Investigations of the $^{15}N(\alpha,\gamma)^{19}F$ Reaction at Resonance Energies E_r = 1.3 and 1.4 MeV at Notre Dame

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Outline

- Motivations
  - Stellar evolution
  - Astrophysical origin of ^{19}F is unclear
  - Discrepancies in previous measurements
- Solid $Ti^{15}N$ target γ-spectroscopy experiment in forward kinematics
  - Experimental setup
  - Energy, strength, and alpha width from γ-spectroscopy
- Summary and outlooks

Astrophysical Origin of ^{19}F

- Asymptotic Giant Branch (AGB) stars
  - Direct observation: Overabundance up to a factor of 50 times solar (Jorissen et al., A&A, 1992)
  - $^{14}N(\alpha,\gamma)^{18}F(\beta^{+})^{18}O(p,\alpha)$**$^{15}N(\alpha,\gamma)^{19}F$**
  - $^{14}N(n,p)^{14}C(\alpha,\gamma)^{18}O(p,\alpha)$**$^{15}N(\alpha,\gamma)^{19}F$** (Forestini et al., A&A, 1992)
- Wolf-Rayet stars
  - ^{19}F is synthesized at the beginning of He-burning (Meynet and Arnould, A&A, 2000)
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- Core-collapse supernovae
  - Neutrino spallation on ^{20}Ne (Woosley and Haxton, Nature, 1988)
  - $^{20}Ne(\nu,\nu'p)^{19}F$

^{19}F origin and abundance in the solar neighborhood?

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Within observational uncertainties, but not main source (Abia et al., A&A, 2019; Vescovi et al., A&A, 2021)

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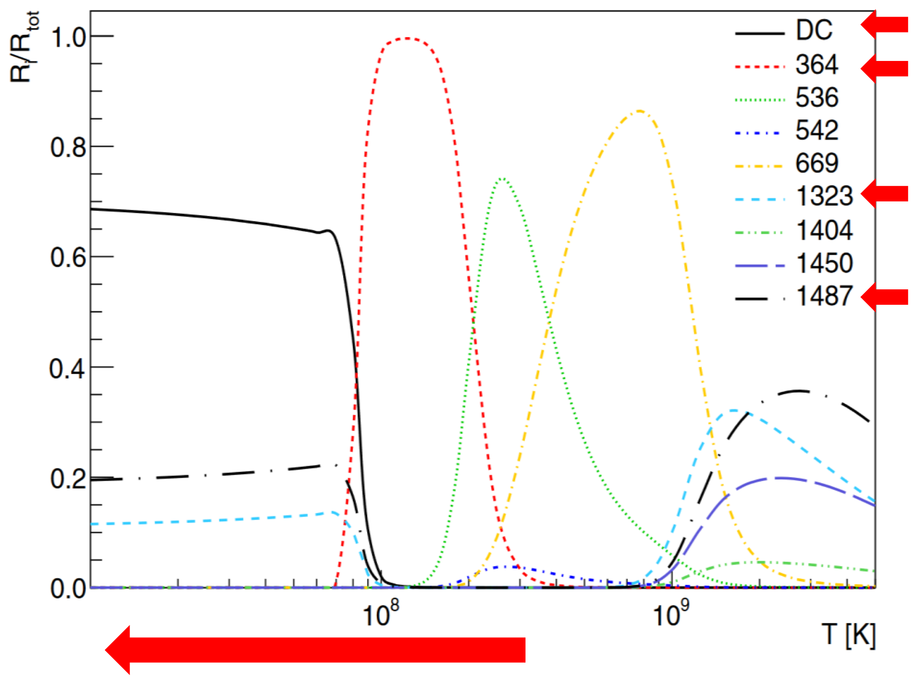
$^{15}N(\alpha,\gamma)^{19}F$ Reaction Rate in AGB Stars

Resonance reaction rate:

$$N_A\langle\sigma v\rangle = N_A\left(\frac{2\pi}{\mu kT}\right)^{3/2}\hbar^2(\omega\gamma)e^{-E_R/kT}$$



T < 0.3 GK

Figure from Di Leva et al., Phys. Rev. C, 2017

Resonance strength:

$$\omega\gamma = \omega\frac{\Gamma_\alpha\Gamma_\gamma}{\Gamma_\alpha+\Gamma_\gamma}$$

- $E_{c.m.}$ = 364 keV resonance strength has an uncertainty of 100% (de Oliveira et al., Nuc. Phys. A, 1996)
- Direct Capture (DC) contribution has 40% uncertainty (Iliadis et al., Nuc. Phys. A, 2010)
- Tails from two resonances at $E_{c.m.}$ = 1323 and 1487 keV

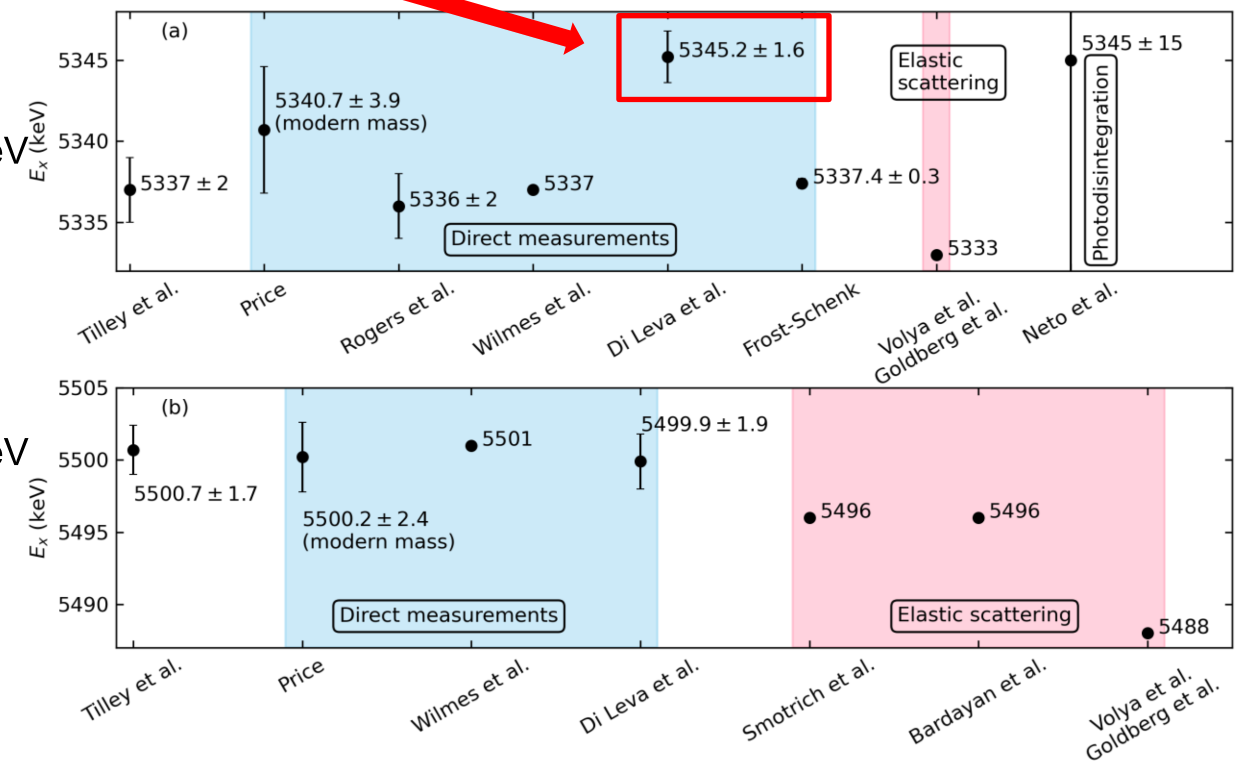
Previous Measurements – Res. Energy

~8 keV increase

$$N_A\langle\sigma v\rangle = N_A\left(\frac{2\pi}{\mu kT}\right)^{3/2}\hbar^2(\omega\gamma)e^{-E_R/kT}$$

$E_{c.m.}$ = 1323 keV

$E_{c.m.}$ = 1487 keV

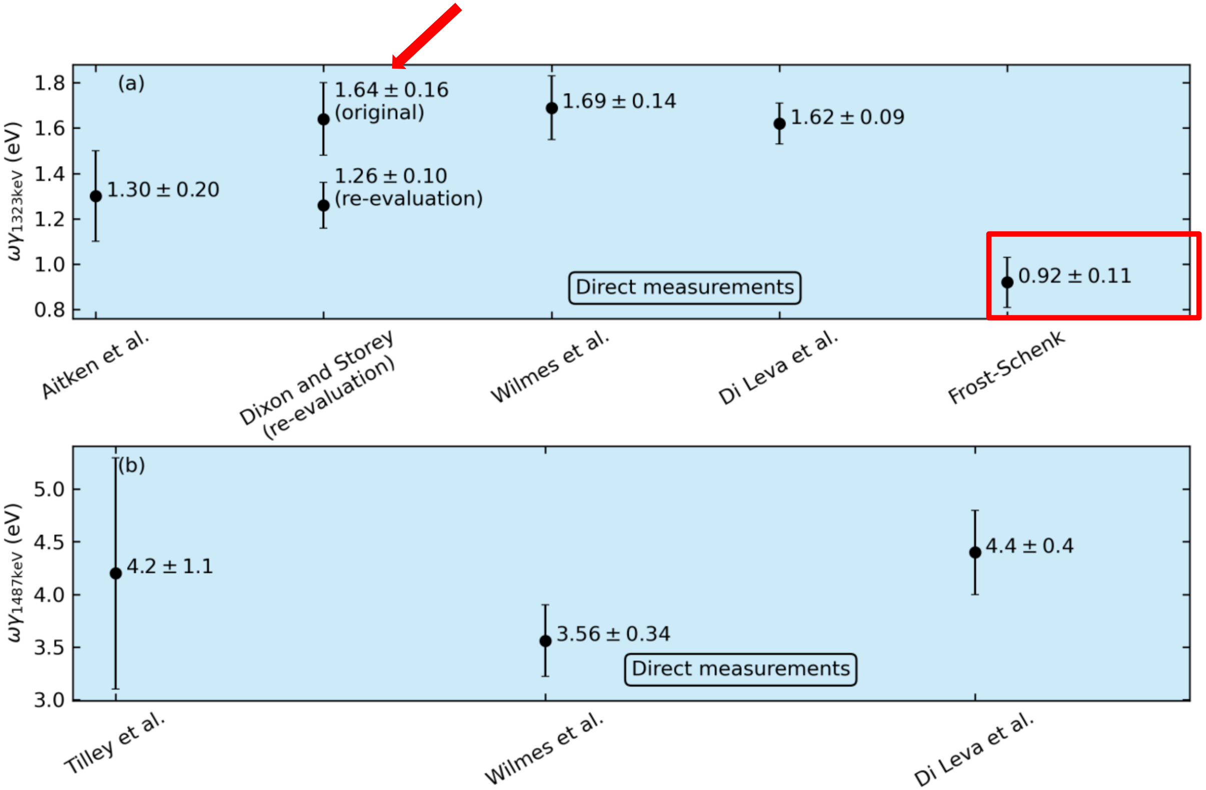


Possible lower excitation energy?

Previous Measurements – Strength

$E_{c.m.}$ = 1323 keV

$E_{c.m.}$ = 1487 keV

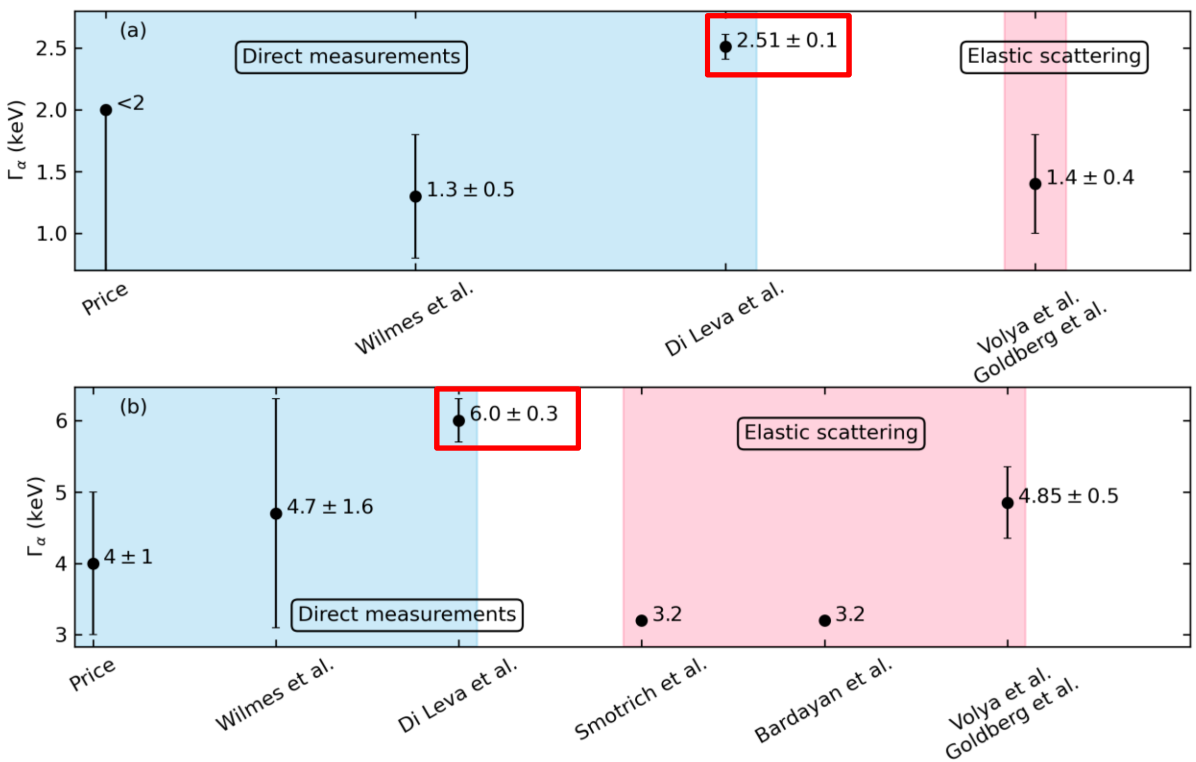


$$N_A\langle\sigma v\rangle = N_A\left(\frac{2\pi}{\mu kT}\right)^{3/2}\hbar^2(\omega\gamma)e^{-E_R/kT}$$

Previous Measurements – α width

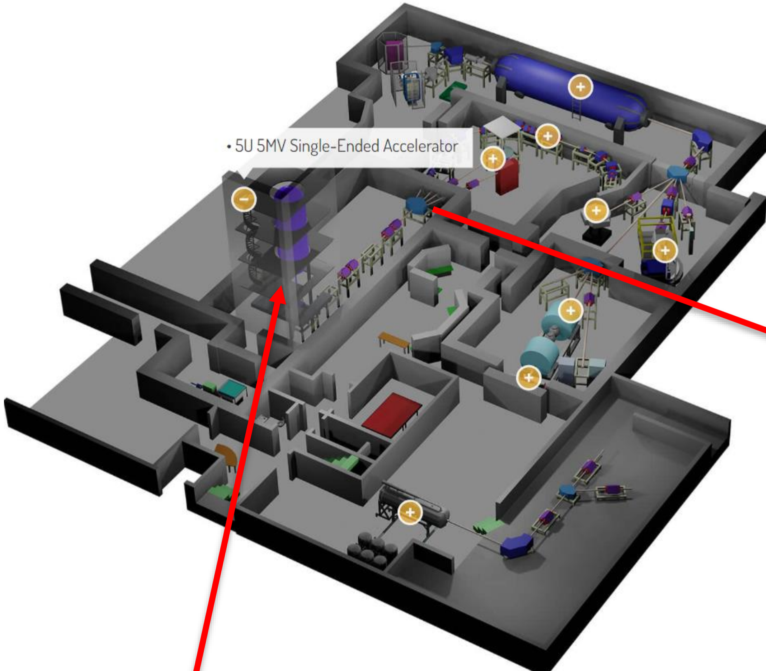
$E_{c.m.}$ = 1323 keV

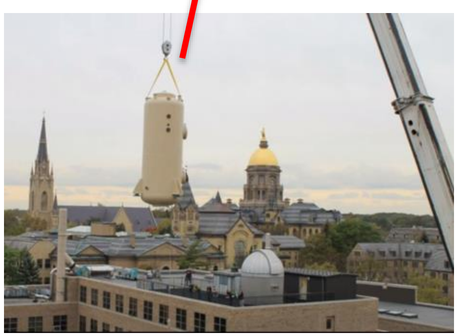
$E_{c.m.}$ = 1487 keV

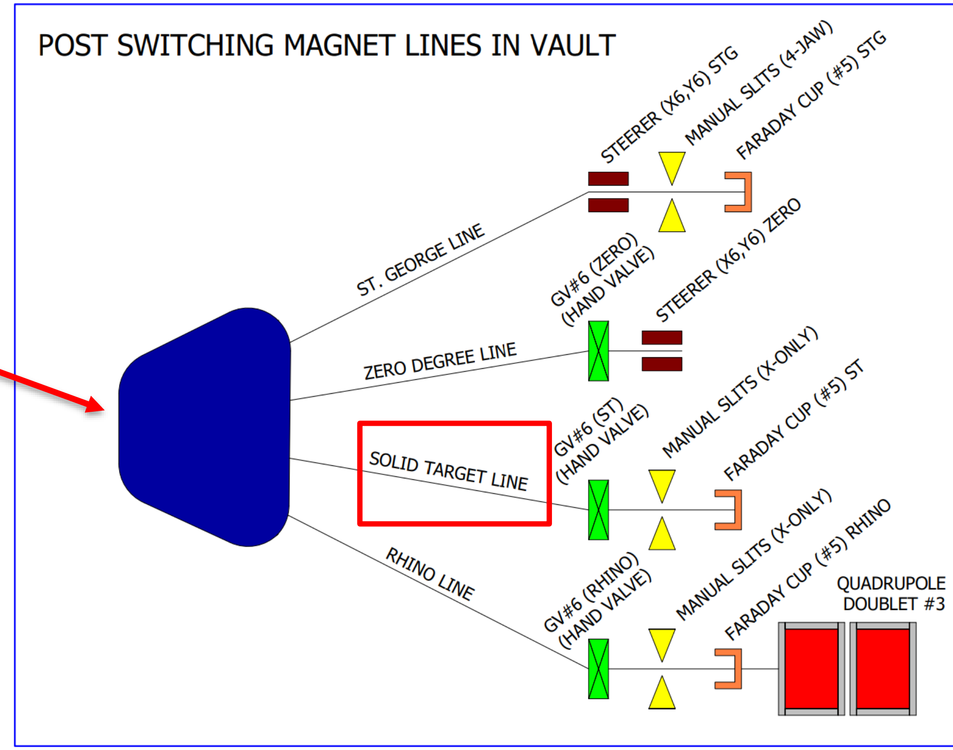


Tails from two resonances at $E_{c.m.}$ = 1323 and 1487 keV may increase reaction rate 15% due to the larger alpha widths (Di Leva et al., Phys. Rev. C, 2017)

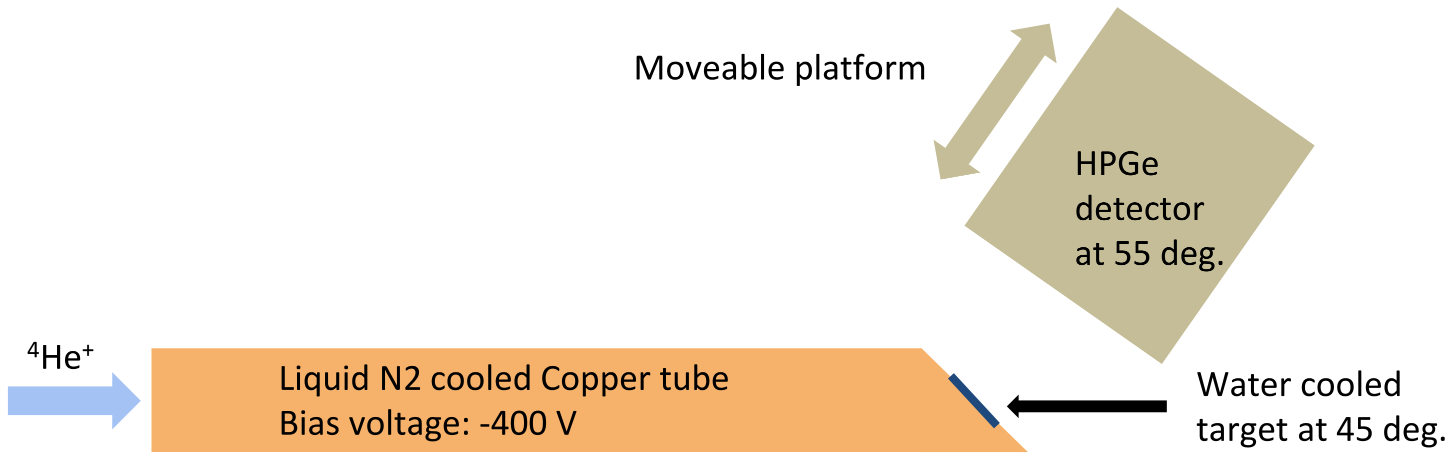
Nuclear Science Laboratory at ND





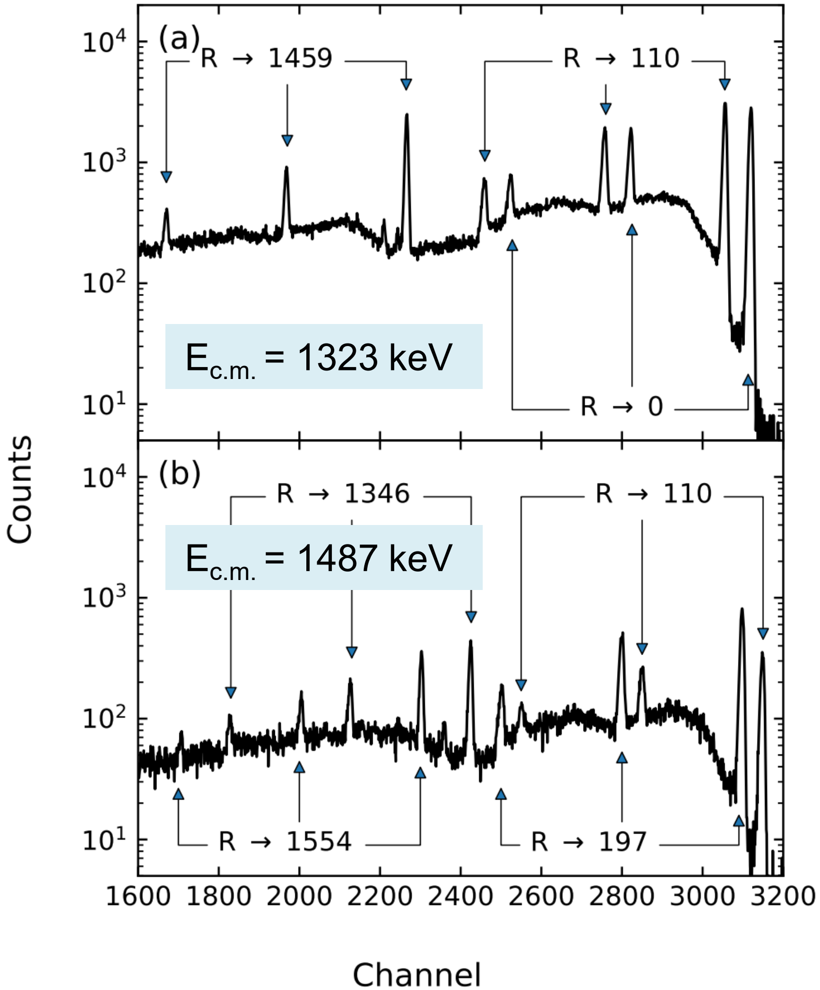


Solid Target γ-spectroscopy Setup



- $Ti^{15}N$ target was fabricated at Forschungszentrum Karlsruhe
  - Reactive sputtering of Ti in a 99.5% enriched ^{15}N environment.
  - Stoichiometry of 1:1 with a tolerance of < 2%
- Detector was set at 55° to minimize any angular distribution effects
- Detector energy and efficiency calibration
  - ^{60}Co and $^{27}Al(p,\gamma)^{28}Si$ E_p = 992 keV narrow resonance
  - Energy uncertainty < 1 keV. Efficiency uncertainty < 7%.

γ-ray Spectrum

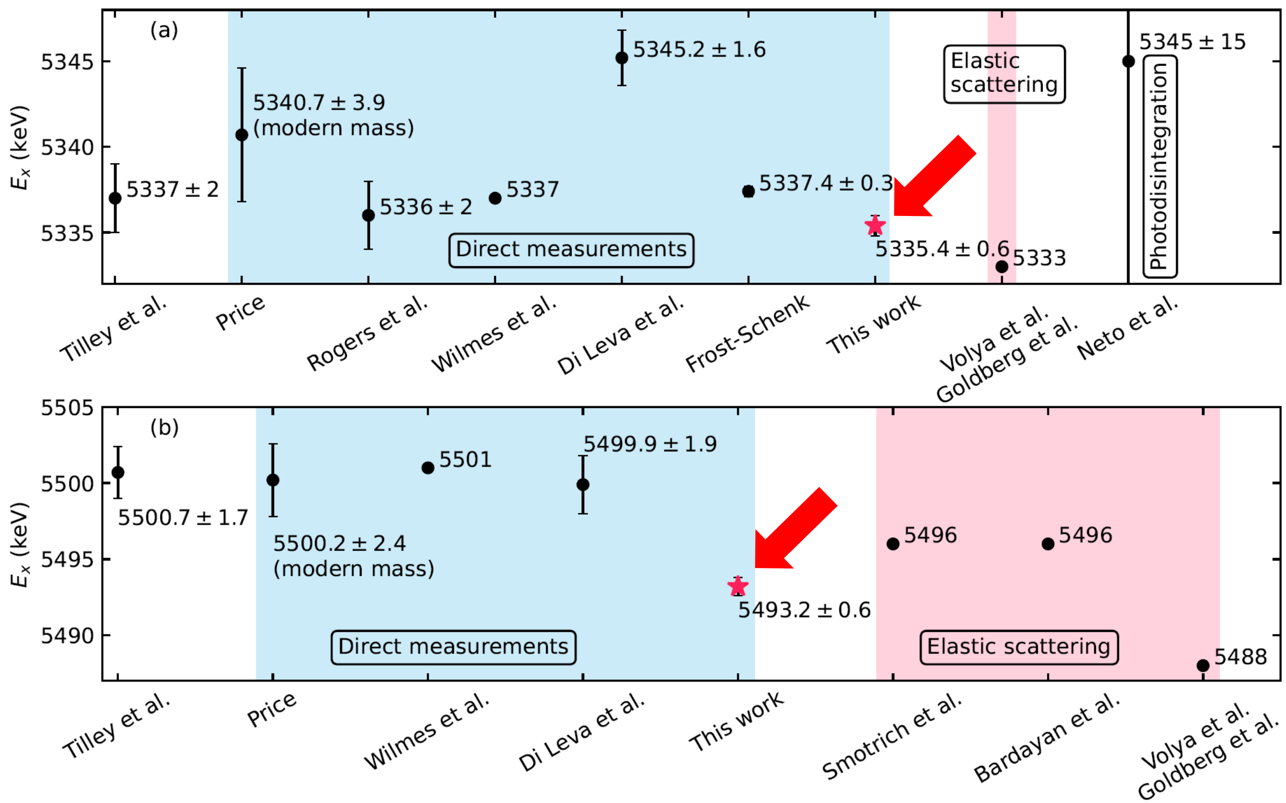


- Deduced the excitation level (resonance energy) using Doppler shifted γ-ray energy

Comparison to Previous Measurements

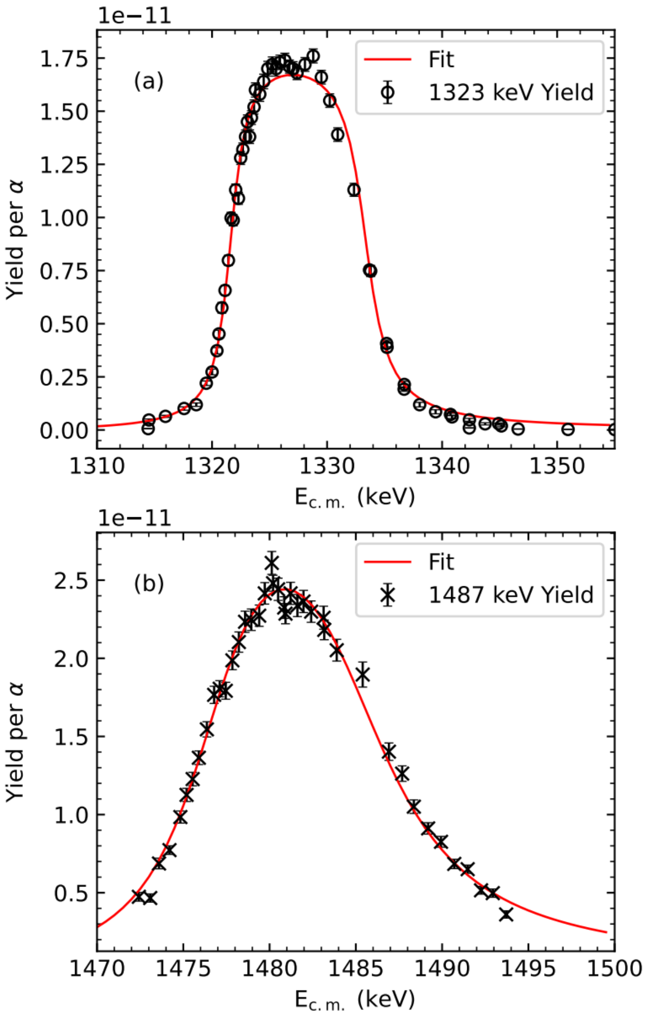
$E_{c.m.}$ = 1323 keV

$E_{c.m.}$ = 1487 keV



- Discrepancies in ~~energy~~, strength, α width

Deducing Strength and α Width



- Fitting of the Breit Wigner cross section

$$Y(E_0) = \frac{\lambda_r^2}{2\pi}\frac{\omega\gamma}{\epsilon_{\rm eff}}\left[\arctan\left(\frac{E_0 - E_r}{\sqrt{\Gamma^2 + \Delta^2_{\rm beam}}/2}\right) - \arctan\left(\frac{E_0 - E_r - \Delta E}{\sqrt{\Gamma^2 + \Delta^2_{\rm beam} + \Theta^2_{\rm target}}/2}\right)\right]$$

Beam energy resolution

Target inhomogenity

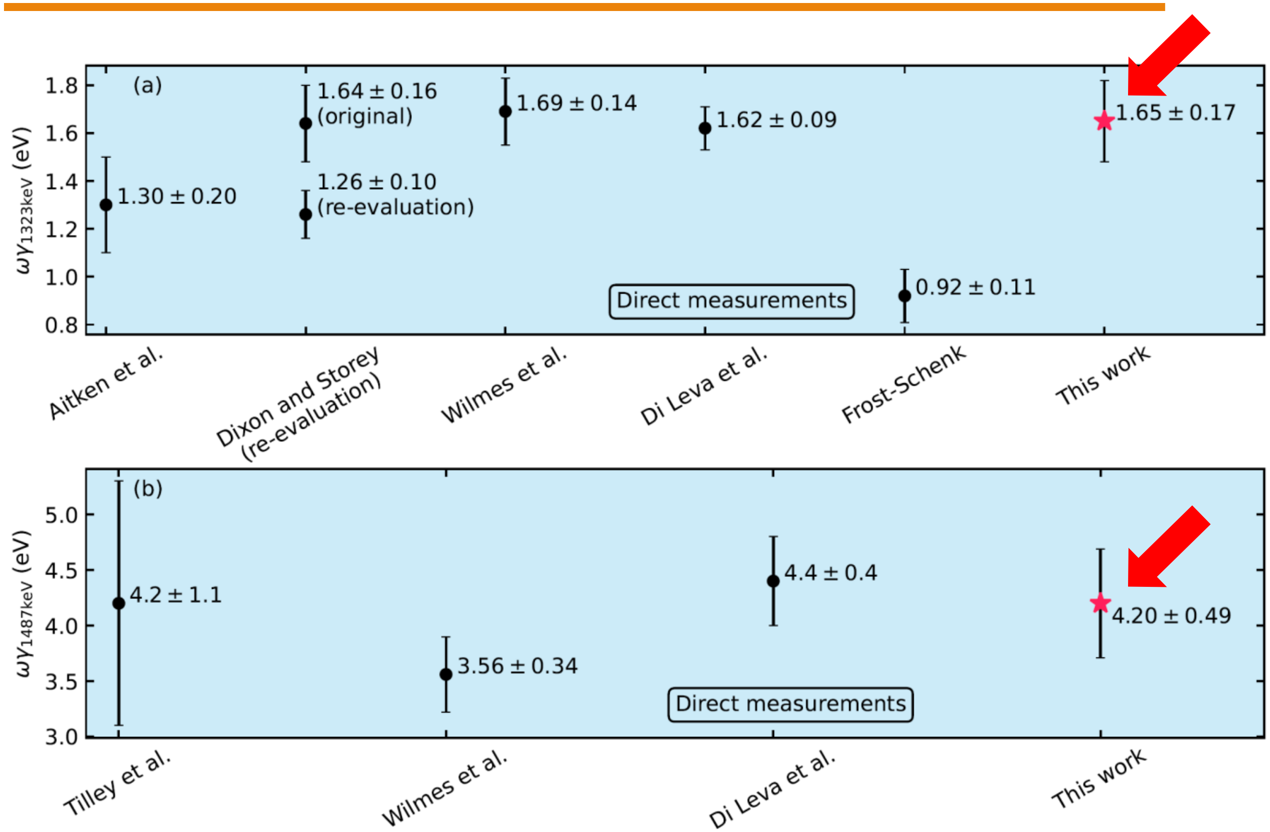
$$\epsilon_{\rm eff} = \frac{m_{^{15}\rm N}}{m_{^4\rm He} + m_{^{15}\rm N}}\left[\epsilon_{^{15}\rm N} + \left(\frac{N_{\rm Ti}}{N_{^{15}\rm N}}\right)\epsilon_{\rm Ti}\right]$$

- Monte Carlo procedure to deduce uncertainties from beam energy loss and stopping power.

TABLE III. Summary of systematic uncertainties for $\omega\gamma$

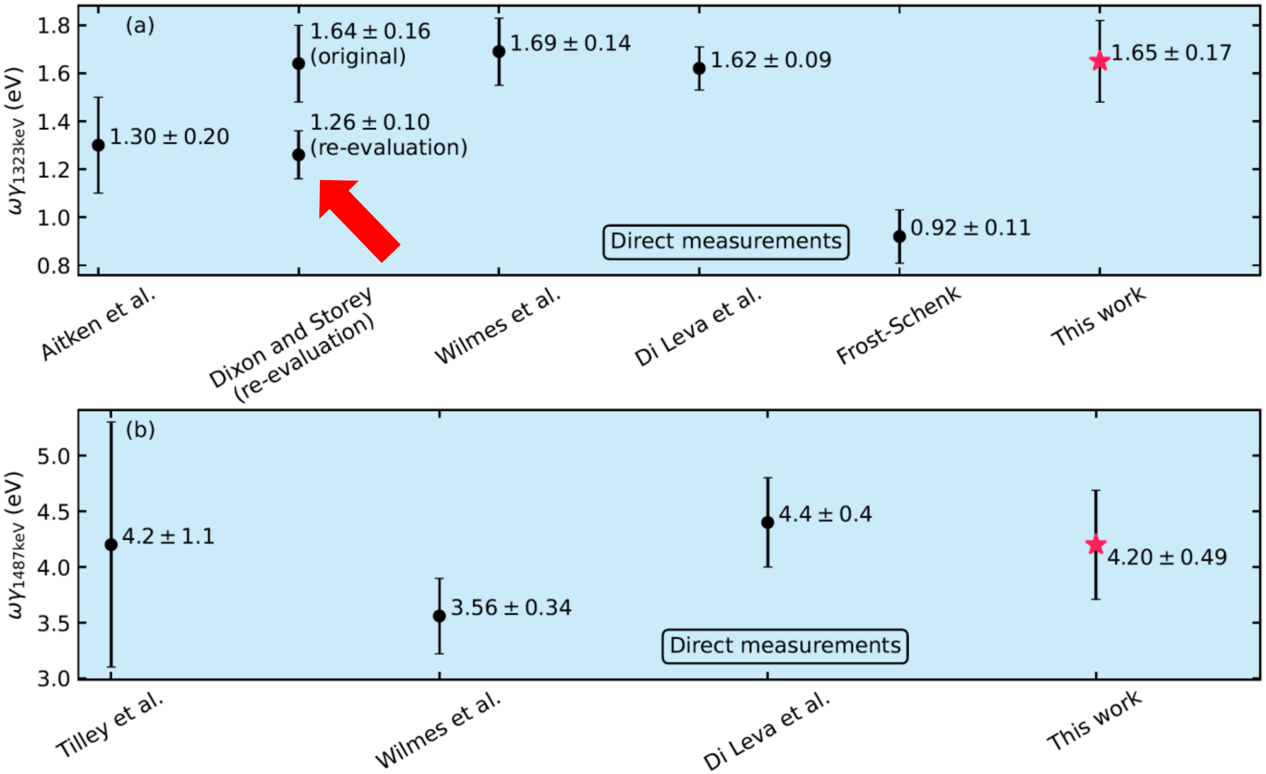
Relative contribution	$\omega\gamma_{1323\ \rm keV}\%$	$\omega\gamma_{1487\ \rm keV}\%$
MC procedure	7.9	9.3
Branching ratio [33]	2.7 (R→110)	3.5 (R→197)
$\epsilon_{\rm det}$	4.6	4.6
Summing effect	0.6	0.6
Charge collection	3.0	3.0
Target degradation	-	2.6
Total	10.0	11.7

Resonance Strength Results



- Both strengths are compatible with most literature values

Resonance Strength results



Re-evaluation of Dixon and Storey two relative comparison measurements

- $^{14}N(\alpha,\gamma)^{18}F$

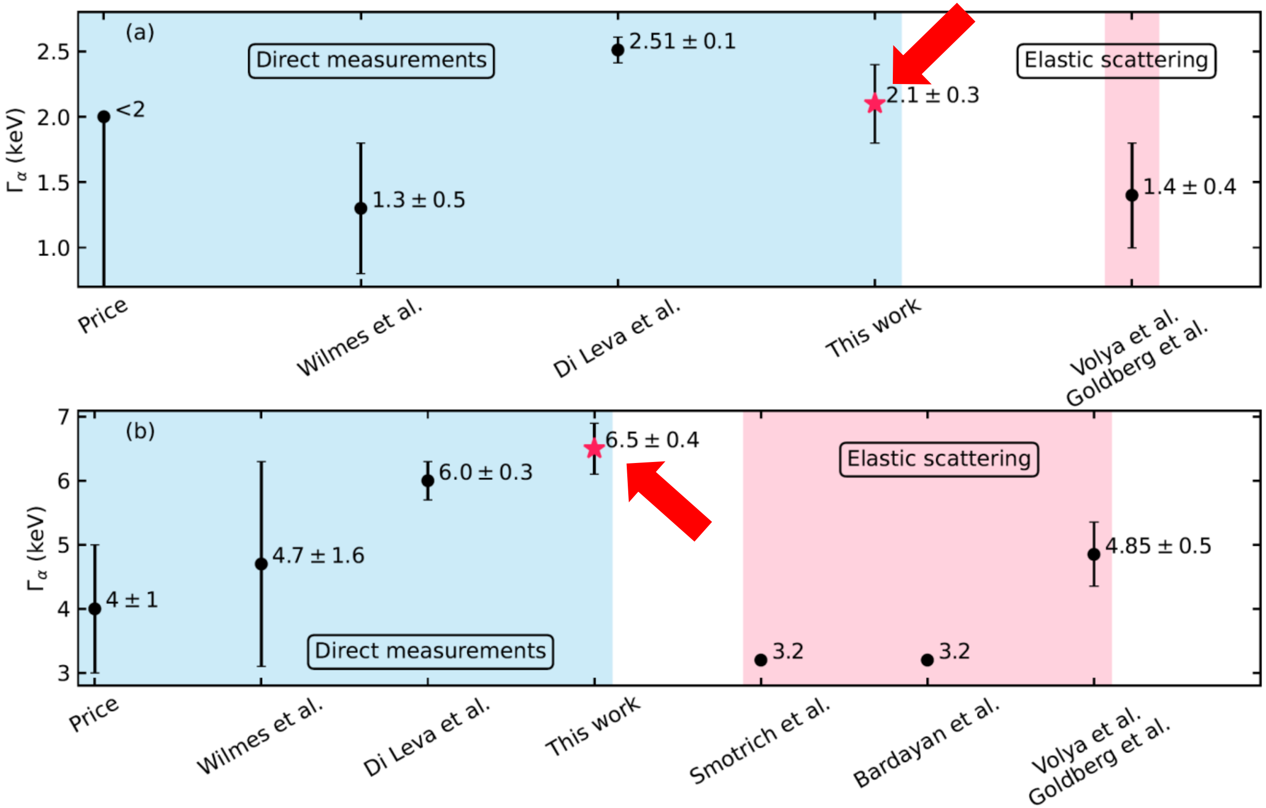
  E_α = 1532 keV resonance

- $^{15}N(p,\alpha_1\gamma)^{12}C$

  E_p = 892 keV resonance

17 higher levels corresponding strengths were calibrated against 1323 keV

α Width Results



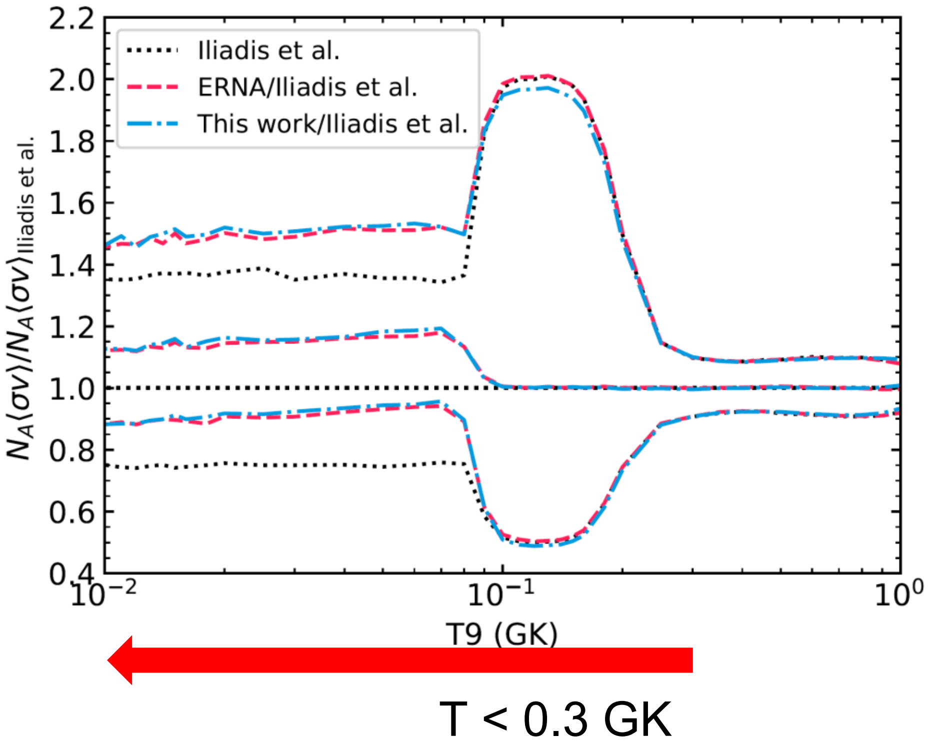
$E_{c.m.}$ = 1323 keV

$E_{c.m.}$ = 1487 keV

$\Gamma_{tot} = \Gamma_\alpha + \Gamma_\gamma \approx \Gamma_\alpha$

- Larger α width for $E_{c.m.}$ = 1487 keV resonance

Impact to Reaction Rate

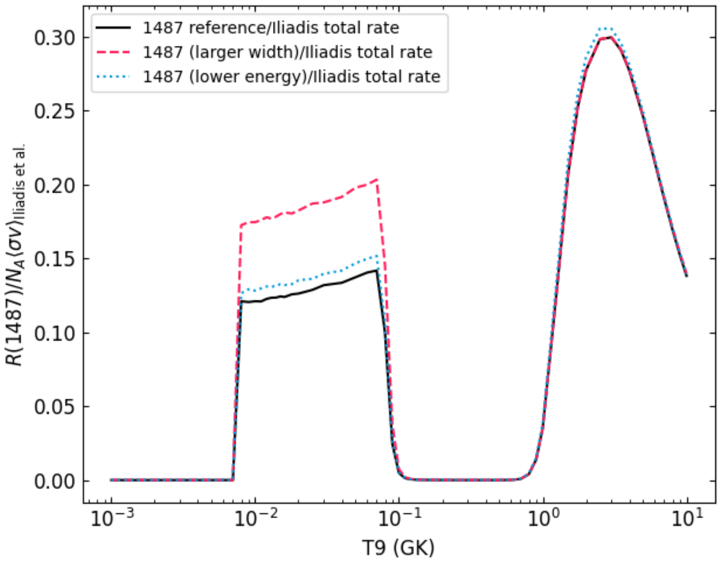


- Reaction rate calculated using RatesMC (Longland et al., Nuc. Phys. A, 2010)
  https://github.com/rlongland/RatesMC
- Proposed energy change in the higher energy resonance has negligible impact to the reaction rates
- Confirmed the 15% reaction rate increase by Di Leva et al. from the larger alpha widths at T < 0.1 GK

Future Work and Conclusions

$^{15}N(\alpha,\gamma)^{19}F$:

- Discrepancies in α width measurements
  - Zero-degree elastic scattering measurements on St. George (Adam Sanchez)
  - Elastic scattering measurements on RHINOCEROS gas target at NSL in forward kinematics
- Direct measurements of the 364 and 536 keV resonances are needed.
- Impact of reaction rate increase on ^{19}F synthesis in at low-mass AGB stars relevant temperatures needs to be investigated.



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Research group

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Backup Slides

Stellar Evolution

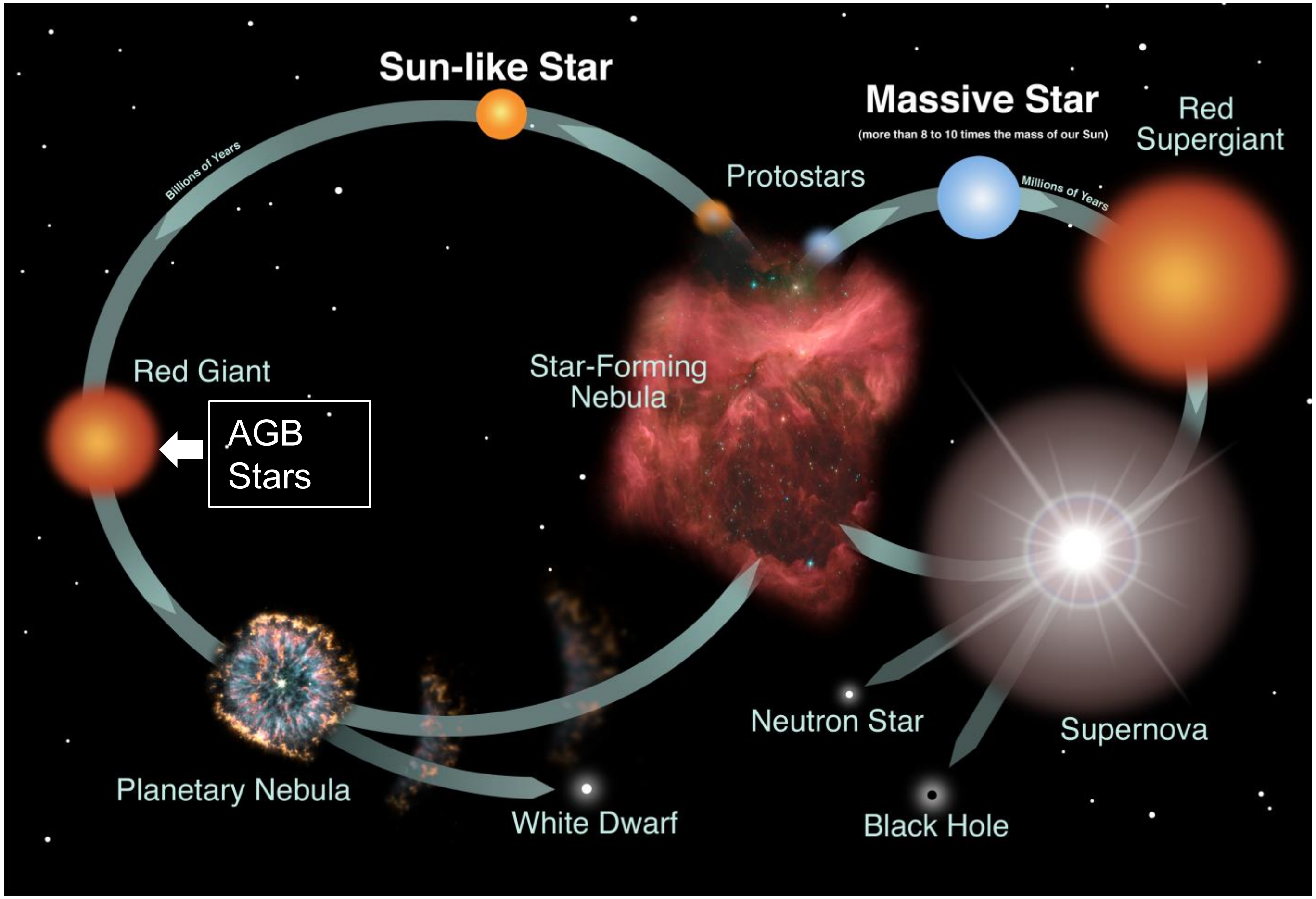

Figure from: https://imagine.gsfc.nasa.gov/educators/lessons/xray_spectra/background-lifecycles.html

$^{15}N(\alpha,\gamma)^{19}F$ in AGB Stars

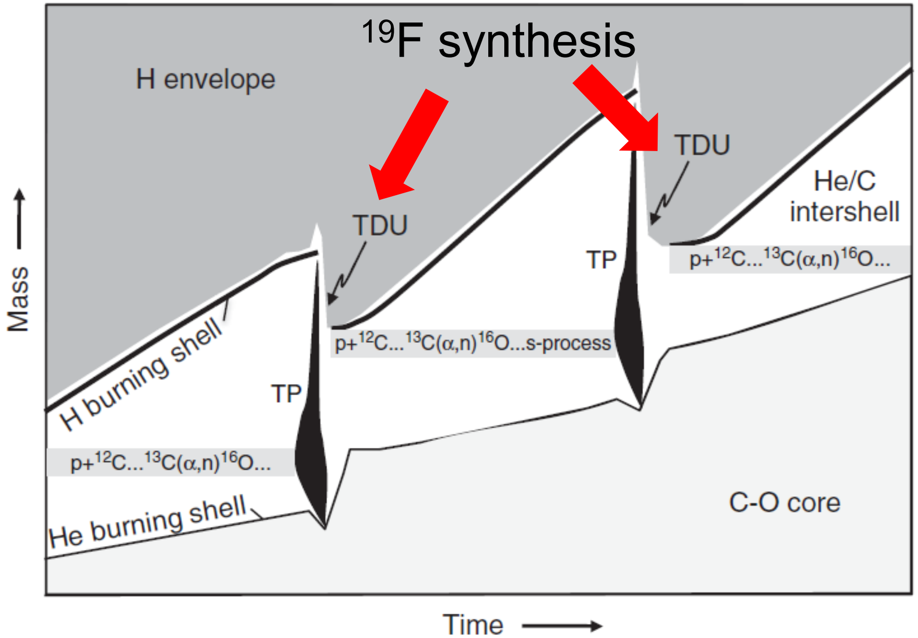

Figure from Iliadis, *Nuclear Physics of Stars*, 2015

Thermal Pulsing (TP):

- Accumulation of He from CNO cycle in H burning shell
- Temperature and energy output increase in He burning shell
- Create a convection zone that mixes H, He, and CNO products

Third Dredge Up (TDU)

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Re-evaluation of Dixon and Storey

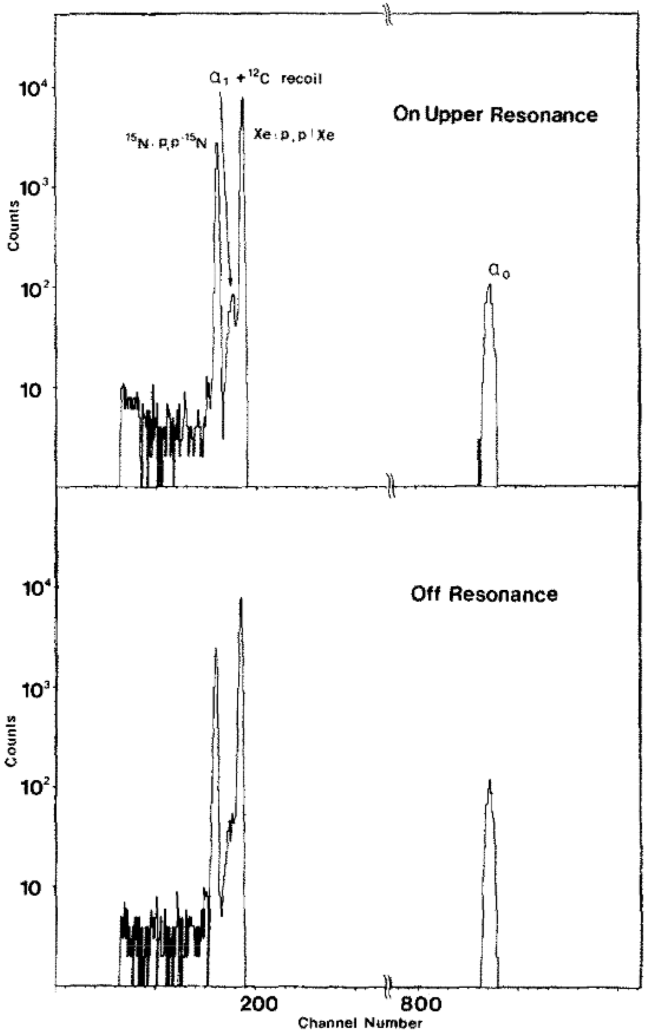

Figure from Leavitt et al., Nuc. Phys. A, 1983

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  ~40% decrease in strength comes from the ^{12}C (g.s.) background in the charged particle spectroscopy by Leavitt et al.