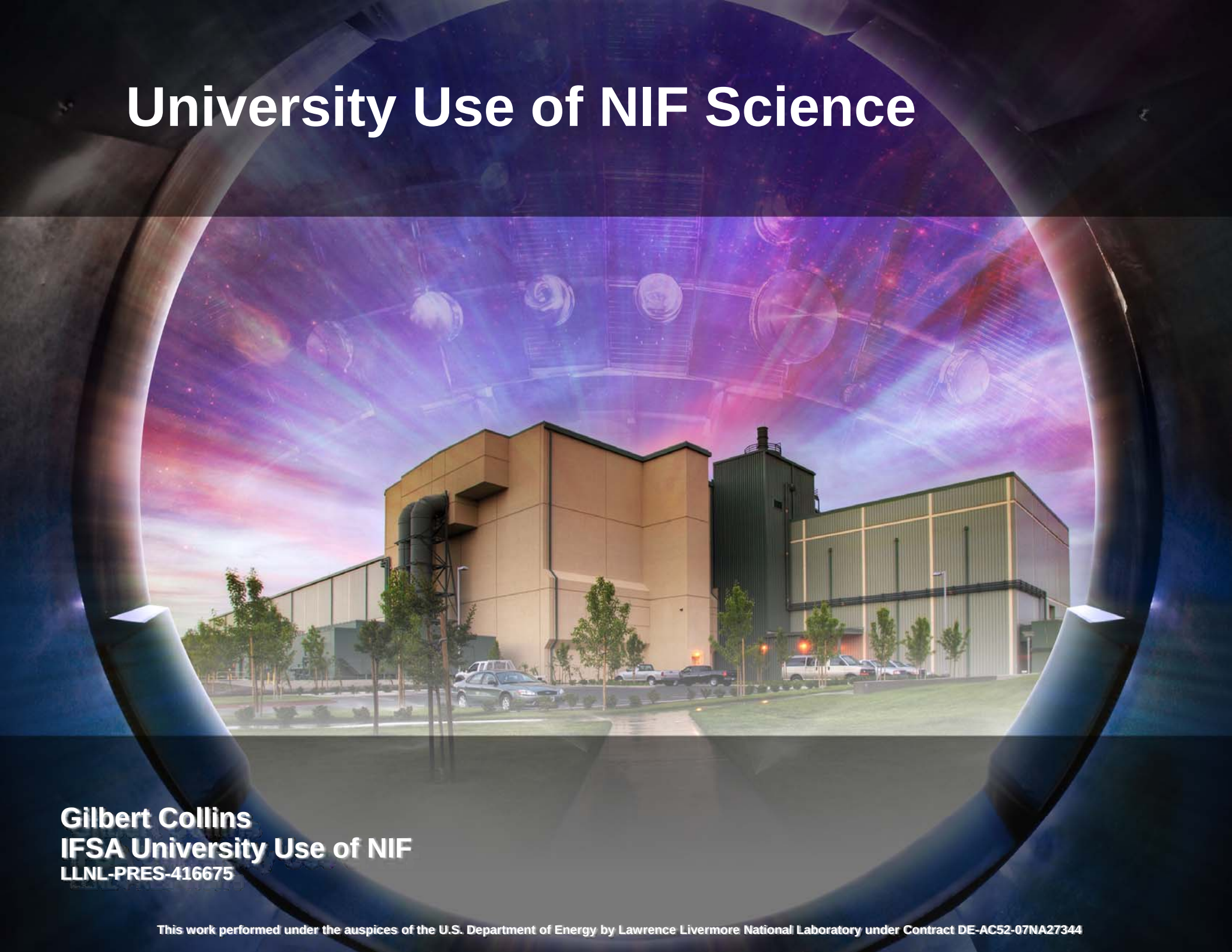
University Use of NIF Science

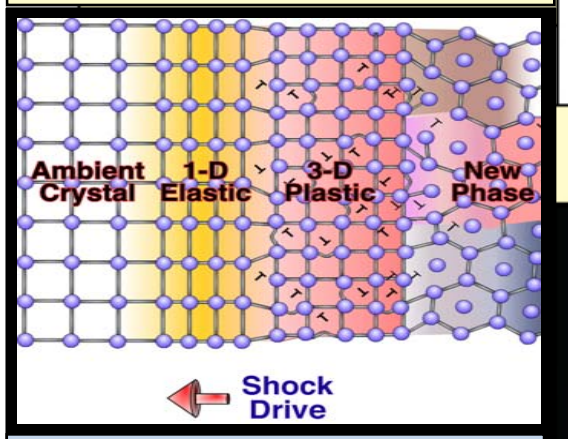


Gilbert Collins
IFSA University Use of NIF
LLNL-PRES-416675

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

High-energy density conditions

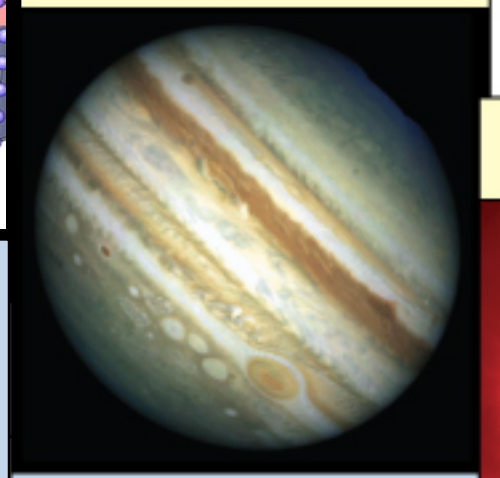
dynamic compression



MBar compression
P∆V ~ eV, Bonds change

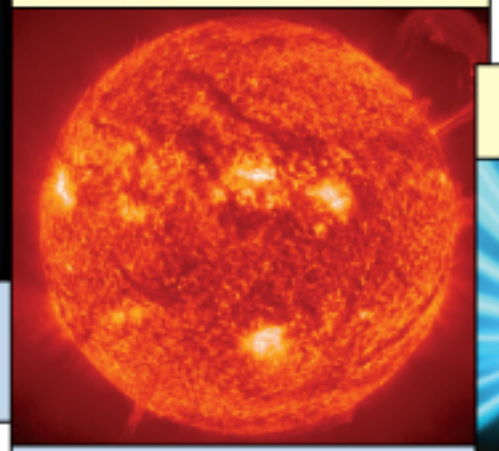
GBar compression
P∆V ~ KeV, Atoms change

Jupiter



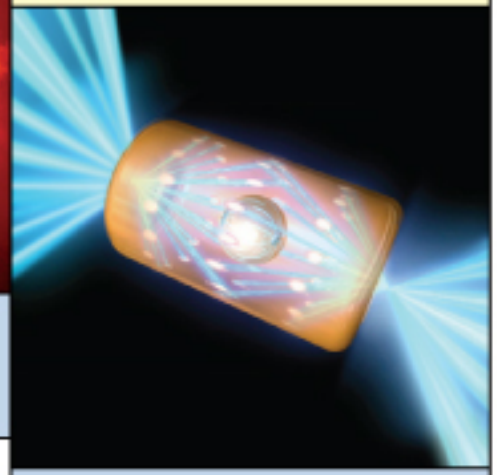
P ~ 80 MBar (core)

Sun



P ~ 3×10^5 MBar (core)

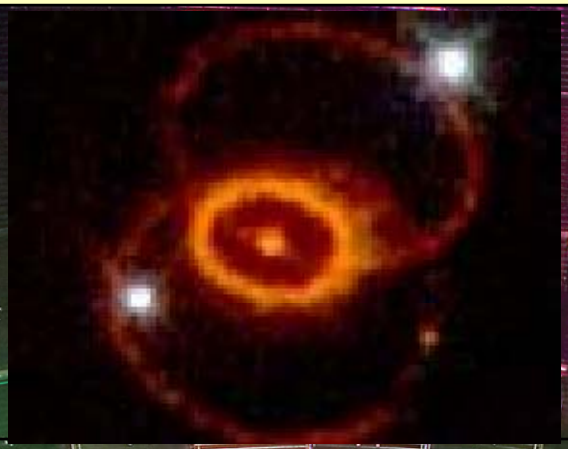
Fusion Target



P ~ 2×10^6 MBar (peak burn)

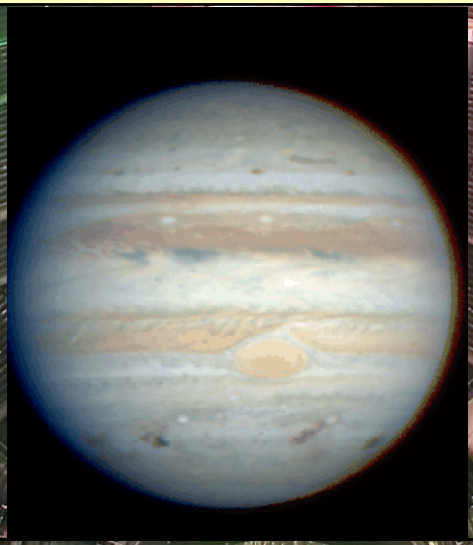
1 atm = .98 Bar

NIF will create ≥10^{33} neutrons per cm^2 per second, equivalent to a supernova



NIF will create thermal plasmas at the conditions of stellar interiors

NIF generates pressures found at the center of Jupiter



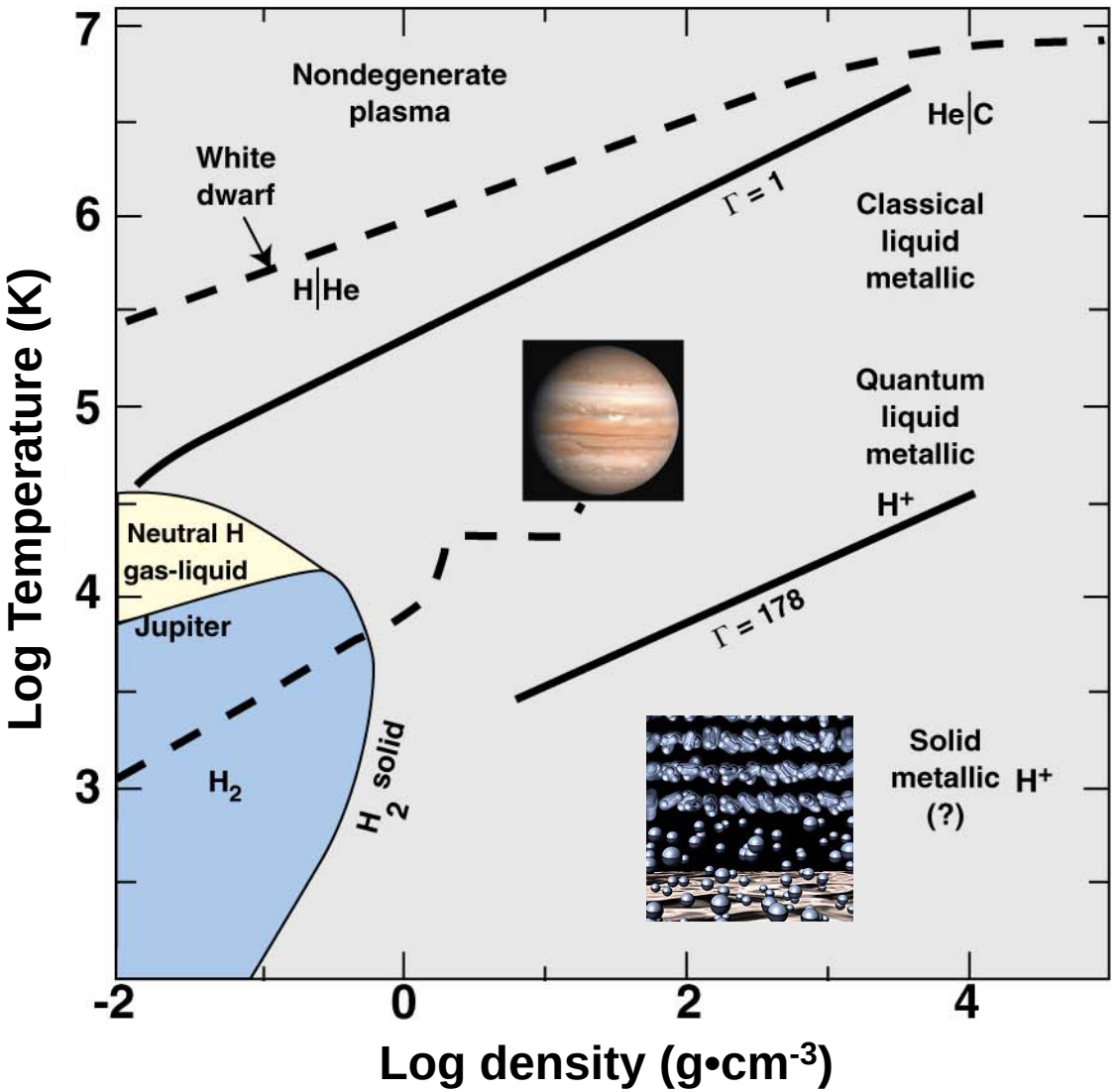
NIF will produce enough x-ray flux to simulate conditions in an accretion disk

NIF will access unprecedented energy densities

NIF-0506-12157
22EIM/sb

Hydrogen Phase space for high energy density science

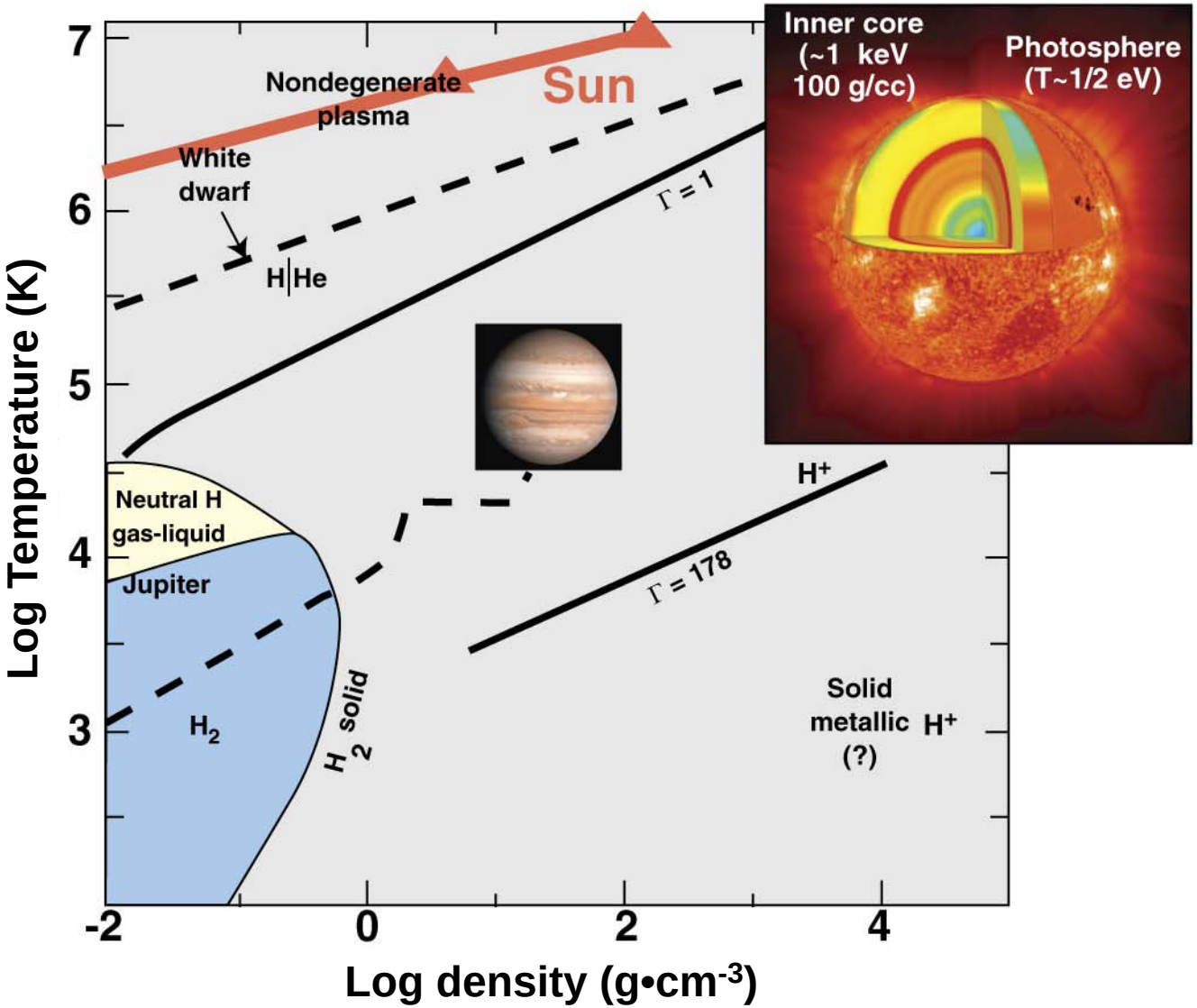
The National Ignition Facility



NIF-0309-16091L1
13RC/ld

Hydrogen Phase space for high energy density science

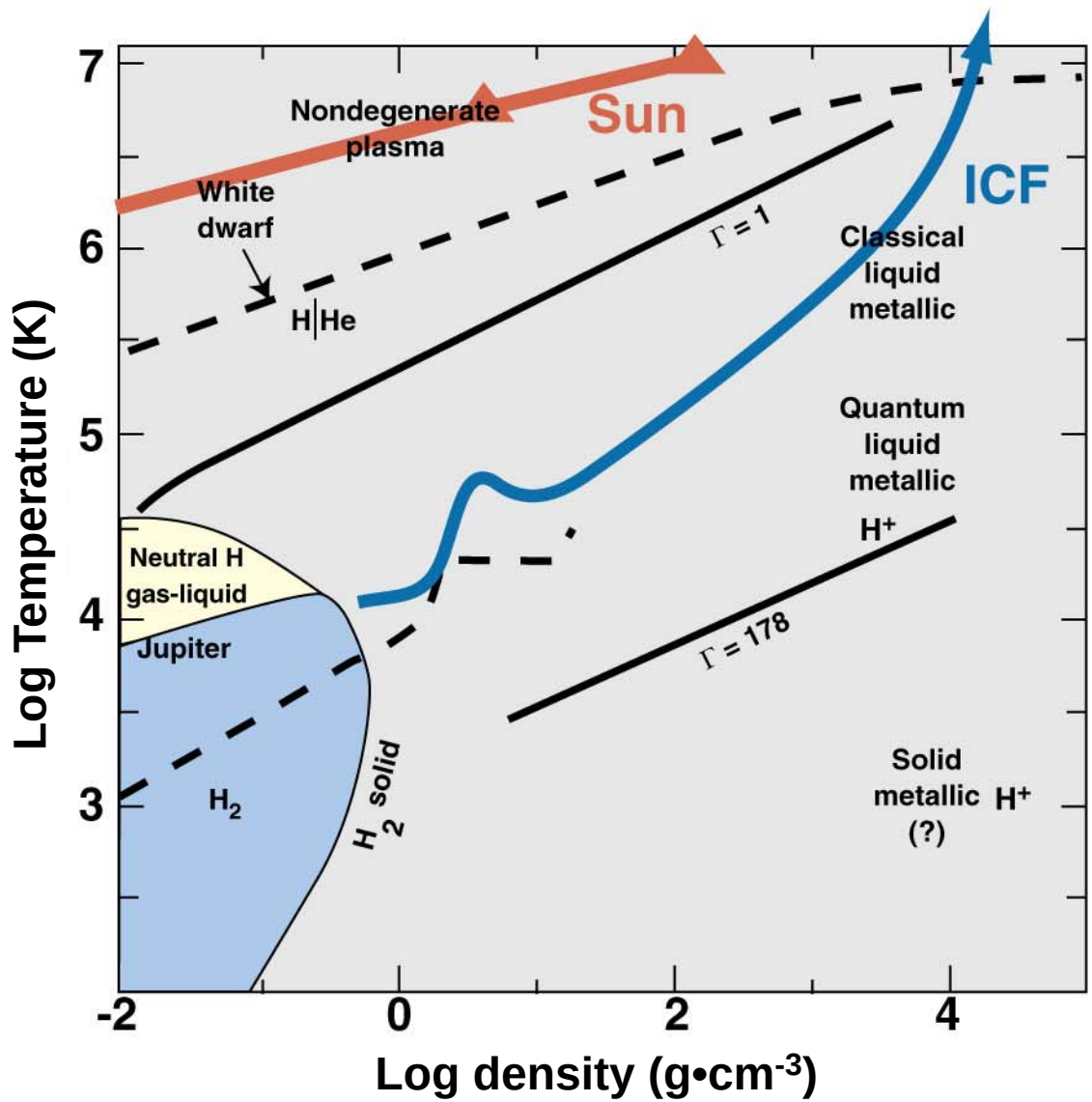
The National Ignition Facility



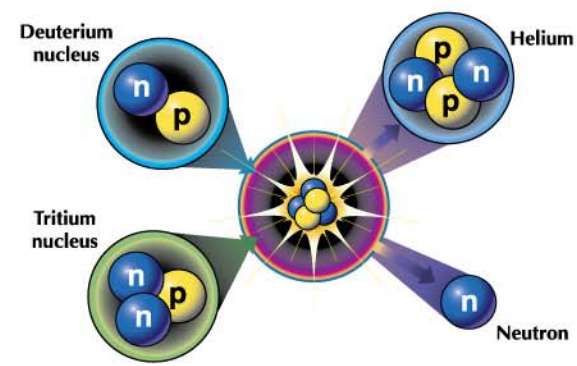
NIF-0309-16091L2
13RC/ld

Hydrogen Phase space for high energy density science

The National Ignition Facility



Path for Inertial confinement fusion

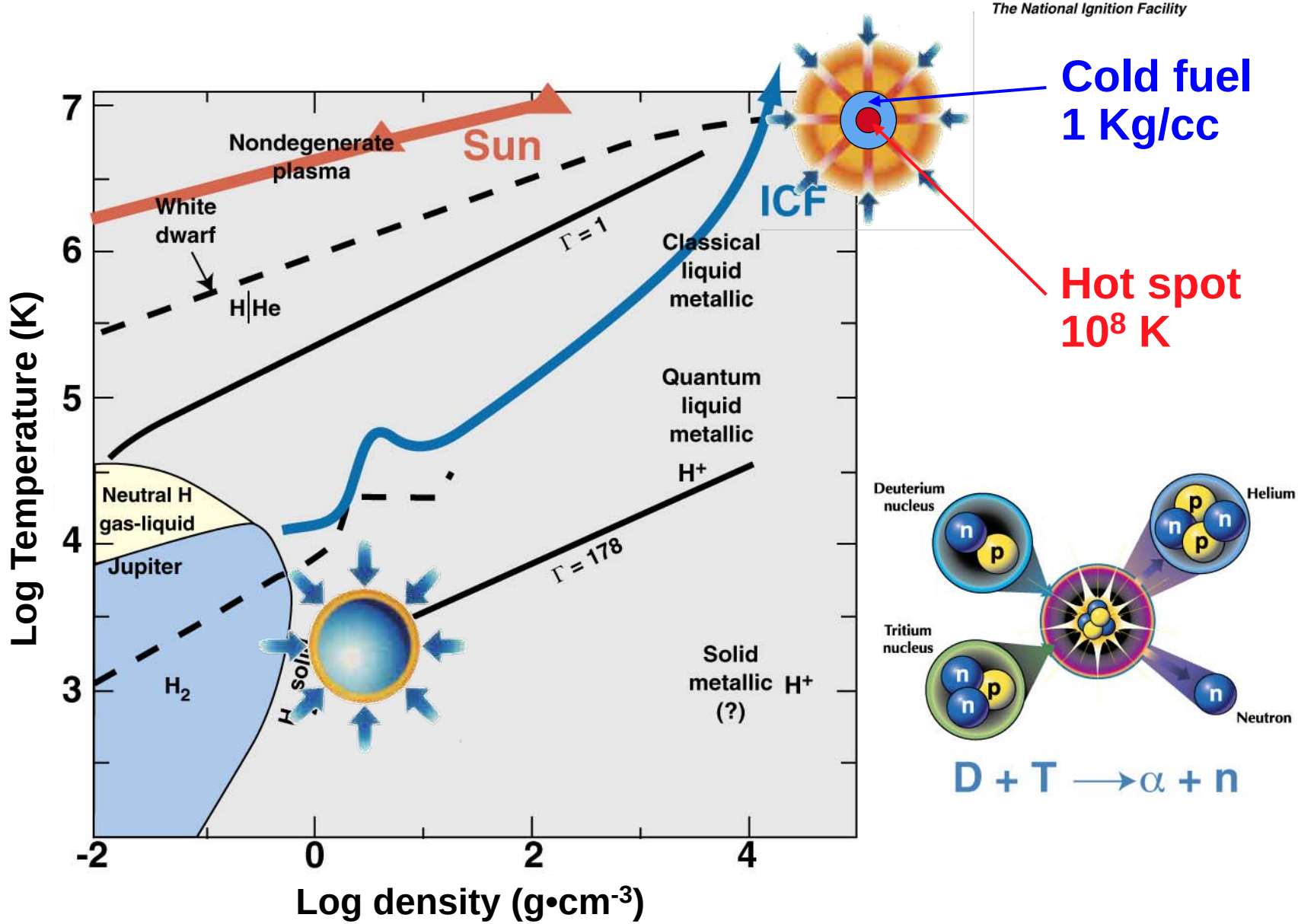


$D + T \longrightarrow \alpha + n$

NIF-0309-16091L3
13RC/ld

Hydrogen Phase space for high energy density science

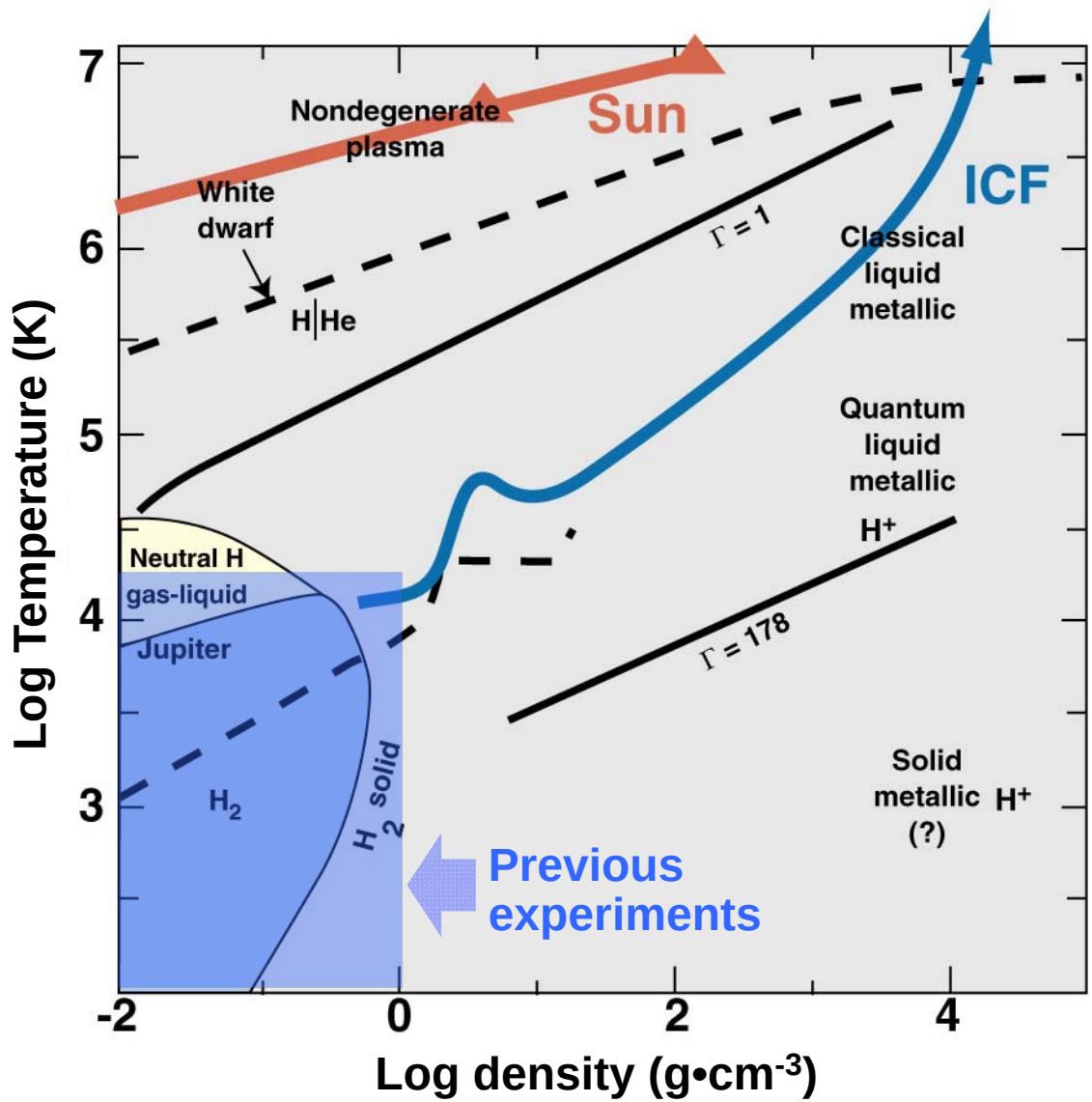
The National Ignition Facility



NIF-0309-16091L3
13RC/ld

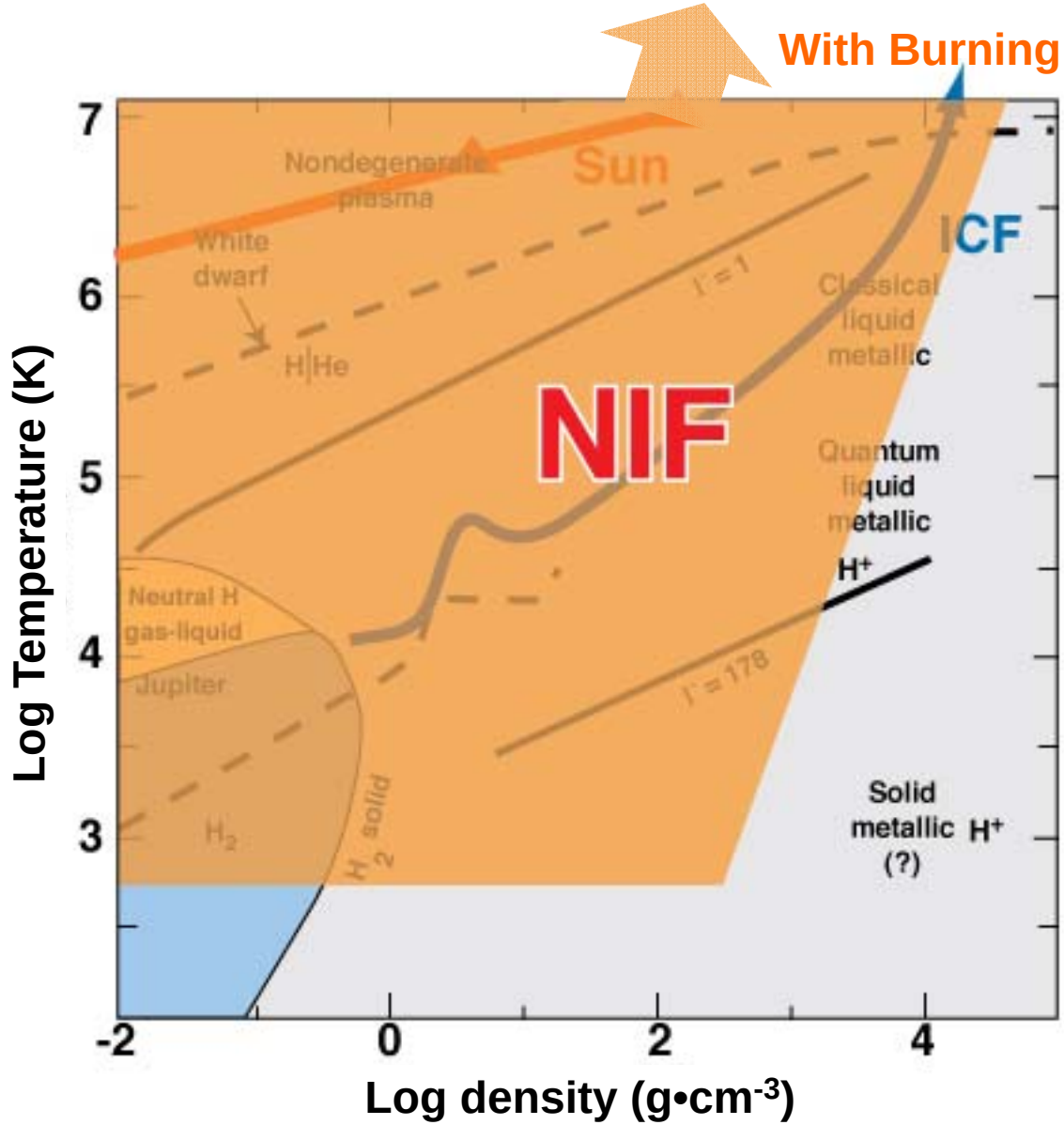
Hydrogen Phase space for high energy density science

The National Ignition Facility



Hydrogen Phase space for high energy density science

The National Ignition Facility

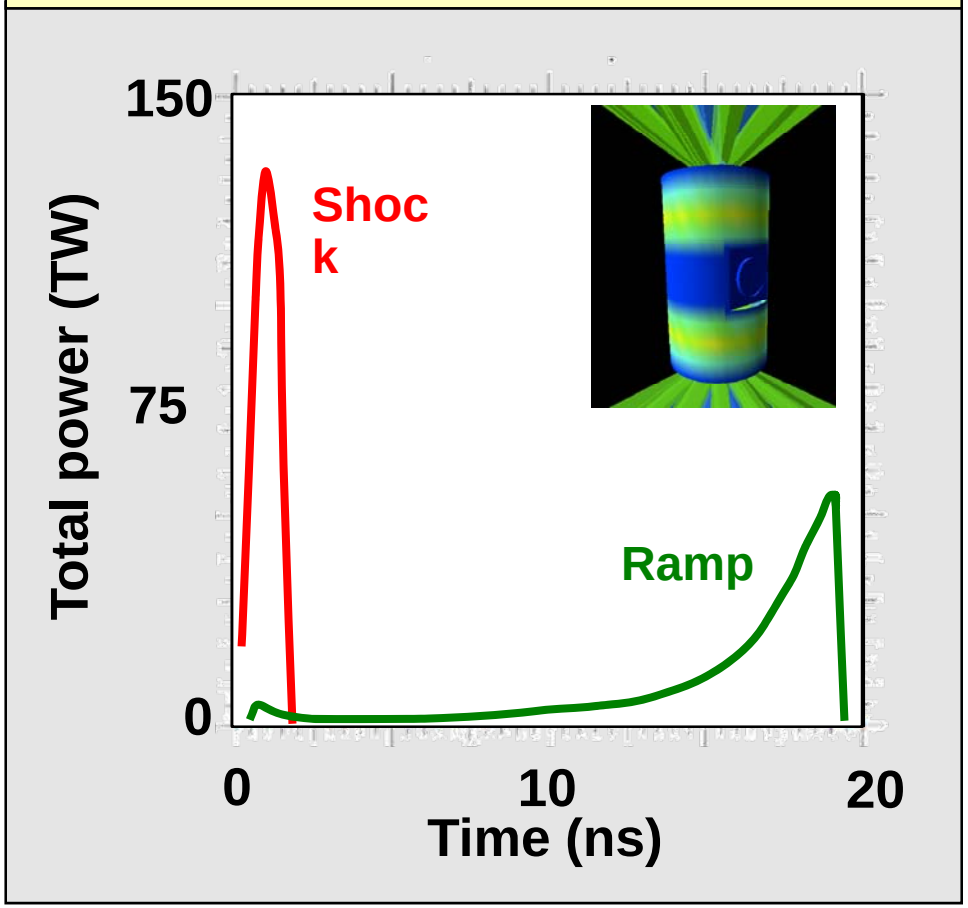


High energy density regime to explore with NIF

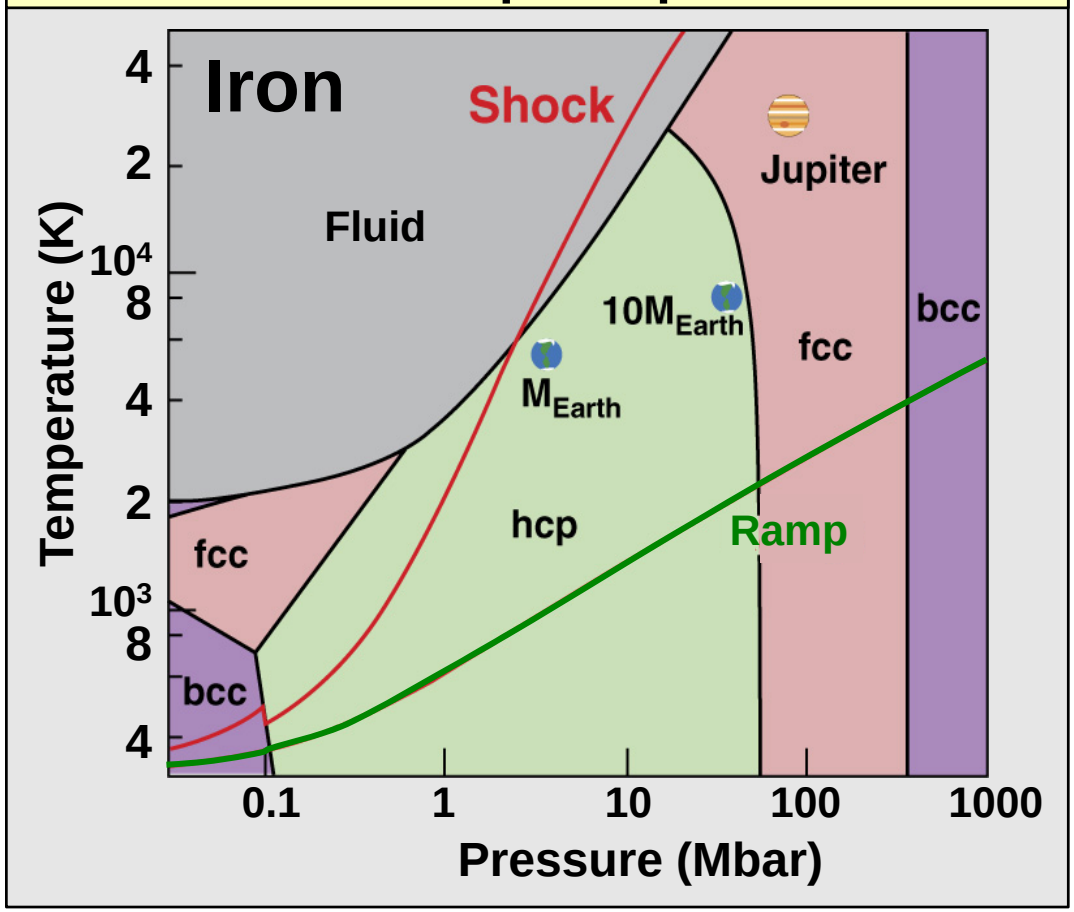
NIF's Pulseshaping and Burn will enable extreme solid state to fusion experiments

The National Ignition Facility

Pulse shape ultra-high pressure plasma and solid-state experiments



NIF can produce P > 1 Gbar shocks, P> 10's Mbar for Ramp compression

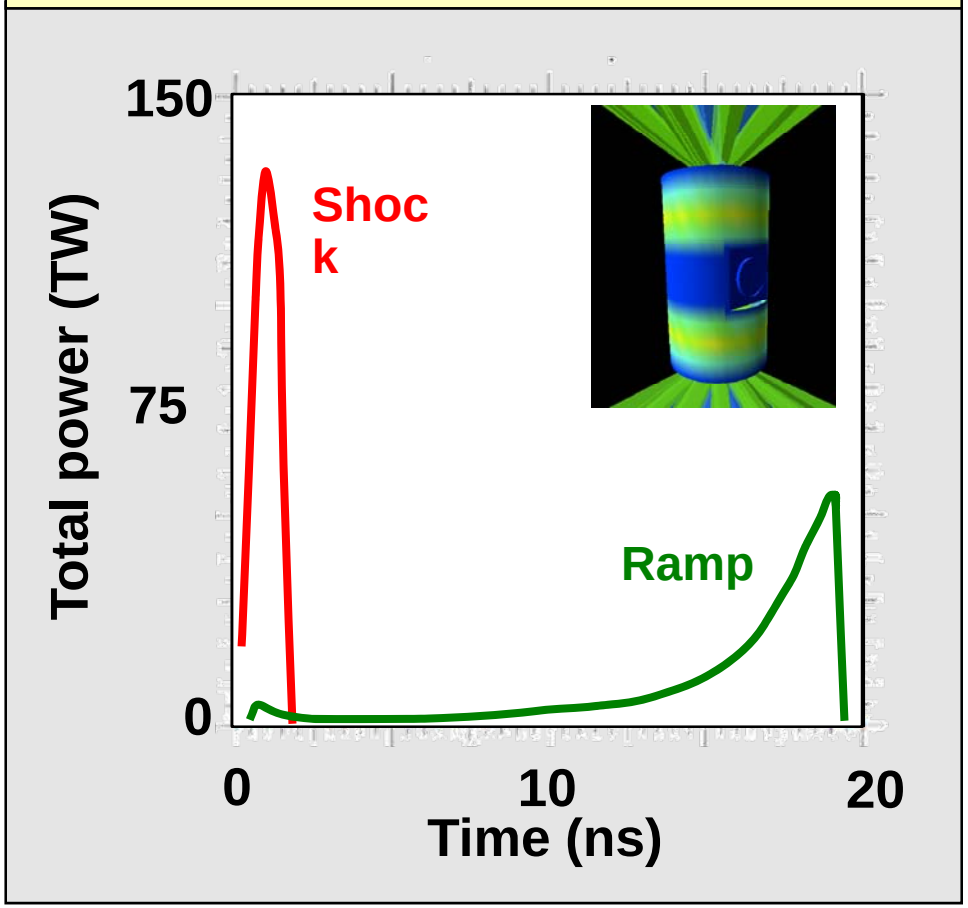


Stixrude, 2008

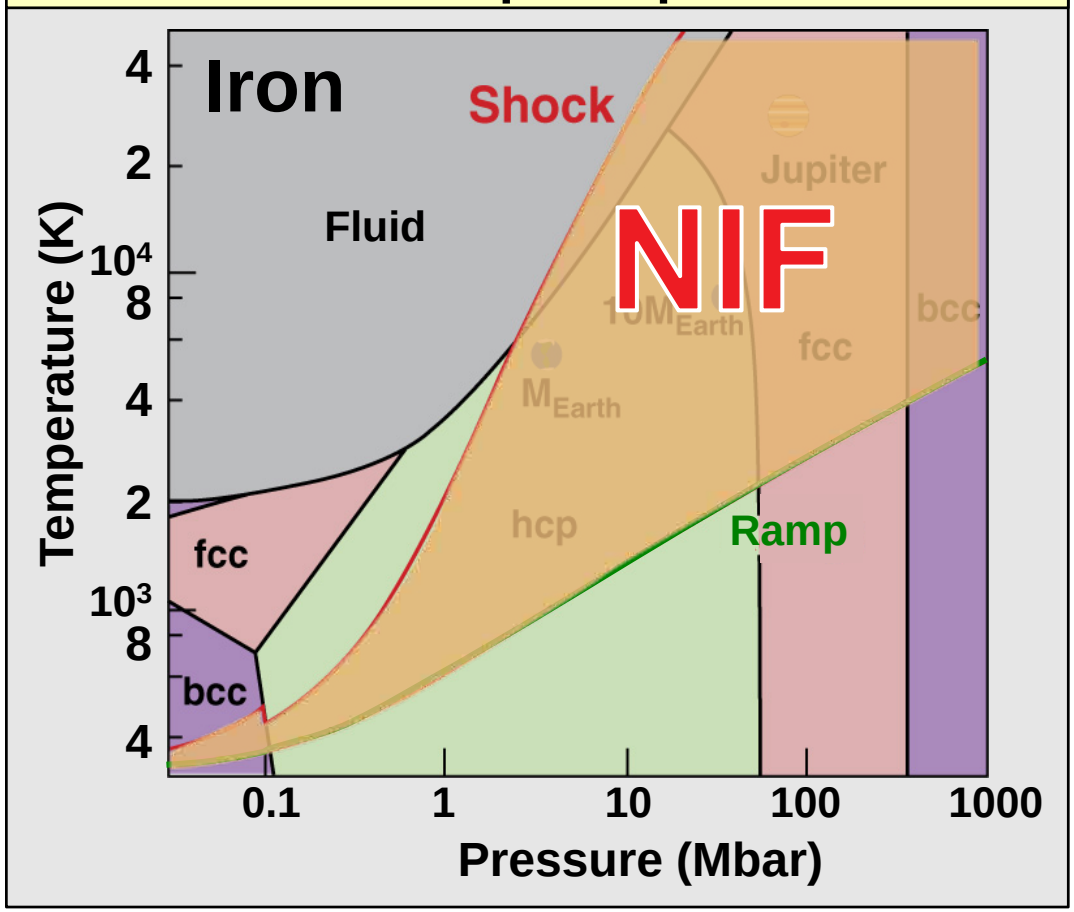
NIF's Pulseshaping and Burn will enable extreme solid state to fusion experiments

The National Ignition Facility

Pulse shape ultra-high pressure plasma and solid-state experiments



NIF can produce P > 1 Gbar shocks, P> 10's Mbar for Ramp compression

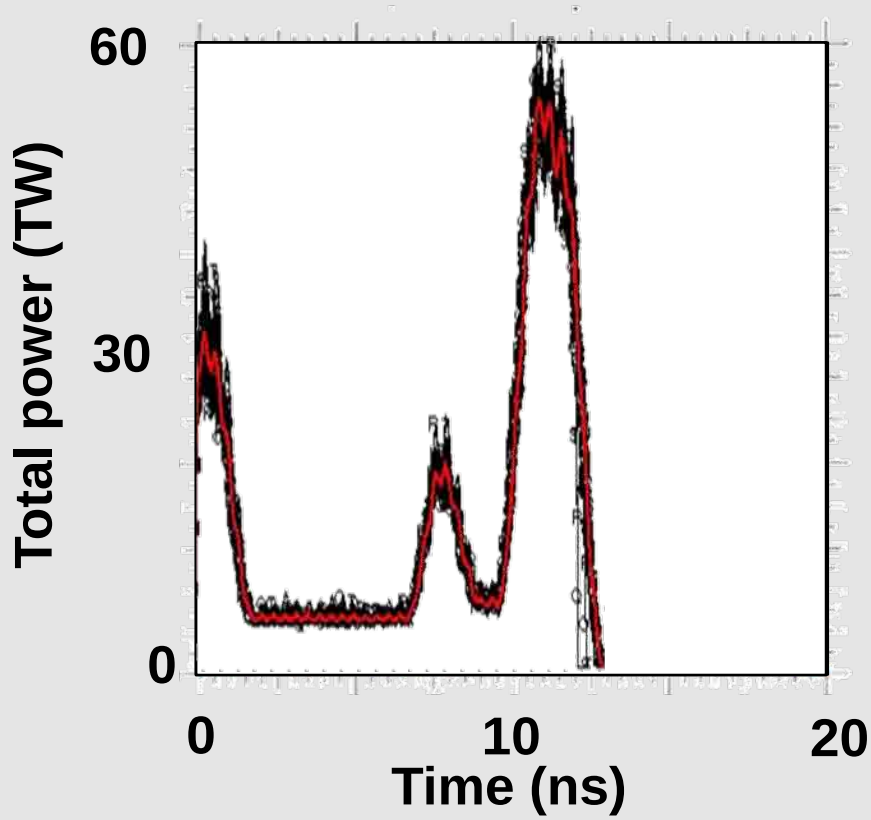


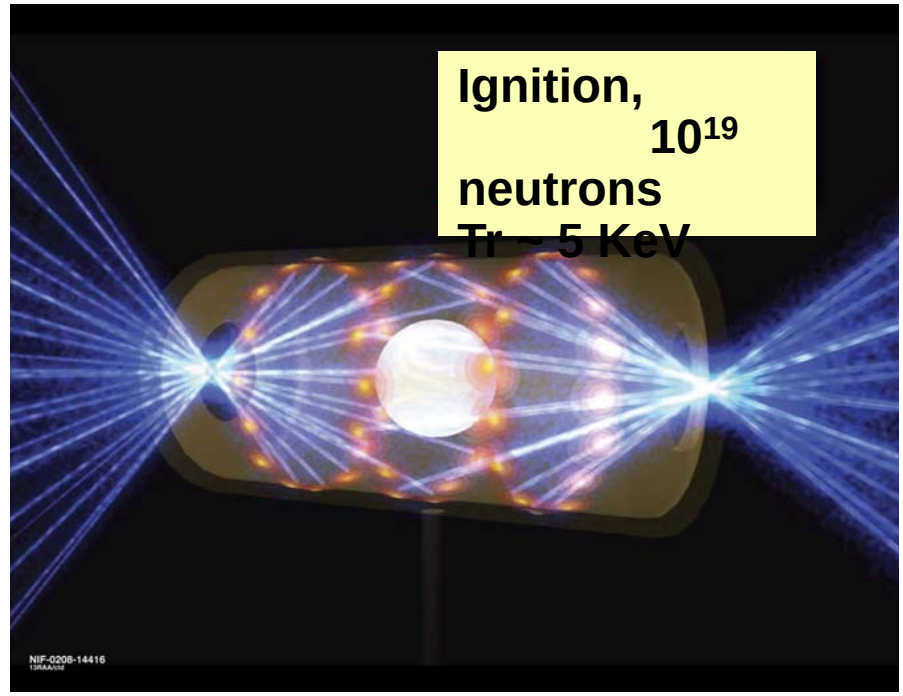
Stixrude, 2008

NIF's high energy and pulseshaping will enable extreme solid state to fusion experiments

The National Ignition Facility

Pulse shape for ignition





With ignition, the regimes we will be able to access are still more extreme

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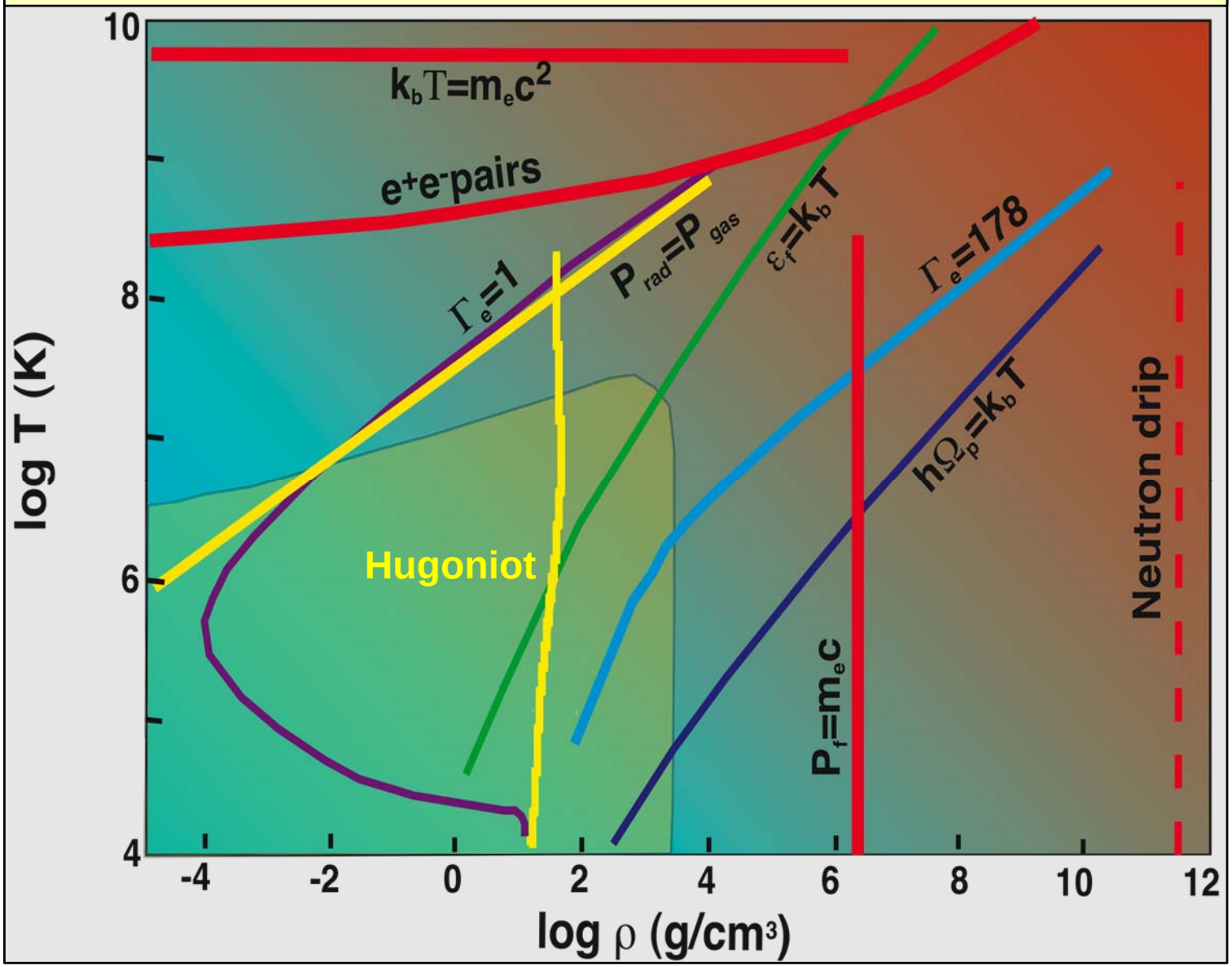
We are just now trying to determine regimes accessible with ignition, this example is again for Fe



VanHorn

We are just starting to develop science "platforms" to explore this new frontier of science

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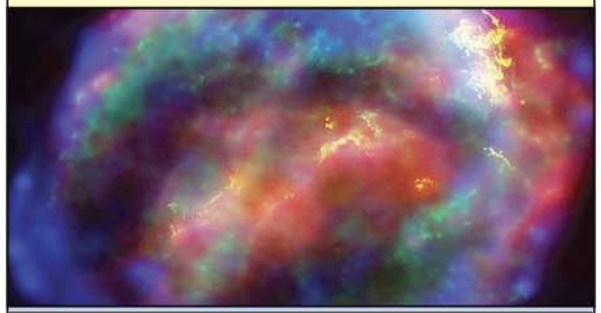
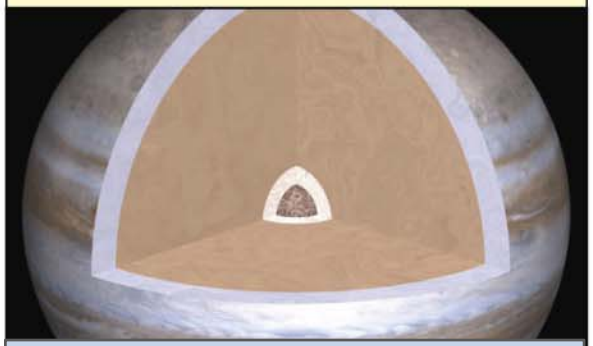
Astro/Nuclear Physics



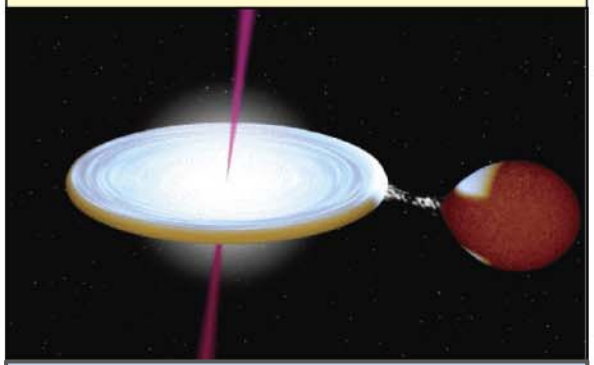
G. Fuller, U. Greife, Z. Shayer, C. Brune, R. Boyd, L. Bernstein

Ultra-Dense Matter



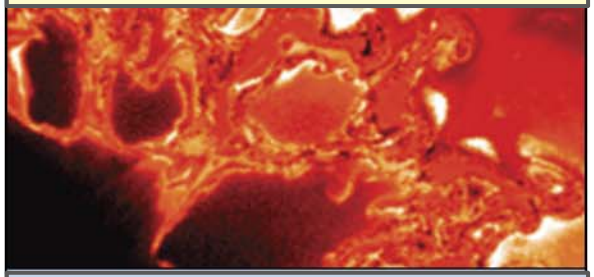
R. Jeanloz, T. Duffy, R. Hemley, Y. Gupta, P. Loubeyre, L. Stixrude, S. Rose, J. Wark, G. Collins

Burning Plasmas



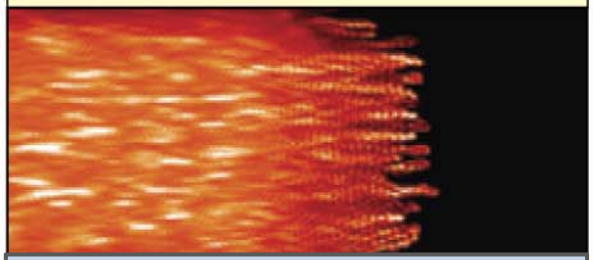
S. Rose, R. Betti, J. Meyer-Ter-Vehn, S. Atzeni, G. Collins

Astro/Rad-transport & Hydrodynamics



P. Drake, D. Arnett, A. Frank, T. Plewa, T. Ditmire, A. Takabe, B. Remington

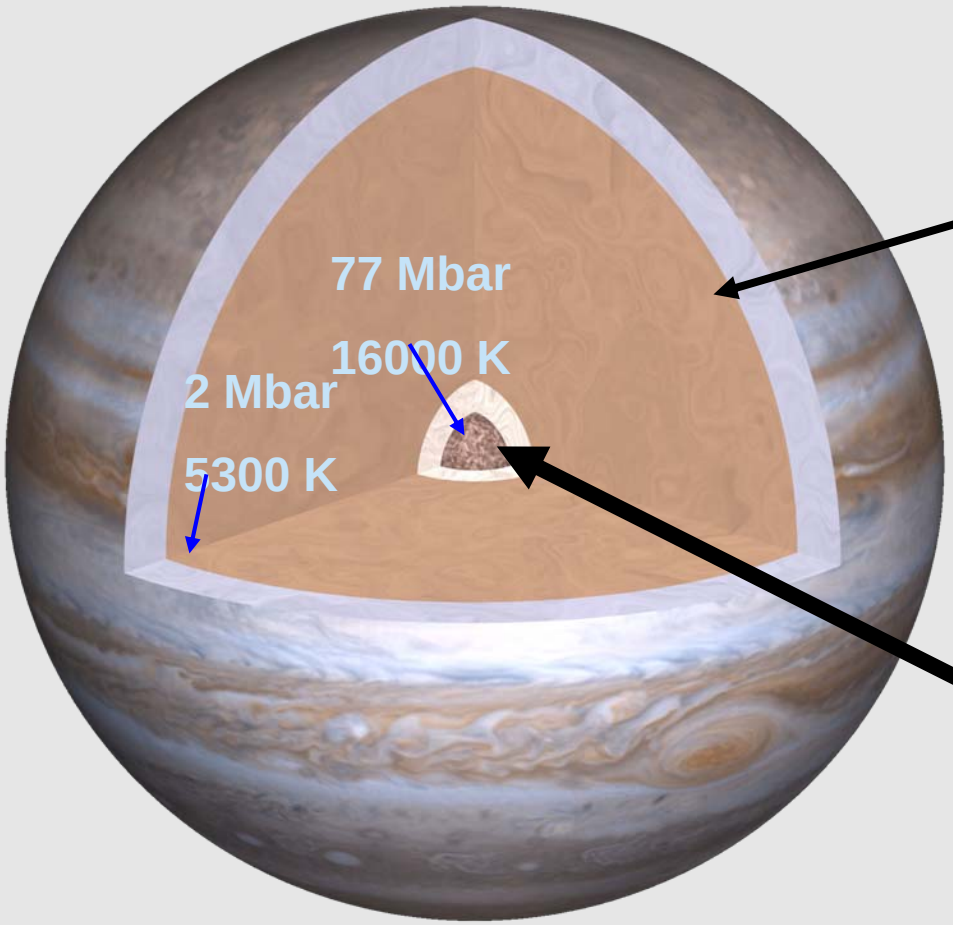
LPI and Ultra-Intense Light Sources



N. Fisch, C. Niemann, C. Joshi W. Mori, B. Afeyan, D. Montgomery, A. Schmitt, B. Kirkwood

NIF will be able to recreate the most extreme conditions of any planet

The National Ignition Facility



Omega experiments can access the few Mbar regime, ~0.8 * $R_{Jupiter}$

NIF experiments can access the most extreme conditions in any planet

C. J. Hamilton

Some Key Issues:

- What is a solid at >10 Mbars
- How does H behave at 5,10,…g/cc
- What chemistry occurs at Mbar-Gbar conditions

The team of leading scientists in the field of ultra-dense matter continues to grow

Russ Hemley
Carnegie Institute
Kev Chemistry

Raymond Jeanloz
U.C.Berkeley

Tom Duffy
Princeton
Elastic consts & rigidity

Yogi Gupta
Washington State
Solids at P>20Mbar

Paul Loubeyre
CEA
H & H/He at P>10 Mbar

W. Mao (Stanford), K. Lee (Yale), R. Wentzcovitch, C. Bolme (LANL), T. Guillot, (Obs. Nice)

D. Stevenson
CalTech
Planet Models

LLL
NIF, DNT, PLS, Eng

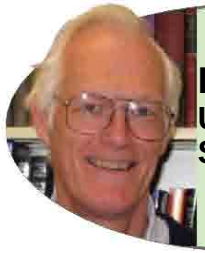
W. Hubbard
U. Arizona
Planet theory

Lars Stixrude
Univ. of Michigan
Extreme Chemistry

Steven Rose
Imperial College, London
Plasma Physics Group

Burkhard Militzer
Earth and Planetary Science

Justin Wark
Oxford University



Richard Martin
U. Illinois
Solid State Theory

Many of the techniques have been benchmarked on the Omega, Jupiter, and Vulcan laser facilities

The National Ignition Facility

PRL 97, 025502 (2006) PHYSICAL REVIEW LETTERS week ending 14 JULY 2006

Dissociation of Liquid Silica at High Pressures and Temperatures

THE JOURNAL OF CHEMICAL PHYSICS 125, 014701 (2006)

Laser-driven shock experiments on precompressed water: Implications for "icy" giant planets

PRL 95, 075502 (2005) PHYSICAL REVIEW LETTERS week ending 12 AUGUST 2005

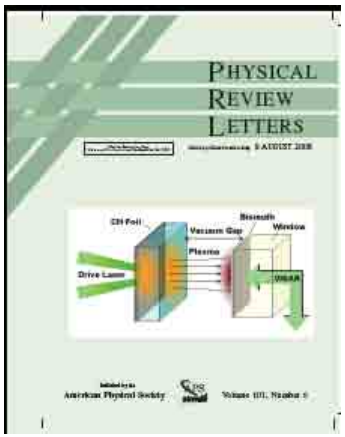
Direct Observation of the α-ε Transition in Shock-Compressed Iron via Nanosecond X-Ray Diffraction

L 96, 255003 (2006) PHYSICAL REVIEW LETTERS week endir 30 JUNE 20

Broadband Dielectric Function of Nonequilibrium Warm Dense Gold

LETTERS

Laser-shock compression of diamond and evidence of a negative-slope melting curve



JOURNAL OF APPLIED PHYSICS 105, 036107 (2009)

Large elastic wave amplitude and attenuation in shocked pure aluminum

Y. M. Gupta,[1] J. M. Winey,[1,a)] P. B. Trivedi,[1] B. M. LaLone,[1] R. F. Smith,[2] J. H. Eggert,[2] and G. W. Collins[2]

PRL 102, 075503 (2009) PHYSICAL REVIEW LETTERS 20 FEBRUARY 2009

Diamond at 800 GPa

D. K. Bradley, J. H. Eggert, R. F. Smith, S. T. Prisbrey, D. G. Hicks, D. G. Braun, J. Biener, A. V. Hamza, R. E. Rudd, and G. W. Collins

PHYSICAL REVIEW B 79, 014112 (2009)

Laser-driven single shock compression of fluid deuterium from 45 to 220 GPa

D. G. Hicks,[1,*] T. R. Boehly,[2] P. M. Celliers,[1] J. H. Eggert,[1] S. J. Moon,[1] D. D. Meyerhofer,[2,†] and G. W. Collins[1]

PRL 101, 065701 (2008) PHYSICAL REVIEW LETTERS week ending 8 AUGUST 2008

Ultrafast Dynamic Compression Technique to Study the Kinetics of Phase Transformations in Bismuth

R. F. Smith, J. H. Eggert, M. D. Saculla, A. F. Jankowski, M. Bastea, D. G. Hicks, and G. W. Collins

PRL 100, 124503 (2008) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2008

Hugoniot Data for Helium in the Ionization Regime

J. Eggert,[1] S. Brygoo,[1,2] P. Loubeyre,[2] R. S. McWilliams,[1,3] P. M. Celliers,[1] D. G. Hicks,[1] T. R. Boehly,[4] R. Jeanloz,[3] and G. W. Collins[1]

PHYSICAL REVIEW B 78, 174102 (2008)

High-precision measurements of the diamond Hugoniot in and above the melt region

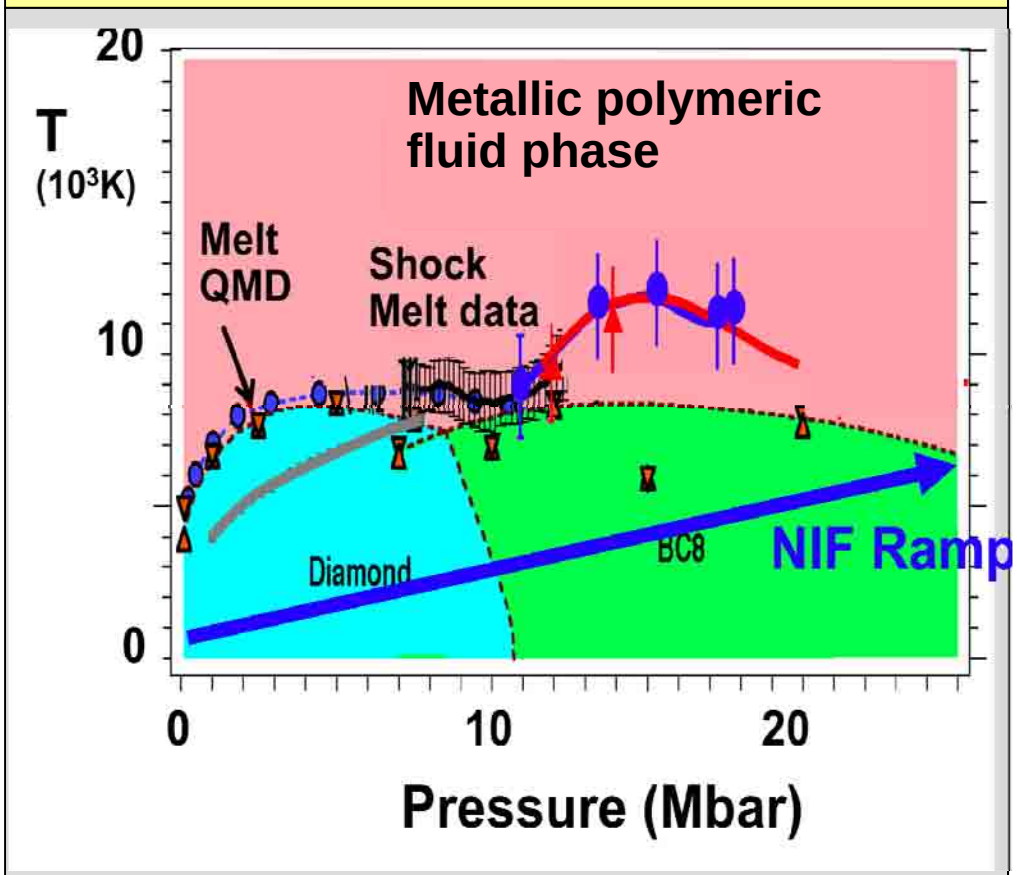
D. G. Hicks,[1,*] T. R. Boehly,[2] P. M. Celliers,[1] D. K. Bradley,[1] J. H. Eggert,[1] R. S. McWilliams,[1,3] R. Jeanloz,[3] and G. W. Collins[1]

Achieving high-density states through shock-wave loading of precompressed samples

Raymond Jeanloz*†‡, Peter M. Celliers§, Gilbert W. Collins§, Jon H. Eggert§, Kanani K. M. Lee¶, R. Stewart McWilliams* Stéphanie Brygoo‖, and Paul Loubeyre‖

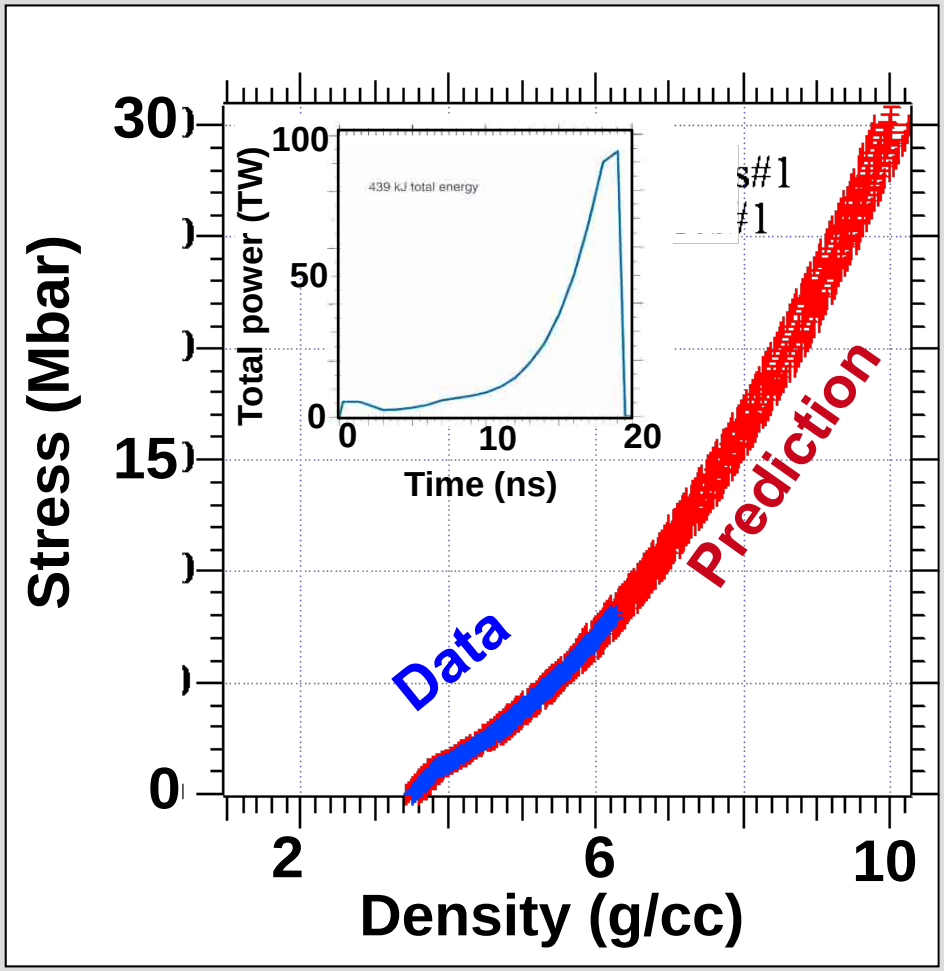
Next year we will extend solid state physics to 30 Mbars on NIF

We will discover if carbon stays solid and strong at 10's of Mbar



Eggert, Hicks

30 Mbar NIF design is scaled from 8 Mbar Omega experiments

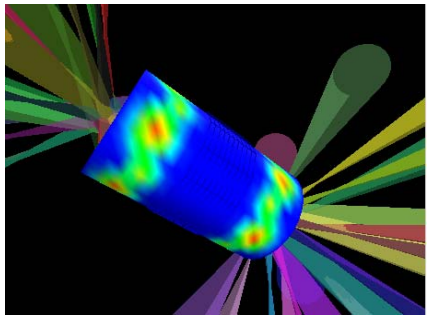


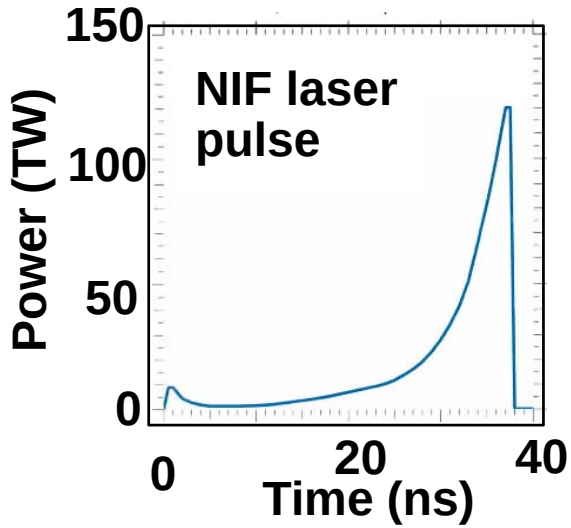
Eggert, Braun

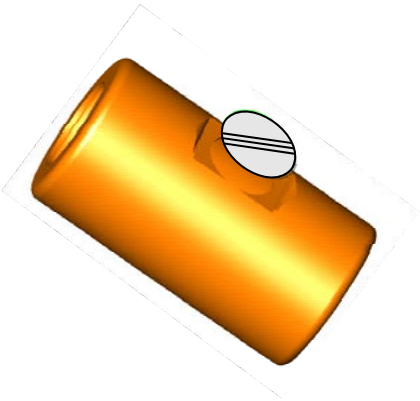
Materials science/planetary interiors platform- ramp condition of Fe to super-earth conditions (~ 20 Mbar)

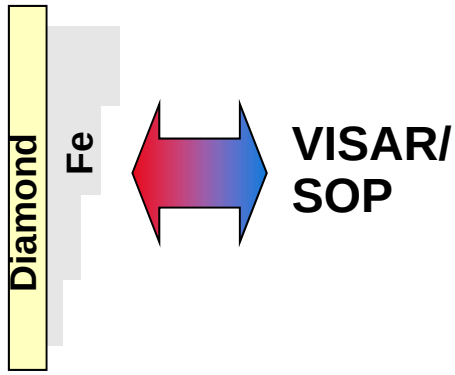
The National Ignition Facility

Target: ignition hohlraum, phase plates; specialized drive, package

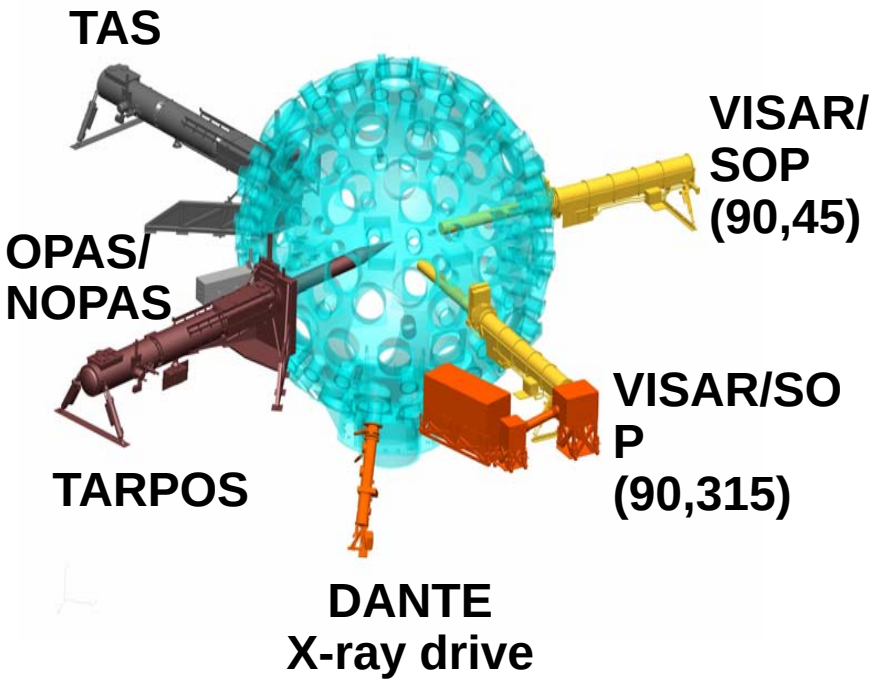








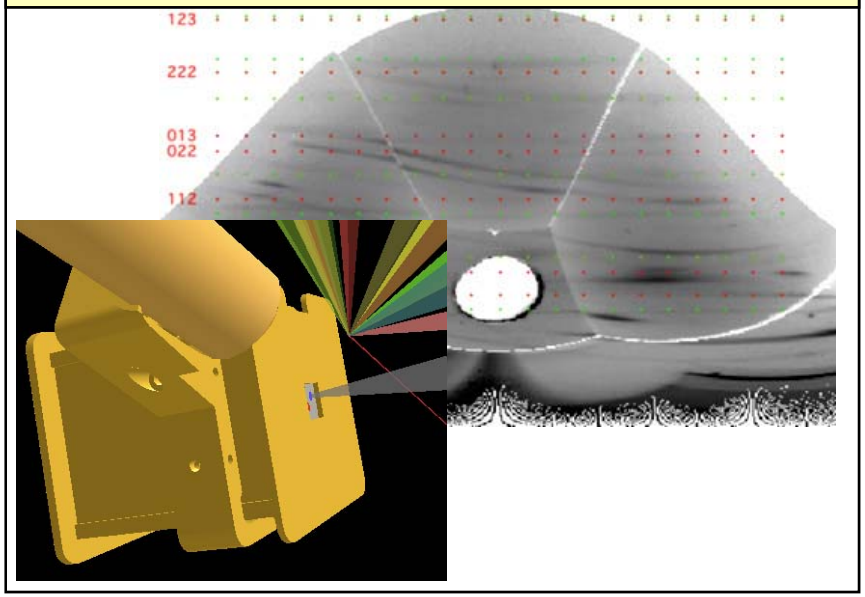
Diagnostics



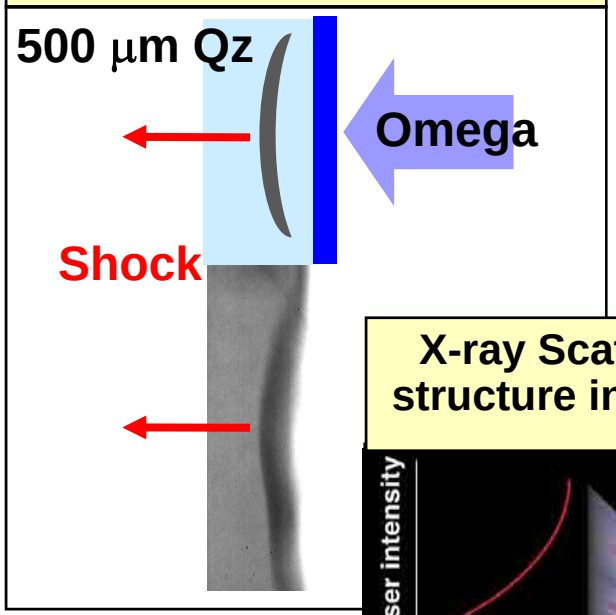
In addition to being able make solids at 10's of Mbar, we can now study these solids with diffraction, EXAFS, velocimetry, and broad band reflectance

Advanced diagnostics are being developed to explore the microscopic physics in this dense matter regime

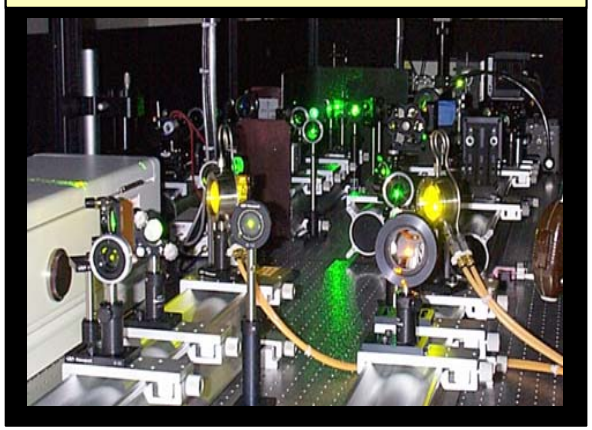
Diffraction for structure & strength =>Fe is HCP to 5 Mbar (Wark, Duffy, Gupta, Eggert, Harweliak, Rygg et al)



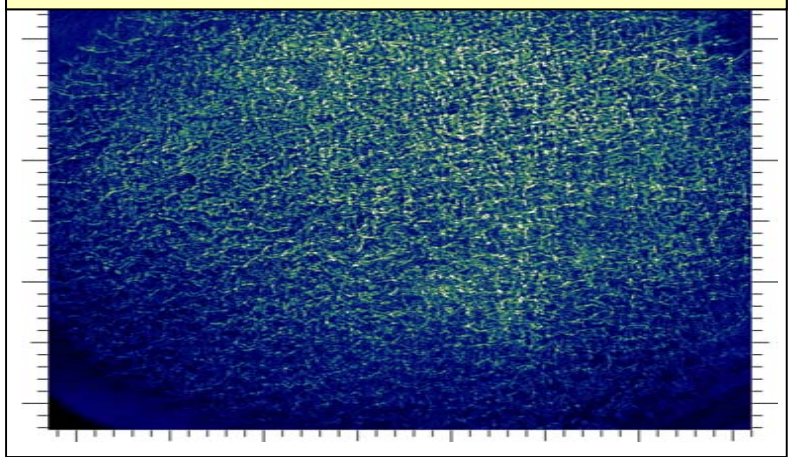
Imaging 17.5 KeV image of shocks (Hicks, Park, et al)



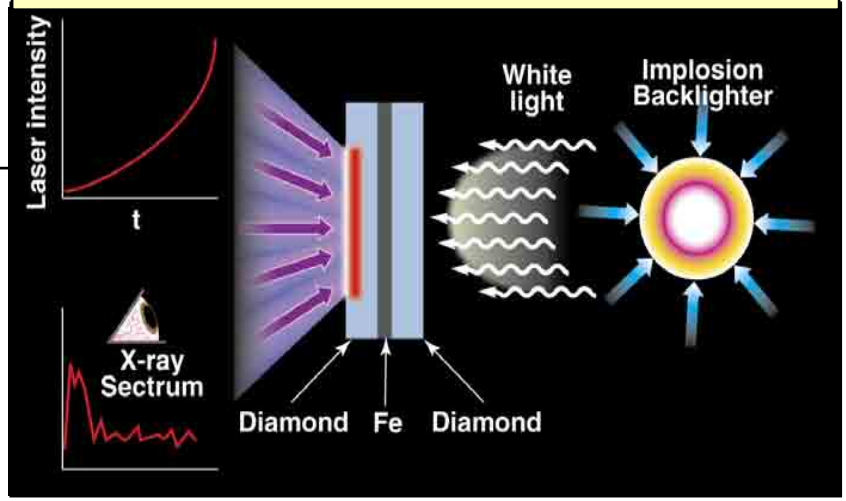
Optical spectroscopy to determine bonding (Bolme, Hemely,)



Hi-res interferometry for shock structure (Celliers, Smith, Brygoo)

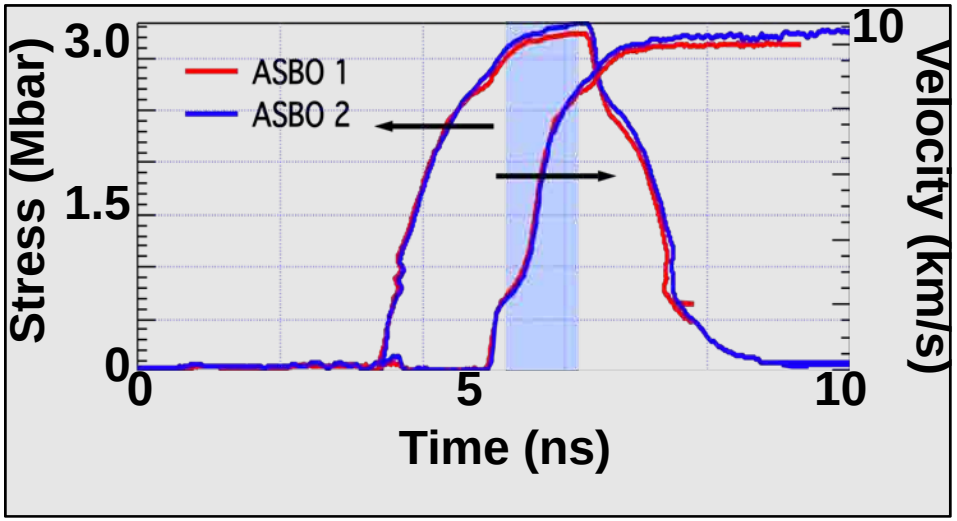


X-ray Scattering/absorption => local structure in Fe to 3 Mbar (Hemely, Hicks)

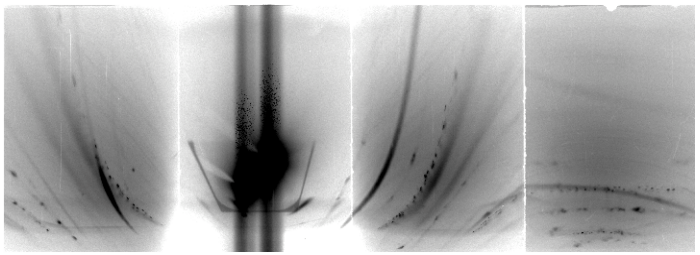


Simultaneous diffraction and velocity measurements give compressibility and phase to 5 Mbar

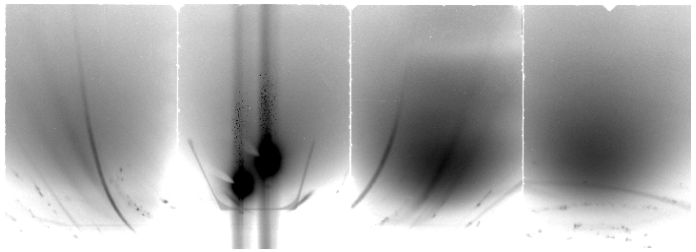
The National Ignition Facility



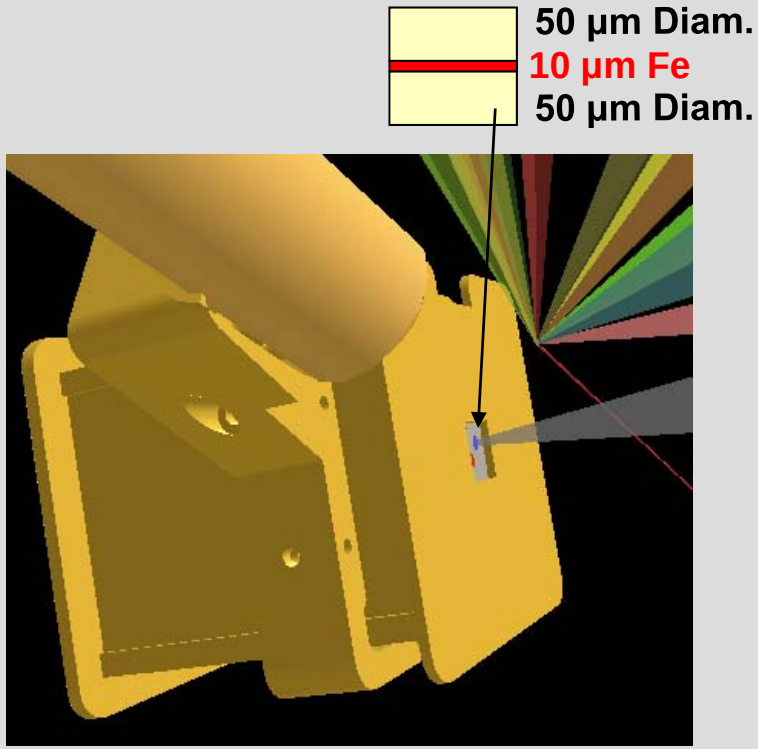
1.85 Mbar



3.24 Mbar



Powder diffraction on ramp compressed samples



Eggert, Rygg

This is by far the highest P diffraction ever collected and sets the stage for NIF experiments

We also developed EXAFS for Ultra-hi-P solids
Determines Fe structure + coordination+T

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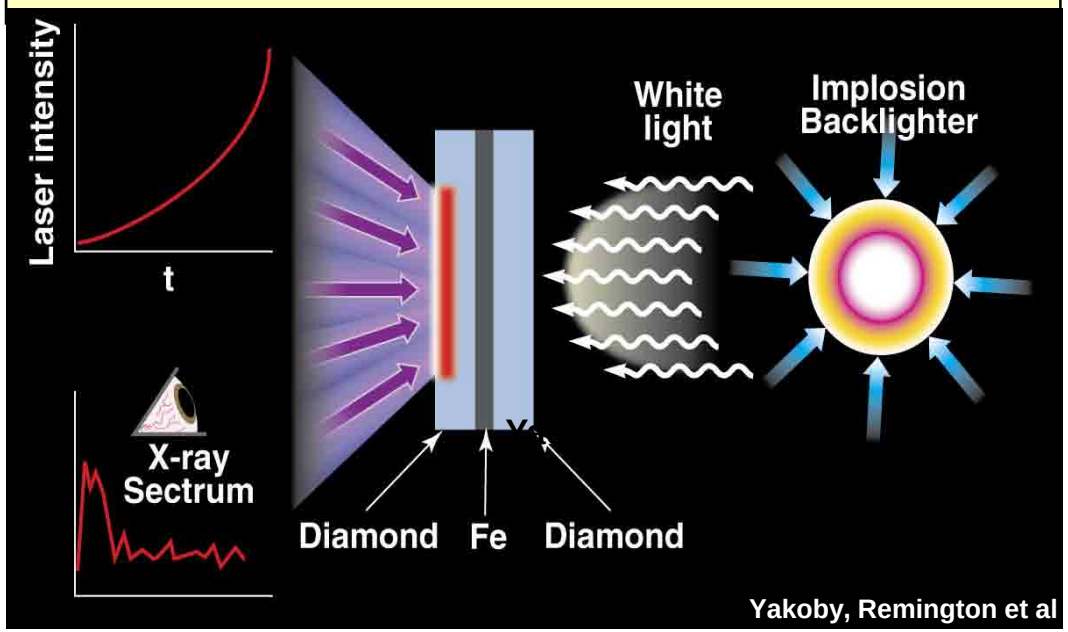
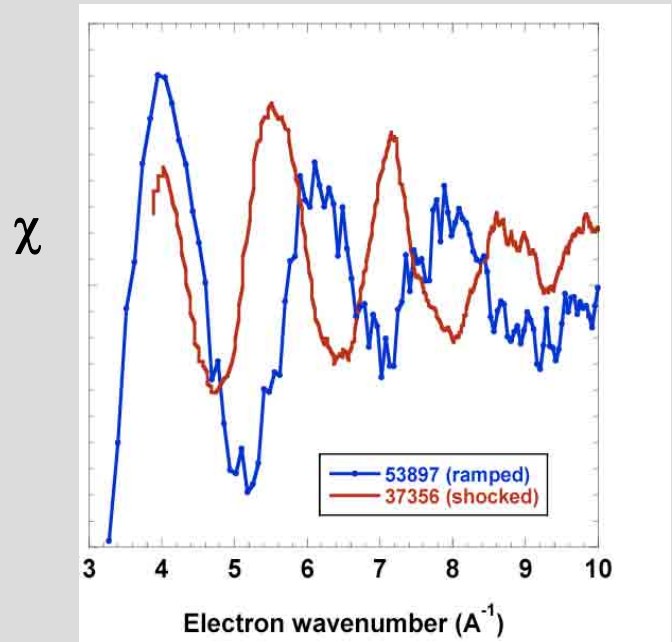
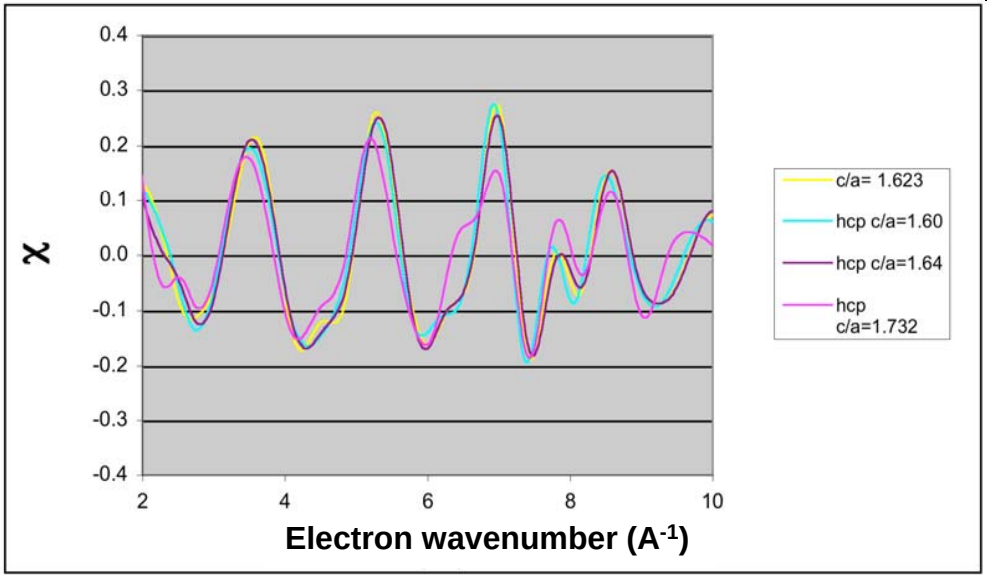
X-ray Scattering/absorption shows local structure in Fe to 3 Mbar (Hicks)



Data at P = 3 Mbar





Preliminary analysis suggests HCP with c/a ~1.73

We expect the combination of Diff. + EXAFS will give T

Hicks,Ping

Coupling diamond cells to laser shocks enables access to ultra-high density states for He, H2, He+H2

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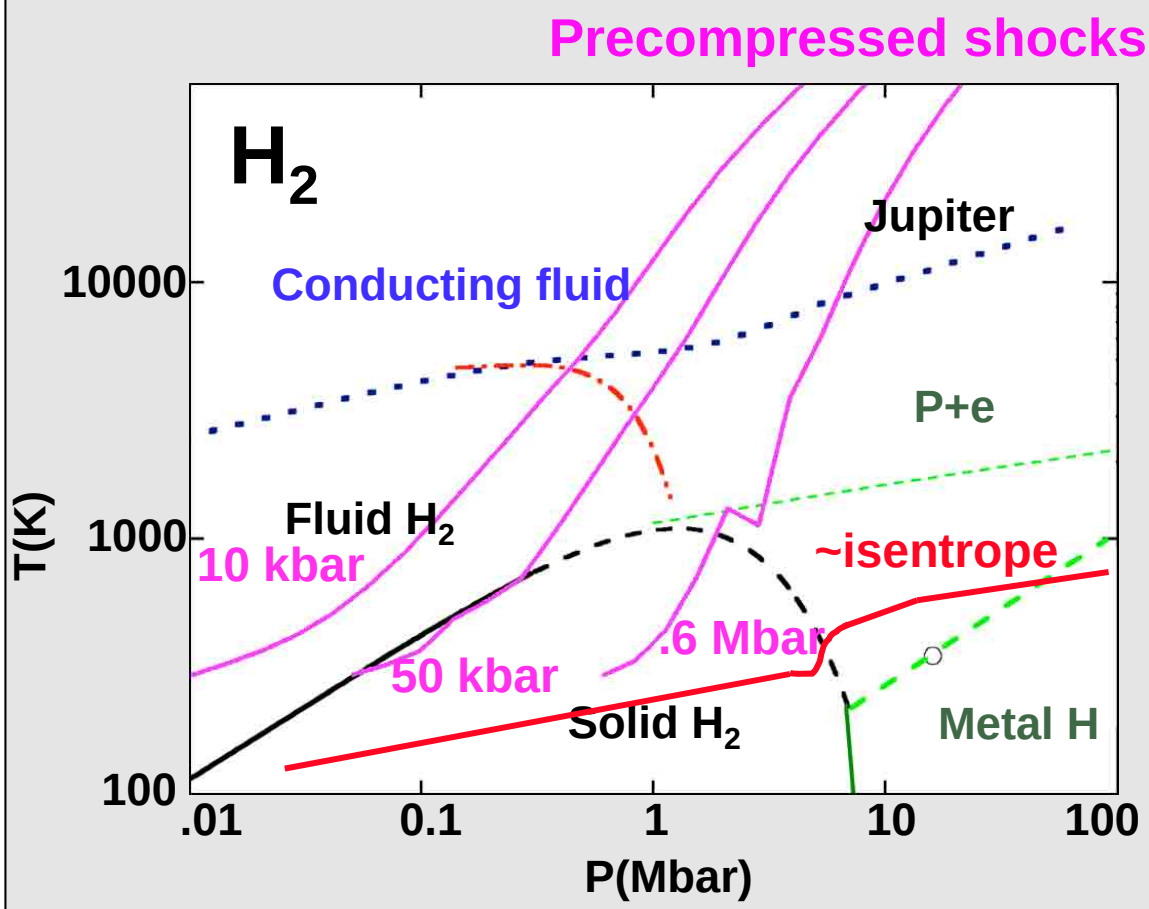

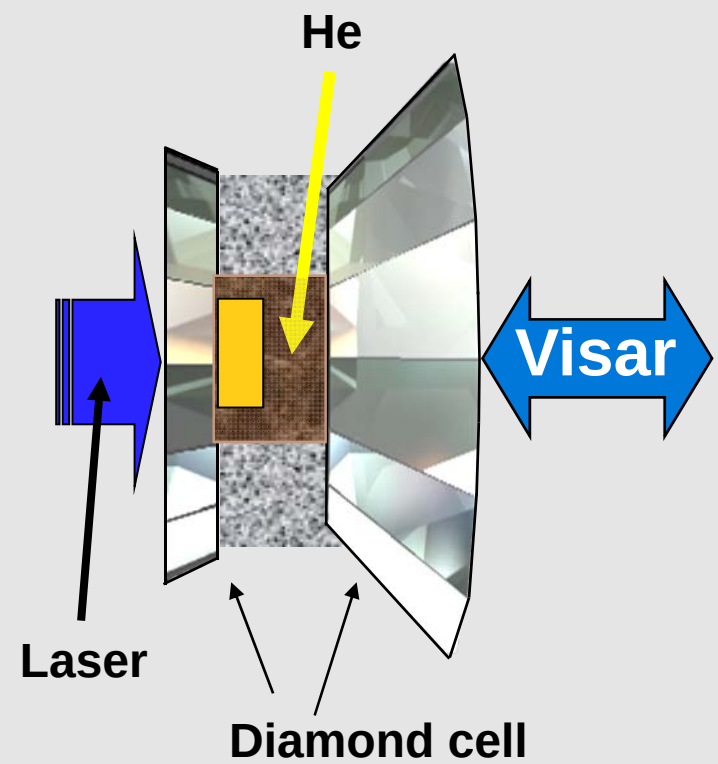

Loubeyre 06

The technique has been demonstrated on Omega to 200 GPa, and is expected to scale to 10+ TPa on NIF (Eggert PRL 08, Jeanloz PNAS 07, Lee JCP 06, Loubeyre JHP 06)

Coupling diamond cells to laser shocks enables access to ultra-high density states for He, H2, He+H2

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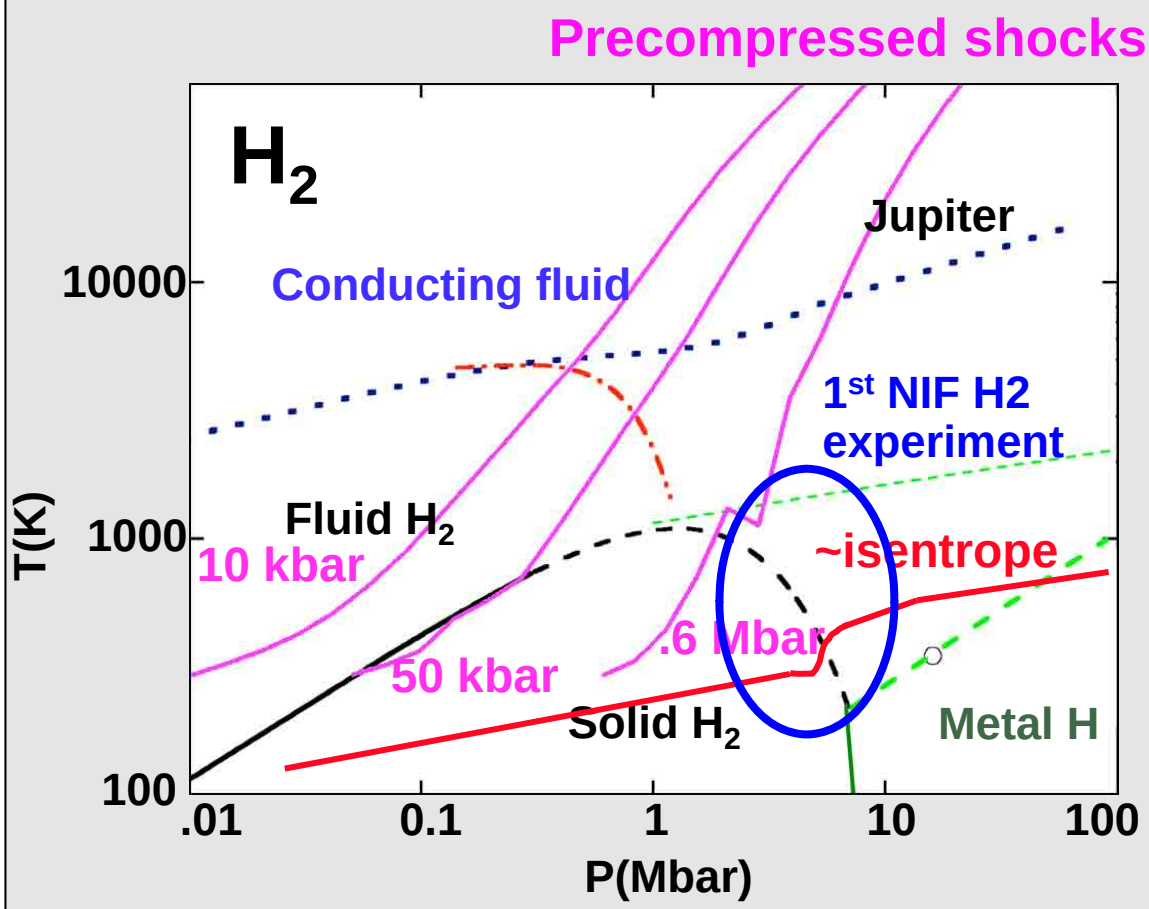
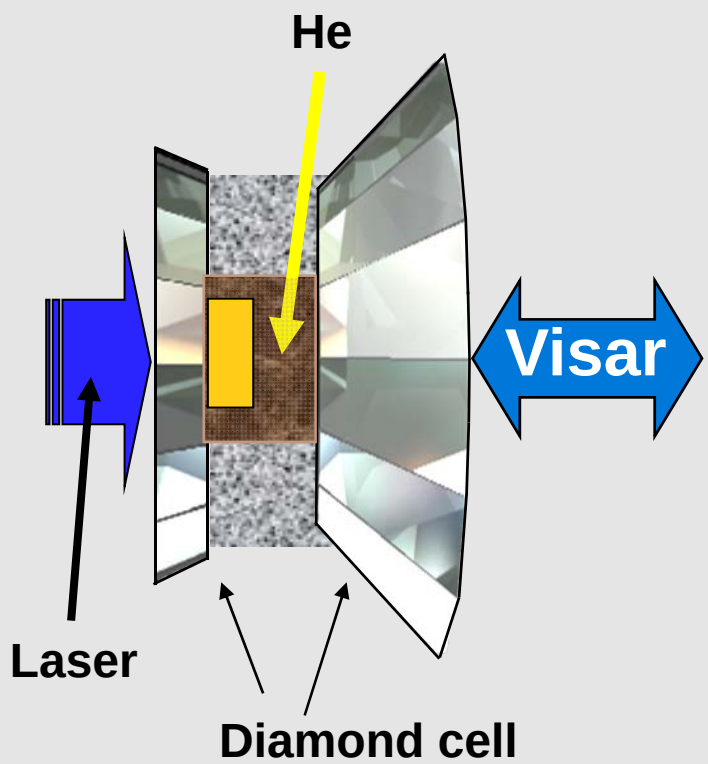


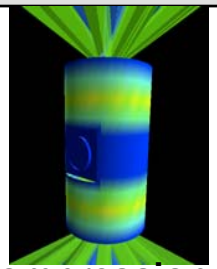


Loubeyre 06

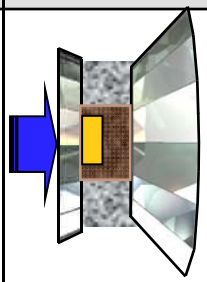
The technique has been demonstrated on Omega to 200 GPa, and is expected to scale to 10+ TPa on NIF (Eggert PRL 08, Jeanloz PNAS 07, Lee JCP 06, Loubeyre JHP 06)

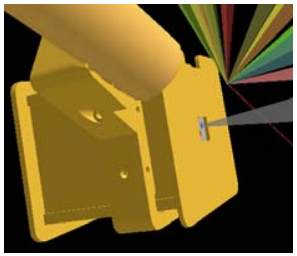
Currnet ultra-dense matter plans for NIF include 10's Mbar solids & 10's of Gbar dense plasmas

	FY10	FY11	FY12
New regime of Solid-state – 10 to 100's of Mbar	△ 30 Mbar Carbon 6 shots △ Fe-ramp to 20 Mbar, 4 shots	△ Diffraction structure & T 4 shots △ EXAFS for local order 4 shots	△ EXAFS/diffraction at >100 Mbar 4 shots
Ultra-dense Hydrogen		D2 to 6 g/cc 4 shots △ △ 50 Mbar He/H2 4 shots	△ H-D 100 Mbar (Pycnonuclear) △ H @ many Gbar
Kilovolt chem/Gigabar press.		Shock Fe to 1 Gbar 4 shots △	△ Fe @ 10's Gbar 4 shots

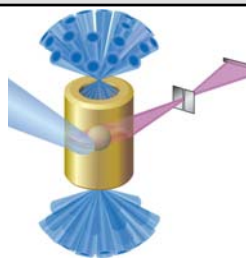


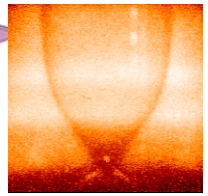
1-D compression
Ignition hohlraums
VISAR/SOP





Atomic scale data & H in new regime





t

Convergent experiments

Burning Plasmas

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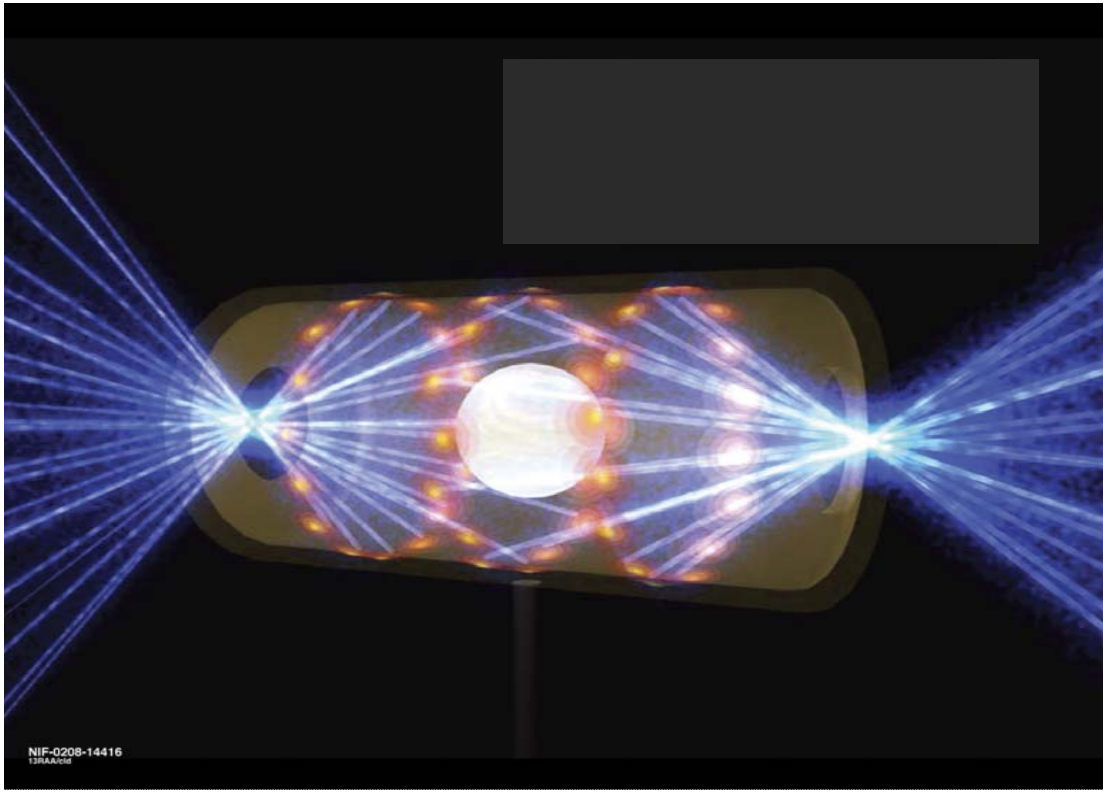
- **What physics limits optimizing burn?**
- **How does matter behave in DT burning environment, ie. Radiation and relativistic regimes?**
- **What are the next advanced ignition concepts?**



NIF will open a new field of Burning Plasma physics, what are the key questions

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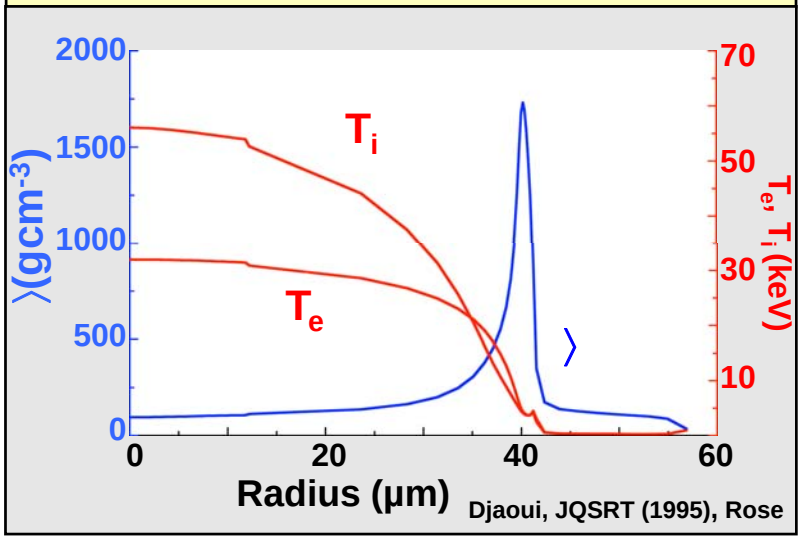
- Understand/optimize the burning plasma
  - e-ion equilibration
  - Alpha deposition
  - EOS/opacities and non-equilibrium
  - Effects of extreme fields
  - Plasma effects on nuclear reactions

- New burning plasma physics?
  - Extreme neutron and photon flux
  - e+e- pairs
  - Photonuclear processes

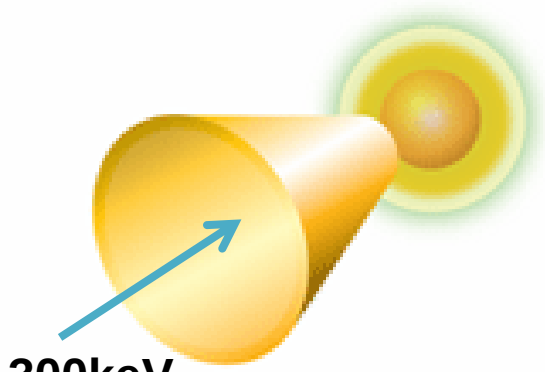
Does a deep understanding of burning plasmas enable new ignition concepts?

Density-temperature at peak rho-R



Djaoui, JQSRT (1995), Rose

Faster Ignition



300keV
DT ions

Previous Photoionised plasmas achieved ξ=20ergcms^{-1}, NIF will achieve >1000ergcms^{-1}

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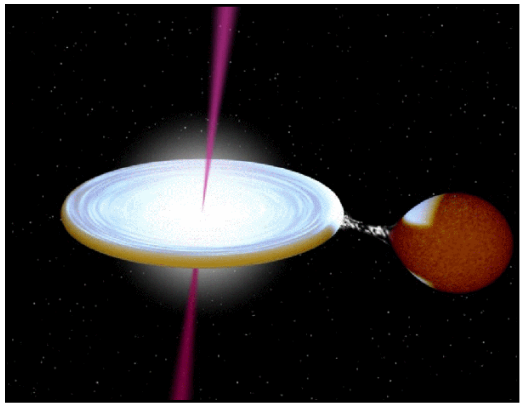
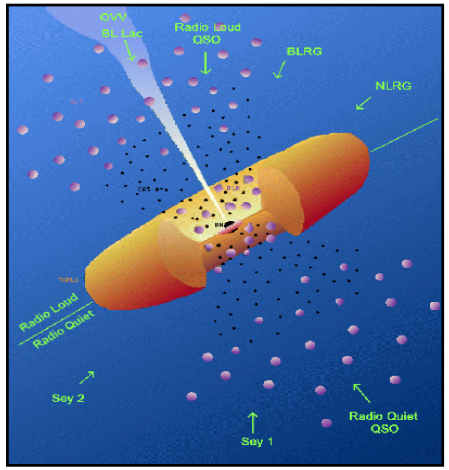
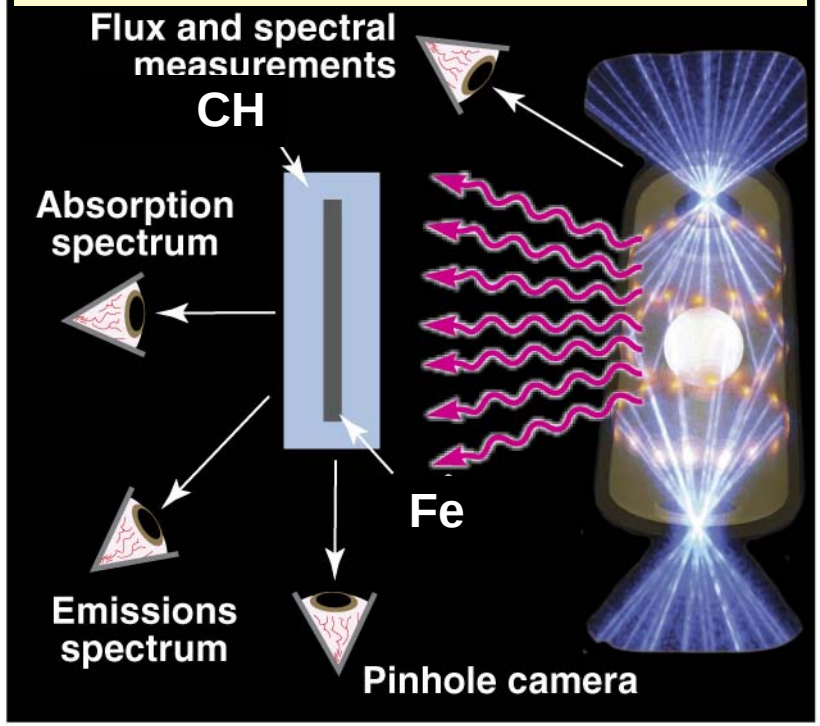
Low mass X-ray binary
ξ=30 ergcms^{-1}



Seyfert galaxy
ξ=300 ergcms^{-1}



NIF with burning capsule



Laboratory Astro/Nuclear Physics

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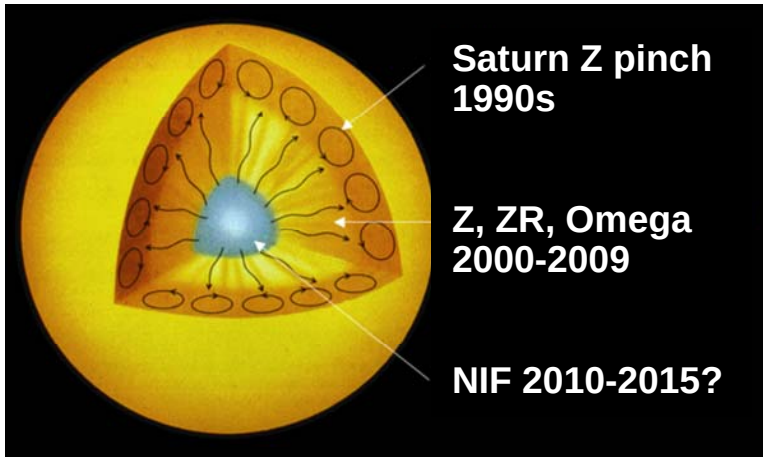
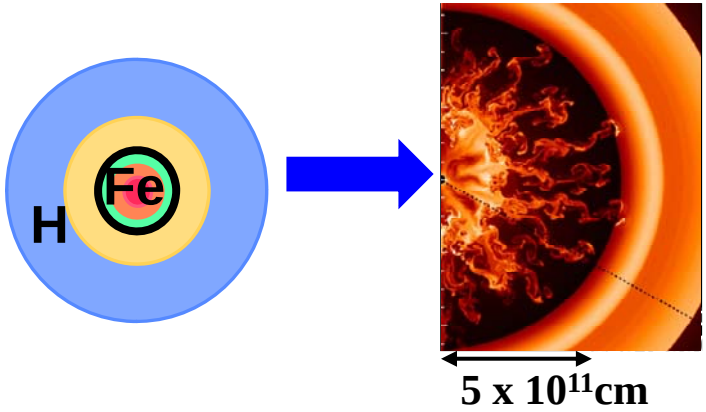
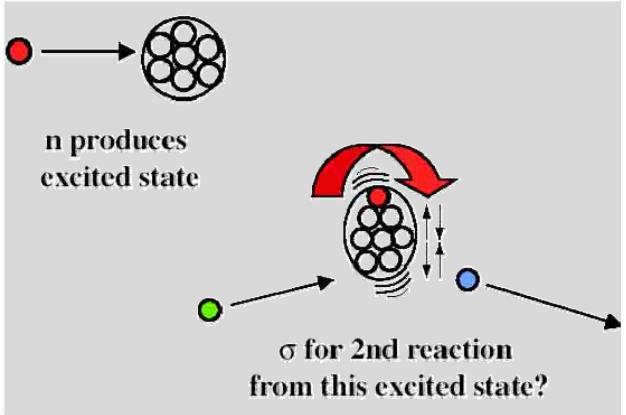
- **Measure opacities relevant to stellar evolution**
  - **Can measure LTE and non-LTE conditions at high T and high or low rho**



- **Test codes modeling turbulence on NIF**
  - **Supernovea simulations suggest significant mix: NIF can benchmark these simulations**
  - **How were heavy elements dispersed in the Universe**



- **Test nuclear physics models**
  - **Benchmark excited state nuclear physics**
  - **Dense plasma effects on reaction rates**
  - **Test models for big bang nucleosynthesis**
  - **Helps to determine temperatures of stars**



NIF will reach near core conditions of the sun and measure $\kappa_{Rosseland}$ to ~10%

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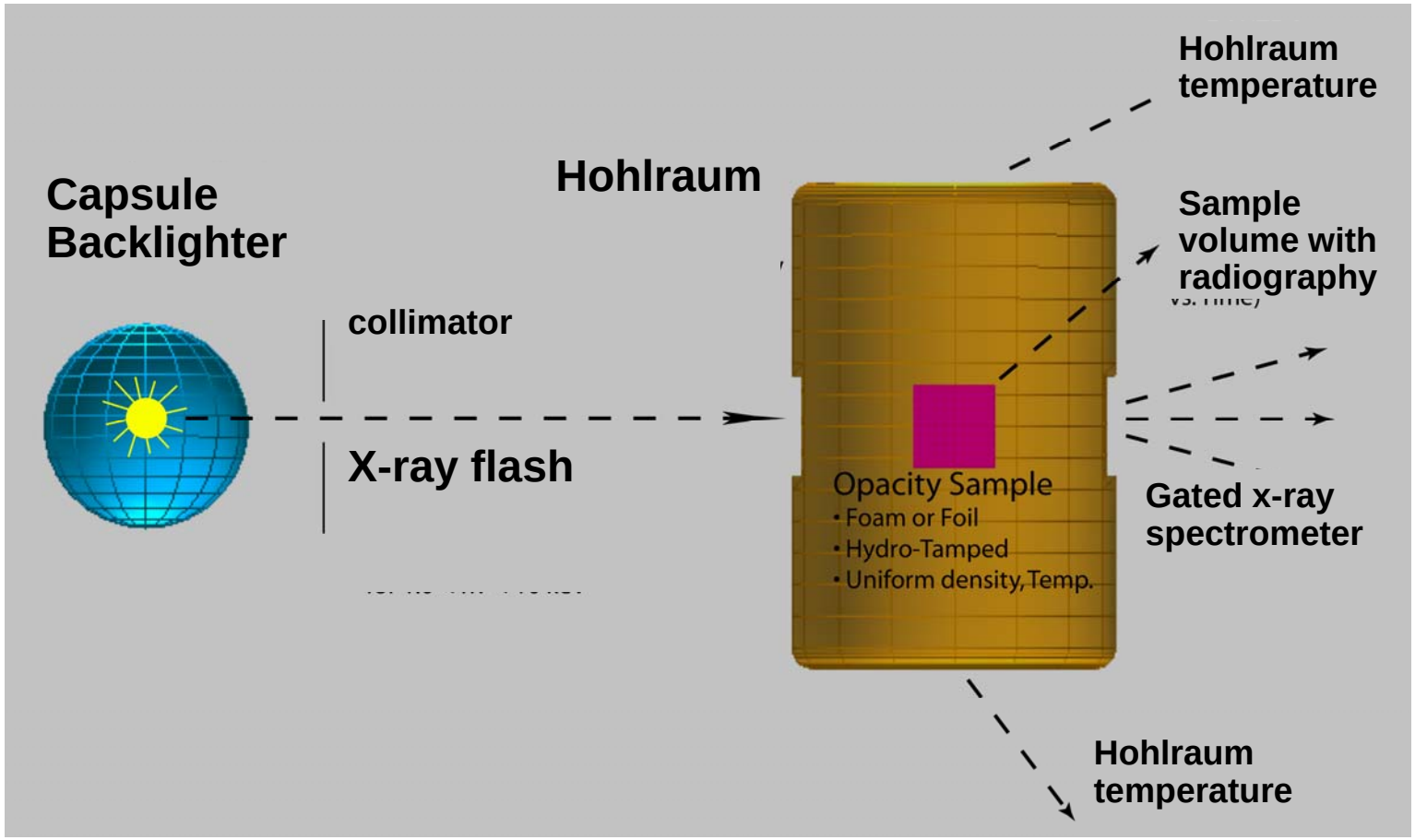
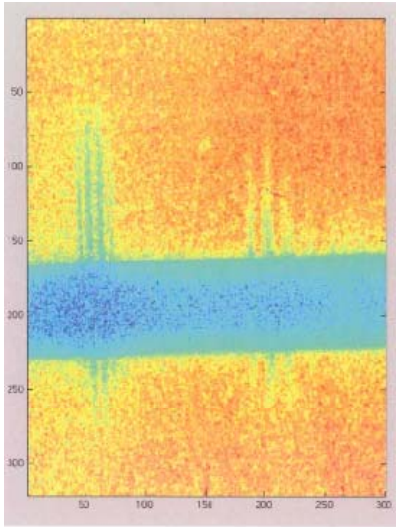


Ti data at Omega .05 g/cc, 125 eV,



Ti n=2 to n=1

Ti n=3 to n=1

Solar Radiative Region: 200-1350 eV

(Bahcall, *Rev. Mod. Phys.* 67, 781, 1995)

NIF 750 TW estimate from semi-emperical scaling: >700 eV

(Dewald PRL 95, 215004(2005).)

Supernovae come in two general categories

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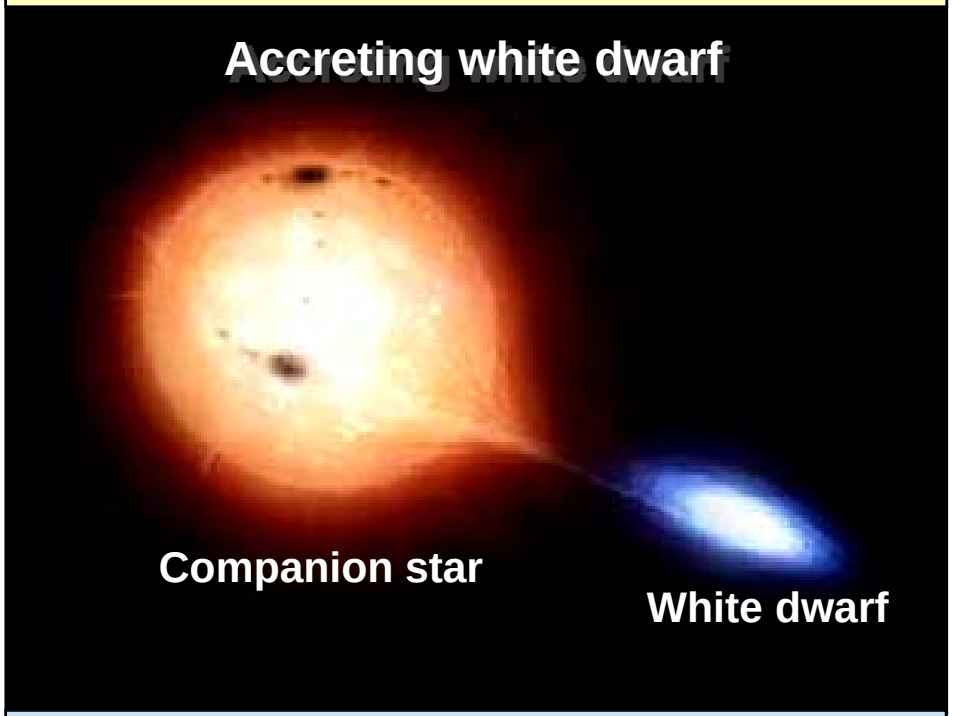
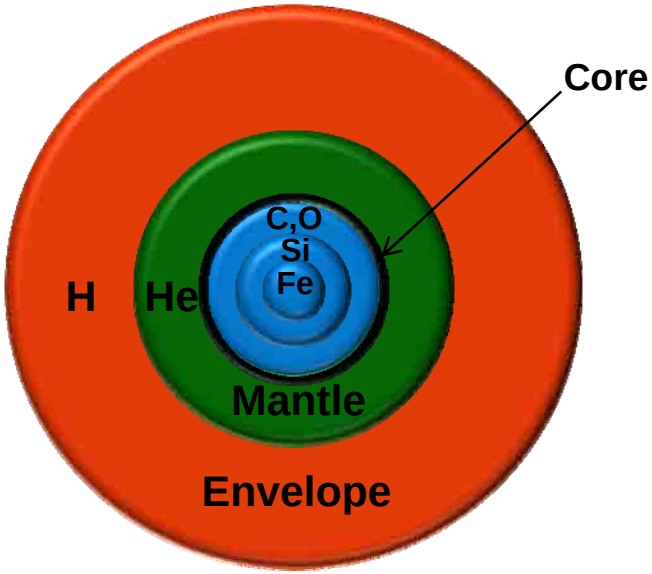
Type 1A: Thermonuclear



- Involve M~M_{sun} stars
- Optically brighter
- Standardized candles
- Serve as distance indicators

Type II: Core Collapse

Fe core in massive star collapses



- Involve M >> M_{sun} stars
- More energetic
- More frequent
- Leaves a neutron star behind

Supernovae come in two general categories

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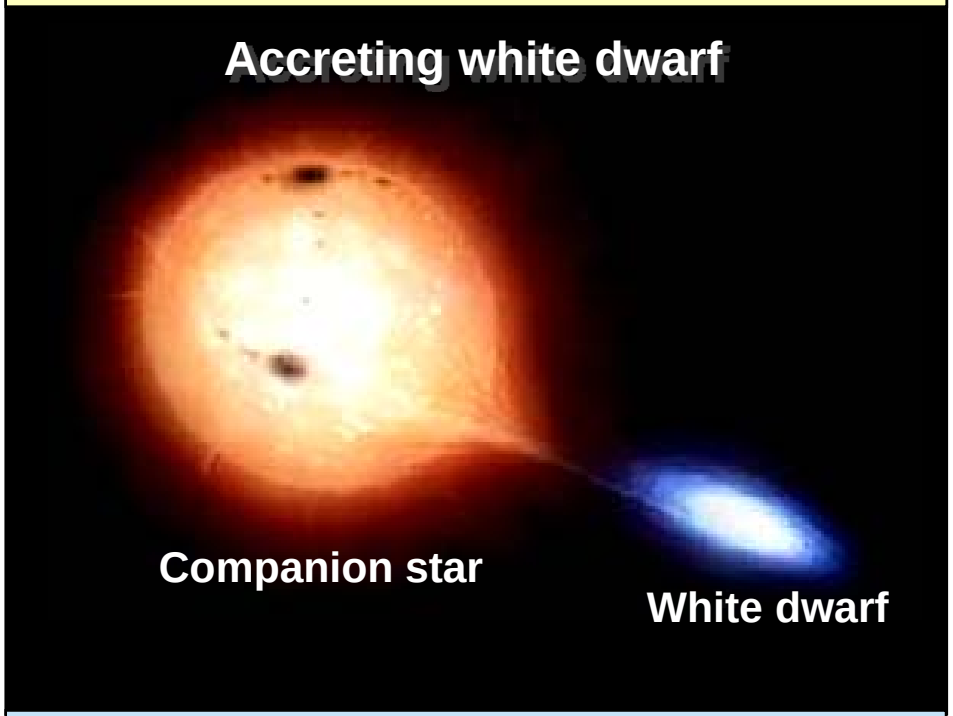
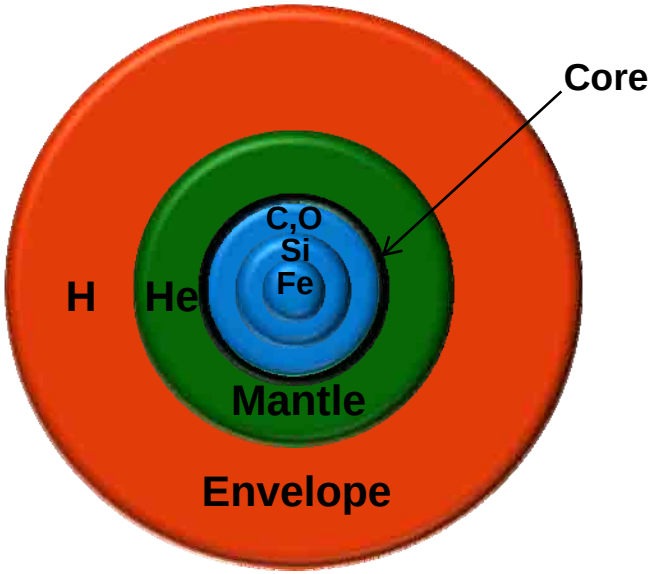
Type 1A: Thermonuclear



- Source of the elements up to Z ~ 26
- Data behind the accelerating universe and dark energy

Type II: Core Collapse

Fe core in massive star collapses



- Source of the heavy elements, Z > 26
- Questions:
  - How are these elements made?
  - How are they ejected?

Type II supernovae result from the death of a massive star

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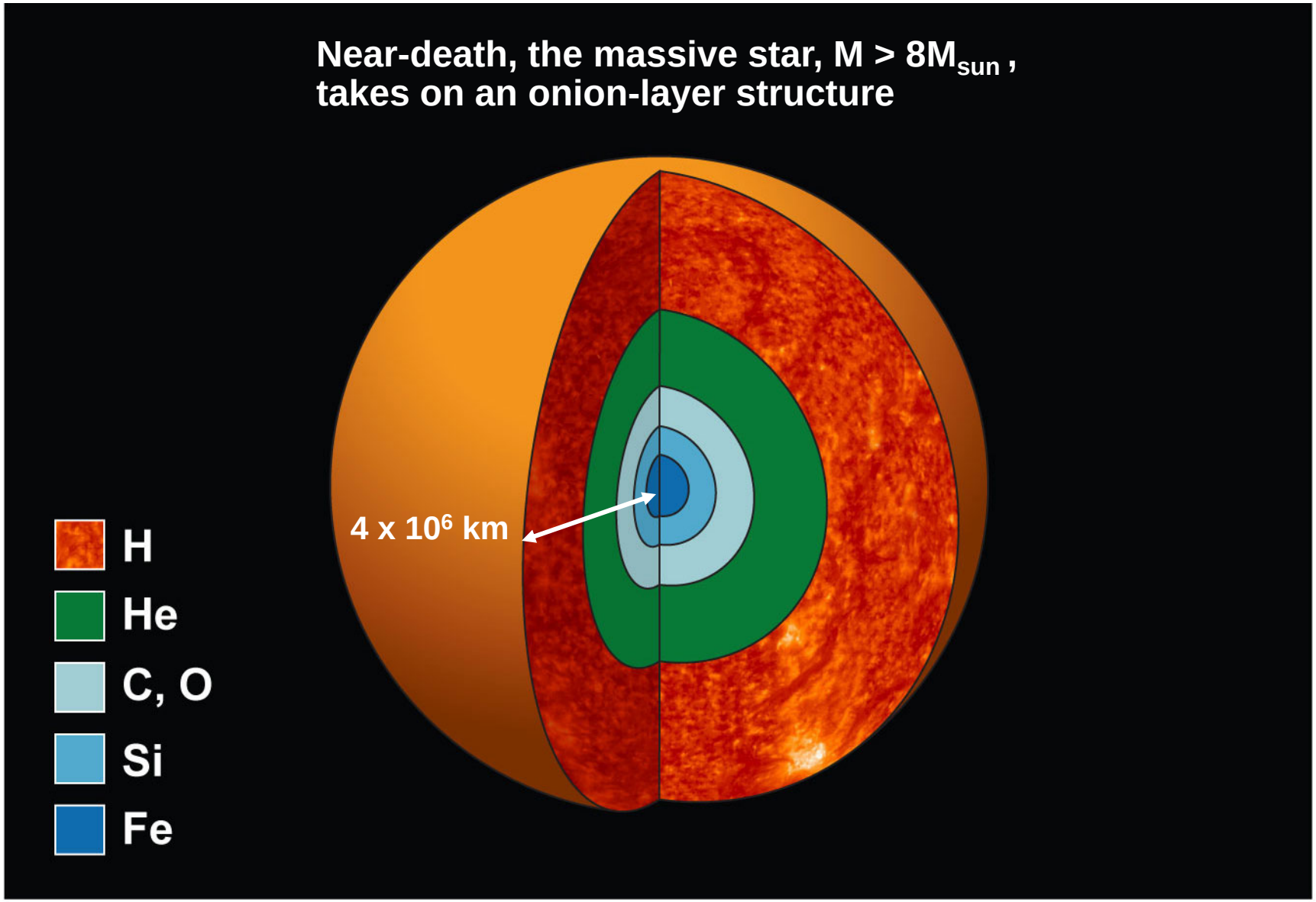

[Hillebrandt, Sci. Am., 43 (Oct. 2006)]

NIF-0409-16186L1
08BR/al

Type II supernovae result from the death of a massive star

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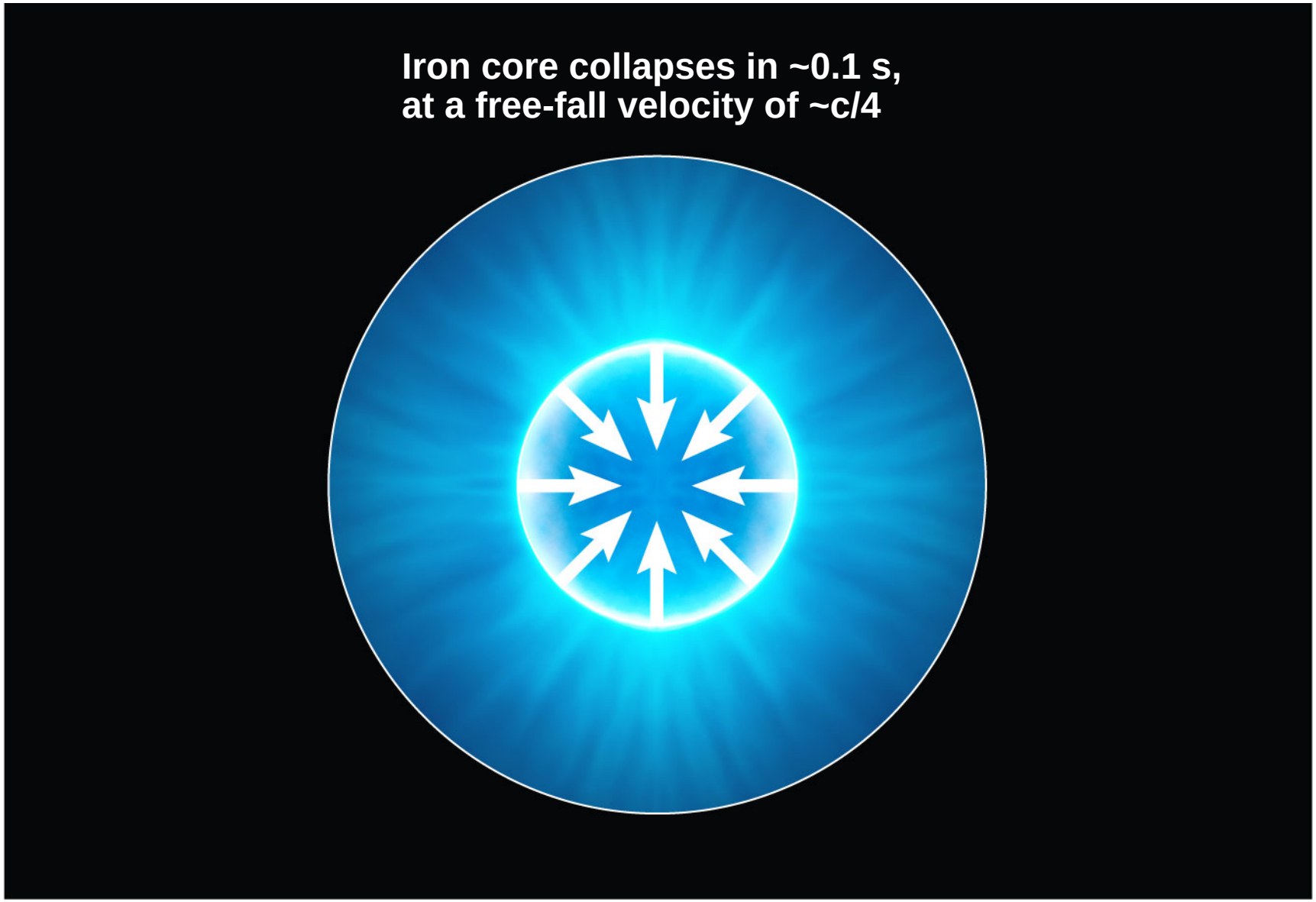

[Hillebrandt, Sci. Am., 43 (Oct. 2006)]

NIF-0409-16186L2
08BR/al

Type II supernovae result from the death of a massive star

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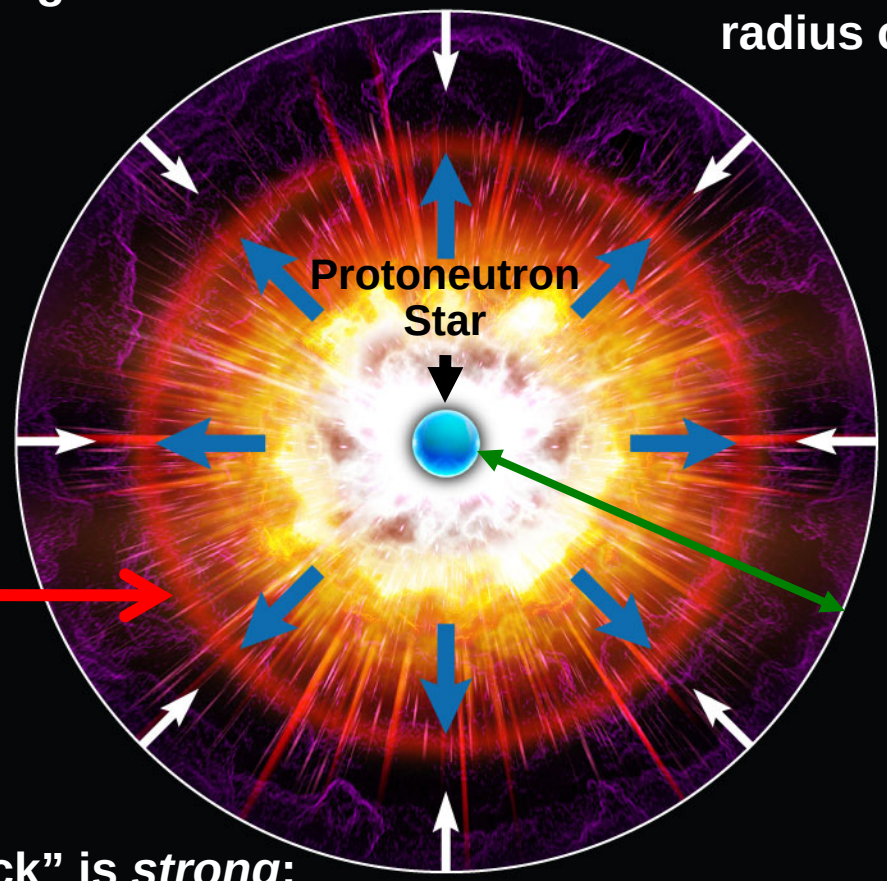
Rebound occurs when core reaches nuclear density, launching a *strong* shock

At nuclear density, $\rho_{nuclear} \sim 2 \times 10^{14}$ g/cm^3, the Earth would have a radius of only ~192 m



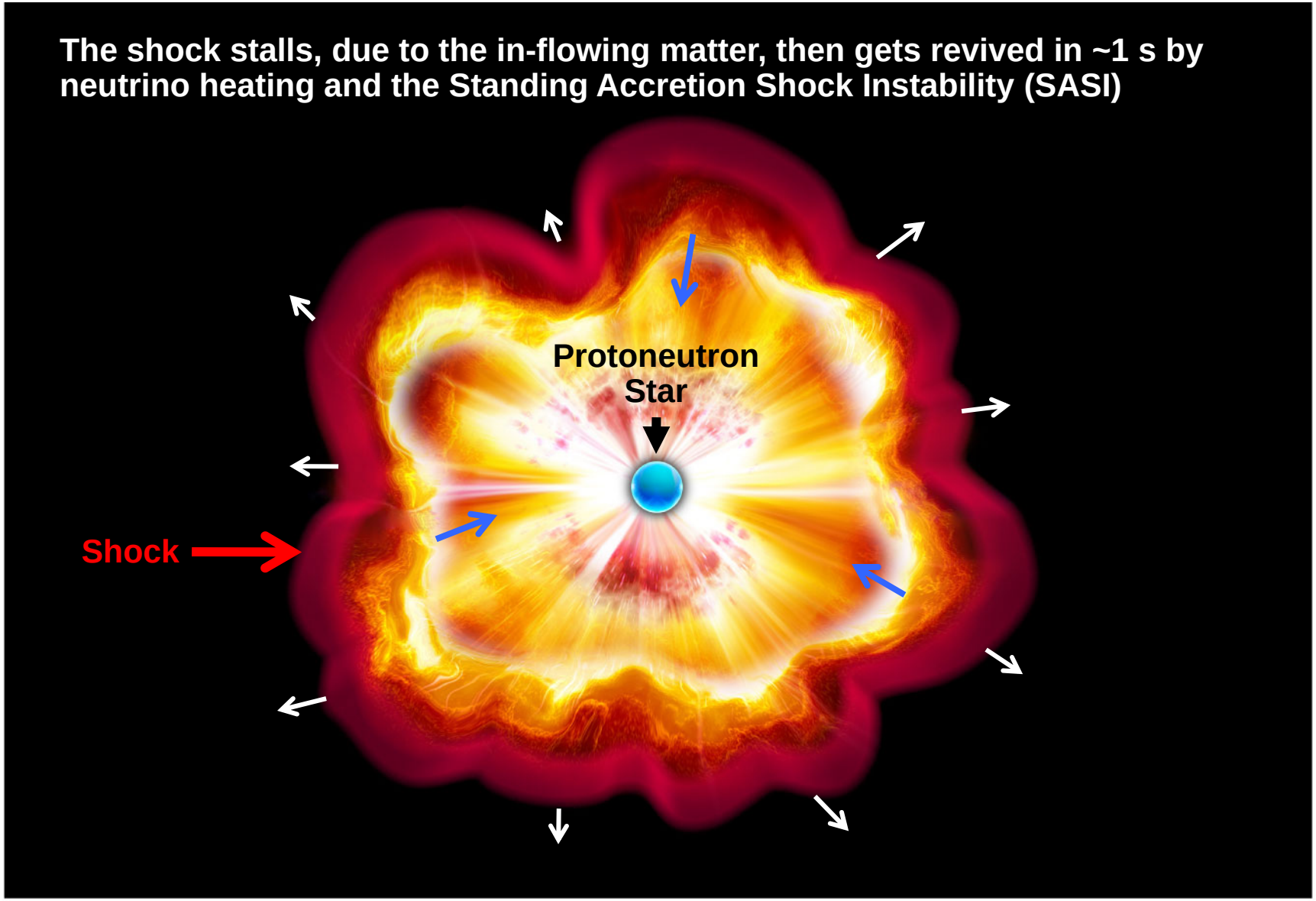
A "nuclear shock" is *strong*:
$P_{shock} \sim 1$ MeV / fm^3 ~ 10^{21} Mbar

[Hillebrandt, Sci. Am., 43 (Oct. 2006)]

NIF-0409-16186L3
08BR/al

Type II supernovae result from the death of a massive star

The National Ignition Facility

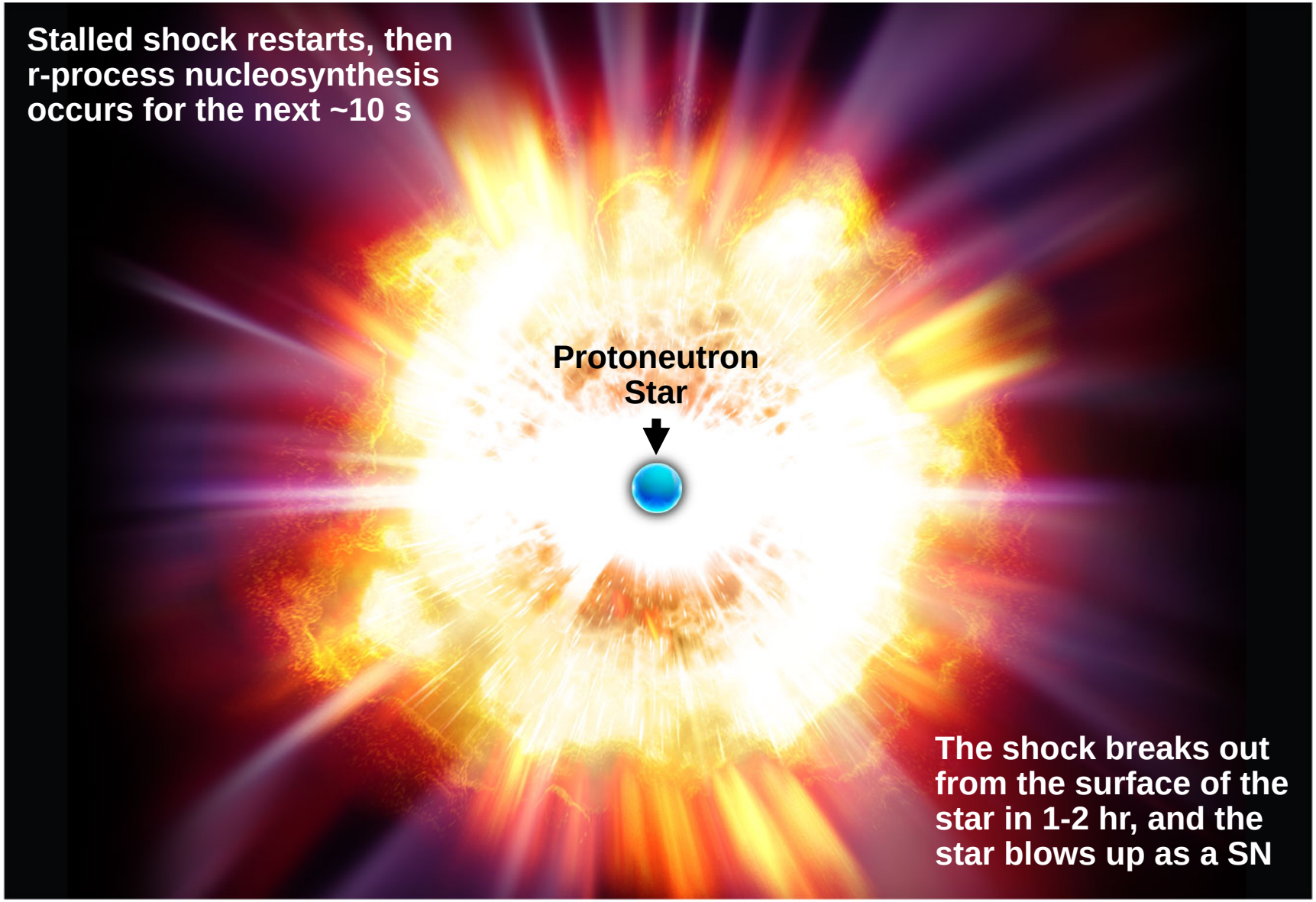


[Hillebrandt, Sci. Am., 43 (Oct. 2006)]

NIF-0409-16186L4
08BR/al

Type II supernovae result from the death of a massive star

The National Ignition Facility

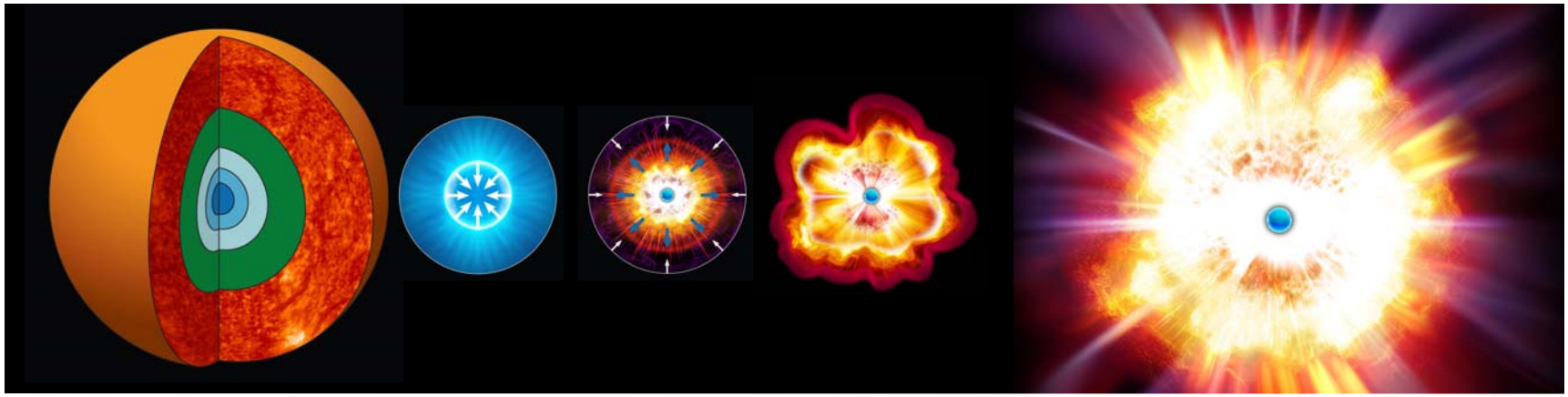


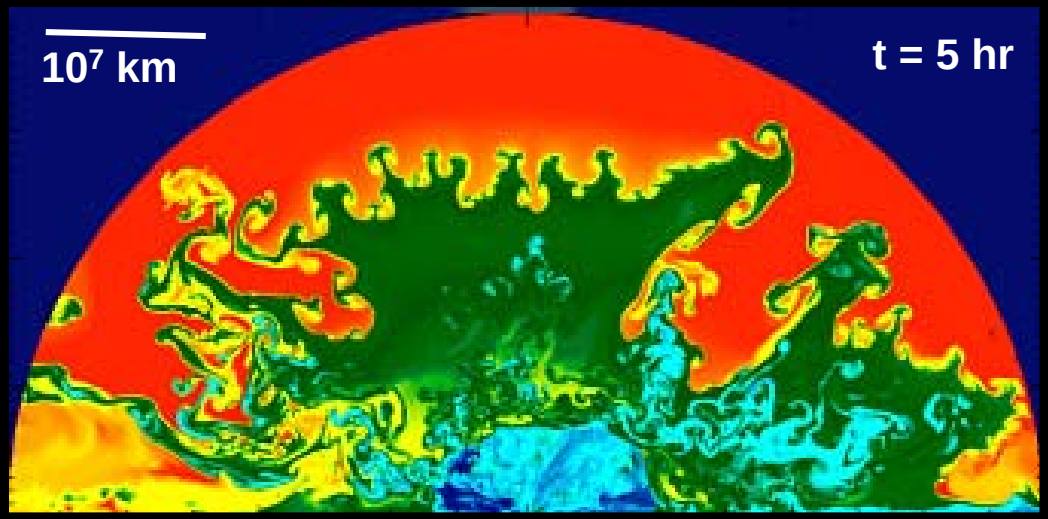
[Hillebrandt, Sci. Am., 43 (Oct. 2006)]

NIF-0409-16186L5
08BR/al

Type II supernovae result from the death of a massive star

The National Ignition Facility





Turbulence mixes core (blue) into the overlying He mantle (green) and H envelope (red). Some fraction of the core, carrying the synthesized heavy elements, gets ejected.

[Hillebrandt, Sci. Am., 43 (Oct. 2006)]

P. Drake et al. are developing designs to recreate a scaled supernova explosion on NIF

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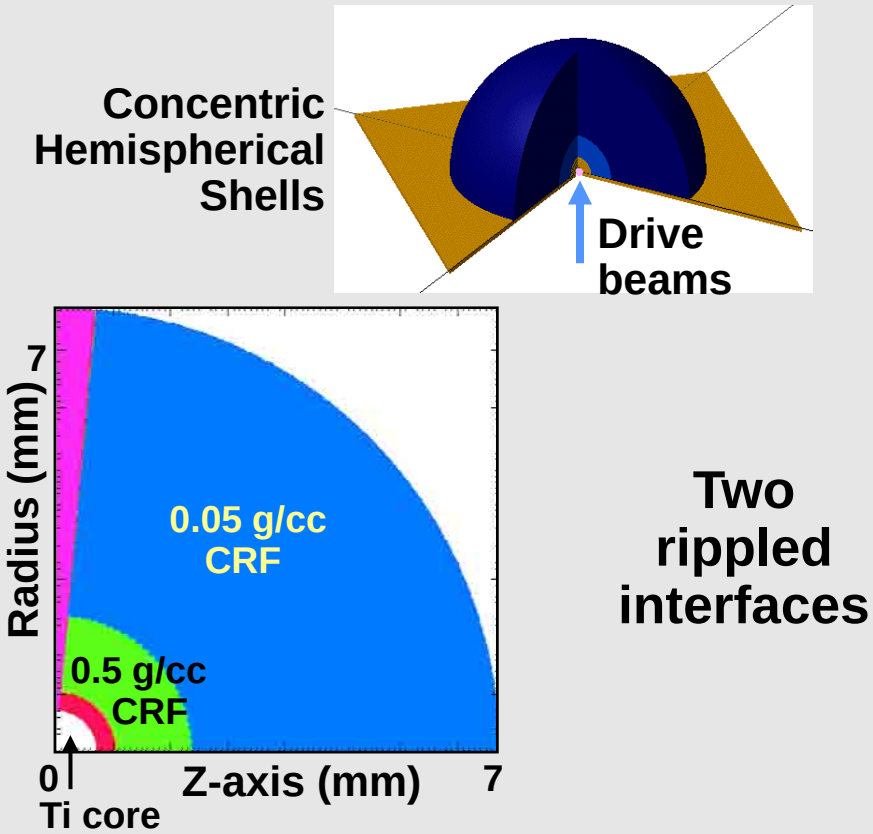
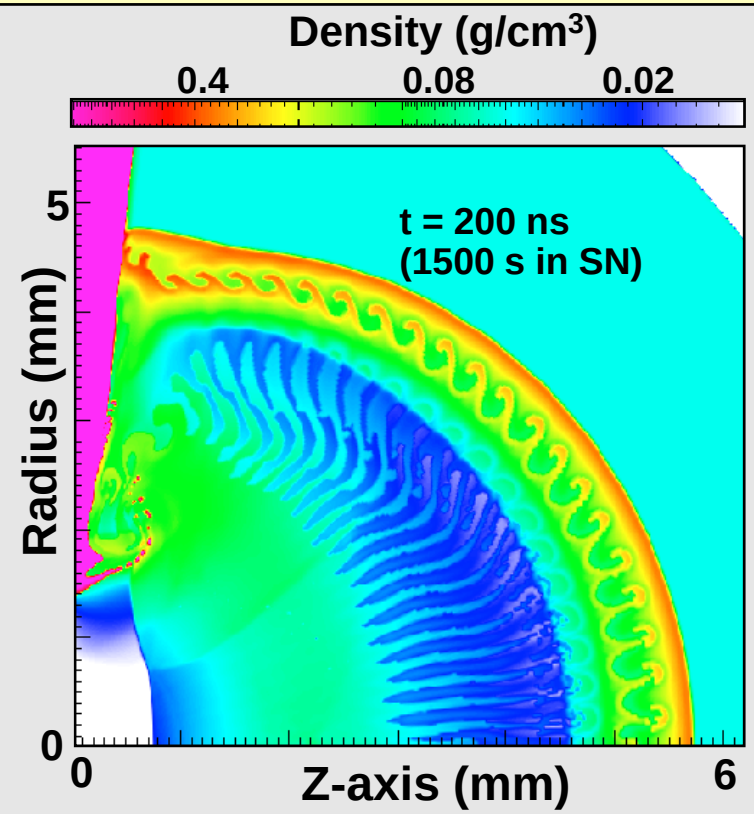
Scaled SN1987A on NIF



Two rippled interfaces

Simulation of Proposed Experiment



- Simulations show deep nonlinear mixing relevant to SN1987A
- Rho-t scaling described in Ryutov *et al*., Ap.J. 518, 821 (1999); Ap.J. Suppl. 127, 465 (2000); Phys. Plasmas 8, 1804 (2001)]
- fully developed turbulence will be experimentally studied at NIF

HED Plasma induced excited state population is believed to play a role in s-process nucleosynthesis

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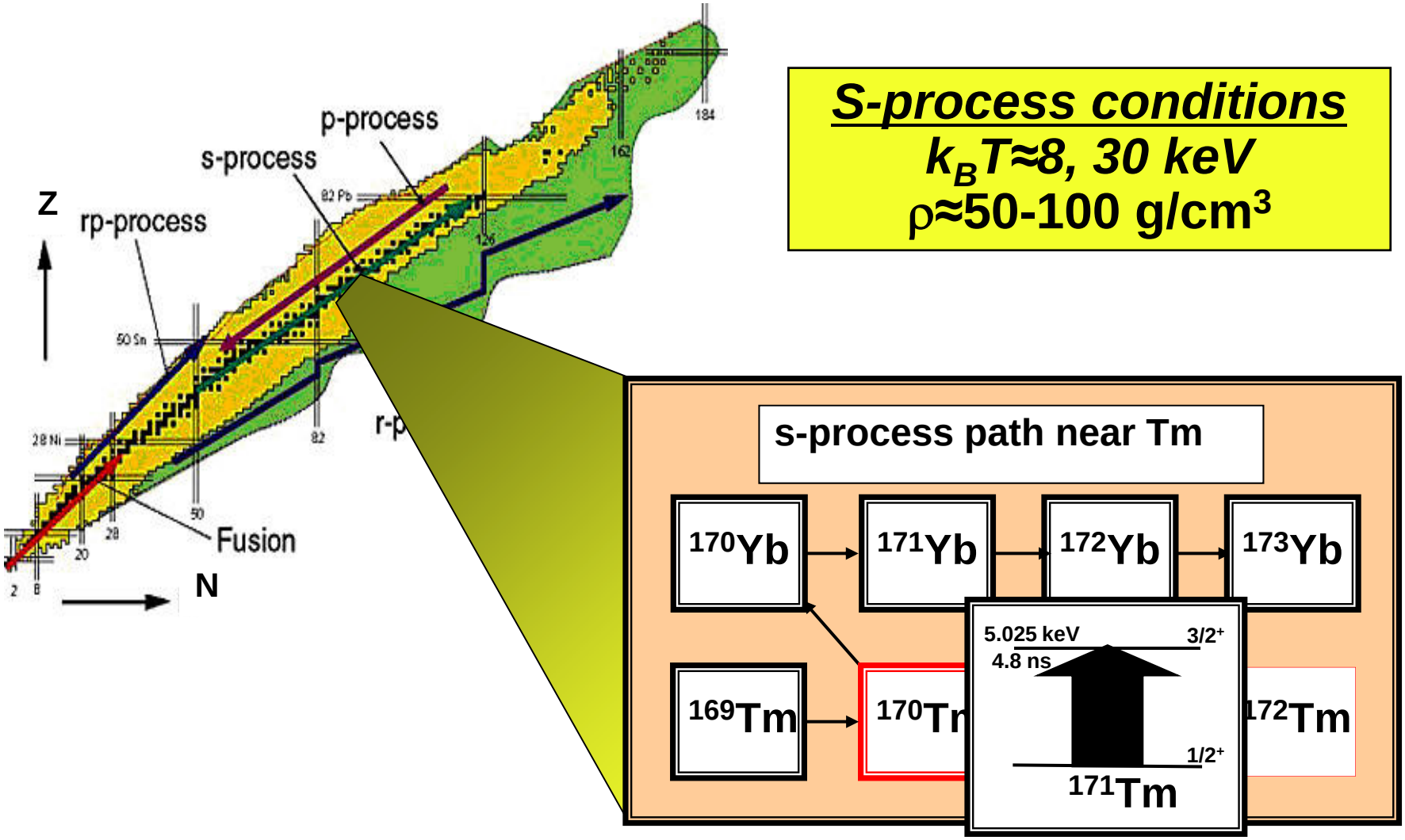

Dope ICF capsule with Tm, capture products from debris, measure ratio of 172/170 to determine s-process cross section enhancement factors

Extreme laser intensities

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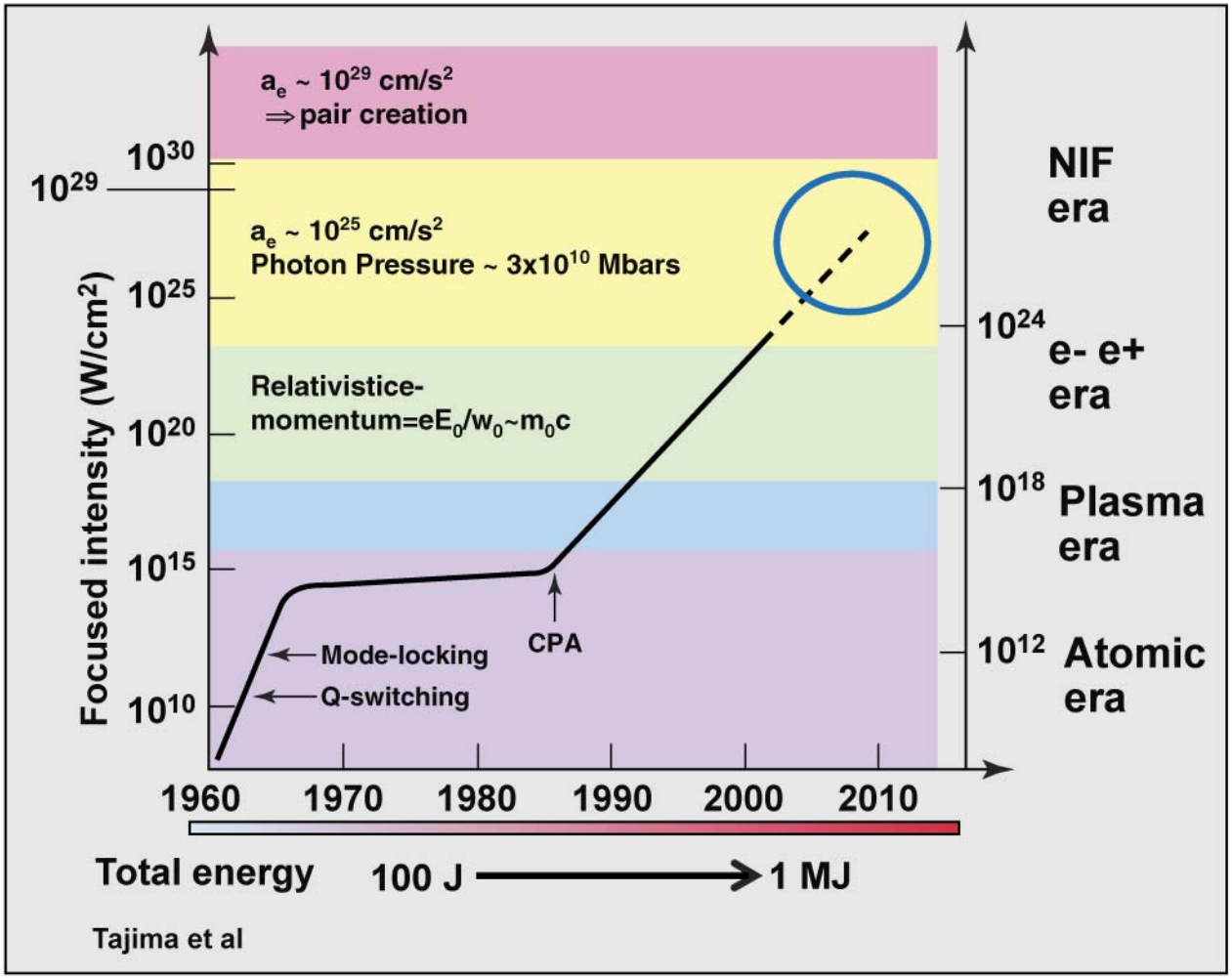


- What happens at 10^{25} W/cm^2 ? =>photon pressure ~ 10^{10} Mbars
- Can we learn how cosmic accelerators work?
- Nature of laser-matter interaction at high energy & intensity

Plasma pulse amplification and compression at NIF can produce unprecedented intensities on target

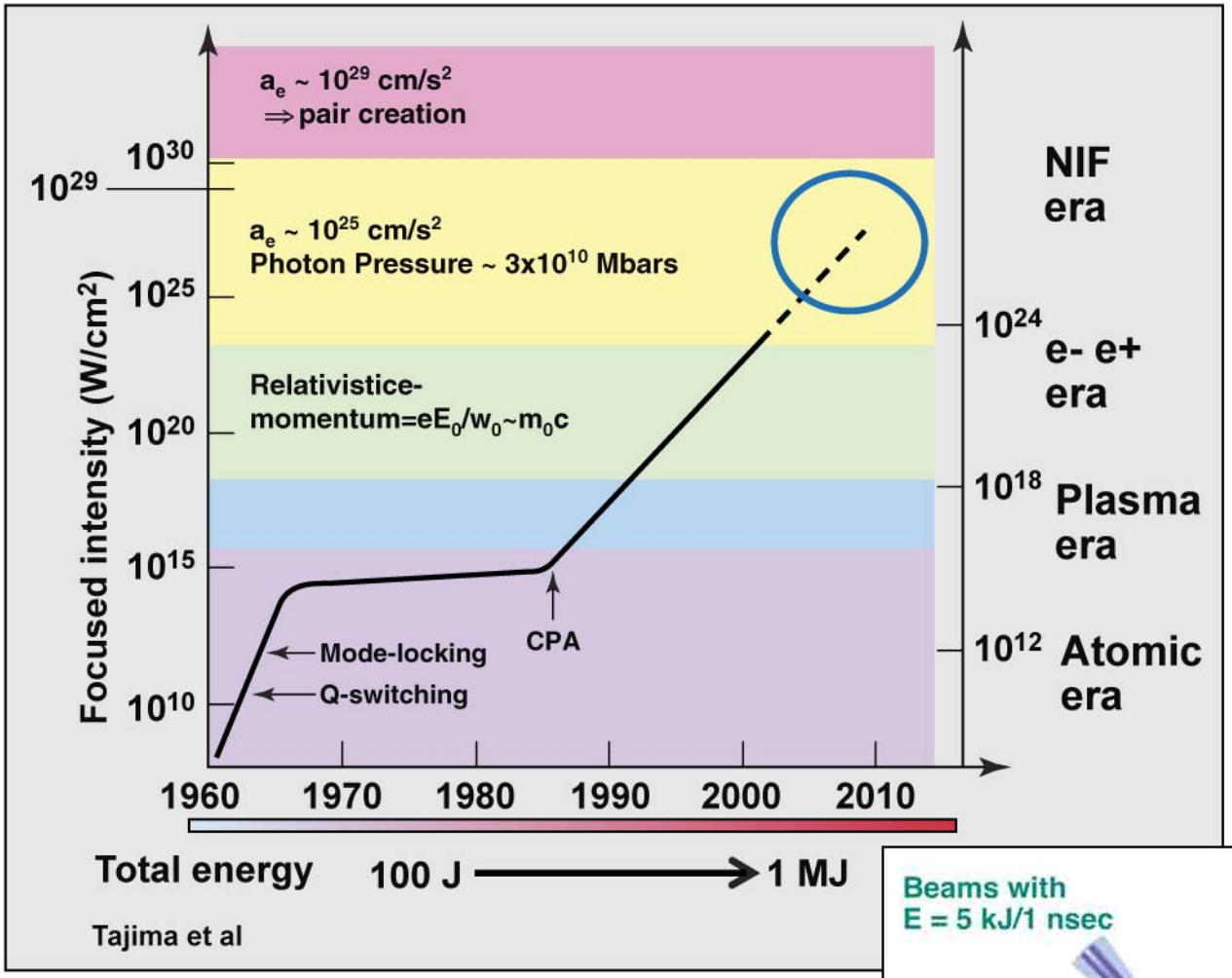
R. Kirkwood, Physics of Plasmas 2007

J. Ren, Nature Physics, 2007

R. Kirkwood, Physics Rev. Lett., 1996

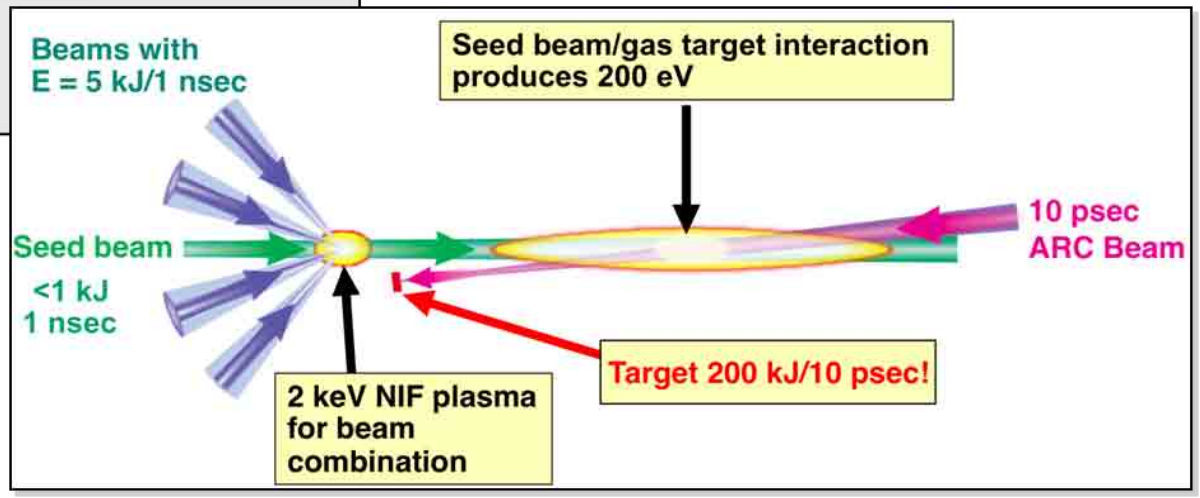
Y. Ping Submitted PRL

Extreme laser intensities



- What happens at 10^{25} W/cm^2 ? =>photon pressure ~ 10^{10} Mbars
- Can we learn how cosmic accelerators work?
- Nature of laser-matter interaction at high energy & intensity

Plasma pulse amplification and compression concept for NIF



We are just starting to develop science "platforms" to explore this new frontier of science

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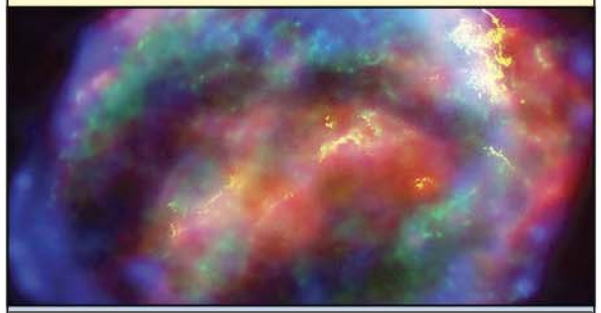
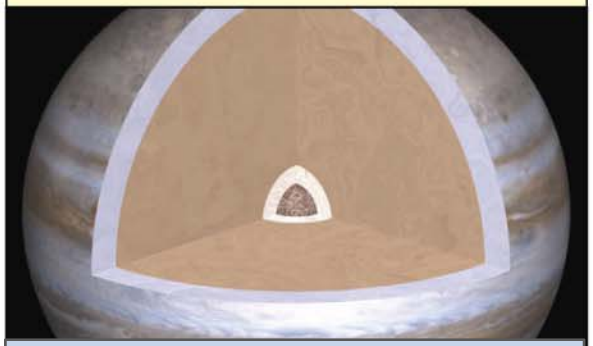
Astro/Nuclear Physics



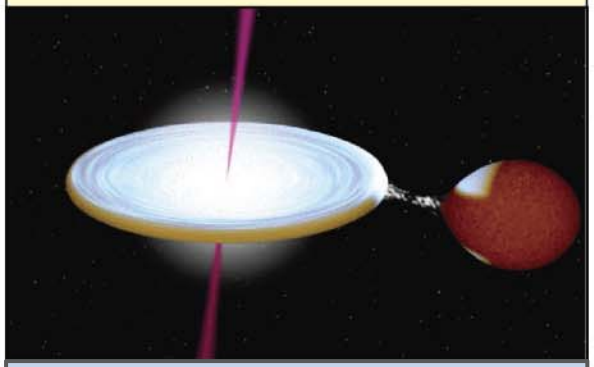
G. Fuller, U. Greife, Z. Shayer, C. Brune, R. Boyd, L. Bernstein

Ultra-Dense Matter



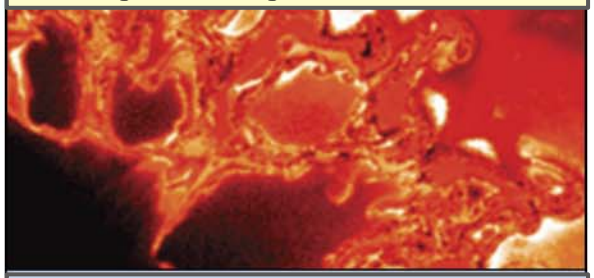
R. Jeanloz, T. Duffy, R. Hemley, Y. Gupta, P. Loubeyre, L. Stixrude, S. Rose, J. Wark, G. Collins

Burning Plasmas



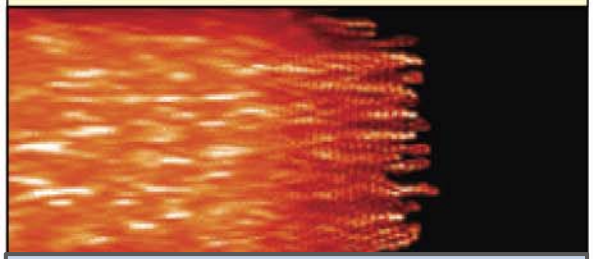
S. Rose, R. Betti, J. Meyer-Ter-Vehn, S. Atzeni, G. Collins

Astro/Rad-transport & Hydrodynamics



P. Drake, D. Arnett, A. Frank, T. Plewa, T. Ditmire, A. Takabe, B. Remington

LPI and Ultra-Intense Light Sources



N. Fisch, C. Niemann, C. Joshi W. Mori, B. Afeyan, D. Montgomery, A. Schmitt, B. Kirkwood

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