Low-energy neutrons and the prospects for neutron capture nucleosynthesis measurements using NIF

Presentation to the

NIF Users Group Meeting

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LLNL

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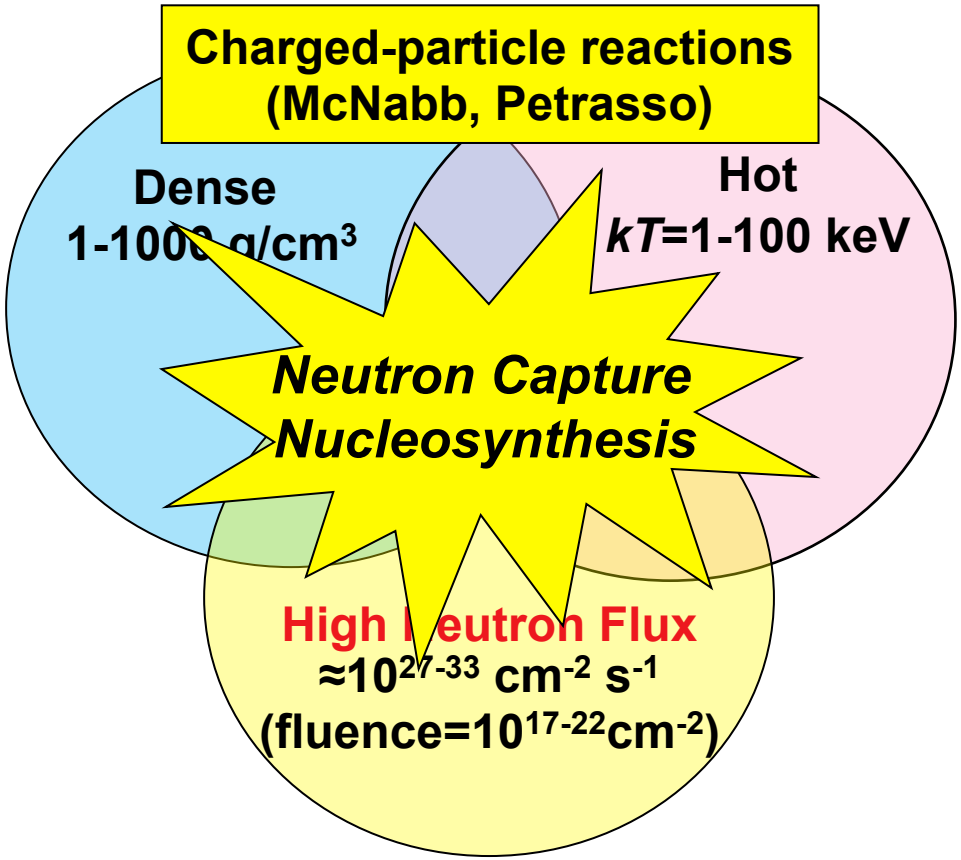
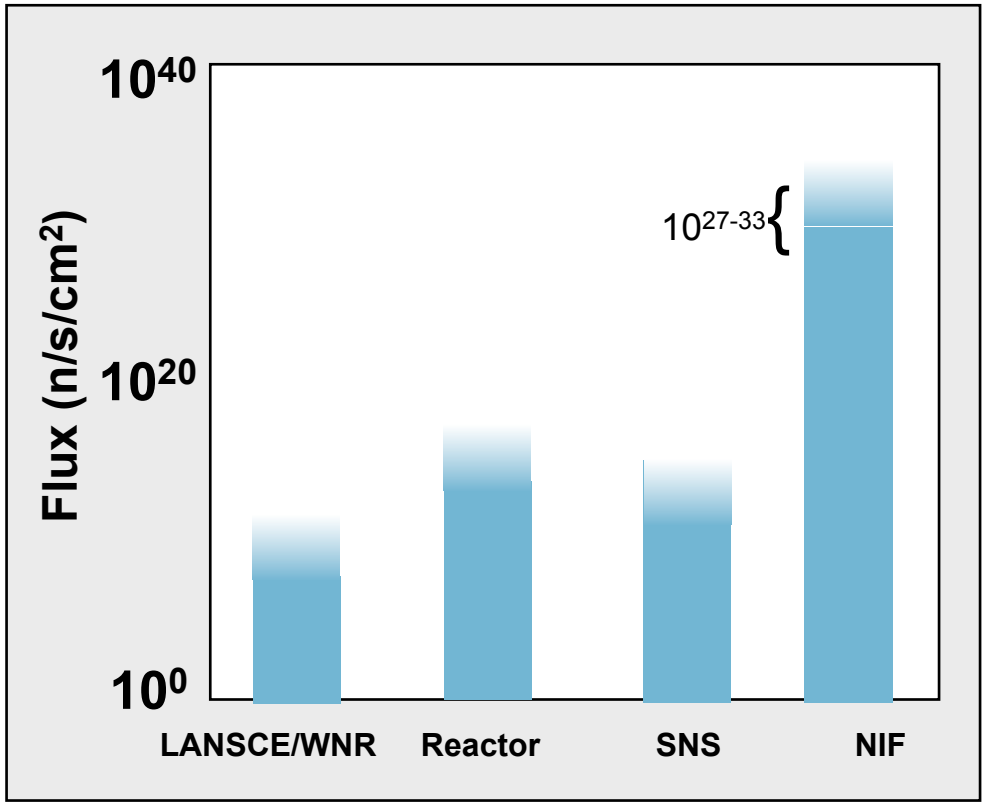
NIF allows studies of nuclear physics *in a plasma environment*





We have results from *two different diagnostics* showing that neutron capture experiments can be done at NIF right now

Nuclear Physics @ NIF Philosophy

"Only do things at NIF that can't be done anywhere else"

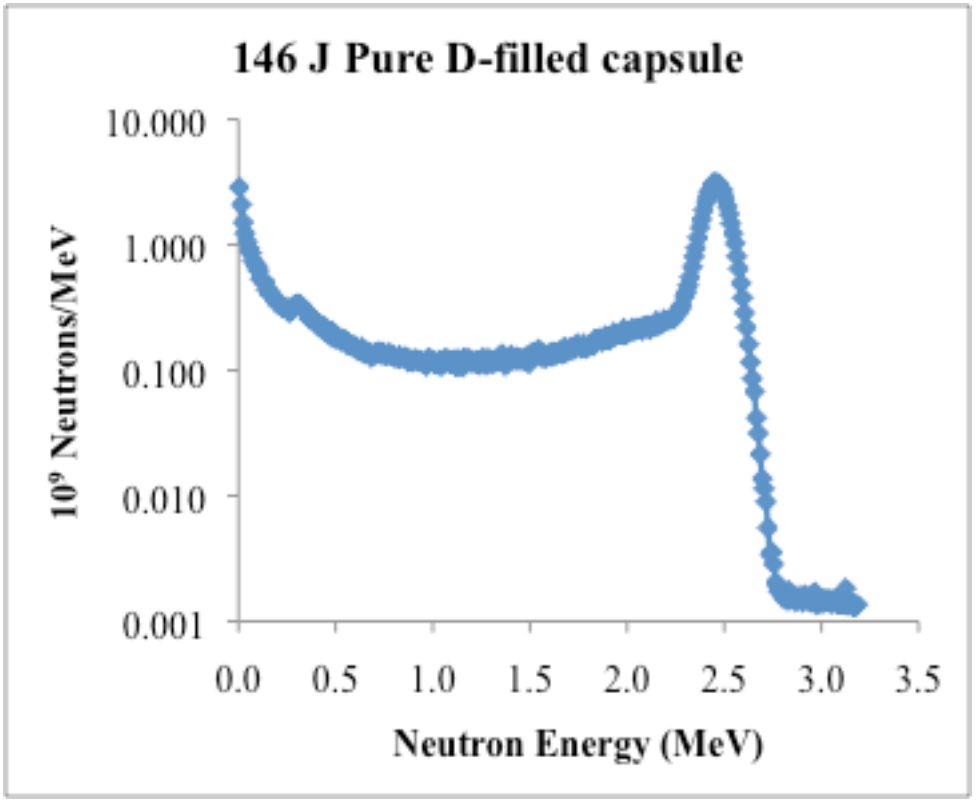
"Experiments that complement NIC and WCI program goals are more likely to get shot time and diagnostic support sooner"

Neutron Capture Nucleosynthesis

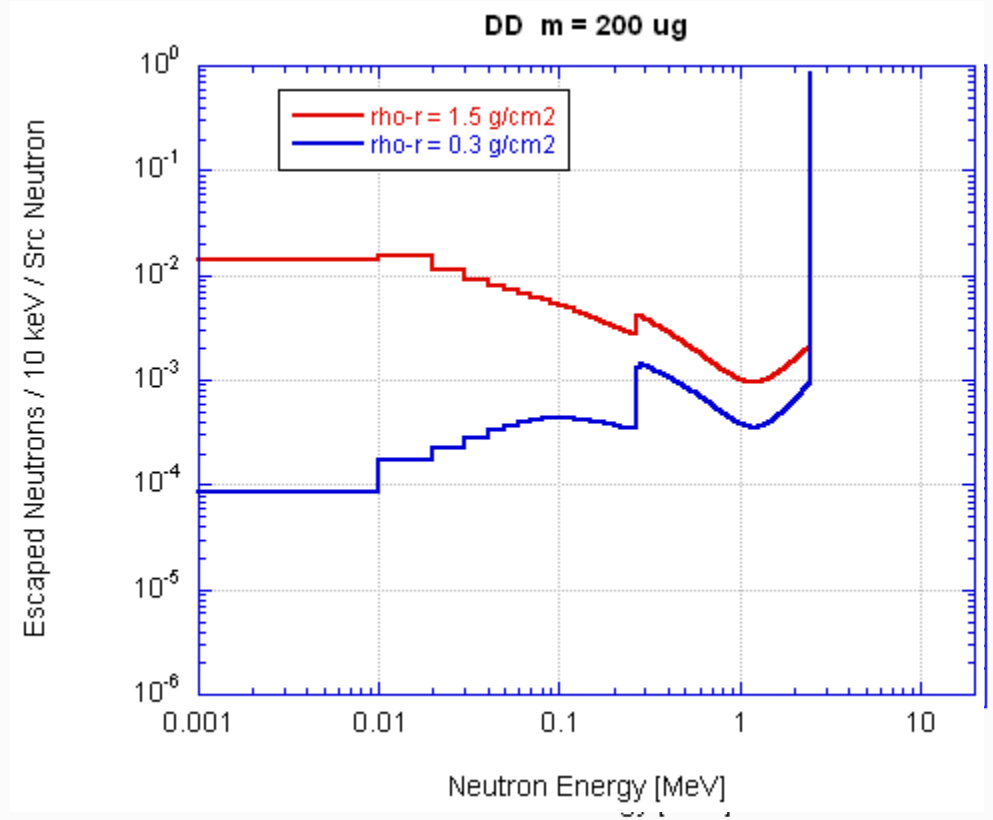
(…asking to be ride-along means you probably won't be turned down…)

Step #1: Are stellar-like (< 1 MeV) neutrons present at NIF? Predictions are that shots with ρR_{fuel} > 1 g/cm^2 make many

HYDRA (Cerjan/Sepke)



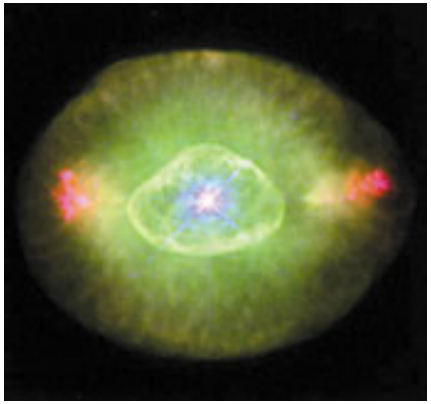
MCNP (Hagmann)

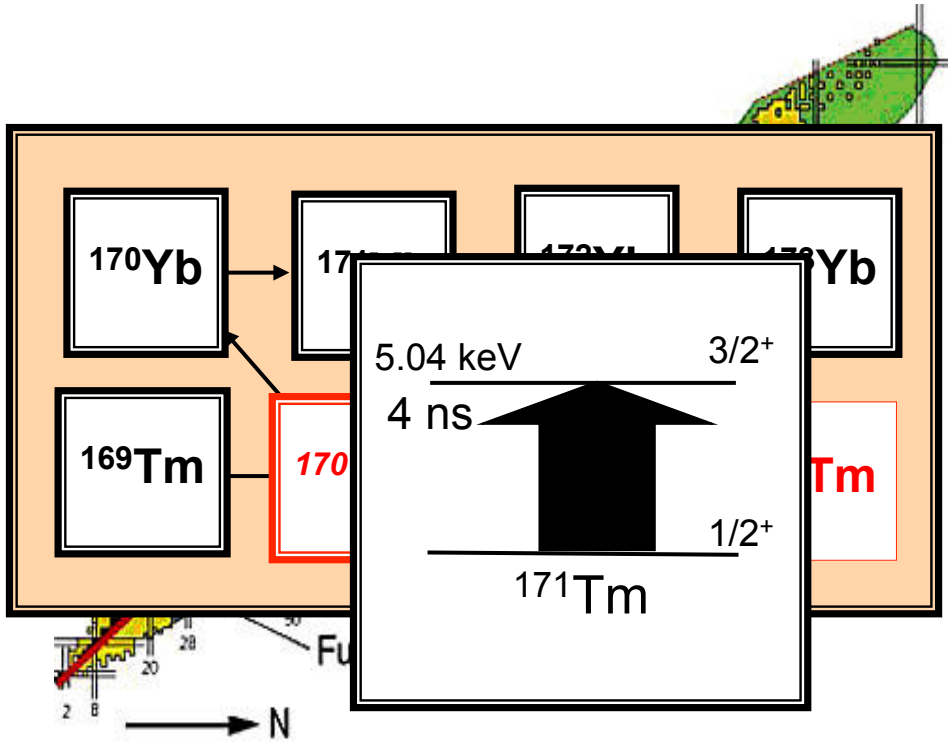


But these are only predictions…

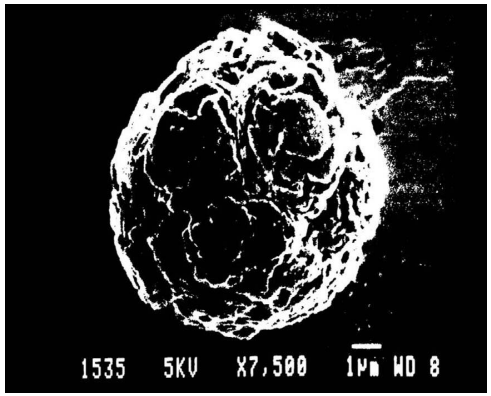
This huge *predicted* neutron fluence (10^{18} cm^{-2}) suggests neutron capture nucleosynthesis could be studied at NIF

AGB stars ➔ disperse elements





Pre-solar grains

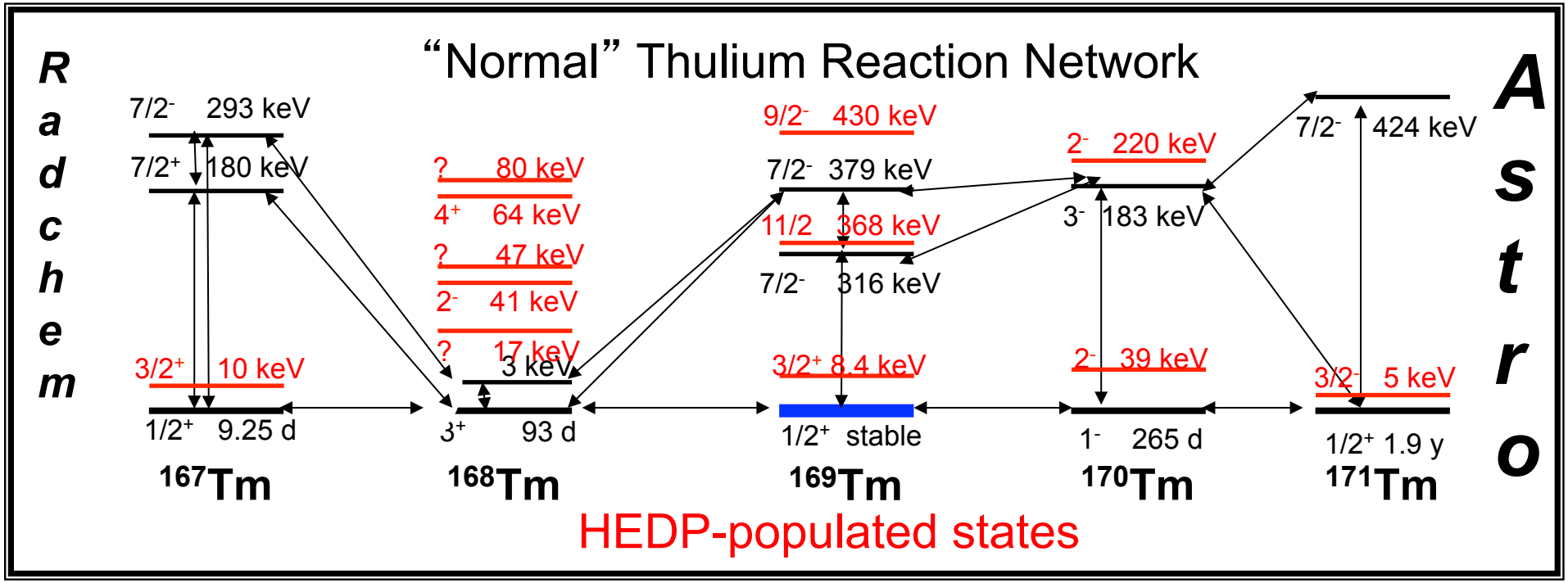


(n,γ) cross sections on branch-point nuclei in a thermal distribution of excited states cannot be measured with even the most intense neutron beams

NIF crams 2800 years* of neutron capture into every shot

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

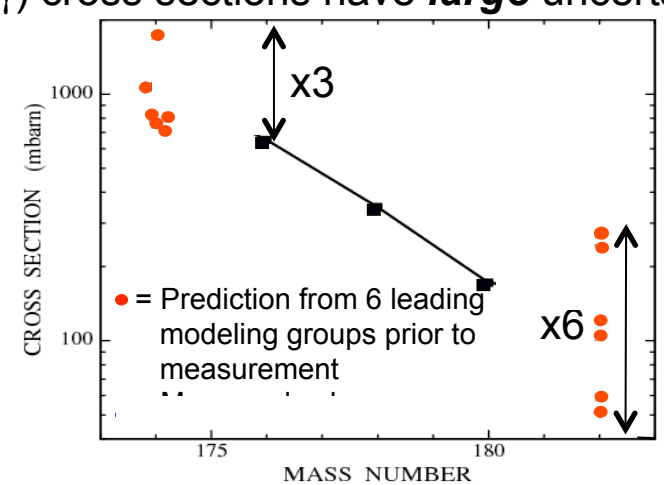
The Thulium reaction network is important for both Astrophysics *and* Stockpile Radchem



- These states have been left out of network calculations
  - Their population depends plasma conditions (T and ρ)

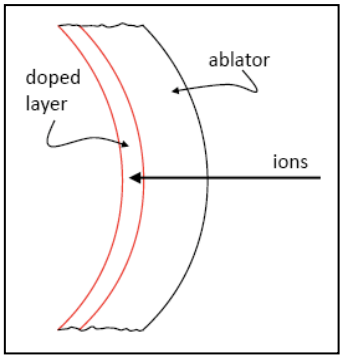
Thulium was the most fielded radchem tracers in UGTs

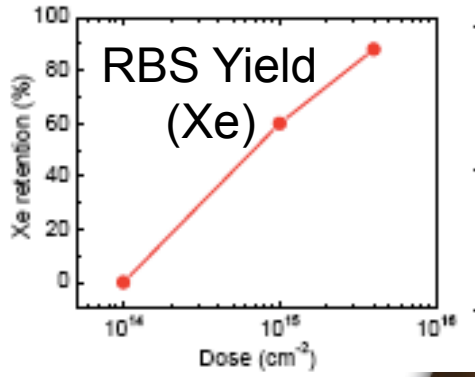
F. Kappeler *et al.*, has shown that modeled (n,γ) cross sections have ***large*** uncertainties

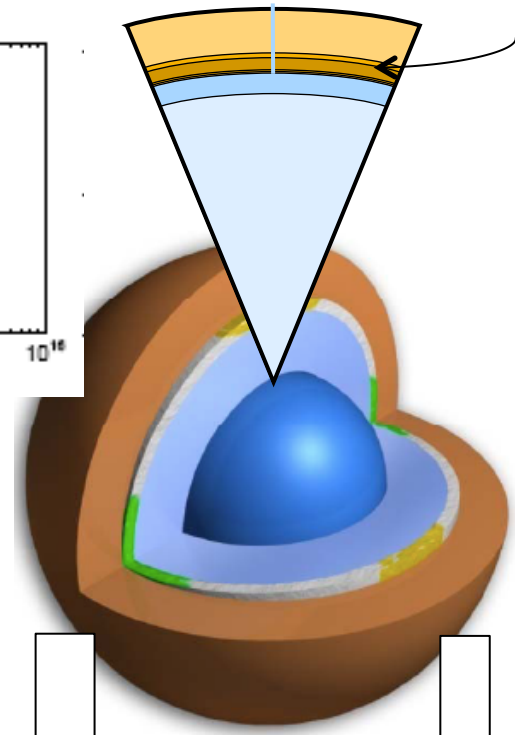


We have two ways to simultaneously measure sub-MeV (n,γ) on samples loaded into a NIF capsule

≤10^{17} atoms can be implanted in a NIF capsule (Kucheyev, Hamza)



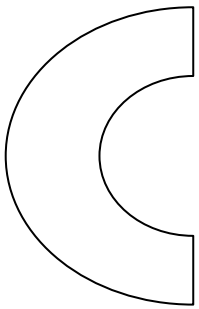


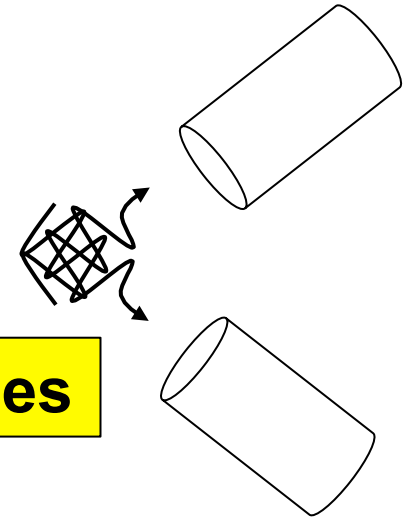


$7x10^{16}$ Ge atoms in layers 2 & 3

Collect "debris" & count
Gostic, Shaughnessy, Moody, Greife

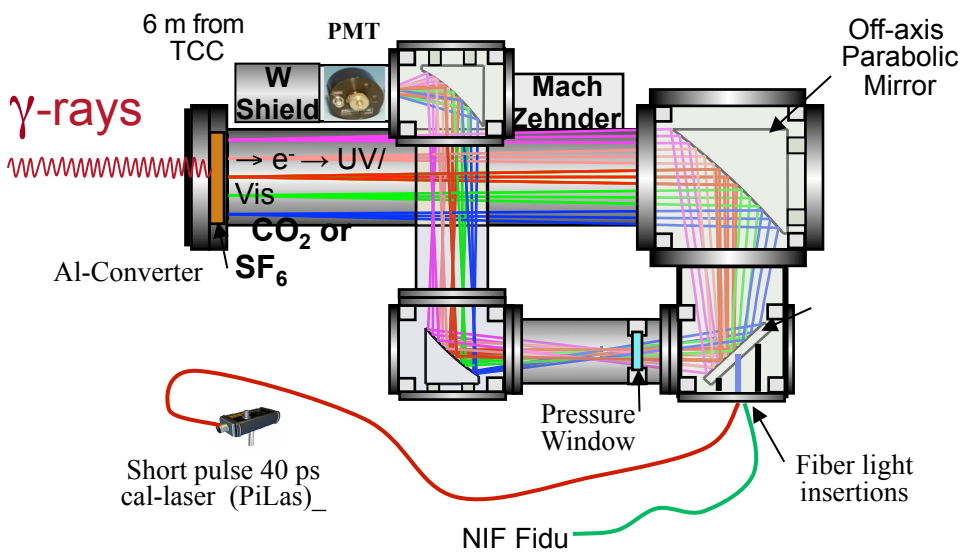
Measure prompt γ-rays following capture
(Stoeffl, Herrmann)



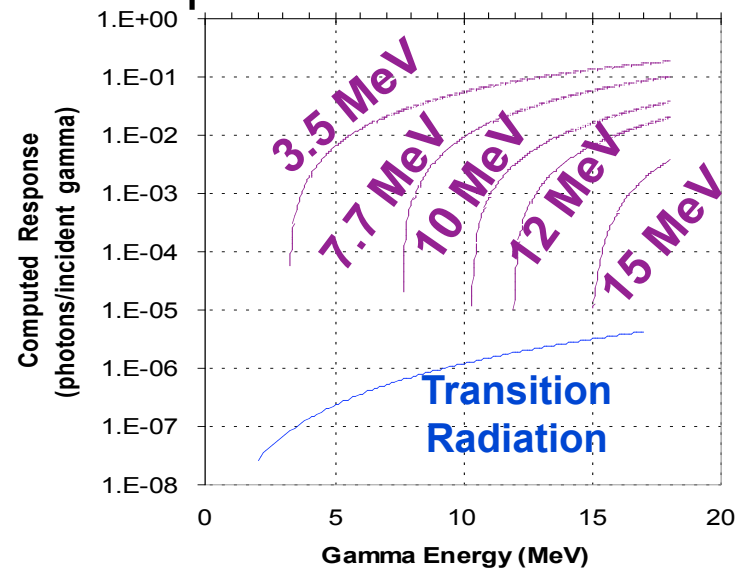


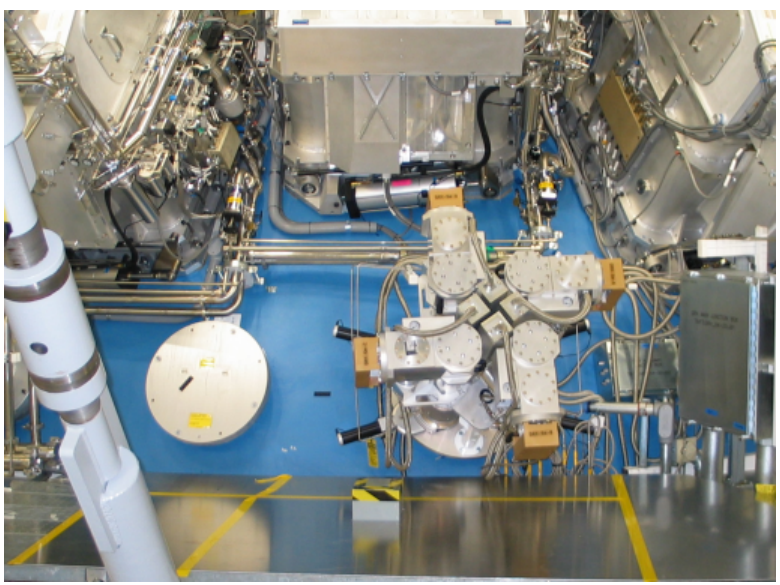
I will show data from both approaches

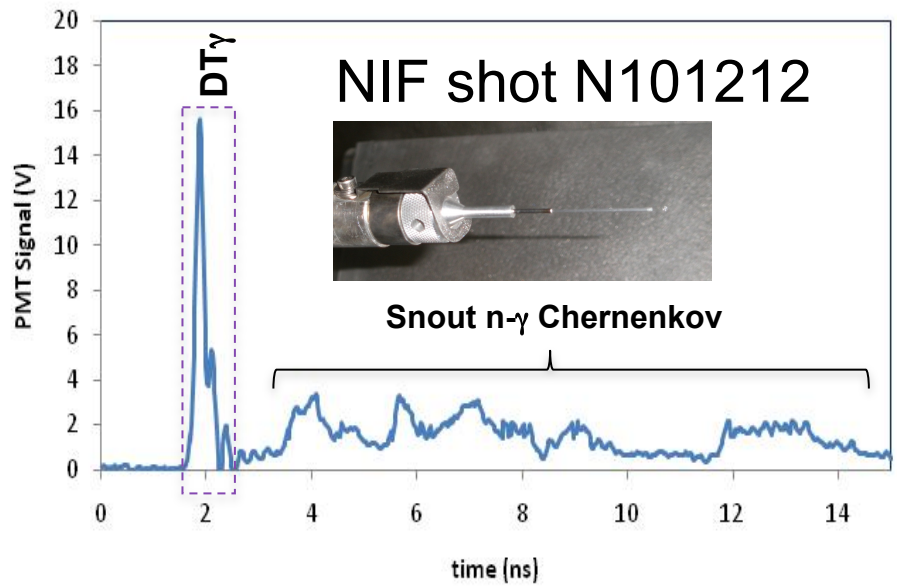
Diagnostic #1: γ-rays from (n,xγ) are measured using a Gas Cherenkov-based system: GRH (Gamma Reaction History)



Gas pressure determines E_{th}

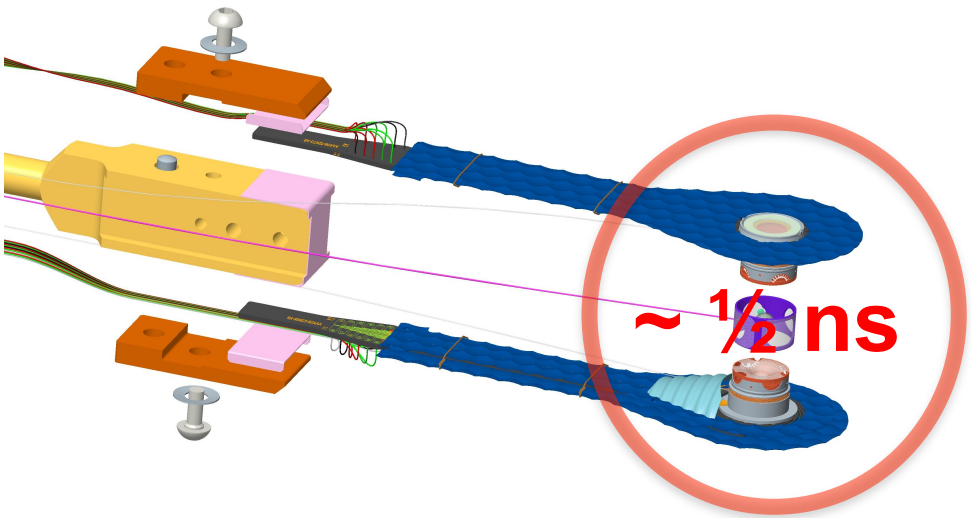


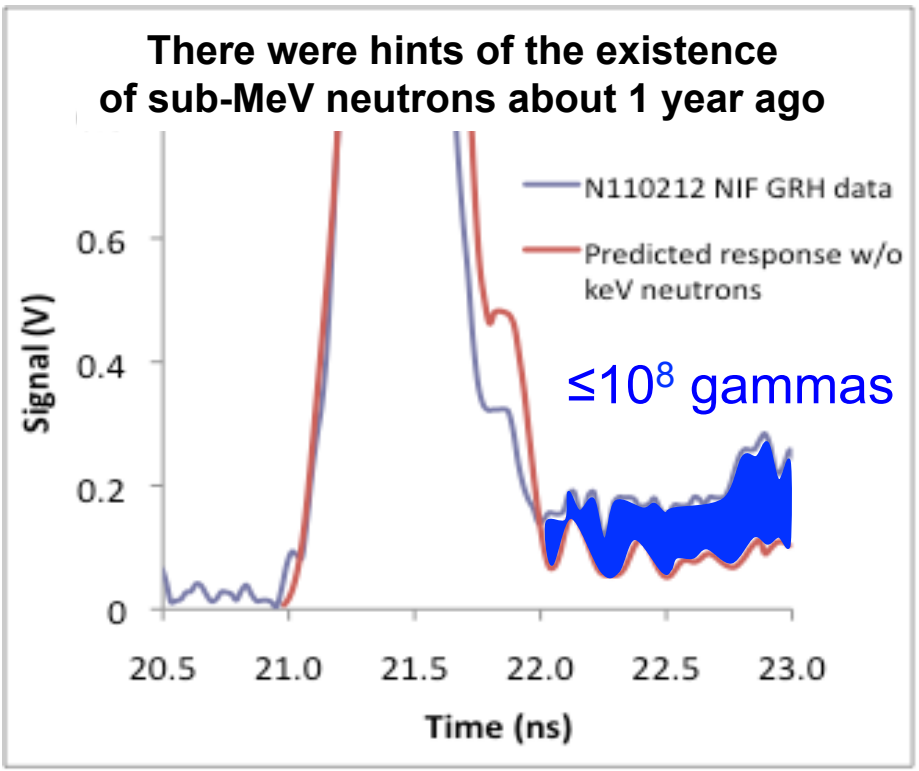




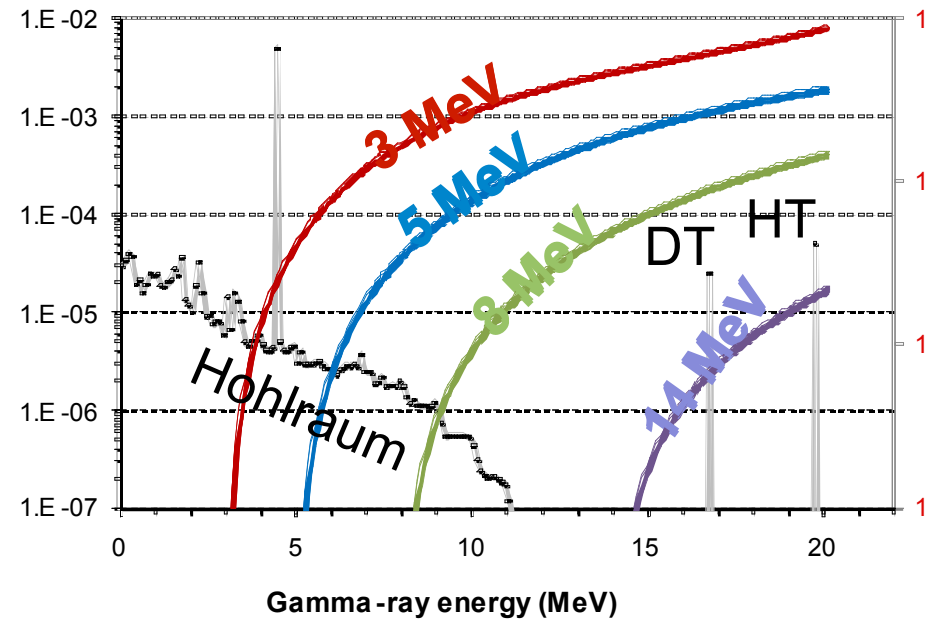
(H. Herrmann & W. Stoeffl)

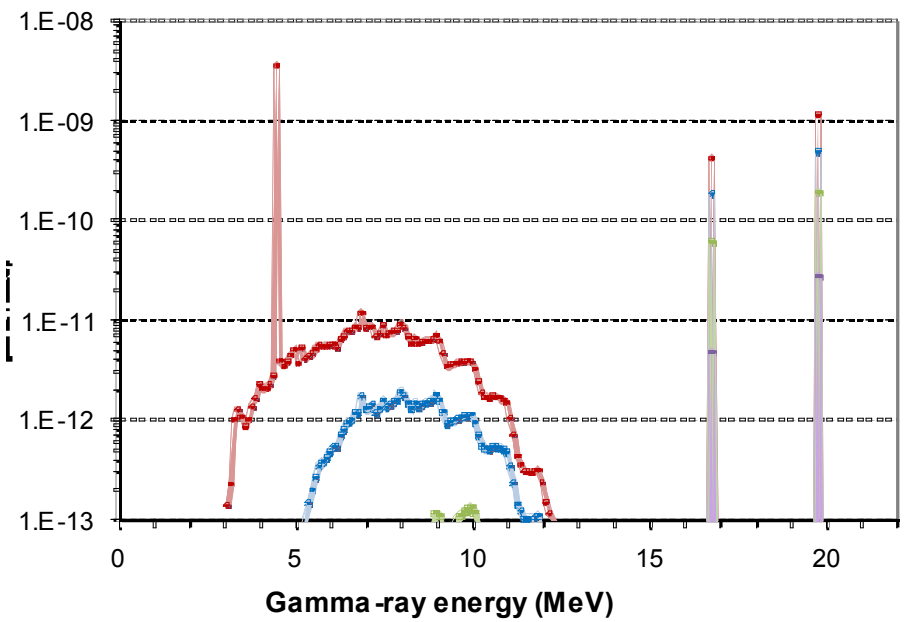
Interpreting GRH data requires good knowledge of the (n_{14},xγ) cross sections on materials near TCC (Al, Si, Au etc.)





T/H/D: 74/24/2, $t_0 \pm ¼$





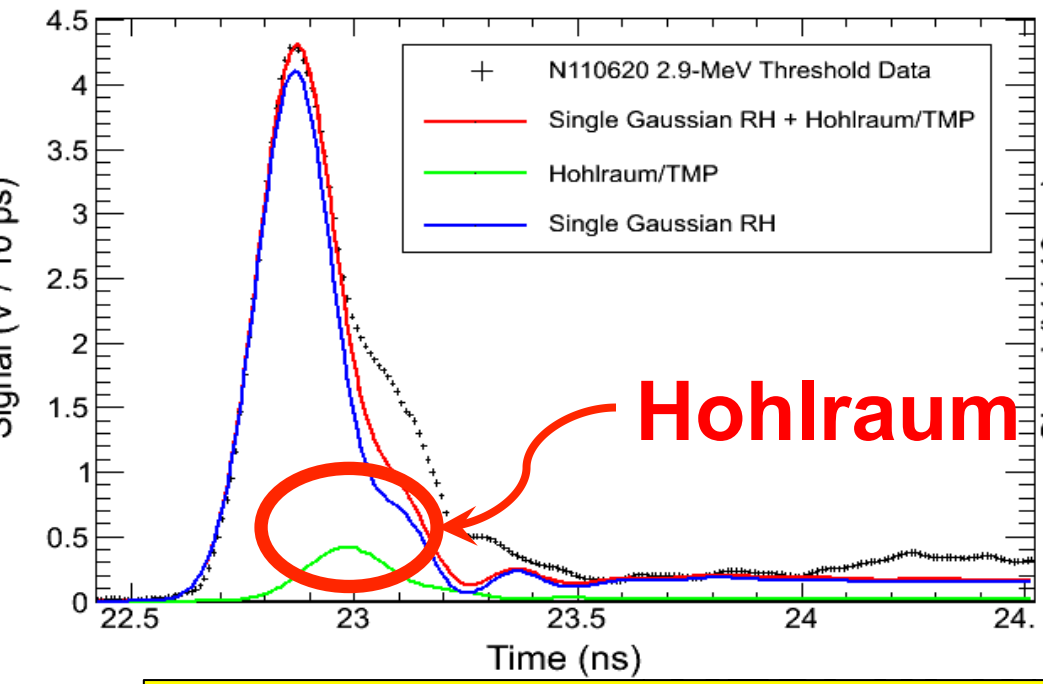
Our plan (Dan Sayre) is to perform a ***multi-shot*** analysis of NIF GRH data

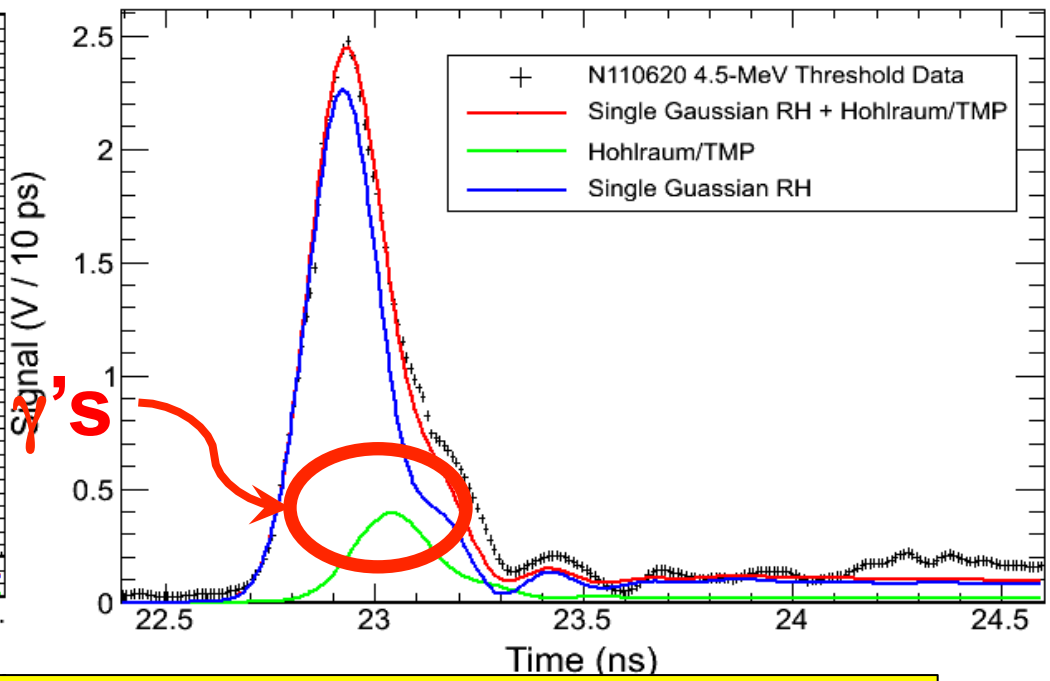
Input

4 $I_\gamma(t)$ for lowest 2 lowest GRH channels (2.9 and 4.5 MeV) for 5 shots (≈40 observables)

Model

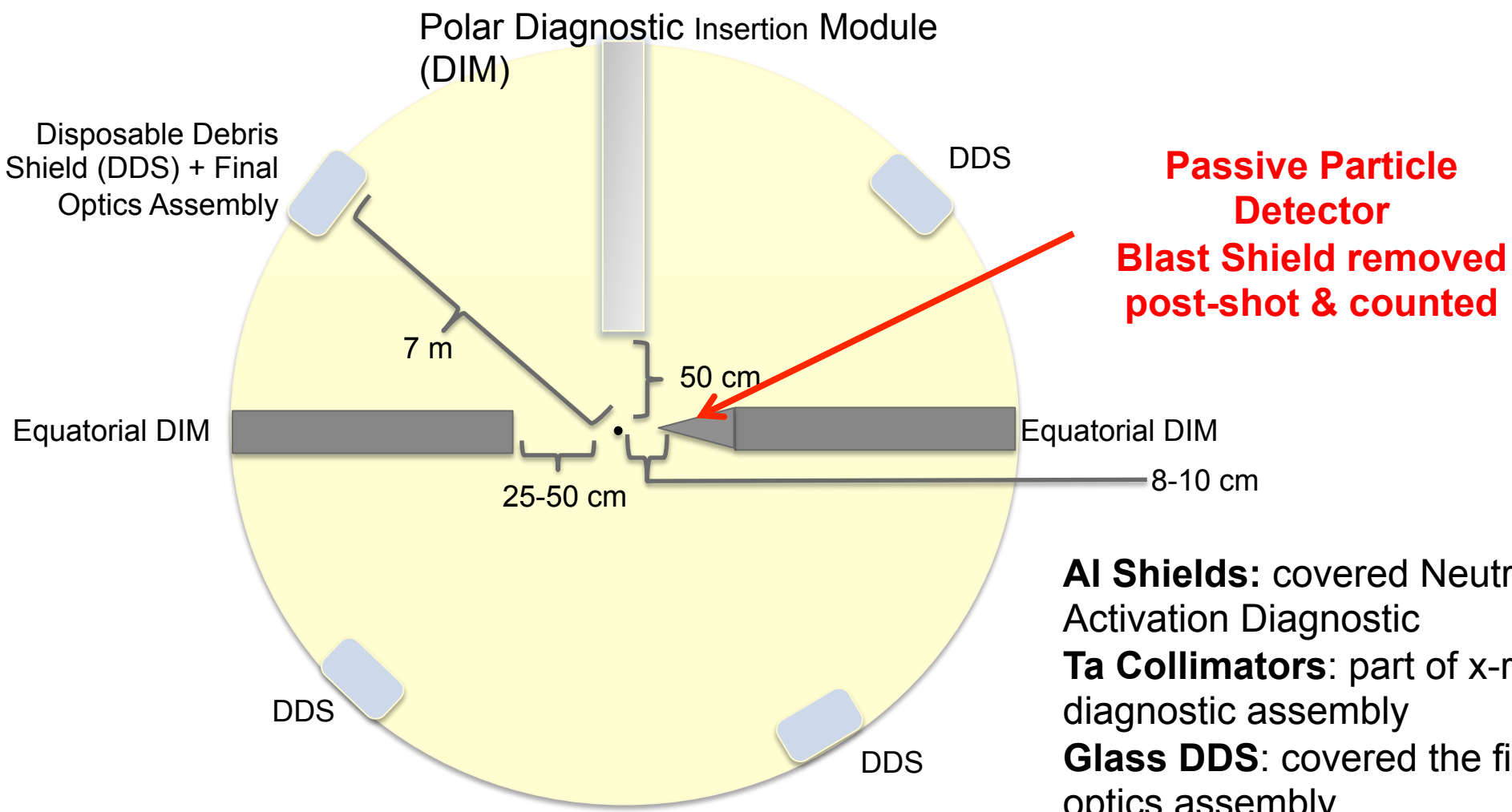
4th order poly. IRF for 2.9/4.5 chan.: 8
Gamma source terms for 2.9/4.5: 2
$\rho R_{ablator}$ for 2.9 MeV channel: 5
1 gaussian RH (X_0, W, H):15
(30 variables)





All we need is a mass model (MCNP) for the 575 hohlraum

Diagnostic #2: Solid radchem (SRC)
Dawn Shaughnessy, Julie Gostic, Ken Moody

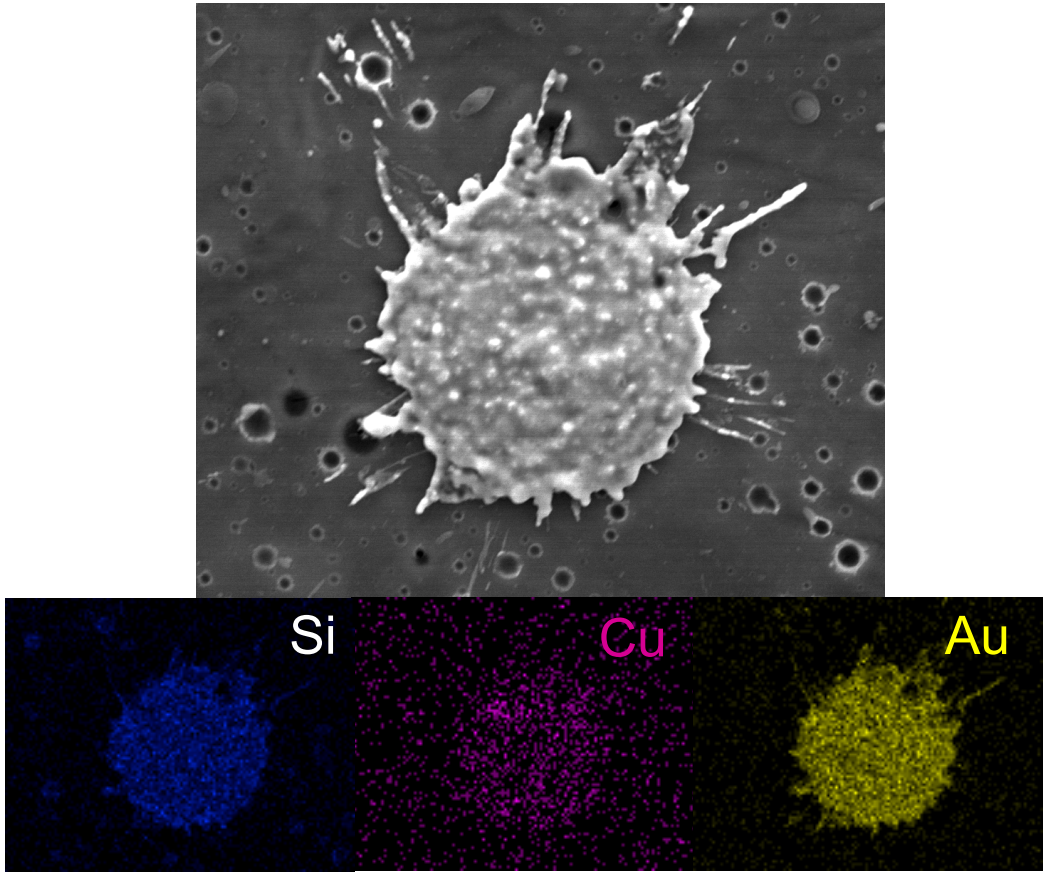


Al Shields: covered Neutron Activation Diagnostic
Ta Collimators: part of x-ray diagnostic assembly
Glass DDS: covered the final optics assembly

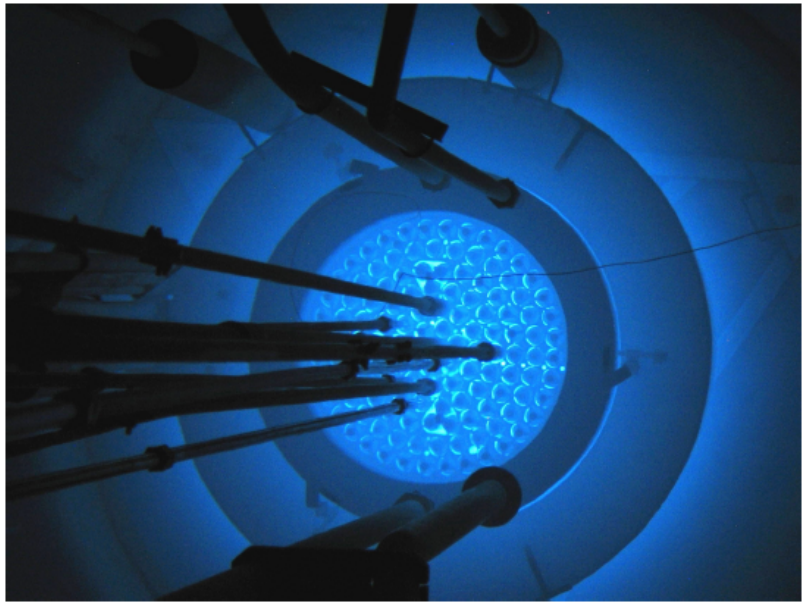
Chamber diameter: 10 meters (Drawing not to scale)

Gold debris, mainly from the Hohlraum/TMP was identified via SEM/EDS & neutron activation

Secondary Electron Microscopy
& Energy Dispersive Spectroscopy



USGS Federal Center
TRIGA Reactor

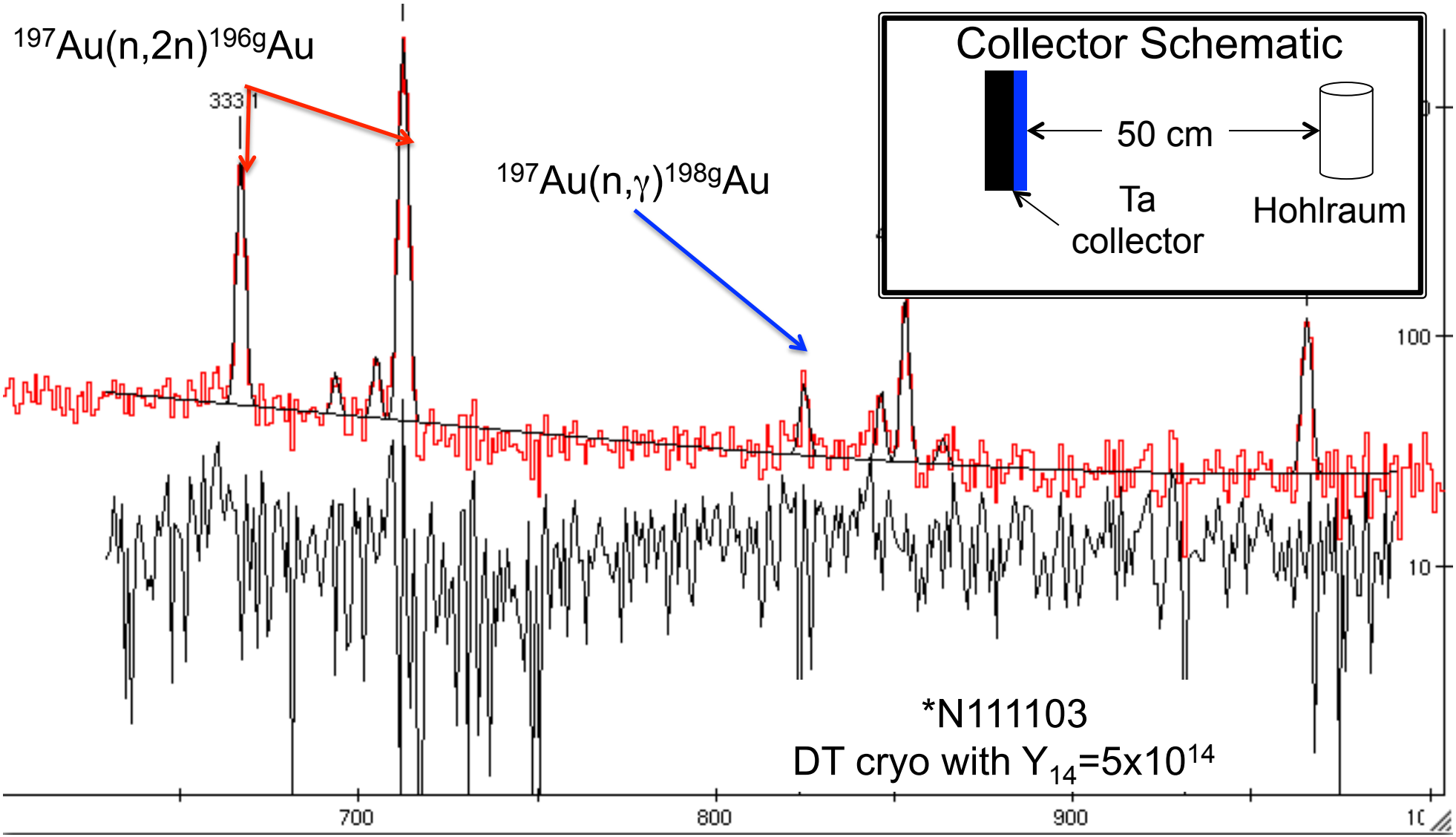


Laser Energy (kJ)	Observed Au μg/cm^2 (50 cm from TCC) (Expected=4)	Laser Energy (kJ)	Observed Au μg/cm^2 (25 cm from TCC) (Expected=15)
516	20.14	46*	0.03*
568	12.95	689	35.6
574	21.15	729	26.71
668	15.97	831	31.52
837	24.08	836	25.94
567	0.05**		

≈120(25)% of Solid Angle collection efficiency obtained

Thanks to Julie Gostic, Dawn Shaughnessy and Ken Moody!

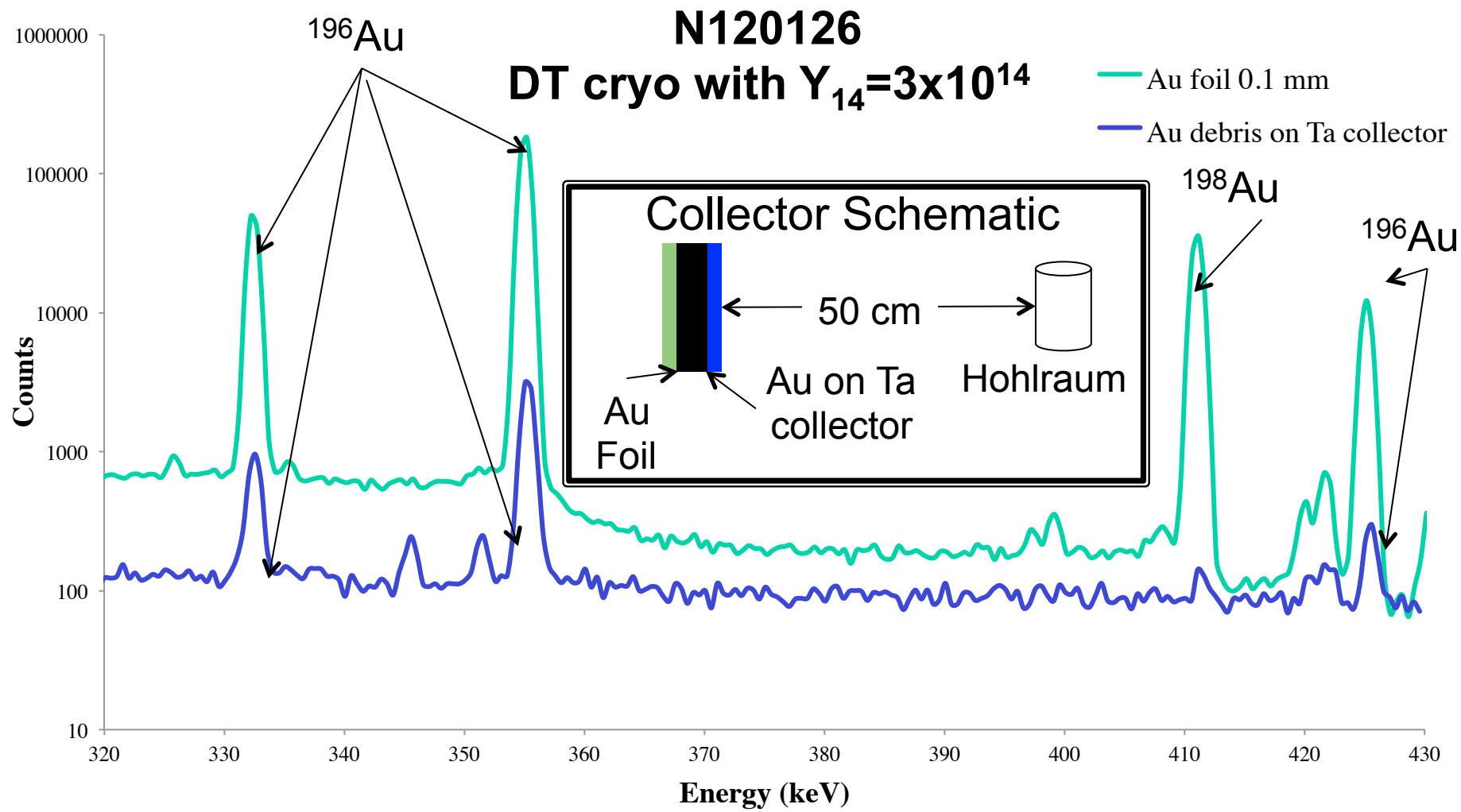
^{196,198}Au from the hohlraum has been observed on Ta plates 50 cm from TCC at NIF*



Ratio **of Au, Ta (n,γ) to (n,2n) activity determined to ≈±20%**

Thanks to Julie Gostic, Dawn Shaughnessy and Ken Moody!

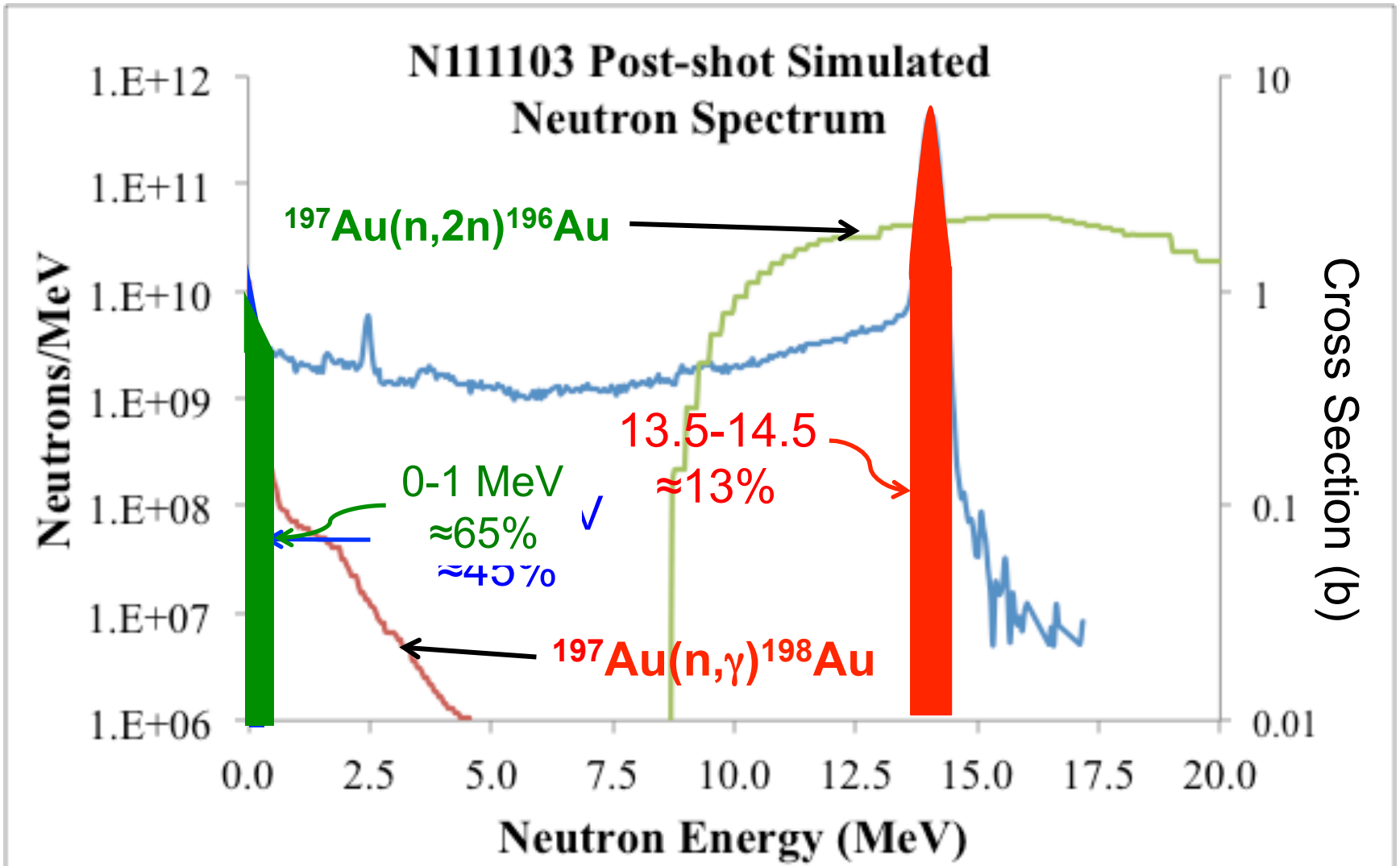
A Gold foil was then behind the Ta collector @ 50 cm to see the (n,γ) activation from scattered neutrons



The foil shows that low-energy from neutrons scattered off of material in the target chamber do not contribute to (n,γ) from the hohlraum

Thanks to Julie Gostic, Dawn Shaughnessy and Ken Moody!

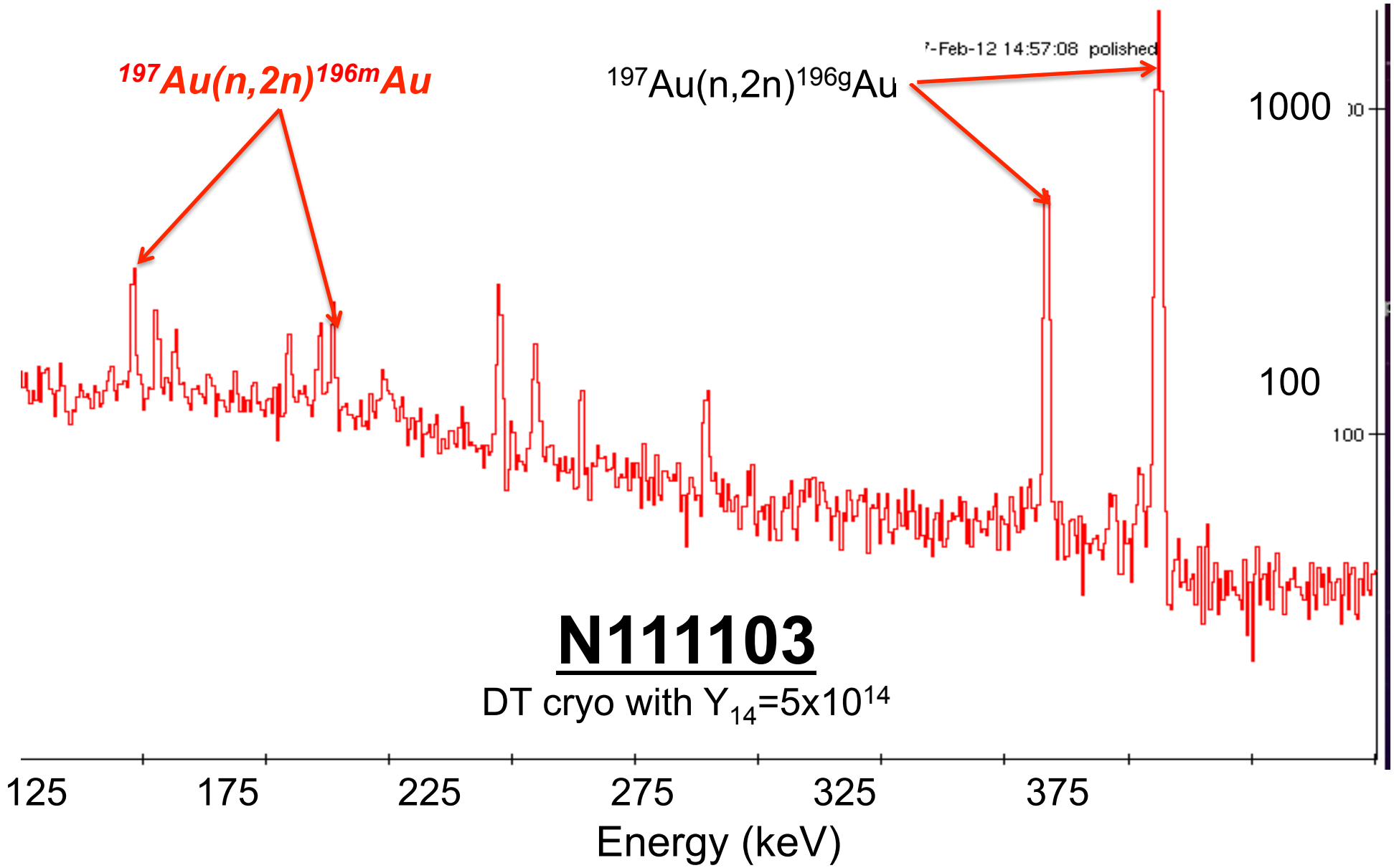
The N111103 post-shot simulated neutron spectrum* is consistent with measured Gold ratio



Predicted ratio of Gold (n,γ) to (n,2n): 4.46×10^{-3}
Observed ratio: $4.28 \pm 1.1 \times 10^{-3}$

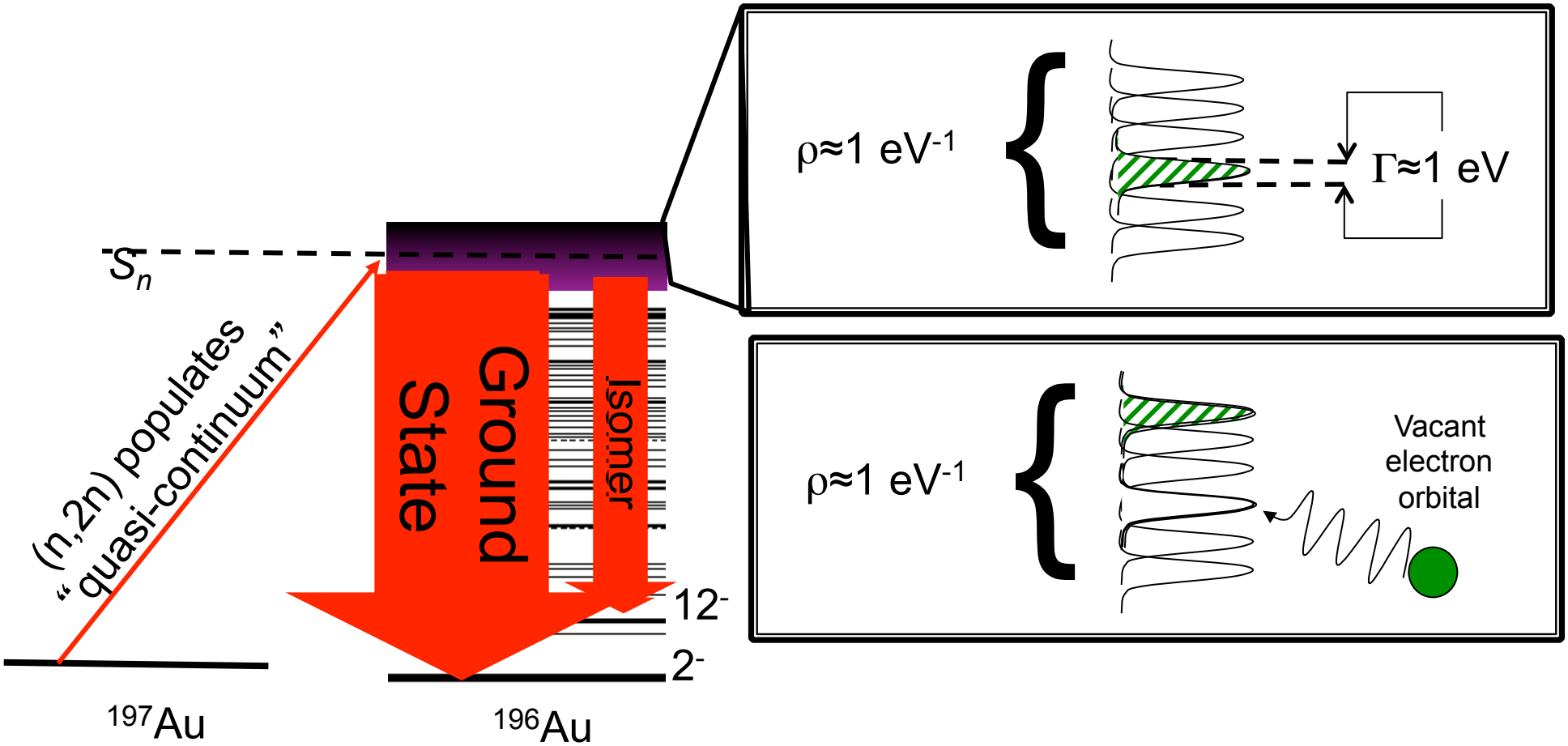
*Thanks to C. Cerjan & O. Jones

We not only saw γ-rays from the decay of the ^{196}Au ground state but also from a 9.7 hour isomer ($J^{\pi}=12^{-}$)



Isomer-to-ground state ratio previously measured as being 8(2)%

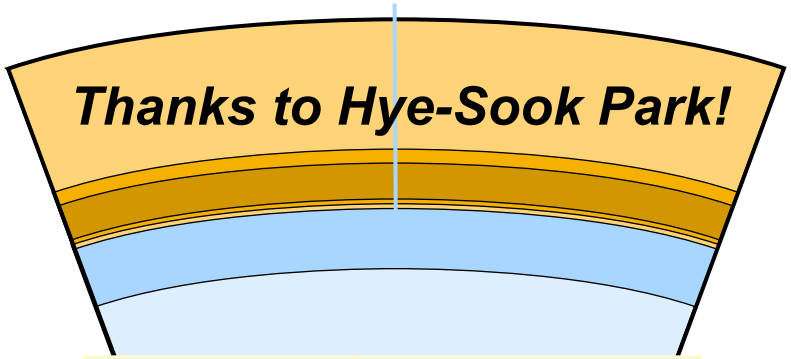
Nuclear-plasma interactions on $E<6$ MeV states could change the isomer-to-ground ratio in ^{196}Au



This experiment requires a "thinned Gold" hohlraum (2-3 μm)

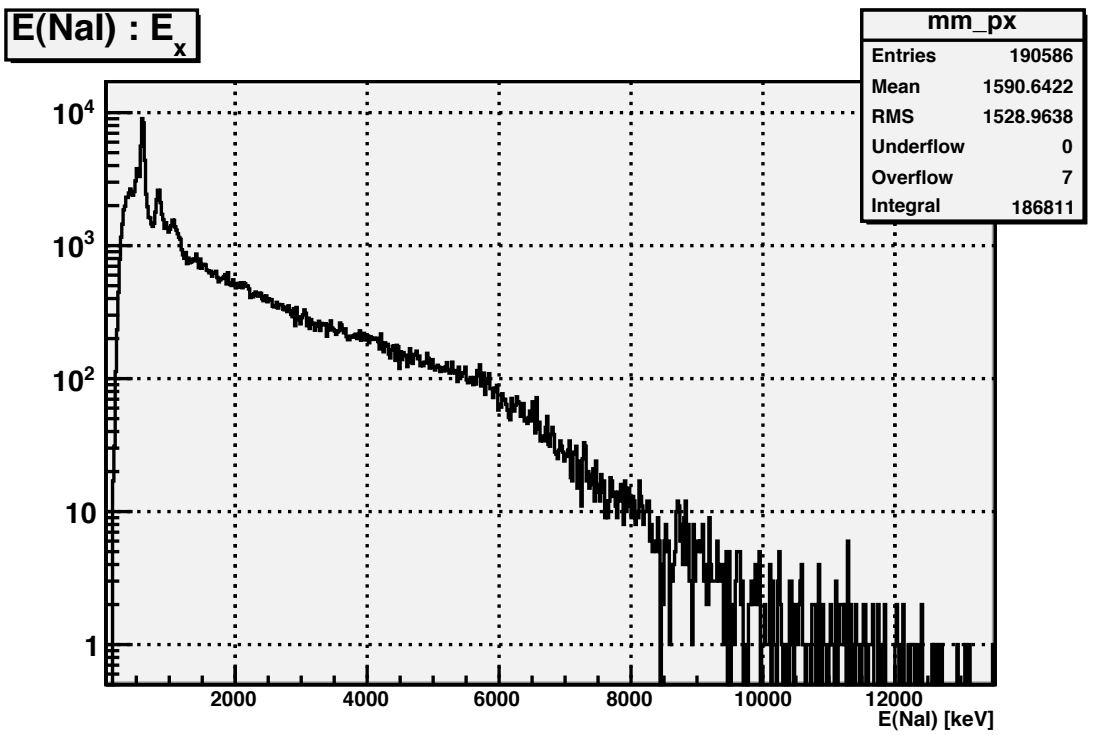
Here there be dragons…

Tri-doped capsules (Si, Ge and Cu) (16 February+) offer the first opportunity to observe γ-rays/debris from *in situ* capsule dopants



Layer	Dopants (at%)
1 (inside)	No Si (<0.05) No Ge (<0.02) Cu 0.10 ± 0.02
2	Si 0.7±0.2 Ge 0.15±0.02 No Cu (<0.02)
3	Si 1.7±0.2 Ge 0.15±0.02 No Cu (<0.02)
4	Si 1.0±0.2 No Ge (<0.02) No Cu (<0.02)
5 (outside)	No Si (<0.05) No Ge (<0.02) No Cu (<0.02)

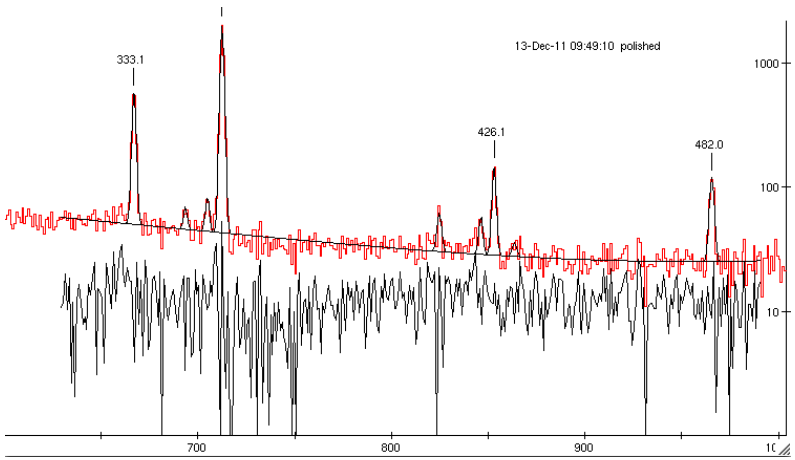
…and Oslo just measured the γ-ray spectrum for ***Ge***, Al and Si (last week)…

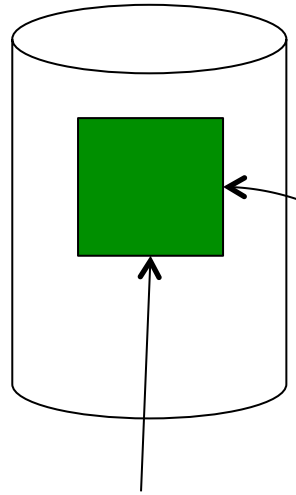


Thanks to Therese Renstrøm and everyone at the Univ. of Oslo

External "targets" can now be loaded on the Hohlraum for cross section measurements (NIC ride-along)

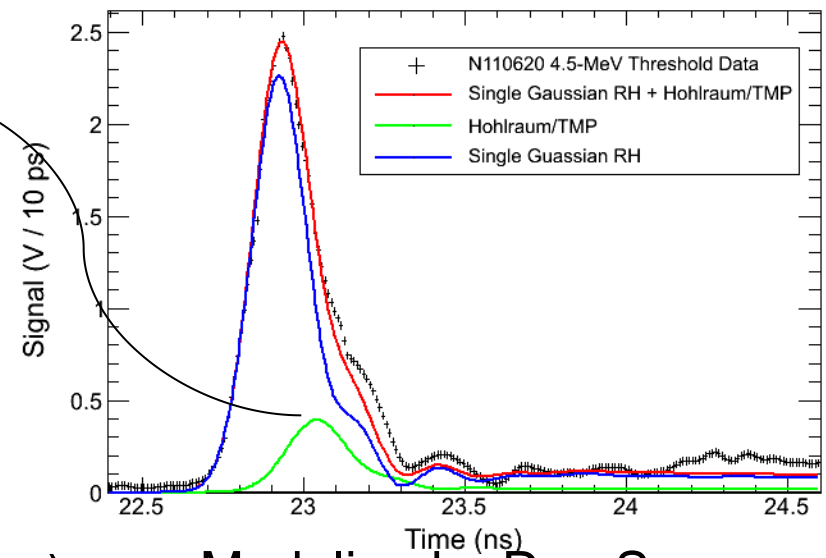
Decay γ-rays using RAGS





10-50% of 4π
200-1000 mg
(≈1.5-7.5 x current M_{Au})

Prompt γ-rays using GRH



Modeling by Dan Sayre

Quantity	NIF (<225 keV)	NIF (<1 MeV)	NIF (13-15 MeV)
# of neutrons in bin	6.96E+11	1.30E+12	8.88E+13
Collected atoms/shot/barn	2.48E+05	4.63E+05	3.16E+07
Observed gammas/shot/bar	6.20E+03	1.16E+04	7.91E+05
Ratio to DANCE (per day)	1.34	25.06	85623.59

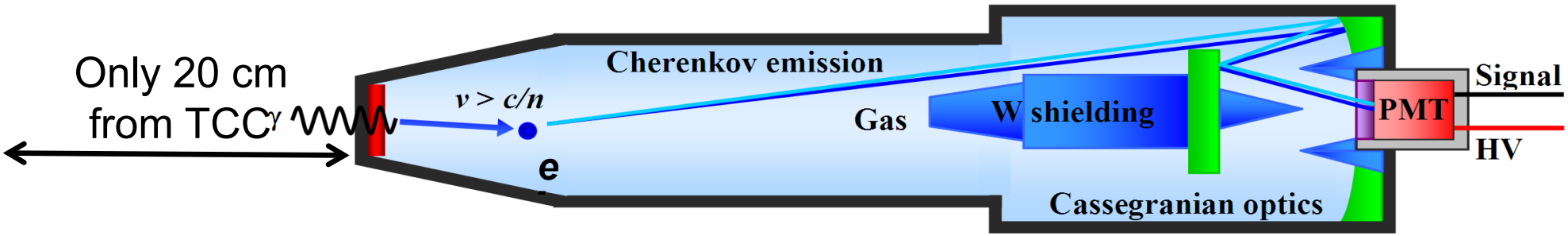
NIF is complementary to existing state-of-the-art (n,x) measurements facilities

Future Improvements

- Improve the existing/add new diagnostics
  - γ-rays: Super-GCD (increased solid angle)
  - Highly-segmented detector “Furlong”
  - Compton Spectrometer/Bent Crystal
  - Low-energy neutron spectrometer (LENS)
  - Increased/faster solid radchem (SRC)
    - Including capsule debris!
- “Ride-along” nuclear physics experiment
  - External hohlraum “targets”
  - Thinned-out Gold hohlraums (treasure hunt!)

Next Step for Diagnostics – Greater Efficiency

- **Solid Radchem**: Simple - More real estate near TCC
  - Chemical separation of debris prior to counting would help w/bkgrnd.
- **Prompt Gammas**: "Super GCD"

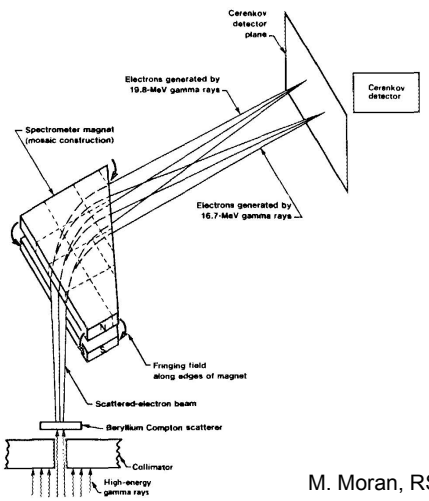


- ***Real*** γ-ray spectroscopy (Energy resolved)

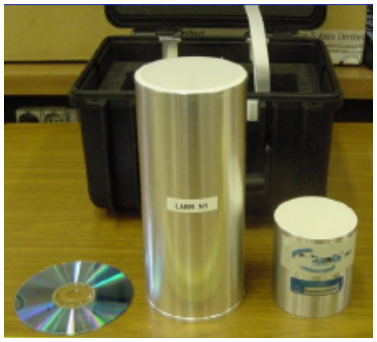
Compton Spect.

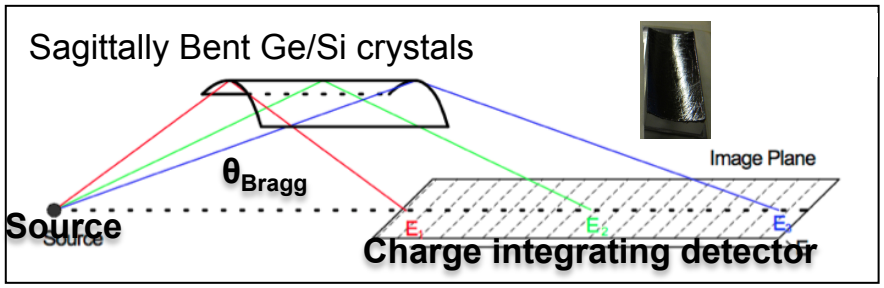
Pixilated Single-Hit at a "Furlong"

Bent Crystal (<1.5 MeV)



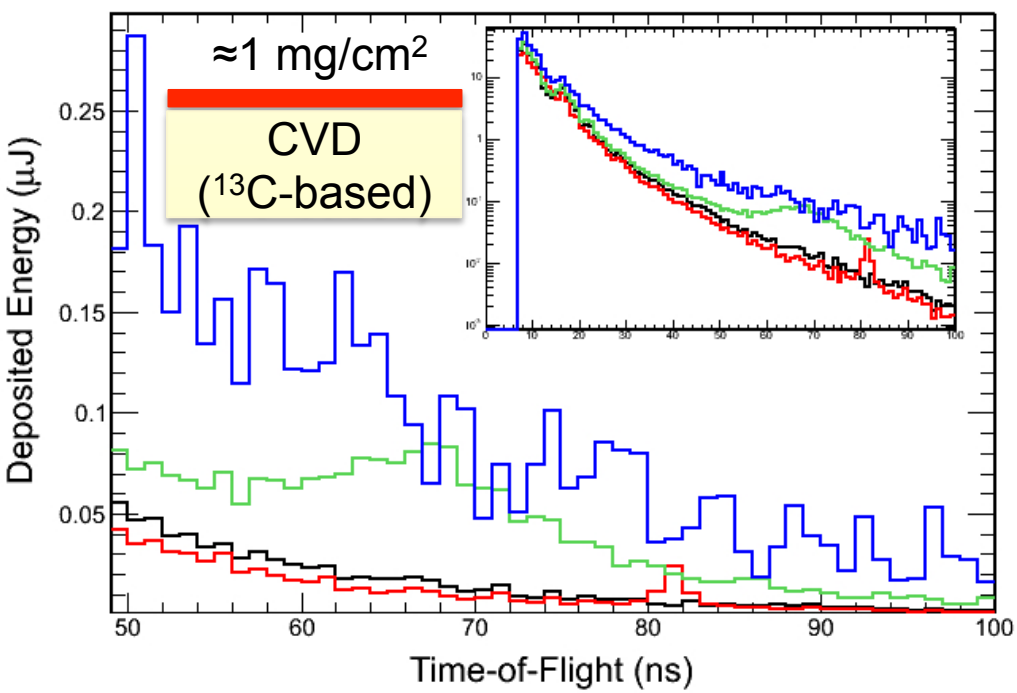
M. Moran, RSI 56, 1066 (1985)

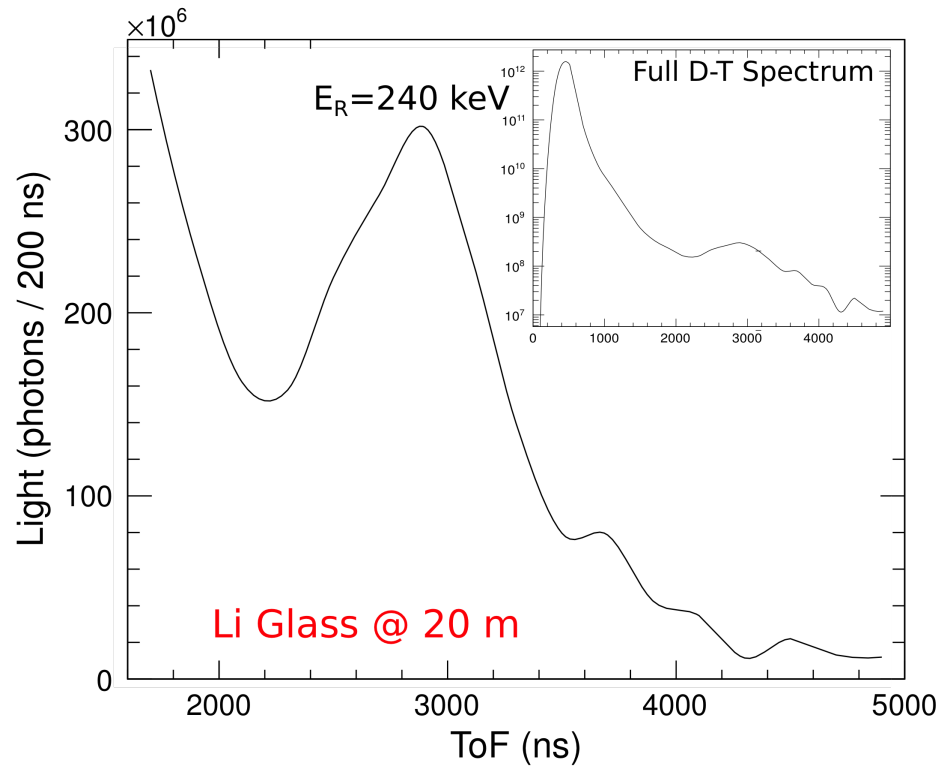




A spectrally resolved measurement of the low-energy neutron spectrum is now essential

- Approach #1: CVD diamond + a layer of ^{235}U or ^{6}Li (E_n=250 keV resonant break-up to T+α) to enhance low-energy response
- Approach #2: ^{6}Li scintillator in the 20 m alcove





GEANT Models by D. Sayre

Conclusions

- Simulations have predicted large numbers of sub-MeV neutrons at NIF from multiple scatter in the cold, dense fuel
- These neutrons allow studies of the (n,γ) reactions responsible for heavy element formation in stellar cores (s-process)
- Recent results from both GRH and Solid Radchem suggest the presence of a large NIF-thermal neutron component in DT and THD capsules.
- The role of nuclear-plasma interactions on neutron capture rates can now be explored using NIF (^{196m}Au/^{196g}Au)
- NIC ride-along nuclear physics experiments can now be considered
- Often these experiments provide valuable info for NIC
  - Example: ρR_{fuel} from the ^{198}Au/^{196}Au ratio

We are poised to perform unique neutron capture measurements on material on the hohlraum, *and possibly in the capsule itself*

This work has *many* different parts – Lots of room for collaboration!

Thanks for your attention


NIF