Nuclear-Plasma Interactions at NIF and accelerator labs

Exotic Beams Summer School
Lawrence Berkley National Laboratory
Berkeley CA

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August 3, 2013

LLNL PRES pending

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

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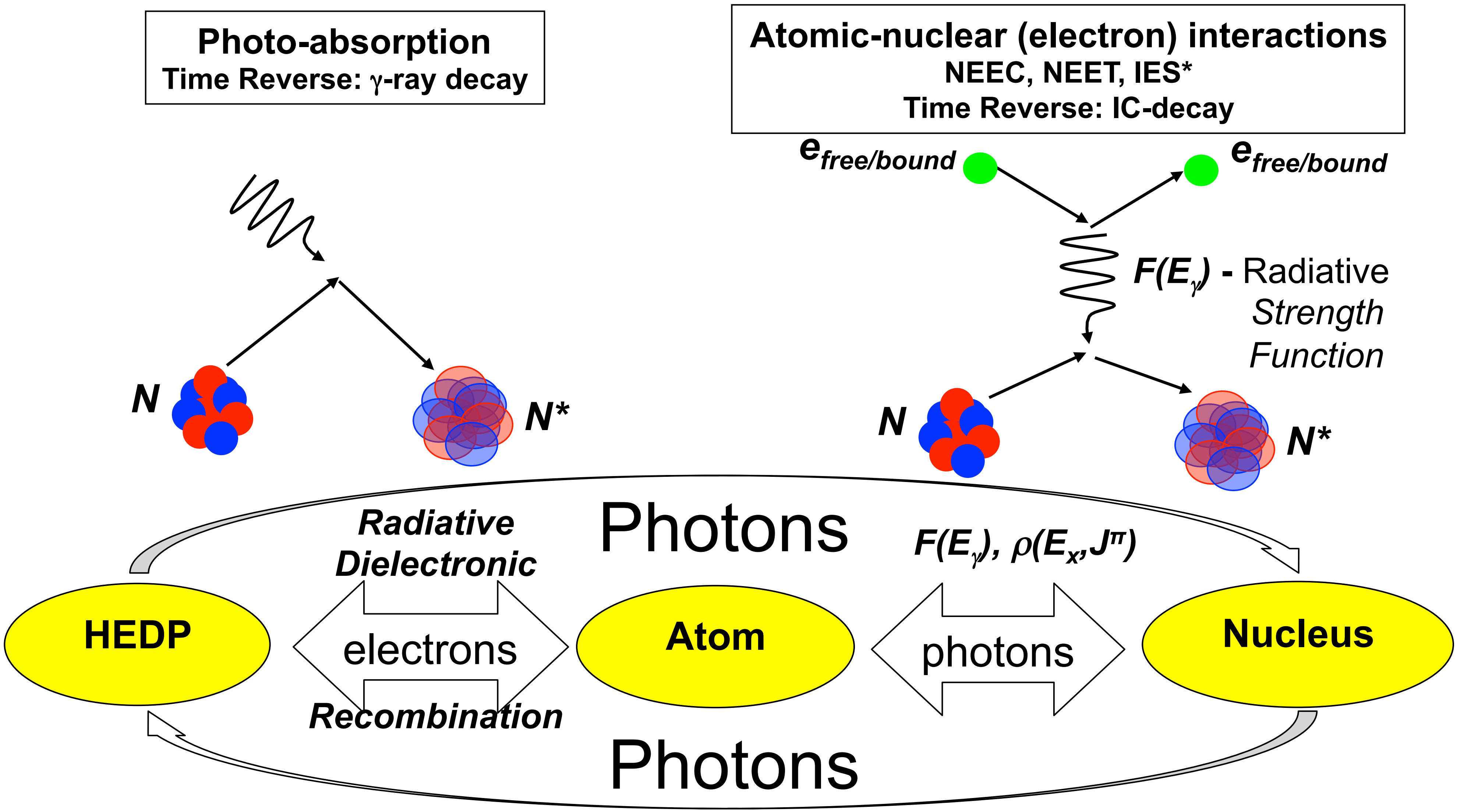
Introduction

- Nuclear-plasma interactions in Neutron-rich High Energy Density Plasmas (nHEDP)
- Nucleosynthesis in stellar nHEDPs
- Nucleosynthesis at the National Ignition Facility
- 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)*

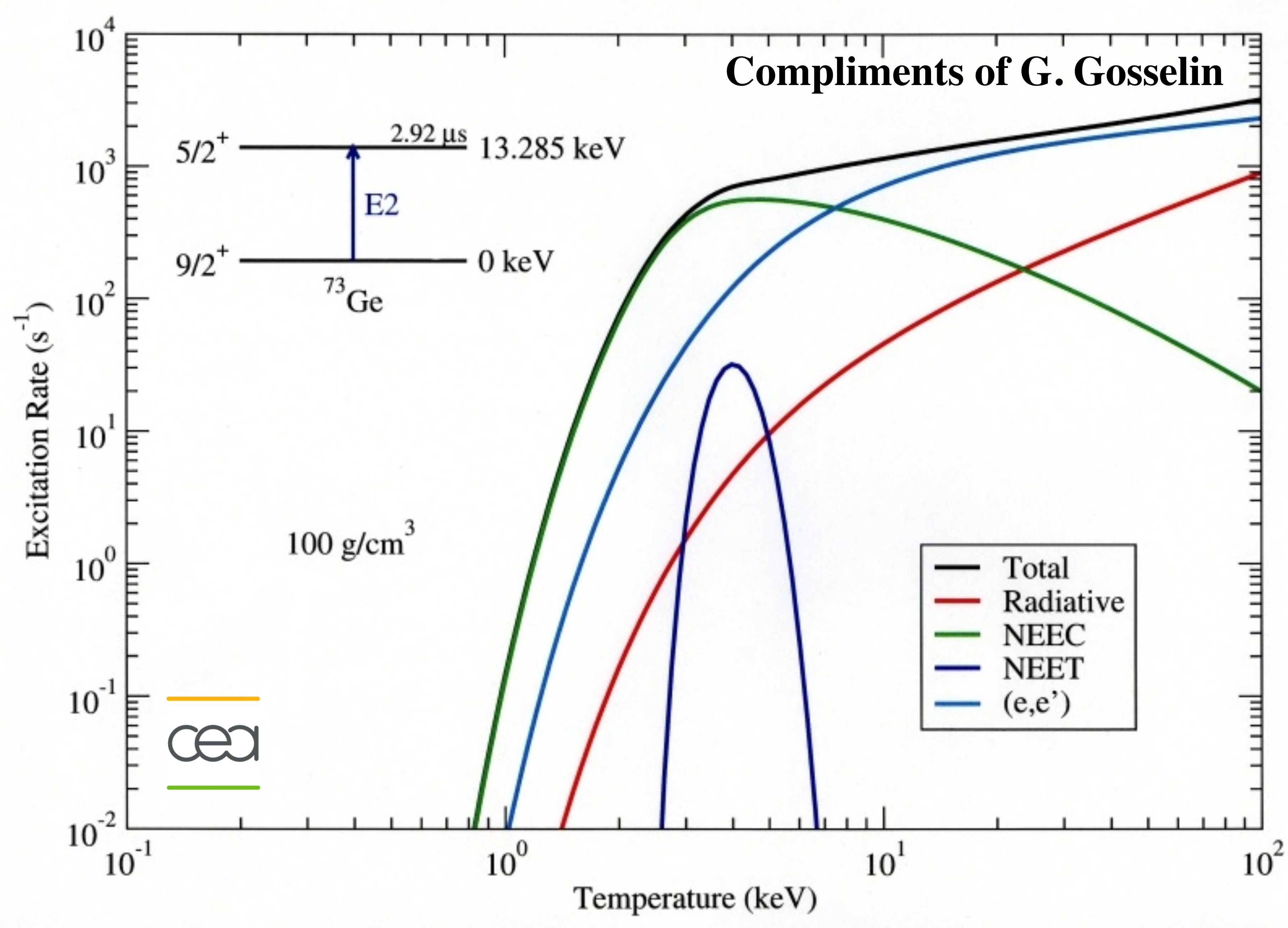
Nuclear Level Density and Radiative Strength is crucial to understanding the formation of elements in nHEDPs

Nuclear-Plasma Interactions (NPI) can excite nuclear states with energies comparable to those of the surrounding plasma

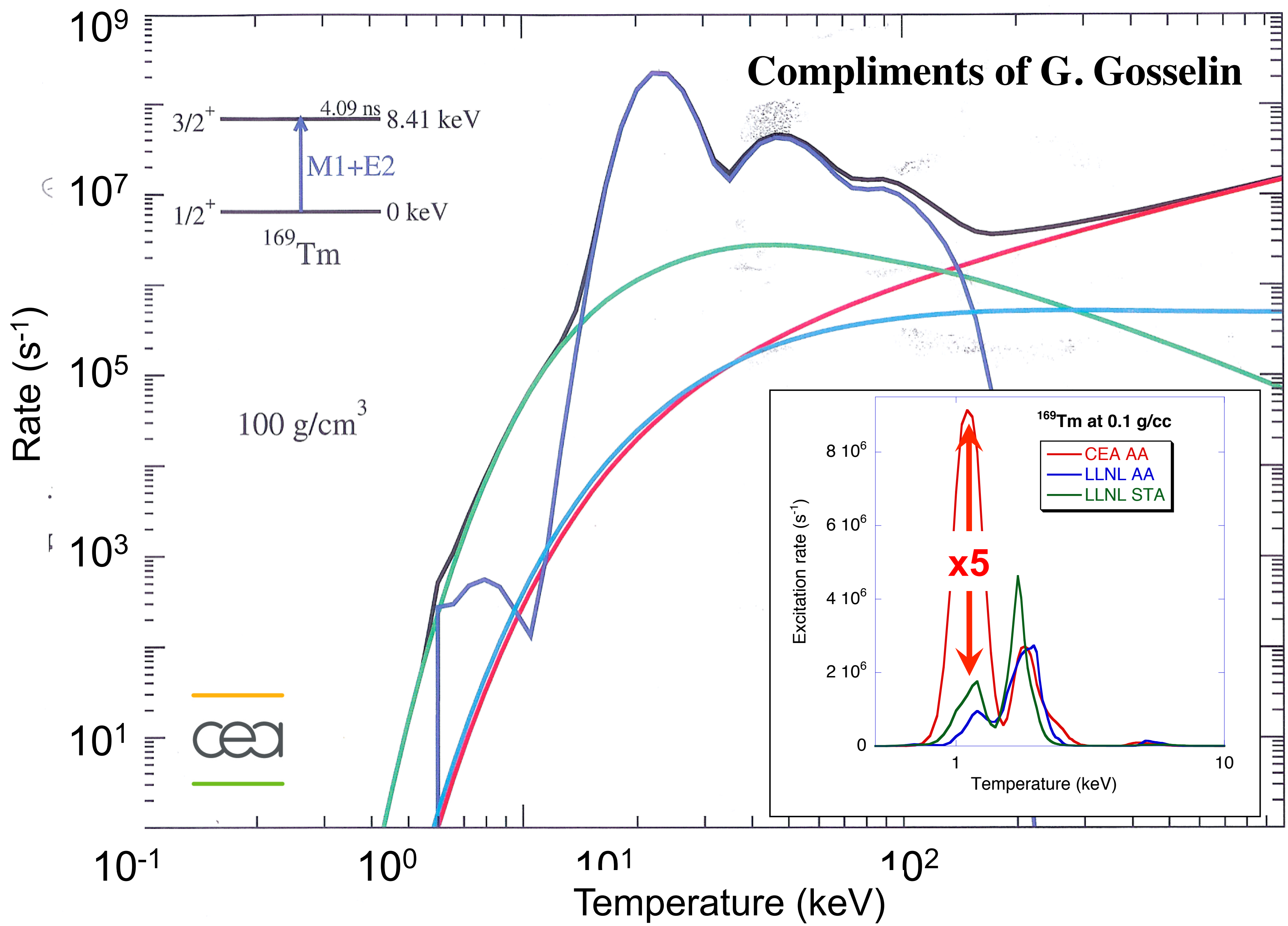


How rapid are these interactions?

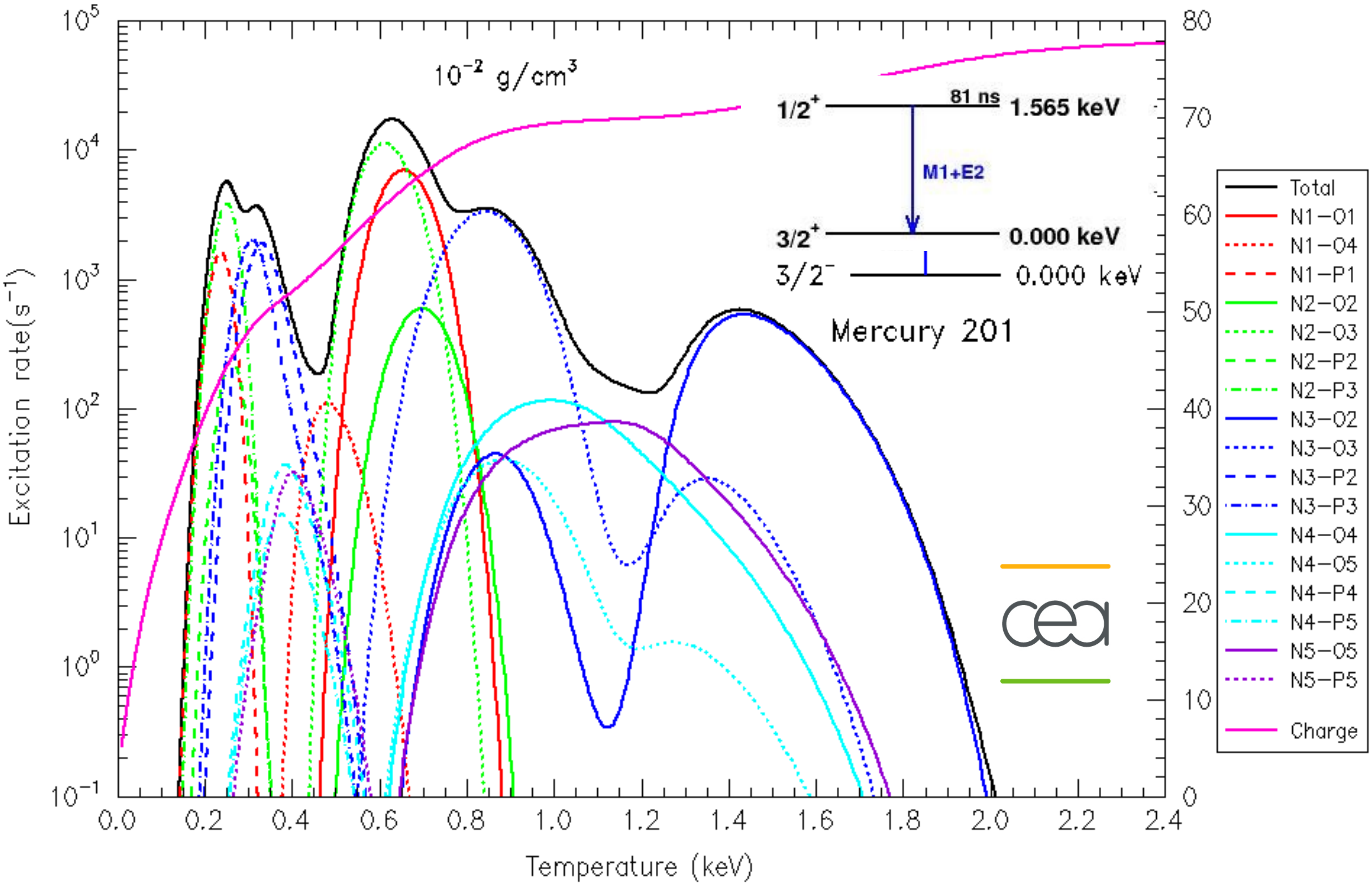
Excitation time scales for ^{73}Ge



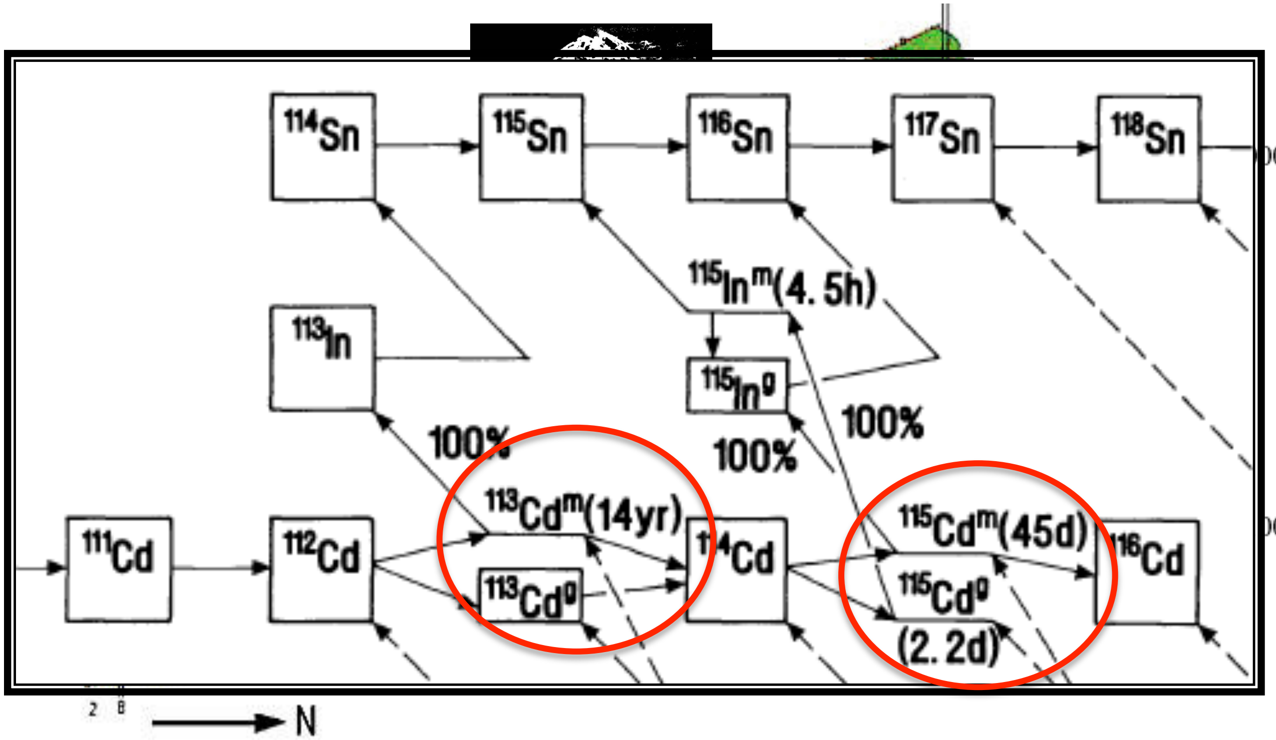
Excitation time scales for ^{169}Tm

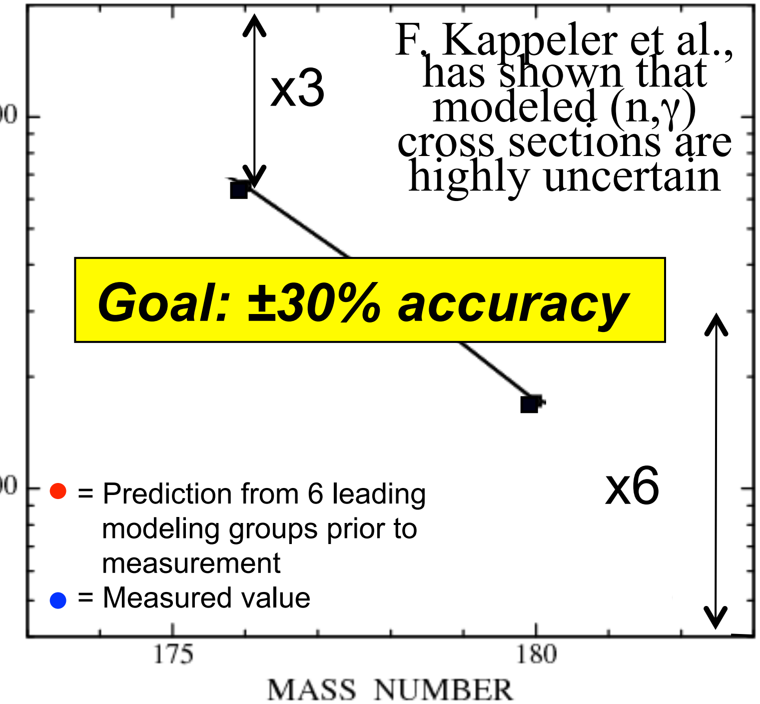


NEEC/NEET rates are very sensitive to the underlying atomic structure



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

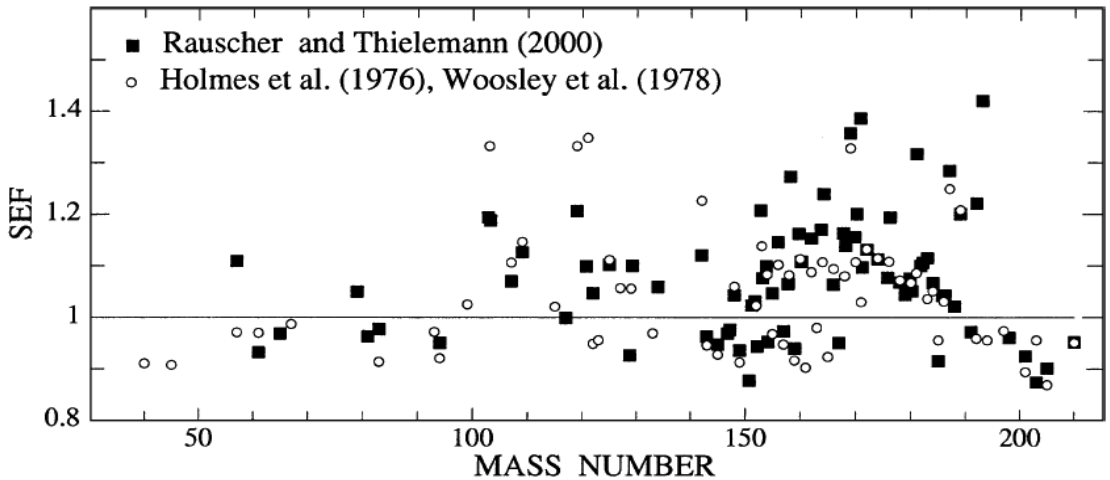
R.A. Ward, Ap. J. **216**: 540-547, 1977, ***Z.S. Nemeth et al., Ap. J. 426 357-365, (1994)***
T. Hayakawa, *et al.,* AIP Conf. Proc. **1238**, 225 (2010), doi: 10.1063/1.3455935

An additional complication is that many important* s-process branch point nuclei have low-lying excited states whose population can influence $\sigma_{(n,\gamma)}$ and β-decay lifetimes

S-process (n,γ) enhancement due to excited states*

$$SEF(kT) = \frac{\sigma_{HEDP}}{\sigma_{GS}} = \frac{\sum_{i=0}^{\infty}(2J_i+1)\sigma(E_x=E_i)e^{-E_i/kT}}{\sigma_{GS}\sum_{i=0}^{\infty}(2J_i+1)e^{-E_i/kT}}$$

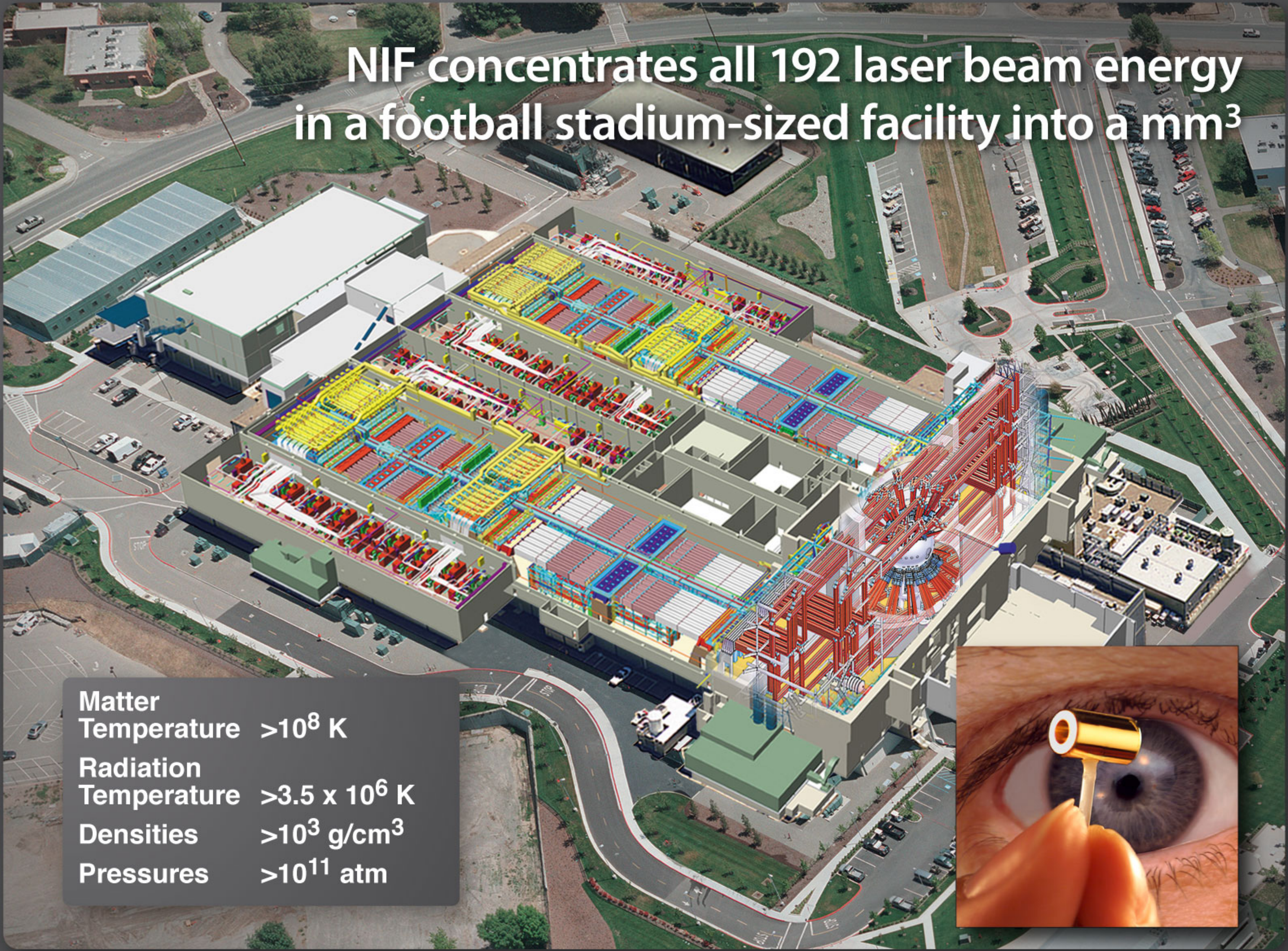
*Bao & Kappeler At. Dat. Nucl. Dat. Tables **76,** 70–154 (2000)



Branch Point	Gnd State Jπ	1st Exc. State E_x (keV)	1st Exc. State Jπ
^{79}Se	7/2+	95.77	1/2-
^{85}Kr	9/2+	304.871	1/2-
^{147}Pm	7/2+	91.1	5/2+
^{151}Sm	5/2–	4.821	3/2-
^{163}Ho	7/2–	100.03	9/2-
^{170}Tm	1-	38.7139	2-
^{171}Tm	1/2+	5.0361	3/2+
^{179}Ta	7/2+	30.7	9/2+
^{204}Tl	2-	414.1	4-
^{205}Pb	5/2-	703.3	7/2-
^{185}W	3/2-	23.547	1/2-

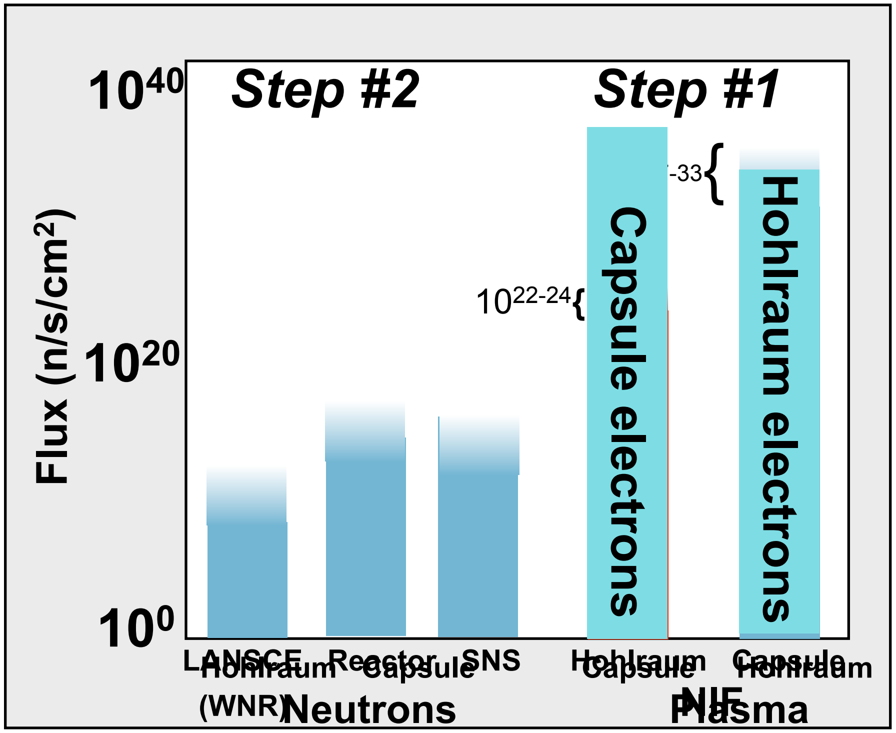
NIF (or LMJ) are the *only* places where (n,γ) might be measured on ground+excited states

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

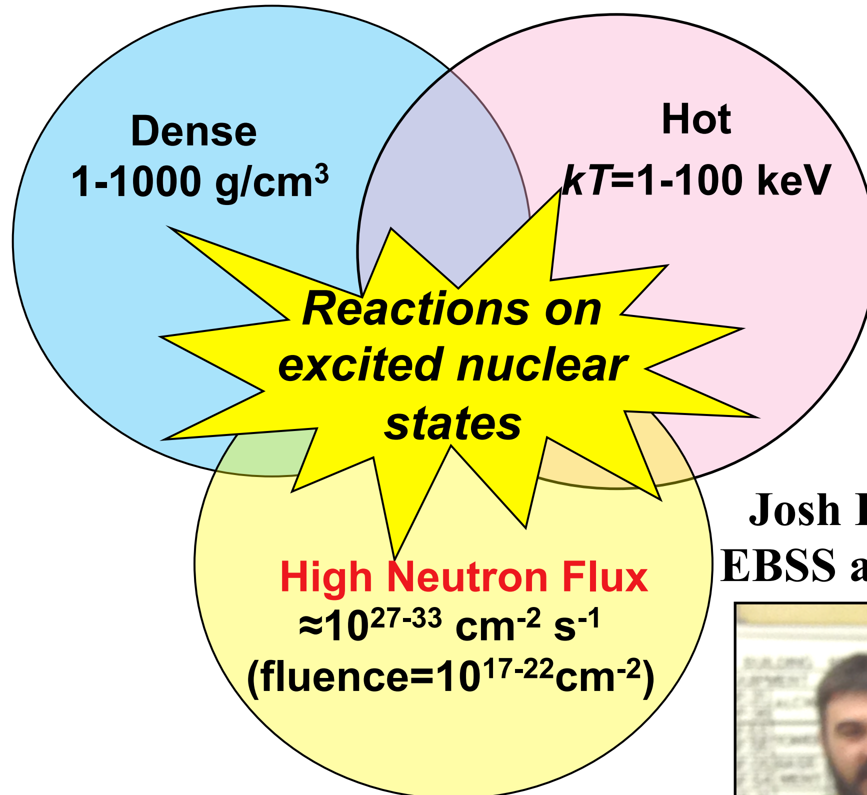


Matter Temperature	$>10^8$ K
Radiation Temperature	$>3.5 \times 10^6$ K
Densities	$>10^3$ g/cm^3
Pressures	$>10^{11}$ atm

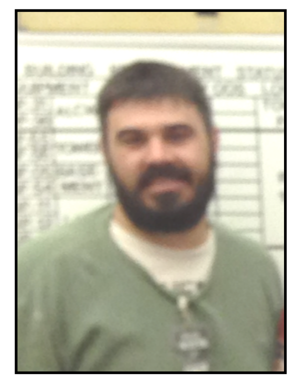
The high e, γ and n-flux in a NIF capsule might allows us to explore reactions on short-lived nuclear states



NIF capsule/hohlraum



Josh Brown
EBSS attendee

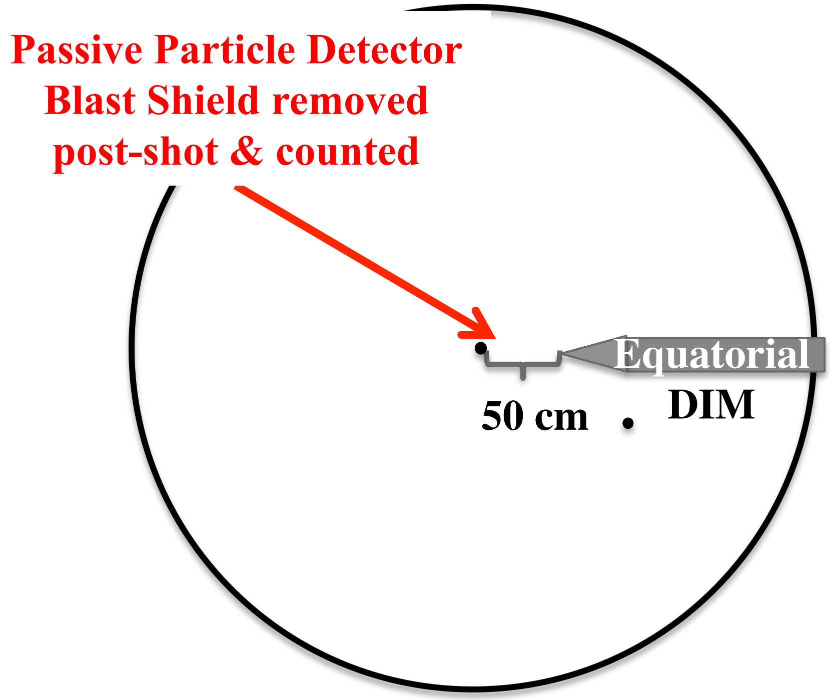


Excited State Reaction Possibilities

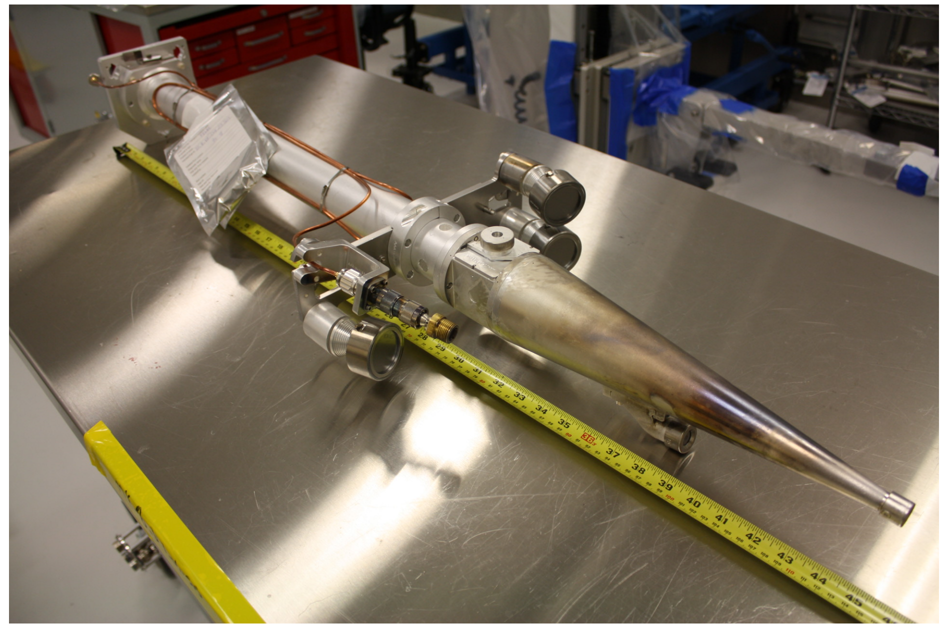
Option #1: Excite a target nucleus with the plasma then hit it with neutrons

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

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



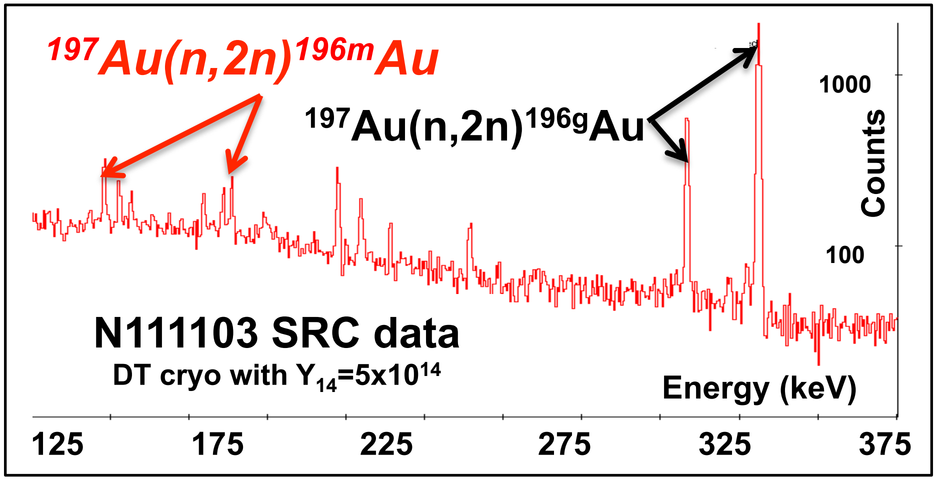
Diagnostic Insertion Manipulator (DIM)

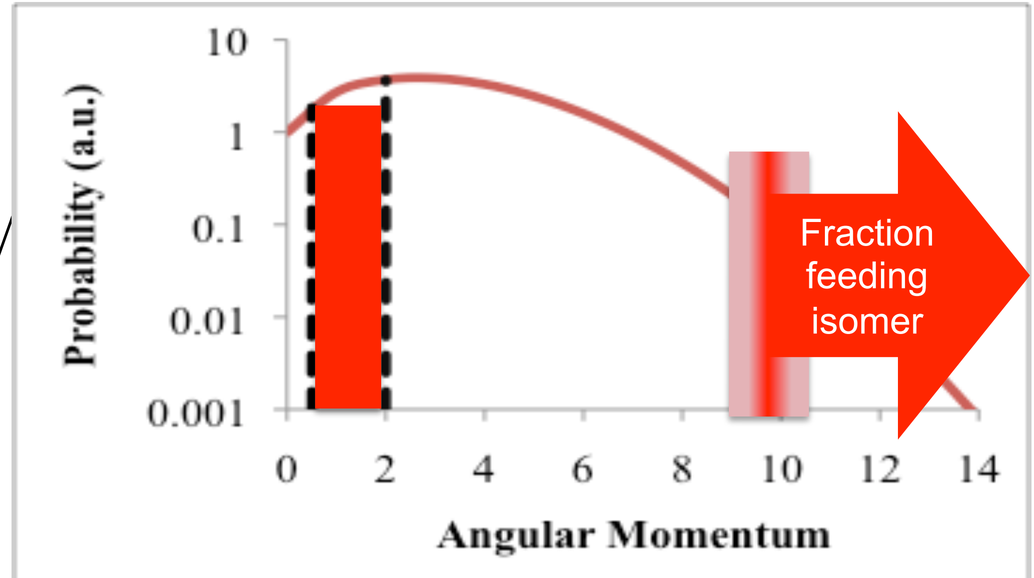


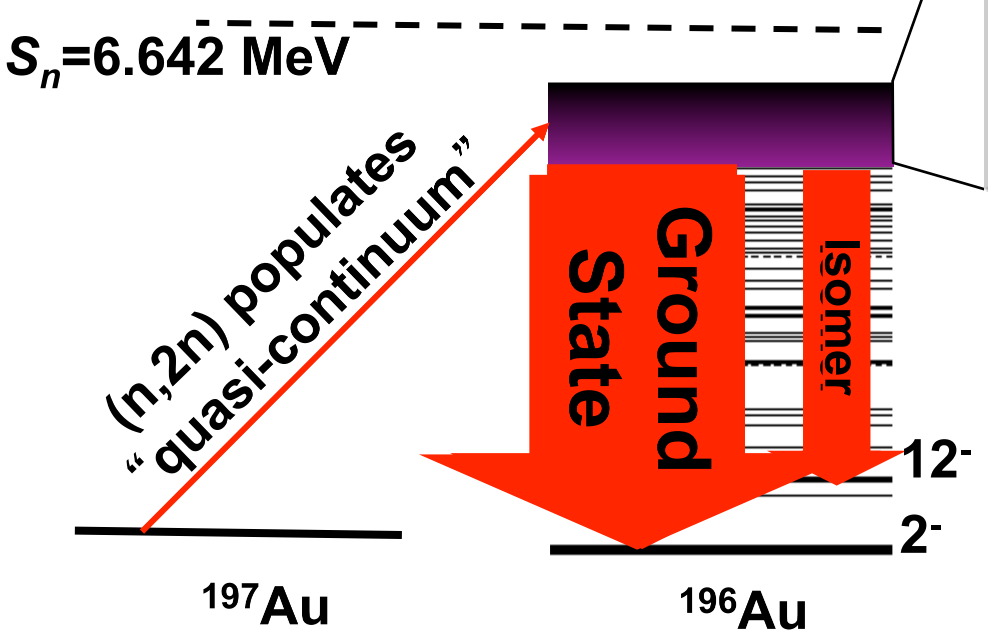
Time Sequence

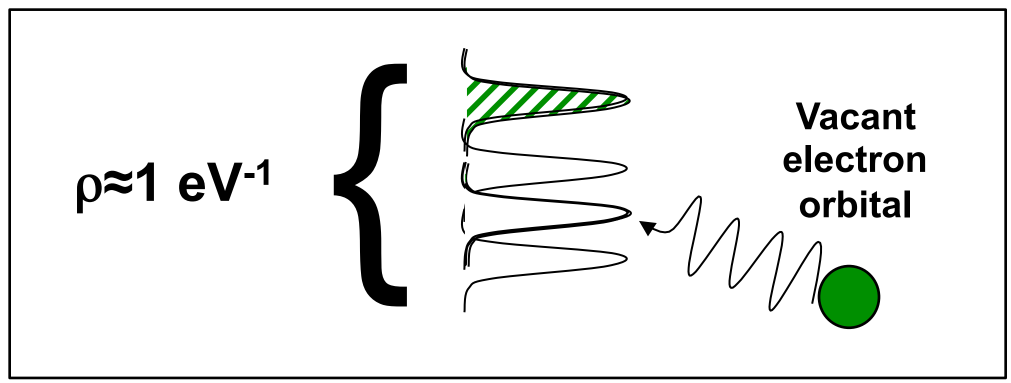
1. Shot
2. 6-12 hours later DIM removed, samples collected and transported to Building 151 counting facility
3. 2-3 days later data becomes available

The 9.7 hour 12^- isomer in ^{196}Au might allow us to explore the interaction of highly-excited states with a HEDP?



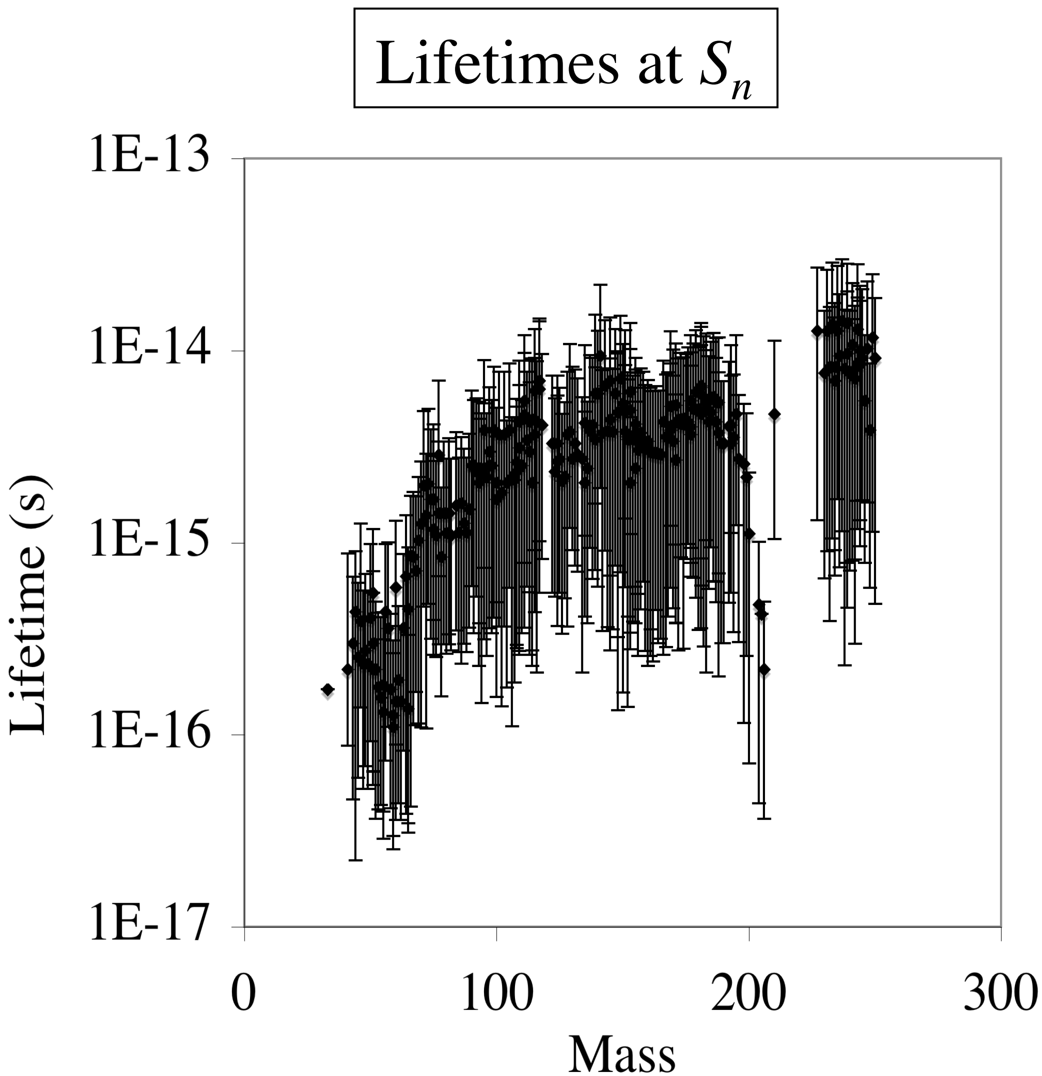


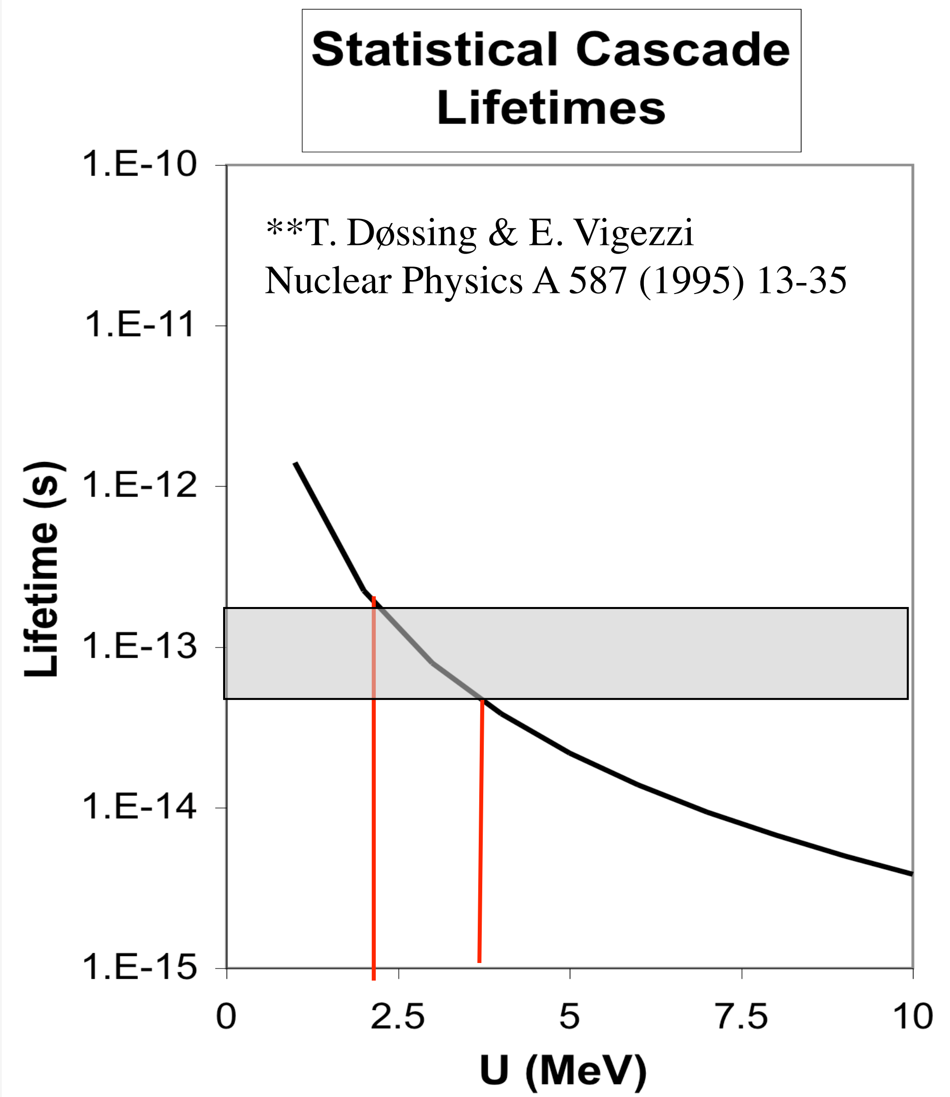




This is entirely new Nuclear Physics

A survey of (n,γ) resonance widths* shows that $E_x \approx 4\text{-}5\ MeV$ quasi-continuum lifetime are on the order of $\tau_{DT\text{-}burn}/P$

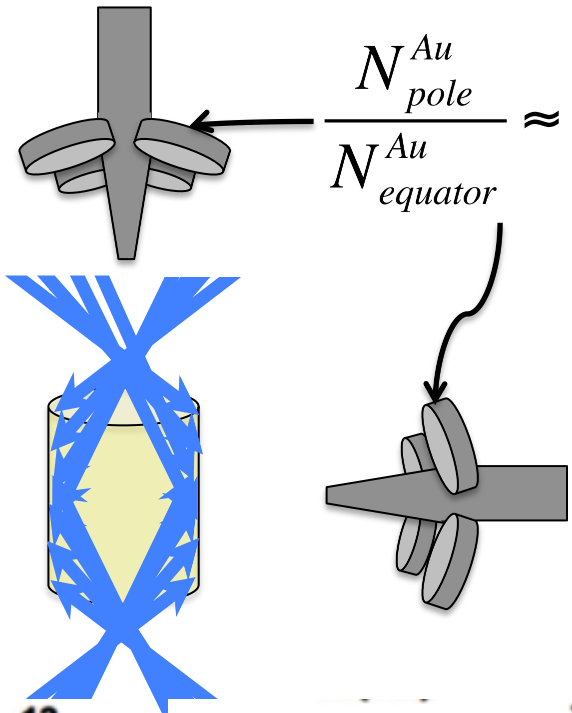




This could play a role in high-flux astrophysical scenarios (supernovae, etc.)

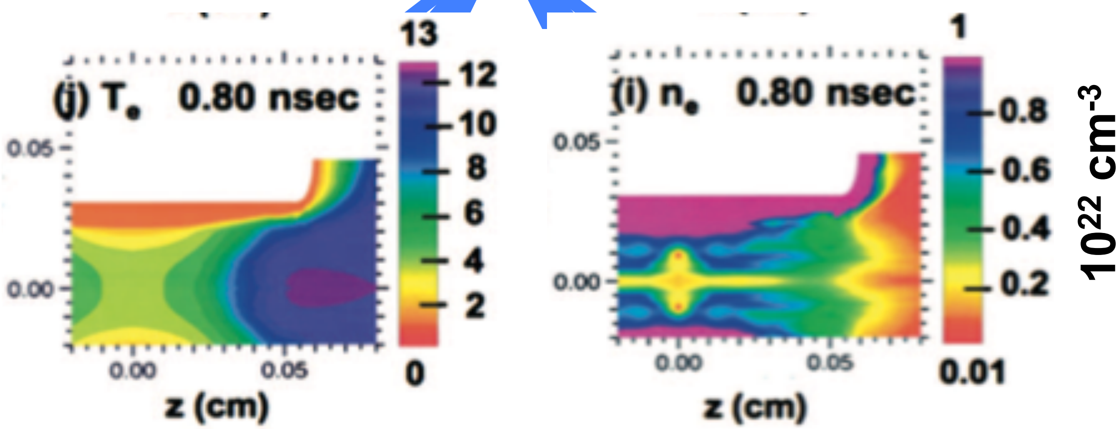
*RIPL-2 "obninsk" compilation

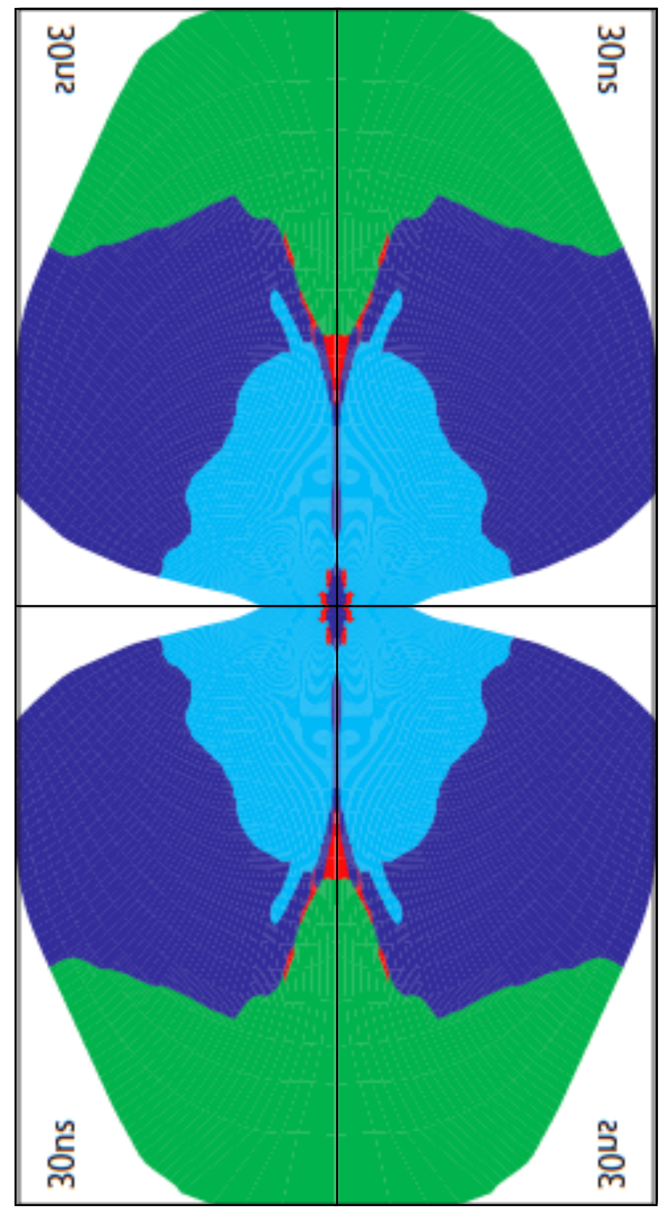
Radioactive ^{196}Au collected from the pole and waist of the NIF come from very different plasma conditions



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

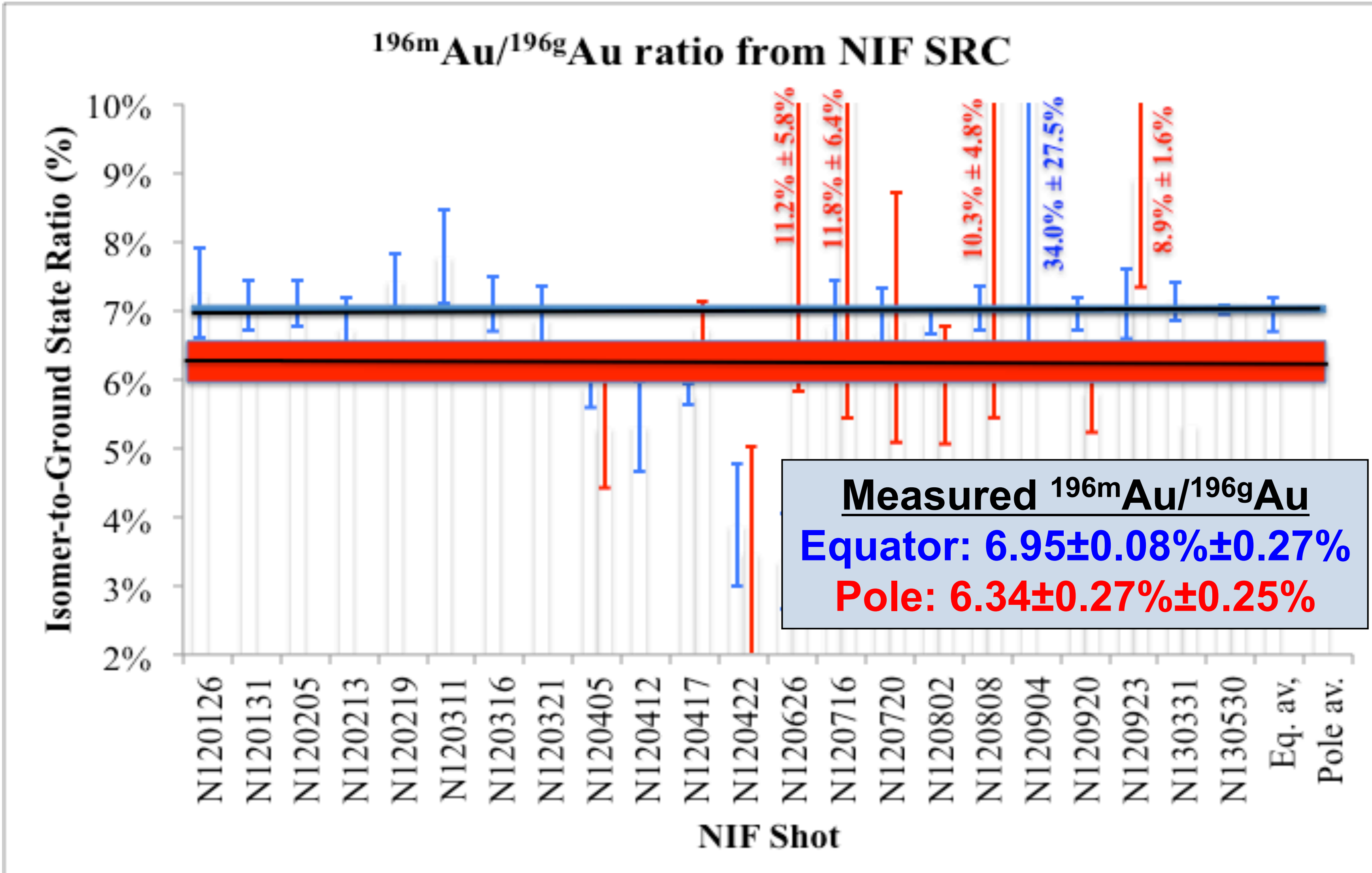
D. Eder *et a.*, UCRL-JRNL-206693





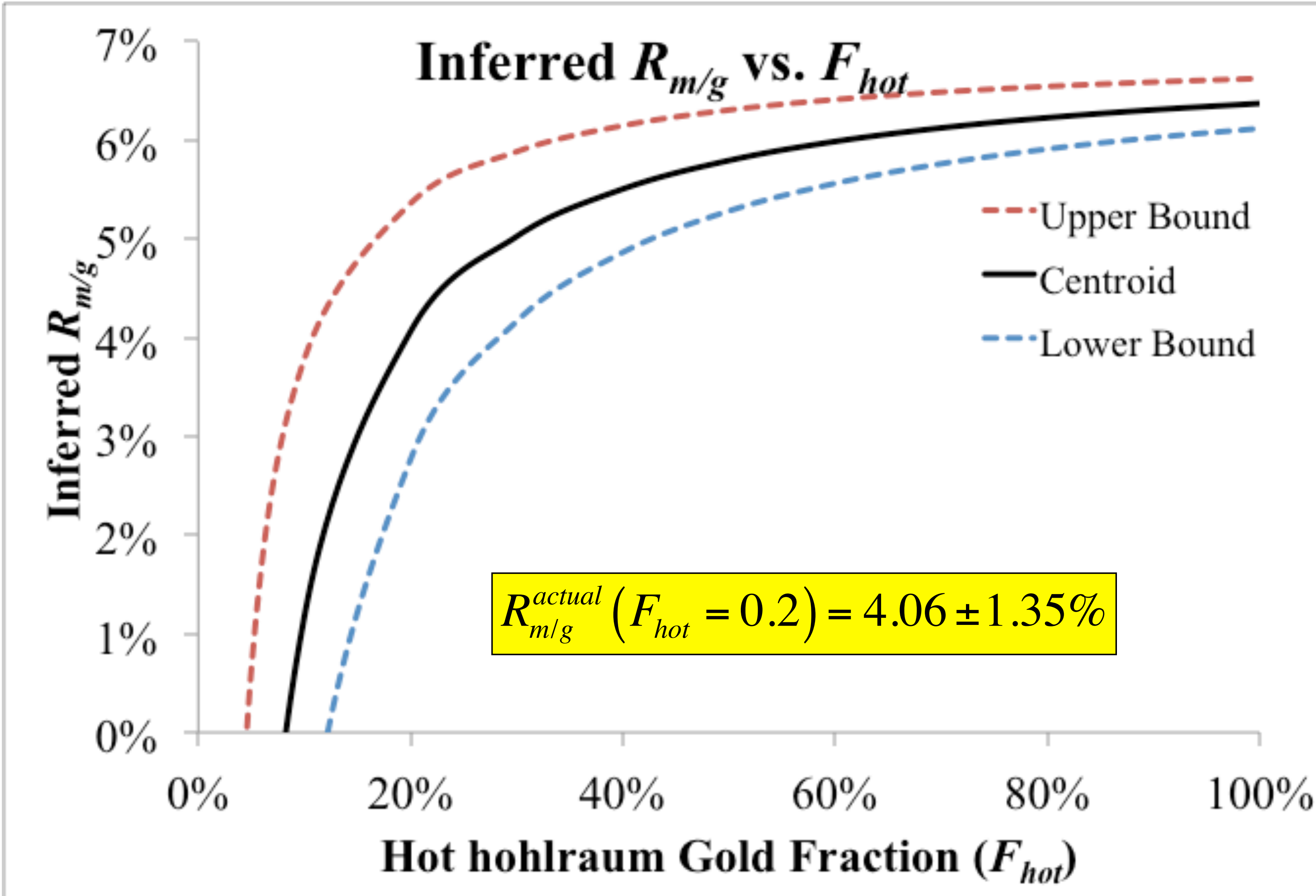
Polar Au comes from a HEDP while equatorial Au does not

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



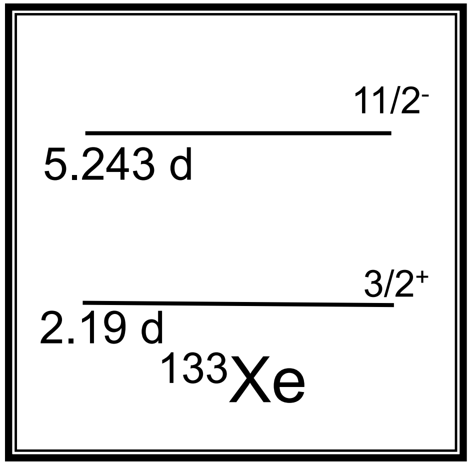
$$\frac{R_{m/g}^{pole}}{R_{m/g}^{equator}} = 0.91 \pm 0.04\%$$

If we assume a given fraction of the poiar Au is hot we can determine the actual m/g ratio

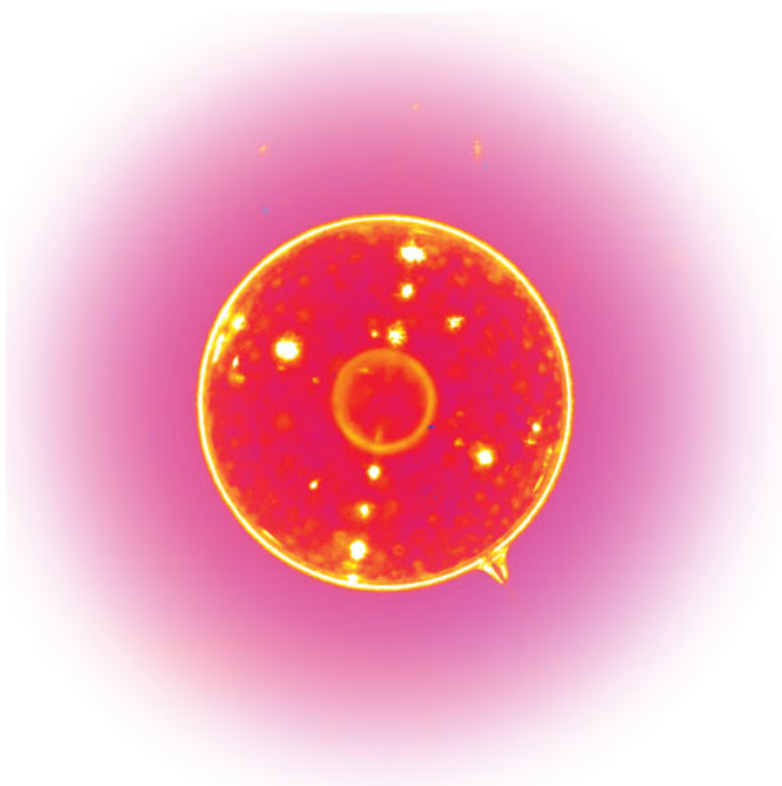


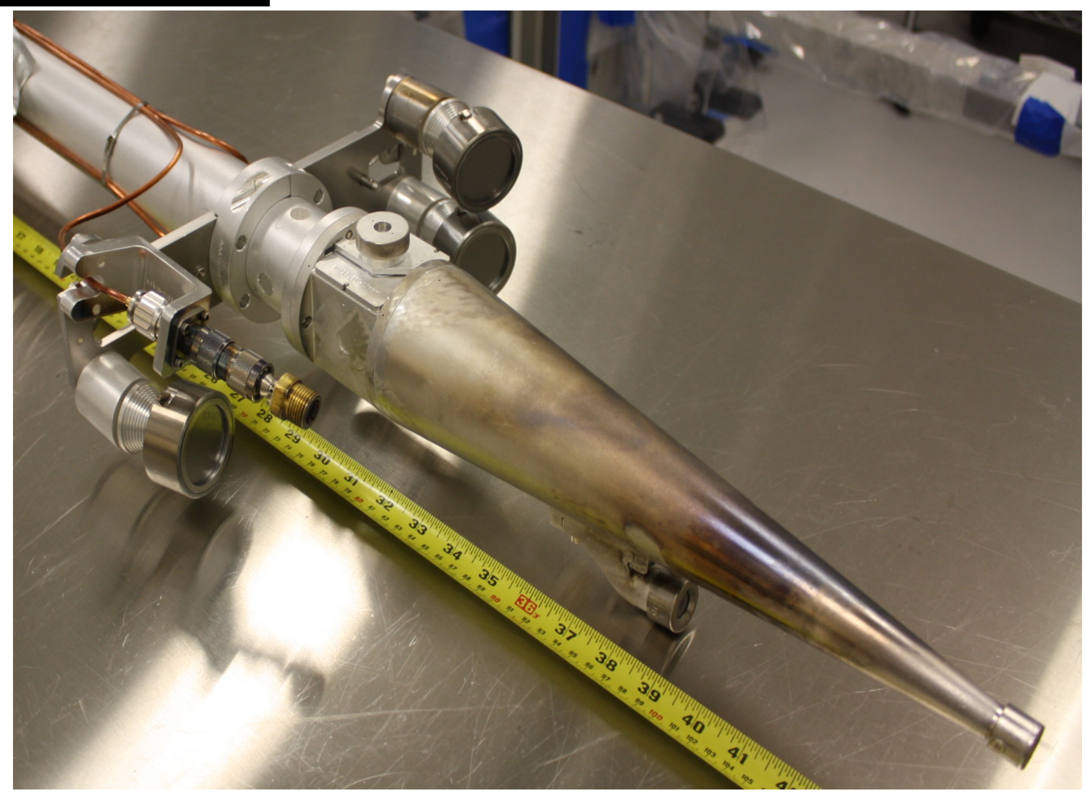
Option #2: A “better” NIF experiment using a ^{134}Xe-doped “exploding pusher” capsule

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

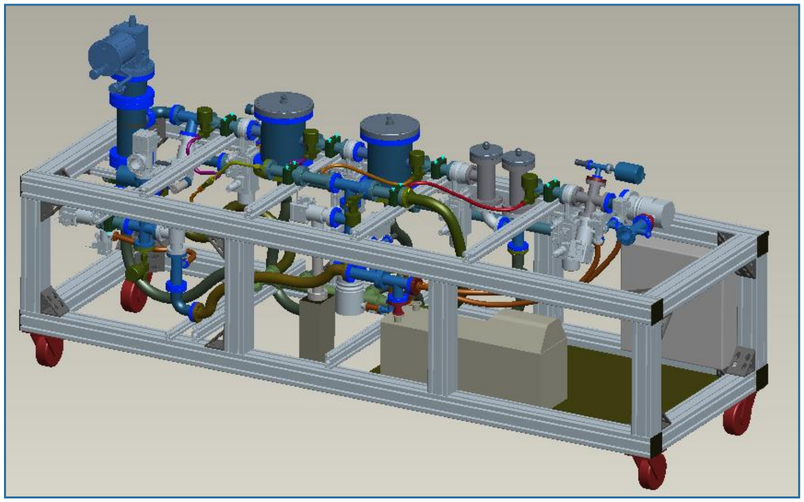


…plus a “control” sample outside the plasma in a sample positioner 50cm from the target





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

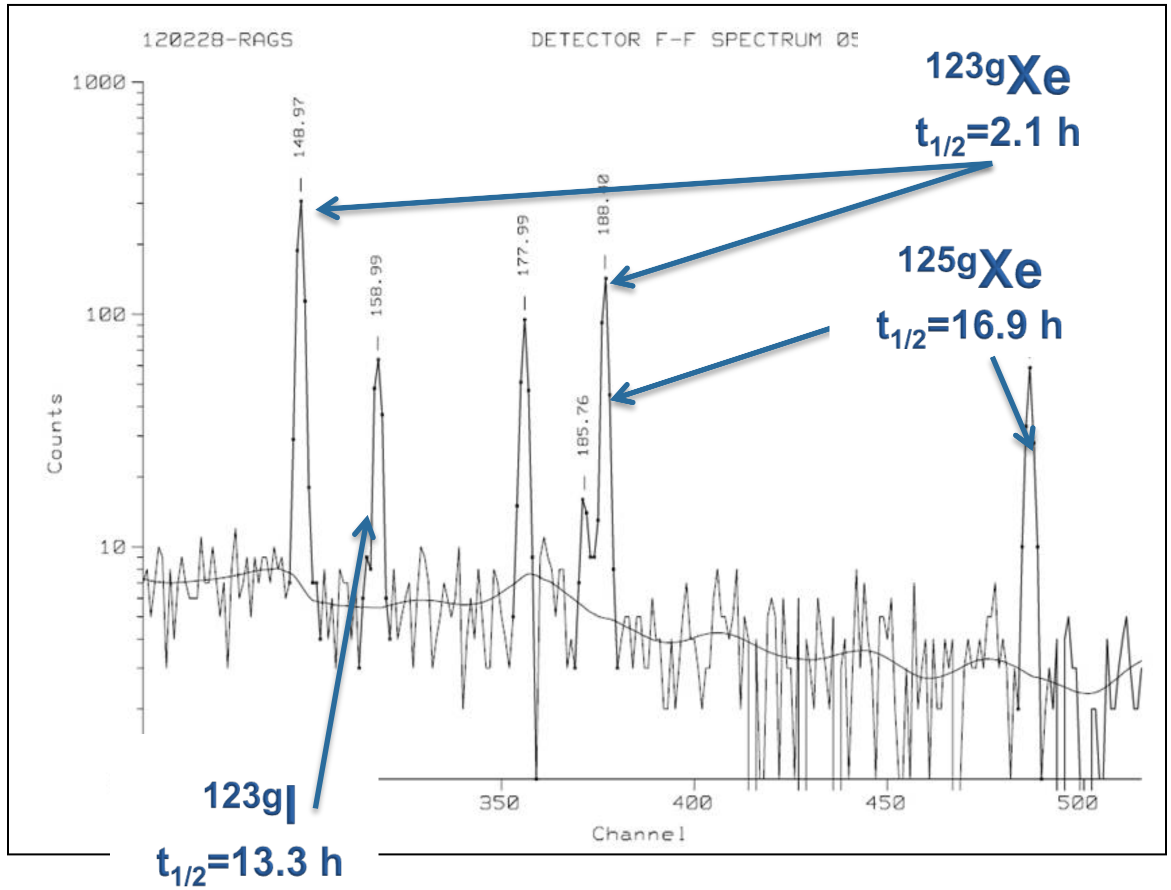


NPI effects can observed using the *Double-Isomer-to-Ground State* (DIGS) Ratio

$$R_{DIGS} \equiv \frac{N_{capsule}^{133m\,Xe} \big/ N_{capsule}^{133g\,Xe}}{N_{SRC}^{133m\,Xe} \big/ N_{SRC}^{133g\,Xe}}$$

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

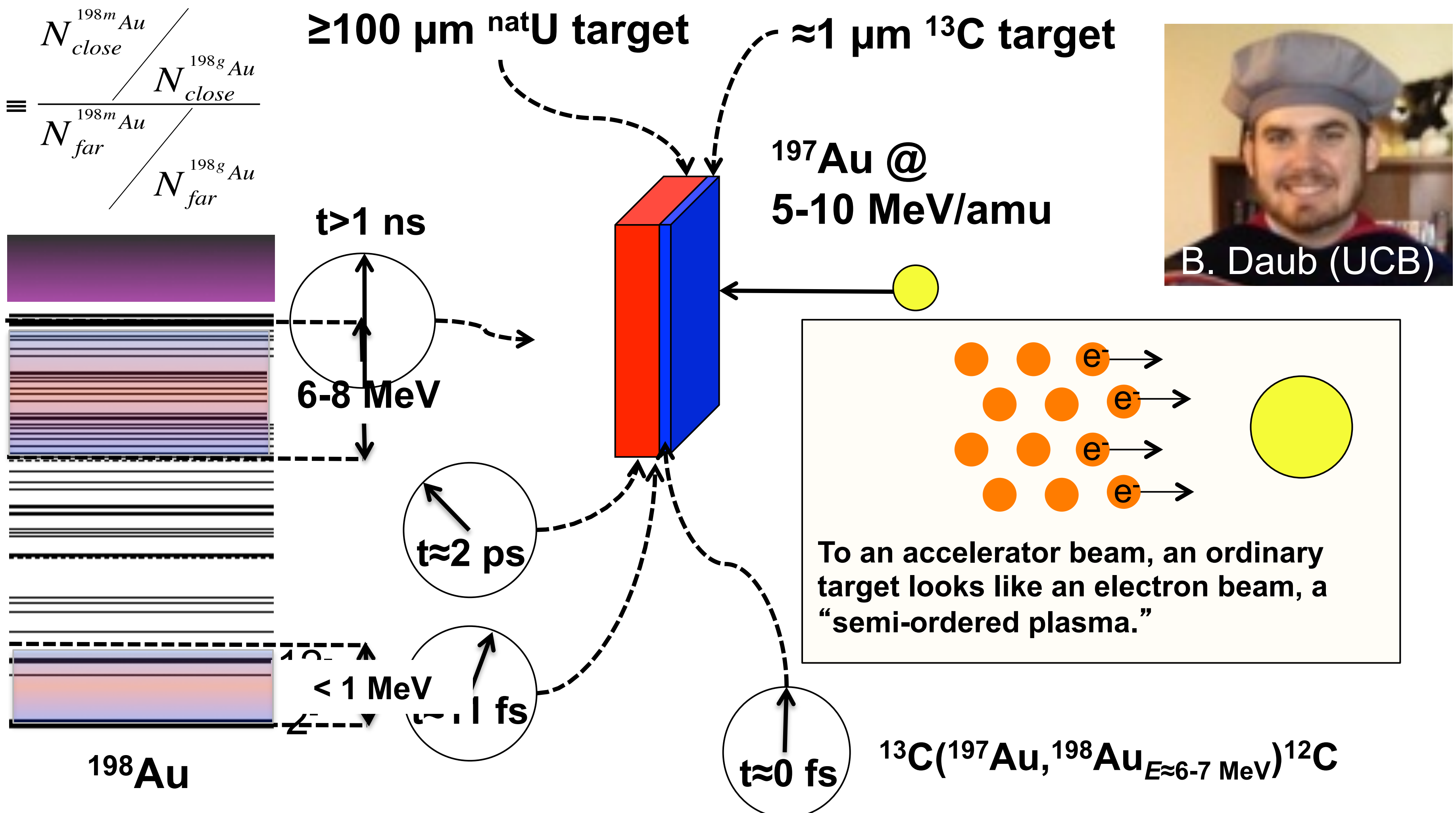
NIF shot N120228-001-999



Collection efficiency > 63% has been demonstrated

Option #3: A complementary accelerator-based experiment can also be performed using *GeV* Au beams

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

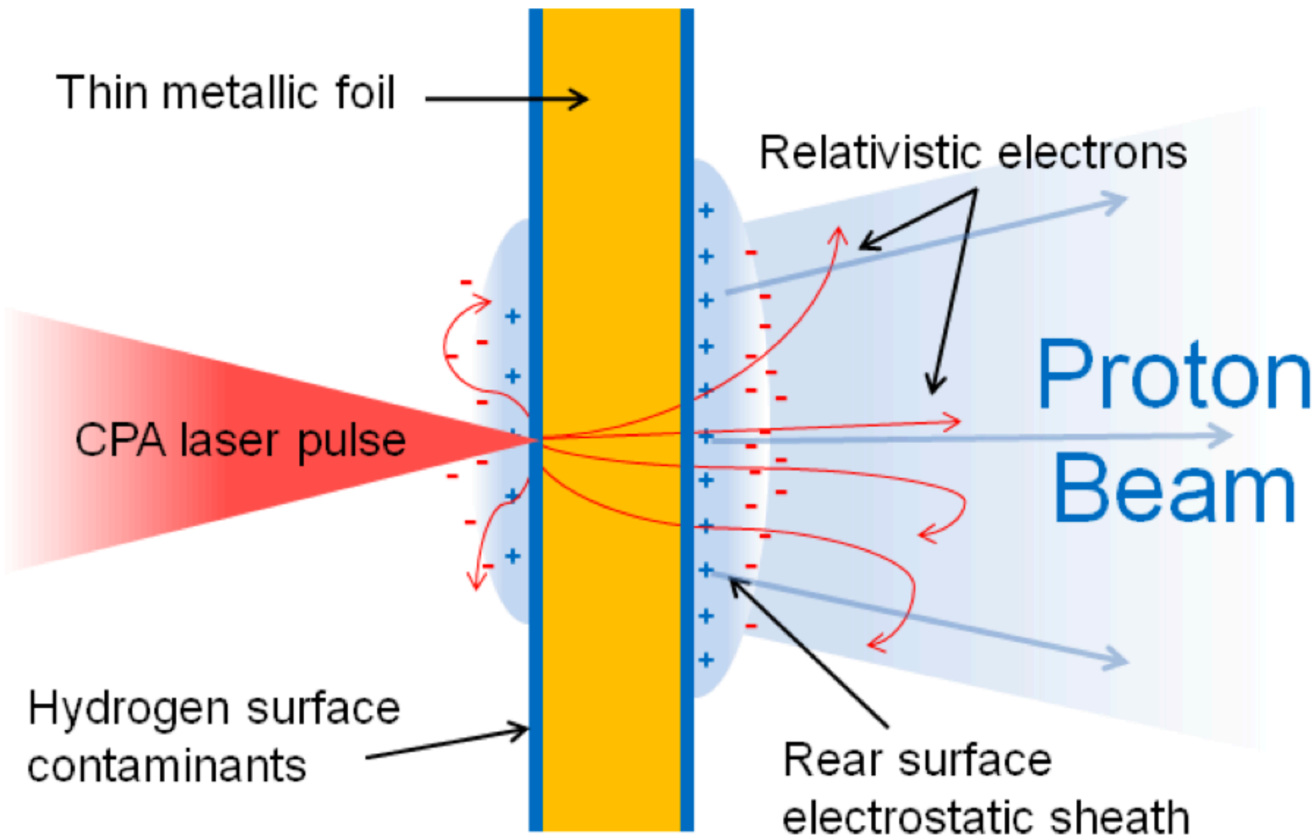


First test experiment fielded at LBNL 3/13 – ^{198}Au formed, but no isomer was formed due to low beam energy (4.2 MeV/amu)

Plasma Properties	NIF	LBNL
Electron Fluence (cm^{-2})	≈3x10^{22}	≈10^{20}
Temperatures (keV)	T_e≈5-50, T_g=0.3	T_e≈2-20, T_g=n.a.

Option #4: We can use protons from a petawatt laser to make excited ^{196}Au via $^{198}Pt(p,3n)$

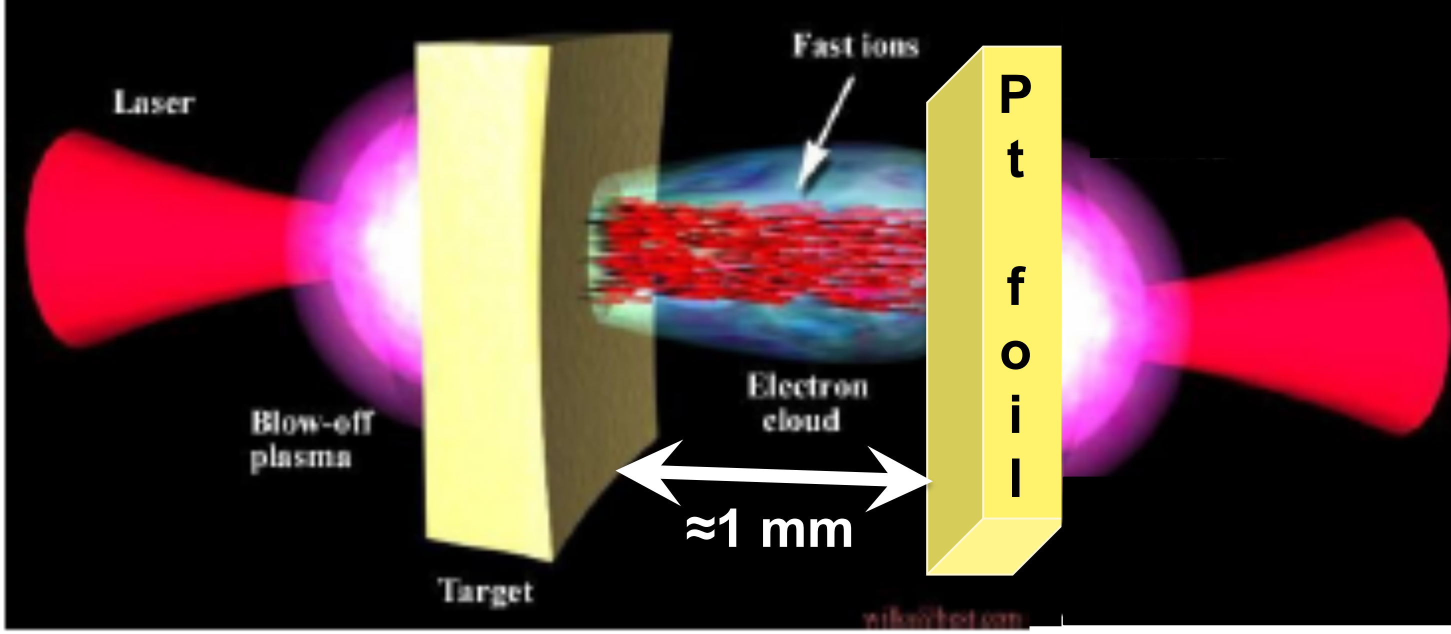
<u>Target Normal Sheath Acceleration</u>



K. Markey

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

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



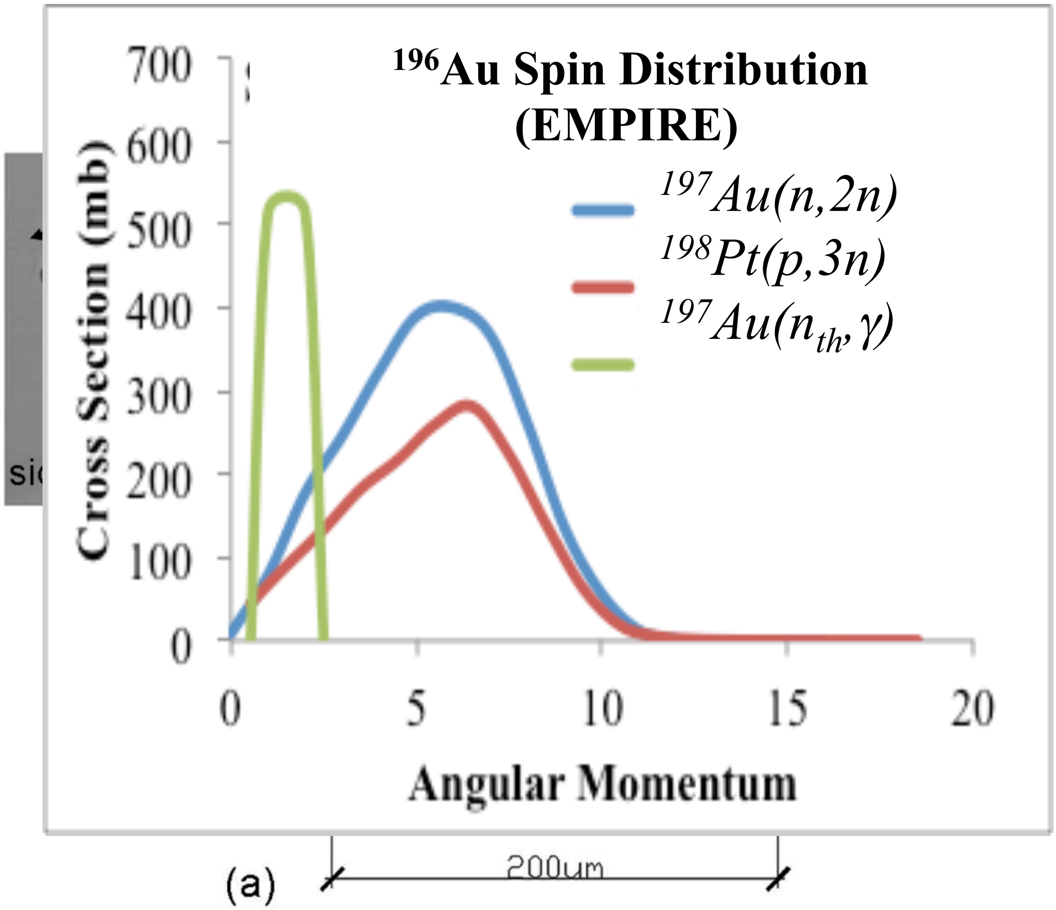
Use a long pulse (ns) laser to place the target nuclides into an HED plasma state a fixed amount of time after the TNSA protons arrive

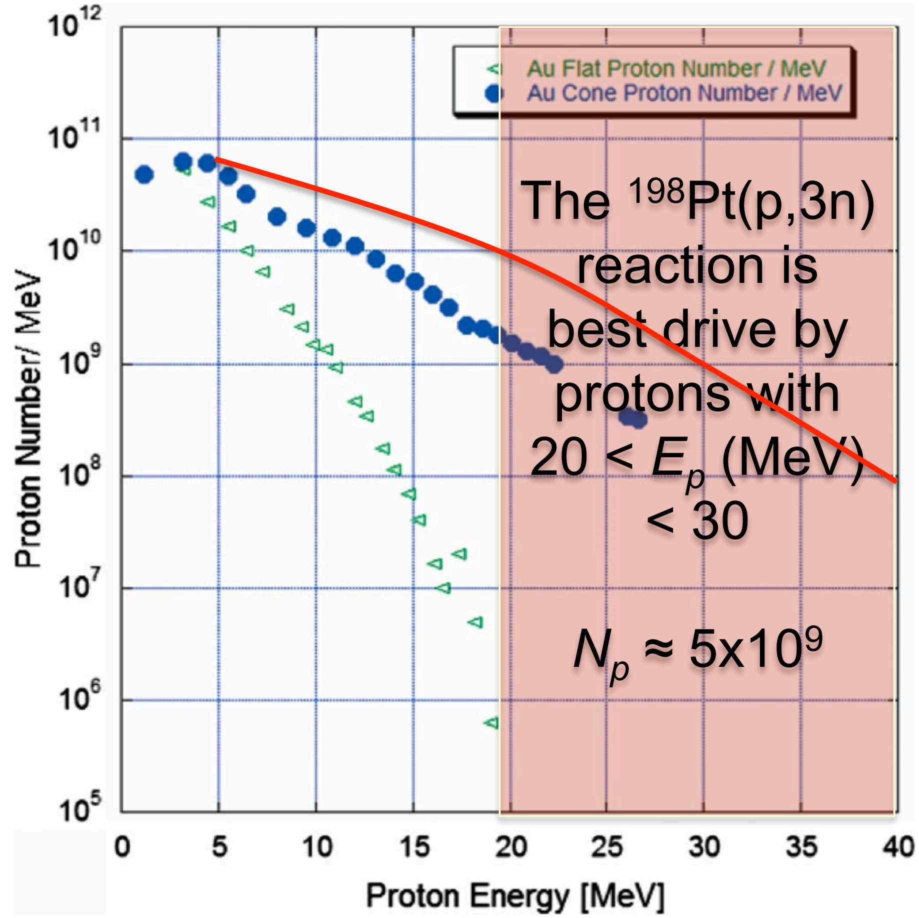
First experiment: Platinum in a plasma state when the protons hit

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*



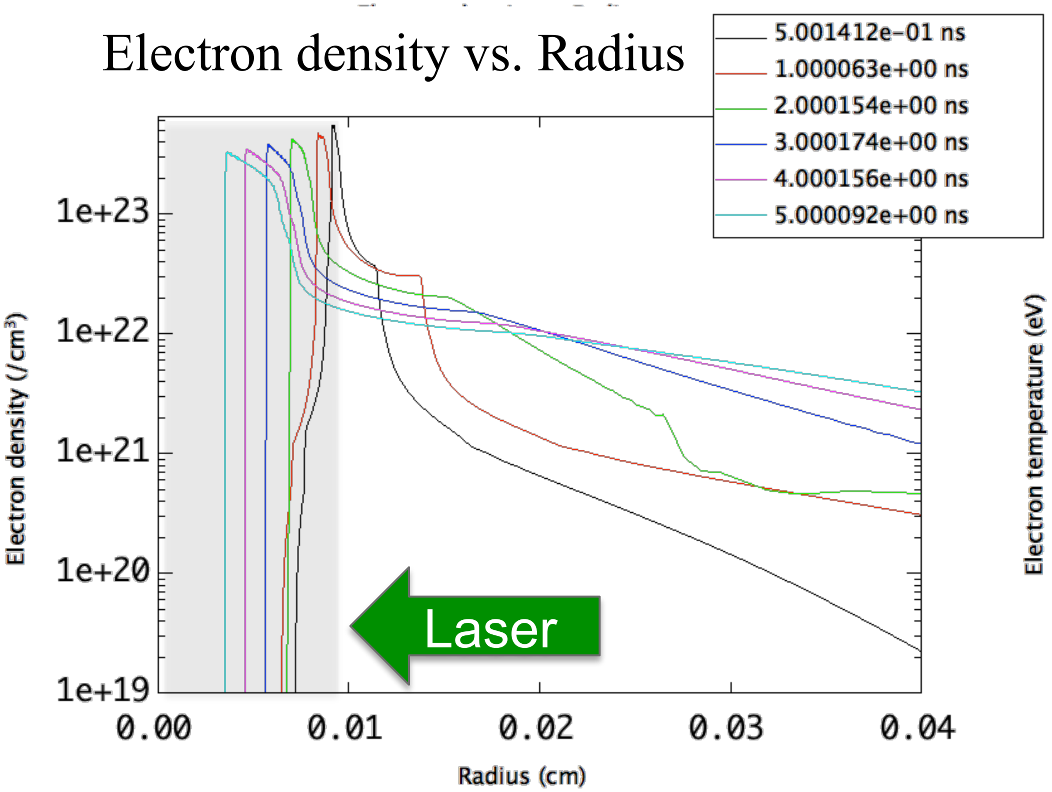


More recent results from *Roth* suggest an even harder proton flux From the related ***BOA*** mechanism (***B****reak* ***O****ut* ***A****fterbuner)*

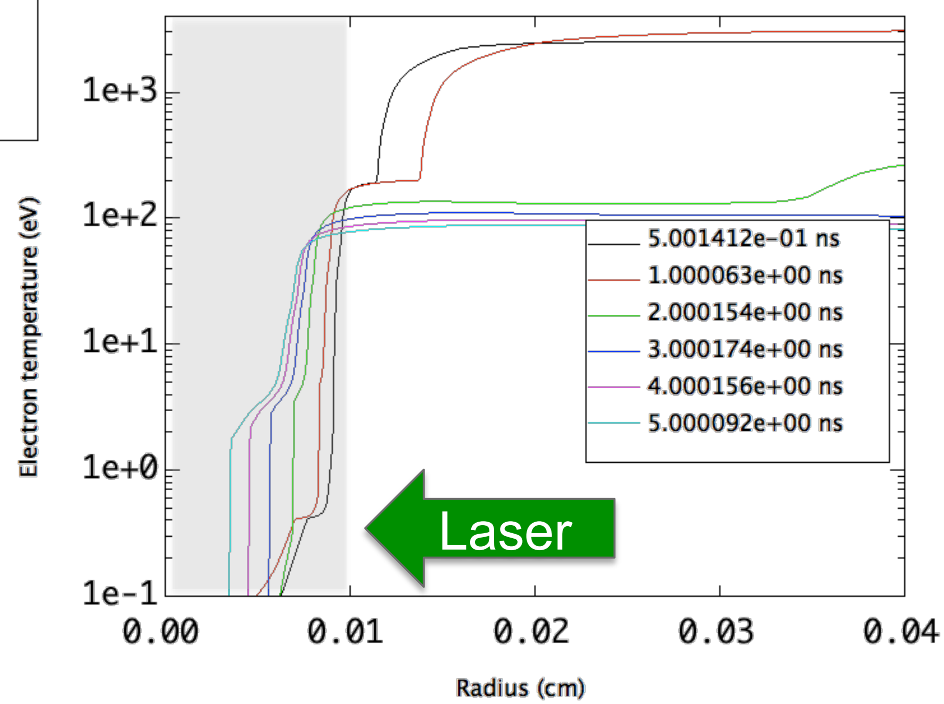
Long-pulse laser produces a variety of plasma conditions

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

Electron density vs. Radius



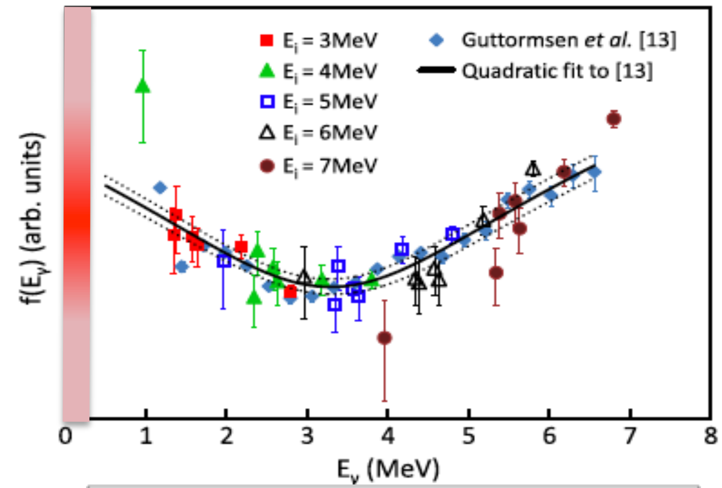
Electron temperature vs. Radius

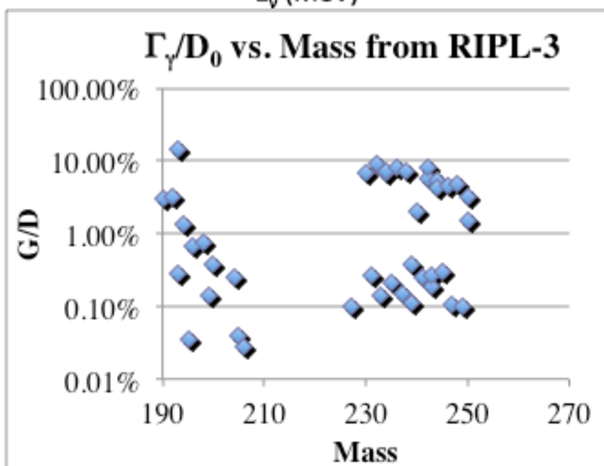


Plasma Properties	NIF	TNSA
Electron Fluence (cm^{-2})	$\approx 3 \times 10^{22}$	$\approx 10^{20-21}$
Temperatures (keV)	$T_e \approx 5\text{-}50, T_g = 0.3$	$T_e \approx 0.2\text{-}3, T_g = 0.2$

Summary

- Interactions between highly-excited nuclear states and HEDPS can profoundly effect nucleosynthesis
- We have hints of this happening right now at NIF
- Outstanding questions:
  - What are the appropriate atomic rates?





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


NIF