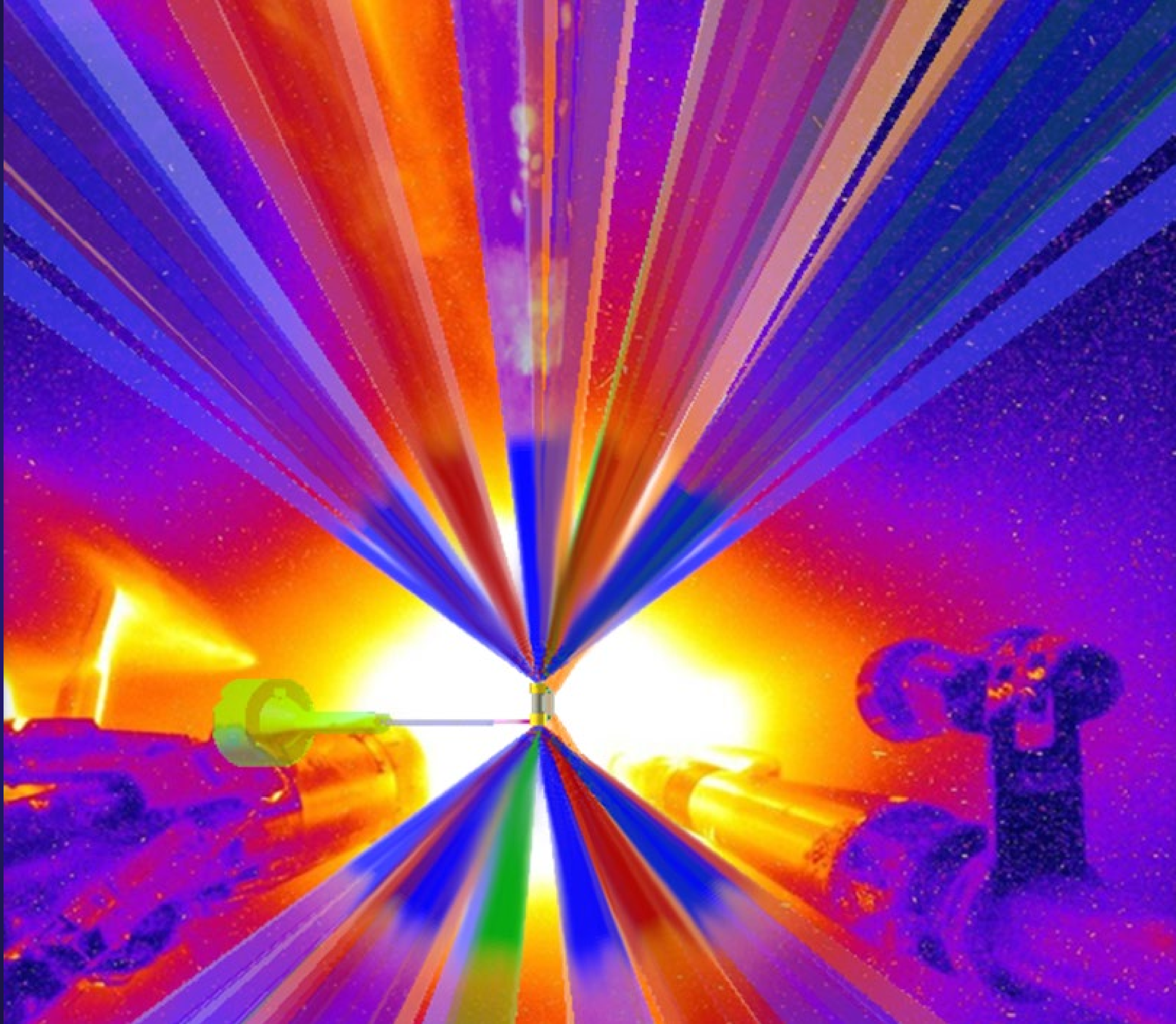
Los Alamos NATIONAL LABORATORY

Laser-driven HED Plasmas

PPPL Intro to Fusion Energy and Plasma Physics 2021

E.C. Merritt

LA-UR-21-25843

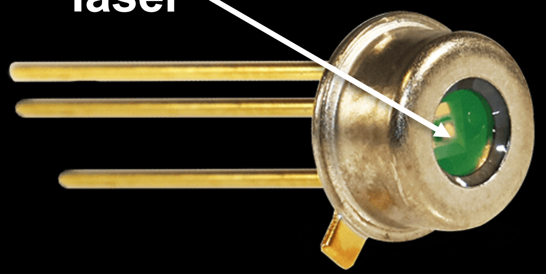


Not every career is a straight path

2003 - 2007

MOUNT HOLYOKE

Tiny, tiny telecom lasers…



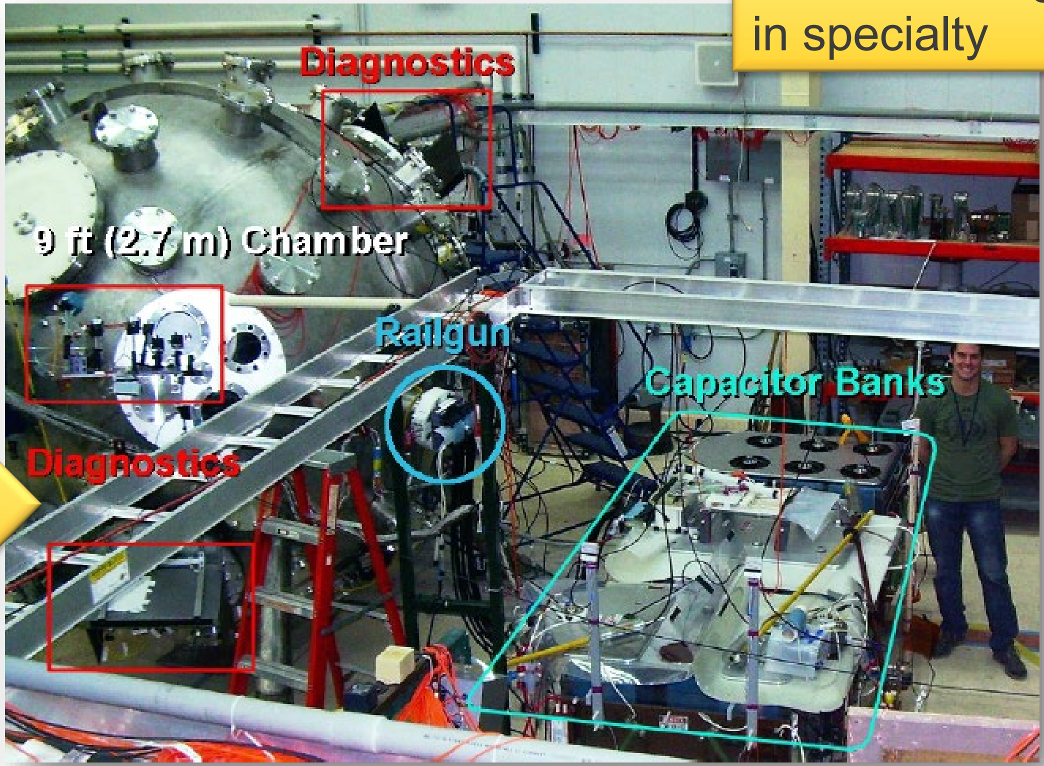
flir.com

First change in specialty

THE UNIVERSITY OF NEW MEXICO

2007 - 2013

Meter-scale plasmas….



Second change in specialty

2013 - now

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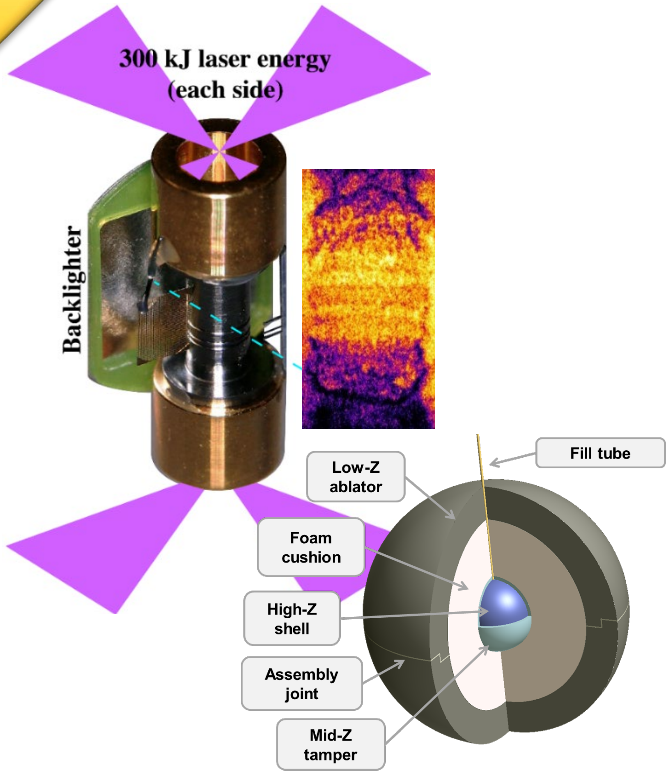
HED hydro & ICF



I got my start in plasmas at the PPPL summer program back in the day…

Outline

- What is HED science, and why do we care?
- How do we make and measure HED systems on earth?
- Inertial Confinement fusion, hydrodynamic instabilities and astrophysics
- A sampling of LANL HED and ICF work

I would like to acknowledge all of the many, many colleagues that contributed slides to this work…

Double Shells	Rad Transport	Marble	Cylinders	Neutron Imaging	Gamma Diagnostics
J. P. Sauppe	T.S. Perry	B. M. Haines	J. P. Sauppe	P. L. Volegov	K. D. Meaney
E. N. Loomis	R.F. Heeter	R. C. Shah	S. Palaniyappan	S. H. Batha	Y. Kim
T. Cardenas	Y.P. Opachich	J. M. Smidt	B. J. Tobias	V. Geppert-Kleinrath	H. Geppert-Kleinrath
D. S. Montgomery	H.M. Johns	B. J. Albright	J. L. Kline	C. R. Danly	H. W. Herrmann
W. S. Daughton	J.A. King	T. Cardenas	K. A. Flippo	F. E. Merrill	L. Berzak Hopkins
D. C. Wilson	E.S. Dodd	M. R. Douglas	O. L. Landen	C. H. Wilde	N. M. Hoffman
J. L. Kline	B.G. DeVolder	C. Forrest	D. Shvarts	D. C. Wilson	C. Cerjan
S. F. Khan	M.E. Sherrill	V. Yu Glebov	S. H. Batha	D. T. Casey	O. L. Landen
M. Schoff	B.G. Wilson	M. A. Gunderson	P. A. Bradley	D. Fittinghoff	K. Baker
M. Hoppe	C.A. Iglesias	C. E. Hamilton	E. N. Loomis	B. Appelbe	J. Carrera
F. Fierro	J.L. Kline	K. C. Henderson	N. N. Vazirani	J. P. Chittenden	E. Mariscal
R. B. Randolph	K.A. Flippo	Y. Kim	C. F. Kawaguchi	J. Crilly	
B. Patterson	T. Cardenas	M. N. Lee	L. Kot	K. McGlinchey	
L. Kuettner	M.B. Schneider	T. J. Murphy	D. W. Schmidt		
R. F. Sacks	D.A. Liedahl	J. A. Oertel	T. H. Day		
E. S. Dodd	T.J. Urbatsch	R. E. Olson	A. B. Zylstra		
W. C. Wan	M.R. Douglas	B. M. Patterson	E. Malka		
S. Palaniyappan	J.E. Bailey	R. B. Randolph			
S. H. Batha	G.A. Rochau	D. W. Schmidt			
P. A. Keiter					
J. R. Rygg					
V. Smalyuk					
Y. Ping					
P. Amendt					

…especially the HED Hydro Team

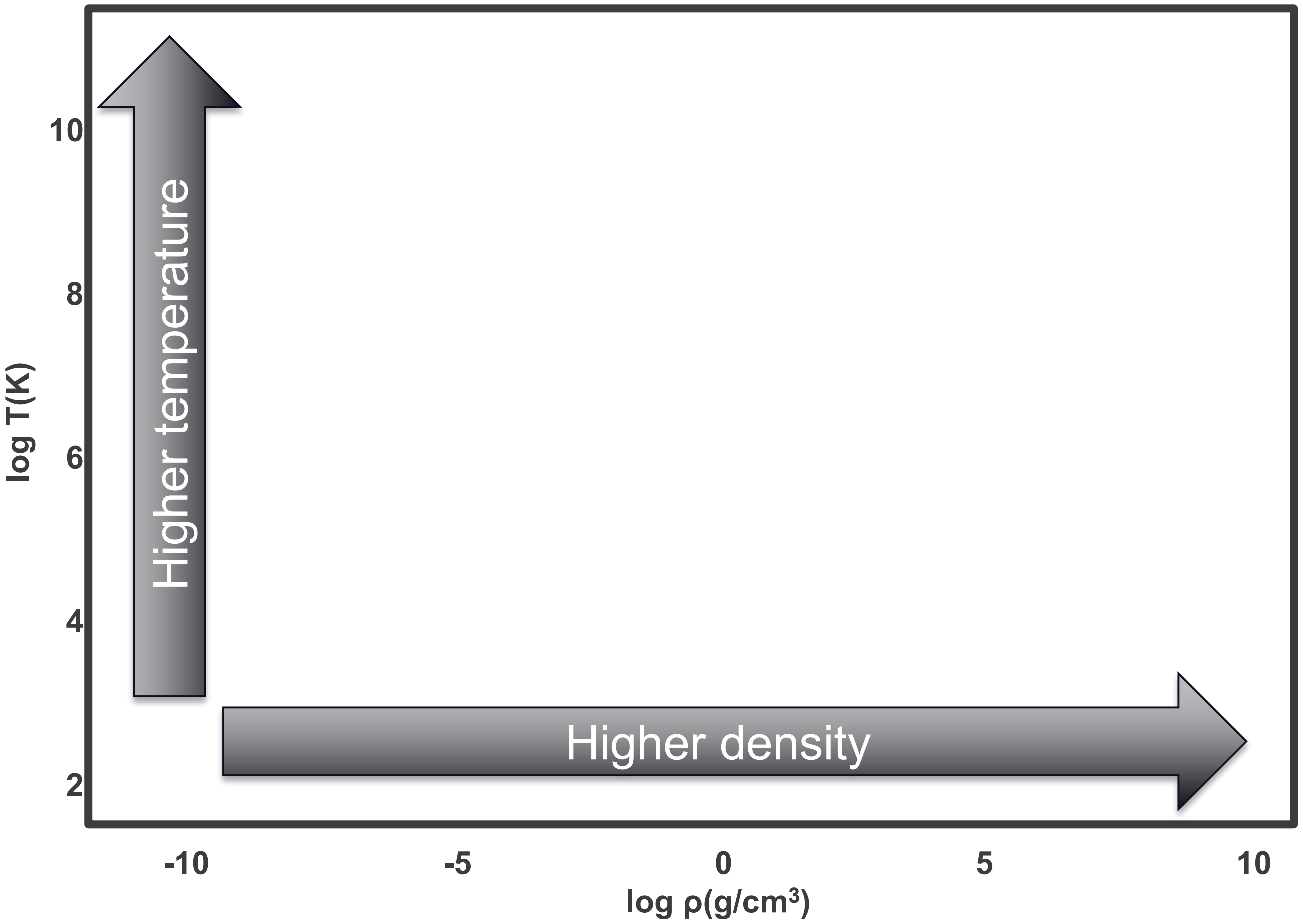
Design
Forrest Doss
Carlos Di Stefano
Ryan Sacks
Harry Robey

Experiment
Elizabeth Merritt
Kirk Flippo
Ben Tobias
Alex Rasmus
Joseph Levesque
Codie Fiedler-Kawaguchi
Noah Dunkley
Sam Wilkins

Target Fabrication
Derek Schmidt
Alexandria Strickland
Nik Christiansen
Tana Morrow
R.B. Randolph
Chris Wilson

What is high-energy-density science?

High-energy-density (HED) systems are defined as systems having pressures >1 Mbar or energy densities above 100 GJ/m^3



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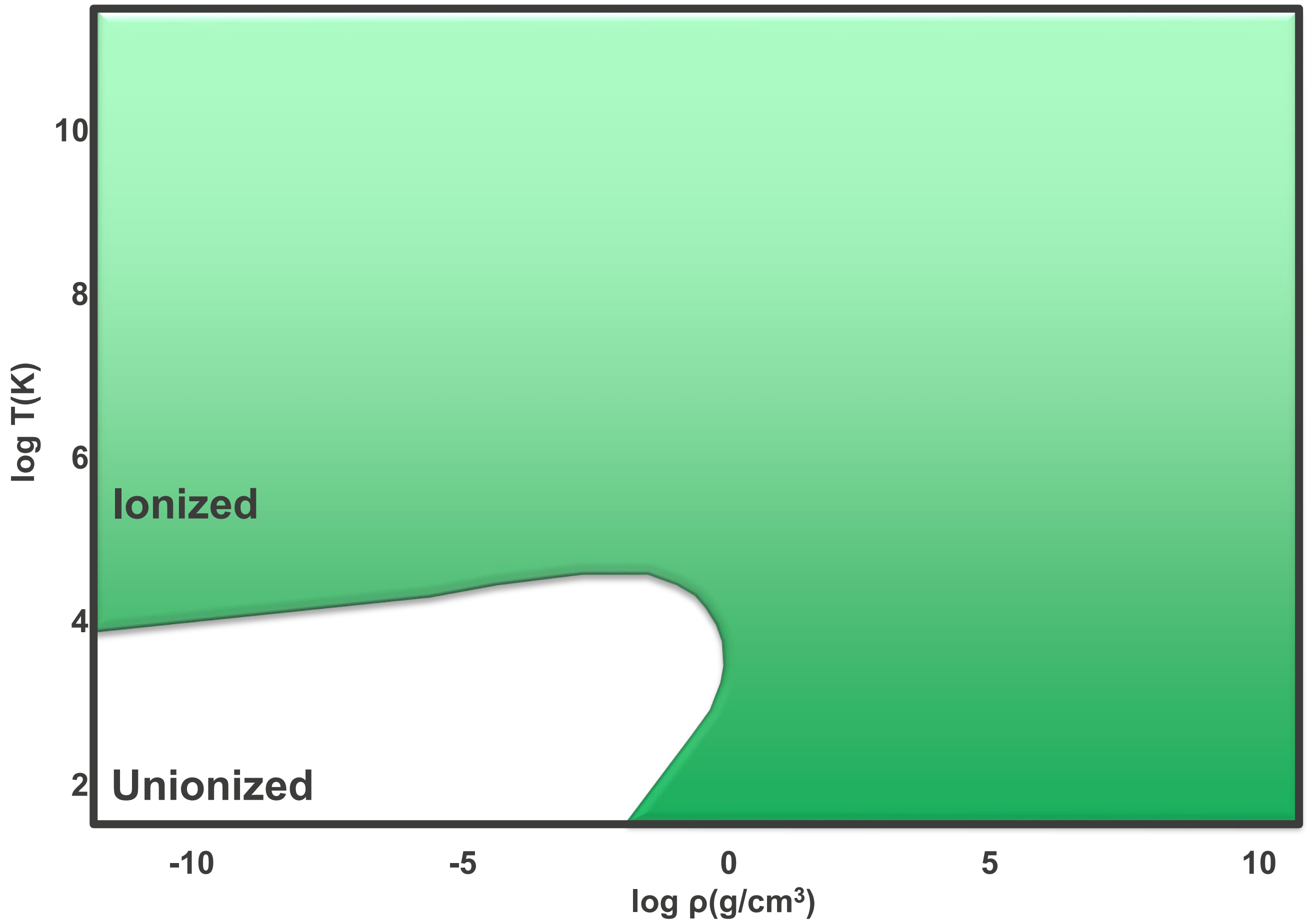

Get something hot and/or dense enough and it becomes a plasma

- What is a plasma?
  - Ionized matter made up of *unbound* positive and negative particles
  - Overall material charge is still zero (neutral)
  - Particles show collective behavior even though individual positive and negative particles are not bound together

You can think of plasma like a fluid that also has embedded electromagnetic fields

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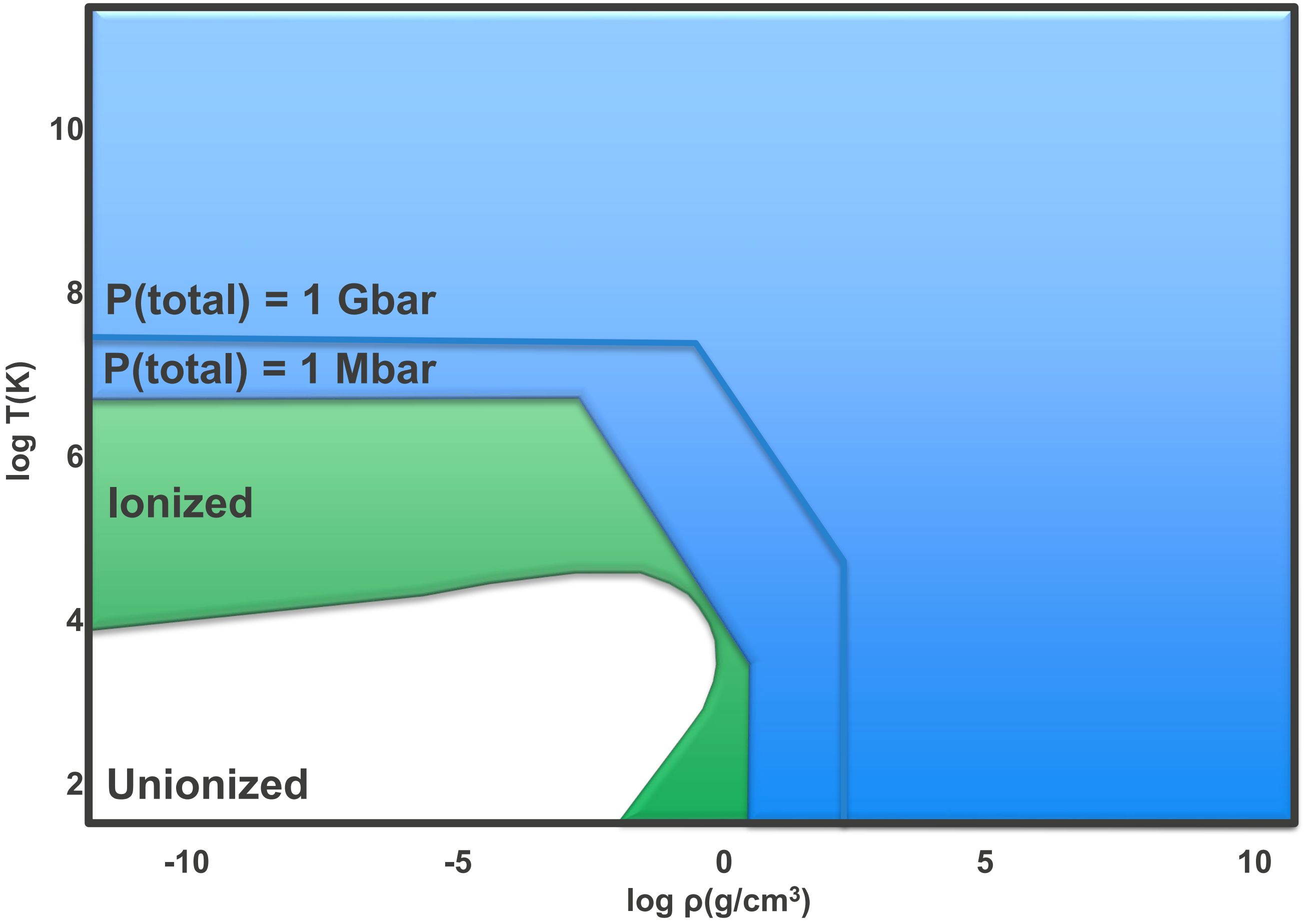


Energy/Volume ~ 1 Mbar
similar to chemical bond

↓

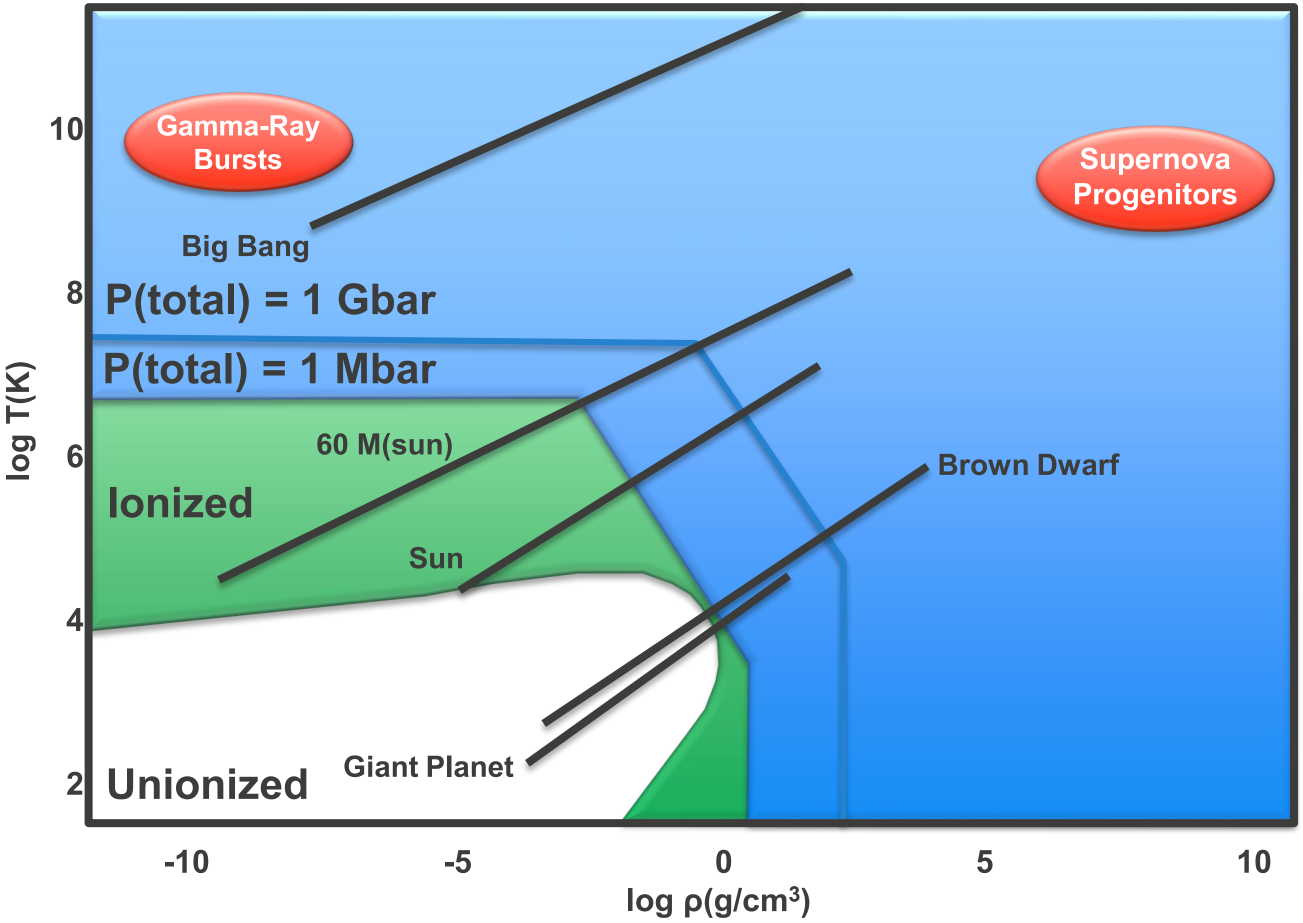
chemical properties can change

Energy/Volume ~ 100 Mbar
similar to atomic inner core electrons

↓

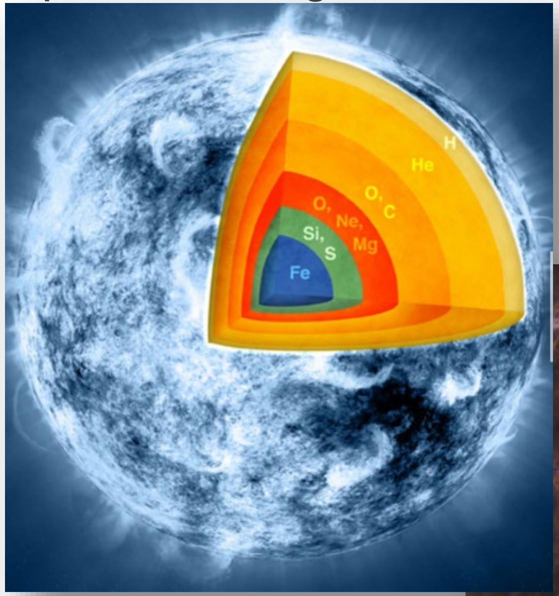
atomic properties can change

High-energy-density (HED) systems are defined as systems having pressures >1 Mbar or energy densities above 100 GJ/m³

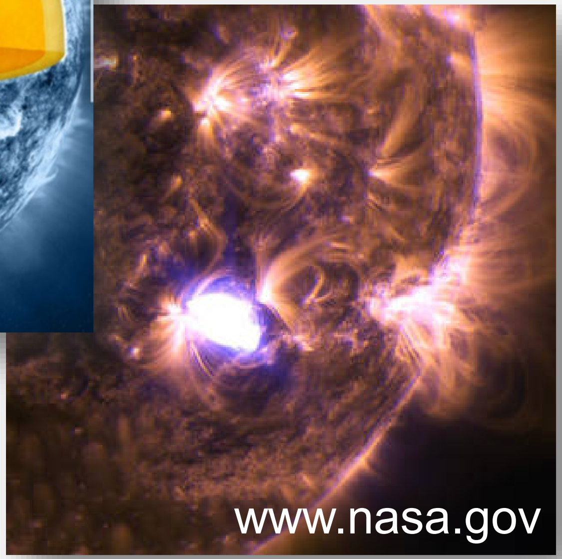


Many astrophysical objects reach HED conditions

Supernova Progenitor



Our Sun



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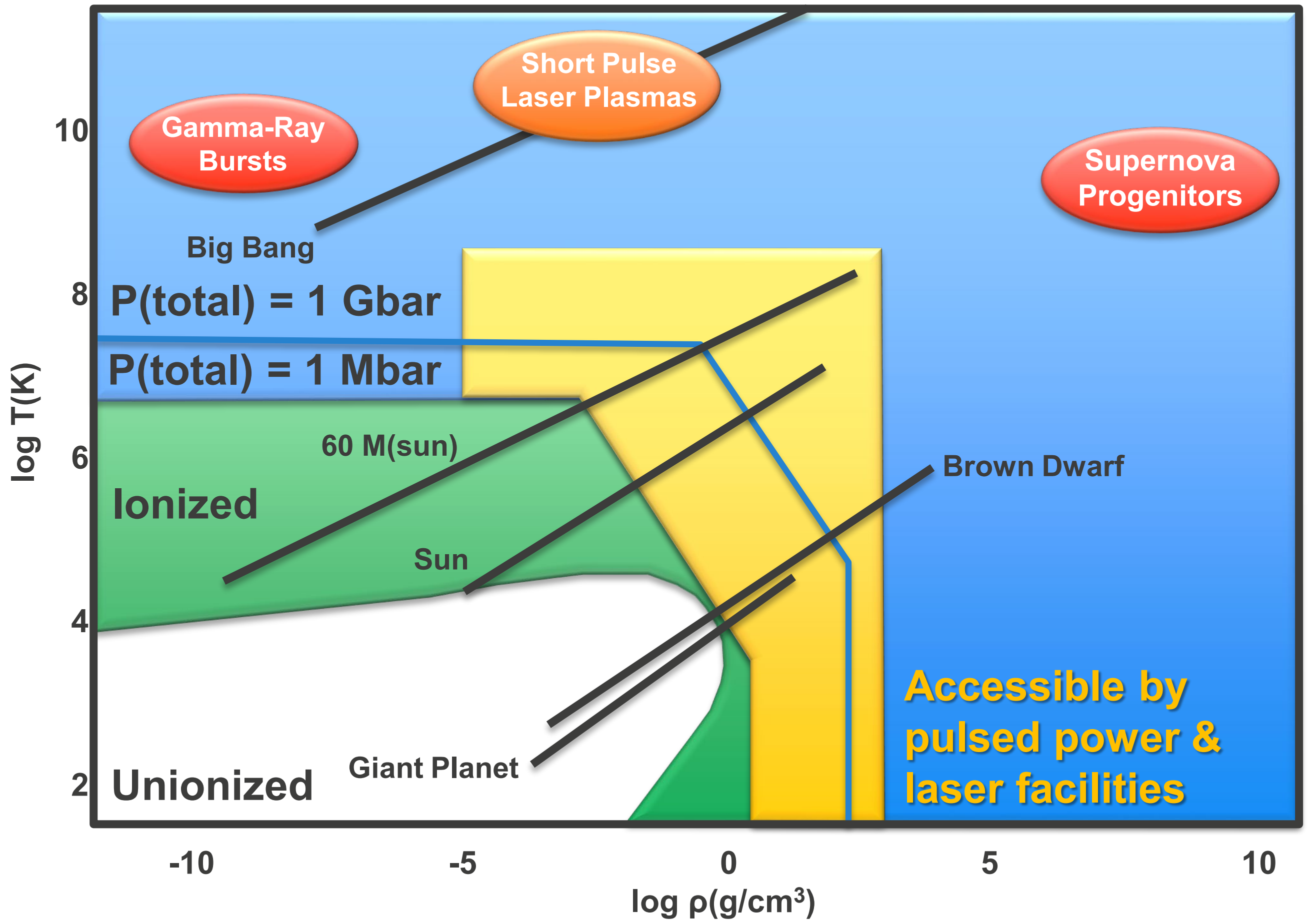


One of the biggest challenges of HED science is how to make a high energy density system in a lab

$$\rho_E = \frac{E}{V}$$

Make the deposited energy large

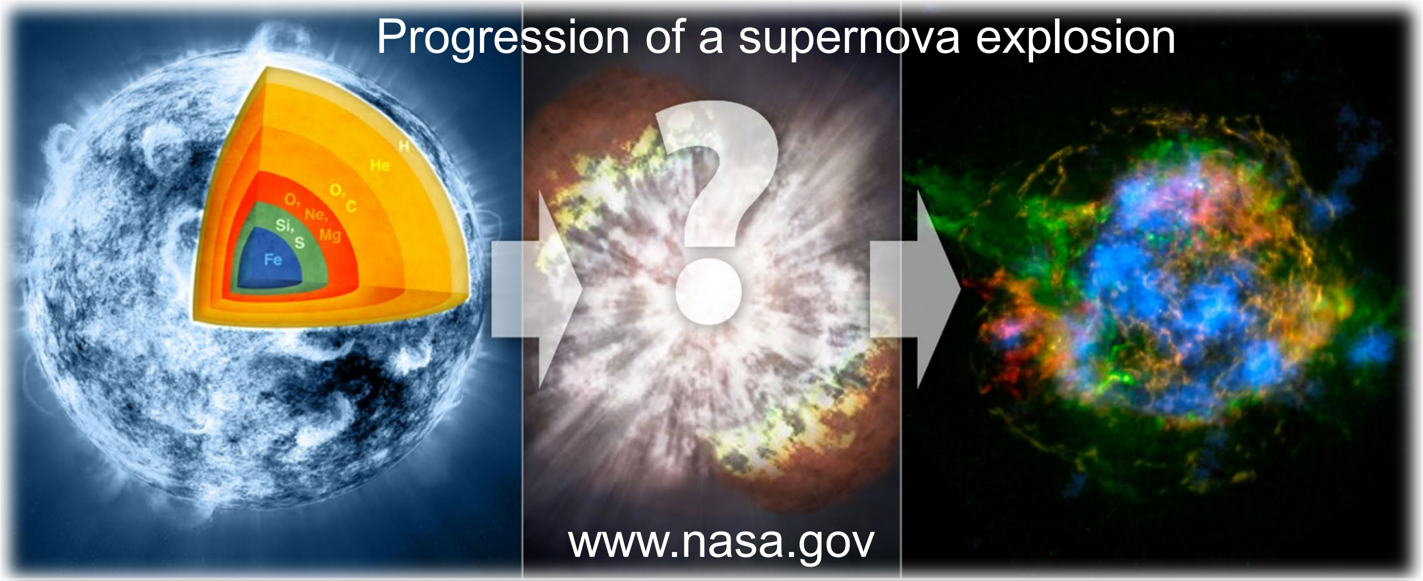
Make the system really small

Lasers (or pulsed power) are a great way to deposit a lot of energy into very small system because they don't add volume

Understanding how matter behaves under ‘extreme’ conditions may help us answer long-standing science questions

Some examples:

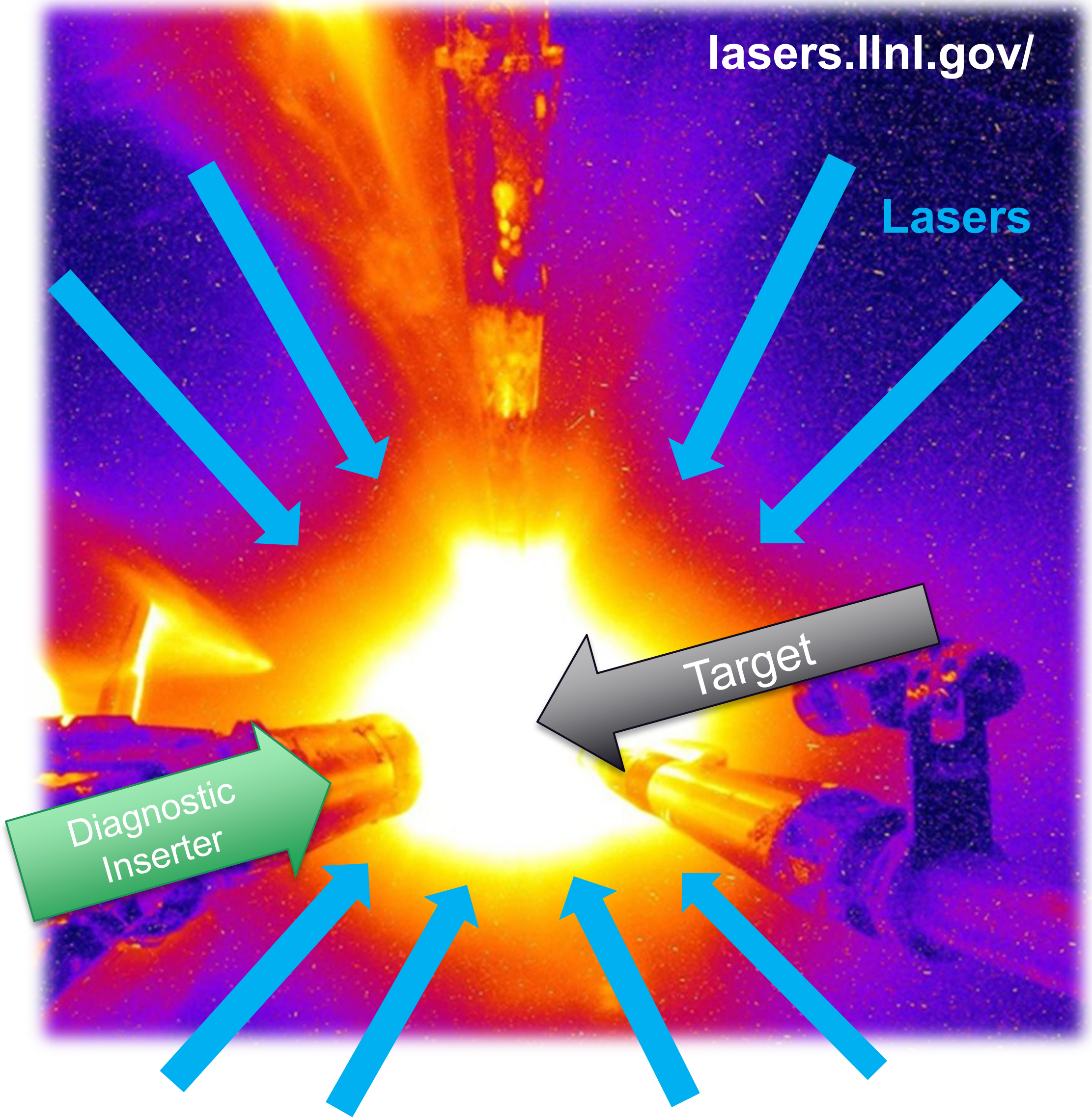
- Why do supernovae explode and not just become black holes?
  - What kind of elements should a supernova produce? And how much?



- Is a planetary core a solid or a liquid or something else?
  - How does this change how the planet’s magnetic dynamo should act?
- Can we create a human-made power source than uses nuclear fusion similar to stars?

How do we make and measure HED systems on earth?

Laser light is one of the best ways to get a *large* amount of energy into a *small* system extremely *quickly*



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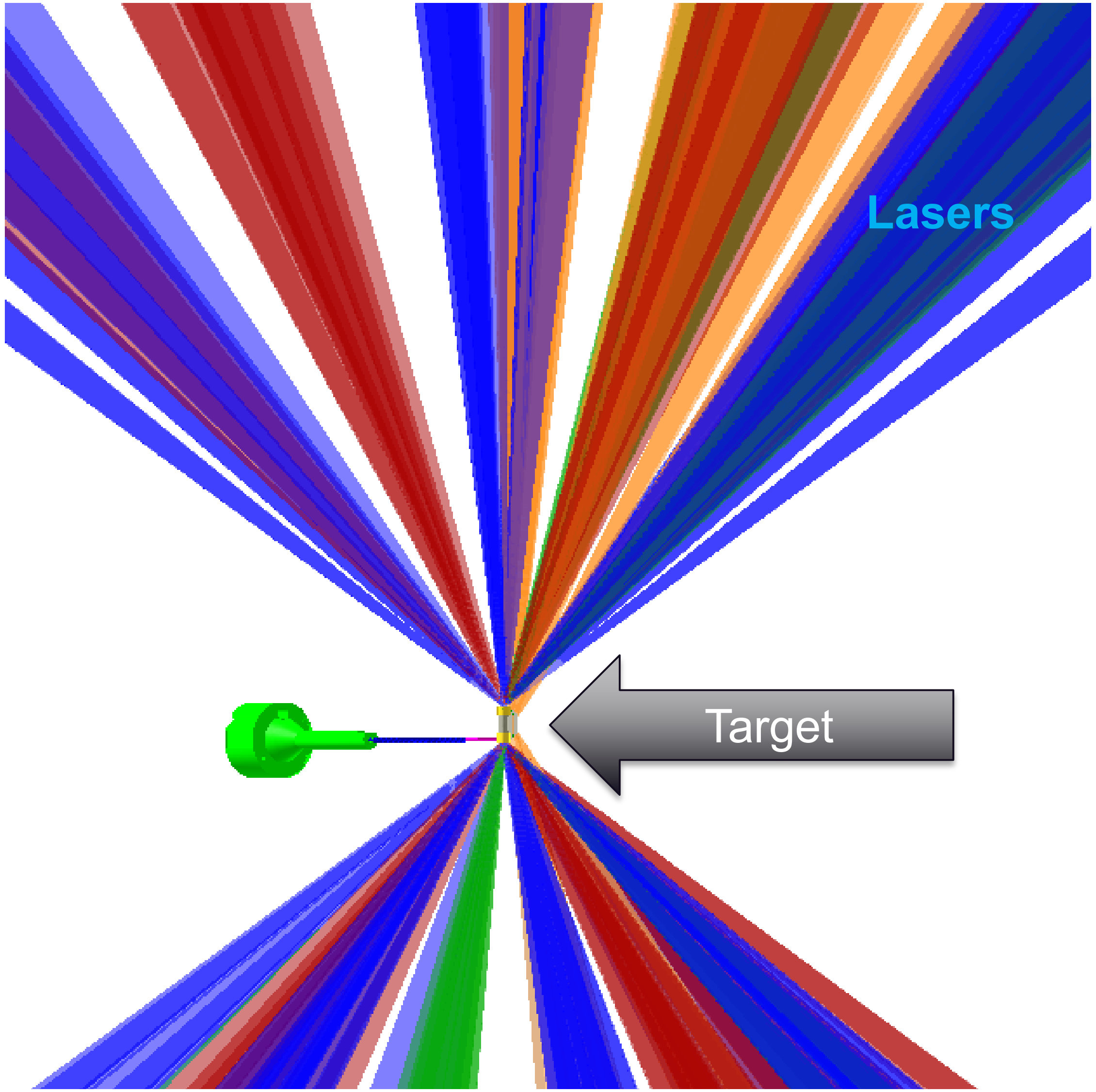

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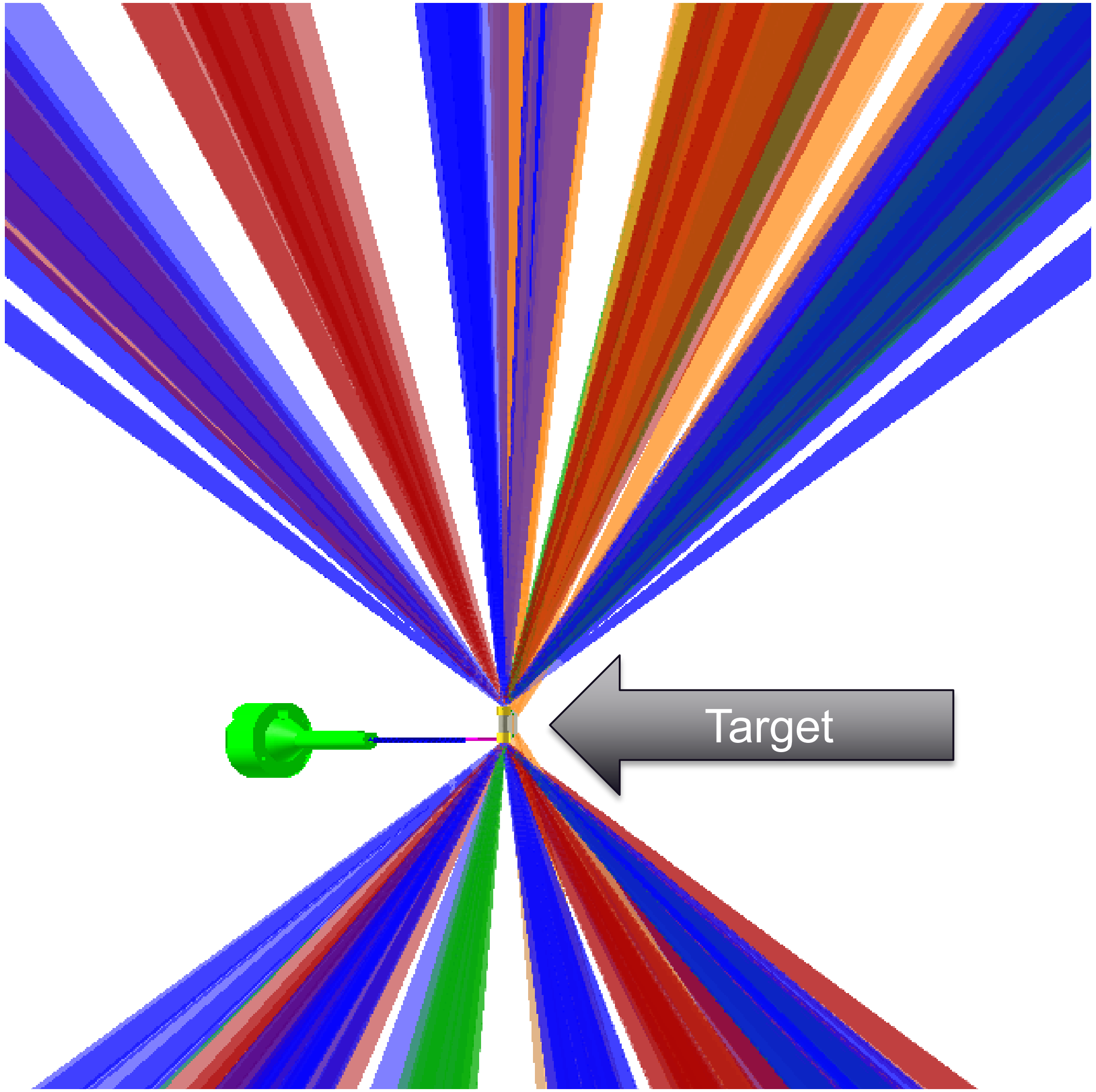
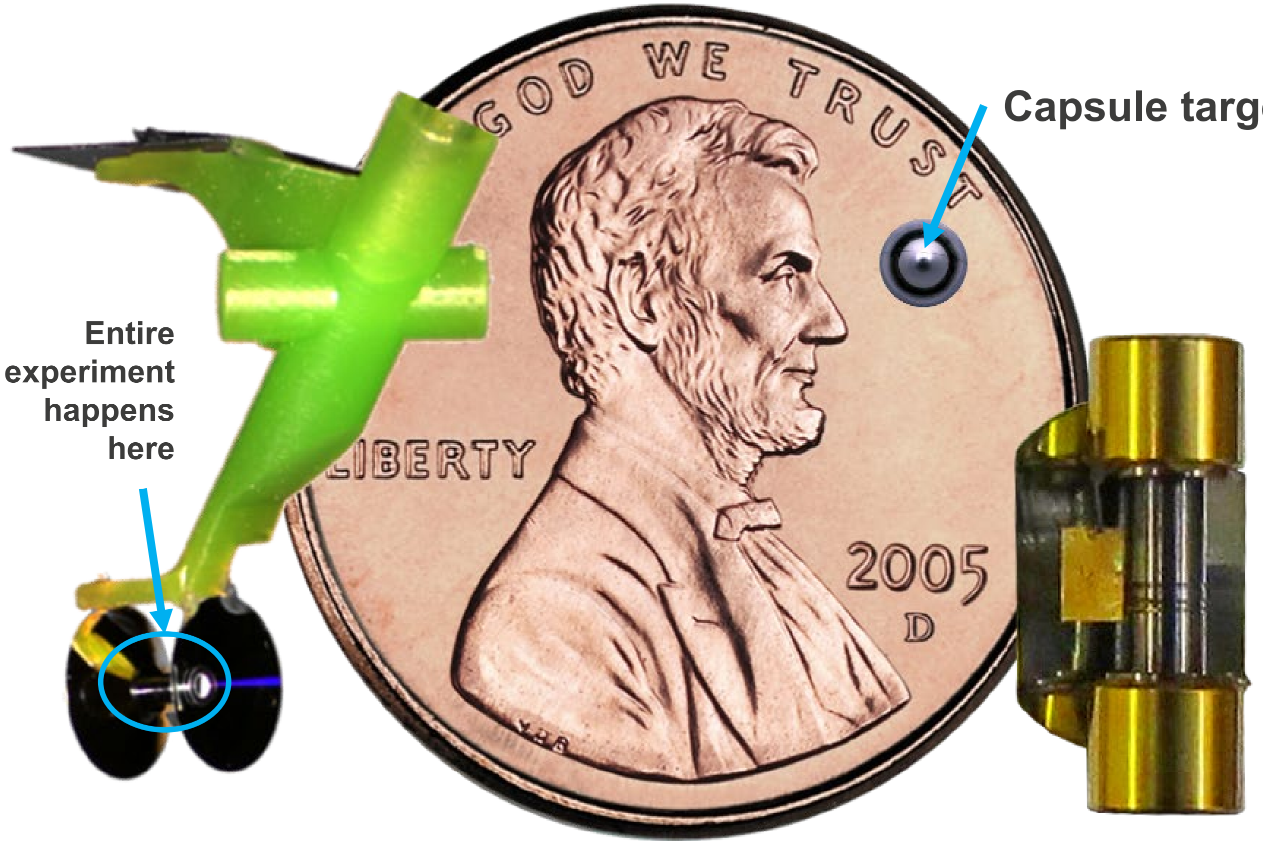


Example targets to scale

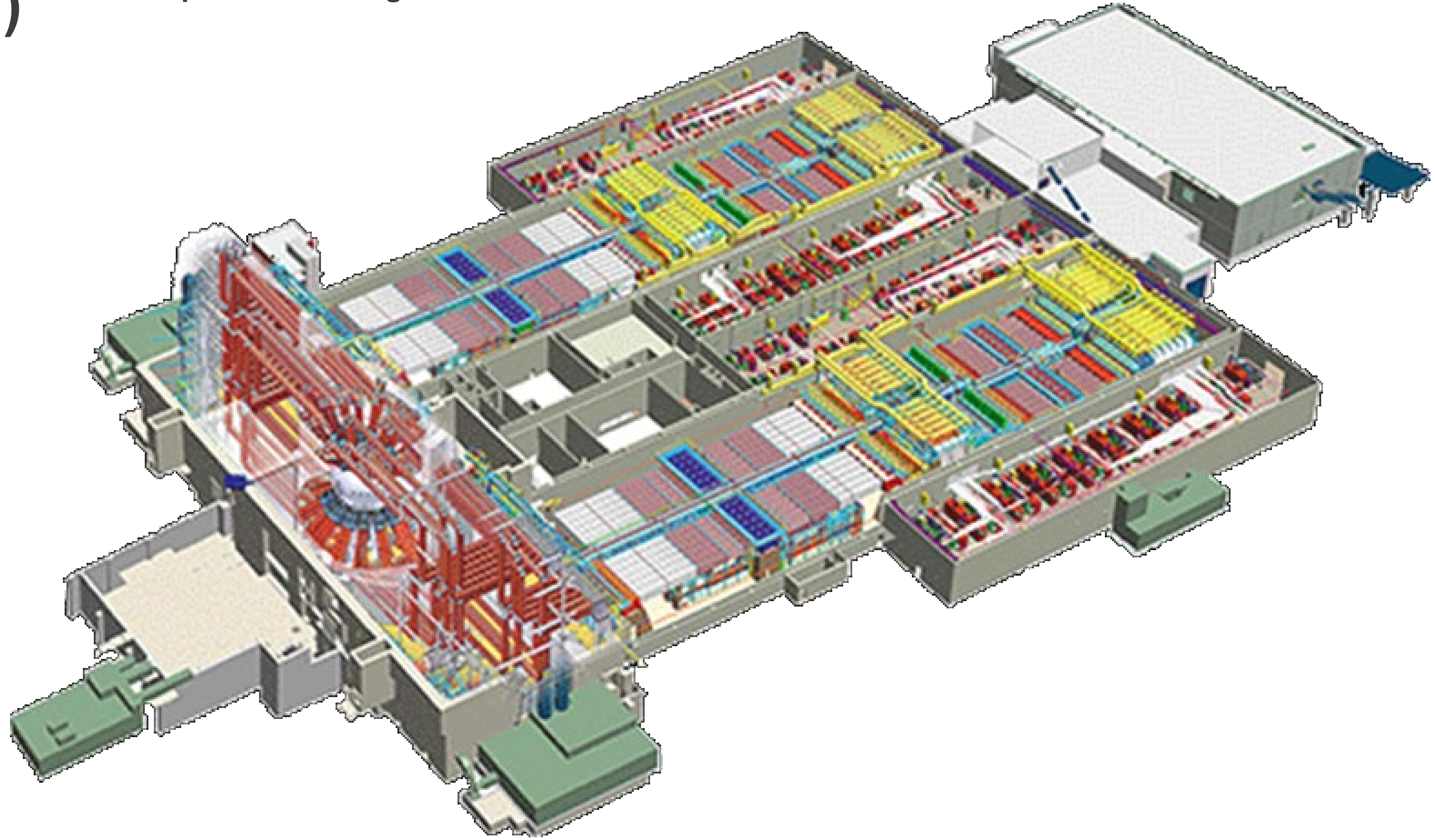


Deposit ~0.01 – 1 MJ into a mm scale target in ~1-10 billionths of a second

Laser light is one of the best ways to get a *large* amount of energy into a *small* system extremely *quickly*

- **National Ignition Facility (NIF)**
  - 192 Beams
  - 2 MJ
  - ~10 ns pulses

https://lasers.llnl.gov/about/what-is-nif



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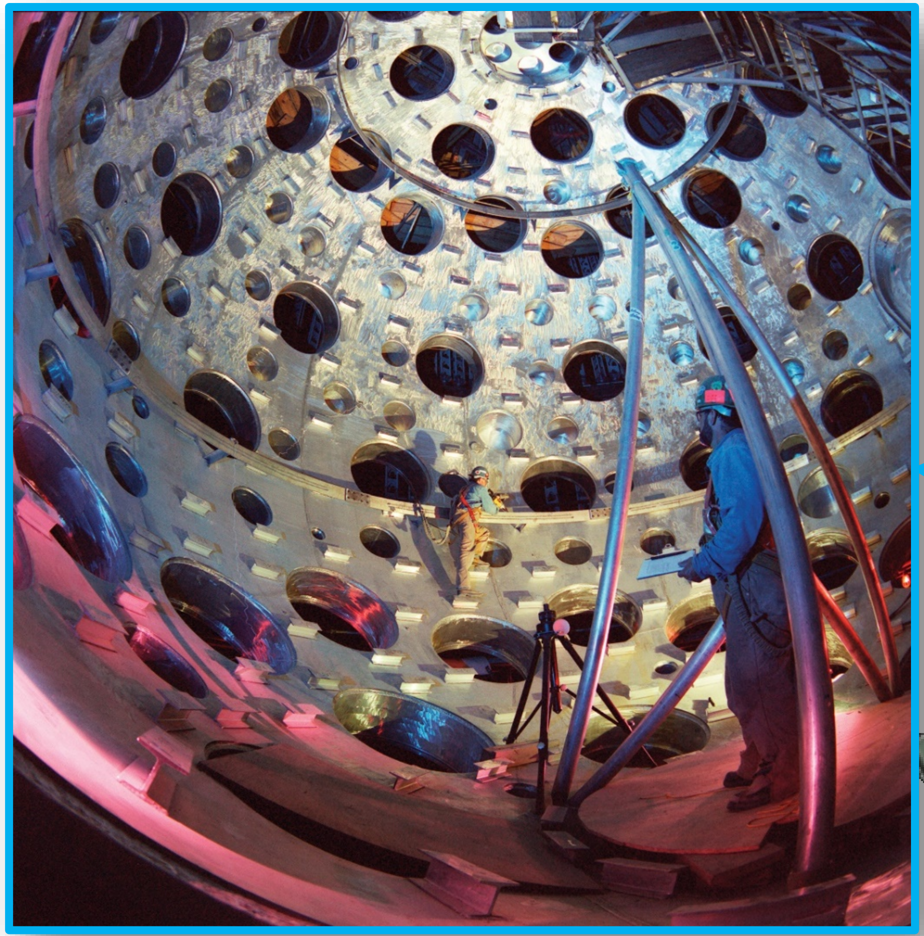

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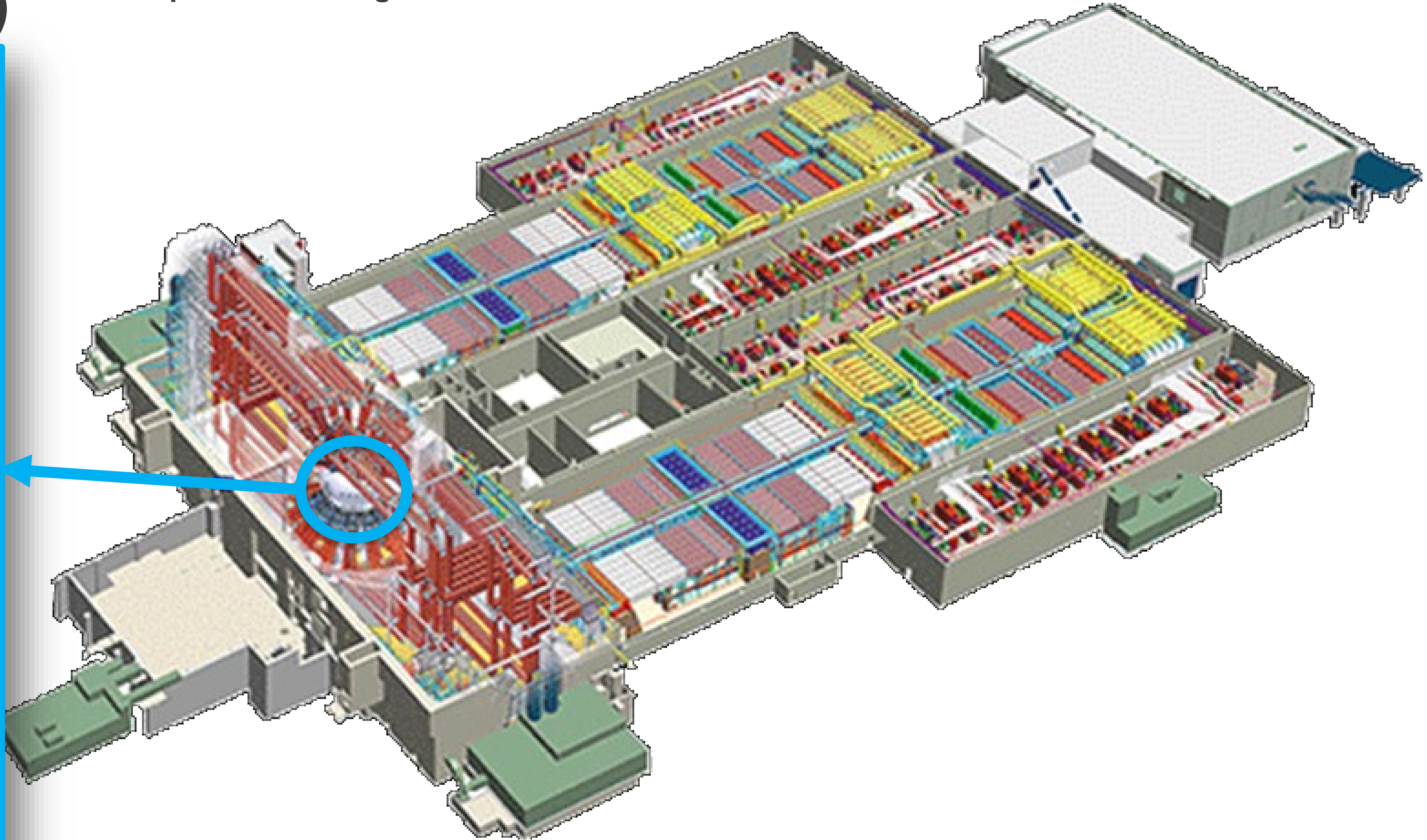

One of the biggest challenges of HED science is how to *make* and *measure* a high energy density system in a lab

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Problem

Add energy → Material heats up → Pressure increases → Material expands → Pressure decreases

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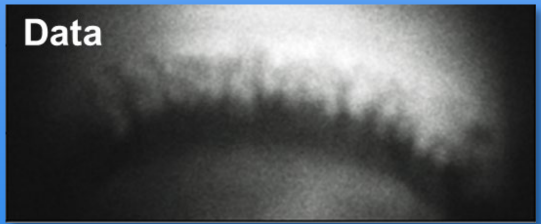
Solution: Measure while the pressure is still high

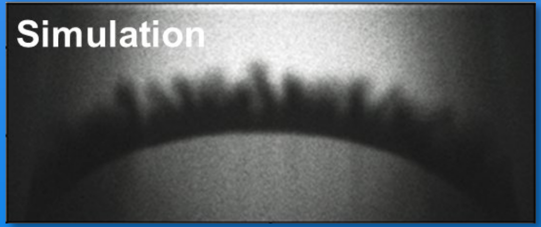
So our diagnostics have to be very fast and applicable to small systems

HED diagnostics overwhelmingly rely on non-intrusive, light- and particle radiation-based measurements

Imaging

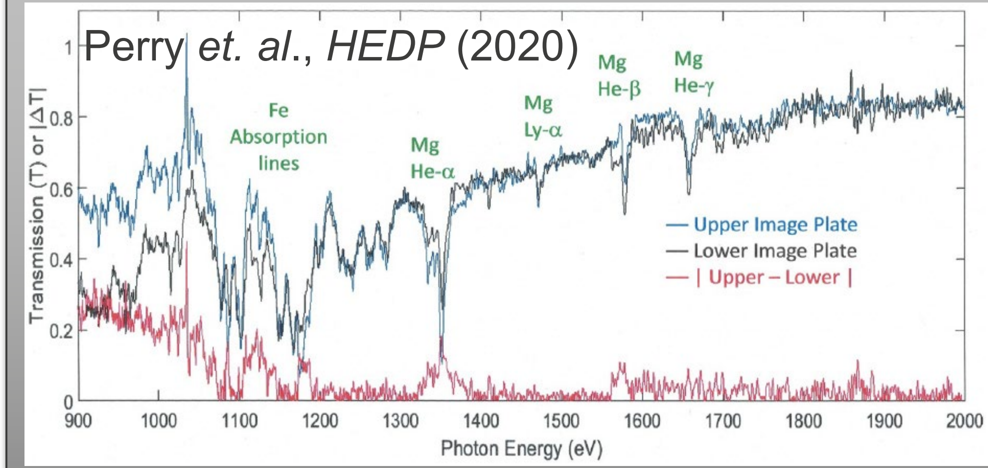
J.P. Sauppe



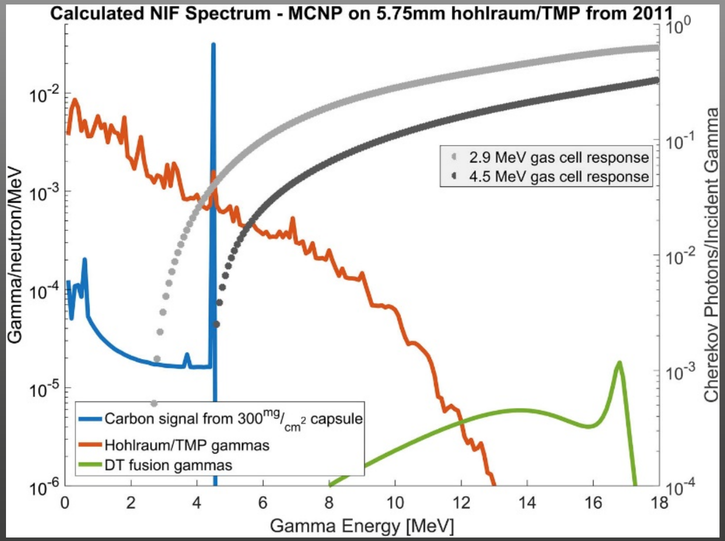


C. Di Stefano & A. Rasmus

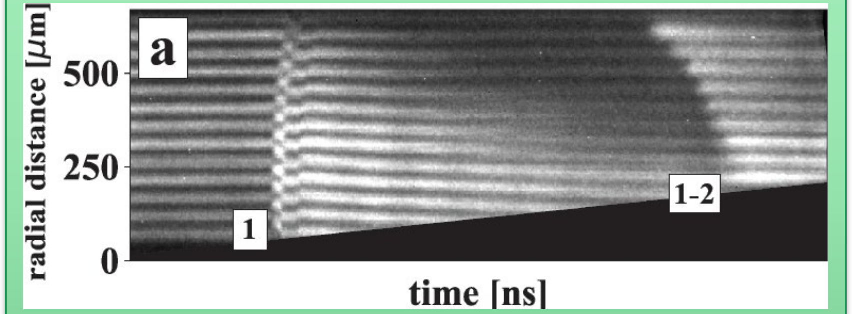
Spectroscopy (EM & particle)

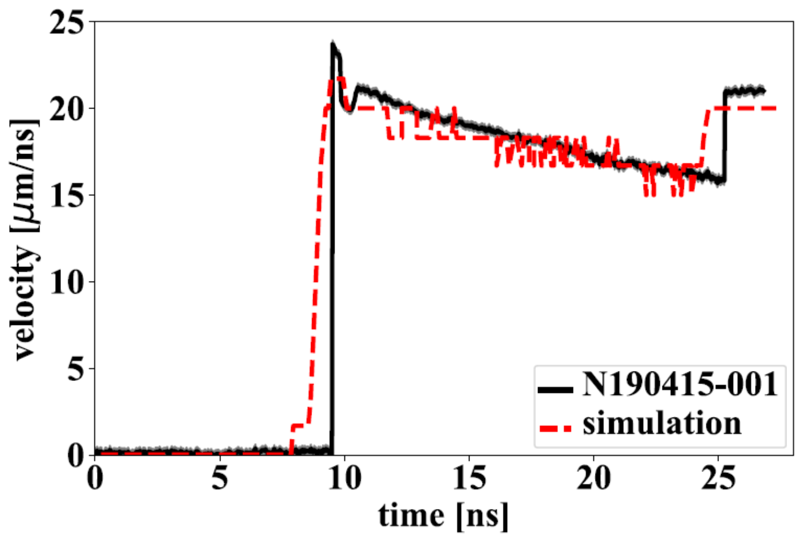


Meaney *et. al.*, *RSI* (2019)



Interferometry





Di Stefano *et. al.*, *in submission to PRE*

Inertial Confinement Fusion

Understanding how matter behaves under 'extreme' conditions may help us answer long-standing science questions

Some examples:

- Why do supernovae explode and not just become black holes?
  - What kind of elements should a supernova produce? And how much?

- Is a planetary core a solid or a liquid or something else?
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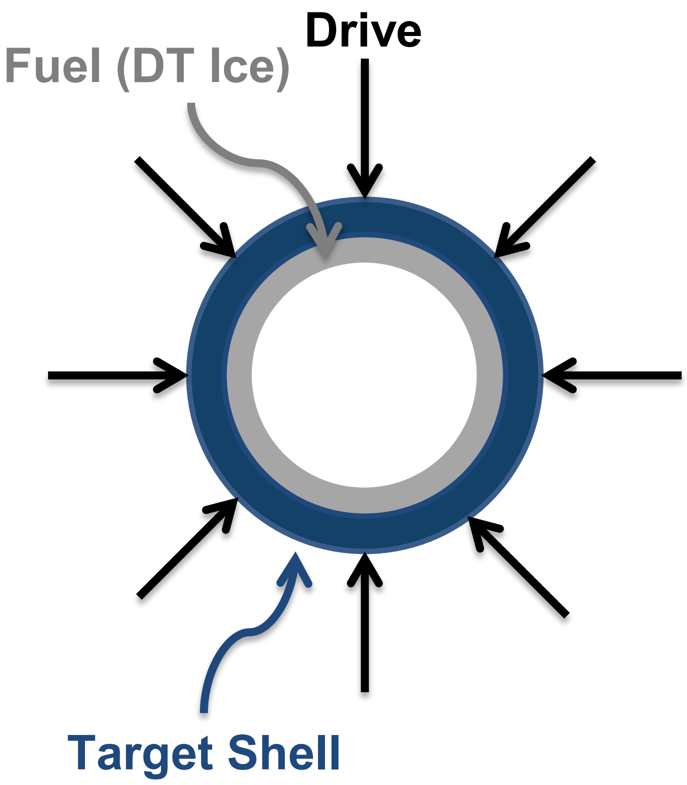
- **Can we create a human-made power source than uses nuclear fusion similar to stars?**

Inertial Confinement Fusion (ICF) to generate fusion energy is a main focus of HED work at LANL and other DOE laboratories

ICF is method which attempts to compress a hydrogen (DT) fuel target to (sun-like) fusion conditions using inertia



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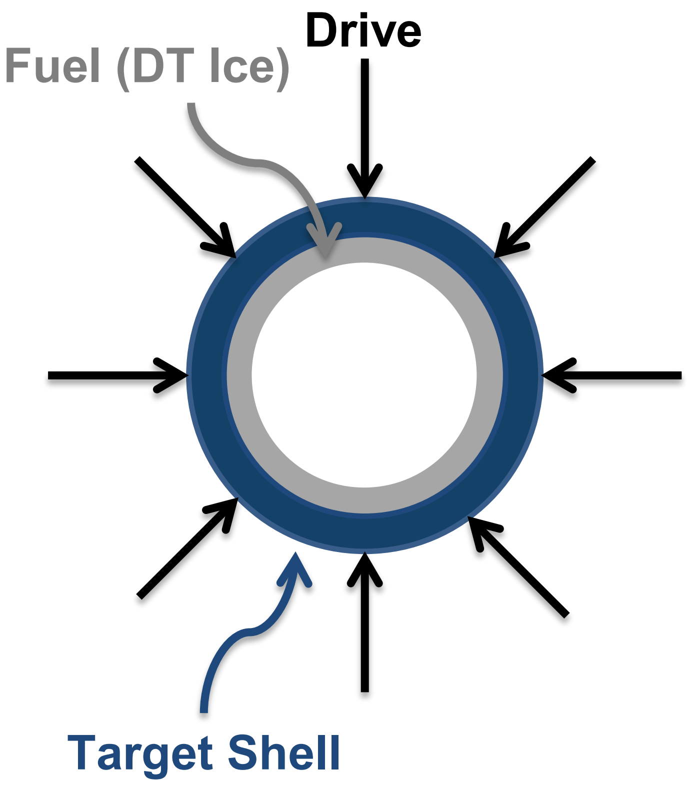

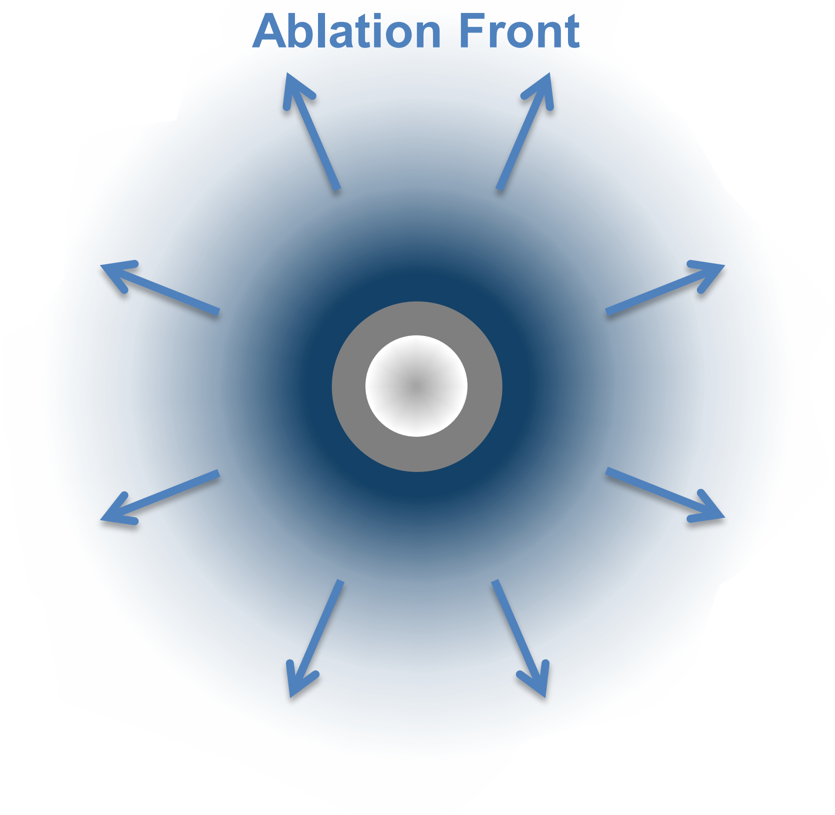

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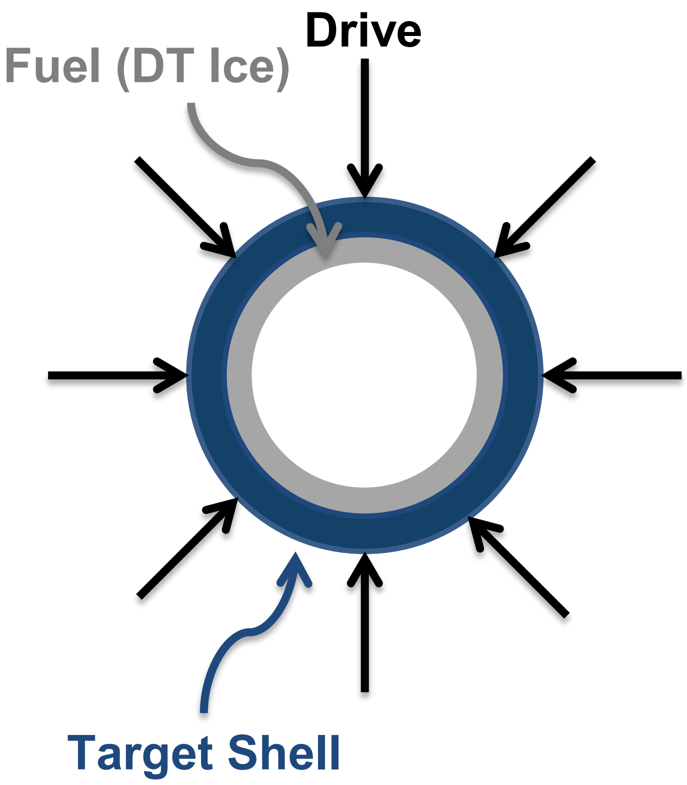

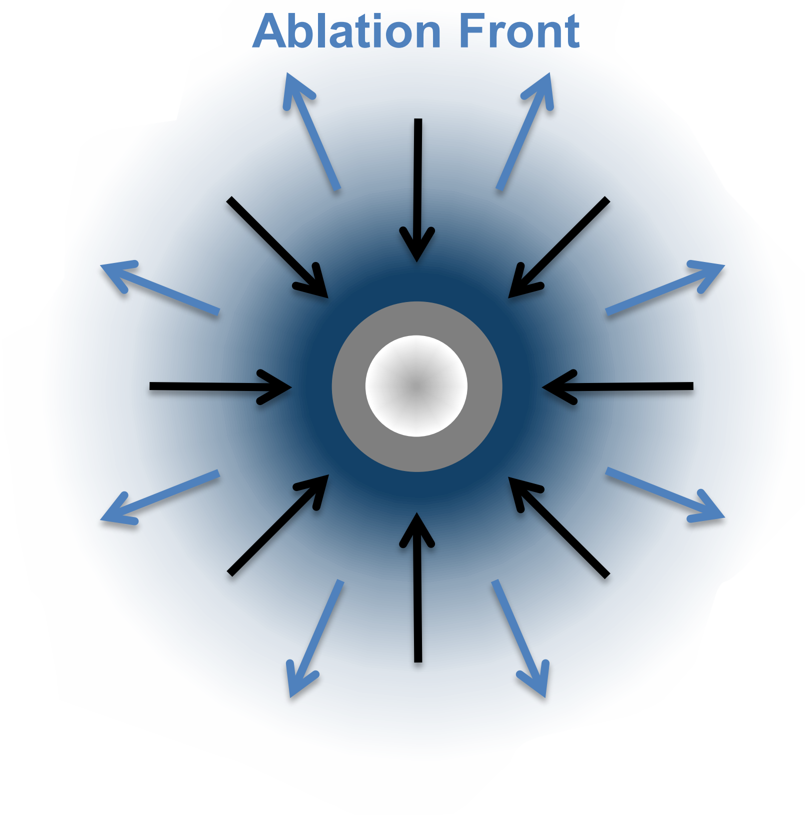

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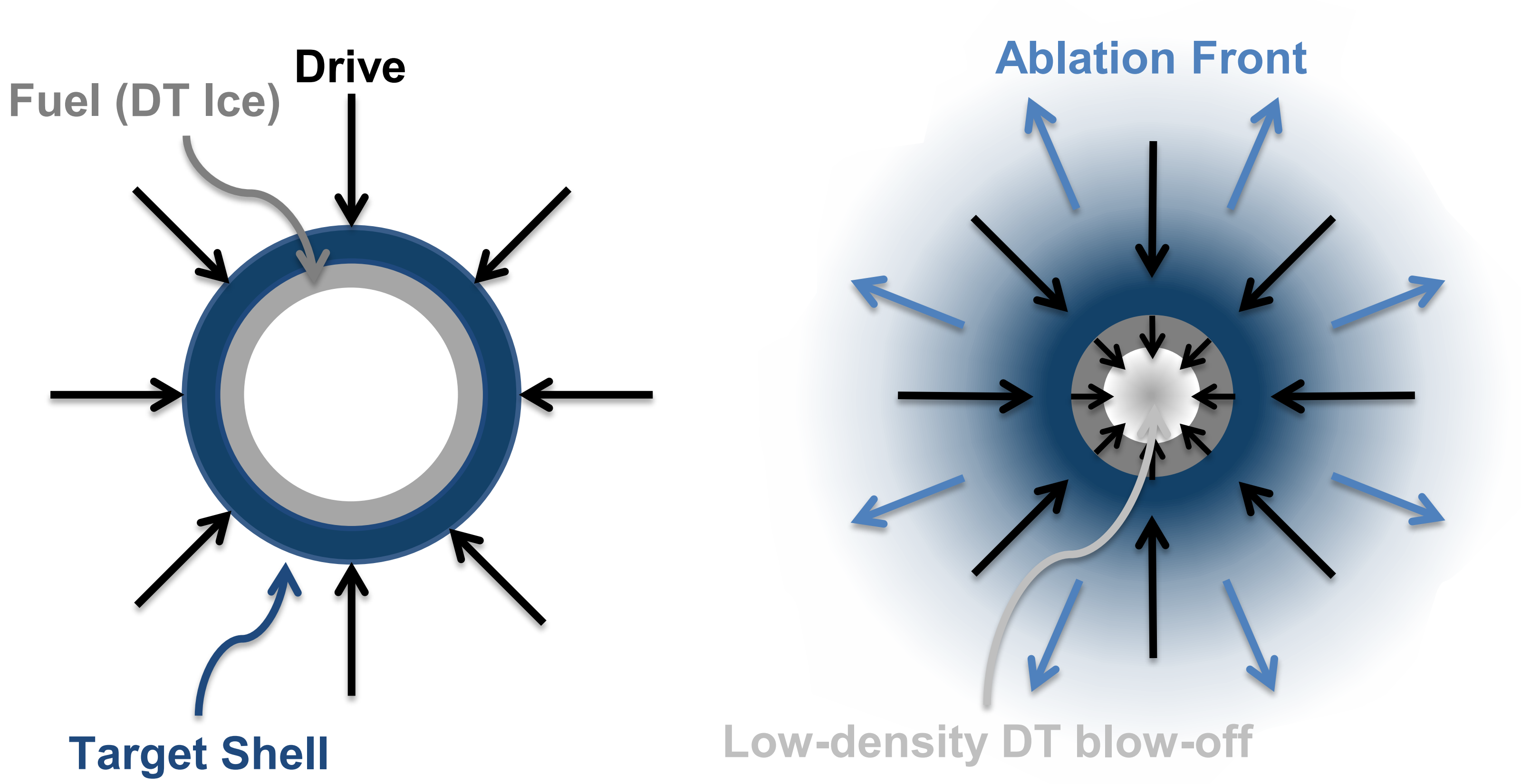

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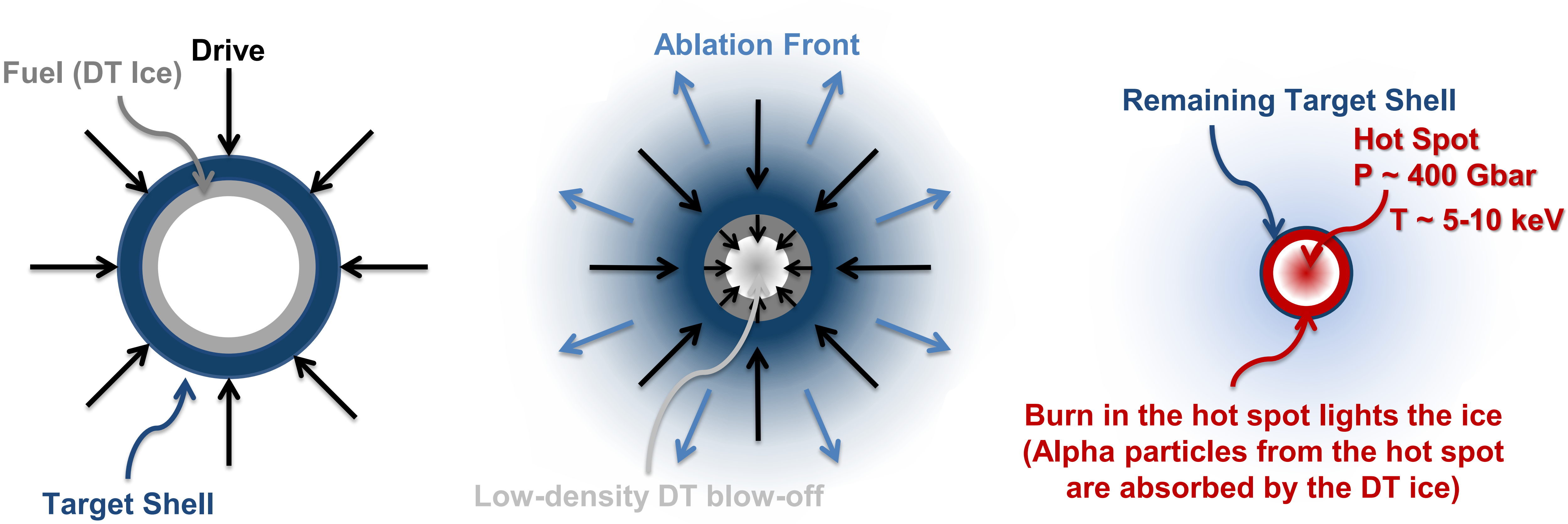
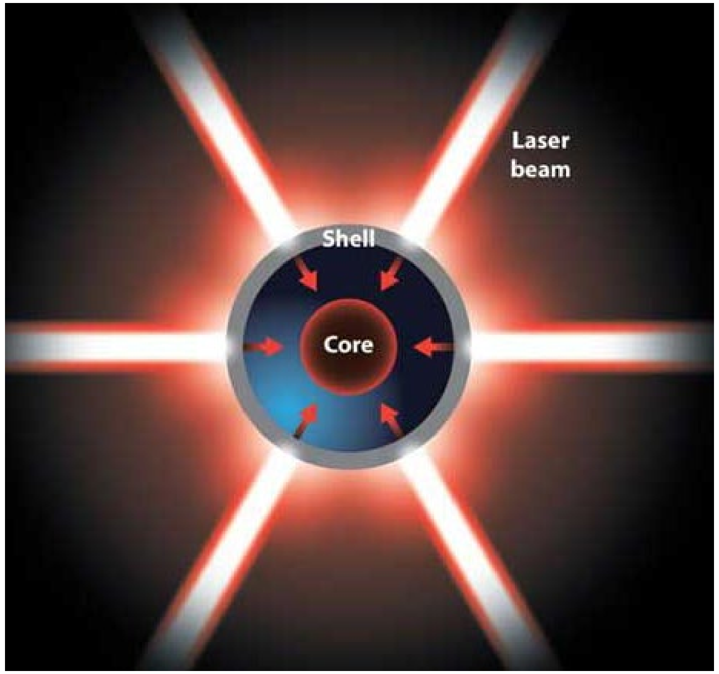


Not to scale. Real CR ~ 40

There are multiple ways to drive implosions, each with their own strengths and weaknesses

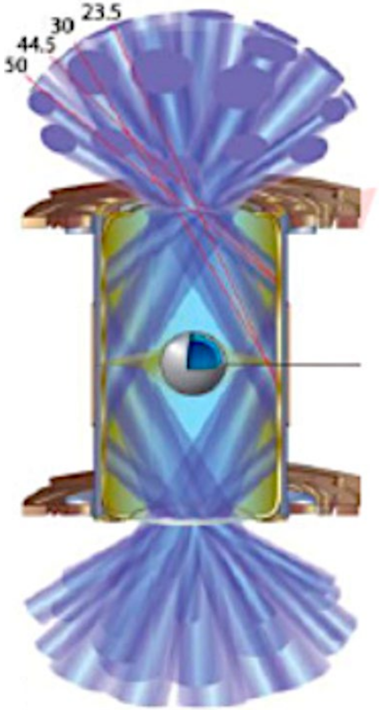
Direct Drive

https://phys.org/news/2016-09-direct-drive-fusion.html



- Efficient energy coupling
- Potential beam spot imprinting can seed instabilities

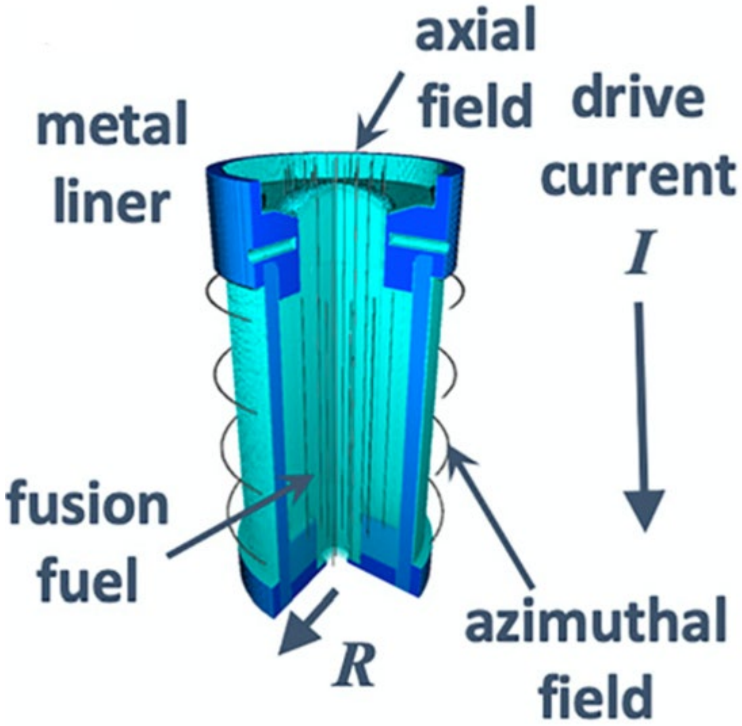
In-direct drive



- Lower energy coupling
- Smoother drive profile seeds fewer instabilities

Magnetized-Liner (MagLIF)

https://www.sandia.gov/Pulsed-Power/res-areas/inertial_confinement/



- Current drive instead of lasers
- Cylindrical instead of spherical

https://iopscience.iop.org/article/10.1088/1741-4326/ab1ecf

ICF, Supernovae, and Hydrodynamic instabilities

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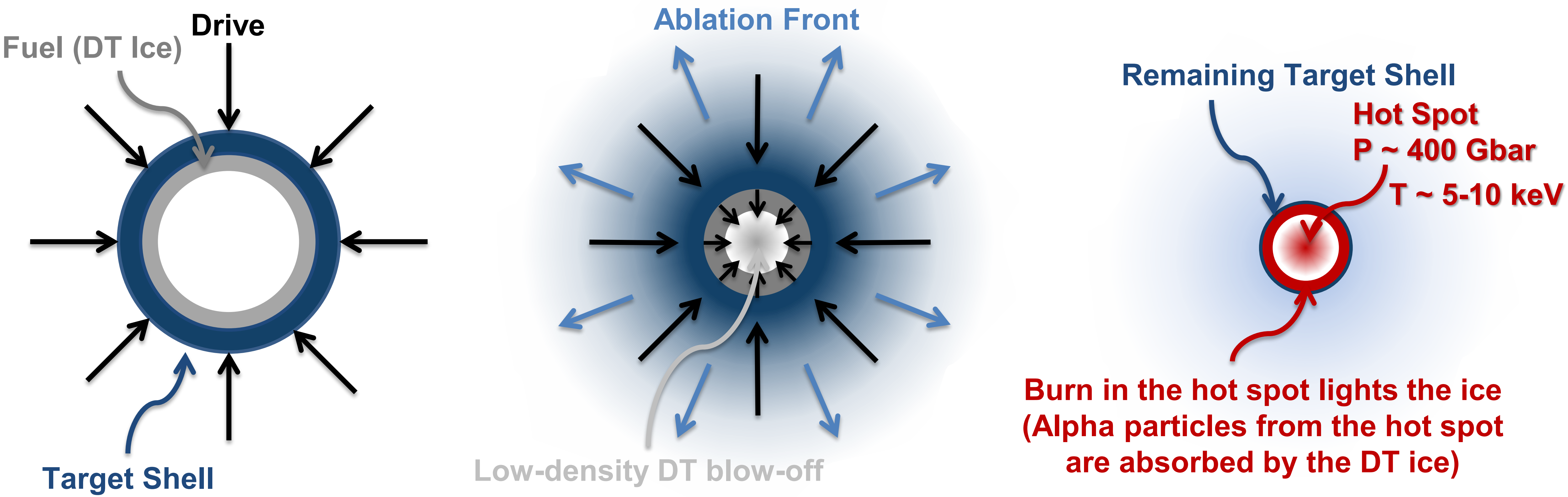
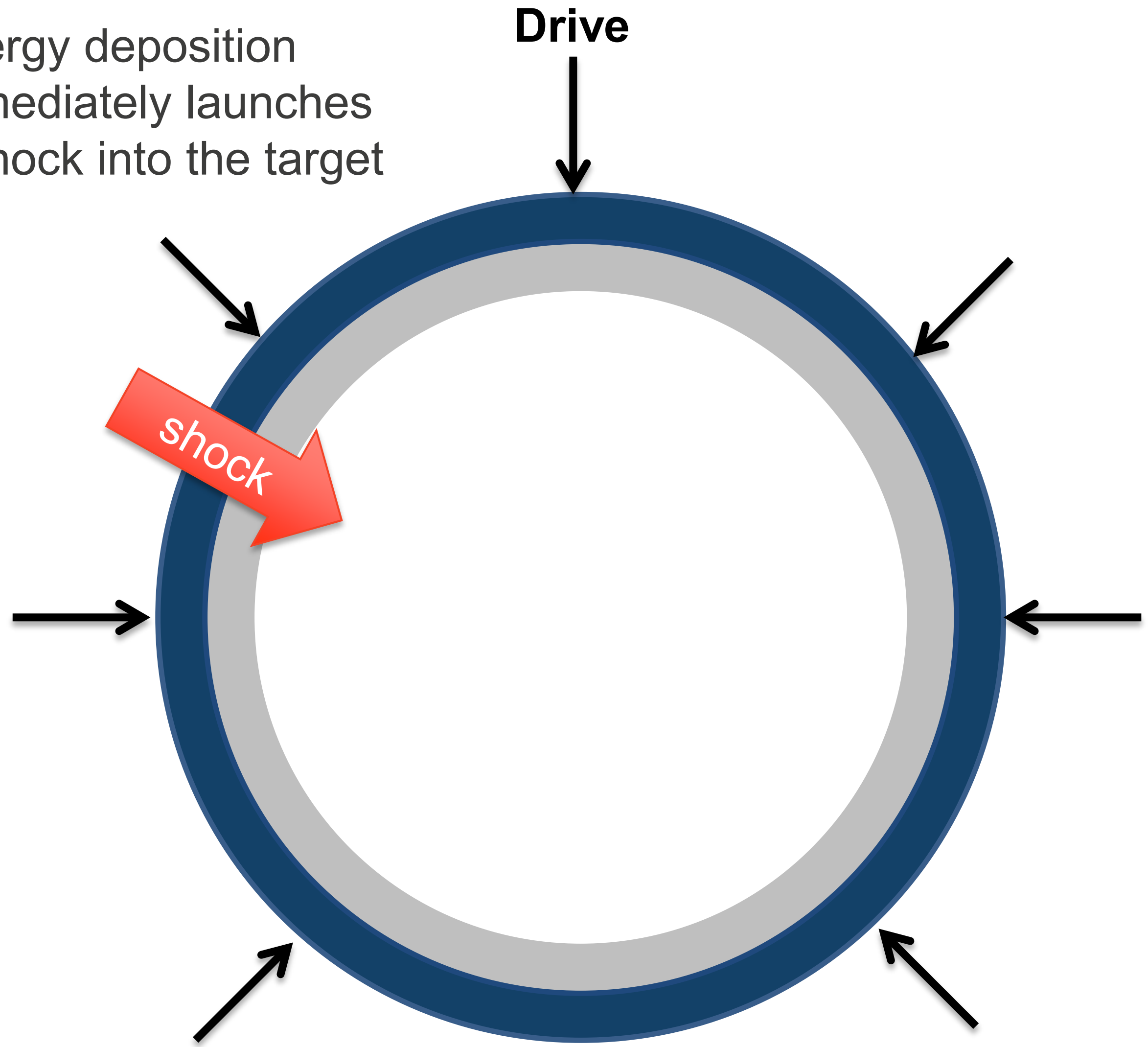


This is ideally how the process should work, but…

… real ICF systems aren't that simple

Energy deposition immediately launches a shock into the target



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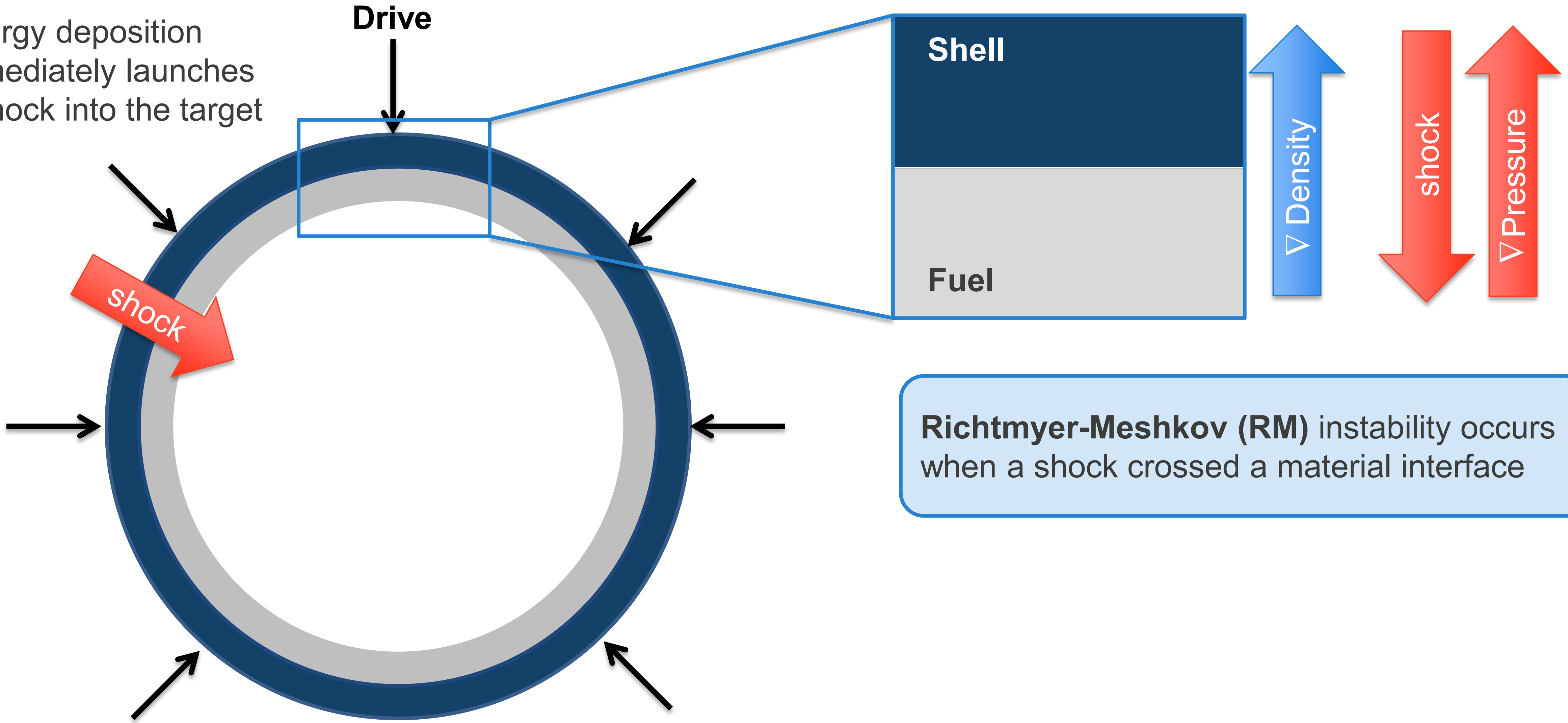

Richtmyer-Meshkov (RM) instability occurs when a shock crossed a material interface

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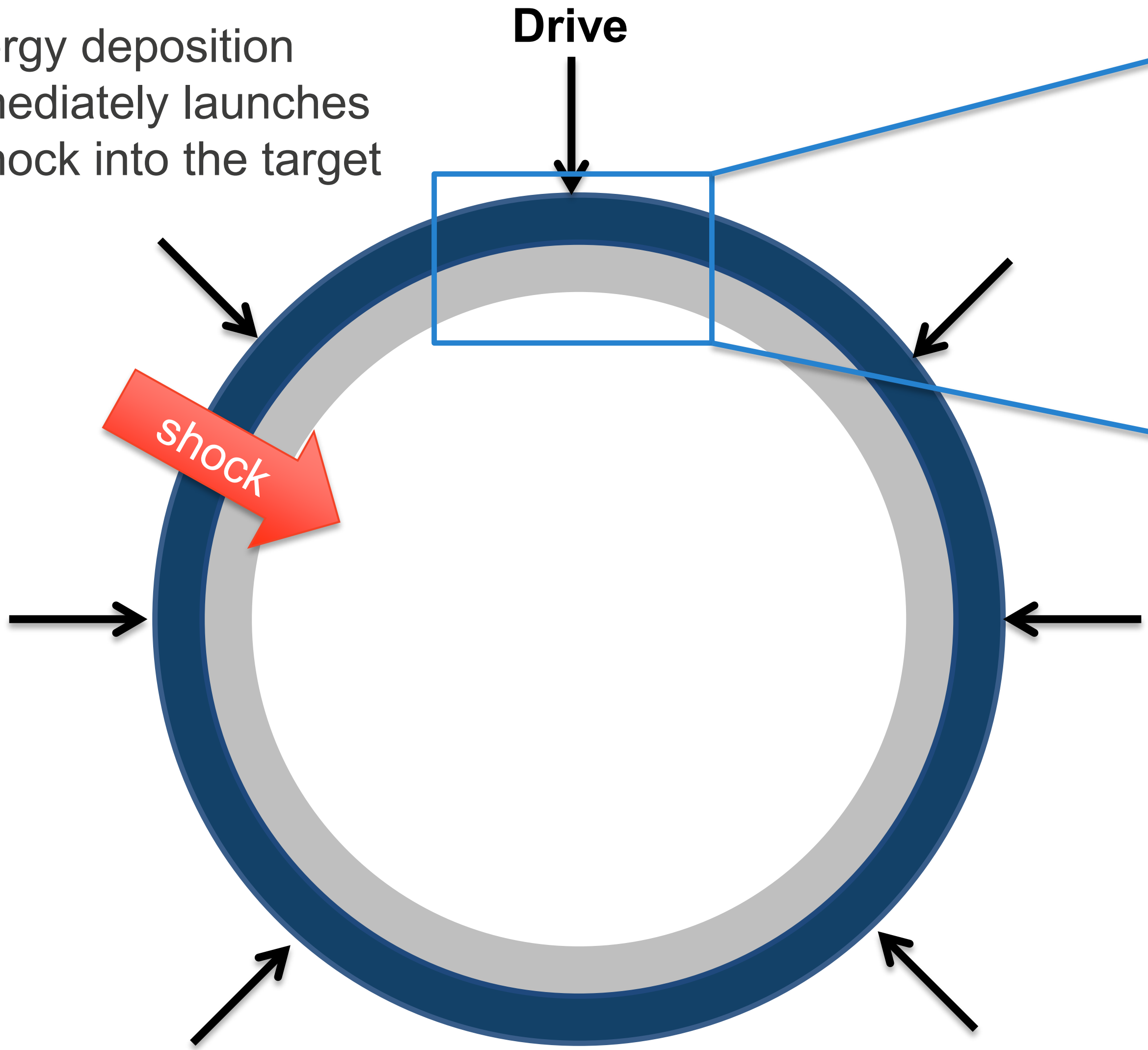

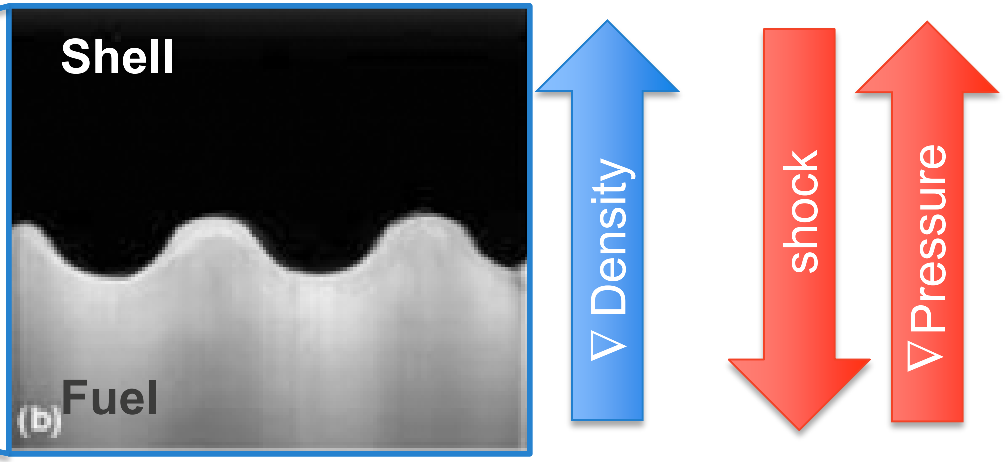

Niederhaus and Jacobs (2003), J. Fluid Mech.

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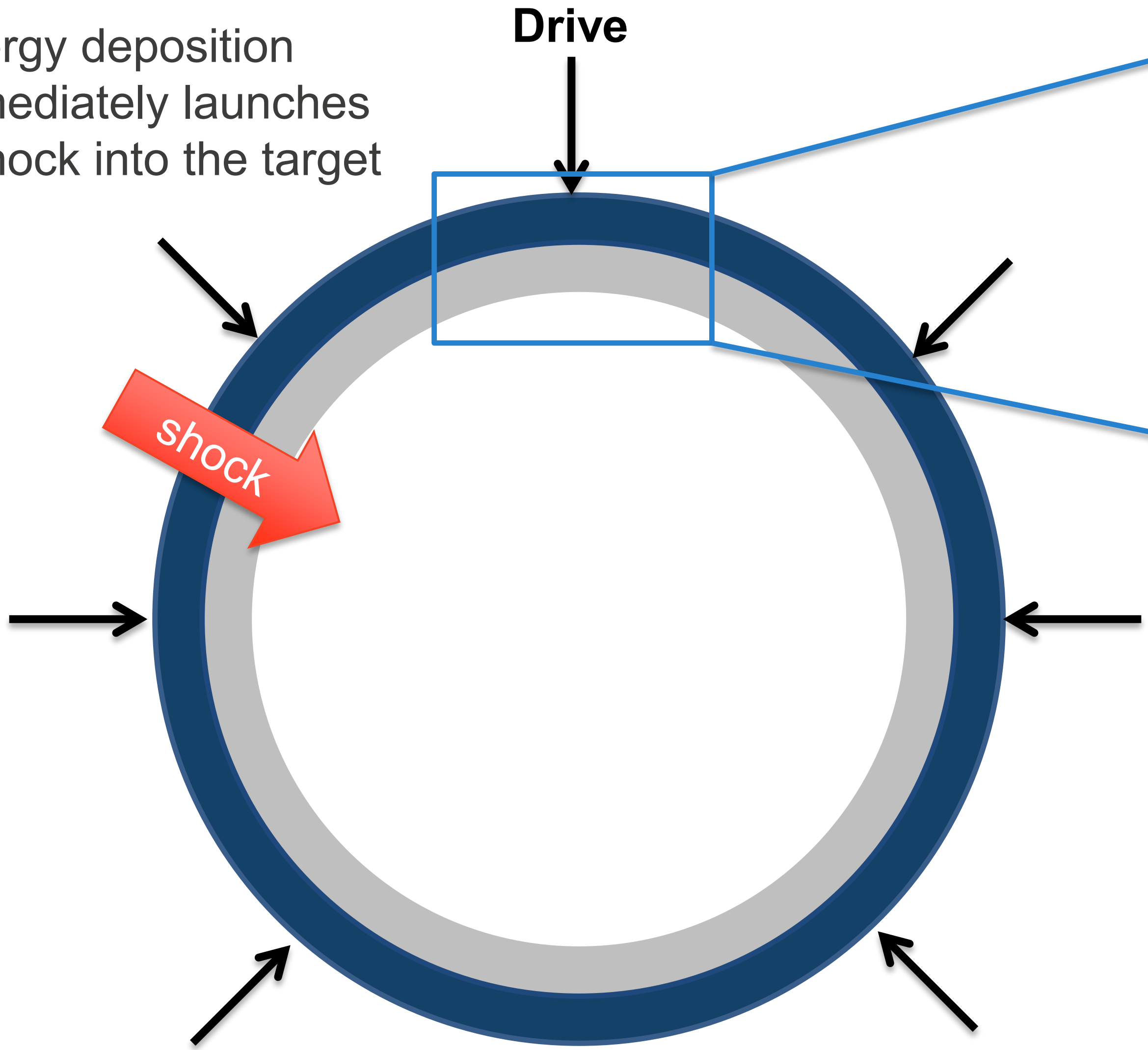

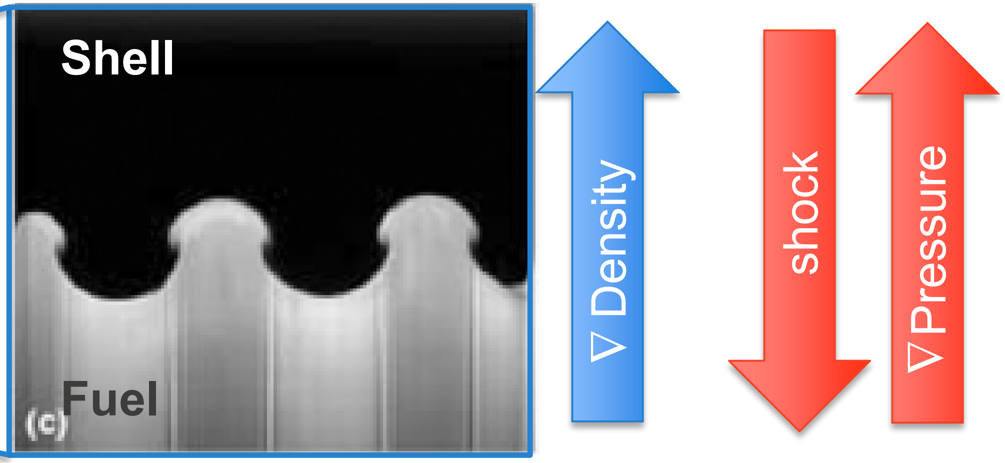

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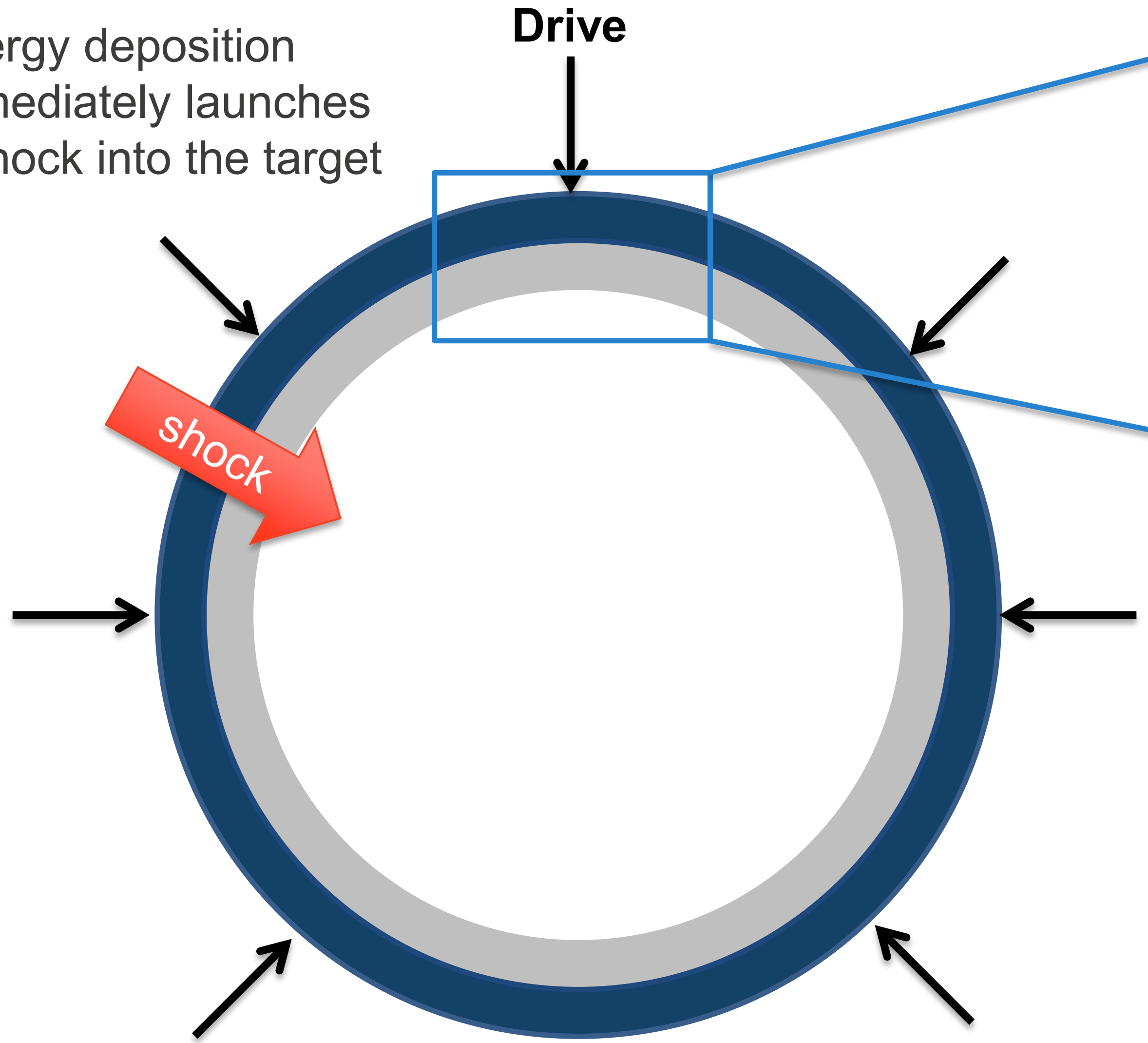

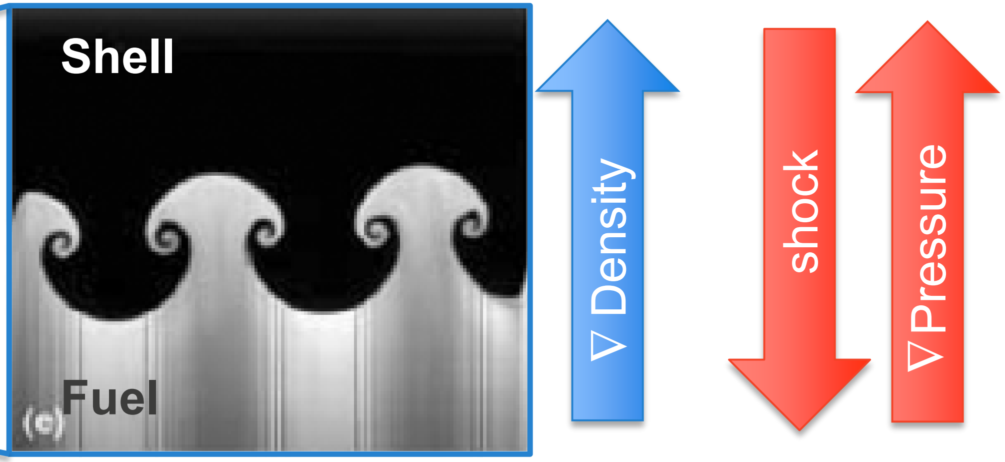

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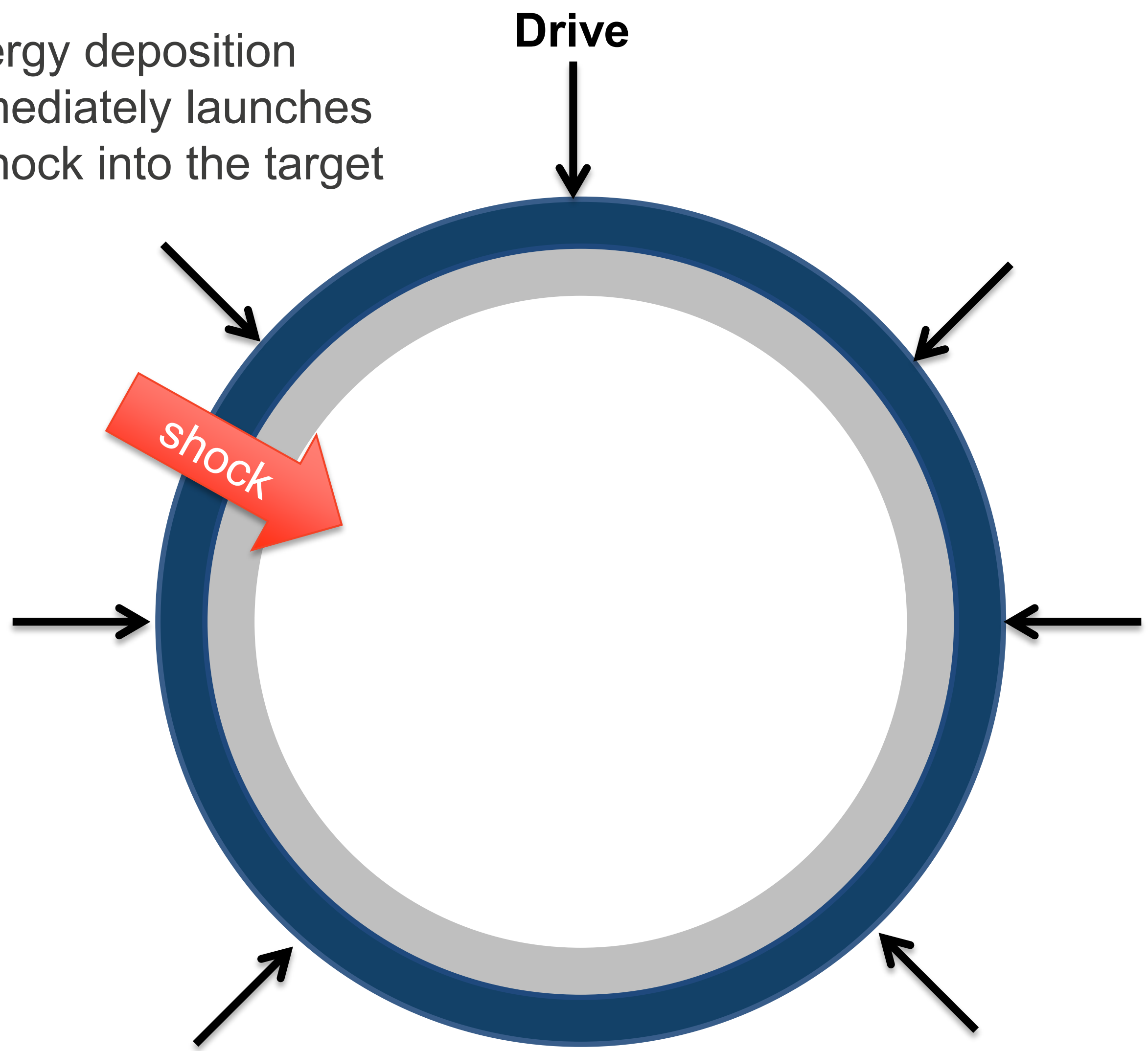
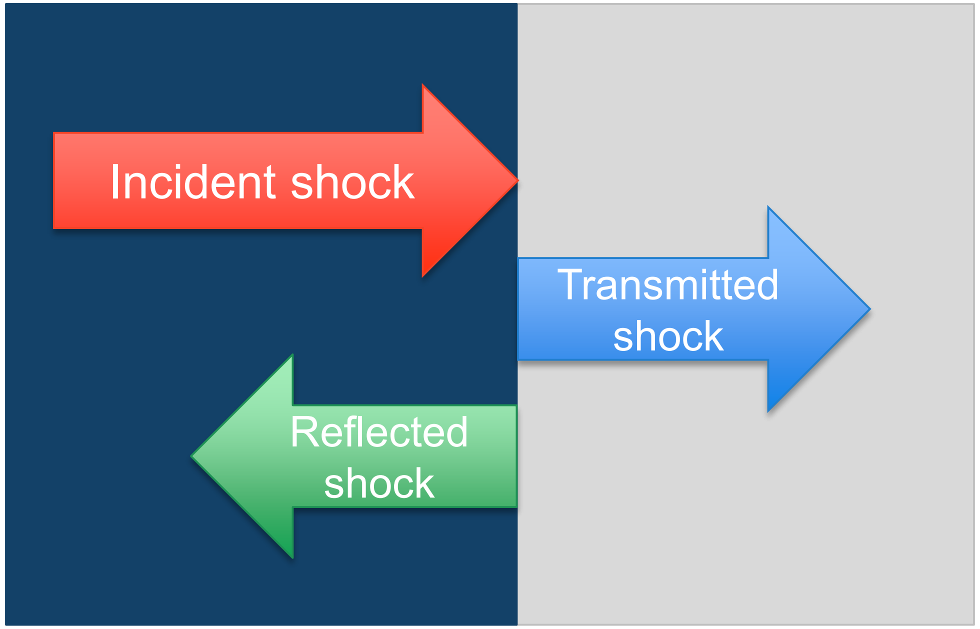


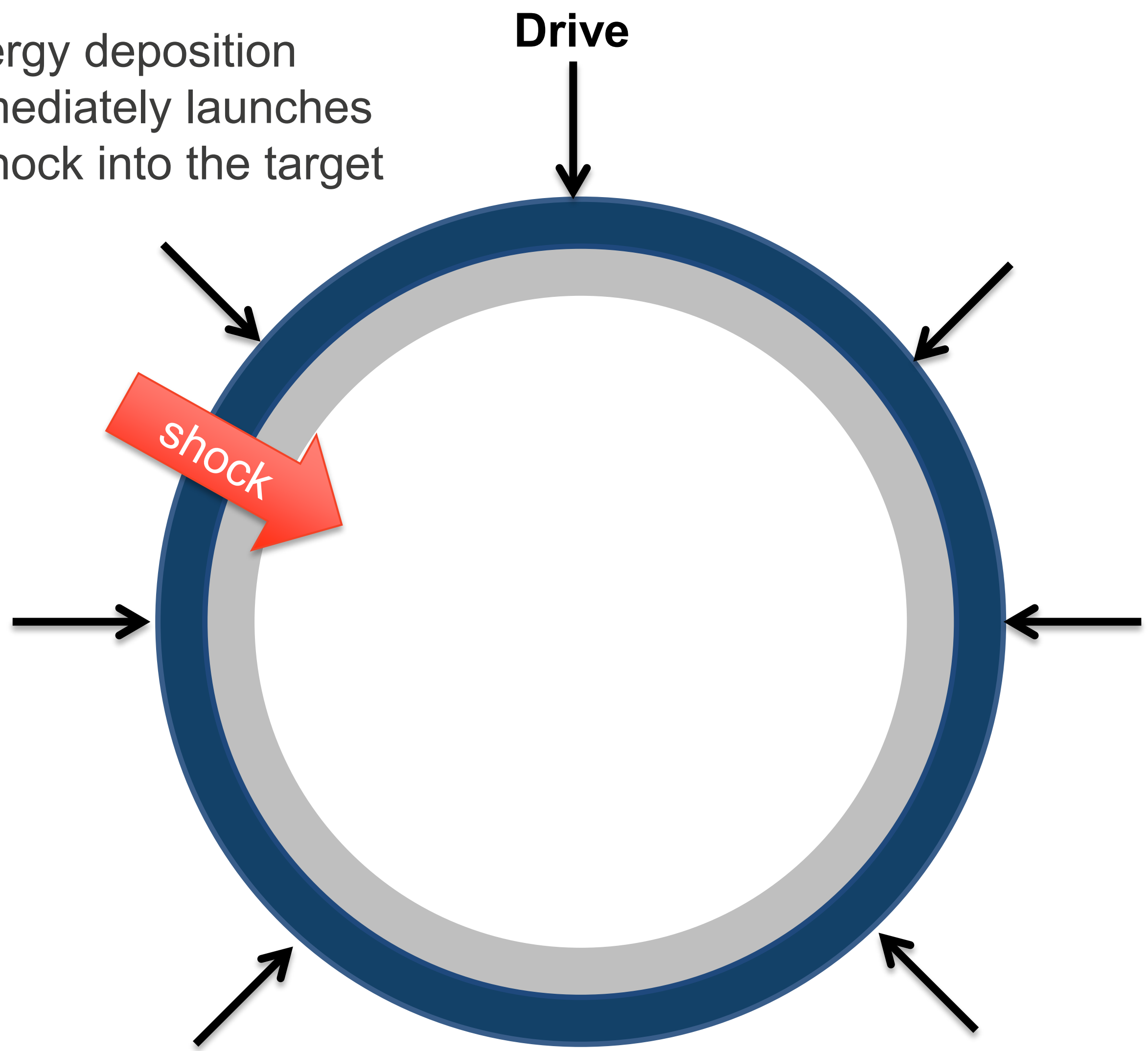
Shocks across boundaries also give rise to more shocks



…so every one of these systems is a multi-shock system

… real ICF systems aren't that simple

Energy deposition immediately launches a shock into the target



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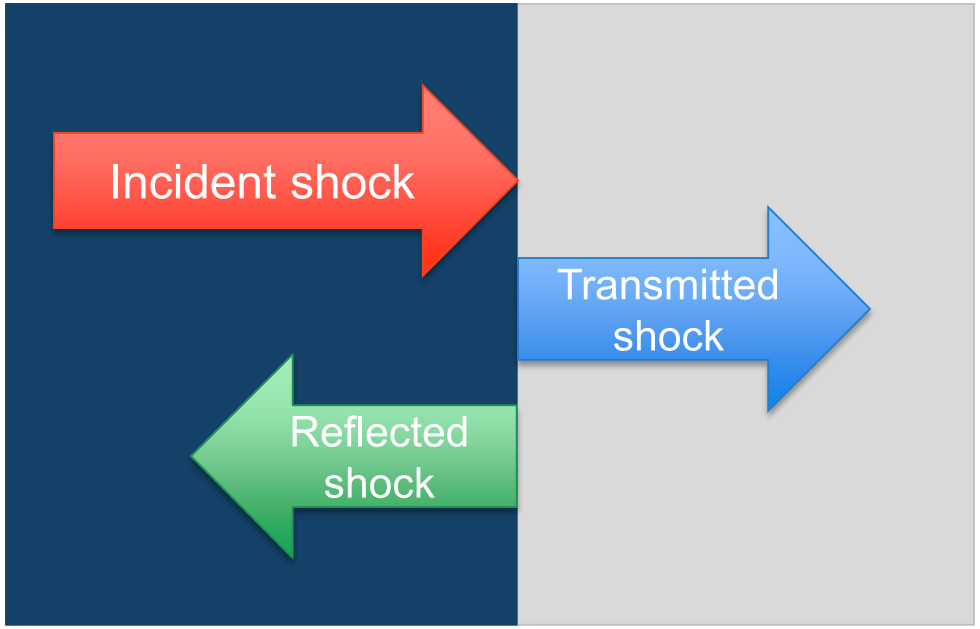
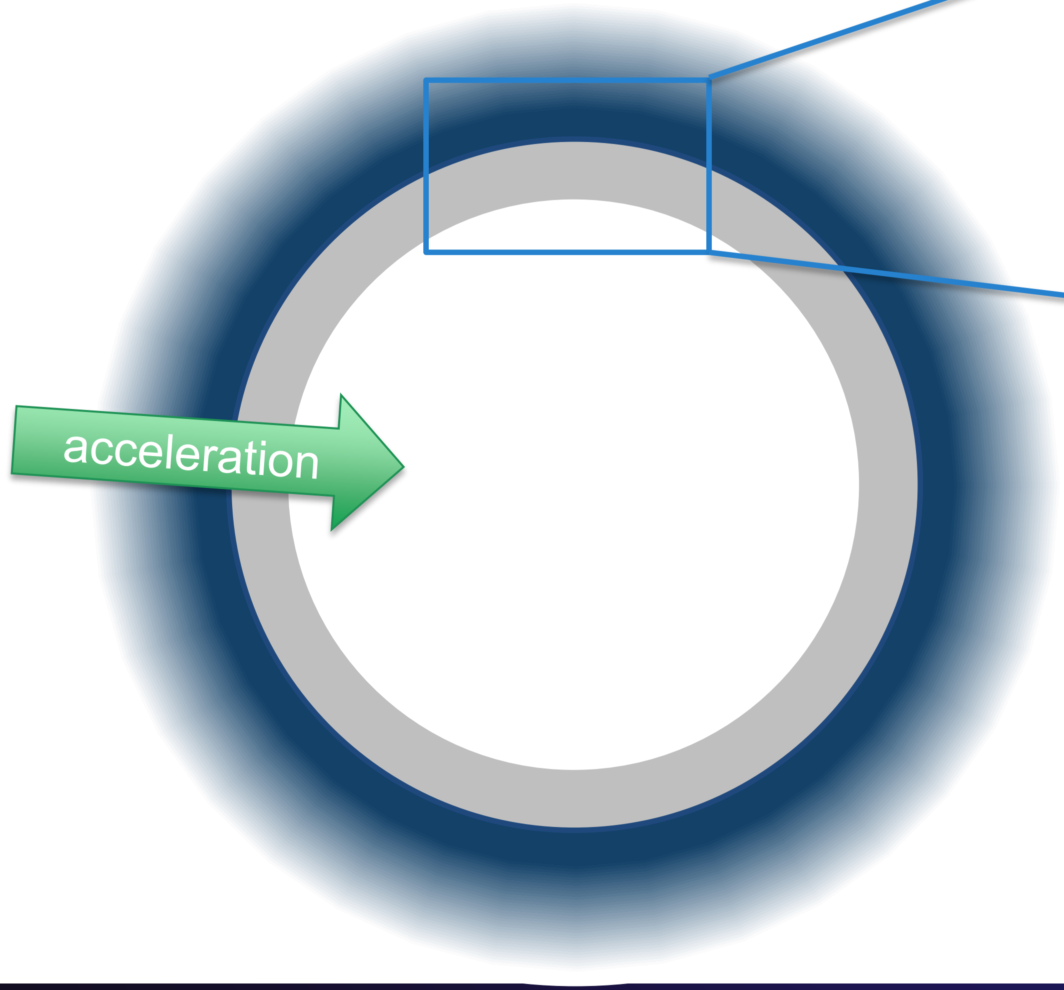


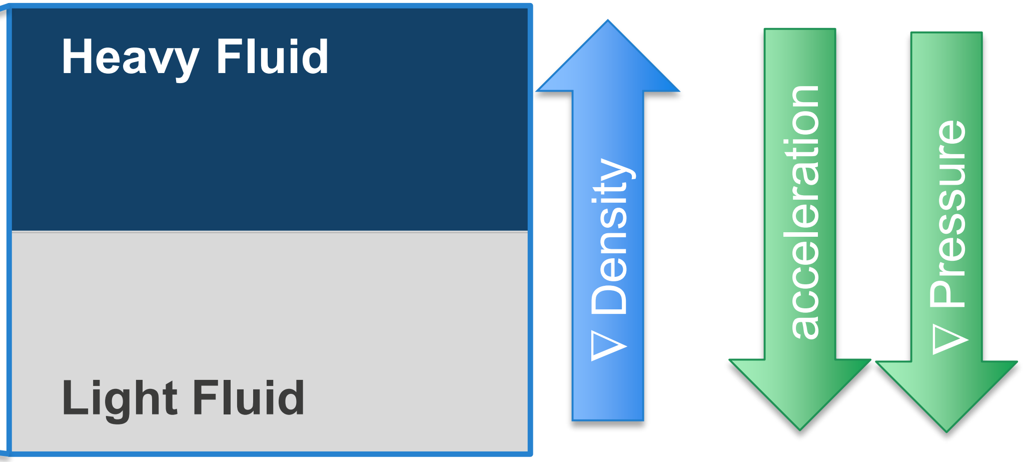
…so every one of these systems is a multi-shock system

And many ICF systems deliberately use more than one shock to drive the implosions

… real ICF systems aren't that simple

When the shell begins to move, we are pushing heavy material against lighter material





Rayleigh-Taylor (RT) instability occurs when a heavy fluid is accelerated against a lighter fluid

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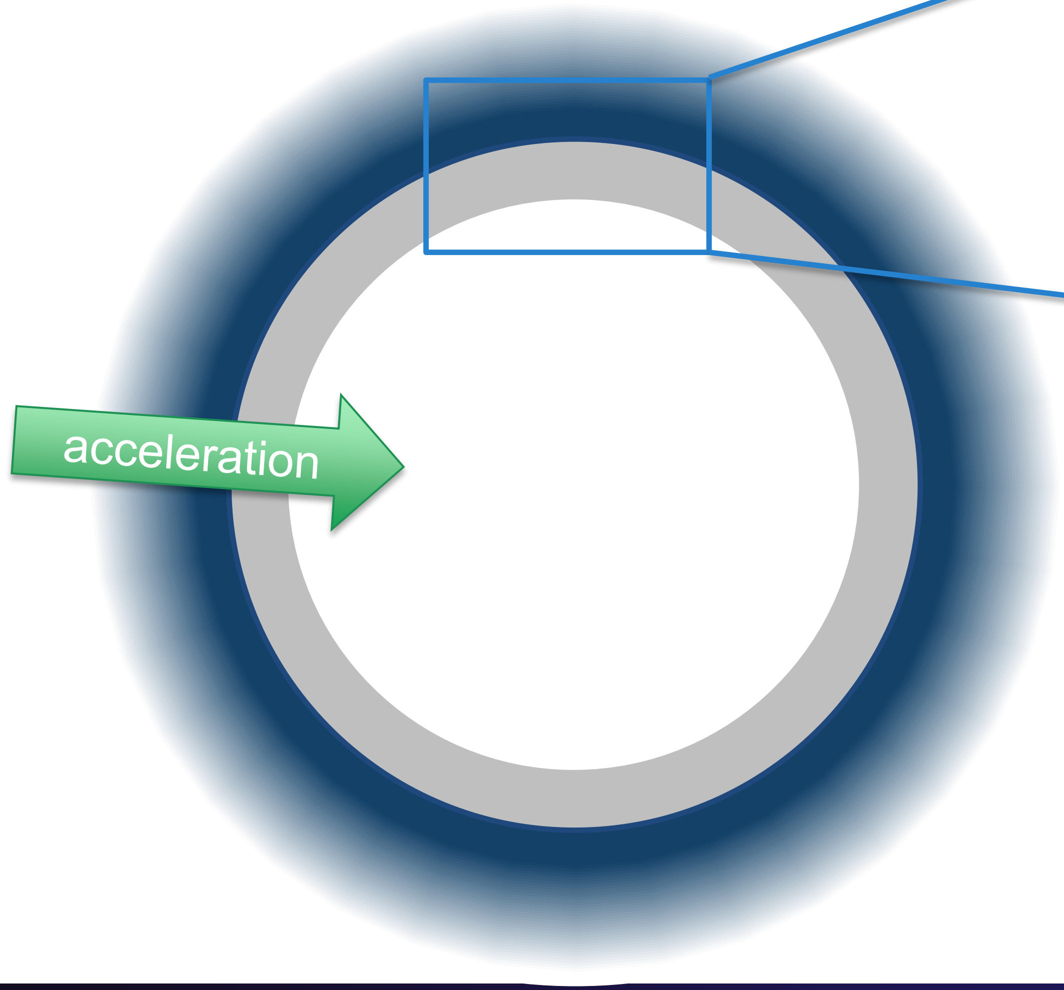
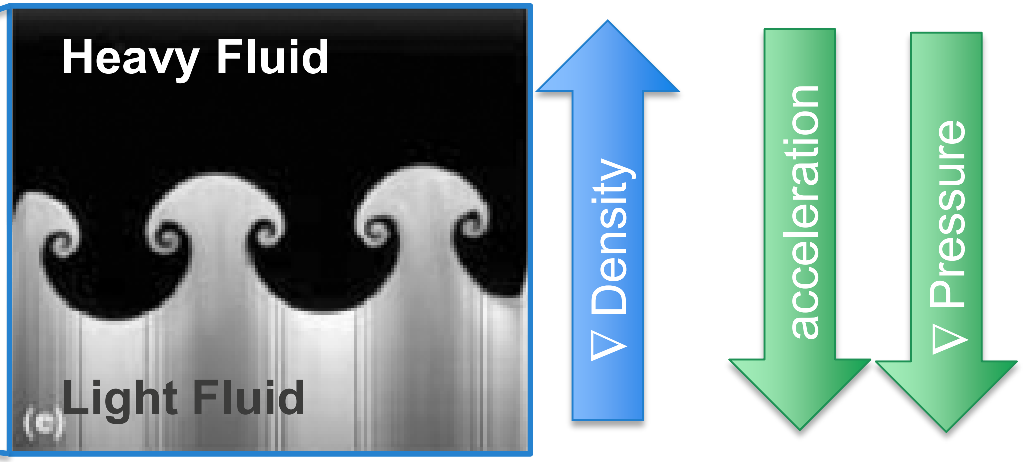
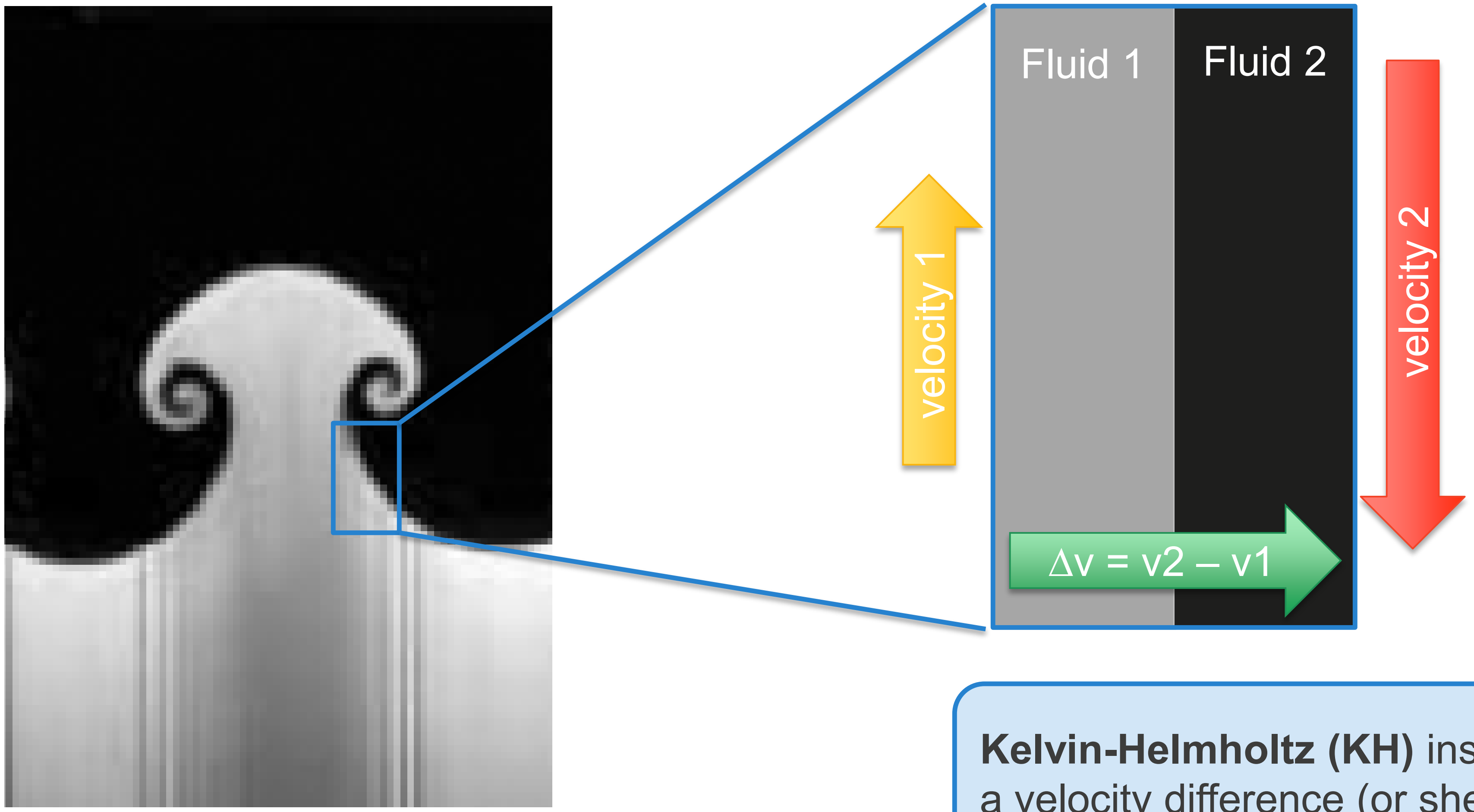




Rayleigh-Taylor (RT) instability occurs when a heavy fluid is accelerated against a lighter fluid

RT structures have the same form as RM structures

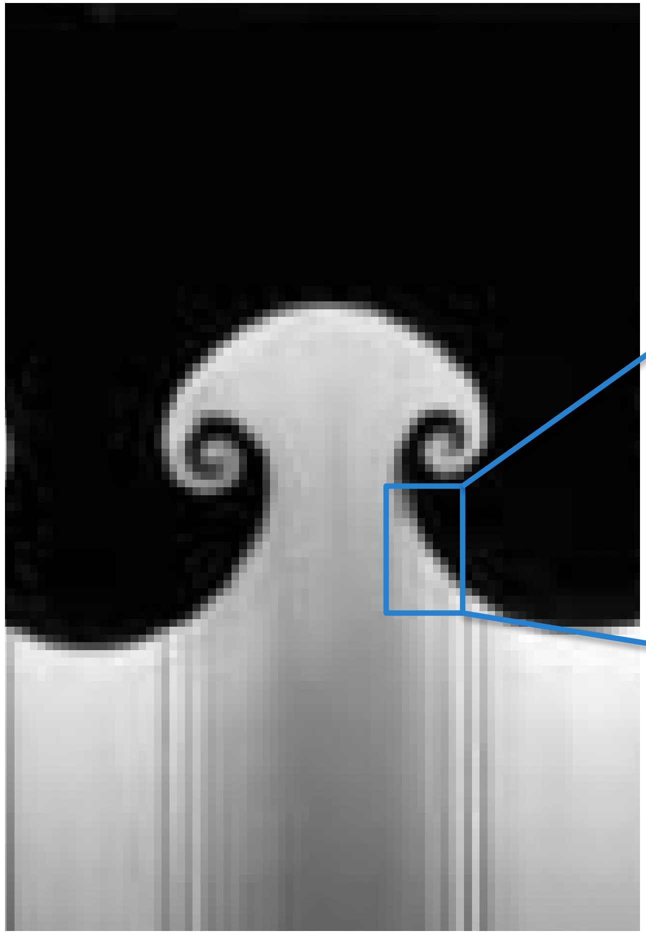
RM & RT structures can generate strong shear flows



Kelvin-Helmholtz (KH) instability occurs when there is a velocity difference (or shear) between two fluids

… real ICF systems aren't that simple

RM & RT structures can generate strong shear flows



Kelvin-Helmholtz (KH) instability occurs when there is a velocity difference (or shear) between two fluids

Hydrodynamic instabilities are a significant degradation mechanism in Inertial Confinement Fusion

ICF implosions are susceptible to instability formation at interfaces and target fabrication artifacts

- Different target layer densities
  - Rayleigh-Taylor
- Multiple shocks
  - Richtmyer-Meshkov
- Strong Shear flows
  - Kelvin-Helmholtz

Instabilities can mix ablator material into the fuel and degrade and/or prevent ignition

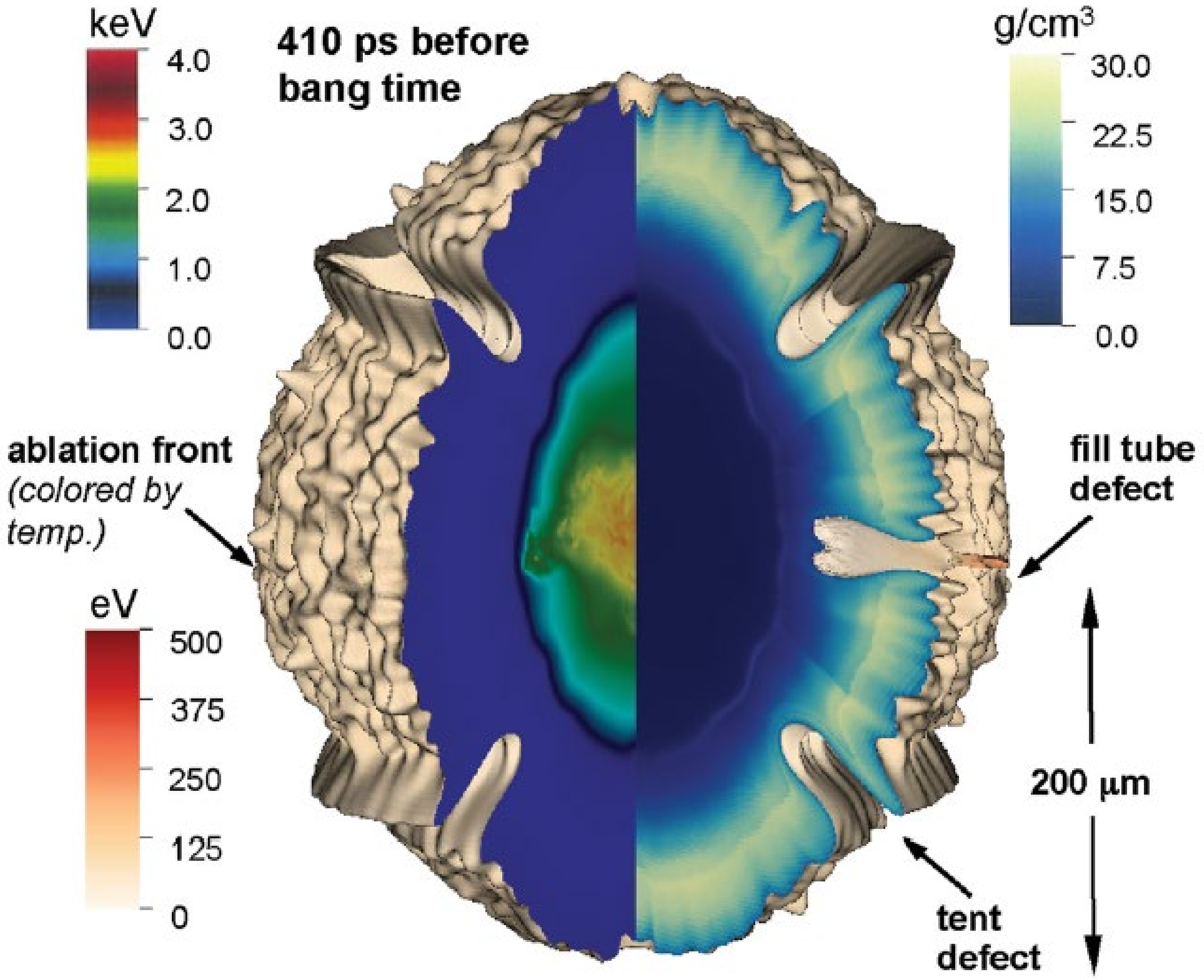


*Figure from D.S. Clark et al., Physics of Plasmas **23** 056302 (2016)*

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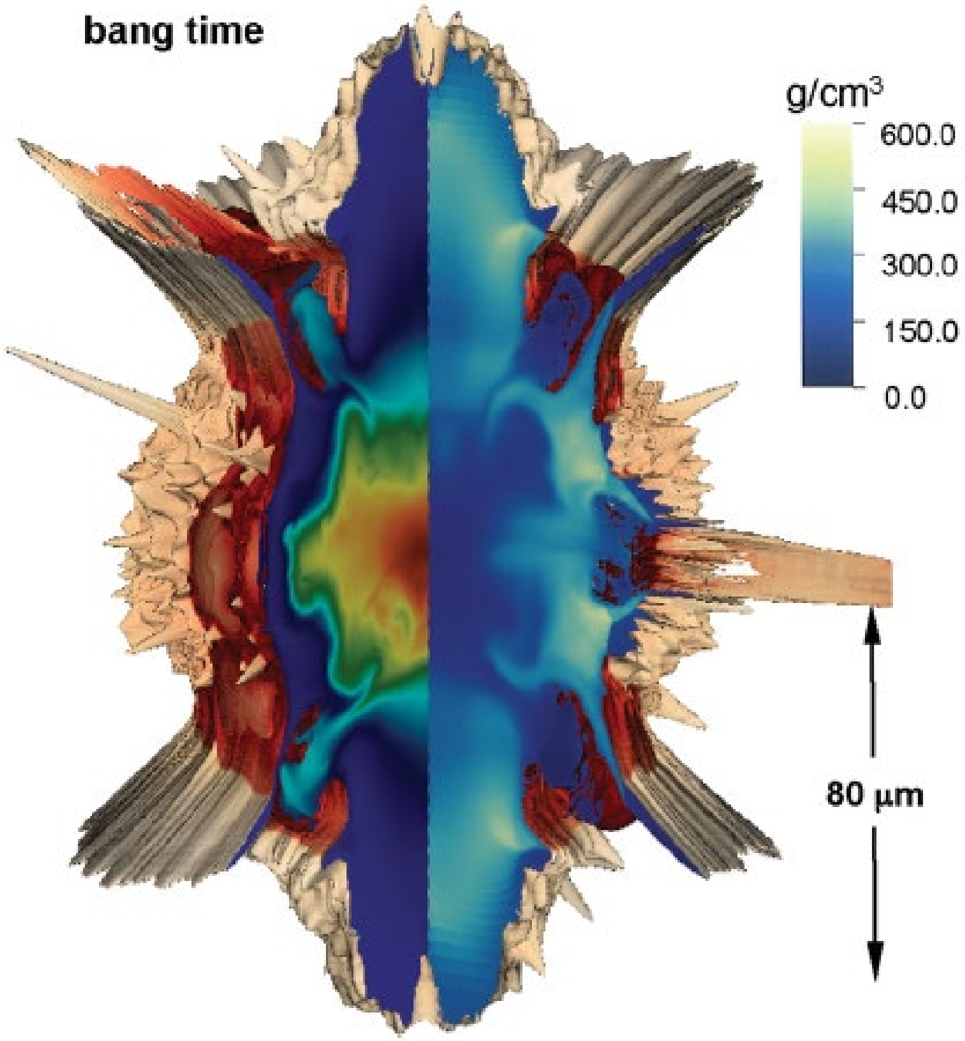
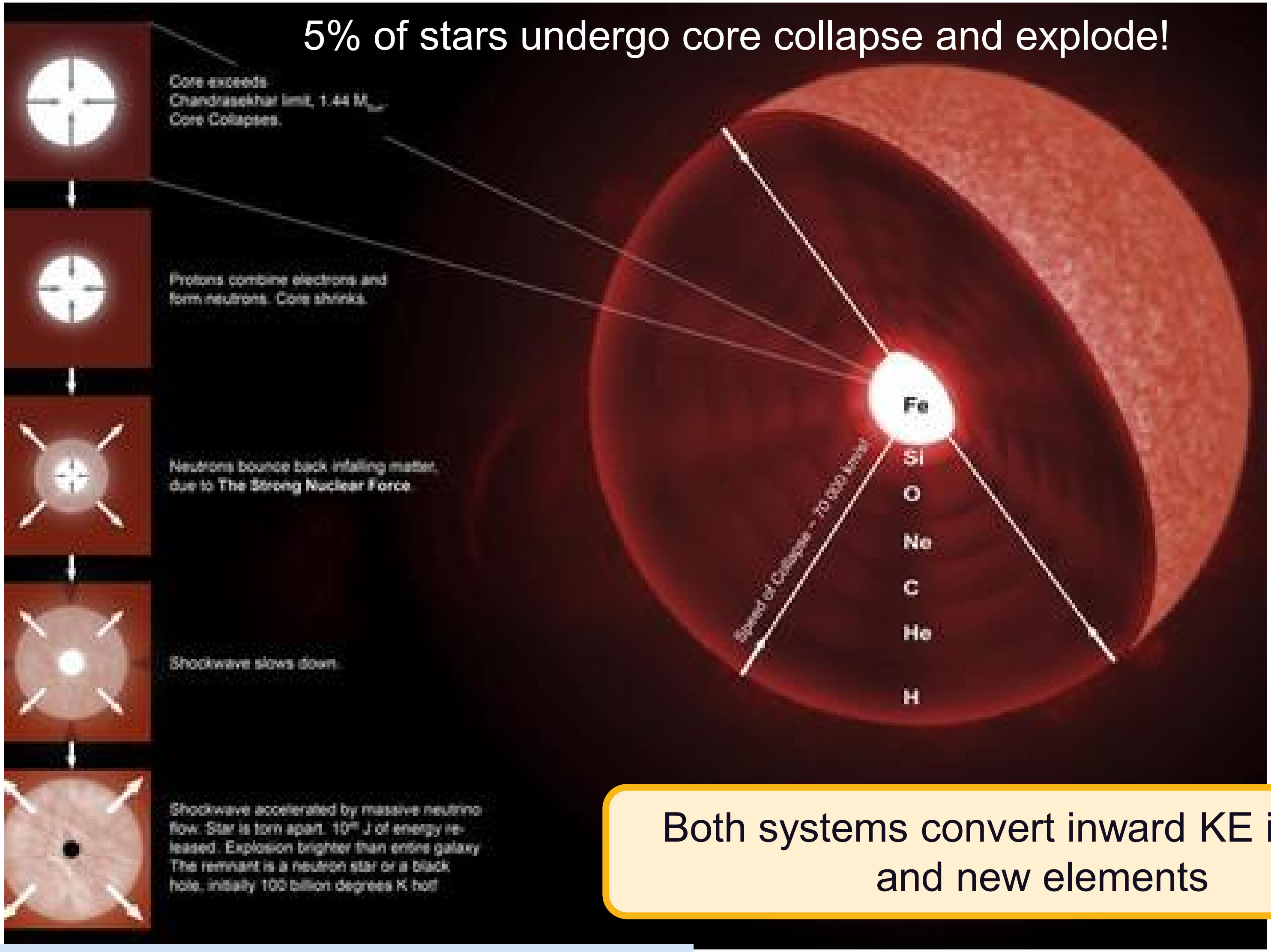


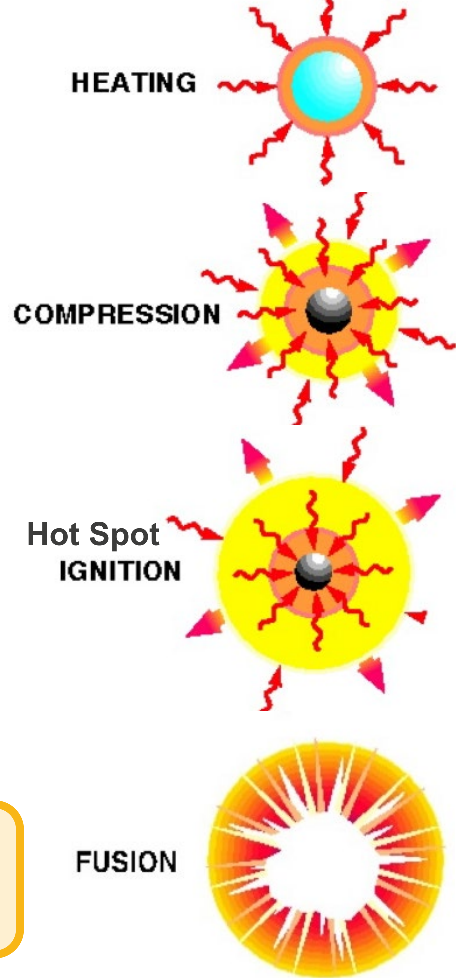
Figure from D.S. Clark et al., Physics of Plasmas ***23*** *056302 (2016)*

An old large star and inertial confinement fusion are very similar

5% of stars undergo core collapse and explode!



0% of ICF capsules undergo ignition (to date) but they do make lots of n's



Both systems convert inward KE into heat and new elements

Here neutron (strong force) pressure stops implosion and neutrinos help with the explosion

Here electron degeneracy stops implosion and fusion alphas help drive the explosion

The same instabilities are also important in astrophysical systems

Supernovea implosions and explosion also involved shocks and different layers of materials

- Different target layer densities
  - Rayleigh-Taylor
- Multiple shocks
  - Richtmyer-Meshkov
- Strong Shear flows
  - Kelvin-Helmholtz

Instabilities are important in:
- Pre-ignition conditions
- Triggering ignition
- Final chemical structure

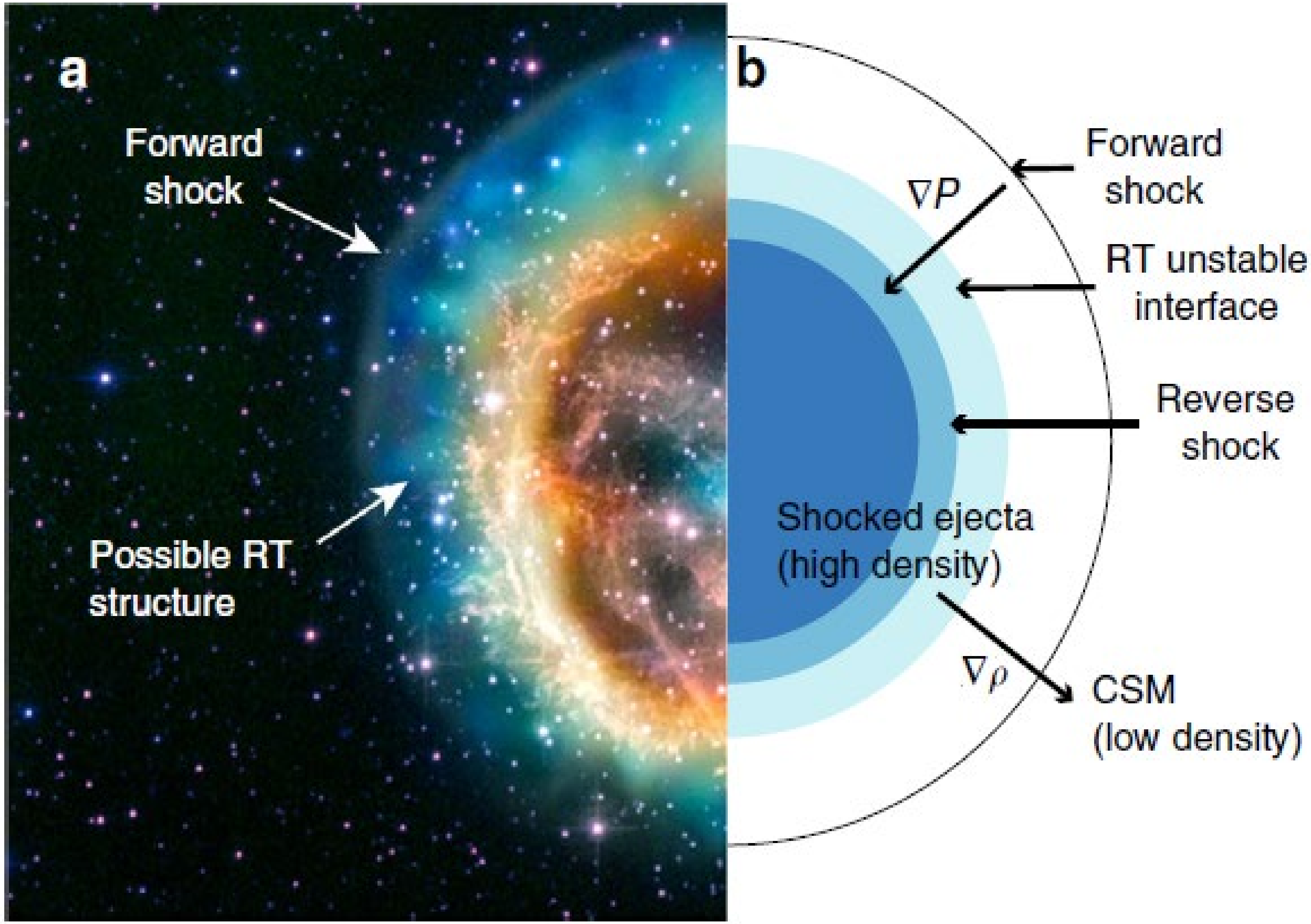
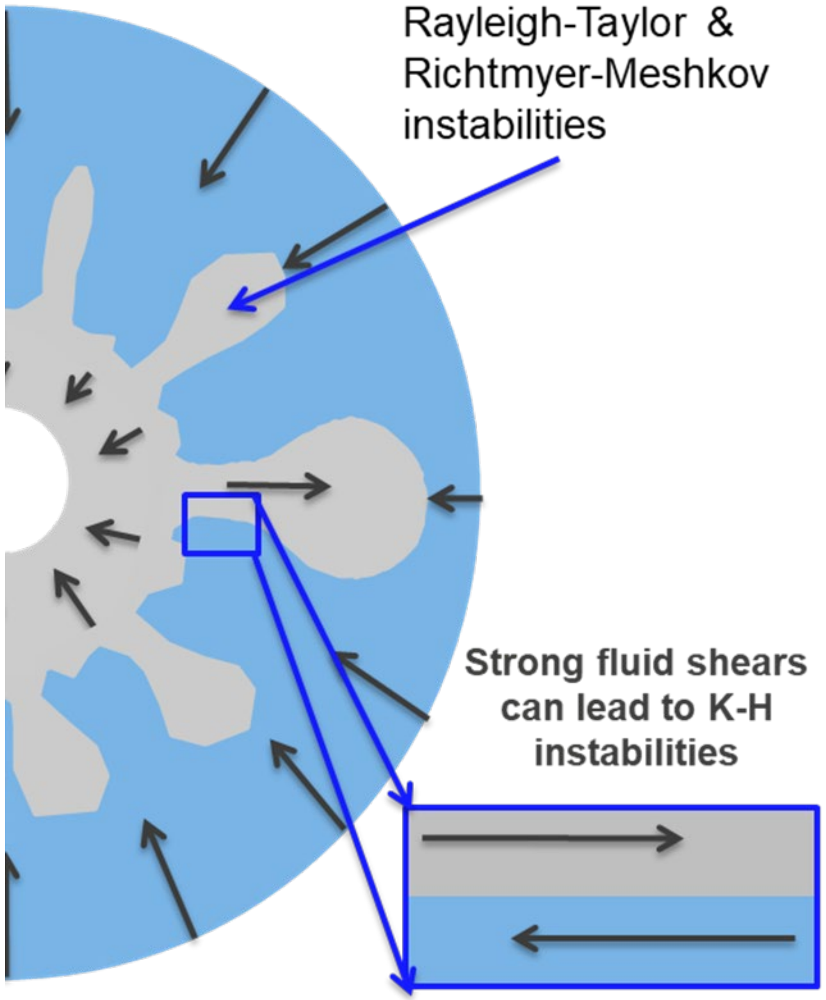


Figure from SNR E0102.2-72, Chandra/Hubble Composite

In imploding capsules and astrophysical systems, classical hydrodynamics will break down



- Compressibility, very high density ratios, very strong shocks, plasma transport effects (including plasma viscosity), magnetic fields, radiation, etc. all come into play in extreme integrated systems.

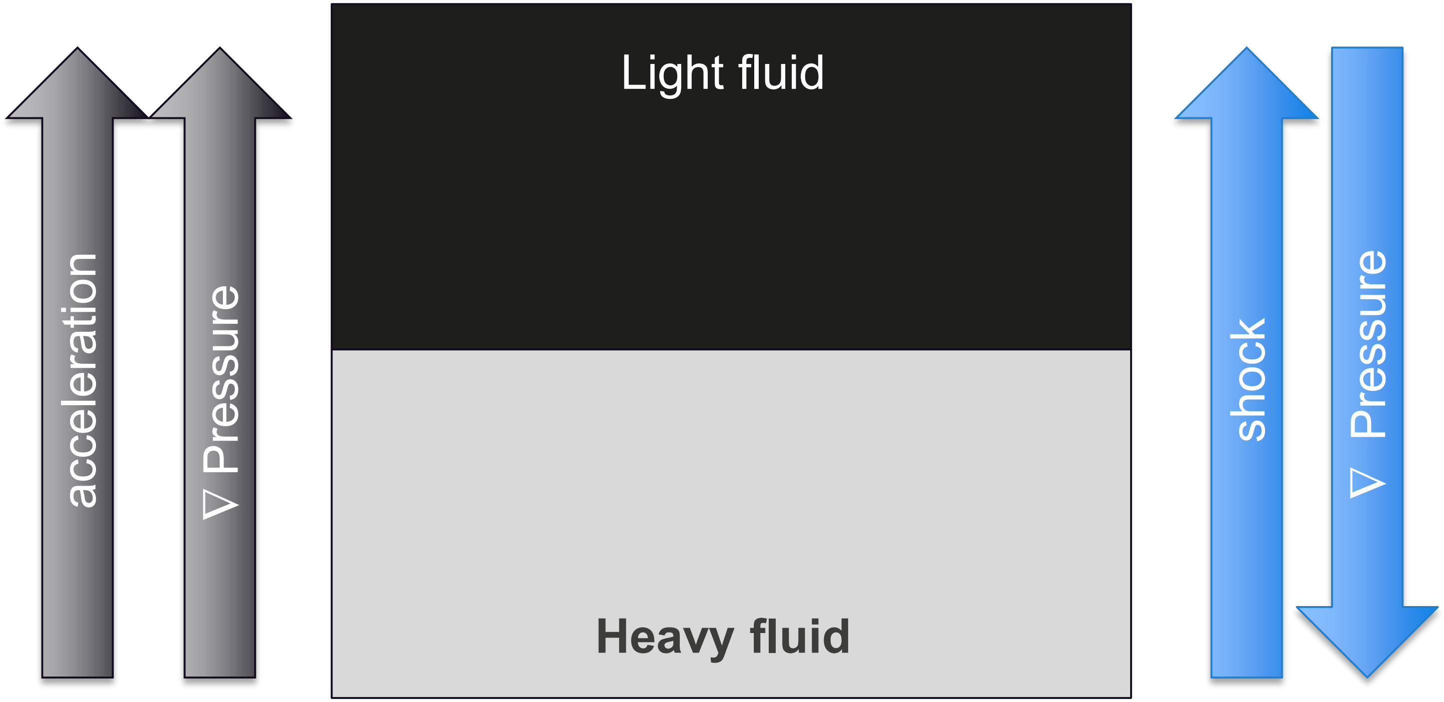
- Most of our computational models are calibrated/benchmarked by our experience in the low-energy-density world.

Determining when and which extended physics effects are important in HED is a common goal of many experiments.

Since imploding systems are complicated, many HED experiments use simplified geometries to isolate specific physics effects for study

Rayleigh-Taylor
Layers of different densities

Richtmyer-Meshkov
Shocks across material interfaces



Niederhaus and Jacobs (2003), J. Fluid Mech.

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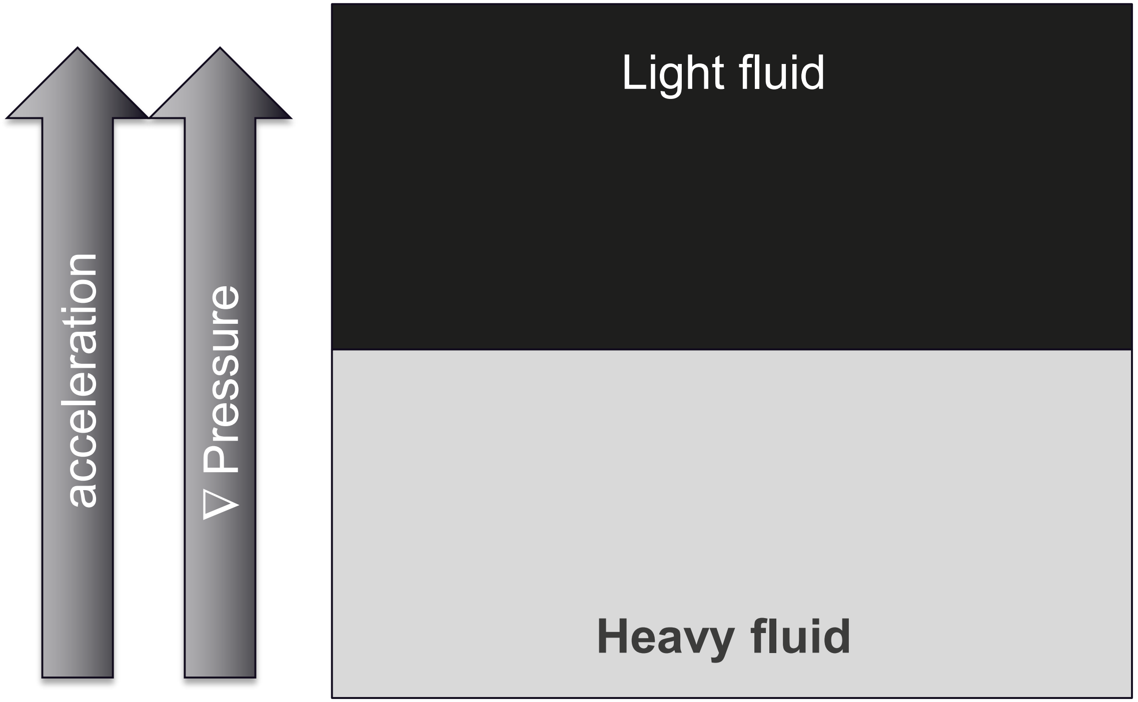

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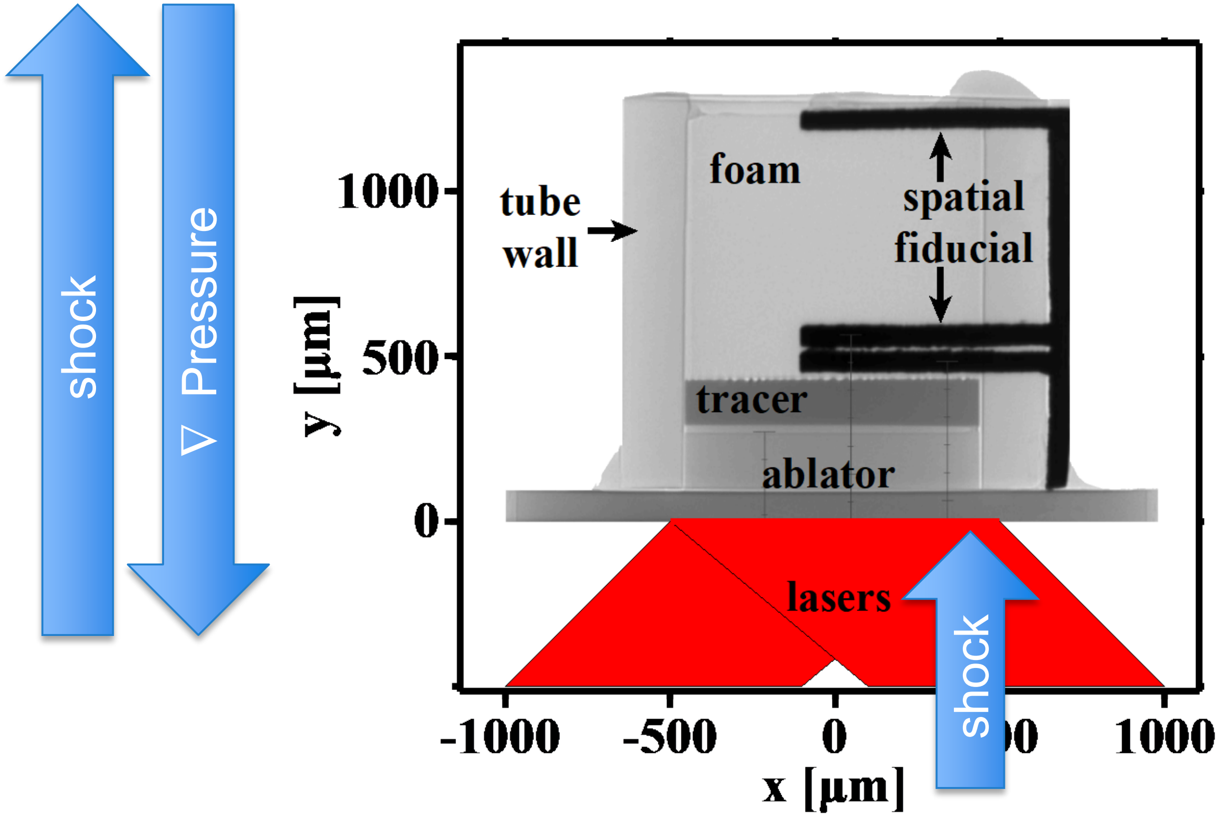

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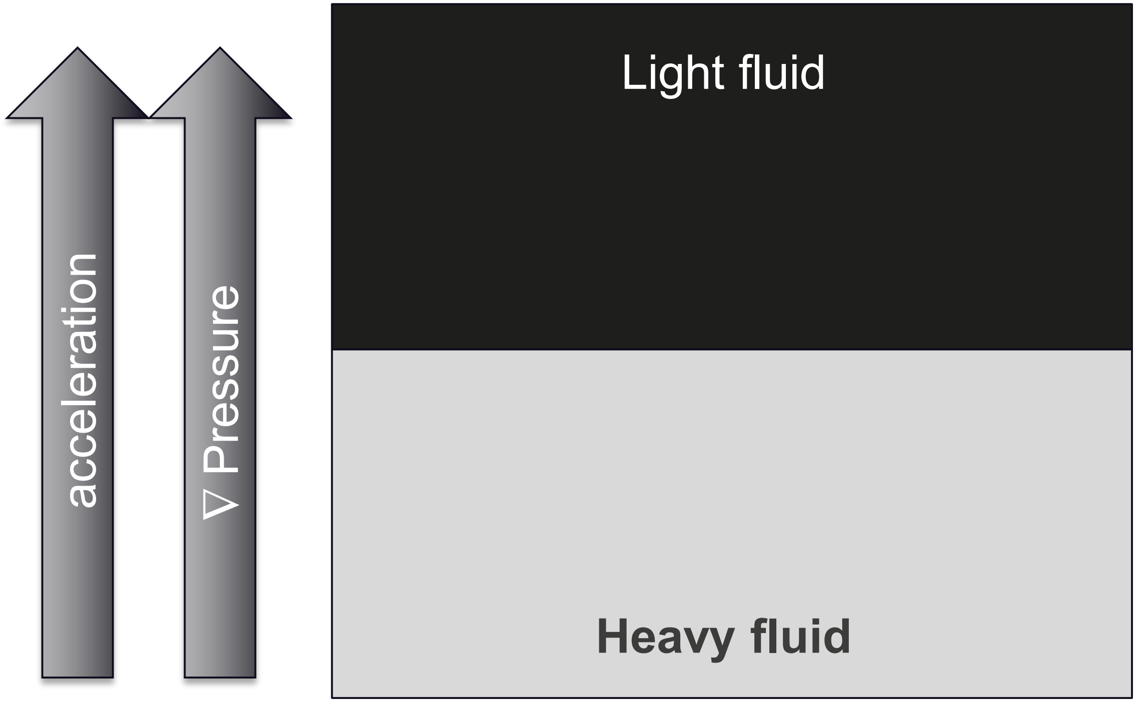

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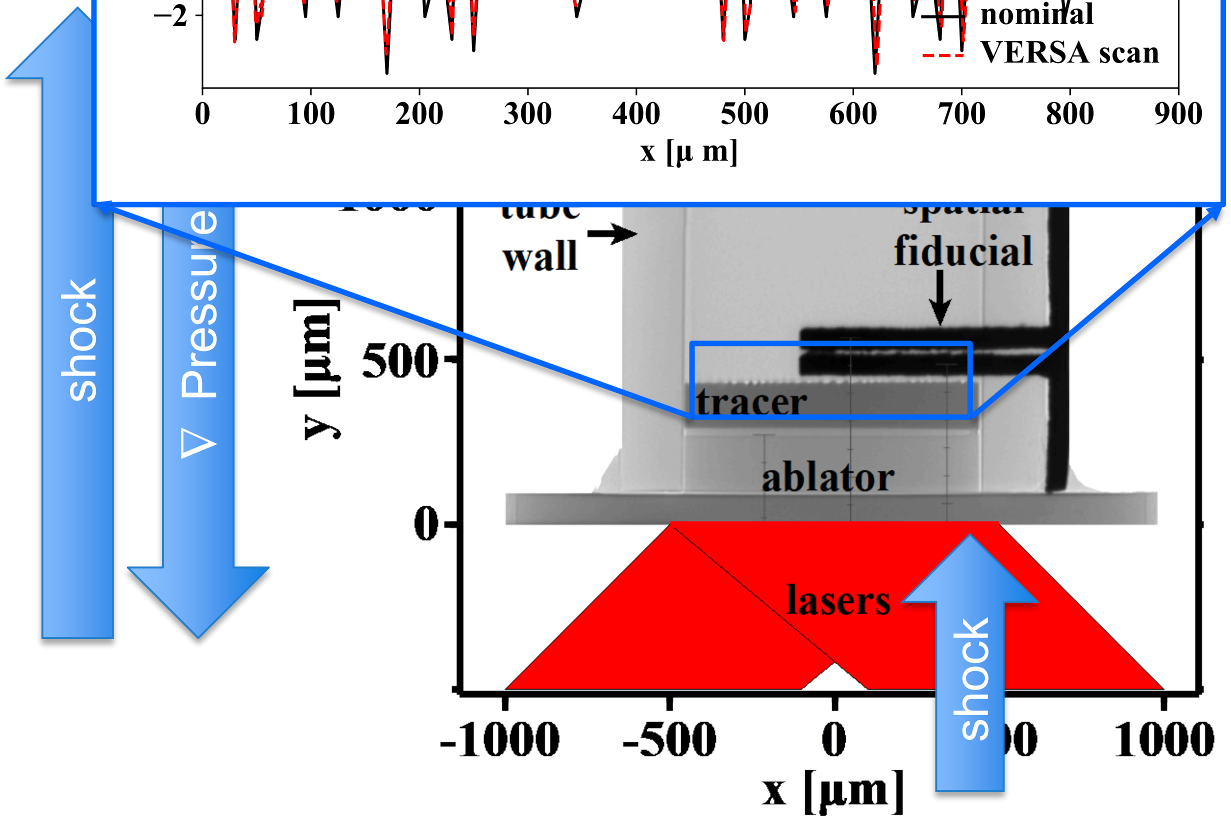
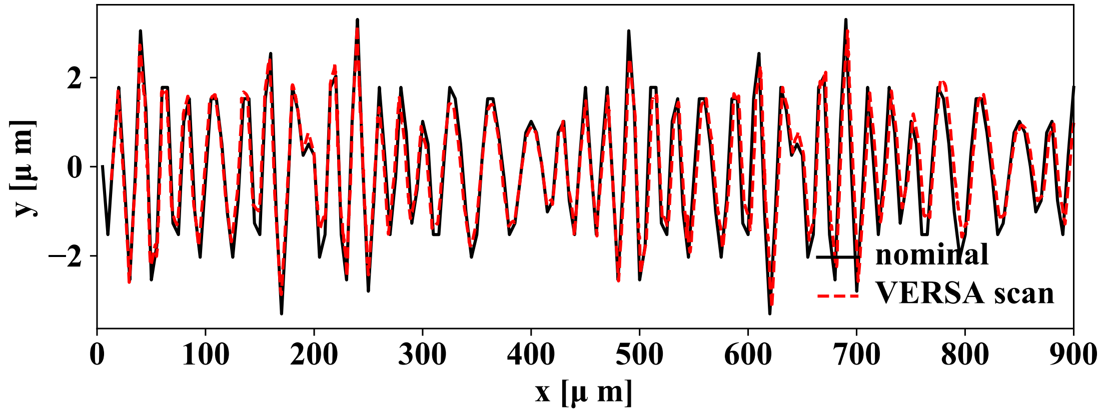


We can machine extremely complicated and precise interface profiles



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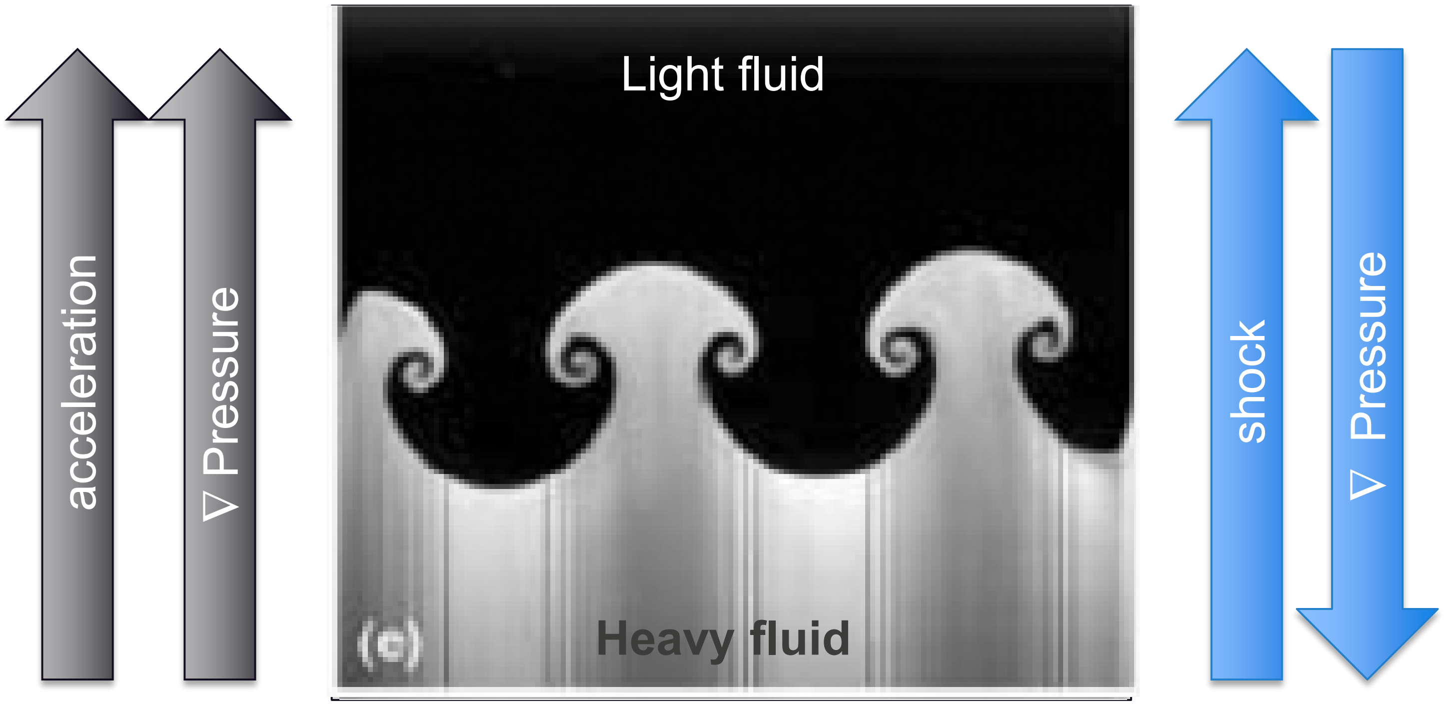

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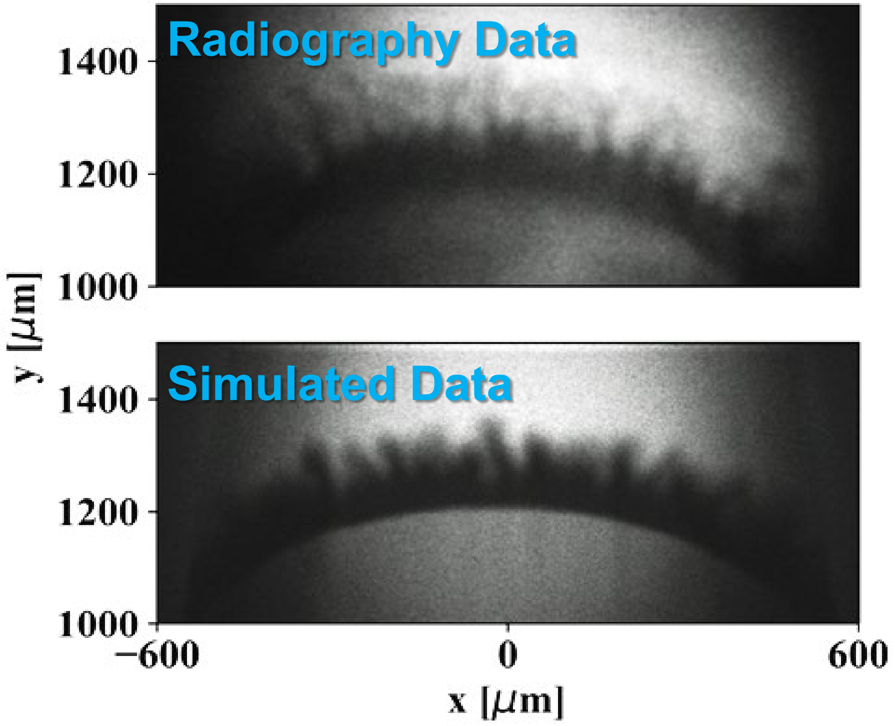

We can image the instability structure growth for comparison to theory and models

Some examples of LANL HED & ICF work

The challenge of ICF is compressing the DT fuel to high enough pressure to ignite over many potential degradation mechanisms in the imploding system

Some Examples

- Traditional single-shell capsules need extremely high convergence ratios, CR~40, to reach high pressure
  - High CR means large amplification of imperfections via hydrodynamic instability growth
  - Large instability growth leads to both “bulk” mix and potentially turbulent mixing of colder material into the hot fuel
  - Mixing cold material into the hot fuel cools the fuel and prevents burn

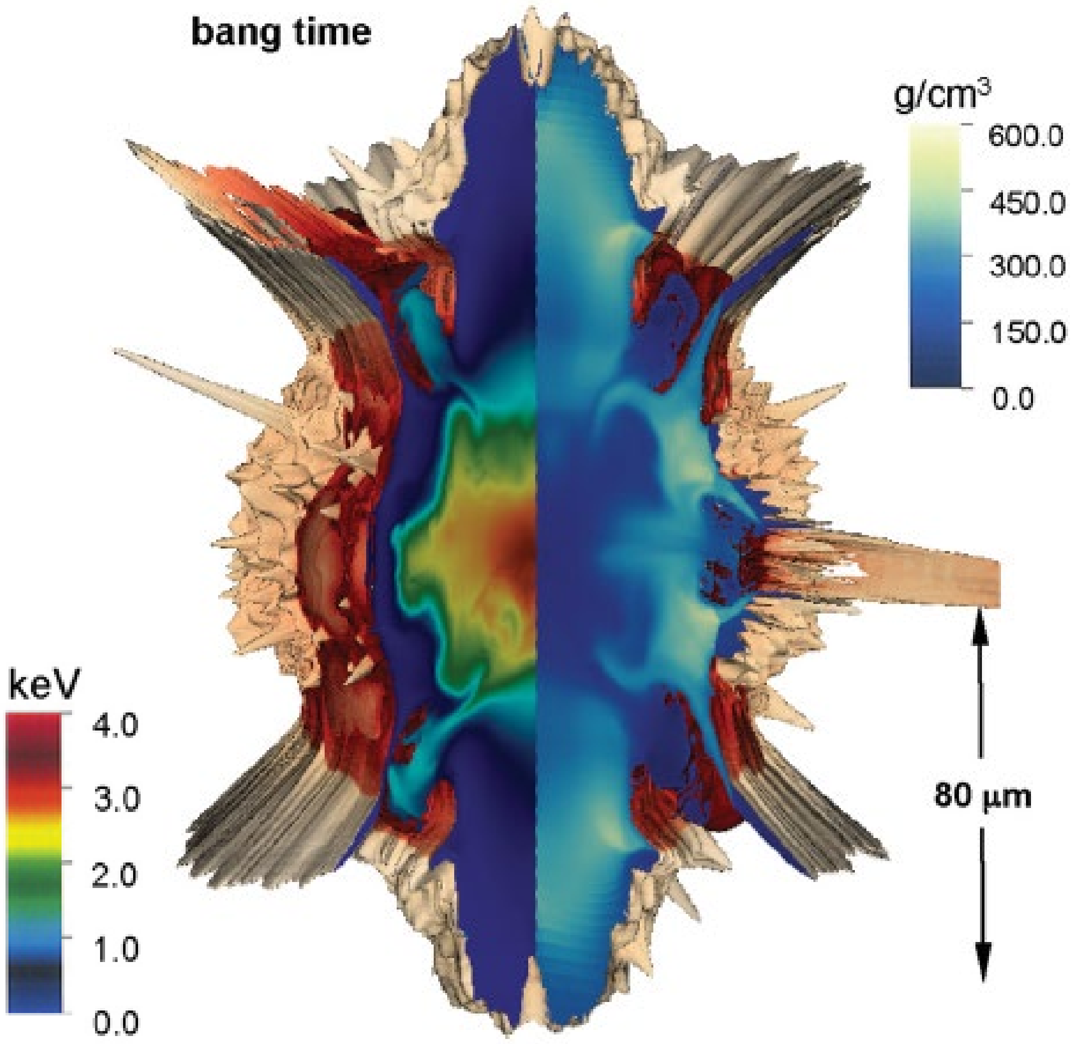

Figure from D.S. Clark et al., Physics of Plasmas ***23*** *056302 (2016)*

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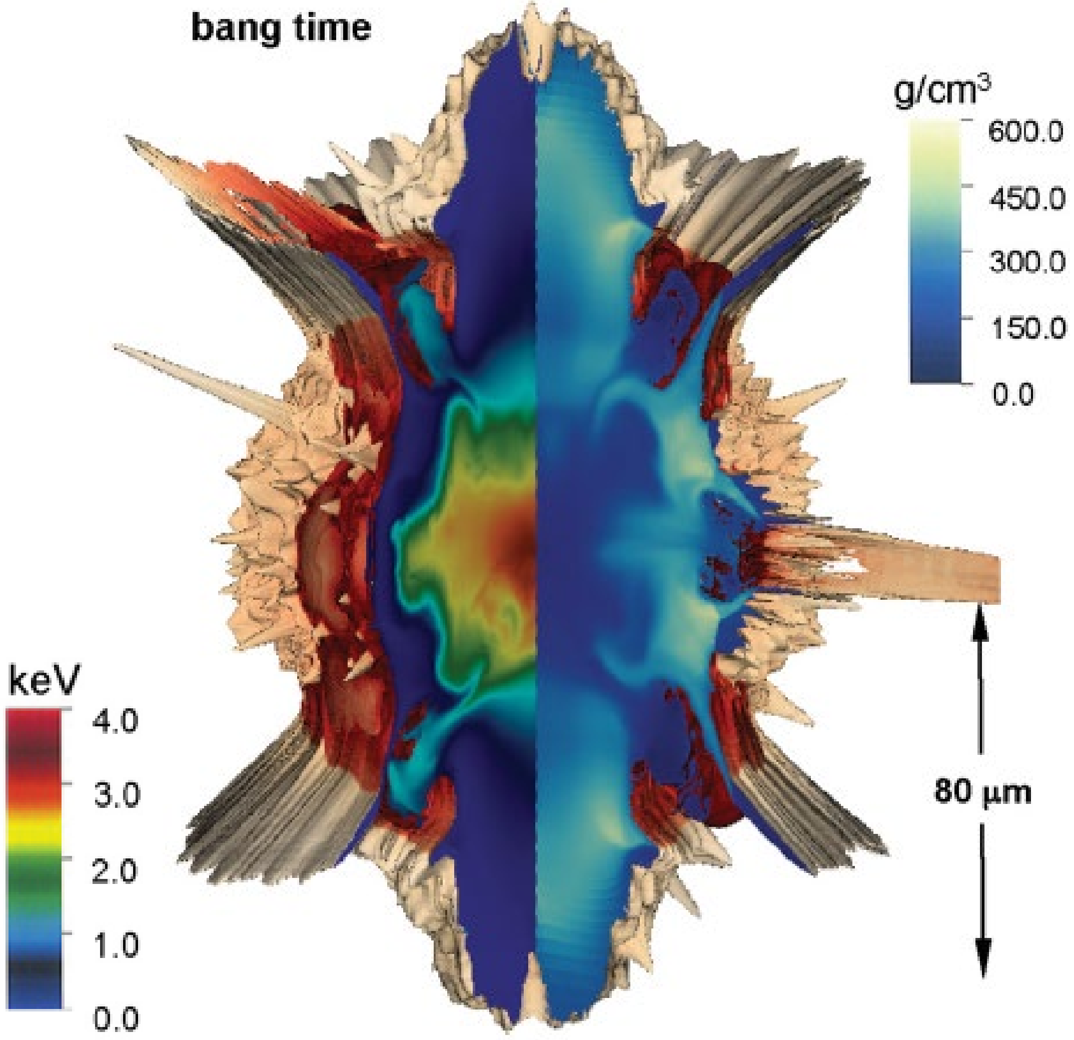

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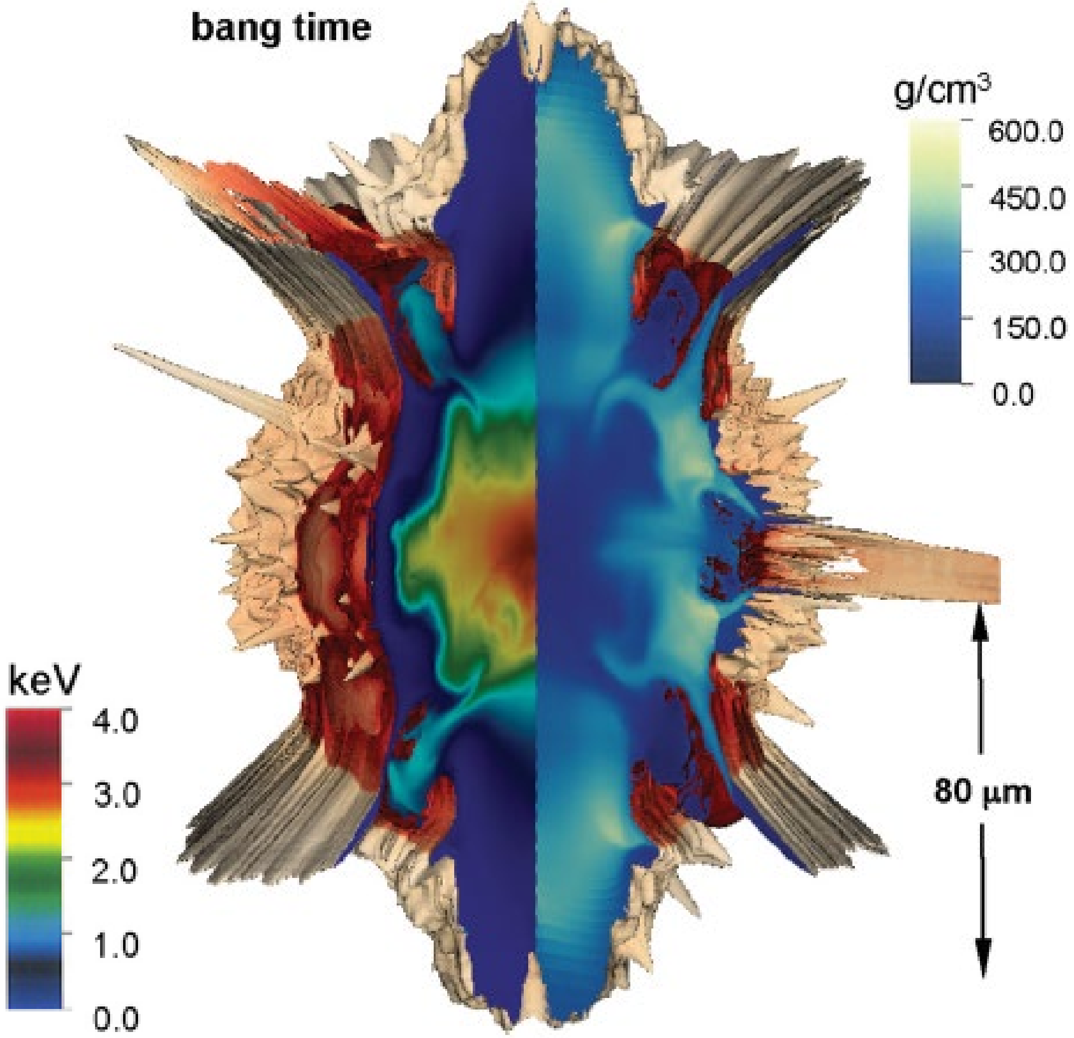

*Figure from D.S. Clark et al., Physics of Plasmas **23** 056302 (2016)*

The LANL ICF program is focused on understanding the basic science of ICF implosions in order to answer "What will it take to get fusion?"

Double Shells
Low CR implosion w/ heavy metal inner shells and liquid DT fill

Some Examples

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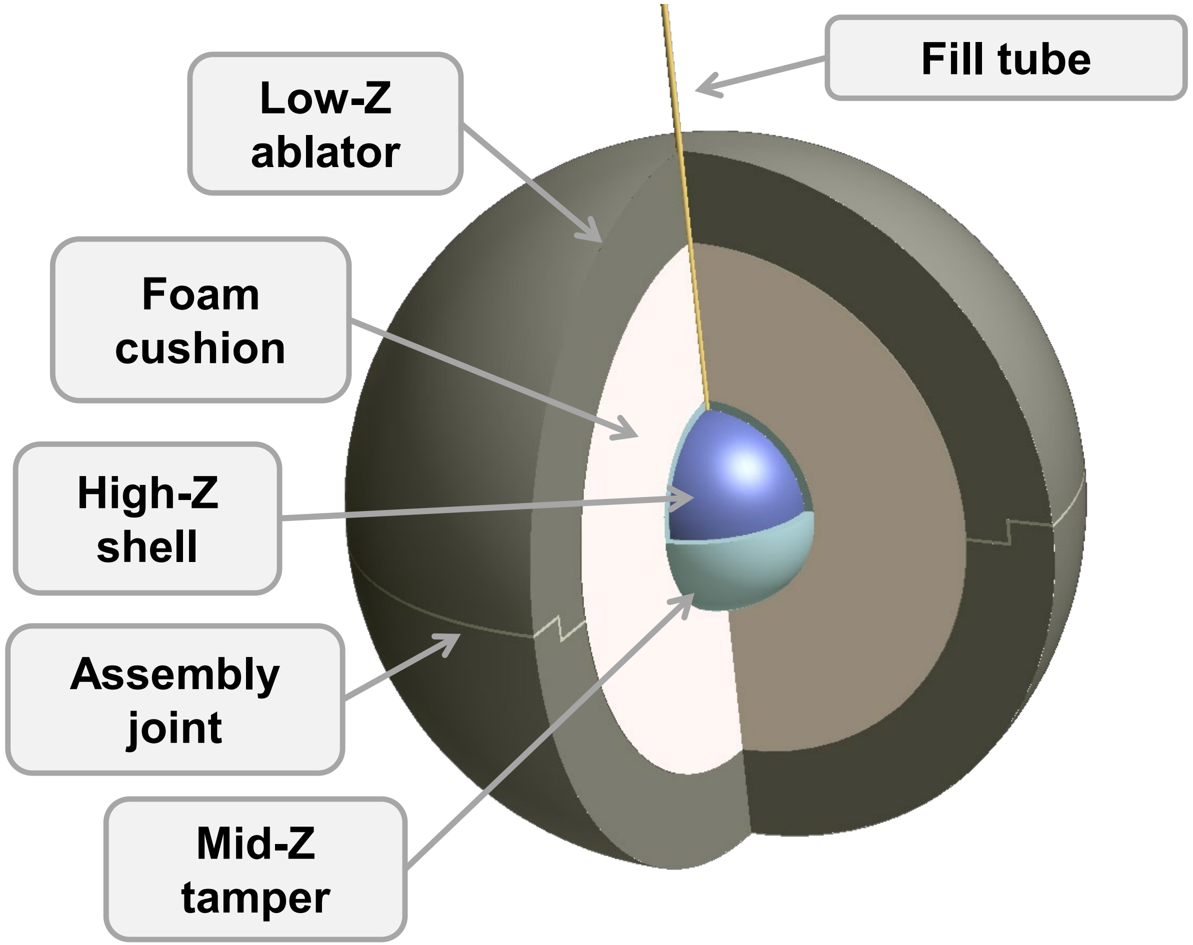
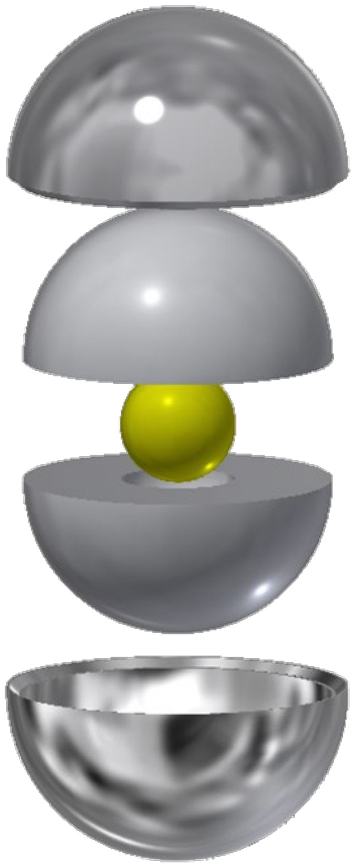
HED Hydrodynamics
Study of instability growth in ICF-like systems

MARBLE
Study of how mix effects burn in DT

Diagnostics
Gamma spectroscopy and neutron imaging give insight in how the hot spot preforms

Double Shells are an alternate capsule design intended to study α-heating and burn





The Double-Shell capsule design is a complimentary approach to the traditional single-shell capsules

Montgomery *et al., Phys. Plasmas* (2018)

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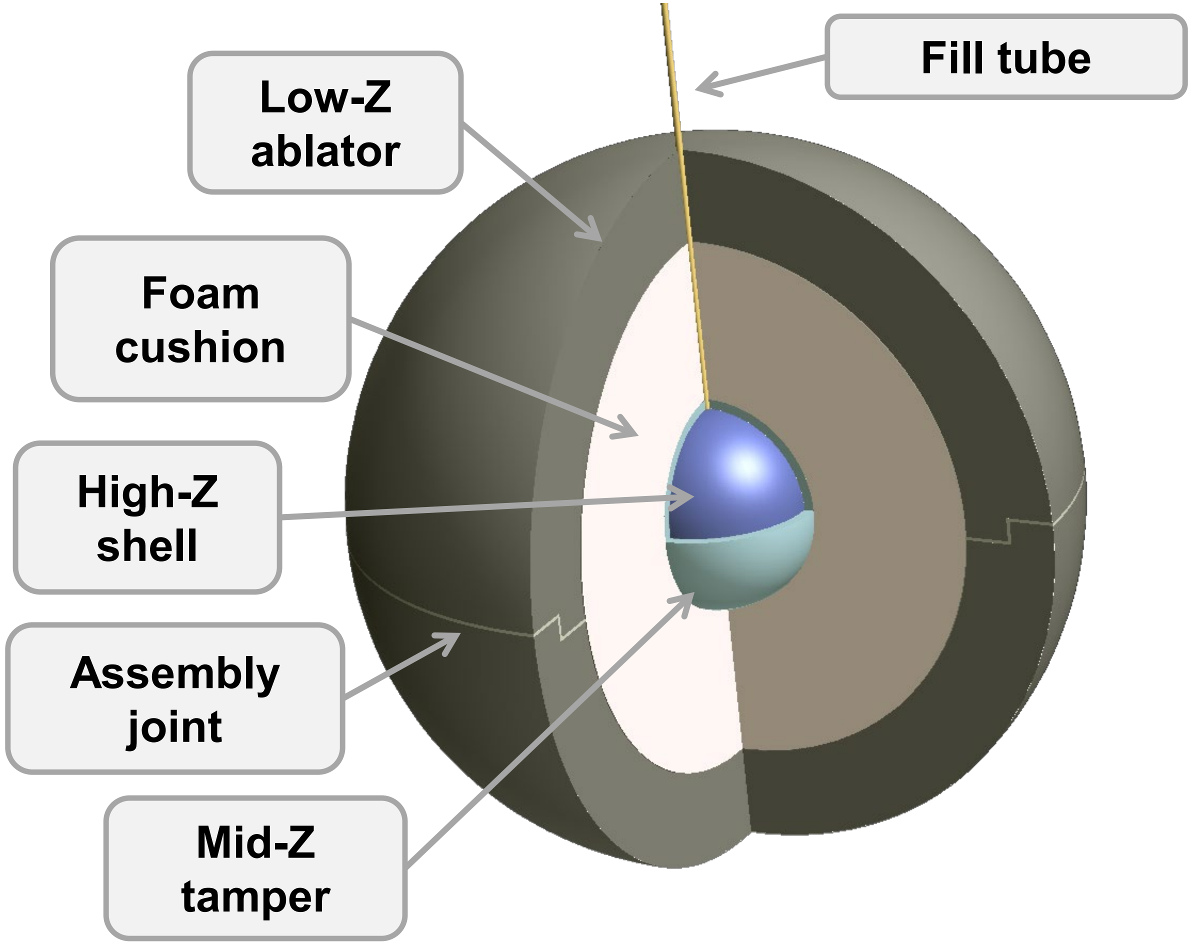


- **Double-Shell capsules are:**
  - Able to achieve burn at lower convergence ratios, and implosion velocities and temperatures
  - Less sensitive to Laser Plasma Instabilities (LPI) and uncertainties in the ablative drive physics
  - Less susceptible to radiation losses
  - Volume ignition instead of hot spot ignition
- **In exchange, Double-Shell capsules:**
  - Have lower potential yield
  - Are more difficult to build and diagnose
  - Have a greater number of hydrodynamically unstable interfaces

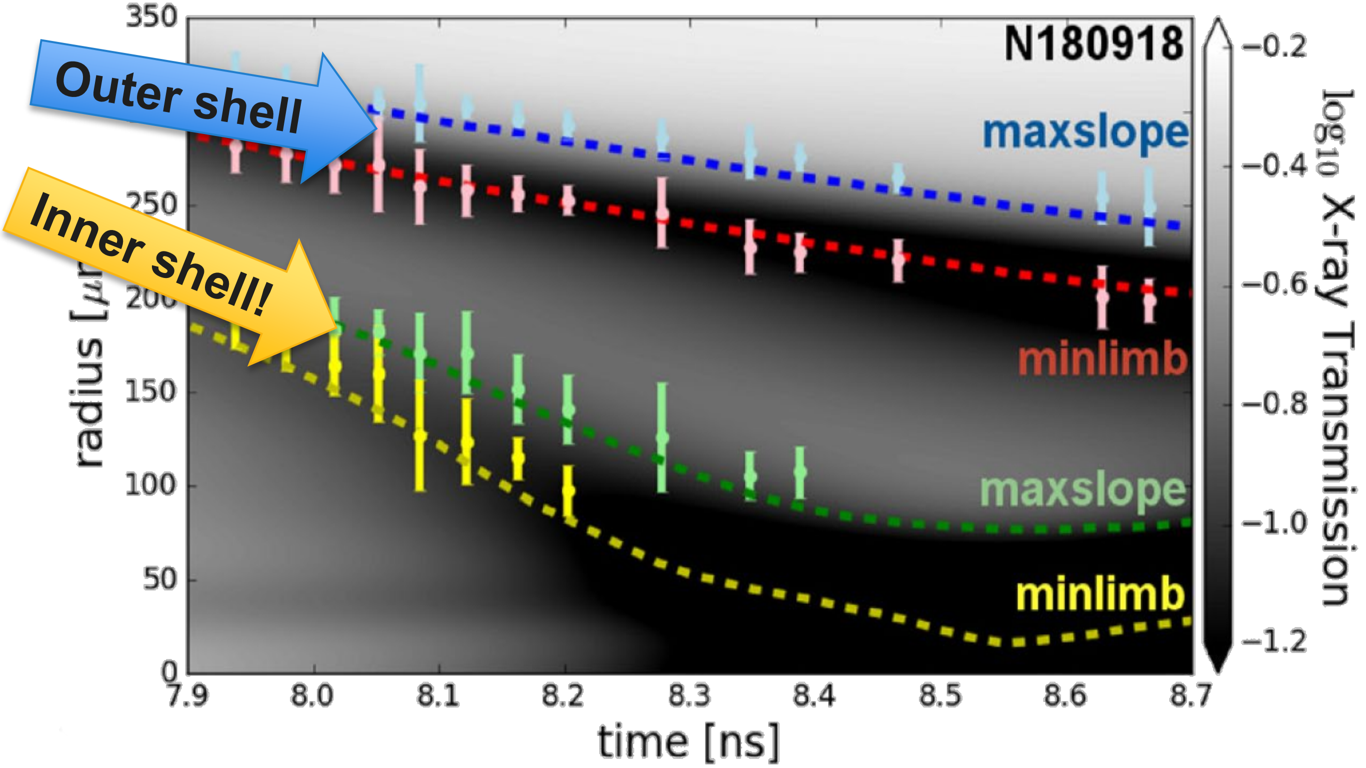
The Double-Shell capsule design is a complimentary approach to the traditional single-shell capsules

Montgomery *et al.*, *Phys. Plasmas* (2018)

The Double Shell campaign is focused on assessing how well our simulations capture key implosion features like energy transfer and imperfection growth

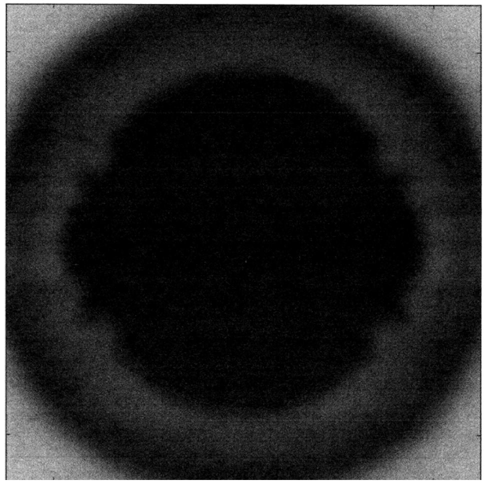
We need to confirm our simulations are capturing the important physics for us to have any confidence that our final experiments will be able to create a burning plasma

Early experiments with surrogate inner shells ***give us confidence in our simulations*** by showing we are simulating energy transfer to the inner shell to within ~ 5%*



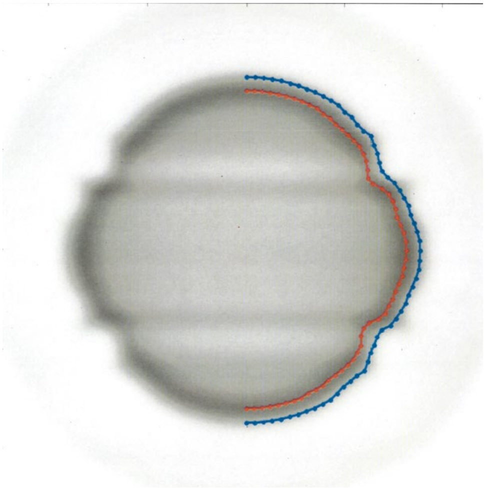
Current capability

16.3 keV



Under development

40 keV

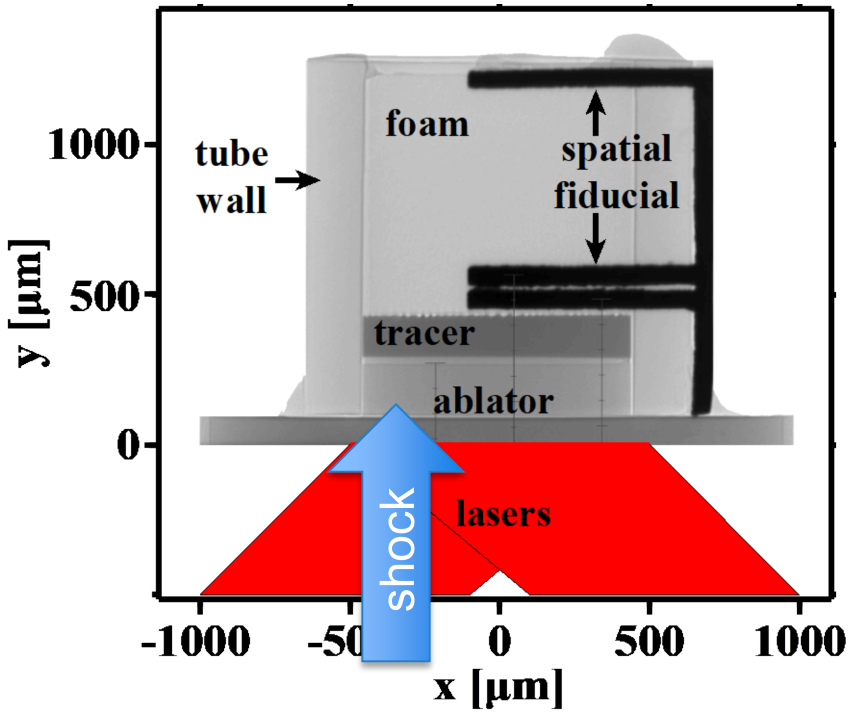


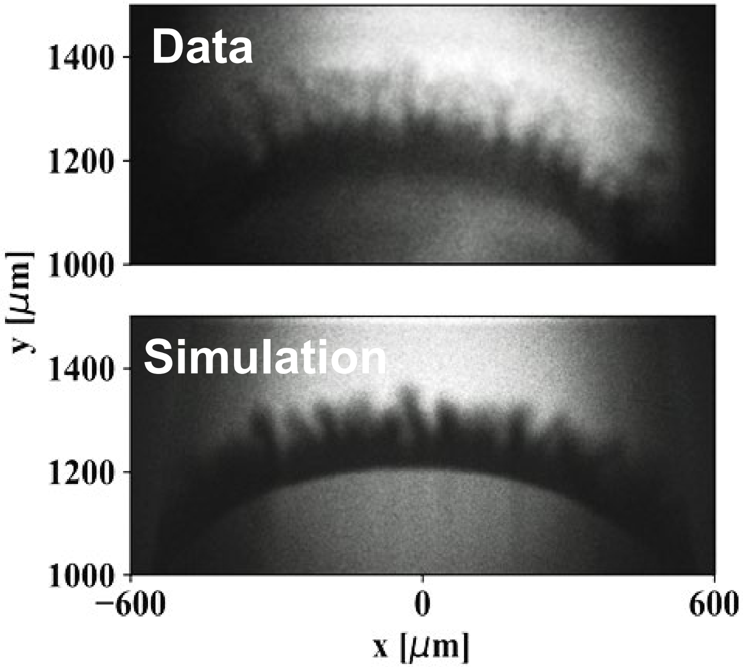
We are currently developing the imaging capability needed to study energy transfer and imperfection impact on the real, high-Z inner shell materials

*Merritt *et al.*, *Phys. Plasmas* (2019)

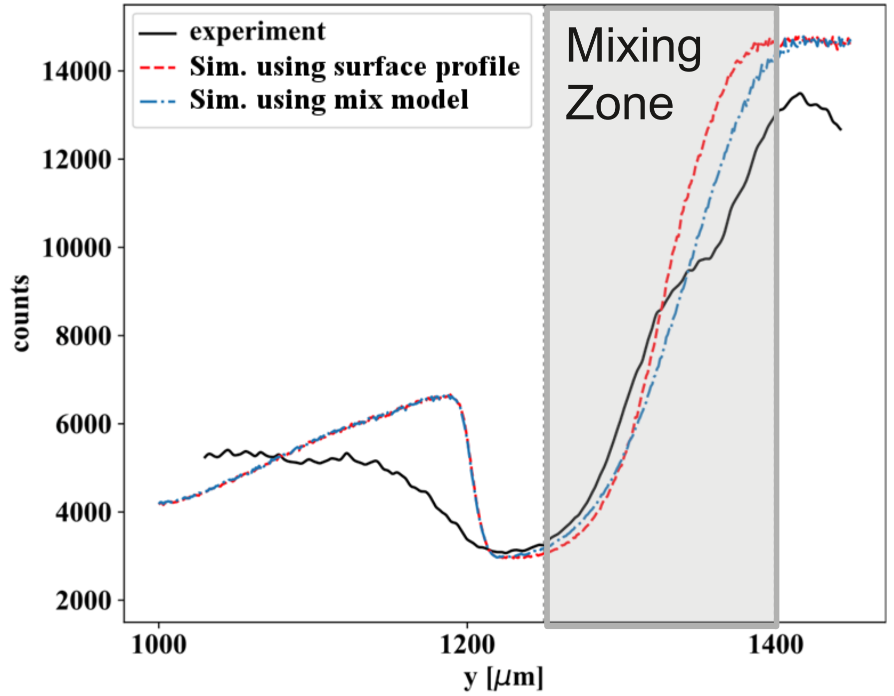
xRAGE simulations by J.P. Sauppe

The ModCons campaign on Omega-EP focus on ensuring we can calculate the evolution of complex, multi-mode surface profiles correctly including fine-feature growth and mode coupling





Lineout of mixing region

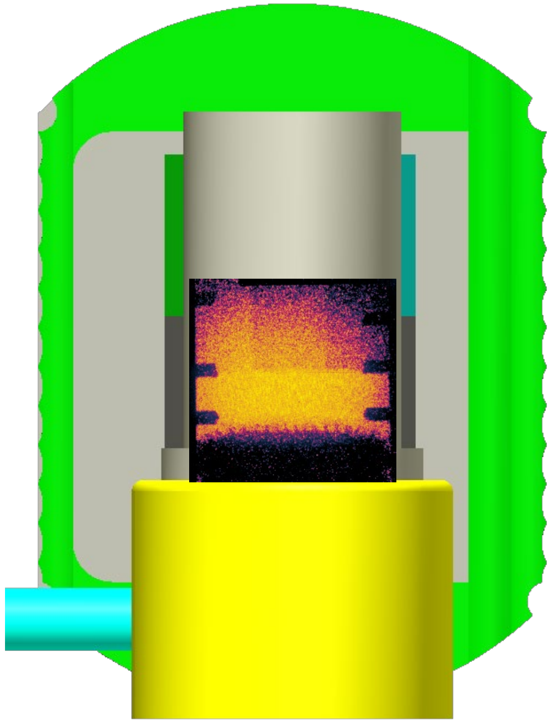


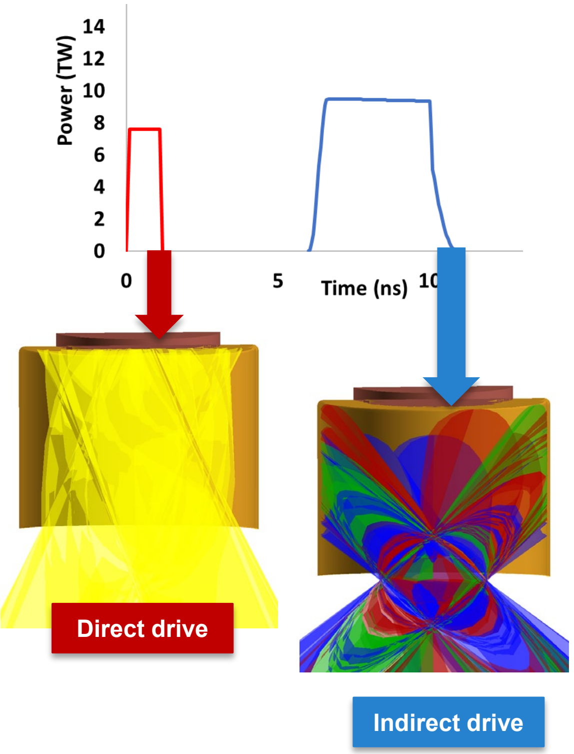
Simulated 1D growth of a complex noise profile shows reasonable agreement with experiment even with multimode initial conditions, giving us confidence in our hydrodynamics code (xRAGE) and turbulence model (BHR) performance for HED systems

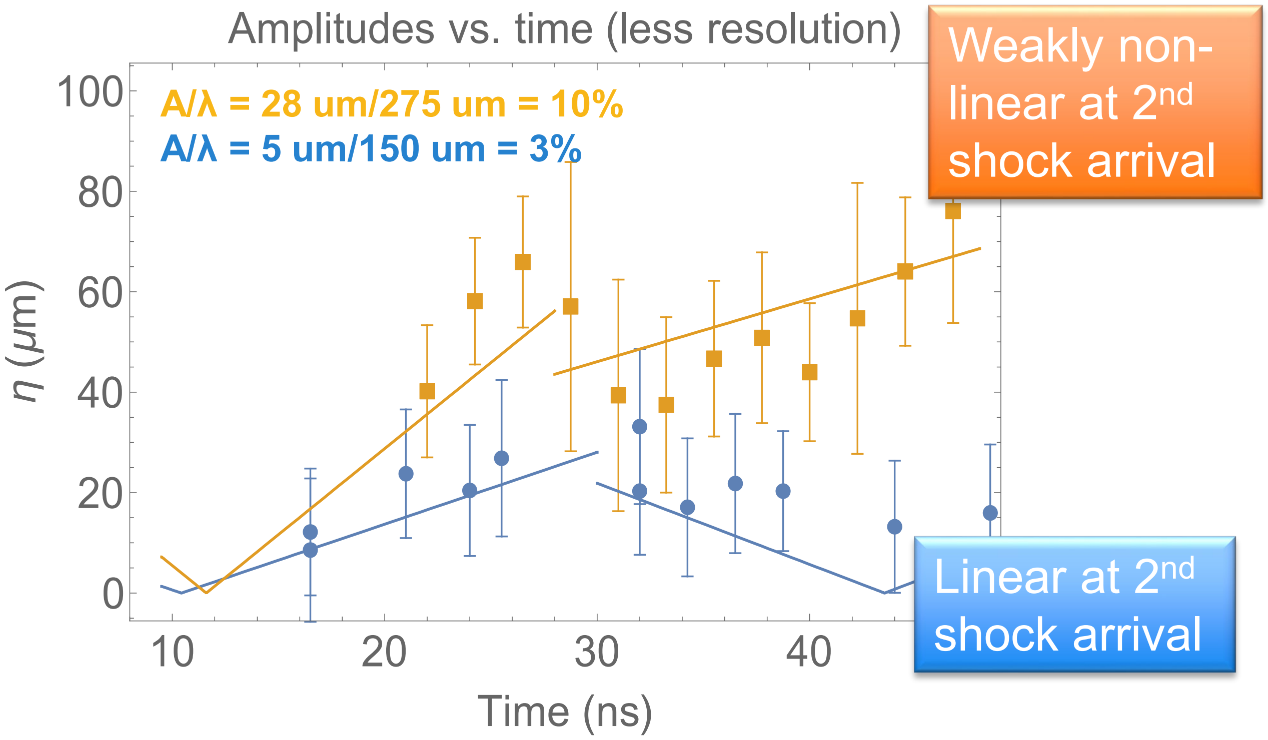
Di Stefano *et al.*, *Phys. Plasmas* (2019)

The NIF Mshock campaign has one of the only platforms in HED or traditional fluids capable of investigating how instabilities grow when shocked multiple times from the same direction

Ideal theory* predicts 15 perturbation growth cases for a single mode under successive shocks



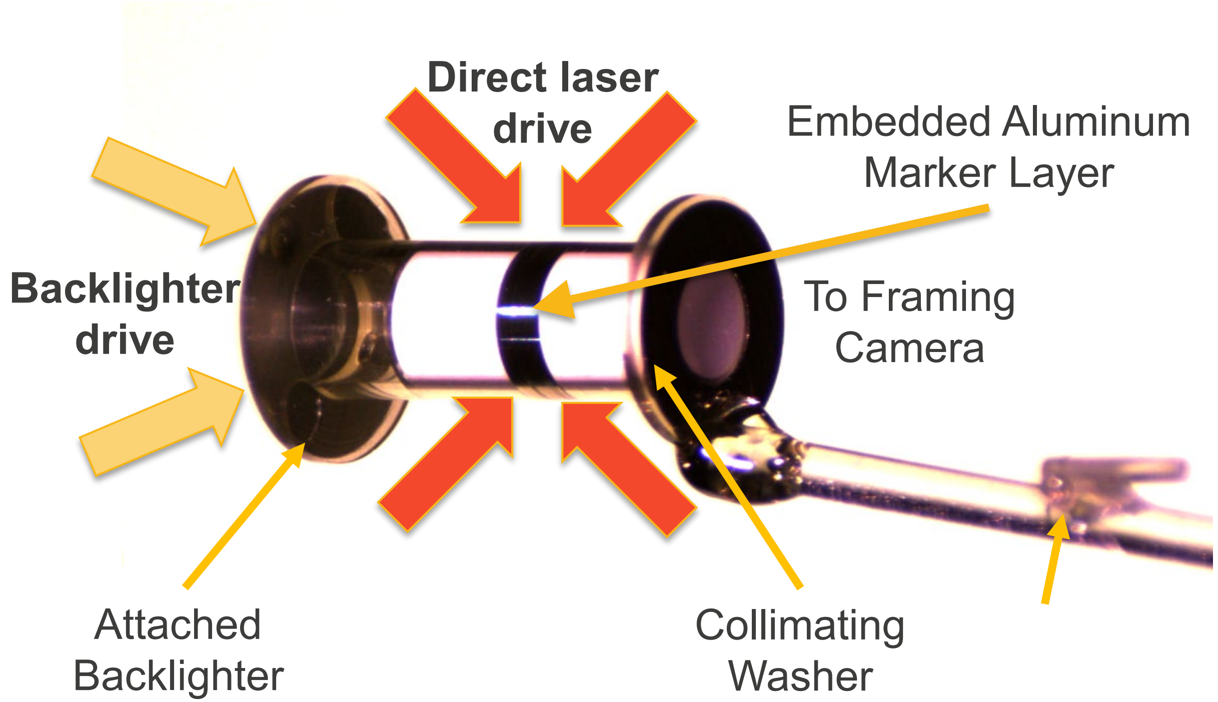


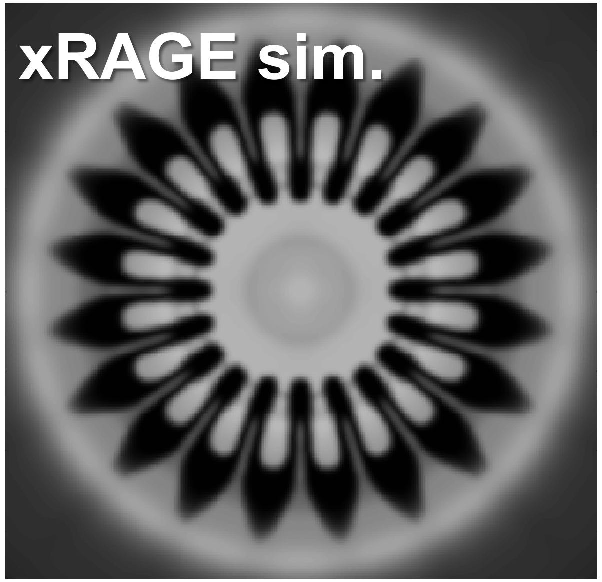


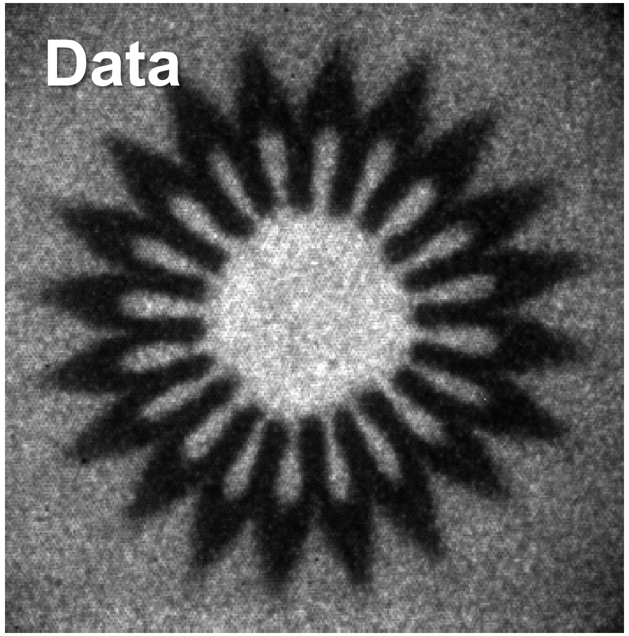
Initial experiments (in 2020) demonstrated the ability to vary the growth of a single-mode interface growth post-2nd shock, establishing that the state of the perturbations when the 2nd-shock arrives can either cause the perturbation to grow or shrink which can significantly change the amount of mix in the system

**Theory from Mikaelian, PRA 1985*

In addition to the planar instability experiments, we are developing cylindrically imploding experiments to study the same physics with convergence effects







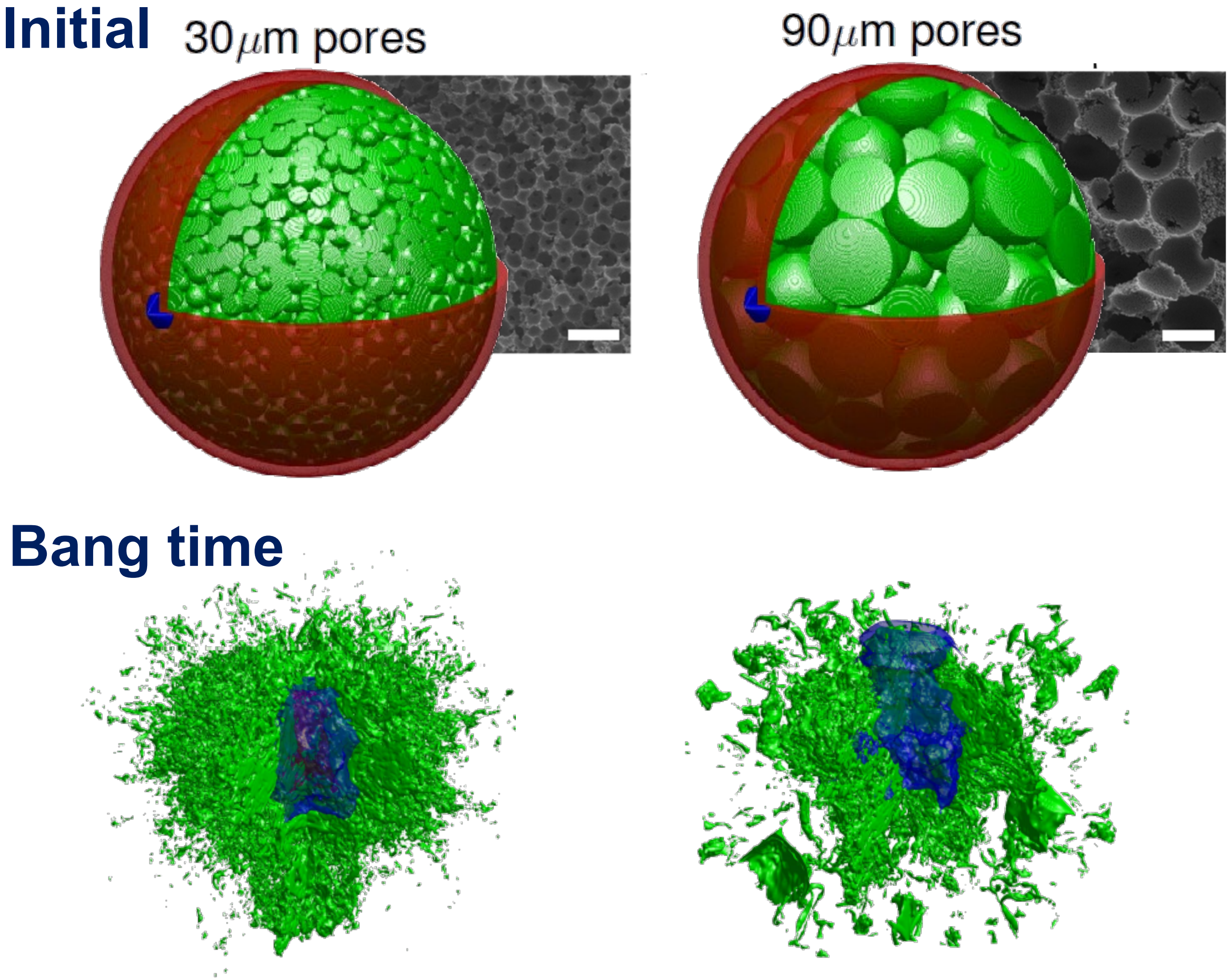
Current experiments have demonstrated feasibility at CR~ 5, and are pushing toward CR~10 (similar to Double Shells)

1. J. P. Sauppe et al. *Phys. Rev. Lett.* **124**, 185003 (2020)
2. S. Palaniyappan et al. *Phys. Plasmas* **27**, 042708 (2020)
3. J. P. Sauppe et al. *High Eng. Dens. Phys.* **36**, 100831 (2020)

The Marble campaign on NIF aims to understand the interplay between contaminant mixing and thermonuclear burn.

Experiments implode plastic capsules filled with cryogenic H-T gas fills and deuterated plastic foam containing engineered voids of known sizes and locations, which allow control of the degree of heterogeneity in the implosions.

"Recent results indicate that the amount of contaminant mass in the hot spots of high-yield implosions is routinely underestimated… This suggests that there is significant margin for improving the performance of capsule implosions through decreasing …capsule asymmetries or … [making] them more robust to hydrodynamic instabilities."

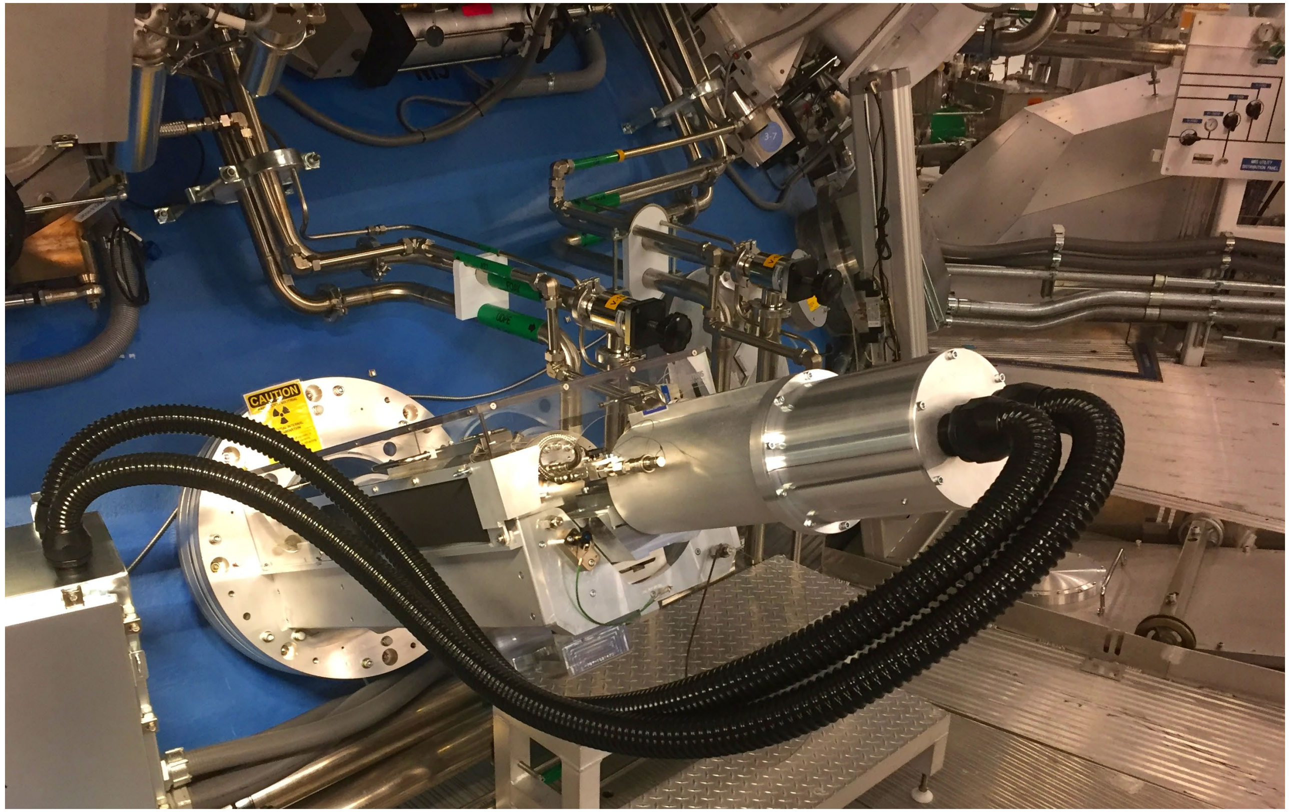


Haines *et al.*, *Nature Communications* (2020)

LANL develops transformative diagnostics at the Omega and NIF laser facilities, including time resolved gamma ray spectroscopy and neutron imaging.

Gamma ray measurements of the evolution of the nuclear fusion burn give insight into how a burning hot spot forms.

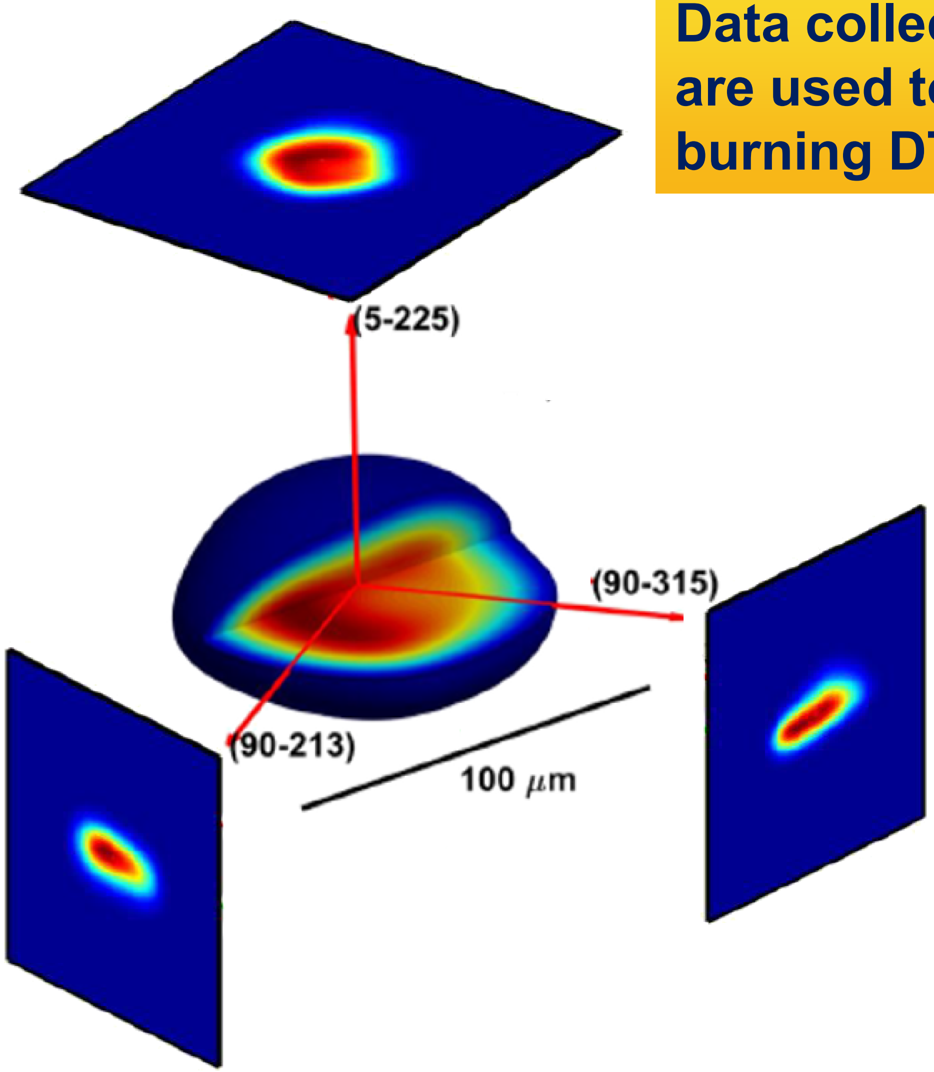
Gamma Ray Detectors on NIF

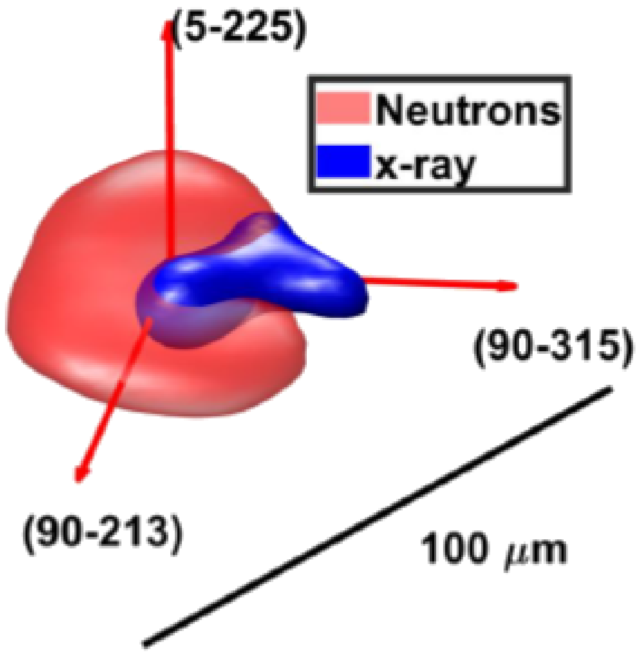


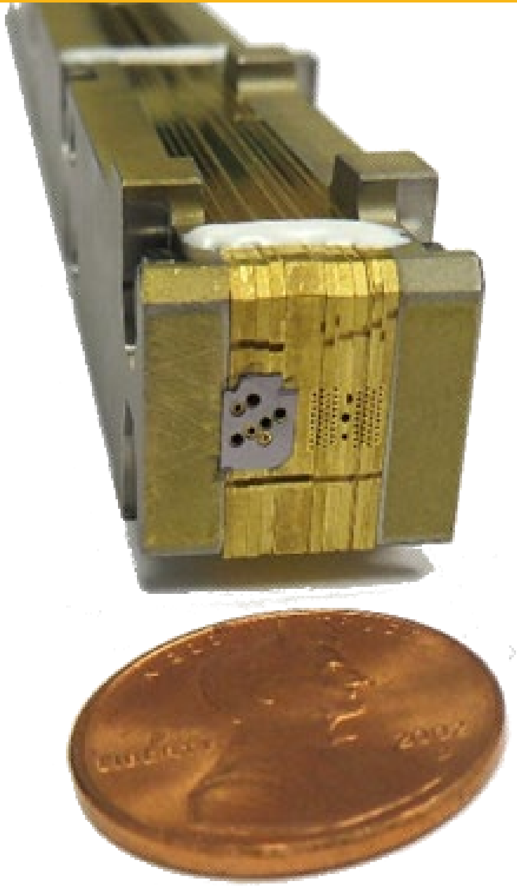
Images courtesy of the Gamma Diagnostics Team

LANL develops transformative diagnostics at the Omega and NIF laser facilities, including time resolved gamma ray spectroscopy and neutron imaging.

Data collected from 3 nearly orthogonal neutron imaging systems are used to create a 3D reconstruction of the size and shape of the burning DT plasma during the ignition stage of ICF implosions.

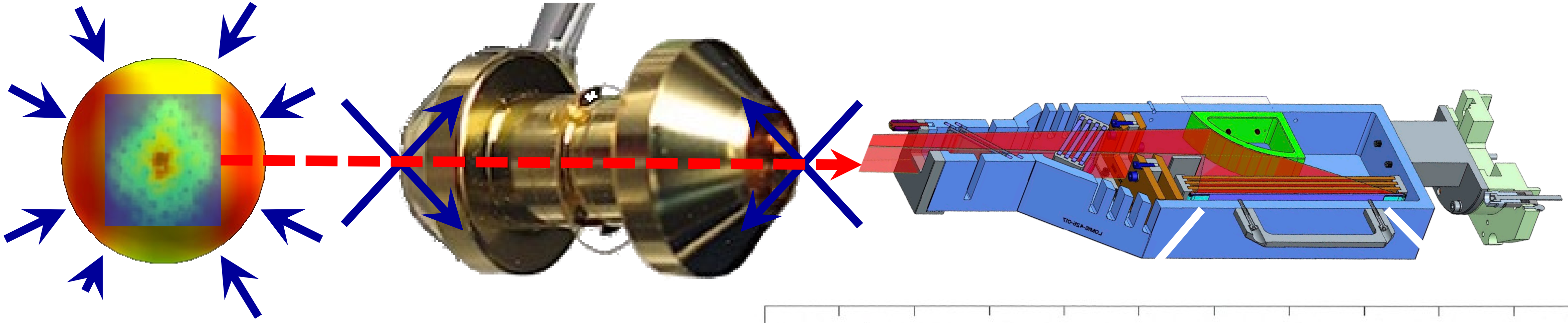




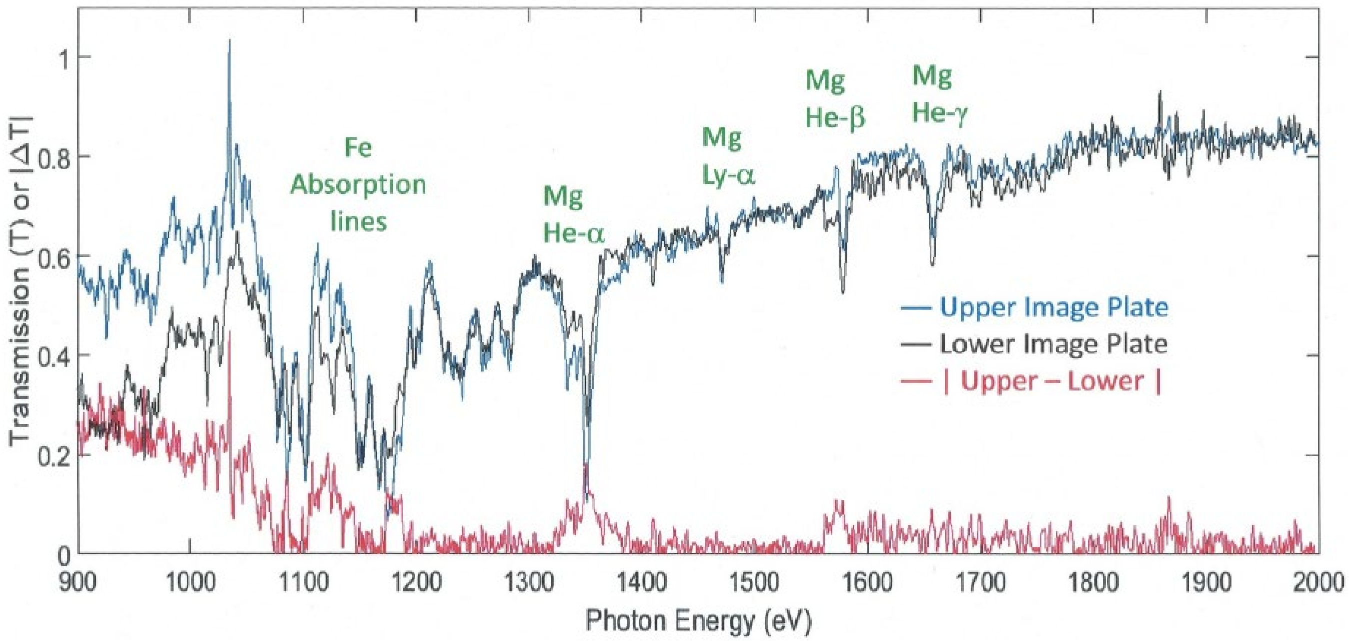


Images courtesy of the Neutron Imaging Team

LANL (as part of multi-laboratory collaboration*) Opacity-on-NIF experiments will help resolve a long standing discrepancy concerning the location of the boundary between the radiative and convective zones of the sun.



Recent experiments on the Sandia Z machine have shown large discrepancies between measured and calculated opacities of iron at certain solar conditions, which changes the predictions of the R-C boundary location. To help address these discrepancies, LANL is developing experiments to replicate these opacity measurements on the NIF.



*LANL, LLNL, SNL, LLE, GA, NNSS

Perry *et al.*, *HEDP* (2020)

Things I hope I have taught you today…

HED systems are plasmas at pressures so high they can change the chemical and atomic properties of matter

Laser light is one of the best ways to drive an HED system since it can get a large amount of energy into a small volume extremely quickly

Inertial confinement fusion attempts to implode DT fuel targets to fusion conditions of 100s of Gigabar pressures

Studying basic HED science gives us insight in wide variety of topics from ICF to astrophysics

Thank you!

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Delivering science and technology
to protect our nation
and promote world stability