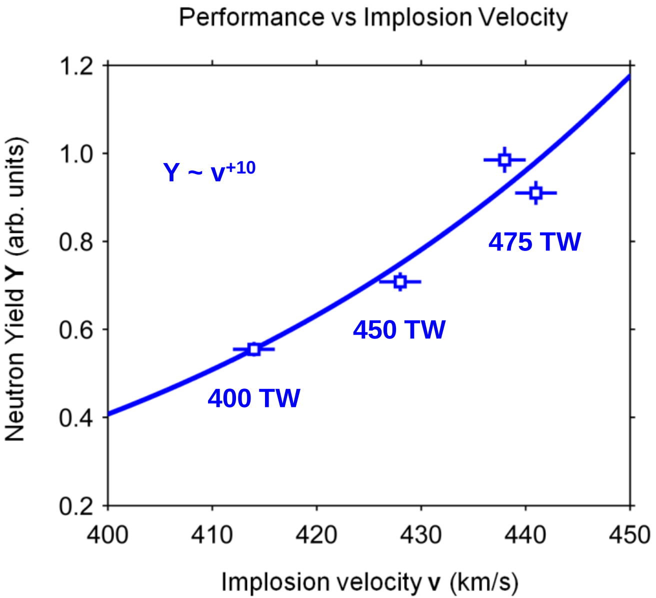
** Converted to 1D yield assuming $\mathbf{Y \sim 1 - 0.045\,|P_2|}$

Yield increases with implosion velocity = v
(at constant laser energy)





Theory:

Adiabatic hotspot.

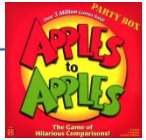
$Y \sim S^{+4}\, T^{+2.5}$ ⟵ $T \sim (v\, C)^{+2}$

$Y \sim S^{+4}\, v^{+5}\, C^{+5}$

Neglects small changes in self-heating and C(v); data should scale faster.

It is important to optimize velocity ~ function of ablator and DT ice mass

Sensitivity to laser energy exceeds no-alpha theory ~ E^{+5} (at constant scale)



BigFoot experiments
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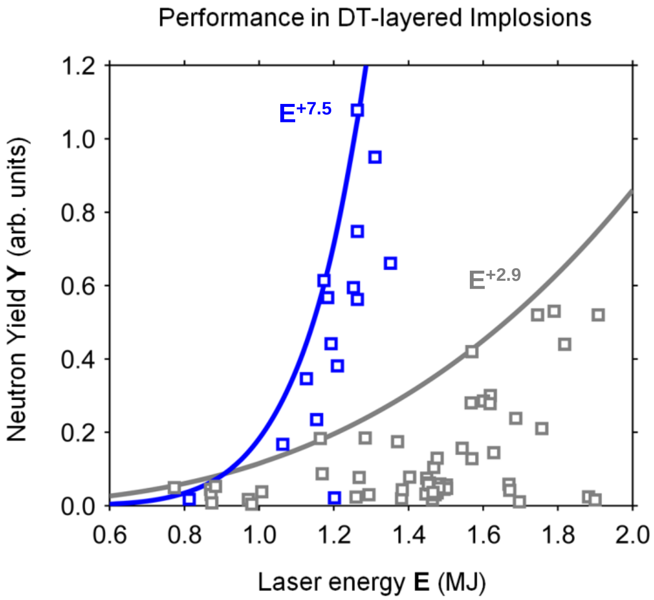


Theory:

High adiabat limit.

$Y \sim S^{+4}\, v^{+5}\, C^{+5}$ ⟵ **$C \sim v\, \alpha^{-0.5}$**

$Y \sim S^{+4}\, v^{+10}\, \alpha^{-2.5}$ ⟵ **$E \sim mv^2$**

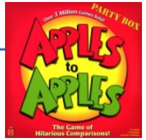
$Y \sim S^{+4}\, (E/m)^{+5}\, \alpha^{-2.5}$

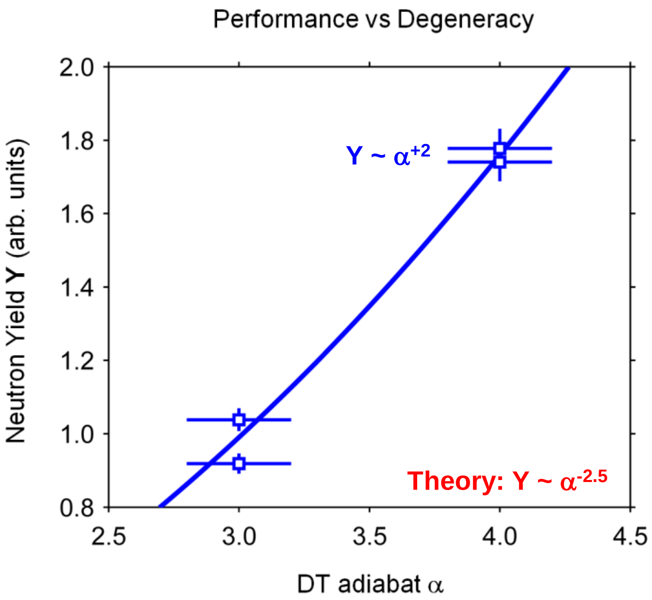
Neglects small changes in self-heating, m(E), and adiabat(E); data should scale faster.

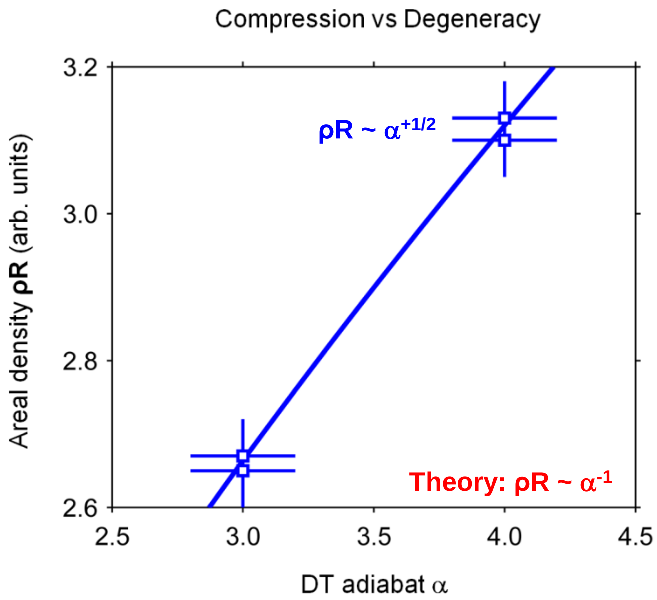
Suggests alpha-heating ~ $E^{+2.5}$, consistent with Betti-type analysis

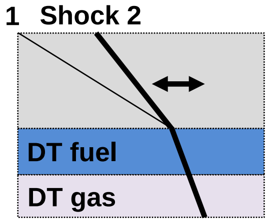
** Converted to a common scale assuming **$Y \sim S^{+4}$**

Performance is inconsistent with expectations on DT adiabat (at constant symmetry, scale, velocity, energy, etc.)





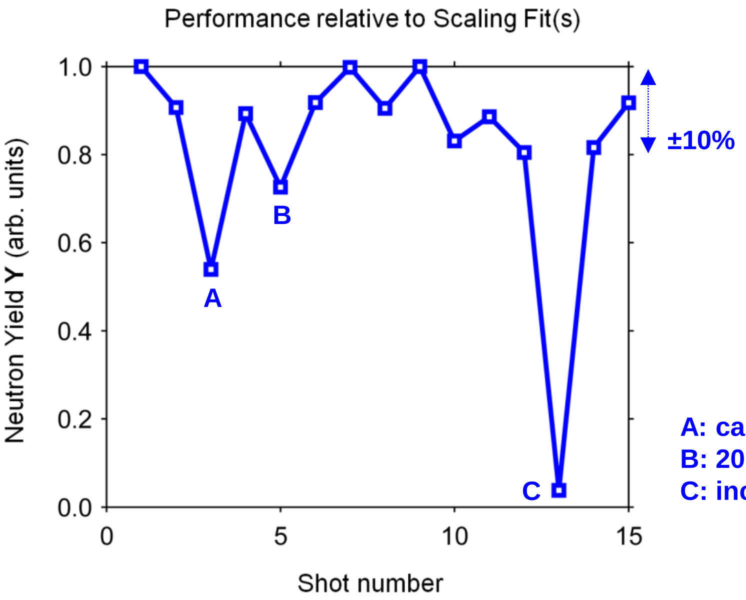


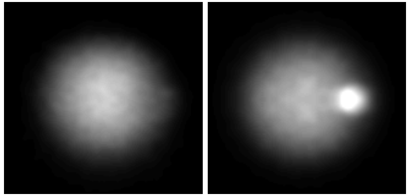


Rad-hydro calculations are unable to predict 2D/3D stability?

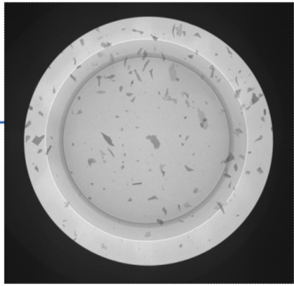
Reproducibility: can be a challenge ~ 1 shot in 5 (including variability in symmetry, ~ 1 shot in 2)

$Y/Y(P_2,S,E,\alpha)$





*Same target and laser power vs time, but different response to capsule fill tube. ***



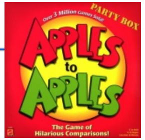
Au flakes on capsule?

A: capsule with largest fill tube hole (more mix?)
B: 200 um offset in target alignment (3D implosion?)
C: increased x-ray emission from hotspot (more mix?)

Need to apply care with individual data points, 'equivalent shots', etc.

** Capsule filled with Hydrogen gas, not a cryogenic DT layer

Physics scaling(s) can be used to set priorities



- Test mechanisms predicted to matter (e.g. pulse-shaping)
- Hot electron preheat, hard x-ray radiation, high-Z dopant
- New models for equation-of-state, stagnation adiabat, etc.

Theory/Simulations: $Y \sim S^{+4}\,(E/m)^{+5}\,\alpha^{-2.5}$

In addition to prior assumptions, this formula also neglects changes in hohlraum albedo, radiation temperature, x-ray preheat, hot electrons, laser backscatter etc. that depend on S, E, etc.

Data: $Y \sim S^{+4}\,(E/m)^{+7.5}\,\alpha^{+2}$

Increase adiabat?

Decrease scale at maximum energy?

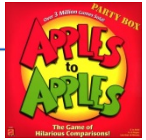
$$Y \sim S^{+4}\,(E/S^3 m_o)^{+7.5}\,\alpha^{+2}$$

$$Y \sim S^{-18.5}\,\alpha^{+2}$$

BigFoot data are at smaller scale (S), higher energy density (E/m), and higher adiabat (α) than prior data, and achieve higher yield (Y) and gain (Q). Even when compared to data using advanced hohlraums (more effective energy) and high quality targets (smoother capsules, smaller fill tube, polar tent, etc.).

Can also gain insight by careful comparisons with other data

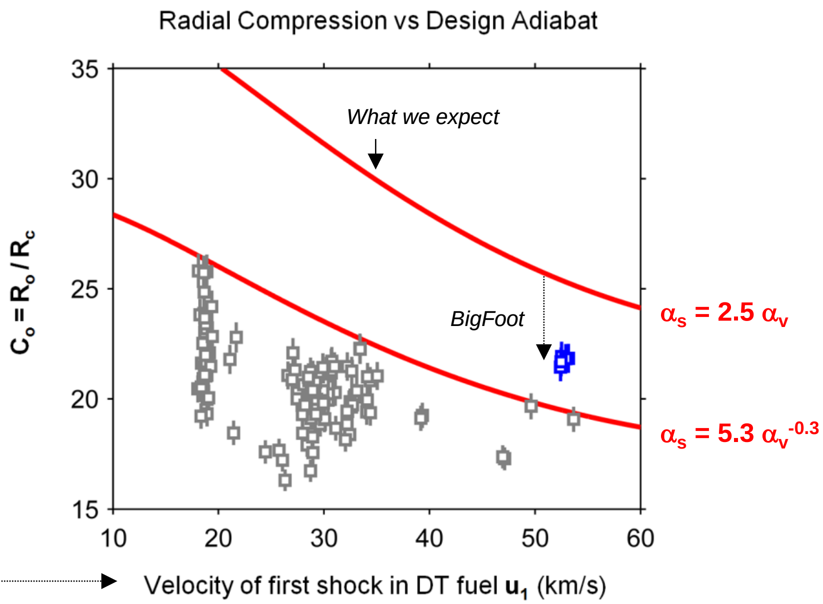
Performance should depend on energy density



$\rho_o R_o^2 t_o = \rho_c R_c^2 t_c \leftarrow$ 20 DSR** $= \rho_c\, t_c$

$\rho_o R_o^2 t_o =$ 20 DSR** R_c^2

$C_o^2 =$ 20 DSR** $/\ \rho_o t_o$



$\alpha_v = 1 + 1.4\text{E-}3\ u_1^2 - 1.4\text{E-}7\ u_1^4$

Theory:

$Y \sim S^{+4}\, v^{+5}\, C^{+5} \leftarrow C \sim v\ \alpha^{-0.5}$

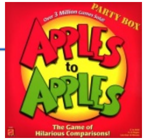
$Y \sim S^{+4}\, v^{+10}\, \alpha^{-2.5}$

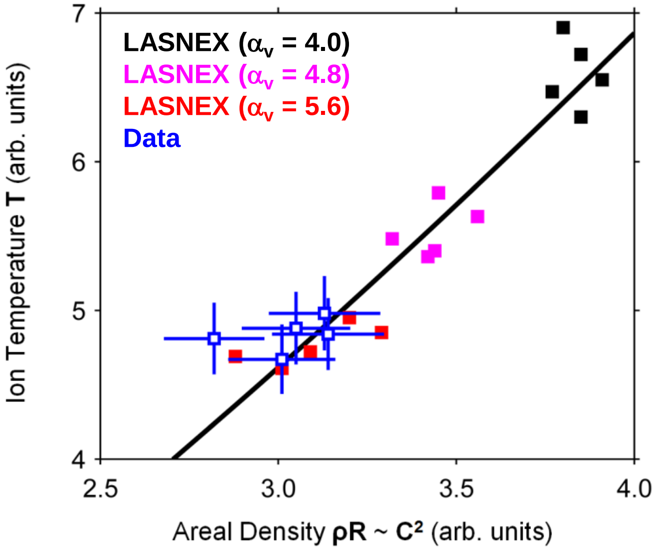
Ignition criteria can be defined in terms of compression or adiabat, but compression is measured.

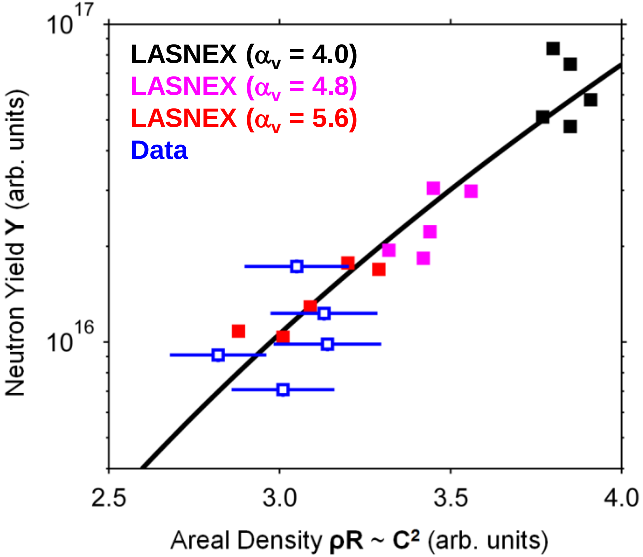
BigFoot data are 10-15% low in compression relative to expectations

** DSR = down-scatter neutron ratio = neutron emission at 10-12 MeV vs 13-15 MeV ~ 3 to 4%

Rad-hydro simulations are able to reproduce data if we correct for the measured compression ratio = C



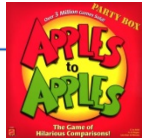




Improvements in understanding/compression could increase performance

Conclusion

BigFoot implosions have been used to investigate the physics that work/don't in ICF



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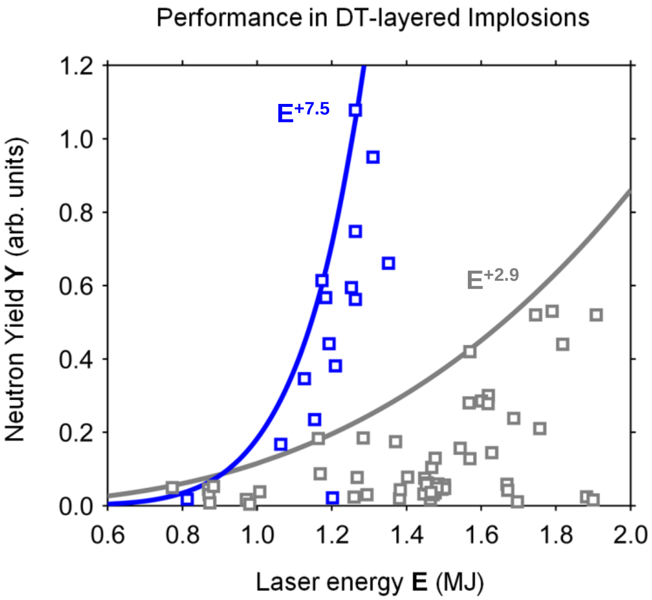

Yield quantified versus:
1. **Hotspot symmetry = P_2**
2. **Target scale = S**
3. **Implosion velocity = v**
4. **Laser energy = E**
5. **DT adiabat = α**
6. **Shot number (reproducibility)**
7. **Compression = C**

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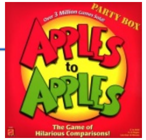
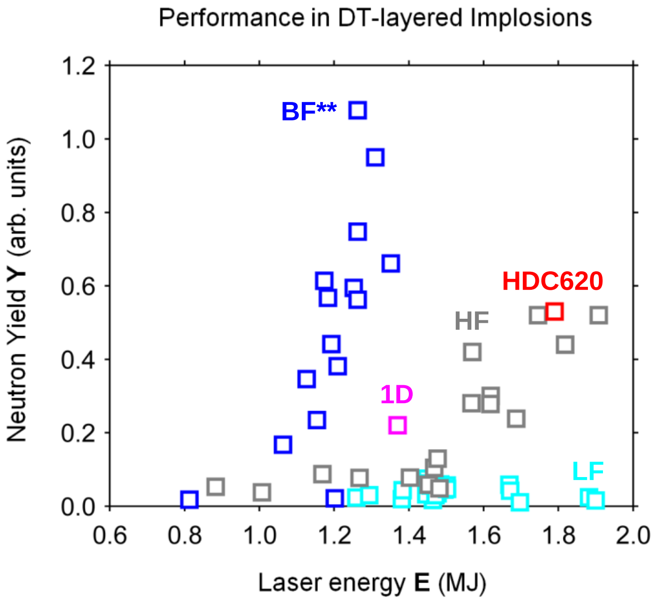

PARTY BOX
Over 3 Million Games Sold!
APPLES
to
APPLES
The Game of
Hilarious Comparisons!

Ignition at NIF will require a high return on energy (~ scaling)



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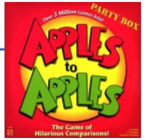
** Converted to a common scale assuming **Y ~ S^{+4}**

BigFoot meant to emphasize coupling, predictability, and stability, and a conservative approach to collecting and analyzing data



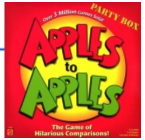
Target and pulse:

1. **Low Gas Fill LGF hohlraum (0.3 mg/cc): reduce risk of laser-plasma instabilities at max power and energy**
2. **High Density Carbon HDC ablator: shorten the laser pulse**
3. **12 Mbar “BigFoot” 1st shock: avoid phase coexistence in ablator, shorten the laser pulse, reduce hydrodynamic growth**
4. **High DT adiabat (4) by 1-2 shock overtake: shorten the laser pulse, reduce hydrodynamic growth, simplify pulse-shaping studies**
5. **Cone-and-quad split laser pointing: reduce intensity at the hohlraum wall, reduce wall motion, make experiments less 3D**
6. **Large Laser Entrance Hole (LEH): reduce sensitivity to target alignment and laser pointing**
7. **Truncation of final pulse: limit laser backscatter**

- **Most implosions (~ 40) were posed as single variable sensitivity studies**
- **All primary design variables were tested (e.g. cone fraction, pulse length, hohlraum radius, etc.)**
- **Many “tuning shots” were actually repeats**
    - **1 keyhole was shot 3x at scale 844, 3x at scale 950**
    - **Same target and pulse were compared in keyhole, SymCap, ConA, and DT experiments, 2x**

No change in design or strategy for “BF” campaign from 2015 to 2019

Shots with BigFoot “BF” label in archive



N161205-003-999 SymcapDTHDCS8BF
N171022-002-999 SymcapDTHDCS8BF
N171112-002-999 SymcapDTHDCS8BF
N171120-001-999 SymcapDTHDCS8BF
N181211-001-999 SymcapDTHDCS8BF
N190206-002-999 SymcapDTHDCS8BF
N170831-001-999 SymcapDTHDCS9BF
N150809-001-999 SymcapHDCS8BF
N151221-001-999 SymcapHDCS8BF
N160405-001-999 SymcapHDCS8BF
N160410-001-999 SymcapHDCS8BF
N160414-002-999 SymcapHDCS8BF
N160628-001-999 SymcapHDCS8BF
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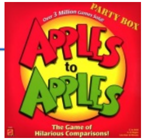
N180909-003-999 DTHDCS9BF
N180930-001-999 DTHDCS9BF
N190707-002-999 DTHDCS9BF
N190730-001-999 DTHDCS9BF

Shots with HDC ablator before N150809-001-999



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N130813-002-999 SymcapHDC
N141019-001-999 SymcapHDC
N141111-004-999 SymcapHDC
N150228-002-999 SymcapHDC
N150301-003-999 SymcapHDC
N150426-001-999 SymcapHDC
N150506-002-999 SymcapHDC
N150128-001-999 SymcapHDC620
N150321-001-999 SymcapHDC620
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N140826-002-999 ShockHDCDT672

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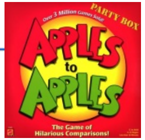
N140513-004-999 ConvAbl2DHDC
N140213-003-999 ConvAbl2DHDC672
N140303-003-999 ConvAbl2DHDC672
N140310-001-999 ConvAbl2DHDC672
N140701-002-999 ConvAbl2DHDC672
N140702-001-999 ConvAbl2DHDC672
N140720-002-999 ConvAbl2DHDC672
N140915-001-999 ConvAbl2DHDC672
N130408-002-999 ConvAblWHDC
N130621-002-999 ConvAblWHDC
N150223-001-999 ConvAblWHDCS8
N150224-002-999 ConvAblWHDCS8

N131212-001-999 DTHDC
N140722-001-999 DTHDC
N141116-001-999 DTHDC
N150422-002-999 DTHDC
N150429-002-999 DTHDC620
N150625-001-999 DTHDC620
N140926-001-999 DTHDC672

N150326-002-999 CRHDCS8Warm
N140812-001-999 HGRHDC672
N140210-003-999 ReemitHDC
N140522-001-999 ReemitHDC
N140816-001-999 ReemitHDC672
N140916-001-999 ReemitHDC672
N130920-002-999 THDConvAbl2DHDC

Additional shots with HDC ablator after N150809-001-999



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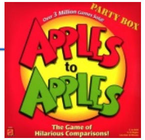

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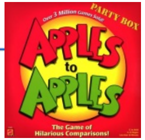
Shots with “HF” label in archive



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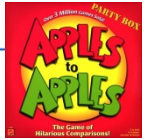

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