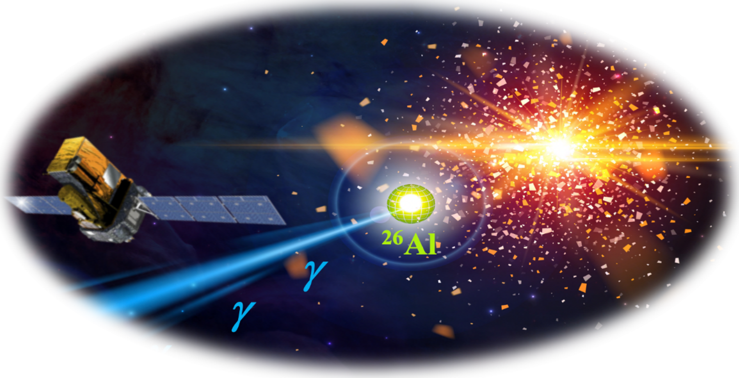
Direct measurements of astrophysically important reactions using rare isotope beams at TRIUMF

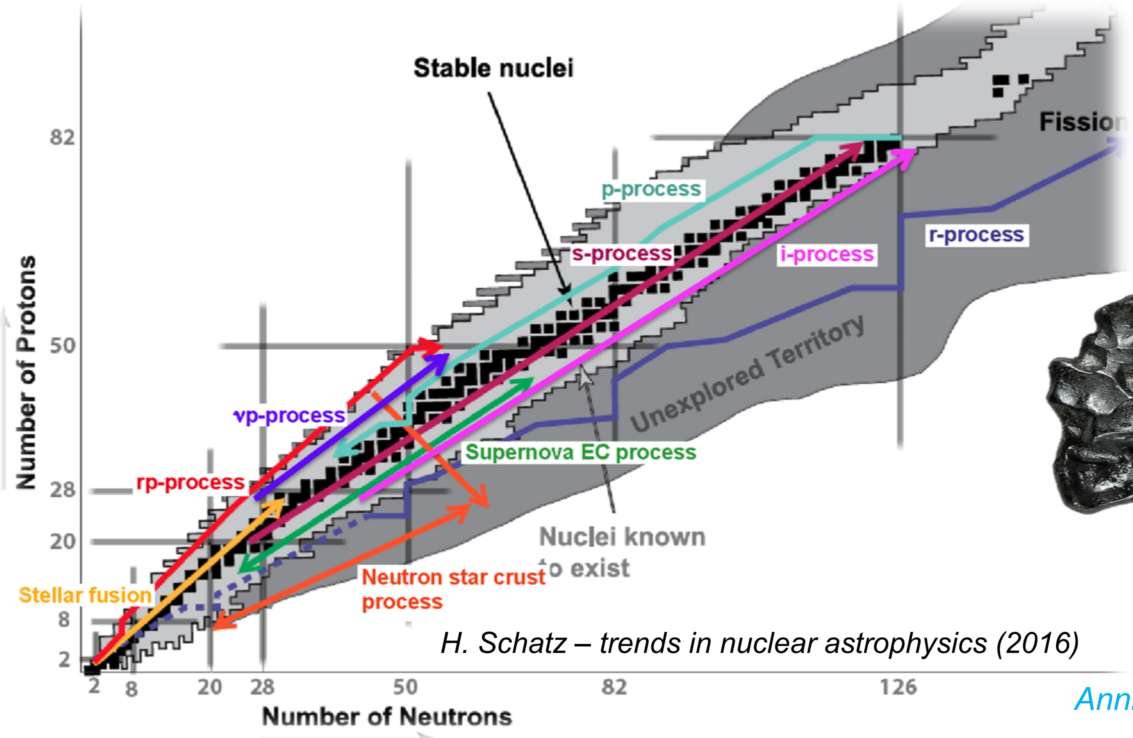
Annika Lennarz
Division of Physical Sciences | TRIUMF
on behalf of the DRAGON collaboration

**Advances in Radioactive Isotope Science - ** June 4-9, 2023

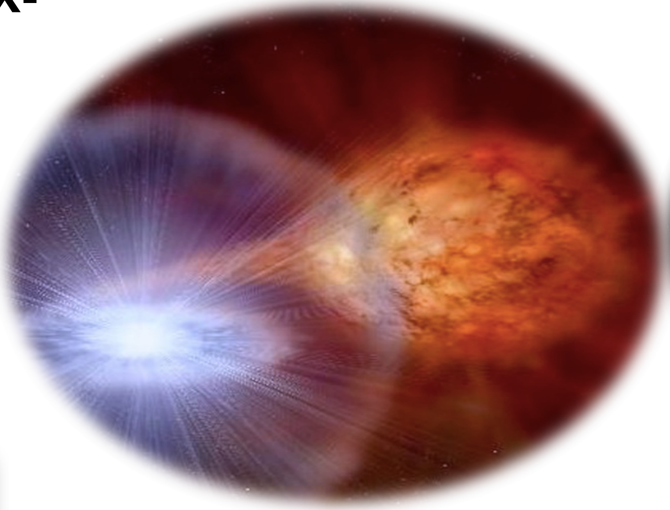


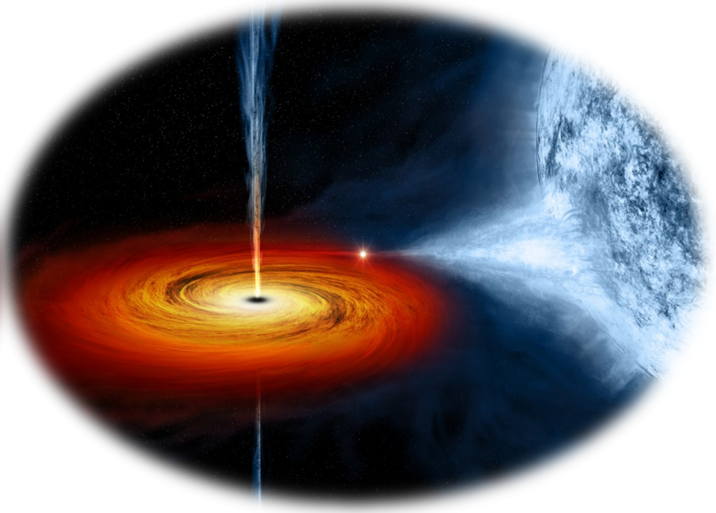
Key question: Origin of the chemical elements?

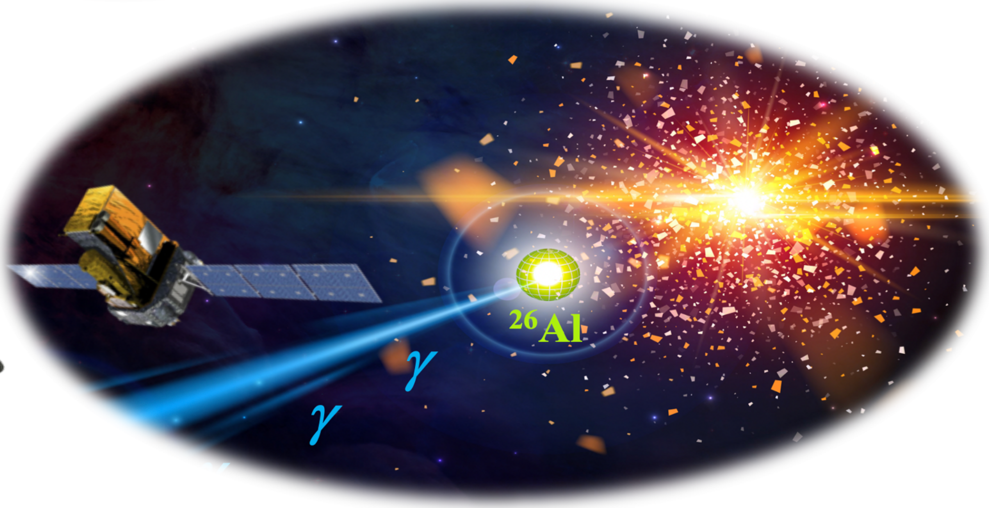
- Astronomical events like **supernovae**, **novae or X-ray bursts** leave imprints in form of **chemical elements**
- *Nature and role of nuclear reactions that govern* ***energy release*** *&* ***nucleosynthesis*** *path in explosive scenarios?*



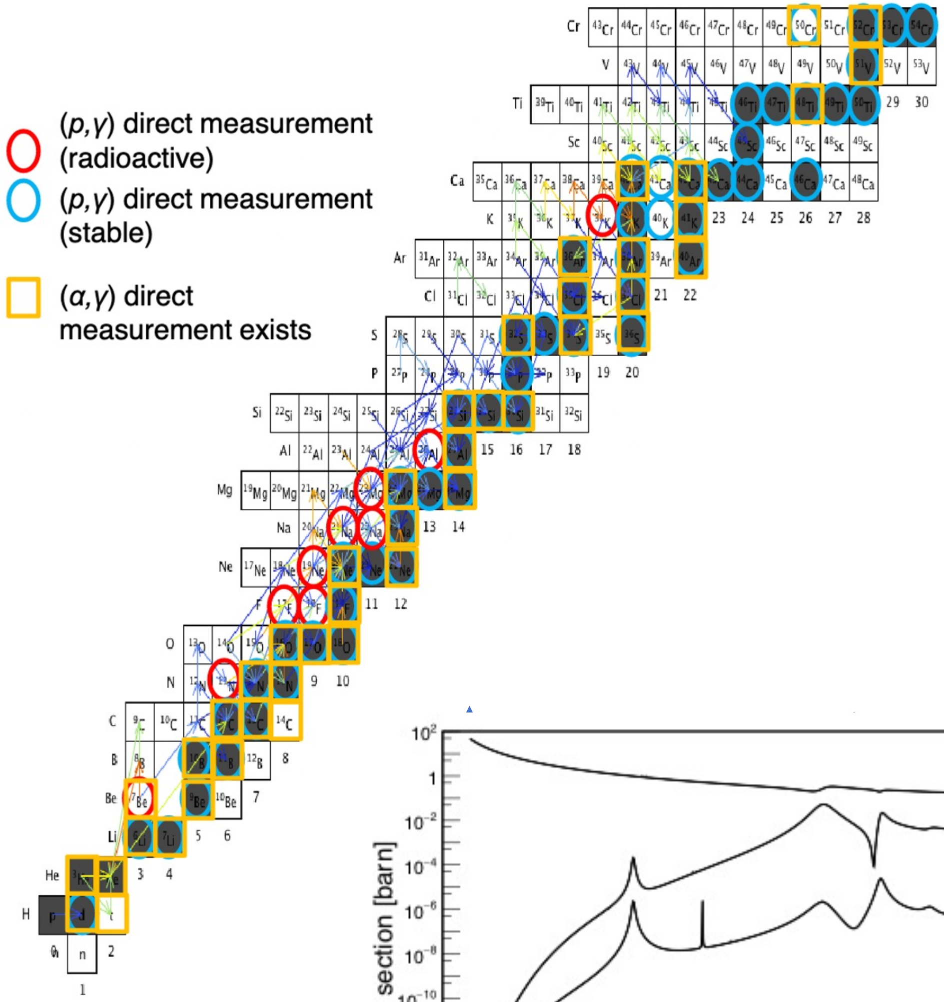
H. Schatz – trends in nuclear astrophysics (2016)

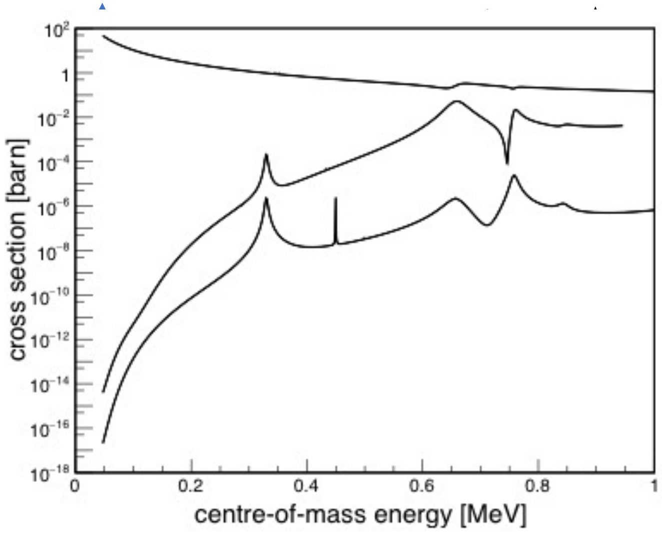






Radiative Capture Reactions





- Fusion of nucleus with one or more nuclei via emission of electromag. radiation:
- Occurs **directly** into bound state or via particle unbound states (**resonant**)
- **Influential in nuclear astrophysics**
- pp-chains, CNO cycle, explosive nucleosynthesis in novae, X-ray bursts, supernovae

- p- & α-induced reactions with positive Q-value

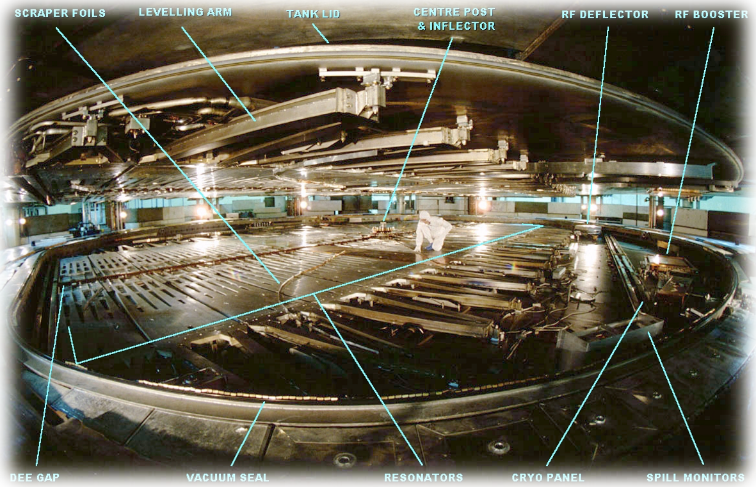
➔ Knowledge important for reaction pathways!
- Proceed relatively slowly, thus **rate-limiting** step in reaction pathways

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

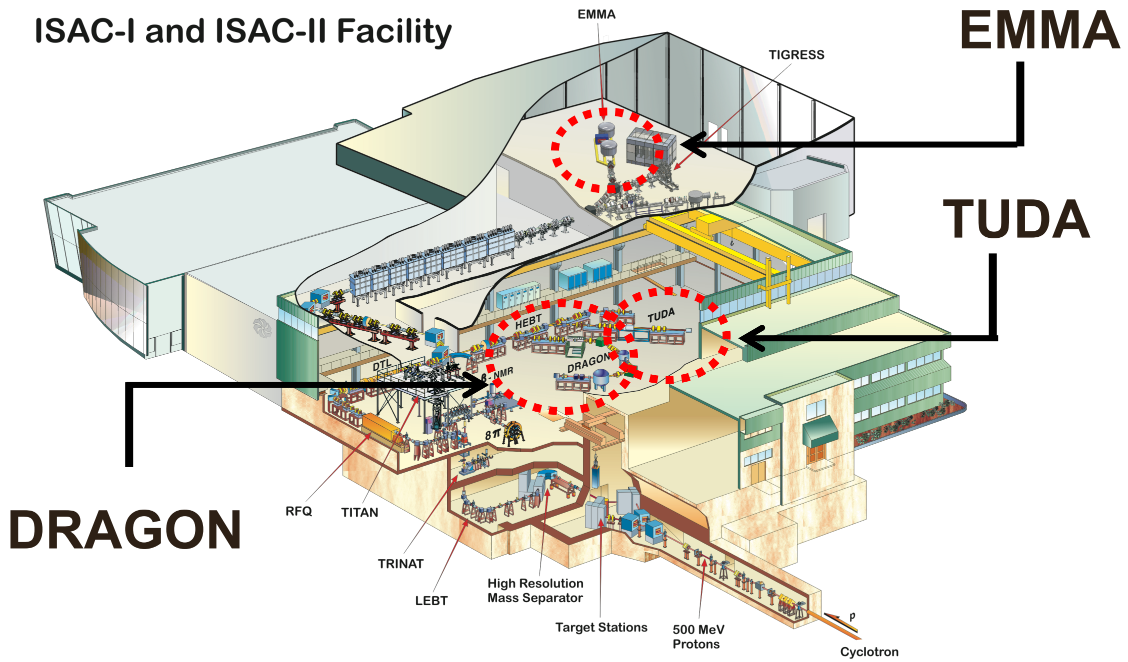
  → **Need intense beams, low background, long run times, feasible targets, …**

TRIUMF/ISAC

- Production of rare ion beams
- TRIUMF: Canada's particle accelerator center
- Irradiation of thick production target with proton beam
- Generated in sector-focused H$^-$ cyclotron (23 MHz)



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



- Beams re-accelerated through 35 MHz RFQ with A/q<30
- 105 MHz variable energy DTL (3 ≤ A/q ≤ 6)
- Energies between 0.15 MeV/u & 1.8 MeV/u
- Low-energy regime well suited for reaction studies for novae & X-ray bursts

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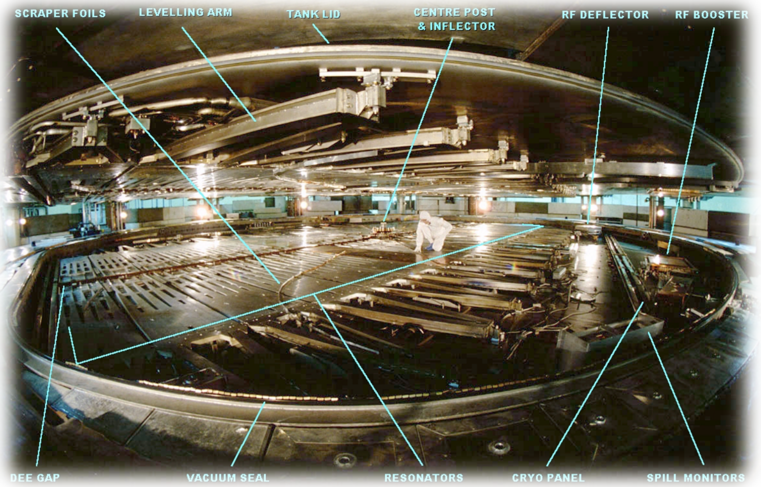
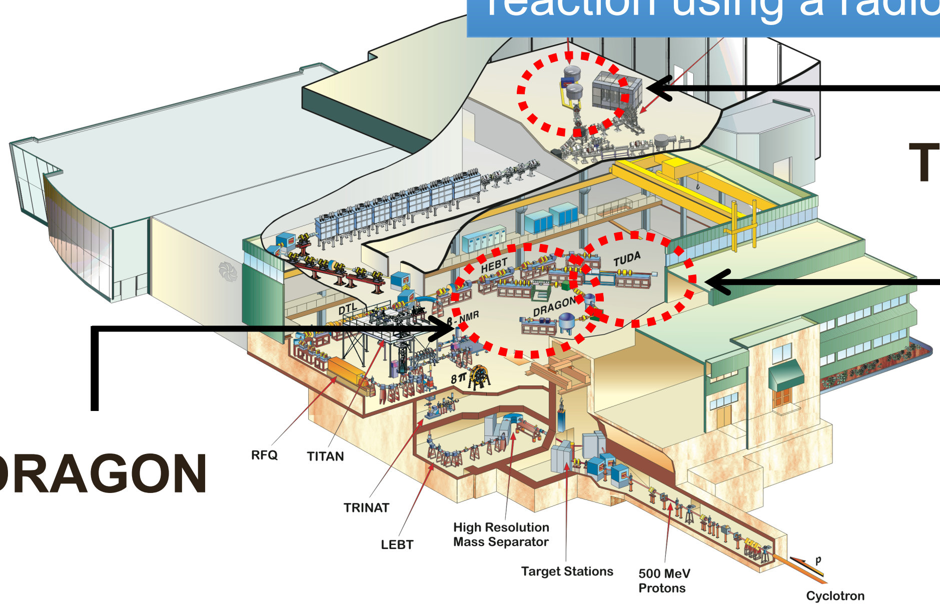


500 MeV proton beam

μA (~5000 hrs/year)

^{83}Rb(p,γ)^{84}Sr - "First measurement of a p-process reaction using a radioactive ion beam" – M. Williams

ISAC-I and ISAC-II Facility



TUDA

DRAGON

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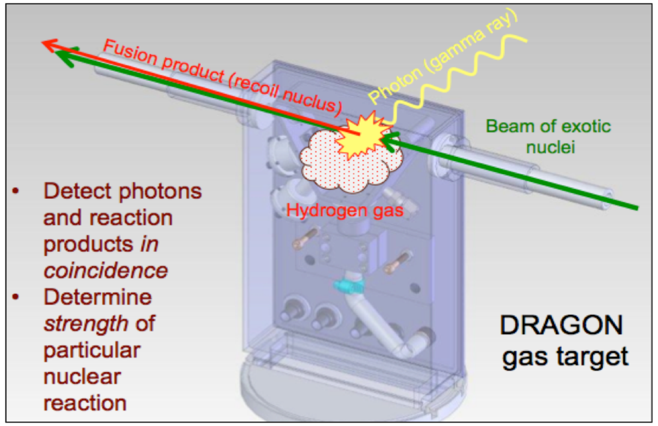
DRAGON – Detector of Recoils and Gammas of Nuclear Reactions

① Windowless gas target

② BGO γ-detection array

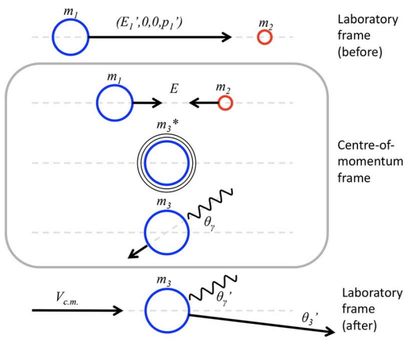
③ MEME mass separator

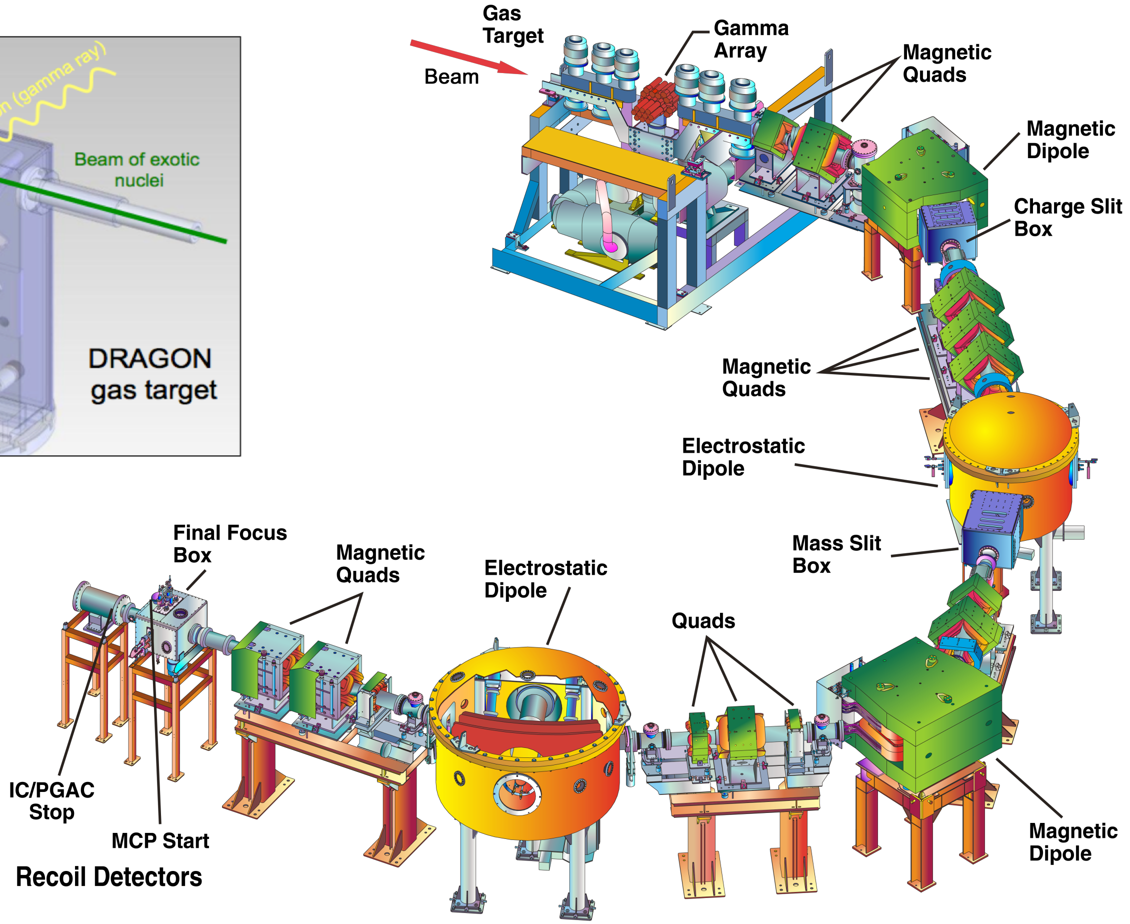
④ Recoil detection system



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

#reactions per incident ion

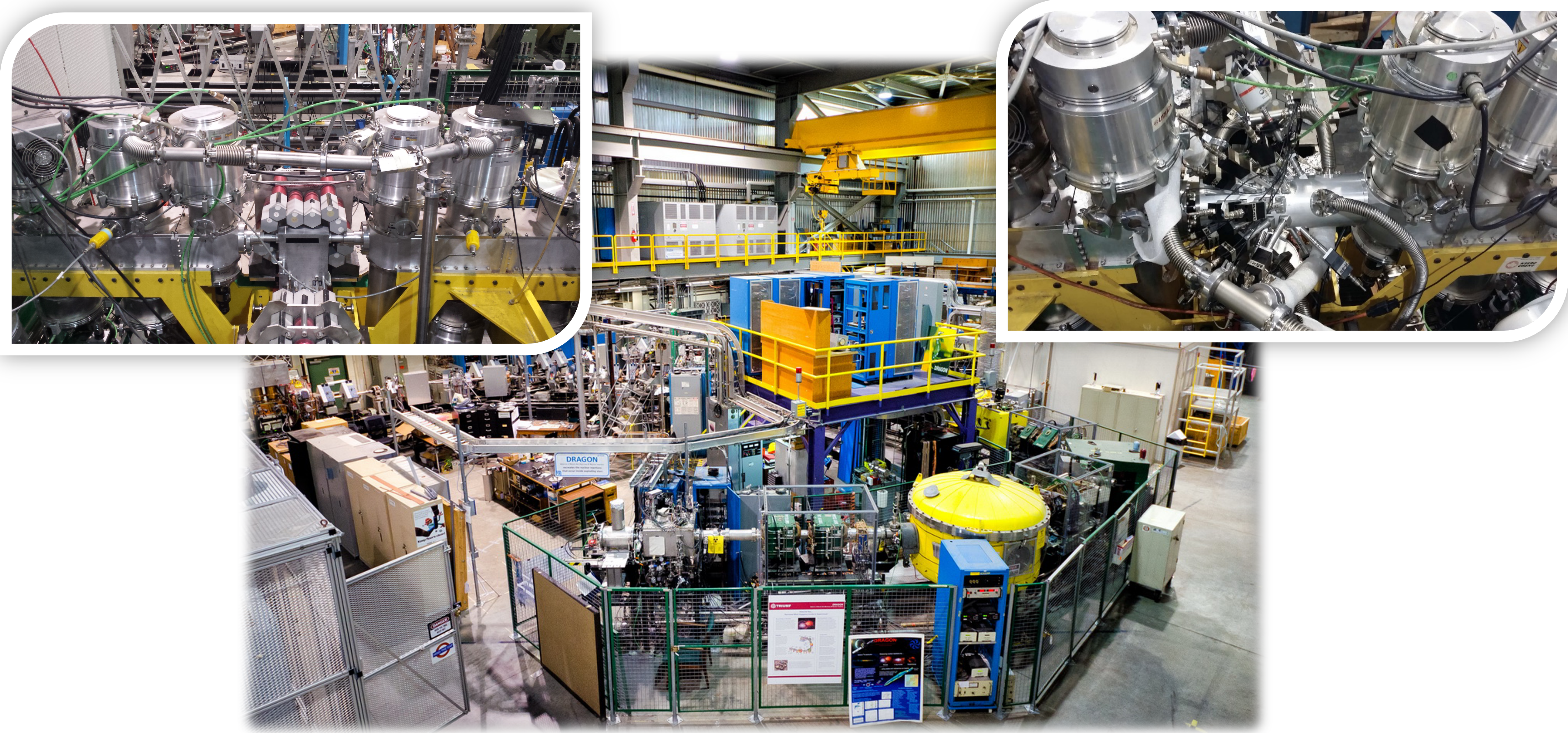




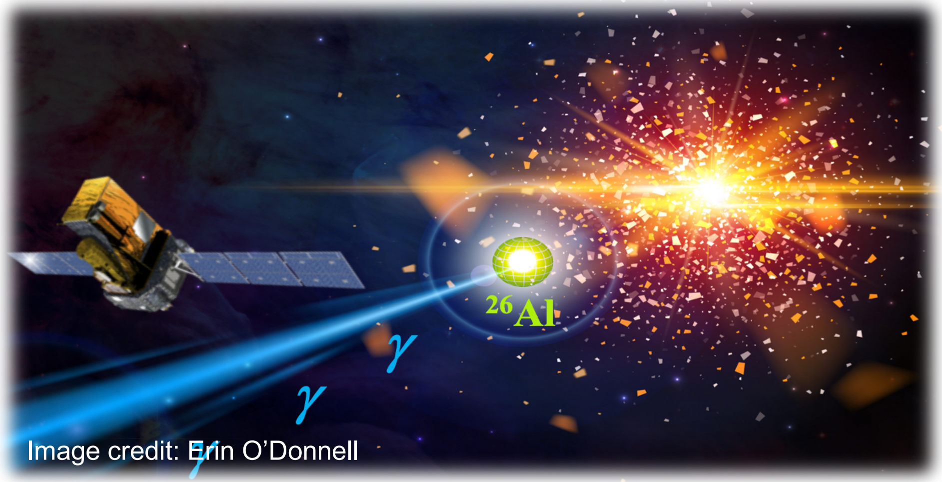
$$\boxed{N_A\langle\sigma v\rangle = 1.54\times 10^{11}\left(\mu T\right)^{-3/2}\omega\gamma\cdot\exp\left(-11.605\,\frac{E_R}{T_9}\right)}$$

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

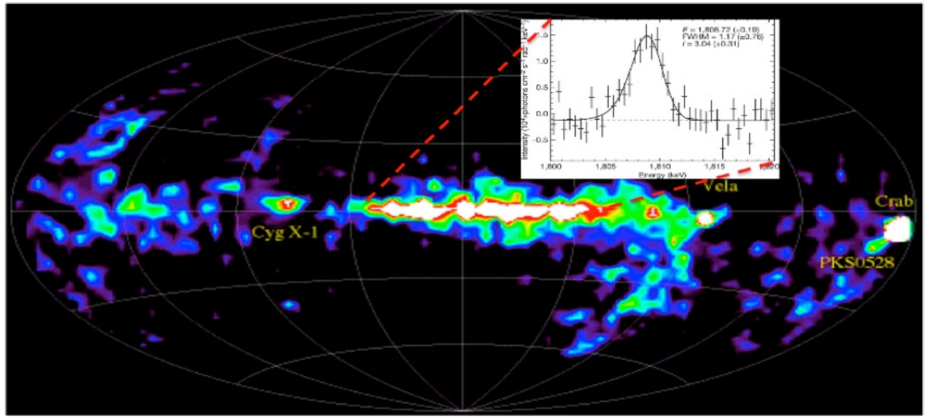
DRAGON



Cosmic γ-ray emitter ^{26}Al



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 <u>**active**</u> 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!

The astrophysical origin of ^{26}Al

*Need to understand **production & destruction of ^{26}Al** in stellar scenarios!*

- Experimental physics has focused on reactions on nuclear ground states

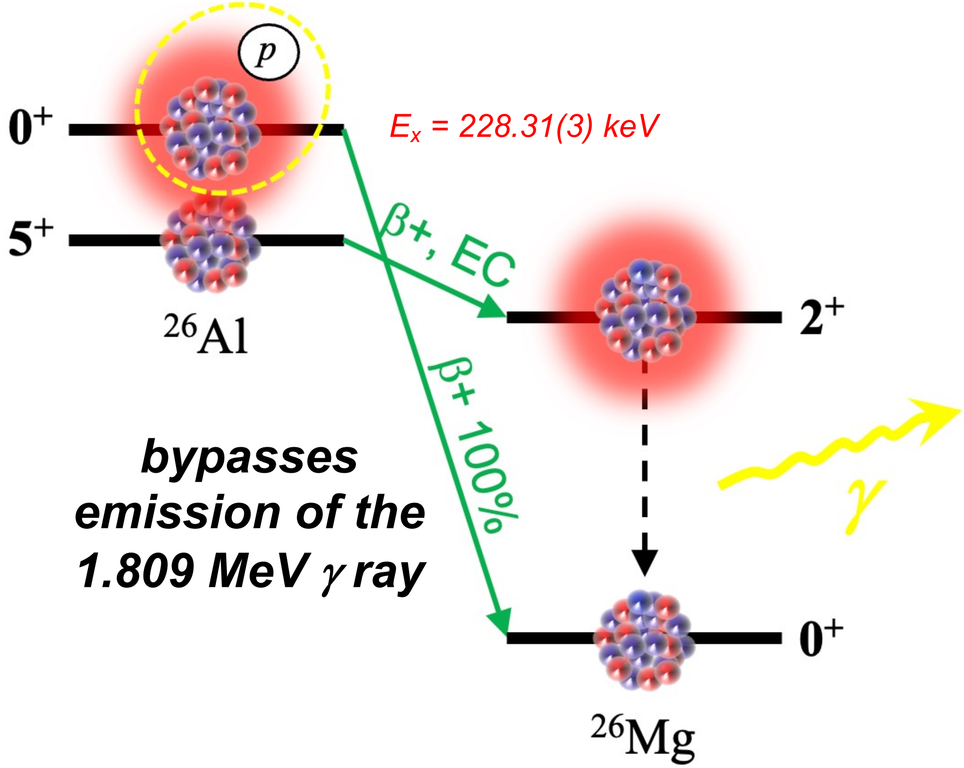
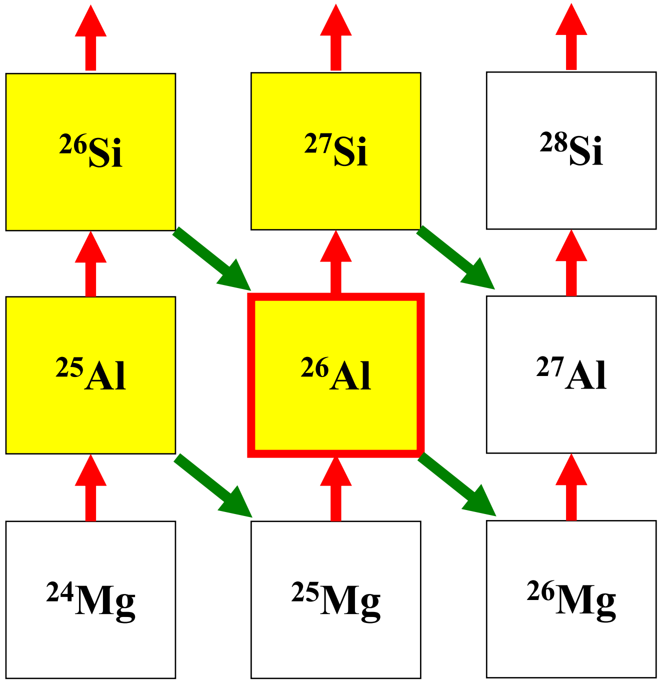
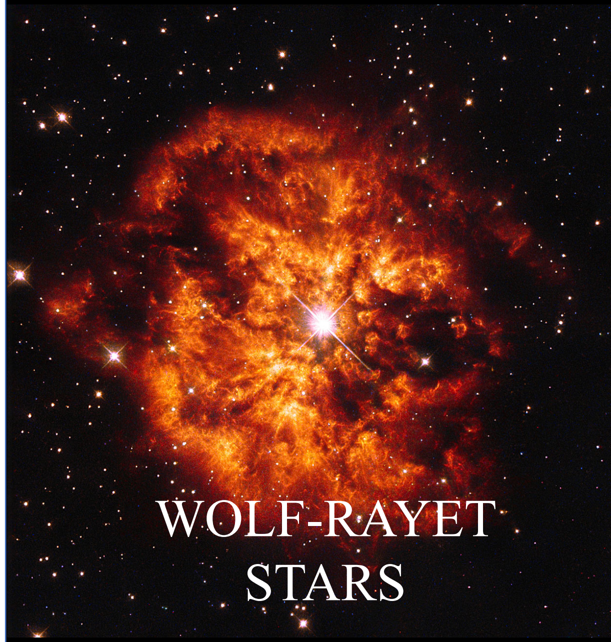


Figure from G. Lotay

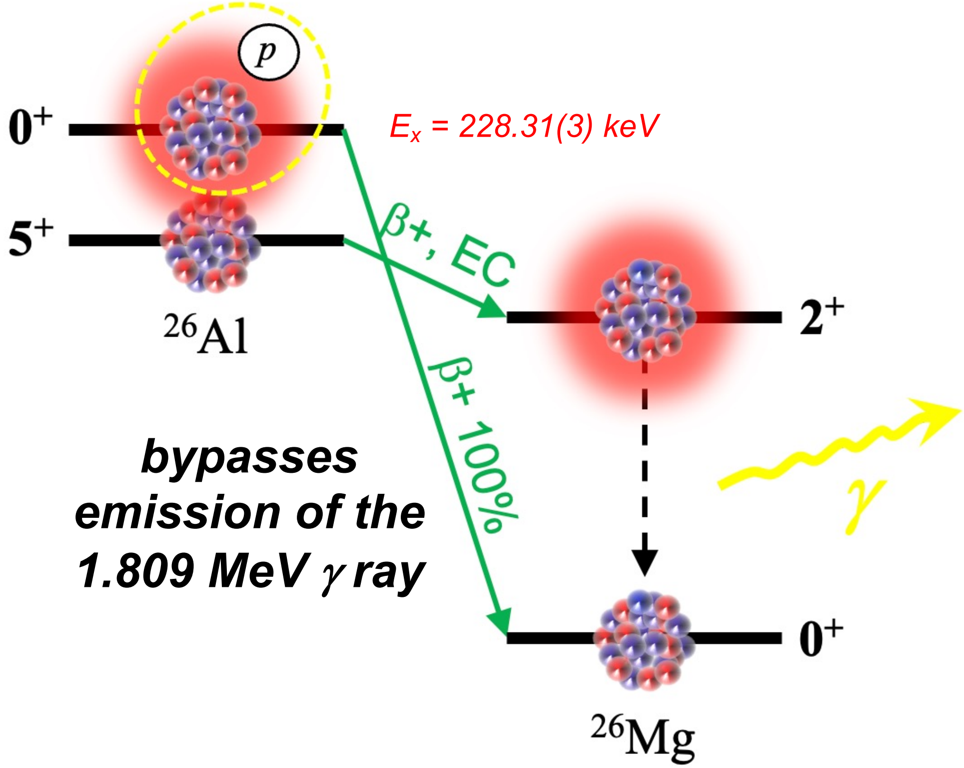




The astrophysical origin of ^{26}Al

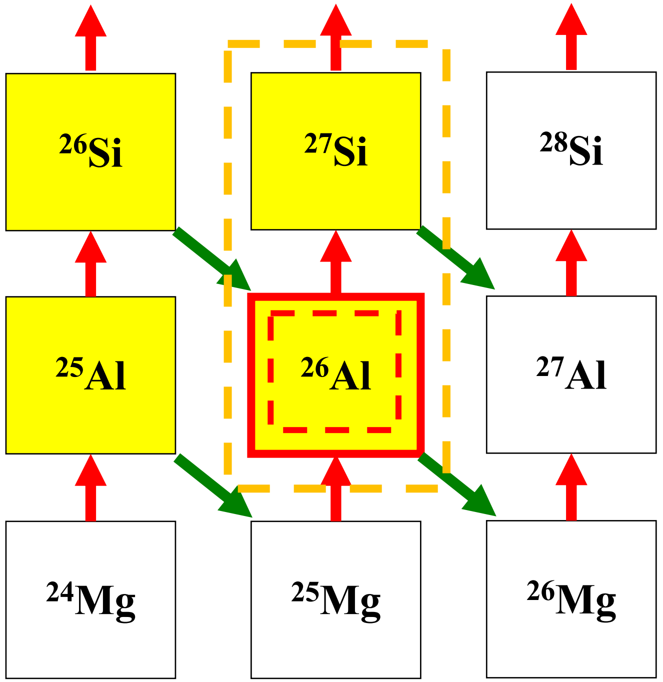
Nucleosynthesis of ^{26}Al is ***complicated by the presence of an isomer*** *(E_x = 228.31(3) keV)*

Can act as entirely separate nuclei!



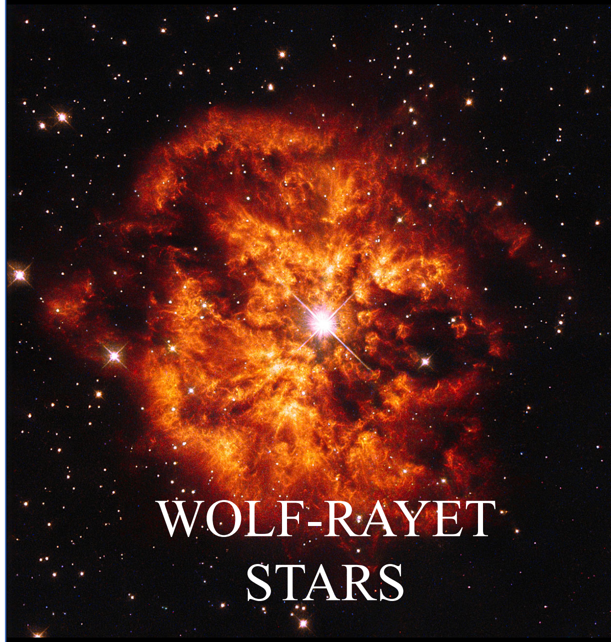
bypasses emission of the 1.809 MeV γ ray

Figure from G. Lotay

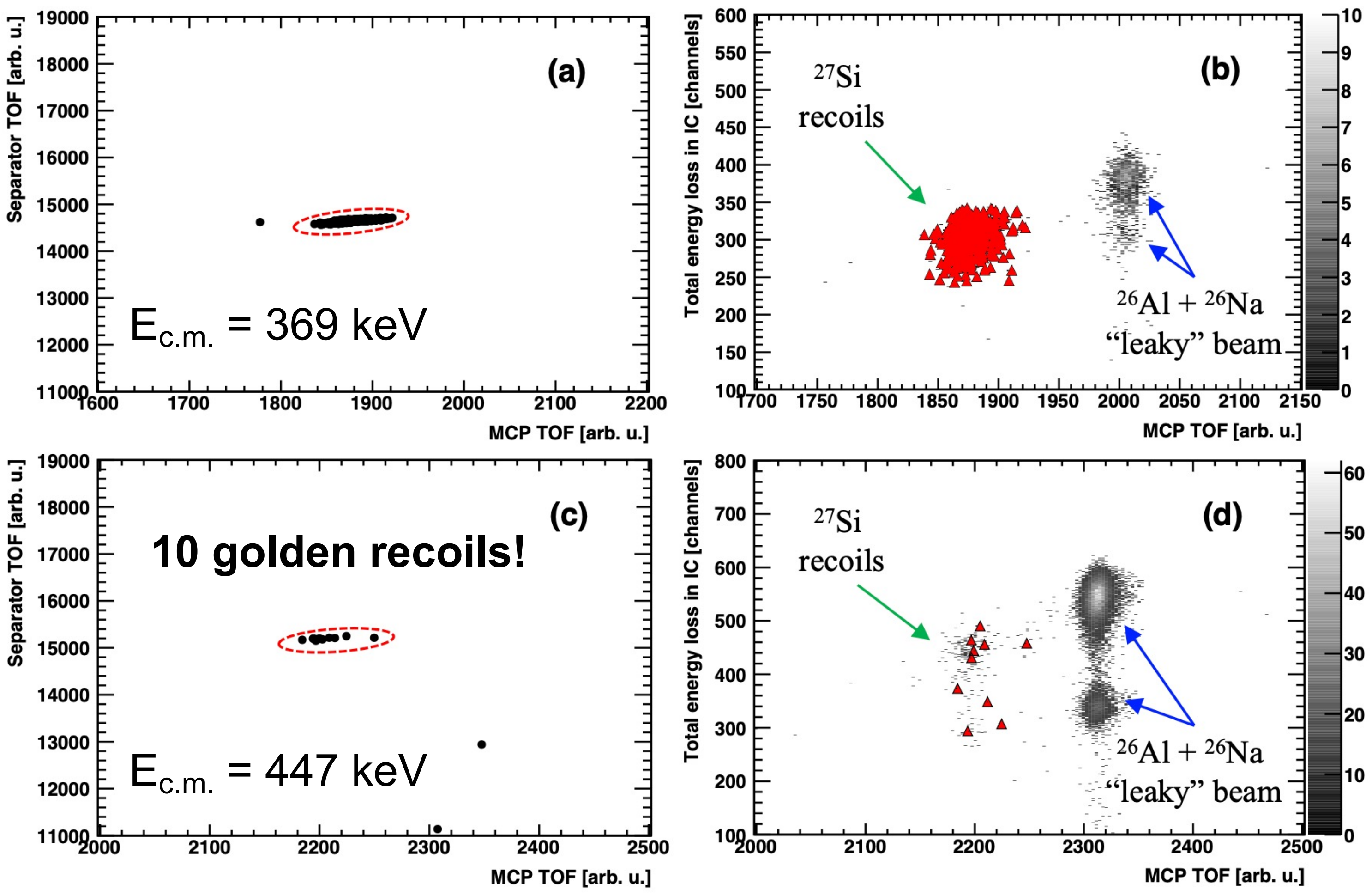


➔ Need to measure proton capture on excited quantum state of ^{26}Al

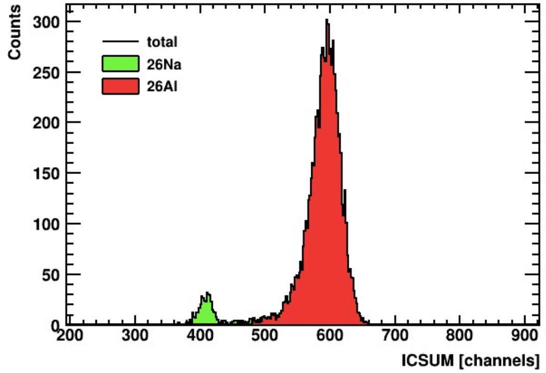
EXPERIMENTAL CHALLENGE



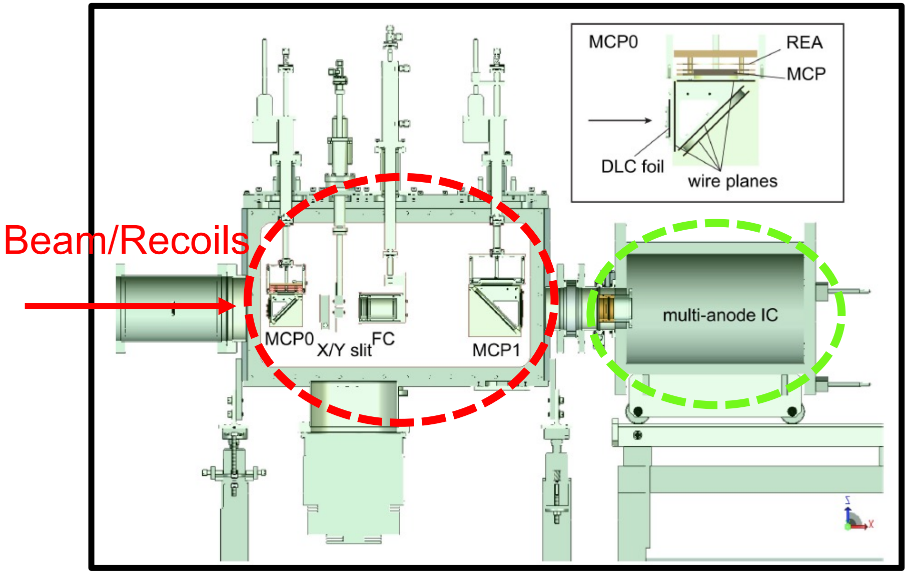
Radiative capture on nuclear isomer – Direct measurement of ^{26m}Al(p,γ) at DRAGON



Incoming beam composed of ^{26m}Al, ^{26g}Al, ^{26}Na



DRAGON end detector system



Used Ionization chamber & MCPs for recoil detection

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

Results

- **Reference** resonance: $\omega\gamma$(369keV) = 61 +/- 8(stat.) +/- 6(sys.) meV (singles & coincidence analysis in good agreement). **Good agreement** with previous measurements ➔ Verifies exp. methodology.
- **Off-resonance** measurements were taken at a beam energy of 484 A keV

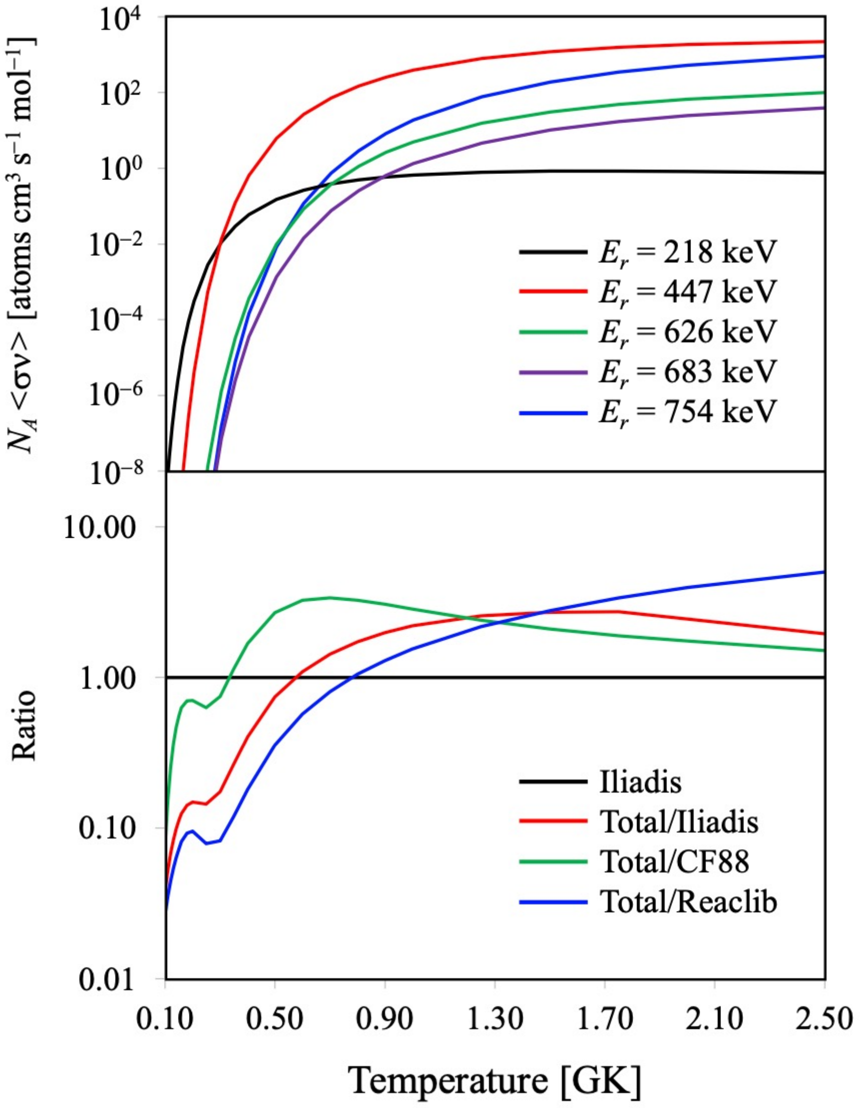
  ➔ **No coincident events** were observed in those data runs, confirming zero background counts in the region of interest.
- **Strength** for 447 keV resonance is **high!** Consistent with constraints given in Hallam, Lotay et al. (PRL126, 2021)

TABLE I: Summary of parameters used for the determination of resonance strengths. The values N_{inc} and N_{det} represent the number of incident particles and number of detected events, respectively, while the parameters η_{BGO}, η_{MCP}, $\eta_{trans.}$, η_{IC} and η_{CSF} correspond to the BGO array, MCP, transmission, ionization chamber and charge state fraction efficiencies.

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.)

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

Conclusions – contribution to reaction rate



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

➔ With present result for ωγ, **$E_{c.m.}$ = 447 keV resonance** governs the entire ^{26m}Al(p,γ) stellar reaction rate over the peak temperature range of classical novae and supernovae

- *But, keep in mind, strengths of resonances in ^{26m}Al + p with E_r > 447 keV remain uncertain*

➔ *could still increase the overall ^{26m}Al(p,γ) rate considerably at high temperatures!*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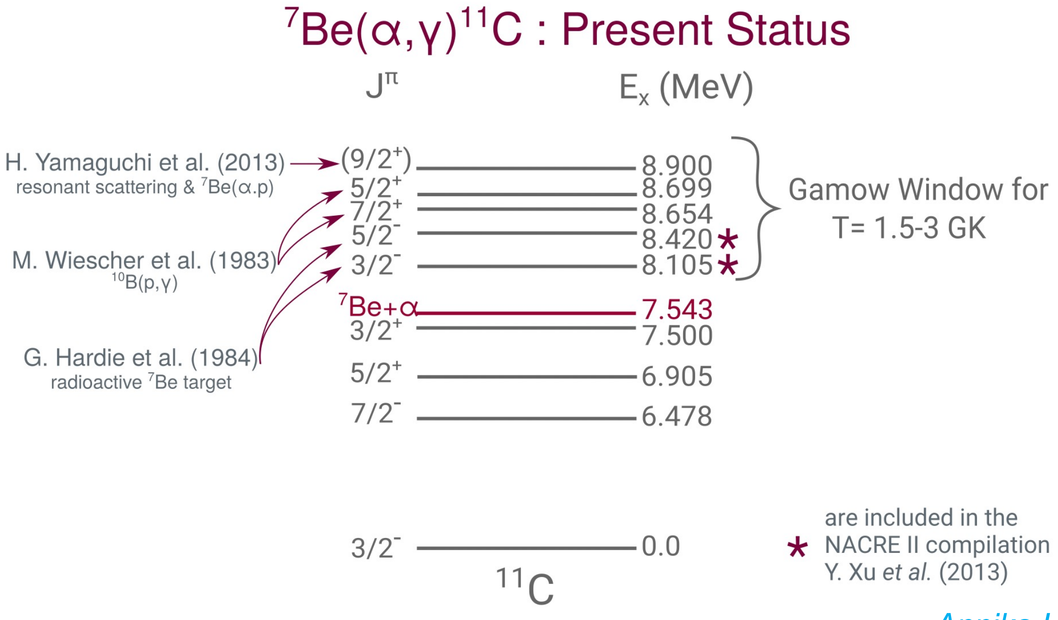
Radiative Capture on Nuclear Isomers: Direct Measurement of the $^{26m}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$ Reaction

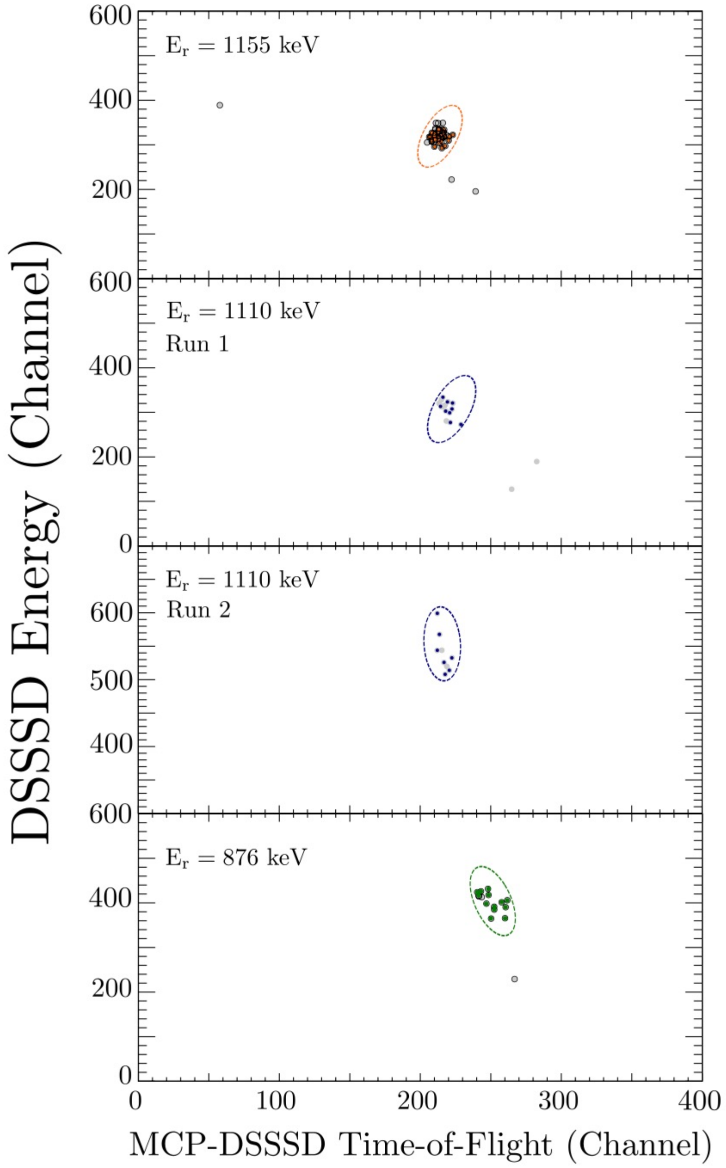
G. Lotay, A. Lennarz, C. Ruiz, C. Akers, A. A. Chen, G. Christian, D. Connolly, B. Davids, T. Davinson, J. Fallis, D. A. Hutcheon, P. Machule, L. Martin, D. J. Mountford, and A. St. J. Murphy

Phys. Rev. Lett. **128**, 042701 – Published 27 January 2022

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

- Breakout reaction from pp-chains to CNO cycle
- Affects proton-to-seed ratio in early νp-process in **CCSN**
- DRAGON performed first measurement of the E_r = 1155 & 1110 keV resonances + confirmed 2 known strengths
- Uncertainty of reaction rate is now ~ 9.4 − 10.7% over T= 1.5–3 GK (relevant temperature window for νp–process nucleosynthesis)





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

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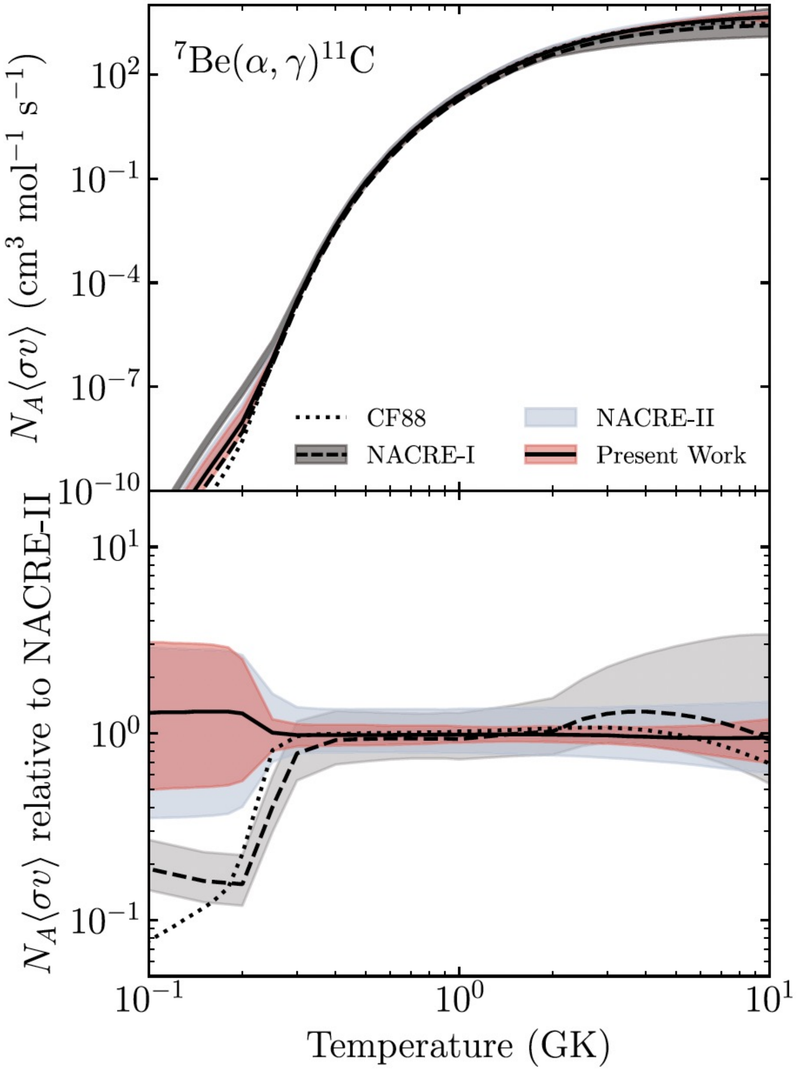
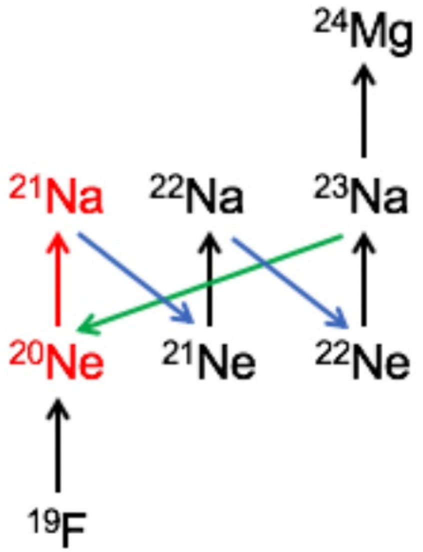


Conclusions:

- The new $^7Be(\alpha,\gamma)^{11}C$ reaction rate is sufficiently constrained for nucleosynthesis calculations
- Does not significantly affect production of neutron-deficient heavy elements (p-nuclei)
- **New avenue** for future experiments using DRAGON, that were previously thought to be **inaccessible due to acceptance**

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

Study of the ^{20}Ne(p,γ)^{21}Na reaction rate



NeNa cycle & **^{22}Na production**

^{20}Ne(p,γ)^{21}Na(β+)^{21}Ne(p,γ)^{22}Na

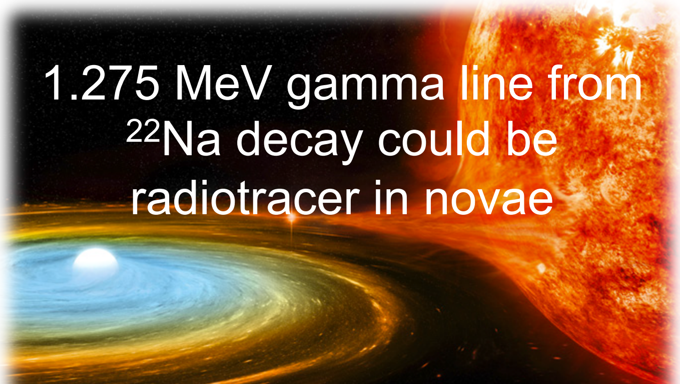


Image credit: NASA/CXC/M.Weiss

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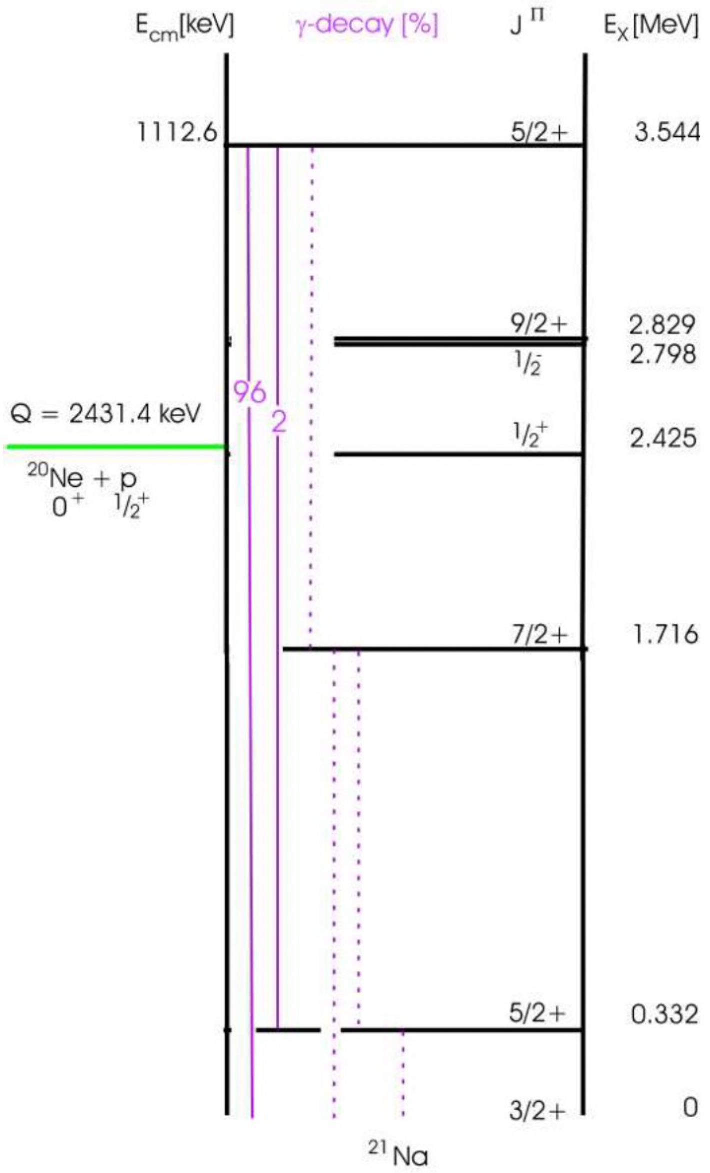
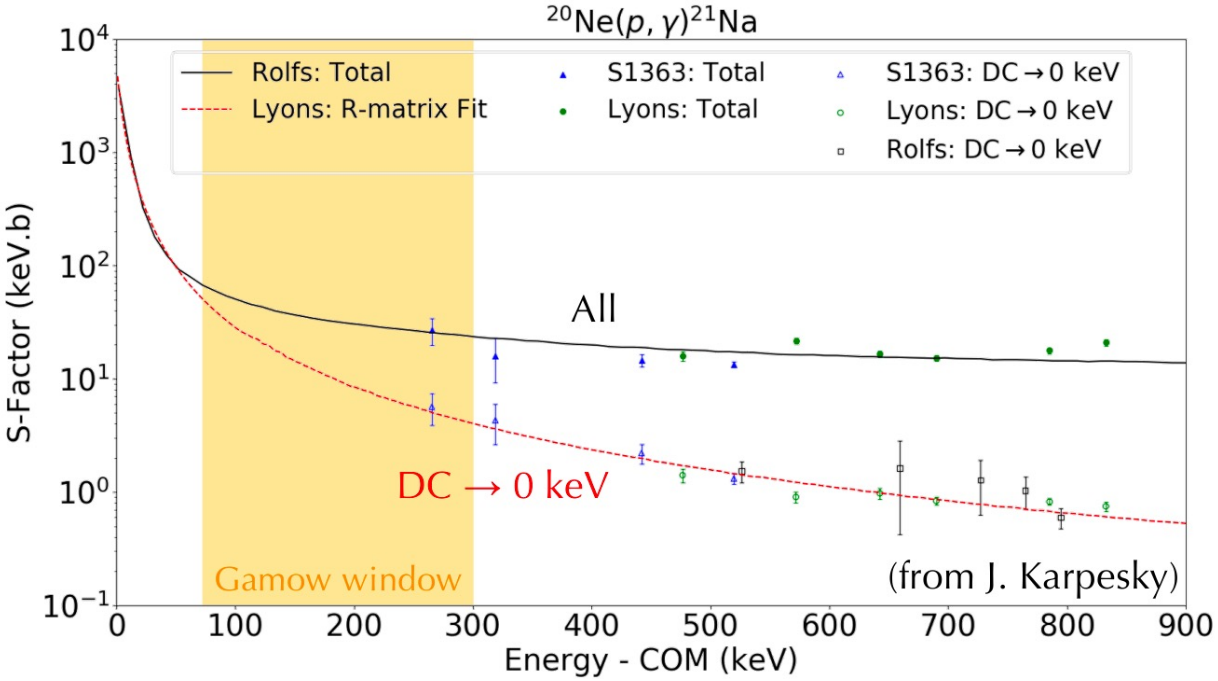
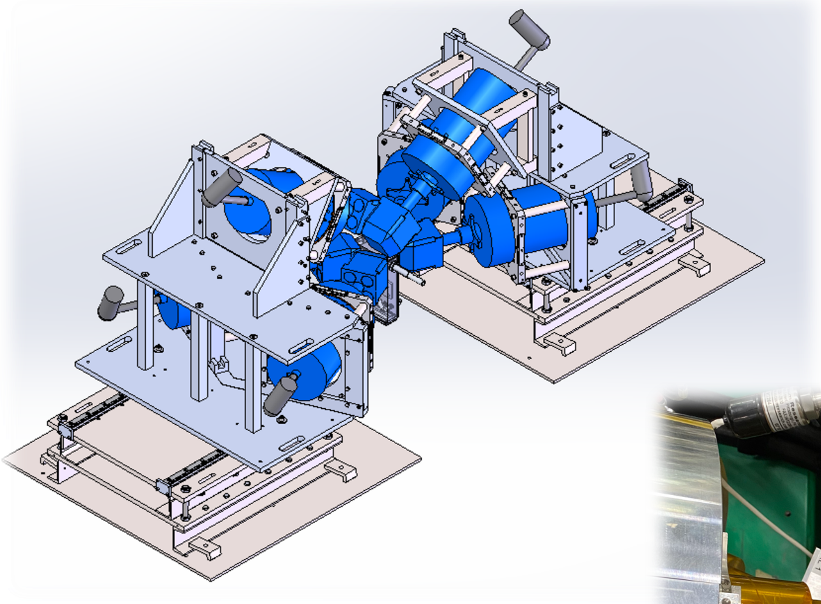




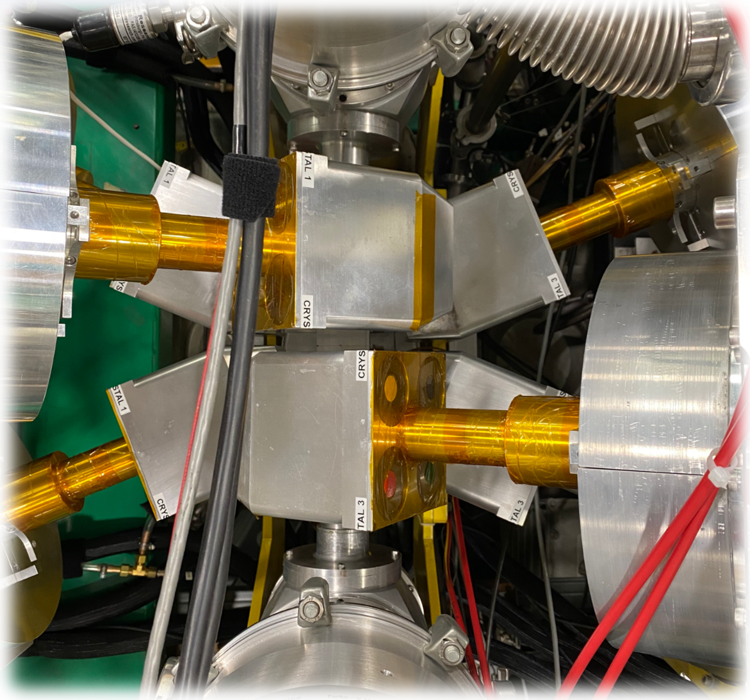
- Rate thought to be dominated by state in ^{21}Na ~7 keV below S_p
- Need improved energy resolution ➔ distinguish between individual contributions:
  - direct capture to 1/2+ state + γ-decay to g.s.
  - resonant capture in tail then γ-decay g.s.
- No data for DC→2424 keV or DC→332 keV (target Gamow window)

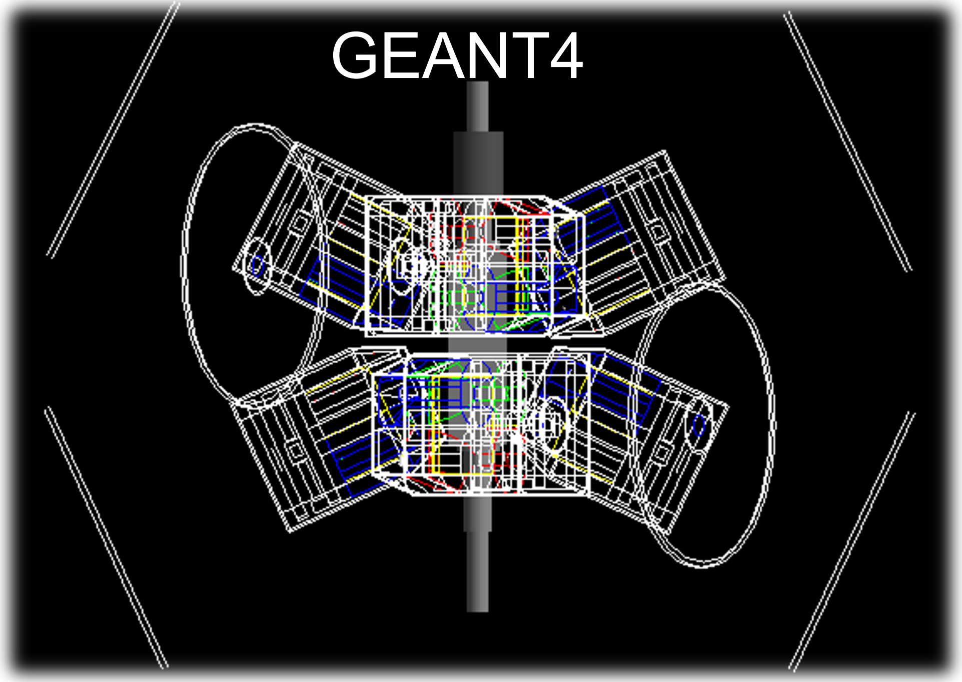
Proposal by Greife, Sarazin, Ruiz *et al.*

GRIFFIN HPGe detectors at DRAGON gas target

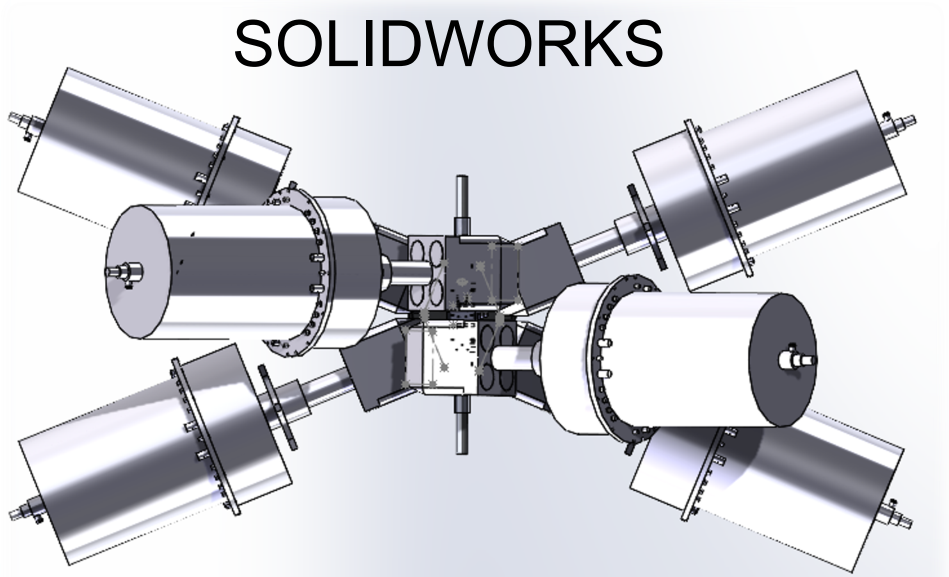


Temporarily replaced BGO array with GRIFFIN HPGe detectors





DRAGON & GRIFFIN DAQs Merged for coincidence measurements

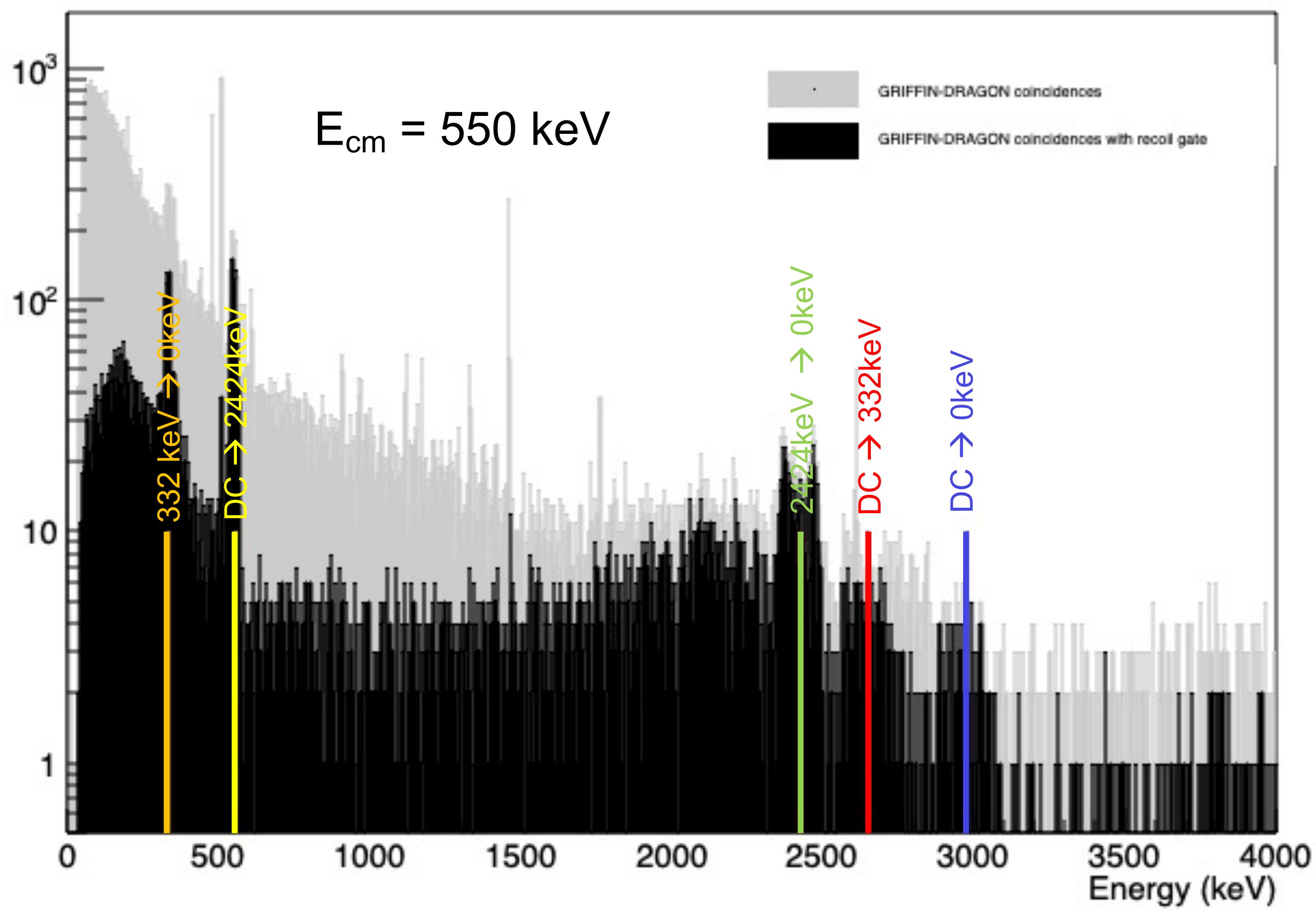


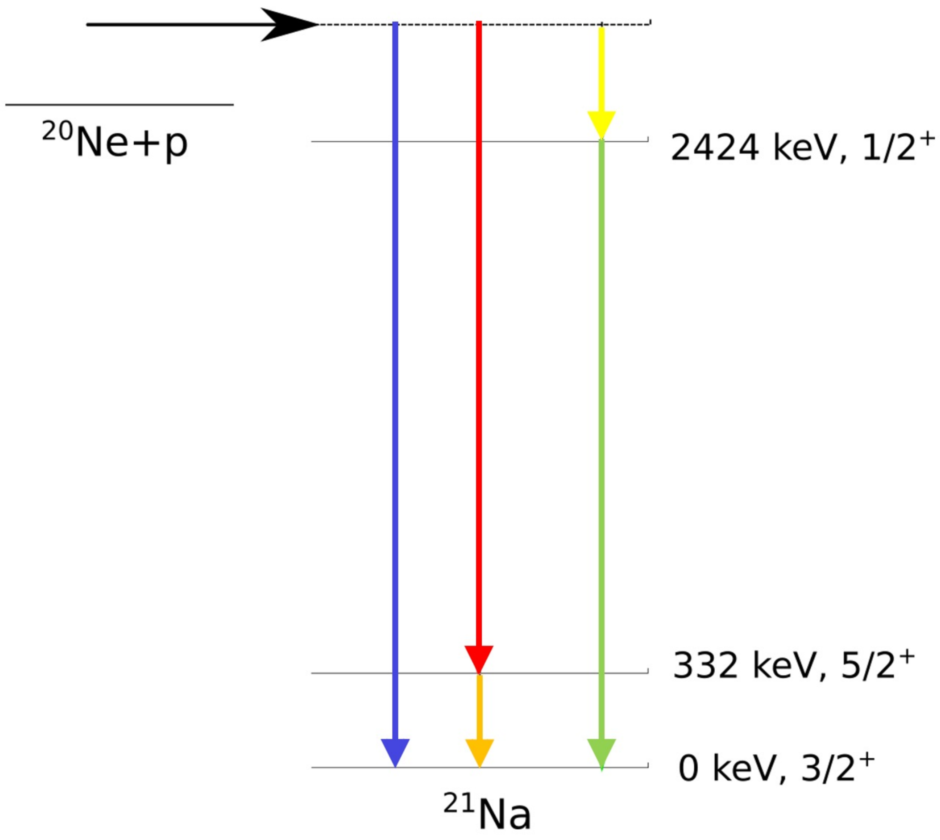
CAD drawings by S. Georges

Analysis & simulations by Madeleine Hanley
Colorado School of Mines

Proof of principle at 550 keV in $^{20}Ne(p,\gamma)$

GRIFFIN-DRAGON coincidence spectrum



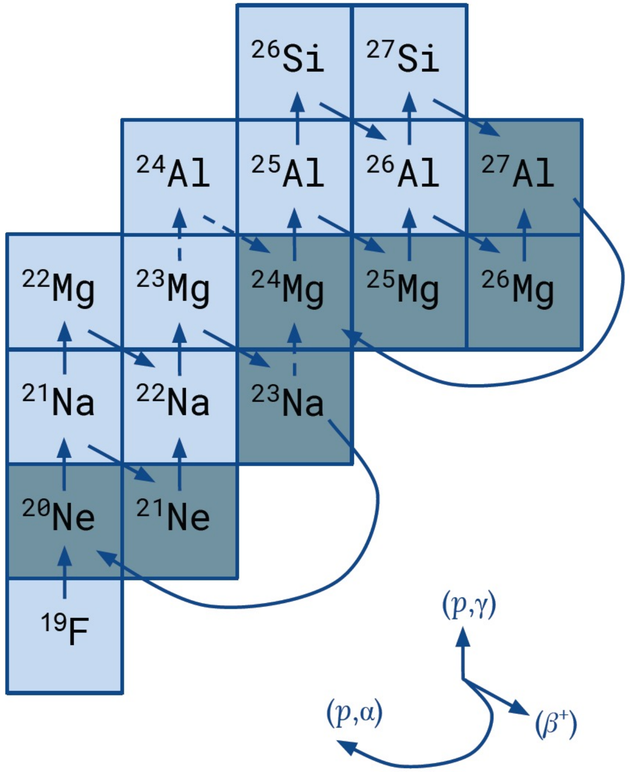


Remaining energies of 250, 300, and 450 keV C.O.M in 2023

- Beam intensities ~7.5e12 pps
- 4-days of beamtime

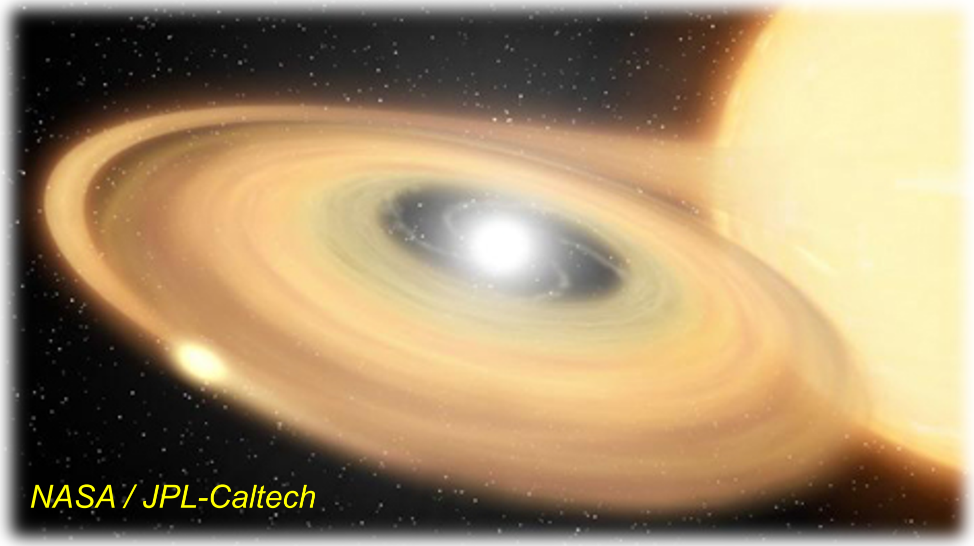
Analysis by Madeleine Hanley
Colorado School of Mines

Outlook: ^{23}Mg(p,γ)^{24}Al – Nova nucleosynthesis



Affects abundances of γ**-ray emitters ^{26}Al & ^{22}Na**

Collaboration with Surrey (UK) and St. Mary's U.



Bridge between the NeNa & MgAl cycles (T ~0.2 – 0.4 GK)

Rate likely dominated by ~475 keV resonance!

Previous work at DRAGON by **L. Erikson *et al.* - PRC 81, 045808 (2010):**

- **Uncertainties** in the resonance **energy**

➔ Resonance was placed far upstream in the DRAGON gas target

Second attempt **this July** w/ new detector configuration (**LaBr3, CeBr3**, BGO):

- Target ~663 keV and ~475 keV resonances (perform energy scan)
- Careful placement of potential contaminating resonance in ^{23}Na(p,γ)!

Proposal by Christian, Connolly, Lennarz, Ruiz *et al.*

Outlook: Upgrade to $LaBr_3$ array – resonant timing technique

- Medium with **better timing properties (sub-ns)** and/or energy resolution
- High-efficiency scintillation material → **$LaBr_3$**
- Timing between **prompt γ-rays & accelerator beam bunch** arrival time → **Reaction position**

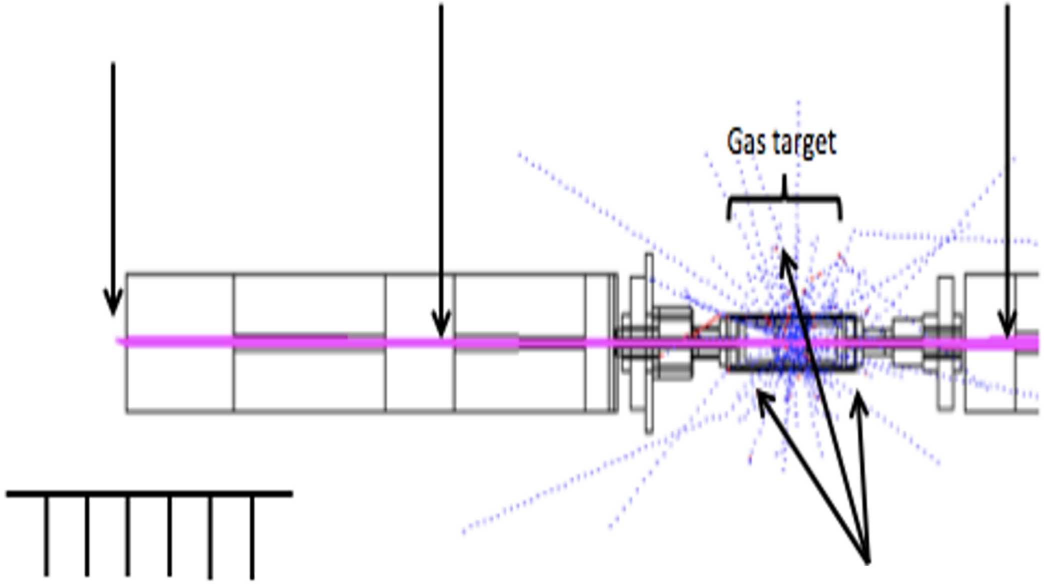
Extra sensitive, precise measure of resonance energy!

z_0 within a few events, to ~ ±0.3cm accuracy

Beam bunch generated with (ΔE, Δt) according to ISAC emittance

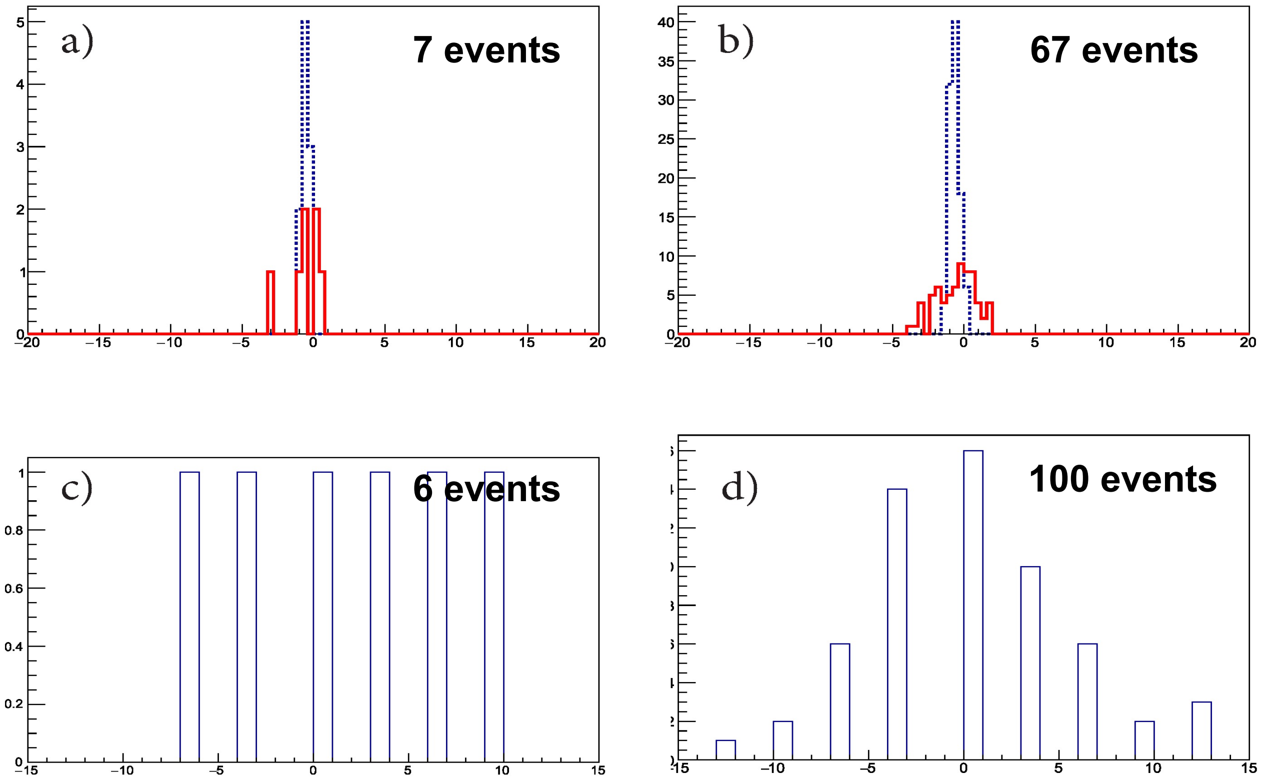
Incoming energy (measured in expt.)

Outgoing energy (measured in expt.)



ISAC 11MHz signal → 84ns

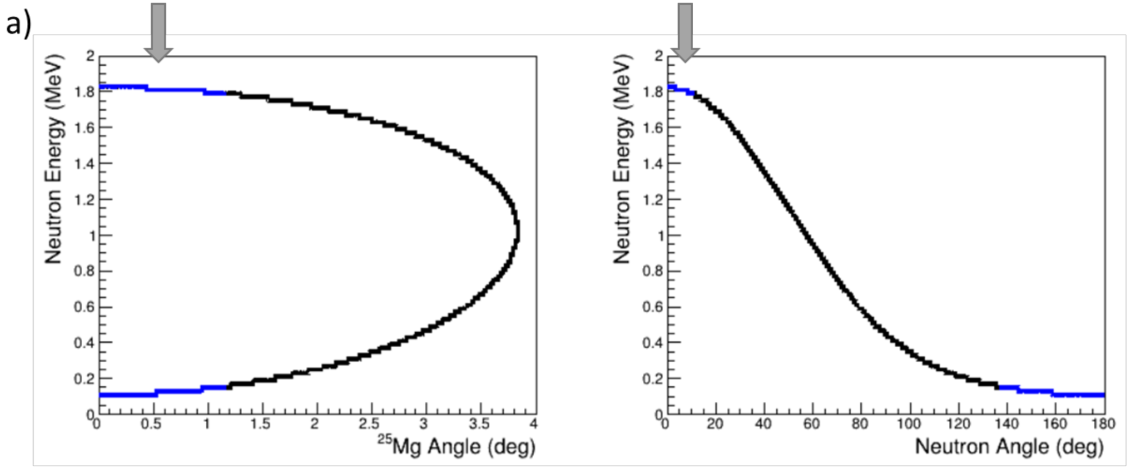
γ hits TDC signals w.r.t. RF

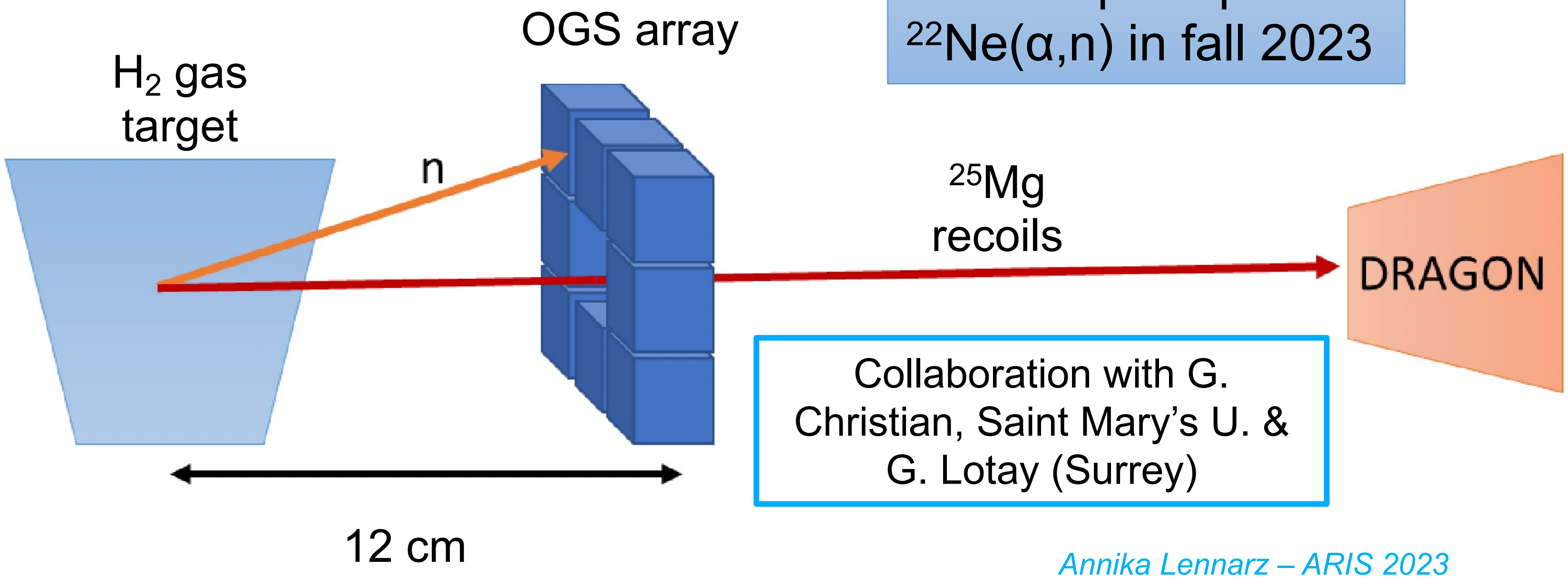


Resonance Z Position [cm]

Outlook: Plans for neutron detector array - ^{22}Ne(α,n)

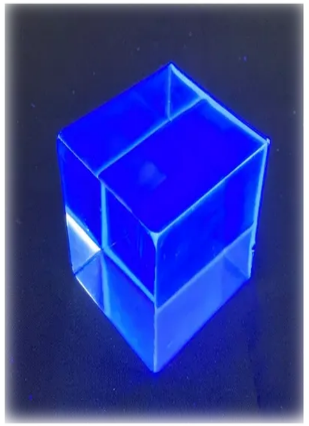
- Organic glass scintillators for neutron detection
- 1 × 1 × 1 & 3 × 3 × 3 cm^3 OGS cubes, each coupled to a PMT
- For e.g.: $^{22}\mathrm{Ne} + \alpha \rightarrow {}^{25}\mathrm{Mg} + \mathrm{n}$ (s-process n-source)
- Populate E_x = 11.83 MeV resonance in the ^{22}Ne(a,n)^{25}Mg reaction





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

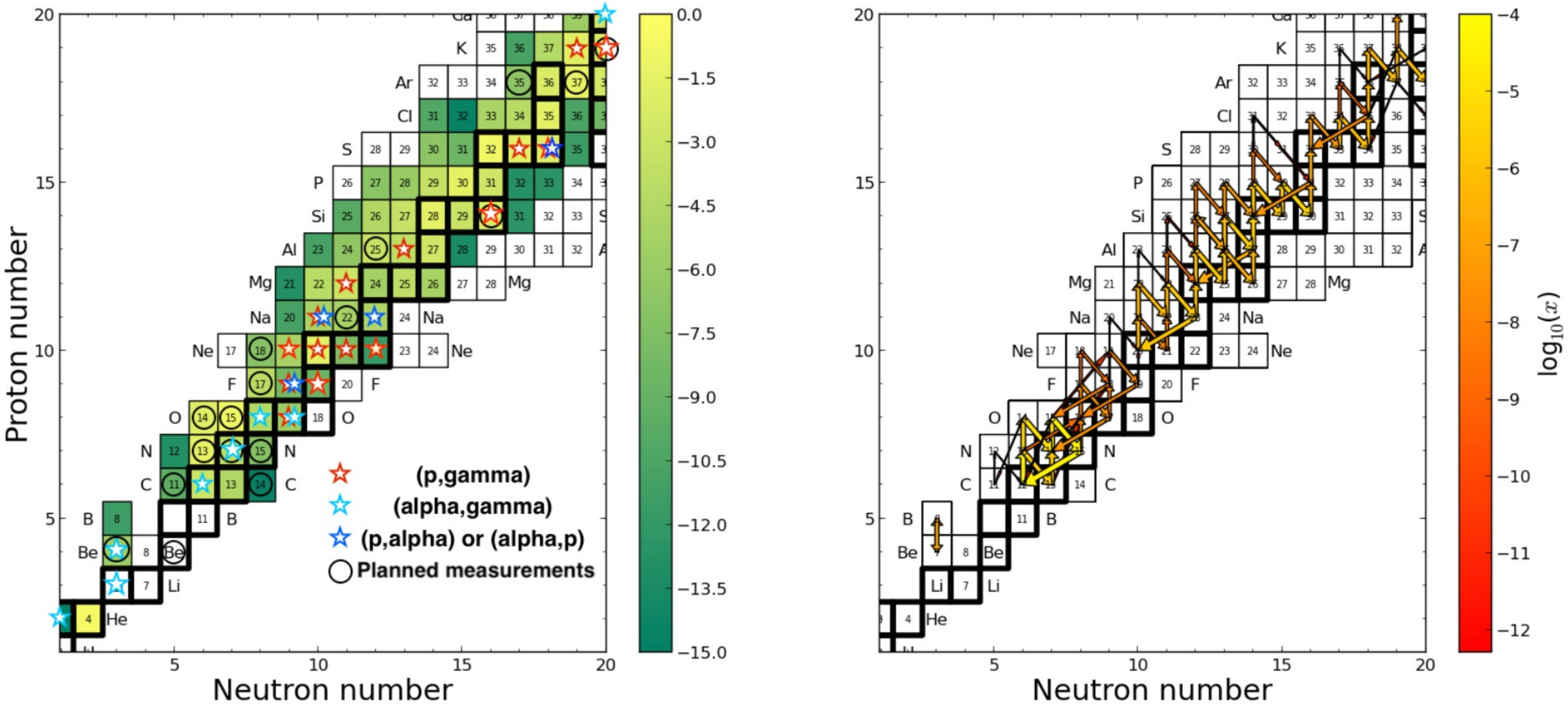
Collaboration with G. Christian, Saint Mary's U. & G. Lotay (Surrey)



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

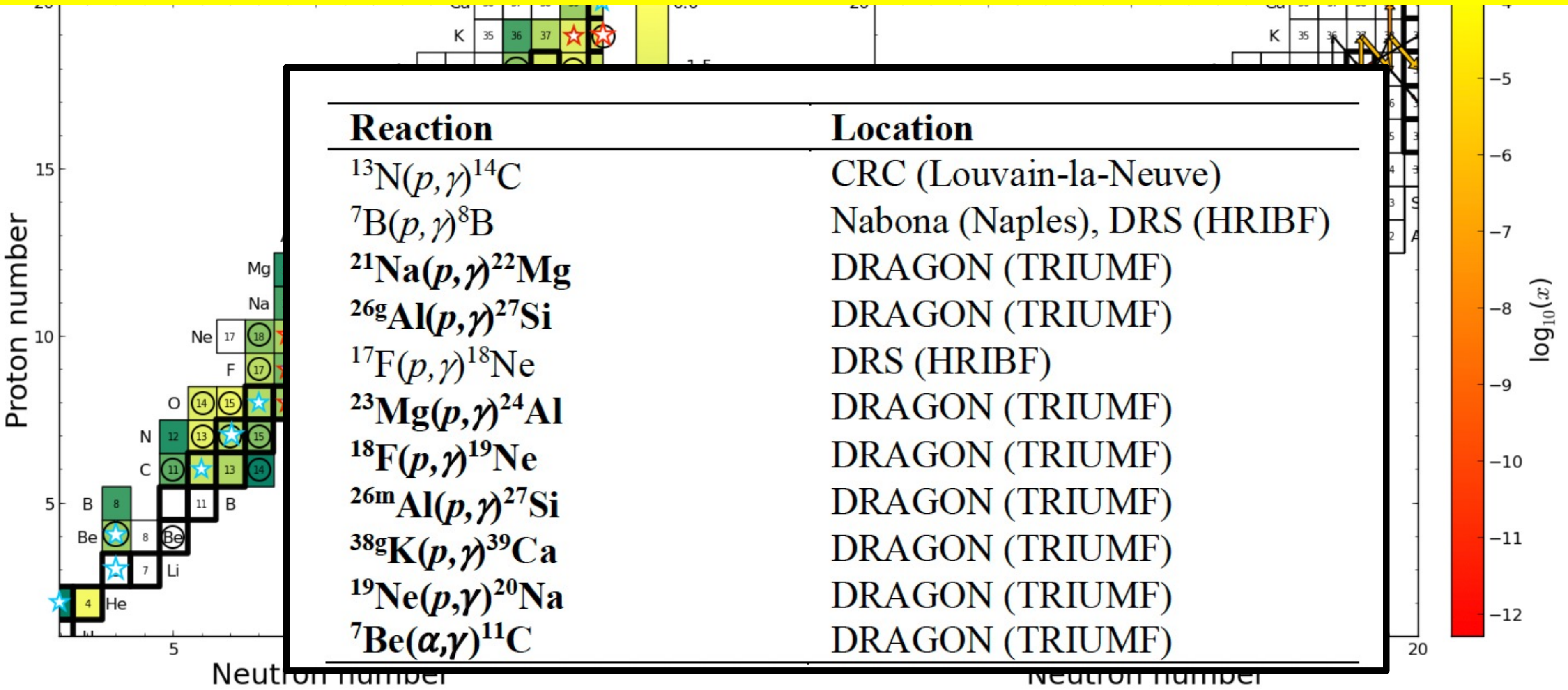
Successful program at DRAGON



Reactions measured are important for scenarios, including novae, type I x-ray bursts, core-collapse supernovae, main sequence Sun-type stars and late-stage massive stars.

Successful program at DRAGON

DRAGON holds **record** with 8 out of 11 **RIB measurements** of radiative capture **world-wide**!



Reaction	Location
^{13}N(p,γ)^{14}C	CRC (Louvain-la-Neuve)
^{7}B(p,γ)^{8}B	Nabona (Naples), DRS (HRIBF)
^{21}Na(p,γ)^{22}Mg	DRAGON (TRIUMF)
^{26g}Al(p,γ)^{27}Si	DRAGON (TRIUMF)
^{17}F(p,γ)^{18}Ne	DRS (HRIBF)
^{23}Mg(p,γ)^{24}Al	DRAGON (TRIUMF)
^{18}F(p,γ)^{19}Ne	DRAGON (TRIUMF)
^{26m}Al(p,γ)^{27}Si	DRAGON (TRIUMF)
^{38g}K(p,γ)^{39}Ca	DRAGON (TRIUMF)
^{19}Ne(p,γ)^{20}Na	DRAGON (TRIUMF)
^{7}Be(α,γ)^{11}C	DRAGON (TRIUMF)

Reactions measured are important for scenarios, including novae, type I x-ray bursts, core-collapse supernovae, main sequence Sun-type stars and late-stage massive stars.

Future experiments

Exp. No.	Reaction	RIB	Facility	Motivation	Status	Priority
S813LOI	$^{15}O(\alpha,\gamma)^{19}Ne$	Y	DRAGON	Ignition of Type I XRB	*Endorsed*	1
S870LOI	$^{18}Ne(\alpha,p)^{21}Na$	Y	TUDA	Ignition of Type I XRB	*Endorsed*	1
S922LOI	$^{25}Al(p,\gamma)^{26}Si$	Y	DRAGON	Production of Galactic ^{26}Al	*Endorsed*	1
S946LOI	$^{17}F(p,\gamma)^{18}O$	Y	DRAGON	Breakout of Hot CNO cycle, ^{18}F	*Endorsed*	1
S996	$^{18}F(p,\alpha)^{15}O$	Y	TUDA	511 keV flux from ^{18}F in novae	Approved	High
S1152LOI	$^{14}C(\alpha,\gamma)^{18}O$	Y	DRAGON	Ignition of type 0.Ia supernovae	*Endorsed*	1
S1289LOI	$^{44}Ti(p,\gamma)^{45}V$	Y	DRAGON	Production of ^{44}Ti in CCSN	*Endorsed*	1
S1289LOI	$^{44}Ti(\alpha,p)^{47}V$	Y	TUDA	Production of ^{44}Ti in CCSN	*Endorsed*	1
S1398	$^{11}C(p,\gamma)^{12}N$	Y	DRAGON	Stellar evolution and *ab-initio* theory	Approved	Medium
S1425	$^{15}O(\alpha,\gamma)^{19}Ne$	Y	DRAGON	511 keV flux from ^{18}F in novae	Approved	High
S1690	$^{22}Na(p,\gamma)^{23}Mg$	Y	DRAGON	1275 keV line emission from novae	Approved	High
S1763	$^{11}C(p,p)^{11}C$	Y	TUDA	Stellar evolution and *ab-initio* theory	Approved	High
S1796LOI	$^{37}Ar(p,\gamma)^{38}K$	Y	DRAGON	Nucleosynthesis in novae	*Endorsed*	1
S1799	$^{23}Mg(p,\gamma)^{24}Al$	Y	DRAGON	γ-ray emission from novae	Approved	High
S1819	$^{18}Ne(d,p)^{19}Ne$	Y	TUDA	511 keV flux from ^{18}F in novae	Approved	High
S1880	$^{20}Ne(p,\gamma)^{22}Na$		DRAGON	Weakly-bound “proton halo” states	Approved	High
S1881LOI	$^{35}Ar(p,\gamma)^{36}K$	Y	DRAGON	Rp-process in Type I XRB	*Endorsed*	1
S2013	$^{7}Be(p,\gamma)^{8}B$	Y	DRAGON	Solar neutrinos	Approved	High
S2018	$^{7}Be(\alpha,\alpha)^{7}Be$	Y	DRAGON	Nucleosynthesis & NIF calibration	Approved	High
S2034	$^{7}Be(p,p)^{7}Be$	Y	DRAGON	Production of solar neutrinos	Approved	High
S2054LOI	$^{29}Si(p,\gamma)^{30}P$		DRAGON	Presolar Grains	*Endorsed*	1
S2136LOI	$^{51}Mn(p,\gamma)^{52}Fe$	Y	DRAGON	Gamma-ray astronomy	*Endorsed*	1
S2172	$^{6}He(p,p)^{6}He$	Y	TUDA	Ab-initio nuclear theory	Approved	Medium
S2186	$^{19}F(p,\gamma)^{20}Ne$		DRAGON	Nucleosynthesis in the first stars	Approved	High
S2230	$^{22}Ne(\alpha,n)^{25}Mg$		DRAGON	Weak r-process	Approved	High

Summary

- We seek to understand the nature and role of nuclear reactions that govern **energy release** & **nucleosynthesis** path in explosive scenarios
- **Radiative capture reactions** play crucial role in many astrophysical scenarios
- DRAGON holds **record** with 8 out of 11 **RIB measurements** of radiative capture **world-wide**!
- At DRAGON we have performed the **first ever direct study of excited state proton capture**
- Recent experimental upgrades (variable setups):
  - Installation of HPGe detectors instead of BGO ➔ ^{20}Ne(p,γ)
  - Mixed $LaBr_3$, $CeBr_3$ & BGO ➔ ^{23}Mg(p,γ) in July 2023
- **Outlook:**
- Plans for neutron detector array ➔ Direct measurement of ^{22}Ne(α,n) reaction
- RIB experiments: ^{23}Mg(p,γ), **^{15}O(α,γ)^{19}Ne, ^{7}Be(p,γ), ^{11}C(p,γ)^{12}N, ^{11}C(p,p)^{11}C, ^{22}Na(p,γ)^{23}Mg, …**

Acknowledgements

C. Ruiz, M. Alcorta, C. Brune, A.A. Chen, G. Christian, R. deBoer, D. Connolly, B. Davids, A. Edwin, A. Garnsworthy, U. Greife, M. Hanley, D. Hutcheon, A. Katrusiak, A. M. Laird, A. Lennarz, M. Loria, G. Lotay, P. Machule, L. Martin, S. Paneru, A. Parikh, A. Psaltis, F. Sarazin, A. Shotter, S. Upadhyayula, V. Vedia, L. Wagner, M. Williams

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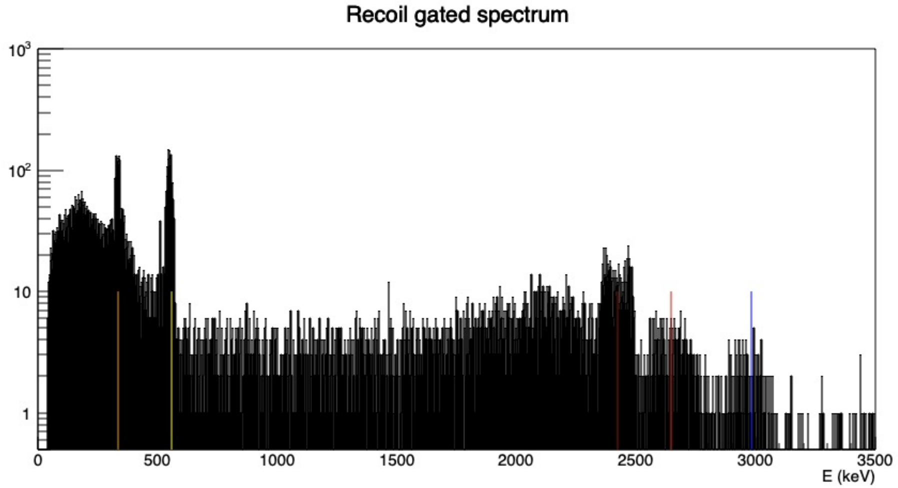
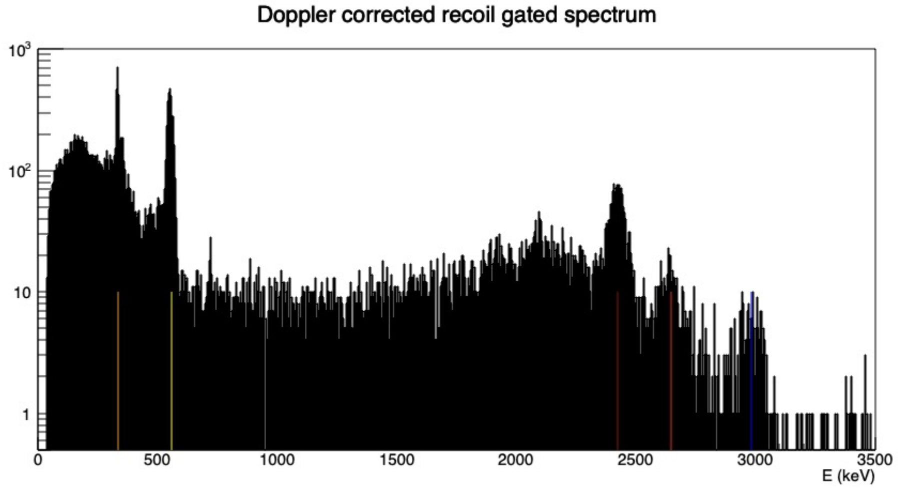
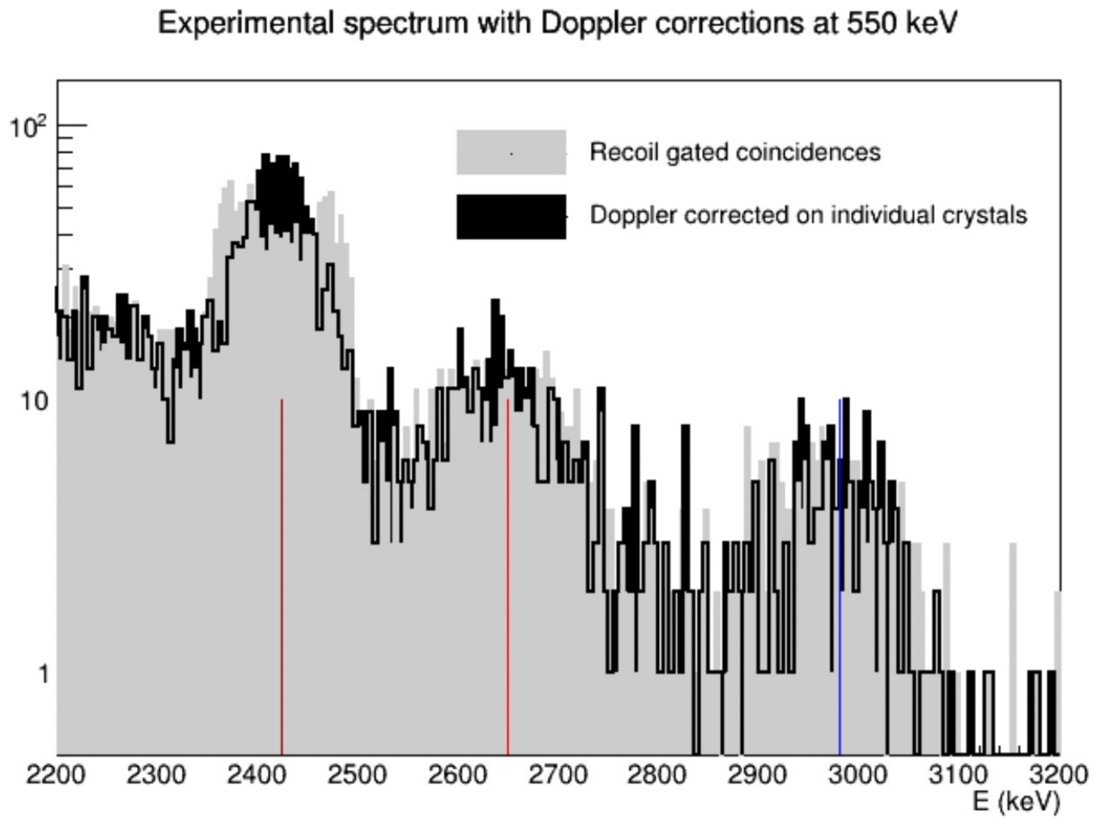
$^{20}Ne(p,\gamma)$ – Doppler corrected spectrum



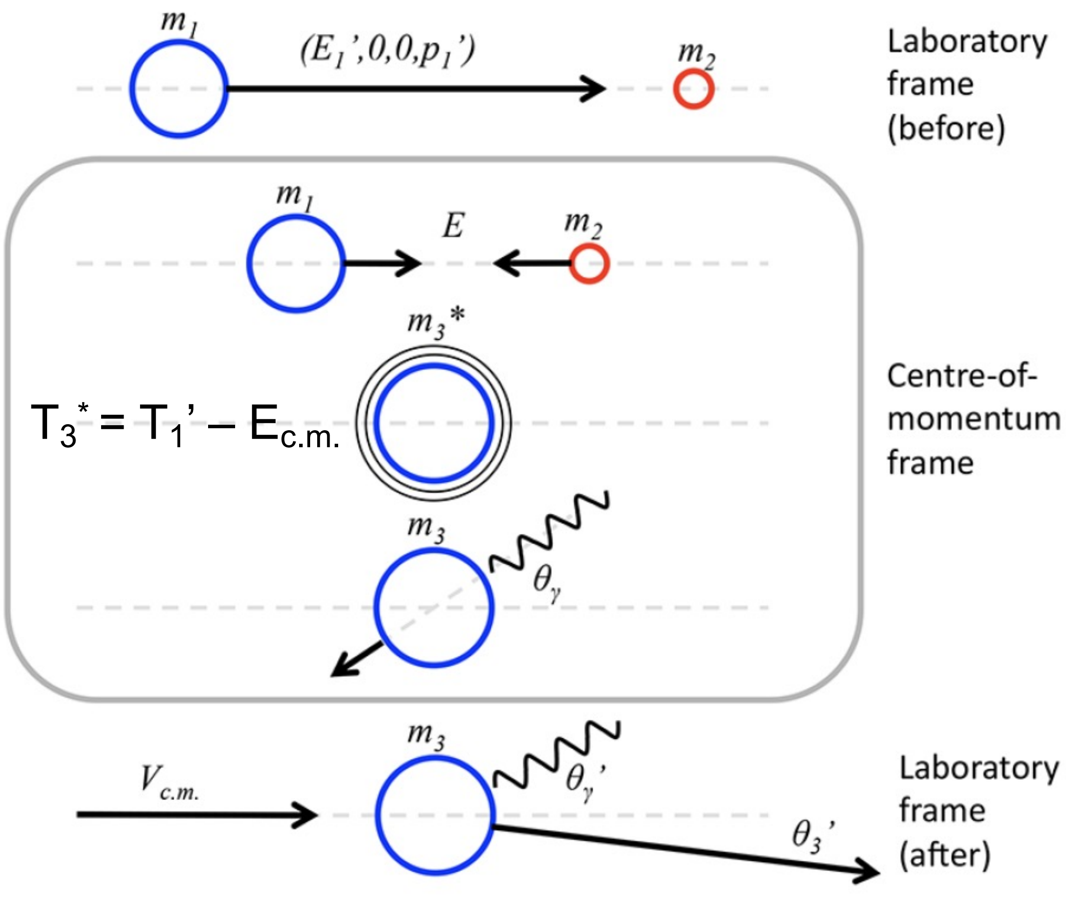




Doppler corrections applied to individual crystals in bottom four detectors

Analysis & simulations by Madeleine Hanley
Colorado School of Mines

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

Normalization

All measurements of cross sections/resonance strength require knowledge of the number of particles incident on the target

- Faraday Cup readings cannot distinguish between beam components
- ➔Isomeric component was identified by its associated β+ decay to the ^{26}Mg g.s.
- Beam deposited on left mass slit downstream of ED1
- Emitted positrons are "guided" up a horn at the center of two NaI scintillators positioned 180 degrees to each other.
- Allows for β+ detection via annihilation in the horn and subsequent detection of 511 keV coincidence photons.

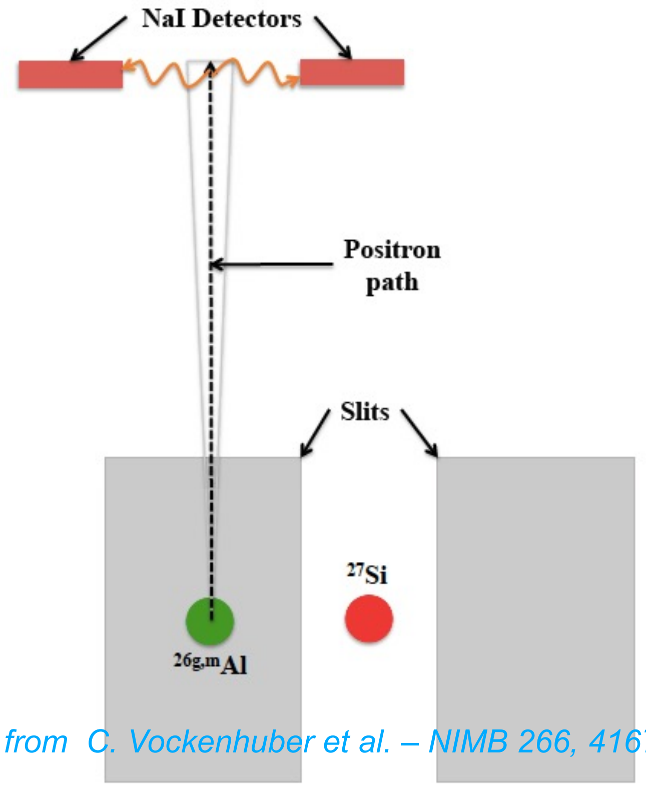


Figure from C. Vockenhuber et al. – NIMB 266, 4167 (2008)

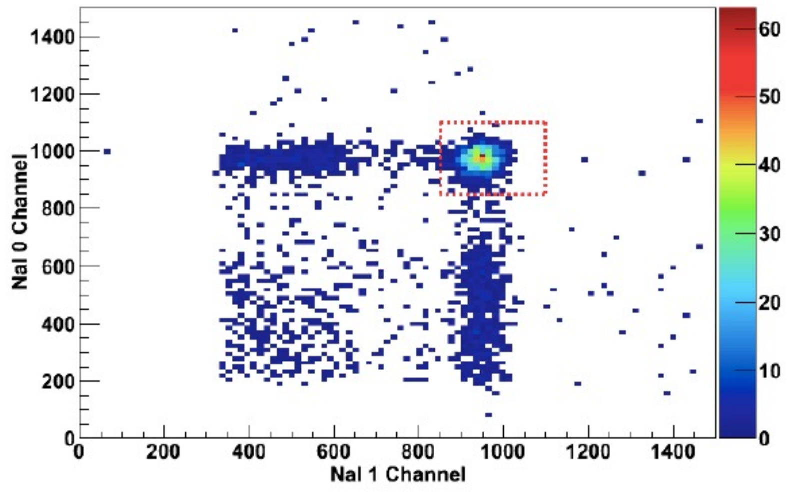
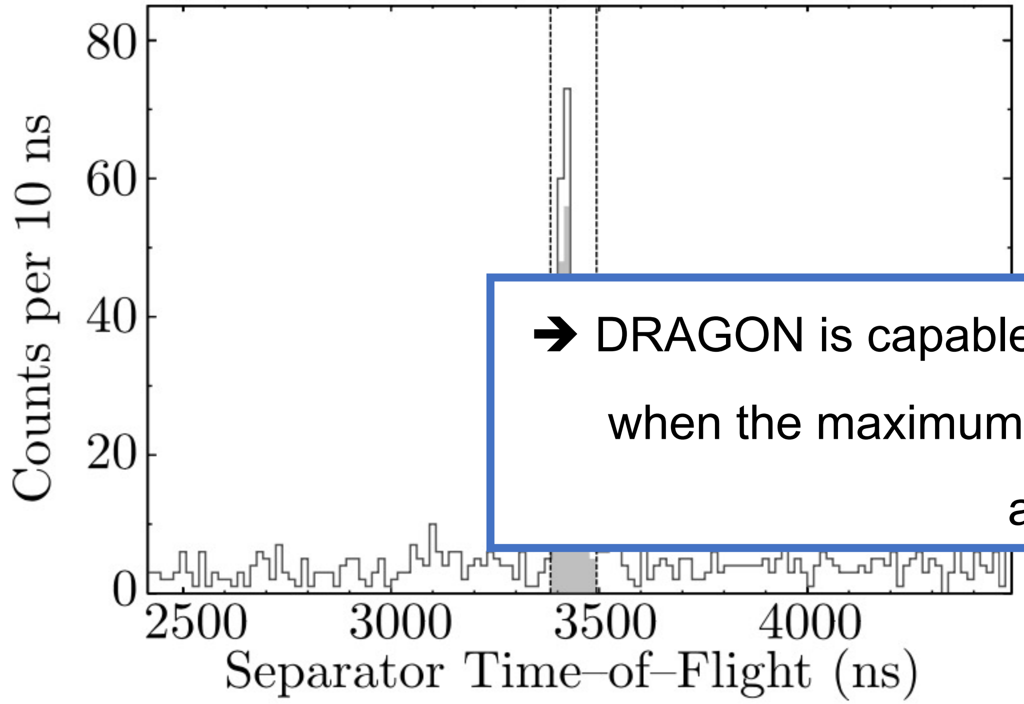
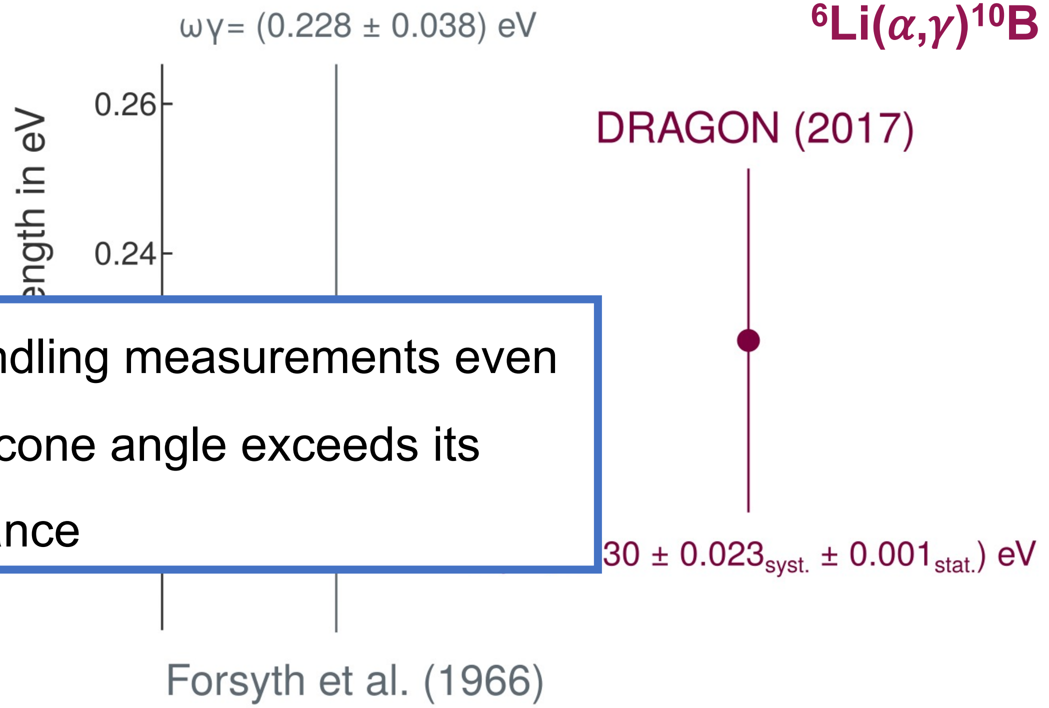


Figure from D. Mountford

Benchmark GEANT3 acceptance of DRAGON

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





^{6}Li(α,γ)^{10}B

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

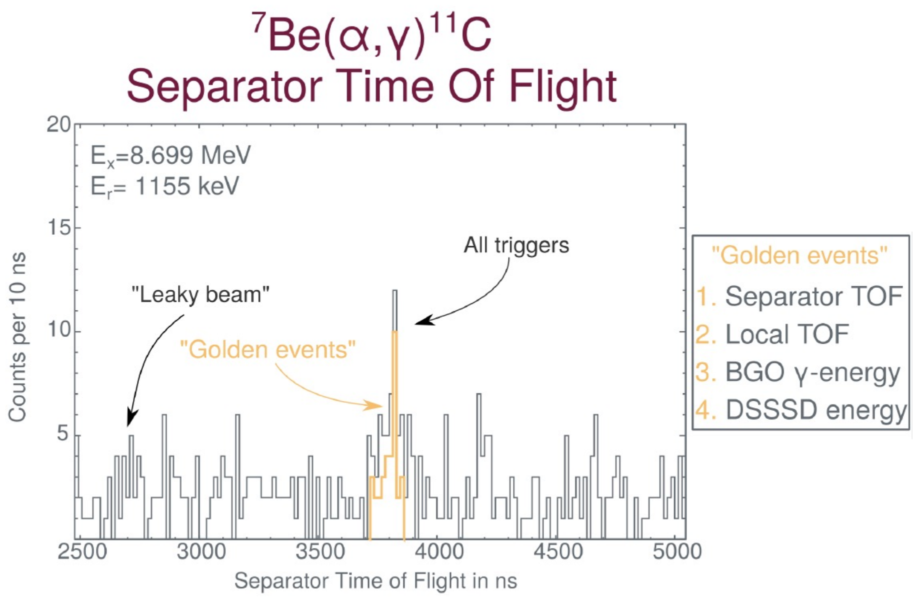
A. Psaltis et al. - NIMA 987 (2021) 164828

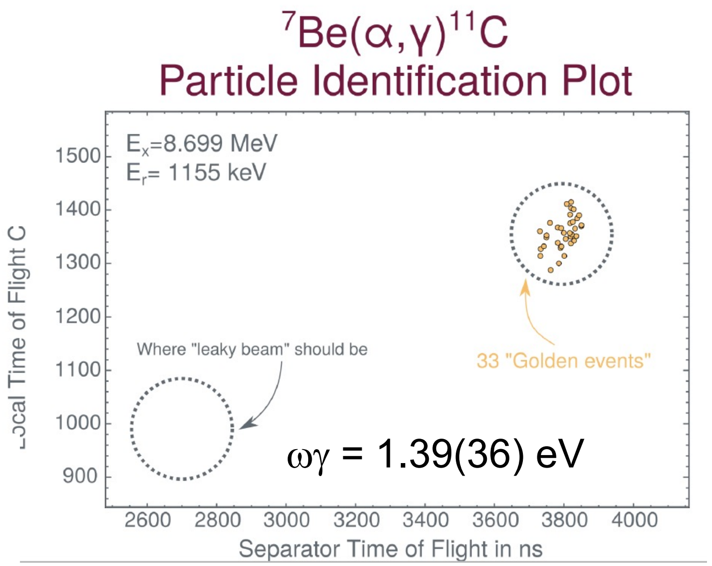
- GEANT3 simulation includes raytracing
- Benchmarked against α-source measurements

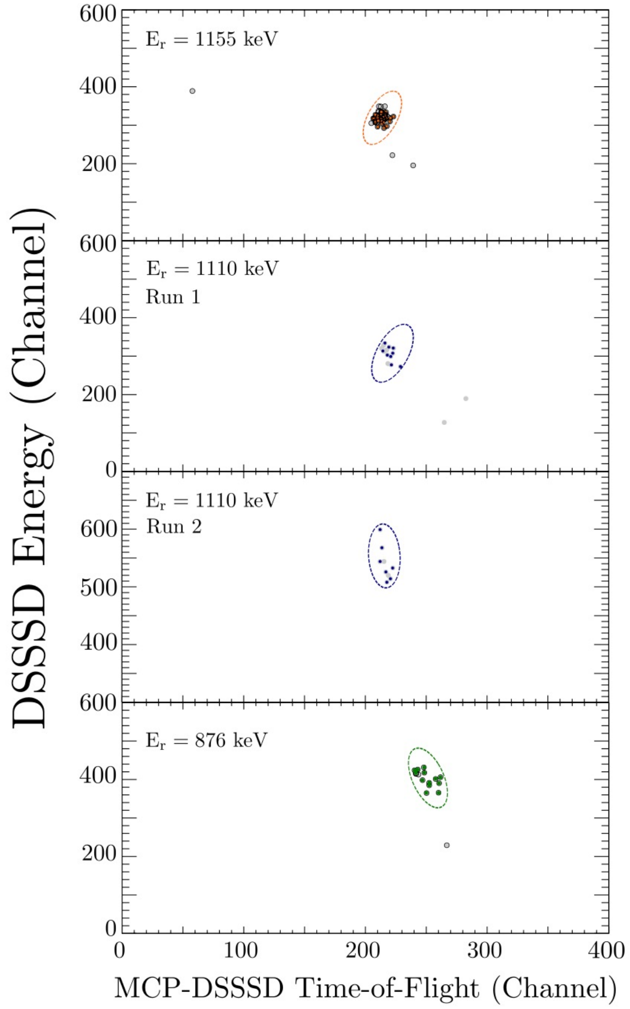
- Includes reaction simulation, cascade decays, angular distributions, BRs, energy levels, etc.

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

$^{7}Be(\alpha,\gamma)^{11}C$ – results







- Recently performed direct measurement of various resonances in $^{7}Be(\alpha,\gamma)^{11}C$
- 2 previously **unknown** strengths!
- Re-measured E_r = 876 keV resonance strength & results agrees with previous measurement
- Work submitted to PRL and PRC

A. Psaltis et al. – Submitted to PRC/PRL

Figures courtesy of A. Psaltis

Back-up

PHYSICAL REVIEW LETTERS **126,** 042701 (2021)

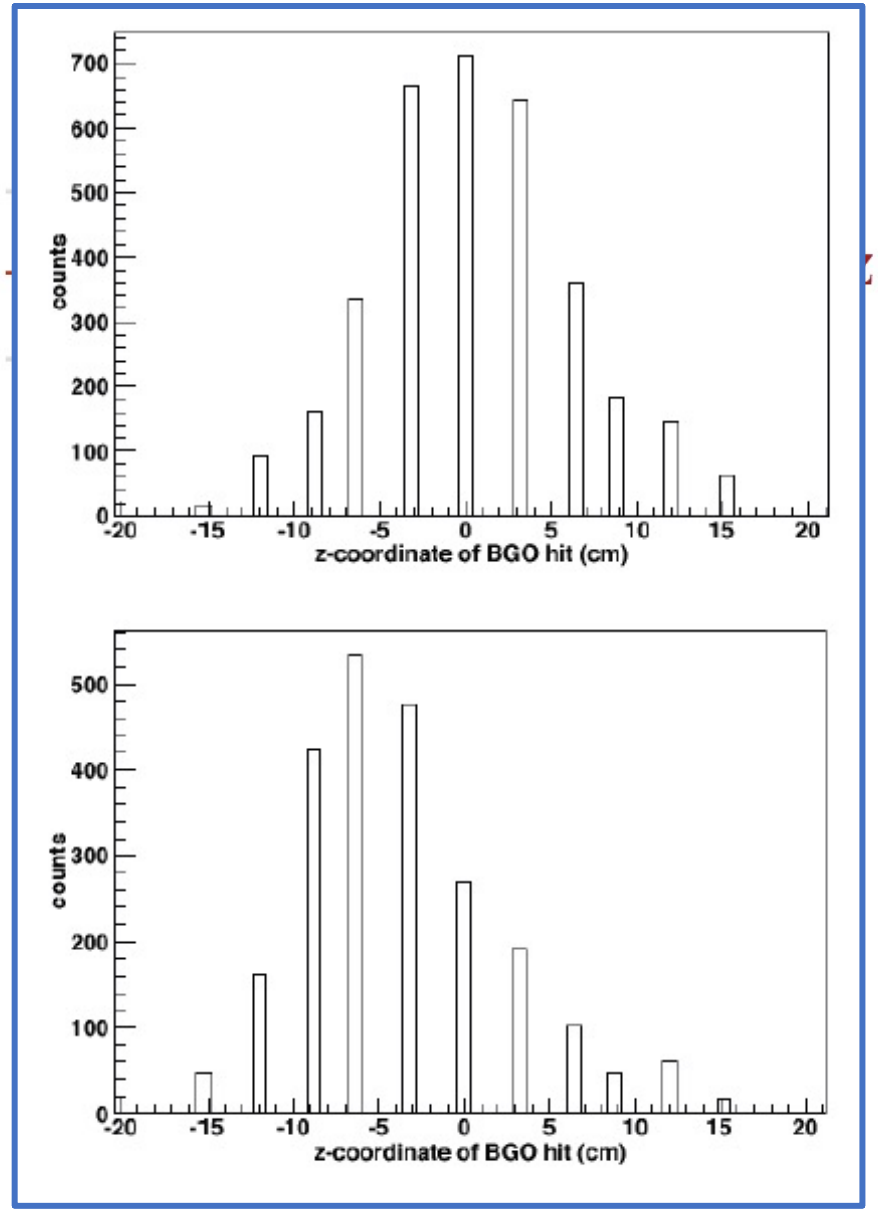
TABLE II. Properties of resonant states in the $^{26m}Al(p,\gamma)^{27}Si$ reaction. Upper limits for proton partial widths have been estimated using present cross sections, while γ-ray widths have been determined using a lifetime lower limit of 1 fs, for γ-decaying states, unless otherwise noted. In the case of the 218- and 448-keV resonances, we present strength estimates for both even- and odd-parity assignments.

E_x	E_γ [27]	E_r [27]	J^π	σ	$C^2S_{^{26}Si(d,p)}$ [a]	$C^2S_{^{26m}Al(p,\gamma)}$ [a]	Γ_p	Γ_γ	$\omega\gamma$
	[keV]	[keV]		[μb]			[meV]	[meV]	[meV]
7838	6879.6(2)	146.3(3)	$5/2^+$	≤ 168	≤ 0.03	≤ 0.015	$\leq 4.9 \times 10^{-6}$	≤ 658	$\leq 1.5 \times 10^{-5}$
7909	7127.1(7)	217.8(7)	$3/2^-$	≤ 43	≤ 0.01	≤ 0.005	$\leq 2.7 \times 10^{-2}$	≤ 658	≤ 0.054
			$3/2^+$		≤ 0.01	≤ 0.005	$\leq 7.1 \times 10^{-4}$	≤ 658	$\leq 1.4 \times 10^{-3}$
8070	7111.5(30)	378.3(30)	$3/2^+$	≤ 14	≤ 0.003	≤ 0.0015	≤ 0.16	≤ 658	≤ 0.33
8140	7180.9(6)	447.7(6)	$1/2^+$	≤ 58	≤ 0.09	≤ 0.045	683 [b]	890 [c]	385
			$1/2^-$		≤ 0.02	≤ 0.01	≤ 190	≤ 658	≤ 147
8184	7401.7(4)	492.2(4)	$3/2^-$	≤ 15	≤ 0.002	≤ 0.001	≤ 45	165 [27]	≤ 70

[a] $C^2_{(d,p)} = 2/3$ and $C^2_{(p,\gamma)} = 1/3$
[b] $C^2S = 0.01$– see text for details
[c] Adopted from shell-model calculations for the $1/2^+_7$ state

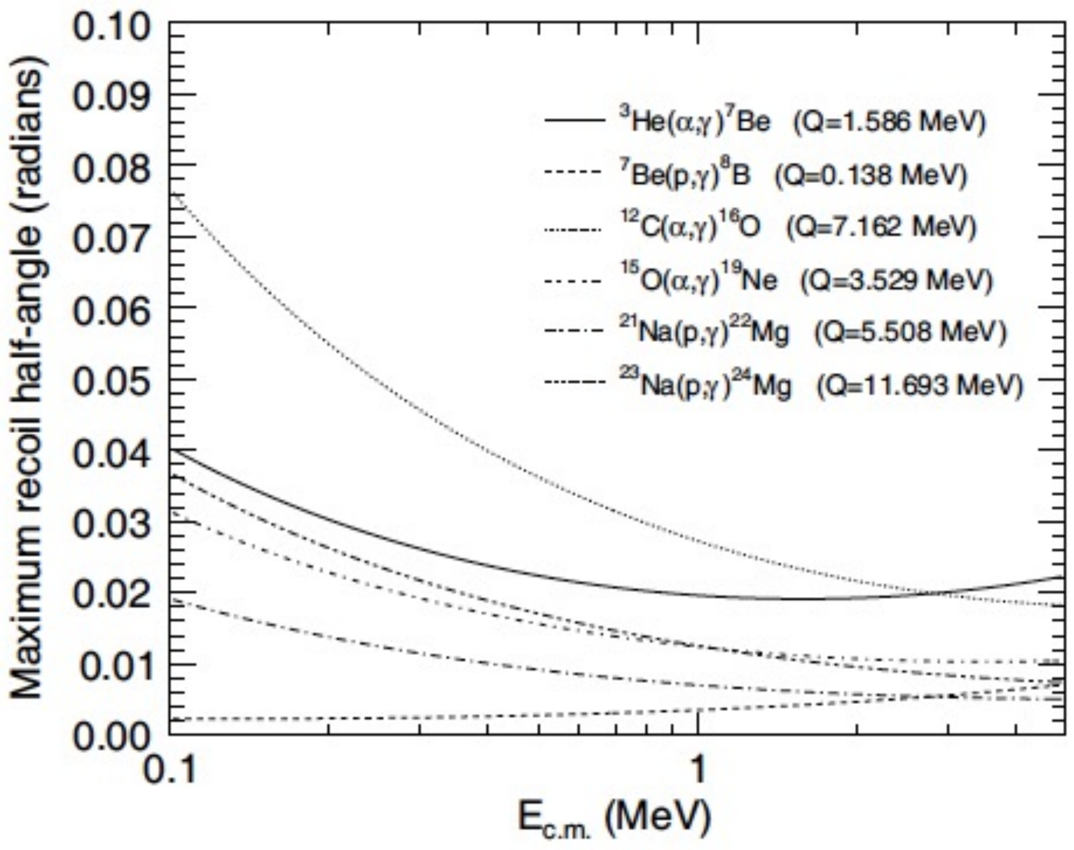
BGO detector array – Coincidence measurements

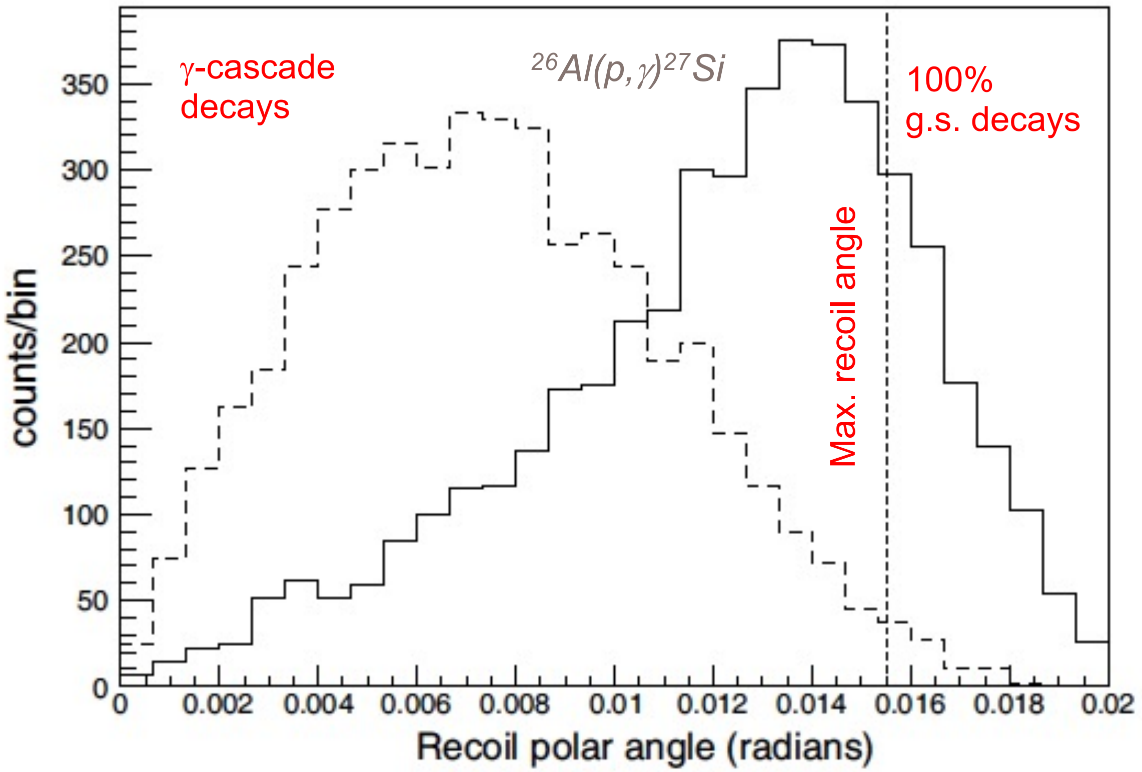
- **BGO** ($Bi_4Ge_3O_{12}$) array (30 detectors)
- High γ-ray detection efficiency (40 to 80%, depending on multiplicity & energy)
- Combined with TOF → **low random** coincidence rate!
- **Caveat:**
  - Rely on **simulation** for detection efficiency
  - → dominates syst. error of the experiment!
  - Limited γ-ray energy resolution (FWHM ~9%)
- **Segmented** BGO array along beam axis → Information about location of reaction
- BGO hit pattern → **resonance energy** (0.5%)



Geometric acceptance

Minimum at E_{cm} = Q





Figures from C. Ruiz et. al., Eur. Phys. A 50, 99 (2014)