The National Ignition Facility: Strategic Security, Energy Security and Fundamental Science

LLNL-PRES-609739

Presented to Steve Koonin on his Birthday

Ed Moses
Director, NIF & Photon Science, Lawrence Livermore National Laboratory

December 17, 2012


San Francisco
(45 mi.)
National Ignition Facility
Lawrence Livermore National Laboratory

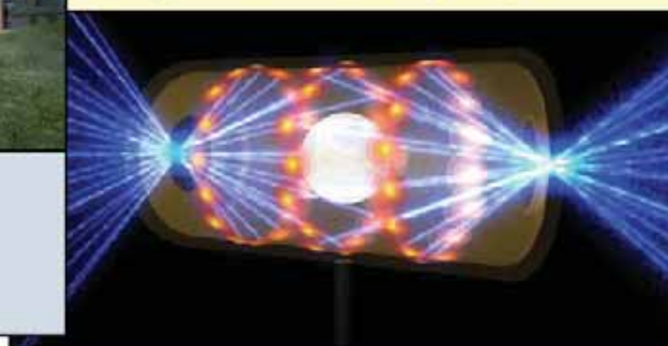

NIF is now operational and
ignition campaigns are underway
NIF is the world's most energetic laser by 100x

NIF Master Strategy

NIF Project

1997 – 2009
A continuing work in progress

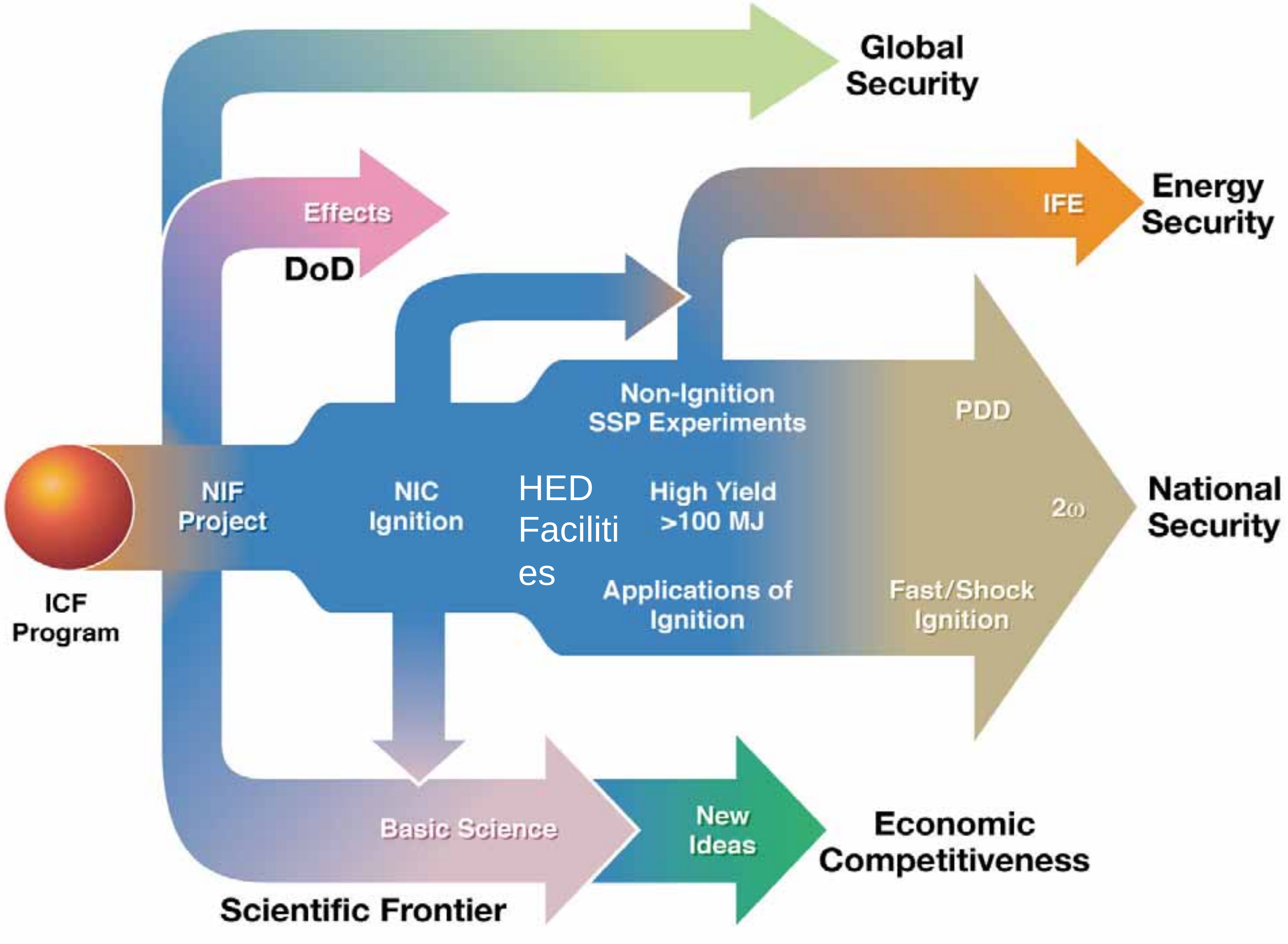
National Ignition Campaign



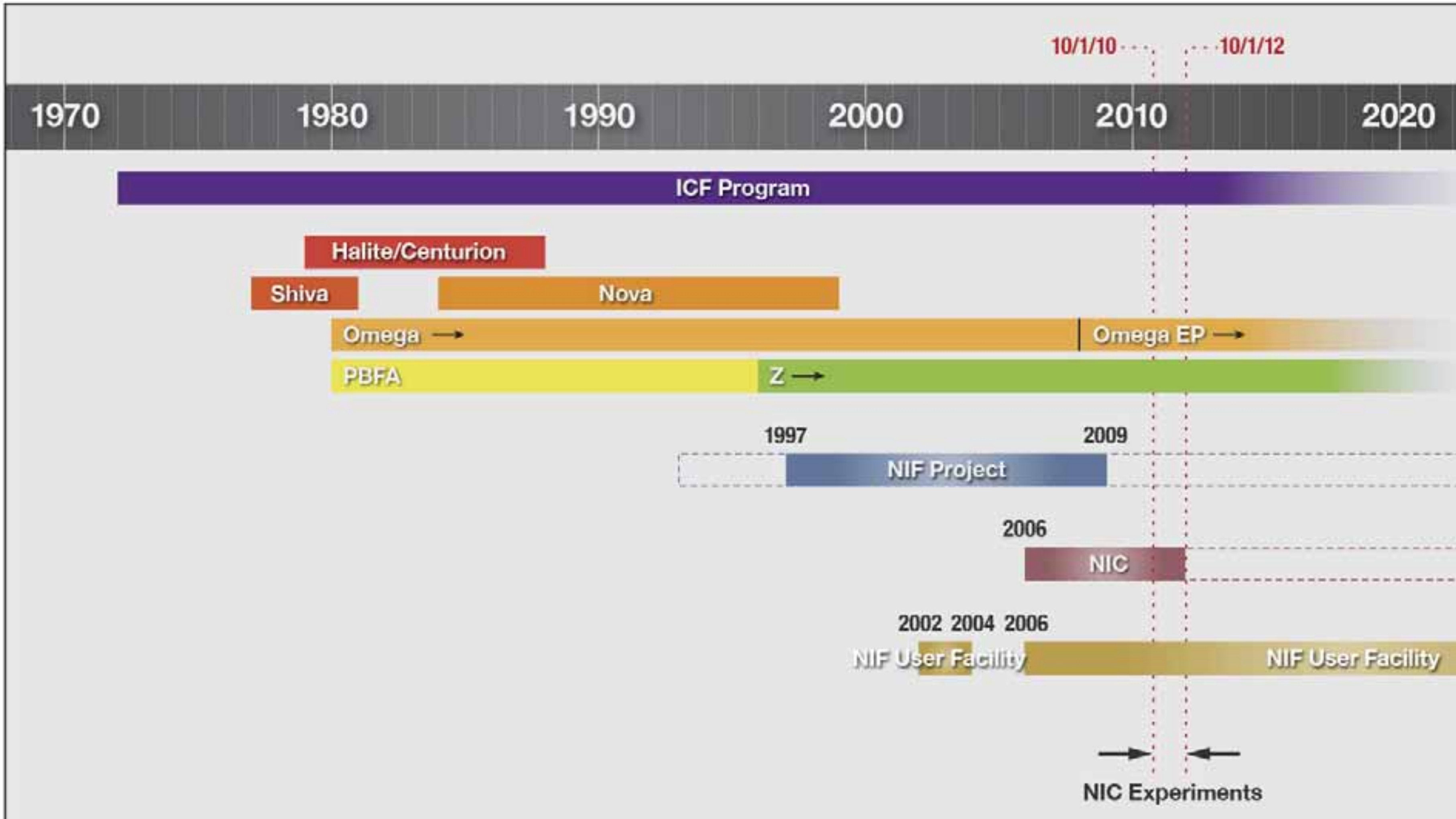
2006 – 2012
A continuing work in progress

National User Facility

2009 – 2030
The next major thrust


Global Security
Effects
DoD
IFE
Energy Security
Non-Ignition SSP Experiments
PDD
NIF Project
NIC Ignition
HED Faciliti es
High Yield >100 MJ
2ω
National Security
Applications of Ignition
Fast/Shock Ignition
ICF Program
Basic Science
New Ideas
Economic Competitiveness
Scientific Frontier
NIF-0208-14427
14CK/cld

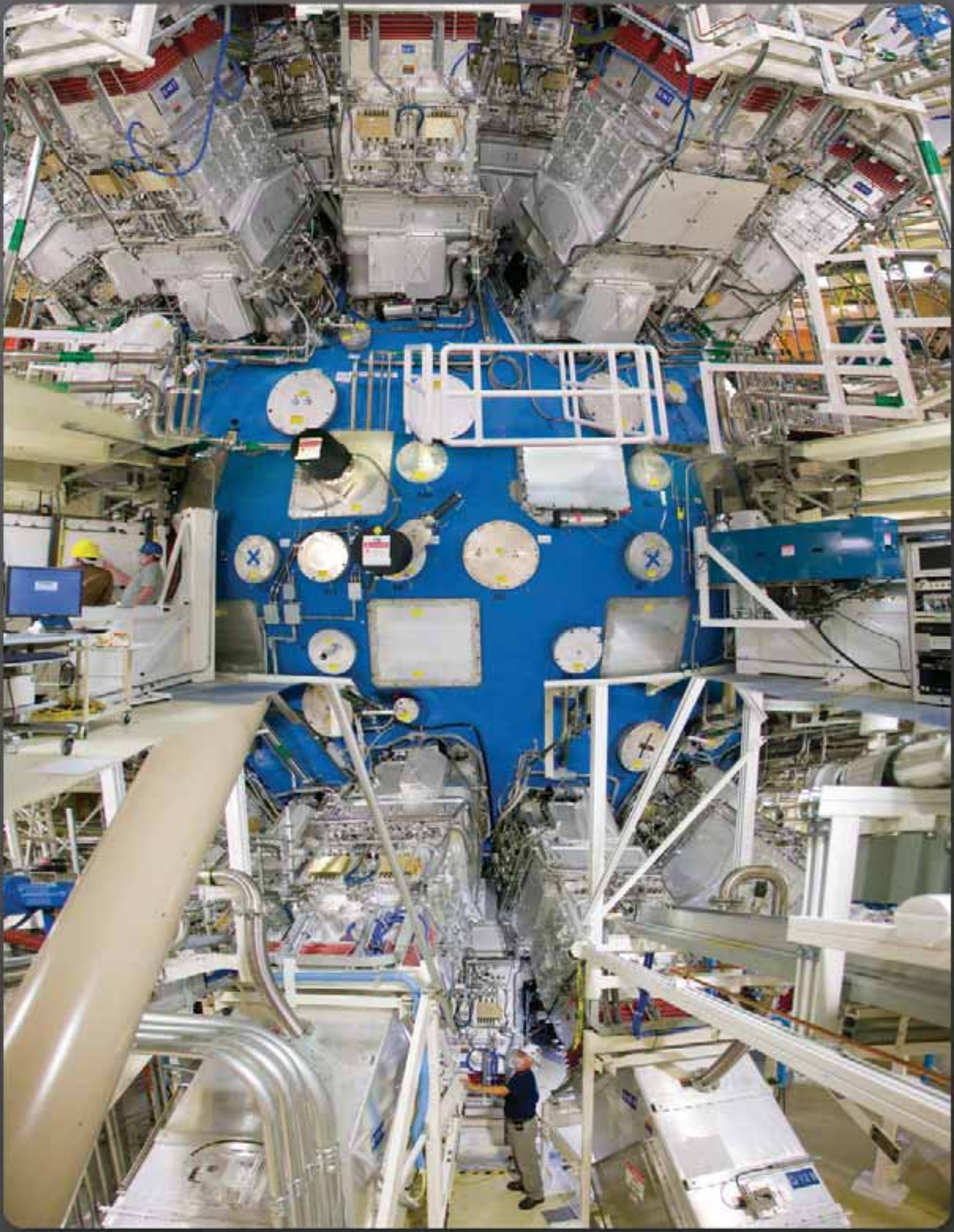
Story of ICF Program, NIF, and Ignition



NIF concentrates all 192 laser beam energy in a football stadium-sized facility into a mm³

Matter Temperature	**$>10^8$ K**
Radiation Temperature	**$>3.5 \times 10^6$ K**
Densities	**$>10^3$ g/cm^3**
Pressures	**$>10^{11}$ atm**

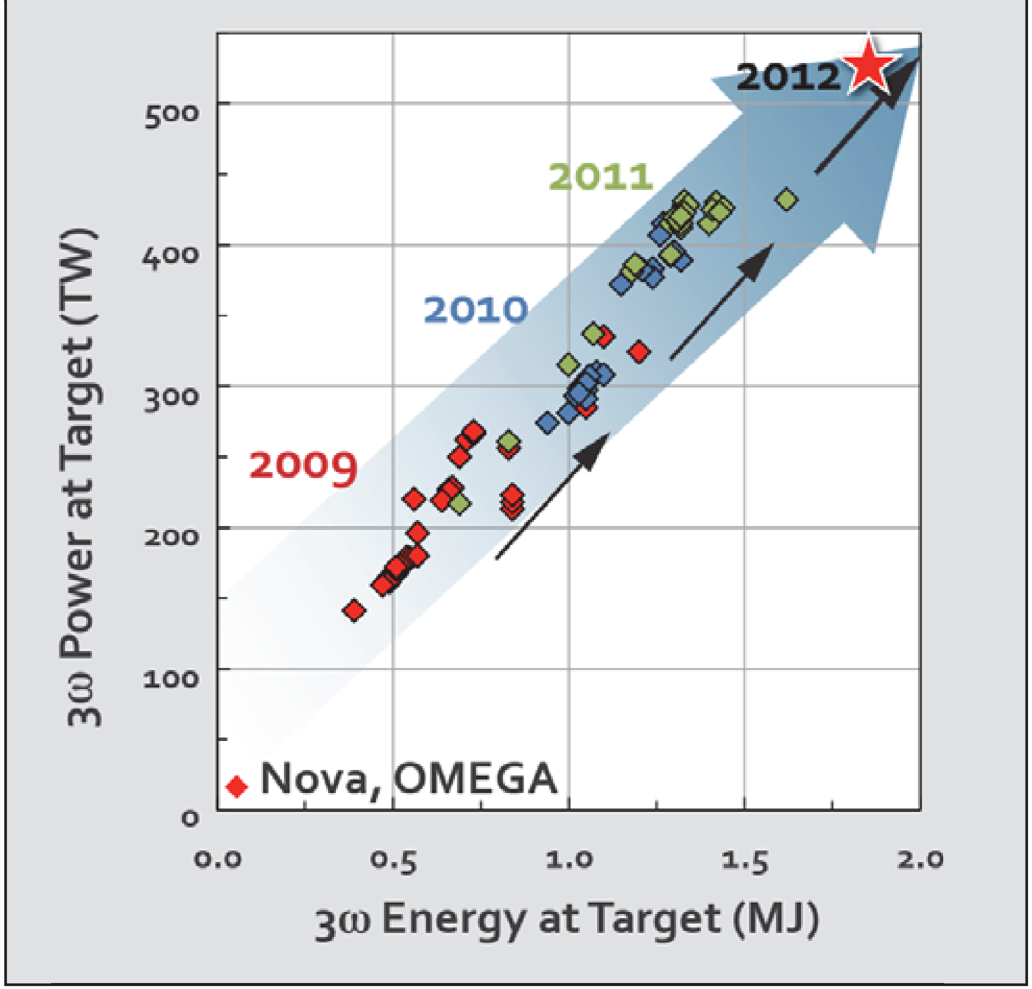
NIF-0609-16540s1



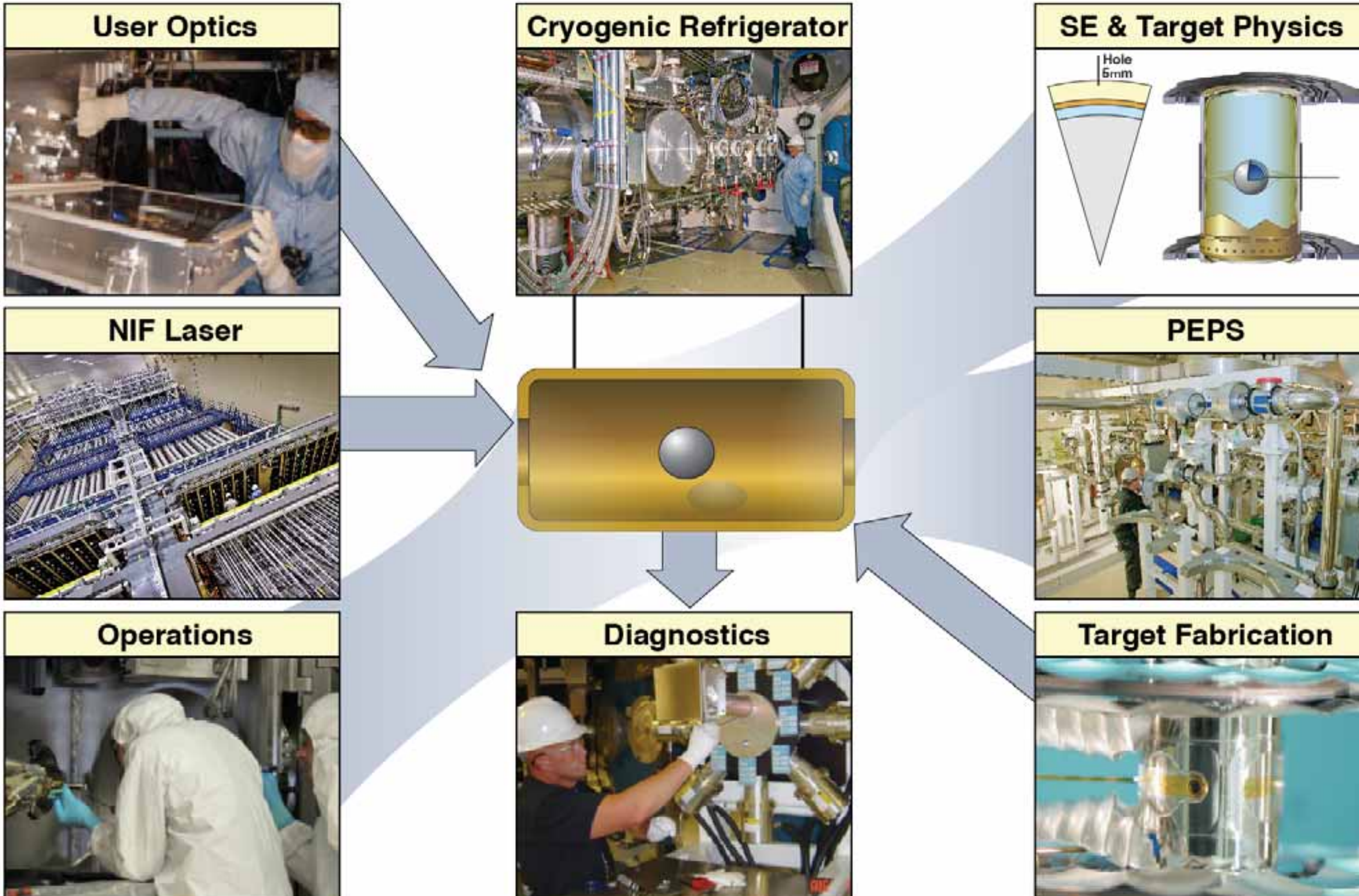
NIF operational capabilities — laser energy/power

- NIF laser is steadily increasing the laser energy and power
- NIF Laser is operating 24/7 with exceptional reproducibility and reliability (99%)
- Currently supporting the NIC at 1.4 to 1.8 MJ
- We have achieved the 1.8 MJ milestone and a power of 522 TW in a NIC-relevant pulse format
- The NIF has intrinsic capability to continue on this growth path for several more years

The laser energy and power available for experiments have been steadily increasing



NIF is much more than the laser



NIC has put in place the capabilities required for a broad range of ignition and other experiments

Laser

Wide variety of pulse shapes, peak intensities, w/ better than 2% reproducibility and precision

Diagnostics

Over 50 photon and particle diagnostics w/ high spatial, temporal, spectral resolution

Targets

Spherical, planar, machined perturbations, exotic materials,..

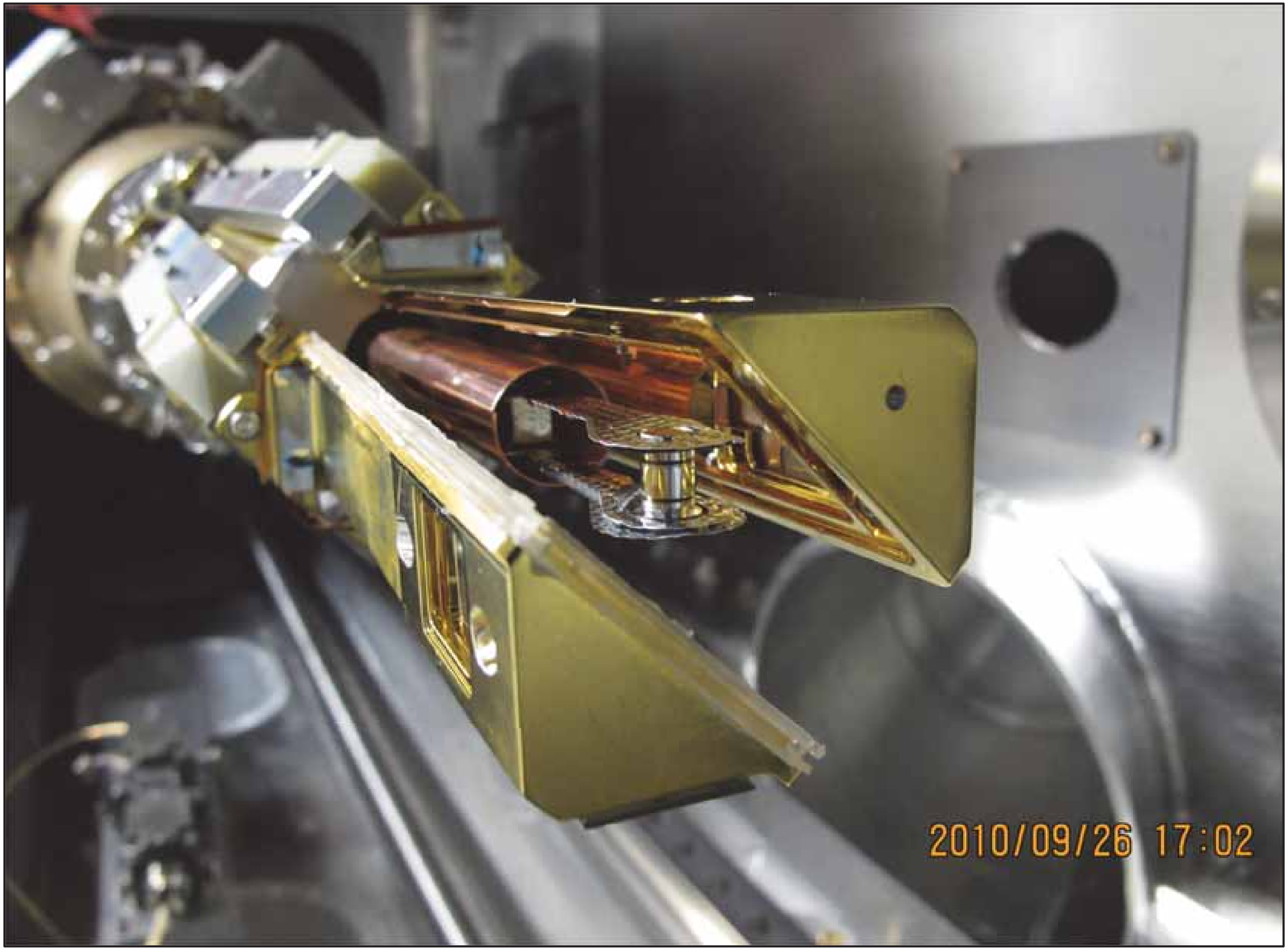
Simulation

Experimental design via target and laser simulation tools

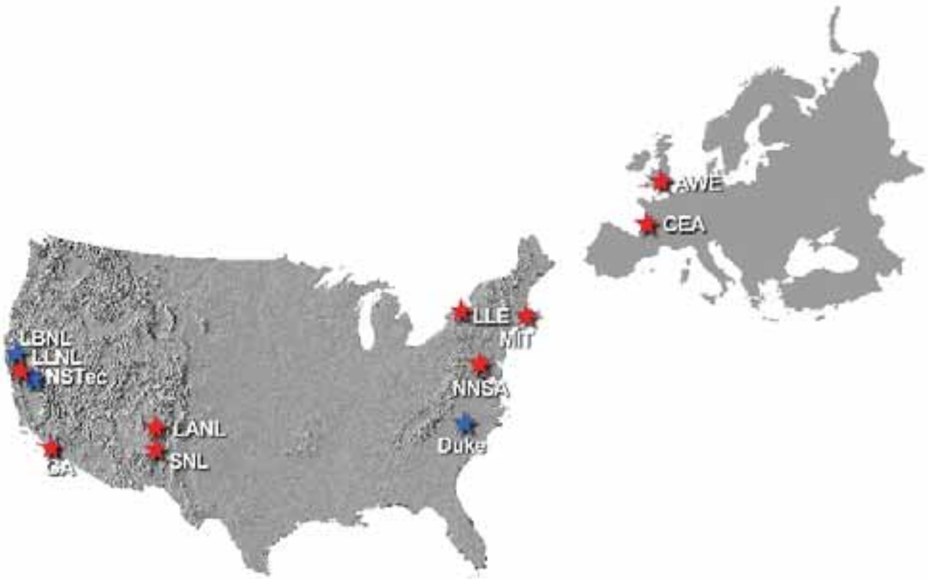
NIF is the world's leading facility for research in high energy density science

NIF Target

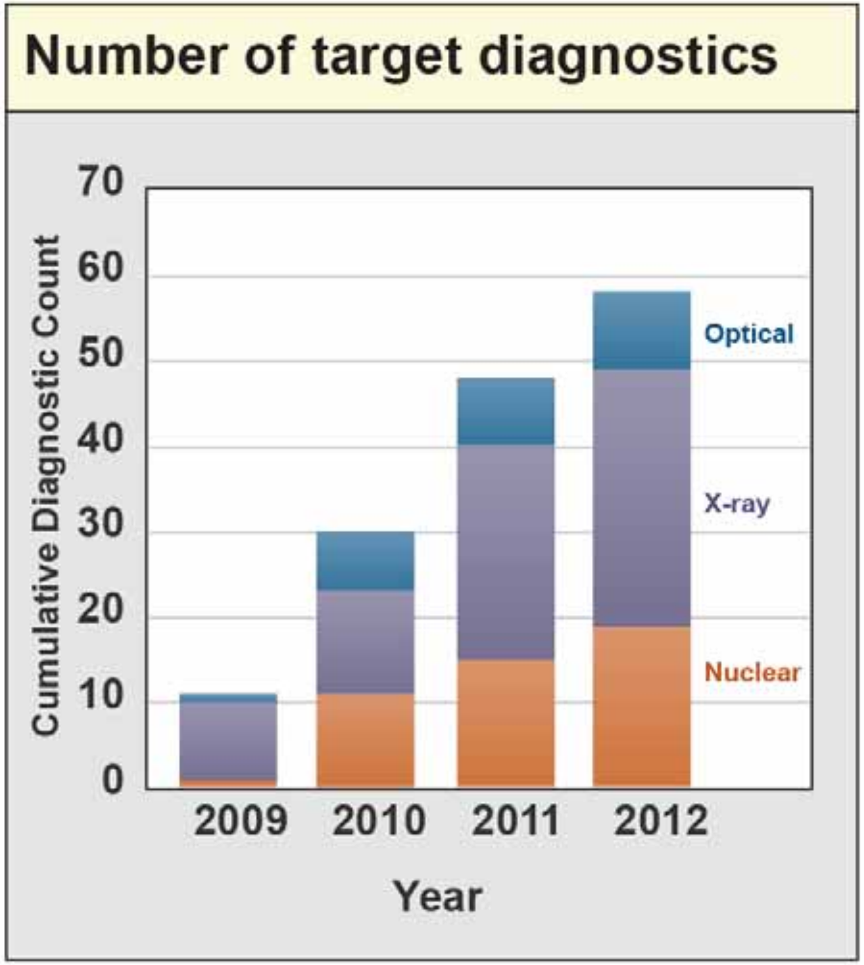
All systems required to field and diagnose a cryogenic ignition target on NIF are operational, with 37 layered implosions executed

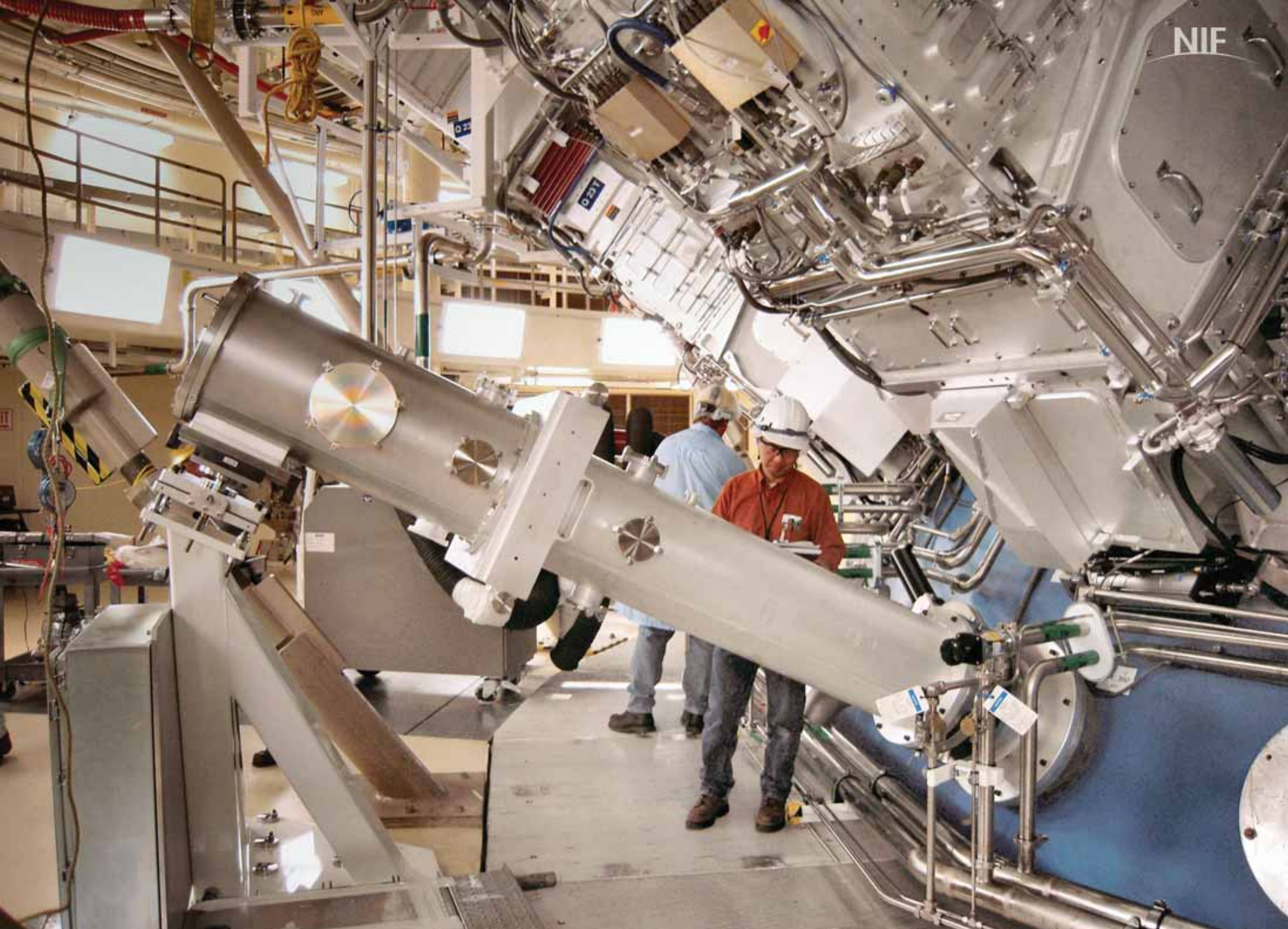


57 target diagnostics enable cutting edge science on the NIF

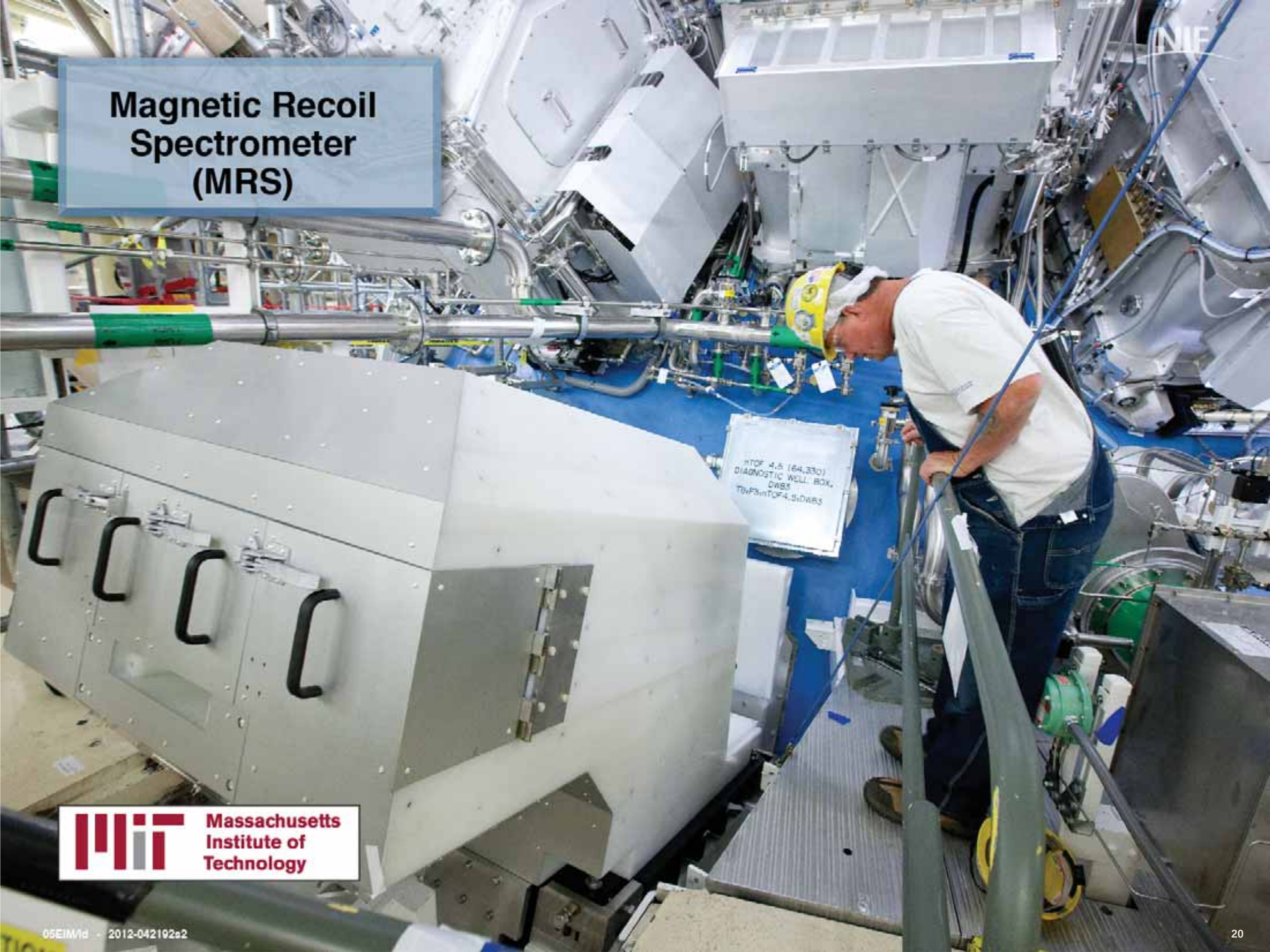


- LLNL
- LANL
- LLE
- NSTec
- U of M
- LBNL
- AWE
- MIT
- CEA
- Duke
- SNL
- GSI





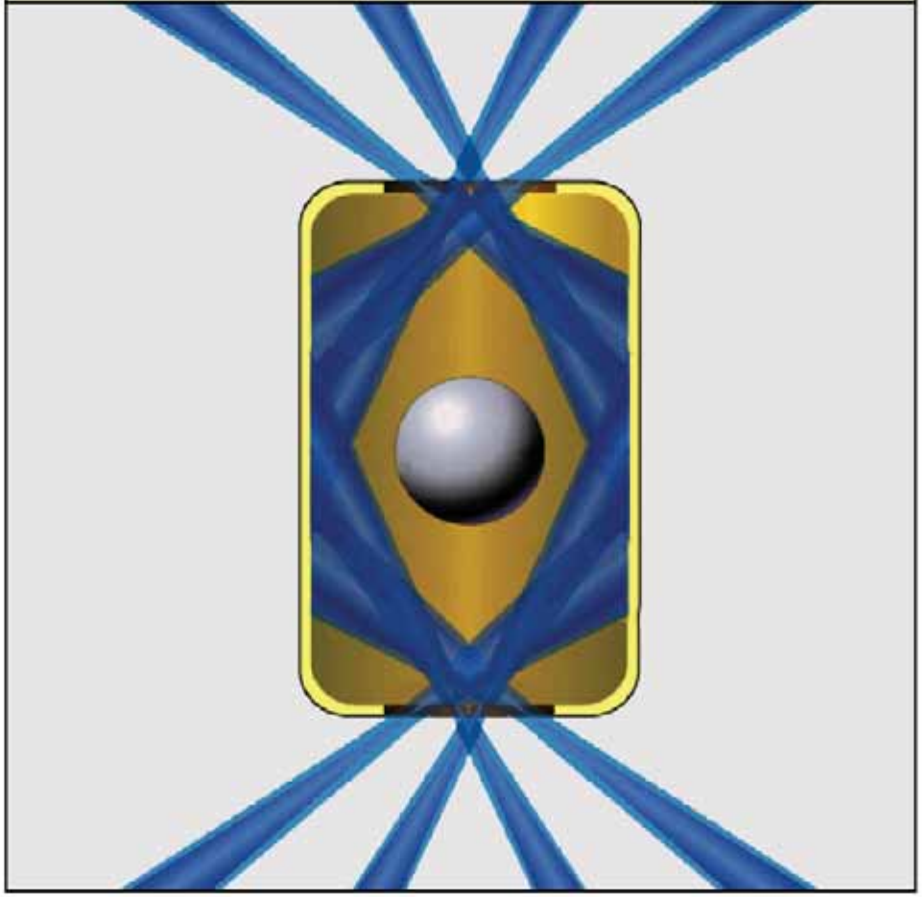

NIF
N28
DISC
PMT NO 4
WARNING
D5


Magnetic Recoil Spectrometer (MRS)
NIF
nTOF 4.5 (64,330)
DIAGNOSTIC WELL BOX,
DWB3
Massachusetts Institute of Technology

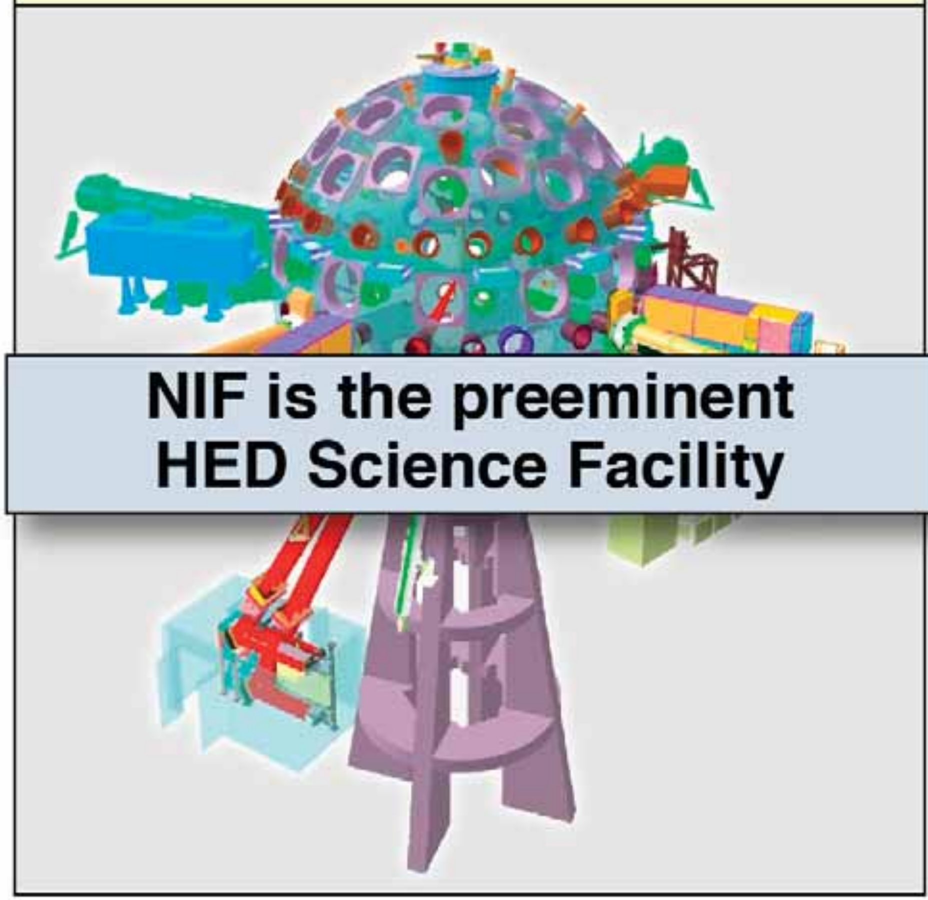
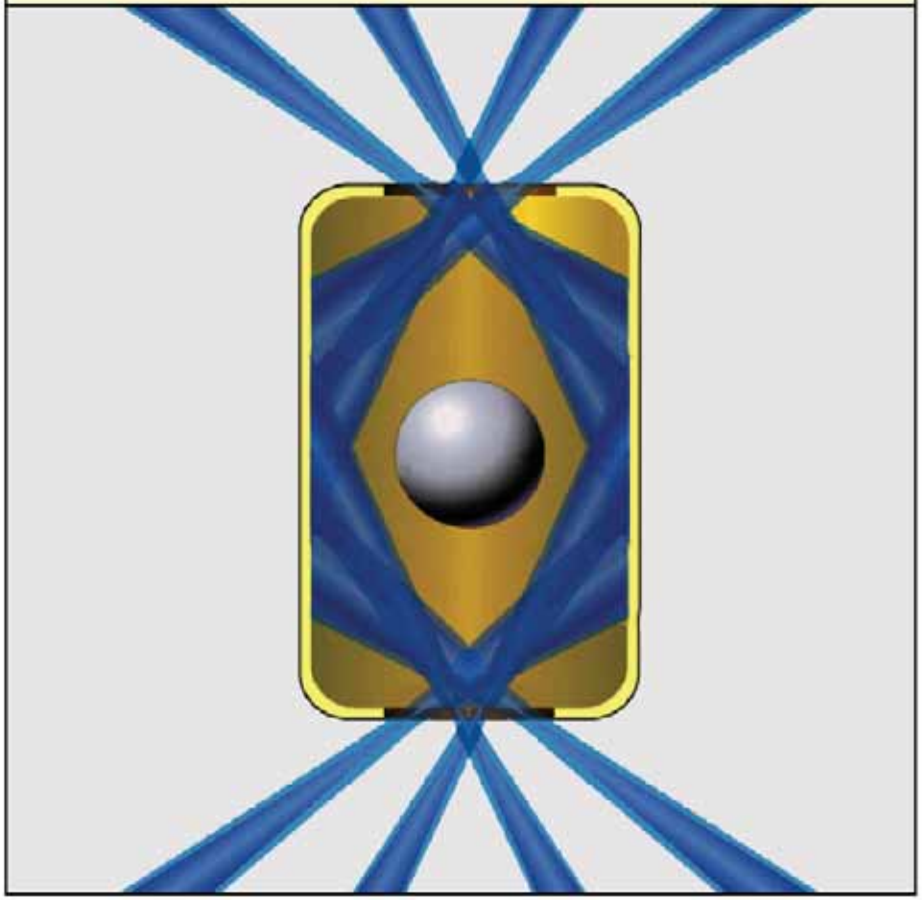
NATIONAL IGNITION CAMPAIGN

NNSA National Nuclear Security Administration
GENERAL ATOMICS
UR LLE
Lawrence Livermore National Laboratory
Los Alamos NATIONAL LABORATORY
Sandia National Laboratories
MIT
AWE
cea
NSTec
BERKELEY LAB
Duke UNIVERSITY

National Ignition Campaign Goals

Transition to a User Facility	Develop an ignition platform
	

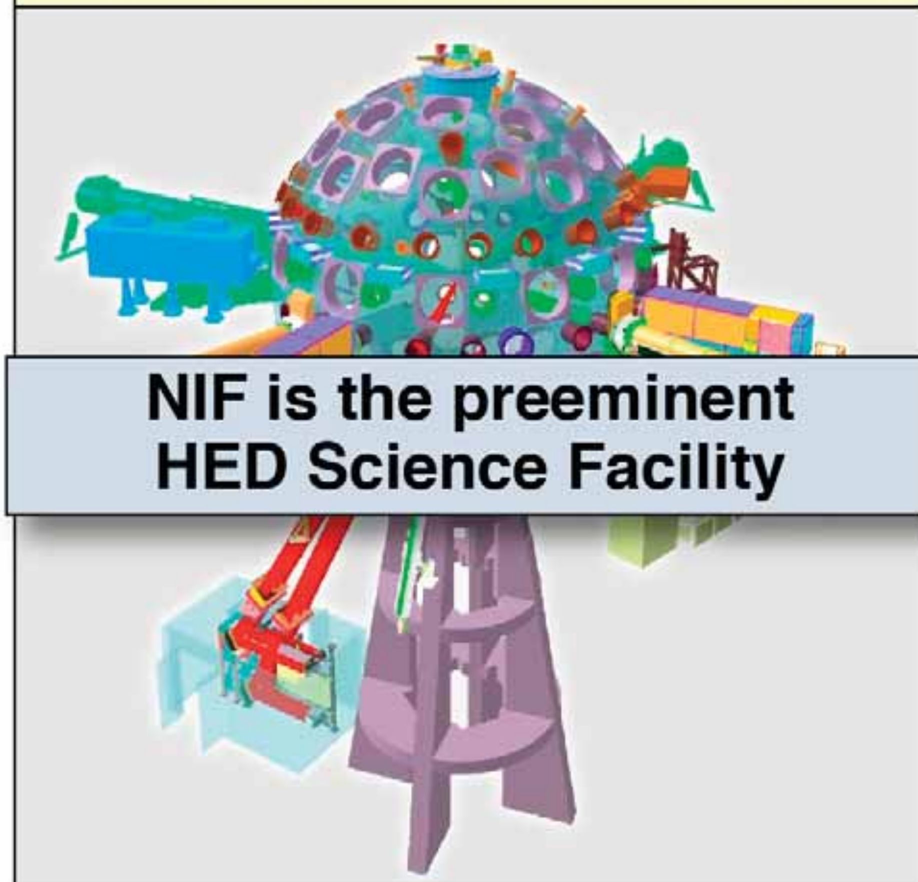
National Ignition Campaign: How did we do?

Transition to a User Facility	Develop an ignition platform
	

NIF is the preeminent HED Science Facility

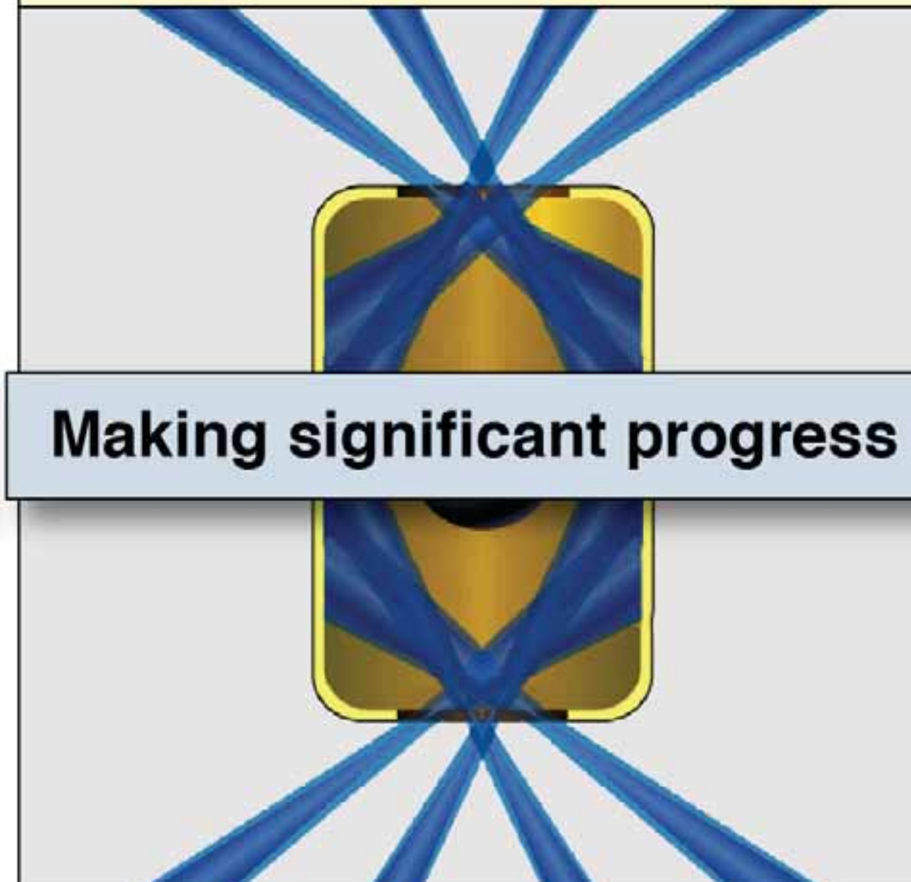
National Ignition Campaign: How did we do?

Transition to a User Facility



NIF is the preeminent HED Science Facility

Develop an ignition platform



Making significant progress

The NIF ignition program has made strong progress

From NNSA Defense Programs Stockpile Stewardship Quarterly (Volume 2, Number 3, Nov. 2012):

"A similar multi-disciplinary, multi-organizational effort has led to tremendous progress on the path to ignition. Although our longstanding goal and milestone for ignition by 2012 was not accomplished, we are much, much closer to achieving that goal than we ever have been. The exciting news is that the remaining challenges appear at the heart of the physics of implosions—resonant with the work we must do in stewardship.

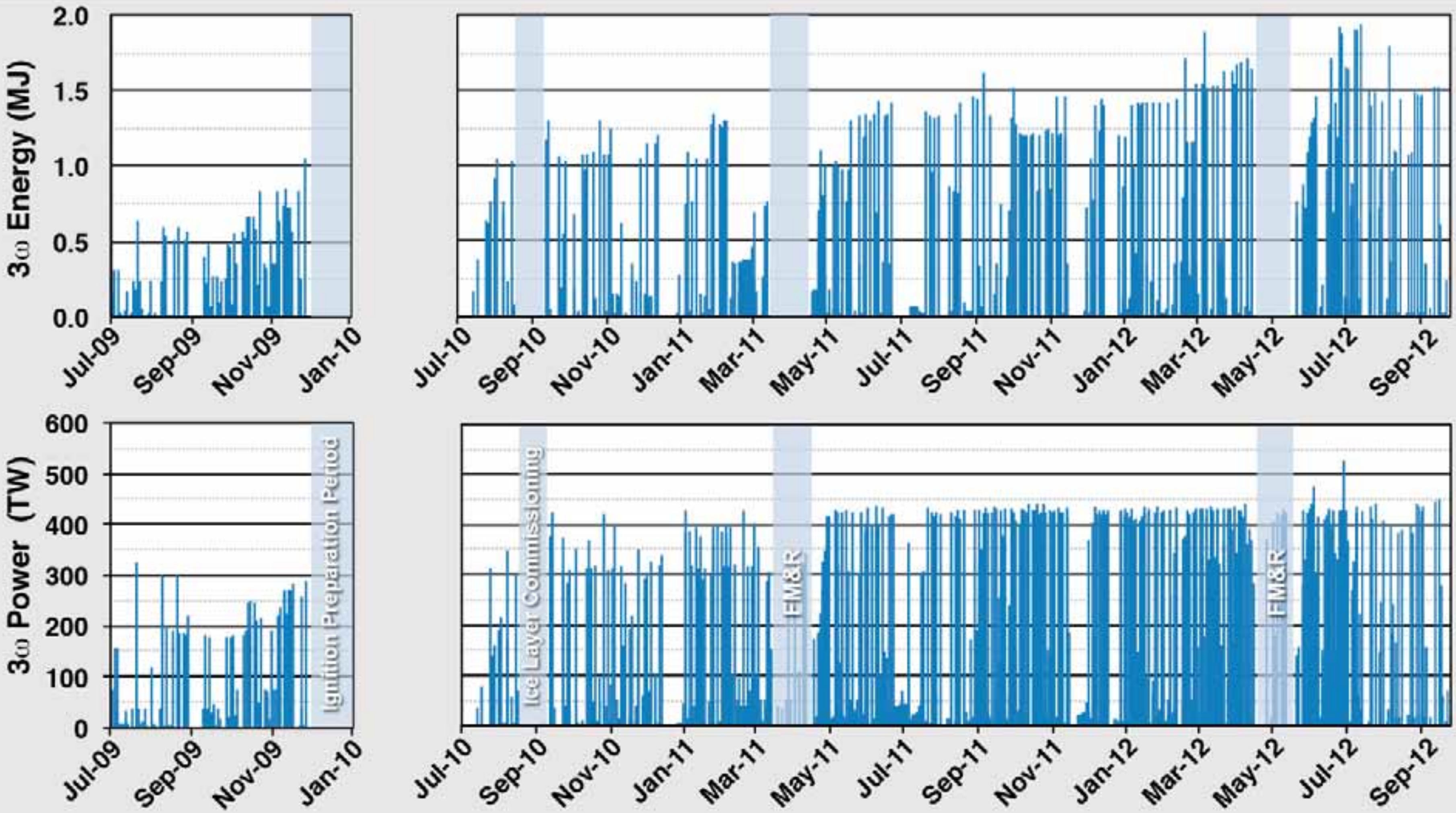
We remain committed to achieving ignition, and the community has developed a path forward. I want to personally thank the community for their efforts, both in bringing us to this point and in laying out the next programmatic efforts."

Dr. Christopher J. Deeney
NNSA Assistant Deputy Administrator
for Stockpile Stewardship

The NIF laser is routinely delivering shots with energy and power that meet user requirements

NIF

Time history of 3ω target shots from 2009 through September 2012

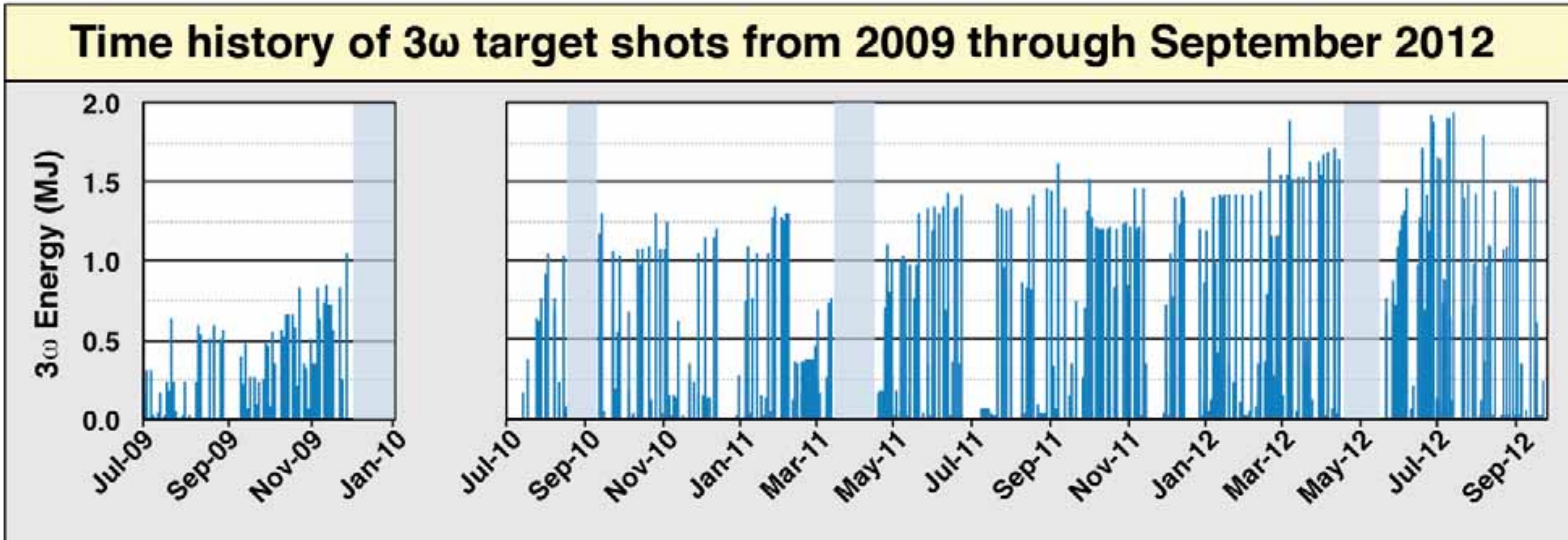


Shot History on NIF (Nov. 1, 2008 – Nov. 29, 2012)*

Type	Specific Purpose	Cryo	Layer	Warm	Total
Target shots – Program Data (354 = 32%)	SSP – ICF**	157	42	35	234
	SSP – HEDSS		16	79	95
	Nat'l Security Applications			14	14
	Fundamental Science			11	11
Target shots – Capabilities (147 = 14%)	Target Diagnostics Commissioning/Calibration			102	102
	System Qualification			45	45
Laser shots only (595 = 54%)	Optics Performance/ Conditioning			139	139
	Laser Performance			208	208
	Laser Calibration			248	248
Total		157	58	875	1096

* No ICCS or Faux shots counted
** Includes NIC shots

NIF has supported non-ignition users, opening new physics regimes with unprecedented precision



Stockpile Stewardship

- Rad Transport Commissioning → Pleiades Drive, Ta Strength, Rad Target data → Ta EOS 10 Mbar, Pleiades Commissioning, Ta Strength 10 Mbar Comm., Defect Hydrodynamics, Mix Platform

Other National Security

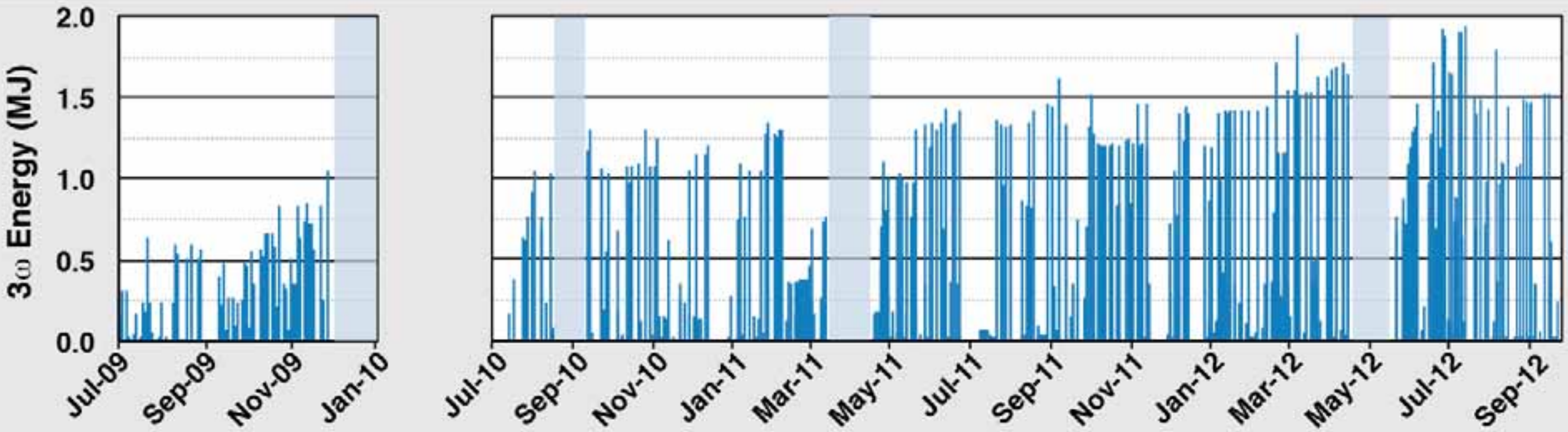
- NSA – x-ray source applications (XRSA) → EPEC Drive → EPEC Experiment, XRSA Source

Fundamental Science

- Fundamental Science - Supernova RT (SNRT) → C EOS 50 Mbar data → C 100 Mbar, Fe EOS Commissioning

NIF laser, diagnostics, targets and operations infrastructure have enabled incredible progress in NIC

Time history of 3ω target shots from 2009 through September 2012



Energetics
- Trad ~290 eV
- Coupling >85%
- Δλ tuning
- Cryo targets

Ignition Experiment Commissioning
- 1st THD 09-29-10
- Shock timing
- Storm windows

Begin optimization
- 3λ HS shape tuning
- DU hohlraum
- Mirrored keyhole
- Yield incr. to 9e14

FMR/System requal.

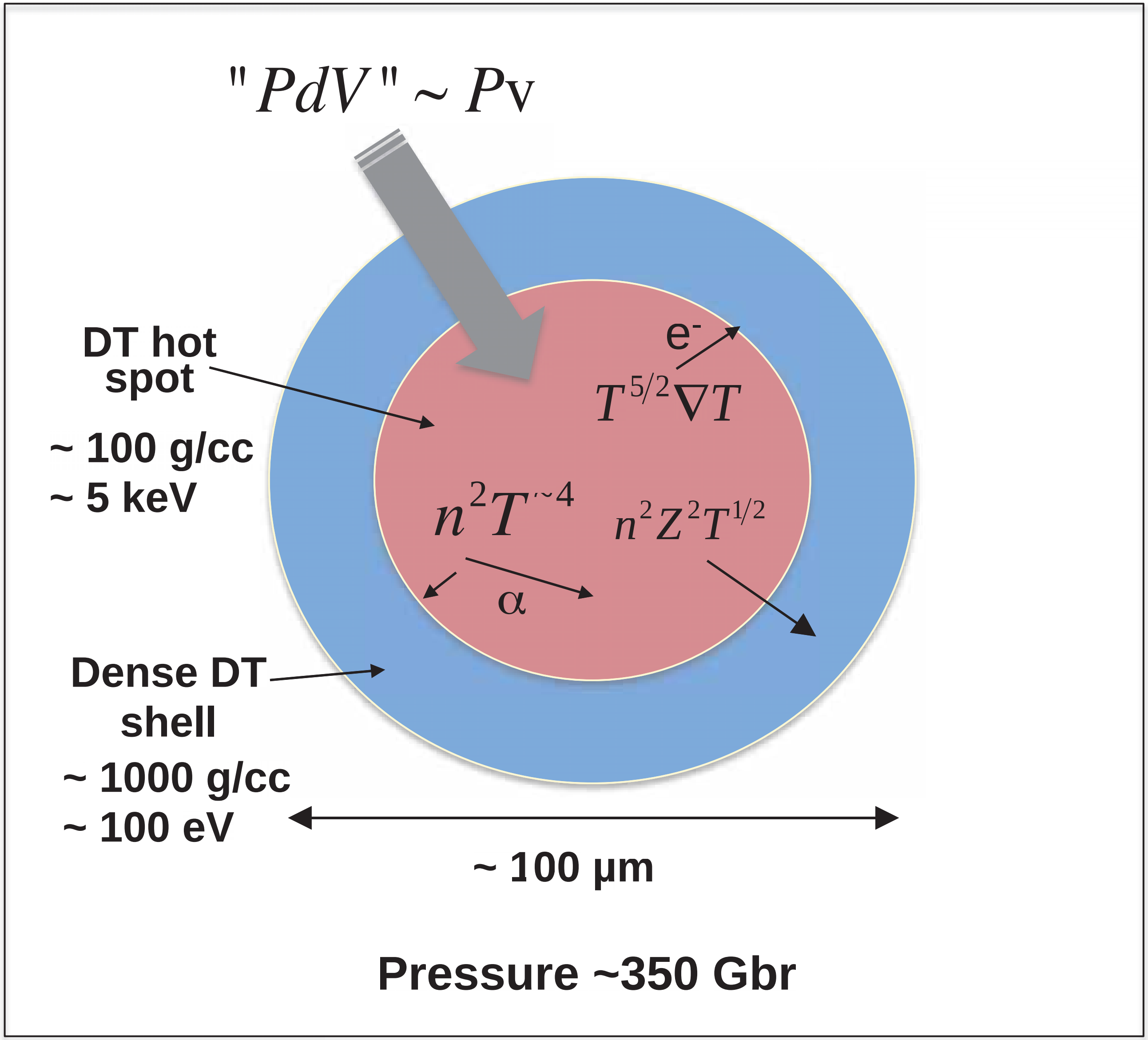
Cold fuel shape diag. commissioning

Ignition Preparation
- THD/DT positioner
- PEPS
- 1st nuclear diagnostics

1st THD/DT Campaign
- DSR incr. to ~4.5%
- Hot spot P2 ~ -25%
- Vel ~ 15% low

Increase DSR/Pressure
- "No coast" 4th rise
- DSR incr. to ~6.5%
- Identified "mix cliff"
- Low mode cold fuel asymmetry

To achieve ignition we have to assemble a hot spot surrounded by cold fuel

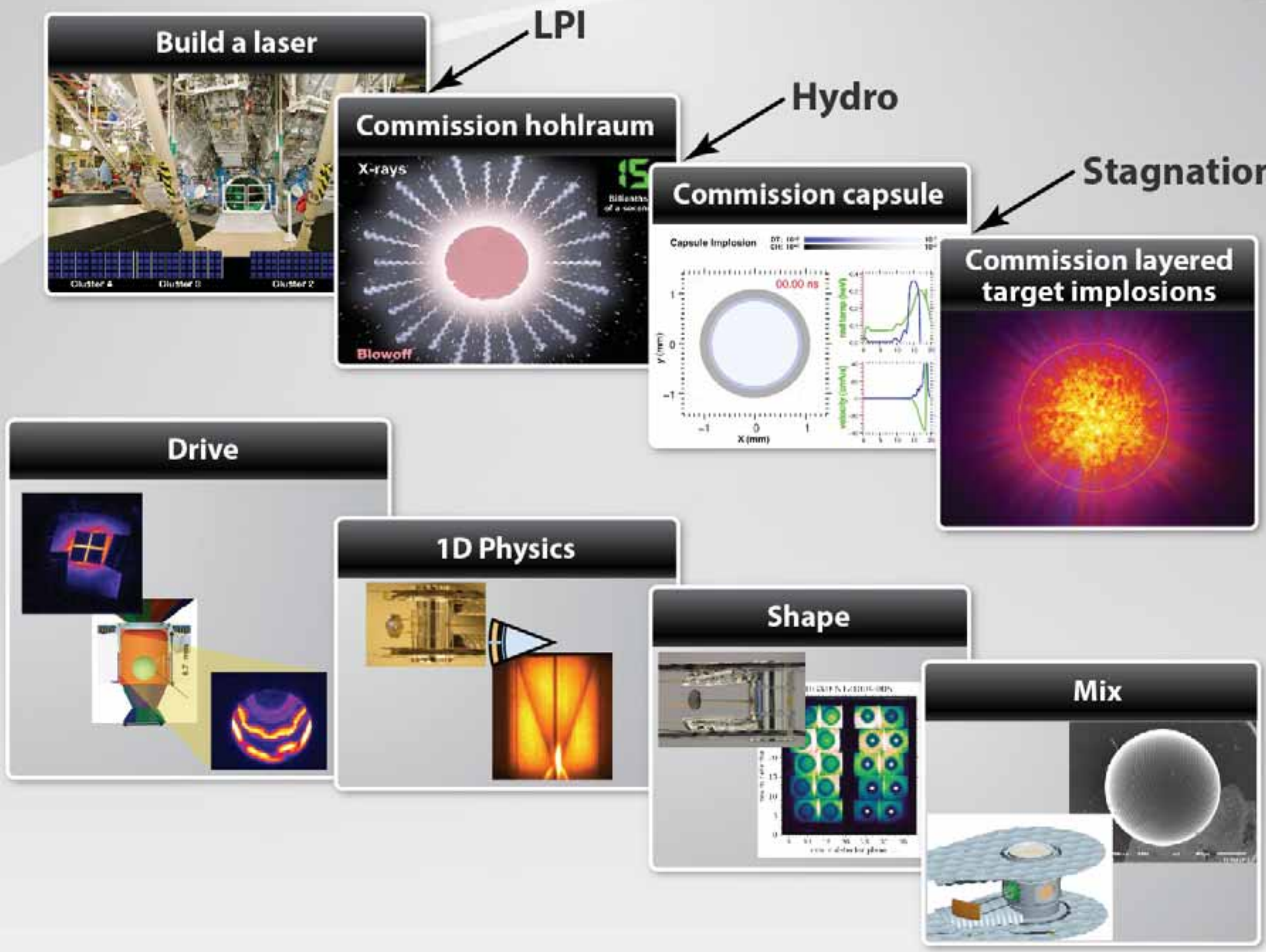


We are making good progress towards understanding ignition target performance on the NIF

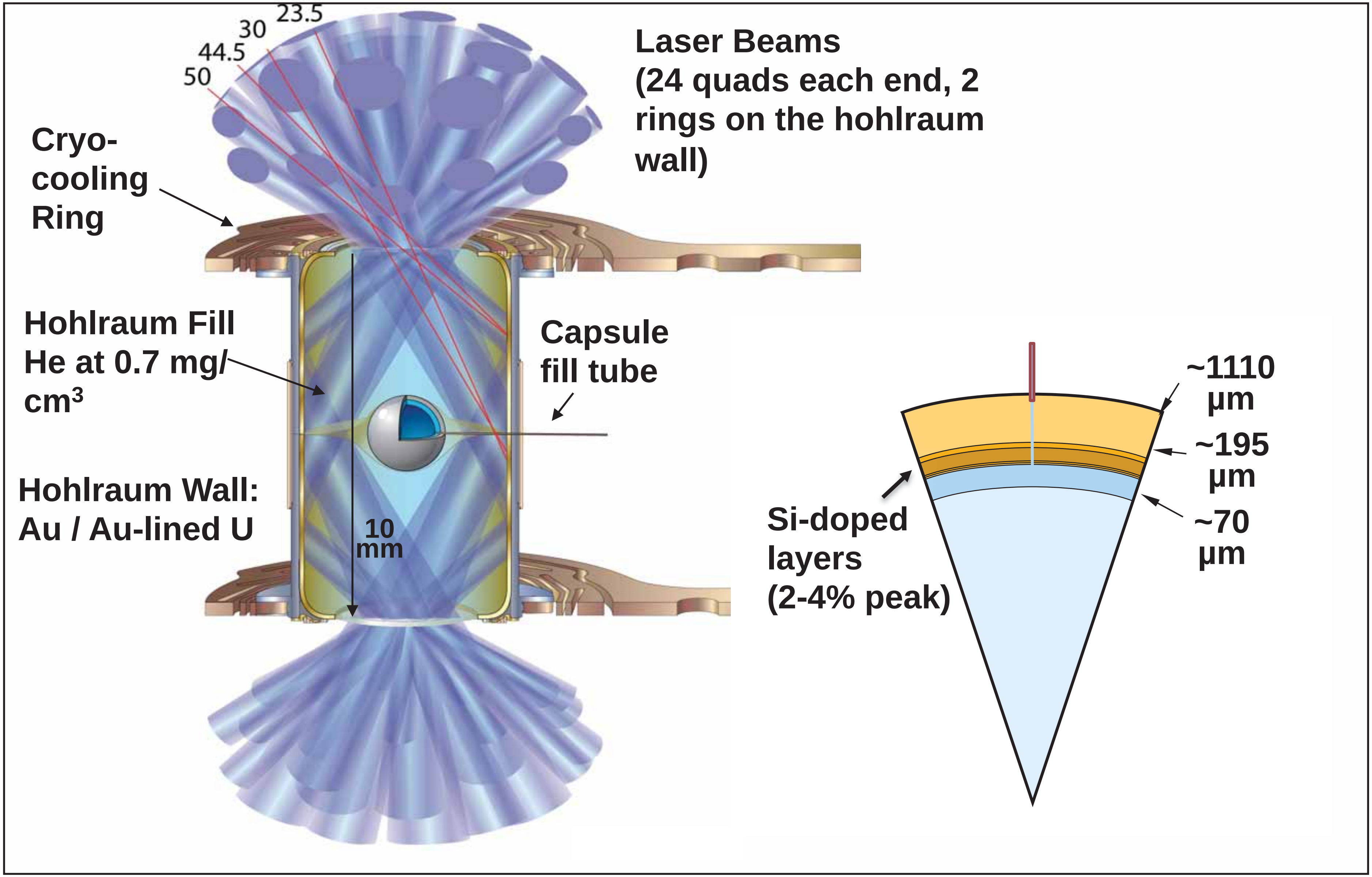
- The NIF laser and targets have met the highly demanding specifications for accuracy and control set by the point design (Rev5)
- We have developed capabilities to field cryogenic experiments including DT layered implosions and have in place diagnostics to measure many aspect of target performance with the required accuracy – but not all
- 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 respectively
- Nuclear yields are ~ 3-10X from alpha dominated regime - hotspot densities, pressures ~ 2-3X lower than needed, and predicted
- It is likely 3D hydrodynamics due to long wavelength X-ray drive asymmetry, and hydrodynamic mix are larger than predicted and major contributors to performance deficit

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

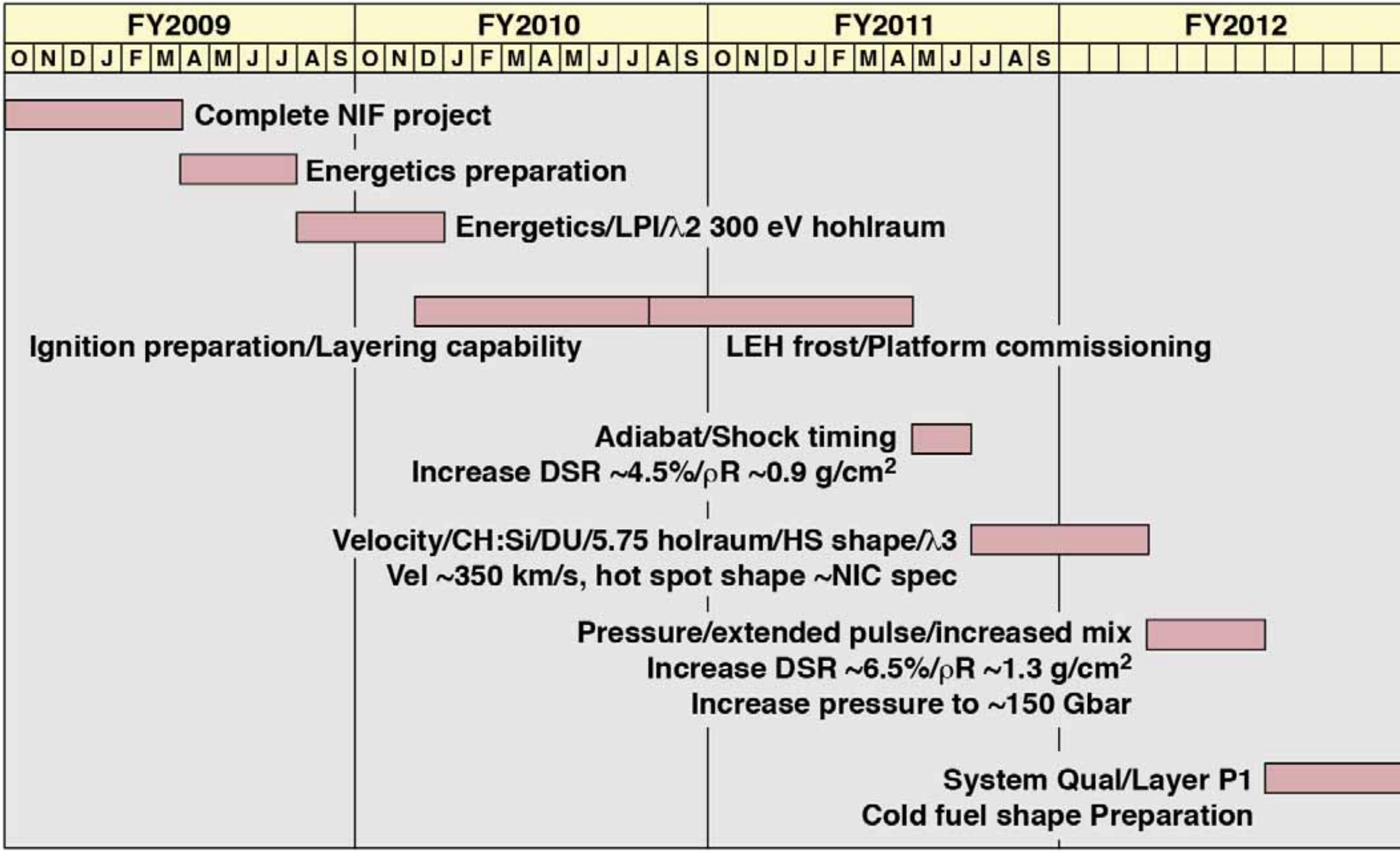
Path to ignition – Working Groups



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



NIC in 6 steps



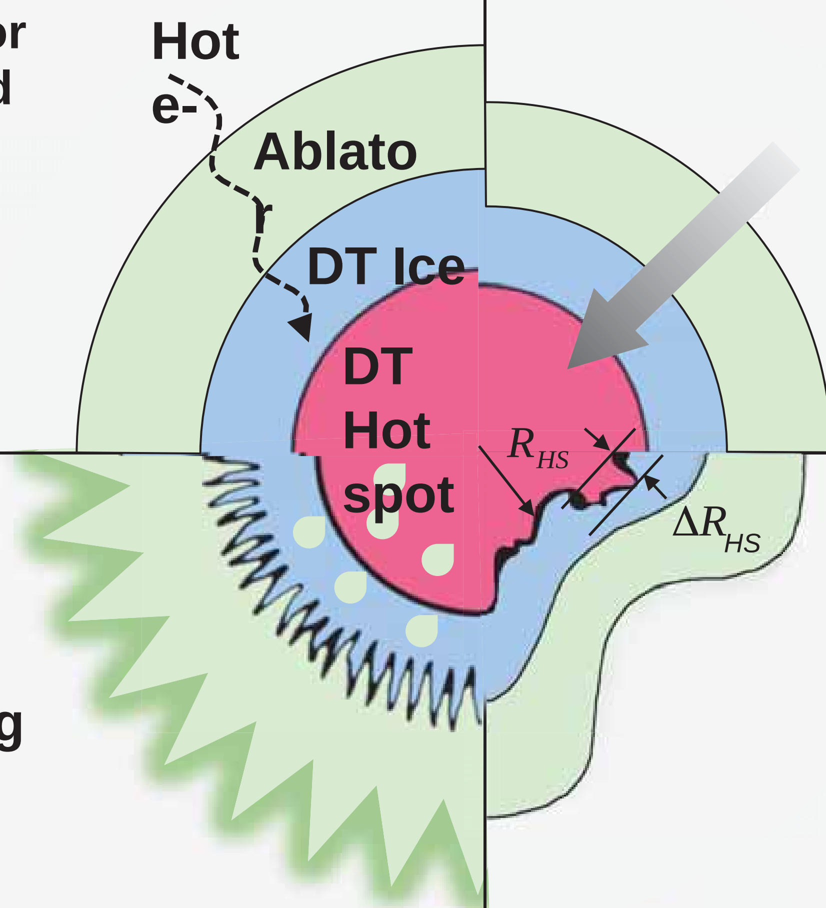
Point design sets requirements on implosion properties to achieve the stagnated fuel conditions for ignition

α Adiabat

High compression for ρR – trap alphas, and confinement

Velocity V

PdV power to heat hot spot



Radiative cooling

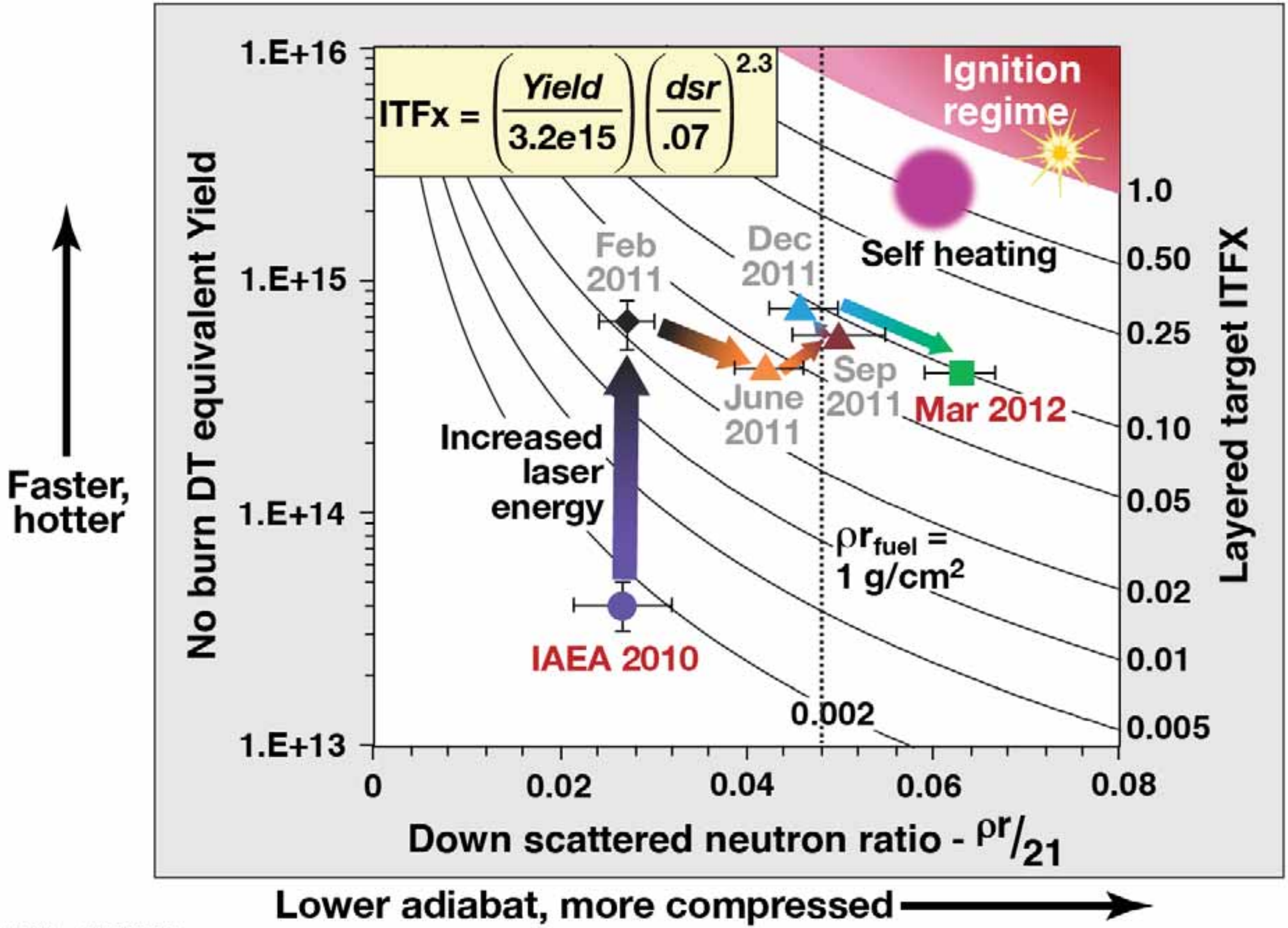
Efficient conversion of implosion KE to hot spot thermal energy

M Mix

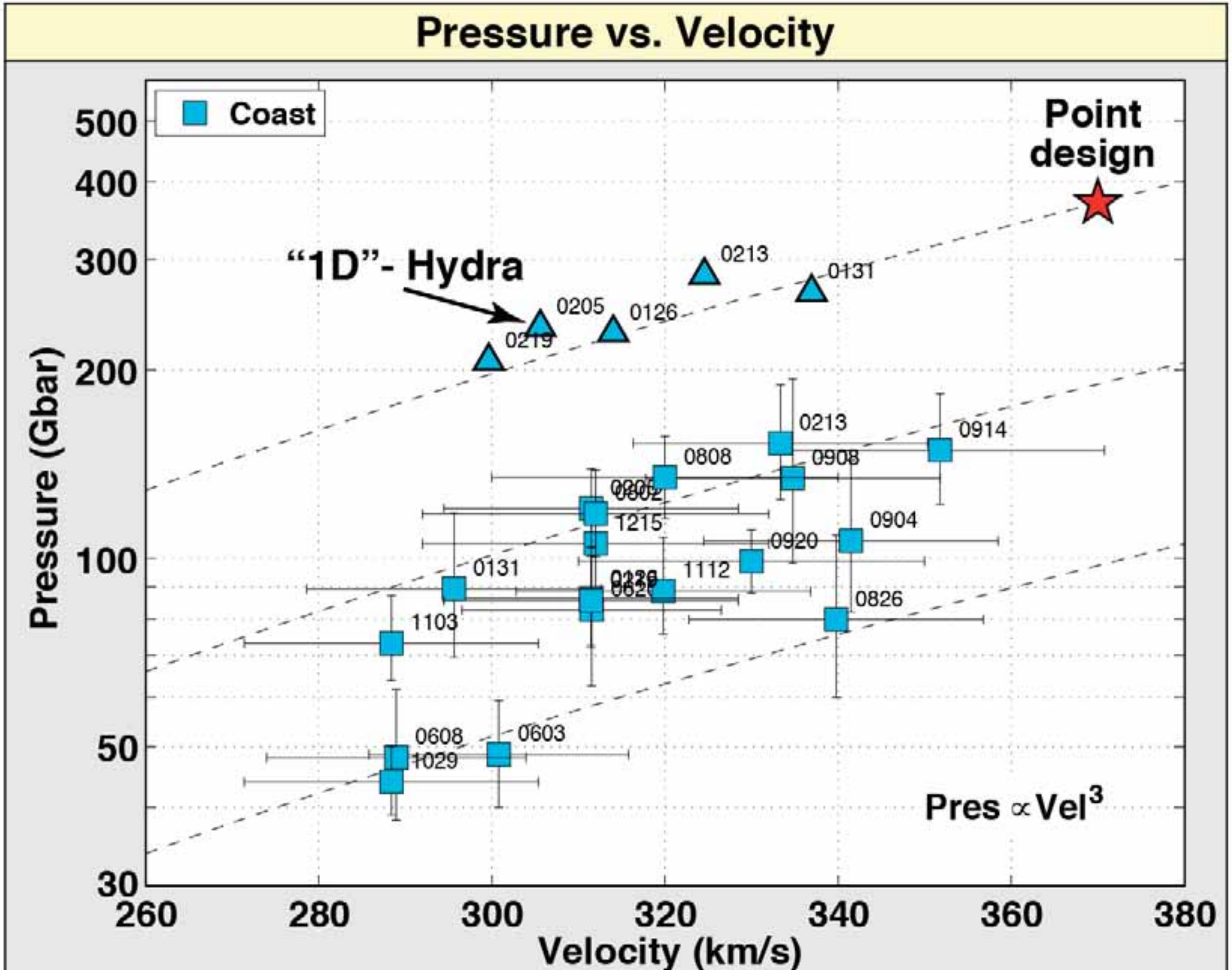
Shape S

Adjustments to laser energy and pulse duration, along with shock timing, have demonstrated ITFX ~ 0.1 with fuel ρR at 85% of ignition goal

NIF

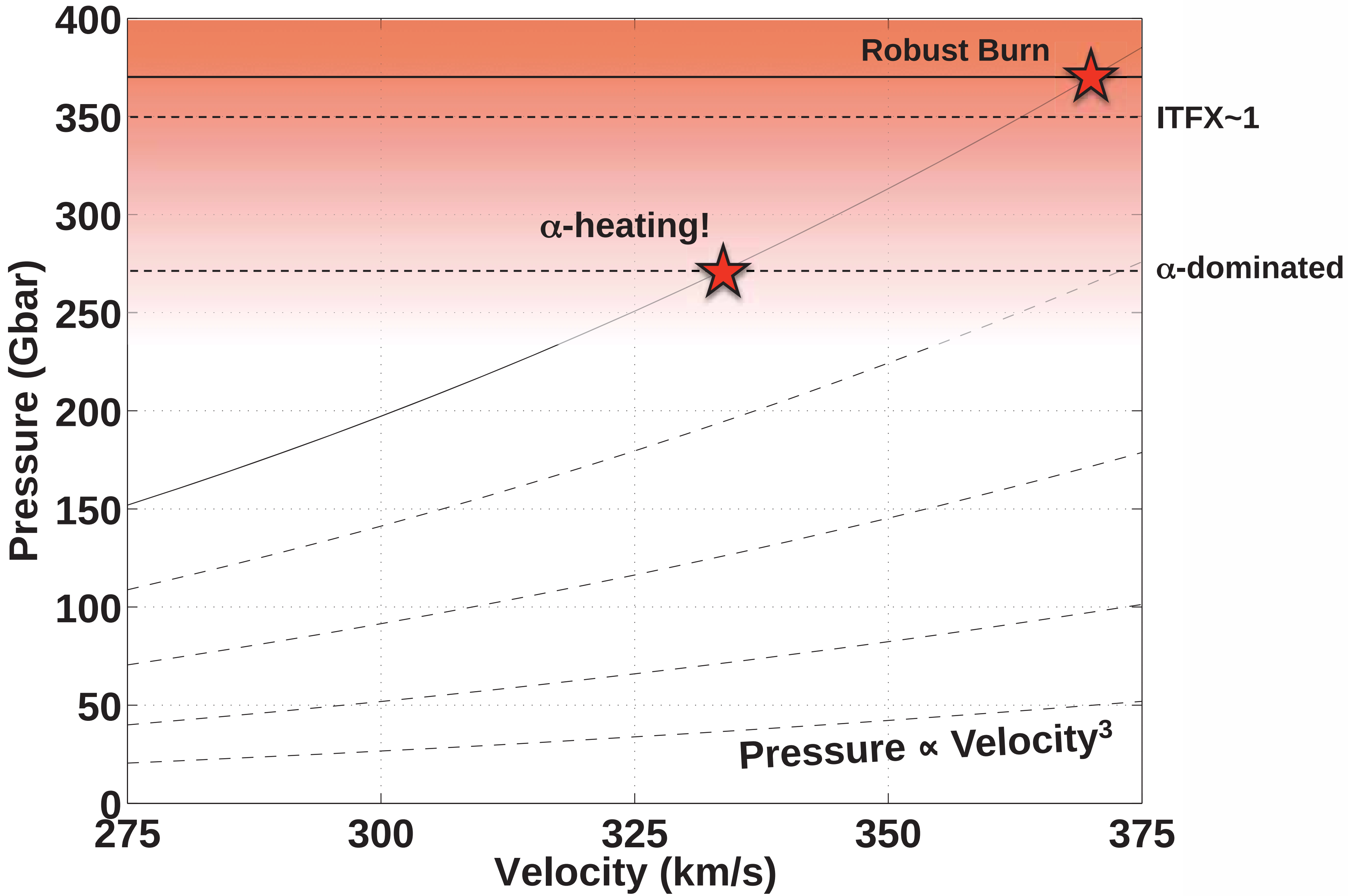


Pressure scales with velocity³ as expected – but are low compared to post shot simulation*



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

Another way to look at implosion physics and performance-Stagnation pressure vs Velocity



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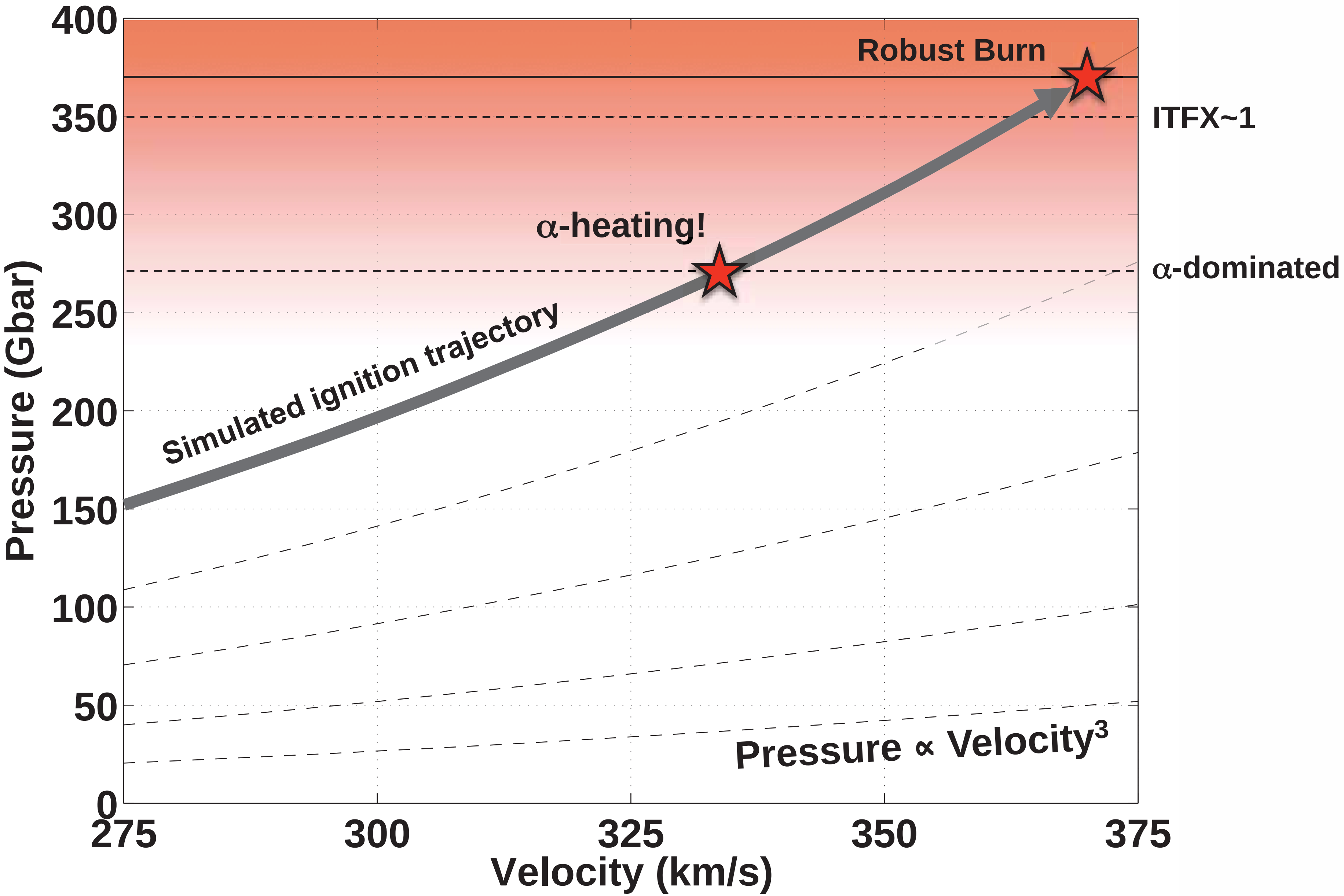
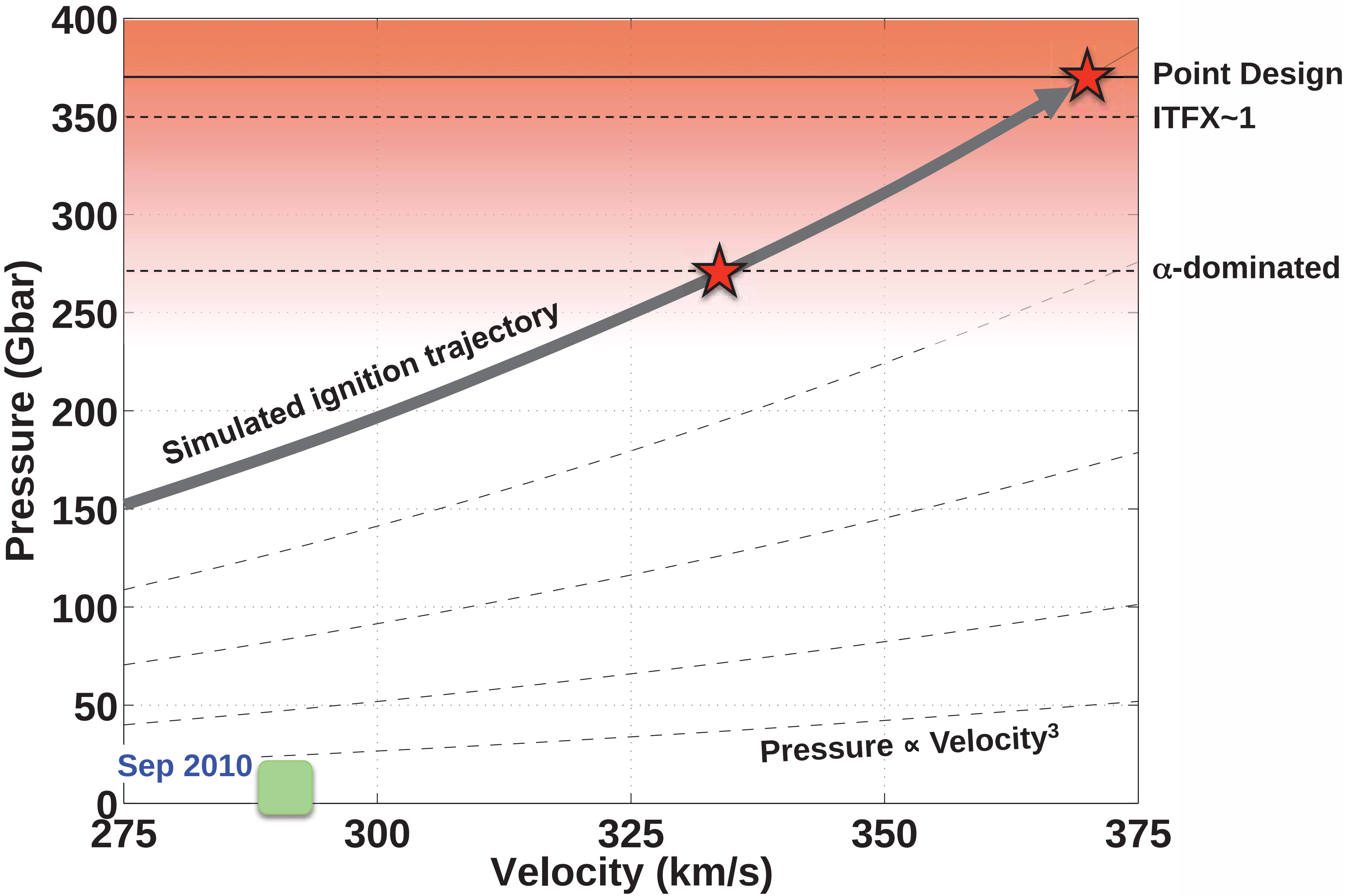
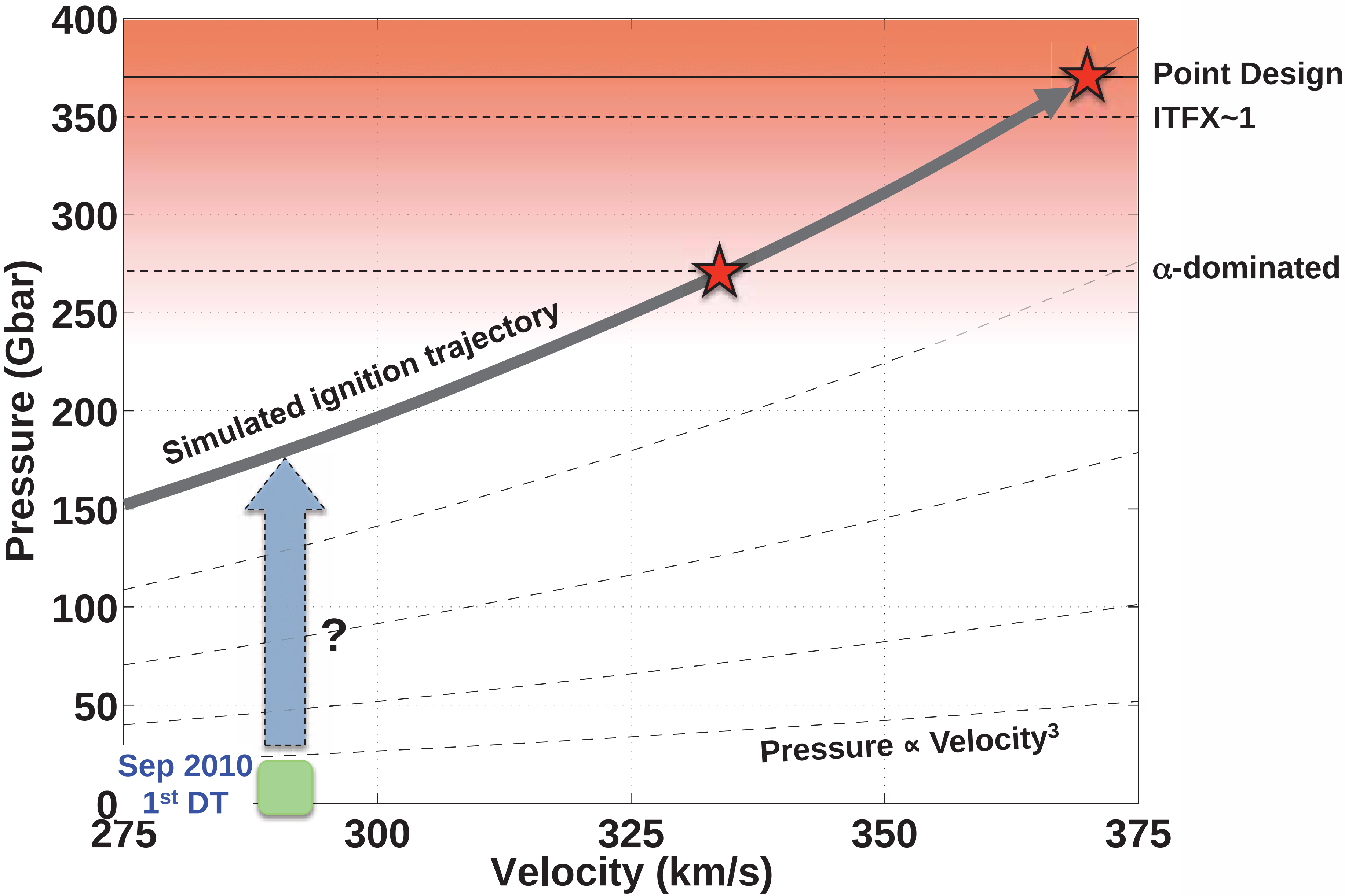


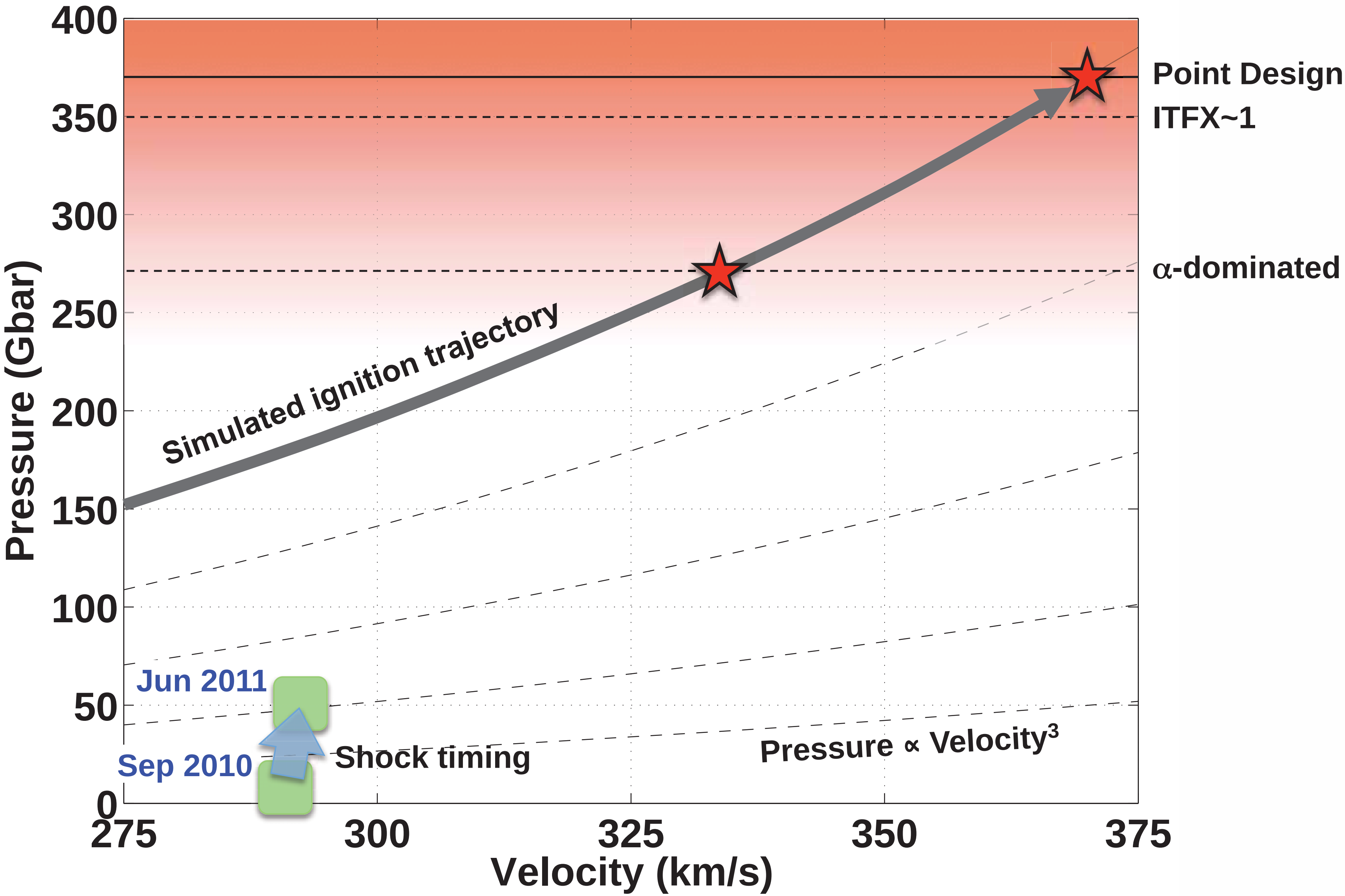
First experiments in two years ago



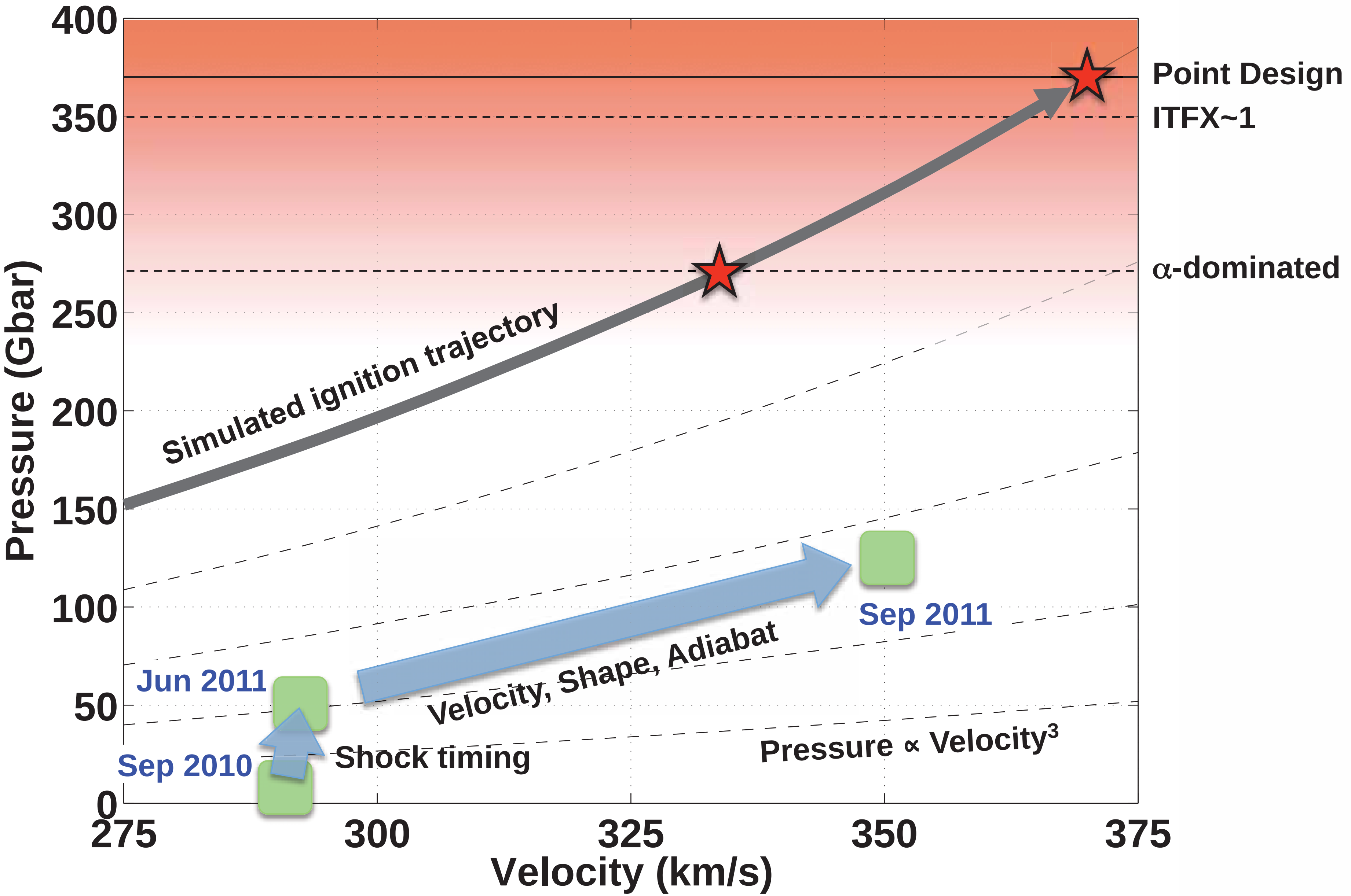
Before precision experiments the fuel pressure was ~35 times lower than required for ignition and off the trajectory of interest by a factor of 10



Shock timing marked the beginning of the precision experiment campaign in May 2011



Experimental plan unfolded during the summer of 2011



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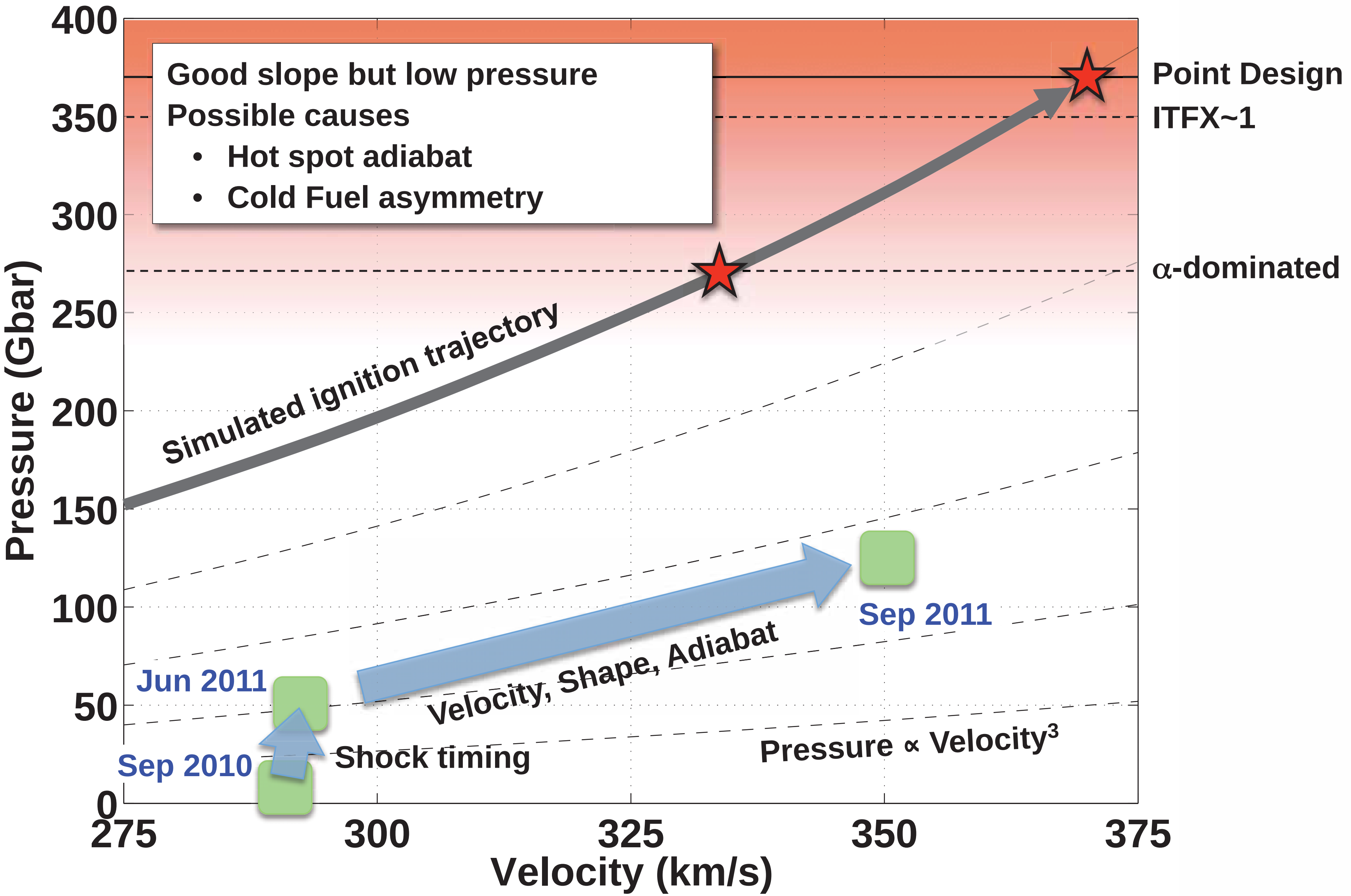

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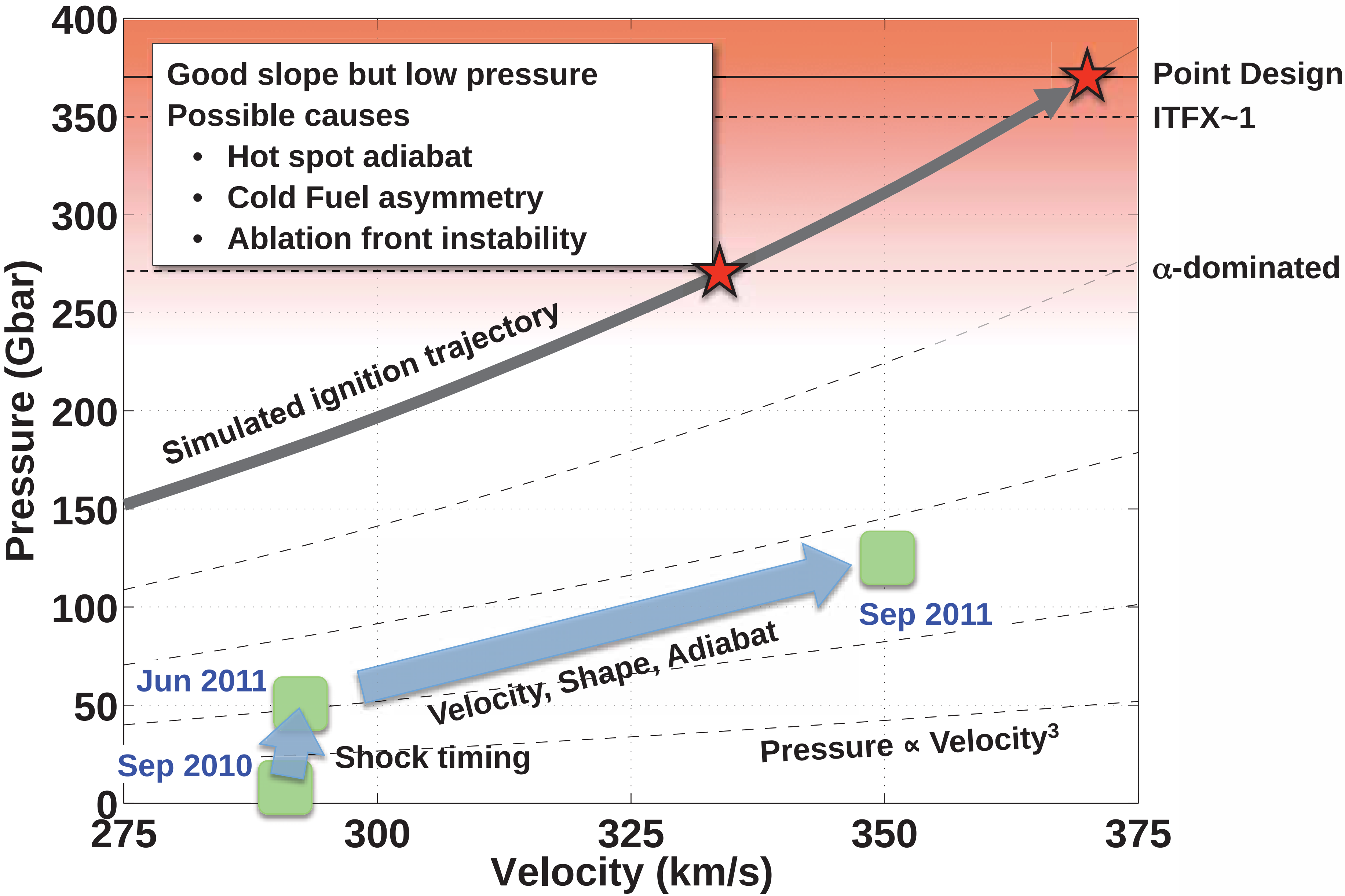
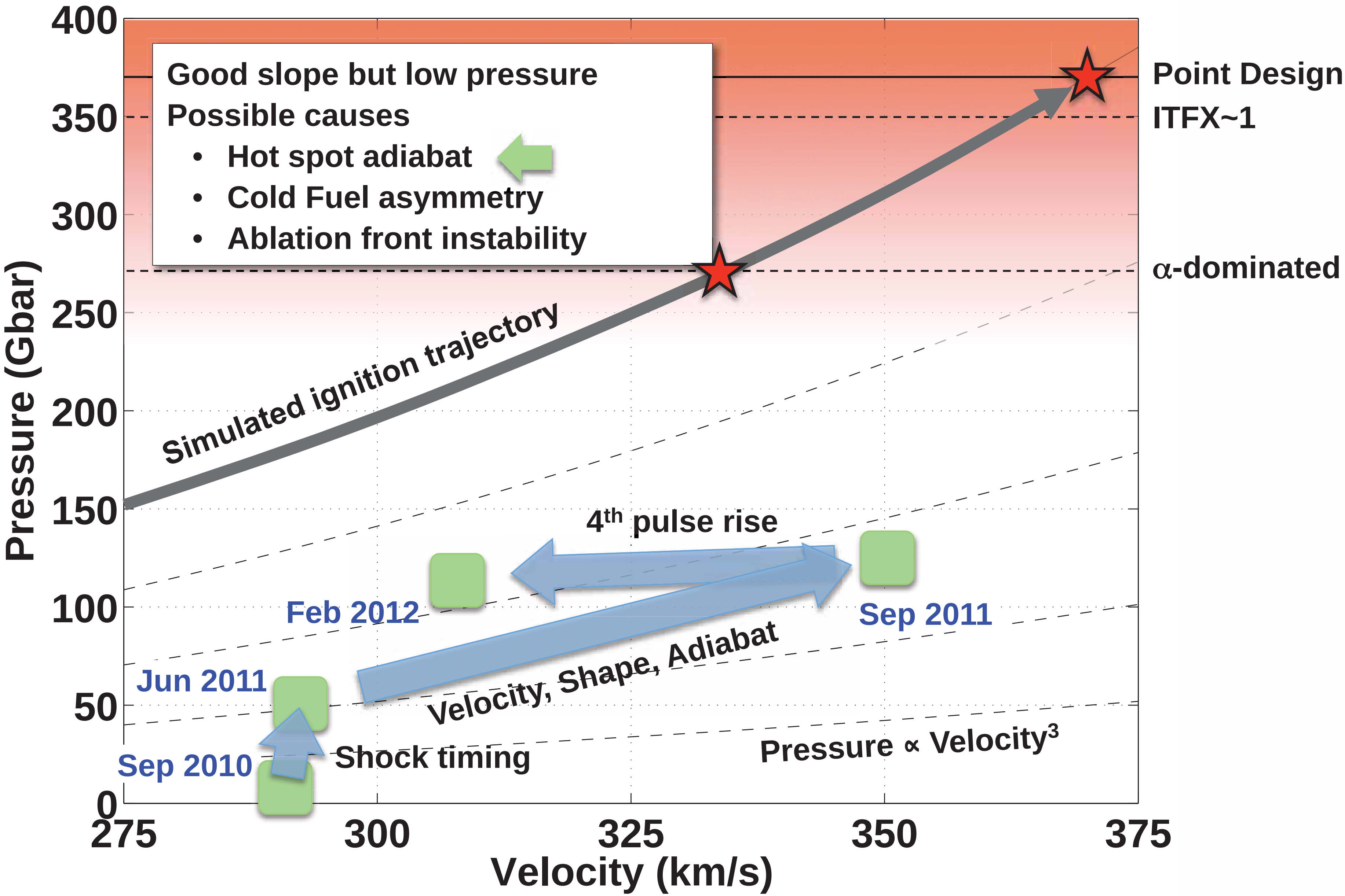
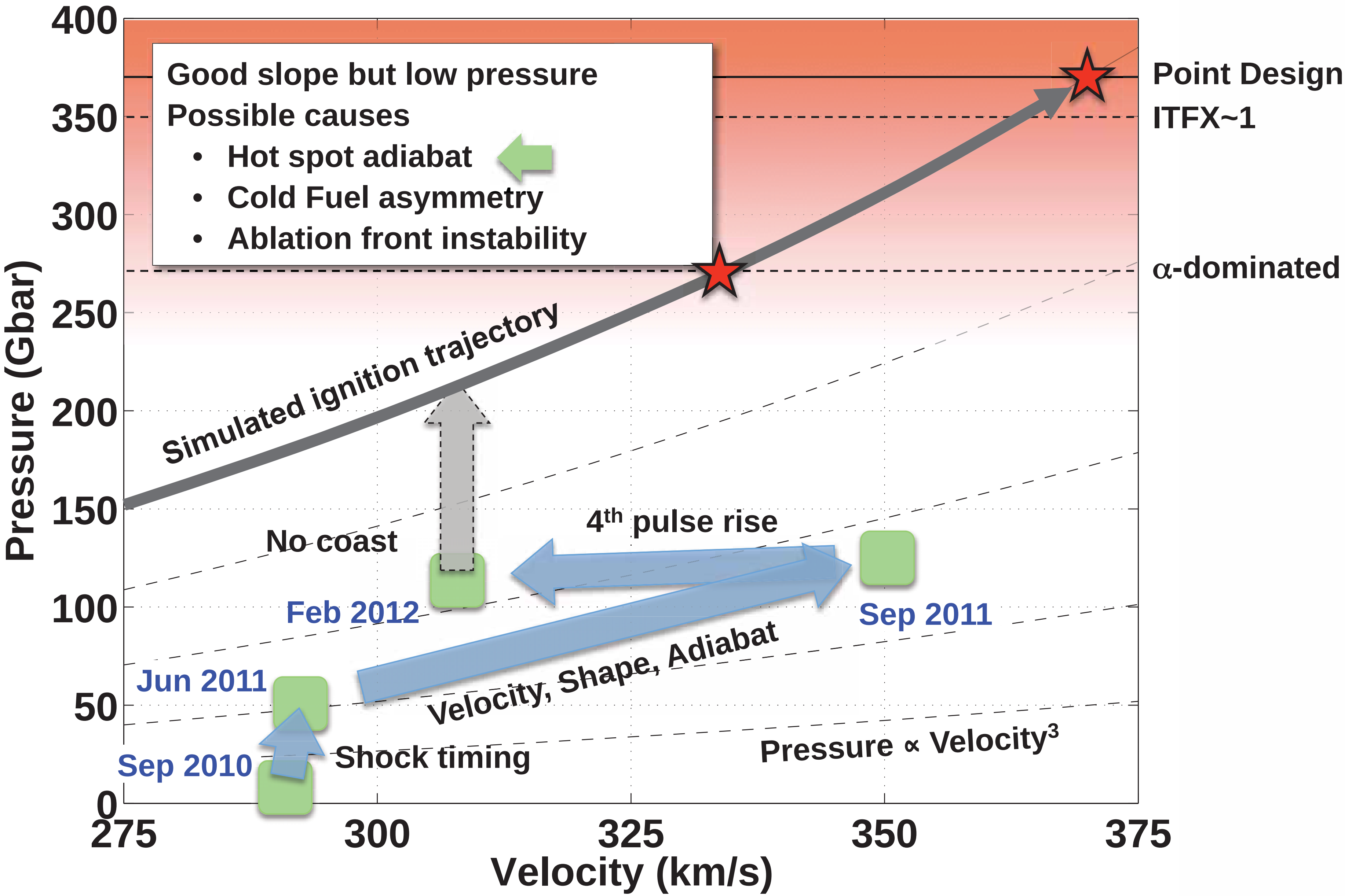


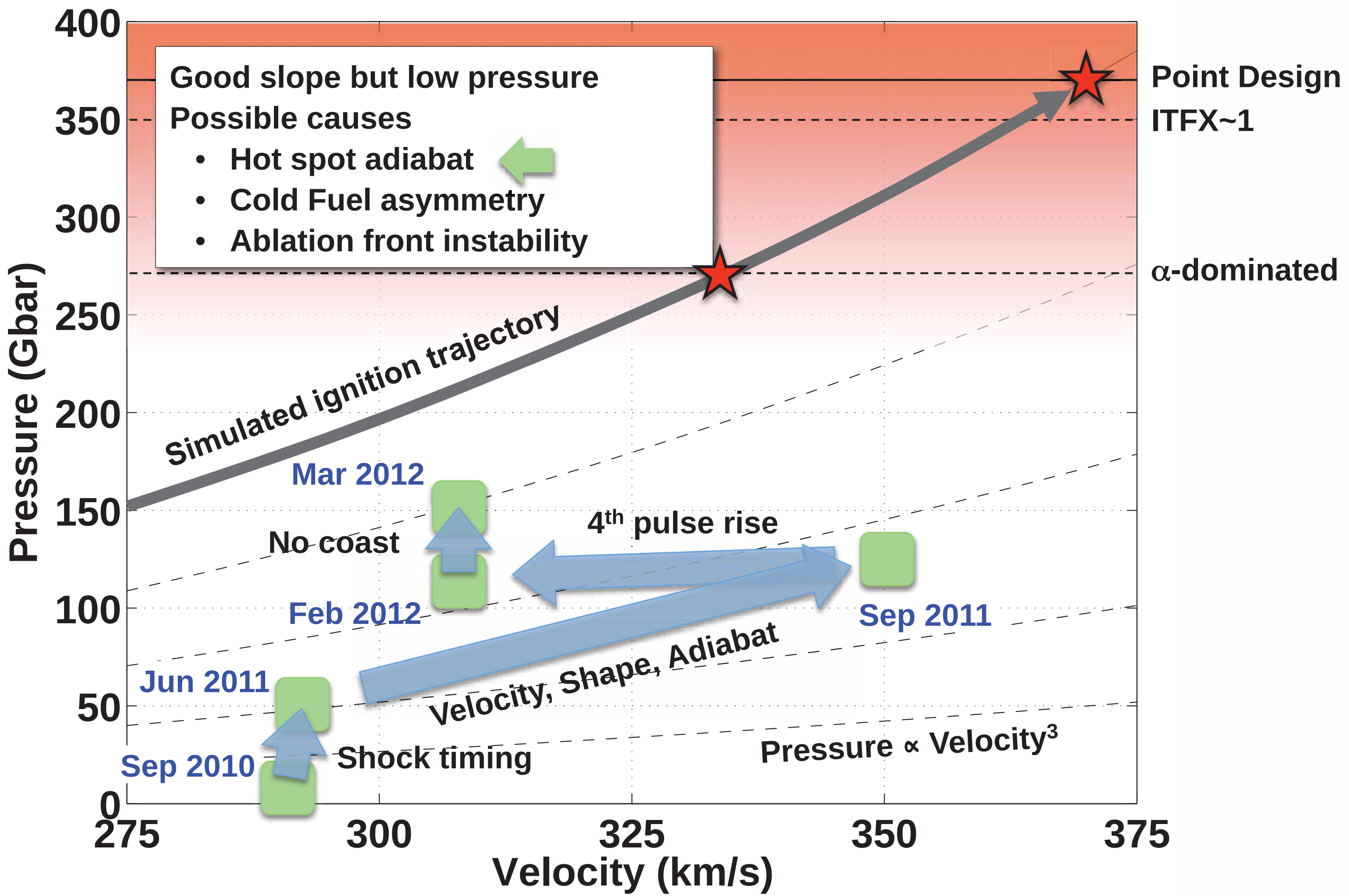
4th pulse shape improved hot spot adiabat — higher pressure at lower velocity



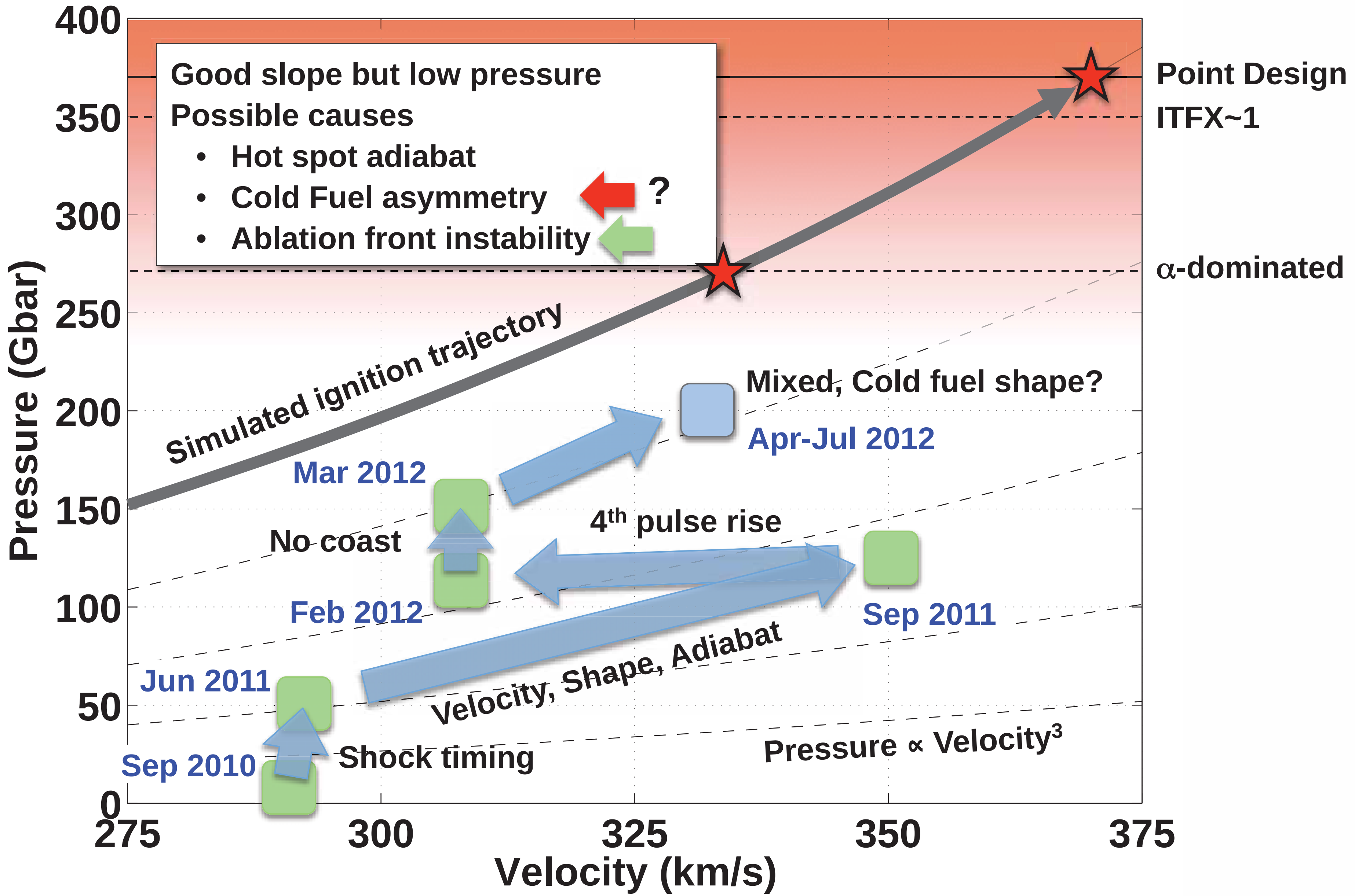
Eliminating coasting—goal was 200 Gbar, on the trajectory for ignition



No coast drive made it part of the way, to 150 Gbar

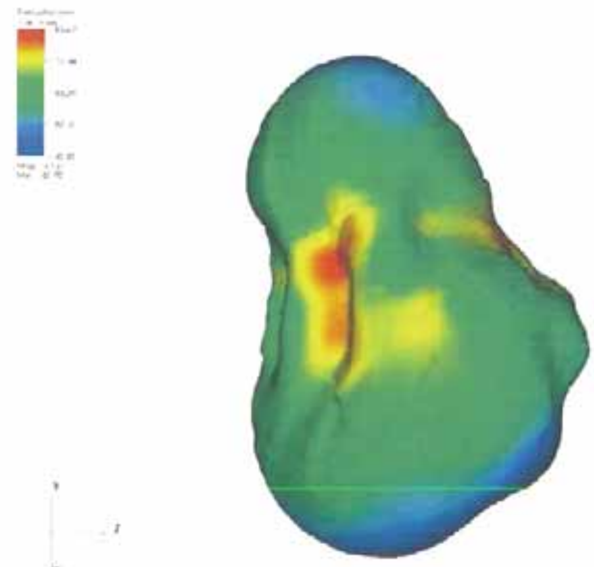


Increasing velocity increased pressure, but also increased mix variability



Evidence suggests 3D hydro is a significant factor affecting performance of current DT implosions

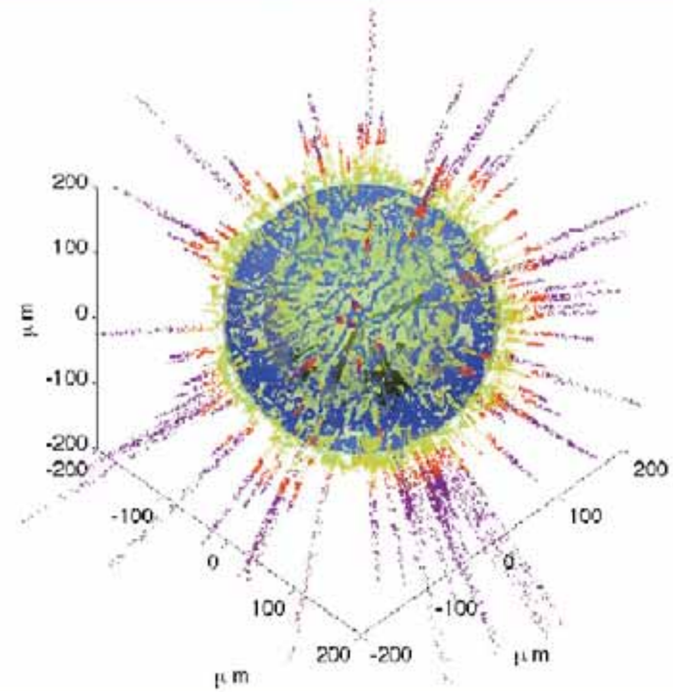
Low modes



Hot spot surface

- Hohlraum drive asymmetry
- Ablator / ice low modes
- ……

High modes



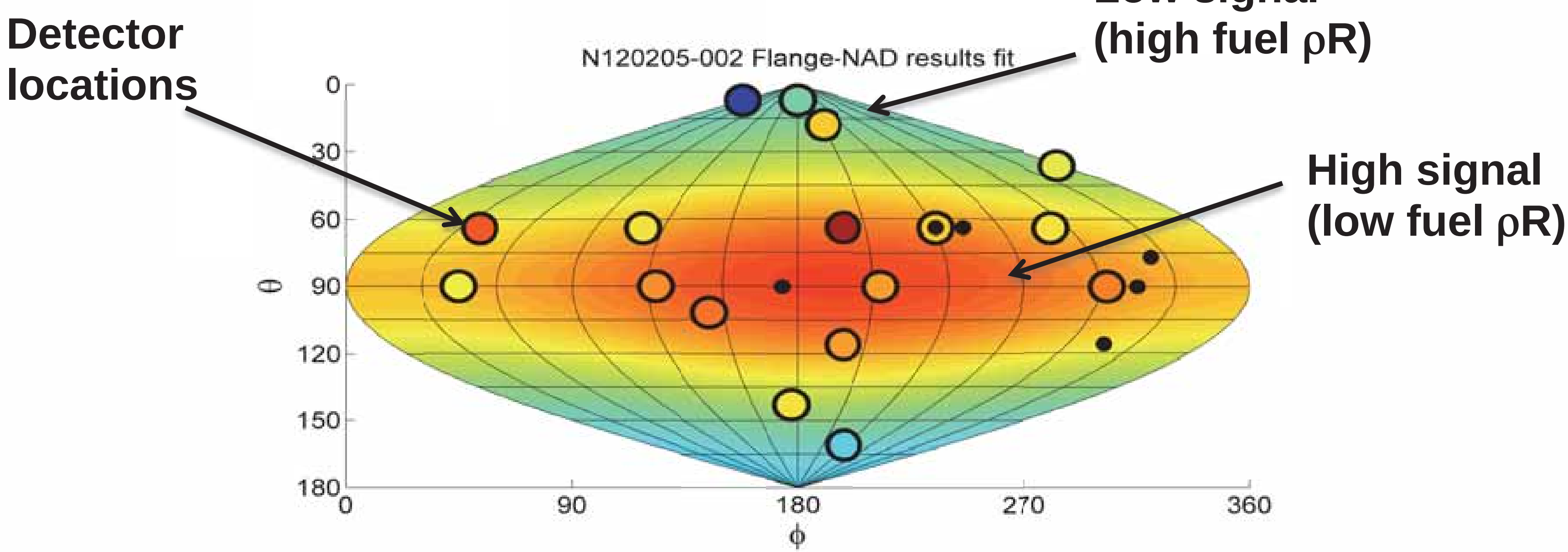
- Capsule roughness
- Dust
- ……

How the capsule behaves depends on
- Initial conditions – roughness, dust, ……..., and growth
- Boundary conditions – hohlraum drive and symmetry

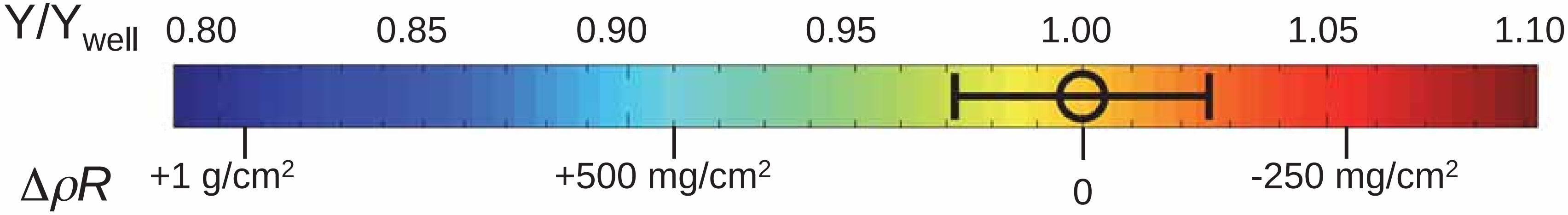
Neutron activation detectors indicate significant fuel ρR asymmetry ~ 50-100% - May 2012 NNSA review

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

Low order fit to > 13MeV neutron activation signals

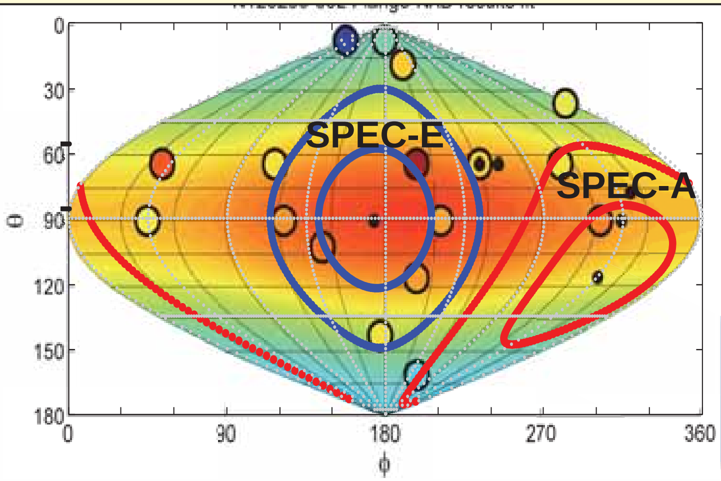


- **Average ρR ~ 1 g/cm²**
- **~ 50% variations**

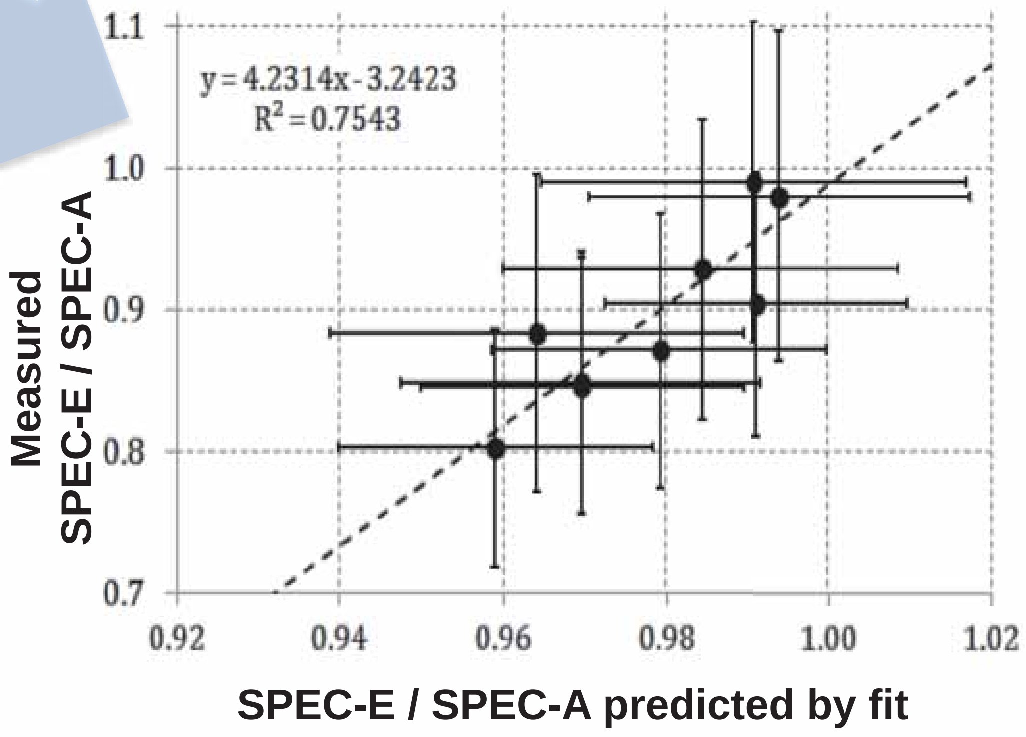


ρR distribution from activation detectors consistent with longstanding SPEC-E/SPEC-A asymmetry

Activation data can predict neutron spectrometer (SPEC) signals

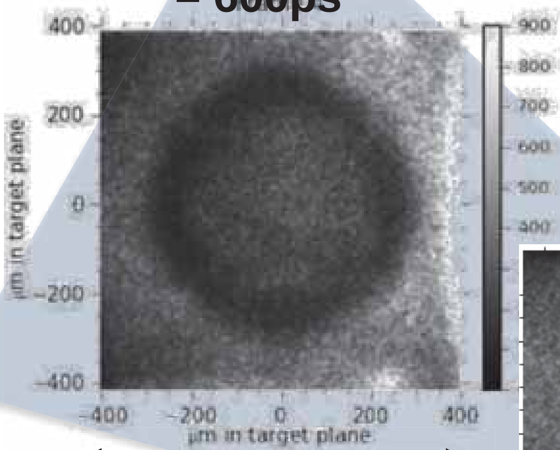


Measured vs. predicted neutron downscattered (ρR) signals along 2 LOS



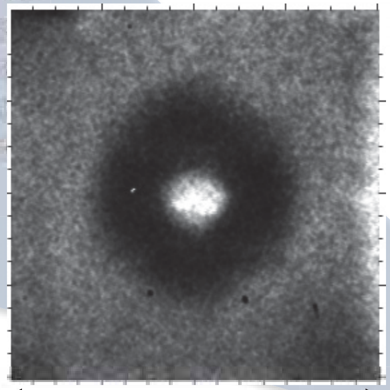
The large P4 asymmetry has a significant effect on stagnation

N121004
Bang time – 600ps

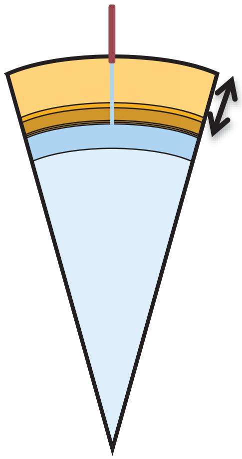


800 µm

N121004
Bang time – 300ps

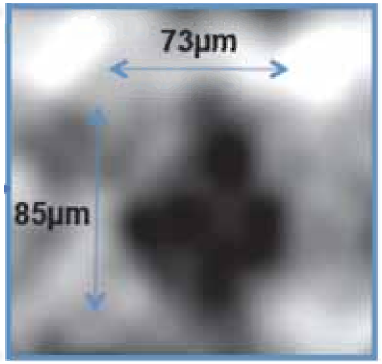


800 µm



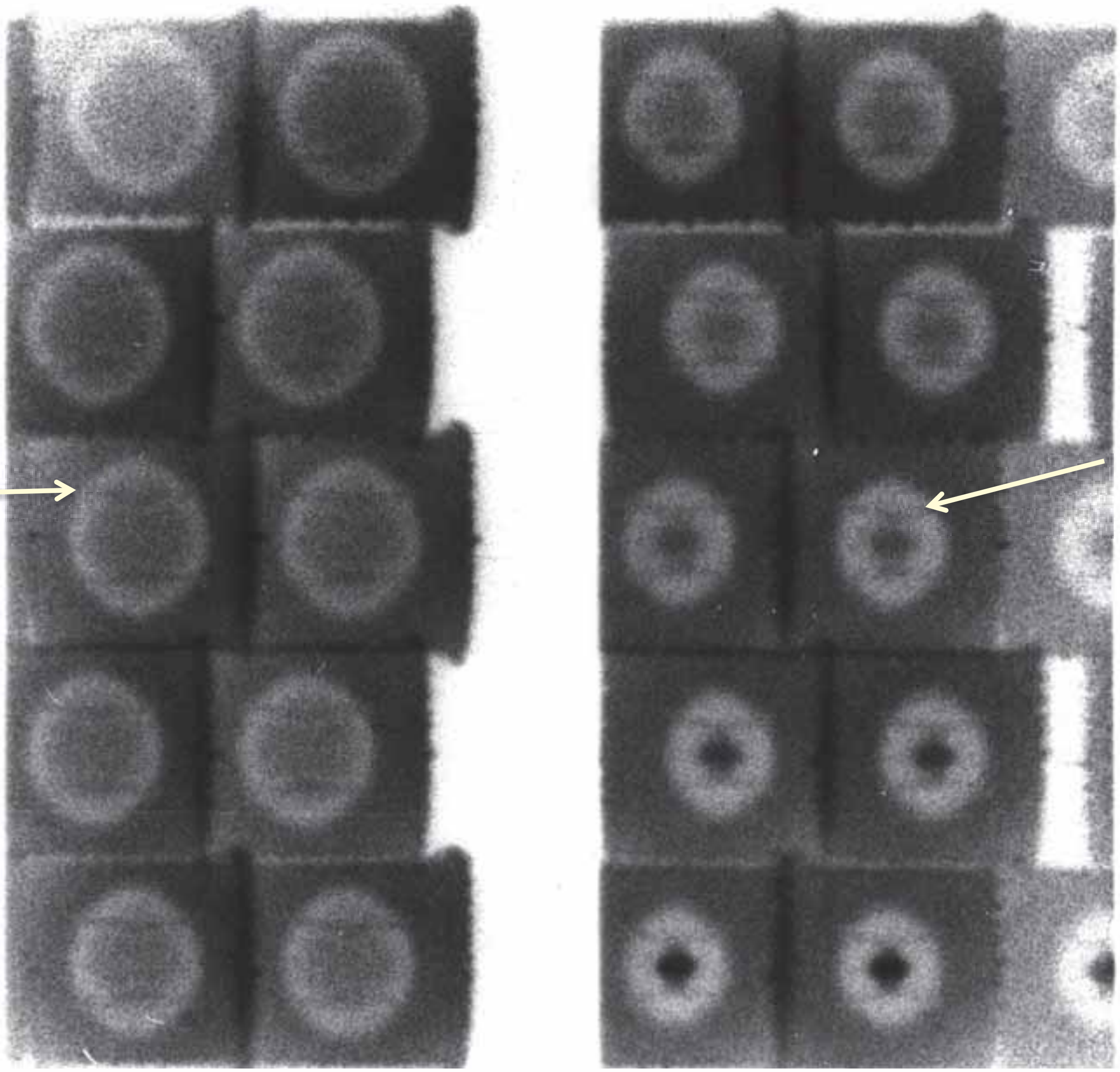
- **Simulations predict significant impact on performance**
- **Understanding and correcting this is a focus of ongoing experiments**
- **Experiments include longer hohlraums, and new hohlraum designs**

Preliminary analysis
Compton radiograph THD N121005



120 µm

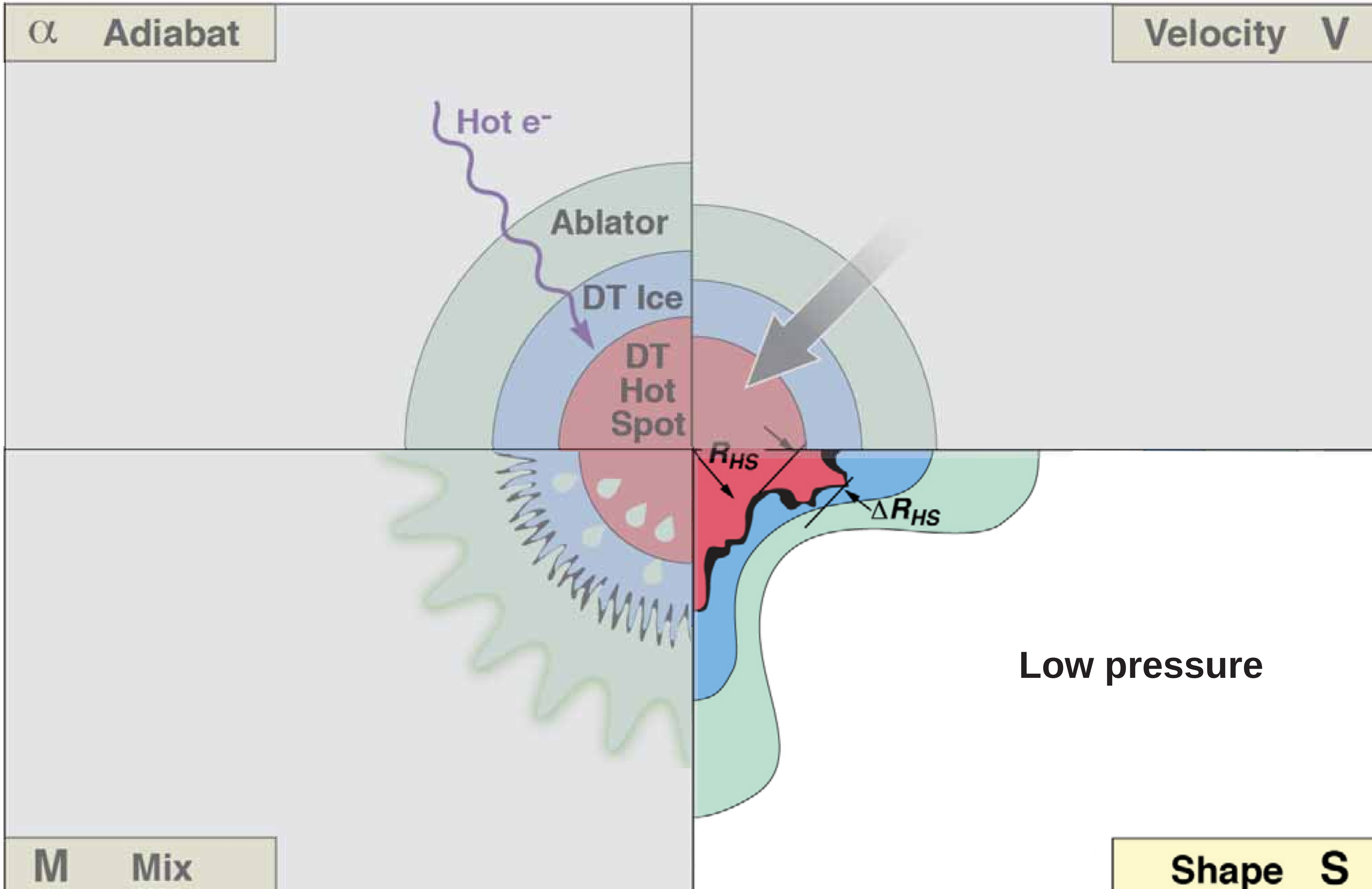
Current experiments continue to study low mode shape and ablator hydro (N121202)



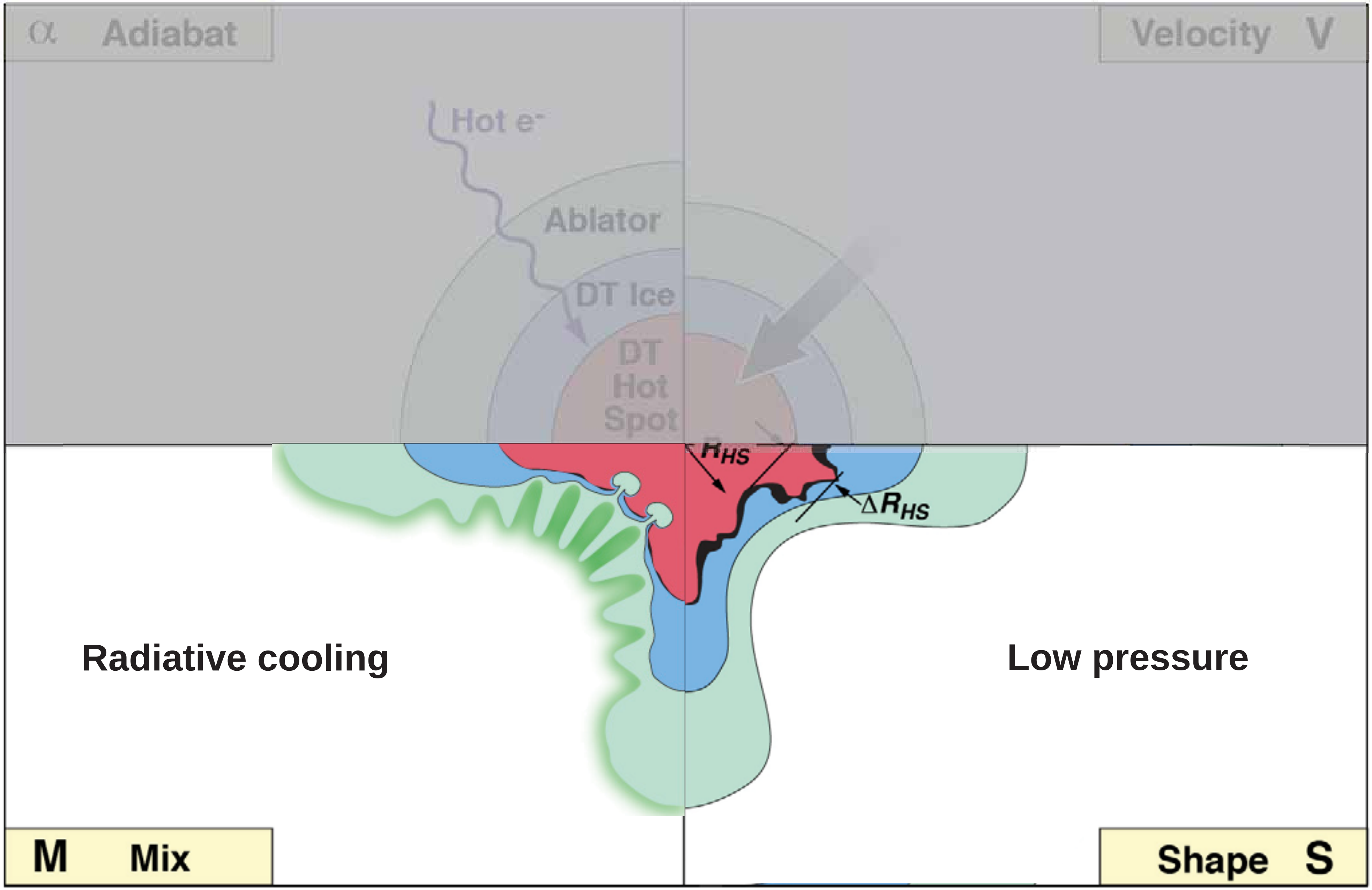
P4 shape repeated

Tent feature?

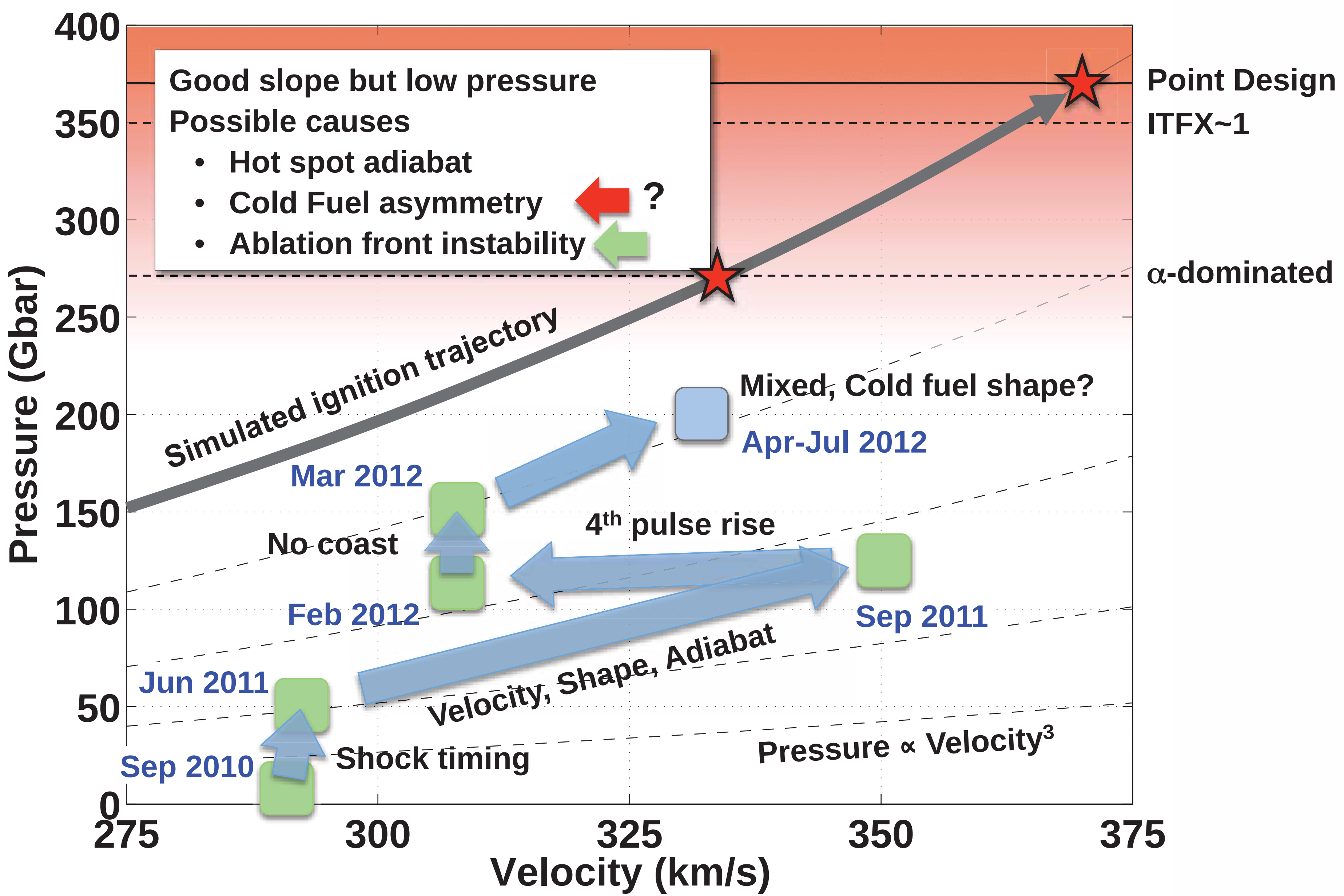
Low mode asymmetry leads to thin spots in the shell and results in low pressure and large ρR variations –



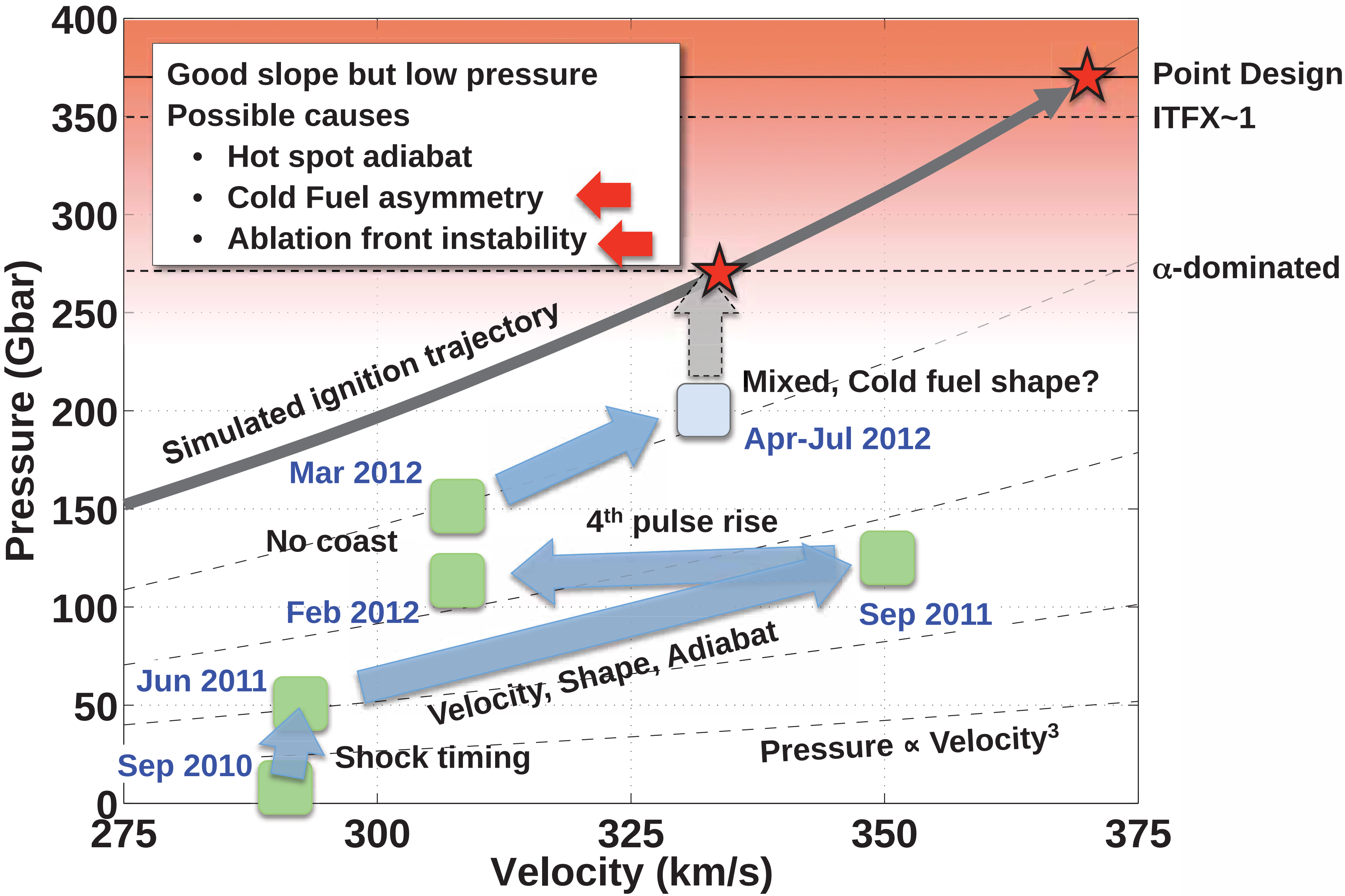
Thin spots may allow mix to penetrate more easily



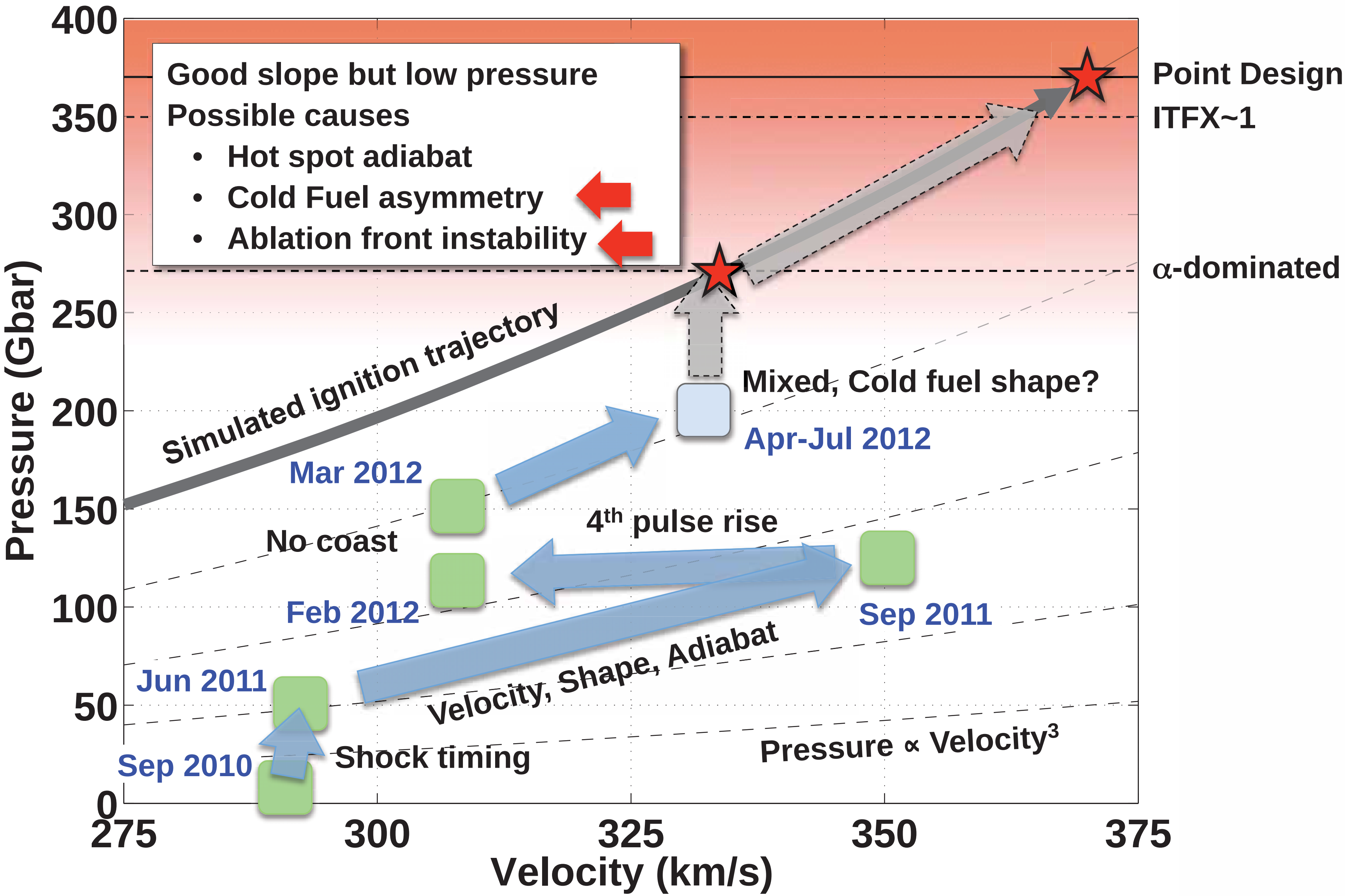
Increasing velocity increased pressure, but also increased mix variability



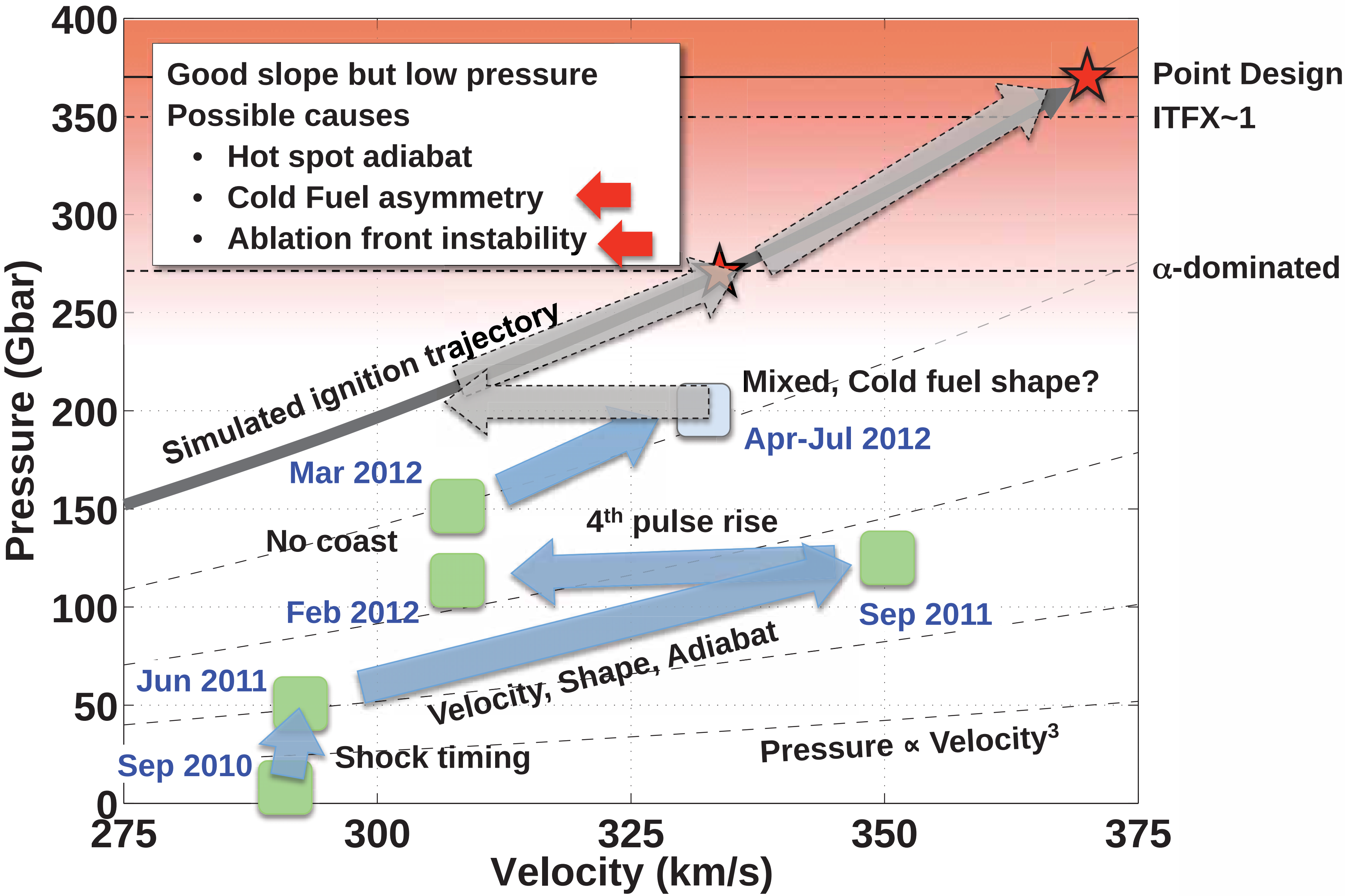
Current experiments are focused on understanding and controlling asymmetry – goal ~ 200 Gbar



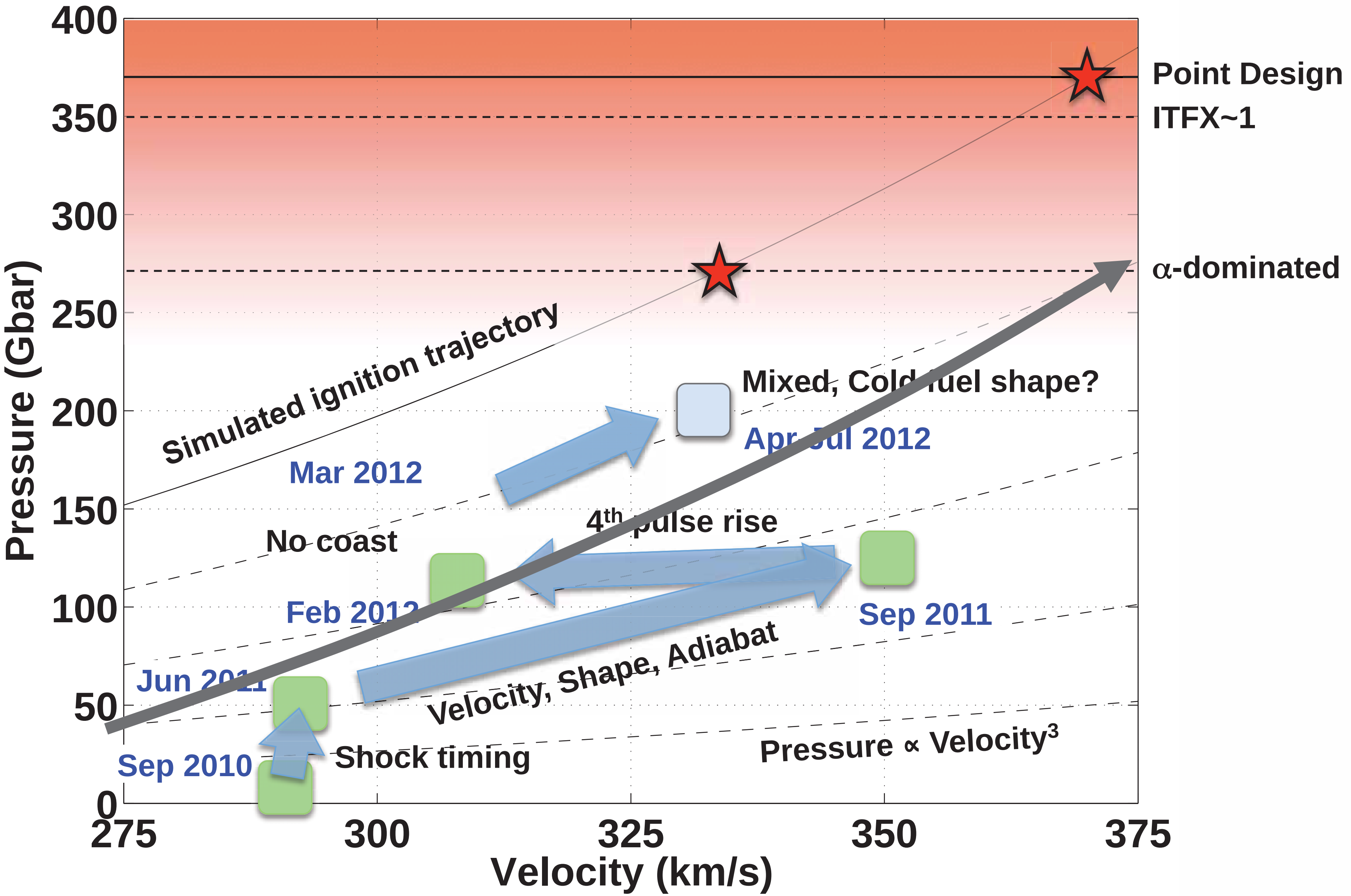
Current experiments are focused on understanding and controlling asymmetry – goal ~ 200 Gbar



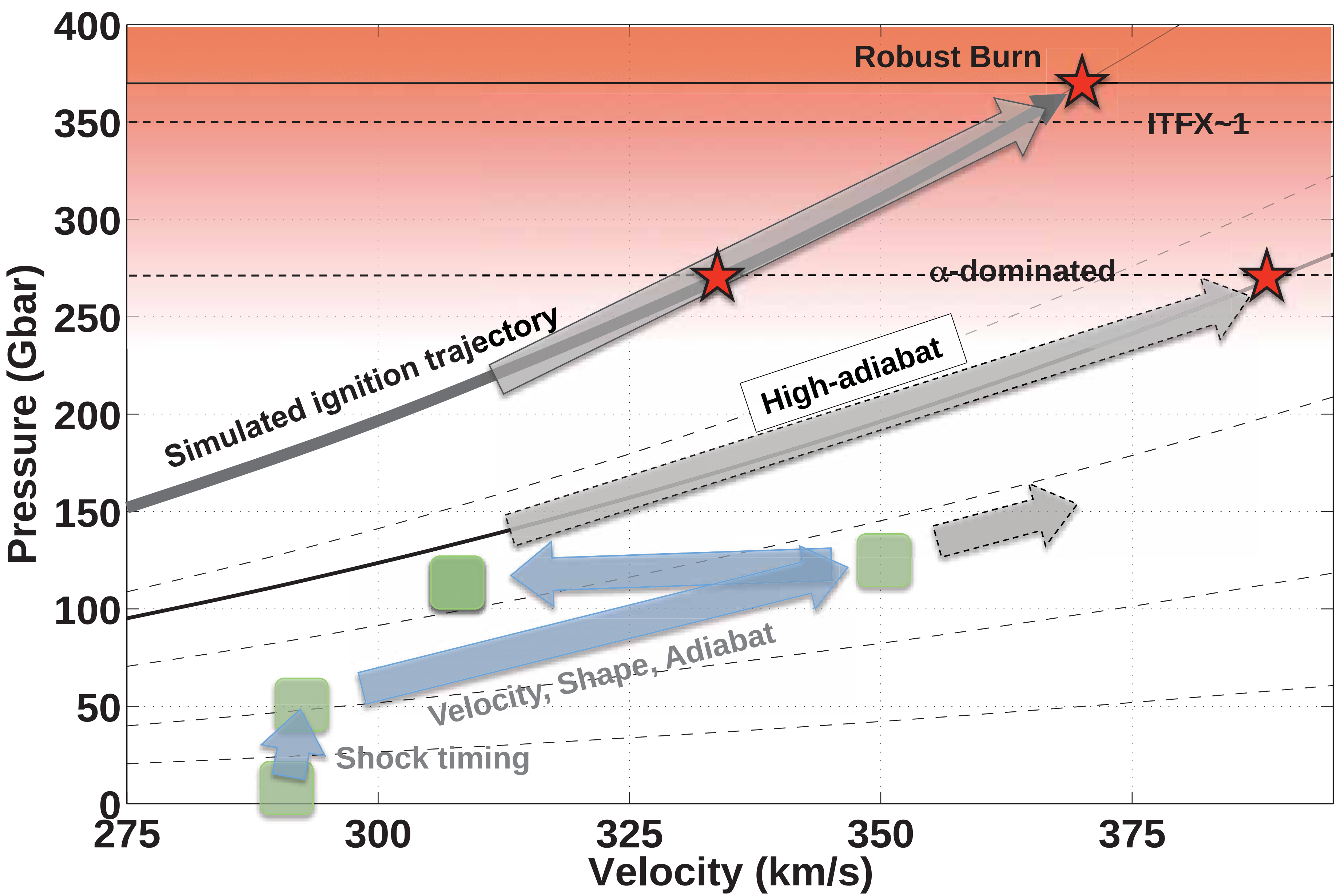
Current experiments are focused on understanding and controlling asymmetry – goal ~ 200 Gbar



Or some have proposed a high adiabat strategy…

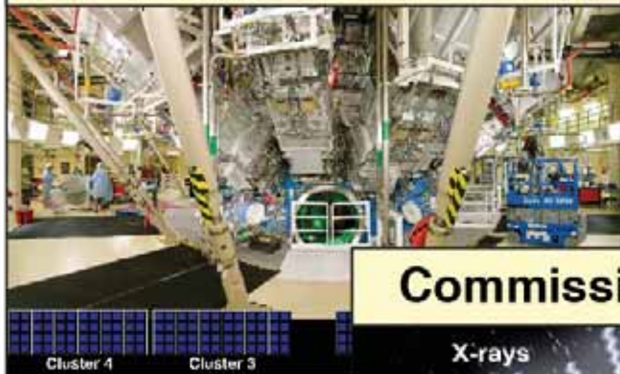


Two paths to alpha heating have been developed



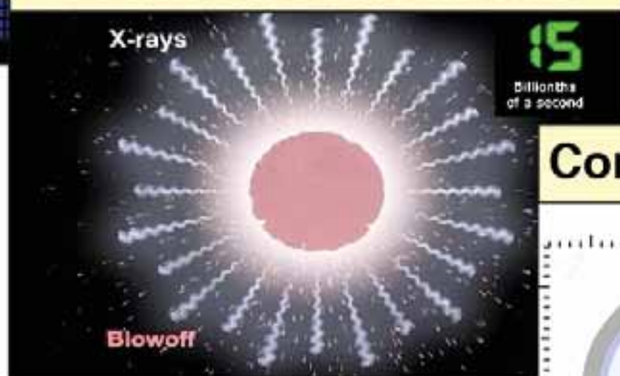
Highlights of progress towards ignition

Commission laser



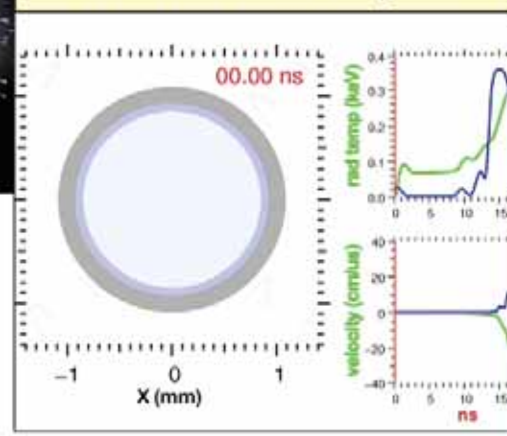
1.855 MJ
523 TW
300:1 contrast

Commission hohlraum



330 eV
~85% absorbed energy

Commission capsule



Convergence ratio ~35,
ρR ~1.3 gm/cm^2 (85% of requirement)
$V_{implosion}$ ~350 km/sec

Pressure ~150 GBar

Y~9e14

Commission layered target implosions

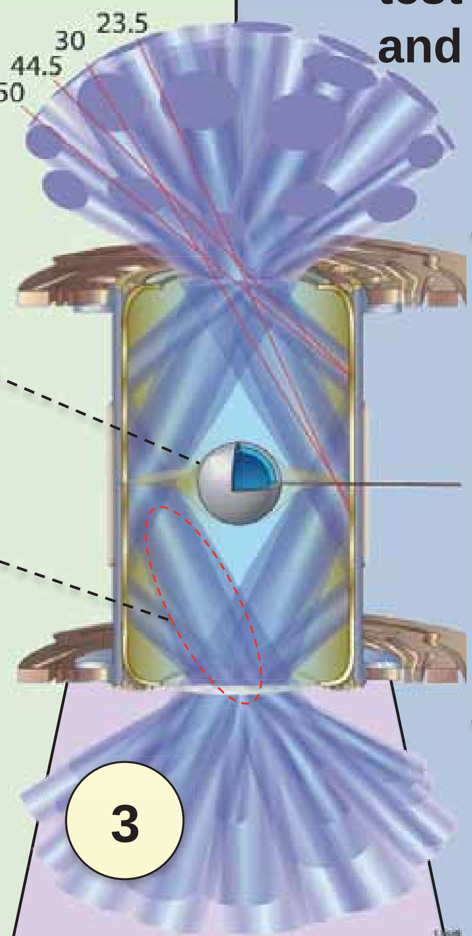
Indirect drive ignition path forward has three elements

1 Focused experiments:

understand key aspects of ignition target behavior, improve predictive capability

- Capsule physics
- Hohlraum physics
- Fundamental physics

(e.g. EOS, opacity, transport)



2 Integrated implosions:

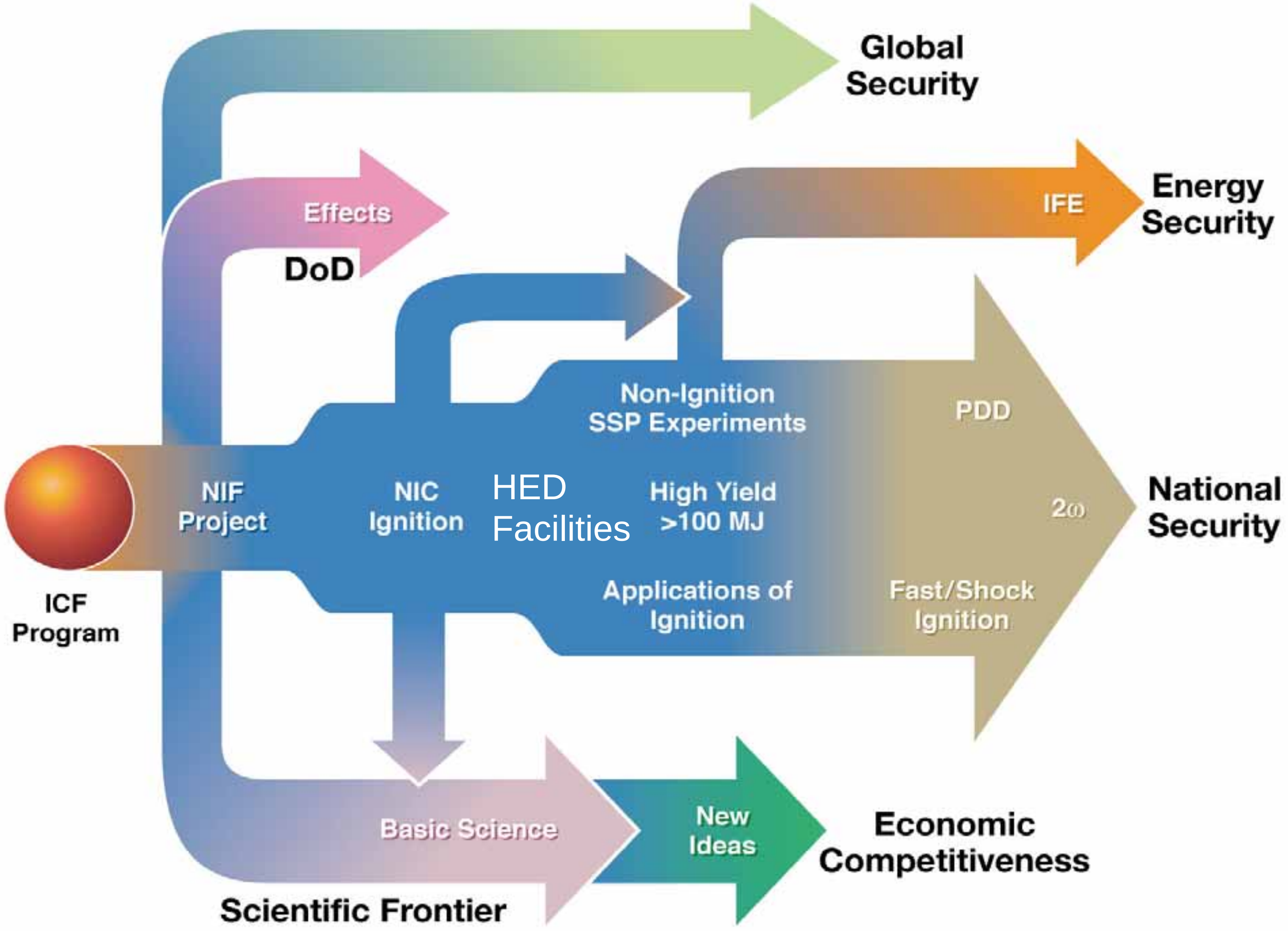
test new understanding, designs, and models in integrated implosion

- Improvements to the point design
- Lower convergence, more 1D implosion
- New hohlraum geometries, and alternate ablators

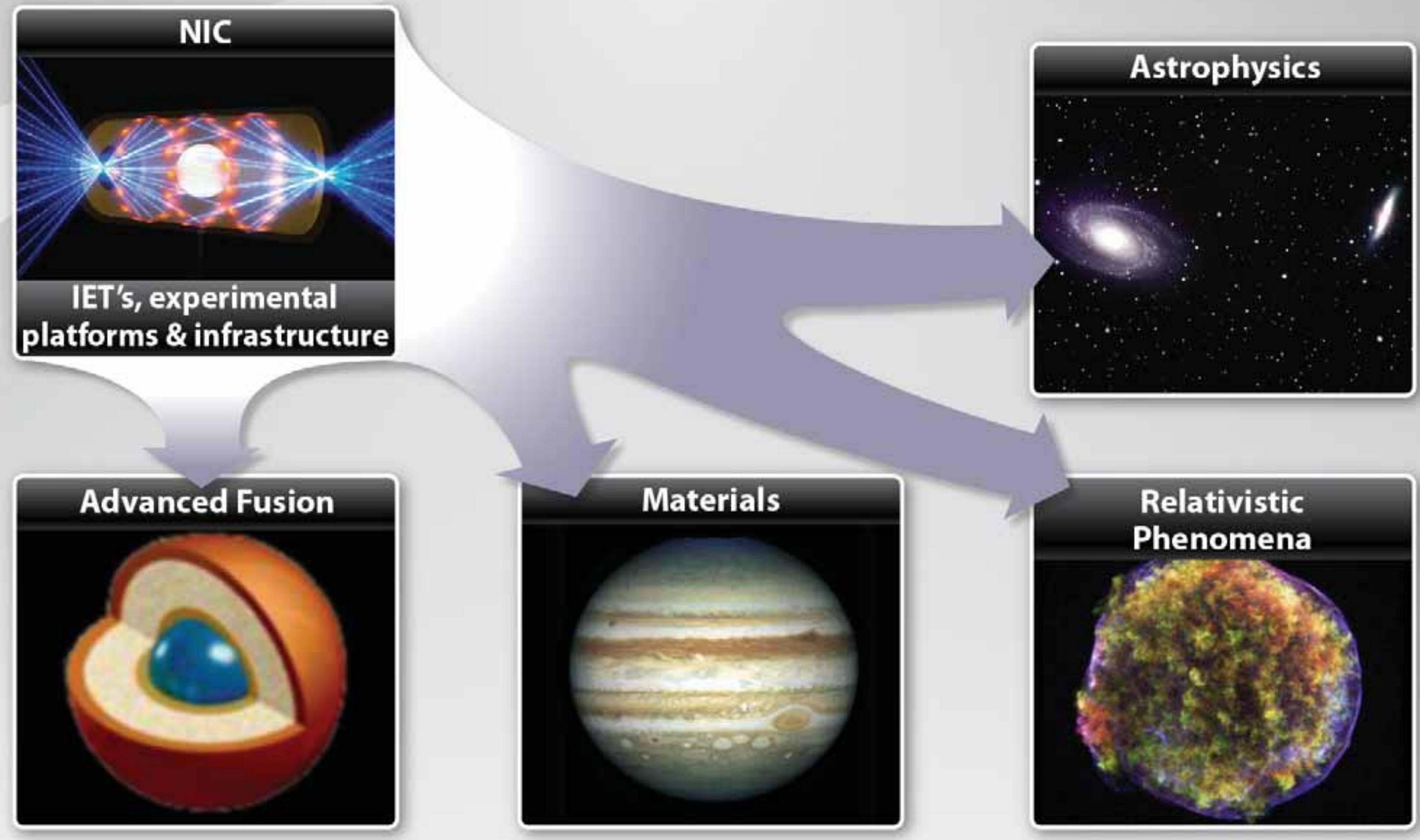
3 Alternate X-ray drive concepts

The NIC team has made strong progress towards ignition, with yields within a factor of 5-6 of that required to initiate alpha dominated burn

- Key physics achievements
  - Hohlraum T_r's in excess of the 300 eV goal with hot spot symmetry and shock timing near ignition specs
  - Main fuel ρR as high as 85% of the ignition goal; hot spot density must be increased 2-3x for ignition
  - Implosion velocities near the point design values of 370 km/sec; mix becomes significant for thinner in-flight shell widths
  - Approximately 10-15% of fusion yield produced by alpha-heating, with more fusion energy produced than energy put into the hot spot
- Current experiments are examining low-mode asymmetry and hydrodynamic instability in further detail
- The NNSA Congressional report outlines an effective path forward for the ICF Program – LLNL supports the submitted milestones (modulo budget)

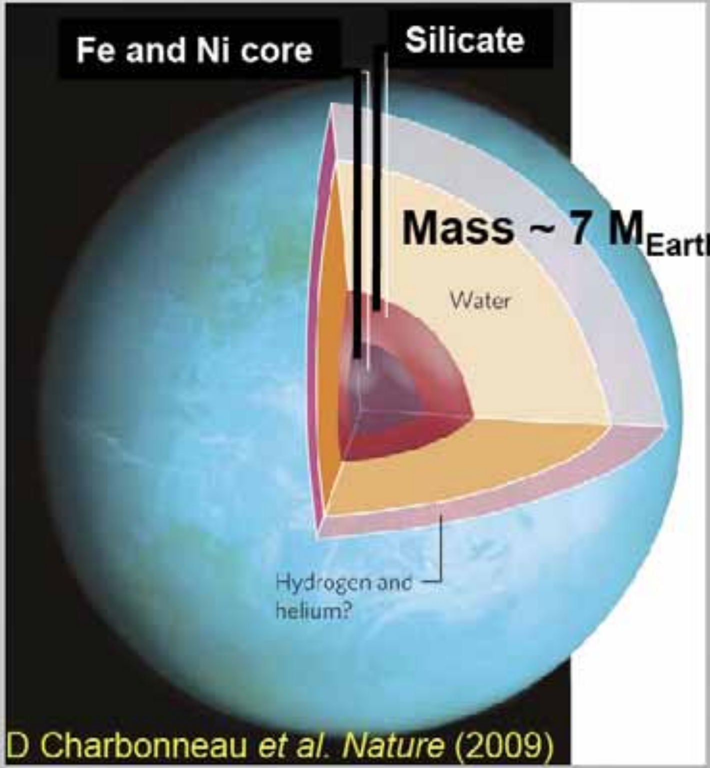

Global
Security
Effects
DoD
IFE
Energy
Security
Non-Ignition
SSP Experiments
PDD
NIF
Project
NIC
Ignition
HED
Facilities
High Yield
>100 MJ
2ω
National
Security
ICF
Program
Applications of
Ignition
Fast/Shock
Ignition
Basic Science
New
Ideas
Economic
Competitiveness
Scientific Frontier
NIF-0208-14427
14CK/cld

NIC and other recent experiments are showing the way to a rich scientific future at NIF



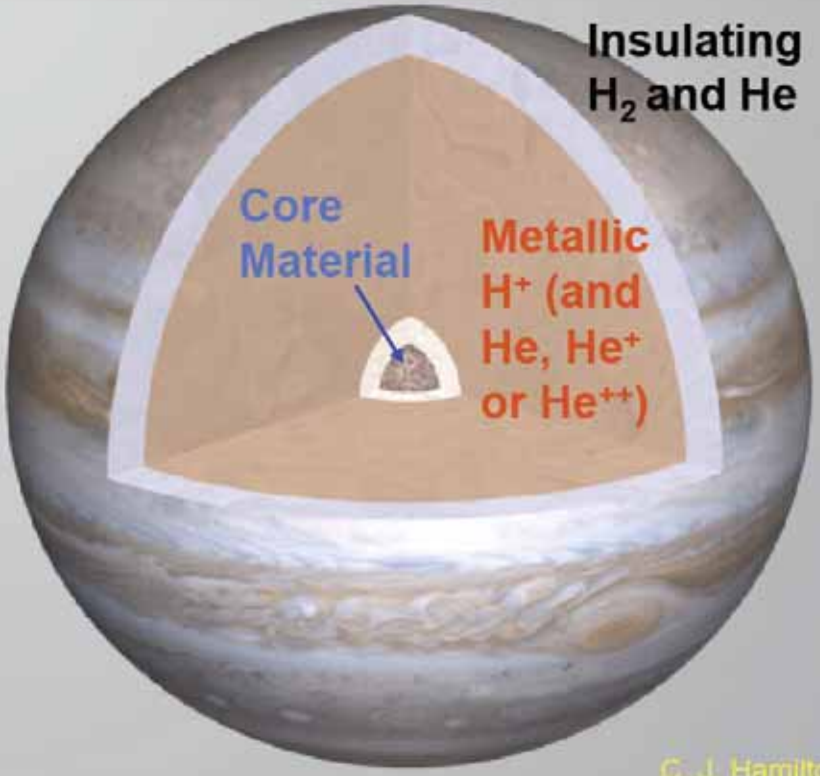
More than 1500 new planets have been discovered, many so massive they challenge current planet evolution models

Super-Earths: P_{center} ~30Mbar
GJ1214b – A Water Planet?



D Charbonneau *et al. Nature* (2009)

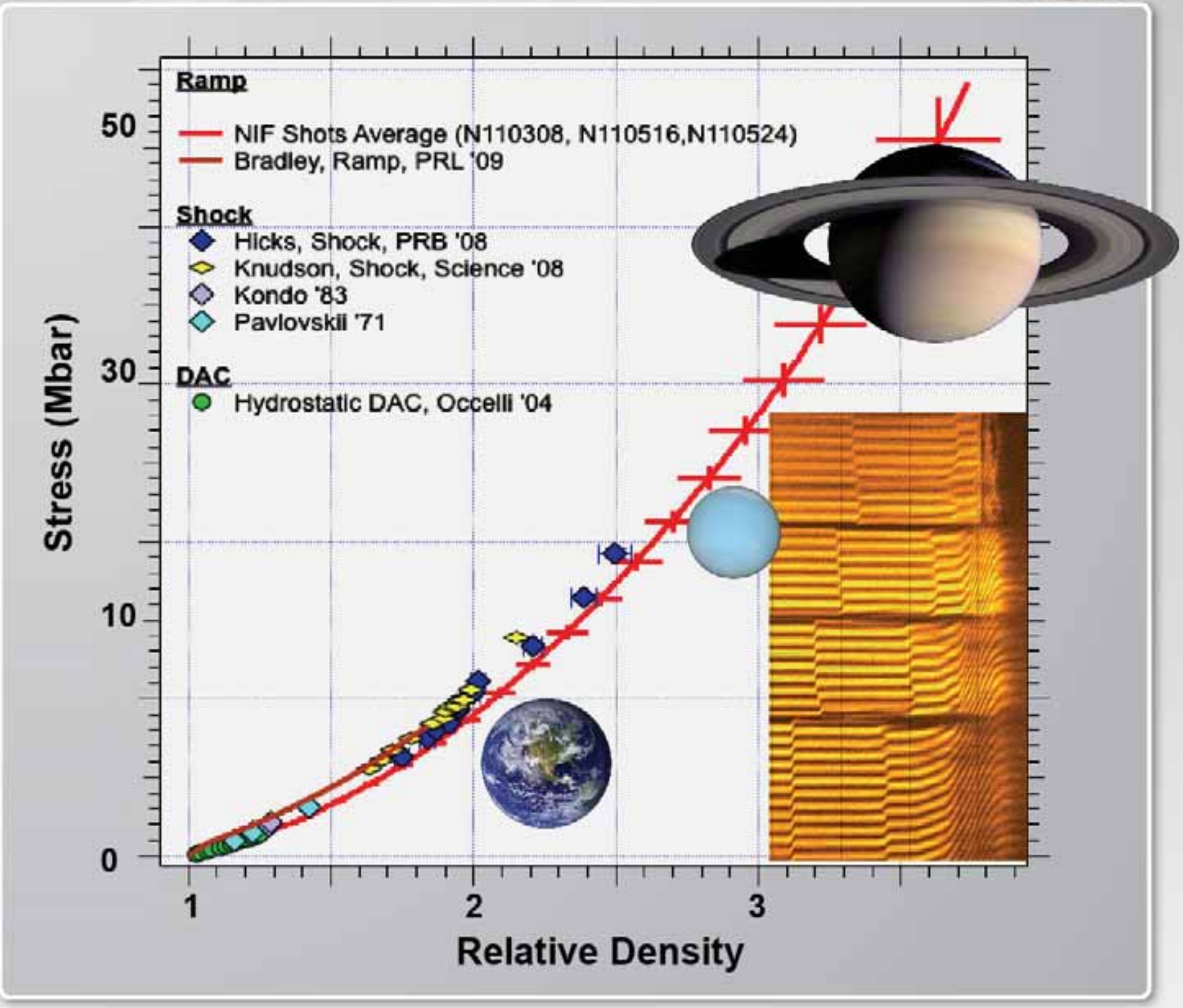
Jupiter: central pressures ~77 Mbar and temperatures ~16000 K



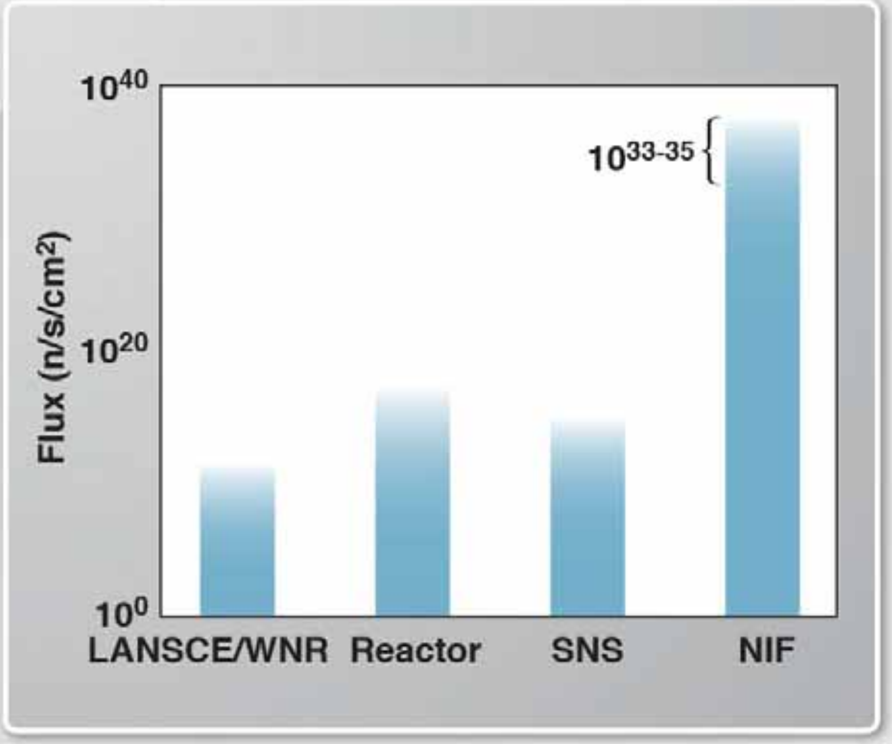
C. J. Hamilton

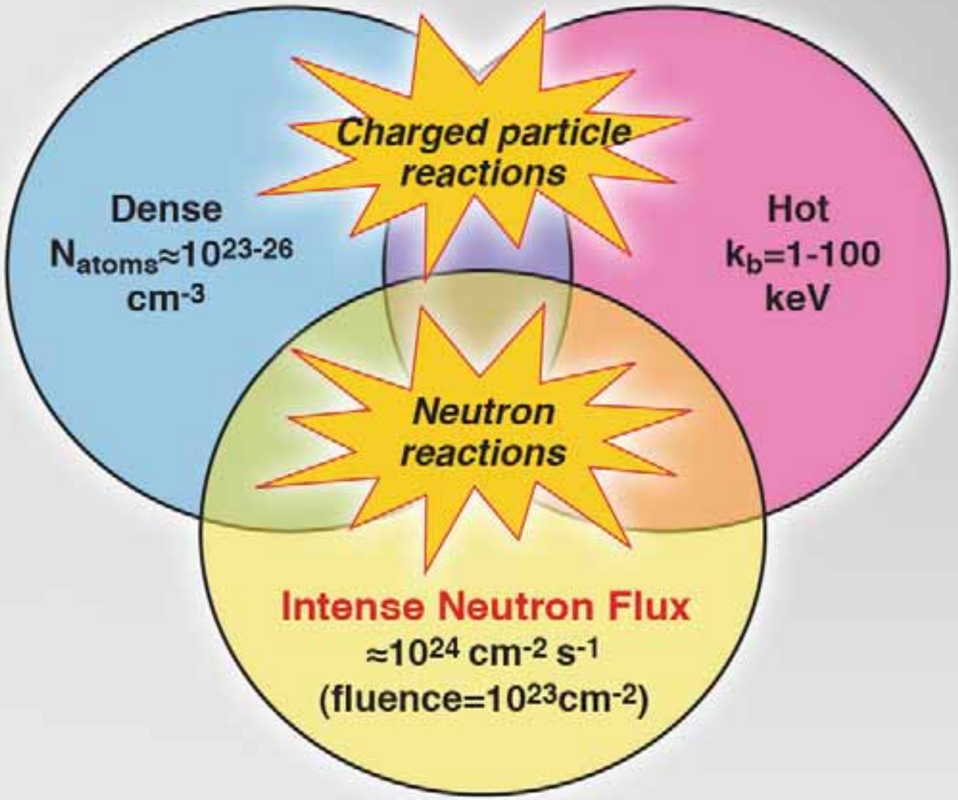
Planet evolution models depend critically on material properties at extreme pressure and compression

NIF ramp compressed diamond to > 50 Mbar recreating the most extreme conditions in our solar system



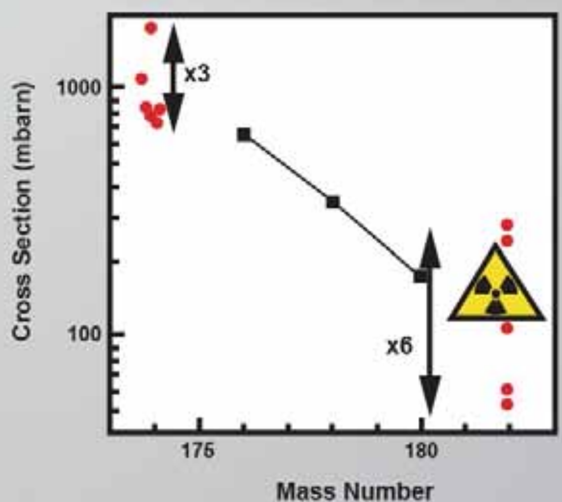
NIC diagnostics and other capabilities enable study of nuclear physics in dense plasmas at NIF





The workshops identified key areas where nuclear data were needed

Modeled (n,γ) cross sections have large uncertainties

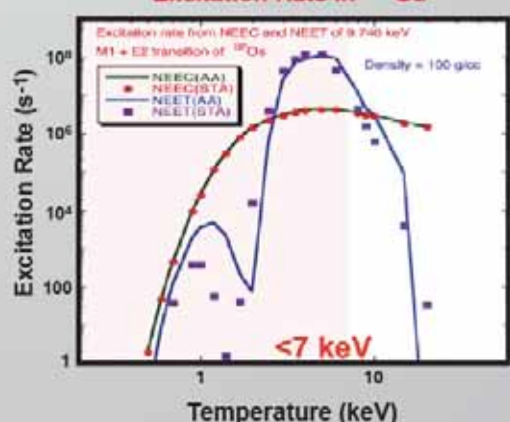


Kaeppler, Karlsruhe

Nuclear excitation by atomic processes are also hard to model accurately

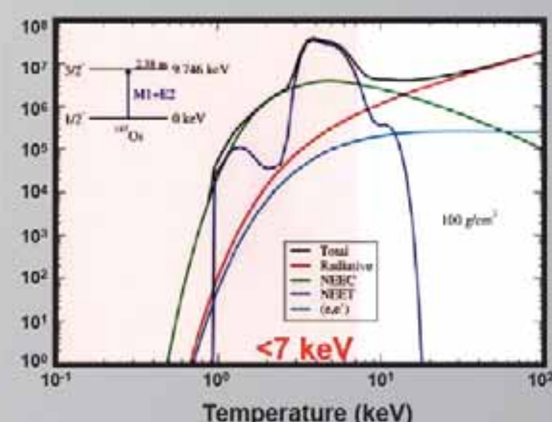
^{187}Os

Excitation Rate in ^{187}Os



NEEC or NEET > 10x Radiative, (e,e')

CEA

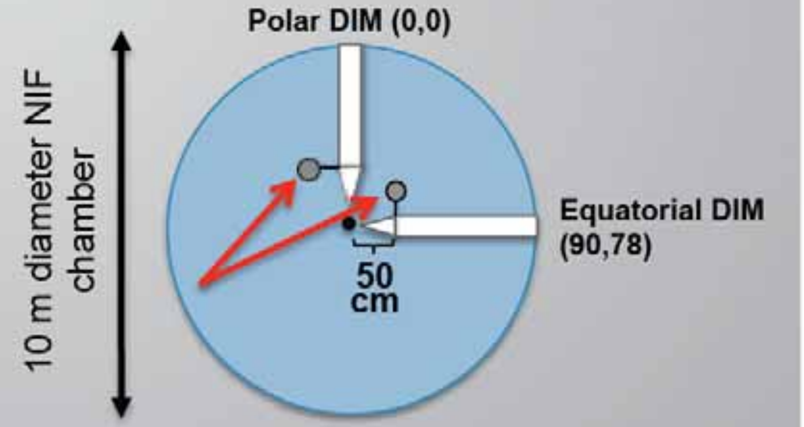


NEEC or NEET > 10x Radiative, (e,e')

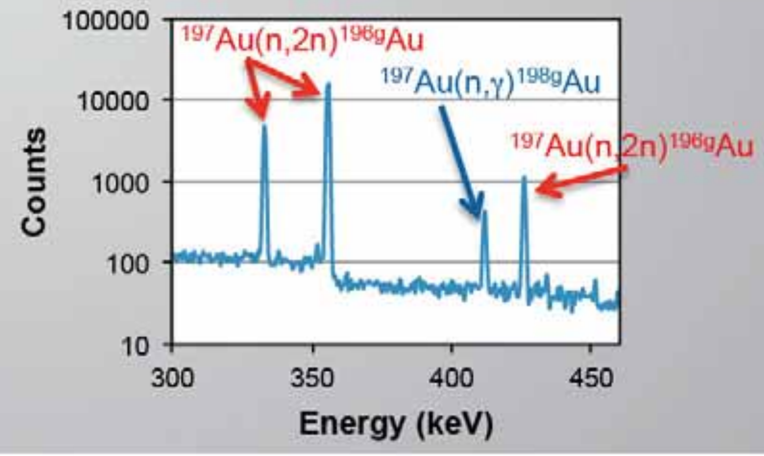
Calculations differ as much as a factor of 10

NIF provides a unique environment for measuring neutron induced cross sections

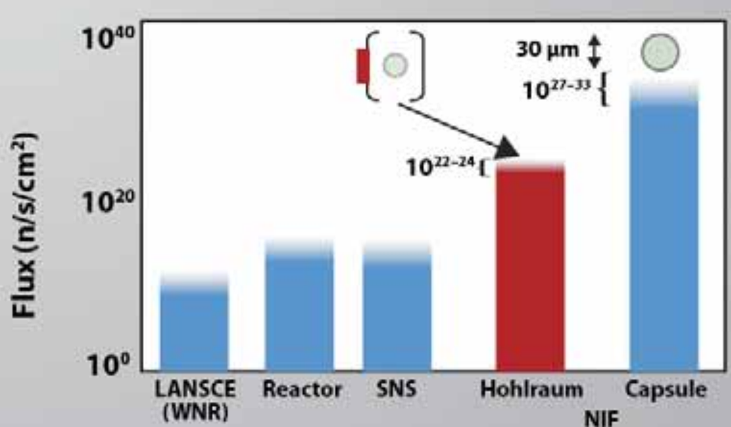
Geometry for collection of Radioactive Debris



First Measurements of activated gold from hohlraum



Neutron Flux in NIF environment

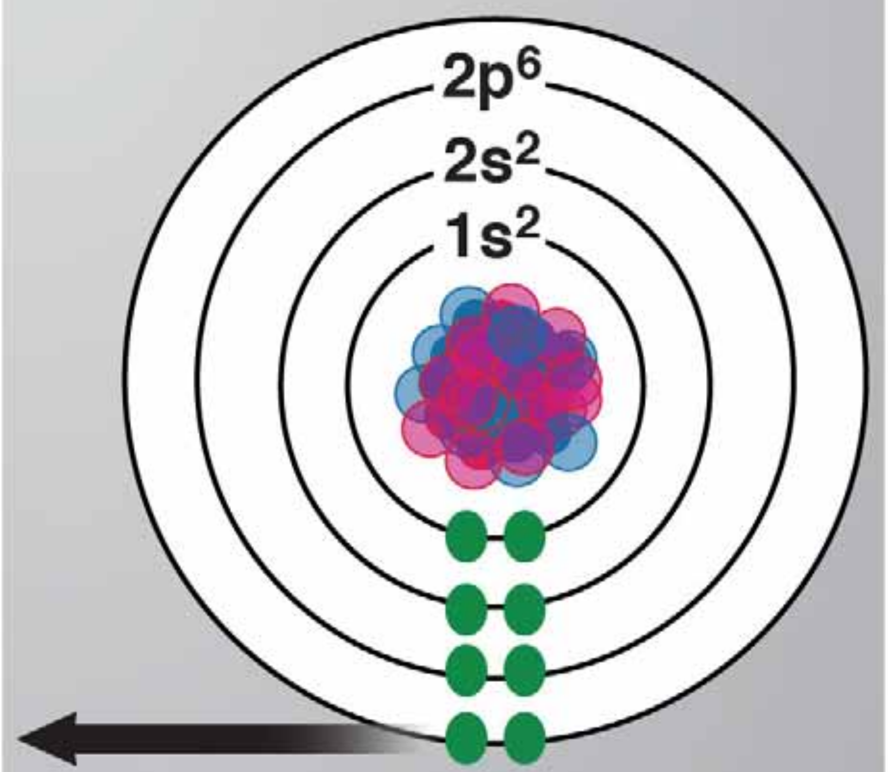


Environment at NIF is unique

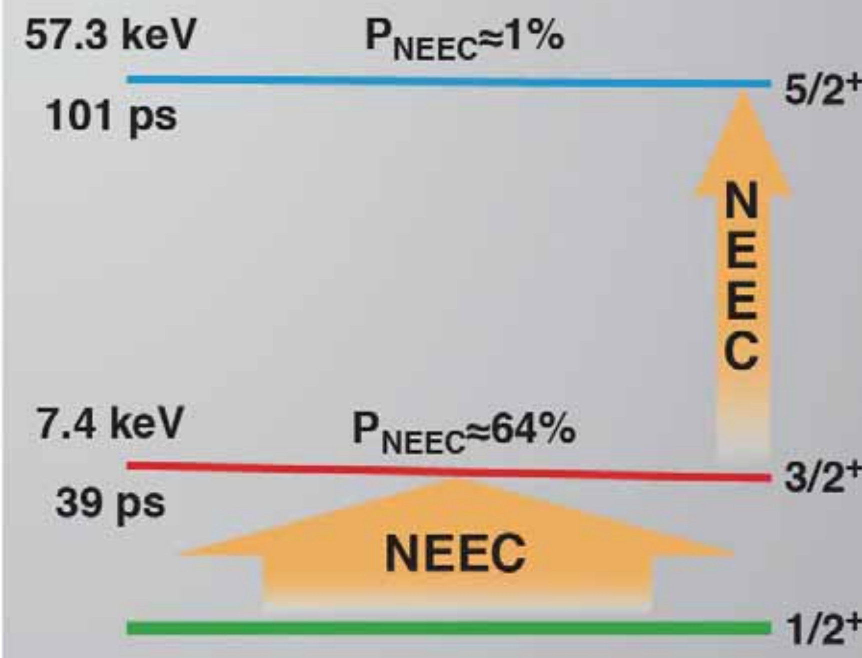
- Low energy neutron spectra determined by temperature of cold fuel (~200 eV)
- "Room Return" is not an issue for NIF
- Plasma effects are observed in capsule

Nuclear Excitation by Electron Capture (NEEC) couples high-Z nuclei to the plasma environment

Low-lying nuclear states in high-Z nuclei decay almost entirely via internal conversion



The high e⁻ flux in some plasmas can populate these states via the reverse mechanism



Resonant atomic transitions can also excite the nucleus (NEET)

Infrastructure to support NIF as a user facility is being put in place

Facility management and governance

Proposal submission and evaluation process

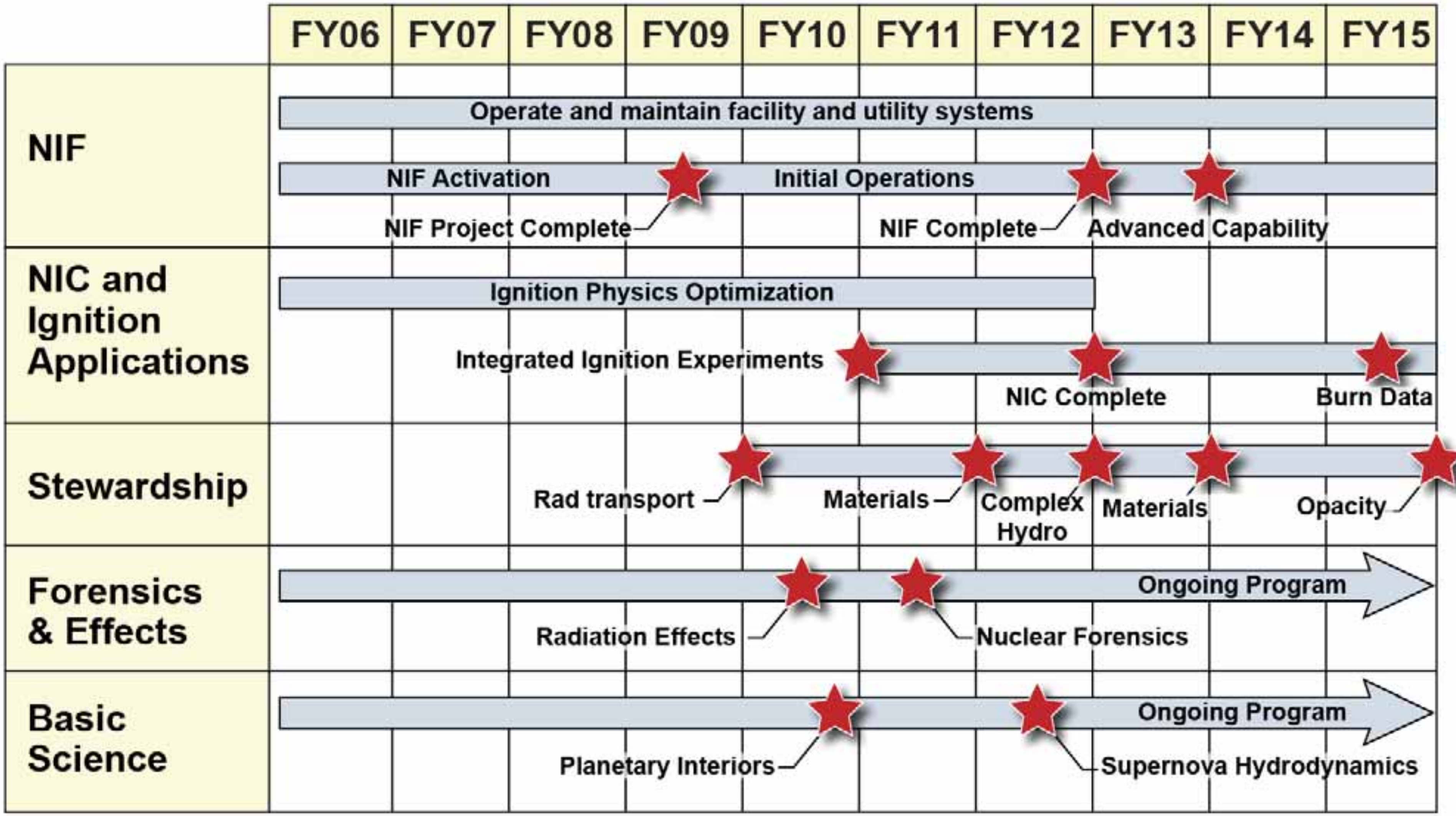
HED campus

Data access capability

Experimental support/liaison scientists

Post-experiment support

NIF is a unique experimental platform for multiple missions



Steve has made major research contributions in a number of areas; his work continues to influence fundamental research today

- Strong, early advocate for high-performance computing

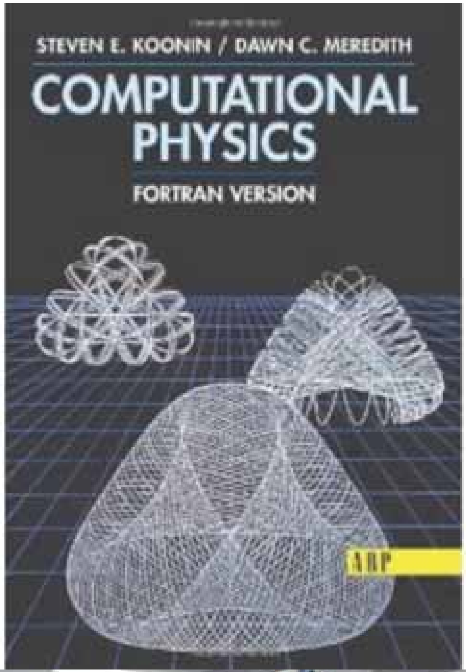
- Got to the heart of nuclei, microscopically and computationally
  - Time-dependent Hartree-Fock
  - Monte Carlo approaches to the nuclear many-body problem
  - Statistical theory of multi-step compound and direct reactions
  - Using particle-particle correlations to image heavy-Ion collisions

- Involved in compelling physics mysteries over the last few decades
  - WIMPs and search for Axions
  - Solar neutrinos: Fate of ^{7}Be in the Sun
  - Heavy element nucleosynthesis: $^{12}C(\alpha,\gamma)^{16}O$ reaction in astrophysics

- Climate and other topics
  - Quantitative understanding of the Earth's albedo by measuring Earthshine on the Moon
  - Fusion issues: electron screening, sub-barrier fusion
  - Fission and nuclear fragmentation

Steve's leadership in advancing computational simulation has been important for ICF

- Recognized high-performance computing as critical to the future of theoretical physics by 1990
  - Led strong research efforts at Caltech exploiting HPC for scientific discovery
  - Influenced a generation of theoretical physicists
- Routine 2D and advanced 3D calculations for NIF ignition are enabled by decades of work on advanced computing



Influence on nuclear physics is still being felt

- Nuclear reactions
  - Statistical theory of multi-step compound and direct reactions – Feshbach, Kerman, and Koonin

ANNALS OF PHYSICS 125, 429-476 (1980)

The Statistical Theory of Multi-Step Compound and Direct Reactions*

HERMAN FESHBACH,[†] ARTHUR KERMAN,[†] AND STEVEN KOONIN[‡]

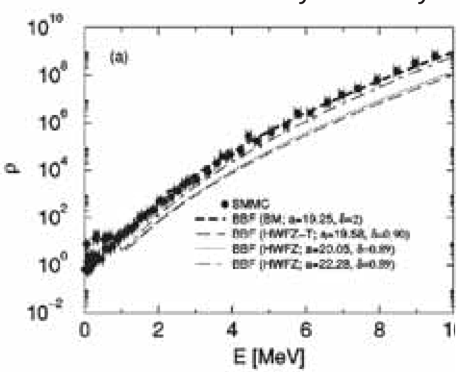
[†]*Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139; and*
[‡]*California Institute of Technology, Pasadena, California 91109*

Received June 19, 1979

Important early work devoted to understanding nuclear reactions, especially (n,X), which is central to most LLNL programs ~ 600 citations

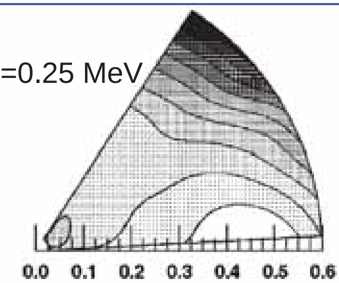
- Solutions to many-fermionic systems
  - Nearly a decade of research arose from a novel Monte Carlo approach to treat systems inaccessible by traditional methods

Calculated level density for ^{154}Dy



Fully microscopic calculations for the properties of rare-earth nuclei N ~ 10^{20} White, Koonin, and Dean PRC 61, 034303 (2000)

T=0.25 MeV



Calculated free-energy for ^{144}Ba

PHYSICAL REVIEW C VOLUME 48, NUMBER 4 OCTOBER 1993

Monte Carlo evaluation of path integrals for the nuclear shell model

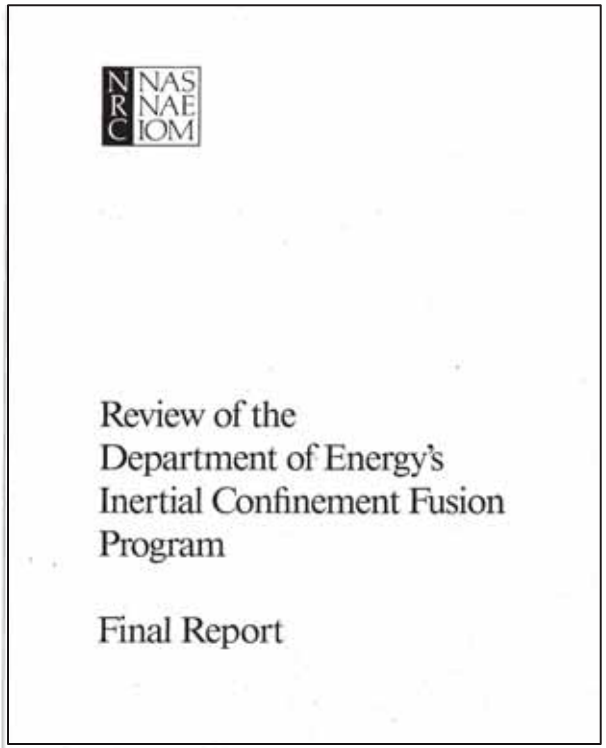
G. H. Lang, C. W. Johnson,* S. E. Koonin, and W. E. Ormand
W. K. Kellogg Radiation Laboratory, 106-38, California Institute of Technology, Pasadena, California 91125
(Received 12 May 1993)

ELSEVIER Physics Reports 278 (1997) 1-77 PHYSICS REPORTS

Shell model Monte Carlo methods

S.E. Koonin, D.J. Dean[1], K. Langanke
W.K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena CA 91125, USA

Steve chaired 2 major NAS reviews of ICF: the 1990 review established strategic direction for the US ICF Program and set the stage for NIF



NRC NAS NAE IOM

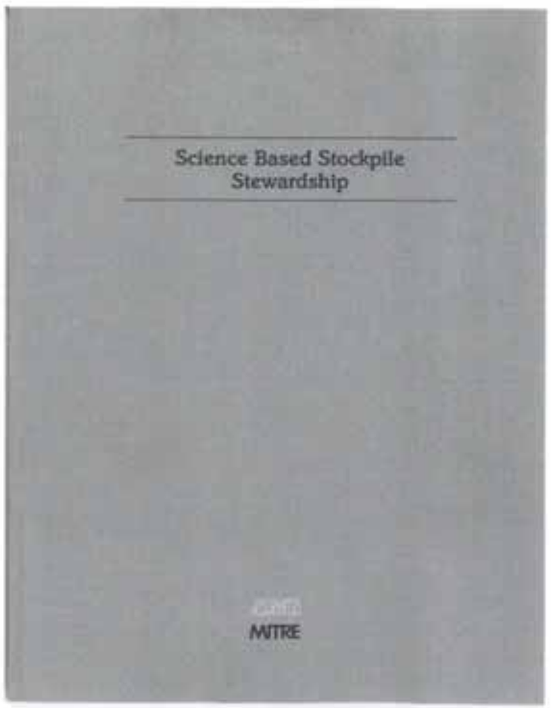
Review of the Department of Energy's Inertial Confinement Fusion Program

Final Report

Members: S. Koonin (Chair); G. Carrier, R. Christy, R. Conn, R. Davidson, J. Dawson, B. DeMaria, P. Doty W. Happer, Jr., G. Kulcinski, C. Longmire, J. Powell, M. Rosenbluth, J. Ruina, R. Sproull, M. Tigner, R. Wagner

- Established ignition with a few- MJ driver as the major goal of the US ICF Program (vs. previous "LMF" proposal)
- Defined program strategies and activities key to advancing the ICF Program towards ignition
  - Nova Technical Contract to validate high T_r approach to ignition
  - Beamlet
  - Omega upgrade
  - Termination of Centurion/Halite
  - Light ion fusion metrics
  - "No" to KrF upgrade and further development of HIF
  - Establishment of federal advisory committee (ICFAC) to review program progress

Steve played a significant role in the 1994 JASON study on stockpile stewardship



- "A strong SBSS program, such as we recommend in this report, is an essential component for the U.S. to maintain confidence in the performance of a safe and reliable nuclear deterrent under a comprehensive test ban."
- "Such an SBSS program can be consistent with the broad non-proliferation goals of the United States. This requires managing it with restraint and openness, including international scientific collaboration and cooperation where appropriate…"
- "The NIF is without question the most scientifically valuable of the programs proposed for the SBSS, particularly in regard to ICF research and a "proof of principle" for ignition, but also more generally for fundamental science."

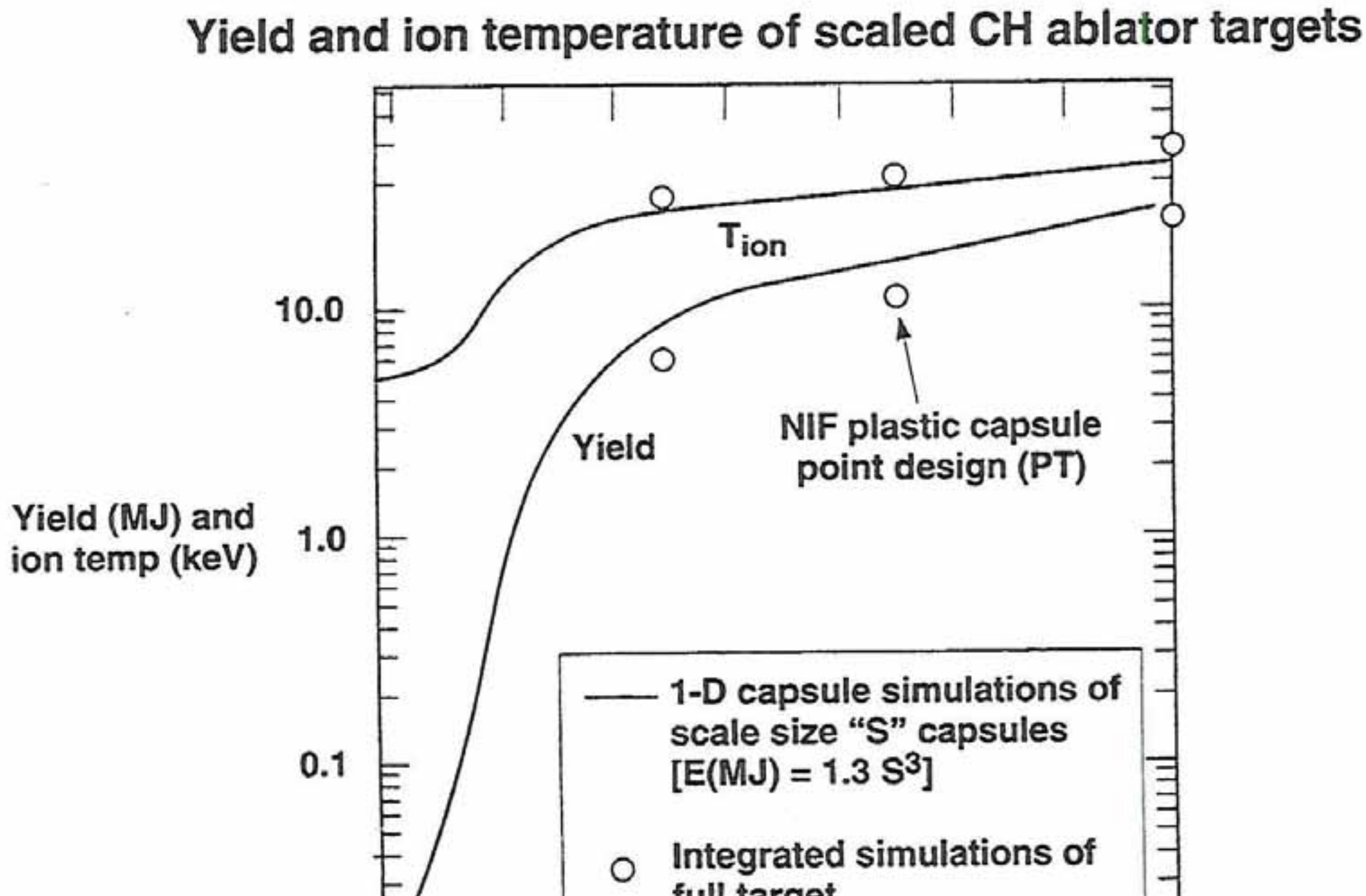
Members: S. Drell (Chair); C. Callan, M. Cornwall, D. Eardley, J. Goodman, D. Hammer, W. Happer, J. Kimble, S. Koonin, R. LeLevier, C. Max, W. Panofsky, M. Rosenbluth, J. Sullivan, P. Weinberger, H. York, F. Zachariasen

Steve chaired 2 major NAS reviews of ICF: the 1997 review examined NIF scientific and technological readiness and the value of NIF to the SSP

Members: S. Koonin (Chair); D. Arnett, R. Byer, R. Conn, R. Davidson, A. DeMaria, P. Dimotakis, J. Dongarra, R. Falcone, H. Grunder, H. Kendall, A. Kerman, S. Orszag, M. Rosenbluth, G. Trilling, P. VanDevender

- **"In the collective judgment of the committee, the NIF should stimulate the scientific imagination and attract excellent scientists and engineers more than any other proposed element of SBSS."**
  - **"The steady scientific and technological progress in ICF during the 6 years since the last NRC review, the plausibility of ignition estimates based on the experimental and modeling results and the capabilities in hand, and the flexibility of the proposed facility all support the committee's finding that the NIF project is technologically and scientifically ready to proceed as planned with reasonable confidence in the attainment of its objectives."**
  - **"Ignition appears likely but not guaranteed."**

The 1997 NAS review also defined $E_{fusion} > E_{laser}$ as the condition for achievement of NIF ignition



"This curve leads to the operative definition of ignition adopted by the committee: *gain greater than unity.*"

Yield vs. laser energy (from 1997 NRC ICF Review report, p. 10)

More recently, Steve has led quarterly reviews of NIC which have been highly effective and influential

NIF Dedication
May 2009

- "Surprises encountered on the path to ignition make it impossible to predict confidently the rate of progress on those issues of greatest concern to the NIC and so ignition by the end of FY2012 is not ensured." (Nov. 2011 report)

The May 2012 ignition workshop arising from these and other reviews has been very successful in enhancing involvement of the broader scientific community in NIF ignition

NIF will be a premier international center for experimental science

CERN

Chandra x-ray observatory

APS

SLAC


NIF