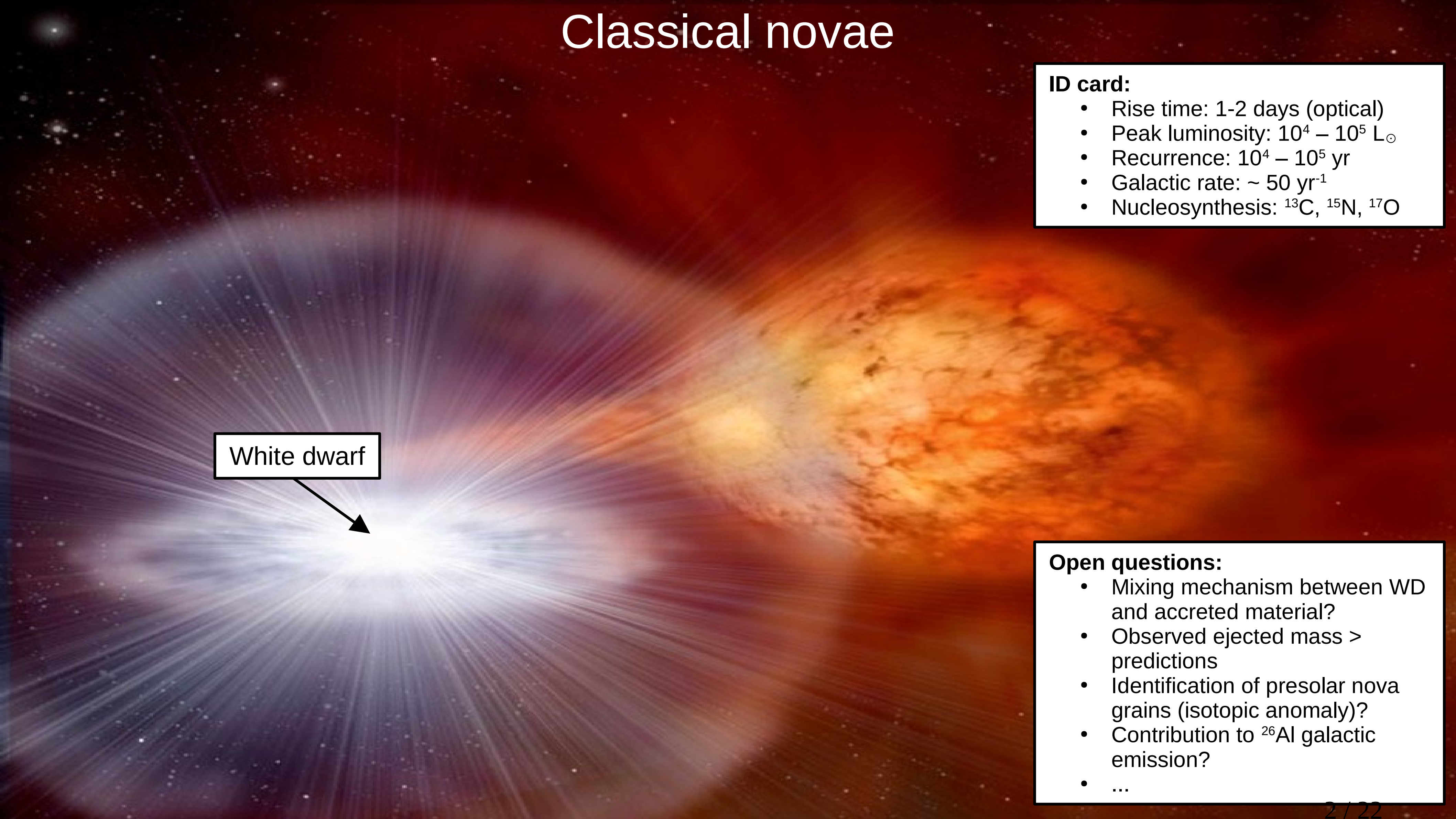
Experimental studies of explosive nucleosynthesis in binary systems

Nicolas de Séréville
IJCLab – Laboratoire de Physique des 2 Infinis Irène Joliot-Curie
nicolas.de-sereville@ijclab.in2p3.fr

Classical novae



ID card:

- Rise time: 1-2 days (optical)
- Peak luminosity: $10^4 – 10^5\ L_\odot$
- Recurrence: $10^4 – 10^5$ yr
- Galactic rate: ~ 50 yr^{-1}
- Nucleosynthesis: ^{13}C, ^{15}N, ^{17}O

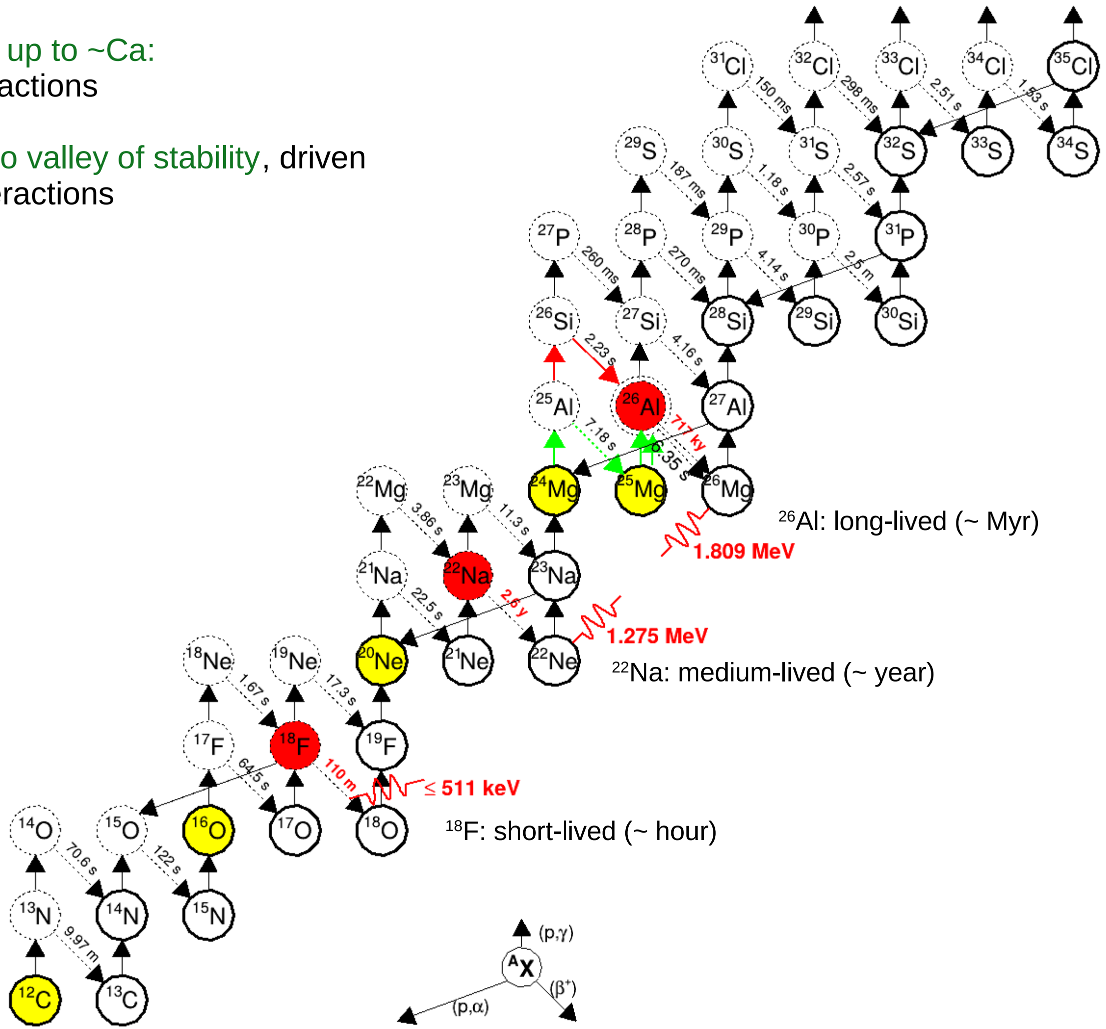
Open questions:

- Mixing mechanism between WD and accreted material?
- Observed ejected mass > predictions
- Identification of presolar nova grains (isotopic anomaly)?
- Contribution to ^{26}Al galactic emission?
- ...

Nuclear physics in classical novae explosions

Nucleosynthesis network up to ~Ca:
~ 100 nuclides, ~ 180 reactions

Main nuclear path close to valley of stability, driven by (p,γ), (p,α) and β+ interactions



Nuclear physics in classical novae explosions

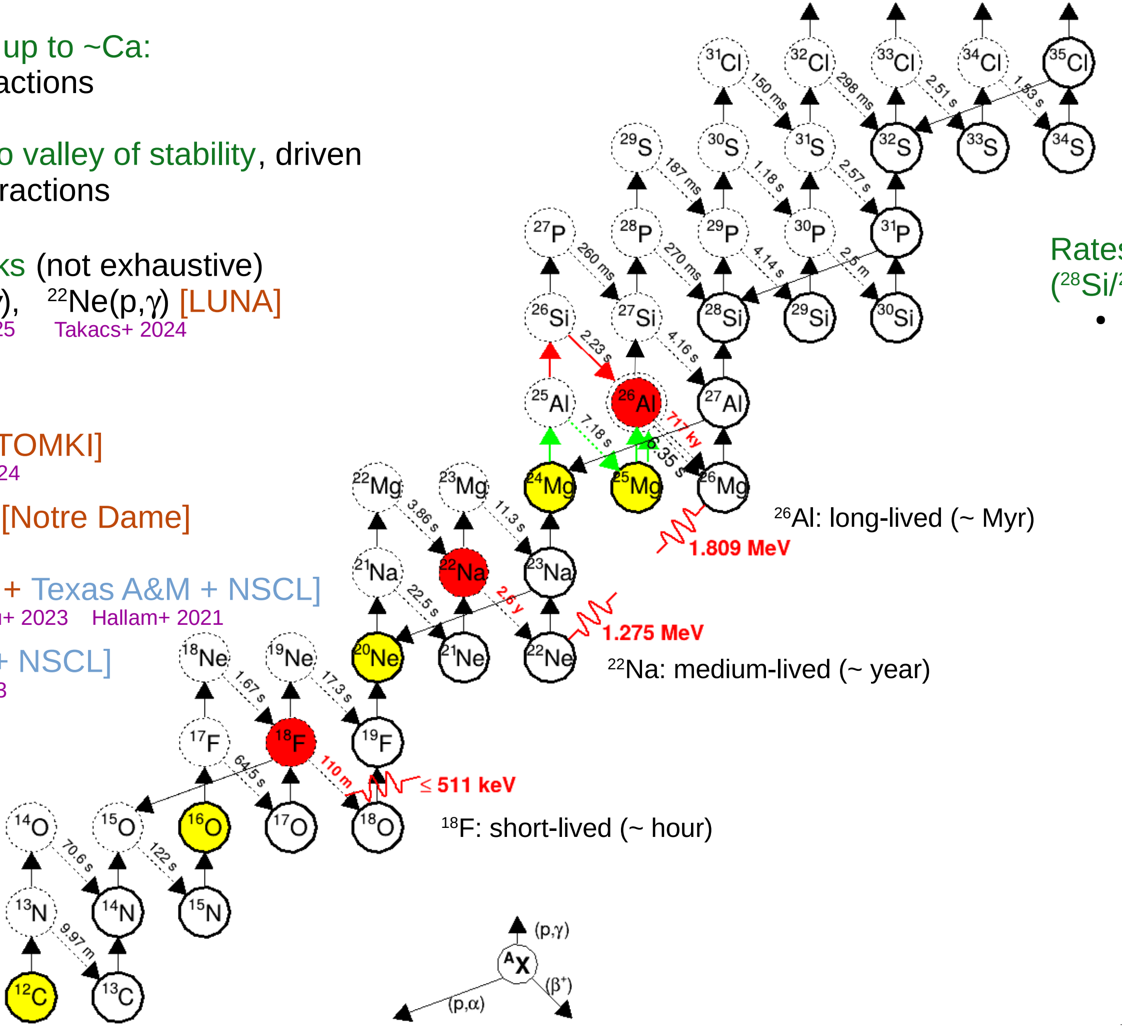
Nucleosynthesis network up to ~Ca:
~ 100 nuclides, ~ 180 reactions

Main nuclear path close to valley of stability, driven by (p,γ), (p,α) and β+ interactions

Recent experimental works (not exhaustive)

- ^{20}Ne(p,γ), ^{21}Ne(p,γ), ^{22}Ne(p,γ) [LUNA]
  Masha+ 2023 Sidhu+ 2025 Takacs+ 2024
- ^{22}Na(p,γ) [GANIL]
  Fougères+ 2025
- ^{29}Si(p,γ) [LENA + ATOMKI]
  Downen+ 2022, Matyus+ 2024
- ^{39}K(p,γ), ^{40}Ca(p,γ) [Notre Dame]
  Scholz+ 2023 Sidhu+ 2025
- ^{26m}Al(p,γ) [TRIUMF + Texas A&M + NSCL]
  Lotay+ 2023 Stefanescu+ 2023 Hallam+ 2021
- ^{30}P(p,γ) [Garching + NSCL]
  Kamil+ 2023 Budner+ 2023

Classical novae will be soon the first stellar explosions for which all reaction rates are experimentally determined



Remaining main nuclear uncertainty:

- ^{18}F(p,α)^{15}O, ^{25}Al(p,γ)^{26}Si and ^{30}P(p,γ)^{31}S José+ 2007, 2024
  → unstable species!

Rates affecting nova grain identification (^{28}Si/^{29}Si, ^{32}S/^{33}S):

- ^{30}P(p,γ)^{31}S and ^{33,34}S(p,γ)^{34,35}Cl Ward+ 2025

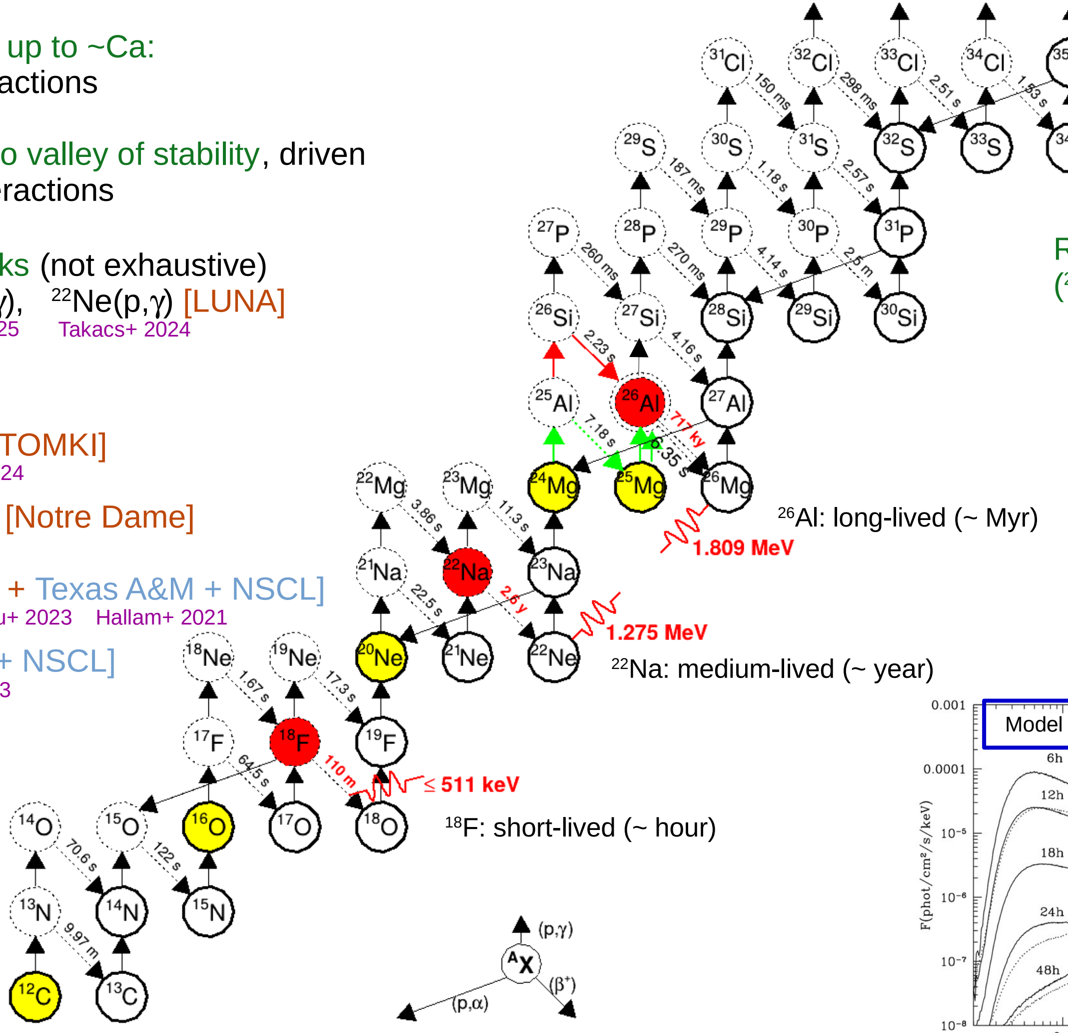
Nuclear physics in classical novae explosions

Nucleosynthesis network up to ~Ca:
~ 100 nuclides, ~ 180 reactions

Main nuclear path close to valley of stability, driven by (p,γ), (p,α) and β+ interactions

Recent experimental works (not exhaustive)

- ^{20}Ne(p,γ), ^{21}Ne(p,γ), ^{22}Ne(p,γ) [LUNA]
  Masha+ 2023 Sidhu+ 2025 Takacs+ 2024
- ^{22}Na(p,γ) [GANIL]
  Fougères+ 2025
- ^{29}Si(p,γ) [LENA + ATOMKI]
  Downen+ 2022, Matyus+ 2024
- ^{39}K(p,γ), ^{40}Ca(p,γ) [Notre Dame]
  Scholz+ 2023 Sidhu+ 2025
- ^{26m}Al(p,γ) [TRIUMF + Texas A&M + NSCL]
  Lotay+ 2023 Stefanescu+ 2023 Hallam+ 2021
- ^{30}P(p,γ) [Garching + NSCL]
  Kamil+ 2023 Budner+ 2023



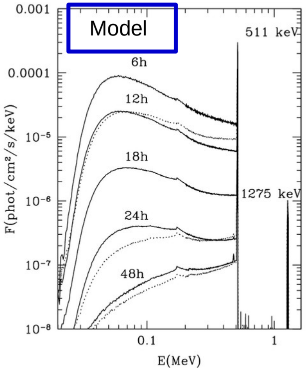
Remaining main nuclear uncertainty:

- ^{18}F(p,α)^{15}O, ^{25}Al(p,γ)^{26}Si and ^{30}P(p,γ)^{31}S José+ 2007, 2024
  → unstable species!

Rates affecting nova grain identification (^{28}Si/^{29}Si, ^{32}S/^{33}S):

- ^{30}P(p,γ)^{31}S and ^{33,34}S(p,γ)^{34,35}Cl Ward+ 2025

Classical novae will be soon the first stellar explosions for which all reaction rates are experimentally determined



M. Hernanz+ (2001)

γ-ray emission critically depends on destruction of ^{18}F via **^{18}F(p,α)^{15}O**

Nuclear physics in classical novae explosions

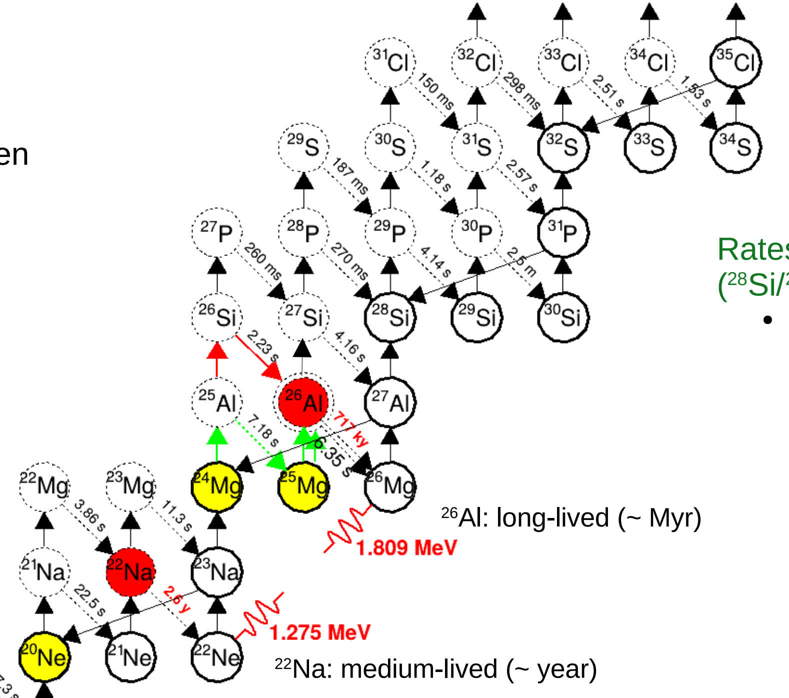
Nucleosynthesis network up to ~Ca:
~ 100 nuclides, ~ 180 reactions

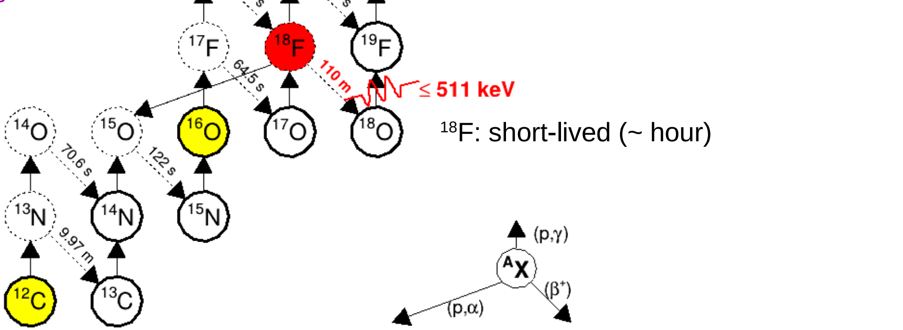
Main nuclear path close to valley of stability, driven by (p,γ), (p,α) and β+ interactions

Recent experimental works (not exhaustive)

- ^{20}Ne(p,γ), ^{21}Ne(p,γ), ^{22}Ne(p,γ) [LUNA]
  Masha+ 2023 Sidhu+ 2025 Takacs+ 2024
- ^{22}Na(p,γ) [GANIL]
  Fougères+ 2025
- ^{29}Si(p,γ) [LENA + ATOMKI]
  Downen+ 2022, Matyus+ 2024
- ^{39}K(p,γ), ^{40}Ca(p,γ) [Notre Dame]
  Scholz+ 2023 Sidhu+ 2025
- ^{26m}Al(p,γ) [TRIUMF + Texas A&M + NSCL]
  Lotay+ 2023 Stefanescu+ 2023 Hallam+ 2021
- ^{30}P(p,γ) [Garching + NSCL]
  Kamil+ 2023 Budner+ 2023

Classical novae will be soon the first stellar explosions for which all reaction rates are experimentally determined



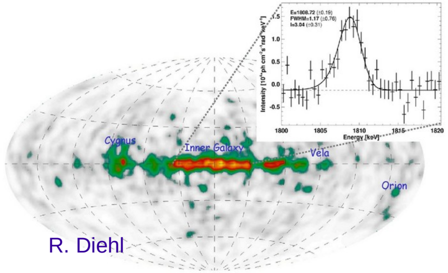


Remaining main nuclear uncertainty:

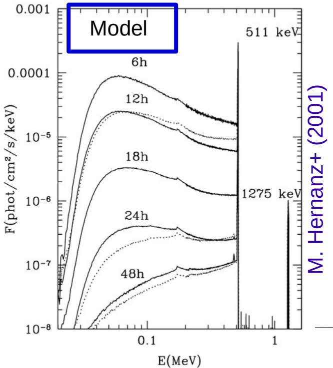
- ^{18}F(p,α)^{15}O, ^{25}Al(p,γ)^{26}Si and ^{30}P(p,γ)^{31}S José+ 2007, 2024
  → unstable species!

Rates affecting nova grain identification (^{28}Si/^{29}Si, ^{32}S/^{33}S):

- ^{30}P(p,γ)^{31}S and ^{33,34}S(p,γ)^{34,35}Cl Ward+ 2025



^{25}Al(p,γ)^{26}Si bypasses population of $^{26}Al_{g.s.}$ (1.809 MeV γ-ray emission)

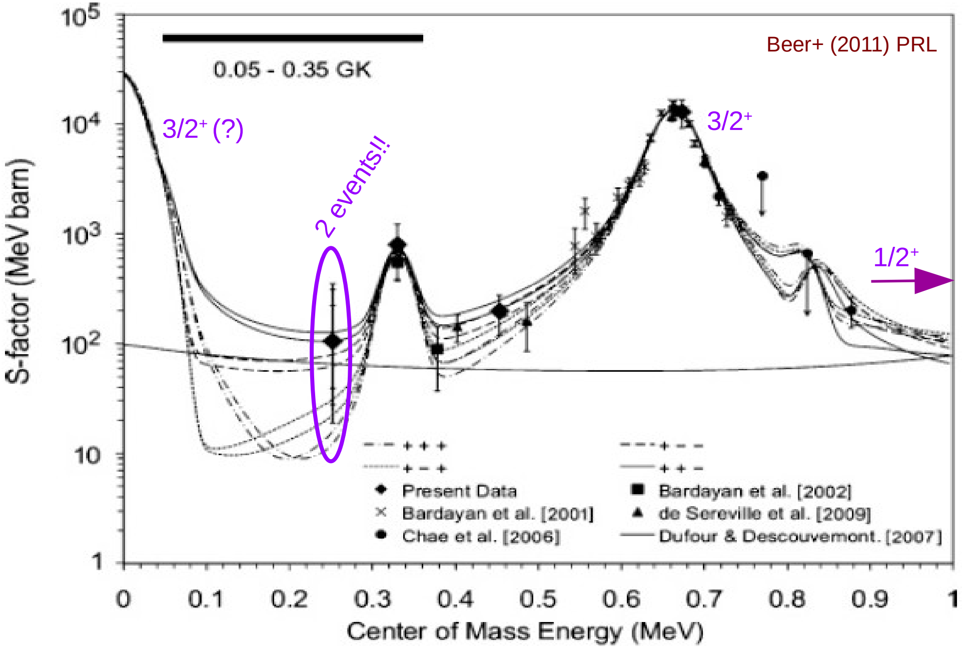


γ-ray emission critically depends on destruction of ^{18}F via **^{18}F(p,α)^{15}O**

Status of the $^{18}F(p,\alpha)^{15}O$ reaction

- ^{18}F ($T_{1/2}$ = 110 min) produces γ-ray emission at ≤ 511 keV which critically depends on the $^{18}F(p,\alpha)^{15}O$ reaction
- Future observations (COSI, e-ASTROGAM) should provide information on the ejecta dynamics

Direct measurements



New results from direct measurement coming... (TRIUMF; A. M. Laird et al.)

G. Carter-Richardson, PhD

Main challenge

interference between ℓ = 0 states:
$3/2^+$ (E_R = 665 keV, Γ = 40 keV);
$1/2^+$ (E_R = 1.5 MeV, $\Gamma \approx$ 350 keV)

- Close to proton threshold
  - Existence of $3/2^+$ states? How many?
- Below proton threshold
  - Theoretical predictions (GCM) M. Dufour+ (2007)
  - Several ℓ = 0 resonant states identified, but J^{Π} = $1/2^+$? $3/2^+$?

References (recent, non exhaustive):
de Oliveira Santos (2025), Kim+ (2025), Kahl+ (2021)

$^{18}F(p,\alpha)^{15}O$: below proton threshold

E_X = 6133 keV, E_R = - 277 keV

- Identified as *s*-wave state
- **1/2⁺**, 3/2⁺ (charge exchange, intermediate energies) or

  D. Kahl+ (2019)

  3/2⁺ (charge exchange + angular correlations) ?

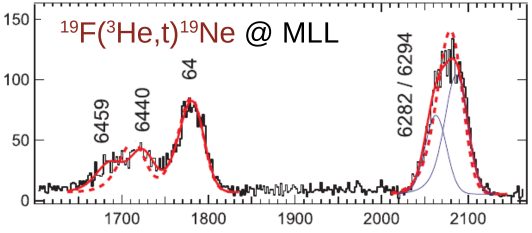
  A. M. Laird+ (2013), A. Parikh+ (2015),
  J.C. Dalouzy+ (2008) unpublished

Doublet @ E_X = "6288" keV, E_R = - 122 keV

- First observed as a **single state...**
  - Low spin (**1/2⁺**) v.s. high spin (**≥ 5/2**) **controversy**

    D. Bardayan+ (2015) A. M. Laird+ (2013)

- … but is in fact a **doublet**
  -

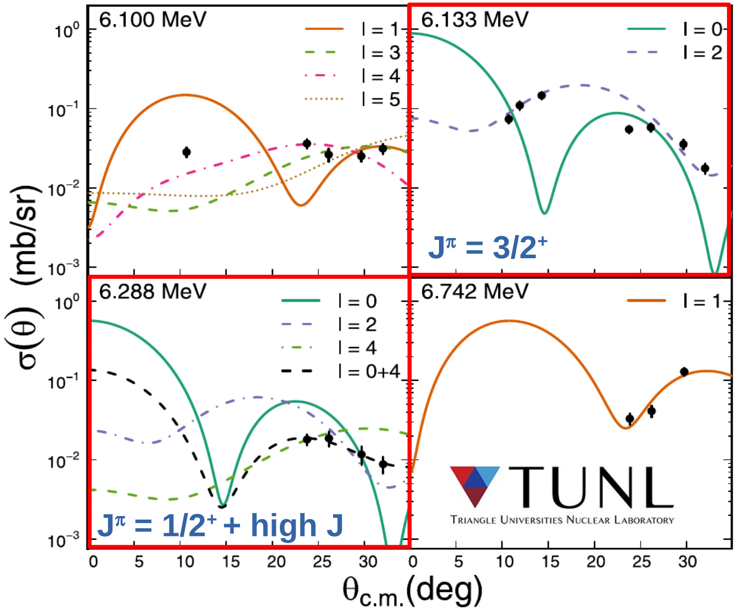


A. Parikh+ (2015)

  - Observation of high spin component (γ-ray spectroscopy, **11/2⁺** 6294 keV; angular correlations, **≥ 7/2**)

    M. R. Hall+ (2019) J. Riley+ (2021)

$^{20}Ne(^3He,^4He)^{19}Ne$ [Split-Pole spectrometer]



F. Portillo+ (2023)

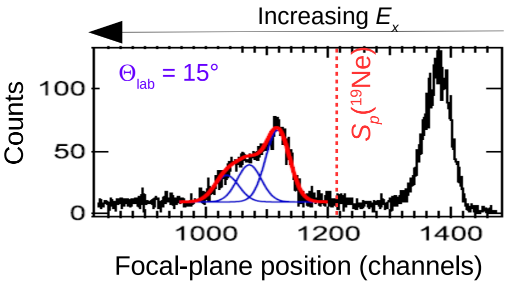
- **Consensus for spin-parities** of sub-threshold *s*-wave resonances
- **BUT**
  - no analog state in ^{19}F for $E_X(^{19}Ne)$ = 6133 keV, 3/2⁺
  - Γ_α from mirror states

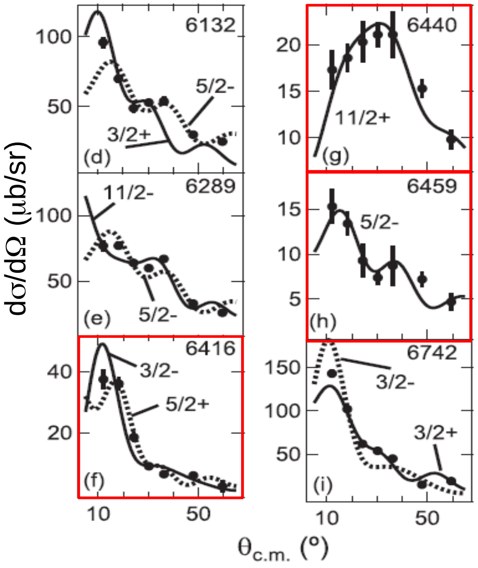
$^{18}F(p,\alpha)^{15}O$: above proton threshold

Two new states at 8- and 38-keV above ^{18}F+p threshold: analog of known $3/2^+$ states in mirror ^{19}F nucleus?

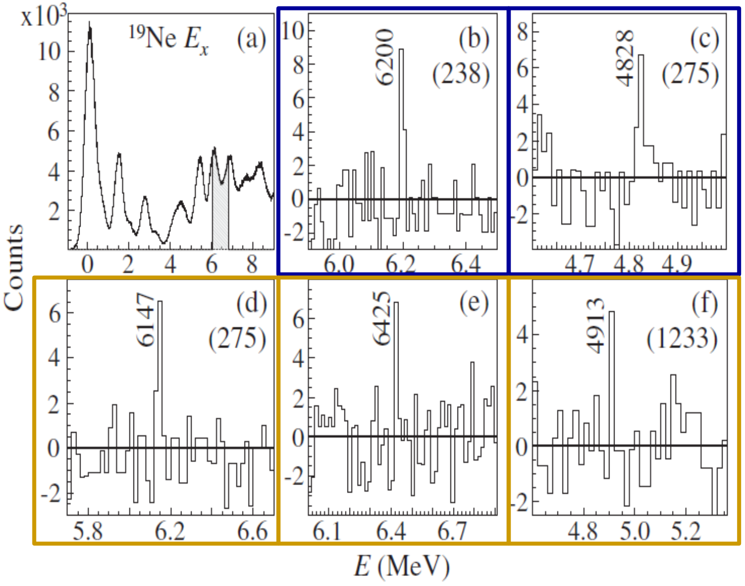
Utku+ (1998)

$^{19}F(^3He,t)^{19}Ne$: particle v.s. γ-ray spectroscopy





A. M. Laird+ (2013), A. Parikh+ (2015)



M. R. Hall+ (2019)

- **Q3D:** 3 states, no 3/2+ state
- **Gammasphere + Orruba:** 2 3/2+ states

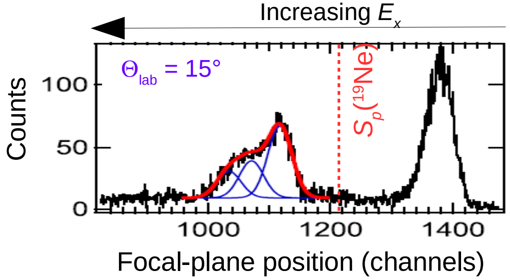
→ **Uncertainty on reaction rate ~ factor of 2**

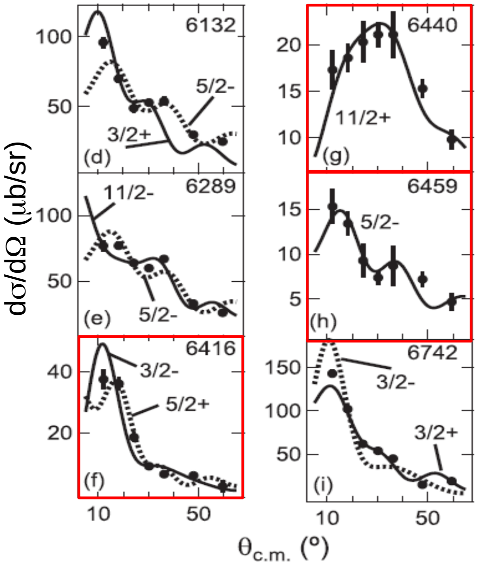
$^{18}F(p,\alpha)^{15}O$: above proton threshold

Two new states at 8- and 38-keV above ^{18}F+p threshold: analog of known $3/2^+$ states in mirror ^{19}F nucleus?

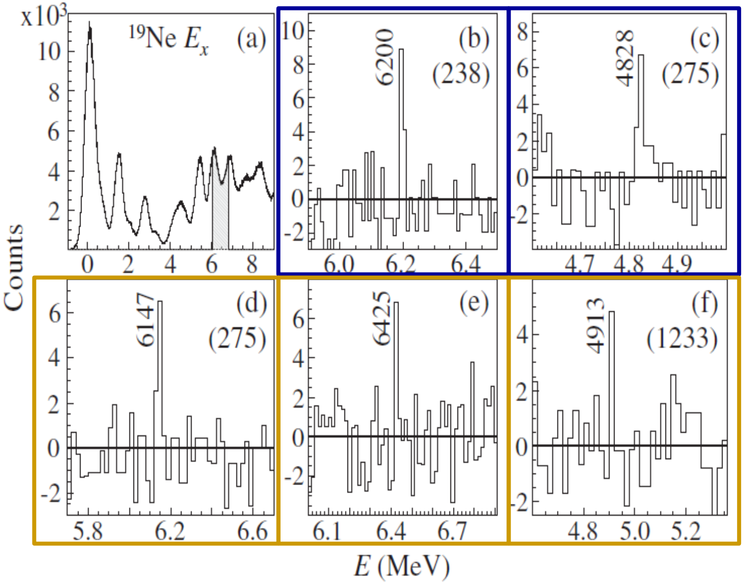
Utku+ (1998)

$^{19}F(^3He,t)^{19}Ne$: particle v.s. γ-ray spectroscopy





A. M. Laird+ (2013), A. Parikh+ (2015)



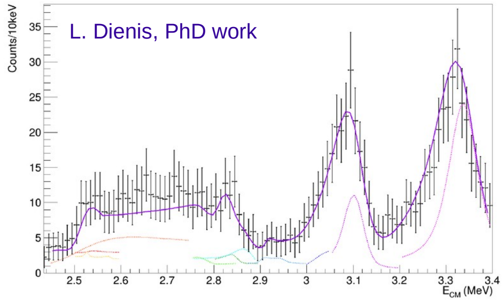
M. R. Hall+ (2019)

- **Q3D:** 3 states, no 3/2+ state
- **Gammasphere + Orruba:** 2 3/2+ states

→ **Uncertainty on reaction rate ~ factor of 2**

Prospects

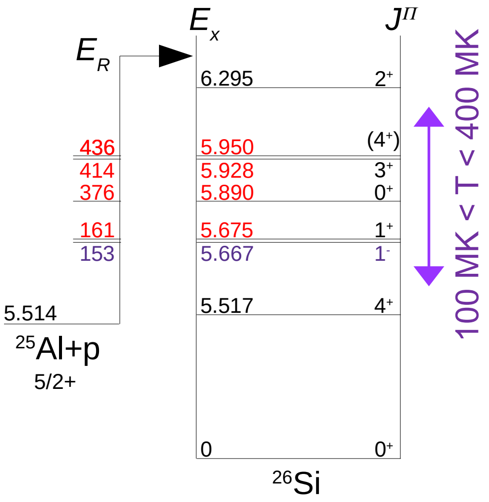
- High resolution resonant elastic scattering $^{15}O(\alpha,\alpha)^{15}O$
  - Existing: D. Torresi+ (2017)
  - New set-up @ GANIL
    - Commissioned successfully with $^{15}N(\alpha,\alpha)^{15}N$



    - Good agreement with known ^{19}F spectroscopy D. Bardayan+ (2005)
- Ion storage ring CRYRING
  - CARME setup

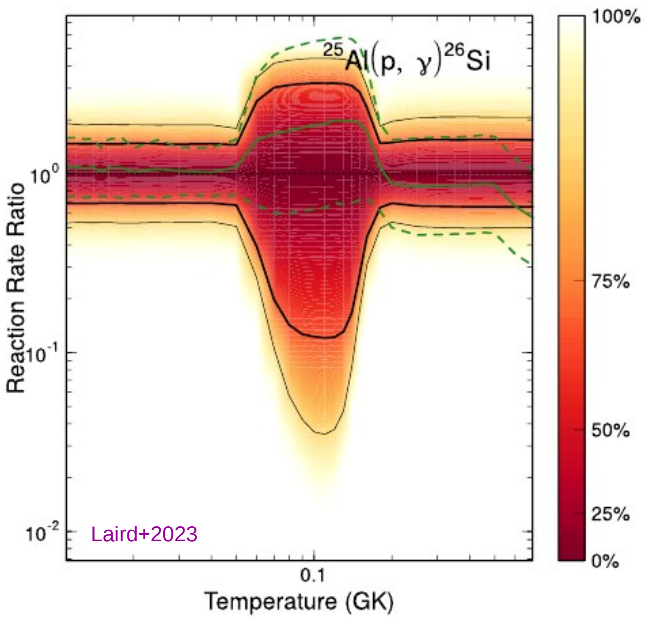
C. Bruno+ (2023)
J. Marsh+ (2024)

Status of the $^{25}Al(p,\gamma)^{26}Si$ reaction

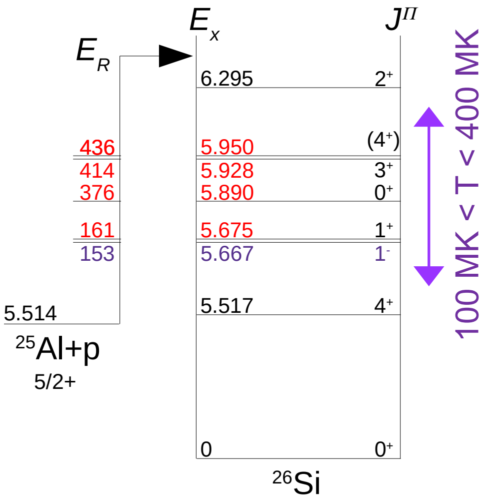


5 states within 500 keV above ^{25}Al + p threshold
(shell-model + experiments) Chipps+ 2016

- Excitation energy + resonance energy known
  → accurate ^{26}Si mass excess Eronen+2009; Kwiatkowski+ 2010
- Spin/parity mostly known



Status of the ^{25}Al(p,γ)^{26}Si reaction

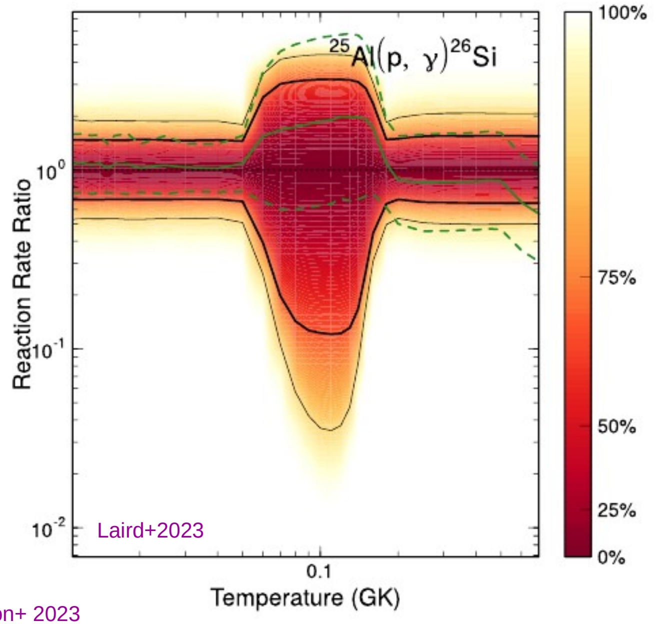


5 states within 500 keV above ^{25}Al + p threshold
(shell-model + experiments) Chipps+ 2016

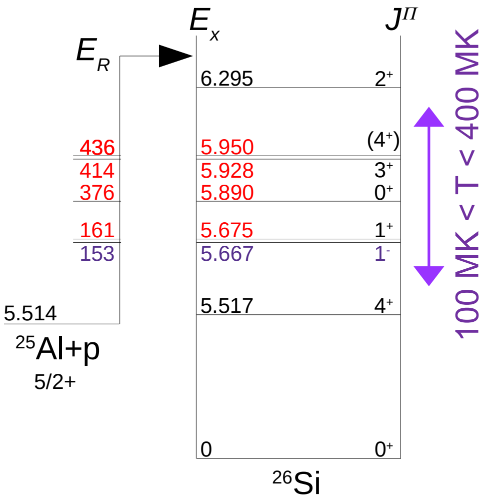
- Excitation energy + resonance energy known
  → accurate ^{26}Si mass excess Eronen+2009; Kwiatkowski+ 2010
- Spin/parity mostly known

Dominating resonances:

- T > 200 MK: ℓ = 0, 3+, E_x = 5928 keV
  $\omega\gamma \approx \omega\Gamma_\gamma$ (proton emission dominates)
  - lifetime measurement of ^{26}Mg analog state Canete+ 2021
  - $\Gamma_\gamma = \Gamma_p \times \frac{\Gamma_\gamma}{\Gamma_p}$
    - $\frac{\Gamma_\gamma}{\Gamma_p}$ → ^{26}P β+ decay Liang+ 2020
    - Γ_p → ^{25}Al(d,n)^{26}Si transfer Temanson+ 2023



Status of the ^{25}Al(p,γ)^{26}Si reaction

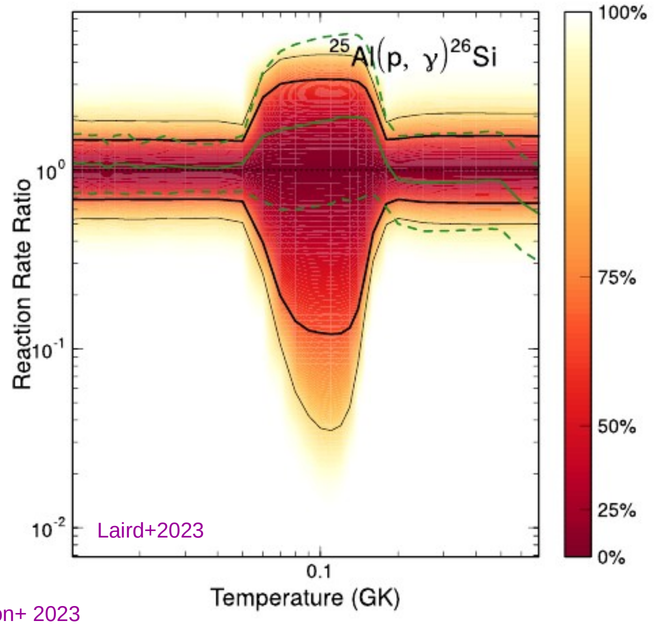


5 states within 500 keV above ^{25}Al + p threshold
(shell-model + experiments) Chipps+ 2016

- Excitation energy + resonance energy known
  → accurate ^{26}Si mass excess Eronen+2009; Kwiatkowski+ 2010
- Spin/parity mostly known

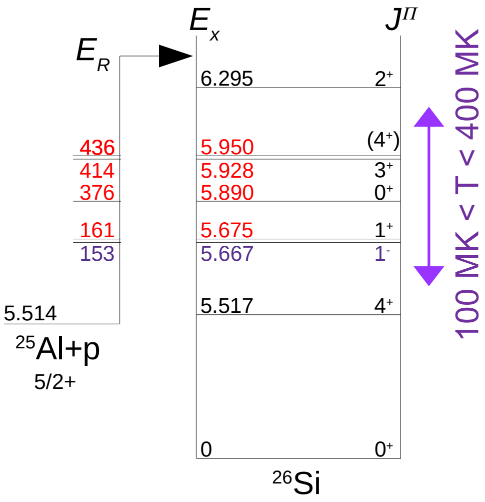
Dominating resonances:

- T > 200 MK: ℓ = 0, 3+, E_x = 5928 keV
  $\omega\gamma \approx \omega\Gamma_\gamma$ (proton emission dominates)
  - lifetime measurement of ^{26}Mg analog state Canete+ 2021
  - $\Gamma_\gamma = \Gamma_p \times \frac{\Gamma_\gamma}{\Gamma_p}$
    - $\frac{\Gamma_\gamma}{\Gamma_p}$ → ^{26}P β+ decay Liang+ 2020
    - Γ_p → ^{25}Al(d,n)^{26}Si transfer Temanson+ 2023



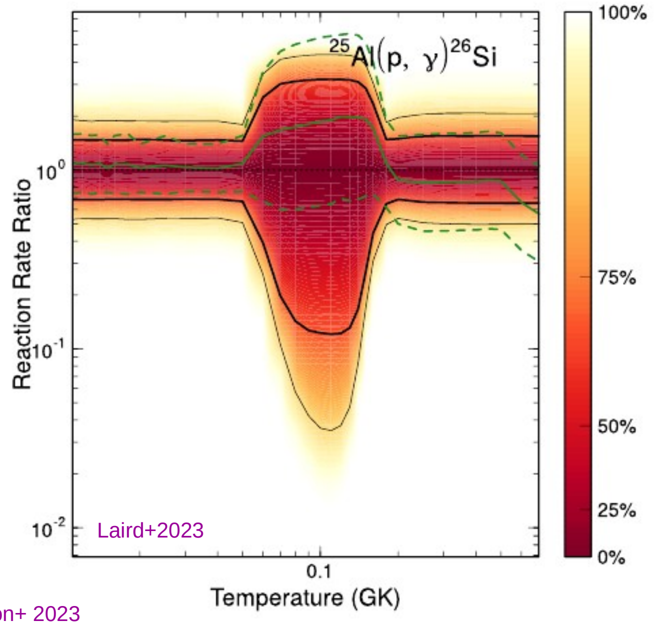
- T < 200 MK: ℓ = 2, 1+, E_x = 5675 keV
  $\omega\gamma \approx \omega\Gamma_p$ (γ-ray decay dominates)
  - Shell-model Richter+ 2011
  - upper limit from ^{26}Mg analog state Hamill+ 2020 → see N. Giha's talk

Status of the ^{25}Al(p,γ)^{26}Si reaction



5 states within 500 keV above ^{25}Al + p threshold (shell-model + experiments) Chipps+ 2016

- Excitation energy + resonance energy known → accurate ^{26}Si mass excess Eronen+2009; Kwiatkowski+ 2010
- Spin/parity mostly known



Dominating resonances:

- T > 200 MK: ℓ = 0, 3+, E_x = 5928 keV
  $\omega\gamma \approx \omega\Gamma_\gamma$ (proton emission dominates)
  - lifetime measurement of ^{26}Mg analog state Canete+ 2021
  - $\Gamma_\gamma = \Gamma_p \times \frac{\Gamma_\gamma}{\Gamma_p}$
    - $\frac{\Gamma_\gamma}{\Gamma_p}$ → ^{26}P β+ decay Liang+ 2020
    - Γ_p → ^{25}Al(d,n)^{26}Si transfer Temanson+ 2023
- T < 200 MK: ℓ = 2, 1+, E_x = 5675 keV
  $\omega\gamma \approx \omega\Gamma_p$ (γ-ray decay dominates)
  - Shell-model Richter+ 2011
  - upper limit from ^{26}Mg analog state Hamill+ 2020 → see N. Giha's talk

Observation of 1- resonance

- ^{26}Si: E_x = 5667 keV Canete+ 2023
  - direct γ-ray transition to g.s.
- ^{26}Mg: E_x = 5711 keV Canete+ 2021
  - new γ-ray transition to 0+ → J = 1, 2
  - ^{25}Mg(d,p)^{26}Mg: → J^π = 1-
    - ℓ = 1 (Canete+ 2021) or ℓ = 3 (Burlein+ 1984)

→ clarification needed

$d(^{25}Al,n\gamma)^{26}Si$ experiment @ FRIB

GRETINA **&** **S800** **@ FRIB/ARIS** *C. Fougères et al (2023)*

^{25}Al @ **24 MeV/u**

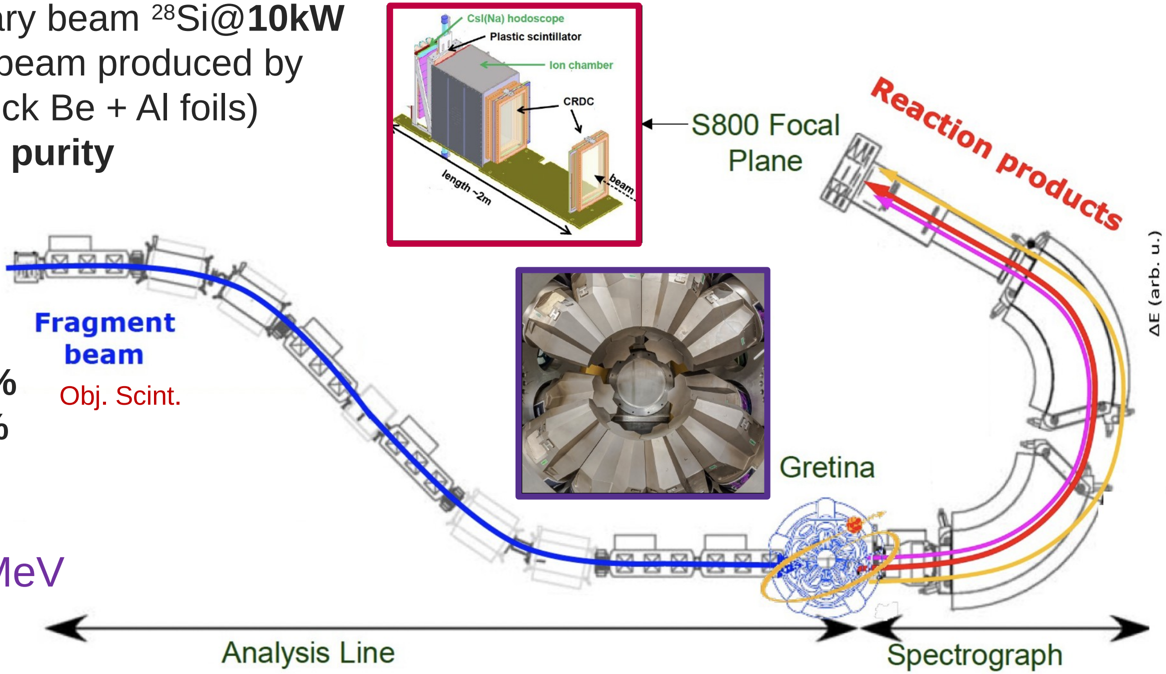
- High-power primary beam ^{28}Si@**10kW**
- Slow radioactive beam produced by fragmentation (thick Be + Al foils)
- **2×10^6 pps, >95% purity**

S800 line

- Lowest energy
- Transmission **56%**
- FP efficiency **65%**

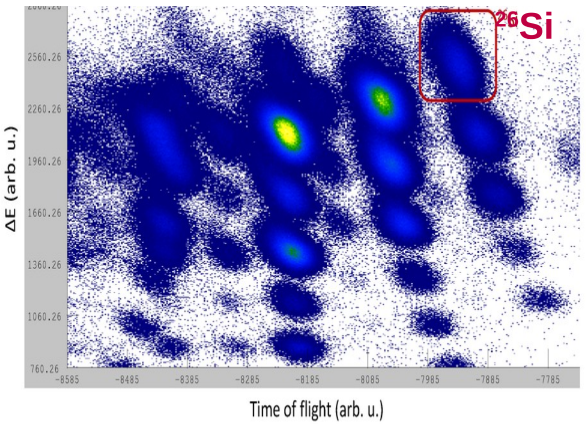
GRETINA @ 1.8MeV

- FWHM_DC **0.7%**
- efficiency **4.6%**



CD_2 target
($9.4\ mg/cm^2$)

Online PID



Focal Plane Scint. vs Obj. Scint.

Assessing resonance strength via angle-integrated measurement

Approach: extension of a recent method measuring **C^2S_p** and **Γ_p** (NSCL) : d(^{26}Al,nγ)^{27}Si Kankainen+2016,2017

$$\sigma^{exp}_{transfer} = C^2 S_p \times \sigma^{DWBA}_{transfer} \quad \text{and} \quad \Gamma_p = C^2 S_p \times \Gamma_{s.p.}$$

Direct transfer d(^{26}Al,nγ)^{27}Si

Step 1: tagging of ^{26}Si* on γ-ray transitions → angle-integrated measurement of the (*d*,n) transfer cross-section σ_{transfer}

$$\mathrm{N}_\gamma = \mathrm{BR}_\gamma \times \sigma^{\text{exp}}_{\text{transfer}} \times \epsilon^{\text{tot}}_{\text{det.}} \mathrm{N}_{\text{target}} \mathrm{I}_{\text{beam}} \mathrm{T}_{\text{UT}}$$

Step 2: it is possible to write the resonance strength as

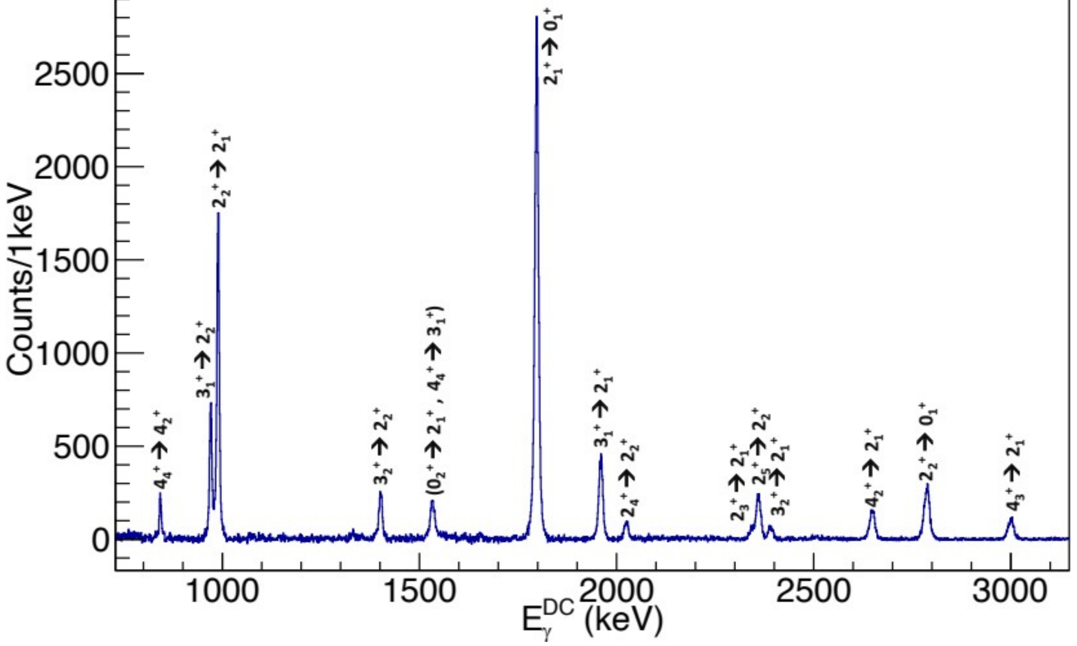
$$\omega\gamma = \frac{\mathrm{N}_\gamma}{\mathrm{N}_{\text{target}} \mathrm{I}_{\text{beam}} \epsilon^{\text{tot}}_{\text{det.}} \mathrm{T}_{\text{UT}}} \times \frac{\Gamma^{\text{s.p.}}_{\text{p}}}{\sigma^{\text{DWBA}}_{\text{transfer}}} \times \frac{(2J+1)}{(2j+1)(2J_{^{25}Al}+1)}.$$

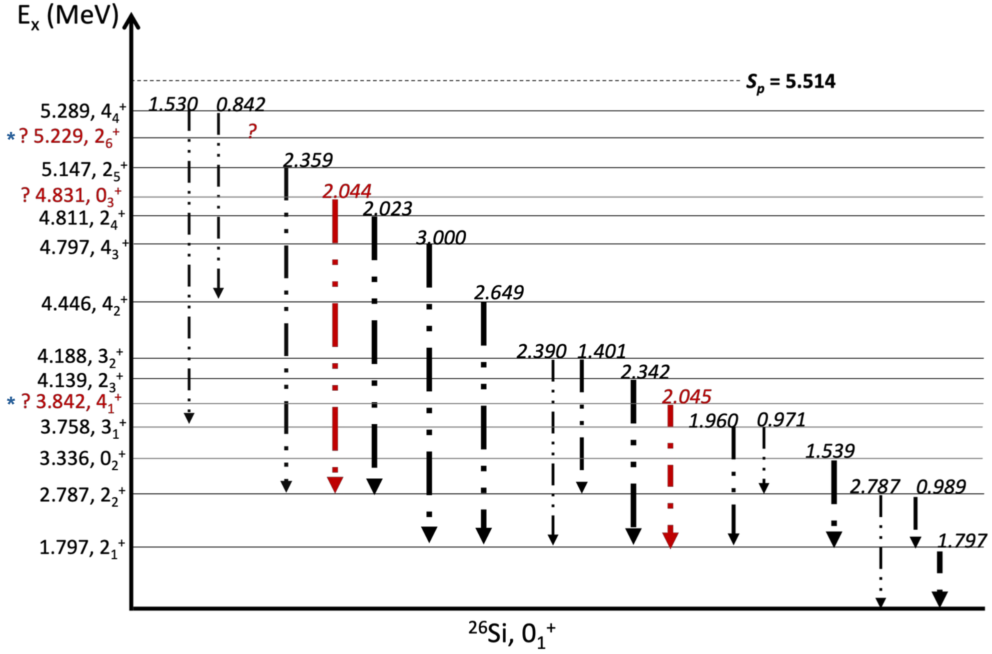
Resonance strength (ωγ) determined from measured γ-rays and $\dfrac{\Gamma^{s.p.}_p}{\sigma^{DWBA}_{transfer}}$

→ statistical + systematic uncertainties ~ 30% from optical potential parameters

^{26}Si bound states

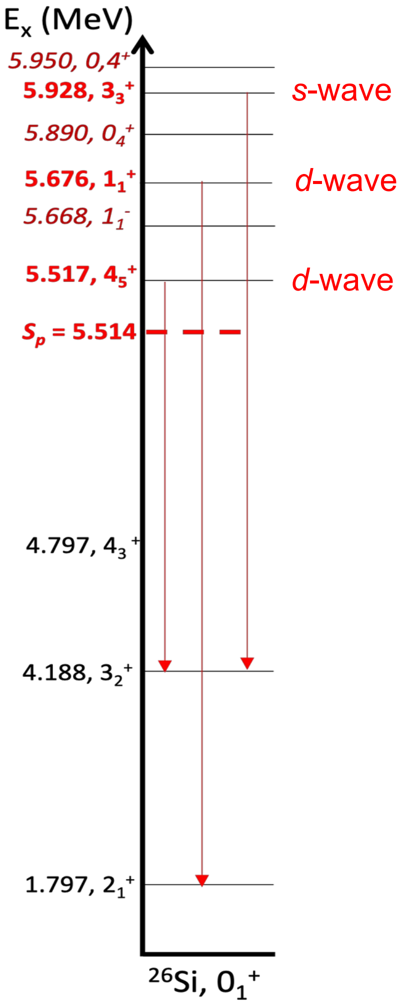
11 states identified among 14 referenced ones in ^{26}Si

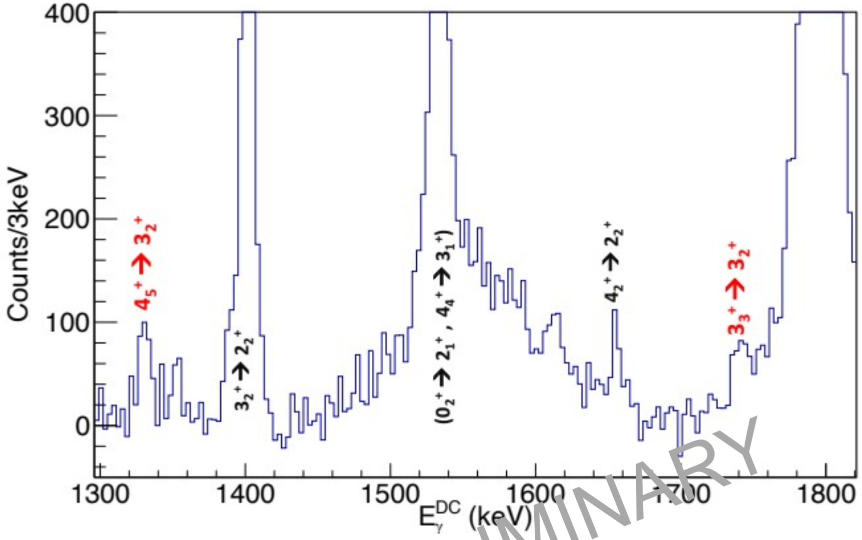


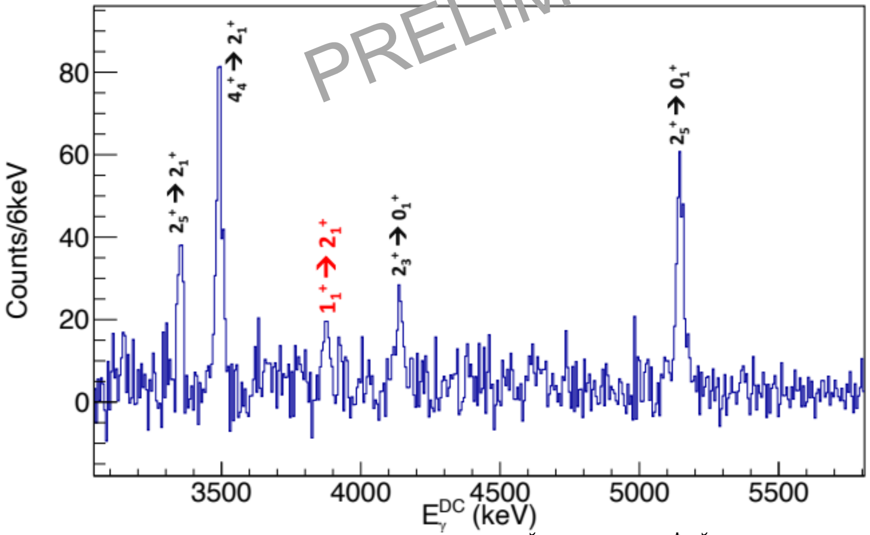


- Extraction of proton spectroscopic factor → direct radiative capture contribution
- Comparison with analog states in ^{26}Mg → insights on ^{26}Si/^{26}Mg (unbound) mirror states

^{26}Si unbound states







Resonance strength measurements
(first time)

E_X = 5676 keV, 5928 keV
ℓ = 2 ℓ = 0

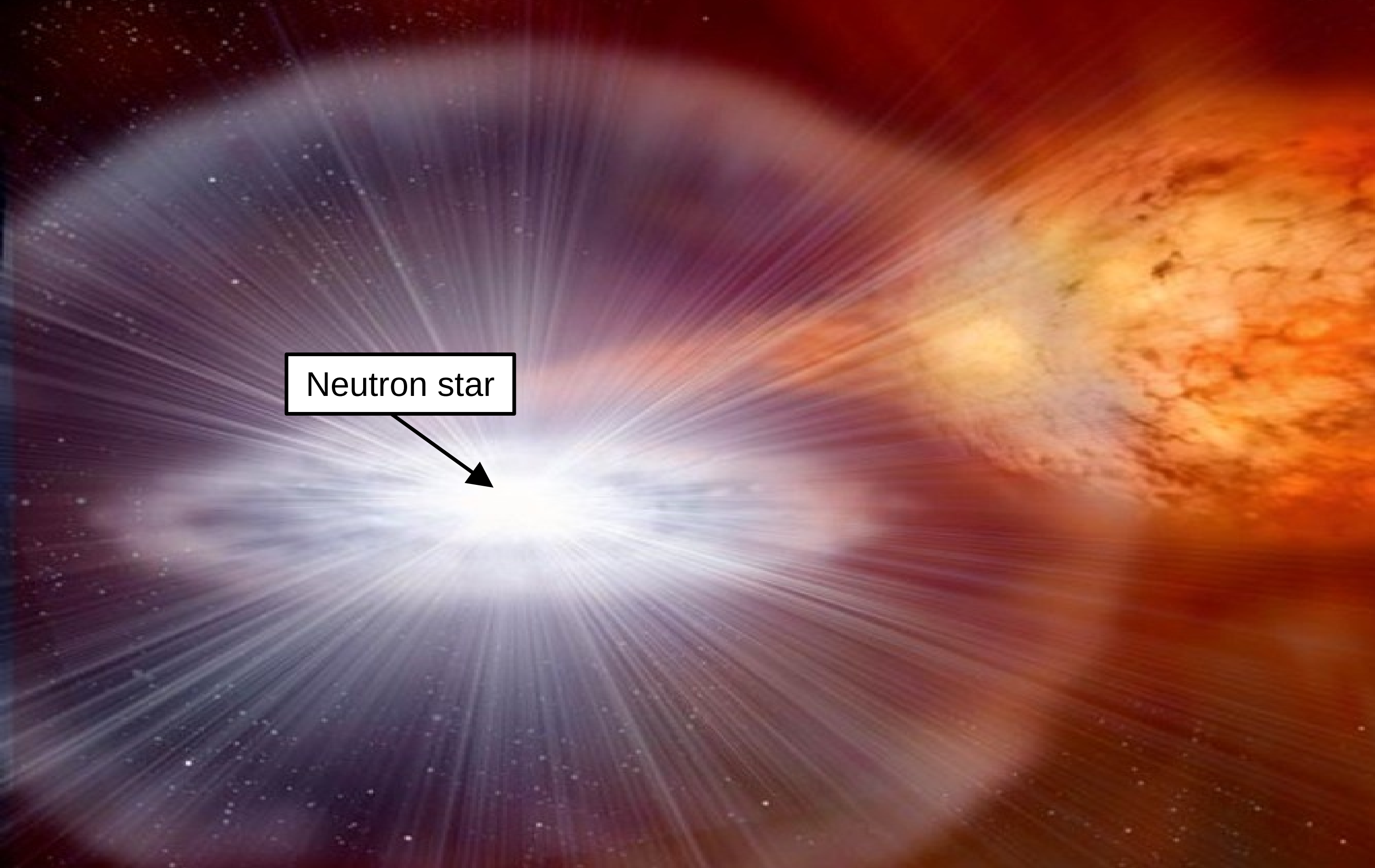
1_1^+	3_3^+	
$< 2.6 \times 10^{-6}$	$23(13)$	A. M. Laird+ (2023)
$2(1) \times 10^{-6}$	$35(15)$	Present work **preliminary**

So far, no indication of 1$^-$ state

Prospects

- Re-evaluation of ^{25}Al(p,γ)^{26}Si rate

Type I X-ray bursts



ID card:
- Rise time: 2 – 10 s
- Peak luminosity: 10^{38} erg.s^{-1}
- Duration: 10 – 100 s
- Recurrence: ~hours – days

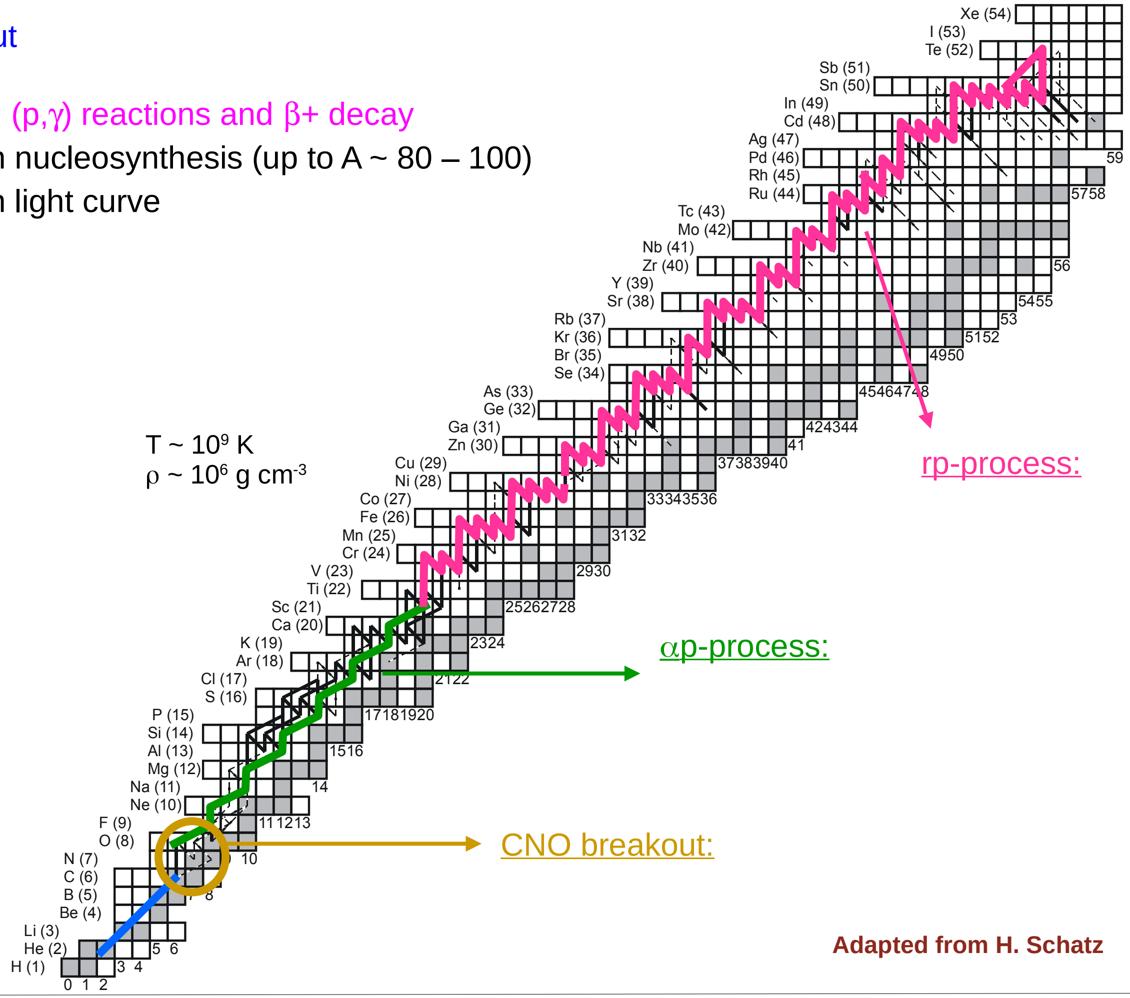
Open questions:
- Extraction of neutron star properties from light curve? (surface redshift → compactness (mass, radius))
- Is mass ejected? Contribution to Galactic enrichment (light *p*-nuclei)?
- ...

X-ray bursts: nuclear network

- **Triggered by the 3α → ^{12}C** reaction and hot CNO break-out

- **(α,p) process**: (α,p) (p,γ) reactions
  → up to A < 60 (radioactive nuclides)
  → impact on energetics and light curve

- ***rp*-process:** (p,γ) reactions and β+ decay
  → impact on nucleosynthesis (up to A ~ 80 – 100)
  → impact on light curve



Adapted from H. Schatz

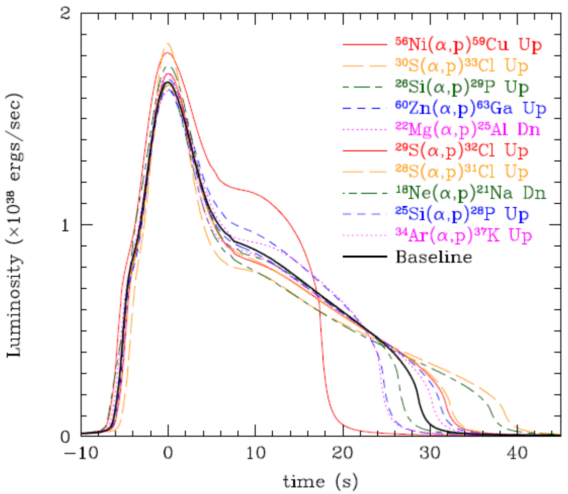
X-ray bursts: nuclear network

- **Triggered by the 3α → ^{12}C** reaction and hot CNO break-out
- **(α,p) process**: (α,p) (p,γ) reactions
  → up to A < 60 (radioactive nuclides)
  → impact on energetics and light curve
- ***rp*-process:** (p,γ) reactions and β+ decay
  → impact on nucleosynthesis (up to A ~ 80 – 100)
  → impact on light curve

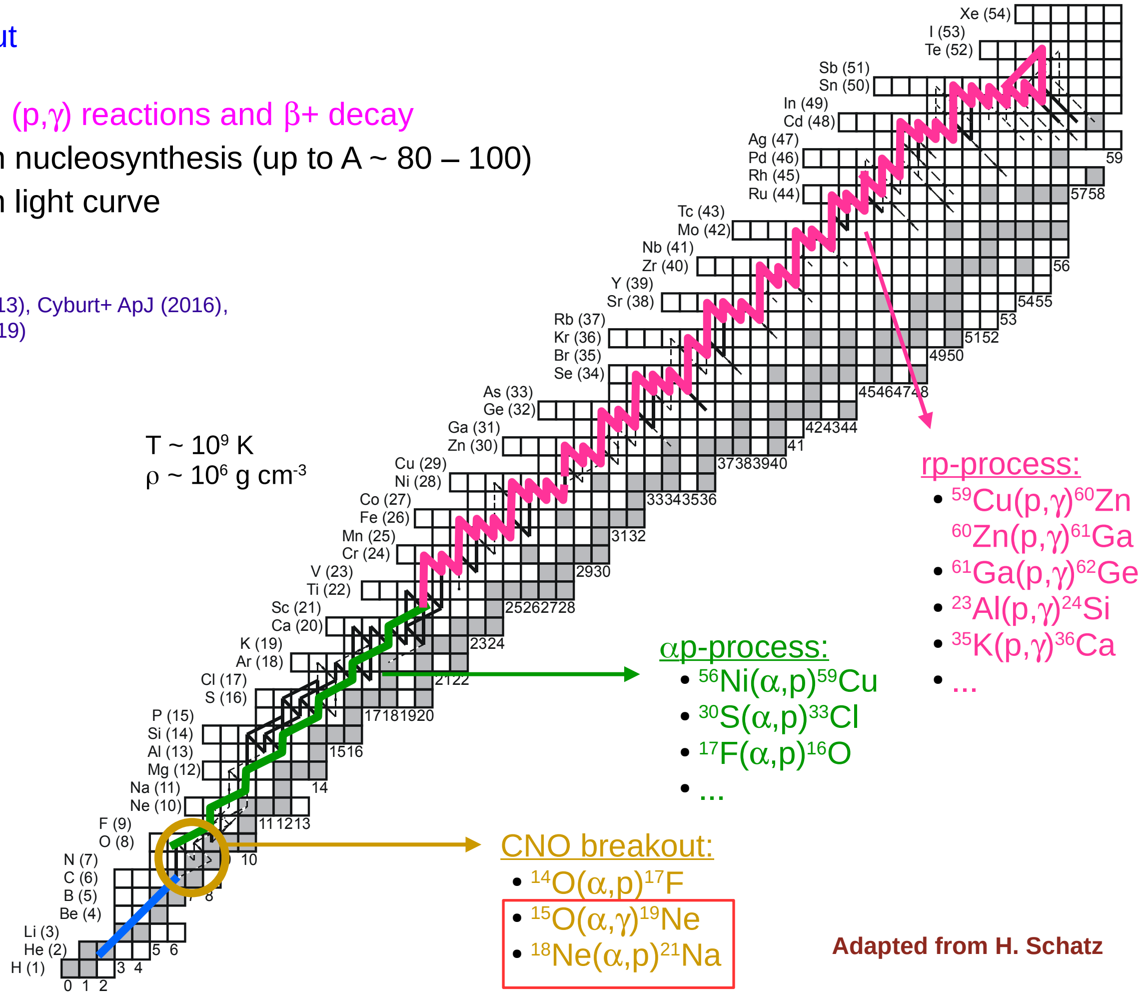
Sensitivity studies: crucial role of waiting points

Parikh+ ApJ (2013), Cyburt+ ApJ (2016), Meisel+ ApJ (2019)

- Few tens of (α,p) and (p,γ) reactions
- Masses along *rp*-process path

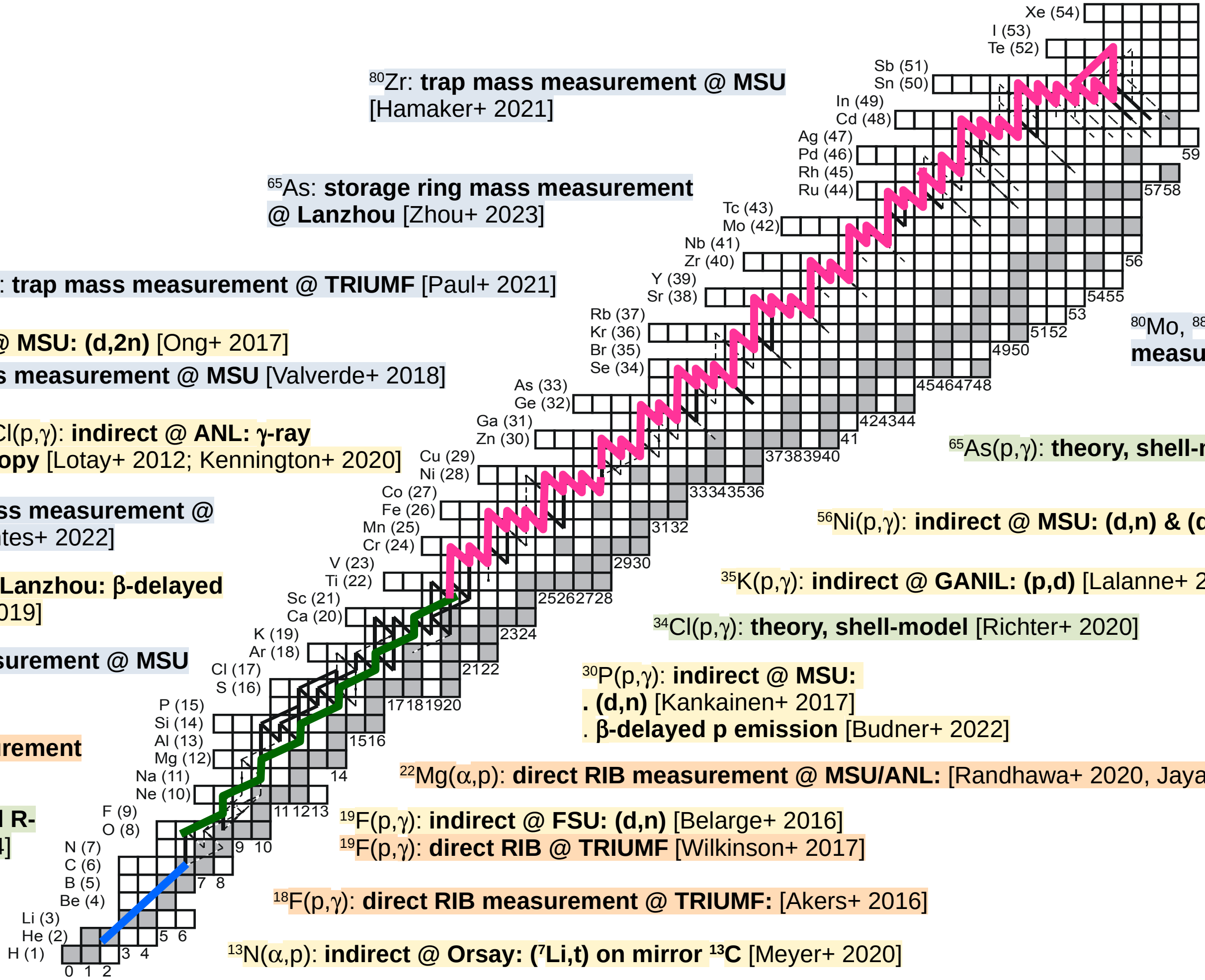


Cyburt+ ApJ (2016)



Adapted from H. Schatz

Recent nuclear physics updates in X-ray burst



^{80}Zr: **trap mass measurement @ MSU** [Hamaker+ 2021]

^{65}As: **storage ring mass measurement @ Lanzhou** [Zhou+ 2023]

^{61}Ga: **trap mass measurement @ TRIUMF** [Paul+ 2021]

^{55}Ni(p,γ): **indirect @ MSU: (d,2n)** [Ong+ 2017]

^{55}Ni(p,γ): **trap mass measurement @ MSU** [Valverde+ 2018]

^{29}P(p,γ), ^{33}Cl(p,γ): **indirect @ ANL: γ-ray spectroscopy** [Lotay+ 2012; Kennington+ 2020]

^{30}S(p,γ): **trap mass measurement @ Jyväskulä** [Puentes+ 2022]

^{26}Si(p,γ): **indirect @ Lanzhou: β-delayed p emission** [Sun+ 2019]

^{23}Al(p,γ): **trap mass measurement @ MSU** [Puentes+ 2022]

^{17}F(p,γ): **direct RIB measurement @ ORNL** [Chipps+ 2008]

^{14}O(α,p): **theory, improved R-matrix analysis** [Hu+ 2024]

^{80}Mo, ^{88}Ru, ^{78}Sr, ^{83}Nb: **MR_TOF mass measurement @ RIKEN-KEK** [Sota+ 2025]

^{65}As(p,γ): **theory, shell-model** [Lam+ 2022]

^{56}Ni(p,γ): **indirect @ MSU: (d,n) & (d,p) on mirror** [Kahl+ 2019]

^{35}K(p,γ): **indirect @ GANIL: (p,d)** [Lalanne+ 2021]

^{34}Cl(p,γ): **theory, shell-model** [Richter+ 2020]

^{30}P(p,γ): **indirect @ MSU:**
. **(d,n)** [Kankainen+ 2017]
. **β-delayed p emission** [Budner+ 2022]

^{22}Mg(α,p): **direct RIB measurement @ MSU/ANL:** [Randhawa+ 2020, Jayatissa+ 2021]

^{19}F(p,γ): **indirect @ FSU: (d,n)** [Belarge+ 2016]

^{19}F(p,γ): **direct RIB @ TRIUMF** [Wilkinson+ 2017]

^{18}F(p,γ): **direct RIB measurement @ TRIUMF:** [Akers+ 2016]

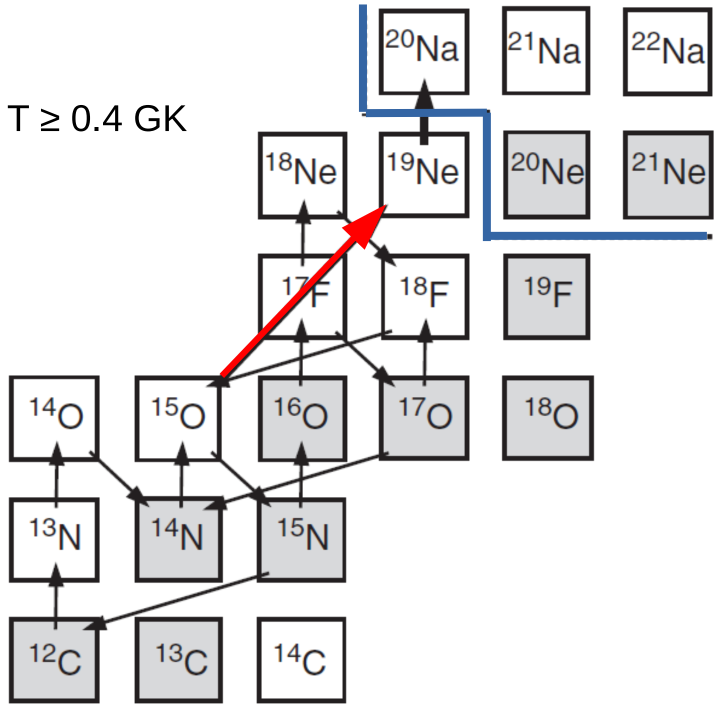
^{13}N(α,p): **indirect @ Orsay: (^{7}Li,t) on mirror ^{13}C** [Meyer+ 2020]

Adapted from H. Schatz

Y. Xu+ (2026)

Hot CNO cycle break-out and the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction

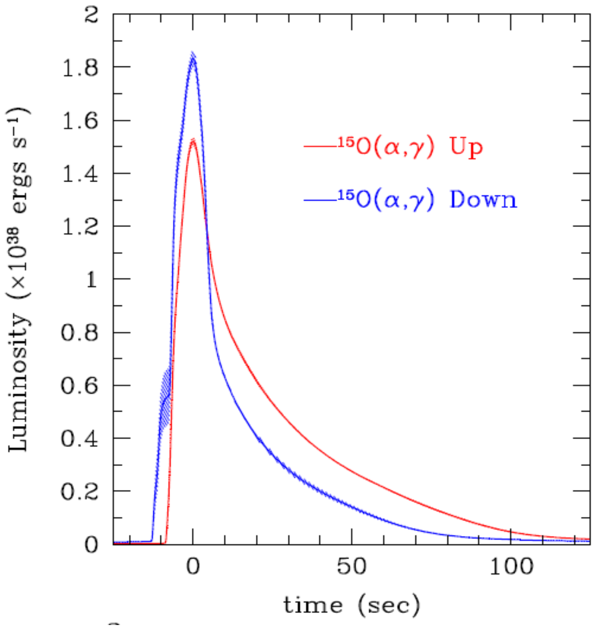
$^{15}O(\alpha,\gamma)^{19}Ne$ provides a way to break out from hot CNO cycle



- **$^{15}O(\alpha,\gamma)^{19}Ne$** much slower than $^{19}Ne(p,\gamma)^{20}Na$

$^{15}O(\alpha,\gamma)^{19}Ne$ affects the onset and shape of the burst light curve

Parikh+ ApJ (2013), Cyburt+ ApJ (2016), Meisel+ ApJ (2019)

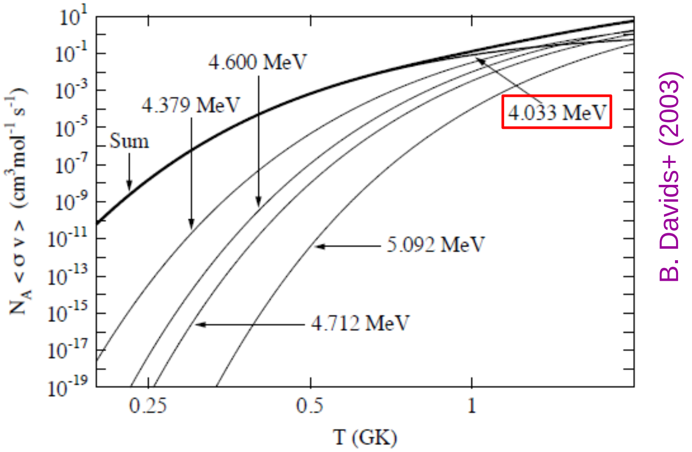


Cyburt+ (2016)

- Effects are greater than natural variations observed in GS 1826-24 Meisel+ ApJ (2018)

State of the art for the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction

Thermonuclear reaction rate



- Dominant state at E_x = 4.033 MeV
  (E_R = 505 keV; J^π = 3/2$^+$; ℓ_α = 1)
- Resonance strength

$$\omega\gamma \approx 0.5 \times (2J_R + 1)\,\Gamma_\alpha$$

Key experimental target for more than 3 decades

Previous works

$$\Gamma_\alpha = \frac{\Gamma_\alpha}{\Gamma} \times \Gamma = B_\alpha \times \Gamma$$

- Measurement of α branching ratio B_α
- Measurement of state lifetime $\tau \propto 1/\Gamma$

Lifetime measurement (DSAM)

- Tan+ (2005) 13^{+9}_{-6} fs
- Kanungo+ (2006) 11^{+4}_{-3} fs
- Mythili+ (2008) $6.5 \pm 1.6 \pm 0.7$ fs

Agreement within 1σ

α-particle branching ratio

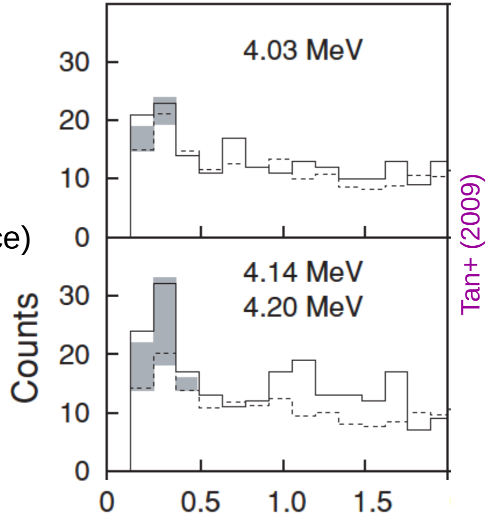
- Davids+ (2003) $\leq 4.3 \times 10^{-4}$
- Tan+ (2007,2009) $2.9 \pm 2.1 \times 10^{-4}$

(**consistent with 0** at 90% confidence)

α-particle width

- $\Gamma_\alpha = 17 \pm 13\,\mu$eV Tan+ (2009)
- $\Gamma_\alpha = 24 \pm 18\,\mu$eV Fortune+ (2010)

(combining lifetime measurements)



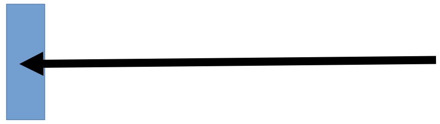
The MUGAST + VAMOS + AGATA experimental set-up

^{7}Li(^{15}O,t)^{19}Ne* → γ + ^{19}Ne$_{g.s.}$

J. Sanchez Rojo (2022 PhD)

^{15}O @ 4.7 MeV/u

- ~ 2x10^{7} pps
- SPIRAL1 beam
- ^{15}N contaminant < 0.5 %



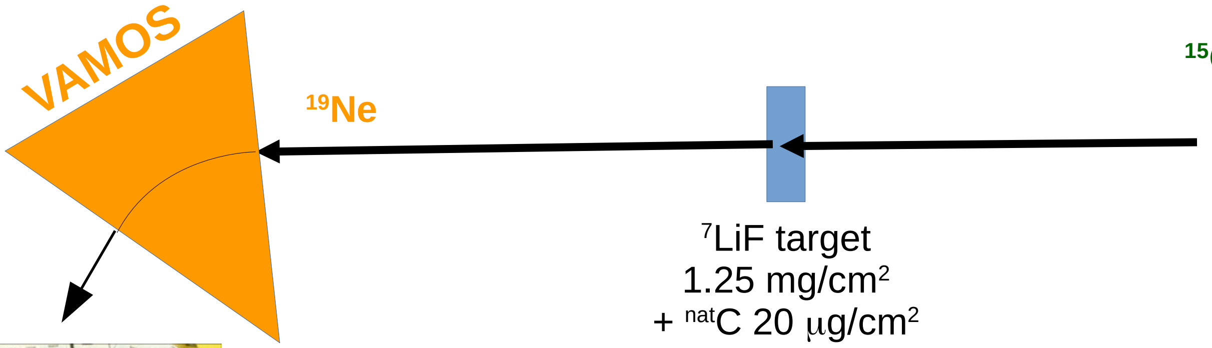
^{7}LiF target
1.25 mg/cm^{2}
+ ^{nat}C 20 μg/cm^{2}

The MUGAST + VAMOS + AGATA experimental set-up

J. Sanchez Rojo (2022 PhD)

$^{7}Li(^{15}O,t)^{19}Ne^{*} \rightarrow \gamma + {}^{19}Ne_{g.s.}$

GANIL Spiral2 – laboratoire commun CEA/DRF CNRS/IN2P3



^{7}LiF target
1.25 mg/cm^{2}
+ ^{nat}C 20 μg/cm^{2}

^{15}O @ 4.7 MeV/u

- ~ 2x10^{7} pps
- SPIRAL1 beam
- ^{15}N contaminant < 0.5 %

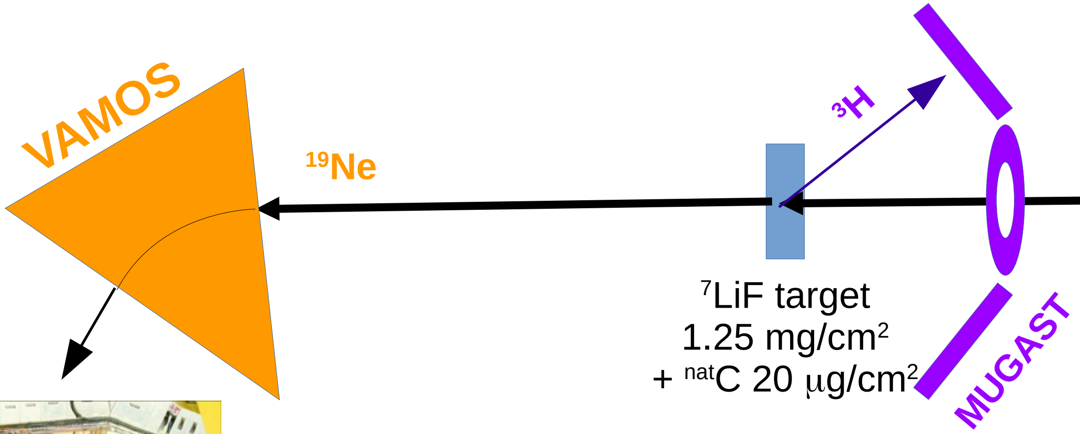
VAMOS @ 0°

- ΔΘ ± 7°
- ΔBρ ± 5%

The MUGAST + VAMOS + AGATA experimental set-up

$^{7}Li(^{15}O,t)^{19}Ne^{*} \rightarrow \gamma + {}^{19}Ne_{g.s.}$

J. Sanchez Rojo (2022 PhD)



^{15}O @ 4.7 MeV/u

- ~ 2×10^{7} pps
- SPIRAL1 beam
- ^{15}N contaminant < 0.5 %

VAMOS @ 0°

- $\Delta\Theta \pm 7°$
- $\Delta B\rho \pm 5\%$

MUGAST

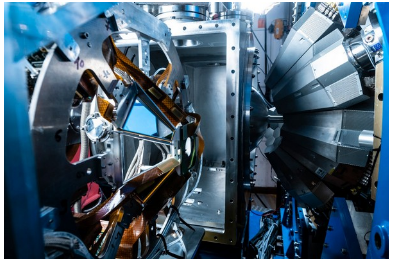
- DSSSD 500 µm
- Trapezoid (x5), annular (x1), square (x2)
- 128+128 strips

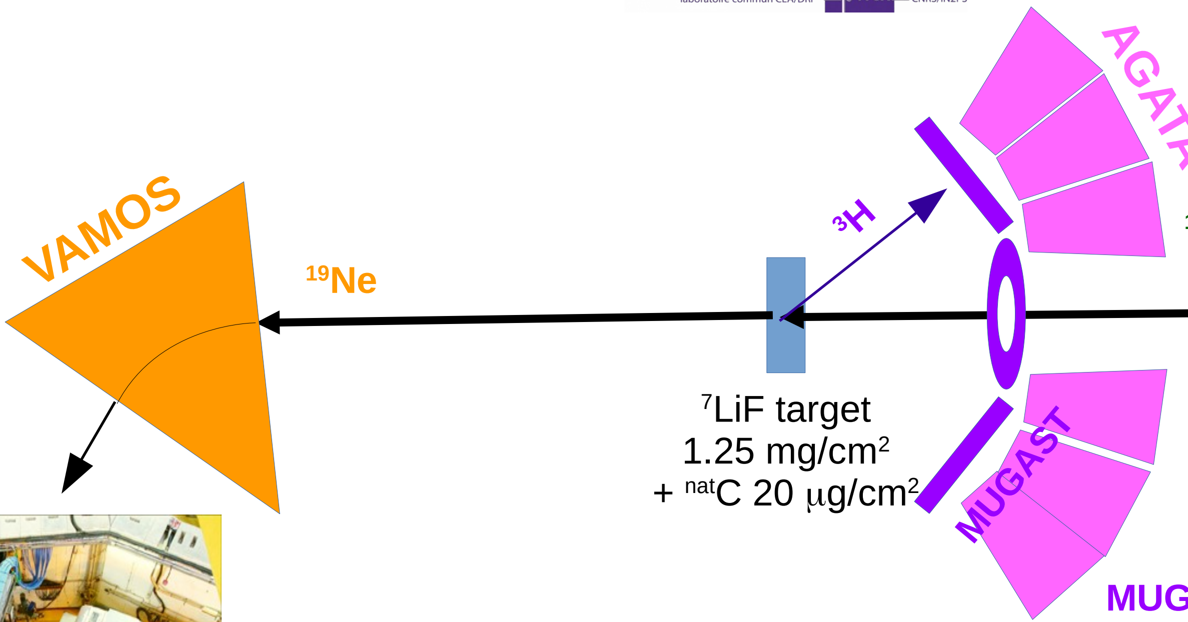
The MUGAST + VAMOS + AGATA experimental set-up

^{7}Li(^{15}O,t)^{19}Ne* → γ + ^{19}Ne$_{g.s.}$

J. Sanchez Rojo (2022 PhD)

AGATA @ 18 cm
- 37 crystals
- ε(1 MeV) ~ 8% w/ add-back





^{15}O @ 4.7 MeV/u
- ~ 2x10^{7} pps
- SPIRAL1 beam
- ^{15}N contaminant < 0.5 %

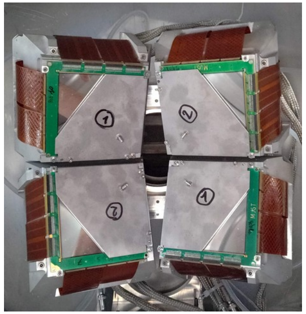
VAMOS @ 0°
- ΔΘ ± 7°
- ΔBρ ± 5%

MUGAST
- DSSSD 500 μm
- Trapezoid (x5), annular (x1), square (x2)
- 128+128 strips

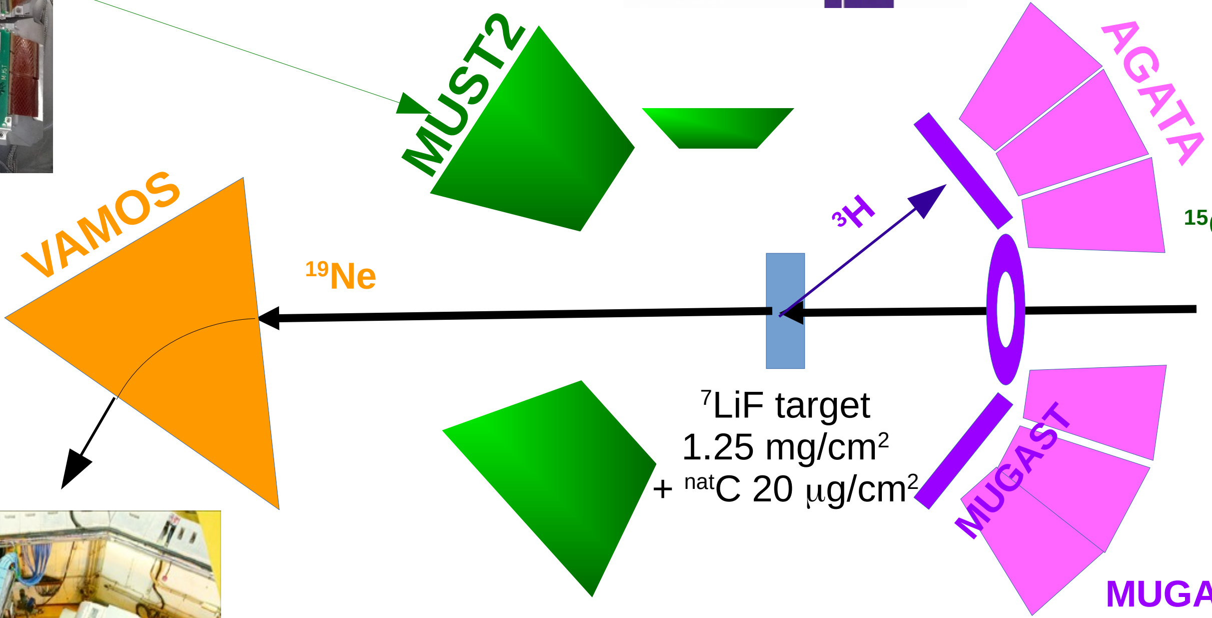
The MUGAST + VAMOS + AGATA experimental set-up

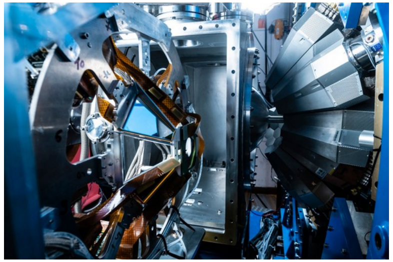
J. Sanchez Rojo (2022 PhD)

^{7}Li(^{15}O,t)^{19}Ne* → γ + ^{19}Ne$_{g.s.}$



MUST2
- DSSSD 300 µm + CsI
- 128+128 strips (10x10 cm^2)





AGATA @ 18 cm
- 37 crystals
- ε(1 MeV) ~ 8% w/ add-back

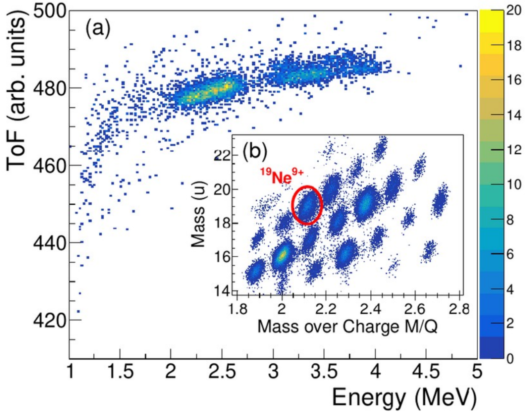
^{15}O @ 4.7 MeV/u
- ~ 2x10^7 pps
- SPIRAL1 beam
- ^{15}N contaminant < 0.5 %

VAMOS @ 0°
- ΔΘ ± 7°
- ΔBρ ± 5%

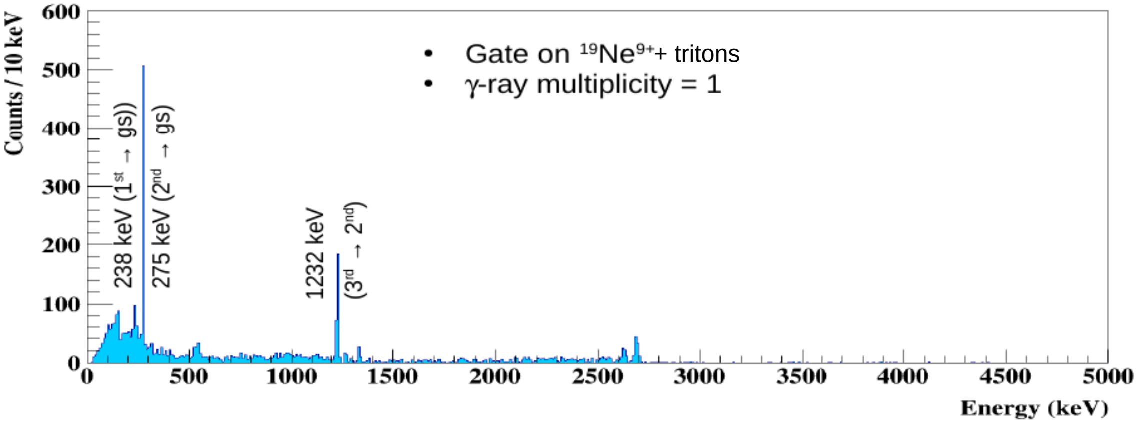
MUGAST
- DSSSD 500 µm
- Trapezoid (x5), annular (x1), square (x2)
- 128+128 strips

^{19}Ne – t – γ triple coincidences

VAMOS & MUGAST PID

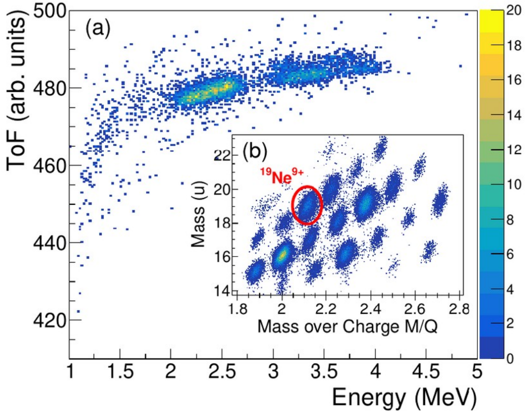


AGATA γ-ray energy spectrum

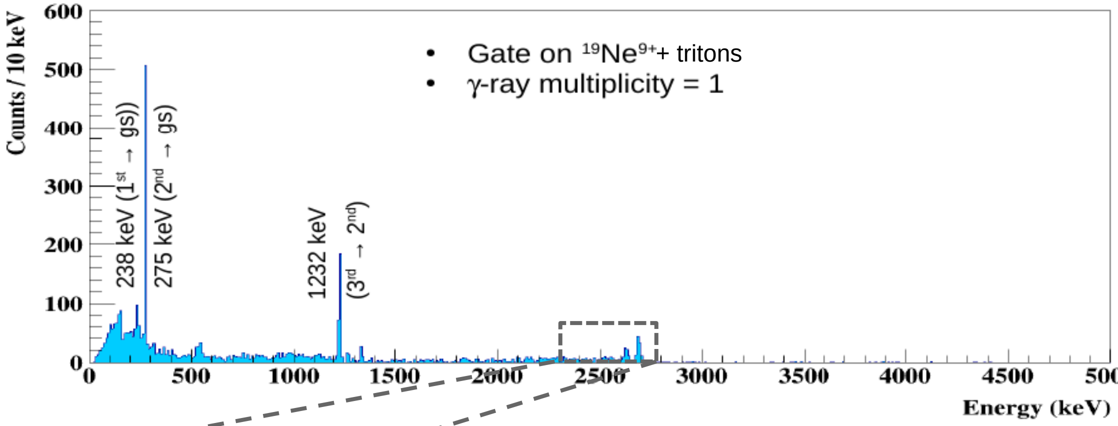


^{19}Ne – t – γ triple coincidences

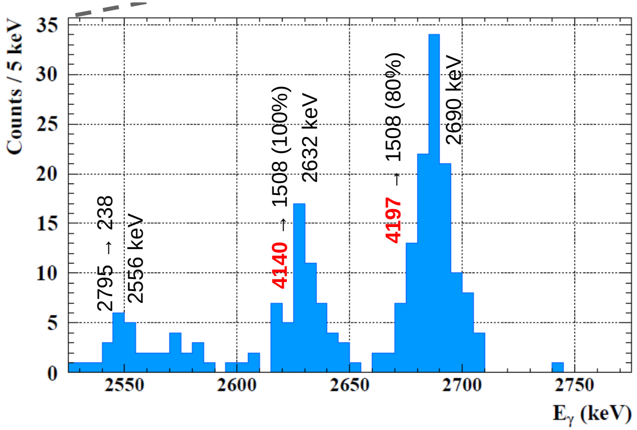
VAMOS & MUGAST PID



AGATA γ-ray energy spectrum

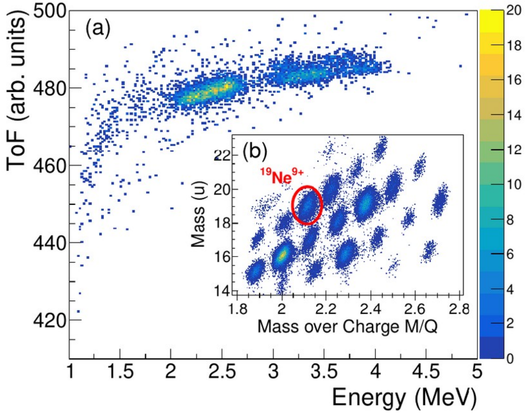


γ-ray transitions from the doublet at 4140 keV and 4197-keV

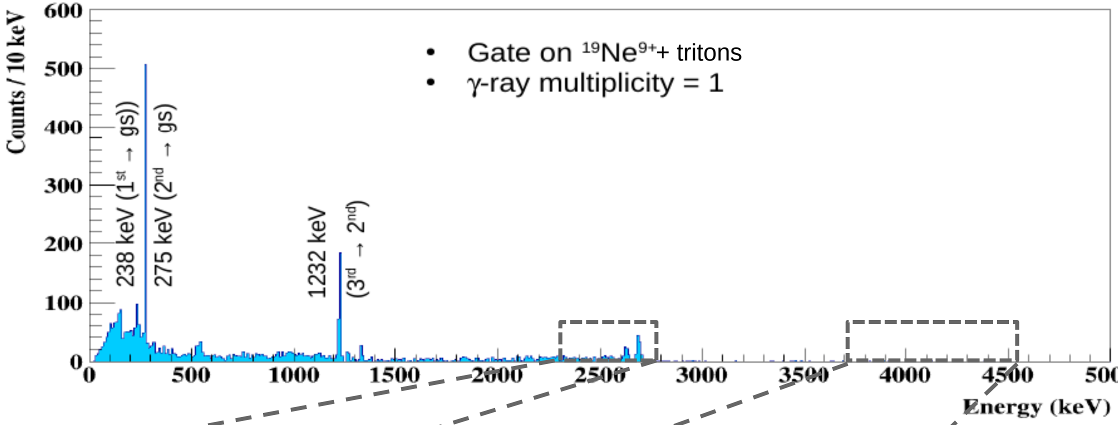


^{19}Ne – t – γ triple coincidences

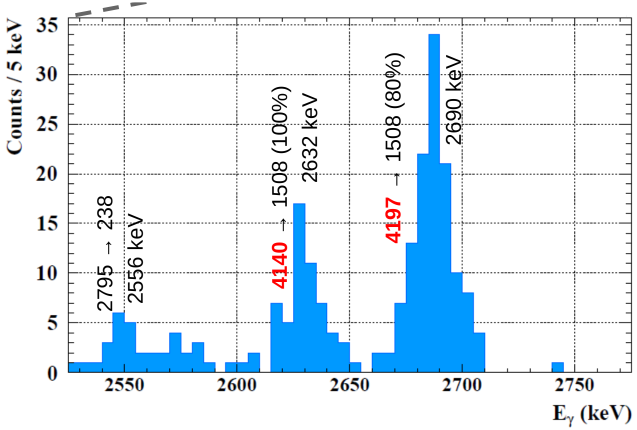
VAMOS & MUGAST PID



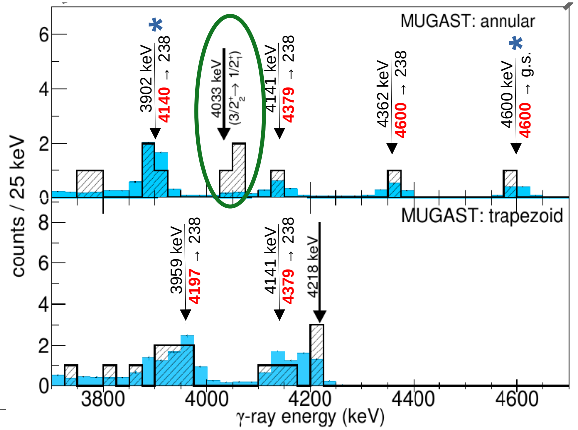
AGATA γ-ray energy spectrum



γ-ray transitions from the doublet at 4140 keV and 4197-keV



Observation of the 4033 keV → g.s. transition

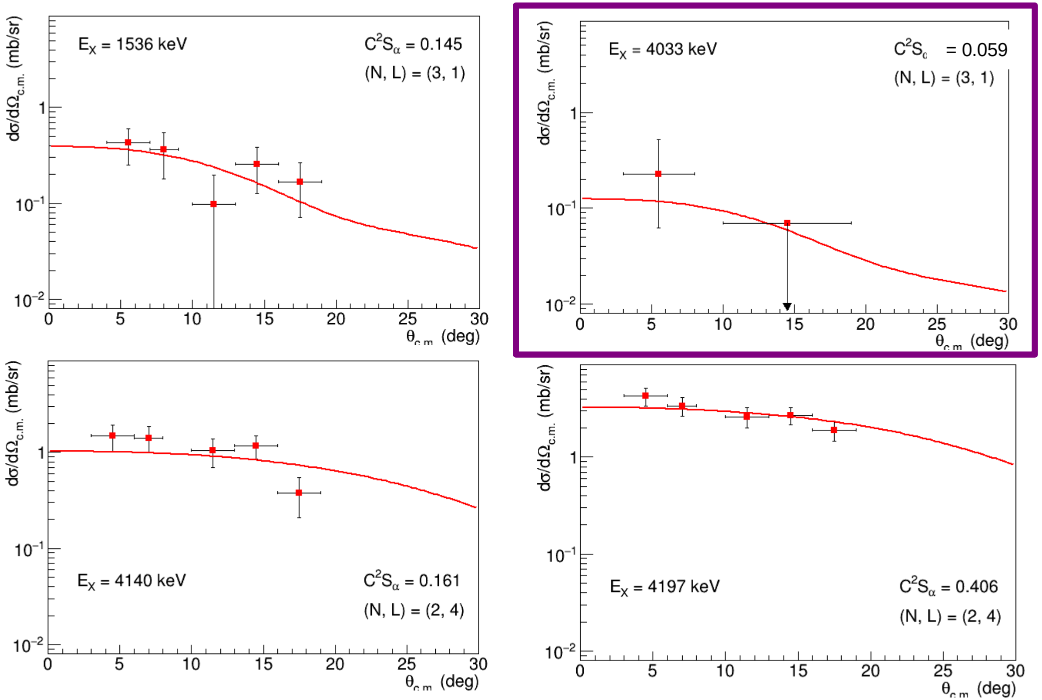


Source of background

- Compton events from high-energy γ-ray lines
- Small leaking (2.3 %) of ^{20}Ne in VAMOS $^{19}Ne^{9+}$ selection

* confirmation of Hall+ 2019

Angular distributions and α-particle spectroscopic factors



Comparison with analog states in ^{19}F

		^{19}Ne		^{19}F	
J^π	Q=2N+L	E_x (keV)	C^2S_α	E_x (keV)	C^2S_α [a]
5/2-	8	1508	**0.25**	1346	0.20
3/2+	7	1536	**0.15**	1554	0.21
3/2-	8	1615	**0.23**	1459	0.20
9/2+	7	2794	**0.22**	2780	0.16
3/2+	7	**4033**	**$0.063^{+0.064}_{-0.034}$**	3908	≤ 0.09
(7/2-)	8	4140	**0.14 (2)**	3999	0.29
(9/2-)	8	4197	**0.37 (4)**	4033	
7/2+	7	4379	**$0.019^{+0.018}_{-0.010}$**	4378	0.01
		4549		4556	
(5/2+)	7	4600		4550	

[a] F. de Oliveira Santos et al. (1996)

- Good agreement with analog states (within a factor of 2)
- Small C^2S_α for the E_x(^{19}Ne) = 4033 keV state
- C^2S_α determined for the 2 components of the E_x(^{19}Ne) = 4140 + 4197 keV doublet

FR-DWBA analysis (FRESCO)

- Optical potentials from mirror reaction: ^{15}N(Li,t)^{19}F
  F. de Oliveira Santos et al. (1996)
- C^2S_α determination: prescription from Becchetti+ (1978)
  - $L \geq 2$: α-cluster bound by 50 keV
  - $L < 2$: C^2S_α extrapolation to actual α-separation energy
- Uncertainty due to optical potential ~ 40%

Updated $^{15}O(\alpha,\gamma)^{19}Ne$ reaction rate

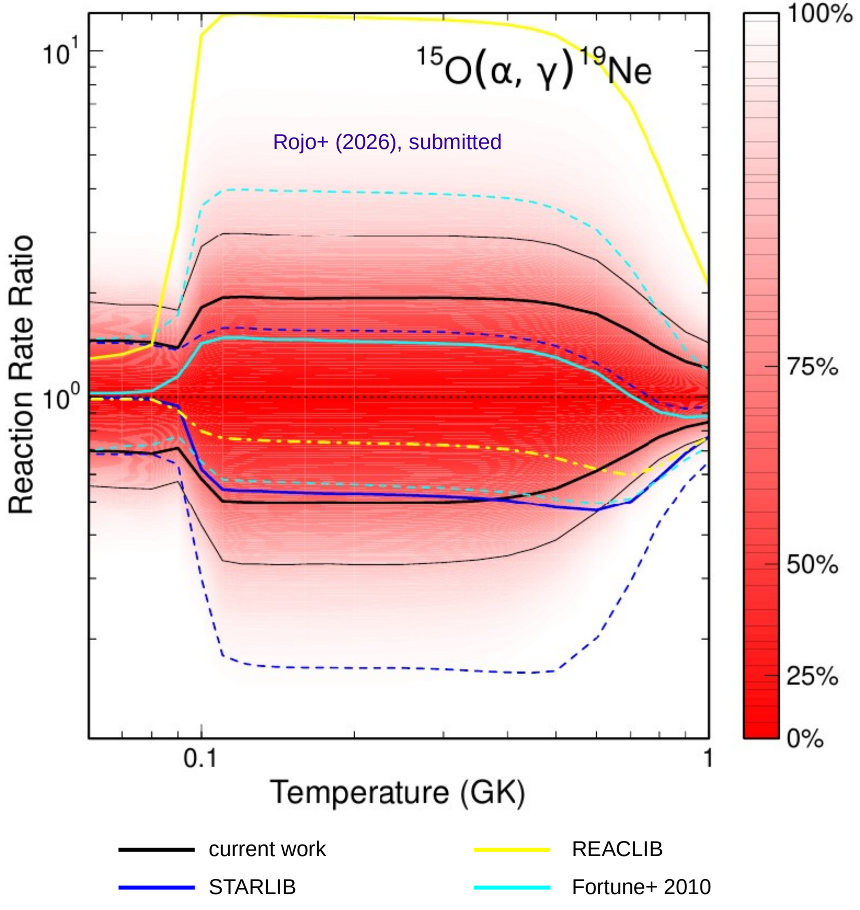
α-particle widths (present + literature)

	Present work		Tan+ (2009)			Fortune+ (2010)	
E_x (keV)	Γ_α (μeV)	B_α (x 10^{-4})	Γ_α (μeV)	B_α (x 10^{-4})	τ (fs)	Γ_α (μeV)	τ (fs)
4033	$11.2^{+10.9}_{-5.9}$		**17 (13)**	2.9 (2.1)	13^{+9}_{-6}	**24 (18)**	7.9 (1.5)
4140	0.93 (13)	0.3	**44 (20)**	12 (5)	18^{+2}_{-3}		
4197	11.7 (1.1)	8.2	**18 (9)**		43^{+12}_{-9}		

Good agreement with literature

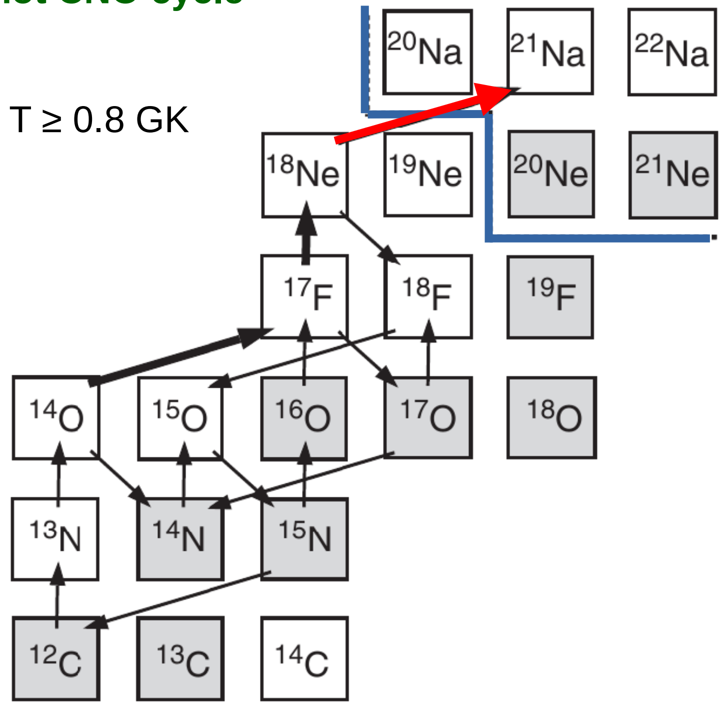
- 4033 keV state: $\Gamma_\alpha = 11.2^{+10.9}_{-5.9}$ μeV
  → determination from a single experiment
- 4140 keV + 4197 keV doublet
  → α-particle partial width for each component

- Current recommended rate compatible with previous rate
- Current rate uncertainty (68% coverage) is a factor of 2 smaller than the spread in current available reaction rates



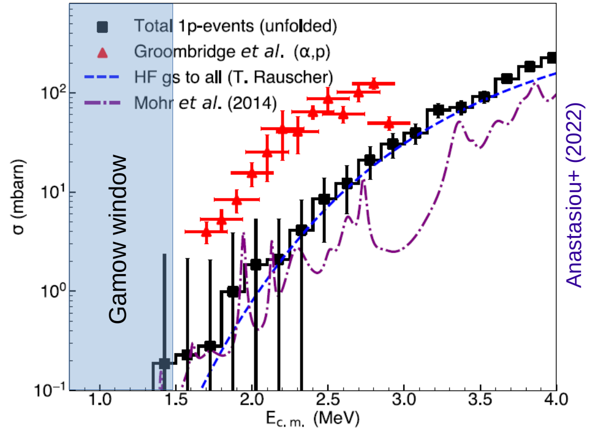
Hot CNO cycle break-out and the ^{18}Ne(α,p)^{21}Na reaction

The ^{18}Ne(α,p)^{21}Na break out reaction from hot CNO cycle



^{18}Ne(α,p)^{21}Na experimental status

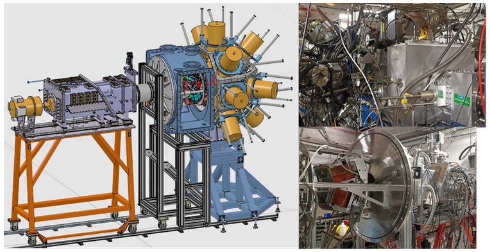
- Direct measurement challenging in the lower part of the Gamow window
- Hauser-Feshbach estimate
  → high level density ~1 state / 125 keV (E_X > 8.5 MeV)
  → but only 3 L = 0 and 4 L = 1 states



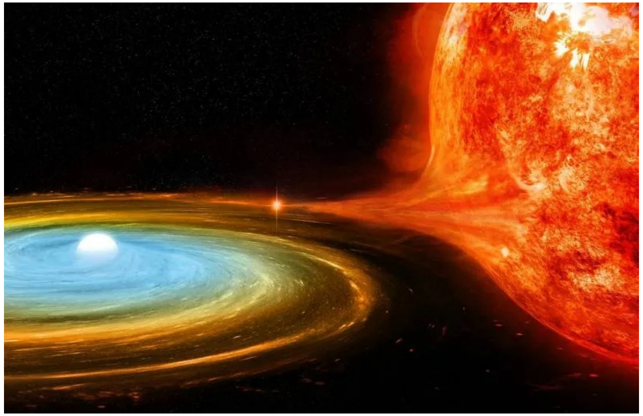
- Properties of states in compound ^{22}Mg [Γ_α from analog ^{22}Ne states or assuming $\langle\theta_\alpha^2\rangle$] Giesen+ (1994), Mohr+ (2014)

Strategy and prospects (MUGAST + EXOGAM + ZDD)

- Resonance strength $\omega\gamma = \omega\frac{\Gamma_\alpha\Gamma_p}{\Gamma} = \omega\Gamma_\alpha \times BR_p$
  - Γ_α → (^{7}Li,t) transfer reaction
  - BR_p → proton decay measurement
  - p_0 vs p_1 decay → ^{21}Na* prompt γ-ray decay
- Successful commissioning in 2026, experiment scheduled in 2027



Summary



- Classical novae and type I X-ray bursts are the most frequent thermonuclear explosions in our Galaxy
  - Laboratories providing insights into the origin of the elements, explosive hydrodynamics, and dense matter physics
  - Tackling open questions requires
    - nuclear physics input (neutron-deficient nuclides)
      - mass measurements, stable & RIB facilities (+ variety of experimental techniques and setups)
    - combined effort with
      - modeling (multi-dimensional hydrodynamics studies)
      - observations (multi-messengers, including next MeV γ-ray mission)