Use of NIF in Nuclear Astrophysics:
Examples of Experiments

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Science Director, National Ignition Facility

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NIF has 3 Missions

National Ignition Facility

- *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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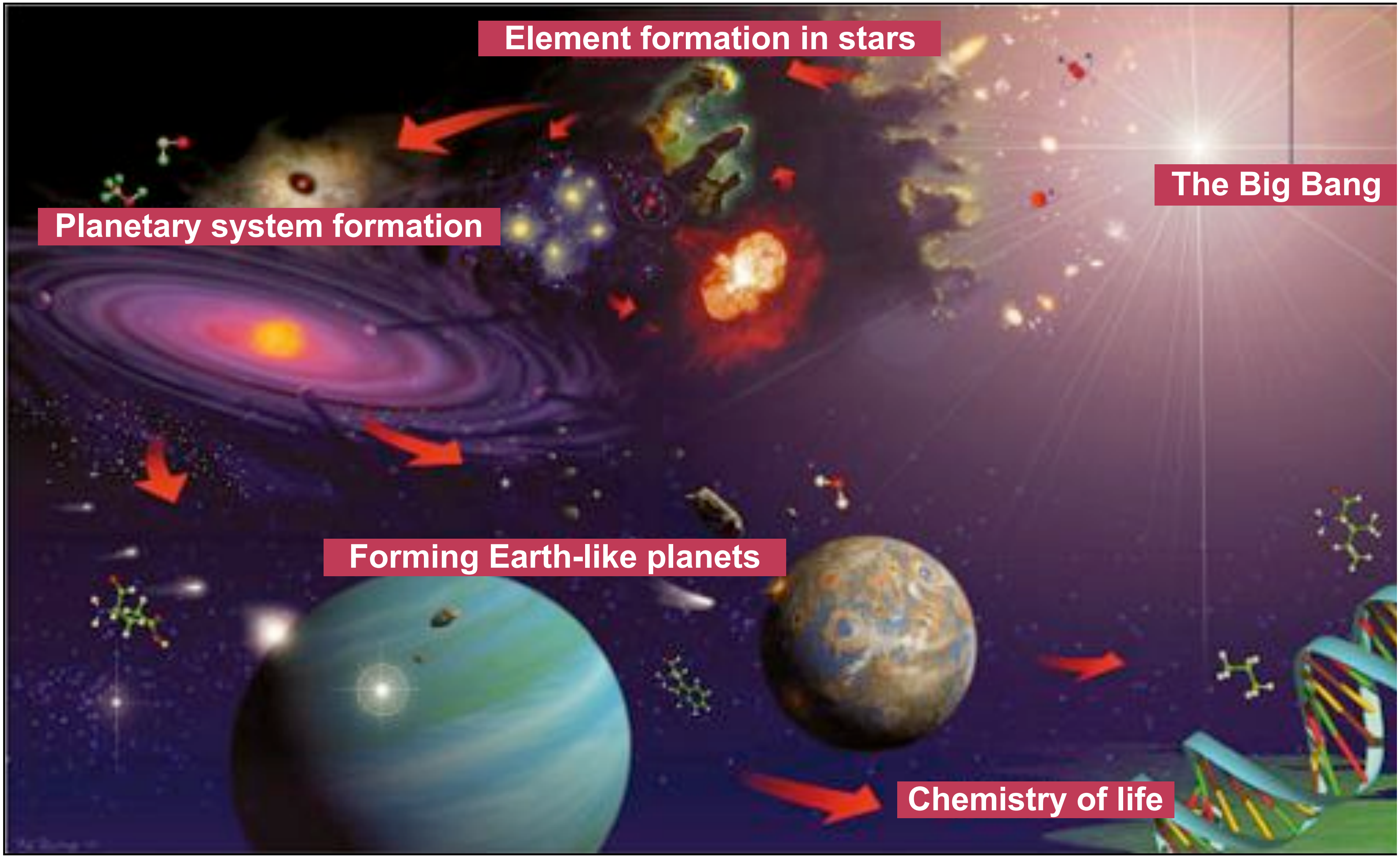
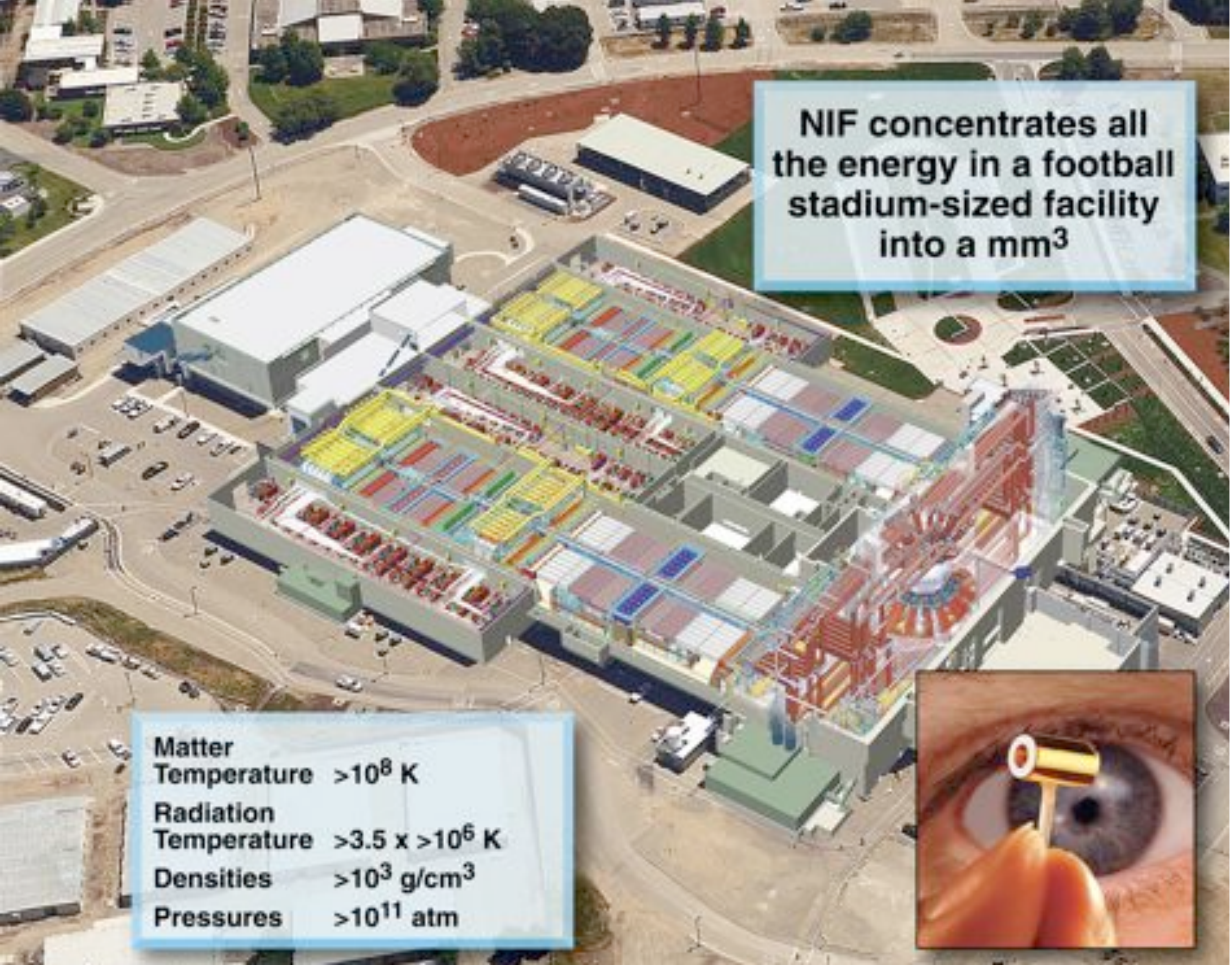


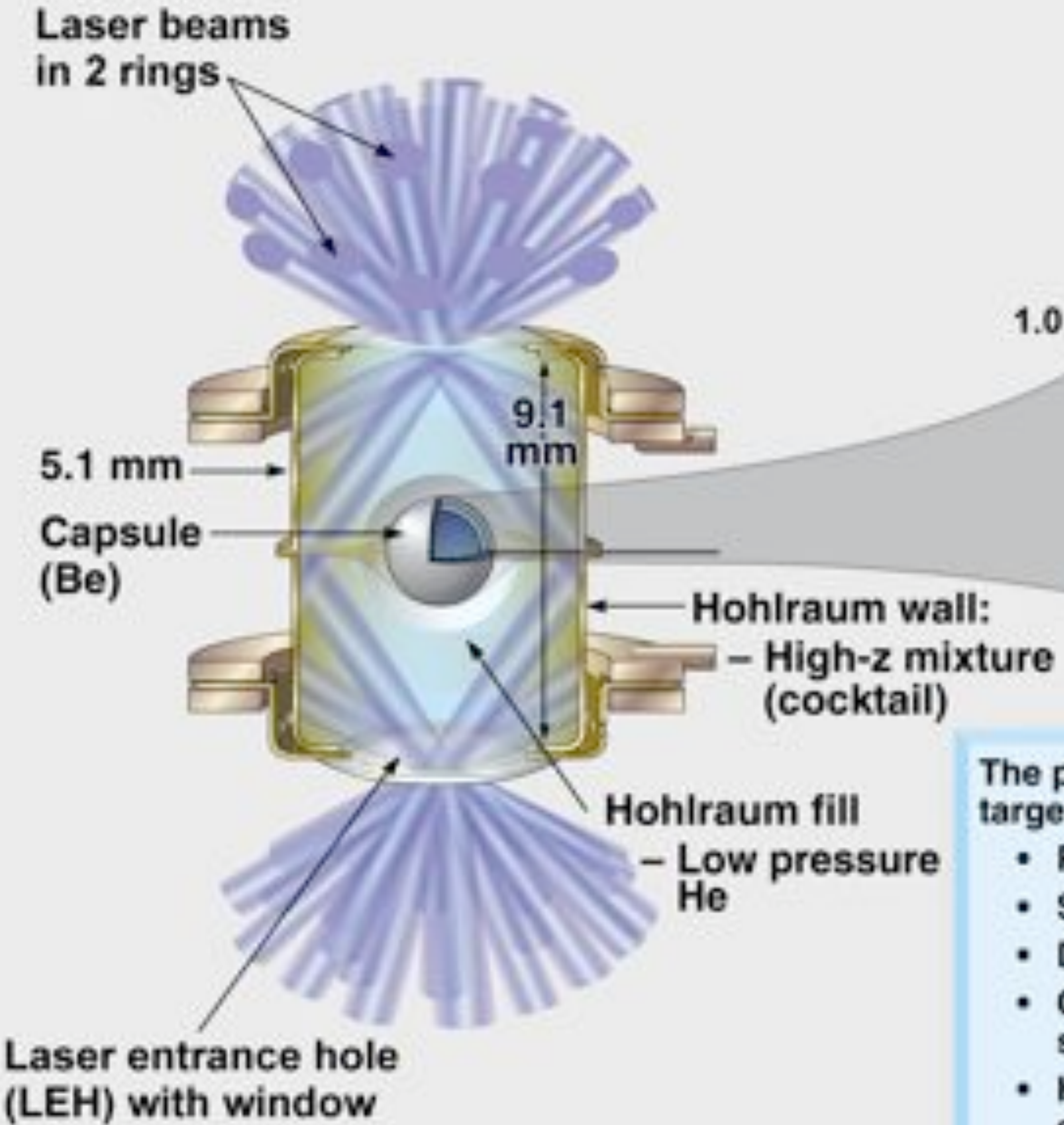
[http://www.nas.edu/bpa/reports/cpu/index.html

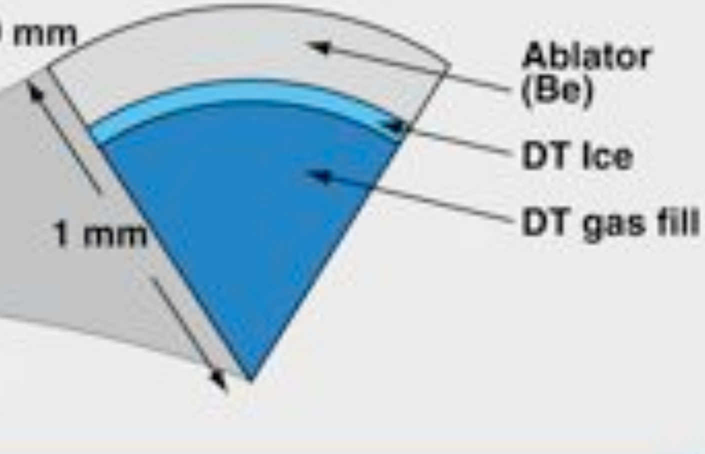


NIF concentrates all the energy in a football stadium-sized facility into a mm^3

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

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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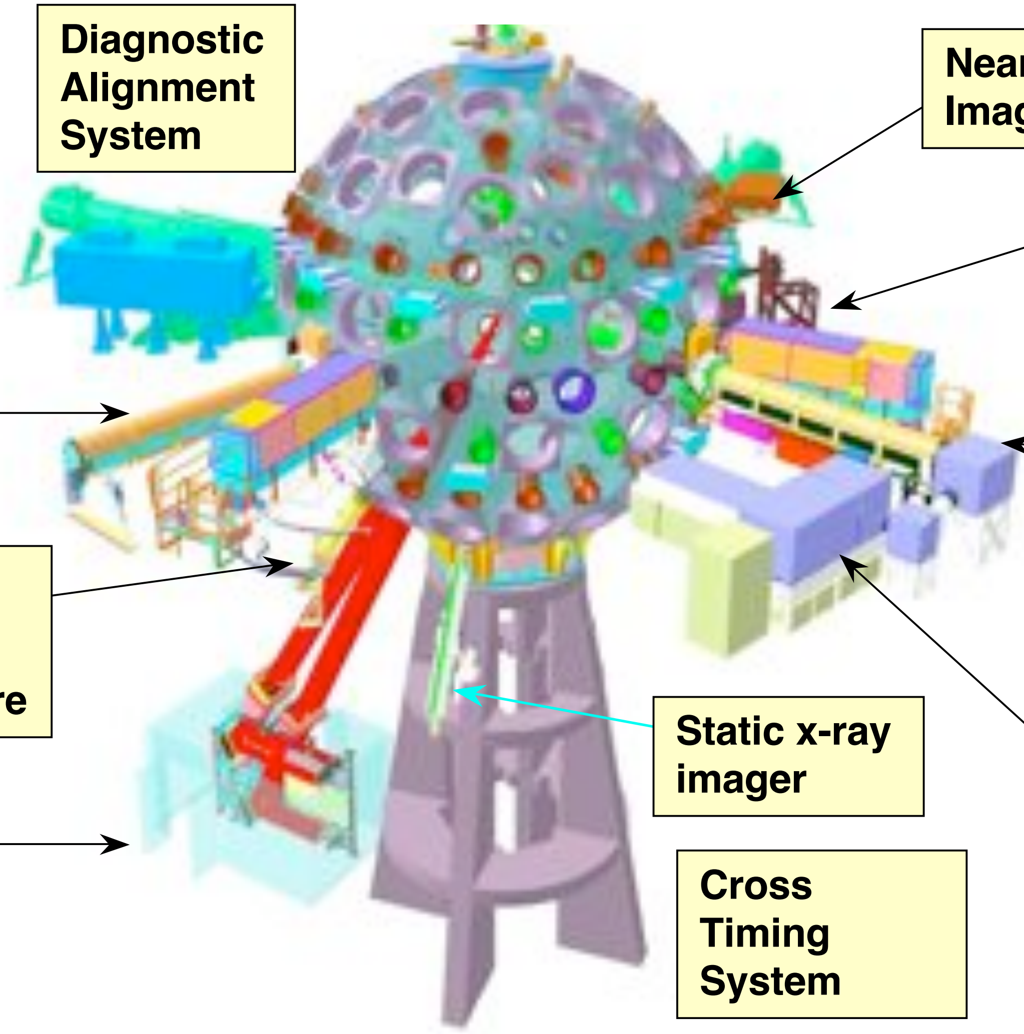


Diagnostic Alignment System

Diagnostic Instrument Manipulator (DIM)

X-ray imager

Streaked x-ray detector

Near Backscatter Imager

FFLEX

Hard x-ray spectrometer

Diagnostic Instrument Manipulator (DIM)

DANTE

Soft x-ray temperature

Static x-ray imager

VISAR

Velocity Measurements

Full Aperture Backscatter

Cross Timing System

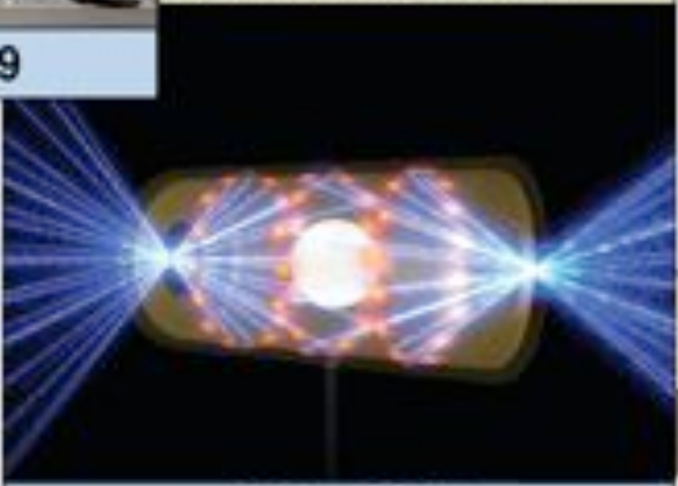
We have already fielded ~ half of all the types of diagnostic systems needed for NIF science

NIF Master Strategy

NIF Project

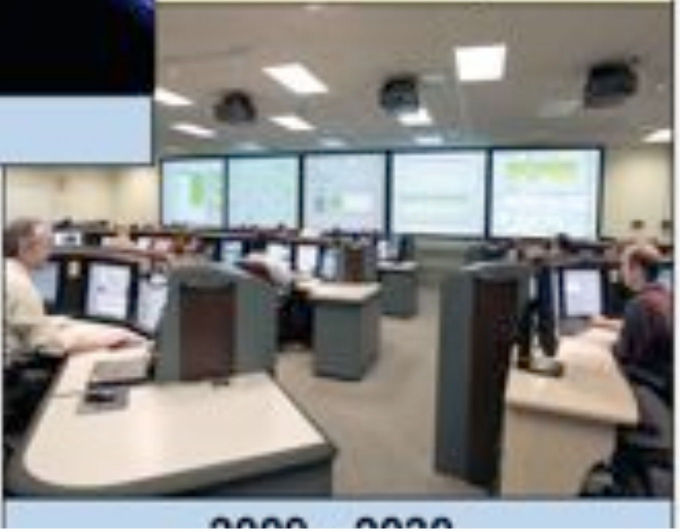
Completion in 2009

National Ignition Campaign



2006—2012

National User Facility



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

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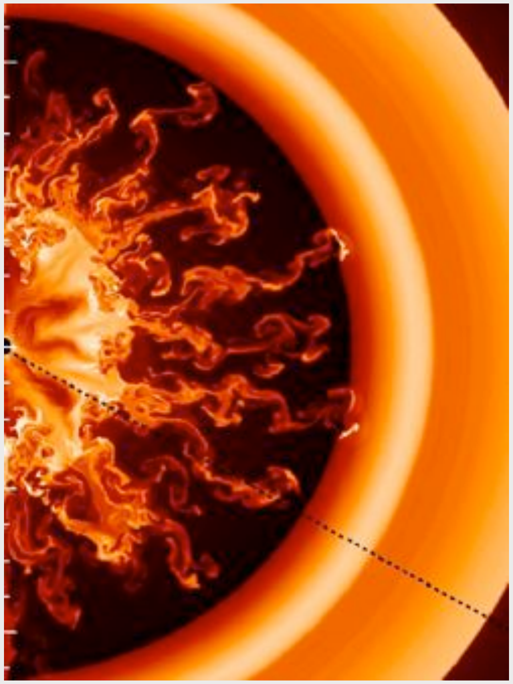
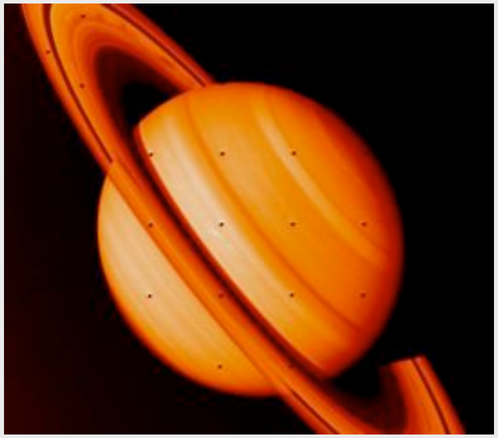
Astrophysics - hydrodynamics



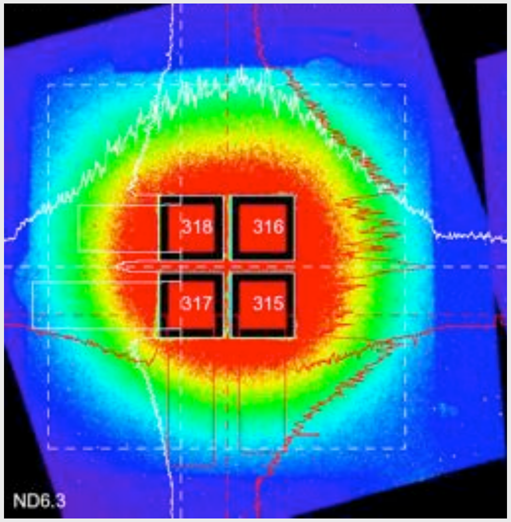
Paul Drake, PI, U. of Mich.
David Arnett, U. of Arizona,
Adam Frank, U. of Rochester,
Tomek Plewa, U. of Chicago,
Todd Ditmire, U. Texas-Austin
LLNL hydrodynamics team

Planetary physics - EOS



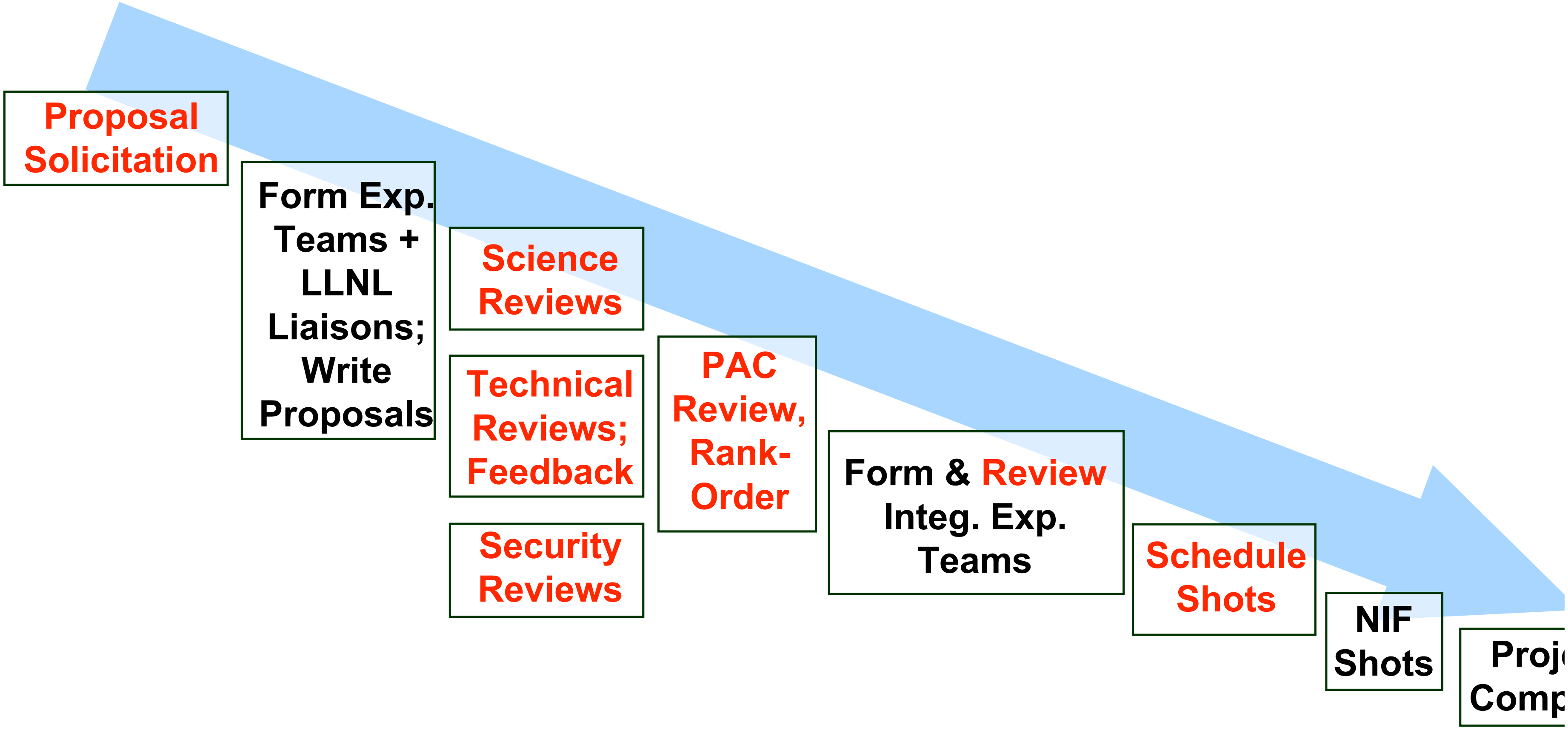
Raymond Jeanloz, PI,
UC Berkeley
Thomas Duffy, Princeton U.
Russell Hemley, Carnegie Inst.
Yogendra Gupta, Wash. State U.
Paul Loubeyre, U. Pierre & Marie
Curie, and CEA
LLNL EOS team

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

Inception to Completion Flow Chart



Proposal Solicitation

Form Exp. Teams + LLNL Liaisons; Write Proposals

Science Reviews

Technical Reviews; Feedback

Security Reviews

PAC Review, Rank-Order

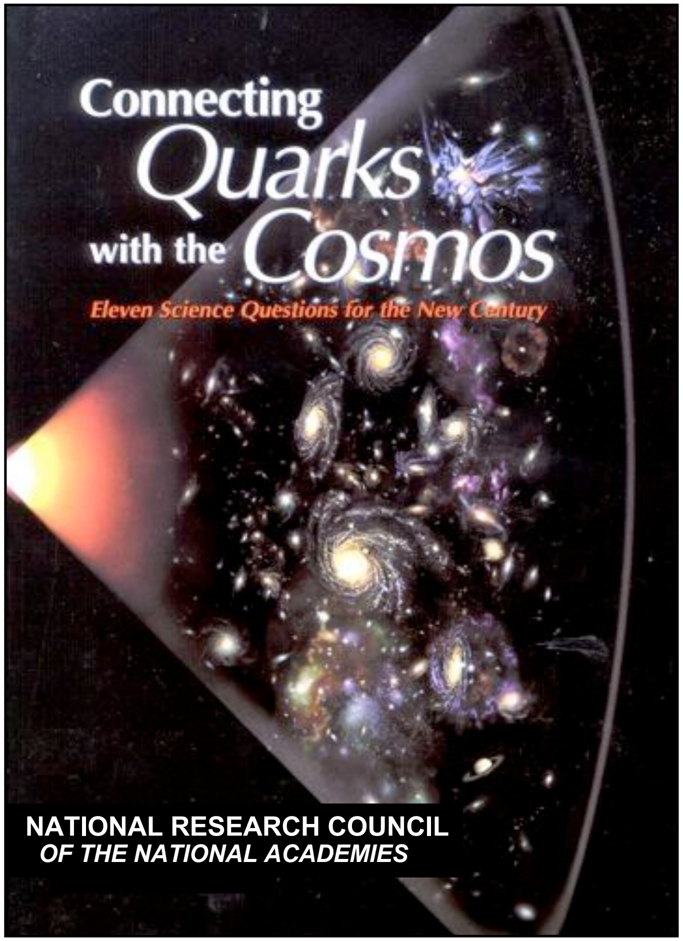
Form & Review Integ. Exp. Teams

Schedule Shots

NIF Shots

Proj
Comp

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



Connecting Quarks with the Cosmos

Eleven Science Questions for the New Century

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

Eleven science questions for the new century:

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

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 exceedingl 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, nuclear reactions, turbulent hydro, rad flow)

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

NIF's Unprecedented Scientific Environments:

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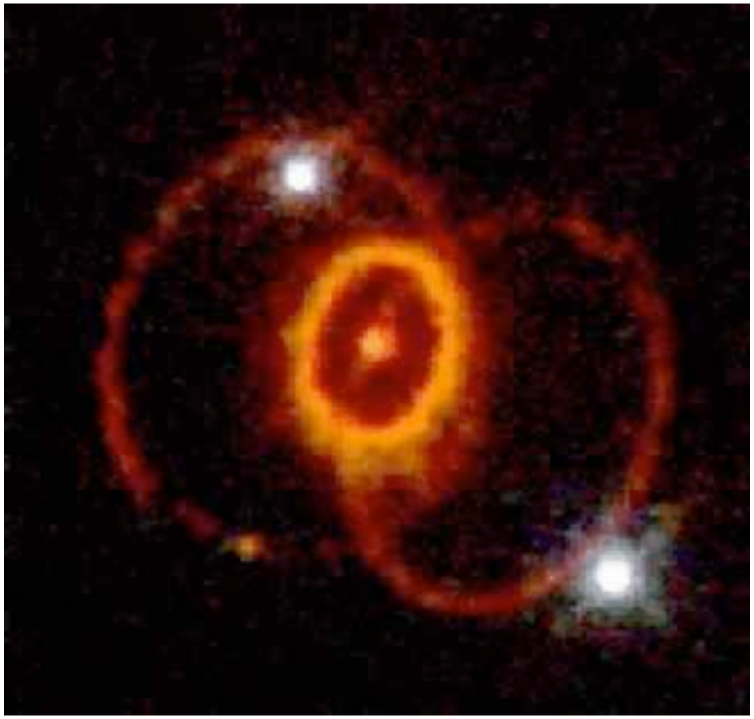
- T >10^8 K matter temperature
- ρ >10^3 g/cc density

Those are both 7x what the *Sun* does! Helium burning, stage 2 in stellar evolution, occurs at $2\text{x}10^8$ K!

- $\rho_n = 10^{26}$ neutrons/cc



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

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

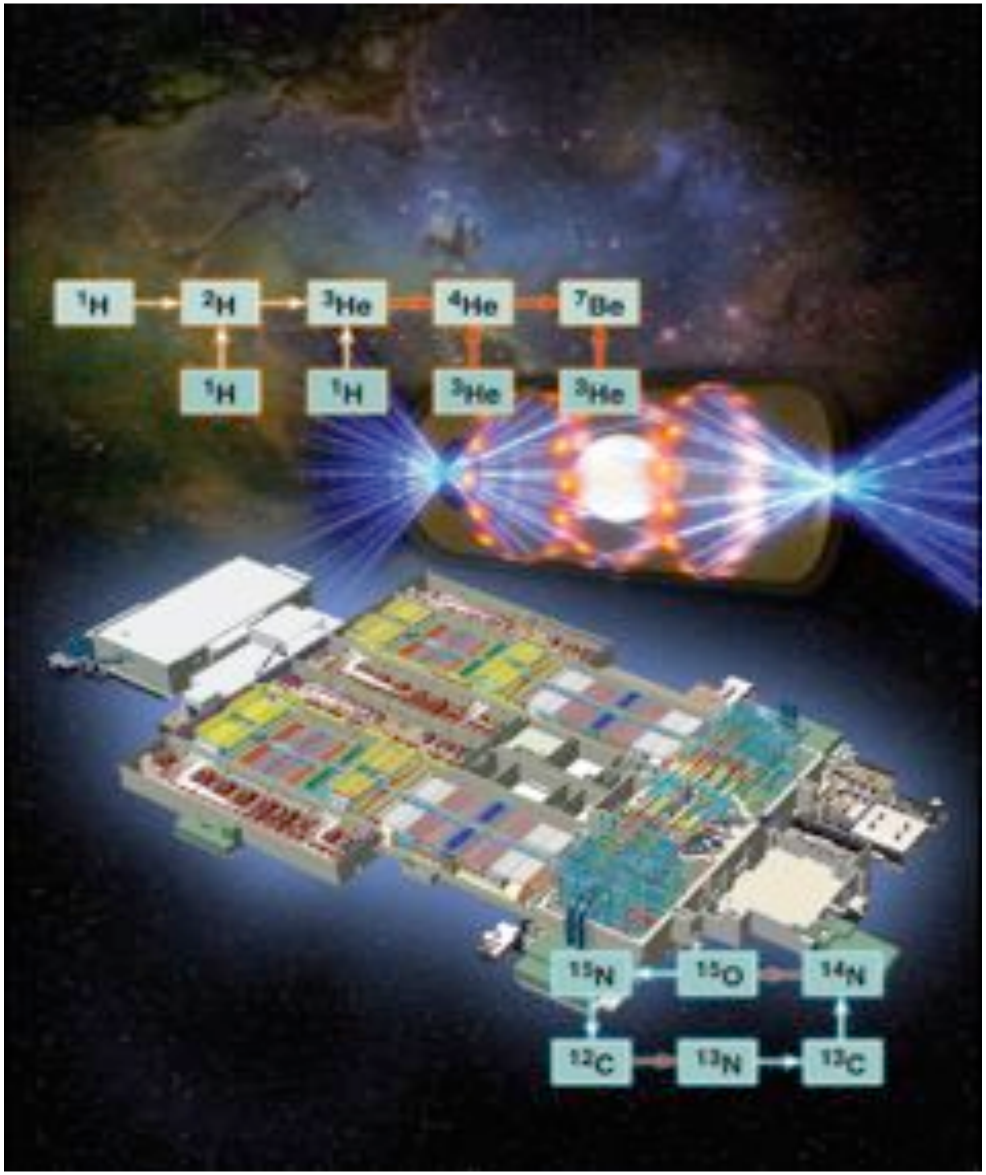
These apply to Type Ia Supernovae!

- Pressure > 10^{11} bar

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

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

Reaction Studies for Nuclear Astrophysics



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

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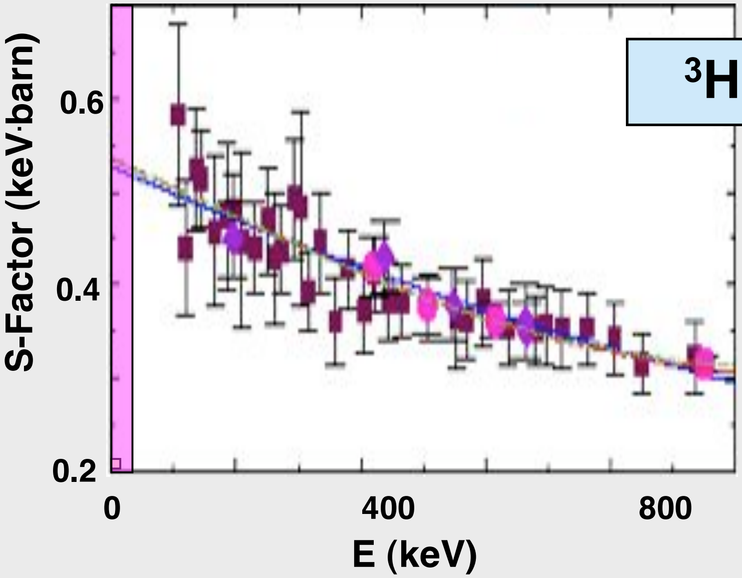
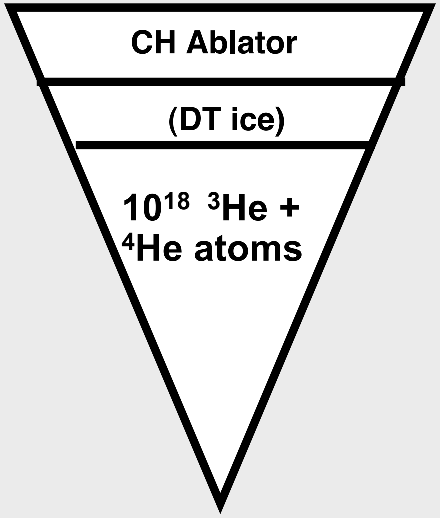
Accelerator-Based Experiments



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

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

NIF-Based Experiments



- ✓ High Count rate (4×10^{4} atoms/shot)
- ✓ Integral experiment
- ✓ Energy window is better
- ✗ ^{7}Be background

Issues: Detecting ^{7}Be? Screening?

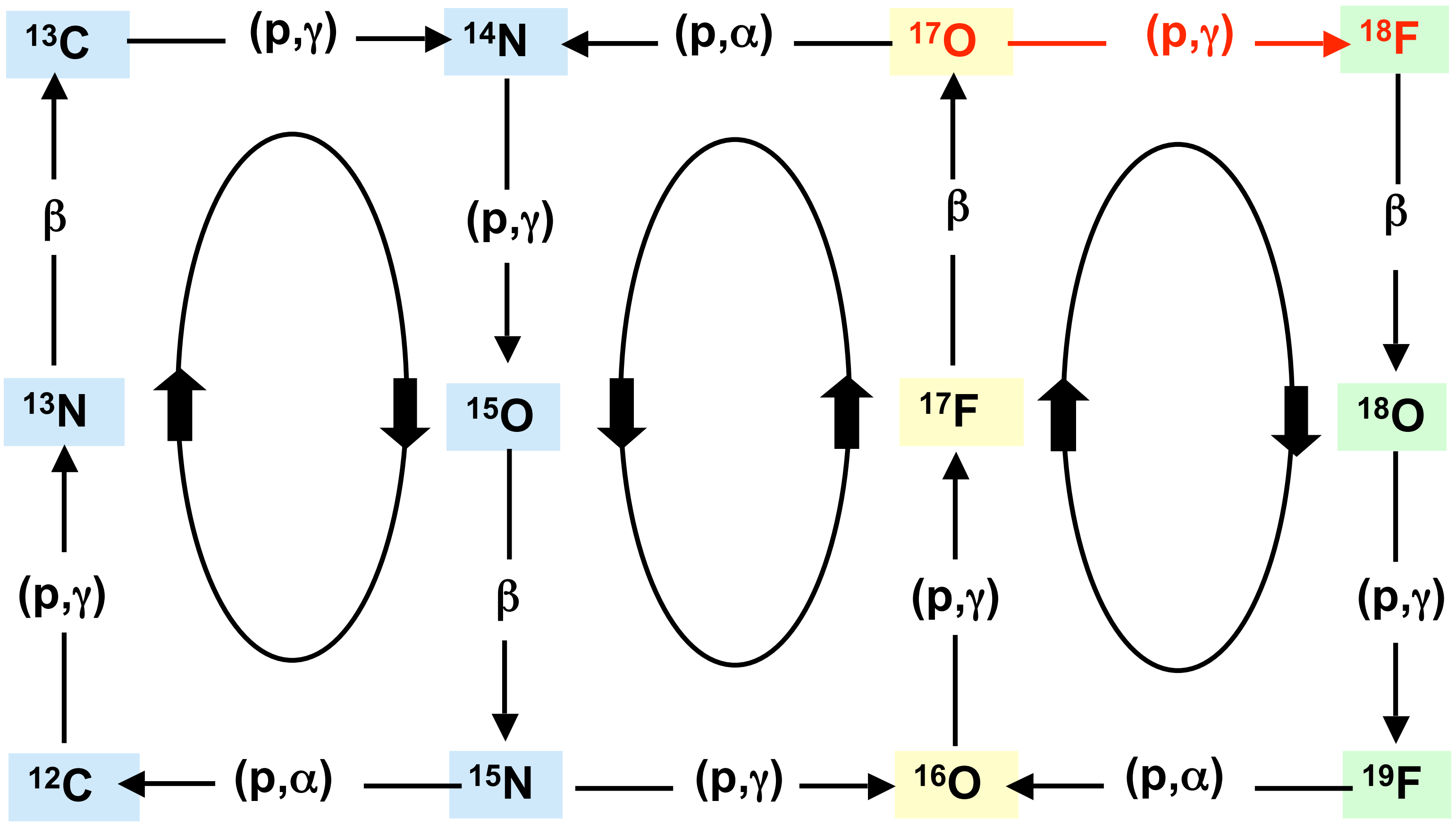
Some Estimated Thermonuclear Reaction Yields at NIF:

$^{3}He(^{3}He,2p)\alpha$	~ 10^{10} reactions at 10^{8} K in 50 ps (10^{18} initial nuclei)	Detect protons—could be difficult, won't be monoenergetic
$^{4}He(^{3}He,\gamma)^{7}Be$	~ 4 x 10^{4} reactions at 10^{8} K	Detect ^{7}Be using RadChem or AMS; $T_{1/2}$ = 53 days
$^{12}C(p,\gamma)^{13}N$	~ 3 x 10^{5} reactions at 10^{8} K	Detect ^{13}N using RadChem; $T_{1/2}$ = 10 minutes
$^{14}N(p,\gamma)^{15}O$	~ 6 x 10^{6} reactions at 10^{8} K	Detect ^{15}O using RadChem; $T_{1/2}$ = 2 minutes

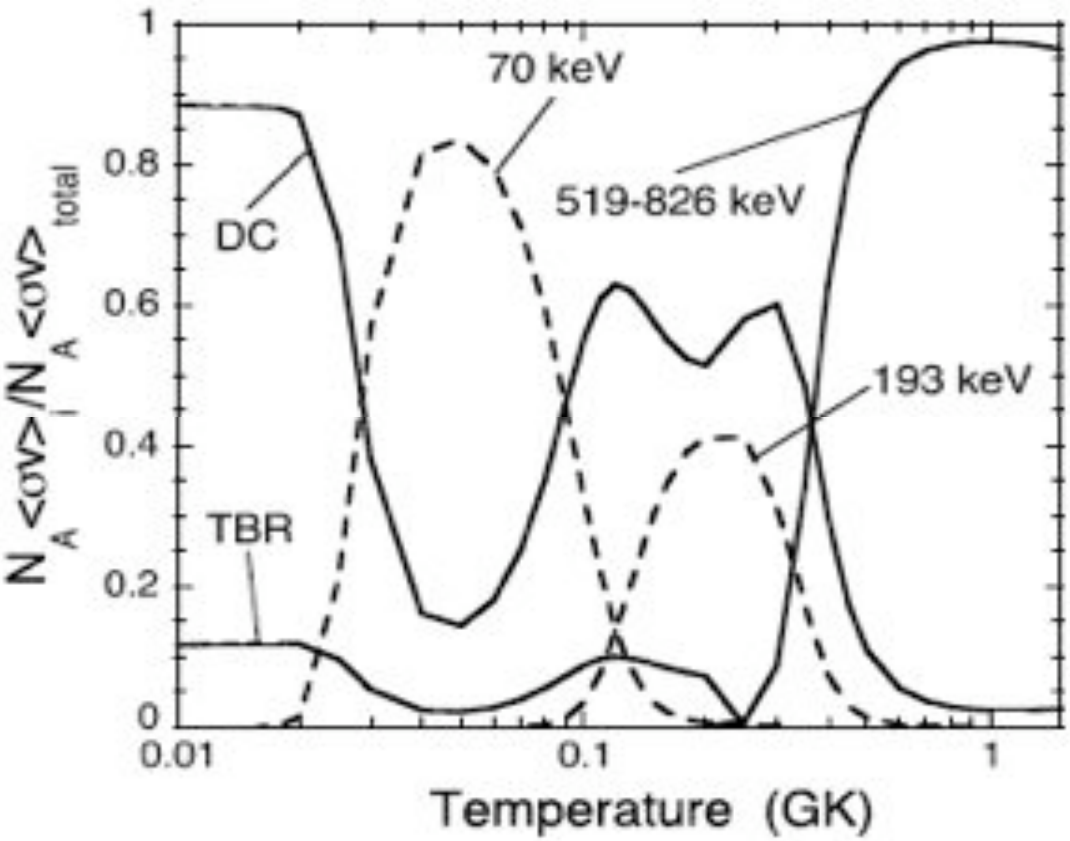
Some other potential reactions:

- $^{17}O(p,\gamma)^{18}F$ (interesting case for CNO cycles, strong resonances)
- $^{21}Ne(p,\gamma)^{22}Na$ (strong yield due to an unmeasured resonance at 94 keV)
- $^{22}Na(p,\gamma)^{23}Mg$ (difficult, since a radioactive target)
- $^{24}Mg(p,\gamma)^{25}Al$ and $^{25}Mg(p,\gamma)^{26}Al$ (which might allow study through $^{26}Al^{m}$).

Some CNO Cycle Reactions—



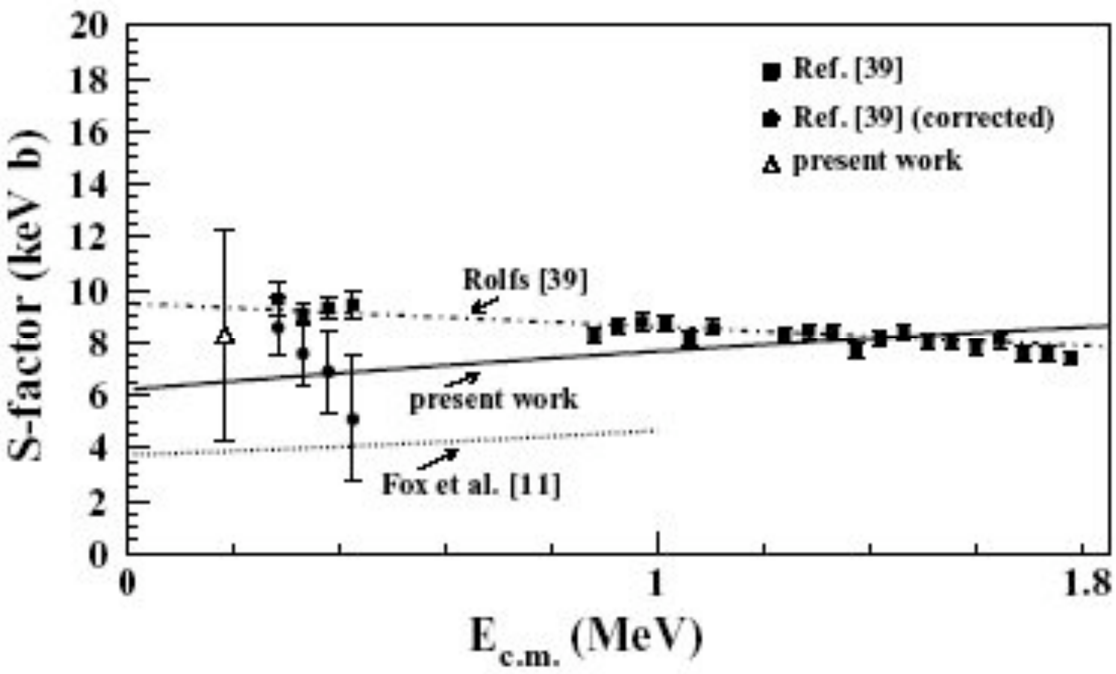
Resonances (CN States!) do matter—



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

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

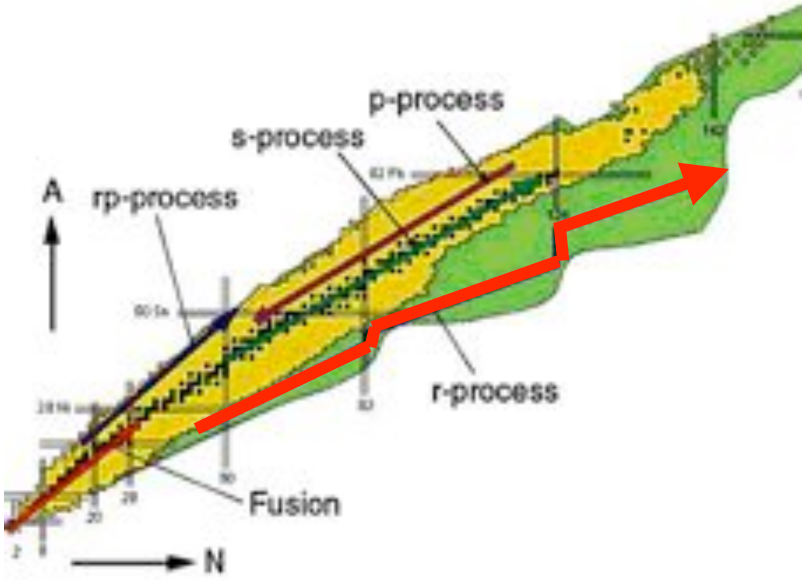


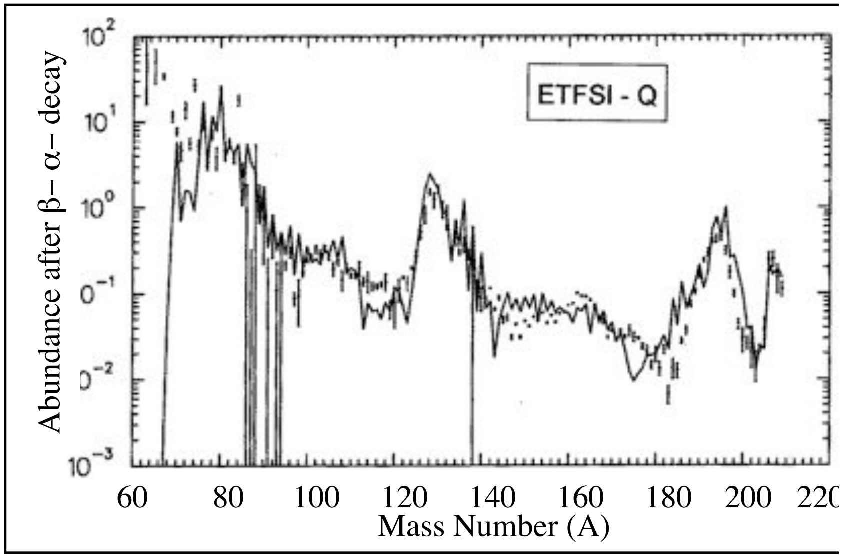
Extrapolation of higher energy data and theoretical estimates of the direct capture S-factor of the reaction $^{17}O(p,\gamma)^{18}F$ [A. Chafa et al., Phys. Rev. C 75 (2007) 035810]. (E_{GAMOW} = 53 keV at T = 50×10^6 K.)

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

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

Supernova 1987A • November 28, 2003
Hubble Space Telescope • ACS





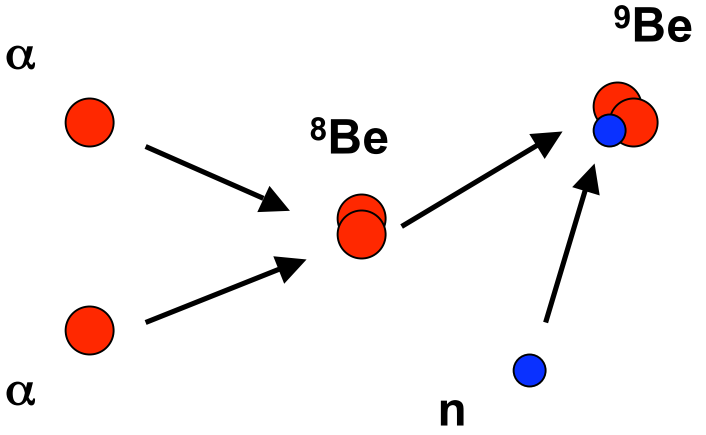
- Currently believed to take place in supernovae, but we don't know for sure
- r-process abundances depend on:
  - — Weak decay rates far from stability
  - — Nuclear Masses far from stability
- The cross section for the $\alpha+\alpha+n\rightarrow{}^{9}Be$ reaction

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

- 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*

How to detect the reaction products from NIF?

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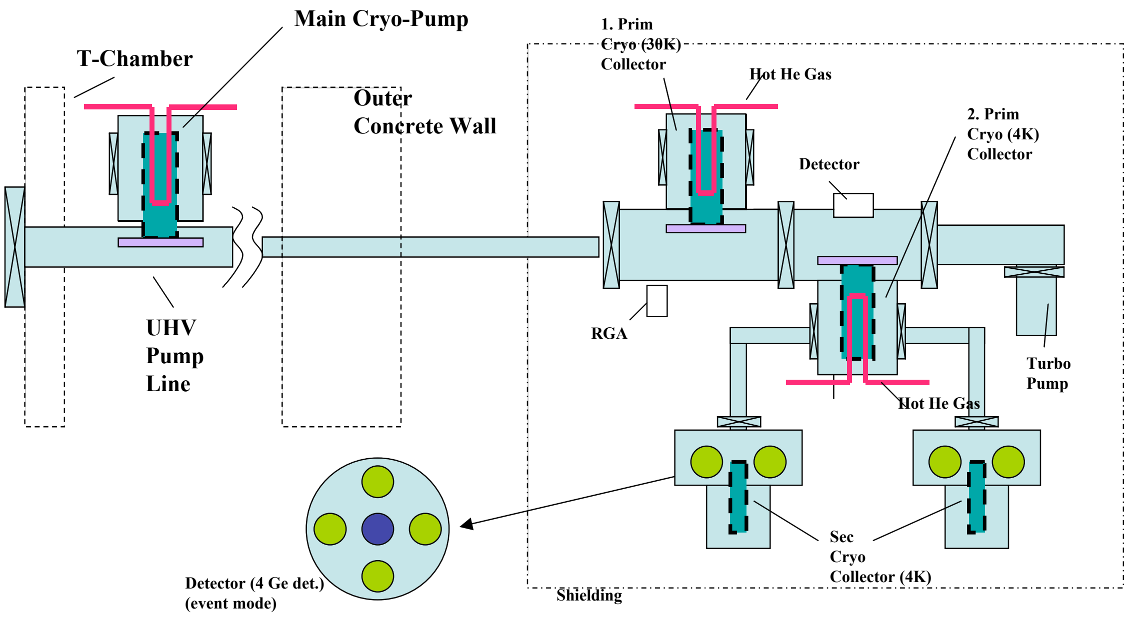
Dedicated Radchem Gas Collection System at NIF



Core-collapse supernova explosion mechanisms remain uncertain

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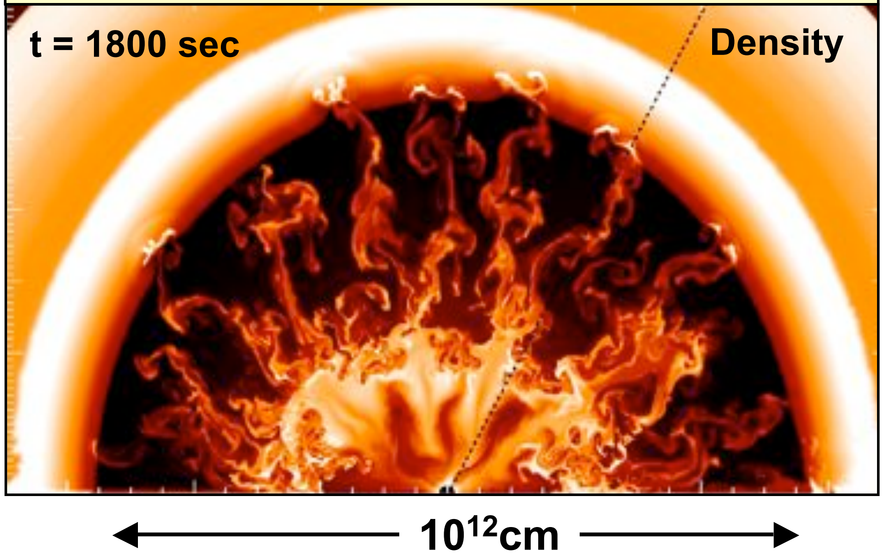
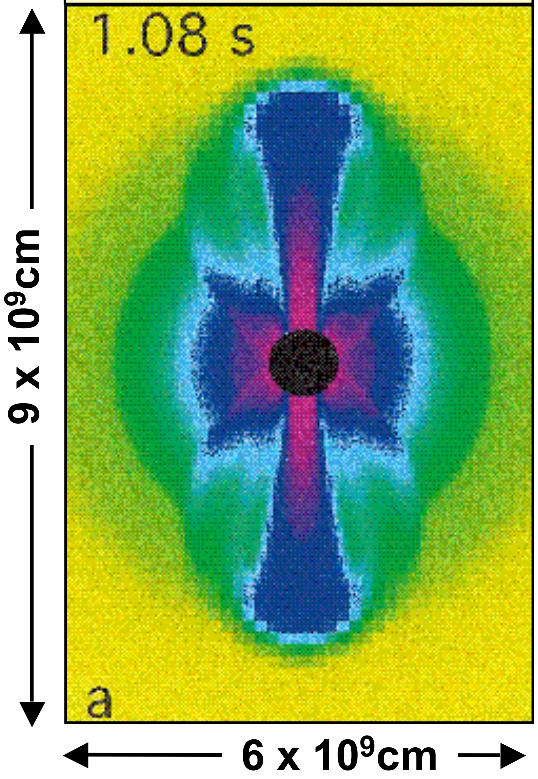
- SN observations suggest rapid core penetration to the “surface”
- This observed turbulent core inversion is not yet fully understood

Standard (spherical shock) model



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

Jet model

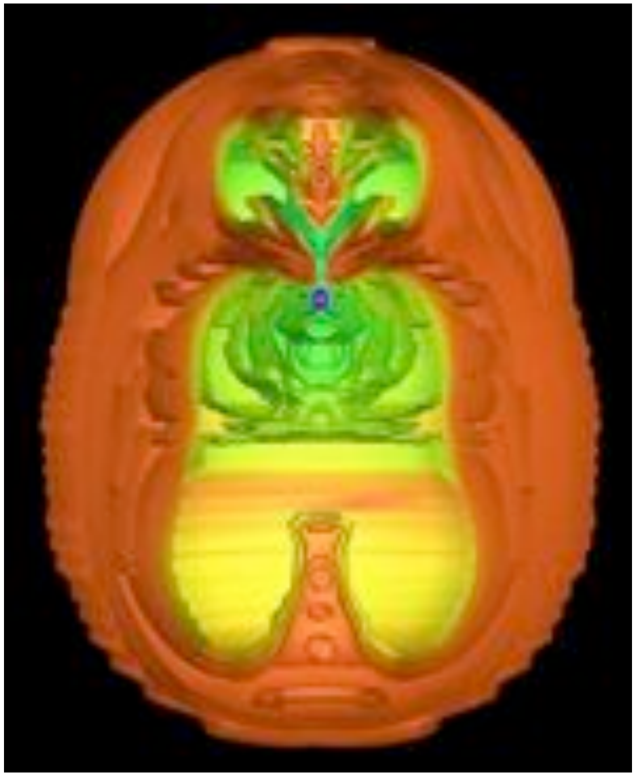


[Khokhlov et al., Ap.J.Lett. 524, L107 (1999)]

- 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

Core-collapse supernova explosion mechanisms remain uncertain

- 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

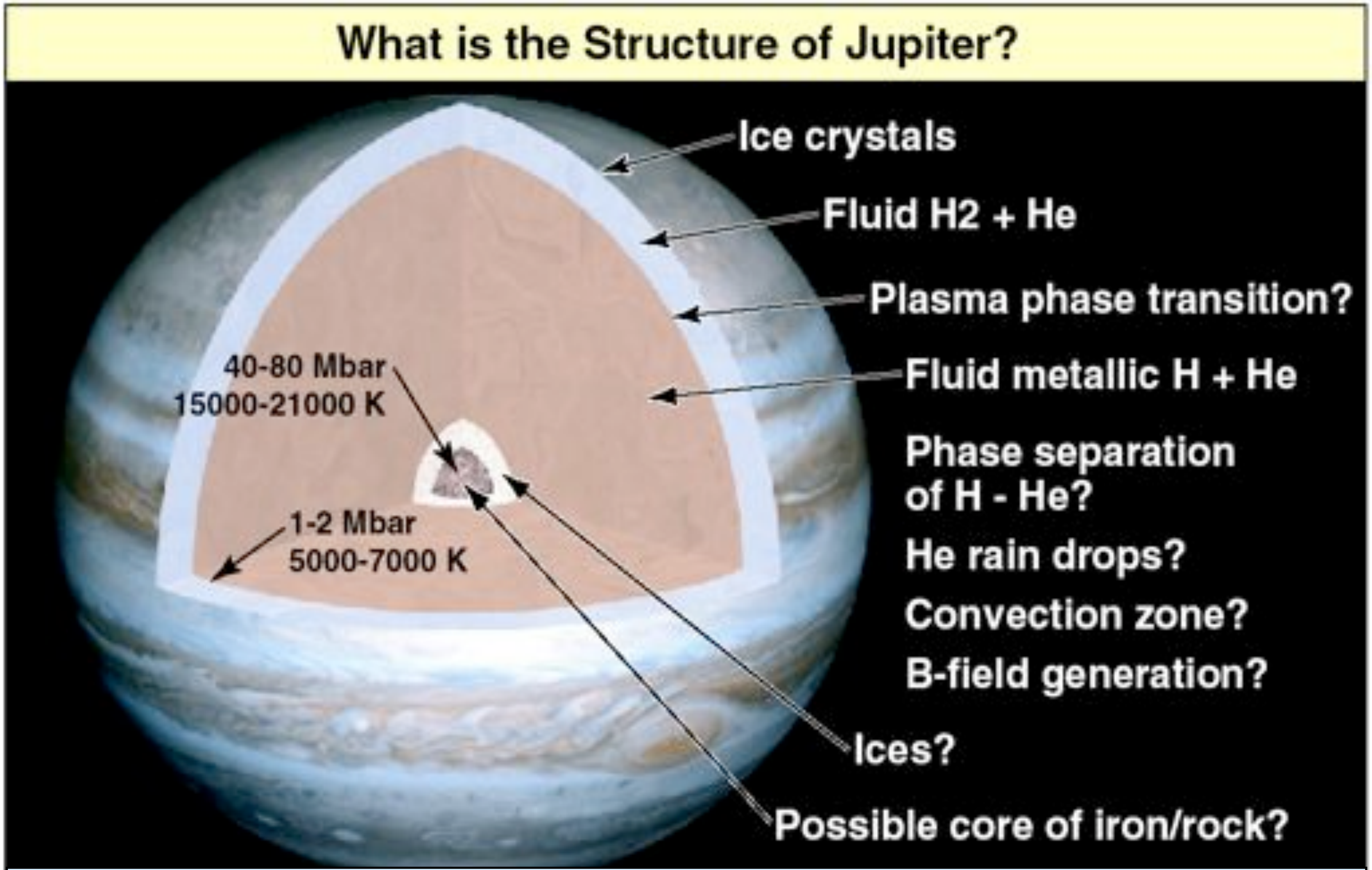


From http://www.msnbc.msn.com/id/11463498/

- 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

- 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



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

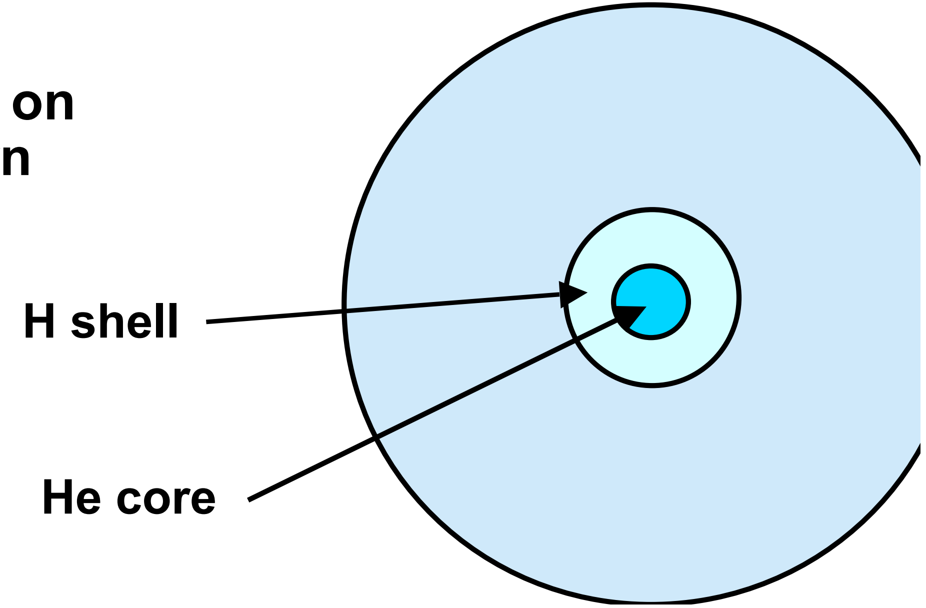
A Hydrogen-Helium Phase Transition At High Pressure?

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.



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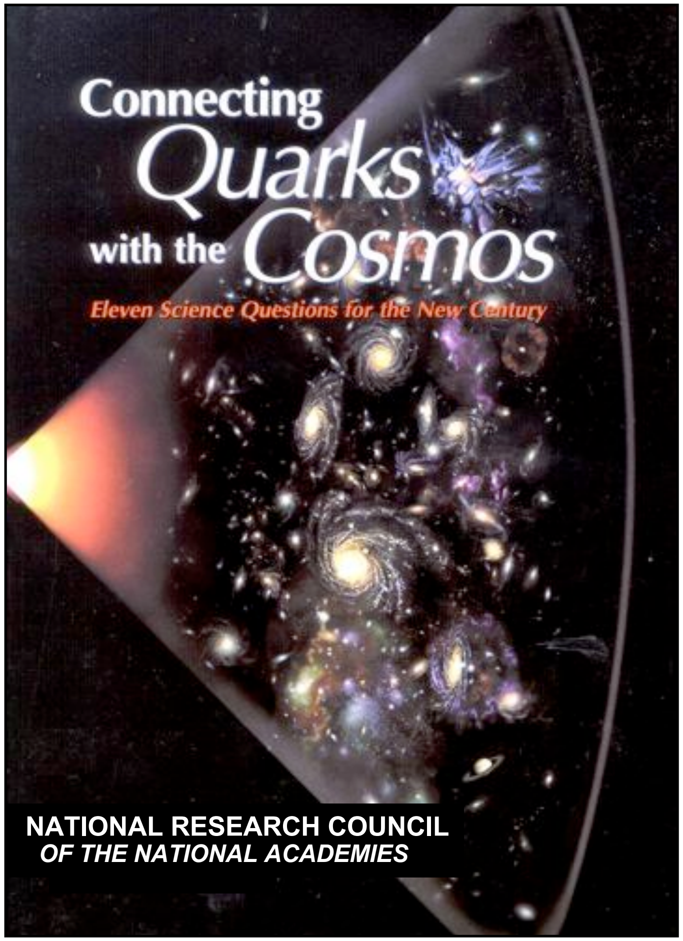

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- **HEDP provides crucial experiments to interpreting astrophysical observations**
- **We envision that NIF will play a key role in these measurements**


NIF
NATIONAL
IGNITION
FACILITY

NIF is the culmination of a long line of large glass laser systems

Janus

100 J
1.05 µm

1972

Shiva

10 kJ
1.05 µm

1978

Nova

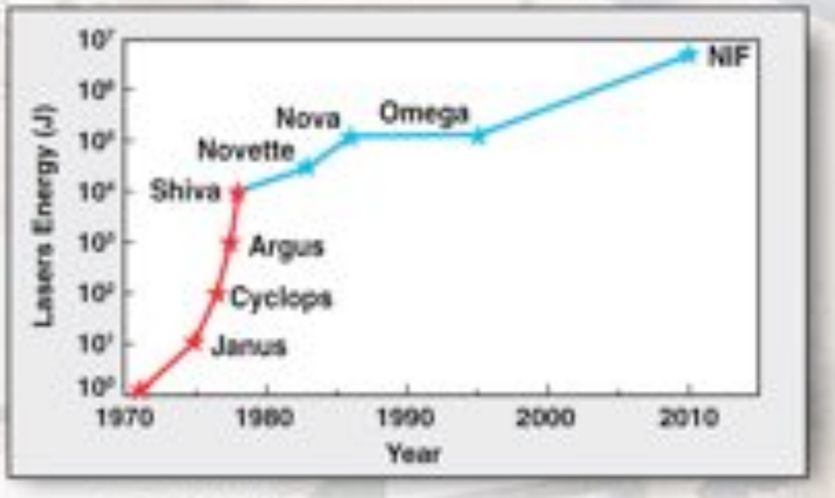
30 kJ
351 nm

1984

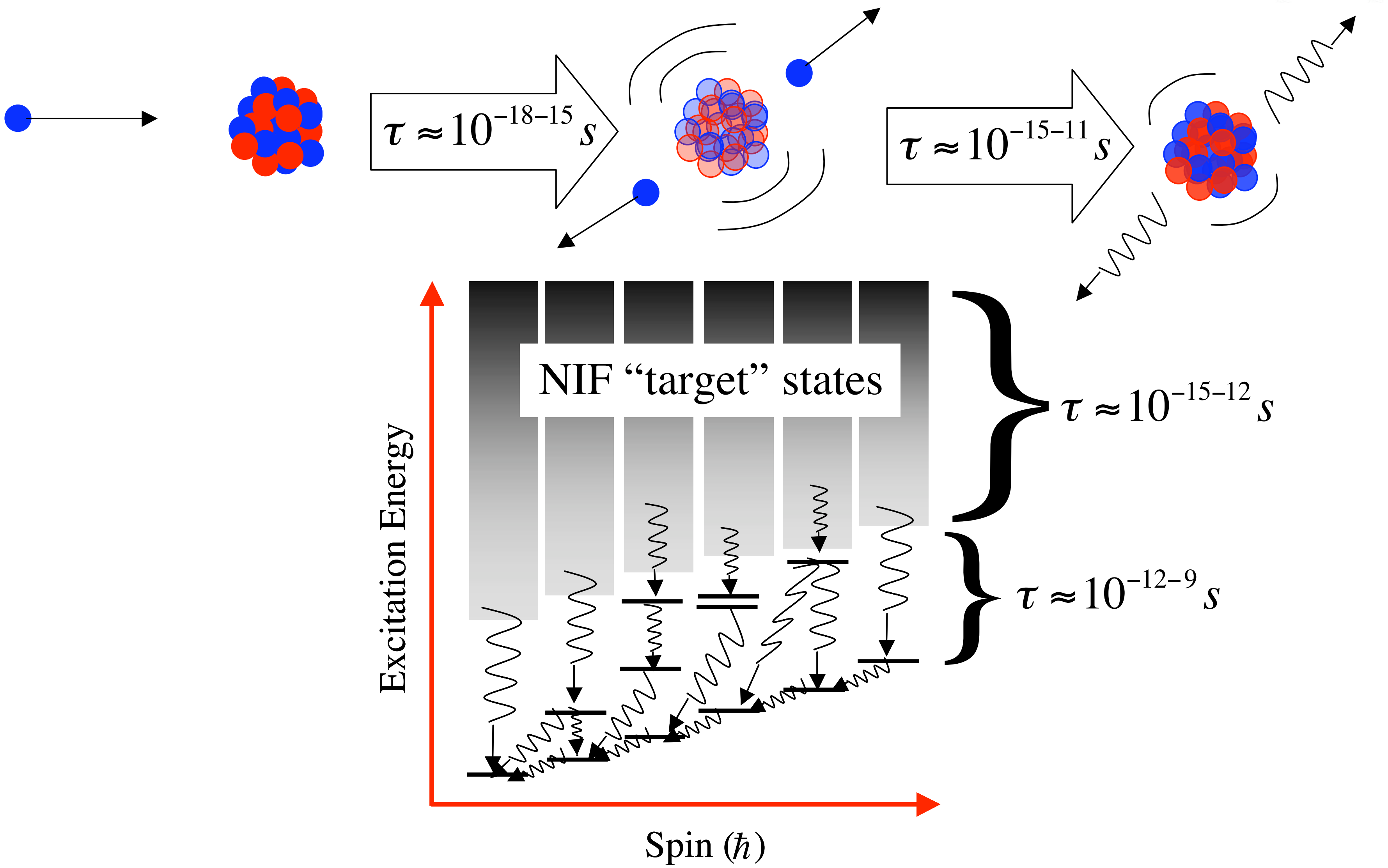
NIF

1.8 MJ
351 nm

2009



The short time scale of a NIF burn matches the lifetime of “quasi-continuum” states



NIF will cause reactions on *non-isomeric* short-lived states

A simple toy model can be used to model reactions on excited states at NIF

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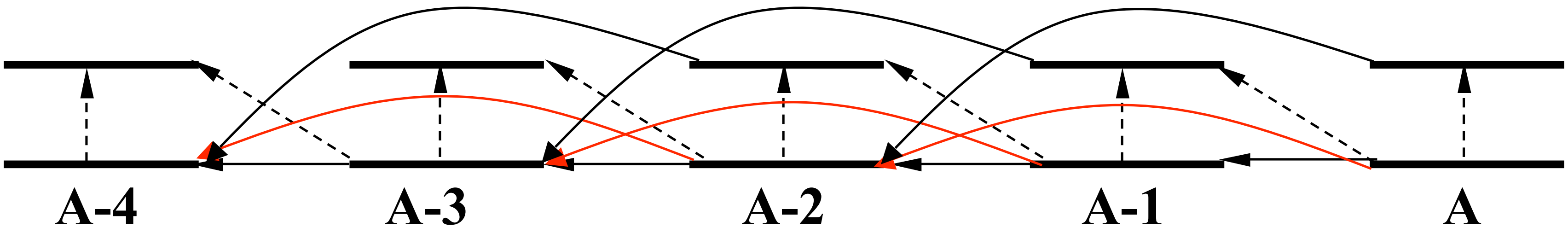
- Divide NIF "burn" time into 100 equal-flux time bins ($\Delta t \approx 50\text{-}400$ fs)

- Assume 14 MeV neutrons induce (n,3n) rather than (n,2n) on all nuclei still at $E_x \approx S_n$ after 1 bin and that these nuclei

- Include two neutron energy bins:
  - — 14 MeV: can do (n,n') & (n,2n) on ground and (n,3n) on excited states
  - — Tertiary ($E_n > 14$ *MeV*) neutrons ($10^{3\text{-}5}$ fewer than at 14 MeV) do (n,3n) on ground states



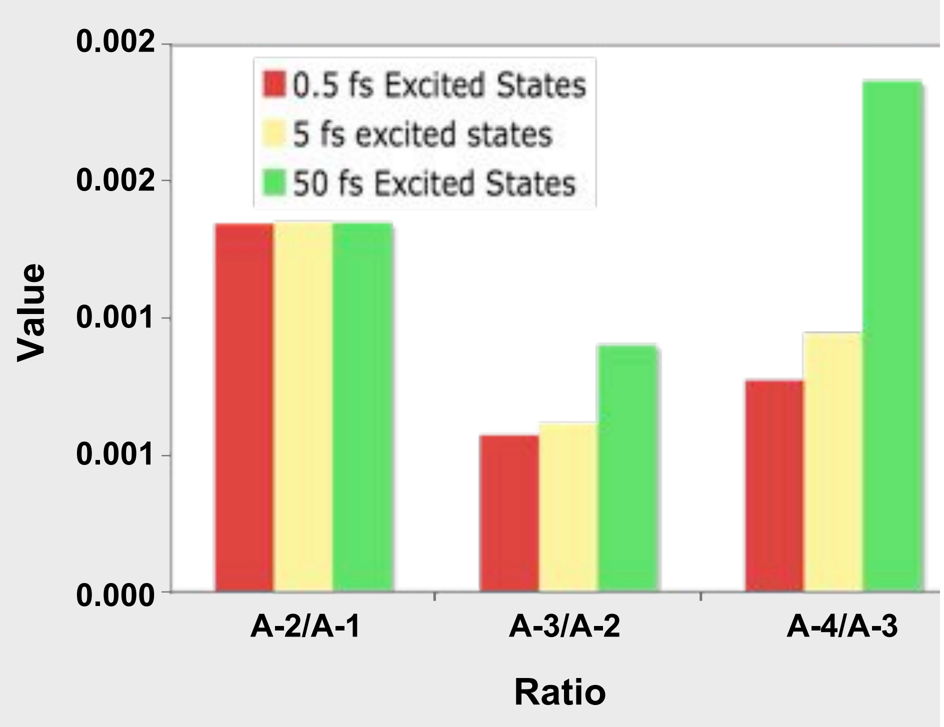
This type of analysis is quantitatively understood at LLNL

Reactions on excited states are responsible for almost all of the higher order (n,xn) products at NIF

Assumptions

- 5 x 10^{15} neutrons
  - Higher yield shots produce a weaker signal due to competition from multi-step (n,2n)
- 250 µm initial diameter
- $\Delta\tau_{bin}$ = 50 fs
- 1:10^3 high energy "tertiaries"
  - Tertiaries also mask excited state effects

Reaction Product Ratios for Different Excited State Lifetimes



NIF allows us to measure the lifetimes of *very* short-lived states

NIF flux ($cm^{-2}s^{-1}$) vs other neutron sources

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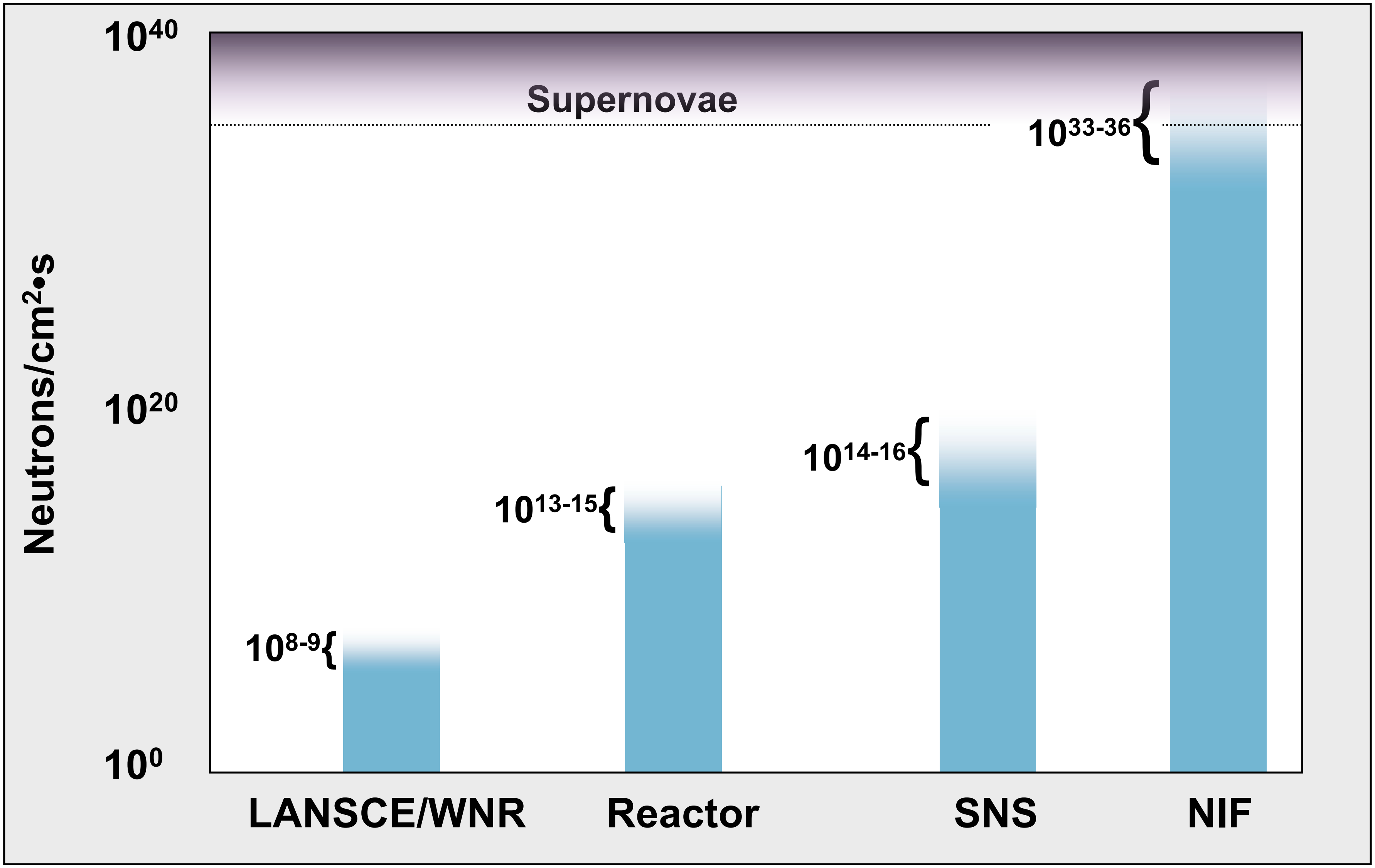
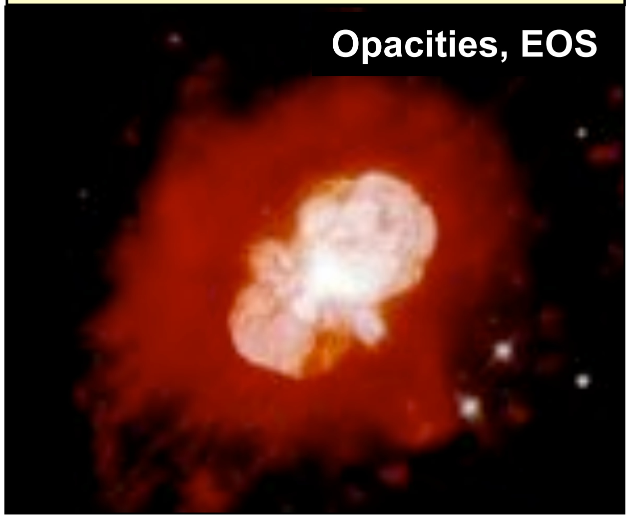


Experiments on NIF can address key physics questions throughout the stellar life cycle

Ques. 2, 10
(Dark energy;
the elements)

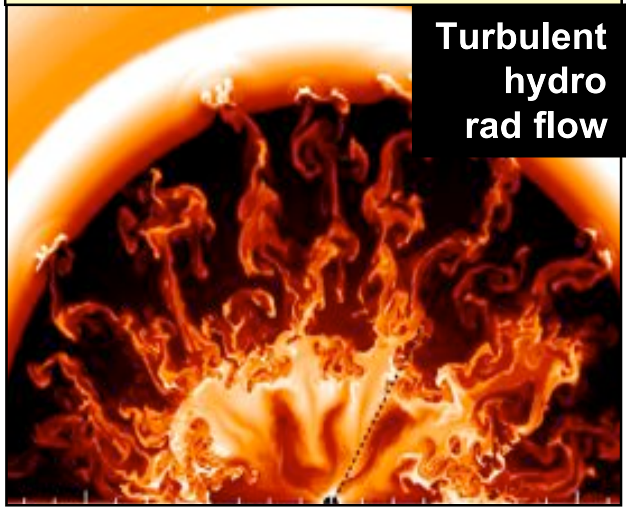
Stellar life



Opacities, EOS

Ques. 2, 10
(Dark energy;
the elements)

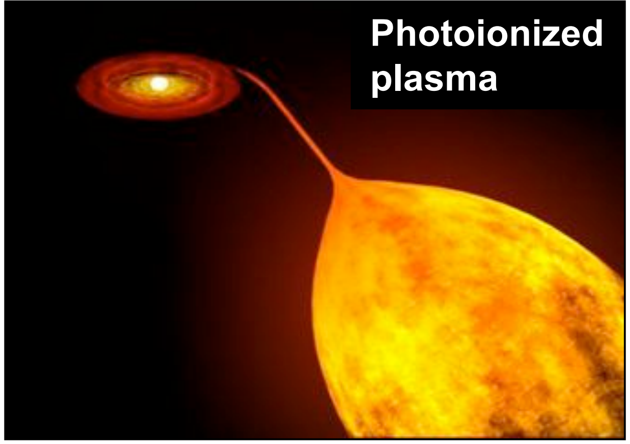
Stellar death



Turbulent hydro rad flow

Ques. 4, 8
(Gravity;
HED matter)

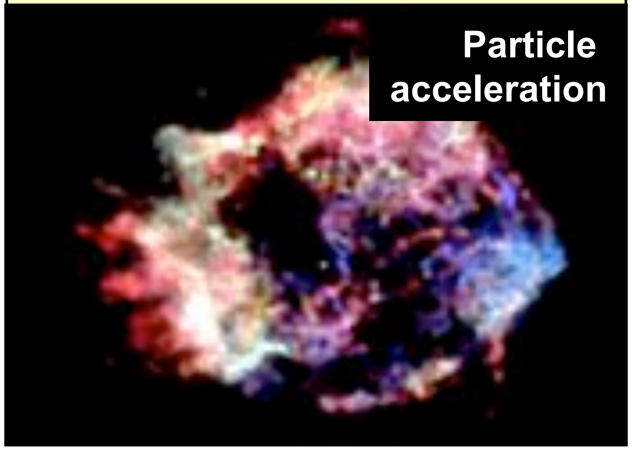
Stellar post-mortem



Photoionized plasma

Ques. 6
(Cosmic
accel.)

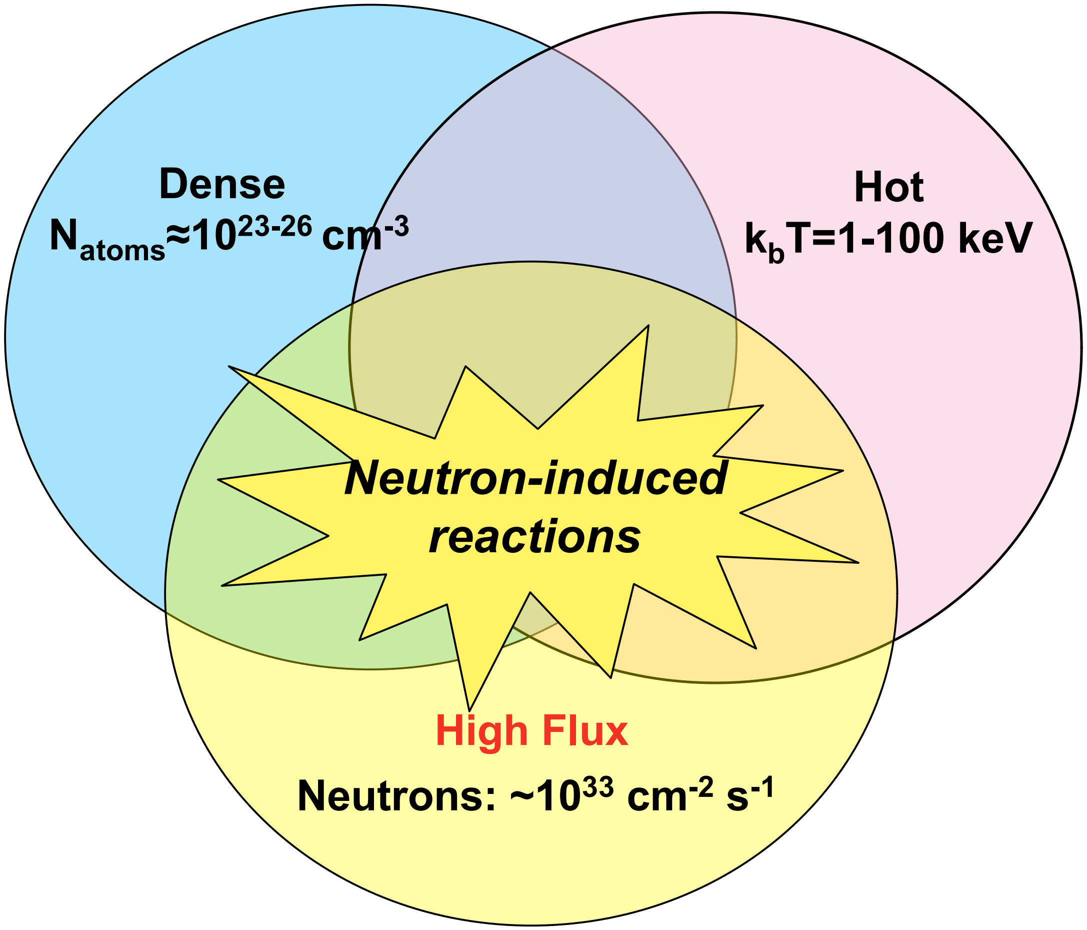
Supernova shocks



Particle acceleration

Thoughts on Nuclear Physics at NIF: NIF has a *tremendous* neutron flux

The National Ignition Facility



Dense

$N_{atoms} \approx 10^{23-26}$ cm^{-3}

Hot

k_bT=1-100 keV

Neutron-induced reactions

High Flux

Neutrons: ~10^{33} cm^{-2} s^{-1}

Neutron -induced reactions are central to both the nuclear astrophysics and weapons science communities