TRIUMF

The Early Science Program of ARIEL

Science Week 2023

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Outline

Things I'll talk about

- Life and Accelerator Sciences Experiments Underway
- Particle Physics Opportunity
- ARIEL as an R- and I-process factory
- Needed measurements and experimental equipment (most is already here)
- Examples of First Experiments with "Day 1" yields

Things I won't talk about

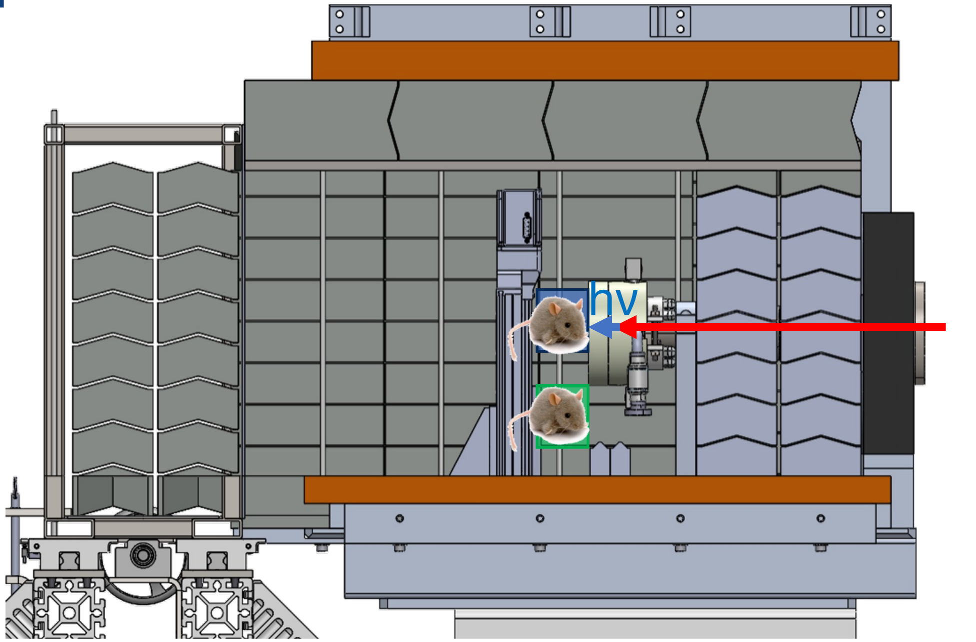
- CMMS (talk upcoming anyway)
- Benefits of Simultaneous RIB Beams (self-evident)
- Details of RIB production
- Anything much past "day 1"
- Radiopharmaceuticals
- Stuff that Conny H, Nicole V and Alex G already said properly

X-Ray FLASH Radiotherapy Research

- Radiotherapy but with much higher instantaneous dose rates than conventional treatments
  - Conventional doses 0.01 Gy/s
  - FLASH doses >40 Gy/s
- Shown to be more effective at treatment with fewer side effects
  - Less effect on healthy tissue for same effect on malignancies
  - Detailed reason still not well understood
- In principle can use *any* form of external particles
- 10 MeV (or MV as they say in biology) photons are an option
- Only two places in the world that can generate high enough *photon* flux
  - Hospital e-linacs don't have high enough current to convert to enough *photon* flux
  - Their studies use direct electrons – not an apples-to-apples therapeutic comparison

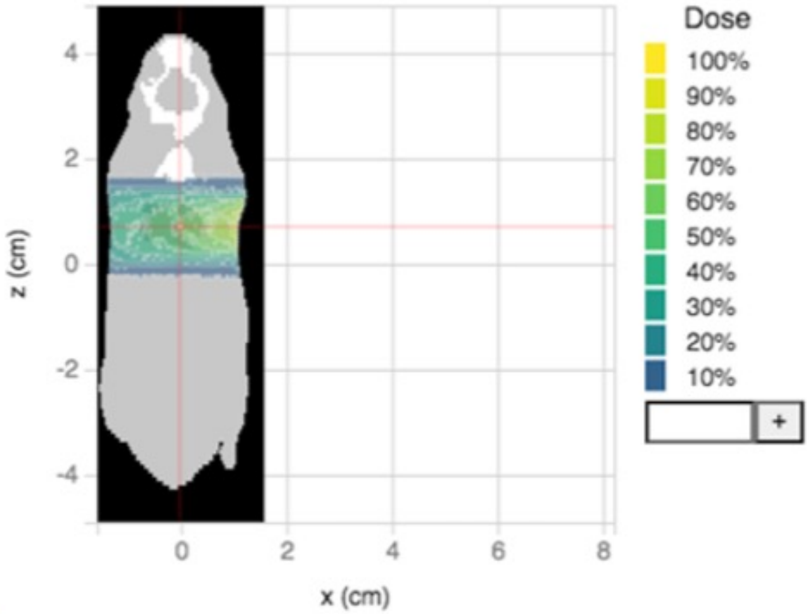
X-Ray FLASH Radiotherapy Research

- Alex G, Conny H et al. use ARIEL electron beam to generate 10 MV photons
- ARIEL beam dump replaced with photon converter assembly
- Downstream mechanism to hold mice



X-Ray FLASH Radiotherapy Research

- 15 and 30 Gy integrated total doses
- FLASH: ~0.15, 0.3 seconds
- CONV: ~300, 600 seconds
- Targeted on lung tissue
- 6 healthy mice each plus one control group of 6 mice
- Diagnostics post irradiation: weight, breathing function, CAT scans, biopsies



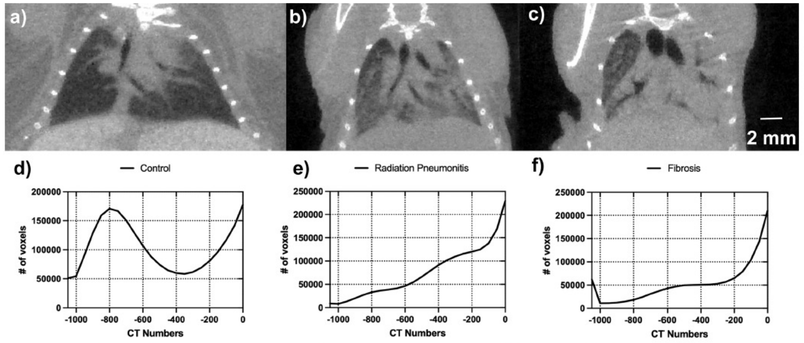
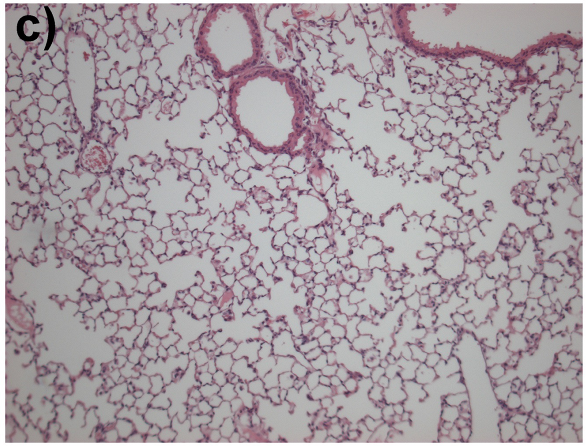


Figure 2 Sample images of (a) control mouse at 18 weeks with no pathology, (b) a 30 Gy FLASH-RT mouse at 12 weeks showing radiation pneumonitis, and (c) a different 30 Gy FLASH-RT mouse at 18 weeks (endpoint) showing fibrosis. Micro-CT images were obtained during peak inspiration, reconstructed at 0.075 mm voxel size, and are all scaled with the same window and level. The histograms of the CT numbers measured within the lungs during peak inspiration are shown in panels (d-f) to demonstrate the shift in CT numbers corresponding to reduced air in the lungs from an accumulation of fluid or scar tissue.

X-Ray FLASH Radiotherapy

- Stained microscope images of cross-sections of lung tissue
- Reddish parts show presence of cellular nuclear material
- Lungs are mostly air – don’t expect a lot of tissue material
- Control mouse shows very little material -- spongy

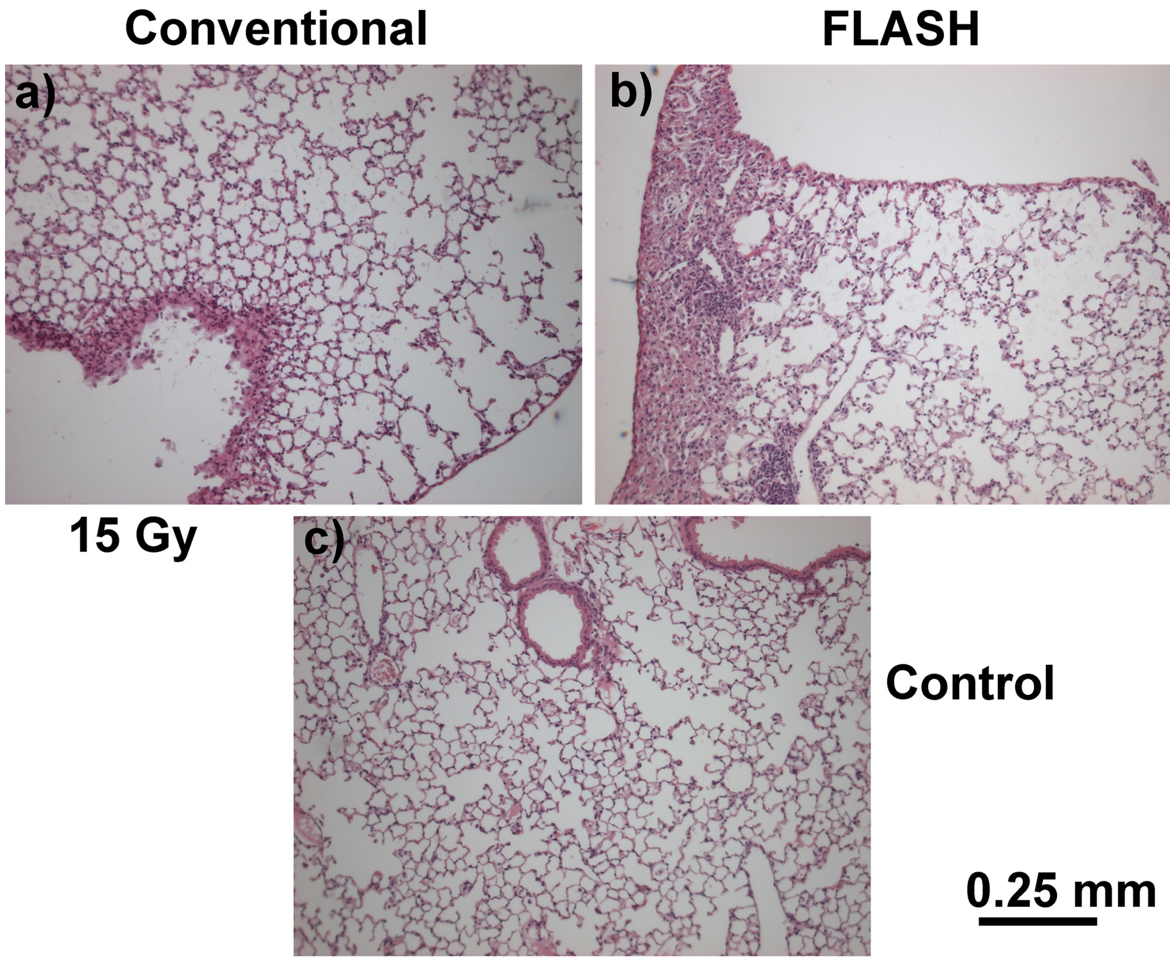


Control

0.25 mm

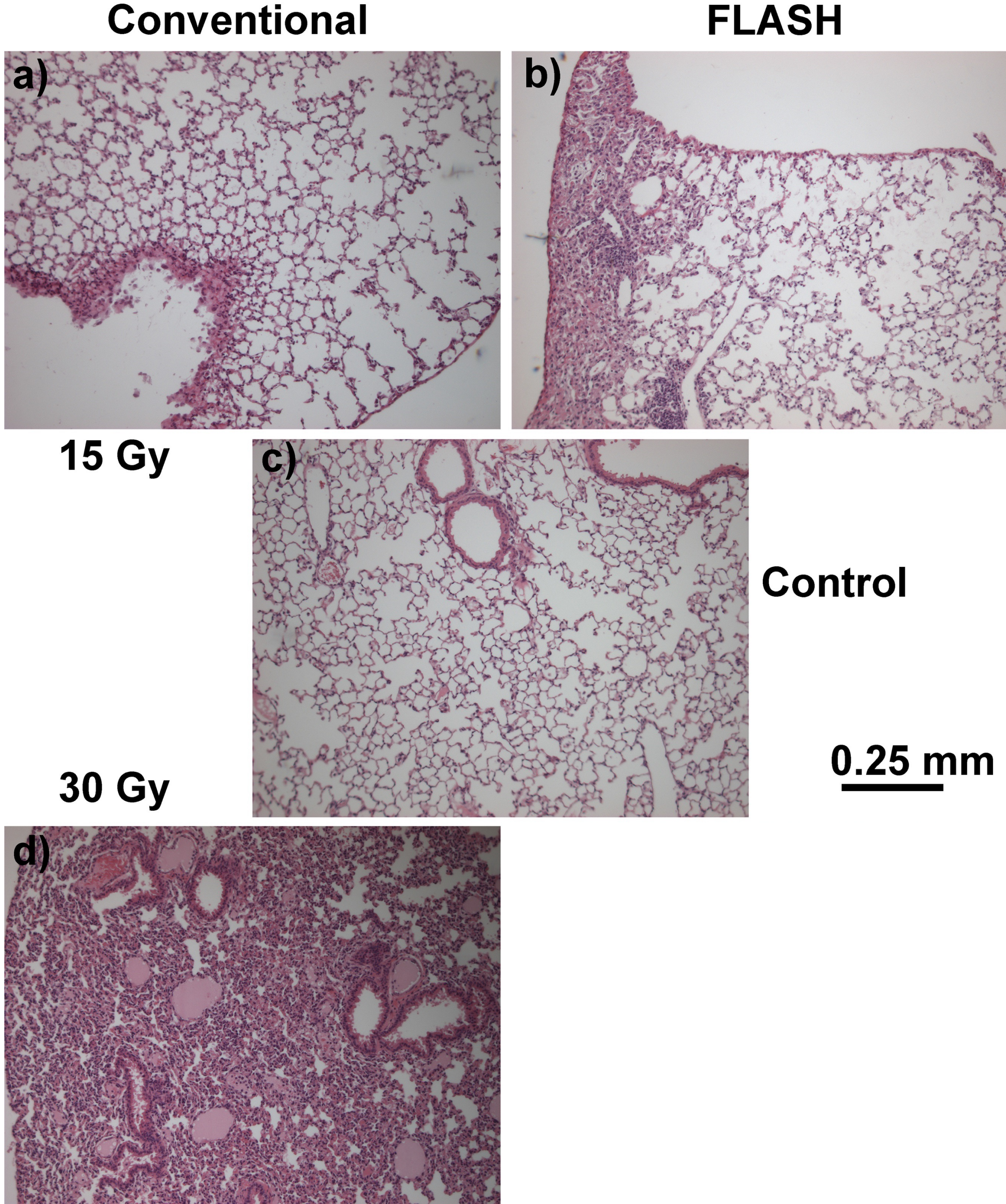
X-Ray FLASH Radiotherapy

- Stained microscope images of cross-sections of lung tissue
- Reddish parts show presence of cellular nuclear material
- 15 Gy doses both conventional and FLASH show some sign of scar tissue – more red area



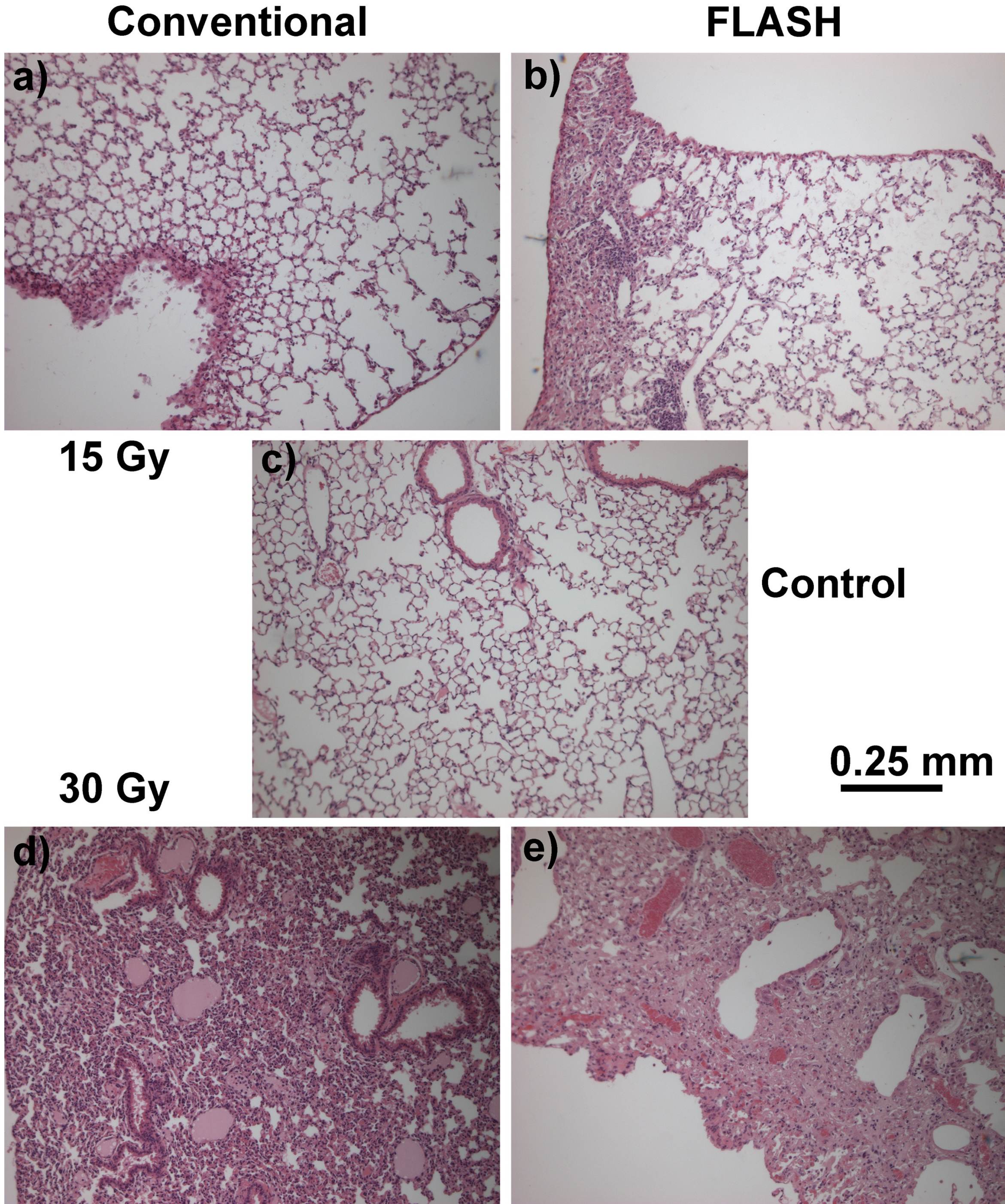
X-Ray FLASH Radiotherapy

- Stained microscope images of cross-sections of lung tissue
- Reddish parts show presence of cellular nuclear material
- 30 Gy conventional treatment shows VERY significant scar tissue



X-Ray FLASH Radiotherapy

- Stained microscope images of cross-sections of lung tissue
- Reddish parts show presence of cellular nuclear material
- 30 Gy FLASH shows much lower density of scar tissue
  - Still worse than 15 Gy as expected
- Interpret this as evidence of less damage to healthy tissue in FLASH than conventional



X-Ray FLASH Radiotherapy: ~~Early~~ First! ARIEL Science

Dosimetric characterization of a novel UHDR megavoltage x-ray source for FLASH radiobiological experiments

Nolan Esplen[1,*], Luca Egoriti[2,3], Thomas Planche[2], Stephanie Rädel[2], Hui-Wen Koay[2], Brandon Humphries[2], Xi Ren[4], Nancy Ford[5], Cornelia Hoehr[1,2], Alexander Gottberg[1,2], and Magdalena Bazalova-Carter[1]

[1]University of Victoria, Physics and Astronomy, Victoria, V8P 5C2, Canada
[2]TRIUMF, Vancouver, V6T 2A3, Canada
[3]University of British Columbia, Chemistry, Vancouver, V6T 1Z1, Canada
[4]University of British Columbia, Physics and Astronomy, Vancouver, V6T 1Z1, Canada
[5]University of British Columbia, Department Oral Biological and Medical Sciences, Vancouver, V6T 1Z1, Canada
[*]nolane@uvic.ca

Respiratory-Gated Micro-Computed Tomography Imaging to Measure Radiation-induced Lung Injuries in Mice Following FLASH and Conventional Radiation Therapy

Nancy Lee Ford*[1,2], Xi Ren[2], Luca Egoriti[3], Nolan Esplen[4], Stephanie Radel[5], Brandon Humphries[5], Hui-Wen Koay[5], Thomas Planche[4,5], Cornelia Hoehr[4,5], Alexander Gottberg[4,5], Magdalena Bazalova-Carter[4]

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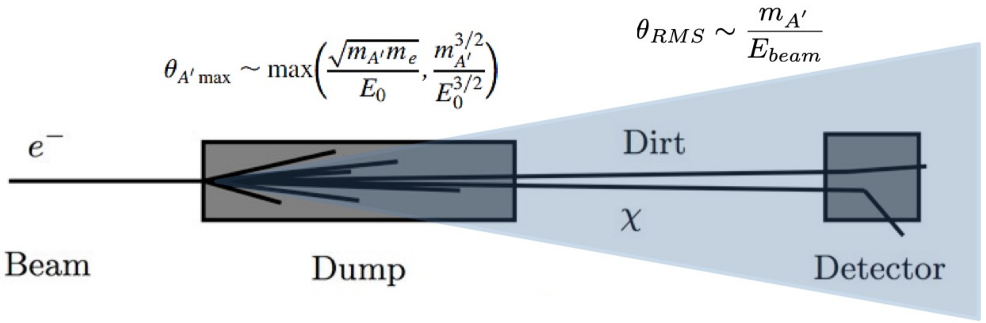
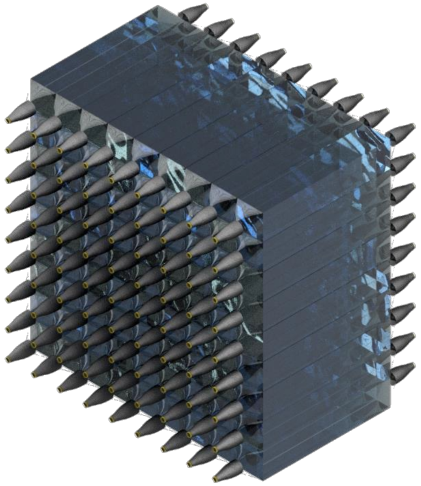
604-822-6641

- Two manuscripts submitted to Nature: Scientific Reports
  - one in June, one in July

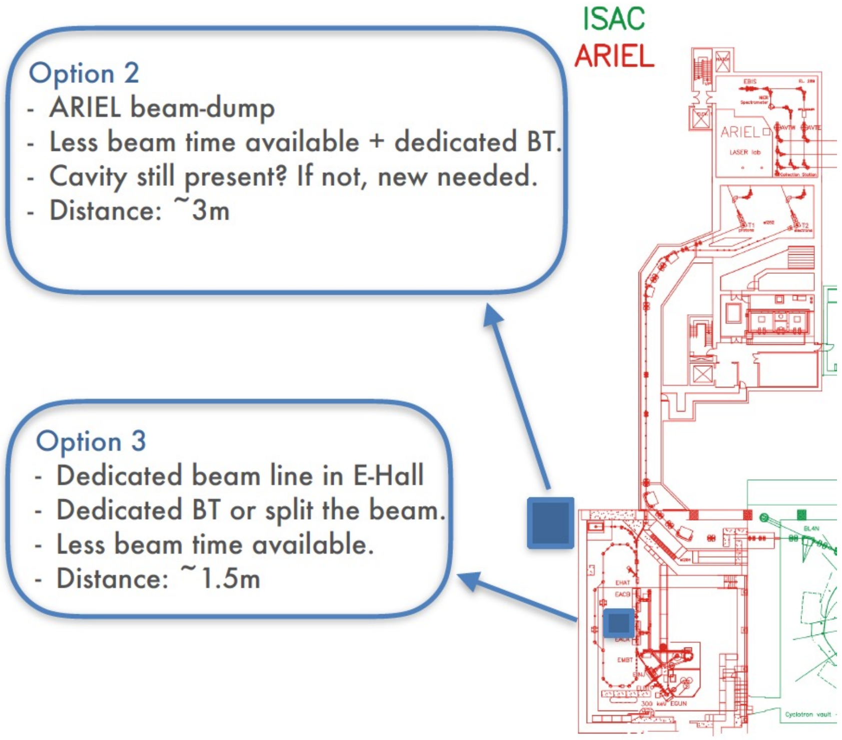
Early suggestions for a dark-matter search with ARIEL

- Reminder: Luca Doria reviewed options for a beamdump-style dark matter search in a 2018 Ariel Science Workshop
- https://meetings.triumf.ca/event/29/contributions/1786/attachments/1135/1301/doria-asw18.pdf if you're curious



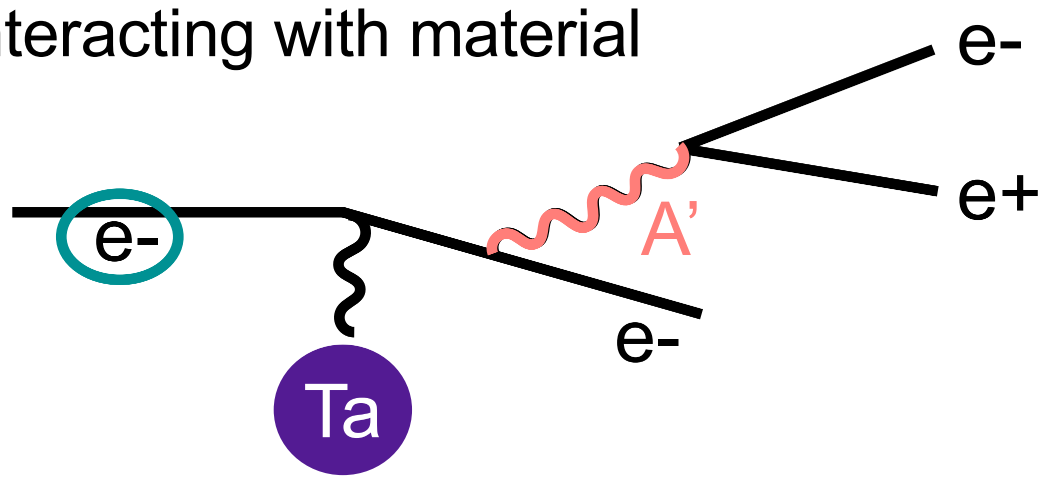


2.7x2.7x1.5 m



Darklight: Search for new light boson

Recall electrons radiate photons when interacting with material



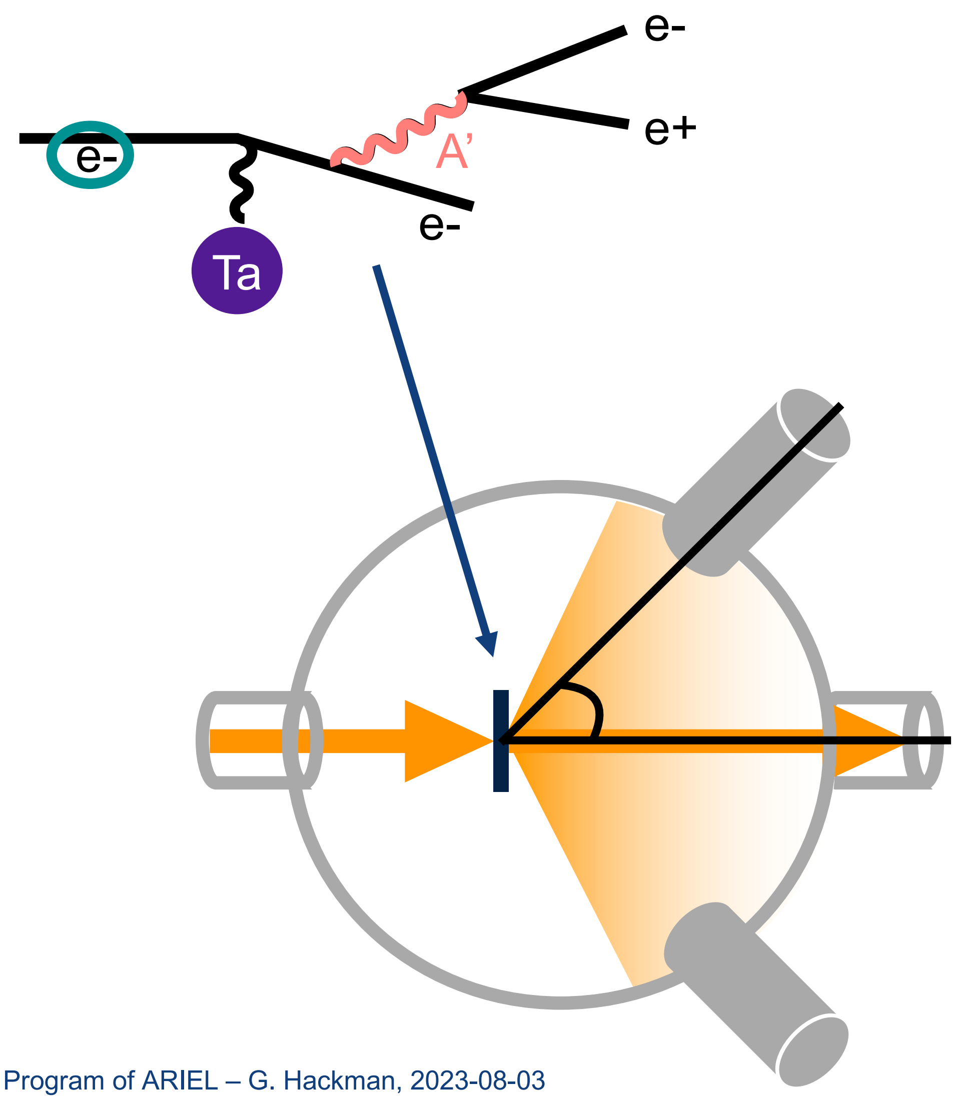
But if a **new boson** has a mass 12 to 20 MeV, could radiate that instead

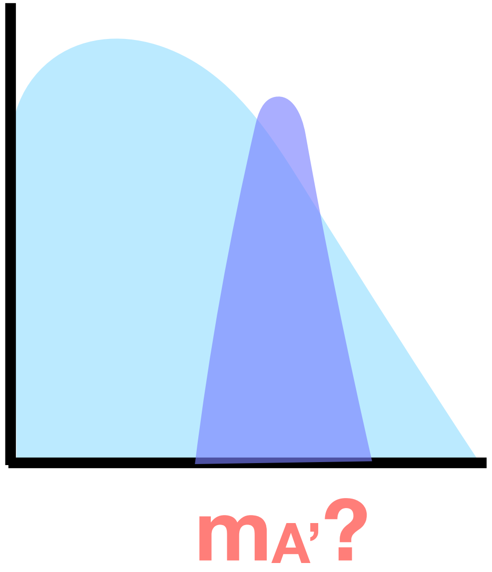
New boson could decay to dark matter, or back to e+e-

Nominal experiment:
1 μm Tantalum foil target

DarkLight experiment will look for this process

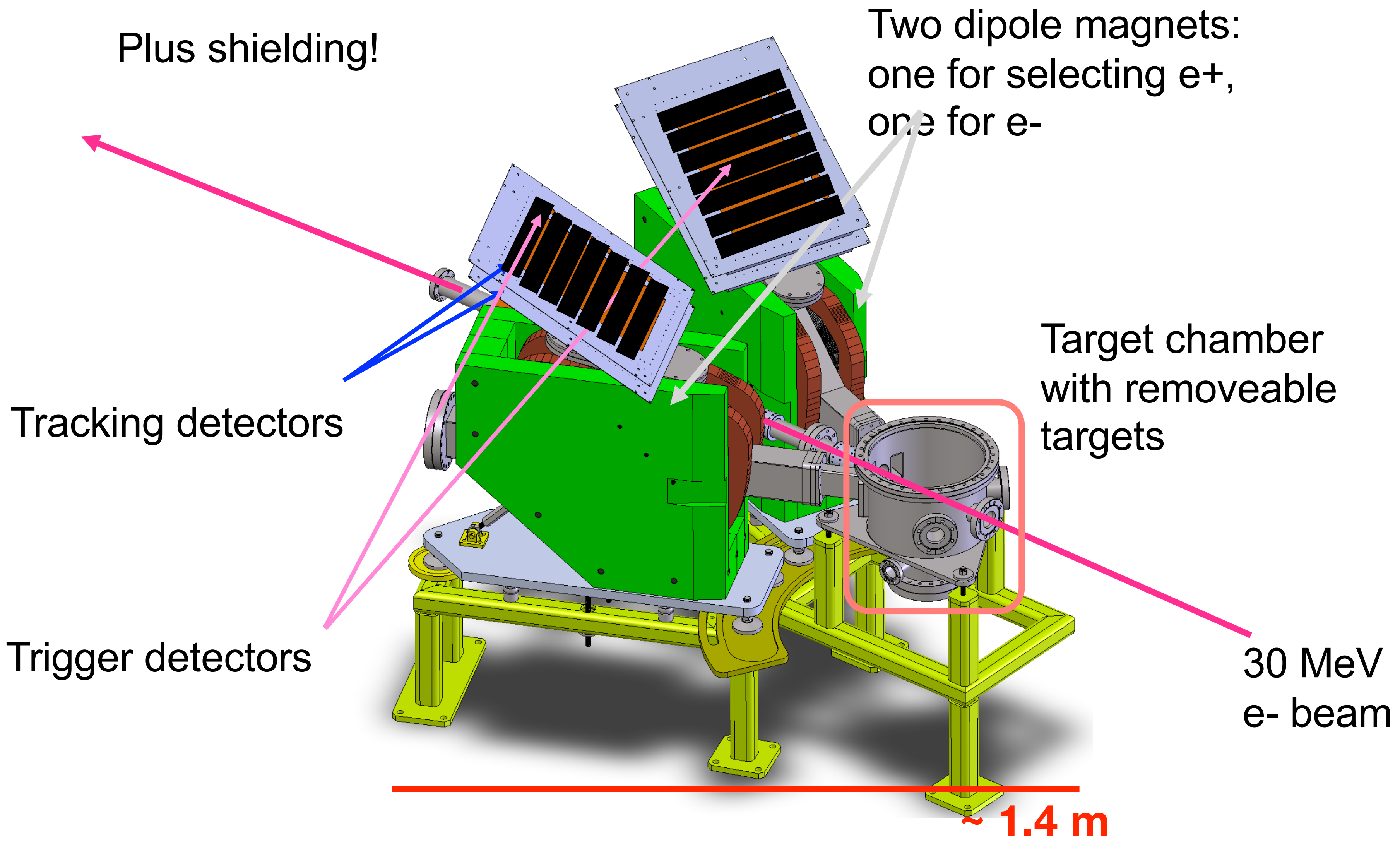
Darklight: Search for new light boson



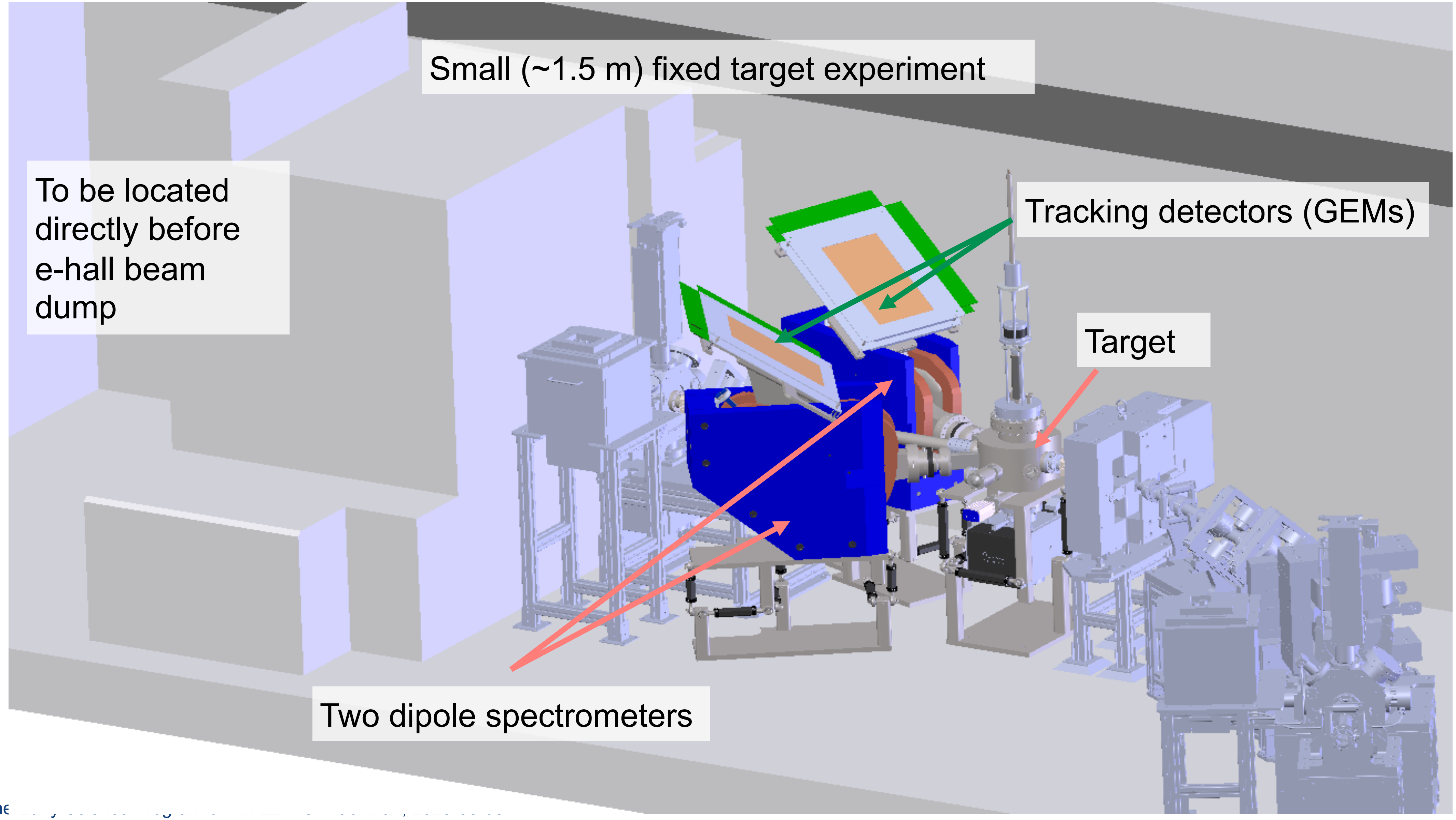


- Measure electron & positron momenta in coincidence, calculate mass of produced particle
- "Bump search"

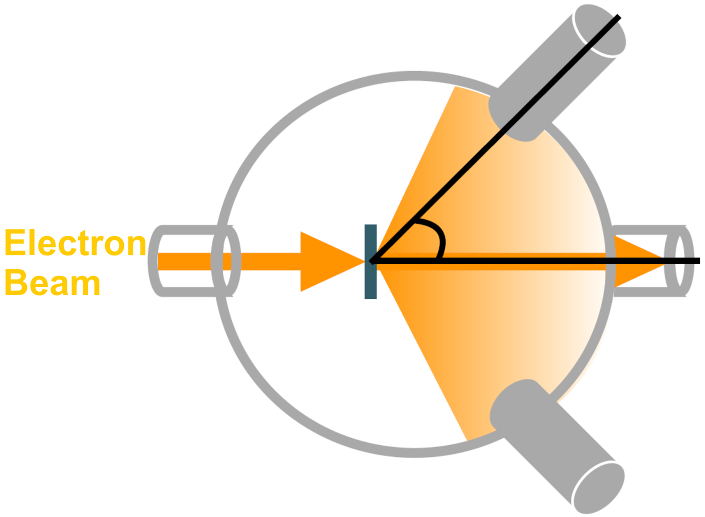
Darklight: Search for new light boson

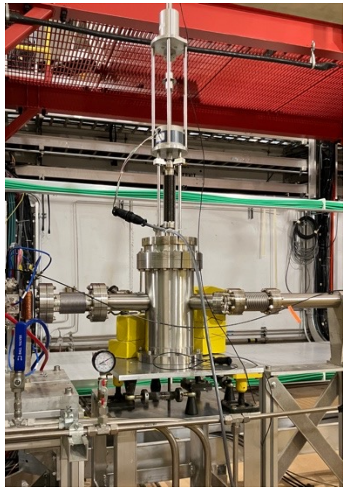


Darklight


Small (~1.5 m) fixed target experiment
To be located directly before e-hall beam dump
Tracking detectors (GEMs)
Target
Two dipole spectrometers

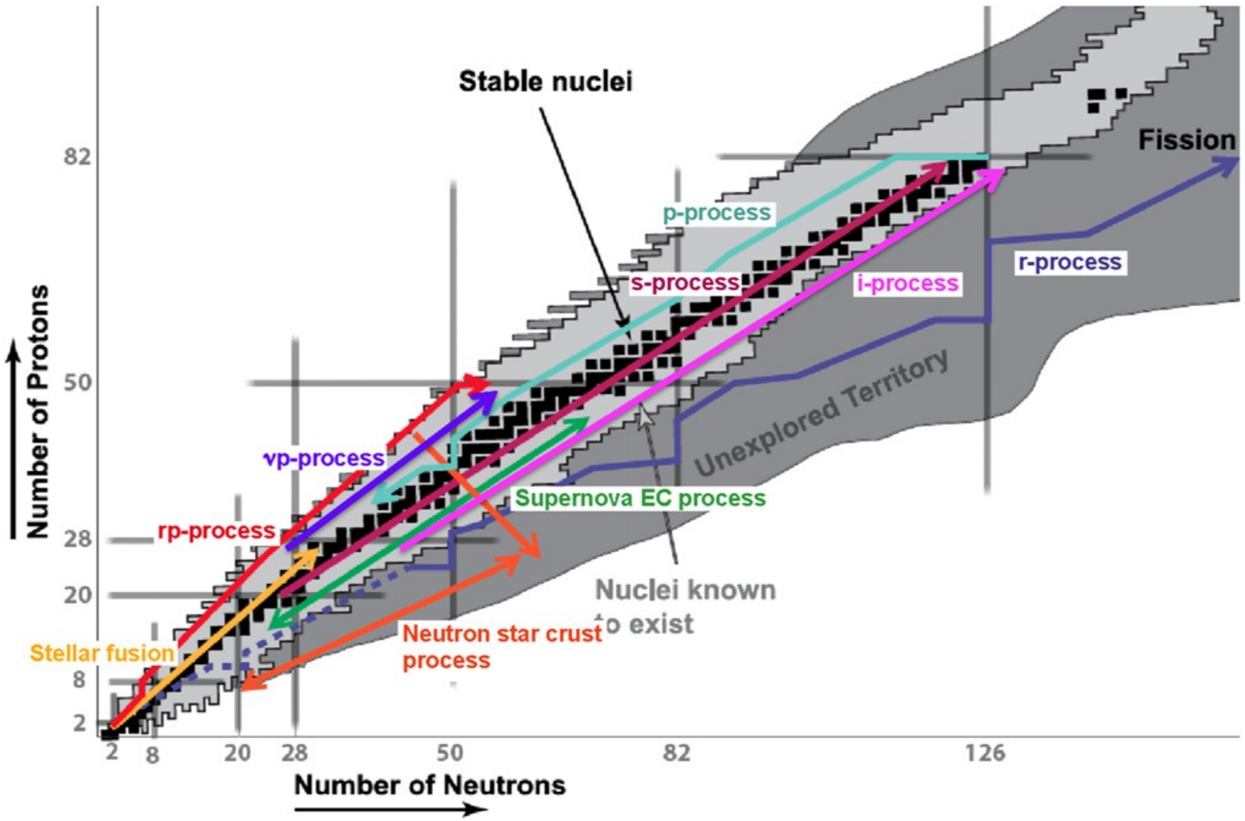
Darklight – Search for Dark Photons





Saint Mary's University · Jefferson Lab · University of Manitoba · The University of Winnipeg Foundation · Hampton University · Arizona State University · Stony Brook University · Massachusetts Institute of Technology · Johannes Gutenberg Universität Mainz · UBC

ARIEL as an R- and I-process Factory:
So many, many processes.

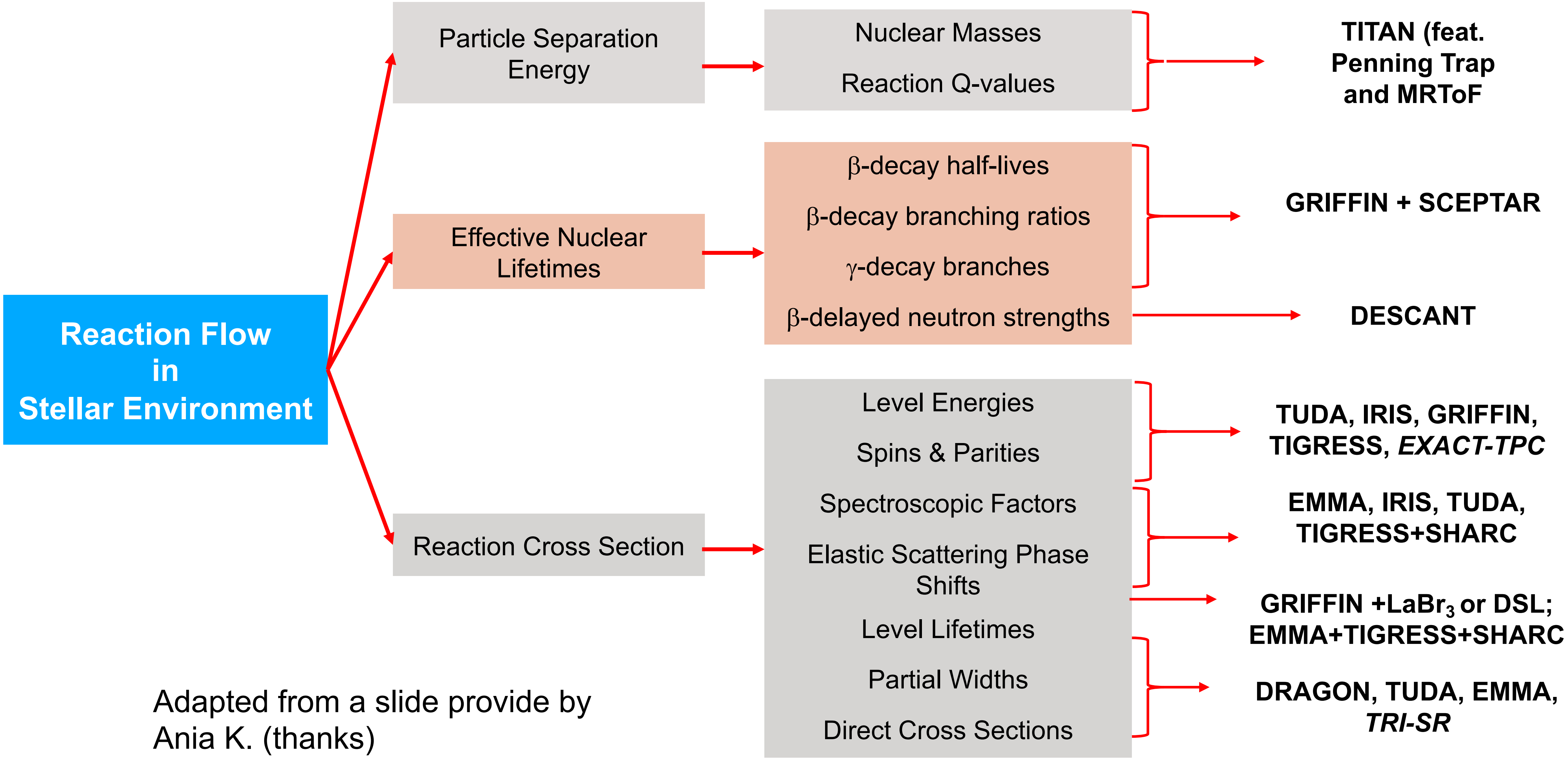


H. Schatz, J. Phys. G: Nucl. Part. Phys. 43.6 (2016): 064001.

Slide prepared by C. Griffin, TRIUMF post-doc

- *Slow* neutron capture (*s*-)process:
  - Low n density ($N_n \sim 10^{11}$ cm^{-3})
  - Close to stability
- *Rapid* neutron capture (*r*-)process:
  - High n density ($N_n \sim 10^{23}$ cm^{-3})
    - E.g. neutron star mergers
  - Far from stability
- *Intermediate* neutron capture (*i*-)process:
  - Intermediate to *s*- and *r*-process in terms of neutron density, timescale and path
- Nicole V gave an excellent summary Monday of these processes, why they are interesting, and the challenges of modelling them

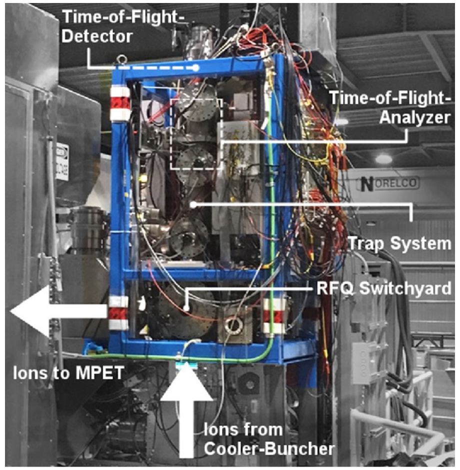
Measurements and Tools Needed

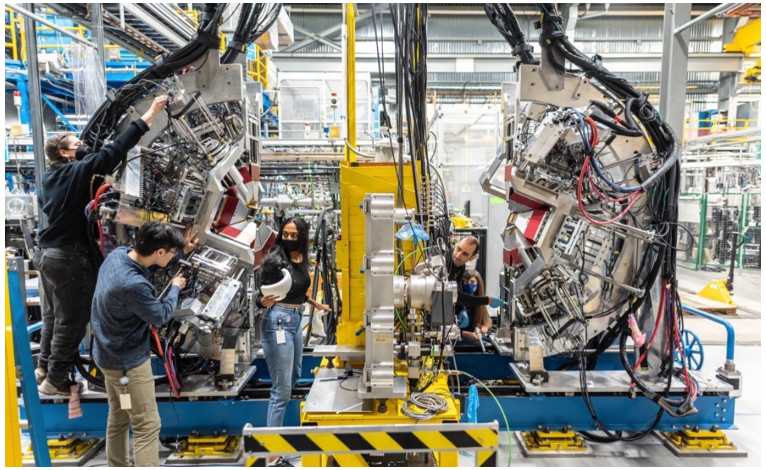


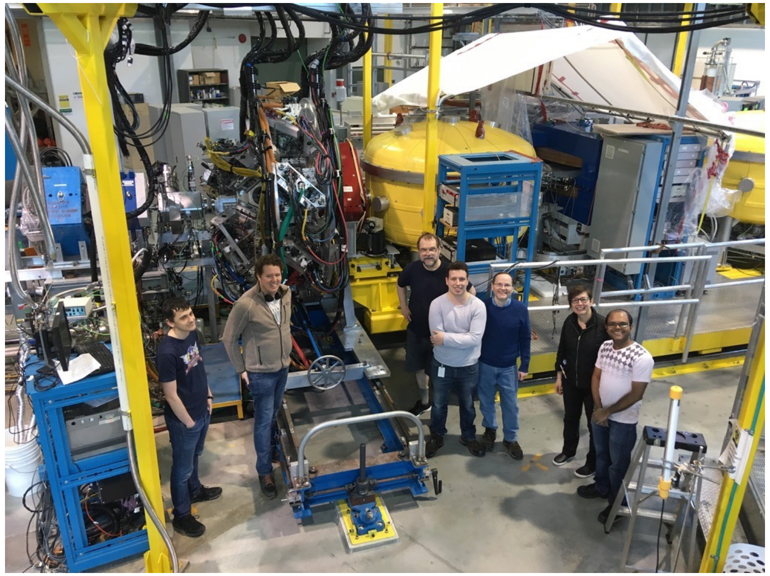
Adapted from a slide provide by Ania K. (thanks)

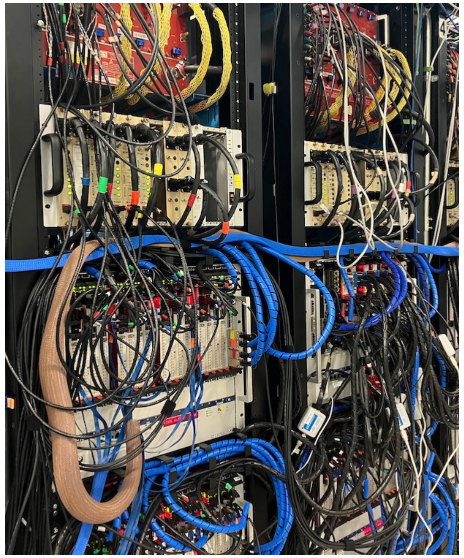
What have we done to upgrade our equipment in anticipation of the “ARIEL Era”?

- TITAN: Added multi-reflection time-of-flght (MRToF)
  - Sensitive to ion production rates of 1 per minute or so (mentioned Monday by Ali M.)
- 8pi+SCEPTAR replaced with GRIFFIN+ARIES, added fast timing capabilities
  - Order of magnitude efficiency improvement
- TIGRESS+EMMA coupled, DAQ upgraded
  - x20 data throughput









Recent r-process paper from TITAN MR-ToF

- First measurement of masses of ^{84,85}Ga
- with MR-ToF
- Uncertainty ~30 keV
- Previous “knowledge” was extrapolation with estimated uncertainty of 300 keV
- Range of abundances in astrophysics scenarios decreased commensurately
- See also Izzo et al. PRC 103 025811 (2021) – In isotopes

M. P. REITER *et al.* PHYSICAL REVIEW C **101**, 025803 (2020)

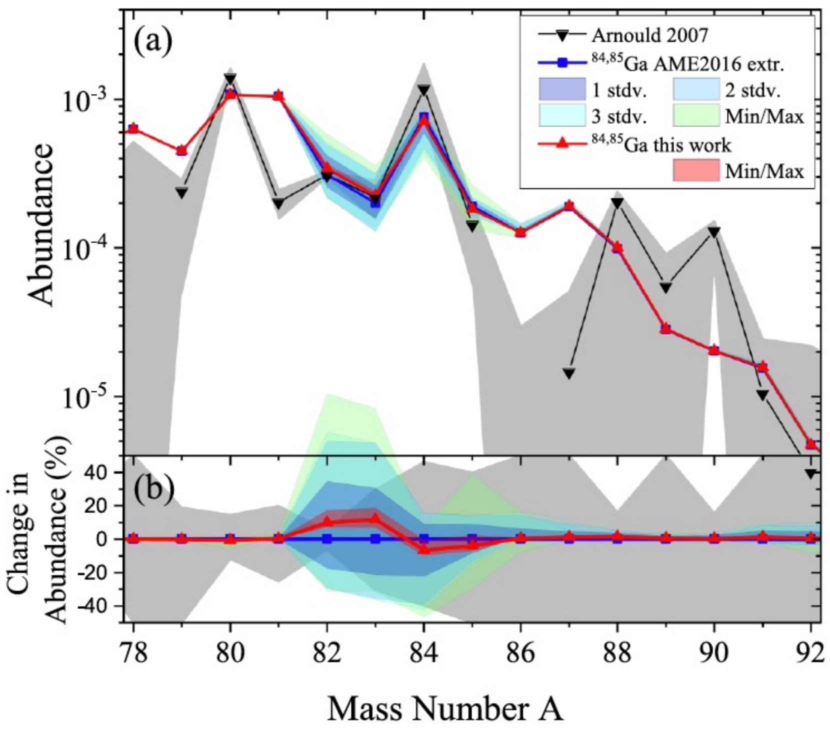


FIG. 4. (a) Final abundances averaged over calculations with $Y_e = 0.35$-0.38 compared to the solar *r*-process abundance [7], with uncertainty shown as gray band. The colored bands show the 1-, 2-, and 3σ change in calculated production, as well as the maximum and minimum abundance from the Monte Carlo variation of the nuclear masses of ^{84,85}Ga following a Gaussian distribution with σ of 200 and 300 keV, respectively. For the new mass values only the maximum and minimum abundance band from the variation within their uncertainty is shown. (b) Change, in percentage, of the abundance pattern as a result of using the mass values from this work compared to the extrapolations given in the AME2016.

Recent r-process-related results from GRIFFIN

- ^{130}Cd: three prior half-life measurements 193(35), 162(7),127(2) ms
- GRIFFIN measurement based on gamma rays in ^{130}In: 126(4) ms
  - (influence on r-process discussed elsewhere)
- See also Garcia et al, PRC 103 024301 (2021); Dunlop et al. PRC 99, 045805 (2019); Whitmore et al. PRC 102, 024337 (2020); Saito et al., PRC 102, 024337 (2020)

R. DUNLOP *et al.* PHYSICAL REVIEW C **93**, 062801(R) (2016)

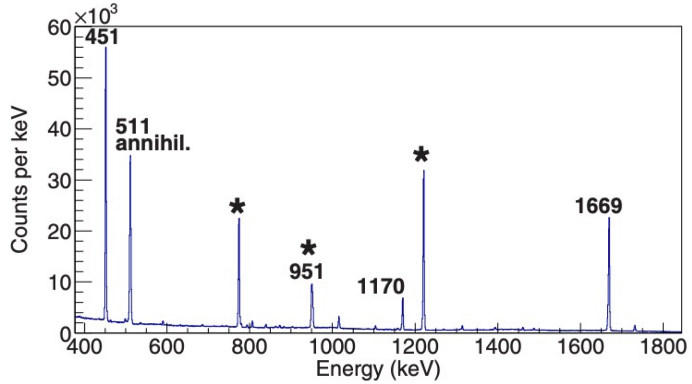


FIG. 5. A portion of the β-gated γ-ray energy spectrum for the ^{130}Cd experiment. The strongest peaks in the spectrum are labeled, including the doublet at 951 keV. The three strong γ rays at 451, 1170, and 1669 keV were used for the half-life analysis. γ rays following the β decay of ^{130}In are labeled with *.

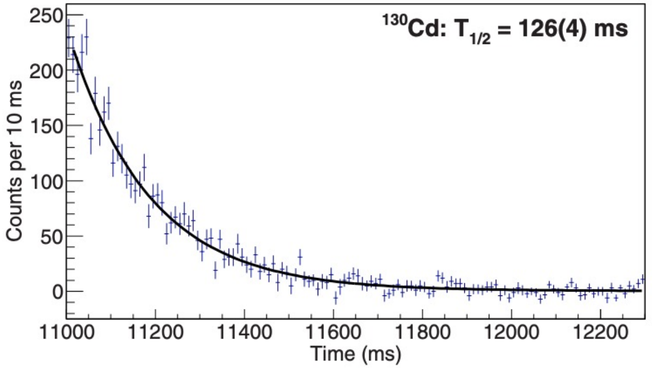
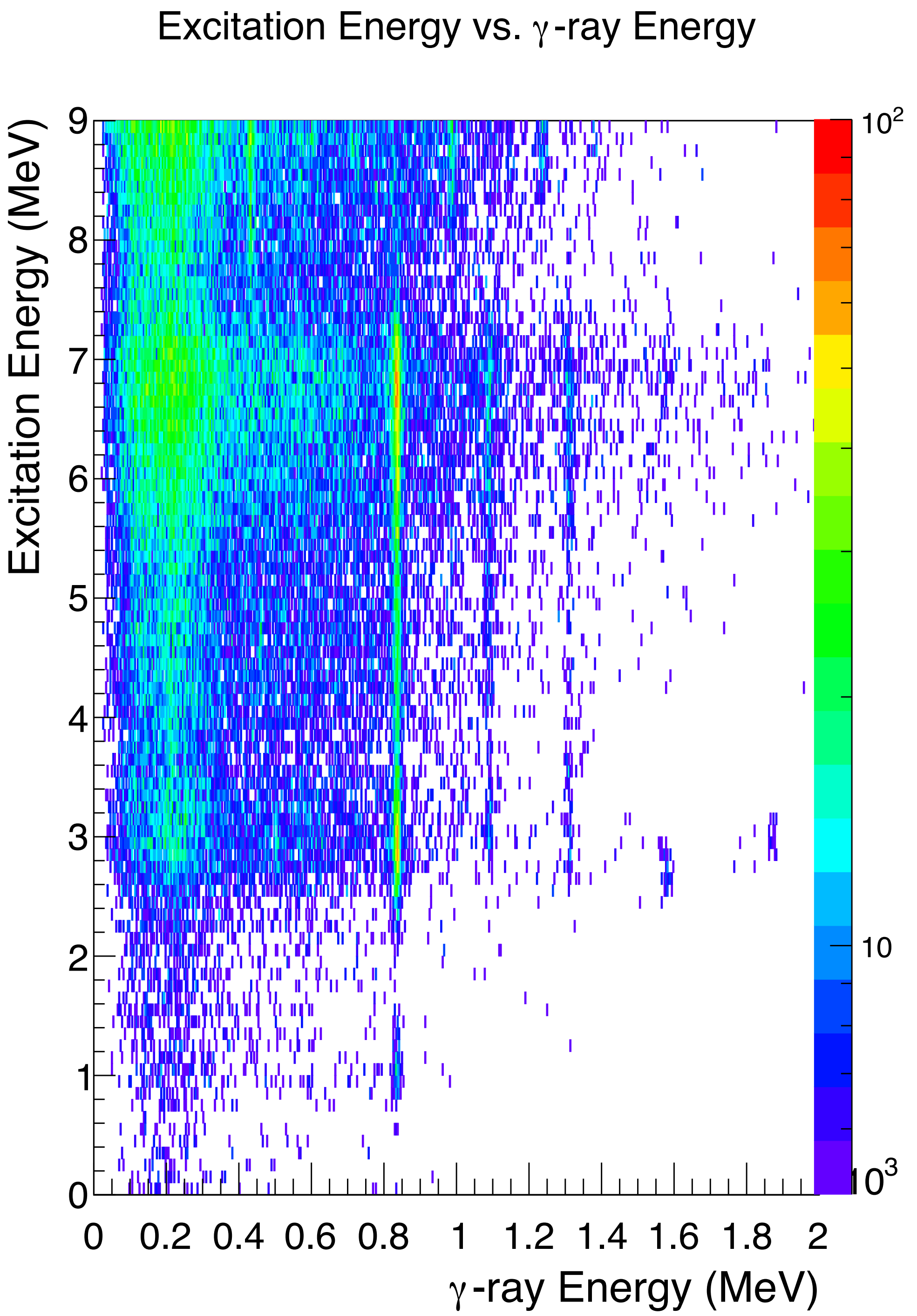


FIG. 6. Sum of the 451, 1170, and 1669 keV γ-ray time distributions. The half-life obtained from the fit is 126 (4) ms. Note that the time represents the amount of time that has elapsed since the start of a cycle.

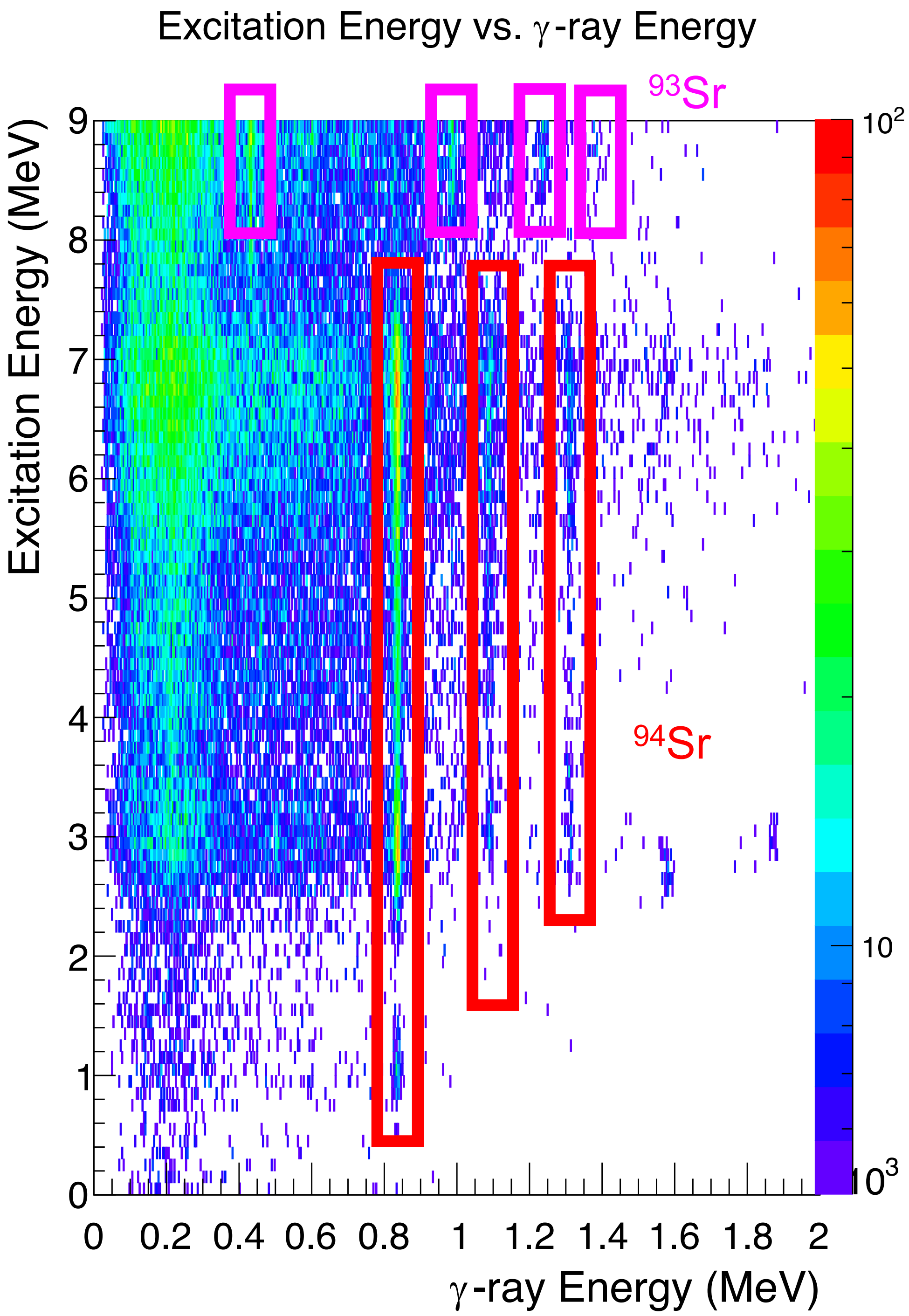
Reaction rates: Surrogate reactions

- Use $(\mathrm{d}, \mathrm{p}\gamma)$ neutron transfer as surrogate for (n, γ) neutron capture
- This example: $^{93}\mathrm{Sr}$ beam impinging on a CD_2 target
  - i-process motivation
- Particles detected with Si detectors (SHARC)
- Any gammas in coincidence detected with TIGRESS
- Plotted here: excitation energy deduced from detected proton kinematics vs. gamma ray energy



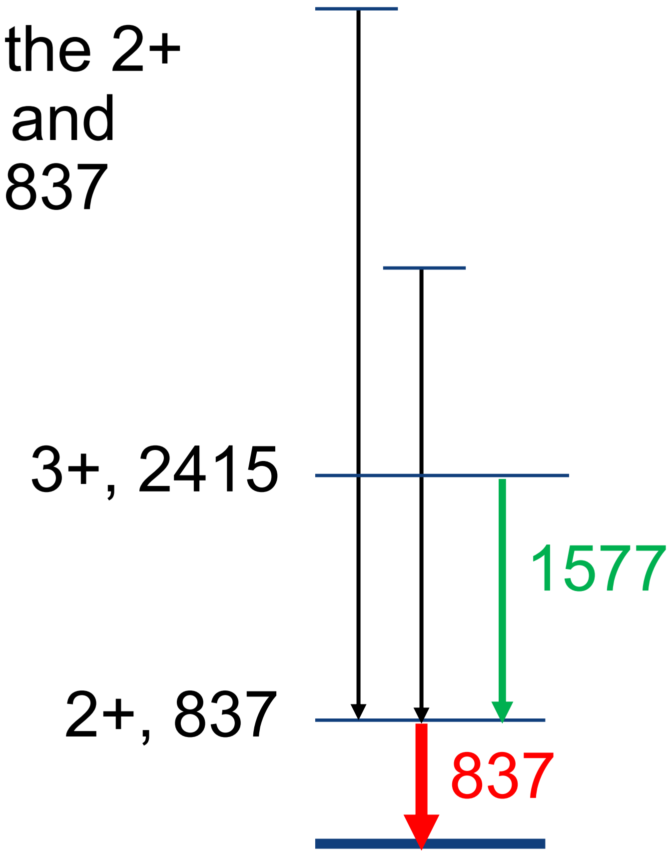
Reaction rates: Surrogate reactions

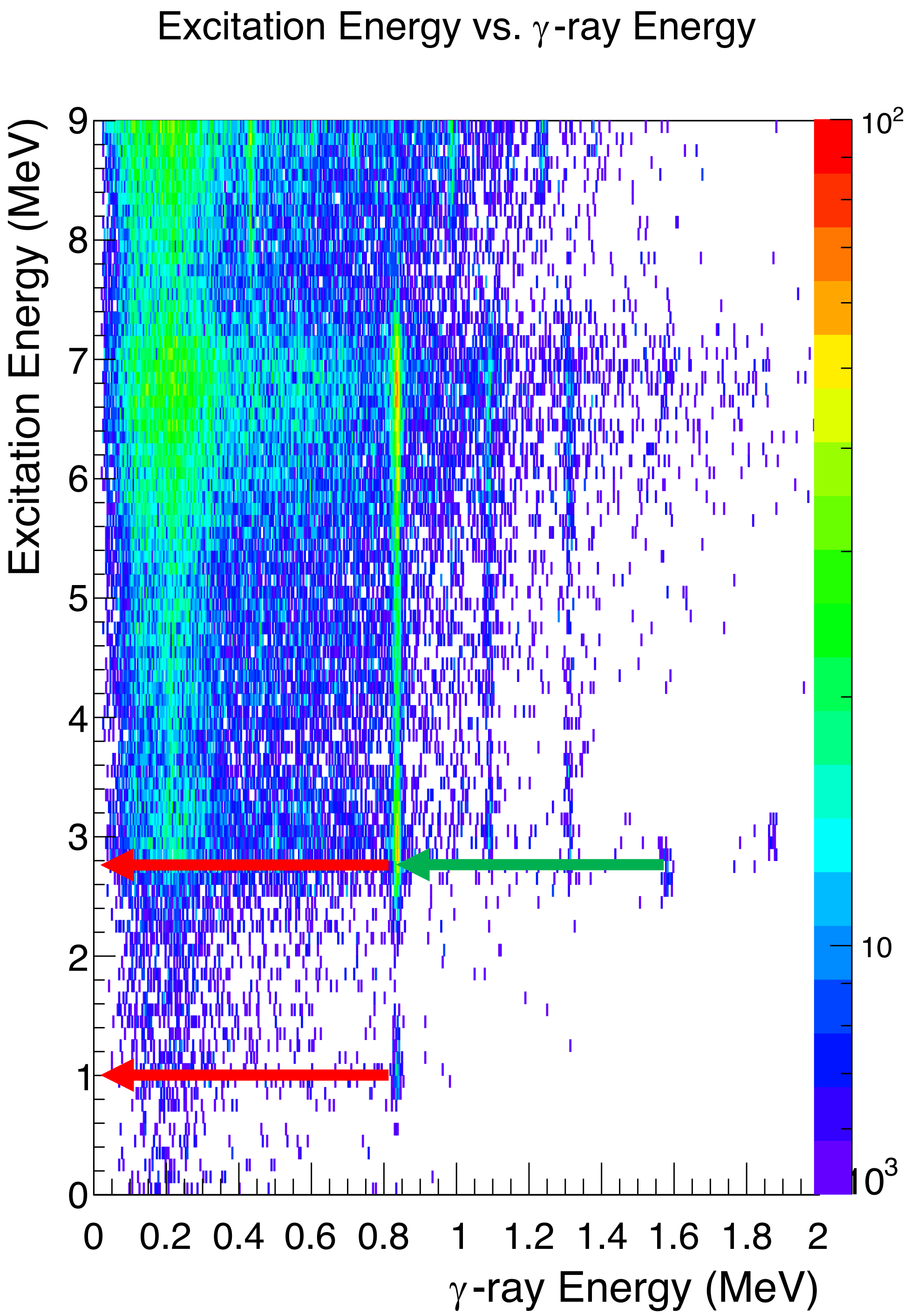
- Can see gammas from $^{93}\mathrm{Sr}(\mathrm{d},\mathrm{p}\gamma)^{94}\mathrm{Sr}$
- Also see gammas from $^{93}\mathrm{Sr}(\mathrm{d},\mathrm{pn}\gamma)^{93}\mathrm{Sr}$



Reaction rates:
Surrogate reactions

- Most states decay in a gamma cascade passing through the 2+ state at 837 keV and then emitting an 837 keV gamma ray



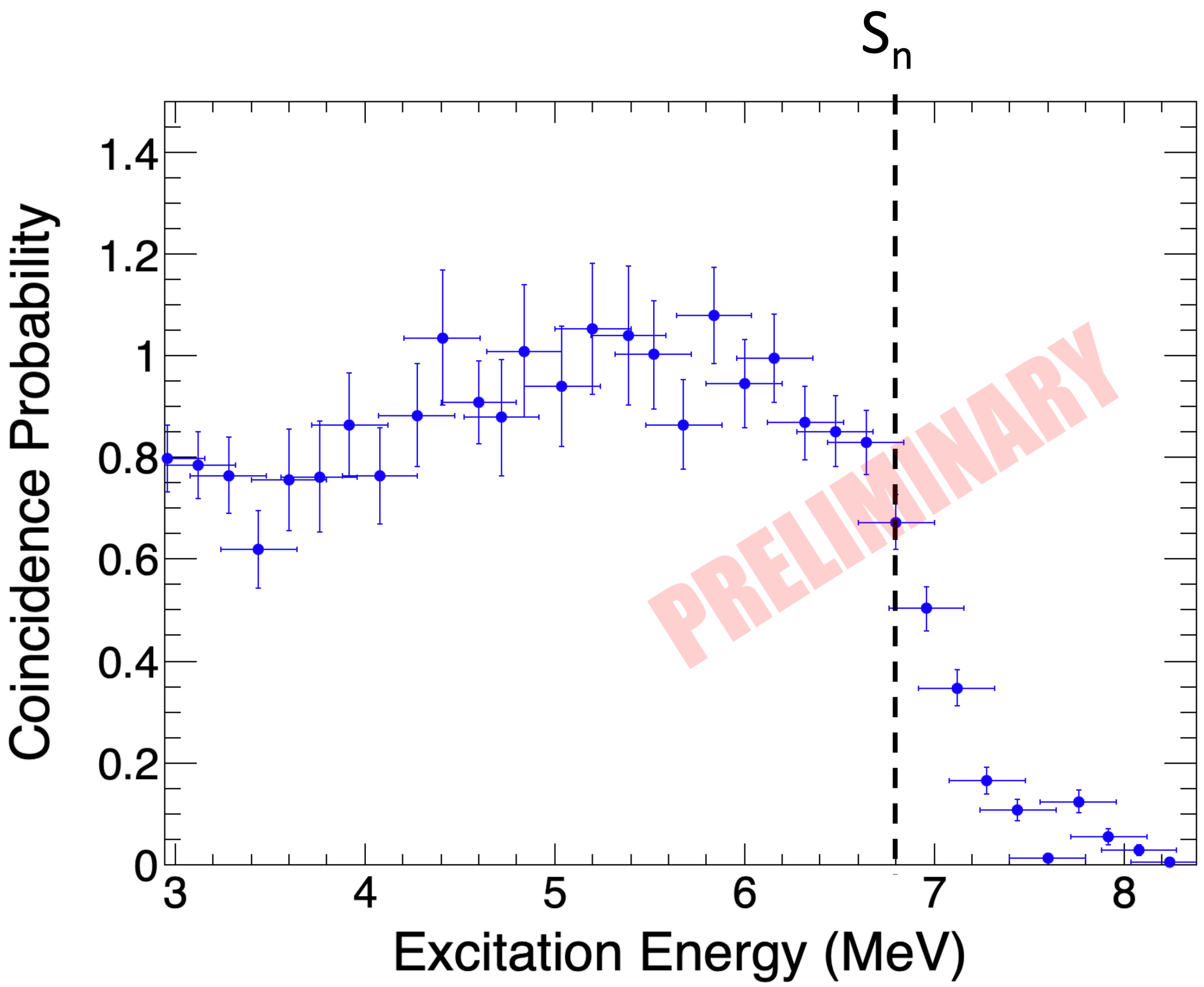


Reaction rates: Surrogate reactions

- Experimental parameter of interest:

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

- Preliminary experimental analysis shown here
- Sophisticated analysis* of this data around the neutron separation energy reveals neutron separation
- A. Richard (mentioned by Nicole V. on Monday), D. Yates, R. Hughes et al., work in progress

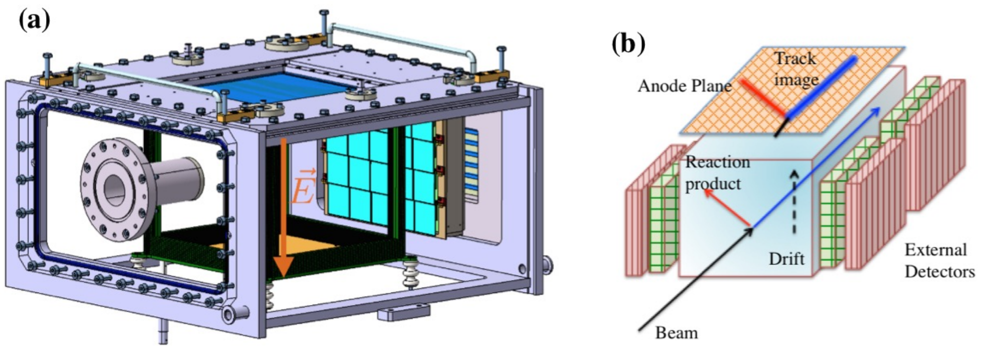


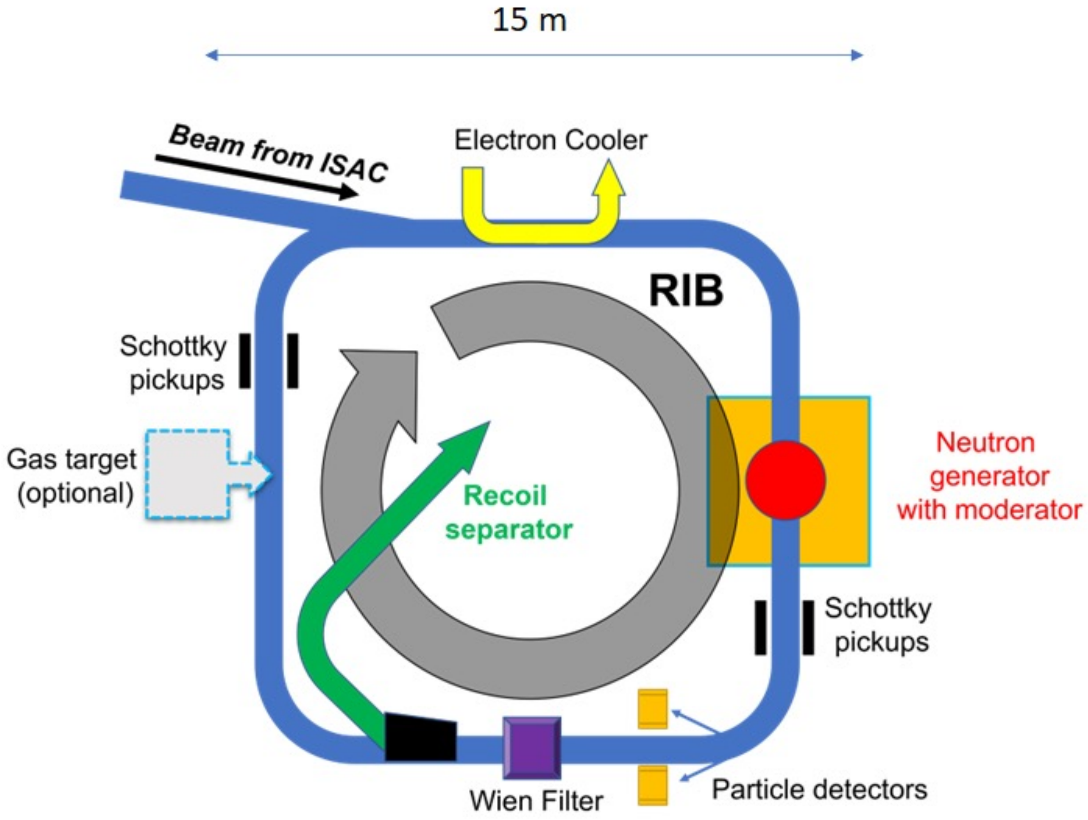
A. Richard, D. Yates, R. Hughes et al, work in progress

* I don't understand it so please don't ask

What new equipment could come online in the "ARIEL Era"?

- EXACT-TPC: Active Target
  - For a variety of reactions with hydrogen, deuterium, helium and 3He gases
  - R. Kanungo, Saint Mary's
- TriSR: Storage Ring and Neutron Source
  - For direct (n, γ) measurements
  - I. Dillmann, TRIUMF
- Time scales a bit longer than "first science"

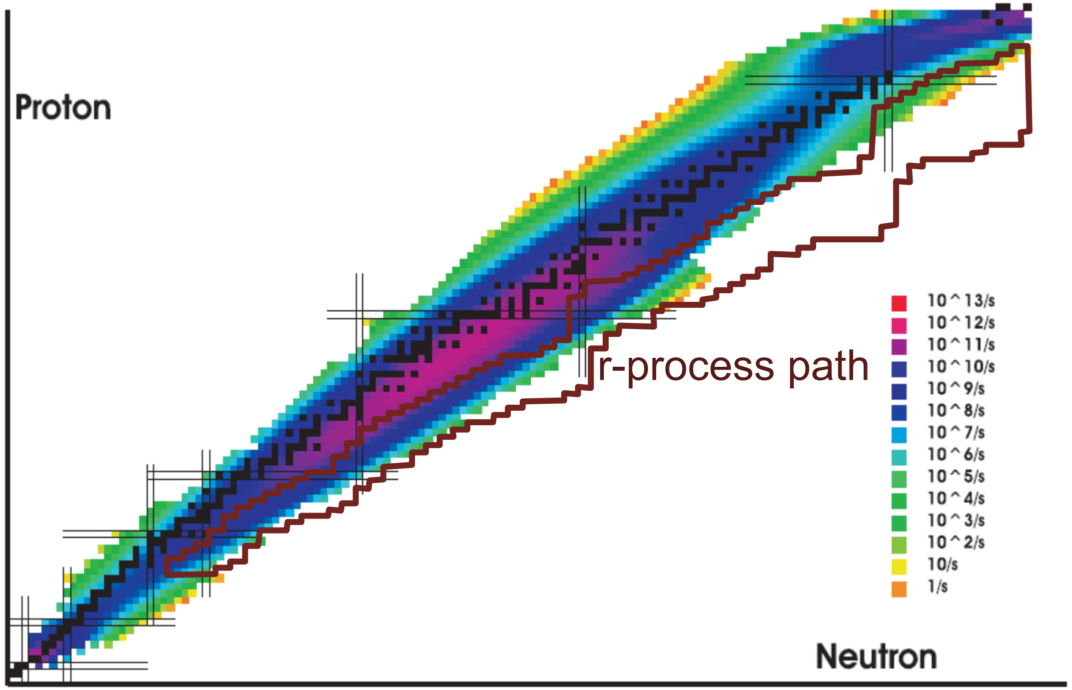




So what are some candidates for first ARIEL experiments?

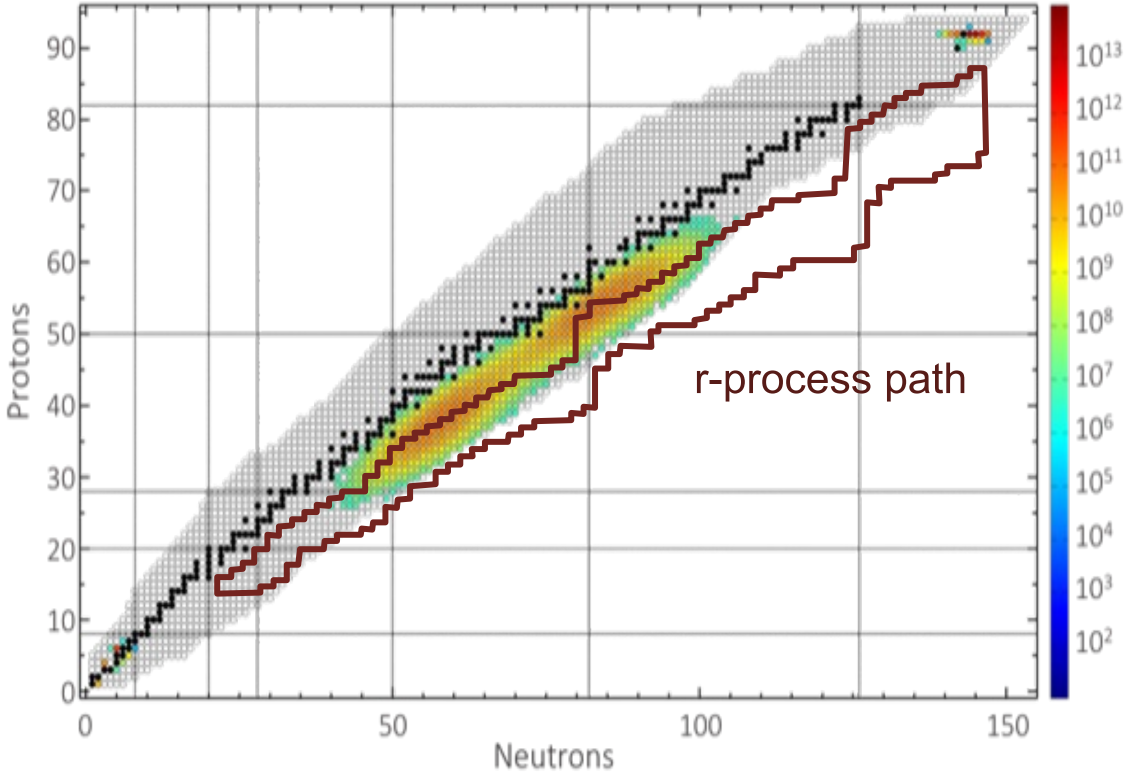
ARIEL In-Target Production Yields (typical) and R-Process

proton spallation yields in uranium target



today: ISAC-TRIUMF

photo-fission yields in uranium target

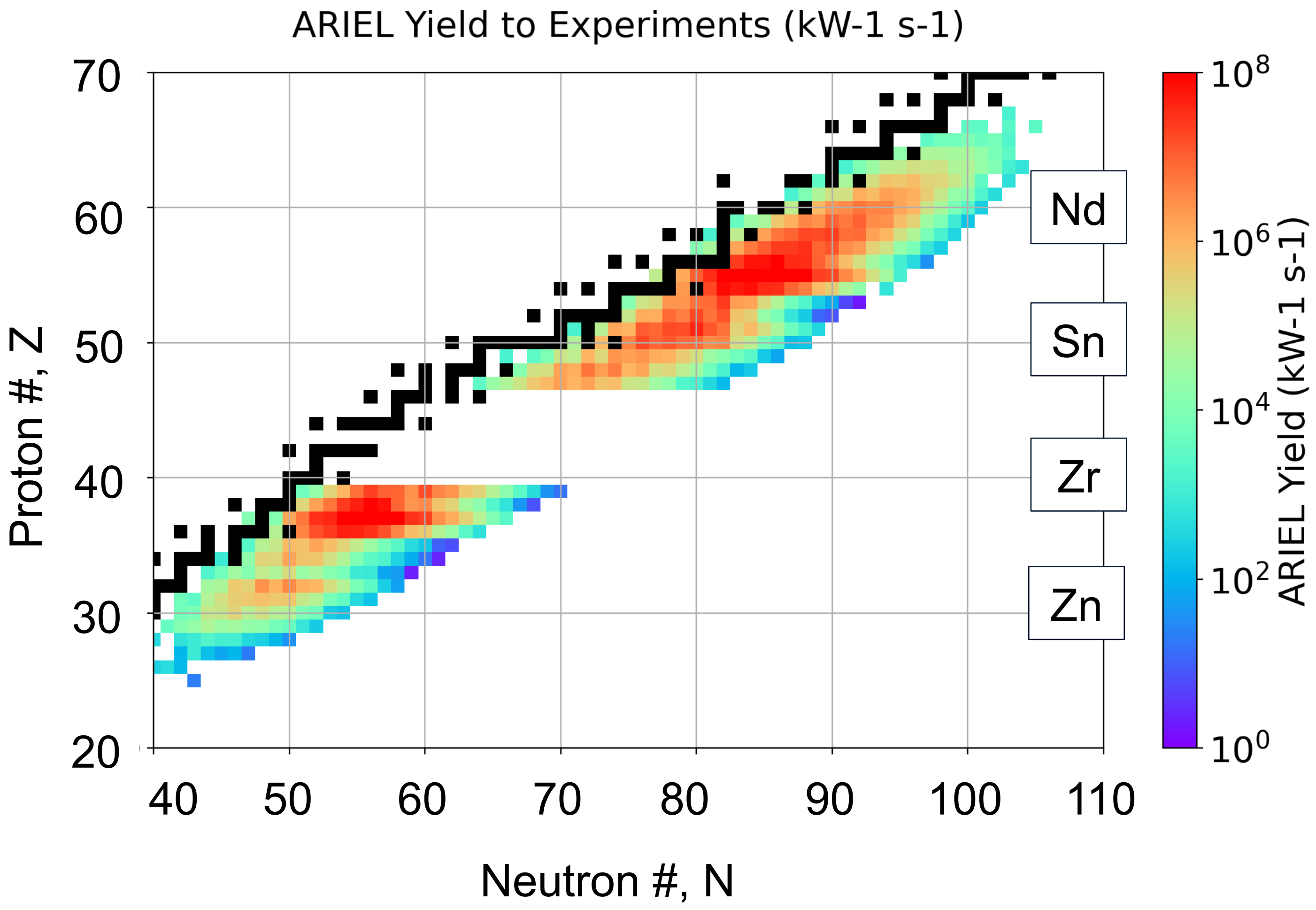


future: ARIEL-TRIUMF

Data from Oliver K/Jens D/Reiner K/Alex G, slide from Ania K.

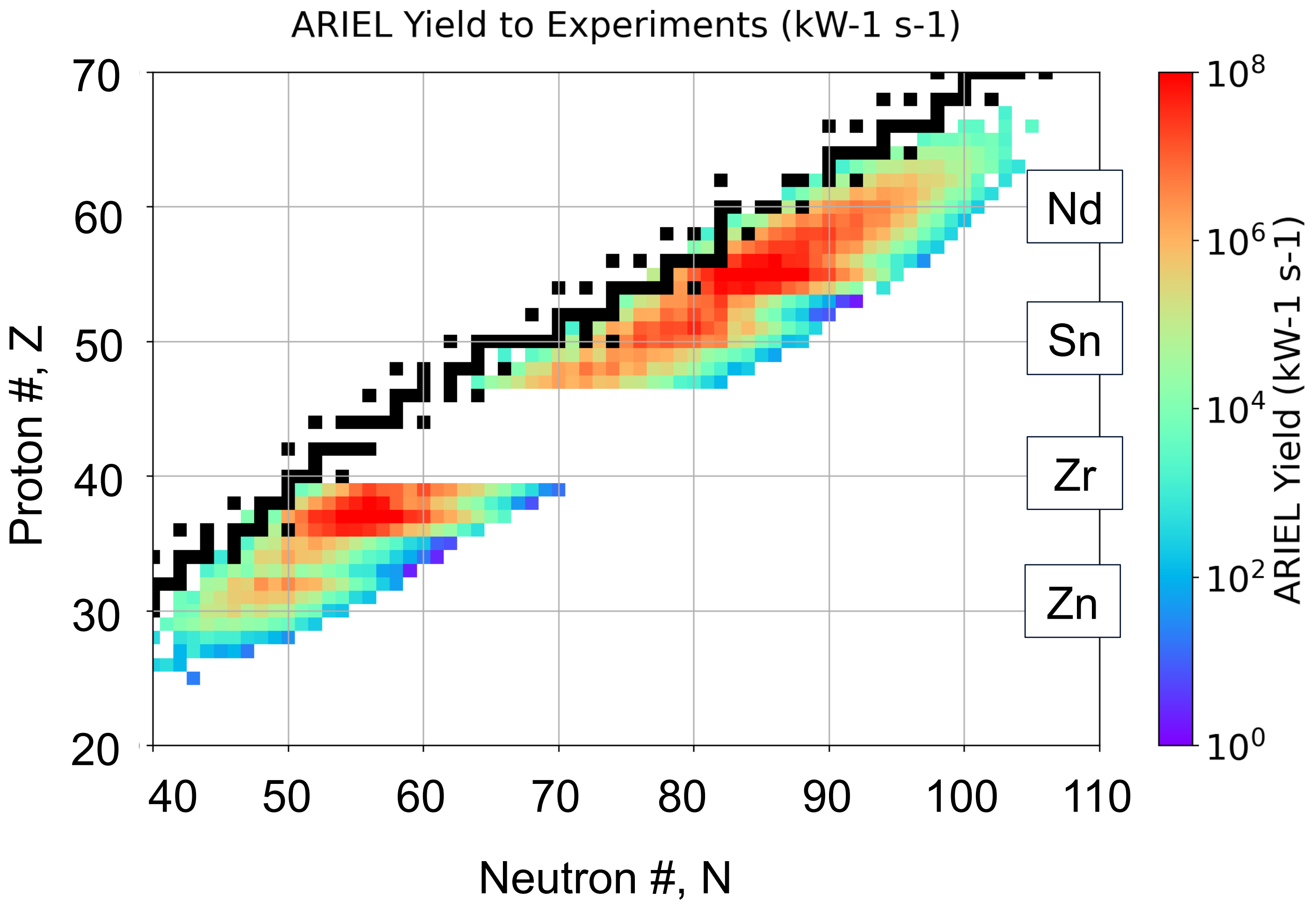
Let's look at what's known and what ARIEL can produce

- In-beam production does not take into account effects like ionization efficiency & diffusion time
- There are some empirical prescriptions one can use for these
- Work done by Kaylee Directo (UG summer student from McMaster) with input from Adam G and Alex G



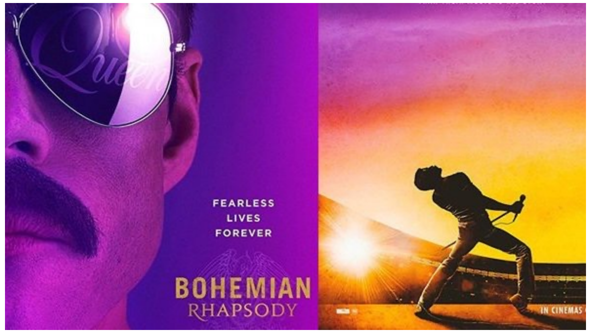
Let’s look at what’s known and what ARIEL can produce

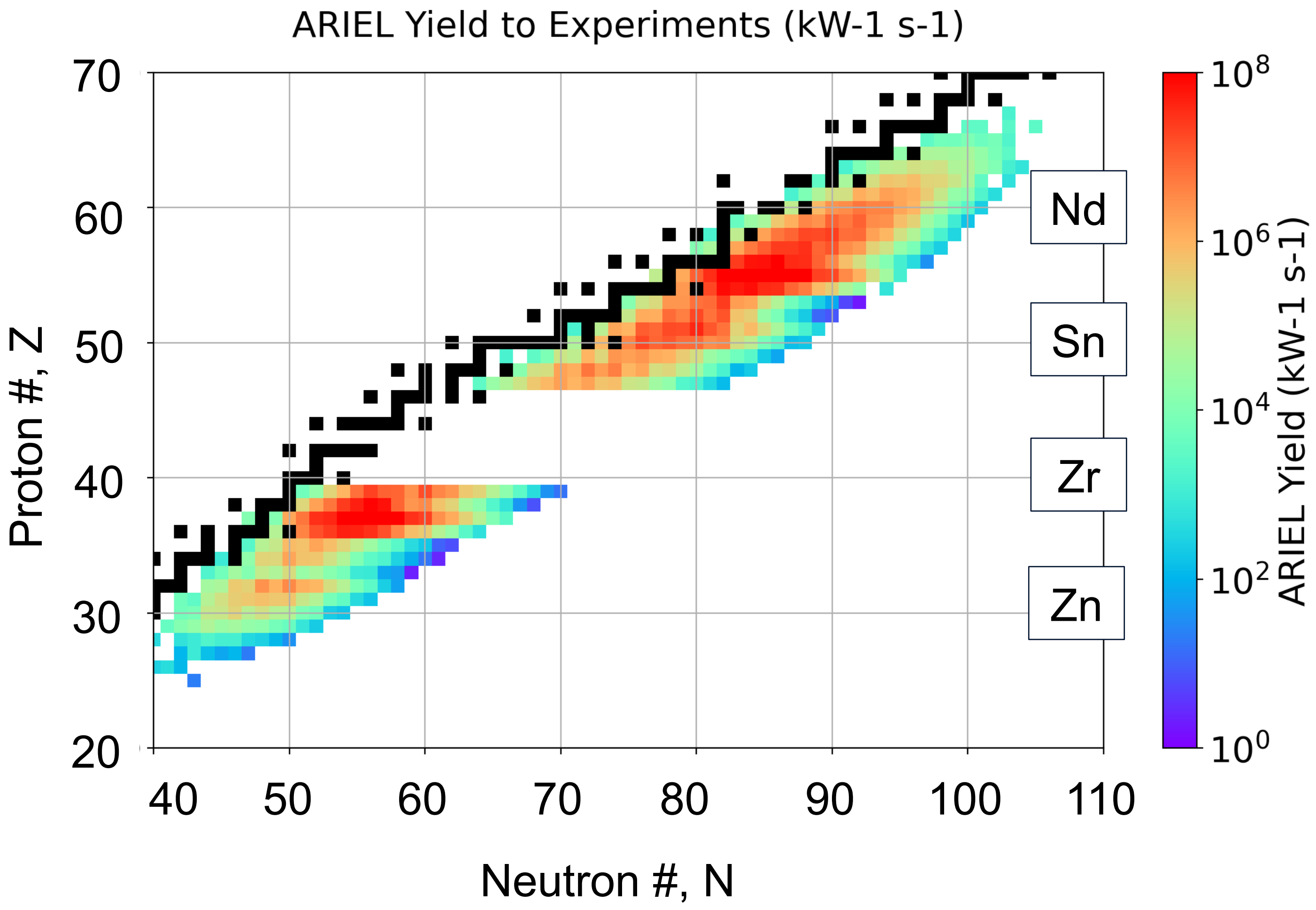
- Alex’s analysis of diffusion & ionization of Ni, Rb, Sr, Sn, Cs, Ba are solid
- Refractories never come out (gap at 40-46)
- Rest of the elements are my guesstimates based on chemical trends



Let's look at what's known and what ARIEL can produce

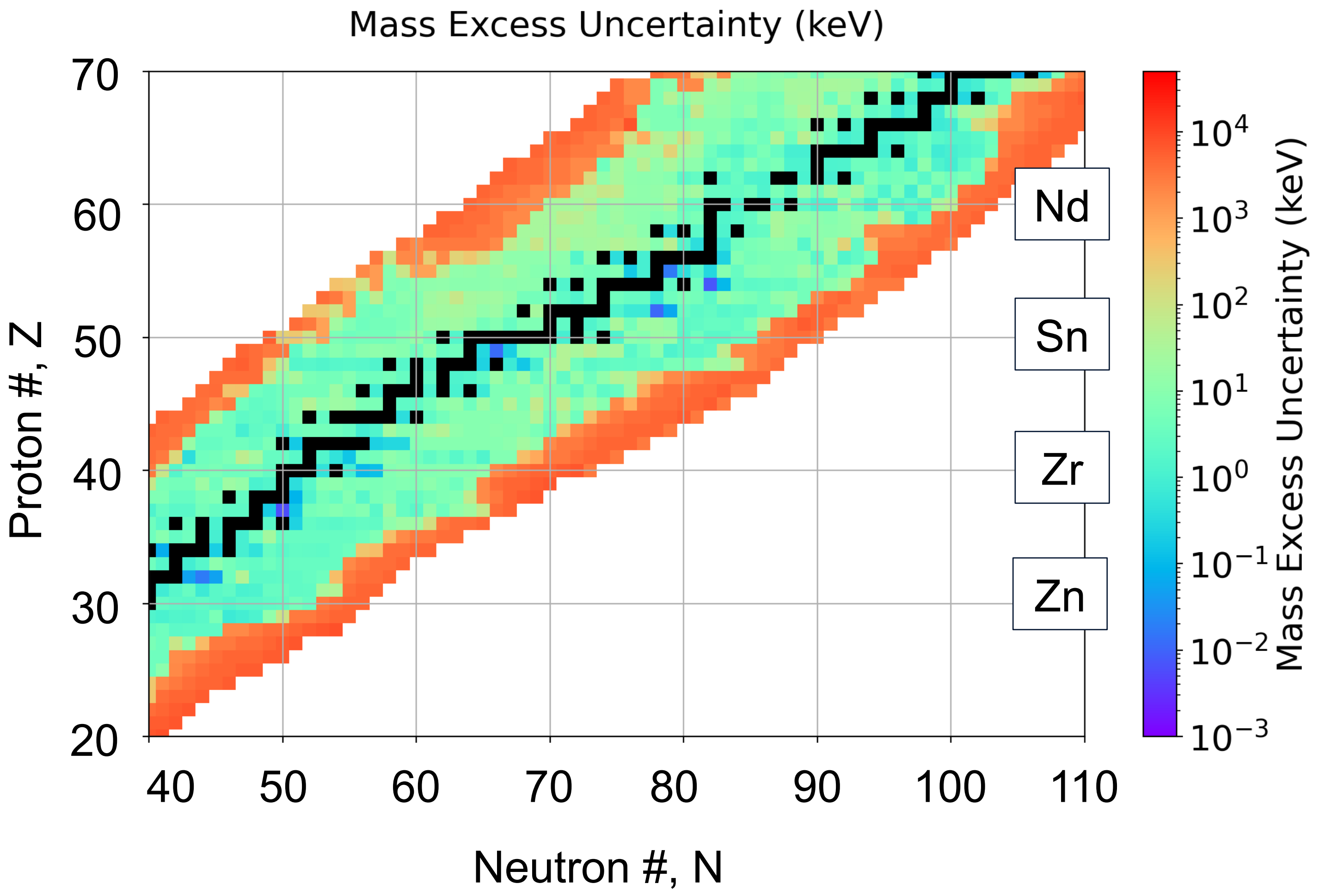
- Alex's analysis of diffusion & ionization of Ni, Rb, Sr, Sn, Cs, Ba are solid
- Refractories never come out (gap at 40-46)
- Rest of the elements are my guesstimates based on chemical trends
  - "Based on a true story"





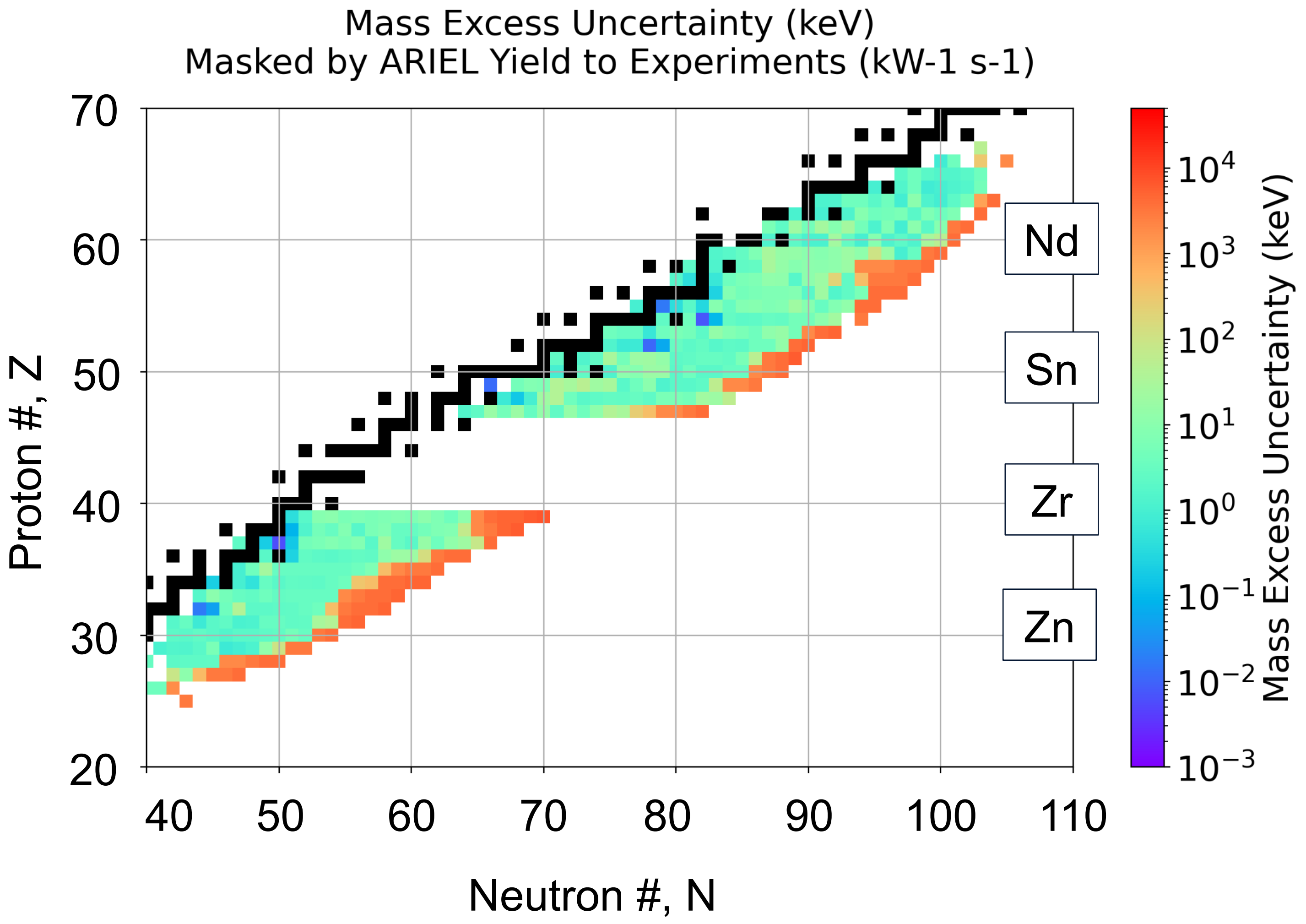
Mass uncertainties

- From AME2020
- Extrapolations exaggerated by x10
  - It's never been measured
- Anything yellow to red is worth (re)measuring
- How many fit within ARIEL yield?
  - Remember we need less than 1 per second



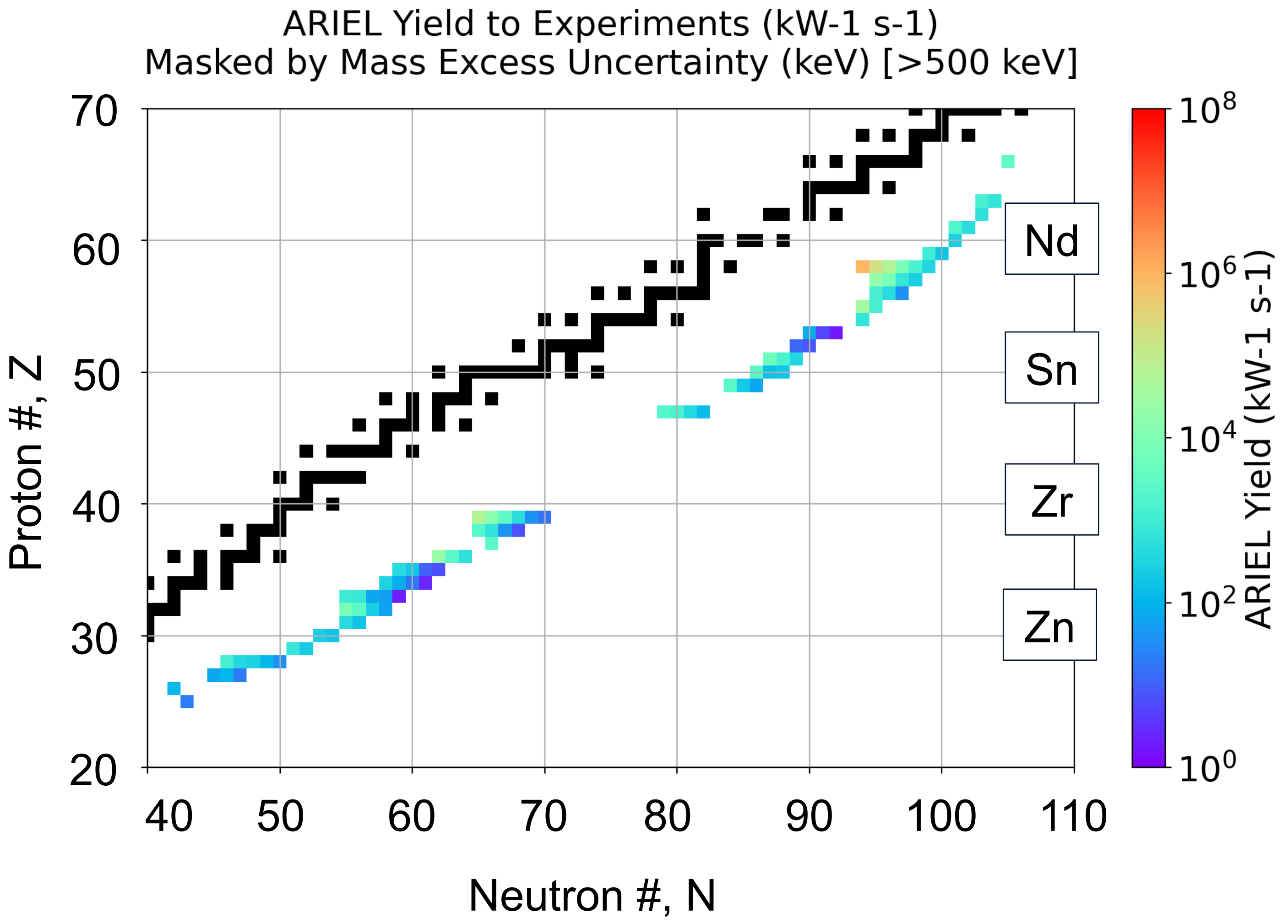
Mass uncertainties

- Erase half-lives outside of ARIEL yield blob from before
- Clearly some of the interesting masses (yellow to red) are within reach of ARIEL ... But do we have enough yield?



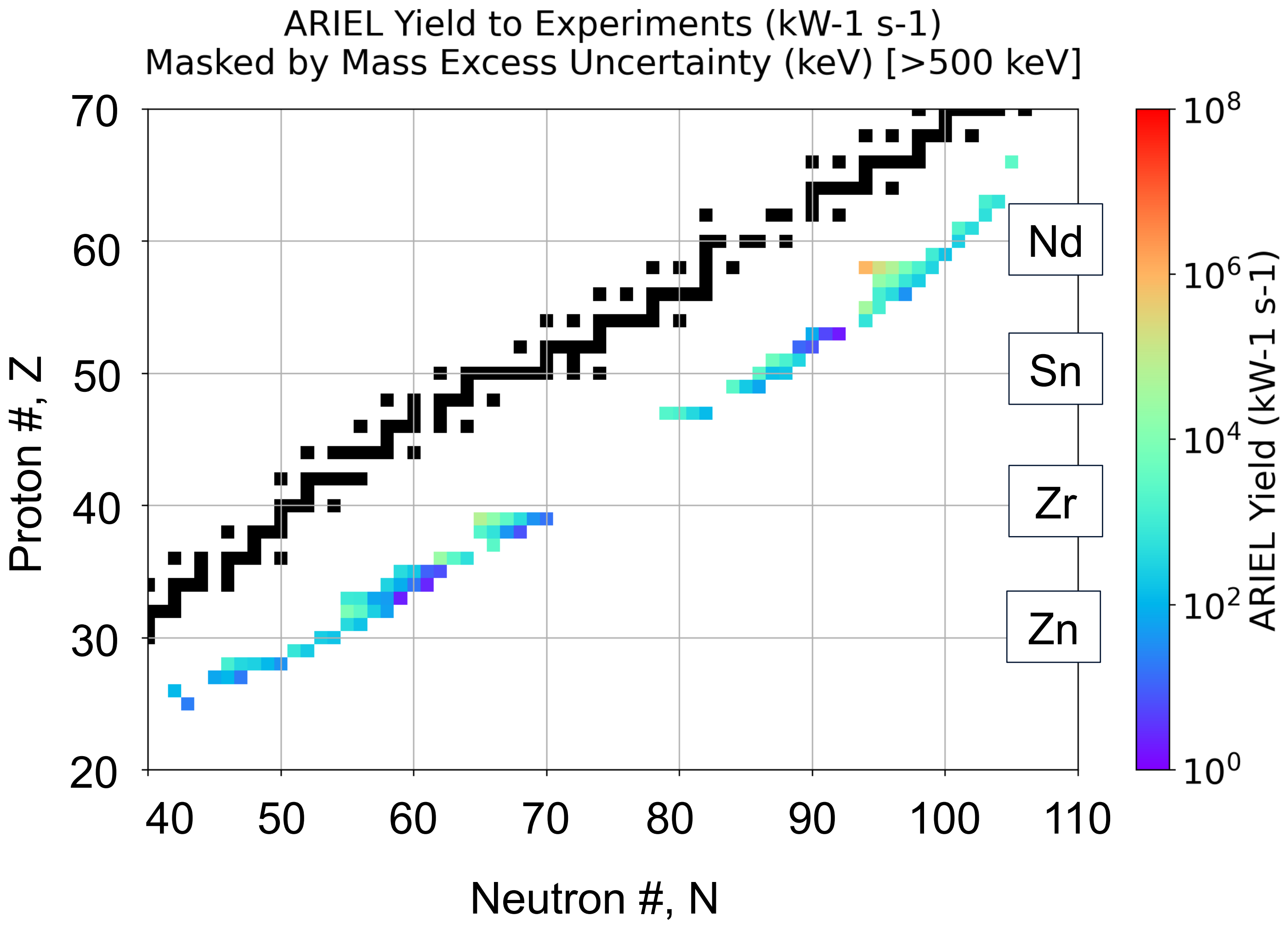
Mass uncertainties

- How about if we look at yields for uncertainty above some threshold?
- Erase ARIEL yields of nuclei with mass uncertaintly less than 500 keV
- Remaining squares are ARIEL products with significant mass uncertainty



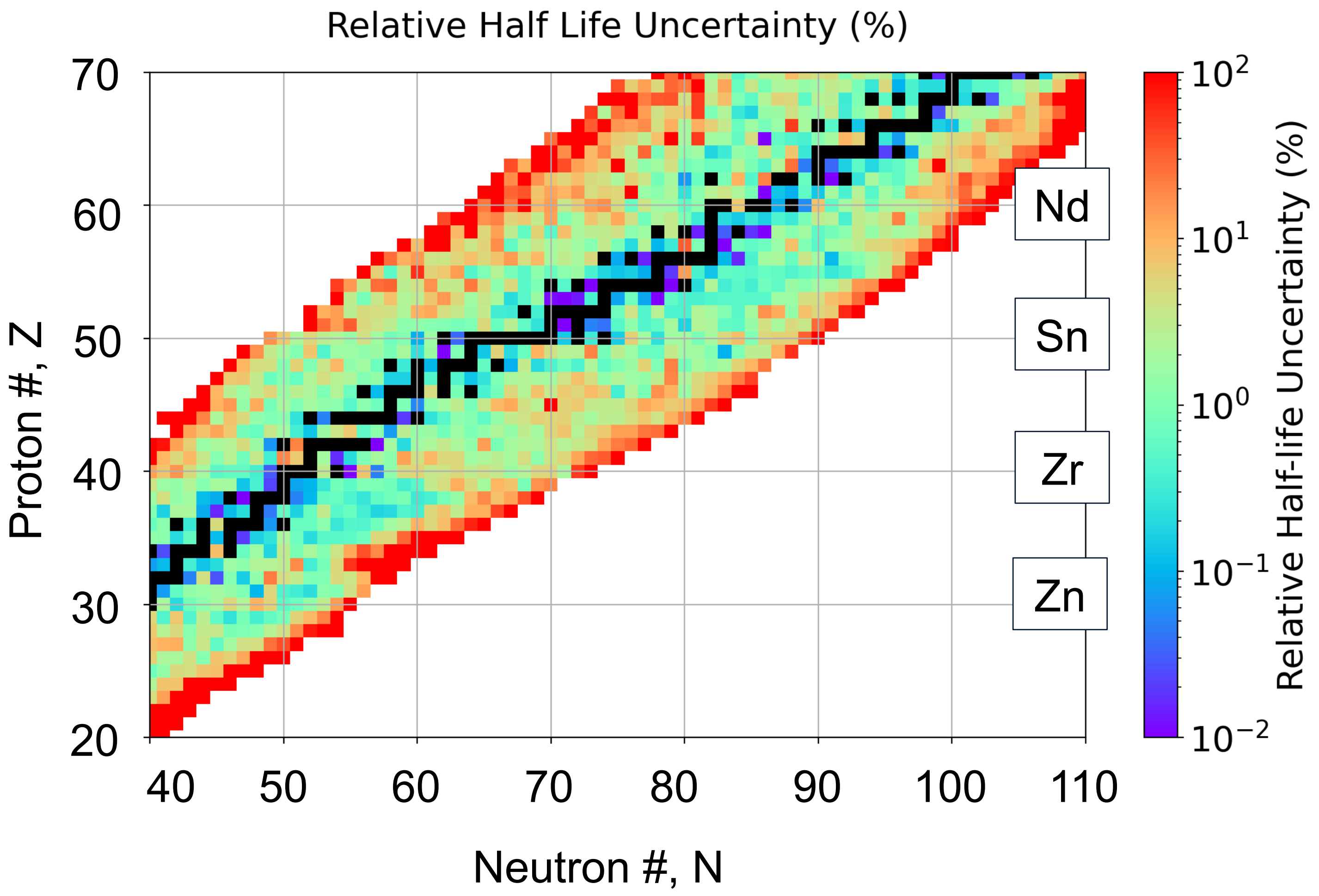
Mass uncertainties

- Yields of ARIEL beams with $\sigma_{\mathrm{Mass}} > 500\ \mathrm{keV}$
- Reiter et al showed that measuring these with MR-ToF can have a meaningful impact on r-process uncertainties
- <1 per second enough
- ~50 strong candidates for The Early Science Program with ARIEL Rare IsotopEs



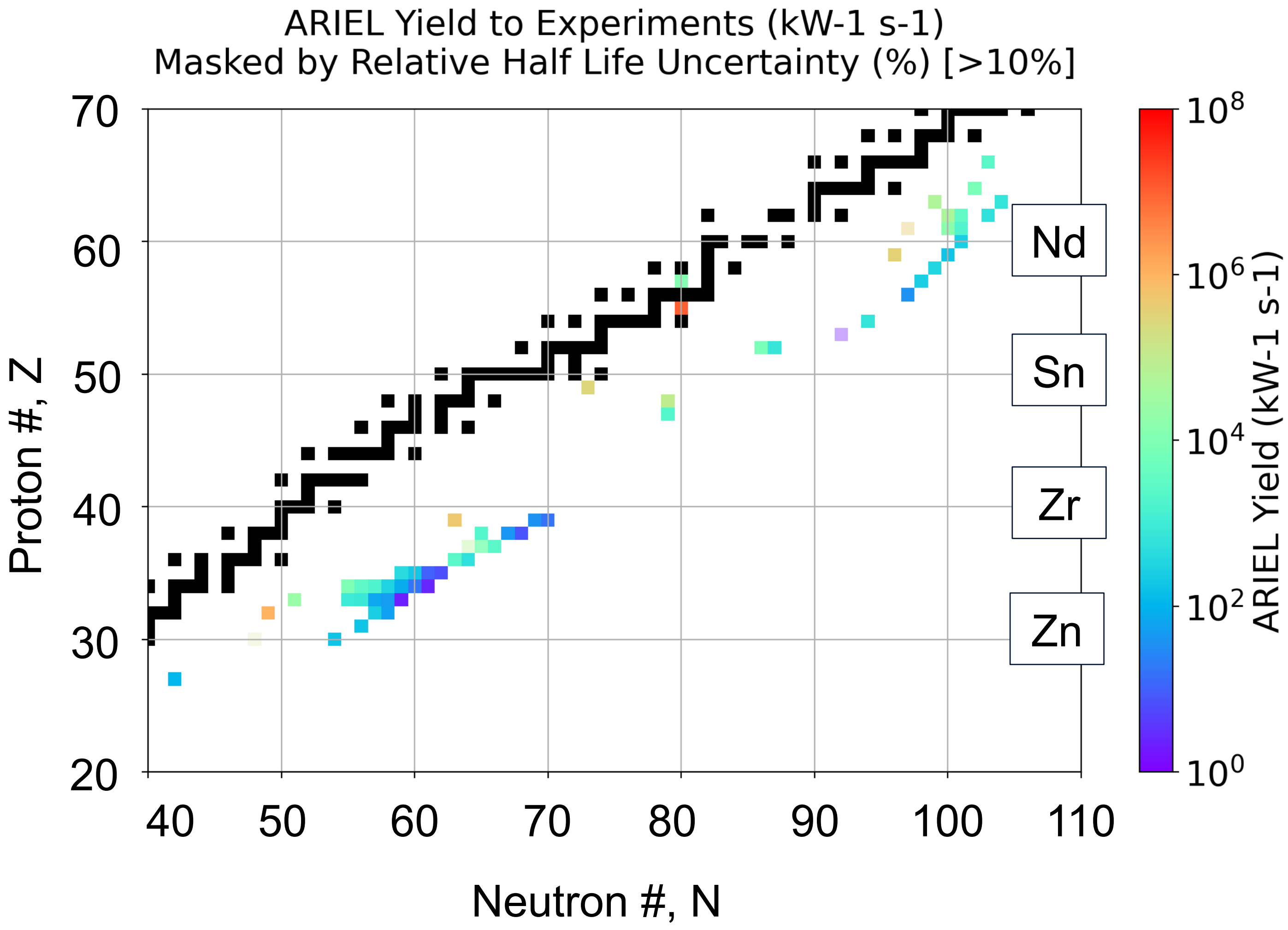
Half-lives – relative uncertainty

- From NuBase20
- Relative uncertainty (not absolute)
- 10% or worse – probably worth remeasuring
  - Again, yellow to red
  - 1-2% easily achievable with GRIFFIN
- What are ARIEL yields for these?



Half-lives – relative uncertainty

- From NuBase20
- ~25 strong candidates for The Early Science Program with ARIEL Rare IsotopEs
  - At extreme neutron excess
- About 15 closer to stability – even easier (maybe less interesting)



Sensitivity studies: r-process

- A more rigorous approach
- Vary "knowledge" (measurement or extrapolation) of nuclei, see how individual nuclei affect solar abundances
- Mumpower et al. PPNP 2016: Monte-Carlo evaluation of Figures of Merit
  - >1 is worth considering for further investigation

M.R. Mumpower et al. / Progress in Particle and Nuclear Physics 86 (2016) 86–126

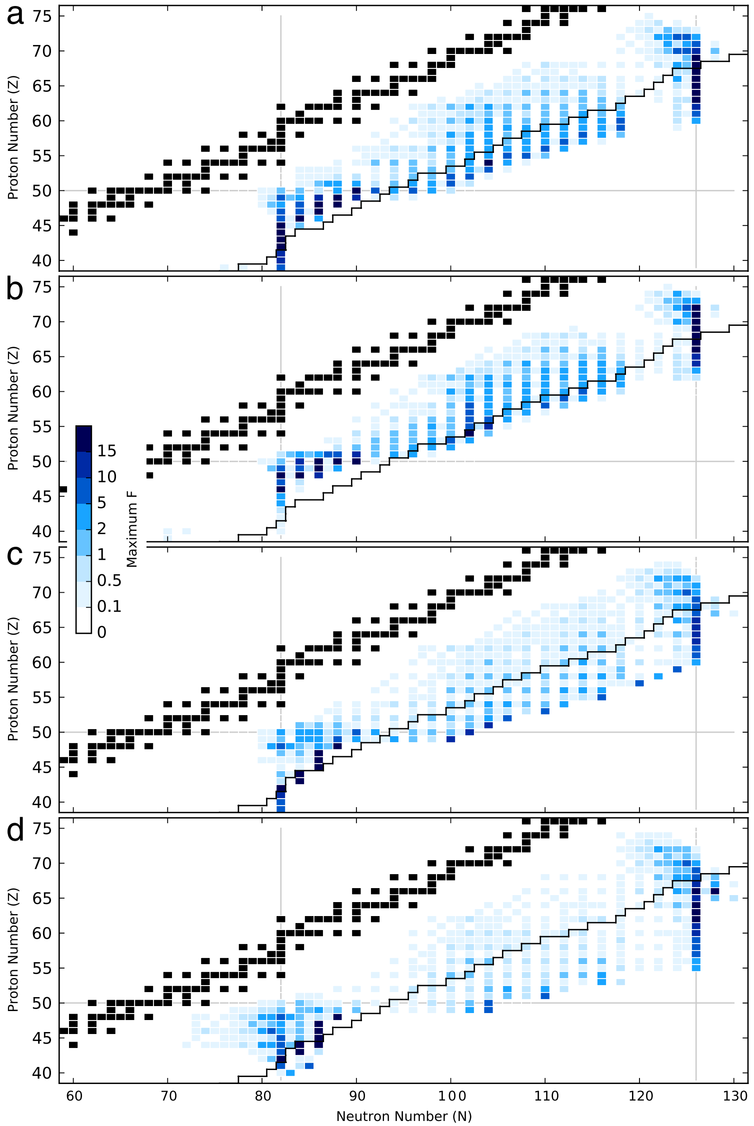
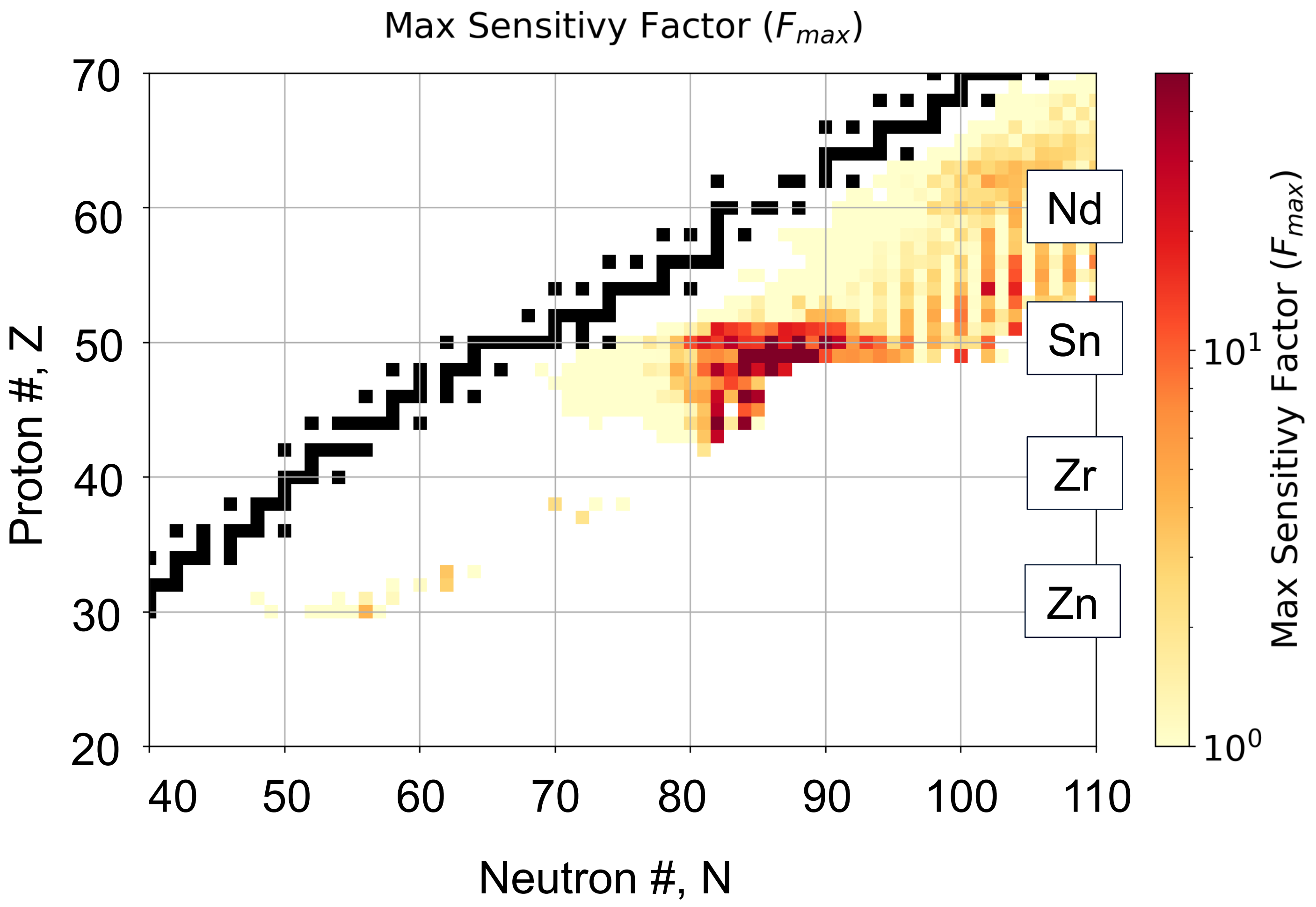


Fig. 14. Important β-decay half-lives in four astrophysical environments (a) low entropy hot wind, (b) high entropy hot wind, (c) cold wind and (d) neutron star merger with stable isotopes in black. Estimated neutron-rich accessibility limit shown by a black line for FRIB with intensity of 10^{-4} particles per second [206].
Source: Simulation data from [127].

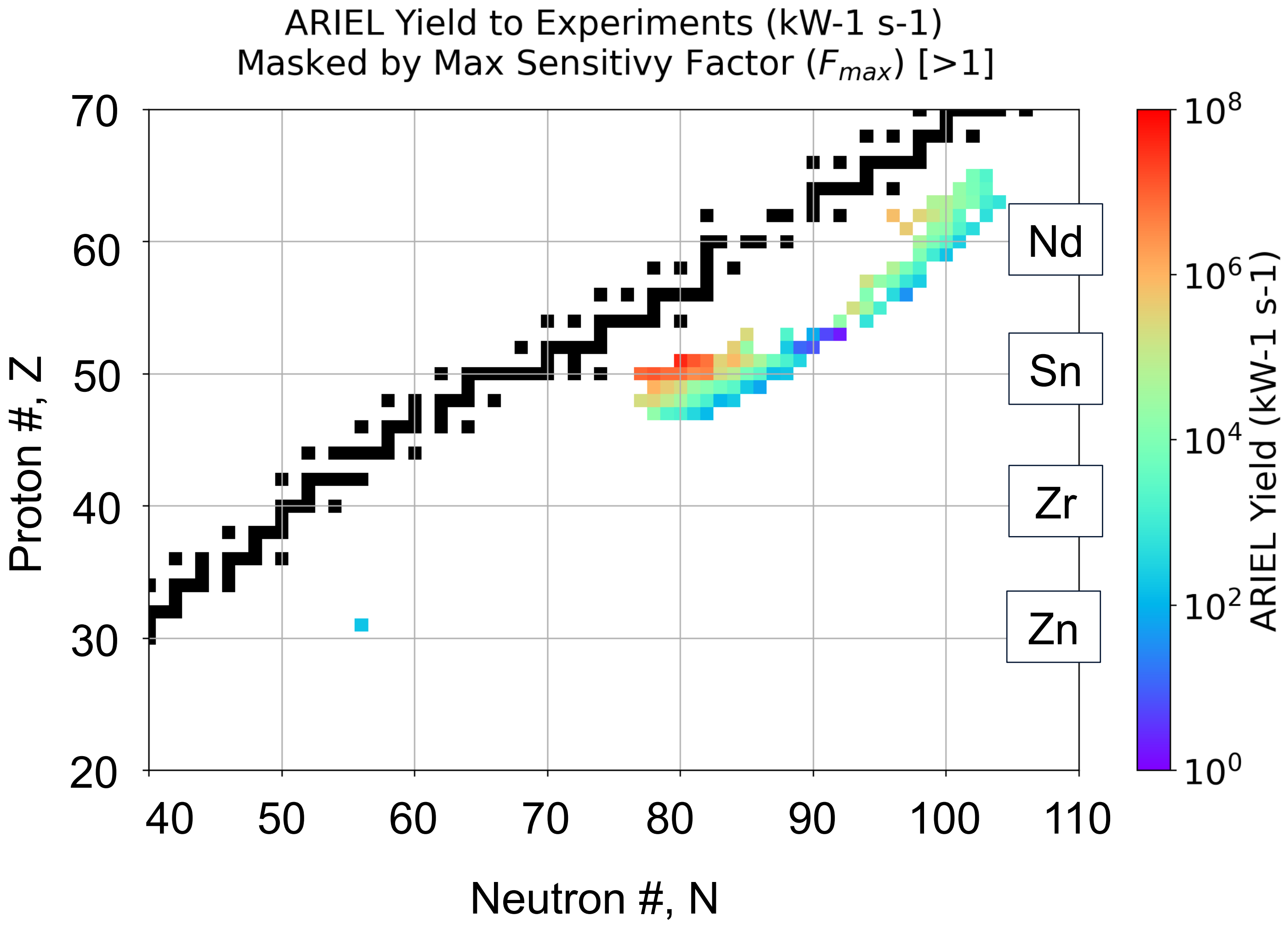
Sensitivity studies: r-process

- Mumpower et al evaluated F for various stellar scenarios and for beta-decay, mass, reaction-rate data
- We took the maximum for any given nucleus
- All F>1 plotted here
- Note dominance around $Z \in [42,52], N \in [79,90]$,
- What are the yields?



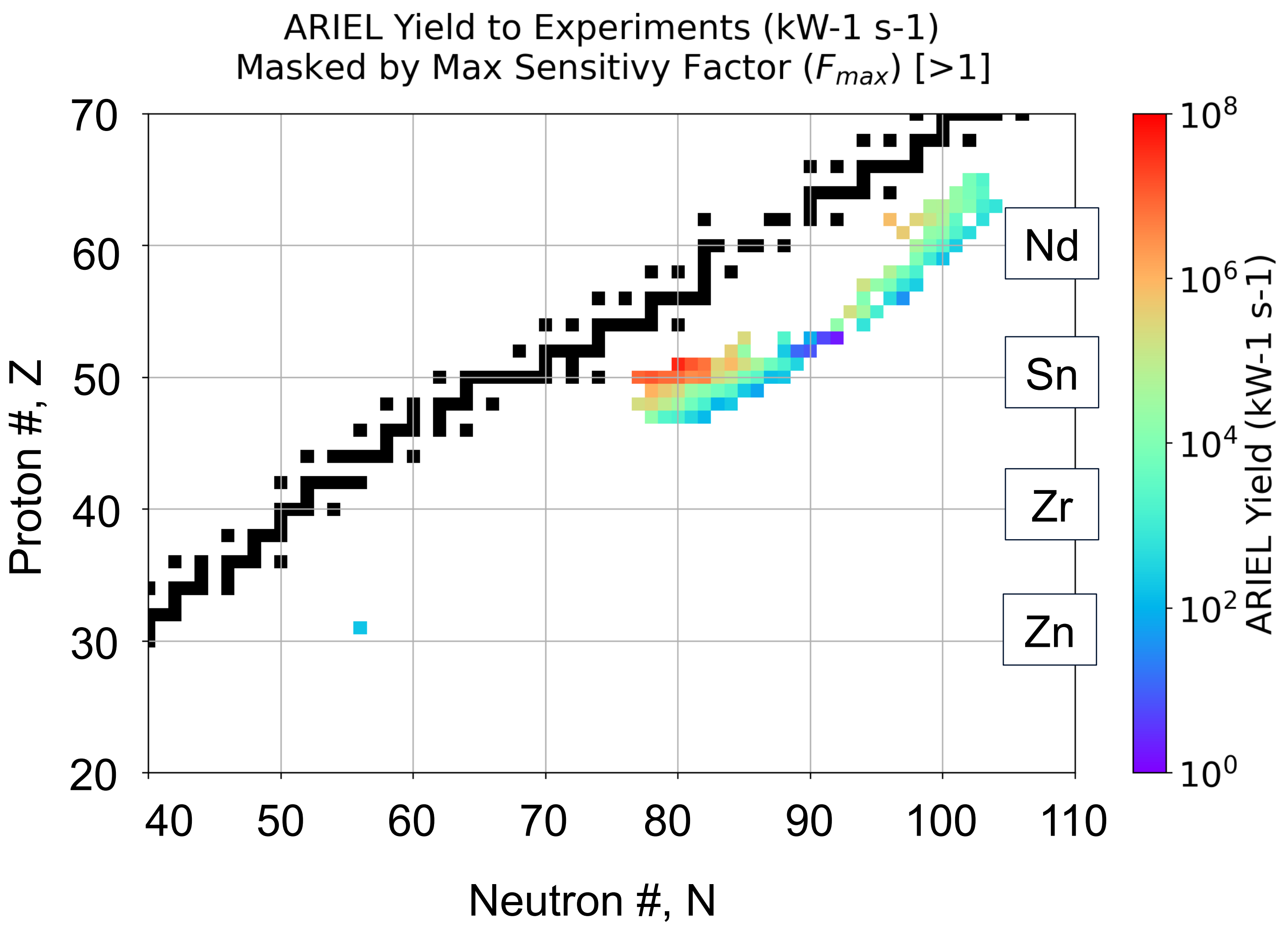
Sensitivity studies: r-process

- Anything shown here: easy mass, beta-decay measurements
- Orange and yellow: possible for surrogate reaction measurements with CANREB EBIS and MRS at design capabilities



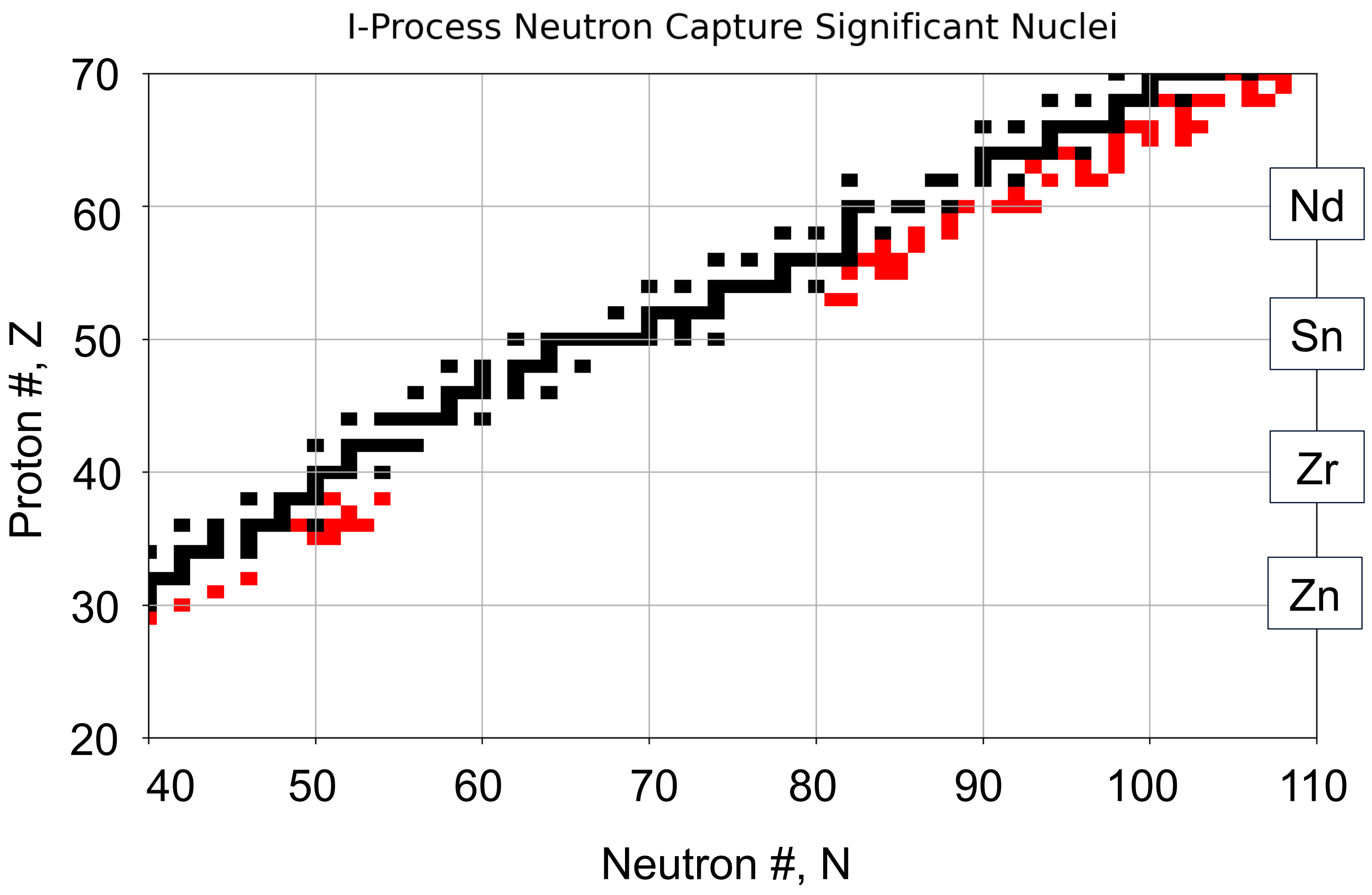
Sensitivity studies: r-process

- ~50 strong candidates for The Early Science Program with ARIEL Rare IsotopEs
- ~10 candidates for surrogate reaction studies



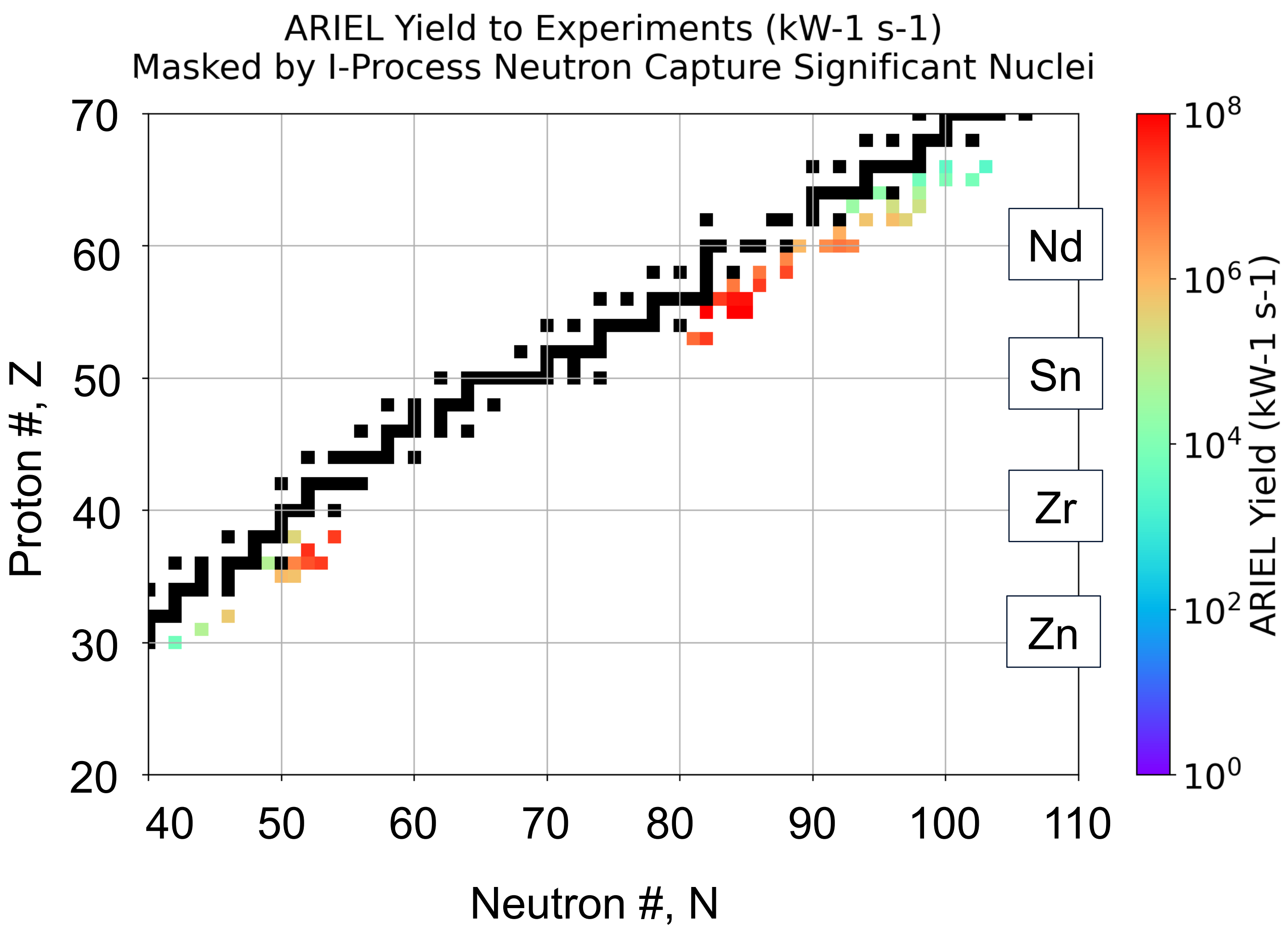
Sensitivity studies: i-process

- Denisenkov, Herwig et al., JPG 45 (2018) 055203, MNRAS 503, 3913 (2021); McKay et al., MNRAS 491, 5179 (2020)
- Evaluated reactions with high impact on i-process
  - I'm taking their threshold as granted
- What are the yields?
  - Need 10^7 or higher to even consider surrogate (d,p)



Sensitivity studies: i-process

- Red and orange-red have enough yield
- ~20 strong surrogate reaction measurement candidates for The Early Science Program with ARIEL Rare IsotopEs



Conclusions

or more precisely, what I hope you got out of this last 35 (or more) minutes

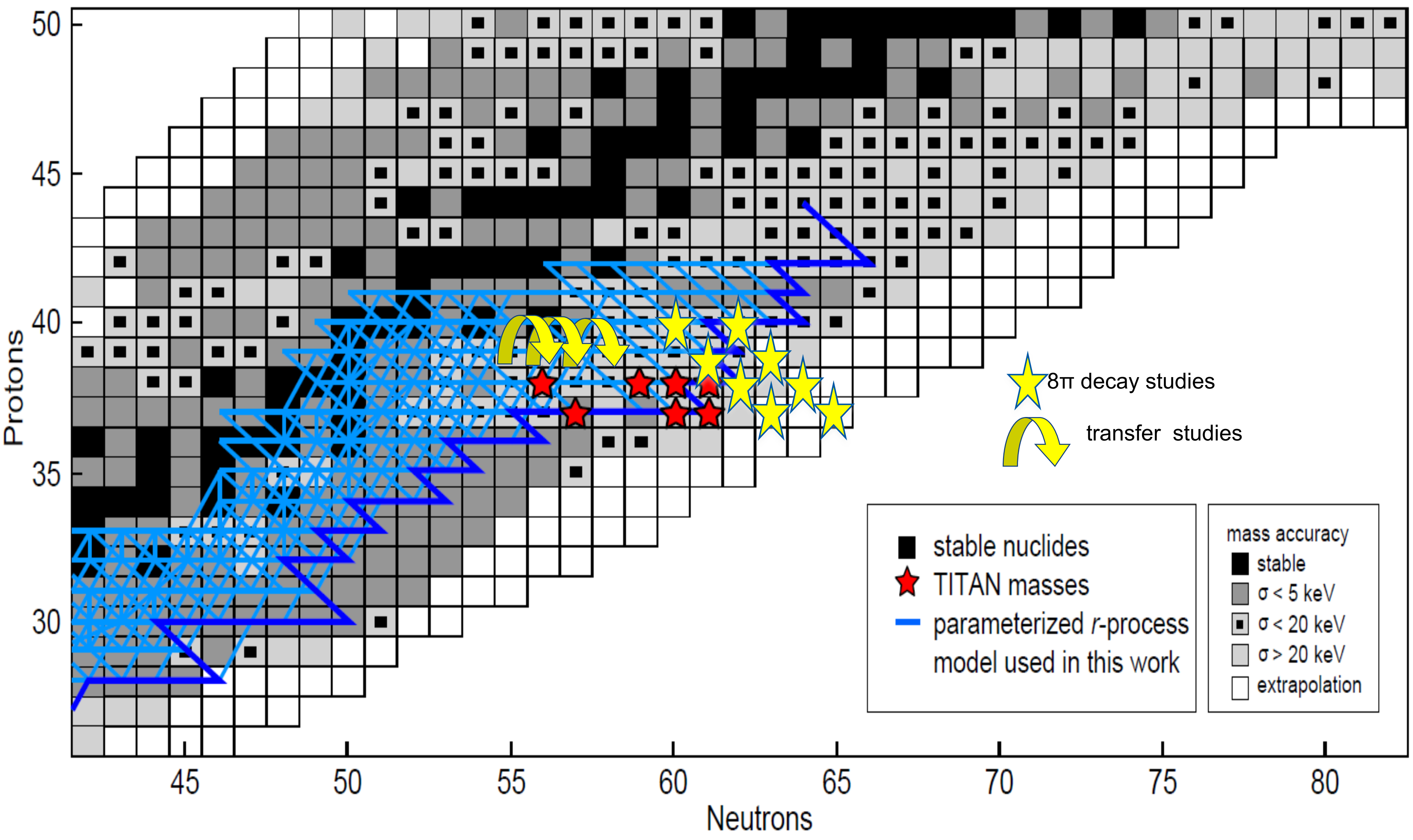
- FLASH radiotherapy studies submitted: The ARIEL Science Era is already here!
- Darklight: Early ARIEL particle physics opportunity coming along
- Approximately 50 opportunities for mesaurements with Rare IsotopEs impacting r- and i-process nucleosynthesis as part of The Early Science Program with ARIEL
  - Tools & techniques (and people!) already in place for them

Thanks!

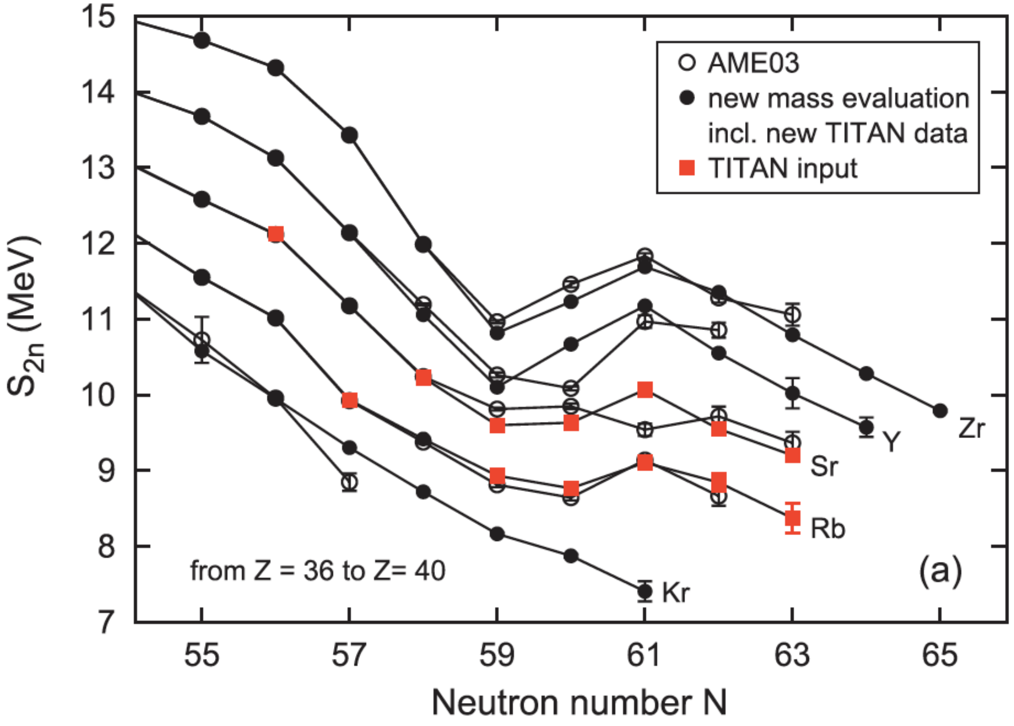
Especially to Kaylee D, Conny H, Kate P, Ania K, Daniel Y, Alex G, Adam G, Iris D, and Nicole V for providing figures, slides, data, valuable discussions

BONUS MATERIAL

Already doing some of this work as early as 2012

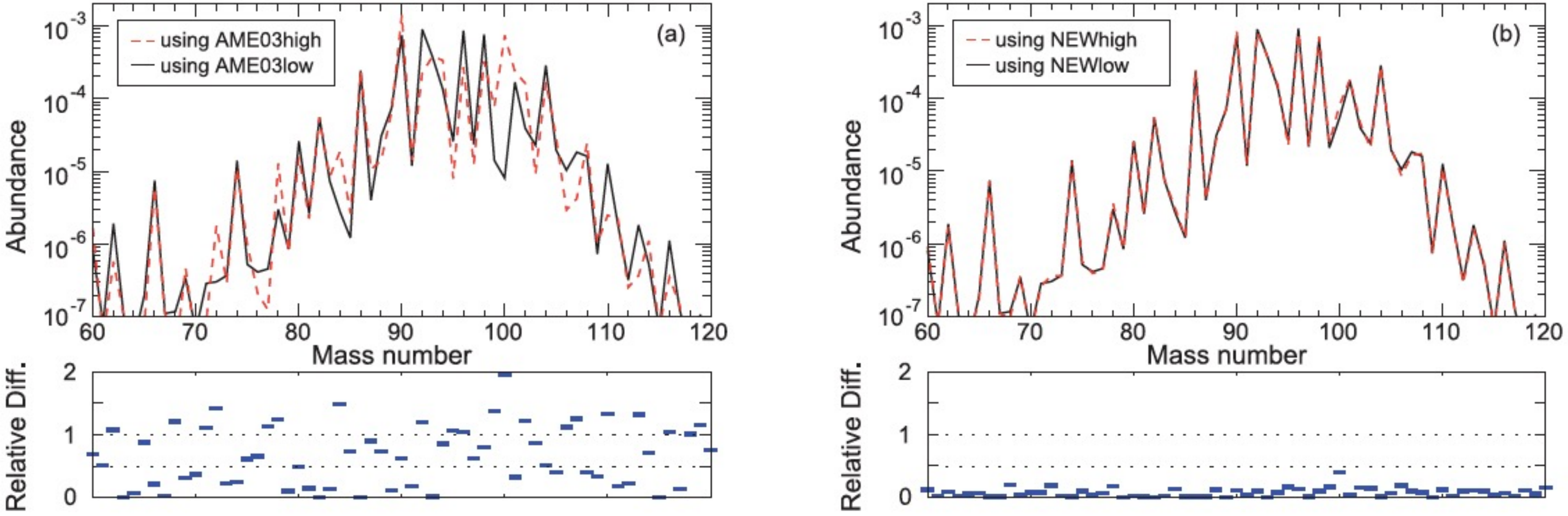


Particle Separation Energies: Mass Measurements



- V. Simon et al, PRC 85, 064308 (2012)
- Mass measurements with TITAN
- Improved mass measurements (TITAN) in A~90 to 100 part of r-process
- S_{2n}: energy to remove 2 neutrons (similar to an ionization potential)
- Kink at N=60 due to shape changes, not magicity
- Note: old values for ^{99}Sr were wrong by >1/2 MeV or about 0.001%
- What does this mean for the r process???

Particle Separation Energies: Mass Measurements



- V. Simon et al, PRC 85, 064308 (2012)
- Left: abundances from the same astrophysical site, but masses of r-process nuclei from 2003, varied over uncertainties in said masses (<0.001%!)
- Right: variation in r-process model due to nuclear physics uncertainties are all but eliminated with new nuclear measurements

Effective Lifetimes: beta-delayed neutron branches

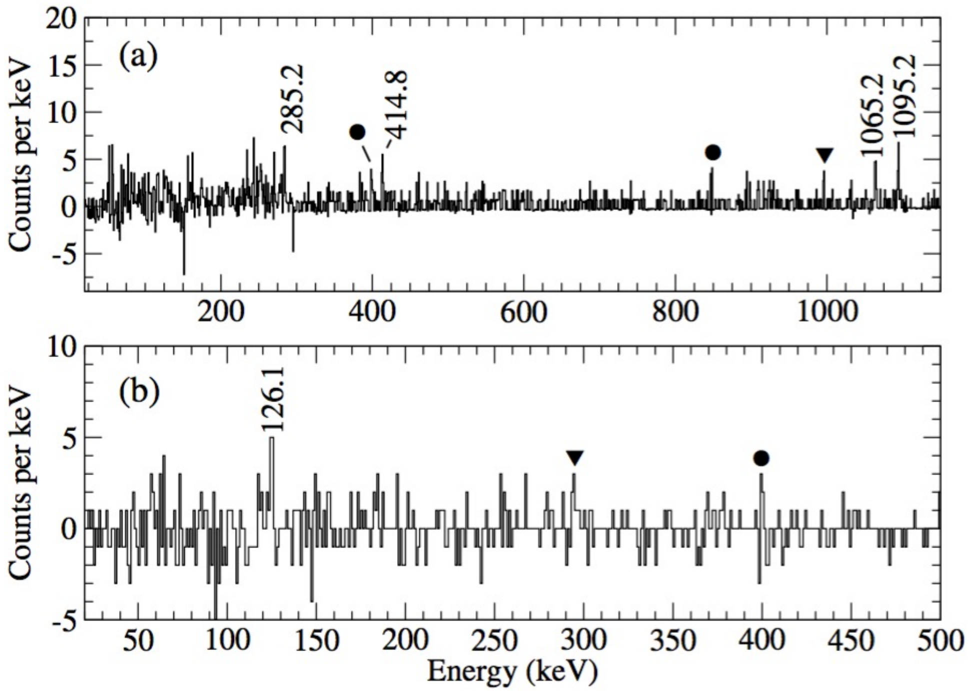
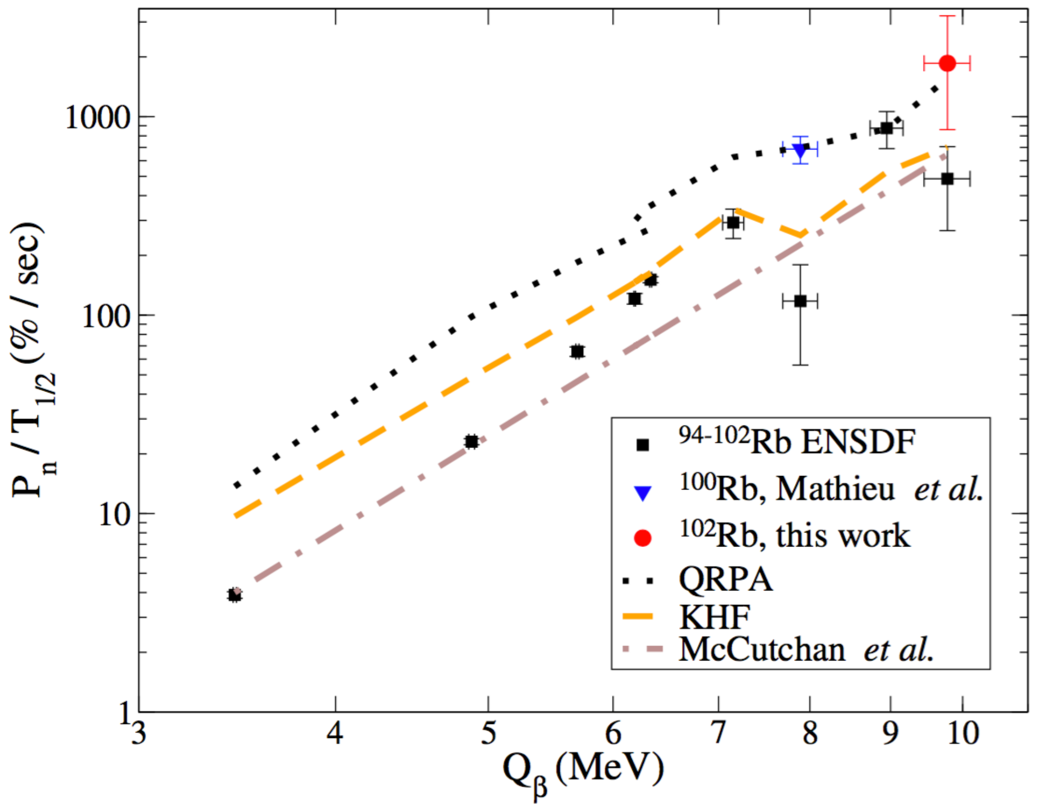


FIG. 1: (a): Portion of the γ-ray energy spectrum in coincidence with the 126.1 keV transition in ^{102}Sr. (b): The γ-ray energy spectrum gated on the 285.2 keV transition in ^{102}Sr. Both spectra require a coincidence with a β particle and are random-background subtracted. Peaks from other decay species are indicated by the symbols; ▼ for ^{101}Sr -^{101}Y and ● for ^{102}Nb -^{102}Mo.

- ^{102}Rb has a beta-delayed neutron branch
- Previous measurements (1986) measured neutrons directly: ~20% branch
- Re-measured recently by gamma-ray yields
- Gamma intensities in ^{102}Sr (pure beta) and ^{101}Sr (beta-delayed neutron) are well known
- Deliver ^{102}Rb, measure gamma ray yields, deduce neutron branches
- New result: 65% of beta decays yield a delayed neutron!

Effective Lifetimes: beta-delayed neutron branches

- Systematic plot of neutron branching ratio divided by half-life vs. Q value for beta decay
- Black data points: tabulated data
- Red data point: new TRIUMF result for ^{102}Rb neuron decay branch
- Blue data point: a new data point measured elsewhere for ^{100}Rb
- Lines: various theories



- New higher neutron branching ratios would move r-process back towards stability
- Wang, Garnsworthy, Andreoiu et al., Phys. Rev. C 93 054301 (2016)