Synergies in inertial fusion energy and inertial confinement fusion research

Michigan Institute for Plasma Science and Engineering Seminar

University of Michigan

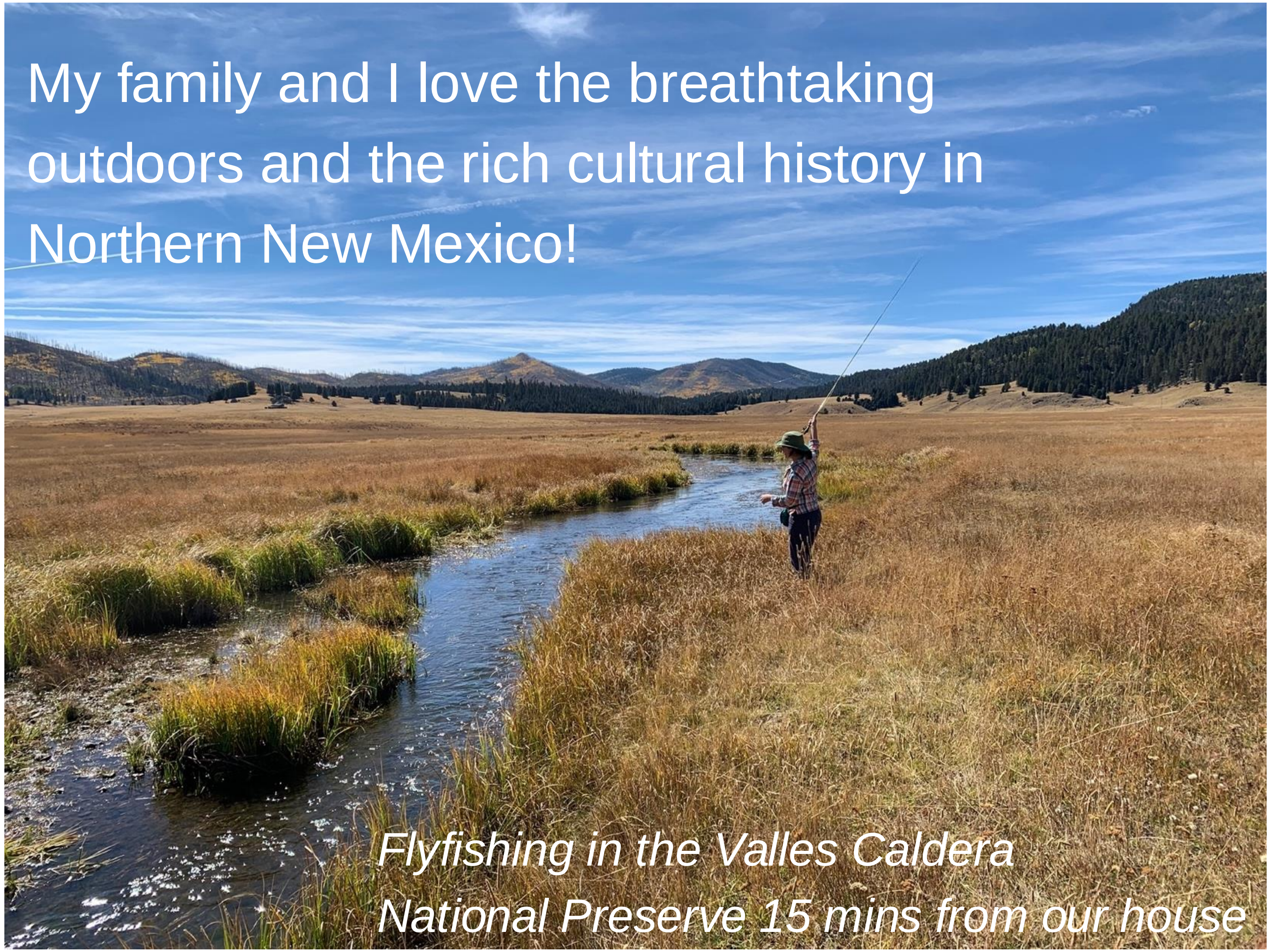
March 12th, 2025

Verena Geppert-Kleinrath

P-1 Dynamic Imaging and Radiography

With contributions from the LANL NIS and GRH teams and our LLNL and LLE collaborators

Why do I enjoy working at Los Alamos National Laboratory?

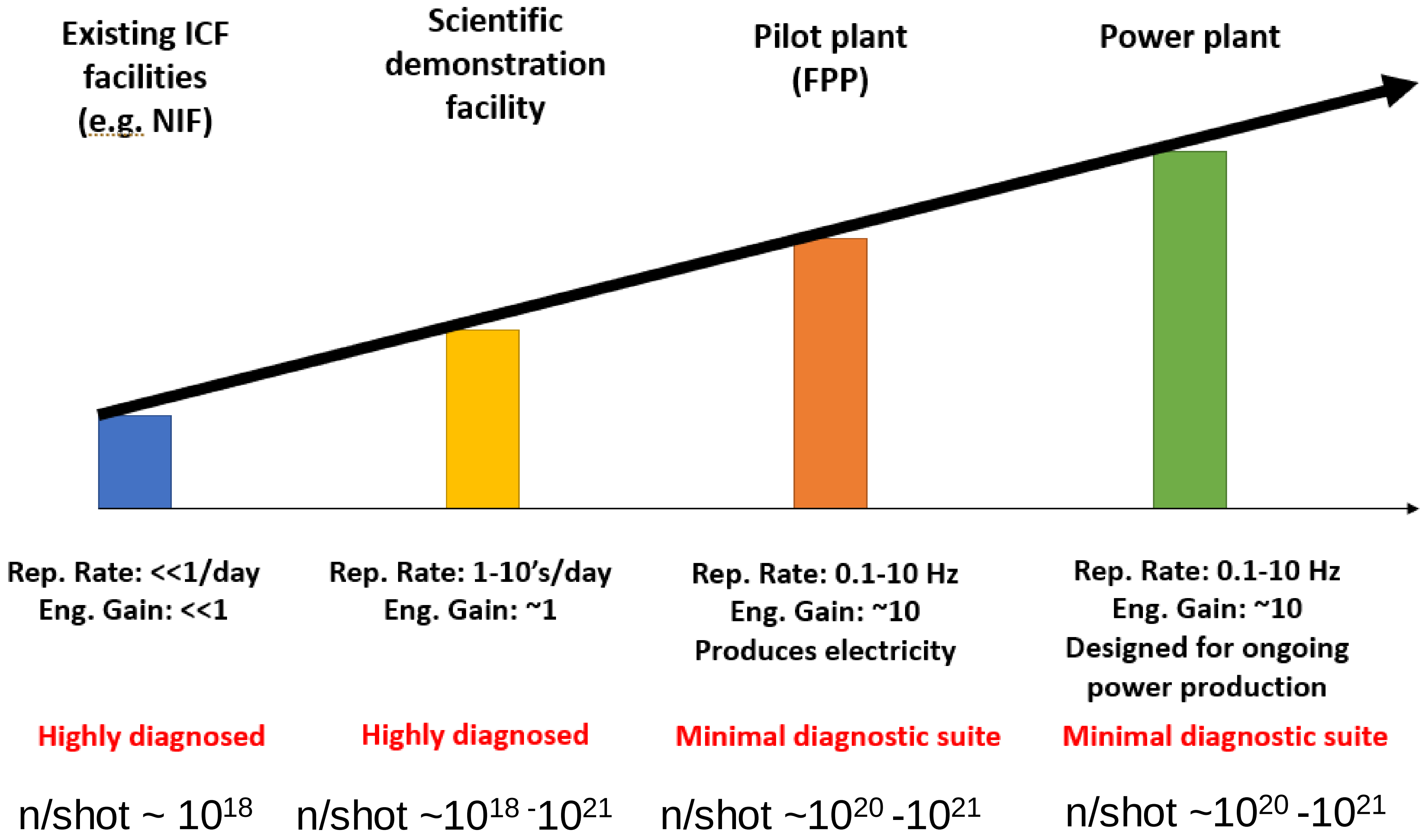


I am a

- PhD Nuclear Physicist
- Deputy Group Leader
- Mom of 2 young kids
- Immigrant
- Outdoor enthusiast

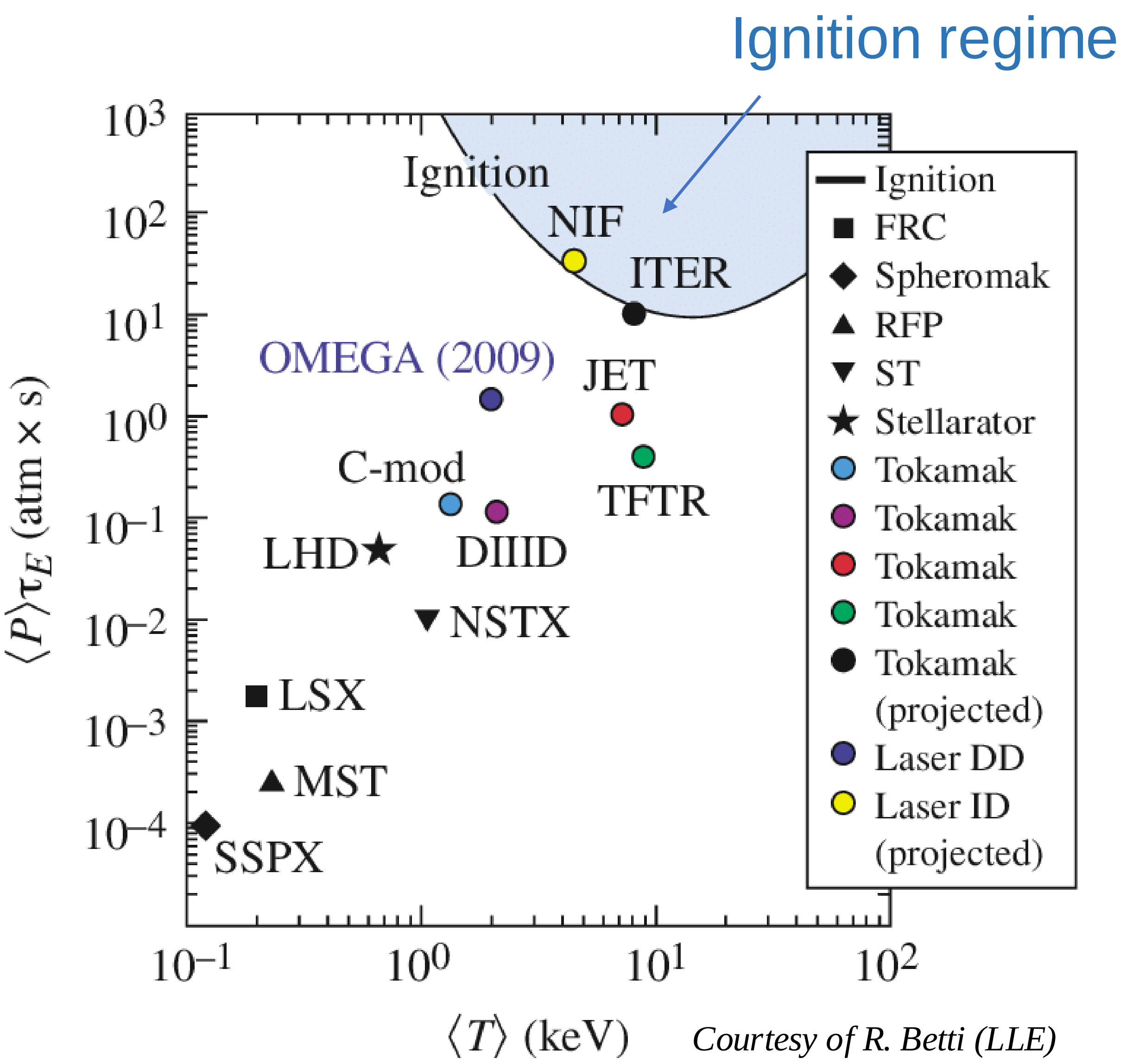
Our world-class staff solve grand challenges for the nation and the world!

The path to a US inertial fusion power plant



[BRN Workshop on Measurement Innovation 2024]

ICF towards IFE: Where are we now?

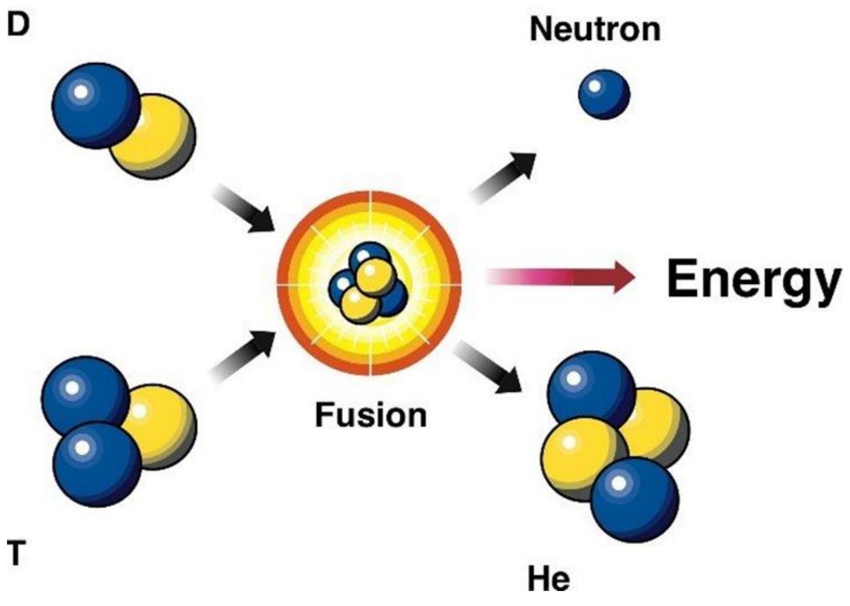


Courtesy of R. Betti (LLE)

	OMEGA	NIF	Z	IFE FPP
Shot cycle	~1/hour	> 1/day	> 1\day	0.1 s - 10 s
DT Neutron Yield	~10^{14}	~10^{18}	10^{15} (DD)	~$2x10^{19}$ - $2x10^{21}$
Energy/shot	1 kJ	5 MJ	2 kJ	50-5000 MJ
Burn duration	~90 ps	~ 90 ps	1-2 ns	40-1000 ps

We are moving towards a different regime for an FPP

The fusion community has been racing towards a shared goal of ignition to harness the power of the stars



$D + T \rightarrow \alpha$ (3.5 MeV) + n (14.1 MeV),
Q = 17.6 MeV

Ignition means:

- a **self-sustaining** reaction
- increasing **self-heating** removes the need for external heating (Lawson criterion)

The New York Times

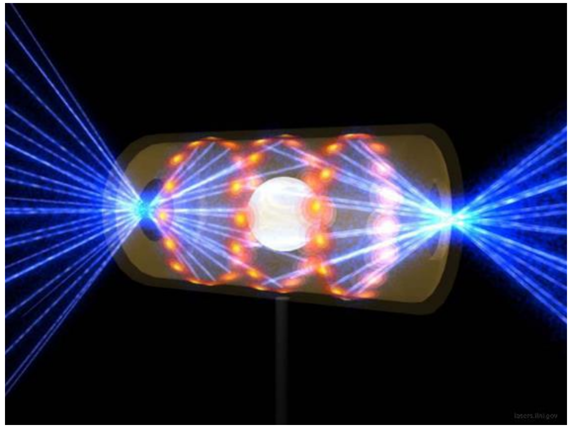
Scientists Achieve Nuclear Fusion Breakthrough With Blast of 192 Lasers

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

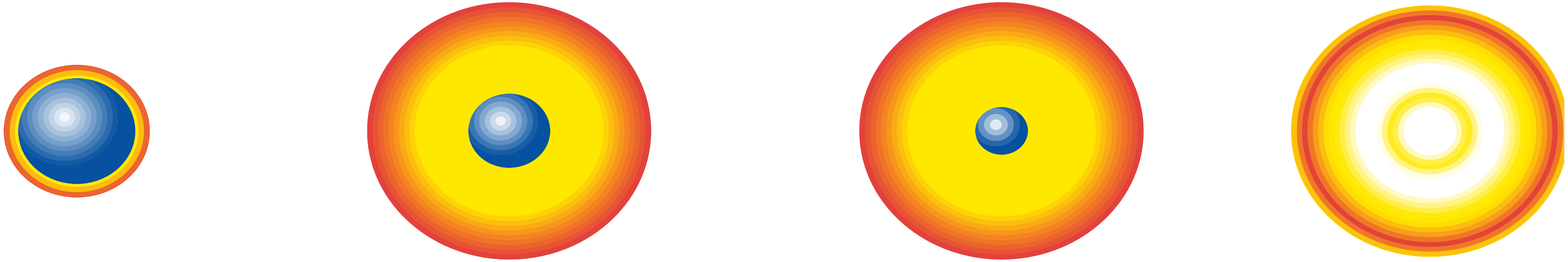
Ignition on NIF was achieved on 08/08/2021 and fusion energy gain > 1.5 on 12/05/2022

Inertial Confinement Fusion at the National Ignition Facility

NIF laser: 260 m long
192 beams
2 MJ energy
10 m diameter target chamber



~1 mm carbon capsule filled with DT



1. Laser drive
2. Ablation
3. Compress & shock
4. Fusion + alpha heating = **Ignition**!

Ignition: Diagnosing a new physics regime at the NIF

NIF: First implosion 6/2011, Ignition 8/2021

2013: Change laser pulse shape - **stability**

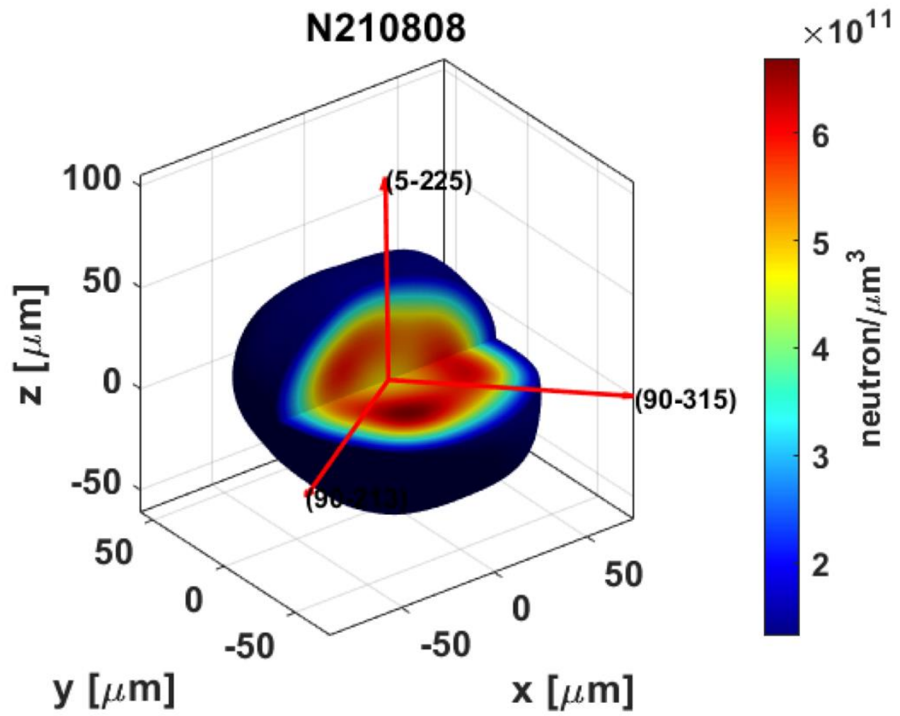
2015: Change ablator from plastic -> diamond - **implosion symmetry**

2018: Increase capsule size, reduce hohlraum size - **energy coupling**

2021: smaller laser entrance hole, more laser energy, target quality - **energy coupling, fewer perturbations**

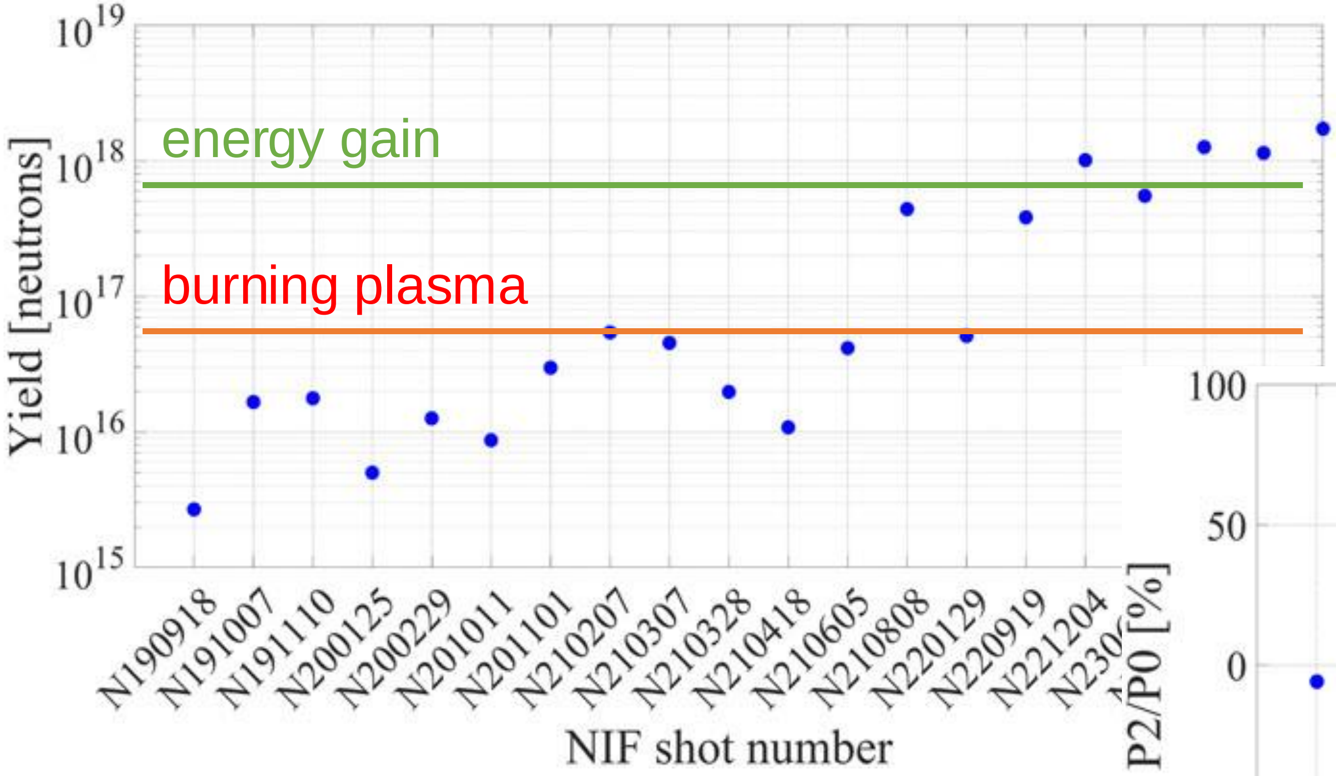
2022 - 25: We now reach the ignition regime regularly!

N210808 reached **~1.3 MJ yield** and **burn propagation** (ignition)!

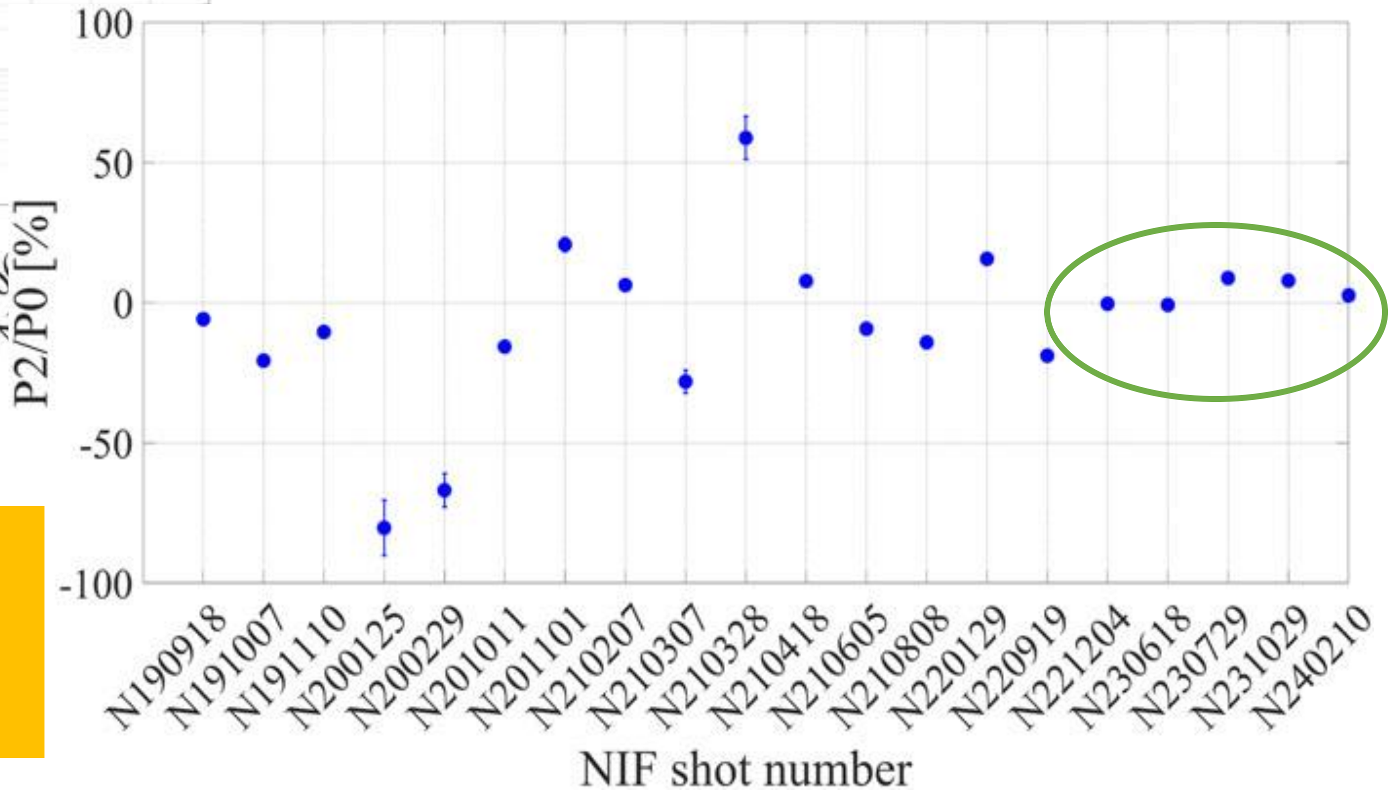


LANL diagnostics provide data in challenging conditions

We have overcome performance limitations and can provide shape information to tune the next shot

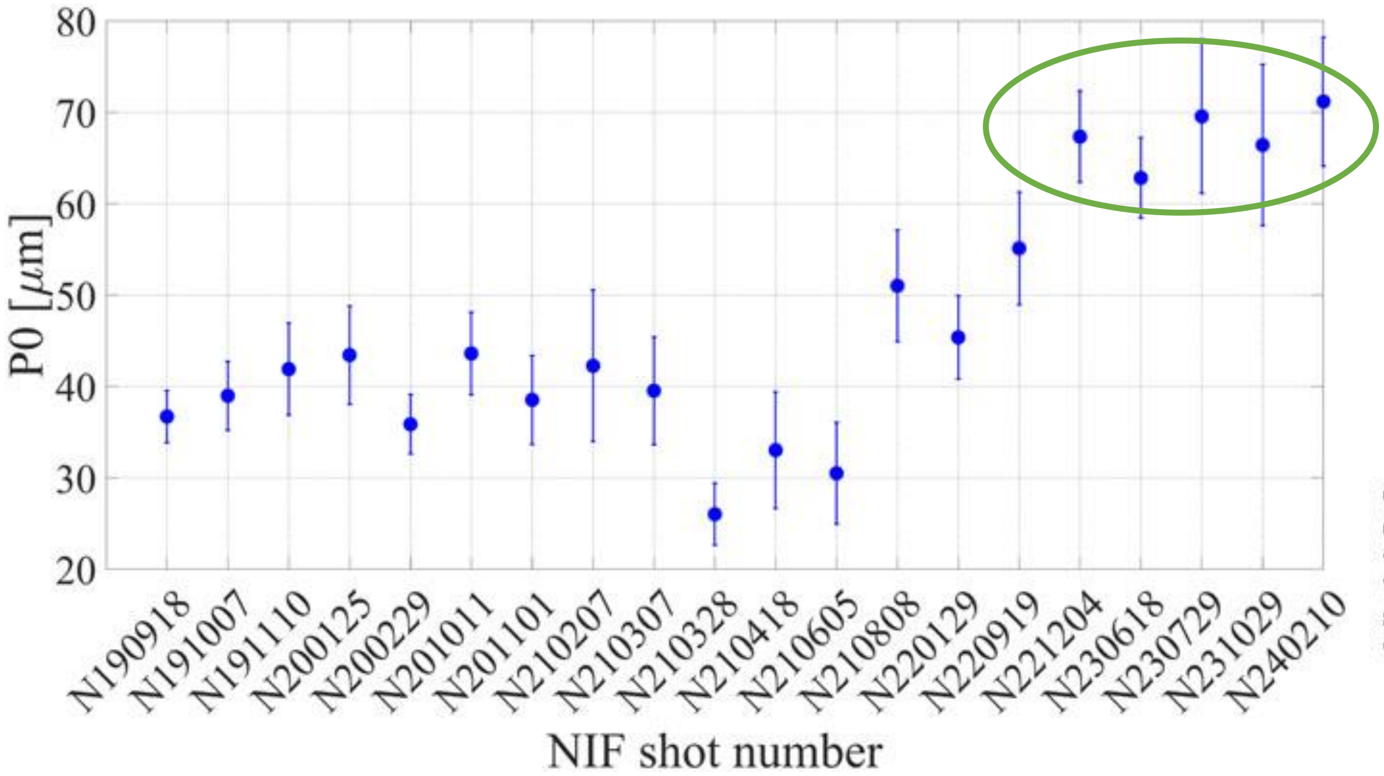


[M. Durocher, et al. Rev. Sci. Instrum. 2024; 95 (9)]

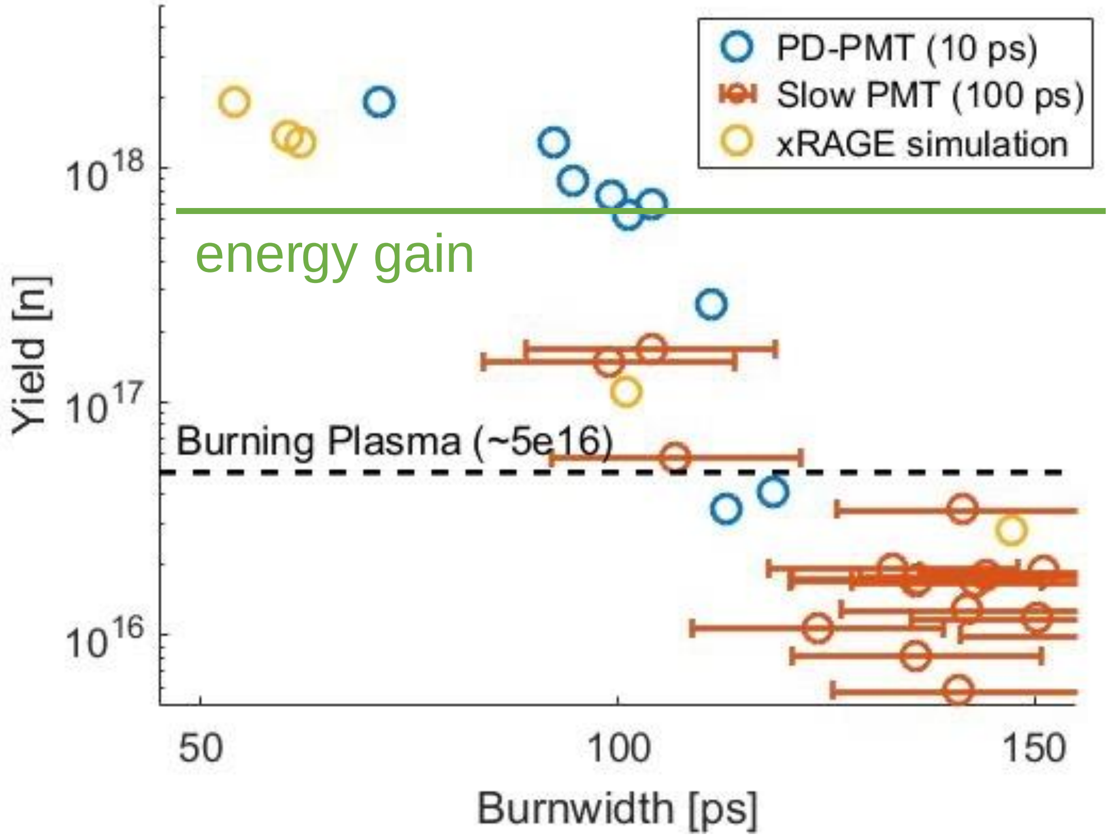


While dynamics become more complicated high yield shots still tend to be very round!

We see markers of ignition in our highly diagnosed plasma



[M. Durocher, et al. Rev. Sci. Instrum. 2024; 95 (9)]

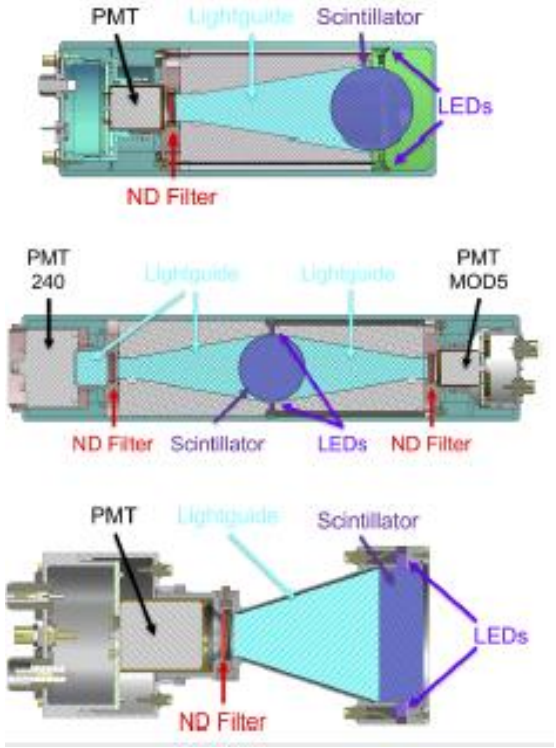


[K. Meaney, APS DPP 2024 presentation]

Burn volumes become larger while burn durations become shorter

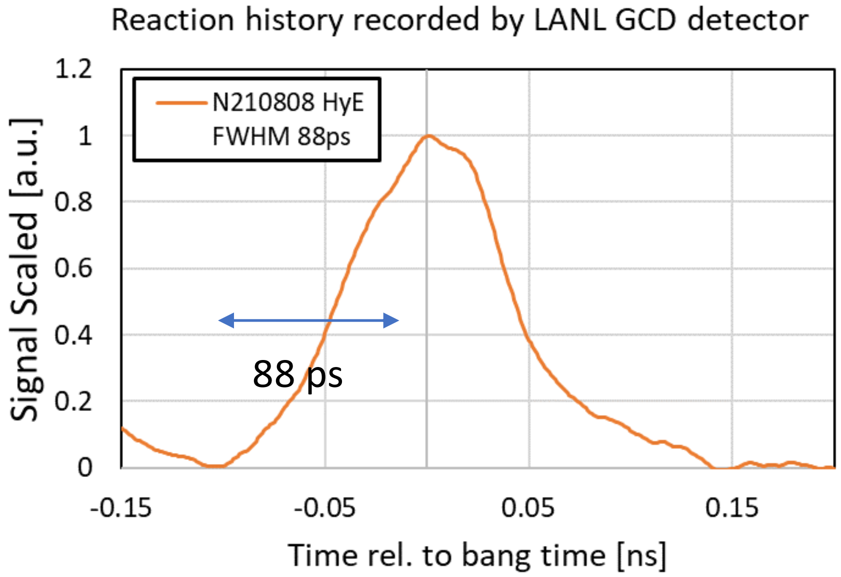
LANL has 80 years of diagnostic experience for single shots

Neutron time of flight



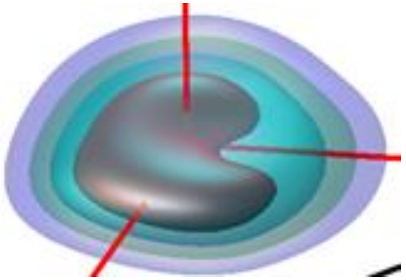
[G. A. Chandler, et al. Rev. Sci. Instrum., 2022; 93 (11)]

Gas Cherenkov detector



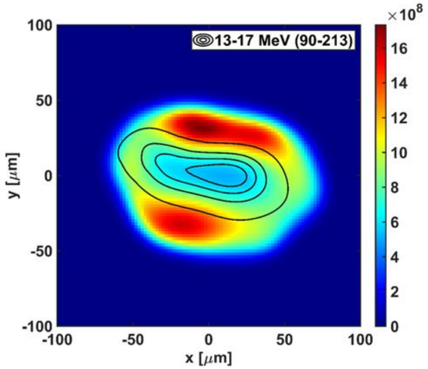
[H. Geppert-Kleinrath, et al., High Energy Density Physics 37, 100862 (2020)]

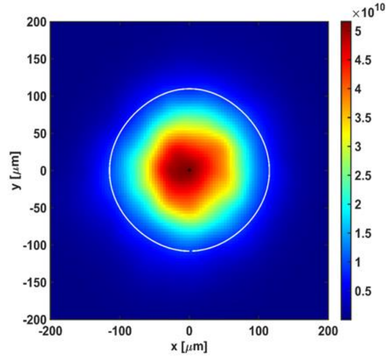
Neutron Imaging (3D)



Fuel Density

Ablator Shape





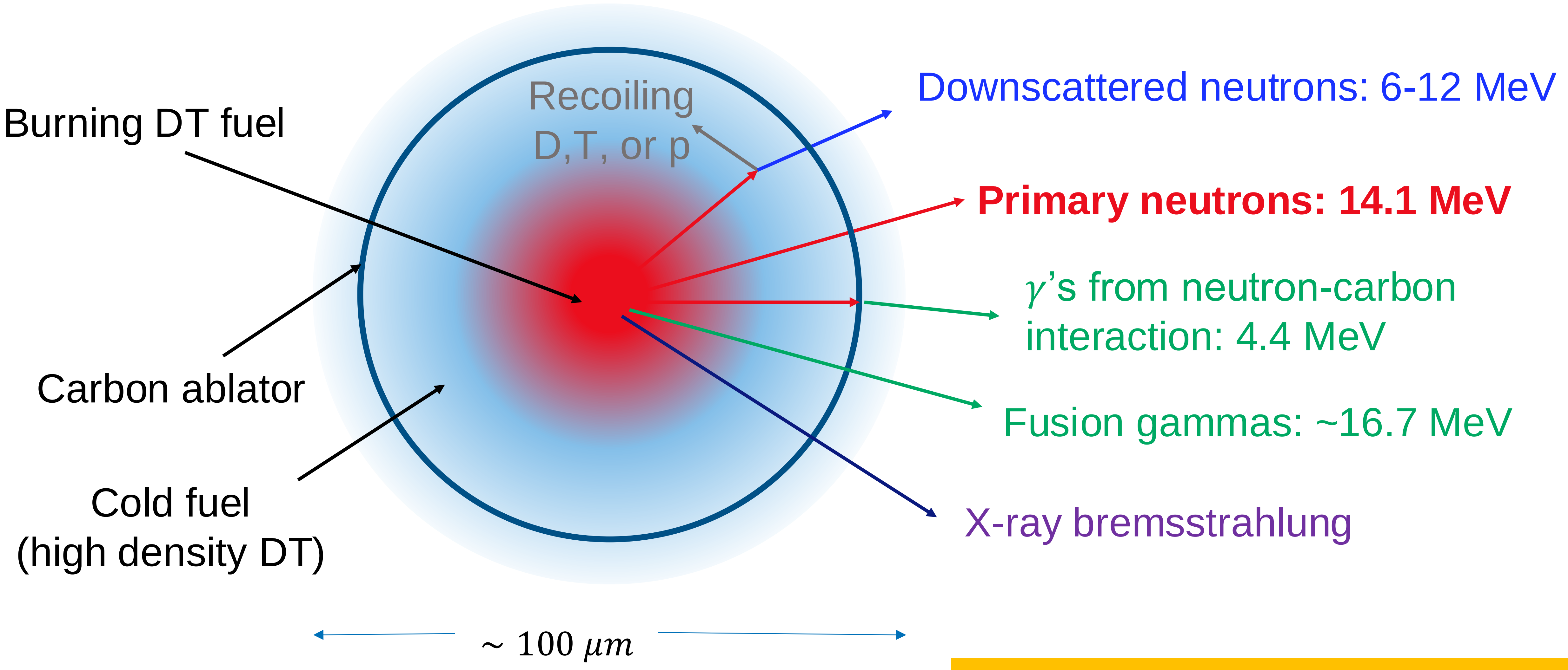
Down-scattered Neutrons

Carbon Gamma rays

[P. Volegov, et al., Rev. Sci. Instrum. 92, 033508 (2021)]

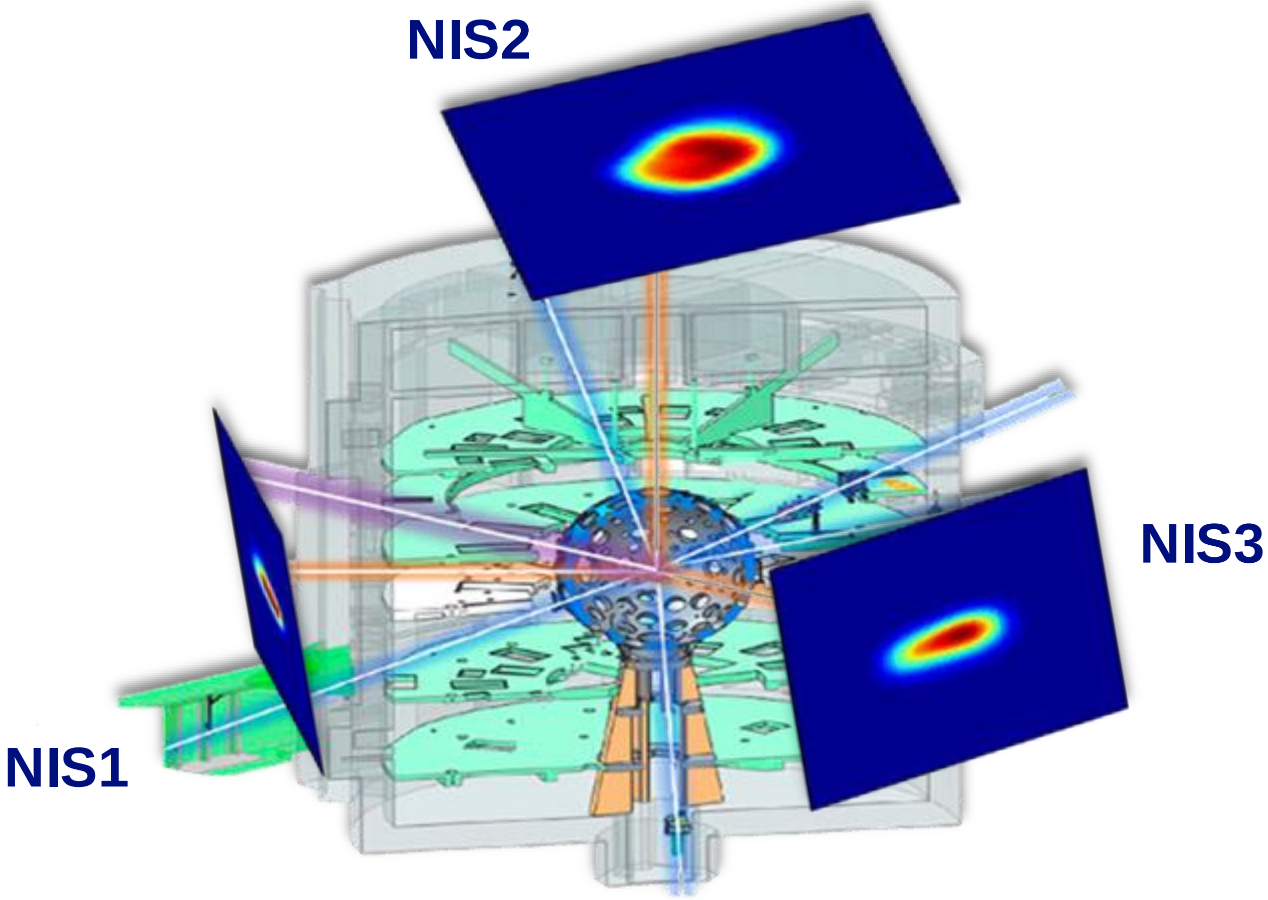
The US lead the world in nuclear detector technologies for fast diagnostics

The nuclear imaging system measures the fuel at stagnation



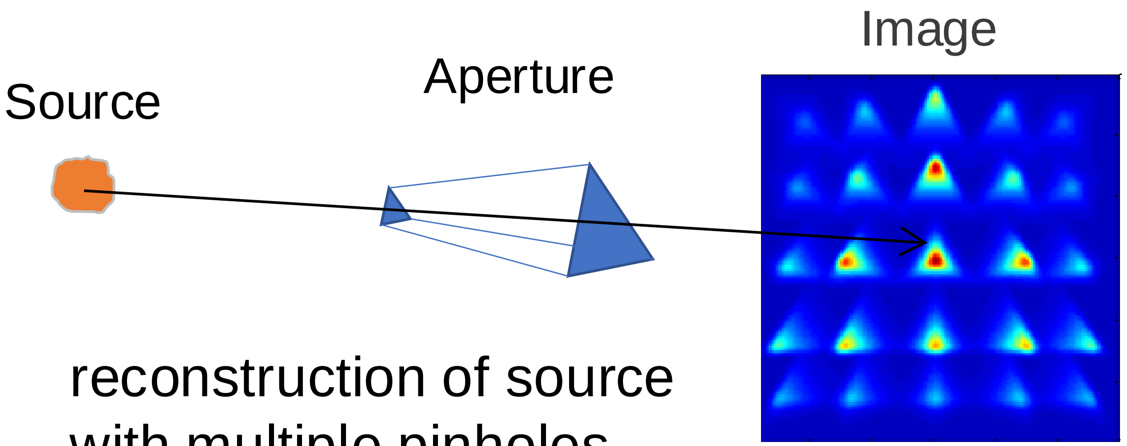
Primary neutron images directly localize the burning fusion plasma

The NIS is a pinhole camera with thick coded apertures

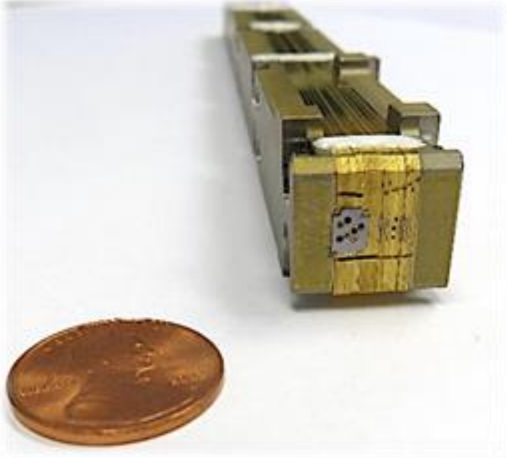


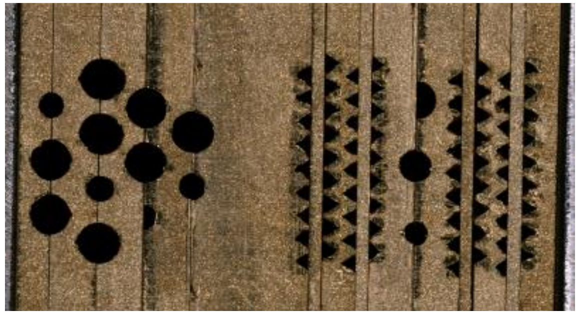
[D. N. Fittinghoff, N. Birge, V. Geppert-Kleinrath, *Rev. Sci. Instrum.* 2023; 94 (2): 021101]

[P. Volegov, et al. Rev. Sci. Instrum. 2014; 85 (2): 023508]



reconstruction of source with multiple pinholes using Bayesian inference

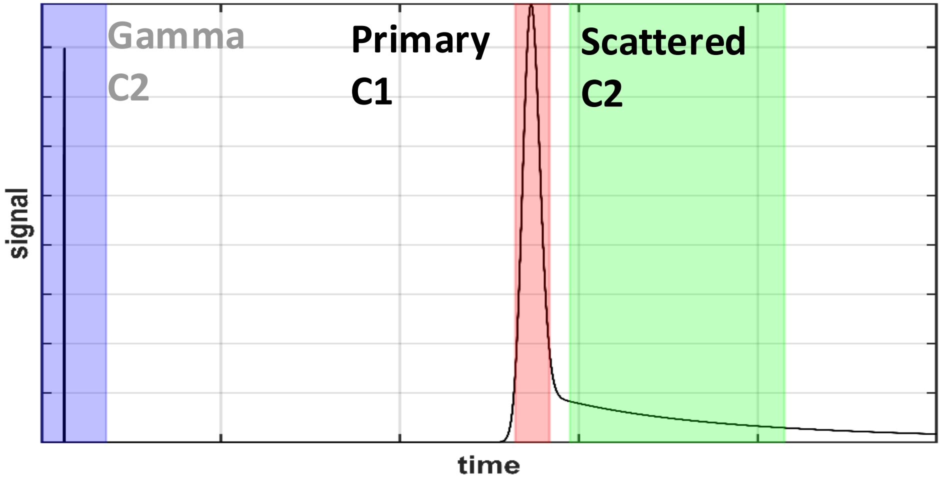




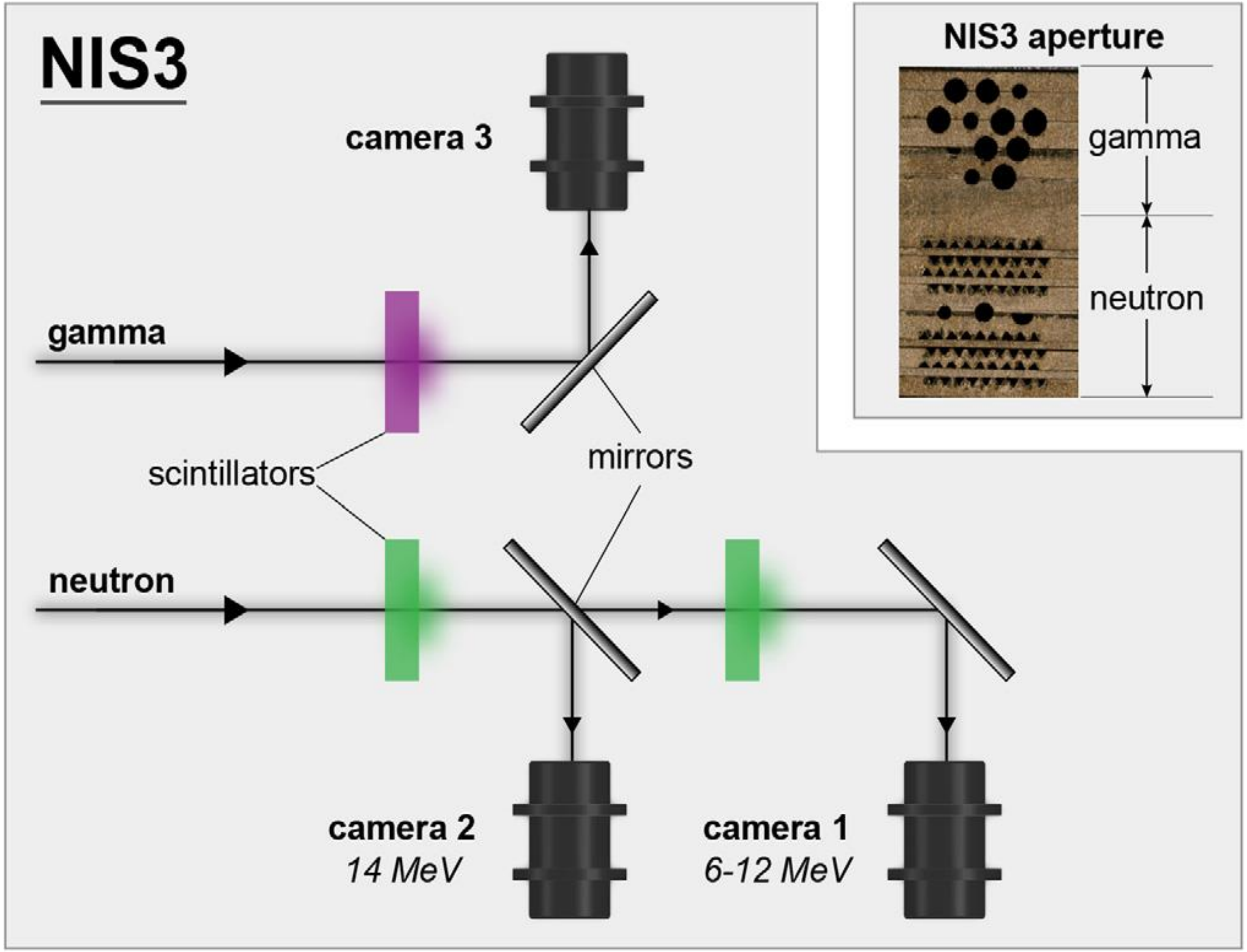
Long mean free path of 14 MeV neutrons (~ 3 cm in Au) requires thick barrier for contrast

The NIS diagnostic provides nuclear and x-ray images

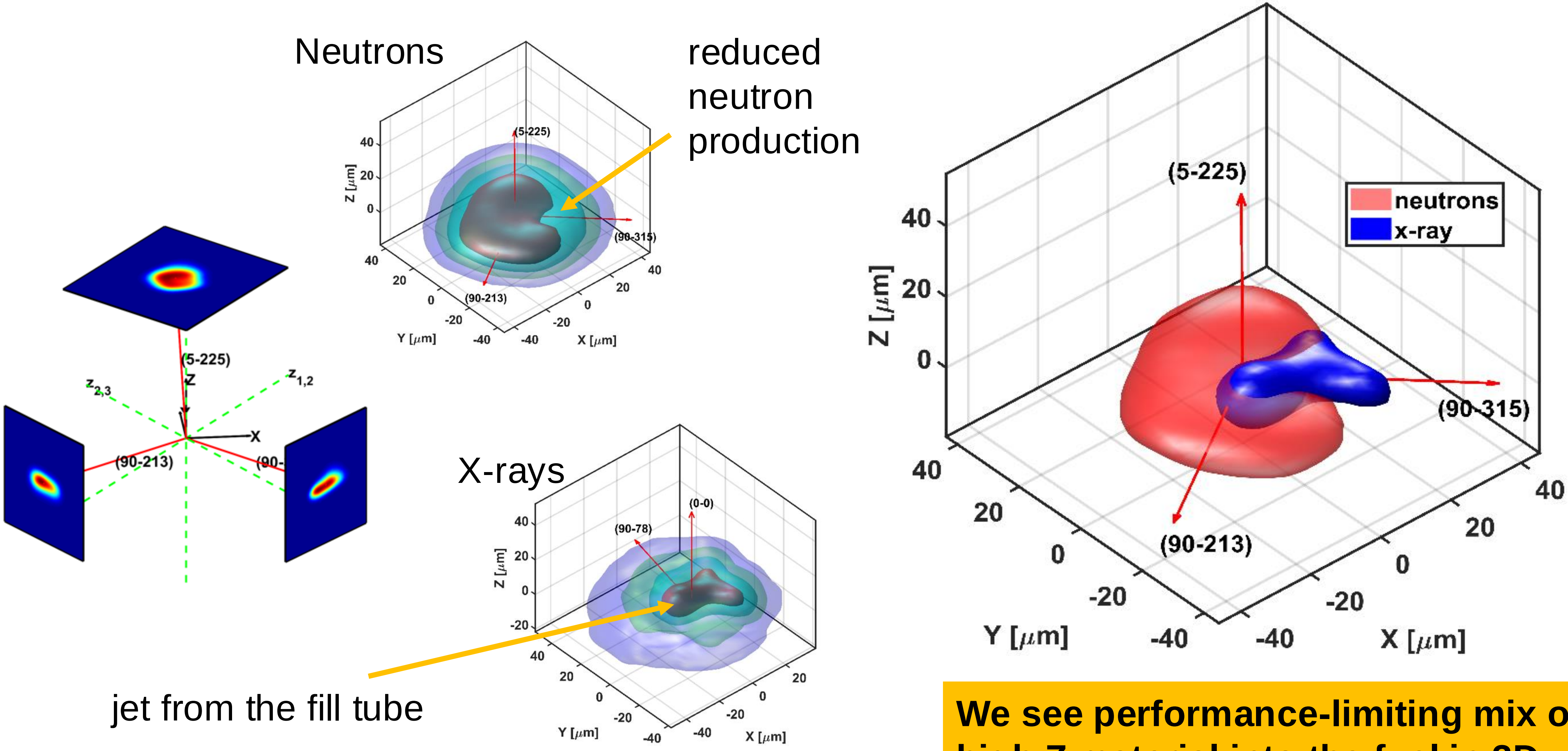
IP detection for x-rays and energy-integrated neutron images



Gated detectors to distinguish scattered neutrons and gammas



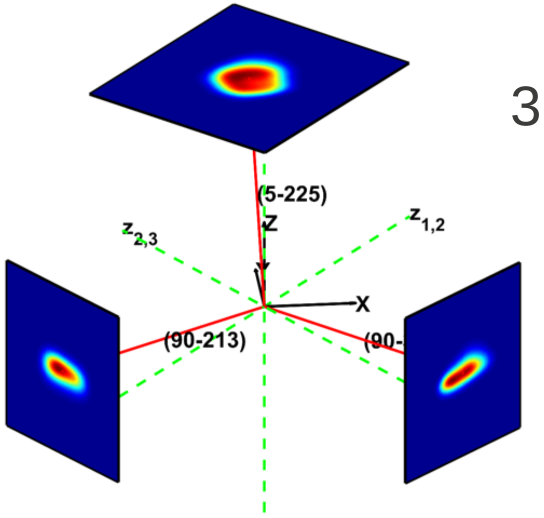
Limited-view tomography allows visualization of 3D effects



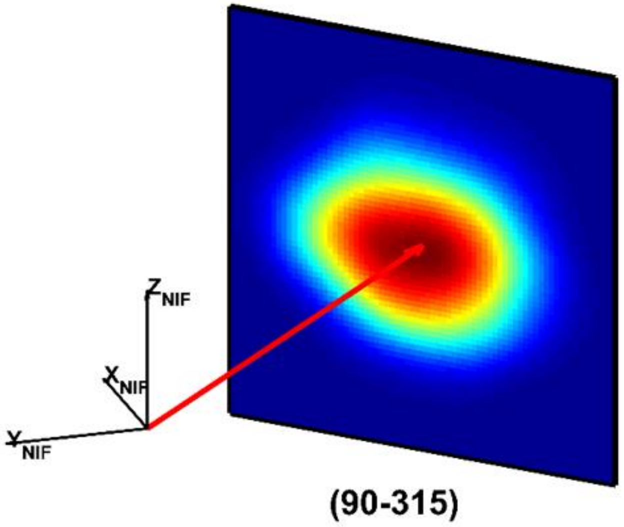
We see performance-limiting mix of high Z material into the fuel in 3D

[P. L. Volegov, et al. Rev. Sci. Instrum. 2021; 92 (3): 033508]

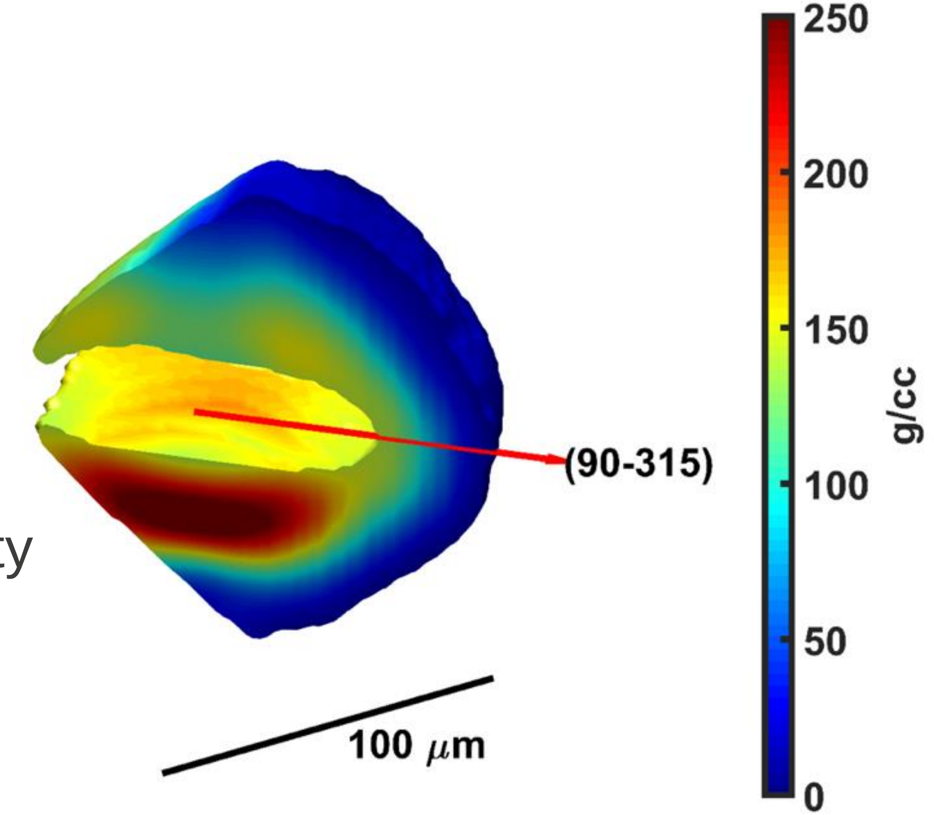
Gated images provide cold fuel density



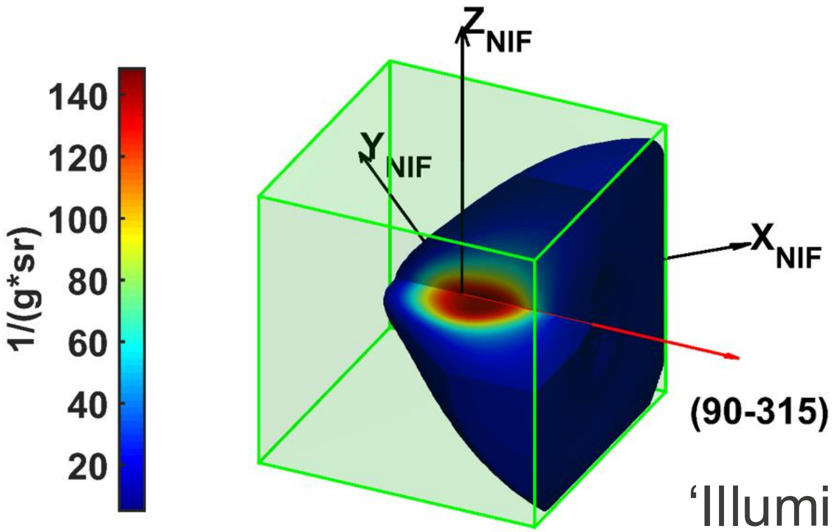
3D hot spot



Downscattered image



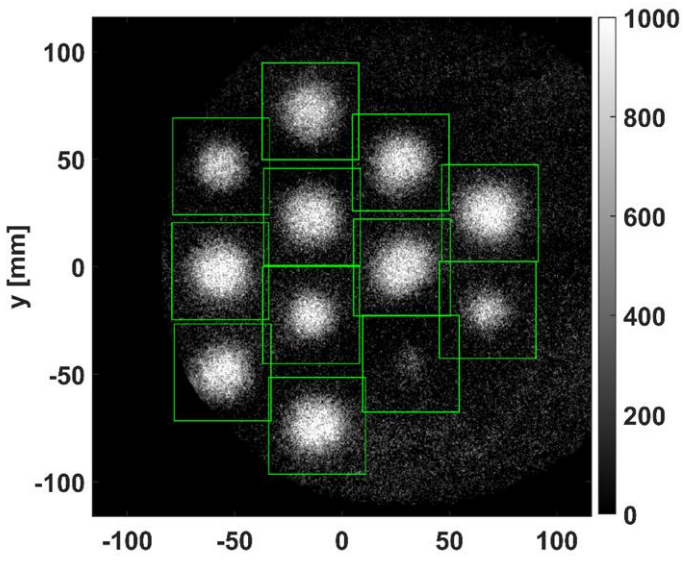
Cold fuel density



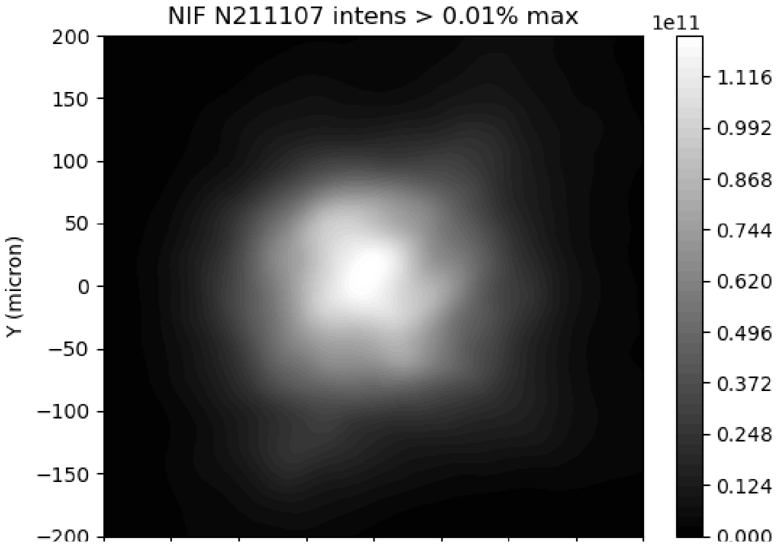
‘Illumination’ function

[*P. L. Volegov, J. Appl. Phys. 2020; 127 (8): 083301*]

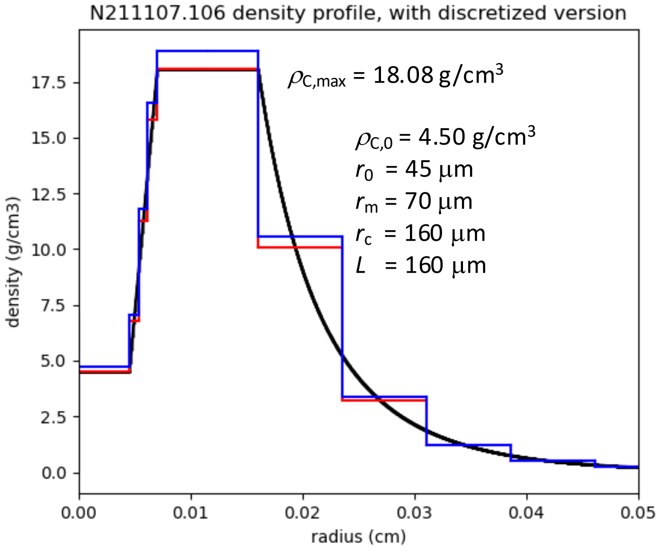
Gamma imaging provides ablator position



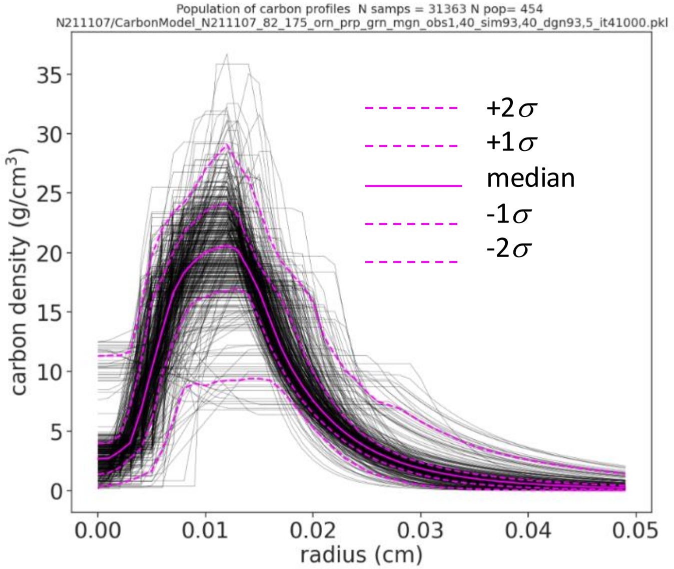
Gamma image



Reconstruction



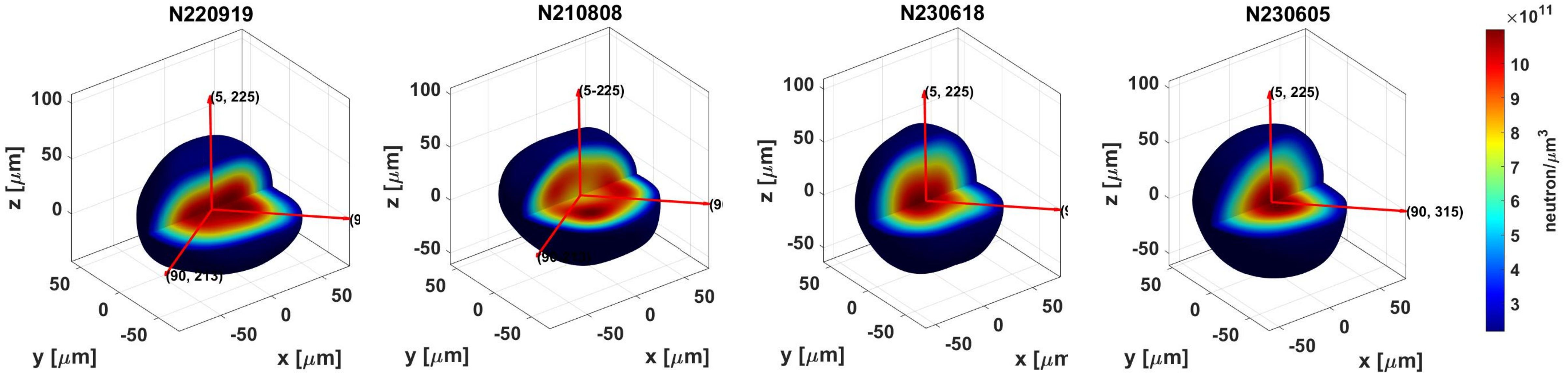
1D MCNP model fit



Carbon density probability

[V. Geppert-Kleinrath, et al Phys. Plasmas 2023; 30 (2): 022703]

We have been tuning the drive for optimal symmetry

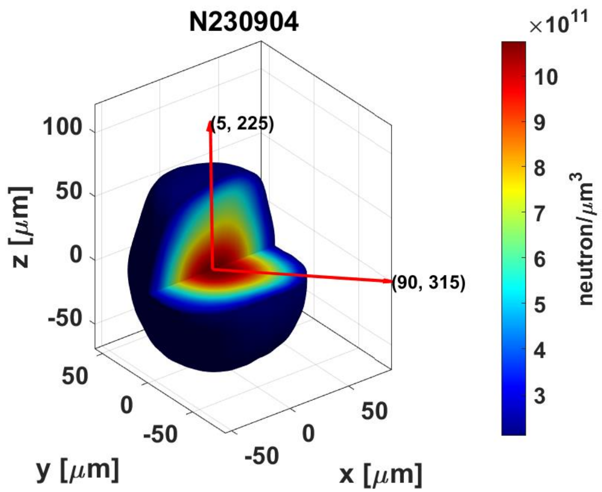


3.8e17	4.3e17	5.4e17	6.1e17

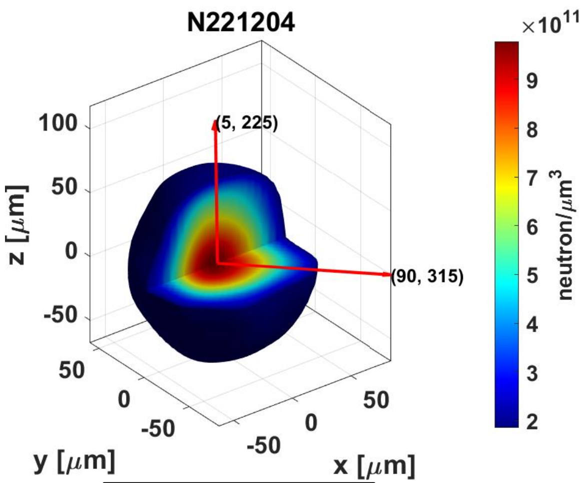
Some low-mode asymmetry (-P2 oblate) in N210808 repeats

Higher yields seem to show less asymmetry

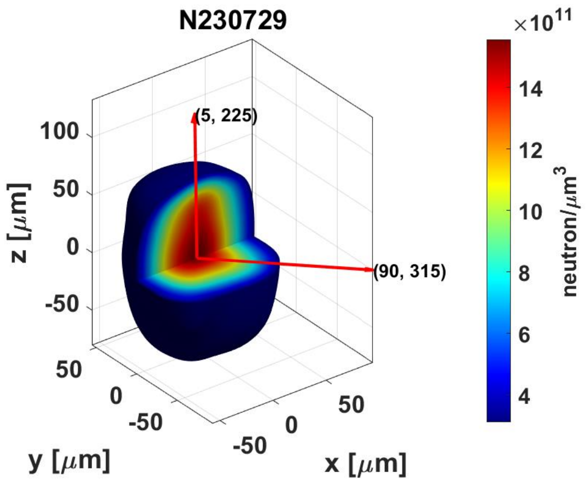
Highest yields seem to exhibit new prolate asymmetry



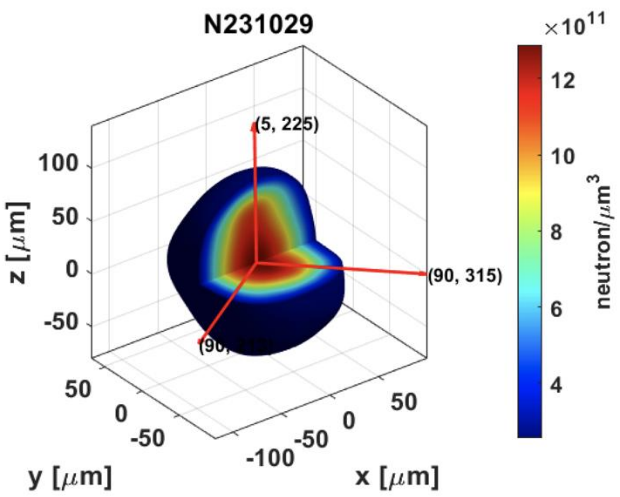
6.7e17



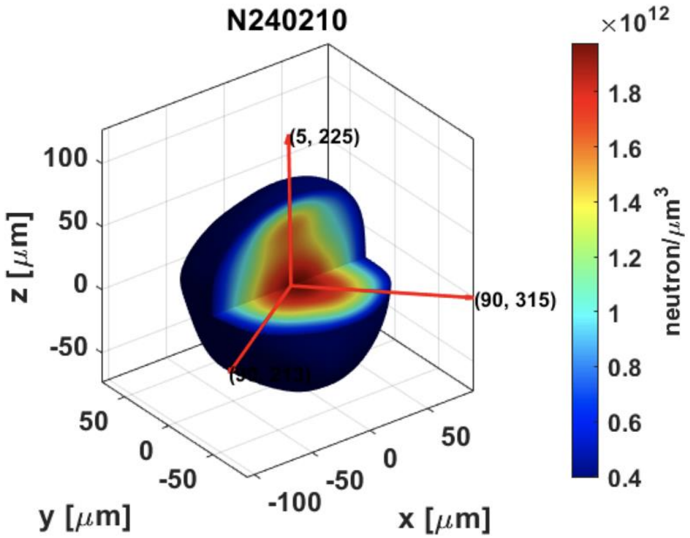
1.0e18



1.3e18



1.1e18



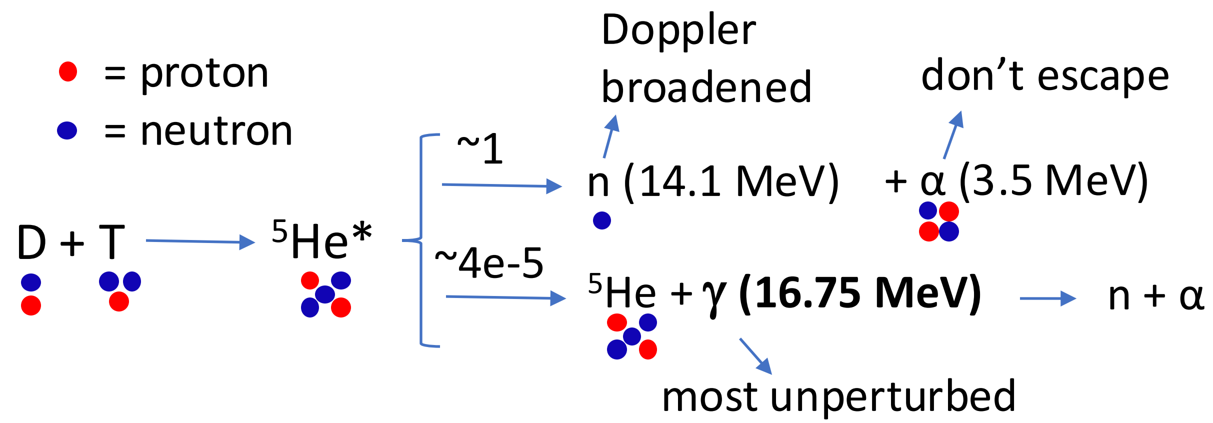
1.7e18

Thicker capsule seems robust

P2 from changed dynamics?

Gain > 1.5 has been reached 5x

How do we measure fusion burn history?

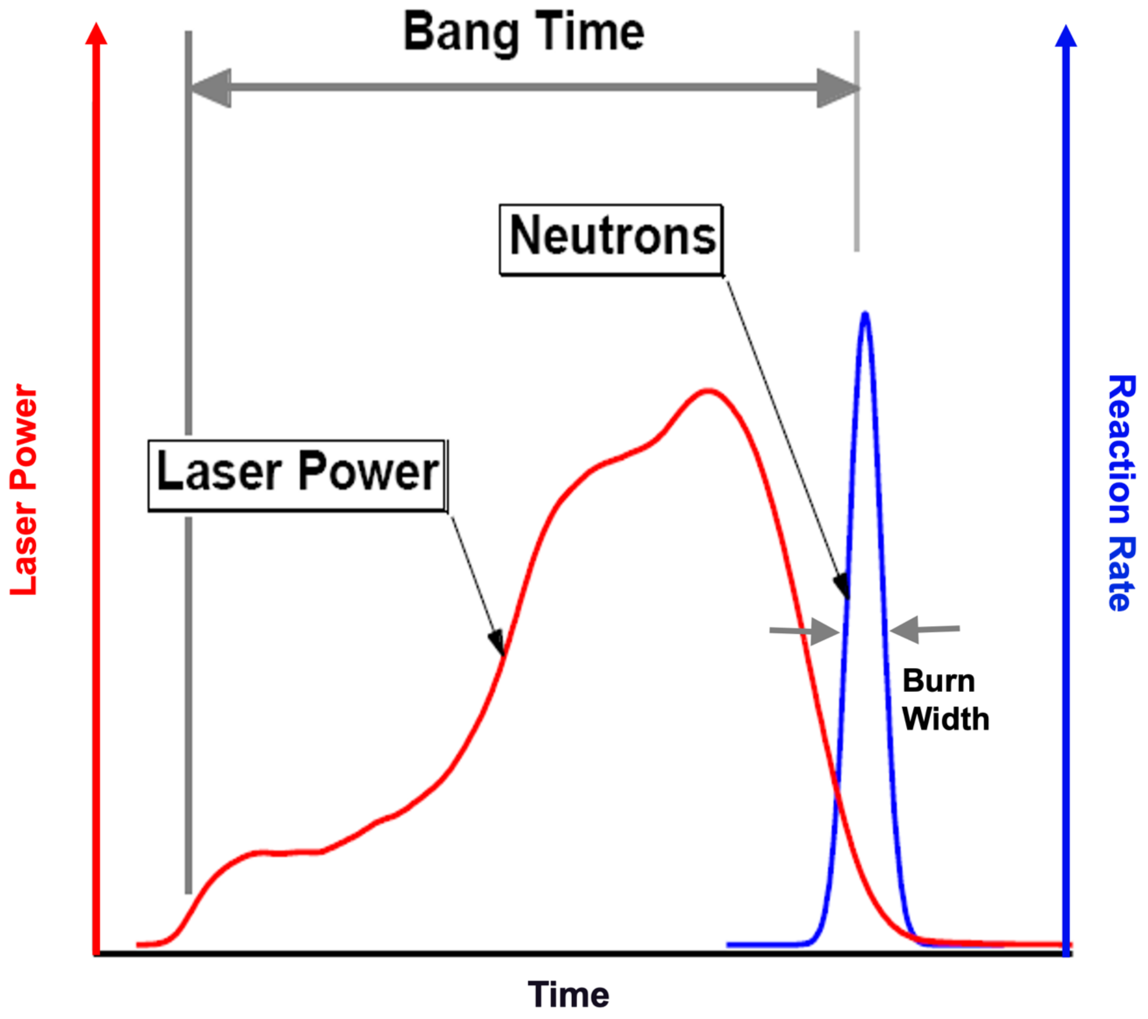


Neutron signal is broadened by Doppler effect. Neutron time of flight allows for yield and burn integrated ion temperature measurement.

Alpha particles are charged and heavy. Alphas heat the hotspot (alpha heating) and provide the energy going into ignition.

Gammas are the most unperturbed signal from DT fusion reactions. Detailed features of the fusion burn can be resolved.

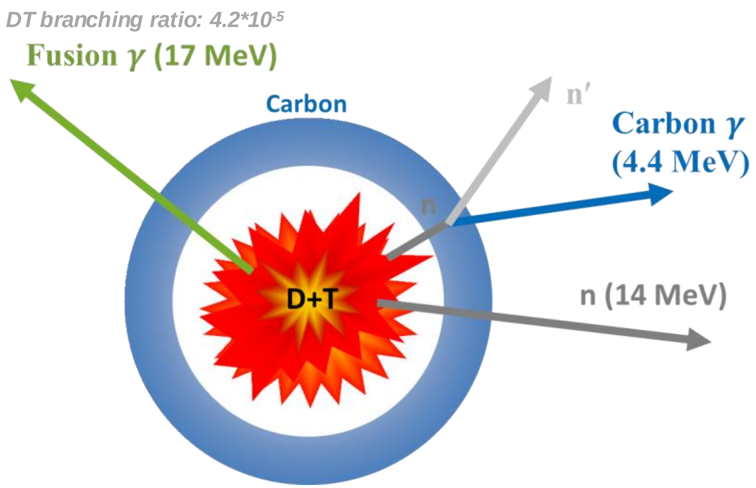
DT gamma reaction history provides crucial information



Gammas directly from burn provide reaction history = Fusion rate as a function of time

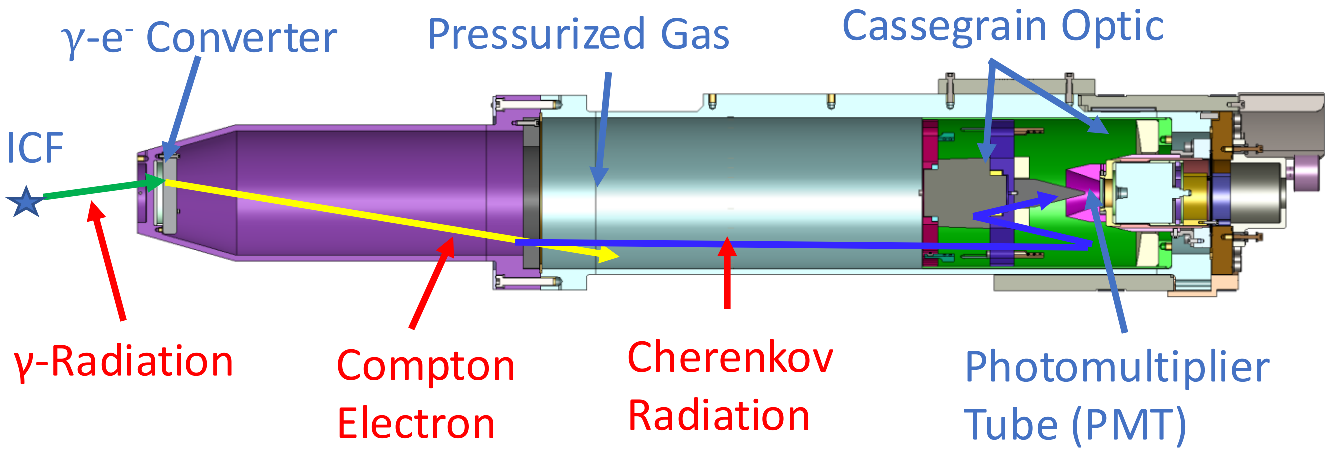
Bang Time:	**benchmarking simulations** **energy absorbed in the capsule**
Burn Width:	**duration of thermo-nuclear condition** **assembly and disassembly process**
Burn Profile:	**shape of reaction history** **gives limits for simulations**

Gas Cherenkov Detectors (GCD) measure reaction rate

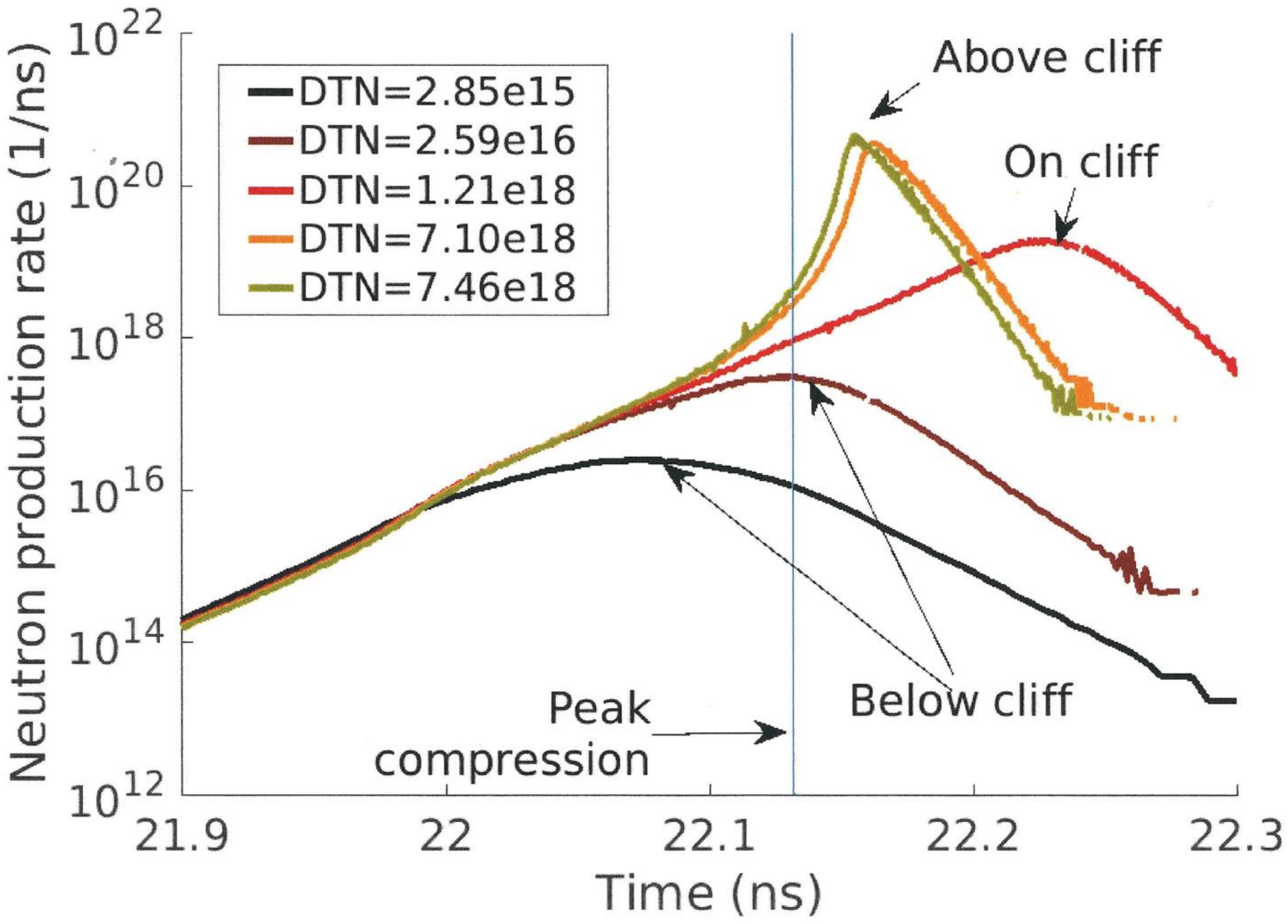


- Measurement threshold set by gas pressure
- Cherenkov process inherently fast
  <10 ps @ 8 MeV threshold
- Photomultiplier Tube (PMT) resolution ~100 ps
- New PD-PMT 10 ps resolution

GCD-3:

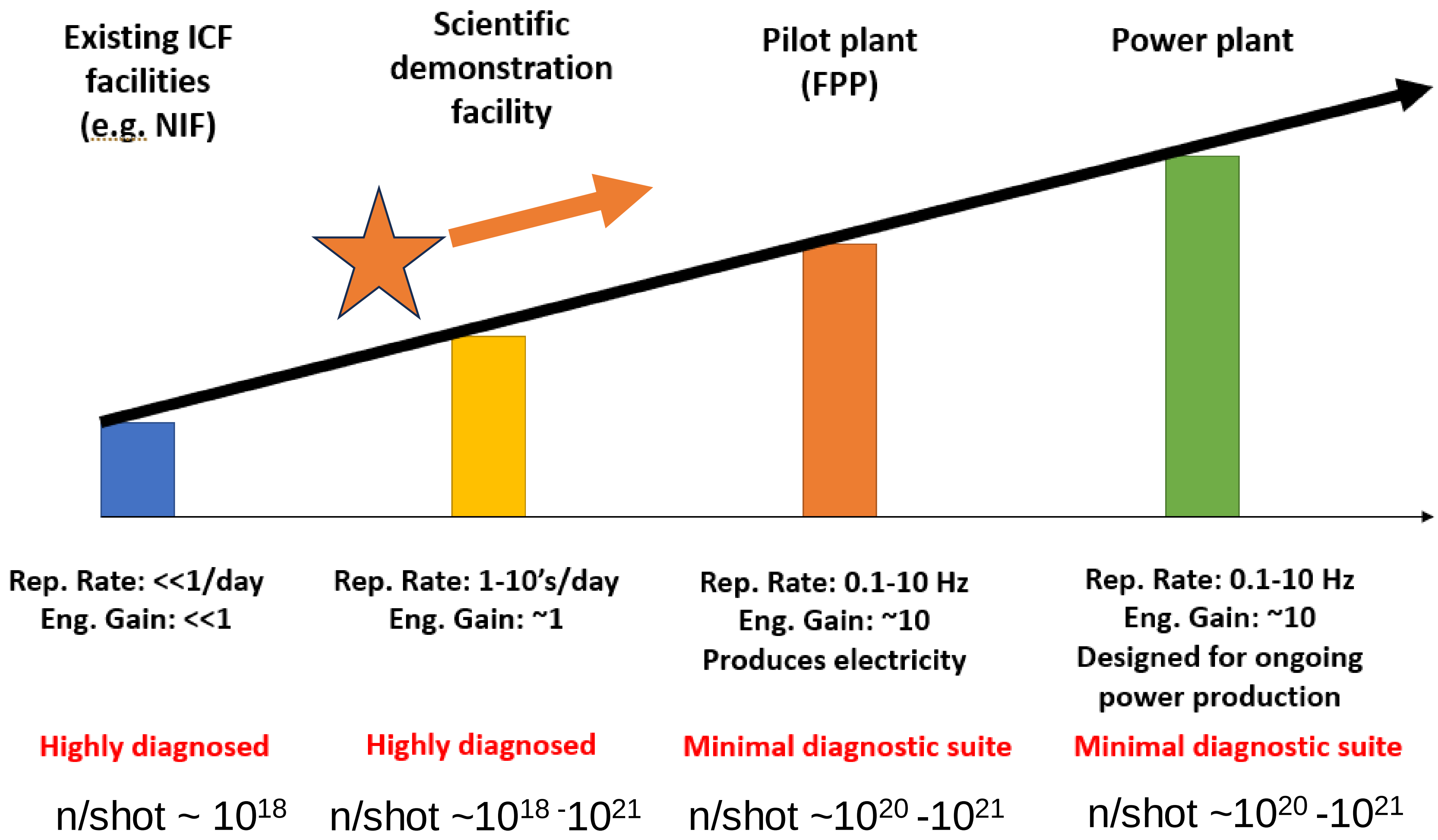


The reaction history changes in the ignition regime

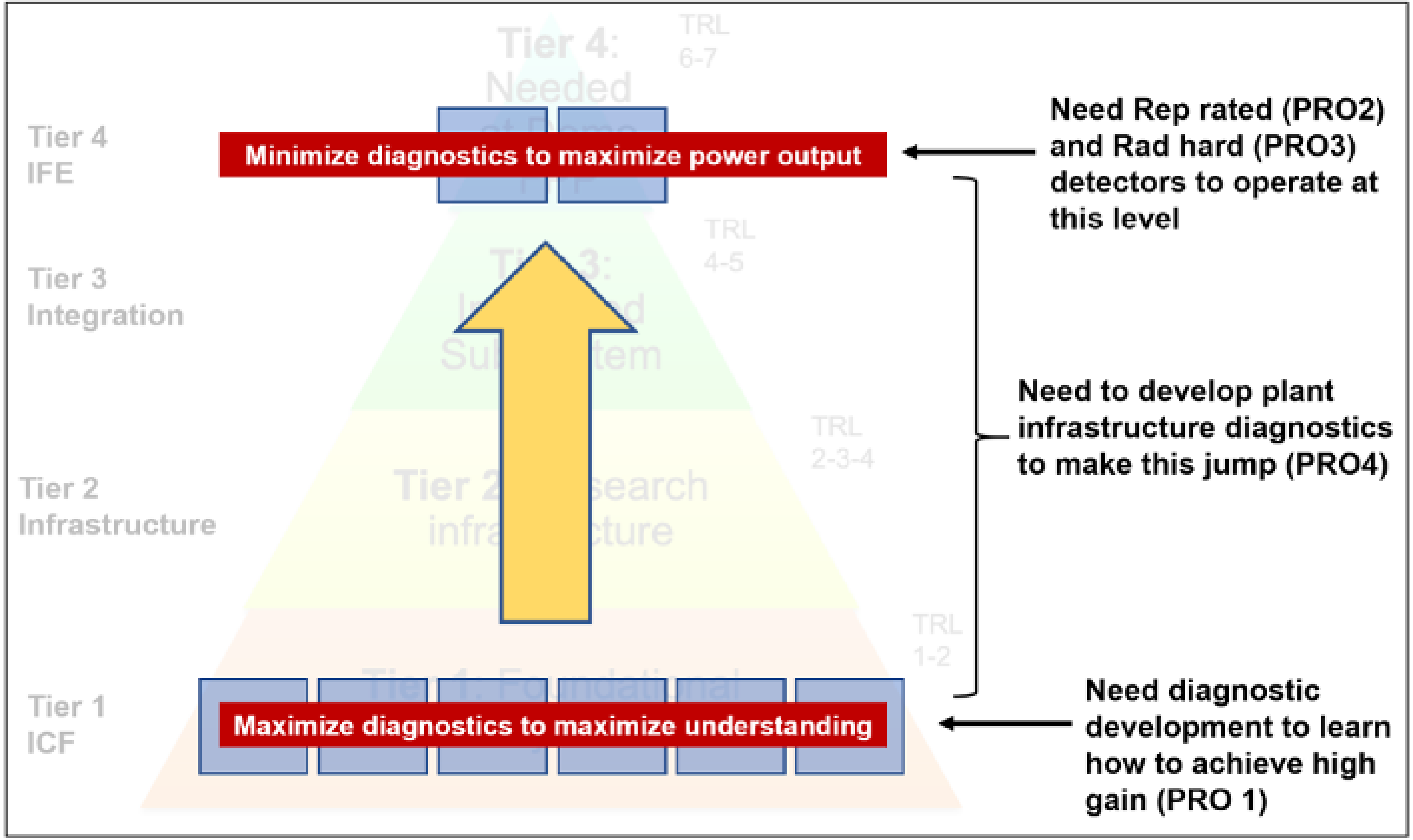


Simulations by B. Haines (LANL)

The path to a US inertial fusion power plant



A pilot plant will have different and minimal diagnostics



Diagnostic needs for a scientific demo and pilot plant

Minimal

- 3.1 Determine a minimum diagnostic suite for an FPP

Reliable

- 3.2 Simulations of high-rad environments in an FPP
- 3.3 Develop & test rad-hard components

Rep-rateable

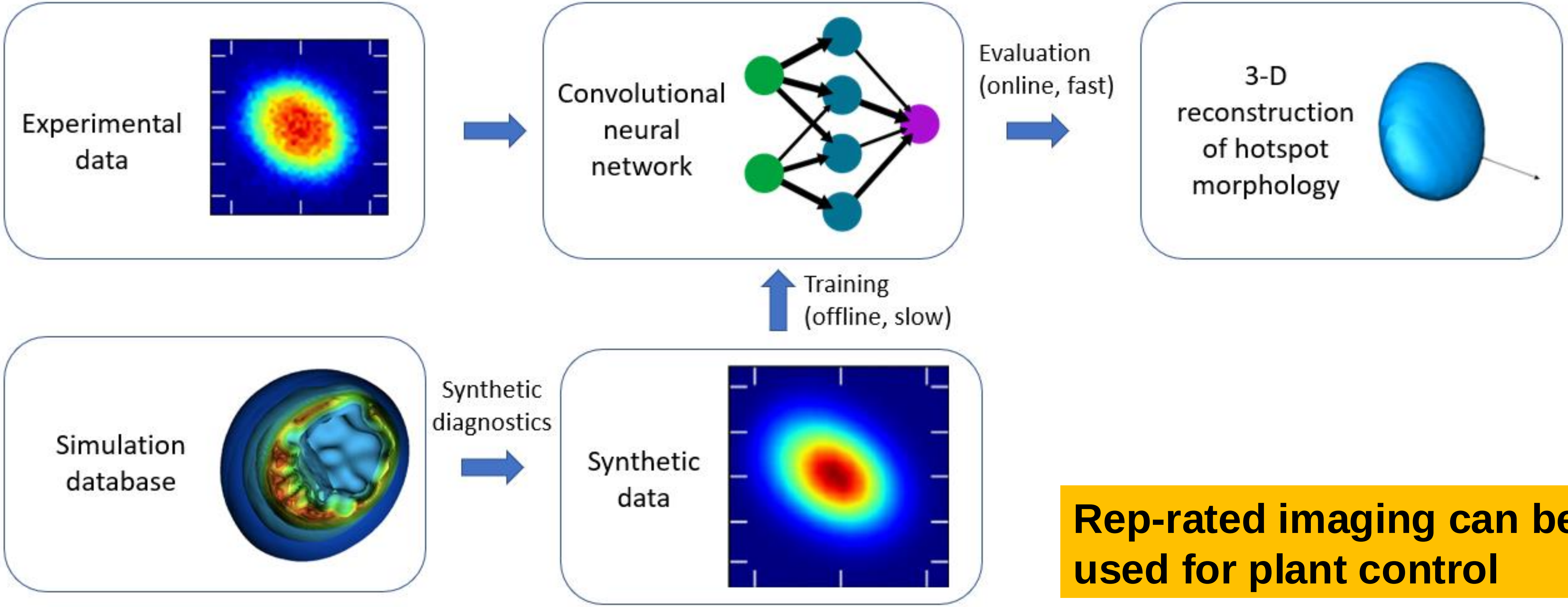
- 3.5 Develop ML-supported high rep-rate analysis codes

Universal

3.4. Develop driver-agnostic detector designs

6. Test concepts & parts at relevant facilities

How our diagnostics can evolve: repetion-rate

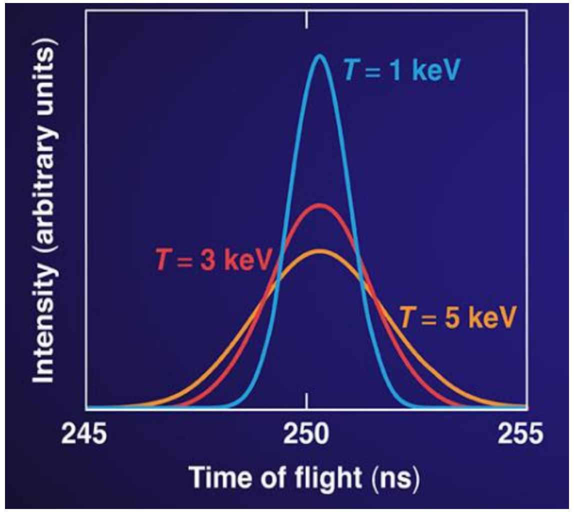


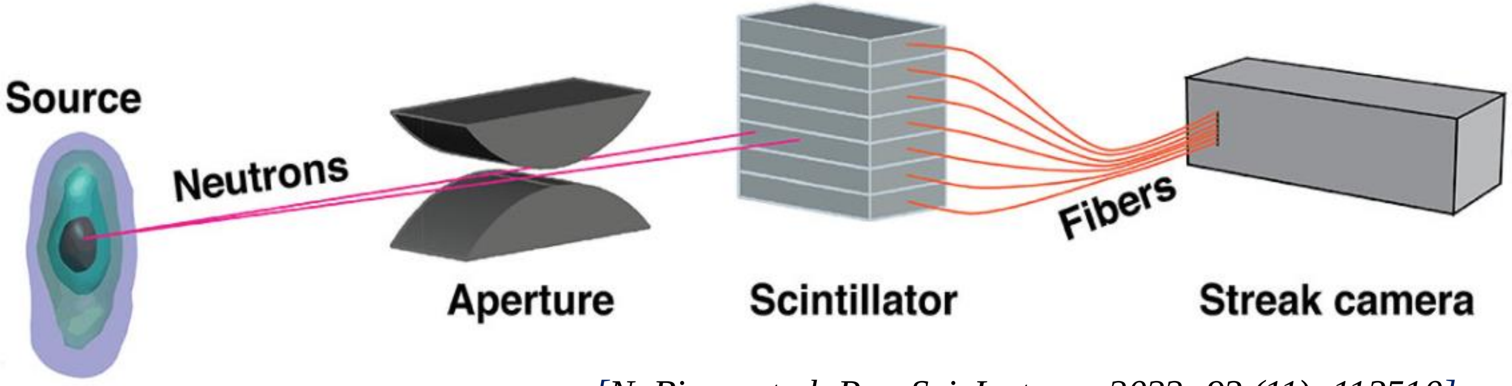
Rep-rated imaging can be used for plant control

training a neural network for rapid online 3-D reconstructions

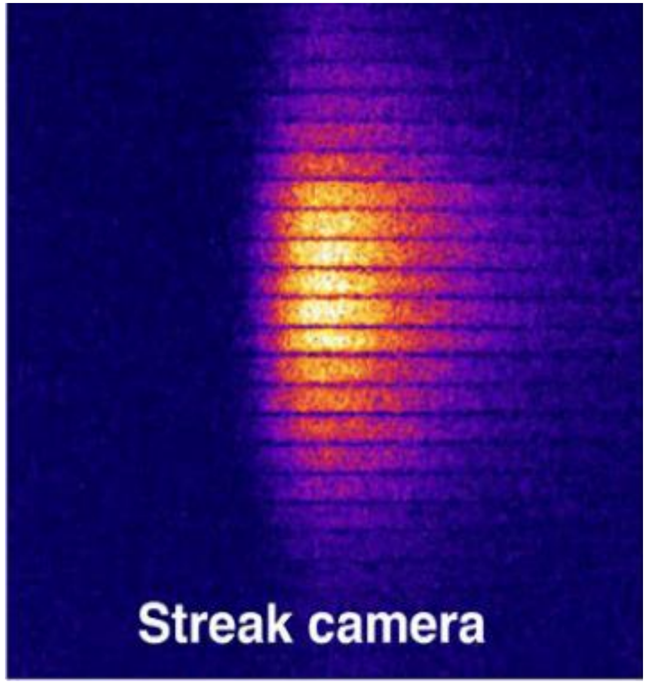
[K. Churnetski, et al, High Energy Density Physics, 52, 2024, 101108,].

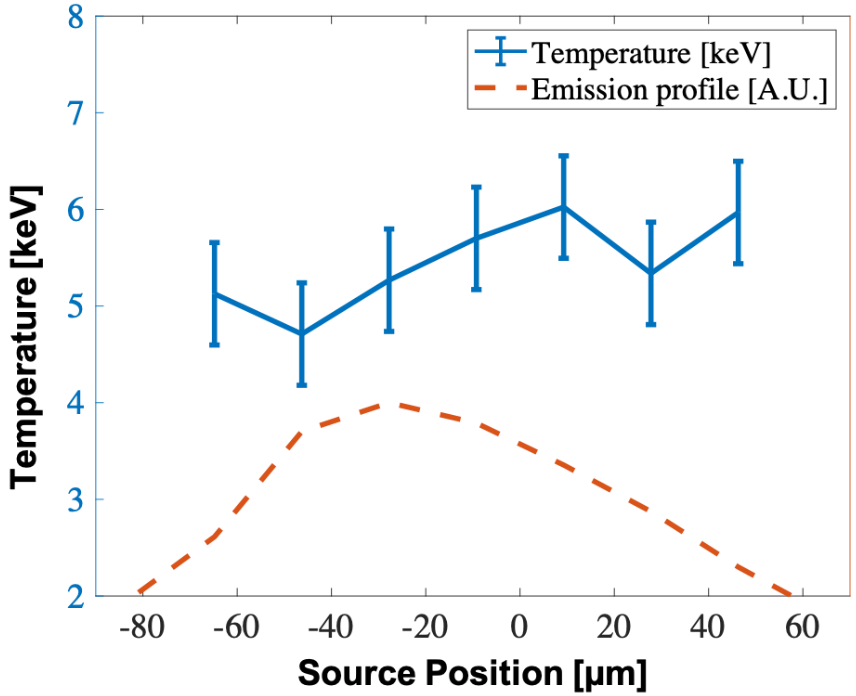
First-ever spatially resolved ion temperature measurement



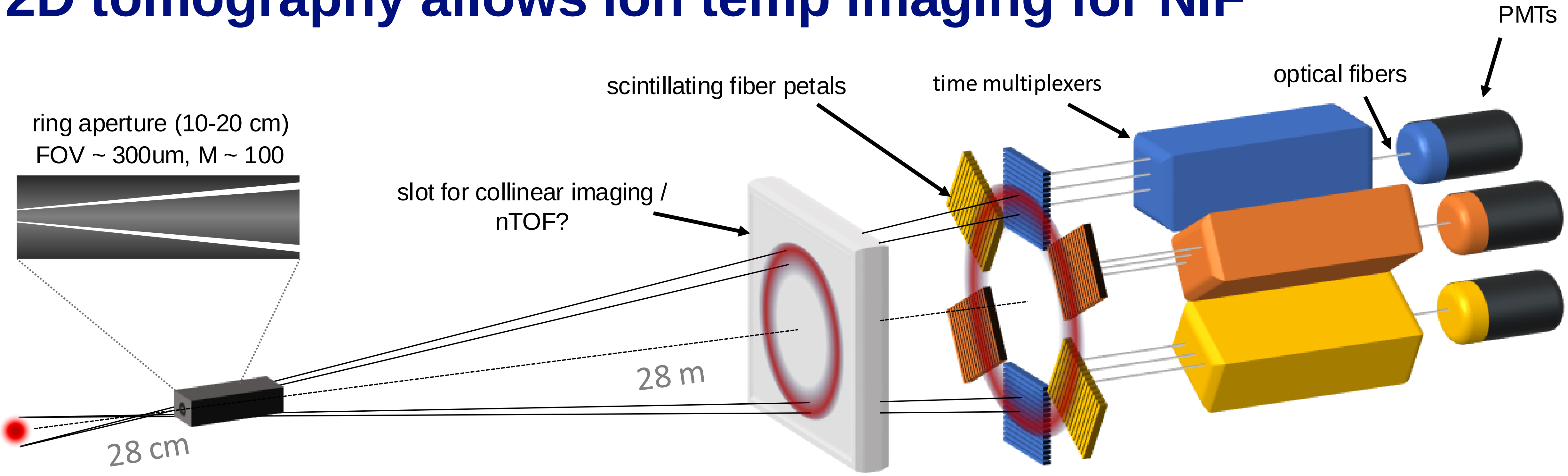


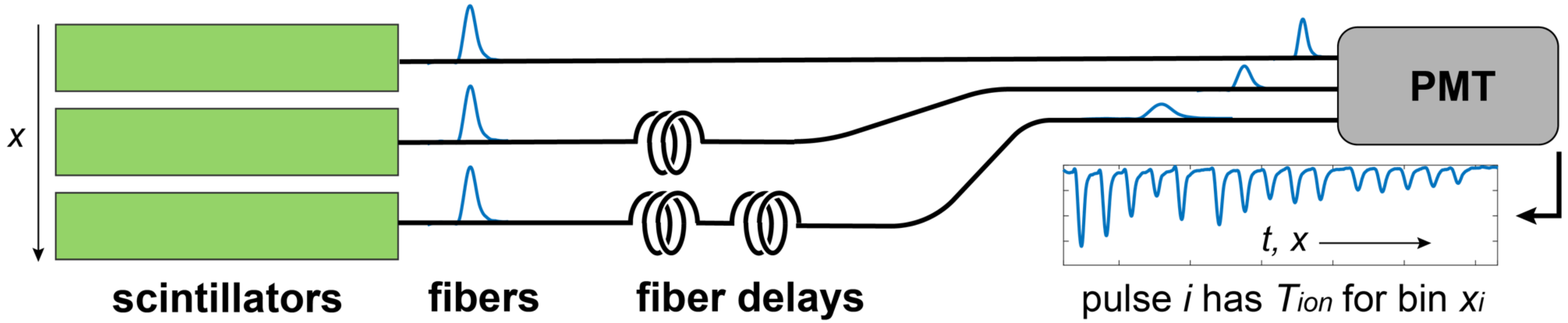
[N. Birge, et al, Rev. Sci. Instrum. 2022; 93 (11): 113510]
[C. R. Danly, et al. Rev. Sci. Instrum. 2023; 94 (4): 043502]





2D tomography allows ion temp imaging for NIF



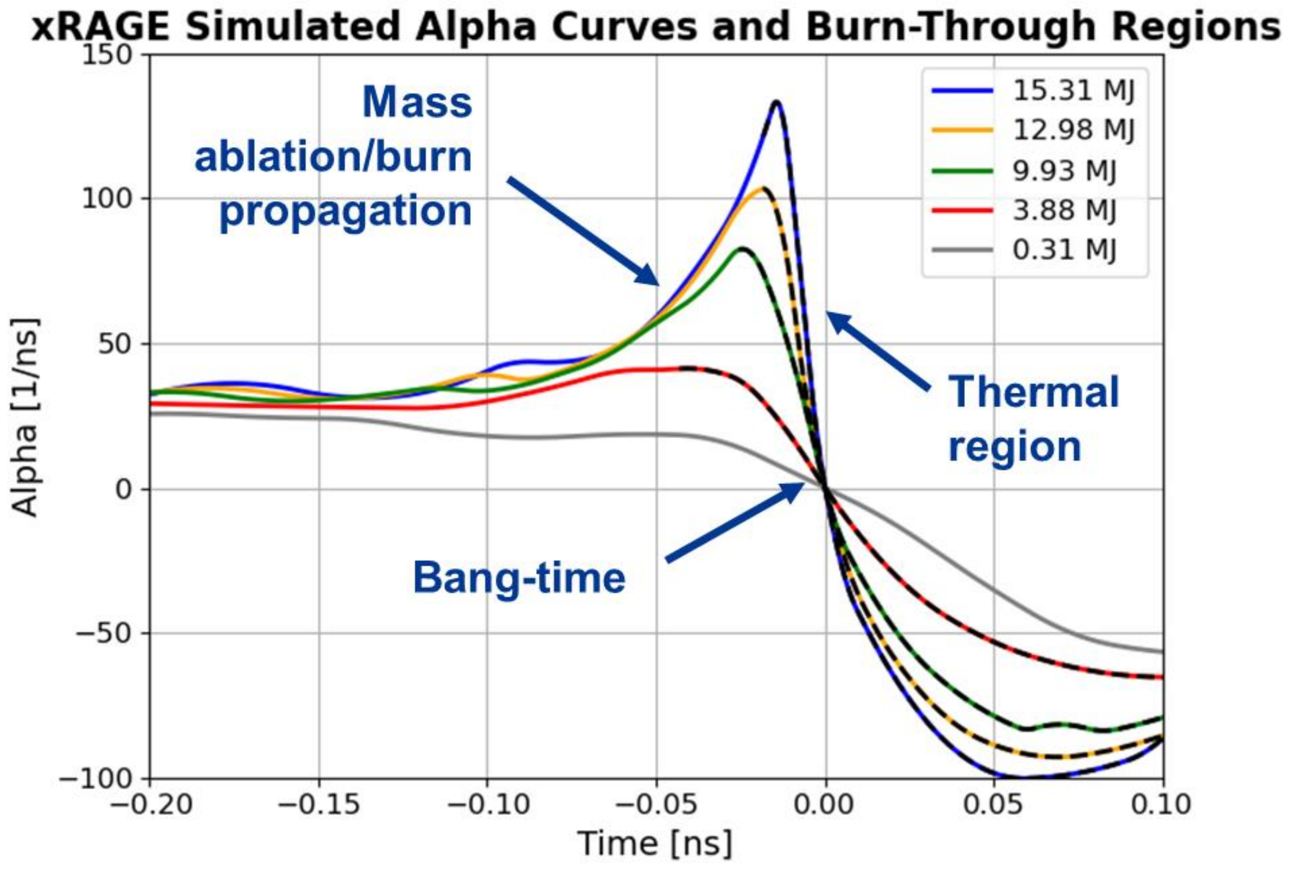


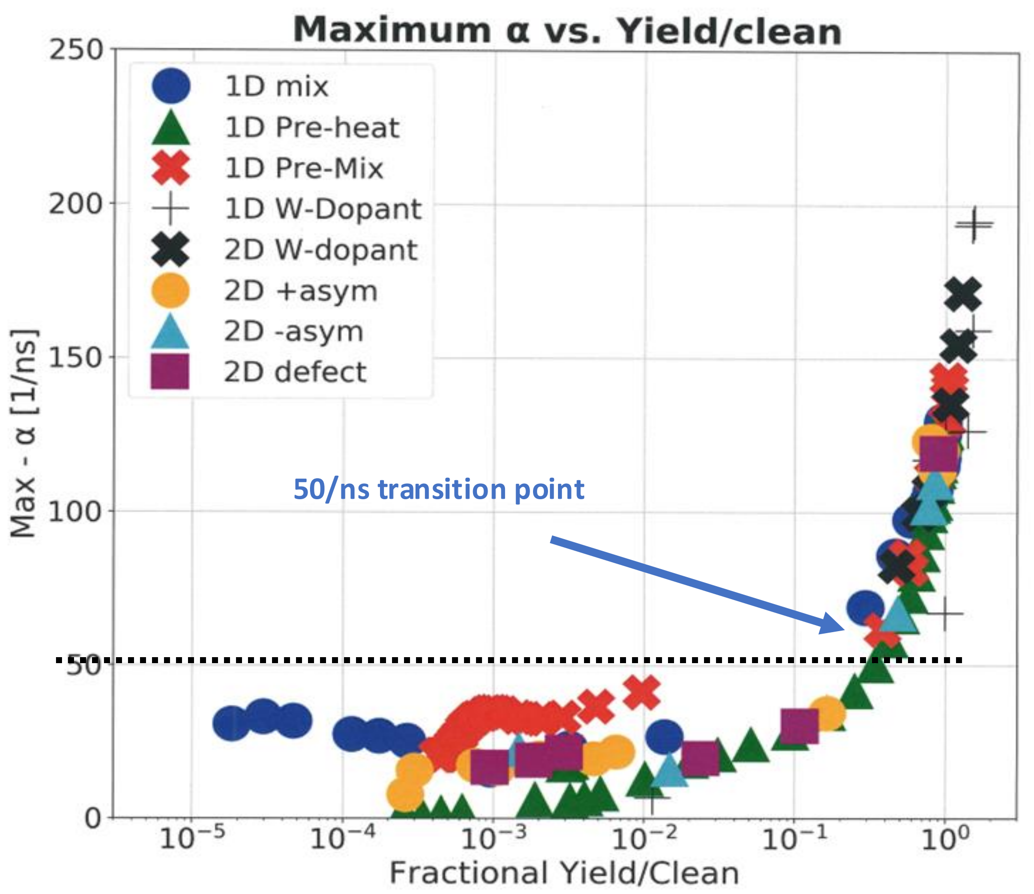
[L. Tafoya, et al. Rev. Sci. Instrum. 2024; 95 (9): 093512.]

Multiplexing technology allows for simpler detectors away from radiation sources

The GRH diagnostic is ideally suited for IFE applications

The GRH diagnostic is radiation hard and has a high repetition rate





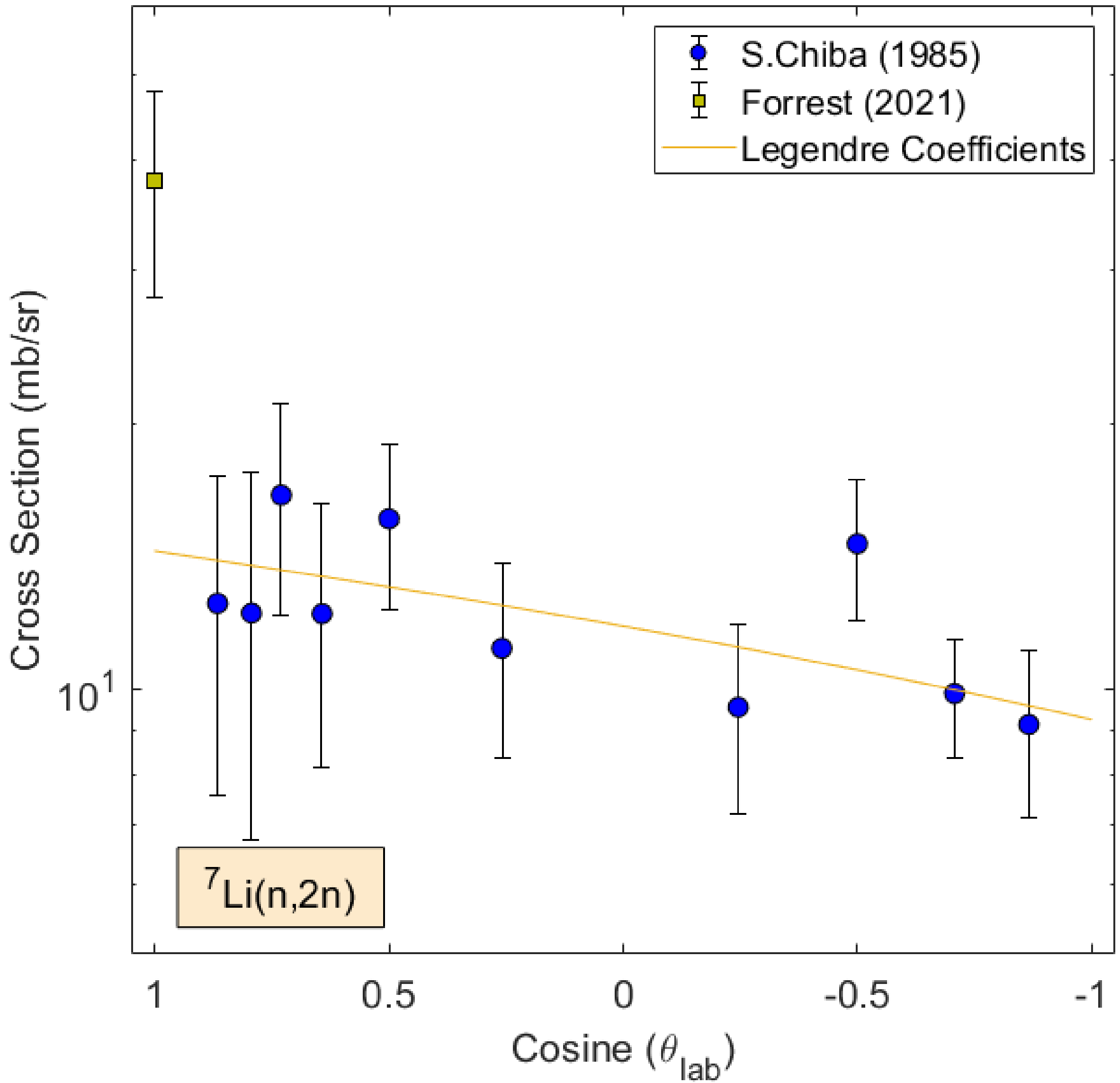
α is the logarithmic derivative of the reaction rate

The reaction history can be used to gauge robustness of each shot in laser IFE in real time.

Beyond diagnostics: fusion relevant nuclear data

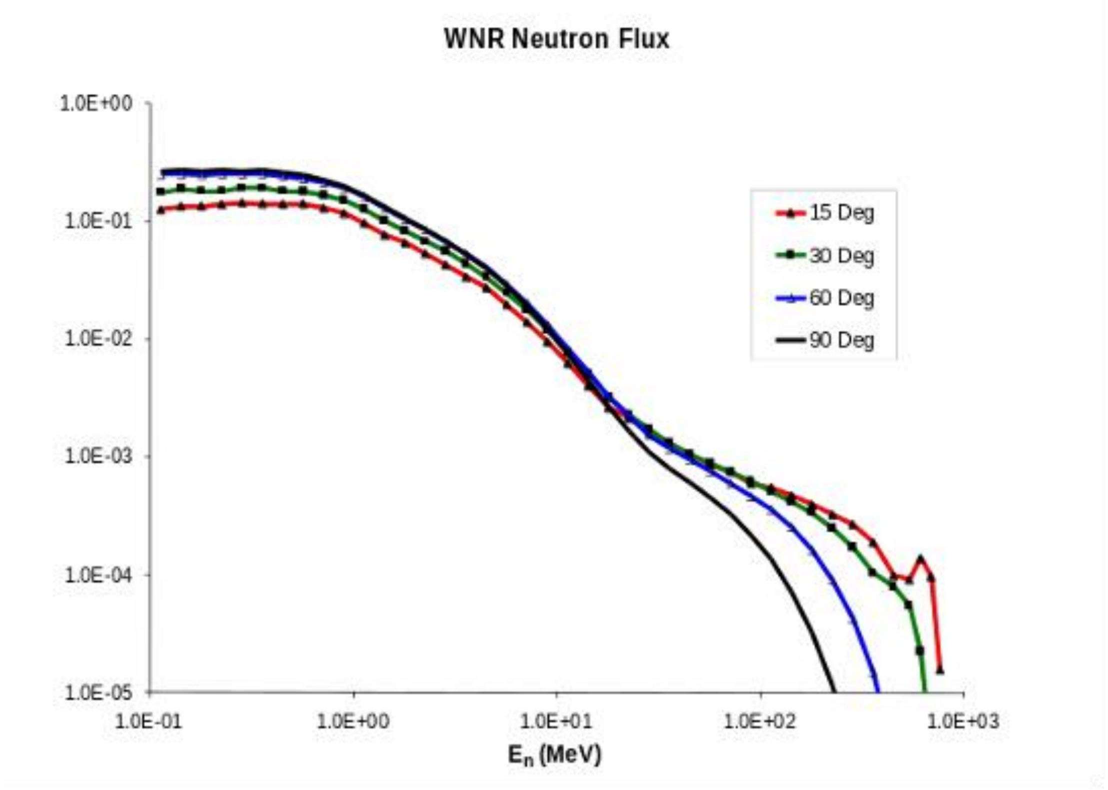
LANL houses one of thew most important nuclear data evaluation catalogues: **ENDF**
The evaluated nuclear data file is used by nuclear physicists around the world.

Nuclear data relevant to fusion is sparse (1-15 MeV neutron energy, light elements)

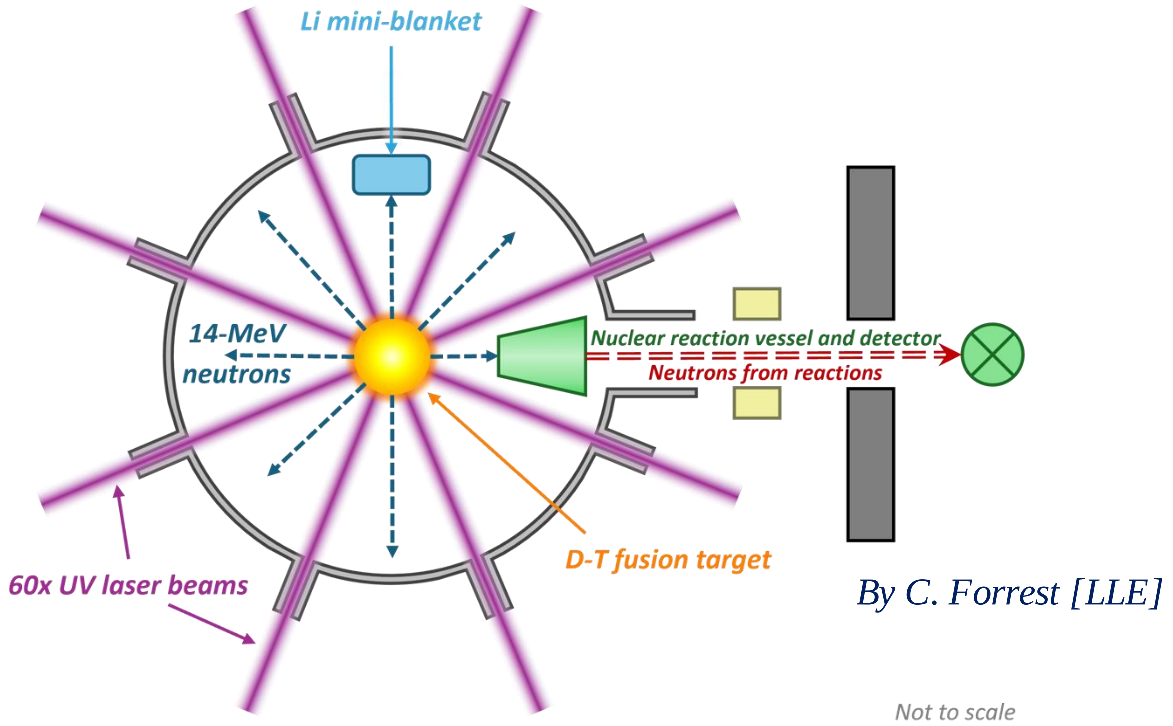


Our community has the tools to measure nuclear data

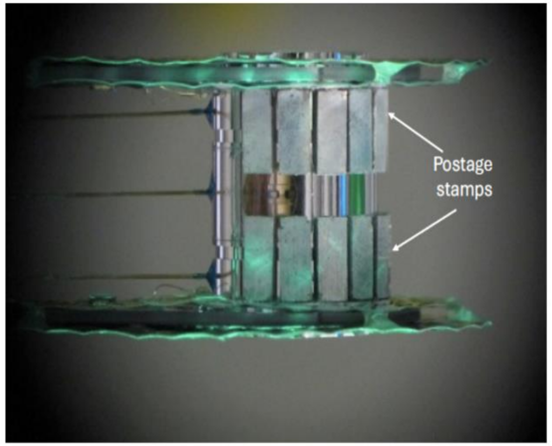
We have the experimental opportunities to fill in these gaps and the evaluation knowledge to produce useable data sets.

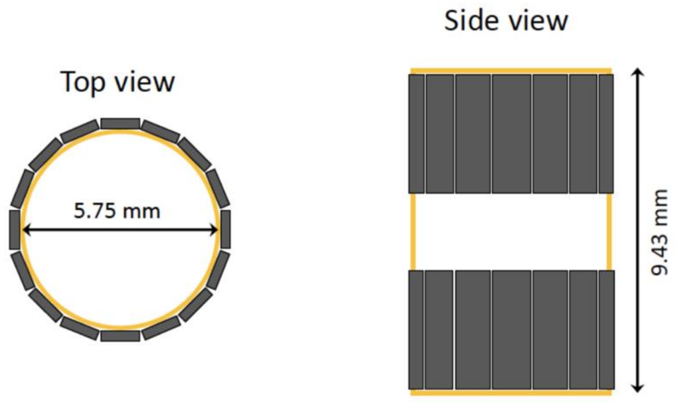


[A. C. Hayes, et al. AIP Advances 2025; 15 (3): 035001.]



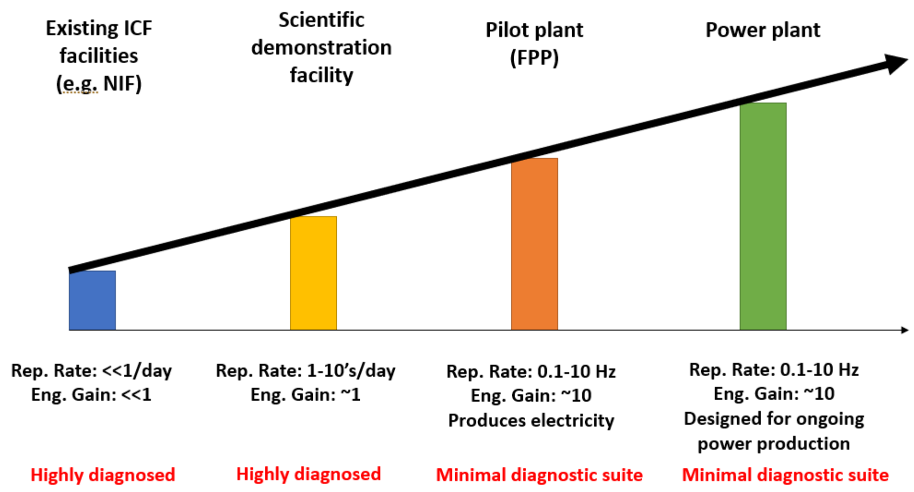
By C. Forrest [LLE]





Benefits to the existing ICF program

- NNSA applications of ignition needs a **robust ignition** platform
- Advances in **data analysis and ML** methods
- Advances in detector materials (**rad-hard and rep-rateable**)
- **Energized workforce** working on IFE



The ICF community has the experience and tools to take on the IFE challenge!

Credits

GRH Team:
Yongho Kim, Hermann Geppert-Kleinrath, Kevin Meaney, Woody VanDervort, Patrick Adrian, Robert Dwyer, Jorge Carrera (LLNL), Eddie Mariscal (LLNL)

NIS Team:
Mora Durocher, Chris Danly, Valerie Fatherley, Matt Freeman, David Fittinghoff (LLNL), Justin Jorgenson, Emily Mendoza, Mike Rubery (LLNL), Britney Sanders, Matt Selwood (LLNL), Landon Tafoya

LANL NNSA OES ICF program:
Ann Satsangi and Joe Smidt

LANL DOE OoS FES program:
John Kline

ICF: “Creating a Star on Earth!”

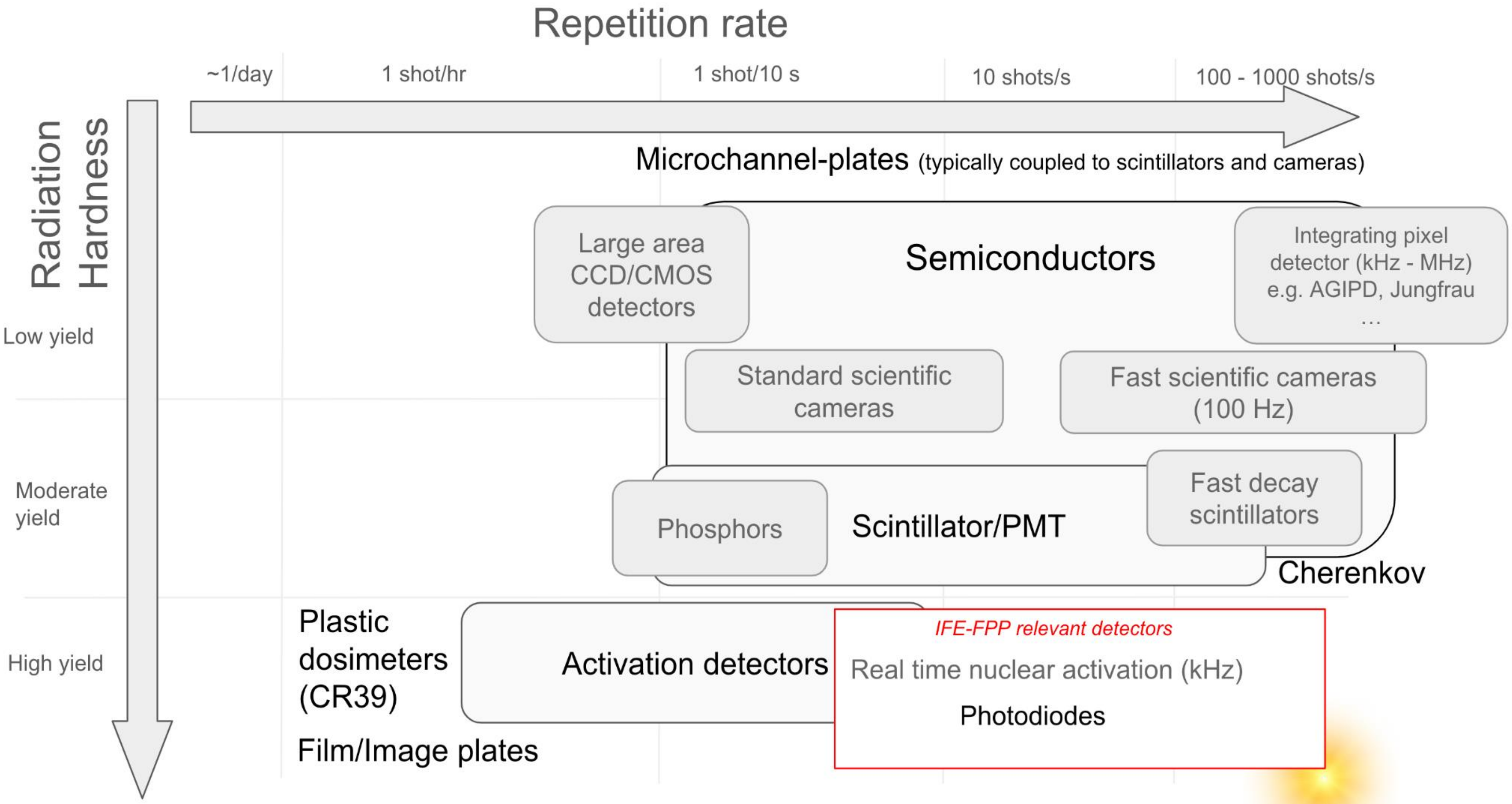
NIF produces ~500 TW of UV laser light for several billionths of a sec (ns):

- The **US electrical energy consumption** is only ~0.5 TW (**0.1% of NIF**)
- Laser drive duration ~5 ns (the laser **beams** are **only ~1.5 m long**)

ICF spherical convergence leads to:

- Temp ~ 150 MK (~**10x hotter than the sun’s center**)
- Pressure ~ 400 Gbar (that’s nearly **half a trillion atmospheres**!)
- Duration ~90 ps (light only travels 3 cm in that time)
- ~3 MJ yield (~**30x the power of human electrical consumption**)

Sensor research and instrument integration needed



*Icons illustrate optimal detector performance in terms of radiation survivability and maximum repetition rate. Note, there is also an inverse relationship between radiation hardness and detector resolution, as well as a similar inverse relationship for resolution and repetition rate.

[BRN Workshop on Measurement Innovation 2024]