Nuclear Science at NIF

NIF Users Meeting

Livermore, CA

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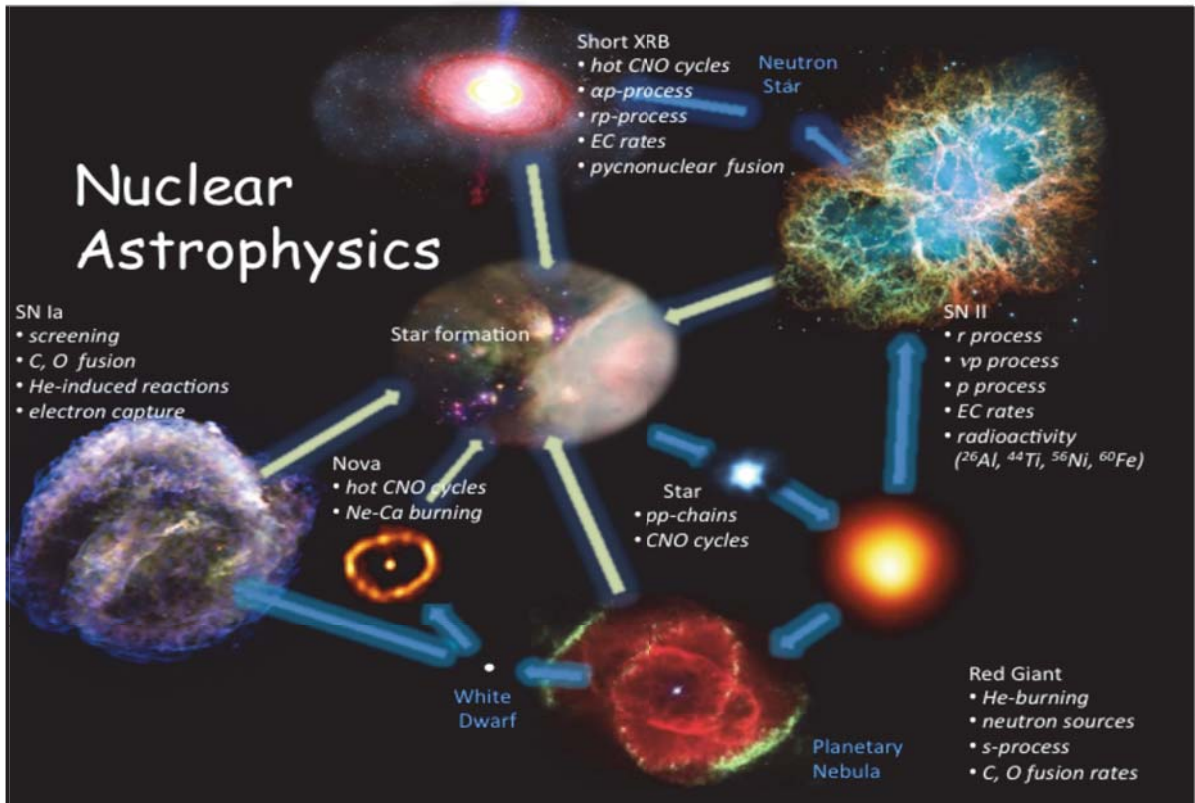
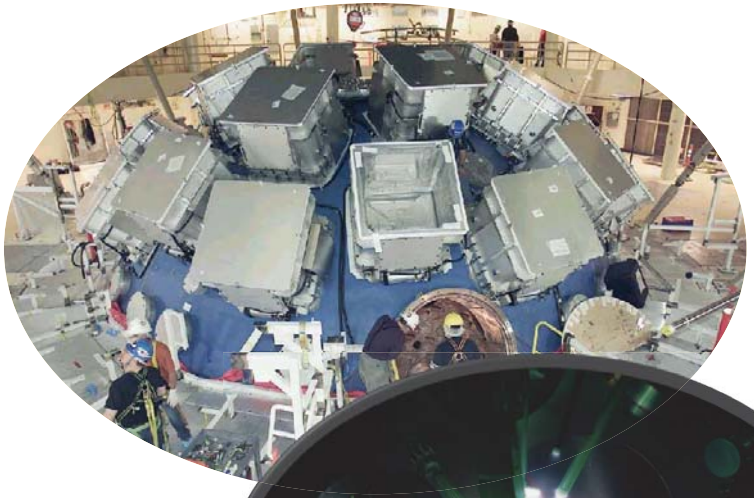
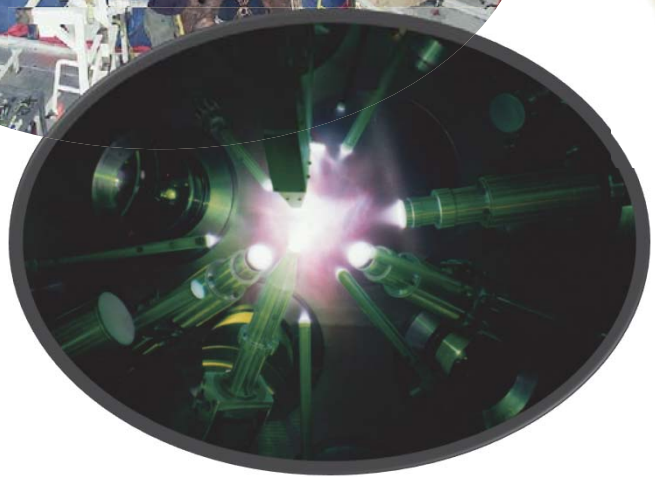


LLNL-PRES-582193
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

ICF can access regimes outside the reach of traditional nuclear labs

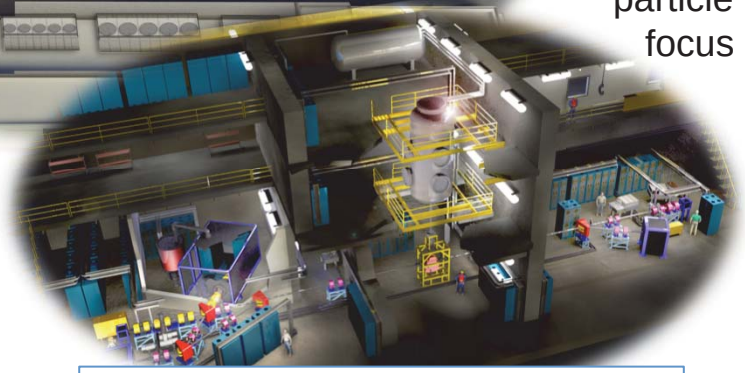




Facility for Rare Isotope Beams
MSU, planned completion 2020

r-process focus

charged particle focus



DIANA – underground accelerator
DUSEL, planned completion ???

NIF and Omega unique capabilities that complement US nuclear astrophysics labs

- Plasma environment, electron screening affects
- Reactions on short-lived states, s process

The issue: Scientific success requires the complicated environment of these dynamic experiments be precisely characterized (<10%)

$$N_{signal} \propto \rho(\vec{r},t)\Phi(\vec{v},\vec{r},t)\sigma(E)$$

- If density profiles are well characterized
  - Measure signal and flux to infer nuclear cross section
- Conversely, using well-known nuclear process
  - Measure signal and flux to infer ρ

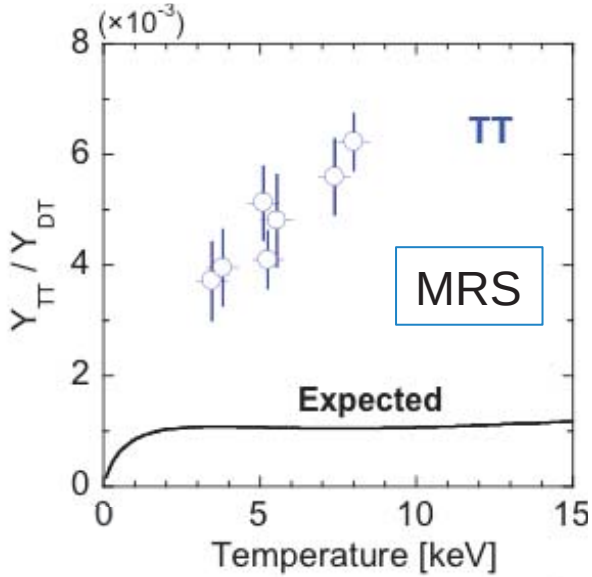
Signals and flux include emitted particles and nuclei (debris)

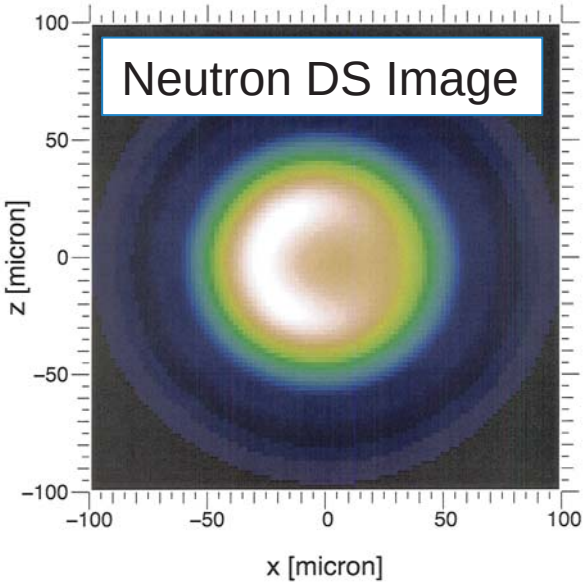
Enough to make the average astrophysicist jealous!

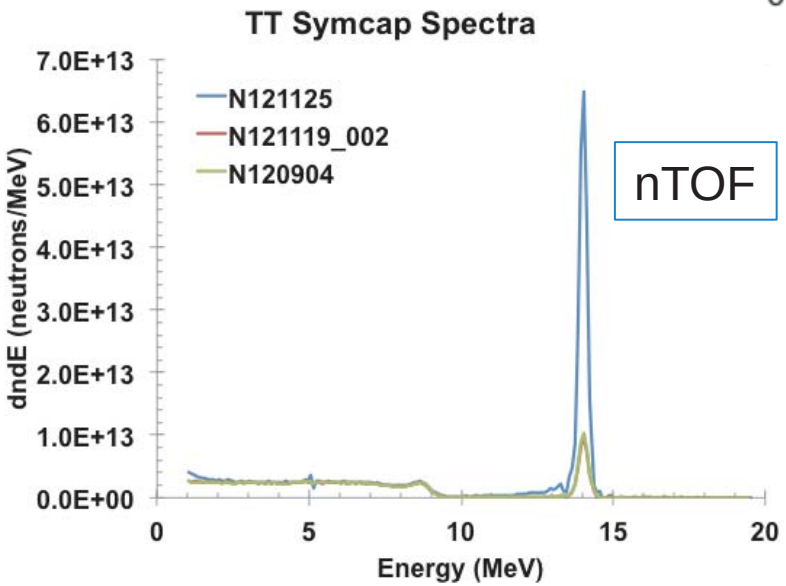
The benefit: Nuclear diagnostics are a powerful microscope into hydrodynamic conditions and internal d.o.f.'s

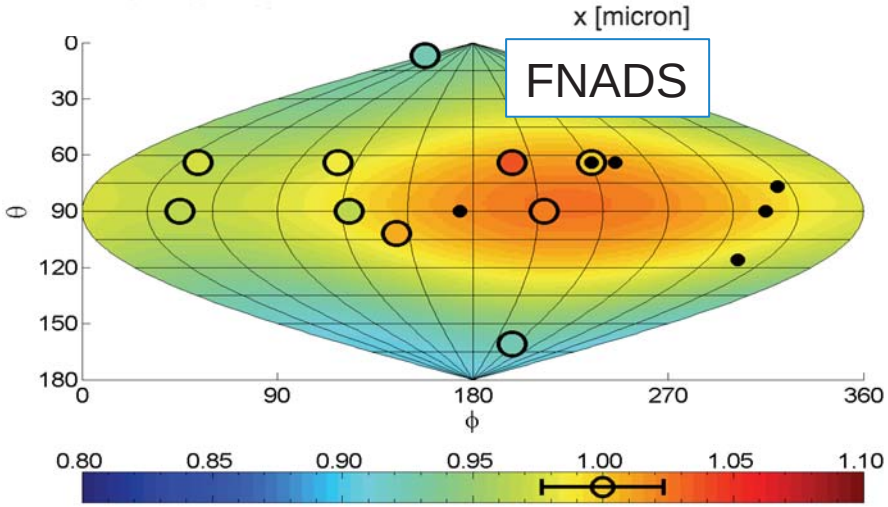
Examples:

- Ion temperature
- Mix
- Ion species separation
- Low-mode mass asymmetries
- Low-mode shock asymmetries









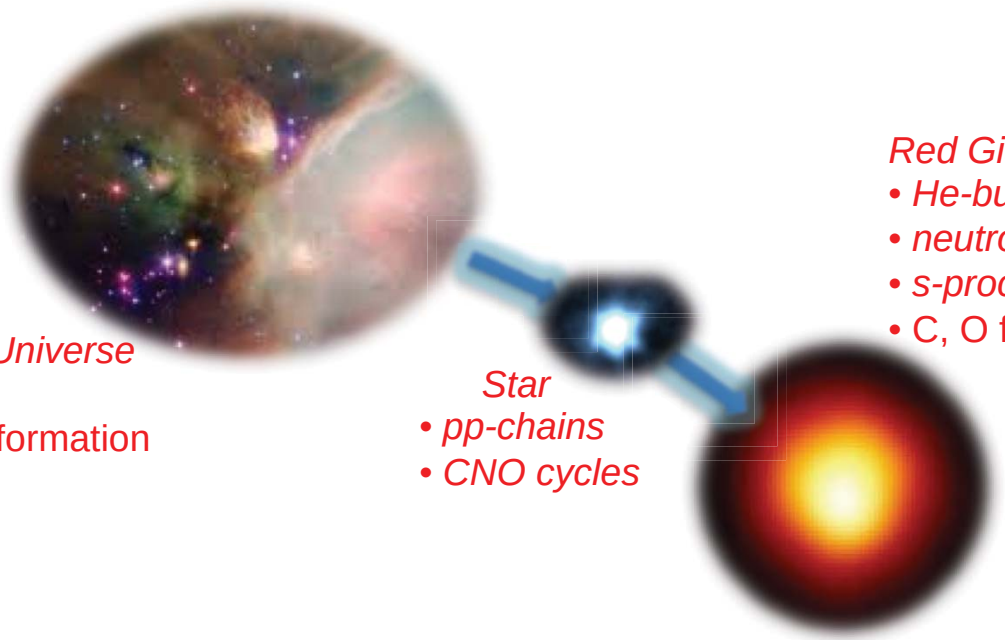
The payoff: Nuclear astrophysics at NIF

Potential scientific impact

- Charged-particle reactions
  - BBN
  - pp chains
  - CNO cycles
  - He-burning, neutron sources
- Neutron reactions
  - S-process
  - Excited states

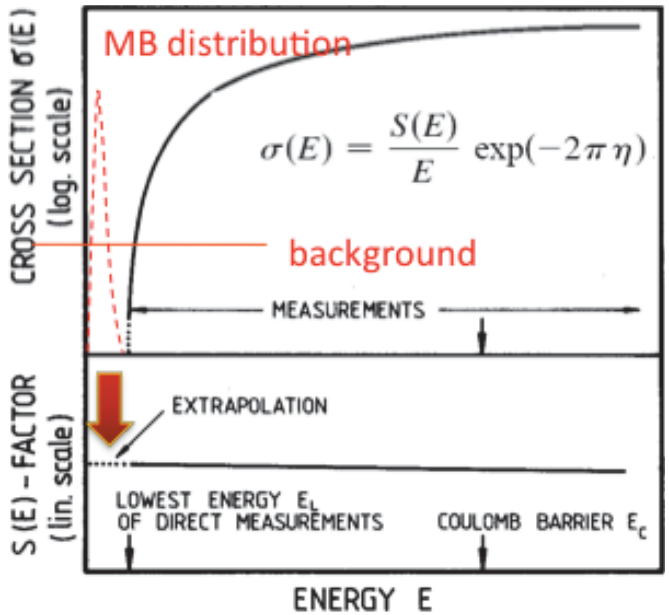
Diagnostic needs

- Low energy neutron spectrometer (LENS)
- Solid Radchem Collector (SRC)



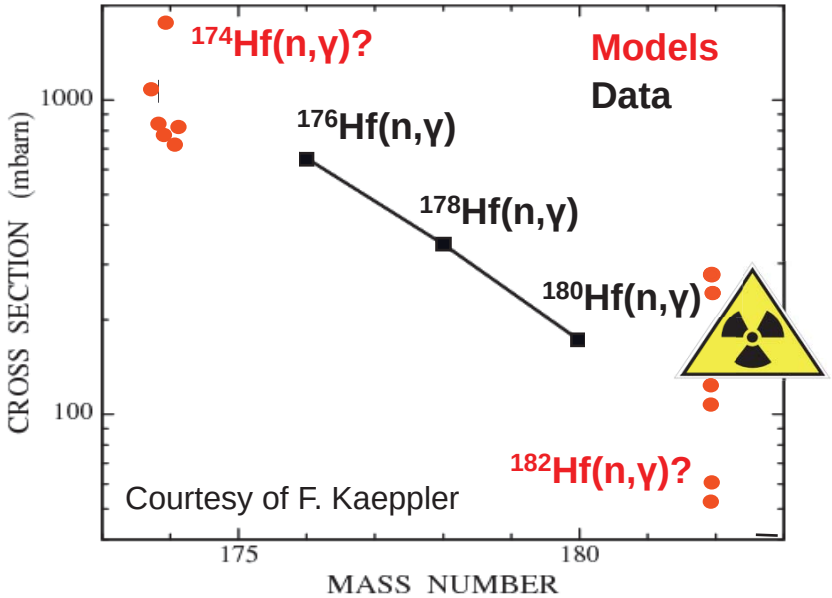
Nucleosynthesis reaction rates are challenging to measure or calculate

Charged particle rates are uncertain at stellar energies



- **Extrapolate from higher energies**
- **Measurements have screening corrections**
- **Plagued by radioactive backgrounds**

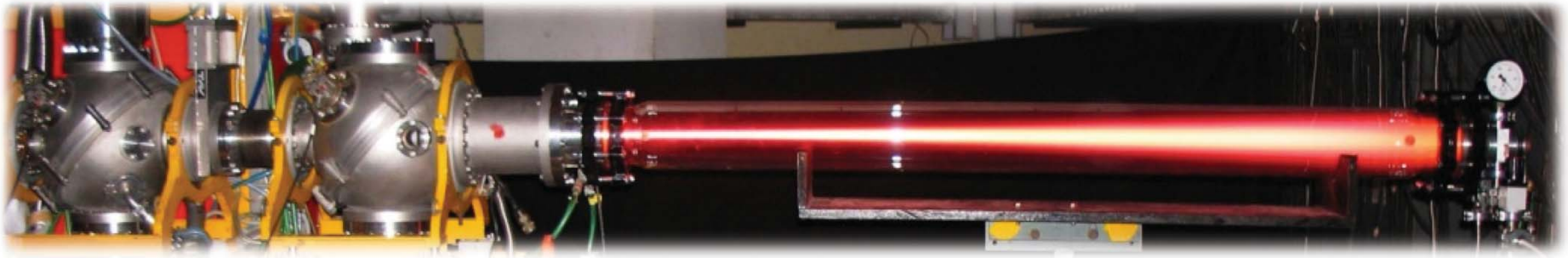
Neutron capture rates on unstable nuclei are highly uncertain



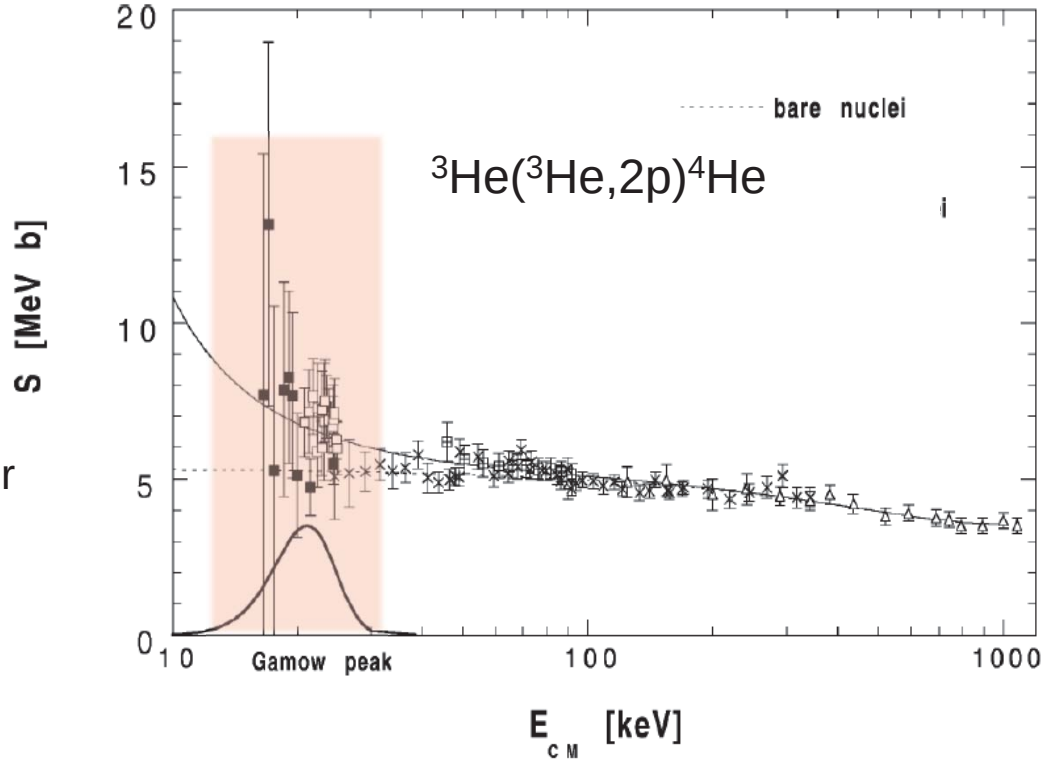
- **Models uncertain due to lack of knowledge**
- **Experiments require radioactive samples and are plagued by "room return" bckgrnds**

Both direct and indirect approaches are desirable

ICF plasma environments complement accelerator experiments to directly measure charged-particle reaction rates

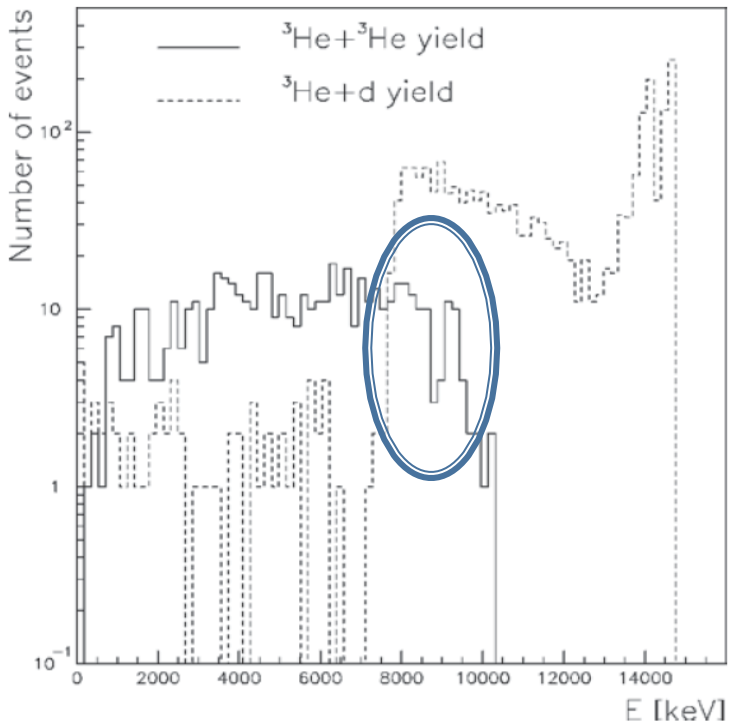


- Rates are low
  - Backgrounds become a problem
  - *NIF data arrives "instantaneously"*
- S-factor increases at low energy
  - e^- screening by the target plasma
  - Also expected for high density stars
  - Not well understood – source of error
  - Additional studies needed
  - *NIF can make measurements WITHOUT screening*

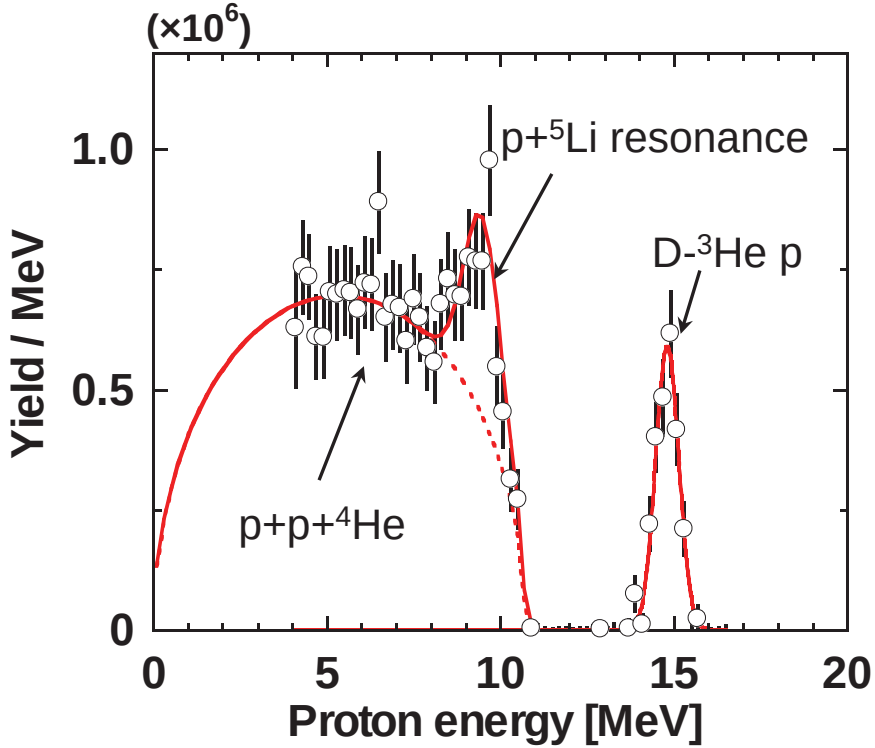


Electron screening in accelerator measurements is particularly large for the Sun's energy-producing reaction: $^3He+^3He$

LUNA underground measurement with proton spectrum at E_{cm}=30keV



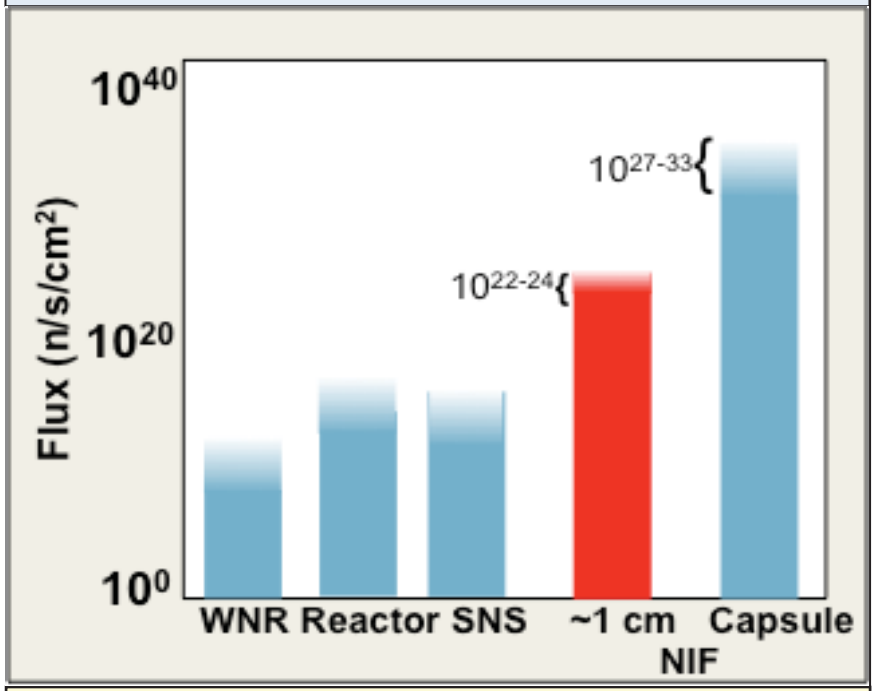
Omega laser plasma measurement with proton spectrum at E_{cm}=90keV



Low energy experiments at plasma conditions are feasible; this provides a unique opportunity to probe reaction plasma interaction

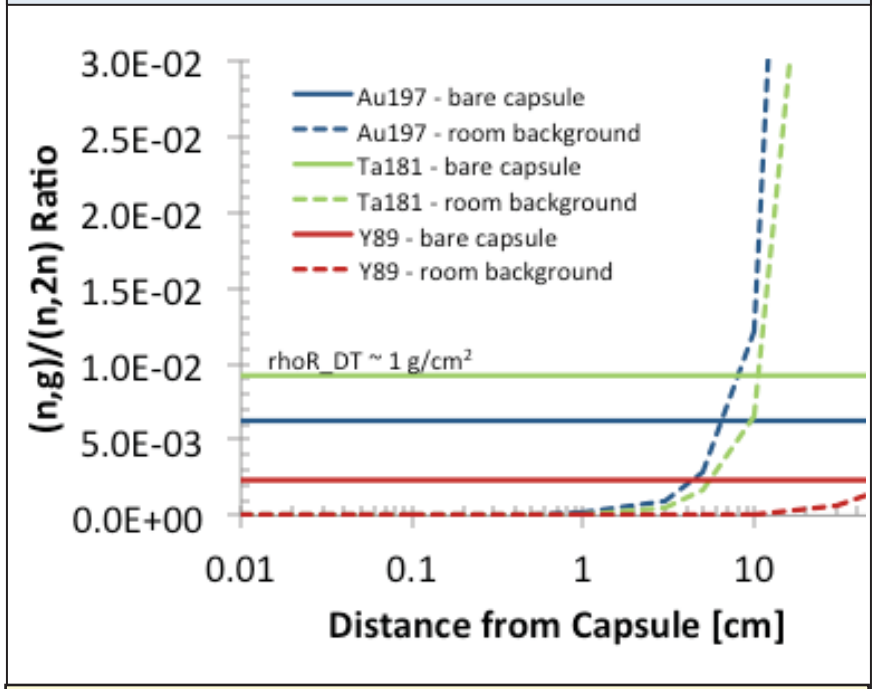
High-neutron brightness at NIF presents new opportunities for studying s-process reactions directly

Brightness much larger than traditional nuclear facilities



- **Smaller targets, not much material needed**
- **Experiment is short, no radioactive bckgrnds**

Room return backgrounds comparable to accelerators at short distances

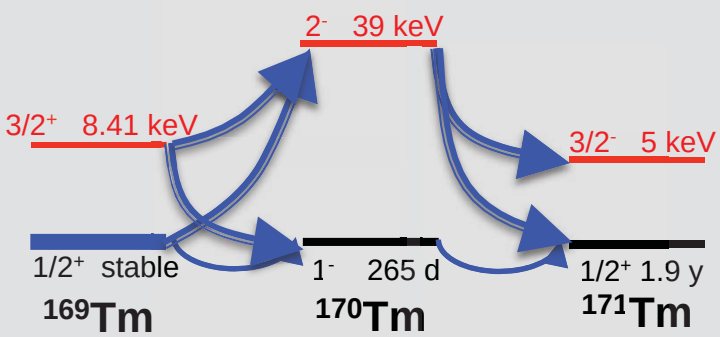


- **Large NIF chamber is unique**
- **Brightness within 1 cm of capsule huge**

Direct measurements on targets with <1 y half-life possible

And perhaps step into uncharted territory and measure plasma-nuclear processes and reactions on "excited" states

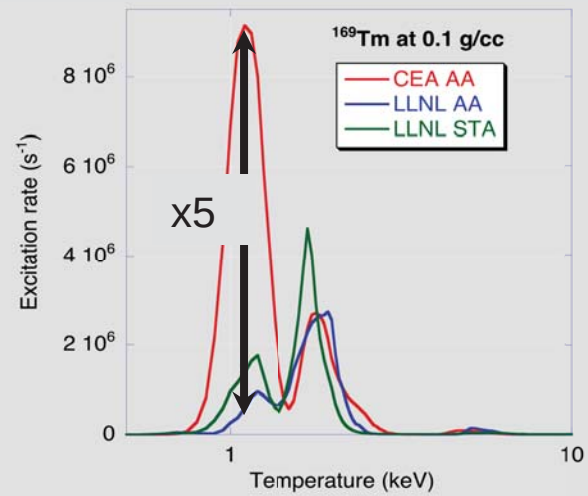
Origins of the elements
Thulium s-process



We know the inverse process happens, but it has never been seen in a plasma

Calculations
Plasma-induced population of *keV* excited states

M. Chen (LLNL) vs. G. Gosselin (CEA-DAM)

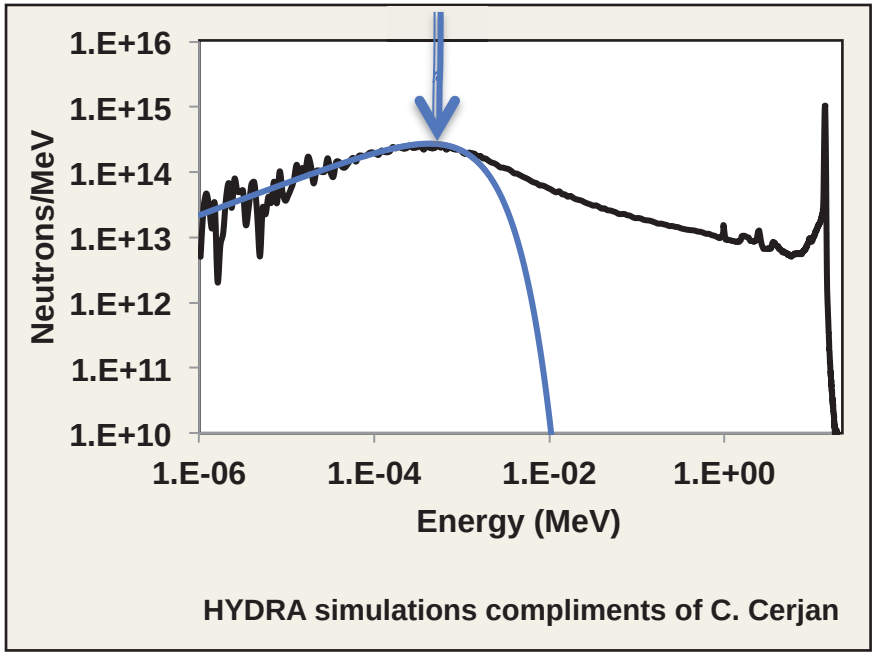


Calculations differ by 100-500%
We need data !

While we have made excellent progress with neutron spectra > 1MeV, we need to create & characterize lower energy components

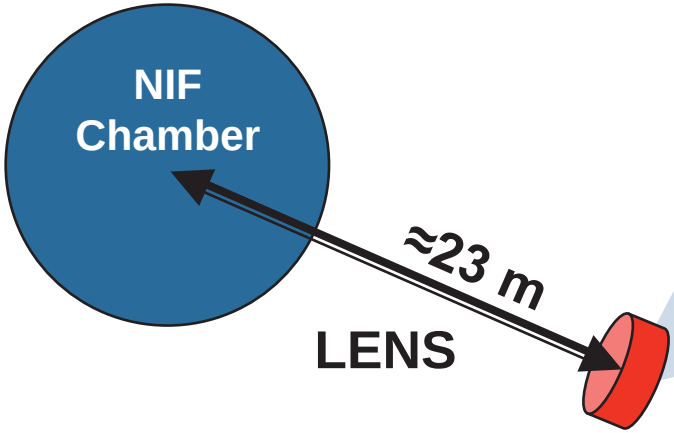
- ~30-keV neutrons are the most important for astrophysical (n,γ) reactions
- High ρR_{fuel}: significant fraction of the neutrons scatter to thermal energies
- Spectral shape correlates with capsule confinement time

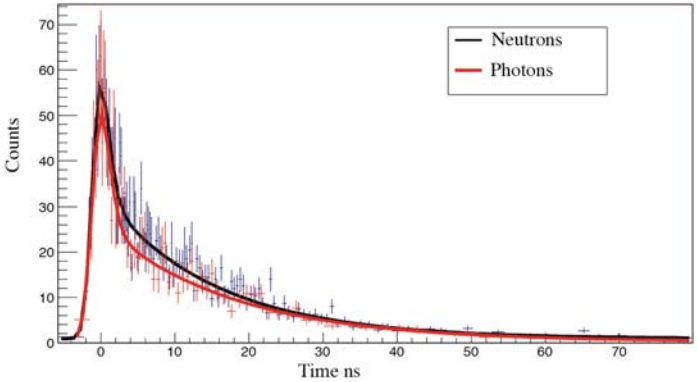
Stellar Thermal Neutrons



A low-energy neutron spectrometer is not only essential for any NIF-based (n,γ) measurement but also provides info about $\tau_{confinement}$ and ρR

The ideal solution is a segmented detector that can be absolutely calibrated with a neutron source





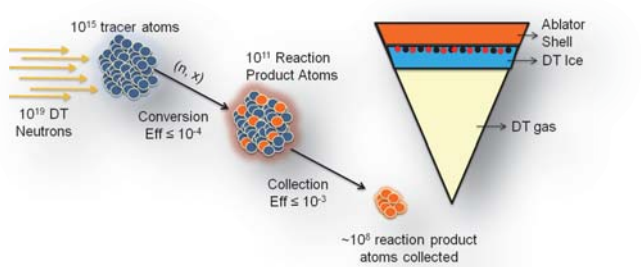
Scintillator testing at LBNL Collaboration w/UCB-NE

Novel plastic scintillators from N. Zaitseva's group

Collecting and analyzing radioactive materials produced in implosions is often the best approach to measuring the number of nuclei produced

^{167}Tm 9 days ← (n,2n) ^{168}Tm 93 days ← (n,2n) ^{169}Tm stable → (n,γ) ^{170}Tm 129 days

Capsule doping

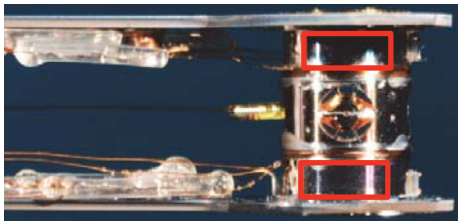


Excited state cross sections

Irradiation experiment

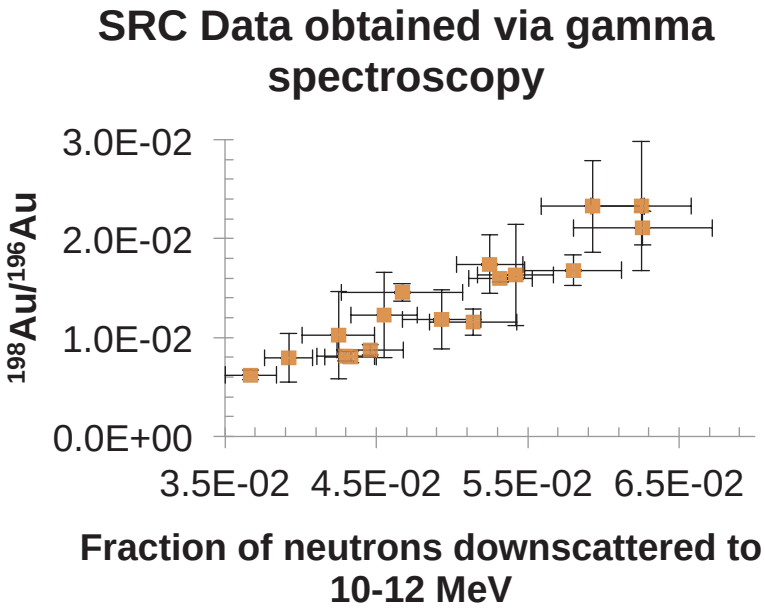
Sample fabrication

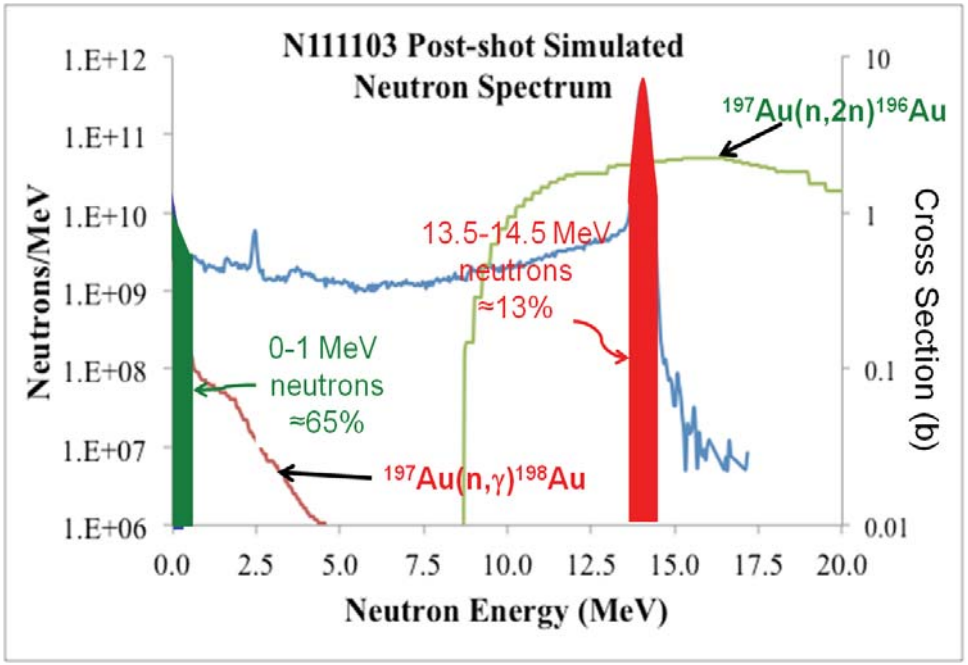
Hohlraum measurement



Astrophysics

The Solid RadioChemistry (SRC) diagnostic at NIF has generated interesting nuclear data from hohlraum debris





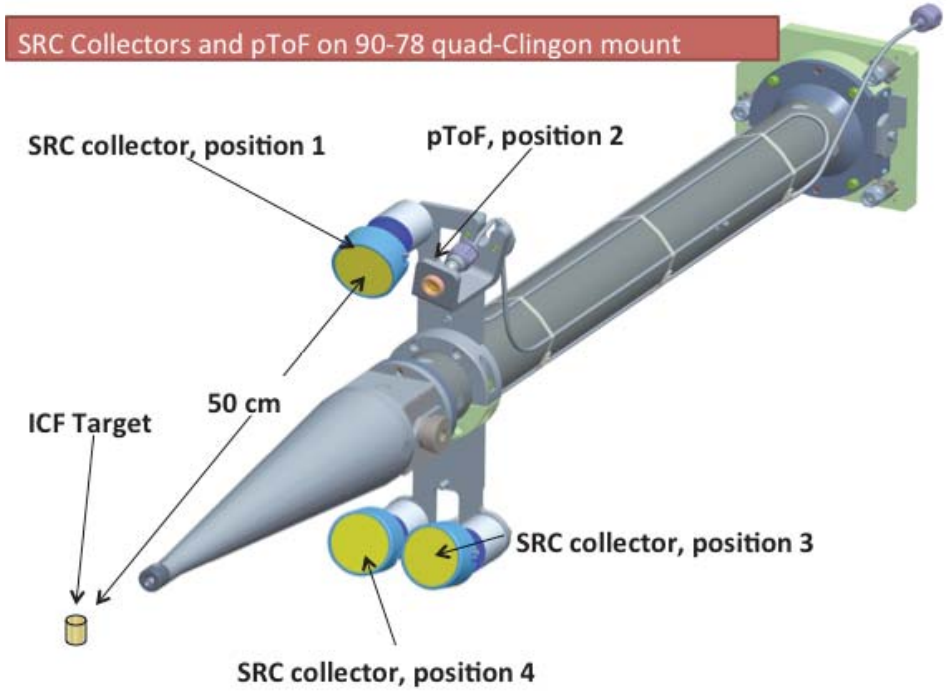
- SRC collectors fielded on cryo DT shots
- Gamma spectroscopy of the collectors:

$^{197}Au(n,\gamma)^{198}Au$ and $^{197}Au(n,2n)^{196}Au$ from activated hohlraum debris

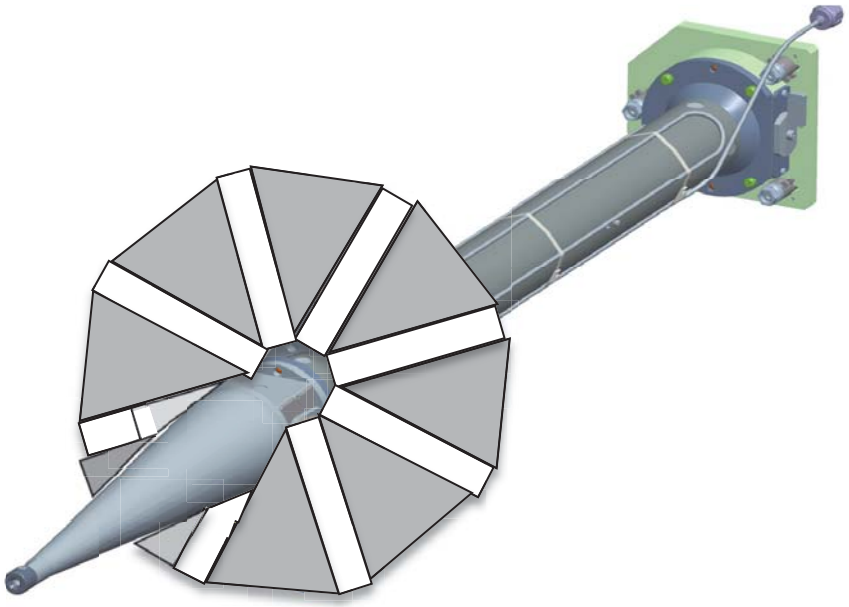
- Post-shot simulations indicate ~65% of neutron captures in the hohlraum are from <1 MeV neutrons
- DT yield of 10^{14} neutrons provides (n,γ) signal ~10X day at accelerator

SRC needs improved efficiency and rapid retrieval or in-situ counting to meet science needs

Current setup (4E-4)



Future concept



Designs goals:

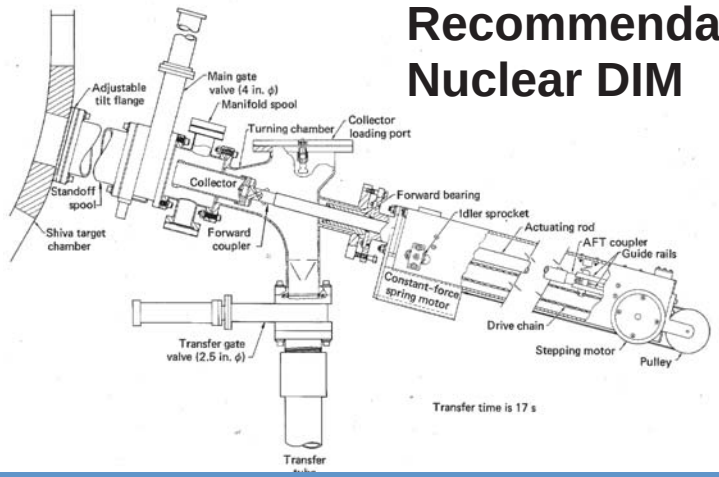
1. Collectors that open to a larger area inside the target chamber
2. In-situ counters or rapid retrieval system (<1 day half lives)
3. Ability to field at different distances

Collector designs including traps, biased grids, and alternate materials will be investigated.

NIF can deliver unique insights into nuclear astrophysics

- Unique capabilities for
  - Charged-particle reactions
  - Neutron reactions
- New diagnostics needed
  - Low-energy neutron spectrometer (LENS)
  - Solid Radio-Chemistry (SRC)
- ***Also needed: nuclear DIM!***

Recommendation: Nuclear DIM

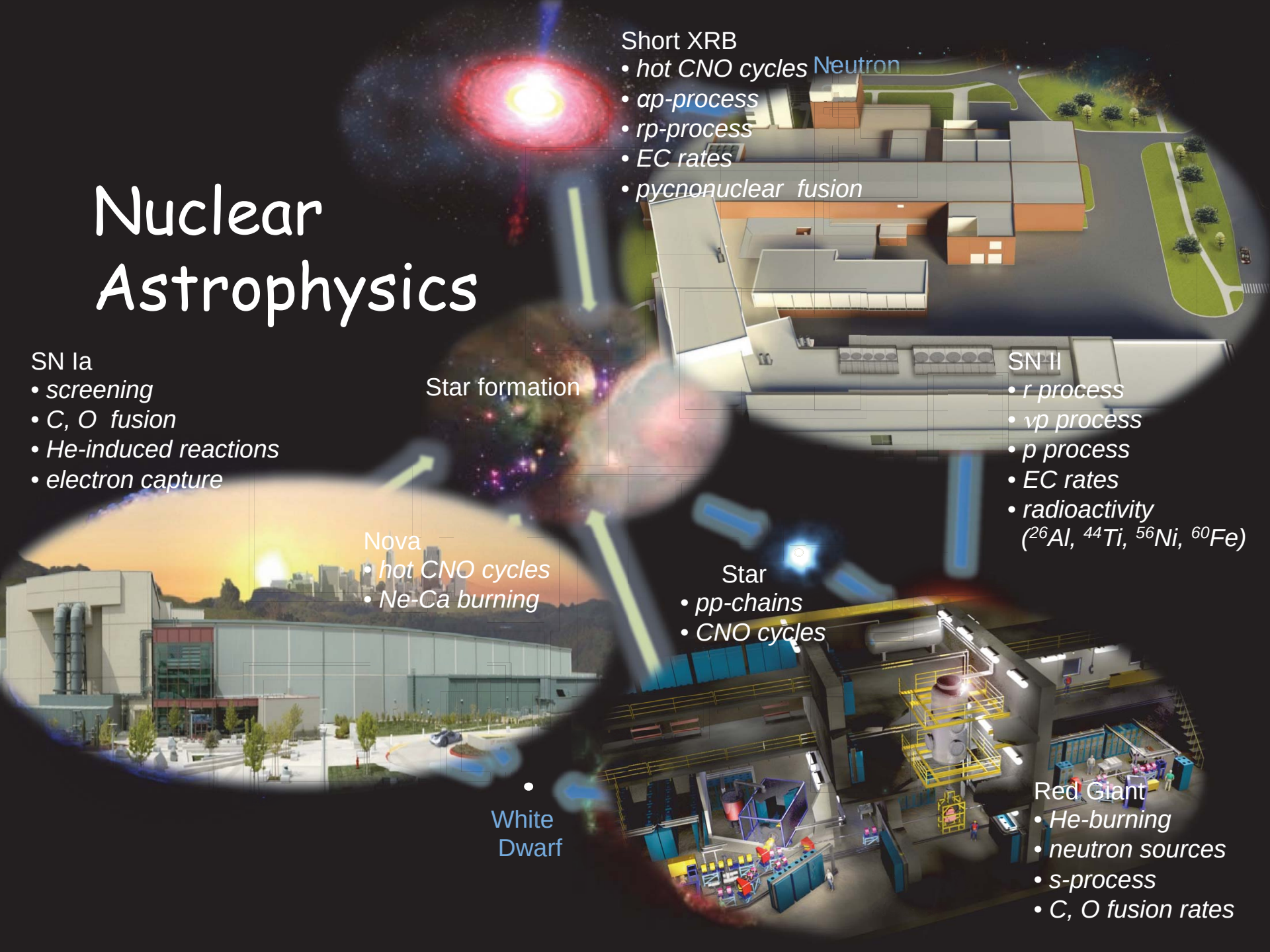


The SHIVA radiochemistry extraction system – a similar system could be designed at NIF for extraction and counting of short-lived nuclides – and include more space for particle detectors.

Science productivity at NIF is a major problem – not enough shots.

Path to success is to enhance ride-along productivity and increase shot rate.

Nuclear Astrophysics



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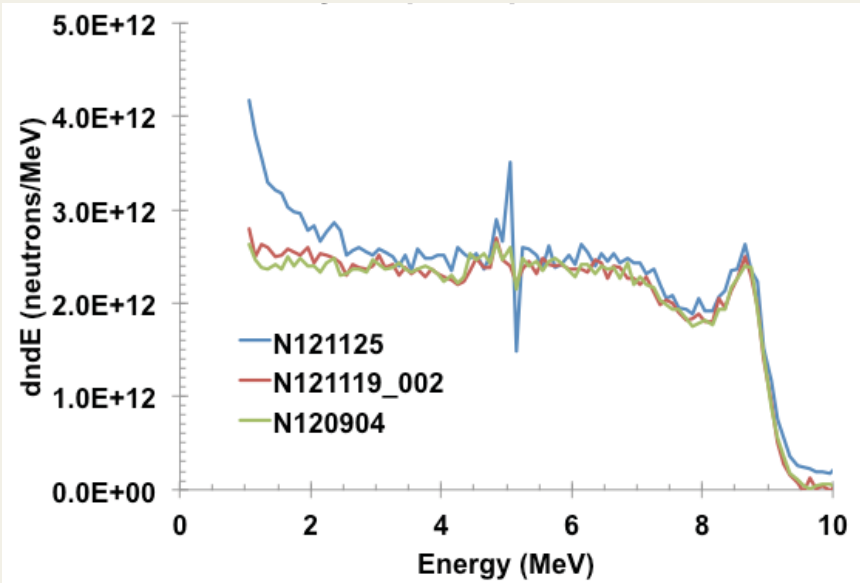
TT neutron spectrum



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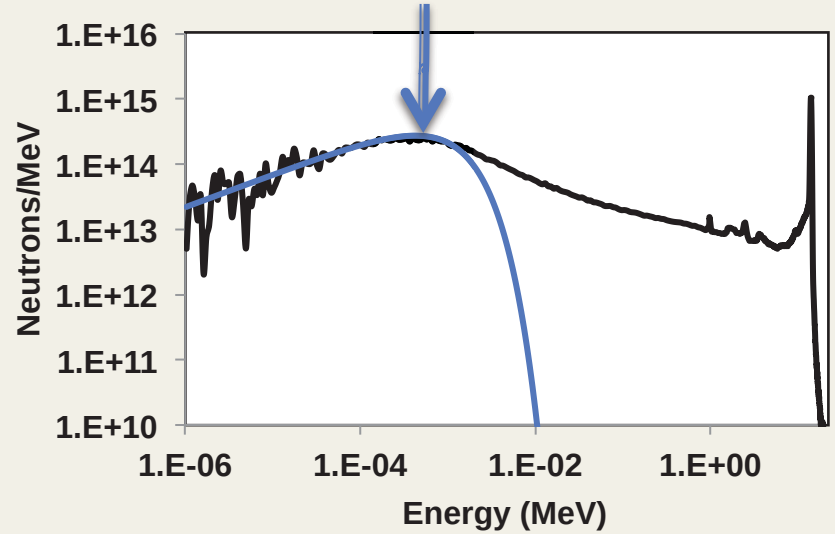


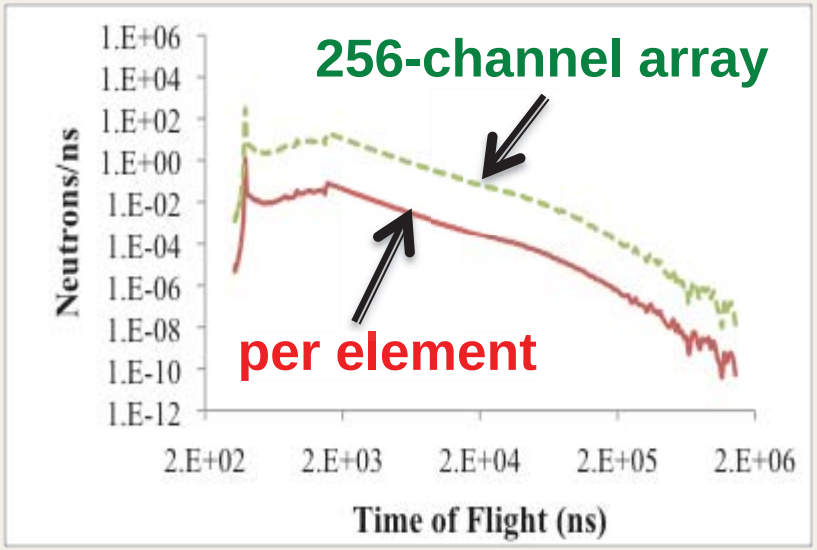
HYDRA simulations compliments of C. Cerjan

- High ρR_{fuel}: significant fraction of the neutrons scatter to thermal energies
- Spectral shape correlates with capsule confinement time
- Sub-MeV neutrons are the most important for astrophysical (n,γ) reactions

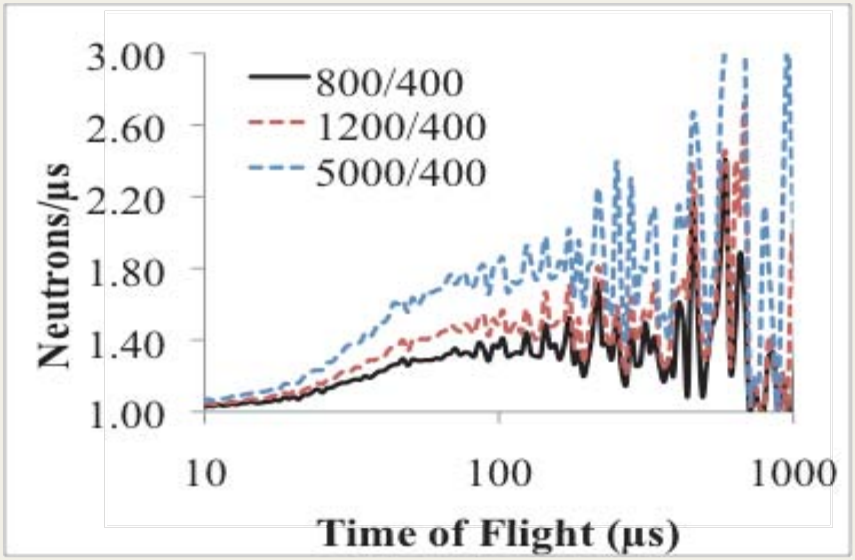
A LENS is not only essential for any NIF-based (n,γ) measurement but also provides info about $\tau_{confinement}$

The shape and magnitude of the low energy spectrum together determine the confinement and ρR_{fuel}

Time-of-Flight for τ_{conf}=400 ps



Sensitivity to confinement time



HYDRA simulations compliments of C. Cerjan

We are working on developing a LENS right now at LBNL/UCB