Nuclear-Plasma Interactions on highly excited states

Workshop on Level Densities and Gamma Strength
University of Oslo
Oslo, Norway

Lee Bernstein
May 27, 2013

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

Collaborators – We need lots of them!

D.H.G. Schneider, W. Stoeffl, R. Bionta,
D.L. Bleuel, C. Cerjan, J.A.Caggiano,
R. Fortner, P.M. Grant, A. Kritcher,
L. Dauffy, R. Hatarik, C. Hagmann,
K. Moody, D.P. McNabb, J. Gostic,
D. Shaughnessy, D. Sayre,
C. Yeamans – LLNL

B. Goldblum, N. M. Brickner,
J. A. Brown, B. H. Daub, P. F. Davis,
K. Van Bibber, J. Vujic – *U.C. Berkeley*

R.B. Firestone, S. Basunia, A. M.
Hurst, A. Rogers – LBNL

S. Siem, F. Giacoppo, A. Gorgen,
T. Renstrøm, A.C. Larsen, M. Guttormsen
– U. of Oslo

G. Gosselin, P. Morel,
V. Meot – CEA-DAM (BIII)

M. Wiedeking – iThemba Labs

C. Brune, T. Massey, A. Schiller – Ohio U.

M. Wiescher – Notre Dame

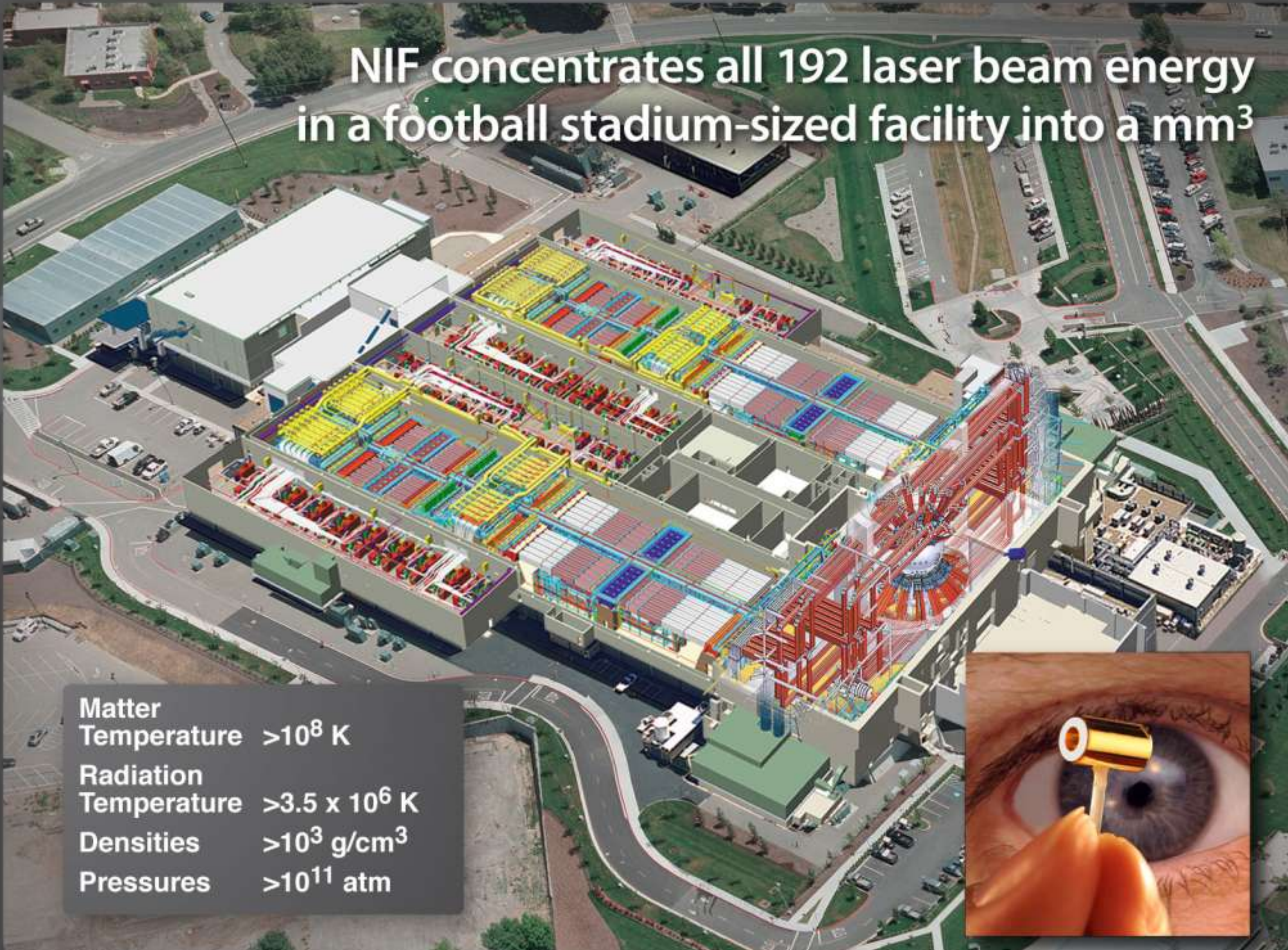
K.-H. Langanke – GSI

Introduction

- Neutron-rich High Energy Density Plasmas (nHEDP) at the National Ignition Facility
- Nucleosynthesis in stellar nHEDPs
- Results from NIF – ^{196m}Au/^{196g}Au
- Other planned and potential experiments
  - NIF-based exploding pusher with ^{134}Xe
  - Accelerator-based using Au beams
  - *Petawatt-laser beam-target experiment (Au)*
- Final questions/Summary

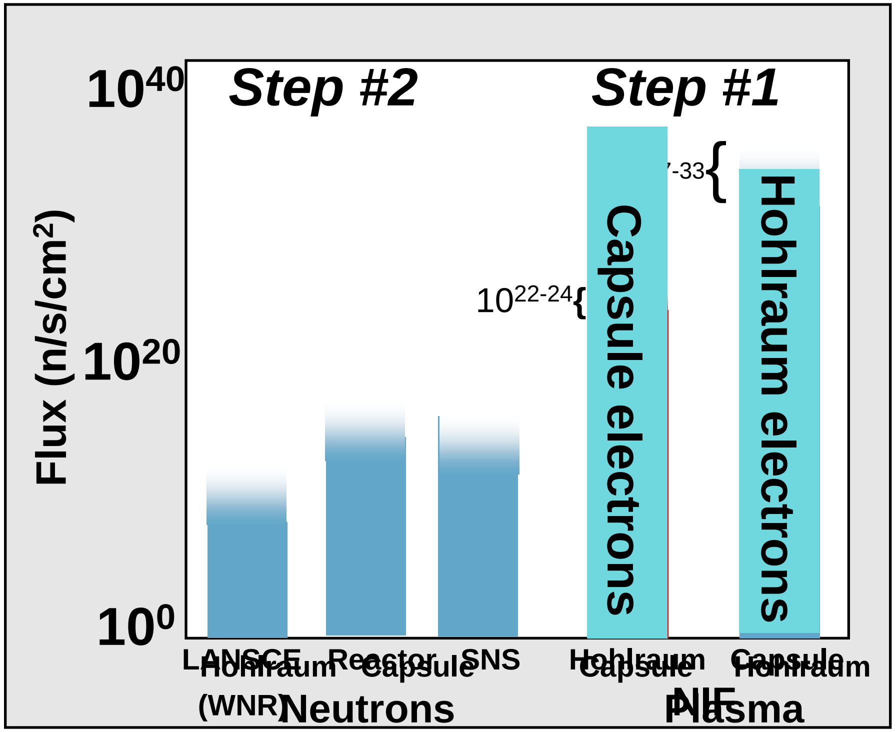
Nuclear Level Density and Radiative Strength is crucial to understanding the formation of elements in nHEDPs

NIF concentrates all 192 laser beam energy in a football stadium-sized facility into a mm^3

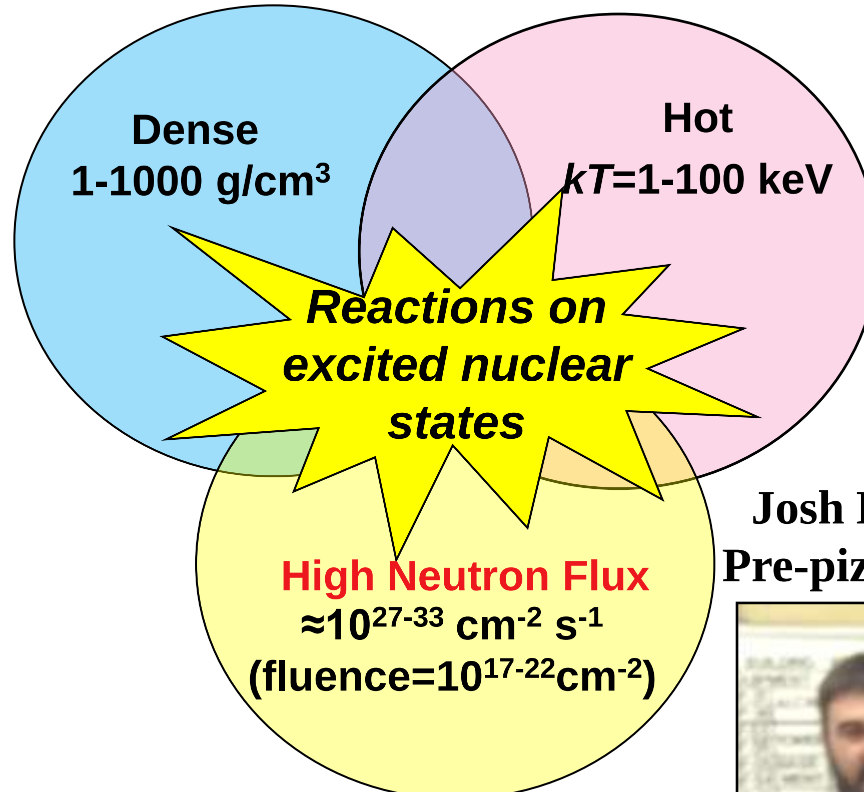


Matter Temperature	**$>10^8$ K**
Radiation Temperature	**$>3.5 \times 10^6$ K**
Densities	**$>10^3$ g/cm^3**
Pressures	**$>10^{11}$ atm**

The high *e*, γ and n-flux in a NIF capsule might allows us to explore reactions on short-lived nuclear states



NIF capsule/hohlraum



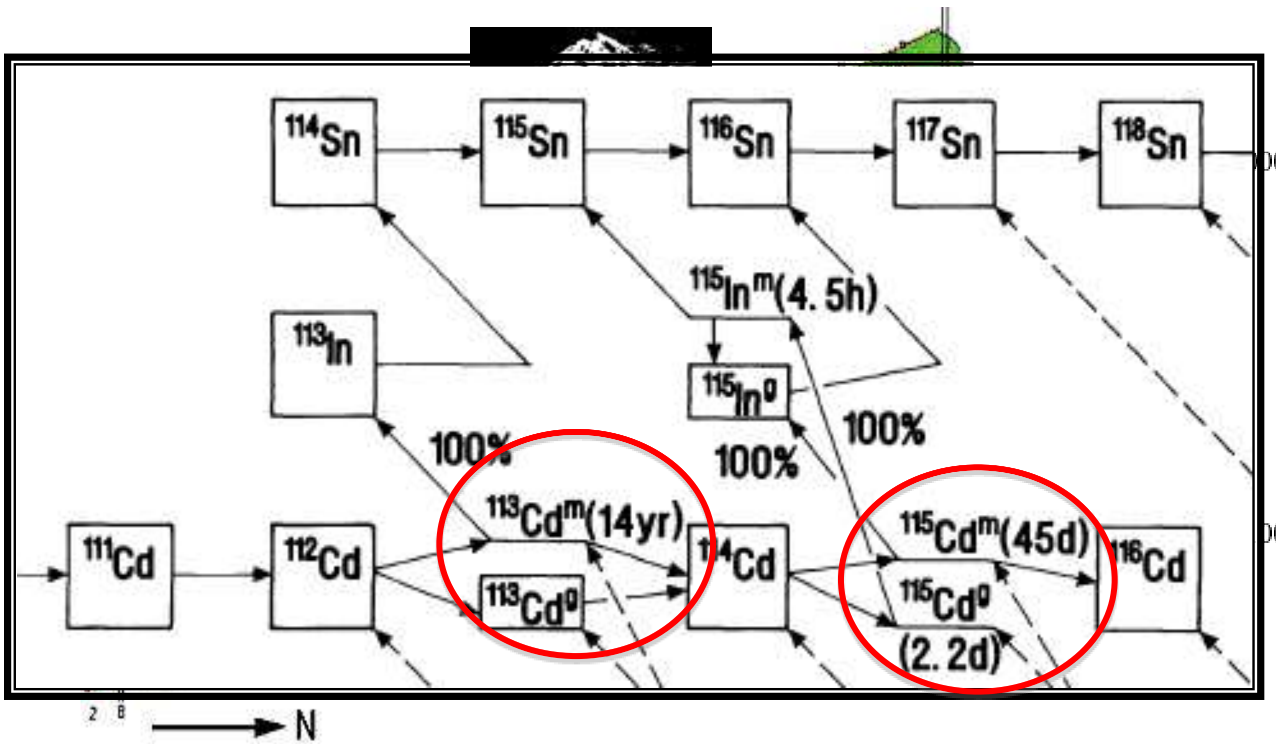
Josh Brown
Pre-pizza talk!

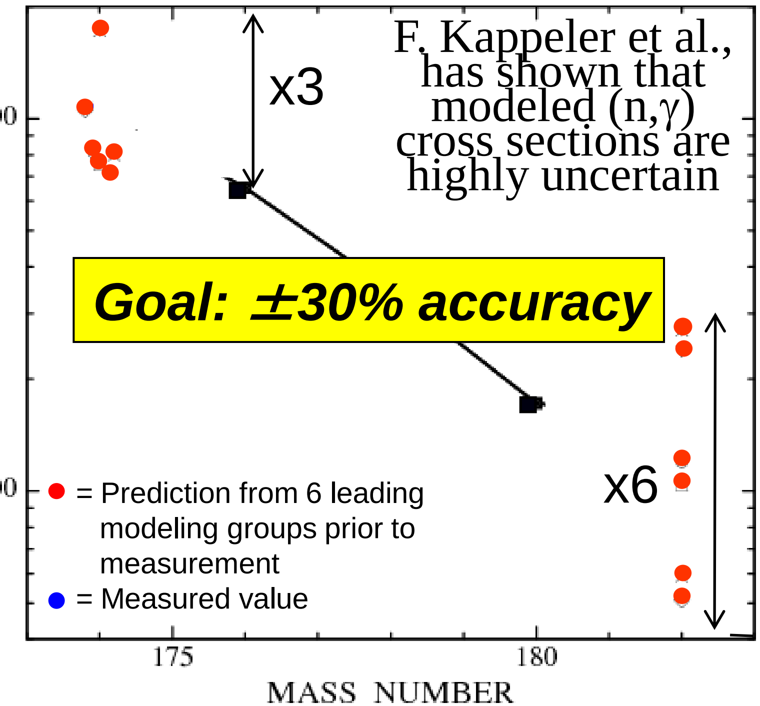
Excited State Reaction Possibilities

Option #1: Excite a target nucleus with the plasma then hit it with neutrons

Option #2: Excite a target nucleus with neutrons then interact with the plasma

Roughly half of the elements with 26≤Z≤83 are formed via slow neutron capture in an *astrophysical high energy density plasmas*





NIF @ 10^{14} neutrons crams 2800 years* of neutron capture into every shot

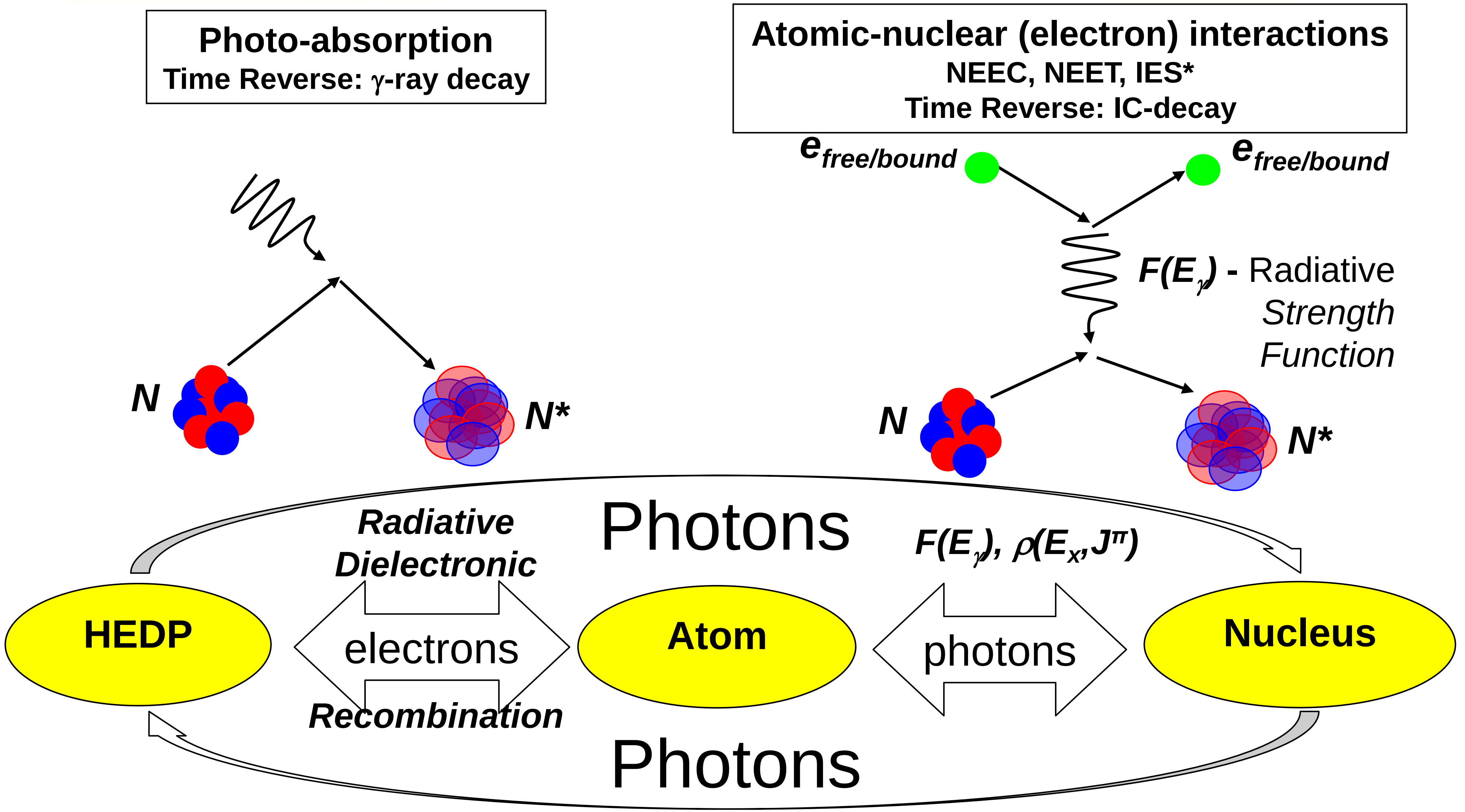
Can we use NIF to study the effects of the HEDP on (n,γ) nucleosynthesis?

*Busso, Gallino and Wasserburg, Annu. Rev. Astron. Astrophys. 1999. 37:239–309

R.A. Ward, Ap. J. **216**: 540-547, 1977, ***Z.S. Nemeth et al., Ap. J. 426 357-365, (1994)***

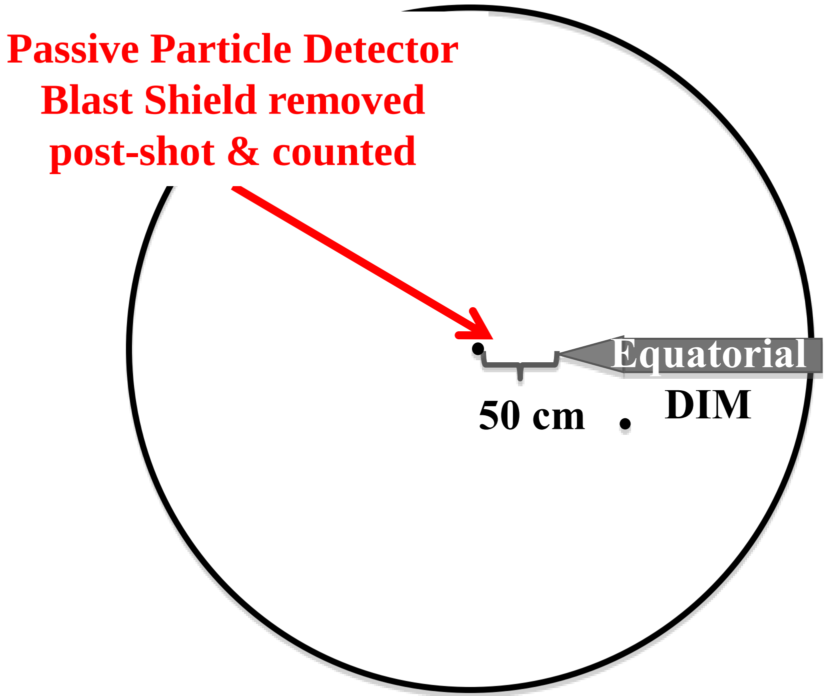
T. Hayakawa, *et al.*, AIP Conf. Proc. **1238**, 225 (2010), doi: 10.1063/1.3455935

Electron-driven Nuclear-Plasma Interactions (NPI) are most likely to cause the excitation of *keV* nuclear states

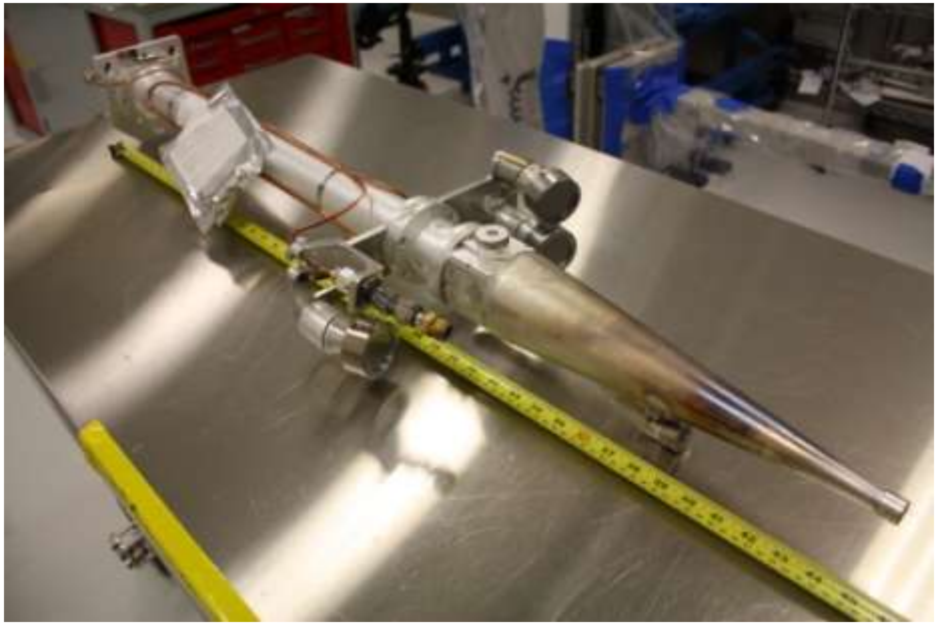


Can we use NIF to see if these interactions fast enough to interact with highly excited nuclear states in a HEDP?

First hints of NPI at NIF: Radioactive ^{196}Au and ^{198}Au from (n,2n) and (n,γ) on the ^{197}Au hohlraum



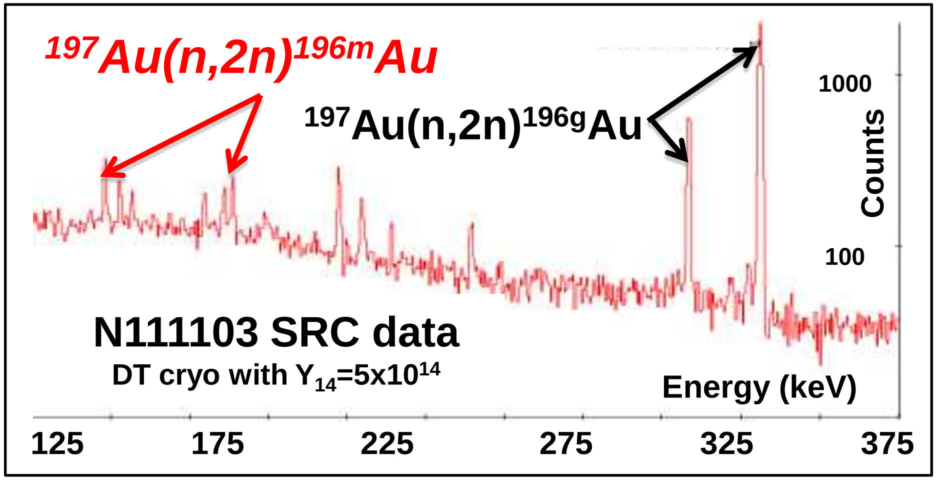
Diagnostic Insertion Manipulator (DIM)

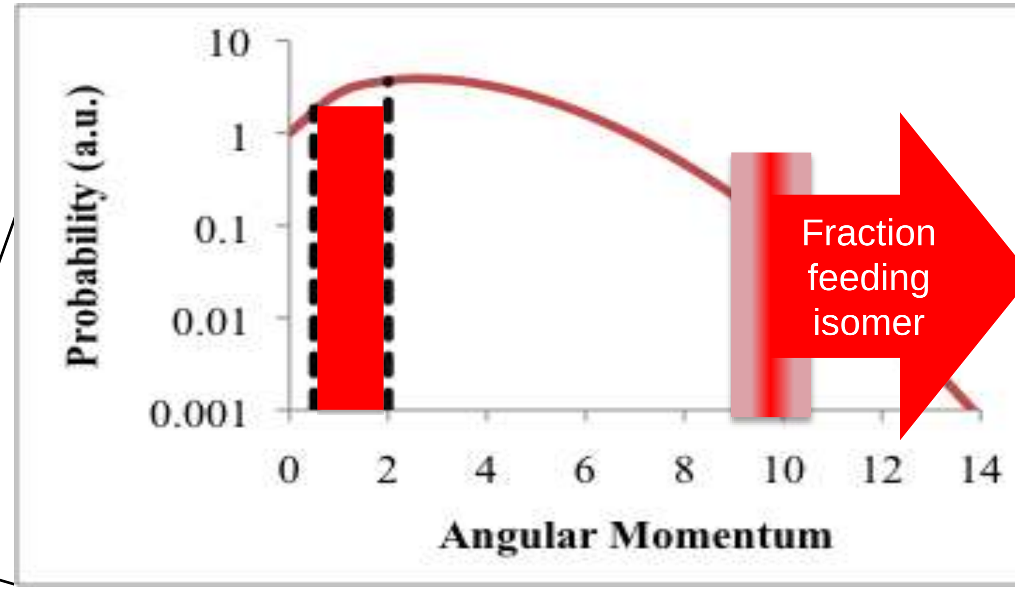


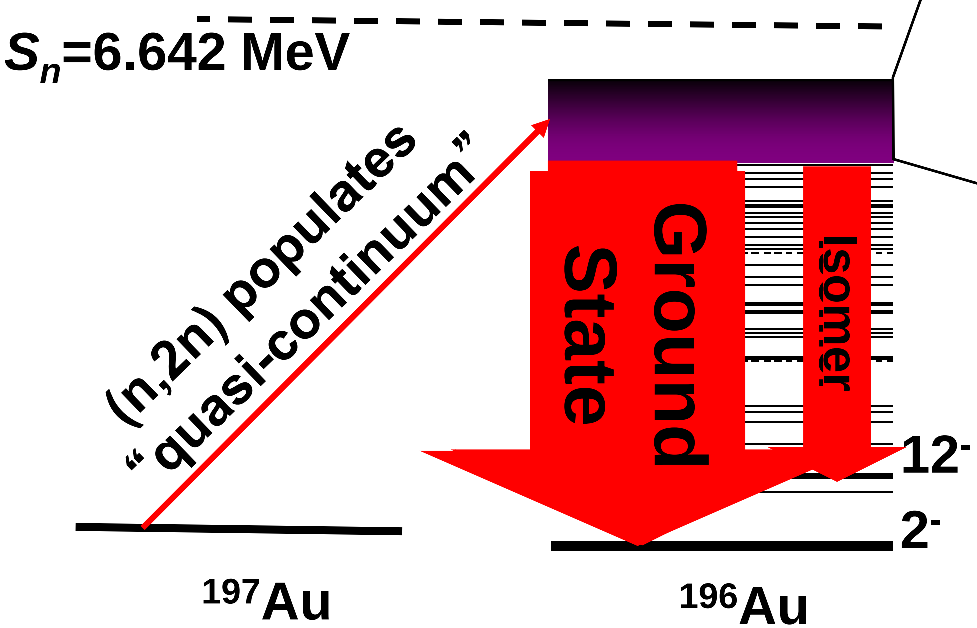
Time Sequence

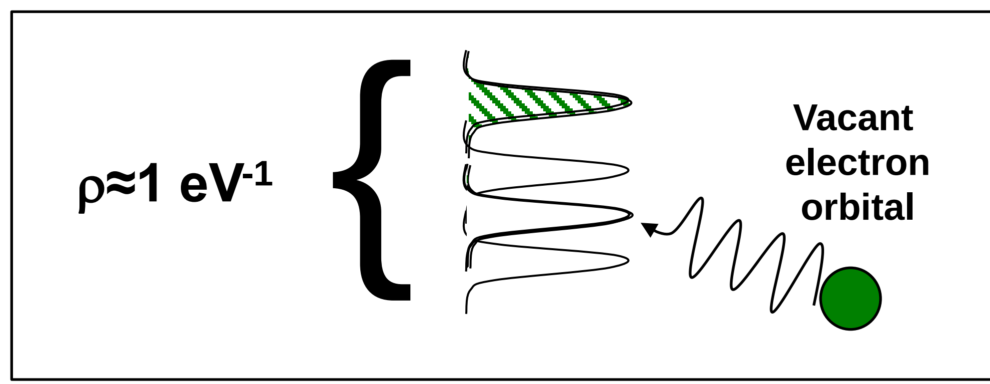
1. Shot
2. 6-12 hours later DIM removed, samples collected and transported to Building 151 counting facility
3. 2-3 days later data becomes available

The 10 hour 12^- isomer in ^{196}Au might allow us to explore the interaction of highly-excited states with a HEDP?





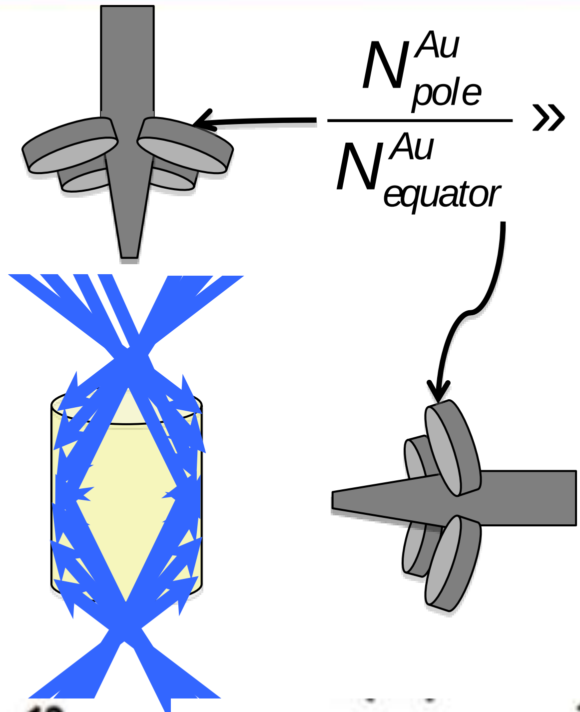




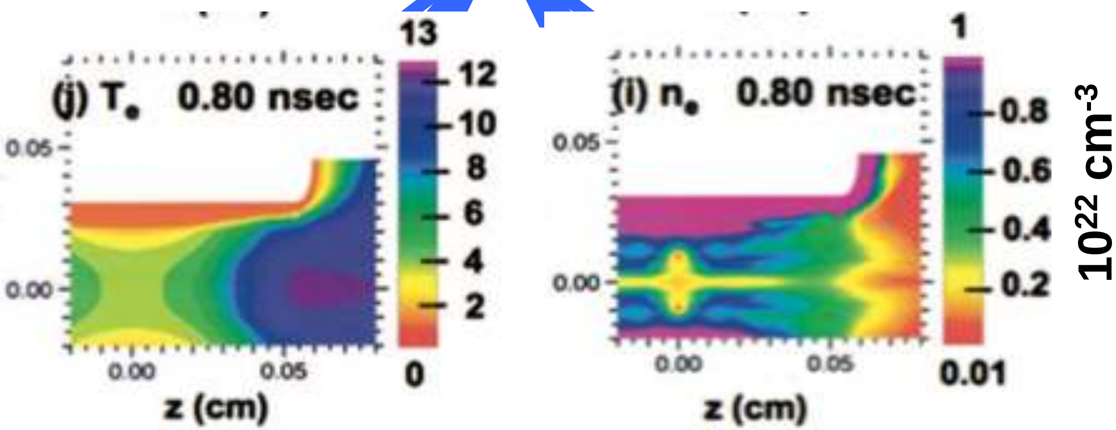
This is entirely new Nuclear Physics

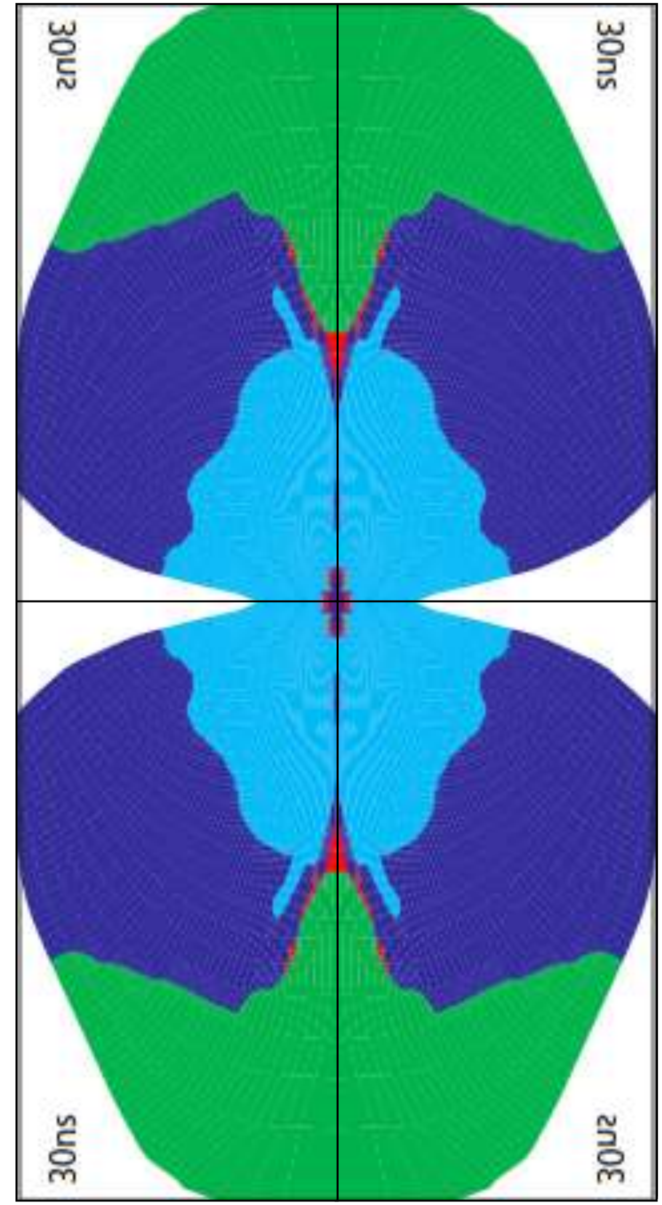
Radioactive 196Au collected from the pole and waist of the NIF come from very different plasma conditions

D. Eder *et a.*, UCRL-JRNL-206693



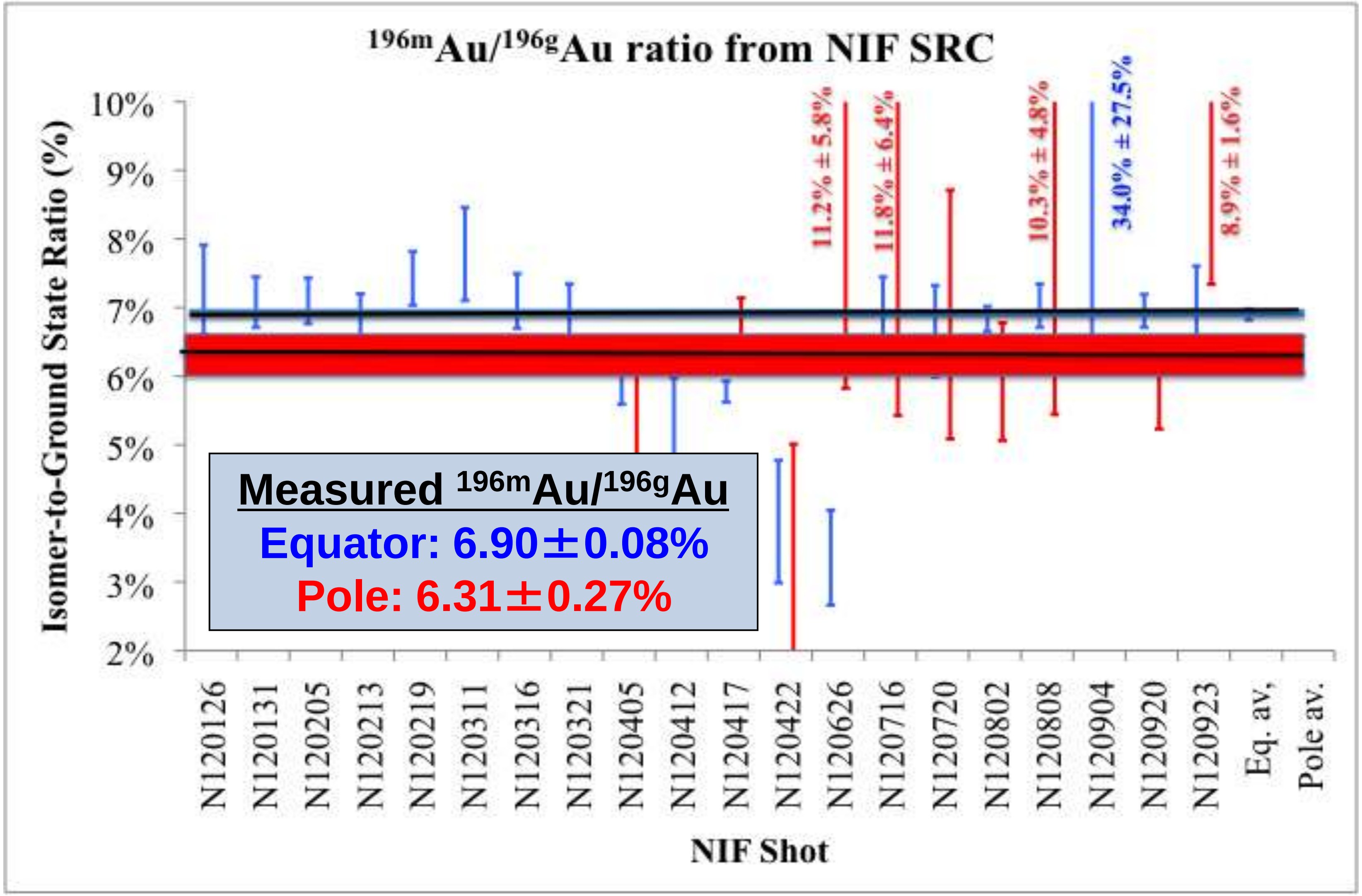
$$\frac{N^{Au}_{pole}}{N^{Au}_{equator}} \gg 10^{-2}$$





Polar Au comes from a HEDP while equatorial Au does not

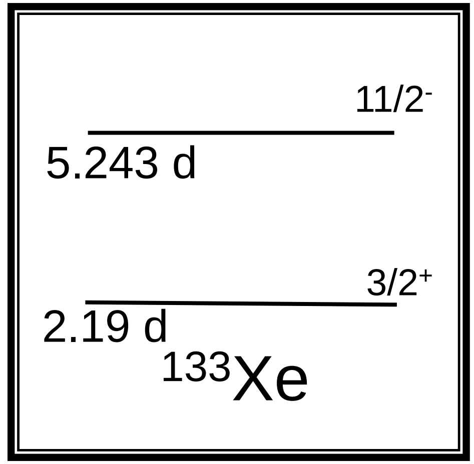
Is debris from the NIF hohlraum suggesting that the $J^{\pi}=12^{-}$ isomer feeding is being effected by NPIs?



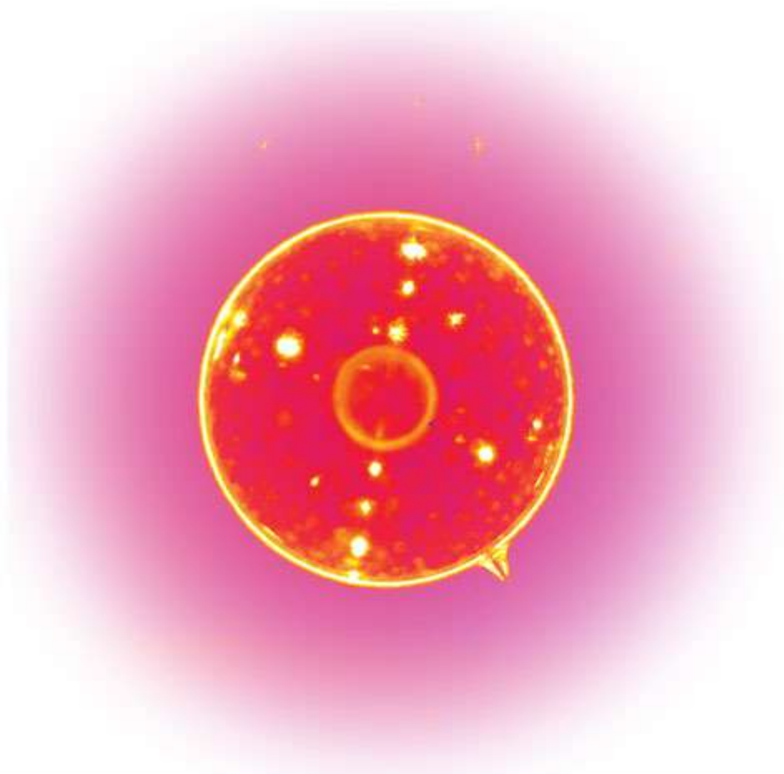
Δ(Pole-Equator)=0.59% ± 0.28%
(≠0 by 2.1-2.2 σ)

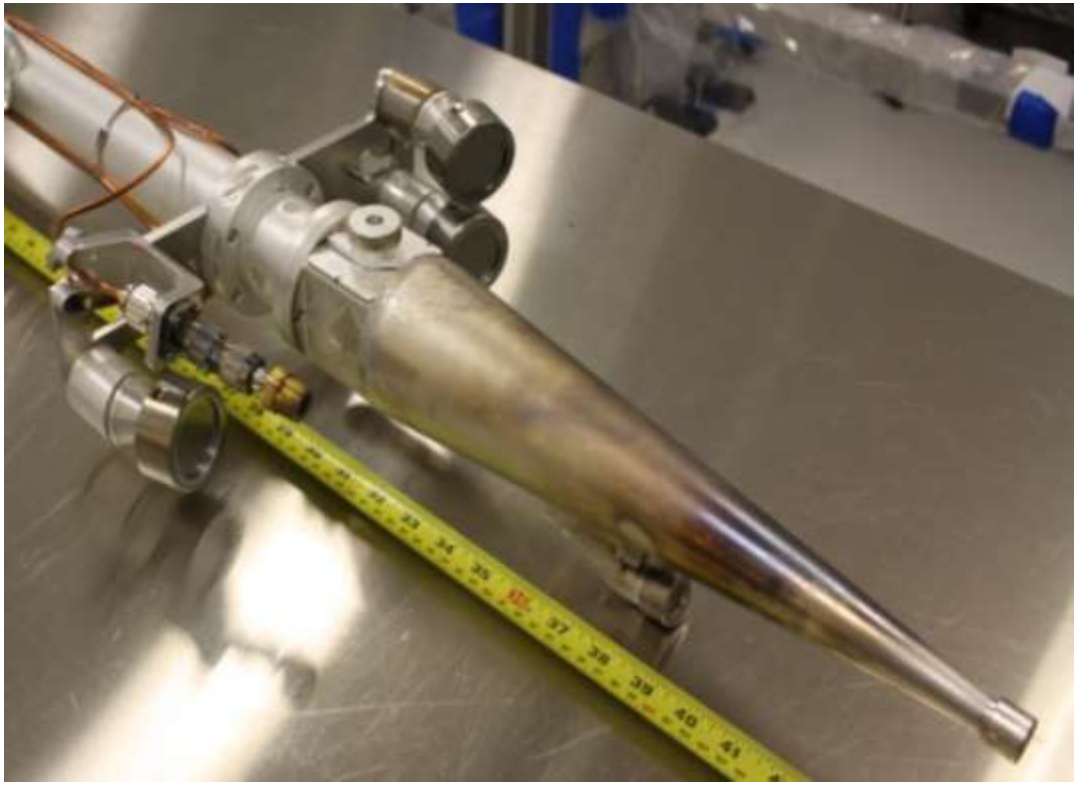
Option #2: A "better" NIF experiment using a ^{134}Xe-doped "exploding pusher" capsule

We maximize both neutron flux and plasma density by placing a ^{134}Xe dopant nuclei in a **direct-drive** target

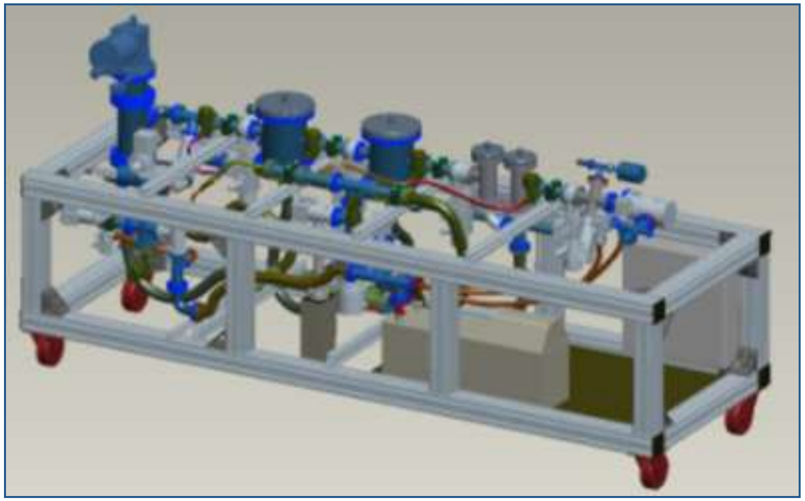


…plus a "control" sample outside the plasma in a sample positioner 50cm from the target





Radioactive $^{133m,g}Xe$ can be pumped out of NIF minutes after a shot using the RAGS (Radiochemical Analysis of Gaseous Samples) system

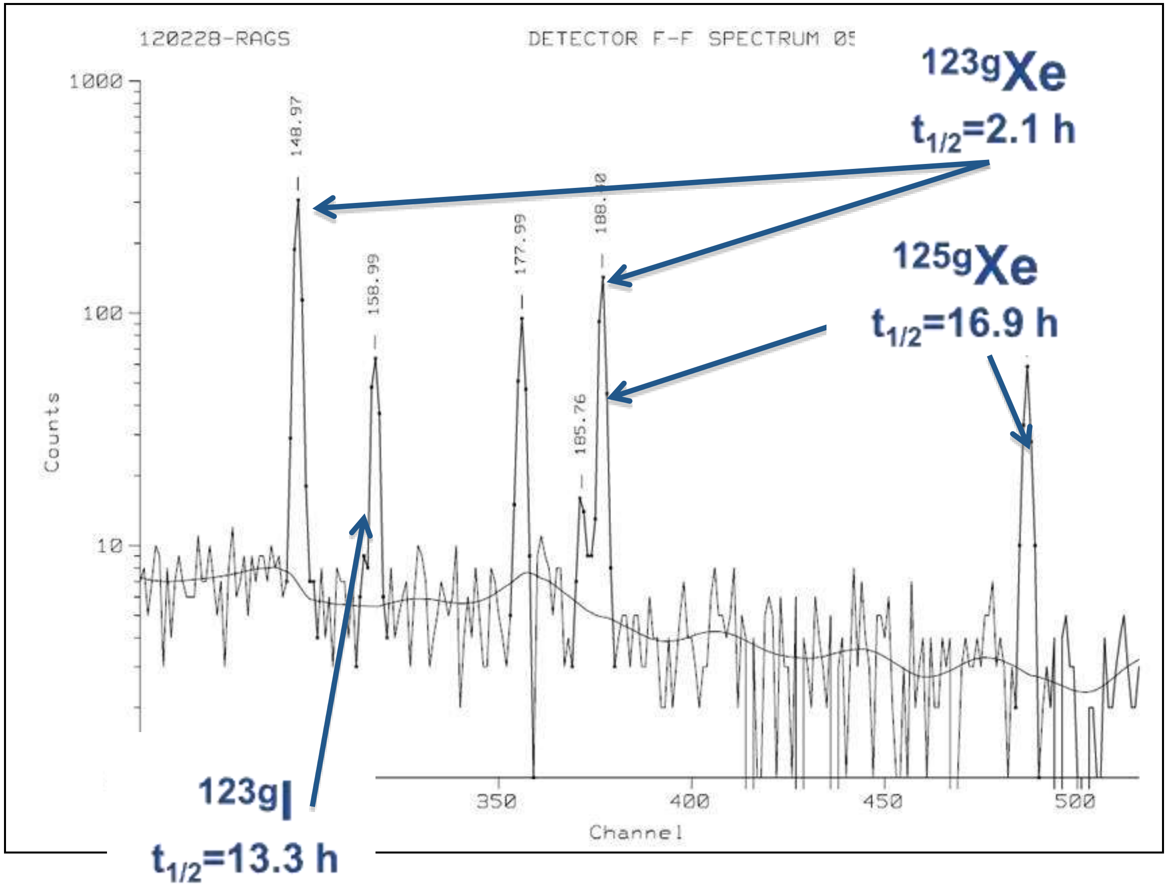


NPI effects can observed using the *Double-Isomer-to-Ground State* (DIGS) Ratio

$$R_{DIGS} \equiv \frac{N^{133m}_{capsule}Xe \Big/ N^{133g}_{capsule}Xe}{N^{133m}_{SRC}Xe \Big/ N^{133g}_{SRC}Xe}$$

Exploding pusher test: ^{124}Xe,^{126}Xe-doped capsule

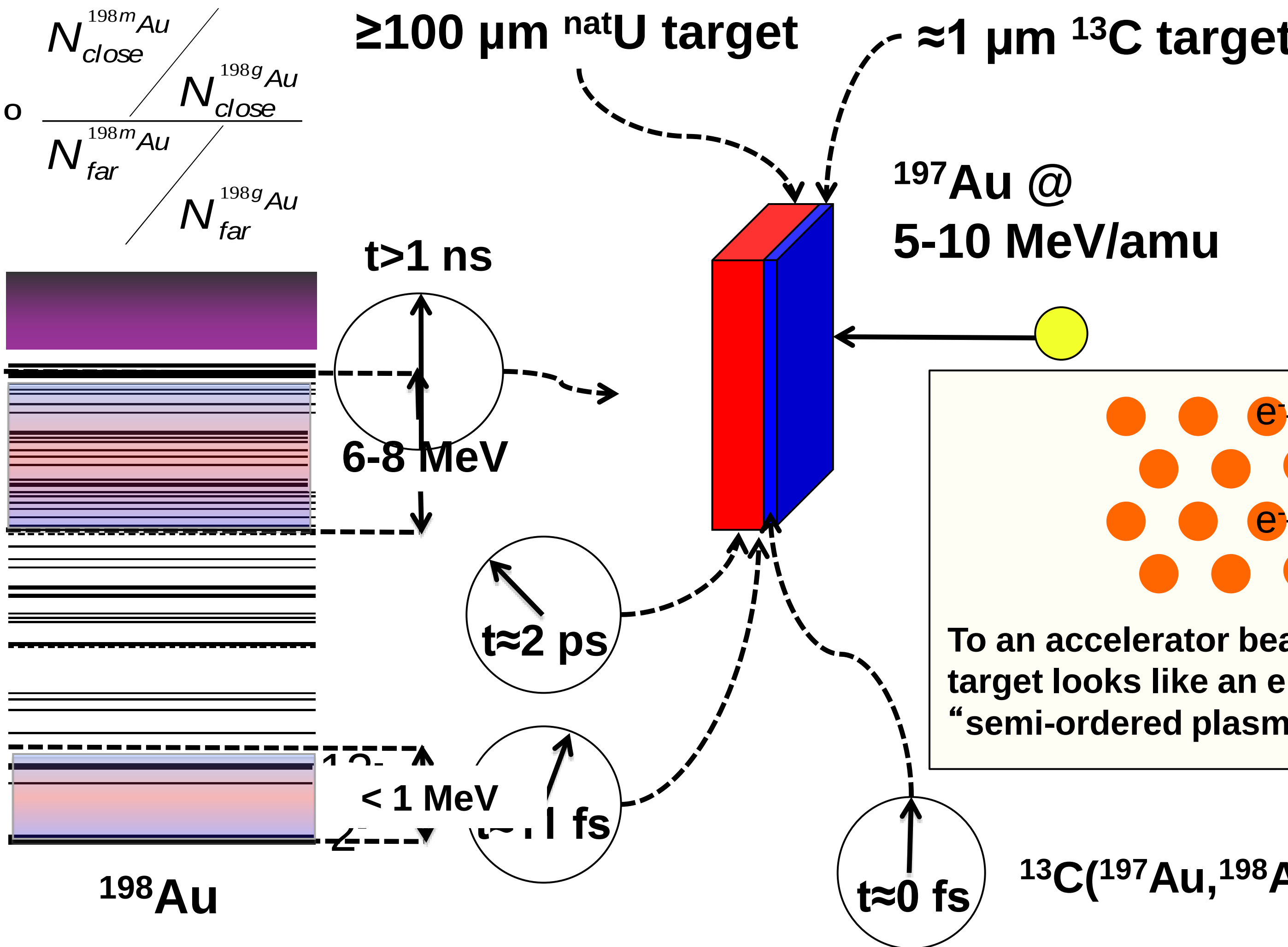
NIF shot N120228-001-999



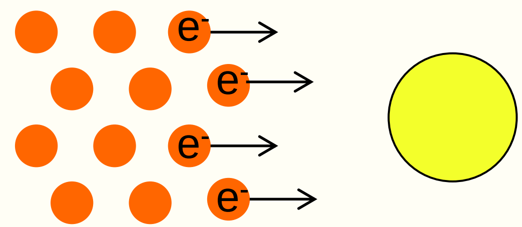
Collection efficiency > 63% has been demonstrated

Option #2: A complementary accelerator-based experiment can also be performed using *GeV* Au beams

$$R \propto \frac{N_{close}^{198m}Au \,/\, N_{close}^{198g}Au}{N_{far}^{198m}Au \,/\, N_{far}^{198g}Au}$$



$^{13}C(^{197}Au,{}^{198}Au_{E\approx 6\text{-}7\ MeV})^{12}C$



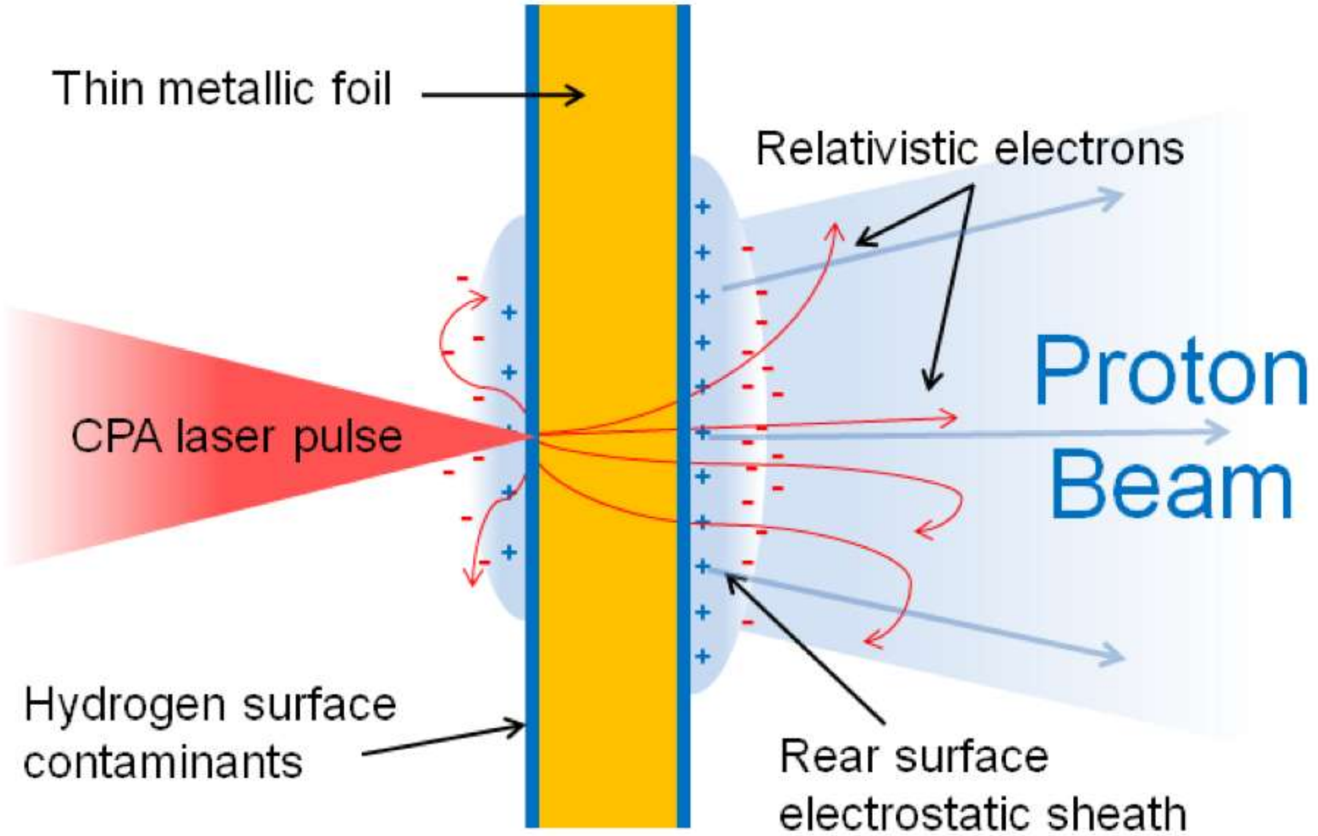
To an accelerator beam, an ordinary target looks like an electron beam, a "semi-ordered plasma."

Plasma Properties	NIF	LBNL
Electron Fluence (cm^{-2})	$\approx 3\times10^{22}$	$\approx 10^{20}$
Temperatures (keV)	$T_e\approx 5\text{-}50, T_g=0.3$	$T_e\approx 2\text{-}20, T_g=$n.a.

First test experiment fielded at LBNL 3/13 – ^{198}Au formed, but no isomer was formed due to low beam energy (4.2 MeV/amu)

New concept: We can use protons from a petawatt laser to make excited ^{196}Au via $^{198}Pt(p,3n)$

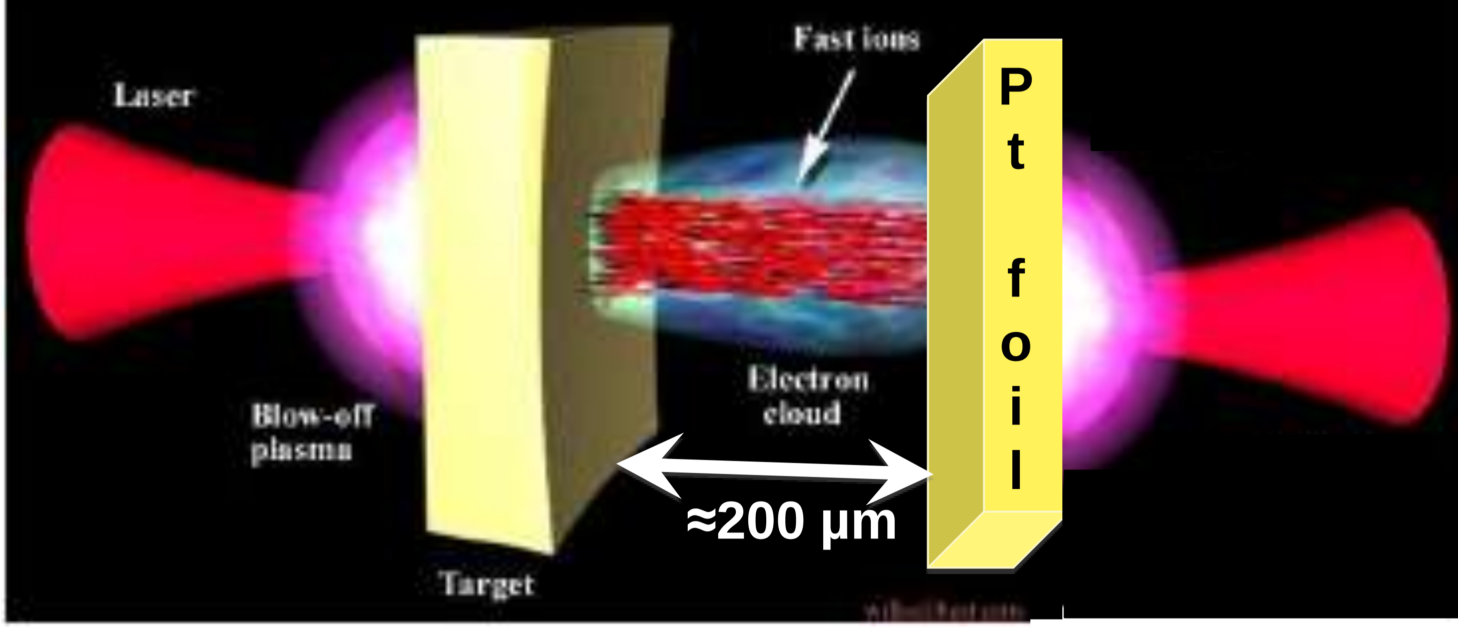
Target Normal Sheath Acceleration



K. Markey

TNSA proton based nuclear-plasma experiment make ^{196m,g}Au using the ^{198}Pt(p,3n) reaction

Step #1: Use TNSA protons from a petawtt laser to make an excited nucleus via the ^{198}Pt(p,3n)^{196m,g}Au



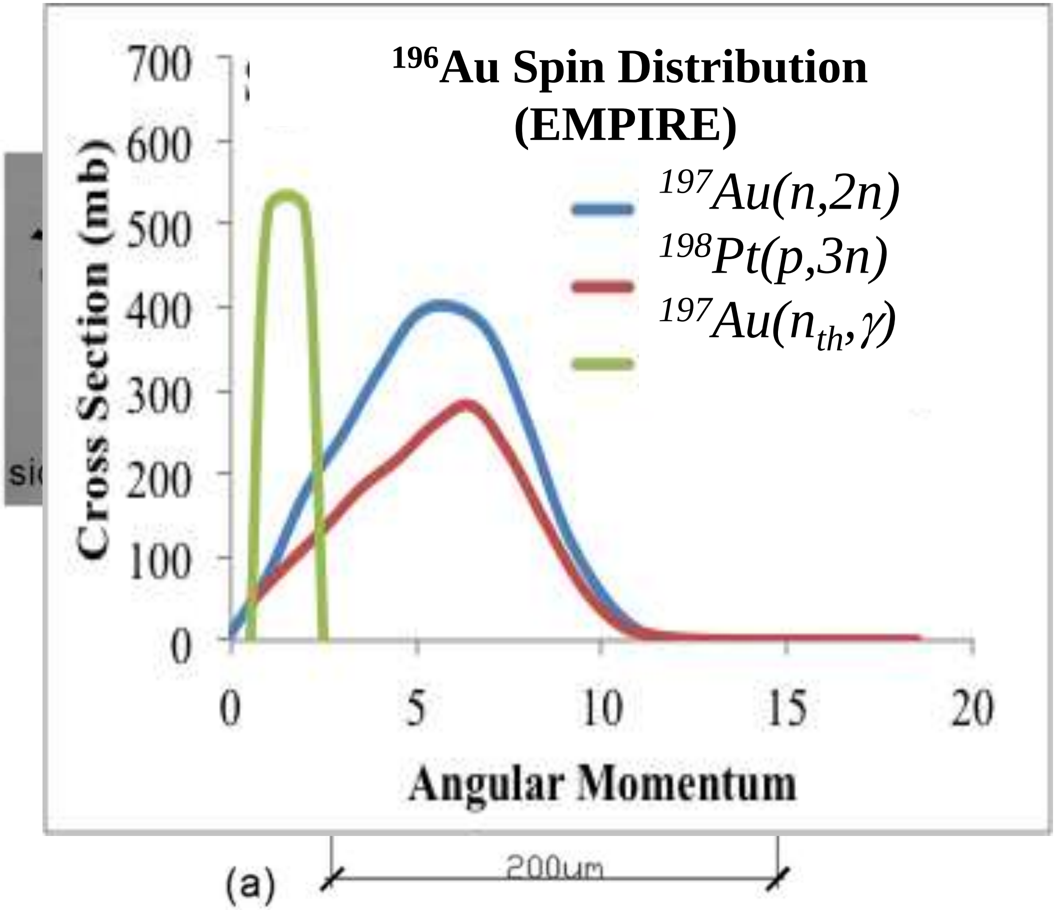
Step #2: Use a long pulse (ns) laser to place the target nuclides into an HED plasma state

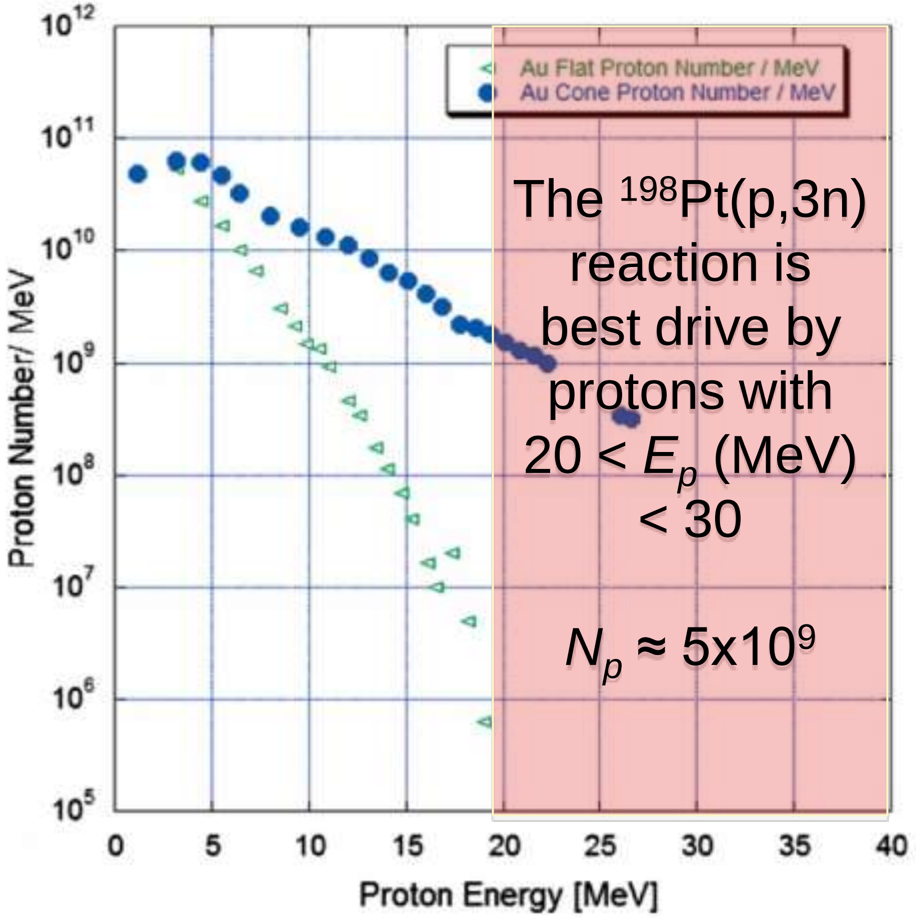
First experiment: Platinum in a plasma state when the protons hit

Control experiment: Platinum put into a plasma state *after* the protons hit

The TNSA proton spectrum can be estimated using recent "state of the art" results

- Results from Flippo (2008) at LANL show >10-fold increase in high-energy proton production in shaped targets. *Laser power < 100 TW.*

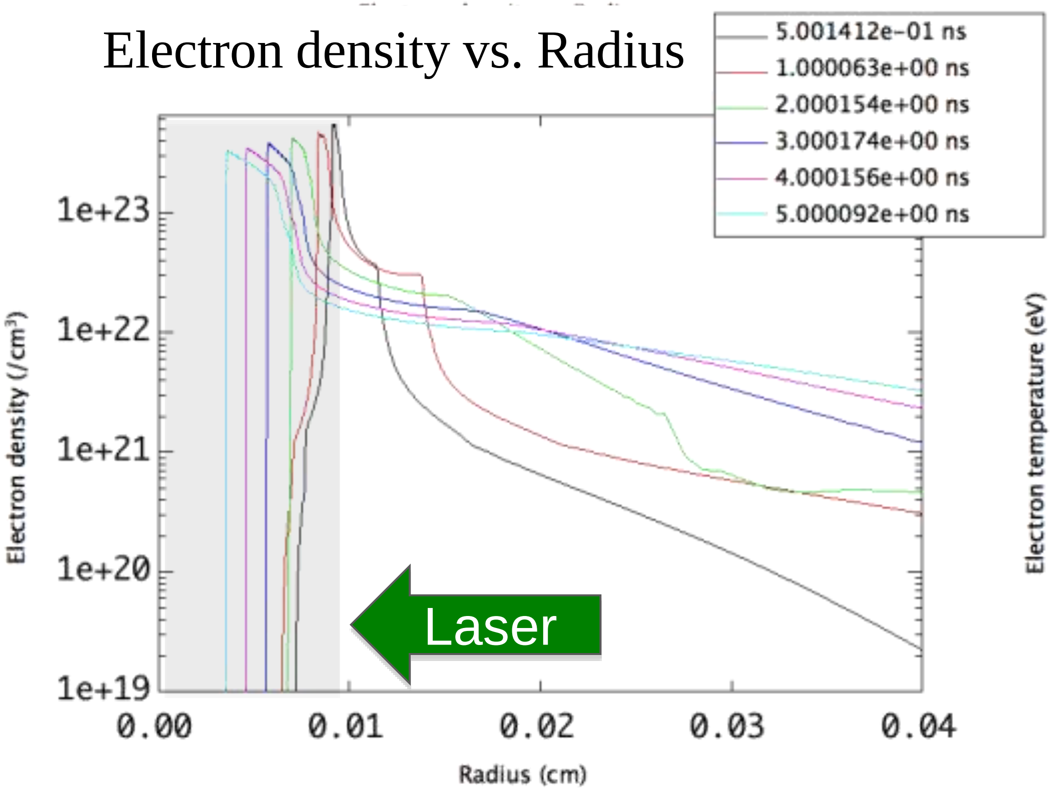




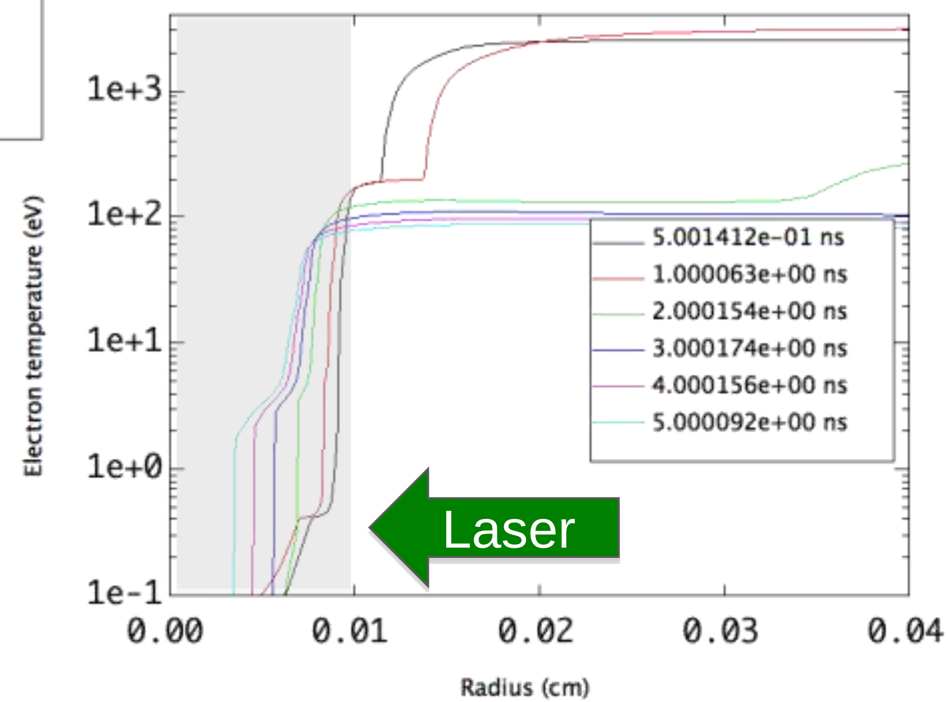
Long-pulse laser produces a variety of plasma conditions

1D Radiation Hydrodynamics simulations complements of P.F. Davis

Electron density vs. Radius



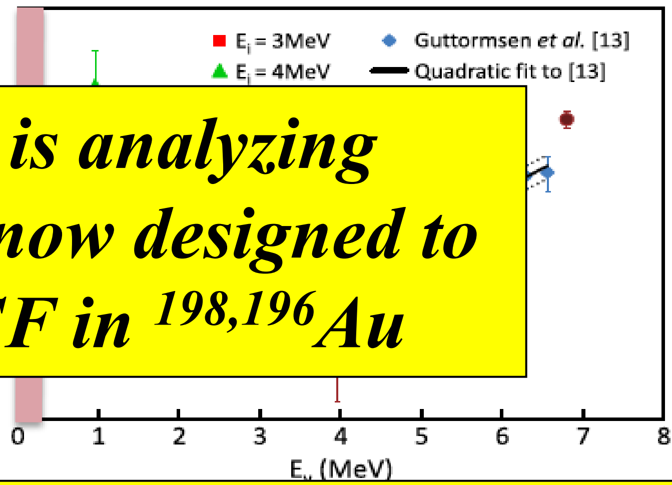
Electron temperature vs. Radius



Plasma Properties	NIF	TNSA
Electron Fluence (cm^{-2})	$\approx 3\times10^{22}$	$\approx 10^{20-21}$
Temperatures (keV)	$T_e \approx 5\text{-}50, T_g = 0.3$	$T_e \approx 0.2\text{-}3, T_g = 0.2$

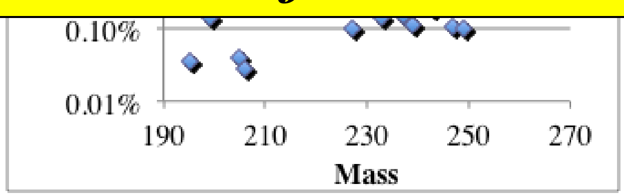
Summary

- Interactions between highly-excited nuclear states and HEDPS can profoundly effect nucleosynthesis
- We have hints of this happening right now at NIF
- Outstandi
  - What a
    atomic



Francesca Giacopo is analyzing an Oslo data set right now designed to measure LD and RSF in ^{198,196}Au

Bethany Goldblum and Darren Bleuel will tell you about other potential experiments and facilities to probe the J$^\pi$ dependence of LD and RSF



M. Wiedeking *et al.,* Phys. Rev. Lett. 108, 162503 (2012)


NIF