TRIUMF

Direct measurements of helium-burning reactions in inverse kinematics using DRAGON

Annika Lennarz

Division of Physical Sciences | TRIUMF

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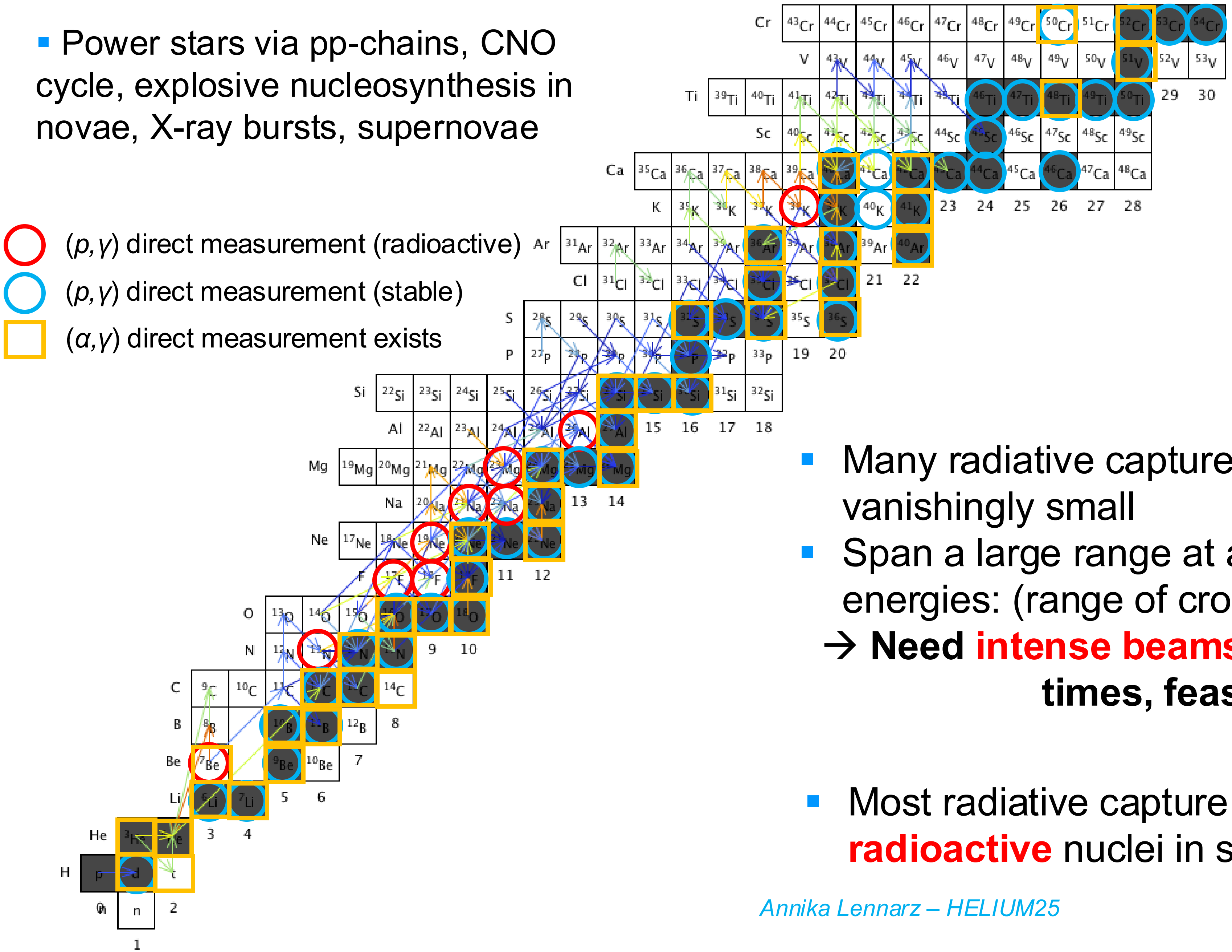
Radiative Capture Reactions

- Power stars via pp-chains, CNO cycle, explosive nucleosynthesis in novae, X-ray bursts, supernovae



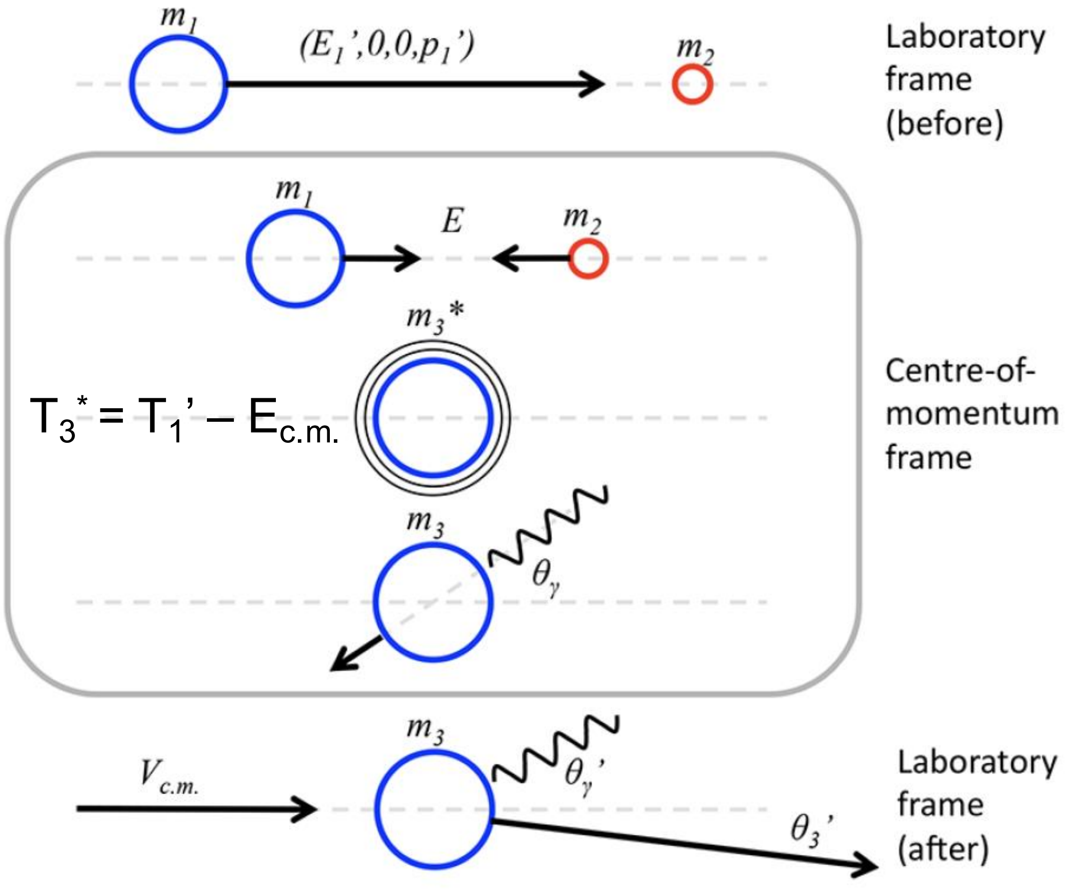
- p- & α-induced reactions with positive Q-value
- ➔ Knowledge important for reaction pathways!
- Proceed relatively slowly, thus **rate-limiting** step in reaction pathways

- Many radiative capture cross sections are vanishingly small
- Span a large range at applicable astrophysical energies: (range of cross sections)

→ **Need** **intense beams**, **low background, long run times, feasible targets, …**

- Most radiative capture reactions on **short-lived radioactive** nuclei in stars remain unmeasured!

Direct Measurements in Inverse Kinematics



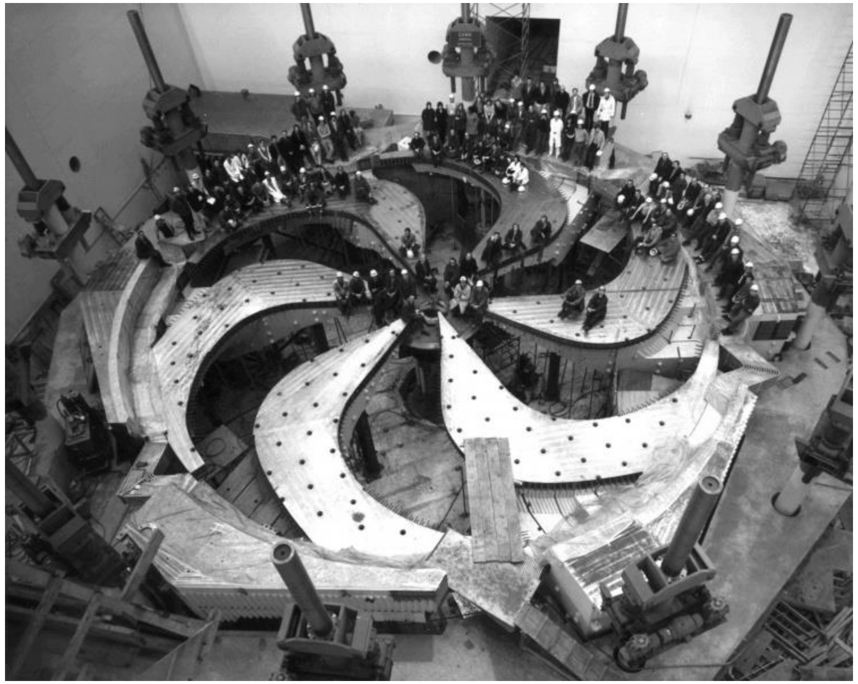
If ratio m_{beam}/m_{target} is large, recoil energy can only be relatively small amount lower than beam energy!

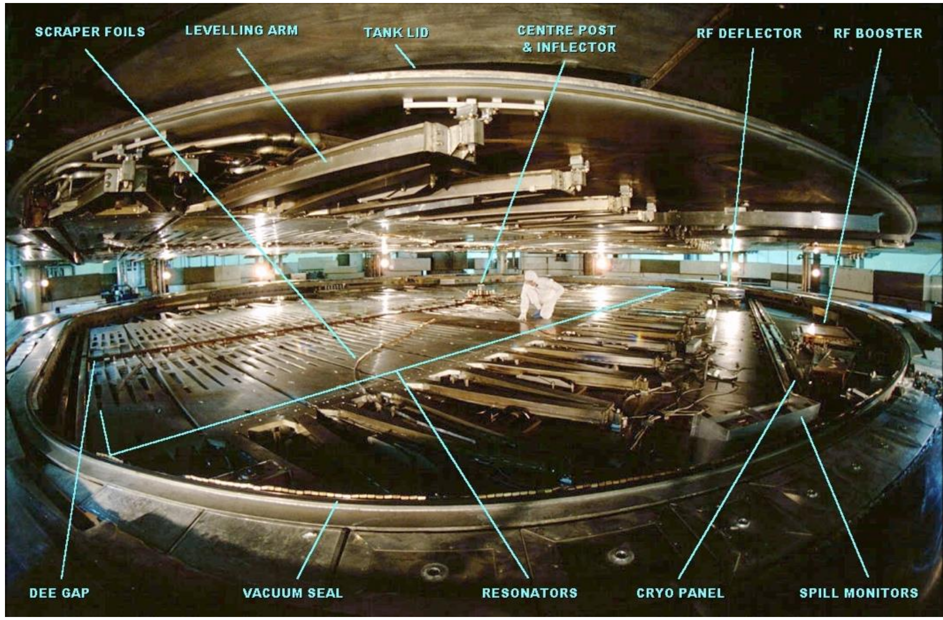
- Necessity due to not being able to make short-lived radioactive targets
- Detect recoiling product nucleus: forward focused
- Problem of separating **rare** reaction products (recoils) from **abundant** beam
  → zero-degree electromagnetic separator
- **Advantages:**
  - Use of gaseous target (H_2 or He) → windowless (jet, extended), purified etc…
  - Detect gamma rays (coincidence tagging)
  - Particle ID (focal plane) on reaction products

Radioisotope Beam Facilities World-Wide

TRIUMF – Canada's particle accelerator center

500 MeV proton beam
Up to ~100 μA (up to ~5000 hrs/year)





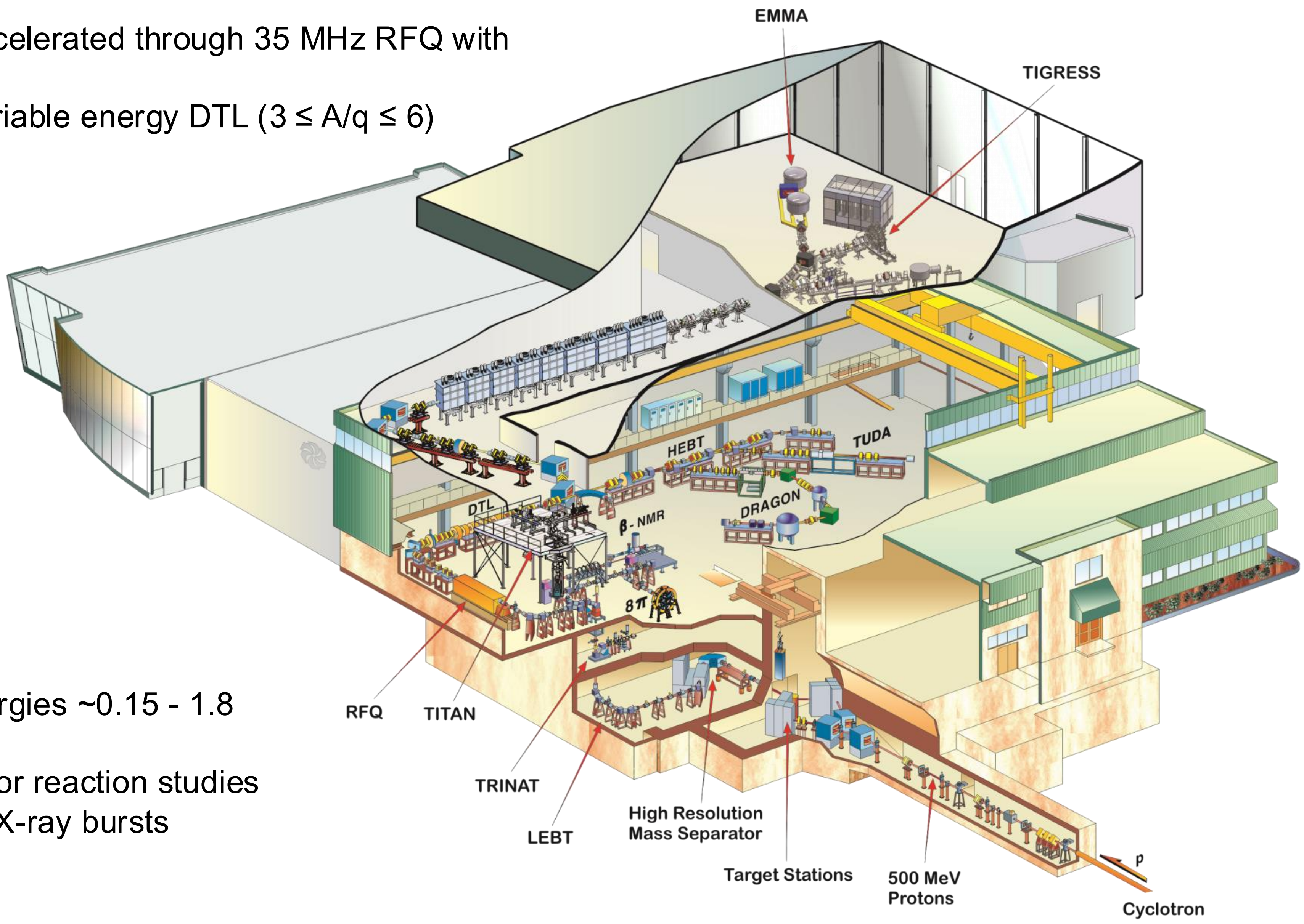
TRIUMF is located on the traditional, ancestral, and unceded territory of thexʷməθkʷəy̓əm (Musqueam) people, who for millennia have passed on their culture, history, and traditions from one generation to the next on this site.

TRIUMF's home has always been a seat of learning.

- Production of rare ion beams via ISOL method
- Irradiation of thick production target with proton beam
- Generated in sector-focused H^- cyclotron (23 MHz)

ISAC-TRIUMF ISOL facility for rare isotope beams

- Beams reaccelerated through 35 MHz RFQ with A/q<30
- 105 MHz variable energy DTL (3 ≤ A/q ≤ 6)



- Medium energies ~0.15 - 1.8 MeV/u
- Well suited for reaction studies for novae & X-ray bursts

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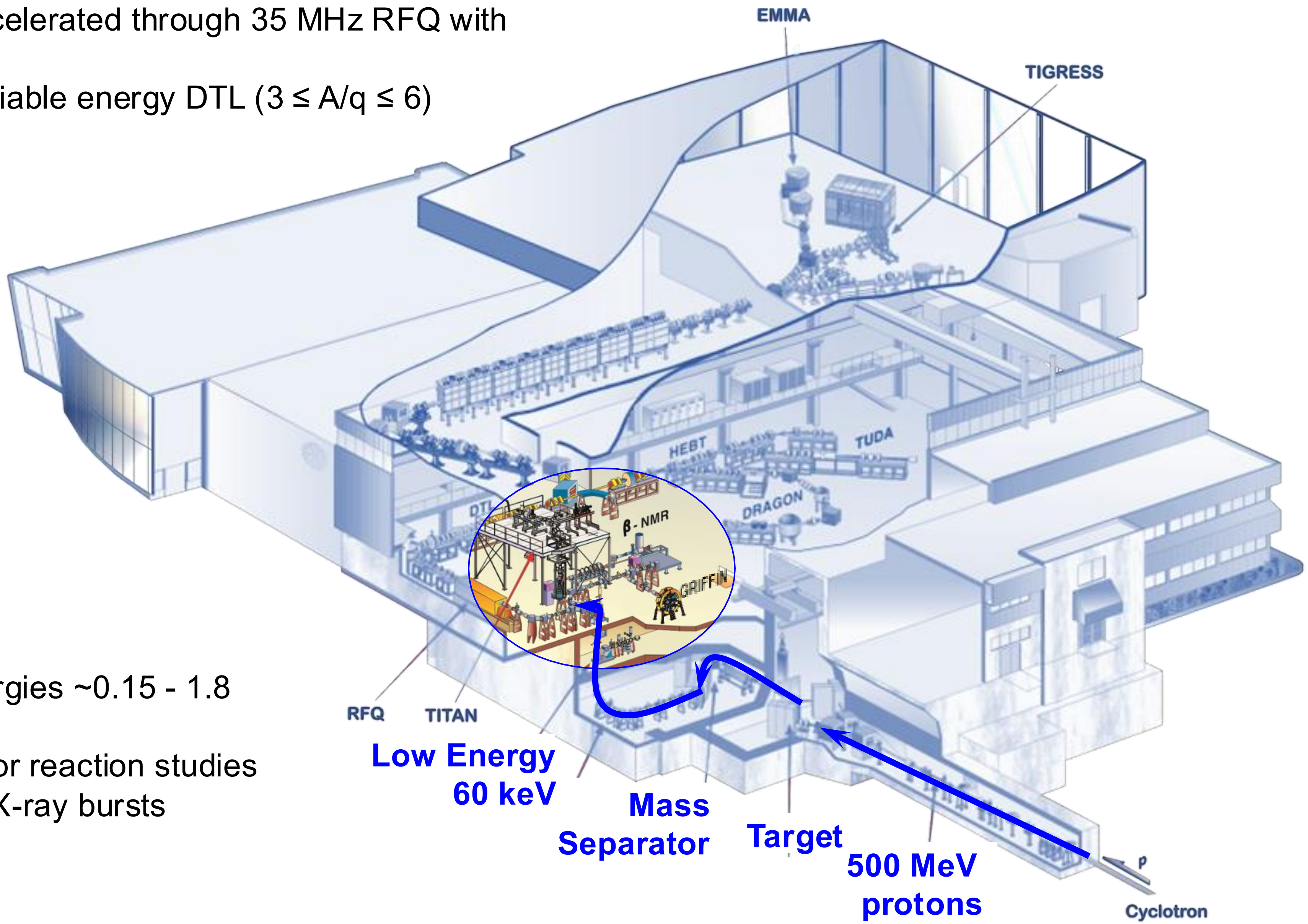

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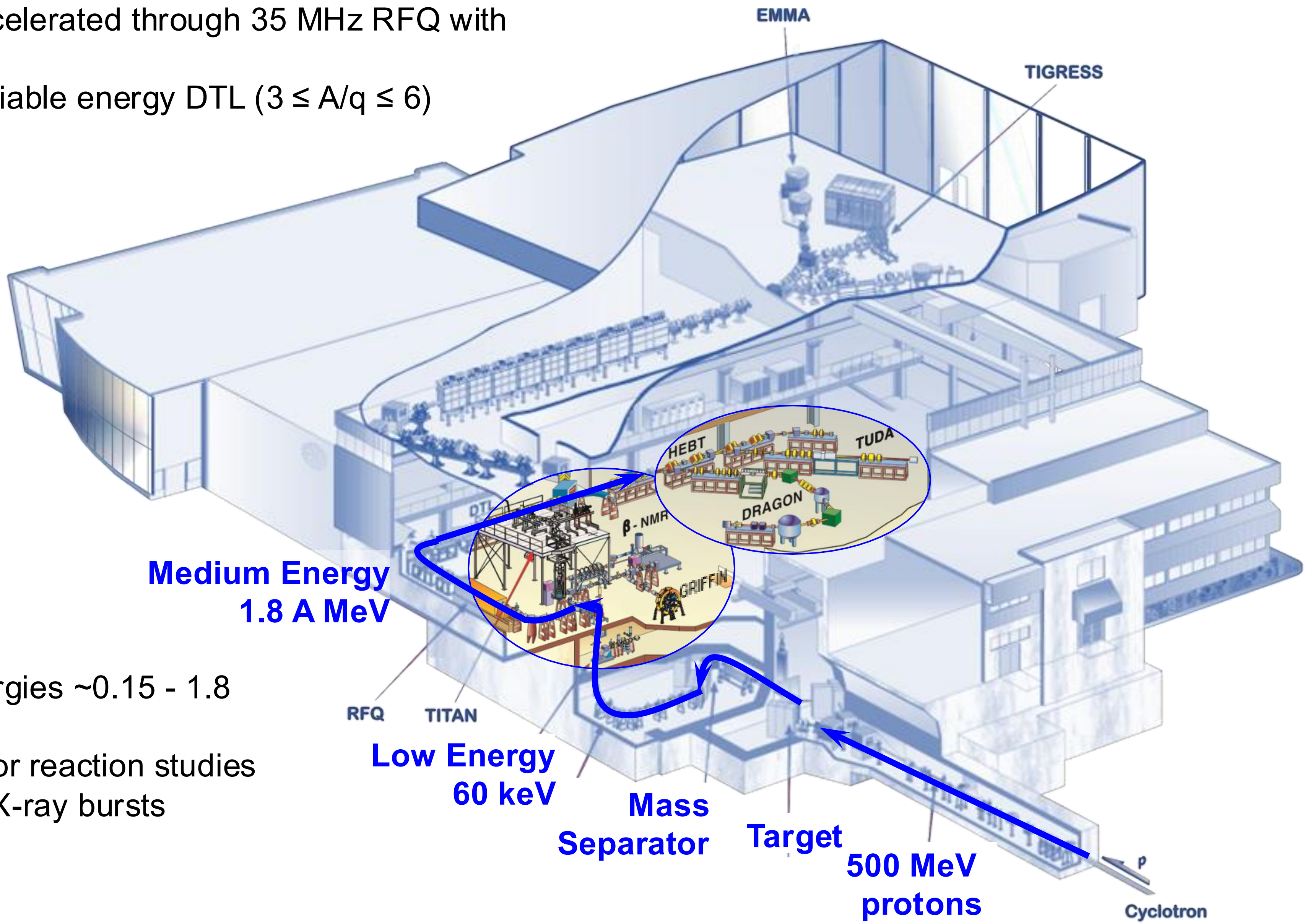

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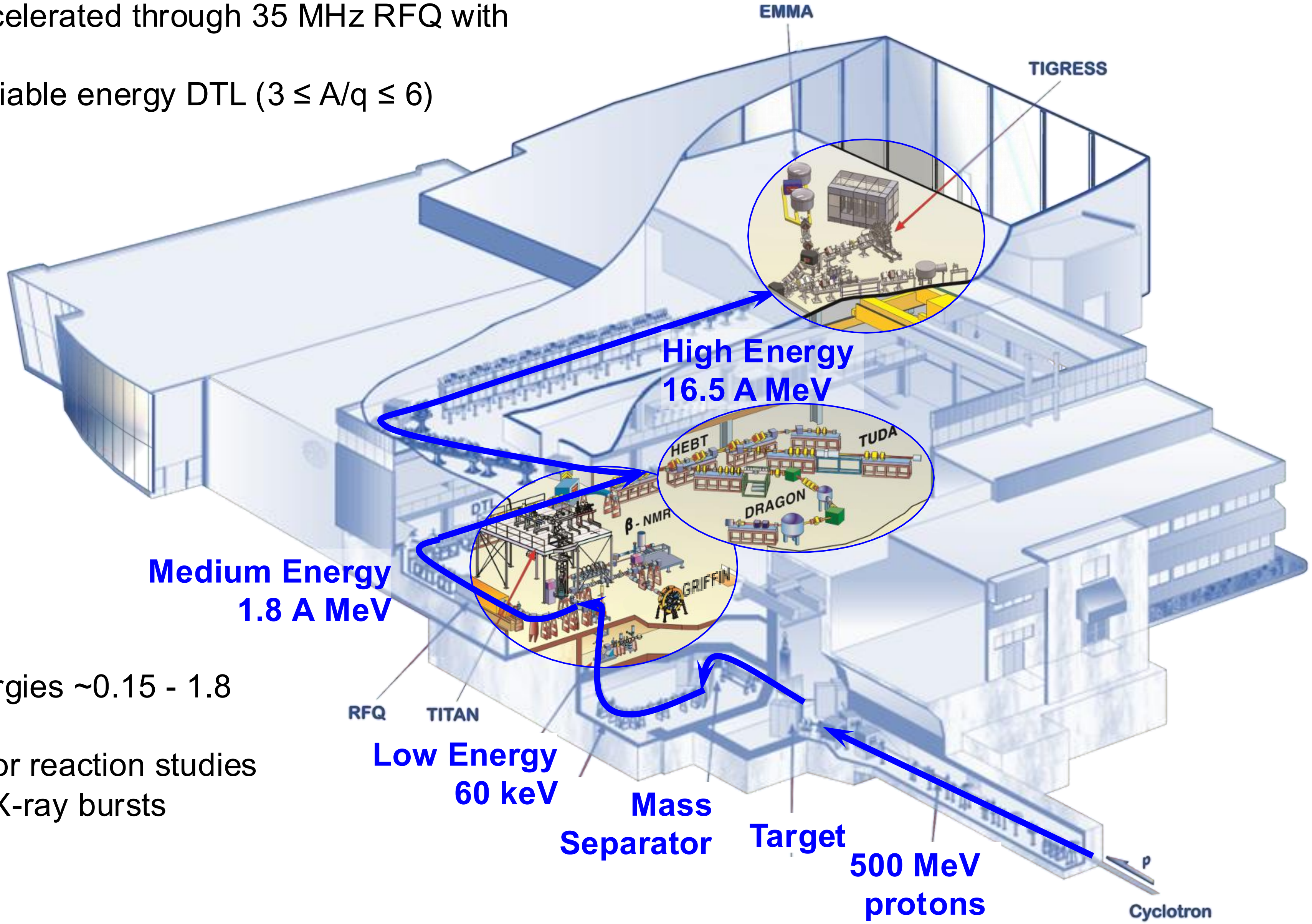

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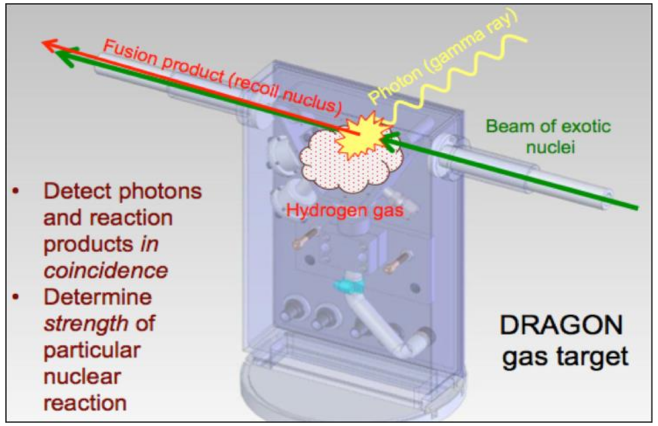
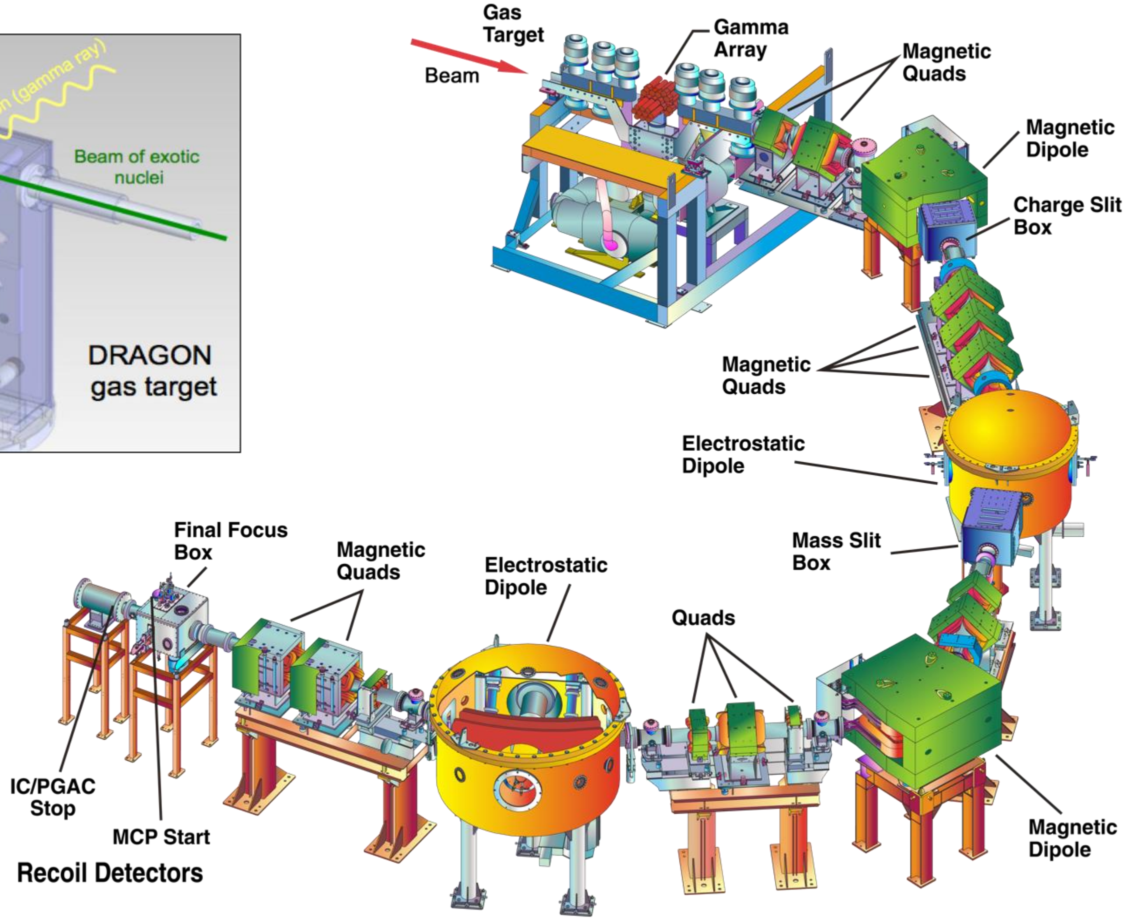
DRAGON – Detector of Recoils and Gammas of Nuclear Reactions

1. Windowless gas target
2. BGO γ-detection array
3. MEME mass separator
4. Recoil detection system





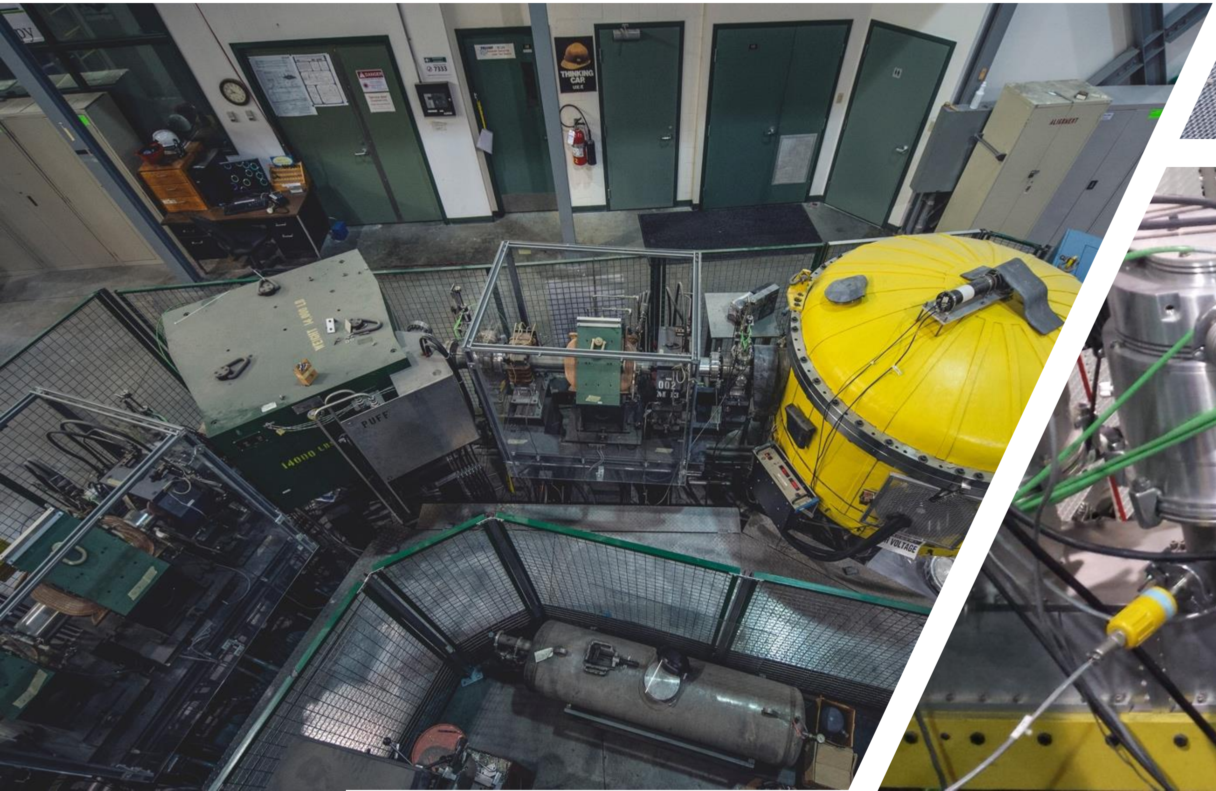
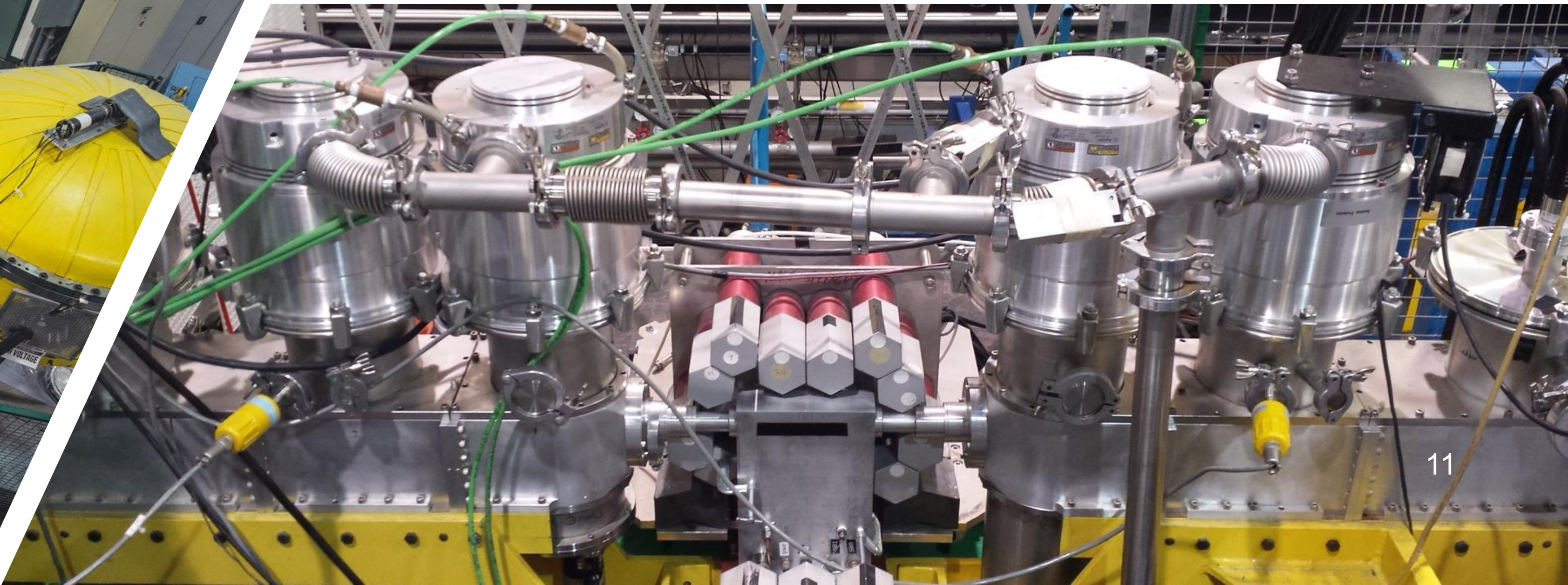
$$Y(\infty) = \frac{\lambda^2}{2}\frac{M+m}{m}\epsilon^{-1}\omega\gamma$$

#reactions per incident ion

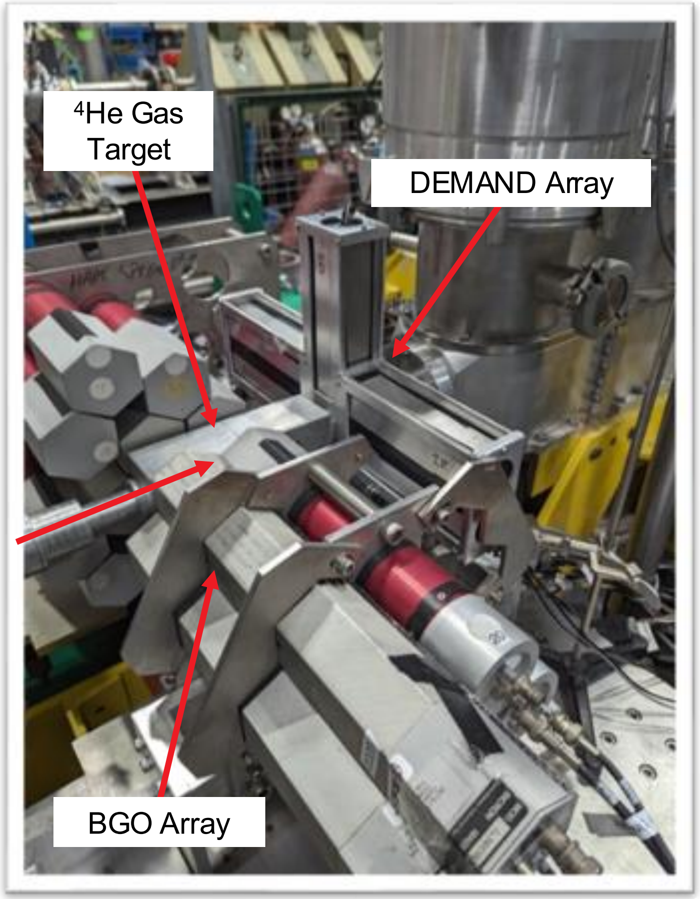
$$N_A\langle\sigma v\rangle = 1.54\times10^{11}(\mu T)^{-3/2}\,\omega\gamma\cdot\exp\left(-11.605\frac{E_R}{T_9}\right)$$

- **Coincidence measurement** with prompt γ-rays & PID cuts & TOF
- **suppression factor** of ~10^{15} for p-capture & ~$5\mathrm{x}10^{17}$ for α-capture



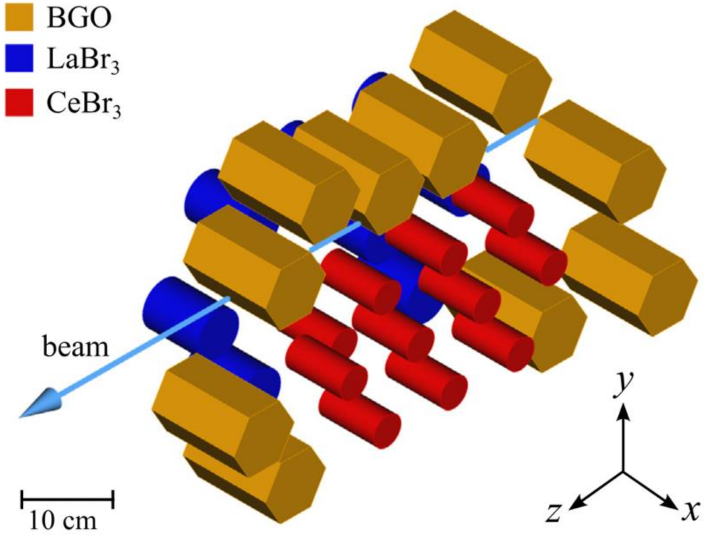
DRAGON



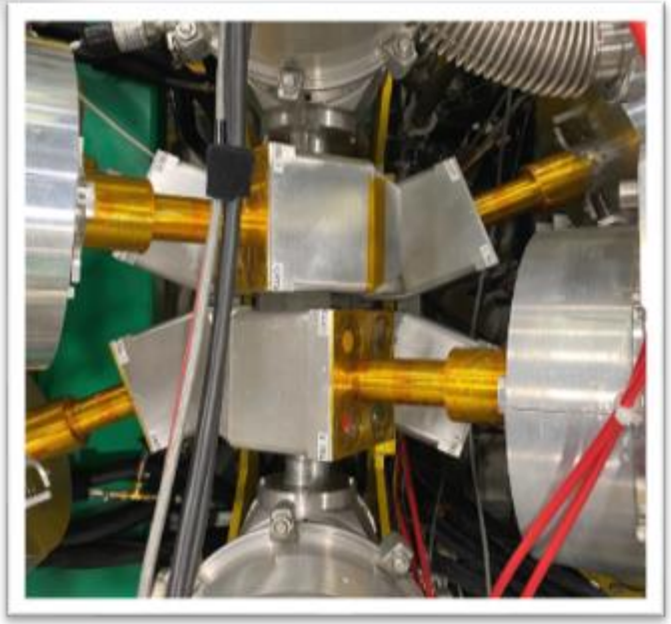
DRAGON's new versatility



- BGO array (high efficiency γ-detection)
- DEMAND (n-detectors)
- LaBr/CeBr (timing resolution, ^{23}Mg(p,g))

- SONIK (Si detectors, elastic scattering measurements (α,α), (*p*,*p*))
- HPGe detectors (high energy resolution, ^{20}Ne(*p*,γ))





DRAGON radiative capture measurement back catalogue

Reaction	Motivation	Intensity (s^{-1})	Purity (desired:contaminant)
$^{21}Na(p,\gamma)^{22}Mg$	1.275 MeV line emission in O-Ne novae	5×10^{9}	(100%)
$^{12}C(\alpha,\gamma)^{16}O$	Helium burning in Red Giants	3×10^{11}	(100%)
$^{26g}Al(p,\gamma)^{27}Si$	Nova contribution to galactic ^{26}Al	3×10^{9}	30,000:1
$^{12}C(^{12}C,\gamma)^{24}Mg$	Nuclear cluster models	3×10^{11}	(100%)
$^{40}Ca(\alpha,\gamma)^{44}Ti$	Production of ^{44}Ti in SNII	3×10^{11}	10,000:1 – 200:1
$^{12}C(^{16}O,\gamma)^{28}Si$	Nuclear cluster models	3×10^{11}	(100%)
$^{23}Mg(p,\gamma)^{24}Al$	1.275 MeV line emission in O-Ne novae	5×10^{7}	1:20 – 1:1,000
$^{17}O(\alpha,\gamma)^{21}Ne$	Neutron poison in massive stars	1×10^{12}	(100%)
$^{18}F(p,\gamma)^{19}Ne$	511 keV line emission in O-Ne novae	2×10^{6}	100:1
$^{33}S(p,\gamma)^{34}Cl$	S isotopic ratios in presolar grains	1×10^{10}	(100%)
$^{16}O(\alpha,\gamma)^{20}Ne$	Stellar helium burning	1×10^{12}	(100%)
$^{17}O(p,\gamma)^{18}F$	Explosive H burning in novae	1×10^{12}	(100%)
$^{3}He(\alpha,\gamma)^{7}Be$	Solar neutrino spectrum	5×10^{11}	(100%)
$^{58}Ni(p,\gamma)^{59}Cu$	High mass tests (p-process, XRB)	6×10^{9}	(100%)
$^{26m}Al(p,\gamma)^{27}Si$	SNII contribution to galactic ^{26}Al	5×10^{9}	(100%)
$^{34}S(\alpha,\gamma)^{38}Ar$	Nucleosynthesis in massive stars & SN	1×10^{11}	(100%)
$^{38g}K(p,\gamma)^{39}Ca$	Endpoint of nova nucleosynthesis	2×10^{7}	1:1
$^{19}Ne(p,\gamma)^{20}Na$	Fluorine detection in O-Ne novae	7×10^{6}	1:3
$^{34}S(p,\gamma)^{35}Cl$	Nucleosynthesis in O-Ne novae	1×10^{11}	(100%)
$^{22}Ne(p,\gamma)^{23}Na$	Sodium production in AGB stars	1×10^{12}	(100%)
$^{6}Li(\alpha,\gamma)^{10}B$	Proof-of-principle measurement	2×10^{10}	(100%)
$^{7}Be(\alpha,\gamma)^{11}C$	νp process & pp-chain breakout	1×10^{7}	1:300
$^{15}N(\alpha,\gamma)^{19}F$	Synthesis of F in AGB stars	1×10^{11}	(100%)
$^{14}N(p,\gamma)^{15}O$	CN Cycle hydrogen burning	6×10^{11}	(100%)
$^{30}Si(p,\gamma)^{31}P$	Pollution of Globular Clusters	5×10^{10}	(100%)
$^{39}K(p,\gamma)^{40}Ca$	Pollution of Globular Clusters	1×10^{11}	(100%)
$^{19}F(p,\gamma)^{20}Ne$	Nucleosynthesis in the first stars	1×10^{12}	(100%)
$^{18}O(\alpha,\gamma)^{22}Ne$	Stellar helium burning	1×10^{12}	(100%)
$^{22}Ne(\alpha,\gamma)^{26}Mg$	Weak r-process	5×10^{12}	(100%)
$^{20}Ne(p,\gamma)^{20}Na$	Weakly bound proton halo state	1×10^{13}	(100%)
~~**$^{37}Ar(p,\gamma)^{38}Ca$**~~	Nucleosynthesis in O-Ne novae	1×10^{7}	

Making use of High-Intensity Stable Beams

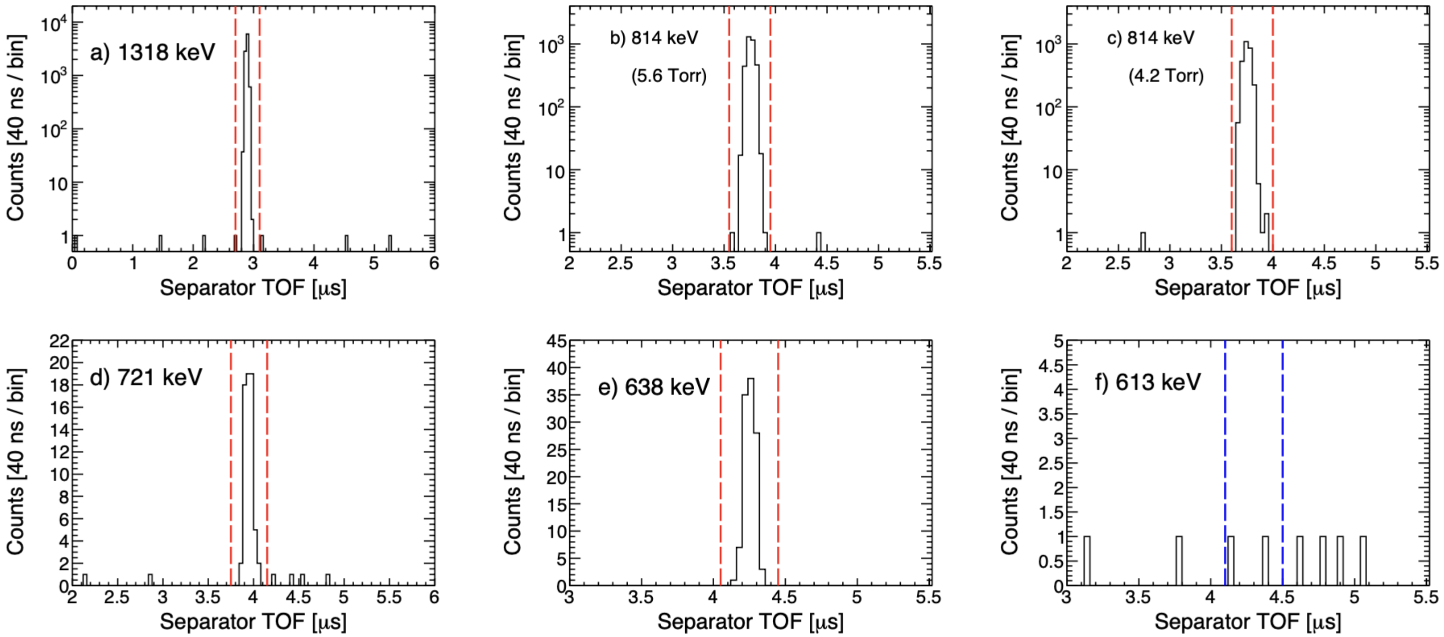
$^{17}O(\alpha,\gamma)^{21}Ne$ – relevance for the s-process

- Understanding the **competition** between **$^{17}O(\alpha,n)$** & **$^{17}O(\alpha,\gamma)$** reaction channels is important for determining the role of ^{16}O as a light-element **neutron poison**
- In metal-poor environments, the $^{16}O(n,\gamma)^{17}O$ reaction makes ^{16}O a strong **neutron poison**
- **Status:** Strengths of key $^{17}O(\alpha,\gamma)^{21}Ne$ resonances within Gamow window for **core helium burning** in massive stars was **not well enough constrained** by experiment.

➔ Measurement at DRAGON at 5 resonance energies (612 , 638, 721, 814 & 1318 keV)

- First measurement on 612 keV resonance → upper limit
- 638 keV: uncertainty reduced (80% → 25%)

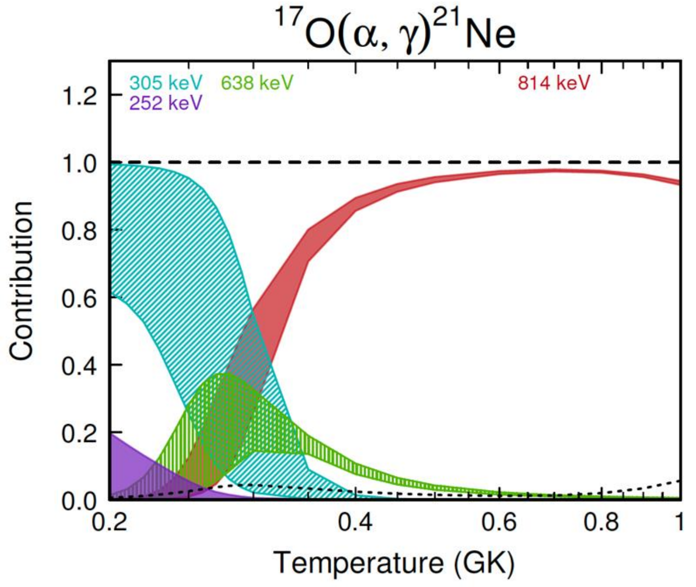
$\omega\gamma$ = 136 ± 13 meV $\omega\gamma$ = 7.72 ± 0.55 meV

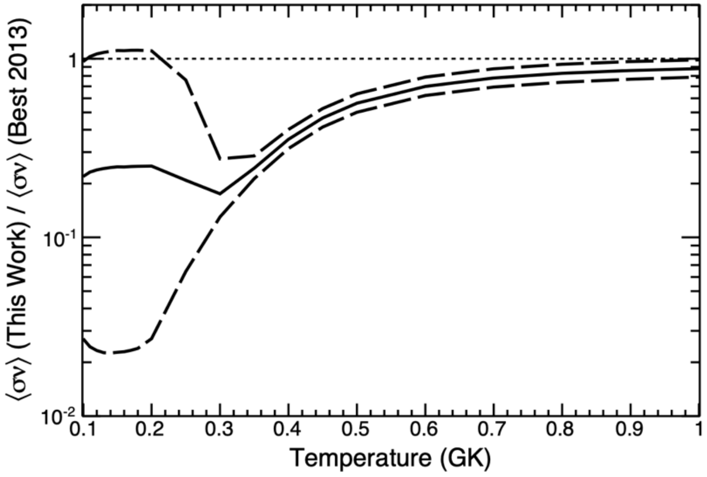


$\omega\gamma = 13.1^{+3.2}_{-2.4}$ μeV $\omega\gamma$ = 4.85(79) μeV $\omega\gamma$ < 0.07 μeV

M. Williams et al.- Phys. Rev. C **105**, 065805 (2022)

$^{17}O(\alpha,\gamma)^{21}Ne$ – Results from DRAGON study





- Upper limit for 612 keV resonance ➔ effectively removes any contribution to the overall reaction rate
- The 638 keV resonance may contribute up-to ~40% within the relevant temperature range.
- This contribution may be greater if the strength of the **305 keV** resonance were measured to be significantly below its estimated value.
- New reaction rate was calculated **~5x lower** than the previous rate at 0.3 GK → Enhancement of weak s-process yields (rotating, massive star models)

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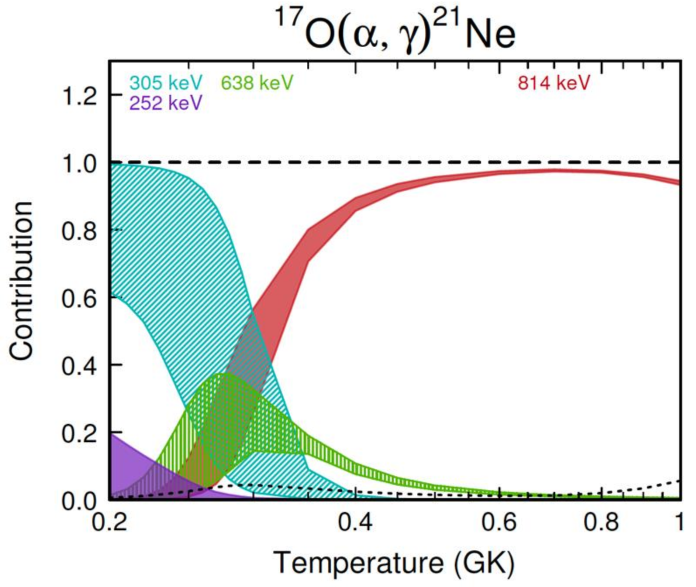

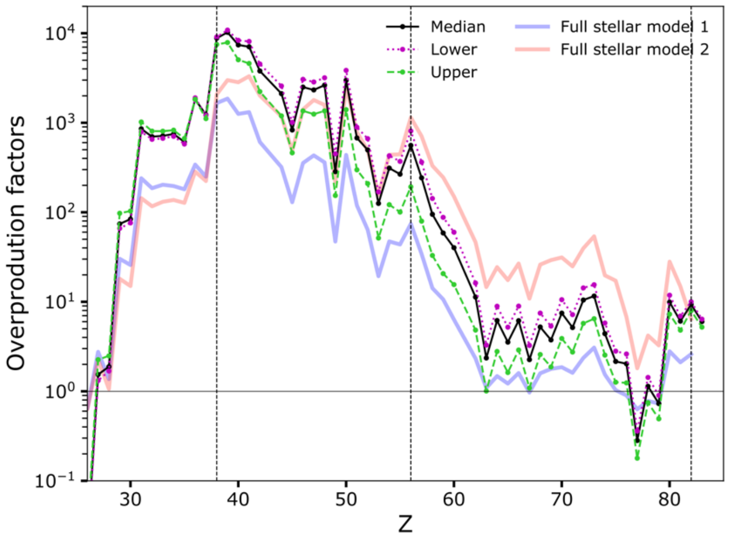

M. Williams et al.- Phys. Rev. C **105**, 065805 (2022)

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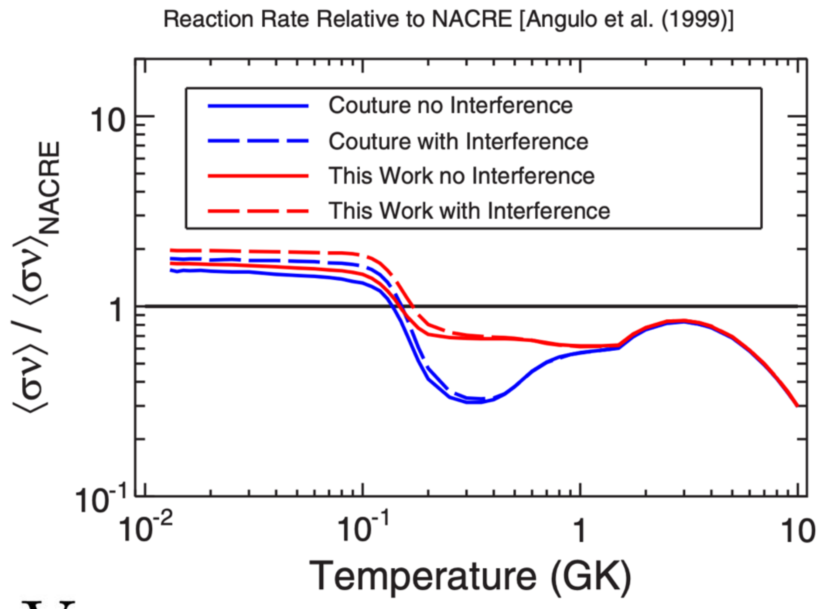
- New reaction rate was calculated **~5x lower** than the previous rate at 0.3 GK → Enhancement of weak s-process yields (rotating, massive star models)
- Impact of uncertainties in the present $^{17}O(\alpha,\gamma)^{21}Ne$ rate were assessed using a post-processing code mimicking the core helium burning phase of a $20M_{\odot}$ rotating star with low metallicity

$^{19}F(p,\gamma)^{20}Ne$ – Breakout path of CNO cycle

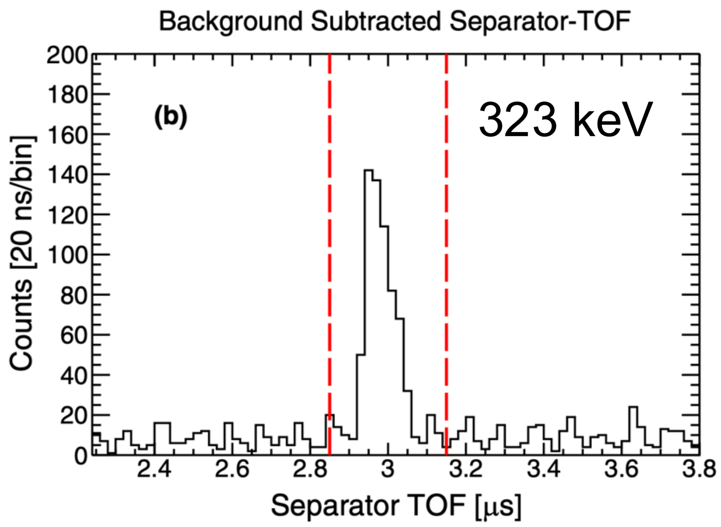


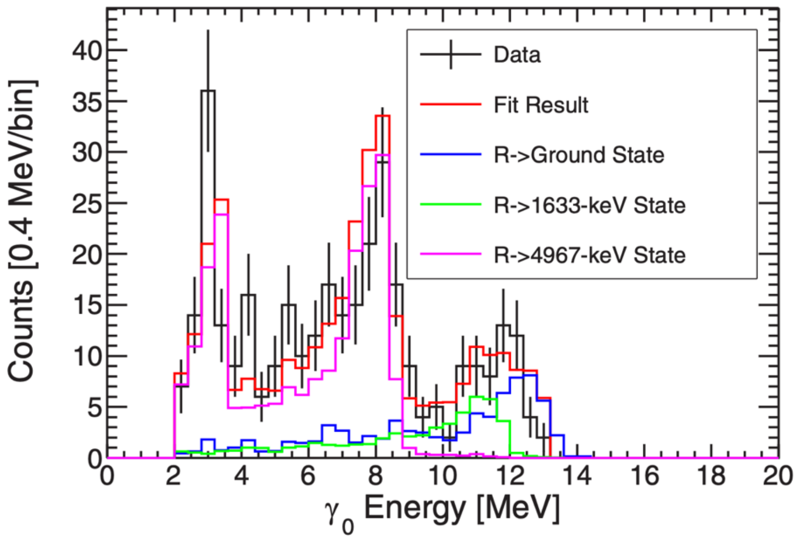
- **$^{19}F(p,\gamma)^{20}Ne$** is extremely important reaction for leakage out of CNO region in hydrostatic burning in Pop-III stars; in competition with stronger **$^{19}F(p,\alpha)^{16}O$**

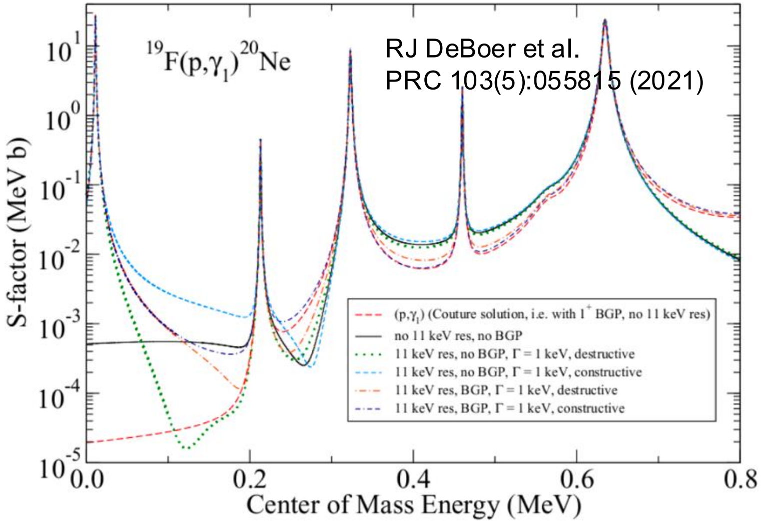
- Experimentally very challenging in normal kinematics due to $^{19}F(p,\alpha\gamma)^{16}O$ background

→ Inverse kinematics extremely advantageous

$$\omega\gamma = 3.3^{+1.1}_{-0.9}\ \text{meV}$$







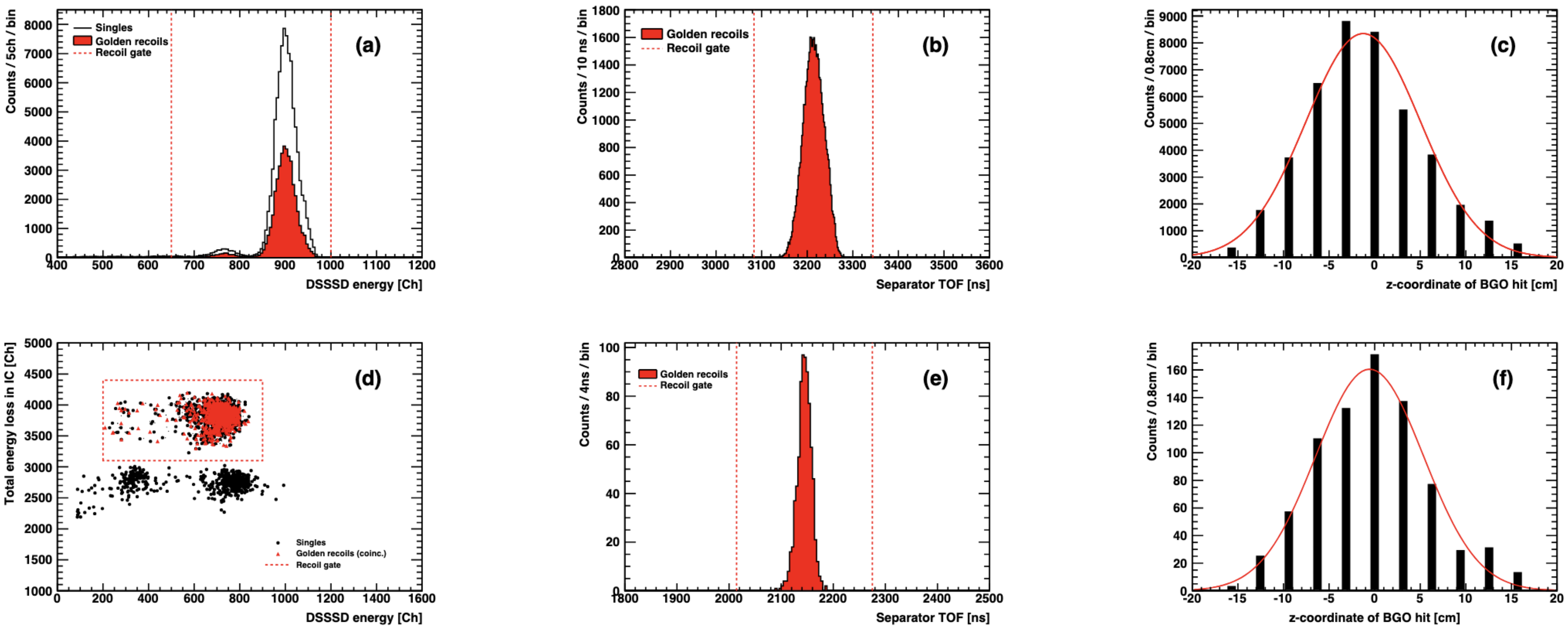
M. Williams *et al.*, Phys. Rev. C 103 (2021)
Second data set (215 – 760 keV) under analysis!

Under analysis: $^{15}N(\alpha,\gamma)^{19}F$ – Nucleosynthetic Origin of ^{19}F

Main ^{19}F production channel when He burning is active

E_{cm} = 1323 keV

E_{cm} = 3152 keV



Status:

- Measurement of 3 resonances and 4 DC data points (E_{cm} ~950 keV to ~3200 keV)
- Confirmed energy of 1323 keV resonance (conflict with ERNA measurement)
- Lower than expected $\omega\gamma$ for 1323 keV triggered re-measurement at DRAGON (see also Fang et al./Notre Dame)
- **New data on 1323 keV resonance and 1487 keV resonances** now under analysis

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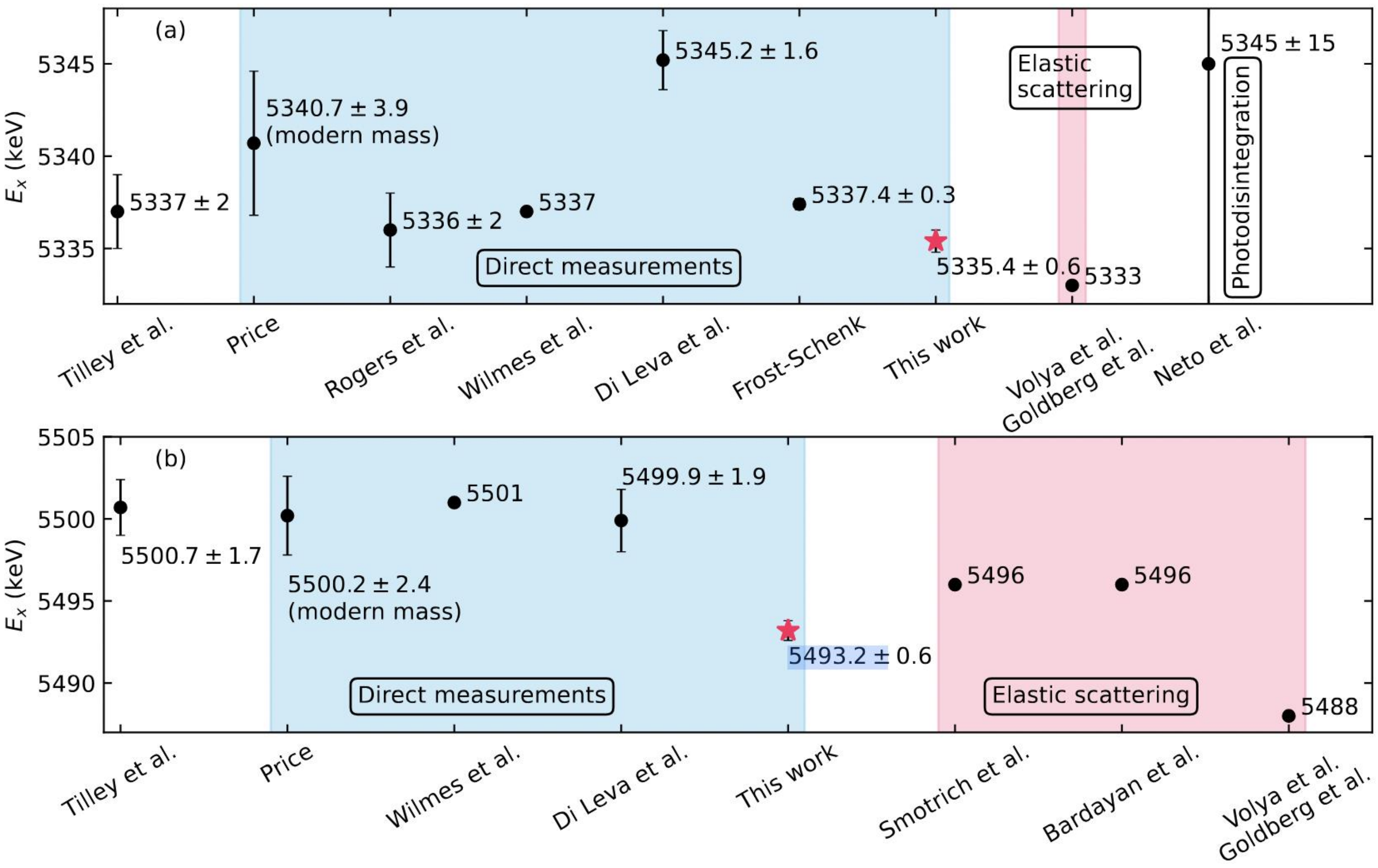
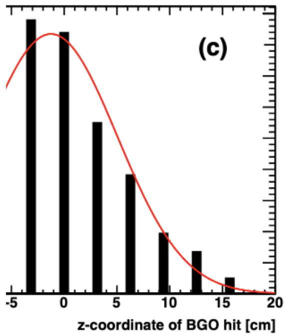
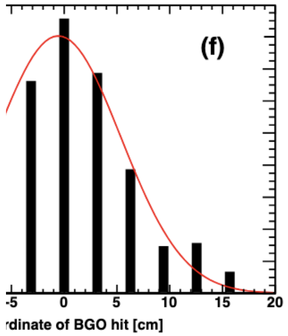




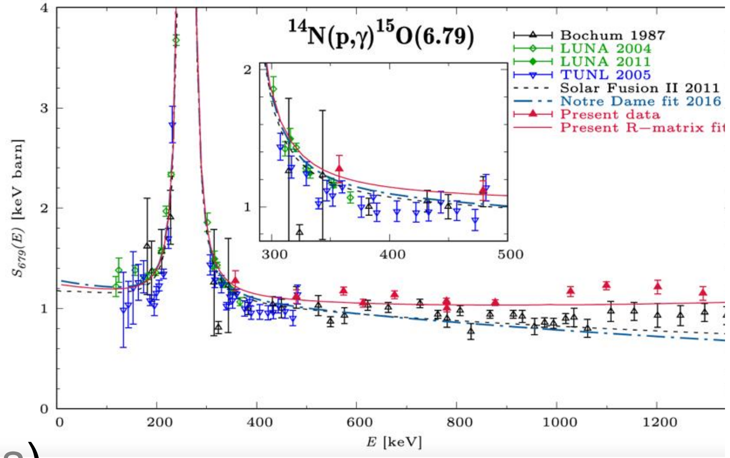


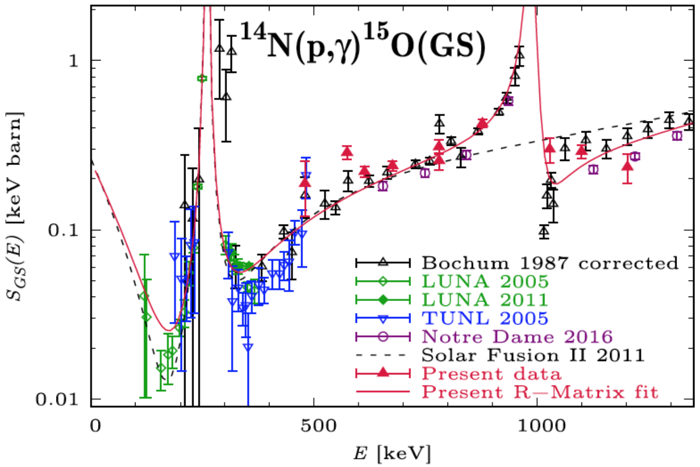
Status:

- Measureme
- Confirmed
- Lower than … Fang et al./Notre Dame)
- **New data on 1323 keV resonance and 1487 keV resonances** now under analysis

Under analysis – $^{14}N(p,\gamma)^{15}O$

Figures from Wagner et al. PRC 97, 2018





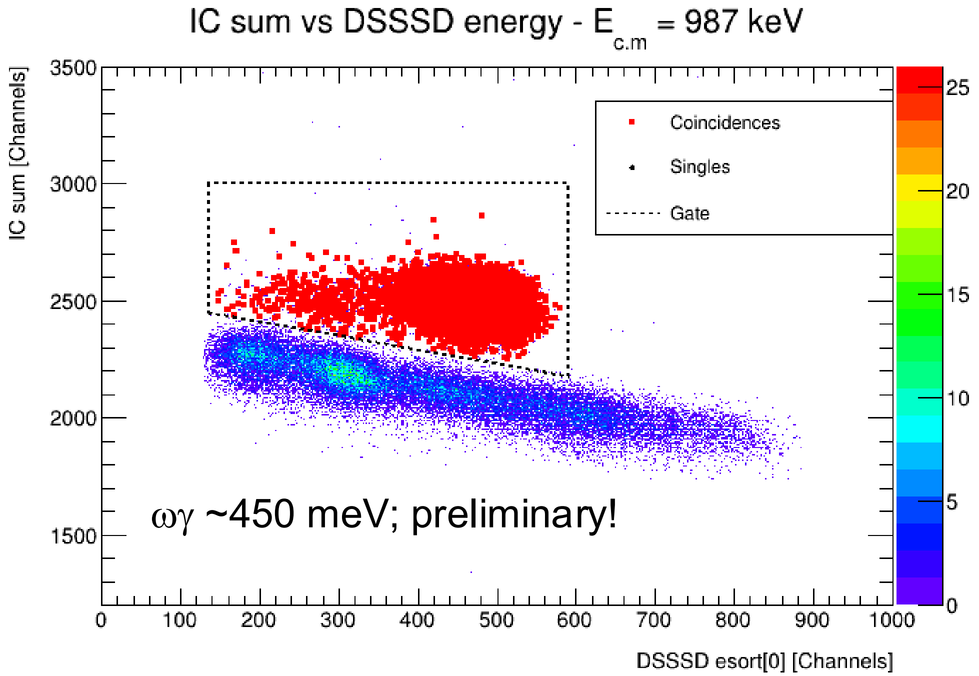
Slowest reaction of the CNO cycle of hydrogen burning in stars ➔ determines the rate of the cycle

Status (DRAGON data):

- Data at 9 energies between E_{cm} = 850 - 1685 keV (overlap with Atomki & new LUNA data sets)
- Resonances at 987 keV & 1685 keV
- Detailed analysis completed on the 987 keV resonance
- DRAGON result consistent in coincidence & singles

➔ Good agreement with Gyürky et al. (2019)

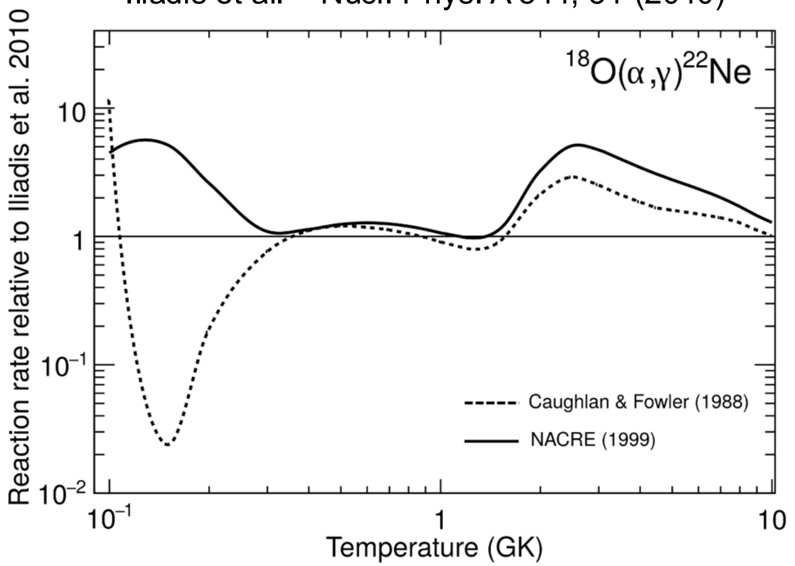
- DC data show good separation
  - *Singles measurement possible (reduce sys. error)*
  - *Use BGO data to separate contributions*



Spokesperson: A. Lennarz
Under analysis by PhD student Mallory Loria, TRIUMF/Uvic

Under analysis: $^{18}O(\alpha,\gamma)^{22}Ne$ – s-process nucleosynthesis

Iliadis et al. – Nucl. Phys. A 841, 31 (2010)



Relevance:

- Stellar helium burning via the $^{18}O(\alpha,\gamma)^{22}Ne$ reaction is important for s–process nucleosynthesis
- Especially the weak component, since it provides the main neutron source generator ^{22}Ne

Status:

- Dominated by individual resonances inside Gamow window, which is at E_{cm}= 155 – 794 keV (**T = 0.1 – 0.4 GK**) for stellar helium burning
- **But:** the most important resonances that determine the **$^{18}O(\alpha,\gamma)^{22}Ne$ reaction rate at helium burning energies** are not very well constrained!

Spokespeople: Psaltis, Chen, Lennarz
Under analysis by PhD student Dhruval Shah, McMaster University

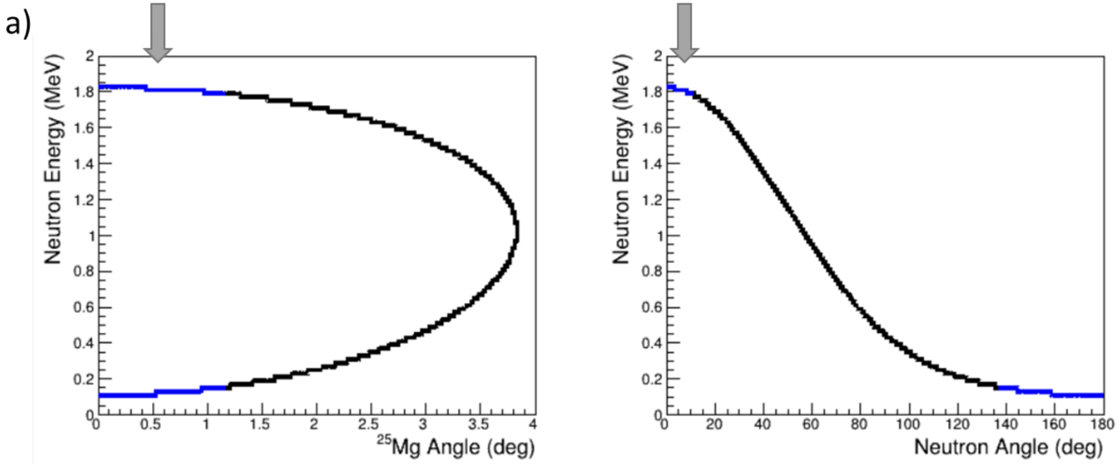
DRAGON measurement:

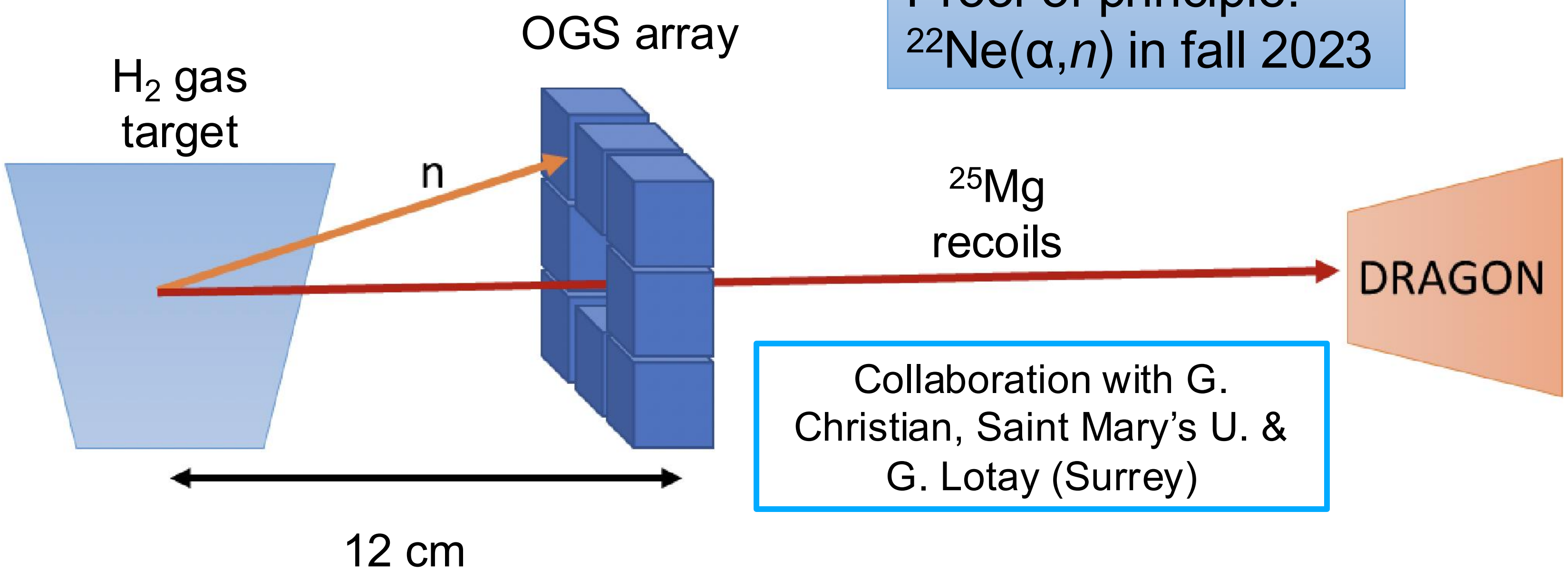
- Phase I – Reference resonances E_{cm} = 542 & 614 keV
- Phase II - 398 & 469 keV (supposed to dominate at He-burning temperatures)
- Challenges: Large recoil cone angle & precise resonance energies

Direct (α,*n*) Reaction Measurements

DEMAND array at DRAGON

- Organic glass scintillators for neutron detection
- 1 × 1 × 1 & 3 × 3 × 3 cm^3 OGS cubes, each coupled to a PMT
- For e.g.: $^{22}\mathrm{Ne} + \alpha \rightarrow 25\mathrm{Mg} + \mathrm{n}$ (s-process n-source)
- Populate E_x = 11.83 MeV resonance in the ^{22}Ne(a,n)^{25}Mg reaction





Proof of principle: ^{22}Ne(α,*n*) in fall 2023

Collaboration with G. Christian, Saint Mary's U. & G. Lotay (Surrey)

T. A. Laplace *et al.*, JINST **15** P11020 (2020).

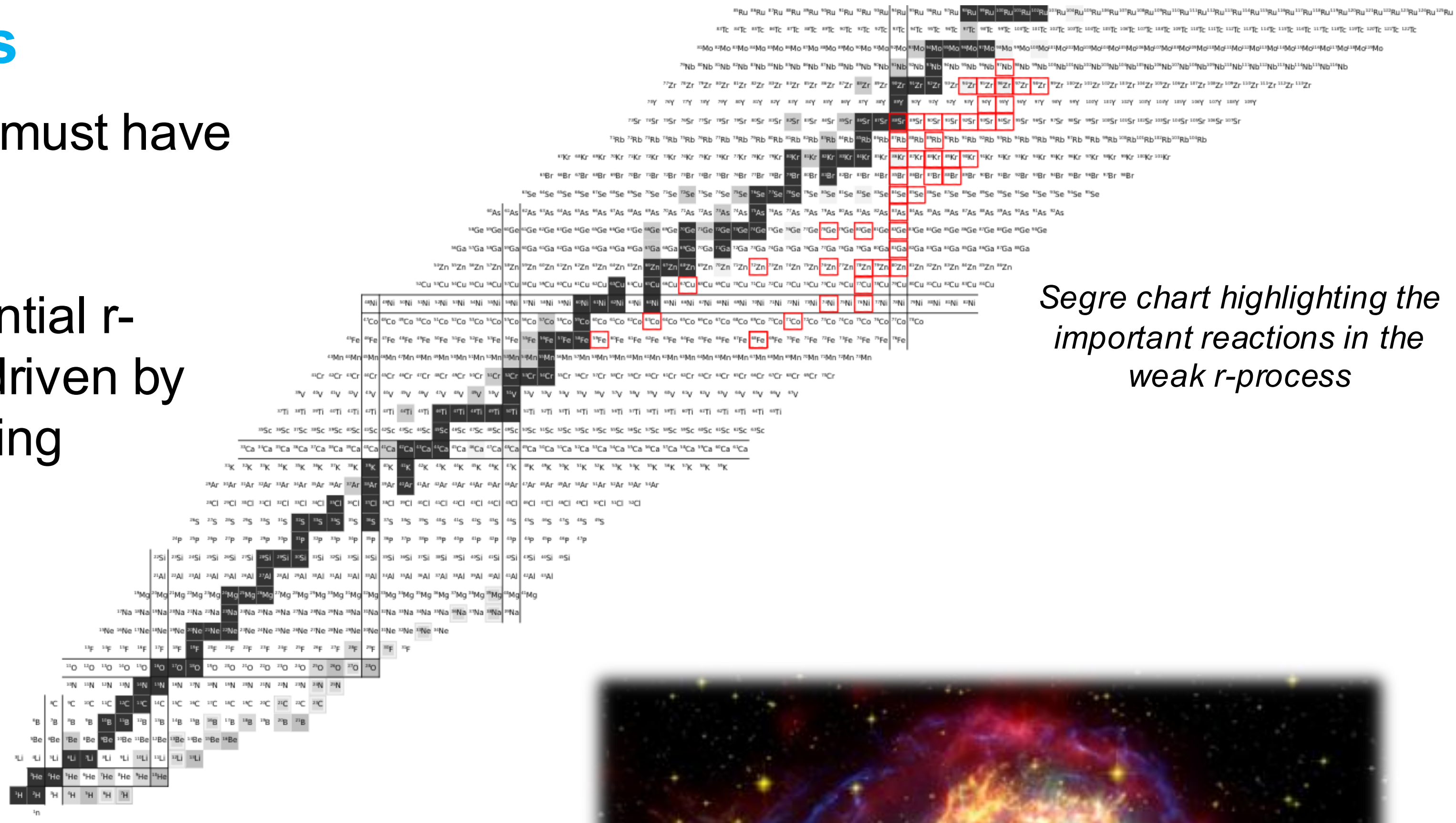
- superb n/γ pulse shape discrimination
- sub-nanosecond timing resolution
- bright, emitting ~17,000 photons/MeVee

Importance of (α,*n*) reaction rates

- Observational evidence that r-process must have occurred in the early Universe

- **Core-collapse supernovae** are a potential r-process site where nucleosynthesis is driven by the alpha- or "**weak" r-process** producing elements up to Ag via **(α,*n*) reactions**

➔ May explain production of lighter heavy elements in the early Universe



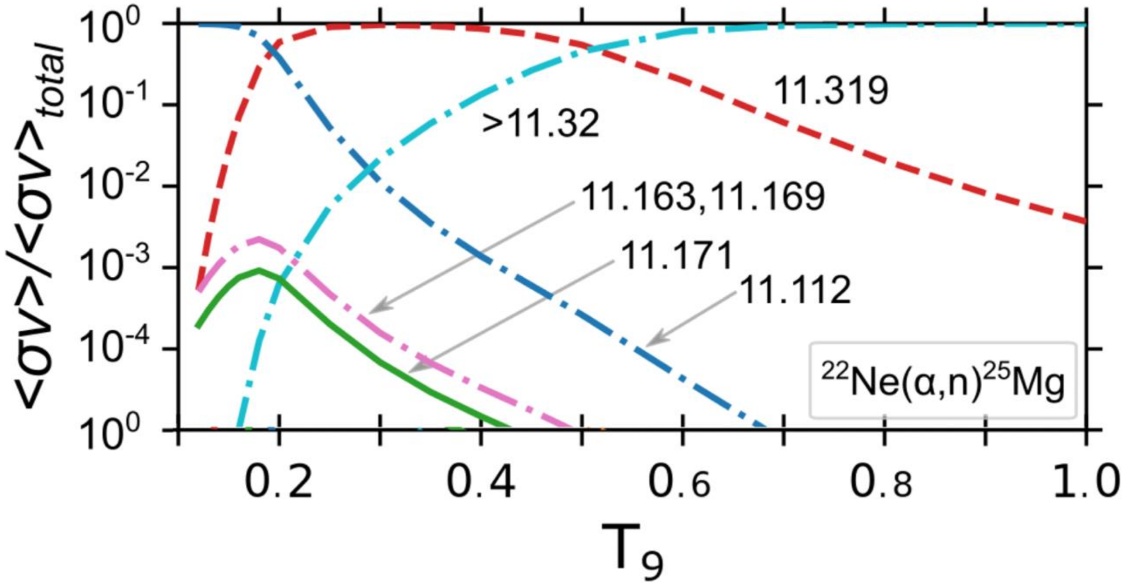
Segre chart highlighting the important reactions in the weak r-process

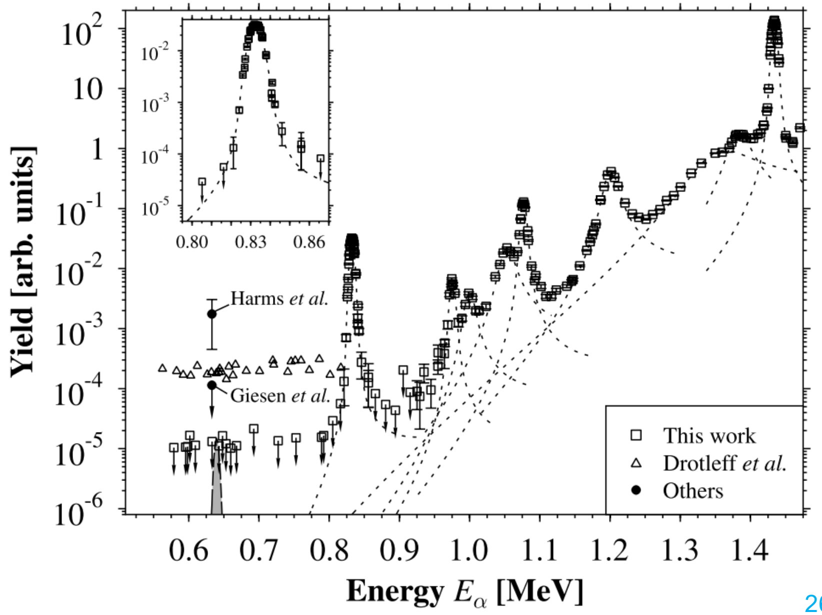
- Sensitivity study has **identified 45 (α,*n*) reactions** which are predicted to be important (Bliss, 2020)

- Presently almost complete lack of exp. data involving radioactive nuclei ➔ RIB facilities to study these reactions **directly** in **inverse kinematics**

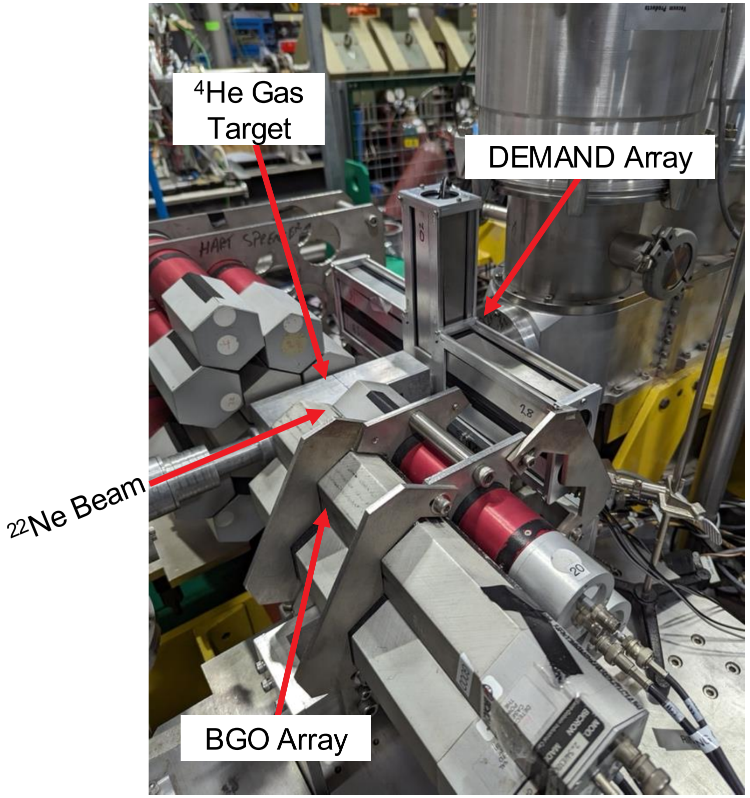
$^{22}Ne(\alpha,n)^{25}Mg$

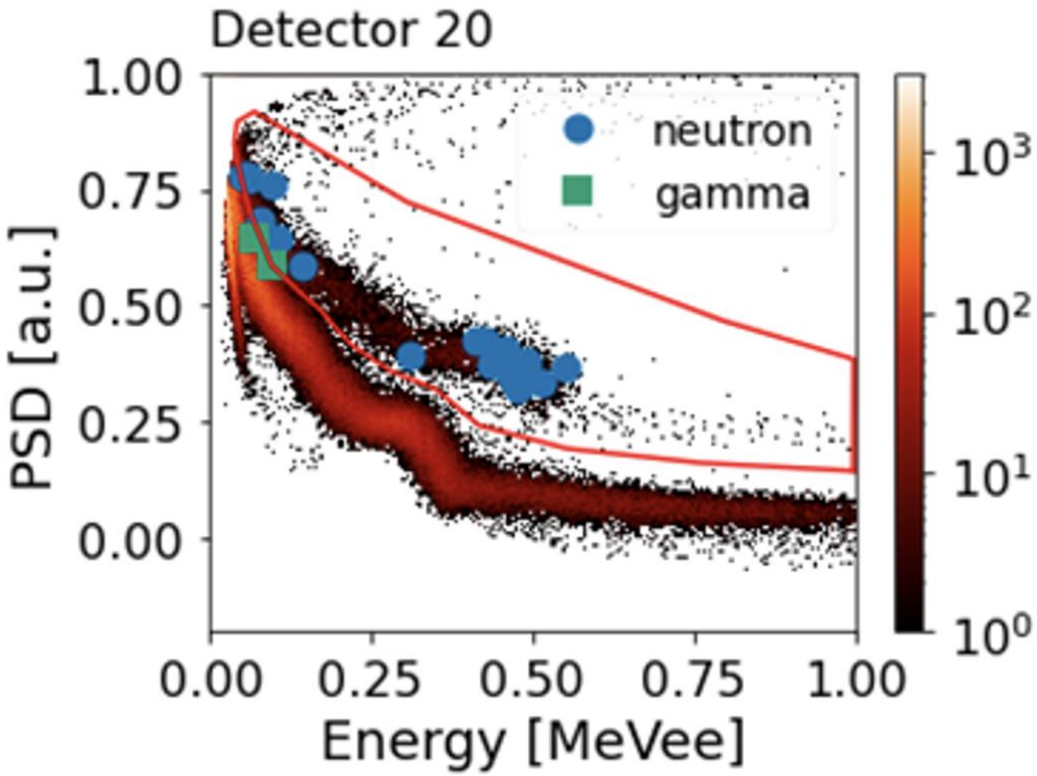
- Main **source of neutrons** for the **s-process** in AGB stars (**competing $^{22}Ne(\alpha,\gamma)^{26}Mg$** reaction)
- Need detailed knowledge of the **$^{22}Ne(\alpha,n)/^{22}Ne(\alpha,\gamma)$** ratio in order to **accurately model** the weak astrophysical *s*-process
- Rate dominated by **703 keV resonance**
- **Issue:** Discrepancies on strengths from direct measurements (83(24) μeV to 234(77) μeV) & indirect studies show factor 3 less
- Resonance at ***E_r* = 1.43 MeV** has a measured **resonance strength** of **1.067 eV**, making it an ideal test cases





Preliminary results – Successful proof-of-principle in Dec. 2023





- A **proof-of-principle experiment** was carried out to measure the strength of the **1.43-MeV resonance** in the **^{22}Ne(α,*n*)^{25}Mg** reaction
- Results show the **excellent PSD** capabilities of the 8 OGS detectors

Figures courtesy of G. Christian

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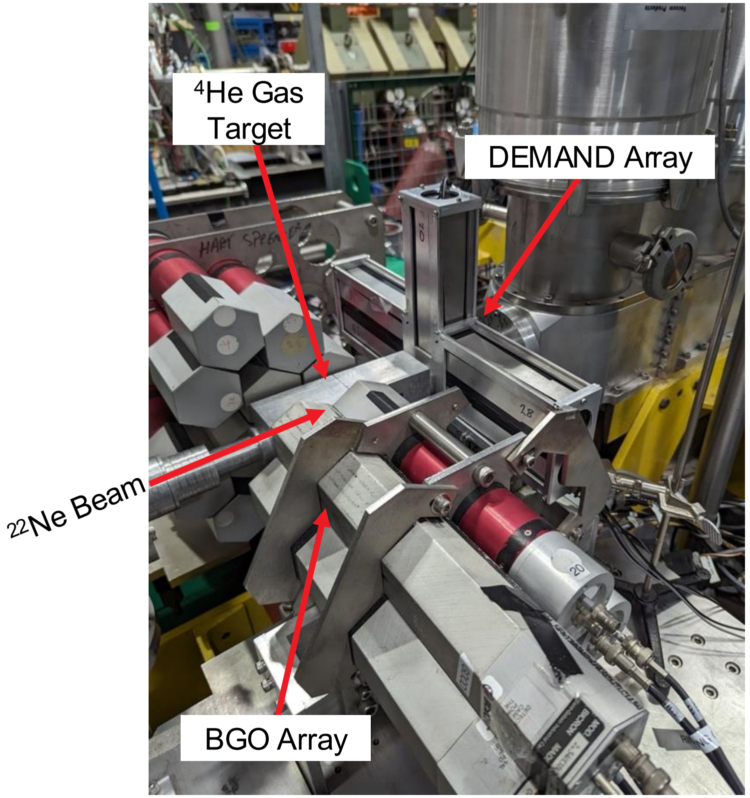
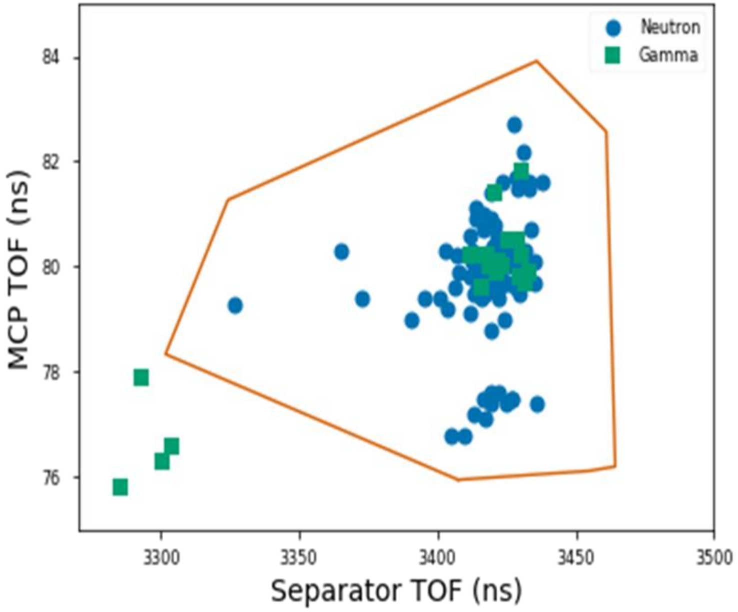
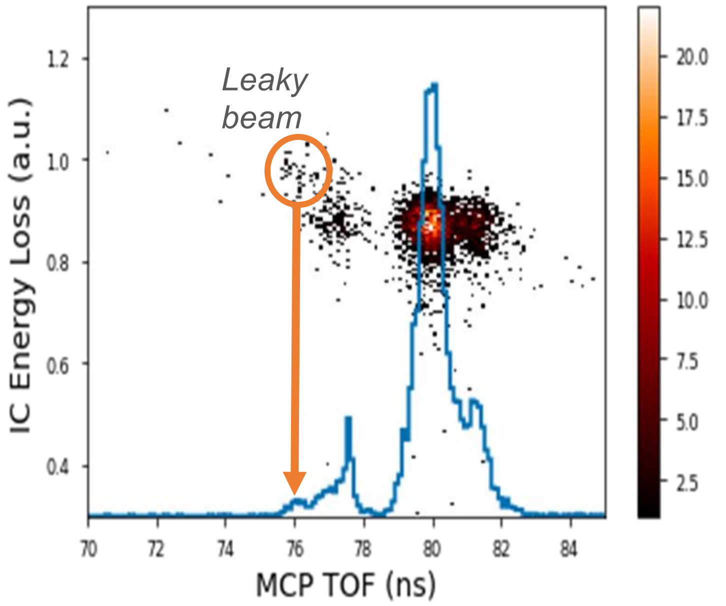


Coincidences – MCP TOF vs. Separator TOF



Singles – Ion Chamber ΔE vs MCP TOF



- A **proof-of-principle experiment** was carried out to measure the strength of the **1.43-MeV resonance** in the **^{22}Ne(α,*n*)^{25}Mg** reaction
- Results show the **excellent PSD** capabilities of the 8 OGS detectors

Preliminary $\omega\gamma$ ~ 790 meV
Good agreement w/literature

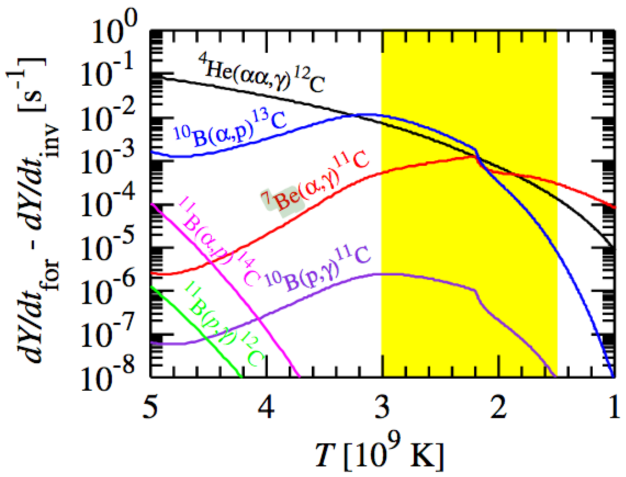
➔ ***Up next, ^{22}Ne(α,n) at 703 keV in December 2025!***
➔ ***Opens new avenue for direct measurements of astrophysical reactions!***

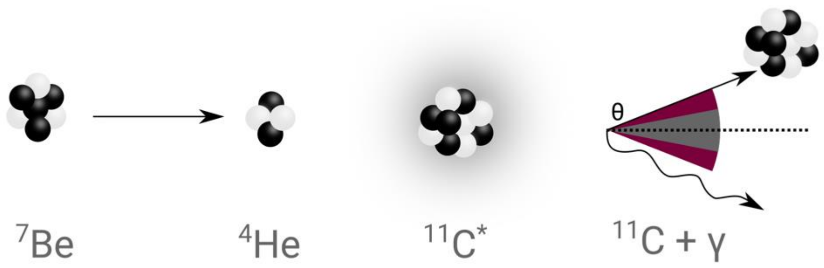
Figures courtesy of G. Christian

Measurements with Radioactive Ion Beams

Direct Measurements at DRAGON – $^{7}Be(\alpha,\gamma)^{11}C$, relevant to νp-process

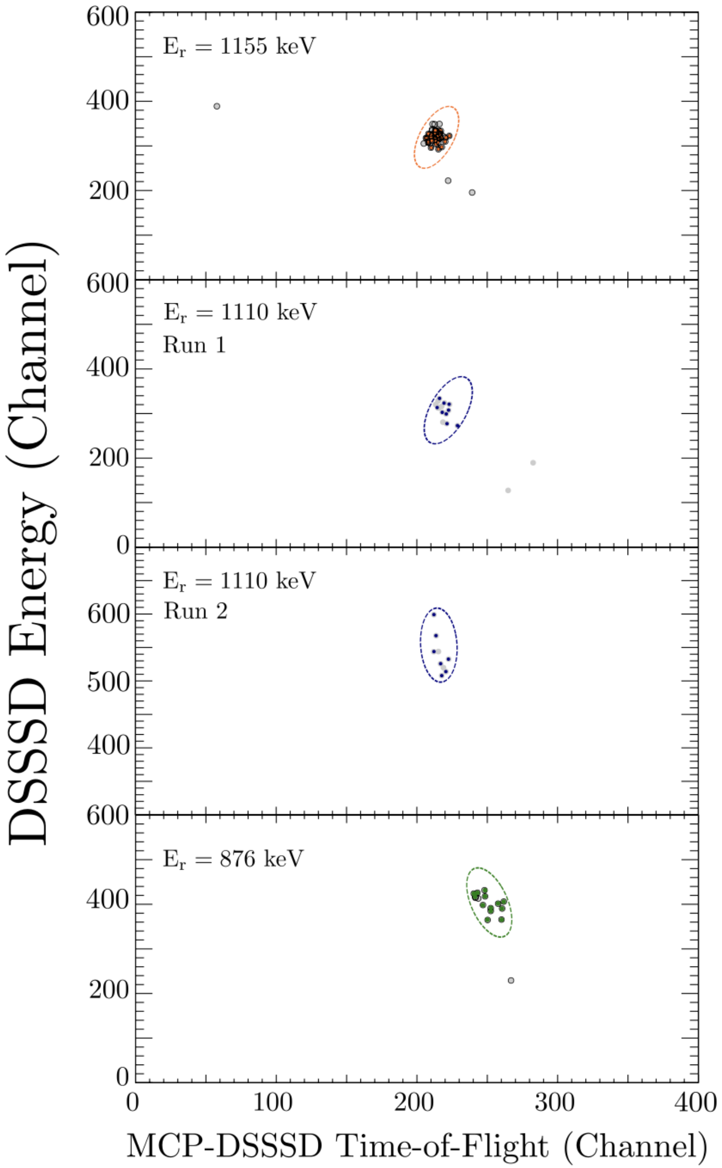
- ***νp*-process:** nucleosynthesis of A>74 nuclei in neutron-rich neutrino-driven winds of CCSN: T=1.5-3 GK
- 3-α reaction is paramount as acts as a throttle to seed-nuclei production thus acting as a "proton poison" ➔ ***νp*-process less efficient**
- $^{7}Be(\alpha,\gamma)^{11}C$ and $^{7}Be(\alpha,p)^{10}B$ can compete with 3-α: order of magnitude variation in p-nuclei 90 < A < 110 yields
- $^{7}Be(\alpha,\gamma)^{11}C$ significant technical challenge as recoil angle exceeds DRAGON separator acceptance ➔ Geant simulations on $^{6}Li(\alpha,\gamma)^{10}B$ to benchmark





DRAGON's acceptance is 22 mrad

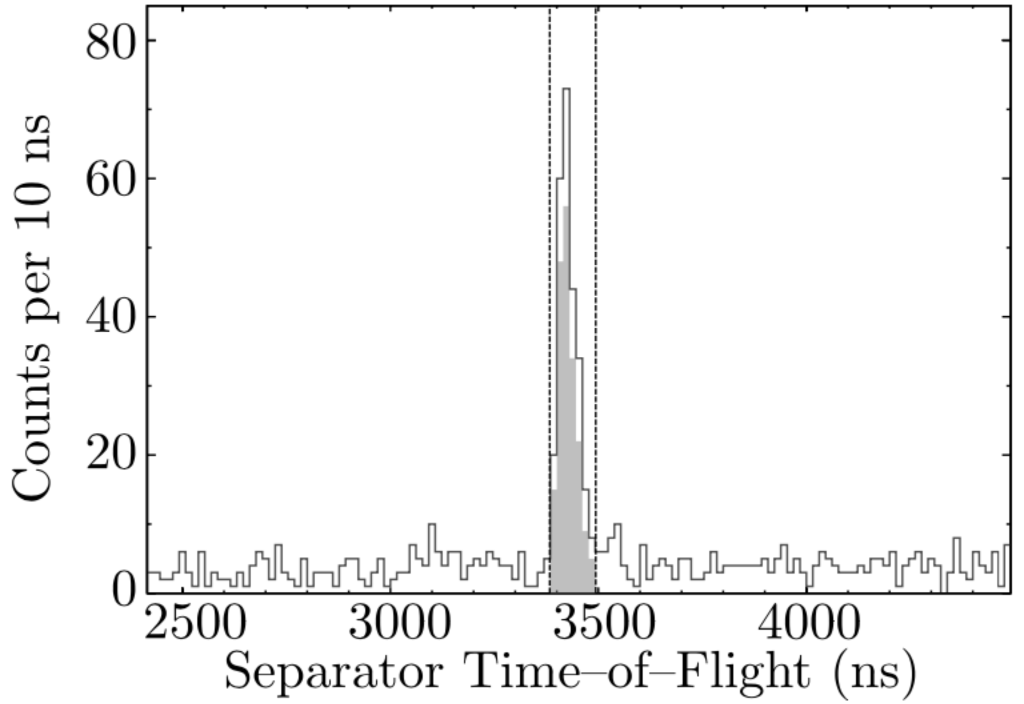
$^{7}Be(\alpha,\gamma)^{11}C$ ~ 43 mrad

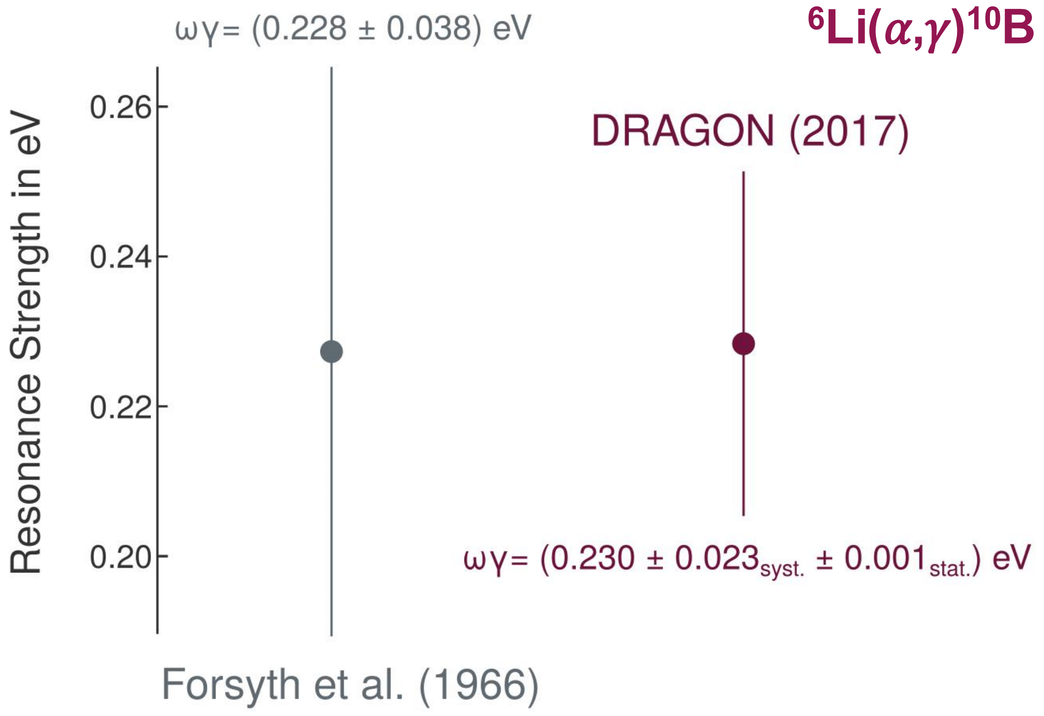


A. Psaltis et al. - PRL 129, 162701 (2022)
A. Psaltis et al. - PRC 106, 045805 (2022)
A. Psaltis et al. - NIMA 987 (2021) 164828

Benchmark GEANT3 acceptance of DRAGON

-Using a high cone angle reaction of known simple γ-decay





A. Psaltis et al. - NIMA 987 (2021) 164828

- GEANT3 simulation includes raytracing
- Benchmarked against α-source measurements

- Includes reaction simulation, cascade decays, angular distributions, BRs, energy levels, etc.

- Successfully benchmarked simulation for large recoil cones with **$^{6}Li(\alpha,\gamma)^{10}B$** reaction (known resonance at 1459 keV)

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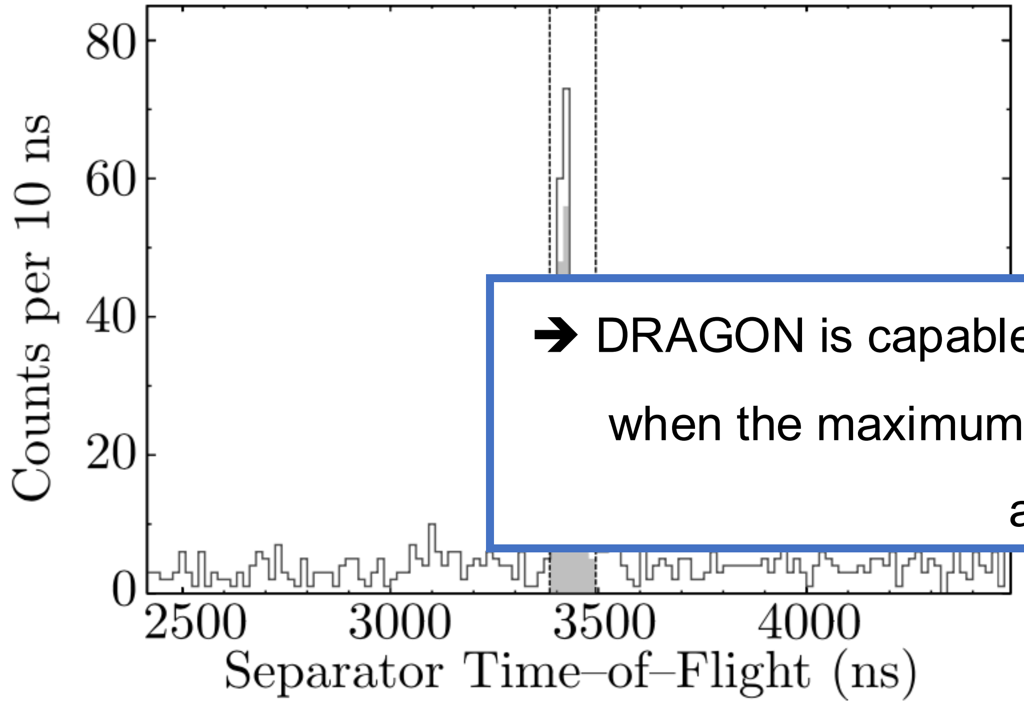

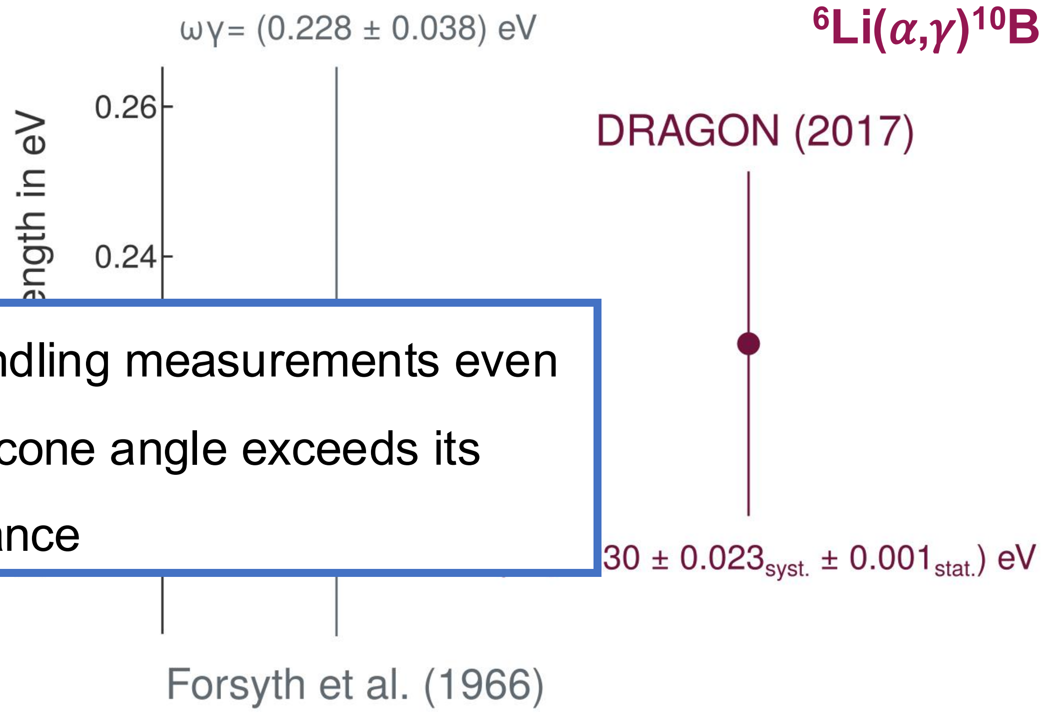

➔ DRAGON is capable of handling measurements even when the maximum recoil cone angle exceeds its acceptance

A. Psaltis et al. - NIMA 987 (2021) 164828

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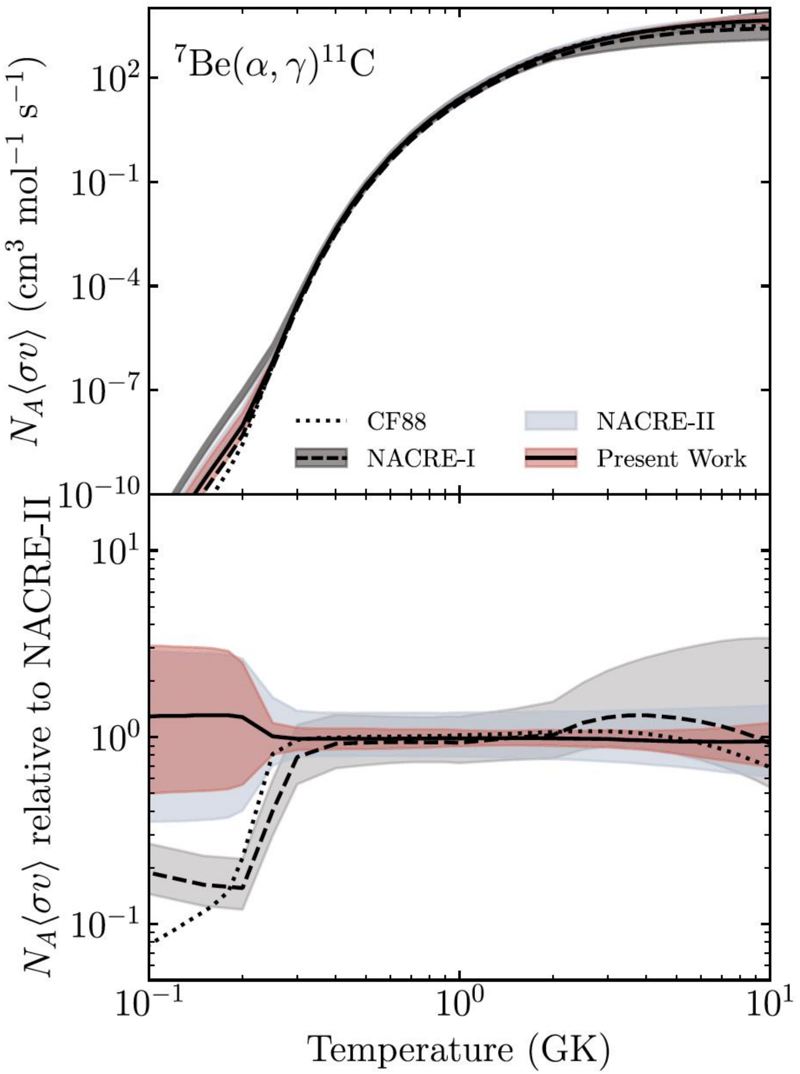
$^{7}Be(\alpha,\gamma)^{11}C$ - Results

- Uncertainty of reaction rate is now ~ 9.4 − 10.7% over T= 1.5–3 GK (relevant temperature window for νp–process nucleosynthesis)
- The new $^{7}Be(\alpha,\gamma)^{11}C$ reaction rate is sufficiently constrained for nucleosynthesis calculations
- **New avenue** for future experiments using DRAGON, that were previously thought to be **inaccessible due to acceptance**

The effect of the rate, along with other measured reactions relevant to nucleosynthesis in neutrino driven winds will be explored in a subsequent study



A. Psaltis et al. - PRL 129, 162701 (2022)
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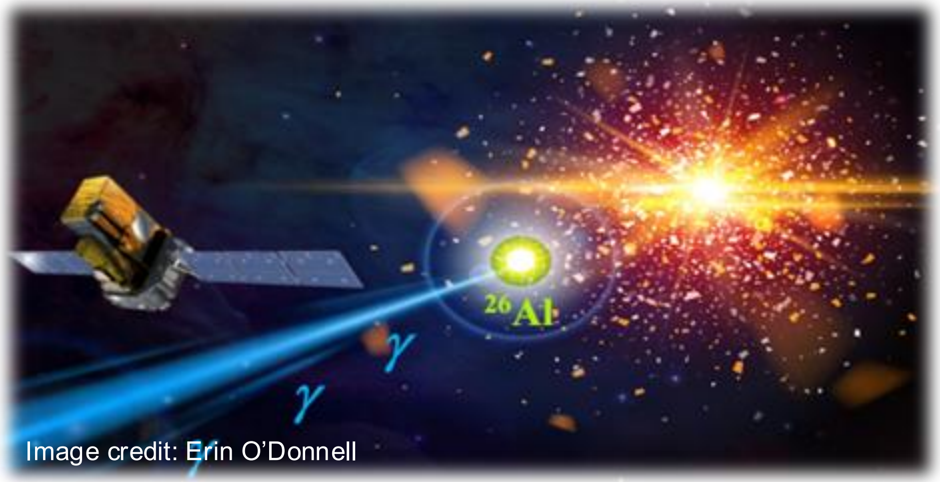
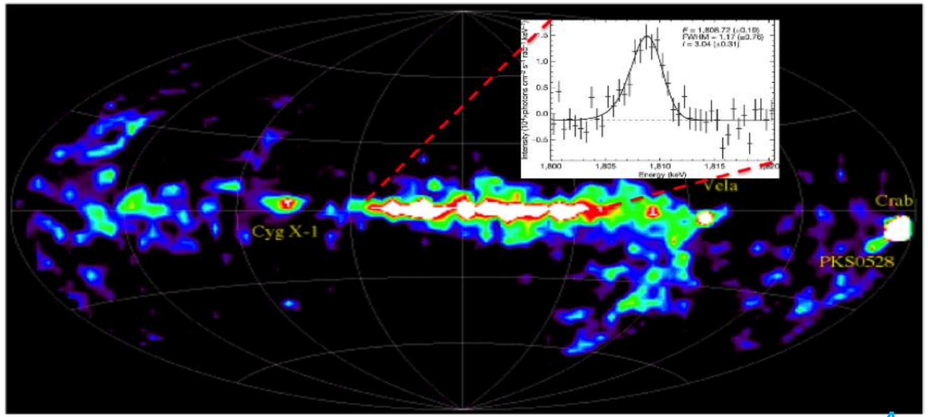
Direct Measurements at DRAGON – Radiative capture on nuclear isomer: ^{26m}Al(p,γ)



The **radioisotope** ^{26}Al provides insight into the **nature of nuclear processes in stars** in the Milky Way.



- Relatively short half-life (0.72 Myr) provided first direct evidence of **active nucleosynthesis** in our Galaxy (1.809 MeV γ-ray)

➔ Tracer for **star formation!**

- ^{26}Mg isotopic excesses in **meteorites**

➔ Early Solar System

Identifying the main sources of ^{26}Al would have far-reaching implications:
- Circumstances & conditions of the solar system birth
- Strong constraints on the chemical evolution of the Galaxy

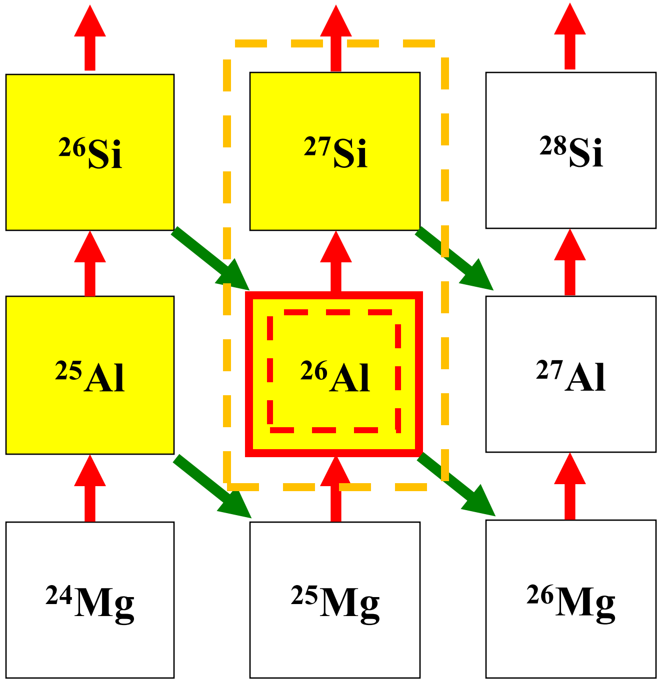
However, it's astrophysical origin is still under debate!

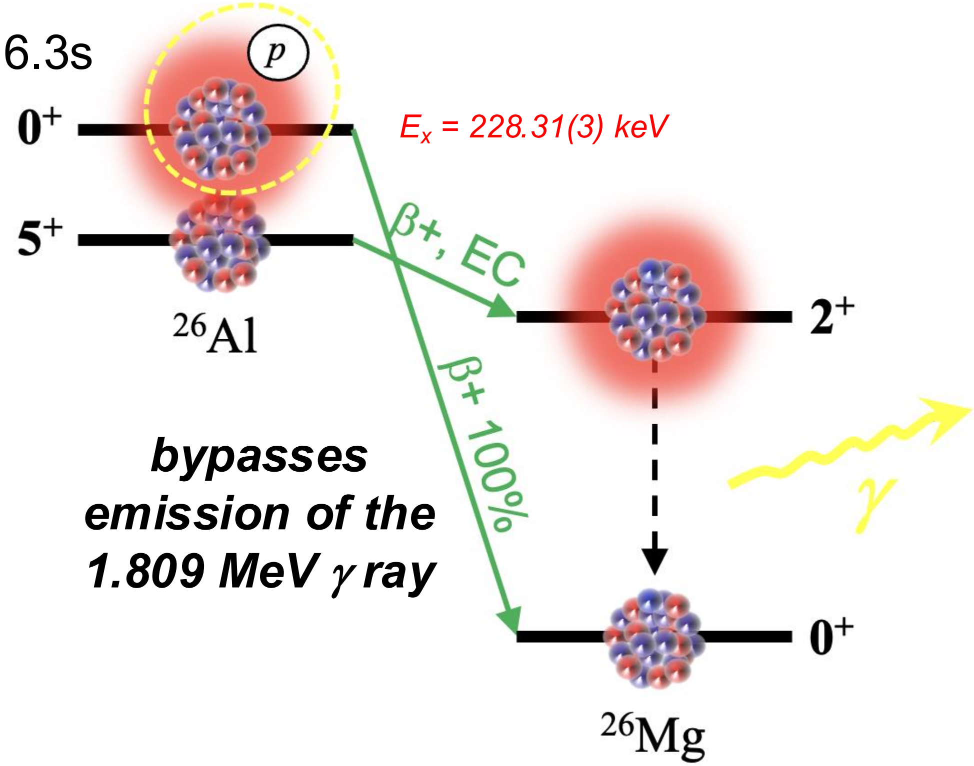
^{26m}Al(p,γ)^{27}Si – Destruction of ^{26}Al

- Previous experiments have focused on reactions on nuclear g.s

*Nucleosynthesis of ^{26}Al is **complicated by the presence of an isomer** (E_x = 228.31(3) keV)*

➔ **Can act as entirely separate nuclei!**

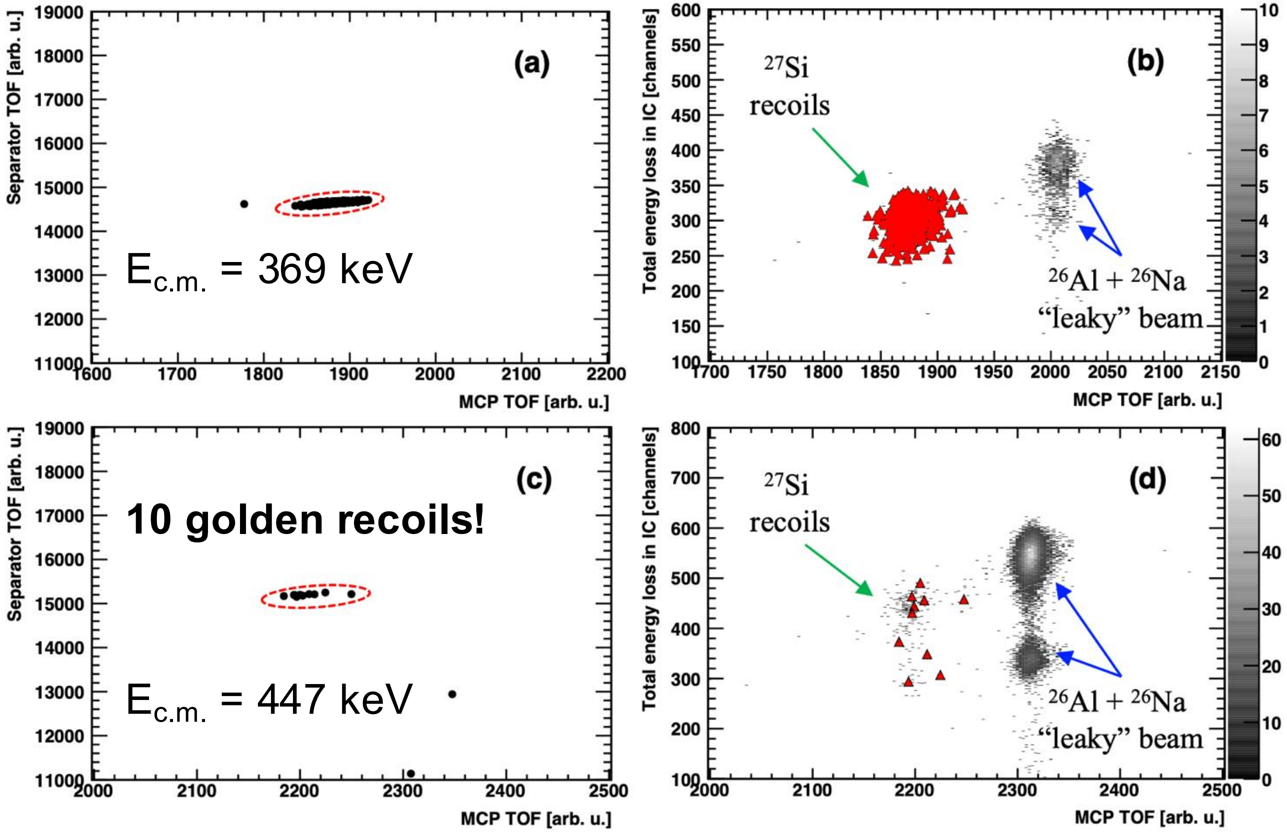


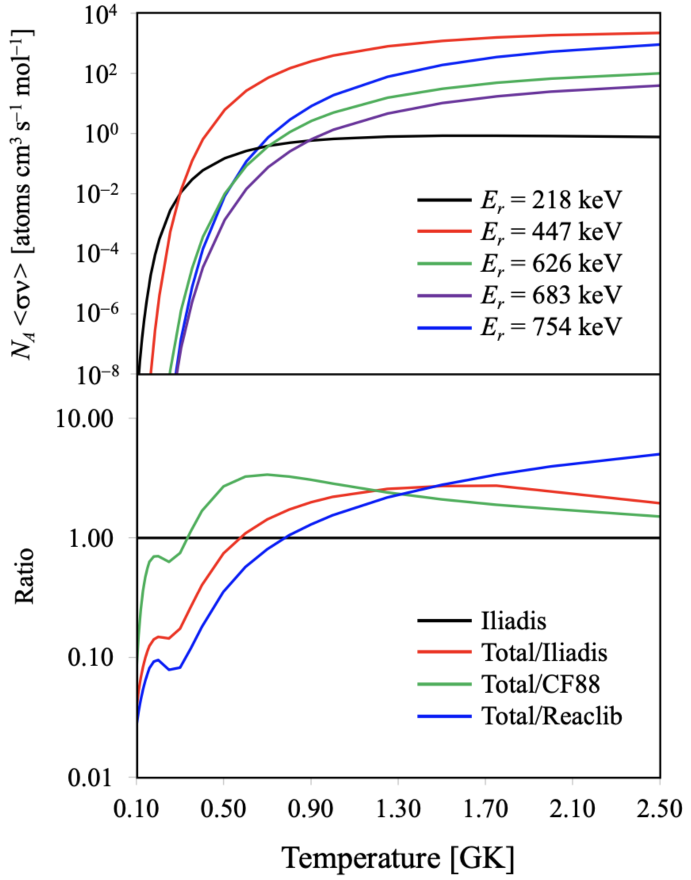


- Proton capture reactions on ^{26m}Al impact all **observational signatures** of ^{26}Al in our universe (directly or indirectly)
- 447-keV resonance thought to **dominate** the entire ^{26m}Al(p,γ) rate for T > 0.3 GK

Direct measurement of ^{26m}Al(p,γ) at DRAGON – Radiative capture on nuclear isomer

G. Lotay, A. Lennarz, C. Ruiz et. al., Phys. Rev. Lett. 128, 042701 (2022)





Reaction	E_r [keV]	N_{inc}	N_{det}	η_{BGO}	η_{MCP}	$\eta_{trans.}$	η_{IC}	η_{CSF}	$\omega\gamma$ [meV]
^{26g}Al + p	369	$1.090(9) \times 10^{13}$	339(18)	0.83(8)	0.99(1)	0.77(1)	0.80(1)	0.40(2)	61 ±8 (stat.) ±6 (sys.)
^{26m}Al + p	447	$6.93(20) \times 10^{10}$	10(3)	0.64(6)	0.99(1)	0.77(1)	0.80(1)	0.37(2)	432 ±137 (stat.) ±51 (sys.)

Acknowledgements

C. Ruiz, M. Alcorta, C. Brune, A.A. Chen, G. Christian, R.J. deBoer, D. Connolly, B. Davids, A. Edwin, L. Enrique Charon, U. Greife, D. Hutcheon, A. Katrusiak, A. M. Laird, A. Lennarz, M. Loria, G. Lotay, P. Machule, L. Martin, S. Paneru, A. Parikh, A. Psaltis, B. Reed, A. Shotter, S. Upadhyayula, L. Wagner, M. Williams

Outlook for DRAGON & TUDA

Plans for 2025…

- $^{7}Be(p,\gamma)^{8}B$ (DRAGON, solar ν spectrum)
- ^{11}B Charge-state distributions
- $^{18}F(p,\alpha)^{15}O$ *(TUDA*, novae*)*

More data under analysis…

- $^{14}N(p,\gamma)$ – CNO cycle, solar abundance
- $^{15}N(\alpha,\gamma)^{19}F$
- $^{19}F(p,\gamma)$
- $^{18}O(\alpha,\gamma)^{22}Ne$
- $^{39}K(p,\gamma)$ – globular clusters
- $^{22}Ne(\alpha,\gamma)/^{22}Ne(\alpha,n)$– s-process
- $^{20}Ne(p,\gamma)$

On the books…

- $^{15}O(\alpha,\gamma)^{19}Ne$ (DRAGON, Ignition of Type I XRB)
- Explore (α,n) reactions in weak r-process regime (DRAGON, DEMAND)
- $^{22}Na(p,\gamma)^{23}Mg$ (γ-ray emitter)
- $^{35}Ar(p,\gamma)^{36}K$ (DRAGON, rp-process in Type I XRB)
- $^{18}Ne(\alpha,p)^{21}Na$ (TUDA - X-ray bursts)
- $^{11}C(p,p)^{11}C$ (TUDA - Pop III)
- $^{7}Be(\alpha,\alpha)^{7}Be$ & $^{7}Be(p,p)^{7}Be$ (DRAGON, SONIK)
- $^{18}Ne(d,p)^{19}Ne$ & $^{18}Ne(\alpha,p)^{21}Na$ (TUDA, novae, XRB)
- $^{20}Ne(\alpha,\gamma)$

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Thank you
Merci

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