TRIUMF

Saint Mary's University

Direct Measurements of (α,n) Reactions Using the DEMAND Array with DRAGON

Ben Reed

TRIUMF & Saint Mary's University

WNPPC 2025, 16th Feb 2025

Discovery, accelerated

Land Acknowledgement

TRIUMF is located on the traditional, ancestral, and unceded territory of the xʷməθkʷəy̓əm (Musqueam) people, who for millennia have passed on their culture, history, and traditions from one generation to the next on this site.

Where do the elements come from?

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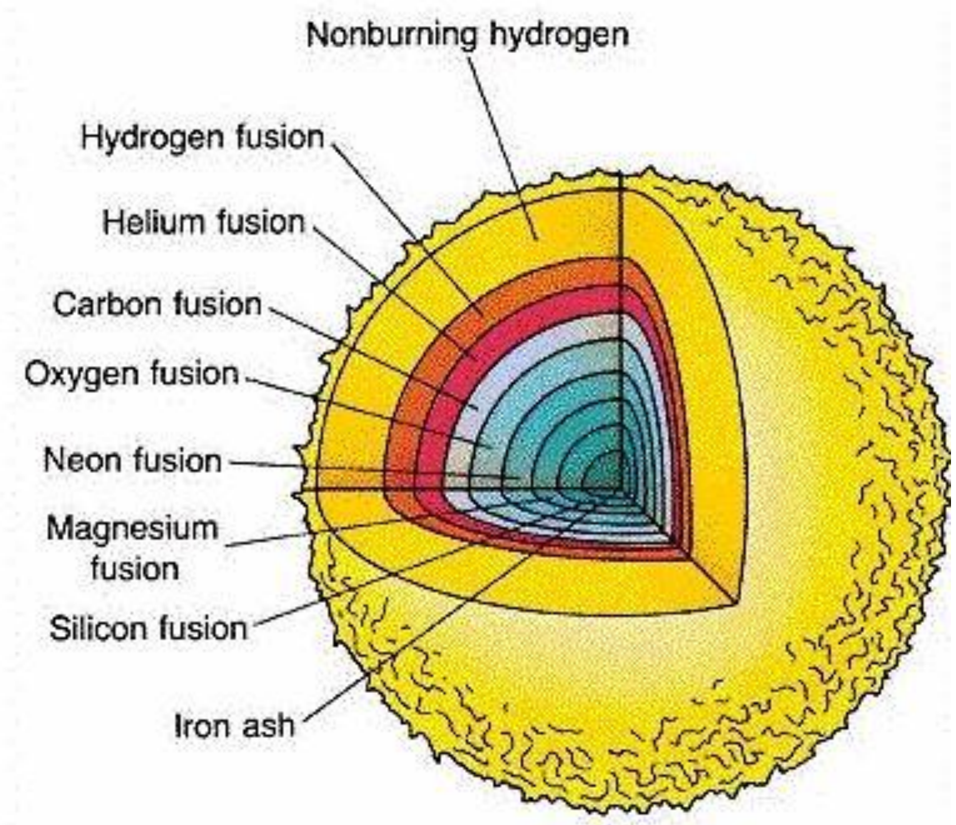

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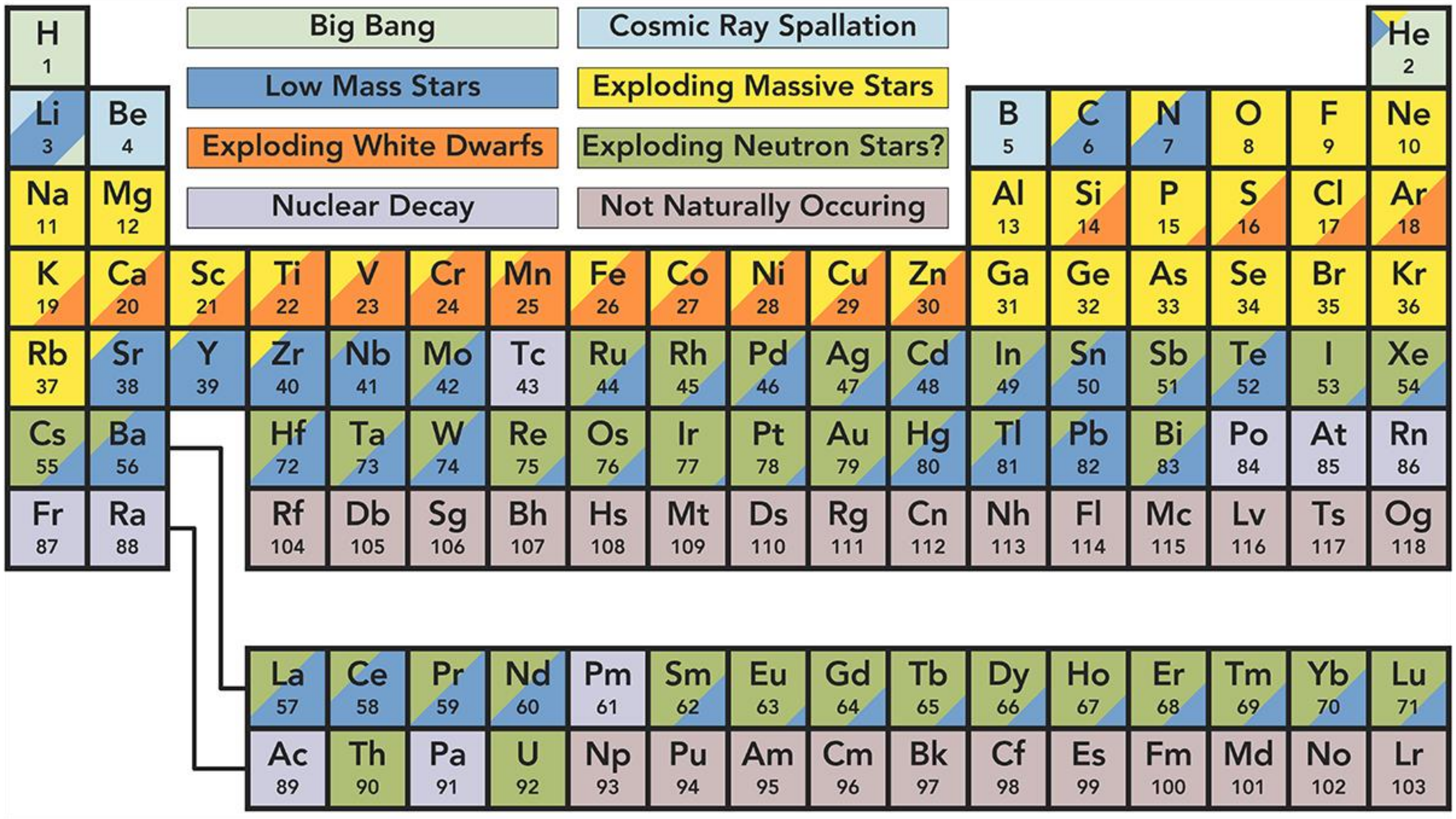
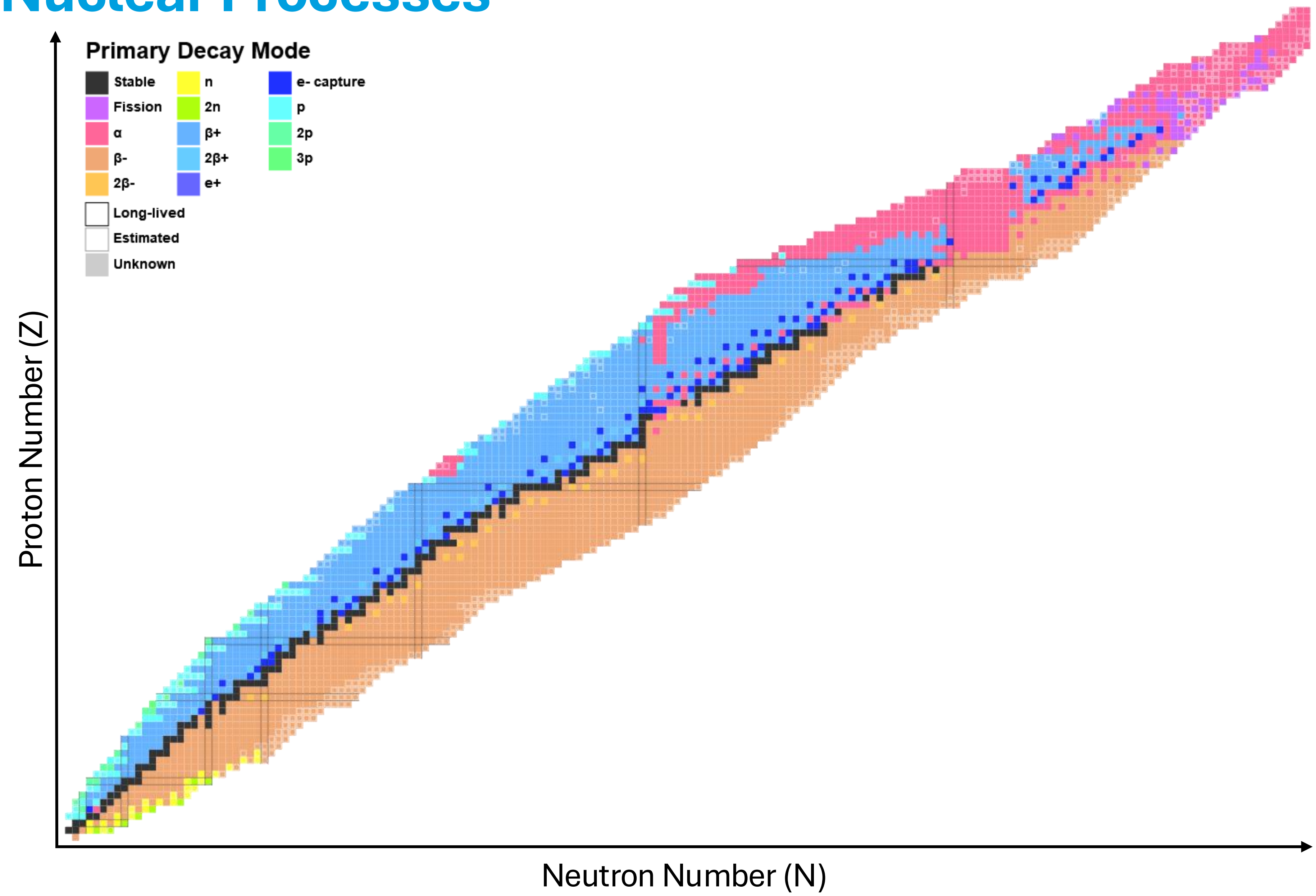


Nuclear Processes



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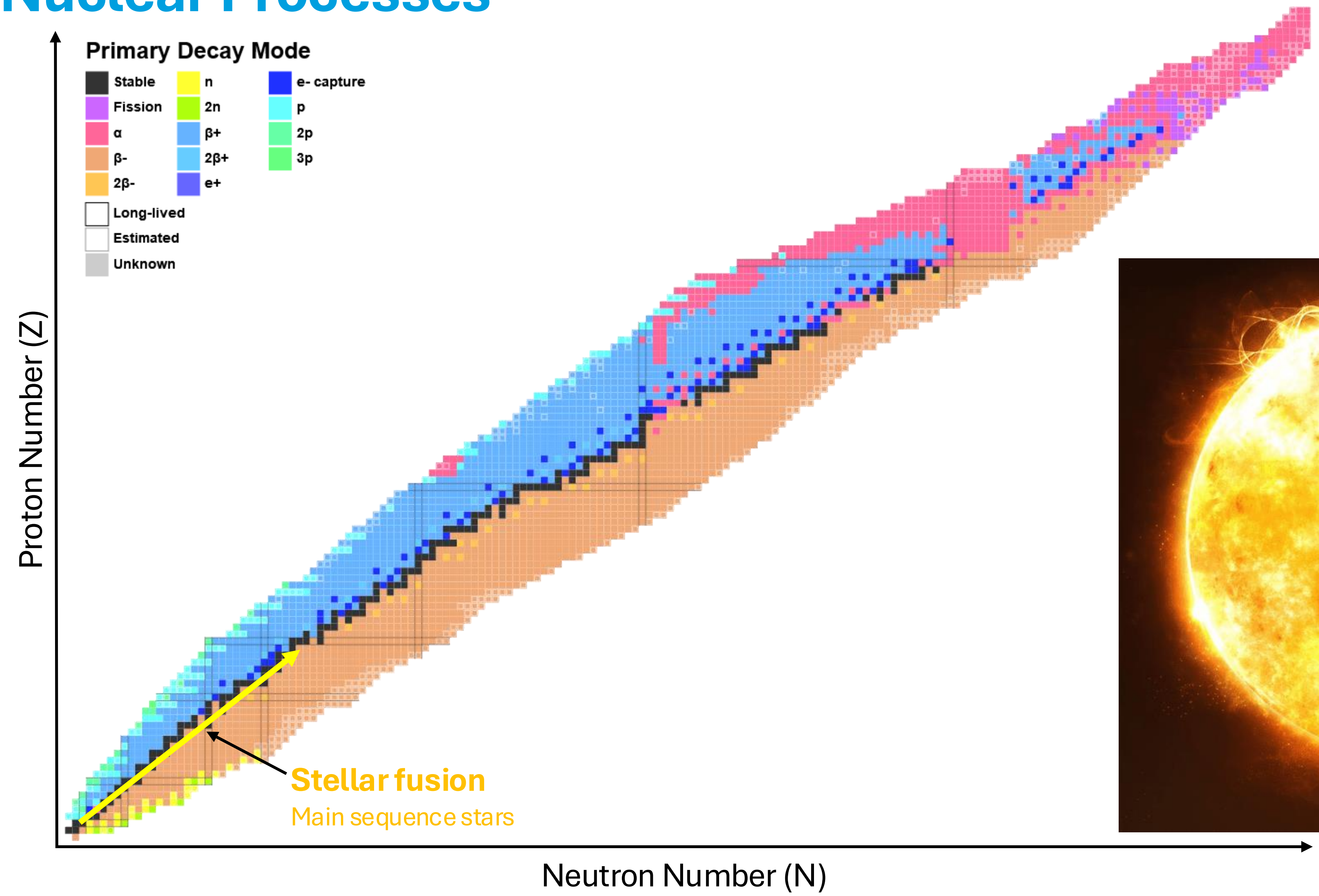

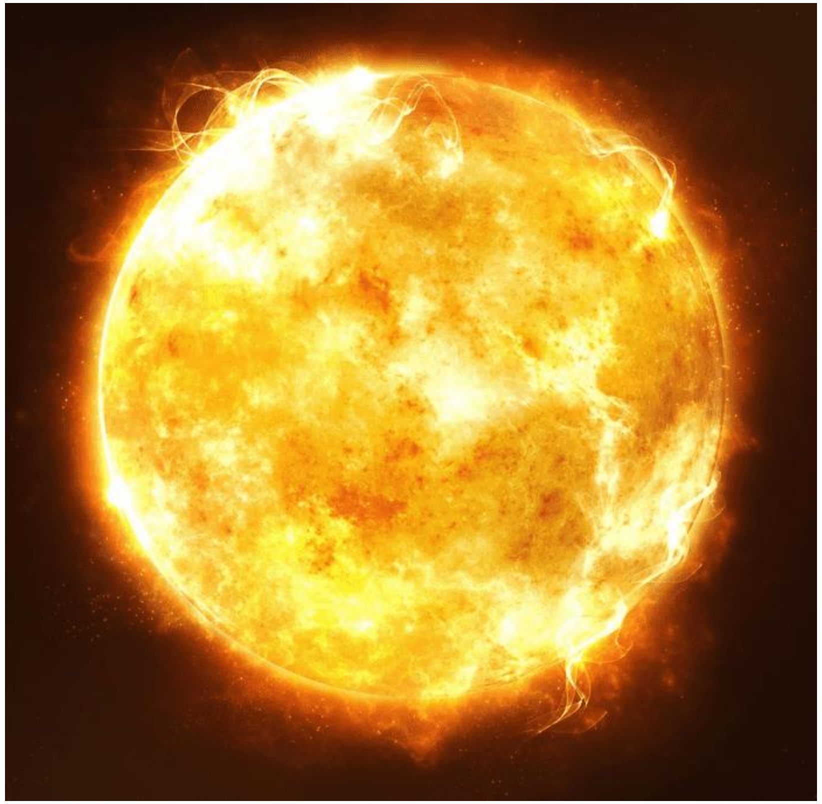

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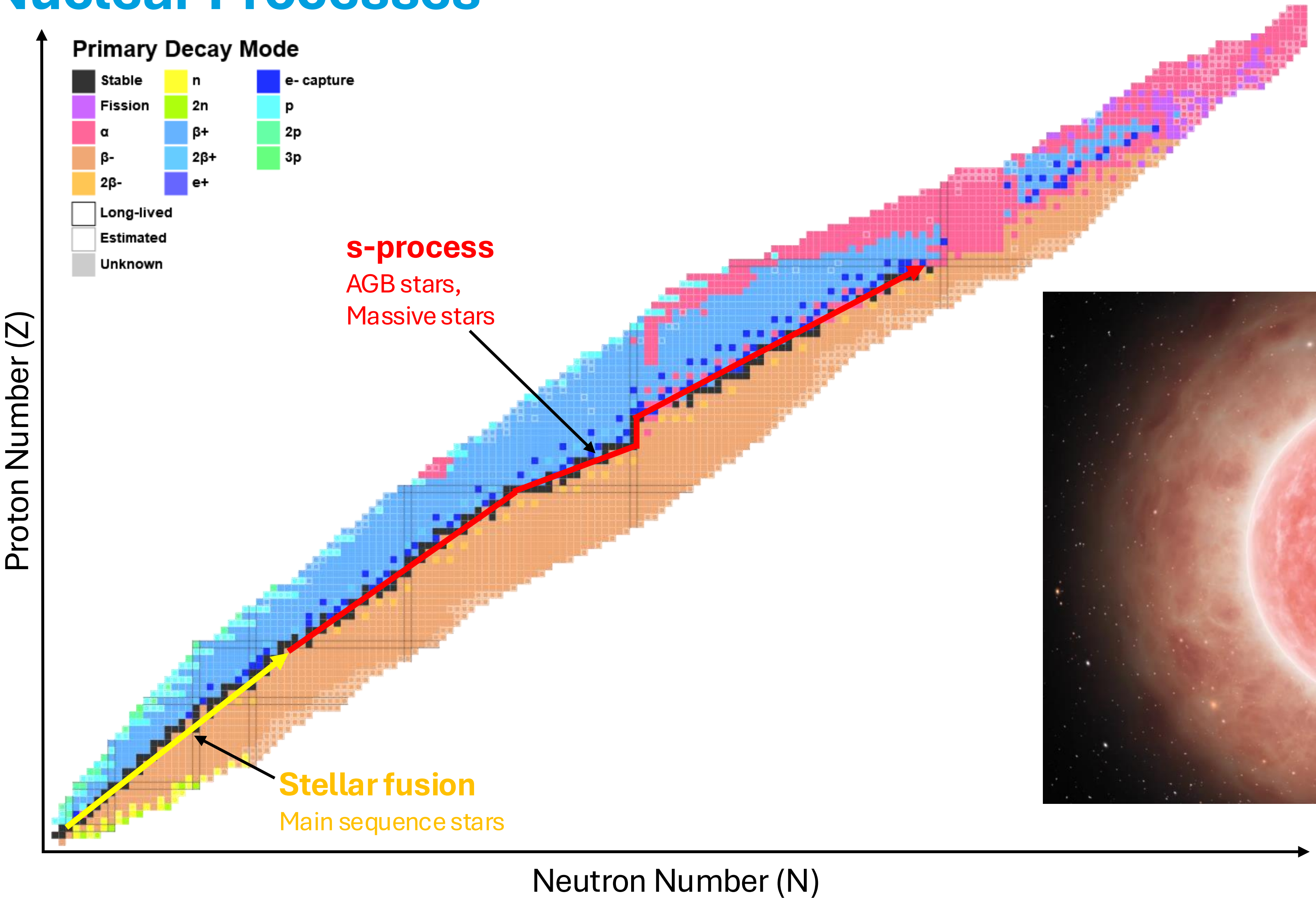

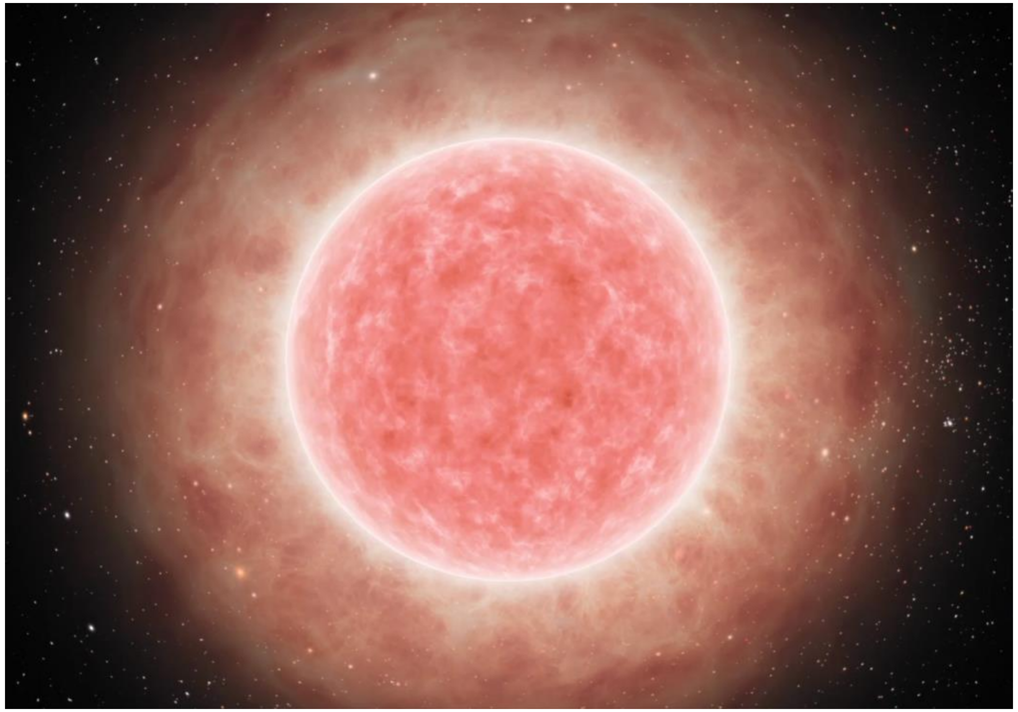

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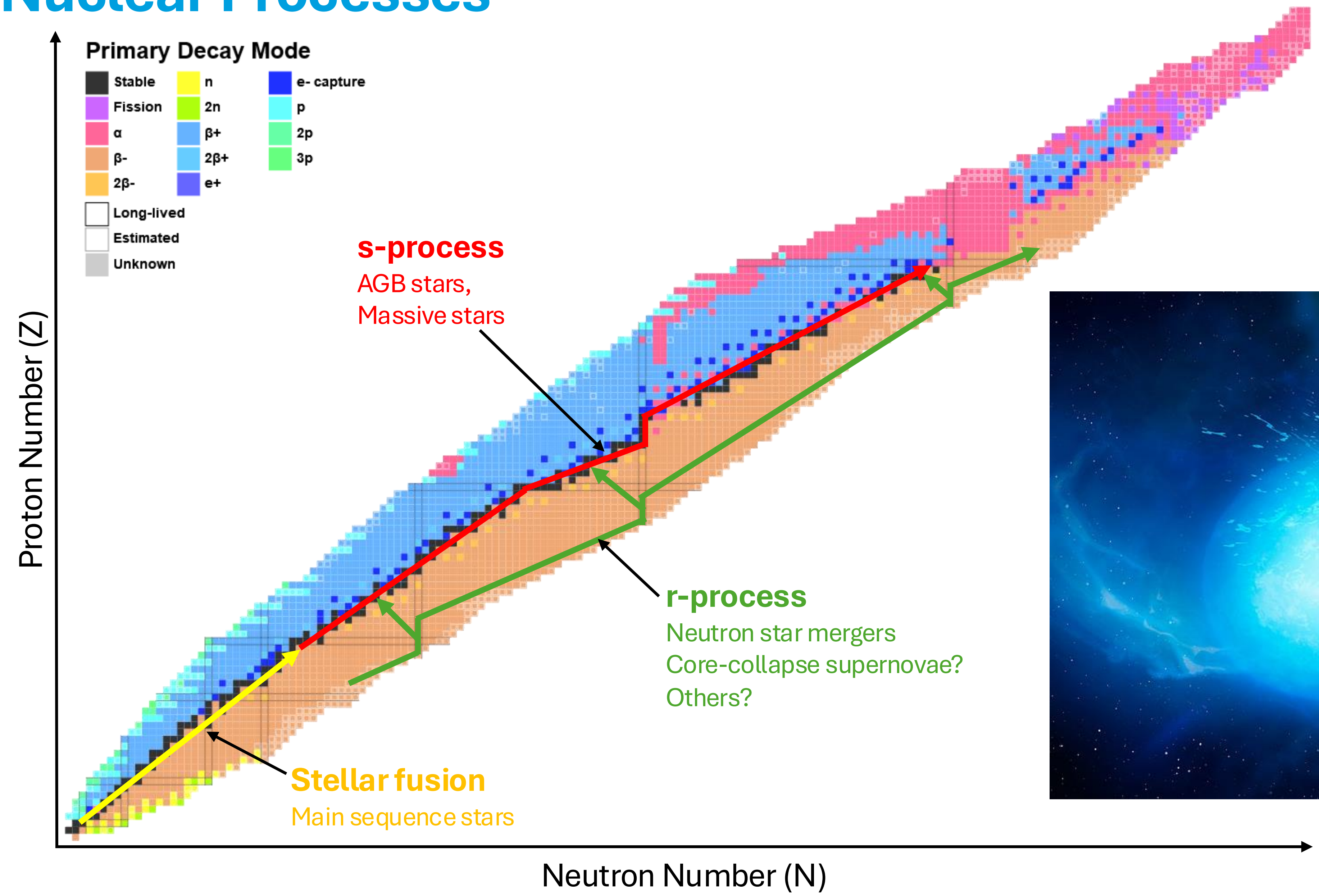

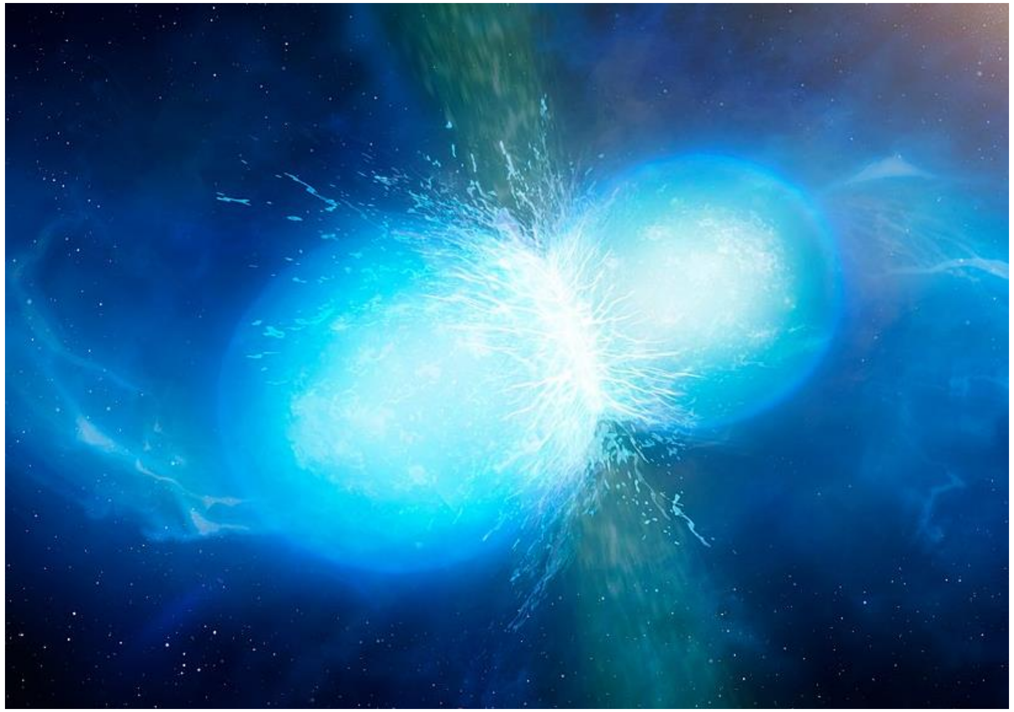

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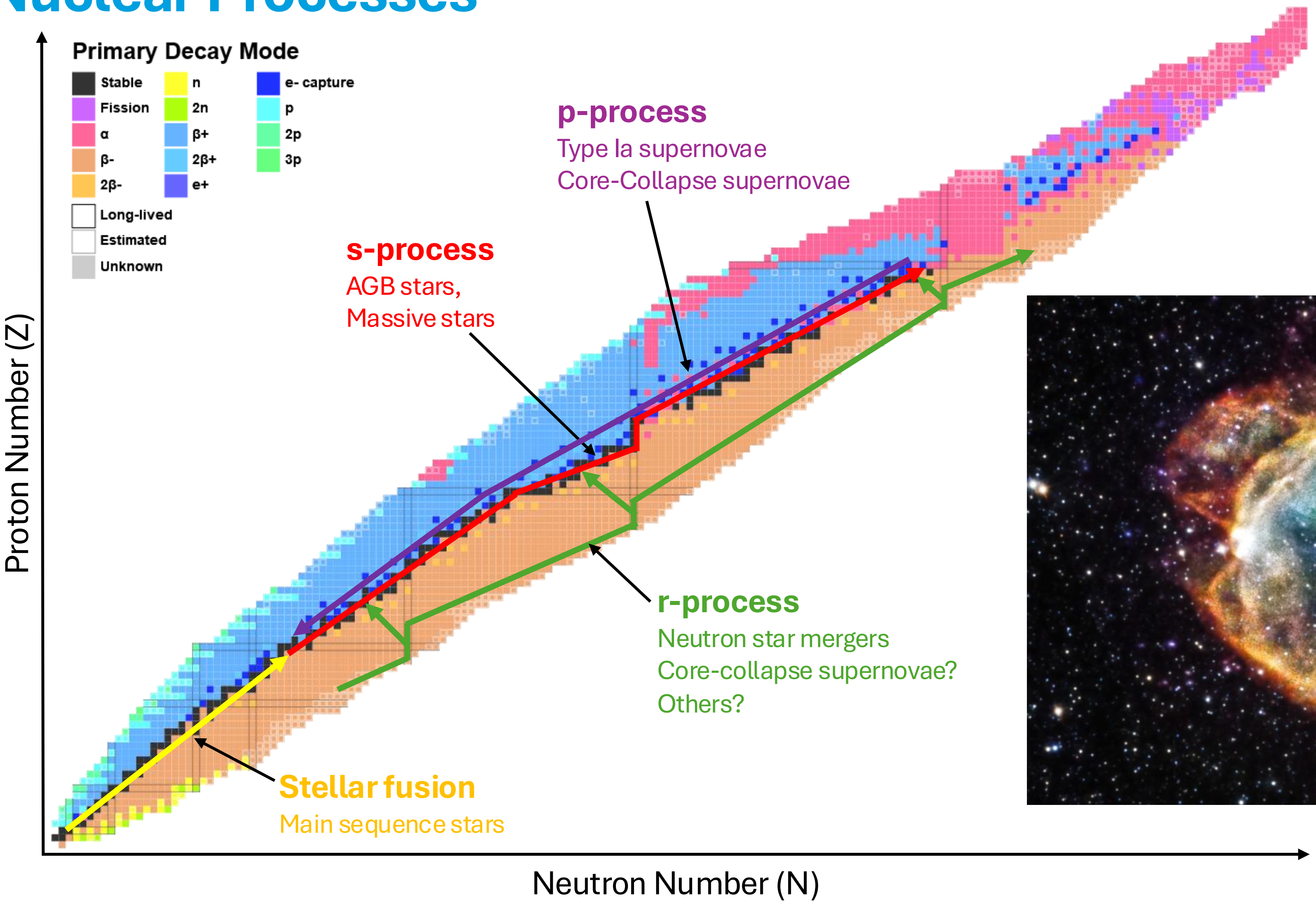

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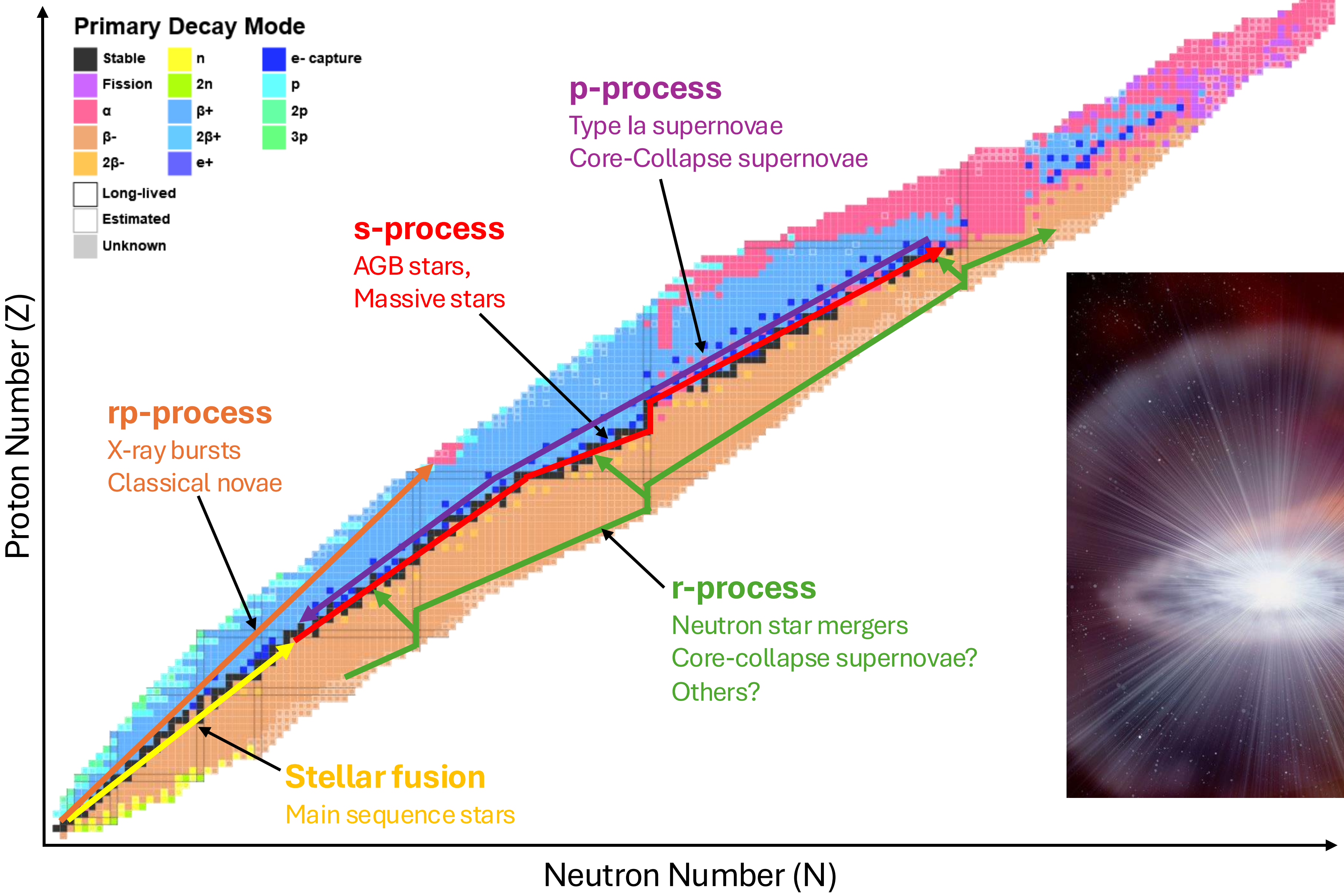
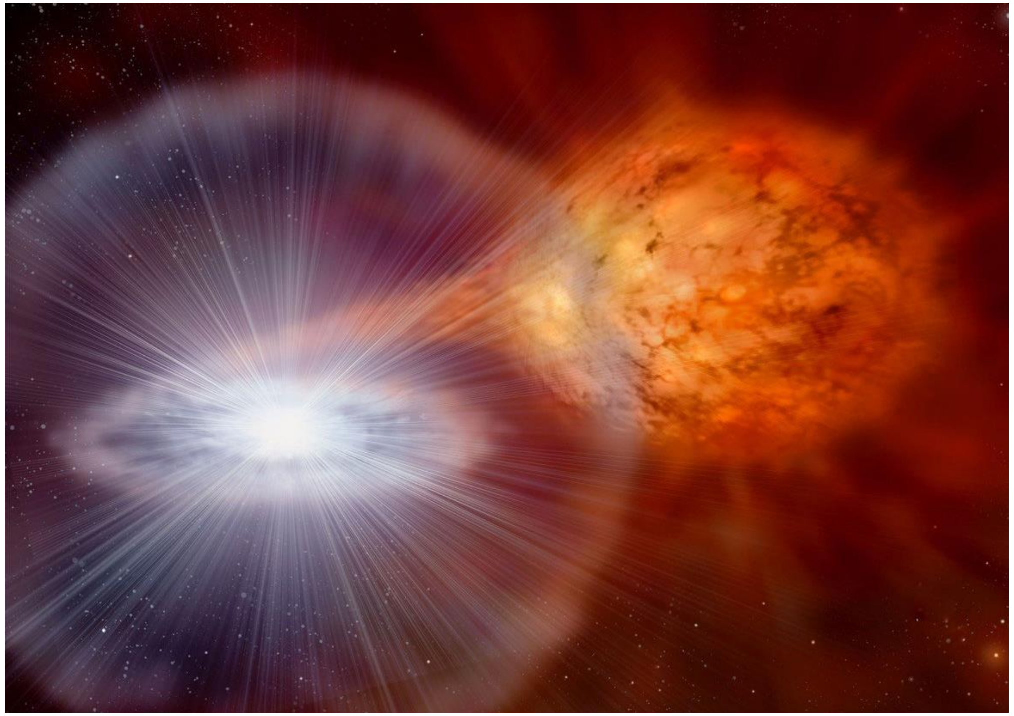




Hydrodynamic Simulations

Simulations of stellar environments depend on:

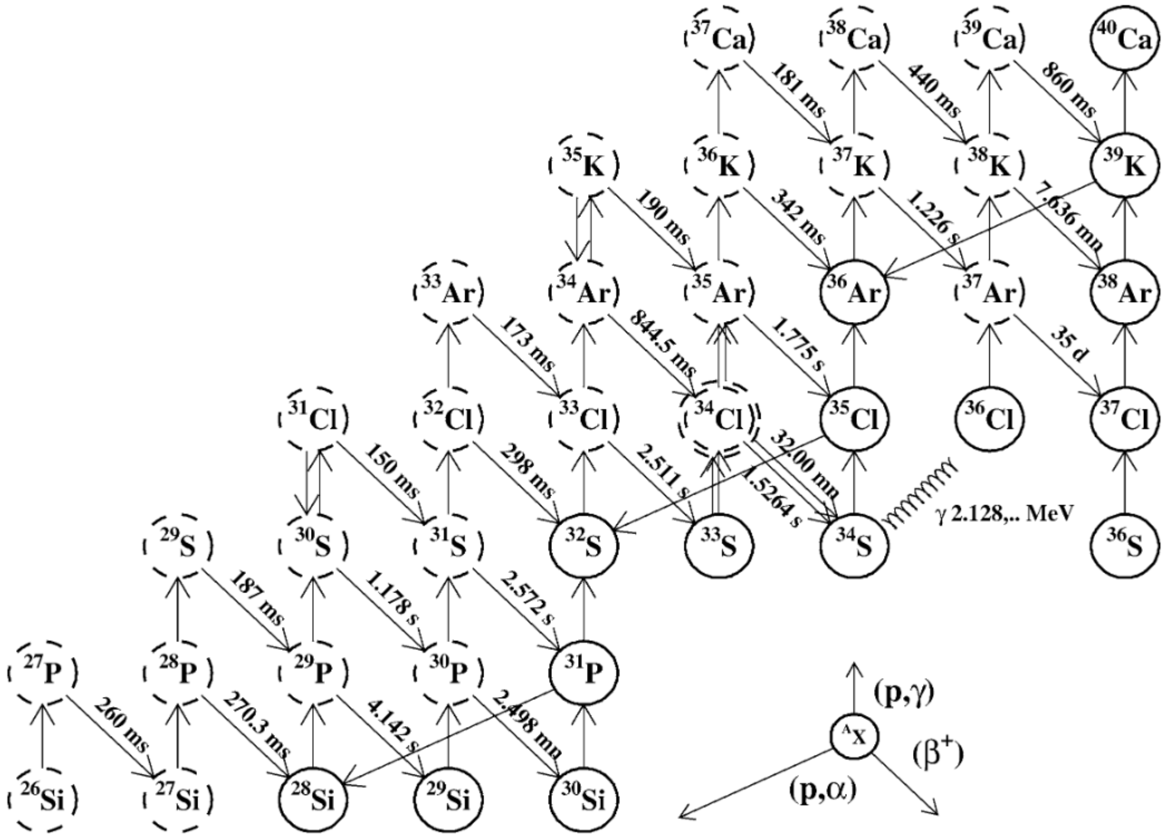
- Nuclear reaction rates and decay times
- Stellar masses
- Initial compositions
- Fluid dynamics and mixing

Able to predict properties such as:

- Composition
- Light curves
- Reoccurrence times
- Ejected & accreted mass
- Peak temperature

Results of simulations are highly dependent on the input reaction rates

Therefore, **better experimental knowledge of reaction rates is required**!



Reaction network in the Si-Ca region for classical novae (J. José, Nucl. Phys. A, 2006)

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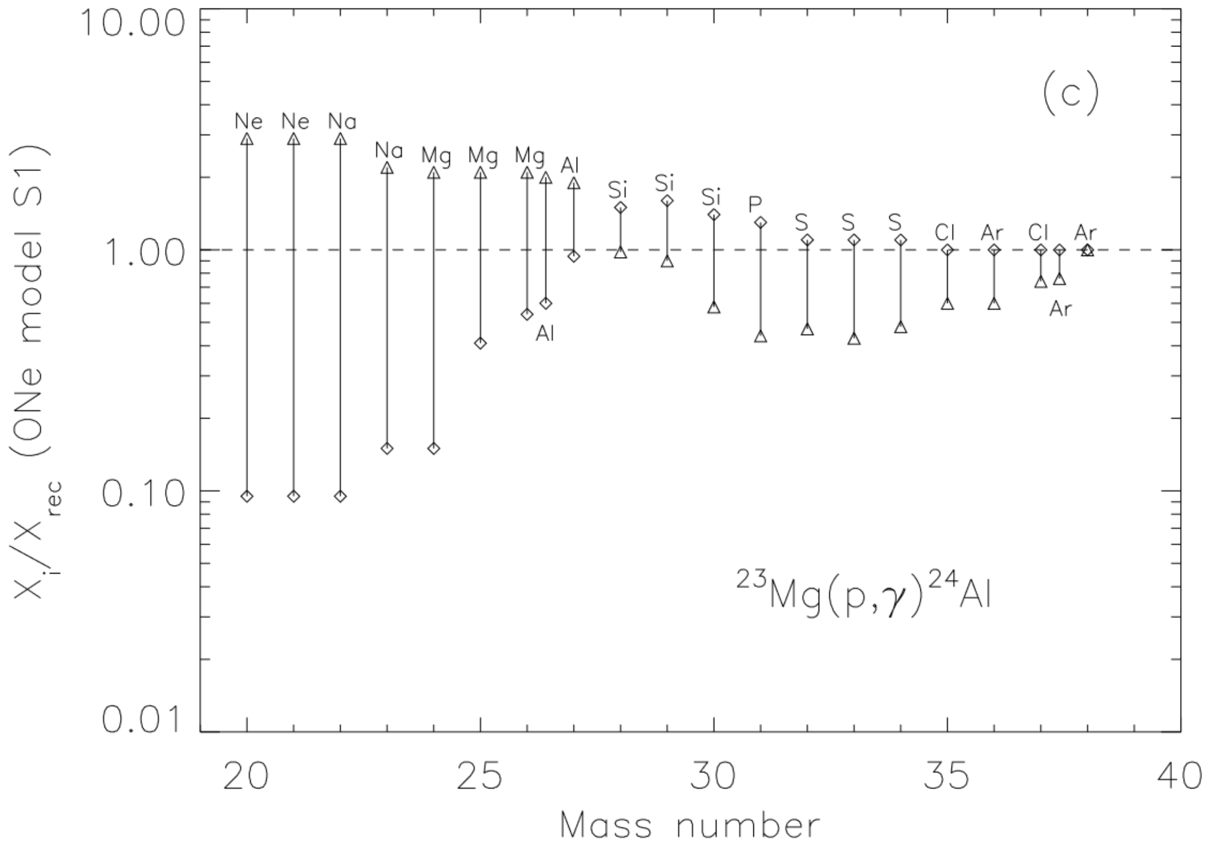

Change factor in final isotopic abundance of an ONe classical nova (C. Iliadis, Astrophys. J. Sup. Series, 2002)

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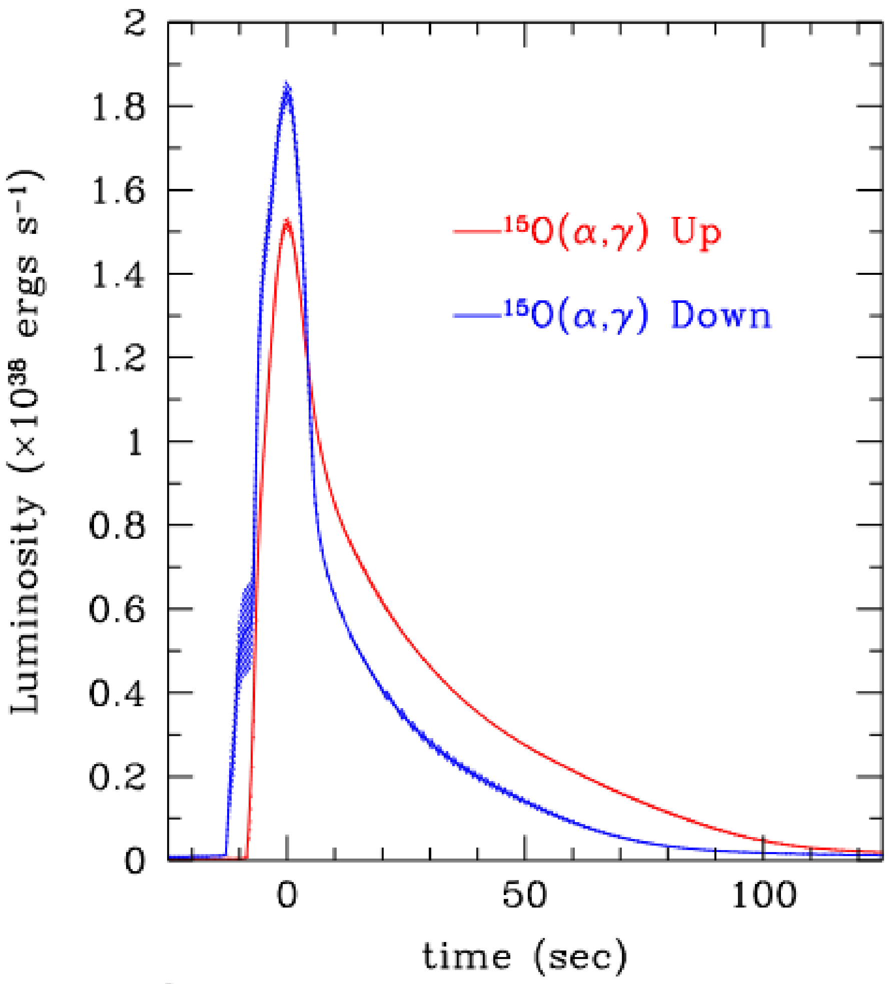


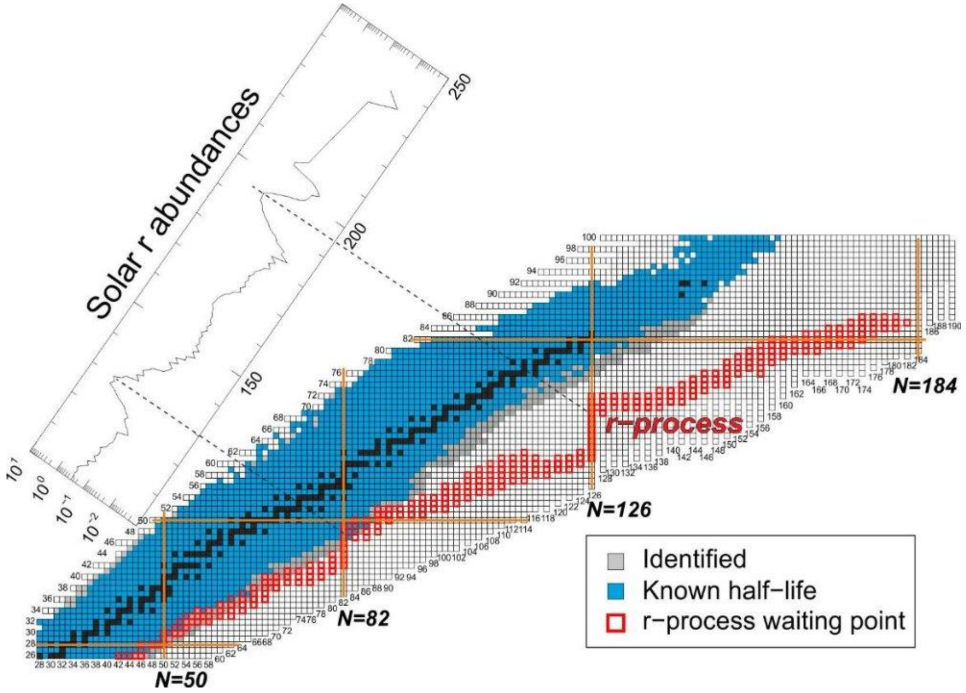
X-ray burst light curve (R. H. Cybert, Astrophys. J., 2016)

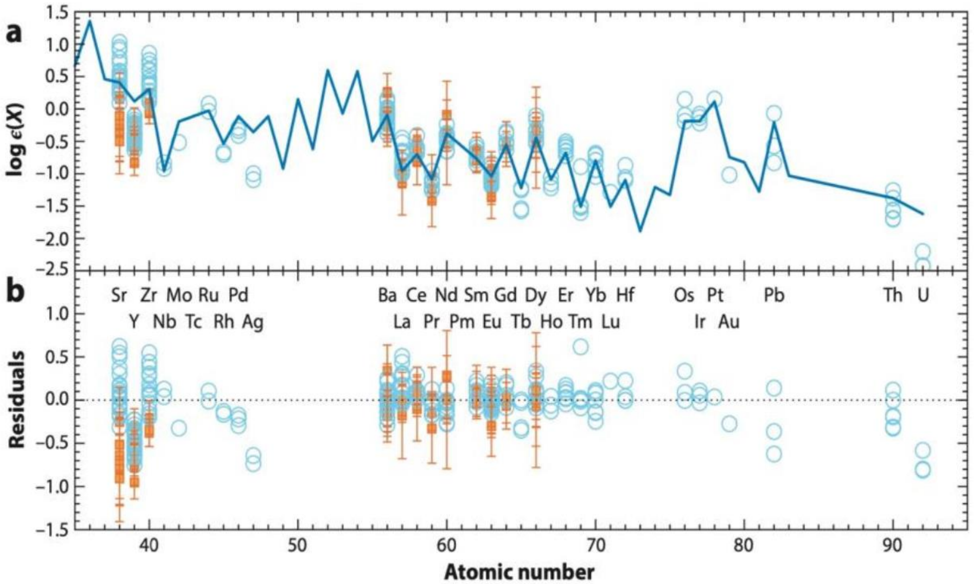
The r-Process

The **r-process** is expected to produce **~50%** of all elements in the galaxy

Occurs in **neutron star mergers**

There is evidence that there **must be other sites:**
1. Stars older than neutron stars contain r-process nuclei
2. Some stars have an enhanced abundance of light r-process nuclei





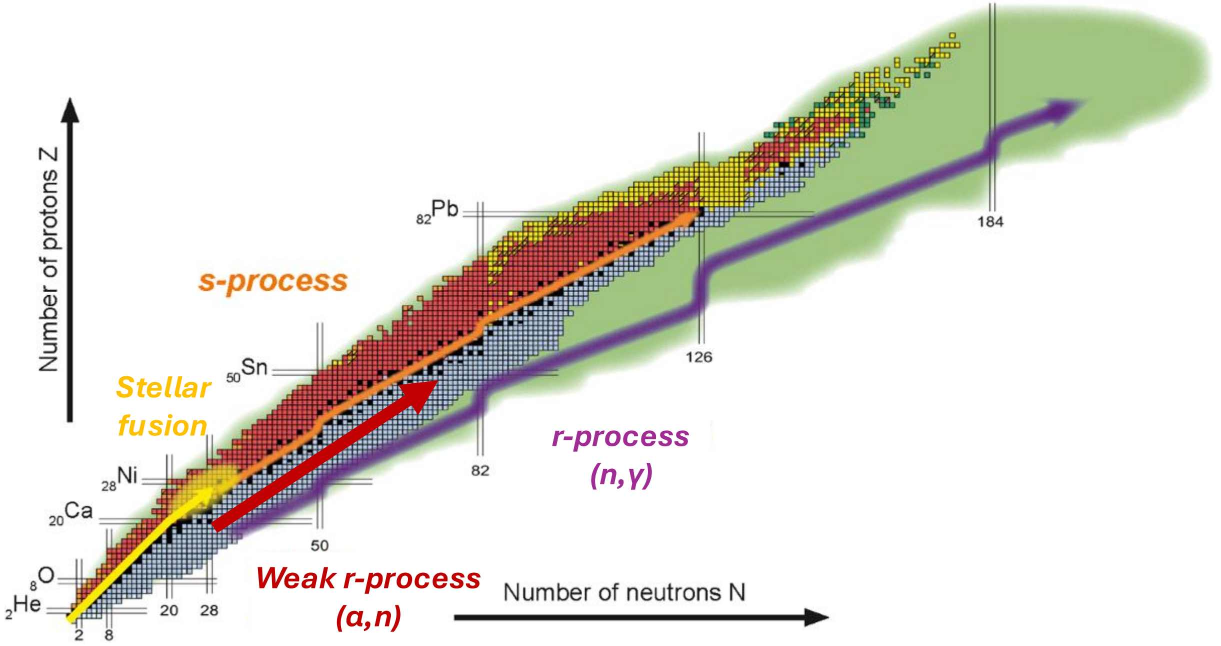
A. Frebel, Ann. Rev. Nucl. Part. Sci. ***68****, 237 (2018)*

The Weak r-Process

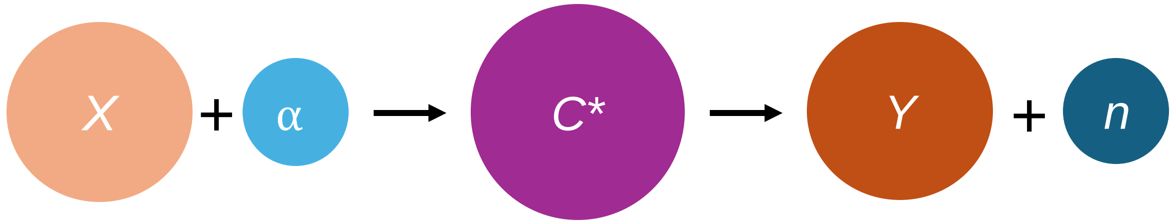
Core-collapse supernovae have been proposed as a potential site for the **weak r-process**

Nuclei up to Ag are produced via a series of **(α,*n*) reactions**

A sensitivity study by Bliss *et al*. identified **45 (α,*n*) reactions** that are **important for the weak r-process** (J. Bliss, Phys. Rev. C, 2020)



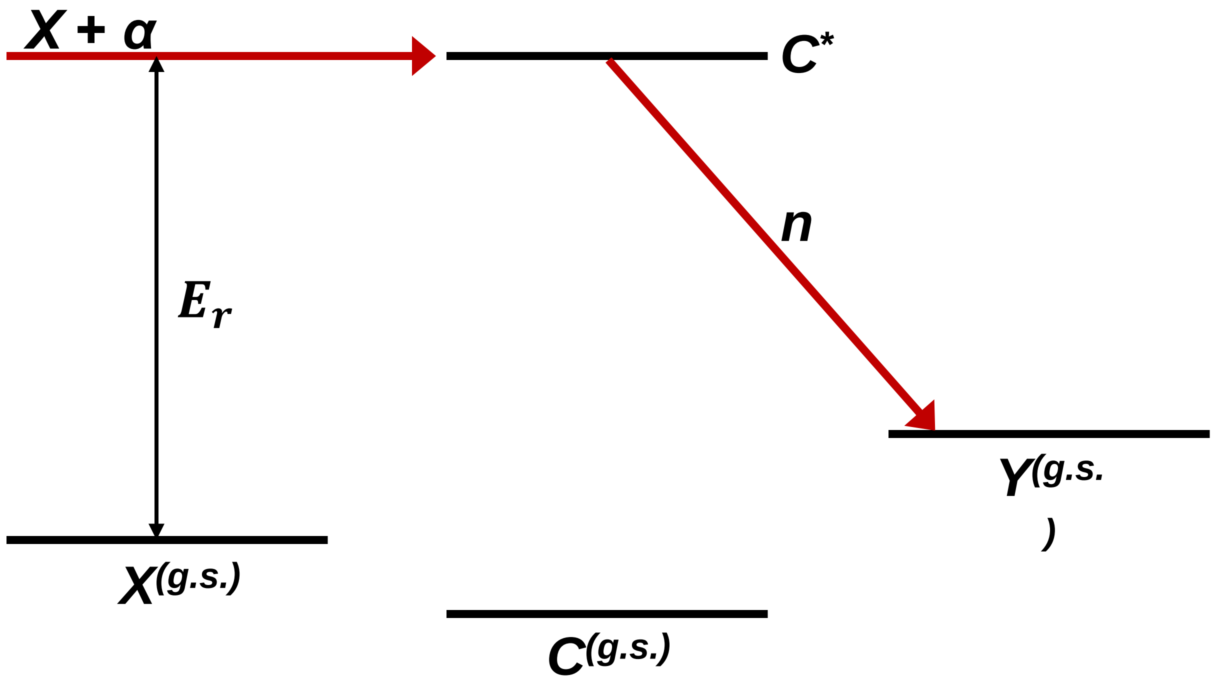
Resonant (α,*n*) Reactions

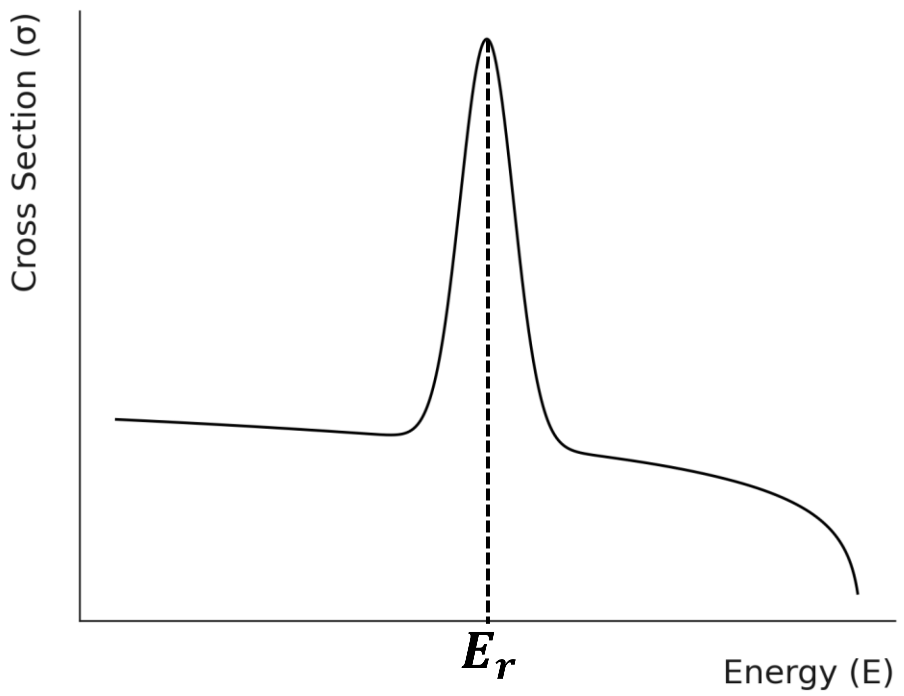


Fusion of a heavy nucleus and an α particle followed by the emission of a neutron

Reaction proceeds through an **excited state** in a **compound nucleus**

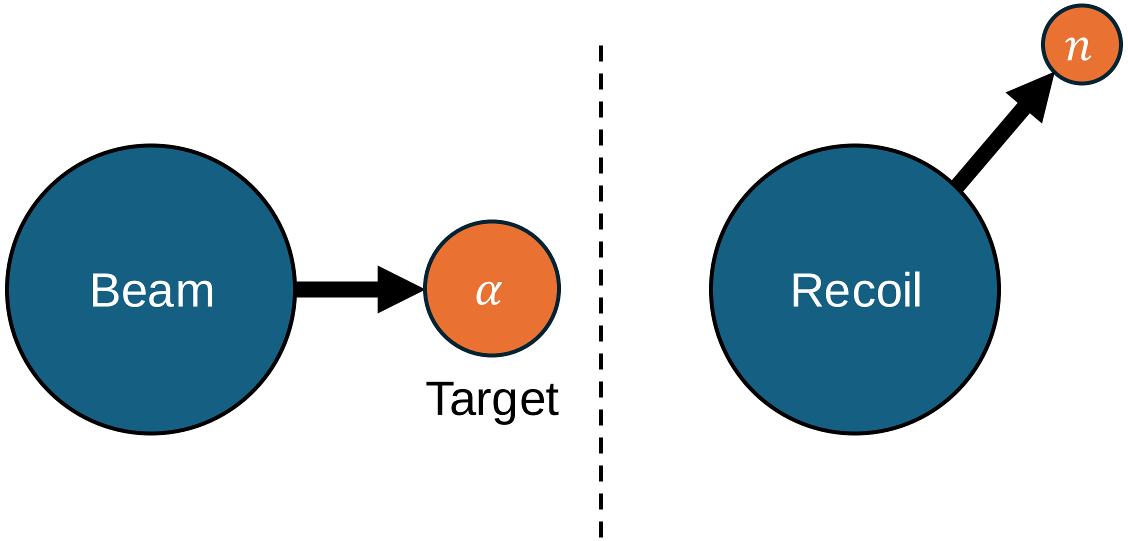
If the energy of the nuclei is equal to the resonance energy, there is a **massive increase in the cross section**





Direct Measurements

$$\langle \sigma v \rangle = \left(\frac{2\pi}{\mu kT}\right)^{3/2} \hbar^2 \sum_i (\omega\gamma)_i \exp\left(-\frac{E_{r,i}}{kT}\right)$$



To determine the reaction rate, we need to know:

1. **Resonance Energy (E_r)**
2. **Resonance strength ($\omega\gamma$)**

The **resonance strength** can be calculated using:

$$\omega\gamma = \frac{2}{\lambda^2}\frac{m}{M+m} Y \frac{dE}{dx}$$

Reaction yield is determined from number of detected coincidences**:**

$$Y = \frac{N_{coinc}^{det}}{N_b \eta}$$

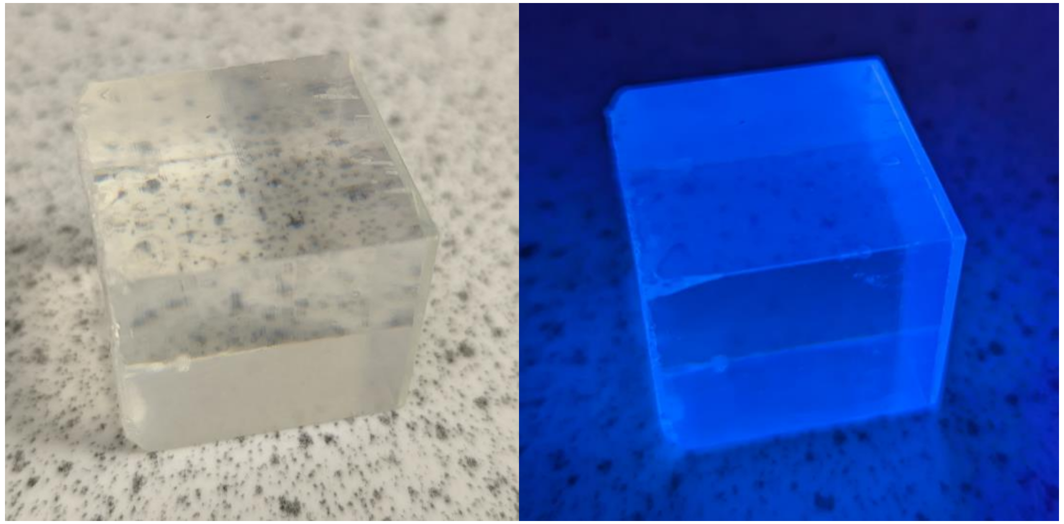
The energy which gives the maximum yield gives the **resonance energy**

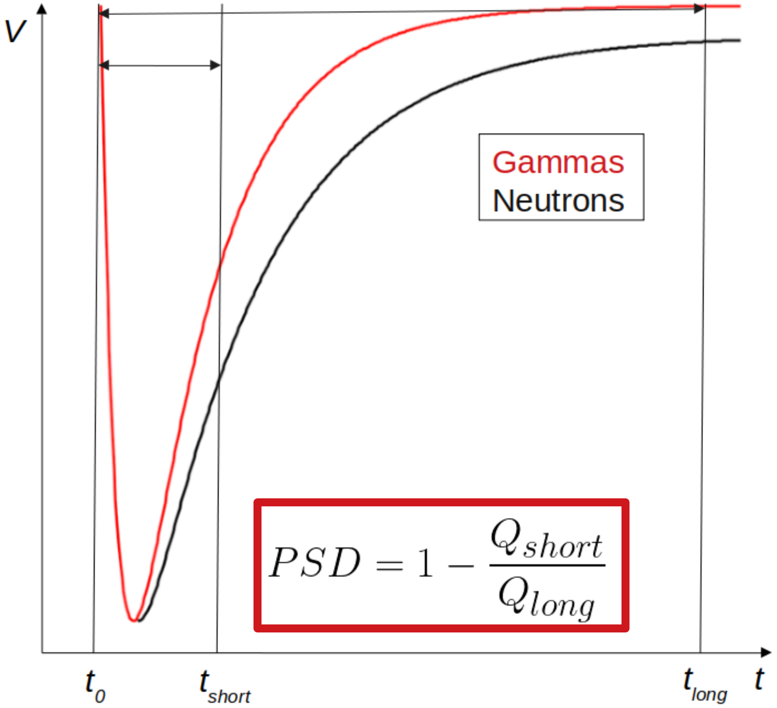
The DEMAND Array

DEMAND = **D**irect **E**xperimental **M**easurements of **A**strophysical reactions using **N**eutron **D**etectors

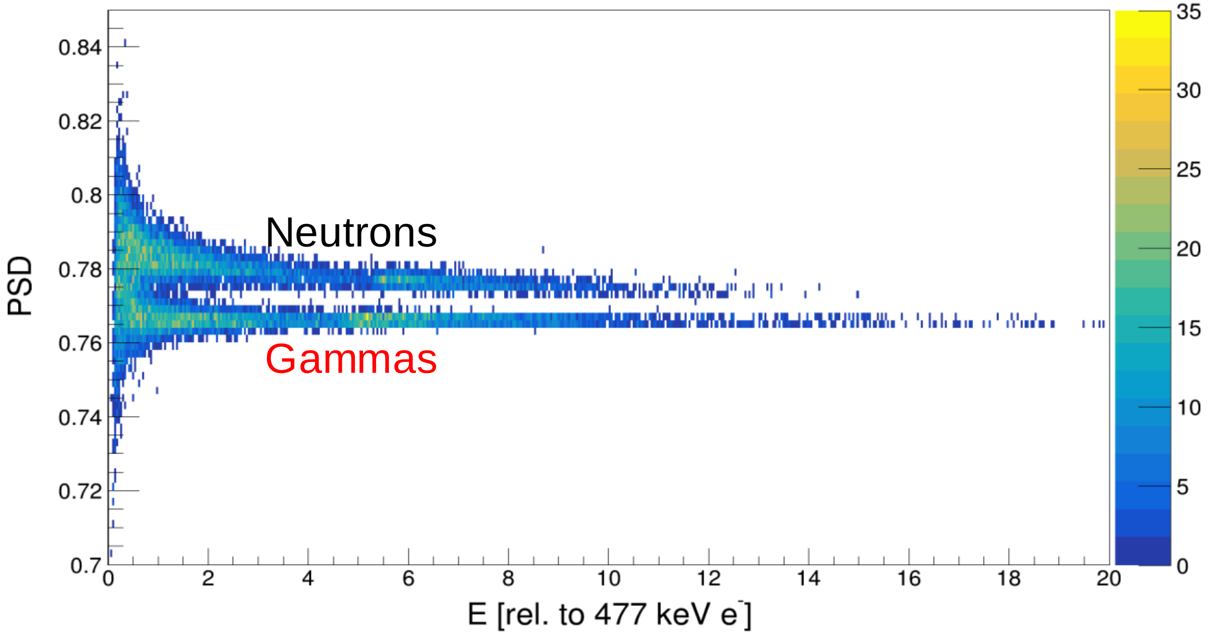
Organic glass scintillator (OGS) detectors produced by BlueShift Optics

OGS detectors have excellent **pulse shape discrimination**, **light output** and **timing** properties





$$PSD = 1 - \frac{Q_{short}}{Q_{long}}$$

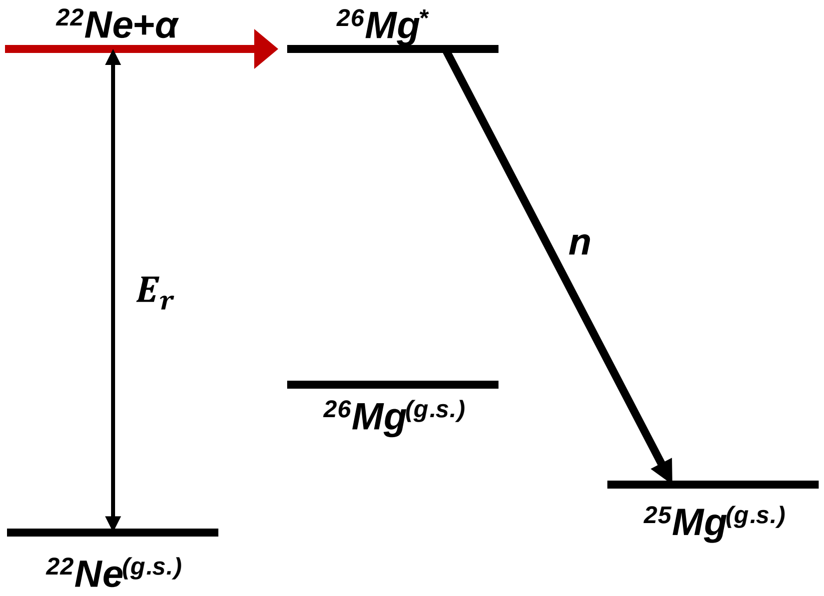


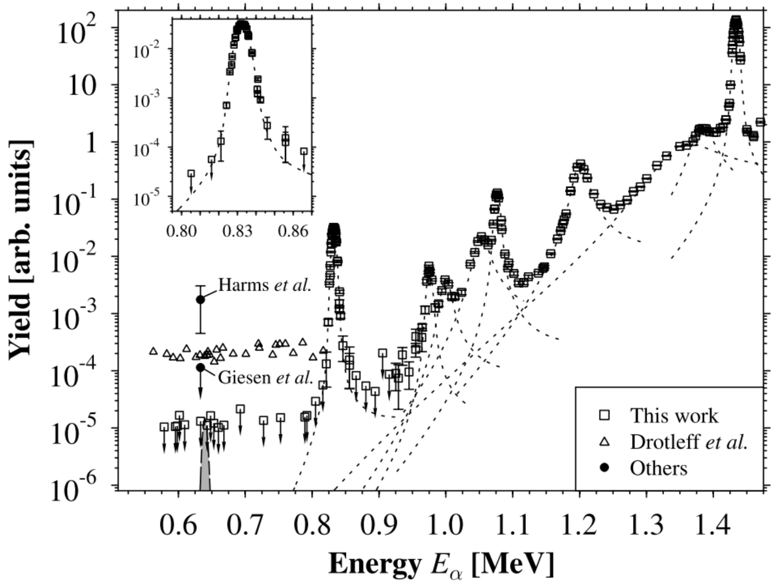
^{22}Ne(α,n)^{25}Mg - a proof of principle

Strong resonances have already been **identified** in a measurement performed in **normal kinematics** (Jaeger, 2001)

Resonance at E_r = **1.43 MeV** has a measured **resonance strength** of **1.067 eV,** making it an ideal test case

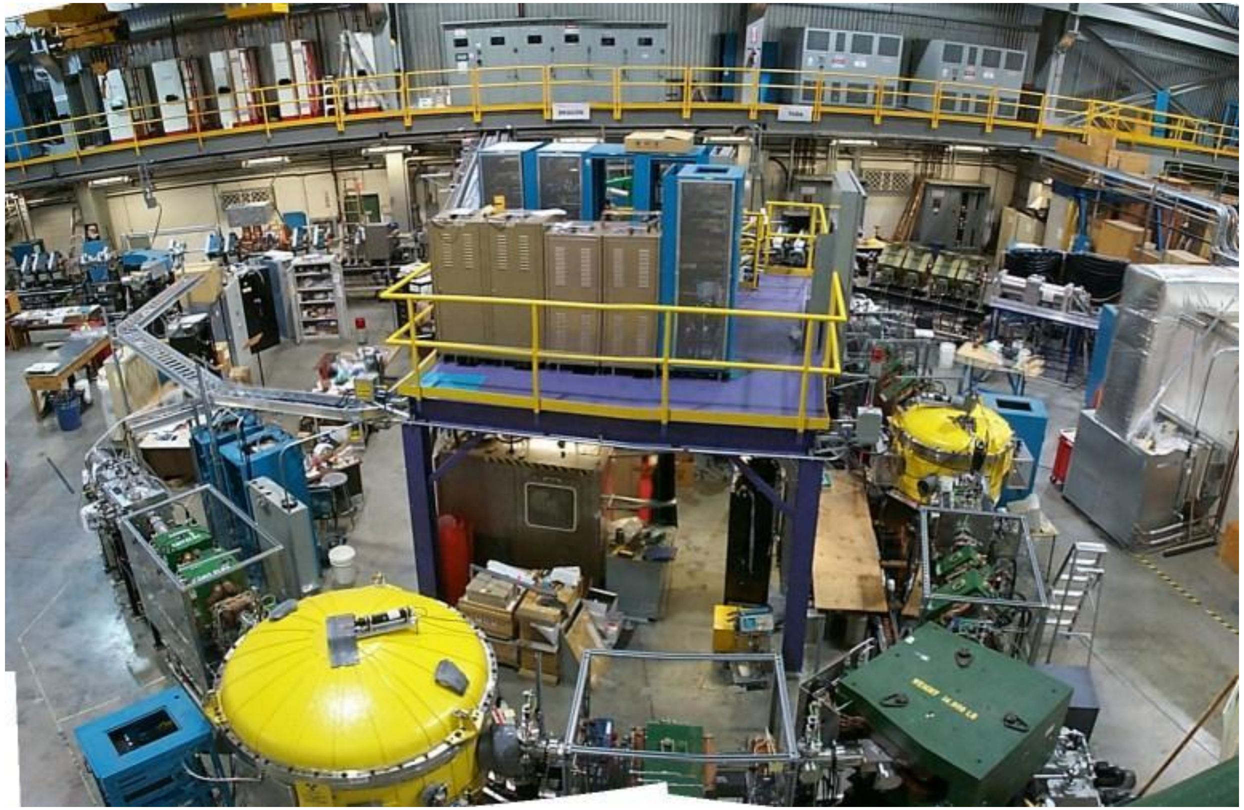
Main **source of neutrons** for the **s-process**





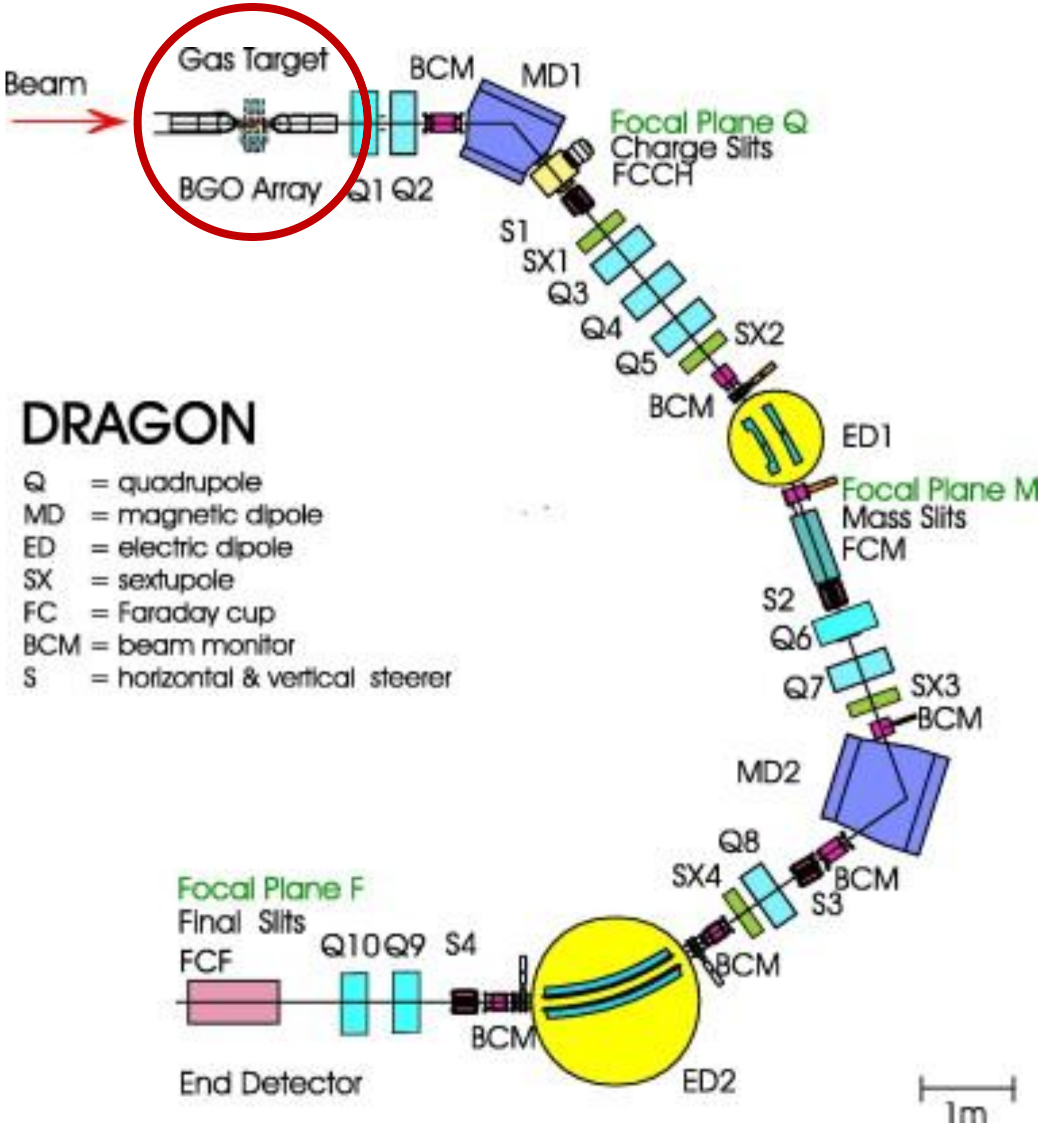
Excitation function of the ^{22}Ne(α,n)^{25}Mg reaction (Jaeger, Phys. Rev. Lett., 2001)

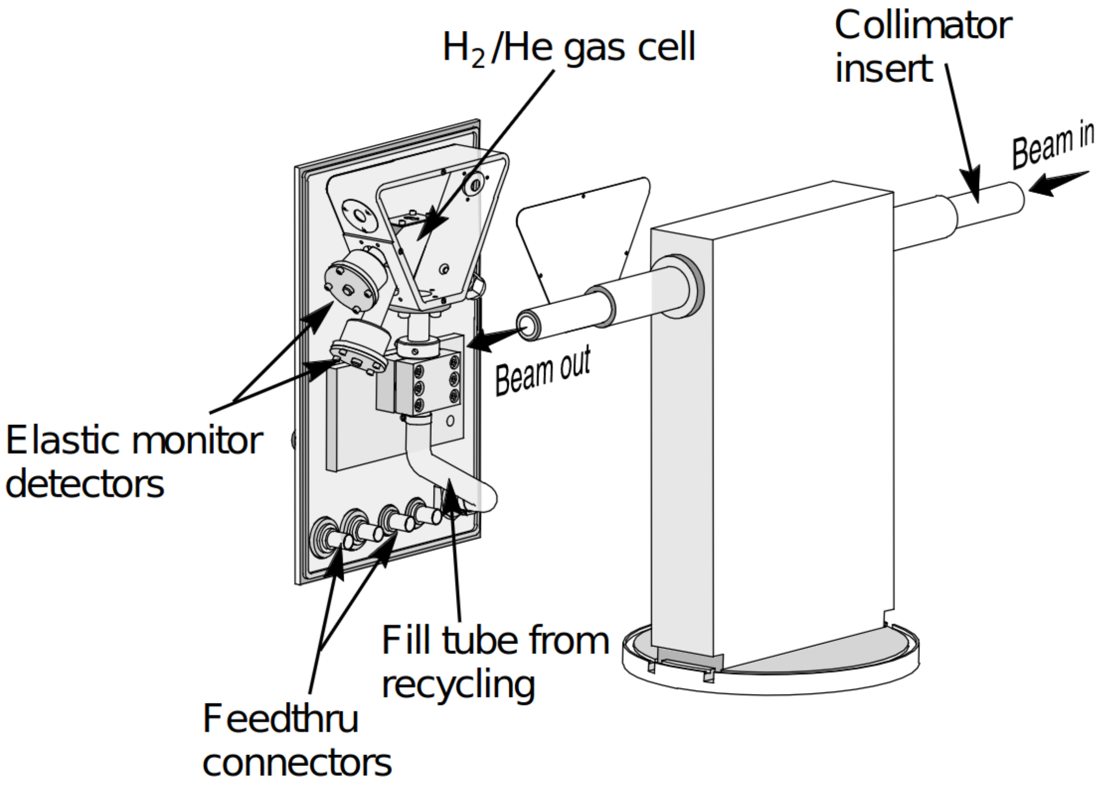
TRIUMF & DRAGON



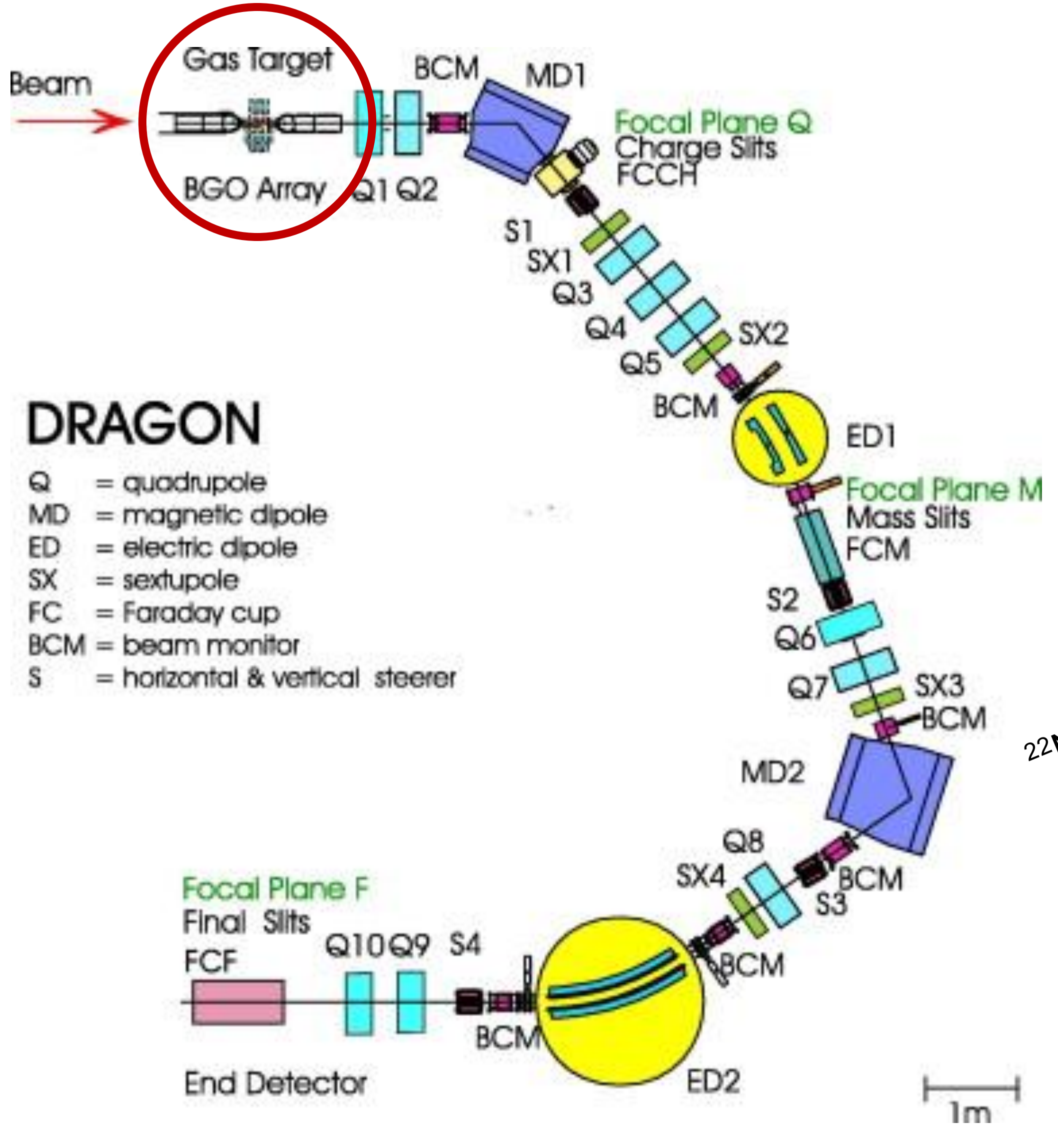
Detector of **R**ecoils **A**nd **G**ammas **O**f **N**uclear Reactions

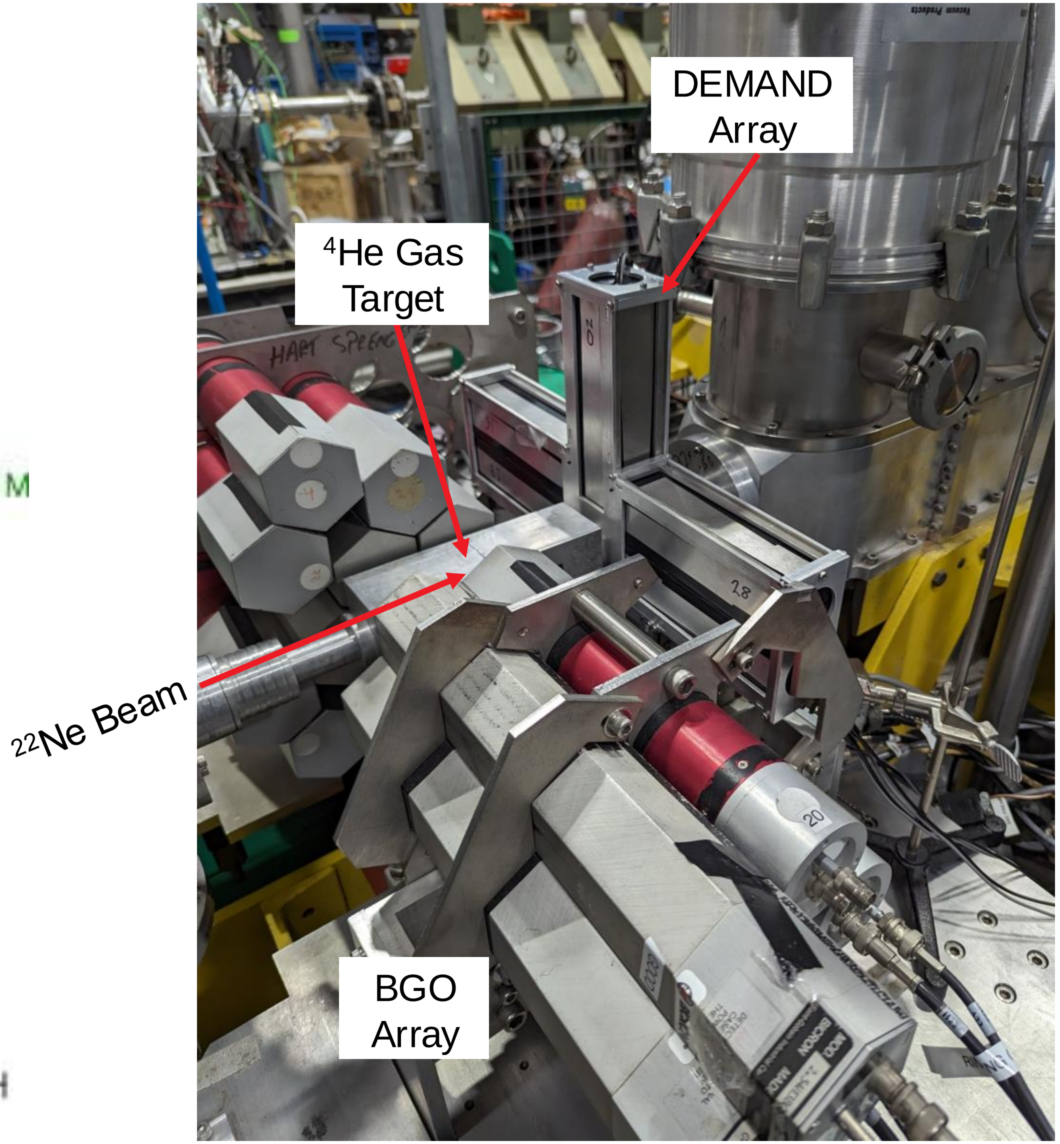
DRAGON – Gas Target



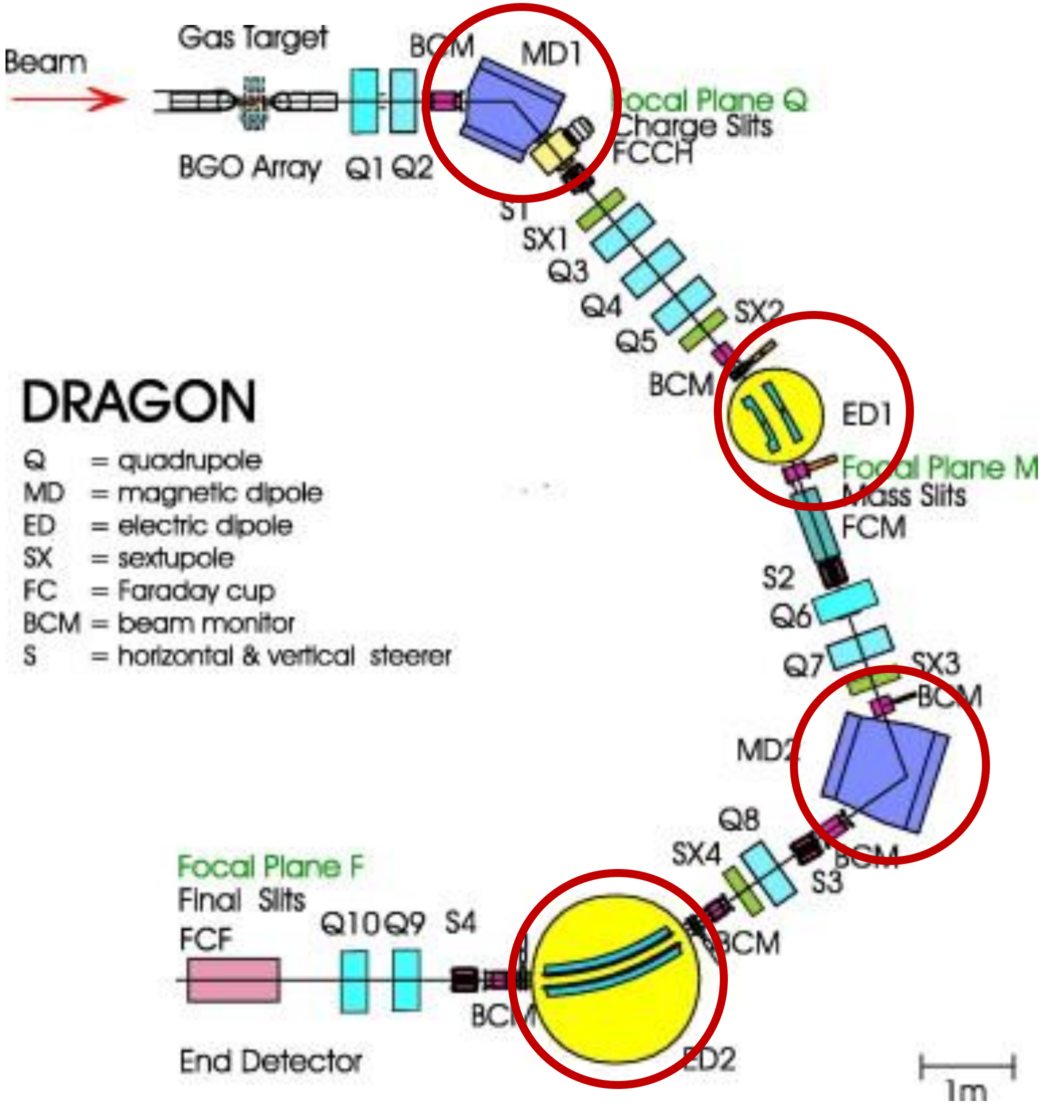


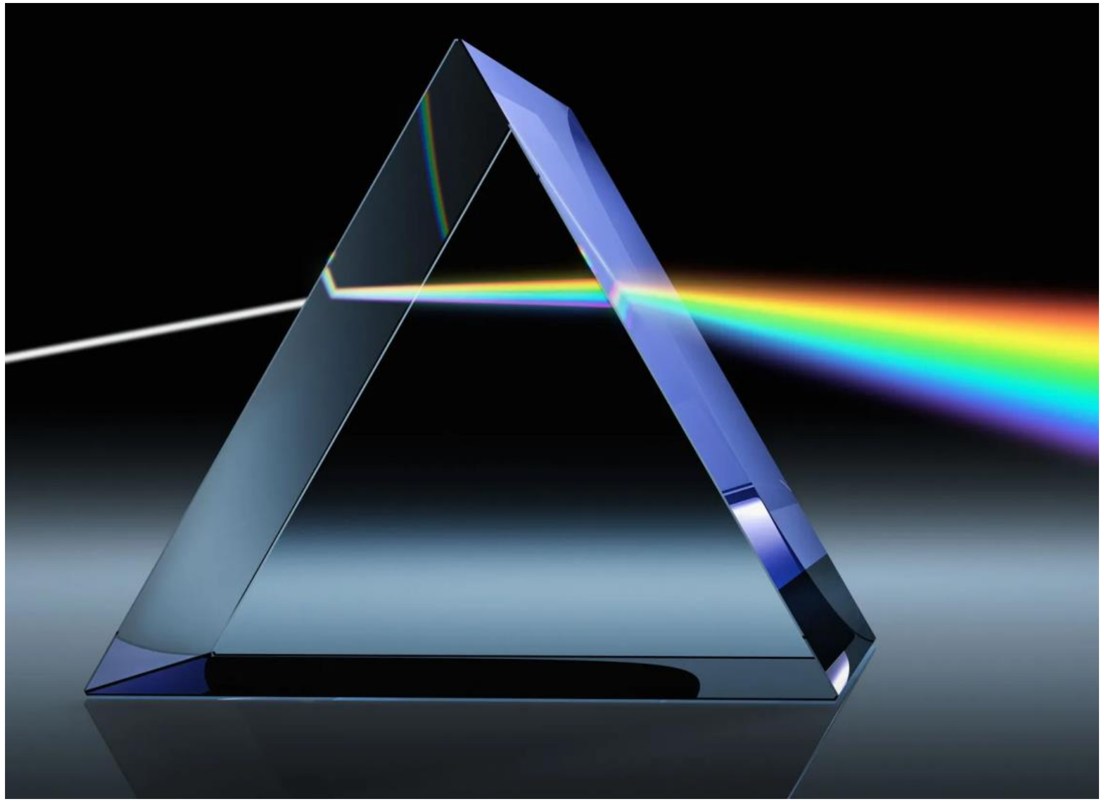
DRAGON – DEMAND Array





DRAGON – Optics





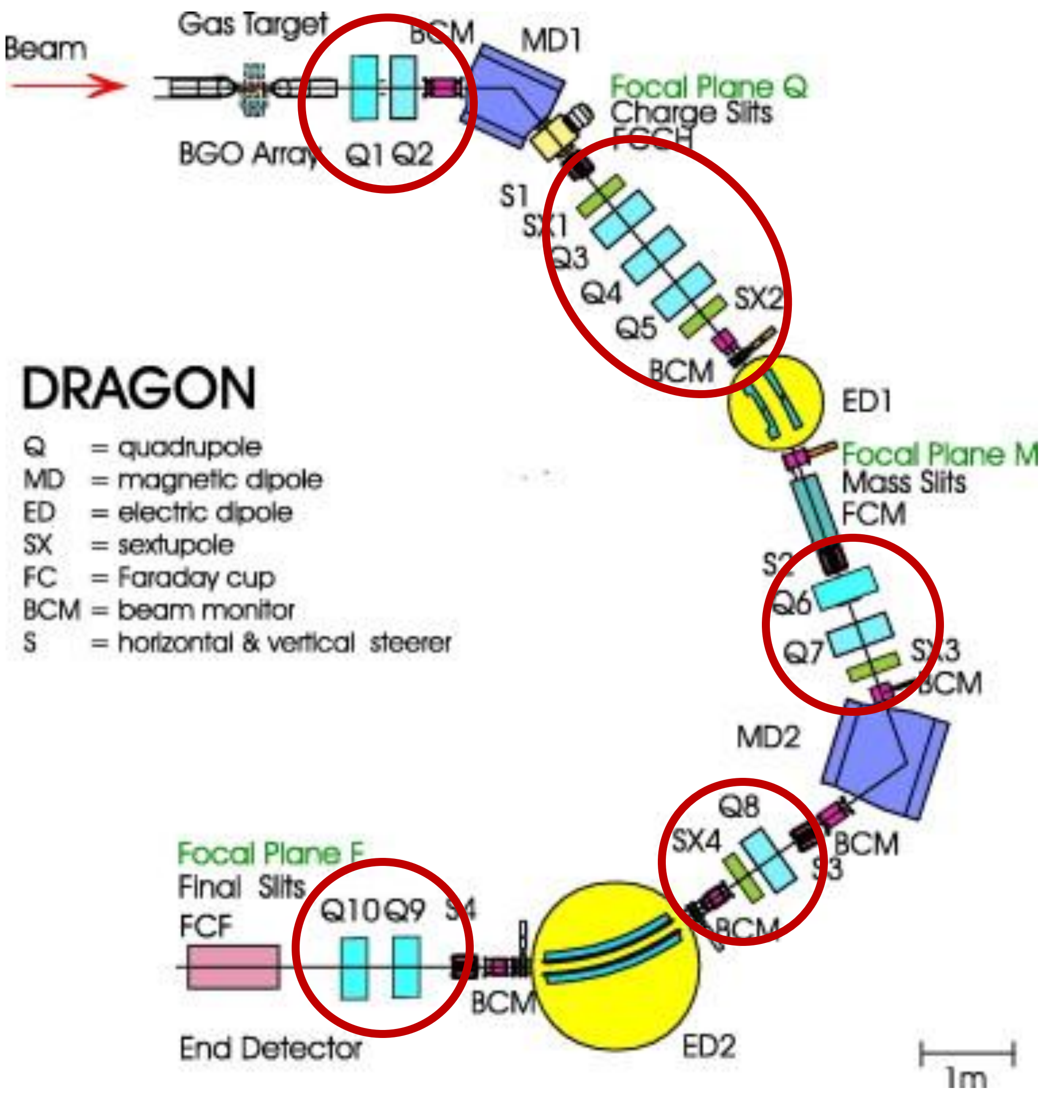
Electric and **magnetic dipoles** behave like prisms

Electric dipoles provide **E/Q separation**

Magnetic dipoles provide **p/Q separation**

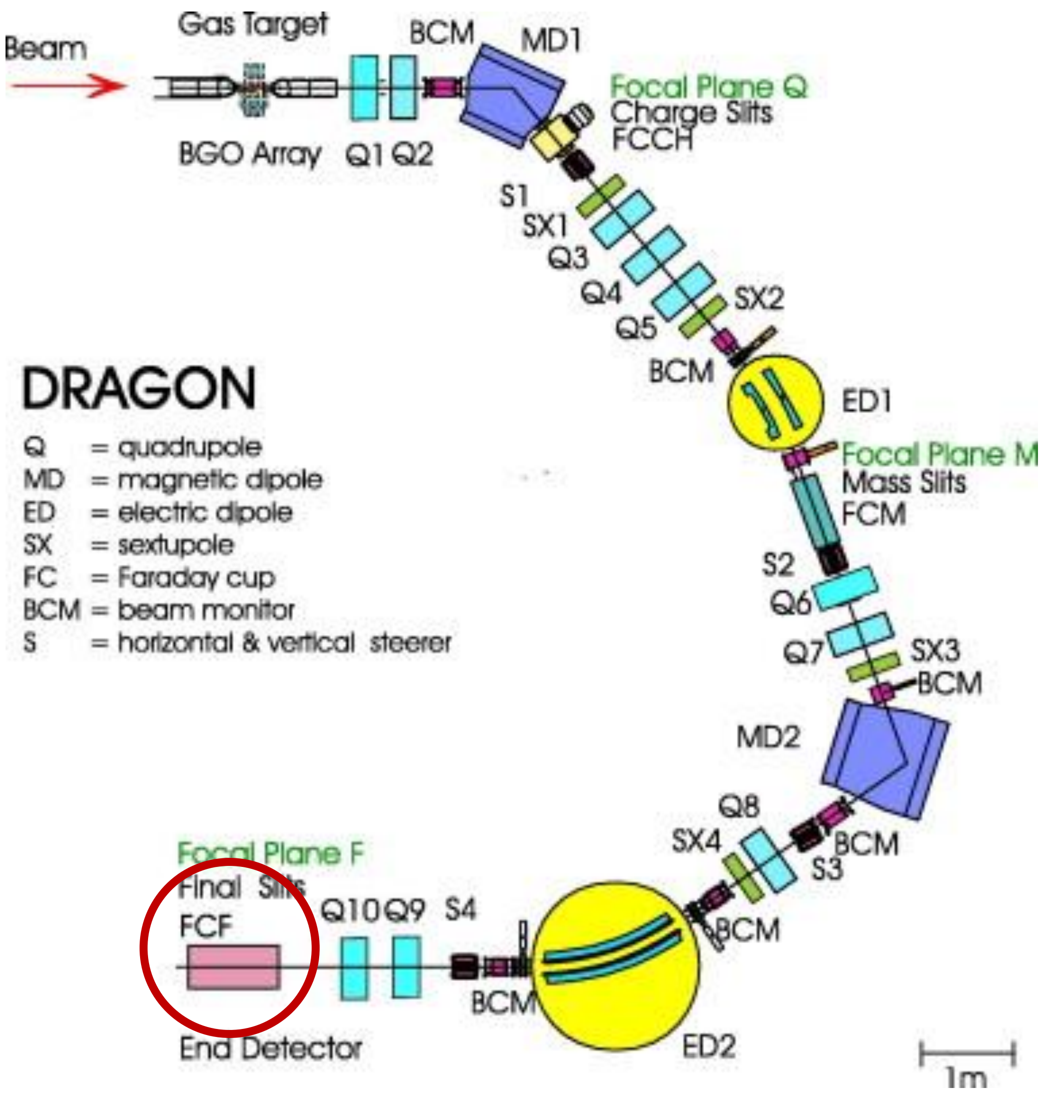
Can select recoils based on their **mass, charge and energy**

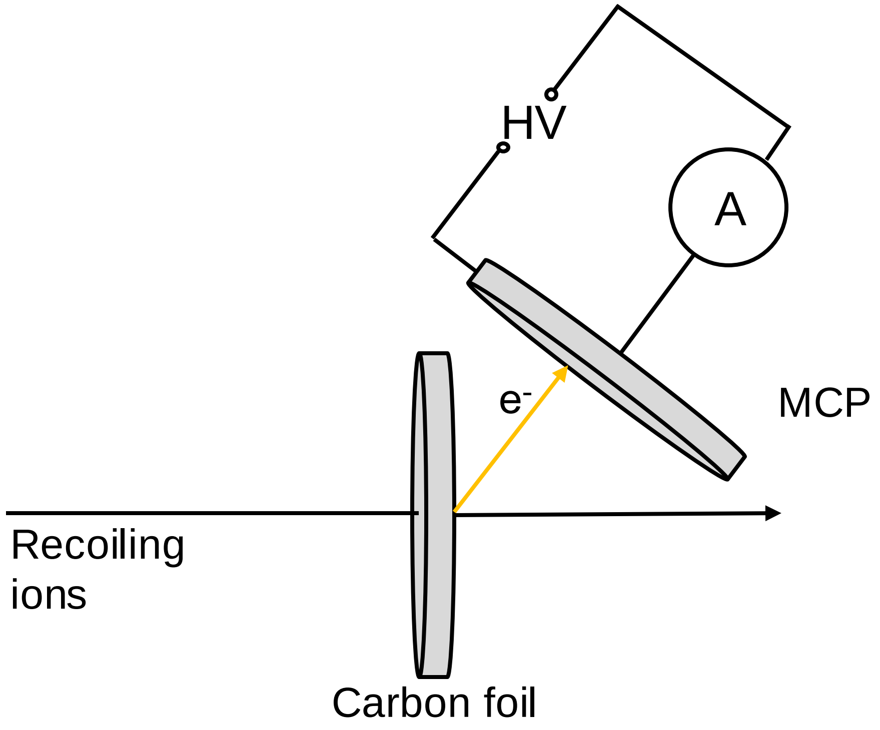
DRAGON – Optics



Quadrupole and **sextuple magnets focus** the recoils back into a beam

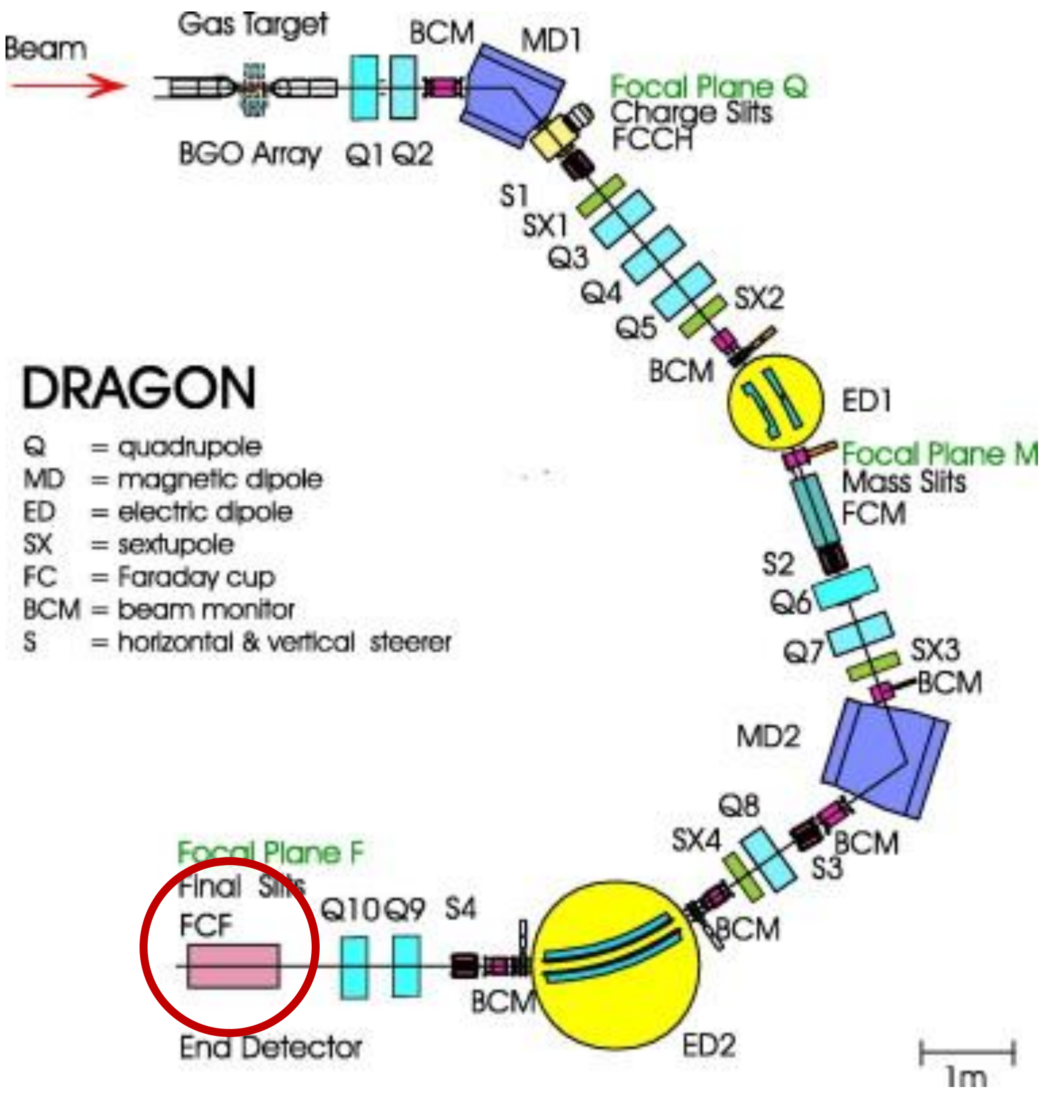
DRAGON – Microchannel Plates (MCPs)

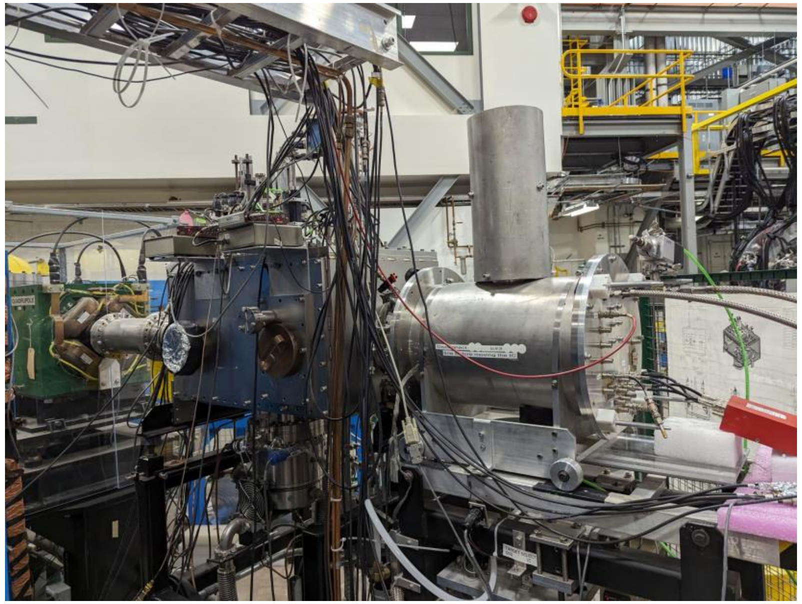


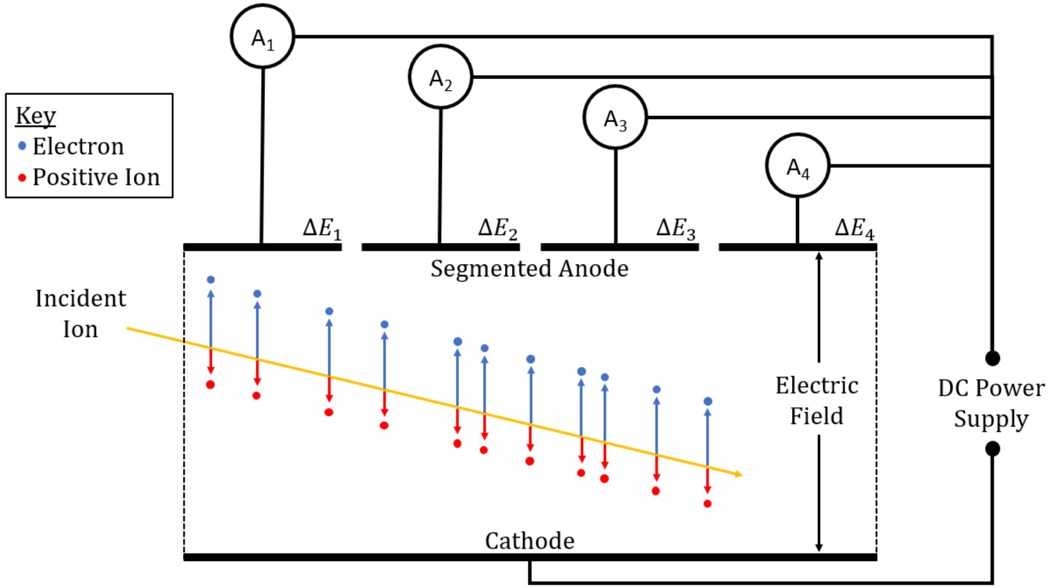


Primarily provide **timing** information but can also give position and number of recoils

DRAGON – Ionization Chamber (IC)

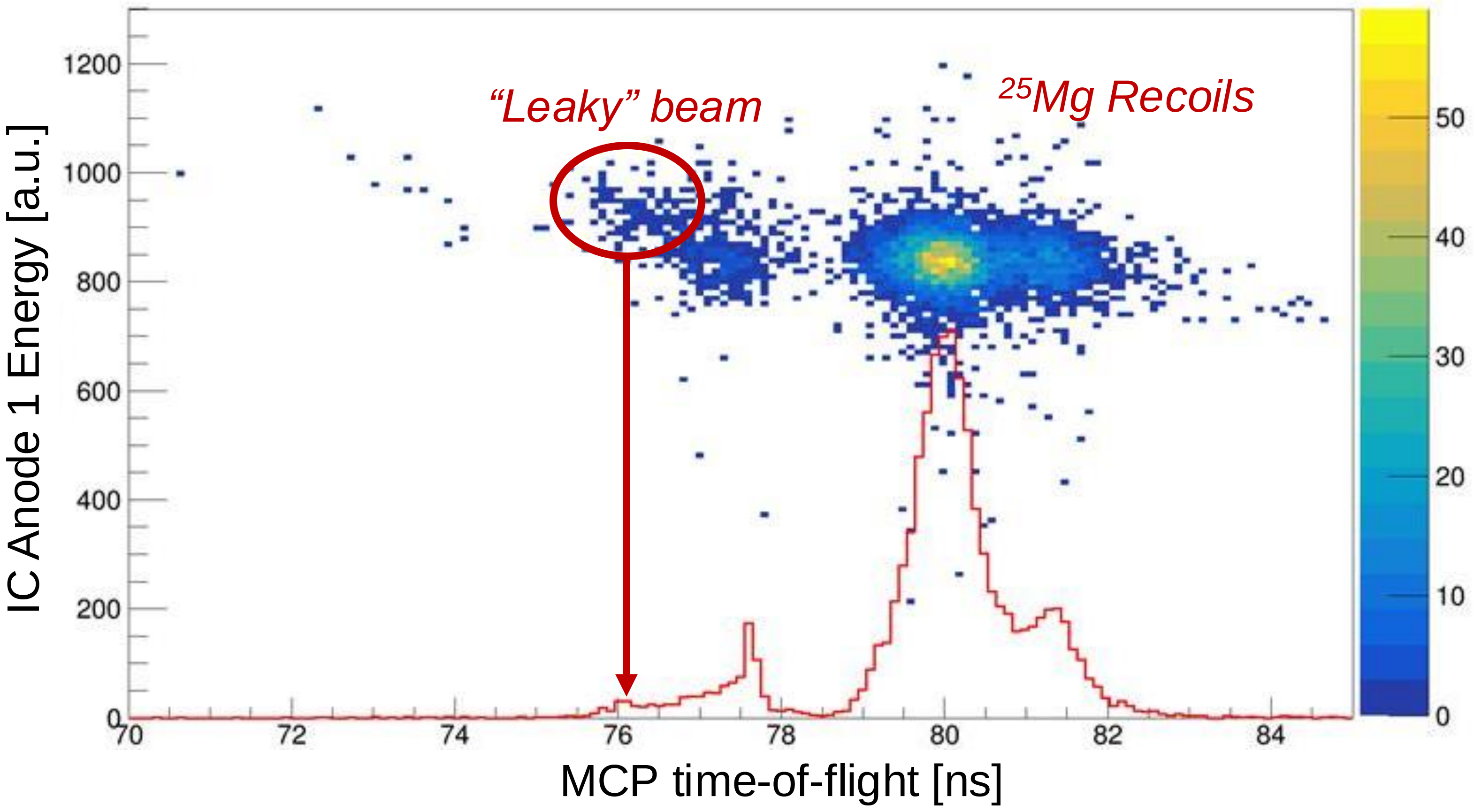






$$\Delta E \propto mZ^2/E$$

Results: Recoil ID



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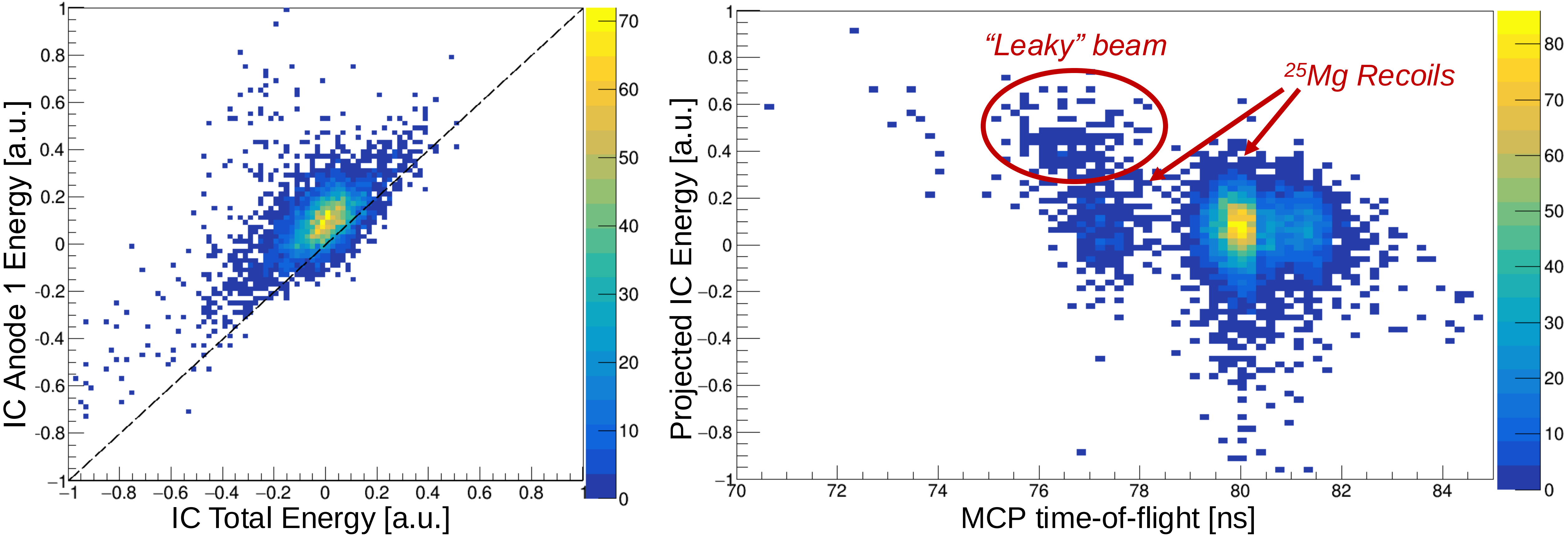
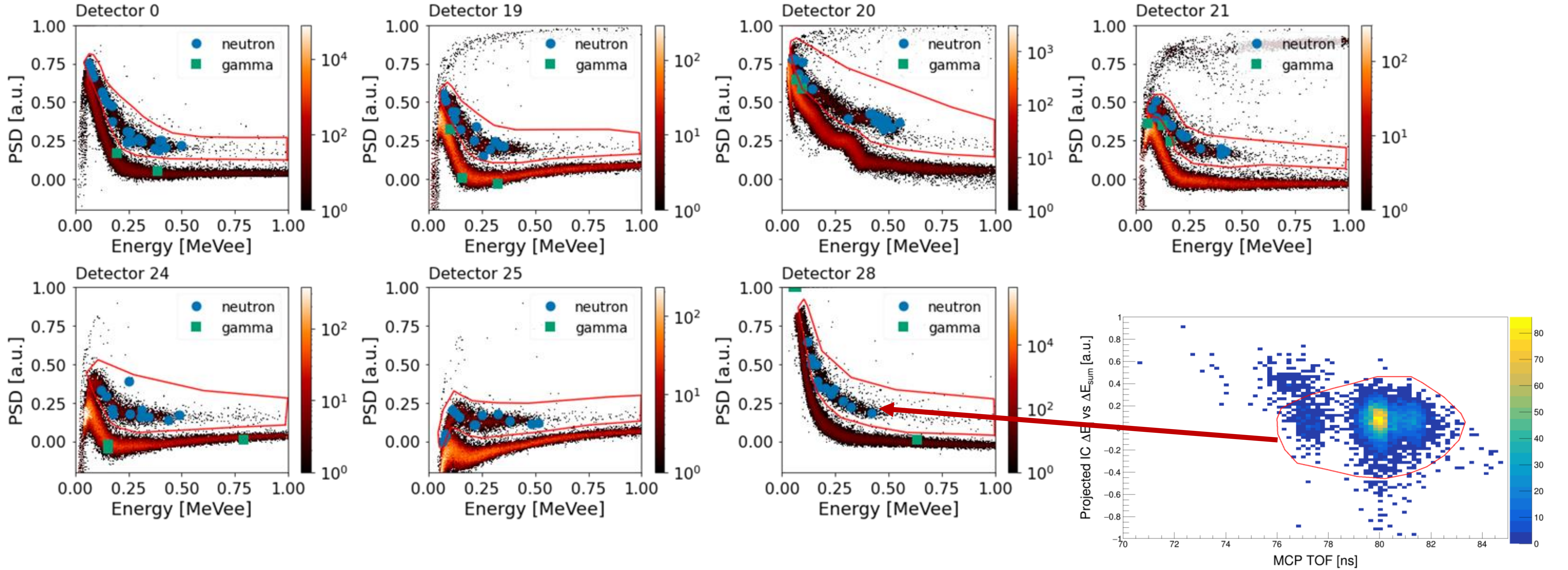


Results: Pulse Shape Discrimination



Yield & Resonance Strength Calculations

$$\boldsymbol{Y = \frac{N_{coinc}^{det}}{N_b \eta}}$$

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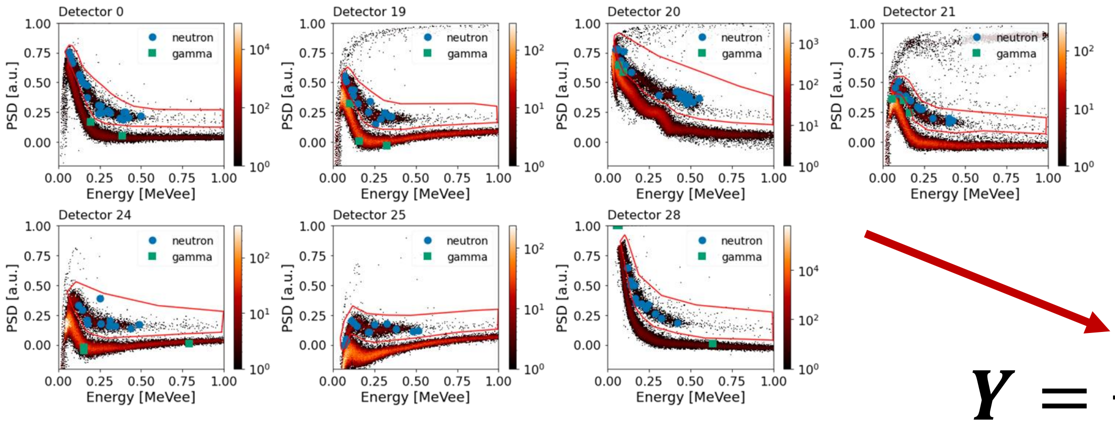

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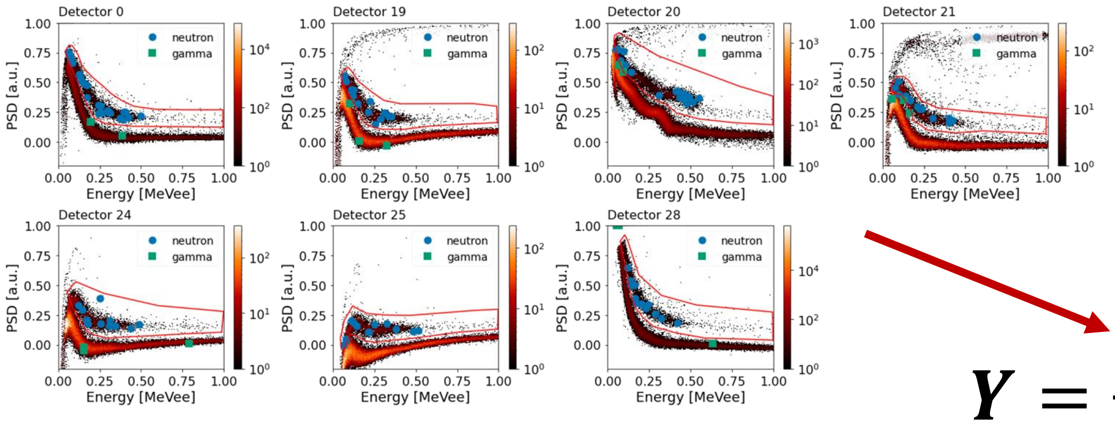

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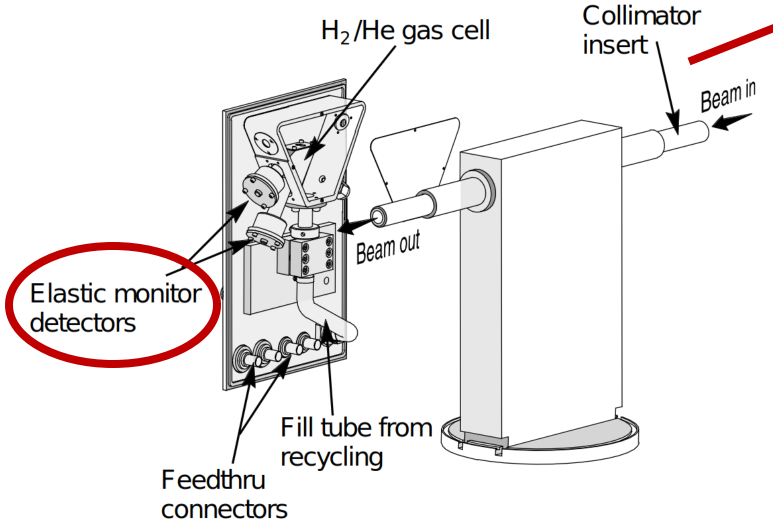

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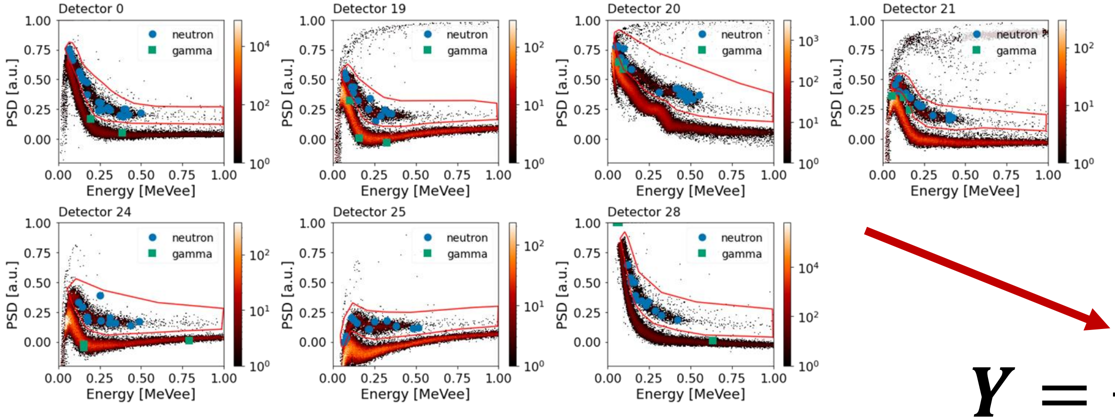

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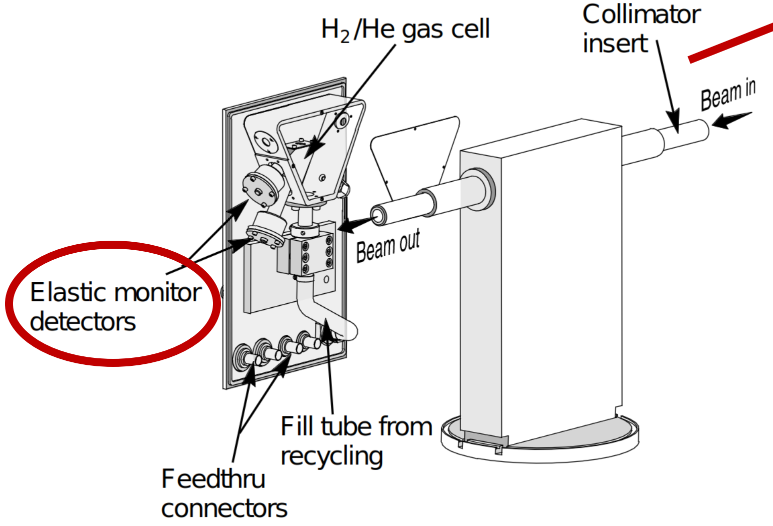
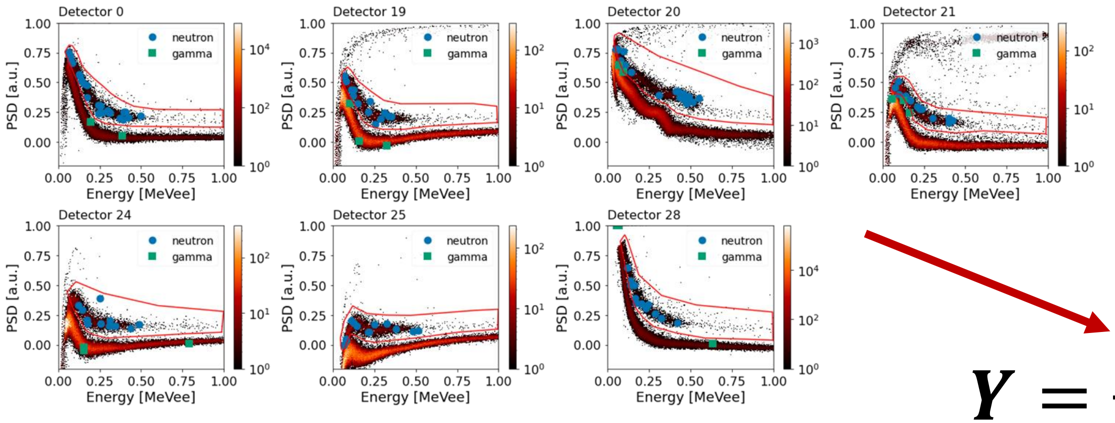


Efficiency	Source	Value
Neutron Detection	Simulation	0.2%*
Charge State Fraction	Experimentally measured	40%*
Separator Transmission	Simulation	4%*
MCP Transmission	Source measurement	76.5%
MCP Detection	Attenuated beam	93.7%
IC Detection	Attenuated beam	67.7%
Live time	Recorded during experiment	97.3%

**Preliminary values – calculations to be finalized*

Yield & Resonance Strength Calculations



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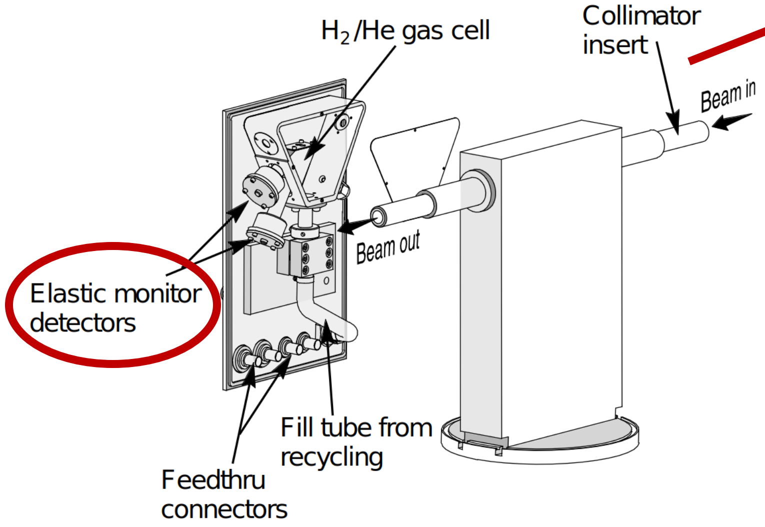

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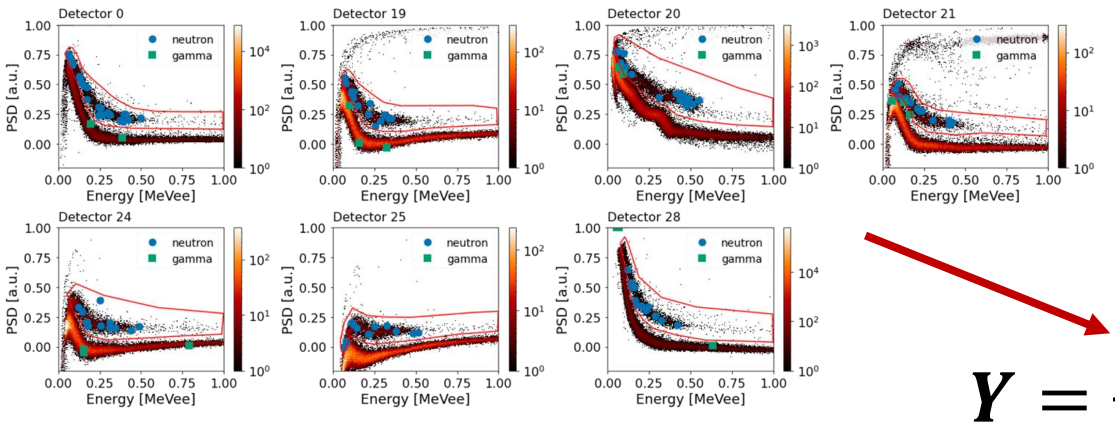
Yield & Resonance Strength Calculations



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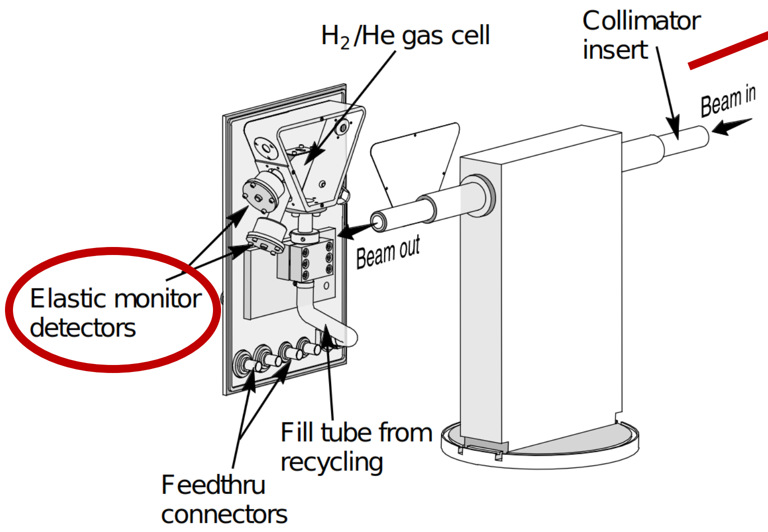


Preliminary measurement of the resonance strength of **1.1 eV**

Close agreement with literature value (1.067 eV)!

Conclusions

The **DEMAND array** has been developed to **directly study (α,*n*)** reactions which are important to both the weak r-process and s-process

Performed a proof-of-principal study of the **1.43 MeV resonance in ^{22}Ne(α,*n*)** and preliminary results show **good agreement with the literature values**

Need to **finalize charge state fraction**, **neutron detection efficiency** and **separator transmission**

Experiment to study the **astrophysical dominant resonance** in **^{22}Ne(α,*n*)** has been **approved** at TRIUMF and will hopefully be scheduled

Thank you!
Merci!

TRIUMF

Chris Ruiz
Dave Hutcheon
Alex Katrusiak
Annika Lennarz
Mallory Loria
Louis Wagner

Saint Mary's University

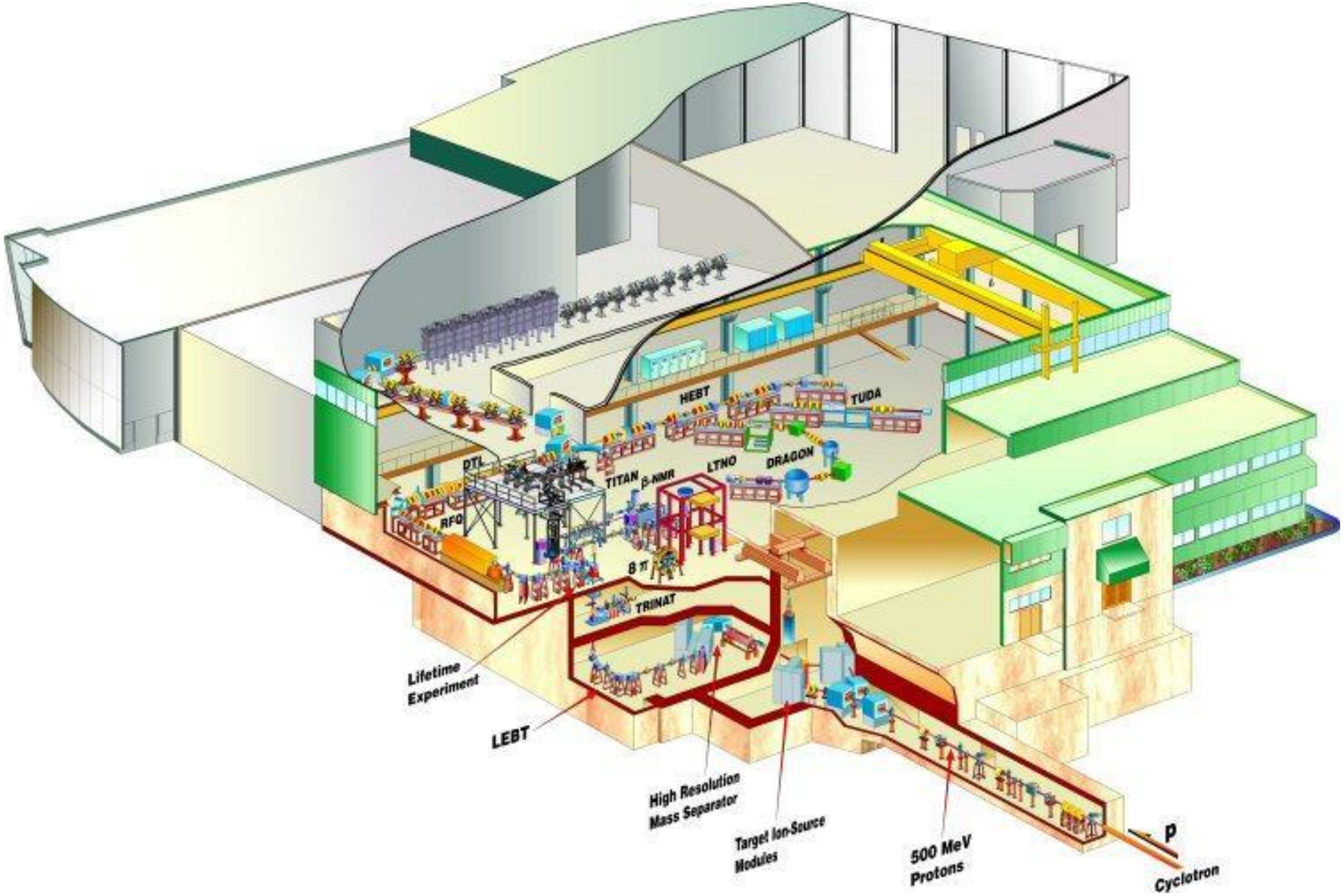
Greg Christian

UKRI Science and Technology Facilities Council

University of Surrey

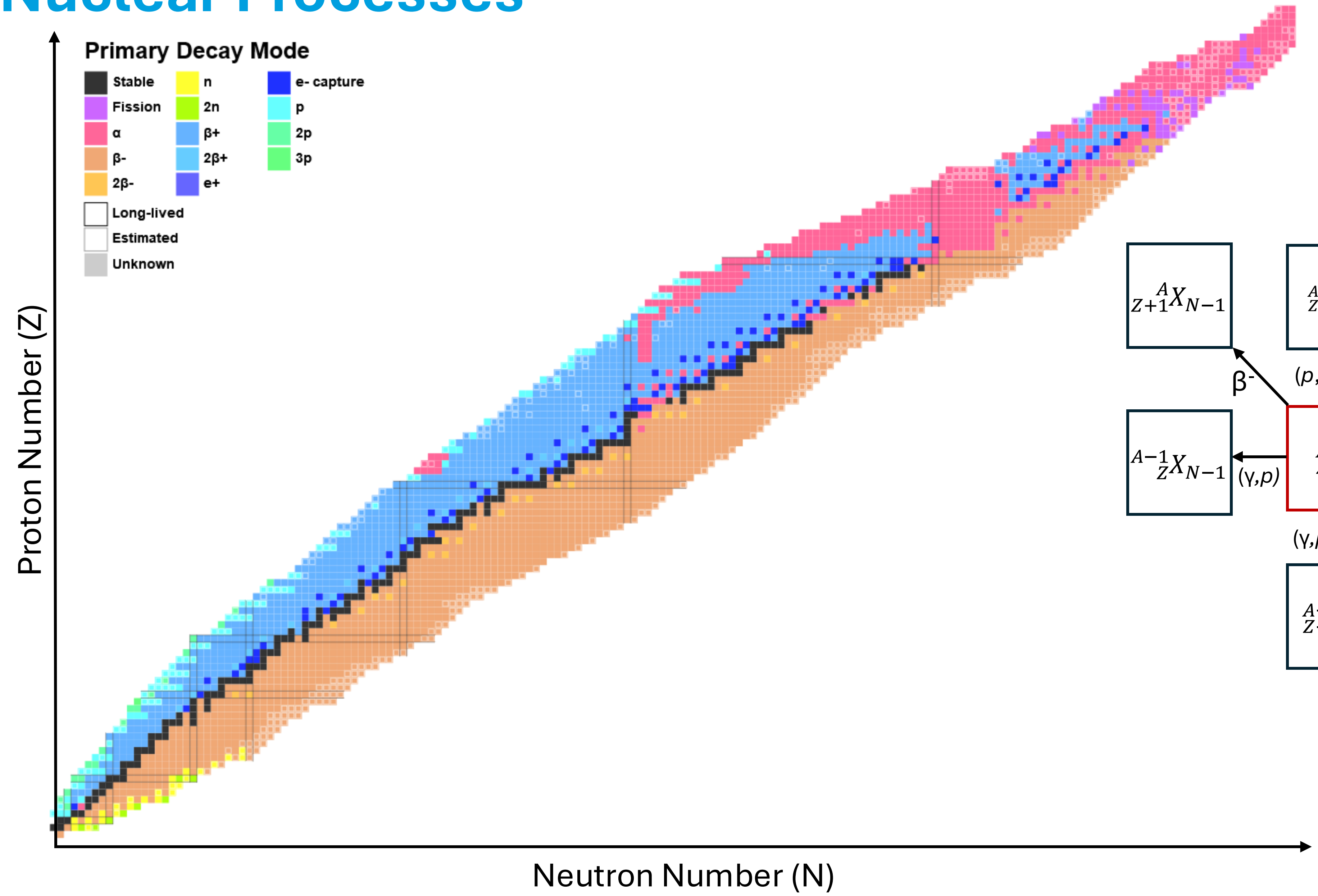
Gavin Lotay
Gee Bartram
Dan Doherty
Jack Henderson
Joey O'Neill
Connor O'Shea
Charlie Paxman
Matt Williams

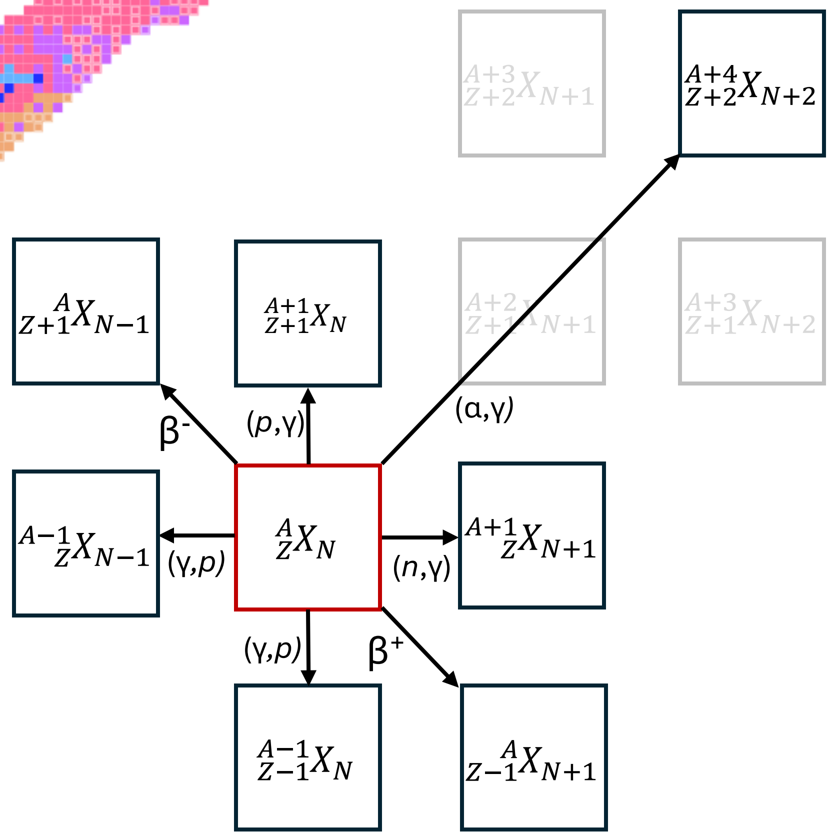
ISAC



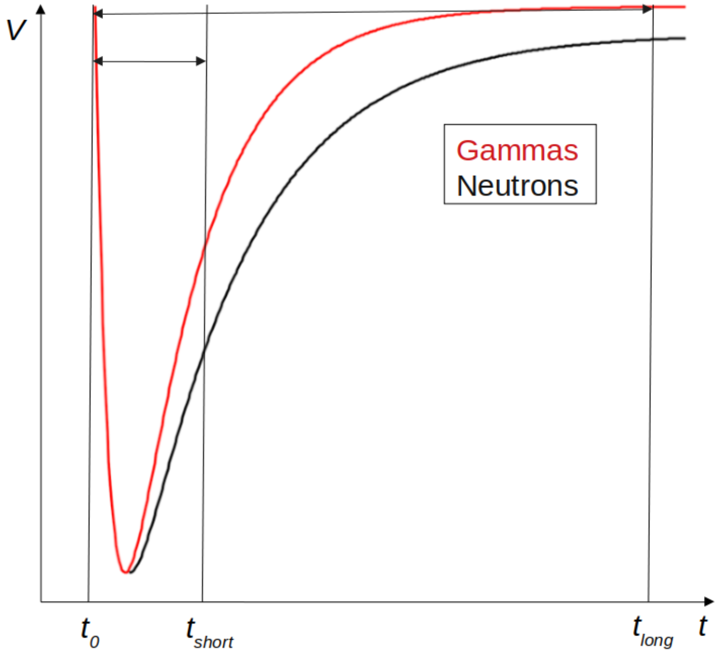
HEBT
TUDA
DTL
TITAN
β-NMR
LTNO
DRAGON
RFQ
8 π
TRINAT
Lifetime Experiment
LEBT
High Resolution Mass Separator
Target Ion-Source Modules
500 MeV Protons
p
Cyclotron

Nuclear Processes



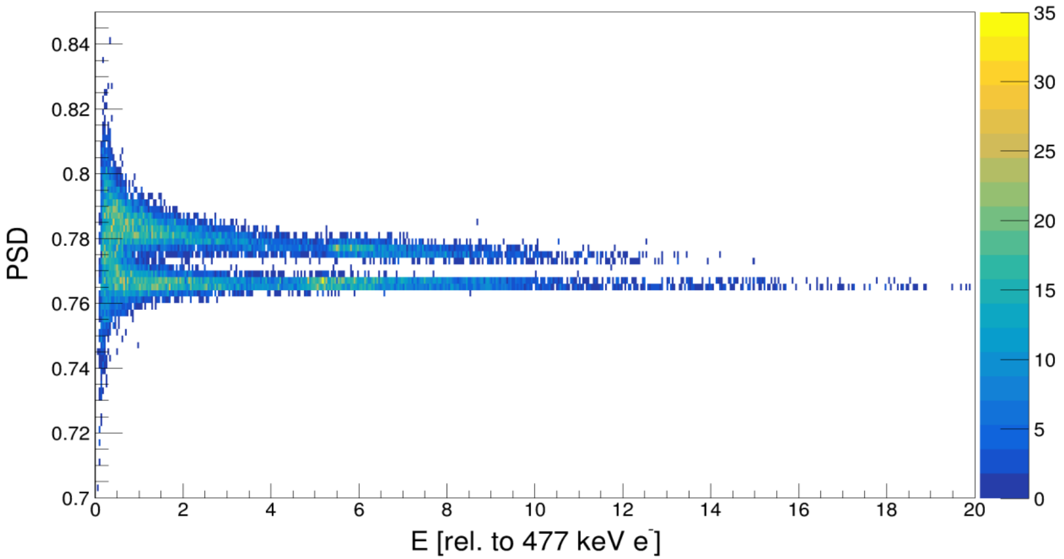


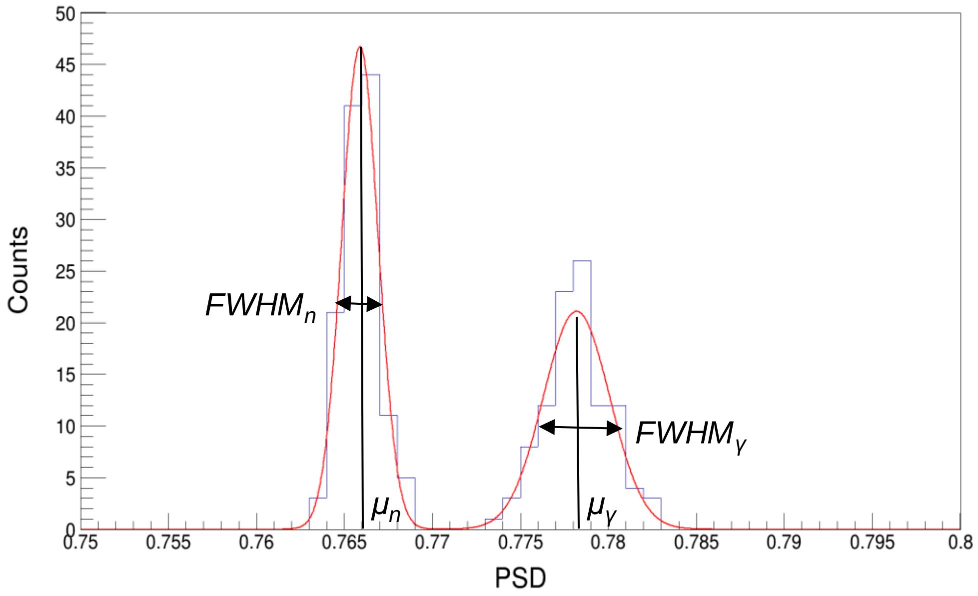
Pulse Shape Discrimination



$$PSD = 1 - \frac{Q_{short}}{Q_{long}}$$

$$FOM = \frac{\mu_n - \mu_\gamma}{FWHM_n + FWHM_\gamma}$$

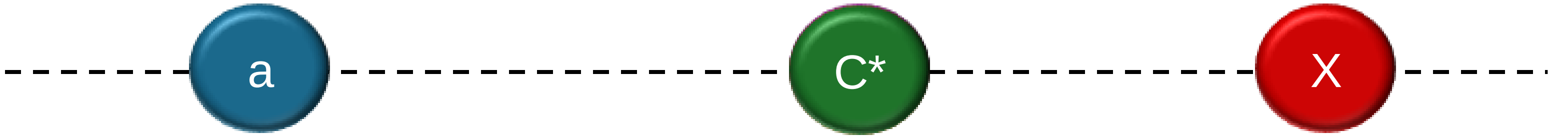


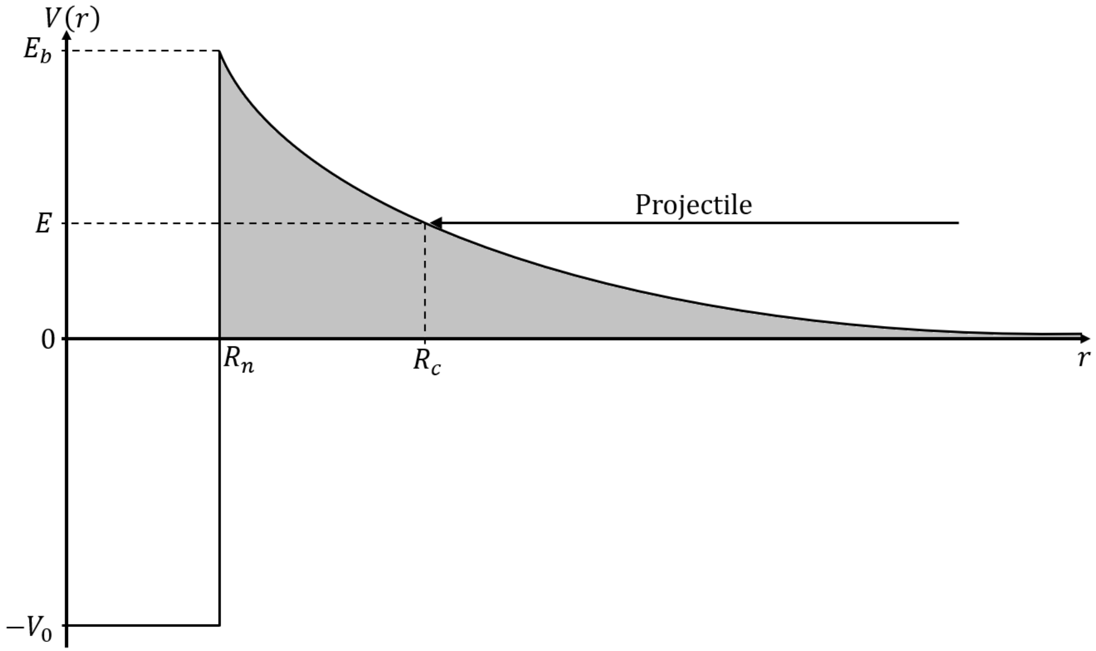


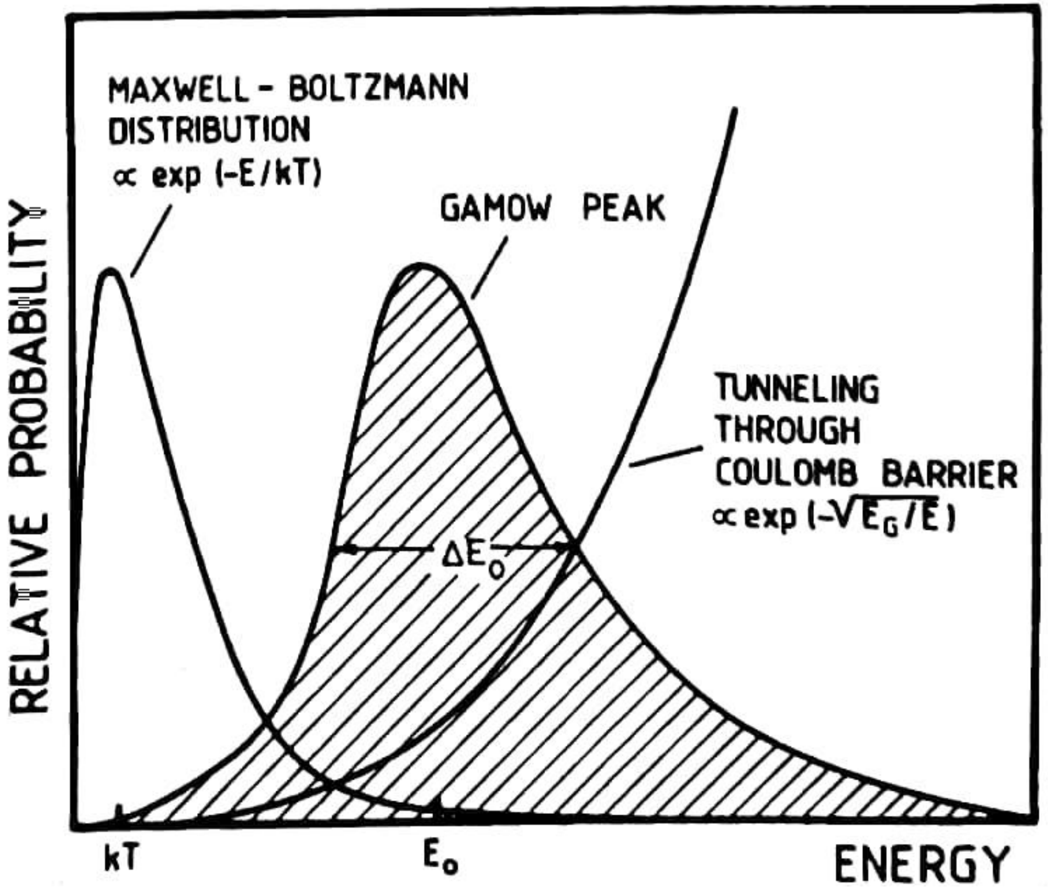
Nuclear Reactions

$$a + X \to C^* \to b + Y$$

or $X(a, b)Y$







Resonant Reaction Rates

$$r = \frac{1}{1+\delta_{aX}} N_a N_X \langle \sigma v \rangle$$

$$\langle \sigma v \rangle = \left(\frac{2\pi}{\mu k T} \right)^{3/2} \hbar^2 \sum_i (\boldsymbol{\omega\gamma})_{\boldsymbol{i}} \exp\left(-\frac{E_{r,i}}{kT} \right)$$

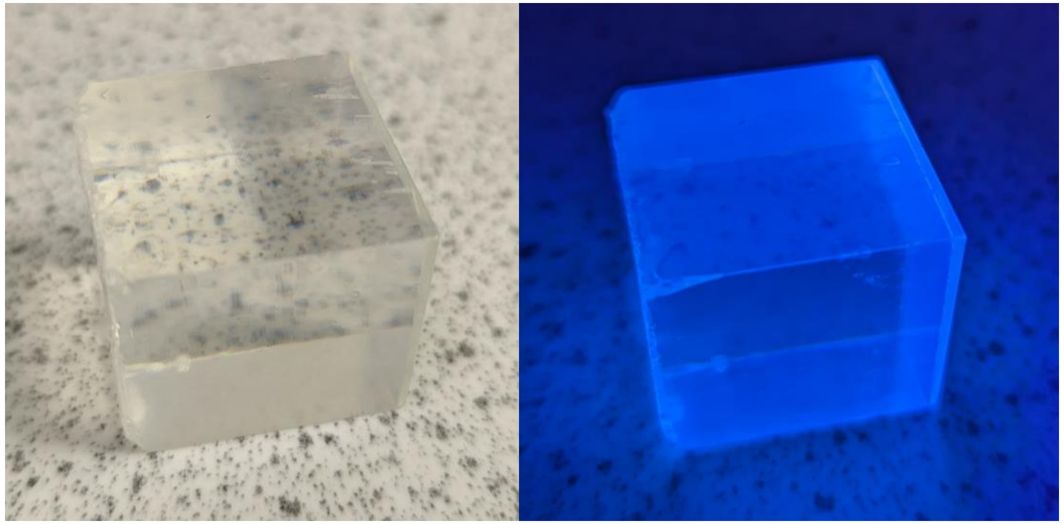
Resonance strength $\boldsymbol{\omega\gamma}$ is
proportional to the cross-section at the
resonance energy

Organic Glass Scintillator (OGS)

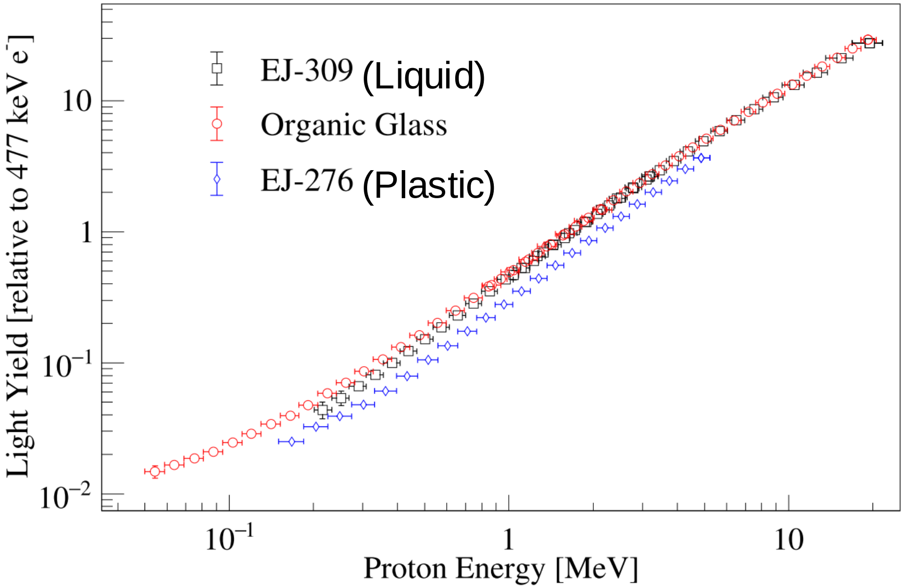
OGS is a scintillator material made by **BlueShift Optics**

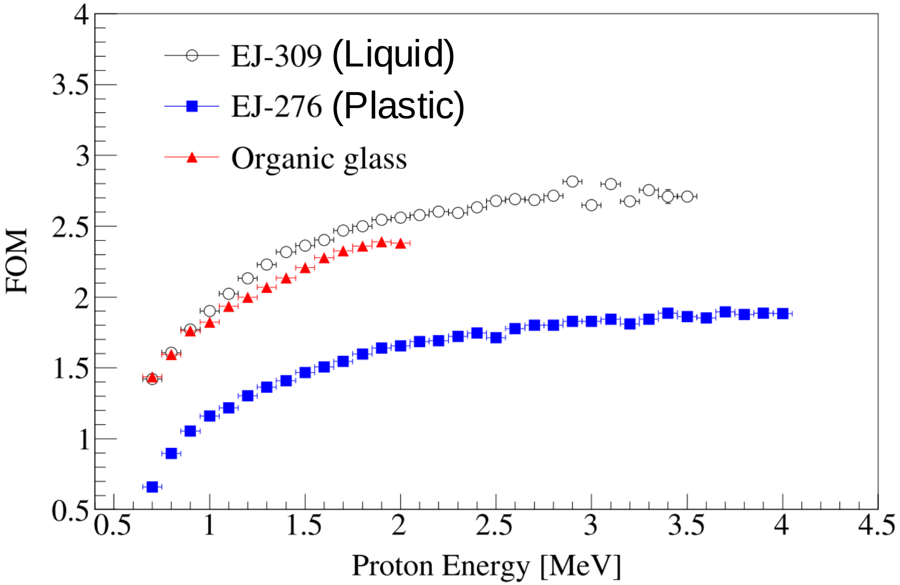
The chemical composition is a 90:10 mixture of bis(9,9-dimethyl-9H-flouren-2-yl)(dismethyl)silane: tris(9,9-dimethyl-9H-flouren-2-yl)(methyl)silane along with 0.2 wt. % of 1,4-Bis(2-methlystyryl)benzane

OGS detectors have excellent **PSD**, **light output** and **timing** properties



An OGS cube scintillating under UV radiation





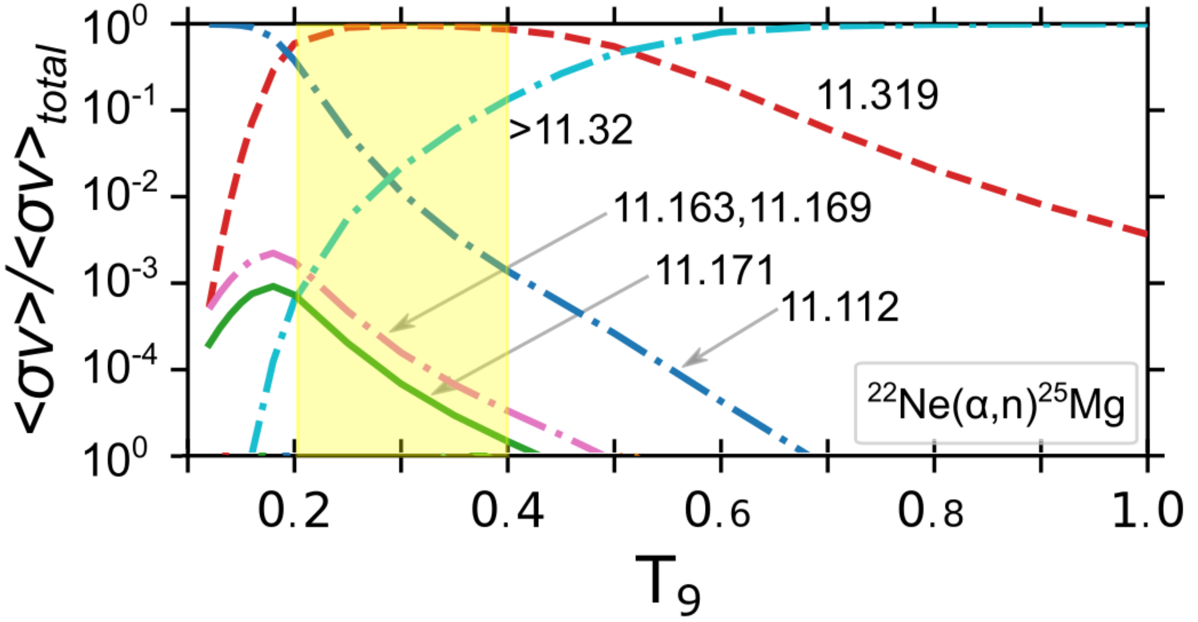
T. A. Laplace, J. Inst., 2020

What is Next?

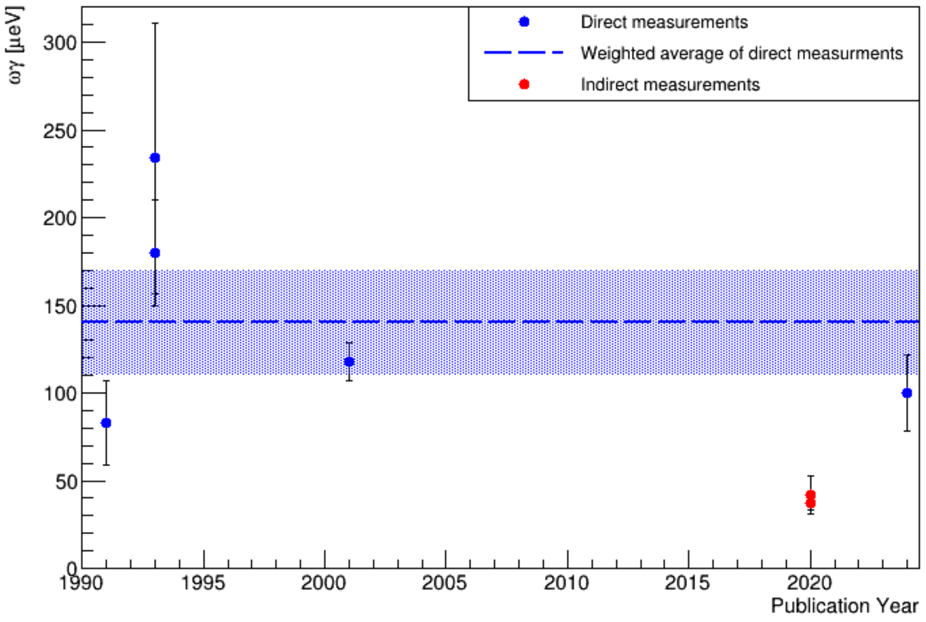
The E_x **= 11.319 keV** resonance is predicted to **dominate** the reaction rate at astrophysical temperatures

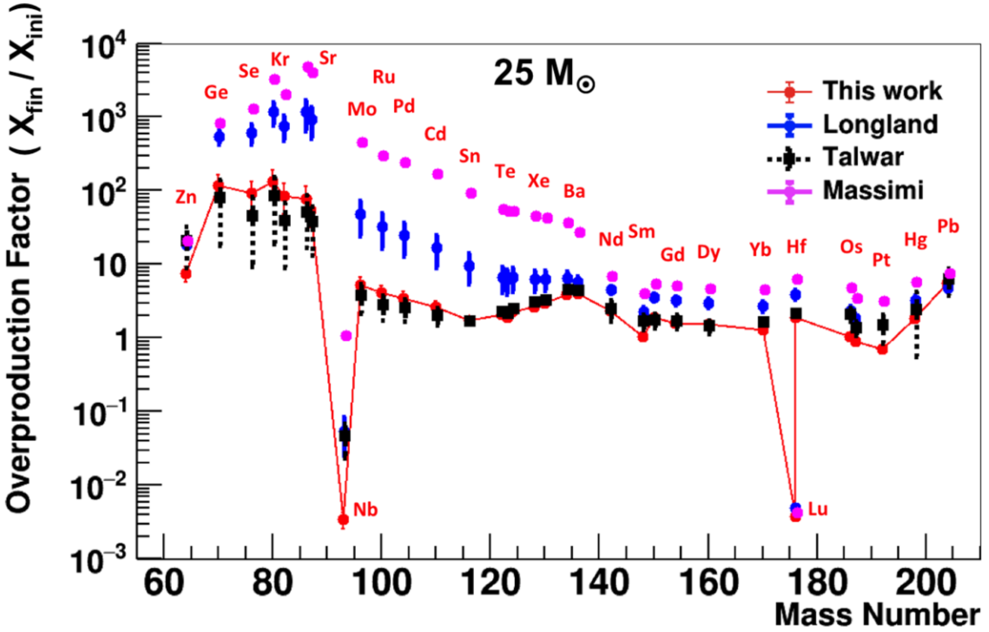
There are **large discrepancies** in previous attempts to measure the **resonance strength**

An experiment to **directly measure the resonance strength** of this state **using DRAGON** has been approved



Contributions to the ^{22}Ne(α,n) reaction rate (S. Ota, Phys. Lett. B, 2020)





Variation in s-process abundances for different resonance strengths (S. Ota, Phys. Rev. C, 2021)