Probing explosive nucleosynthesis with radioactive beams

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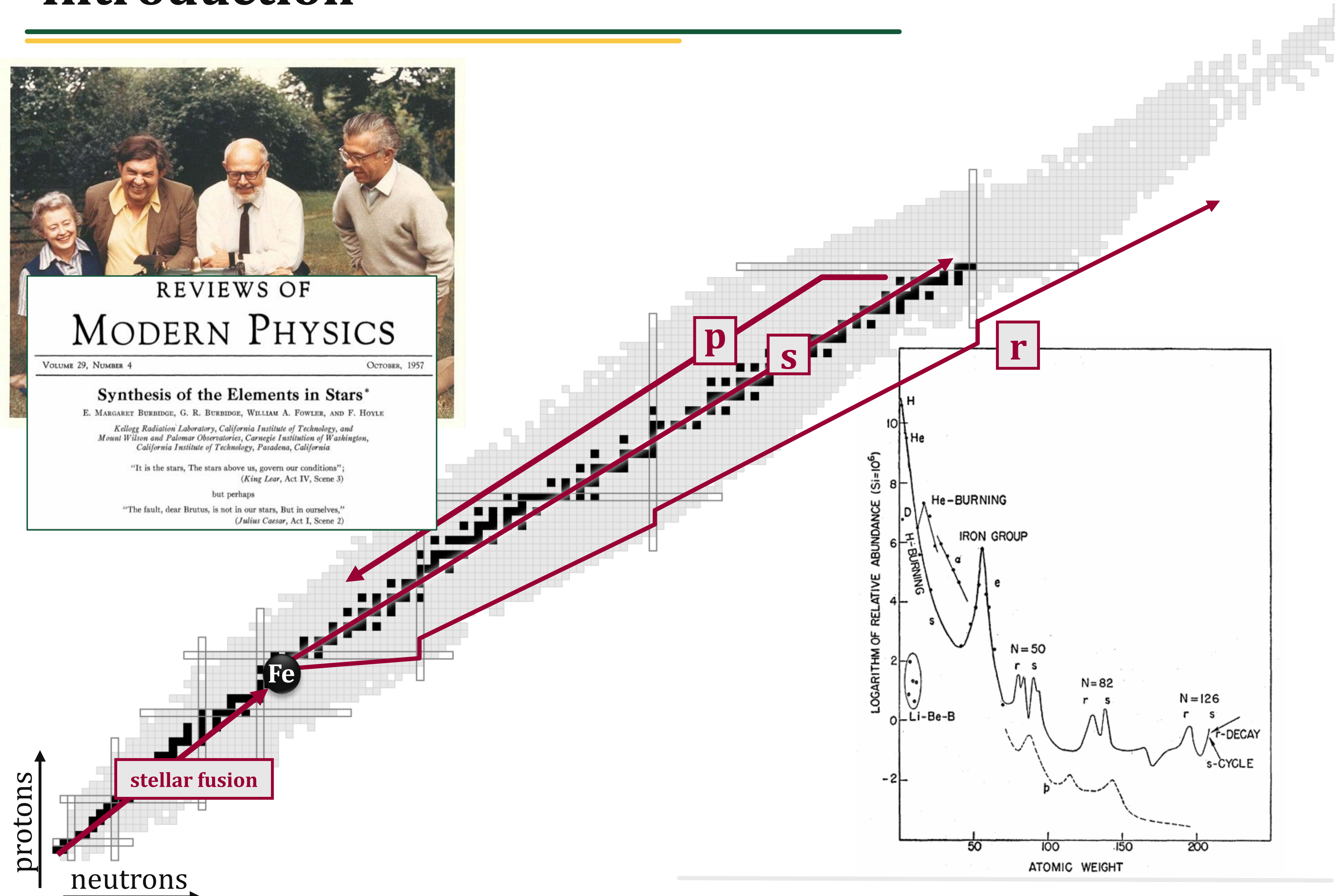
Introduction



REVIEWS OF

MODERN PHYSICS

VOLUME 29, NUMBER 4 — OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

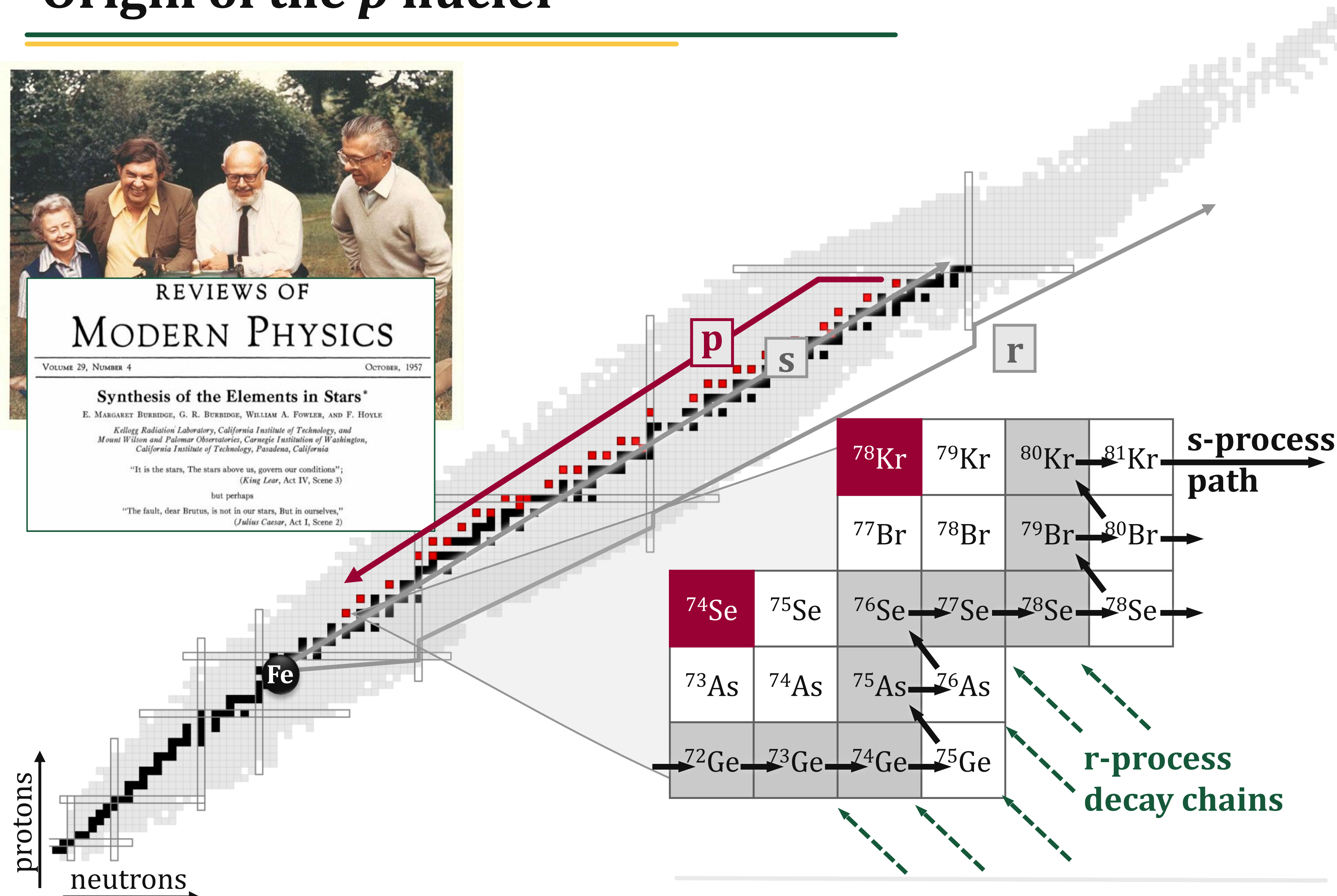
Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

Origin of the *p* nuclei



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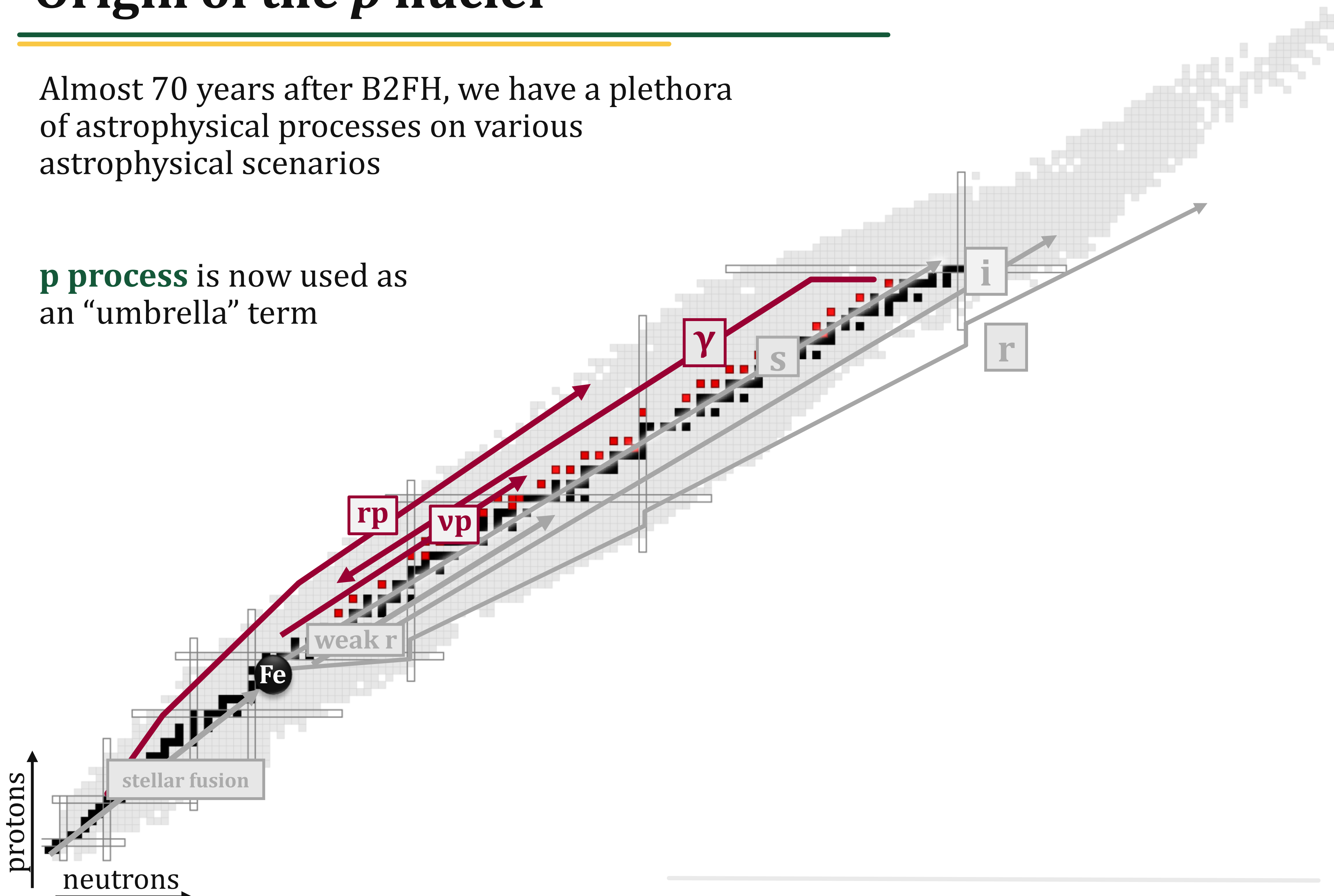
Origin of the *p* nuclei

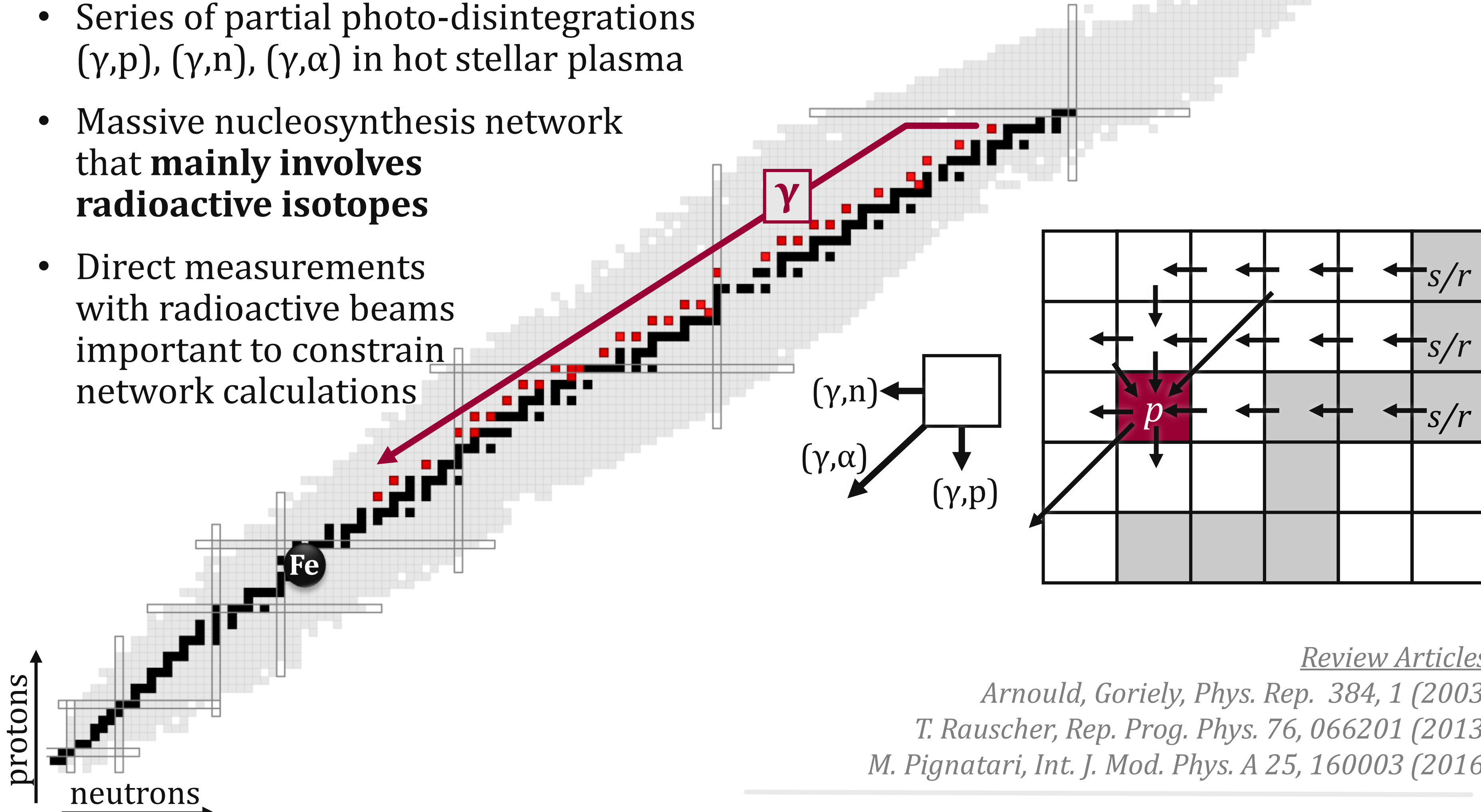
Almost 70 years after B2FH, we have a plethora of astrophysical processes on various astrophysical scenarios

p process is now used as an “umbrella” term



The γ process

- Main production mechanism for ~30 p nuclei from ^{74}Se to ^{196}Hg
- Series of partial photo-disintegrations (γ,p), (γ,n), (γ,α) in hot stellar plasma
- Massive nucleosynthesis network that **mainly involves radioactive isotopes**
- Direct measurements with radioactive beams important to constrain network calculations



Review Articles:
Arnould, Goriely, Phys. Rep. 384, 1 (2003)
T. Rauscher, Rep. Prog. Phys. 76, 066201 (2013)
M. Pignatari, Int. J. Mod. Phys. A 25, 160003 (2016)

Origin of the p nuclei

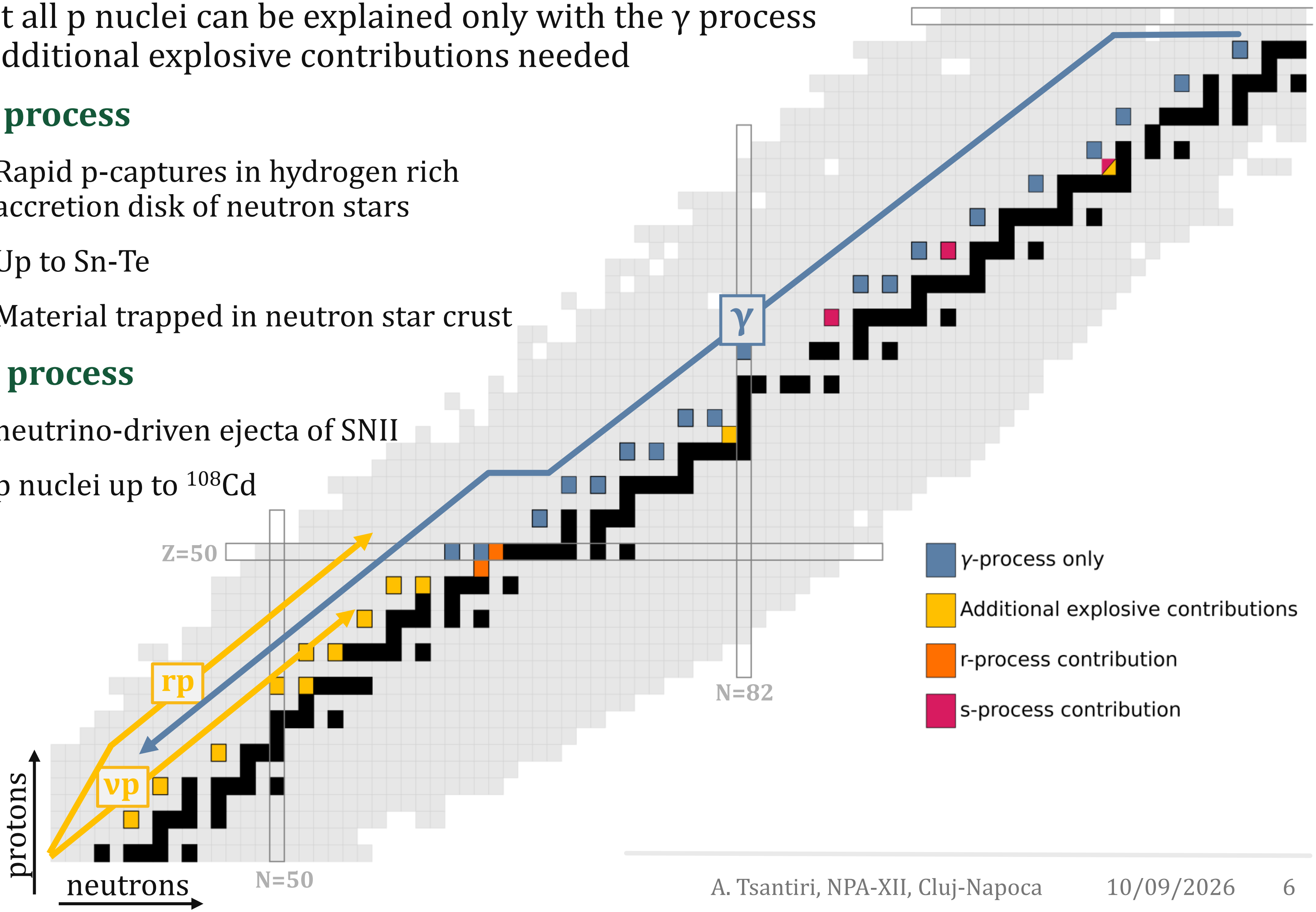
Not all p nuclei can be explained only with the γ process – additional explosive contributions needed

rp process

- Rapid p-captures in hydrogen rich accretion disk of neutron stars
- Up to Sn-Te
- Material trapped in neutron star crust

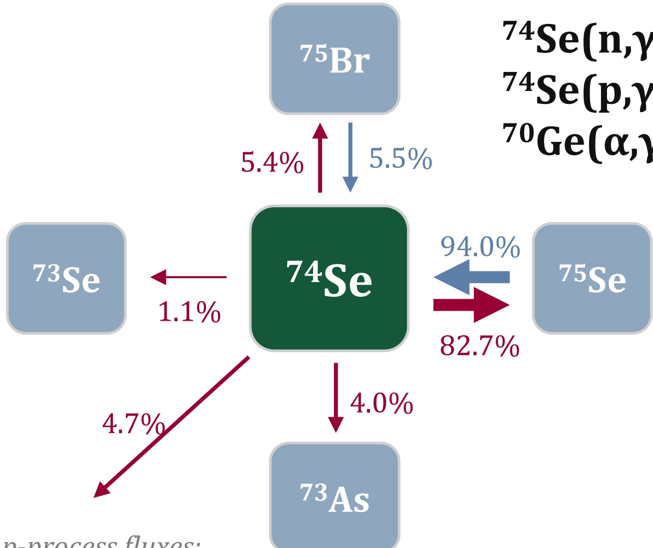
νp process

- neutrino-driven ejecta of SNII
- p nuclei up to ^{108}Cd

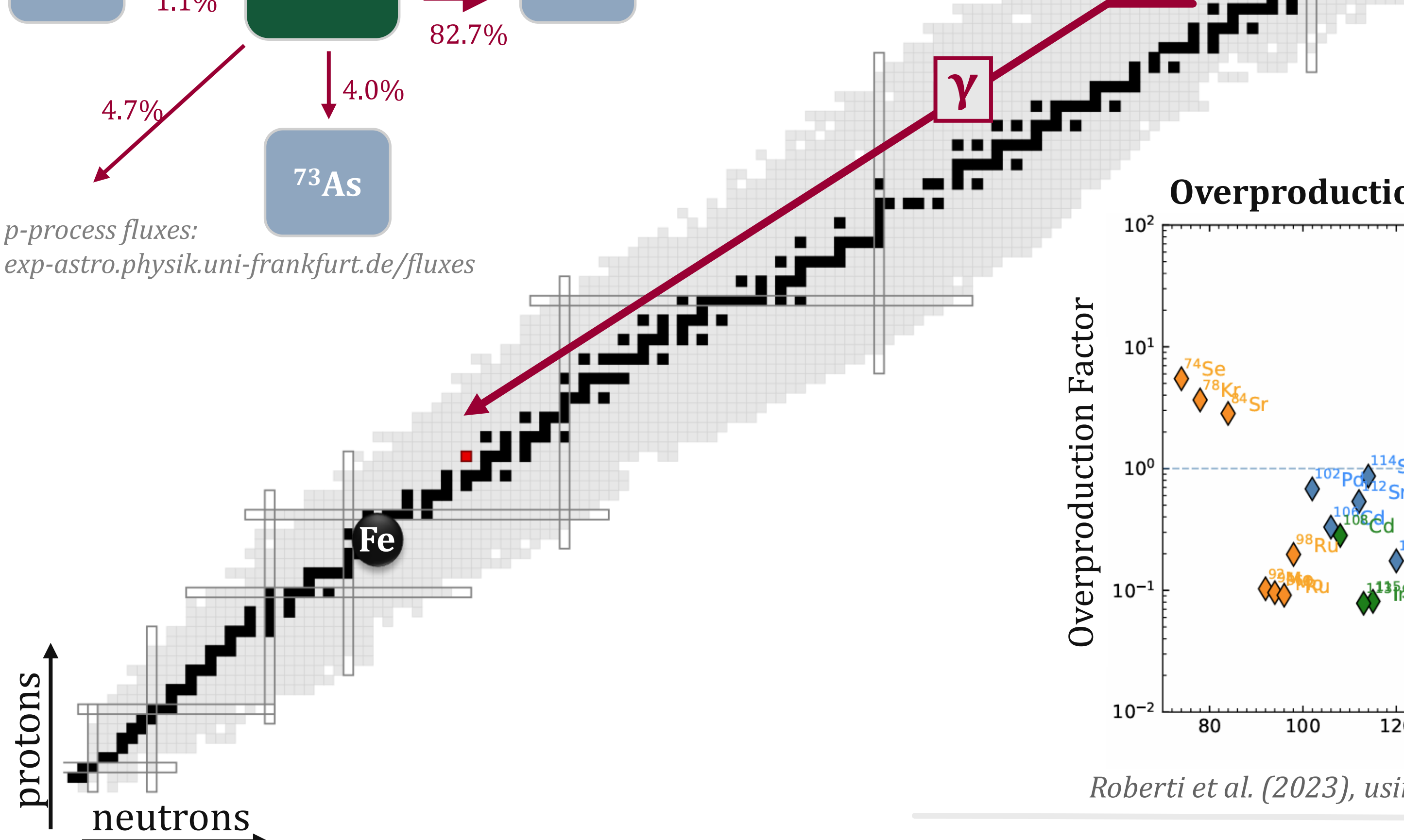


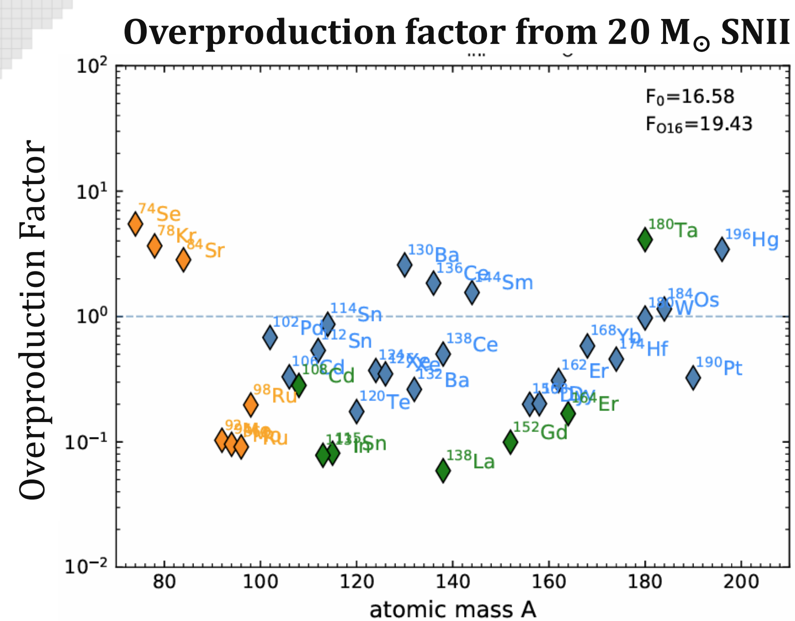
Synthesis of ^{74}Se

^{74}Se(n,γ)^{75}Se: Dillmann et al. (2005)
^{74}Se(p,γ)^{75}Br: Gyürky et al. (2003)
^{70}Ge(α,γ)^{74}Se: Fülöp et al. (1996)



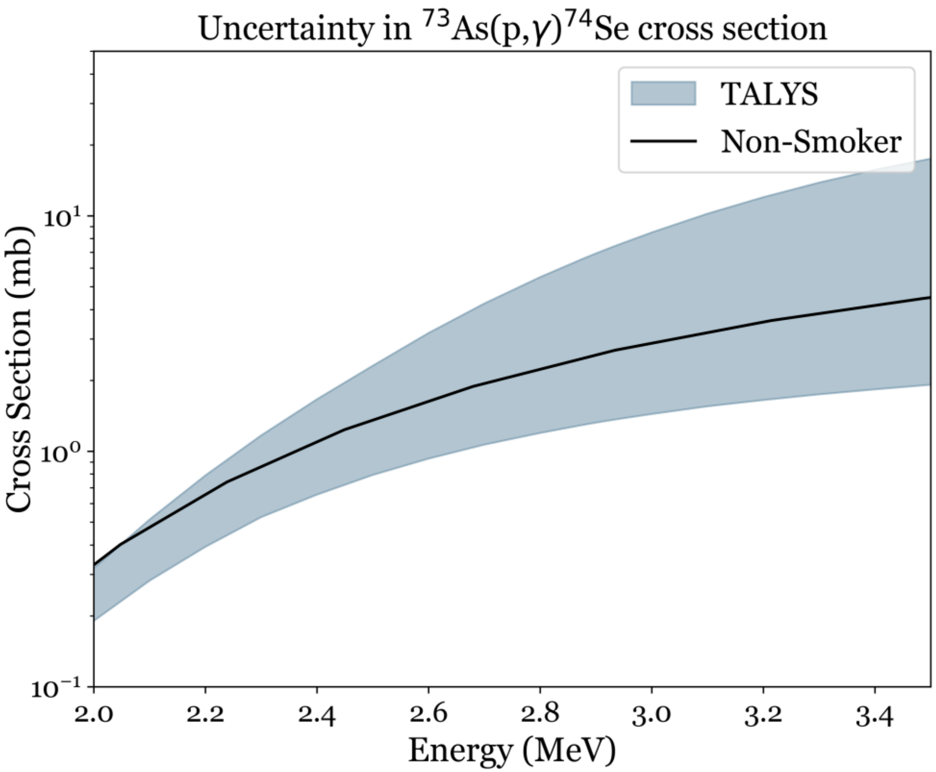
p-process fluxes:
exp-astro.physik.uni-frankfurt.de/fluxes

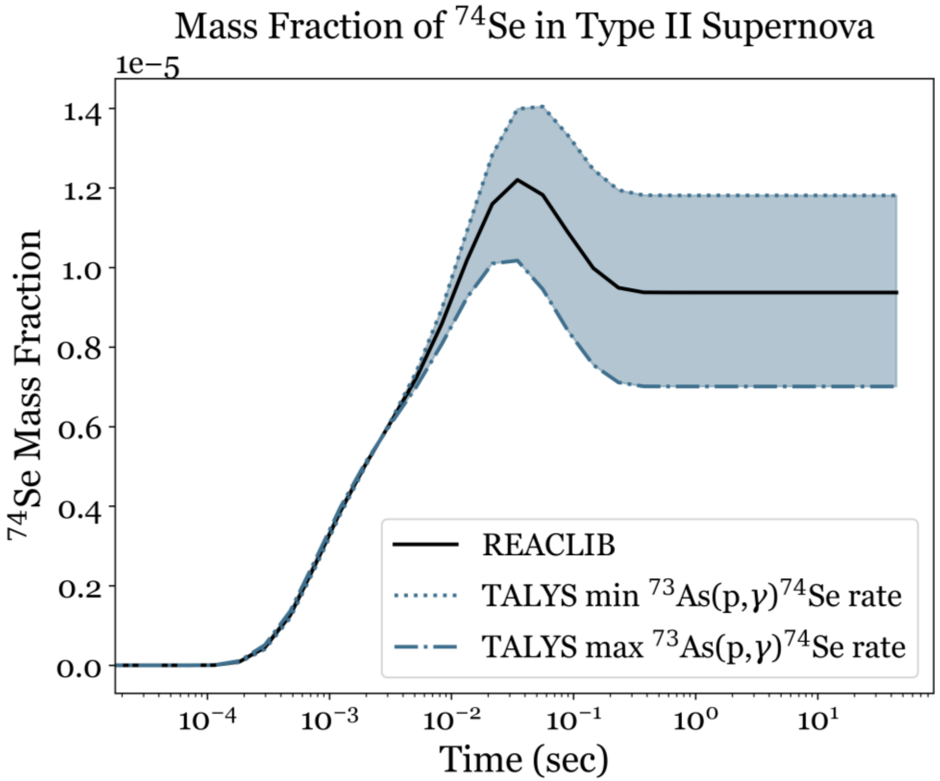




Roberti et al. (2023), using model from Ritter et al (2018)

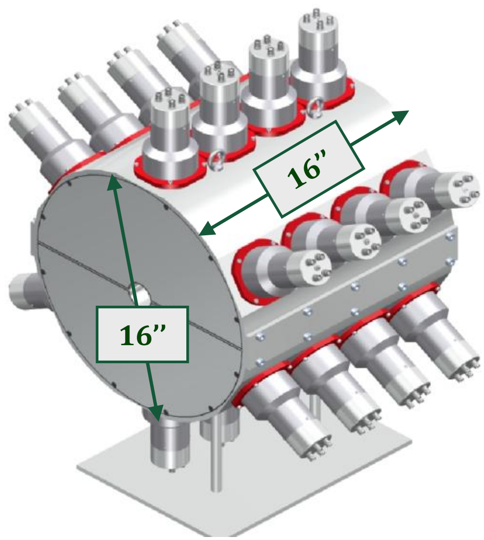
Synthesis of ^{74}Se

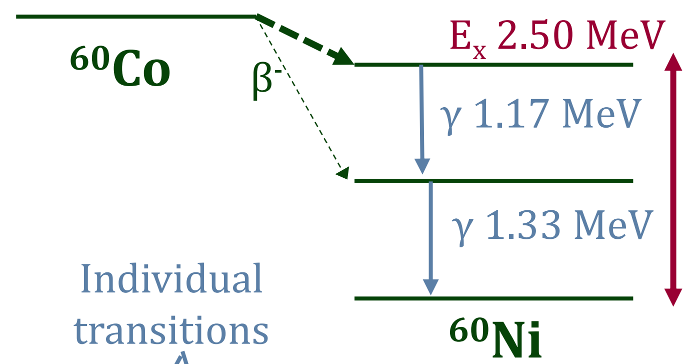


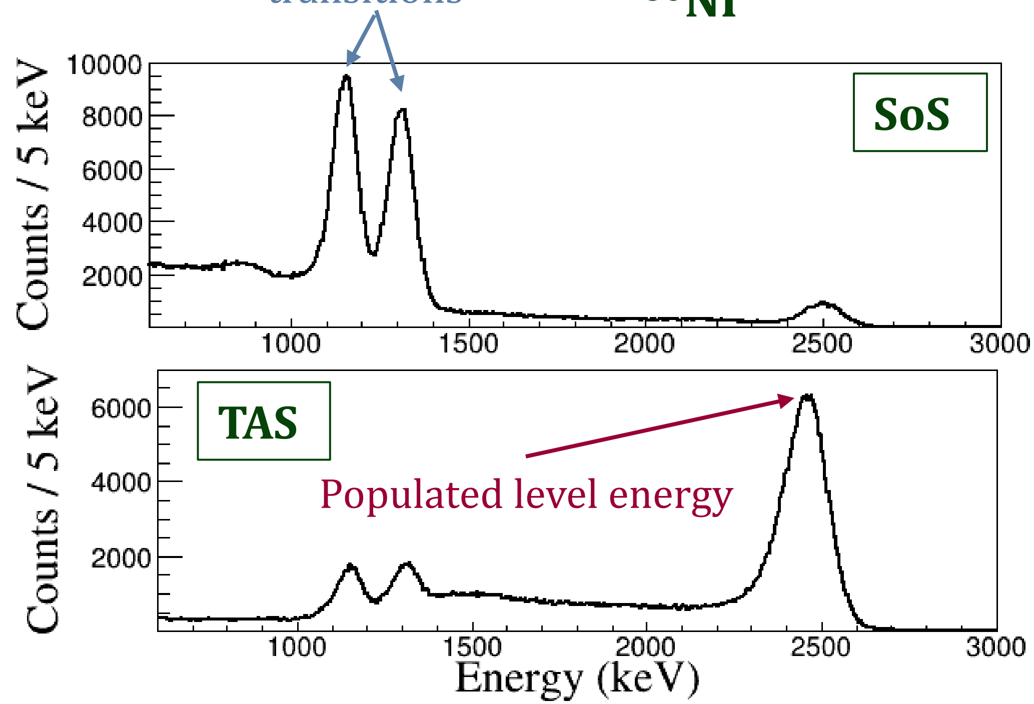


Uncertainty in the cross section of ^{73}As(p,γ)^{74}Se cross section has direct impact on final abundance of ^{74}Se

γ-summing technique with SuN



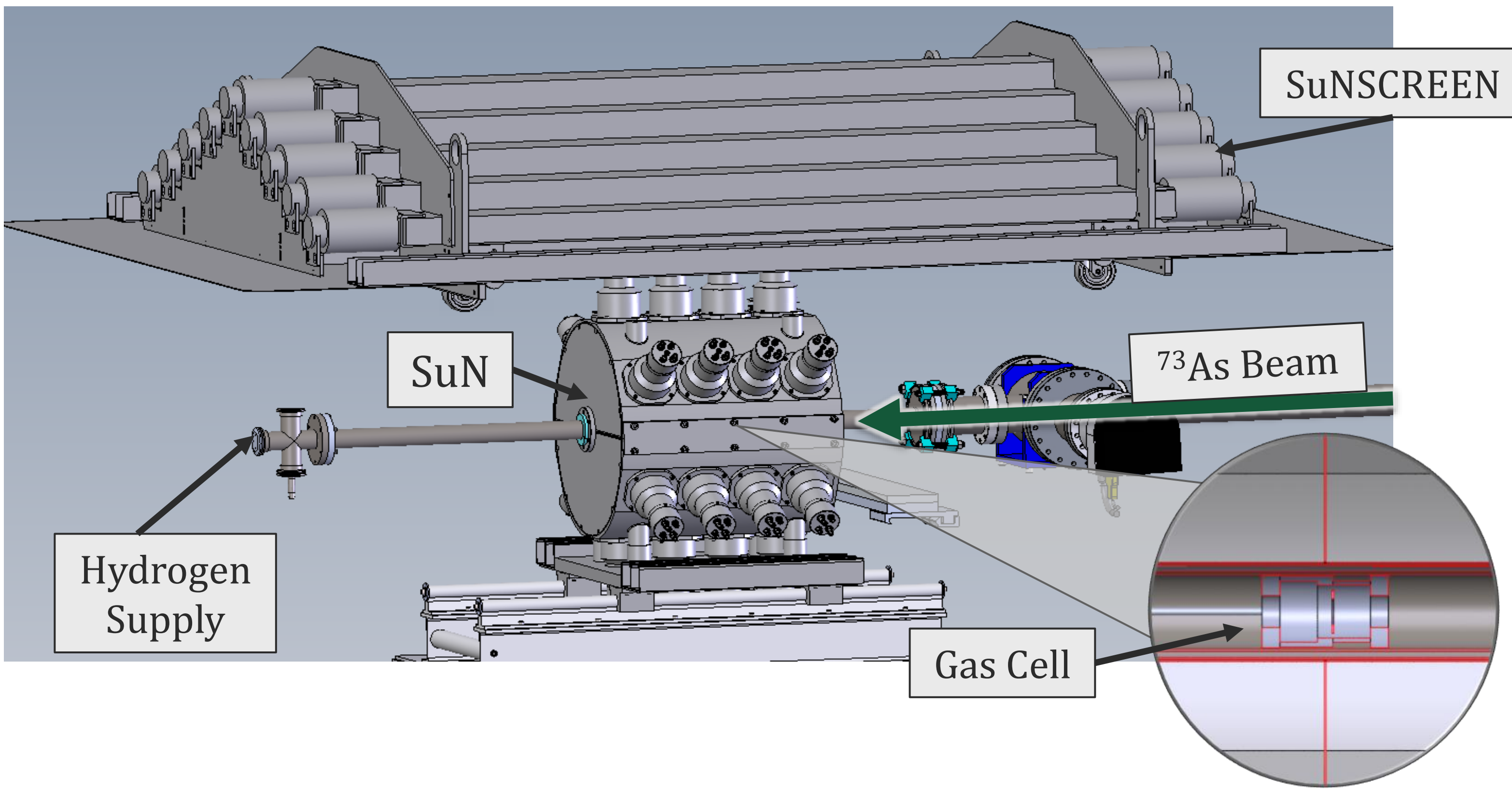




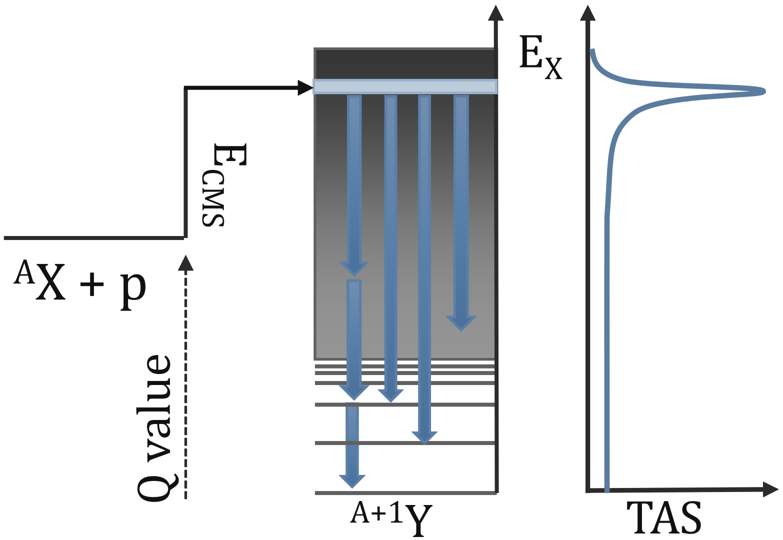
- **Summing NaI(Tl) SuN**: Large size, high efficiency γ-ray detector
- 8 optically isolated segments
- 24 PMTs
- **Sum of Segments (SoS)** → Individual γ-rays
- **Total Absorption Spectrum (TAS)** Total excitation energy Ex

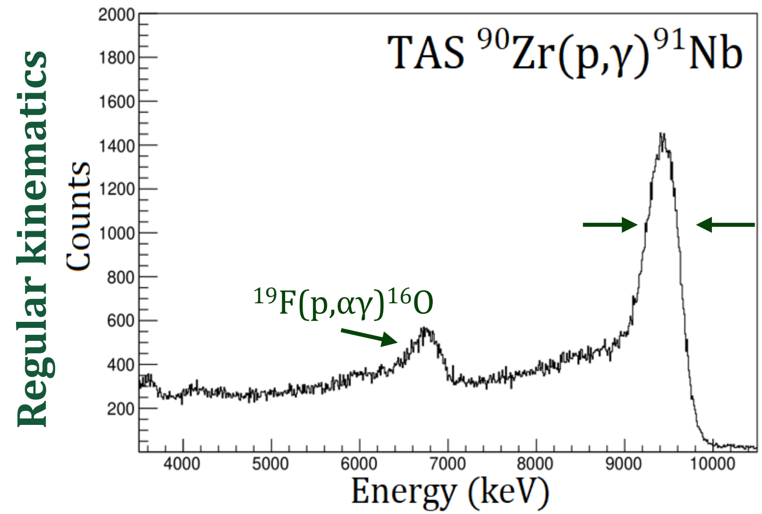
^{73}As(p,γ)^{74}Se measurement at ReA FRIB

- ^{73}As radioactive beam (ReA standalone) (2023) 3.1, 3.7 MeV/u, ~1E5 pps
  - $^{82-84}$Kr stable beam proof-of-principle (2017)
- Summing NaI (SuN) total absorption spectrometer
- Inverse kinematics, hydrogen gas-cell target
- SuNSCREEN detector for cosmic-ray background rejection

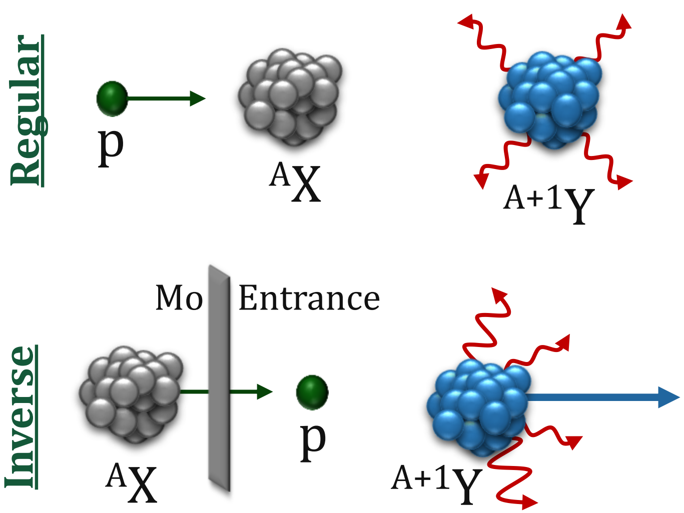


Regular vs inverse kinematics





Spyrou et al. PRC 88 045802 (2013)



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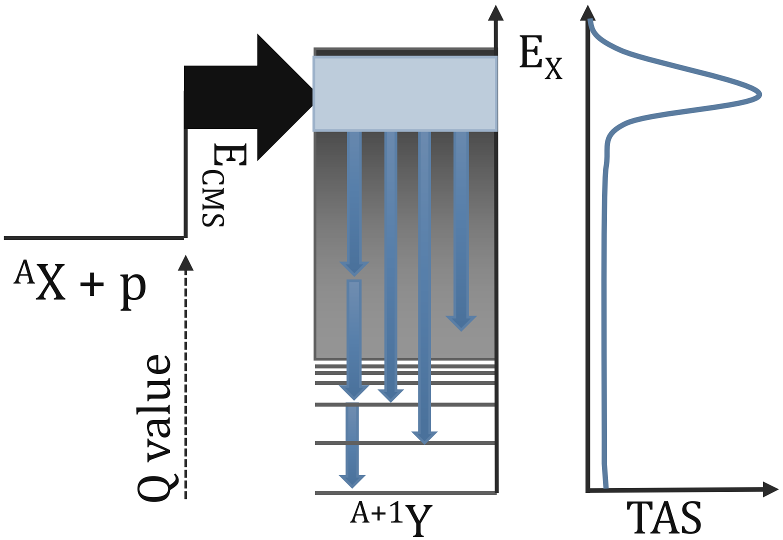

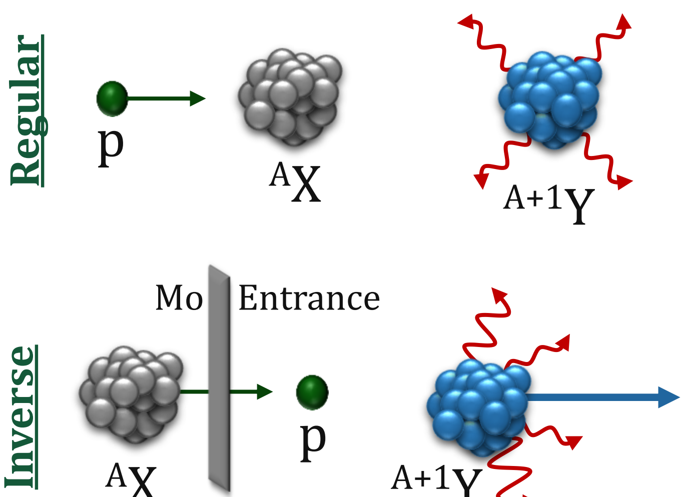

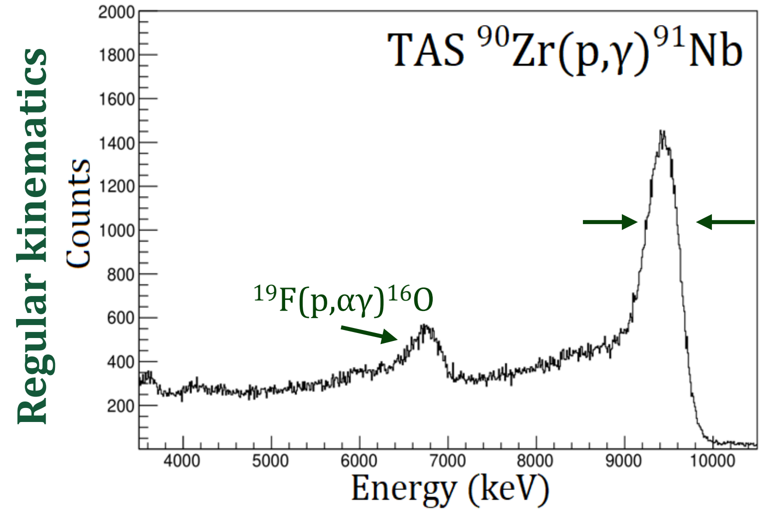

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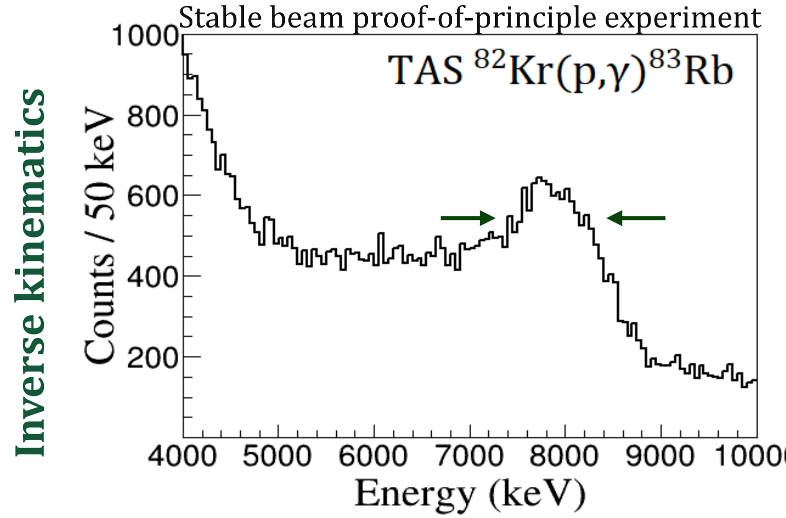
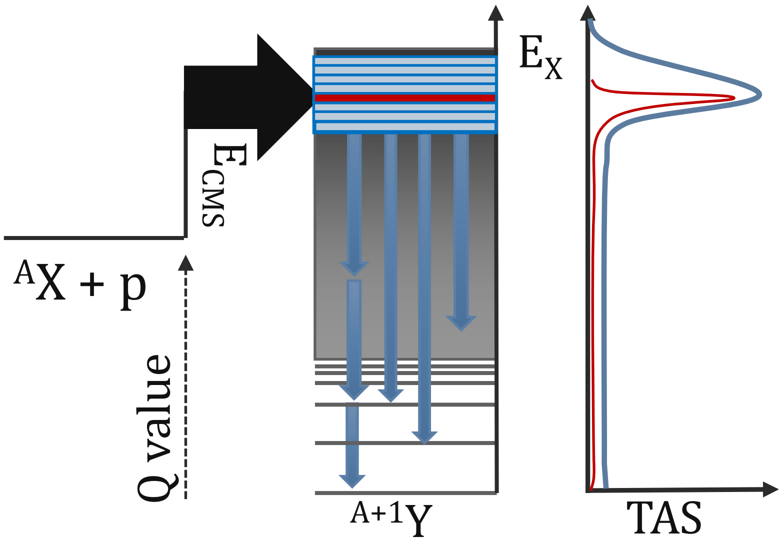
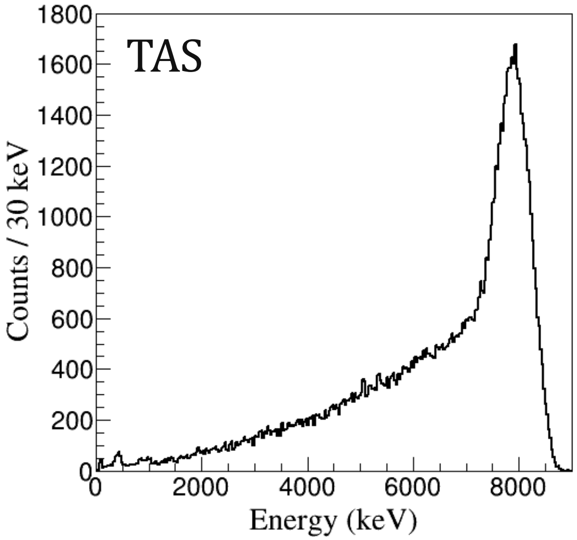


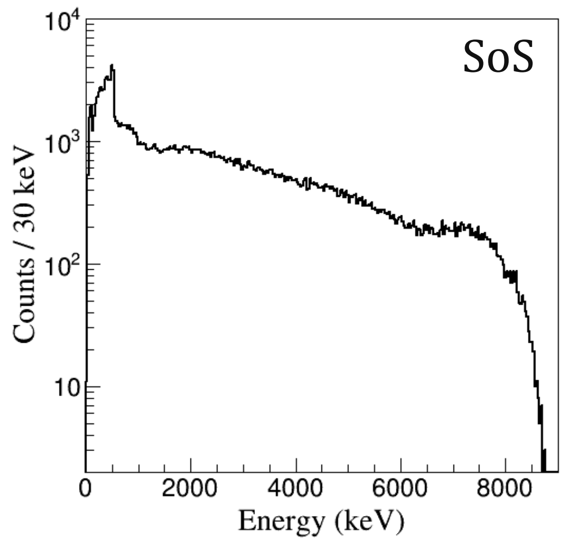
Tsantiri et al, PRC 107, 035808 (2023)

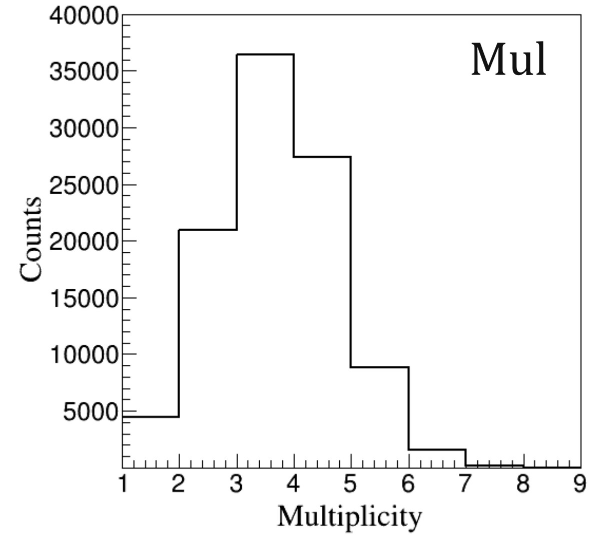
Detection efficiency simulations



- Sum peak includes contributions from many E_X
- ε_{eff} depends on E_γ and the multiplicity of each cascade
- Simulate the de-excitation of every possible E_X with RAINIER and Geant4







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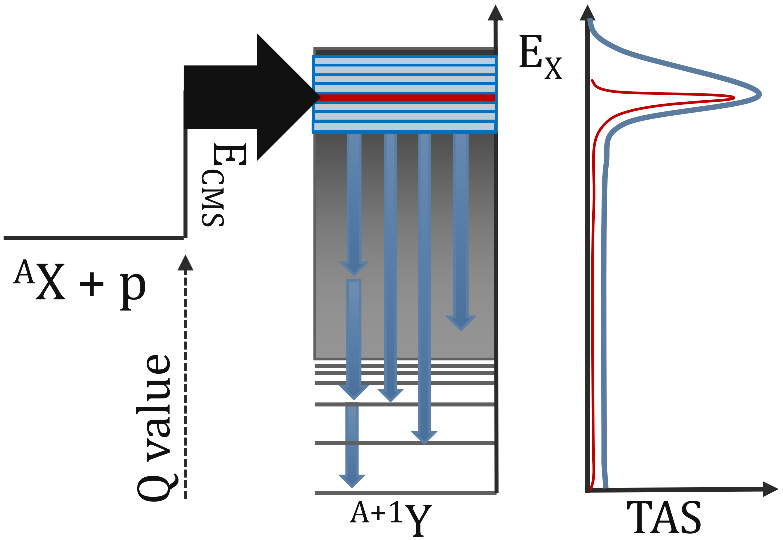

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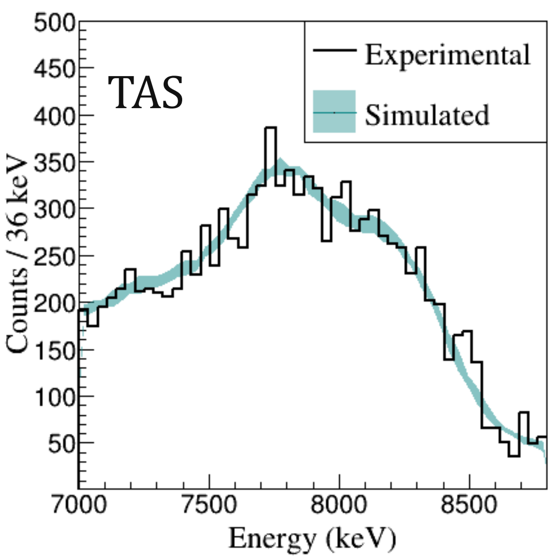
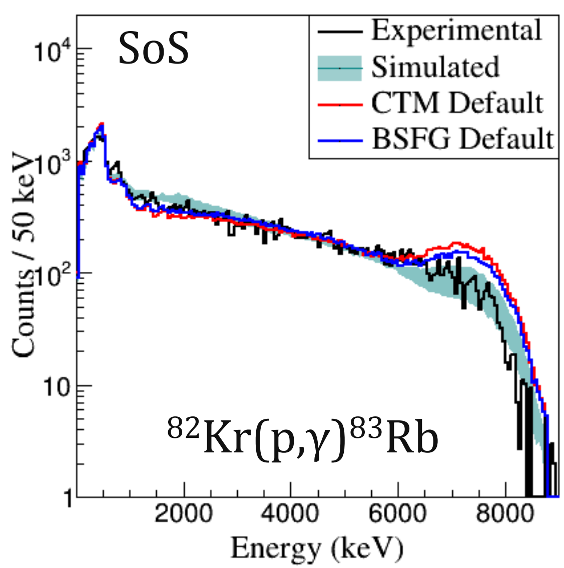
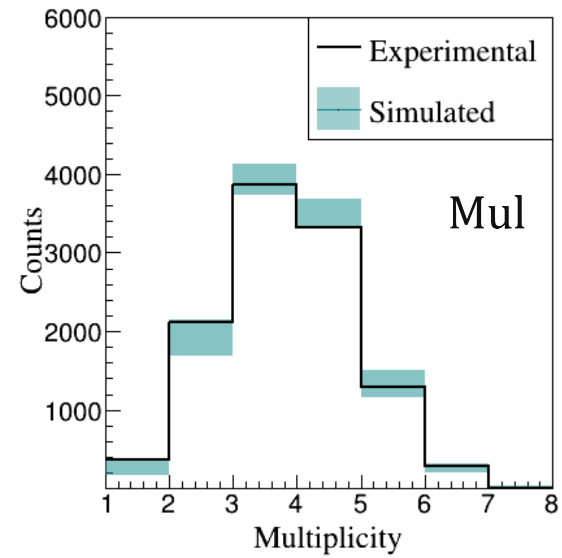
- The choice of statistical properties in RAINIER (NLD and γSF) affect the shape of the SoS







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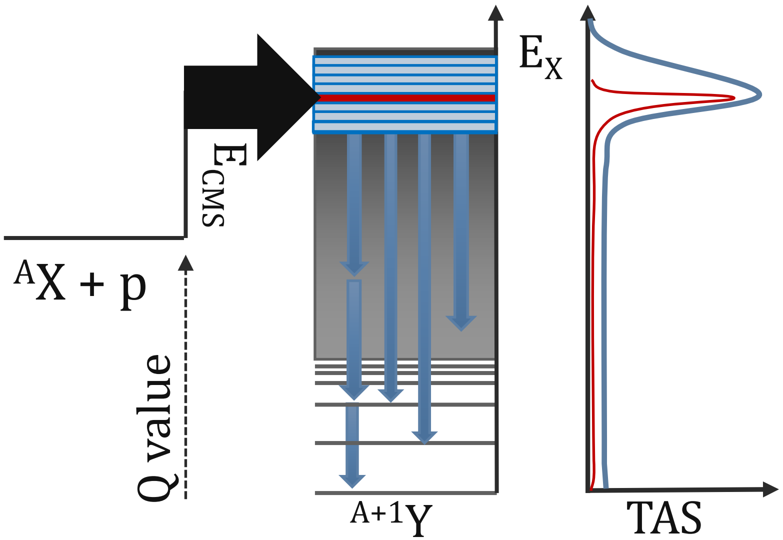

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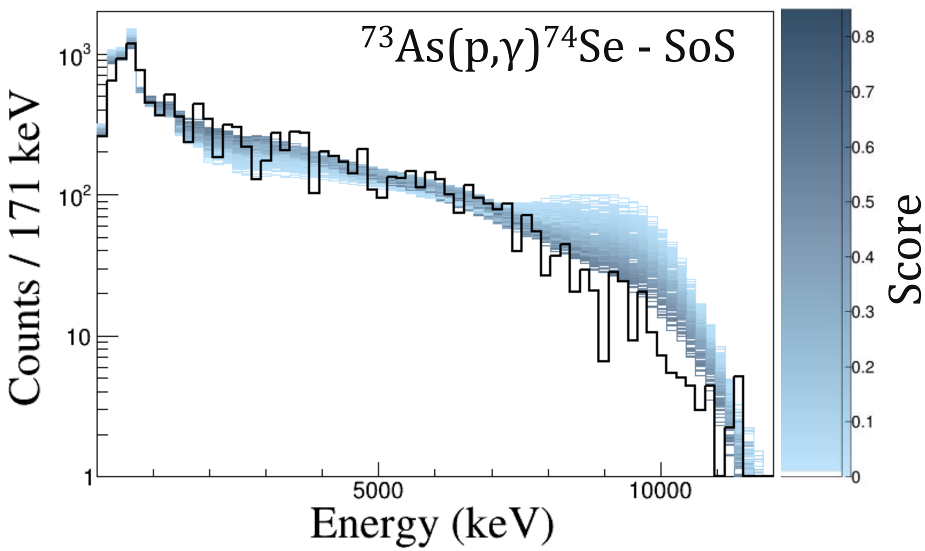
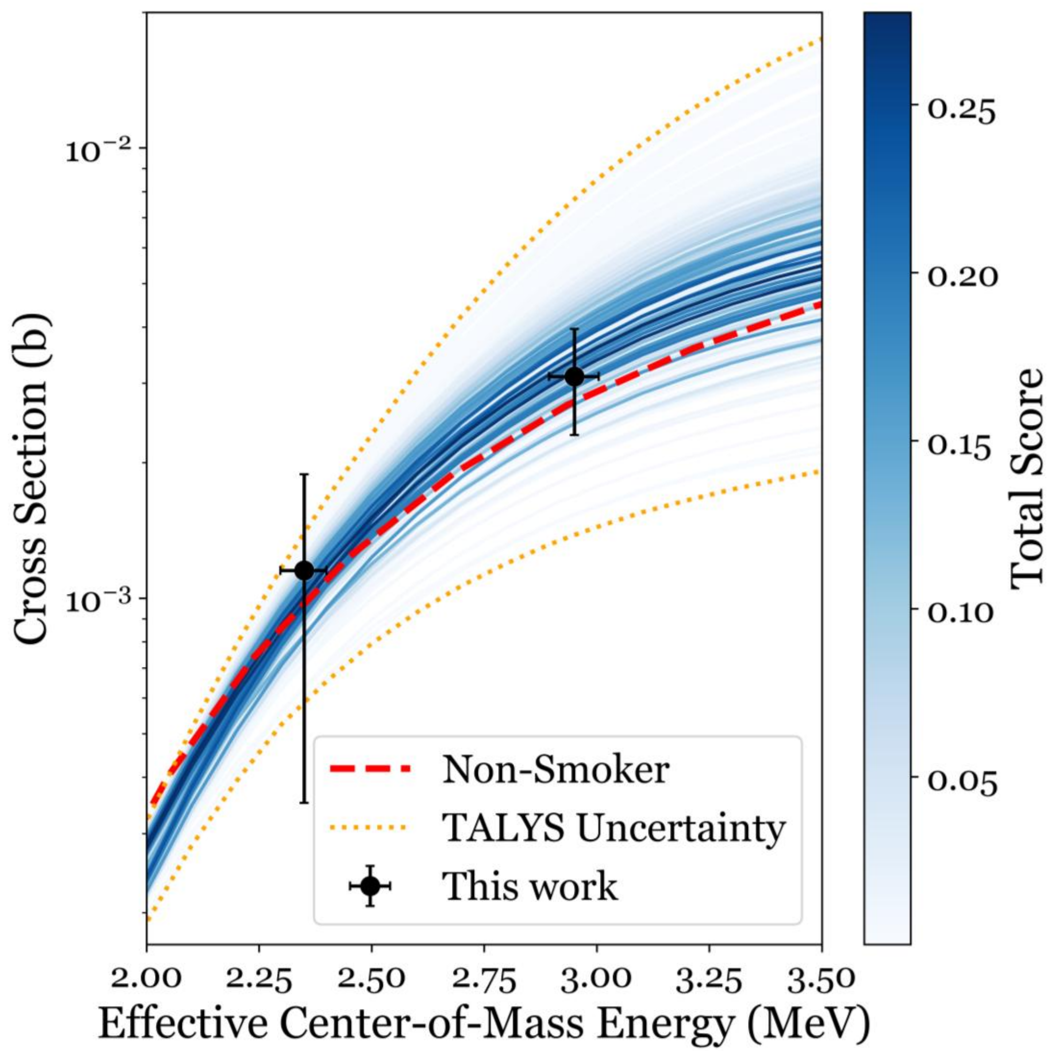


Utilize our sensitivity in the statistical properties of the compound nucleus to characterize the various NLD and γSF model combinations in TALYS for ^{74}Se

$^{73}As(p,\gamma)^{74}Se$ results

- Combining our measured cross section with the score of different statistical descriptions of ^{74}Se we obtain cross-section constraints on a larger energy range
- Only the second γ-process experiment with radioactive beam within the Gamow window

Tsantiri et al. PRL 135, 212701 (2025)

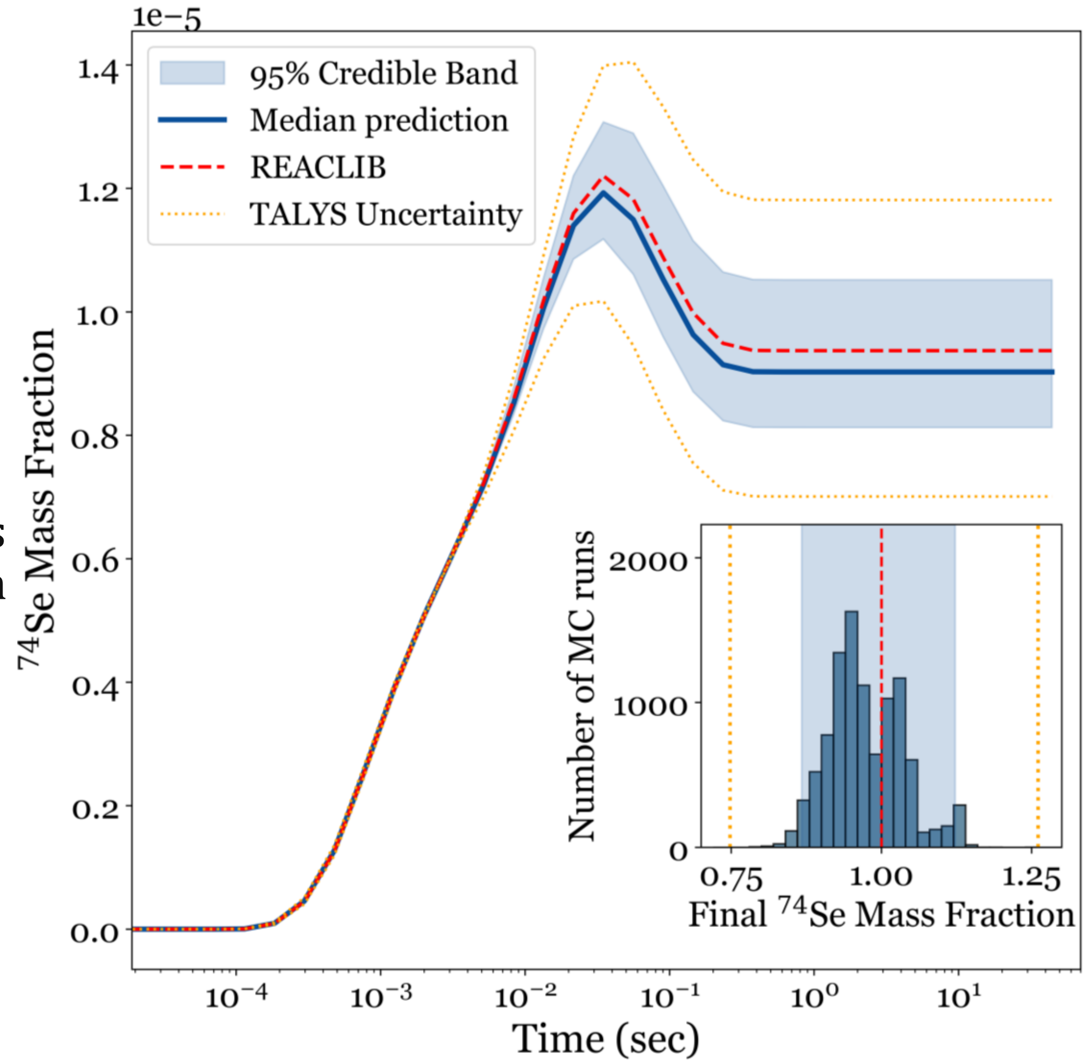


FRIB

^{73}As(p,γ)^{74}Se results

- Combining our measured cross section with the score of different statistical descriptions of ^{74}Se we obtain cross-section constraints on a larger energy range
- Only the second γ-process experiment with radioactive beam within the Gamow window
- Monte Carlo one-zone network simulations of $20M_{\odot}$ SNII to assess the impact of our measurement on ^{74}Se production
- Reduction of uncertainty in final ^{74}Se mass fraction by a factor of 2

Tsantiri et al. PRL 135, 212701 (2025)

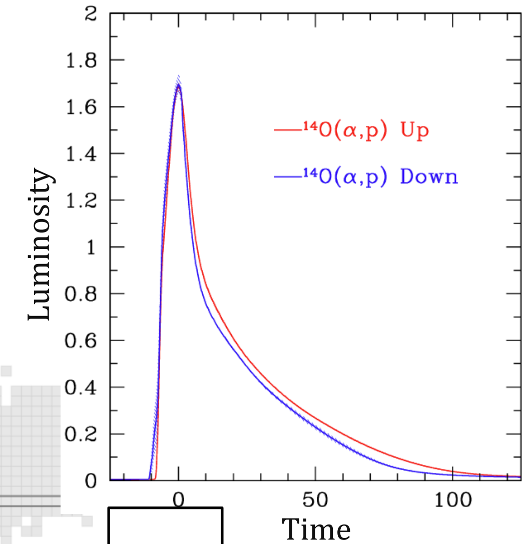


FRIB

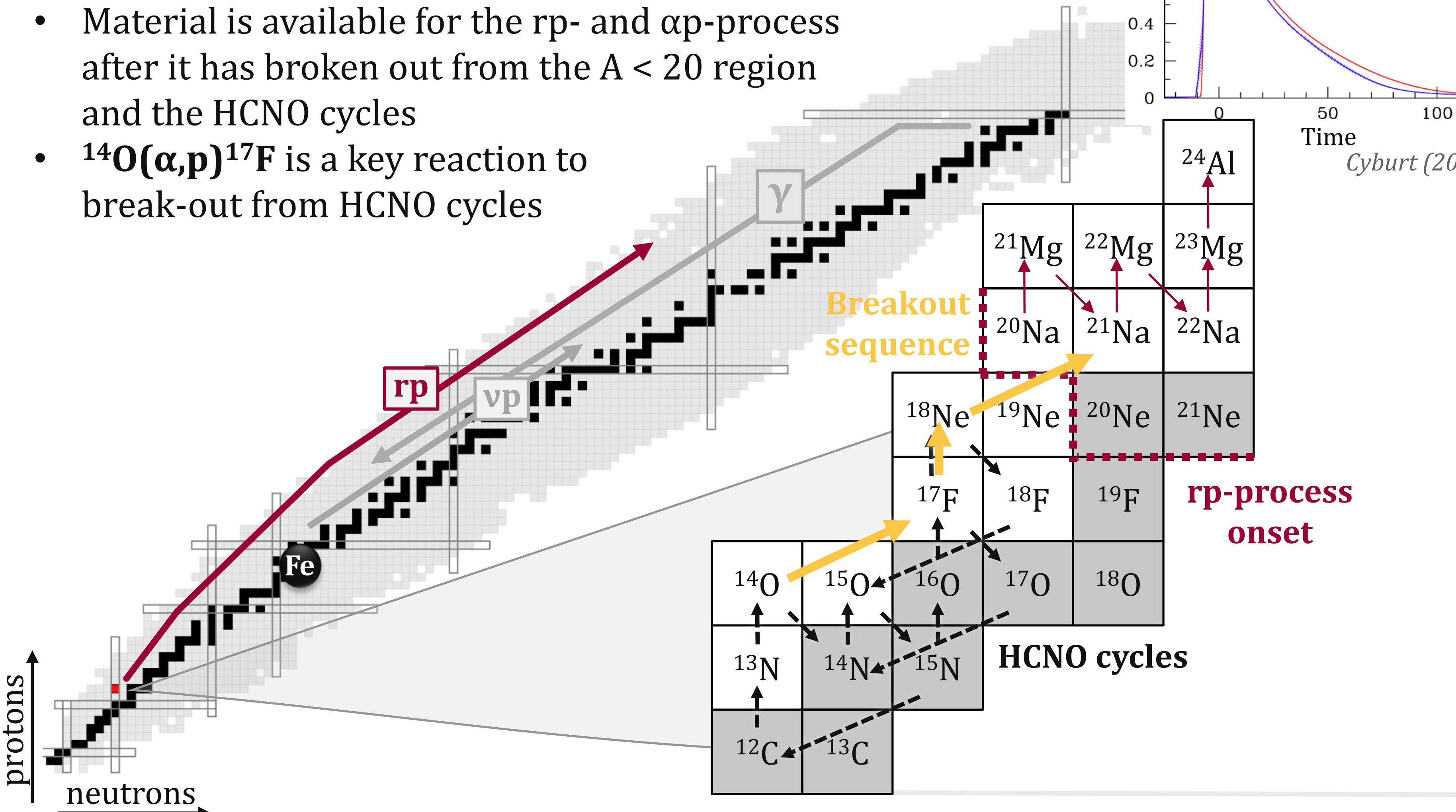
NUGRID

On the onset of the rp-process

- The underlying nucleosynthesis in the rp process can help in understanding the observed light curves
- Material is available for the rp- and αp-process after it has broken out from the A < 20 region and the HCNO cycles
- **^{14}O(α,p)^{17}F** is a key reaction to break-out from HCNO cycles



Cyburt (2016)

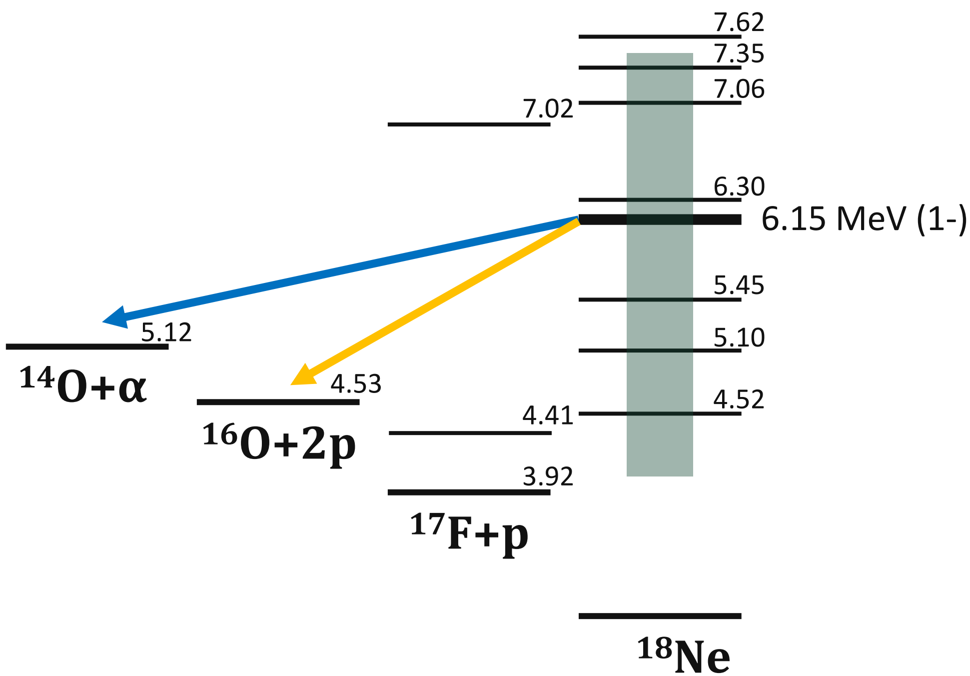


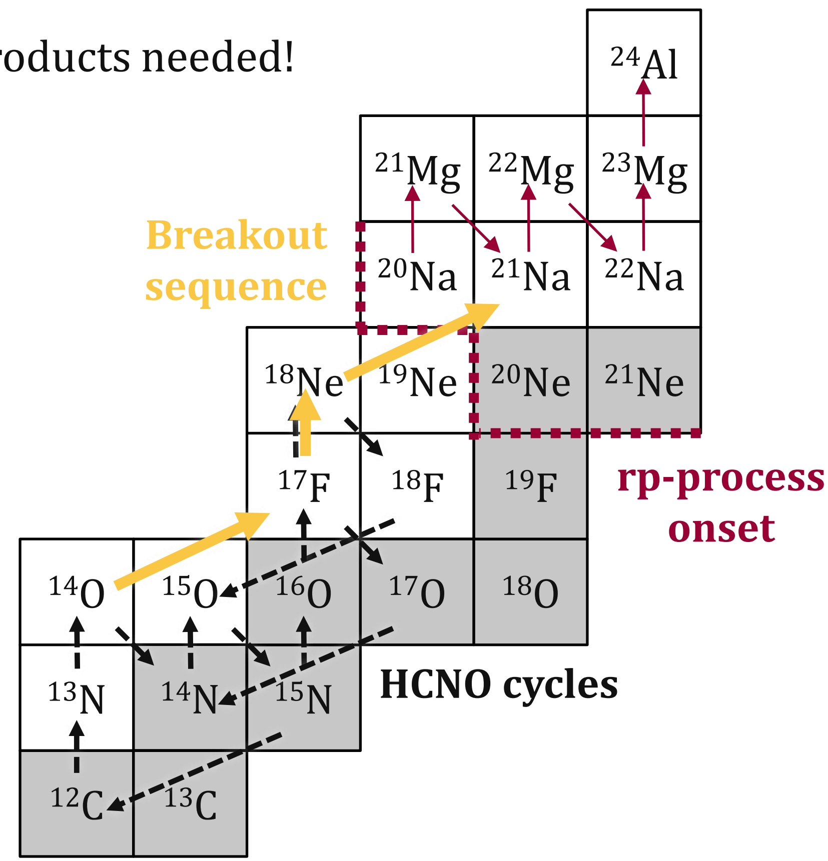
Almaraz-Calderon et al (2012)
Blackmon et al (2001)
Gómez del Campo et al (2001)

The ^{14}O(α,p)^{17}F reaction

- For $T_9 \geq 1.5$, the ^{14}O(α,p)^{17}F reaction proceeds predominantly through a **6.15 MeV (1-) resonance** in ^{18}Ne
- The 1- state is known to decay by single proton, but 2p and α channels are open
- A possible **2p branch** has been reported by previous studies (indirectly), but the results have so far been inconsistent

→ Direct measurement of the final 3-body decay products needed!

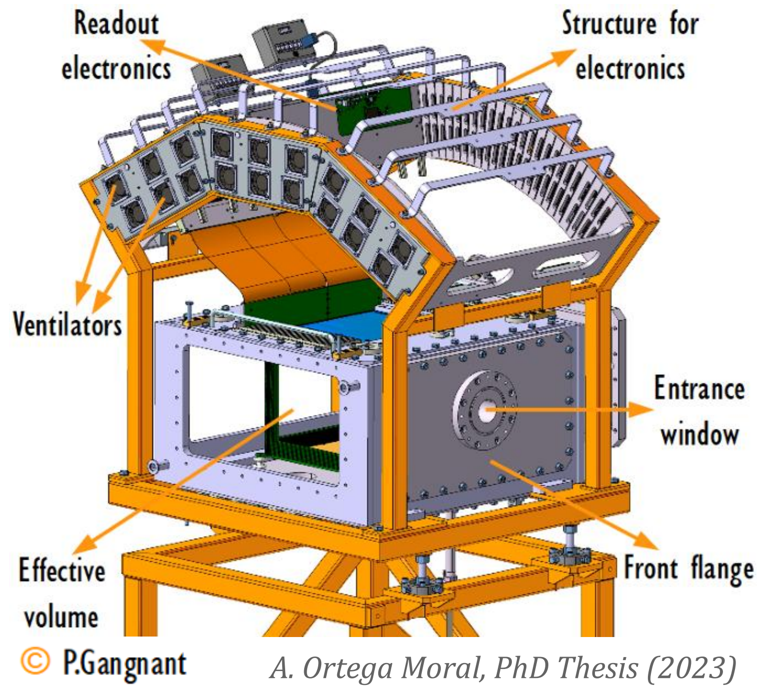




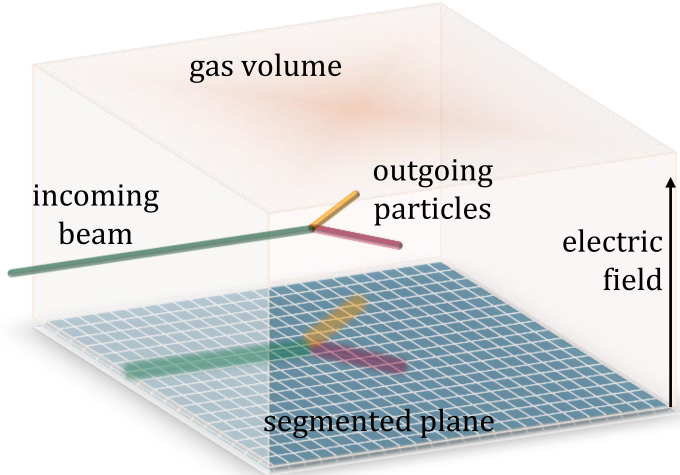
ACTAR TPC

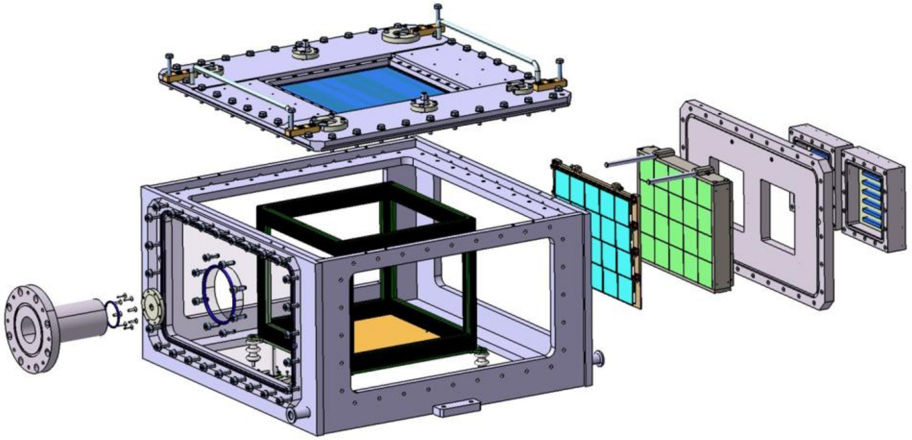
Active Target Time Projection Chamber

- Gas serves as both detection medium and target
    - Highly segmented pad plane → resolution similar to thin solid target
    - High effective thickness
- Detection efficiency close to 4π
- Detection of all reaction products
- Event-by-event 3D reconstruction → Identify rarest decays with only 1 event!



A. Ortega Moral, PhD Thesis (2023)





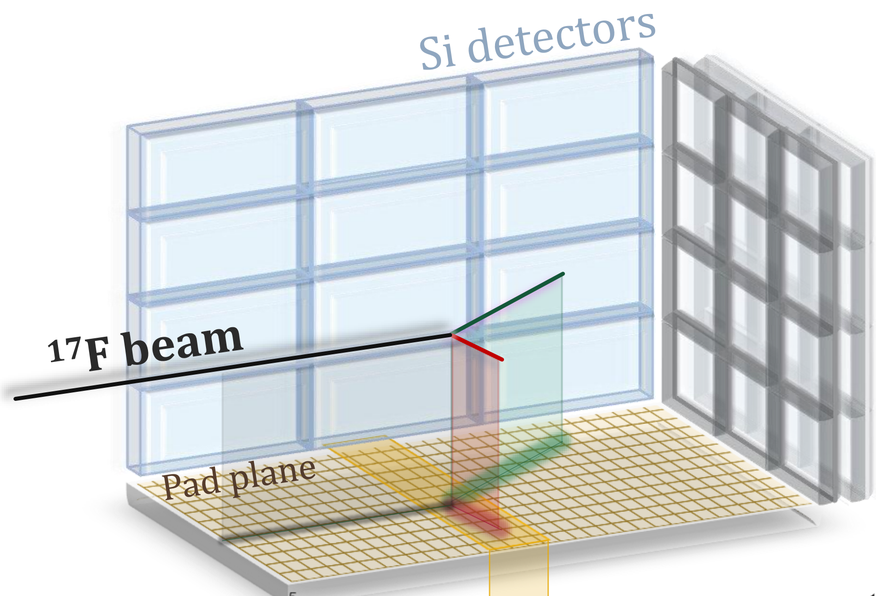
Resonant p scattering on 17F

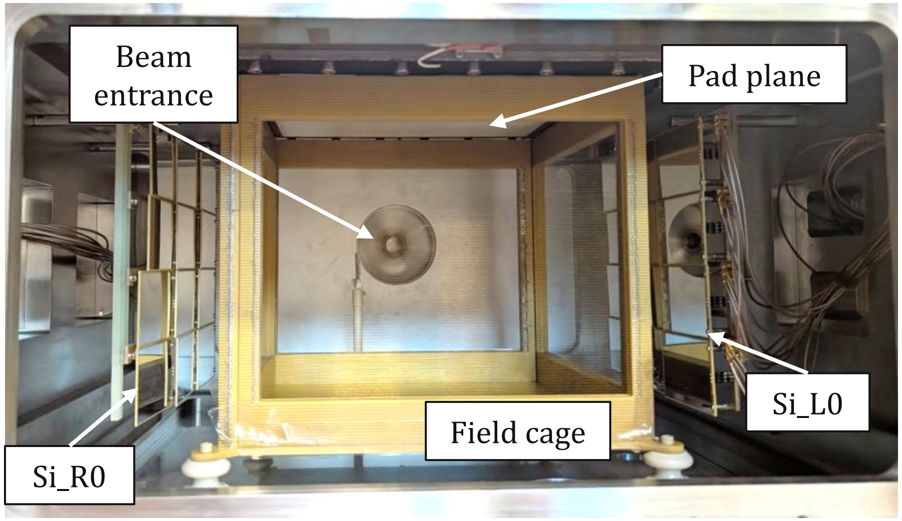
ACTAR Campaign at TRIUMF:

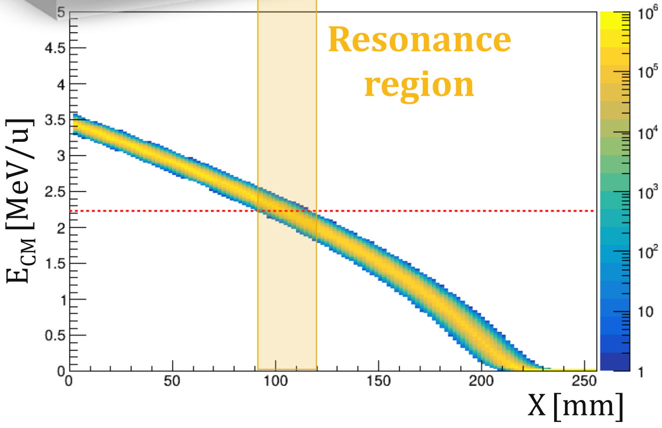
- 3 experiments, July-October 2025

S2029 (G. Grinyer, T. Roger)

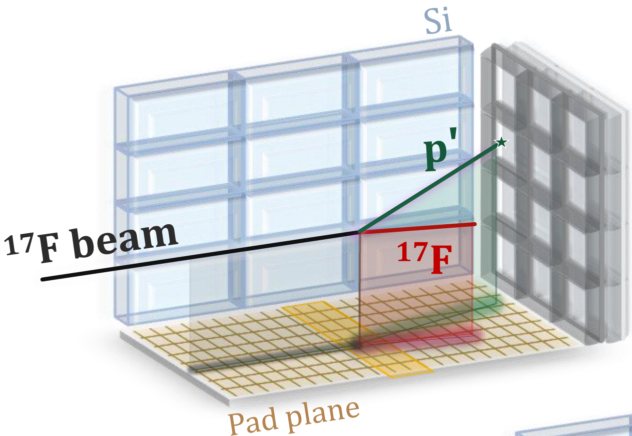
- $^{17}F^{9+}$ beam at 5.0 MeV/u, ~8E3 pps att.
- H_2 (95%) + iC_4H_{10}(5%) @ 750 mbar
- 3 Si walls for high E ejectiles



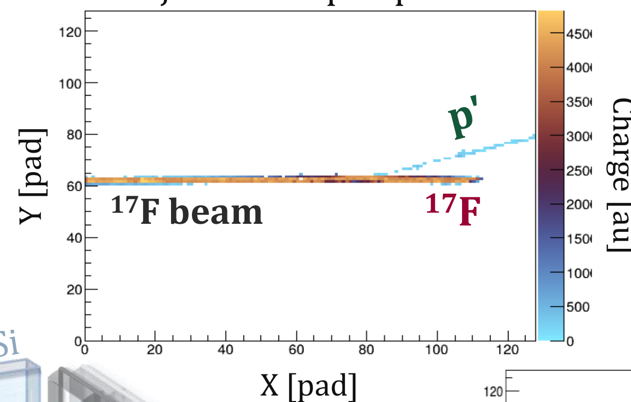


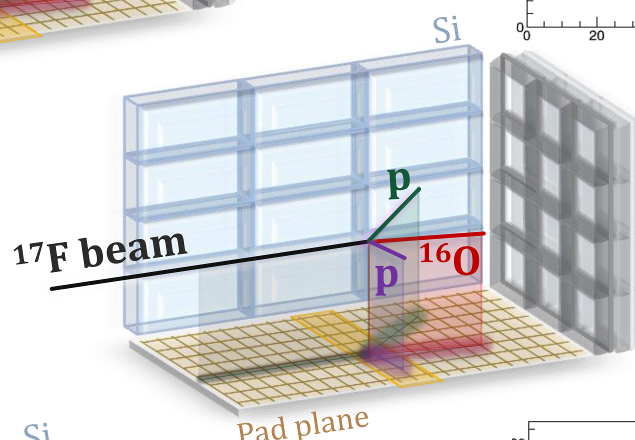


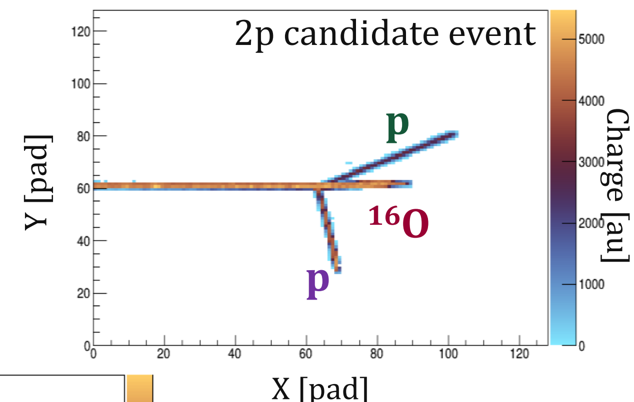
Resonant p scattering on ^{17}F

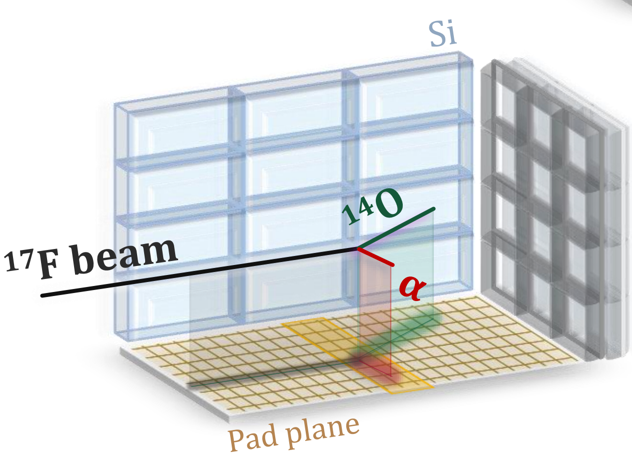


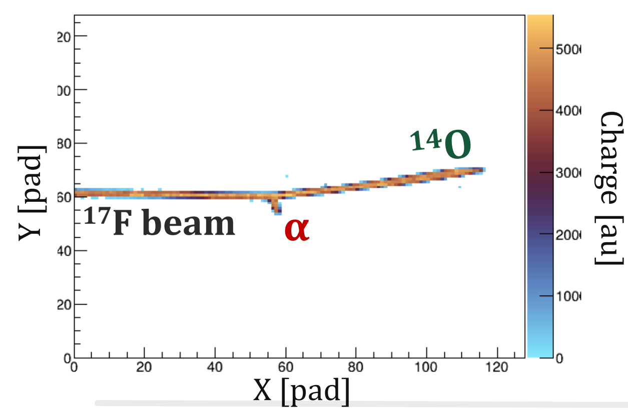
Projection on pad plane







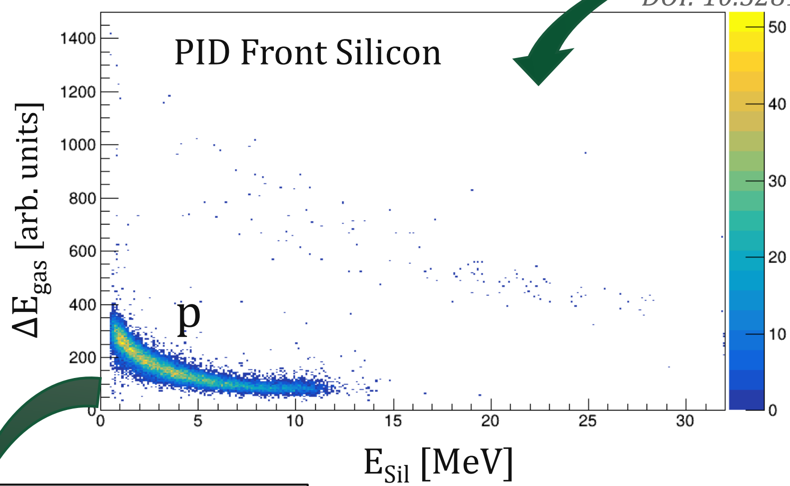


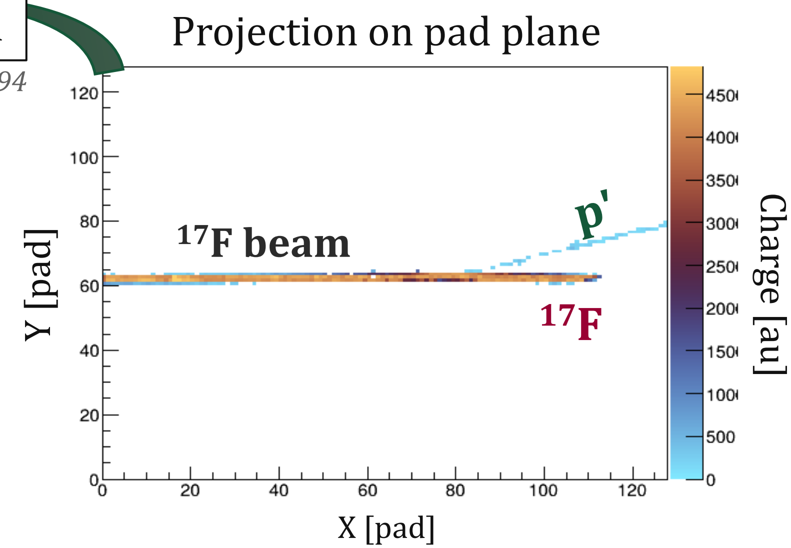


Resonant p scattering on ^{17}F

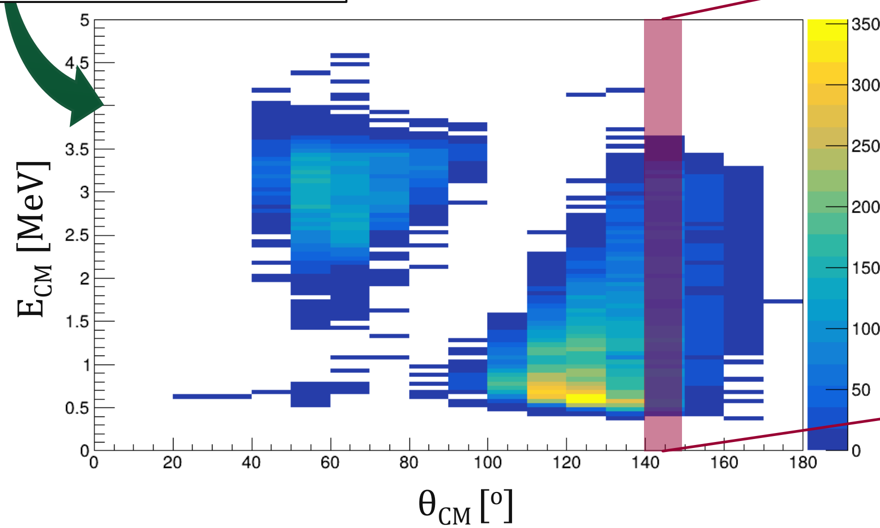
ActRoot Tracking Algorithm

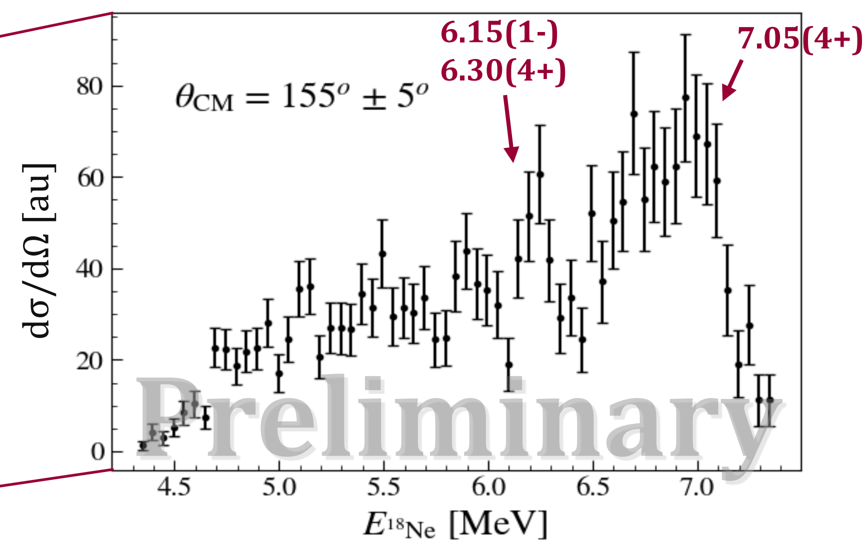
DOI: 10.5281/zenodo.18507194





Reaction kinematics
+ Energy loss tables

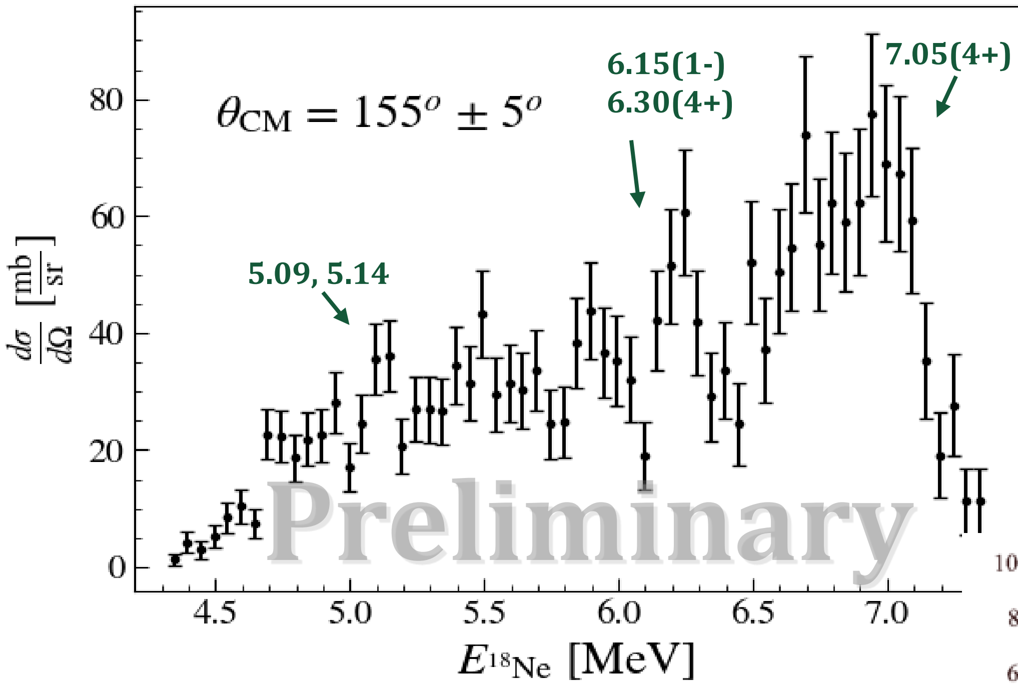




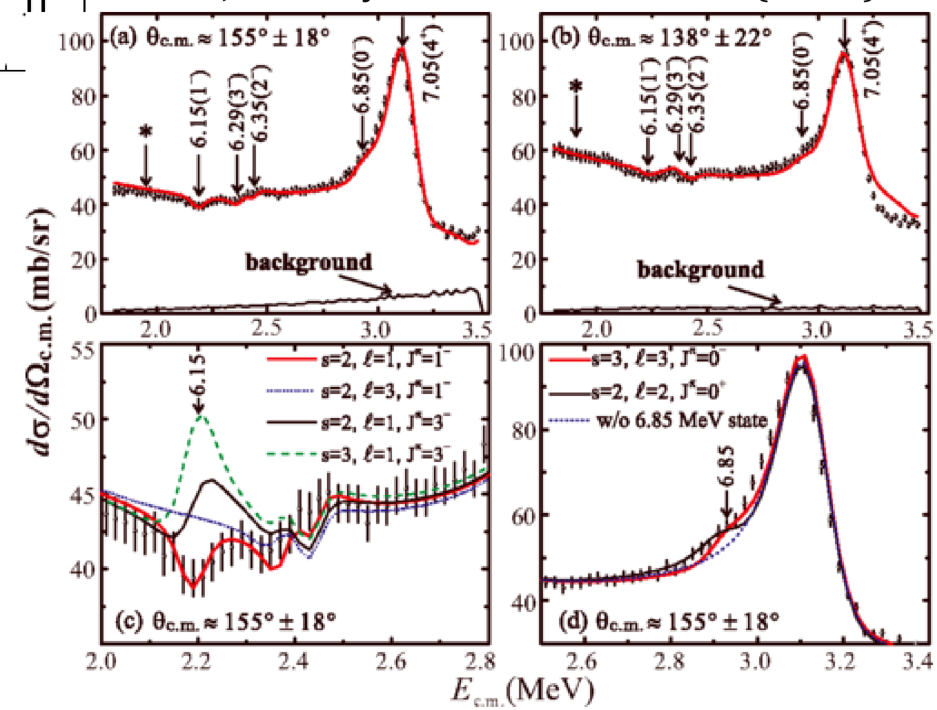
Summary

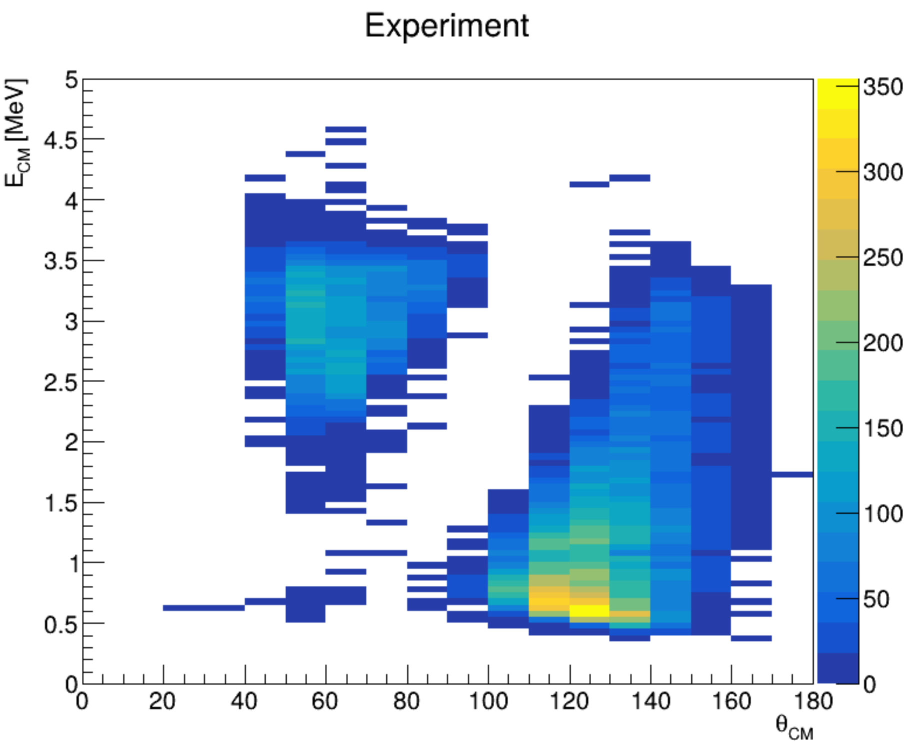
- **Radioactive beam experiments** are crucial to understand explosive nucleosynthesis
- **^{73}As(p,γ)^{74}Se**:
  - Last nuclear uncertainty for synthesis of ^{74}Se p nucleus
  - SuN@FRIB:
    direct measurement of a γ-process reaction with a radioactive beam in the Gamow window
  - Uncertainty of ^{74}Se production reduced by a factor of two
- **^{14}O(α,p)^{17}F**:
  - Breakout from HCNO in novae and X-ray bursts
  - Decay of 6.15 MeV state:
    Possible α and 2p channels?
  - ACTAR TPC @ TRIUMF:
    resonant p scattering on ^{17}F experiment complete

Backup Slides

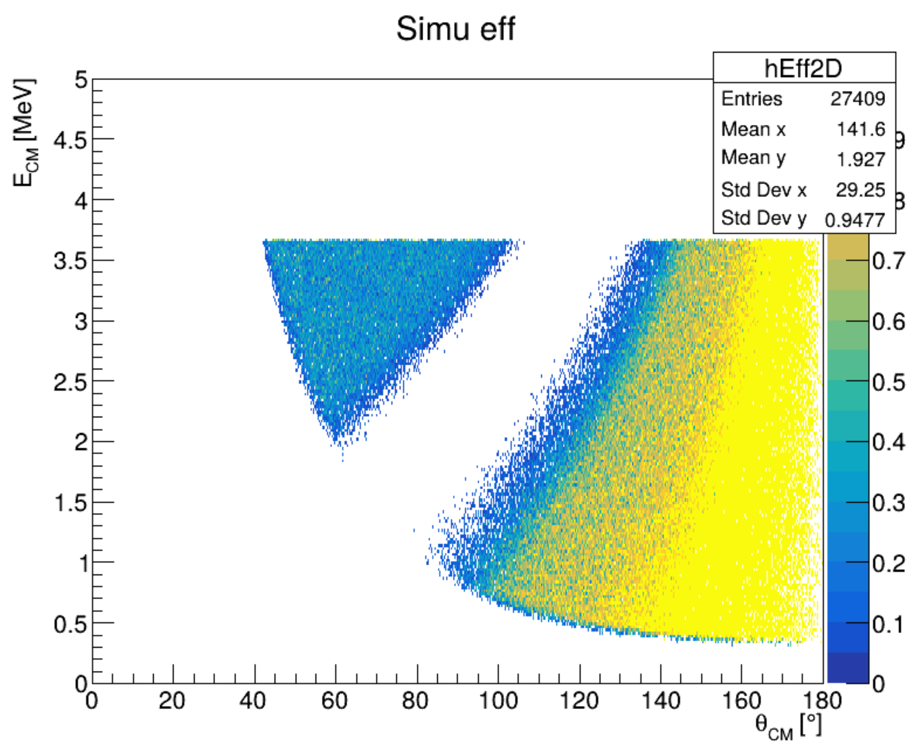


J. Hu Phys. Rev. C 90, 025803 (2014)



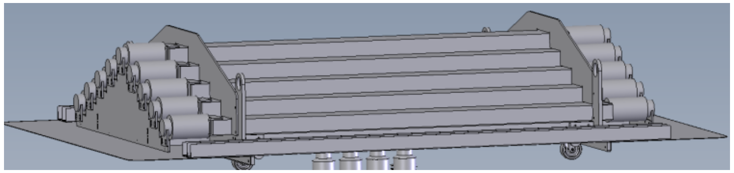


Experiment
E_{CM} [MeV]
θ_{CM}
0
20
40
60
80
100
120
140
160
180
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
50
100
150
200
250
300
350

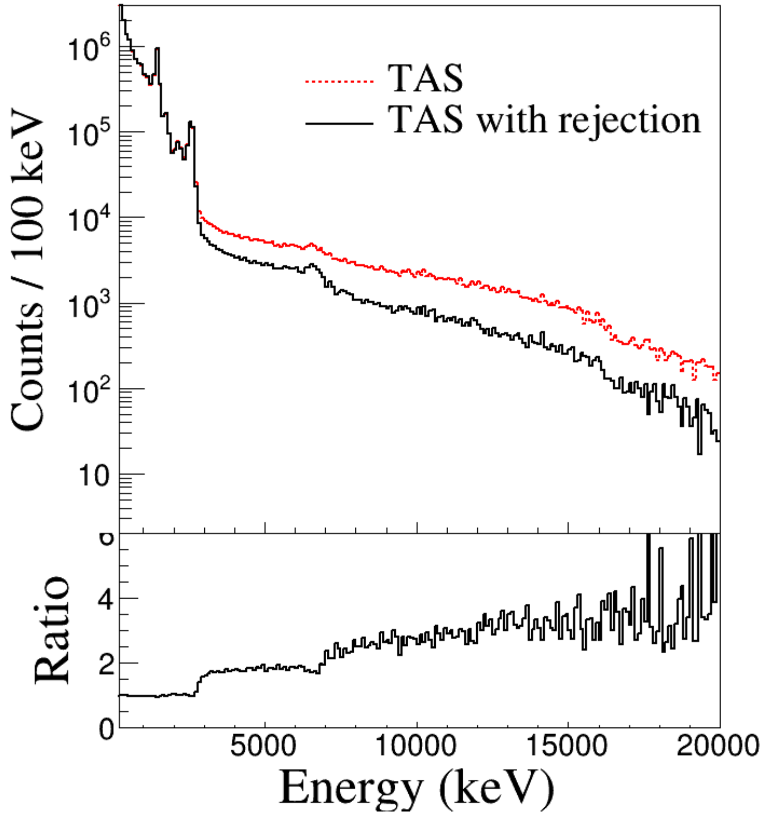


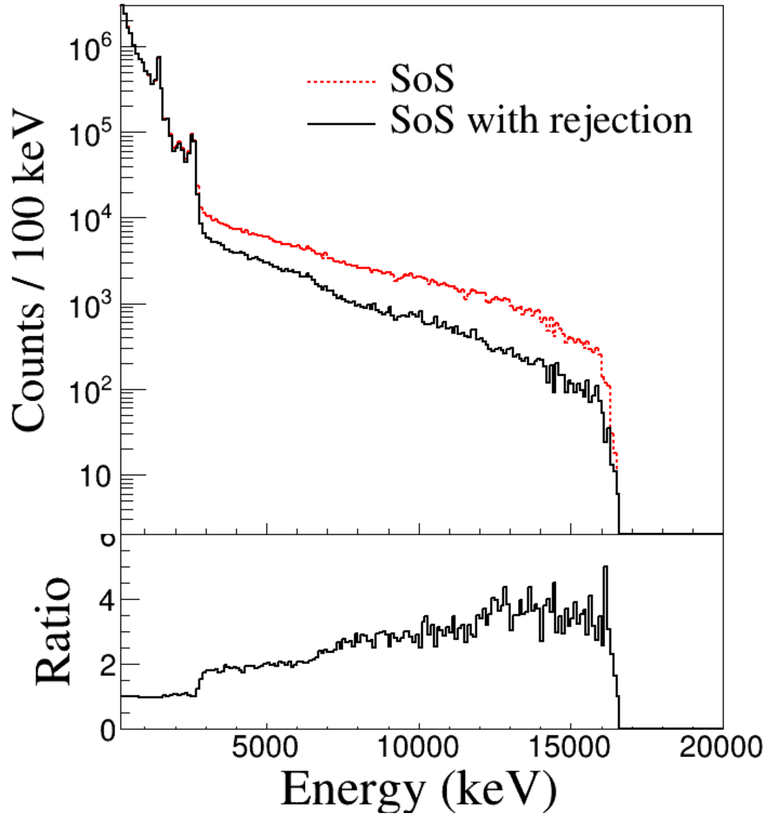
Simu eff
hEff2D
Entries 27409
Mean x 141.6
Mean y 1.927
Std Dev x 29.25
Std Dev y 0.9477
E_{CM} [MeV]
θ_{CM} [°]
0
20
40
60
80
100
120
140
160
180
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

Background Subtractions



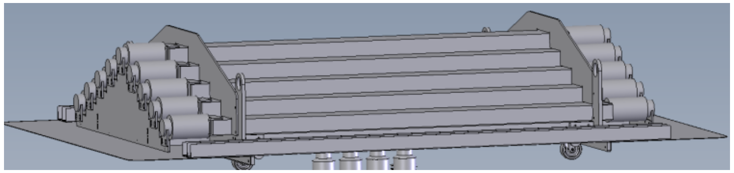
Cosmic rays → SuNSCREEN veto rejection*





*Klopfer et al., NIM-A 788 (2025)

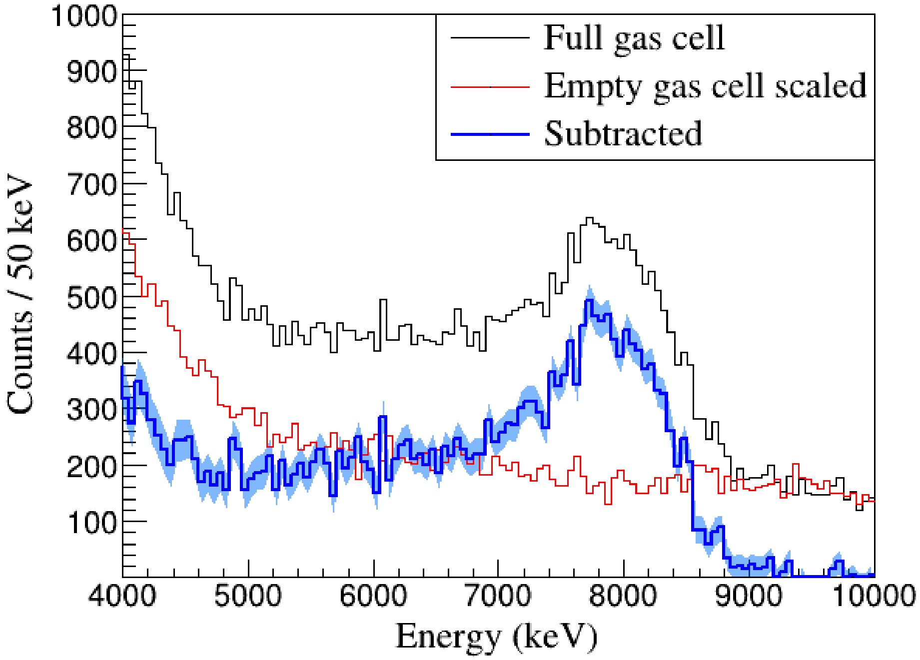
Background Subtractions



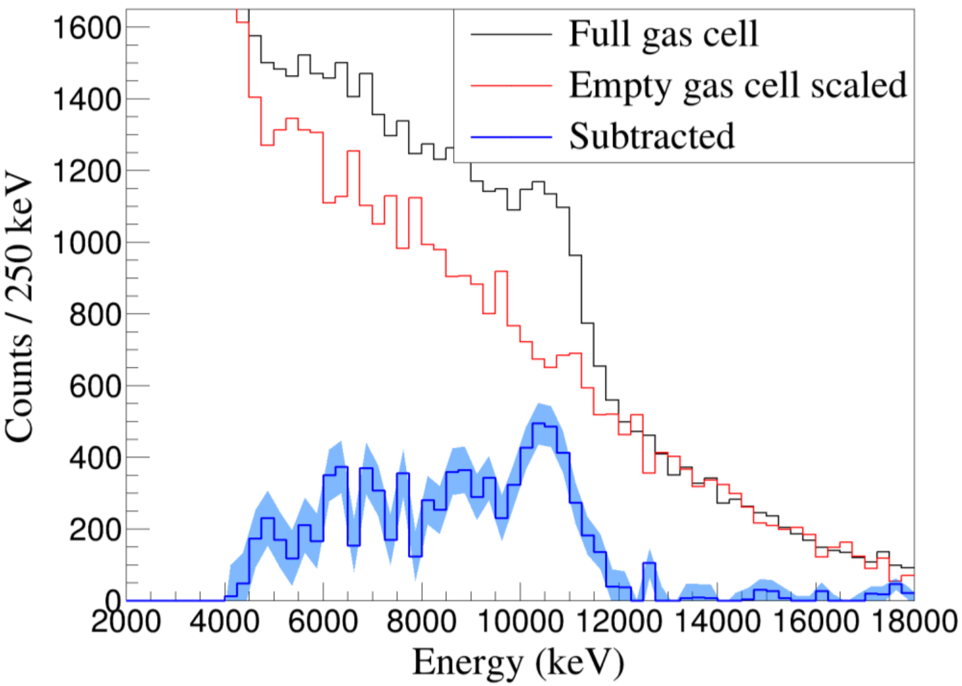
Cosmic rays → SuNSCREEN veto rejection*
→ Pulsed beam

Interaction of the beam with the beam line and the gas cell → gas cell full and empty runs

$^{82}Kr(p,\gamma)^{83}Rb$



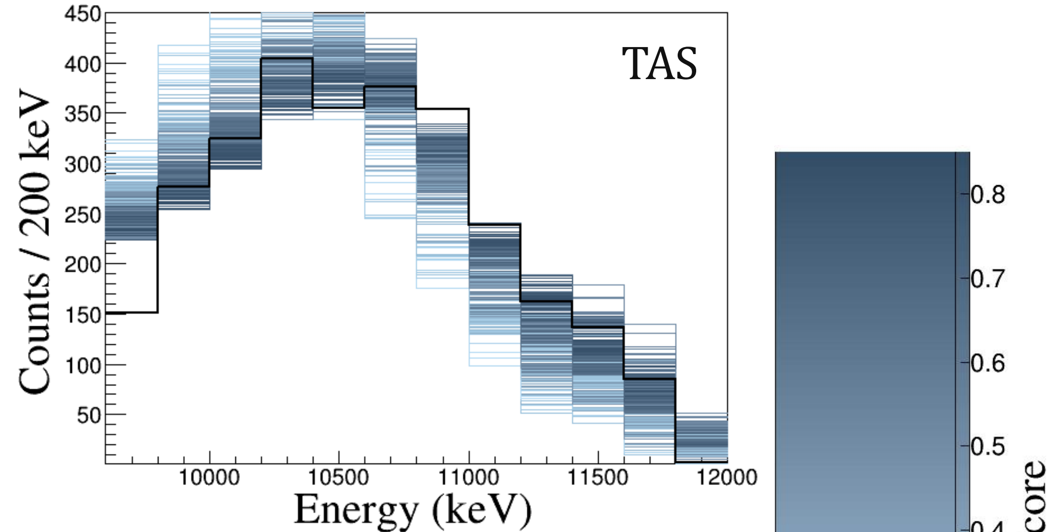
$^{73}As(p,\gamma)^{74}Se$

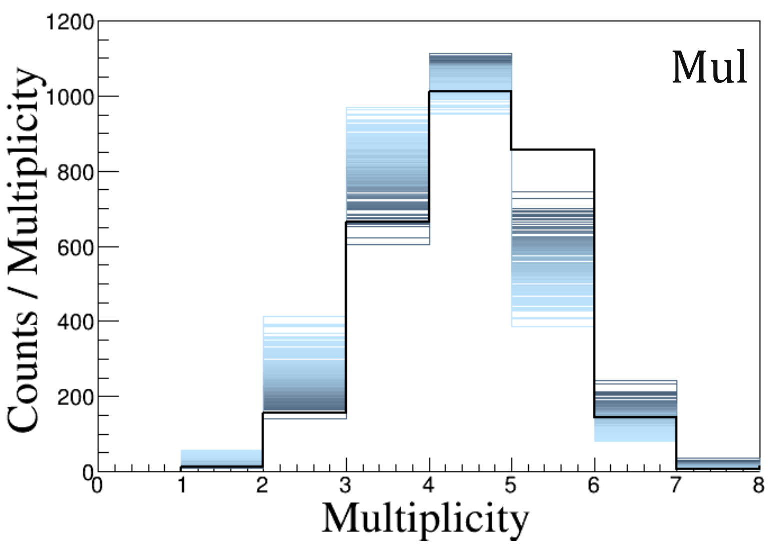


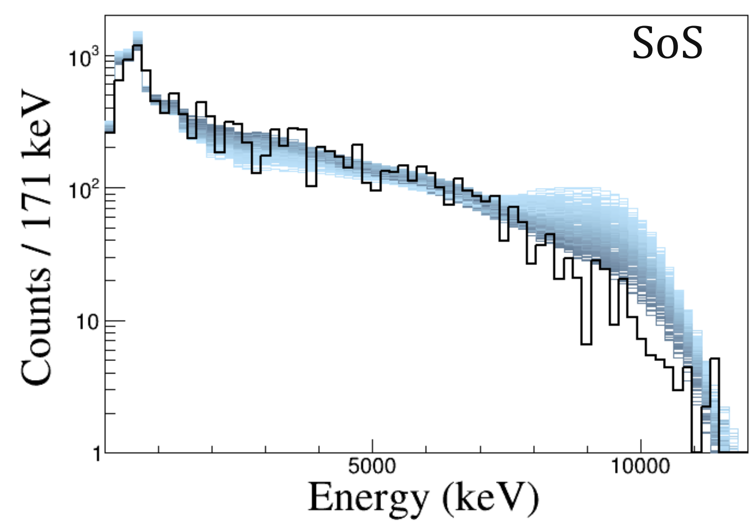
Characterization of NLD/γSF combinations

Utilize our sensitivity in the statistical properties of the compound nucleus to characterize the various NLD and γSF model combinations in TALYS

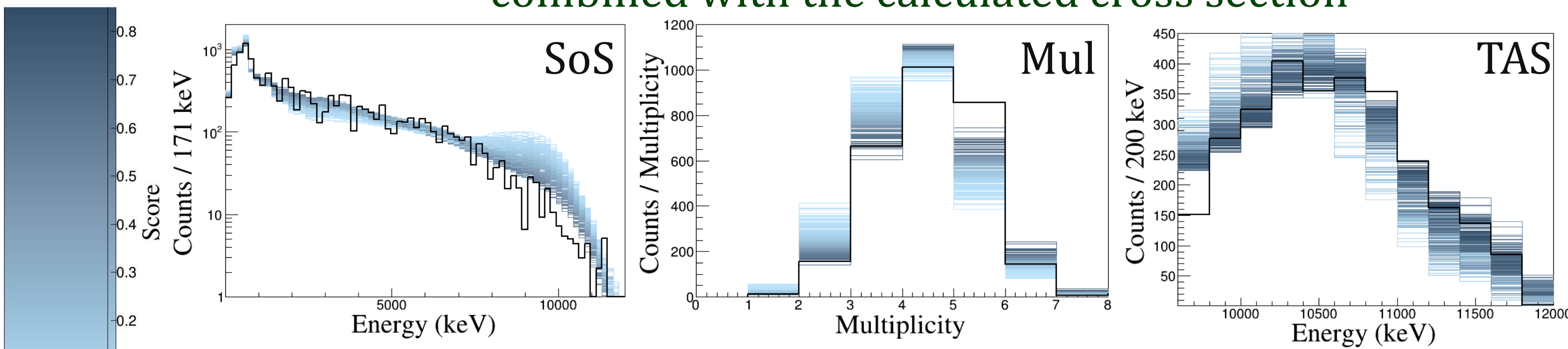
$$Score = \exp\left({}^{-\chi^2}\!\big/_{2N_{bins}}\right)$$

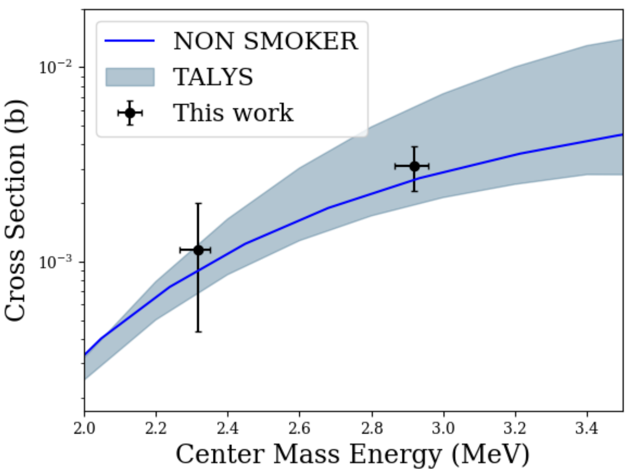


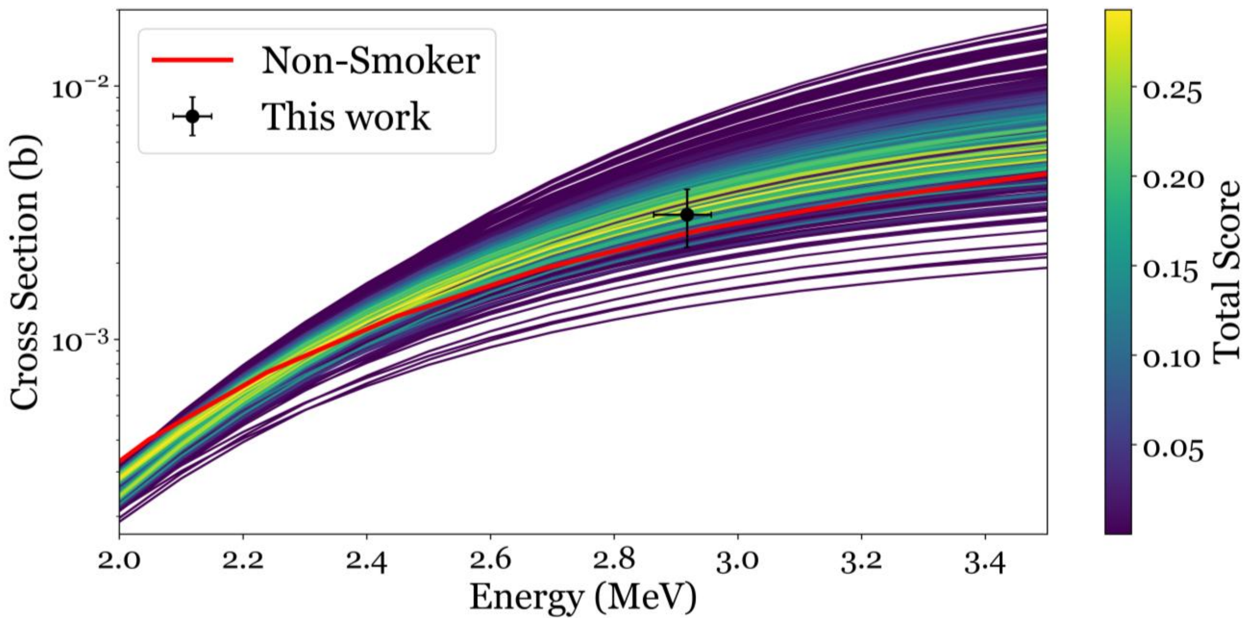




Characterize all Talys models based on their “score” from the TAS, SoS, Mul spectra combined with the calculated cross section

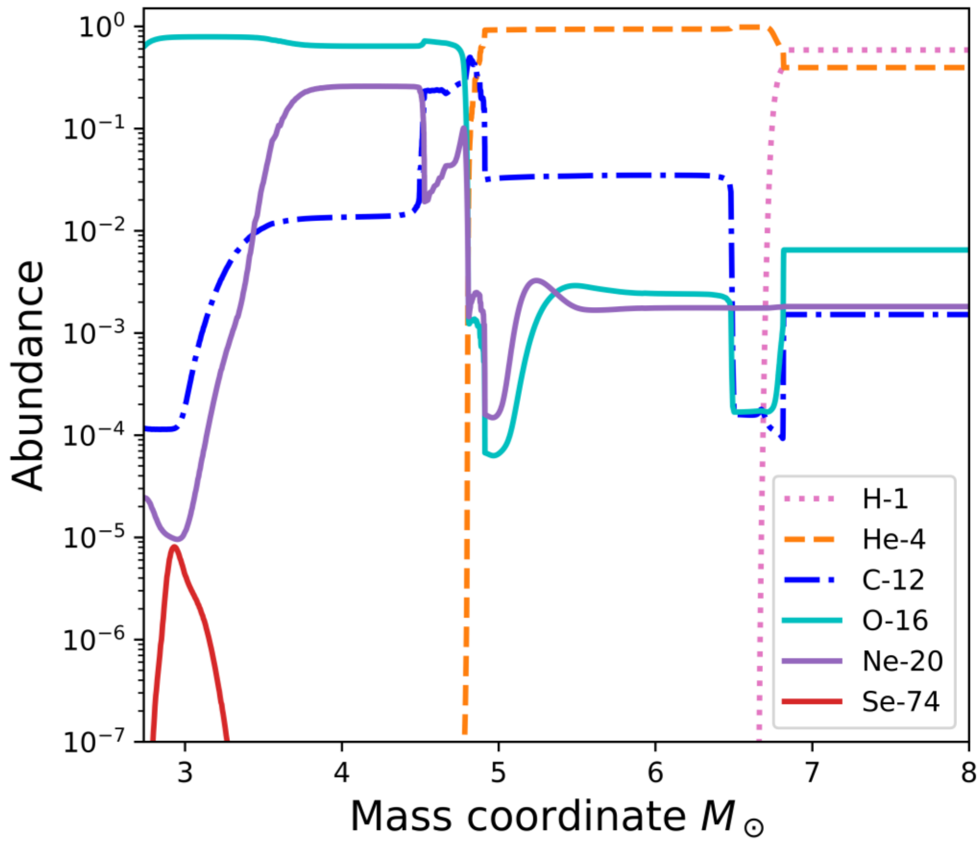






Astrophysical Impact in SNII

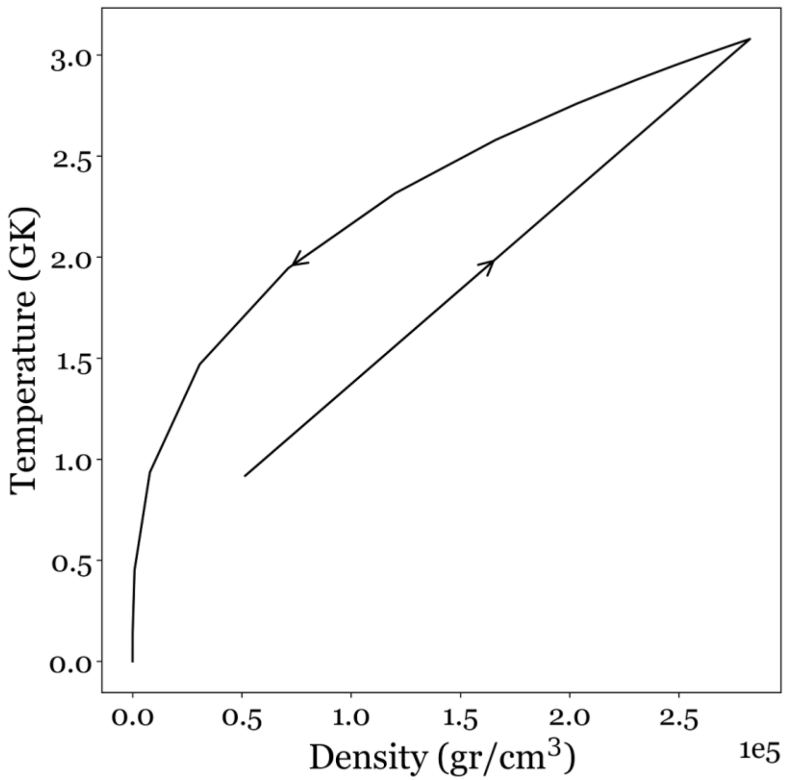
- 20 $M_\odot$ SNII model by NuGrid Collaboration

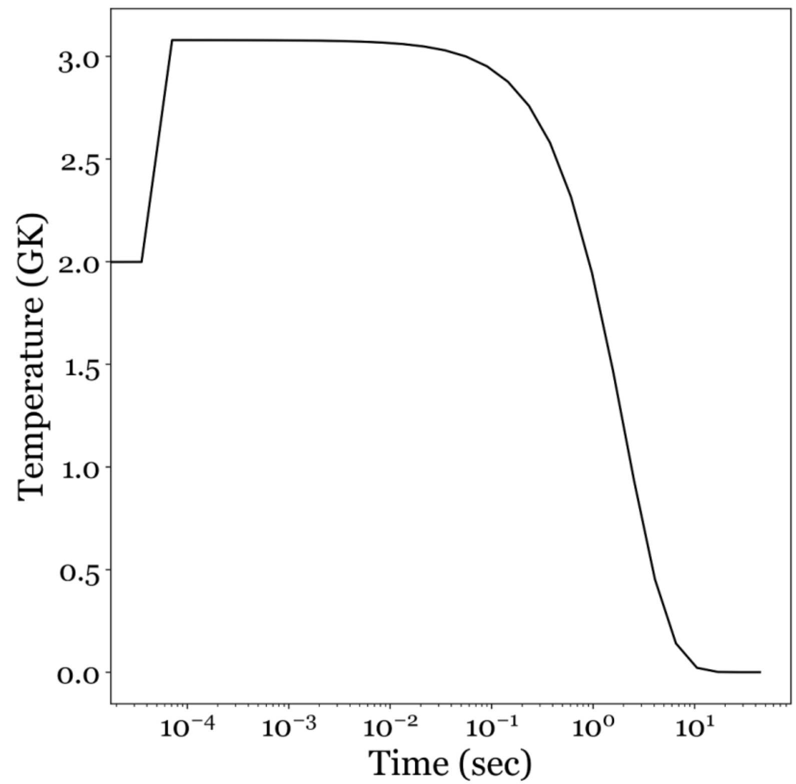


^{74}Se production in 20 $M_\odot$ SNII model by Ritter *et al.* (2020) using NuGridPy tools

Astrophysical Impact in SNII

- 20 $M_\odot$ SNII model by NuGrid Collaboration
- Extract temperature and density trajectories

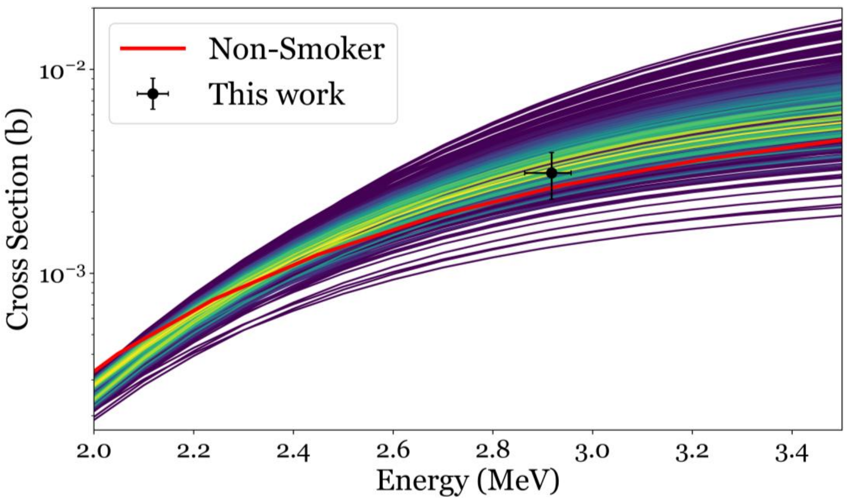


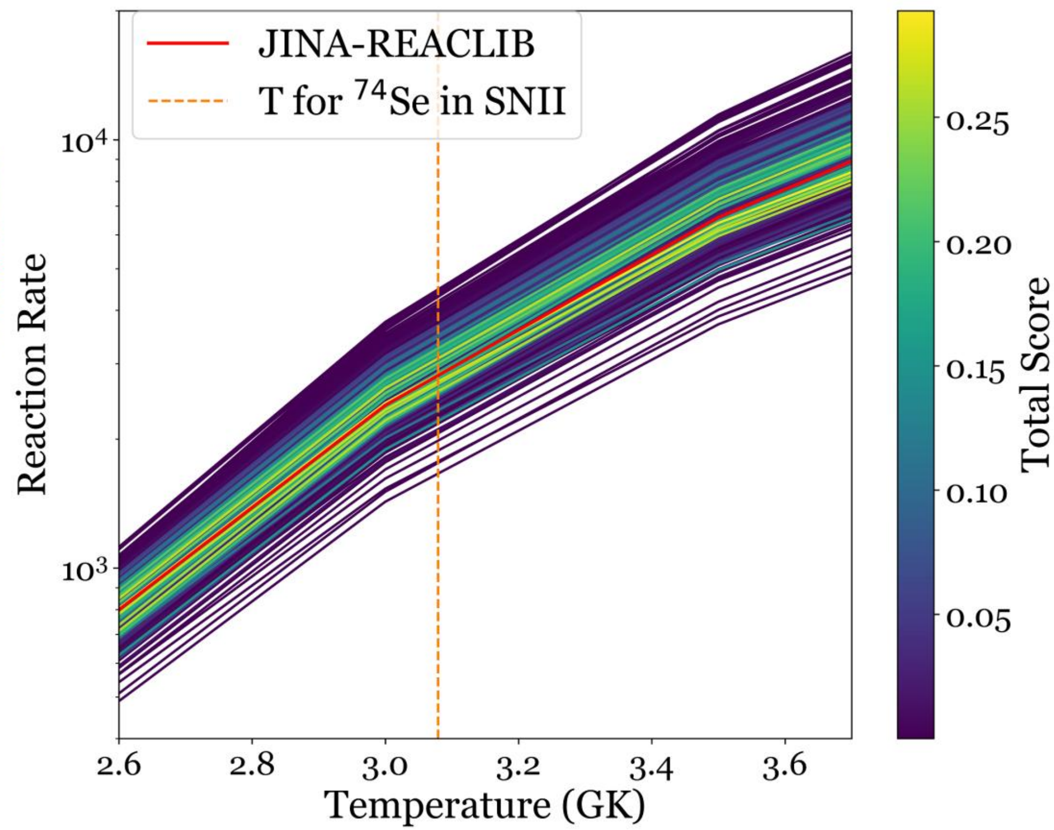


Temperature and density of M=2.9 $M_\odot$ mass coordinate where ^{74}Se is mostly produced

Astrophysical Impact in SNII

- 20 $M_{\odot}$ SNII model by NuGrid Collaboration
- Extract temperature and density trajectories
- Calculate distribution of reaction rates based on total score





Astrophysical Impact in SNII

- 20 $M_\odot$ SNII model by NuGrid Collaboration
- Extract temperature and density trajectories
- Calculate distribution of reaction rates based on total score
- Monte Carlo sampling of rates