STELLAR EXPLOSIONS IN THE LAB: MEASUREMENTS OF KEY NUCLEAR REACTIONS DRIVING NUCLEOSYNTHESIS

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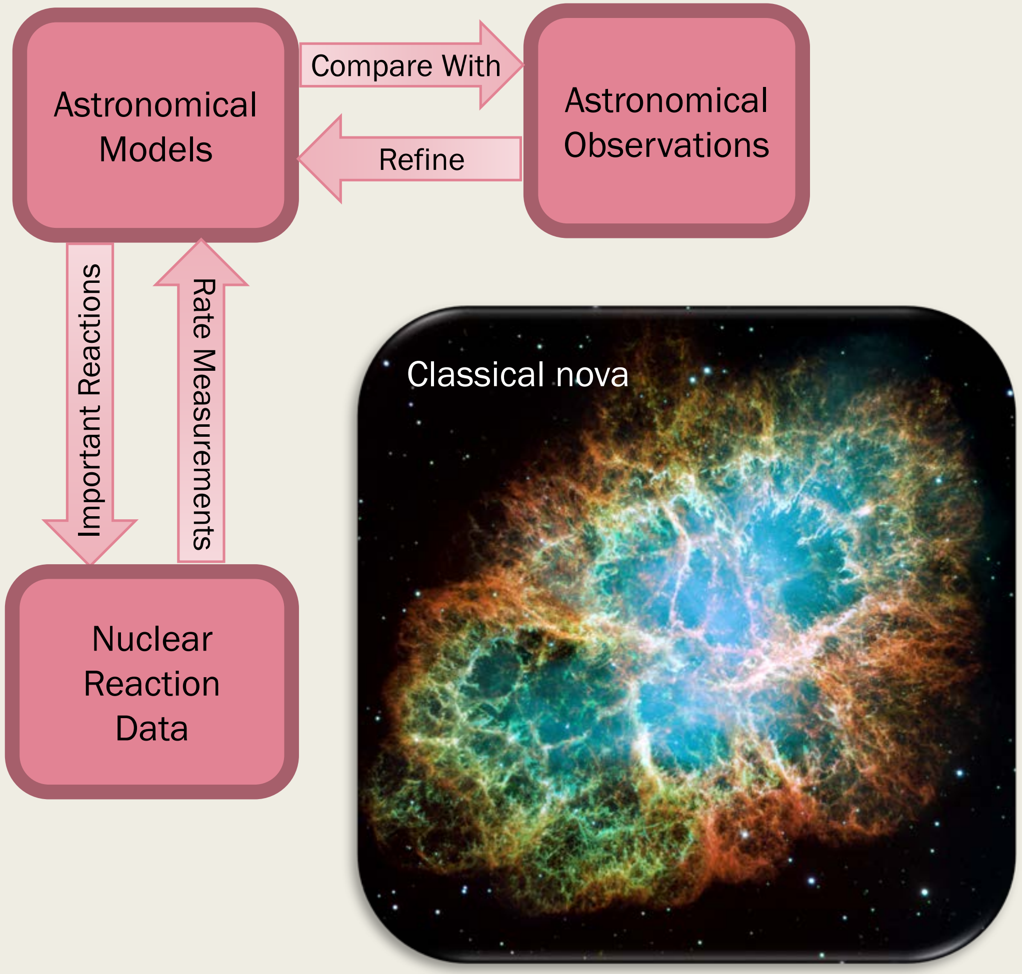
Motivation

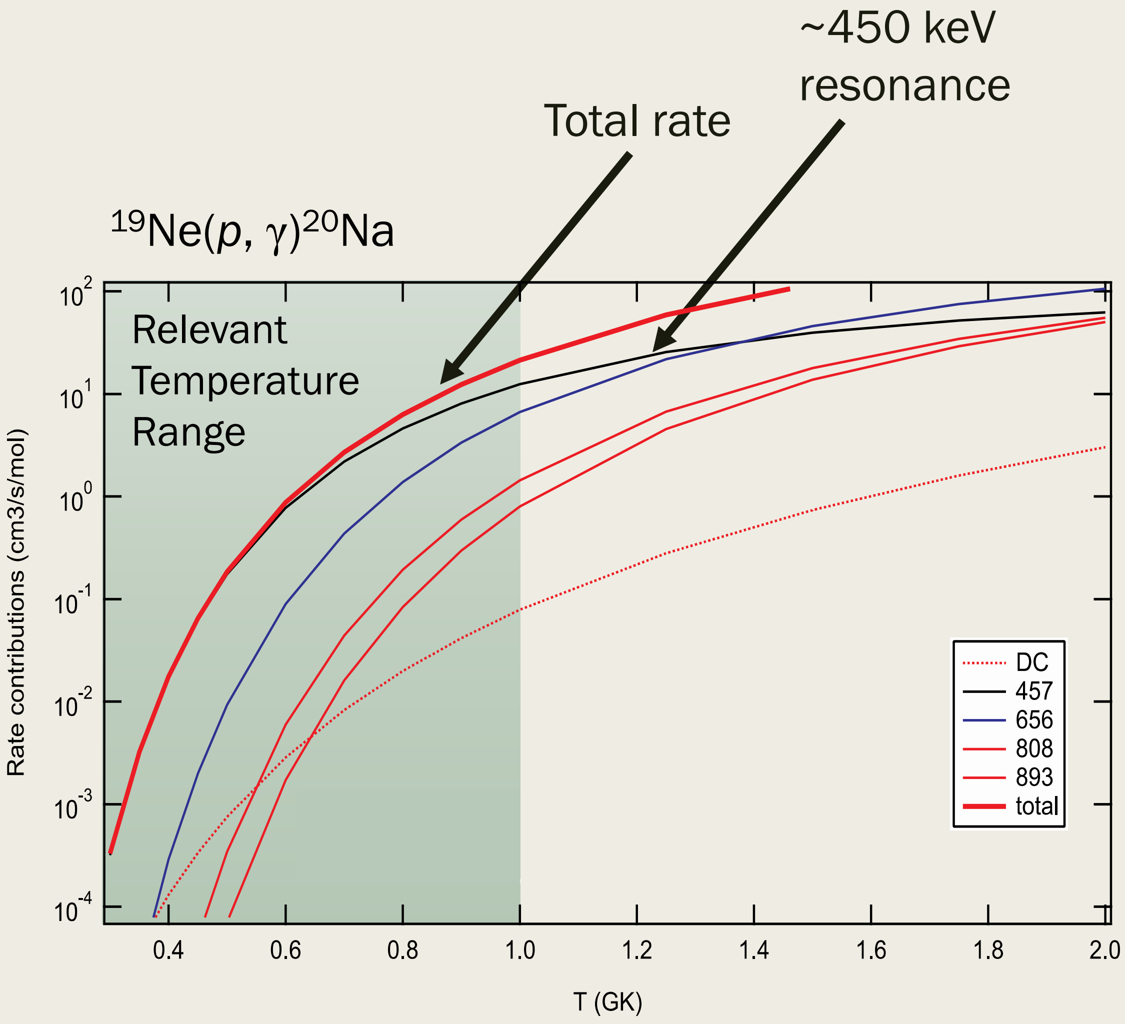
- Understand nucleosynthesis in stellar explosions
  - *Novae*
  - *Supernovae*
  - *X-ray bursts*
- Nuclear physics: laboratory measurements to constrain key reaction rates
  - *Proton and alpha induced reactions primarily*



Reaction Rates

- Rates often dominated by one or a few discrete resonances
- Resonance contribution can be determined by lab measurements:
  - *Resonance energy, E_r*
  - *Resonance strength, $\omega\gamma$*

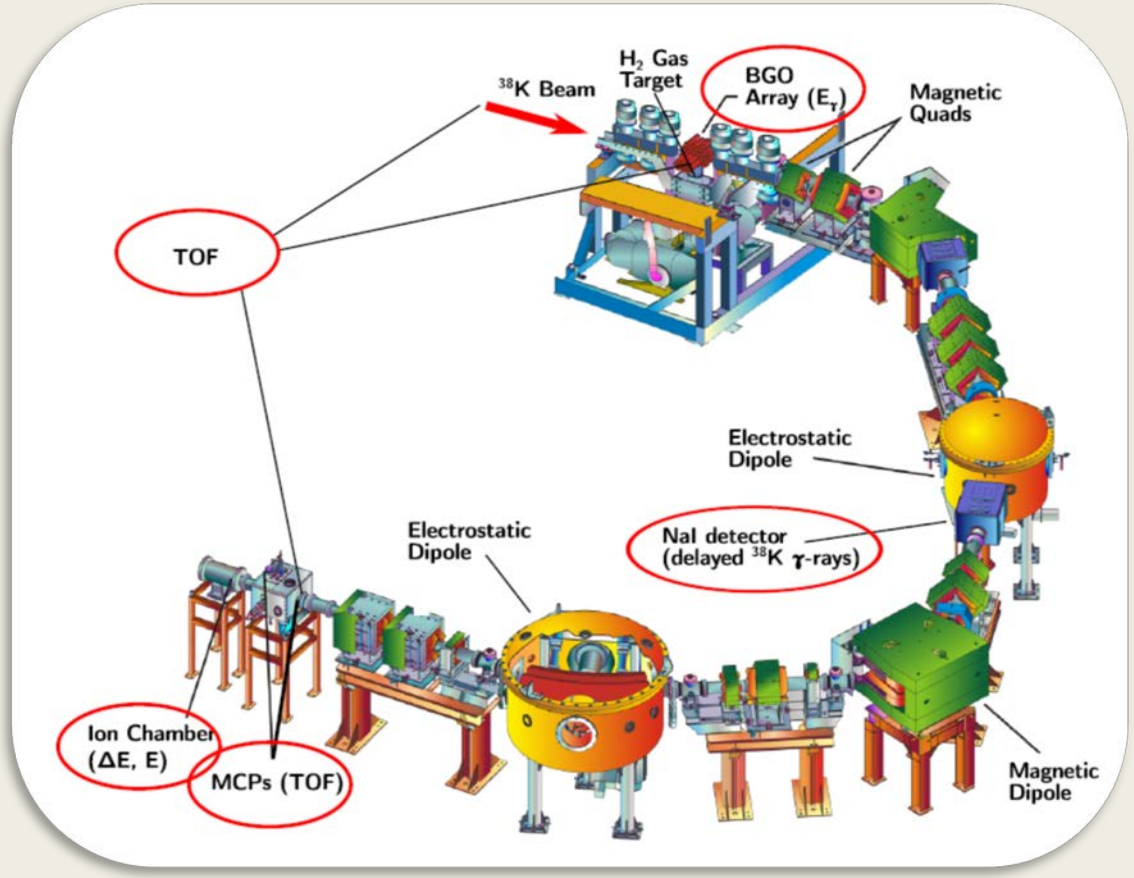
$$N_A\langle\sigma v\rangle = 1.54 \times 10^{11}(\mu T_9)^{-3/2}\,\omega\gamma\cdot e^{(-11.605\,E_r/T_9)}$$



Direct Measurements

- Measure yield of the reaction of interest, on-resonance
- Nowadays, inverse kinematics + recoil separators widely employed
  - *Background suppression*
  - *Measurements w/ radioactive beams*
- Sensitive to both strength (yield) and energy (position in extended target)

DRAGON Recoil Separator at TRIUMF
Vancouver, BC Canada



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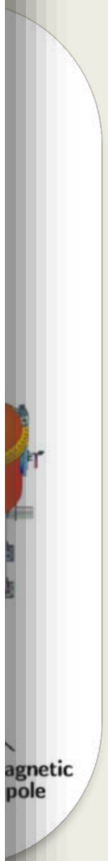
Reaction	Motivation	Intensity (s^{-1})	Purity (desired:contaminant)
$^{21}Na(p,\gamma)^{22}Mg$	1.275 MeV line emission in ONe novae	5×10^9	100%
$^{12}C(\alpha,\gamma)^{16}O$	Helium burning in red giants	3×10^{11}	
$^{26g}Al(p,\gamma)^{27}Si$	Nova contribution to galactic ^{26}Al	3×10^9	30,000:1
$^{12}C(^{12}C,\gamma)^{24}Mg$	Nuclear cluster models	3×10^{11}	
$^{40}Ca(\alpha,\gamma)^{44}Ti$	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}	
$^{23}Mg(p,\gamma)^{24}Al$	1.275 MeV line emission in ONe novae	5×10^7	1:20 - 1:1,000
$^{17}O(\alpha,\gamma)^{21}Ne$	Neutron poison in massive stars	1×10^{12}	
$^{18}F(p,\gamma)^{19}Ne$	511 keV line emission in ONe novae	2×10^6	100:1
$^{33}S(p,\gamma)^{34}Cl$	S isotopic ratios in nova grains	1×10^{10}	
$^{16}O(\alpha,\gamma)^{20}Ne$	Stellar helium burning	1×10^{12}	
$^{17}O(p,\gamma)^{18}F$	Explosive H burning in novae	1×10^{12}	
$^{3}He(\alpha,\gamma)^{7}Be$	Solar neutrino spectrum	5×10^{11}	
$^{58}Ni(p,\gamma)^{59}Cu$	High mass tests (p-process, XRB)	6×10^9	
$^{26m}Al(p,\gamma)^{27}Si$	SNII contribution to galactic ^{26}Al	2×10^5	1:10,000
$^{38}K(p,\gamma)^{39}Ca$	Ca/K/Ar production in novae	2×10^7	1:1

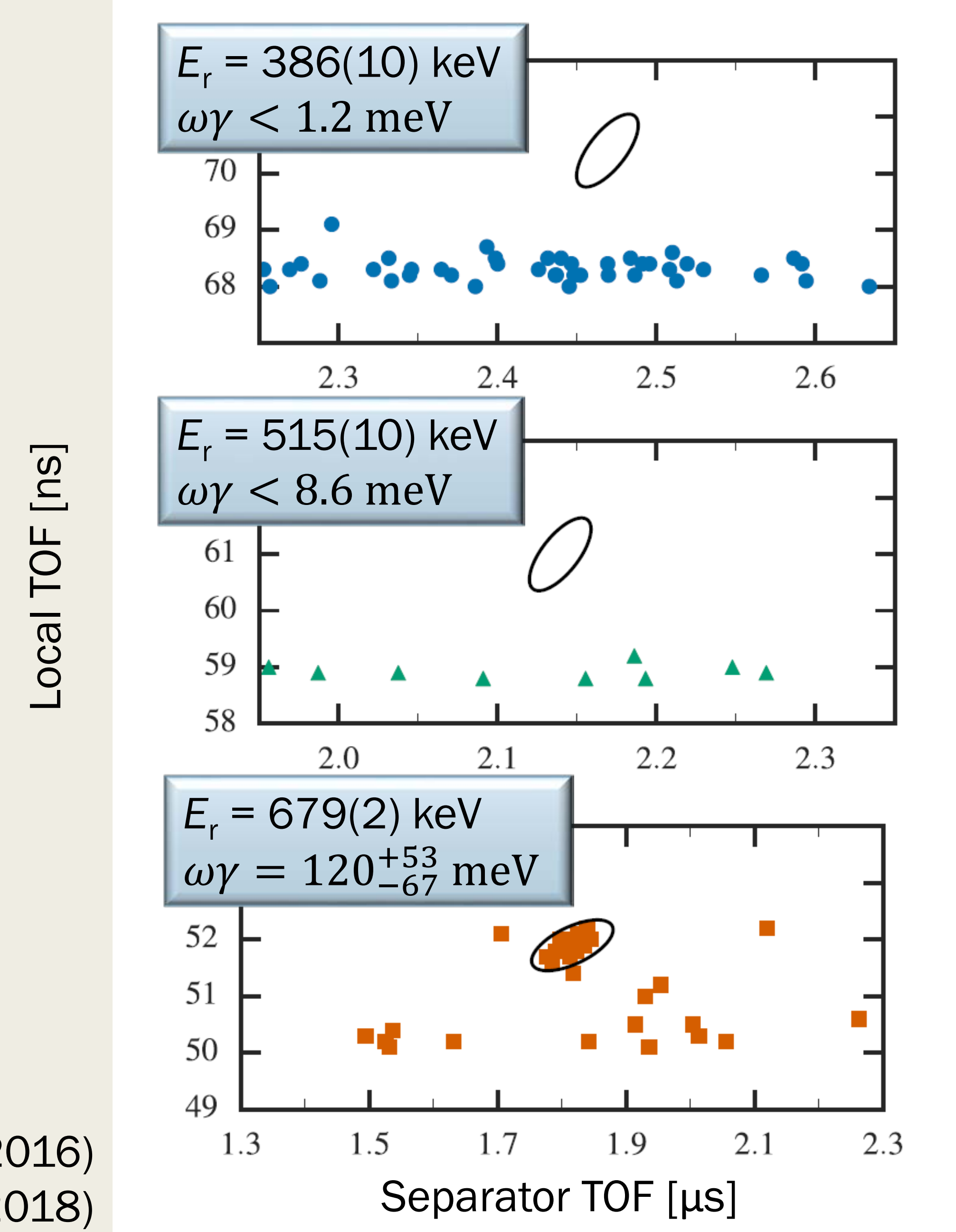
Table credit C. Ruiz



Recent Highlights (from DRAGON)

$^{38}K(p, \gamma)^{39}Ca$

- Significant influence on synthesis of Ar, K, & Ca in hottest novae
- Measured three L = 0 resonances in Gamow window



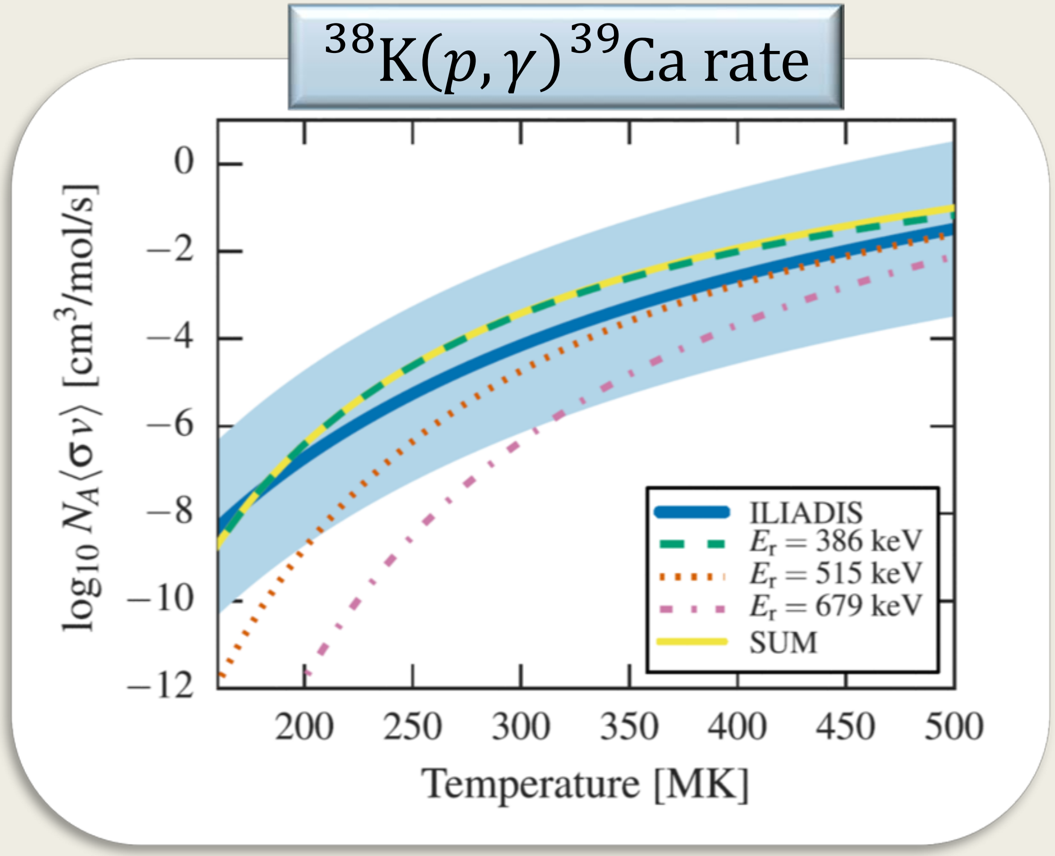
G. Lotay *et al.*, Phys. Rev. Lett., 116, 132701 (2016)
G. Christian *et al.*, Phys Rev. C 97, 025802 (2018)

Recent Highlights (from DRAGON)

- Significant decrease on uncertainty of nucleosynthesis predictions

Element	*Uncertainty change*
Argon	25 → 2
Potassium	136 → 18
Calcium	58 → 9

First ever direct measurement of radiative capture w/ radioactive beam $A > 30$



G. Lotay *et al.*, Phys. Rev. Lett., 116, 132701 (2016)
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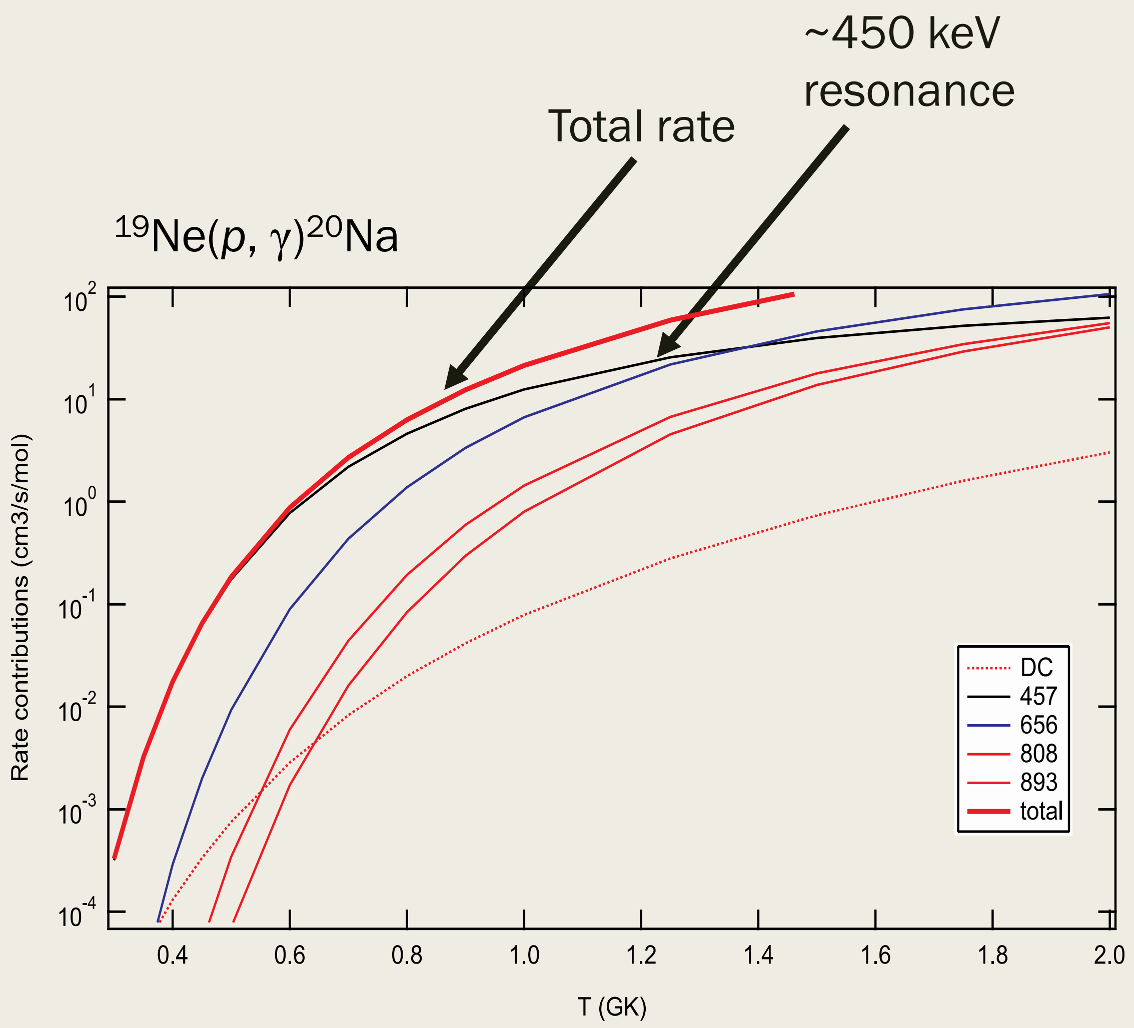
Recent Highlights (from DRAGON)

$^{19}Ne(p, \gamma)^{20}Na$

- Novae
  - *Synthesis of ^{19}F*
- Type-I X-ray bursts
  - *Breakout of hot CNO cycle*
- Rate dominated by single resonance at E_r ~ 450 keV
  - *Under investigation over 20 years, but no "definitive" direct measurement to-date*

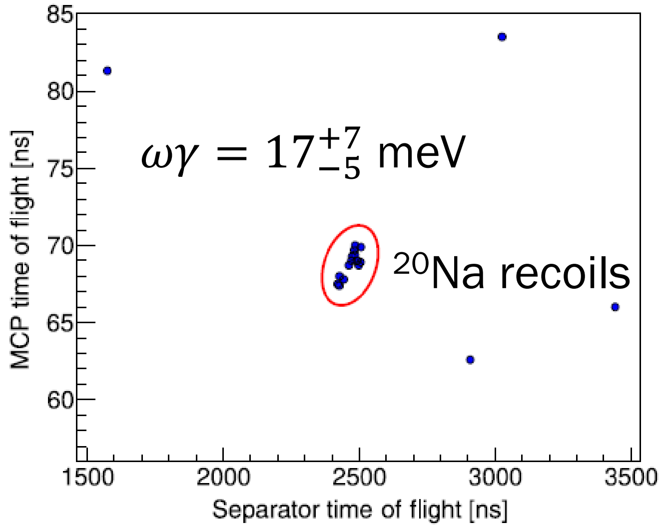


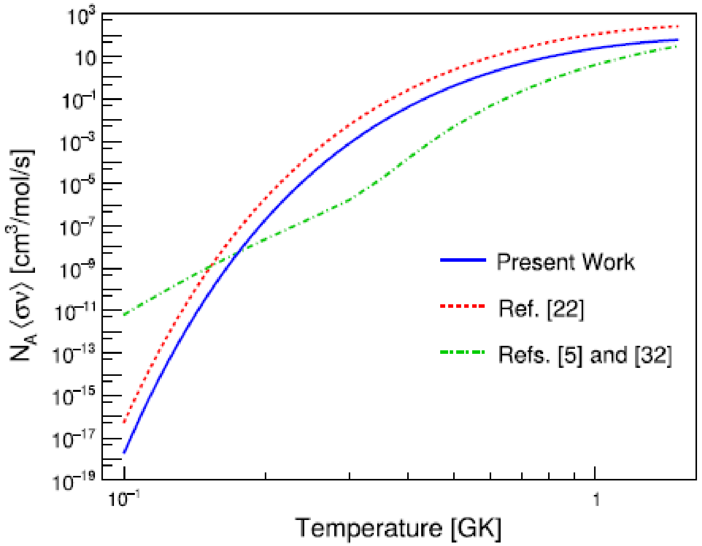
$^{19}Ne(p, \gamma)^{20}Na$

- First establishment of reaction rate based on a ***direct*** measurement
- Established rate higher than previous evaluation[1]
  - *Depletion of ^{19}F → explanation for scarcity of ^{19}F observations in novae?*

U. Surrey PhD student
Ryan Wilkinson

[1]C. Iliadis, A. Champagne, J. Jose, S. Starrfield, & P. Tupper, Astrophys. J. Suppl. Ser. 142, 105 (2002).





R. Wilkinson *et al.*, Phys. Rev. Lett. 119, 242701 (2017)

Indirect Measurements

- Direct measurements often not possible
  - *Low cross sections*
  - *Low beam intensities*
- Spectroscopy of key resonant states (or their mirrors) through nucleon transfer reactions

  → *Indirect determination of* $\omega\gamma$

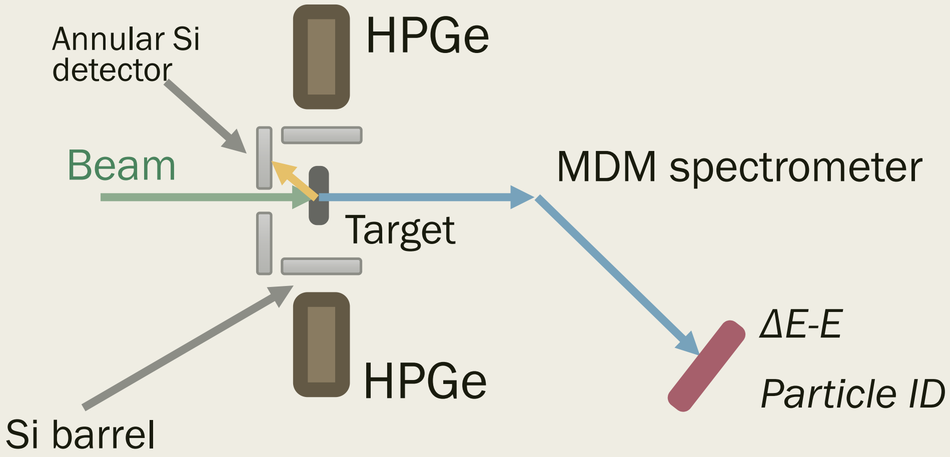
Spins

Single-particle strengths

$$\omega\gamma = \frac{2J_r + 1}{(2j_0 + 1)(2j_1 + 1)} \frac{\Gamma_\gamma \Gamma_p}{\Gamma_\gamma + \Gamma_p}$$

TIARA for Texas Setup
Texas A&M University

- Inverse-kinematics measurements of (*d*, *p*), (^{6}Li, *d*) [+ others]
- Triple-coincidence detection of light ejectile, heavy recoil, gamma rays
- Measure $d\sigma/d\Omega$
  → *spins, spectroscopic factors*
- Heavy recoil PID
  → *decay branches*



Measurements w/ re-accelerated radioactive beams from TAMU Cyclotron Institute upgrade

TIARA for Texas – Commissioning + Stable Beam Campaign

- Four experiments w/ astrophysical motivation

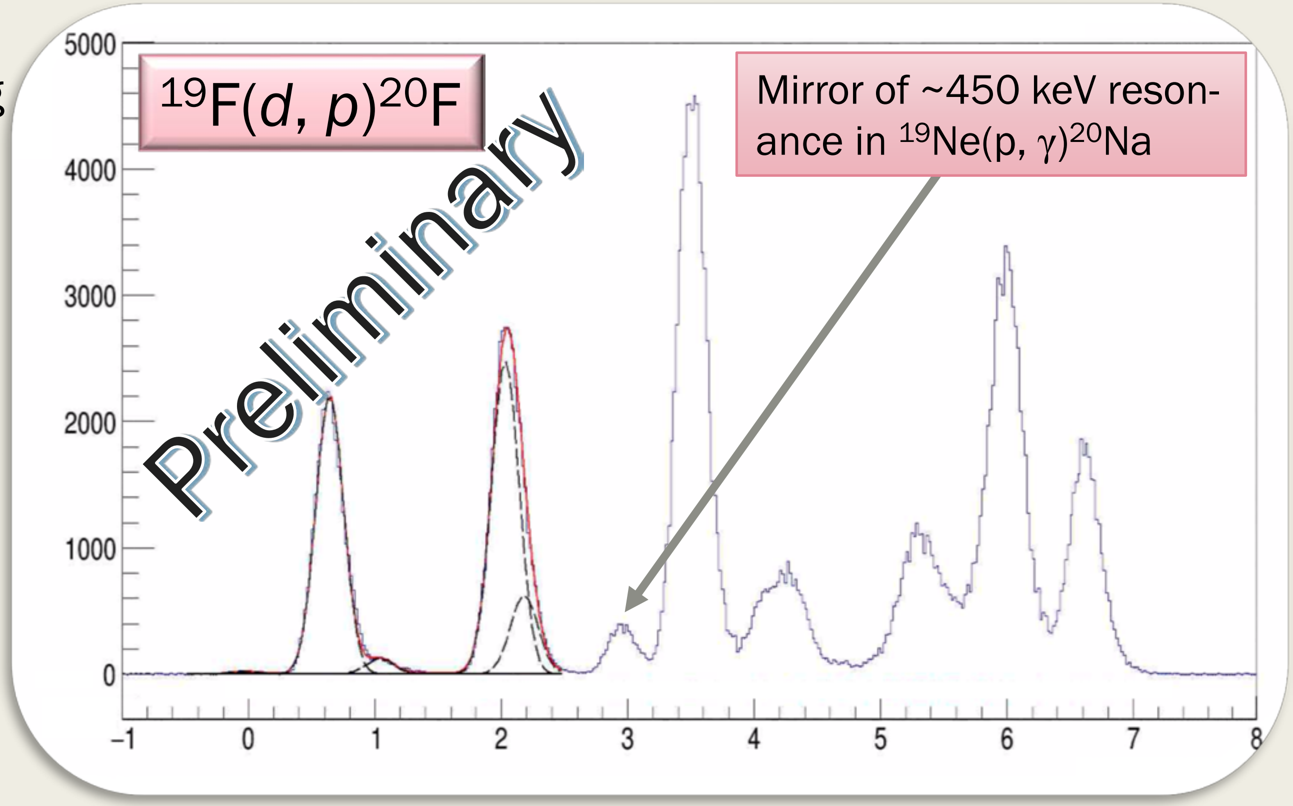
Commissioning

Novae / X-ray bursts

Interesting reaction	*Measured reaction*
$^{19}Ne(p, \gamma)^{20}Na$	$^{19}F(d, p)^{20}F$
$^{23}Mg(p, \gamma)^{24}Al$	$^{23}Na(d, p)^{24}Na$

Neutron source for weak *s*-process

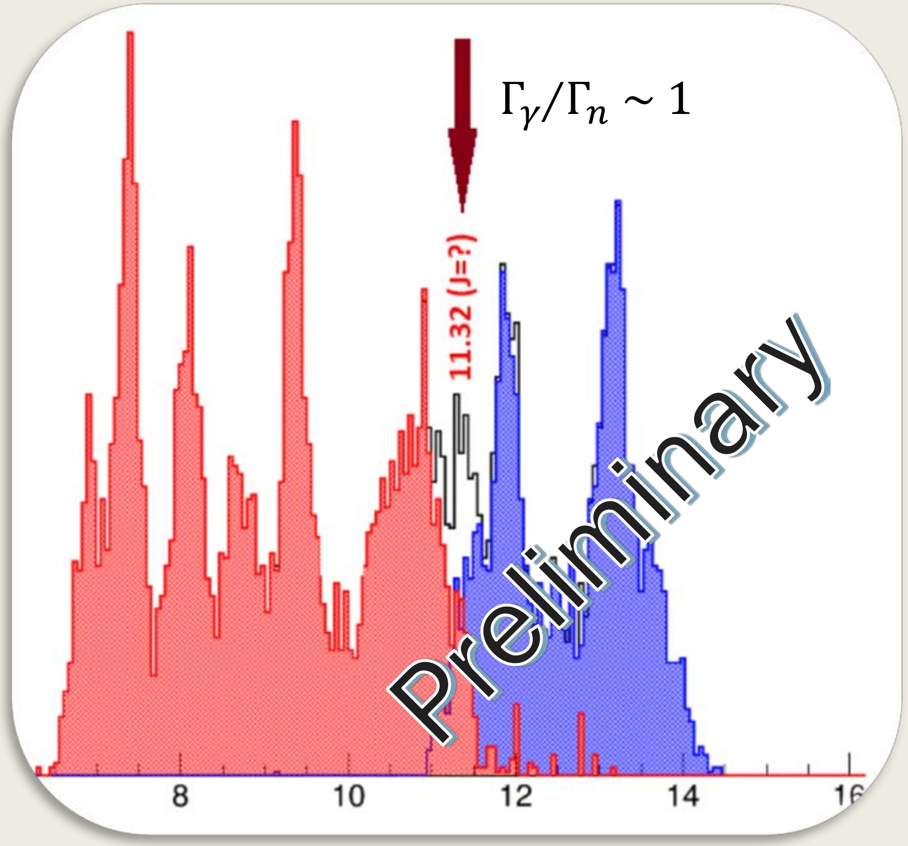
Interesting reactions	*Measured reactions*
$^{22}Ne(\alpha, \gamma)^{26}Mg$ & $^{22}Ne(\alpha, n)^{25}Mg$	$^{25}Mg(d, p)^{26}Mg$ & $^{22}Ne(^{6}Li, d)^{26}Mg$



Excitation Energy [MeV]

Constraining the $^{22}Ne(\alpha, n)^{26}Mg$ Reaction

- Neutron source for the weak *s*-process
- Rate likely dominated by two resonances
  - E_x = *11.17 MeV*
  - E_x = *11.32 MeV*
- $^{22}Ne(^{6}Li, d)^{26}Mg$ @7 MeV/nucleon
  - *Spins*
  - *Alpha spectroscopic factors*
  - *Neutron/Gamma decay branches*



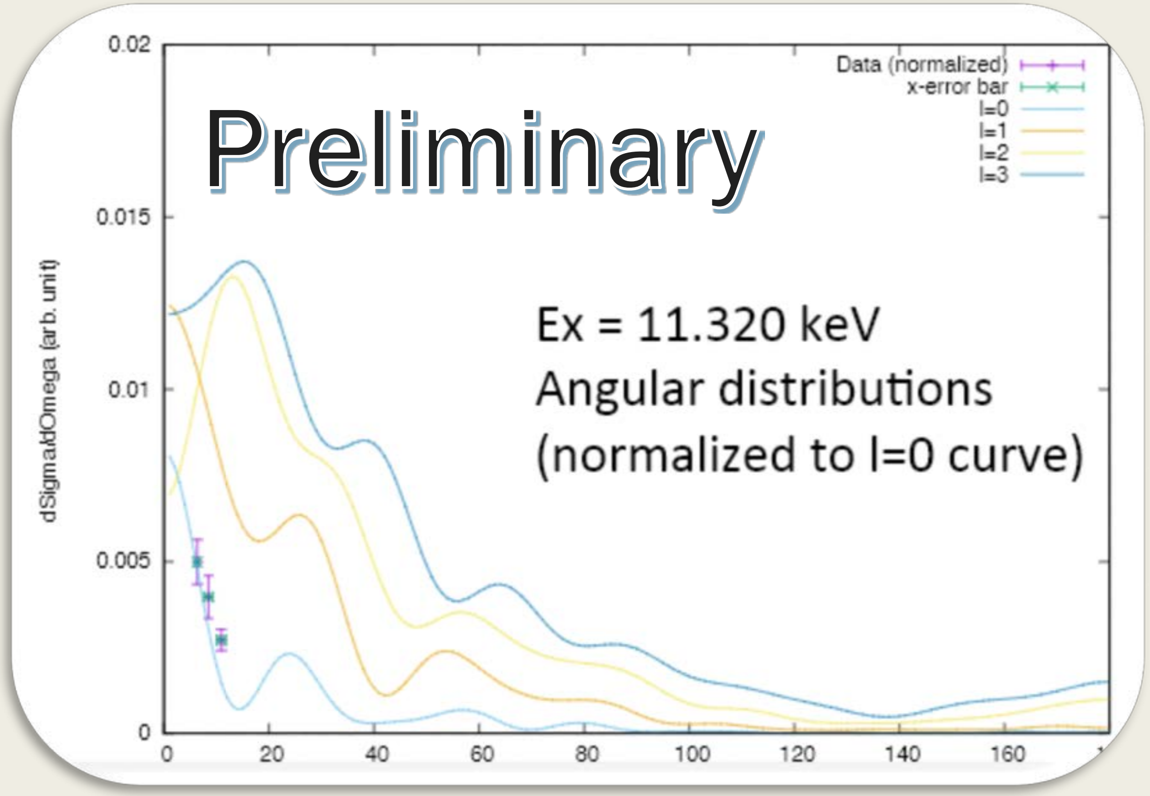
^{26}Mg Excitation Energy

Red: ^{26}Mg coincidence
Blue: ^{25}Mg coincidence
Black curve: sum

Spin of 11.32 MeV Resonance

- Conflicting assignments from previous experiments, but likely 0^+, 1^-, 2^+
- Our angular distributions consistent w/ $J^\pi = 0^+$ or 1^-
- Our Γ_γ/Γ_n suggests L=2 or L=3 neutron resonance
  → $J^\pi = 0^+, 4^+, \text{or } 5^-$
- Combination → likely $J^\pi = 0^+$

TAMU Postdoc
Shuya Ota



Summary

- Nuclear reaction data required for accurate models of explosive stellar nucleosynthesis
- Both direct and indirect measurement techniques widely employed at labs around the world
- Area of active and vigorous interest, in particular as next-generation nuclear physics accelerators come online

Collaborators & Acknowledgements

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  - *C. Ruiz, D. Hutcheon, B. Davids, J. Fallis, A. Lennarz, D. Connolly*
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- … And many more!