Neutron-Capture Constraints from the Oslo and Surrogate Methods via Triton Induced Reactions

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Lawrence Livermore National Laboratory

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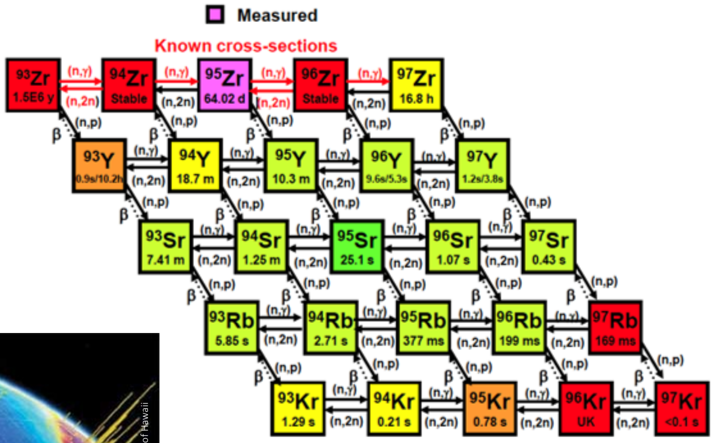
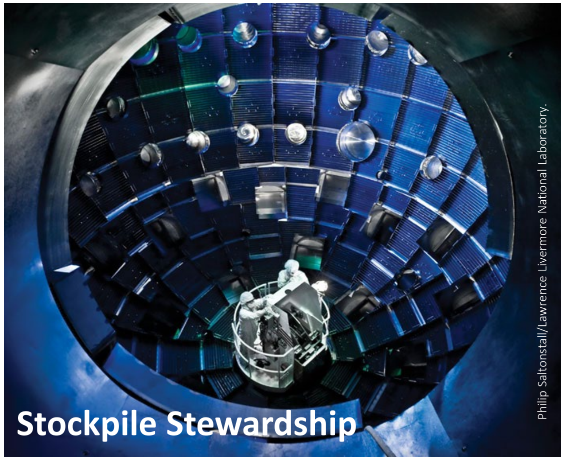
Neutron-capture cross sections play key roles across nuclear science

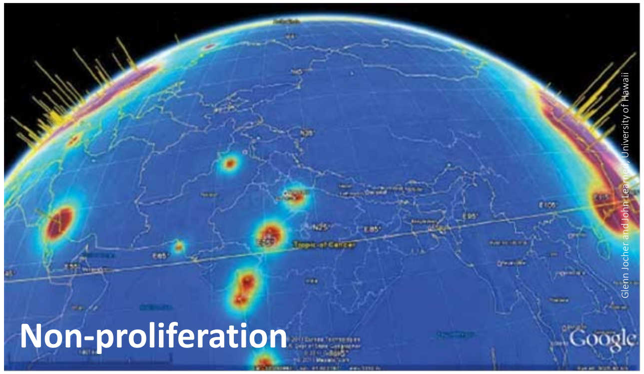
- Reaction networks:
  - Astrophysics
  - Stockpile stewardship
  - Non-proliferation
  - Nuclear Energy
  - …





Stockpile Stewardship

Philip Saltonstall/Lawrence Livermore National Laboratory.

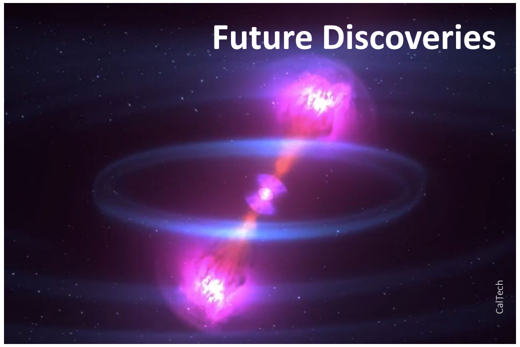


Non-proliferation

Glenn Jocher and John Learned, University of Hawaii

Energy

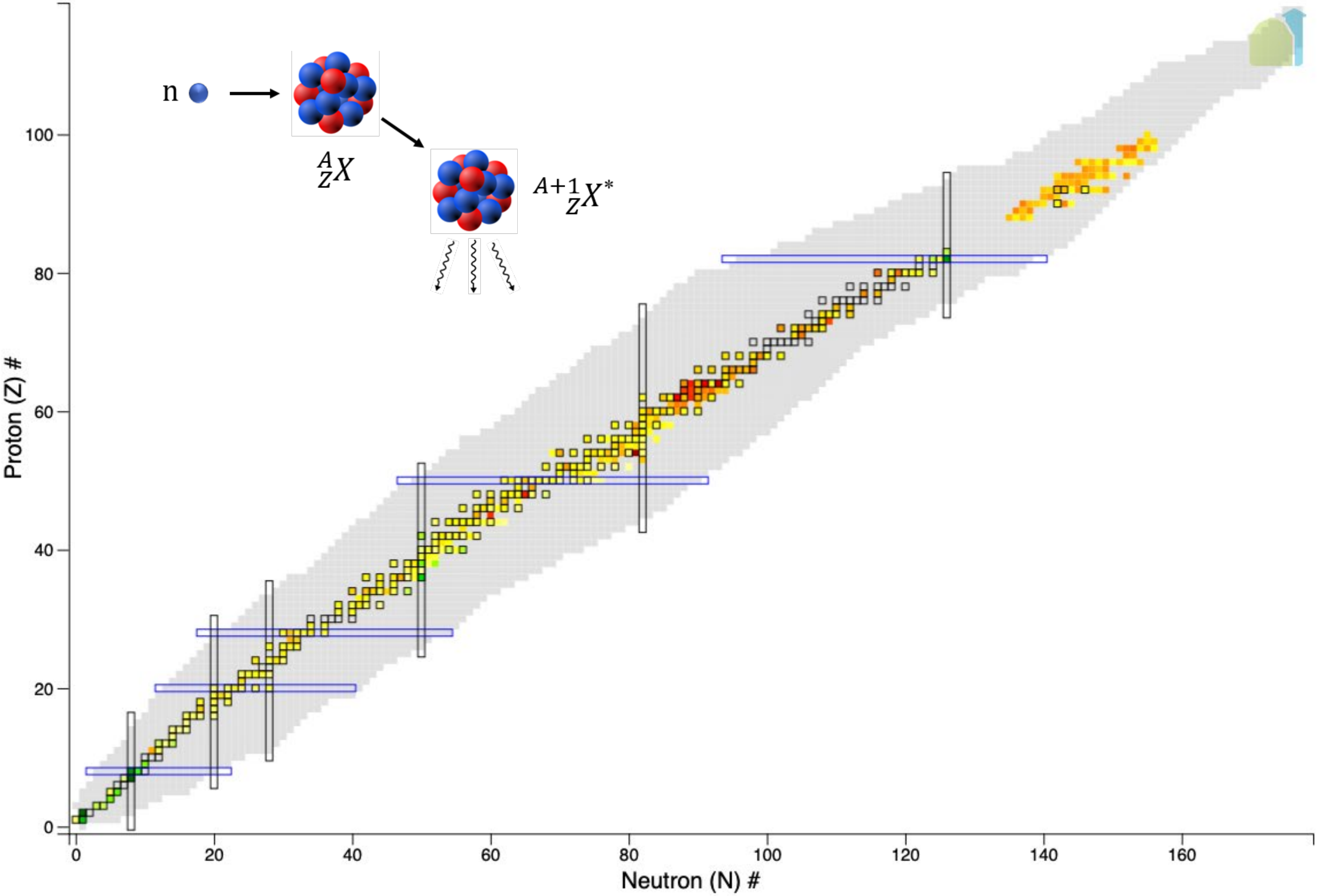
TVA Watts Bar Nuclear Power Plant/TN Valley Authority



Future Discoveries

CalTech

Current Measurements



How do you obtain (n,γ) rates for an isotope?

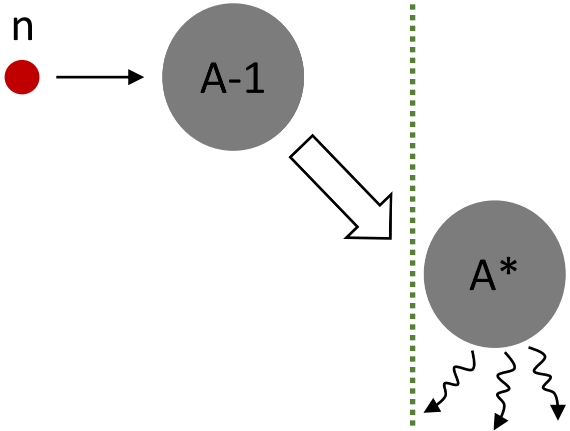
Direct Measurement

- Desired targets are too short-lived
- No feasible neutron target
- Not possible for rare isotopes

Indirect Measurement

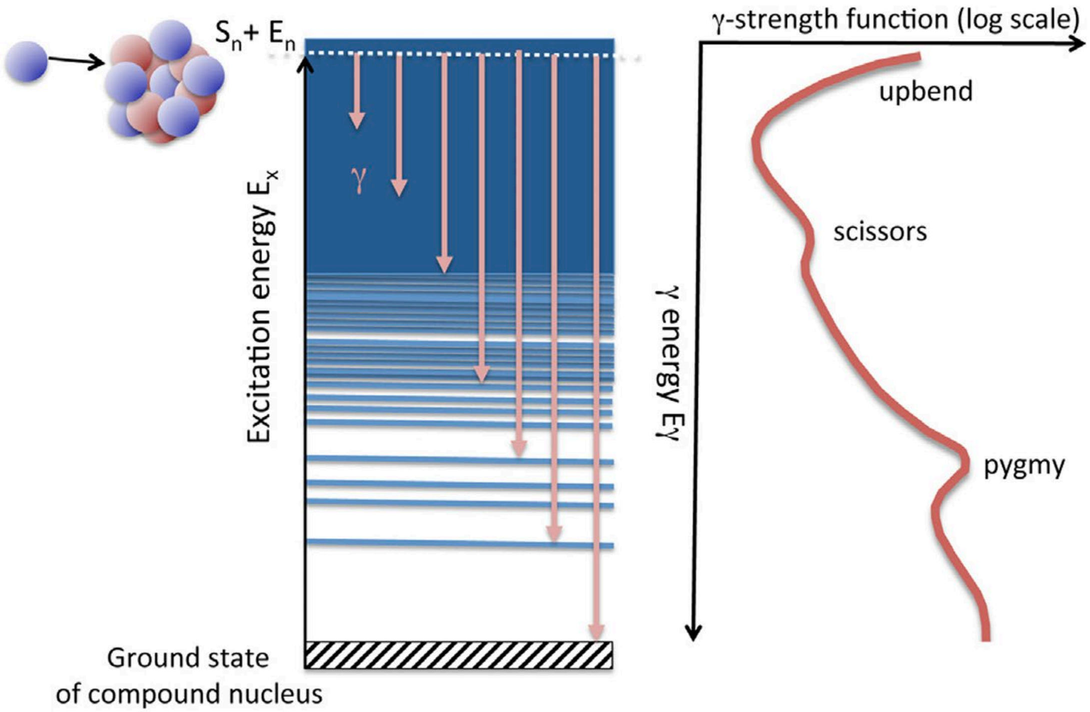
- Access same nucleus through different pathway

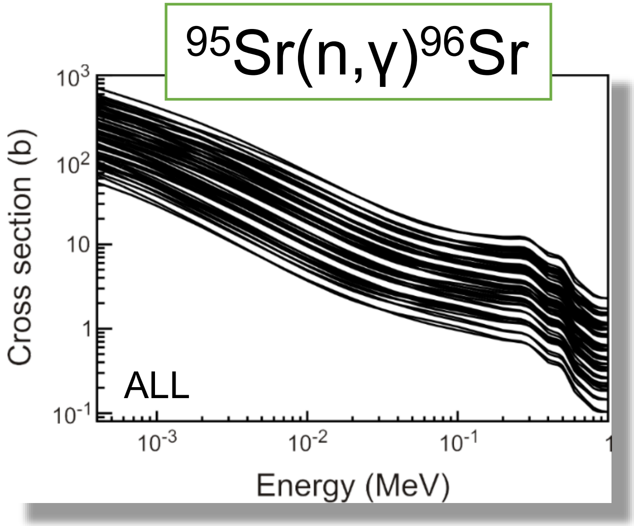
Examples:
Oslo Method
β-Oslo Method
Surrogate Method
Inverse Oslo Method
γ-ray strength method



A. Spyrou *et al.*, PRL **113**, 232502 (2014)
J. Escher *et al.*, PRL **121**, 052501 (2018)
A. Ratkiewicz *et al.*, PRL **122**, 052502 (2019)
H. Utsunomiya *et al.*, PRC **82**, 064610 (2010)
M. Guttormsen *et al.*, NIMA **255**, 518 (1987)
M. Guttormsen *et al.*, NIMA **374**, 371 (1996)
A. Schiller *et al.*, NIMA **447**, 498 (2000)
A.C. Larsen *et al.*, PRC **83**, 034315 (2011)
V. Ingeberg *et al.*, EPJA **56**, 68 (2020)
V. Ingeberg *et al.*, PRC **106**, 054315 (2022)

Theoretical (n,γ) cross section calculations have large uncertainties





Hauser – Feshbach (Statistical Model)

- Nuclear Level Density (NLD)
- γ-ray strength function (γSF)

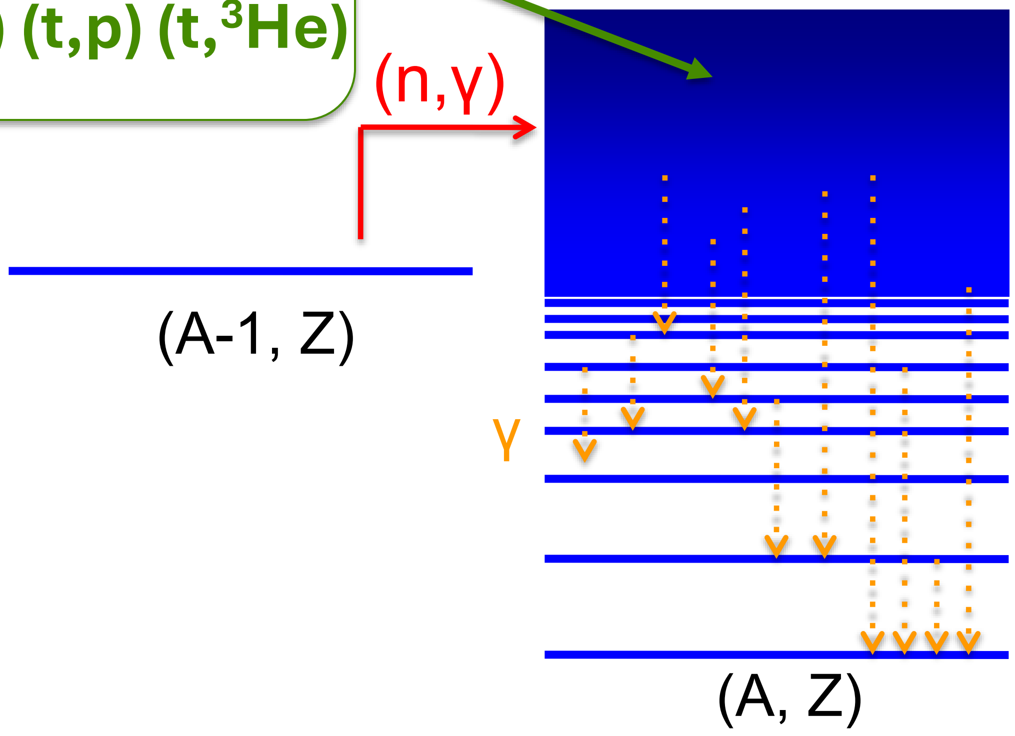
} Dominate uncertainties

- Optical model potential → Large uncertainties further from stability

A.C. Larsen, *et al*. PPNP **107** 69 (2019).
Koning and Rochman, Nucl. Data Sheets **113**, 2841 (2012)
Hauser and Feshbach, Phys. Rev. **87**, 366 (1952)

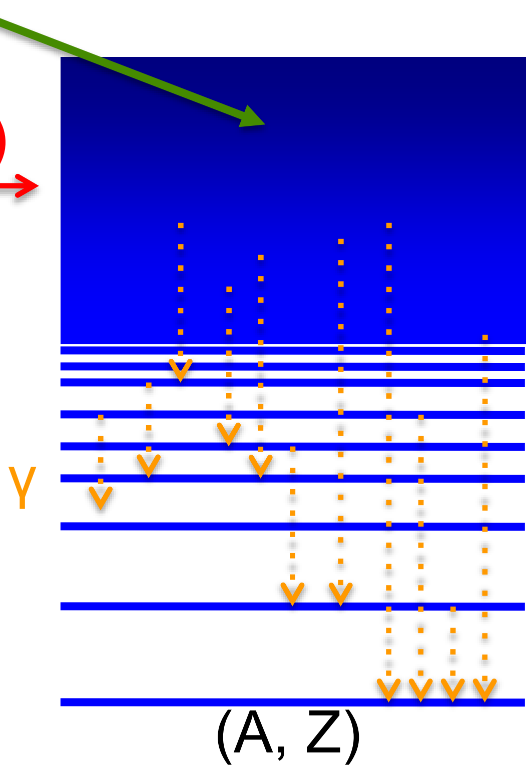
Indirect Techniques are Used to Constrain (n,γ) Rates

(d,p) (^{3}He,^{3}He’)
(p,d) (^{4}He,^{4}He’)
(p,p’) **(t,p) (t,^{3}He)**



Probe/measure level density, γ-ray strength function ⟹ Constrain (n,γ) cross section!

Indirect Techniques are used to constrain (n,γ) rates: Oslo Method

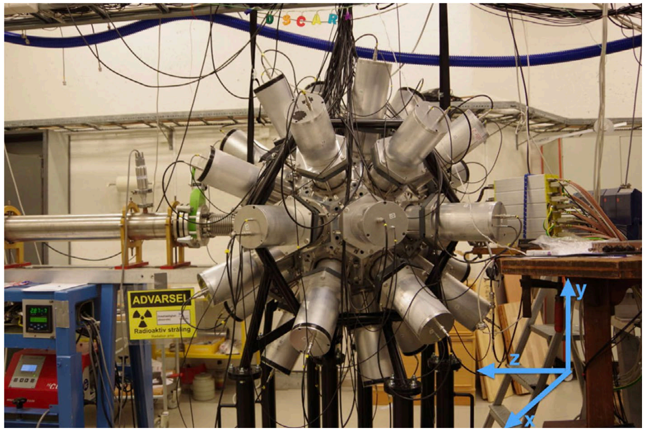


- Populate the compound nucleus via mechanism of choice
- Feasible with beam intensities > 10^6 pps
- Simultaneous measurement of NLD and gSF

Needs:

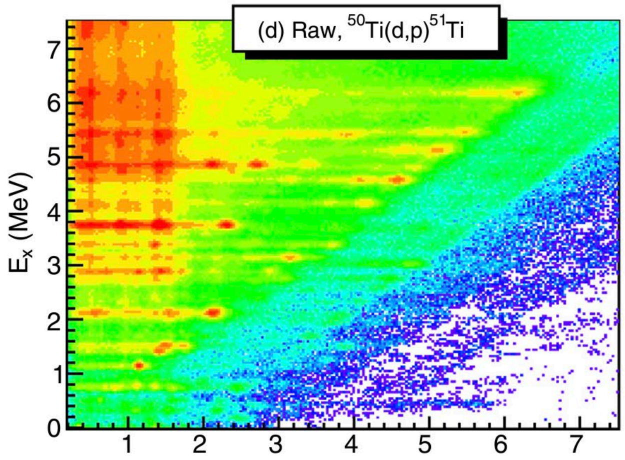
- ✓ Charged particle detector
- ✓ Gamma array (NaI, $LaBr_3$, $CeBr_3$, …)
- ✓ > 30,000 particle-gamma coincidences
- ✓ Resolution vs. Efficiency

OSCAR + SiRi Array at OCL



F. Zeiser, *et al*. NIMA **985** 164678 (2021)

Oslo Method Analysis

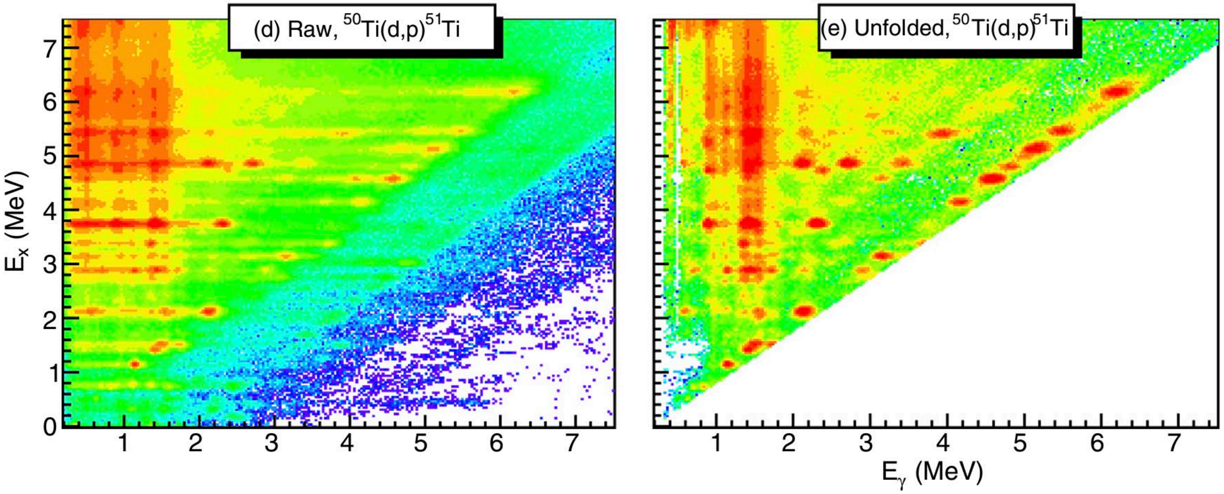


Raw Matrix

- Purely experimental data from SiRi (protons) and CACTUS (gammas)
- Investigate structure of ^{51}Ti

Guttormsen *et al.*, NIMA **255**, 518 (1987)
Allison *et al.*, NIMA **835**, 186 (2016)
Schiller *et al.*, NIMA **447**, 498 (2000)
Guttormsen *et al.*, NIMA **374**, 371 (1996)
S. N. Liddick, *et al.* PRC **100**, 024624 (2019)

Oslo Method Analysis



Raw Matrix

- Purely experimental data from SiRi (protons) and CACTUS (gammas)
- Investigate structure of ^{51}Ti

Unfolded Matrix

- Need to account for the interaction of γ-rays in the detector
- Generate response function for CACTUS in GEANT4
- Iterative procedure to determine the incoming energy

Guttormsen *et al.*, NIMA **255**, 518 (1987)
Allison *et al.*, NIMA **835**, 186 (2016)
Schiller *et al.*, NIMA **447**, 498 (2000)
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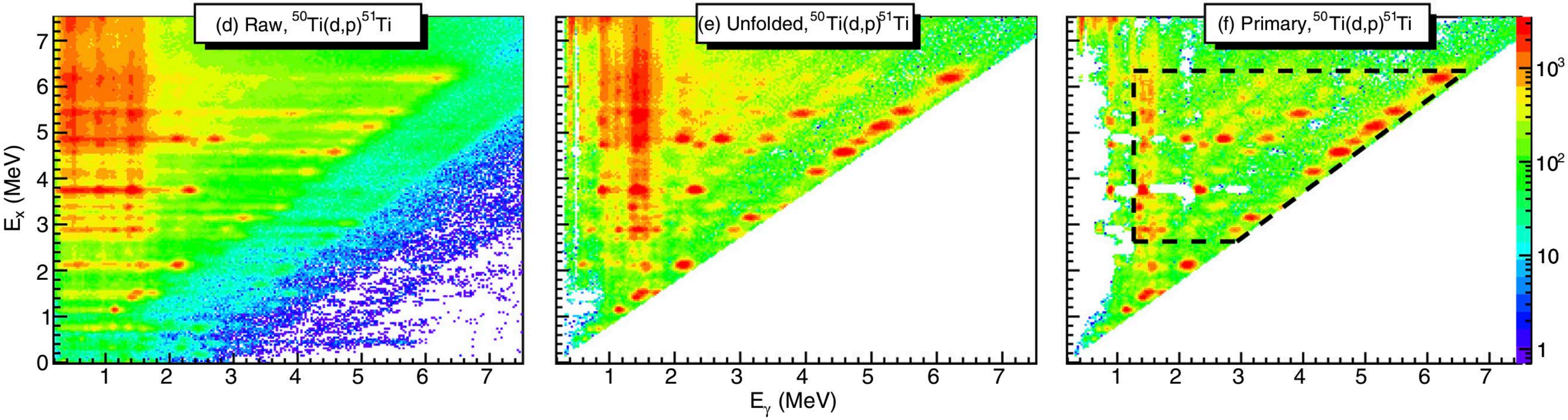
Oslo Method Analysis



First Generation Matrix

- Isolate the first γ-ray to be emitted from each excited state
- Iterative subtraction of the γ-rays emitted from lower excited states
- Becomes the probability matrix needed to extract NLD and γSF

Normalizations

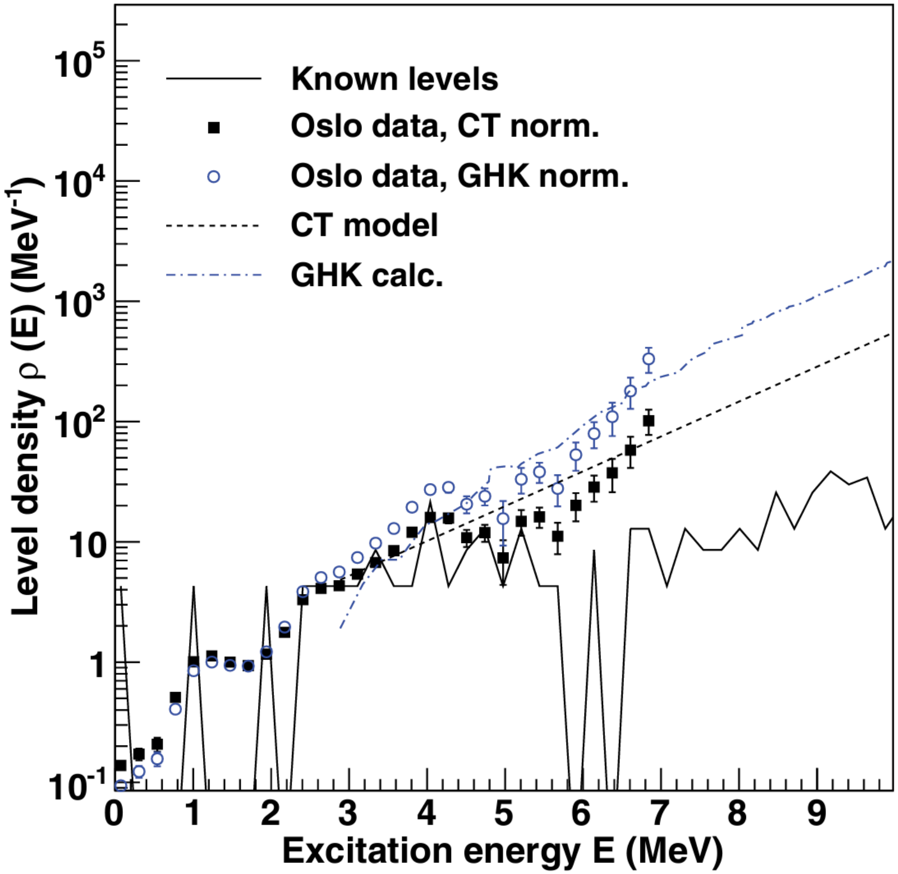
- Discrete levels from NNDC
- Level density at S_n from neutron resonance spacing (D_0)
- Average radiative width (Γ_γ)
- Spin distribution and cutoff

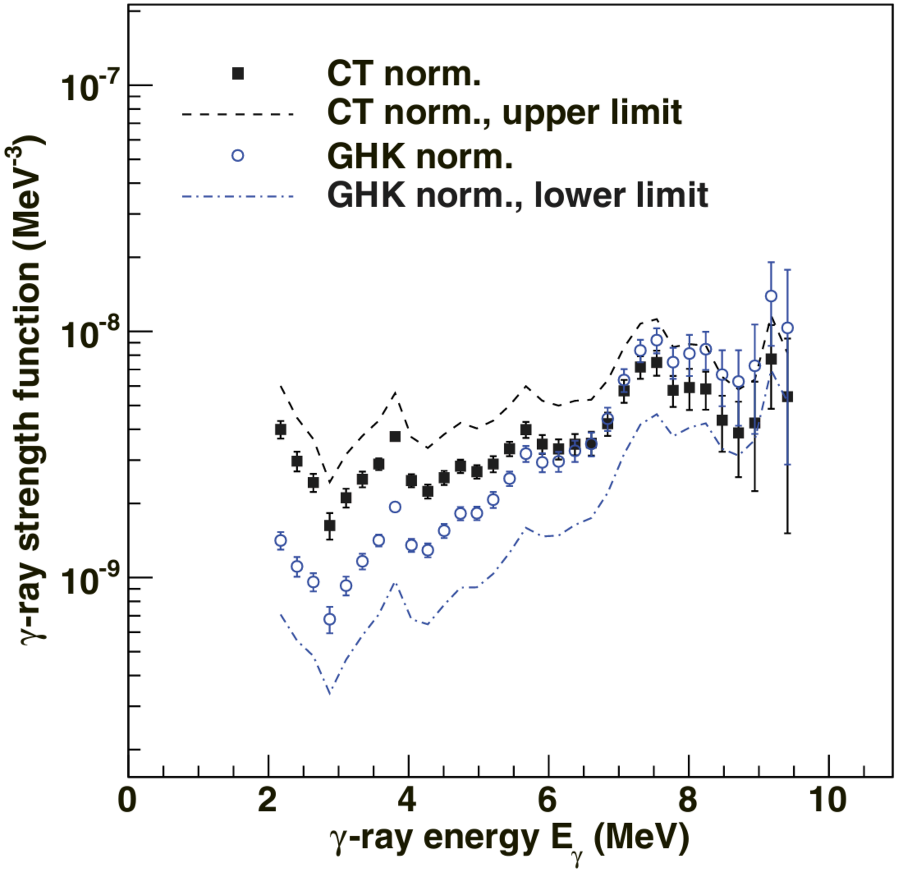
Guttormsen *et al.*, NIMA **255**, 518 (1987)
Allison *et al.*, NIMA **835**, 186 (2016)
Schiller *et al.*, NIMA **447**, 498 (2000)
Guttormsen *et al.*, NIMA **374**, 371 (1996)
S. N. Liddick, *et al.* PRC **100**, 024624 (2019)

Oslo Method for ^{46}Ti(p,tγ)^{44}T

- Experiment at OCL
  - 32-MeV proton beam
  - Self-supporting ^{46}Ti target (3.0 mg/cm^2)
  - ΔE-E telescopes + NaI (CACTUS)

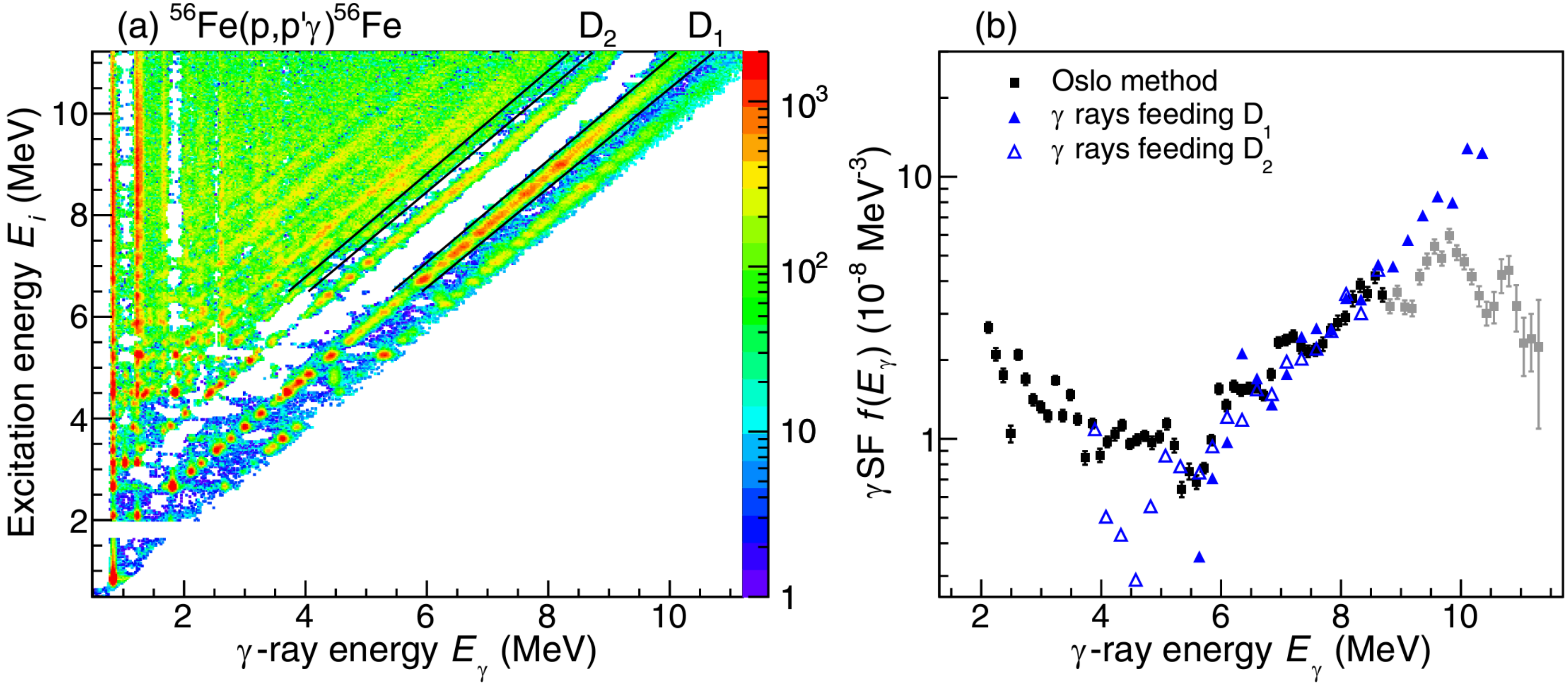
** not for (n,γ) constraint





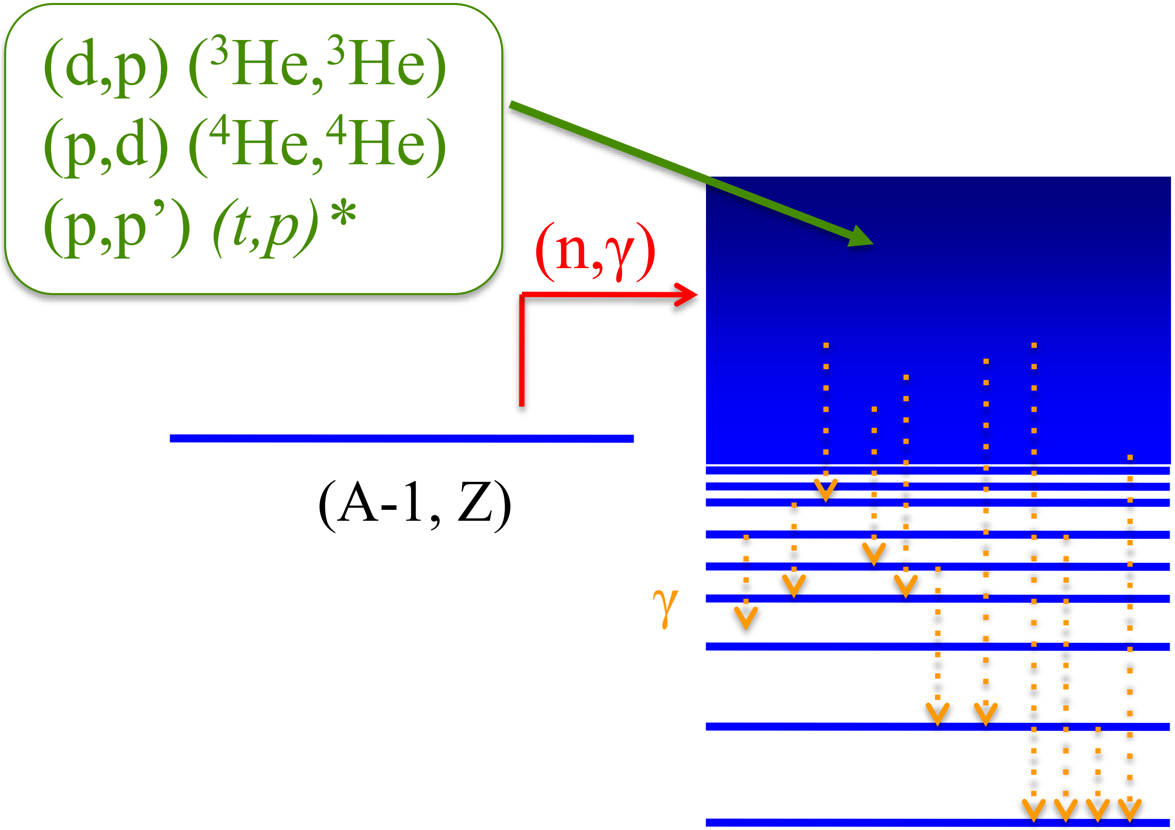
The Shape Method

- Extraction of slope of NLD and gSF without D_0 values



M. Wiedeking, *et al.*, Phys. Rev. C **104**, 014311 (2021)

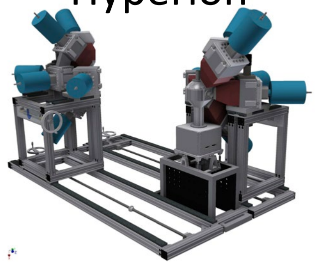
Indirect Techniques are used to constrain (n,γ) rates: Surrogate Reaction Method

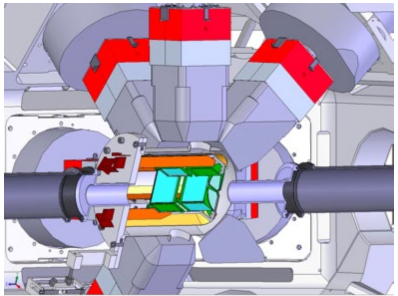


(d,p) (^{3}He,^{3}He)
(p,d) (^{4}He,^{4}He)
(p,p’) *(t,p)**

GODDESS
2021

Hyperion





SHARC + TIGRESS

- Populate the compound nucleus via (d,p), (p,d), inelastic scattering, …
- Study nuclei far from stability
- Feasible with beam intensities > 10^6 pps

•Need:

- ✓ Radioactive or Stable Beam
- ✓ Segmented high-resolution γ-ray array
- ✓ Segmented charged particle arrays

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(Some) Experimental Setups for Surrogate Reactions

- Highly Segmented Silicon Arrays and High-resolution HPGe arrays

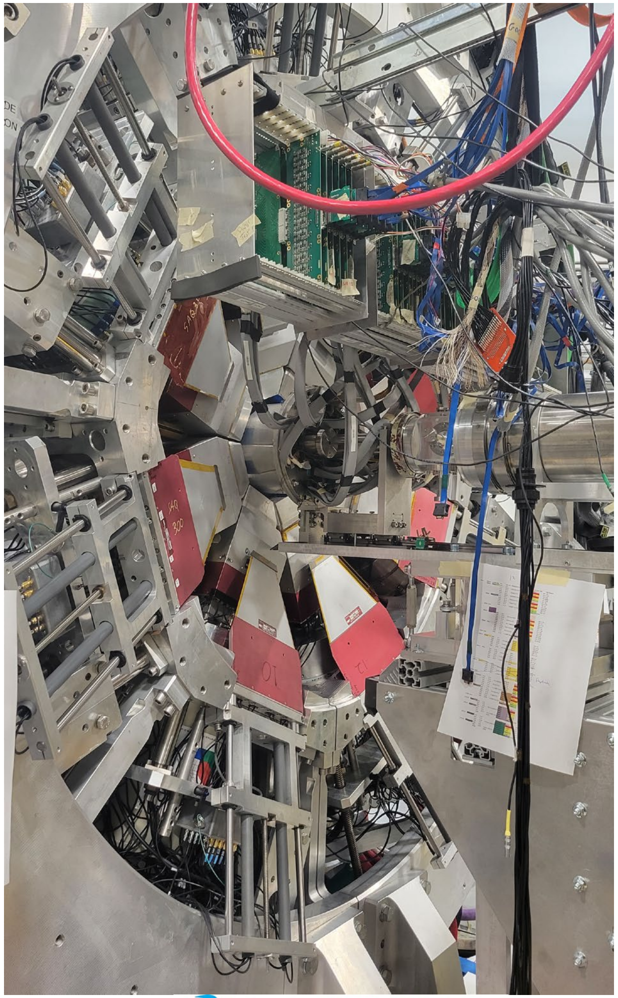
NSCL

FRIB

Argonne NATIONAL LABORATORY

GODDESS: ORRUBA + GRETINA (or GAMMASPHERE)

S. Pain



SHARC + TIGRESS

TRIUMF

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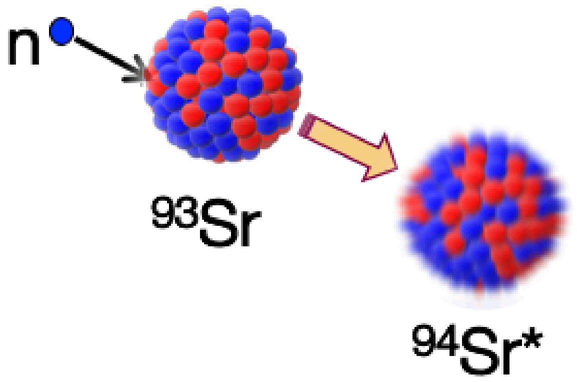
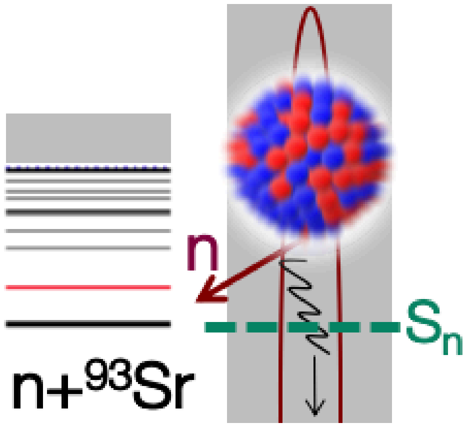
The Surrogate Reaction Method

Neutron capture



CN decay

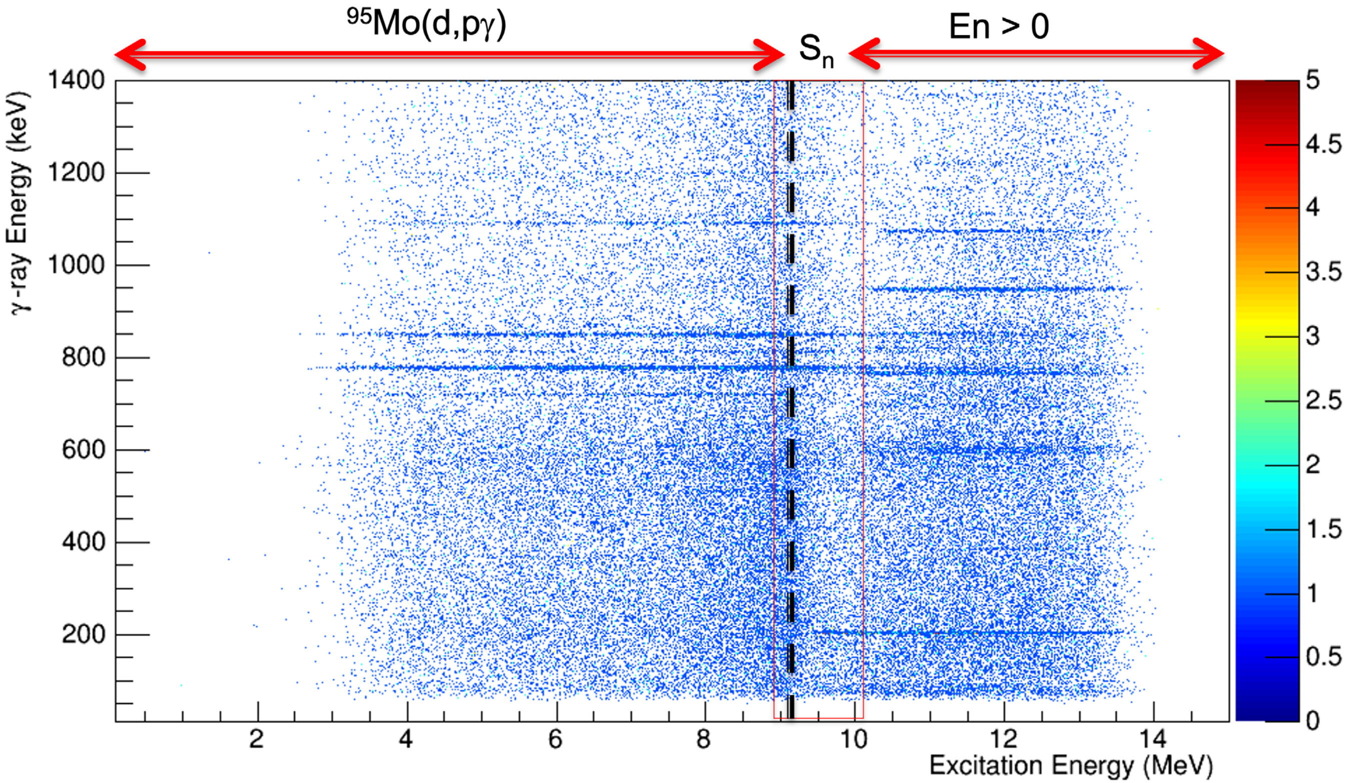


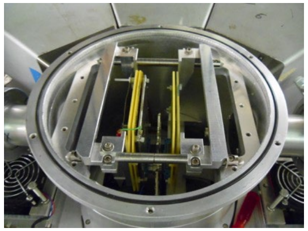
Neutron Capture

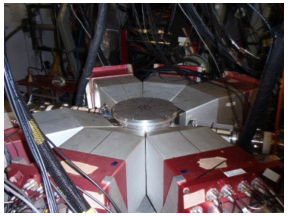
$$\sigma_{(n,\gamma)} = \sum_{J\pi} \sigma_n^{CN}(E_n, J, \pi)\ G_\gamma^{CN}(E_n, J, \pi)$$

Surrogate Method: ^{95}Mo(d,pγ)^{96}Mo

- Measurement of ^{95}Mo(d,pγ) in normal kinematics at TAMU







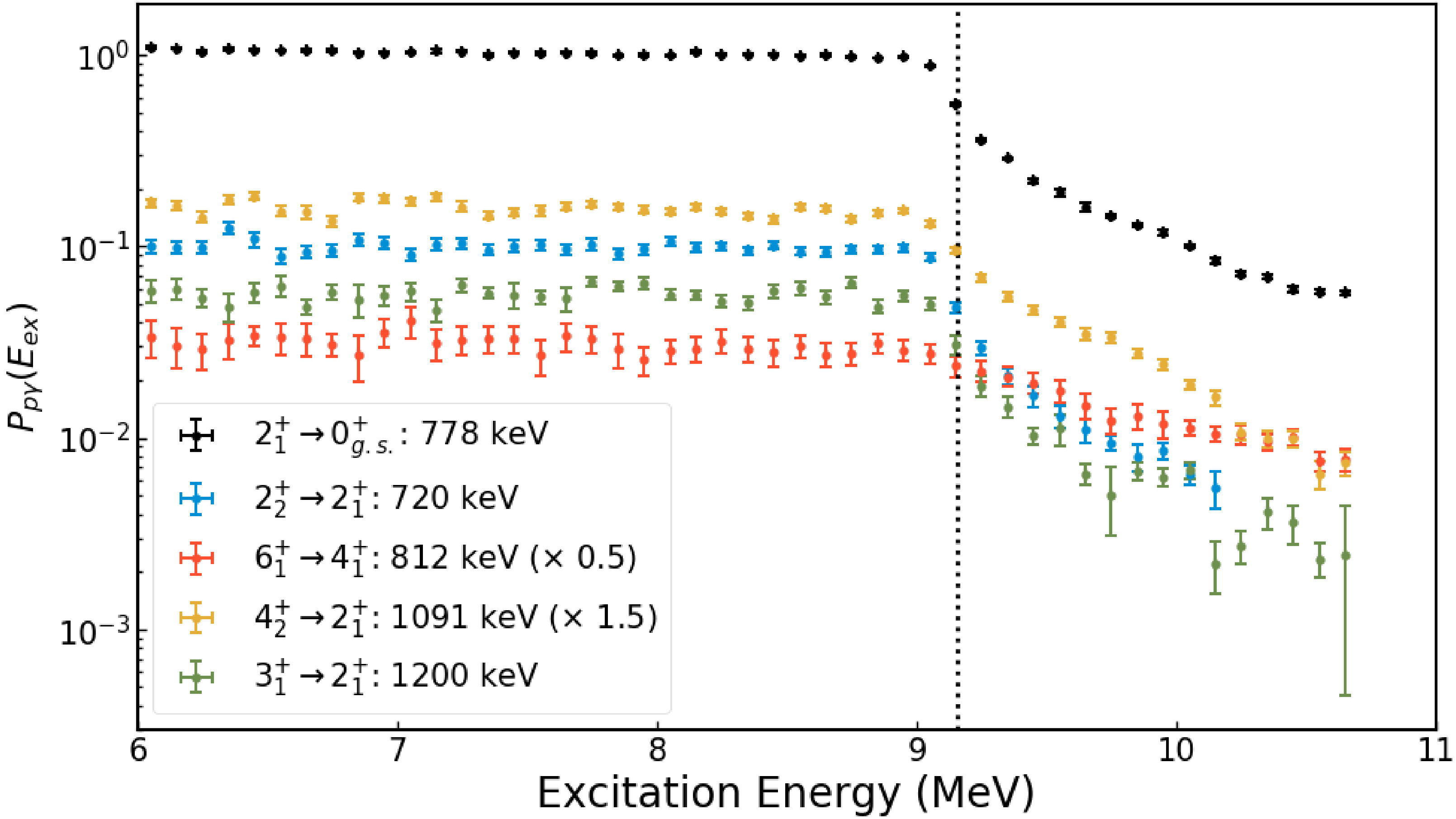
$$P_{p\gamma}(E_{ex}) = \frac{\boxed{N_{p\gamma}(E_{ex})}}{N_p(E_{ex})\epsilon_\gamma}$$

A. Ratkiewicz *et al.*, PRL **122**, 052502 (2019).

Surrogate Method: ^{95}Mo(d,pγ)^{96}Mo

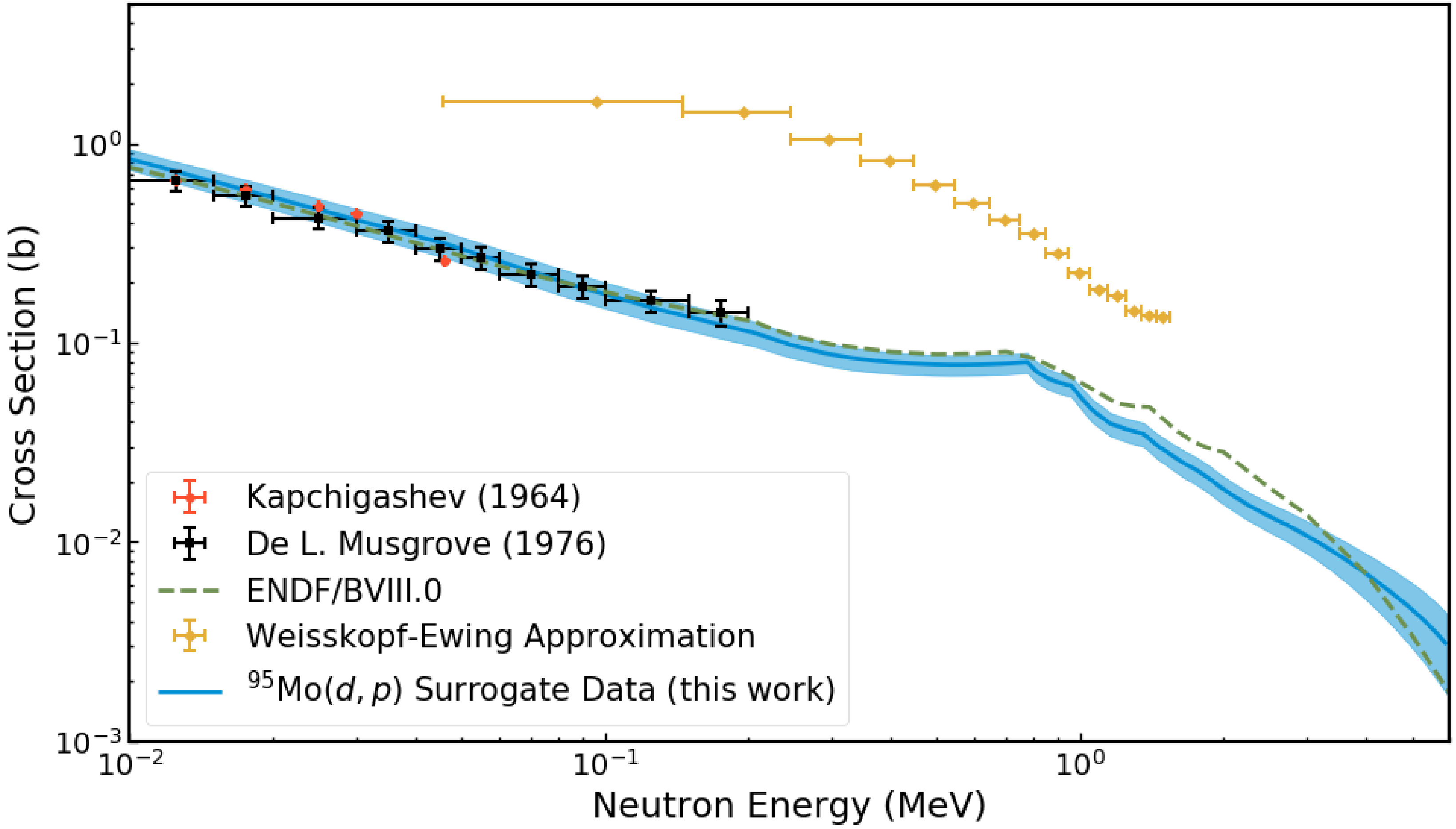
- Experimental coincidence probability

$$\boxed{P_{p\gamma}(E_{ex})} = \frac{N_{p\gamma}(E_{ex})}{N_p(E_{ex})\epsilon_\gamma}$$



A. Ratkiewicz *et al.*, PRL **122**, 052502 (2019).

Surrogate Method: ^{95}Mo(d,pγ)^{96}Mo



A. Ratkiewicz *et al.*, PRL **122**, 052502 (2019).

Current plans: ^{180}Hf(t,pγ)^{182}Hf

^{180}Hf(t,pγ)^{182}Hf experiment with CeBrA + SE-SPS

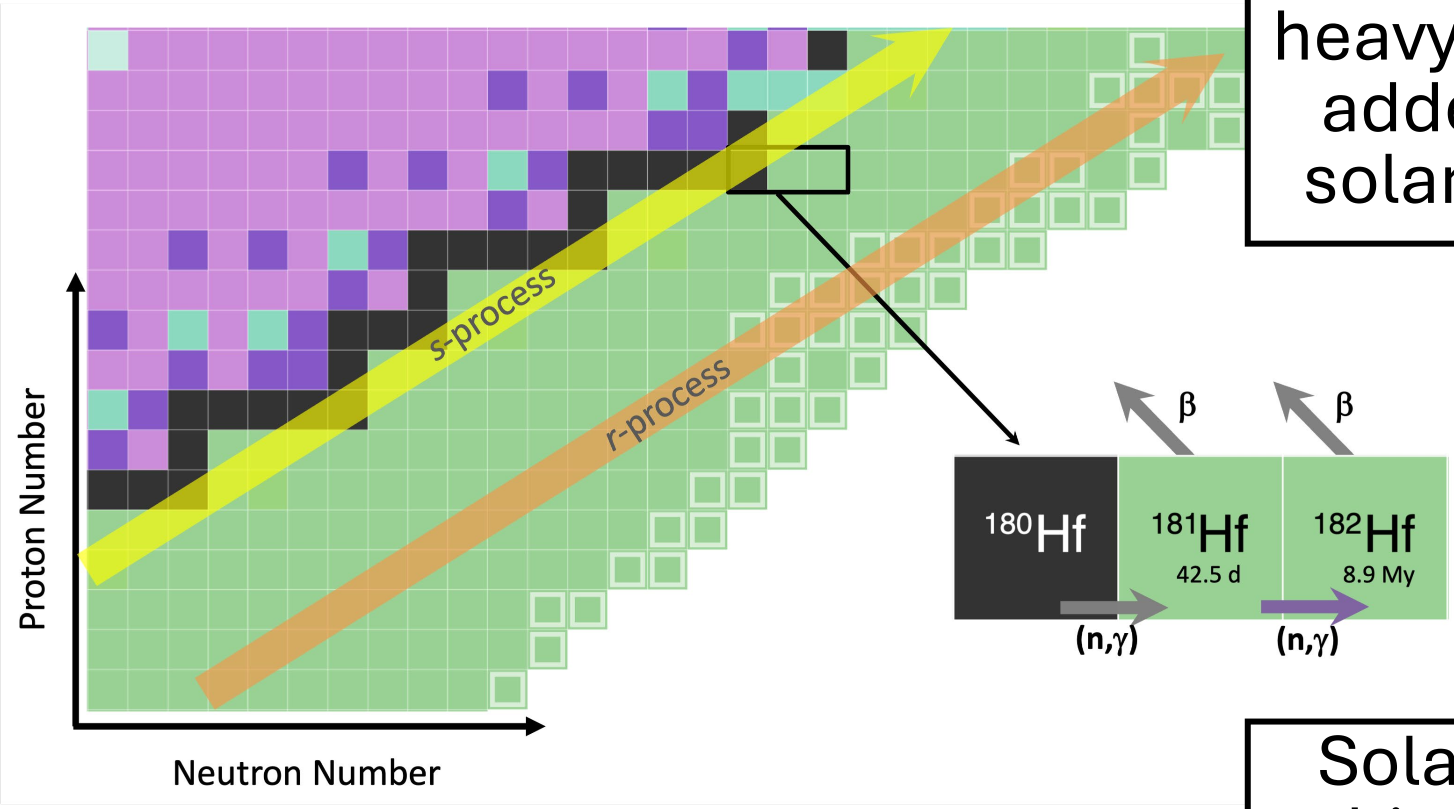
Measure p-γ coincidences

(> 30k)

Oslo (& Shape) Method Analysis

- Constrain NLD and gSF of ^{182}Hf (Nuclear Structure) and ^{181}Hf(n,γ)^{182}Hf reaction rate (Nuclear Astrophysics)
- Fully funded project with LLNL Team (+ OhioU)
  - Recently hired a postdoc!
- Hf beams at RIB facilities not feasible at this time.

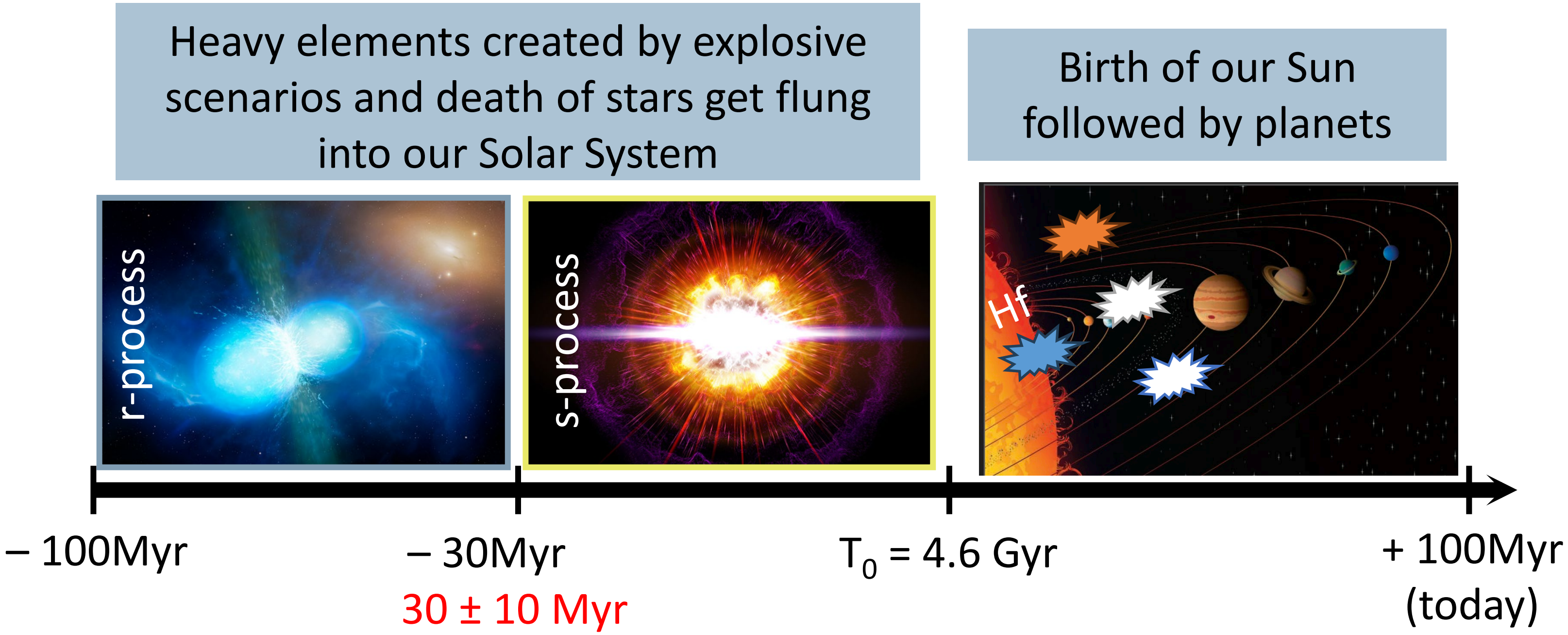
Current plans: $^{180}Hf(t,p\gamma)^{182}Hf$



How and when were the last heavy elements added to our solar system?

Solar system history and evolution

Current plans: $^{180}\text{Hf}(t,p\gamma)^{182}\text{Hf}$



Heavy elements created by explosive scenarios and death of stars get flung into our Solar System

Birth of our Sun followed by planets

– 100Myr

– 30Myr

30 ± 10 Myr

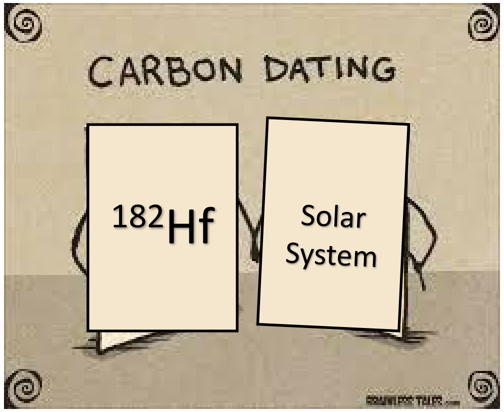
T_0 = 4.6 Gyr

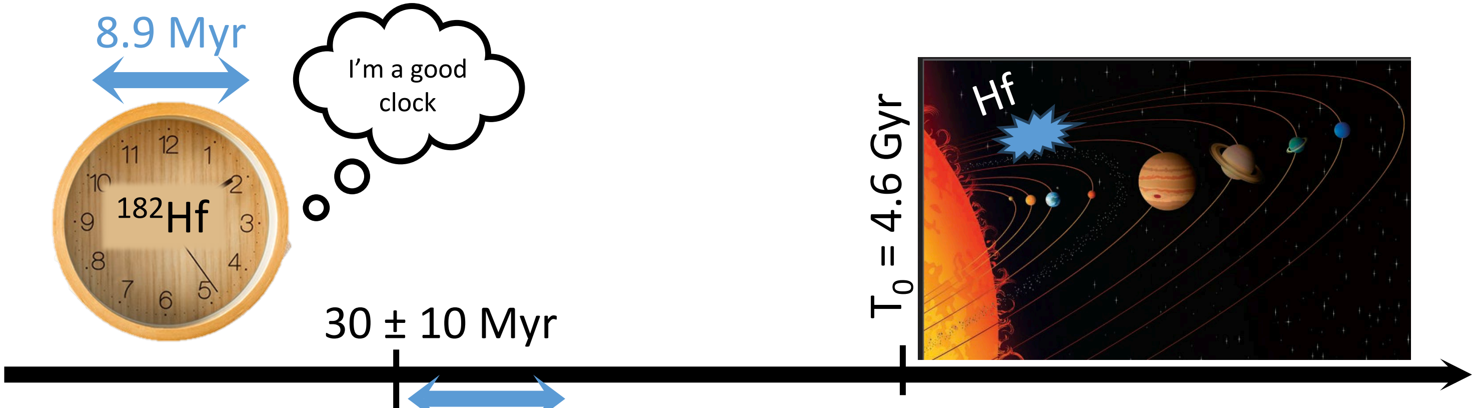
+ 100Myr (today)

- Time interval that elapsed between stellar additions (Hf) and formation of the Sun requires us to know how much radioactive nuclei were present at both times
  - Well known for Sun based on meteorites
  - Not known for final addition of elements and relies on models with large uncertainties

Cosmochronometer dating tells time on cosmic scales

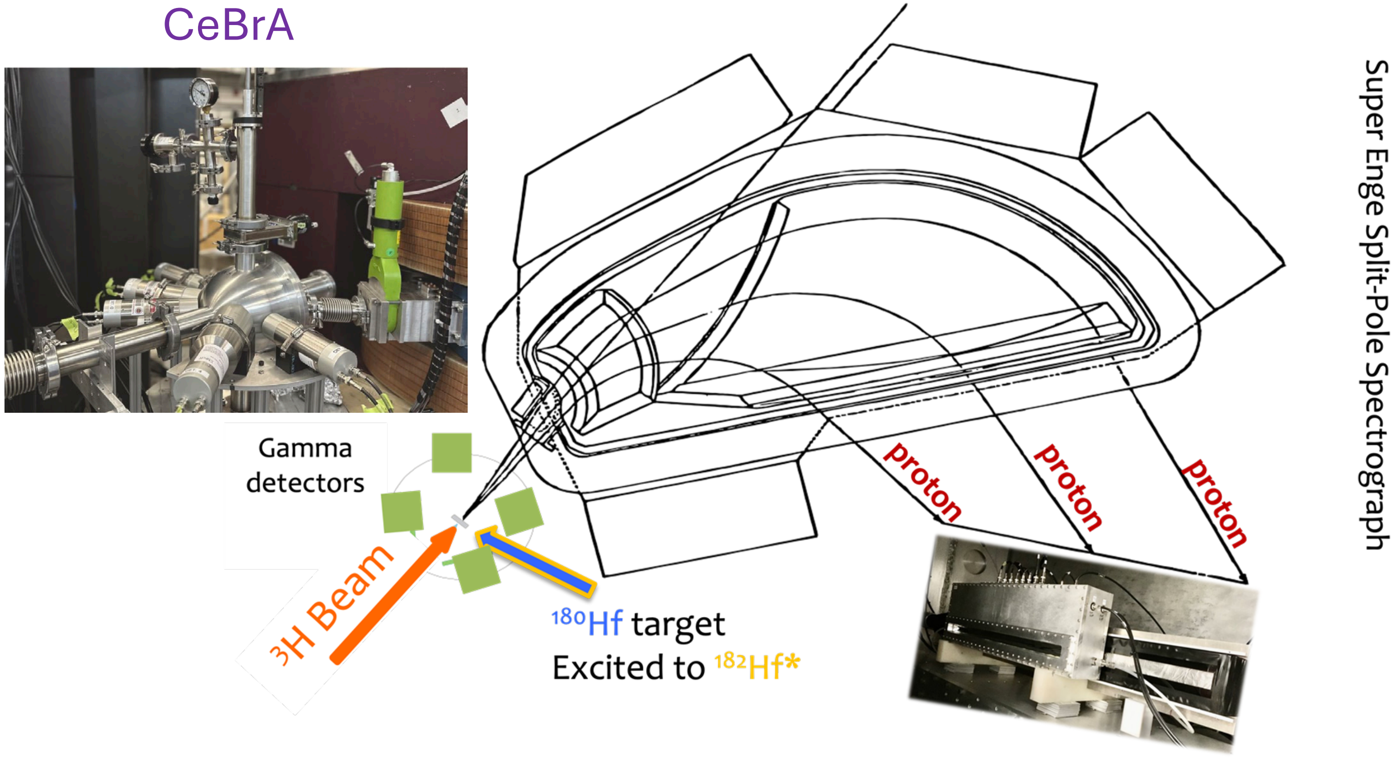
- Very similar to the idea of Carbon Dating (~5,700 years), but much longer time scale and nuclear reactions rates are needed too
- ^{182}Hf is the perfect cosmochronometer – it lives for 8.9 million years
  - No nuclear data to describe how ^{182}Hf is produced so there are large uncertainties!
  - Measure ^{182}Hf production!





No new material added to solar system!

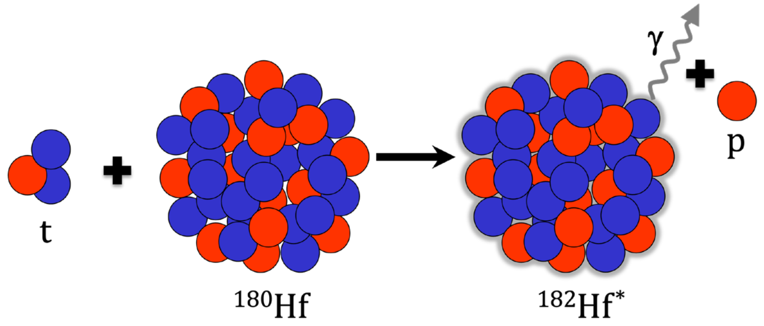
$^{3}H + {}^{180}Hf \rightarrow {}^{182}Hf^{*} + p + \gamma$



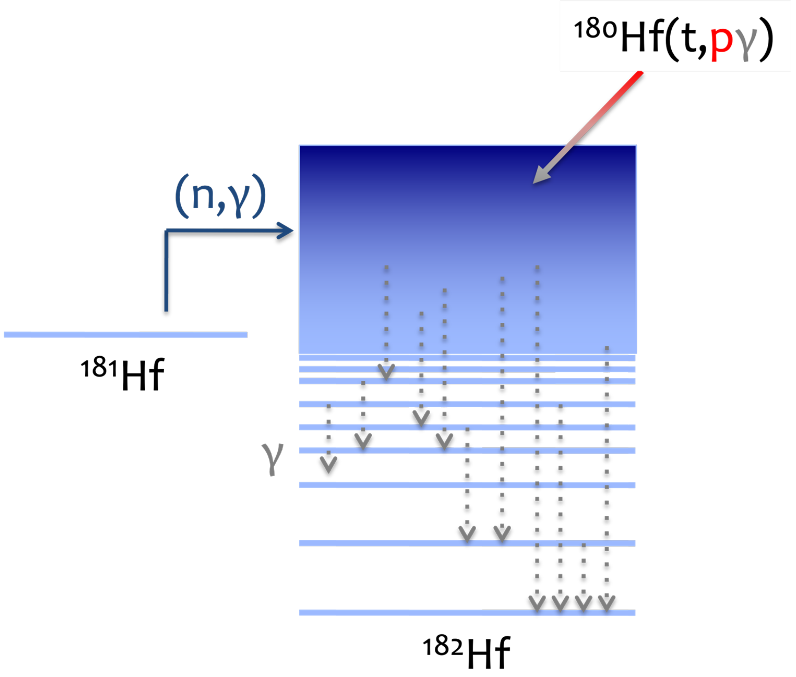
A. Conley *et al.*, NIMA **1058**, 168827 (2024).

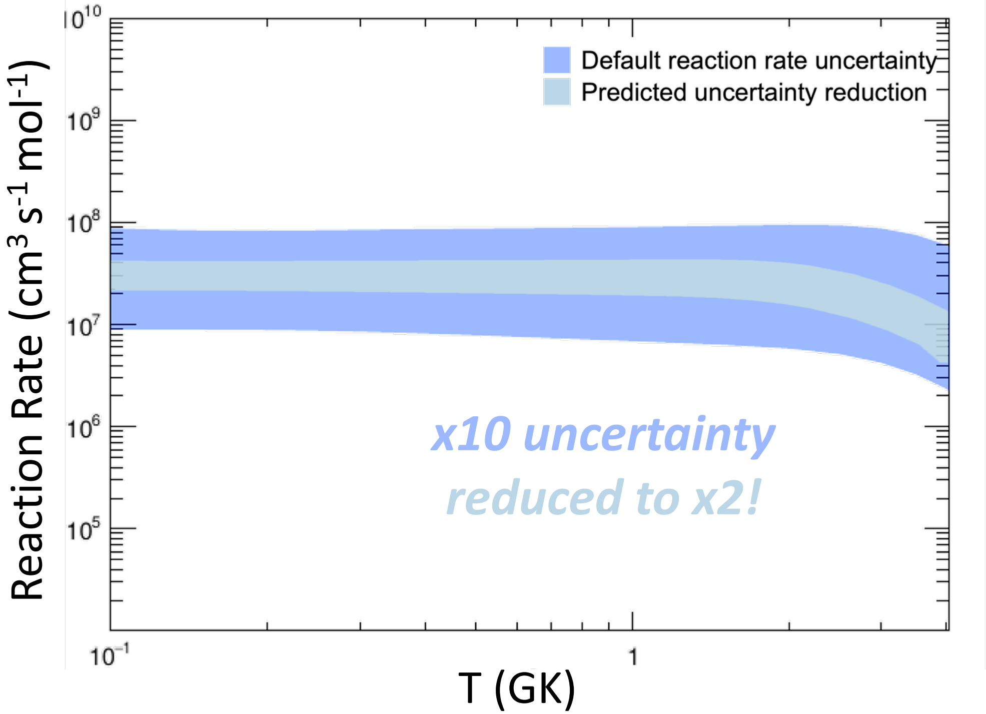
- Excitation energy and gamma-ray energy range: 0 – 6.8 MeV (S_n)
- Tritium beam energies & current: ~ 15 MeV, >1-3 nA
- Target from CATS: ~100 μg/cm2 ^{180}Hf (C backing)

Expected Outcome: ^{180}Hf(t,pγ)^{182}Hf



- NLD and gSF of ^{182}Hf (deformed, scissors mode expected)
- ^{181}Hf(n,γ)^{182}Hf reaction rate
- Cosmochronometer calculations





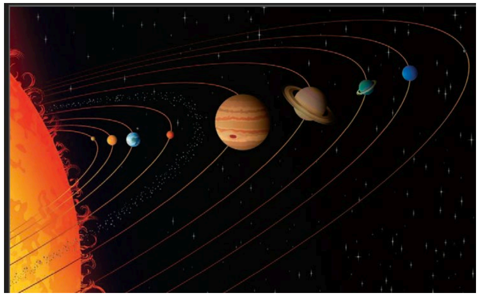
x10 uncertainty reduced to x2!

Future measurements

- Further (t,p) studies
  - Two steps from stability
    - *s*-process, weak *i*-process, applications
    - ^{102}Ru(t,p), ^{176}Yb(t,p), ^{169}Tm(t,p), ^{238}U(t,p), …
  - Extension to Surrogate Reaction measurements coupled with development of (t,p) surrogate theory
- (t,^{3}He) of interest!

Summary and Outlook

- Neutron-capture cross sections are important for basic needs, astrophysics, and applications
- Indirect reactions are needed for constraining (n,γ) reactions
- The Oslo Method is currently feasible for (t,p) and (t,^{3}He) studies
- Surrogate studies are on the horizon!
- ^{180}Hf(t,pγ)^{182}Hf cosmochronometer study will allow us to understand the timeline for solar system formation
- Lots of exciting research to do with triton beams! ☺



Thank you!

Questions?

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