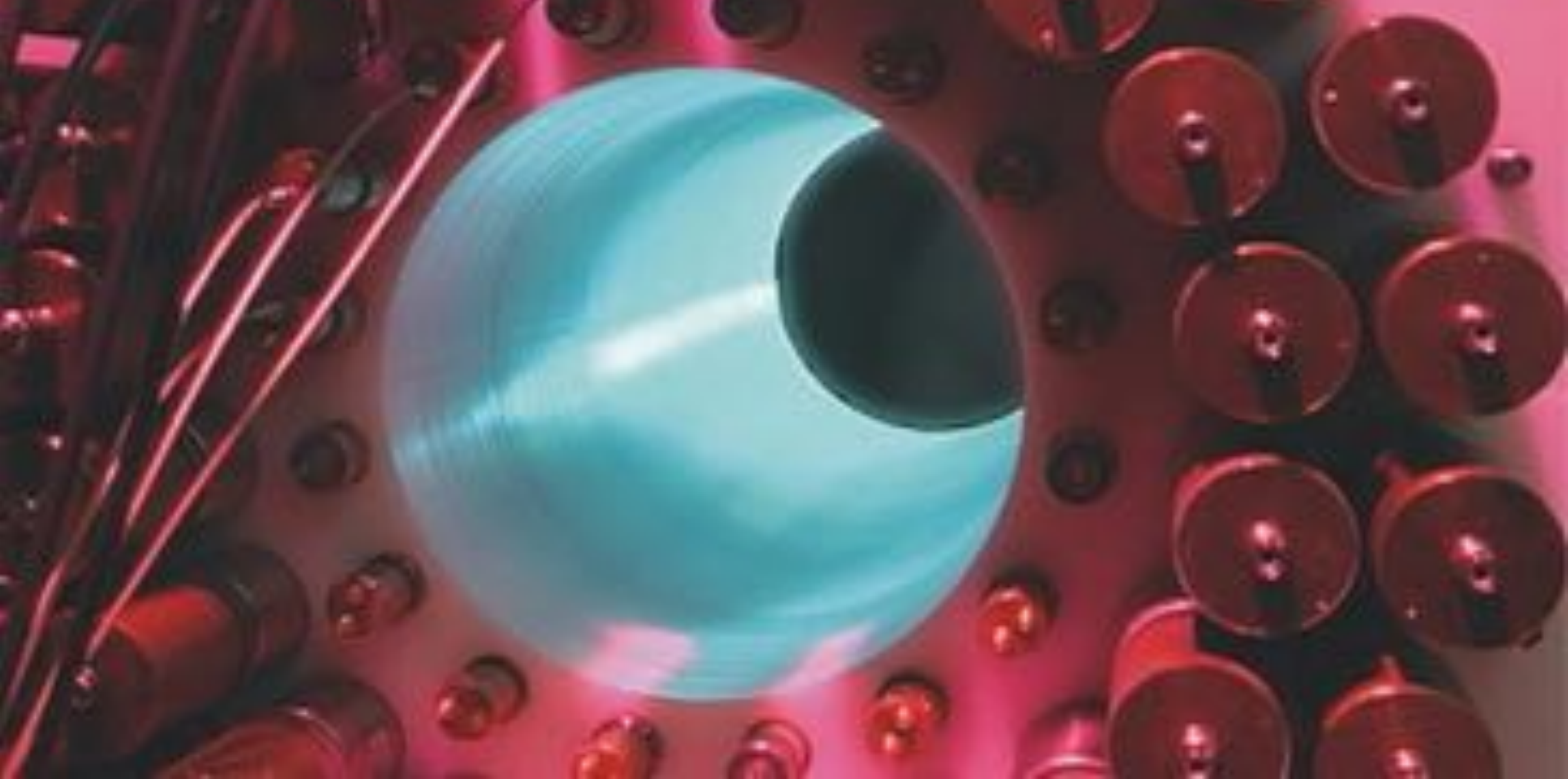
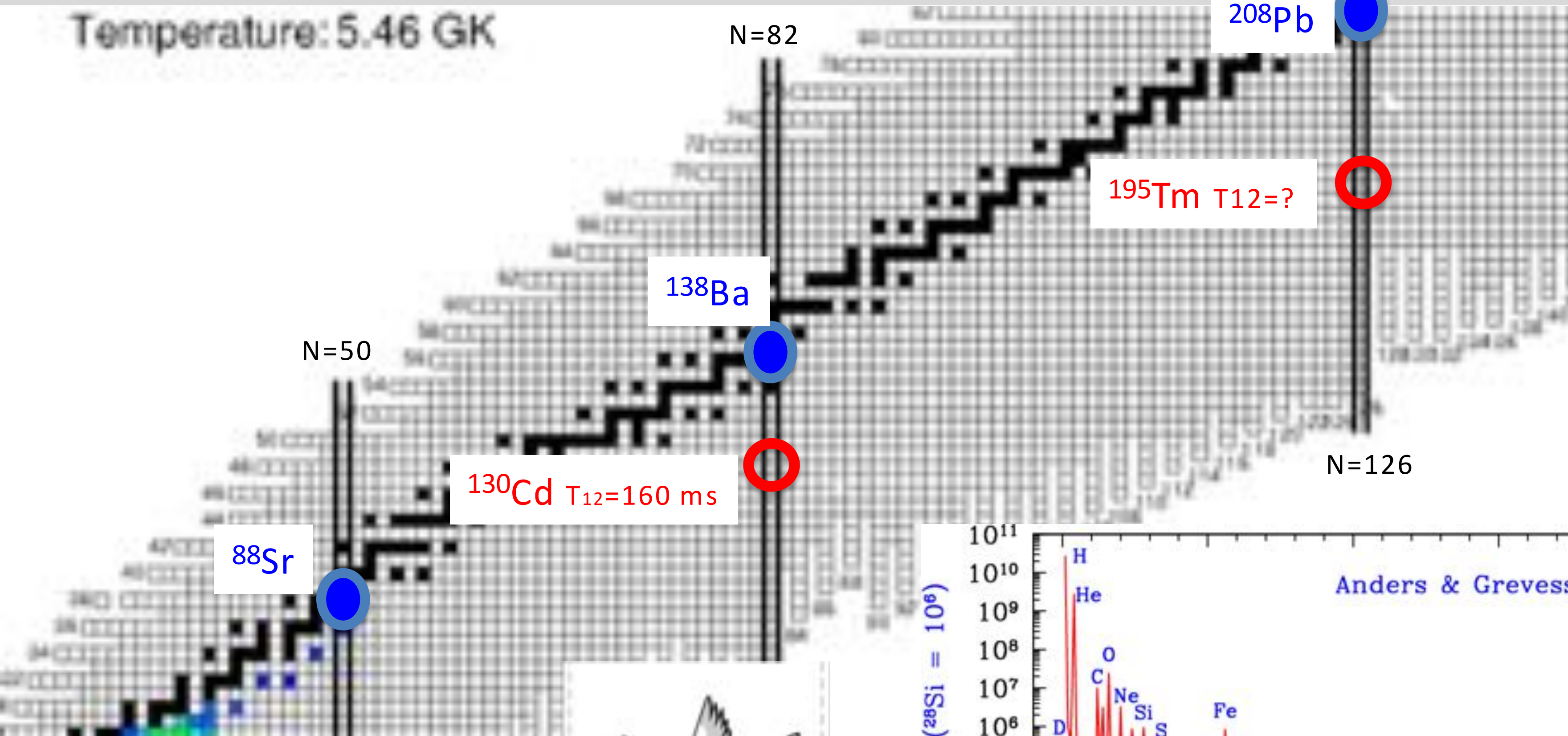
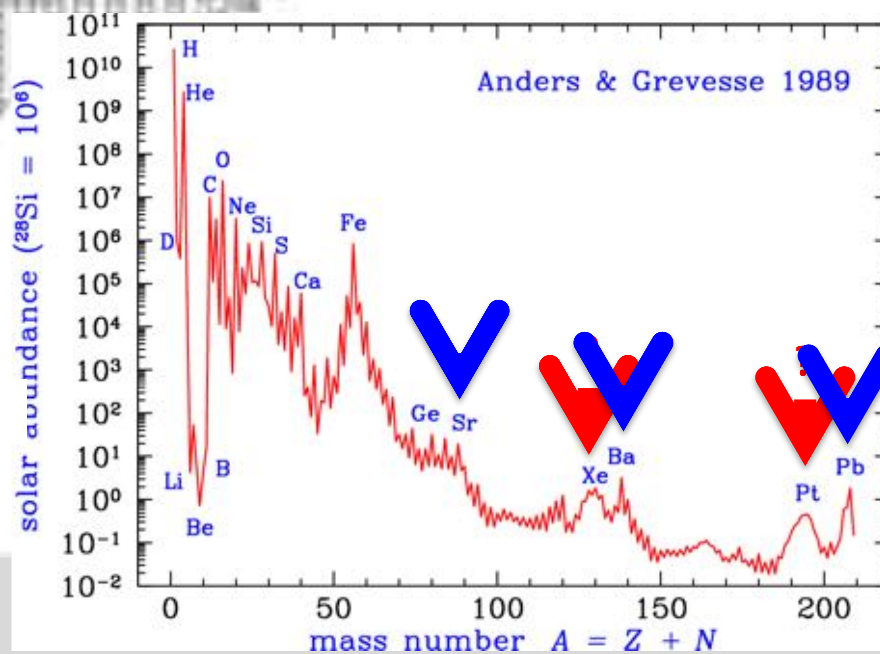
Nuclear Experiments
For Nucleosynthesis in Neutron Star Mergers

Hendrik Schatz
MSU
JINA Center for the Evolution of the Elements



"If it weren't for nuclear experiments and theory we would not even know there is an r-process"





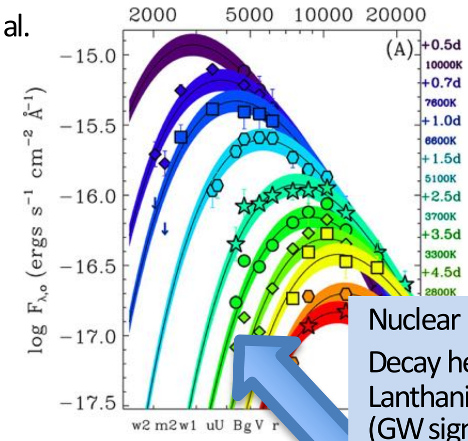
To reach ^{130}Cd with n-capture:
n capture time scale: $$\tau = \frac{1}{n_n < \sigma v >}$$

comparable to decay timescale
With reaction rate $N_A<\sigma v>$ ~ 10^5 cm^3/s/mole
→ n_n ~ 10^{19} /cm^3

Nuclear Physics Connects Observations and Models

Kilo Nova/GW Observations

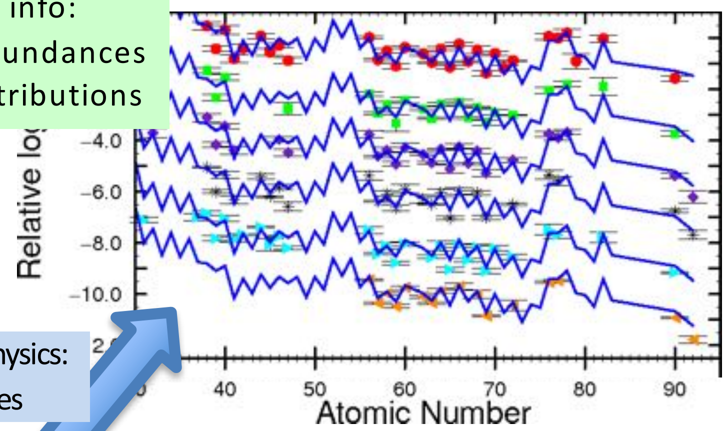
Drout et al. 2017



Nuclear Physics:
Decay heating,
Lanthanide contents/Opacity
(GW signal)

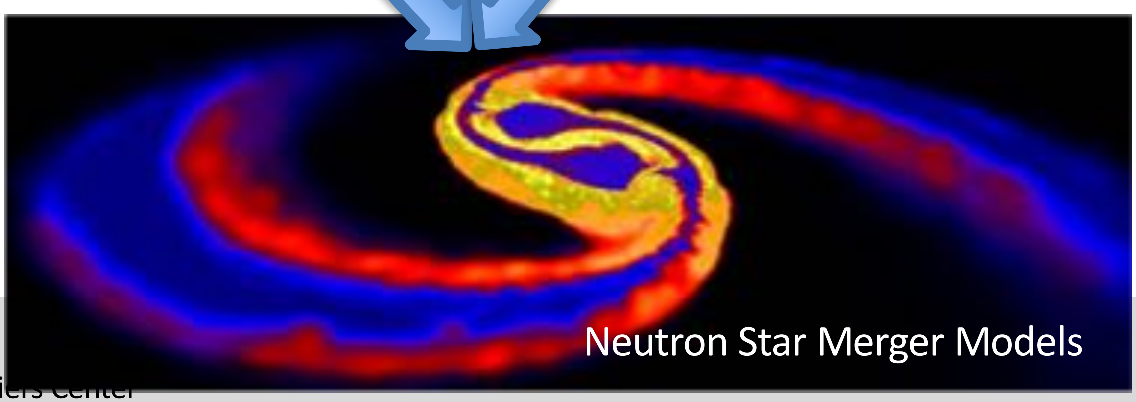
Unique r-process info:
- Elemental abundances
- Multiple contributions

Abundances in metal poor r-stars

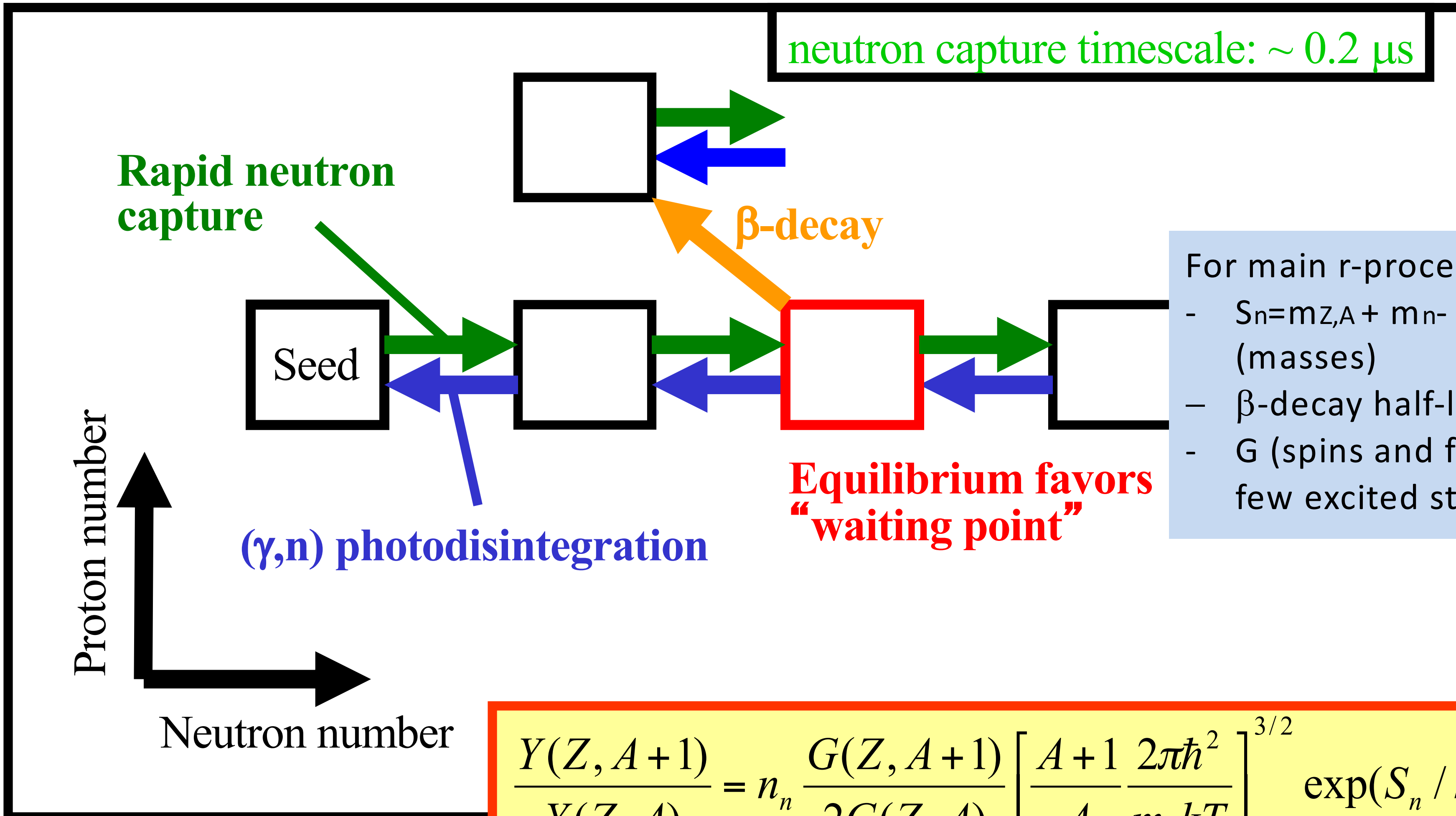


Nuclear Physics:
Abundances

Nuclear Physics:
- What elements are created in NS mergers?
- What are the contributions from different ejecta components to each element?
- What elements are not created in NS mergers and require other sources?
- What information do observations provide about the physical conditions at the nucleosynthesis site?



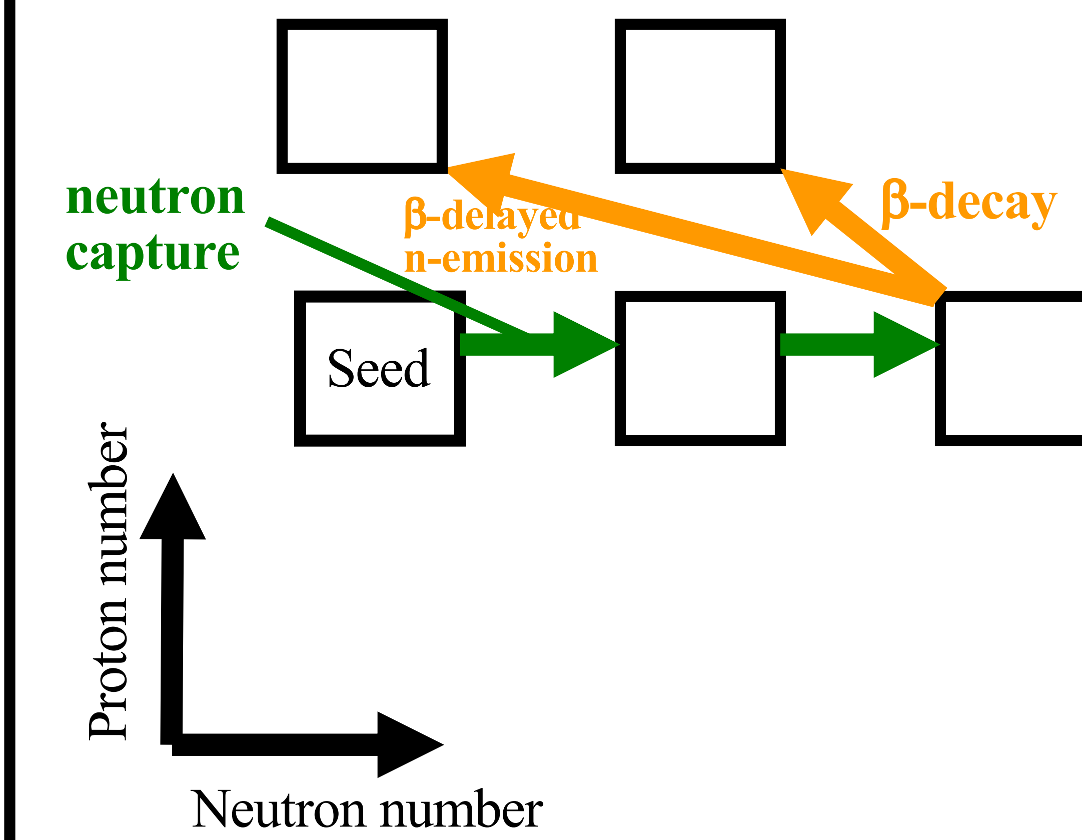
R-process nuclear physics needs [1]



For main r-process:
- $S_n = m_{Z,A} + m_n - m_{Z,A+1}$ (masses)
- β-decay half-lives
- G (spins and first few excited states)

$$\frac{Y(Z,A+1)}{Y(Z,A)} = n_n \frac{G(Z,A+1)}{2G(Z,A)} \left[\frac{A+1}{A} \frac{2\pi\hbar^2}{m_u kT} \right]^{3/2} \exp(S_n / kT)$$

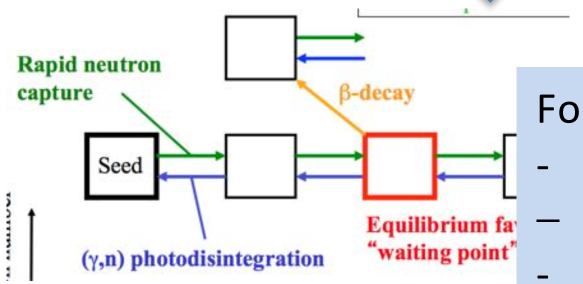
R-process nuclear physics needs [2]



During freezeout
- Neutron capture rates
- β-decay half-lives
- Branchings for β-delayed neutron emission

R-process nuclear physics needs [3]

Endpoint of the r-process
- Fission rates (neutron induced, b-delayed, spontaneous)
- Fission fragment distributions

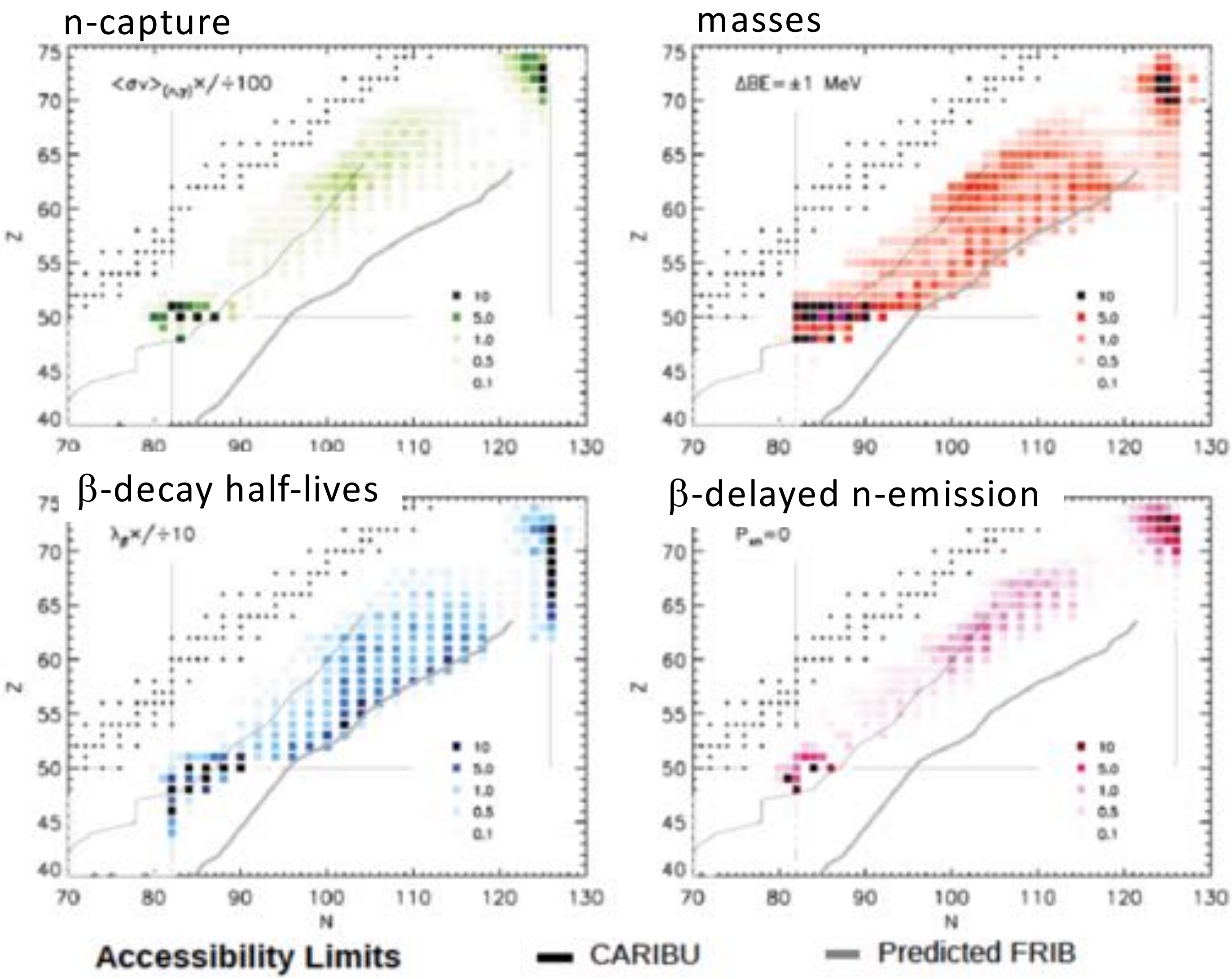


For main r-process:
- masses
- β-decay half-lives
- spins and first few excited states
- β-delayed neutron emission
- Neutron capture rates

Beginning: Seed production
- (α,n)
- $\alpha+\alpha+\alpha$, $\alpha+\alpha+n$, ….

Neutron production
- EOS
- Neutrino physics

“But there are 1000s of nuclei involved – which ones do we need to measure?”



$$F = 100 \sum_A |X(A) - X_b(A)|$$

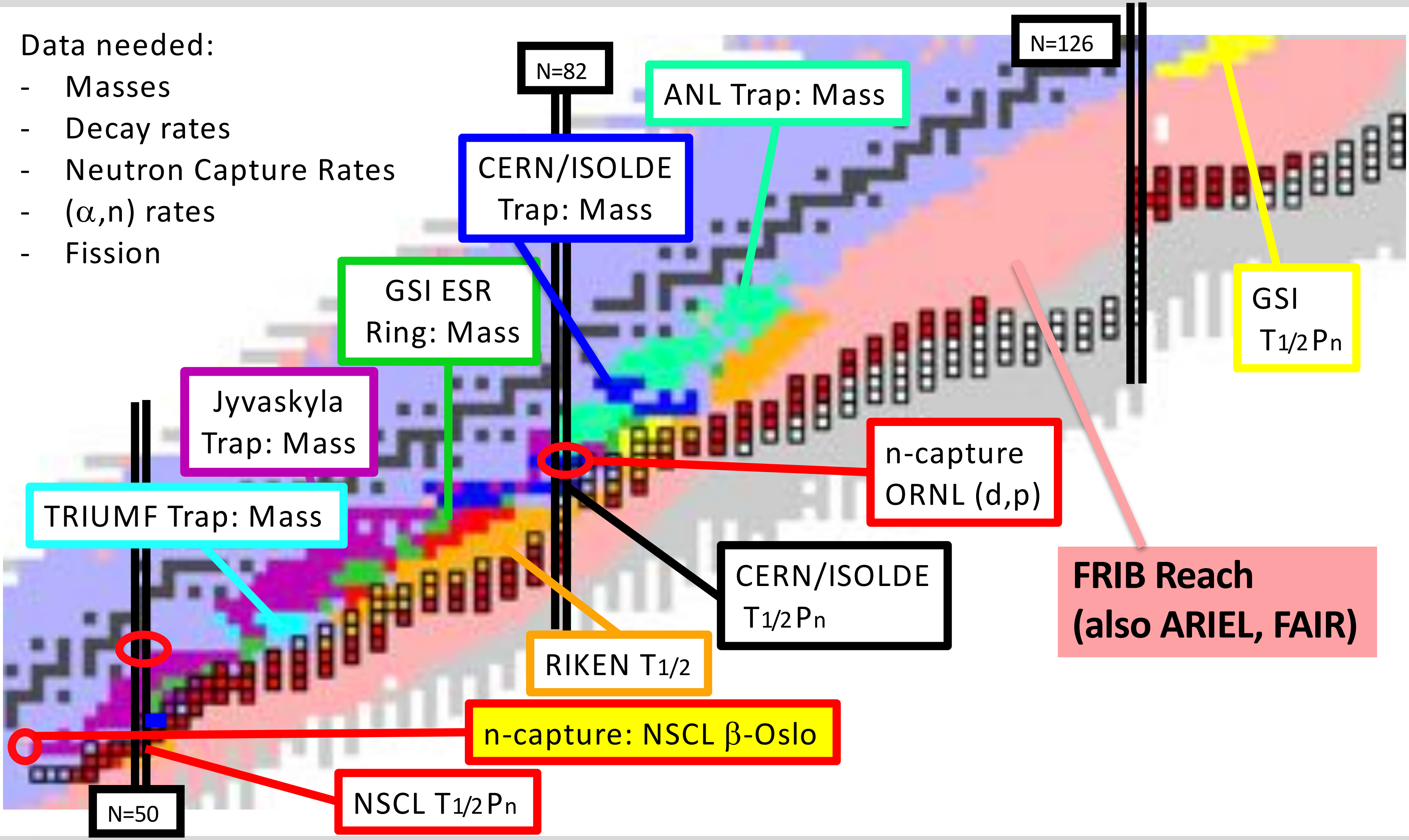
Future:

- F definition? Broader observables
- Correlations
- Broader models

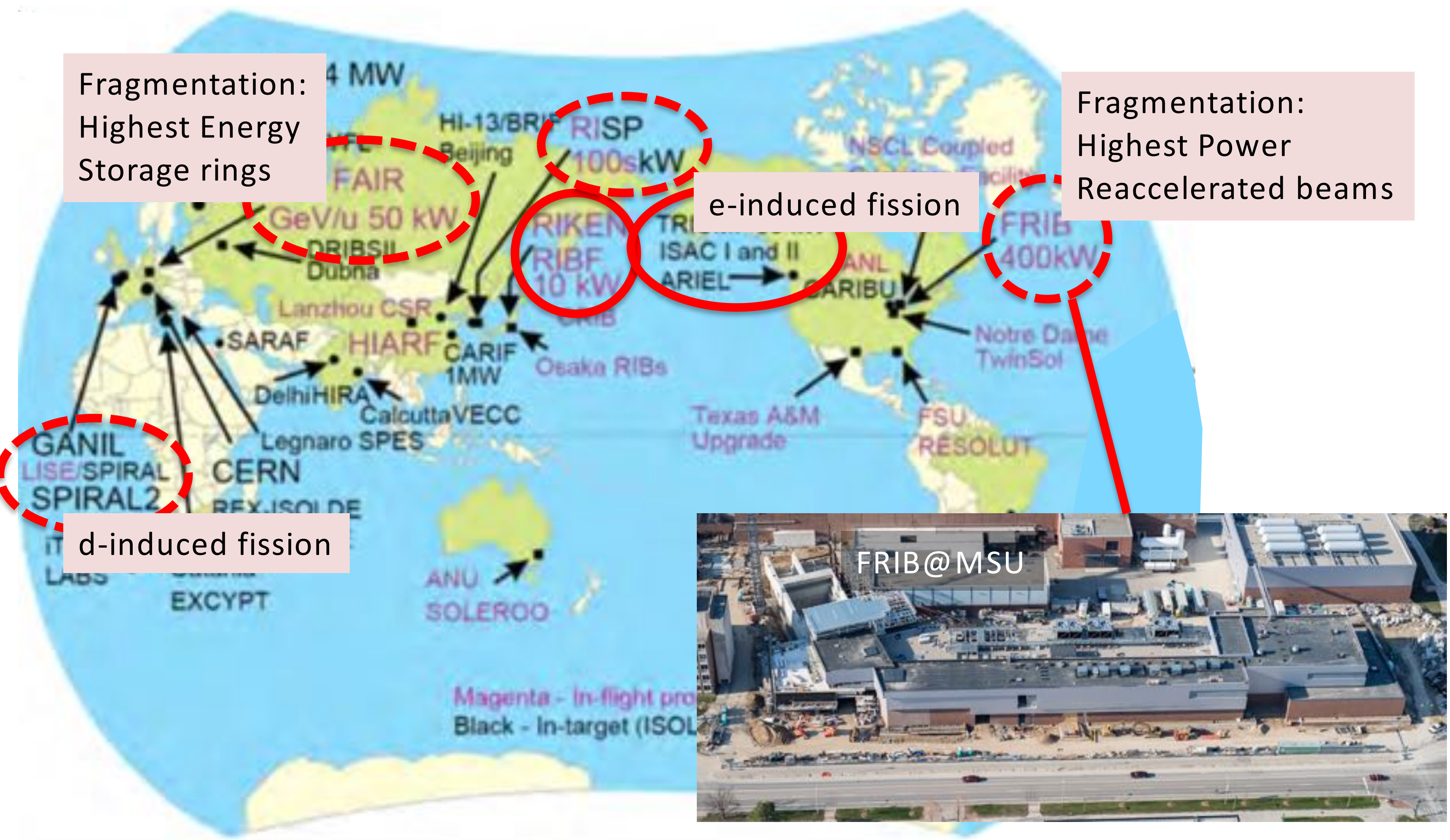
Surman
Mumpower
Aprahamian

Experiments have reached the r-process
New Generation of Facilities Cover Much of the R-process

Data needed:
- Masses
- Decay rates
- Neutron Capture Rates
- (α,n) rates
- Fission



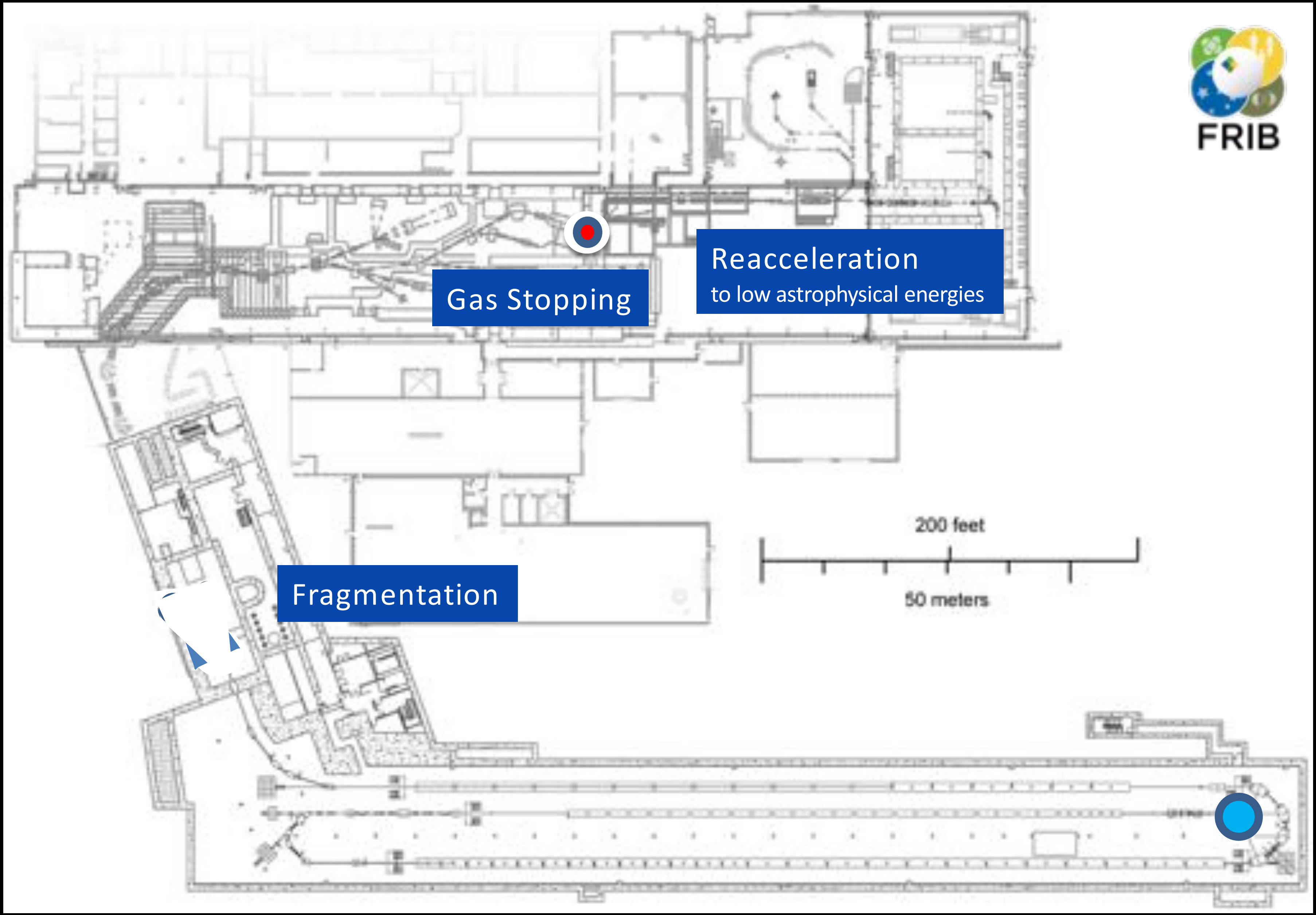
A New Generation of Facilities
Will Transform Rare Isotope Science – Including Astrophysics



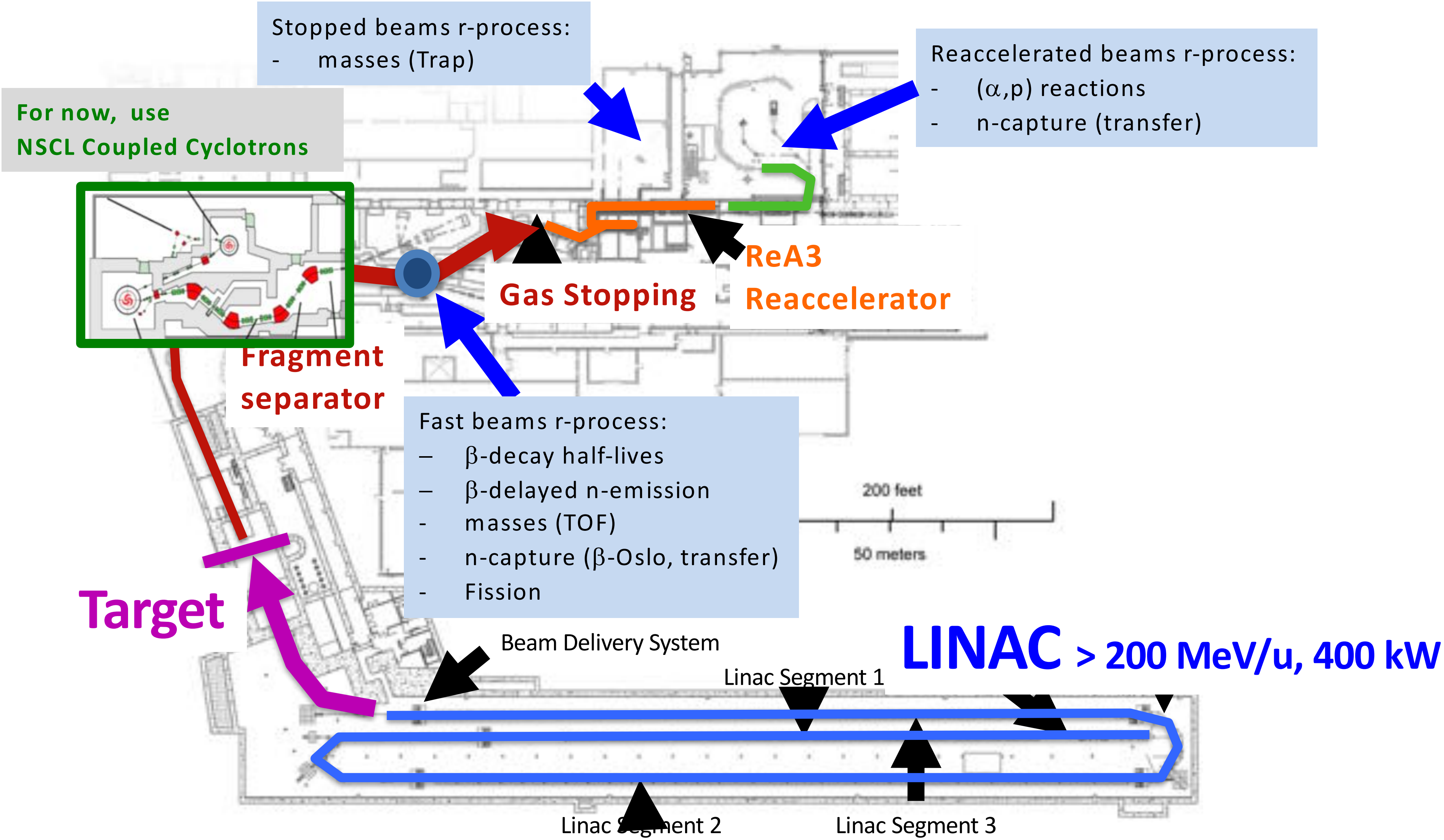
FRIB Project Summary

- FRIB will be a $730 million national user facility funded by the Department of Energy Office of Science (DOE-SC), Michigan State University, and the State of Michigan
- FRIB Project completion date is June 2022, managing to an early completion in fiscal year 2021
- FRIB will serve as a national user facility for world-class rare isotope research, (~1400 scientists currently engaged) and builds on more than 50 years of nuclear science expertise developed at MSU

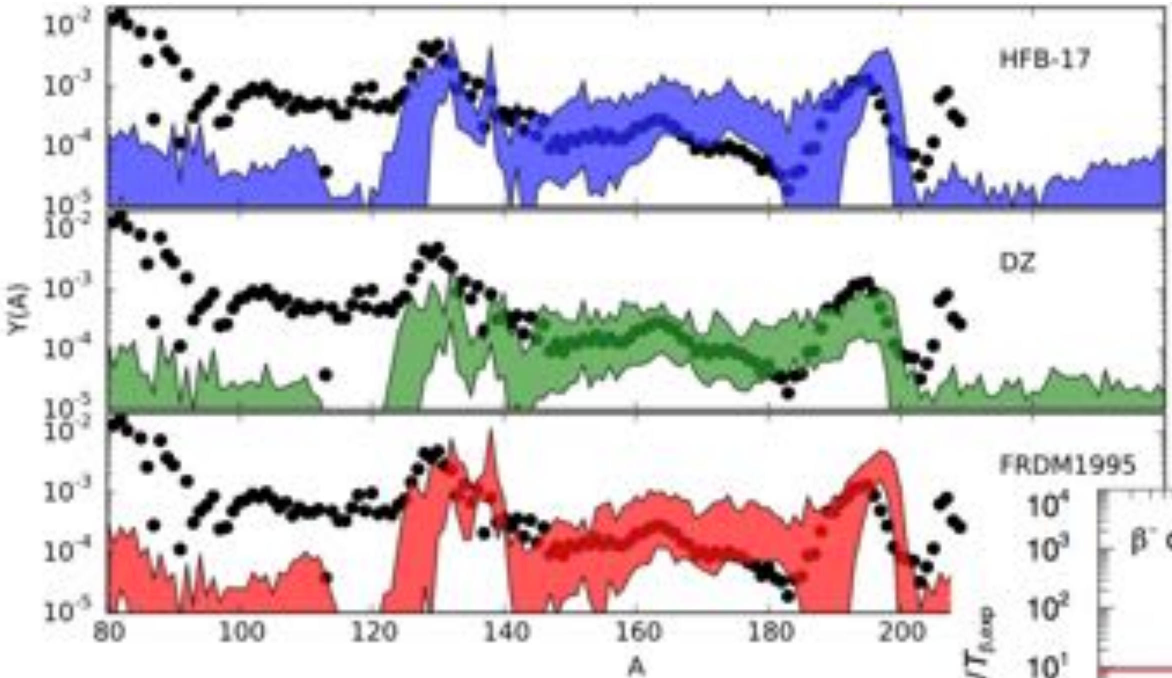
FRIB Provides Fast, Stopped, and Reaccelerated Beams

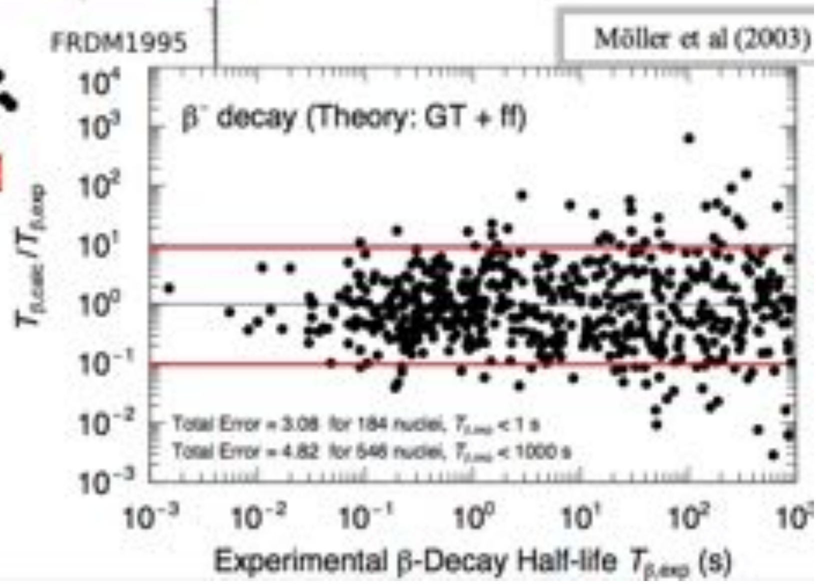


FRIB fast, stopped, and reaccelerated rare isotope beams are needed for r-process studies



β-decay half-lives



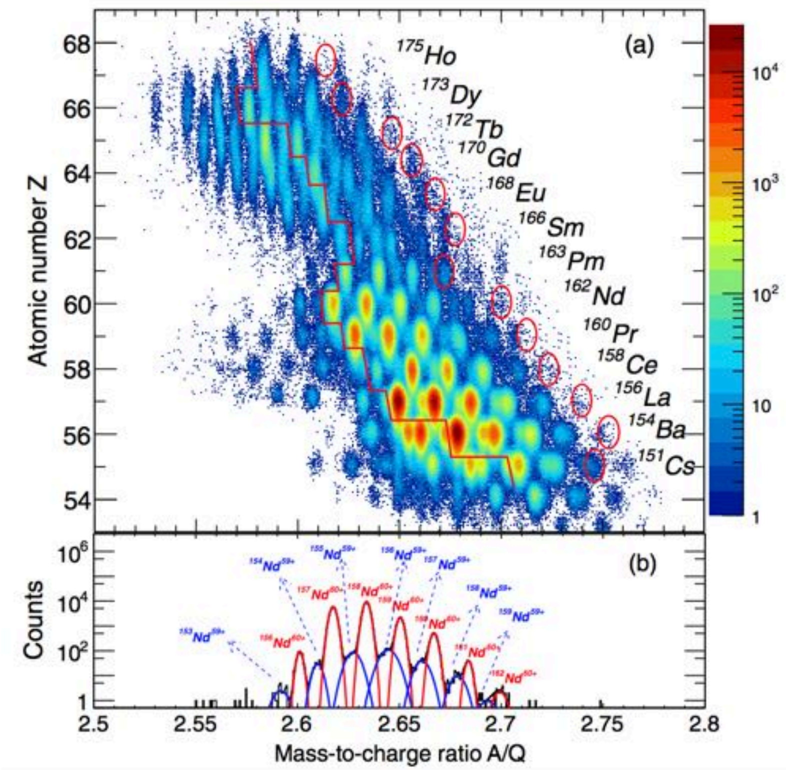


Monte-Carlo variations of half-lives (x10 error)
Mumpower et al.

→ Need much better than x10

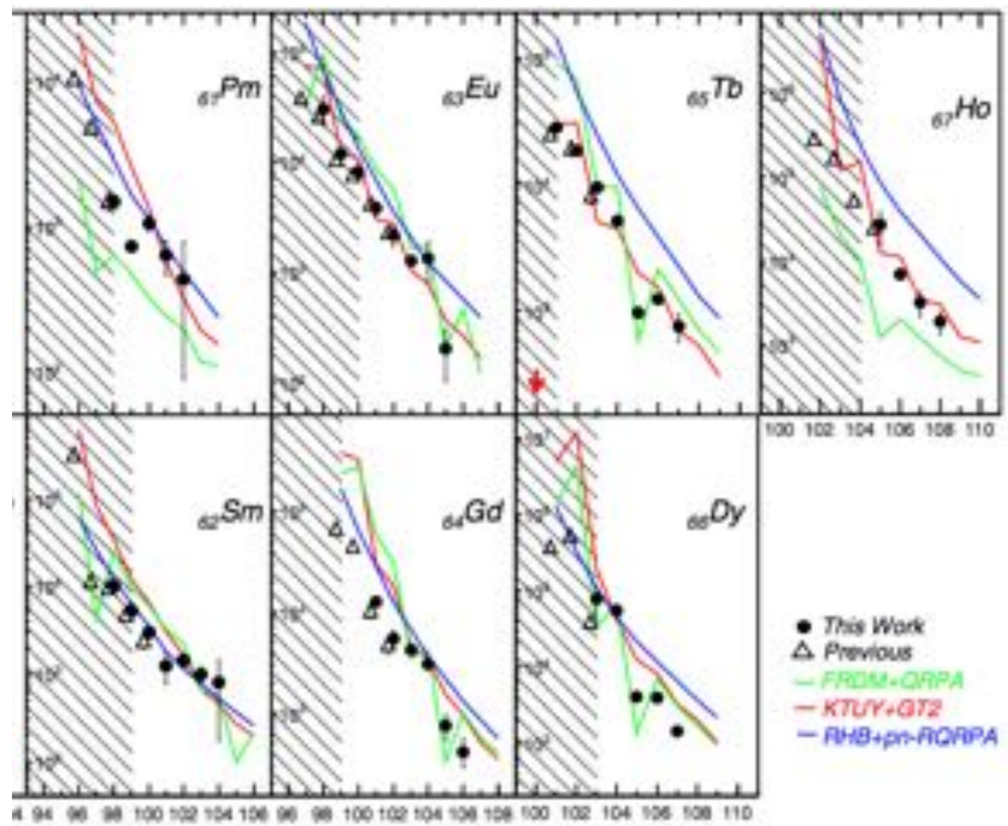
How to measure beta-decay half-lives and branchings for beta-delayed neutron emission?

Recent Results from RIKEN



Wu, Nishimura, Lorusso, et al. 2017, RIKEN

Half-life



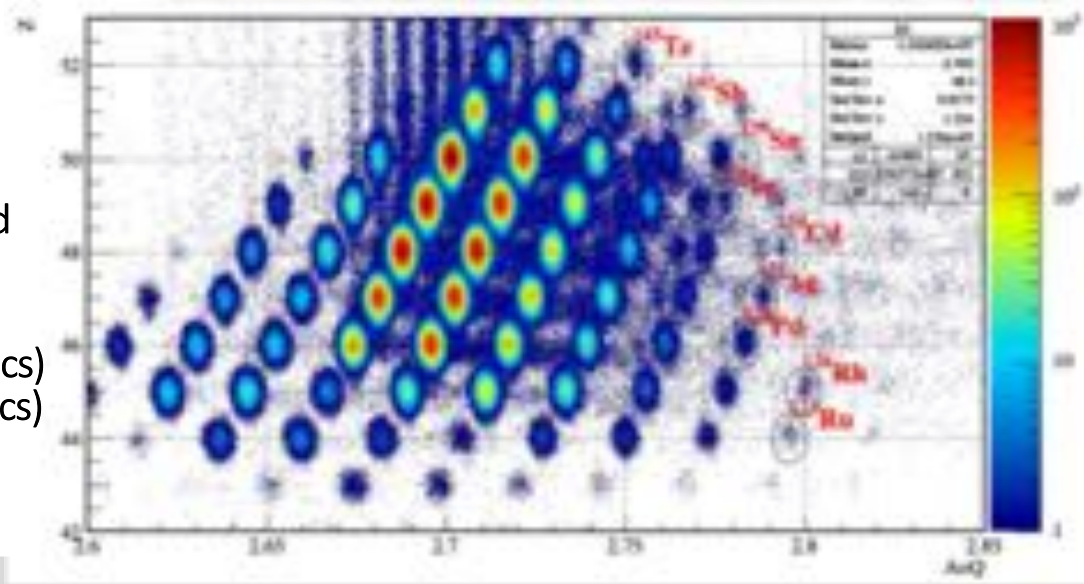
neutron number

→ Starting to reach important half-lives for synthesis of rare earth elements

Beta-delayed neutron emission experiments

Estrade, Montes, Dillmann (CMU, MSU, TRIUMF)

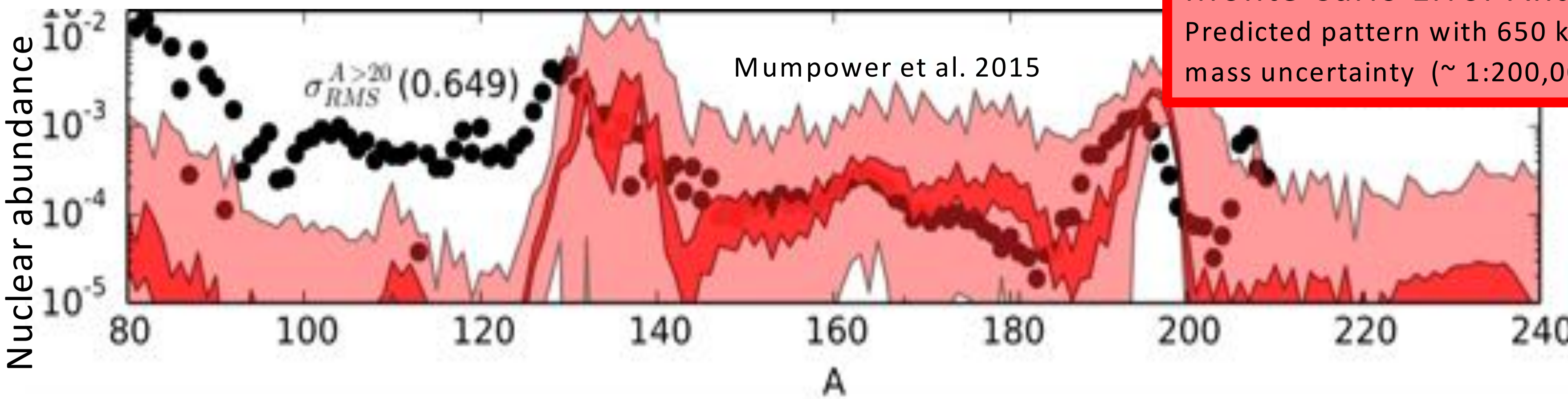
- BRIKEN neutron detector installed at RIKEN
- 148 ^{3}He-filled neutron counters from Germany, Japan, Spain, USA and 2 HPGe clovers (Oak Ridge)
- Implantation detector AIDA (Edinburg, Daresbury)



- First experimental campaign 2016/2017. Second campaign in 2018
- So far, 268 isotopes studied
- Expected 45 new $T_{1/2}$ (+16 depending on statistics)
- Expected 165 new P_n (+19 depending on statistics)

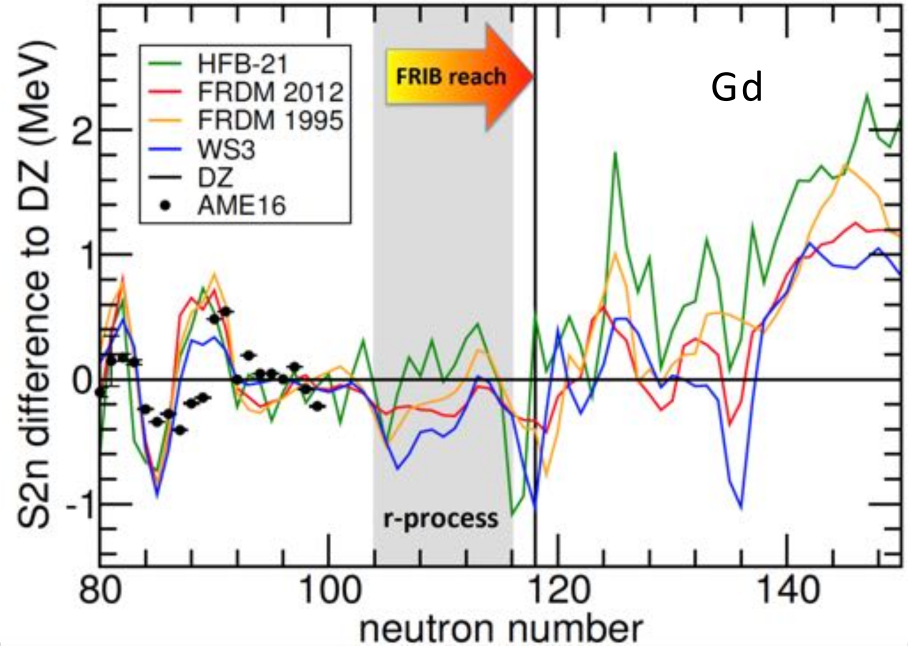
Nuclear Masses

Monte Carlo Error Analysis:
Predicted pattern with 650 keV mass uncertainty (~ 1:200,000)



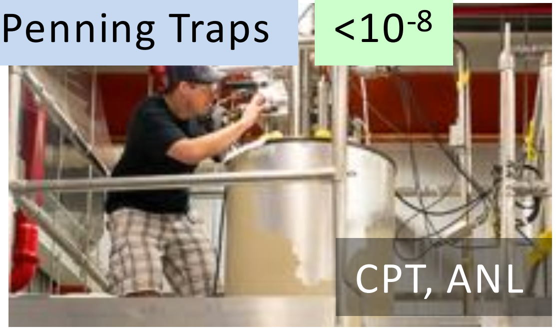
→ Need at least 100 keV
→ 1:1,000,000 precision !!!!

Typical mass model performance for known masses not used to fit: ~600-800 keV
→ Need Experiment

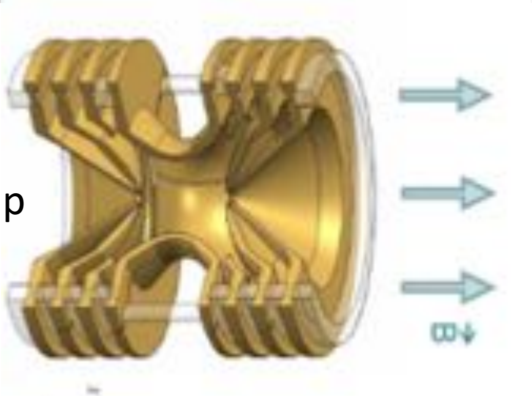


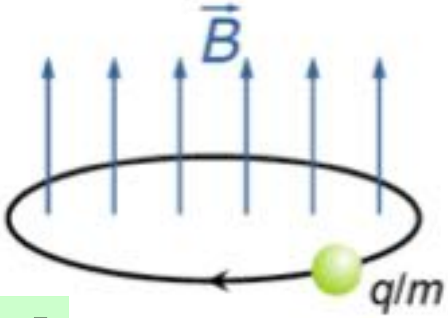
Mass Measurements

Penning Traps $<10^{-8}$



Trap

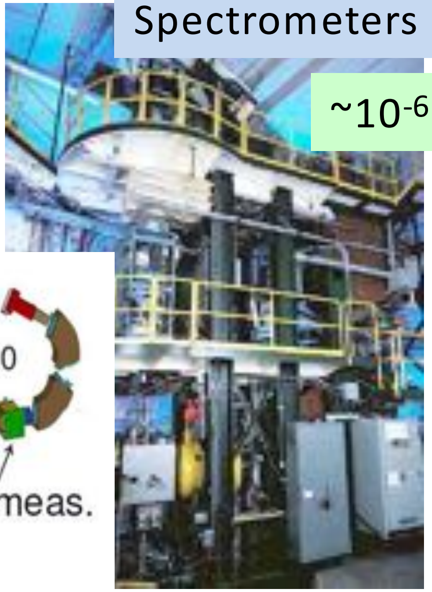




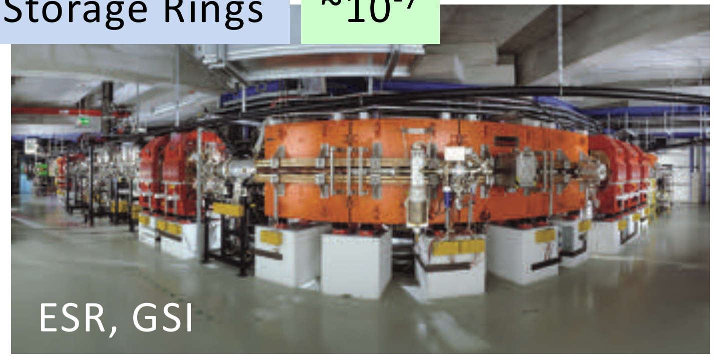
Cyclotron frequency:

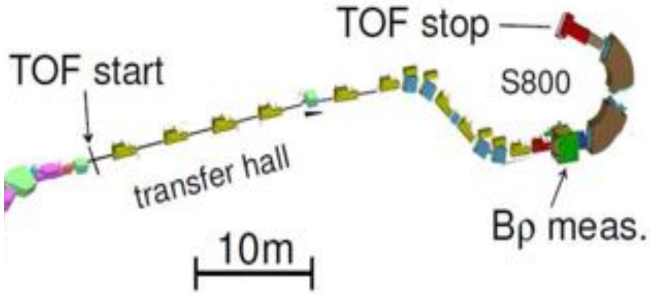
$$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

Spectrometers $\sim 10^{-6}$



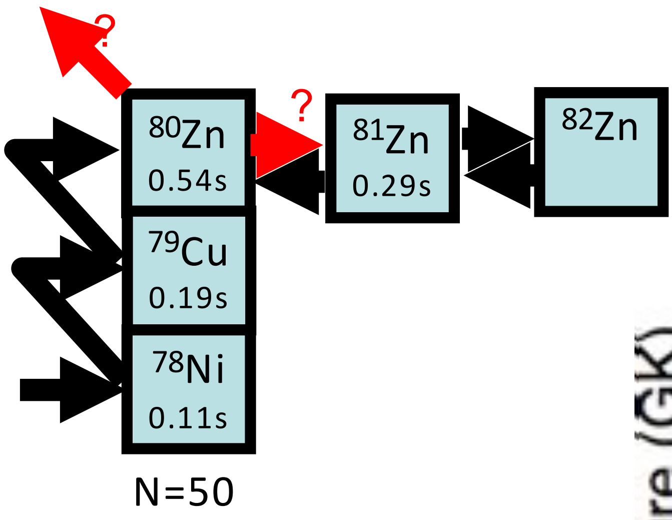
Storage Rings $\sim 10^{-7}$



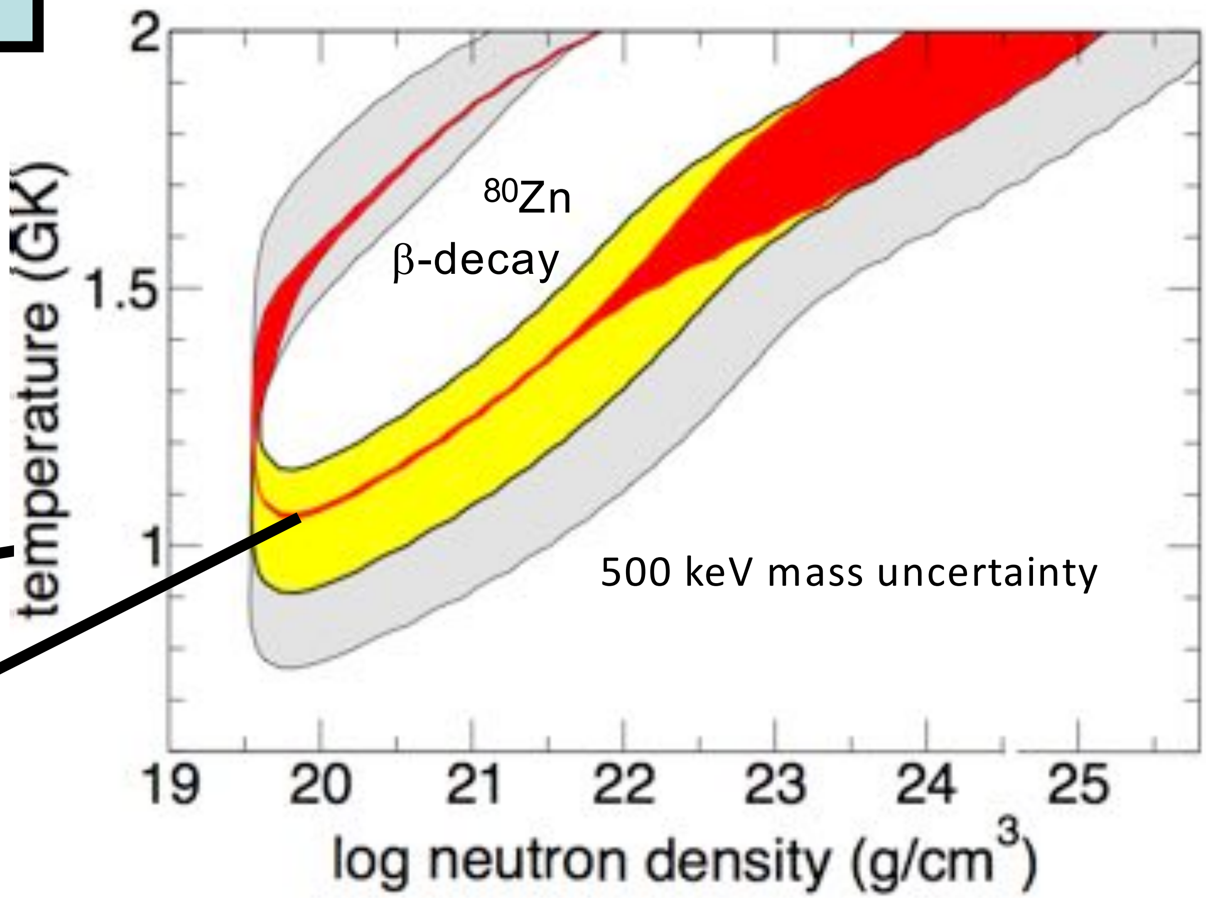


Example Impact of Mass Measurement

Baruah et al. 2008, ISOLTRAP



Conditions for >90% β-branch (^{80}Zn is waiting point)

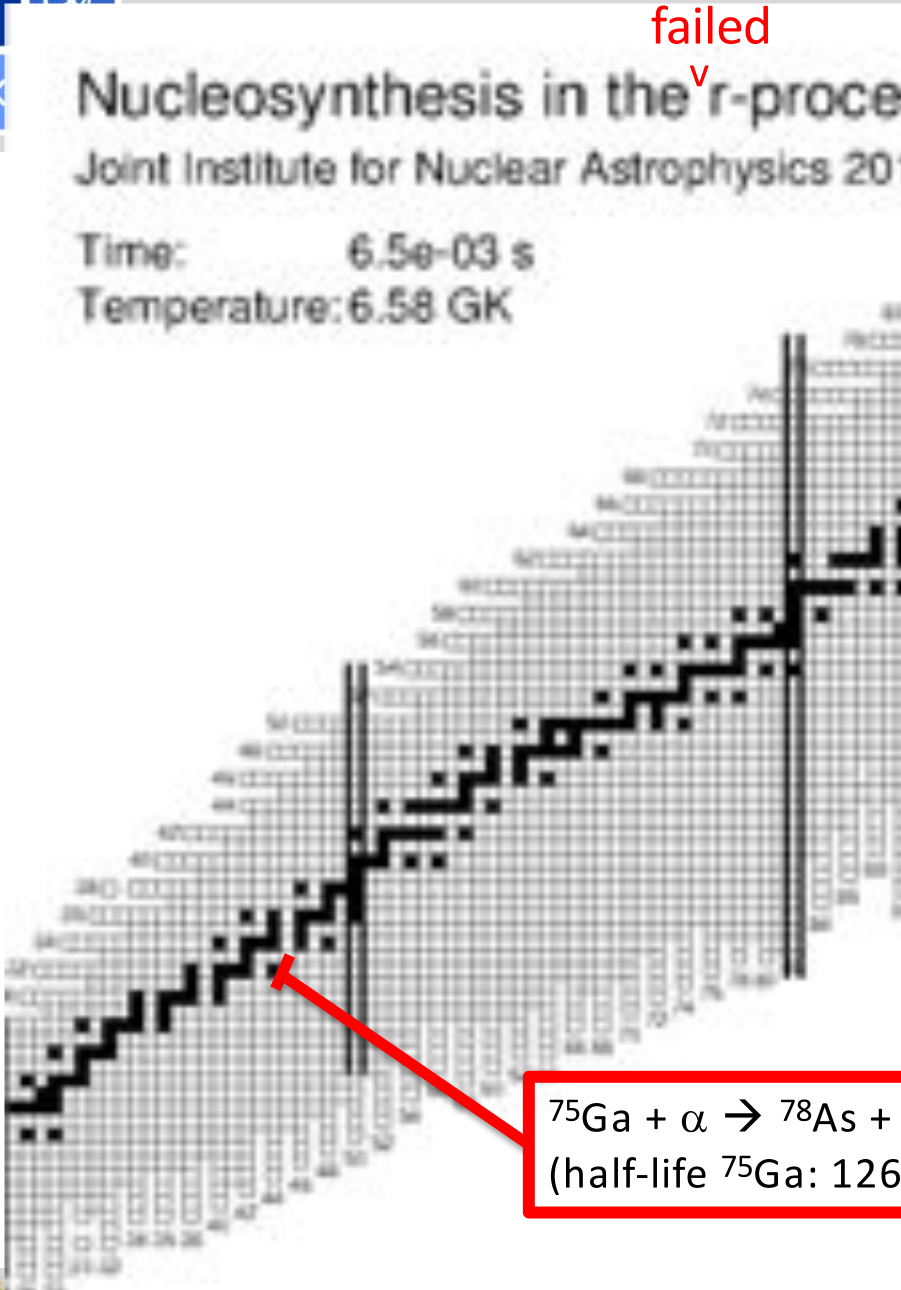


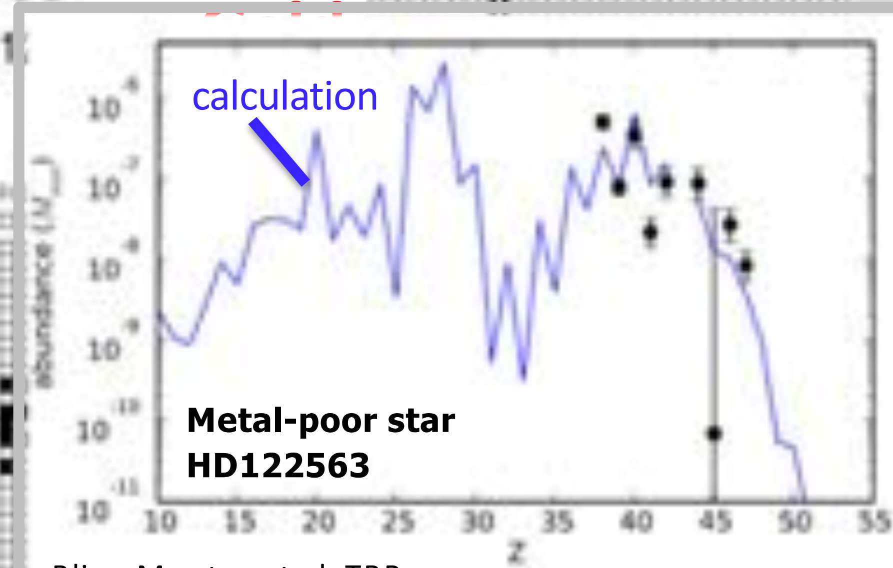
Precision masses up to ^{80}Zn

Precision masses up to ^{81}Zn

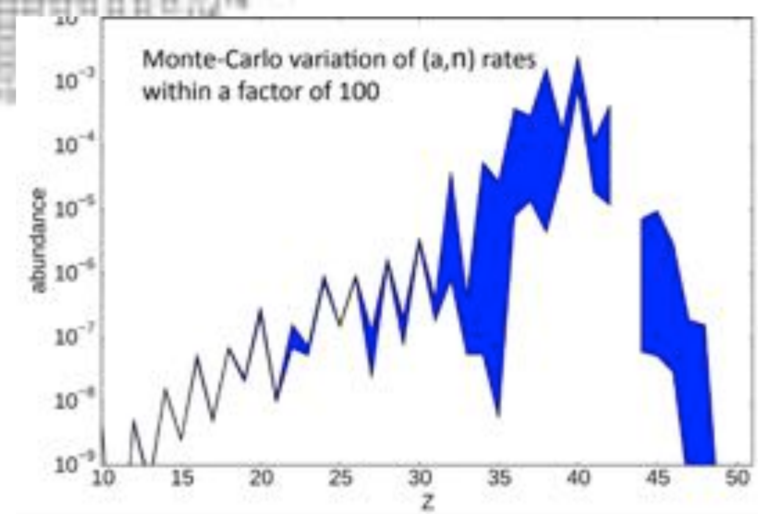
^{81}Zn mass excess: -46199.6(5)

failed





Bliss, Montes et al. TBP

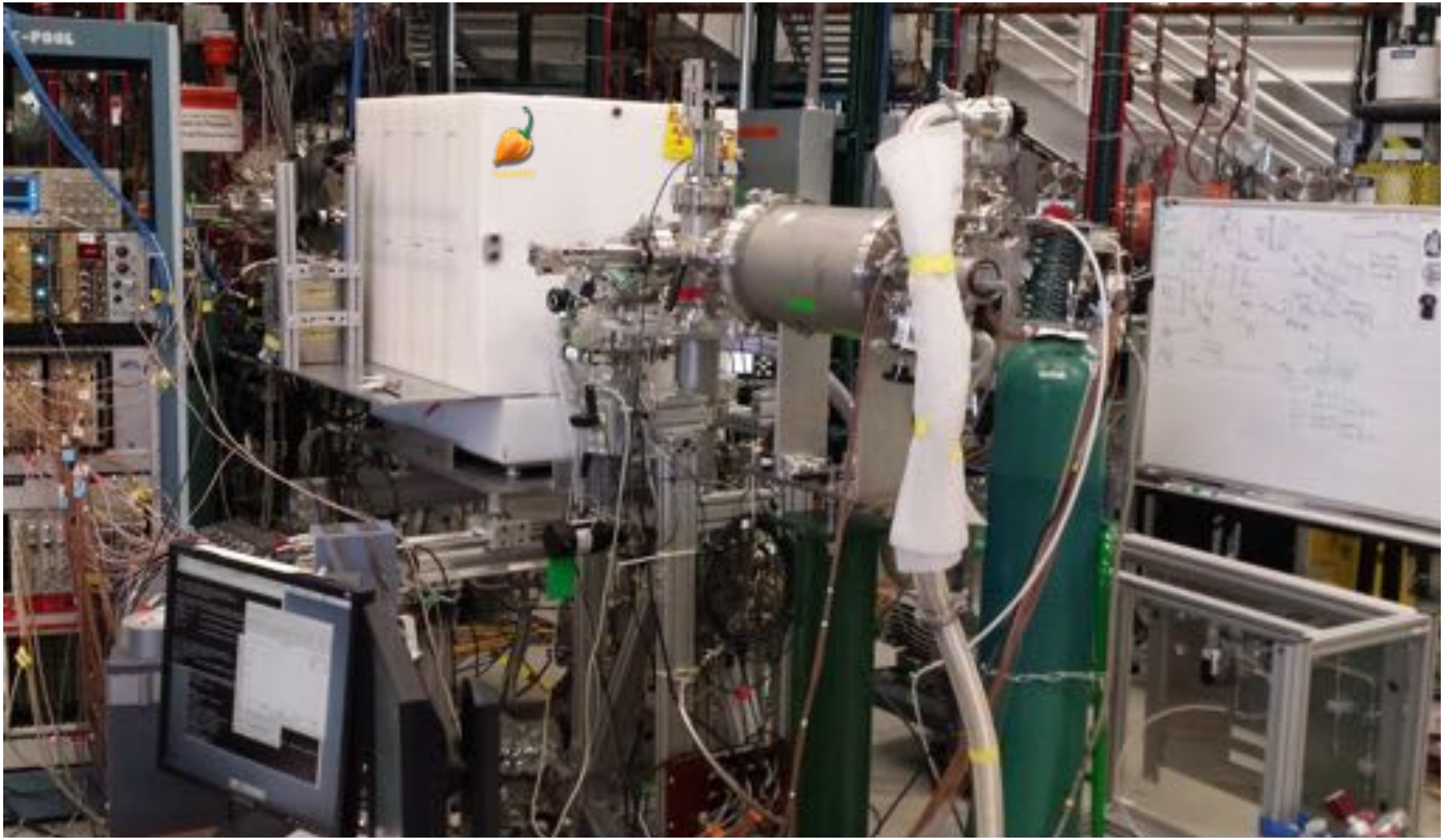


$^{75}Ga + \alpha \rightarrow {}^{78}As + n$
(half-life ^{75}Ga: 126s)

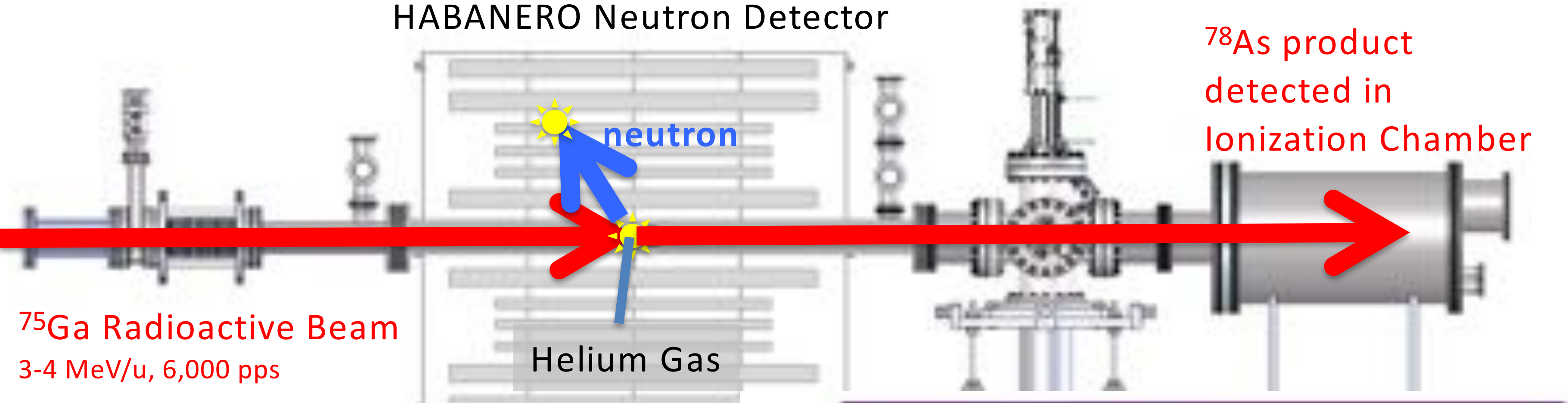
How could one measure the
Alpha + $^{75}Ge \rightarrow {}^{78}As$ + n
Reaction rate?

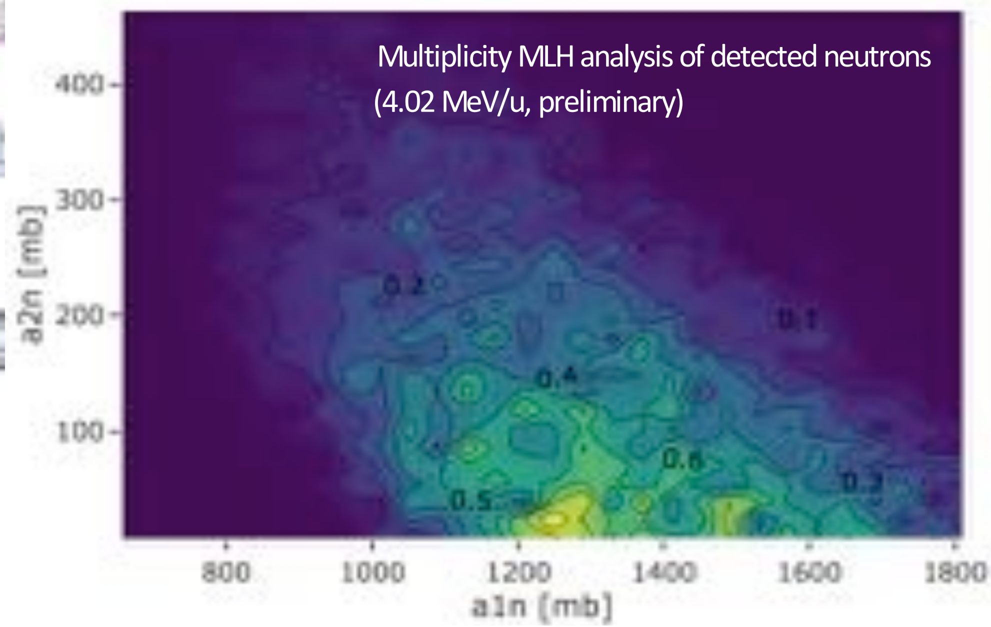
HABANERO Neutron Detector

Heavy ion **A**ccelerated **B**eam induced (**A**lpha, **N**eutron) **E**mission **R**atio **O**bserver



(α,n) Experiements at NSCL ReA3



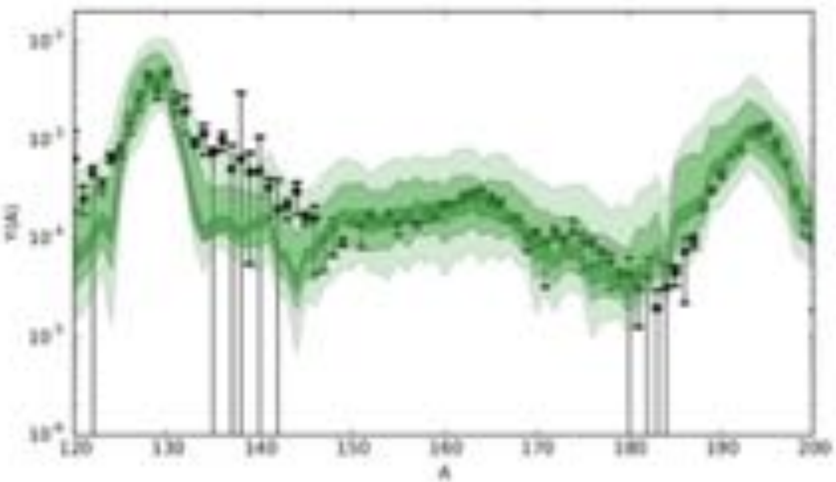


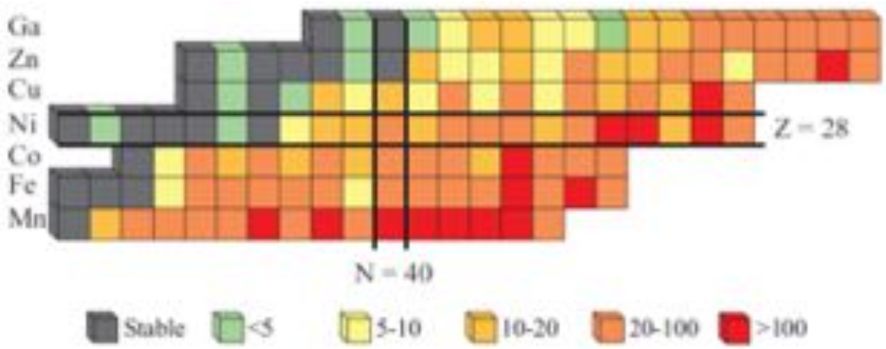
Collaboration:
Meisel, Montes,
Pereira, et al.
MSU, Ohio U,
CMU, LSU, UT,
Notre Dame, ORNL,
TU-Darmstadt

Neutron Capture Rates

Liddick et al. 2016

Estimated uncertainties in theoretically predicted neutron capture rates





Monte-Carlo variations of (n,γ) rates within a factor 100 – 10 – 2 (light – darker – dark bands)

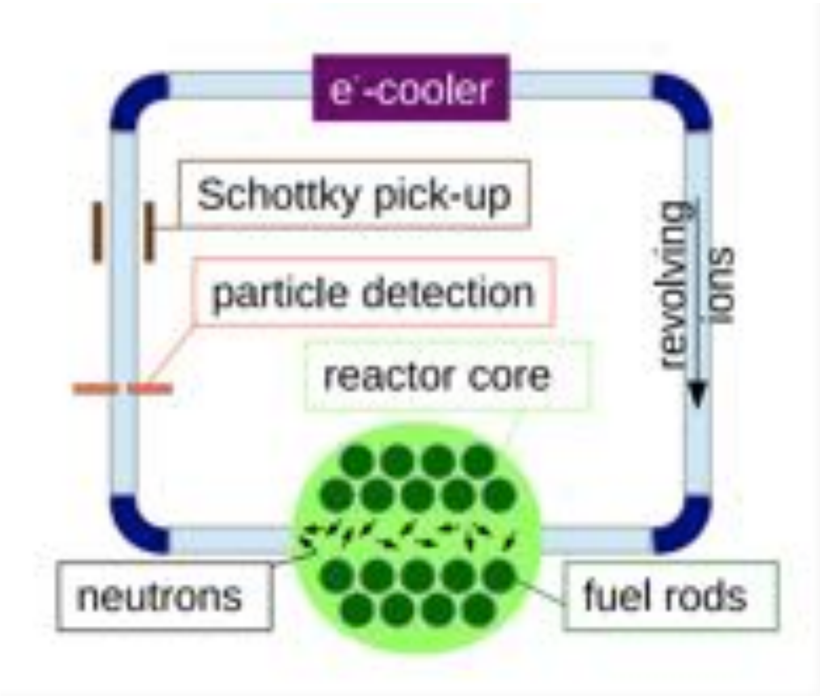
→ Need experimental constraints

How can we measure neutron capture
On unstable rare isotopes?

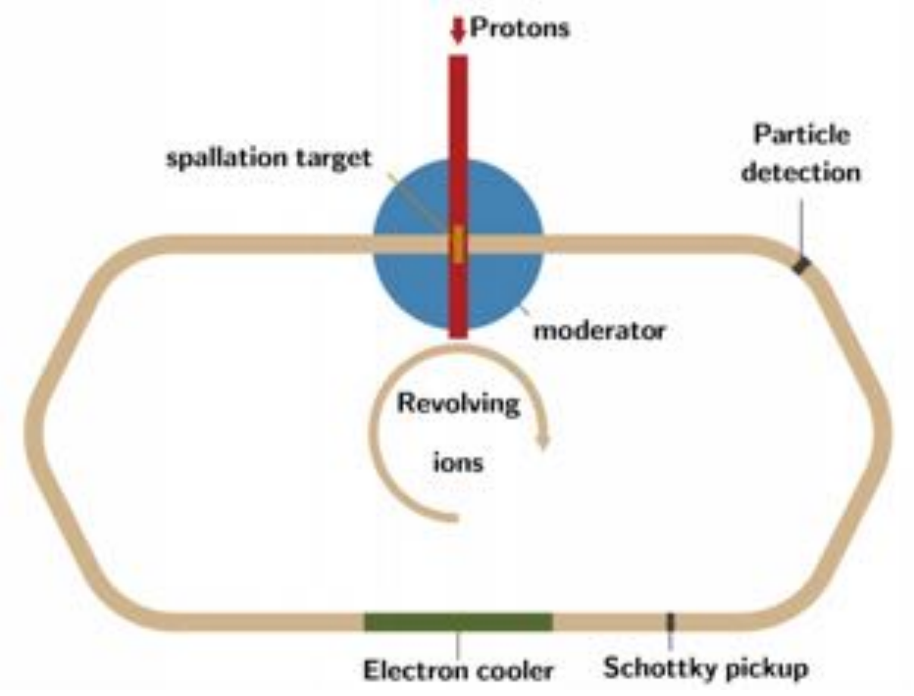
Advanced Ideas

Reifarth et al. 2015, 2018
https://arxiv.org/abs/1803.08678

Reactor as Neutron Target



Spallation Source as Target



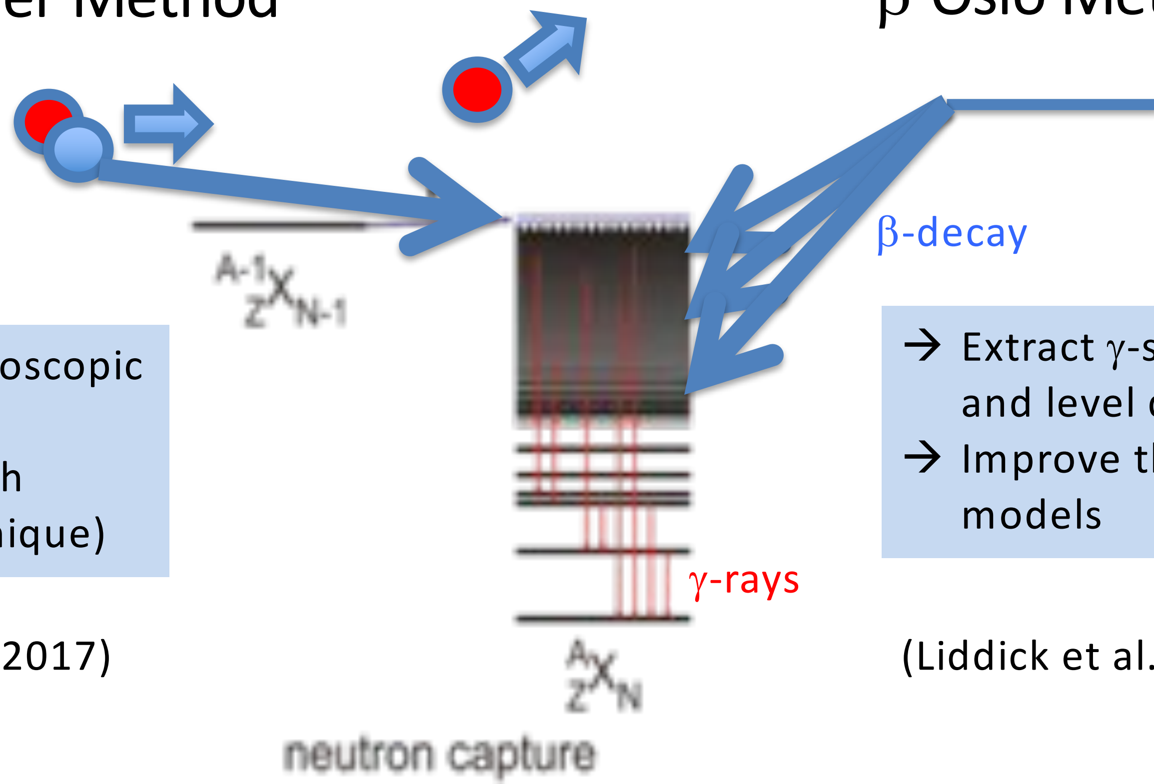
In the Meantime … Recent Approaches

Neutron Transfer Method

for example deuterium

- → Constrain spectroscopic factors
- → Extract γ-strength (Surrogate technique)

(e.g. Cizewski et al. 2017)



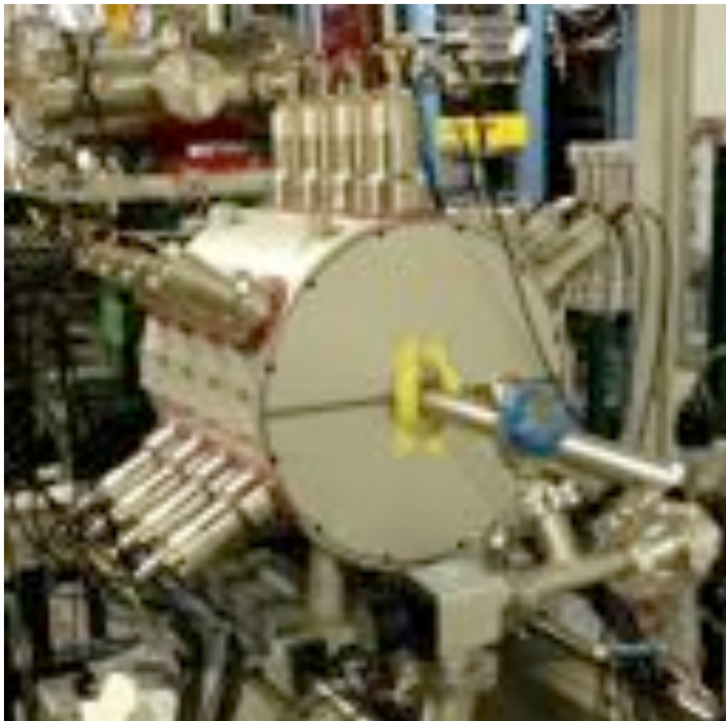
β-Oslo Method

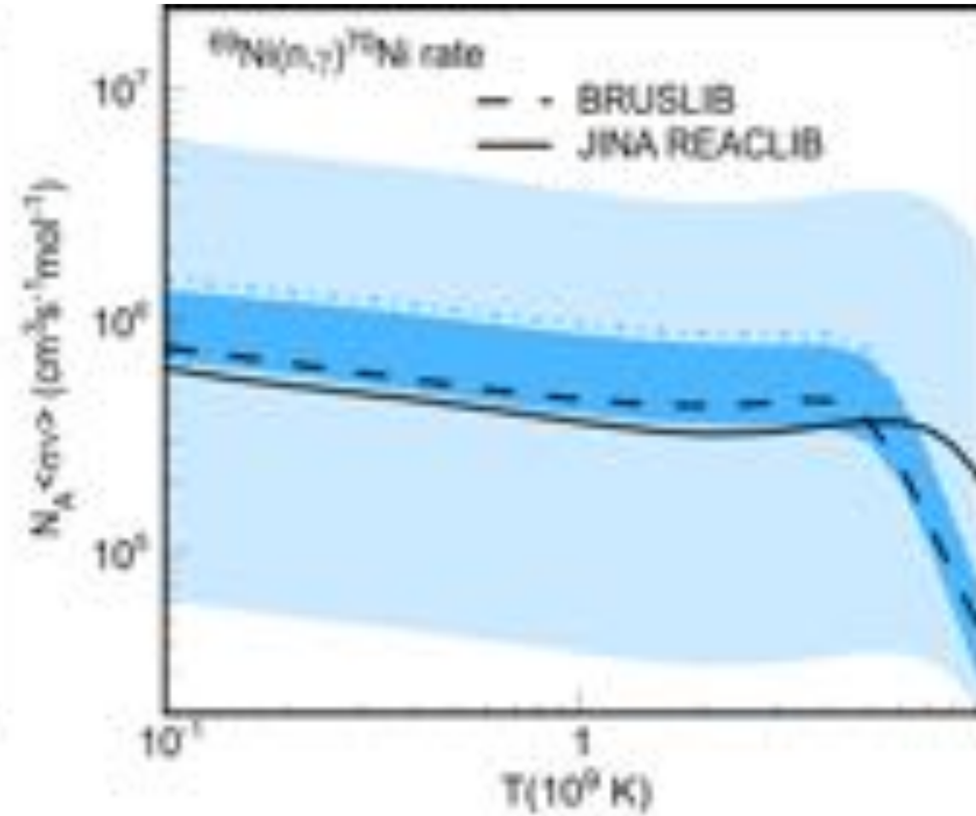
- → Extract γ-strength and level density
- → Improve theoretical models

(Liddick et al. 2016)

Liddick, Spyrou, et al. 2016

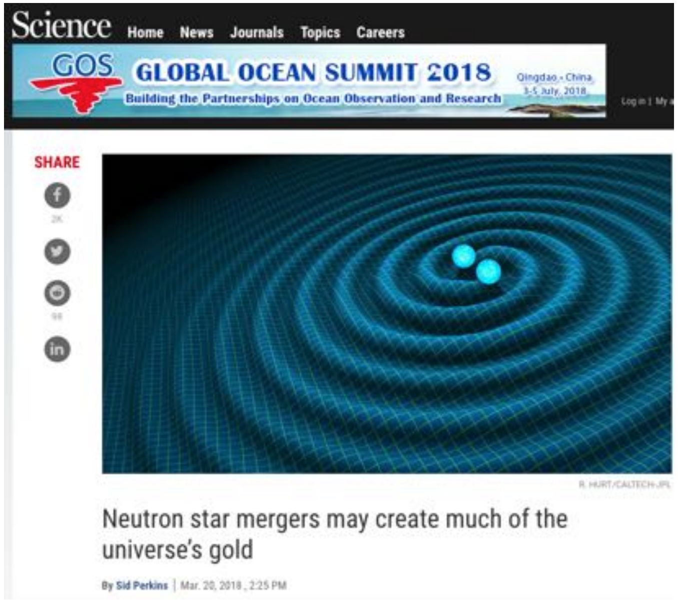
SuN γ-ray detector at NSCL





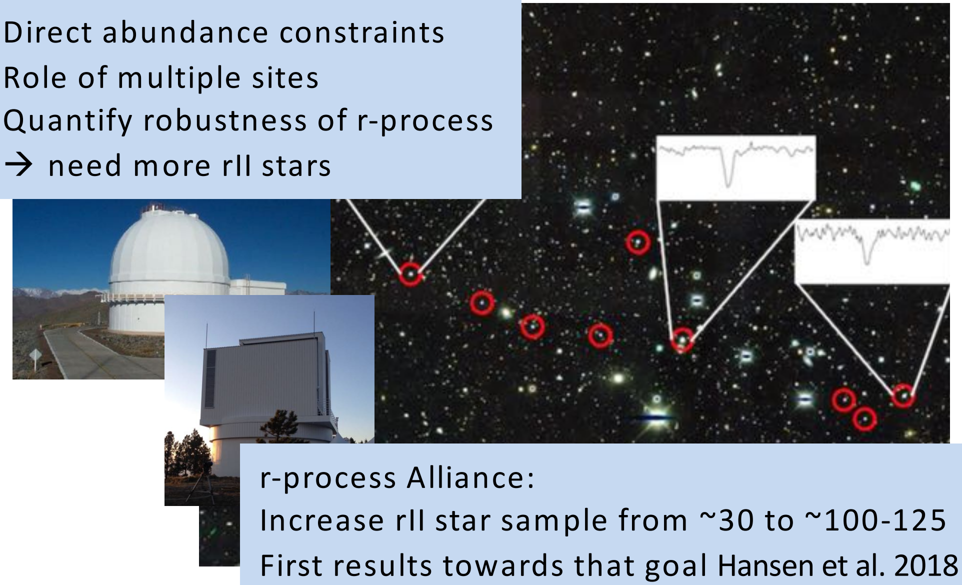
Exciting Times for Nuclear Astrophysics

Gravitational Waves and Followup



Stellar Spectroscopy

Direct abundance constraints
Role of multiple sites
Quantify robustness of r-process
→ need more rII stars

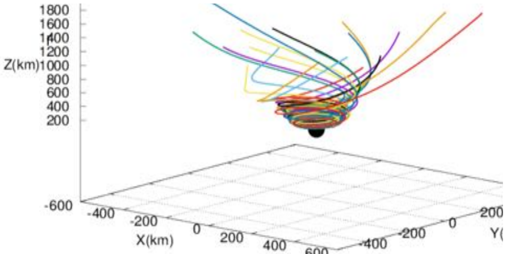


r-process Alliance:
Increase rII star sample from ~30 to ~100-125
First results towards that goal Hansen et al. 2018

New Experimental Results and Developments

FAIR, ARIEL, …

Advances in Computational Models

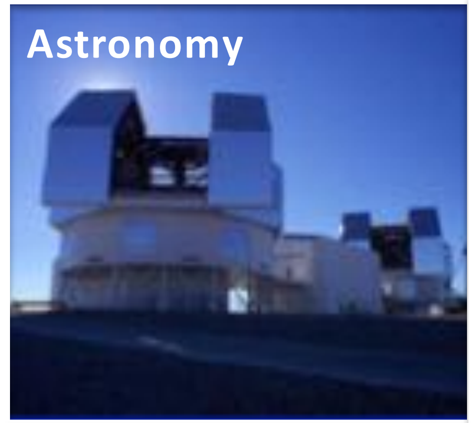


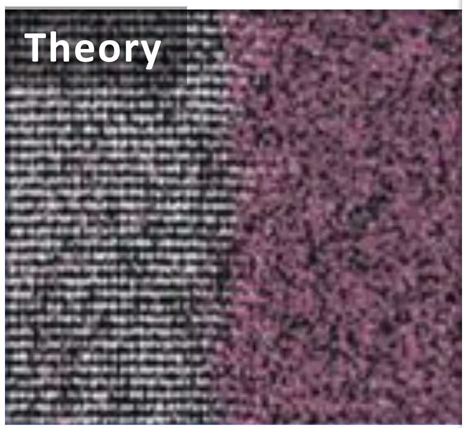
Foucart

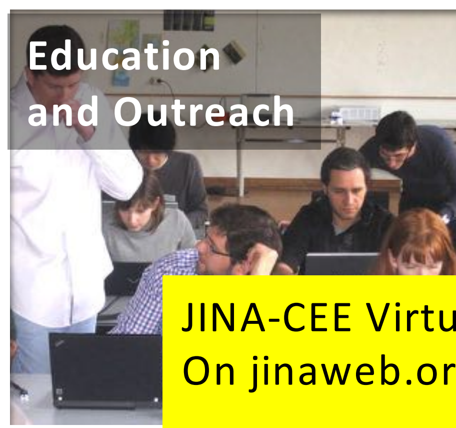
The Joint Institute for Nuclear Astrophysics

Center for the Evolution of the Elements – jinaweb.org

- Collaborative network:
    - Origin of the elements
    - Neutron stars
- Website: jinaweb.org
- Schools, Workshops, Conferences, online courses coming
- 65 Senior Investigators, 24 Institutions, 9 Countries

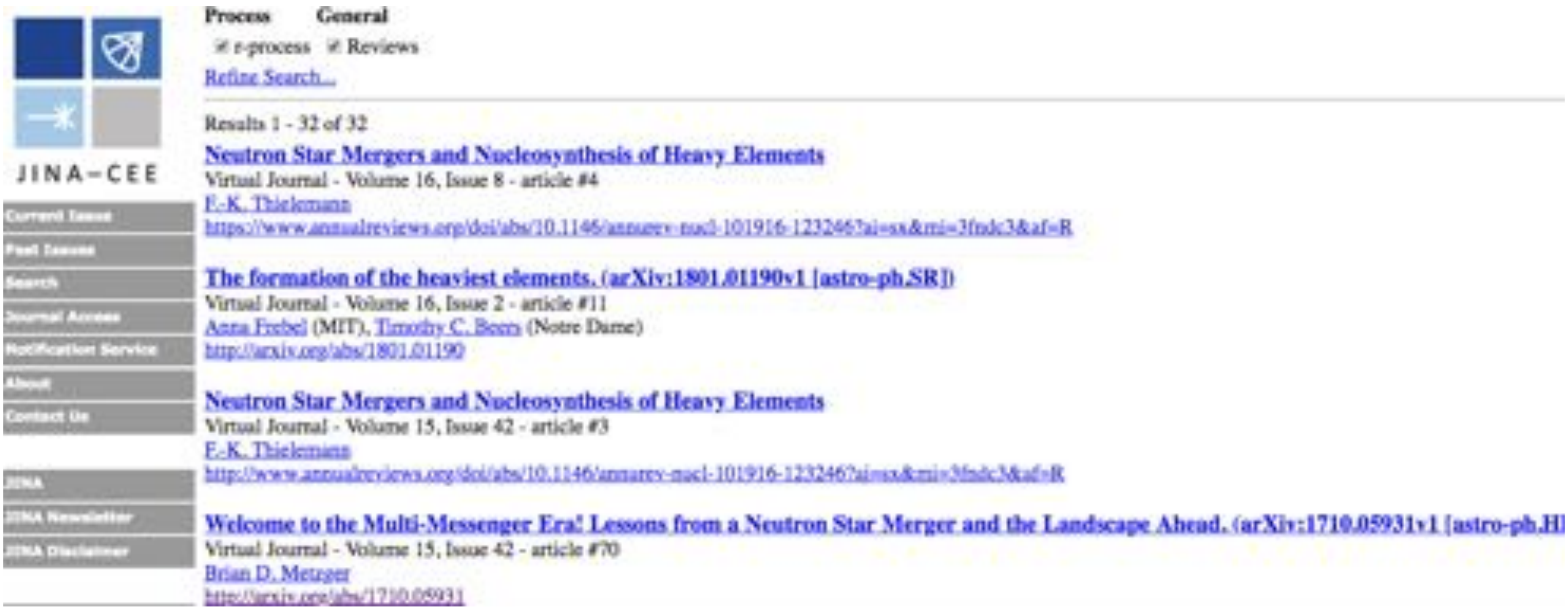






JINA-CEE Virtual Journal
On jinaweb.org

JINA-CEE Virtual Journal



- Each week listing of nuclear astrophysics publications selected from ~20 journals
- Key word searchable

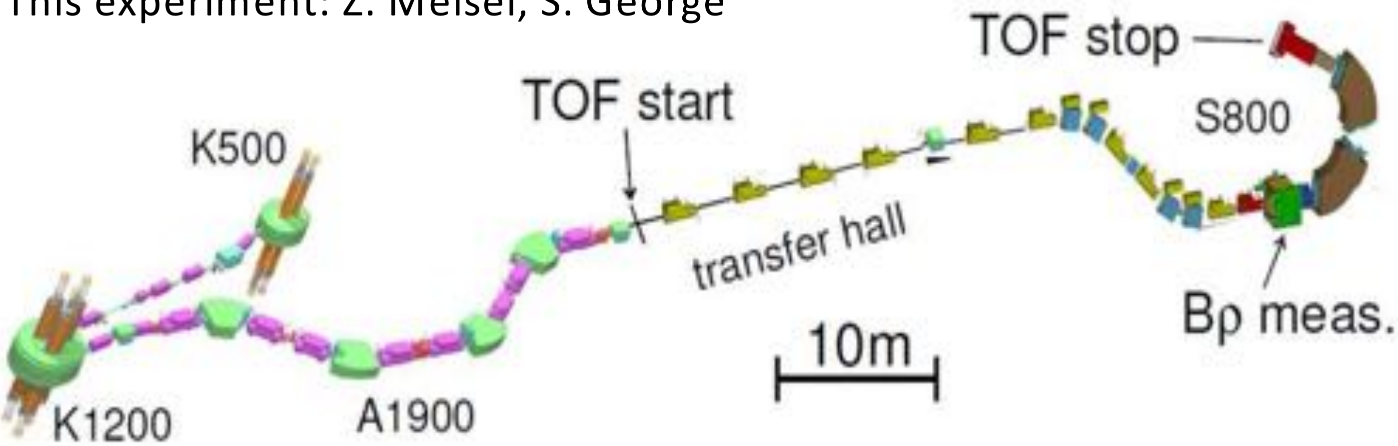
JINA-CEE Virtual Journal
On jinaweb.org

Summary

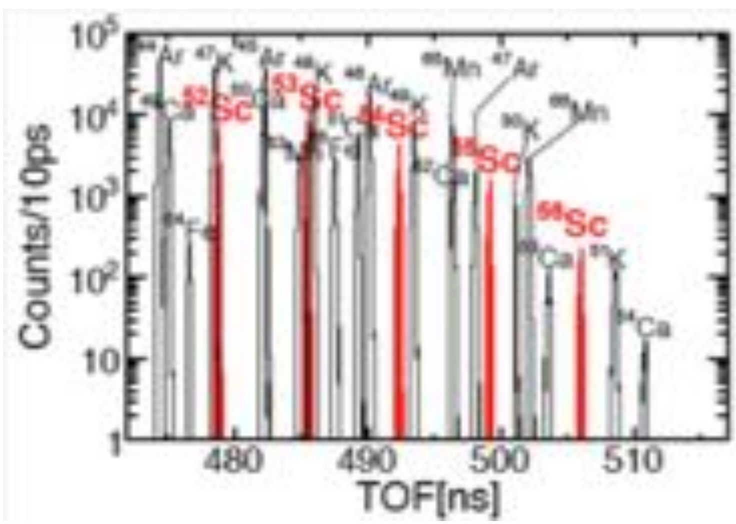
- Nuclear physics is essential for
  - Interpreting observations of neutron star mergers
  - To understand NS merger contributions to the origin of the elements
- Experimental data are needed
  - For reliable merger nucleosynthesis models
  - To develop nuclear theory to predict the broad range of nuclear physics needed
- Obtaining data for r-process nuclei is extremely challenging and has been a long term goal of the community
  - This is now within reach with a new generation of rare isotope facilities
  - Facilities and experimental techniques are under development to obtain broad range of nuclear physics information needed
- Communication across astronomy, astrophysics, gravitational physics, computational physics, nuclear physics is critical
  - Centers like JINA-CEE are building the necessary connections across field boundaries

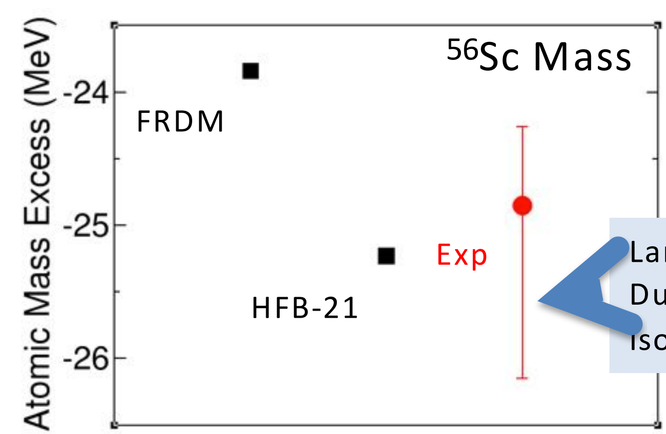
Time-of-Flight Mass Measurements at NSCL

Originally developed at NSCL by A. Estrade, M. Matos, M. Famiano, H. Schatz
This experiment: Z. Meisel, S. George



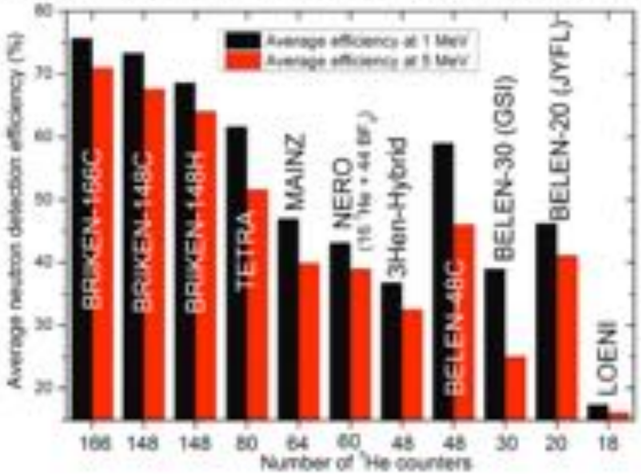
Length: 60 m
Timing: 80 ps
Tracking: 0.3 mm
→ 1.8×10^{-4} resolution
→ ~100 keV systematic error

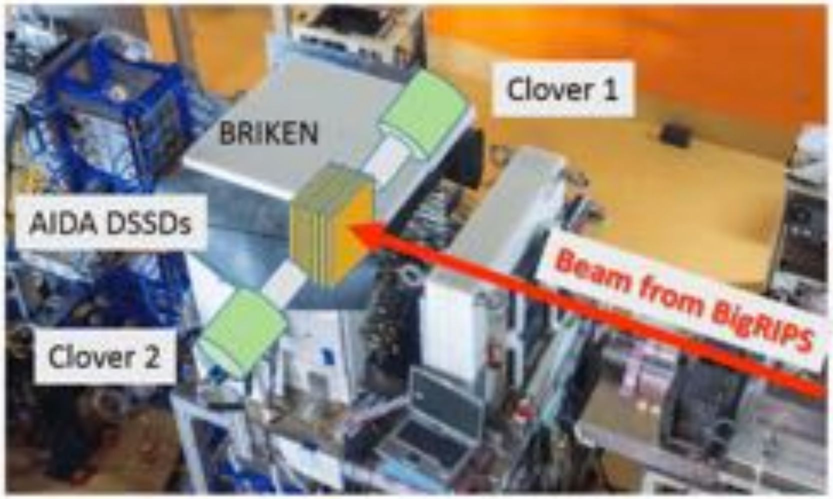




Large error
Due to possible isomer

- BRIKEN neutron detector installed at RIKEN
- 148 ^{3}He-filled neutron counters from Germany, Japan, Spain, USA and 2 HPGe clovers (Oak Ridge)
- Implantation detector AIDA (Edinburg, Daresbury)





- First experimental campaign 2016/2017. Second campaign in 2018
- So far, 268 isotopes studied
- Expected 45 new $T_{1/2}$ (+16 depending on statistics)
- Expected 165 new P_n (+19 depending on statistics)