Nuclear Astrophysics Opportunities with Recoil Separators

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Triangle Universities Nuclear Laboratory
Duke University

TRIUMF Science Week
Vancouver, BC
29.07.2025

Cassiopeia A

Image credit: JWST

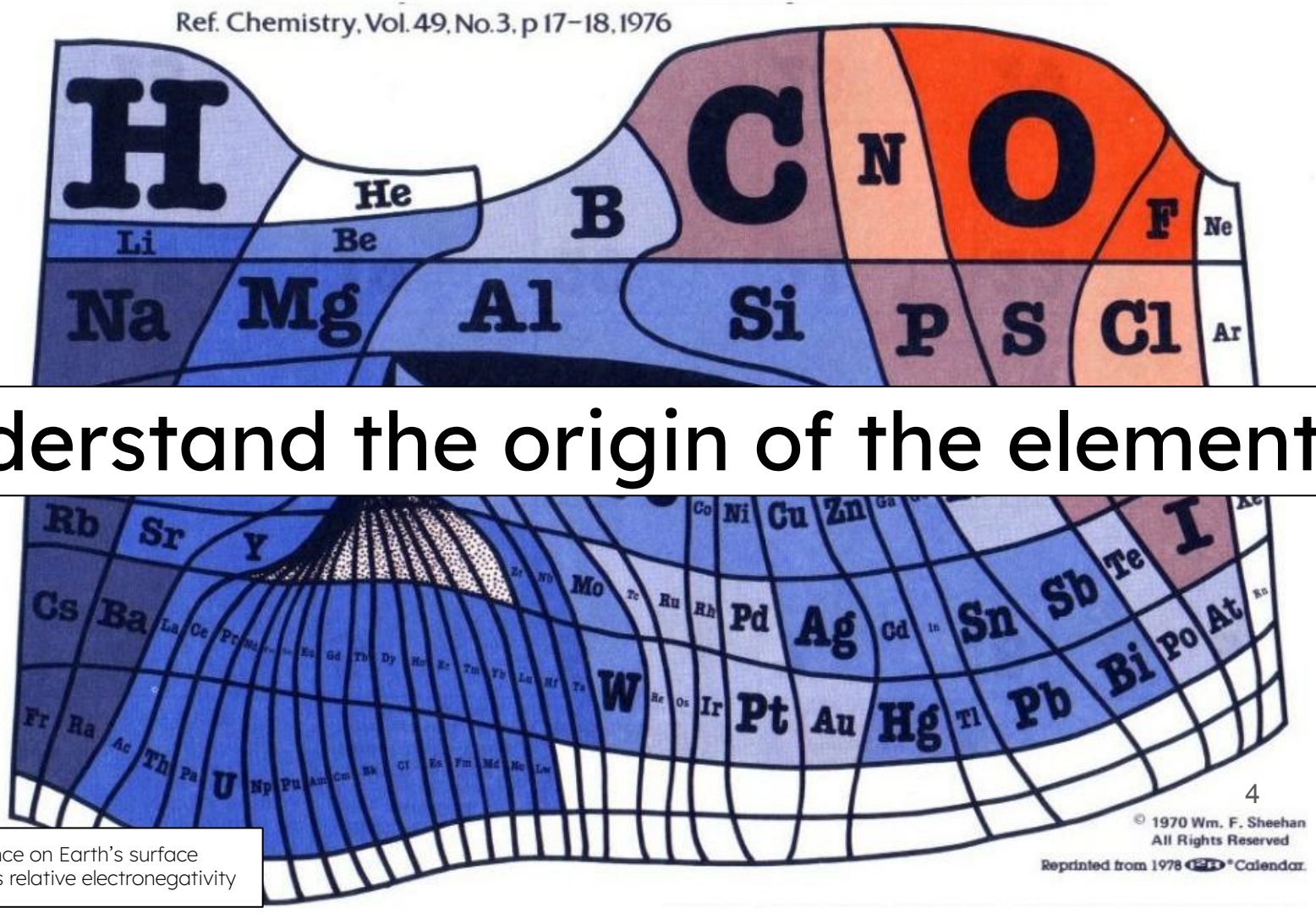
What's Coming Up?

1. Nuclear reactions in stars
2. Recoil separators around the world

   DRAGON and EMMA at TRIUMF, SECAR at FRIB

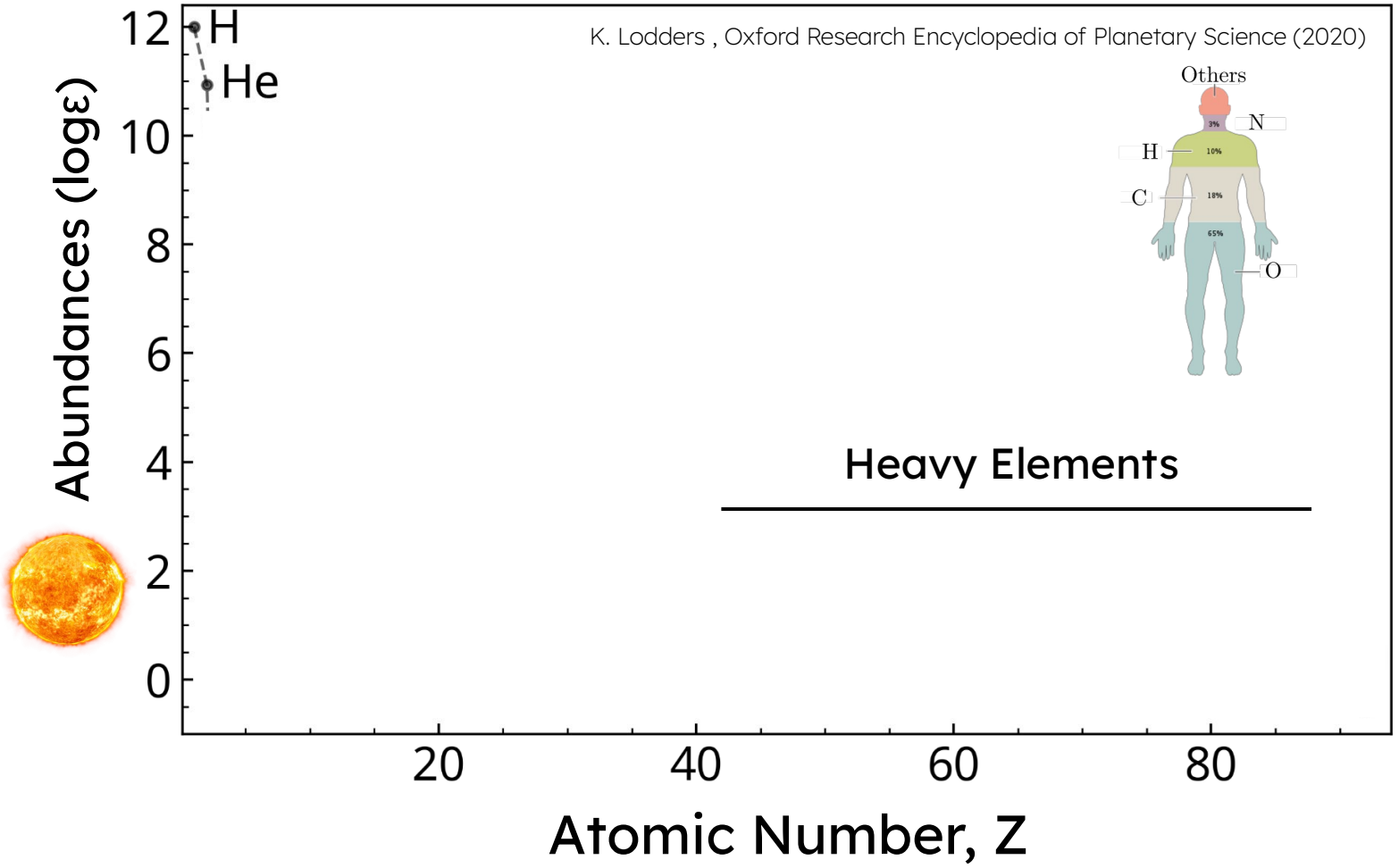
   ESR at FAIR GSI
3. Summary and outlook

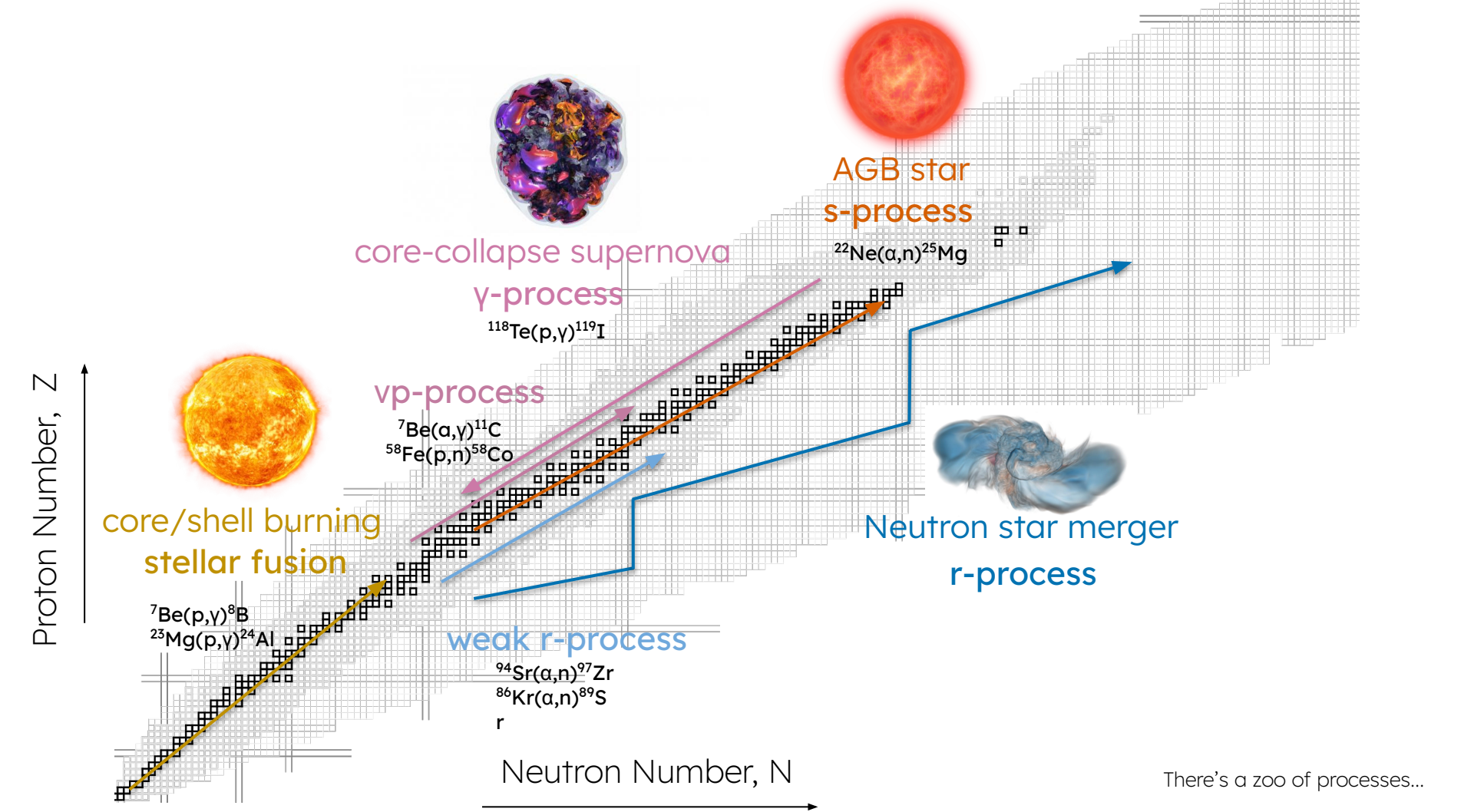
Video credit: NASA/Solar Dynamics Observatory (SDO), AIA 304 Å



Understand the origin of the elements

Relative abundance on Earth's surface
Colour represents relative electronegativity


K. Lodders , Oxford Research Encyclopedia of Planetary Science (2020)
Abundances (logε)
12
10
8
6
4
2
0
H
He
20
40
60
80
Atomic Number, Z
Heavy Elements
Others
N
H
C
O
3%
10%
18%
65%

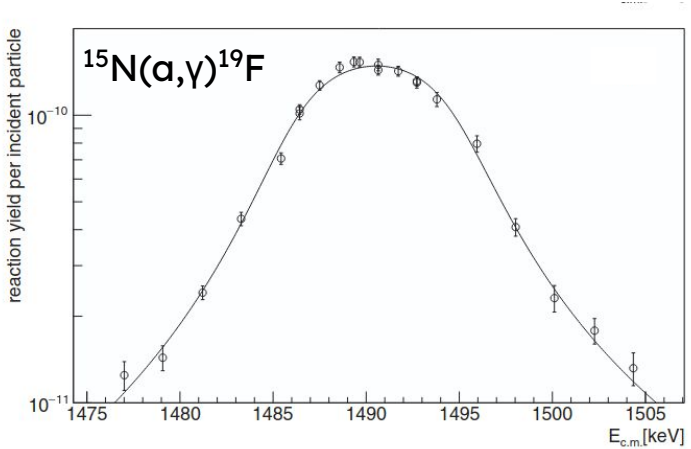


There's a zoo of processes...

observed abundances = astrophysical conditions + nuclear physics

From nuclear reactions to abundances

Bring the stars in the lab



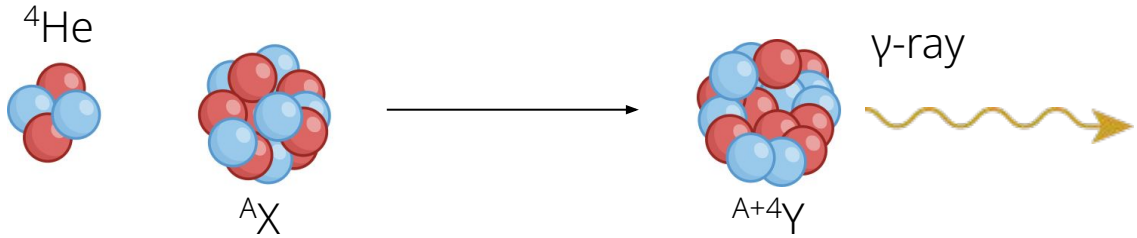
A. DiLeva *et al.*, Phys. Rev. C **95**, 045803 (2017)

$$\langle \sigma v \rangle \sim T_9^{-3/2} \sum_i (\omega\gamma)_i e^{-11.605 E_i / T_9}$$

Reaction Rate

Resonance strength

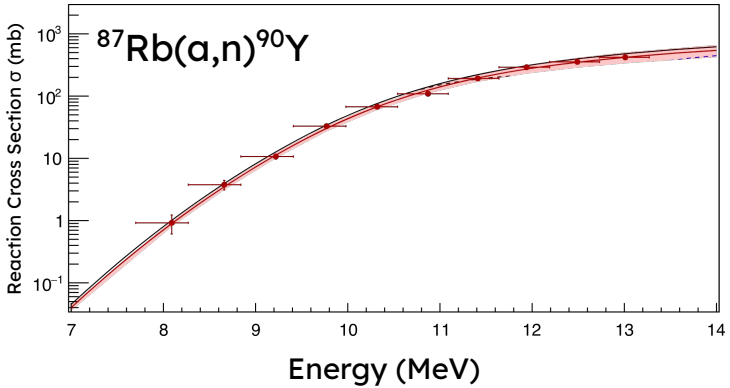
Resonance energy



Detect charged-particles and (or) radiation in the lab

From nuclear reactions to abundances

Bring the stars in the lab



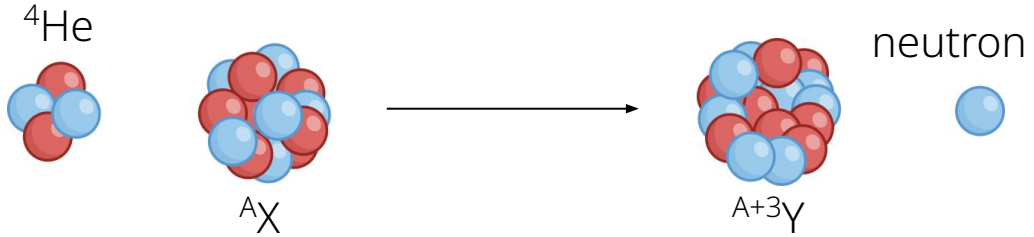
C. Fougères *et al.*, Astrophys. J **983,** 142 (2025)

$$\langle \sigma v \rangle \sim \int_0^\infty E\sigma(E) exp\left(-\frac{E}{kT}\right) dE$$

Reaction Rate

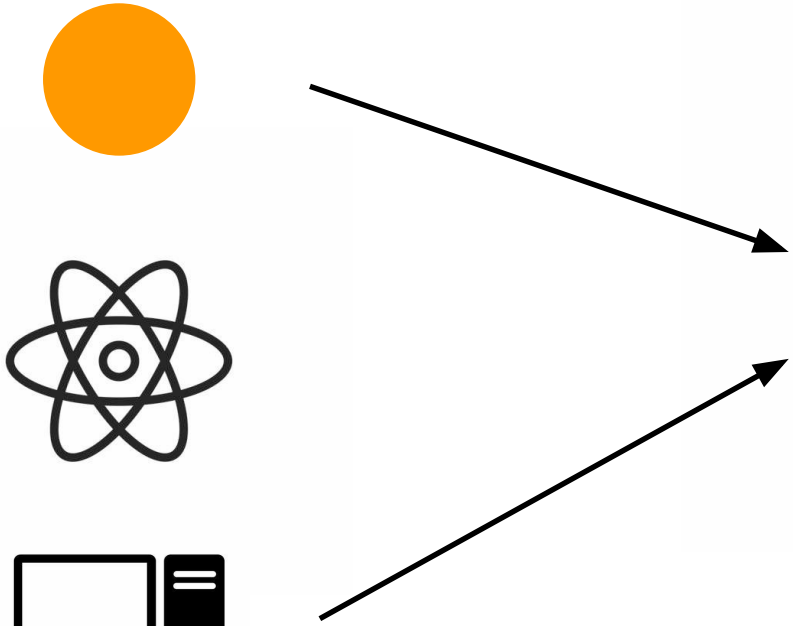
Reaction cross section

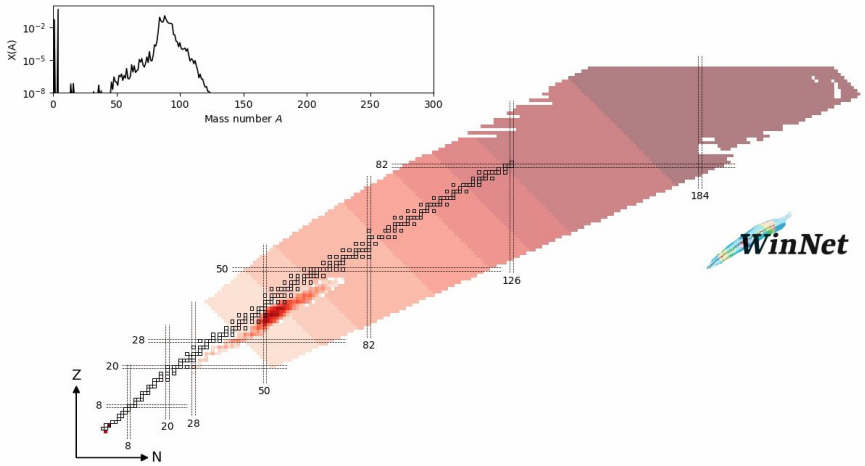
Maxwell-Boltzmann distribution



Detect charged-particles and (or) radiation in the lab

Putting everything together: nuclear reaction networks

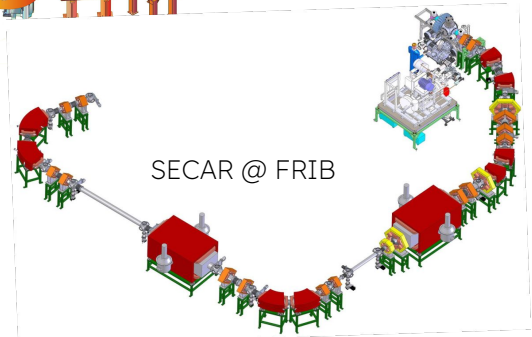


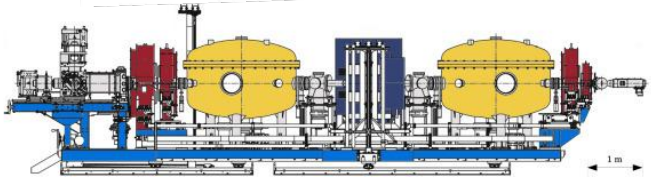


Example of a weak r-process calculation using WinNet
https://github.com/nuc-astro/WinNet

Recoil separators: a versatile experimental setup

- Inverse kinematics (suitable for short-lived isotopes) obtain E_r and ωγ with a single measurement
- Detection of both heavy recoil and light ejectiles
- Controlled systematic uncertainties (simulations)





EMMA @ TRIUMF

C. Ruiz, U. Greife and U. Hager, Eur. Phys. J. A **50**, 99 (2014)
C.R. Brune and B. Davids, Annu. Rev. Nucl. Part. Sci. **65**, 87 (2015)
C. Rolfs and C.A. Barnes, Annu. Rev. Nucl. Part. Sci. **40**, 45 (1990)

How to make a recoil separator

1. Target

   Gas (extended or jet) or solid

2. Electromagnetic separator

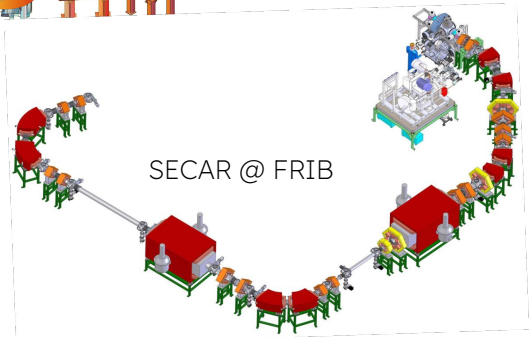
   For beam-like particle rejection
   (electric/magnetic dipoles, Wien filters, …)

3. Detection system

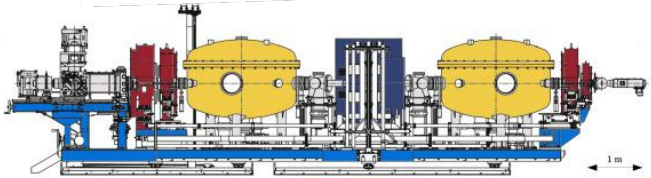
   charged particles, γ-rays, neutrons

DRAGON @ TRIUMF

ESR @ GSI/FAIR



SECAR @ FRIB



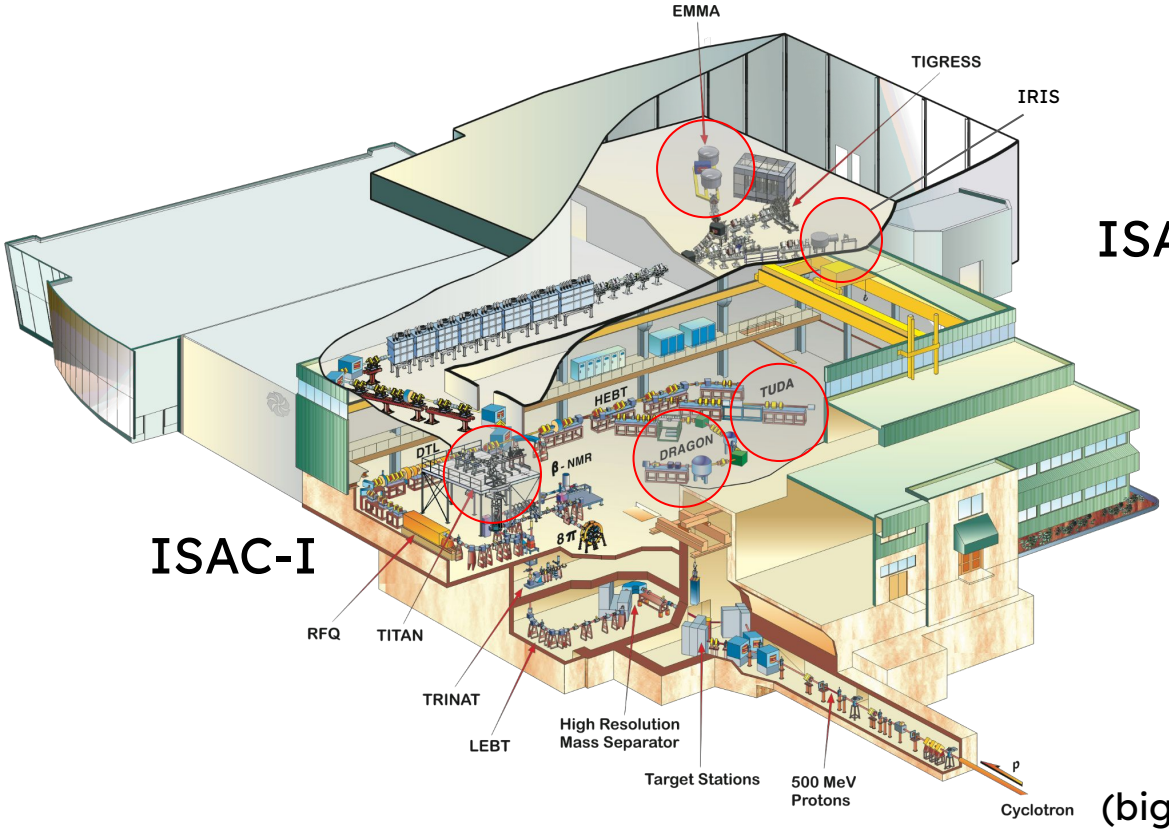
EMMA @ TRIUMF

C. Ruiz, U. Greife and U. Hager, Eur. Phys. J. A **50**, 99 (2014)

Many opportunities worldwide for nuclear astrophysics research!

Many opportunities worldwide for nuclear astrophysics research!

The nuclear astrophysics facilities at TRIUMF

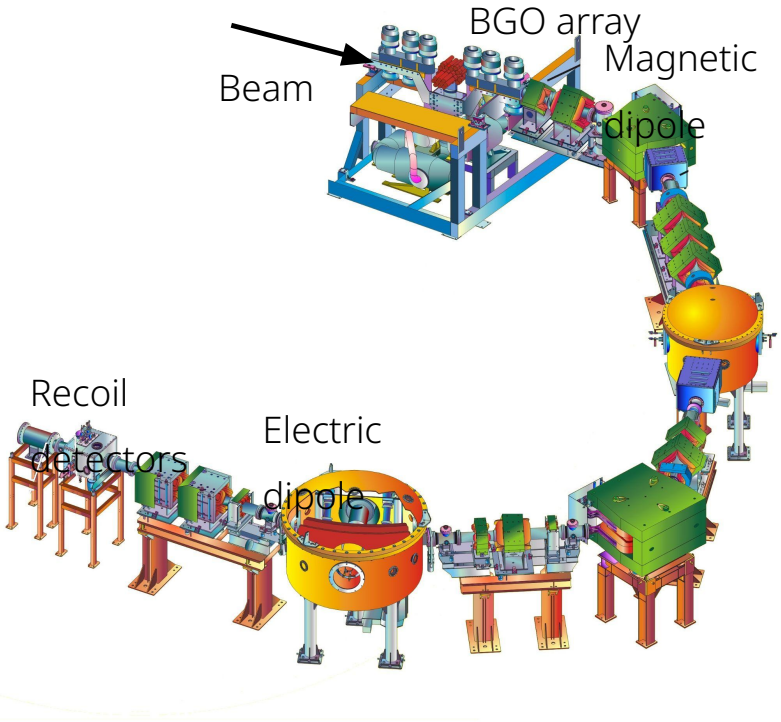


(biggest in the world!)

DRAGON at ISAC-I

Detector of Recoils and Gammas of Nuclear reactions

- Has measured 9 out of the 14 radiative captures using radioactive ion beams
- Beam rejection >10^{14} for (α,γ) <10^{13} for (p,γ)
- Modular detector configuration in the target and focal plane



D. Hutcheon *et al.*, Nucl. Instrum. Methods Phys. Res A **498**, 190 (2003)

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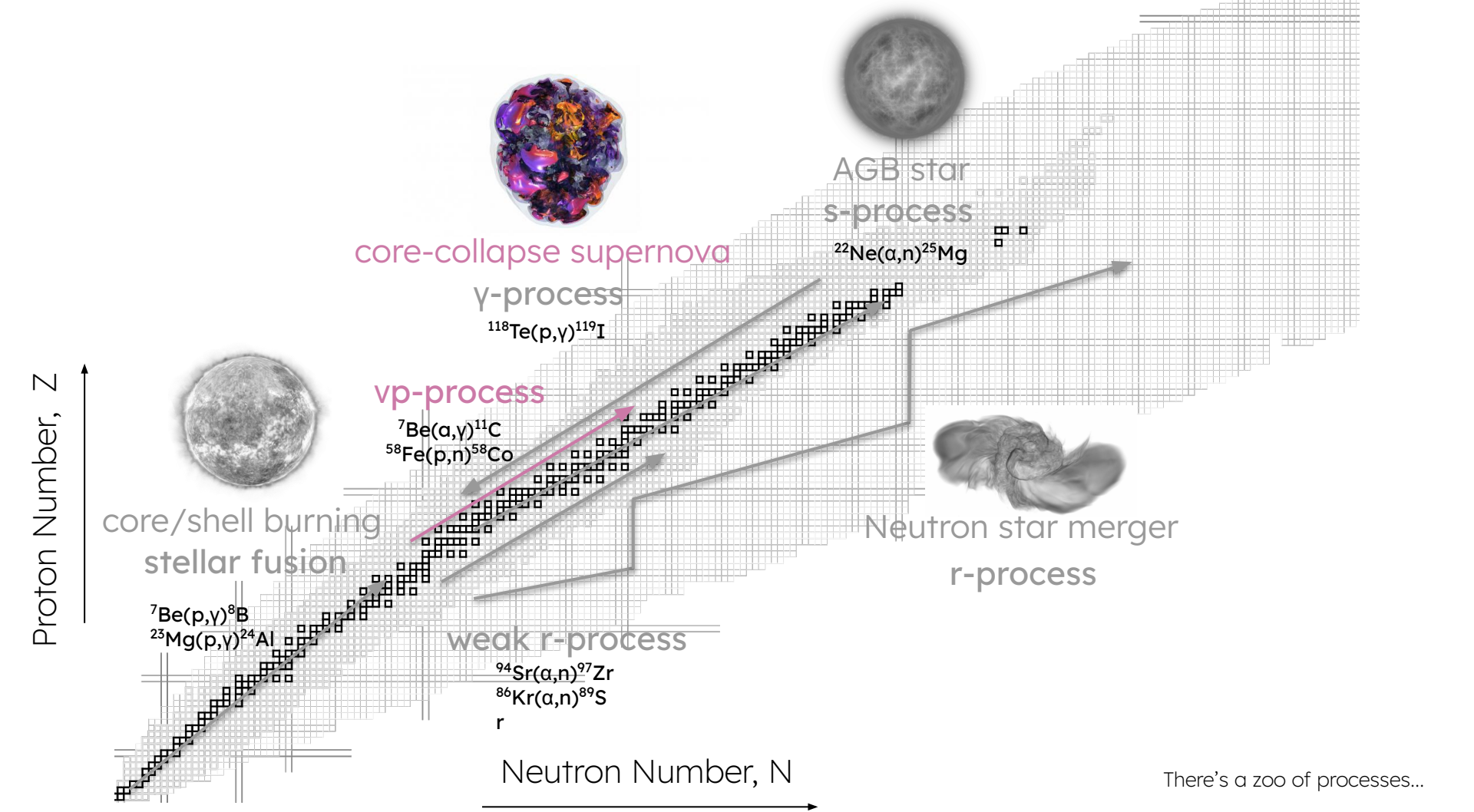
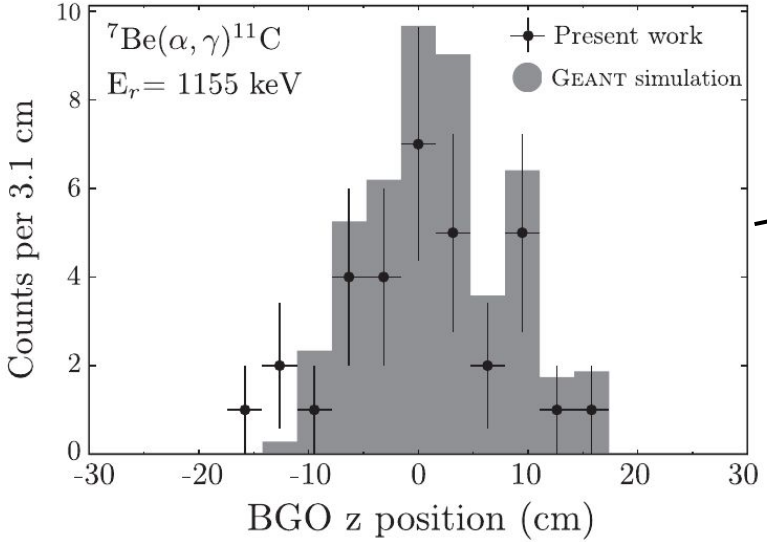
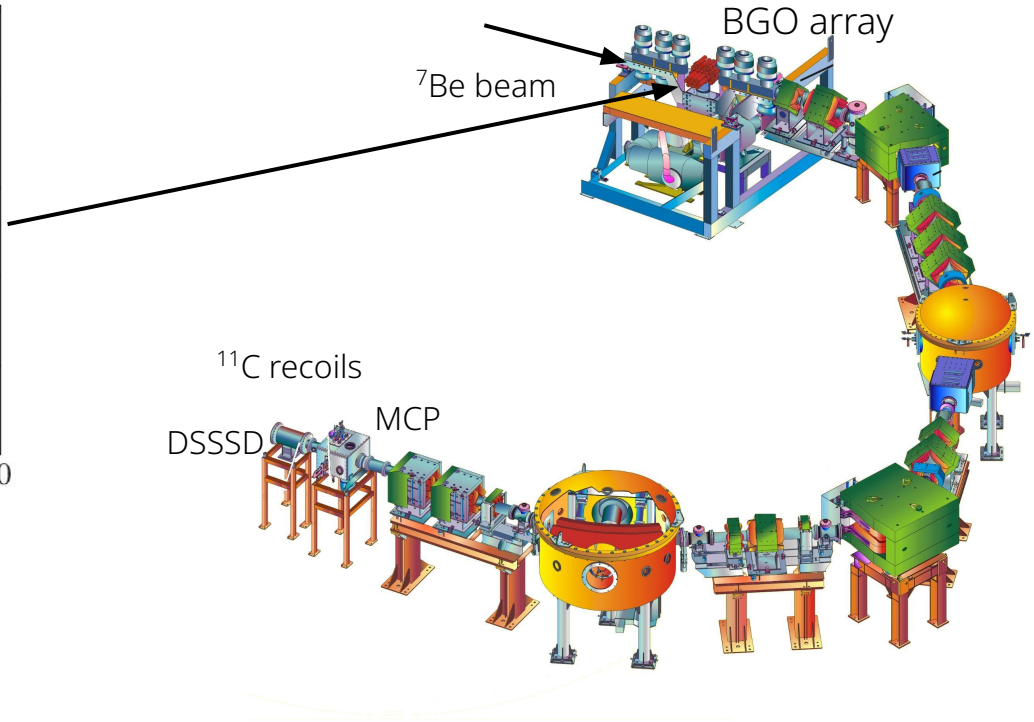


There's a zoo of processes...

^{7}Be + DRAGON = ❤️

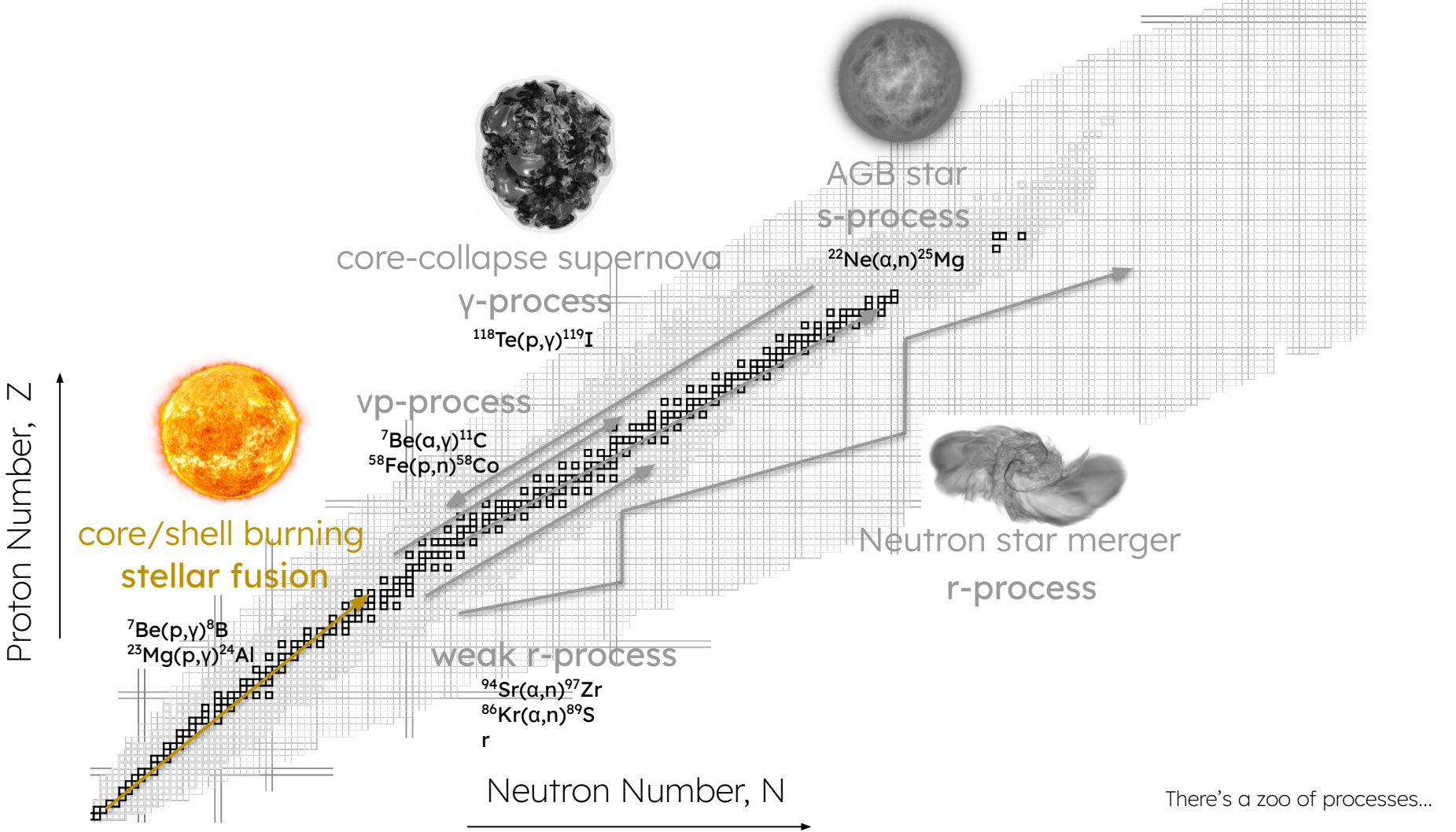


A. Psaltis *et al.*, Phys. Rev. Lett. **129**, 162701 (2022)
A. Psaltis *et al.*, Phys. Rev. C **106**, 045805 (2022)



^{7}Be(**α**,**γ**)^{11}C (S1692, Spokespersons: A. Psaltis, A.A. Chen and D. Connolly)

TRIUMF



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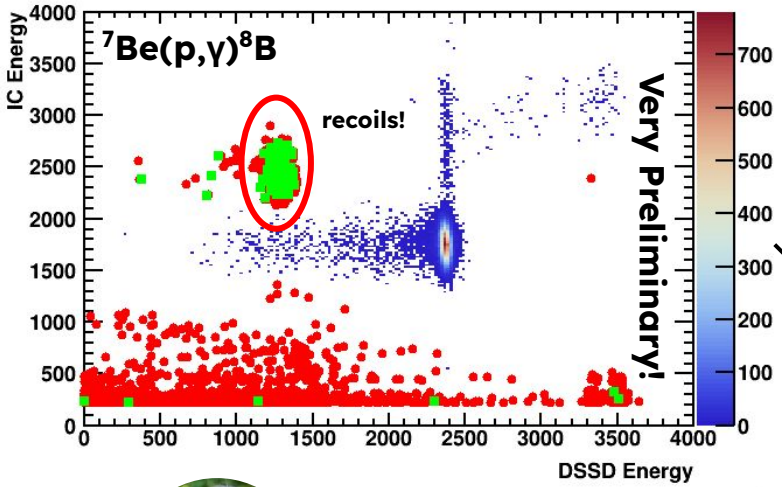
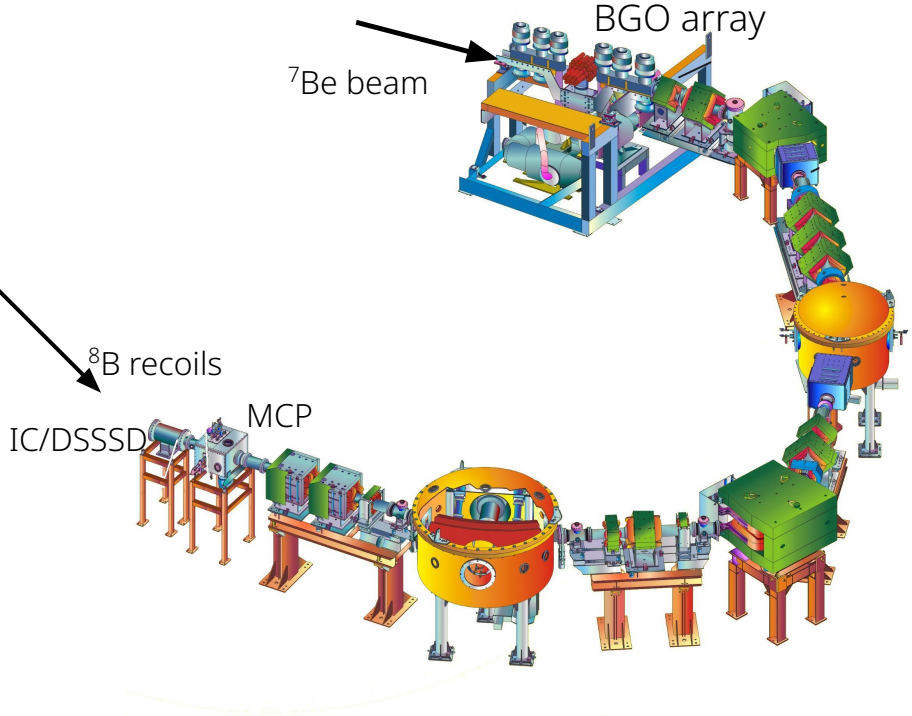


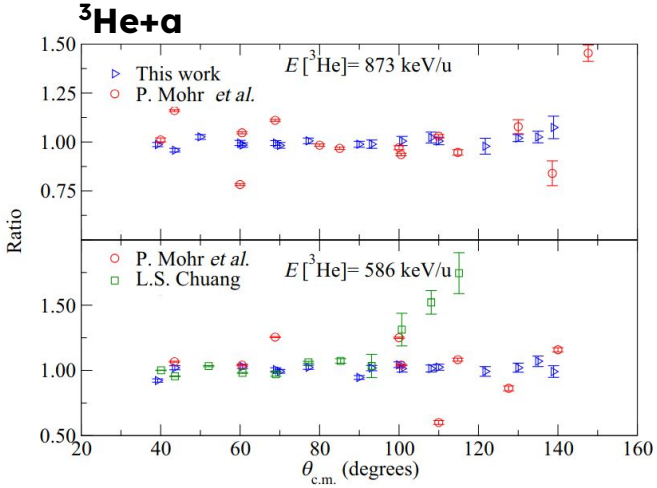
Mallory Loria
(UVic/TRIUMF graduate student)



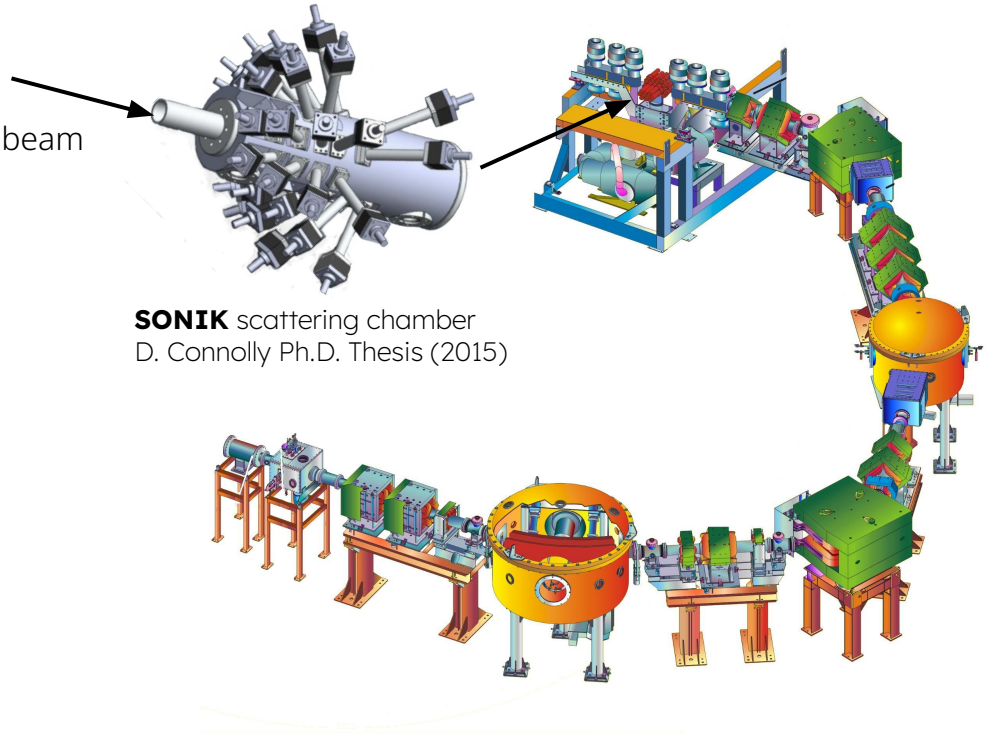
^{7}Be(p,γ)^{8}B (S2013, Spokespersons: M. Williams, B. Davids and U. Greife)

TRIUMF

^{7}Be + DRAGON = ❤️

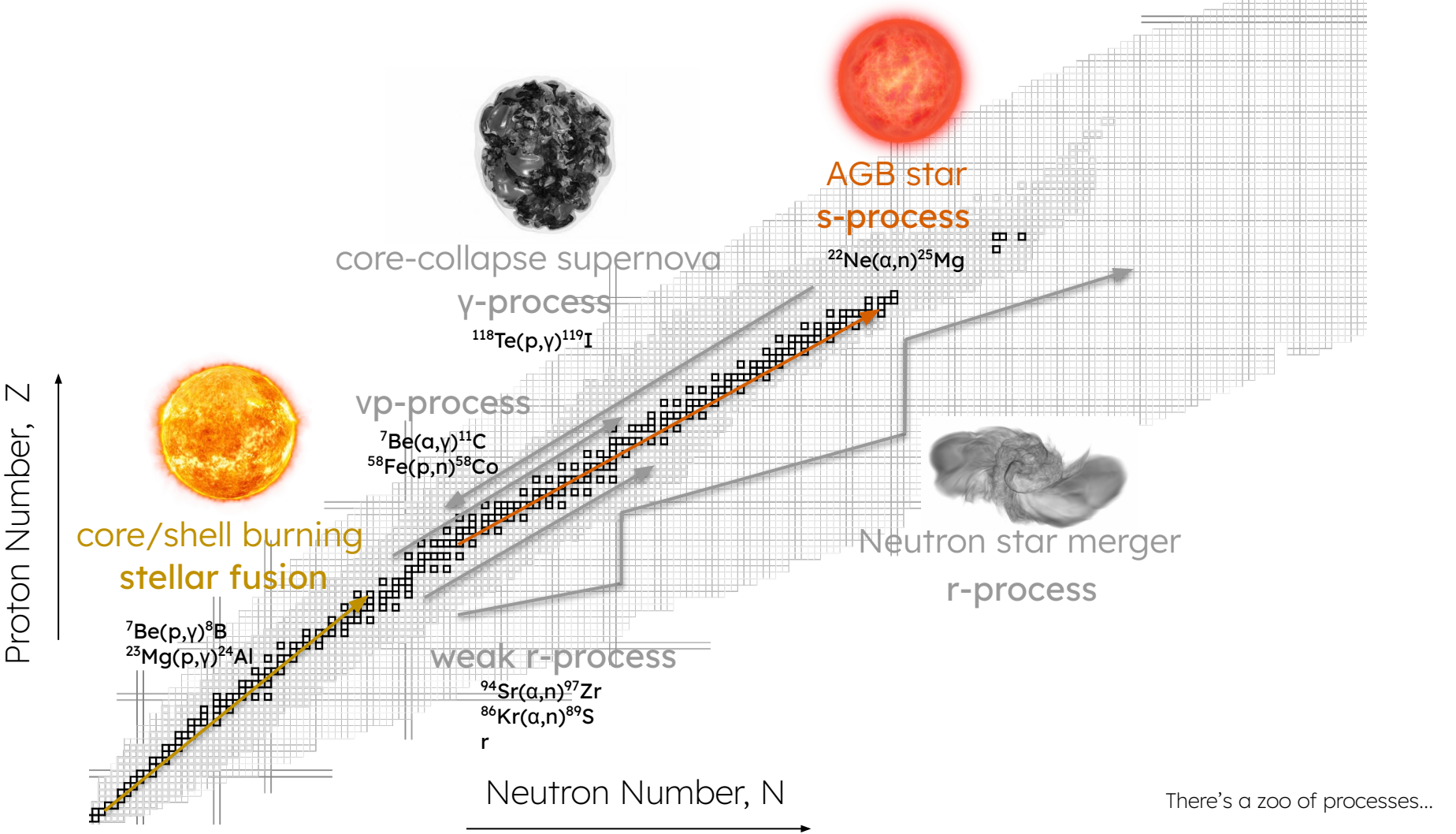


S.N. Paneru *et al.*, Phys. Rev. C **109**, 015802 (2024)



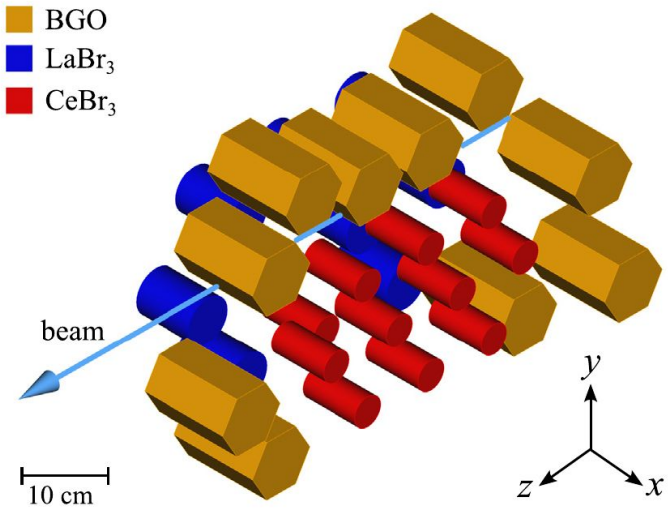
7Be+α (S2018, Spokespersons: R.J. deBoer and C. Ruiz)
7Be+p (S2034, Spokespersons: C. R. Brune and C. Ruiz)

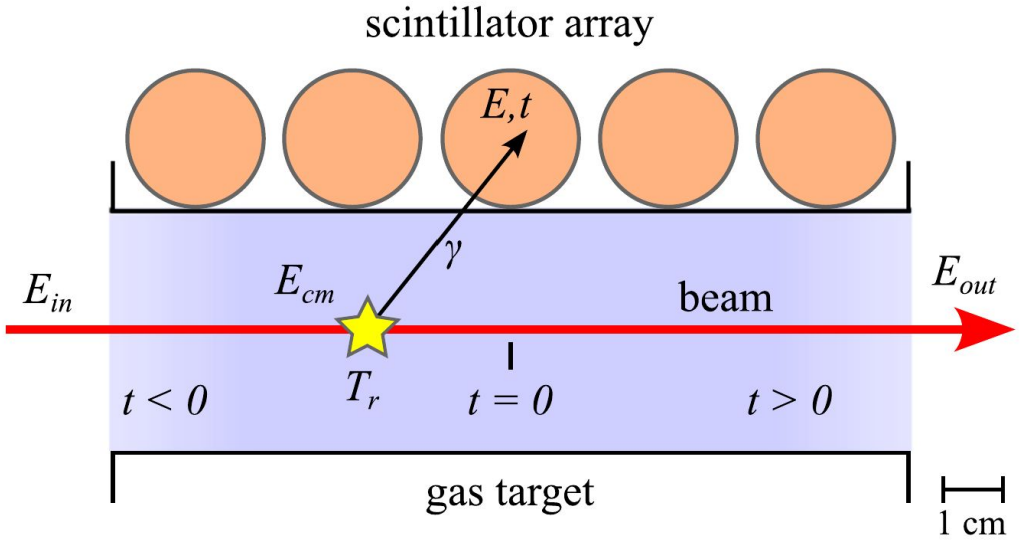
TRIUMF



There's a zoo of processes...

Resonance timing method at DRAGON



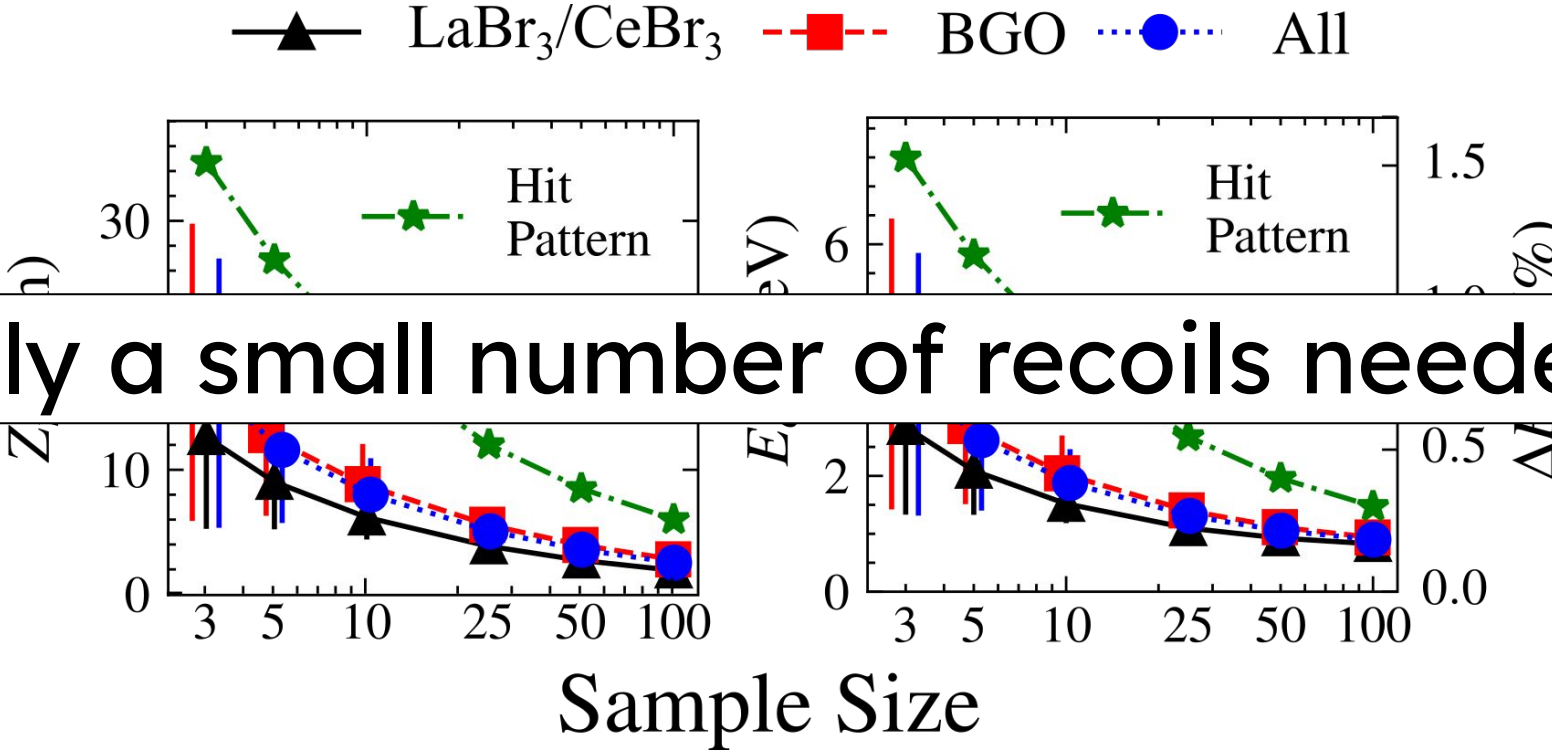


$$\langle \sigma v \rangle \sim T_9^{-3/2} \sum_i (\omega\gamma)_i e^{-11.605 E_i / T_9}$$

D.A. Hutcheon *et al.*, Nucl. Instrum. Methods Phys. Res A **689**, 70 (2012)
G. Christian et al., Eur. Phys. J. A **50**, 75 (2014)
G. Christian et al., Nucl. Instrum. Methods Phys. Res A **1072**, 170199 (2025)

TRIUMF

Resonance timing method at DRAGON

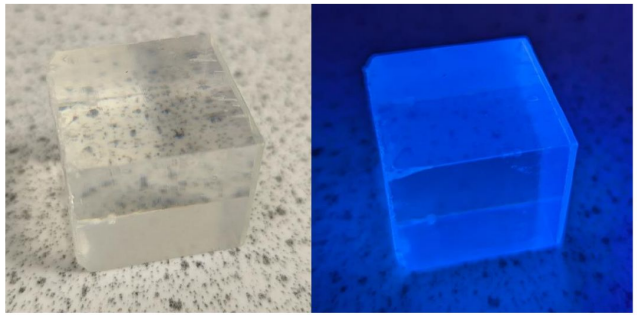


Only a small number of recoils needed!

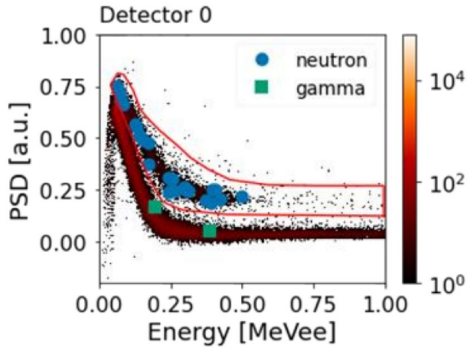
D.A. Hutcheon *et al.*, Nucl. Instrum. Methods Phys. Res A **689**, 70 (2012)
G. Christian *et al.*, Eur. Phys. J. A **50**, 75 (2014)
G. Christian *et al.*, Nucl. Instrum. Methods Phys. Res A **1072**, 170199 (2025)

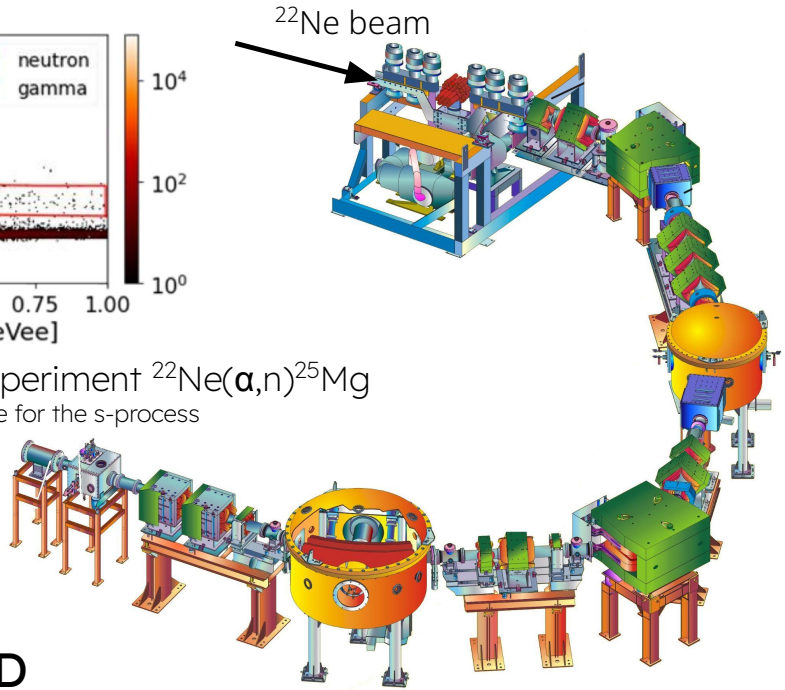
TRIUMF

Upgrade DRAGON to measure (α,n) reactions



Organic Glass Scintillator (OGS) produced by BlueShift Optics





Proof-of-principle experiment ^{22}Ne(α,n)^{25}Mg

neutron source for the s-process

Ben Reed
(SMU/TRIUMF postdoc)

DEMAND

Direct Experimental Measurements of Astrophysical reactions using Neutron Detectors

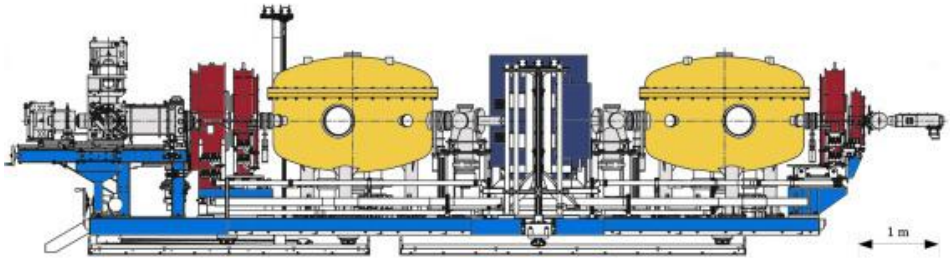
TRIUMF

EMMA at ISAC-II

ElectroMagnetic MAss Analyzer

- Solid Si:He targets for α-induced reactions (n ~ 10^{19} atoms/cm^2)
  Polyethylene $(CH_2)_n$ for (p,γ)

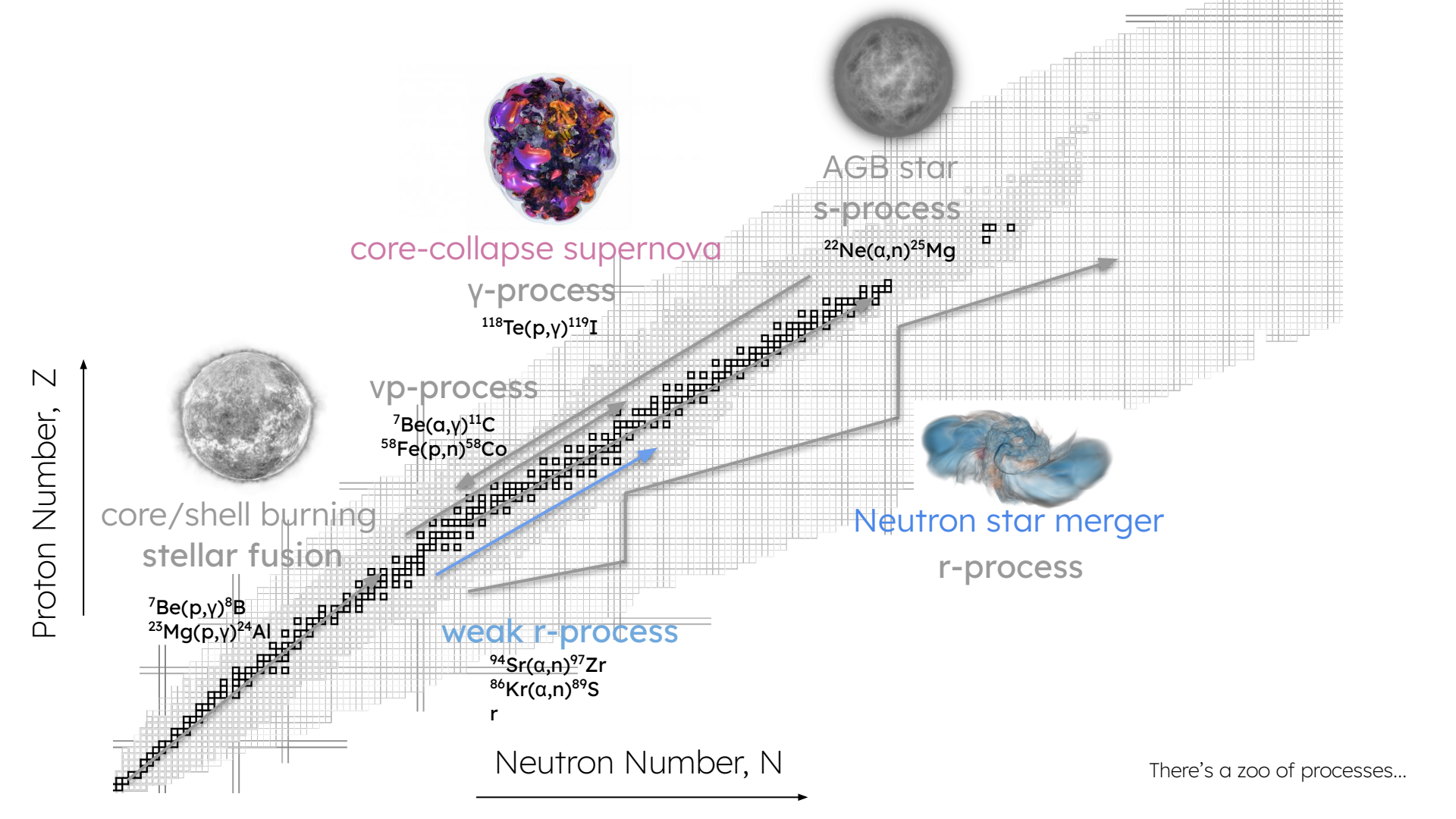
- γ-ray detection from TIGRESS
  12 clover detectors (HPGe)



- Coincidences with detection of heavy recoils at EMMA's focal plane (PGAC/ionization chamber/silicon detector)

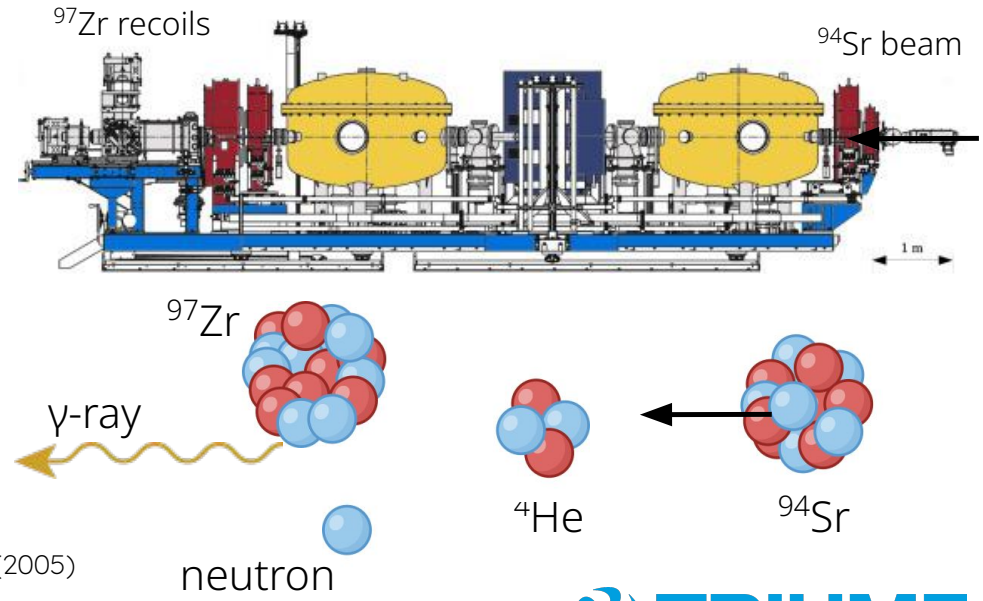
B. Davids & C.N. Davids, Nucl. Instrum. Methods Phys. Res. A **544**, 565 (2005)
B. Davids et al., Nucl. Instrum. Methods Phys. Res A **930**, 191 (2019)
C.E. Svensson *et al.*, J. Phys. G **31**, S1663 (2005)
V. Godinho *et al.*, ACS Omega **1**, 1229 (2016)

TRIUMF



There's a zoo of processes...

First direct weak r-process measurement using a radioactive ion beam



C.E. Svensson *et al.*, J. Phys. G **31**, S1663 (2005)
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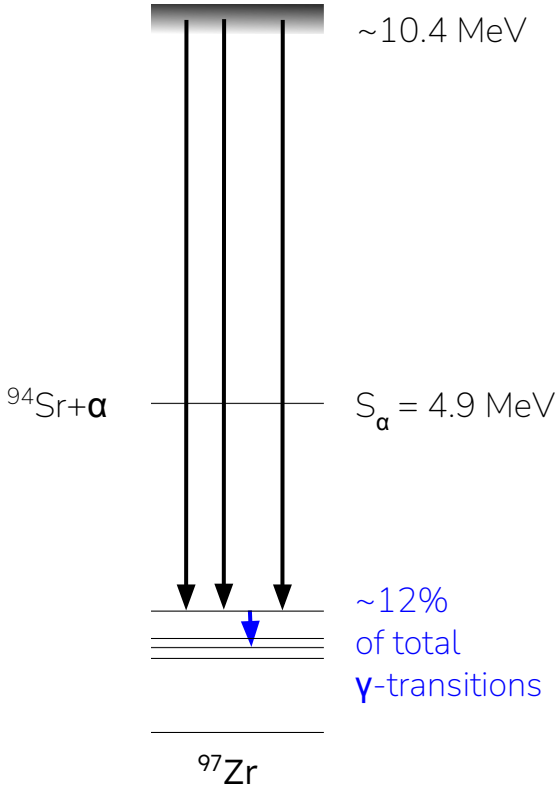
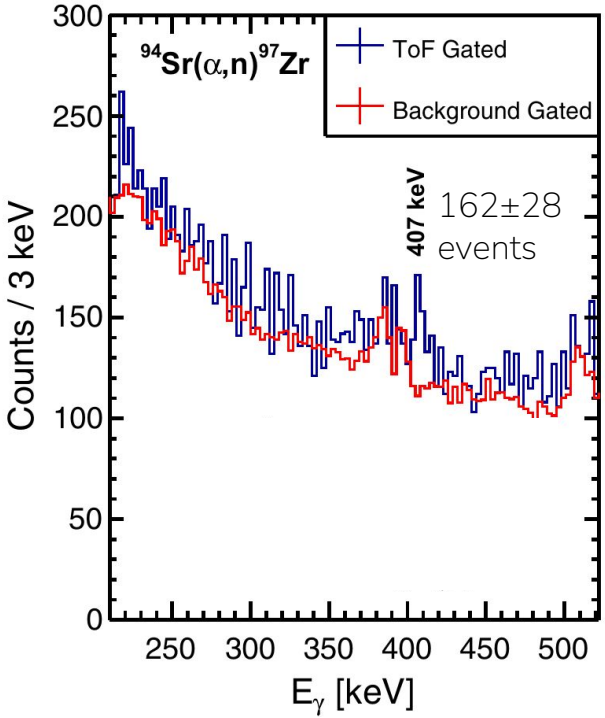
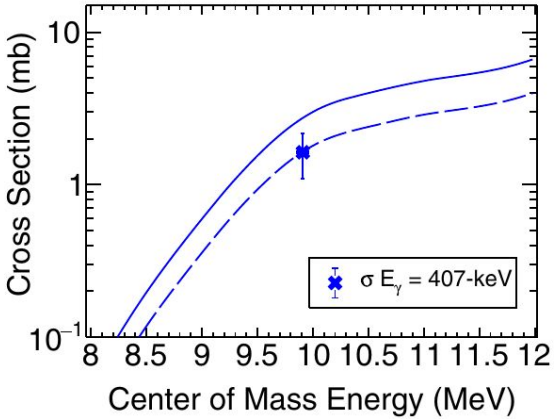






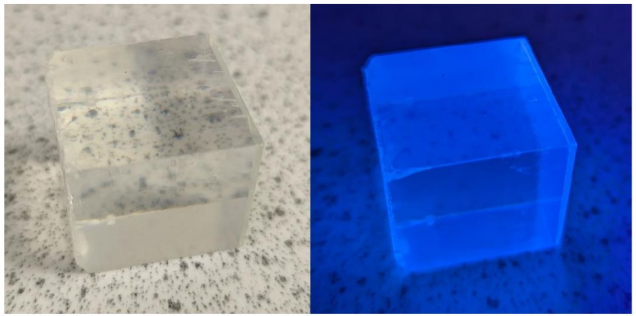
Matt Williams
(Rutherford Fellow at U Surrey)

M. Williams *et al.*, Phys. Rev. Lett. **134**, 112701 (2025)

TRIUMF

DEMAND+EMMA+TIGRESS to measure (α,n) and (d,n) reactions

triple coincidence – heavy recoil (EMMA) + neutron (DEMAND) + γ-ray (TIGRESS)



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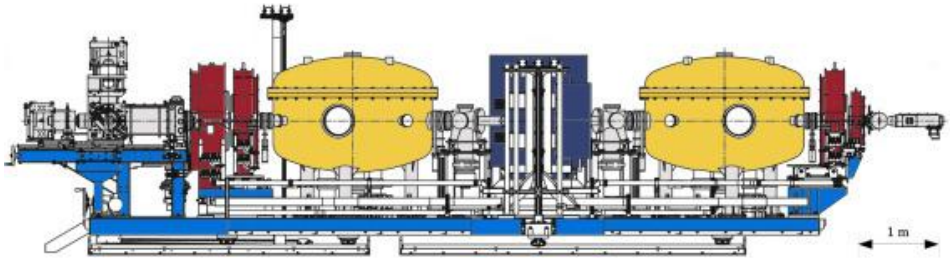


$^{A}X(\alpha,n\gamma)^{A+3}Y$

Ben Reed
(SMU/TRIUMF postdoc)

DEMAND

Direct Experimental Measurements of Astrophysical reactions using Neutron Detectors

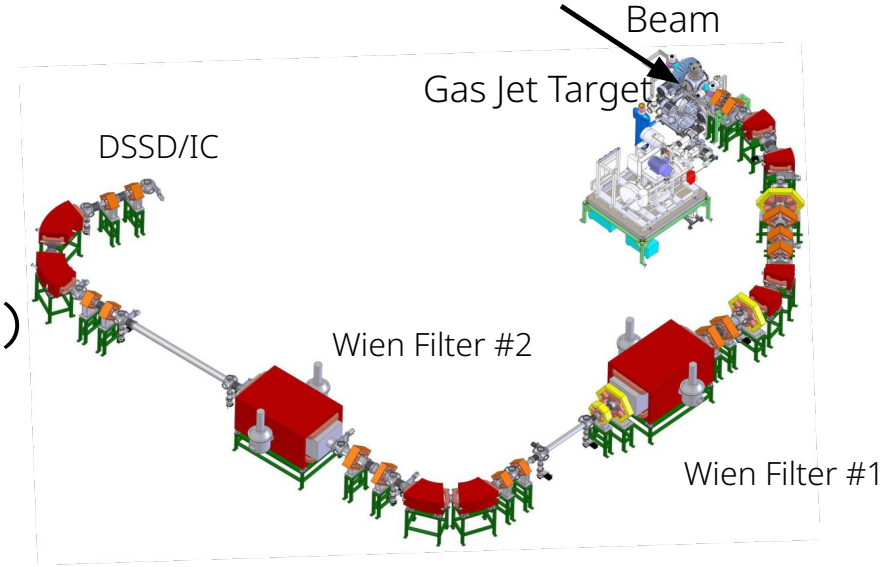
TRIUMF

Many opportunities worldwide for nuclear astrophysics research!

SECAR at FRIB

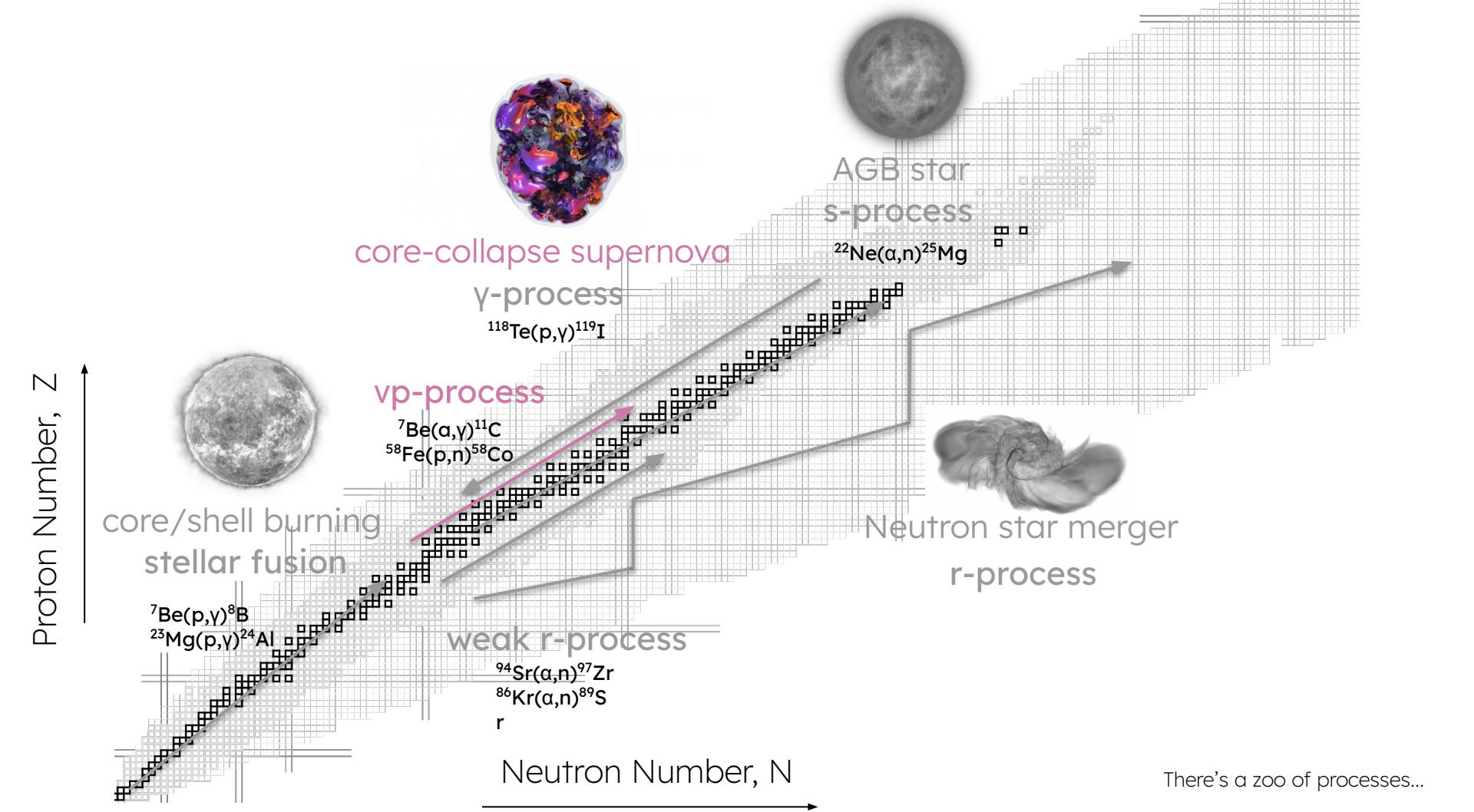
SEparator for CApture Reactions

- JENSA gas jet (n ~ 10^{19} atoms/cm^2) or extended windowless target
- BGO array (γ) or LENDA bars (n) for ejectile detection
- Two velocity (Wien) filters
- DSSD/IC at the last focal plane



G. Berg et al., Nucl. Instrum. Methods Phys. Res A **877**, 87 (2018)

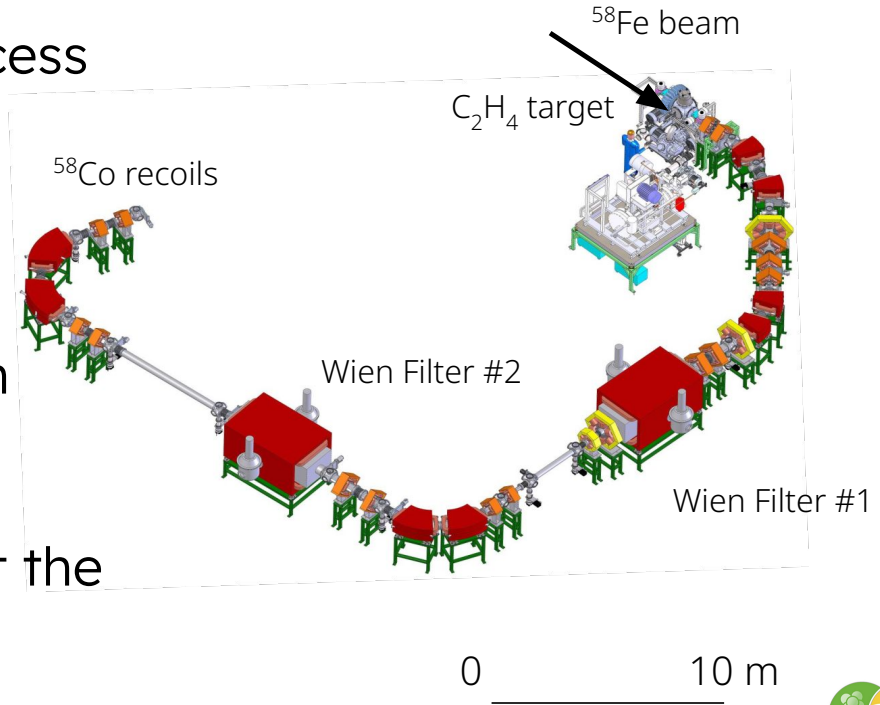
FRIB



There's a zoo of processes...

First results from SECAR: $^{58}Fe(p,n)^{58}Co$

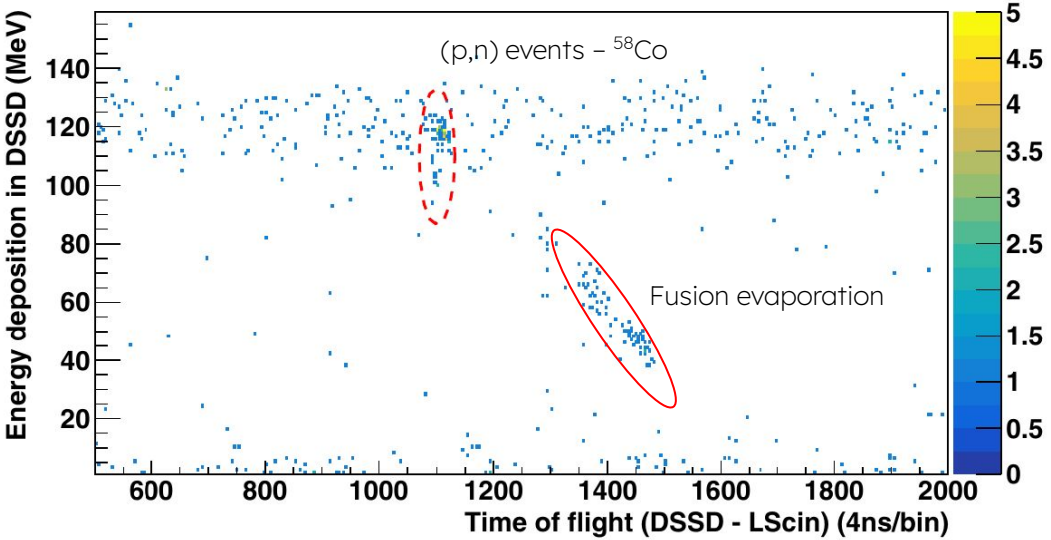
- Study of the inverse of (n,p) reactions, relevant to the vp-process
- C_2H_4 solid target (n ~ 8 x 10^{18} atoms/cm^2)
- 4 organic scintillators for neutron detection
- Ionization chamber and DSSD at the focal plane



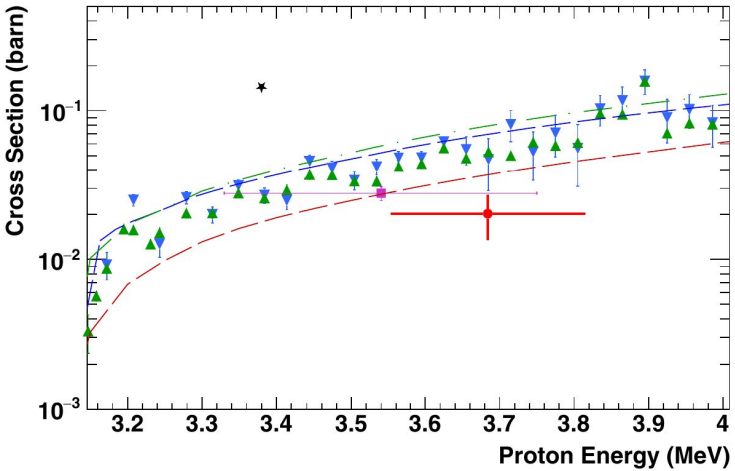
G. Berg et al., Nucl. Instrum. Methods Phys. Res A **877**, 87 (2018)
P. Tsintari et al., Phys. Rev. Res. **7**, 013074 (2025)
P. Gastis et al., Nucl. Instrum. Methods Phys. Res. A **985**, 164603 (2021)

FRIB

First results from SECAR: ^{58}Fe(p,n)^{58}Co



Focal Plane data



Final Cross Section

G. Berg et al., Nucl. Instrum. Methods Phys. Res A **877**, 87 (2018)
P. Tsintari et al., Phys. Rev. Res. **7**, 013074 (2025)
P. Gastis et al., Nucl. Instrum. Methods Phys. Res. A **985**, 164603 (2021)

Pely Tsintari
(Postdoc at FRIB)

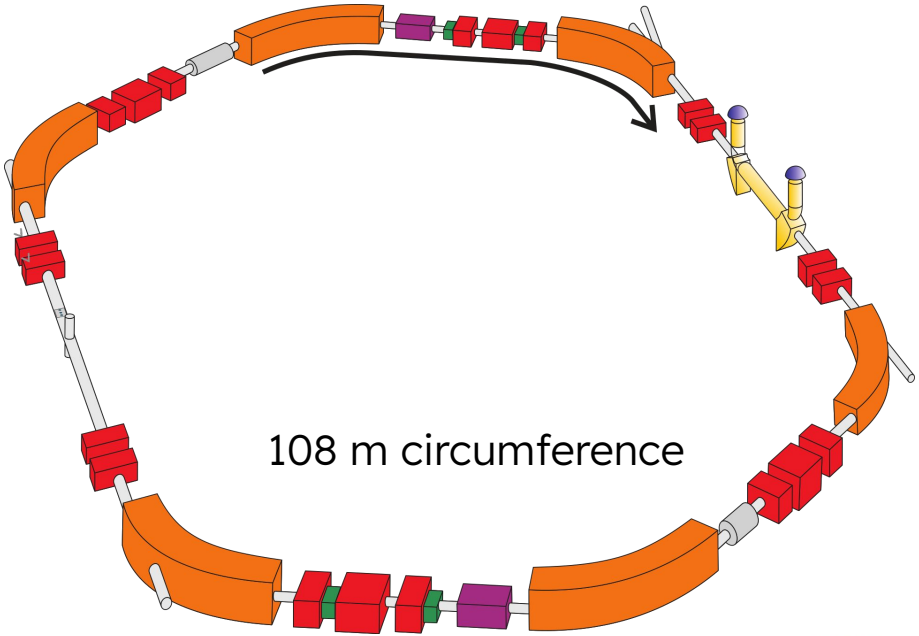
FRIB

Many opportunities worldwide for nuclear astrophysics research!

ESR at GSI/FAIR

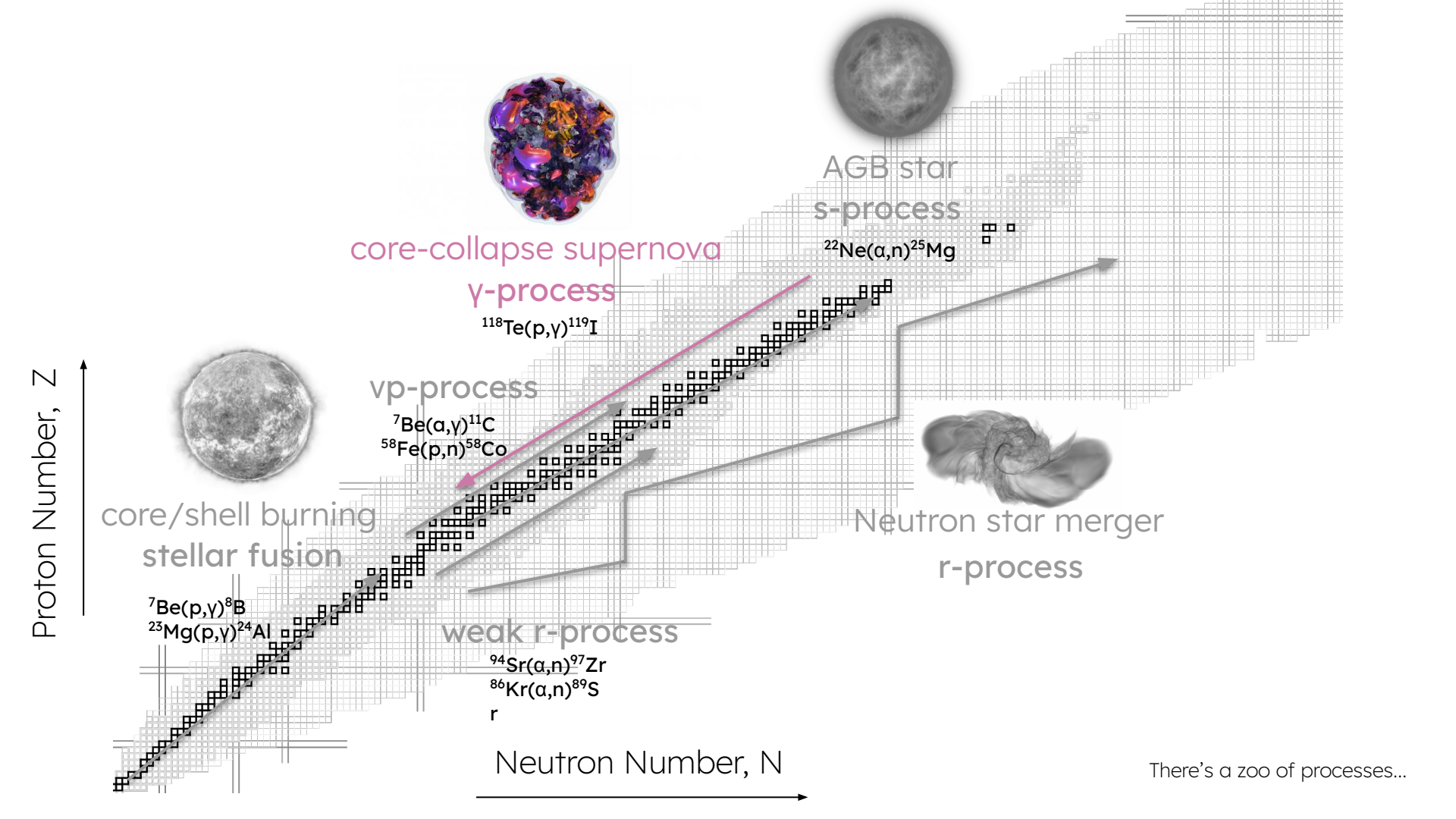
Experimental Storage Ring

- Thin hydrogen jet target
  $n = 10^{14}$ atoms/cm^2
- Revolution frequency
  f= 300-400 kHZ
- Beam is electron-cooled
  to $\Delta p/p \sim 10^{-5}$
- Beam lifetime ~1.5s (vacuum)



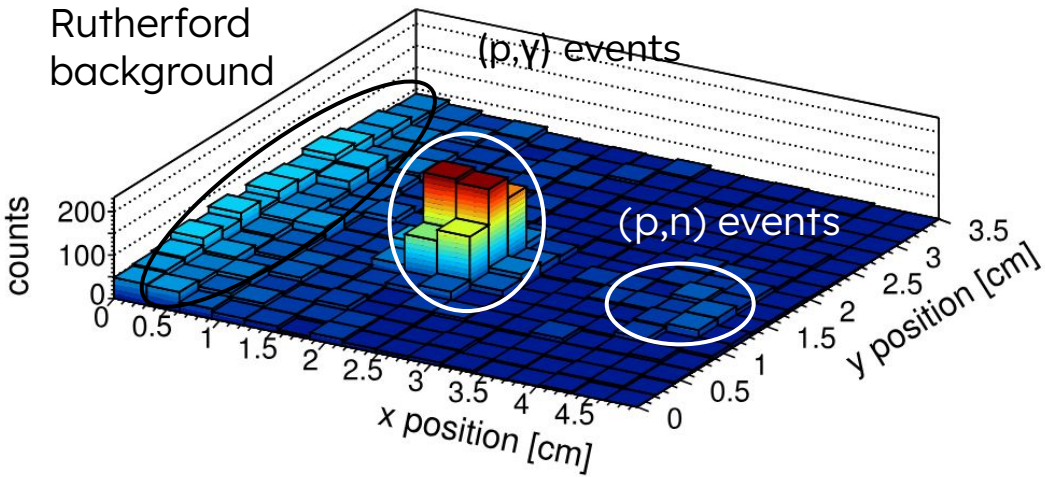
Primarily used for mass measurements and decay studies

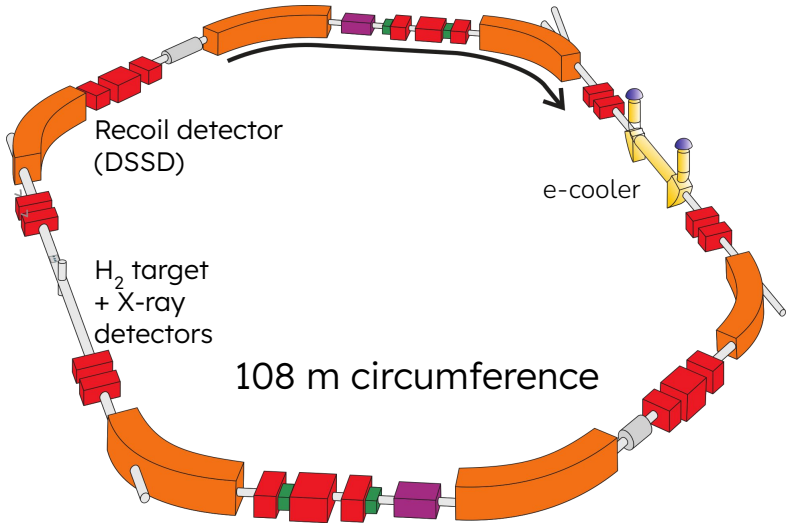
W. Nörtershäuser *et al.*, Phys. Scr. **T156**, 014016 (2013)



There's a zoo of processes...

First direct γ-process measurement using a radioactive ion beam and a storage ring





Events from both the (p,γ) and (p,n) reactions were detected!

J. Glorius *et al.*, Phys. Rev. Lett. **122**, 092701 (2019)
L. Varga *et al.*, Phys. Rev. Lett. **134**, 082701 (2025)
S.F. Dellmann *et al.*, Phys. Rev. Lett. **134**, 142701 (2025)

László Varga
(Postdoc at TU Munich)

Sophia Dellmann
(Postdoc at LANL)

FAIR
GSI

Many opportunities worldwide for nuclear astrophysics research!

Come work with us at SMU!

Support available for undergraduate and graduate students. Lots of nuclear astrophysics projects to work on! 😁

Halifax, NS 🦞🌊⚓

🌐 https://psaltisa.github.io

Saint Mary's University

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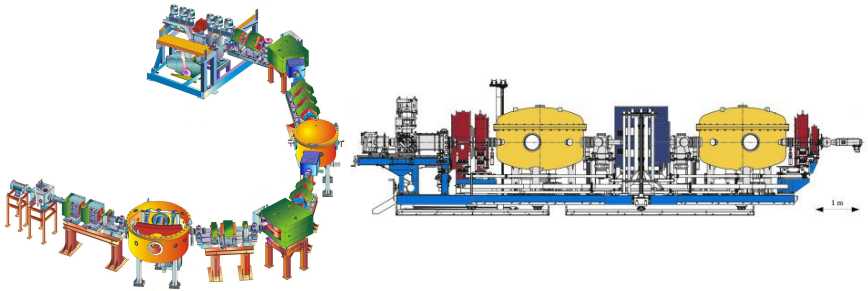
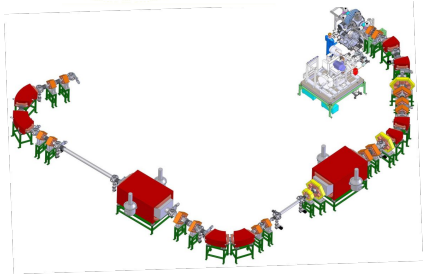
TRIUMF

C. Ruiz, B. Davids, D. Hutcheon, A. Laird, A. Lennarz, D. Connolly, **M. Williams**, G. Lotay, **G. Christian**, **B. Reed**, A. Chen, C. Brune, J. Fallis, **M. Loria**, M. Alcorta, U. Greife, P. Machule, and the DRAGON and EMMA collaborations



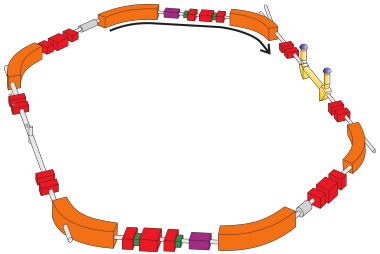
FRIB

H. Schatz, F. Montes, **P. Tsintari**, L. Wagner, K. Chipps, M. Couder, C. Deibel, G. Perdikakis, J. Pereira, M. Smith, and the SECAR collaboration



FAIR GSI

Y. Litvinov, J. Glorius, R. Reifarth, **S.F. Dellmann**, **L. Varga**, I. Dillmann, and the ESR collaboration



Summary & Outlook

1. Nuclear reactions affect stellar evolution in various environments.

2. Recoil separators are key instruments to study important astrophysical reactions.

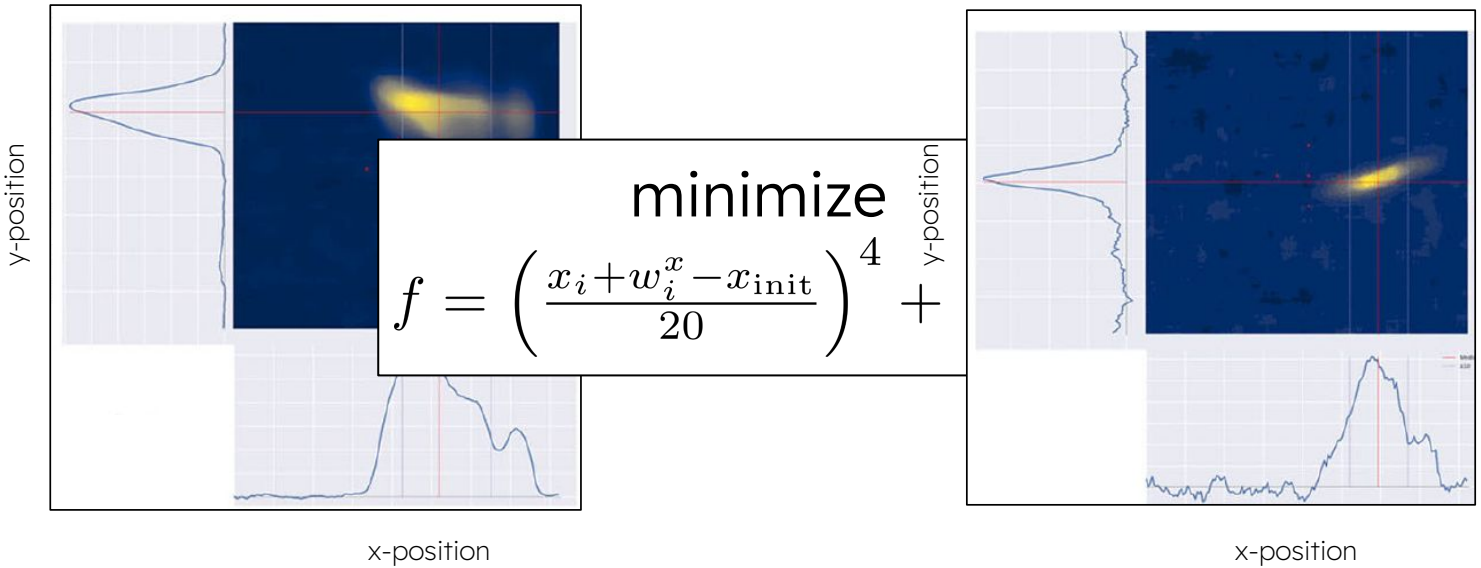
3. Exciting opportunities arise in radioactive ion beam facilities around the world (ARIEL/TRIUMF, FRIB, FAIR and others).

Want to stay in touch? 🌐 https://psaltisa.github.io

Use of ML for beam optimization at SECAR

Before optimization

After optimization



S.A. Miskovich et al., Phys. Rev. Accel. Beams **25**, 044601 (2022)

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