Machine Learning Enabled Quantitative Prediction of the First-Ever Igniting Inertial Confinement Fusion Experiment

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Nov 28, 2023, Vienna
IAEA Workshop on Artificial Intelligence for Accelerating Fusion and Plasma Science

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC
LLNL-PRES-857423

Lawrence Livermore National Laboratory

On Dec 5, 2022, fusion ignition was achieved at the National Ignition Facility in Livermore, California

Department of Energy

DOE National Laboratory Makes History by Achieving Fusion Ignition

DECEMBER 13, 2022

The New York Times

Scientists Achieve Nuclear Fusion Breakthrough With Blast of 192 Lasers

The advancement by Lawrence Livermore National Laboratory researchers will be built on to further develop fusion energy research.

nature

NEWS EXPLAINER | 13 December 2022

Nuclear-fusion lab achieves 'ignition': what does it mean?

Researchers at the US National Ignition Facility created a reaction that made more energy than they put in.

BBC

Breakthrough in nuclear fusion energy announced

Science

NEWS | PHYSICS

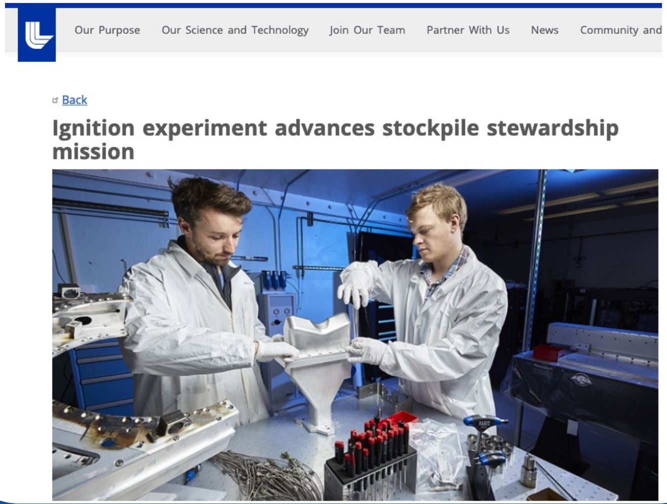
With historic explosion, a long sought fusion breakthrough

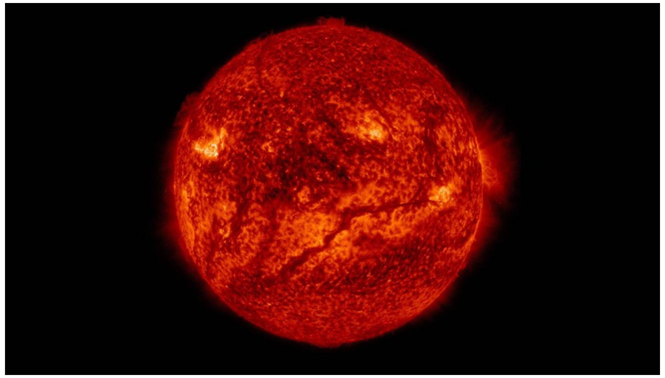
National Ignition Facility achieves net energy "gain" with laser-powered approach

Applications of ignition include stockpile stewardship, IFE, and fundamental science

Clean Energy

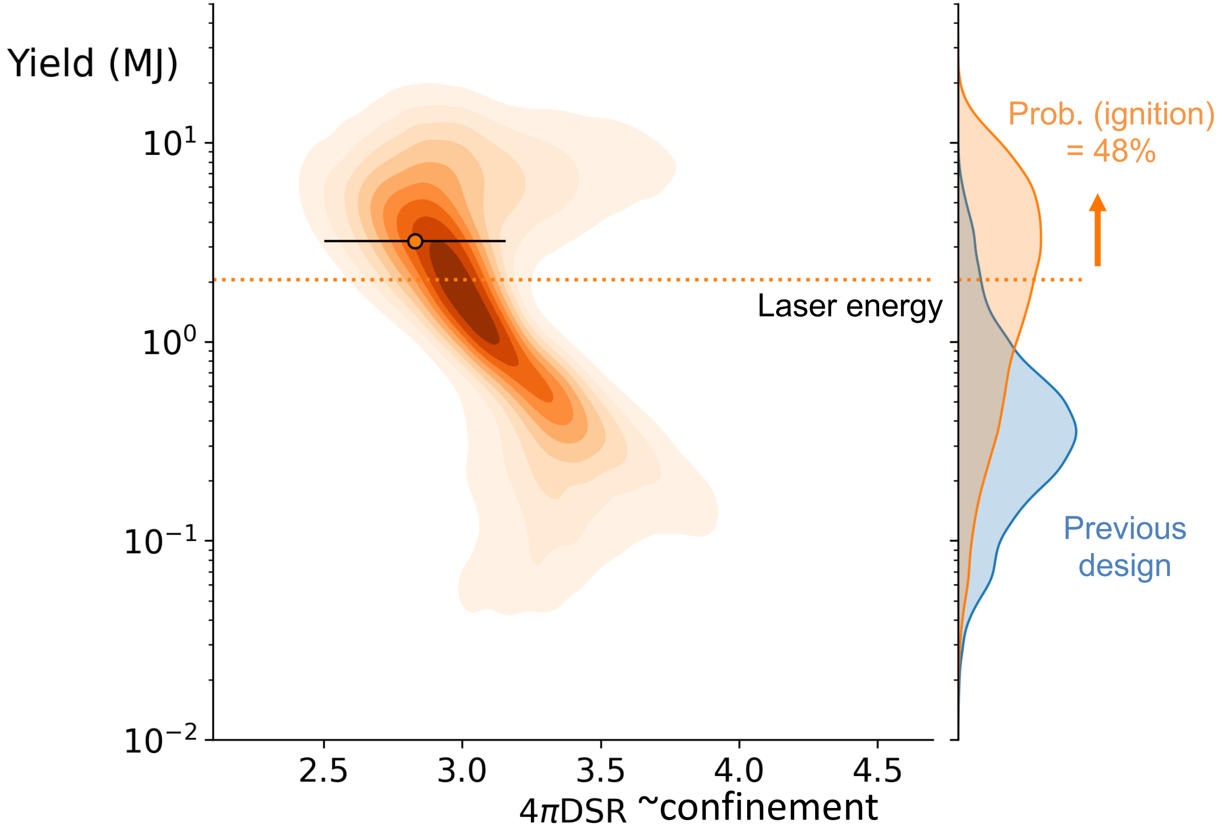
Stockpile Stewardship





Fundamental Science

We predicted a high probability of achieving gain > 1 using data-informed uncertainty on the first-ever ICF experiment to achieve ignition



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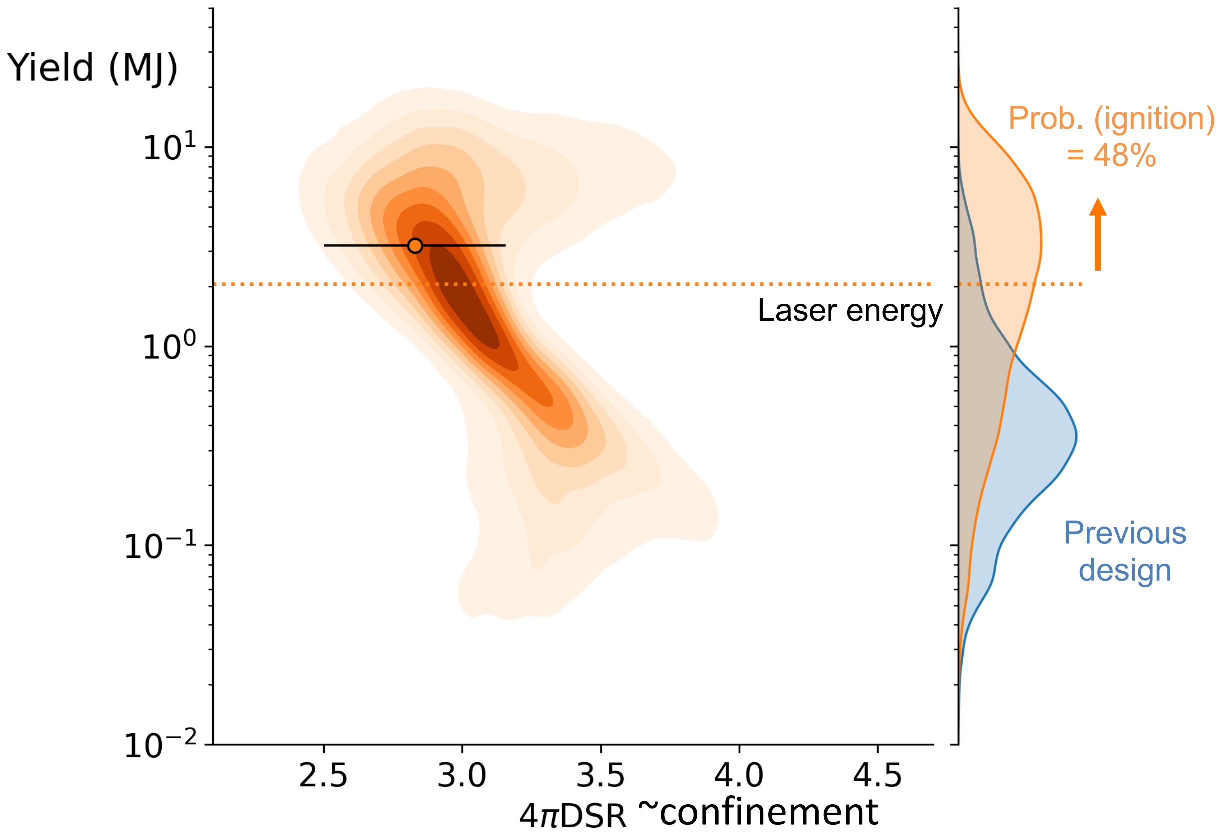
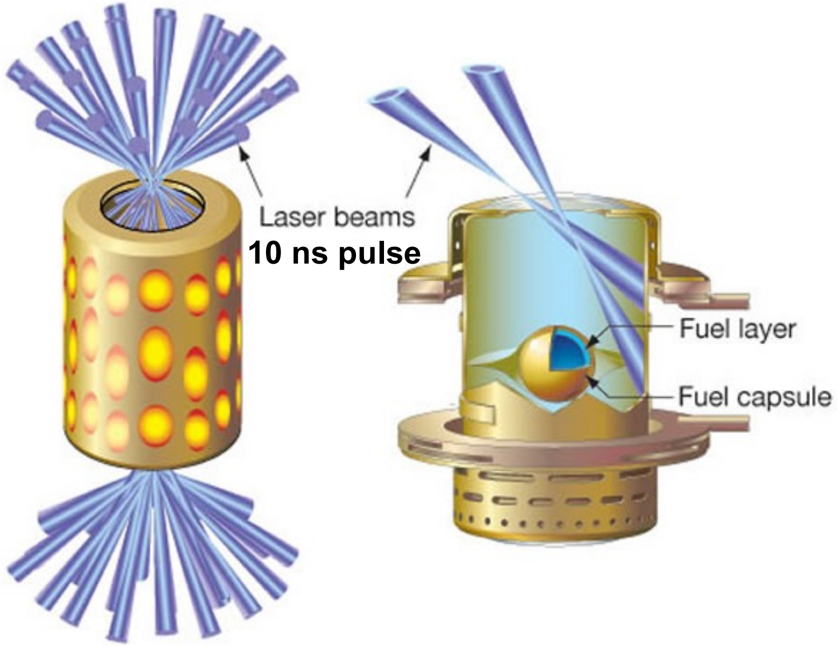


- ICF introduction
- Pre-ignition – designing to improve performance
- Ignition – first repeatability campaign
- CogSim variability model and prediction of Dec 5, 2022 ignition shot
- Predictions of new designs and potential applications in optimization and IFE

National Ignition Facility (NIF) is home to indirect-drive inertial confinement fusion (ICF) experiments

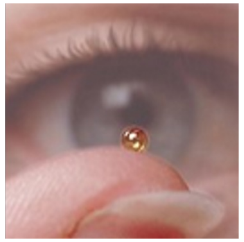
National Ignition Facility (NIF)
Livermore, California

~10 DT (full scale) experiments per year
~ 2 MJ laser energy

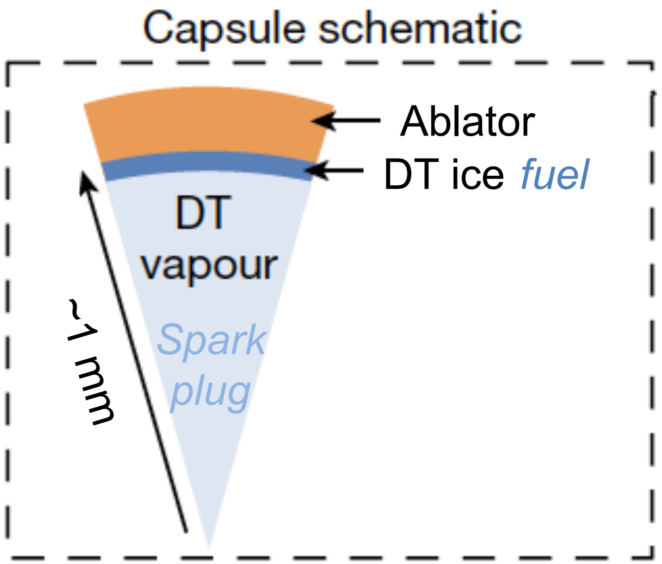


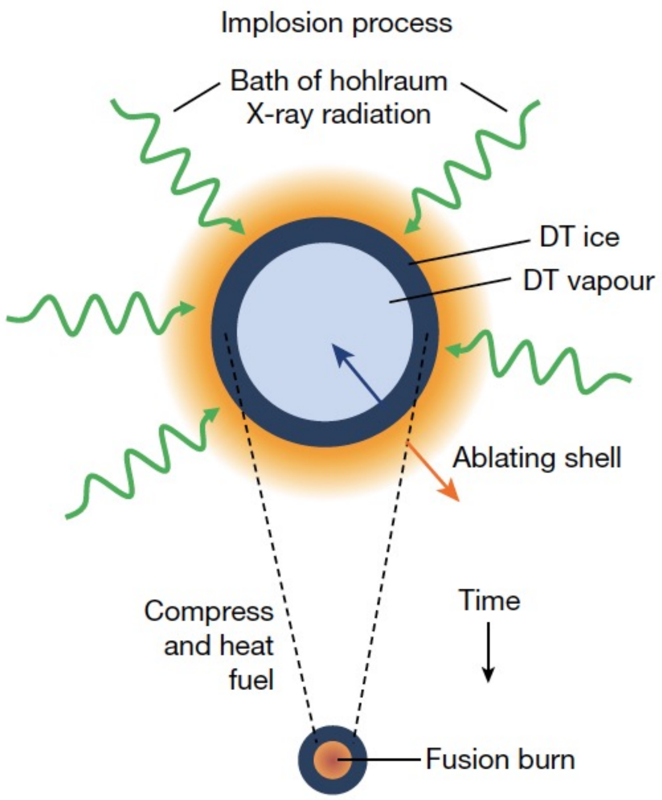
Hohlraum

Capsule

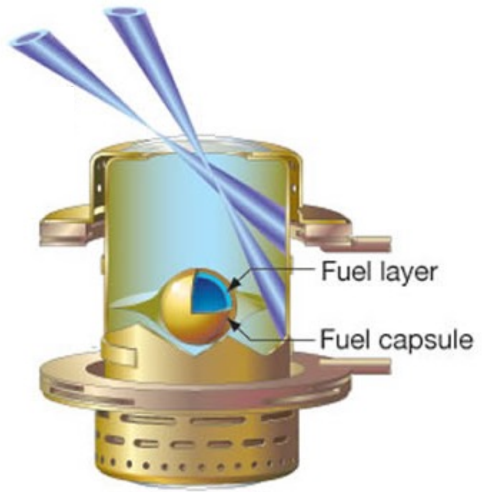


Fraction of the 2.05MJ delivered by laser is delivered to the fuel capsule, ultimately releasing fusion energy

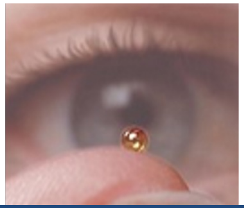




Zylstra et al., Nature 2020

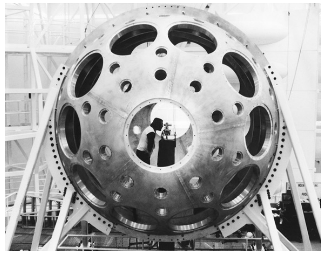


Capsule



We need to get the fuel sufficiently hot and dense for sufficiently long time to ignite

Achieving fusion ignition at the National Ignition Facility has a history spanning at least half a century



- 1972 — Laser driven ignition idea published
- 1975 — First laser Janus. LASNEX simulation paper
- 1977 — Shiva 10 kJ laser
- 1984 — Nova 120 kJ laser
- 1997 — NIF construction started
- NAS ignition definition as target gain > 1
- 2001 — HYDRA simulation paper
- 2010 — First ICF exp. at NIF
- 2012 — 1.85 MJ of laser energy
- 2021 — N210808 1.35MJ Target gain 0.7
- **2022 — N221204 3.15MJ Target gain 1.5**

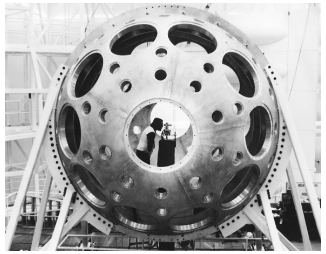
NATURE VOL. 239 SEPTEMBER 15 1972 139

Laser Compression of Matter to Super-High Densities: Thermonuclear (CTR) Applications

JOHN NUCKOLLS, LOWELL WOOD, ALBERT THIESSEN & GEORGE ZIMMERMAN

University of California Lawrence Livermore Laboratory

Achieving fusion ignition at the National Ignition Facility has a history spanning at least half a century



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Cognitive Simulation Team

- Large ensembles of simulations
- Neural network surrogates
- Experiments
- Bayesian inference
- Sparse Sampling
- Physics-informed prediction with data-informed uncertainty

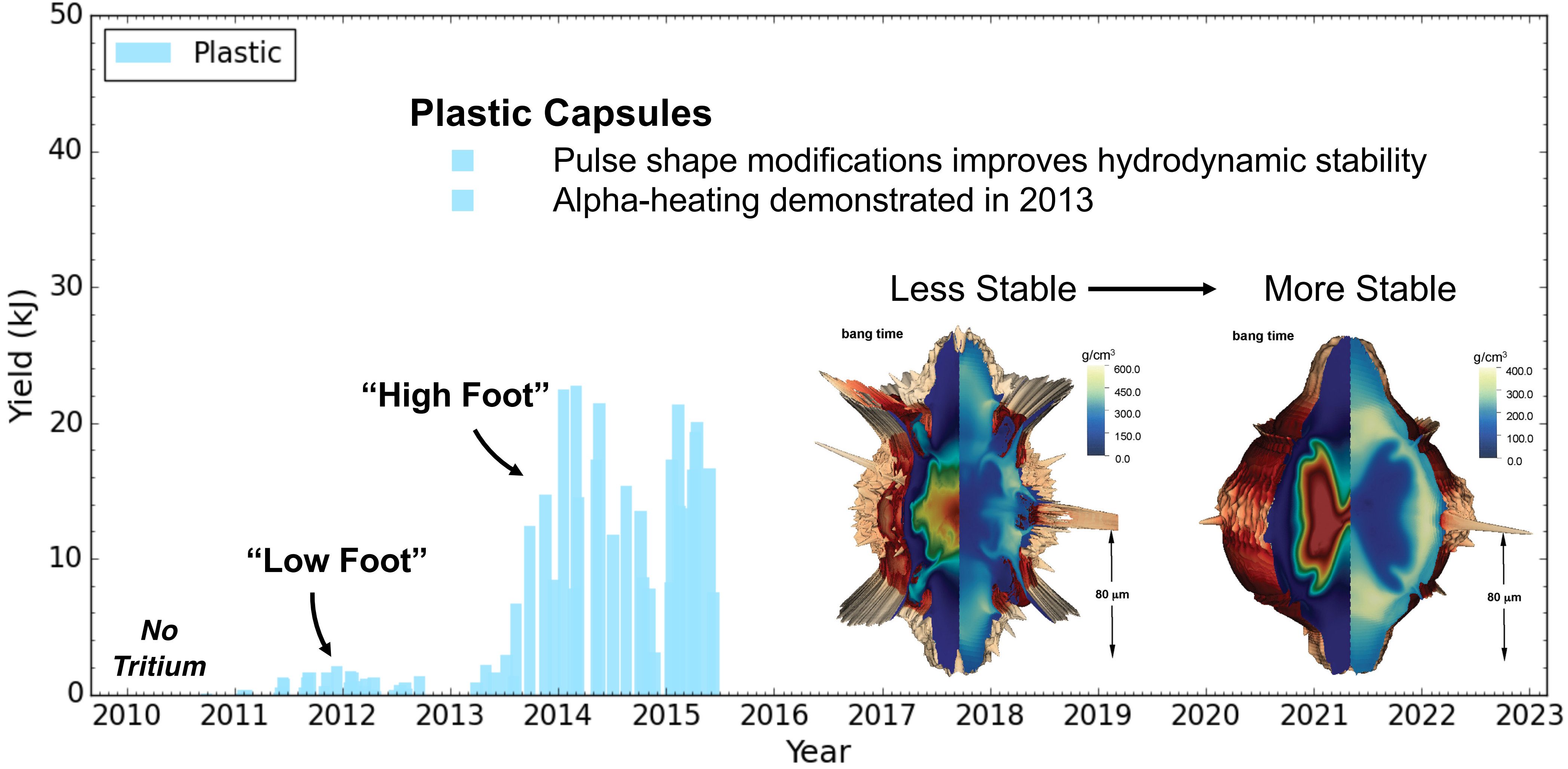
predict

Before N210808, the main focus of the ICF experiments at NIF was to increase the yield and learn

Pre-ignition → Ignition → Applications

Focus on performance and learning

We can identify major turning points by looking at a plot of thermonuclear output versus time



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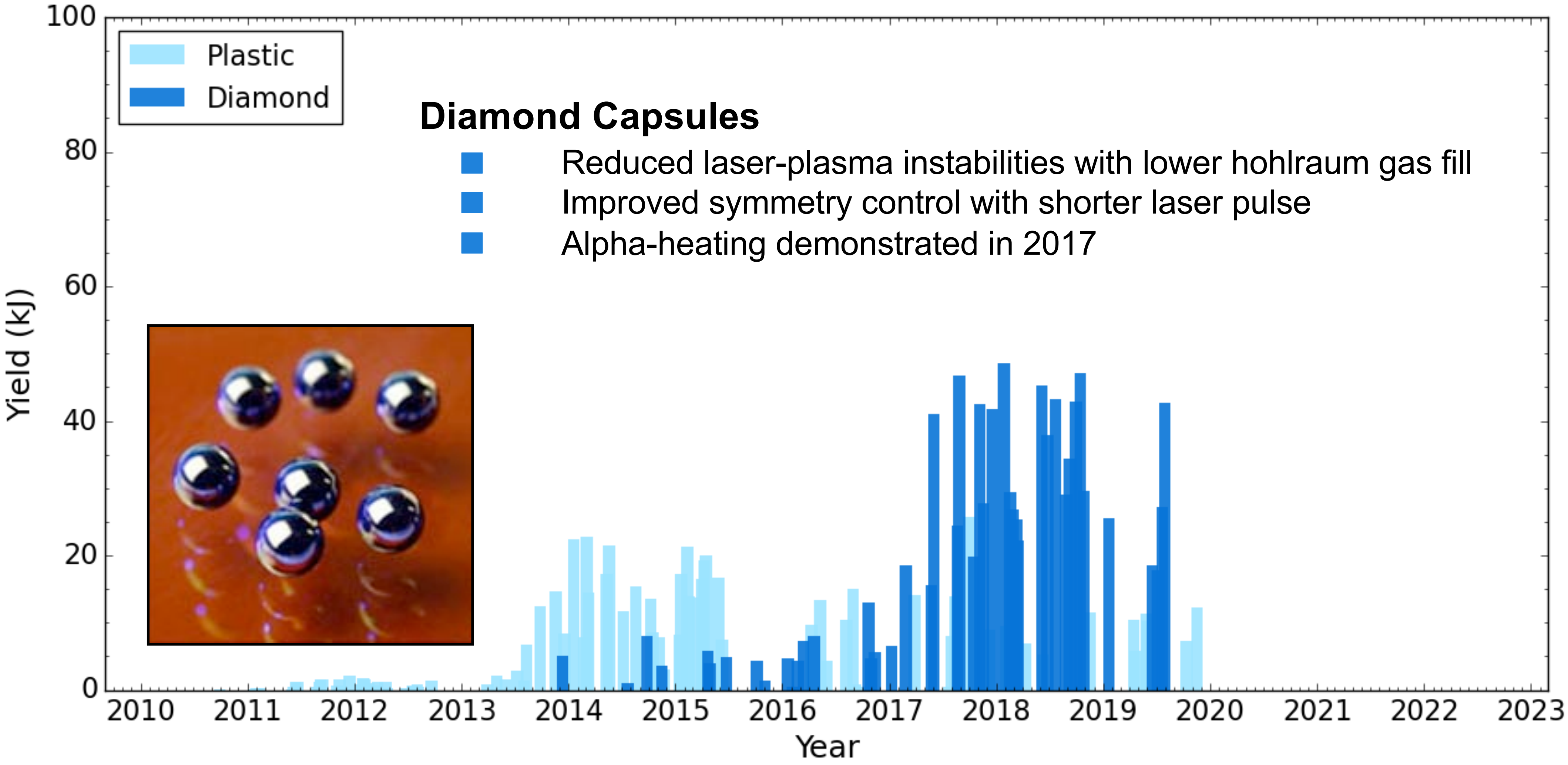

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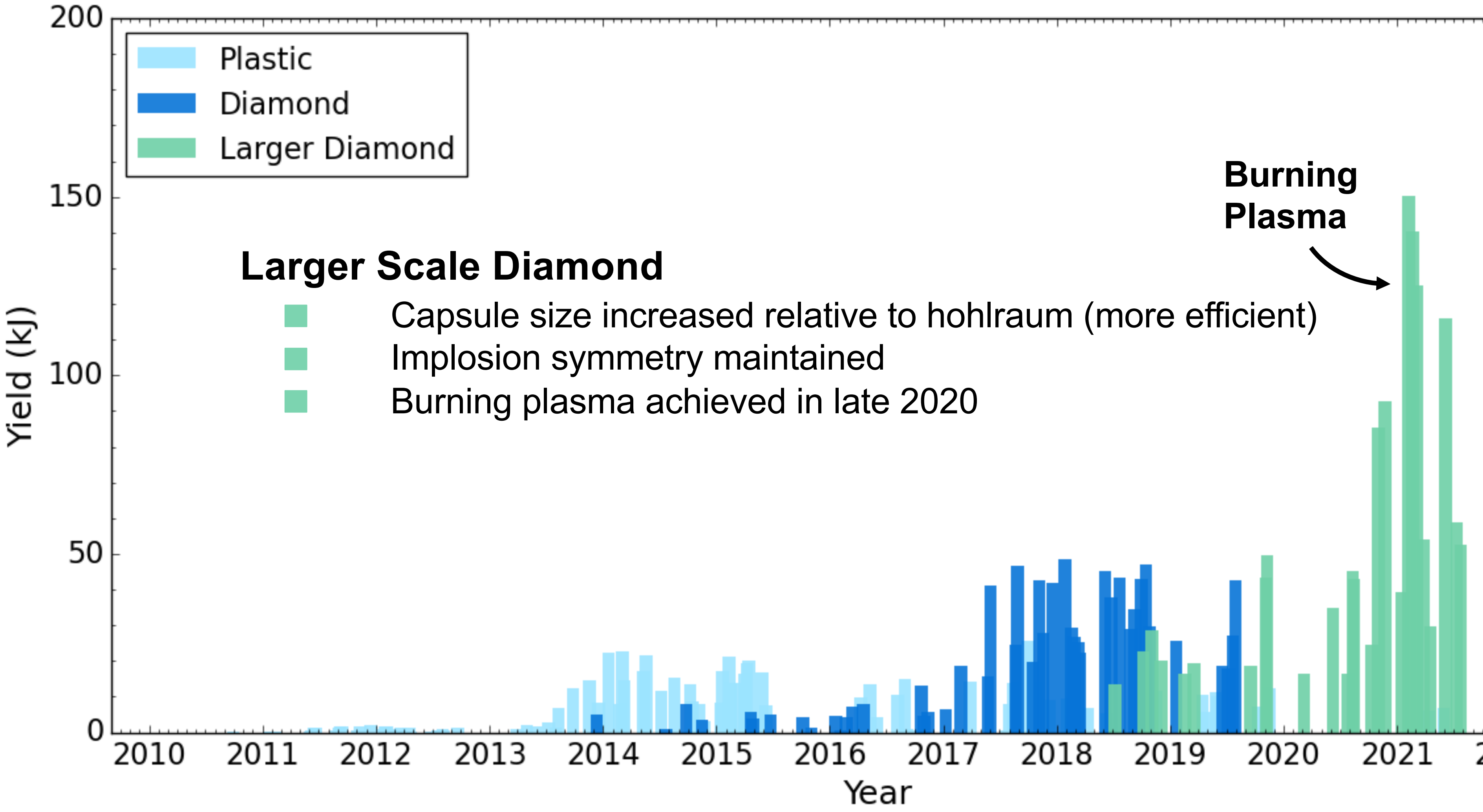
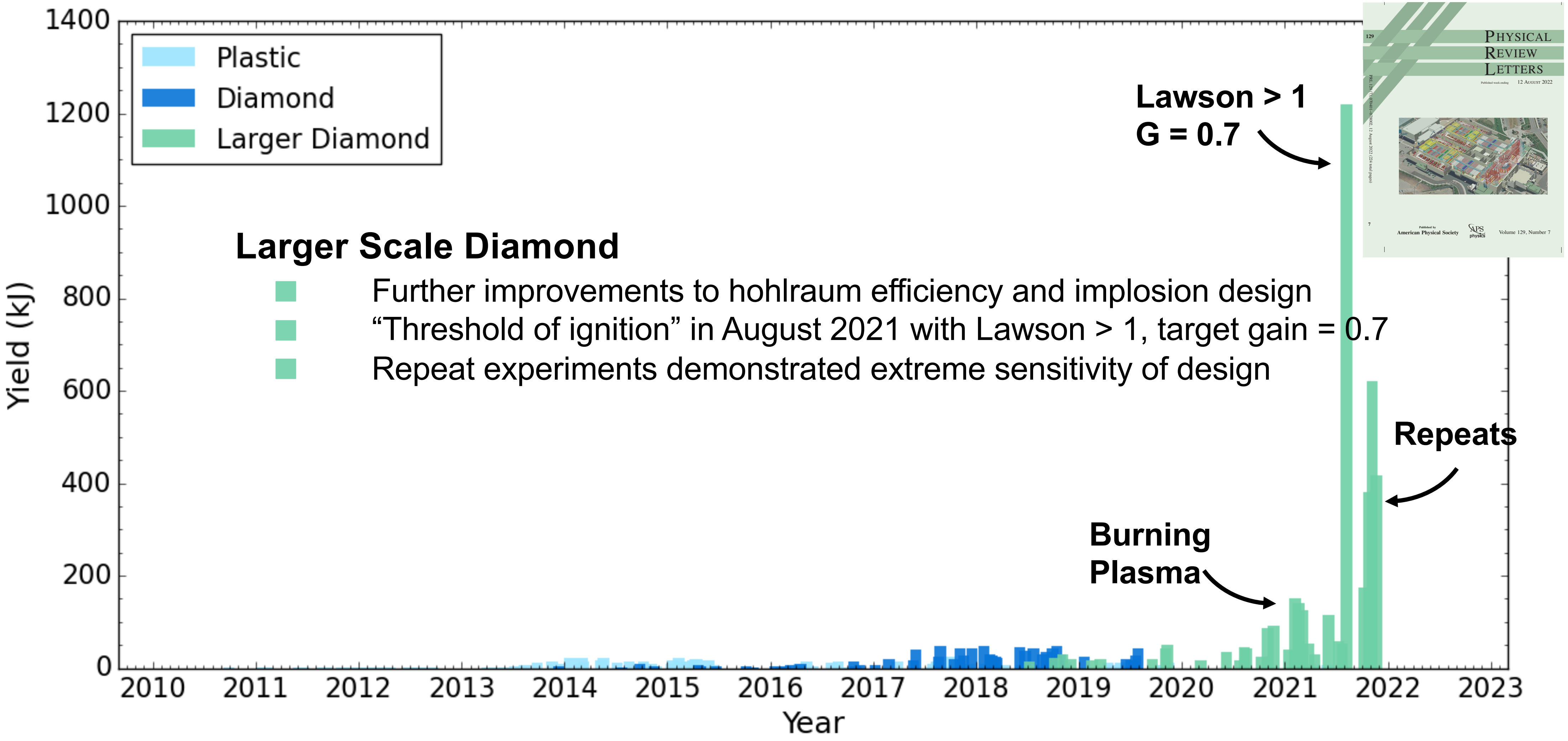


Larger Scale Diamond

- Capsule size increased relative to hohlraum (more efficient)
- Implosion symmetry maintained
- Burning plasma achieved in late 2020

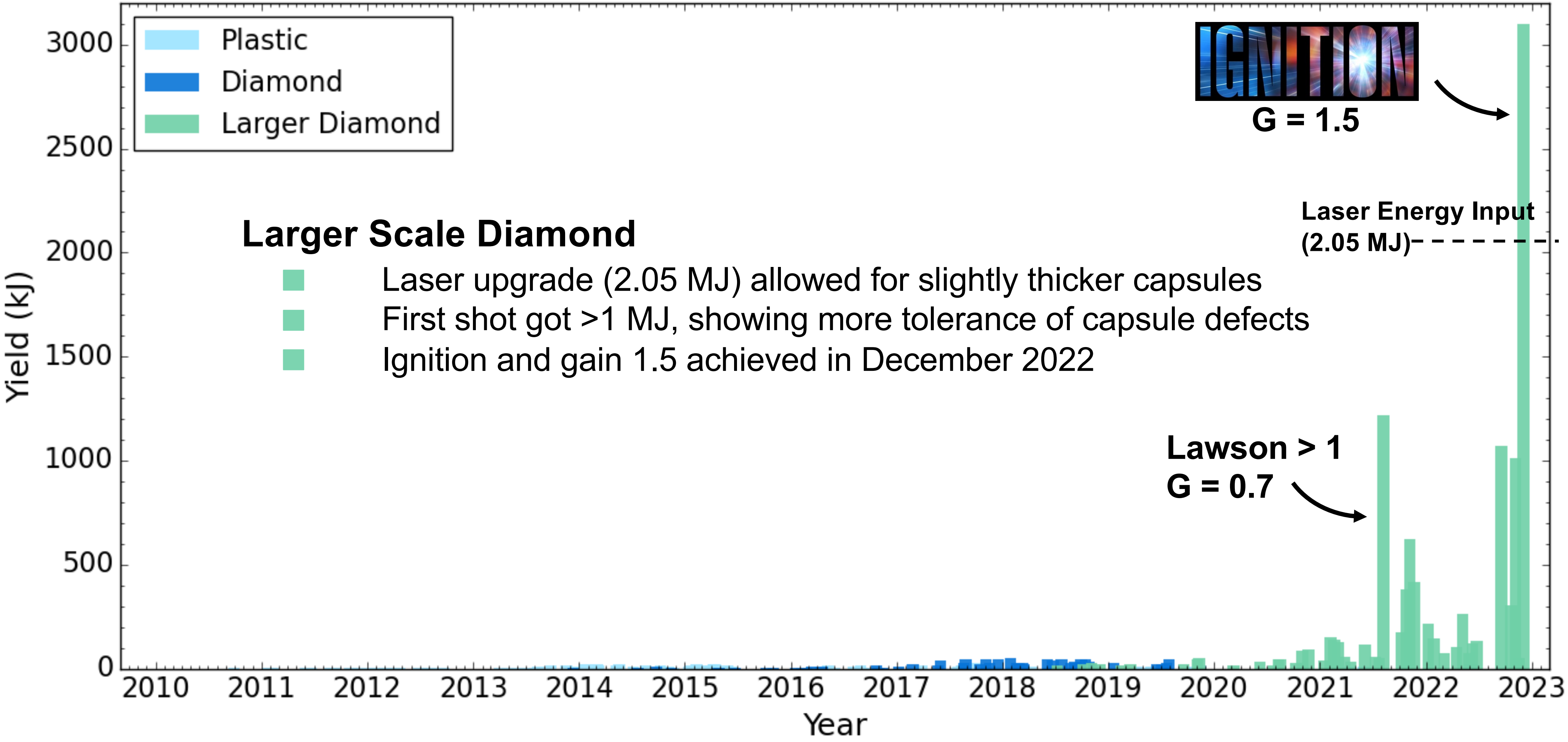
We can identify major turning points by looking at a plot of thermonuclear output versus time



Larger Scale Diamond

- Further improvements to hohlraum efficiency and implosion design
- “Threshold of ignition” in August 2021 with Lawson > 1, target gain = 0.7
- Repeat experiments demonstrated extreme sensitivity of design

We can identify major turning points by looking at a plot of thermonuclear output versus time



Indirect-drive ICF experiments are typically designed using integrated simulations and analyzed using capsule simulations

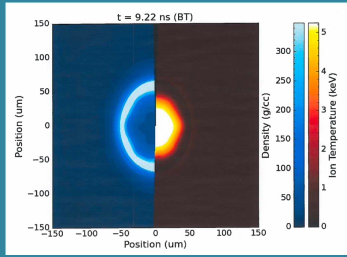
Experimental inputs

laser

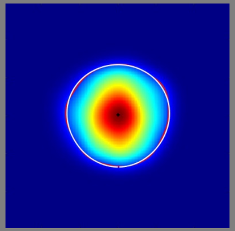
target

Integrated simulation →

Low-res preshot predictions



Experimental measurement



Neutron yield
DSR
Ion temperature
Hot spot velocity
Bang time
Shape
Radius

Indirect-drive ICF experiments are typically designed using integrated simulations and analyzed using capsule simulations

Experimental inputs

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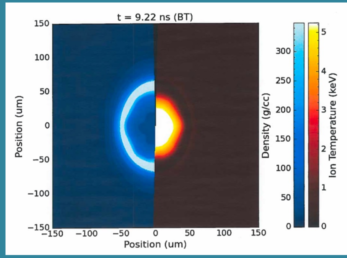
Integrated simulation →

Low-res preshot predictions



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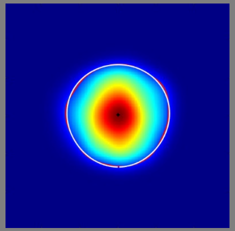

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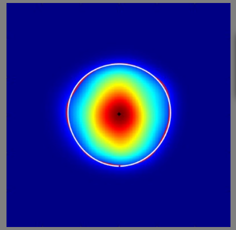
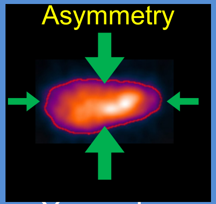


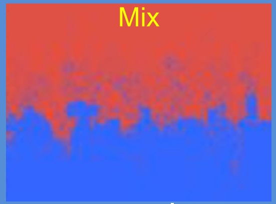
infer →

Capsule inputs ~ degradations

- Hard to observe or simulate
- Explain performance



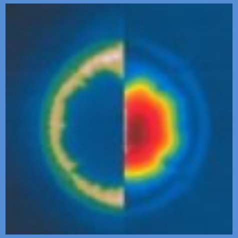
X-ray rive



capsule

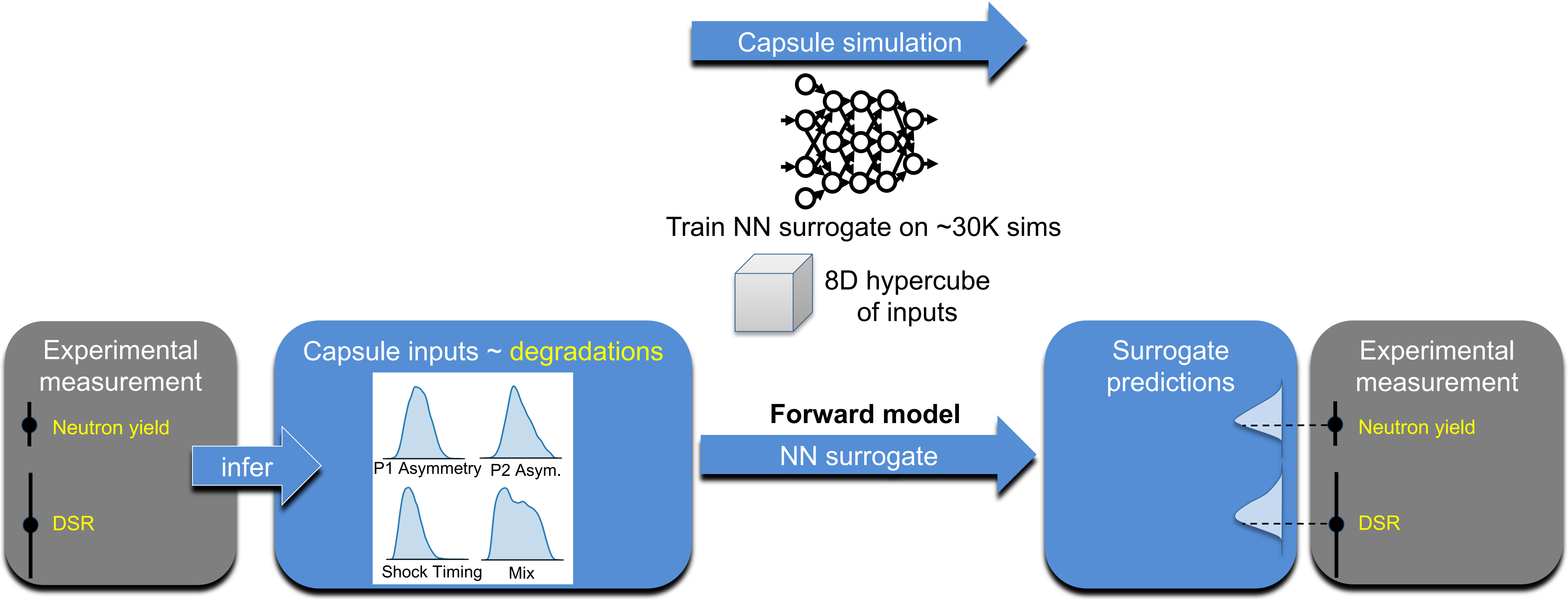
Capsule simulation →

Hi-res postshot analysis



We are using machine learning and Bayesian statistics to improve post-shot analyses and quantify uncertainties

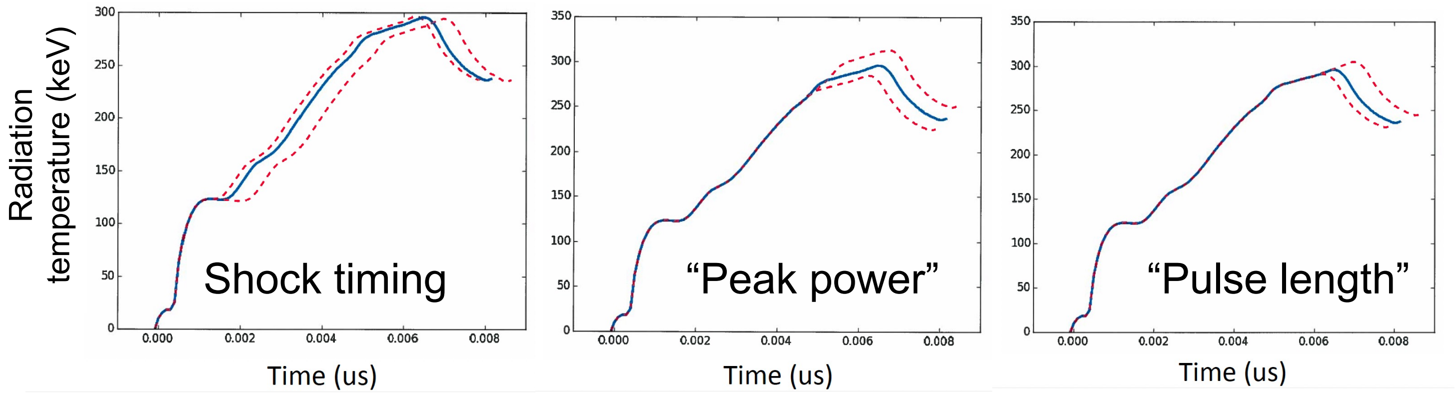
CogSim team uses Markov Chain Monte Carlo method to infer capsule inputs that match the experimental data

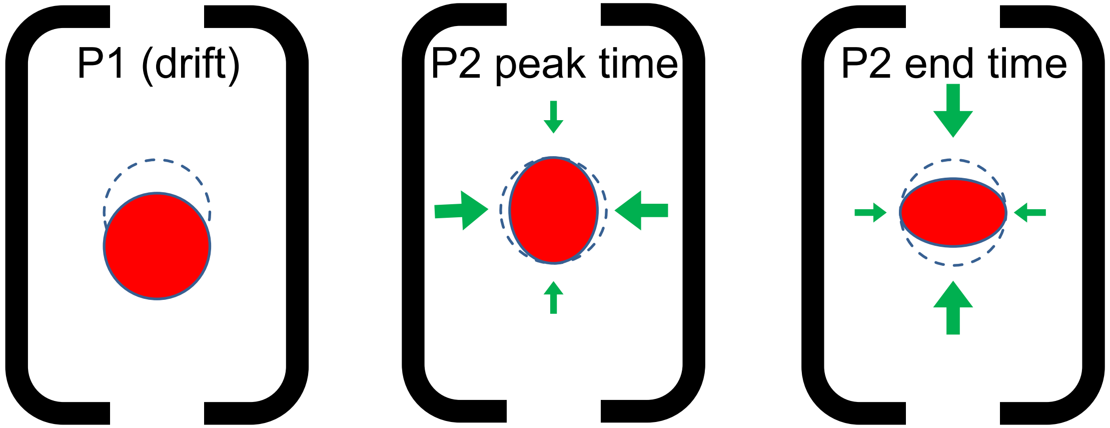


Bayesian inference requires ~10^6 evaluations of the forward model, therefore we cannot use simulations directly

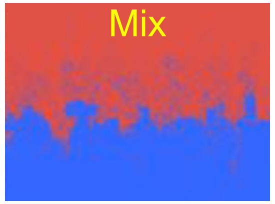
CogSim models include multiple inputs and outputs

Capsule inputs ~ degradations





M-band multiplier



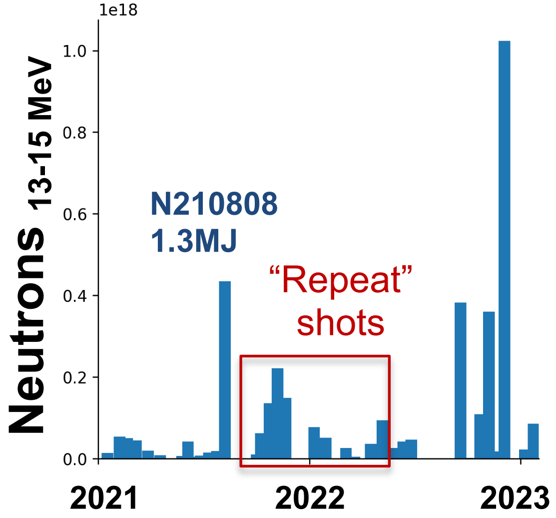
Experimental / simulated outputs

Output	Related to
Neutron yield	Generated energy
DSR	Confinement
Ion Temperature	Cross-section
Hot spot velocity	P1 degradation
Shape	P2 degradations
Radius	Compression
Bang time	Timing

Once the 1 MJ threshold was reached during N210808, a series of “repeat” experiments followed

Pre-ignition → **Ignition** → Applications

Focus on both higher gain and variability

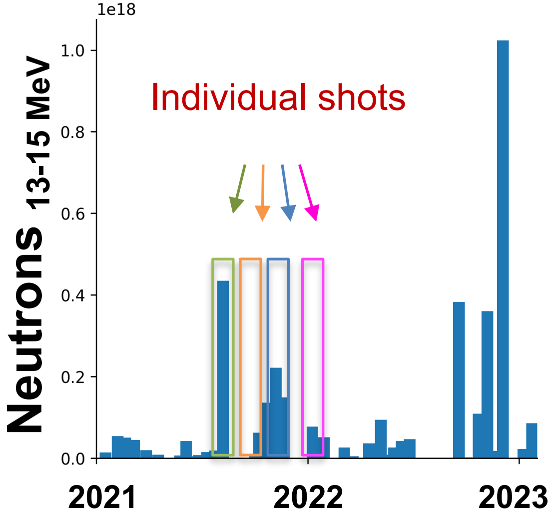


Variations in:
- target delivery
- capsule quality

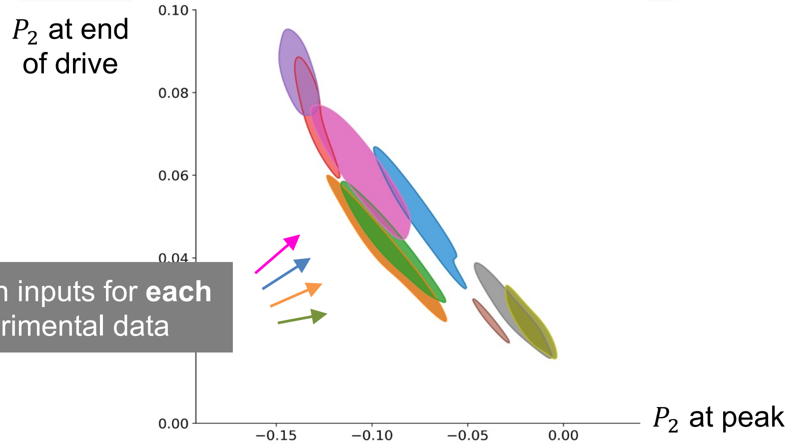
CogSim effort was to turn this new class of experiments into a quantitative model of the variability

One part of our statistical model is inferred capsule inputs for individual shots

Predict individual shots

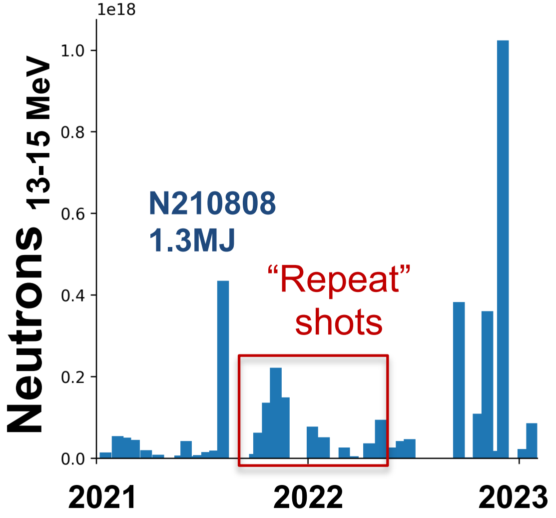


Capsule inputs ~ degradations



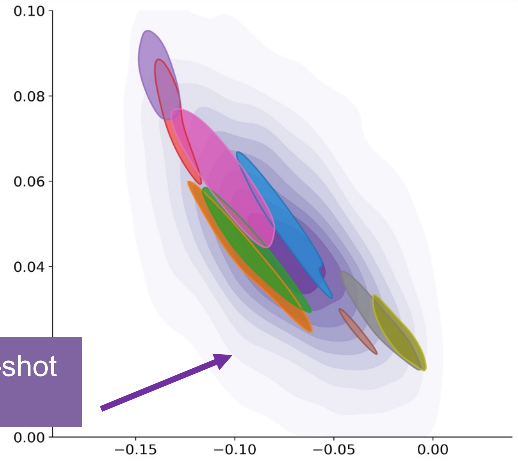
Distribution of simulation inputs for **each shot**, given the experimental data

Using N210808 + repeats, we have built a statistical model of the variability



Predict variations for the entire design

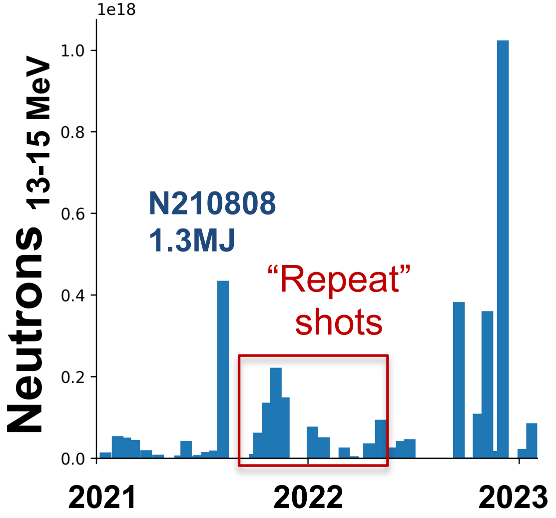
Capsule inputs ~ degradations



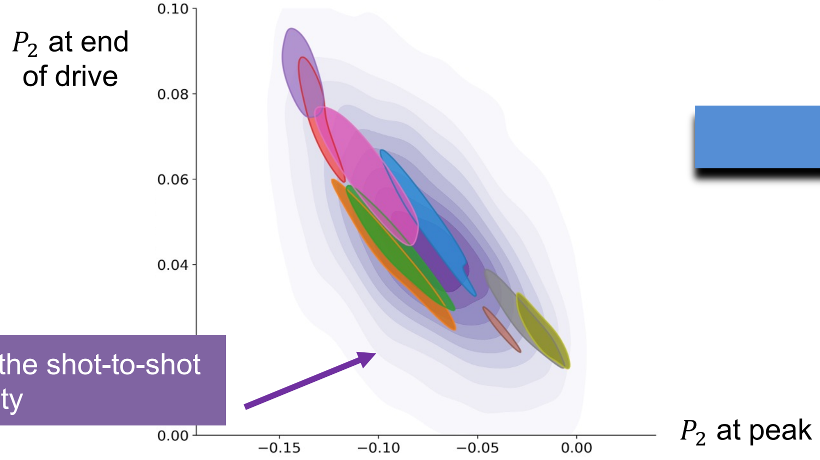
The variability captures the shot-to-shot repeatability

Using N210808 + repeats, we have built a statistical model of the variability

Predict variations for the entire design

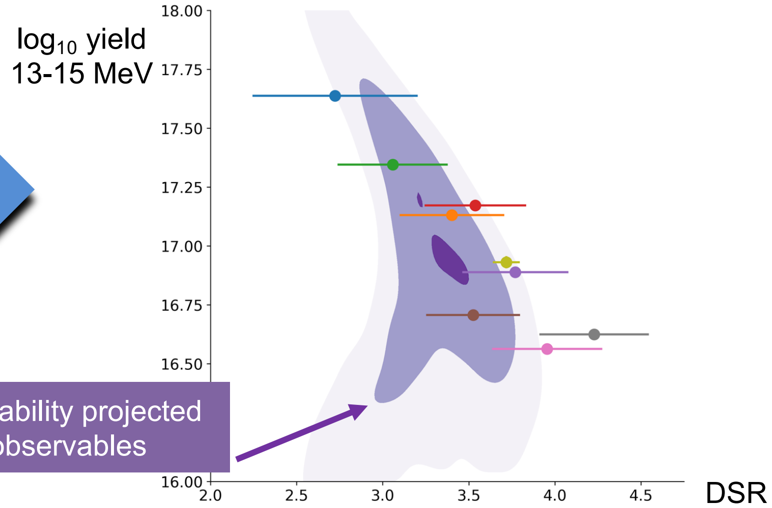


Capsule inputs ~ degradations



The variability captures the shot-to-shot repeatability

NN Surrogate

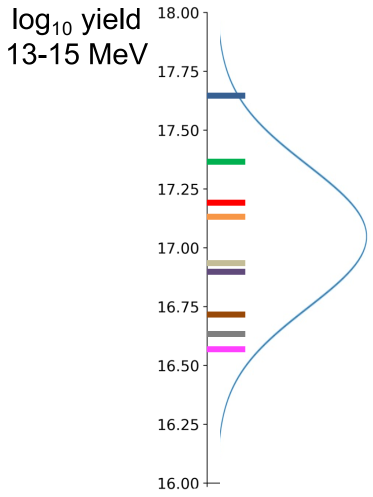


Input variability projected into observables

Our method to estimate the variability has multiple advantages over the naive approach

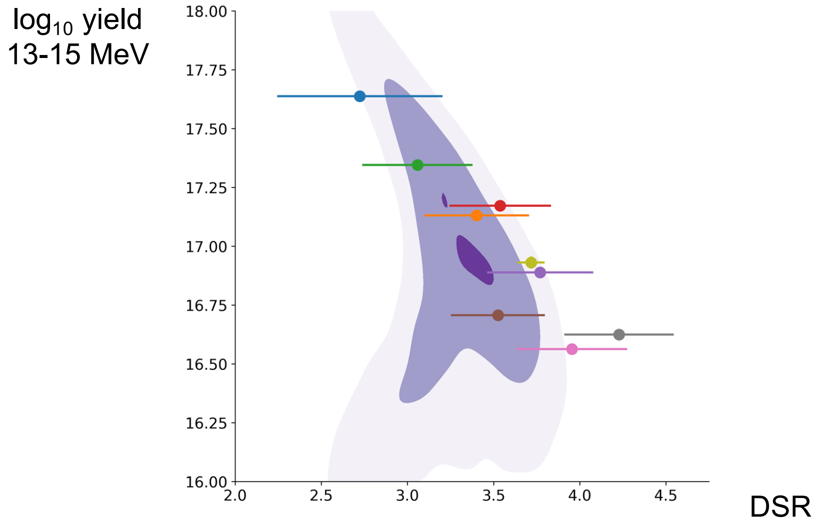
Naive approach

- Fit 1D gaussian to the experimental yield

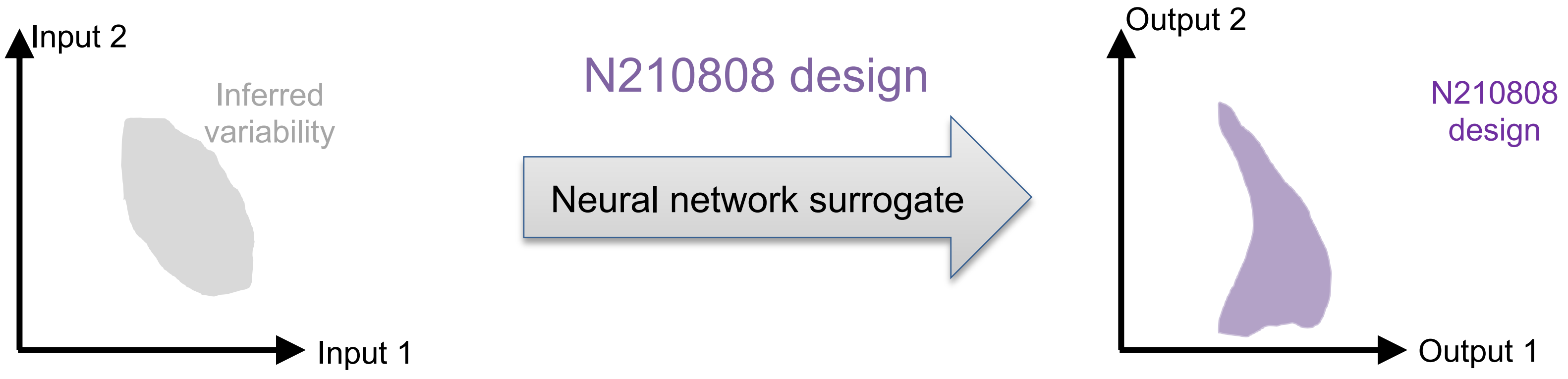


Our approach allows:

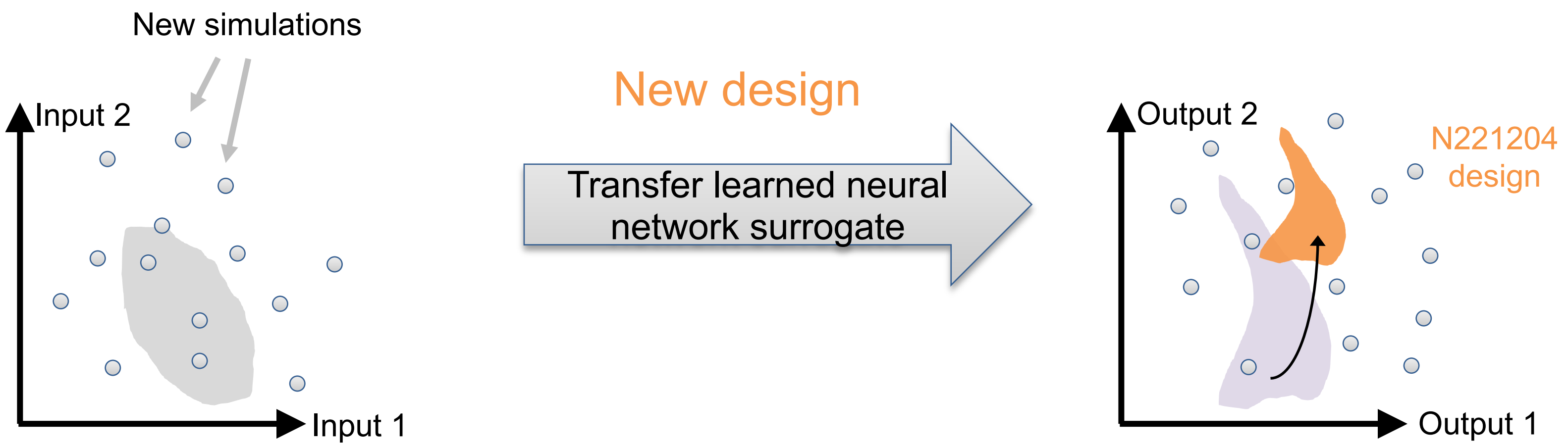
- Outputs to be non-Gaussian
- Multiple outputs: more detailed prediction
- Correlations informed by simulations rather than by experiments alone
- Physical interpretation (degradations can inform future designs)
- Extrapolations that are physically viable (constrained by simulations)
- Transfer to new designs to make predictions



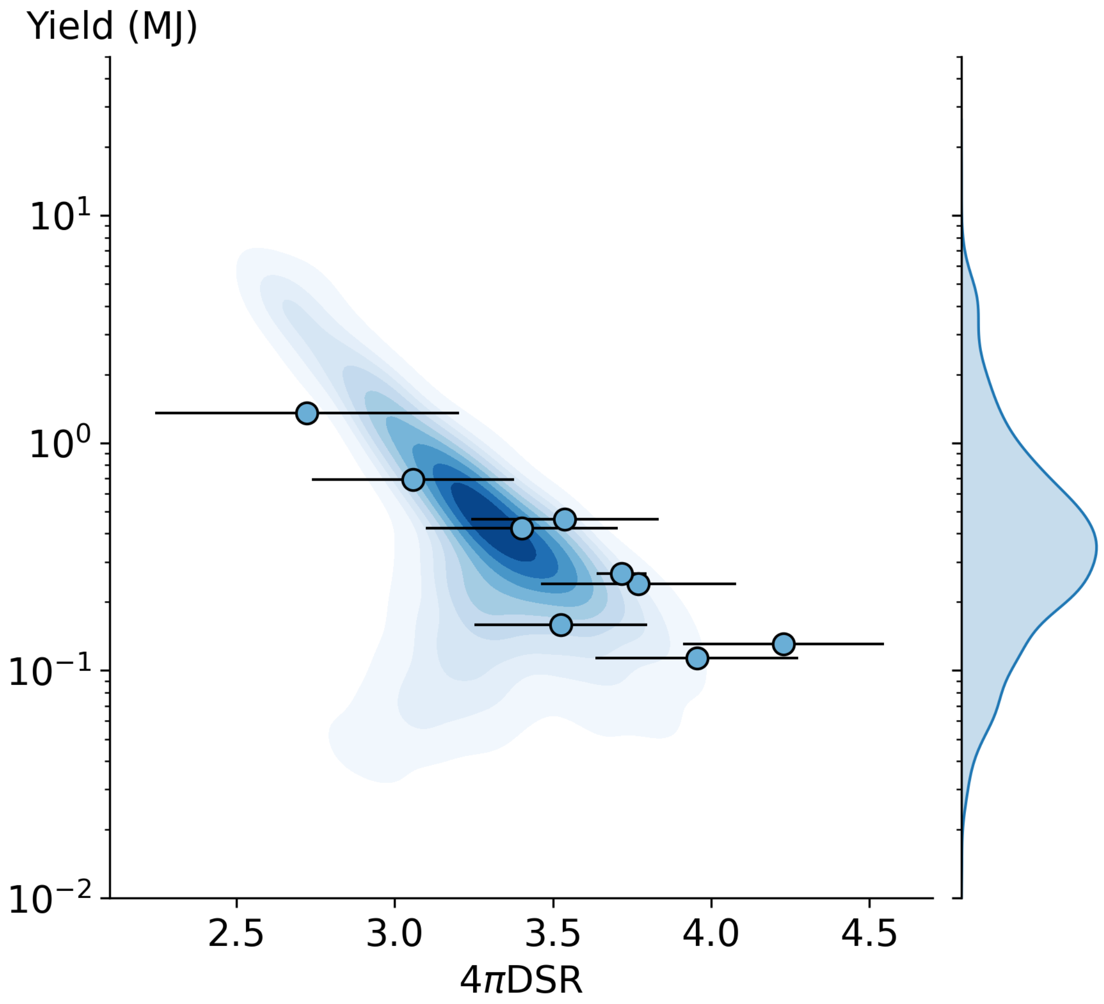
The surrogate model of the simulations can be transformed to predict the output variability in new designs



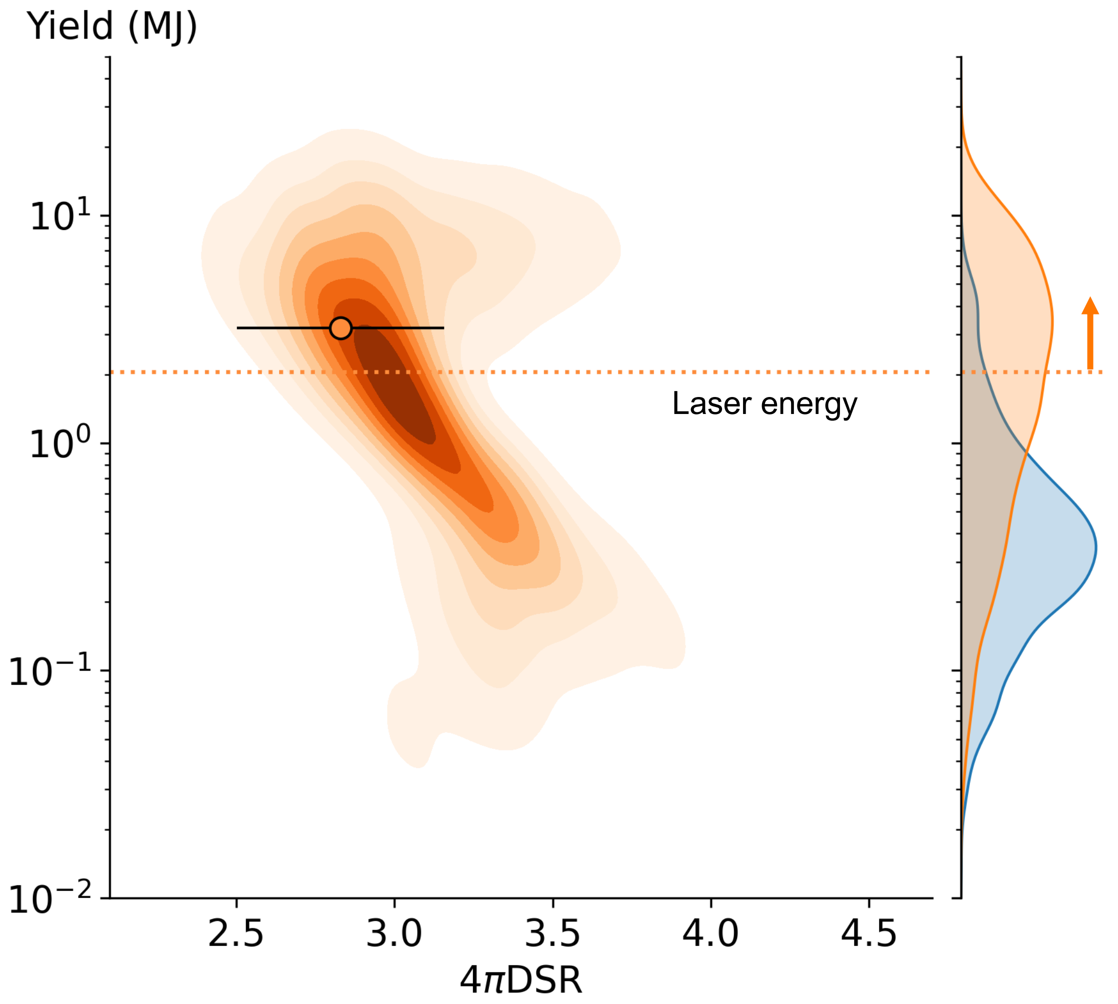
- A standard ICF surrogate in 8D requires ~30K simulations
- We may be limited to a two–week lead time to make predictions
- Solution:
  1) Run dozens of simulations at carefully selected locations determined by Stochastic Collocation
  2) Transfer learn the surrogate model to a new design



The variability model captures the experimental results for the shots with the N210808 (1.9 MJ) design

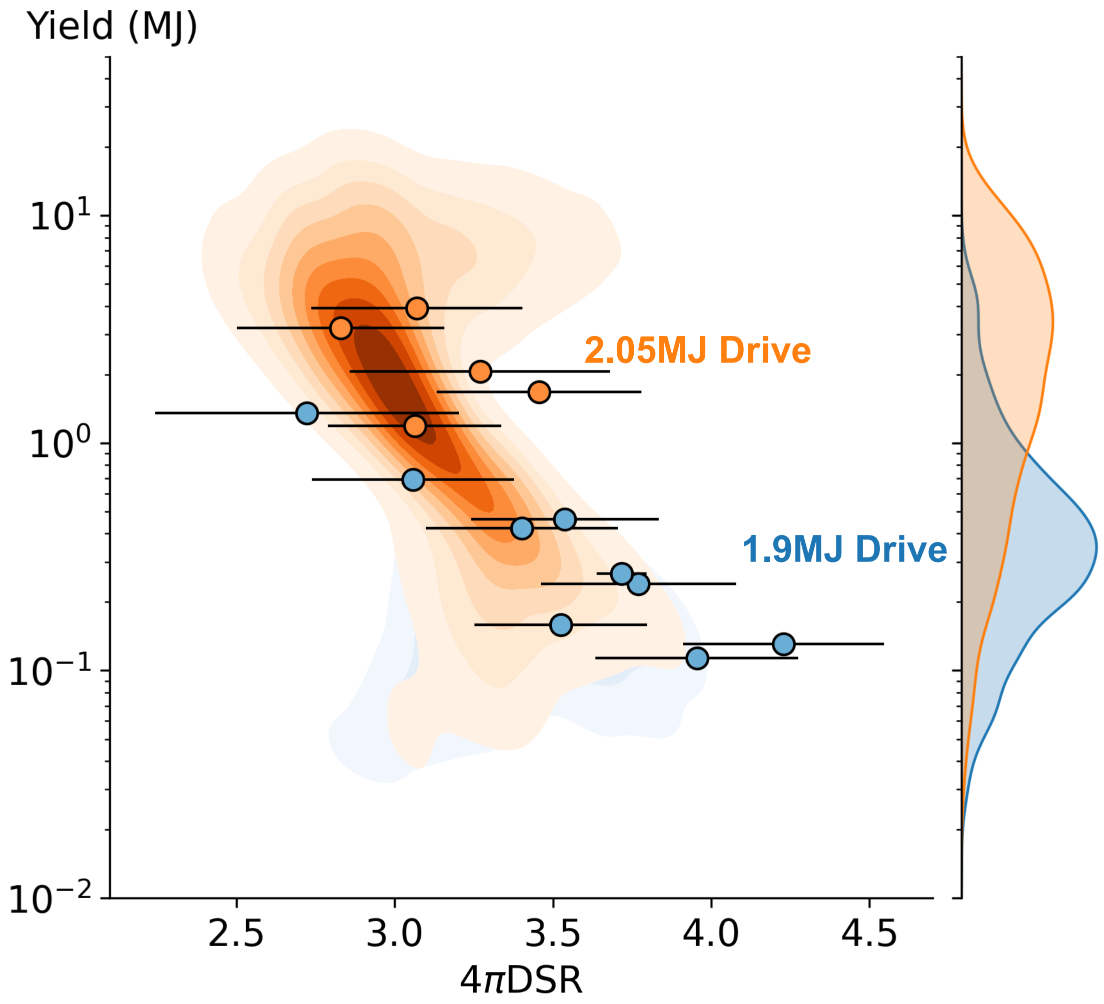


Predictions of N221204 with the new 2.05MJ design indicate a significant increase in the probability of ignition



Shot	Probability of ignition
N210808	7 %
N221204	48 %

Subsequent shots with the 2.05MJ design validated the predictions



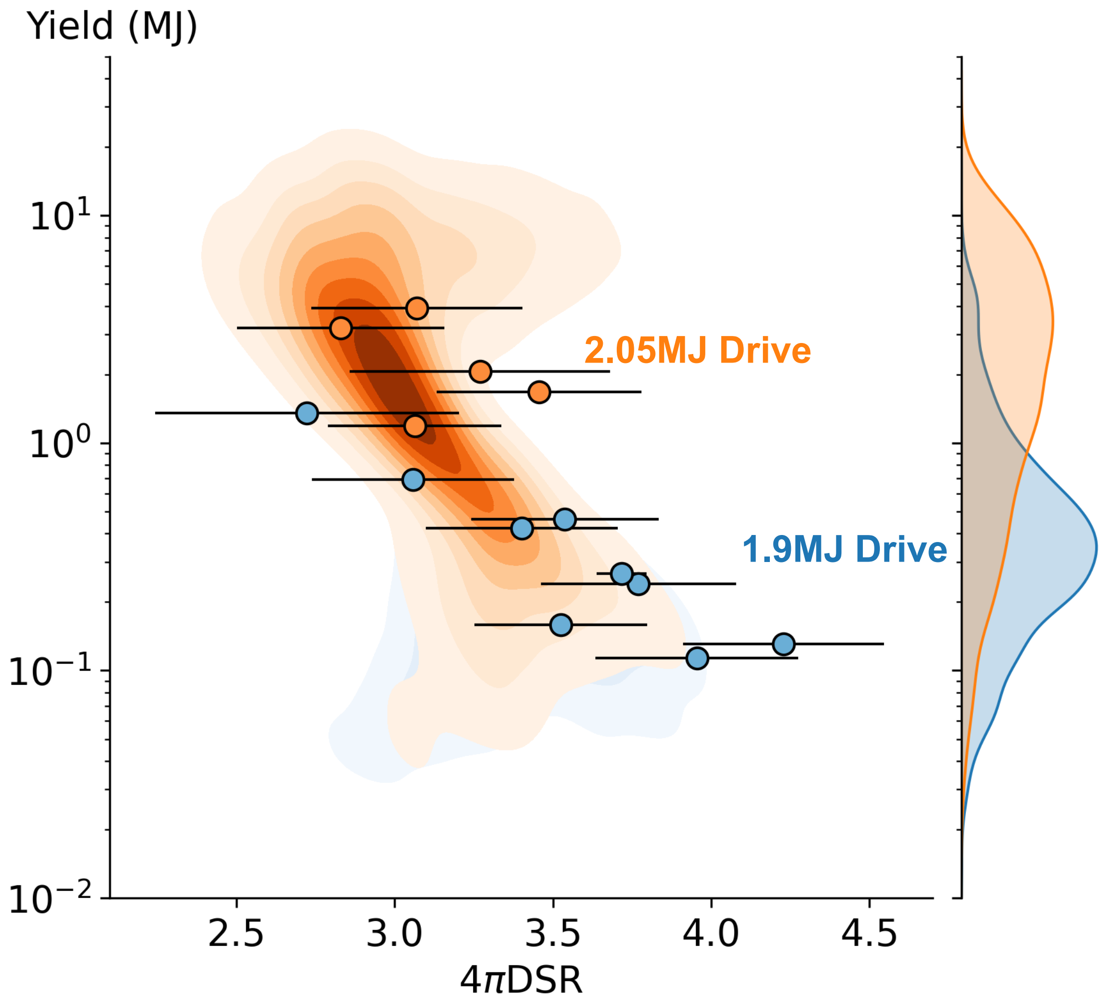
Predicting ignition is just the beginning; our method can be applied in future design decisions

Pre-ignition → Ignition → **Applications**

- Design optimization for higher gains in
  - Stockpile stewardship
  - IFE

Our method can expand design optimization beyond performance and include variability

Subsequent shots with the 2.05MJ design validated the predictions



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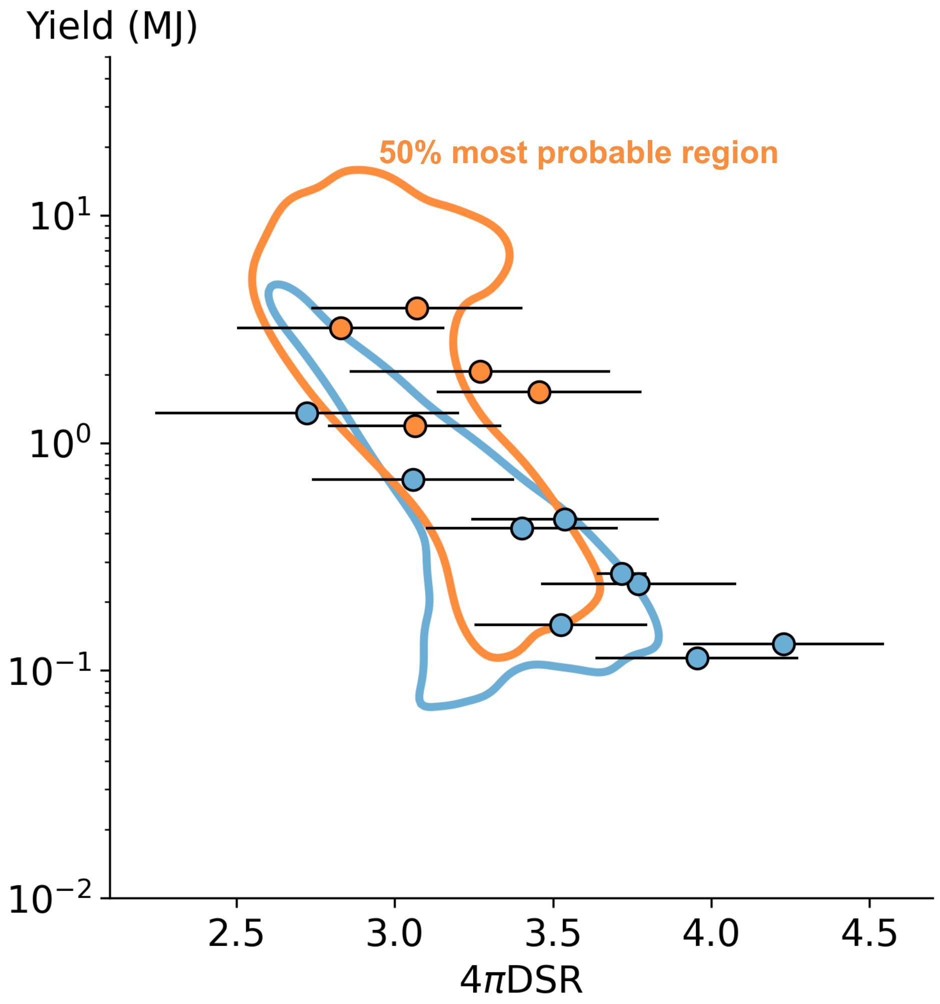
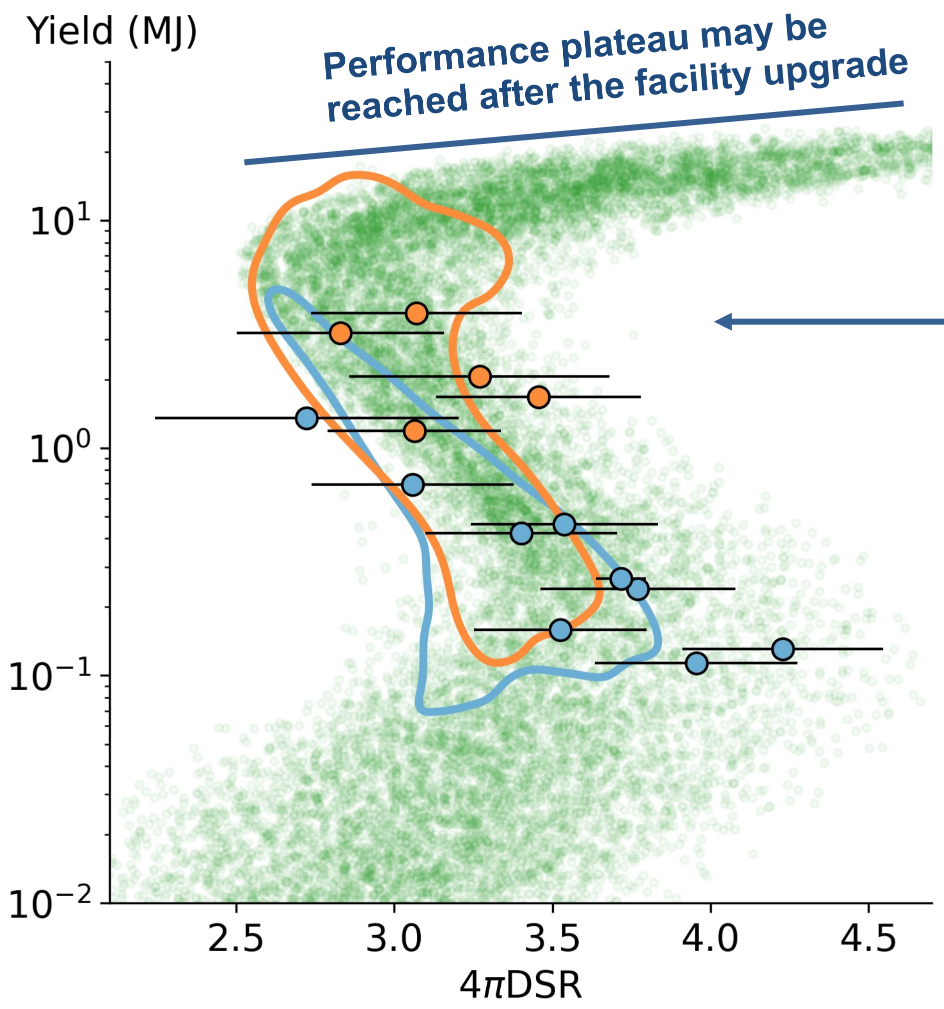


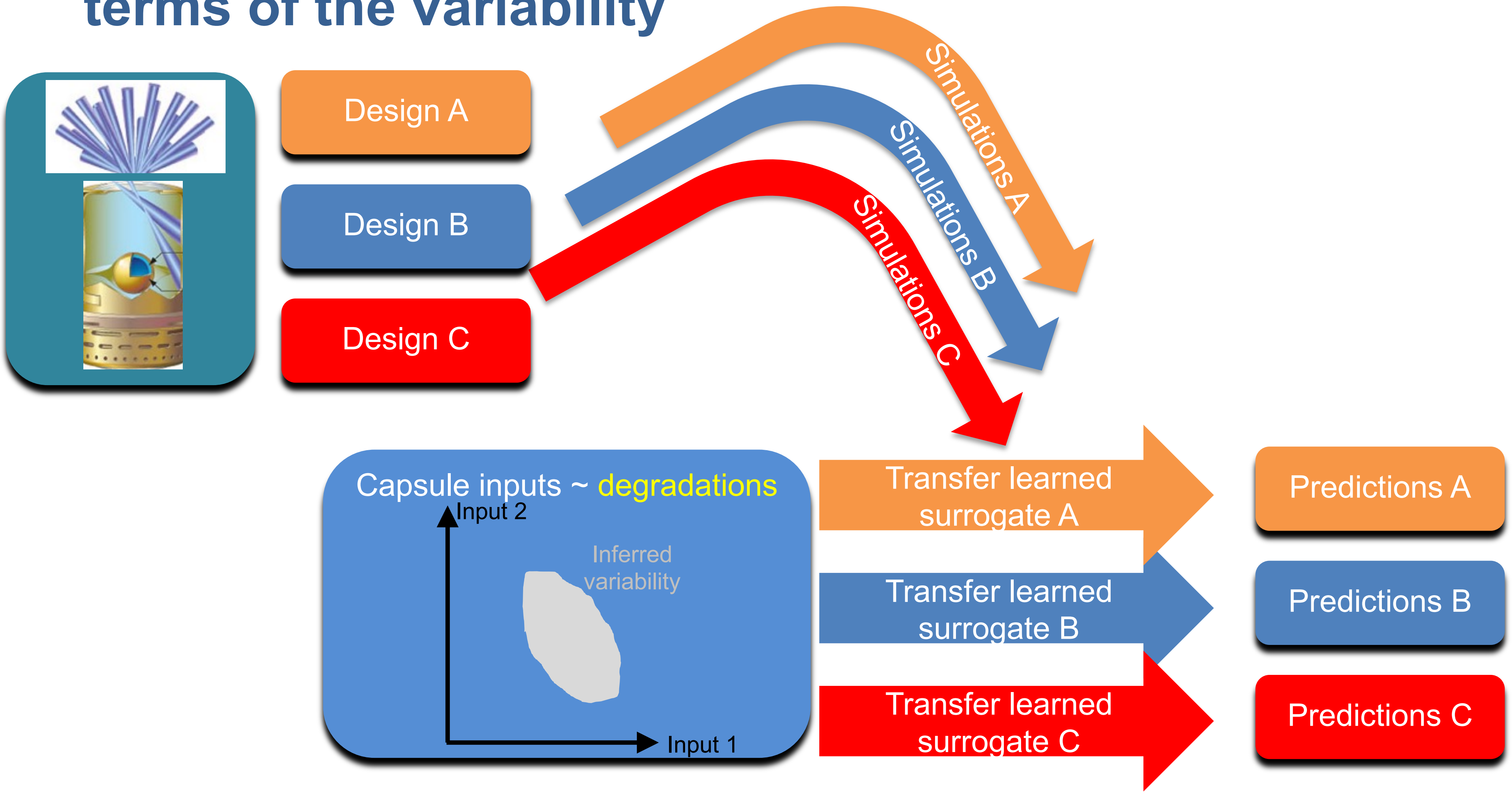
Our predictions could potentially be used to inform decision about future facility upgrades



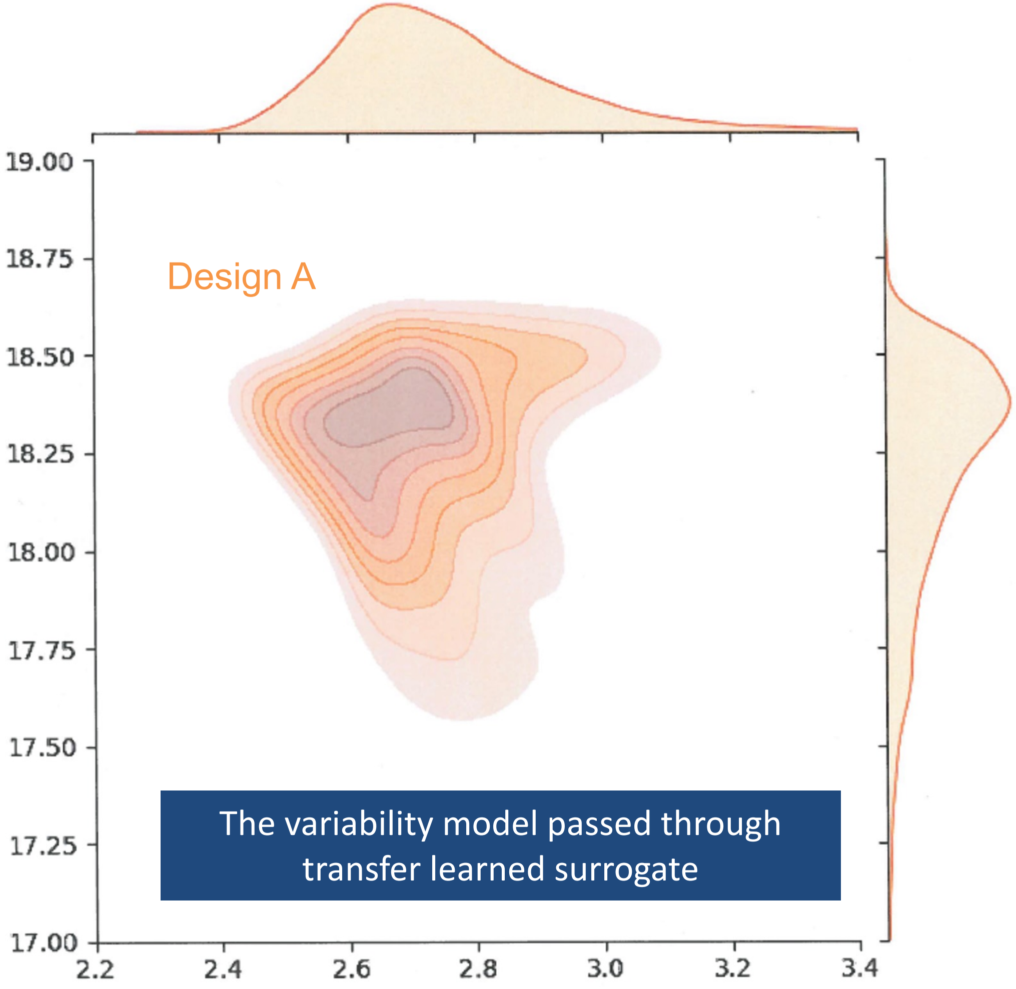
We have made a demonstration in this regime

30,000 2D HYDRA simulations with varying drive, asymmetry, and mix

Different point designs can be compared against each other in terms of the variability



Our technique can estimate the variability in different candidate designs before they are tested experimentally



log$_{10}$ yield 13-15 MeV

4Π DSR [%]

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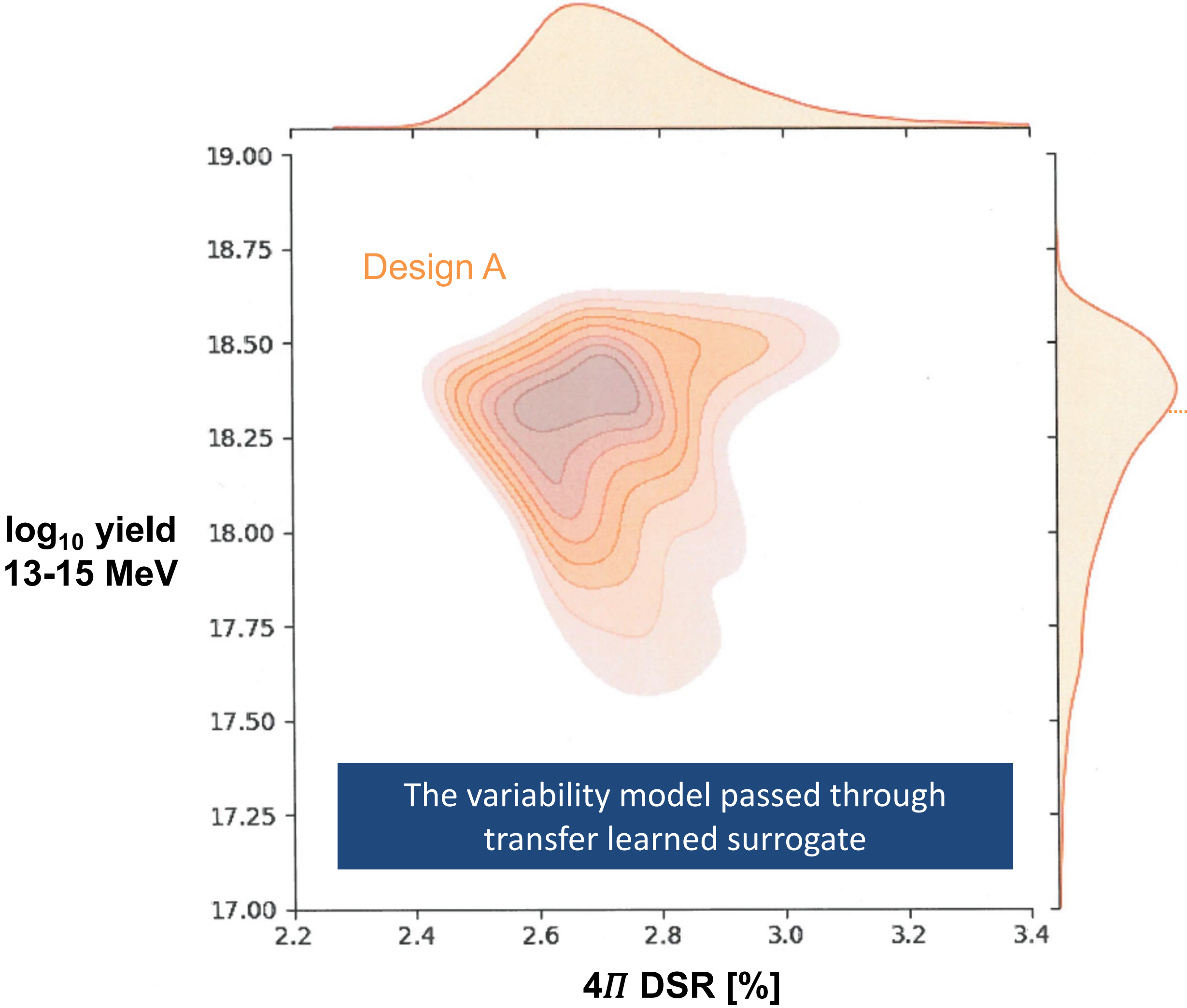
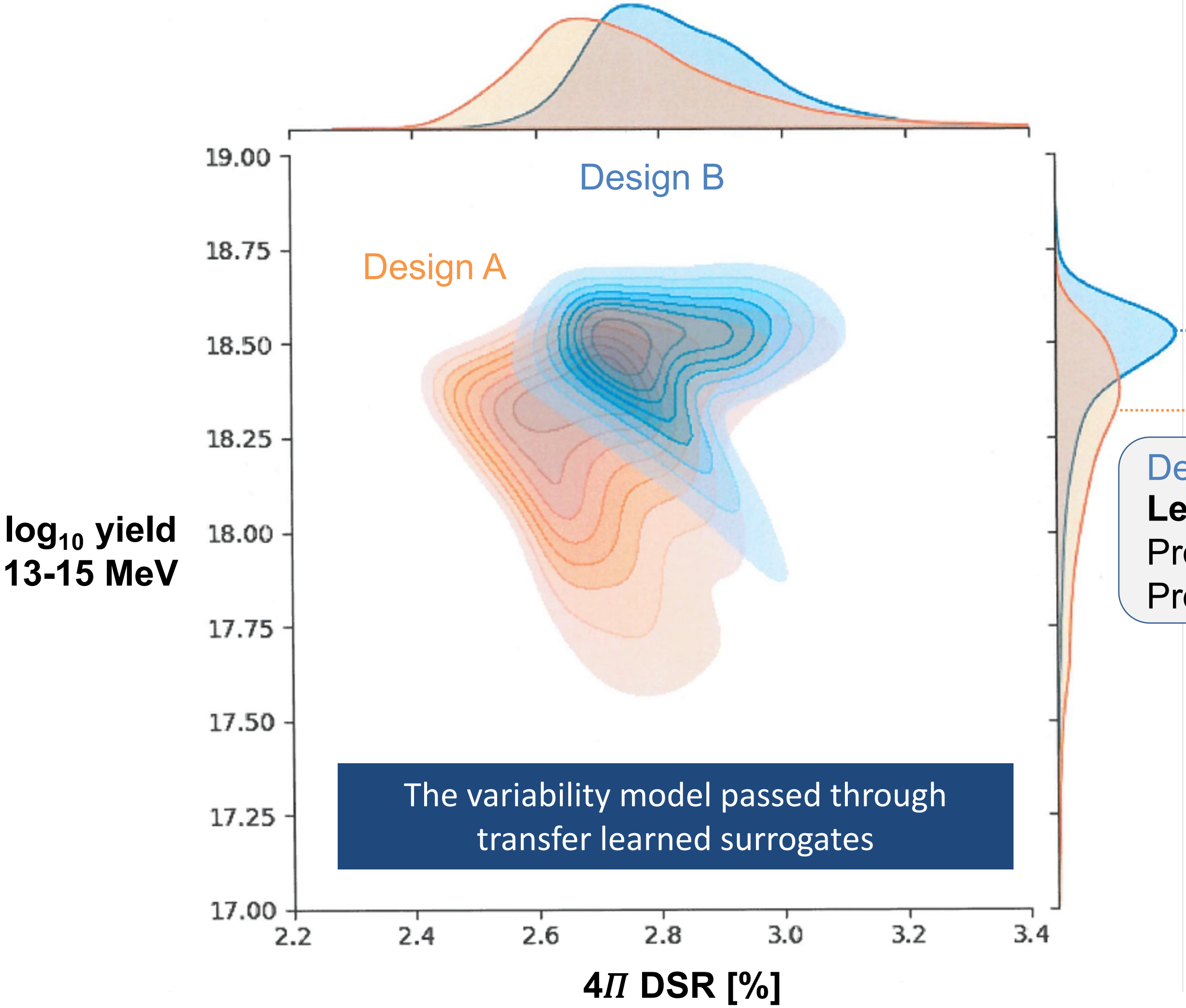


Design A
Baseline variability
Prob. (> 1MJ) = 0.94
Prob. ignition = 0.83

Central 50%

$Y_{25\%}$	$Y_{75\%}$
2.8 MJ	7.3 MJ

Our technique can estimate the variability in different candidate designs before they are tested experimentally



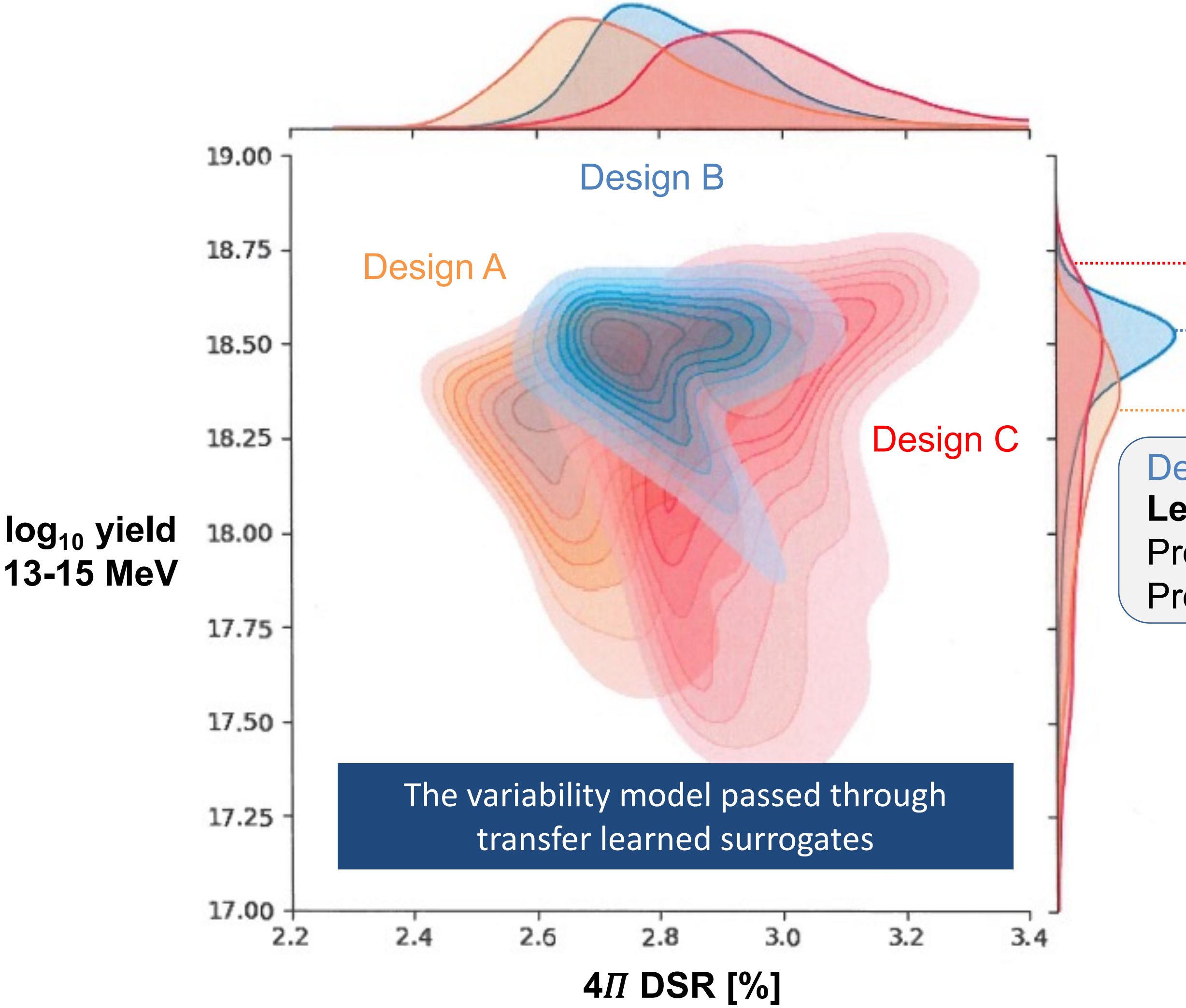
Design B
Less variability
Prob. (> 1MJ) = **0.96**
Prob. ignition = **0.93**

Design A
Baseline variability
Prob. (> 1MJ) = 0.94
Prob. ignition = 0.83

Central 50%

$Y_{25\%}$	$Y_{75\%}$
6.0 MJ	9.9 MJ
2.8 MJ	7.3 MJ

Our technique can estimate the variability in different candidate designs before they are tested experimentally



Design B
Less variability
Prob. (> 1MJ) = **0.96**
Prob. ignition = **0.93**

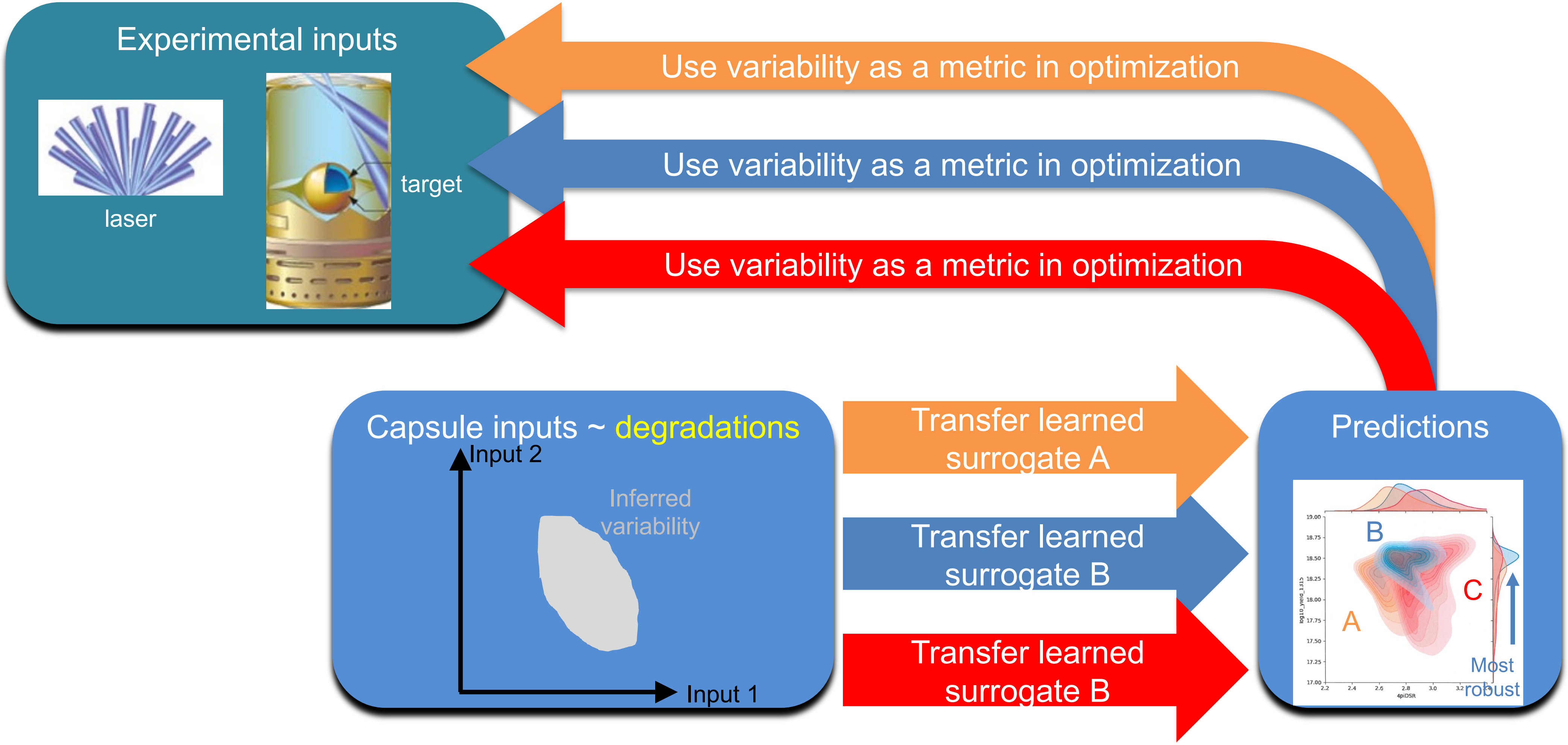
Design A
Baseline variability
Prob. (> 1MJ) = 0.94
Prob. ignition = 0.83

Design C
More variability
Prob. (> 1MJ) = **0.88**
Prob. Ignition = **0.74**

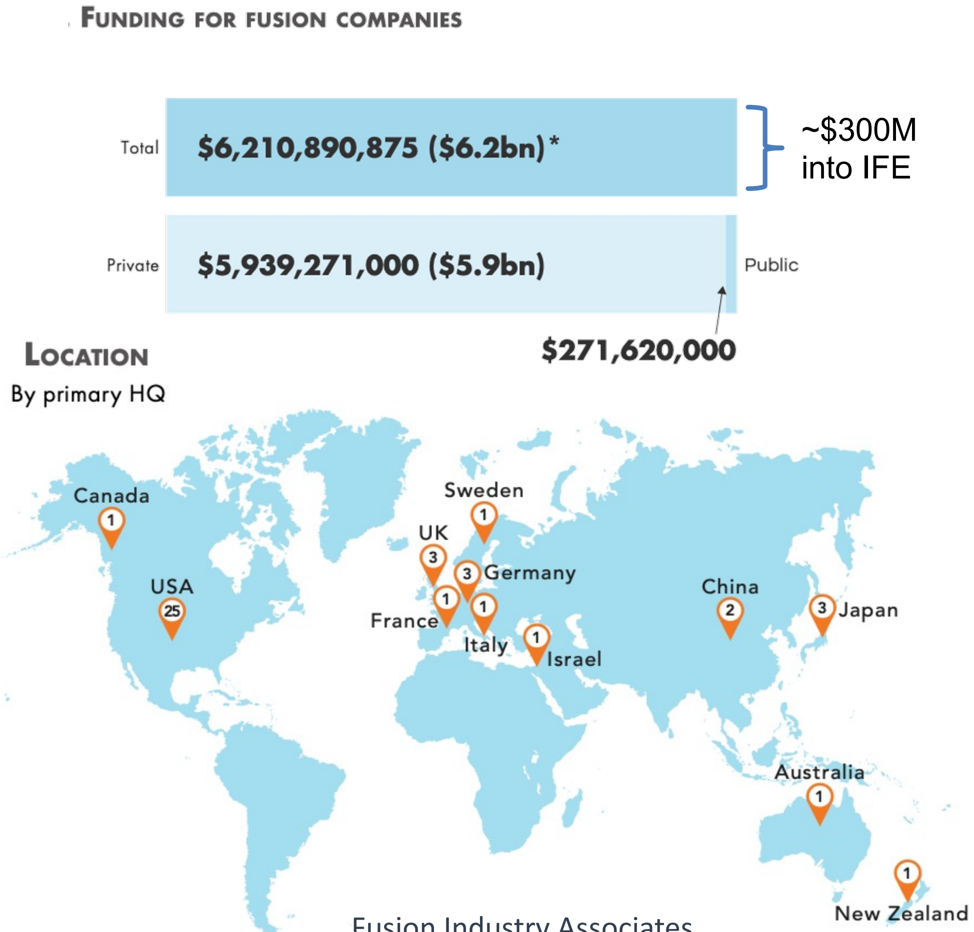
Central 50%

$Y_{25\%}$	$Y_{75\%}$
6.0 MJ	9.9 MJ
2.8 MJ	7.3 MJ
1.9 MJ	8.6 MJ

The variability could potentially be used as a robustness metric in the semi-automated design optimization loop



Our method to compute the variability could potentially be applied in IFE and MFE projects



Fusion Industry Associates
The Global Fusion Industry in 2023

Ignition provides fresh impetus and the scientific foundation for inertial fusion energy

We've formed an "IFE Collaboratory" to facilitate public-private partnerships

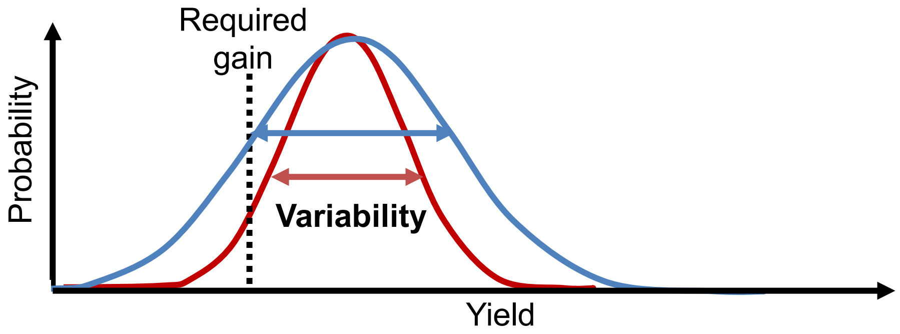
- Living website: *https://events.bizzabo.com/RFI-IFE/home*
- Collaboratory website lists capabilities
- Two Industry Days held
- Currently developing ideas for "hubs" focused on jointly developing technologies of use to multiple institutions/companies/IFE approaches

The Collaboratory promotes fairness of opportunity for partnerships, and ensures strategic alignment with core missions

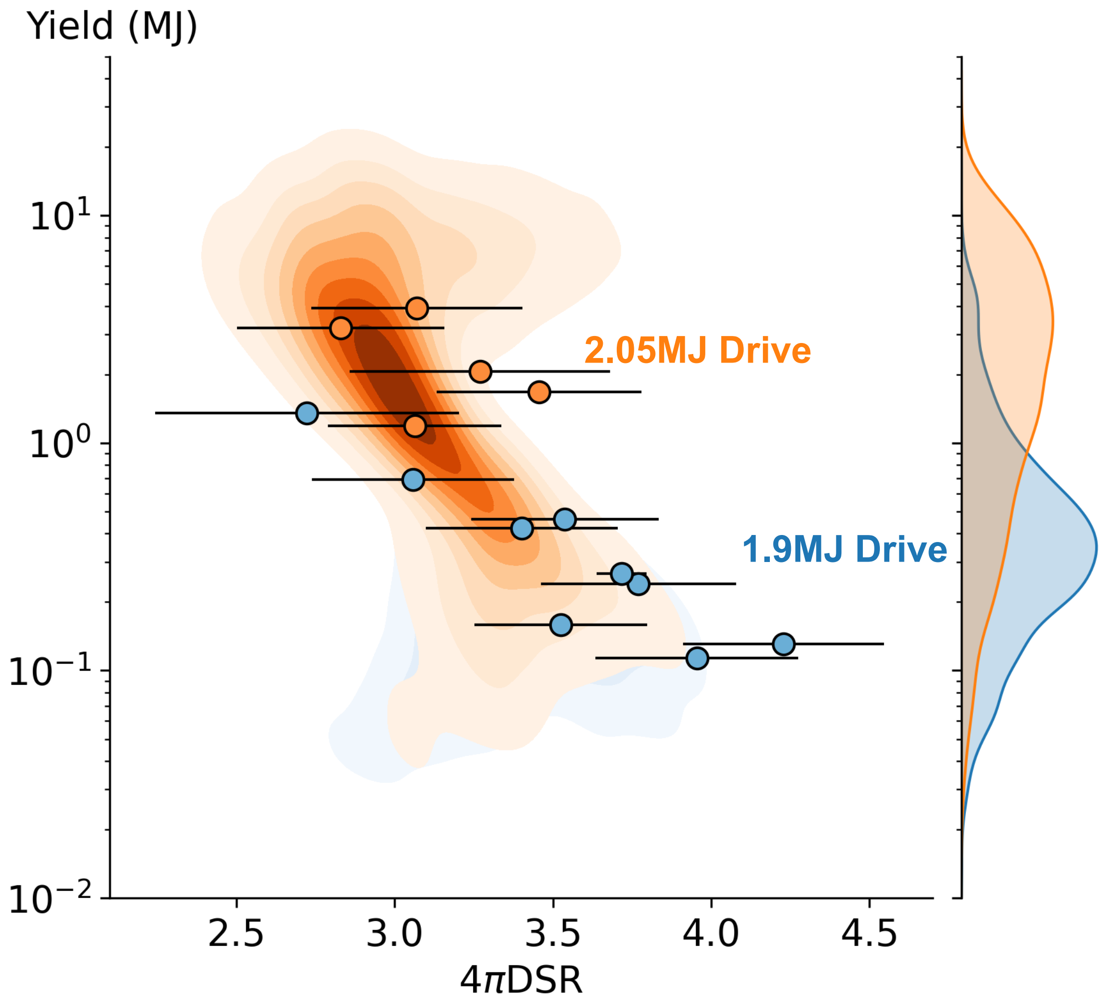
In October, we started a 3-year R&D project for developing targets for IFE

Pre-ignition → Ignition → Applications

- What are the requirements for target production to reach the required gain?

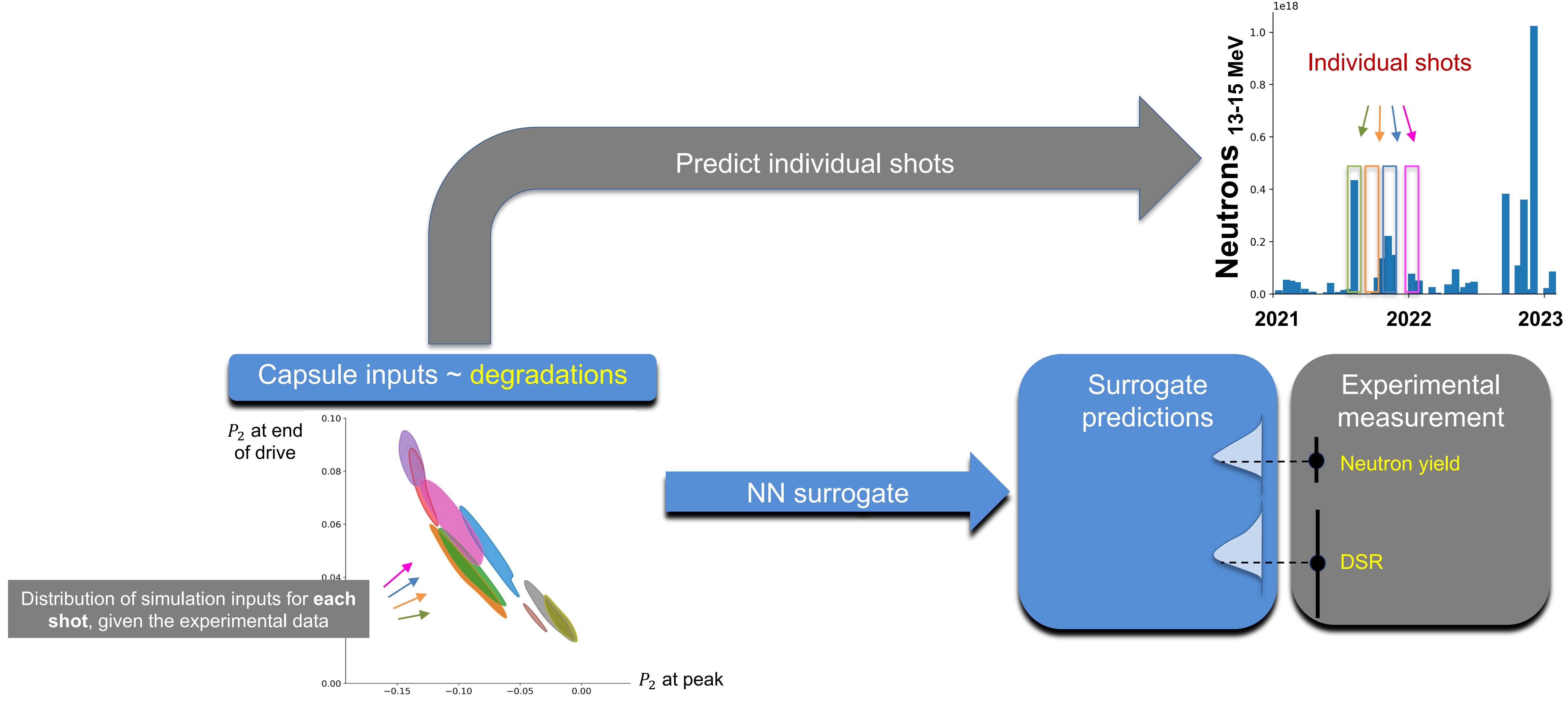


We have made a physics-informed prediction with data-informed uncertainty of the first ICF experiment with target gain>1

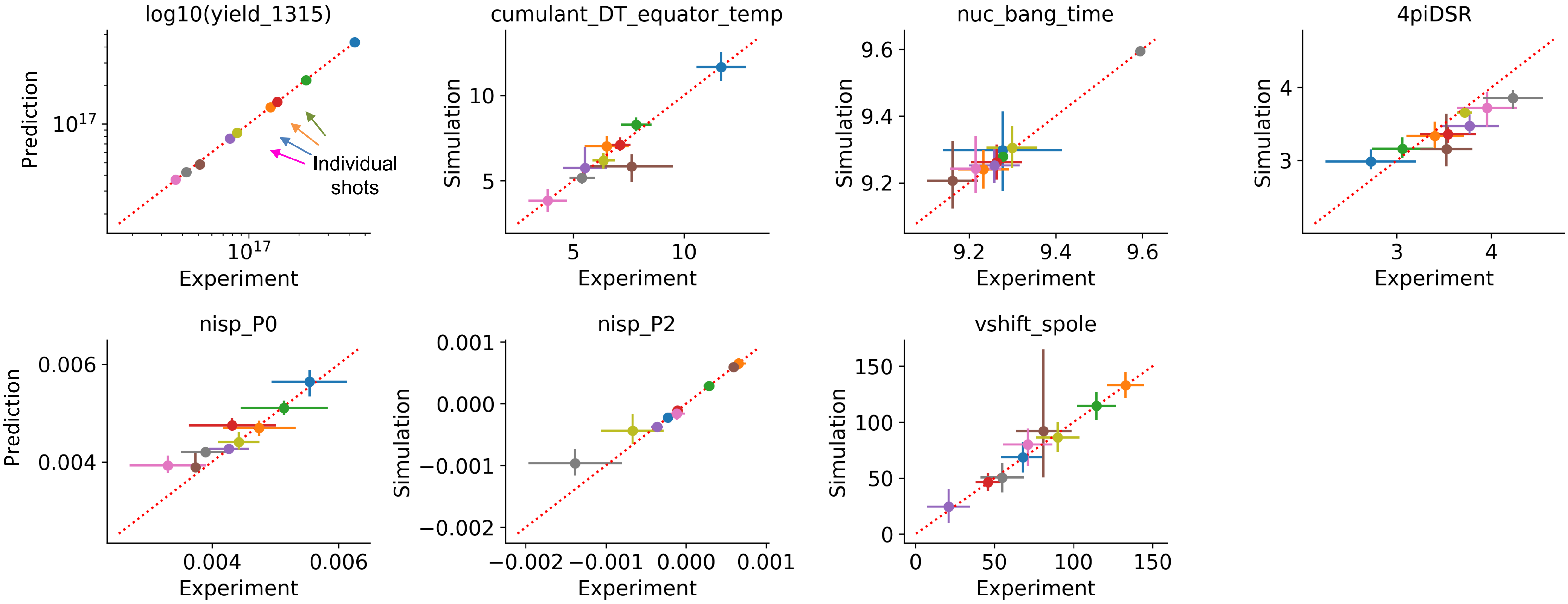


Lawrence Livermore National Laboratory

One part of our statistical model is inferred capsule inputs for individual shots



The model predictions match multiple experimental outputs within experimental error bars



We compare the variability in three experimentally untested designs

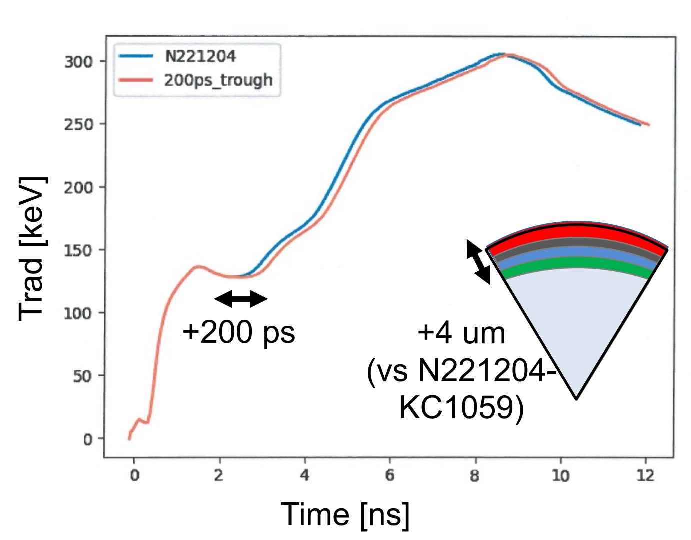
New baseline

KC1059 capsule, 2.05MJ laser

- KC1059 capsules available in mid-2023
- Lower dopant level: 0.42% vs 0.63%
- 1 um thinner ablator

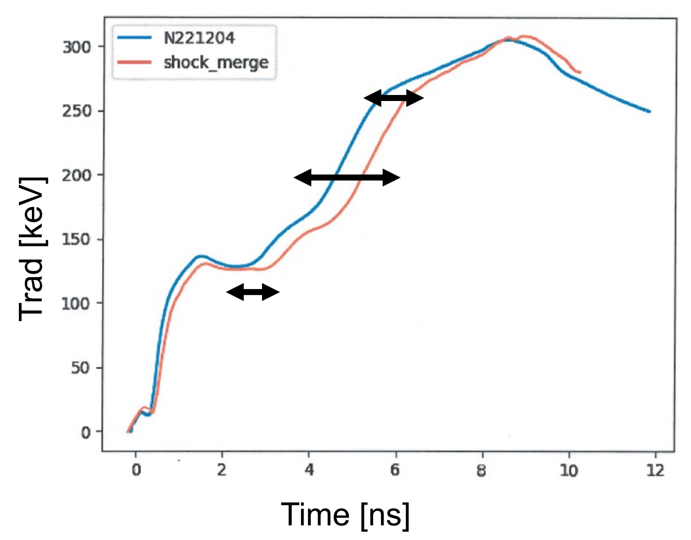
Thicker ablator, shock delay

KC1059 capsule, 2.05MJ laser



Shock merge

KC1059 capsule, 2.05MJ laser



Transfer

Transfer

Transfer

N221204

The variability model combines the individual single-shot Bayesian analysis into one global input variability model

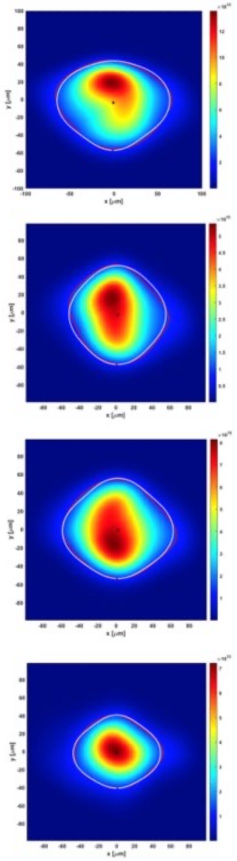
Experimental Data → HYDRA Input Parameters

N210808

N211024

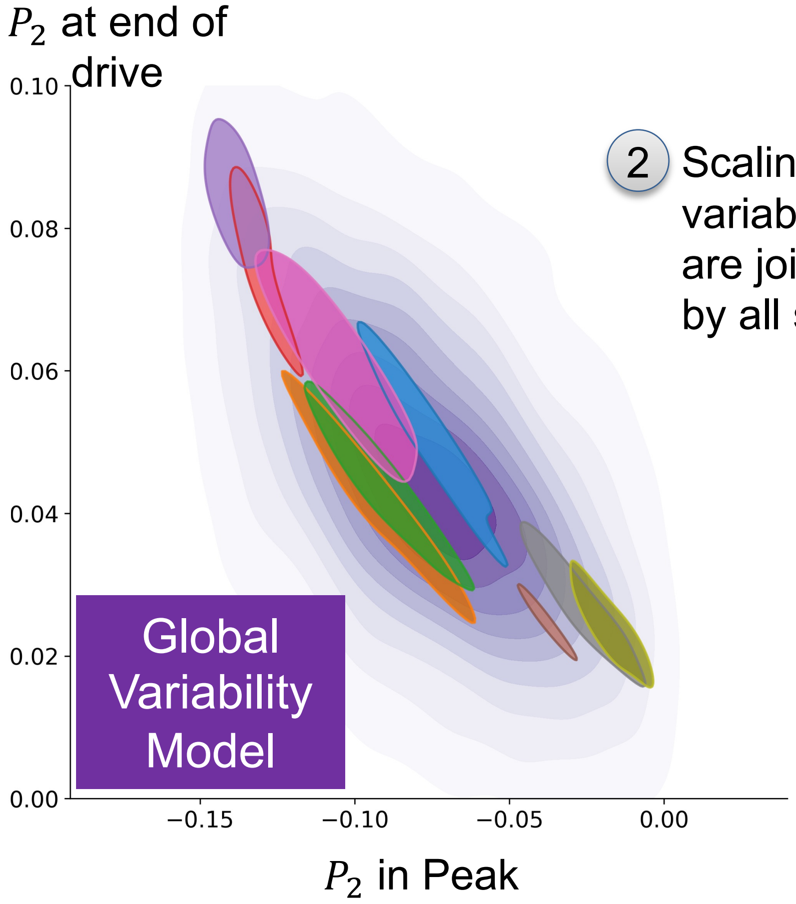
N211107

N211121

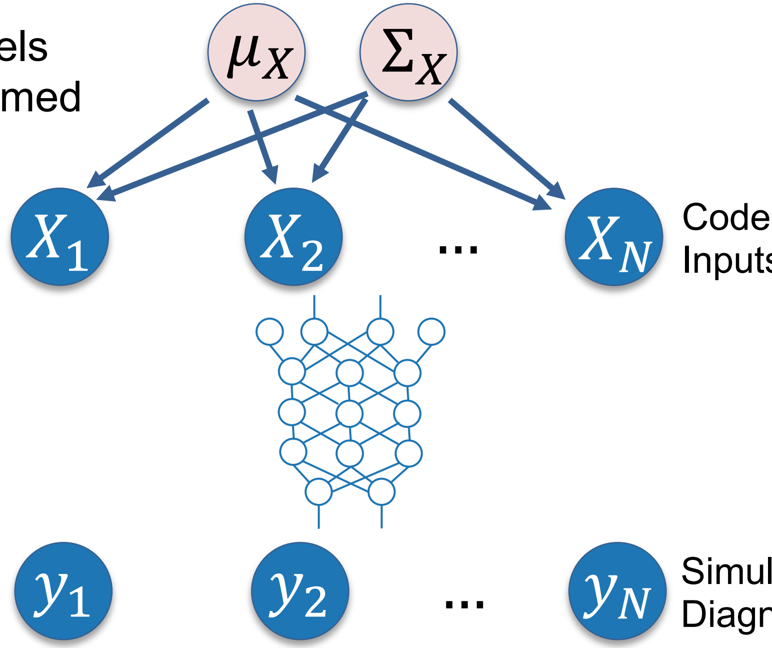


Primary Neutron Image
+yield, Tion, DSR,…

Bayesian Inference

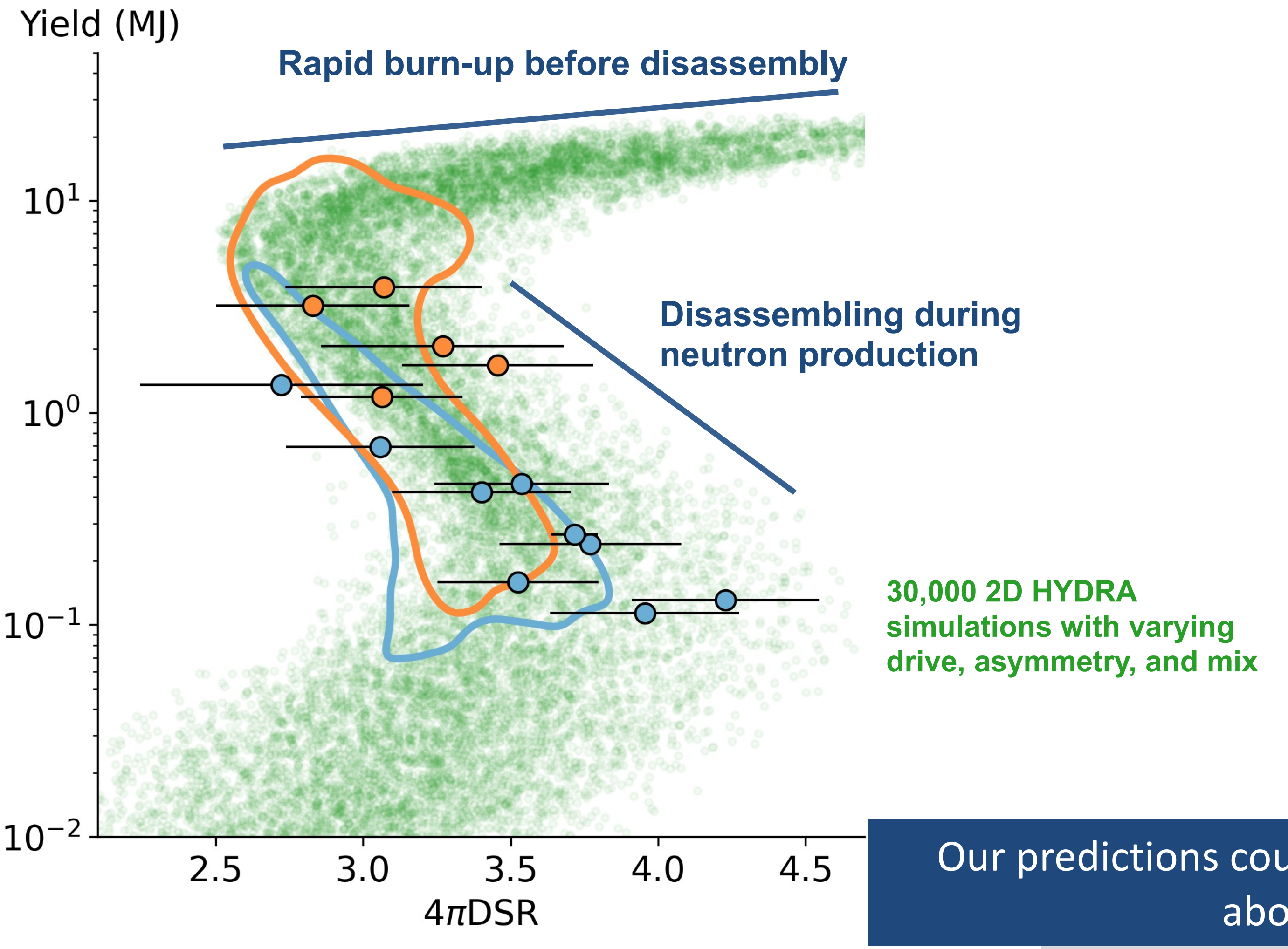


2 Scaling and variability models are jointly informed by all shots



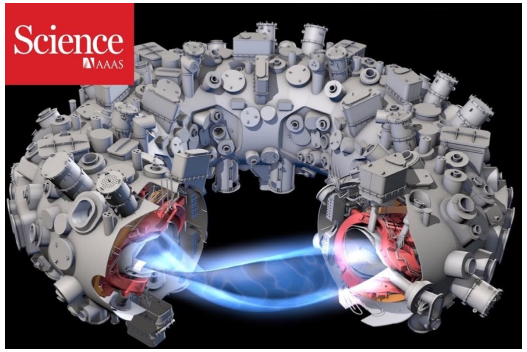
Experimental shots realized at NIF

Codes predict qualitative transitions; experiments approach the compressive ignition phase



Our predictions could potentially be used to inform decisions about future facility upgrades

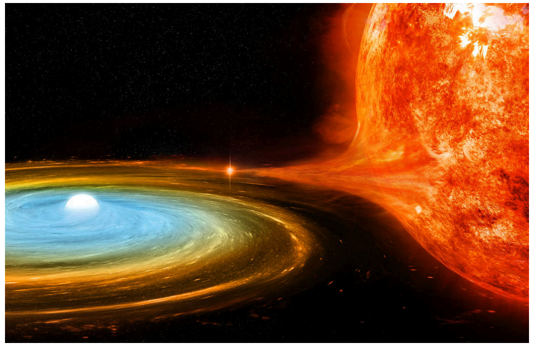
Fusion has different applications and approaches



Clean Energy

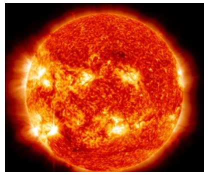
The Inertial Confinement Fusion and High Yield (ICF) Program supports the mission of the U.S. Department of Energy (DOE)/National Nuclear Security Administration (NNSA) to maintain a safe, secure, and effective nuclear deterrent by creating experimentally diagnosable platforms that access extreme temperature, pressure, and density regimes relevant to nuclear weapons performance.[1]

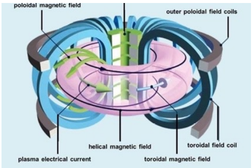
Stockpile Stewardship

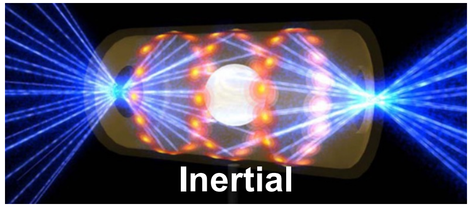


Fundamental Science

Gravitational **Magnetic**

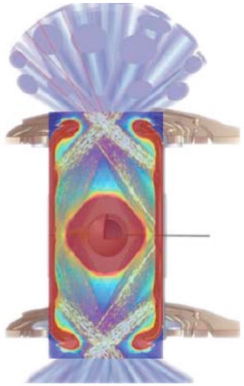




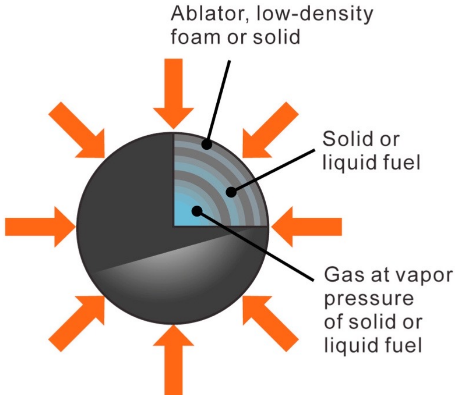


Types of Confinement

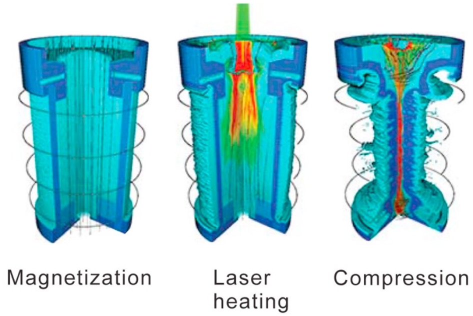
Indirect Drive



Direct Drive



MagLIF

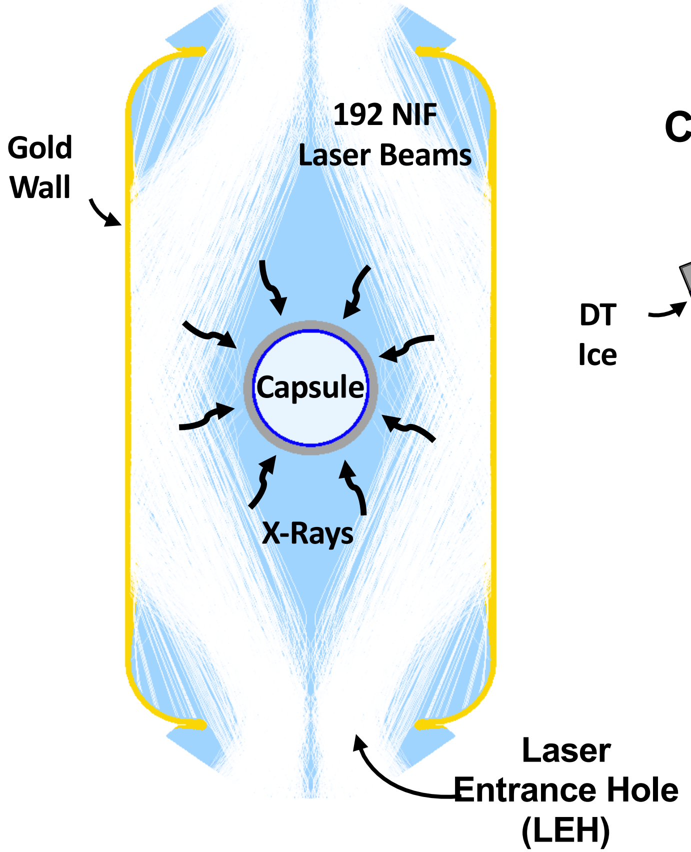


Types of Inertial Confinement Fusion

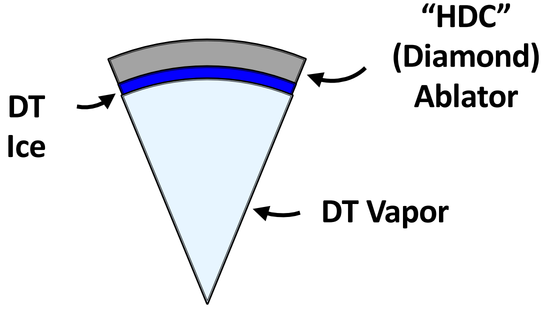
E. M. Campbell et al., Mat. Rad. Extrem. **2**, 37 (2017)
D. Clery, Science Magazine (2015)
[1]2016 ICF Program Framework, NNSA, DOE/NA-0044
A. L. Kritcher et al., Nature **584**, 51 (2020)

Indirect-drive inertial confinement fusion (ICF) adds a "hohlraum" (radiation cavity) to drive the capsule more symmetrically with x-rays

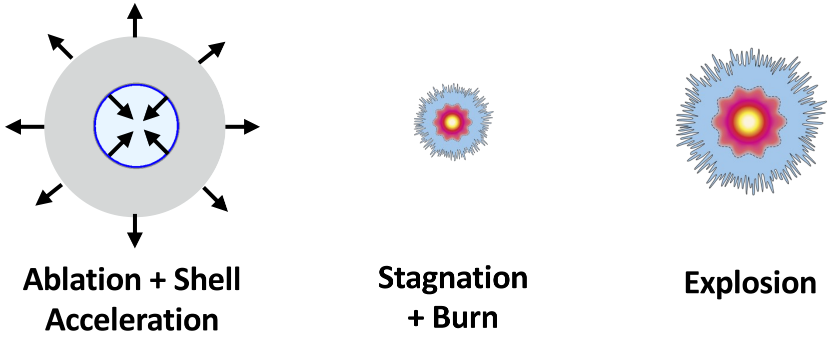
Hohlraum Cross-Section

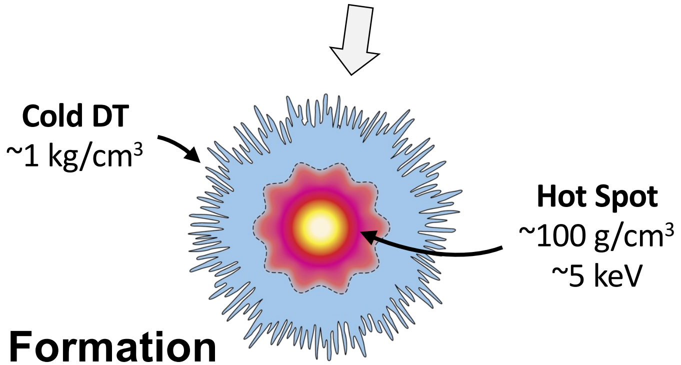


Capsule Cross-Section



Implosion Phases





Hot Spot Formation

$$\mathrm{D} + \mathrm{T} \rightarrow \mathrm{n} + \alpha$$

J. Lindl, Phys. Plasmas **2**, 3933 (1995)
S. Atzeni & J. Meyer-Ter-Vehn (Oxford Univ. Press, 2004)

There is a growing interest in estimating the variability in new laser-driven fusion designs

Pre-ignition → Ignition → Applications