Scientific Advances and Challenges on NIC*

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Lawrence Livermore National Laboratory • National Ignition Facility & Photon Science

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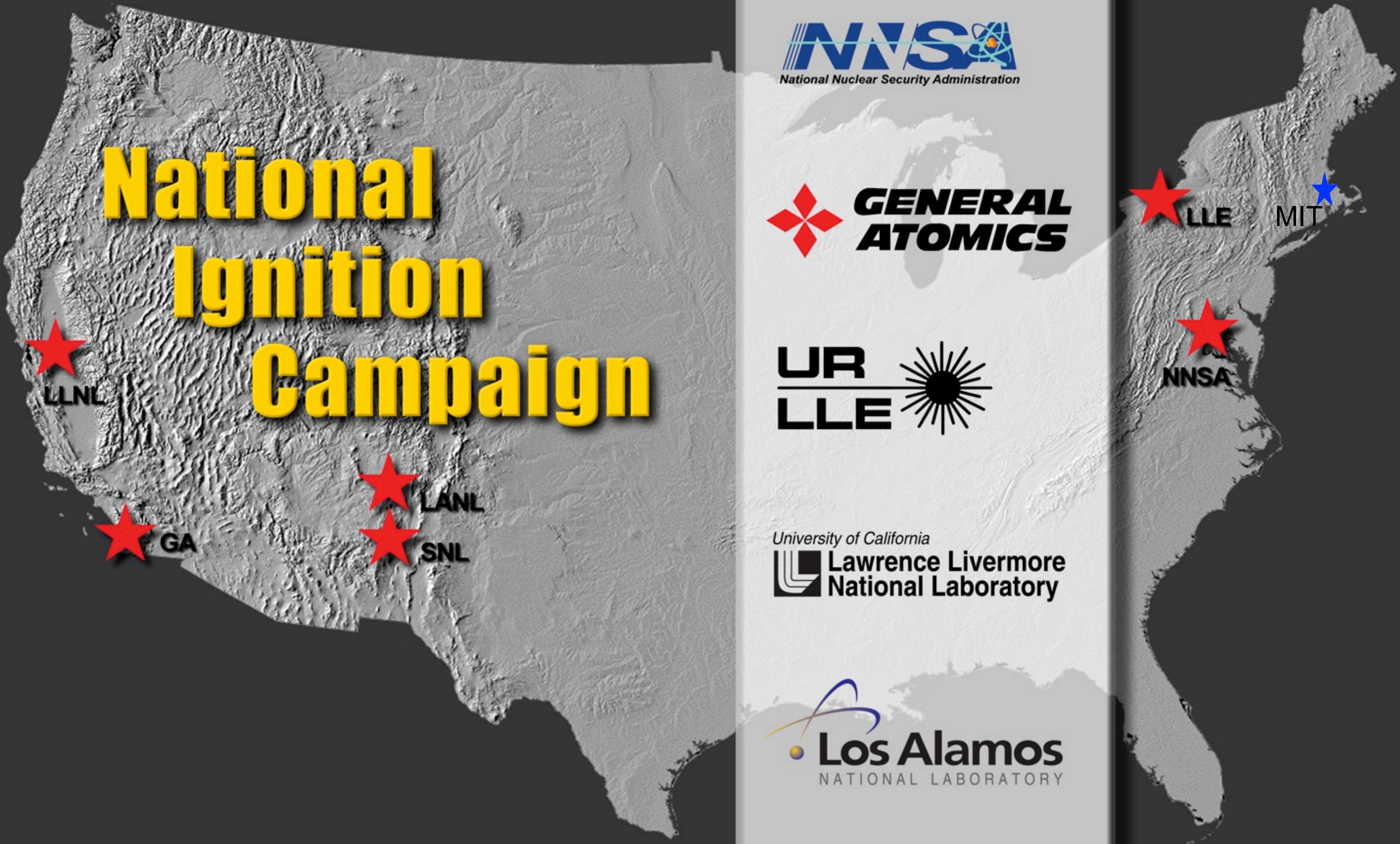
National Ignition Campaign



NNSA
National Nuclear Security Administration

GENERAL ATOMICS

UR LLE

University of California
Lawrence Livermore National Laboratory

Los Alamos
NATIONAL LABORATORY

Sandia National Laboratories

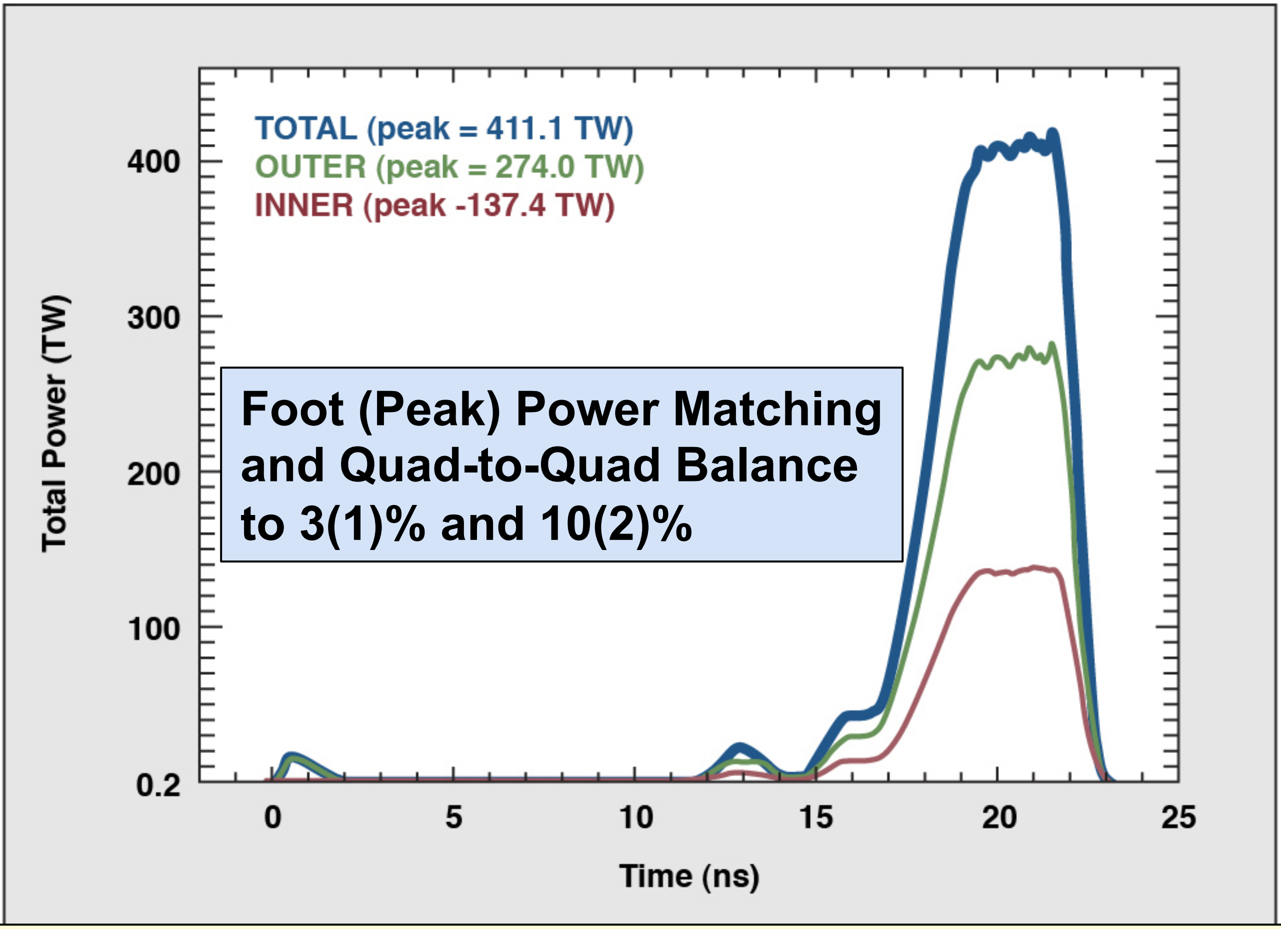
NIC tuning / applied science since May 2011

- **Ignition tuning platforms and techniques first developed at Nova and OMEGA have been critical to uncovering offsets between NIF data and modelling**
  - **Tuning of shock timing and drive symmetry have empirically corrected for physics uncertainties and improved ignition margin parameter "ITFx" from .002 to 0.1**
  - **X-ray radiography has mapped out capsule shell trajectory and profile for comparison to Rocket model and simulations**
  - **Experimental success has motivated more platforms not envisaged at outset (4th Shock VISAR, Dual-axis VISAR, Refraction-Enhanced In-flight Fuel Radiography, Fused Silica Sphere VISAR for Internal Drive, 2D Deceleration Phase Fuel Radiography.…)**

- **Extending pulses ("no coast") has further improved compression and uncovered mix sensitivity to shell width**
  - **Following improved 1D performance, we need to increase velocity while keeping mix low by using more power and thicker capsules, more efficient hohlraums (DU, rugby?) and potentially more efficient ablators**

On March 21, 2012 NIF fires at 2 Million Joules–surpassing its design goal

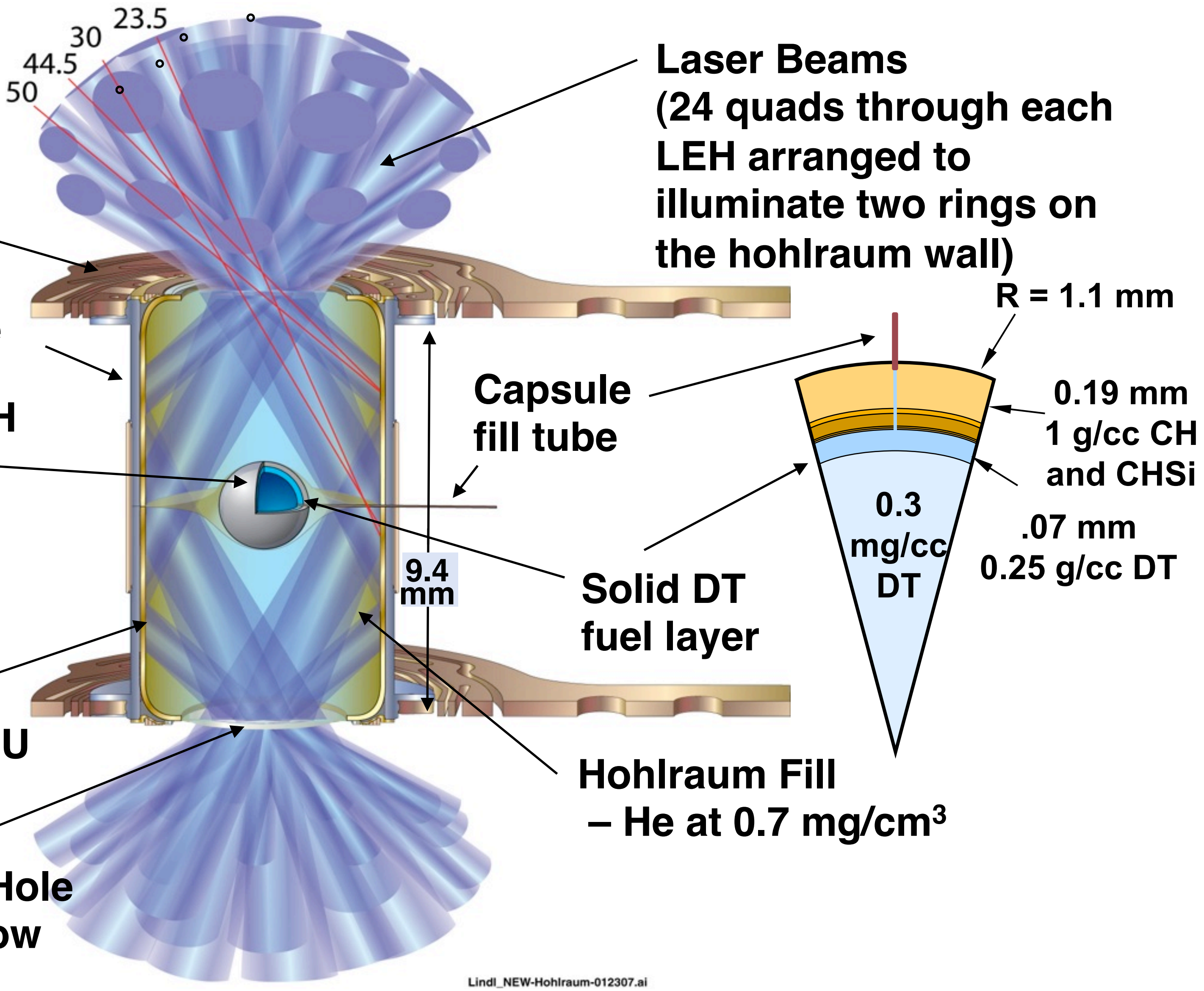
- 2.03 MJ to the final optic
- 1.875 MJ, 411 TW to target chamber center



Foot (Peak) Power Matching and Quad-to-Quad Balance to 3(1)% and 10(2)%

Further improvements in extending useable beam area and AM conditioning should lead to 500 TW peak power operation

The NIF point design has a graded-doped, CH capsule in a hohlraum driven at Tr > 300 eV



Laser Beams (24 quads through each LEH arranged to illuminate two rings on the hohlraum wall)

Cryo-cooling Ring

Aluminum assembly sleeve

Ge or Si-doped CH Capsule (Be and Diamond are alternates)

Capsule fill tube

Solid DT fuel layer

Hohlraum Wall:
- Au or Au-lined U

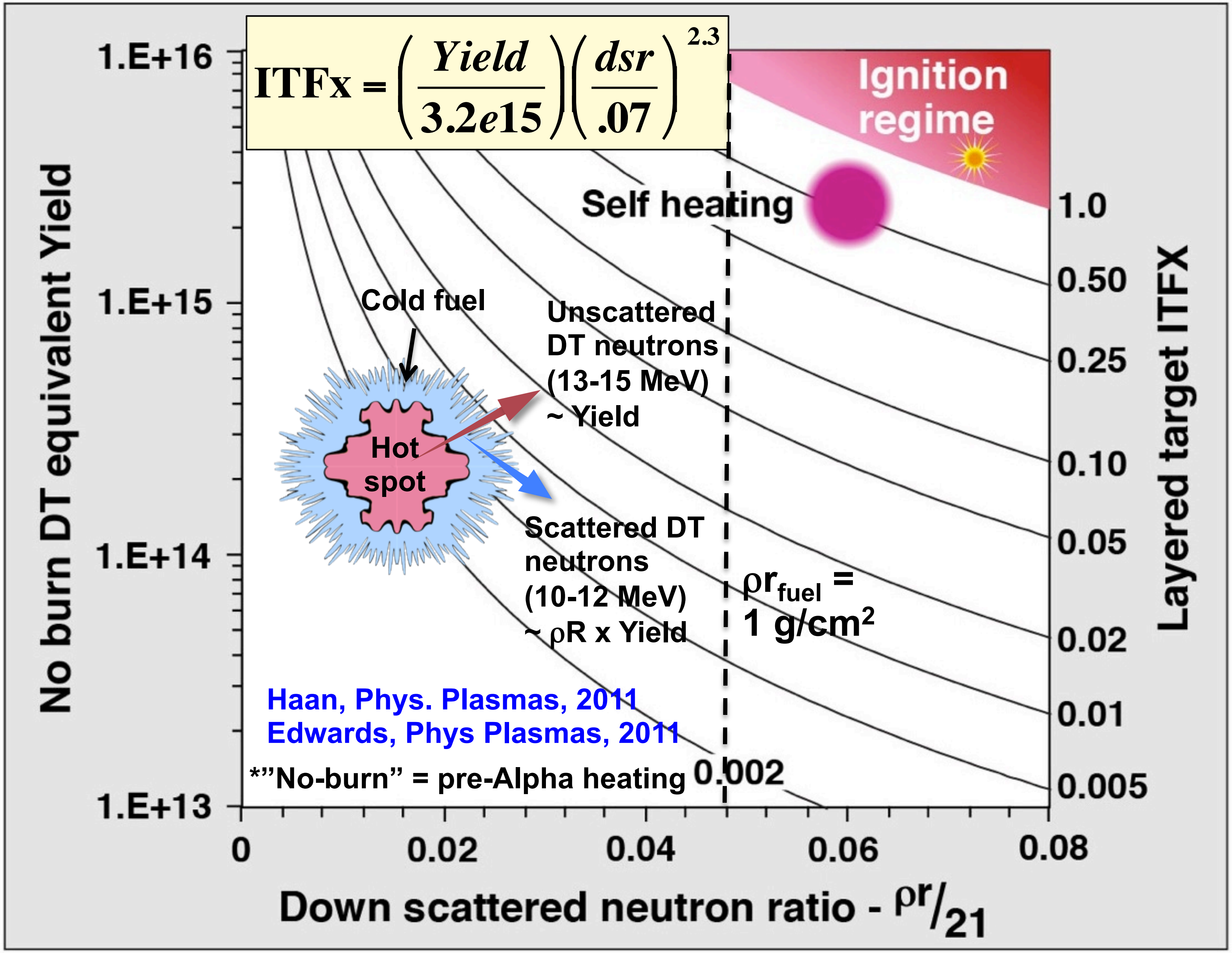
Hohlraum Fill
- He at 0.7 mg/cm^3

Laser Entrance Hole (LEH) with window

Laser Entrance Hole (LEH) covered with 0.5 µm CH window

Lawson Criterion for ICF can be stated as product of no-burn* yield and downscattered fraction (≈ fuel ρr)

Faster, hotter



$$\text{ITFx} = \left(\frac{Yield}{3.2e15}\right)\left(\frac{dsr}{.07}\right)^{2.3}$$

Haan, Phys. Plasmas, 2011
Edwards, Phys Plasmas, 2011

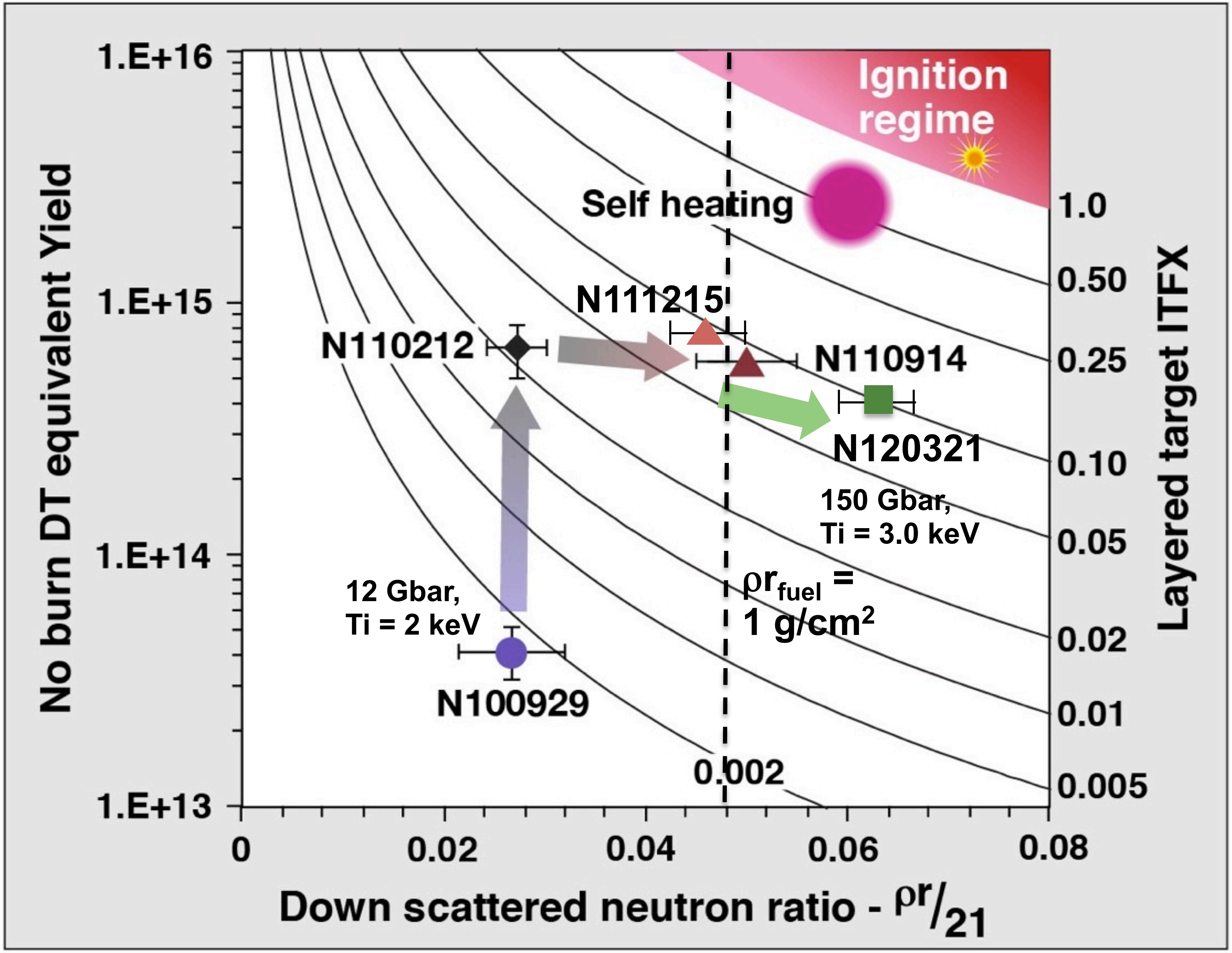
*"No-burn" = pre-Alpha heating

Lower adiabat, more compressed →

Implosion Performance

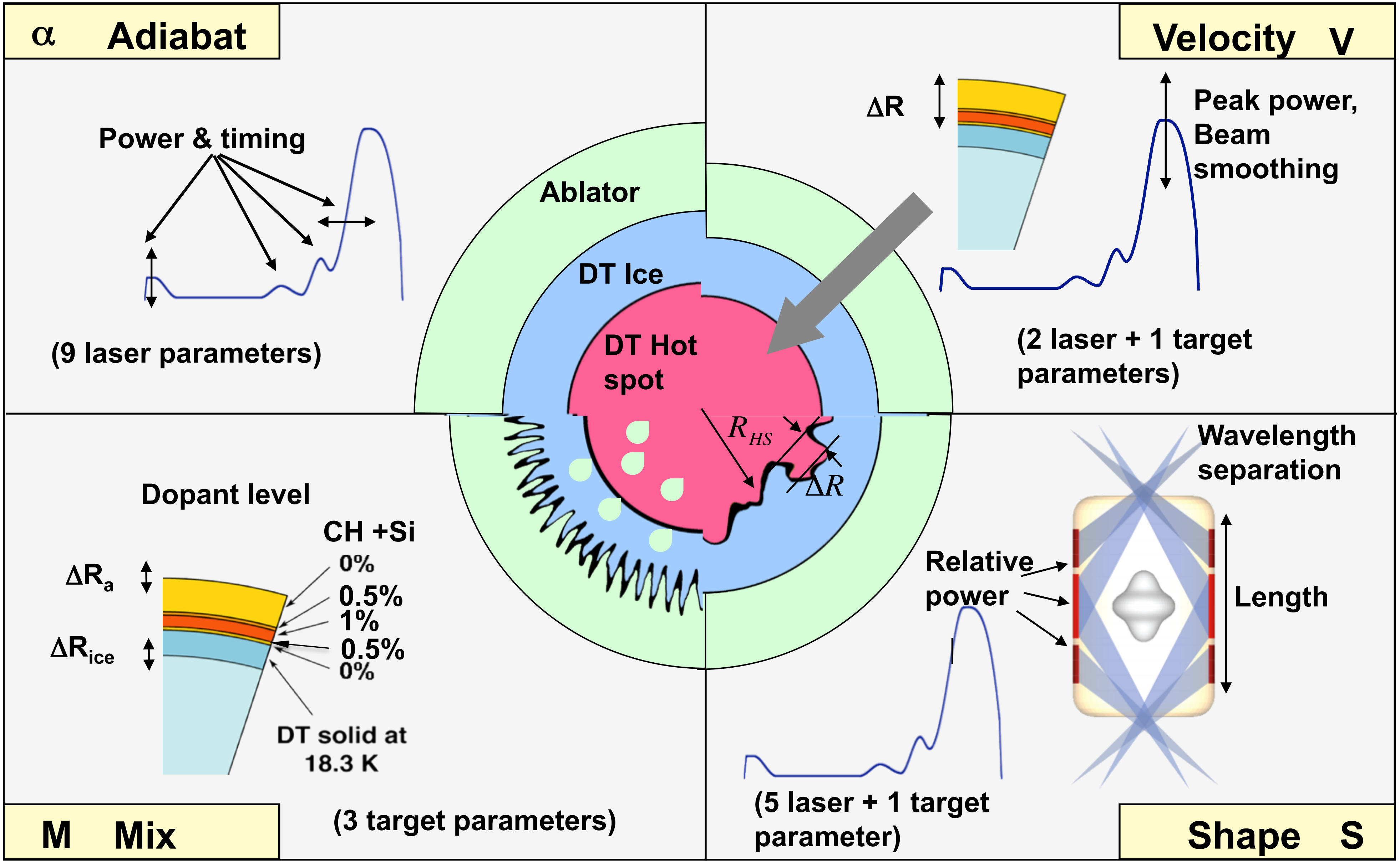
We have increased ITFx from .002 to 0.1 by a series of tuning campaigns optimizing target and laser parameters

Faster, hotter



Lower adiabat, more compressed →

To optimize the target for ignition we adjust the adiabat, velocity, mix and shape



α Adiabat

(9 laser parameters)

Velocity V

(2 laser + 1 target parameters)

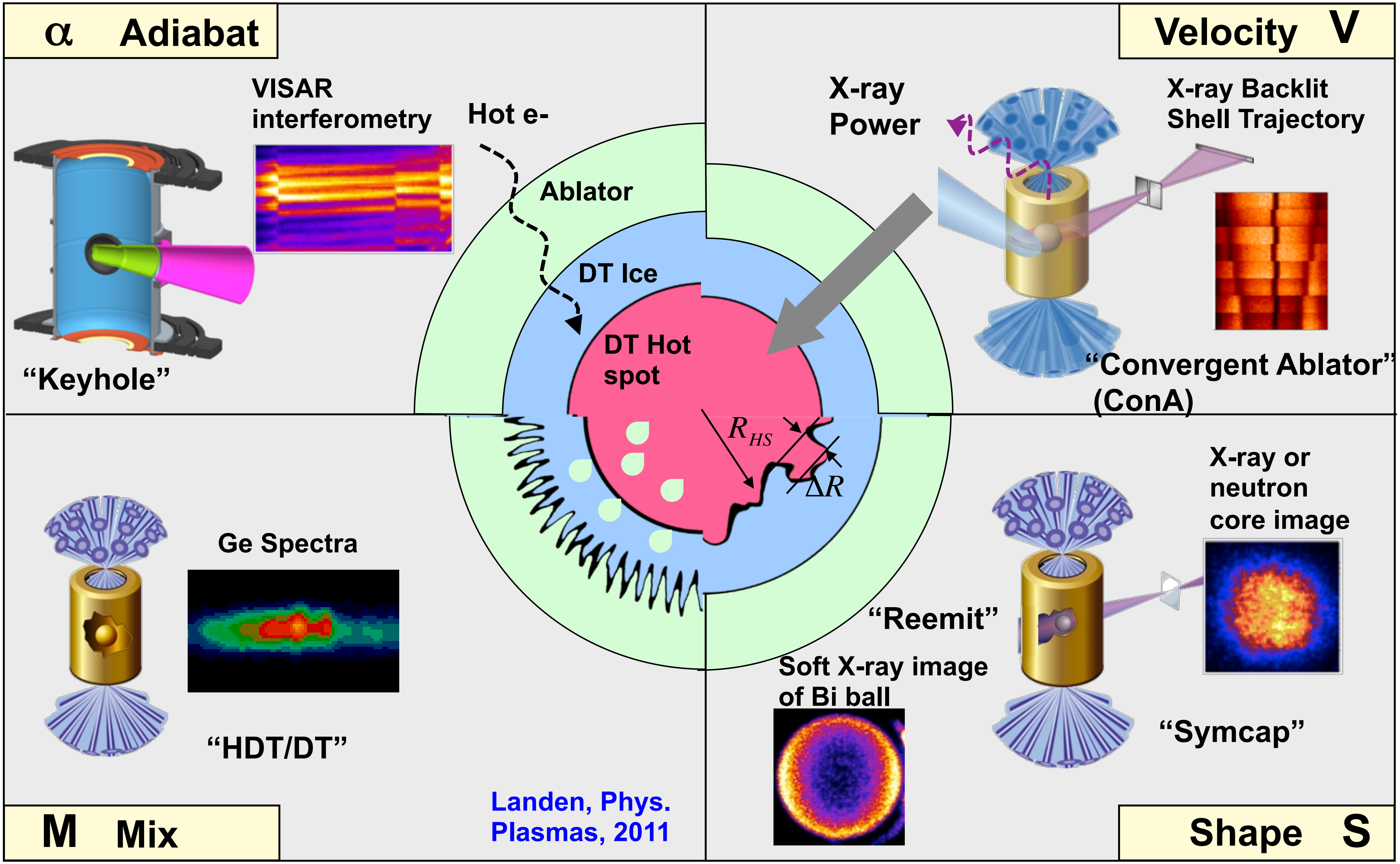
M Mix

(3 target parameters)

Shape S

(5 laser + 1 target parameter)

We use a variety of platforms to assess and tune the capsule adiabat, velocity, mix and shape



α Adiabat

VISAR interferometry

“Keyhole”

Velocity V

X-ray Power

X-ray Backlit Shell Trajectory

“Convergent Ablator” (ConA)

M Mix

Ge Spectra

“HDT/DT”

Shape S

X-ray or neutron core image

“Reemit”

Soft X-ray image of Bi ball

“Symcap”

Landen, Phys. Plasmas, 2011

Applied Science on NIC - Adiabat, velocity and mix are linked through compressibility and mass remaining

α Adiabat

$P_{stag} \sim \rho V_{imp}^2$

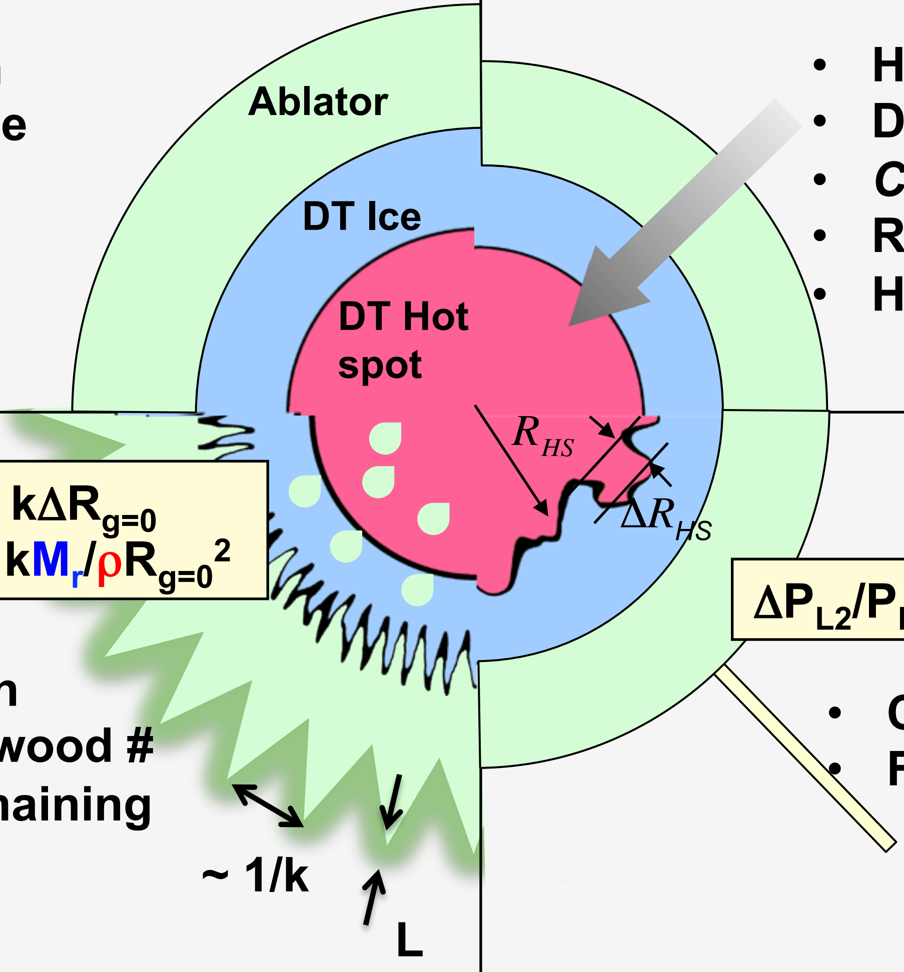
- Fuel compression
- CH EOS on release

Velocity V

$V_{imp} \sim V_e \ln(M_0/M_r)$

$\sim \sqrt{(ZTr/A)} \ln(M_0/M_r)$

- Hohlraum emissivity
- Dopant albedo
- *CH NLTE atomic physics*
- Rocket efficiency
- Hohlraum albedo



M Mix

$\gamma t \sim \sqrt{(kA\#R)}/(1+kL) - k\Delta R_{g=0}$

$\sim \sqrt{(kA\#R)}/(1+kL) - kM_r/\rho R_{g=0}^2$

- Shell compression
- X-ray preheat / Atwood #
- Ablator Mass Remaining

Shape S

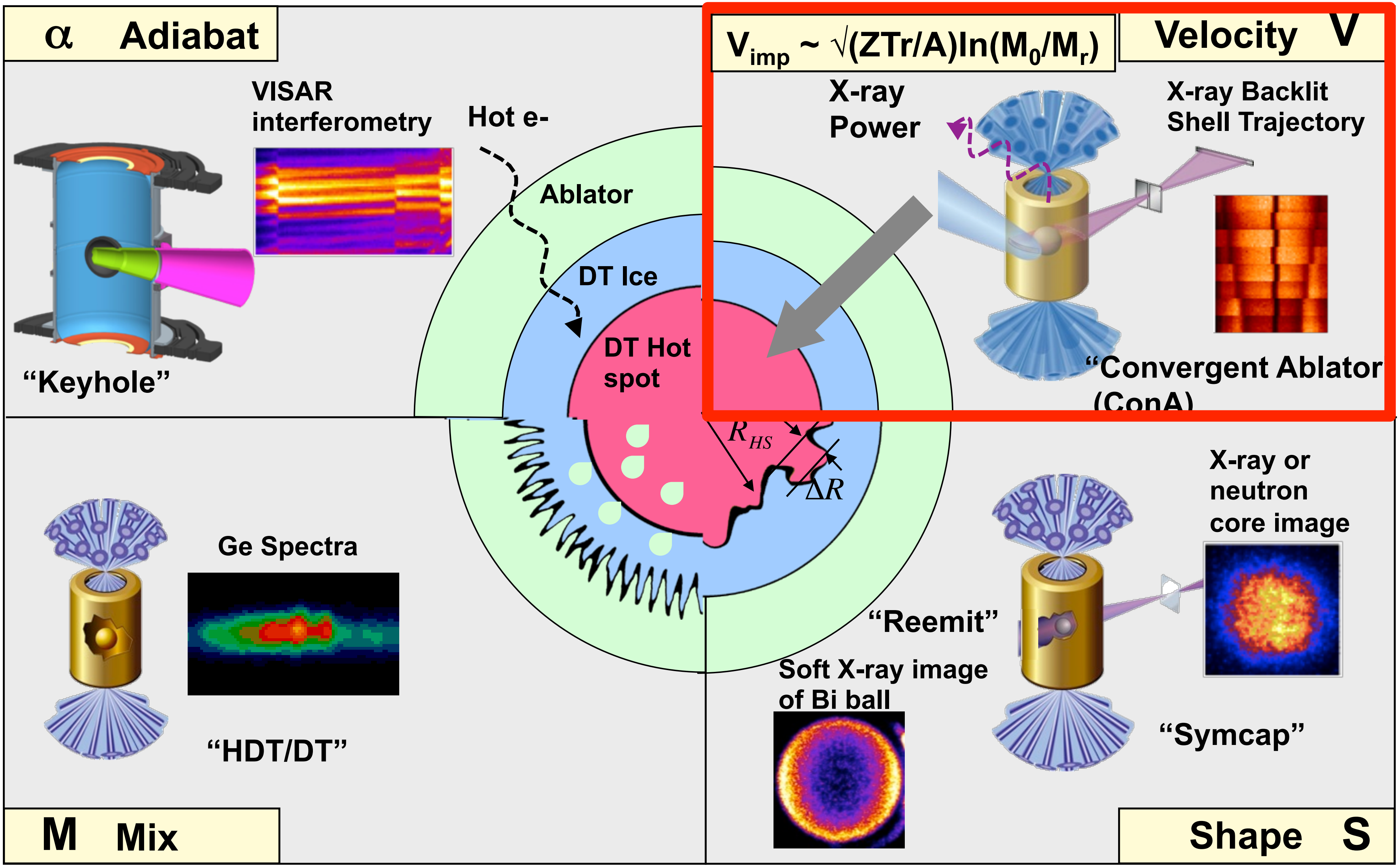
$\Delta R_{HS} \sim R\Delta P_L$

$\Delta P_{L2}/P_{L2} = g(\Delta\lambda, n_e/T_e, \delta n_{sat})P_{L1}$

- Crossbeam flux transfer
- Filltube asymmetry

Velocity

First step was to check peak hohlraum drive and capsule response



α Adiabat

$V_{imp} \sim \sqrt{(ZTr/A)\ln(M_0/M_r)}$

Velocity V

M Mix

Shape S

VISAR interferometry

Hot e-

“Keyhole”

Ablator

DT Ice

DT Hot spot

X-ray Power

X-ray Backlit Shell Trajectory

“Convergent Ablator (ConA)

R_{HS}

ΔR

Ge Spectra

“HDT/DT”

“Reemit”

Soft X-ray image of Bi ball

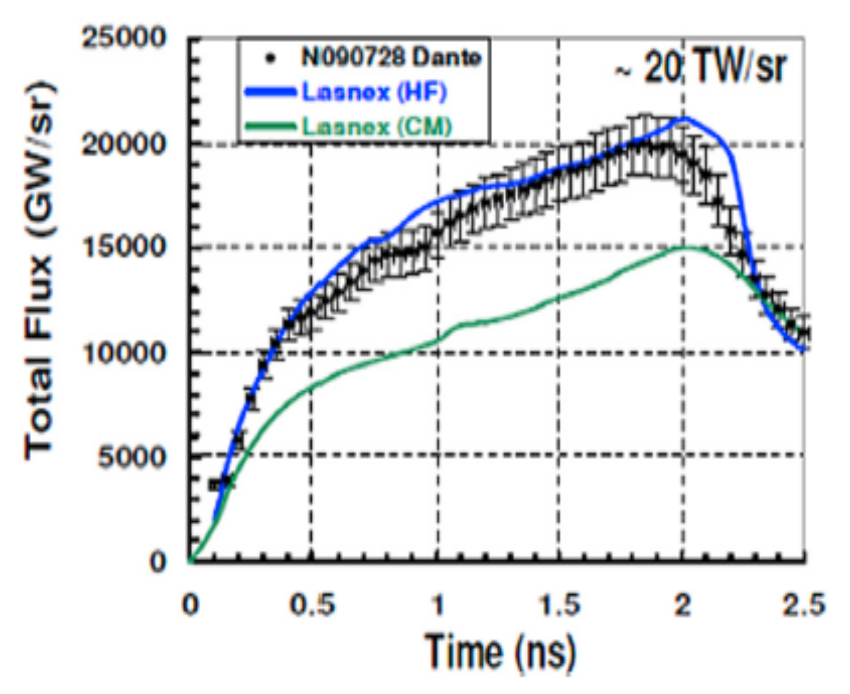
X-ray or neutron core image

“Symcap”

Velocity

Higher than expected hohlraum drive at NIF scale motivated switch to high flux model

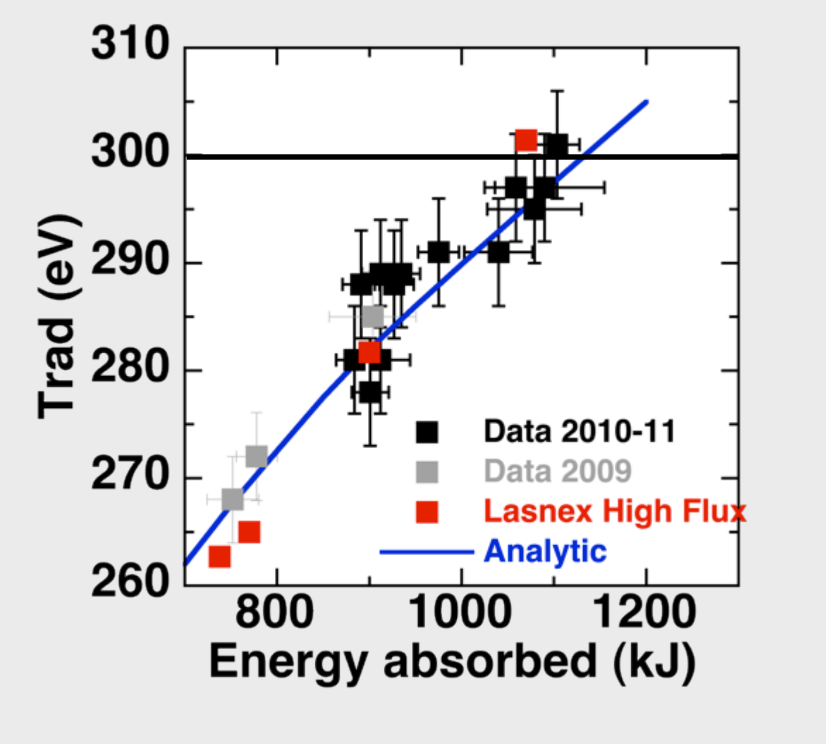
Dante Flux vs Simulations – Vacuum Hohlraums



CM: XSN, f = .05
High Flux: DCA, f = 015

Kline, PRL, 2011
Olson, Phys. Plasmas, to be published 2012

Dante Tr vs. Absorbed laser Energy - NIC Hohlraums

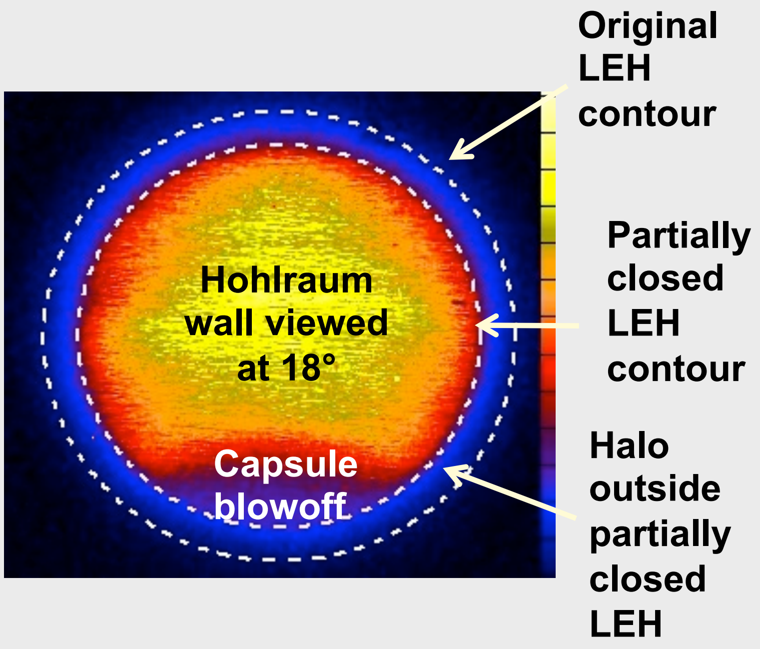


Glenzer, Science, 2010

$V_{imp} \sim \sqrt{}(Z\text{"}Tr\text{"}/A)\ln(M_0/M_r)$

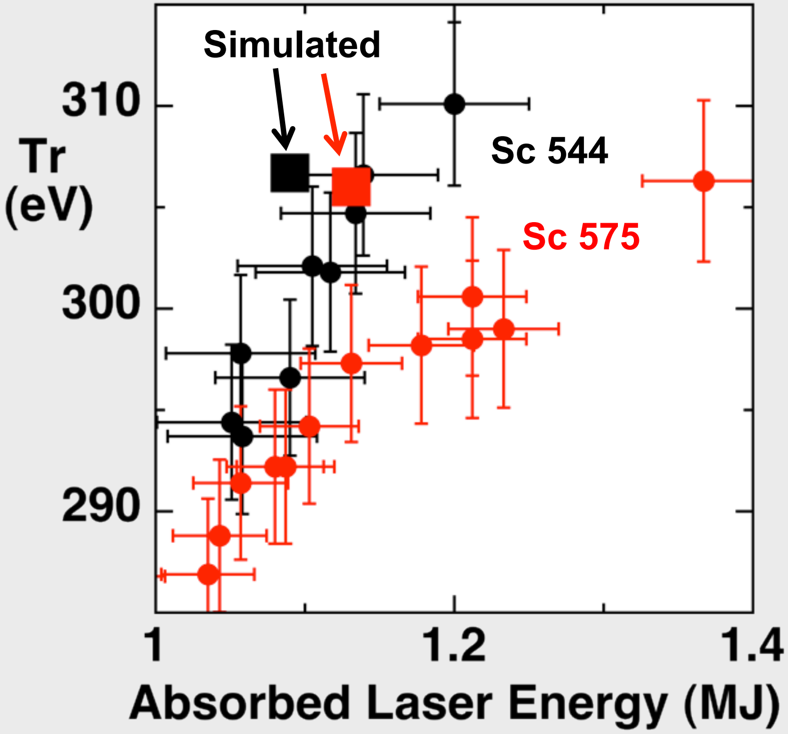
A more careful comparison comparing LEH closure suggests internal drive 5-10% less than originally inferred

870-eV X-ray Image through LEH



LEH size closes by ≈ 15%
Halo is ≈ 10% of total at Planckian 870 eV peak (data and simulation)

Tr vs. Absorbed Laser Energy



Meezan, IFSA 2011 proceedings

Inferred internal Tr from Dante flux and LEH X-ray image is lower principally because final LEH size is ≈ 7% larger in data than simulations

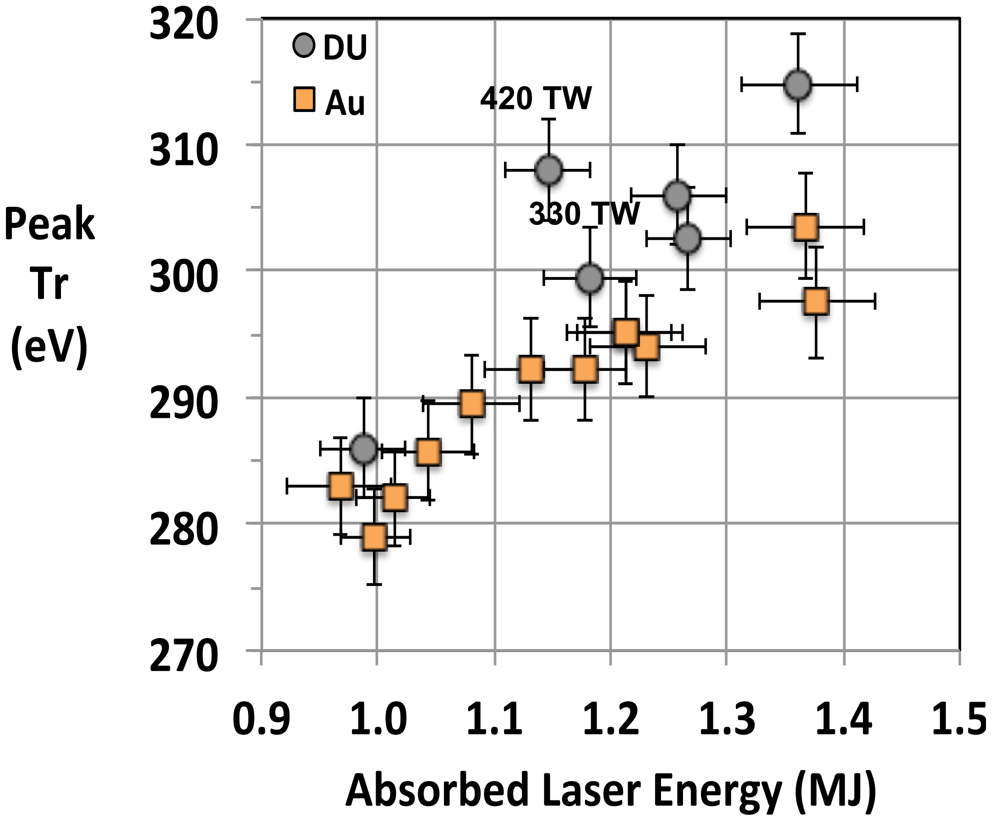
Velocity

Symmetry Capsule

On plus side, Au-lined DU hohlraums provide increased Tr and same laser energy coupling

9.43 mm by 5.75 mm Hohlraum, 3.1 mm LEH

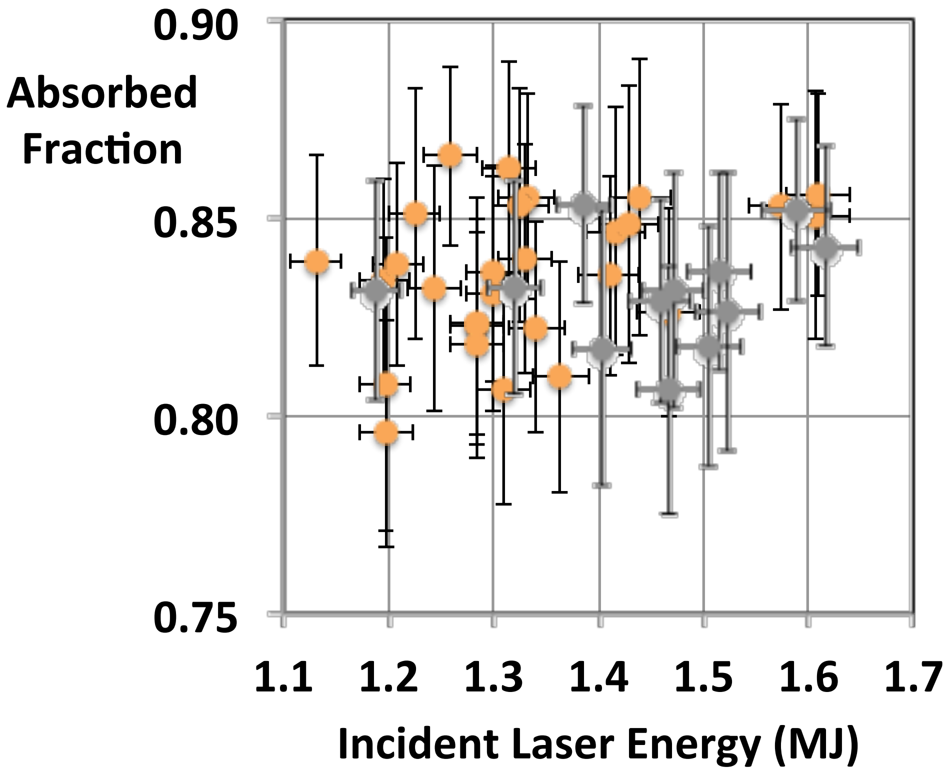
Peak Tr vs Absorbed Laser Energy



Confirms higher albedo of U at high Tr

Callahan, Phys. Plasmas, 2012

Absorbed Fraction vs Incident Laser Energy

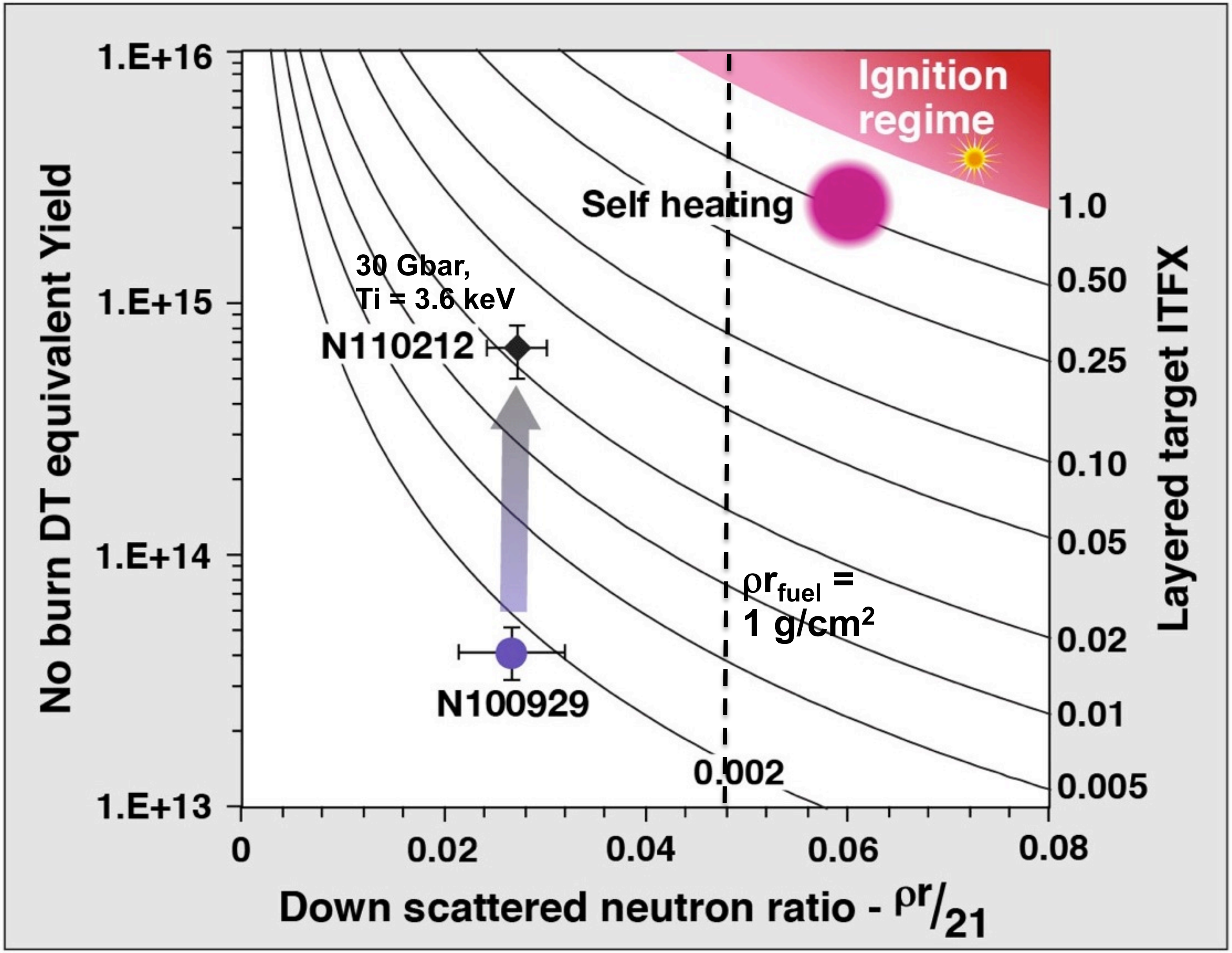


At highest incident energies, absorbed fraction increasing as backscatter drops off on extended pulses

Implosion Performance

Increasing energy from 1 to 1.3 MJ improved yield 10x to ITFx = .02

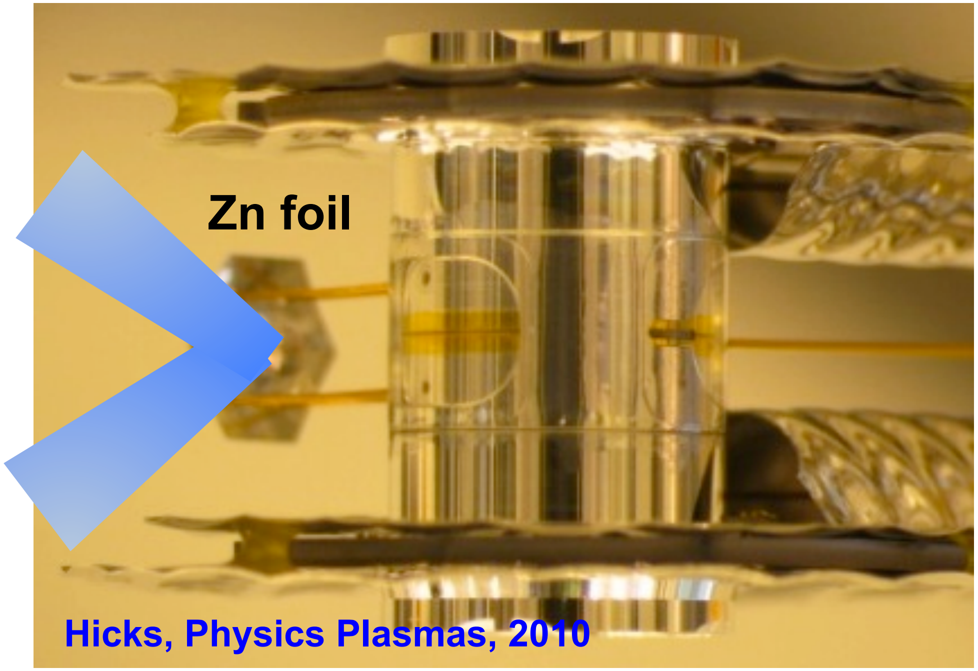
Faster, hotter



Lower adiabat, more compressed →

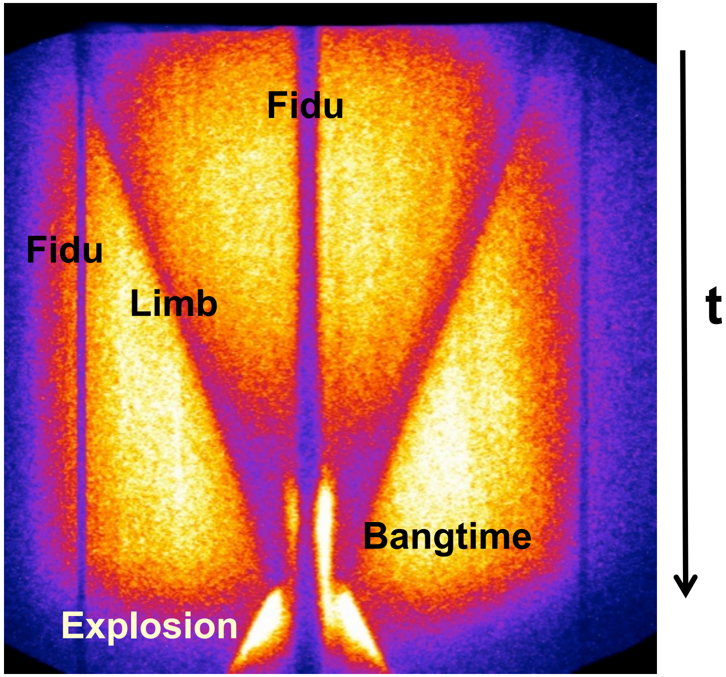
Ablator velocity, mass and thickness are measured using backlit gated and now streaked radiography

Capsule backlit by x-rays from separate laser plasma



Hicks, Physics Plasmas, 2010

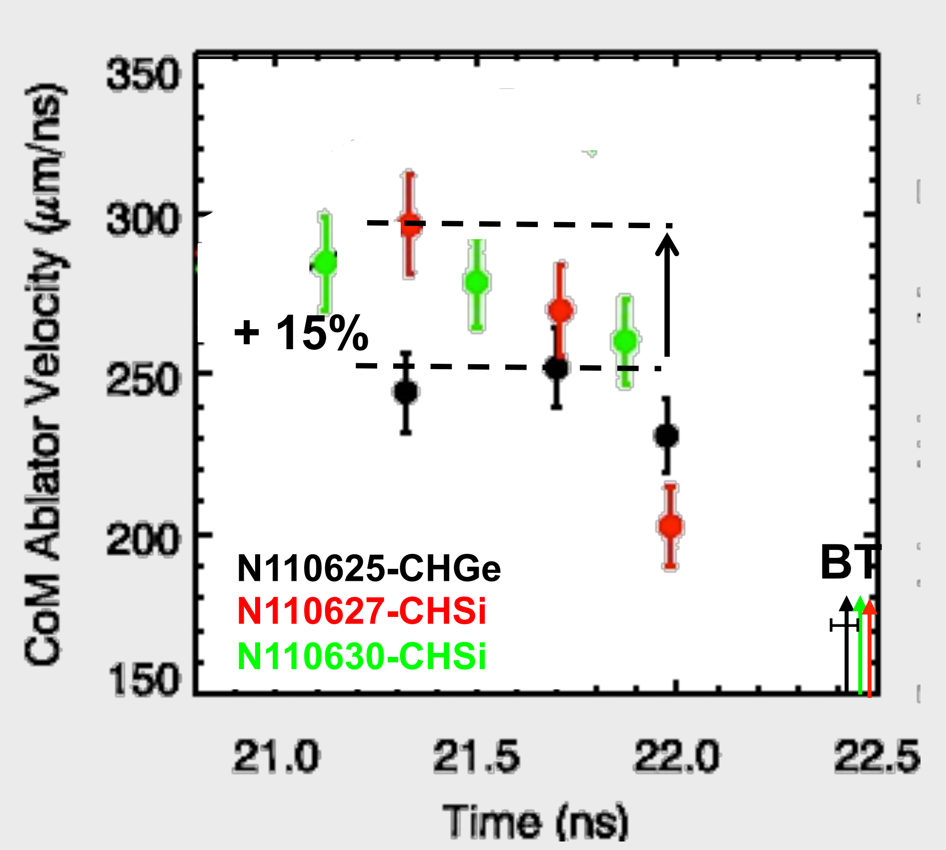
9 keV streaked radiograph



- Technique measures shell radius, velocity, ρR profile, and remaining ablator mass
- Recently, as a by-product, we have been looking at energetics information provided by explosion phase

Radiography confirmed that switch from CHGe to lower albedo, higher ablation rate CHSi increased peak velocity

Center-of-Mass Ablator Terminal Velocities vs Time

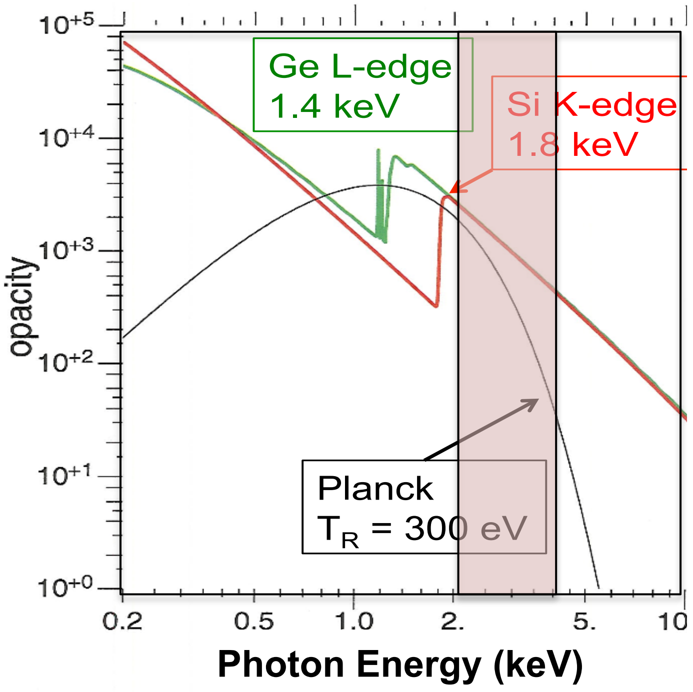


Trend is consistent with high Tr OMEGA planar ablation rate experiments

Olson, Phys. Plasmas, 2011

$P_a = (1 - \alpha)V_{ex}dm/dt$

$V_{imp} \sim \sqrt{(ZT_r/A)}\ln(M_0/M_r)$

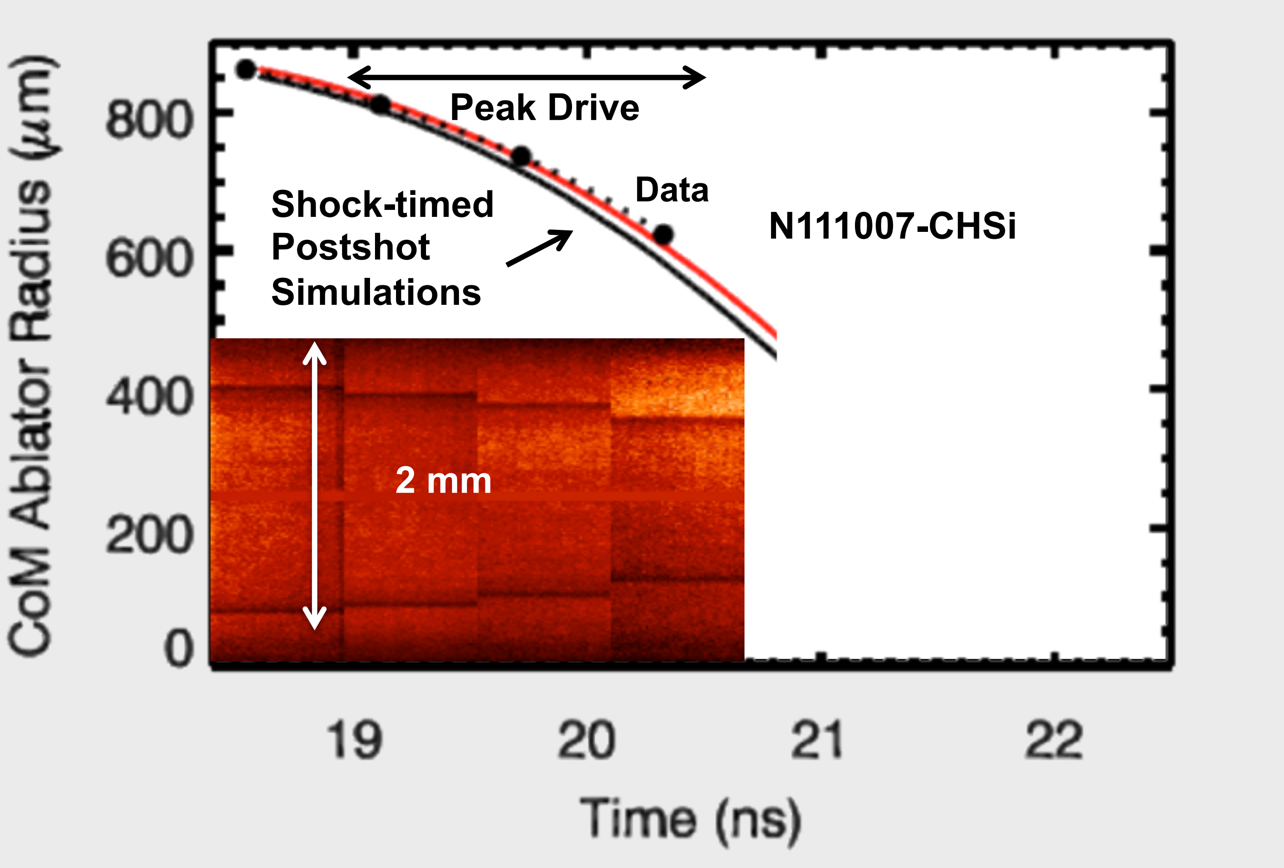


Si still provides same > 1.8 keV shielding as Ge at fuel/ablator interface while only screening 14 vs 30% of thermal 300 eV Planckian

Salmonson, IFSA, 2011

We have extended radiography field-of view to full 2 mm to check early shell trajectory and thickness

Radius vs. Time



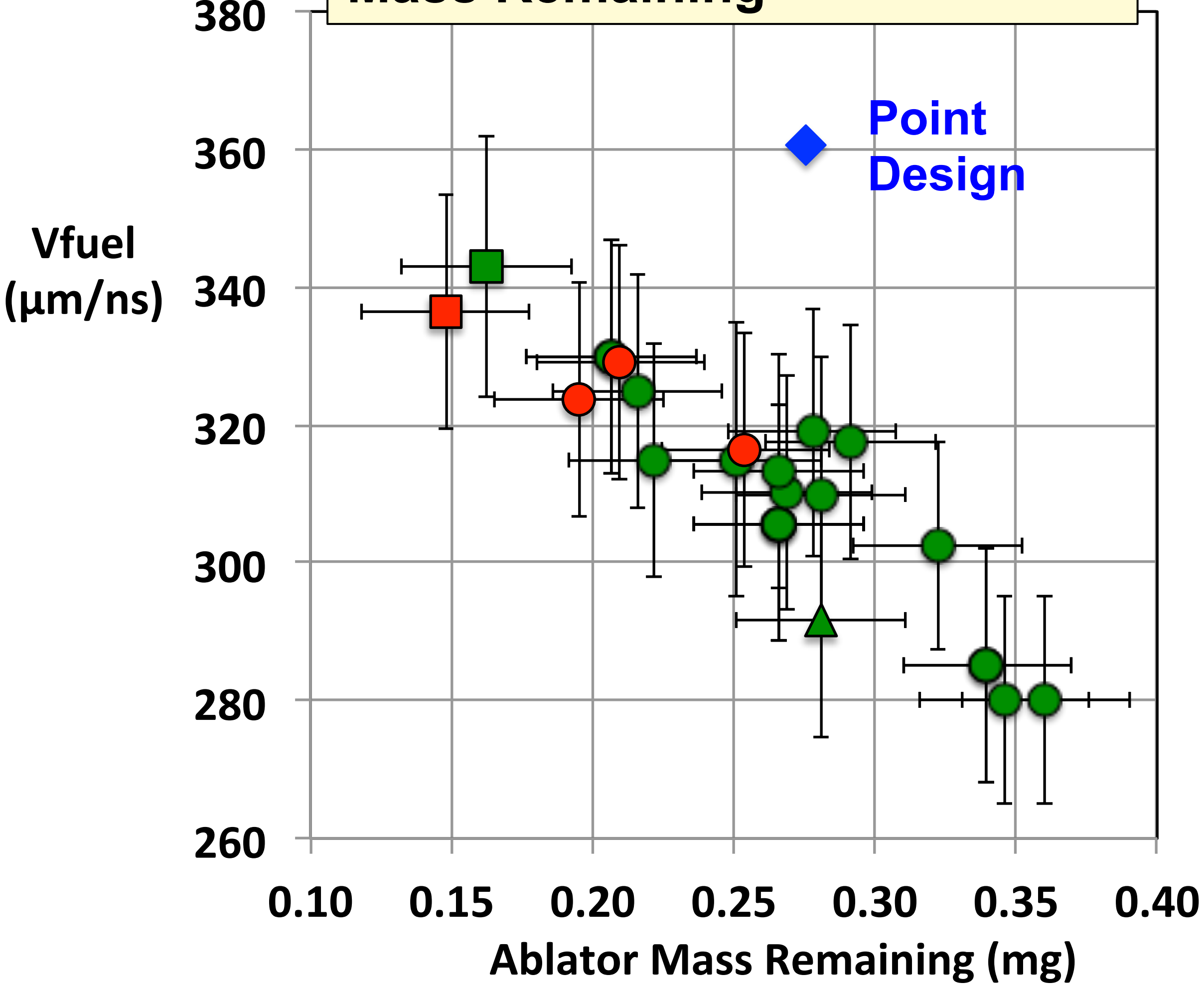
Early trajectory is 10 ± 6% slow consistent with slow 4th shock

Velocity

Backlit Capsule

Perhaps most significant usage has been that x-ray radiography allows us to check Rocket Model

Peak Fuel Velocity vs Ablator Mass Remaining



$V_{imp} \sim \sqrt{(ZTr/A)}\ln(M_0/M_r)$

Currently Peak implosion velocity is ≈ 15% lower than point design for equivalent mass remaining

Suggests lower effective exhaust velocity ~ √(ZTr/A)

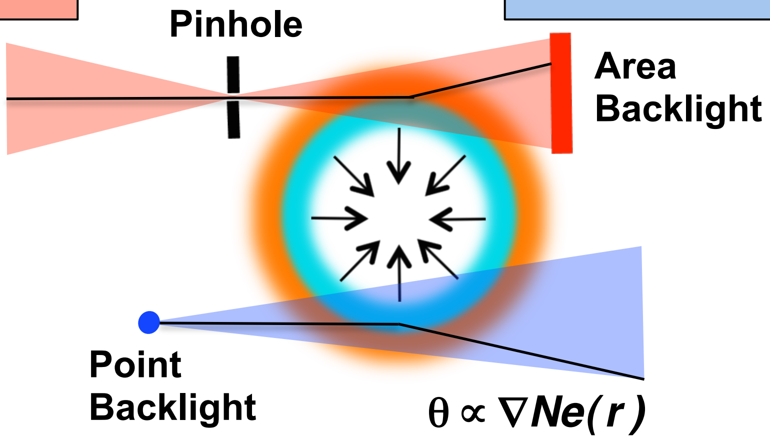
- Tr lower (2% effect)?
- C K-shell ionization lower (NLTE effect)?
- C and H species separation in ablation?

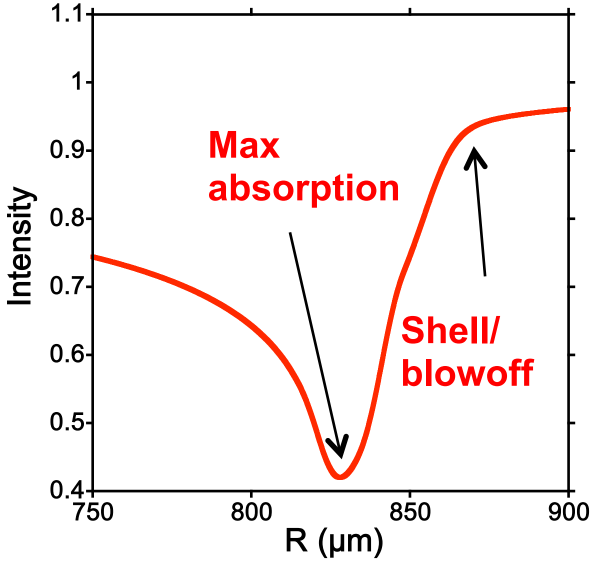
Test latter hypotheses using alternate single element ablators (Be, C, Al)

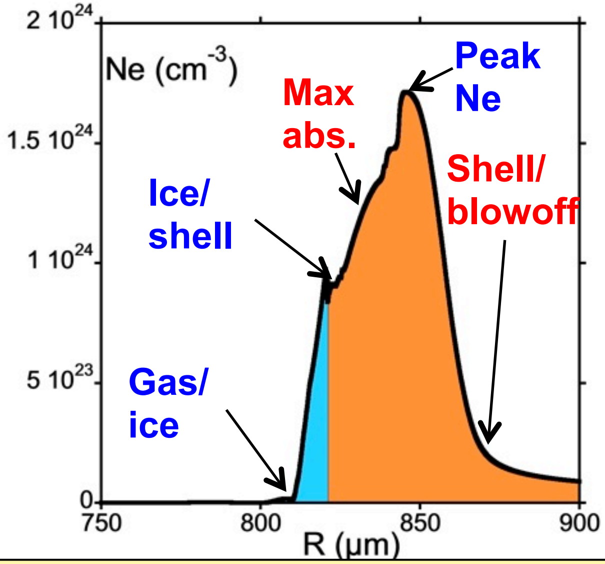
We are also designing a refraction-enhanced streaked radiography experiment to measure in-flight fuel conditions

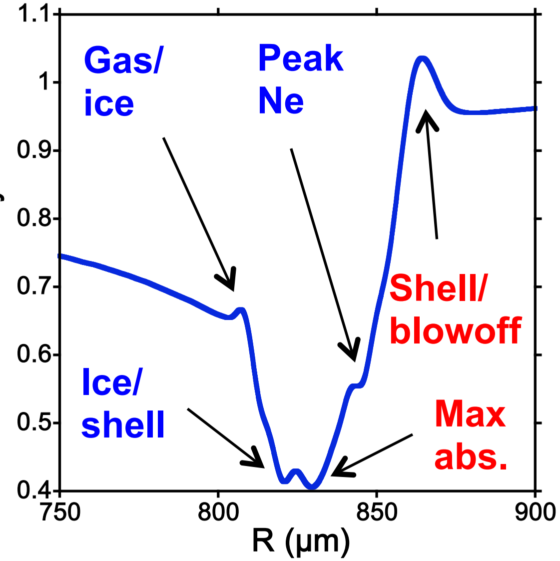
Traditional Radiography
- Area BL negates refraction

Refraction-Enhanced Radiography
- Point BL allows refractive bending









Density profile of higher Z shell

Ice and ablator width (i.e. adiabat), Atwood #

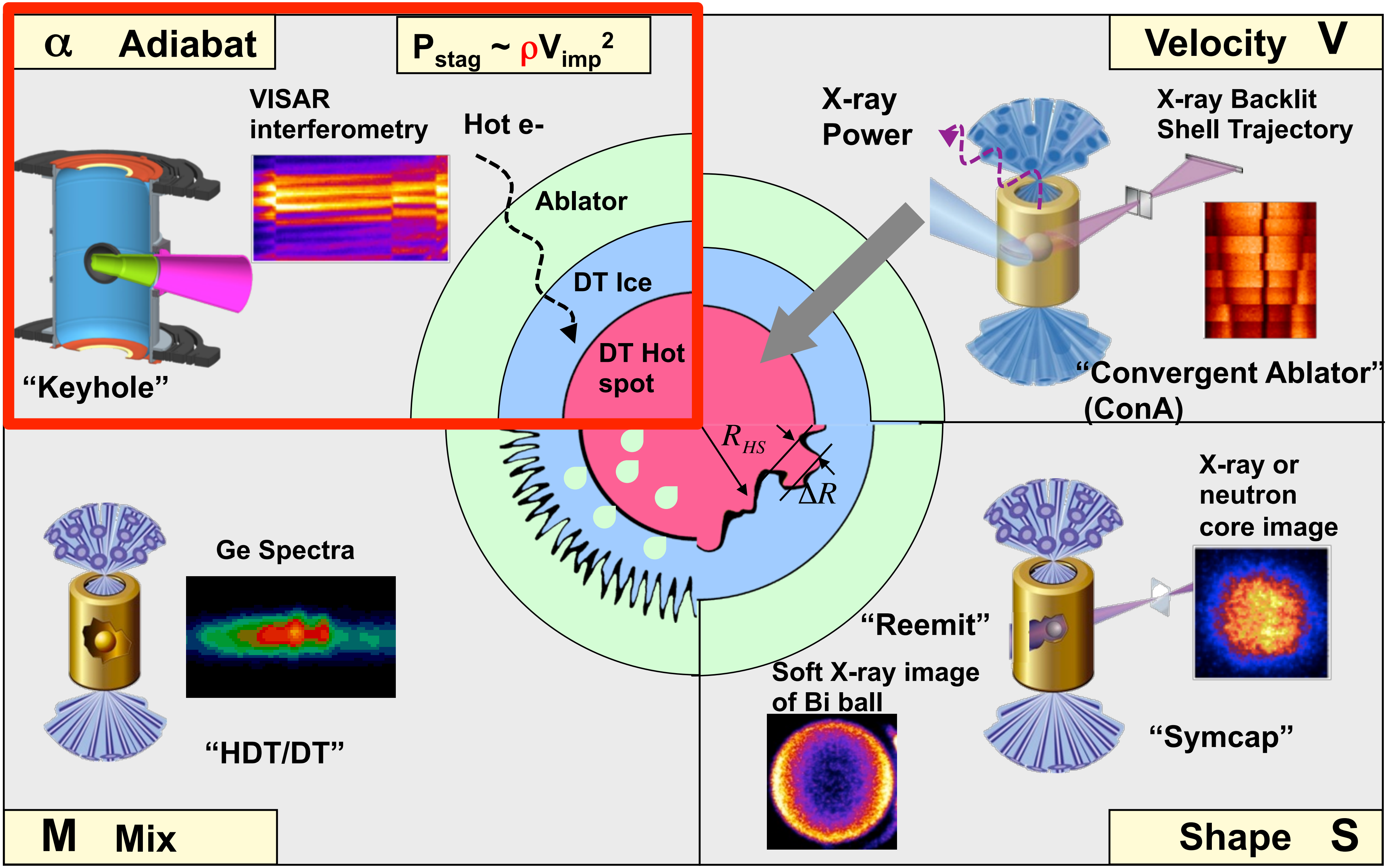
Techniques complement each other

Transient Refraction-enhanced radiography demonstrated at OMEGA

Ping, JInst, 2011

Adiabat

Over last year, we have also tuned the shock launch times to improve fuel compressibility



α Adiabat

$P_{stag} \sim \rho V_{imp}^2$

VISAR interferometry

Hot e-

"Keyhole"

Velocity V

X-ray Power

X-ray Backlit Shell Trajectory

"Convergent Ablator" (ConA)

M Mix

Ge Spectra

"HDT/DT"

"Reemit"

Soft X-ray image of Bi ball

X-ray or neutron core image

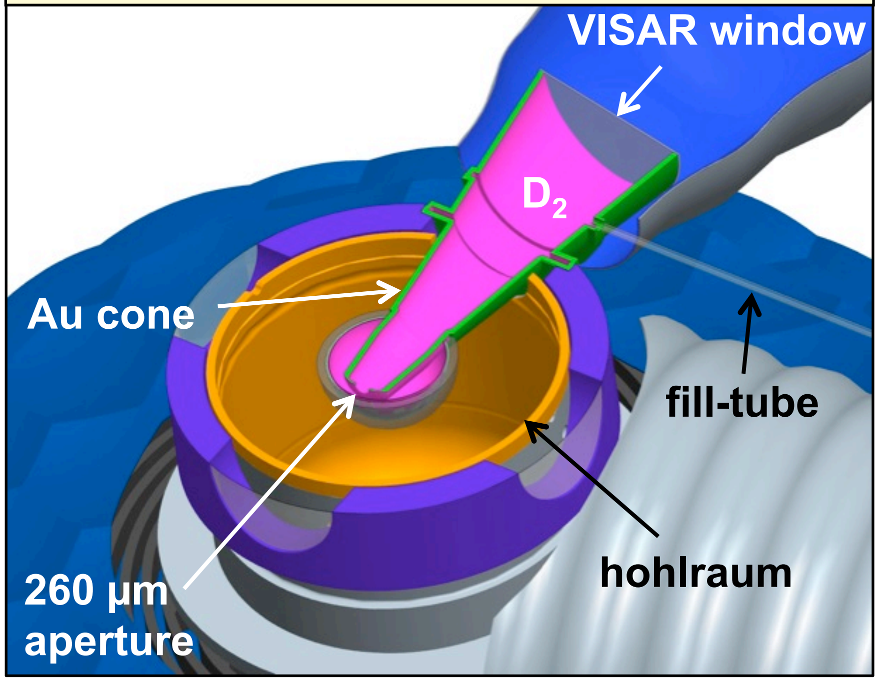
"Symcap"

Shape S

Adiabat

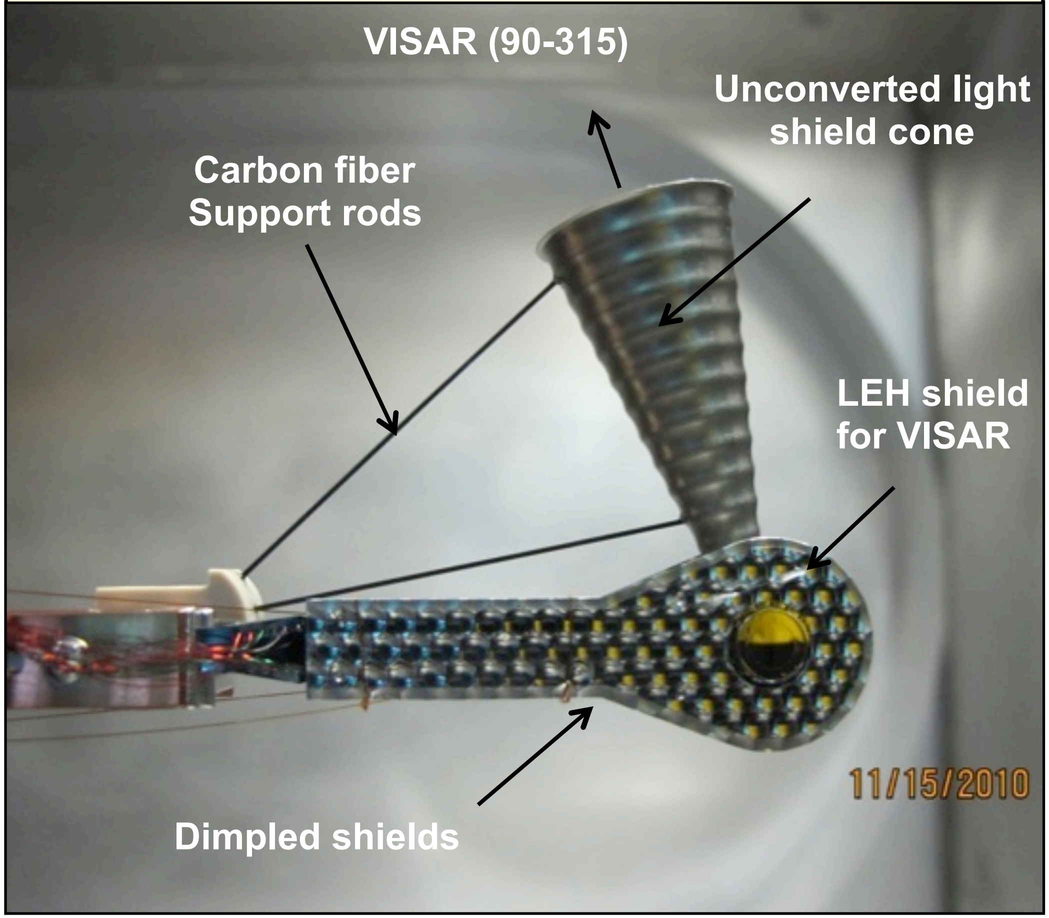
Reentrant cone "Keyhole" now used routinely to measure shock speeds in liquid D_2 as surrogate for solid DT

Model of the "keyhole" target

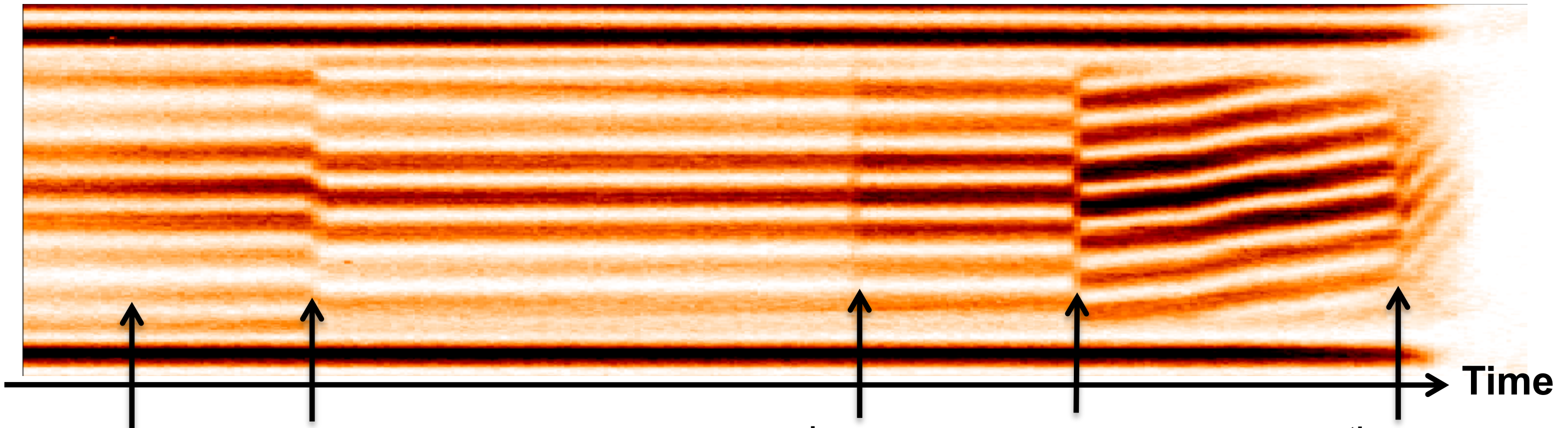


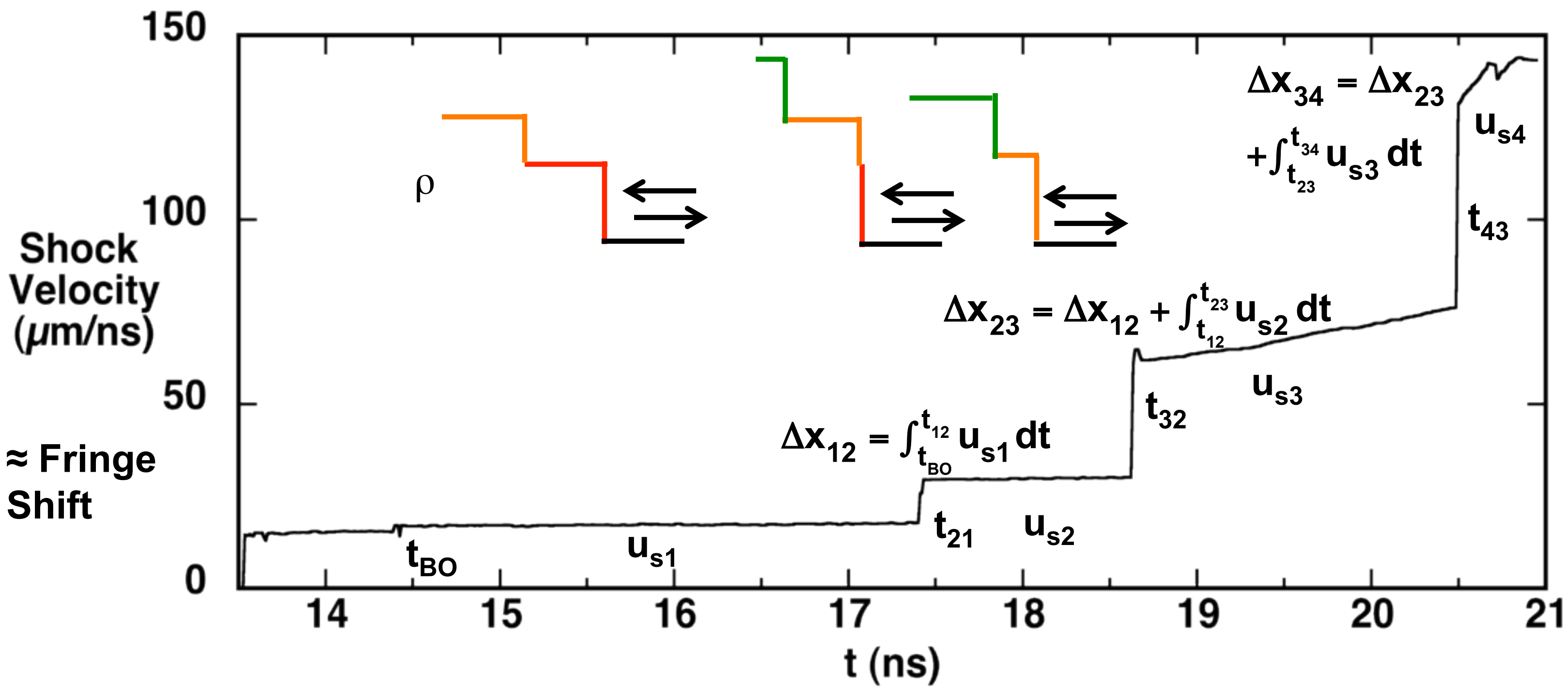
Boehly, Phys. Plasmas, 2011
Robey, Phys. Plasmas, 2012

Top view of keyhole target



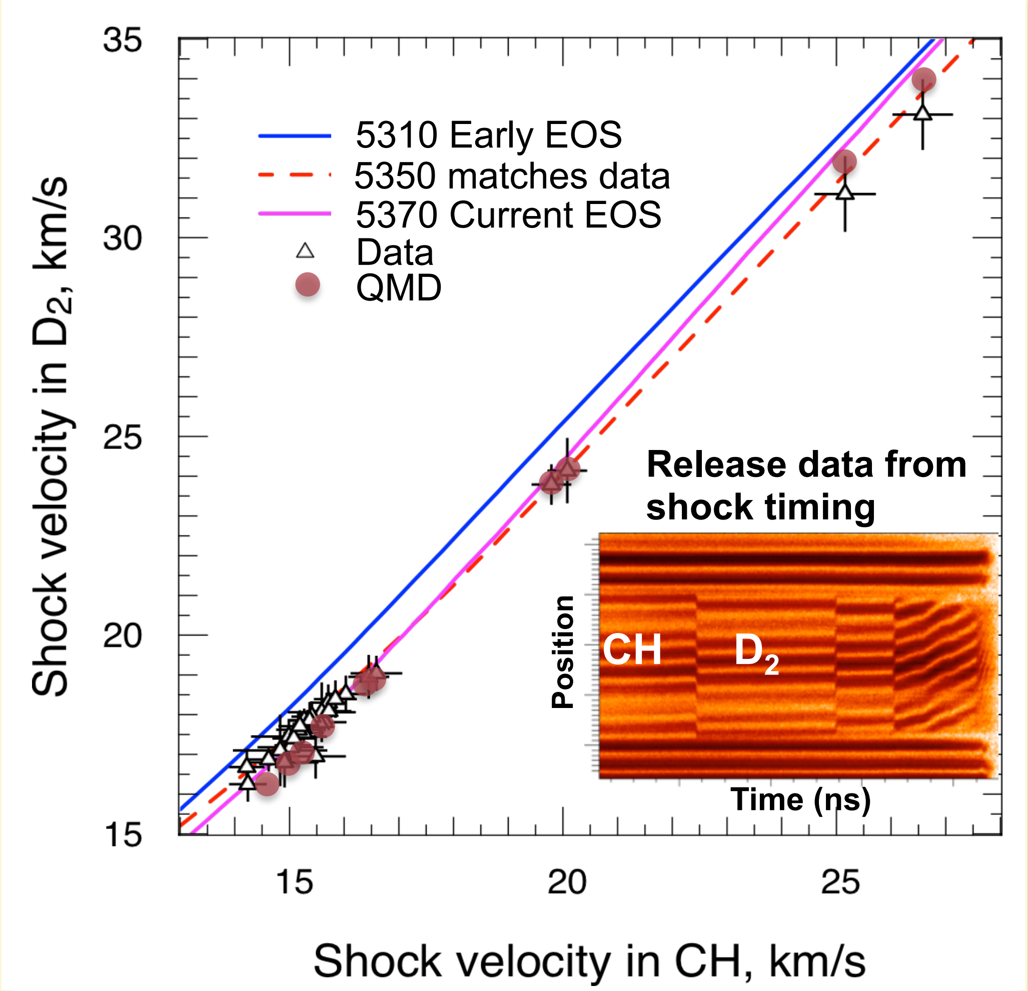
We integrate up leading shock velocity to extract overtake depths (at velocity discontinuities)





By-product: Lower than expected 1st shock velocity jump across CH-D_2 interface led to modified CH EOS table

First Shock Velocity D_2 vs CH



Release data from shock timing

QMD matches release quite accurately

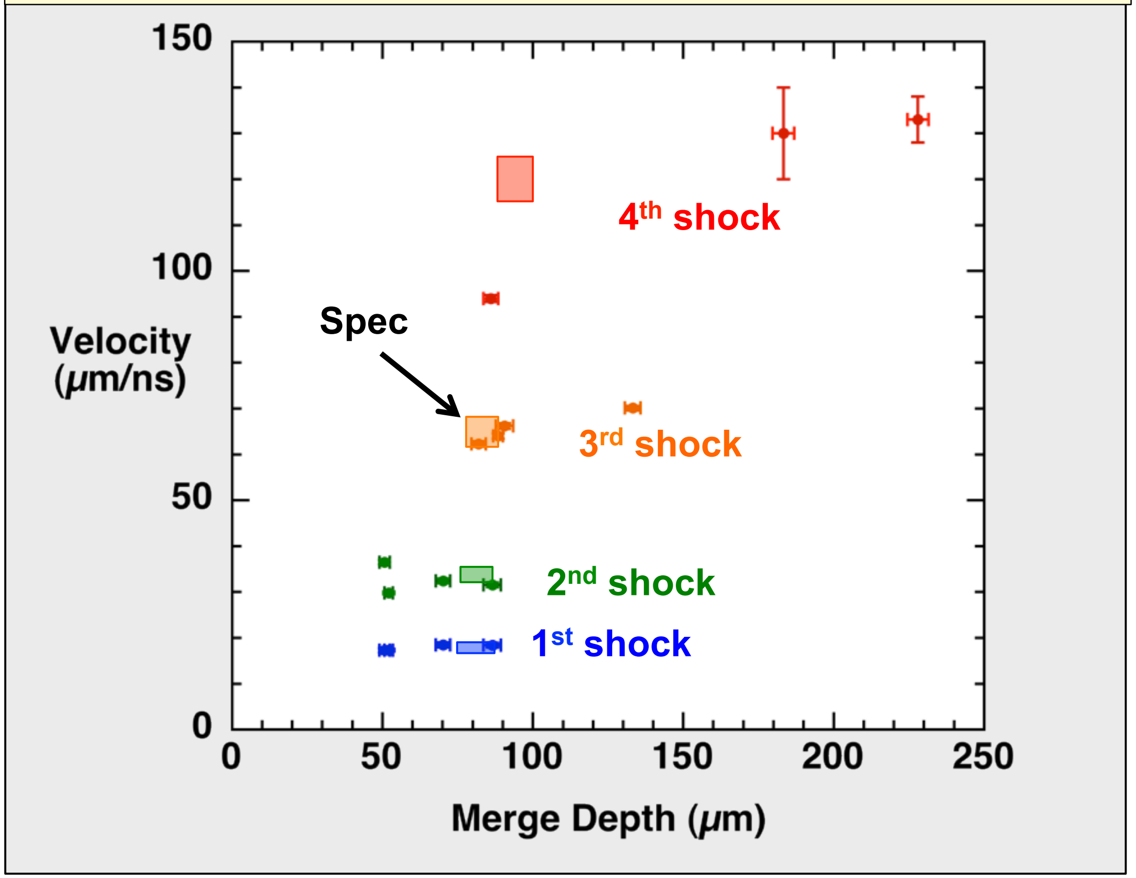
Analysis uses modified Kerley 2003 D_2 EOS

Adiabat

Keyhole

We have set shock velocities and merge depths to design values within 3 shots, and shown reproducibility

Shock Velocities and Merge Depths in Liquid D_2

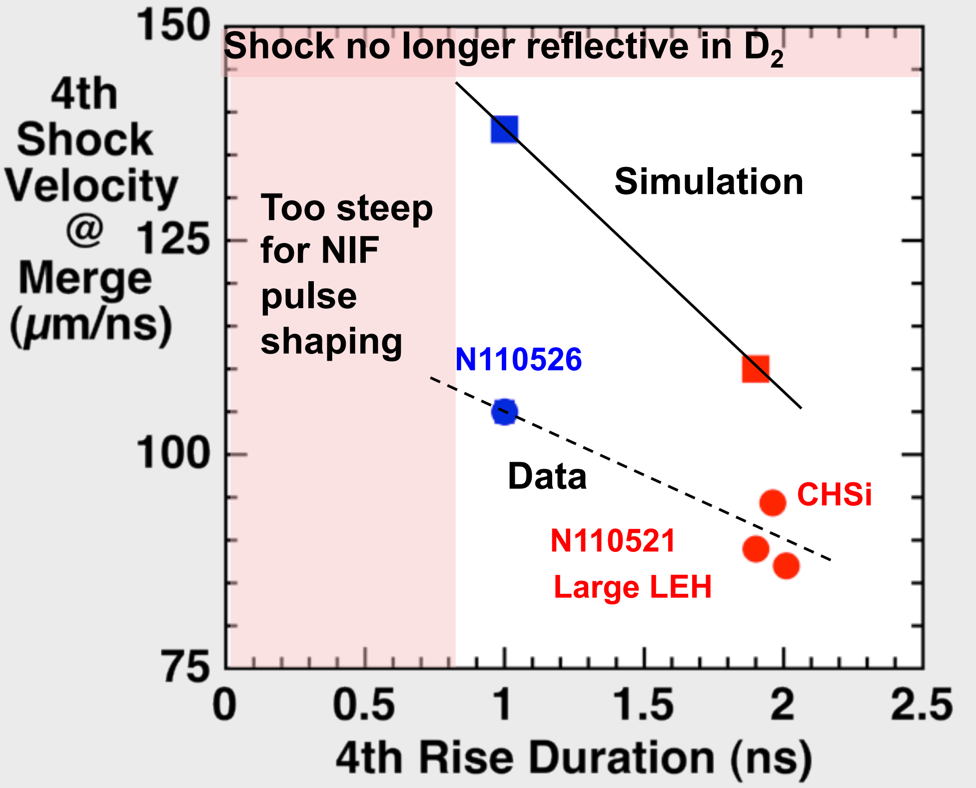


Velocities measured to ± 0.5 μm/ns

Merge depths to ± 2 μm

4th shock velocities are lower and scale more slowly with 4th rise slope than expected

4th Shock Merge Velocity vs. 4th Pulse Rise Time

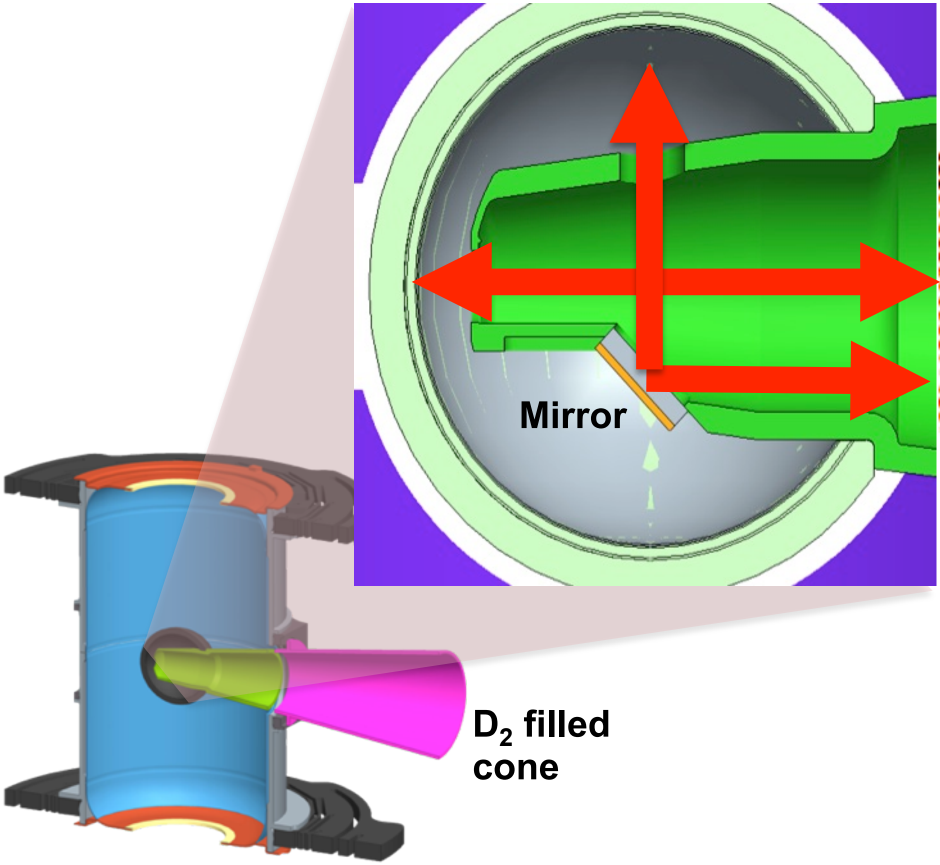


4th shock velocities are 15 – 25% lower than expected

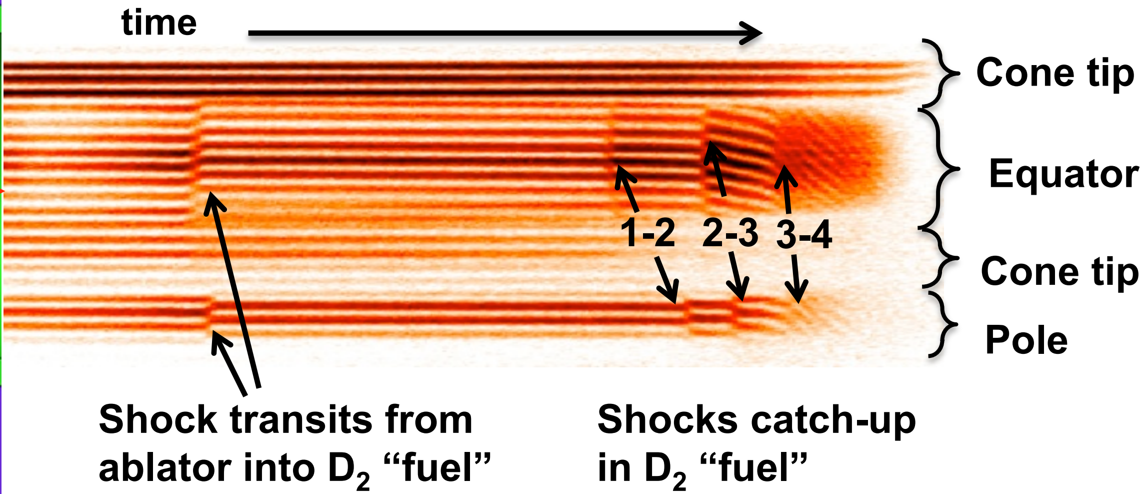
- We have designed a preheat shielded solid fused silica ball in keyhole geometry to follow 4th shock acceleration to later times
- Tested successfully at OMEGA last week to 60 Mbar pressures

Adiabat

Dual axis VISAR was then implemented to uncover and fix 2nd - 4th shock asymmetry



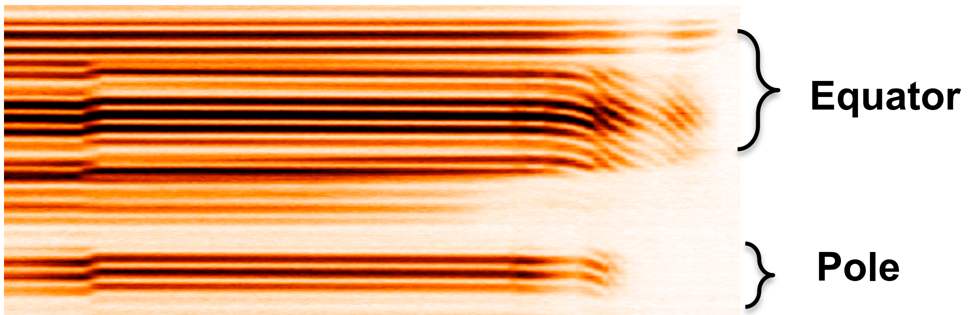
N110823 VISAR data



Shock transits from ablator into D_2 “fuel”

Shocks catch-up in D_2 “fuel”

N111108 VISAR data - fixed



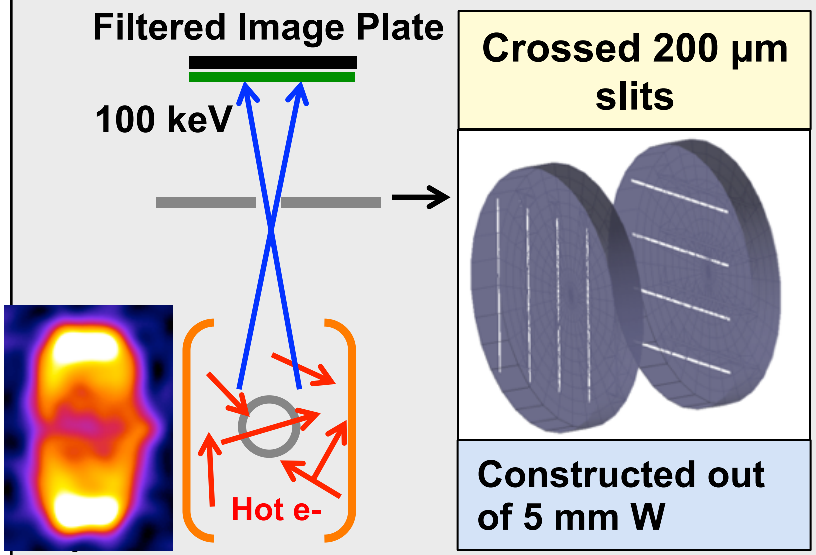
Shock asymmetry contributed to P_2 symmetry swings seen in symcap/DT implosions

Adiabat

Symmetry Capsule

Other source of fuel entropy, hot electron preheat, is inferred by imaging 100 keV capsule Bremsstrahlung

Hard X-ray Bremsstrahlung Imaging



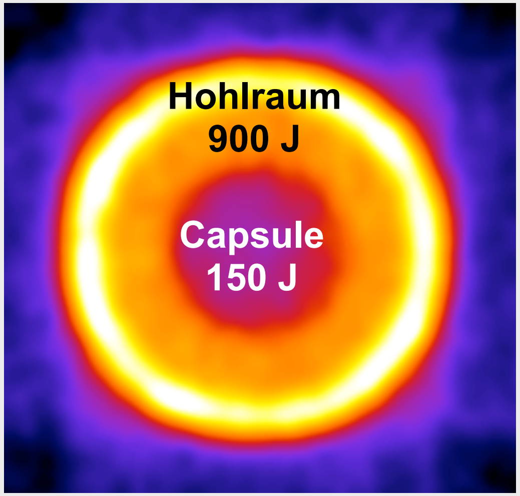
Crossed 200 μm slits

Constructed out of 5 mm W

System absolutely calibrated

Doeppner, PRL (2012)

100 keV Image from Symcap used to Infer Hot Electron Yield

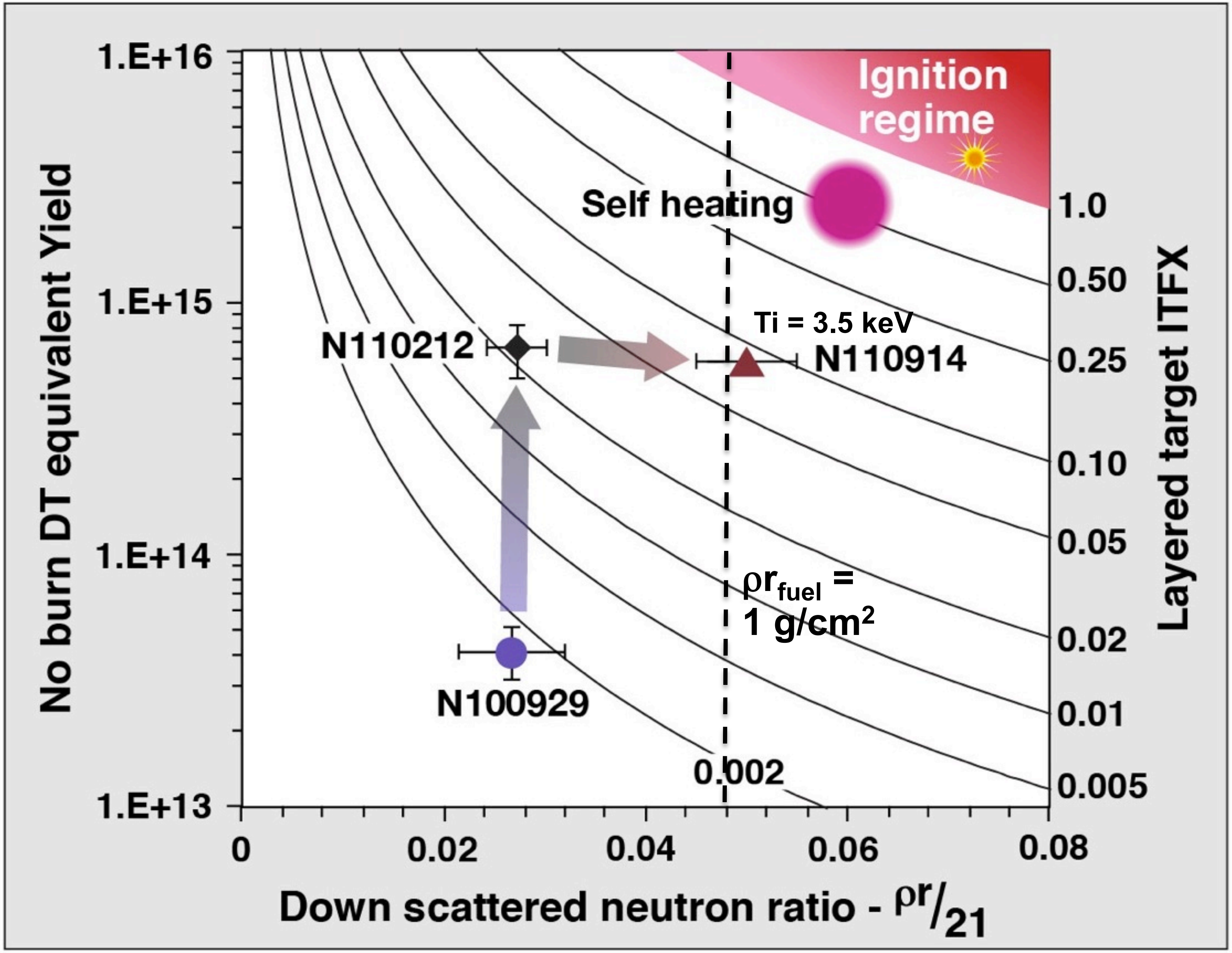


150+25,-100 J > 170 keV* hot e$^-$ @ capsule, acceptable

*Energy of hot electrons that could reach fuel

Shock timing improved fuel ρr by ≈ 2x to over 1 g/cm^2 and ITFx reached .08

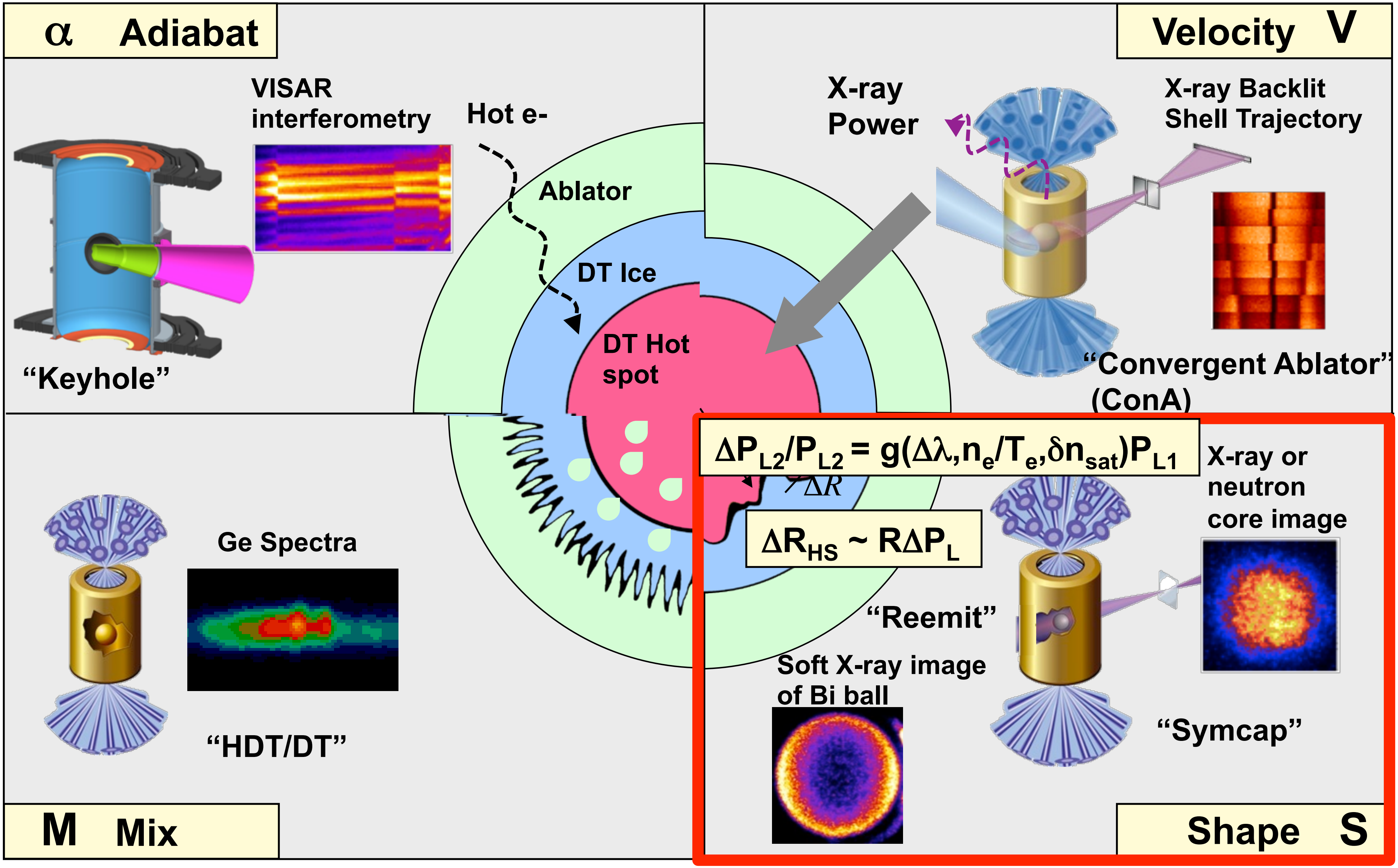
Faster, hotter



Lower adiabat, more compressed

Shape

Time-dependent drive symmetry control was completed during last half of 2011



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$\Delta P_{L2}/P_{L2} = g(\Delta\lambda, n_e/T_e, \delta n_{sat})P_{L1}$

ΔR

$\Delta R_{HS} \sim R\Delta P_L$

X-ray or neutron core image

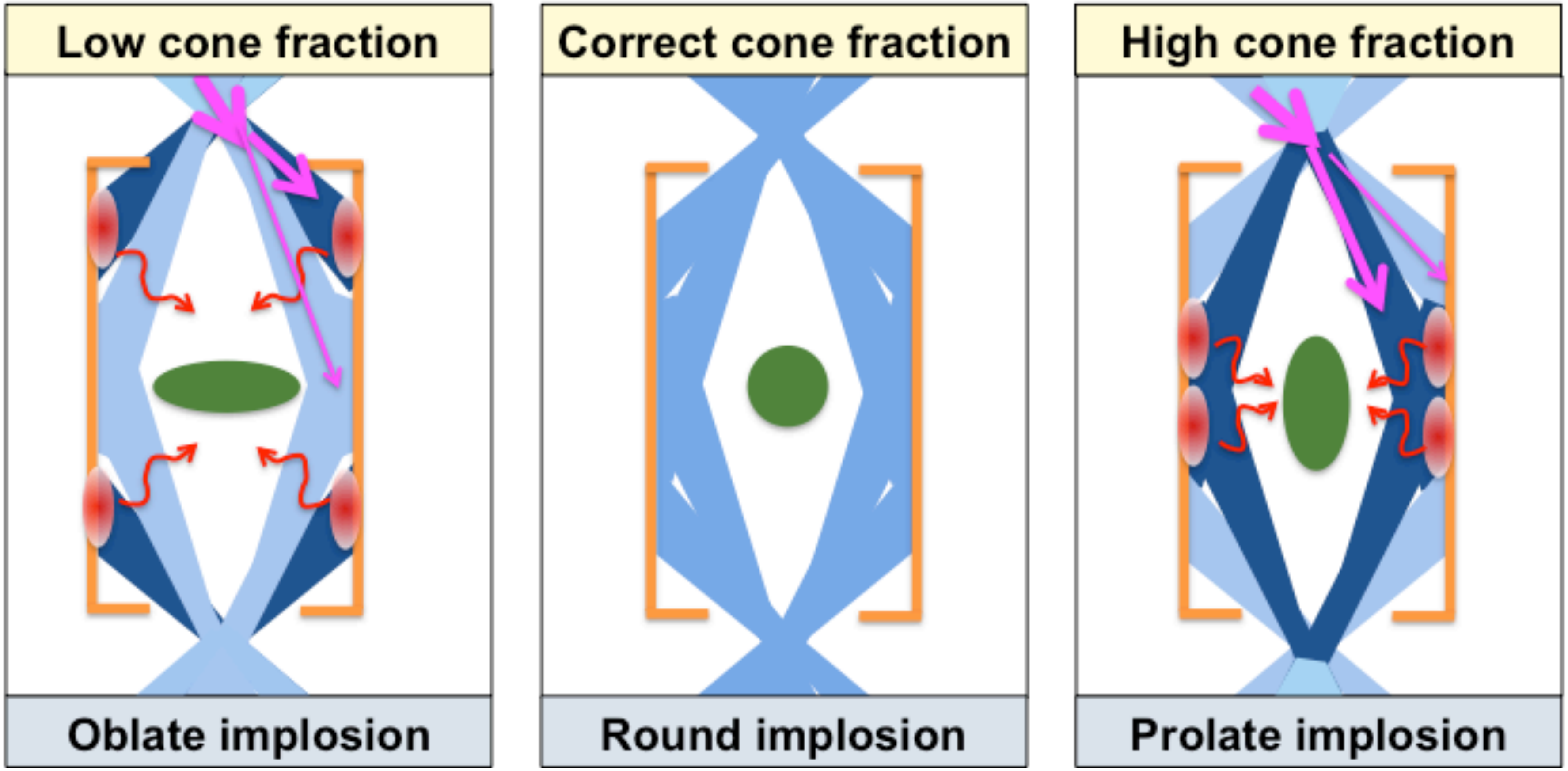
"Reemit"

Soft X-ray image of Bi ball

"Symcap"

Shape

Drive symmetry set by changing laser cone fractions, either externally or by crossbeam transfer

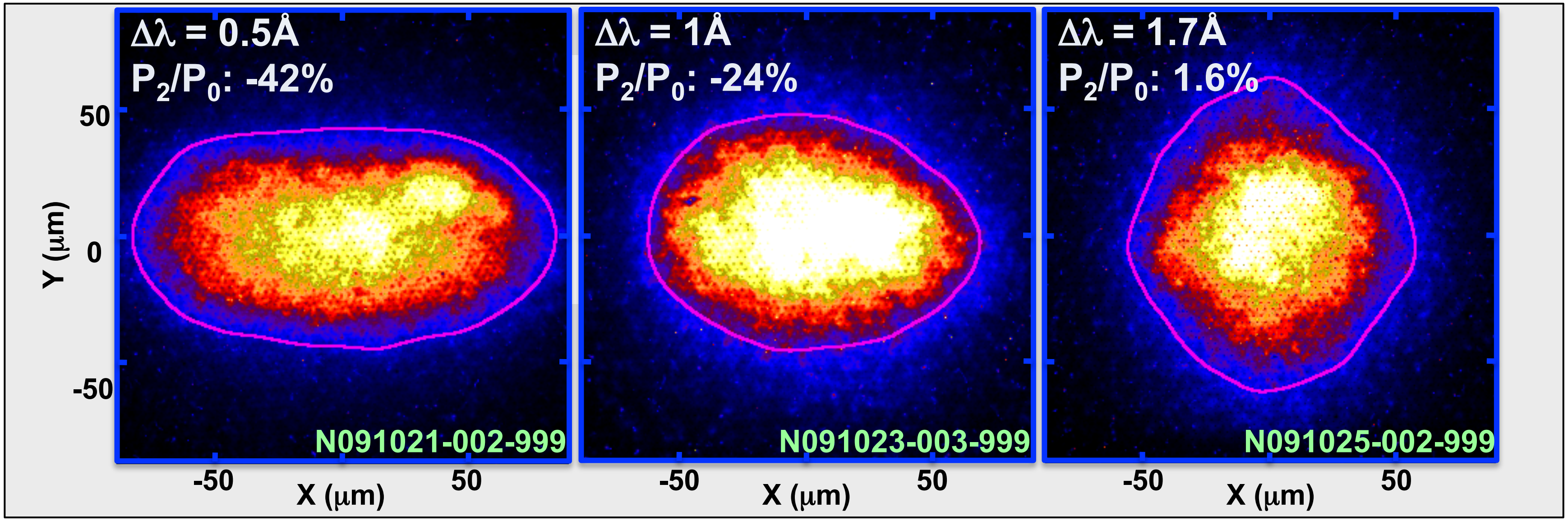


Transfer is through 3-wave mixing process in presence of plasma grating induced by crossing beams, sensitive to $\Delta\lambda$ between beams

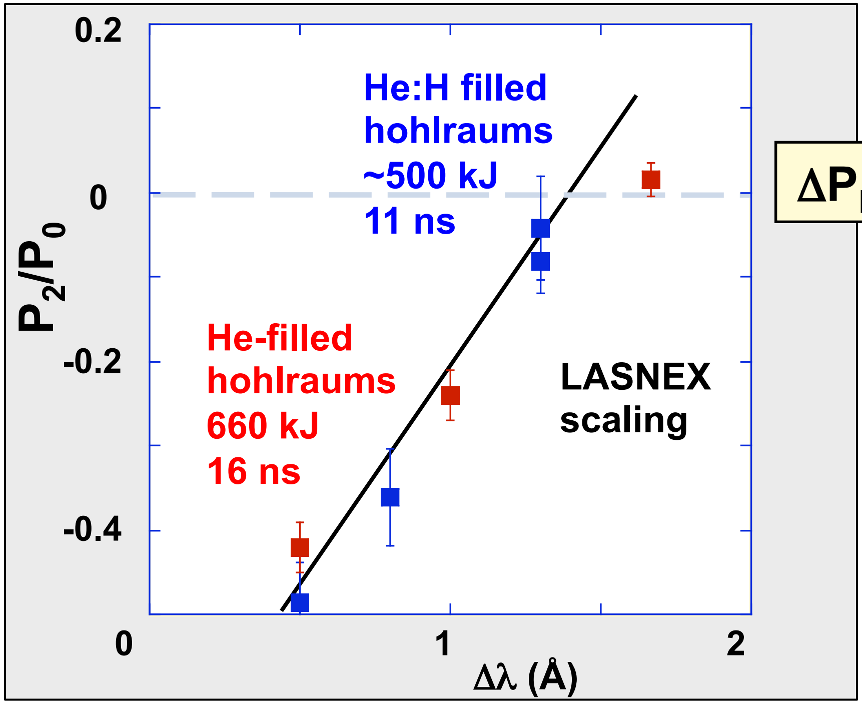
$$\Delta P_{L2}/P_{L2} = g(\Delta\lambda, n_e/T_e, \delta n_{sat})P_{L1}$$

Shape

We have repeatedly utilized crossbeam transfer for core self-emission shape tuning



Michel, Phys. Plasmas, 2010



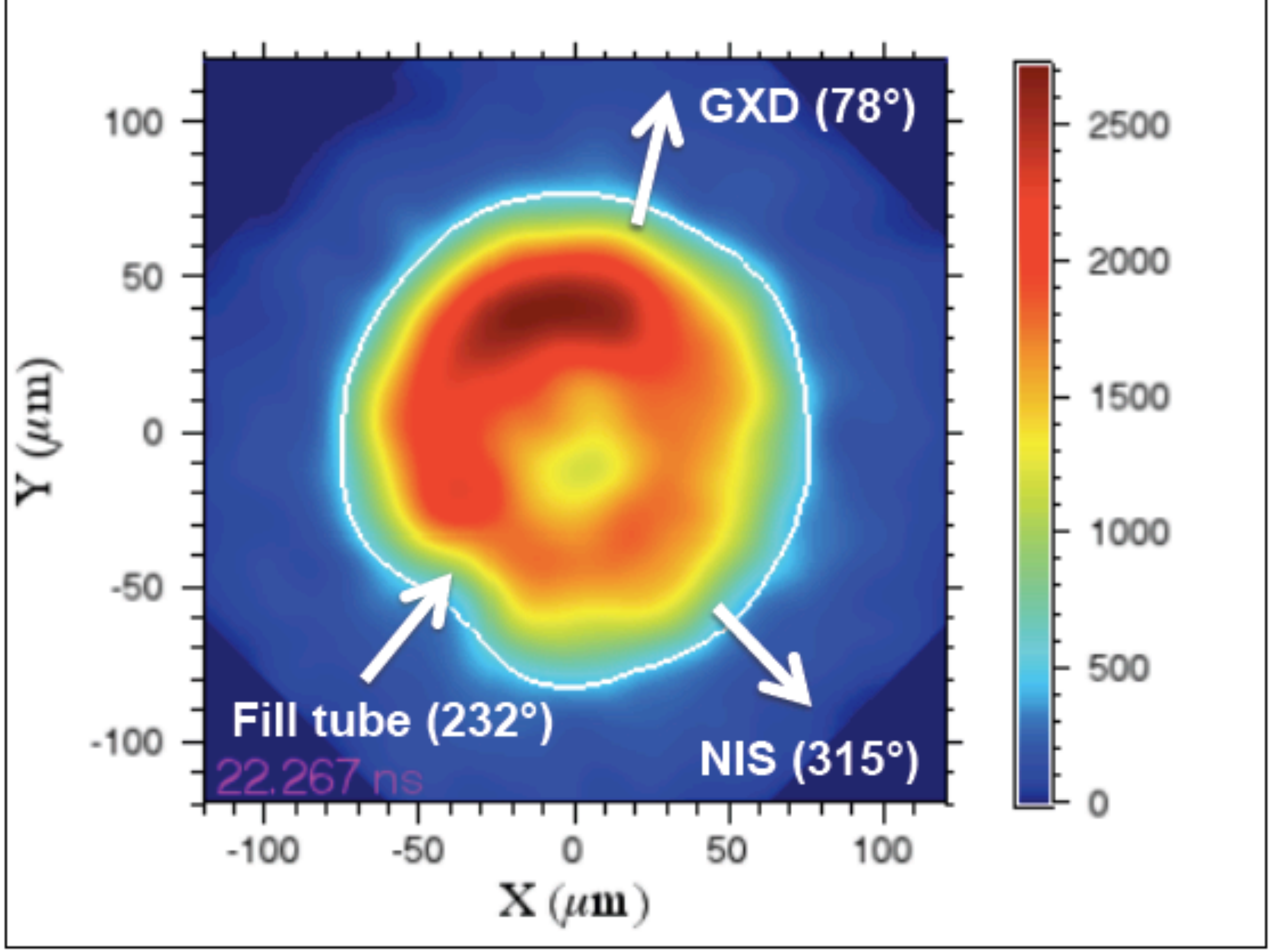
$\Delta P_{L2}/P_{L2} = g(\Delta\lambda, n_e/T_e, \delta n_{sat})P_{L1}$

Lowest order core asymmetries extracted to ± 2 µm accuracy

Complemented/checked by neutron imaging on DT shots

Core imaging has also uncovered effect of filltube on azimuthal symmetry, reproducibly

Gated 9 keV polar x-ray image N111025



Smaller filltube has been developed, ready for testing in June

Future implosions will also test for low mode symmetry improvements with Au-coated diagnostic holes

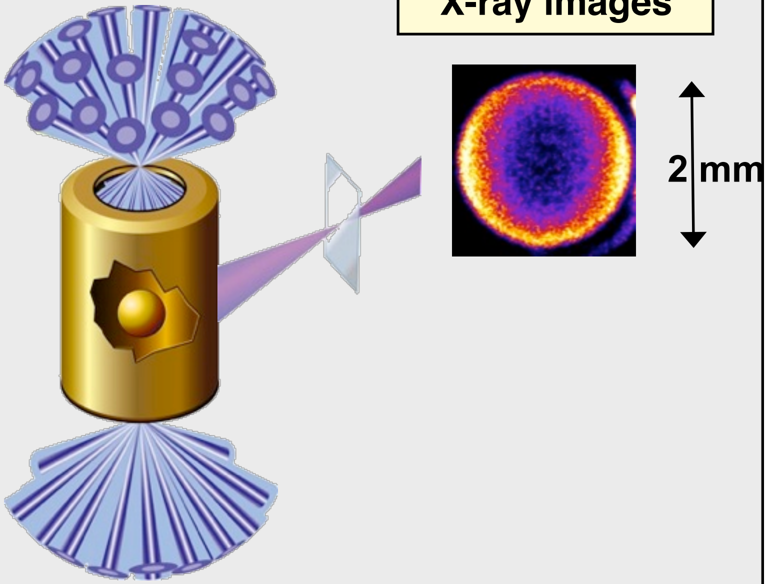
Shape

Reemit

With Δλ fixed, reemission sphere was then used to measure and fix symmetry of early picket drive

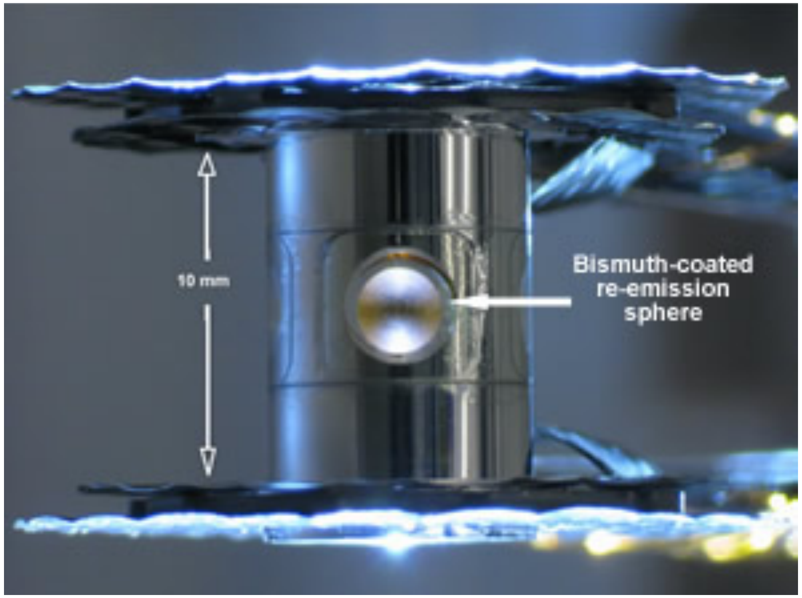
Experimental Geometry

Bi sphere “Reemit” replaces layered capsule



Observable:
Limb brightness vs. angle as picket cone fraction changed

Dewald, RSI (2008), PoP (2011)

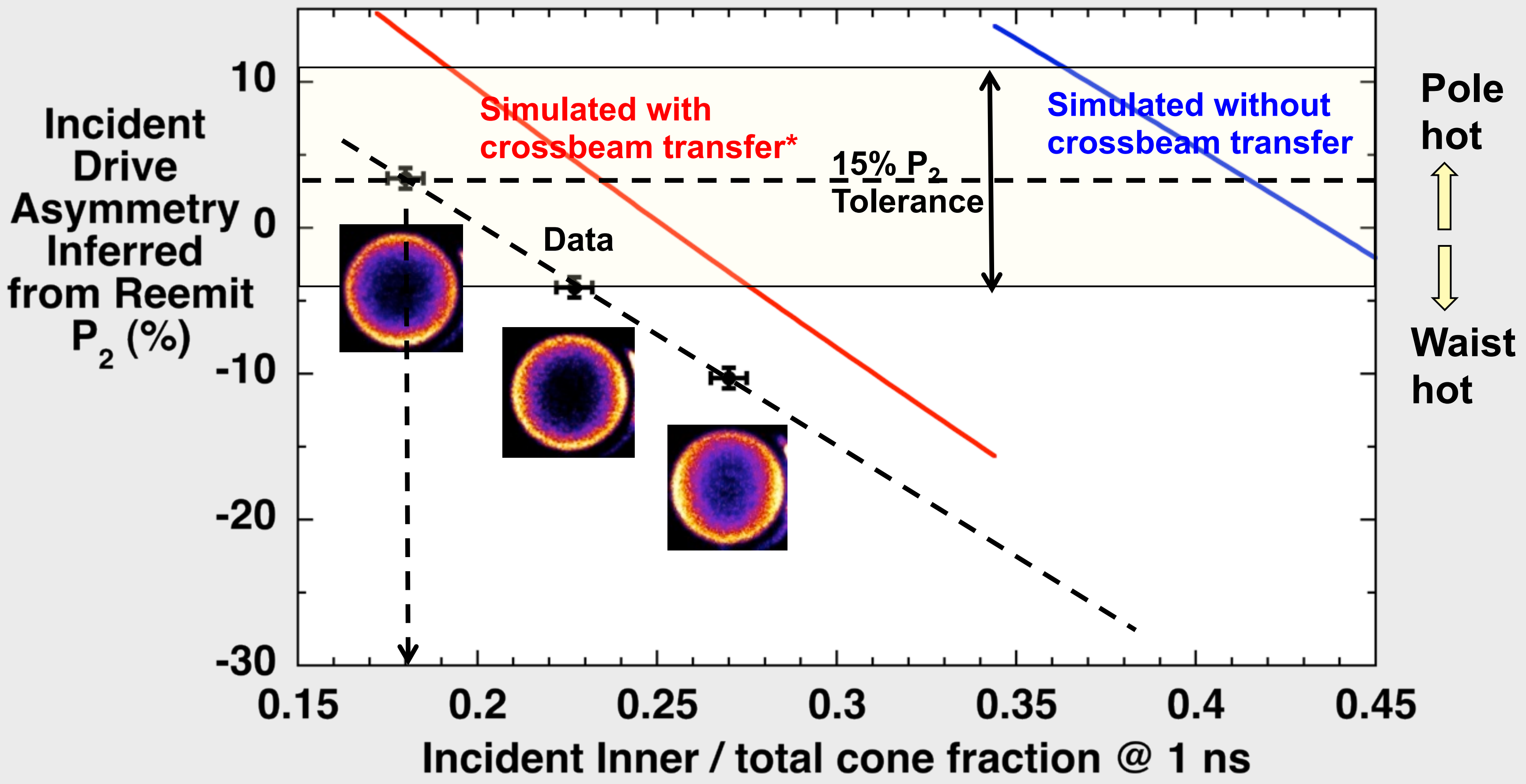


Shape

Reemit

Foot asymmetry, extracted to ±1% accuracy, confirms strong role of cross-beam transfer

P_2 Foot Picket Flux Asymmetry vs. Foot Inner Cone Fraction

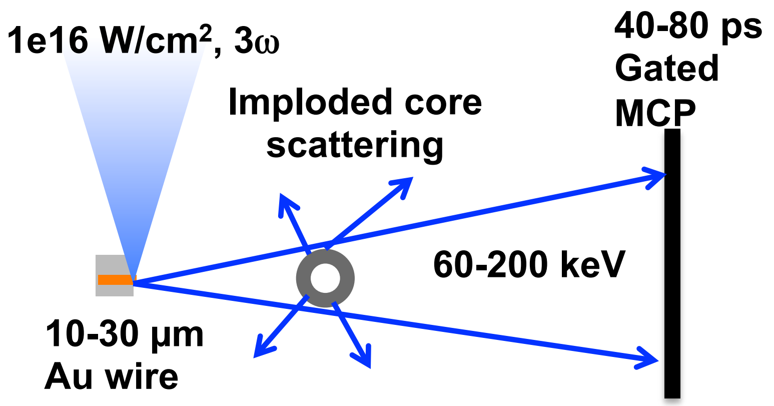


Evidence of more transfer suggests 25% higher n_e/T_e at interaction

$$\Delta P_{L2}/P_{L2} = g(\Delta\lambda, n_e/T_e, dn_{sat})P_{L1}$$

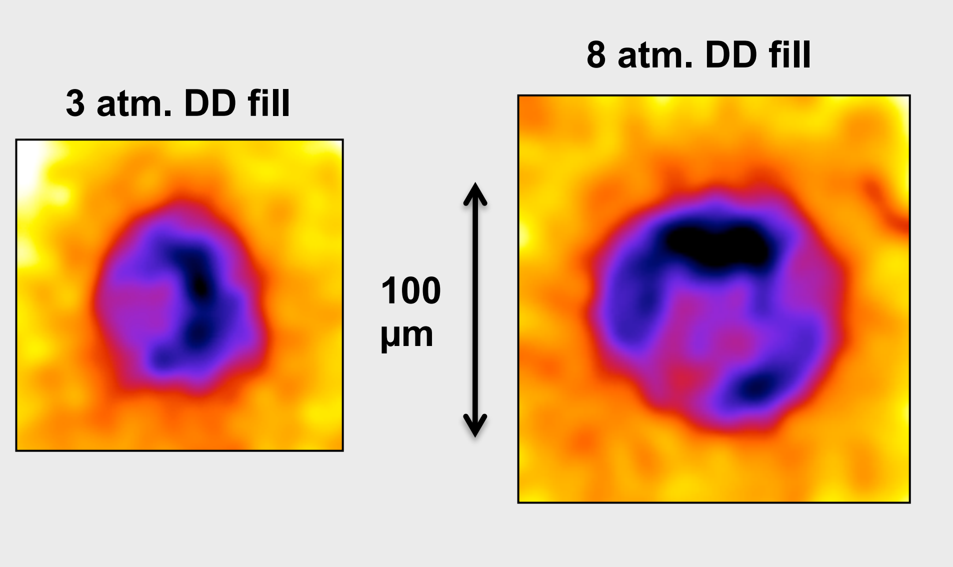
For measuring fuel shape and uniformity directly, “Compton radiography” has been validated at OMEGA

Uses high energy Compton scattering rather than traditional photoabsorption to cast shadow and overcome self-emission



Tommasini, Phys. Plasmas, 2011

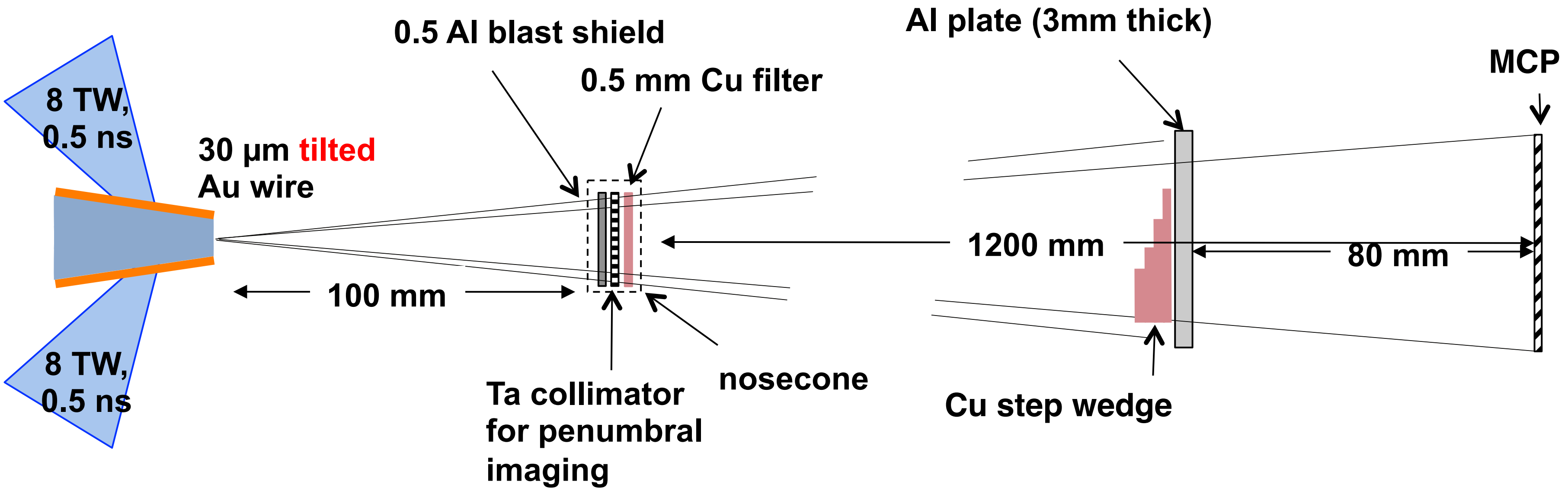
60 -100 keV, 10 µm, 10 ps resolution radiographs of imploded 40 µm CH



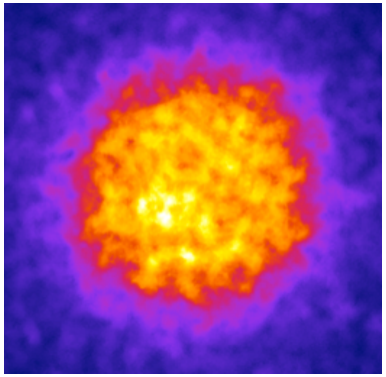
OMEGA Capsules show expected 5% limb darkening representative of $\rho r \approx 0.1$ g/cm^2

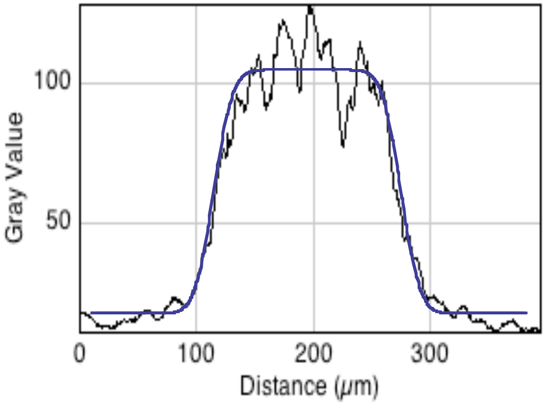
For NIF Compton radiography shot, expect 10x more contrast since 10x more ρr

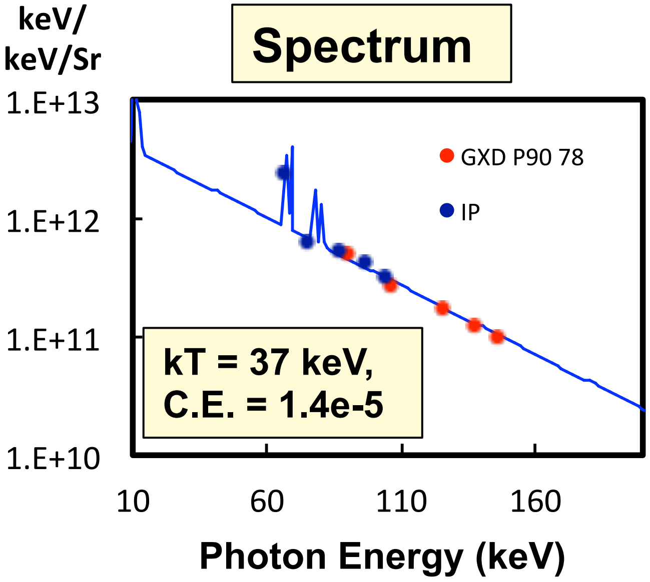
Single quad gated Compton backlighter exceeding hohlraum background has been demonstrated at NIF



> 60 keV Penumbral Imaging shows 30 µm resolution achieved with expected SNR







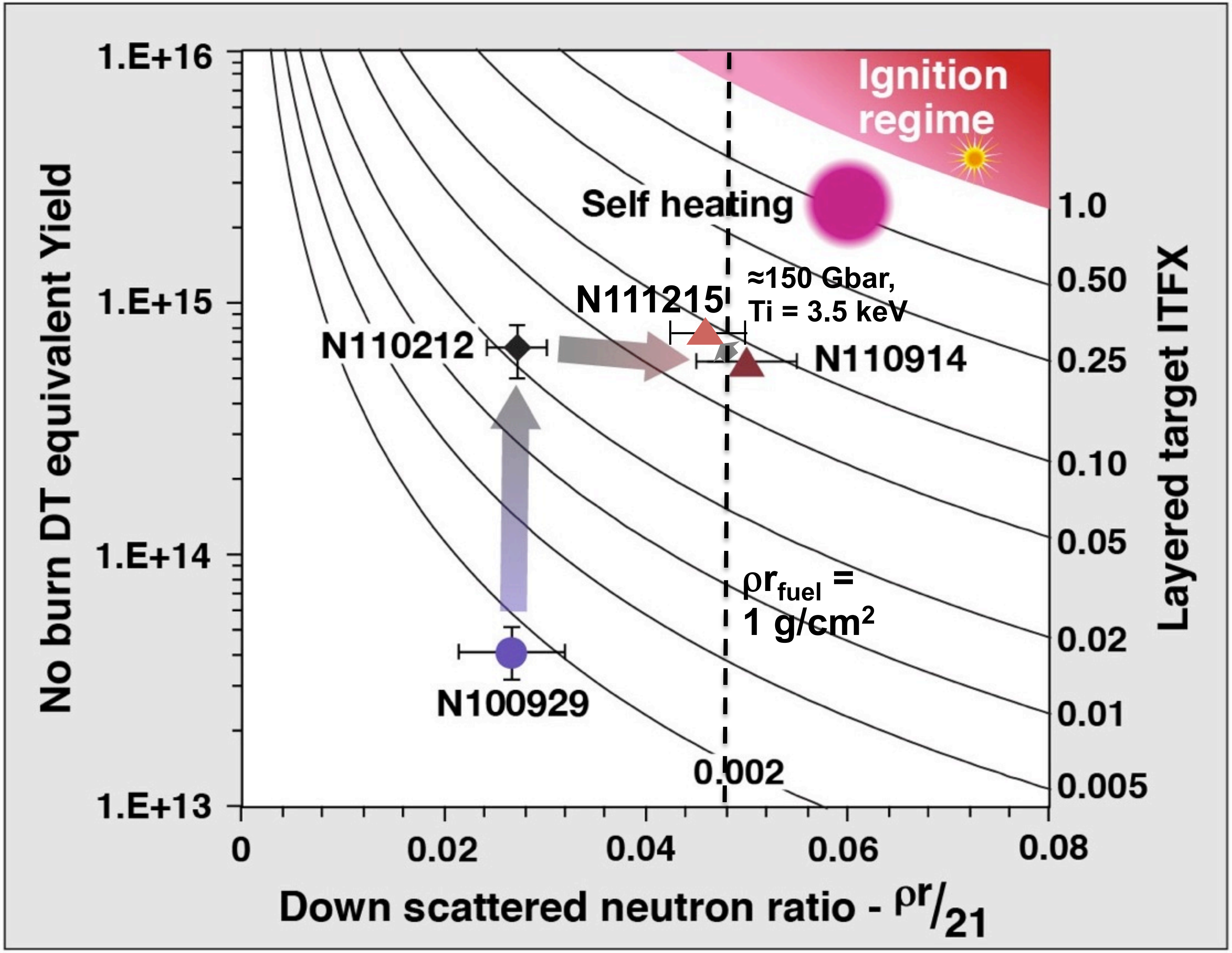
Optimized design to be tested by August

For future higher resolution Compton Radiography:

Petawatt power from the Advanced Radiographic Capability (ARC)

Advanced Radiographic Capability (ARC)

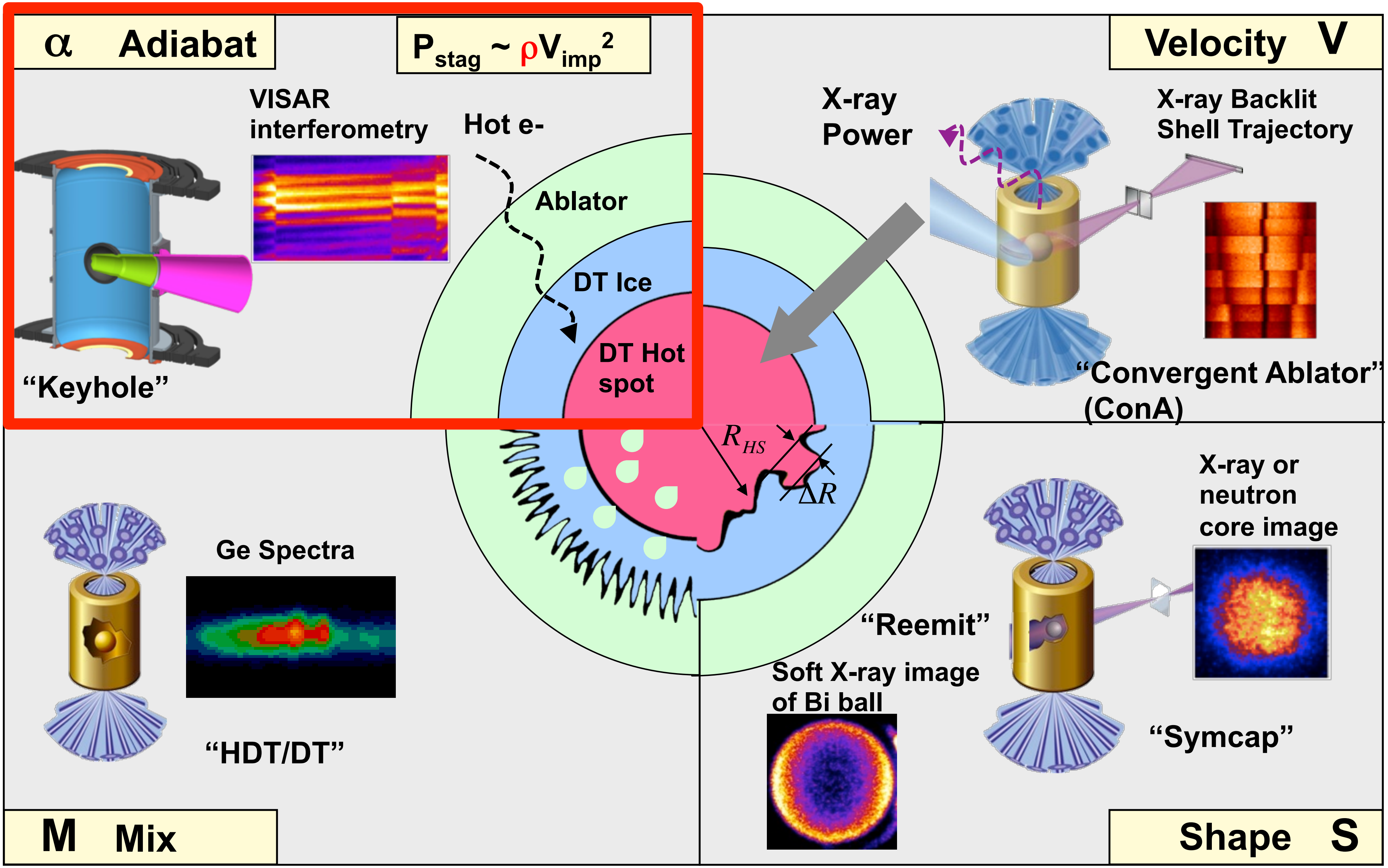
Improving time-dependent intrinsic symmetry improved yield by 20%



Faster, hotter

Lower adiabat, more compressed

We then revisited the limits on shell and fuel compressibility



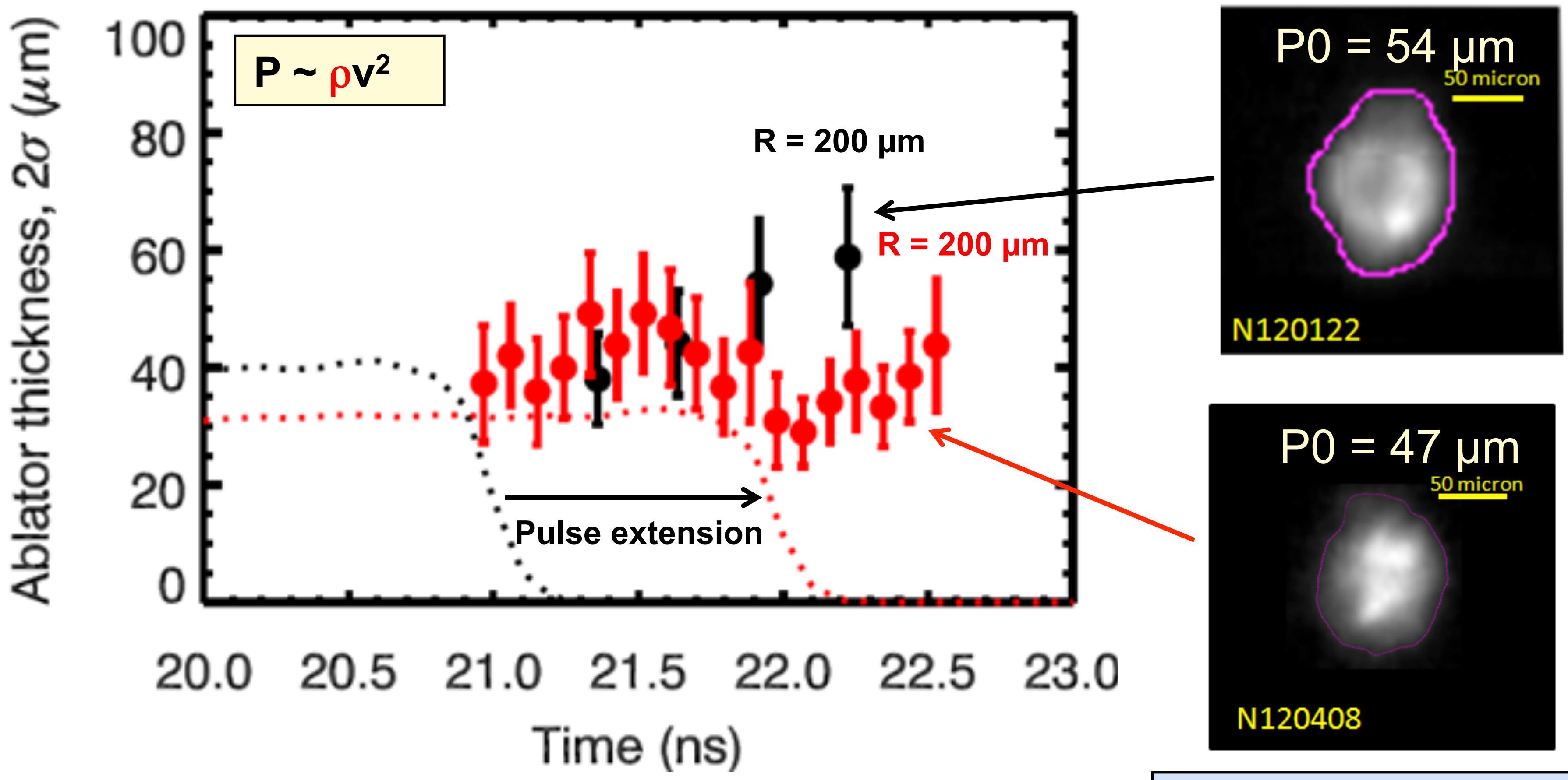
Adiabat

Backlit Capsule

By extending pulse out to R = 300 µm “(No Coast)”, ablator stays compressed down to 200 µm radius

Ablator thickness vs time

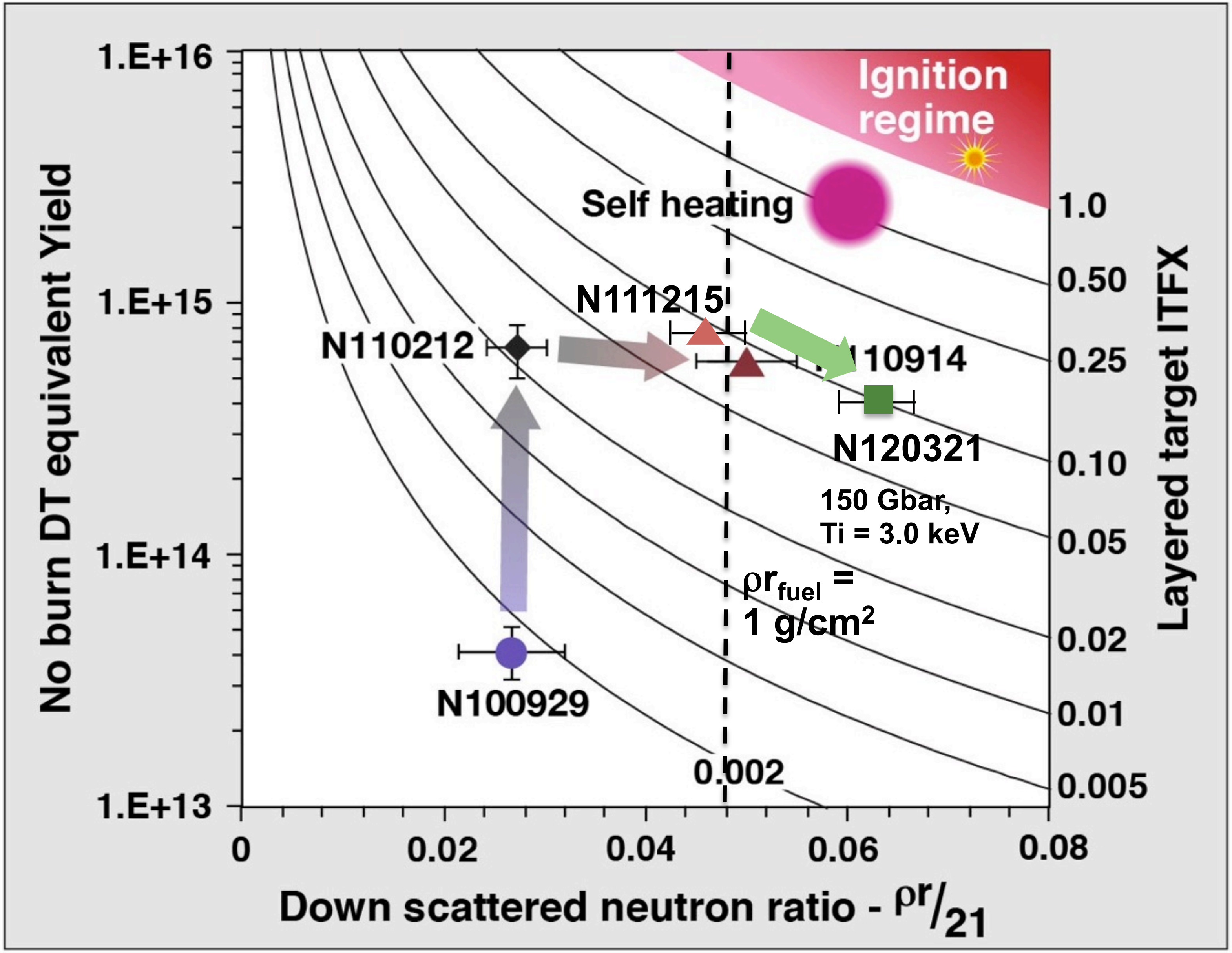
Coast vs No coast X-ray cores



No Coast core size is 13% smaller

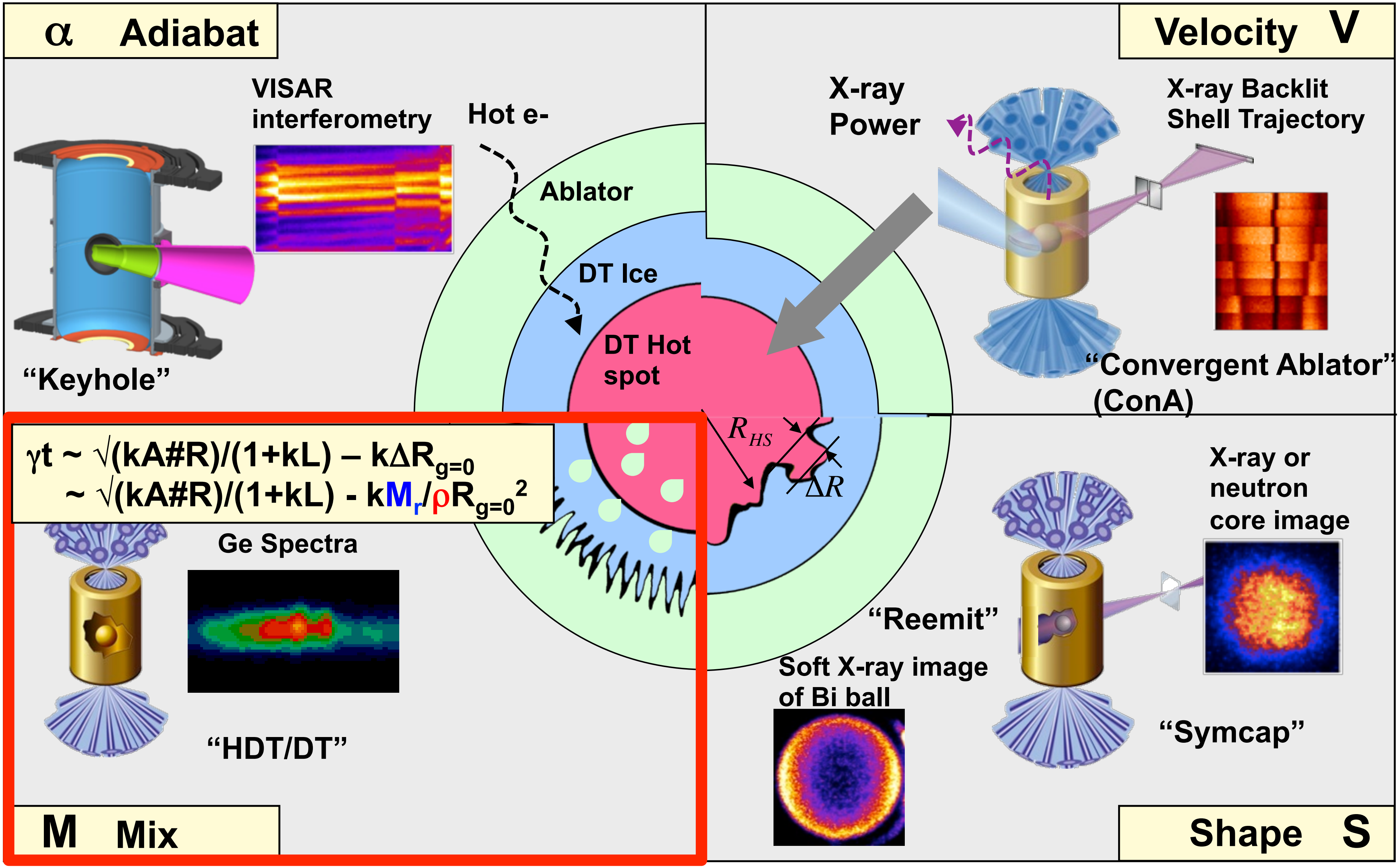
Increasing pulse length increased areal density a further 20% to 1.3 g/cm^2 and ITFx has reached 0.1

Faster, hotter



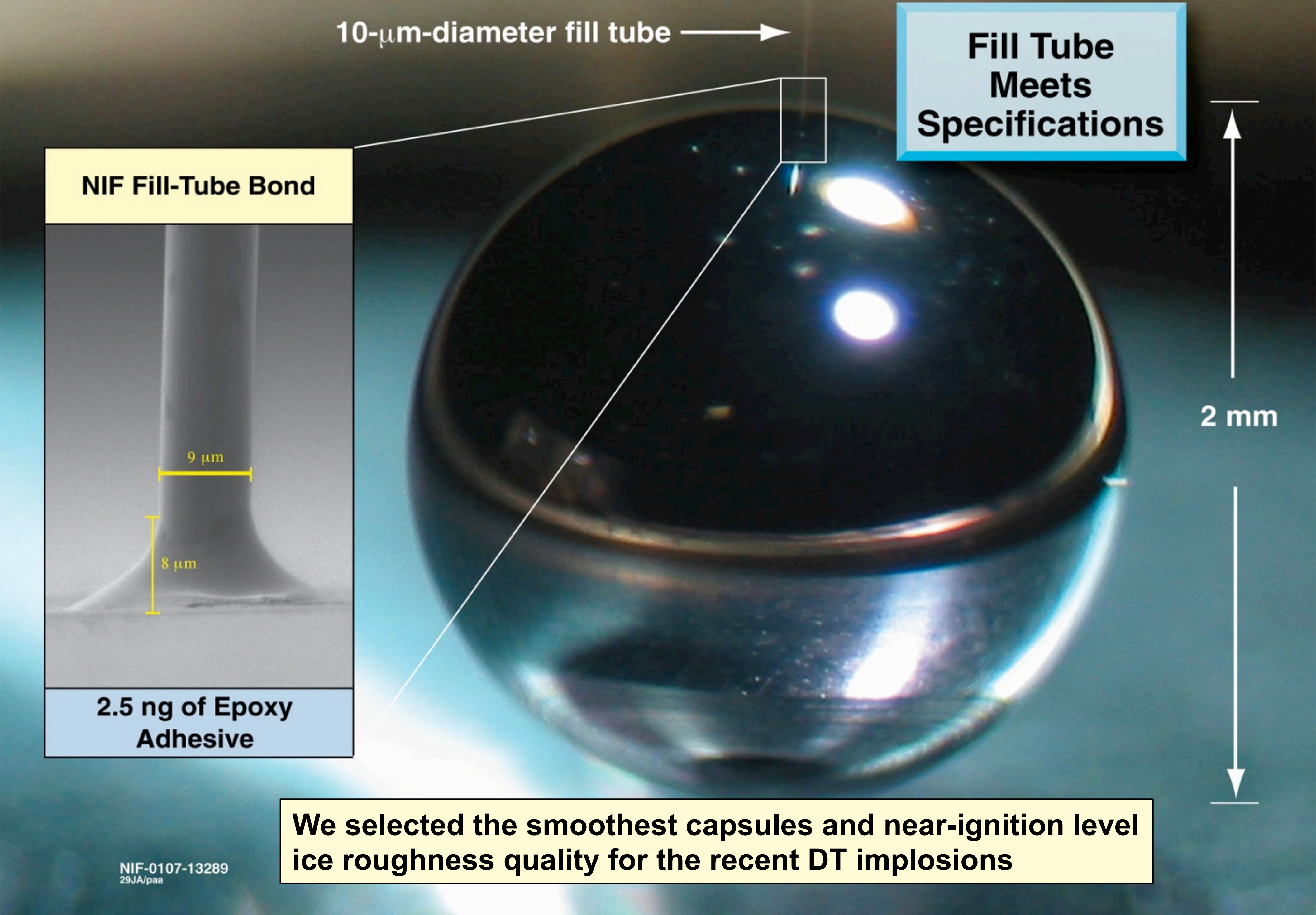
Lower adiabat, more compressed

With demonstrated control on shell and fuel compressibility, we then probed mix "cliff"



$$\gamma t \sim \sqrt{(kA\#R)}/(1+kL) - k\Delta R_{g=0}$$
$$\sim \sqrt{(kA\#R)}/(1+kL) - kM_r/\rho R_{g=0}{}^2$$

10 nm roughness capsule looks optically smooth (λ/30)



10-μm-diameter fill tube →

Fill Tube Meets Specifications

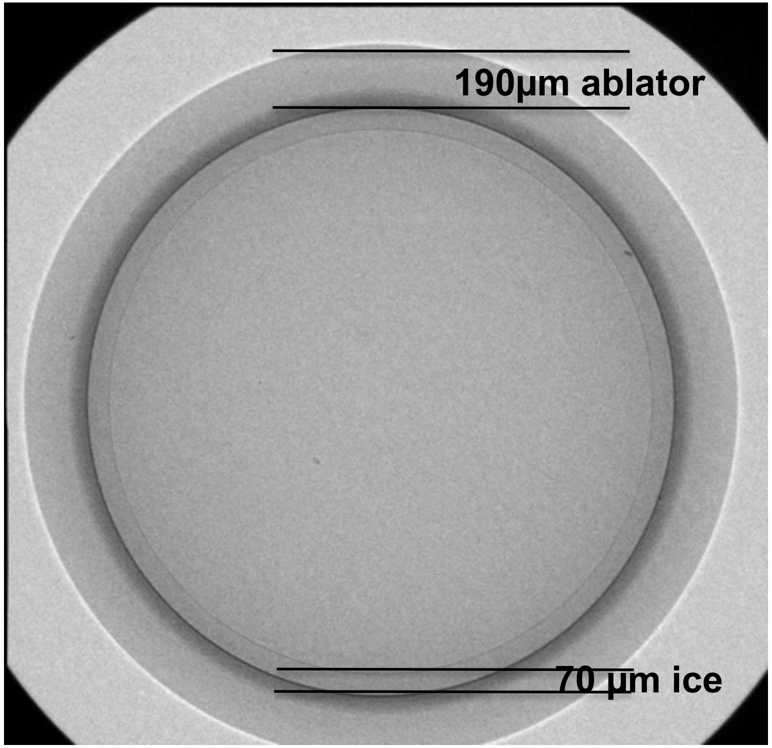
NIF Fill-Tube Bond

2.5 ng of Epoxy Adhesive

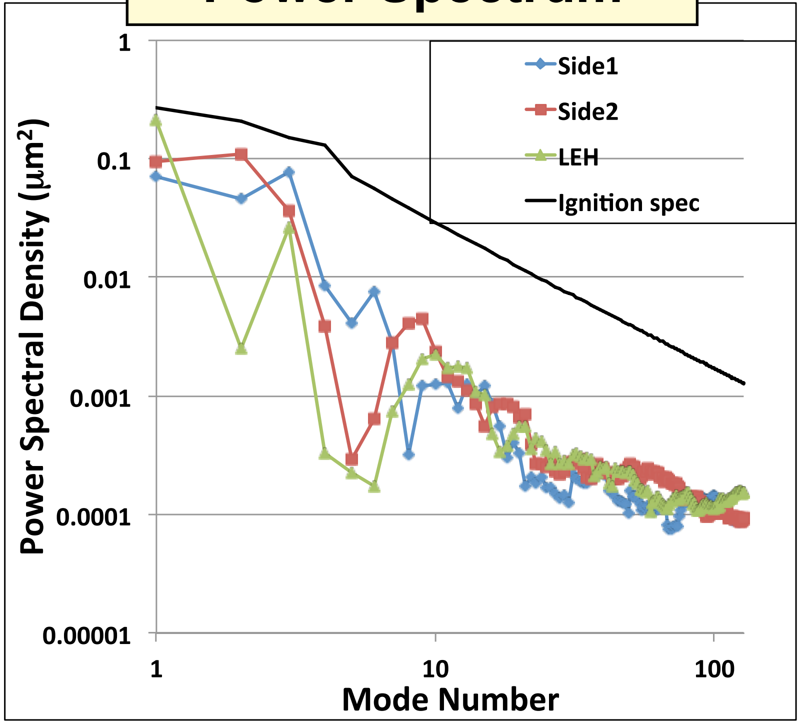
We selected the smoothest capsules and near-ignition level ice roughness quality for the recent DT implosions

THD ice layers are characterized in situ by refraction-enhanced 8 keV radiography

LEH view



DT Ice Roughness Power Spectrum

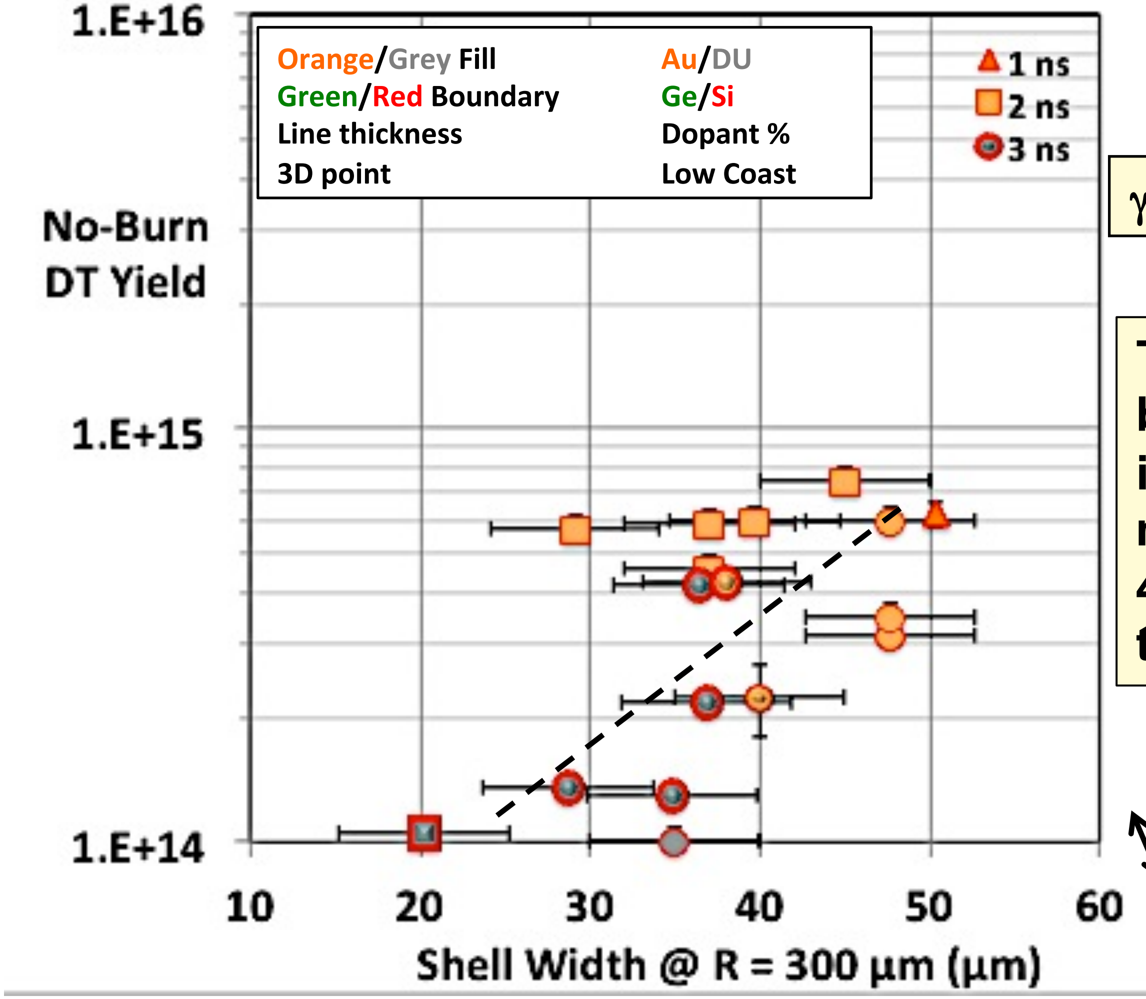


Independent tests have shown that the layer quality is not affected by shroud opening and quench
(cooling from 18.8 K to 17.5 K in last 30s prior to shot)

Mix

We find that DT yield drops for thinner in-flight ablator, suggesting sensitivity to instability feedthrough

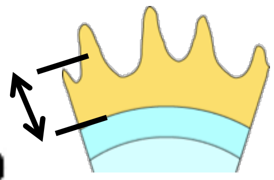
Yield vs In-flight Ablator Thickness



Growth FeedThrough

$\gamma t \sim \sqrt{(kA\#R)/(1+kL)} - k\Delta R_{g=0}$

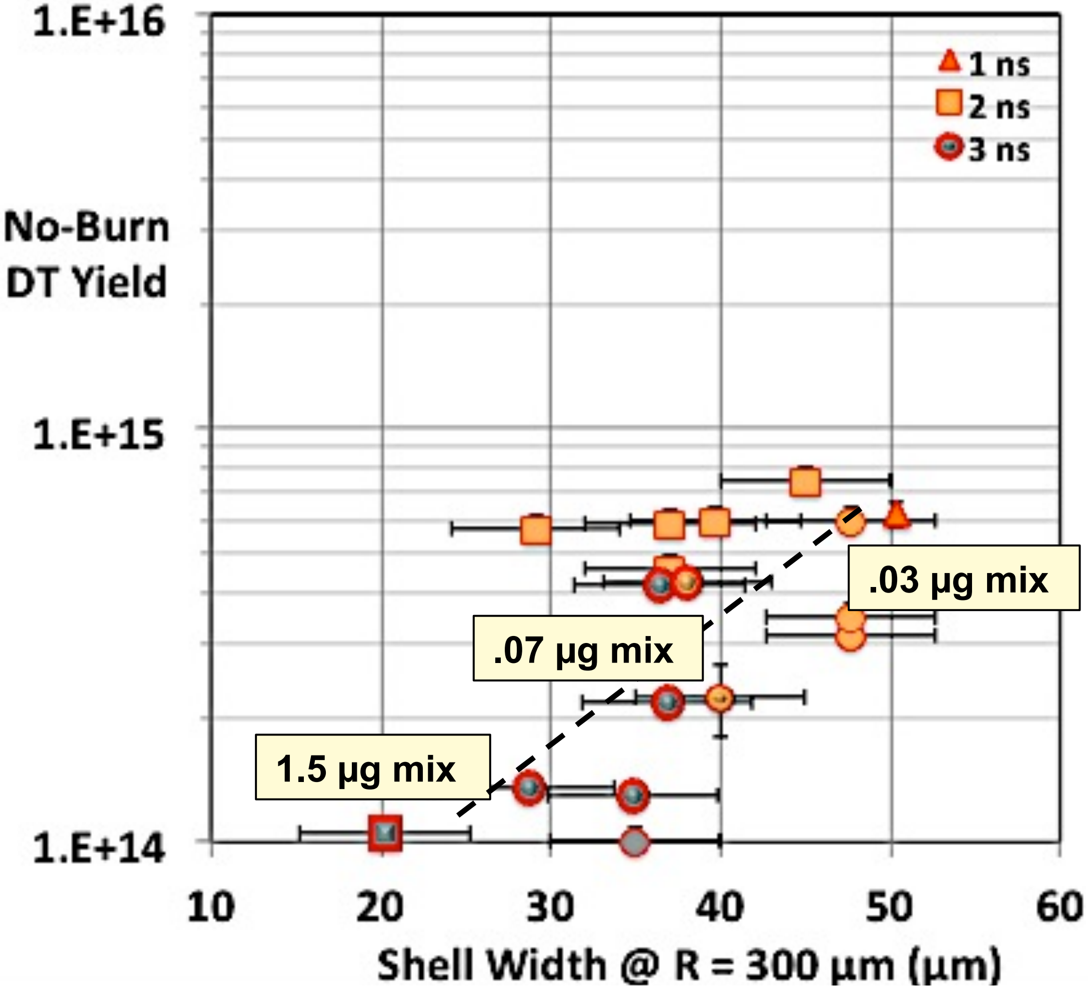
The near universal behavior seen so far is independent of hohlraum material, Si dopant level, 4th pulse risetime and coast time



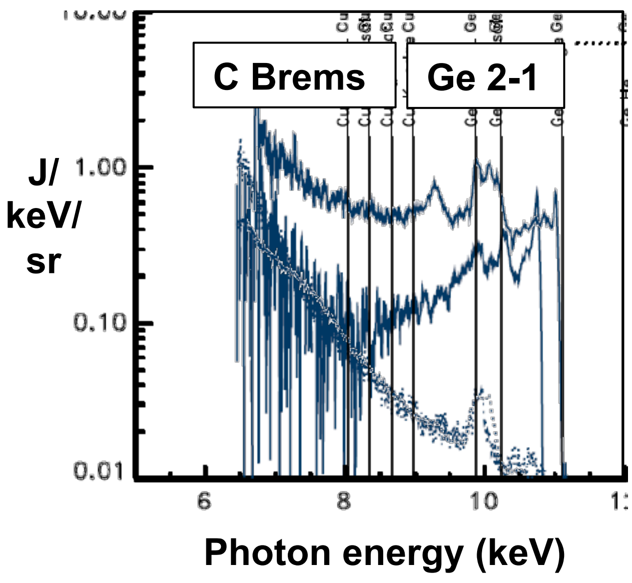
*Scaled from radiography data

Core x-ray Bremsstrahlung and Ge tracer line emission levels confirm higher mix for thinner shells

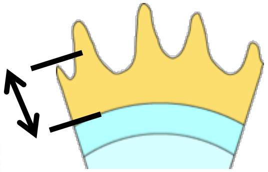
Yield vs In-flight Ablator Thickness



High and Low Mix Core Spectra



$I \sim Z^2 n_e n_i$

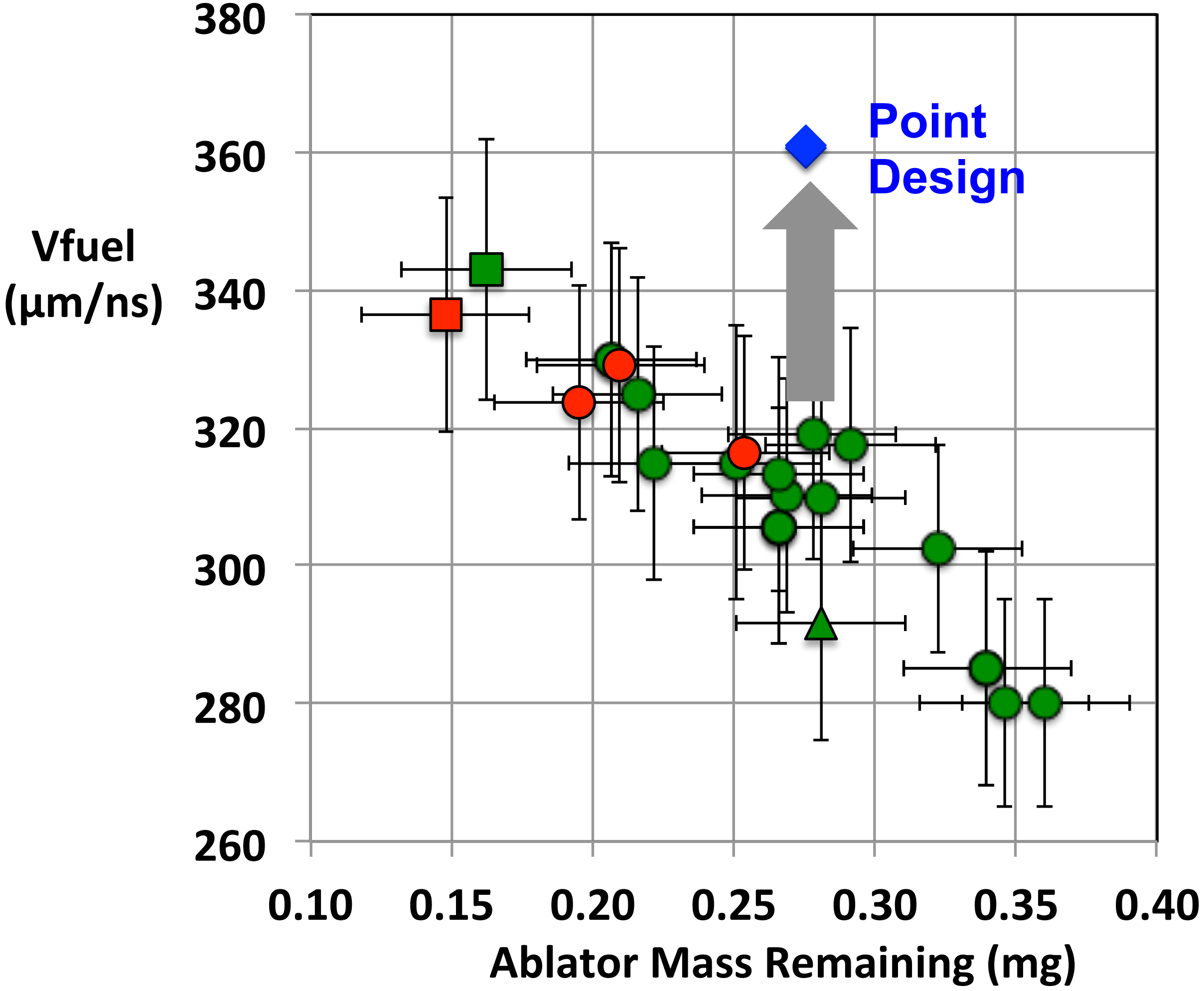


Hammel, Phys. Plasmas, 2011
Regan, Phys. Plasmas, 2012

Velocity

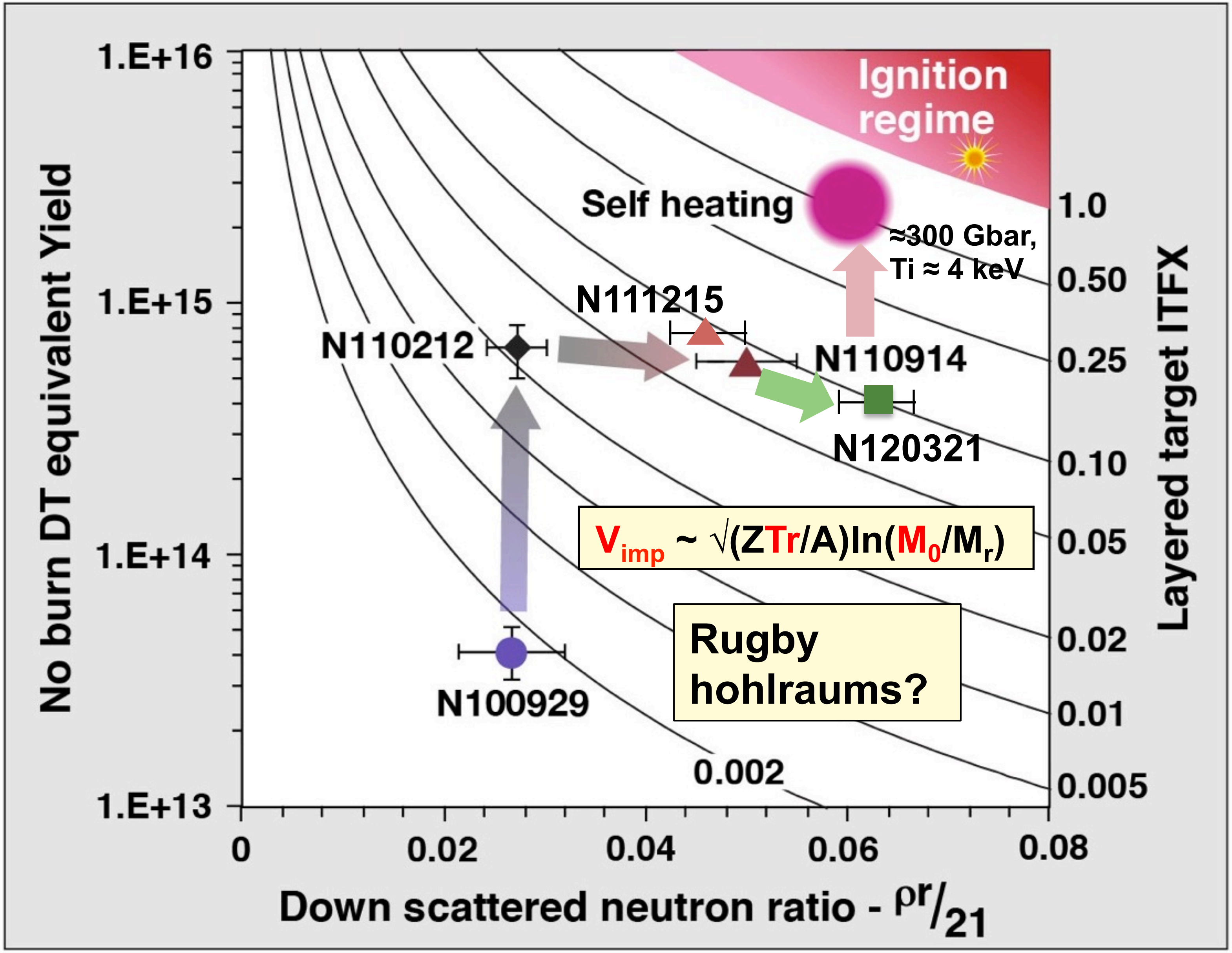
To approach point design, we will need to increase velocity while keeping mass remaining "mix safe"

Peak Fuel Velocity vs Ablator Mass



$V_{imp} \sim \sqrt{(ZTr/A)\ln(M_0/M_r)}$

Increasing velocity and yield will likely require higher Tr drive and thicker capsules available Summer 2012



$V_{imp} \sim \sqrt{}(ZTr/A)\ln(M_0/M_r)$

Rugby hohlraums?

Faster, hotter

Lower adiabat, more compressed

NIC tuning / applied science since May 2011

- Ignition tuning platforms and techniques first developed at Nova and OMEGA have been critical to uncovering offsets between NIF data and modelling
  - Experimental success and need to get better physics understanding has motivated more platforms not envisaged at outset

- Extending pulses ("no coast") has further improved compression and uncovered mix sensitivity to shell width
  - Following improved 1D performance, wewill need to increase velocity while keeping mix low by using more power and thicker capsules, more efficient hohlraums (DU, rugby?) and potentially more efficient ablators

- The initial ignition experiments only scratch the surface of NIF's potential for creativity and accomplishment in applied and basic science


NIF

Implosion Performance

Once optimized low mix 1D performance, we will increase velocity using higher Tr, thicker capsules