Explosive nucleosynthesis on the p-rich side

Artemis Tsantiri

ECT* Workshop, Trento

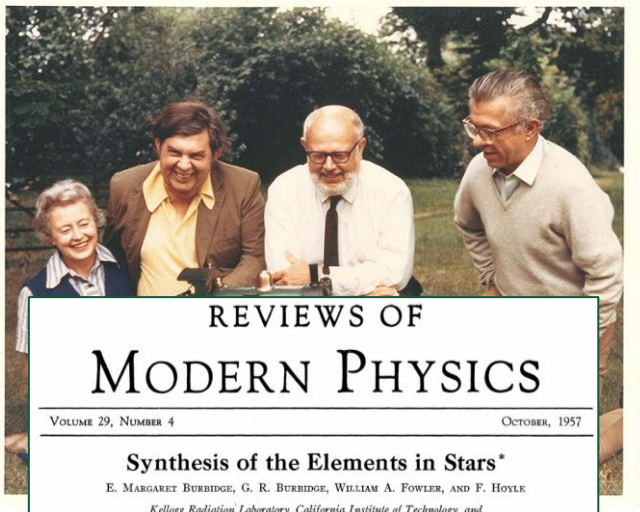
May 18th, 2026

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https://atsantiri.github.io

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

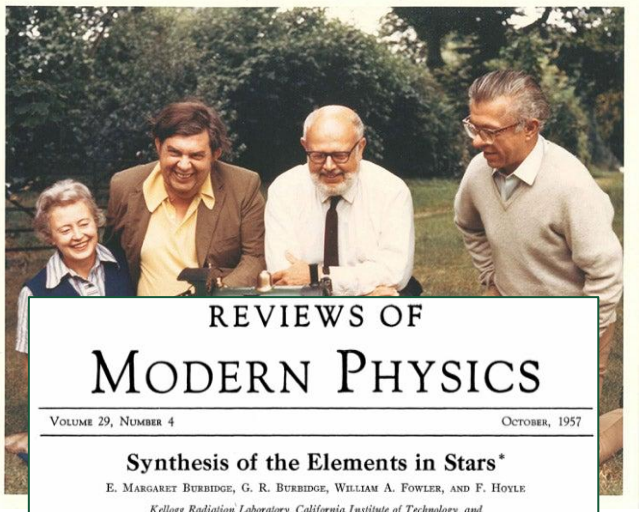
Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

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

but perhaps

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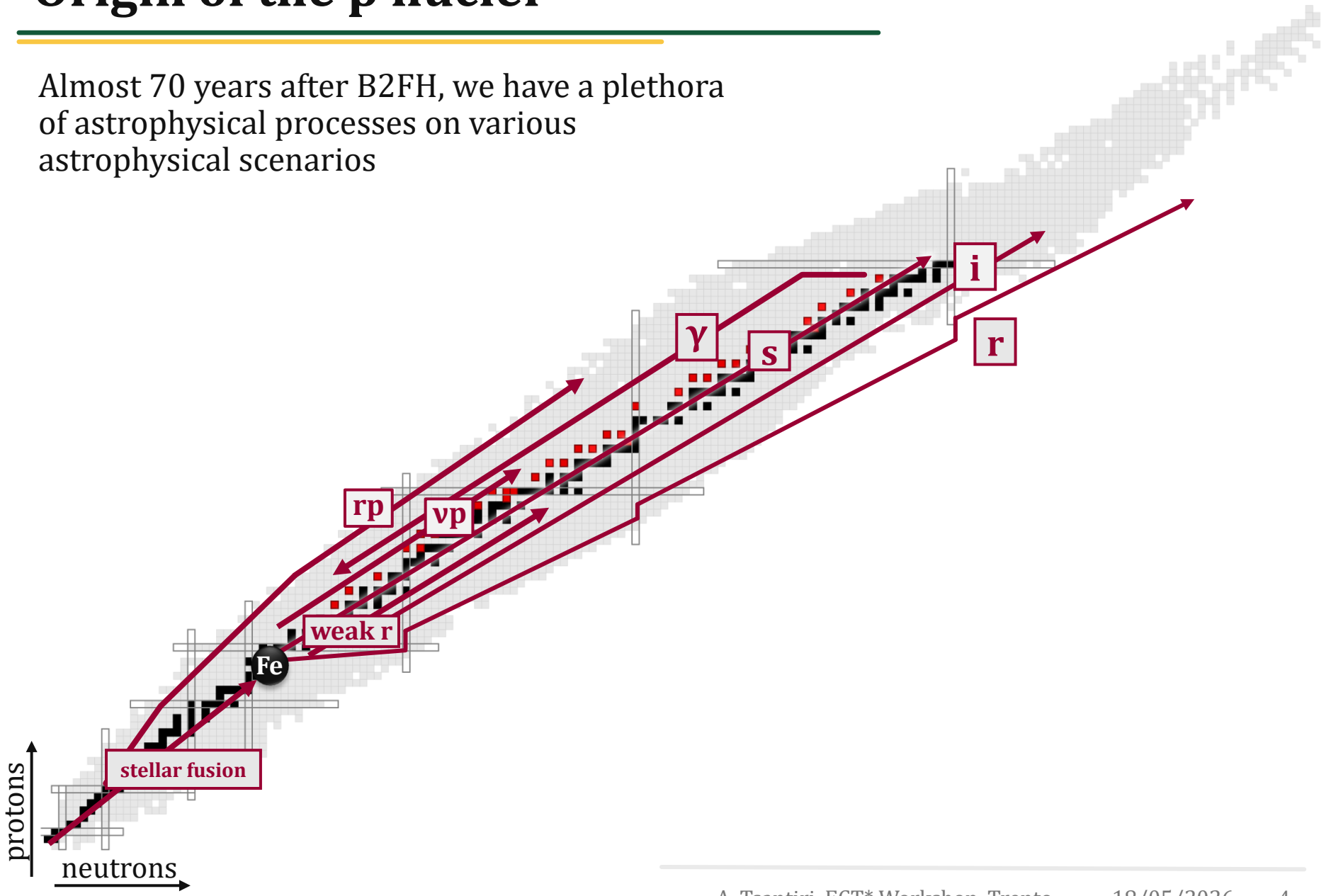
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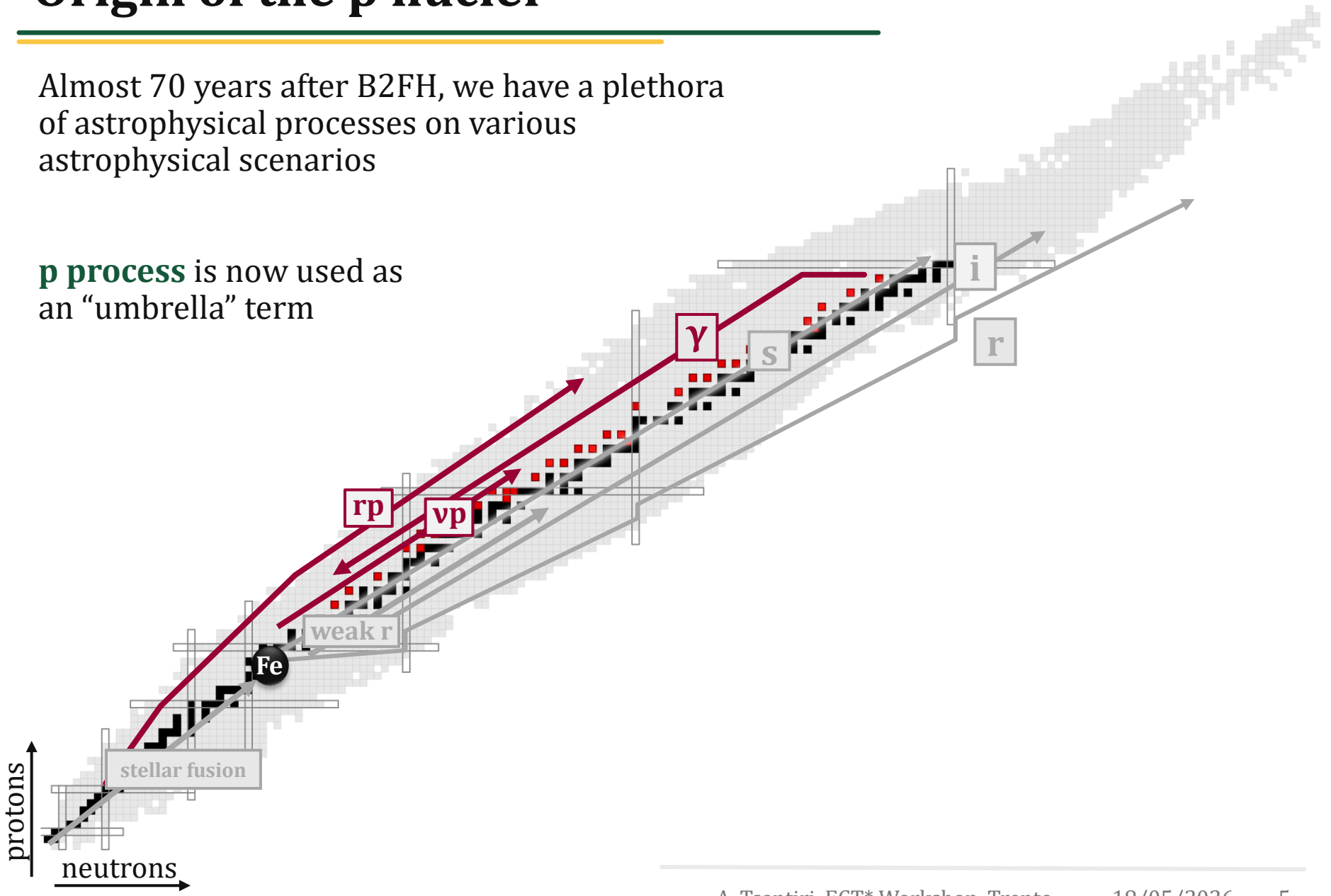
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Origin of the p nuclei

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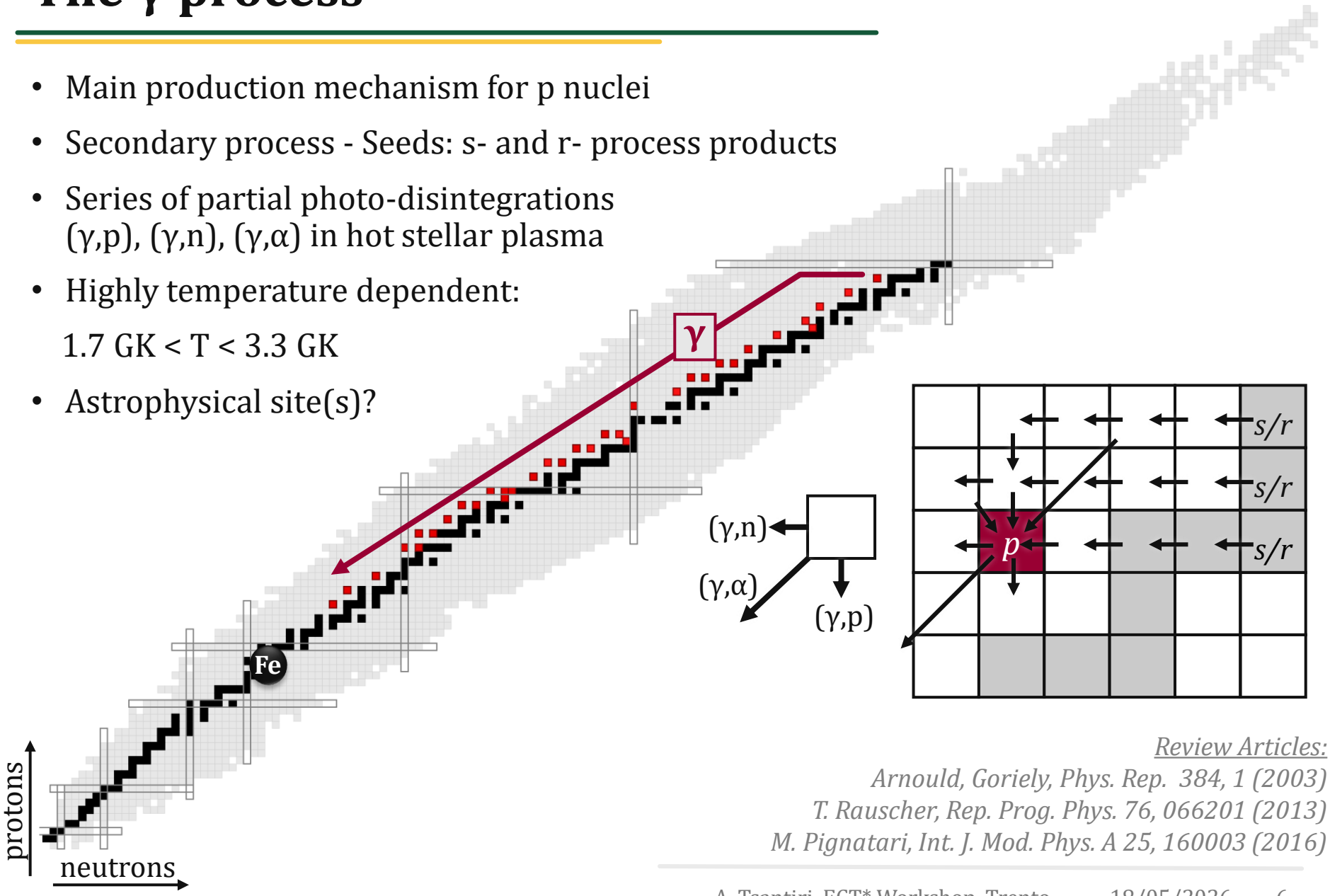
p process is now used as an “umbrella” term



The γ process

- Main production mechanism for p nuclei
- Secondary process - Seeds: s- and r- process products
- Series of partial photo-disintegrations
  (γ,p), (γ,n), (γ,α) in hot stellar plasma
- Highly temperature dependent:

  1.7 GK < T < 3.3 GK
- Astrophysical site(s)?



Review Articles:

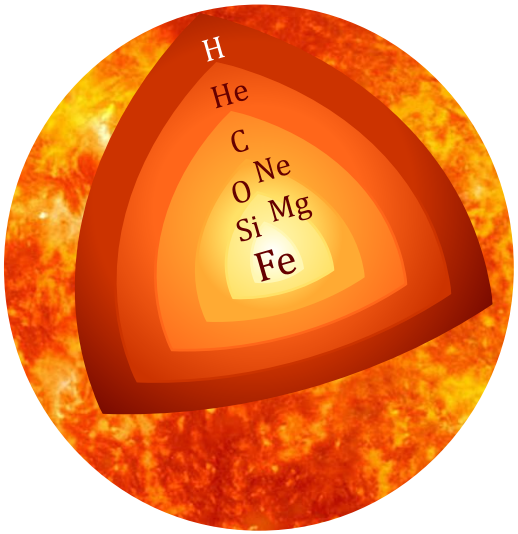
Arnould, Goriely, Phys. Rep. 384, 1 (2003)

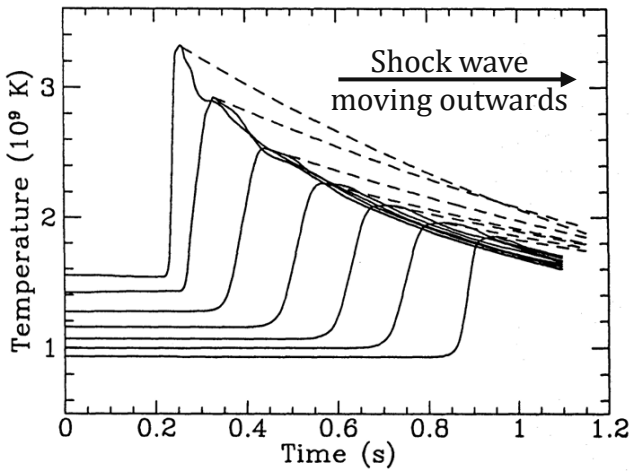
T. Rauscher, Rep. Prog. Phys. 76, 066201 (2013)

M. Pignatari, Int. J. Mod. Phys. A 25, 160003 (2016)

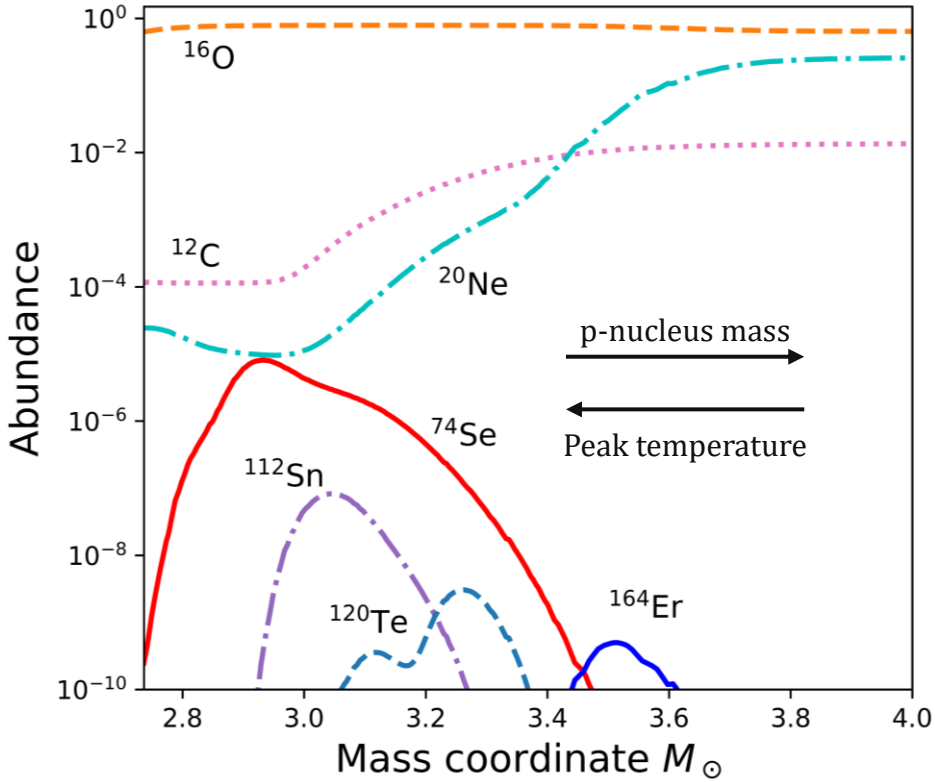
γ process sites

O/Ne layers of Type II supernovae (M > 8-9 $M_\odot$)





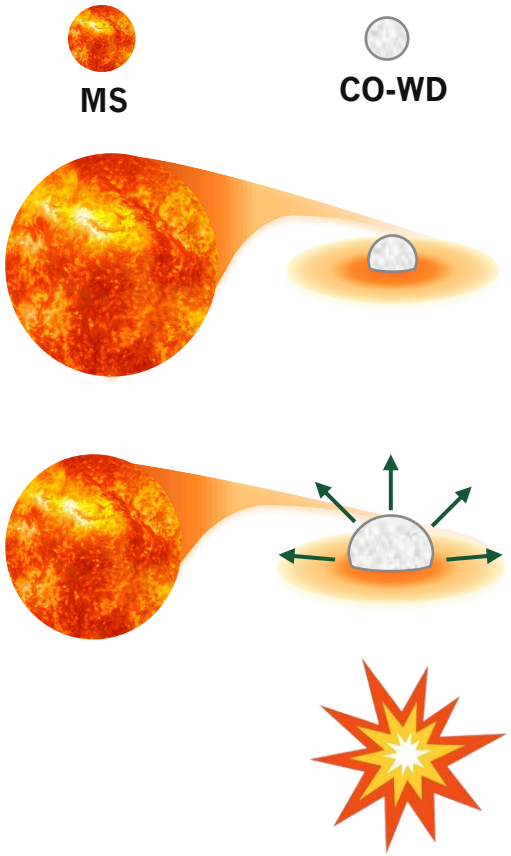
Rayet et al, A&A 298 517 (1995)

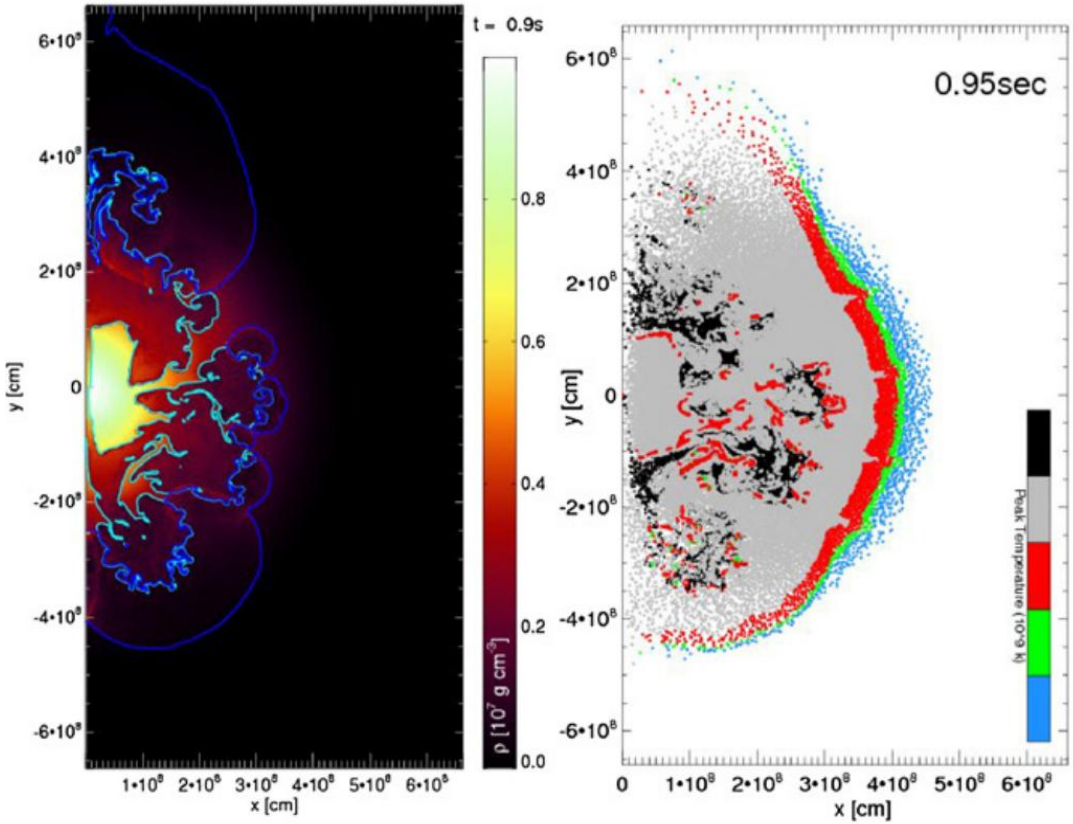


Example *p*-nuclei production in 20 $M_\odot$ SNII model by NuGrid - Ritter et al MNRAS 480, 538–571 (2018)

γ process sites

Type-Ia supernovae



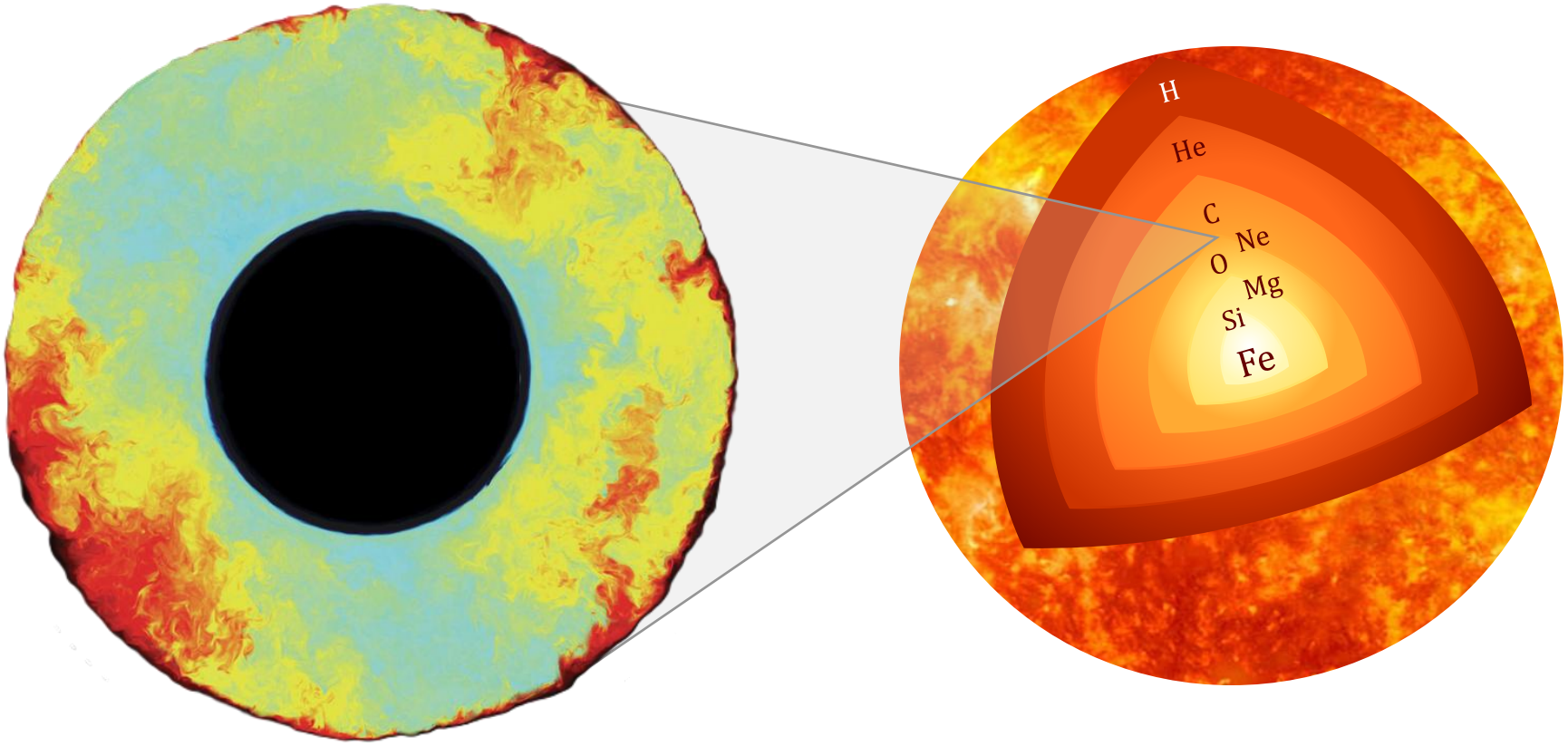


2D SNIa simulation by Travaglio (2011)

γ process sites

Rauscher, ApJ 576, 323 (2002)
Ritter, MNRAS, 474, L1 (2018)
Roberti, A&A, 677, A22 (2023)
Issa, ApJ 997 41 (2026)

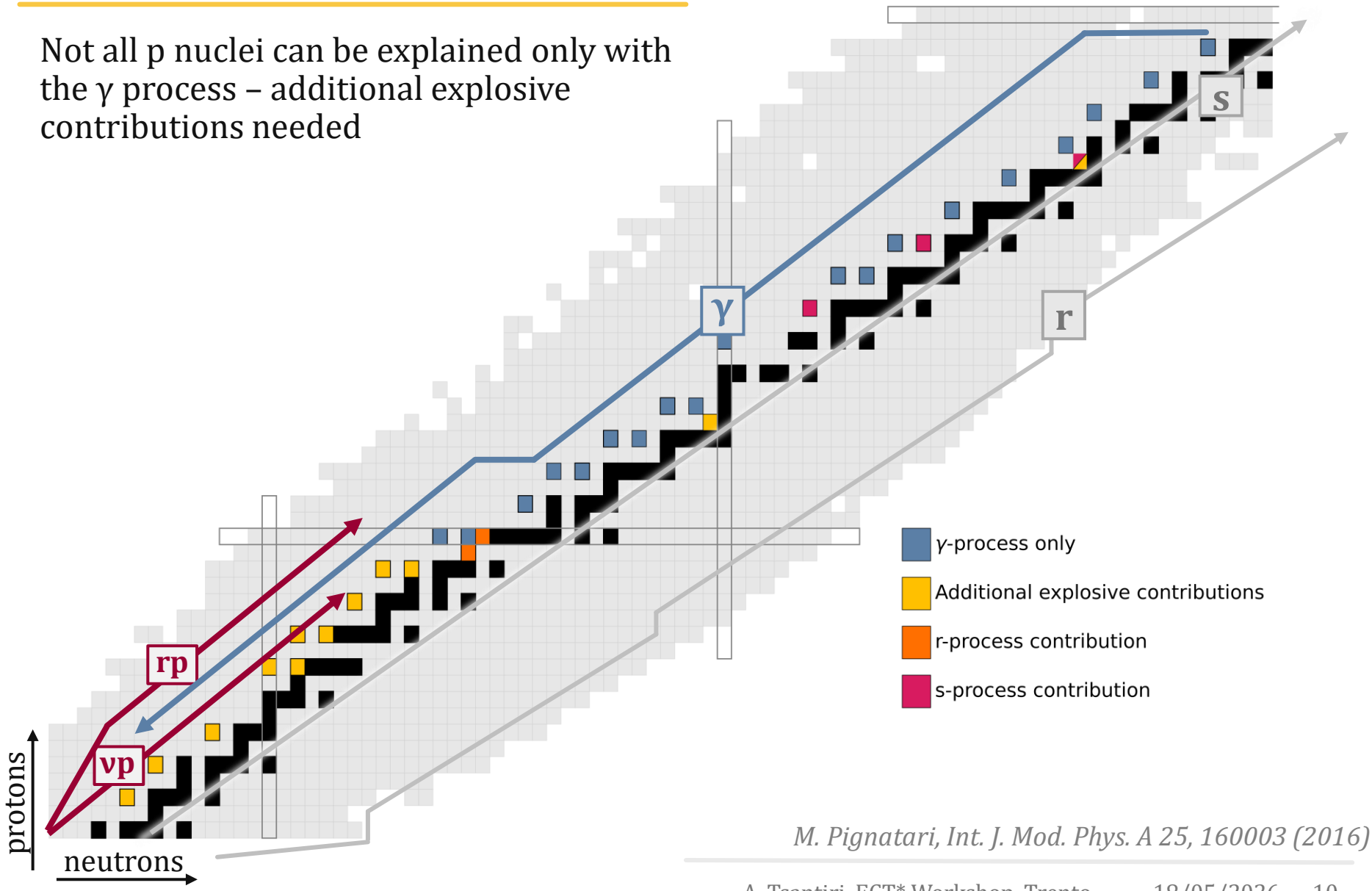
C-O shell mergers (8-9 $M_\odot$ > M > 25-30 $M_\odot$)



3D hydro simulation of C ingestion into a convective O shell,
Andrassy et al, MNRAS491, 972–992 (2020)

Origin of the p nuclei

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

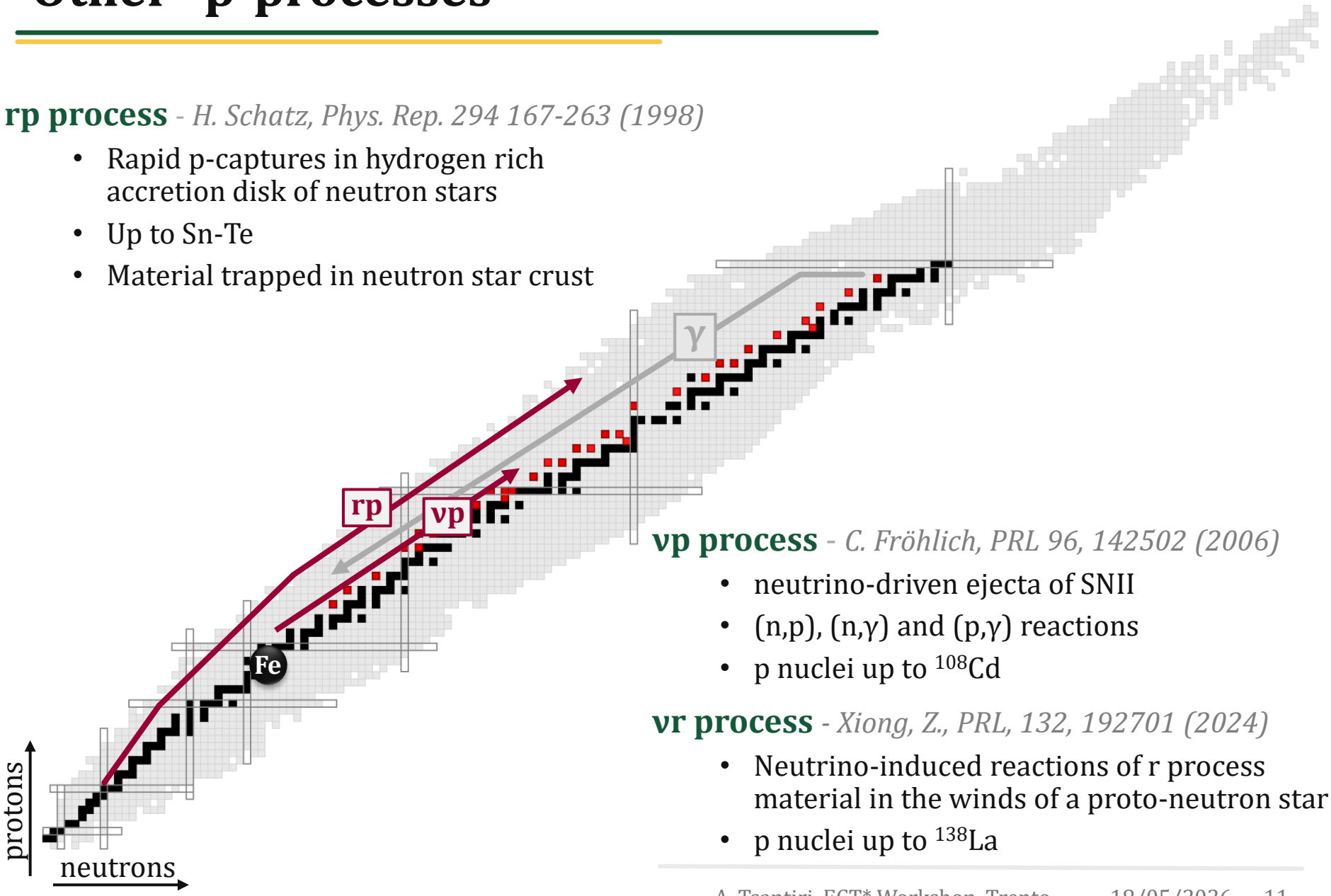


M. Pignatari, Int. J. Mod. Phys. A 25, 160003 (2016)

Other “p-processes”

rp process - *H. Schatz, Phys. Rep. 294 167-263 (1998)*

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



νp process - *C. Fröhlich, PRL 96, 142502 (2006)*

- neutrino-driven ejecta of SNII
- (n,p), (n,γ) and (p,γ) reactions
- p nuclei up to ^{108}Cd

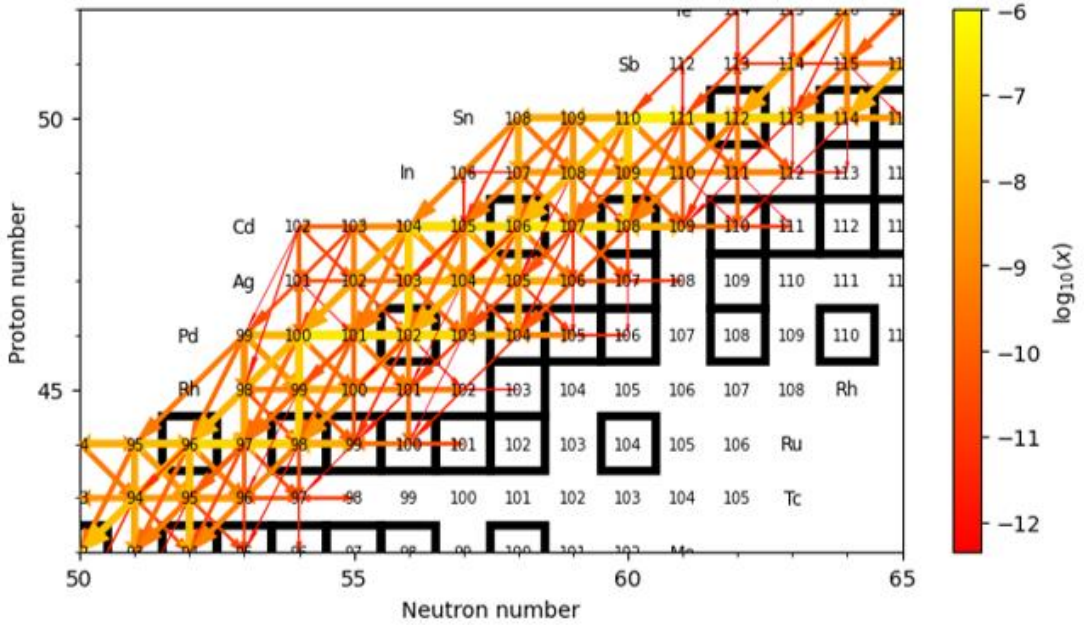
νr process - *Xiong, Z., PRL, 132, 192701 (2024)*

- Neutrino-induced reactions of r process material in the winds of a proto-neutron star
- p nuclei up to ^{138}La

Nuclear data needs

- Masses ✓
- Halflives ✓
- β^+ decay rates ✓
- Reaction rates **(γ,p), (γ,n), (γ,α)**, (p,γ), (p,n) ☹

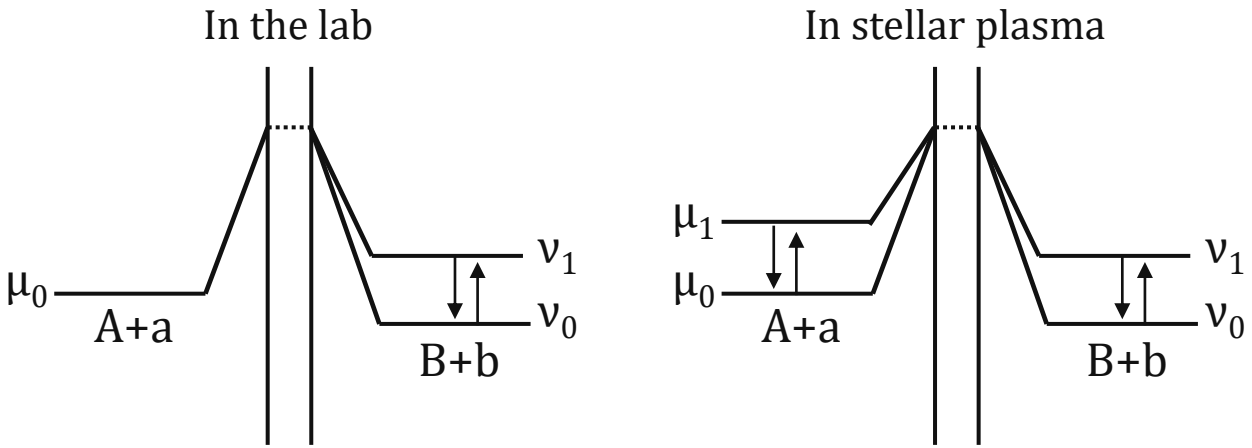
More than 20,000 reactions on more than 2,000 nuclei!



Snapshot of flux in 20 $M_\odot$ SNII model using NuGrid PPN

Nuclear data needs – reaction rates

Reaction rates → cross section $< \sigma v > \propto \int_0^\infty \boldsymbol{\sigma(E)} E \; exp\left(-\frac{E}{kT}\right) dE$

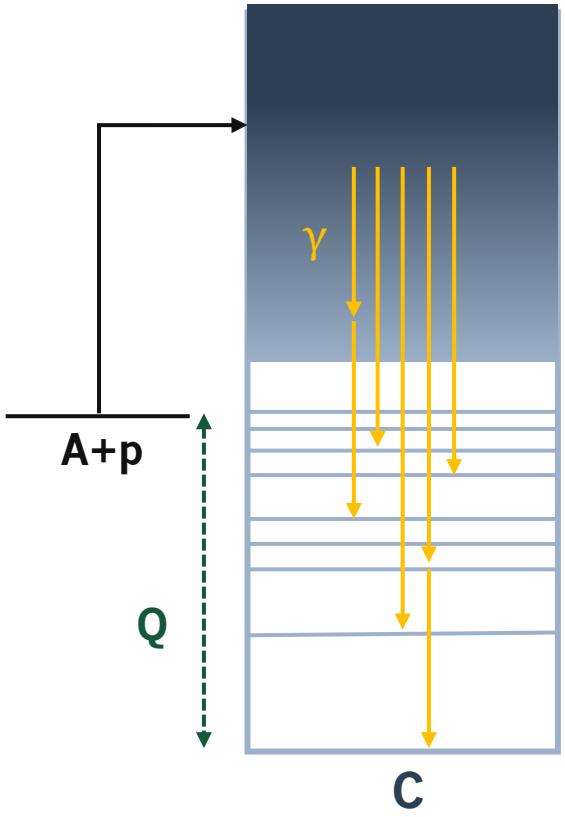


For most rates, ground state contribution is larger for the reaction of Q>0 (capture reaction) than the corresponding photodisintegration reaction.

Need for (p,γ), (n,γ), (α,γ) rates rather than (γ,p), (γ,n), (γ,α)

Rauscher ApJS 201 26 (2012)

How can we measure them?

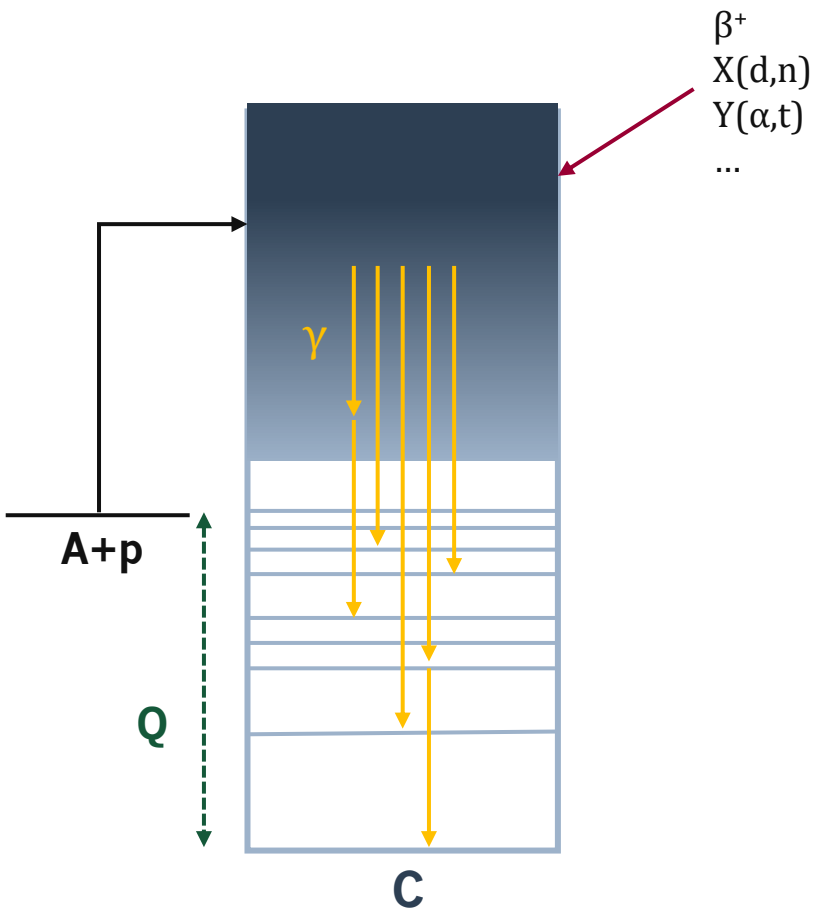


Directly

- p/n/α beam on stable (long-lived) target

- Inverse kinematics: heavy beam on H2 target

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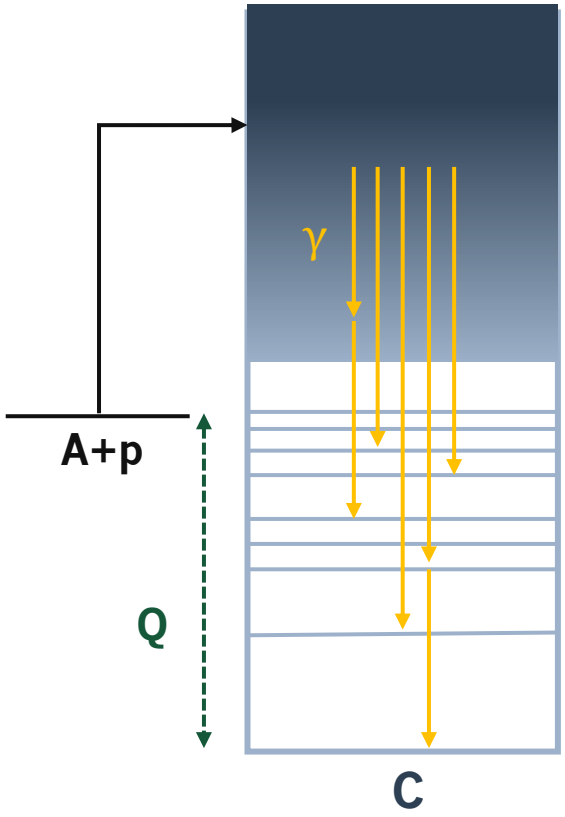
Indirectly

- Populate nucleus with decay/transfer reaction

- Constrain statistical properties of compound nucleus

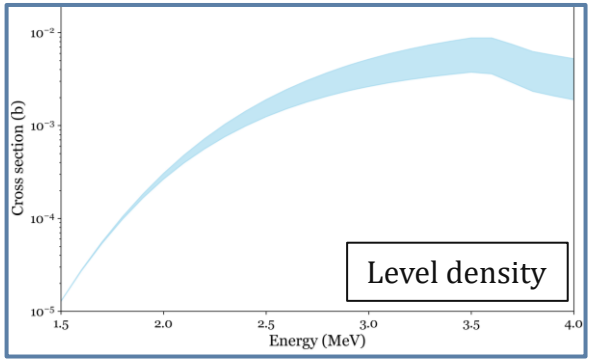
- Examples: (β) Oslo, surrogate method, trojan horse method, coulomb dissociation etc.

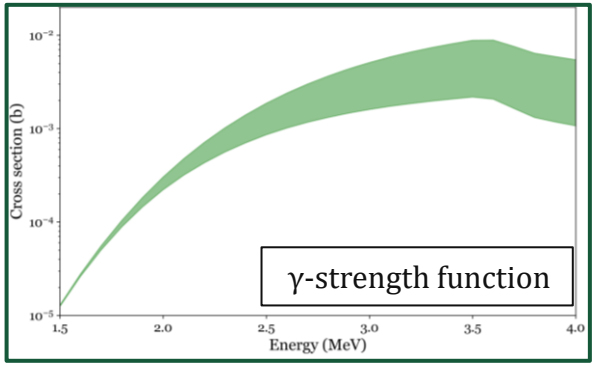
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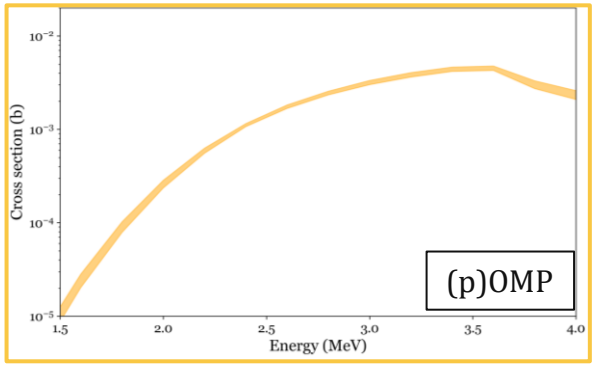


Hauser-Feshbach theory

- Nuclear Level Density
  Constant T+Fermi gas, back-shifted fermi gas, superfluid, microscopic
- γ-ray Strength Function
  Generalized Lorentzian, Brink-Axel, various tables
- Optical Model Potential
  Phenomenological, semi-microscopic

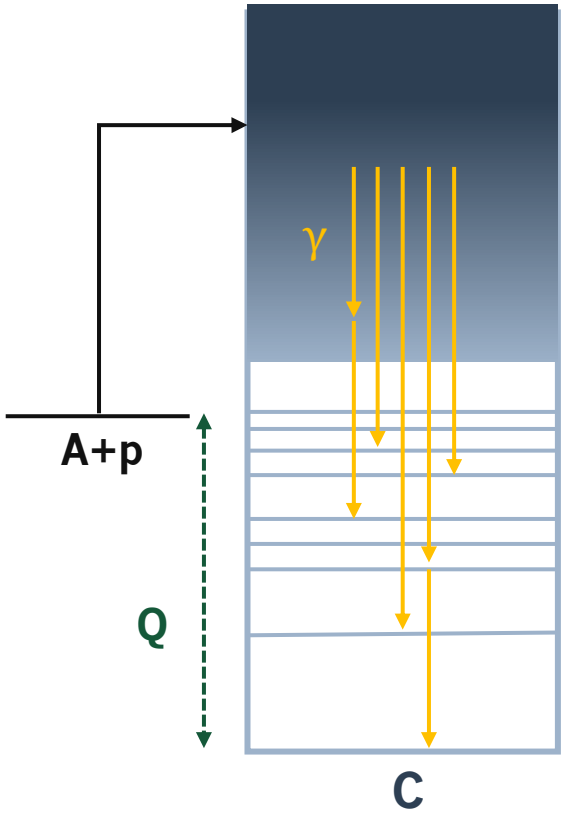






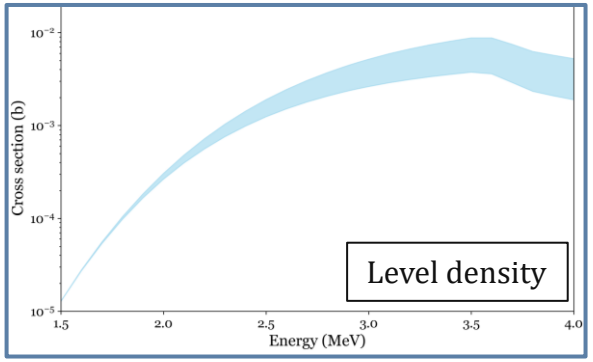
$^{73}As(p,\gamma)^{74}Se$

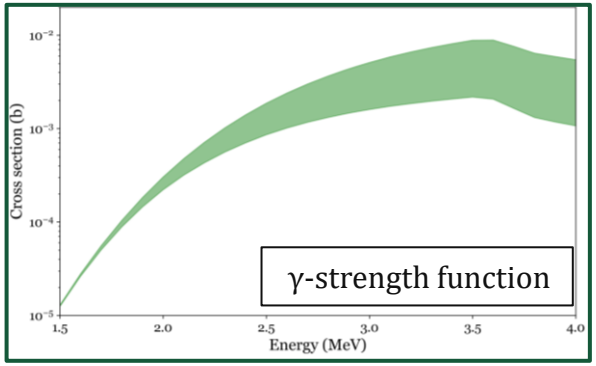
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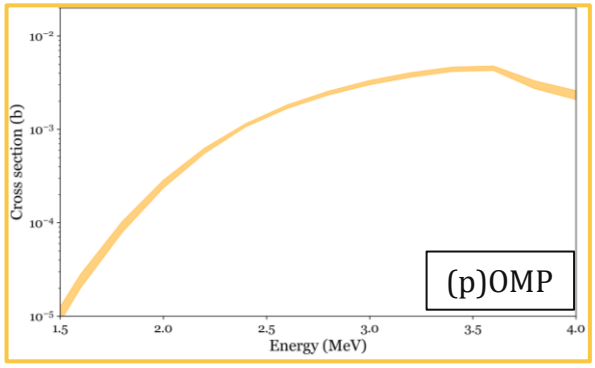


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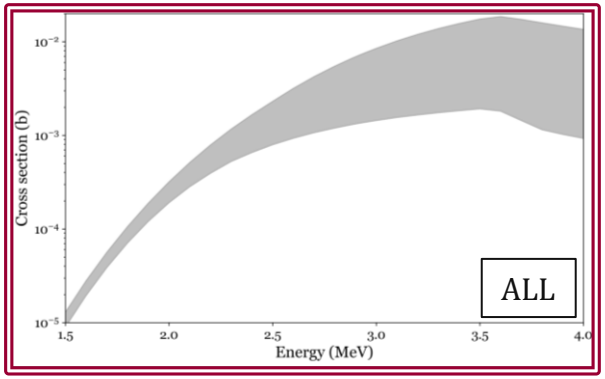
- **Nuclear Level Density**
  Constant T+Fermi gas, back-shifted fermi gas, superfluid, microscopic
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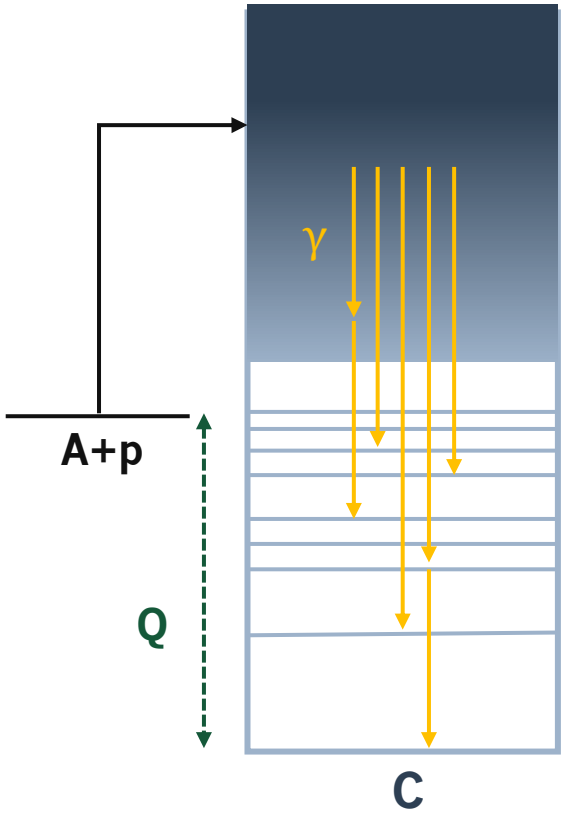




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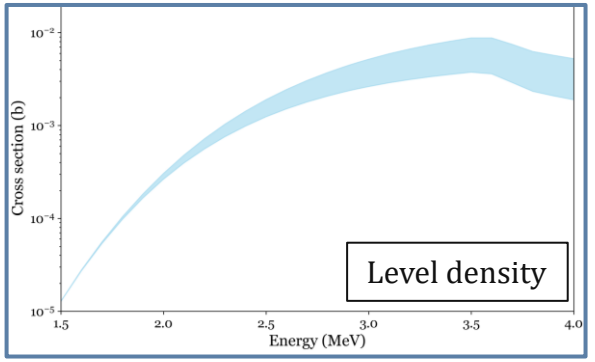


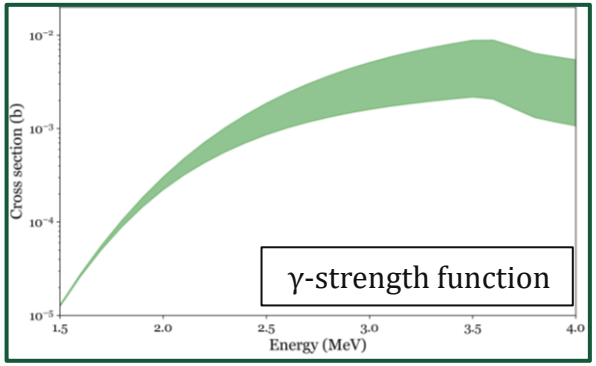
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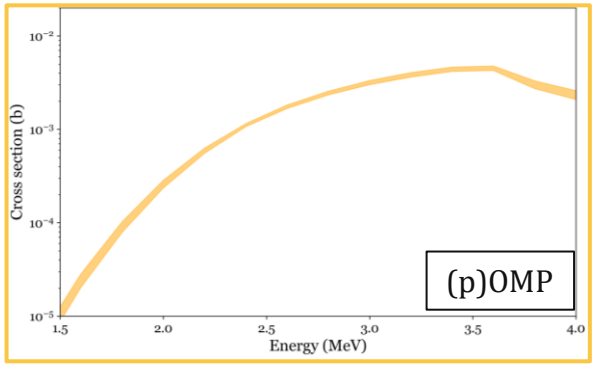


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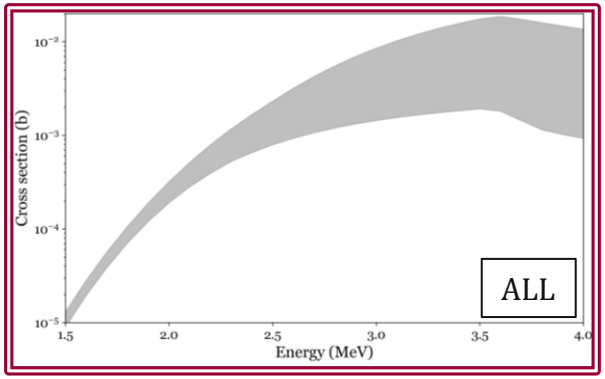
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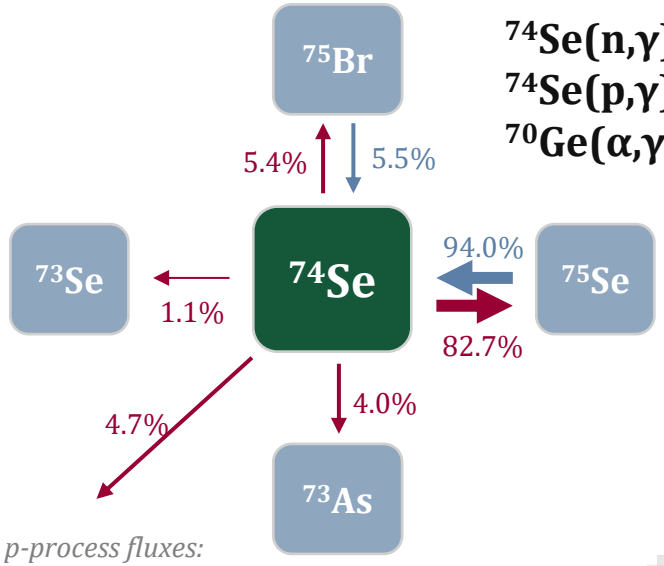


$^{73}As(p,\gamma)^{74}Se$



Different reactions can be more sensitive in different quantities (e.g. αOMP for (α,γ) reactions)

Synthesis of ^{74}Se



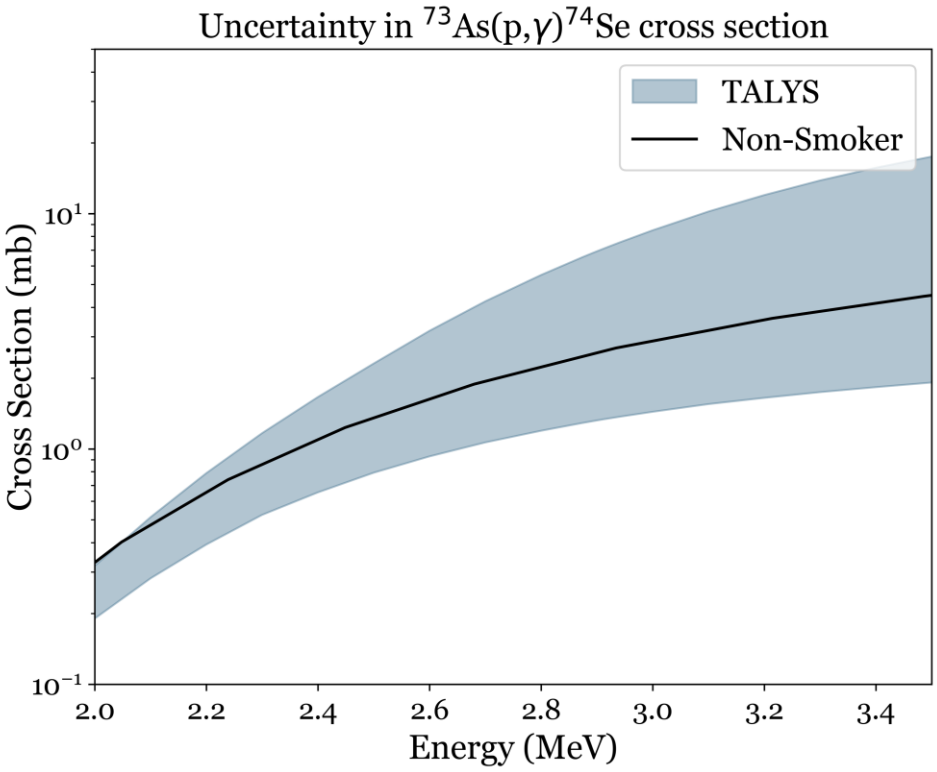
p-process fluxes:
exp-astro.physik.uni-frankfurt.de/fluxes

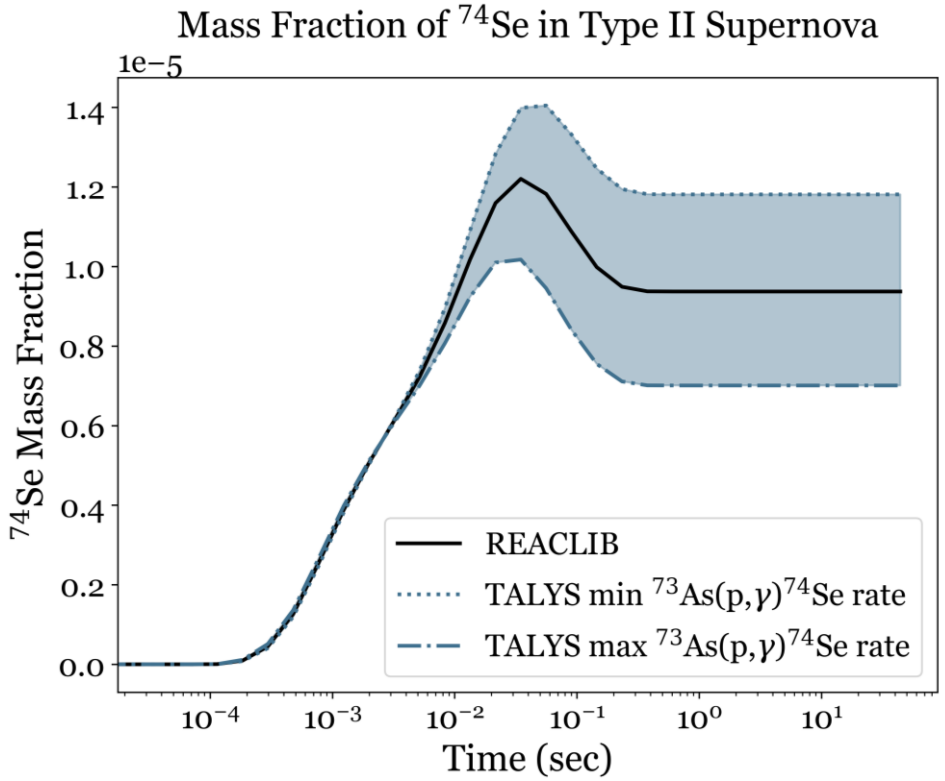
^{74}Se(n,γ)^{75}Se: Dillmann et al. (2005)
^{74}Se(p,γ)^{75}Br: Gyürky et al. (2003)
^{70}Ge(α,γ)^{74}Se: Fülöp et al. (1996)

Overproduction factor from 20 $M_\odot$ SNII

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

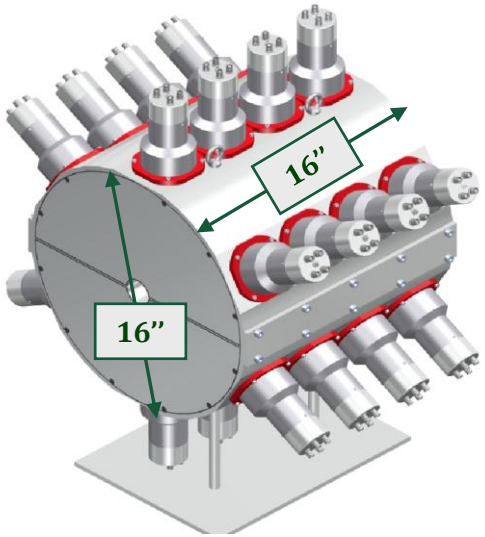
Synthesis of ^{74}Se



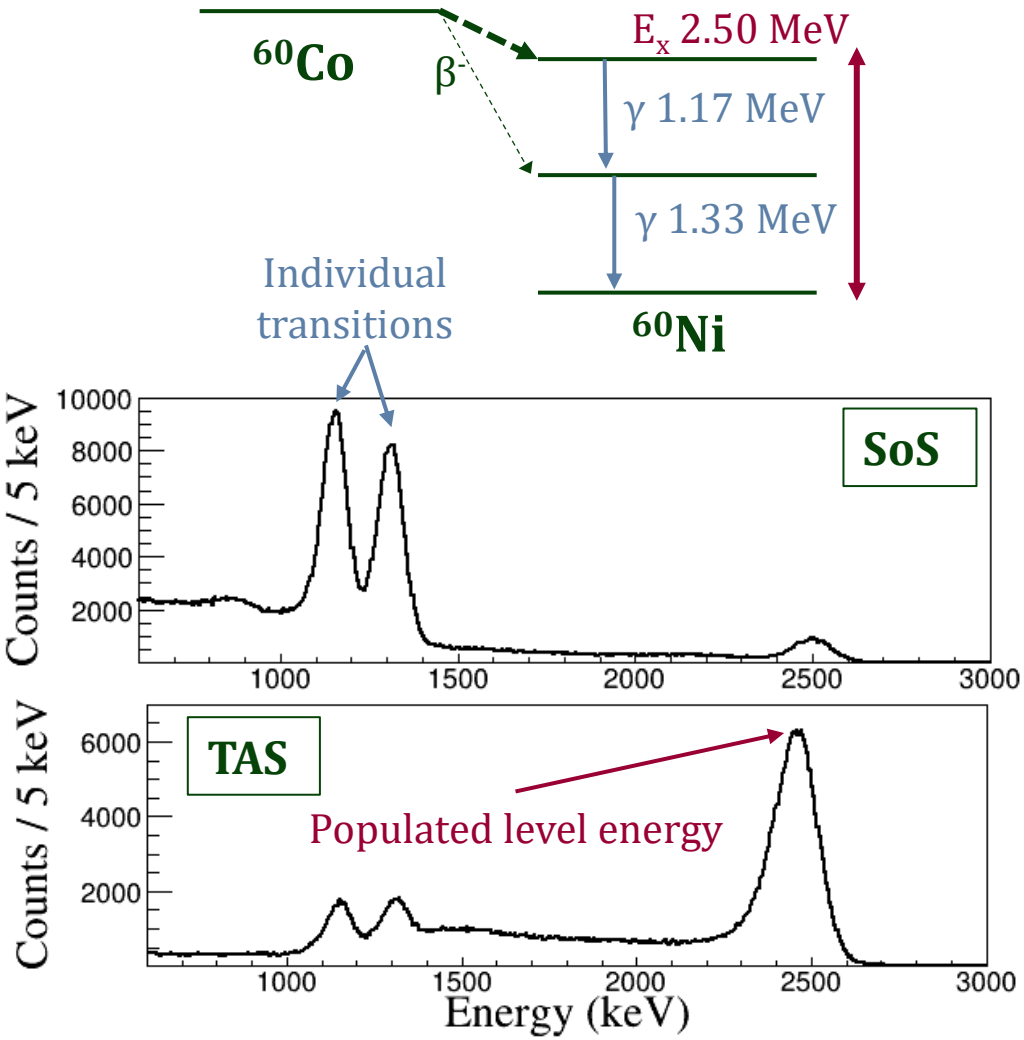


Uncertainty in the cross section of ^{73}As(p,γ)^{74}Se cross section has direct impact on final abundance of ^{74}Se

γ-summing technique with SuN

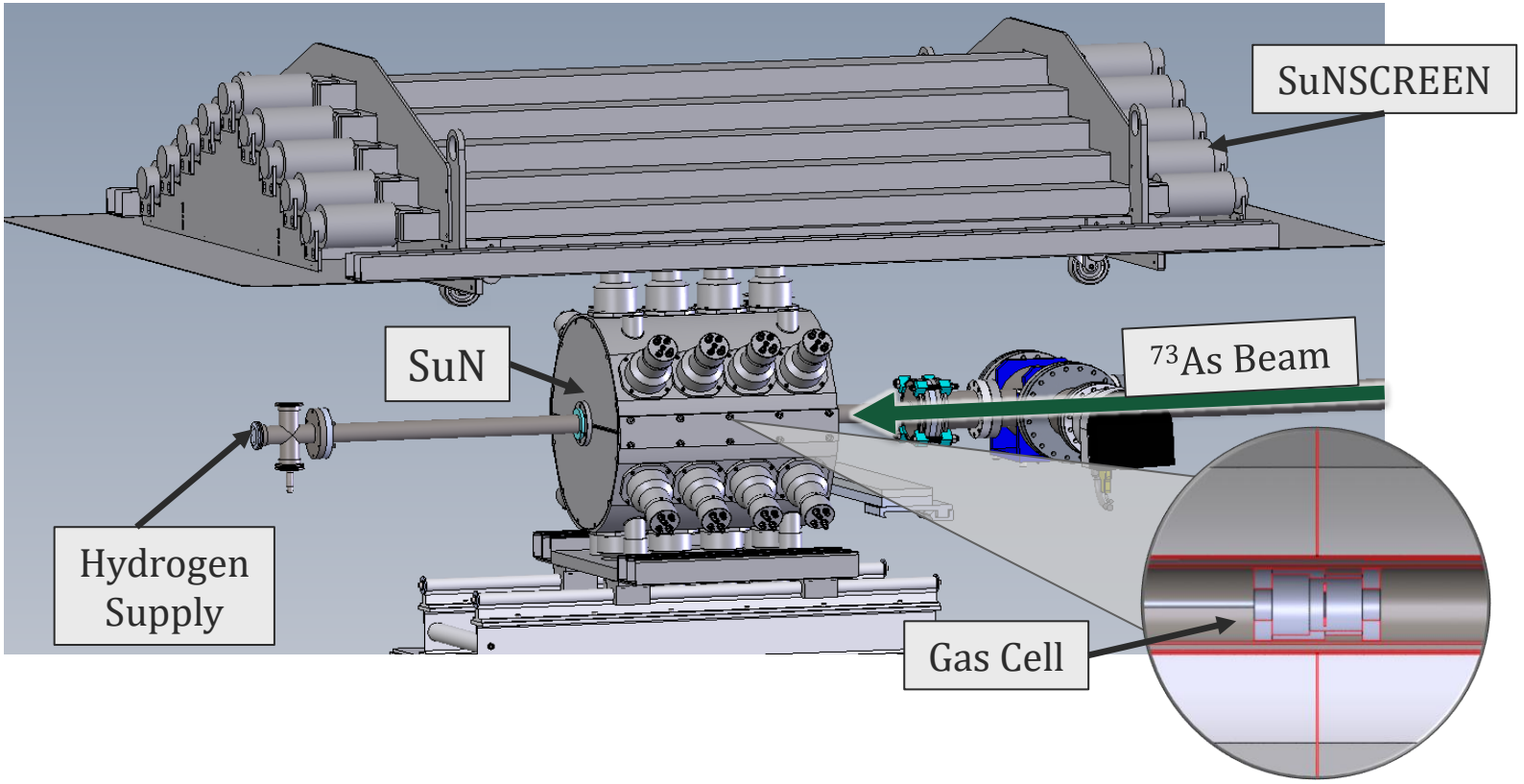


- **Summing NaI(Tl) SuN**: Large size, high efficiency γ-ray detector
- 8 optically isolated segments
- 24 PMTs
- **Sum of Segments (SoS)** → Individual γ-rays
- **Total Absorption Spectrum (TAS)** → Total excitation energy Ex

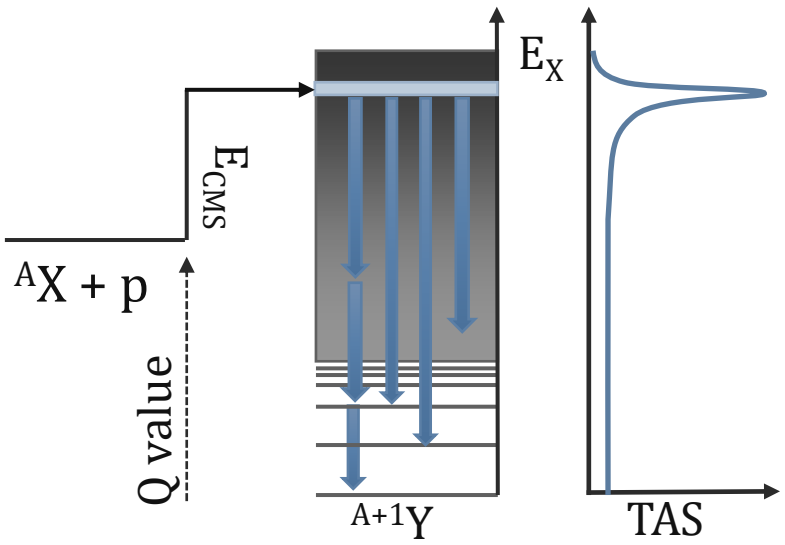


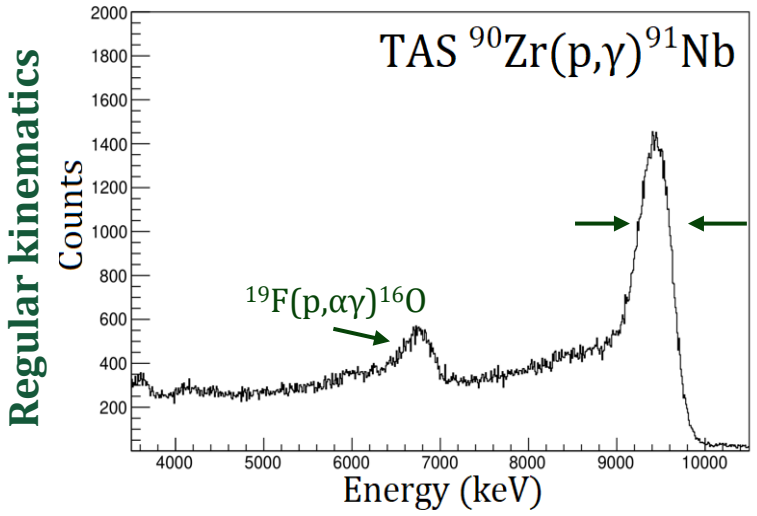
$^{73}As(p,\gamma)^{74}Se$ measurement at ReA FRIB

- ^{73}As radioactive beam (ReA standalone) (2023) 3.1, 3.7 MeV/u
  - $^{82\text{-}84}Kr$ 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

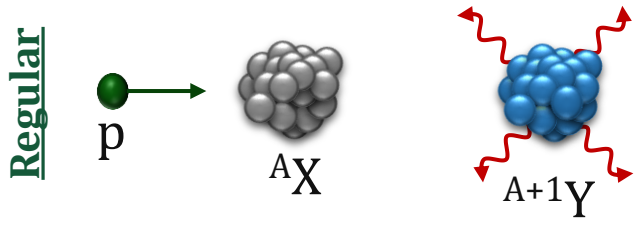


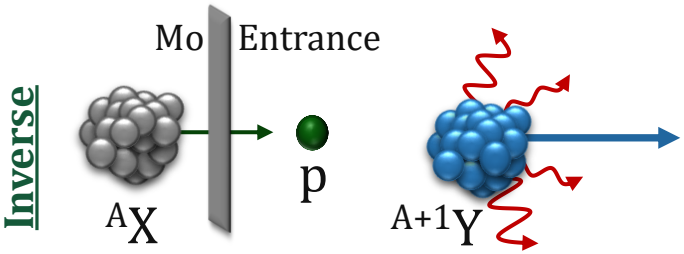
Regular vs inverse kinematics



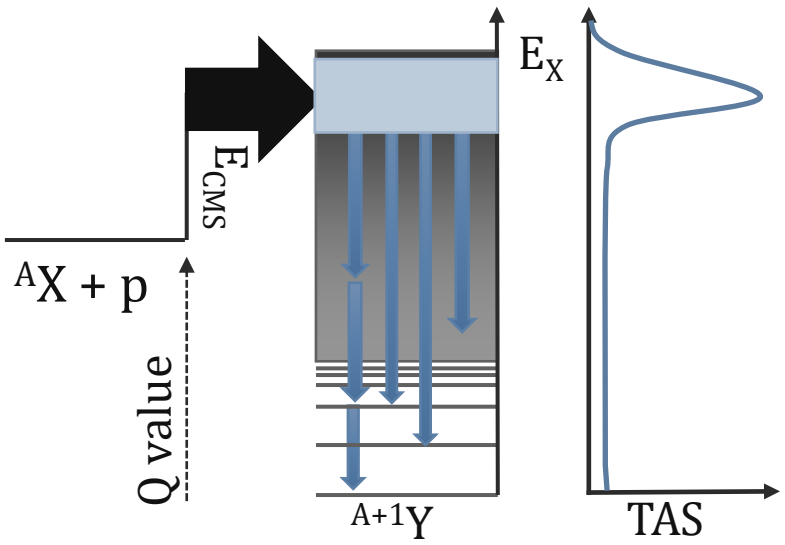


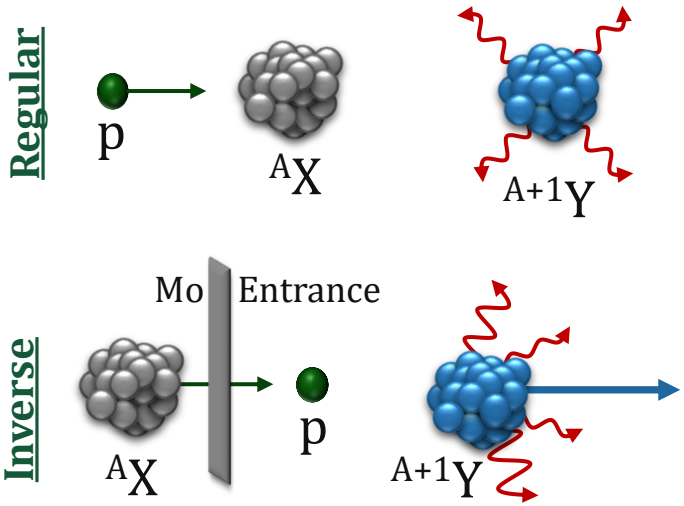
Spyrou et al. PRC 88 045802 (2013)

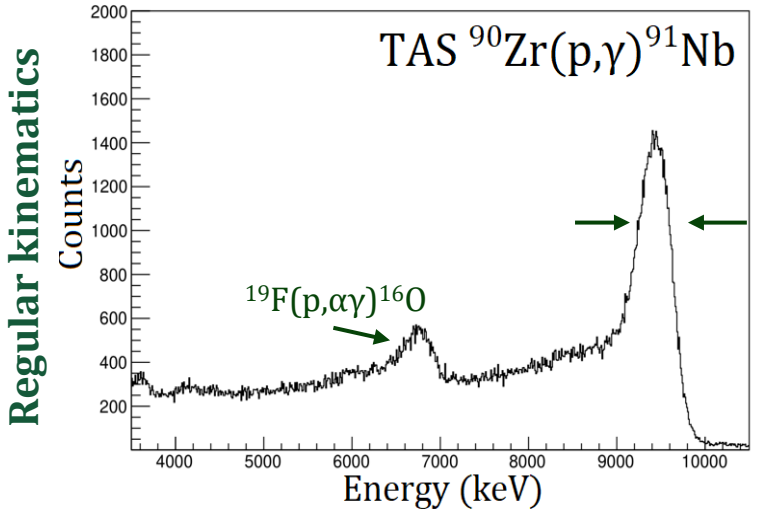




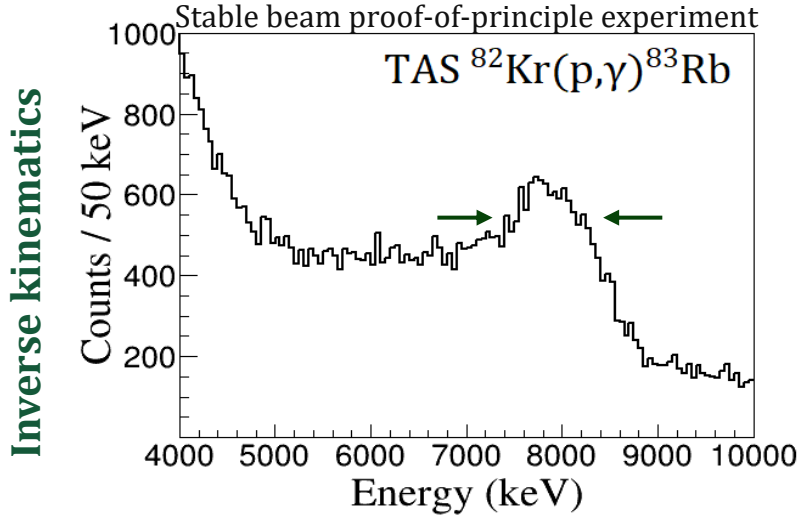
Regular vs inverse kinematics





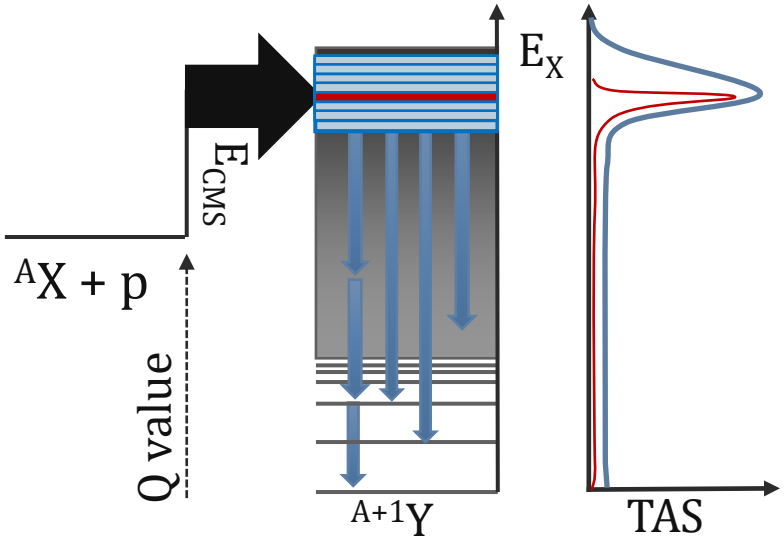


Spyrou et al. PRC 88 045802 (2013)

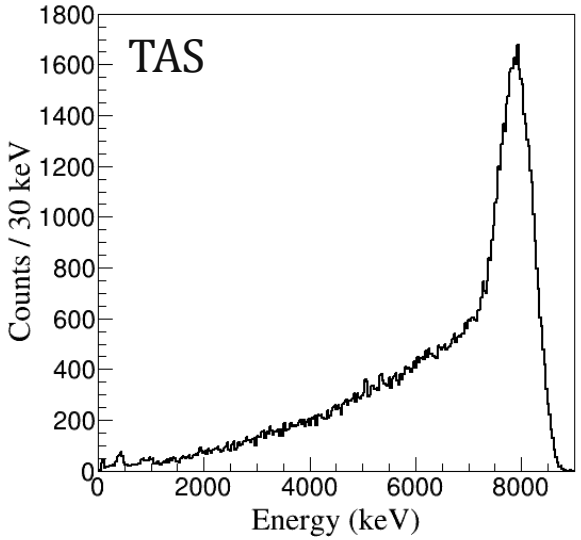


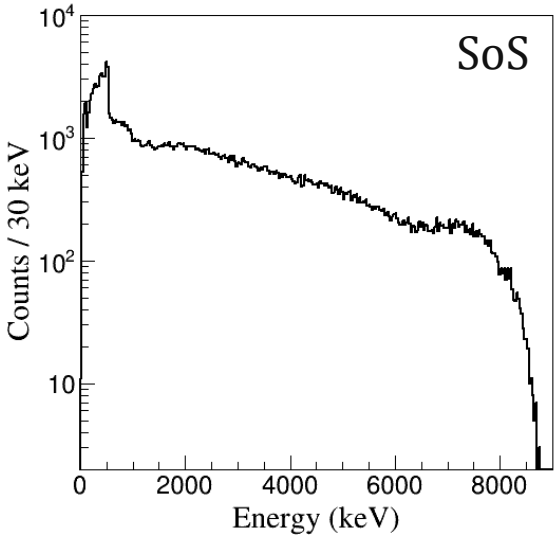
Tsantiri et al, PRC 107, 035808 (2023)

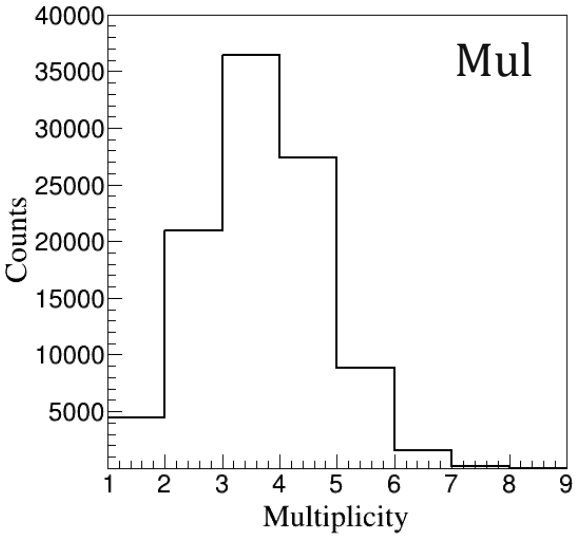
Detection efficiency simulations



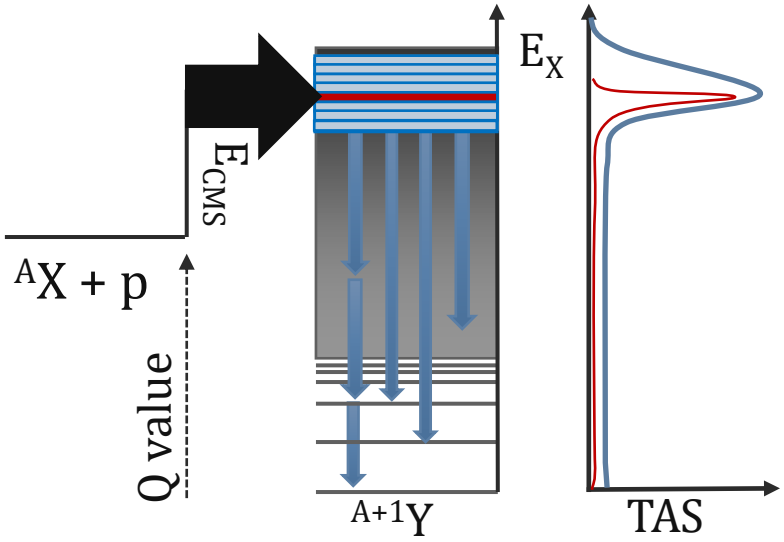
- Sum peak includes contributions from many E_X
- ε_{eff} depends on E_γ and the multiplicity of each cascade
- Simulate the de-excitation of every possible E_X with RAINIER and Geant4



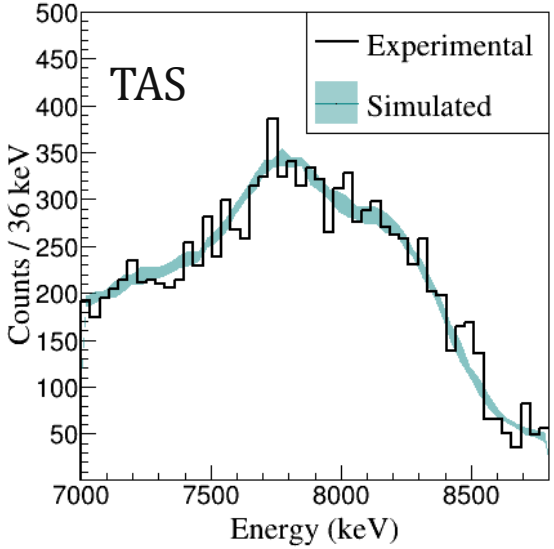


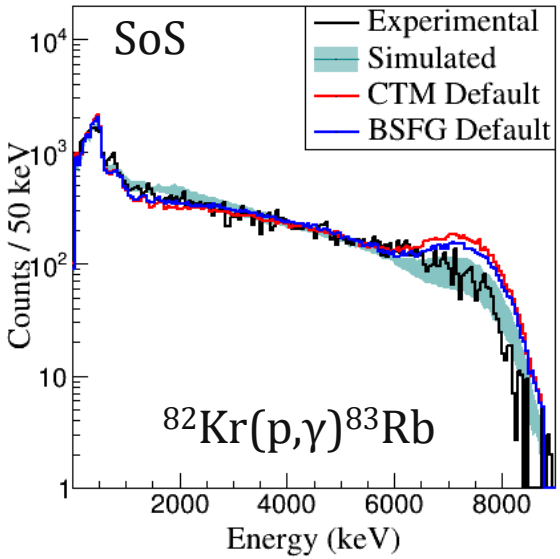


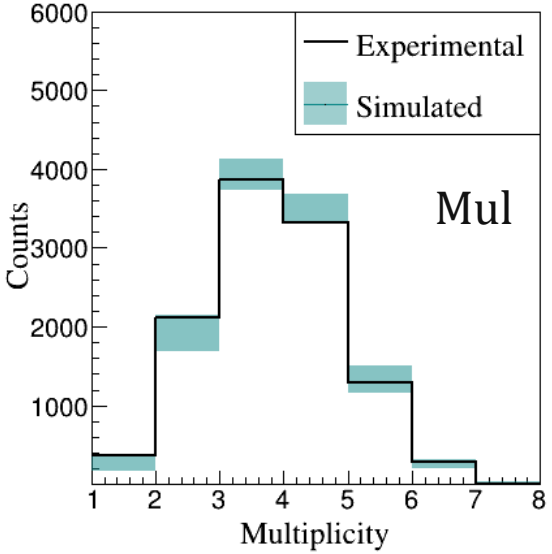
Detection efficiency simulations



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



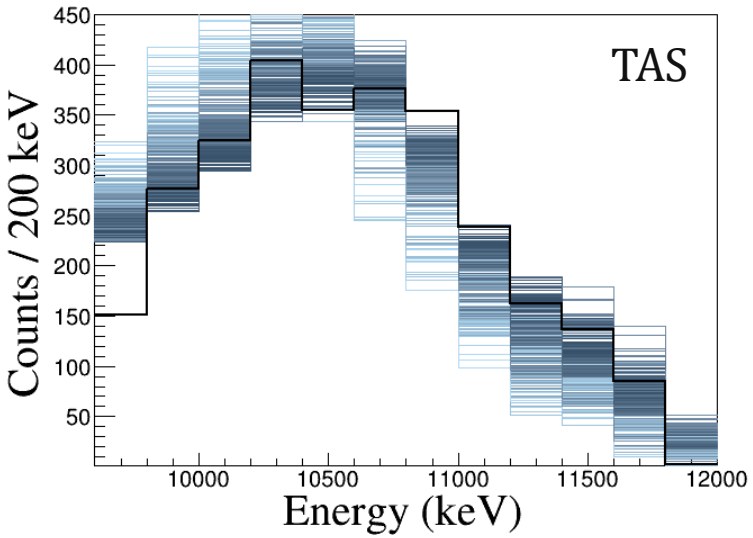


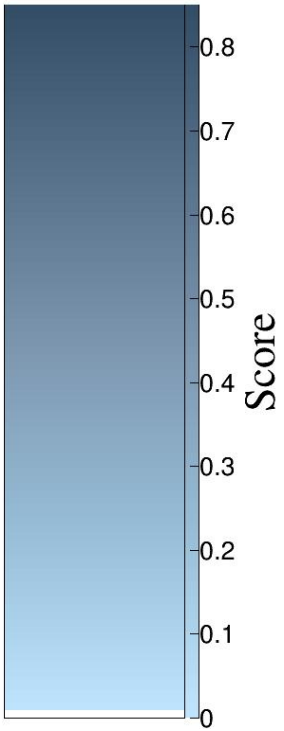


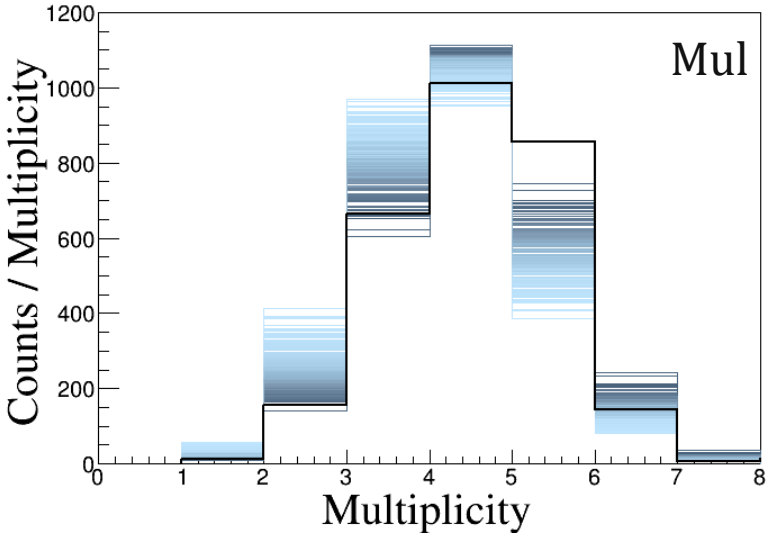
Characterization of NLD/γSF combinations

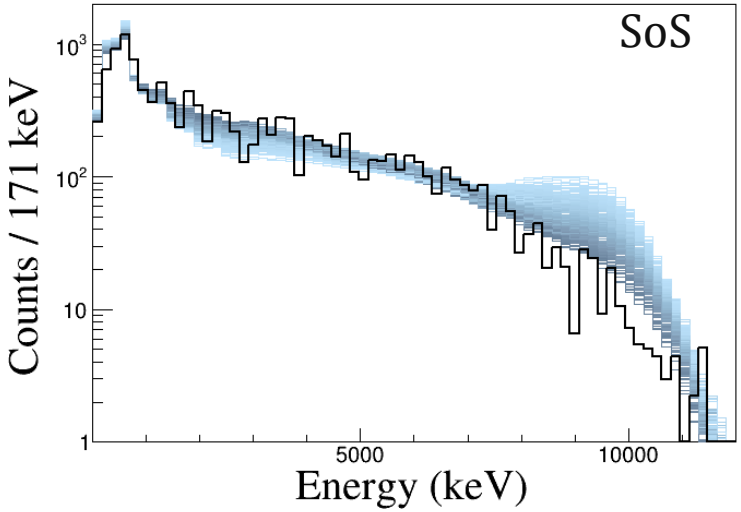
Utilize our sensitivity in the statistical properties of the compound nucleus to characterize the various NLD and γSF model combinations in TALYS

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





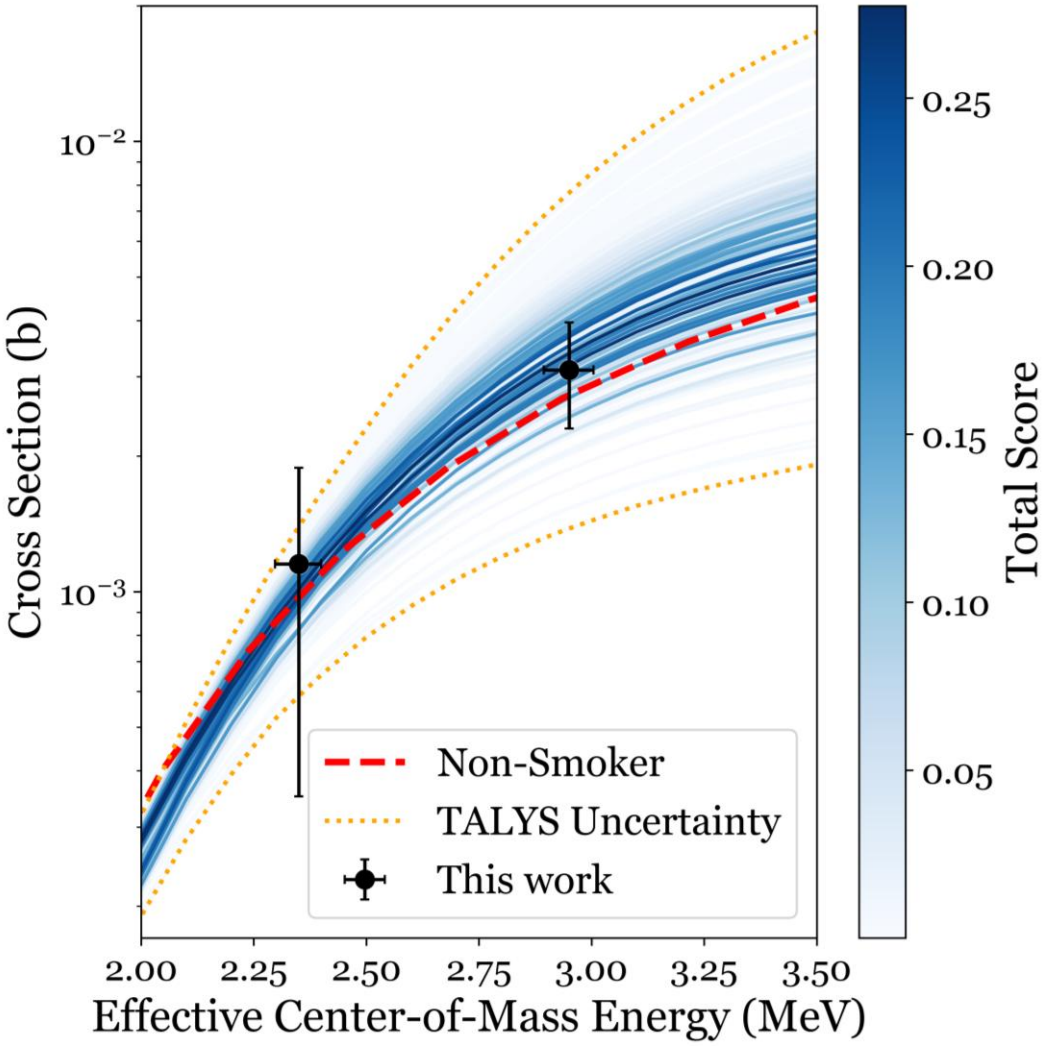




$^{73}As(p,\gamma)^{74}Se$ results

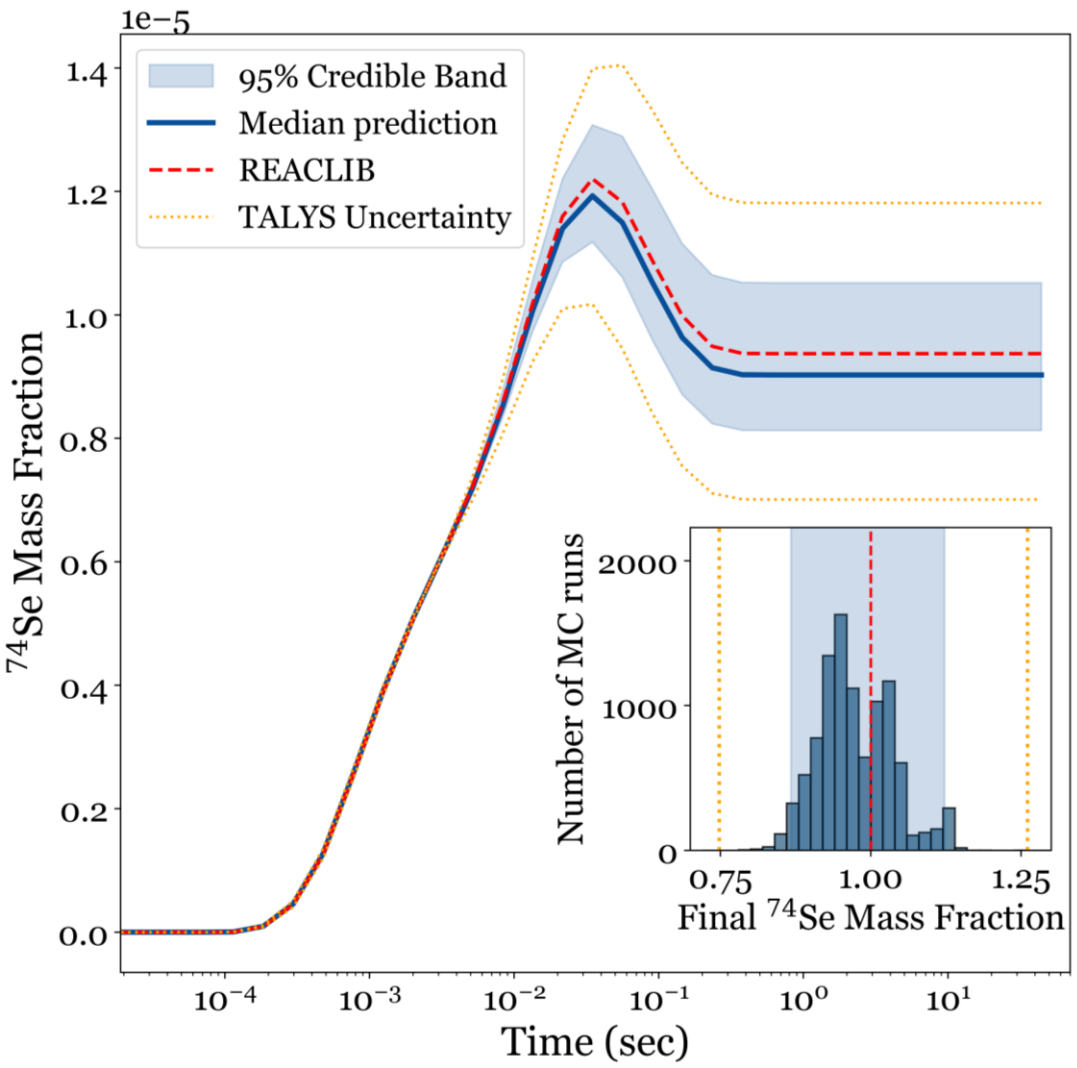
- Combining our measured cross section with the score of each NLD and γSF
  cross section constraints on a larger energy range

- Only the second γ-process experiment with radioactive beam within the Gamow window



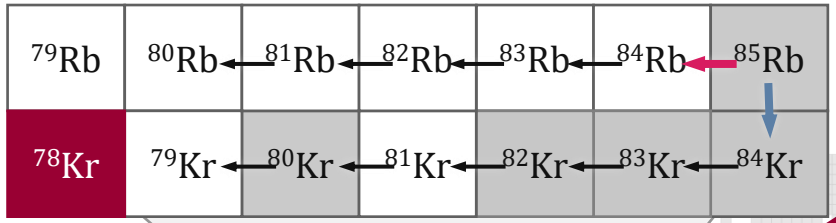
$^{73}As(p,\gamma)^{74}Se$ results

- Combining our measured cross section with the score of each NLD and γSF
  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



Constraining the γSF/NLD of ^{85}Rb

Reanalysis of the proof-of-principle stable beam experiment of ^{84}Kr(p,γ)^{85}Rb for the ^{85}Rb branching point in the γ process

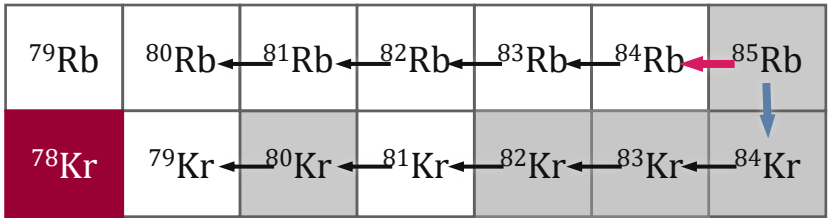


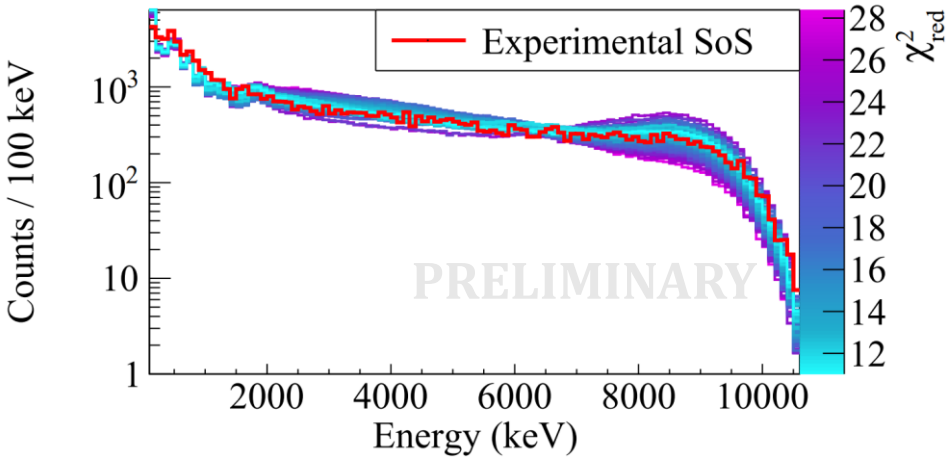
Constraining the γSF/NLD of ^{85}Rb

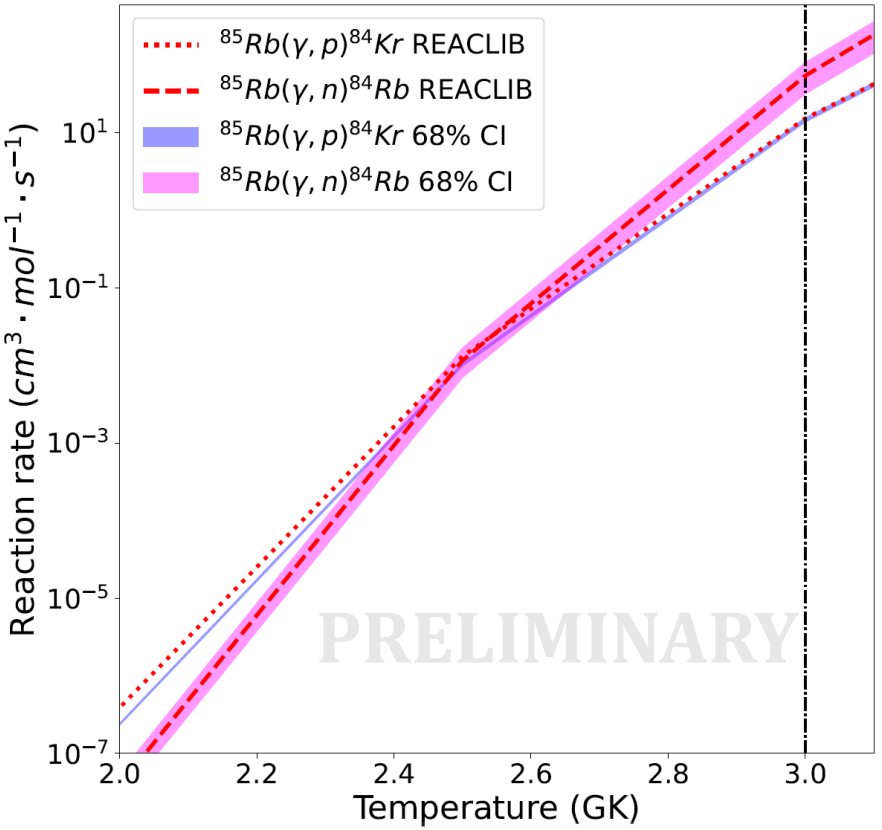


K. Bosmpotinis (FRIB)

Reanalysis of the proof-of-principle stable beam experiment of ^{84}Kr(p,γ)^{85}Rb for the ^{85}Rb branching point in the γ process

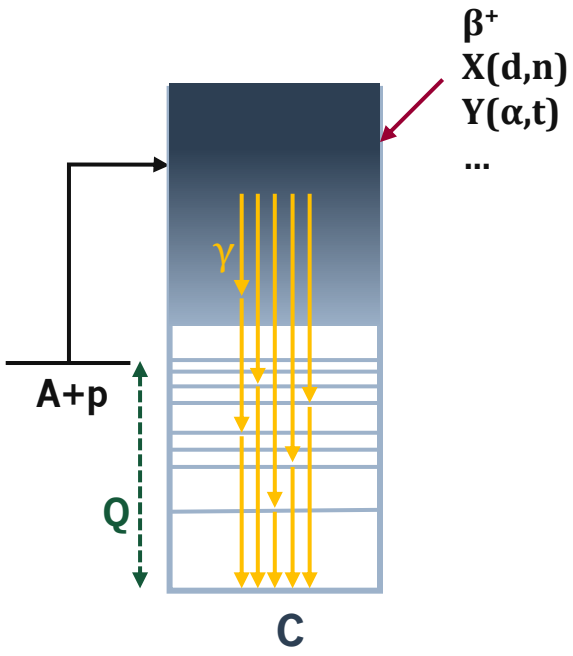






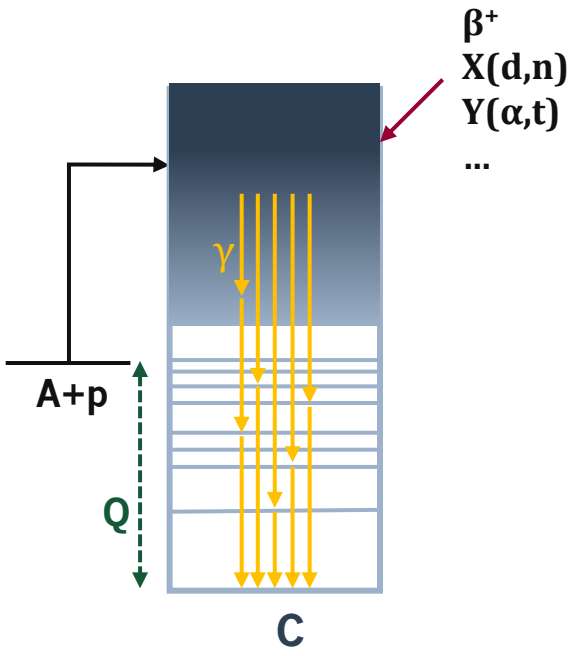
Bosmpotinis, Spyrou, Tsantiri et al (submitted)

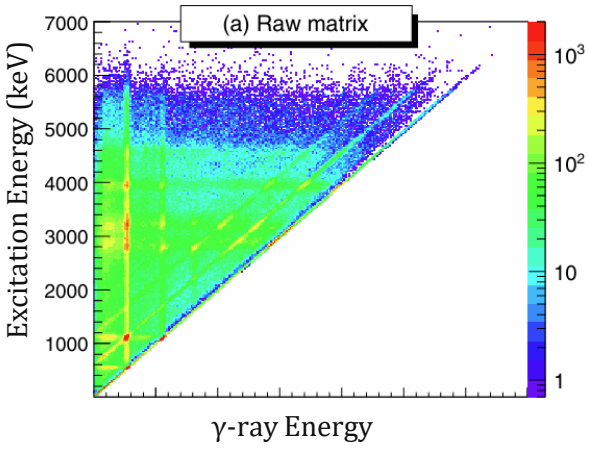
Indirect techniques – the (β)Oslo method



1. Populate nucleus with decay/transfer reaction

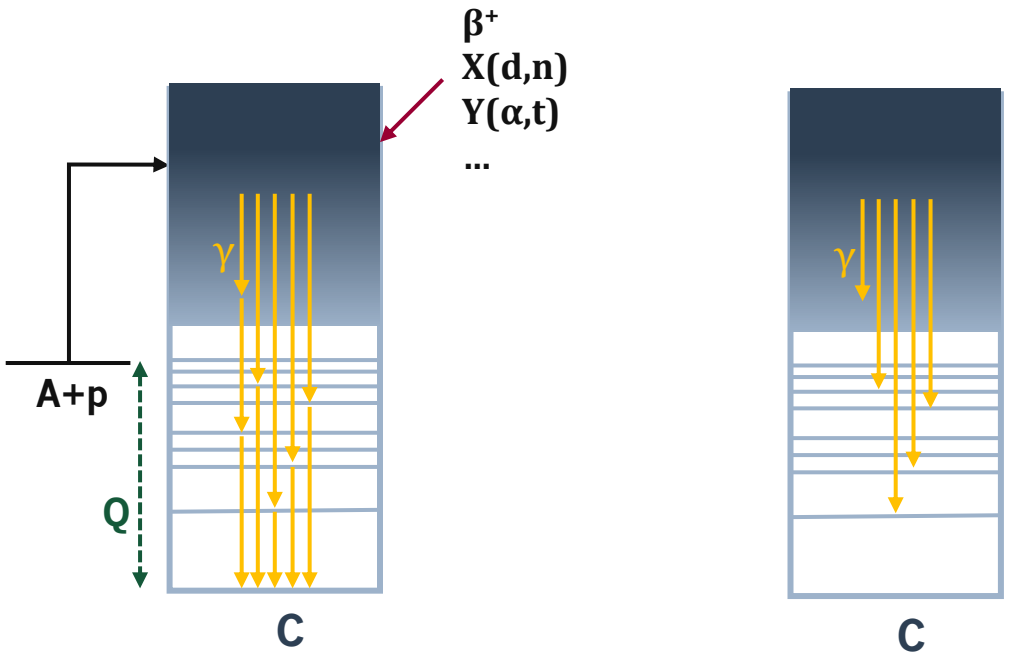
Indirect techniques – the (β)Oslo method



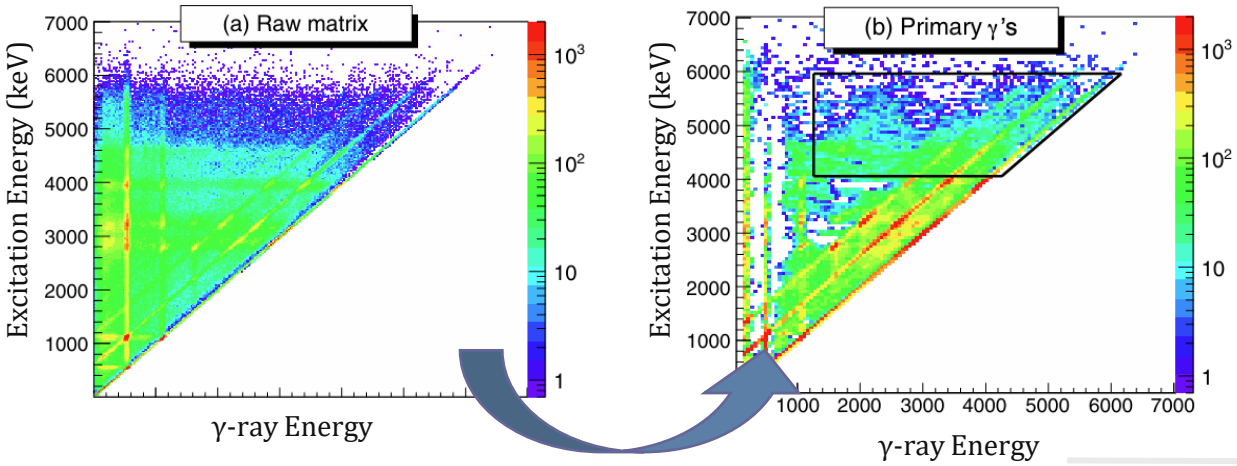


1. Populate nucleus with decay/transfer reaction
2. Measure excitation energy and γ-ray energy

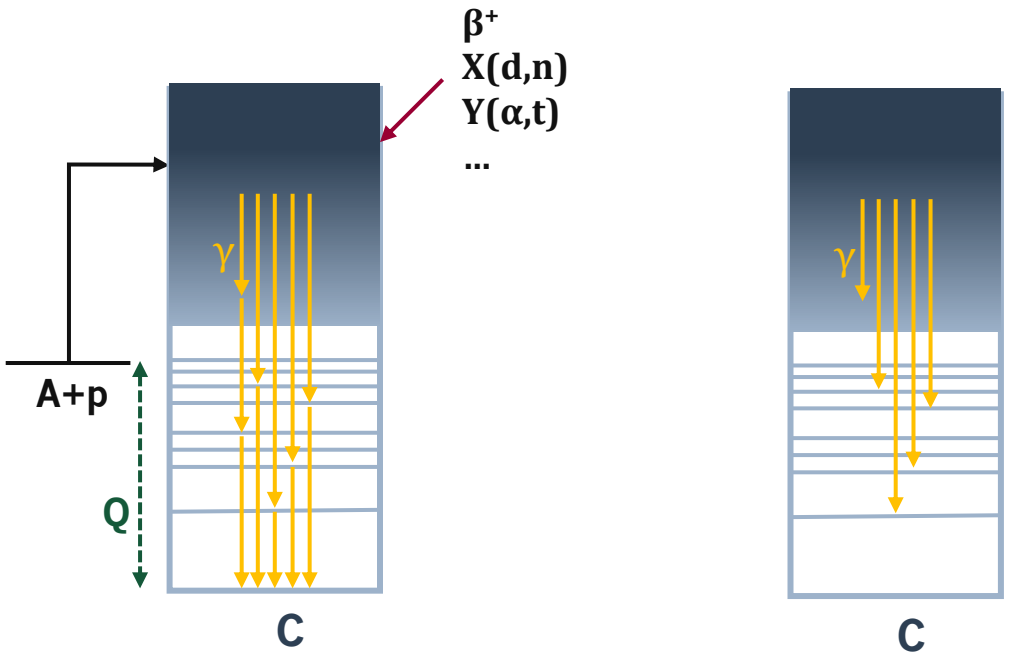
Indirect techniques – the (β)Oslo method



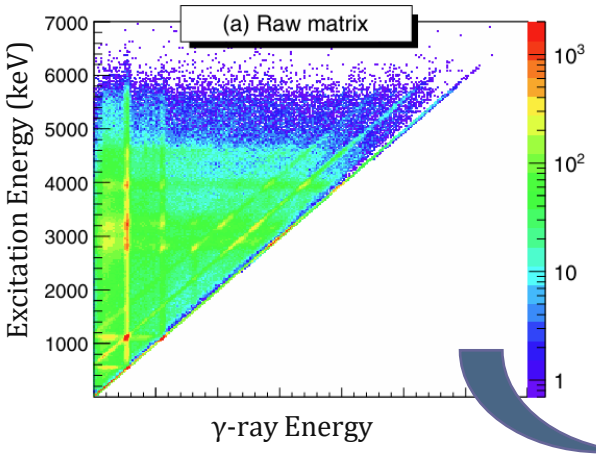
1. Populate nucleus with decay/transfer reaction
2. Measure excitation energy and γ-ray energy
3. Unfolding / iterative subtraction
   → Primary γ-ray matrix

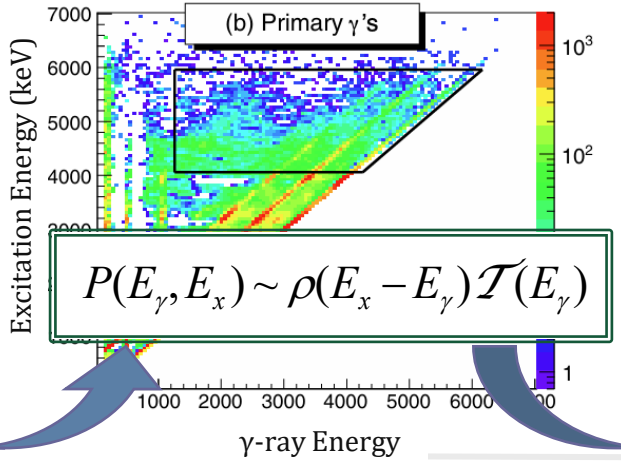


Indirect techniques – the (β)Oslo method

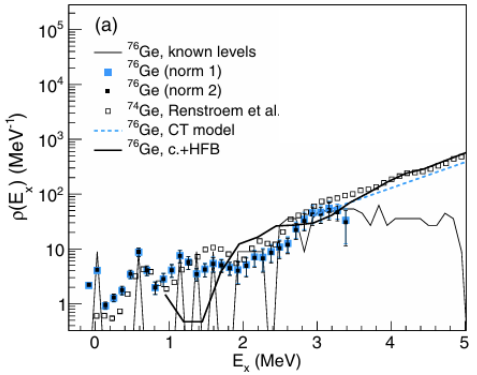


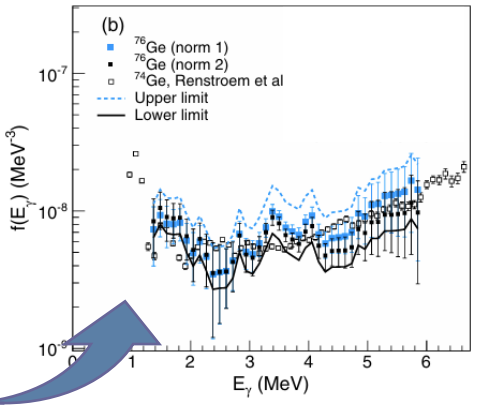
1. Populate nucleus with decay/transfer reaction
2. Measure excitation energy and γ-ray energy
3. Unfolding / iterative subtraction
   → Primary γ-ray matrix
4. Extract NLD and γSF (external normalizations)



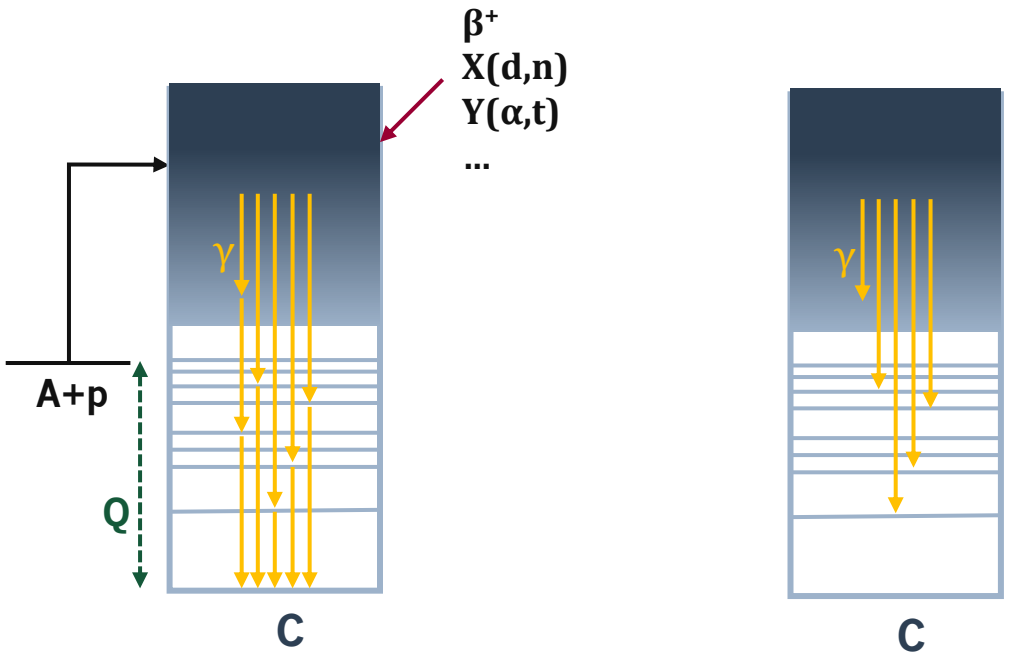


$$P(E_\gamma, E_x) \sim \rho(E_x - E_\gamma)\mathcal{T}(E_\gamma)$$

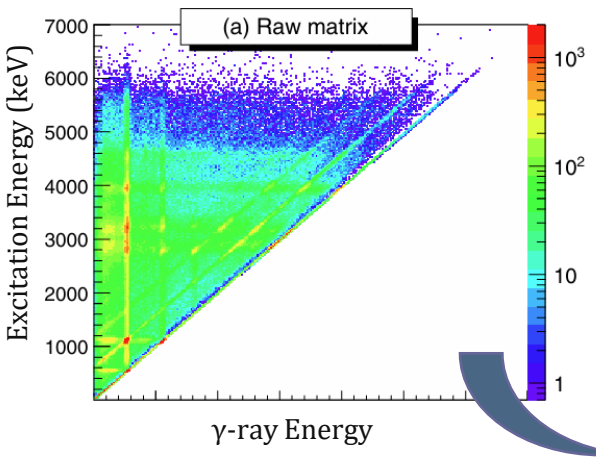


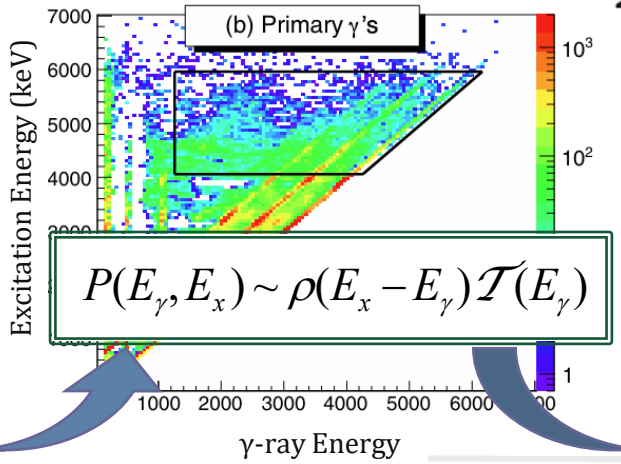


Indirect techniques – the (β)Oslo method

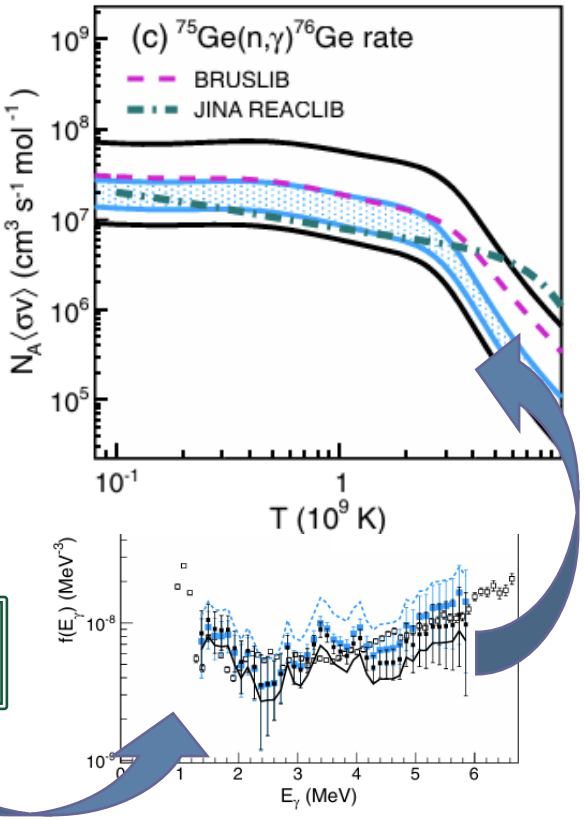


1. Populate nucleus with decay/transfer reaction
2. Measure excitation energy and γ-ray energy
3. Unfolding / iterative subtraction
   → Primary γ-ray matrix
4. Extract NLD and γSF (external normalizations)
5. Calculate "semi-experimental" (x,γ) cross section



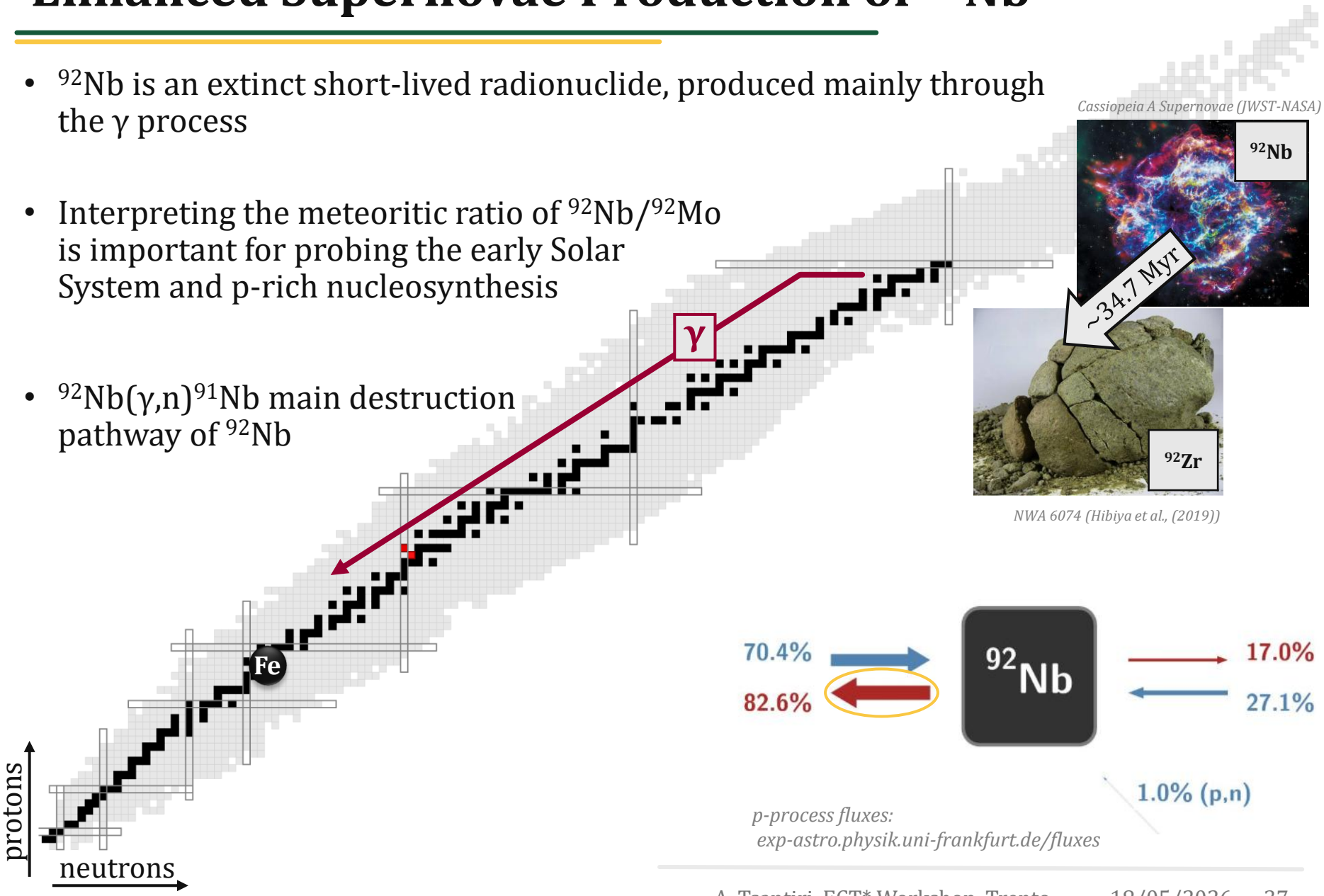


$$P(E_\gamma, E_x) \sim \rho(E_x - E_\gamma)\mathcal{T}(E_\gamma)$$



Enhanced Supernovae Production of ^{92}Nb

- ^{92}Nb is an extinct short-lived radionuclide, produced mainly through the γ process
- Interpreting the meteoritic ratio of ^{92}Nb/^{92}Mo is important for probing the early Solar System and p-rich nucleosynthesis
- ^{92}Nb(γ,n)^{91}Nb main destruction pathway of ^{92}Nb



Cassiopeia A Supernovae (JWST-NASA)

~34.7 Myr

NWA 6074 (Hibiya et al., (2019))

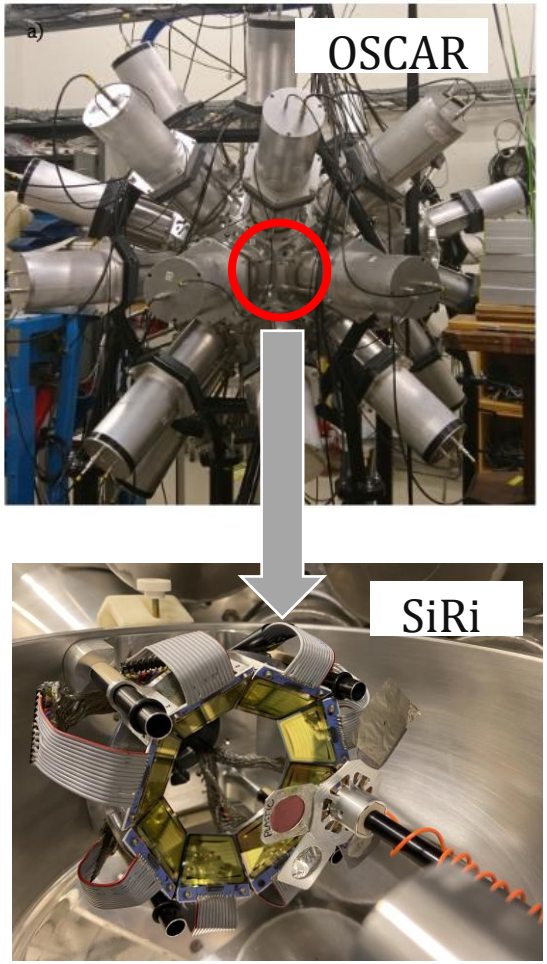
p-process fluxes:
exp-astro.physik.uni-frankfurt.de/fluxes

Enhanced Supernovae Production of ^{92}Nb

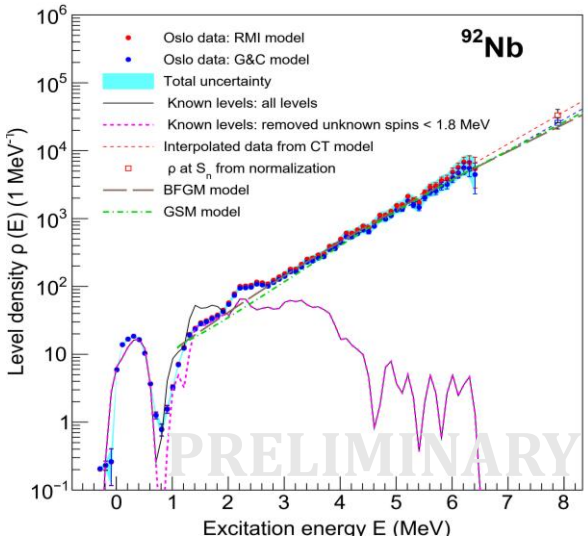


N. D. Pathirana (FRIB)

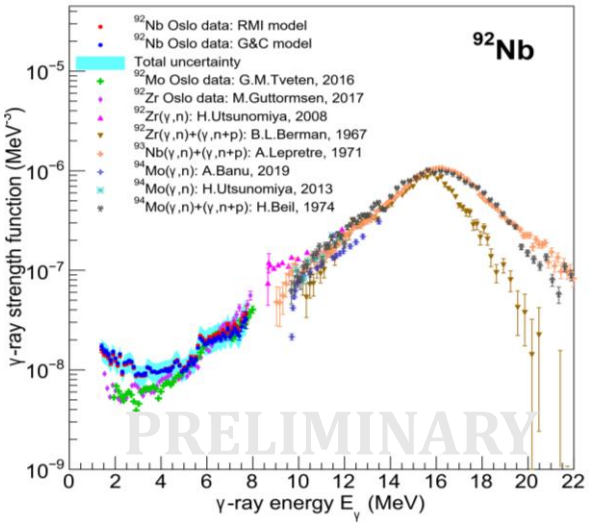
- ^{90}Zr(α,d+γ)^{92}Nb experiment at the University of Oslo using the SiRi particle telescope in coincidence with the Oslo SCintillator ARray (OSCAR)



Nuclear Level Density of ^{92}Nb



γ-ray Strength Function of ^{92}Nb

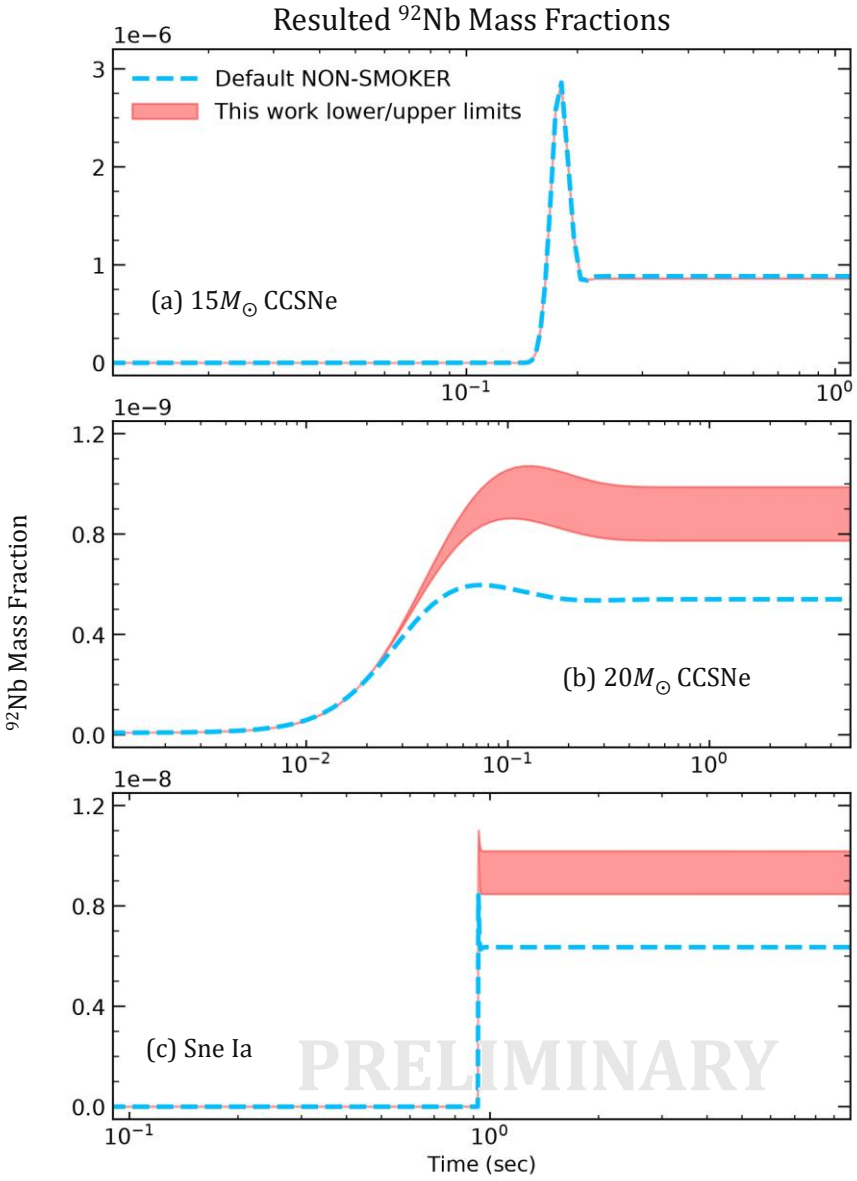


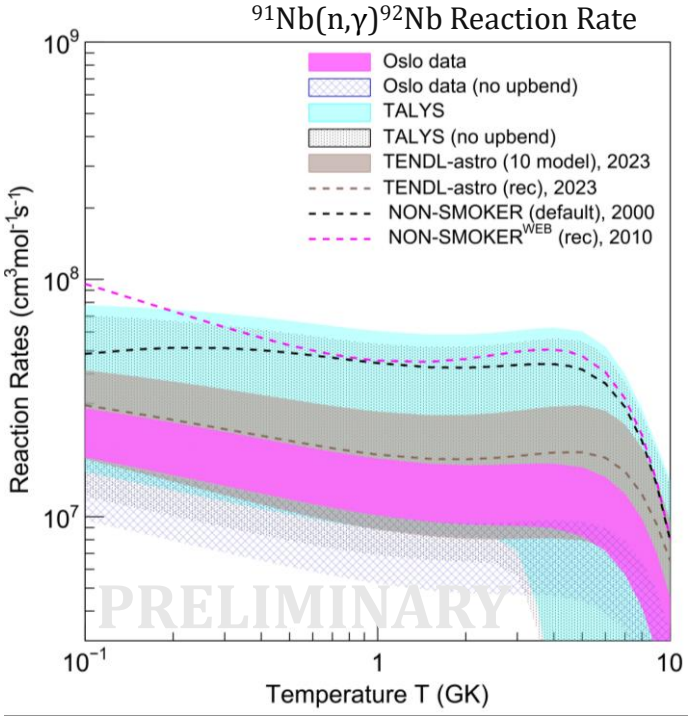
Pathirana, Markova, Larsen, Pignatari, et al (in prep)

Enhanced Supernovae Production of ^{92}Nb



N. D. Pathirana (FRIB)



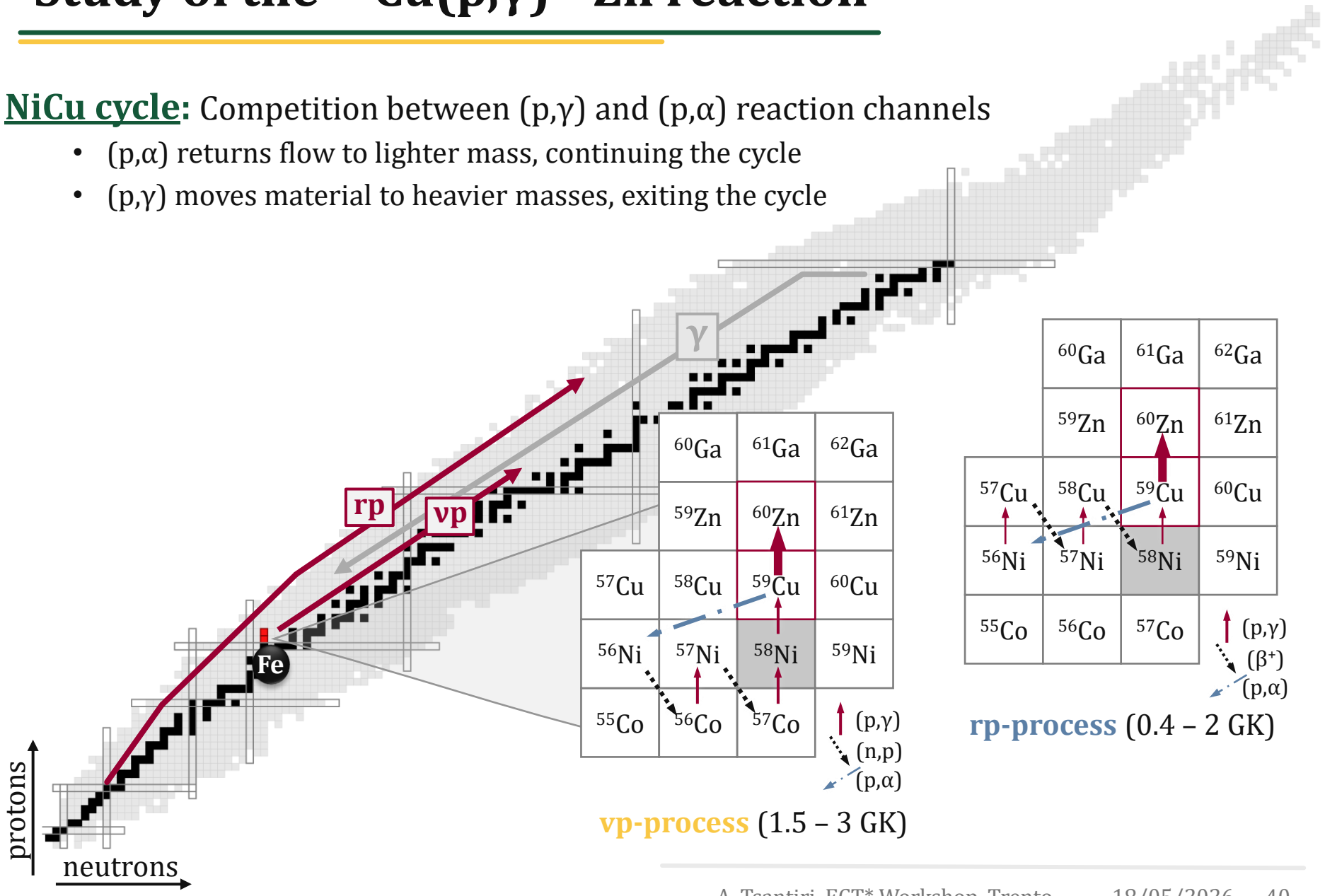


Pathirana, Markova, Larsen, Pignatari, et al (in prep)

Study of the $^{59}Cu(p,\gamma)^{60}Zn$ reaction

NiCu cycle: Competition between (p,γ) and (p,α) reaction channels

- (p,α) returns flow to lighter mass, continuing the cycle
- (p,γ) moves material to heavier masses, exiting the cycle

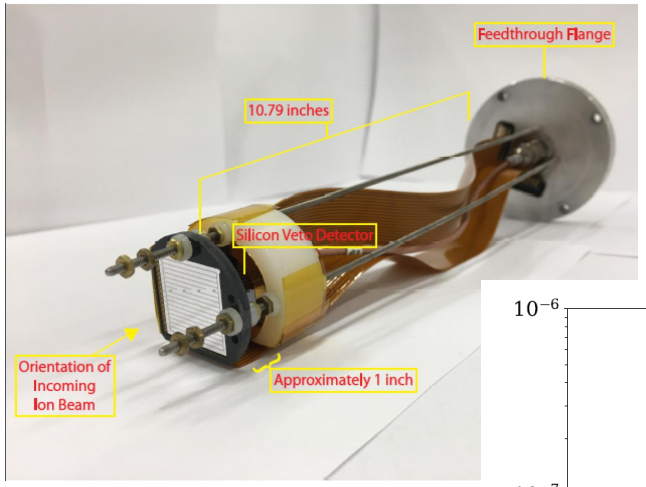


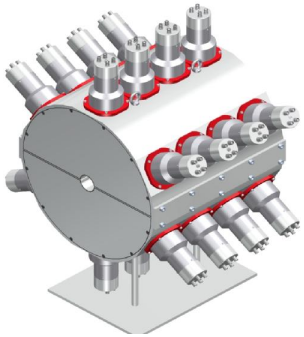
Study of the ^{59}Cu(p,γ)^{60}Zn reaction

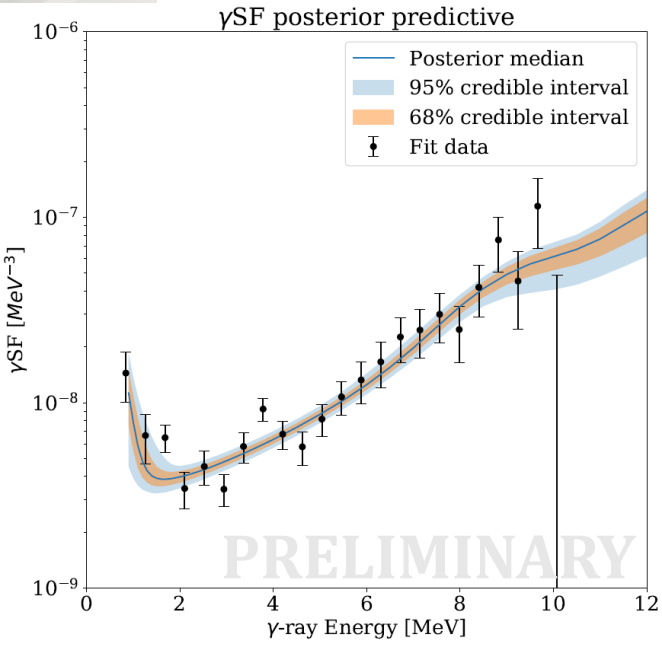


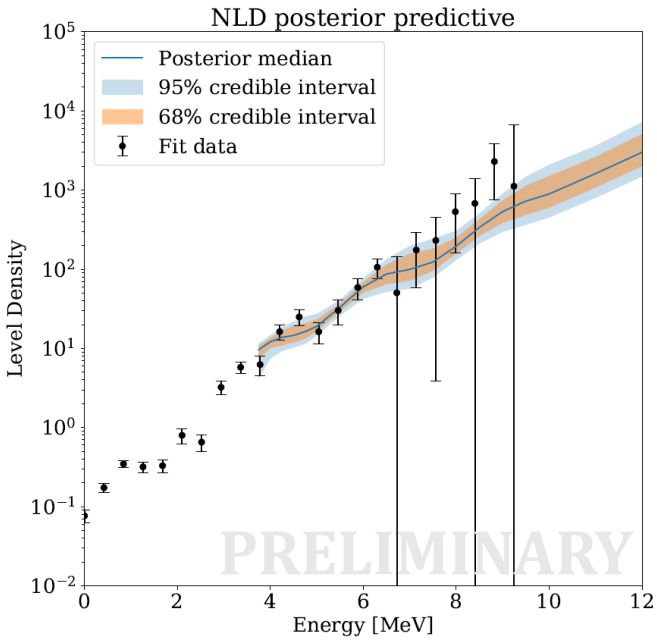
G. J. Owens-Fryar (FRIB)

- First application of the (β+)-Oslo technique through the β+ decay of ^{60}Ga at the NSCL with the SuN detector and a DSSD implantation detector







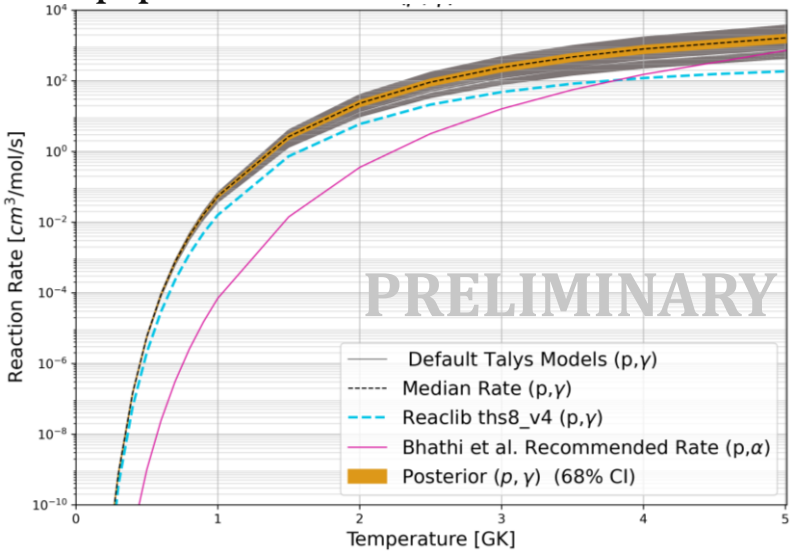


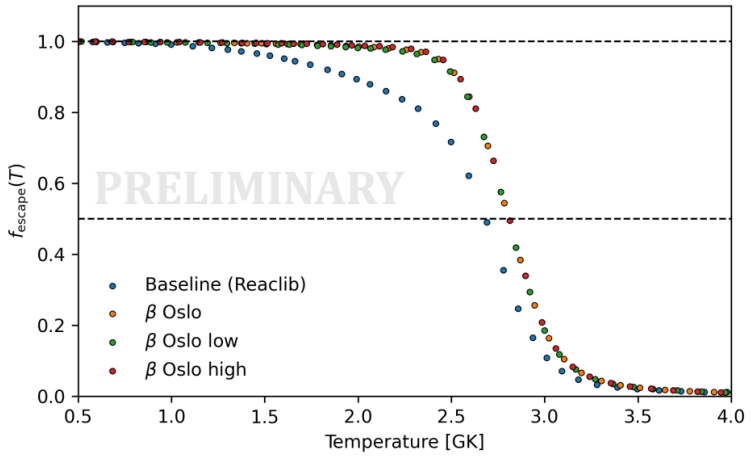
Study of the $^{59}Cu(p,\gamma)^{60}Zn$ reaction

- (p,γ) reaction rate greater than REACLIB
- νp-process: 10% material feeds NiCu cycle

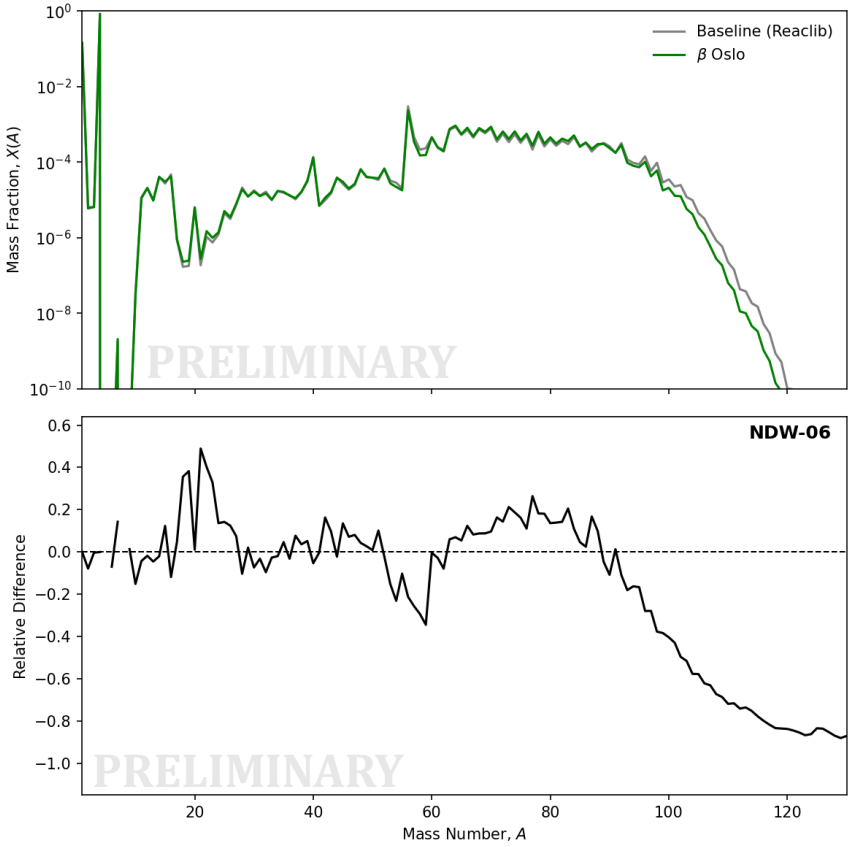


G. J. Owens-Fryar (FRIB)





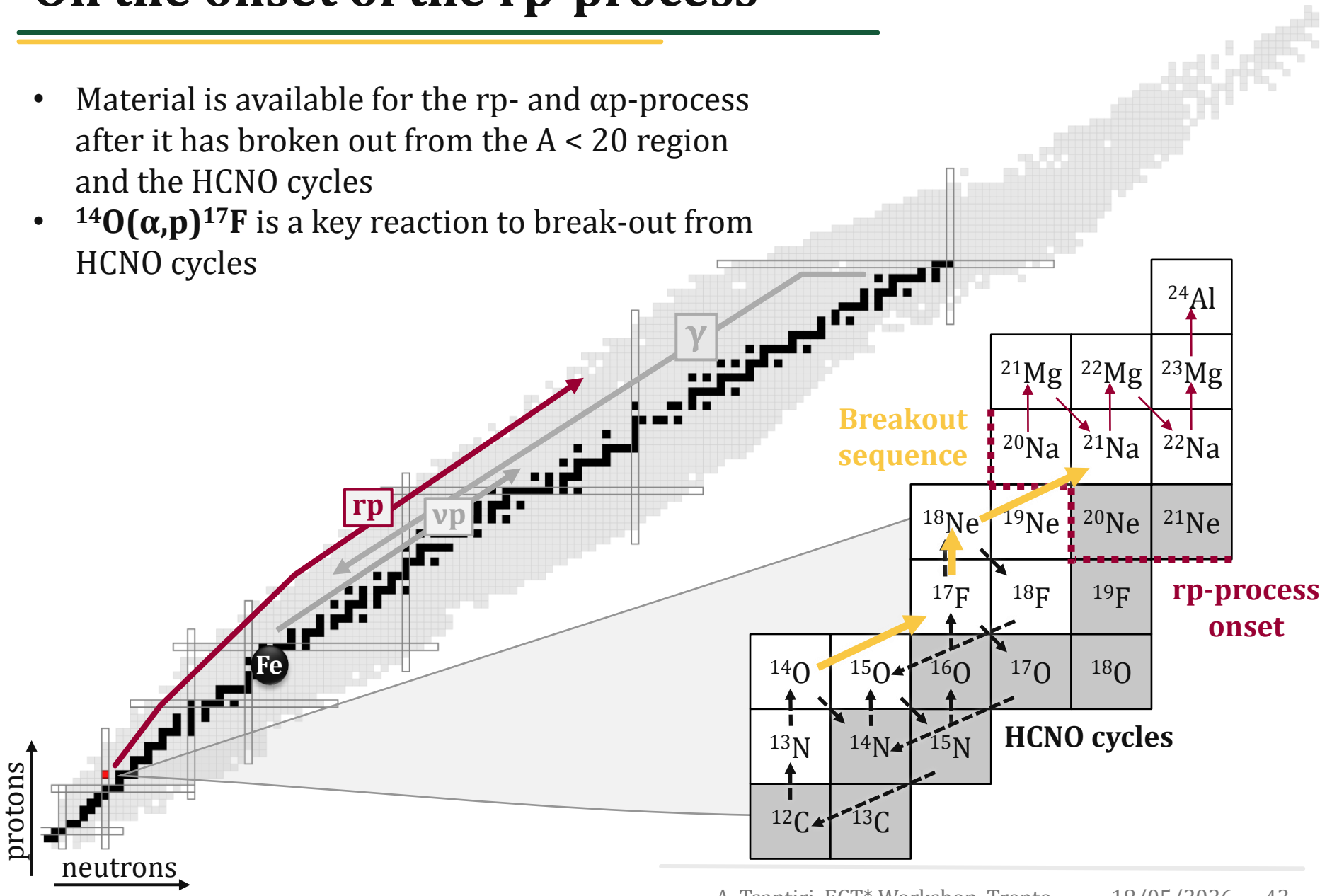
G. Owens-Fryar, A. Spyrou, A. Psaltis, et al (in prep)



A dominant (p,γ) would lead to more heavy mass products but preliminary calculations show the opposite

On the onset of the rp-process

- Material is available for the rp- and αp-process after it has broken out from the A < 20 region and the HCNO cycles
- **$^{14}O(\alpha,p)^{17}F$** is a key reaction to break-out from HCNO cycles

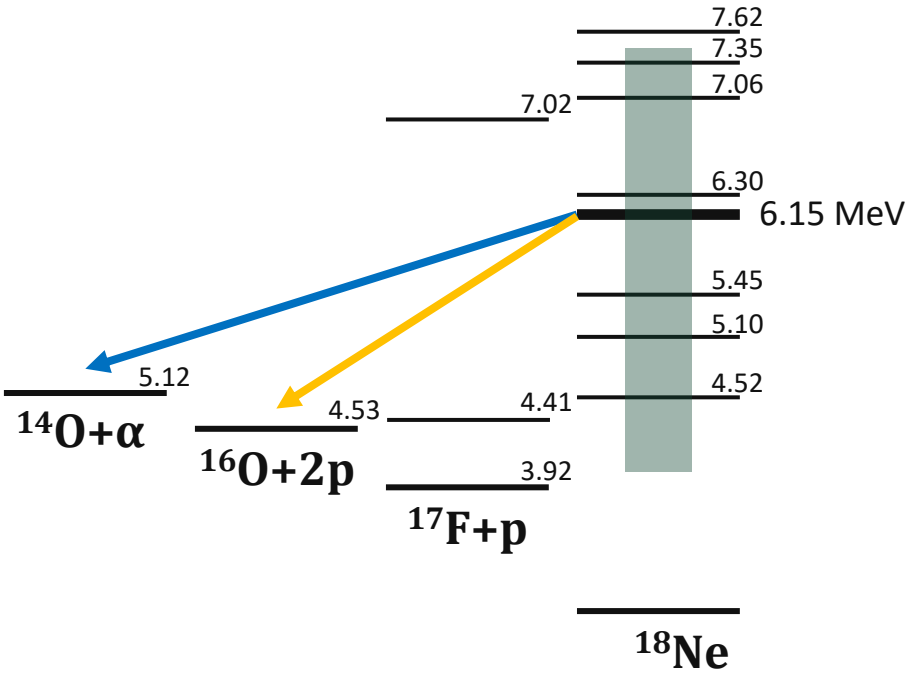


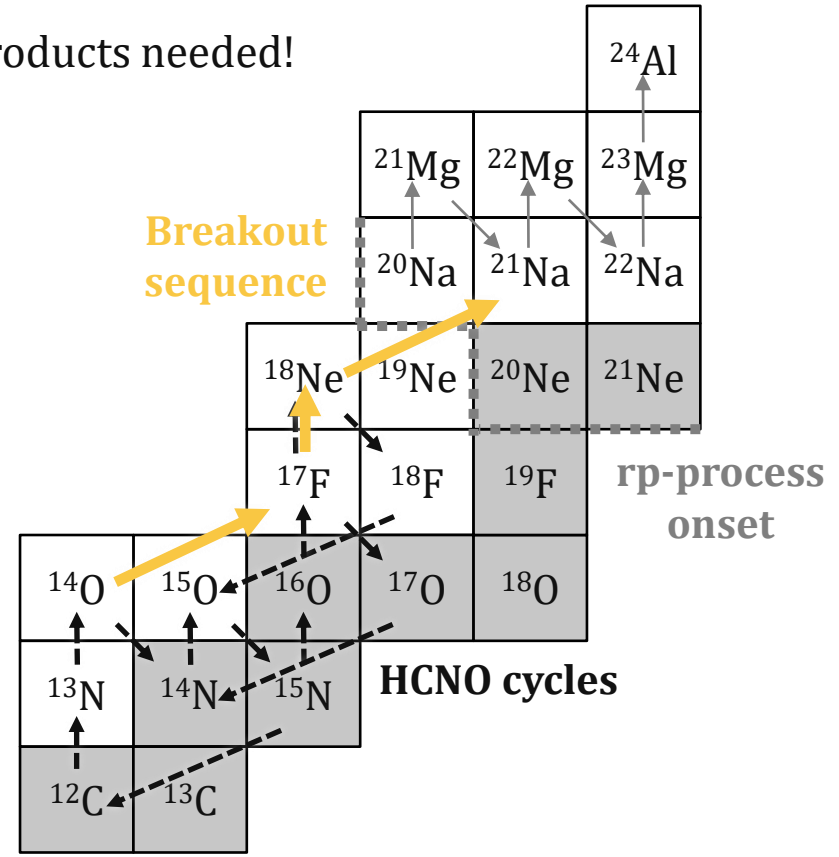
The $^{14}O(\alpha,p)^{17}F$ reaction

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

- For $T_9 \geq 1.5$, the $^{14}O(\alpha,p)^{17}F$ 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, but the results have so far been inconsistent

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

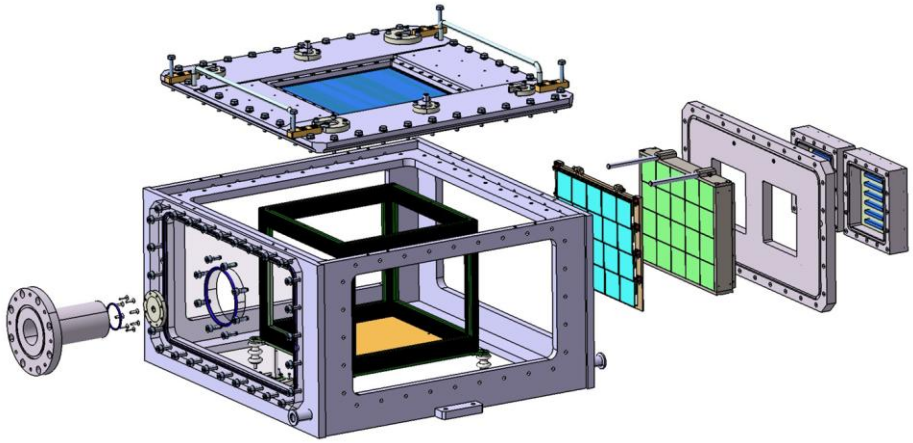


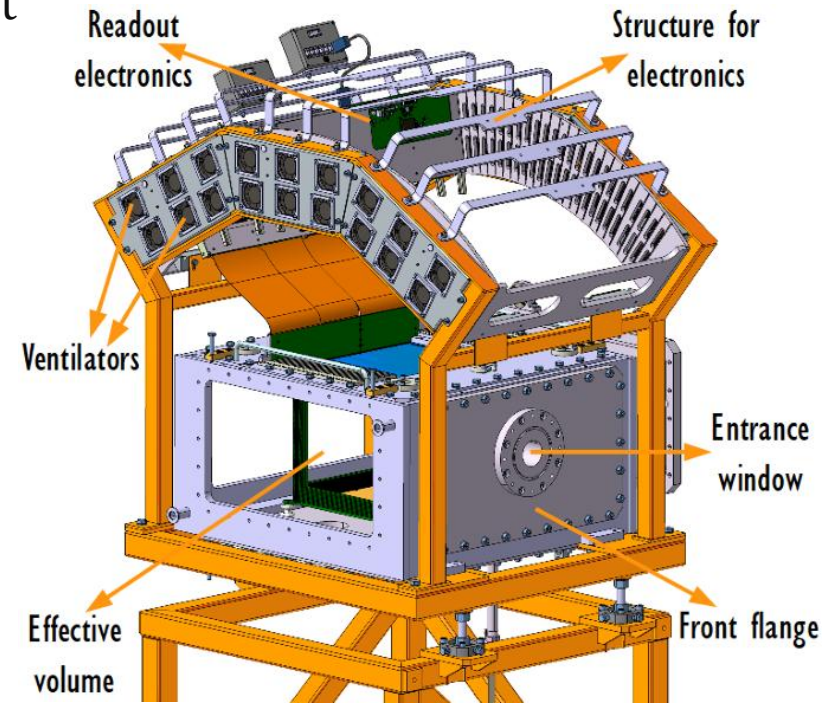


ACTAR TPC

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!

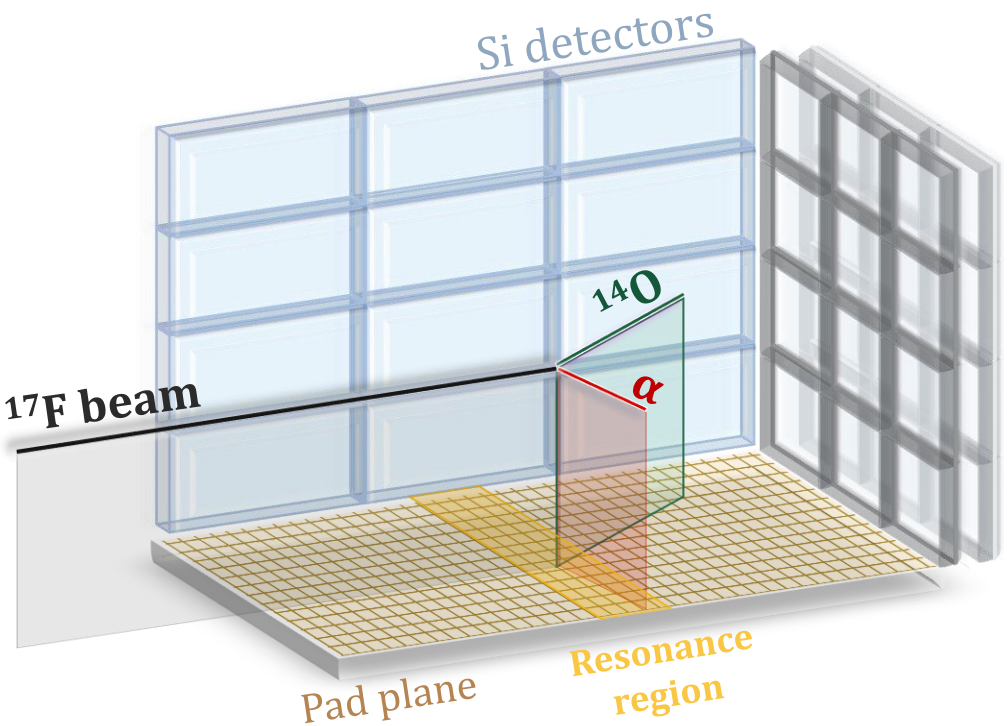


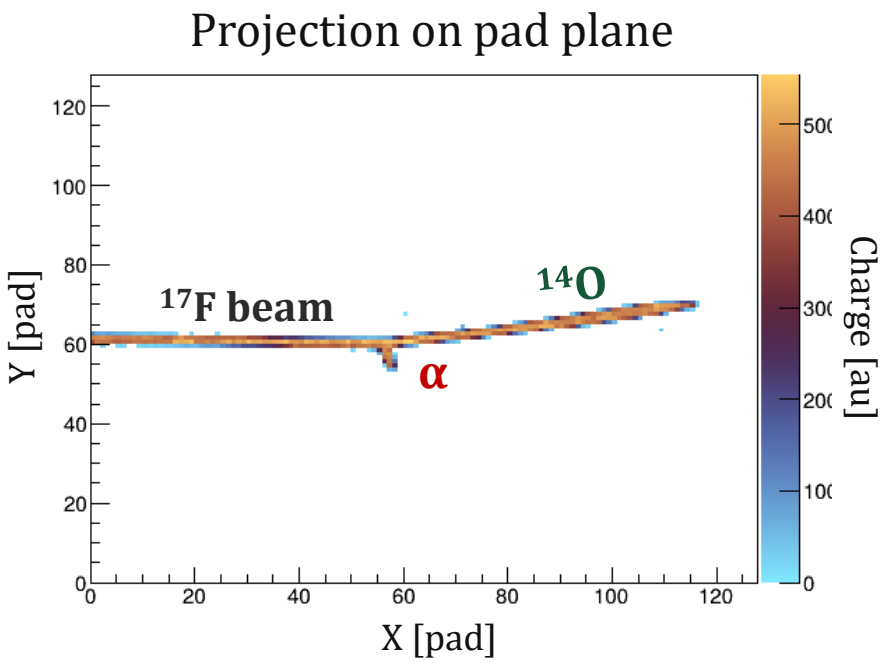


A. Ortega Moral, PhD Thesis (2023)

Resonant p scattering on ^{17}F

- Shipped ACTAR from GANIL to TRIUMF ✓
- Data taking complete (August 2025) ✓
- Analysis ongoing – stay tuned!





Summary

- The synthesis of the p nuclei can have contributions from various nucleosynthetic processes
- To constrain astrophysical network calculations, we need to measure reaction cross-sections on radioactive nuclei
- Valuable constraints can be inferred from both direct (^{74}Se, ^{85}Rb) and indirect measurements (^{92}Nb, ^{59}Zn)

Thank you for your attention ☺

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Backup Slides