Use of NIF in Nuclear Astrophysics: Examples of Experiments

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CSEWG & USNDP

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NIF has 3 Missions

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- *Stockpile Stewardship*
- *Basic Science*
- *Fusion Energy*

Peer-reviewed Basic Science is a fundamental part of NIF's plan

Our vision: open NIF to the outside scientific community to pursue frontier HED laboratory science

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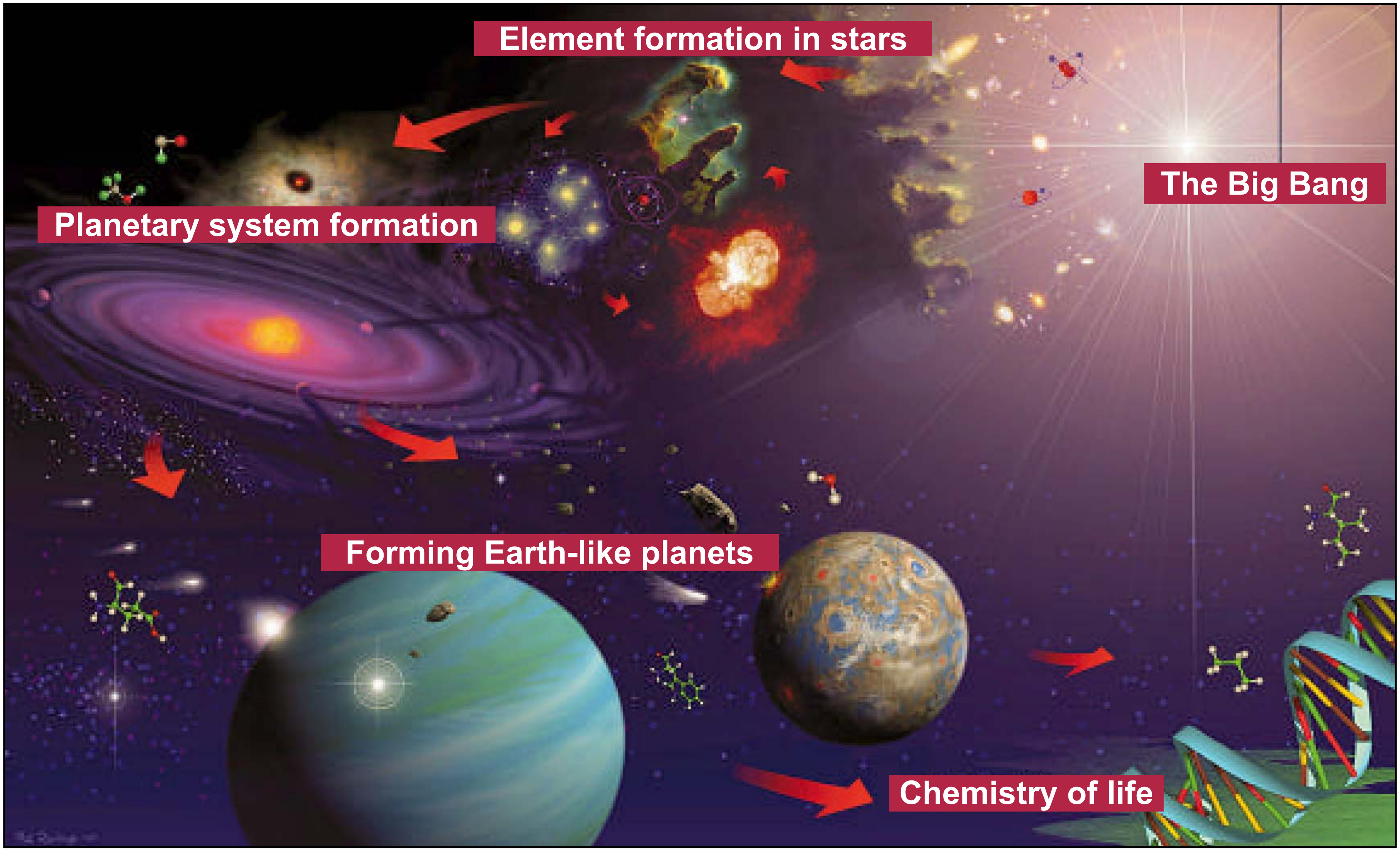
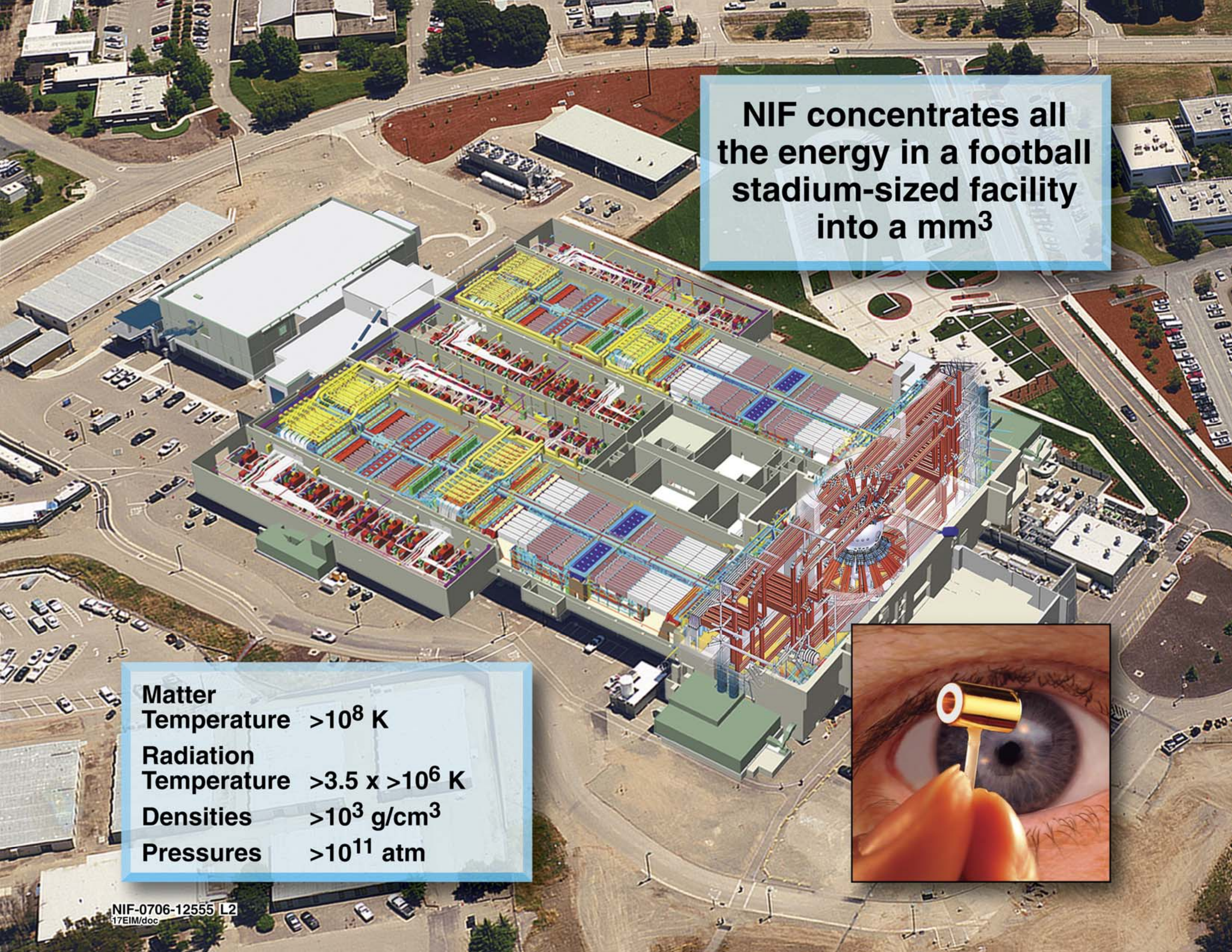


[http://www.nas.edu/bpa/reports/cpu/index.html



NIF concentrates all the energy in a football stadium-sized facility into a mm^3
Matter Temperature >10^8 K
Radiation Temperature >3.5 x >10^6 K
Densities >10^3 g/cm^3
Pressures >10^{11} atm
NIF-0706-12555 L2
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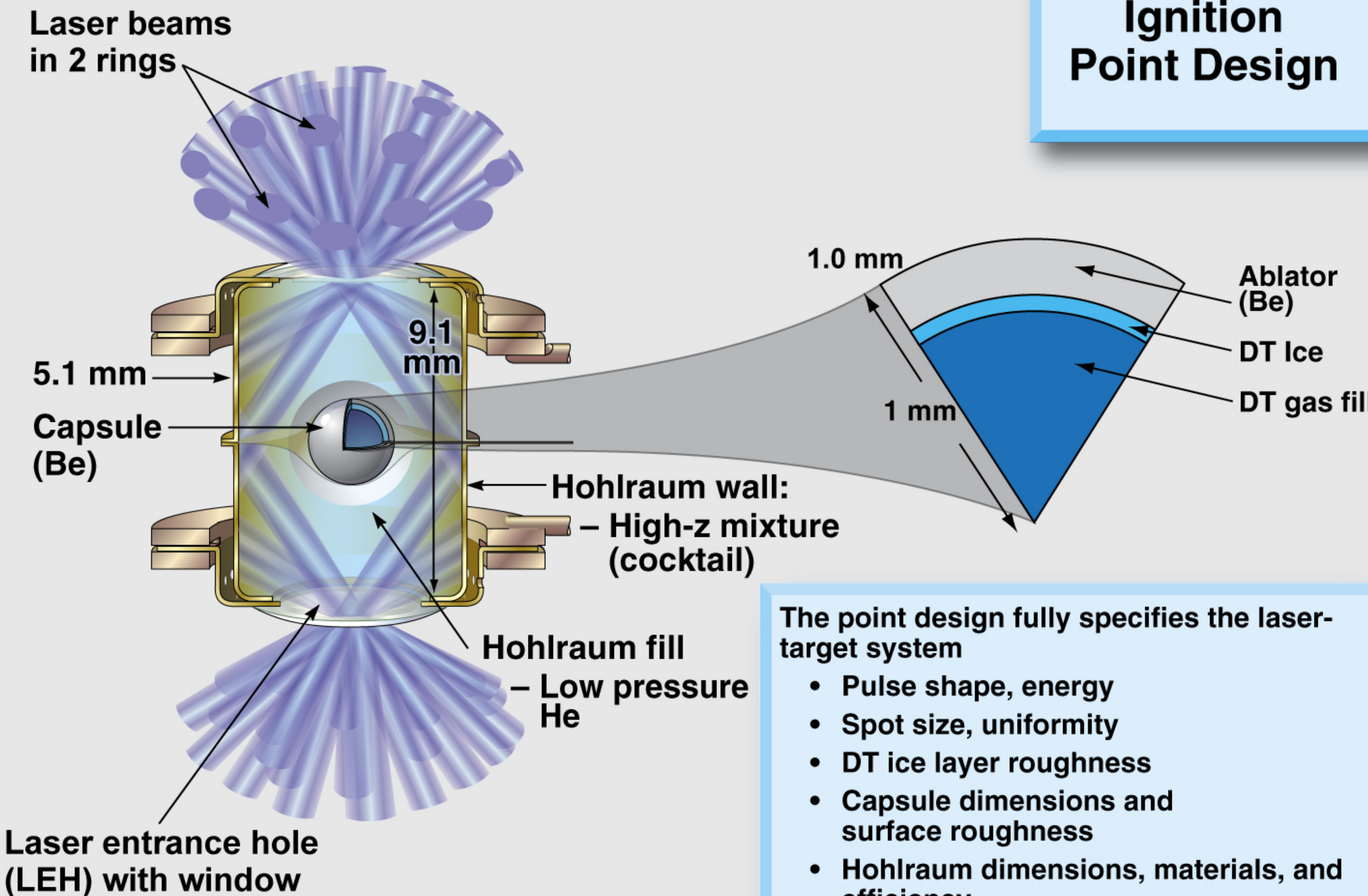
Ignition Point Design



The point design fully specifies the laser-target system

- Pulse shape, energy
- Spot size, uniformity
- DT ice layer roughness
- Capsule dimensions and surface roughness
- Hohlraum dimensions, materials, and efficiency
- Target thermal and positioning stability
- Diagnostics

We have 30 types of diagnostic systems planned for NIC

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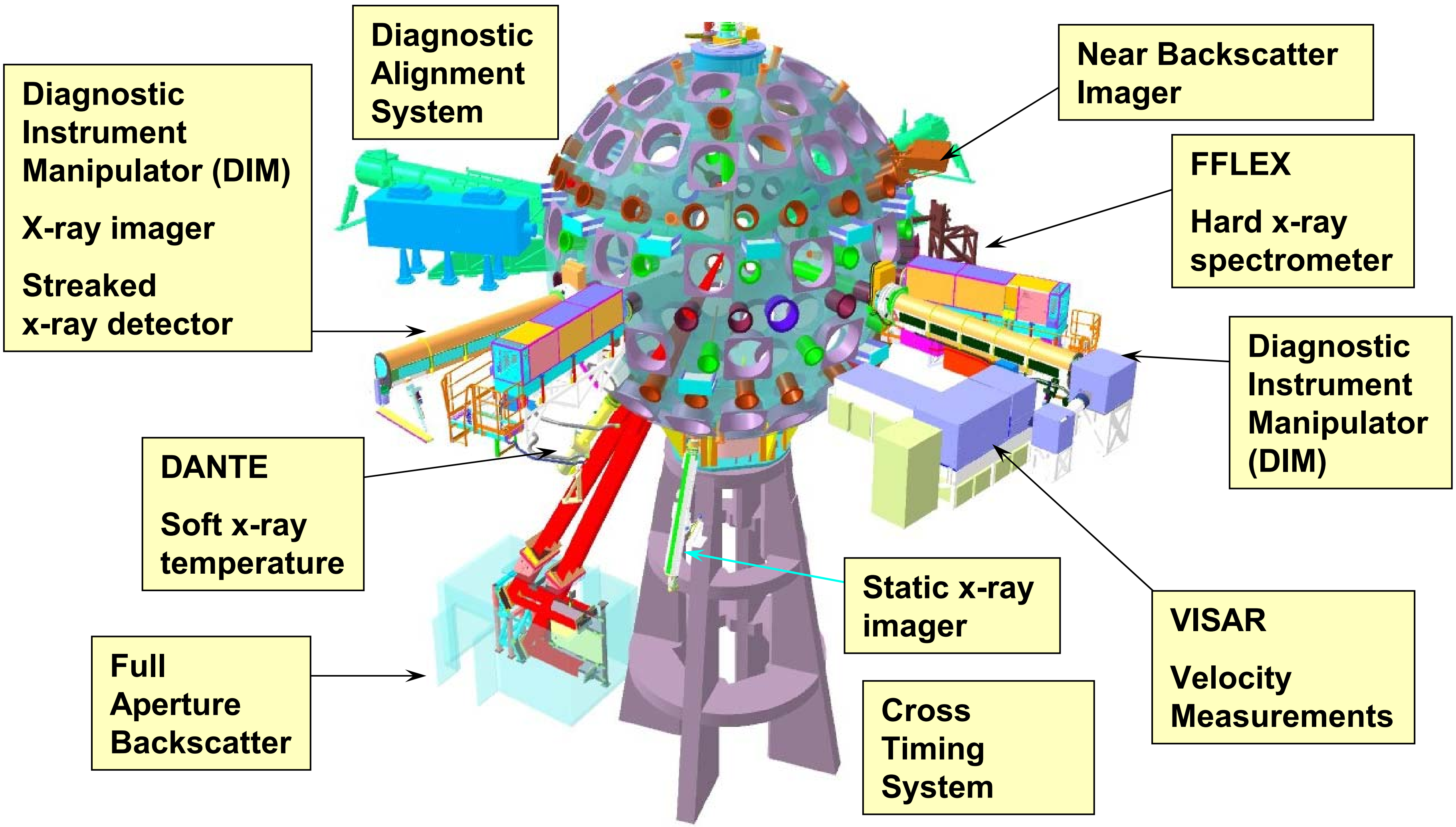


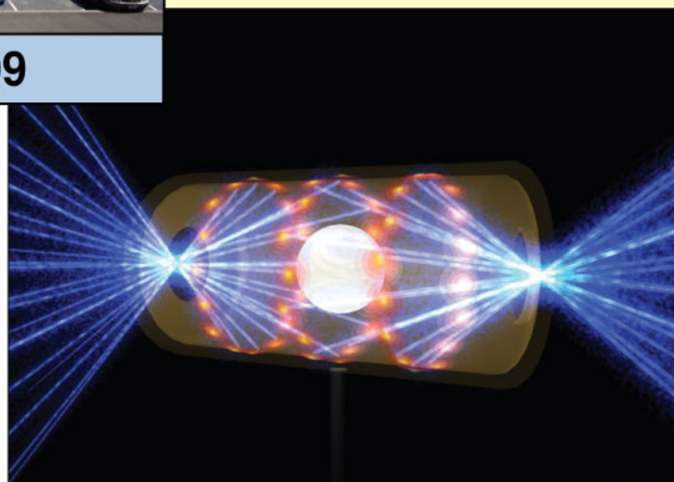
We have already fielded ~ half of all the types of diagnostic systems needed for NIF science

NIF Master Strategy

NIF Project

Completion in 2009

National Ignition Campaign



2006—2012

National User Facility

2009—2030

NIF-0506-12063r9_L1
20/geg

Inception to Completion Flow Chart

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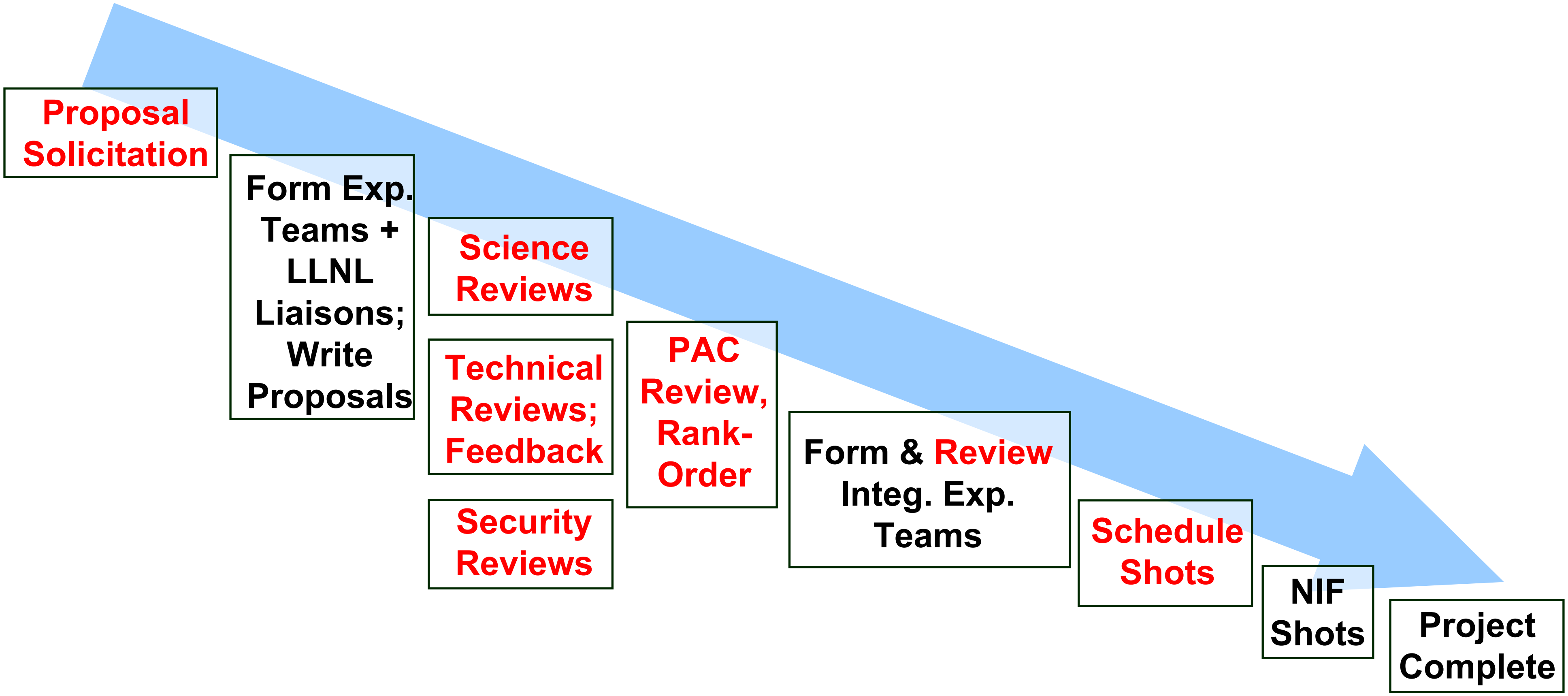

… And Workshops

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- With more to come—on:
  - Condensed matter
  - Nuclear physics
  - Getting up to speed for using NIF

NIF's Unprecedented Scientific Environments:

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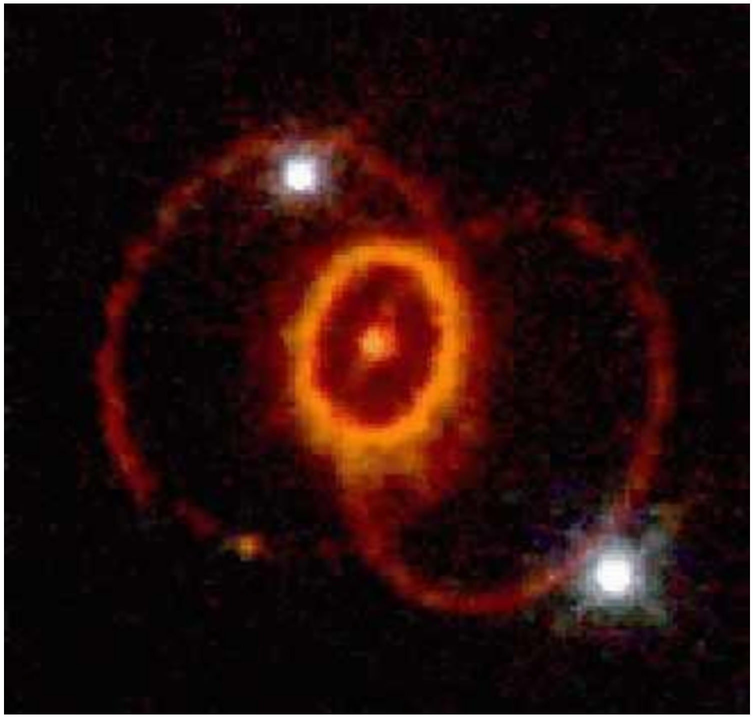
- T >10^8 K matter temperature
- ρ >10^3 g/cc density

Those are both 7x what the *Sun* does! Helium burning, stage 2 in stellar evolution, occurs at 2x10^8 K!

- ρ_n = 10^{26} neutrons/cc

Core-collapse Supernovae, colliding neutron stars, operate at ~10^{20}!



- Electron Degenerate conditions Rayleigh-Taylor instabilities for (continued) laboratory study.

These apply to Type Ia Supernovae!

- Pressure > 10^{11} bar

Only need ~Mbar in shocked hydrogen to study the EOS in Jupiter & Saturn

These certainly qualify as "unprecedented." And *Extreme!*

The NRC committee on the Physics of the Universe highlighted the new frontier of HED Science

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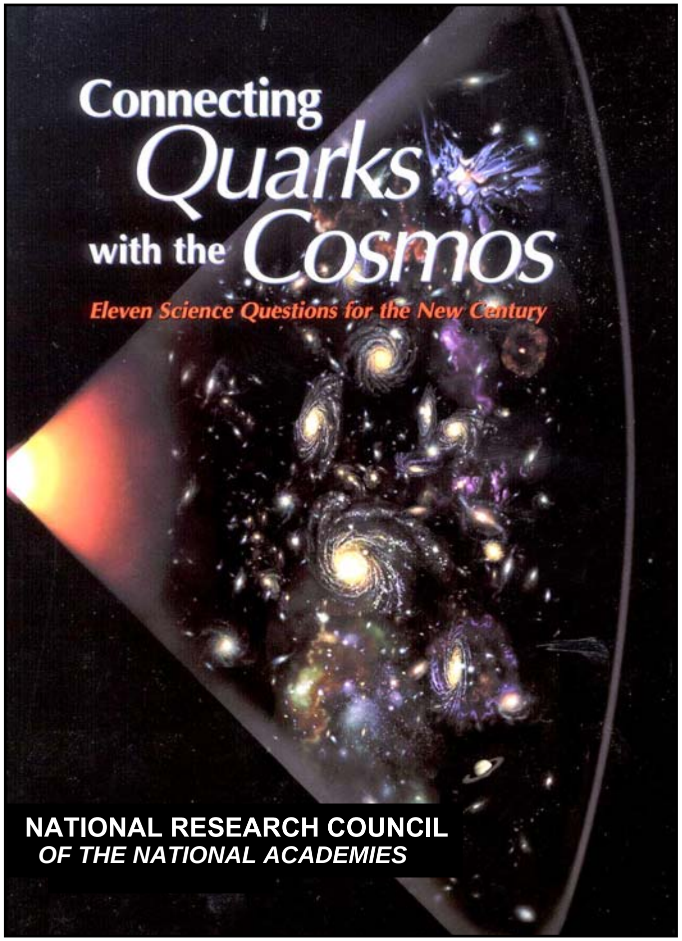

Eleven science questions for the new century:

2. What is the nature of dark energy?
— Type 1A SNe (burn, hydro, rad flow, EOS, opacities)

4. Did Einstein have the last word on gravity?
— Accreting black holes (photoionized plasmas, spectroscopy)

6. How do cosmic accelerators work and what are they accelerating?
— Cosmic rays (strong field physics, nonlinear plasma waves)

8. Are there new states of matter at exceedingly high density and temperature?
— Neutron star interior (photoionized plasmas, spectroscopy, EOS)

10. How were the elements from iron to uranium made and ejected?
— Core-collapse SNe (reactions off excited states, turbulent hydro, rad flow)

- **HEDP provides crucial experiments to interpret astrophysical observations**
- **The field should be better coordinated across Federal agencies**

Three university teams are starting to prepare for NIF shots in unique regimes of HED physics

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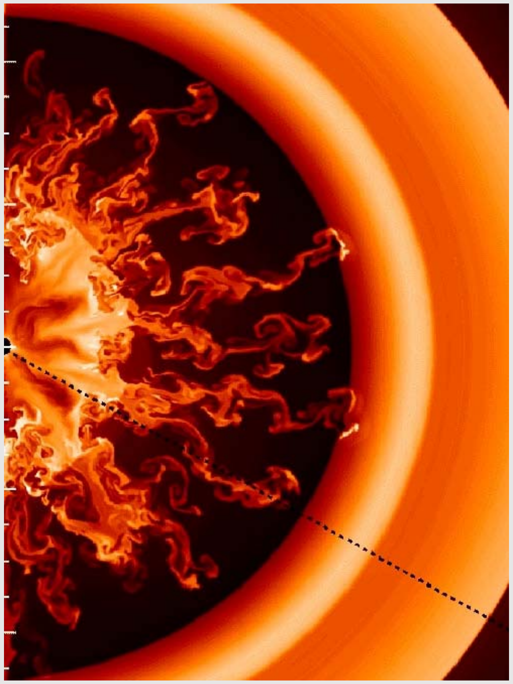
Astrophysics - hydrodynamics

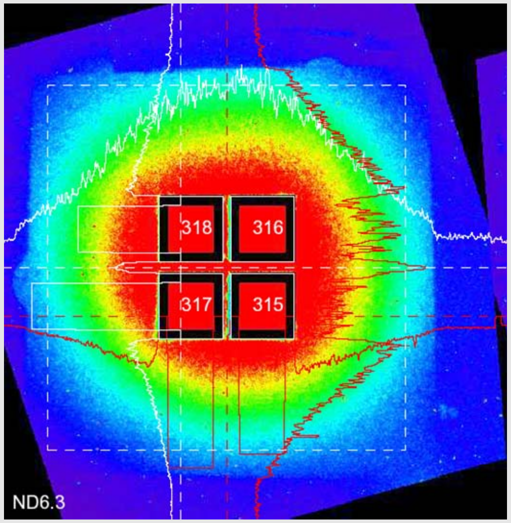


Paul Drake, PI, U. of Mich.
David Arnett, U. of Arizona,
Adam Frank, U. of Rochester,
Tomek Plewa, U. of Chicago,
Todd Ditmire, U. Texas-Austin
LLNL hydrodynamics team

Planetary physics - EOS

Raymond Jeanloz, PI,
UC Berkeley
Thomas Duffy, Princeton U.
Russell Hemley, Carnegie Inst.
Yogendra Gupta, Wash. State U.
Paul Loubeyre, U. Pierre & Marie
Curie, and CEA
LLNL EOS team

Nonlinear optical physics - LPI



Christoph Niemann, PI,
UCLA NIF Professor
Chan Joshi, UCLA
Warren Mori, UCLA
Bedros Afeyan, Polymath
David Montgomery, LANL
Andrew Schmitt, NRL
LLNL LPI team

Reaction Studies for Nuclear Astrophysics

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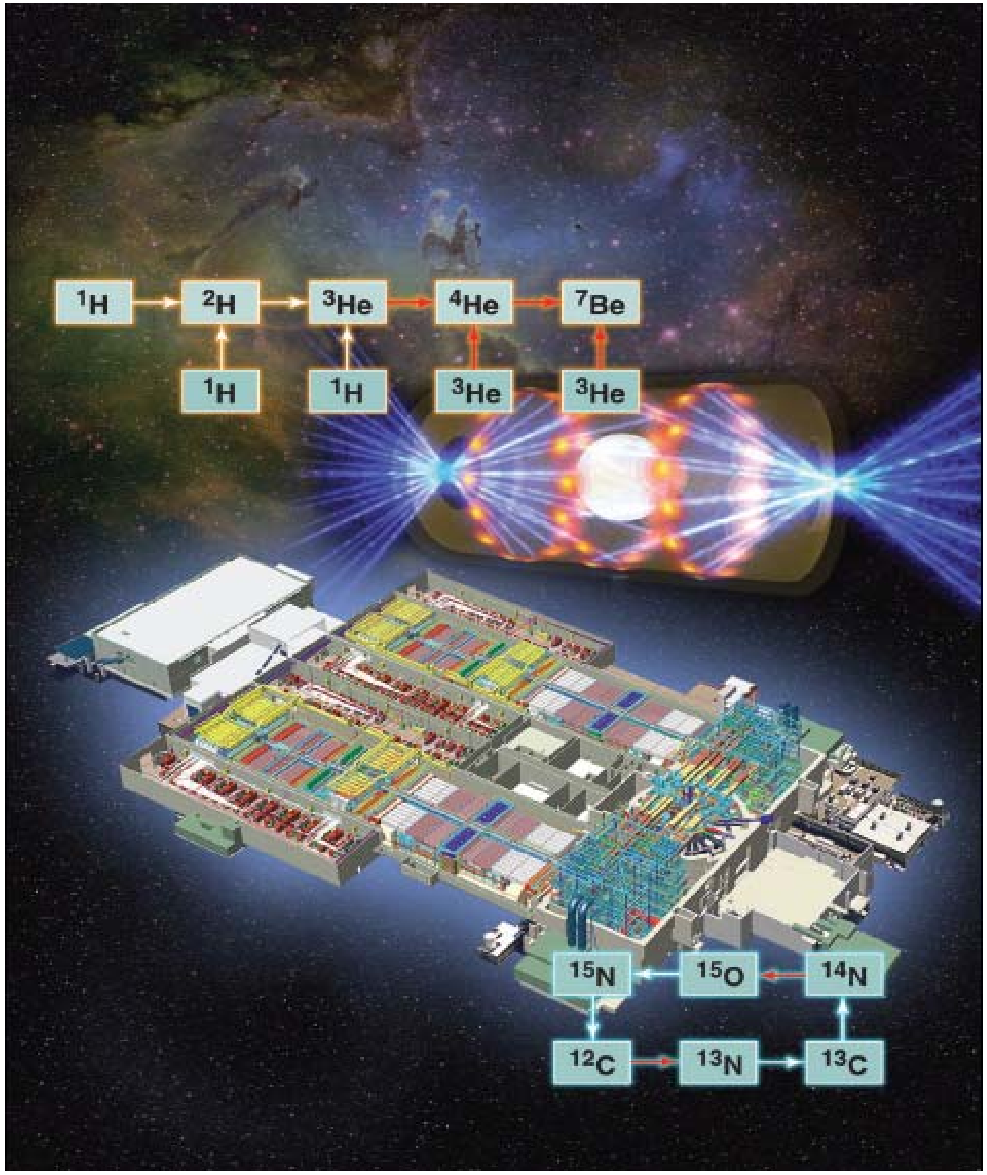

Stellar Astrophysics at NIF: Measurements of Basic Thermonuclear Reactions

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- Thermonuclear Reaction Rates between charged particles are of the form:

$$\text{Rate} \sim \langle\sigma v\rangle = (8/\pi\mu)^{1/2} (k_B T)^{-3/2} \int_0^\infty E\, \sigma(E) \exp[-E/k_B T]\, dE.$$

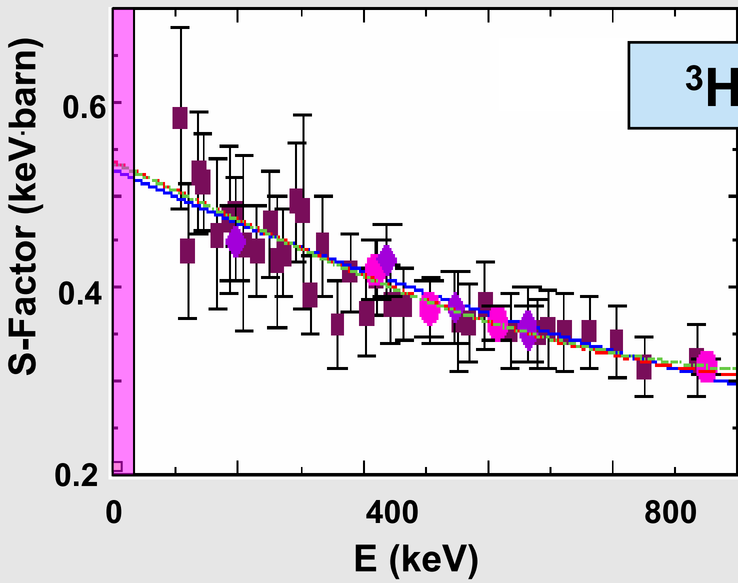
$$\text{Define } \sigma(E) = [S(E)/E] \exp[- bE^{-1/2}],$$

$$\text{where penetrability} = \exp[- 2\pi z_1 Z_1 e^2/\hbar v] = \exp[- bE^{-1/2}]$$

- S factors are extrapolated to the relevant stellar energies, in the Gamow window, from higher energy experimental data
- Screening
    - Laboratory experiments, atomic electron screening effects are significant
    - Stellar electron screening effects are also significant, but quite different
    - NIF screening is due to degenerate electrons; that's different still

Comparison of $^3He(^4He,\gamma)^7Be$ measured at an accelerator lab and using NIF

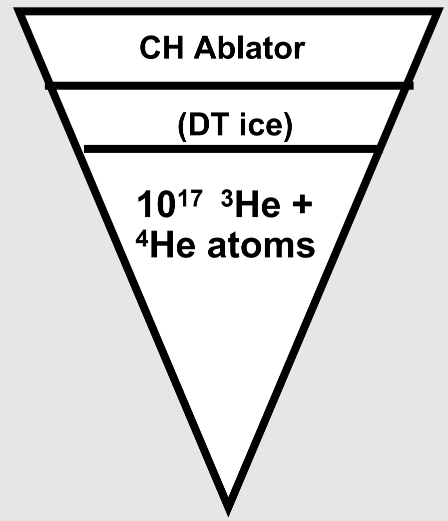
Accelerator-Based Experiments



- Mono-energetic
- ✗ Low event rate (few events/month)
- ✗ *Difficult* at relevant energies

$^3He(^4He,\gamma)^7Be$

NIF-Based Experiments



- High Count rate ($4x10^4$ atoms/shot)
- Integral experiment
- Energy window is better
- ✗ ^7Be background

Issues: Detecting ^7Be? Screening?

Some CNO Cycle Reactions—

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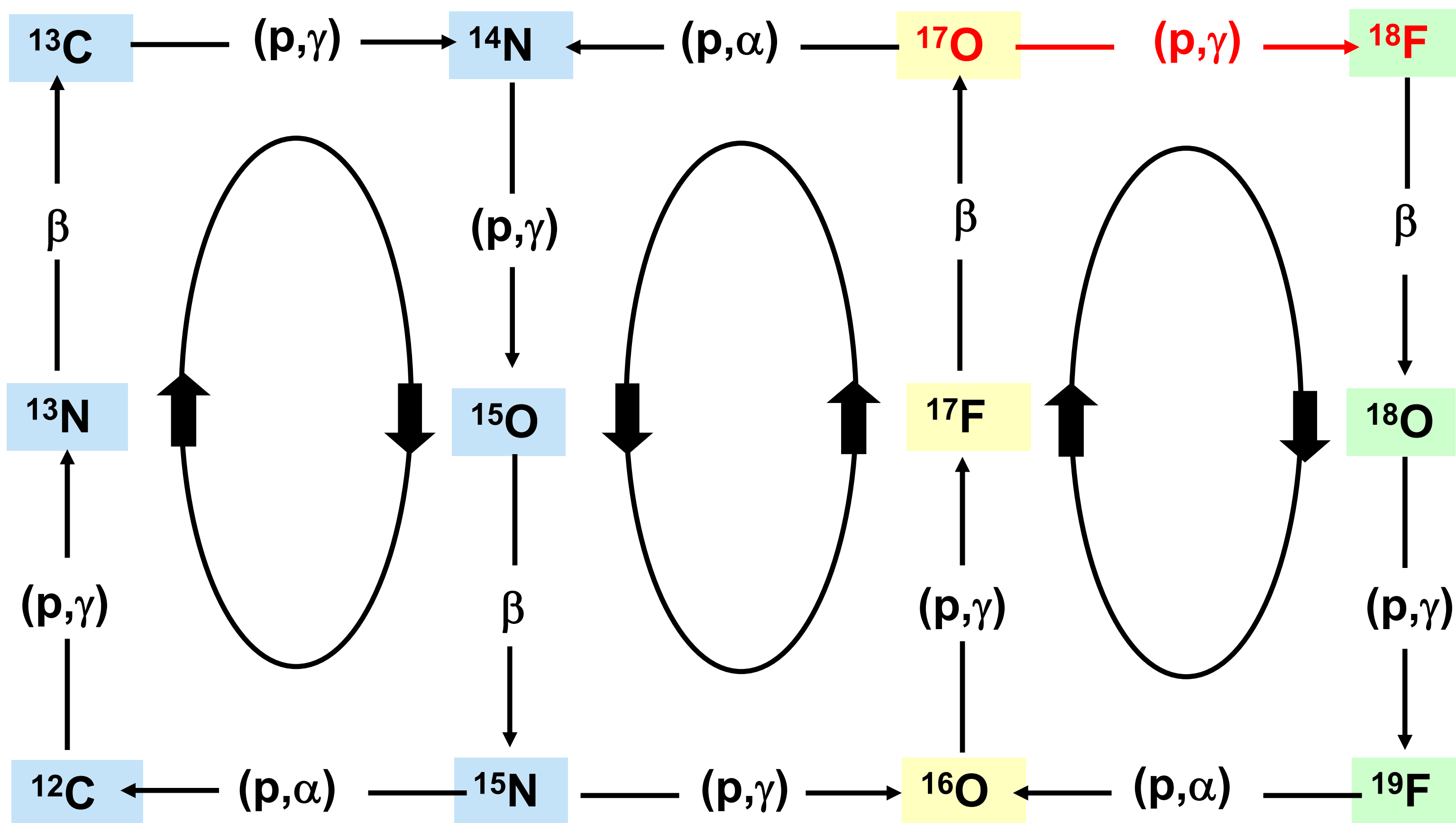

Resonances (CN States!) do matter—

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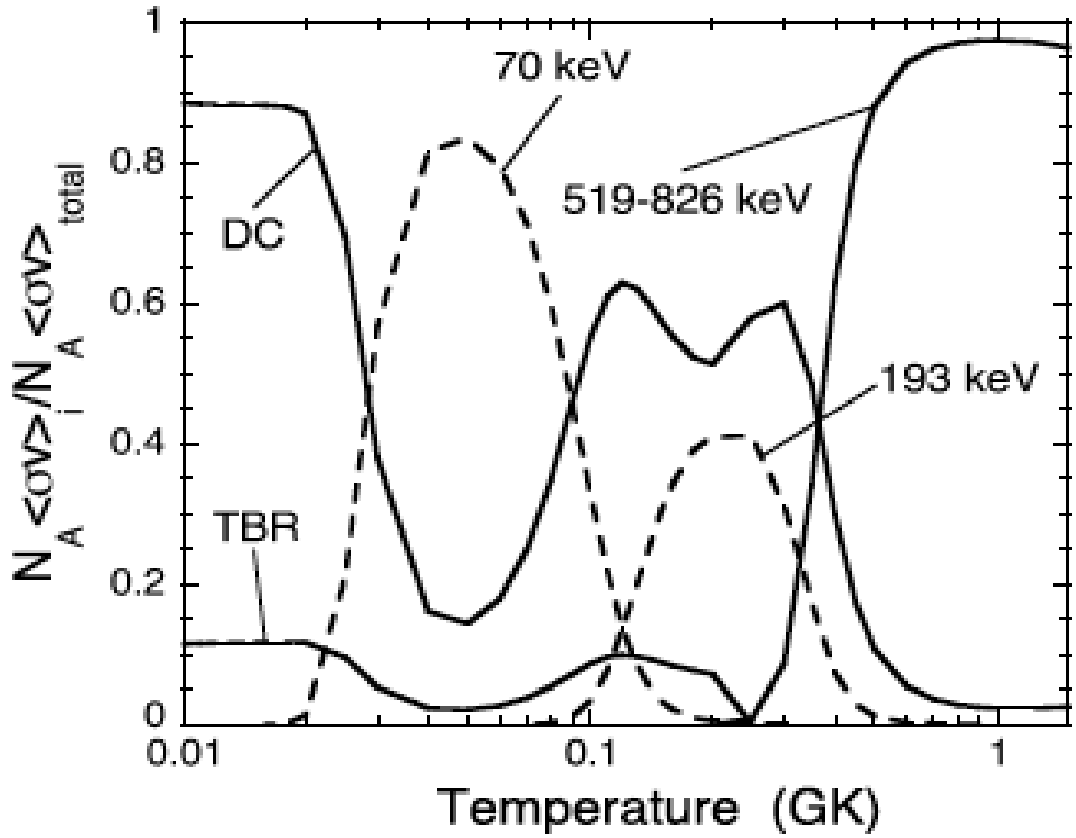

$^{17}O(p,\gamma)^{18}F$

Ratio of the individual contributions to the reaction rate to the total reaction rate as a function of temperature [C. Fox et al., Phys. Rev. C 71 (2005) 055801].

Where we stand with $^{17}O(p,\gamma)^{18}F$

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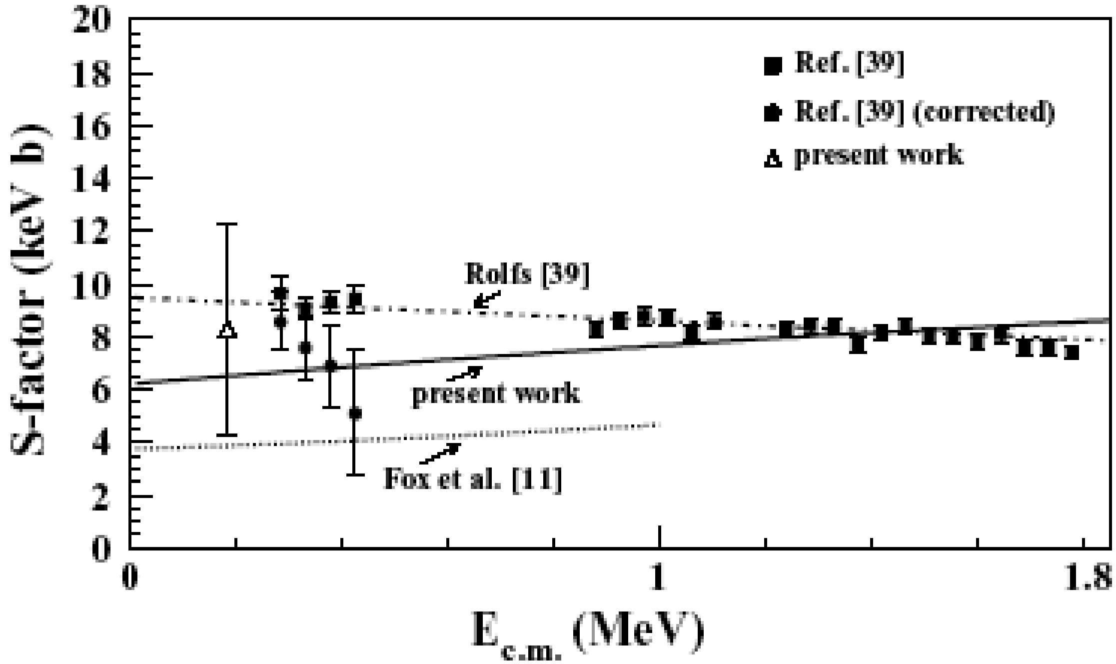

Extrapolation of higher energy data and theoretical estimates of the direct capture S-factor of the reaction $^{17}O(p,\gamma)^{18}F$ [A. Chafa et al., Phys. Rev. C 75 (2007) 035810]. (E_{GAMOW} = 53 keV at T = 50×10^6 K.)

This reaction definitely needs more work!
CN States *might* be detectable with NIF.

The rp-Process

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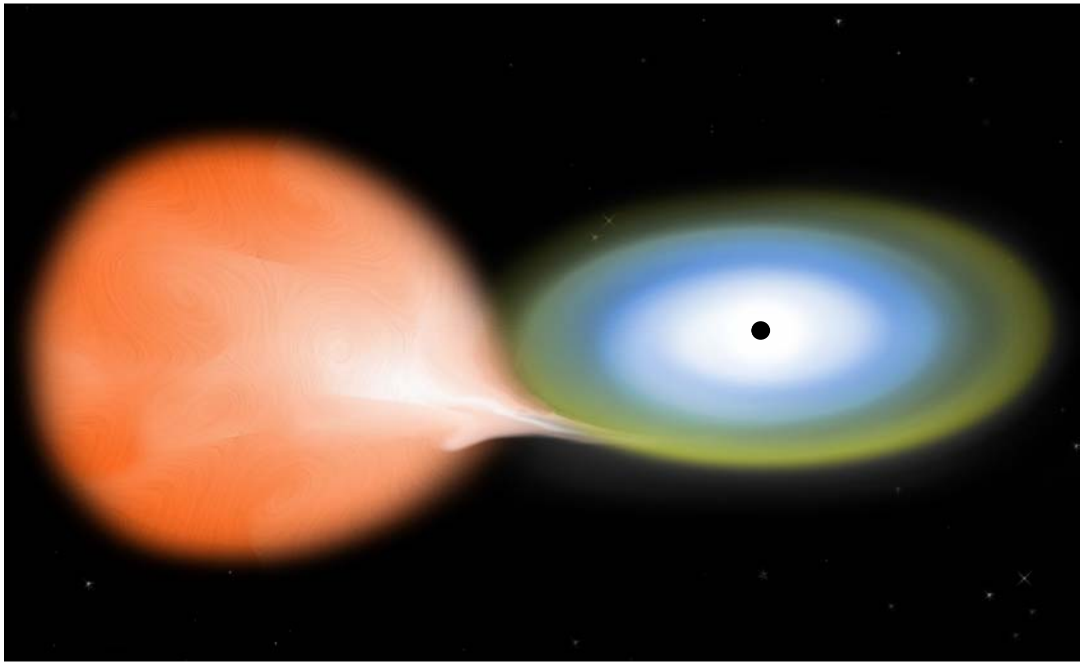
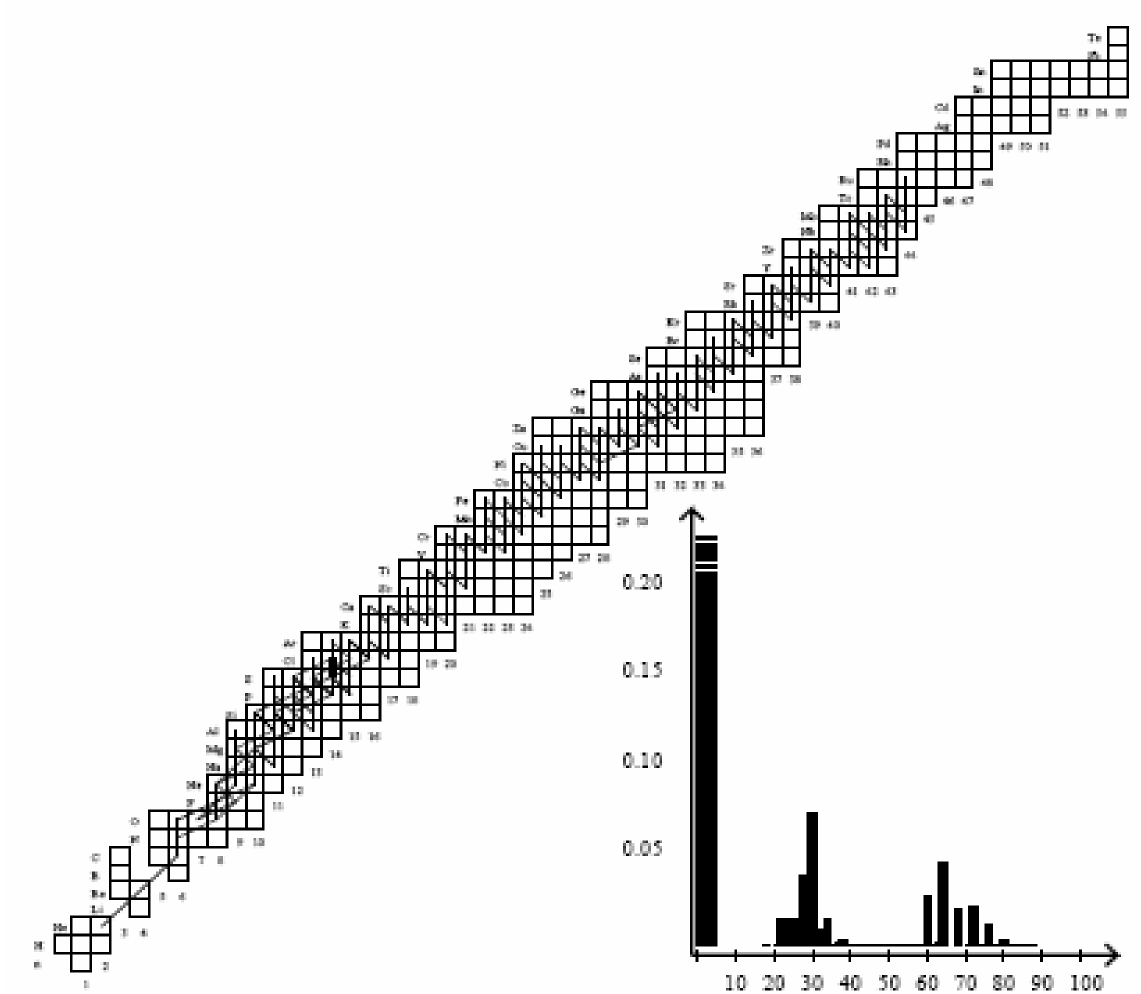
- Occurs in accretion onto a white dwarf or neutron star
- Involves very rapid burning ($t \sim$ few s) via proton and α-particle induced reactions
- Preexisting nuclides are driven to the proton-rich side of stability



- Waiting point nuclides—can't capture another proton, so must wait for β-decay
- ^{26}Si, ^{30}S, ^{34}Ar (all 2 neutrons shy of stability) all have half-lives ~ 1 s
- (α,p) reactions on these nuclei (making ^{29}P, ^{33}Cl, and ^{37}K) can circumvent the waiting points if the temperature is high enough: ~10^9 K

Nuclear Astrophysics with Ignition Shots



rp-Process
T = 8.96×10^8 K
$\rho = 2.07 \times 10^5$ g/cm^3
H no. fraction = 0.327
He no. fraction = 0.326
at 8.0 s before the luminosity peak.

The (α,p) reaction reactions (on the proton-rich side) are crucial in promoting the burning past the ^{26}Si, ^{30}S, or ^{34}Ar waiting points.

From Fisker, Schatz and Thielemann

How to study $^{26}Si(\alpha,p)^{29}P$?

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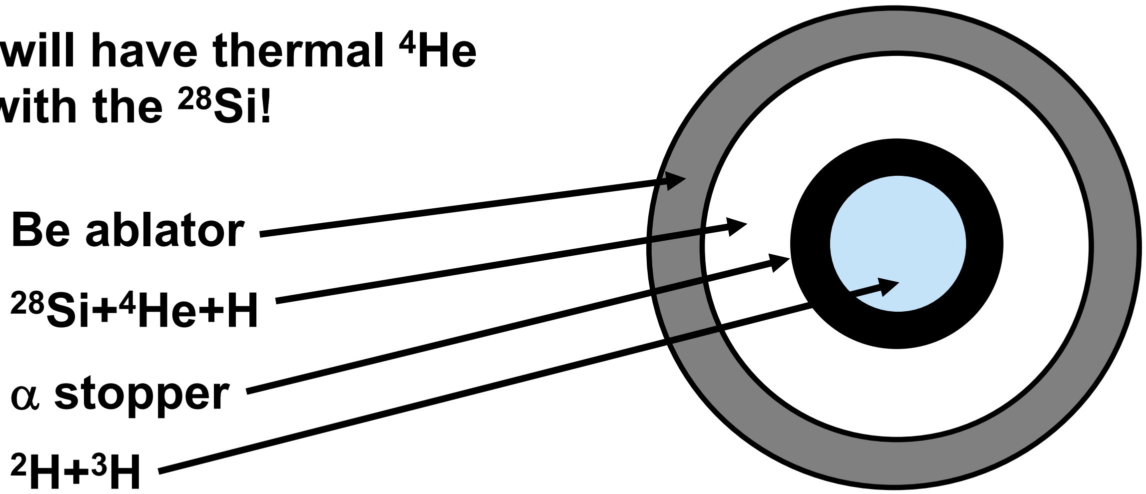
- Need ignition target ($^{2}H+^{3}H \rightarrow ^{4}He+n$) loaded with ^{28}Si: $^{28}Si(n,2n)^{27}Si(n,2n)^{26}Si$
- Include some ^{4}He, so then $^{26}Si(\alpha,n)^{29}P$
- But the "ignition target" also makes ^{4}He, and these are high energy, so will interact with large cross sections with the ^{26}Si
- Design a buffer so the ^{4}He from ignition doesn't get to the region with the ^{28}Si (and more ^{4}He)
- That region will have thermal ^{4}He interacting with the ^{28}Si!



How to detect the reaction products from NIF?

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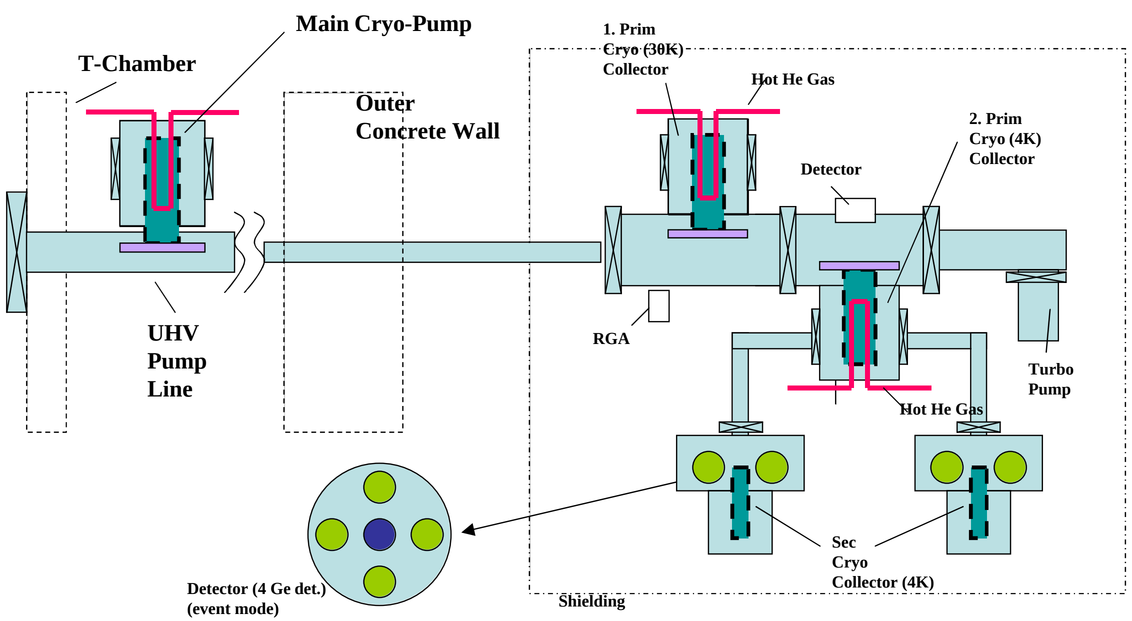
Dedicated Radchem Gas Collection System at NIF



A unique NIF opportunity: Study of a Three-Body Reaction in the r-Process

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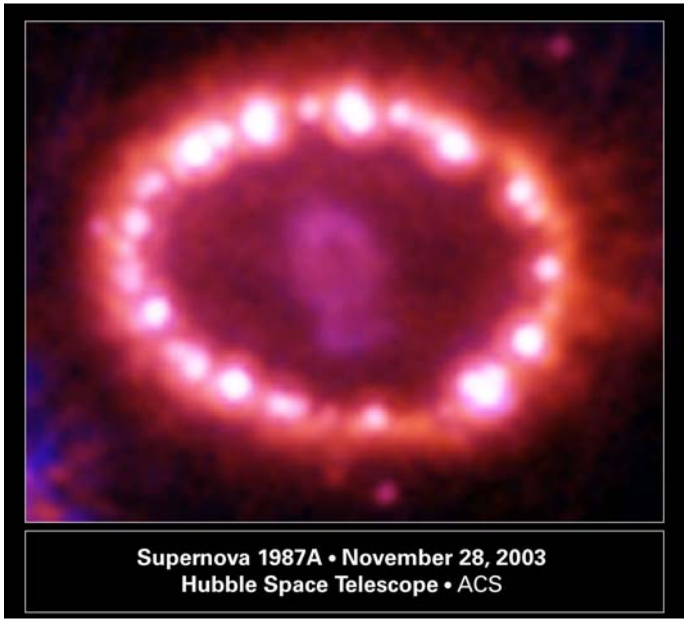
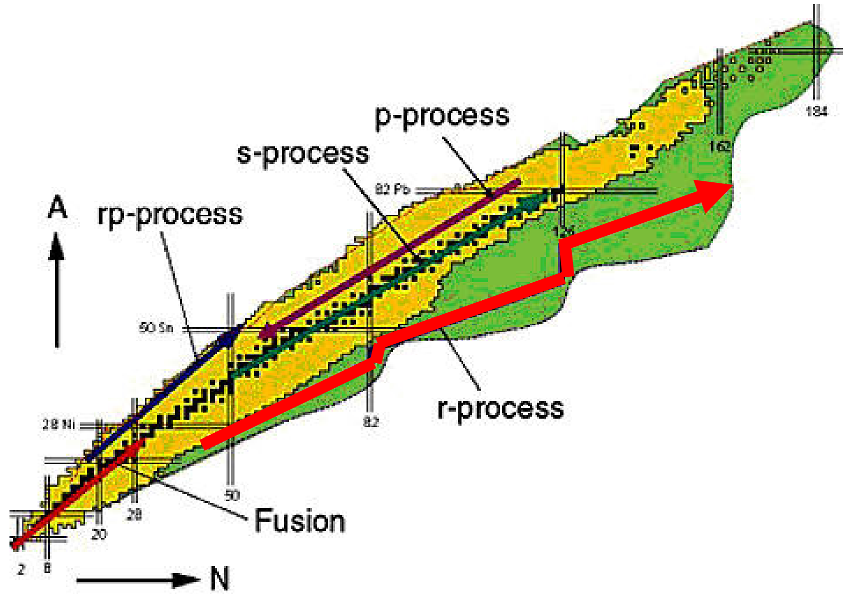
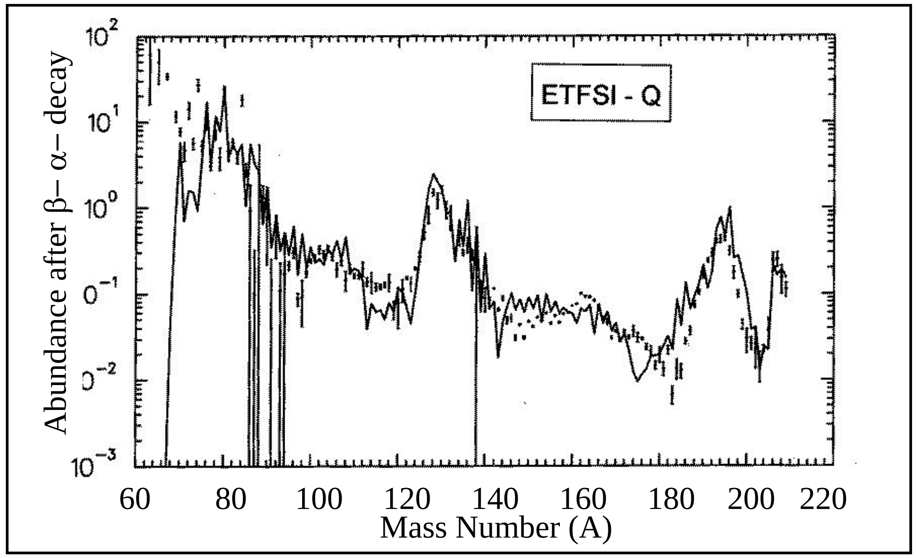




- Currently believed to take place in supernovae, but we don't know for sure
- r-process abundances depend on: Nuclear Masses far from stability
  - — Weak decay rates far from stability
- The cross section for the $\alpha+\alpha+n \rightarrow {}^{9}Be$ reaction



$\alpha+\alpha+n\rightarrow{}^{9}Be$ is the "Gatekeeper" for the r-Process

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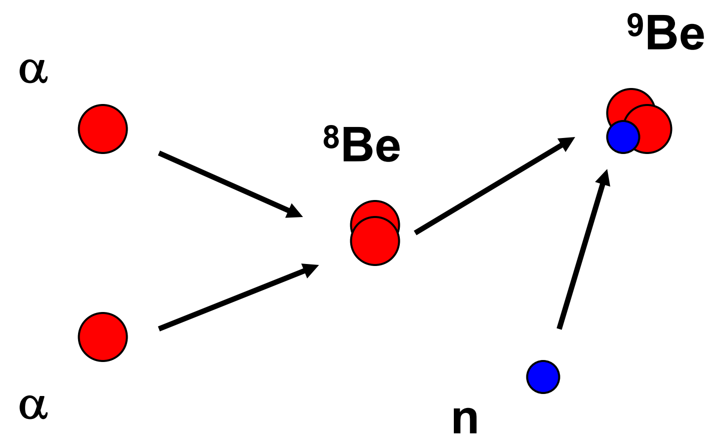
- If this reaction is strong, ^{9}Be becomes abundant, $\alpha+{}^{9}Be\rightarrow{}^{12}C+n$ is frequent, and the light nuclei will all have all been captured into the seeds by the time the r-Process seeds get to ~Fe

- If it's weak, less ^{12}C is made, and the seeds go up to mass 100 u or so; this seems to be what a successful r-Process (at the neutron star site) requires

During its 10^{-16} s half-life, a ^{8}Be can capture a neutron to make ^{9}Be, in the r-process environment, *and even in the NIF target*



- The NIF target would be a mixture of ^{2}H and ^{3}H, to make the neutrons (not at the right energy—but it might be modified), with some ^{4}He (and more ^{4}He will be made during ignition). *This type of experiment can't be done with any other facility that has ever existed*

Core-collapse supernova explosion mechanisms remain uncertain

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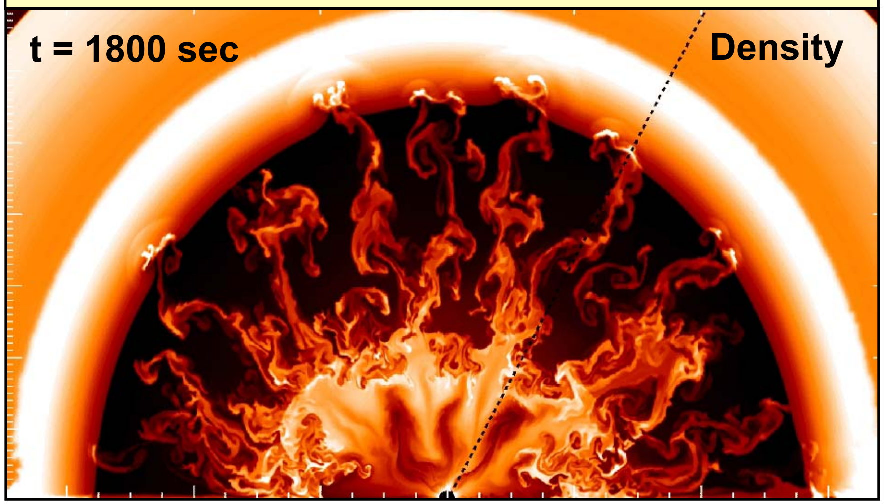
- **SN observations suggest rapid core penetration to the "surface"**
- **This observed turbulent core inversion is not yet fully understood**

Standard (spherical shock) model

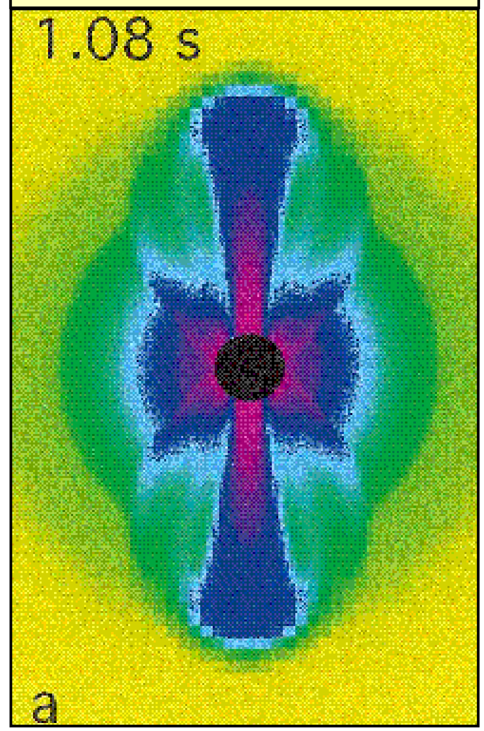


10^{12}cm

[Kifonidis et al., AA. 408, 621 (2003)]

- **Pre-supernova structure is multilayered**
- **Supernova explodes by a strong shock**
- **Turbulent hydrodynamic mixing results**
- **Core ejection depends on this turbulent hydro.**
- **Accurate 3D modeling is required, but difficult**
- **Scaled 3D testbed experiments are possible**

Jet model



9×10^9cm

6×10^9cm

[Khokhlov et al., Ap.J.Lett. 524, L107 (1999)]

Core-collapse supernova explosion mechanisms remain uncertain

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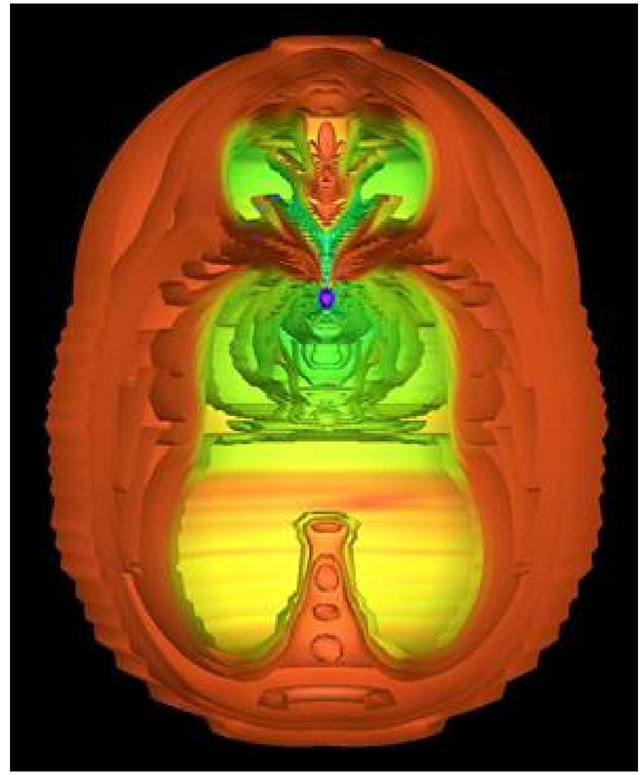
- **A new model of Supernova explosions: from Adam Burrows et al.**
- **A cutaway view shows the inner regions of a star 25 times more massive than the sun during the last split second before exploding as a SN, as visualized in a computer simulation. Purple represents the star's inner core; Green (Brown) represents high (low) heat content**
- **In the Burrows model, after about half a second, the collapsing inner core begins to vibrate in "g-mode" oscillations. These grow, and after about 700 ms, create sound waves with frequencies of 200 to 400 hertz. This acoustic power couples to the outer regions of the star with high efficiency, causing the SN to explode**



From http://www.msnbc.msn.com/id/11463498/

- **Burrows' solution hasn't been accepted by everyone; it's *very* different from any previously proposed. But others (Blondin/Mezzacappa) are also looking at instabilities as the source of the explosion mechanism**

Fundamental questions in planetary formation models can be addressed on NIF

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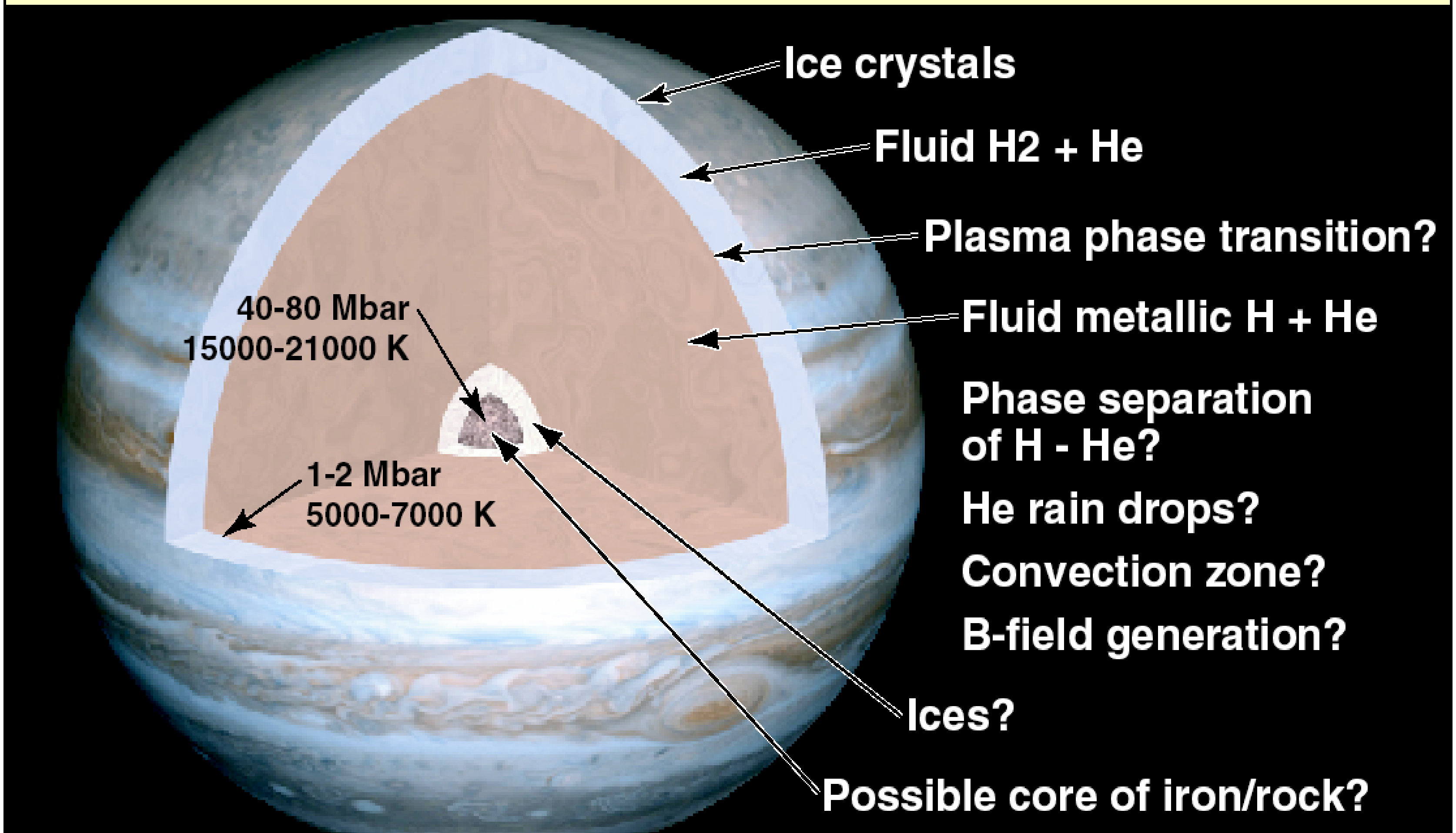
What is the Structure of Jupiter?



NIF will be able to create and characterize a wide range of high - (P, ρ) states of matter found in the interiors of planets

A Hydrogen-Helium Phase Transition At High Pressure?

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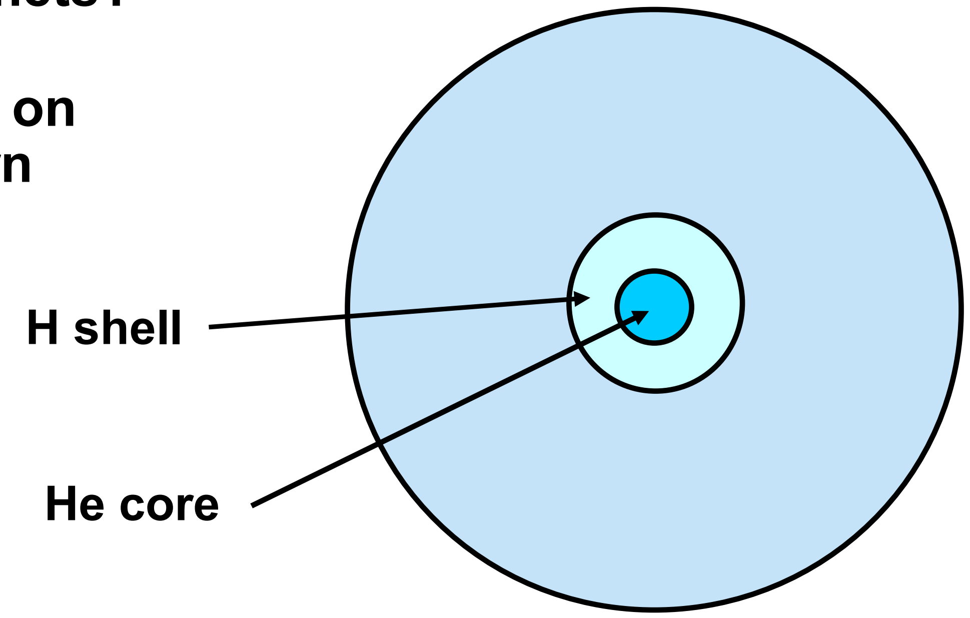
What would be the effect of a phase transition at high pressure (and low temperature) in which He and H can't mix?

The separation might create an object with a core of helium surrounded by a shell of hydrogen

This would certainly look different from conventional planetary models; might that produce the anomalous effects observed in giant planets?

If so, it would depend critically on the mass of the object; Saturn is about right, Jupiter is too massive.



The NRC committee on the Physics of the Universe highlighted the new frontier of HED Science

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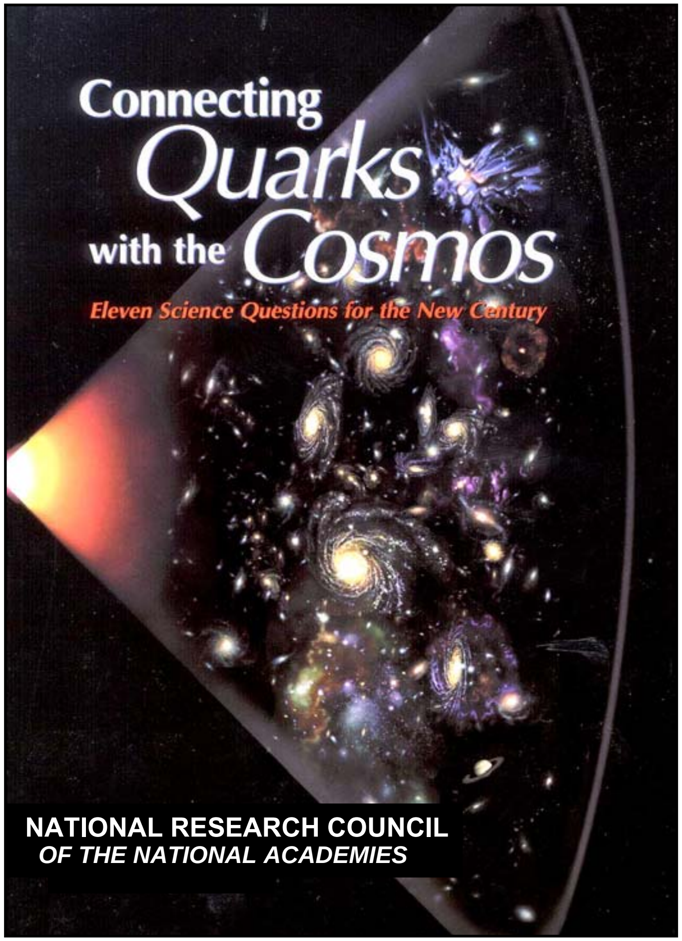

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4. Did Einstein have the last word on gravity?
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- — Neutron star interior (photoionized plasmas, spectroscopy, EOS)

10. How were the elements from iron to uranium made and ejected?
- — Core-collapse SNe (reactions off excited states, turbulent hydro, rad flow)

- **HEDP provides crucial experiments to interpreting astrophysical observations**
- **We envision that NIF will play a key role in these measurements**

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Data Needs for Nuclear Astrophysics

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- Thermonuclear reaction rates (not cross sections, usually!)
  — Tabulations exist for these
  — But many reaction rates needed for reactions on short-lived nuclei, especially proton-rich nuclei

- Masses of proton- and neutron-rich nuclei
  — Where are the neutron shell closures for neutron-rich nuclei?
  — Masses becoming available for many short-lived nuclei, but not for A~195 nuclei ~20 neutrons beyond stability

- Lifetimes of proton- and neutron-rich nuclei
  — Many lifetimes becoming available, but not for the A~195 u nuclei ~20 neutrons beyond stability

- Decay modes of nuclei far from stability
  — β, β-n, β-2n, …
  — β, β-p, β-2p, …