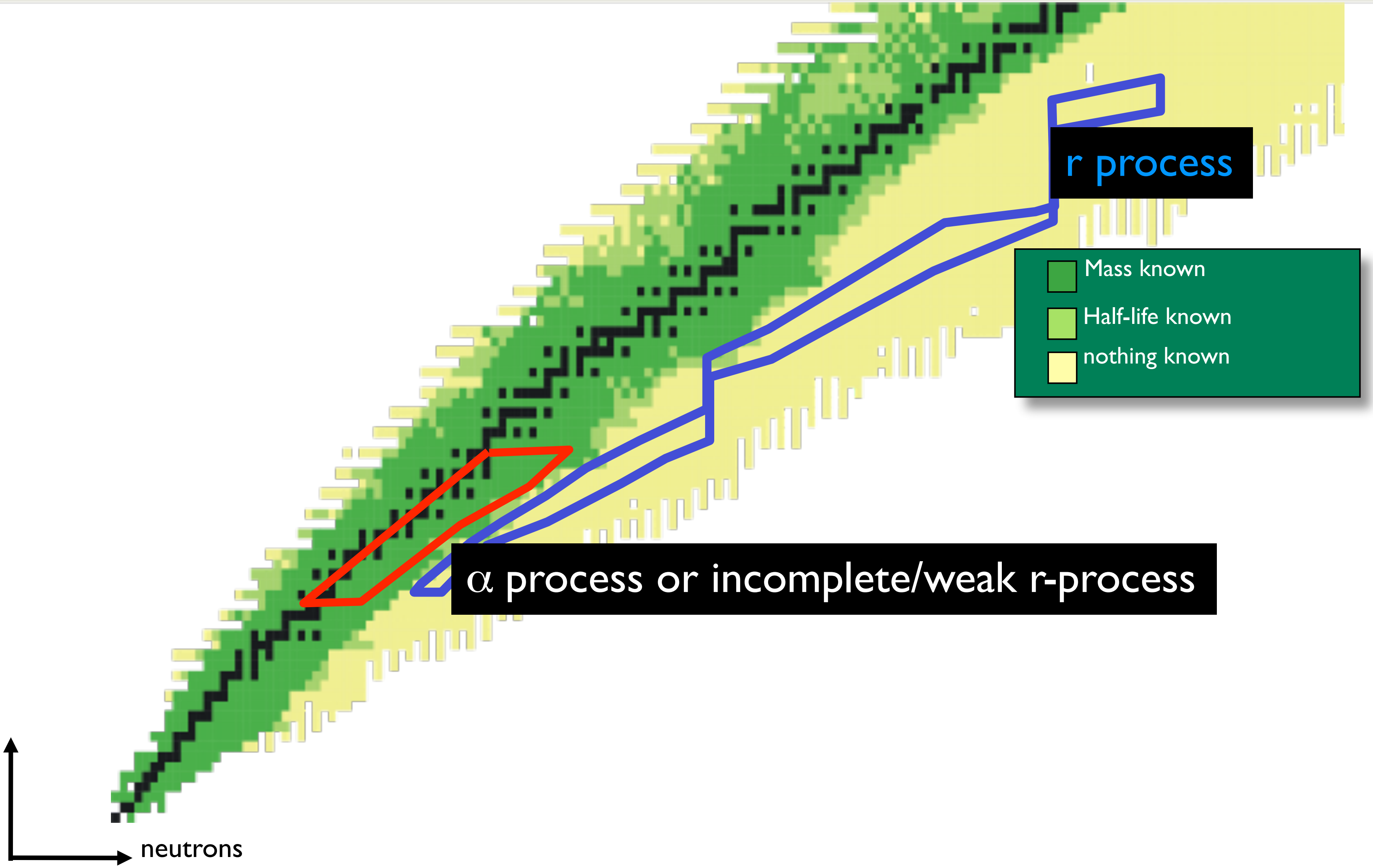
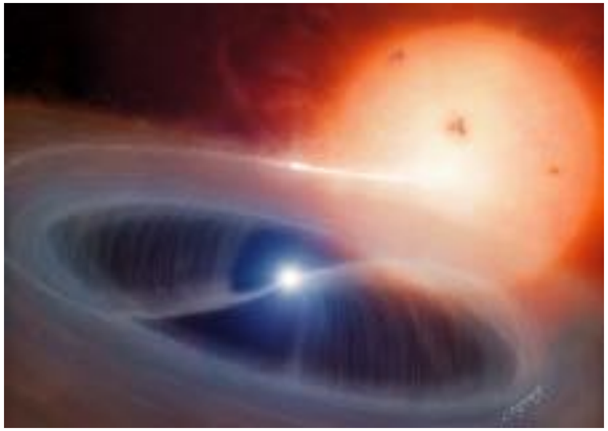
From Stars to the Laboratory: Exploring the (weak) r-Process with Nuclear Reactions

Fernando Montes
Facility for Rare Isotope Beams FRIB
Michigan State University

Nucleosynthesis processes

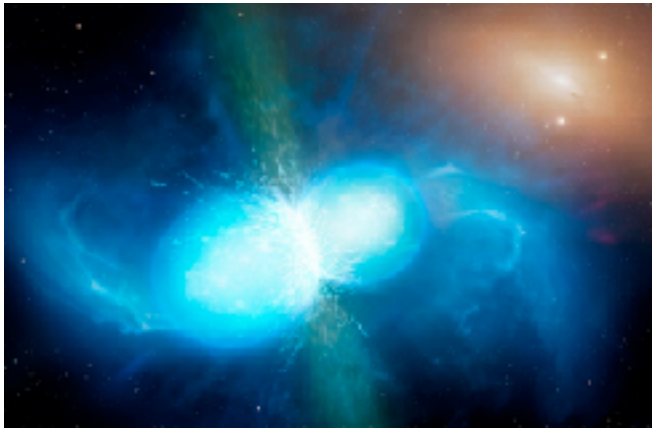


Stellar explosions



David A. Hardy

J. Hester and A. Loll, NASA, ESA



University of Warwick/Mark Garlick

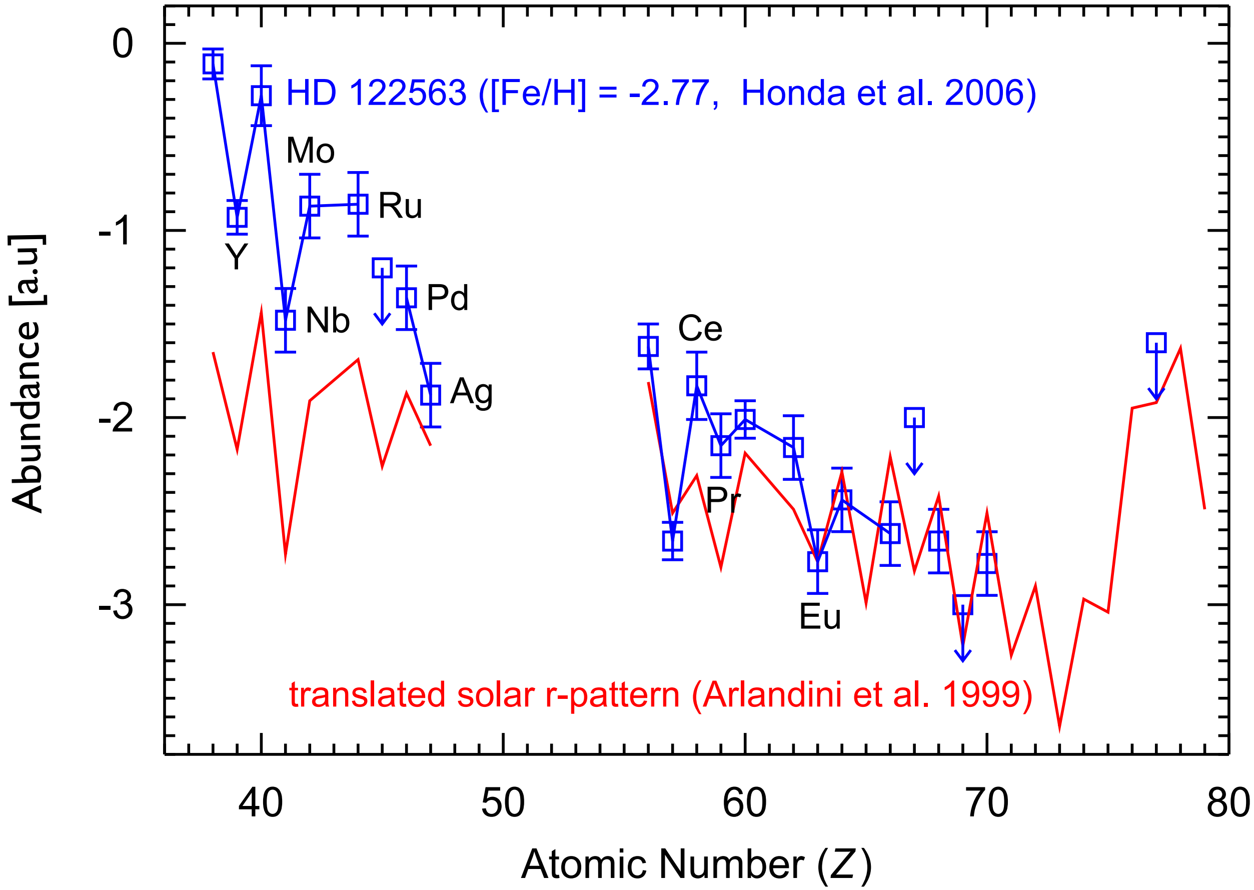
- Extreme environment with complex magneto-hydrodynamics & nuclear physics at play
- Nuclear physics of unstable nuclei is needed to connect observations with the underlying physics
- Proton and alpha capture on unstable nuclei
- Cross sections low at astrophysical energies: 1 in 10^{6-12}
- Current facilities, experiments can address important nuclear physics uncertainties

Weak r-process nucleosynthesis

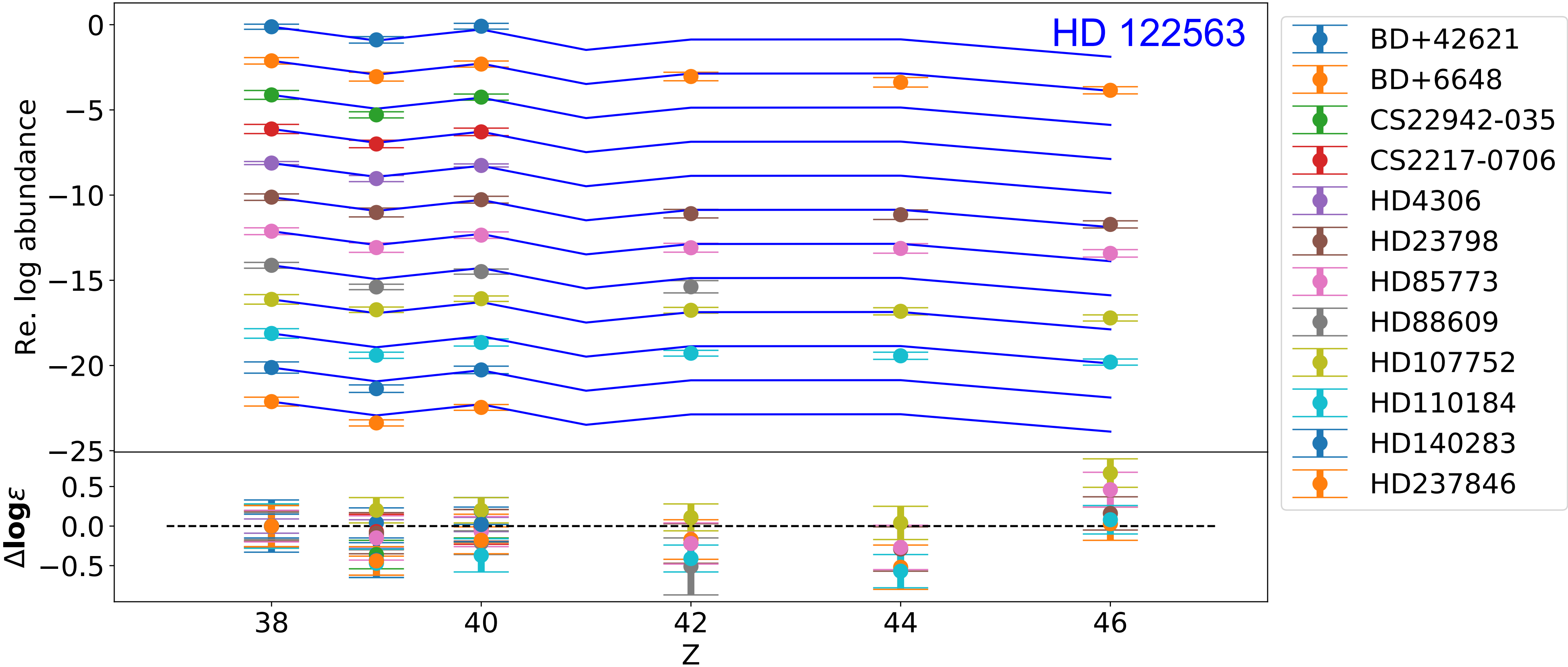
Open questions:

- Are mergers the only site of r-process nucleosynthesis (MHD, MGF, ..)?
- Are mergers the dominant site of r-process nucleosynthesis?
- How important is an incomplete/weak r-process to solar system abundances?

Metal-poor stars with large Z=38 - 47 abundances!



Weak r-process abundances obtained from metal-poor star observations

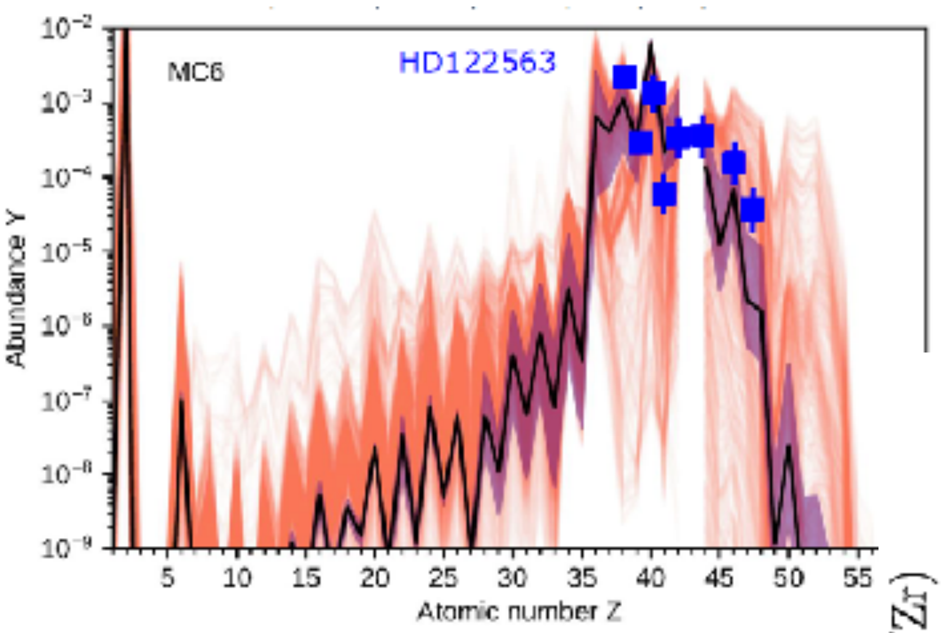


[Fe/H] < -1.5 [Eu/Fe] < 0.3 [Sr/Ba] > 0.5 [Sr/Eu] > 0.0

Weak r-process robust within error bars

Consistency and robustness indication of astro conditions?

Weak r-process nucleosynthesis

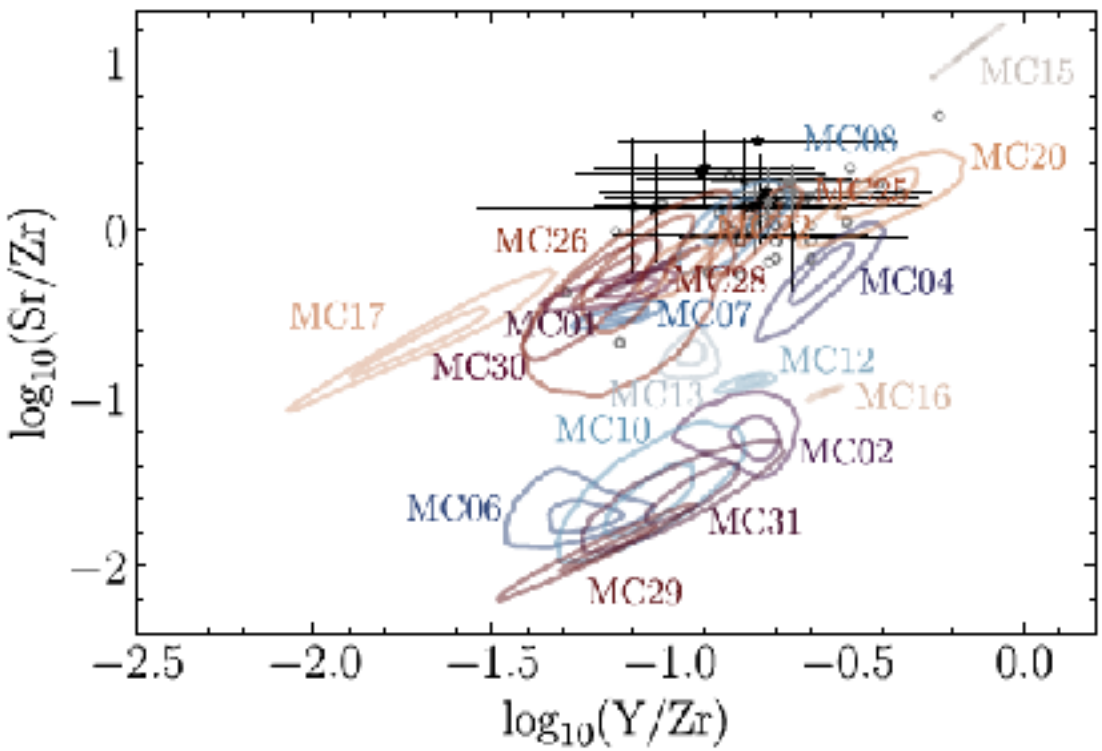


Astro condition uncertainty

Nuclear physics uncertainty

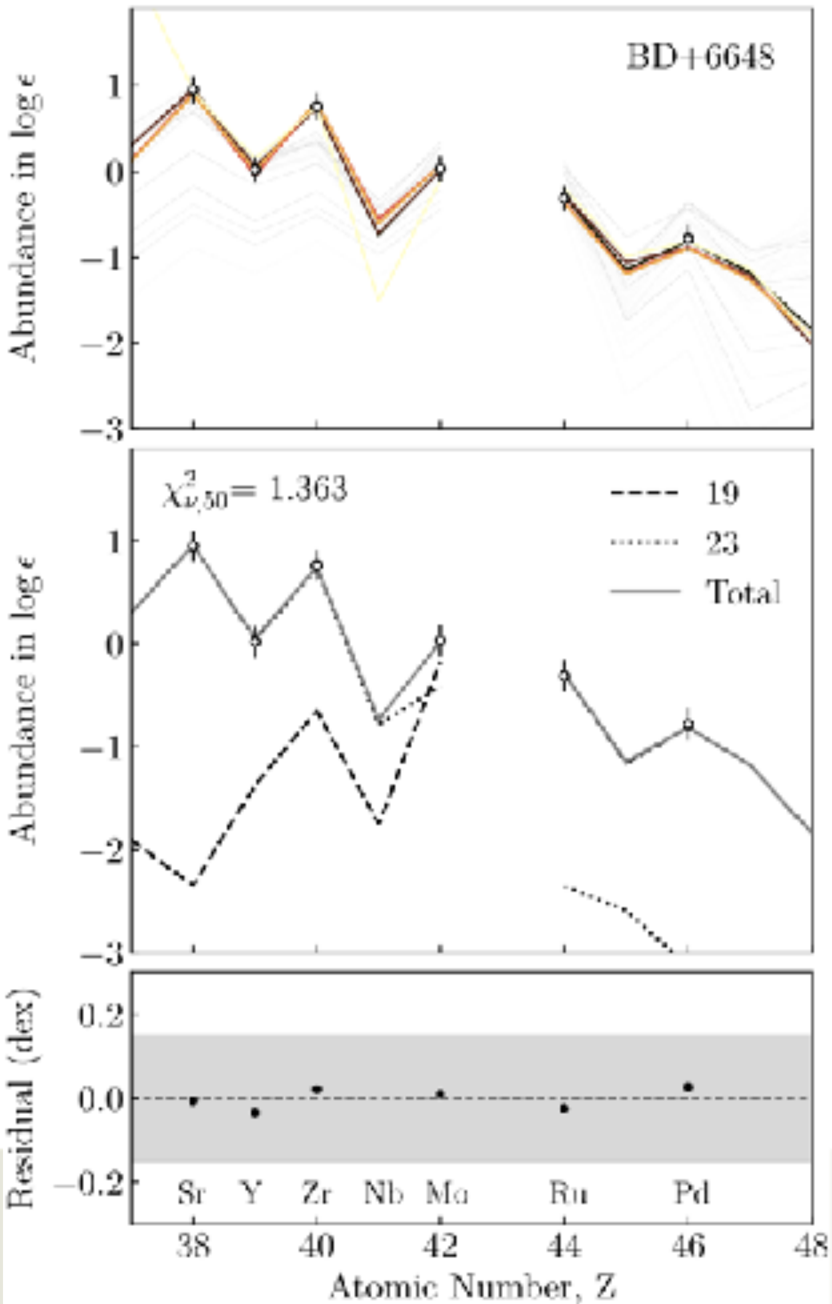
Bliss, Arcones, Montes & Pereira, PRC (2020)

Psaltis et al. ApJ (2022)

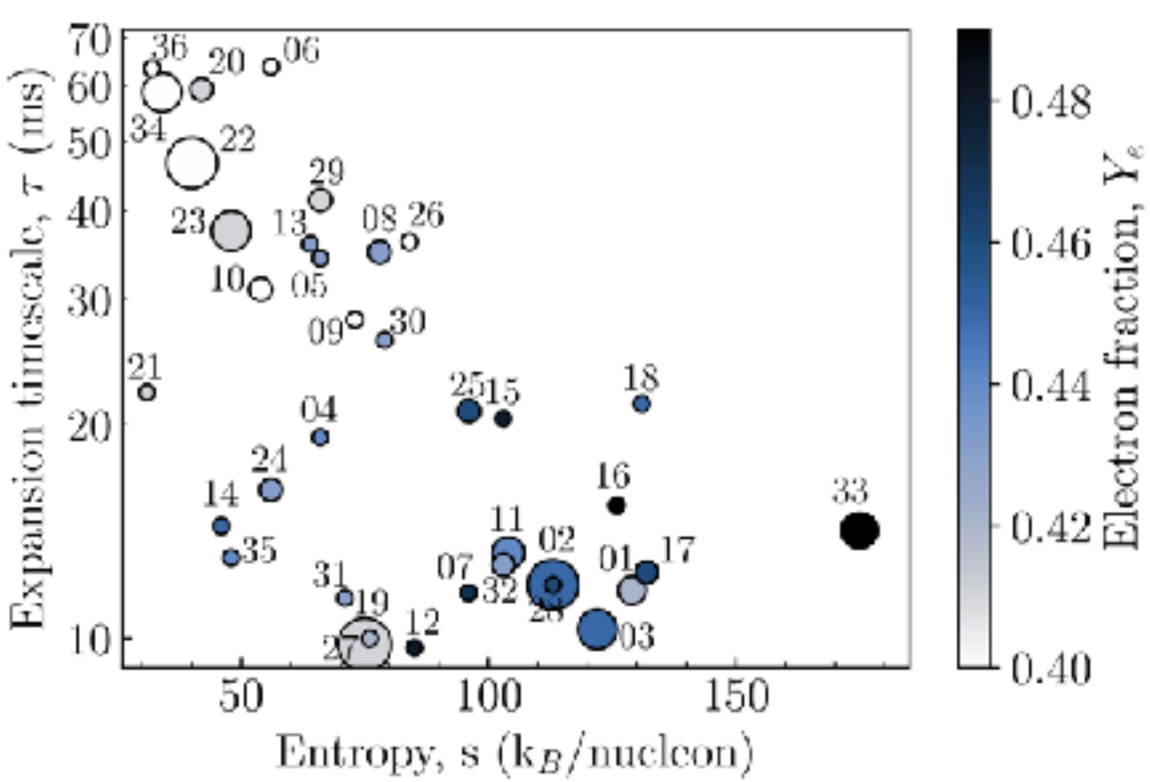


Possible to constrain astrophysical conditions using observations?

Weak r-process conditions needed to explain observations

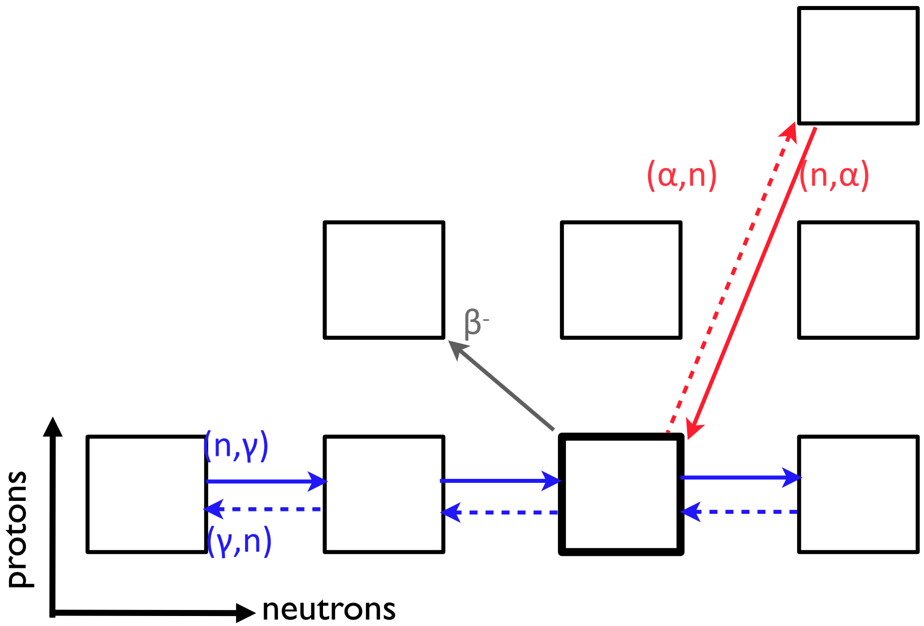


Psaltis et al. ApJ (2024)

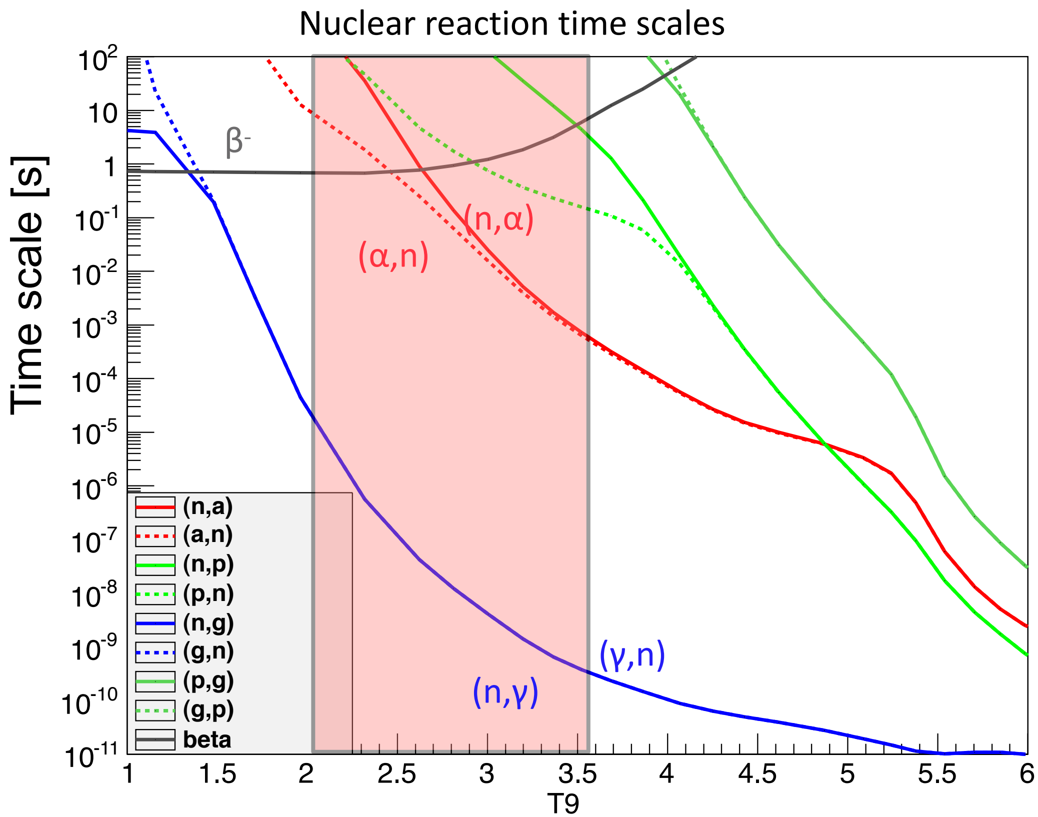


Size of each point is proportional to the number of times it appears in accepted fits when combining only neutron-rich conditions

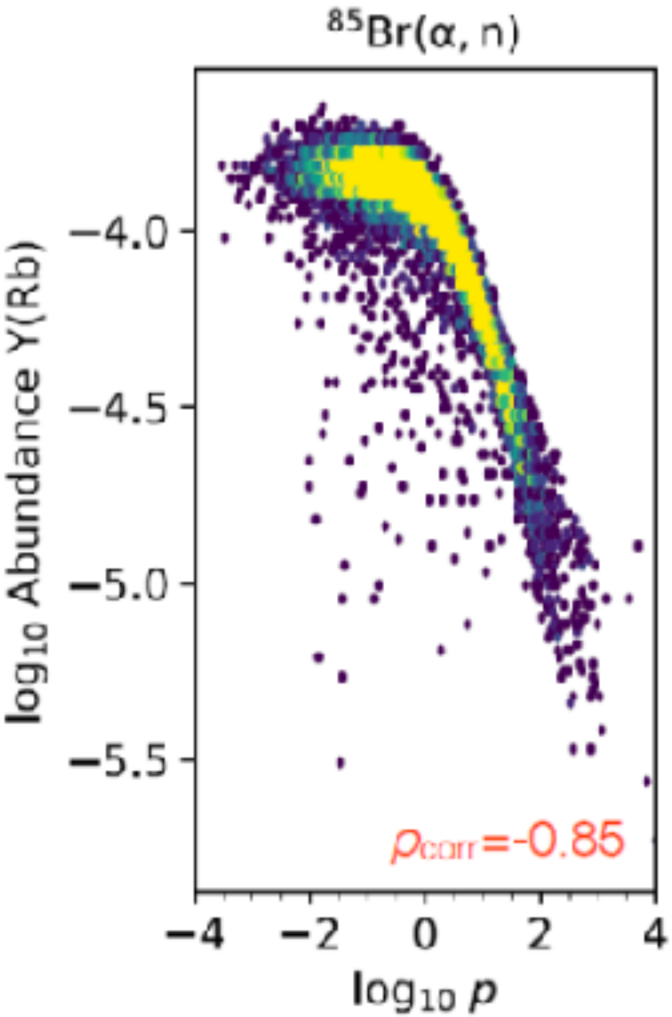
Important nuclear physics needed in weak r-process



Bliss, Arcones, Montes & Pereira, J.
Phys. G (2017)

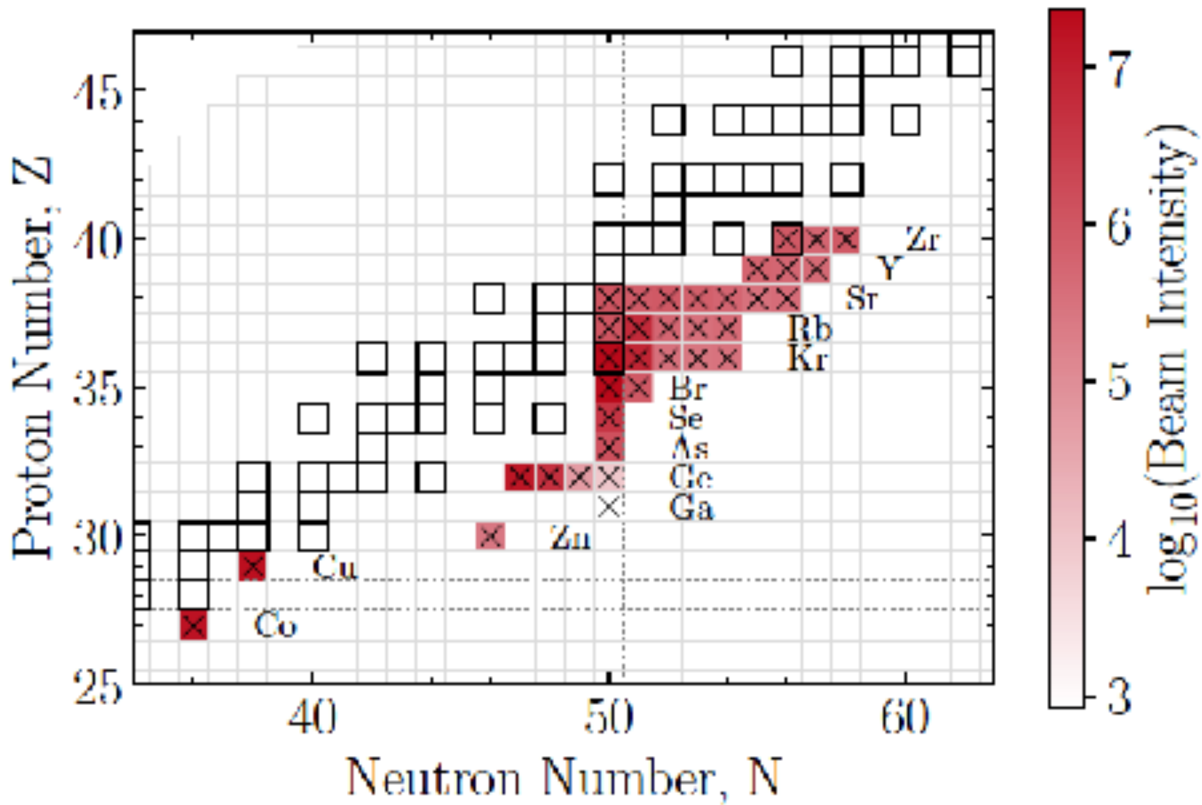


Measurements possible right now



Bliss, Arcones, Montes & Pereira, PRC (2020)

Nuclei with (α,n) conditions affecting elemental abundances in a weak r-process. Estimated FRIB intensities



Psaltis et al. ApJ (2022)

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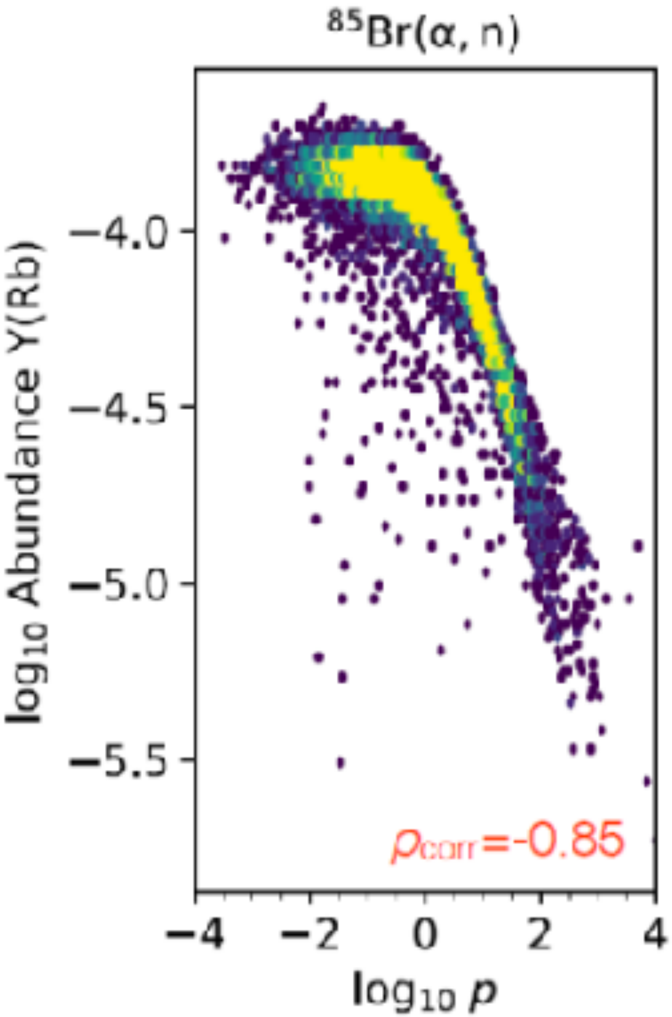

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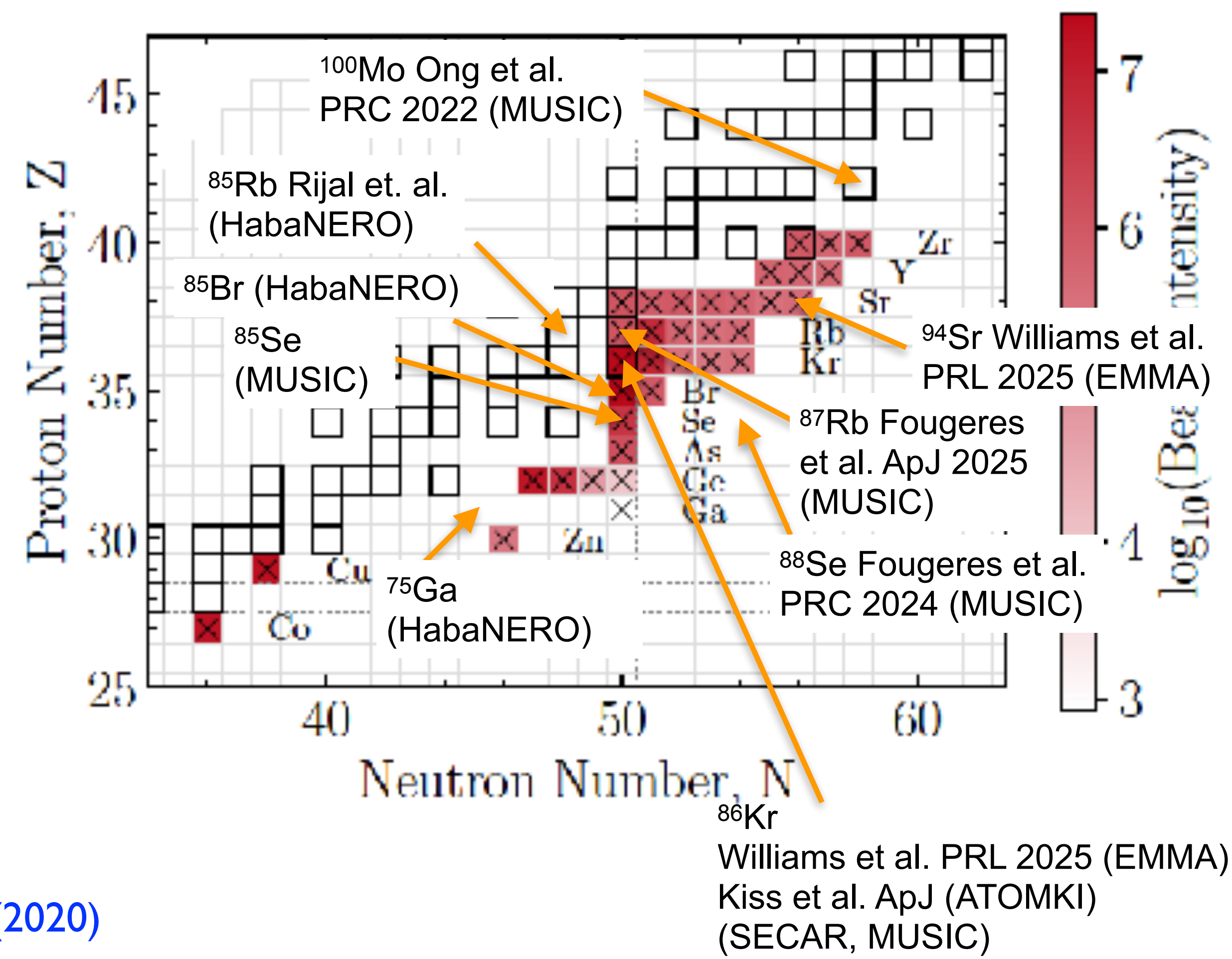
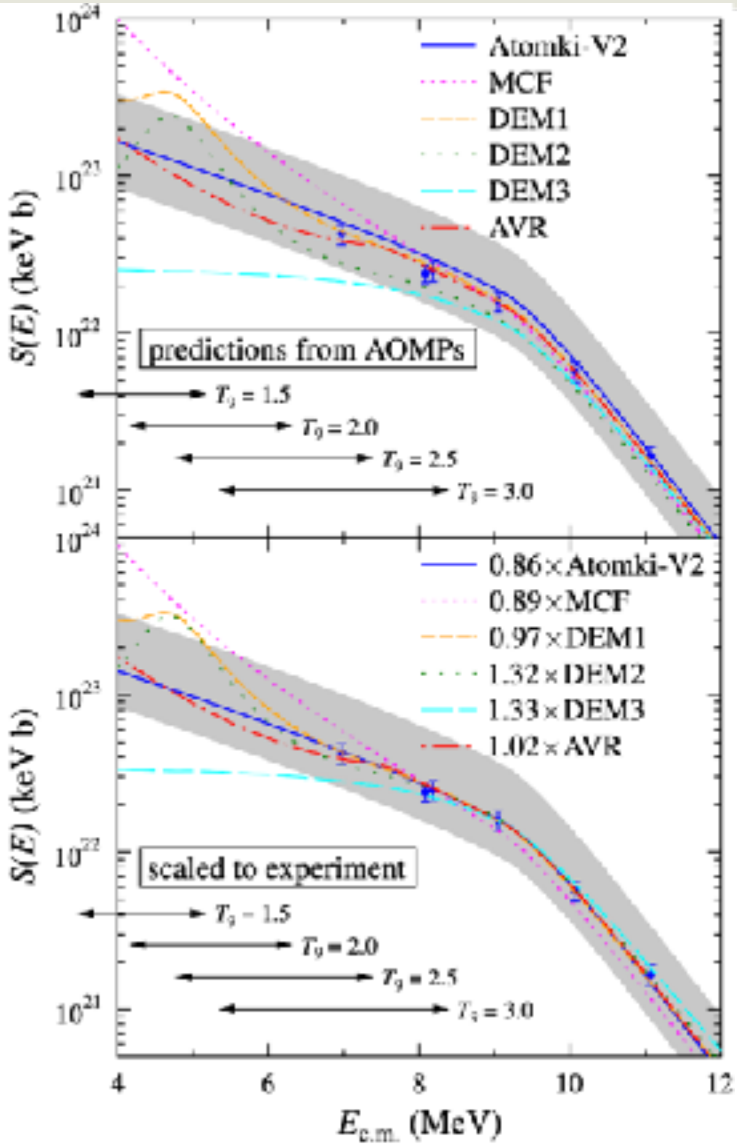


Bliss, Arcones, Montes & Pereira, PRC (2020)

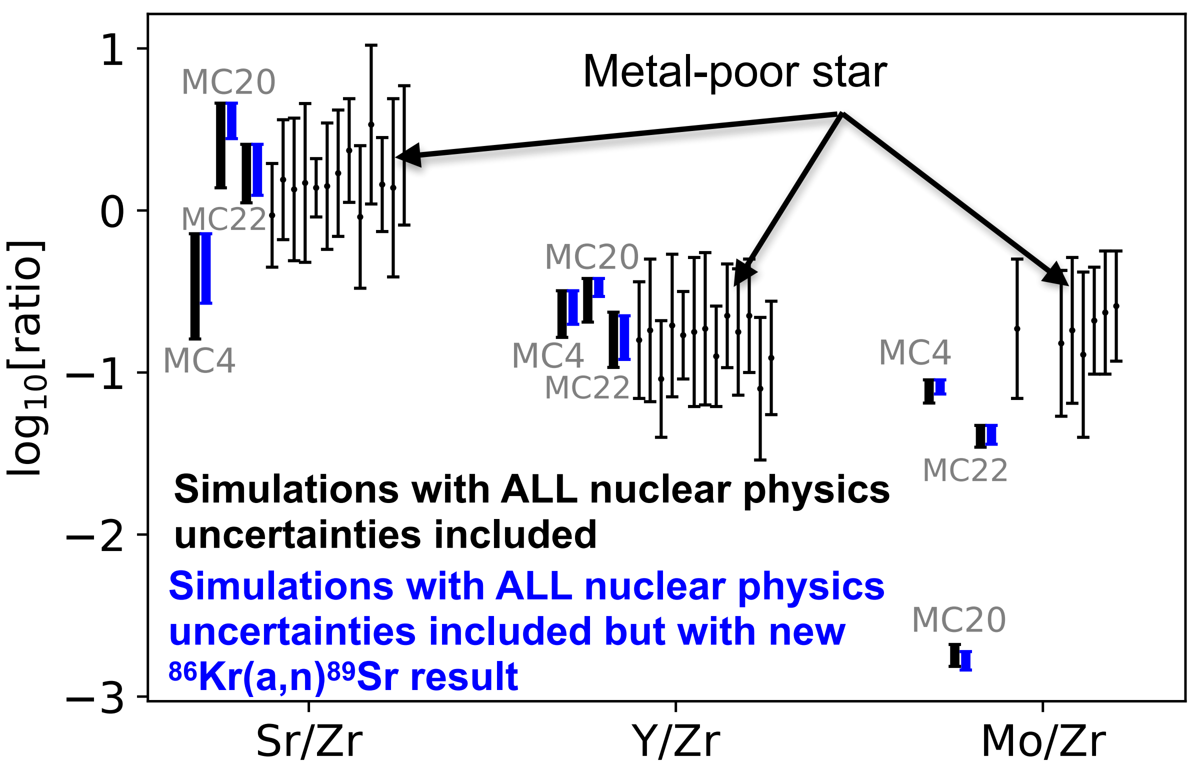
Activation methods



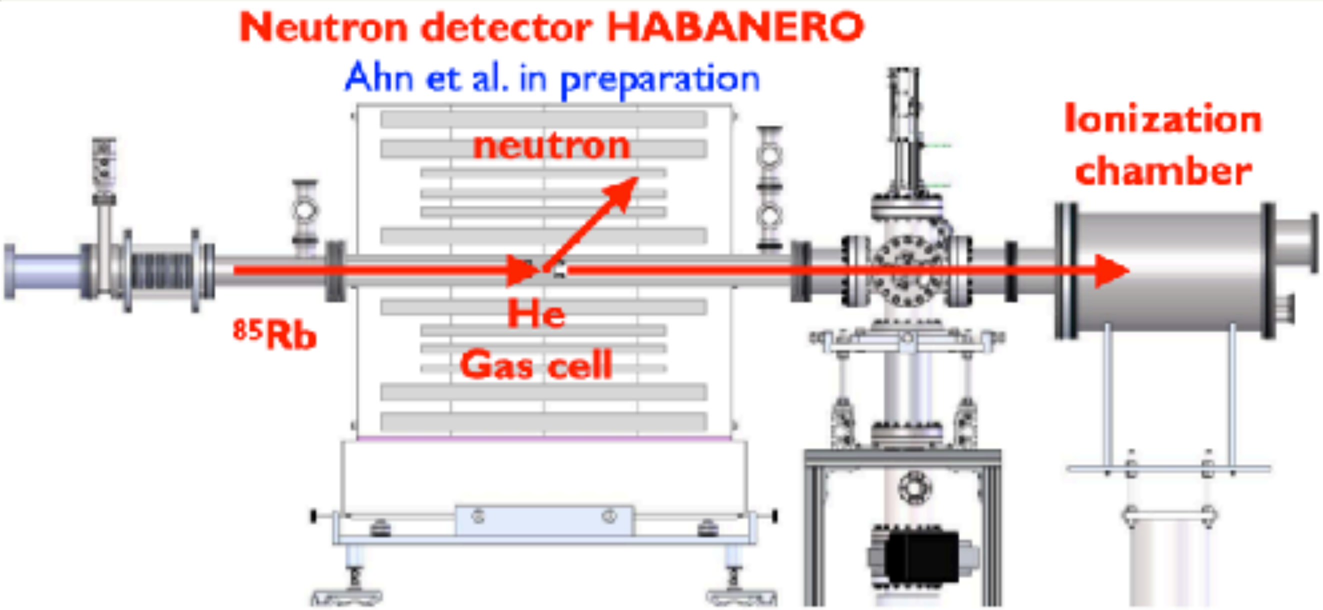
- Alpha beam impinges on target sample
- Reaction products de-excite by emission of g-rays
- Cross section obtained by measuring known gamma transitions
- Precision studies constrain alpha optical potentials

Kiss et al. (submitted to ApJ)

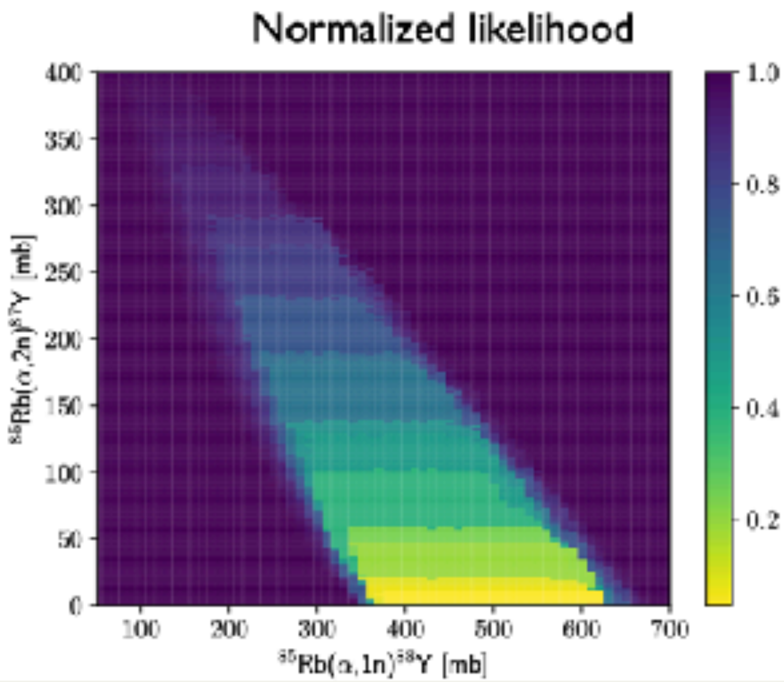
$^{86}Kr(\alpha,n)^{89}Sr$



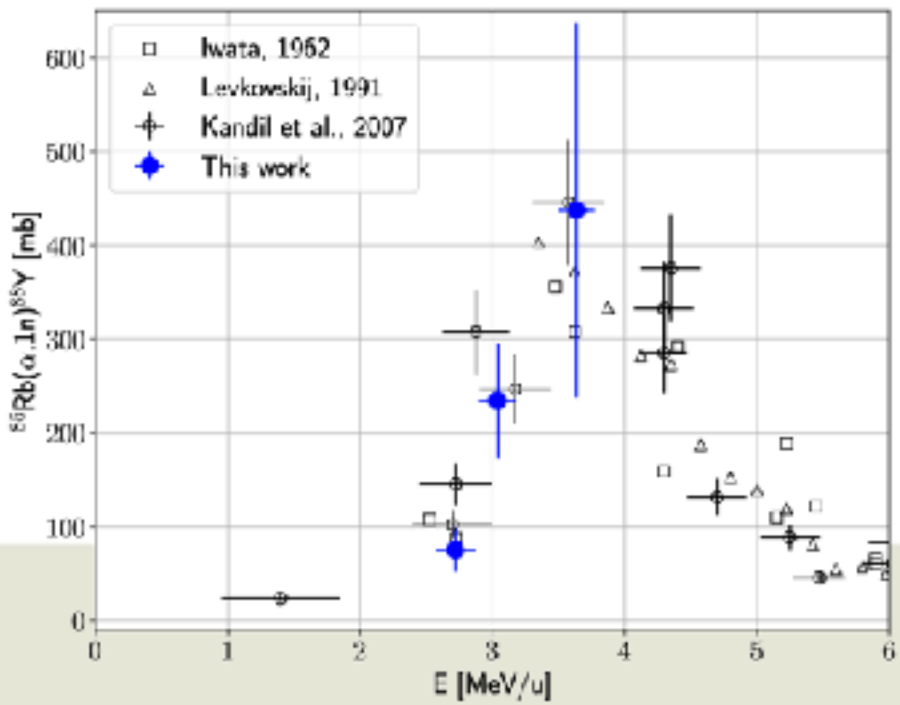
Direct measurements with HabaNERO



- ^{75}Ga(α,n)$^{77-78}$As
- ^{85}Br(α,n)$^{87-88}$Rb
- ^{85}Rb(α,n)$^{87-88}$Y

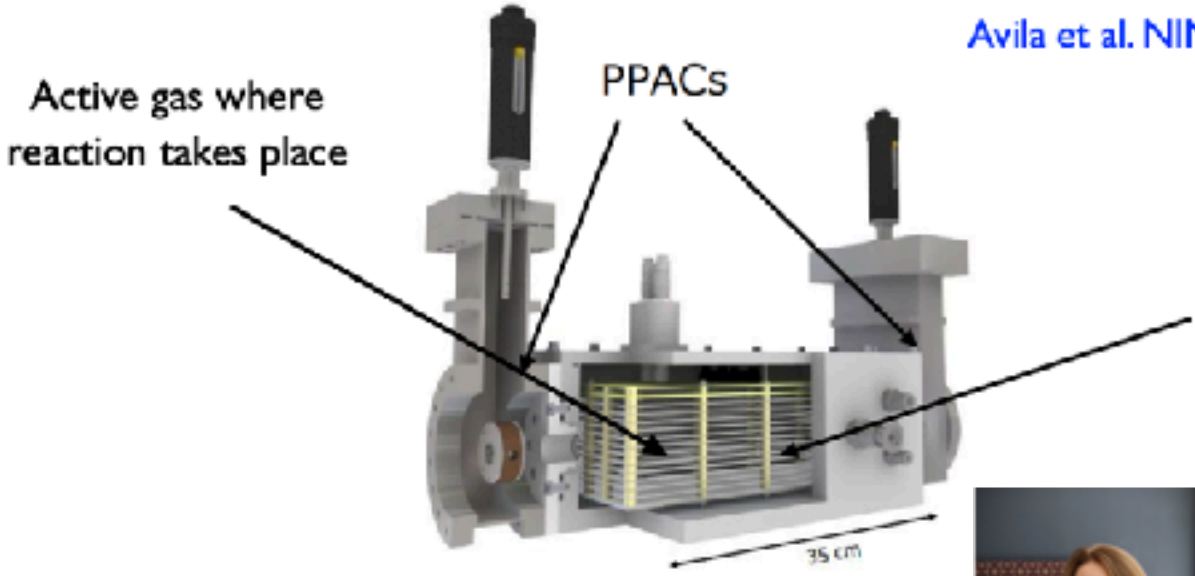


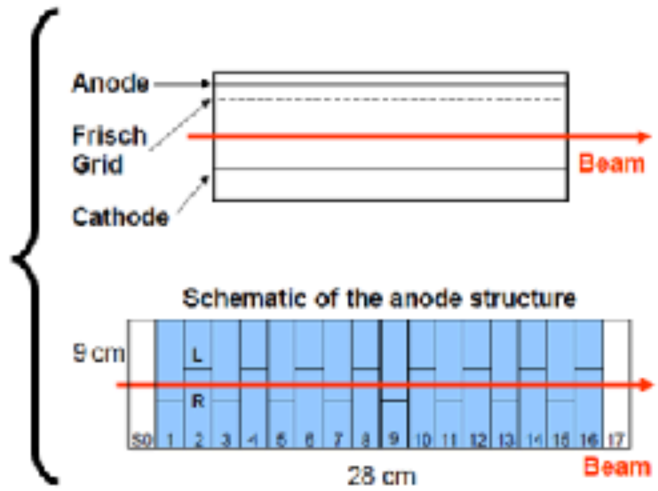
Rijal et al. in preparation



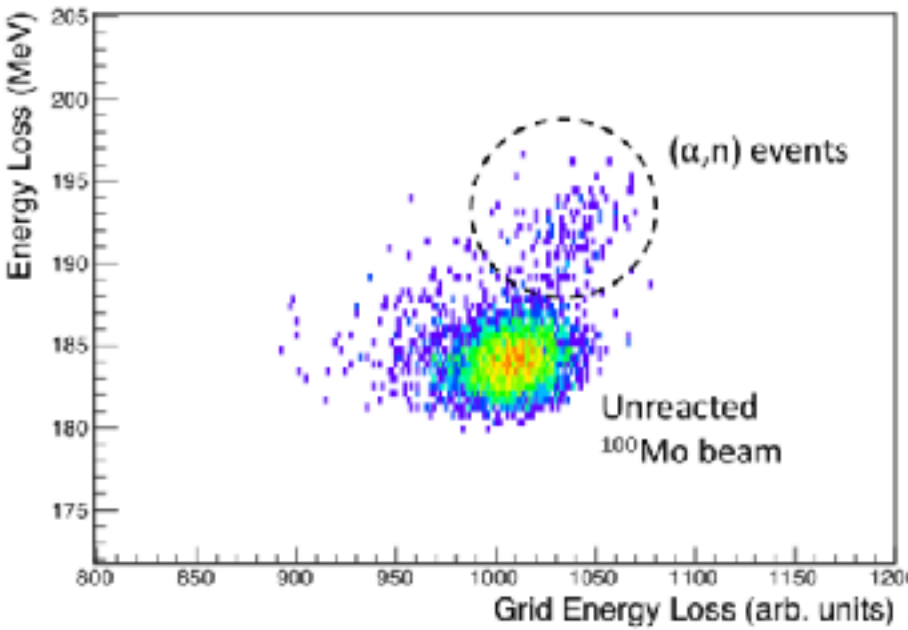
Direct measurements with MUSIC

Avila et al. NIMA (2017)





Ong et al. PRC (2022)



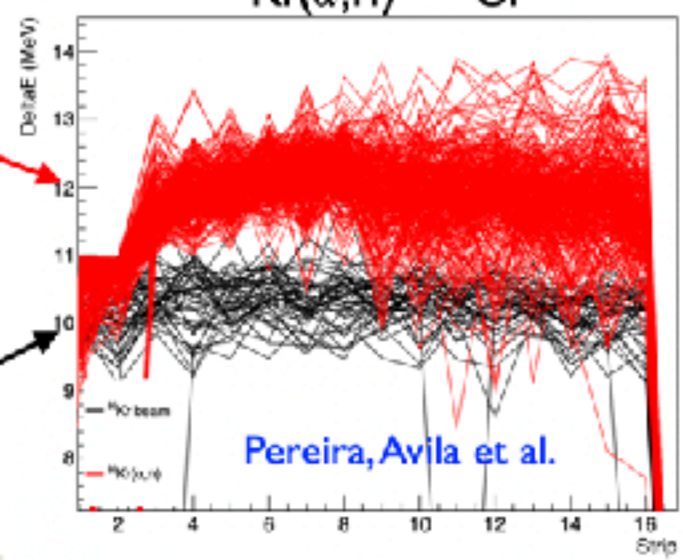
L. Balliet (GD)

PRELIMINARY

^{86}Kr(α,n)$^{88\text{-}89}$Sr

(α,n)
recoils

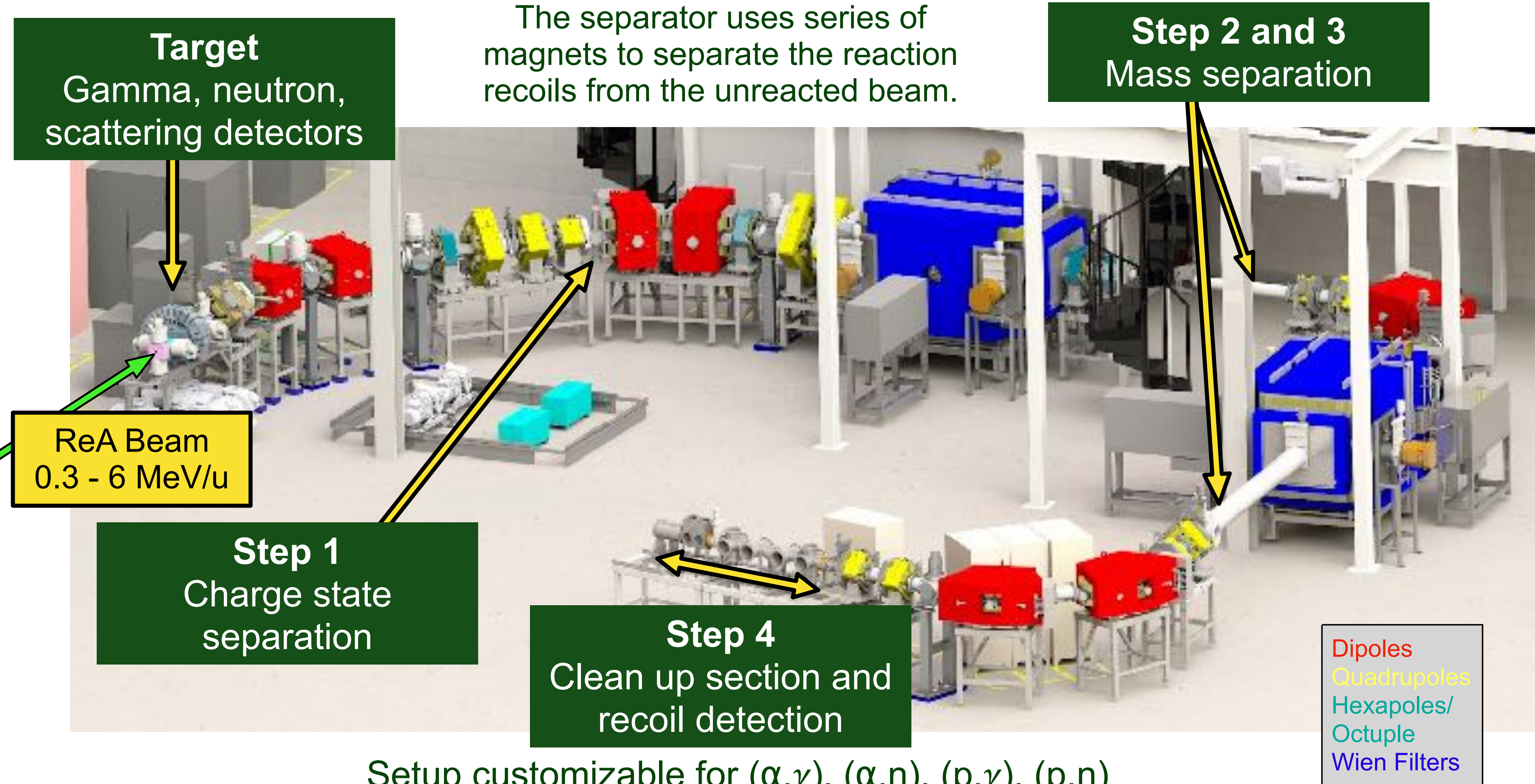
Unreacted
beam



Direct measurements with SECAR

SECAR
SEparator for CApture Reactions

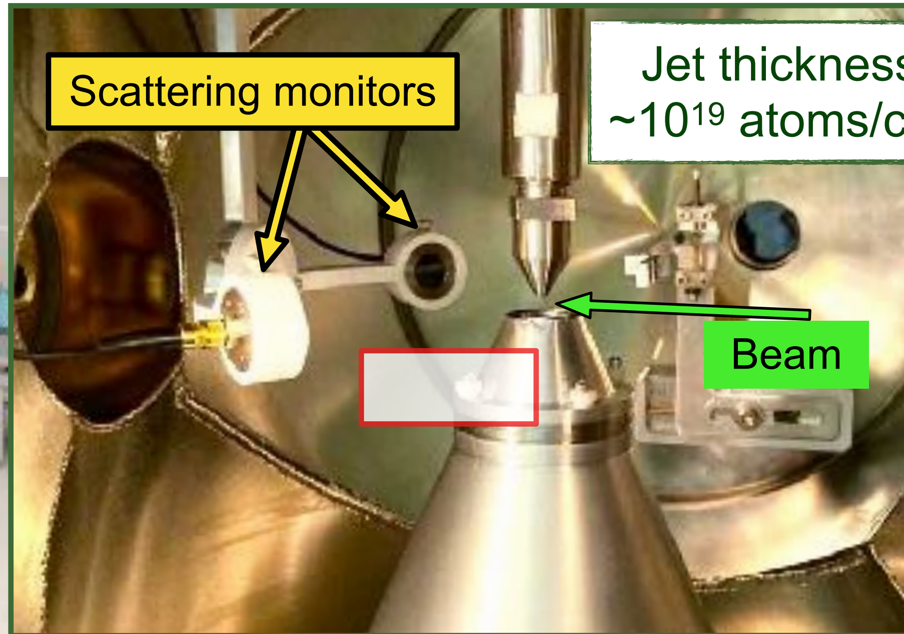
The separator uses series of magnets to separate the reaction recoils from the unreacted beam.

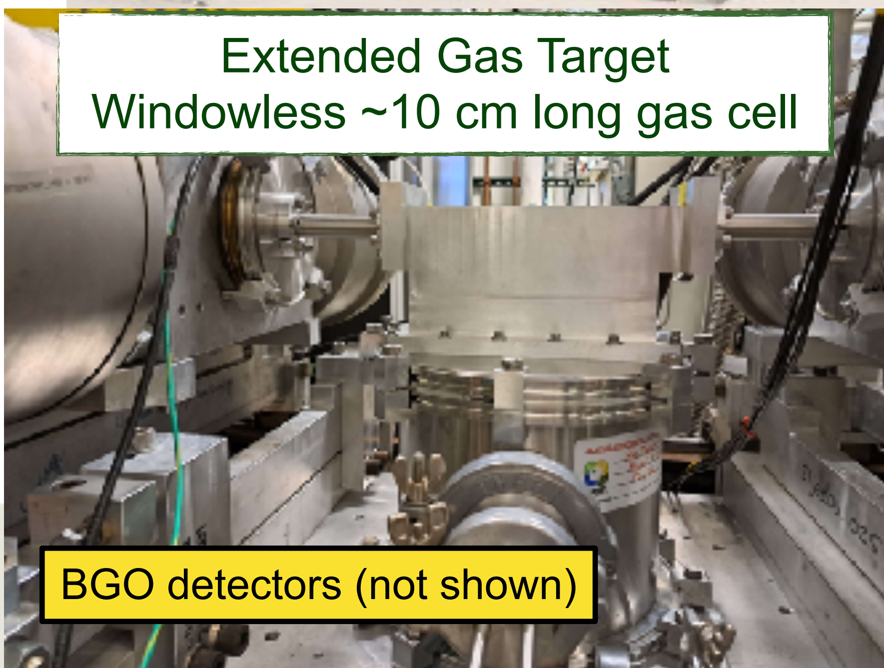


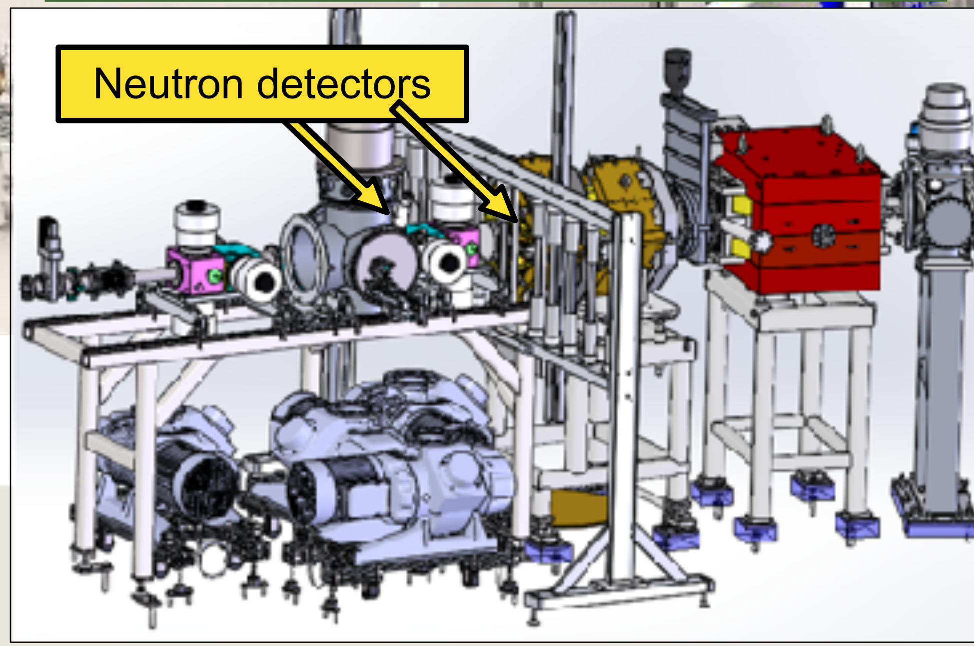
Setup customizable for (α,γ), (α,n), (p,γ), (p,n)

Nominal acceptance ±25 mrad and ±3.1% dE/E

SECAR gas target

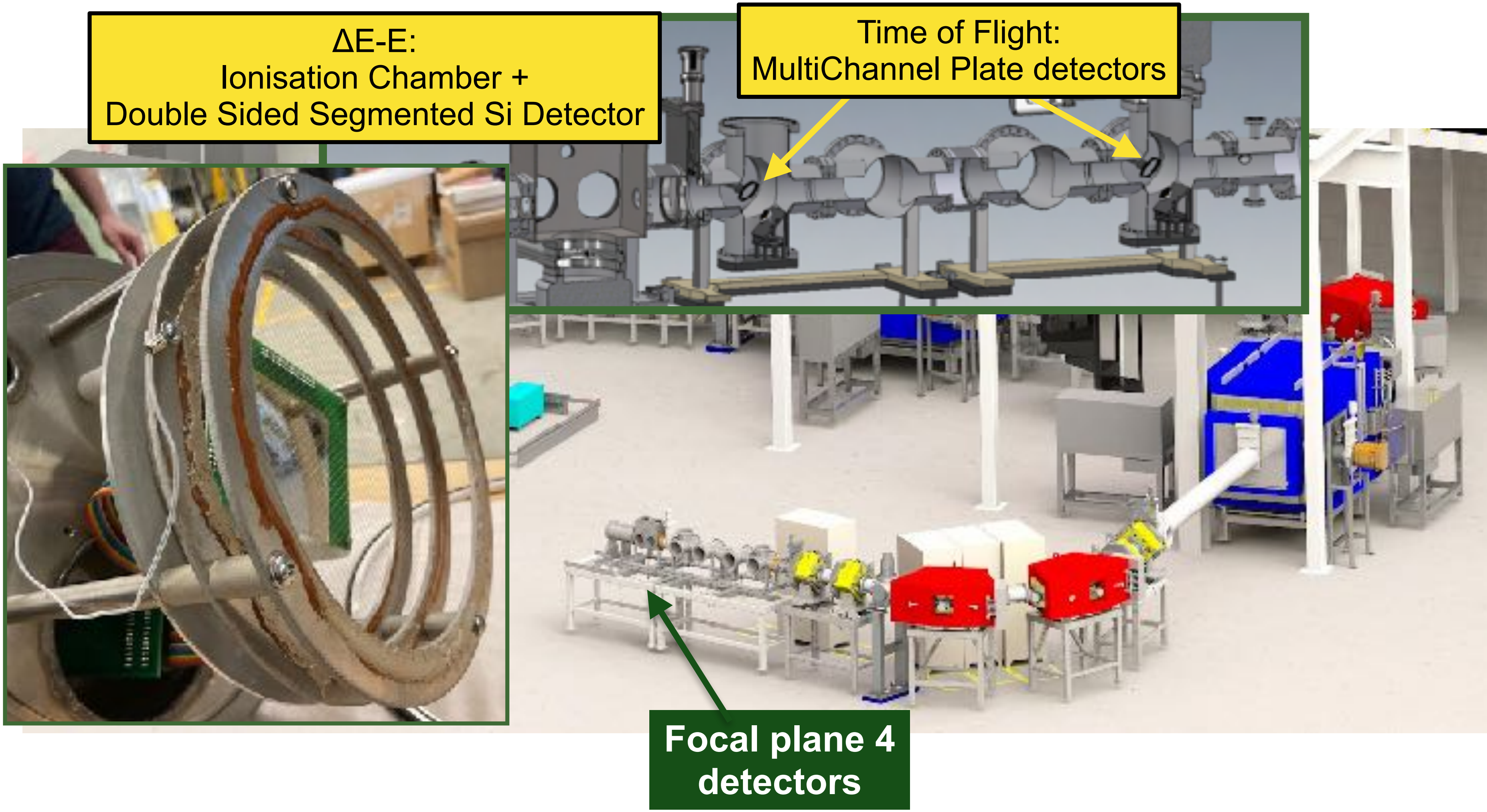






SECAR recoil detection

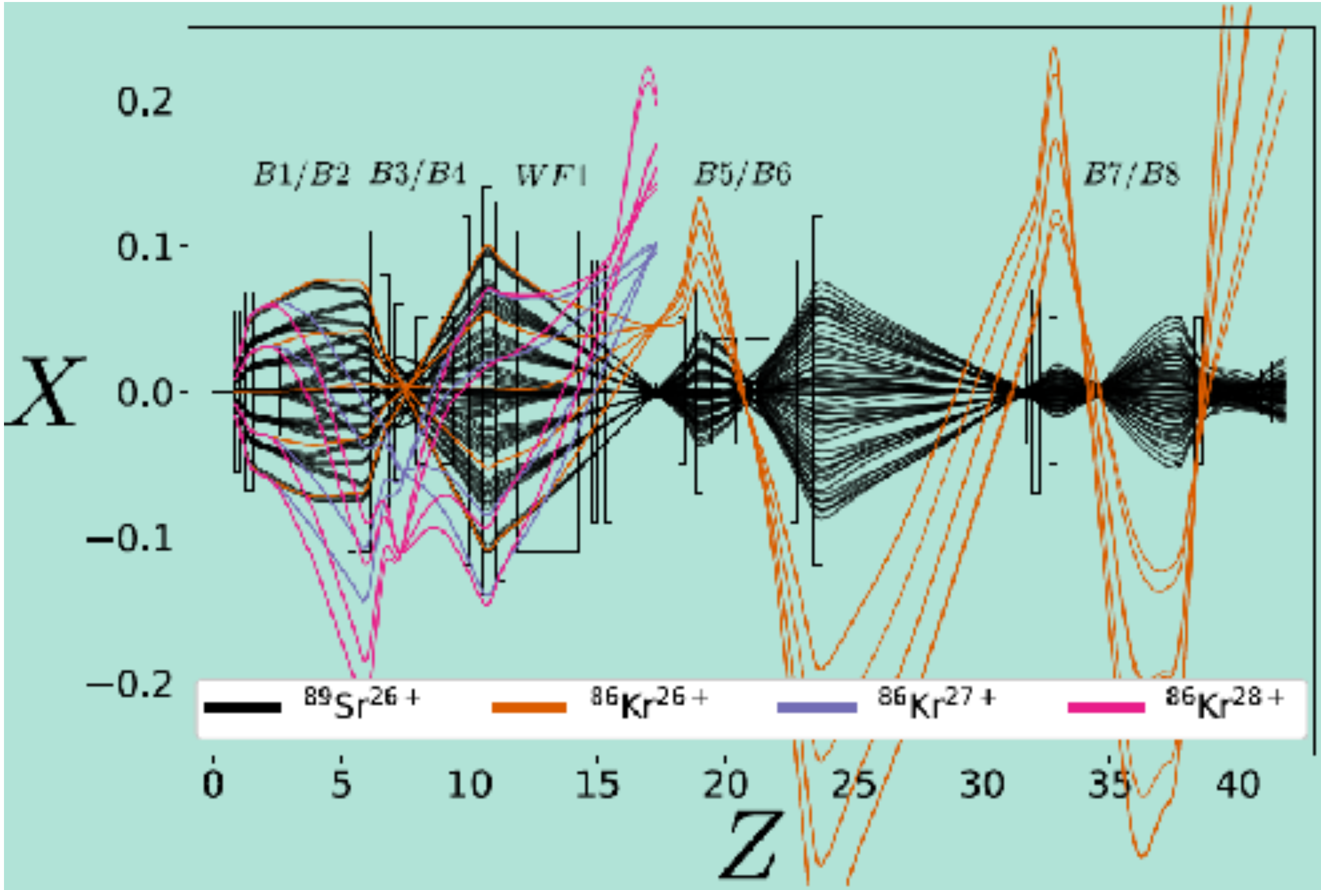
SECAR
SEparator for CApture Reactions

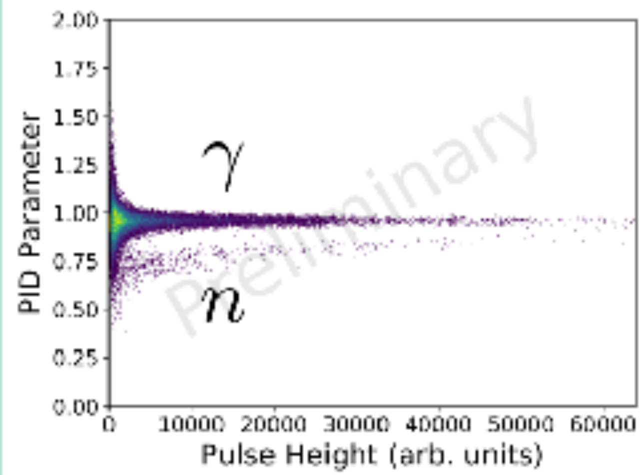


First science experiments with SECAR

SECAR — SEparator for CApture Reactions

- SECAR has performed (α,n) and (p,n) science experiments
- Measurement of ^{86}Kr(α,1n) and (α,2n) channels by tuning SECAR on ^{89}Sr and ^{88}Sr recoils
- Use of neutron detector to provide additional gate on (α,n) channel



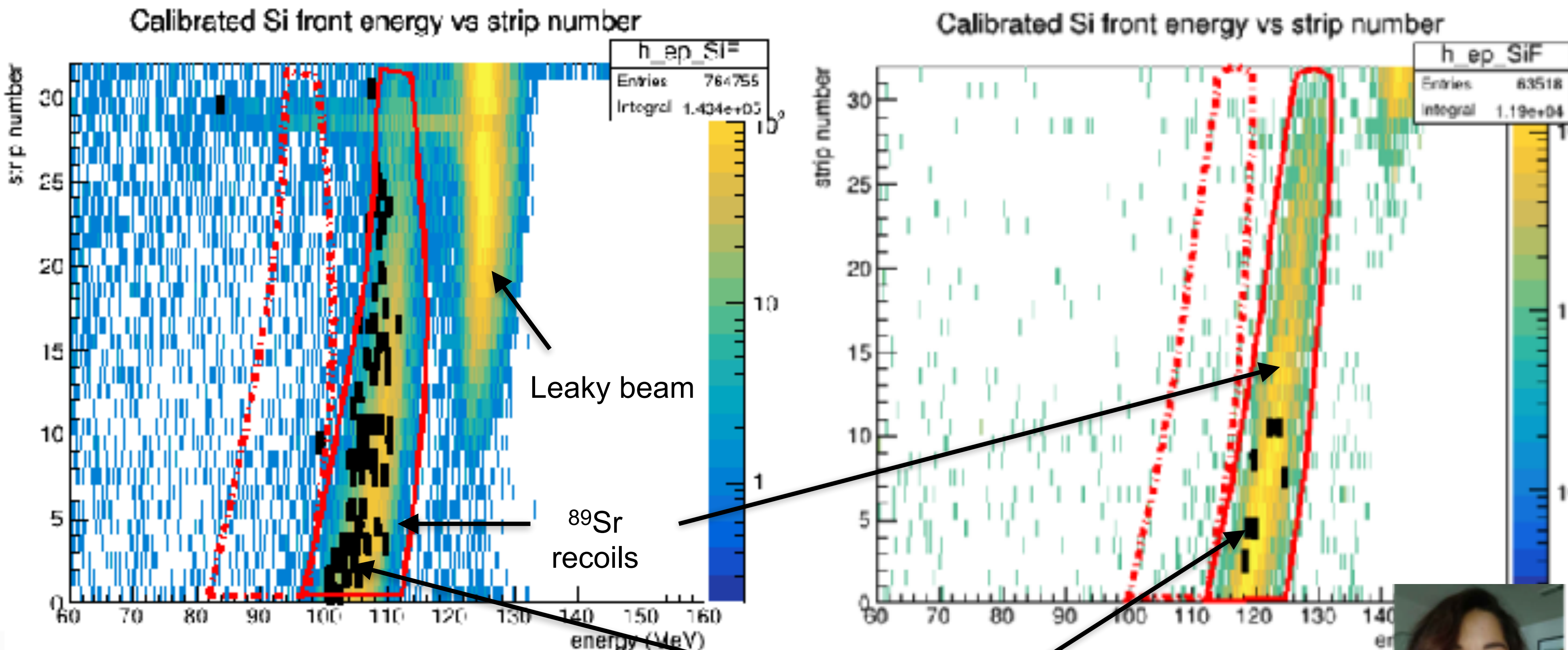


- Pulse shape discrimination to identify neutrons

Weak r-process Experiments with SECAR

SECAR
SEparator for CApture Reactions

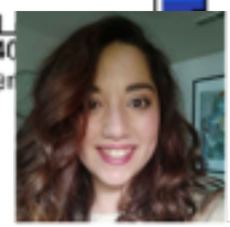
^{86}Kr(α,n)^{89}Sr Recoils reaching final SECAR focal plane Si DSSD



^{89}Sr recoils in coincidence with neutron detection

2.75 MeV/u

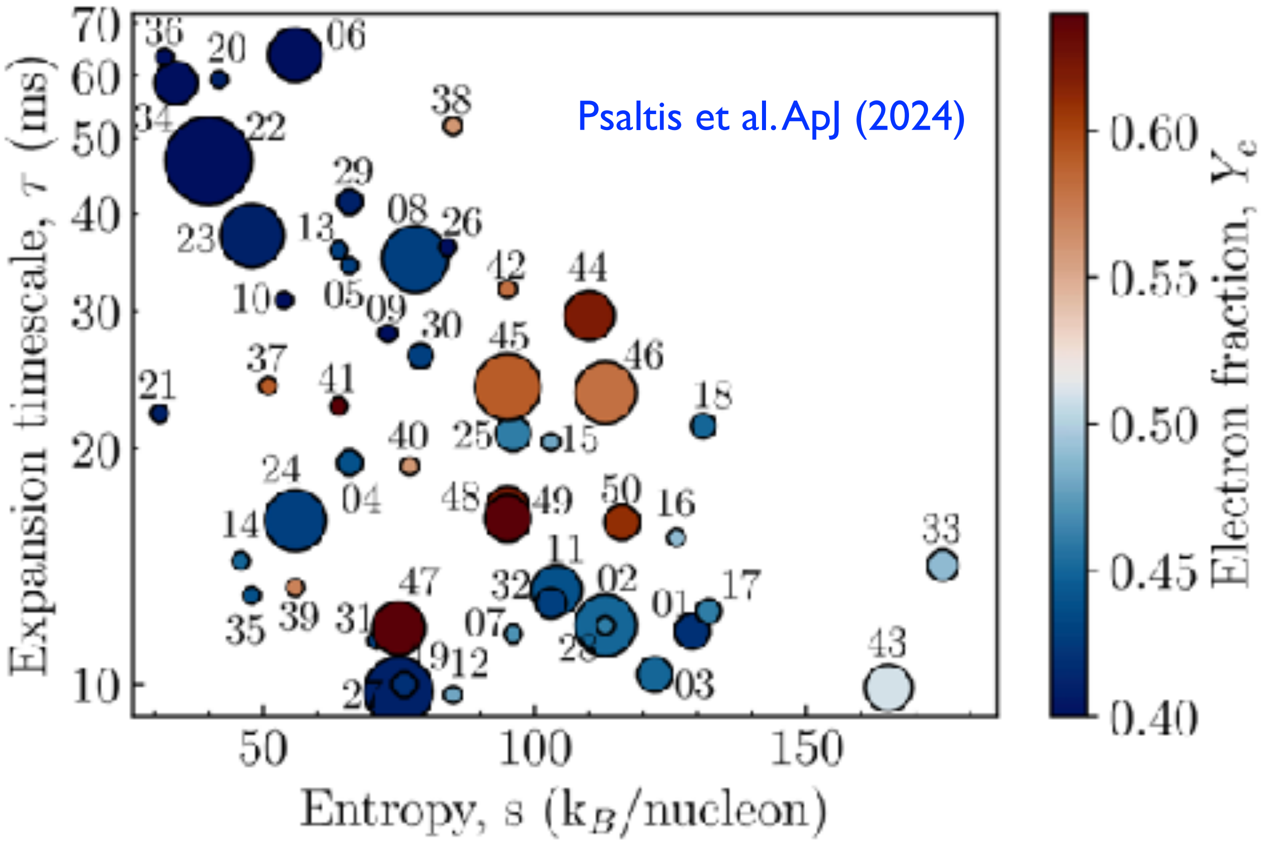
3 MeV/u



P. Tsintari (PD)

Experiments with SECAR: proton-rich side

SECAR
SEparator for CApture Reactions

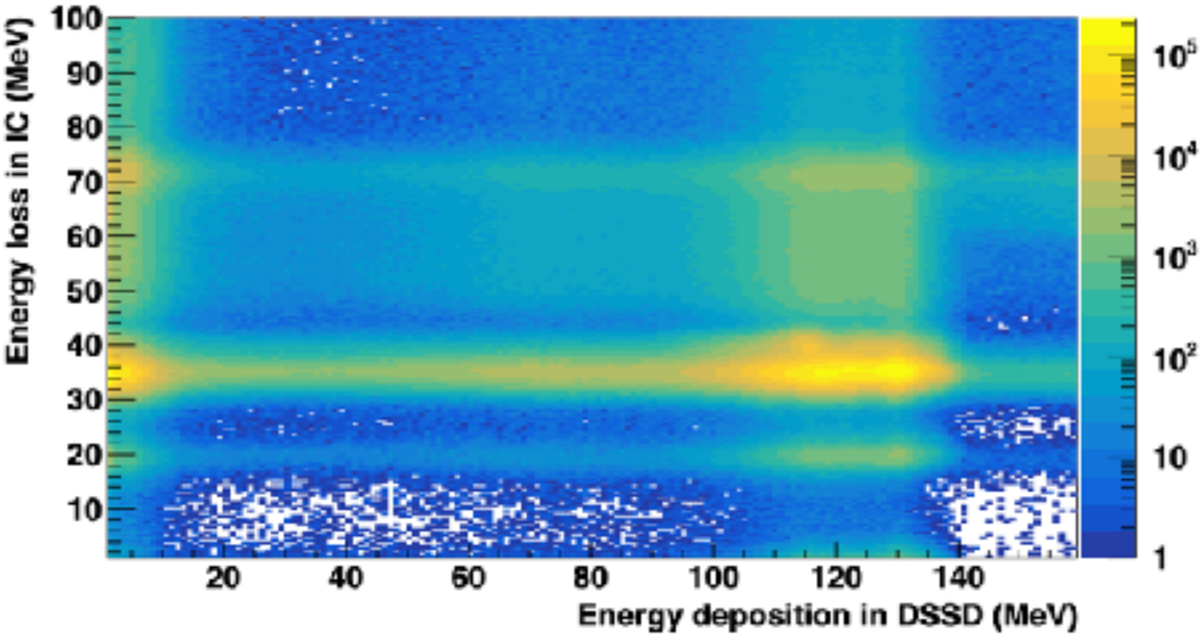


- Type-II core collapse supernova with slightly proton rich conditions νp-process
- Sequence of (n,p) and (p,γ) reactions drive the nucleosynthesis of heavier elements

Experiments with SECAR: proton-rich side

SECAR
SEparator for CApture Reactions

- Measurement of known cross section $^{58}Fe(p,n)^{58}Co$ reaction aims to pave the path for direct (p,n) measurements with SECAR
- Challenging optics since ^{58}Fe and ^{58}Co have almost identical mass



- All particles reaching detectors at the end of SECAR
- Only ~10-500 are actually ^{58}Co

Tsintari et al. PRR (2025)

Experiments with SECAR: proton-rich side

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SEparator for CApture Reactions

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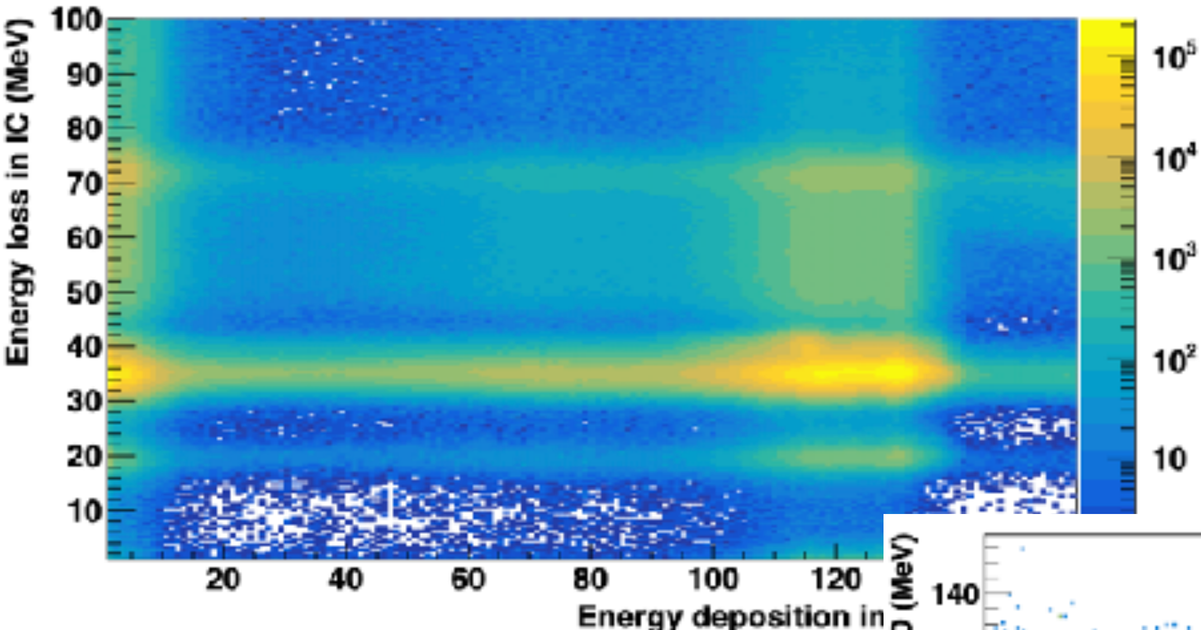
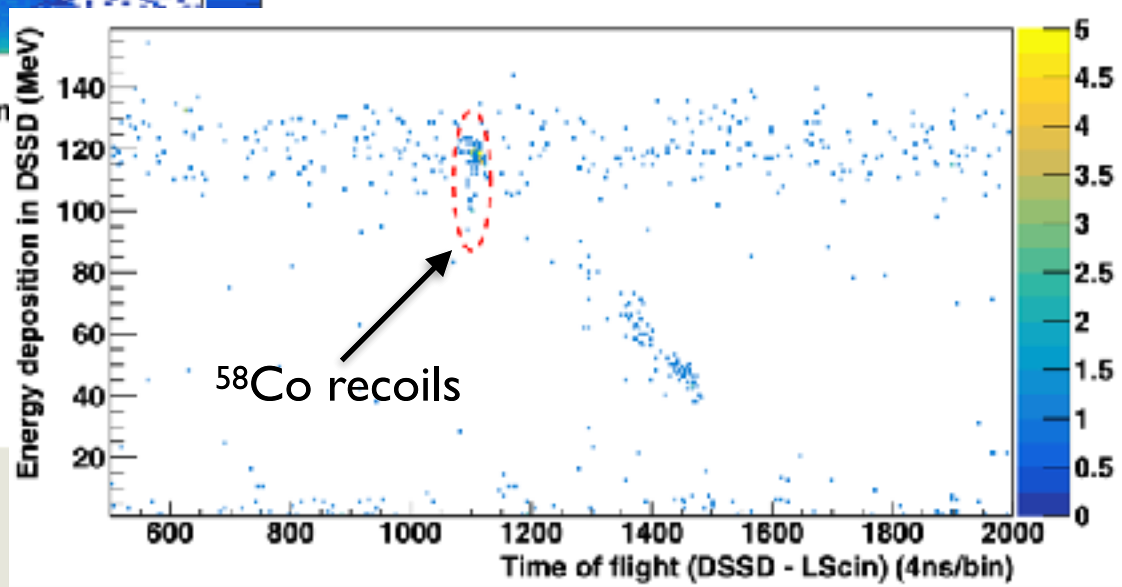


All particles reaching detectors at the end of SECAR
AND
with a valid neutron detector signal

Tsintari et al. PRR (2025)



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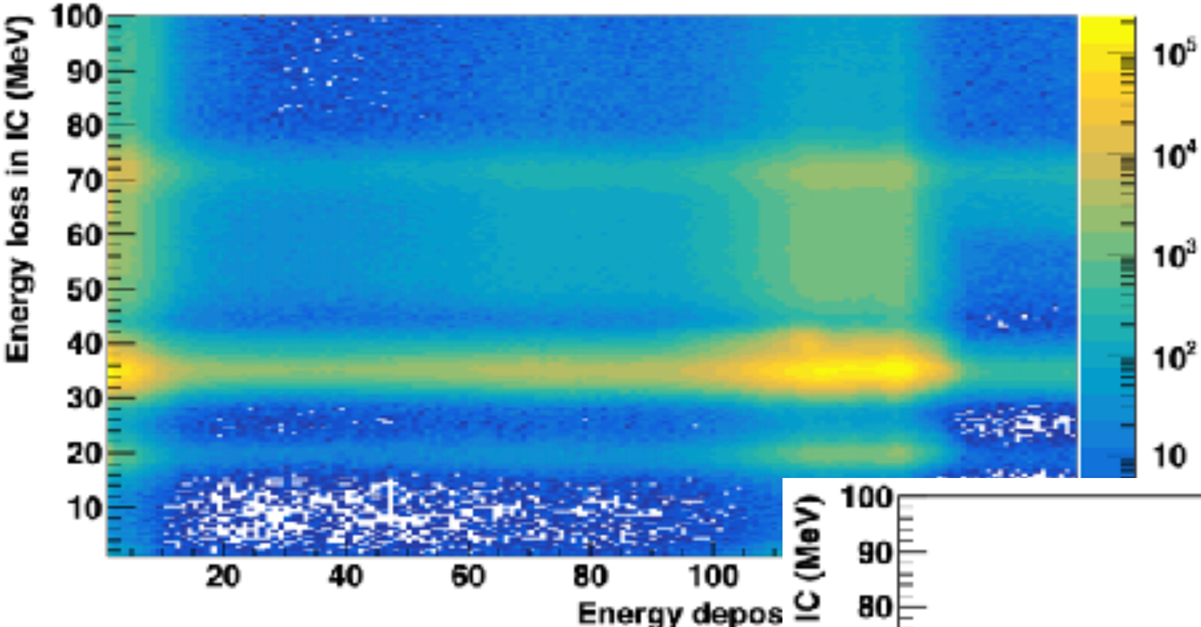
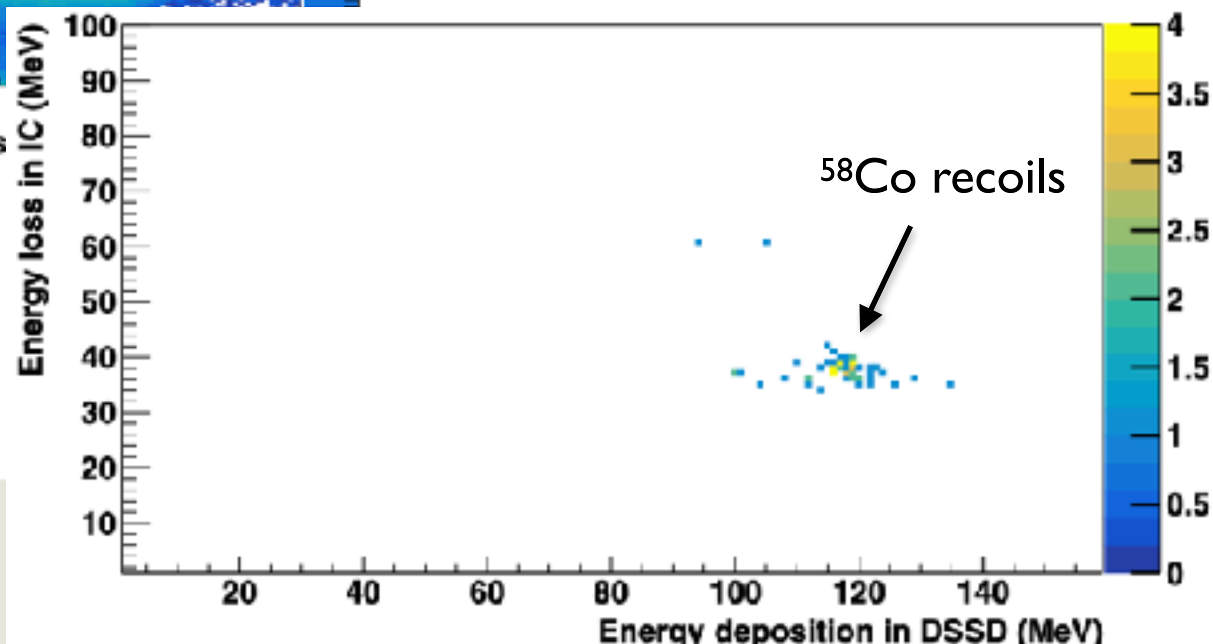


All particles reaching detectors at the end of SECAR
AND
with a valid neutron detector signal
AND
within correct time of flight



Tsintari et al. PRR (2025)

Experiments with SECAR: proton-rich side

SECAR
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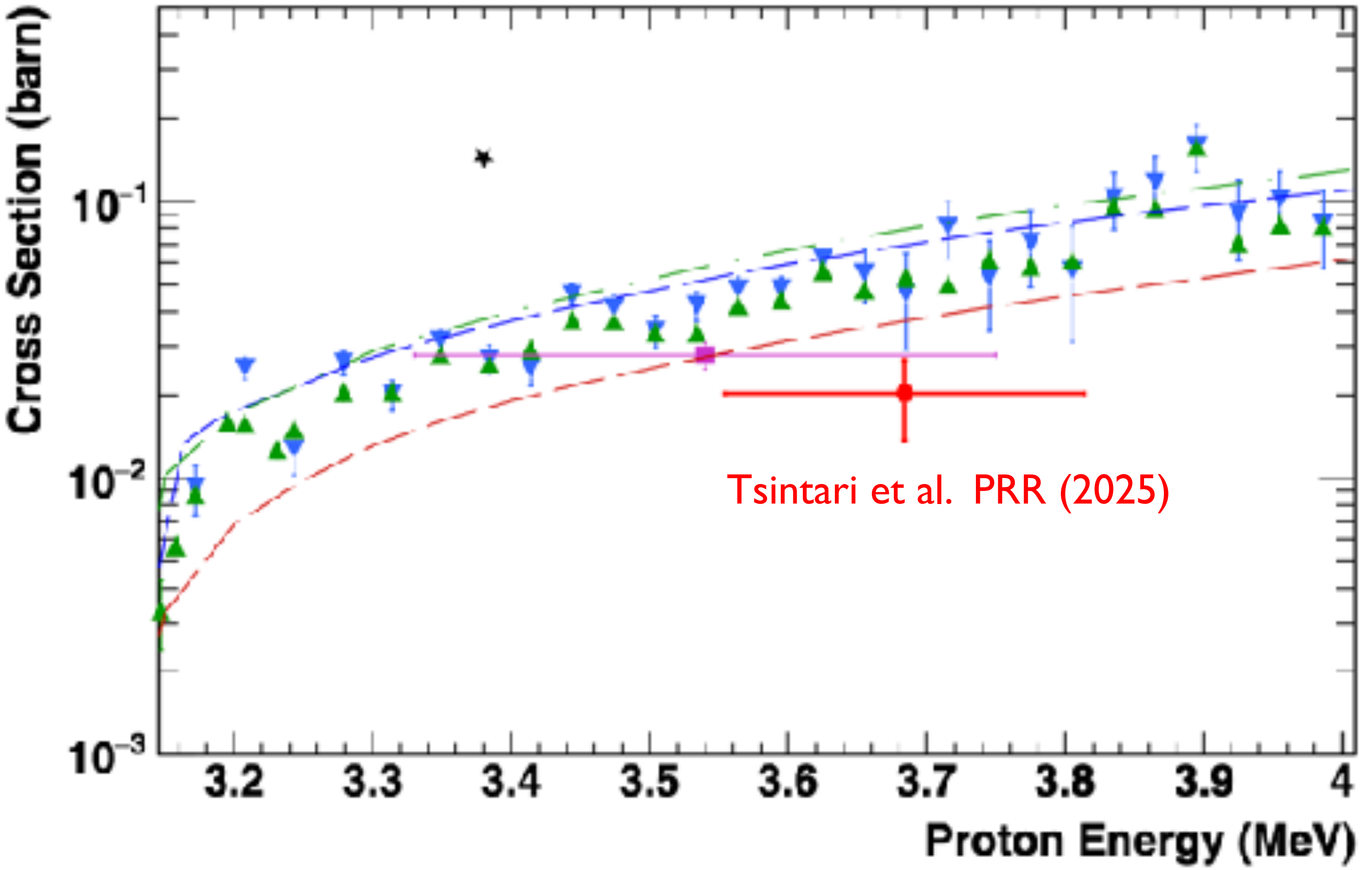

SECAR opens up unique opportunities for ion-optical setups to perform direct low-energy (p, n) reaction measurements on insights into relevant astrophysical processes like the νp-process and explosive silicon burning

Summary

- Strong evidence that multiple sites are contributing to the origin of the "light r-process" elements – need to understand interplay in the era of NS merger observations
- We need reliable nuclear physics to determine the element-by-element contribution from each possible site
  - For weak r-process scenarios: need seed production reactions such as (α,n) bottle neck reaction rates
- Recent observational and experimental progress have advanced the field enormously in the last 5 years.
- Due to large number of experimental endeavors possible within next 10 years, it is is feasible all relevant weak r-process nuclear physics uncertainties may be resolved
- SECAR has been completed and it is ready for experiments (several waiting for beam time). Capabilities demonstrated for radiative capture reactions as well as new applications; (α,n) and (p,n) reactions.
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