LLNL-PRES-618914

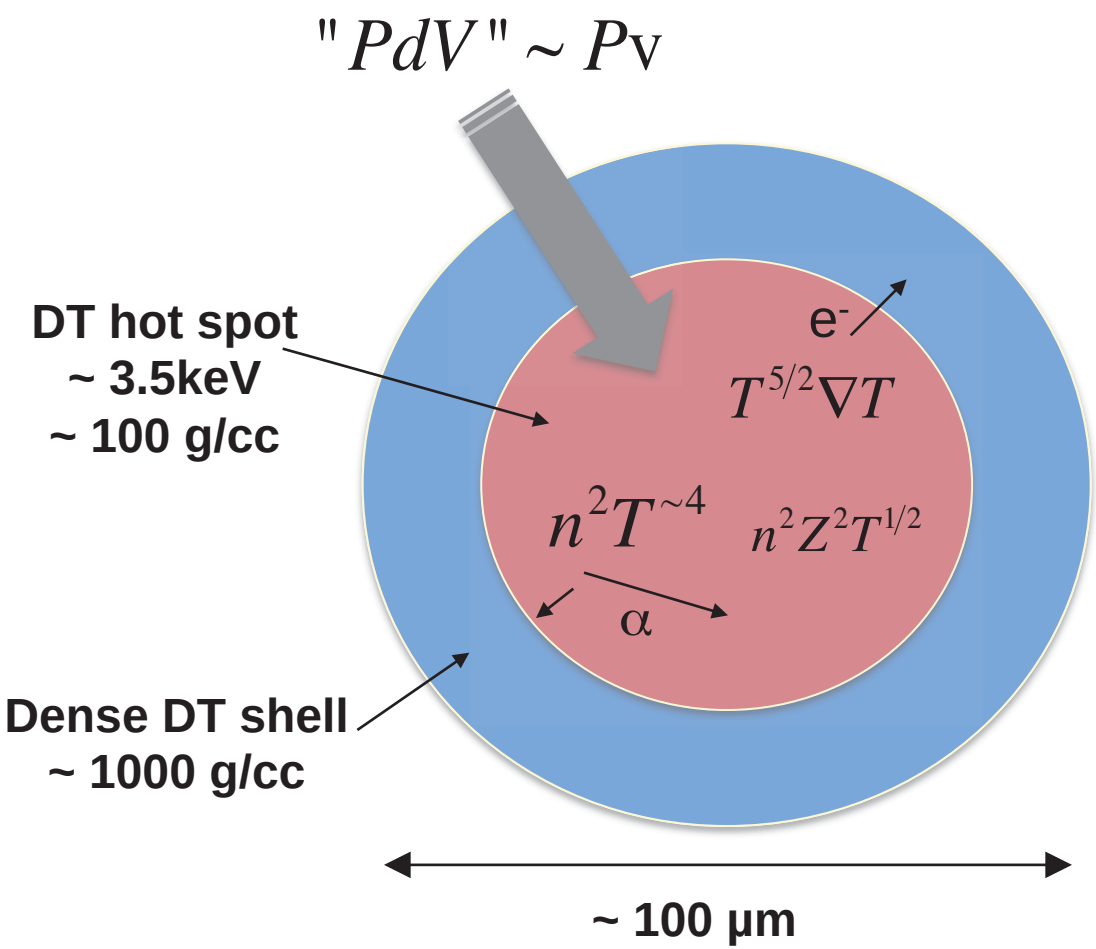
Progress towards ignition on the NIF

John Edwards

February 13, 2013

NIF

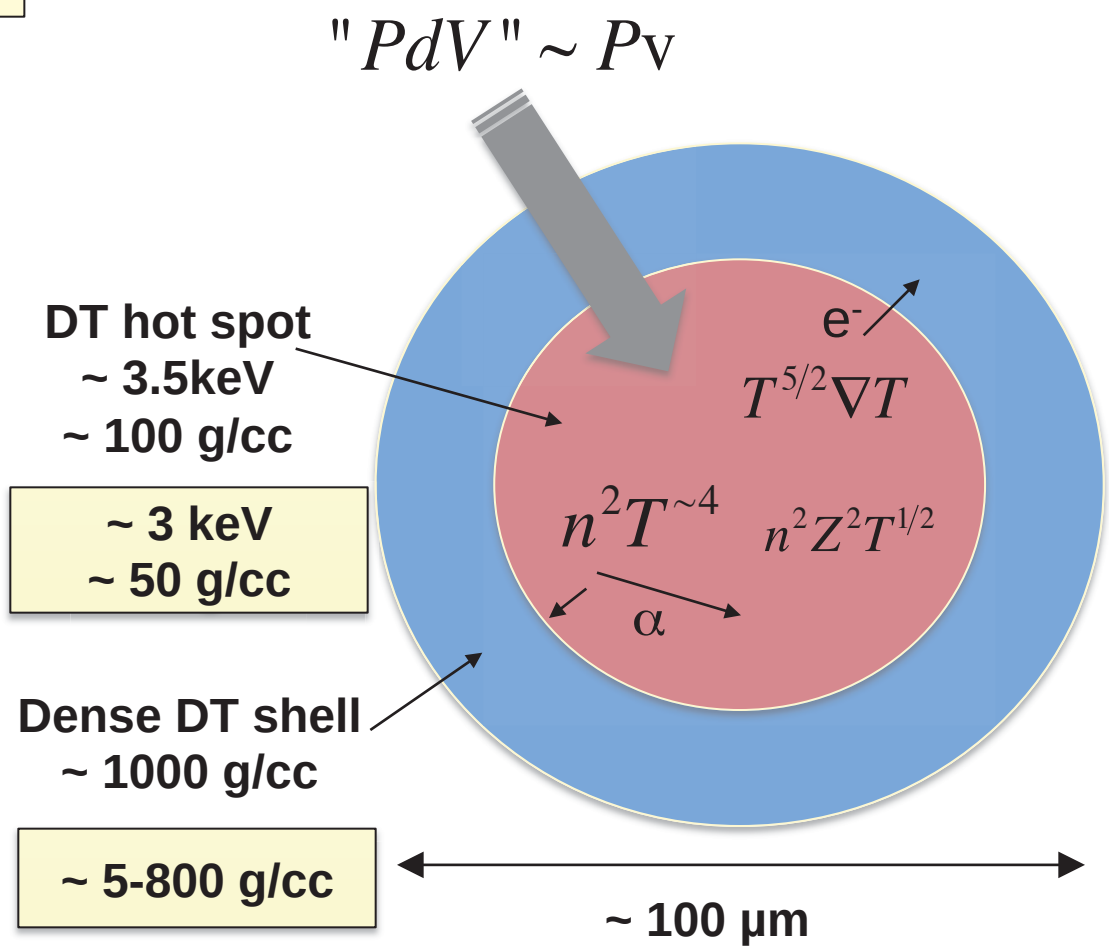
Ignition on the NIF requires extremes in density and temperature



Pressure ~ 350 Gbar
Fuel ρR ~ 1.5 g/cm²

NIF has made good progress towards achieving the conditions necessary for ignition

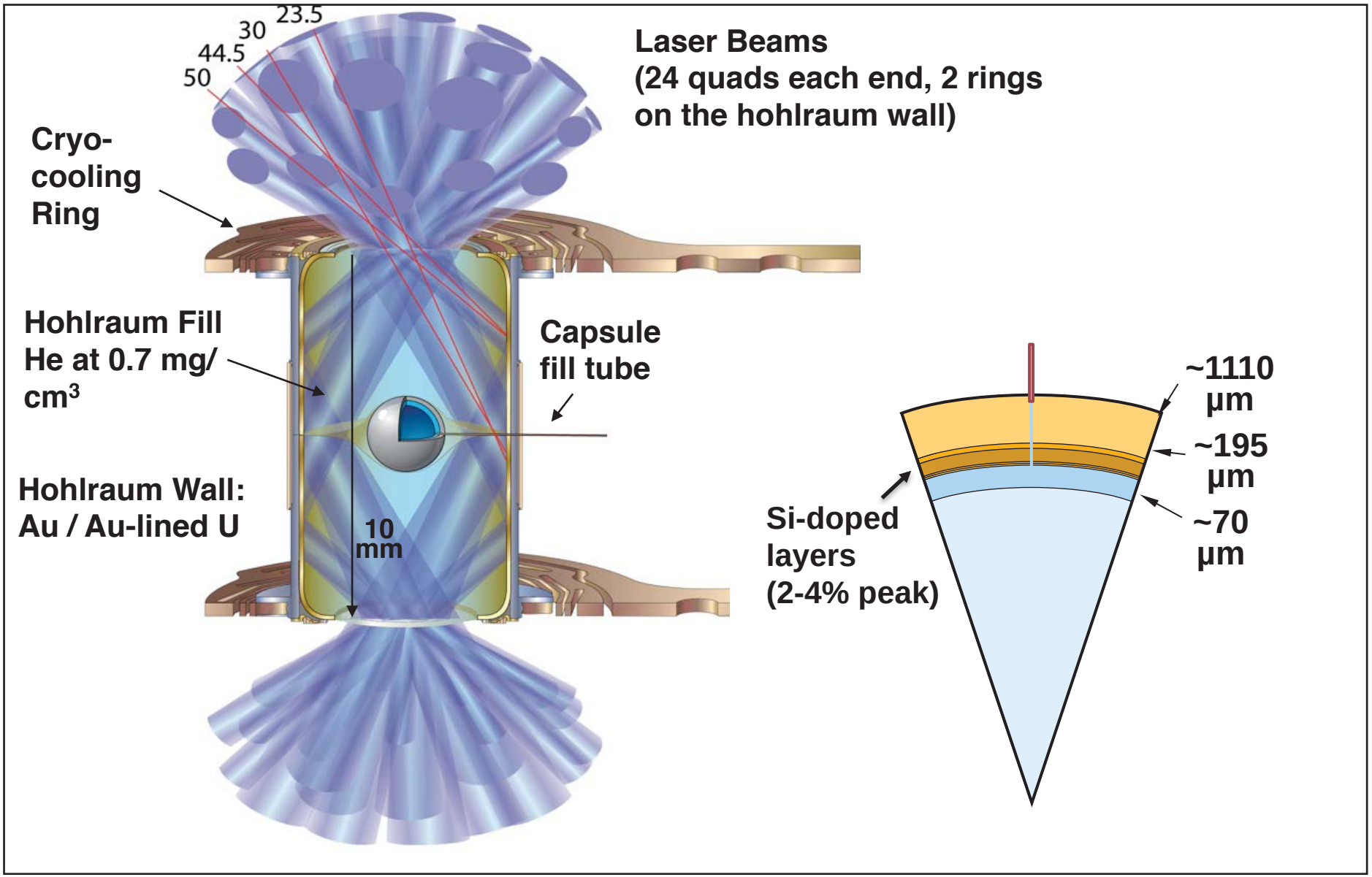
Status



- Peak neutron yields are ~ 10^{15}
- ~ 3-10X from alpha dominated regime

Pressure	~ 350 Gbar	~ 150 Gbar
Fuel ρR	~ 1.5 g/cm^2	~ 1.3 g/cm^2

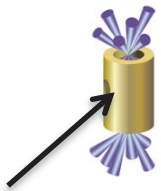
The ignition point design has a graded doped CH capsule in a Au/DU hohlraum



The NIF ignition point design was set by codes calibrated against experiments on Nova and Omega

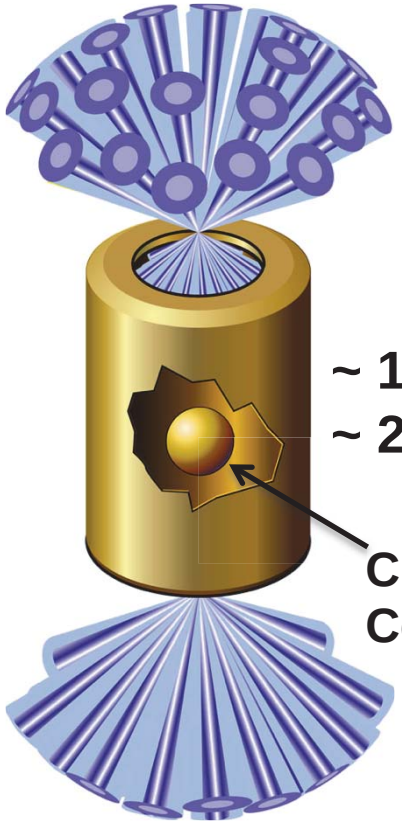
NIF
~ 1.8MJ

Nova / Omega
~ 20 kJ



~ 2.5 mm
~ 2ns, 2-step pulse

Gas filled capsules
Convergence ratio ~ 20



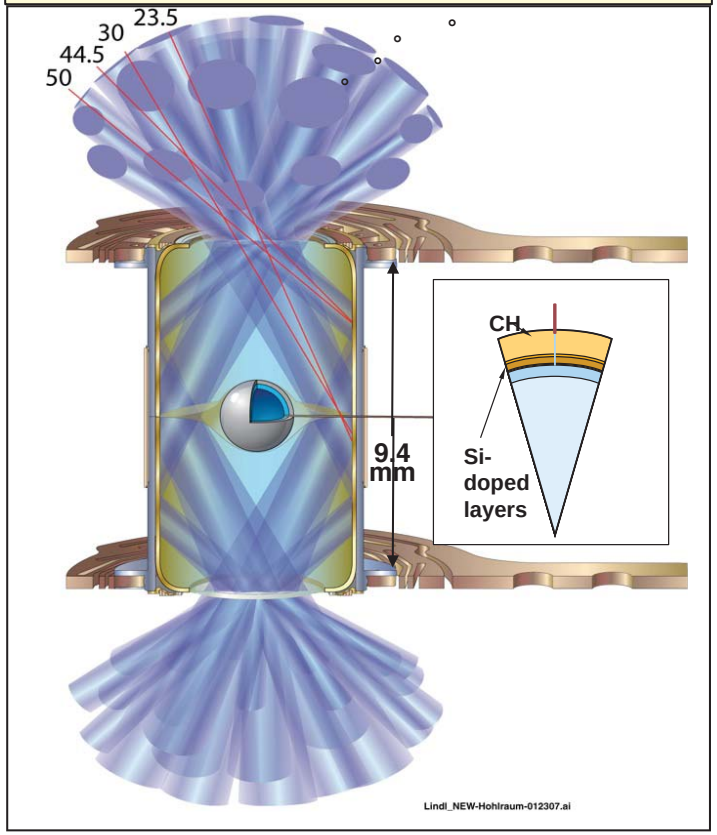
~ 10 mm
~ 20ns, 4-step pulse

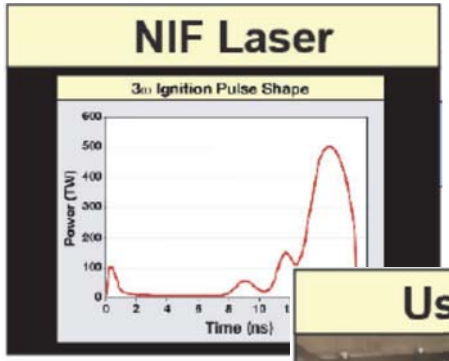
Cryo layered capsules
Convergence ratio ~ 40

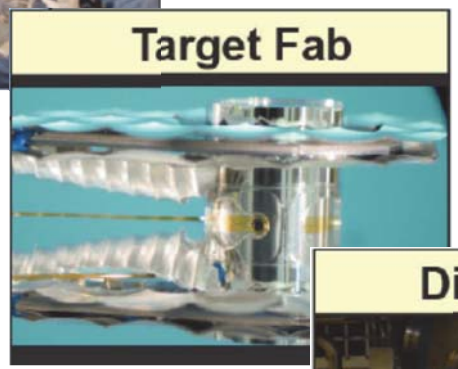
- **Physics uncertainties remained at NIF scale**
- **The point design included an experimental campaign and evolution in the point design was anticipated based on results**

The point design drove demanding technical requirements

Doped plastic cryogenic layered point design

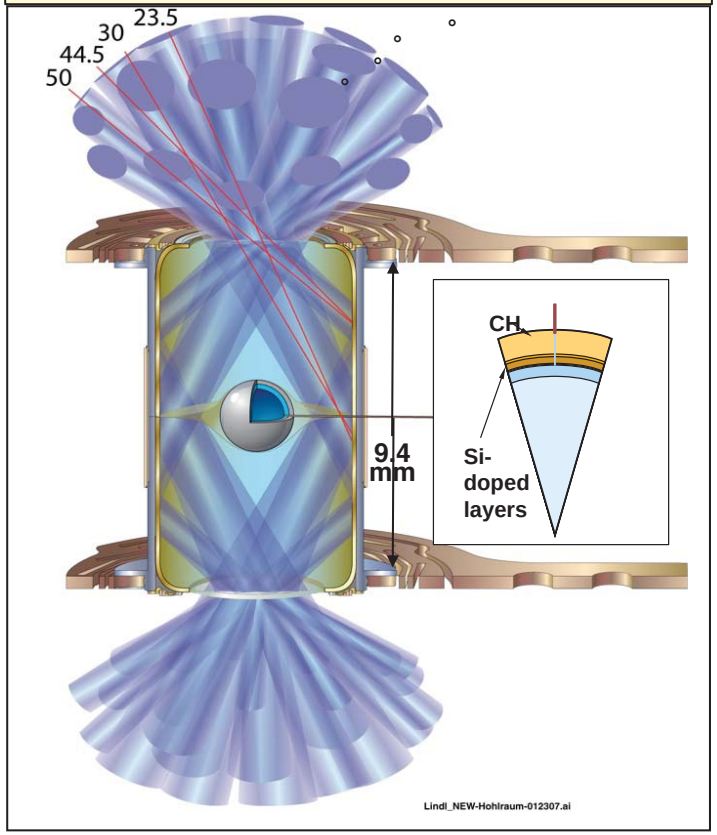


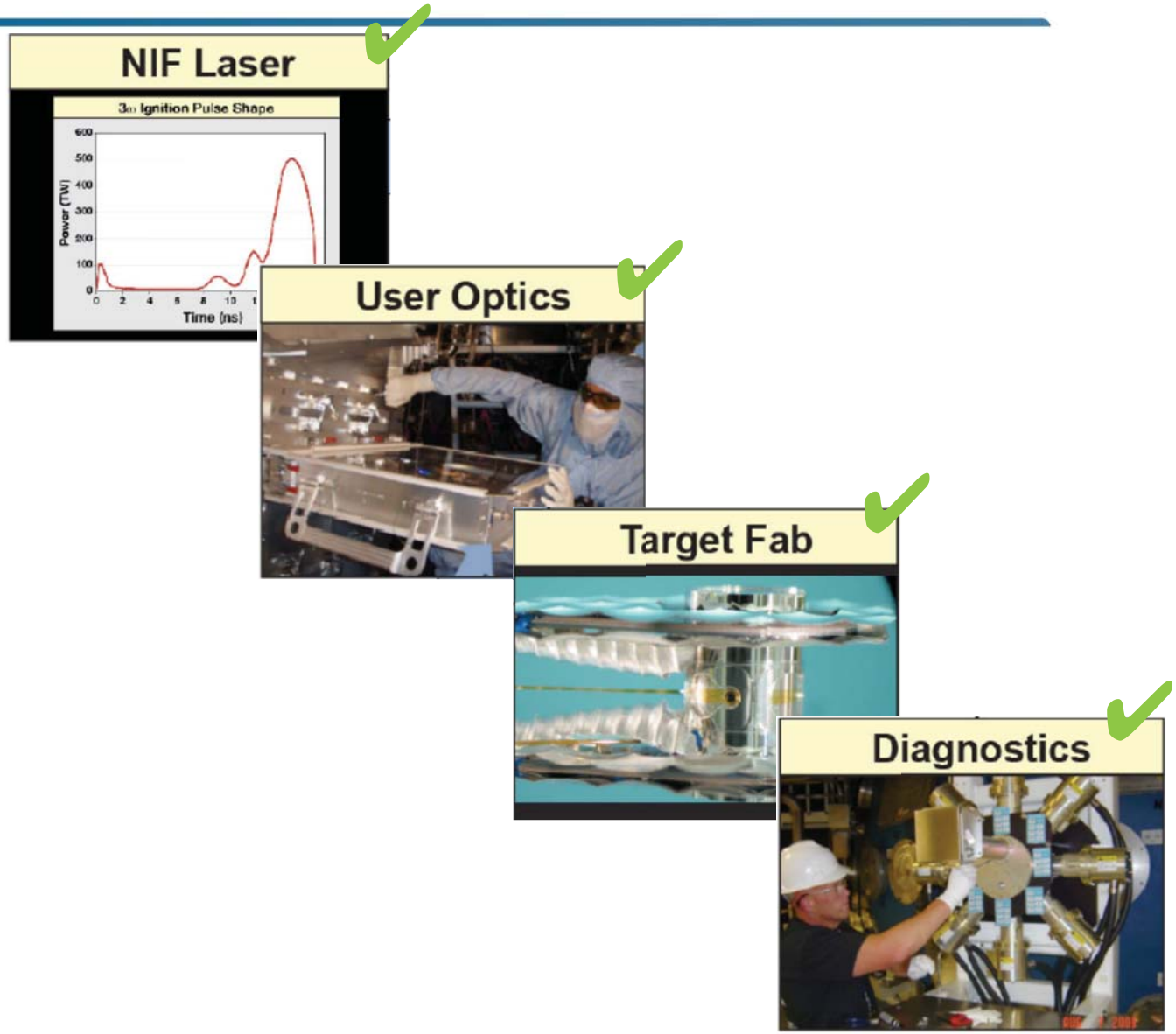




The point design drove demanding technical requirements

Doped plastic cryogenic layered point design





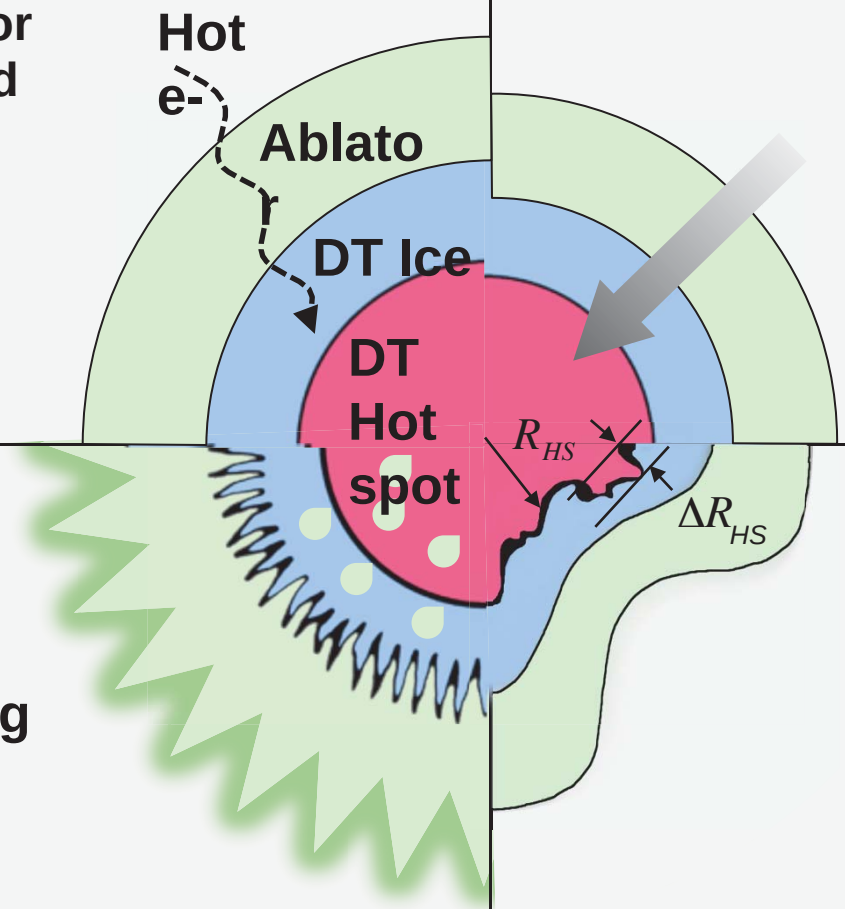
Point design set requirements on implosion properties to achieve the stagnated fuel conditions for ignition

α Adiabat

High compression for ρR – trap alphas, and confinement

Velocity V

PdV power to heat hot spot



Radiative cooling

Efficient conversion of implosion KE to hot spot thermal energy

M Mix

Shape S

Most of the experimental requirements set by the point design have been ~ met individually

α Adiabat

α ~ 1.5
ρR_{DT} ~ 1.45 g/cm^2

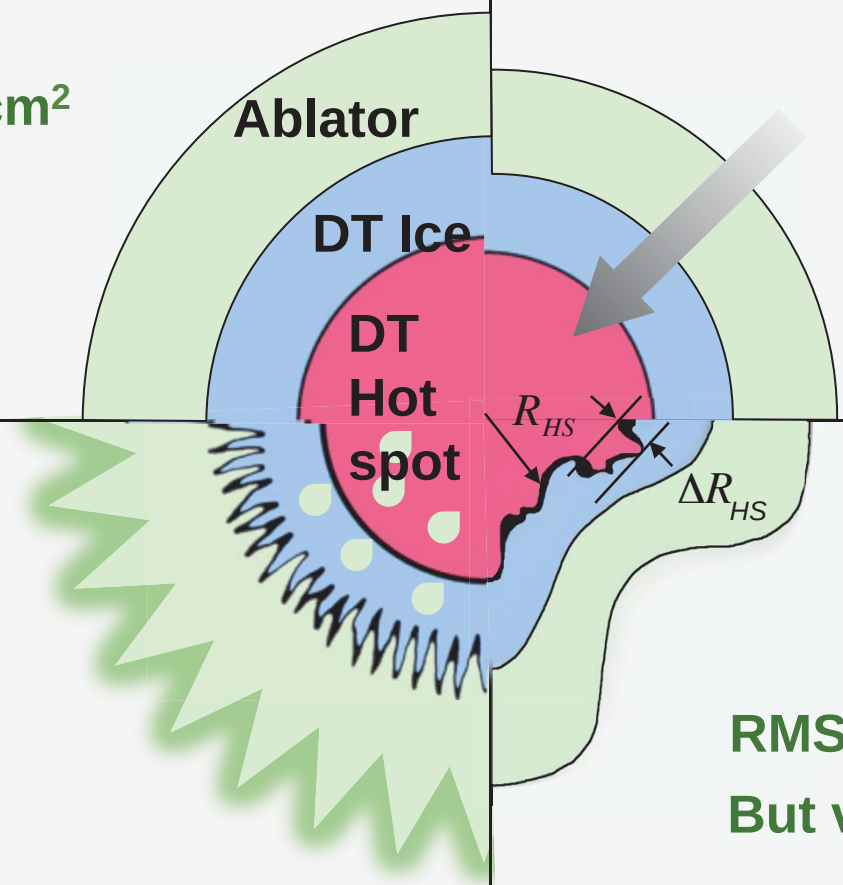
α ~ 1.5
ρR ~ 1.2-1.3 g/cm^2

Velocity V

V_{DT} ~ 370 km/s

V ~ 350-370 km/s

T_{RAD} > 300eV



M Mix

< 100ng
But variable

CH mix in hot spot < 100ng

Shape S

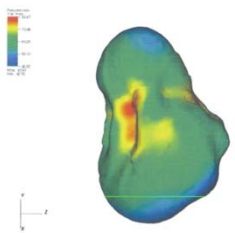
RMS hot spot shape < 10%
But variable

RMS hot spot shape < 10%

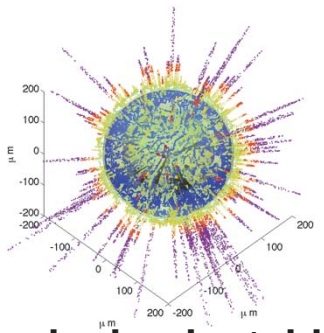
The principal issues and go-forward strategy were summarized in NNSA's report to Congress

- **Nuclear yields are ~ 3-10X from alpha dominated regime - hotspot densities, pressures are ~ 2-3X lower than predicted/required**

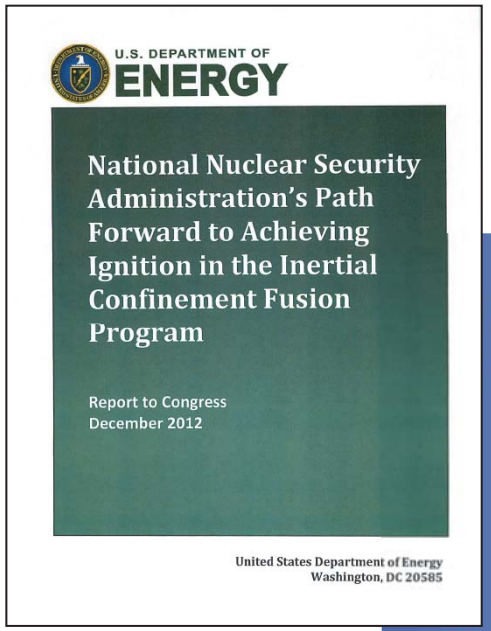
- **Performance deficit likely due to combination of low mode X-ray drive asymmetry/cold fuel shape, and higher than simulated hydrodynamic instability**

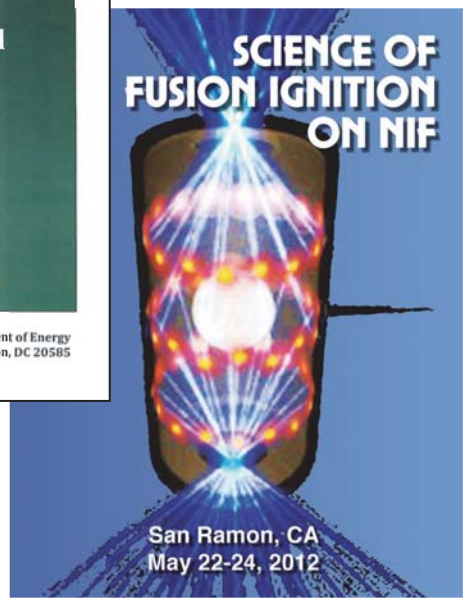


Hot spot



Implosion instability



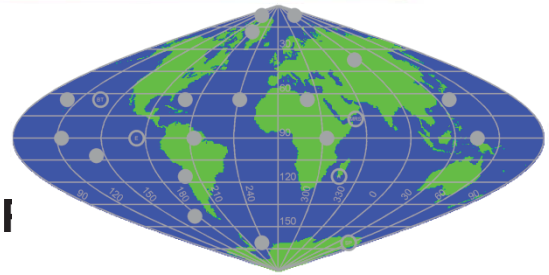


Identifying the reasons for the deficit in pressure/performance and developing mitigation strategies is a key element of the go-forward experimental plan

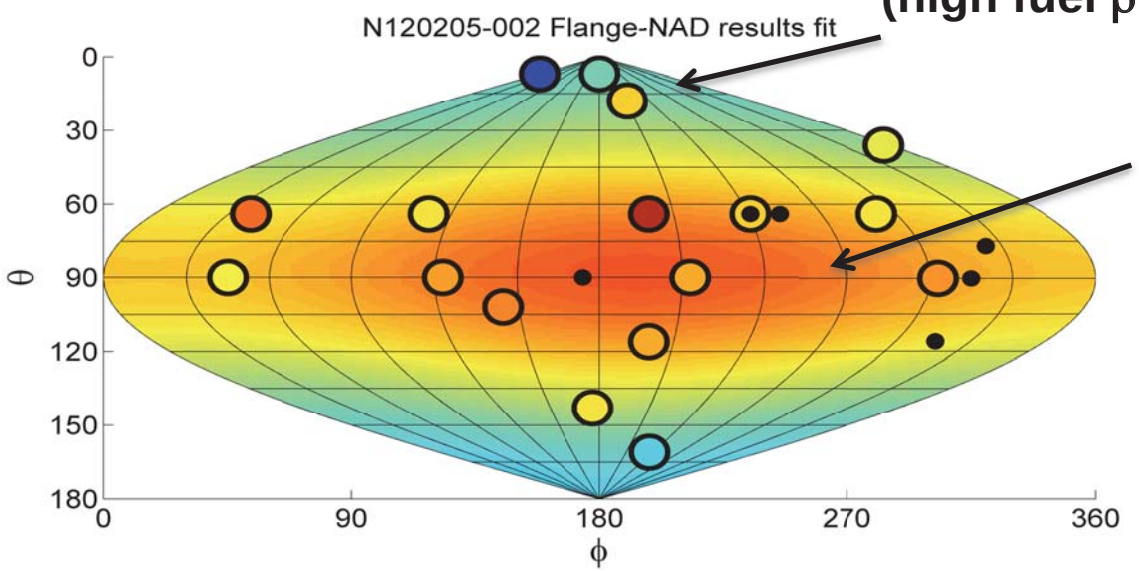
Evidence - low mode fuel asymmetry
Zirconium neutron activation detectors indicate significant fuel ρR asymmetry ~ 50-100%

$^{90}Zr(n,2n) \Rightarrow {}^{89}Zr$

Low order fit to > 13MeV neutrons

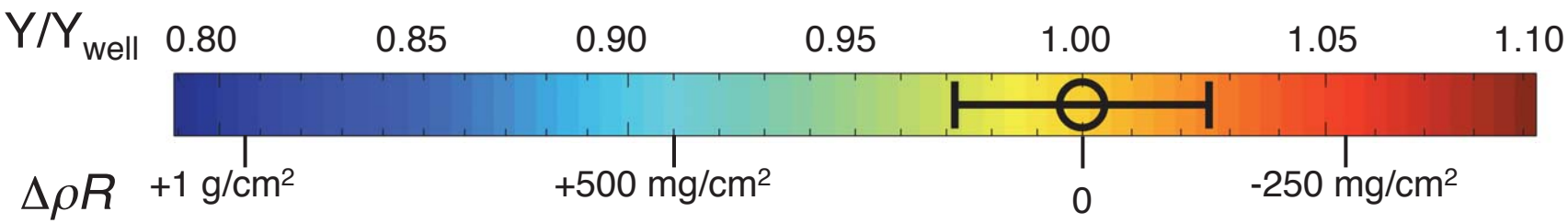


Low signal (high fuel ρR)

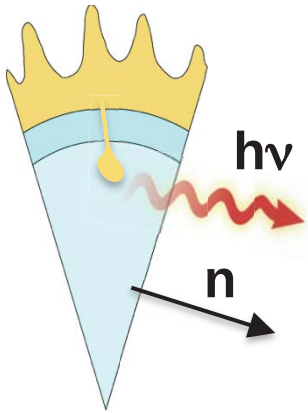


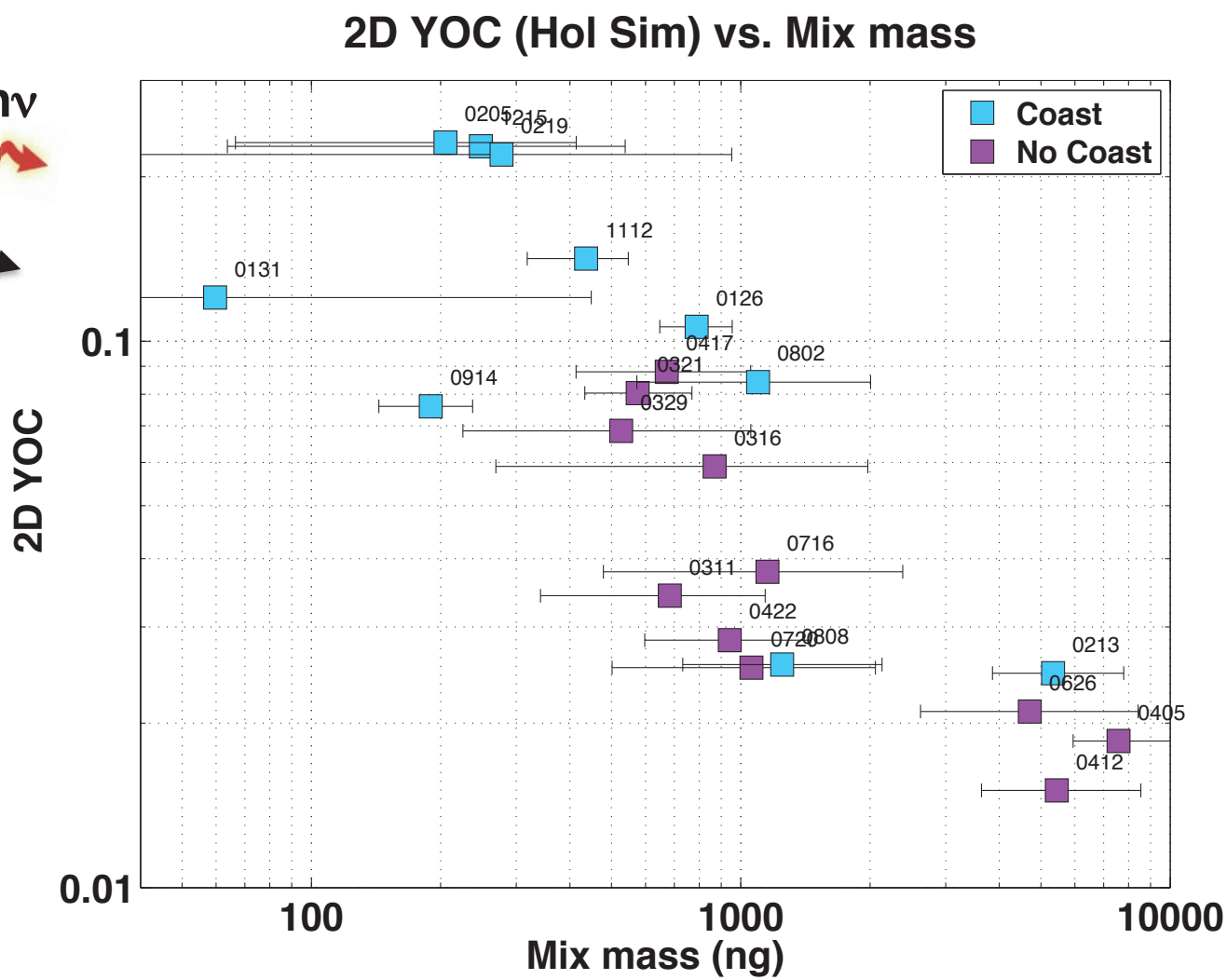
High signal (low fuel ρR)

- **Average ρR ~ 1 g/cm²**
- **~ 50% variations**

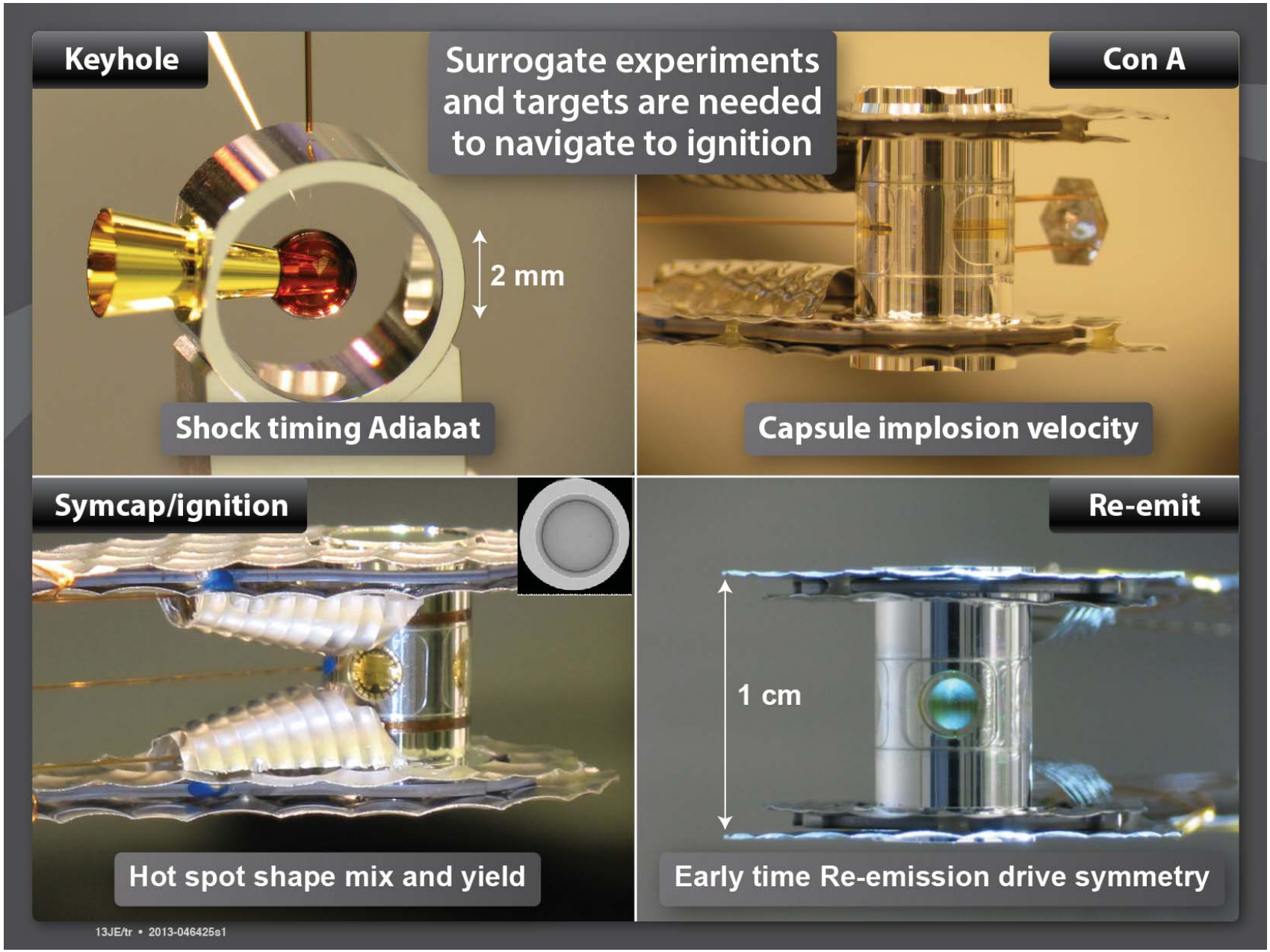


Evidence – Mix
Implosion performance correlates with mix in layered DT implosions



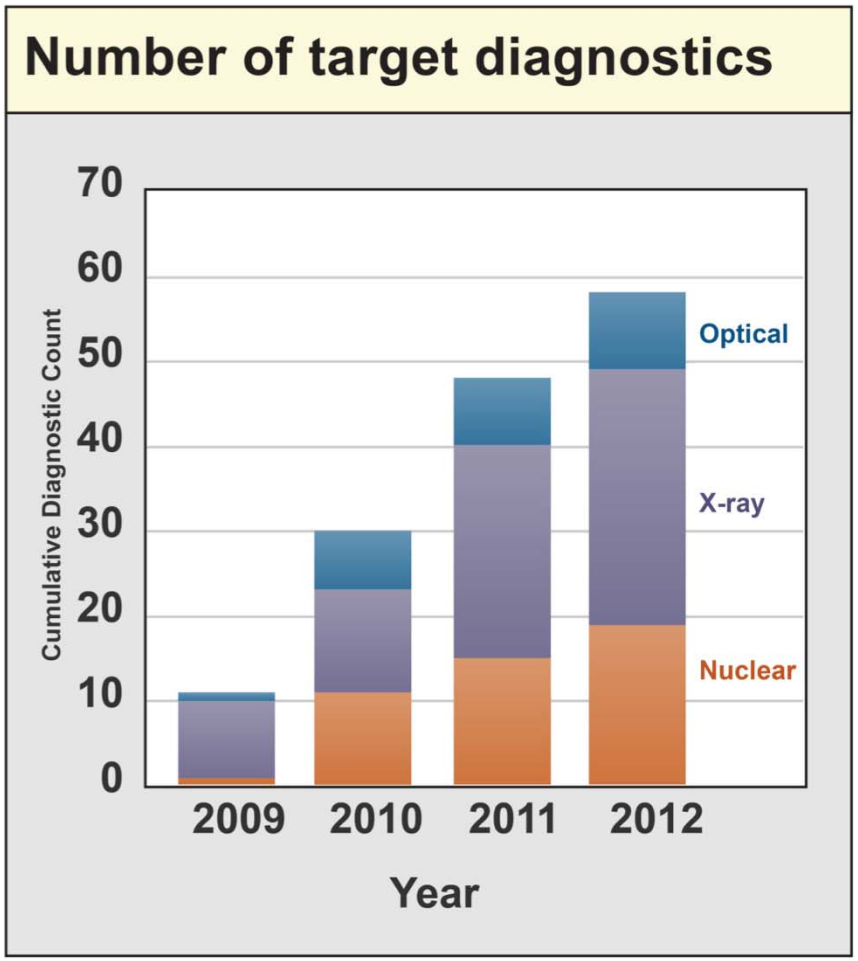


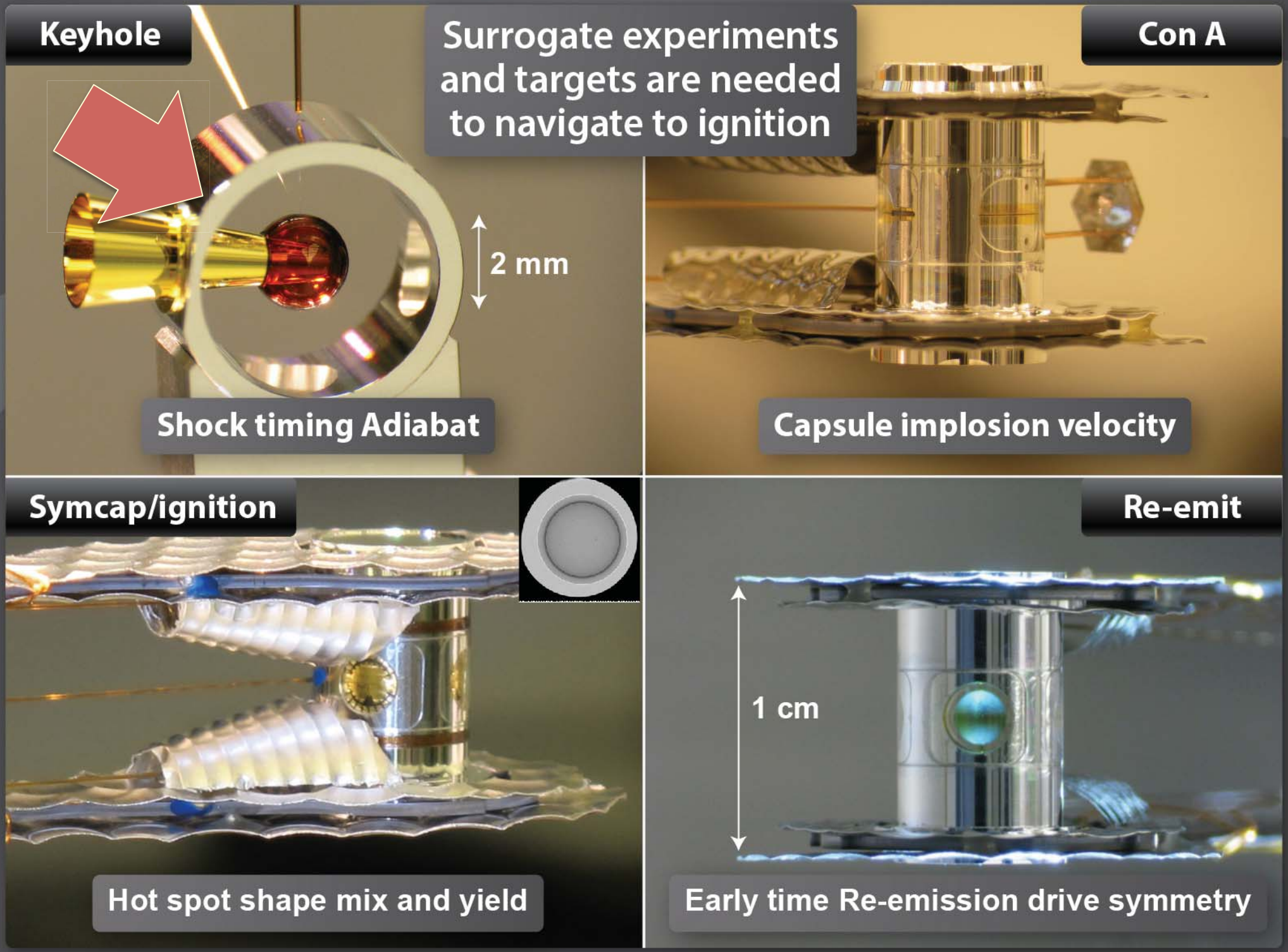
Progress requires experiments for relevant physics > 15 platforms developed and growing



Progress requires state of the art diagnostics ~ 60 and growing

- LLNL
- LANL
- LLE
- NSTec
- U of M
- LBNL
- AWE
- MIT
- CEA
- Duke
- SNL
- GSI





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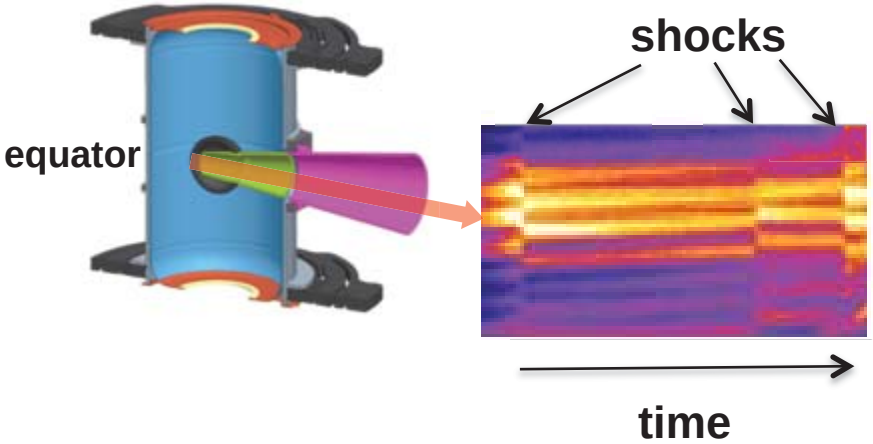
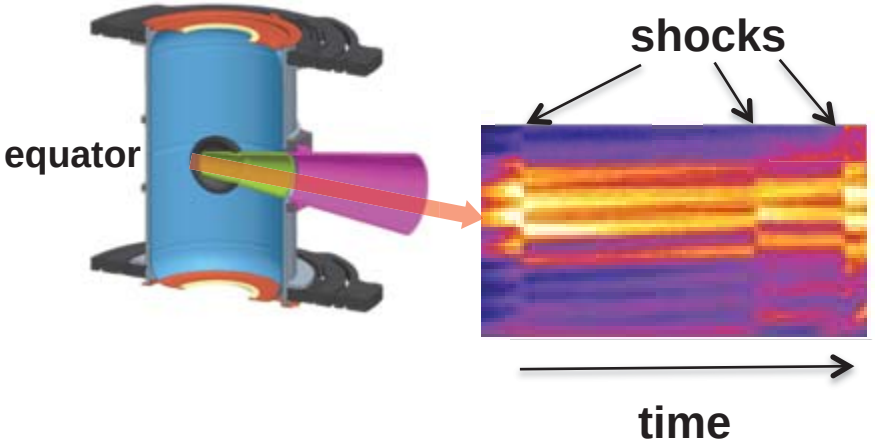
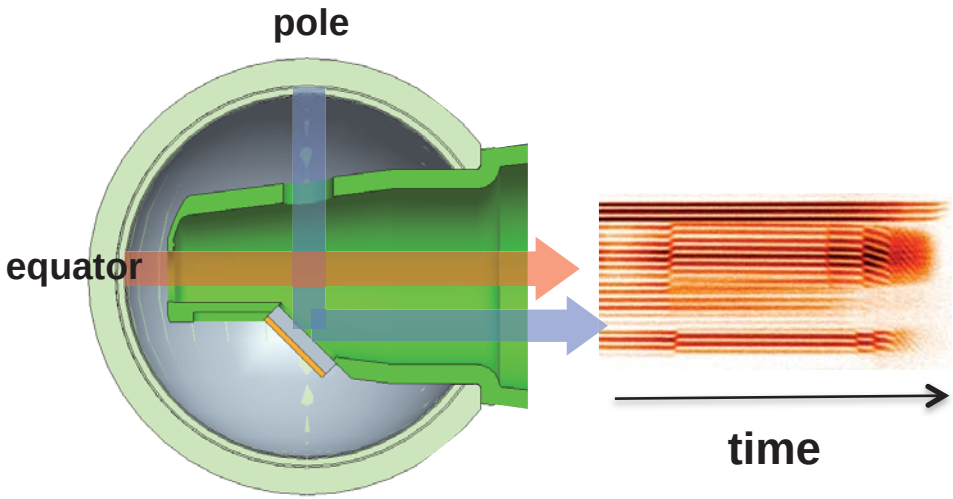
1st gen keyhole – shock timing at waist



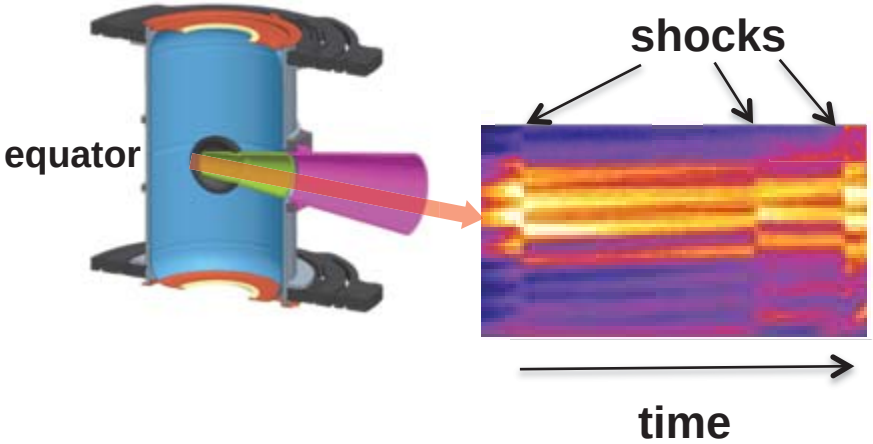
1st gen keyhole – shock timing at waist



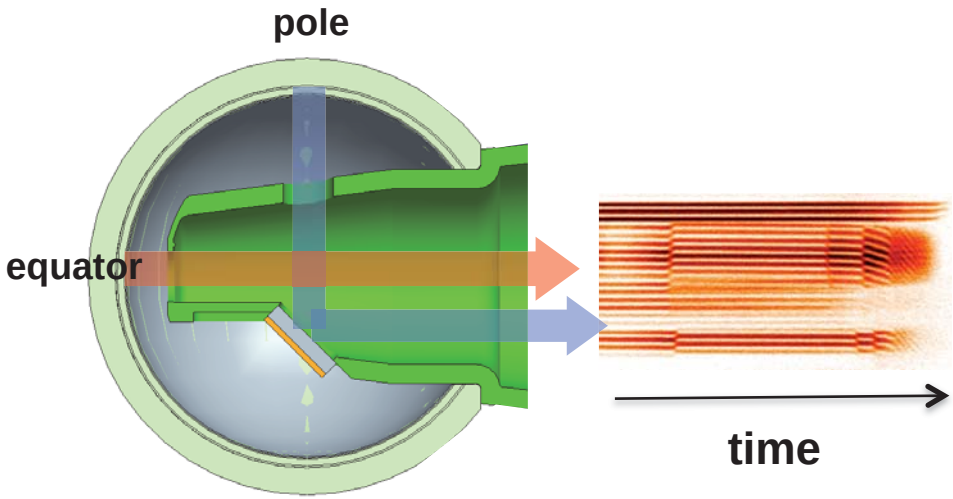
2nd gen keyhole – dual-axis (P2)



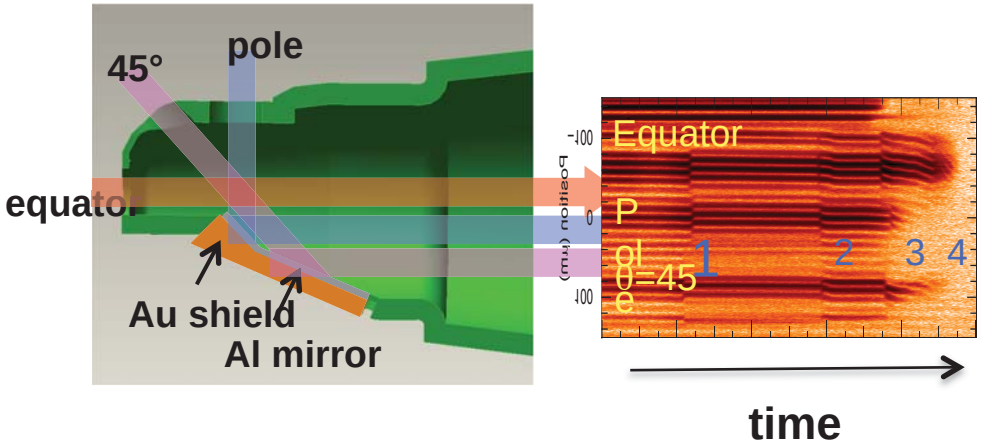
1st gen keyhole – shock timing at waist



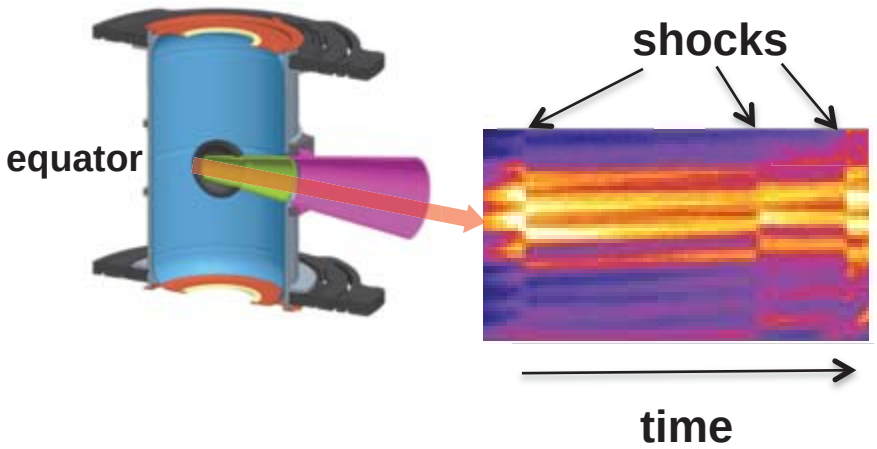
2nd gen keyhole – dual-axis (P2)



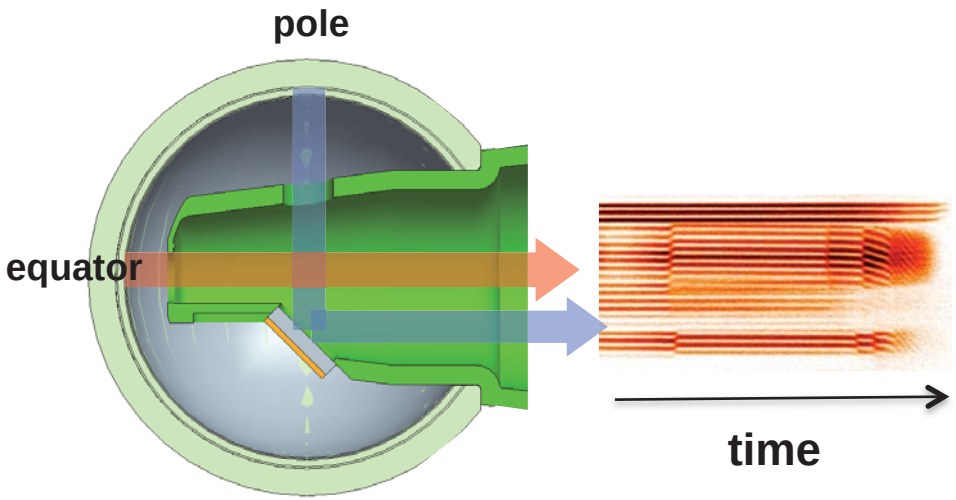
3rd gen keyhole – tri-axis (P1,2,4,m4)



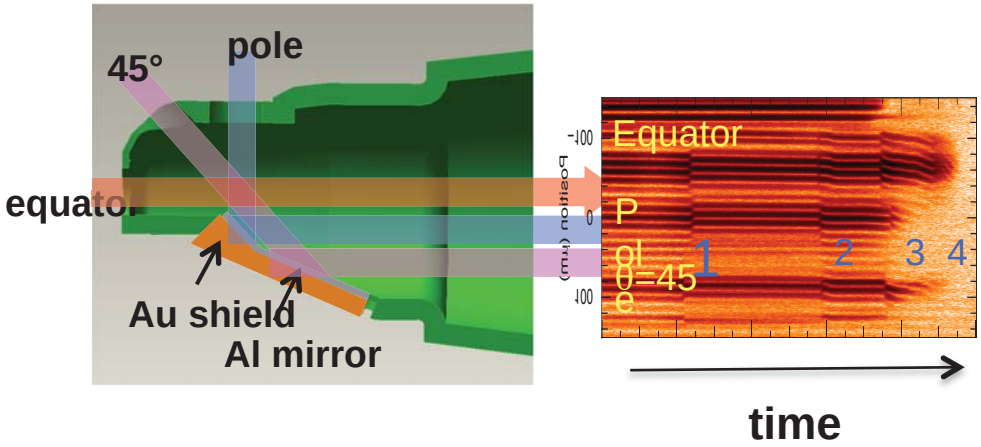
1st gen keyhole – shock timing at waist



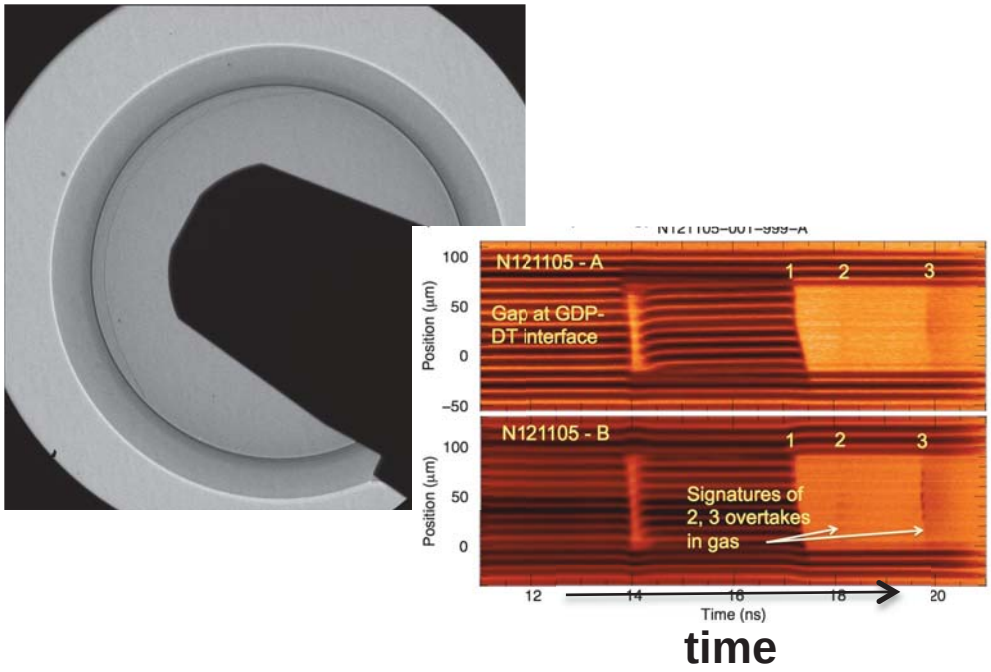
2nd gen keyhole – dual-axis (P2)



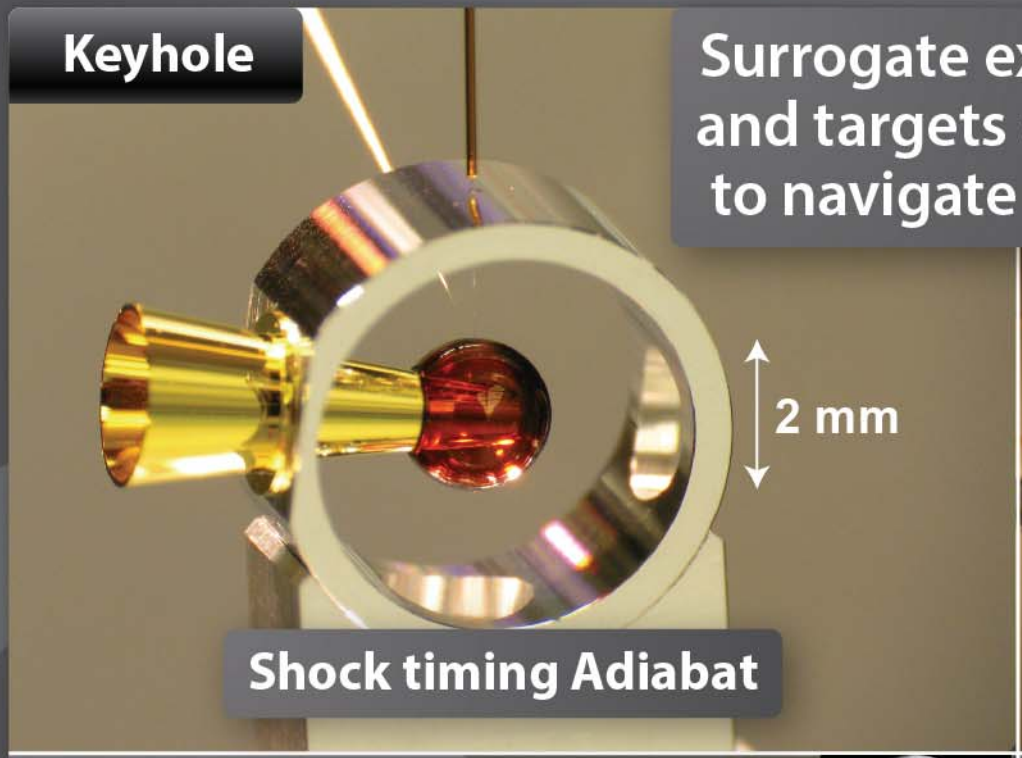
3rd gen keyhole – tri-axis (P1,2,4,m4)

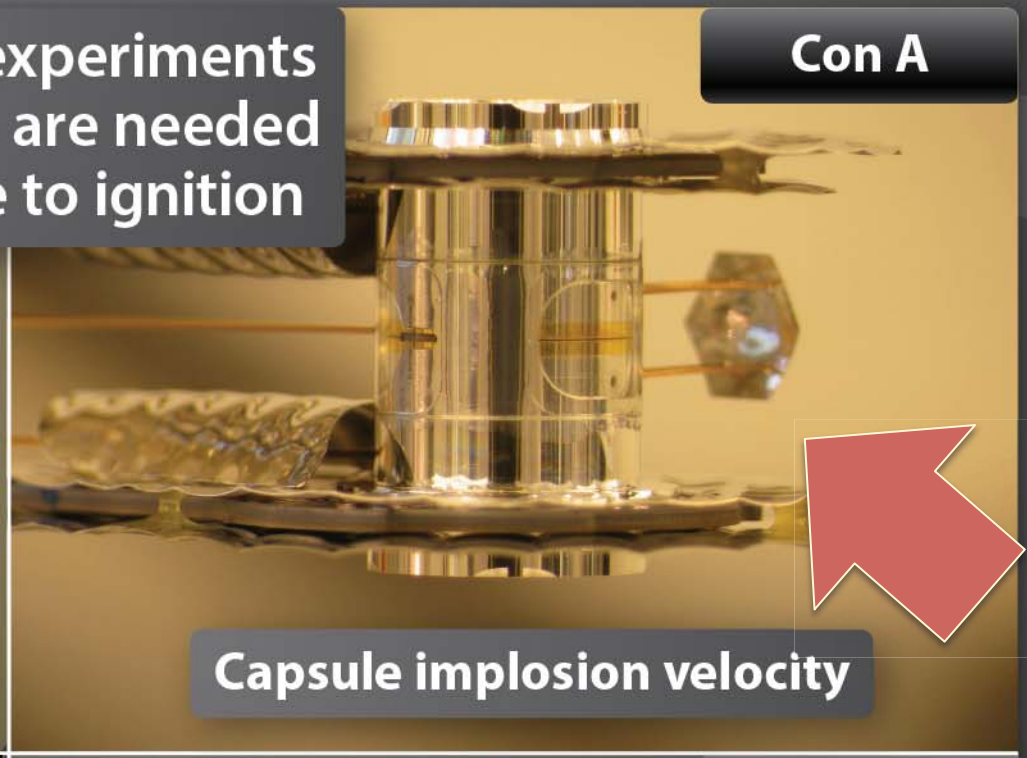


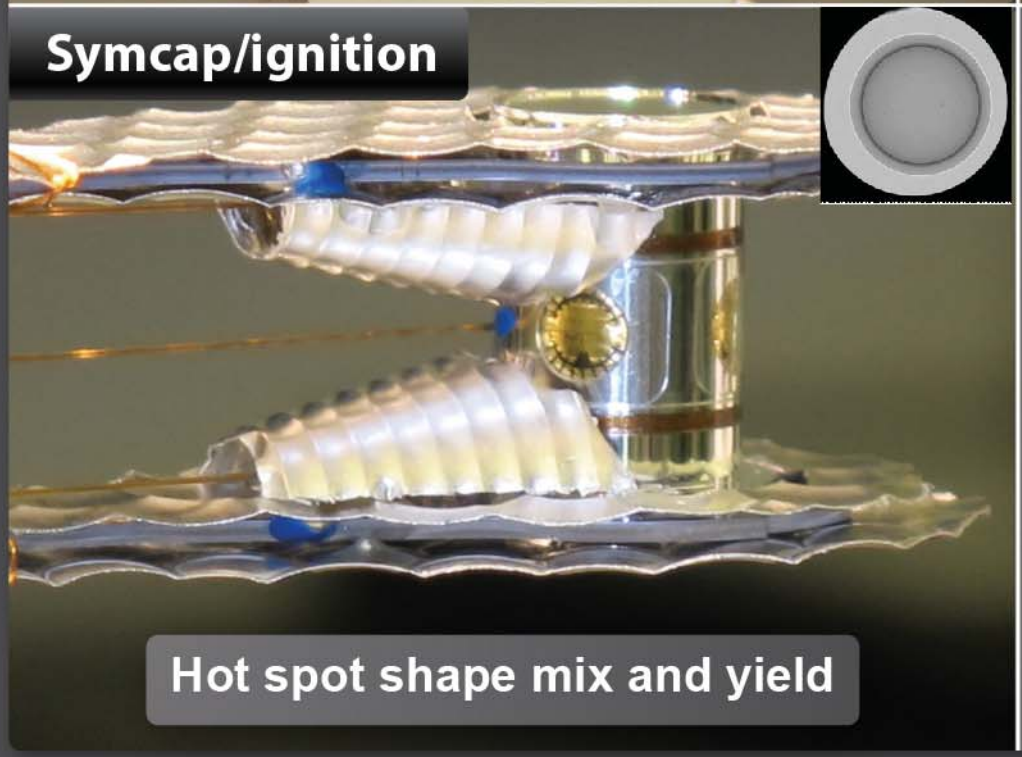
1st gen layered keyhole (DT release)

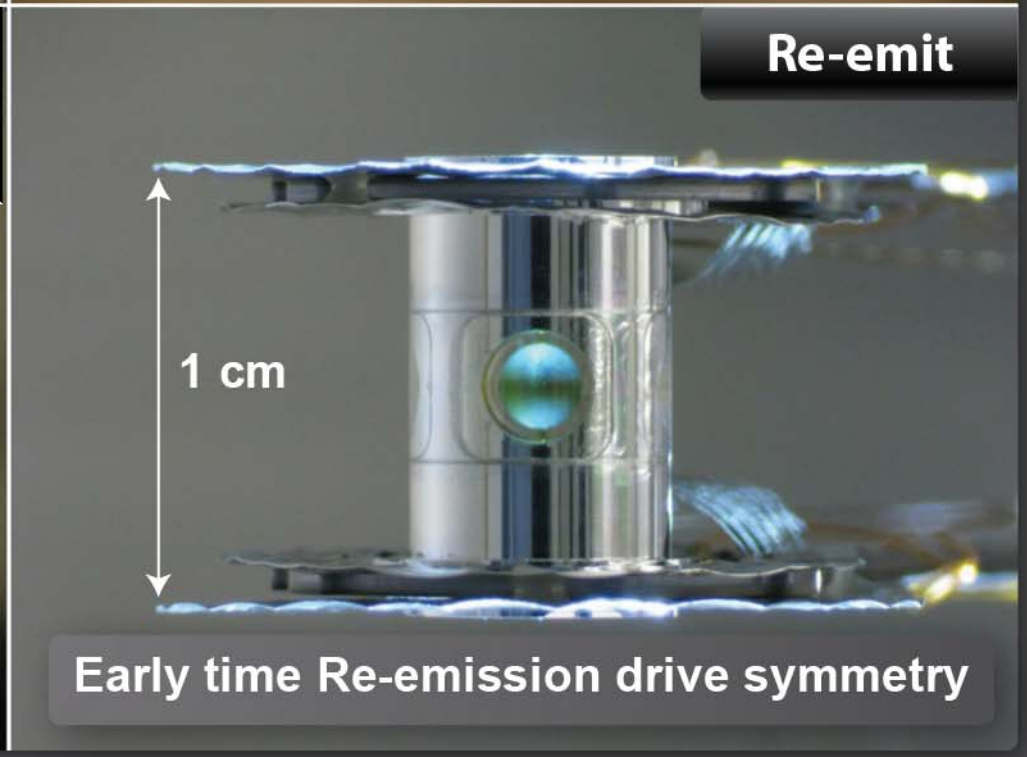


Surrogate experiments and targets are needed to navigate to ignition

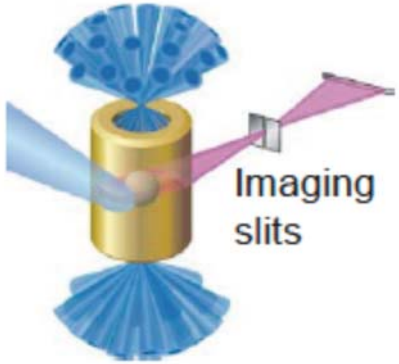


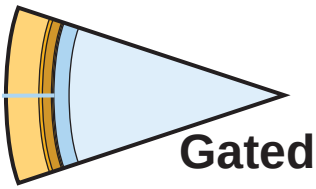




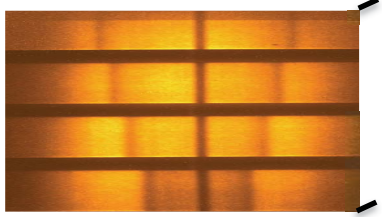


Streaked radiography providing greater insights on implosion dynamics



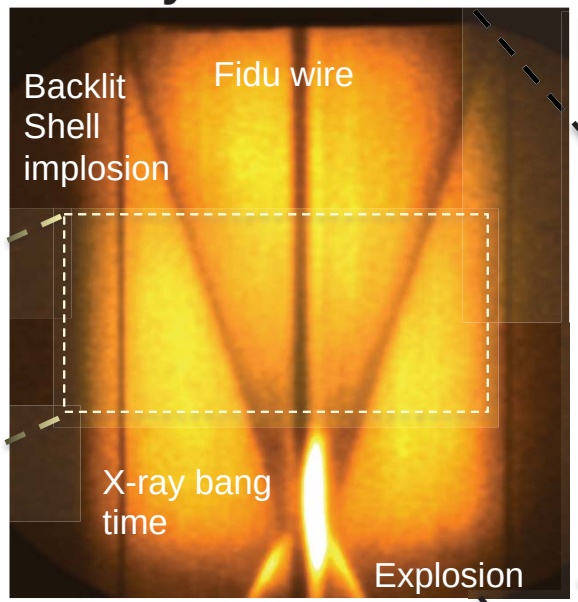


Gated imager
2009



FOV: 1ns x 0.3mm
4 R(t) points

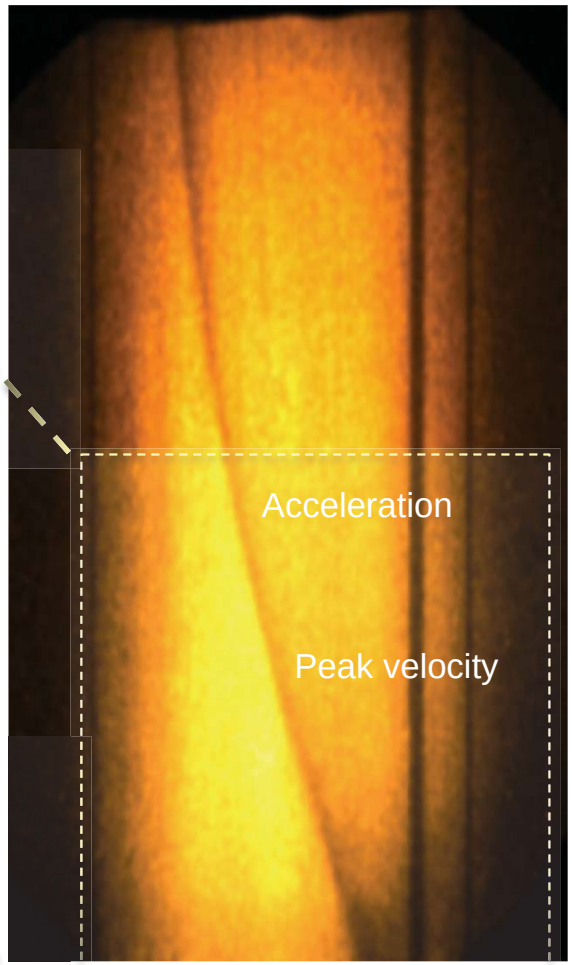
Streaked imager
Peak velocity msmnt
Early 2012



FOV: 2.8ns x 0.6mm

2.8
ns

Long backlighter*
Extended implosion msmnt
N121008



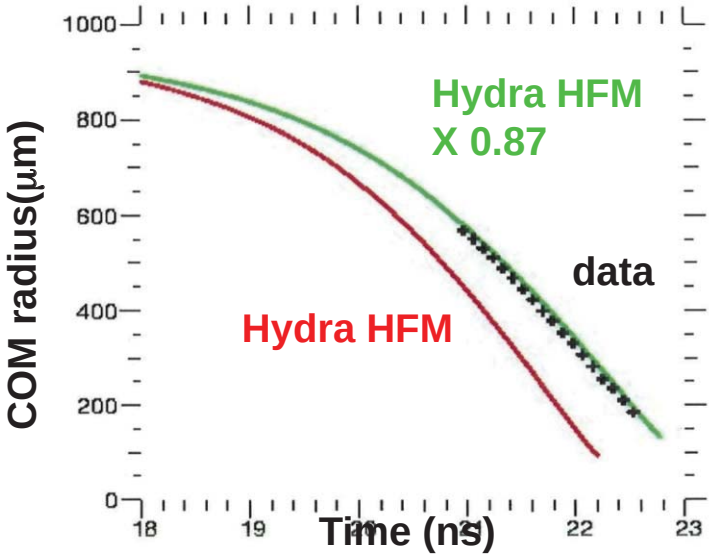
4.6ns

FOV: 4.6ns x 0.9mm

CH (Si2%) capsules in DU hohlraums
Laser drive: 330 TW; 1.4 MJ

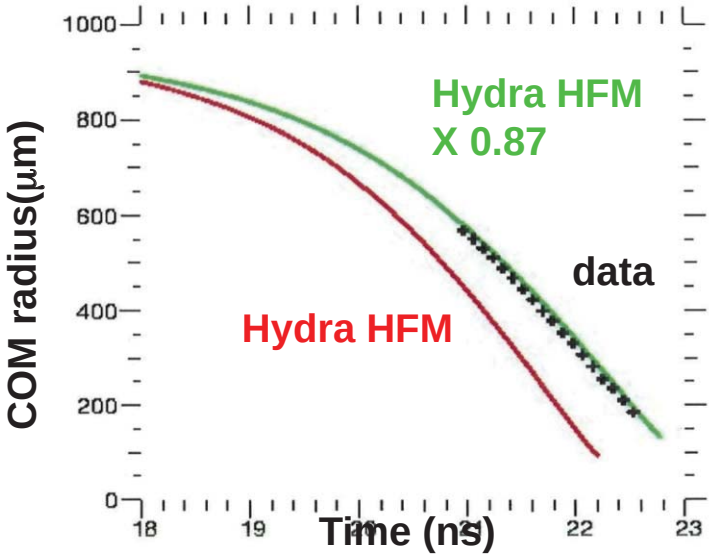
Implosions were slower than the standard hydra high flux model – drive or ablator efficiency?

Measured trajectory requires predicted hohlraum drive to be reduced to ~ 85% ?

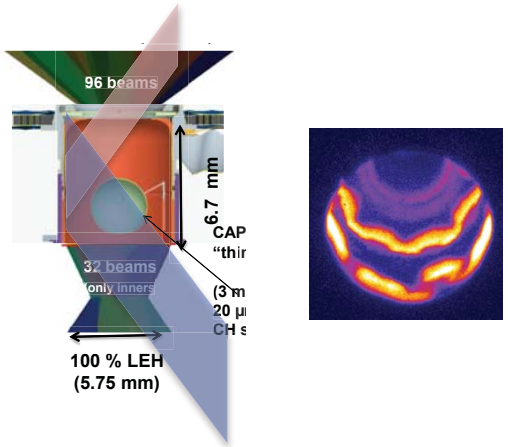


Progress in understanding the 1D implosion

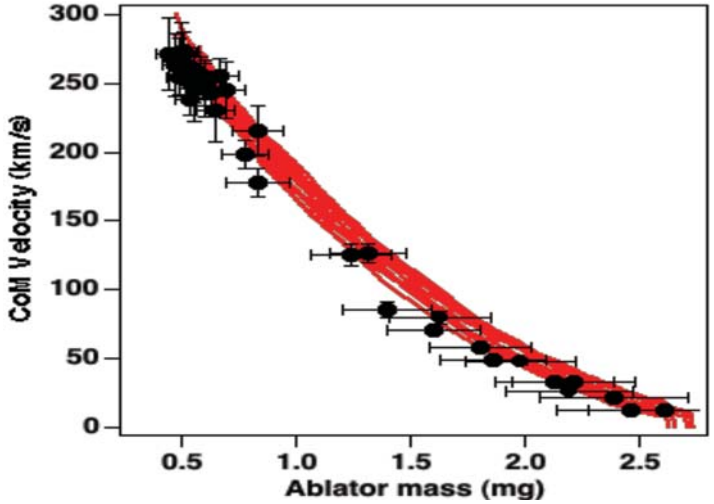
Measured trajectory requires predicted hohlraum drive to be reduced to ~ 85% ?



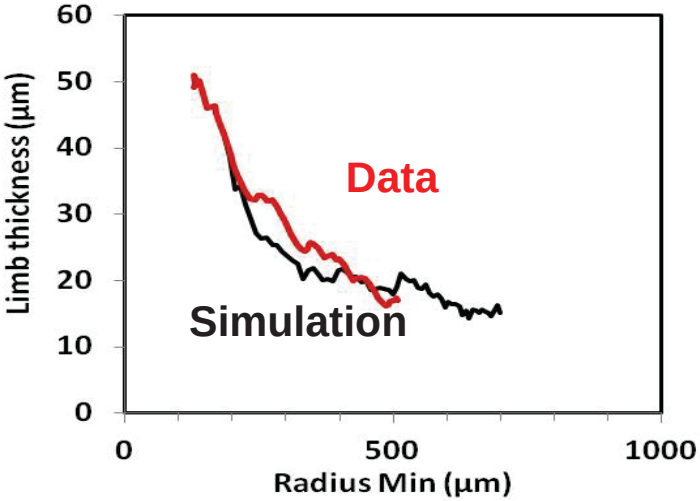
Viewfactor shows X-ray drive on the capsule is lower than simulated by ~ 85% ✔



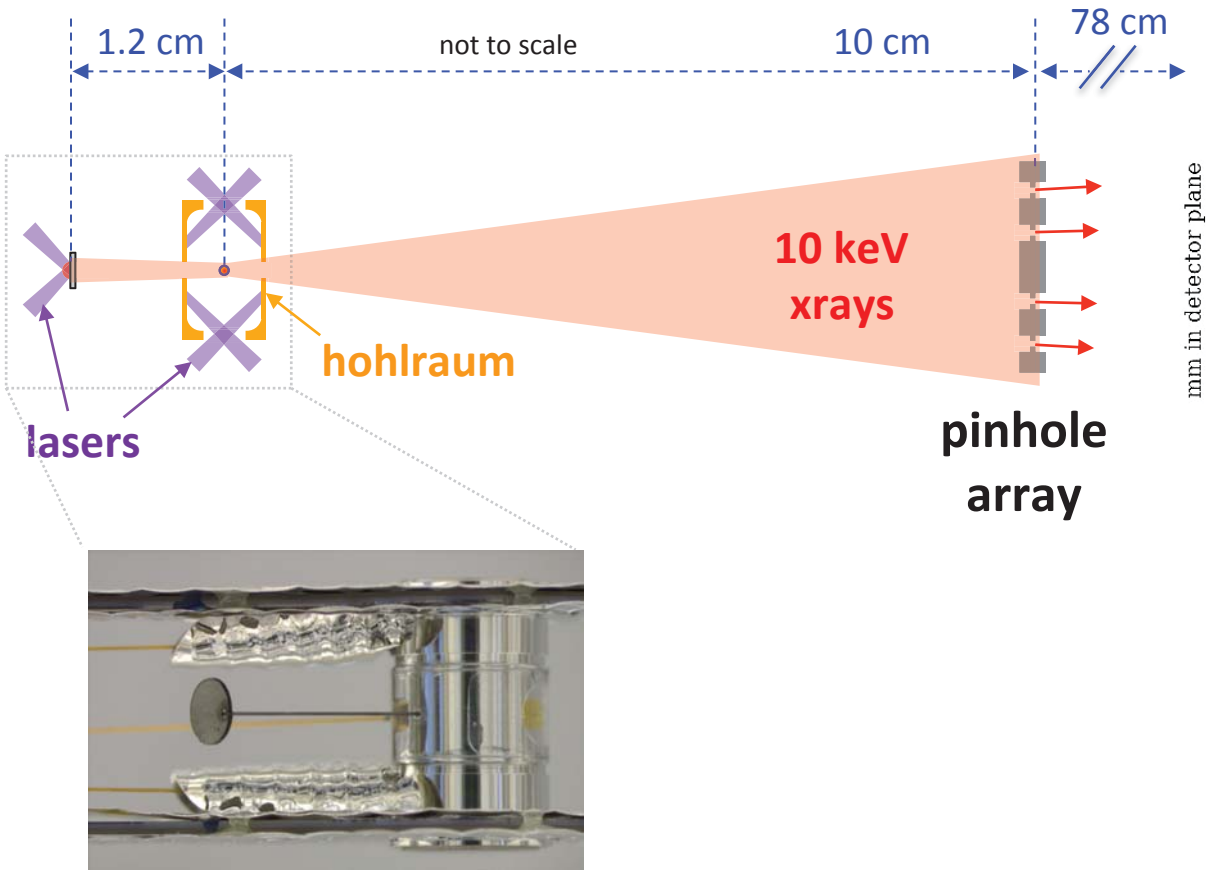
With the reduced drive the CH rocket curve ~ agrees with data within errors ✔



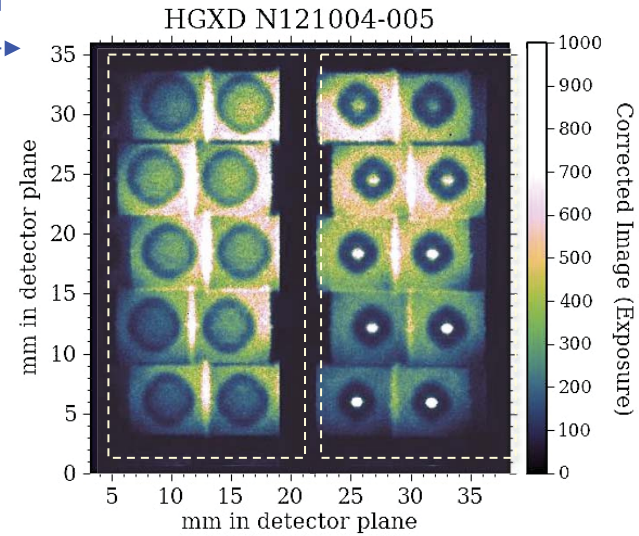
Recent analysis – in-flight thickness becoming consistent with simulations ✔



Backlighting evolved to 2D imaging - “2D ConA” is obtaining excellent data

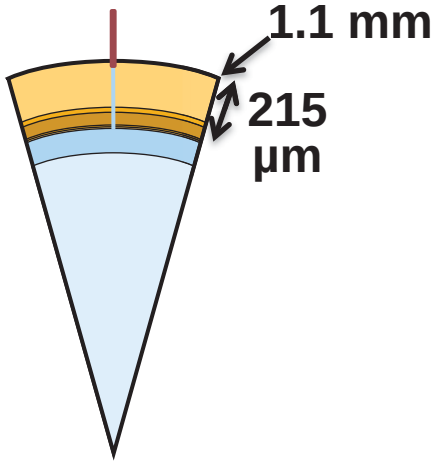


Gated images of imploding capsule on 2-strip camera



N121004

The capsule starts at 2mm diameter

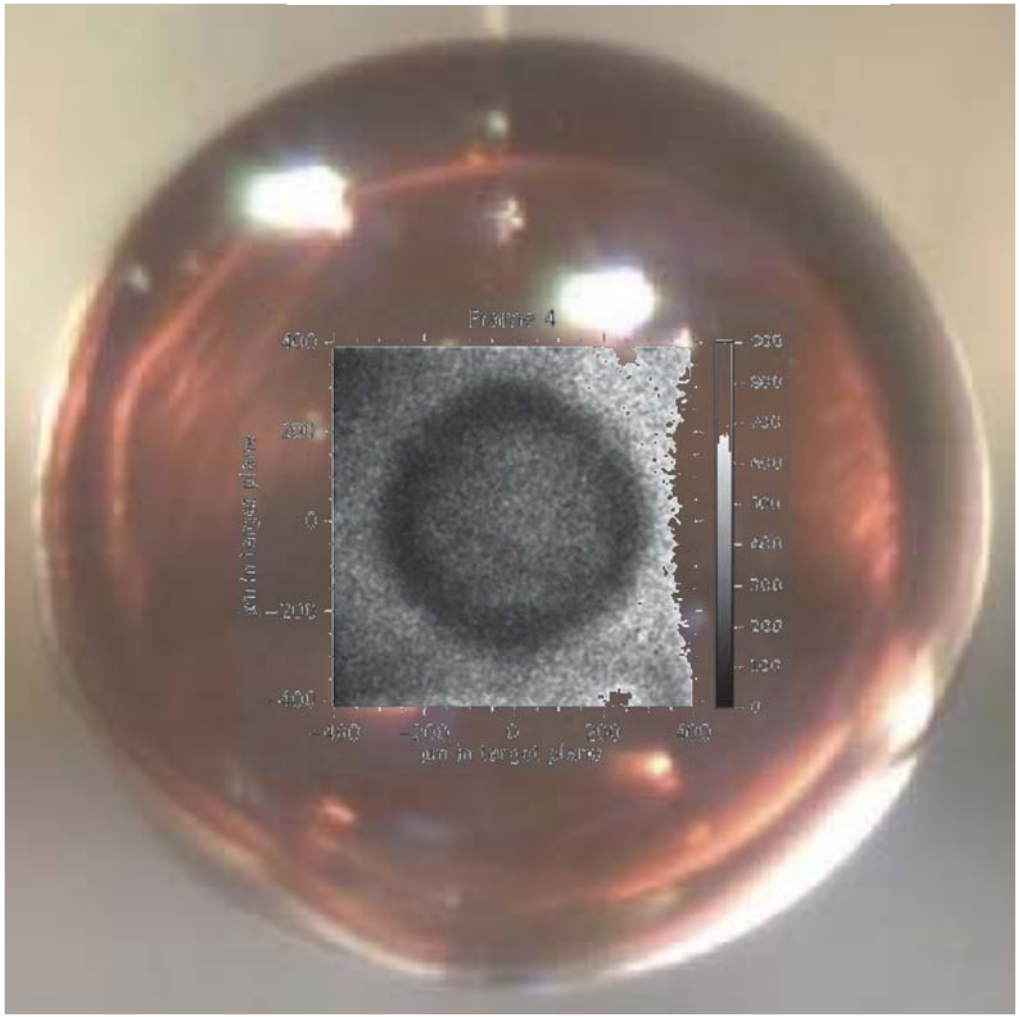


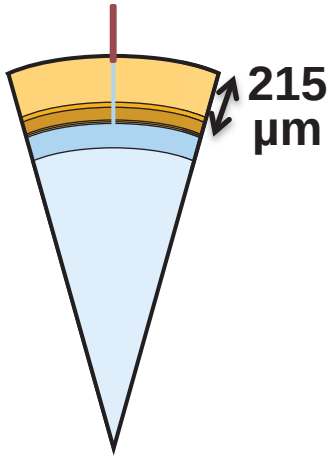
~2 mm

We are in the process of obtaining 2D images of the complete implosion history – 2DConA

N121004

Bang time – 600ps



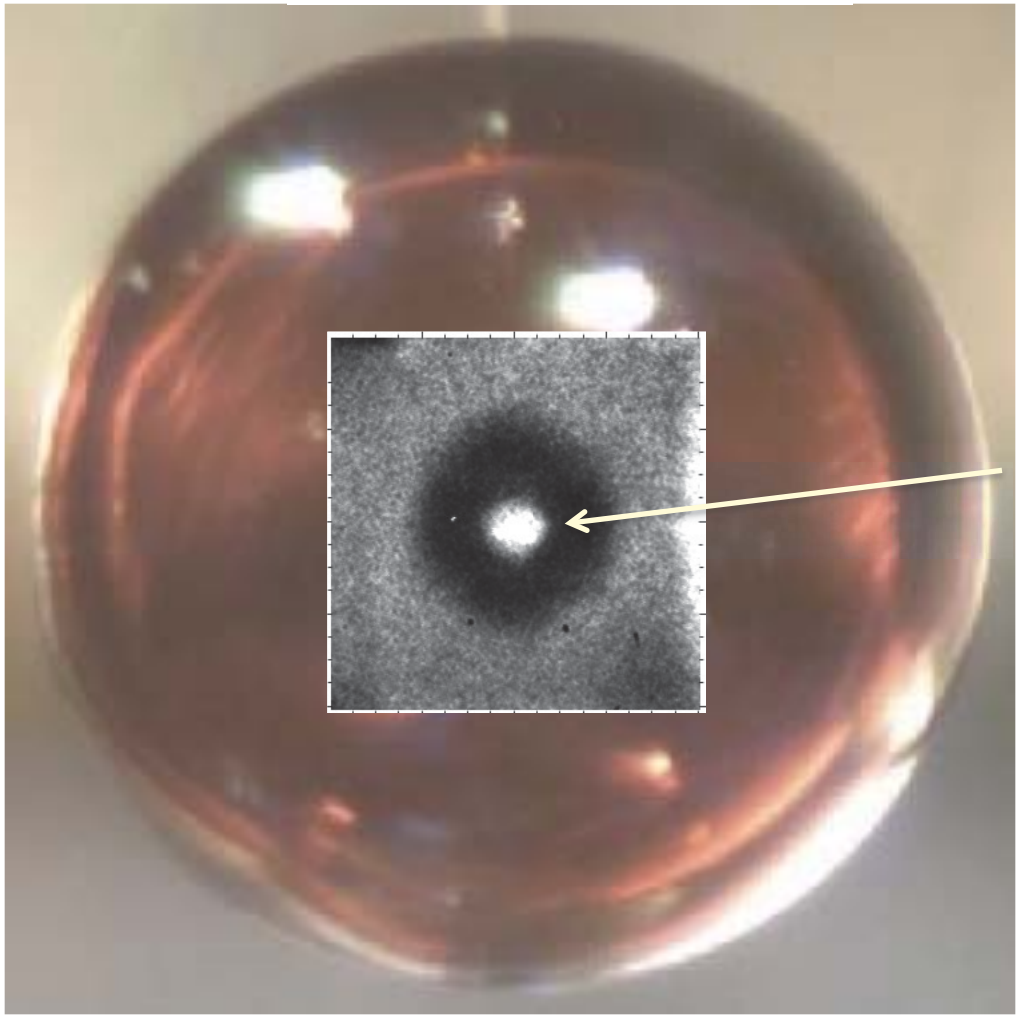


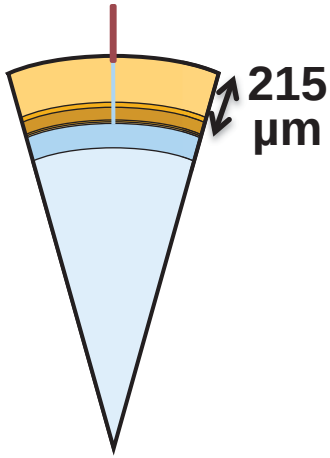
~2 mm

We are in the process of obtaining 2D images of the complete implosion history – 2DConA

N121004

Bang time – 300ps



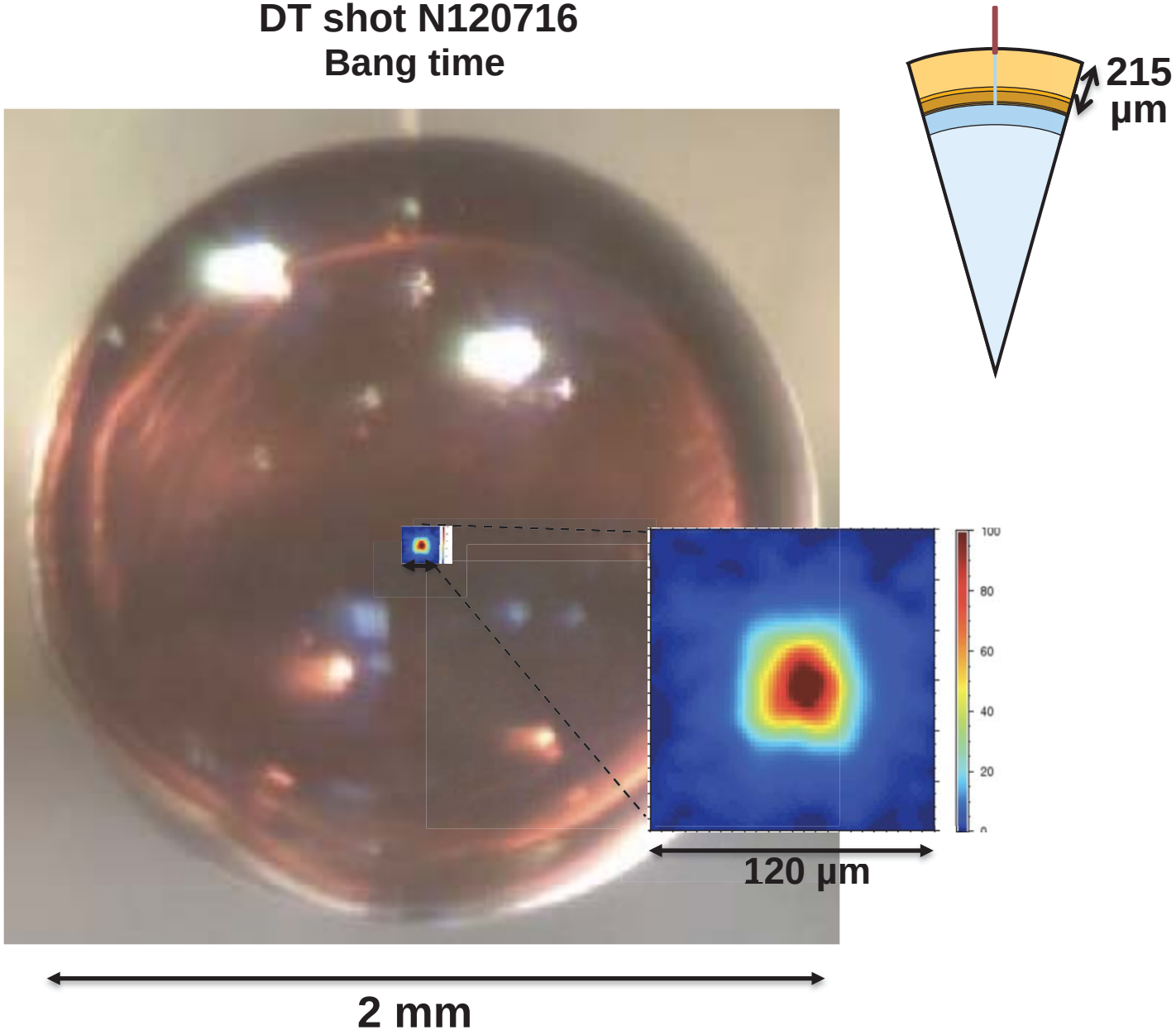


Early hot spot formation

~2 mm

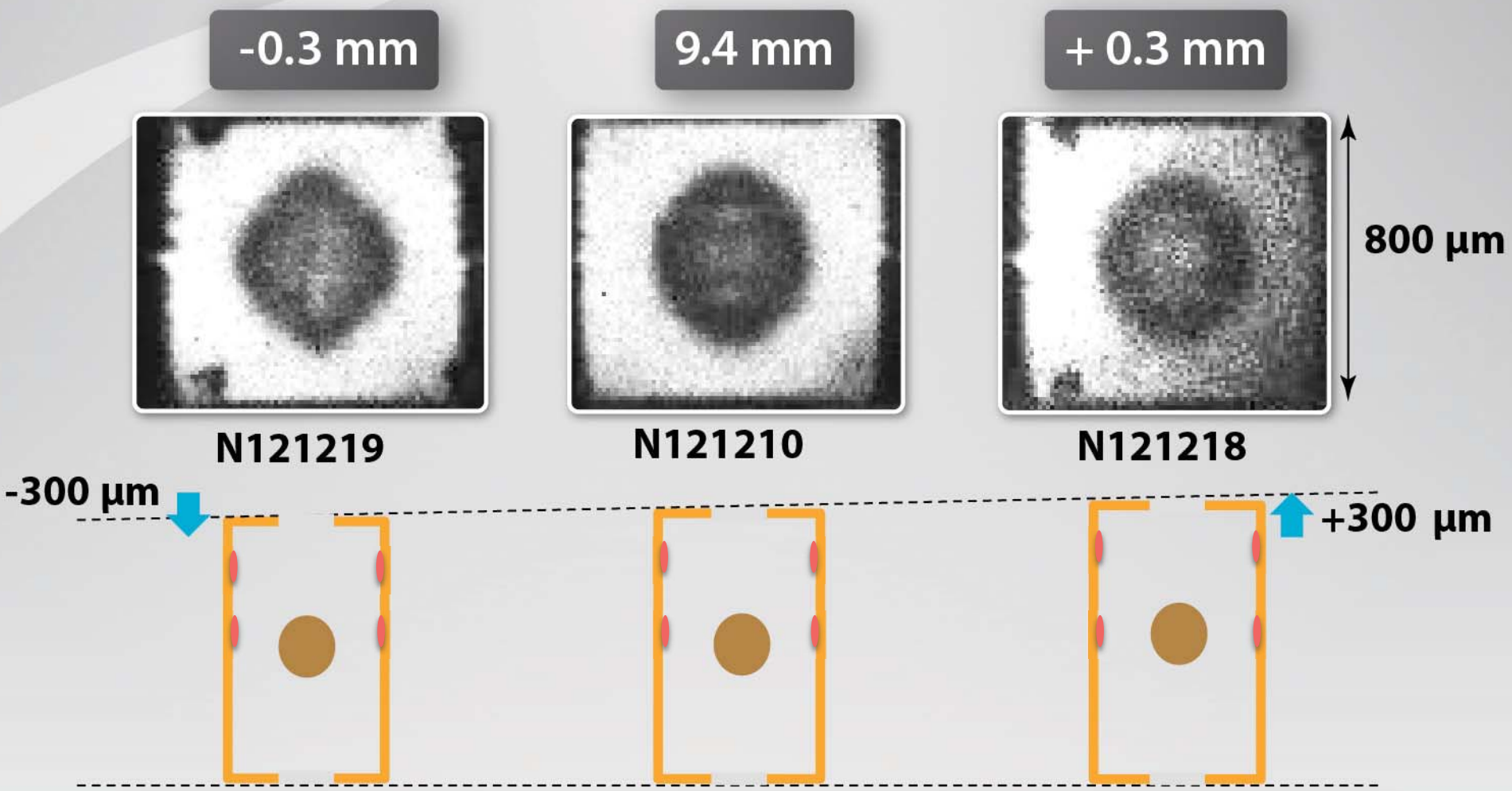
Despite cold fuel asymmetry the hot spot looks quite round

DT shot N120716
Bang time



Experiments are working on the P4 (diamond) shape

Nominal length hohlraum

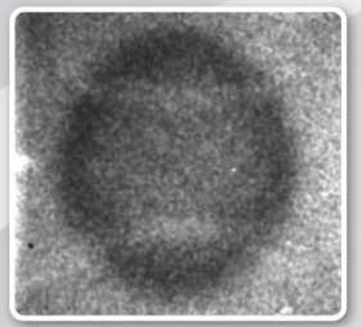


X-ray drive symmetry must be controlled to the ~1% level

Radiography is opening our eyes to implosion hydro

2013-046640

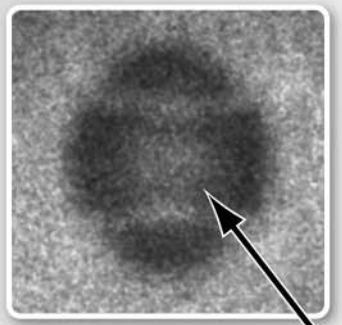
Bang time - 640ps



800 µm

2013-046641

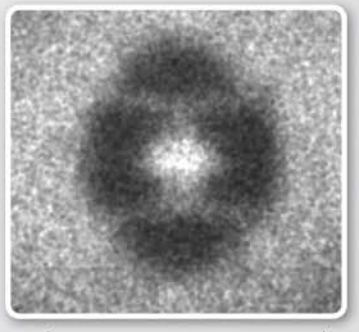
BT - 430ps



800 µm

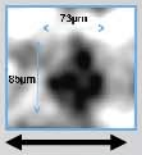
2013-046642

BT - 340ps



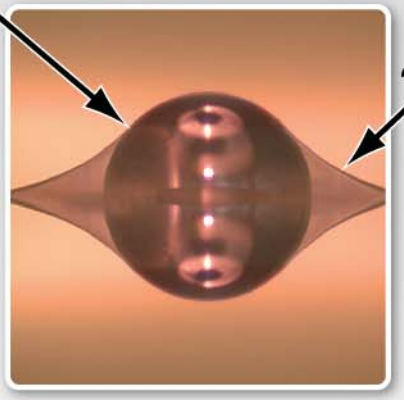
800 µm

BT±50ps



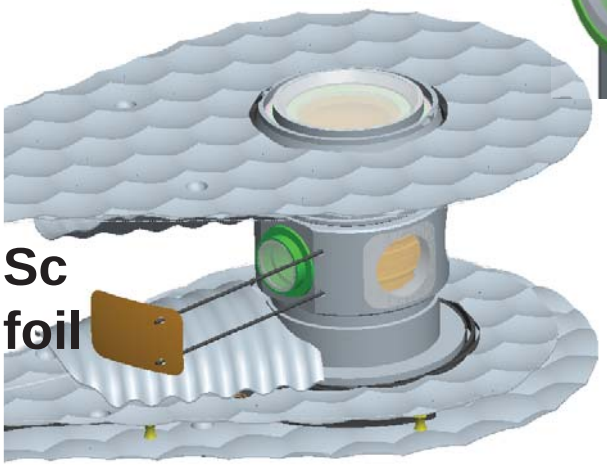
150 µm

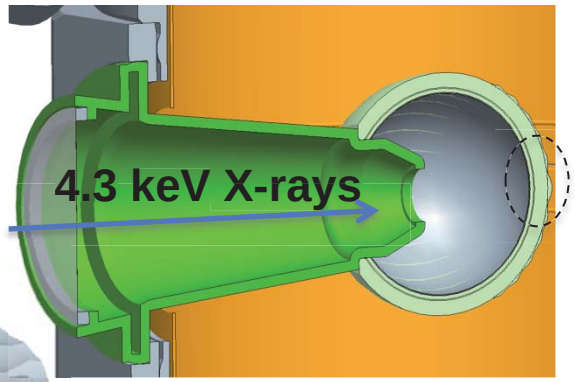
Perturbation seeded by the tent?



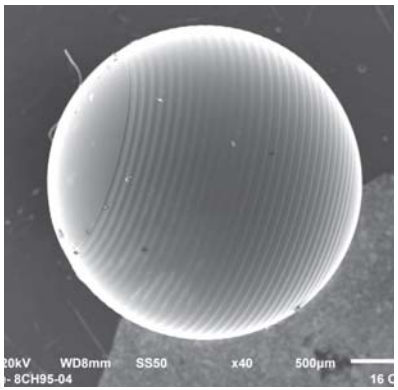
Tent ~ 40 nm

Next generation of backlighting experiments will study ablation front instability growth



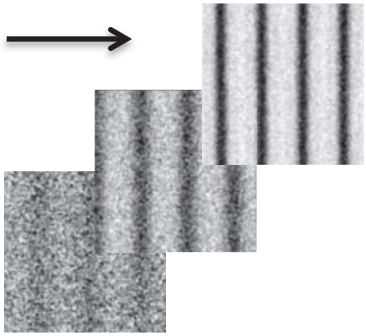


Keyhole design for single pass radiography



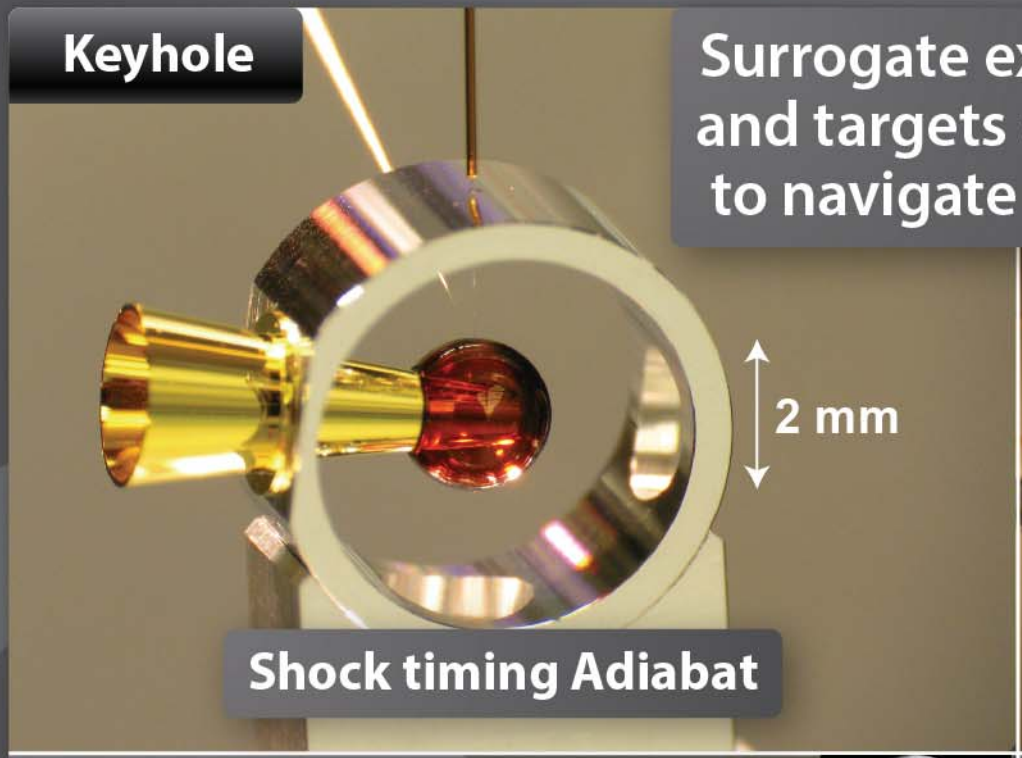
Pre-imposed ripples on capsule

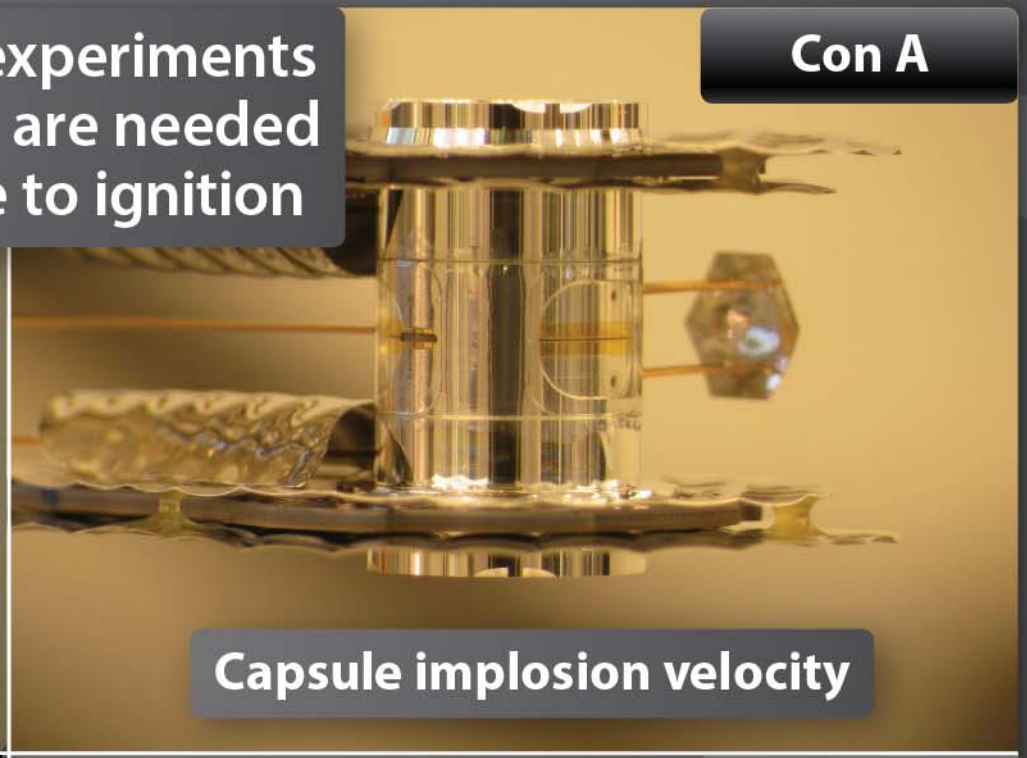
time

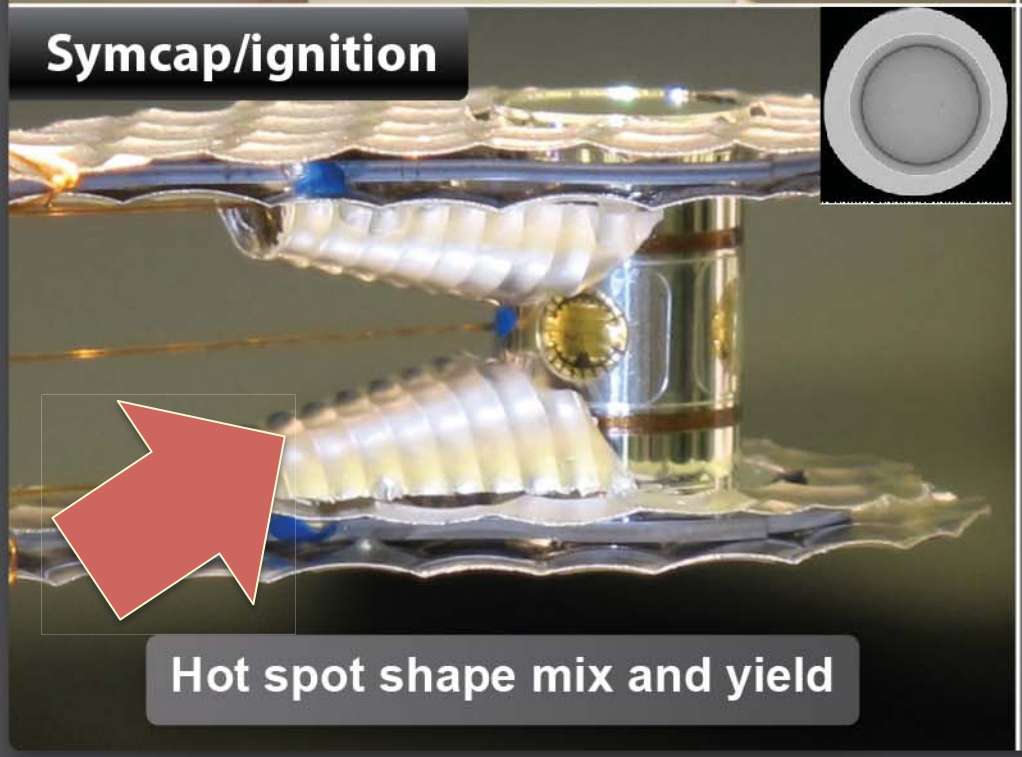


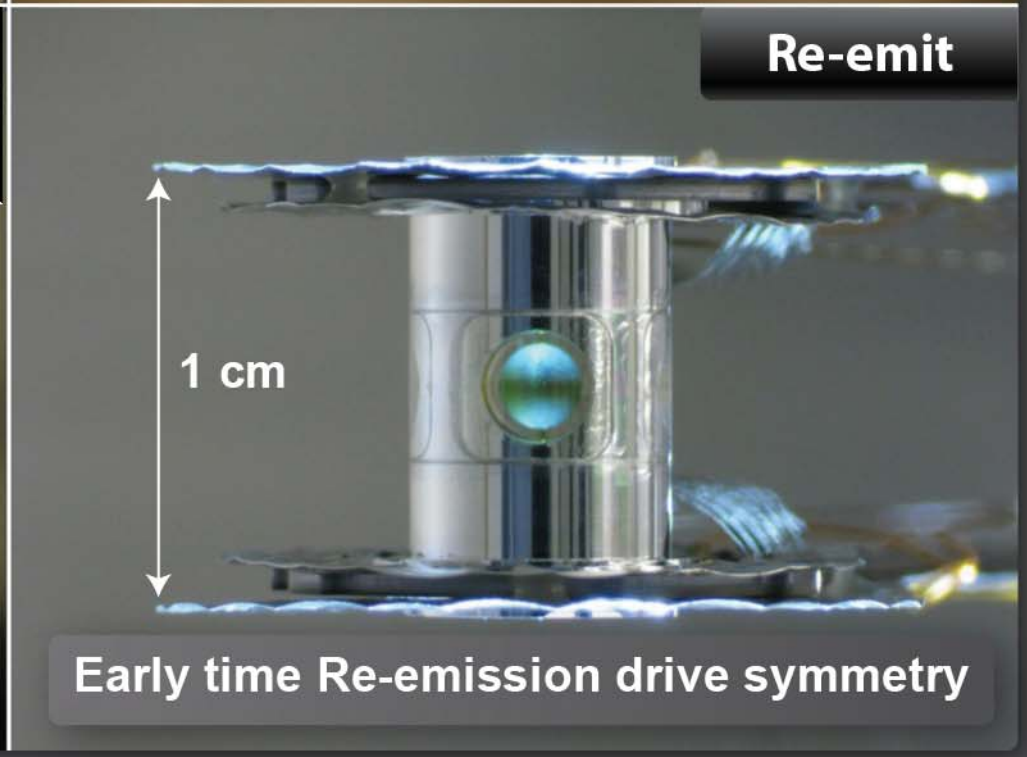
Time sequence of gated X-ray images of perturbation growth

Surrogate experiments and targets are needed to navigate to ignition



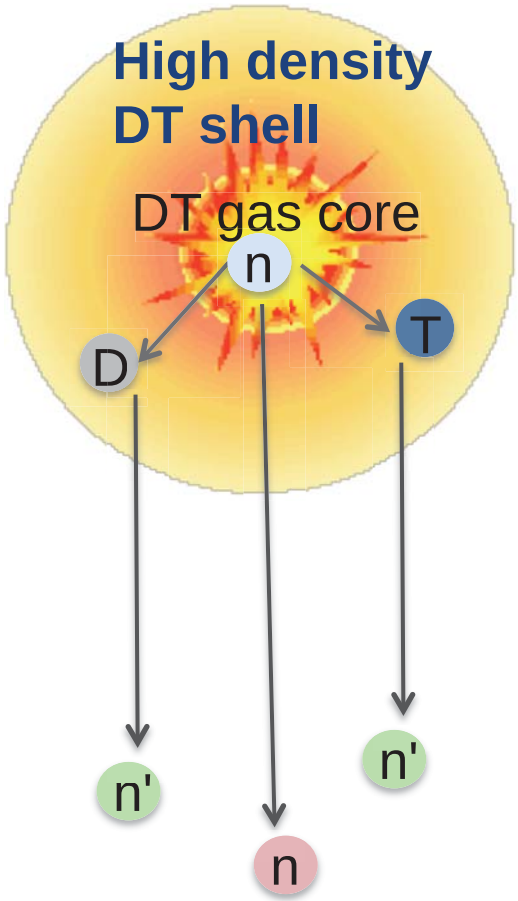






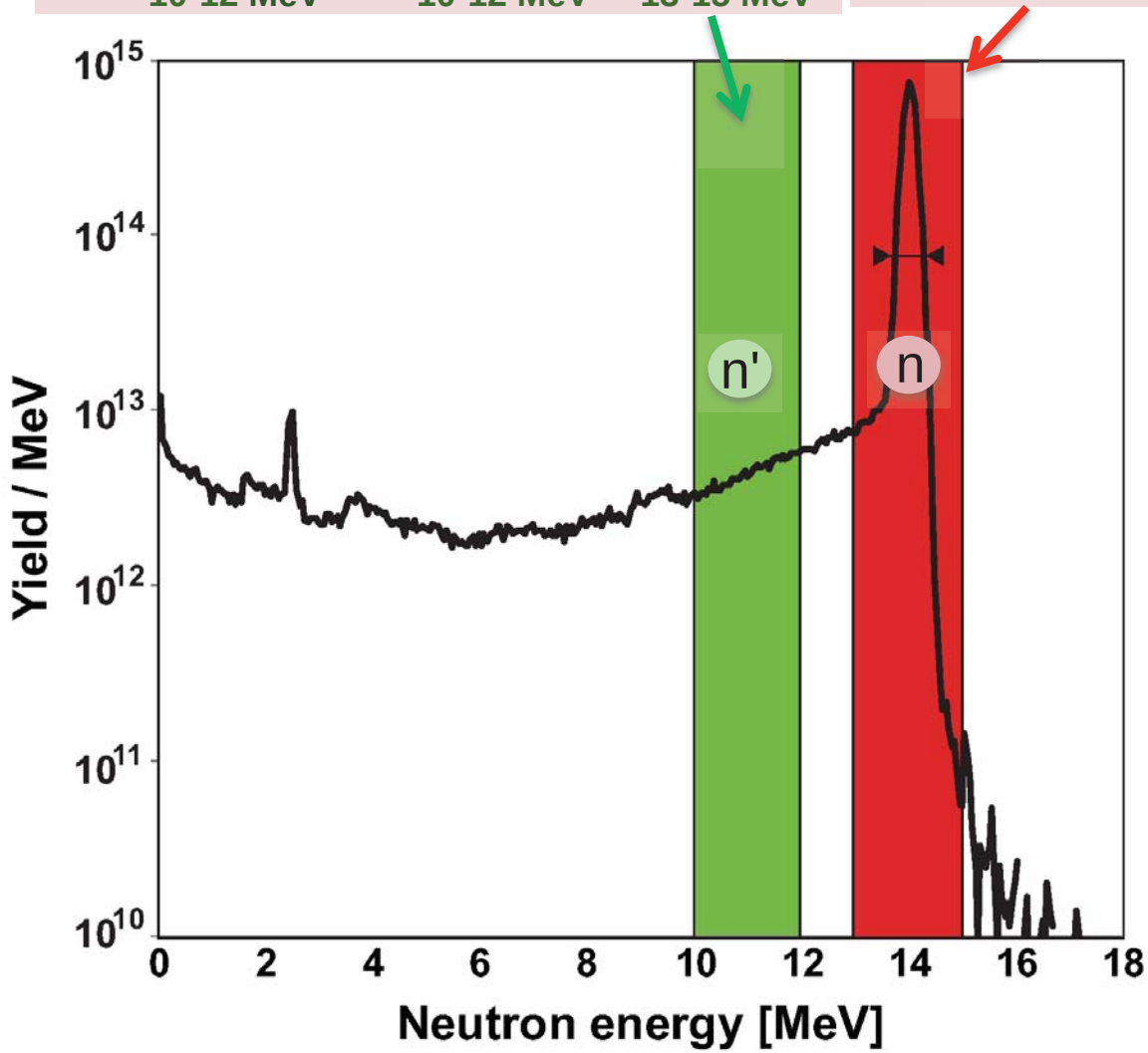
Neutrons measure temperature and fuel ρR

Neutron mean-free-path ~ 4 cm²/g
ρR is~ linearly proportional to DSR



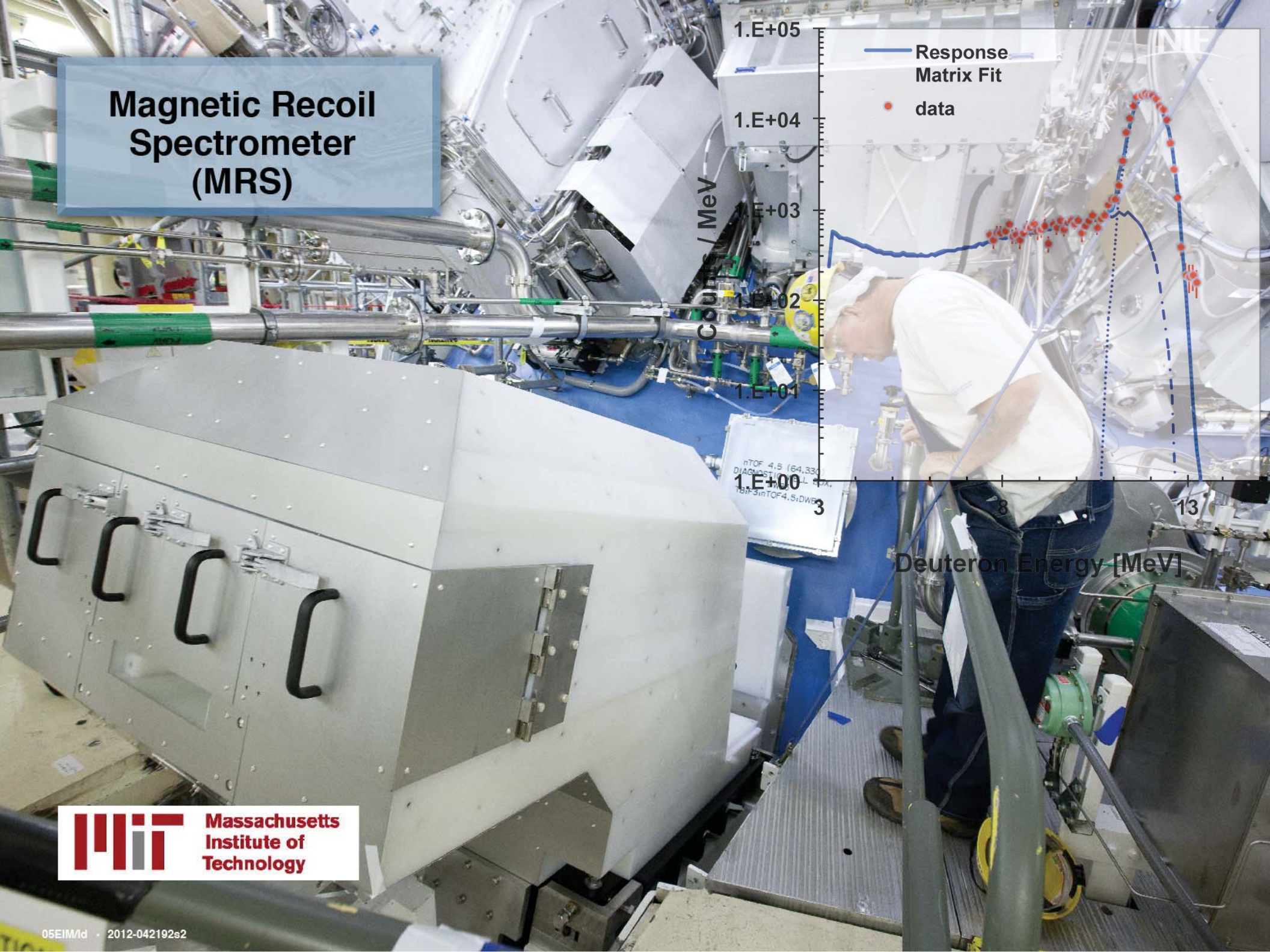
$dsr_{10\text{-}12\ MeV} = Y_{10\text{-}12\ MeV}/Y_{13\text{-}15\ MeV}$

Y_n: $Y_{13\text{-}15\ MeV}$



ρR (g/cm²) ≈21×$dsr_{10\text{-}12\ MeV}$

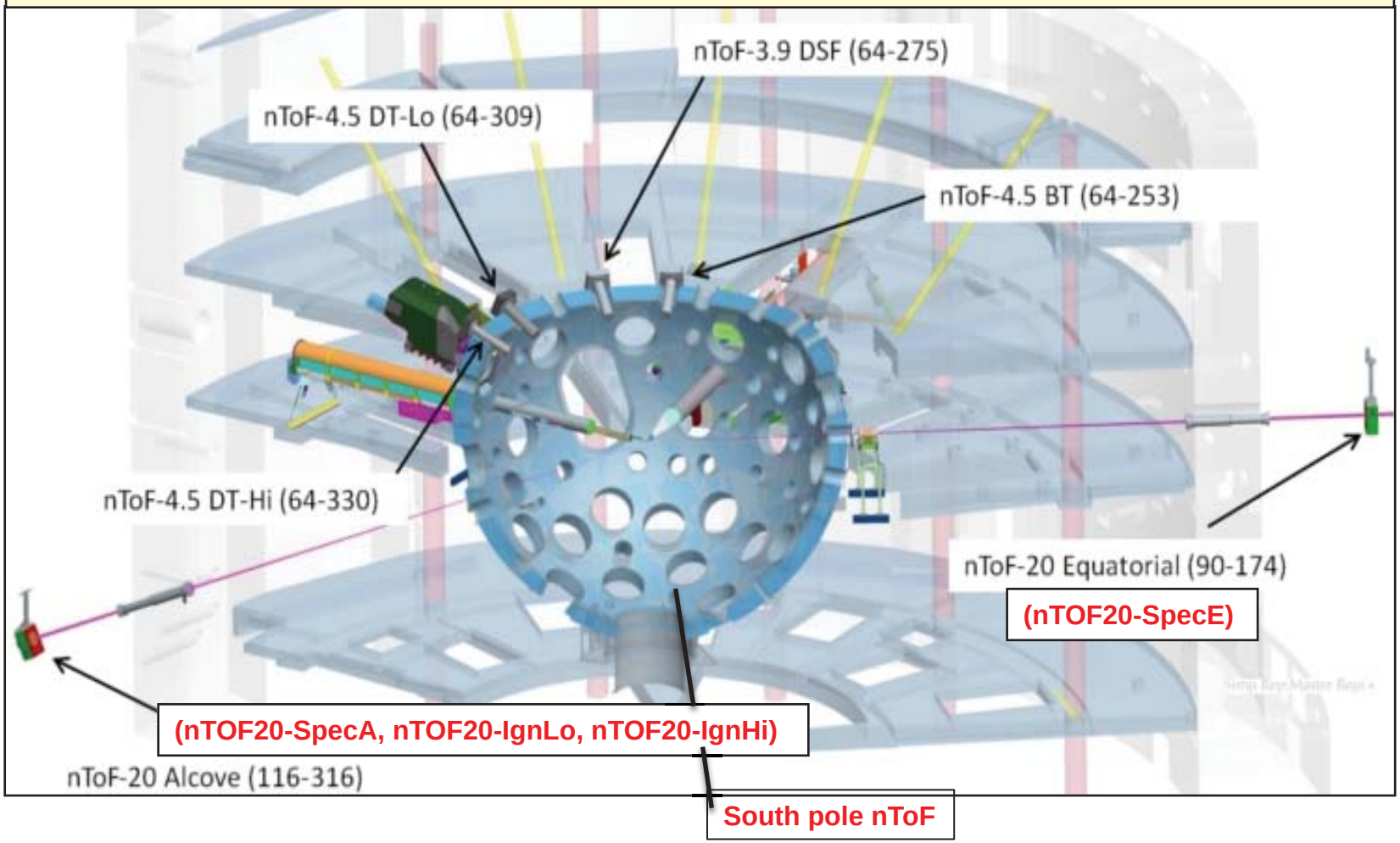
Magnetic Recoil Spectrometer (MRS)



Massachusetts Institute of Technology

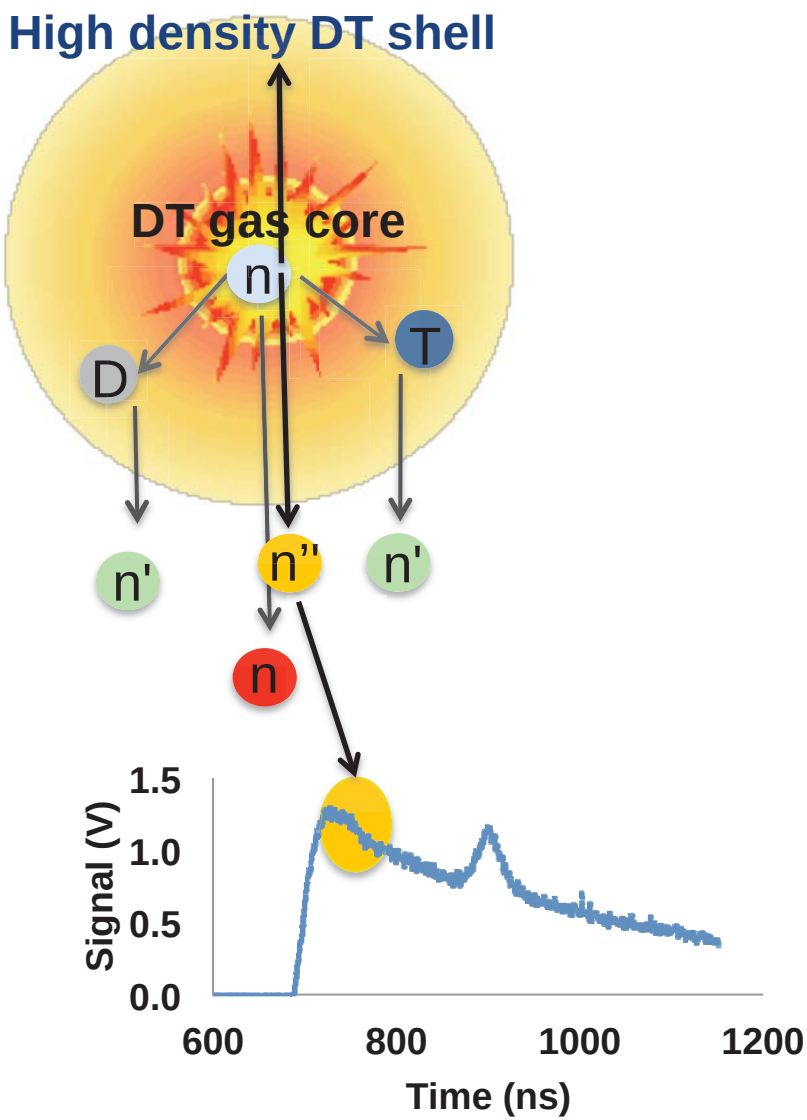
T_{ion} and ρR also measured by multiple Neutron Time of Flight (NToF) detectors

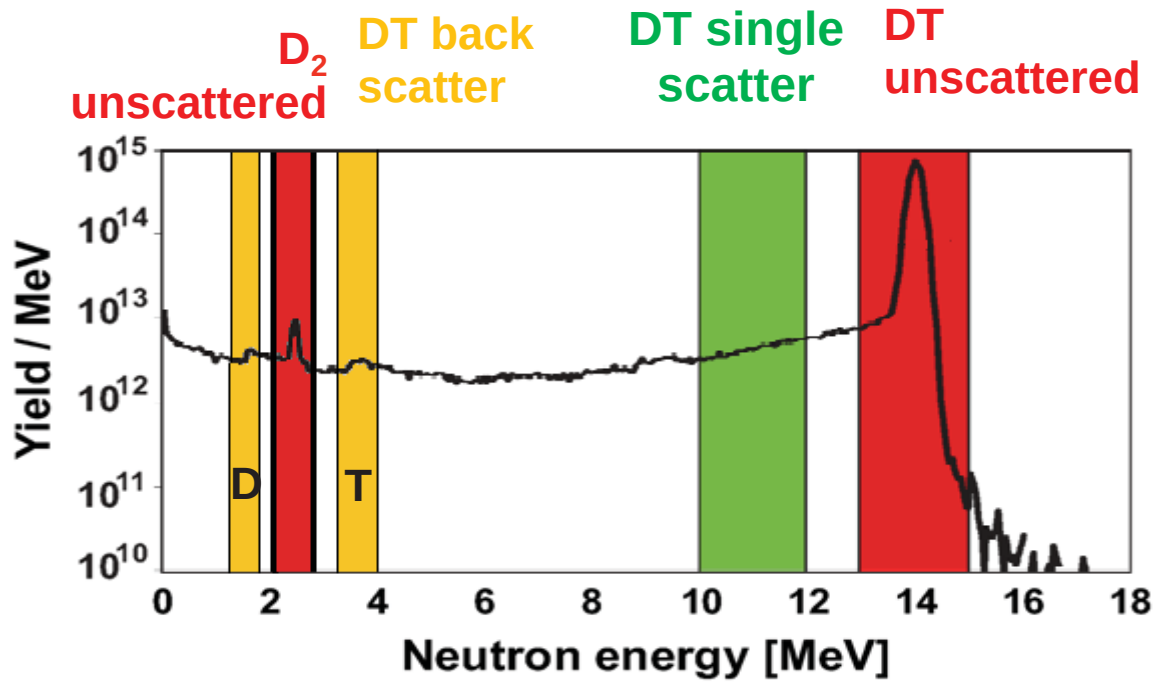
Location of NToFs on the NIF Target Chamber

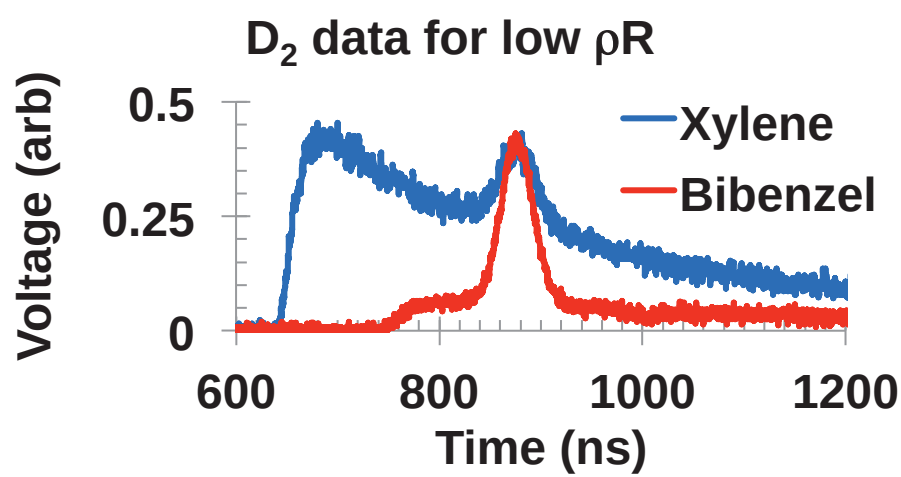


Good design has produced unprecedented data quality

We continue to improve nuclear measurements- lower background detectors open many exciting possibilities





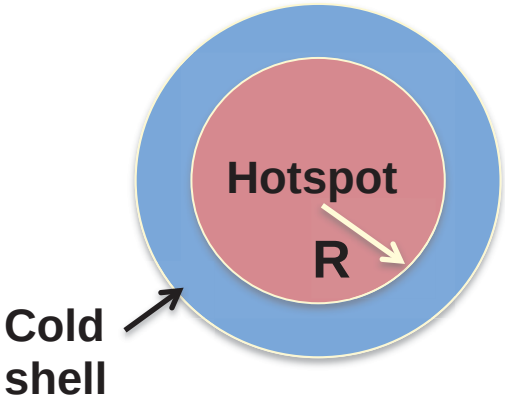


Static isobaric model can be used to estimate hot spot properties

Derive

$$Y \sim \boxed{Vol \times t_{burn} \times \langle \sigma v \sim T^{4.5} \rangle} \times n^2$$

Measure neutrons γ-rays X-rays

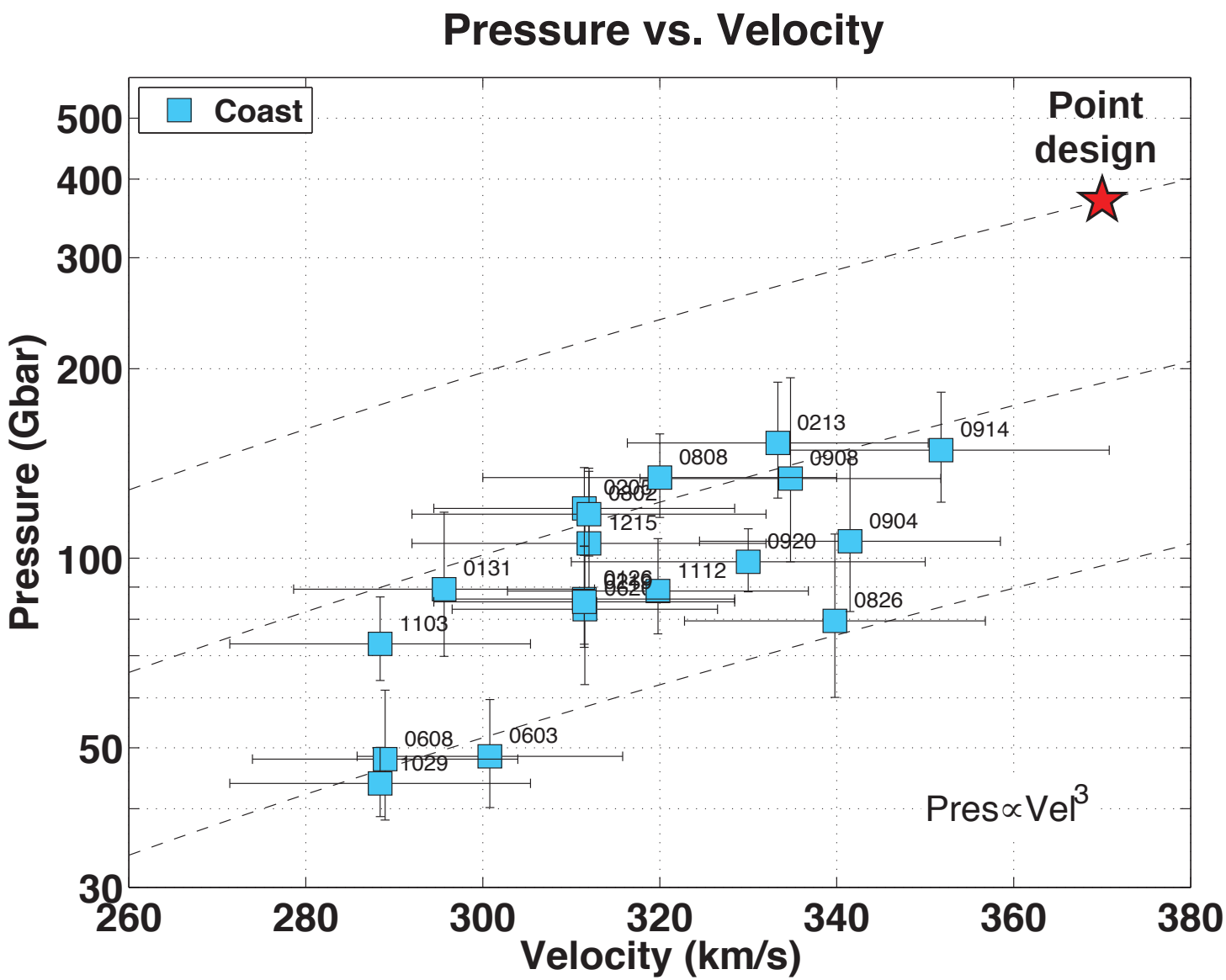


Density, $\rho \sim nA$
Mass, $M_{HS} \sim \rho V$
Pressure, $P \sim nT$
Energy, $E \sim P\,V$

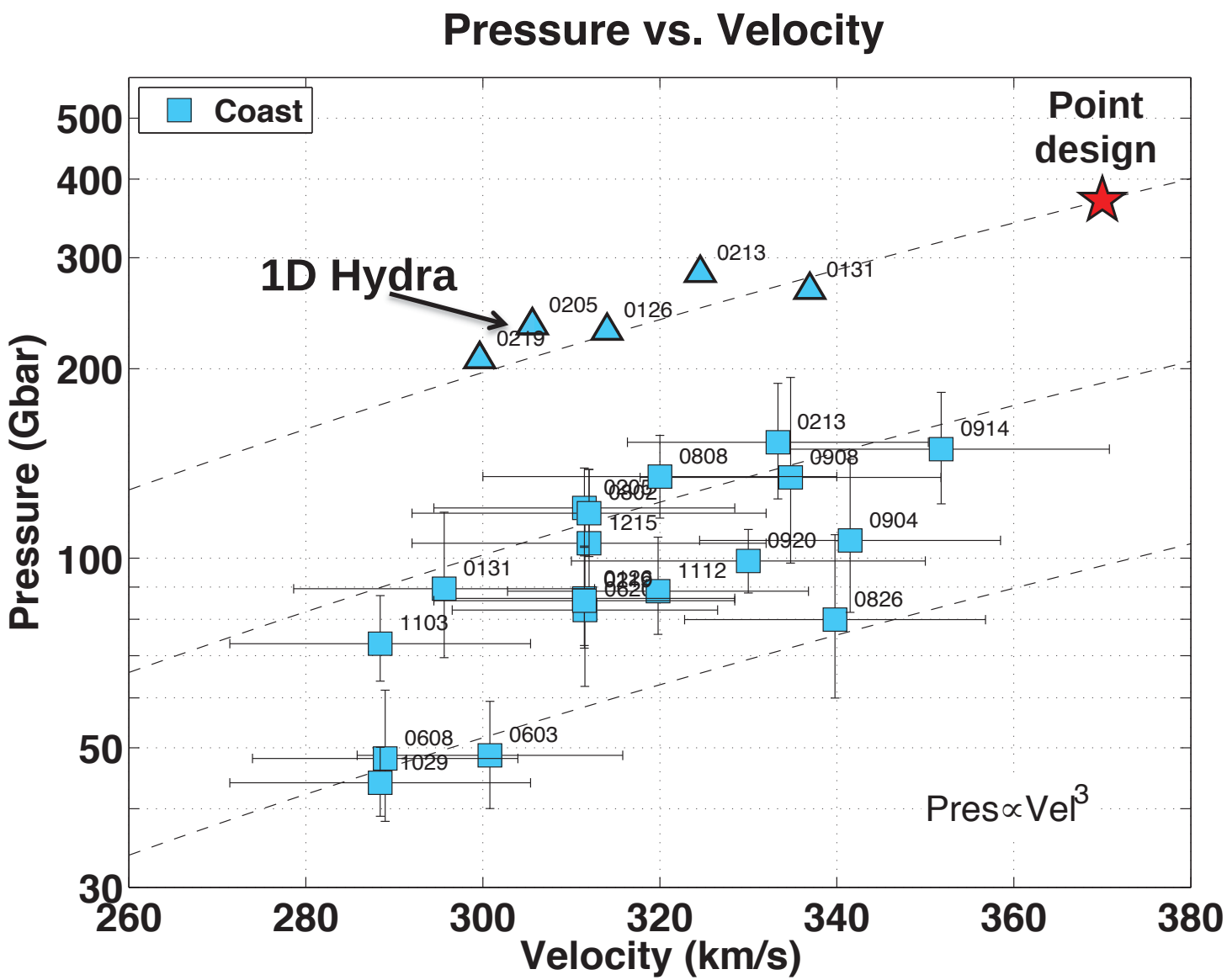
- More sophisticated 3D model fits to the observables, allows for spatial profiles but gives similar answers

BI3.00002: Cerjan

Pressure scales with velocity^3 as expected

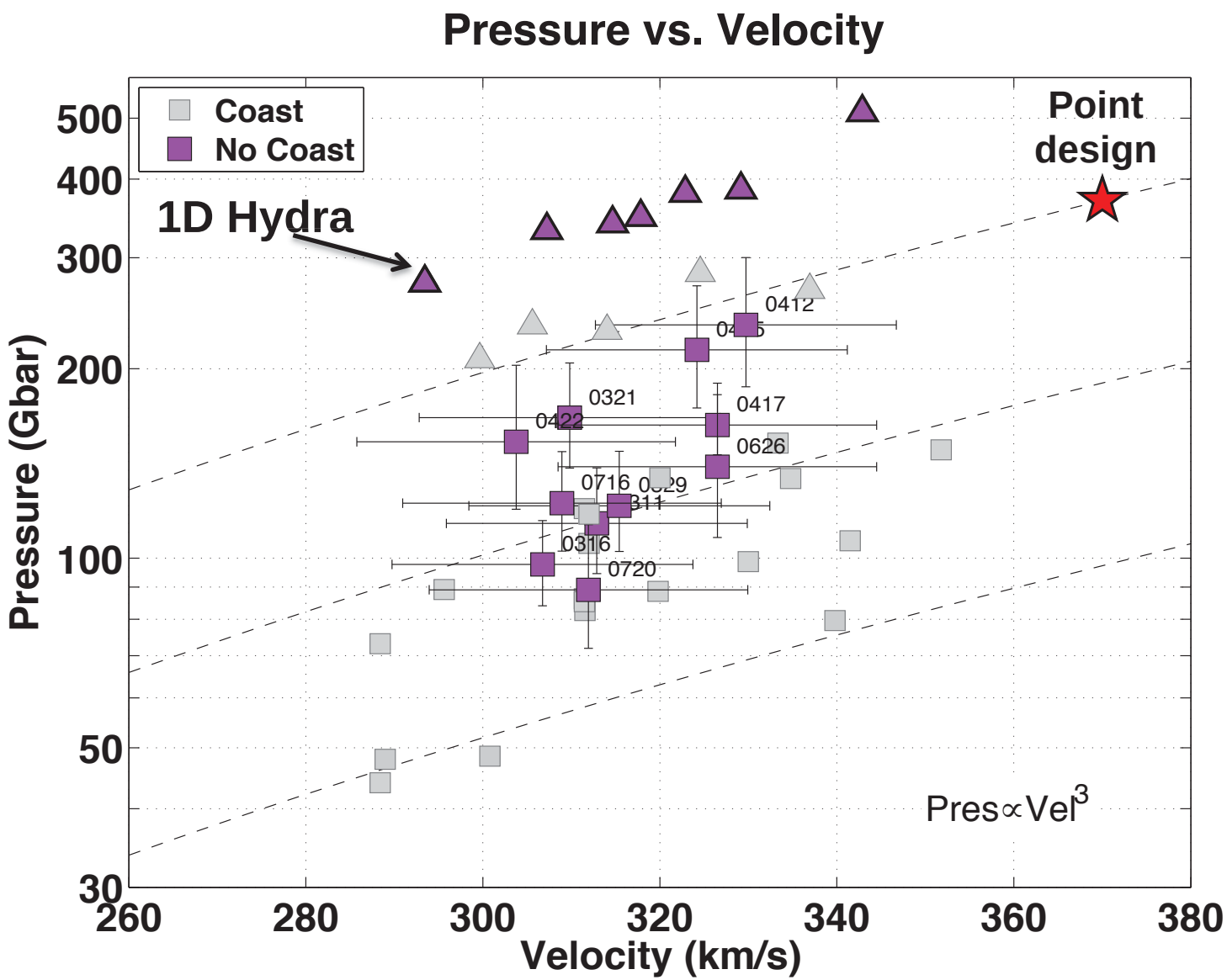


Pressure scales with velocity^3 as expected – but are low compared to post shot simulation*



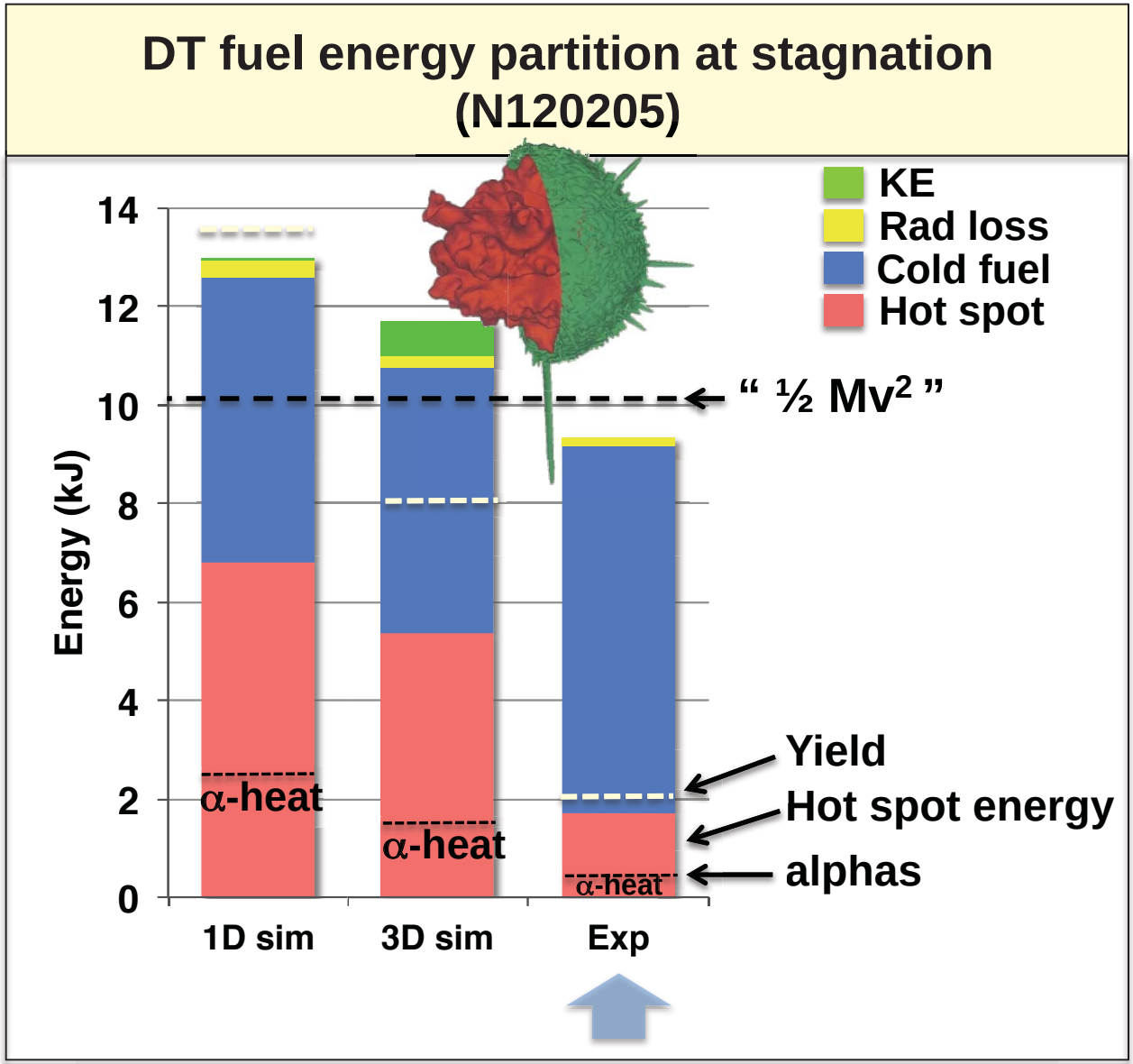
* Post shot simulations adjusted to match shock timing and implosion velocity

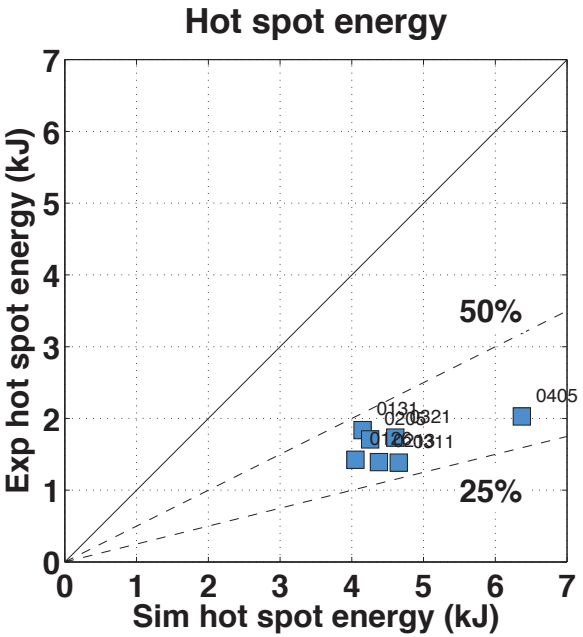
No coast implosions improved pressure but remain below post shot simulation*



* Post shot simulations adjusted to match shock timing and implosion velocity

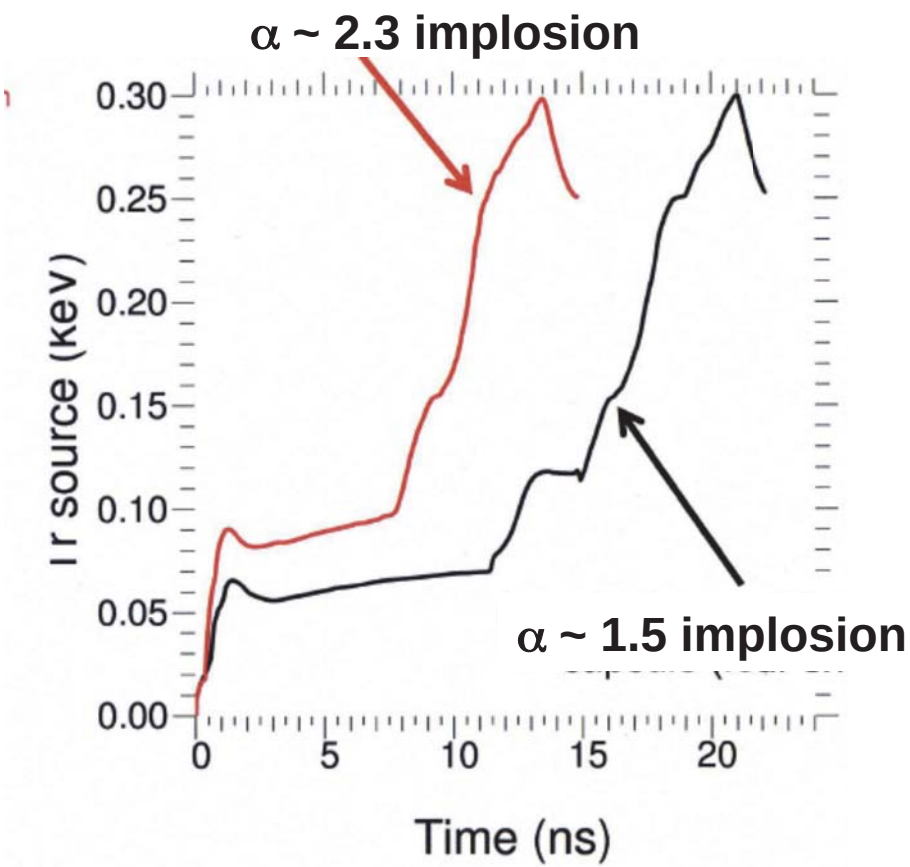
Energy in the hot spot is typically 30% of simulated





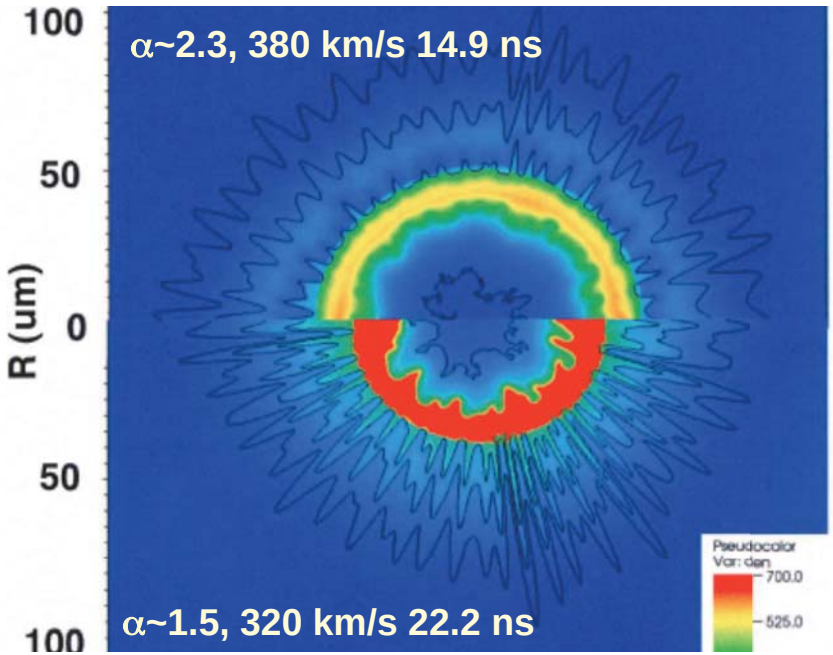
Hurricane et al

New DT implosion - higher adiabat implosion lower convergence



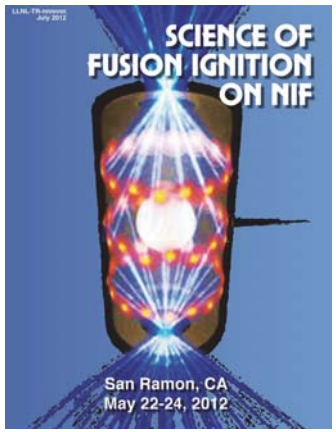
Simulated implosions

CR~27-36



CR~36-47

- Reduced RM/RT predicted
- Different hohlraum physics
- Different ablator path (EOS, NLTE physics)



We have made good progress towards achieving ignition conditions on the NIF

- The NIF laser and targets have met the highly demanding specifications for accuracy and control required by the ignition point design (Rev5)
- The hohlraum X-ray drive exceeded the ignition goal of 300eV accelerating implosions up to ~ 350 km/s, close to the goal of 370 km/s
- The highest observed yields and areal densities to date in DT layered implosions are ~2.5kJ (~ 10^{15} neutrons) and ~1.3 g/cm^2 (85% of the goal) respectively
- Nuclear yields are ~ 3-10X from alpha dominated regime - hotspot densities, pressures are ~ 2-3X lower than predicted/required
- Performance deficit likely due to combination of low mode X-ray drive asymmetry/cold fuel shape, and higher than simulated hydrodynamic instability

Identifying the reasons for the deficit in pressure/performance and developing mitigation strategies is a key element of the go-forward experimental plan

NIF