Rare Isotopes at the Electron-Ion Collider (EIC)

Pawel Nadel-Turonski

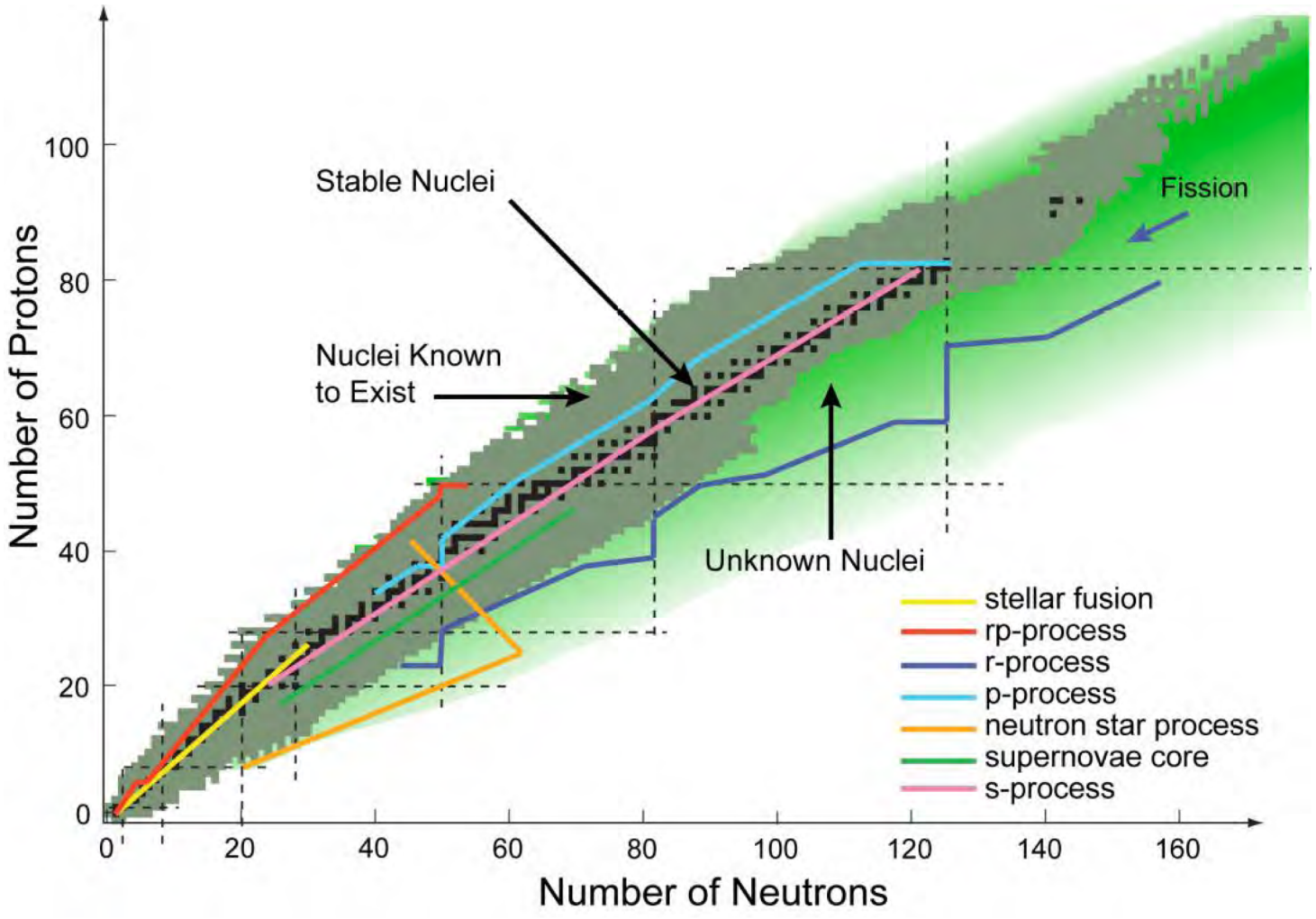
Stony Brook University

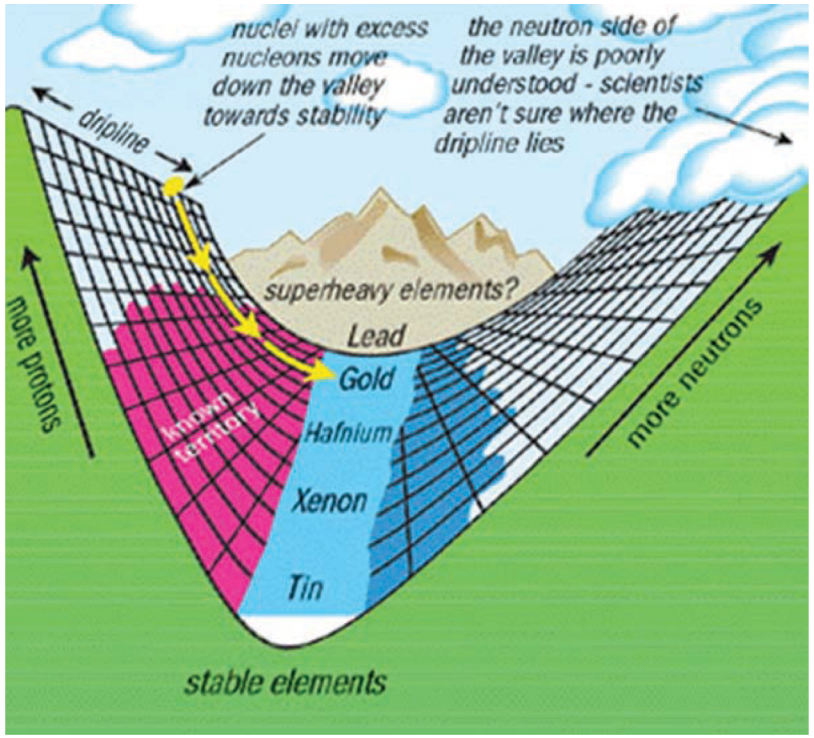
2018 CFNS Workshop on Short-range Nuclear Correlations at an Electron-Ion Collider, BNL, September 5, 2018

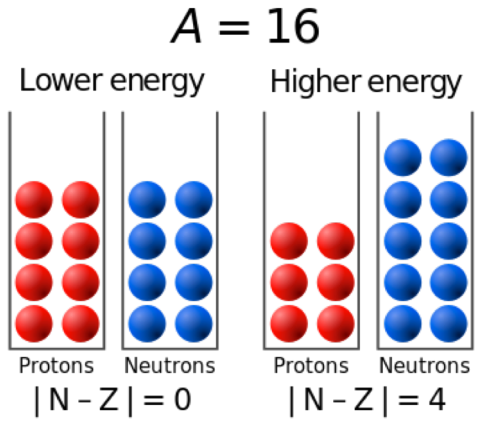
Outline

- Introduction
- Production of rare isotopes at FRIB
- Production of rare isotopes at the EIC
- Detection of forward ions, photons, and electrons (?) at the EIC
- Synergies with other eA measurements at the EIC

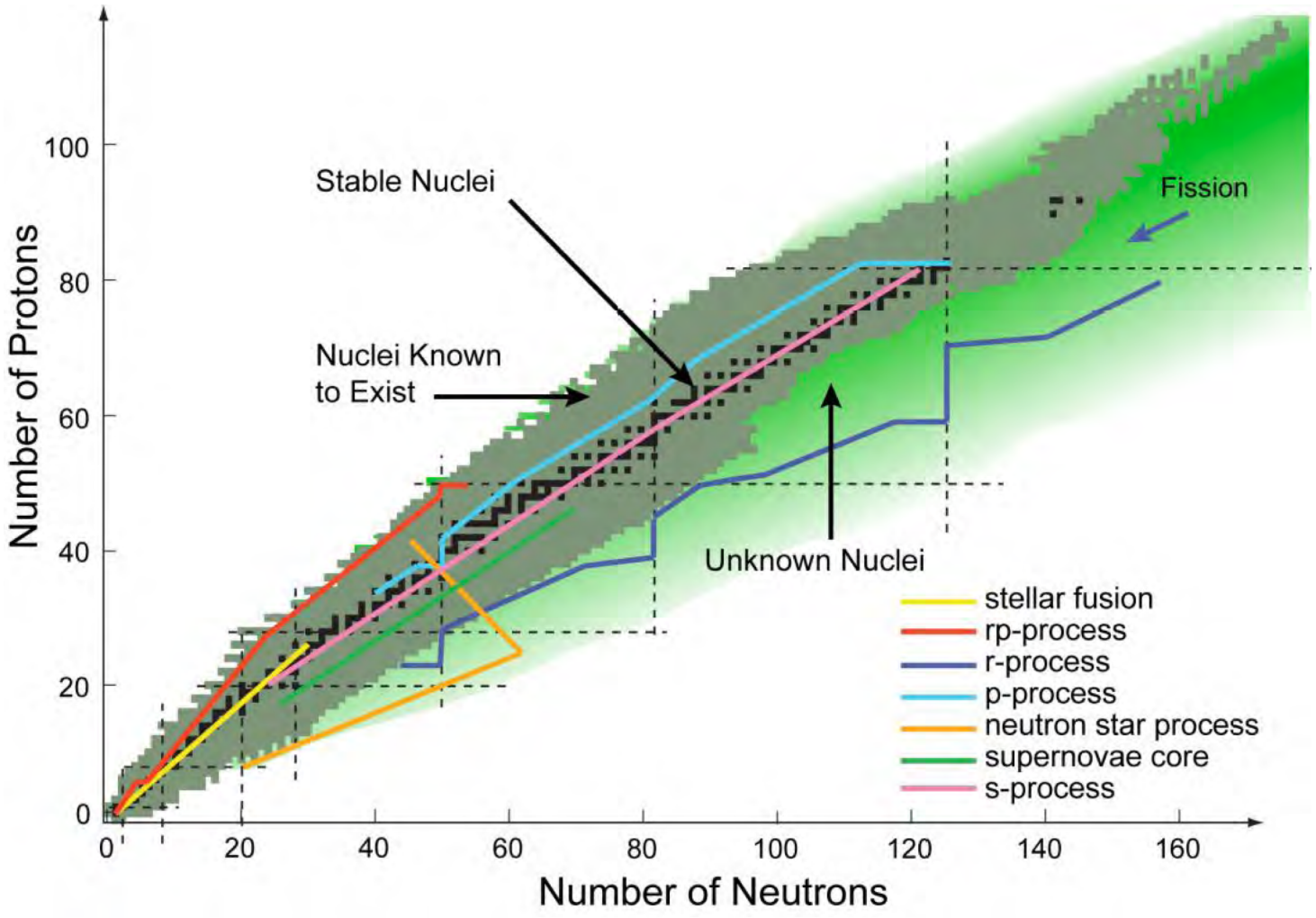
Nuclei away from the valley of stability

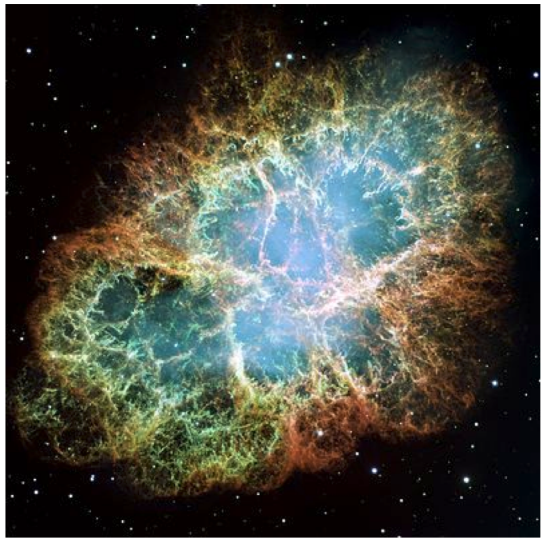






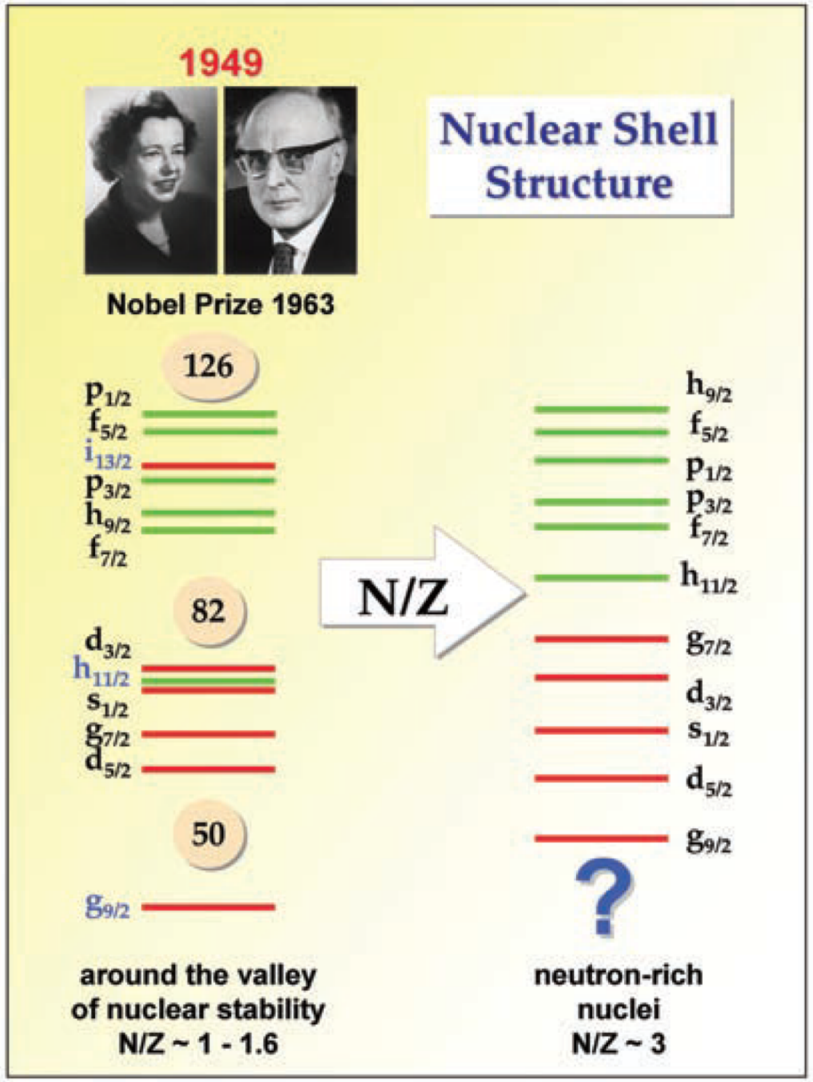
Opportunities for astrophysics

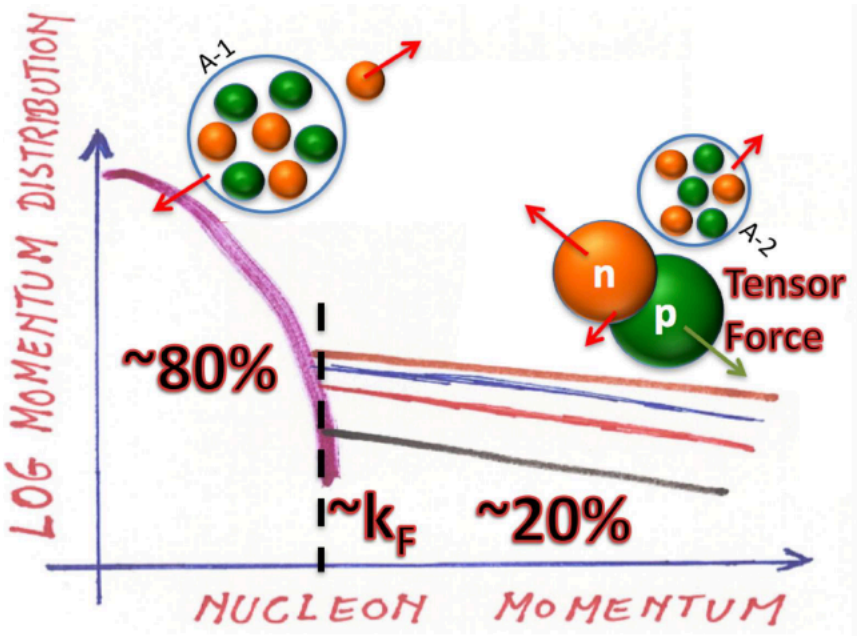




- All elements heavier than iron (the most tightly bound nucleus) have been created in stellar events like supernovae
- The most important mechanism is the rapid neutron capture (r-process) in equilibrium with beta-decay
- The drip-line will not be possible to reach on the neutron-rich side, which means that “all” produces isotopes are bound

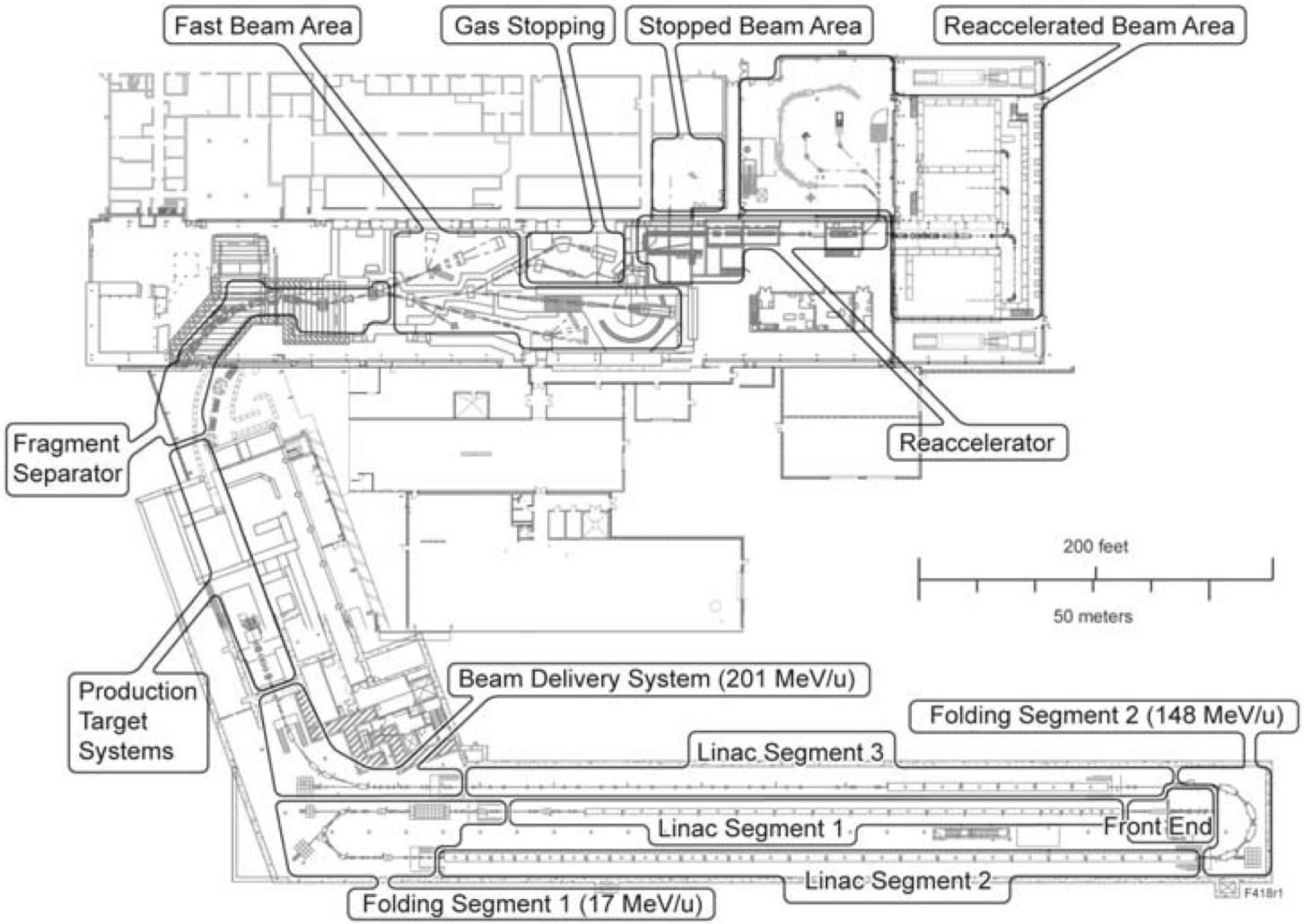
Modified shell structure (mean field) in nuclei far from stability?





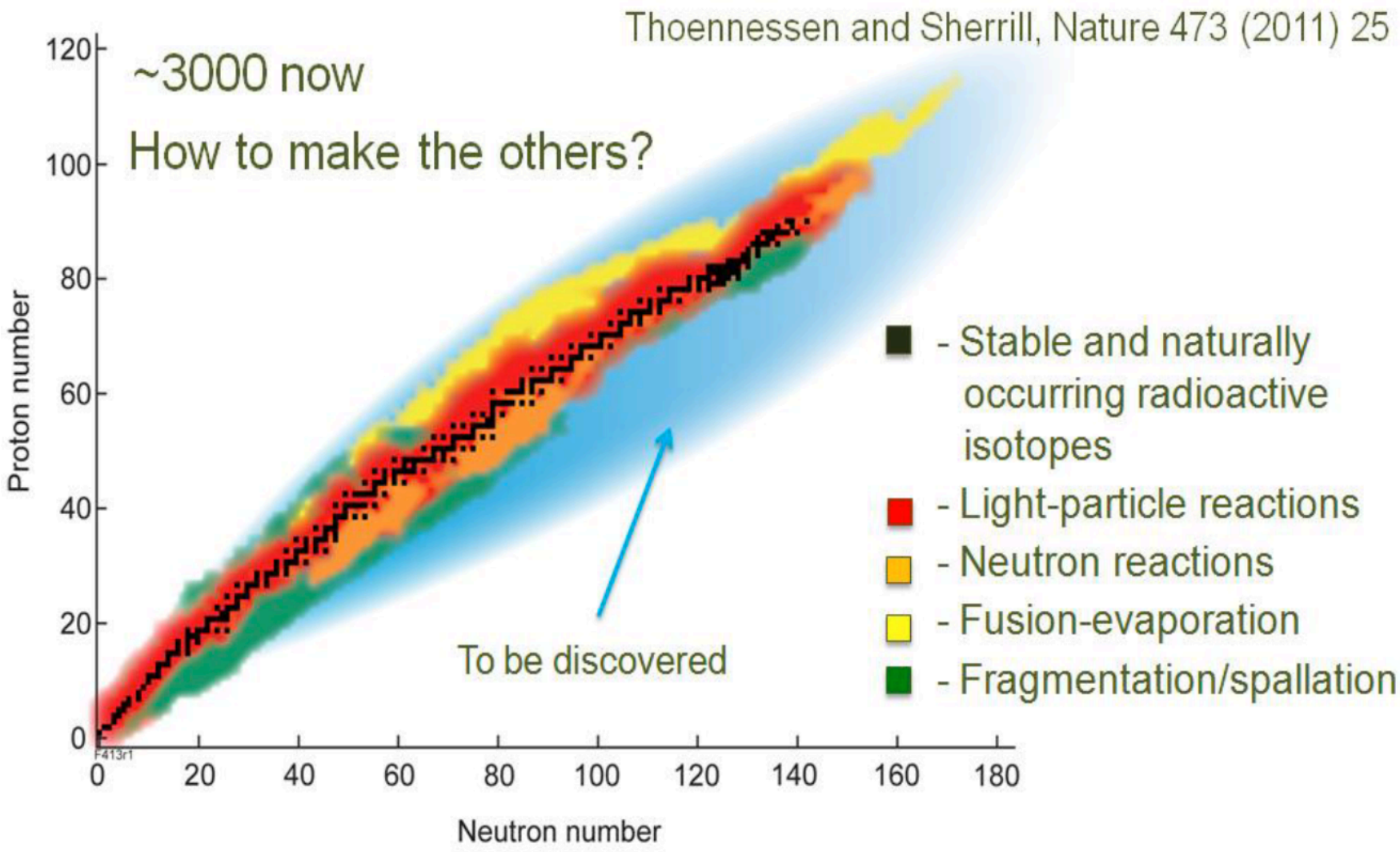
- SRCs (with mostly np pairs) are often presented as an extension of a well-known mean field (with nn and pp pairs).
- But the mean field is expected to change dramatically in nuclei far from stability
- Need to understand both!

Facility for Rare Isotope Beams (FRIB)



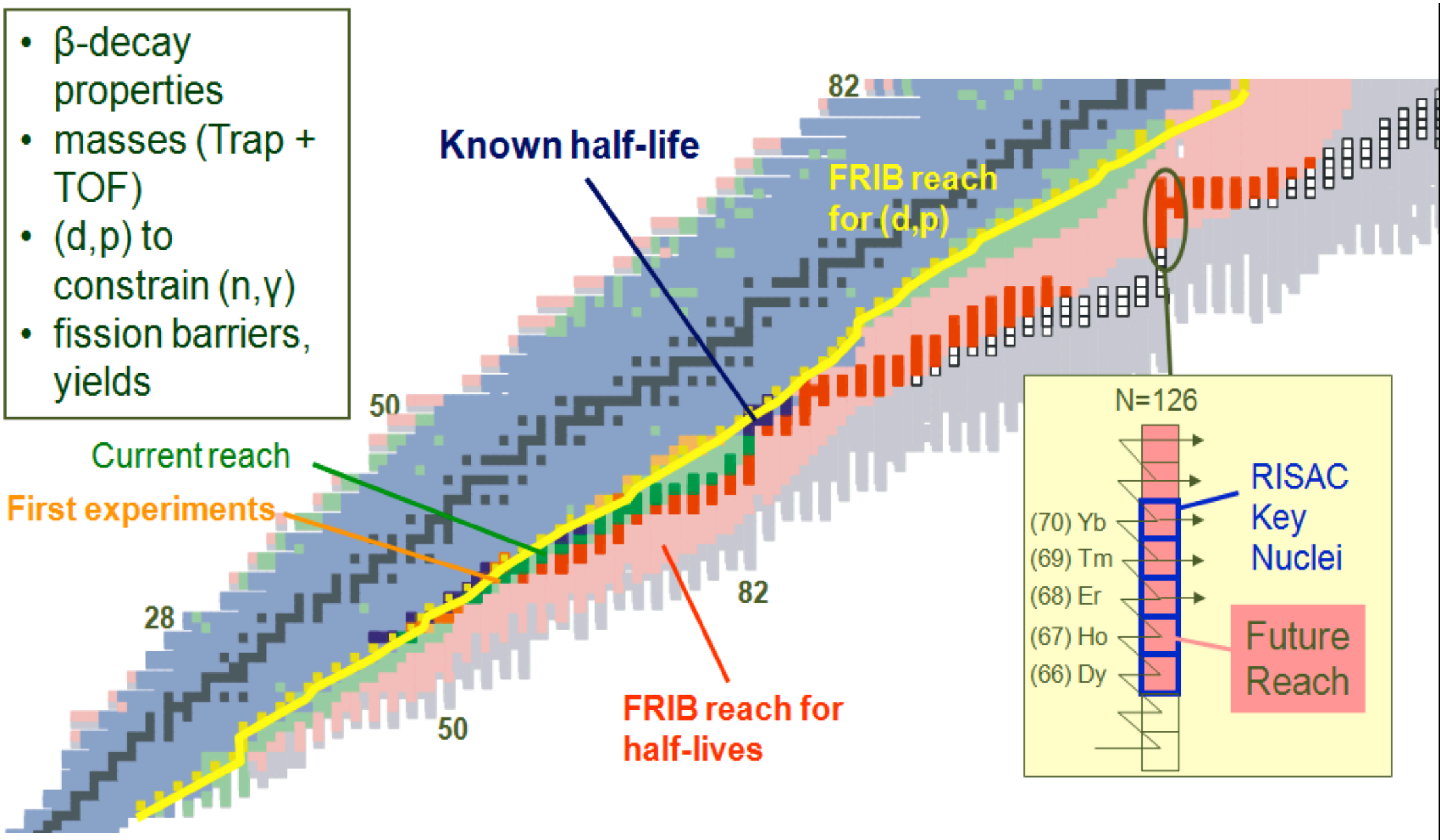
- Close to completion at MSU
- Will produce radioactive beams through in-flight projectile fragmentation - followed by fragment separation in a downstream spectrometer
- Focus in on neutron-rich nuclei

Production mechanisms (not only at FRIB)



Rare isotopes at FRIB

- β-decay properties
- masses (Trap + TOF)
- (d,p) to constrain (n,γ)
- fission barriers, yields



Why is the EIC an interesting place for studies of rare isotopes?

At high energy, lifetimes are longer in the lab frame

- The EIC will accelerate beams up to ~100 GeV/A, extending ion lifetime in the lab frame by a factor of 100.
- The ion detectors will be located ~100 ns away from the production point, corresponding to 1 ns in the rest frame of the ion
- Thus, a large yield can be expected for short-lived isotopes
- Detection of electrons from in-flight beta decay can extend this even further

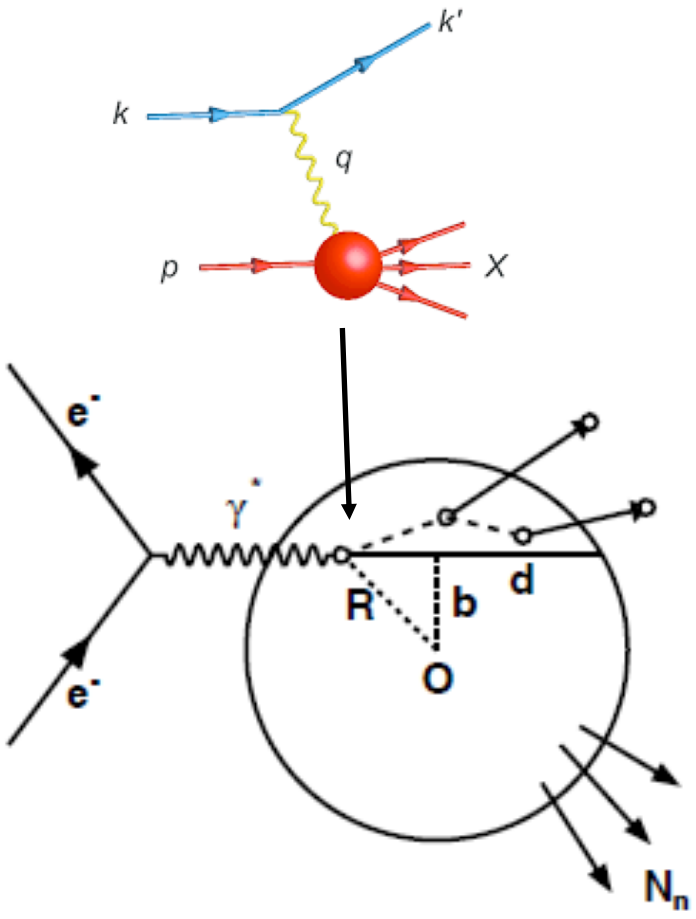
In the lab frame, photons are emitted with high energy in (almost) collinear with the nucleus

- The energy of the photons from nuclear de-excitations is boosted by (up to) a factor of 100
- Since the photons are preferentially emitted in the direction of the ion beam they can be detected at zero degrees (the beam is bent away).

Detection requirements synergetic with other eA experiments

- Compatible with detection requirements for other eA measurements
- Improvements to photon resolution and ion identification would also be generally beneficial

Deep Inelastic Scattering on nuclei

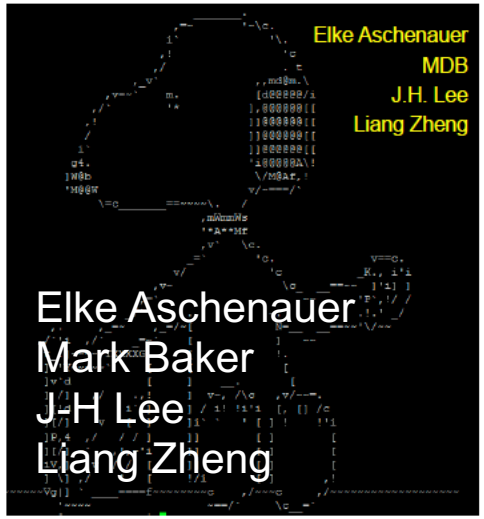


- DIS on nuclei is a multi-stage process.
- First, there is a scattering on a parton
- Debris from the interaction will propagate out of the nucleus, interacting along the way, causing an intra-nuclear cascade typically leading to the knock-out of several nucleons
- The daughter nucleus will usually be left in an excited state, leading to evaporation of nucleons and light nuclei, and sometimes fission.
- At high excitation energies there is no strong preference for emitting charged particles or neutrons, but at low energy neutrons are preferred.
- Finally, when below the nucleon separation energy, the nucleus will emit photons. These transitions between bound states offer detailed insight into the structure of the produced nucleus.

BeAGLE and FLUKA

BeAGLE

Benchmark **eA** **G**enerator for **LE**ptoproduction



26-June-2017

Talk by M. Baker earlier in this session

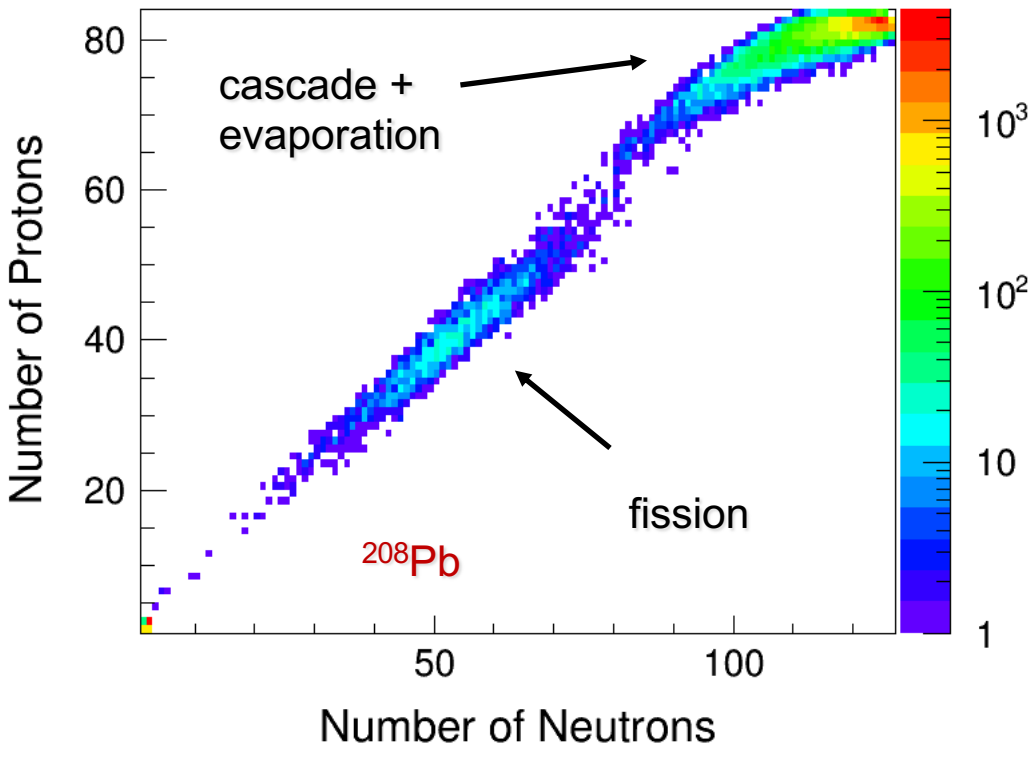
- Simulates nuclear DIS process, using FLUKA for modeling the evaporation (and photon emission).

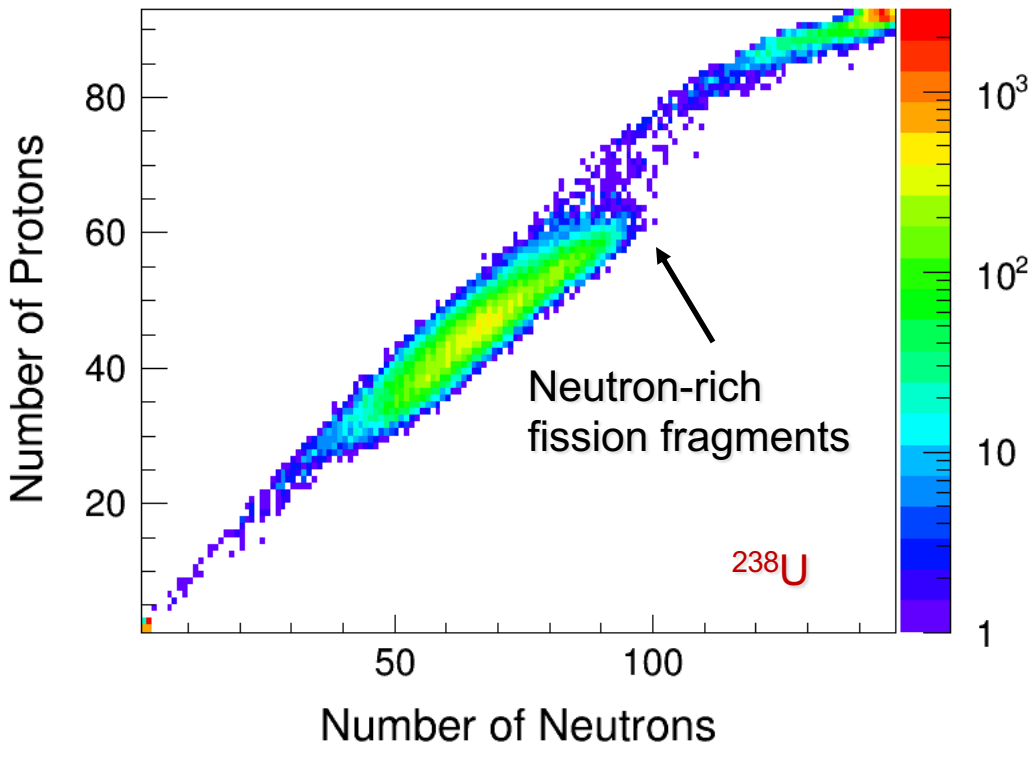
http://www.fluka.org/fluka.php

Simulation challenges

- Neither BeAGLE nor FLUKA have not yet been tuned for exotic nuclei
- Also, generating 40k DIS events (1s) takes 10 minutes on a single core, so 600 cores can generate events in “real time.”
- At this point, it is thus not realistic to simulate 1 trillion events (~1 year) to find the rarest isotopes, and an extrapolation will be needed.
- Some thought will need to be given to how to do the simulations in the most relevant and efficient way.

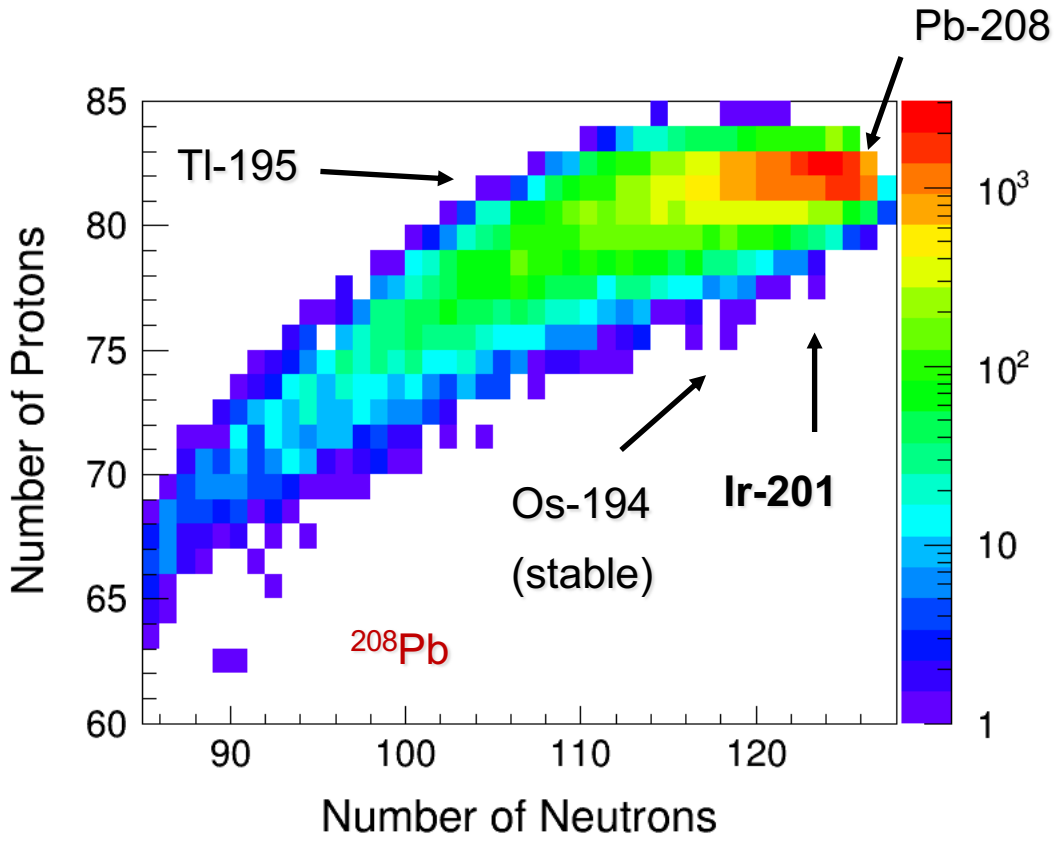
Nuclei from ^{208}Pb and ^{238}U (1s of simulated beam time)

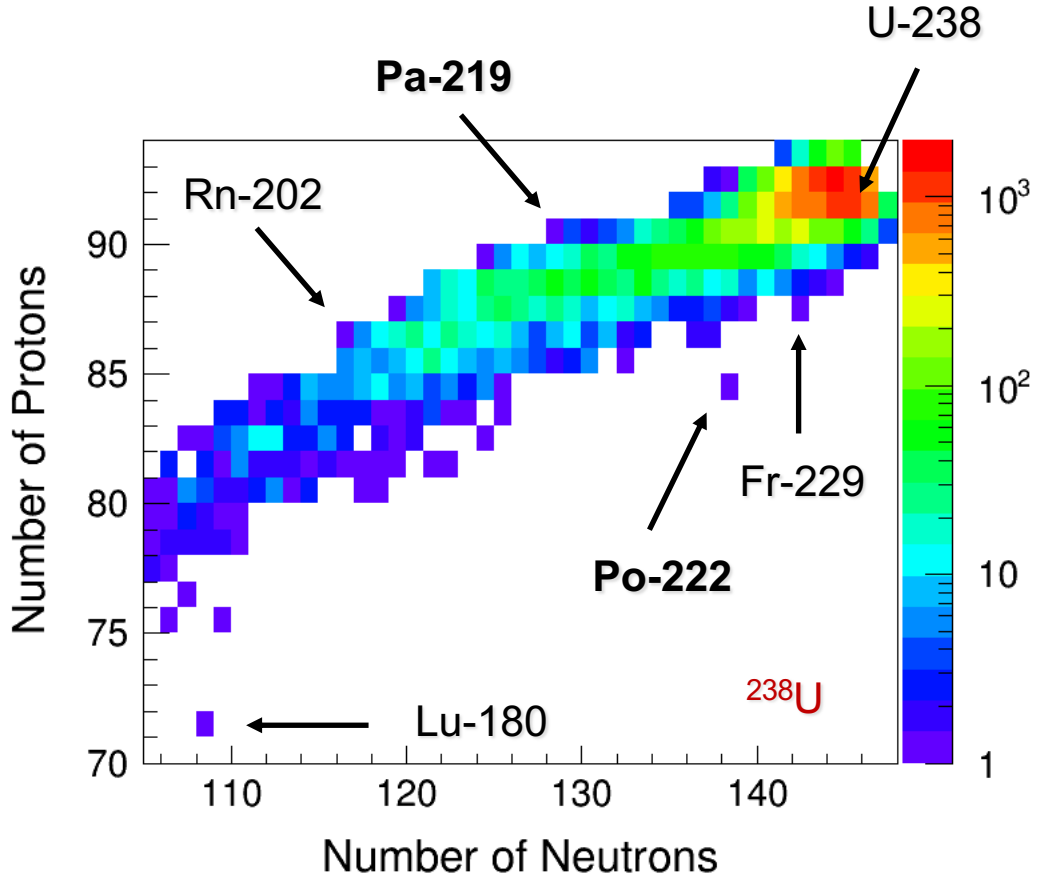




- ^{208}Pb (left) produces mainly heavy isotopes from evaporation only
- ^{238}U (right) produces fewer, but heavier isotopes from evaporation. It also produces some very neutron-rich fission fragments (stable medium mass nuclei have fewer neutrons).

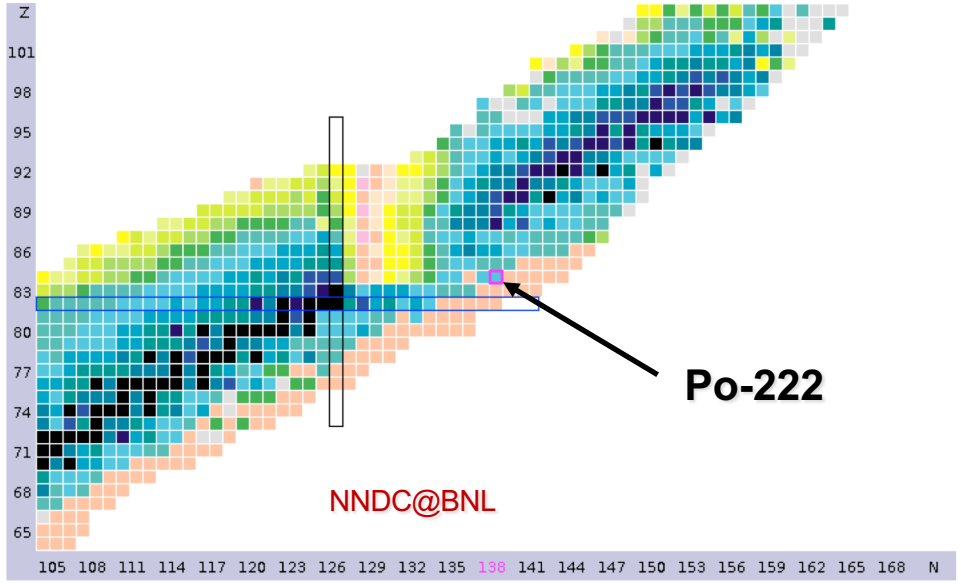
Heavy nuclei from ^{208}Pb and ^{238}U (1s of beam time)

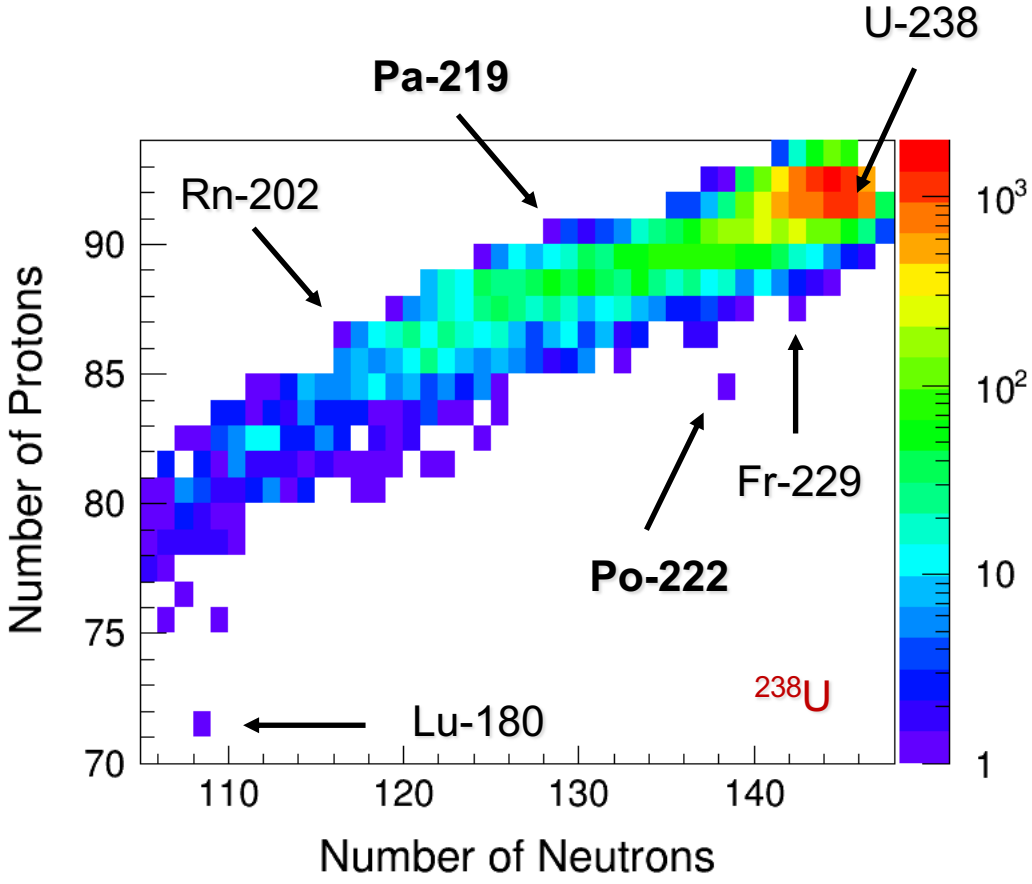




- All simulated nuclei are known (good for benchmarking), but already in 1 s several short-lived ones are produced, both on the proton and neutron side
- The sample contains several interesting isotopes, but the lifetimes change rapidly and it can be difficult to see how far from stability a nucleus is without a reference

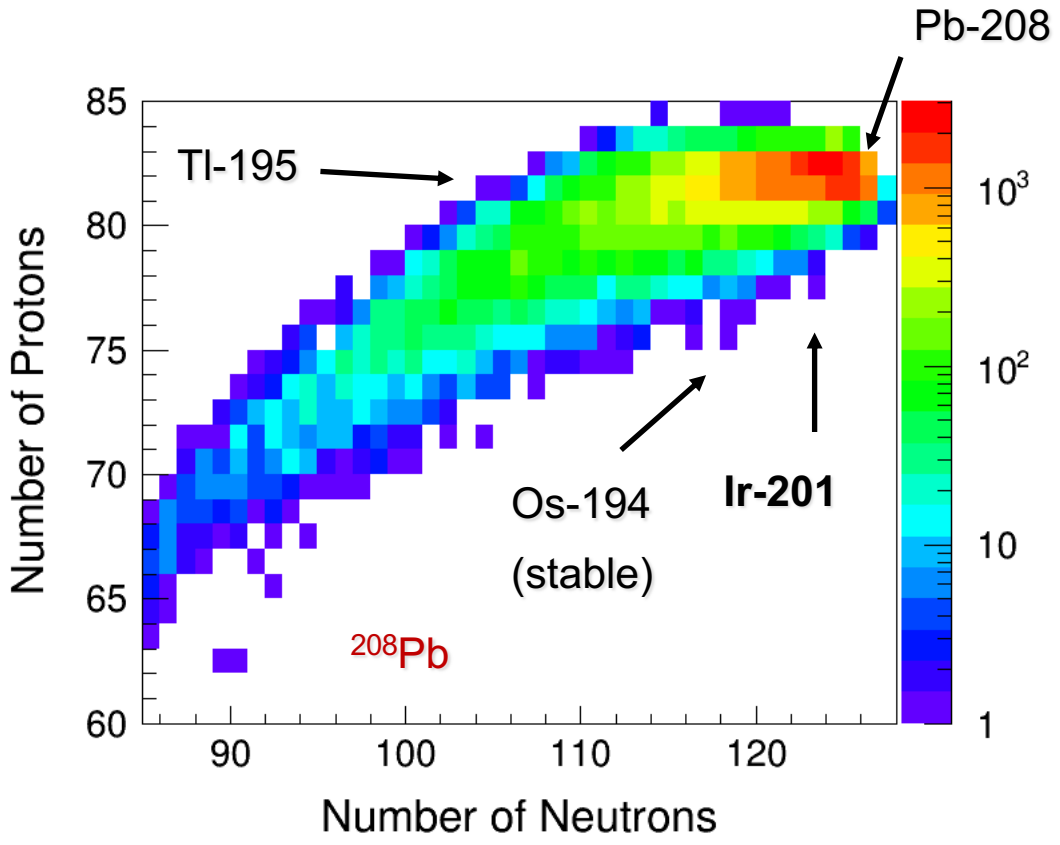
How "exotic" is ^{222}Po?

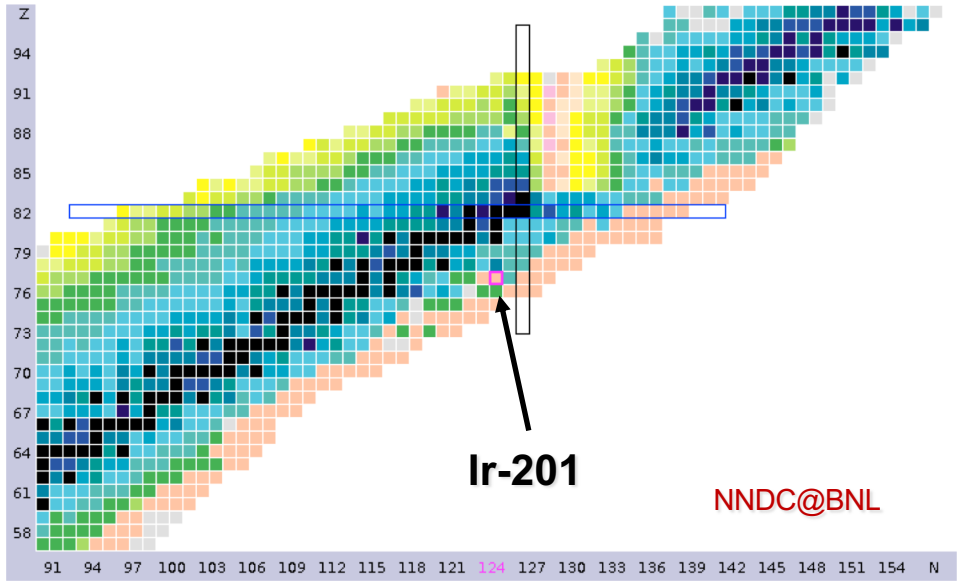




- Lifetime for ^{222}Po: 530 s
- All nuclei heavier than Pb are of particular interest since this is the only way to produce them

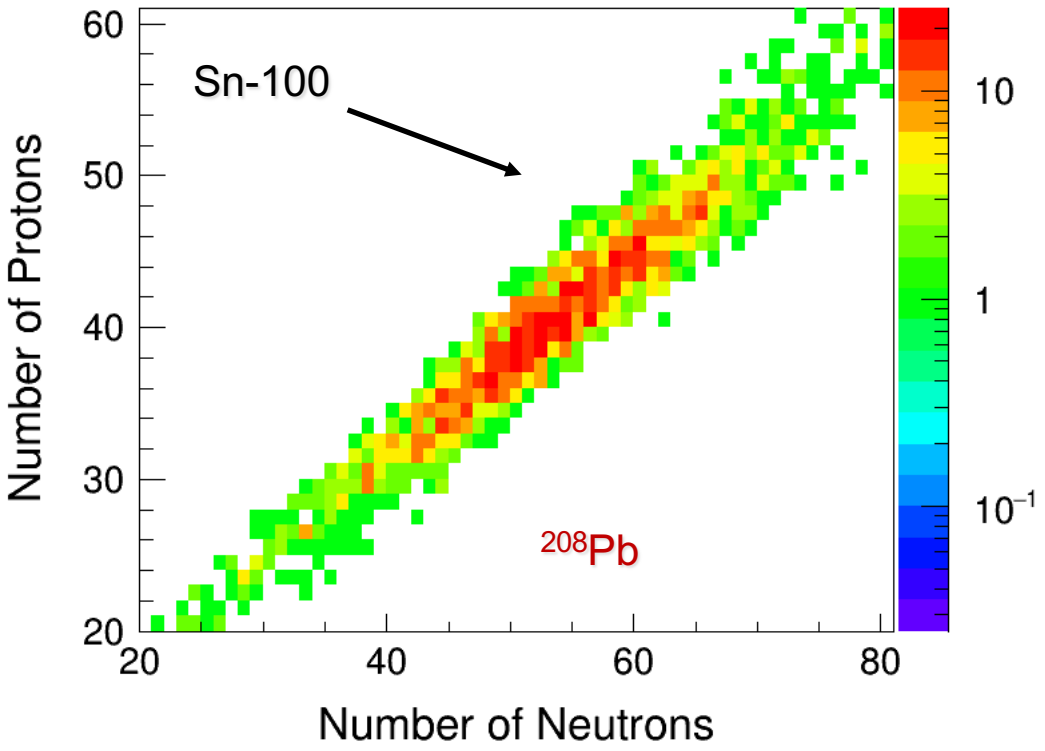
How ”exotic” is ^{201}Ir?

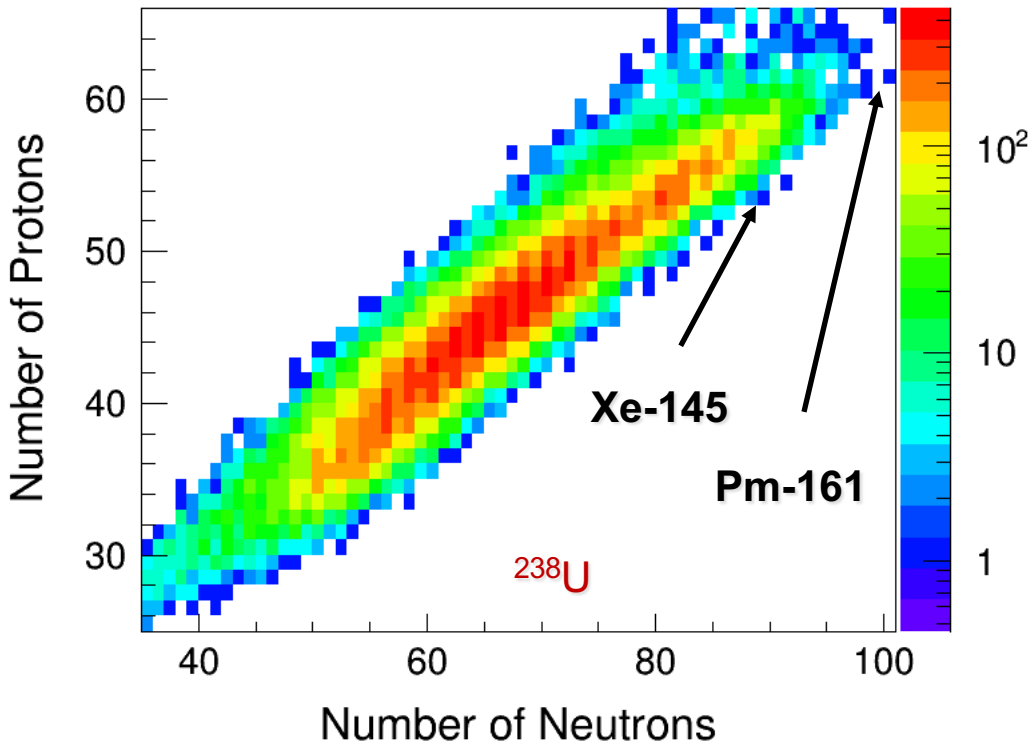




- Lifetime for ^{201}Ir: >300 ns
- Neutron-rich nucleus close to a closed shell – and the r-process path, which moves closer to stability near closed shells

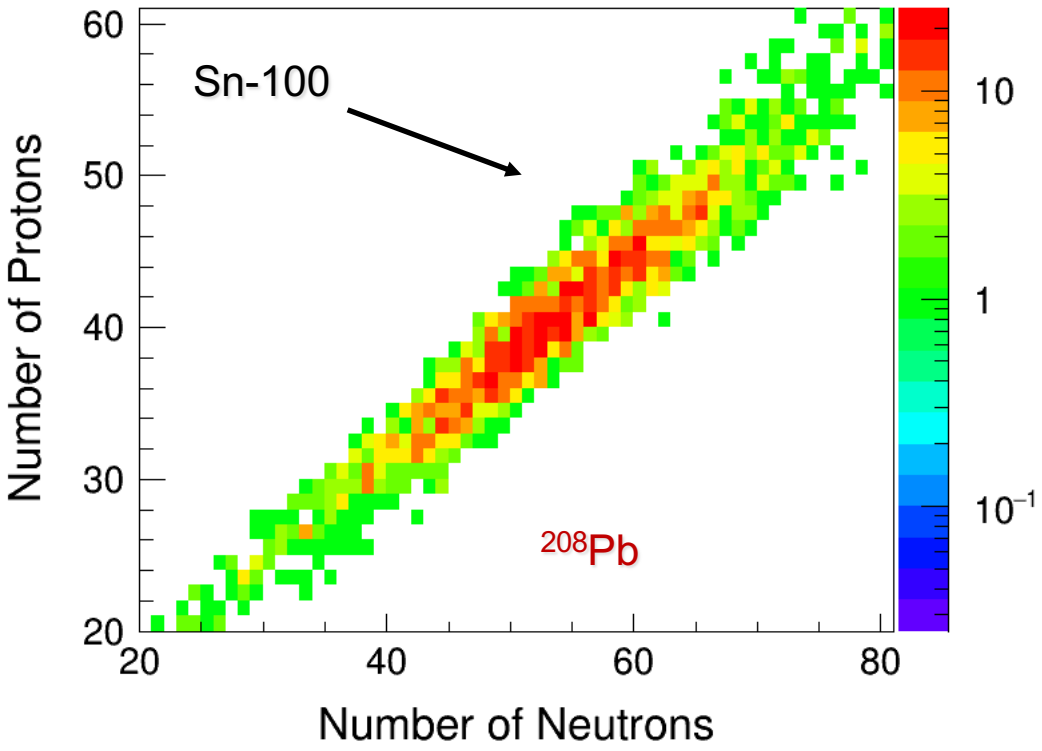
Fission fragments from Pb-208 and U-238 (1s of beam time)

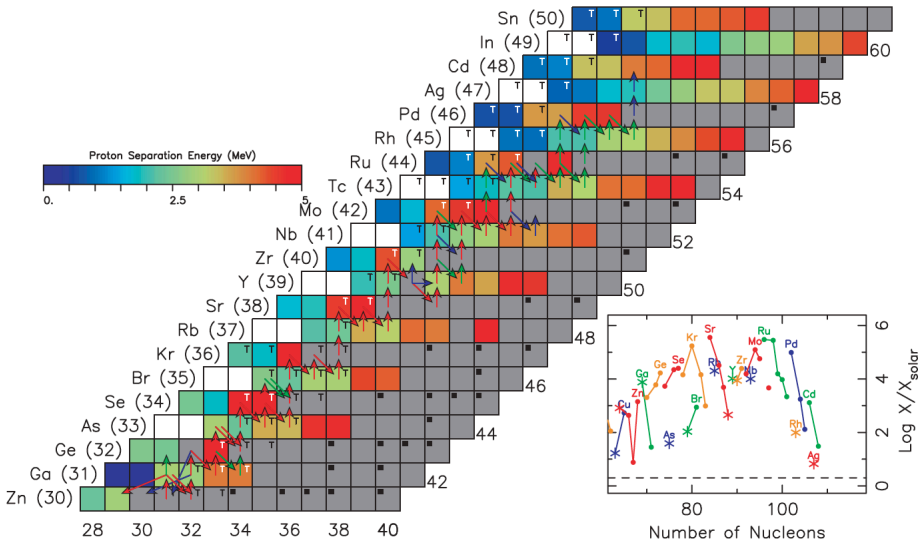




- Heavier nuclei are naturally more neutron rich. Fission fragments thus also tend to be more neutron rich than nuclei produced through evaporation only.
- These are some of the most neutron-rich nuclei that were observed in the simulations
- On the flip side, fission is not a good way to study the proton drip line

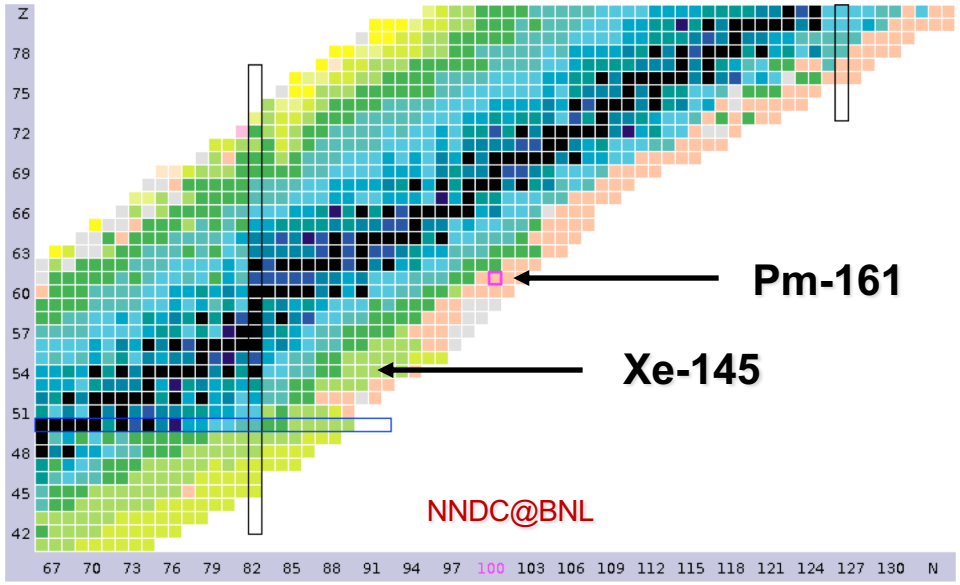
rp-process requires lighter beam nuclei (*e.g.*, ^{90}Zr or ^{112}Sn)

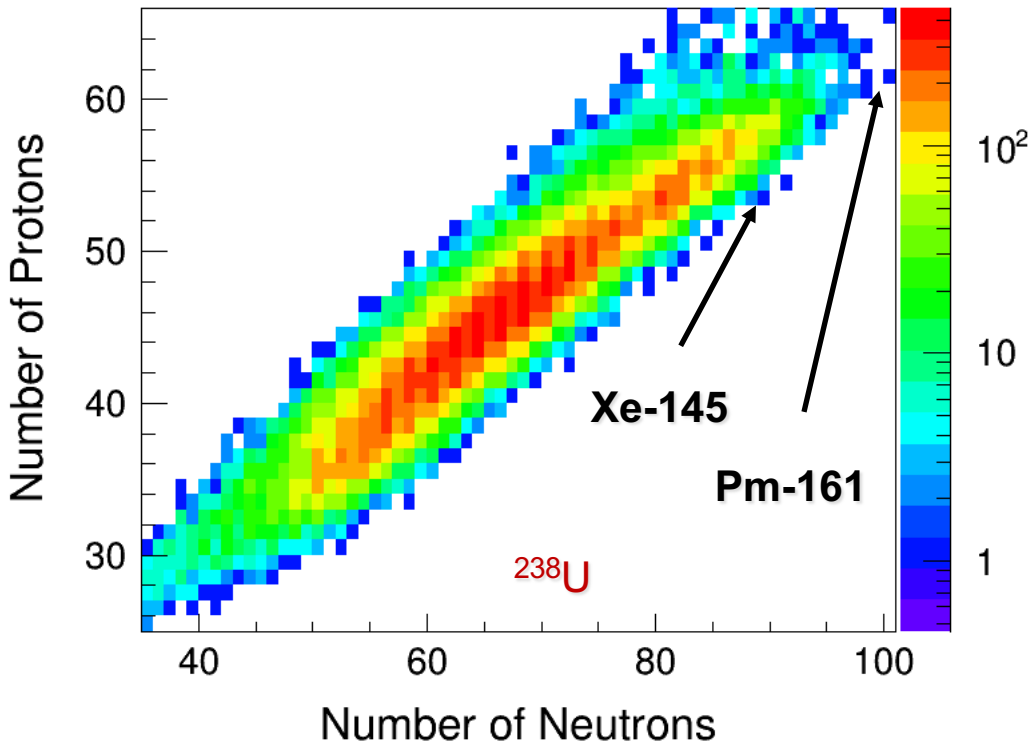




- In contract to fission (shown above), evaporation favors production of proton rich nuclei
- Using beam ions with A~100, the EIC should be able to provide useful input on both the rp-process and nuclei in the vicinity of ^{100}Sn.

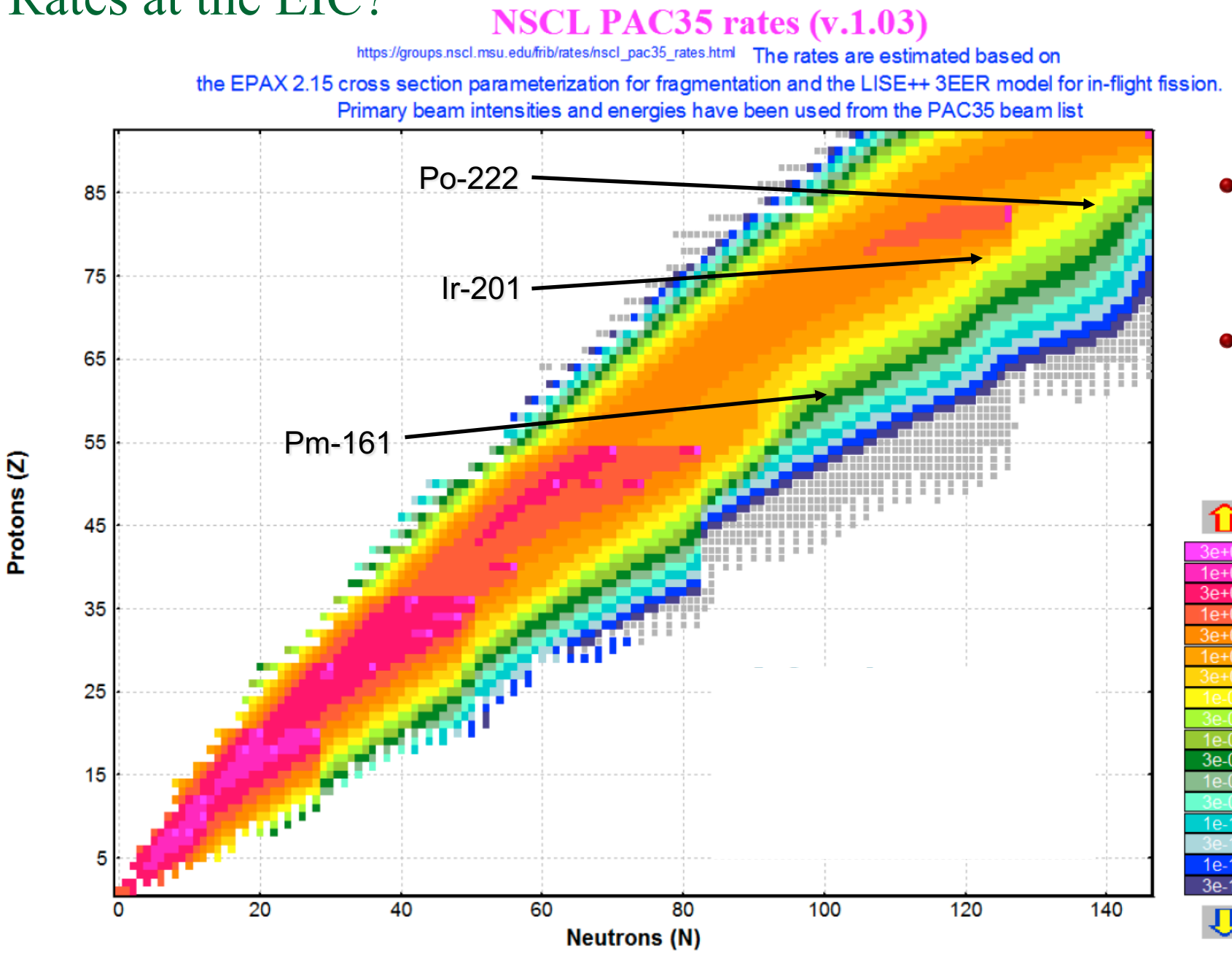
How "exotic" are ^{161}Pm and ^{145}Xe?

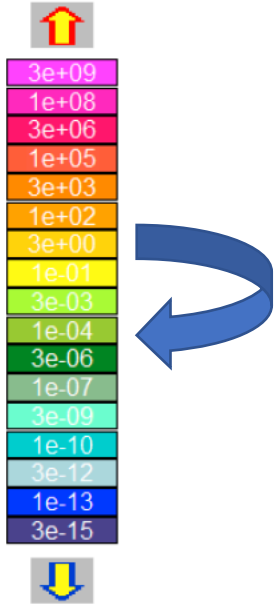




- Lifetime for ^{161}Pm: >130 ns
- Lifetime for ^{145}Xe: 188 ms
- Both nuclei are very close to the most neutron-rich nuclei currently known – and in a spot where rates at FRIB are relatively low

Rates at the EIC?



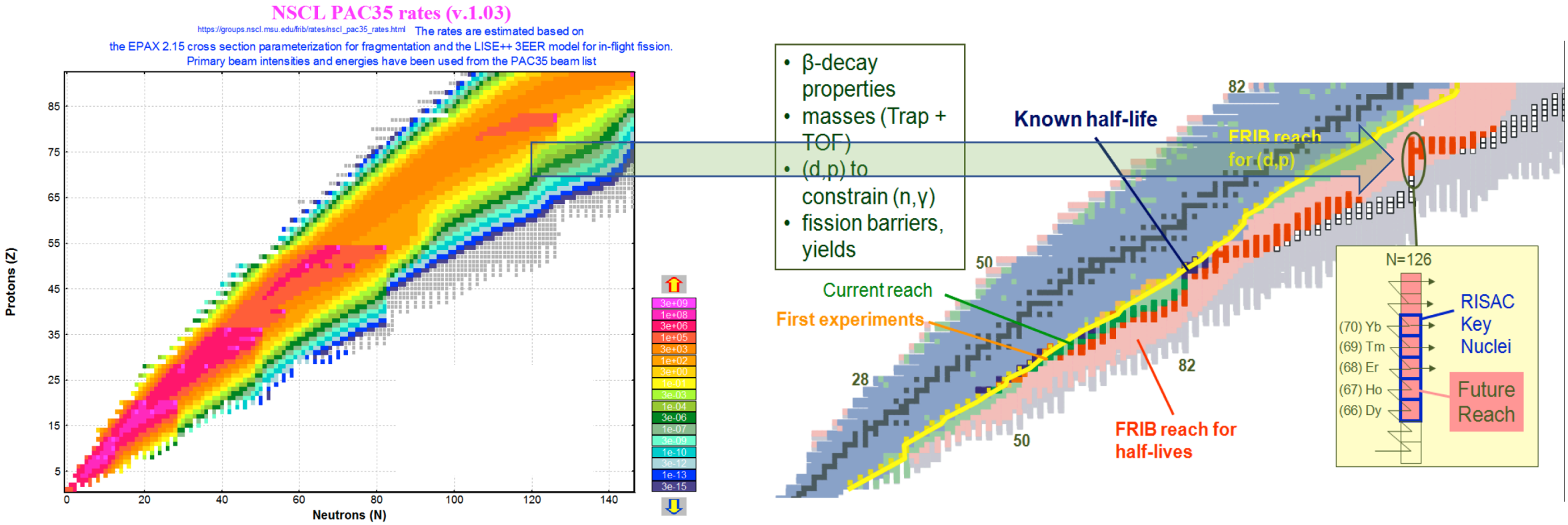


A bold extrapolation

- Let's assume that we have one "yellow-orange" event per second, or 10^8 in a year, distributed over ~100 isotopes of interest
- Further, lets assume that we can use the FRIB rate estimates for the extrapolation.

- Then, if we want to accumulate a total of 10,000 events for the isotopes of interest, in a year we can move from the orange-yellow to light green (although for ^{161}Pm we are there in 1 minute)

How does this compare with FRIB?



- With very large uncertainties, a year of heavy-ion running at the EIC should make it possible to probe parts of the neutron-rich red area on the right where FRIB plans to measure half lives.
- It will also at the same time provide information on proton-rich isotopes

Conclusions from the simulations

Simulations suggest a lot of potential

- ^{208}Pb produces good yields of both neutron- and proton rich nuclei nuclei in the A~200 range.
- ^{238}U gives access to 83 < Z < 92, with reasonable yields of both neutron- and proton rich nuclei.
- ^{238}U produces very neutron rich fission fragments around A~150, where the FRIB yields are low.

More work is needed on simulations

- Applicability of FLUKA to nuclei far from stability
- A more cost-effective way to simulate larger event samples (>> 40k)
- Better ways to extrapolate to rare isotopes
- Input from FRIB community?

Complementarity with FRIB

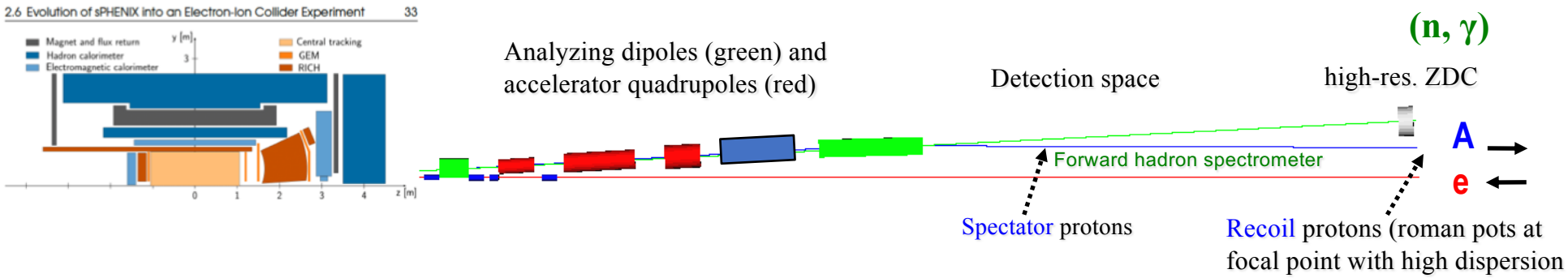
- The EIC can produce rare isotopes through a different method (DIS), with a long lifetime in the lab frame
- Rates should be sufficient to explore mass ranges that could be of interest for comparison with FRIB, and in some cases maybe even more favorable

FRIB goals to which the EIC may be able to contribute

- Shell structure (^{60}Ca rate?)
- Pairing in near-dripline nuclei with A > 34
- r-process
- Limits of stability near A = 100
- New nuclei near dripline
- rp-process

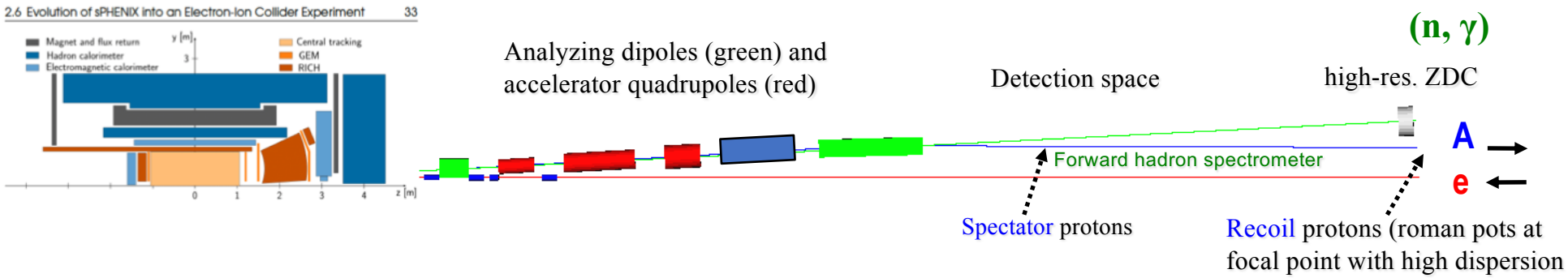
Benchmark	Unique Capability of FRIB	Unique Science Impact of FRIB	Necessary Capability
Shell structure 1	Only facility with yields above 0.01/s to allow study of ^{60}Ca	New doubly magic nuclei are key benchmarks for nuclear theory	Fast beams for experiments at 0.01/s
Super-heavies 2	Facility with the most intense ^{24}O beams	Intensity critical for fastest and most comprehensive exploration	Reaccelerated beams at 4-6 MeV/u
Skins 3	Only facility to allow study of extreme >0.5 fm skins	Exploration of asymmetric matter over a much wider range of shells and mass number	Fast beams for experiments with intensity of 0.01/s
Pairing 4	Furthest reach and only facility to study pairing in near dripline nuclei with A>34	Key insight into pairing in asymmetric matter	Reaccelerated beams of short-lived nuclei
Symmetry 5	Access to the widest range of transitional nuclei	Deeper insight into the origin of symmetries	Fast beams for rates below 100/s Reaccelerated for rates above 10^4/s
EOS 6	Use of probes, such as intermediate-energy heavy ion reactions with beams at the extremes of isospin	Cleanest and most distinctive tests of different neutron matter EOS	Fast beams of 100 to 200 MeV/u
r-Process 7	Constraints on the largest number of astronomical observables	Most complete data to connect models with observations of elemental abundances	Fast for half-life studies Stopped for masses Reaccelerated for (d,p)
^{15}O(α,γ) 8	FRIB may have the highest ^{15}O intensity	First possibility to directly measure this key rate	Low-energy reaccelerated beam
^{59}Fe 9	Provide the largest samples of this key isotope by 10 times	Measurement of (n,γ) on key radioactive isotopes	Isotope harvesting capabilities
Medical 10	Provide a source of material for the U.S. research community	A close proximity of medical and veterinary schools is a benefit	Isotope harvesting capabilities
Steward-ship 11	Wide range of isotopes available to the U.S. community	Access to isotopes involved in reaction networks for nuclear forensics	Harvesting Fast Reaccelerated for indirect studies
Dipole moment 12	Widest search for favorable octupole deformation	FRIB will contribute by exploration of favorable candidates	Fast beams Reaccelerated beams
Limits of stability 13	Will determine the limits of stability to near mass 100	Limits of stability are a key benchmark for nuclear models	3-stage separator and sensitive single isotope identification
New nuclei 14	3x more dripline nuclei having a range of mass and shells	Cases where collective and single-particle degrees compete	Fast experiments with less than 0.01/s
Mass surface 15	More masses available for study than any other facility	Key constraints for nuclear models	Penning trap with stopped beams Fast for some TOF measurements
rp-Process 16	Only facility where sufficient intensity of key nuclides will be available	Only facility where all rates in the rp-process can be determined	Reaccelerated for direct measurements Fast for indirect study
Weak inter-action 17	Ability to determine full range of key electron-capture rates via charge-exchange reactions	The ability to reliably model supernovae core evolution	Fast beams at 100 to 200 MeV/u

Detection of fragments and nuclei



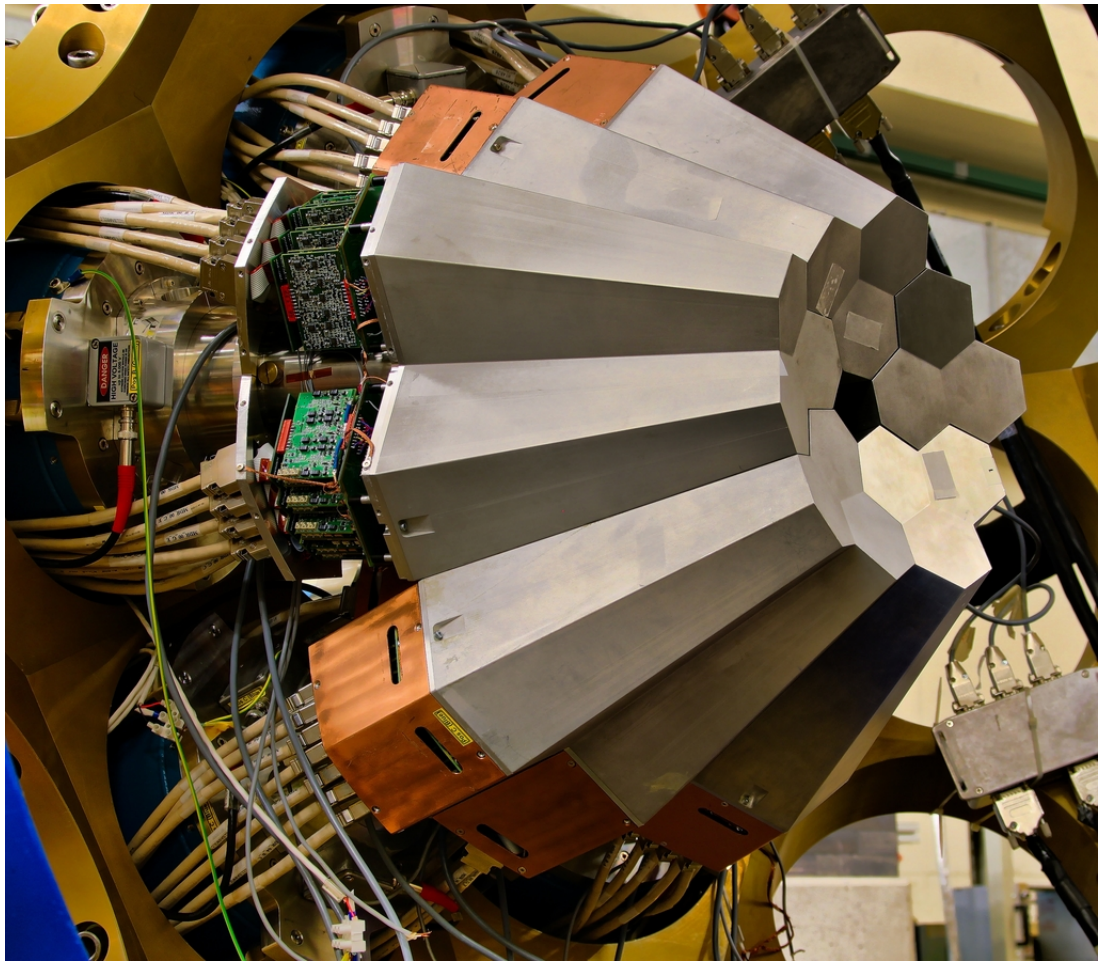
- The EIC needs to detect forward fragments with a wide range of magnetic rigidities (~A/Z).
- Compared to the beam, the relative rigidity of the fragment can anything from 50% for spectator protons from deuterium, to 1% for heavy nuclei that lose one proton
- Measuring small rigidity changes requires a dedicated forward spectrometer with special optics
- For nuclei far from stability, the relative rigidity change is a few percent, e.g., 2.2% for ^{222}Po.
- For fission fragments, the change is typically even larger, although there is an additional challenge (and opportunity in terms of systematics) of detecting both fragments at the same time
- Protons and light ions will have very different rigidities than heavy nuclei, and be detected earlier
- Neutrons and photons will be detected at zero degrees (the beam is bent away)

Identification of the detected nuclei



- The rigidity (~A/Z) is obtained directly from the magnetic spectrometer.
- To obtain N and Z independently, one more measurement is needed
- dE/dx (~Z^2) is a natural candidate technique. Information can even be obtained from the Si-trackers.
- To fully separate Pb (Z=82) from Tl (Z=81), one would need a dE/dx resolution at the 2.5% level.
- Other techniques are also possible, although TOF is challenging at 100 GeV/A
- In a full-acceptance detector, the mass and charge of the ion can also be inferred from the all the other detected fragments

Photon detection: LN-cooled HPGe detectors have excellent performance



Agata prototype with longitudinally segmented Ge crystals

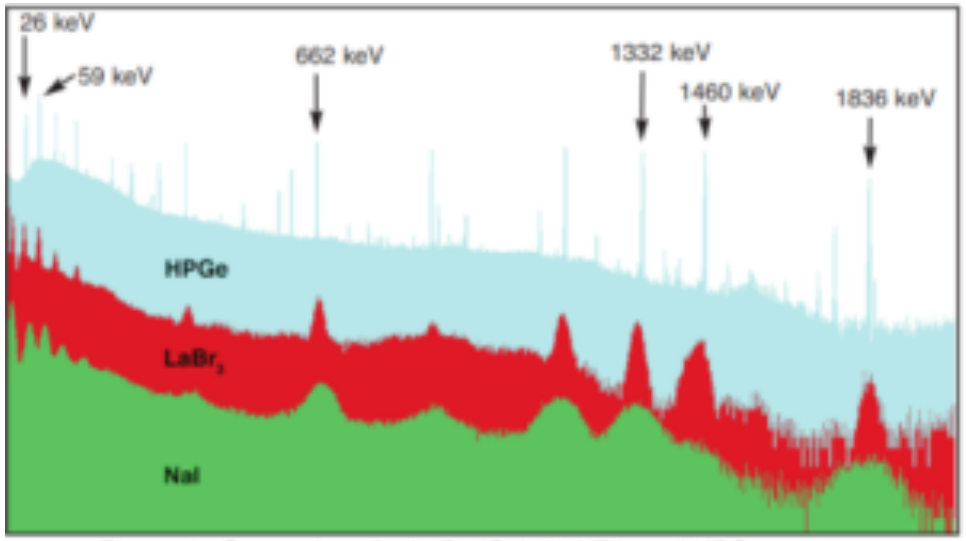


Figure 1. Comparison for $LaBr_3$(Ce), NaI(Tl), and HPGe spectra.

- The best EM calorimeters are based on semiconductors such as Ge
- Performance is order(s) of magnitude better than for crystals
- Excellent baseline, but can we do something simpler for the EIC?

Detection of the de-excitation photons

- At the EIC, the photon energies will be boosted by up to a factor 100, or to about 10-100 MeV.
- An alternative to Ge could be GaAs, which has about the same radiation length, but a larger band gap (1.43 eV at 300K vs 0.74 eV at 0K for Ge), potentially allowing it to operate at room temperature

- It is also possible to use the ubiquitous Si, which has only 1/3 of the radiation length, but long single-crystal ingots are is manufactured on a large scale for cutting into wafers from which chips are made. The bandgap is 1.11 eV at 300K and 1.17 eV at 0K, making some cooling necessary.
- If one nevertheless was to use crystals for the relatively small calorimeter at zero degrees, it would be worthwhile to look at, for instance, LYSO. The performance of PWO_4, which is the best crystal commonly used in high- and medium energy experiments, would probably be marginal.
- We also already know that W-Si sampling calorimeters (developed for CALICE) have very poor performance, and do not need to be pursued for this application.
- Lots of opportunities for detector R&D!

Synergies with coherent diffraction

Heavy nuclei (^{208}Pb) *Talk by M. Baker earlier in this session*

- Vetoing incoherent diffraction requires excellent detection capabilities for fragments, residual nuclei, and photons
- High-resolution photon detection can ‘fingerprint” nuclei in the vicinity of ^{208}Pb

Light nuclei (d, ^{3}He, ^{4}He)

- Exclusive processes (*e.g.*, DVCS) will provide us with a 3D picture of the nucleon
- A comparison with coherent production on light nuclei can lead to new insights (^{3}He, in particular, has the same GPDs as the proton and polarized beams can be produced at the EIC).
- However, recoil nuclei require better detection than protons since the physics is sensitive to the momentum transfer to the nucleus ($t \sim p_T^2$), but the relative angular change is $\sim p_T/A$
- A forward detection system designed for light nuclei will do an excellent job for DVCS on the proton, but the opposite is not true.
- The requirements for diffraction on light ions are, however, also similar to those for rare isotopes!

Summary and outlook

- In DIS on nuclei, the EIC will produce a considerable number of isotopes far from stability
- High-energy collision kinematics are favorable in terms of nuclear lifetimes in the lab
- Good small-angle detection of photons, fragments, and final nuclei in a forward spectrometer will allow the EIC to make high measurements
- The data can be taken in parallel with other measurements, making use of all available eA beam time.
- The detection capabilities are synergetic with other key EIC measurements such as coherent diffraction on heavy and light nuclei

Acknowledgements

- Authors of the BeAGLE event generator (E. Aschenauer, M. Baker, J-H Lee, L. Zheng)

- Collaborators within the Geometry tagging project (M. Maker, R. Dupre, C. Hyde, V. Morozov, *et al*.)

- Authors of borrowed FRIB slides!