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^{22}Ne(p,γ)^{23}Na and the origin of ^{23}Na

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$^{22}Ne(p,\gamma)^{23}Na$ reaction affects ^{23}Na abundance in various stellar sites:

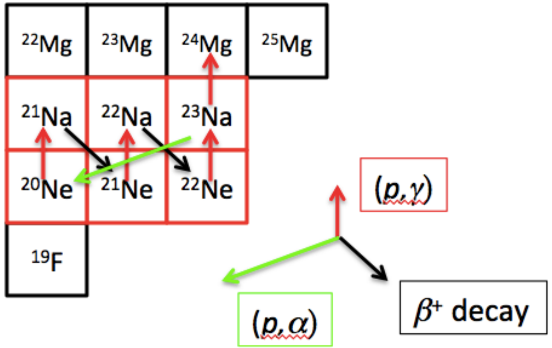
- **Hot-bottom burning** (HBB) in AGB stars (M>4$M_\odot$)
- Convective carbon-shell burning in **massive stars** (competes with $^{22}Ne(\alpha,n)^{25}Mg$)
- **Nova** nucleosynthesis (0.15 < T < 0.45 GK)

*Increased interest in abundance prediction since discovery of **Na-O anti-correlation** in red giant stars of globular clusters*

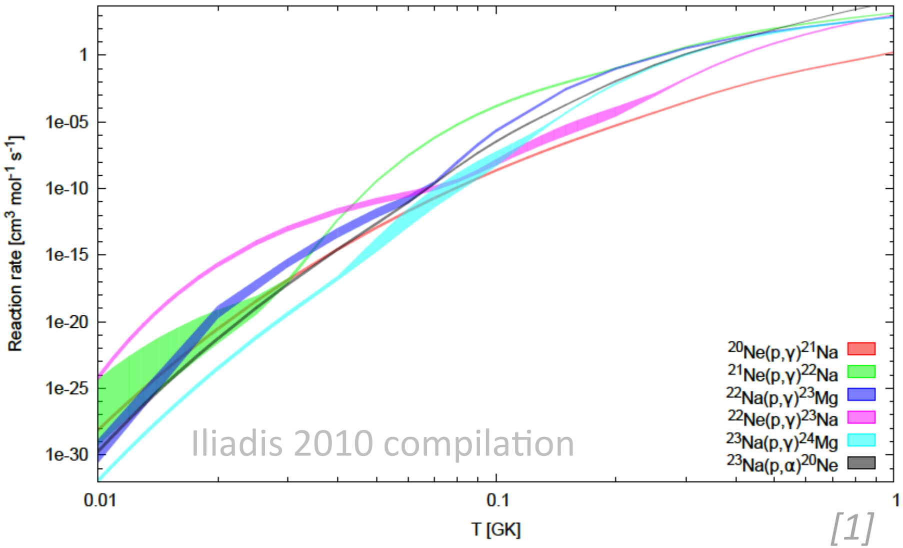
→ ***Anomalies** in O, Na, Mg, Al **abundances** in GC stars as a result of "pollution" from AGB stars undergoing HBB?*

→ Abundance patterns → study nucleosynthesis pathes in all cycles!

NeNa cycle



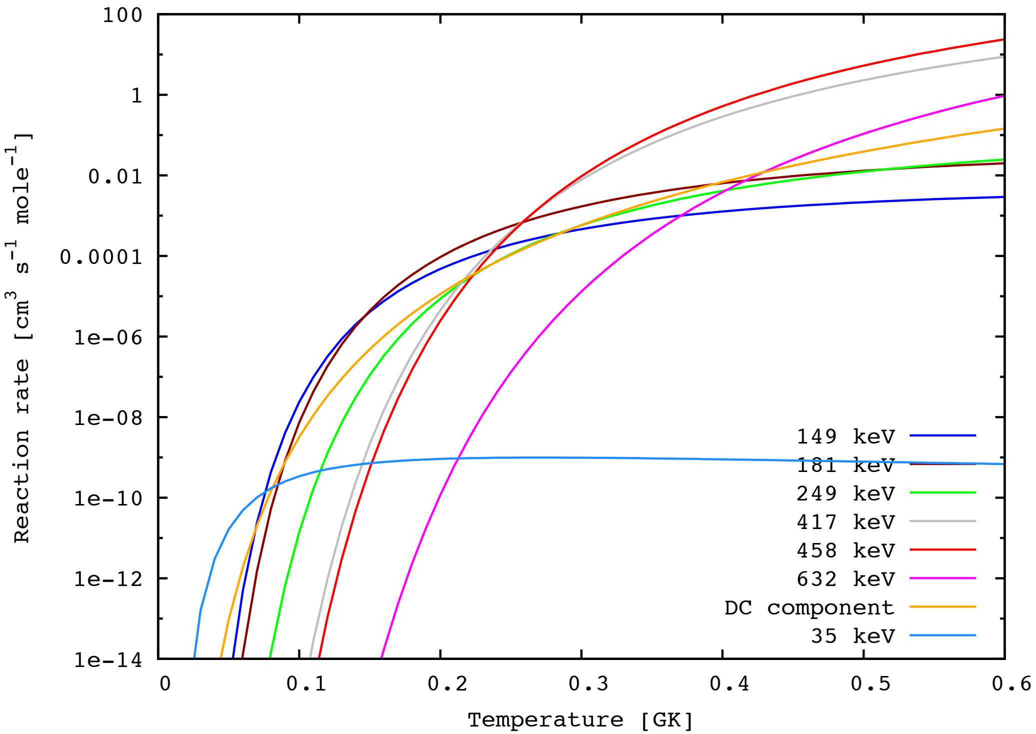
$^{20}Ne(p,\gamma)^{21}Na(e+\ \nu)^{21}Ne(p,\gamma)^{22}Na(e+\ \nu)$**$^{22}Ne(p,\gamma)^{23}Na$**$(p,\alpha)^{20}Ne$

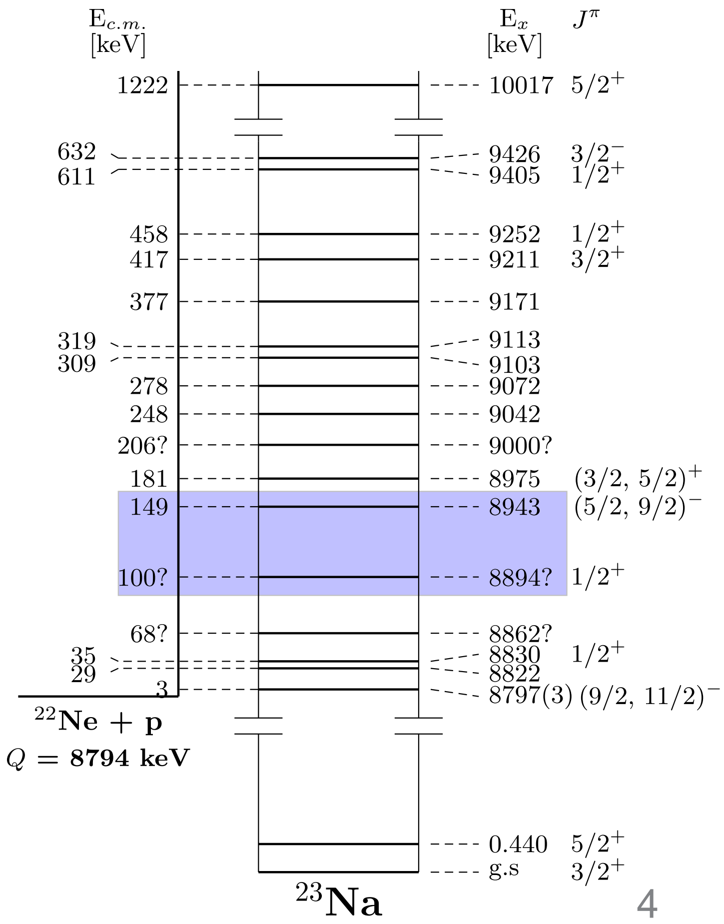


[1]

- NeNa cycle of H-burning (T>0.07 GK)
- Low contribution to energy budget
- **BUT:** Importance for stellar **nucleosynthesis**
- Affects **abundance** of elements between ^{20}Ne & ^{27}Al
- Rate of NeNa cycle determined by $^{20}Ne(p,\gamma)^{21}Na$
- **BUT:** Highest uncertainty in $^{22}Ne(p,\gamma)^{23}Na$

***^{22}Ne(p,γ)^{23}Na** is considered reaction with **highest uncertainty** on reaction rate in NeNa cycle*





$^{22}Ne(p,\gamma)^{23}Na$ reaction rate

- Uncertainties in $\omega\gamma$ for (until recently unobserved) **low-energy resonances**
- → **Discrepancies** between compilations by up to a factor of 1000 (T~0.08GK)
- → Abundance **variations** for nuclides between ^{20}Ne & ^{27}Al by up to 2 orders of magnitude!

***First data** on several low-energy resonances published by LUNA group*

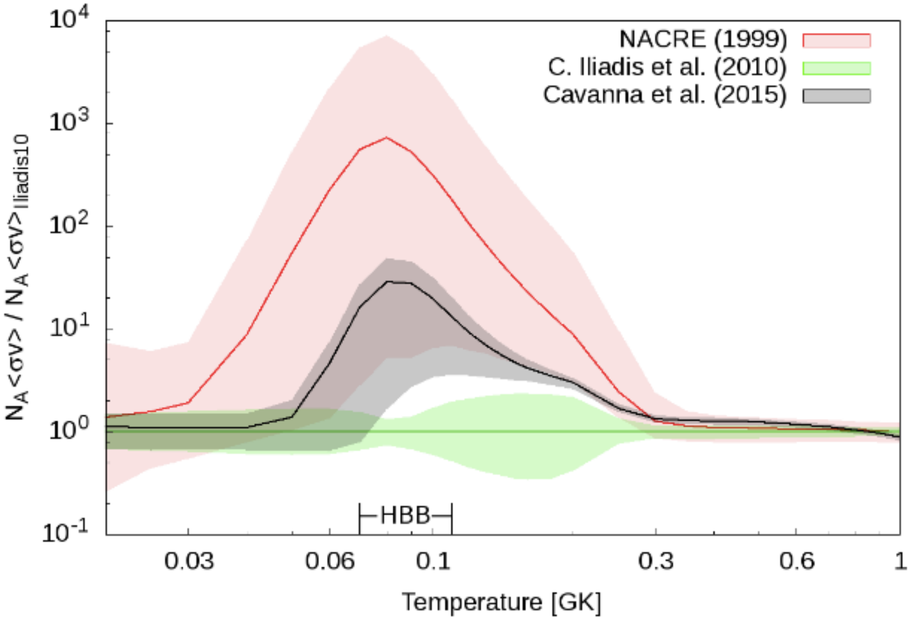
$\omega\gamma(E_{cm}=149\text{ keV}) = $ (**1.48(10) x 10^{-7}**) eV

$\omega\gamma(E_{cm}=181\text{ keV}) = $ (**1.87(6) x 10^{-6}**) eV

$\omega\gamma(E_{cm}=249\text{ keV}) = $ (**6.89(16) x 10^{-6}**) eV

(Cavanna et. al. PRL 115, 252501 (2015)) [2]

→ Confirmation with different method!



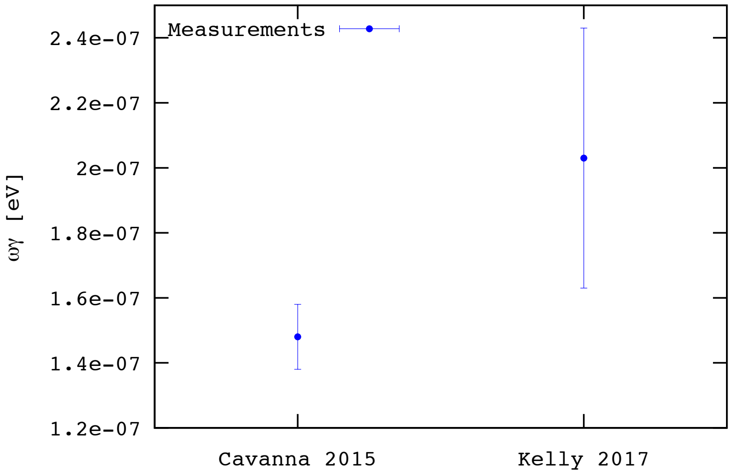
Slemer et. al. arXiv:1611.07742v1 (2016) [3]

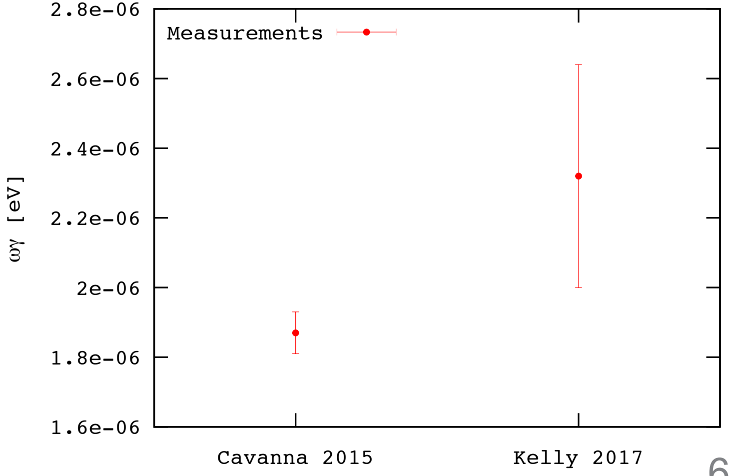
Previous measurements of low-energy resonances

Recent measurement of low-energy resonances by Kelly et. al. (PRC **95**, 015806 (2017)) at Laboratory for Experimental Nuclear Astrophysics (LENA)

- $\omega\gamma(E_{cm}=178\text{ keV}) = (\mathbf{2.32(32)\times 10^{-6}})$ eV
- $\omega\gamma(E_{cm}=151\text{ keV}) = (\mathbf{2.03(40)\times 10^{-7}})$ eV

Higher than LUNA result!
Agreement within 1.4σ level





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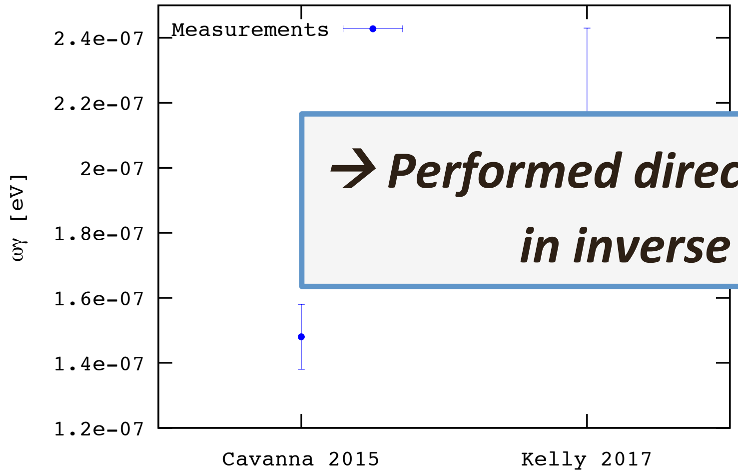

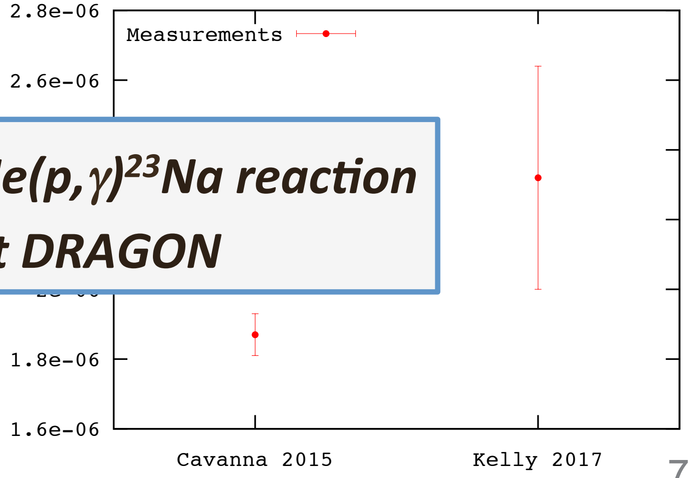

→ ***Performed direct study of $^{22}Ne(p,\gamma)^{23}Na$ reaction in inverse kinematics at DRAGON***

DRAGON Objectives:

- Study energy range relevant to AGB stars and novae for temperatures between 0.1 GK and 0.4 GK
- Direct measurement of $\mathbf{E_{cm}}$**= 149, keV, 181 keV, 249 keV** resonances
- Re-measure “well-known” reference resonances (E_{cm}=458, 611, 632, 1222 keV)
- Provide more stringent limits on cross sections between 280 and 400 keV (**direct capture** contribution)

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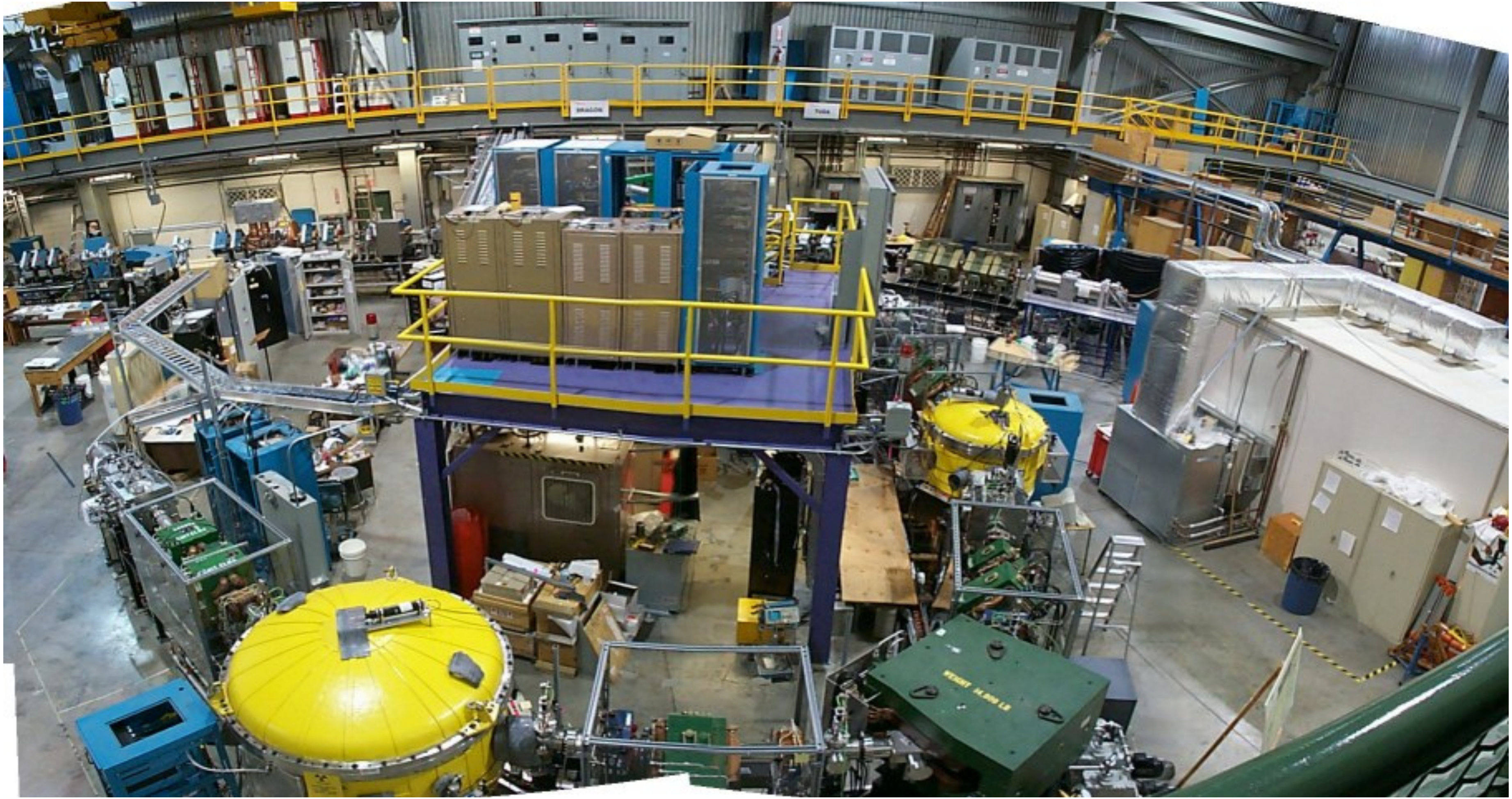
DRAGON – Detector of Recoils And Gamma-rays Of Nuclear reactions



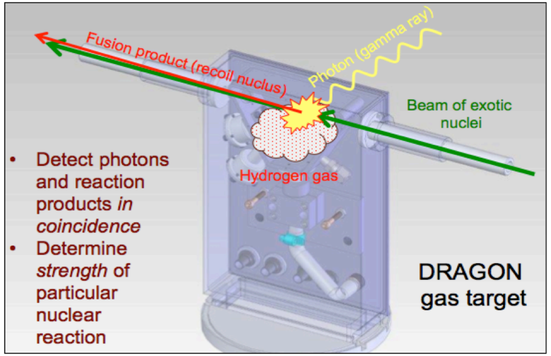
DRAGON – Detector of Recoils And Gamma-rays Of Nuclear reactions

① Windowless gas target

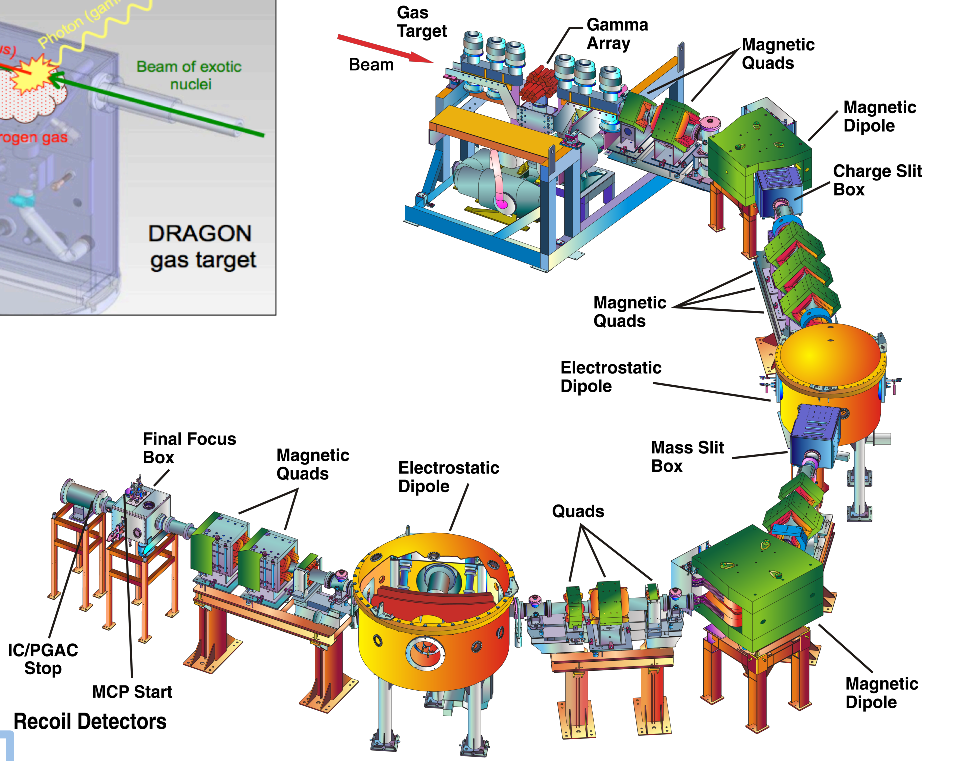
② BGO γ-detection array

③ MEME mass separator

④ Recoil detection system



- Detect photons and reaction products *in coincidence*
- Determine *strength* of particular nuclear reaction



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

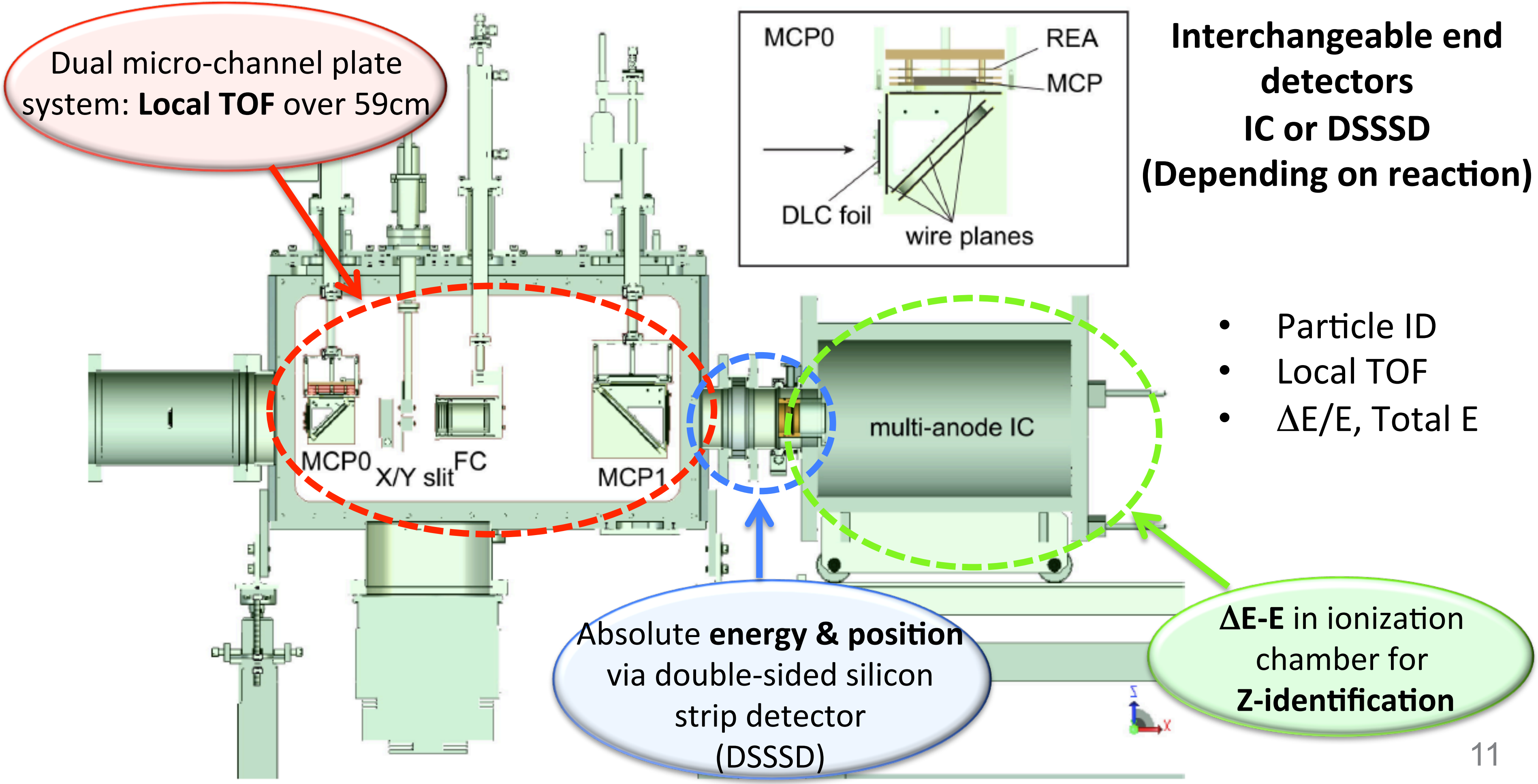
#reactions per incident ion

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

Particle detection – end detectors

Interchangeable end detectors
IC or DSSSD
(Depending on reaction)

- Particle ID
- Local TOF
- ΔE/E, Total E



$^{22}Ne(p,\gamma)^{23}Na$ at DRAGON

First direct** measurement in **inverse kinematics

- **High** beam **intensities** (MCIS, **$2x10^{12}$ pps** at DRAGON)

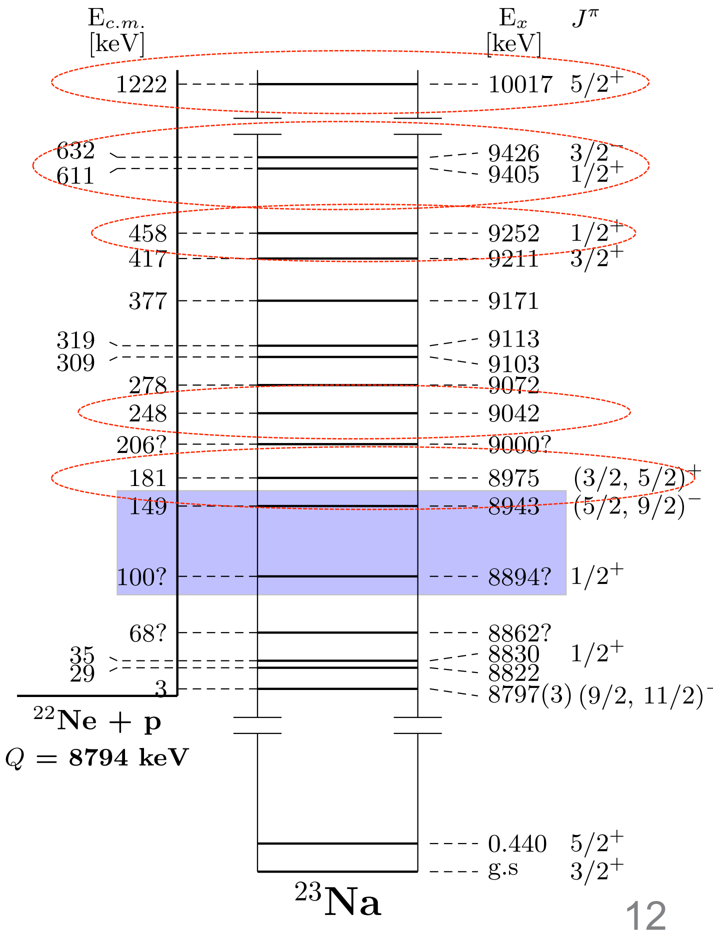
On-resonance:

→ E_{cm}= 149, 181, 249, 458, 611, 632, 1222 keV

(E_{cm}=149 keV **lowest energy** received at DRAGON)

Off-resonance:

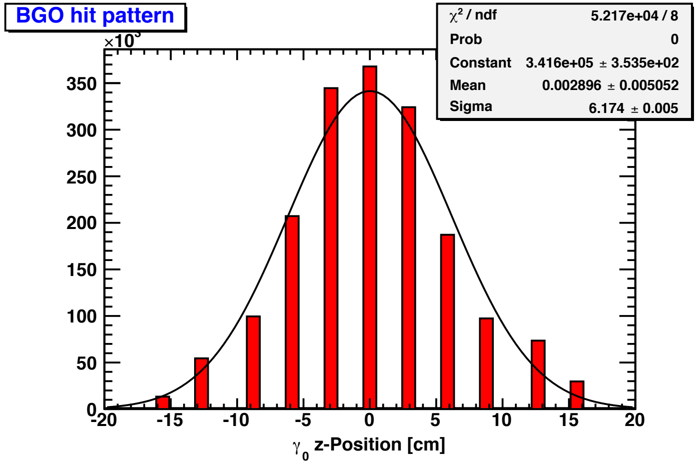
→ Direct capture measurements E_{cm}=280 keV to 400 keV



E_{cm}= 458 keV – DRAGON measurement

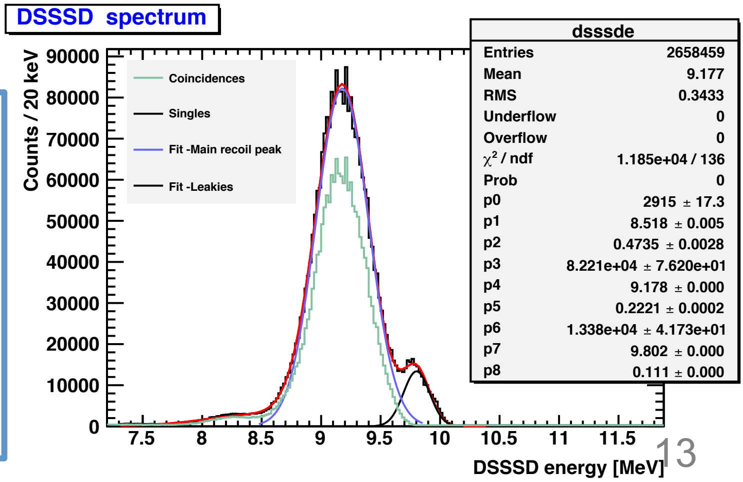
Relevance:

- **Significant contribution** to $^{22}Ne(p,\gamma)^{23}Na$ reaction rate
- Standard ***reference resonance***
- ^{22}Ne-Ta target stoichiometries ($^{22}Ne(\alpha,n)^{25}Mg$ & $^{22}Ne(\alpha,\gamma)^{26}Mg$)



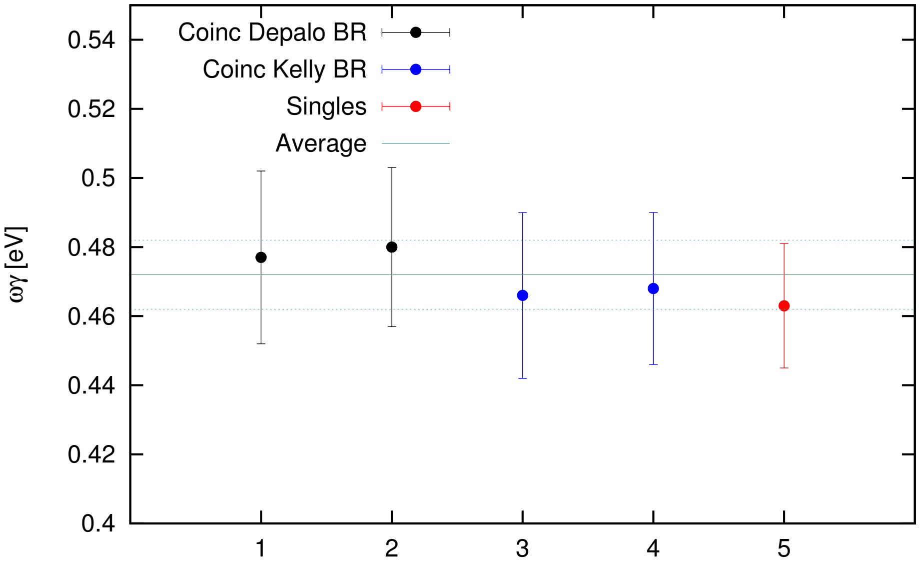
Measurement:

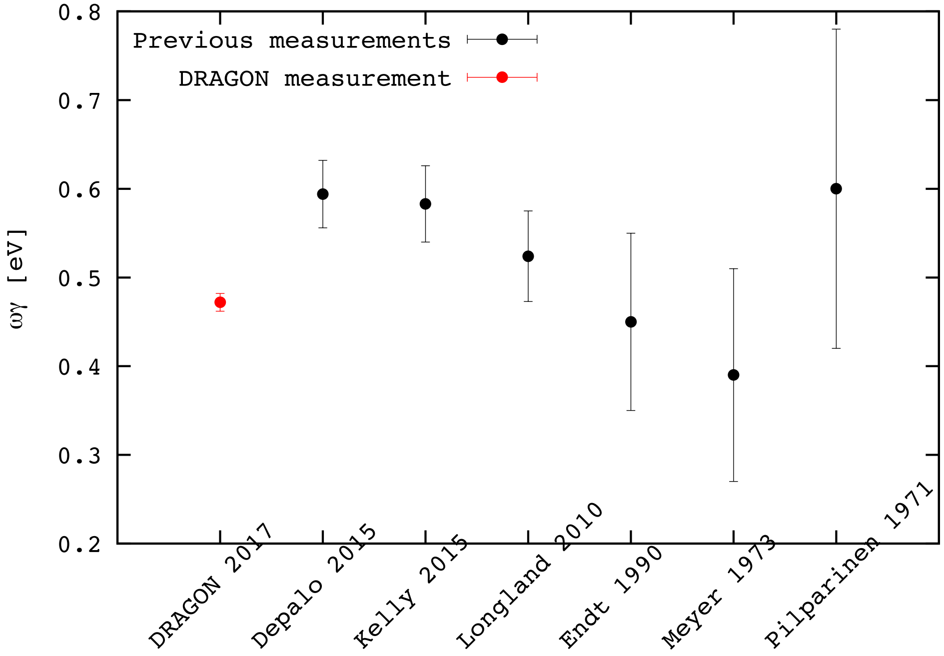
- ~7 hrs of data → High statistics
- High beam suppression with $q_{max}=6^+$ ($q_{beam}=4^+$)
- Measured charge-state distribution and stopping power
- **Singles & coincidence** analysis give consistent results!



E_{cm}= 458 keV – Result

6 previous measurements
(2 in 2015)

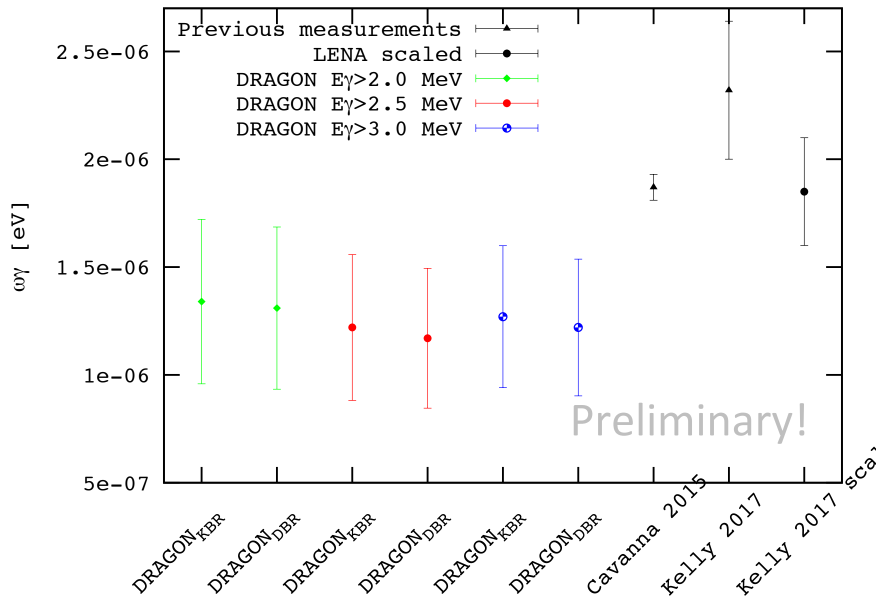


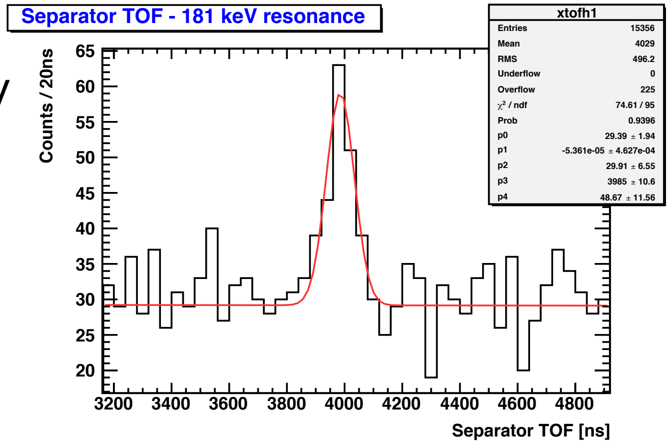


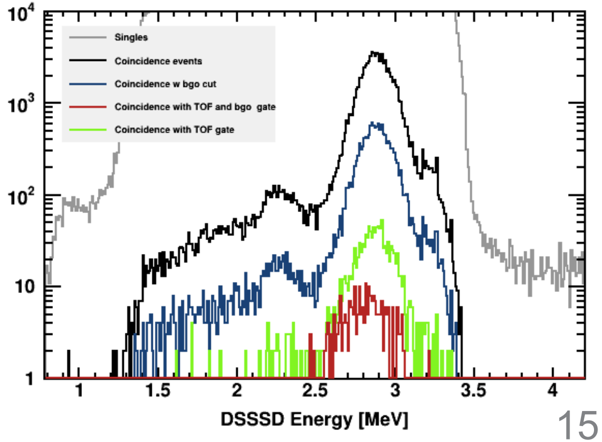
E_{cm}= 181 keV

Challenging measurement…

- Low resonance strength between 1.8*10^{-6} eV and 2.3*10^{-6} eV
- **Second lowest energy** ever received at DRAGON
- **Increased beam emittance** → Higher **background** level
- Recoil cone angle at **limit of geometric acceptance**







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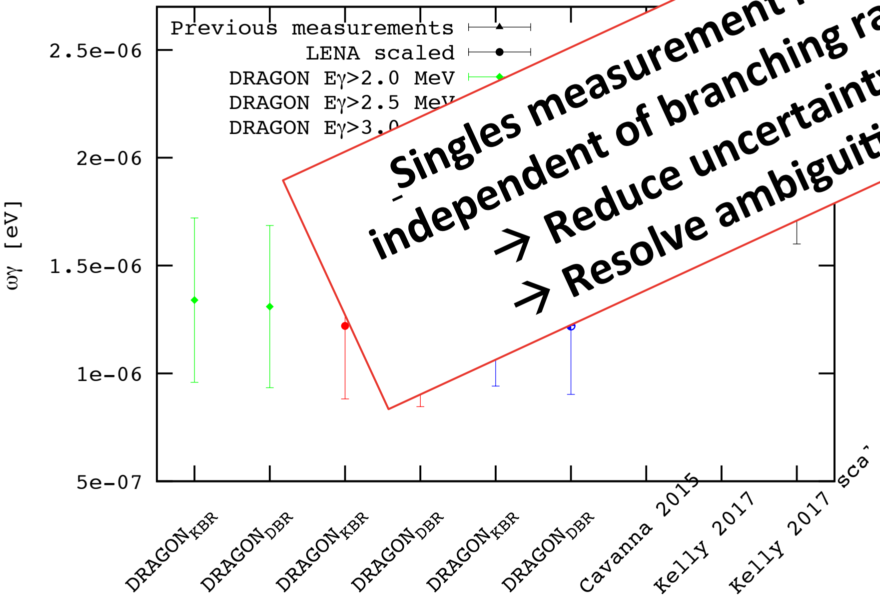
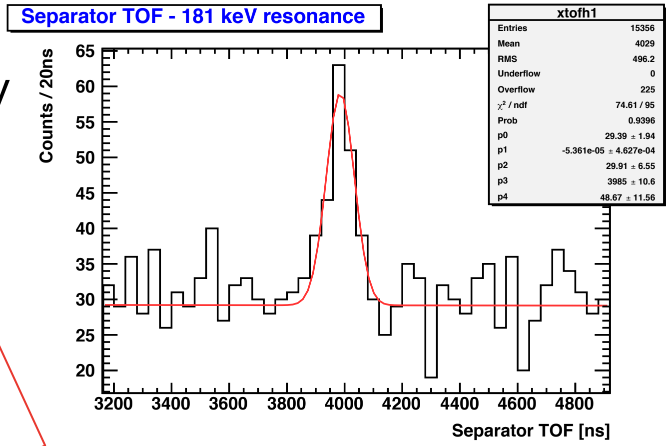
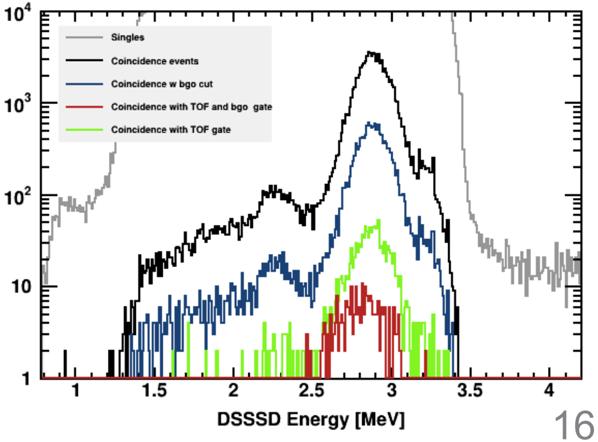
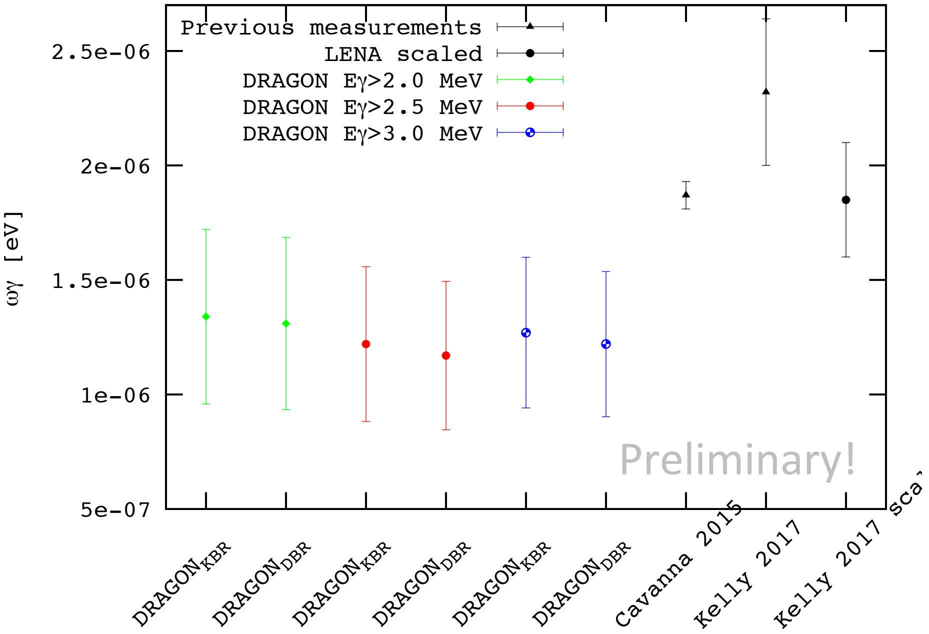


Singles measurement largely independent of branching ratios!
→ Reduce uncertainty
→ Resolve ambiguities

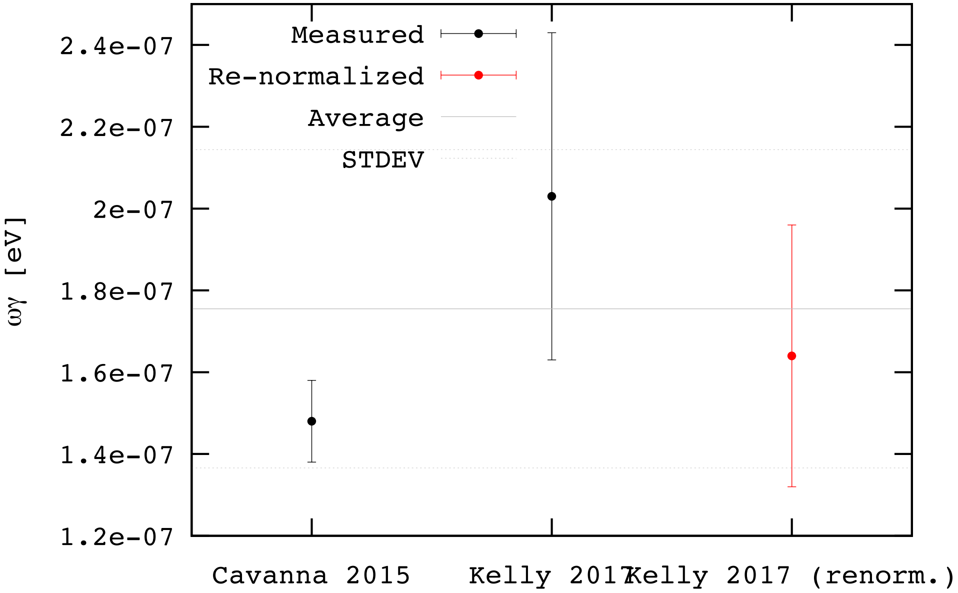




E_{cm} = 181 keV



E_{cm} = 149 keV



Results overview - $\omega\gamma$

E_{cm} [keV]	DRAGON $\omega\gamma$ [eV]	LUNA $\omega\gamma$ [eV]	LENA $\omega\gamma$ [eV]	Longland $\omega\gamma$ [eV]	Meyer $\omega\gamma$ [eV]	Keinonen $\omega\gamma$ [eV]
149	N/A	$1.48(10)\times10^{-7}$	$2.03(40)\times10^{-7}$	N/A	N/A	N/A
181	$1.24(11)\times10^{-6}$	$1.87(6)\times10^{-6}$	$2.32(32)\times10^{-6}$	N/A	N/A	N/A
249	$8.58(48)\times10^{-6}$	$6.89(16)\times10^{-6}$	N/A	N/A	N/A	N/A
458	0.472(10)	0.594(38)	0.583(43)*	0.524(51)	0.45(10)*	N/A
611	3.17(22)	2.45(18)	N/A	N/A	N/A	2.8(3)
632	0.547(18)	$0.032^{+0.024}_{-0.009}$	N/A	N/A	0.35(10)	N/A
1222	11.94 +/- 1.19	10.8(7)*	N/A	N/A	N/A	10.5 +/- 1.0

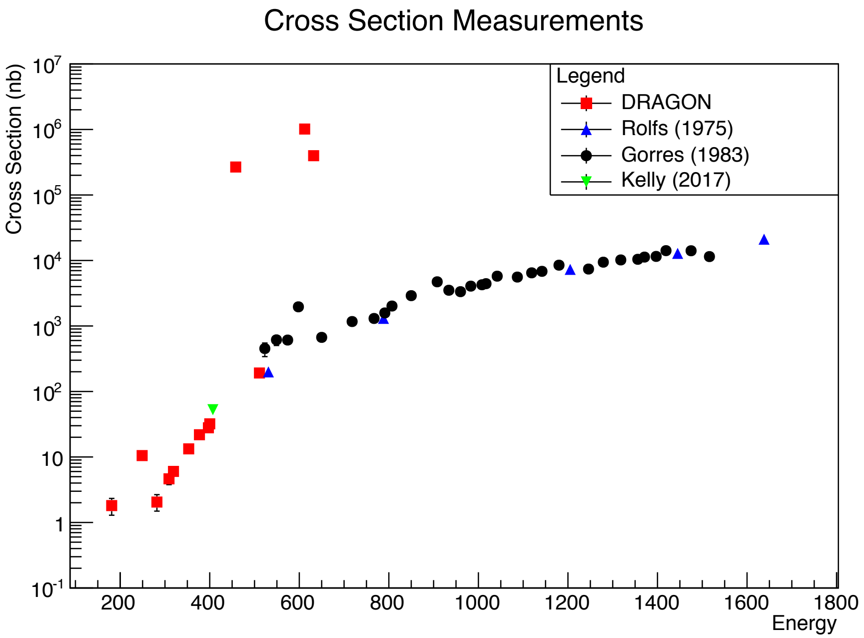
Preliminary!

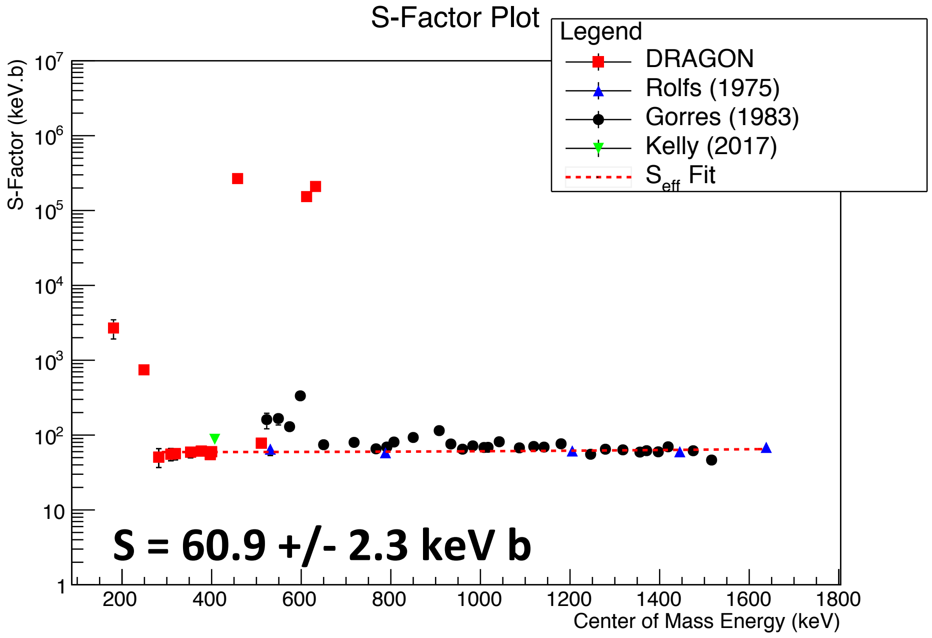
Consistency in ratios

Meyer/Endt: $\omega\gamma(458)/\omega\gamma(612)$ = **0.144** & $\omega\gamma(612)/\omega\gamma(1222)$ = **0.042**

DRAGON: $\omega\gamma(458)/\omega\gamma(612)$ = **0.146** & $\omega\gamma(612)/\omega\gamma(1222)$ = **0.040**

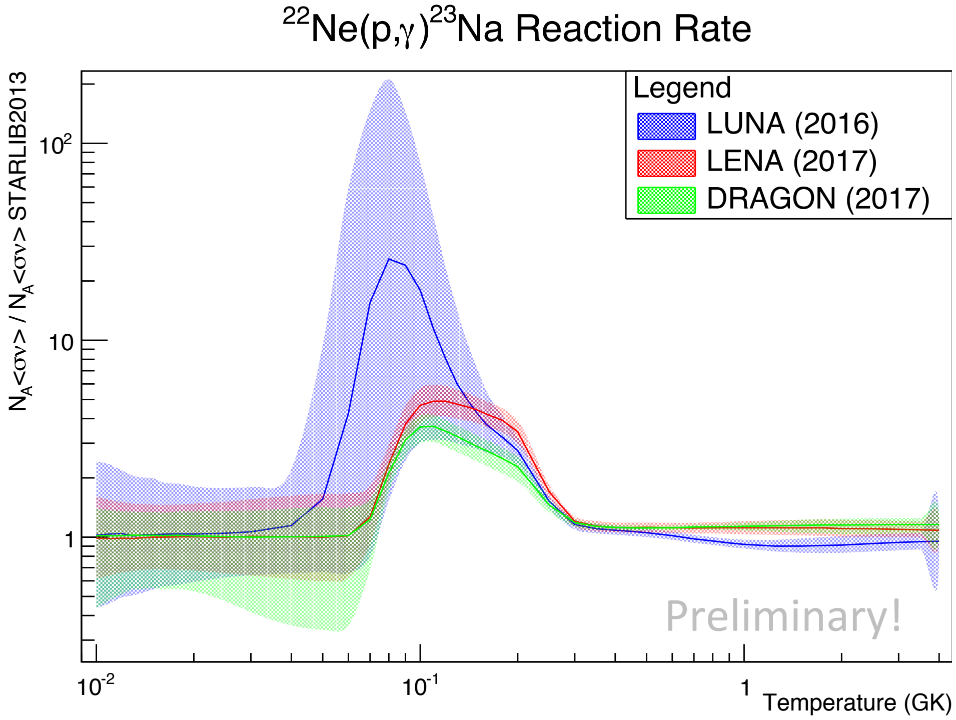
Results





- Görres: S = 62 keV b; Observed DC→ 0 energy dependence [5]
- Rolfs: S = 67 +/- 19 keV b
- LENA measurement at E_{cm} = 407 keV - Normalization to 458 keV results in good agreement
- DRAGON measurement at **low energies** verifies direct capture model extrapolations
- Reduced uncertainty at low energies! 40% → 3.8%

Results



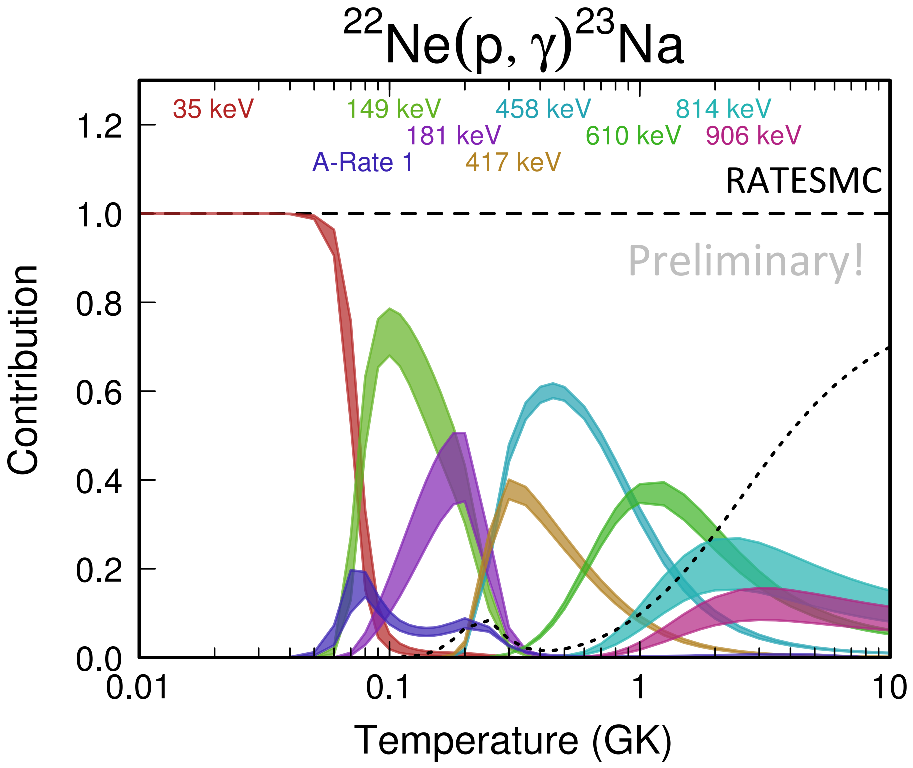


Figure courtesy of R. Longland

Summary

- ***First direct*** study of ^{22}**Ne(*p*,*γ*)**^{23}**Na capture rate** with DRAGON in ***inverse kinematics***
- DRAGON collected data for **7 on-resonance** measurements + DC measurements

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- **ωγ(458 keV) ~20%** lower than 2015 results (LUNA (HZDR) & LENA)

→ Low uncertainty allows for reliable use as reference resonance

- **ωγ(181 keV)** ~34% weaker than LUNA ωγ & ~53% weaker than LENA ωγ

→ **Re-normalization** → Good agreement for low-energy resonances (LUNA, LENA)

- ωγ(458)/ωγ(612) & ωγ(612)/ωγ(1222) **ratios consistent** with Meyer/Endt results
- **Reduced uncertainty on DC contribution 40% → 3.8%**
- DRAGON rate **maps closely** with recent **LENA** rate

Next steps:

- Abundance calculations with revised rate – impact in *other astrophysical sites*?
- 181 keV verification with reduced uncertainty & 149 keV in inverse kinematics

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Many thanks to the DRAGON collaboration!

TRIUMF, BC, CA
University of York, UK
University of Surrey, UK
Collorado School of Mines, CO, US
McMaster University, ON, CA
Ohio University, OH, US
Michigan State University, MI, US
Notre Dame, IN, US

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Thank you!
Merci!

TRIUMF: Alberta | British Columbia | Calgary | Carleton | Guelph | Manitoba | McGill | McMaster | Montréal | Northern British Columbia | Queen's | Regina | Saint Mary's | Simon Fraser | Toronto | Victoria | Western | Winnipeg | York

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[1] Marie Luise Menzel – PhD thesis

[2] Cavanna et. al. PRL 115, 252501 (2015)

[3] Slemer et. al. arXiv:1611.07742v1 (2016)

[4] R. Longland et al., Phys. Rev. C, 81:055804 (2010)

[5] Görres et al. Nucl. Phys. A 408, 372 (1983)

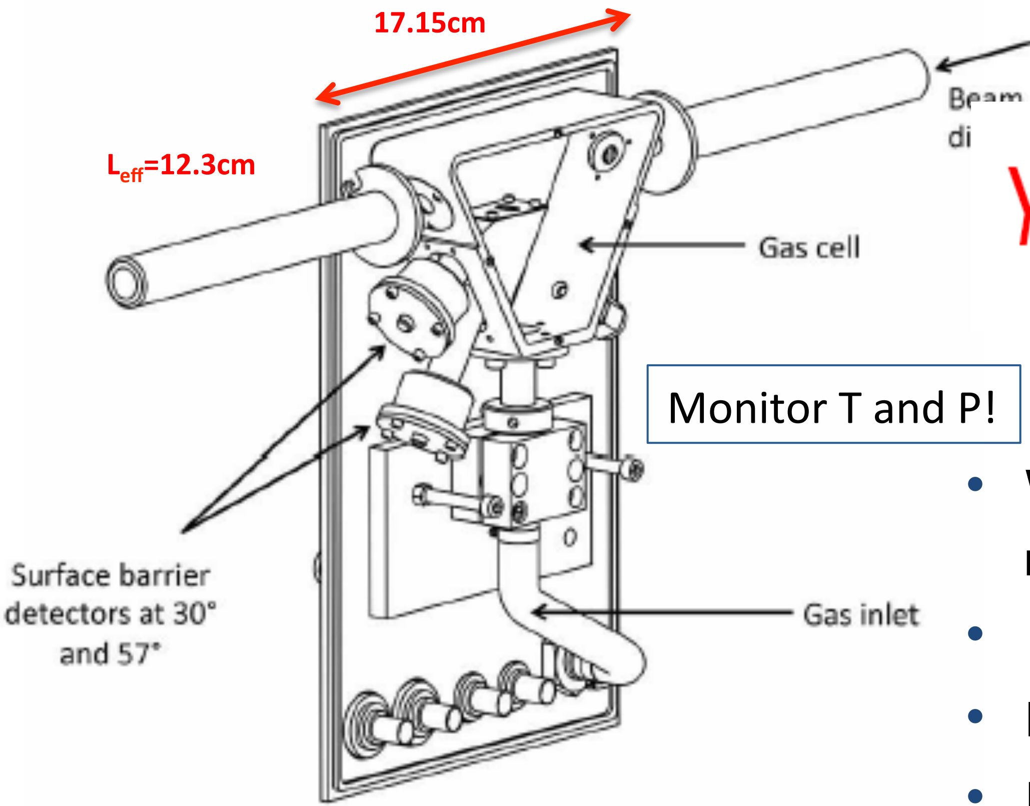
[6] Rolfs et al. Nucl. Phys. A, 241(3):460-486 (1975)

[7] Kelly et al. Phys. Rev. C, 95:015806 (2017)

[8] R. Depalo et al. Phys. Rev. C, 92:045807, 2015

[9] M. A. Meyer and J.J.A. Smit, Nucl. Phys. A, 205:177 (1973)

DRAGON gas target



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

Monitor T and P!

- Windowless, differentially pumped, recirculating **gas target** (H_2 or He)
- 1-10mbar (pumping constraints)
- LN_2 cooled zeolite cleaning trap
- Hourly FC readings + elastic scattering rate for **normalization**