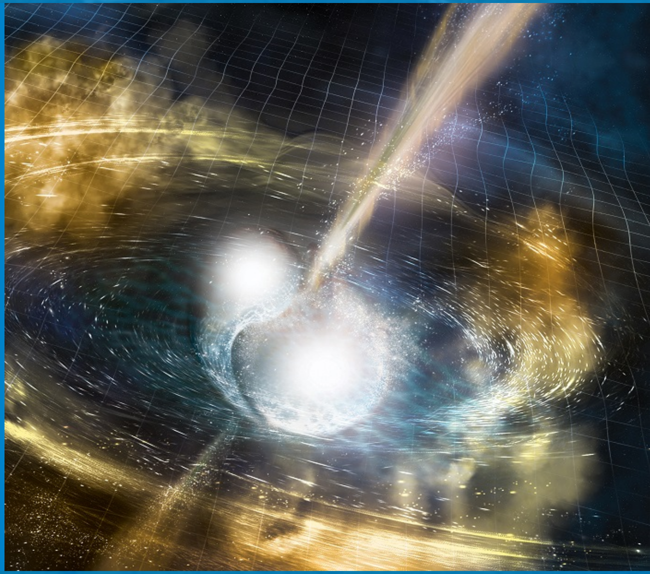
MARCH 14, 2018

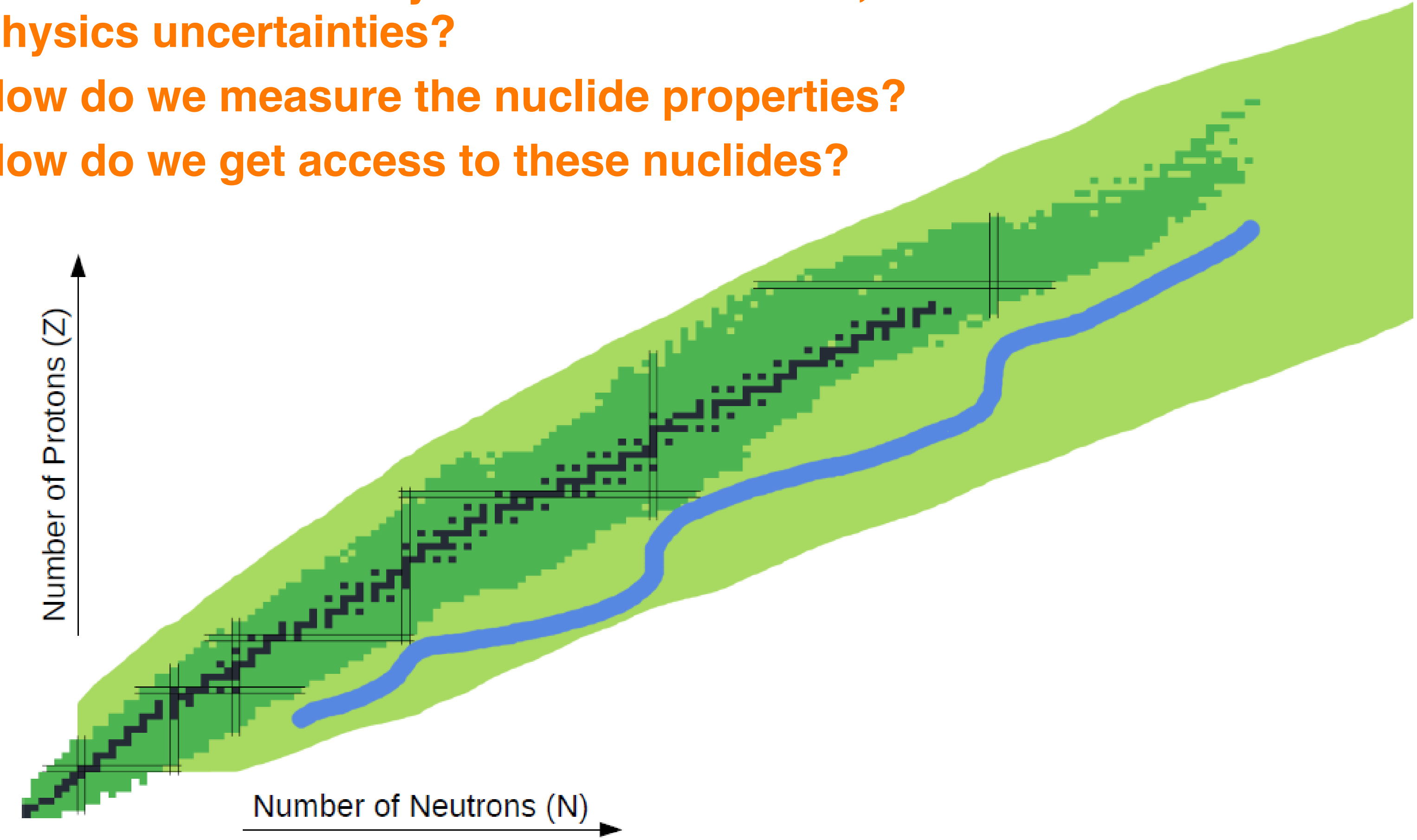
NUCLEAR FACILITY/EXPERIMENT CONTRIBUTIONS TO MERGING NEUTRON STARS



JASON CLARK
INT-JINA Symposium

OUTLINE

- Where do all the elements in the universe come from?
  - Can merging neutron stars account for all the observed elements?
  - The devil is in the details
- For detailed nucleosynthesis calculations, what are the dominant nuclear physics uncertainties?
- How do we measure the nuclide properties?
- How do we get access to these nuclides?

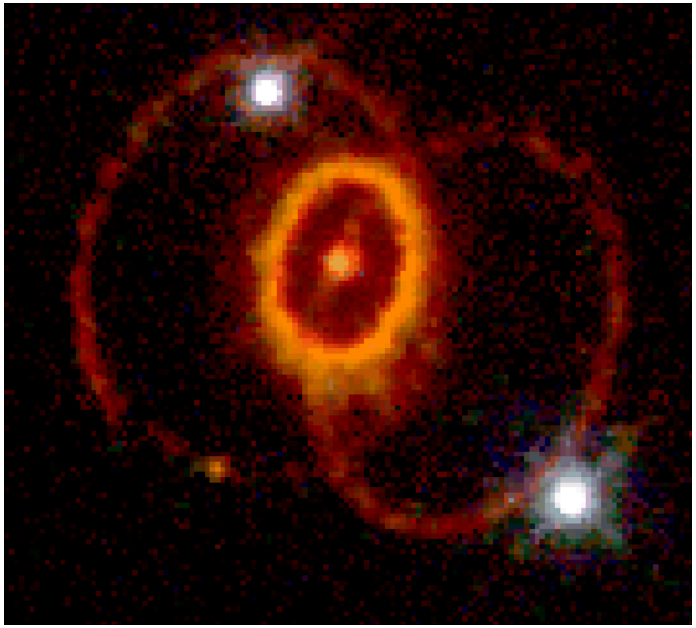


POSSIBLE SOURCES OF THE R-PROCESS

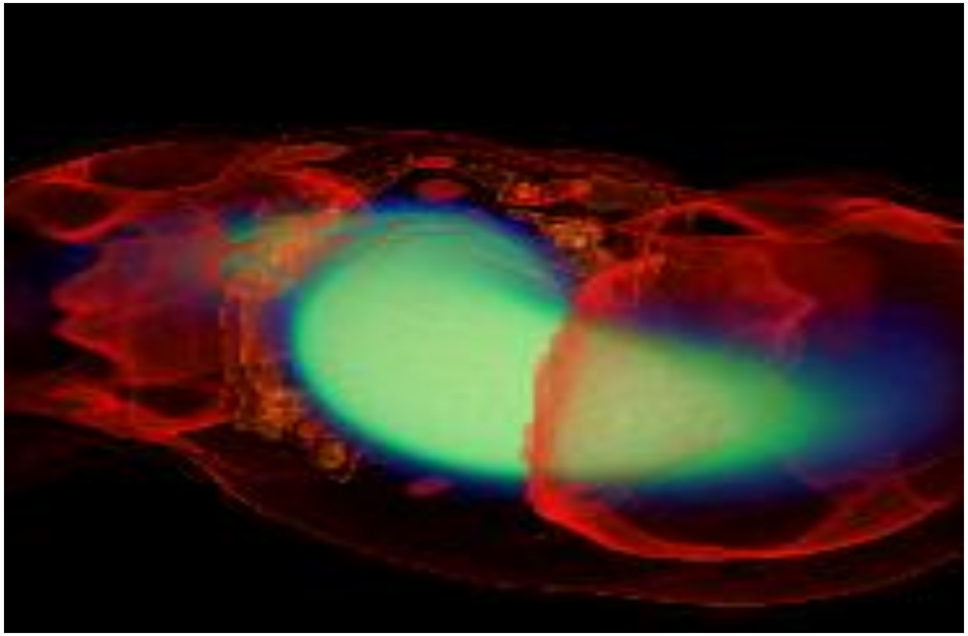
(Slide from 1st Argonne/MSU/JINA/INT RIA Workshop in 2004)

r-process requires: $T \sim 1\text{-}2$ GK

$n_n \sim 10^{24} / cm^3$

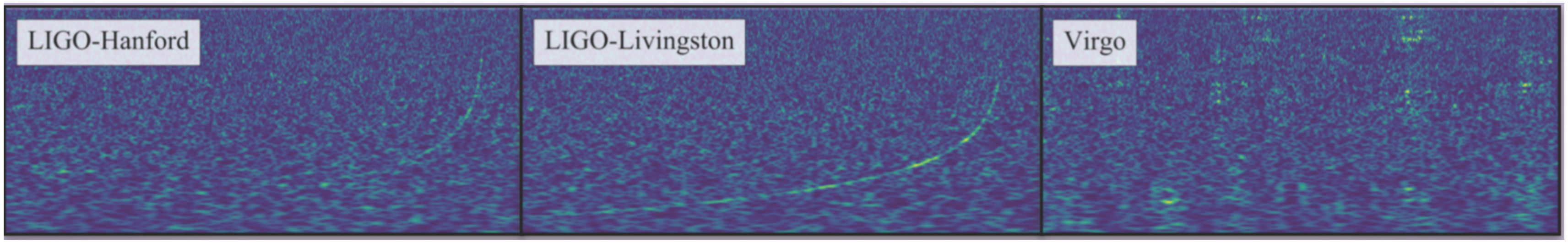


Supernovae???



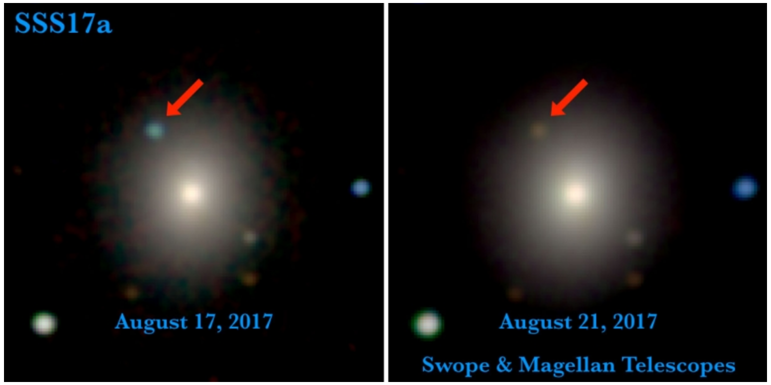
Merging neutron stars???

WHAT THE NS-NS MERGER DOES TELL US

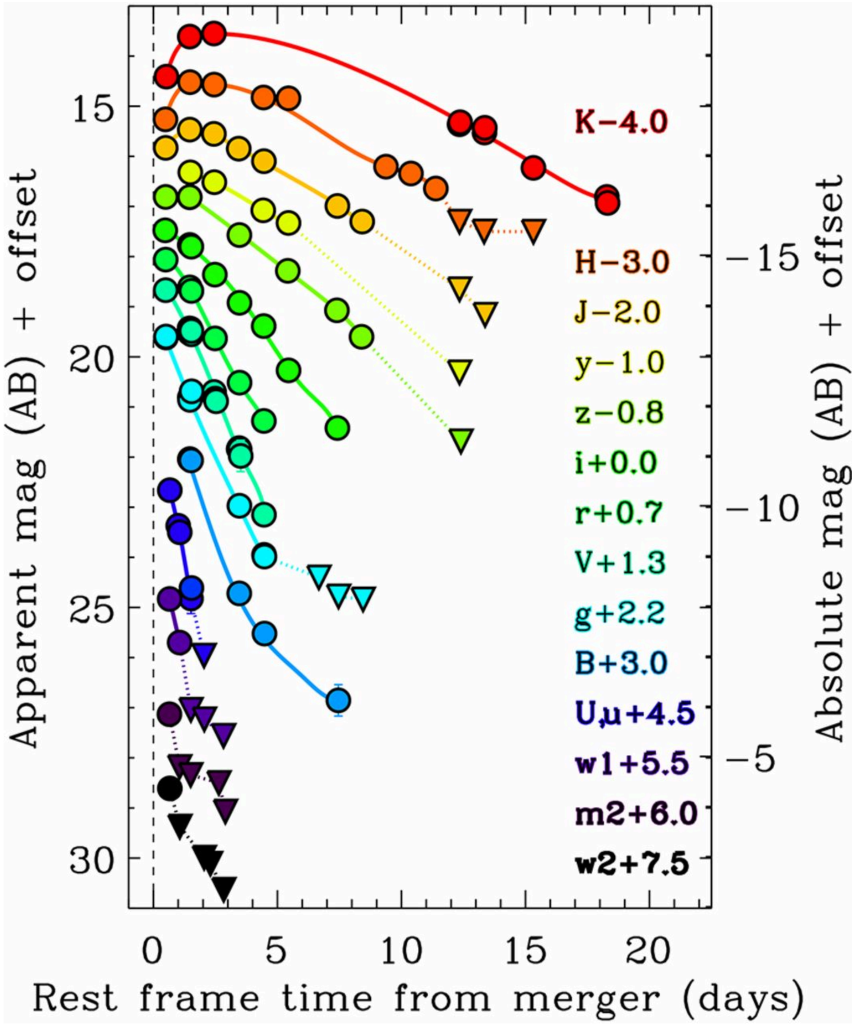


- **Neutron star mergers do happen, and we can detect them!**
- **Merging neutron stars do produce *r*-process elements (from opacity)**
- **There seems to be considerable ejecta from merging neutron stars**

WHAT THE NS-NS MERGER DOES NOT TELL US



- The 'red' component of the GW170817 observation suggests opacity from lanthanides, but doesn't distinguish between different elements produced
- With one observed event, it is hard to determine neutron star merger rate, and therefore hard to determine total contribution of neutron star mergers to element production
- It is difficult to determine if this event is 'typical'



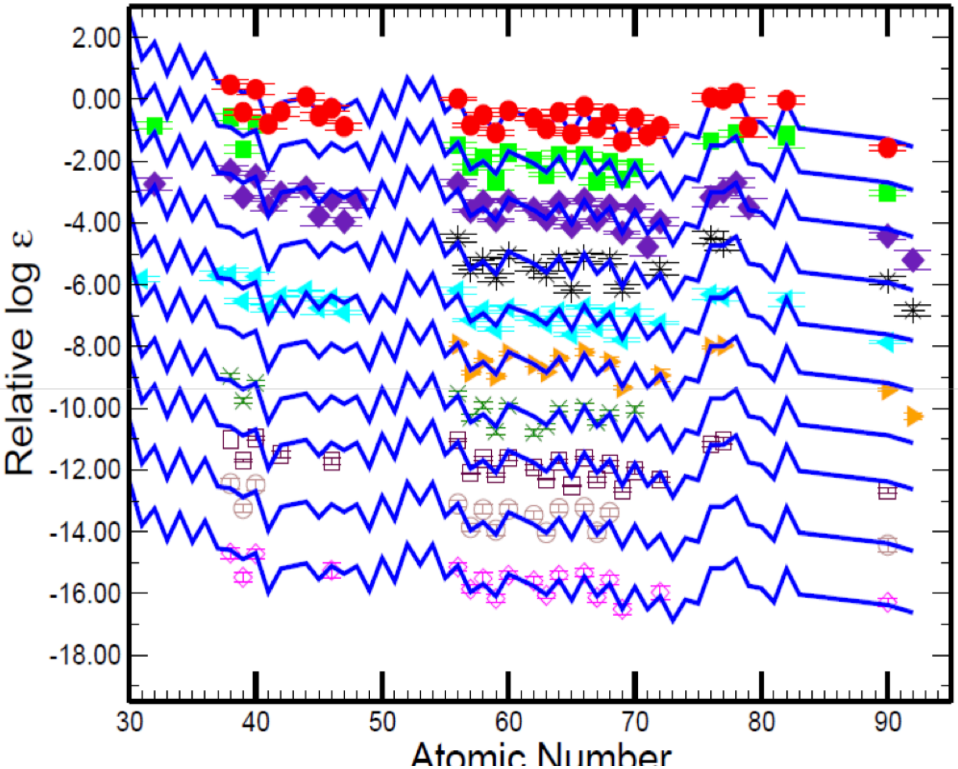
M. R. Drout *et al.*, Science 10.1126/science.aaq0049 (2017).

THERE ARE STILL MANY QUESTIONS, PERHAPS MORE THAN THERE WERE BEFORE

"The outcome of any serious research can only be to make two questions grow where only one grew before."

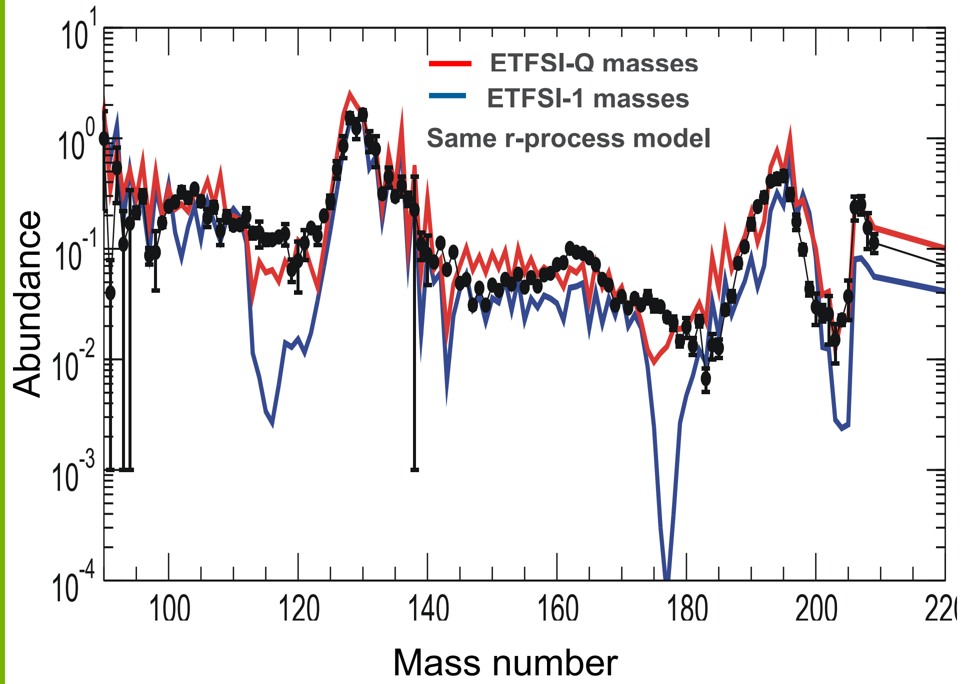
Thorstein Veblen

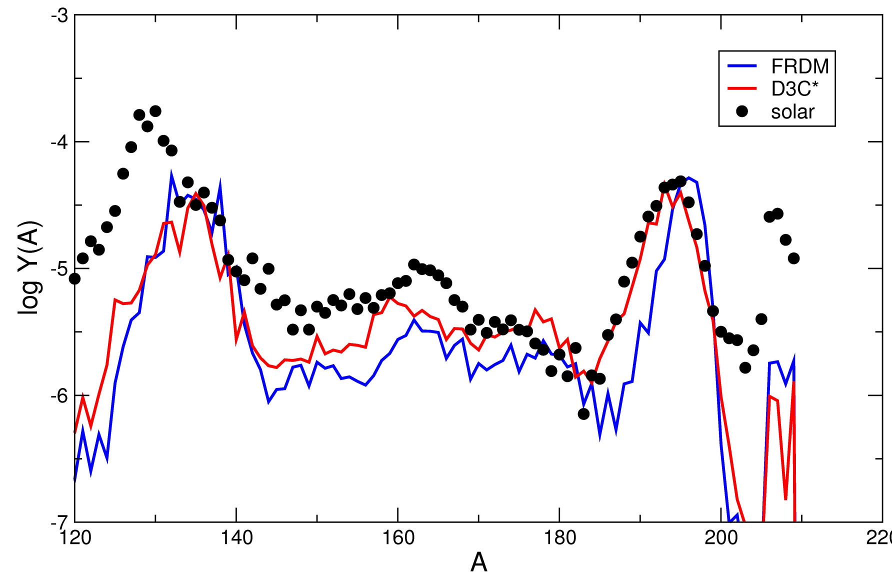
- **Where within the merging neutron stars do the r-process elements get created?**
- **How consistent are merging neutron stars in producing r-process elements?**
  - **Can merging neutron stars explain robustness of heavy r-process elements and variability of light r-process elements?**
- **What is the contribution of merging neutron stars to the total production of heavy elements in the universe?**
  - **How much do supernovae contribute?**



Cowan *et al.*, Carnegie Observatories Astrophysics Series. **5**, 223 (2011).

ROLE OF NUCLEAR PHYSICS

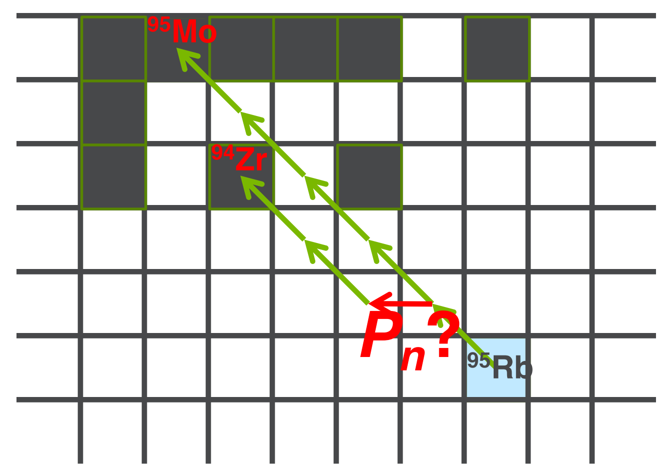




Marketin *et al.*, Phys. Rev. C **93**, 025805 (2016).

Uncertainties in the nuclear physics:

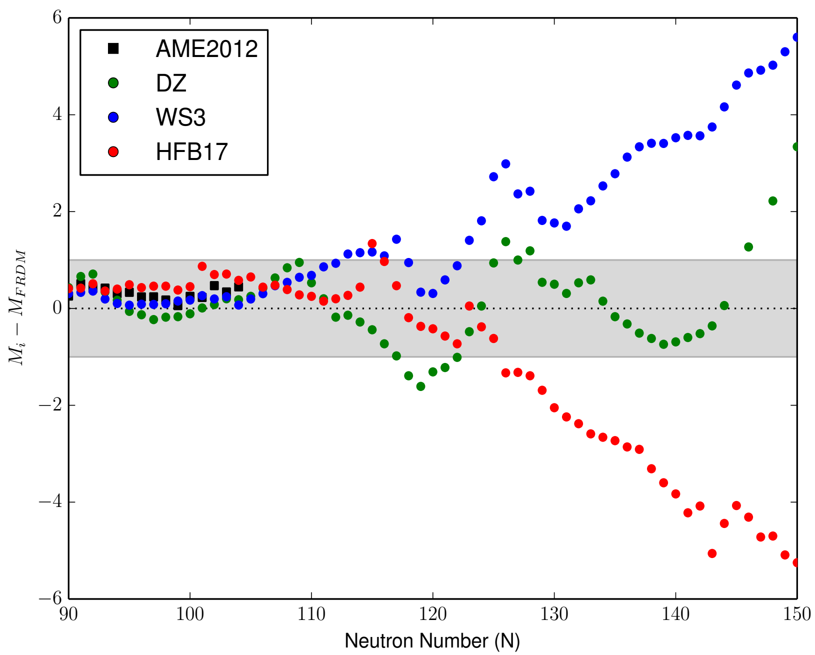
- masses
- β-decay lifetimes
- β-delayed neutron emission
- (n,γ), (α,n) rates
- fissionability



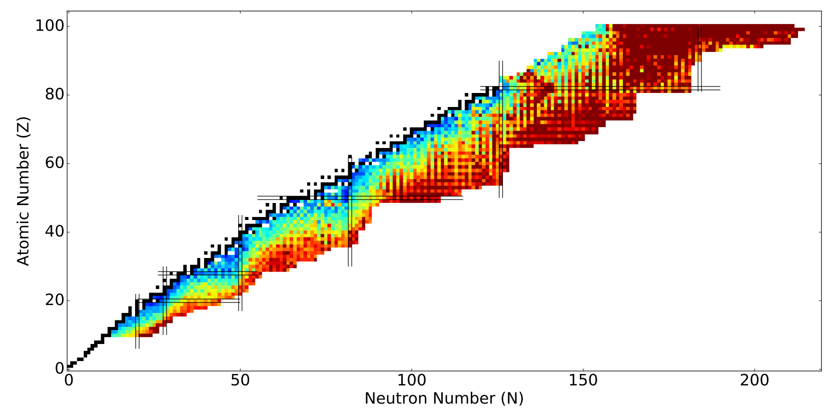
THEORY/MODEL UNCERTAINTIES

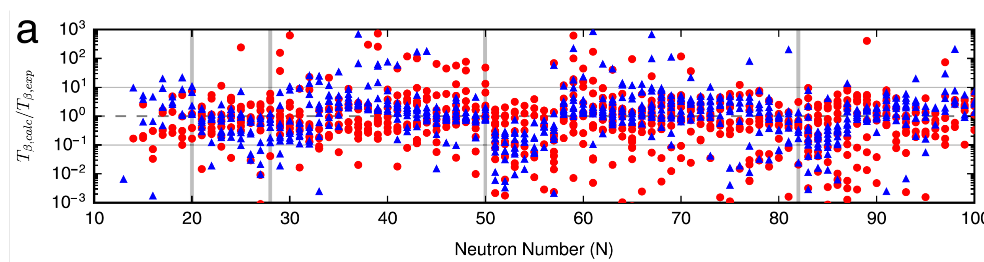
- **Theories/models agree to some extent in regions where data exists (but not necessarily to the precision required)**
- **However, theories/models often diverge quite wildly outside the realm of experimental data**

Courtesy A. Spyrou, from Nikas, Perdikakis (CMU)



M.R. Mumpower *et al.*, J. Phys. G: Nucl. Part. Phys. **42**, 034027 (2015).

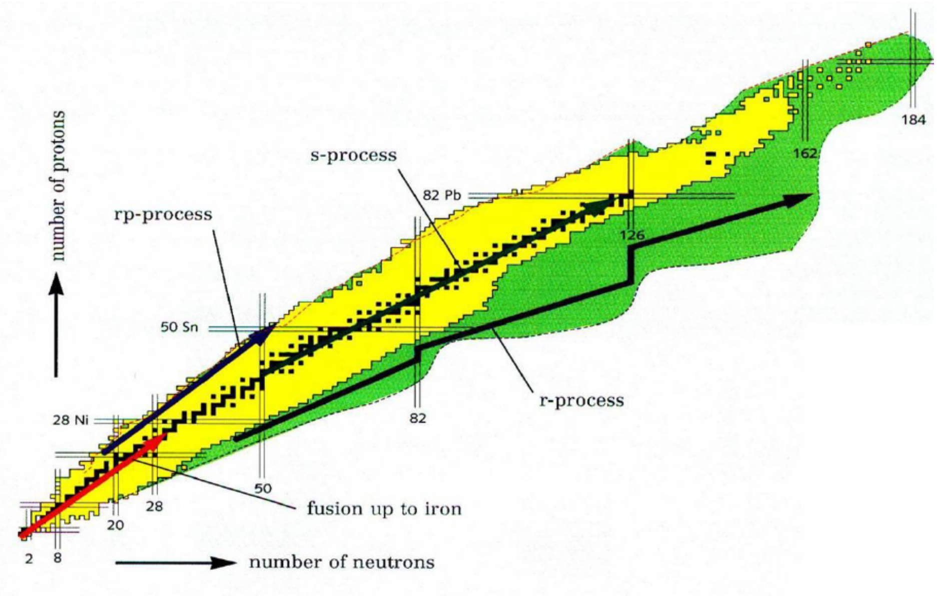




M.R. Mumpower *et al.*, Prog. Part. Nucl. Phys. **86**, 86 (2016).

Best solution: Get data wherever possible!

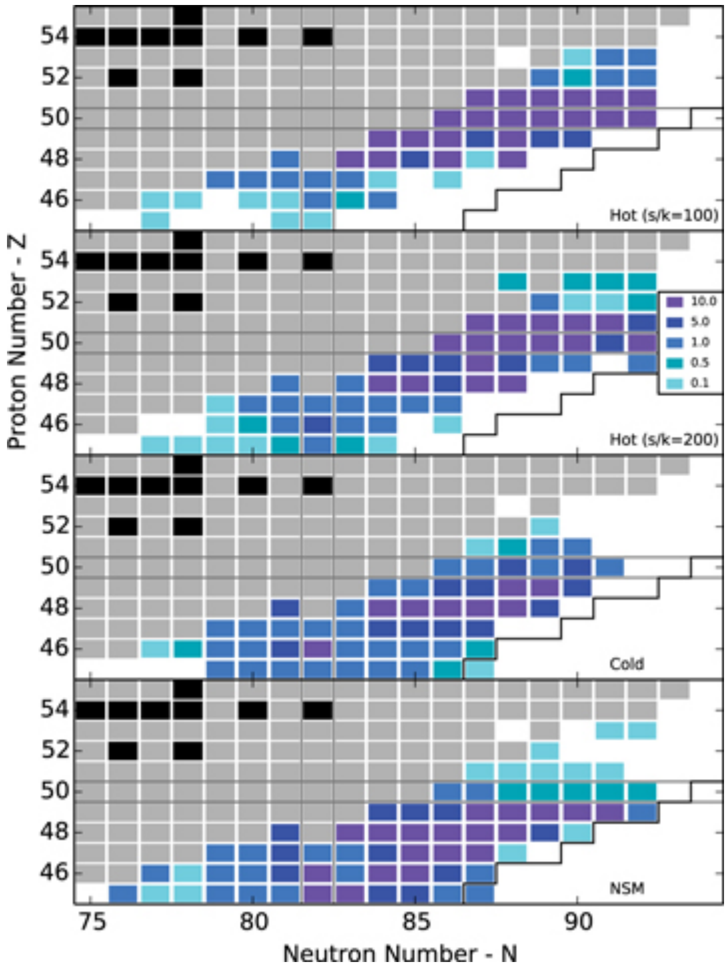
CHALLENGES/OPPORTUNITIES IN NUCLEAR PHYSICS



- **Challenges:**
  - **Some of the more interesting isotopes are the hardest to produce**
  - **These neutron-rich isotopes are also short-lived**
  - **Production of these isotopes generally have contaminants**
  - **Too many nuclides, too little time!**
- **Solutions:**
  - **Develop equipment which are fast, efficient, and can handle contaminants**
  - **Develop new facilities which can produce the interesting neutron-rich isotopes in large quantities**
  - **Have theory/models/simulations guide experiments and prioritize measurements**

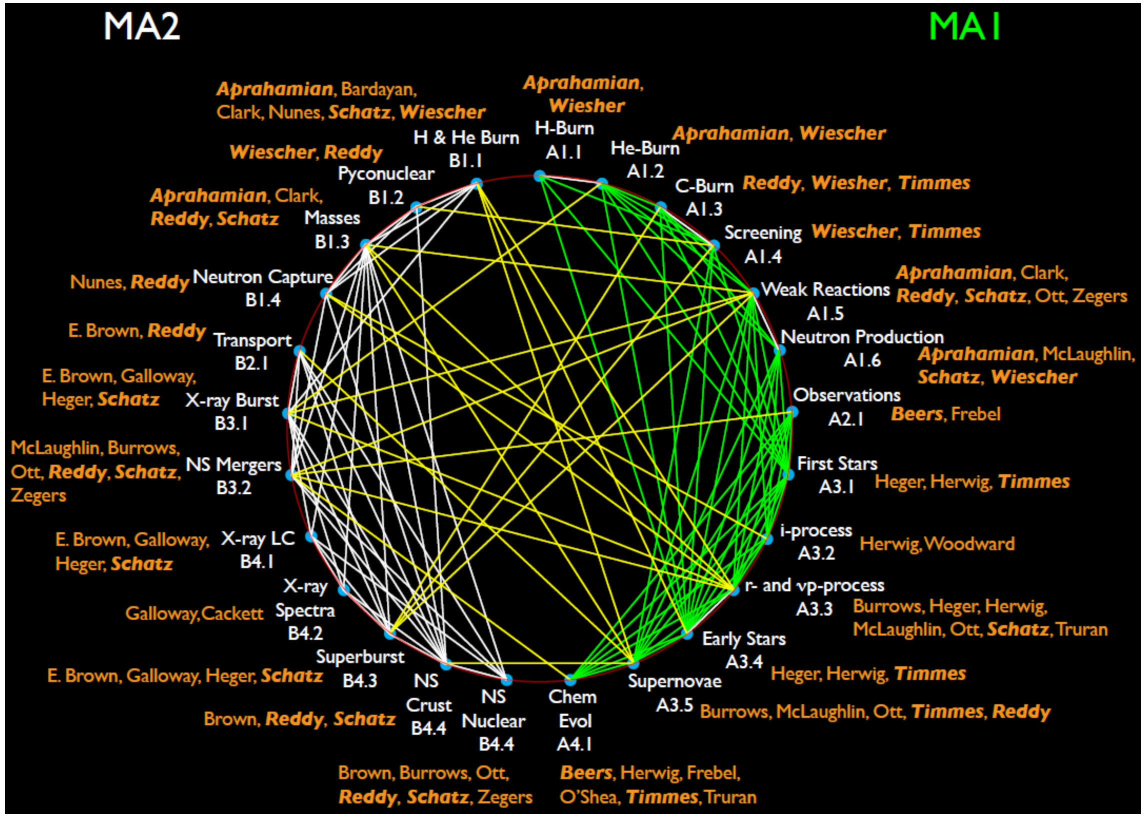
EXPERIMENTALISTS GUIDED BY THEORY

- **We can't just measure 'everything'!**
  - **Too many nuclides, too little time.**
  - **Demand for 'beamtime' at accelerator facilities is high; not every proposal gets accepted, therefore need solid justification as to why particular nuclides need to be measured**
- **Often guided by sensitivity studies to focus research and effort**
  - **Studies either:**
    - **look at how 'good' existing nuclear data/models are at reproducing the observed abundances (for example), and see how the change in one nuclide property affects the distribution (ie: how 'sensitive' it is**
    - **Work backwards (reverse engineer) to determine the nuclear physics that should exist for the particular astrophysical trajectory**
- **Results:**
  - **Which nuclides are important to study**
  - **To what precision do they need to be measured**



M.R. Mumpower *et al.*, Prog. Part. Nucl. Phys. **86**, 86 (2016)

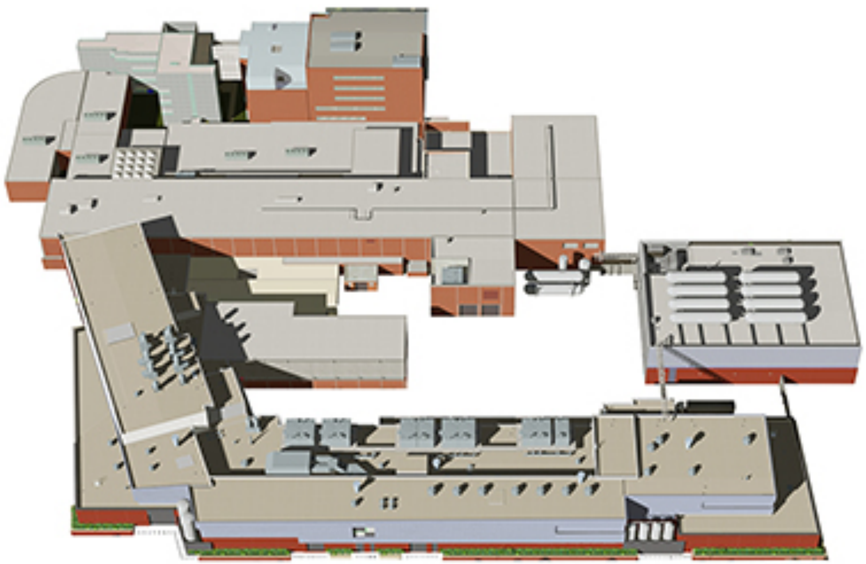
JINA (JOINT INSTITUTE FOR NUCLEAR ASTROPHYSICS)

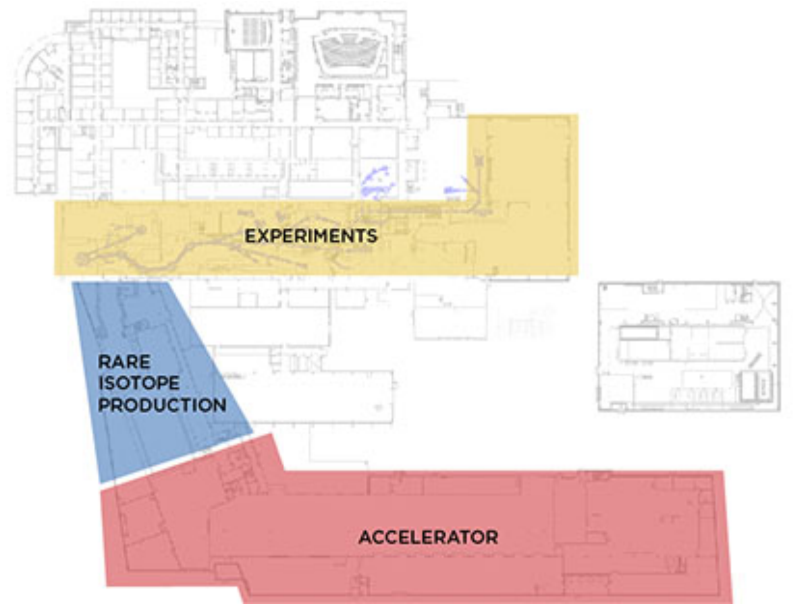


- **True collaborative effort**
  - **Combines observations, theory, models, facilities, experiments, and beer!**
  - **Perfect organization to pool scientists together to address scenarios, like merging neutron stars.**
- **Question: If you're not part of JINA, why not???**

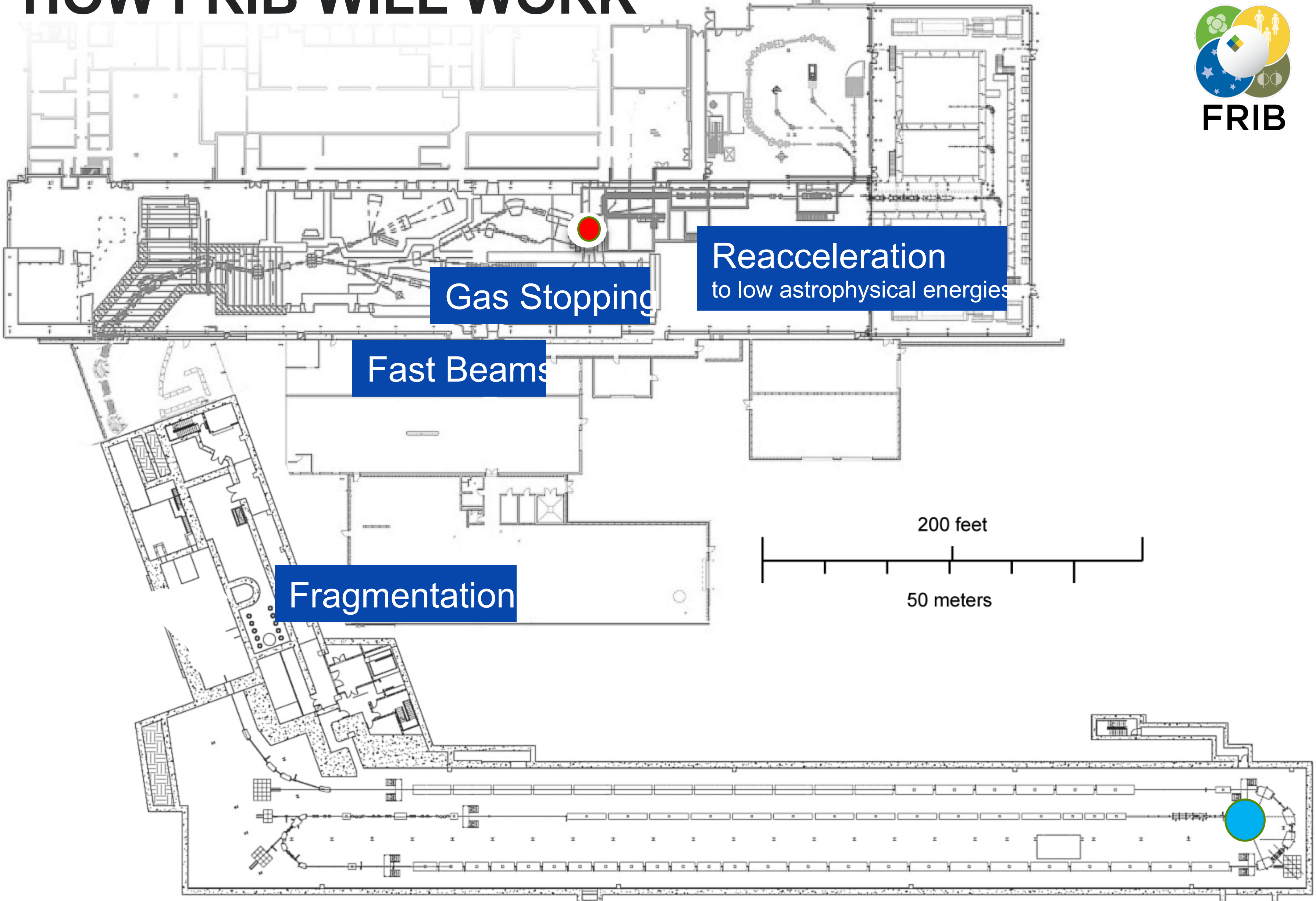
FUTURE FACILITY: FRIB (FACILITY FOR RARE ISOTOPE BEAMS)

- Production of isotopes through fragmentation
- FRIB project completion date is June 2022
- 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





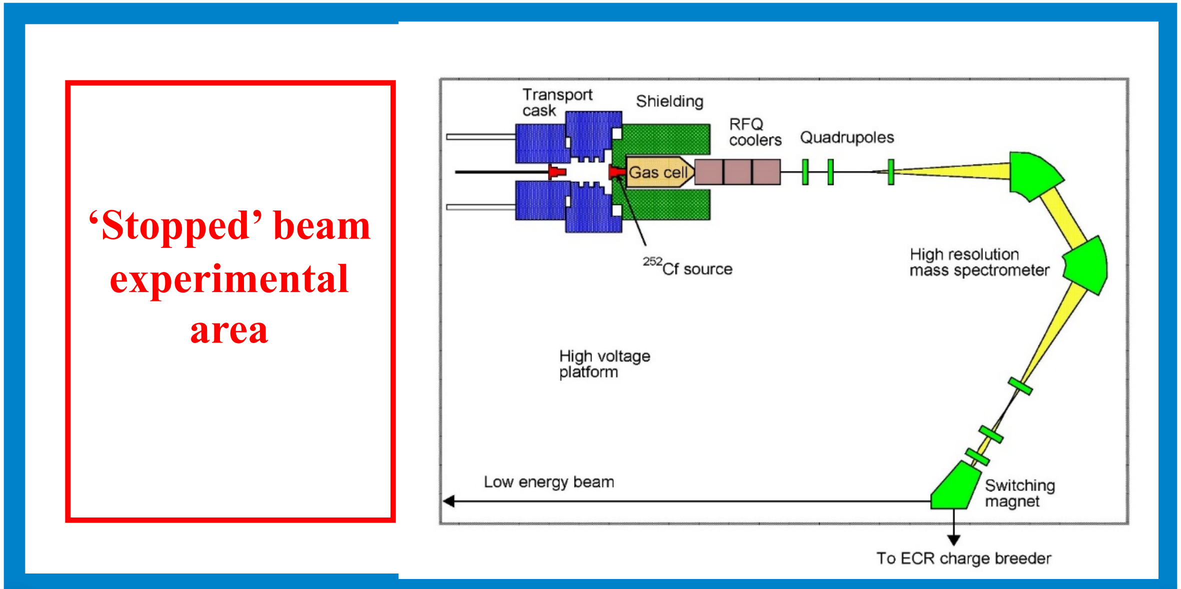
HOW FRIB WILL WORK



FRIB

Courtesy A. Spyrou

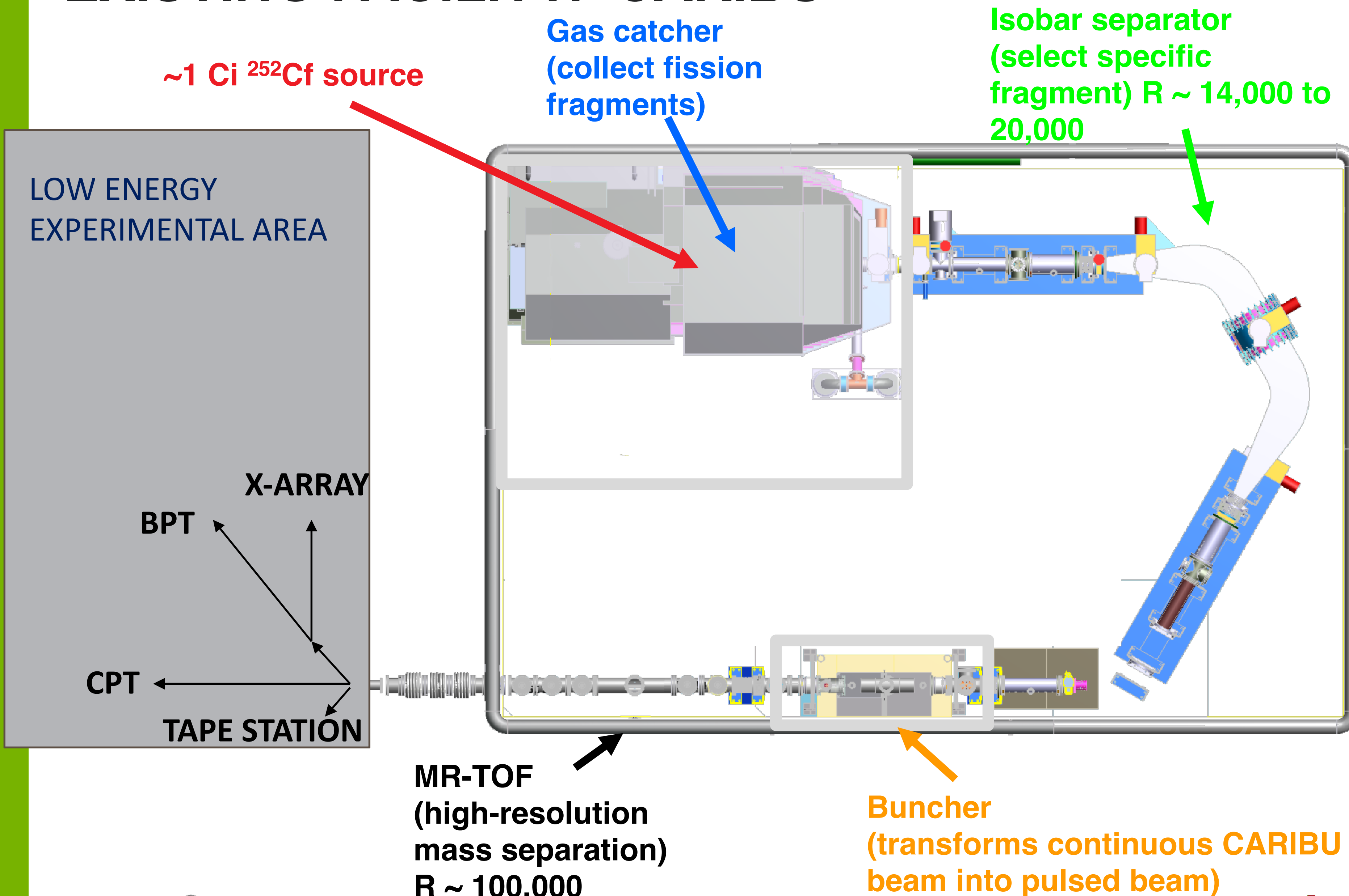
EXISTING FACILITY: CARIBU (CALIFORNIUM RARE ISOTOPE BREEDER UPGRADE)



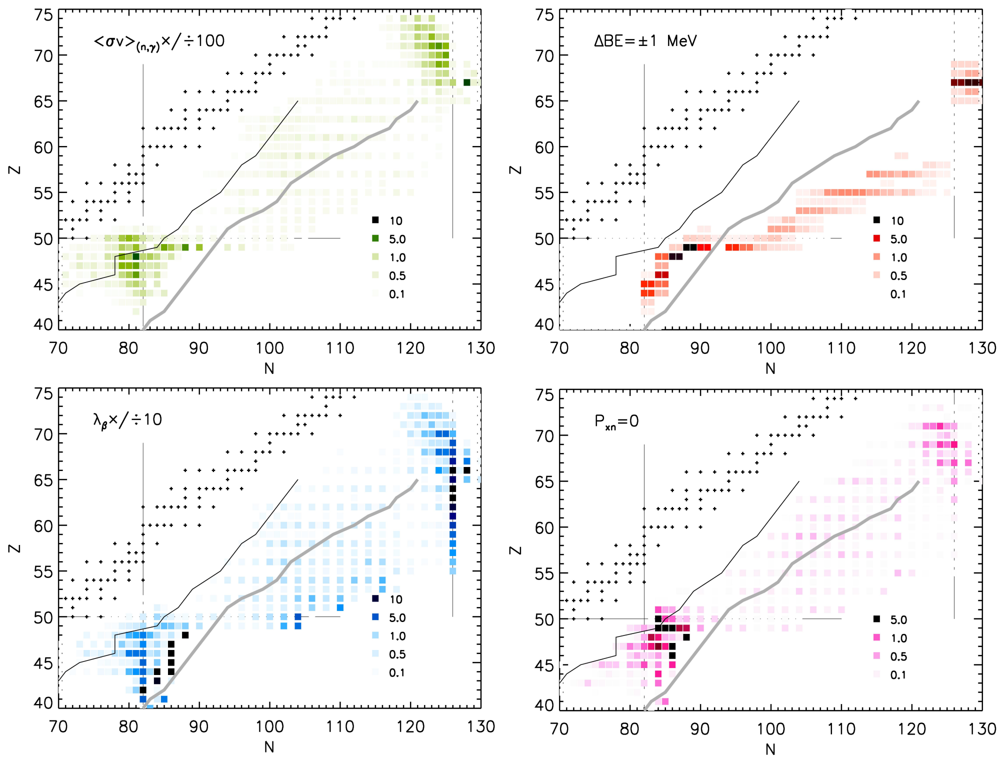
- Production of neutron-rich isotopes through fission (^{252}Cf spontaneous fission source)
- ^{252}Cf source properties:
  - 3% fission branch
  - 2.6 year half-life
  - ~ 1 Ci (40 billions decays / s)

- CARIBU beams can be accelerated through ATLAS to ~ 15 MeV/A
- Basic properties of fission fragments can be measured with instruments in 'stopped' beam area

EXISTING FACILITY: CARIBU



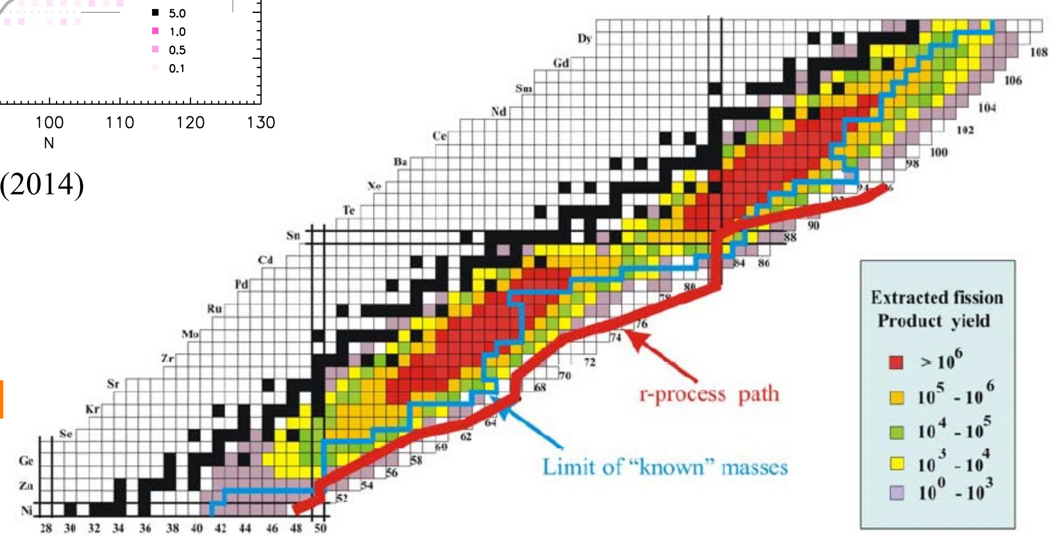
REACH OF PRESENT AND FUTURE FACILITIES



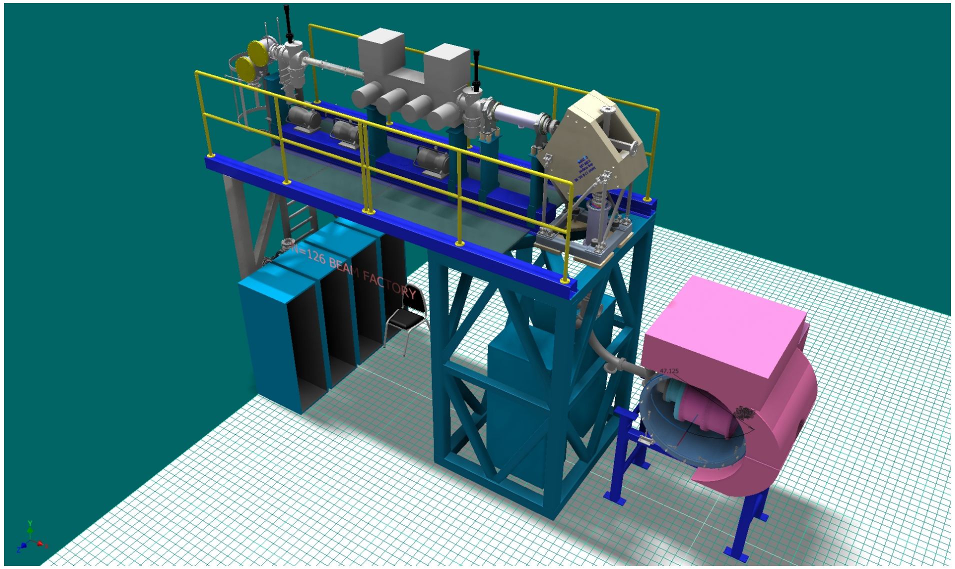
R. Surman *et al.*, EPJ Web of Conferences **66**, 07024 (2014)

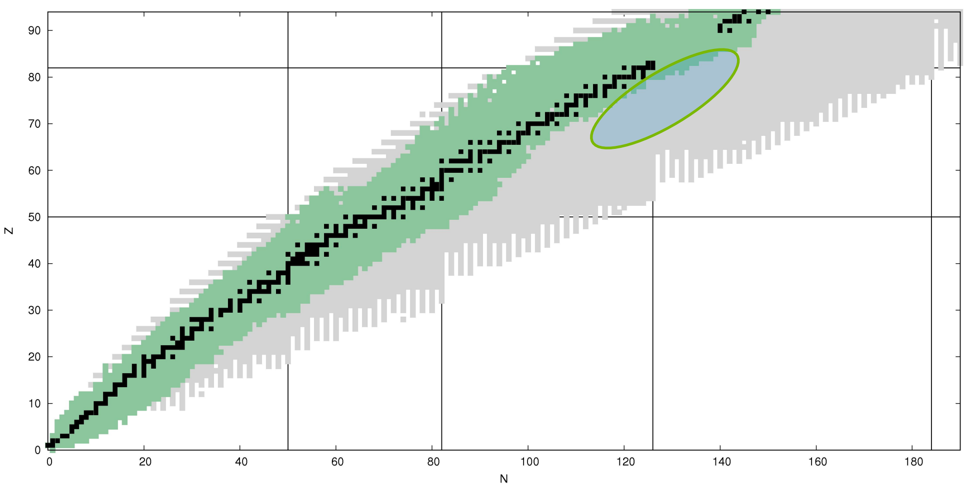
- **Early sensitivity studies for neutron-star mergers (left) show some key nuclides are currently in reach of CARIBU, and others will be within reach of FRIB**

- **Some nuclides may unfortunately never be within reach, but any and all data will help refine models**



NEAR FUTURE: N=126 FACTORY





- Use deep-inelastic reactions to produce neutron-rich isotopes in the N=126 region

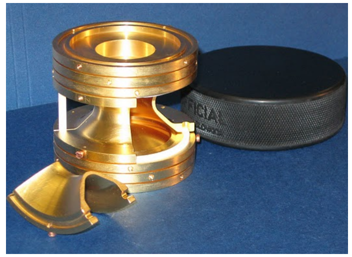
- But there has been a historic challenge of collecting reaction products efficiently:
  - New N=126 facility at Argonne will capitalize on high-intensity beams and high-intensity gas catcher technology

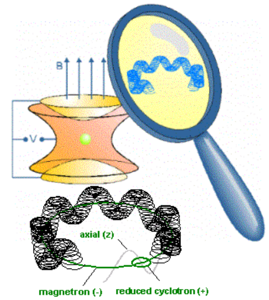
- Will feed suite of low-energy experiments (masses, decay spectroscopy, …)

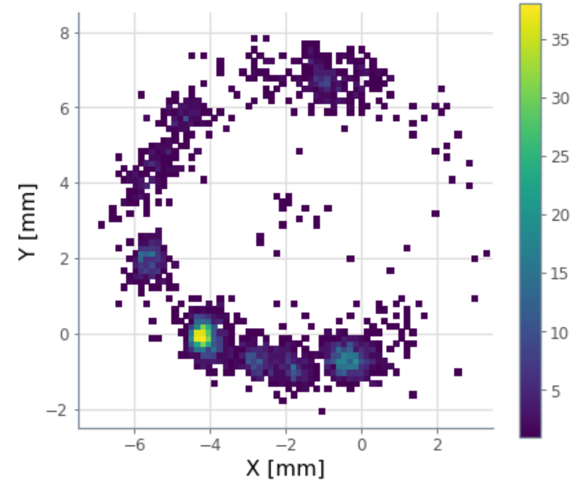
MASS MEASUREMENTS

LEBIT, MSU

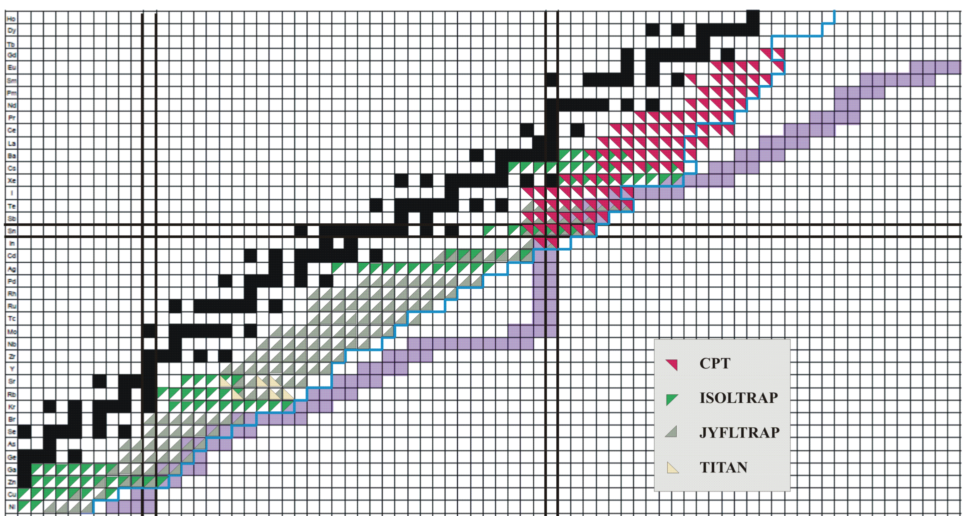
CPT, ANL

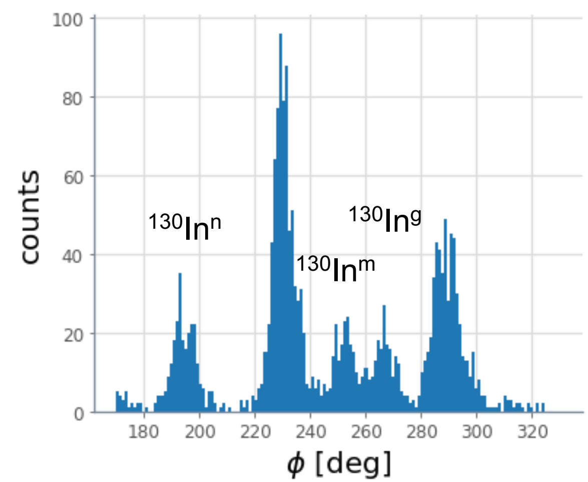






- More than 450 neutron-rich nuclides have been measured to ~ 15 keV (0.1 ppm) precision or better with Penning traps
- Much interest in this region has driven the development of new techniques for the mass measurements of nuclides for the astrophysical r process



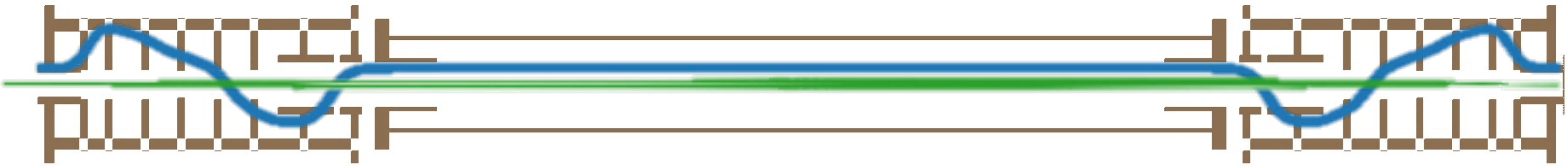


J. A. Clark and G. Savard, Int. J. Mass Spectrom. **349-350**, 81 (2013).

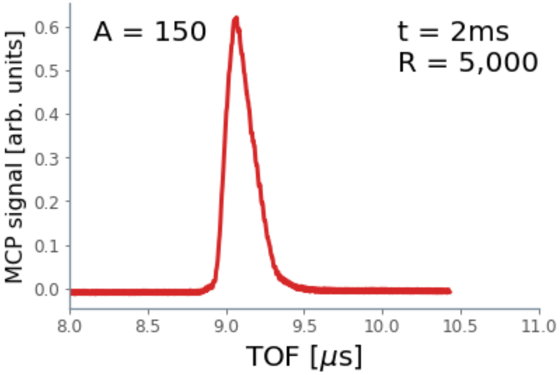
Argonne NATIONAL LABORATORY

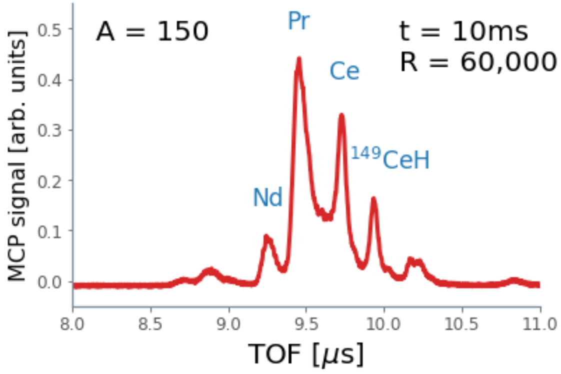
MR-TOF: MULTI-REFLECTION TIME-OF-FLIGHT MASS SEPARATOR

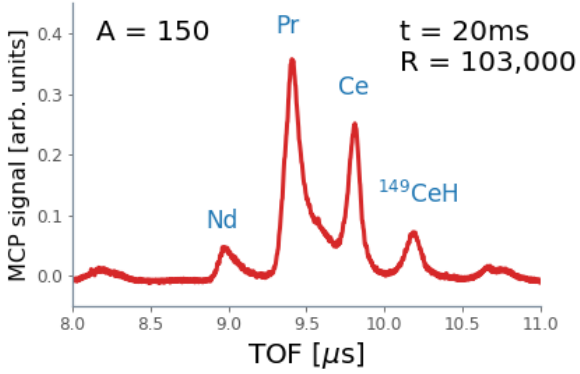
- Ions bounce between mirror electrodes picking up time separation $t \sim \sqrt{m/q}$



- Resolving power, $R = \frac{m}{\Delta m} \sim$ 50,000 within 10s of ms

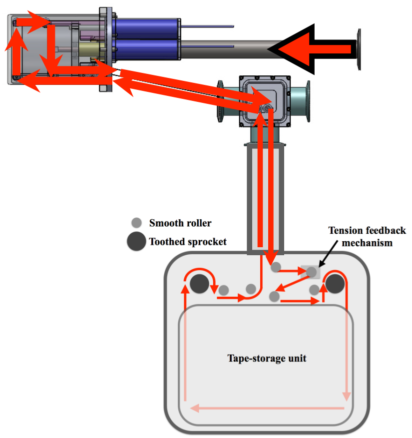


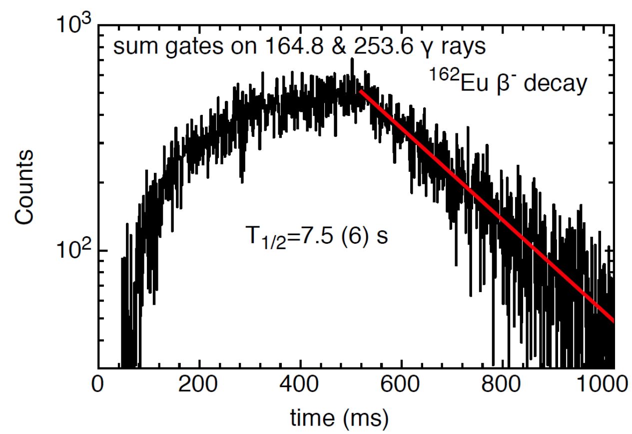




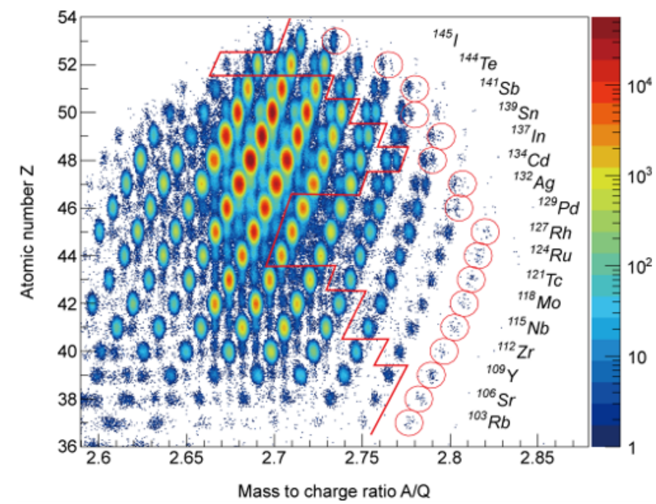
- Can be used as a mass measurement device, or be used with a BNG (Bradbury-Nielsen gate) as a mass separator

HALF-LIFE MEASUREMENTS

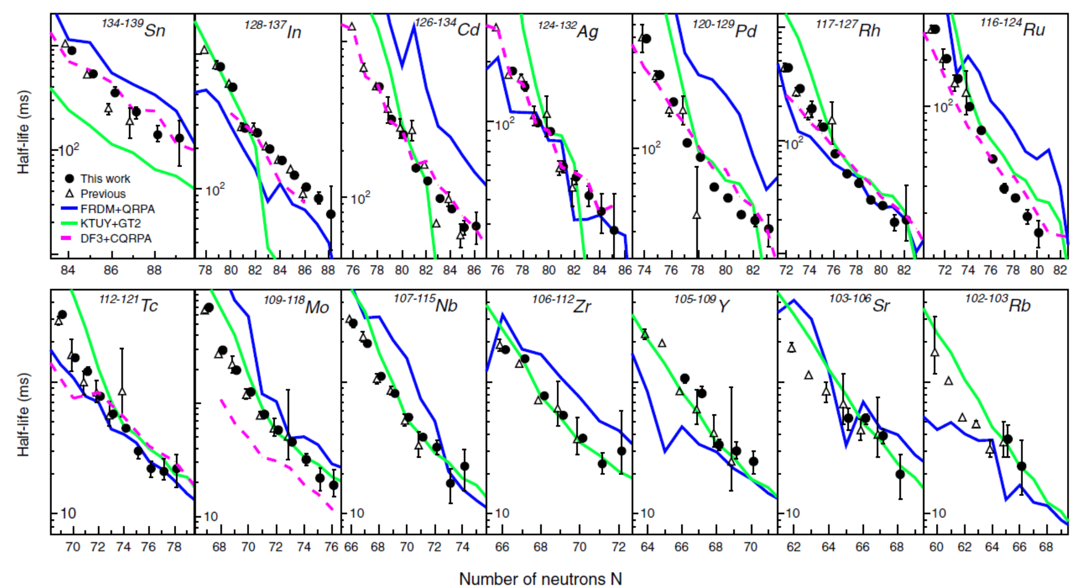




A.J. Mitchell *et al.*, NIMA **763**, 232 (2014).

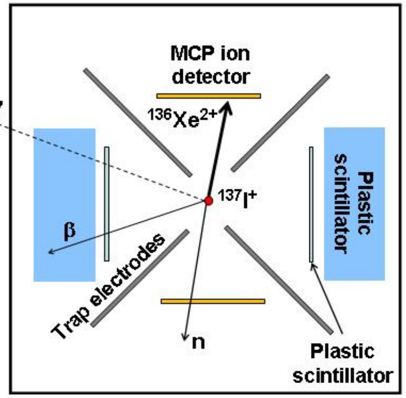


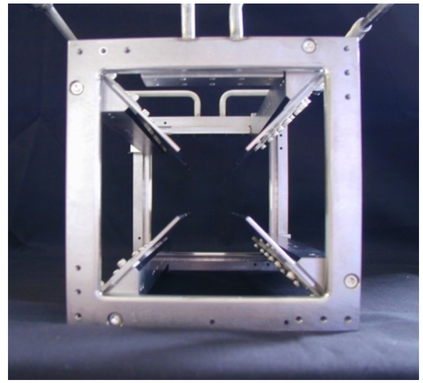
- **More than 200 half-lives in the rare-earth region recently measured at the RIKEN facility in Japan**
- **Results indicate importance in measuring half-lives with different techniques (to sort out systematic effects)**

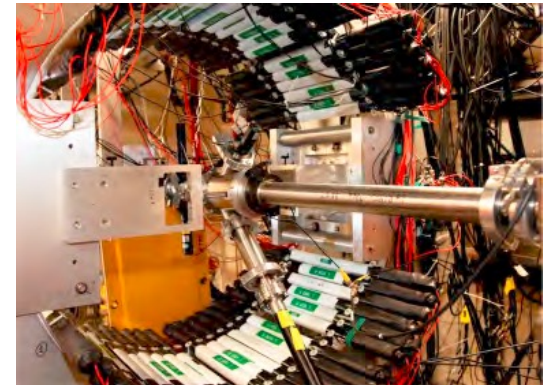


G. Lorusso *et al.*, Phys. Rev. Lett. **114**, 192501 (2015).

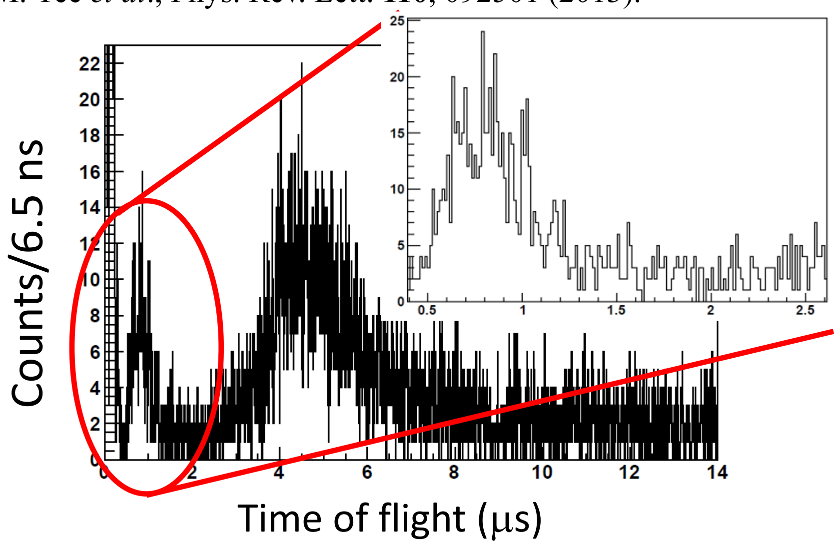
BETA-DELAYED NEUTRON EMISSION

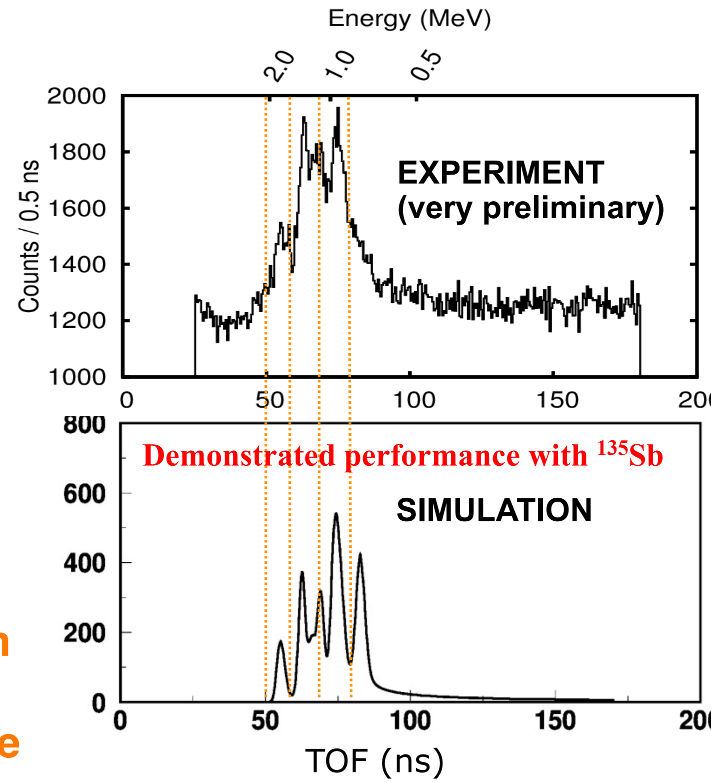






R.M. Yee *et al*., Phys. Rev. Lett. **110**, 092501 (2013).

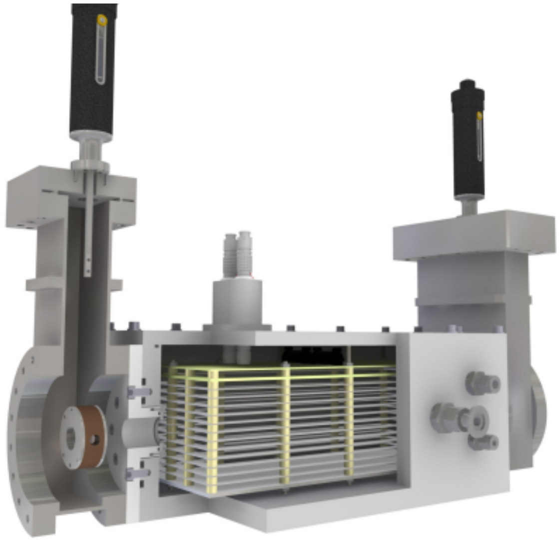


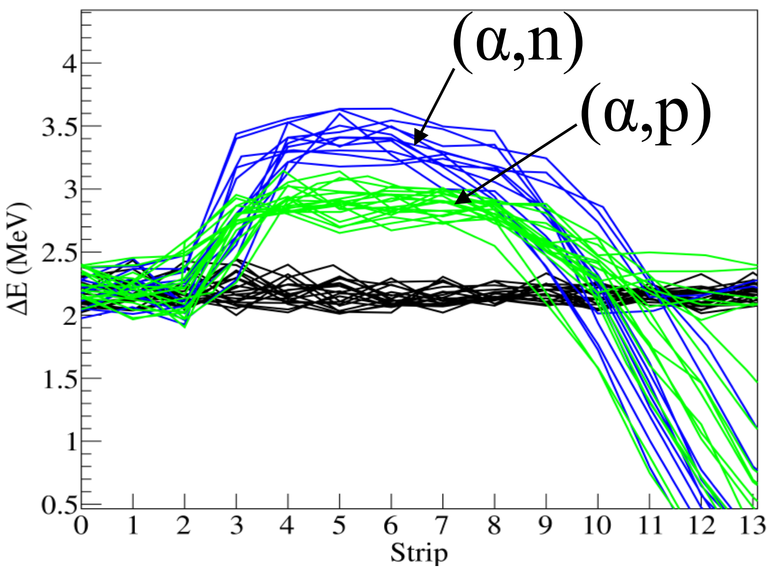


W.A. Peters *et al*., NIMA **836**, 122 (2016).

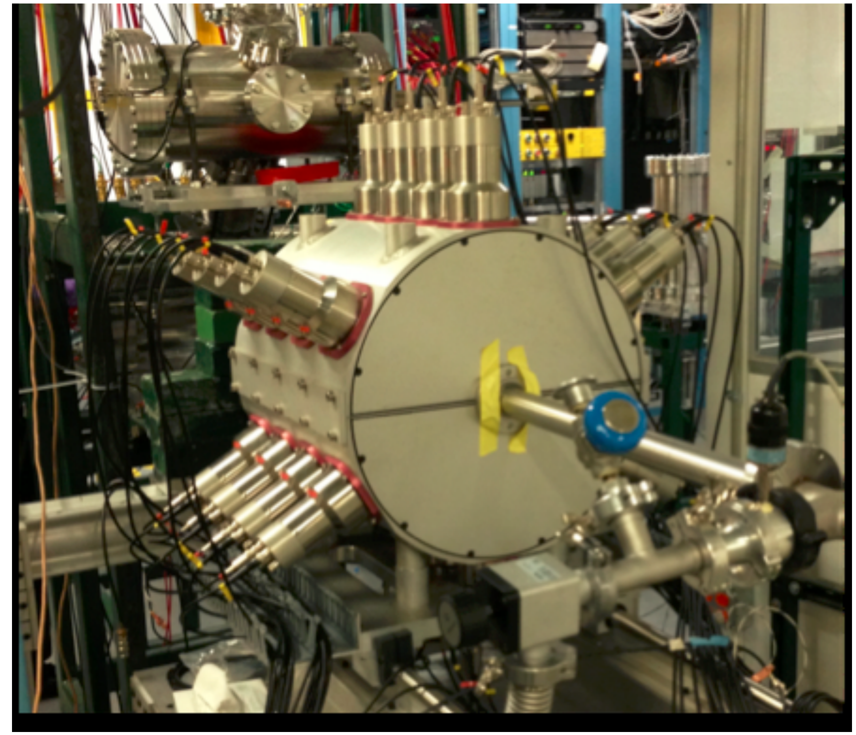
- **Various techniques used which detect the neutron directly, or infer the neutron properties from detecting all other decay products (each technique having their own systematic effects/uncertainties)**

CROSS-SECTION MEASUREMENTS

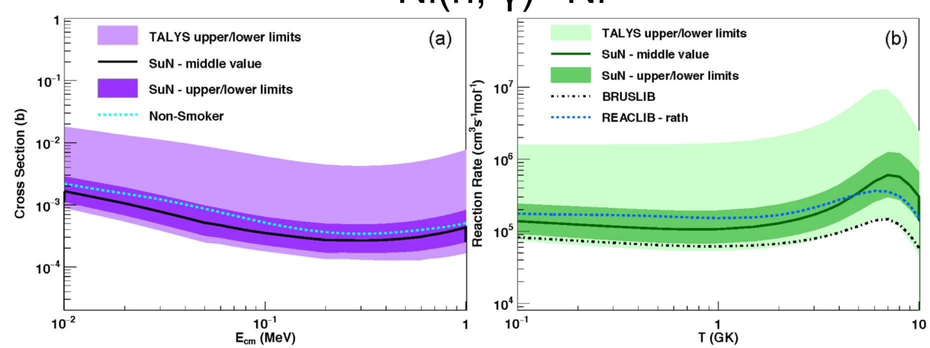




P.F.F. Carnelli *et al.*, NIMA **799**, 197 (2015).



^{68}Ni(n, γ)^{69}Ni



A. Spyrou *et al.*, J. Phys. G: Nucl. Part. Phys. **44**, 044002 (2017).

SUMMARY

- Although we have now observed one merging neutron star event, there are still many unanswered questions.
- Measuring properties of nuclides will help to determine where in NS-NS mergers does nucleosynthesis occur, abundance pattern, other r-process sites.
- Reaching the nuclides involved in the r-process has motivated the construction of new facilities and the development of new measurement techniques.
- With all that is happening now (GW1708107 observation, new facilities, advanced techniques), these are truly exciting times!
  - We're truly making astrophysics great again!!!