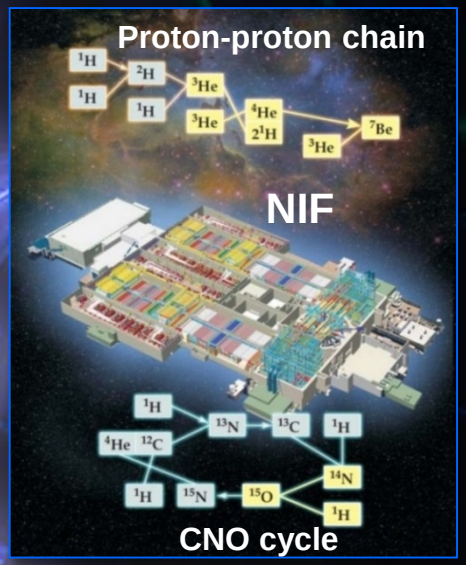
Plasma nuclear science for exploring nuclear physics relevant to stellar nucleosynthesis



Maria Gatu Johnson
Massachusetts Institute of Technology

Frontiers pf Plasma Science Town Meeting
Bethesda, MD, June 30, 2015

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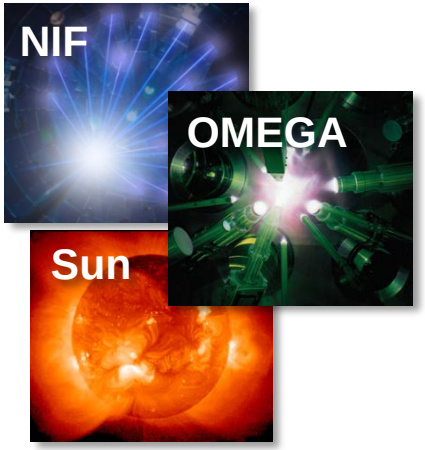
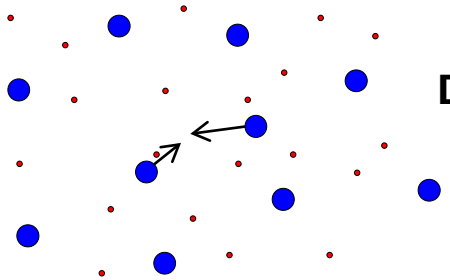
Exploration of Basic Nuclear Science and Nuclear Astrophysics using HED plasmas is a nascent field with much potential

- High-Energy Density (HED) plasmas generated in laser-driven implosions provide a unique environment for studying stellar-relevant nuclear reactions
- Existing and future nuclear diagnostics at the laser facilities enable exploitation of these plasmas for study of nuclear reactions
- Recent experiments at the OMEGA laser provide the first exciting results and demonstrate the potential of this frontier of plasma science
- NIF allows probing of these reactions at lower, more stellar-relevant center-of-mass energies due to larger plasmas and higher laser energy

In contrast to accelerators normally used for nuclear physics experiments, lasers create conditions similar to stellar cores



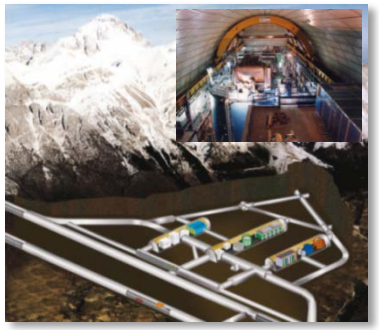
Dense and hot plasma



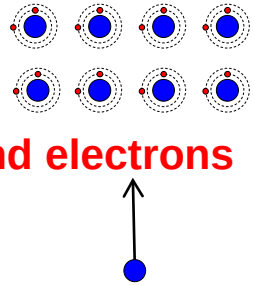
Debye screening

Thermal ions
Thermal electrons

Accelerator experiments

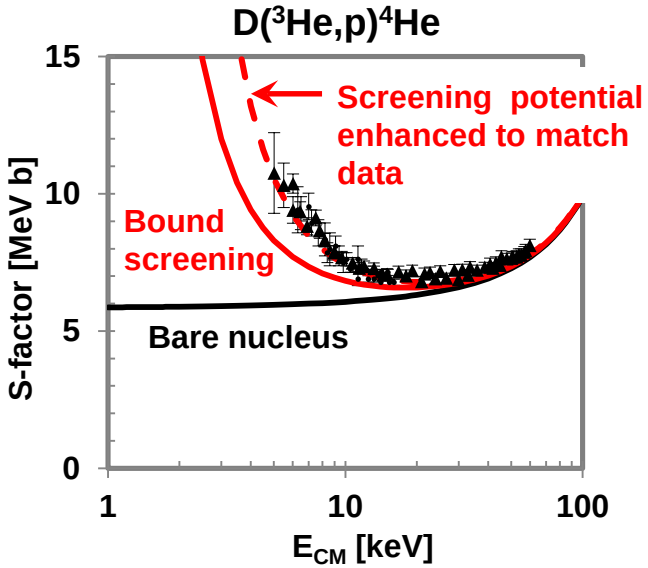


Cold Target



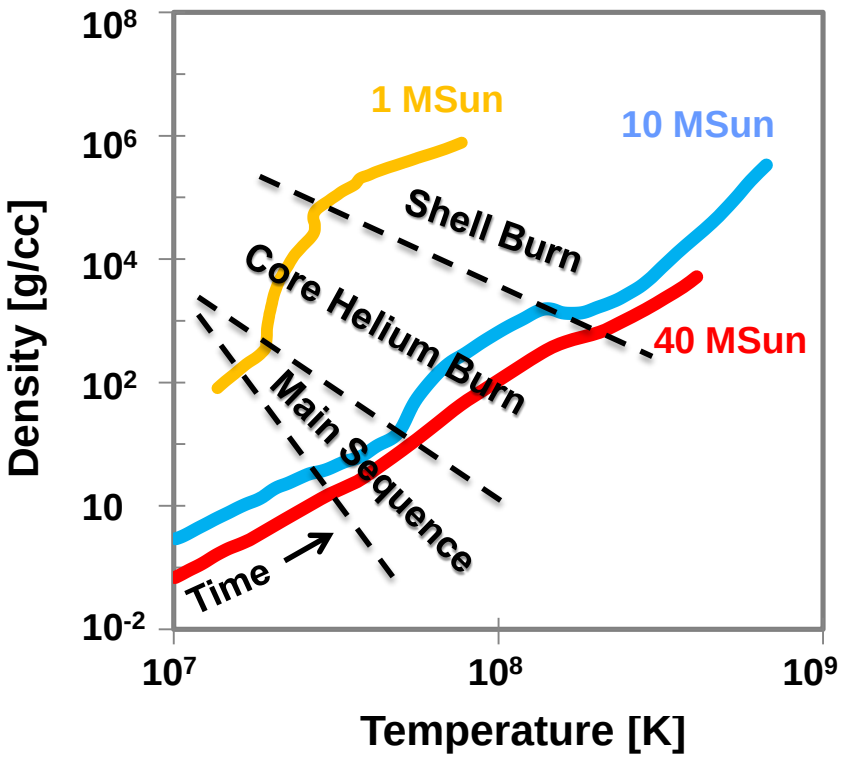
Ions
Bound electrons

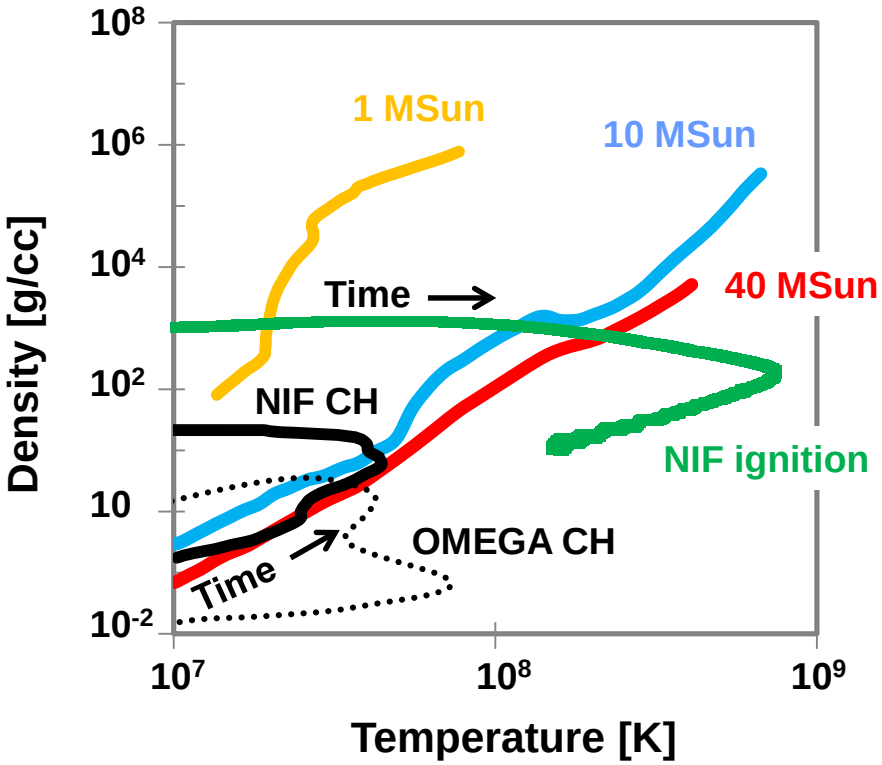
Monoenergetic ion



M. Aliotta *et al*, NP A (2001).
U. Schröder *et al*, NIM B (1989).
H. J. Assenbaum *et al*, ZP (1987).

Capsule implosions at the OMEGA and NIF lasers create HED-plasma conditions that are similar to the interior of a star





Stellar evolution simulations by Dave Dearborn (LLNL).
NIF simulations Harry Robey and Bob Tipton (LLNL).
OMEGA simulation P. B. Radha (UR).

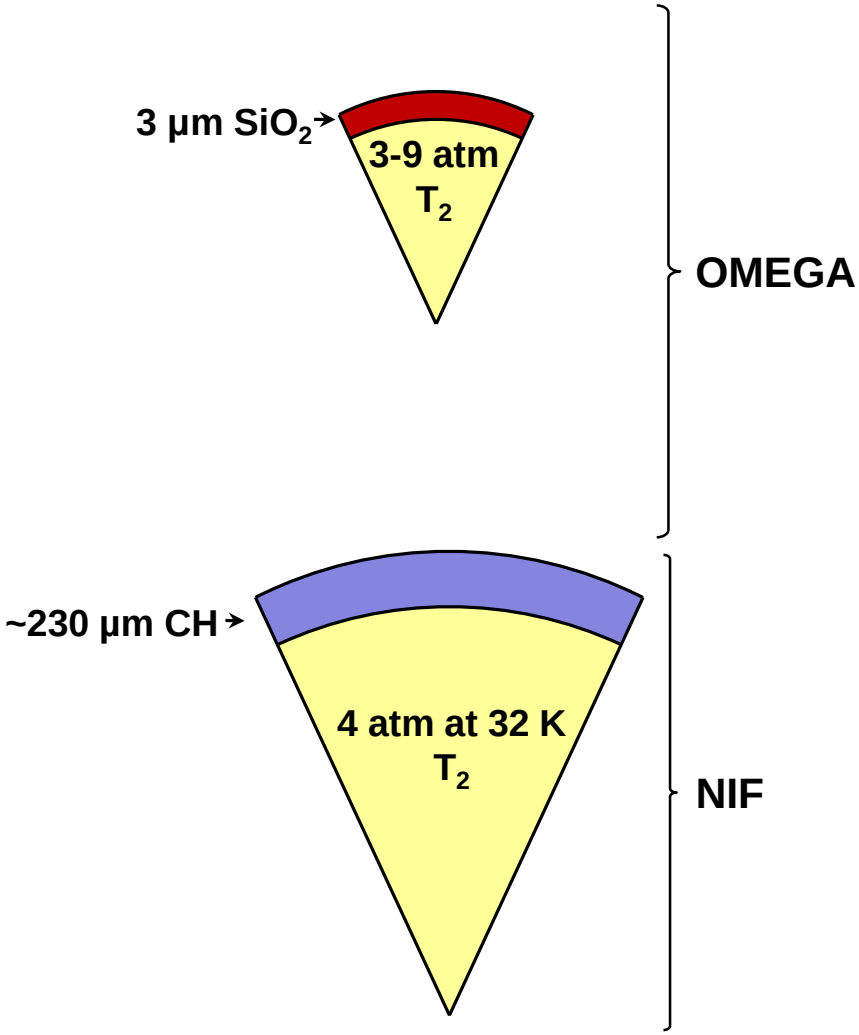
HED plasmas have already been used to probe several nuclear reactions; three examples will be highlighted in this talk

- n+d / n+t elastic scattering[1)] (basic nuclear science)
- D(n,2n) reaction (basic nuclear science)
- T+T reaction[2),4),5)] (mirror reaction to ^{3}He+^{3}He reaction)
- ^{3}He+^{3}He reaction[6)] (hydrogen-burning stars)
- T+^{3}He reaction[6)] (basic nuclear science and BBN)
- D(p,γ)^{3}He (protostars, brown dwarfs and BBN)
- D(t,γ)^{5}He[3)] (basic nuclear science)
- D(^{3}He,γ)^{5}Li (basic nuclear science)

Lessons learned from studies of these reactions together with new enabling diagnostics will be used to probe other light-ion reactions using HED plasmas in the future

[1)] Frenje et al., PRL (2011).
[2)] Casey et al., PRL (2012).
[3)] Kim et al., PRC (2012).
[4)] Sayre et al., PRL (2013).
[5)] Brune et al., ArXiv (2015).
[5)] Zylstra et al., to be submitted (2015).

The T+T reaction has been studied extensively at OMEGA and the NIF at Gamow-peak energies from 16 to 55 keV

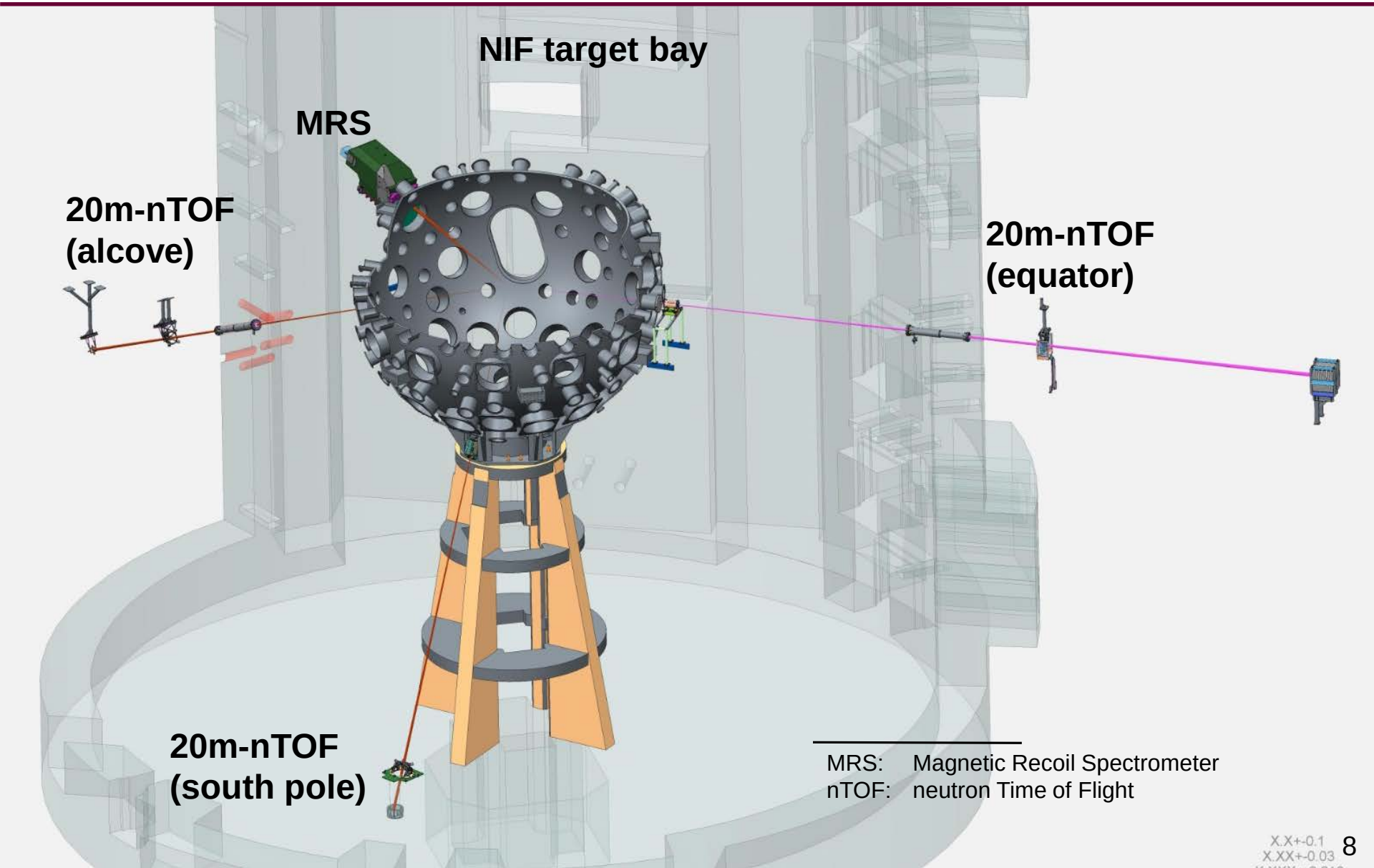


$$T + T \rightarrow \alpha + n + n$$
$$\rightarrow {}^{5}He + n \ (8.7\ MeV)$$
$$\rightarrow {}^{5}He^{*} + n$$
$$\rightarrow {}^{4}He + (nn)$$

Understanding the T+T reaction has important implications for:

1. Basic nuclear physics
2. Stellar Nucleosynthesis
3. Inertial Confinement Fusion

On the NIF, neutron spectrometers, generally used to support the ICF program, were used to study the T+T reaction at low E_{CM}



MRS: Magnetic Recoil Spectrometer
nTOF: neutron Time of Flight

Measurements of the T+T neutron spectrum at E_{CM} = 16 keV provide new insights about the T+T reaction

PRL **111,** 052501 (2013) PHYSICAL REVIEW LETTERS week ending 2 AUGUST 2013

Measurement of the $T + T$ Neutron Spectrum Using the National Ignition Facility

D. B. Sayre,[1,*] C. R. Brune,[2] J. A. Caggiano,[1] V. Y. Glebov,[3] R. Hatarik,[1] A. D. Bacher,[4] D. L. Bleuel,[1] D. T. Casey,[1] C. J. Cerjan,[1] M. J. Eckart,[1] R. J. Fortner,[1] J. A. Frenje,[5] S. Friedrich,[1] M. Gatu-Johnson,[5] G. P. Grim,[6] C. Hagmann,[1] J. P. Knauer,[3] J. L. Kline,[6] D. P. McNabb,[1] J. M. McNaney,[1] J. M. Mintz,[1] M. J. Moran,[1] A. Nikroo,[7] T. Phillips,[1] J. E. Pino,[1] B. A. Remington,[1] D. P. Rowley,[1] D. H. Schneider,[1] V. A. Smalyuk,[1] W. Stoeffl,[1] R. E. Tipton,[1] S. V. Weber,[1] and C. B.

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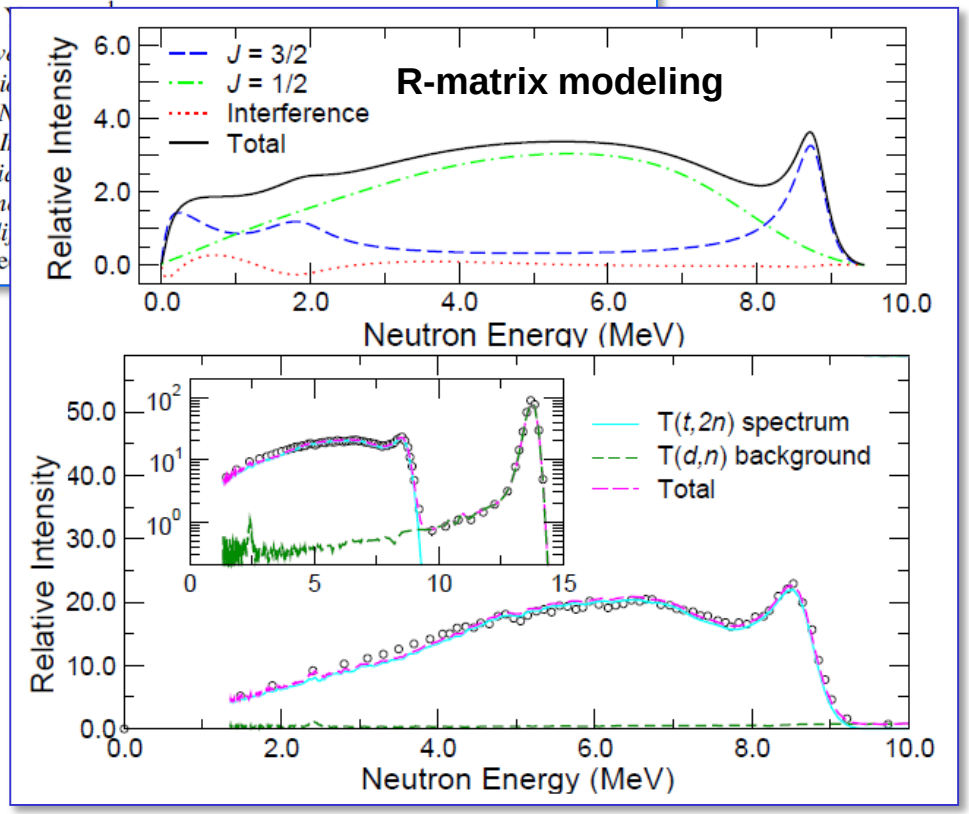
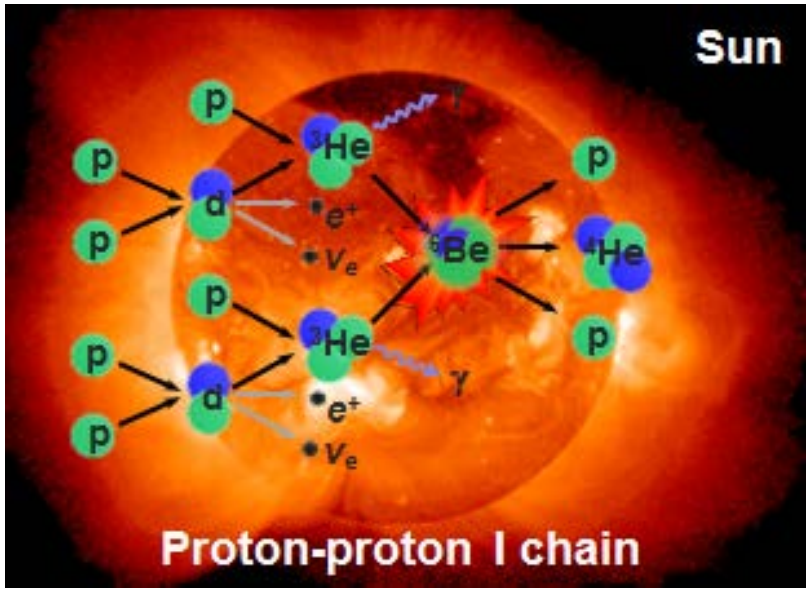
(Received 25 May 2013; publishe

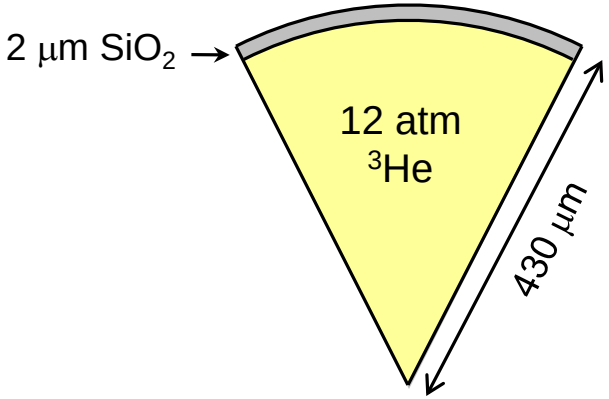


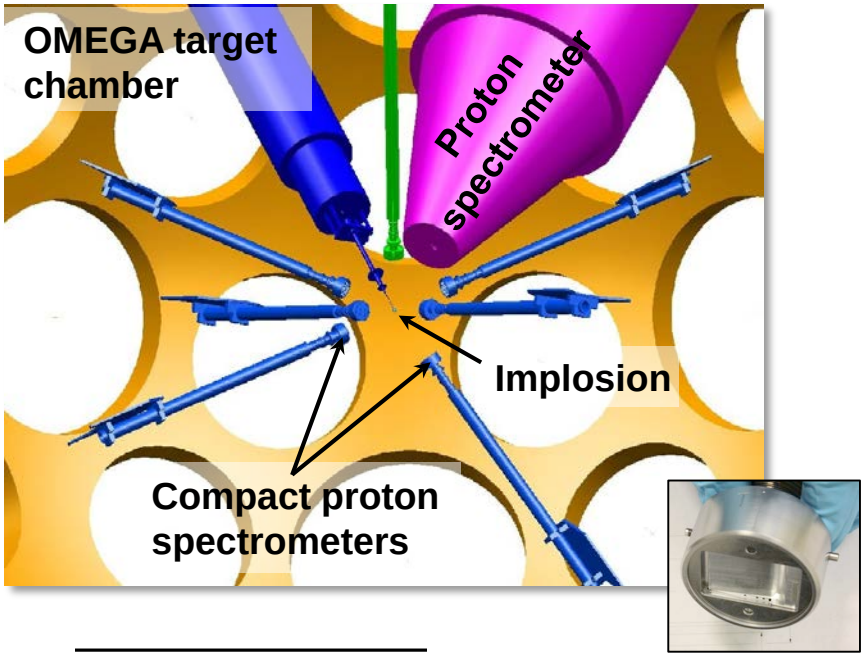
The data and R-matrix modeling indicate that the reaction can be explained by ^{5}He sequential decay

In a proof-of principle experiment, HED plasmas have been used to study the ^{3}He+^{3}He reaction at E_{CM}=165 keV



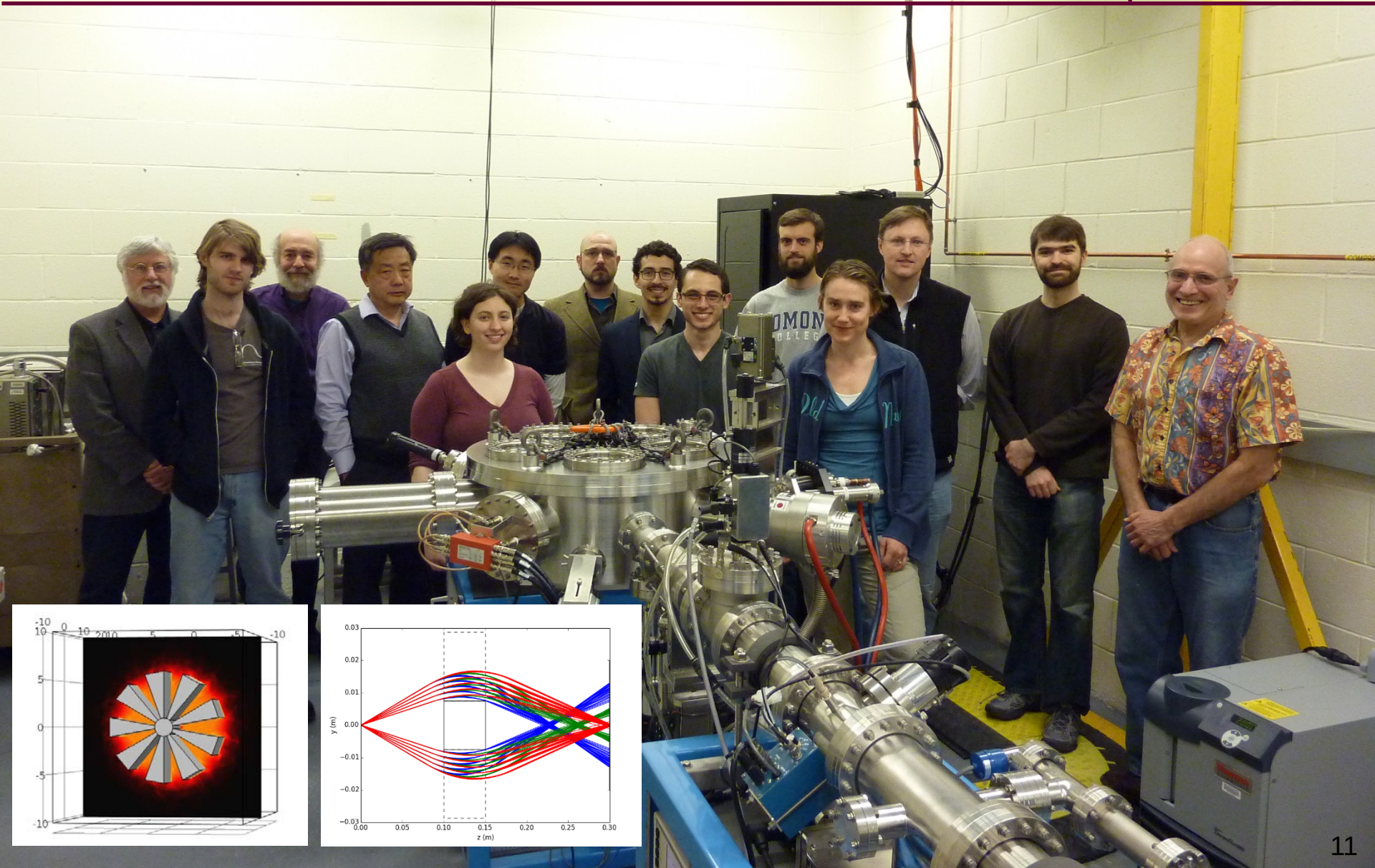
^{3}He + ^{3}He → α + p + p
→ ^{5}Li + p (9.2 MeV)
→ ^{5}Li* + p
→ ^{4}He + (pp)



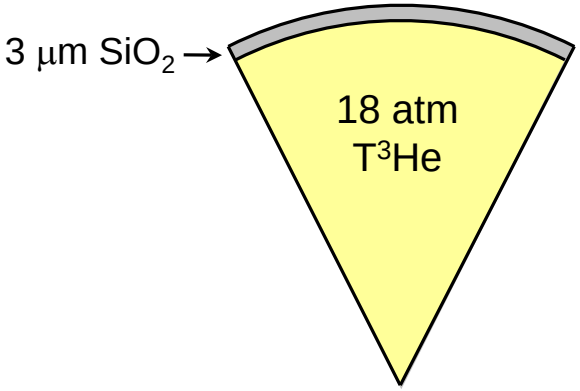


Zylstra et al, to be submitted to PRC (2015).

A new diagnostic being developed at the MIT HED Accelerator Facility will allow probing of $^3He^3He$ spectra below E_p=4 MeV



The T+^{3}He reaction, with two charged-particle branches and a γ branch, has also been studied at OMEGA at E_{CM}=80 keV



$T + {}^3He \rightarrow \alpha + d$ (9.5 MeV)

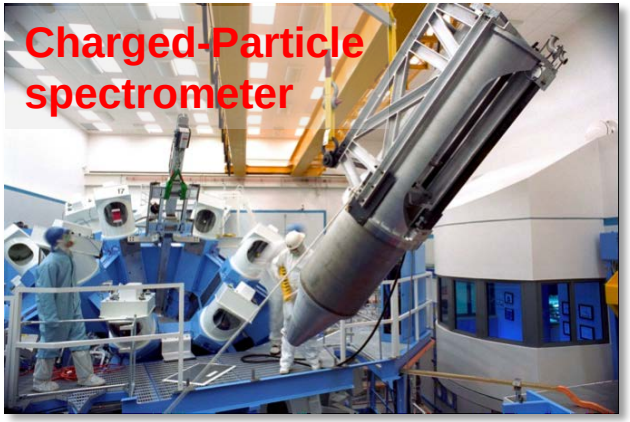
$T + {}^3He \rightarrow \alpha + p + n$

$\rightarrow {}^5He + p$ (9.3 MeV) $\rightarrow {}^4He + p + n$

$\rightarrow {}^5He^* + p$ (6.4 MeV) $\rightarrow {}^4He + p + n$

$\rightarrow {}^5Li + n$ $\rightarrow {}^4He + p + n$

$T + {}^3He \rightarrow {}^6Li + \gamma$



A higher $T({}^3He,\gamma){}^6Li$ reactivity[1,2] than predicted has been proposed to explain the ^{6}Li abundance problem in Big Bang Nucleosynthesis (>100x too high)

[1] Madsen et al., PRD (1990).
[2] Boyd et al., PRD (2010).

Upcoming NIF experiments will allow for probing of nuclear reactions at lower, more stellar-relevant Gamow-peak energies

Reaction	E_G probed at OMEGA	Expected E_G range in first planned NIF experiments
$^3He+^3He$	165 keV	45-90 keV
$T+^3He$	80 keV	30-55 keV
T+T	18-55 keV	20-35 keV
p+D	16 keV	10-13 keV

Due to the higher laser energies and larger plasmas on the NIF, we can probe these reactions accurately at lower E_G than at OMEGA

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- High-Energy Density (HED) plasmas generated in laser-driven implosions provide a unique environment for studying stellar-relevant nuclear reactions
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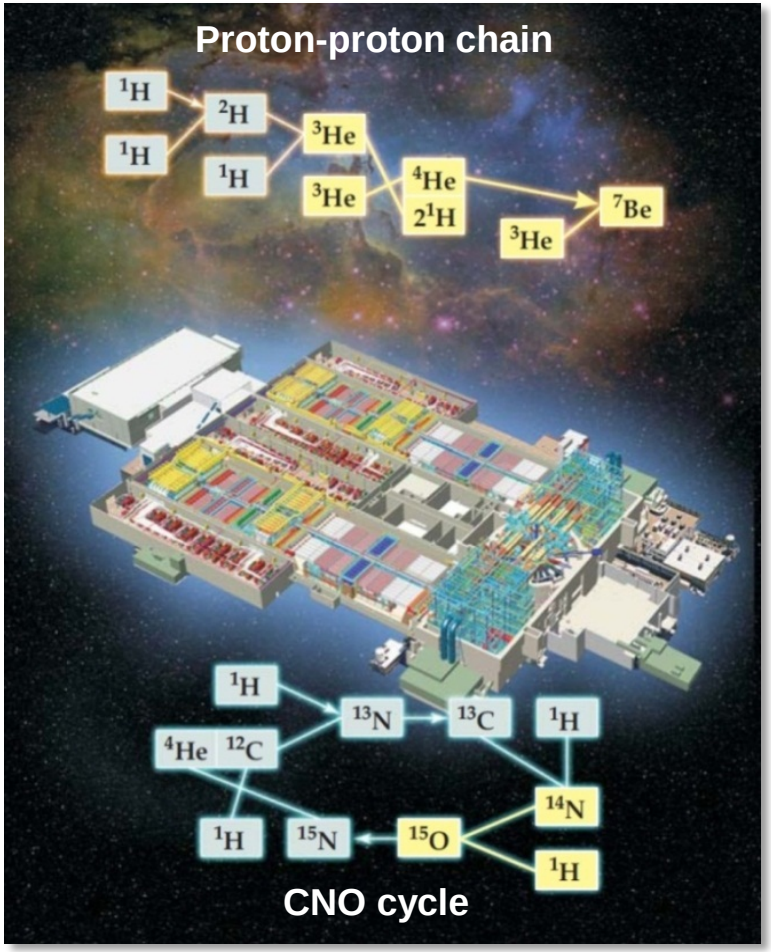
- Recent experiments at the OMEGA laser provide the first exciting results and demonstrate the potential of this frontier of plasma science
- NIF allows probing of these reactions at lower, more stellar-relevant center-of-mass energies due to larger plasmas and higher laser energy

There is a rich set of opportunities to study nuclear reactions at OMEGA and the NIF

Charged-particle induced reactions:

- **T(t,2n)^{4}He** (analogue to ^{3}He(^{3}He,2p)^{4}He).
- **T(^{3}He,np)^{4}He, T(^{3}He,d) ^{4}He, T(^{3}He,γ)^{6}Li** (impact BBN?).
- **^{3}He(^{3}He,2p)^{4}He** (pp-I).
- **D(p,γ)^{3}He** (Brown dwarfs, protostars).
- **^{6}Li(p,α)^{3}He**
- **^{7}Li(p,α)^{4}He**
- **^{7}Be(p,γ)^{8}B** (pp-III).
- **^{11}B(p,α)^{8}Be** (non-Maxwellian ion distributions).
- **^{15}N(p,α)^{12}C** (last step of CNO).
- **^{12}C(α,γ)^{16}O** ?

Current work

Neutron-induced reactions:

- **n-d and n-T** at 14 MeV
- **D(n,2n)** at 14 MeV
- **T(n,2n)** at 14 MeV
- Various (n,γ), (n,2n) processes?