New $^{17}O+\alpha$ reaction rates and impact on the s-process in metal-poor rotating massive stars

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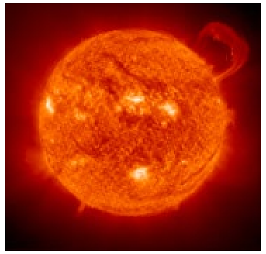
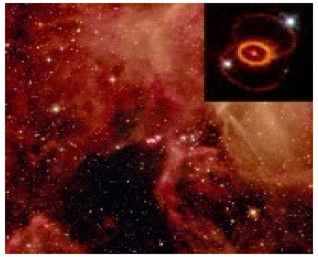
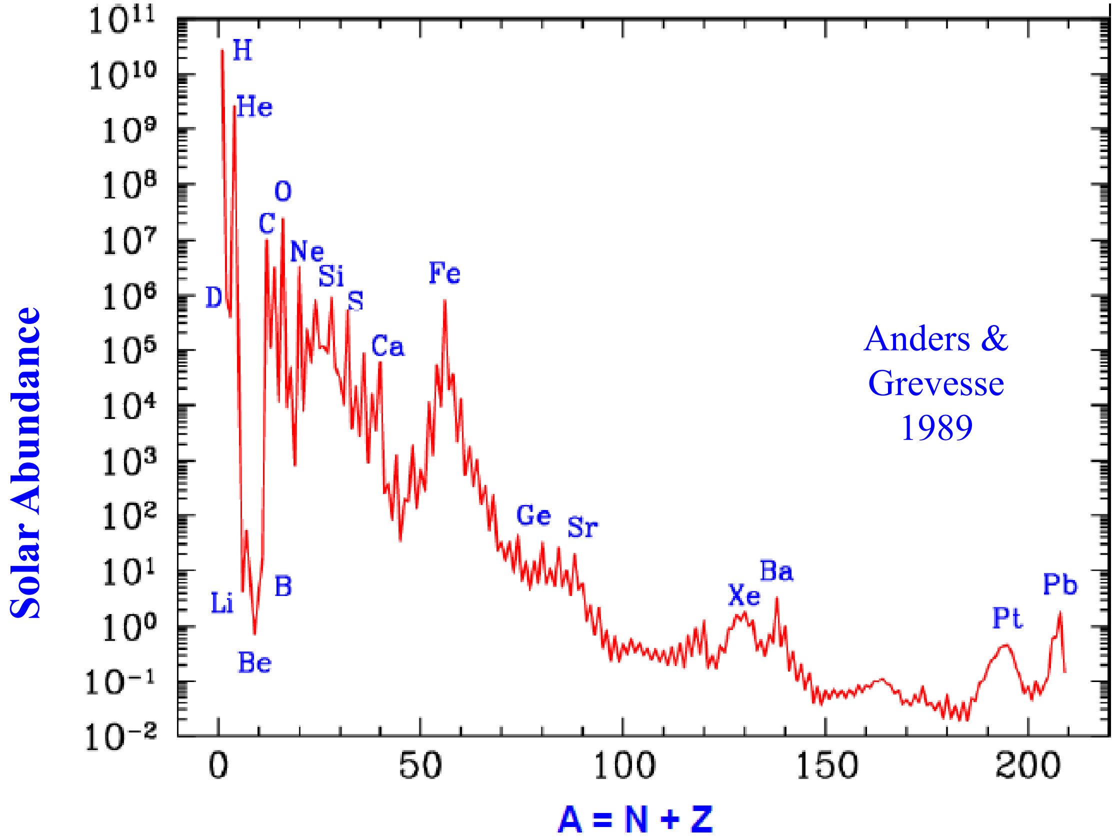
NUCLEAR ASTROPHYSICS



- How do stars form and evolve?
- What powers the stars?
- What is the origin of the chemical elements present in our Universe?
- Which nucleosynthesis processes are responsible of the observed solar abundances ?



Abundance curve of the elements



Data sources:

Earth, Moon, meteorites, solar & stellar spectra, cosmic rays…

Characteristics:

- 12 orders-of-magnitude span
- H ~ 75%
- He ~ 23%
- C → U ~ 2% (“metals”)
- D, Li, Be, B under-abundant
- O the 3rd most abundant
- C the 4th most abundant
- exponential decrease up to Fe
- peak near Fe
- nearly flat distribution beyond Fe with some peaks

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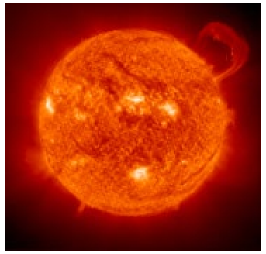

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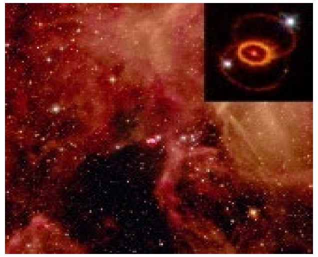

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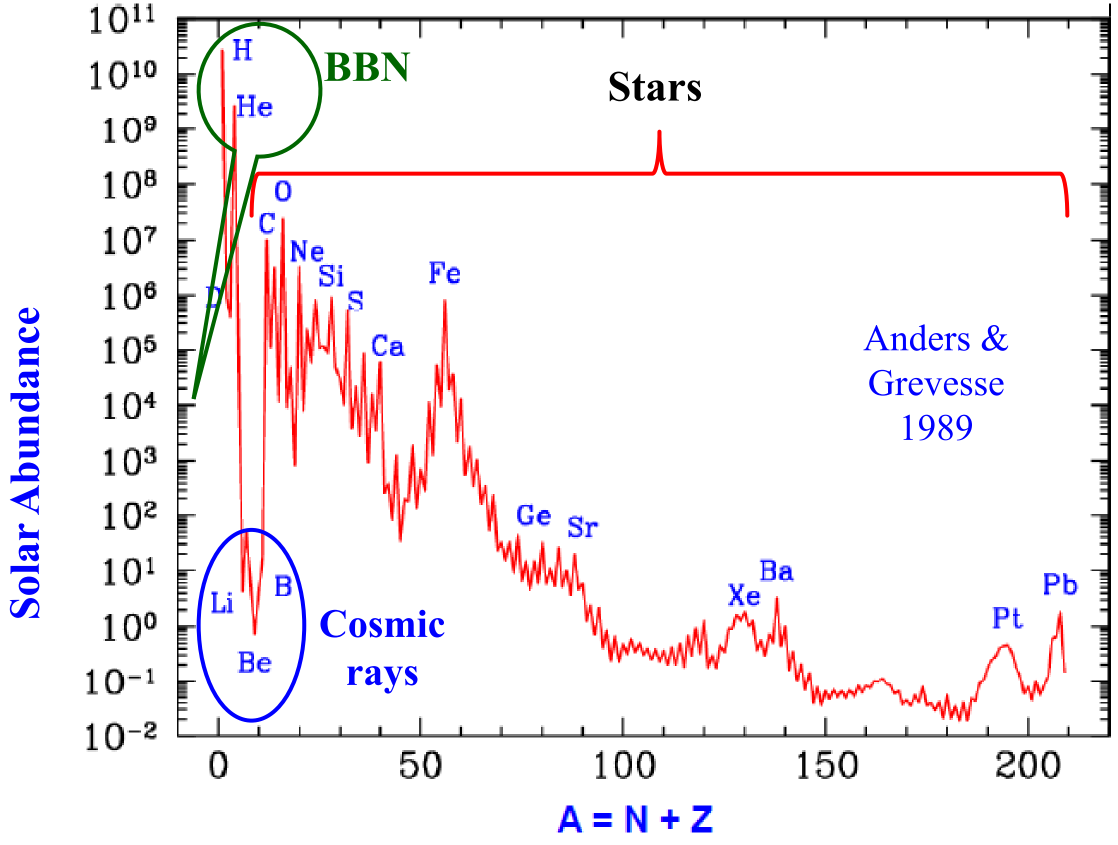

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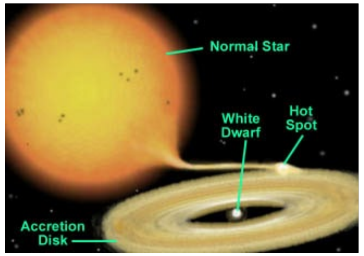
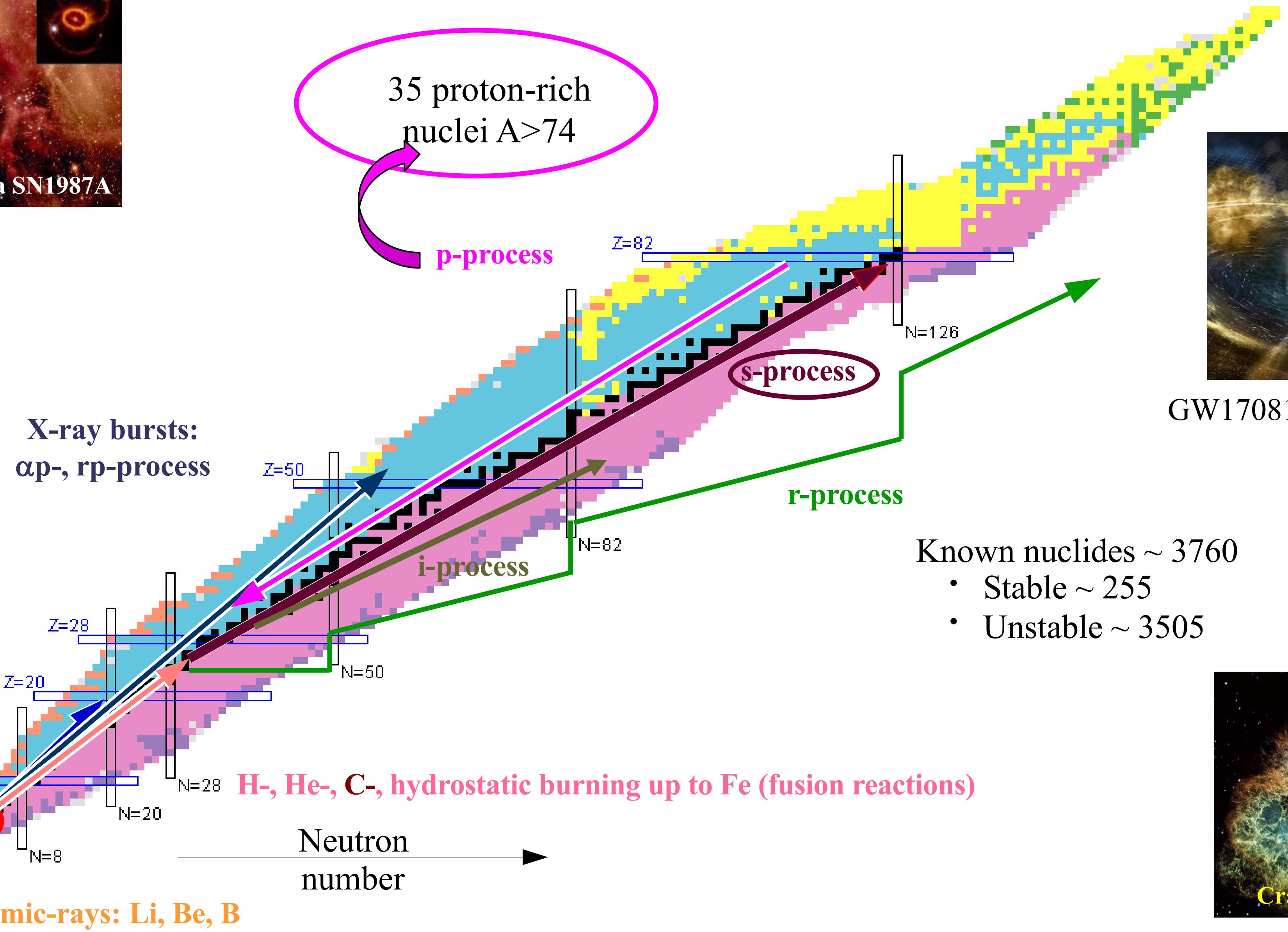
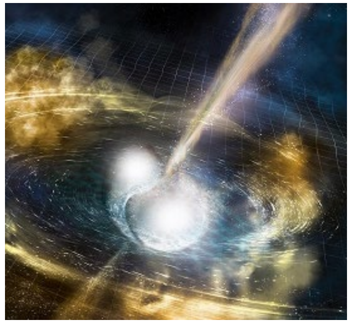
Nuclear landscape and astrophysical processes


Supernova SN1987A






GW170817 (artistic vew)

Known nuclides ~ 3760

- Stable ~ 255
- Unstable ~ 3505

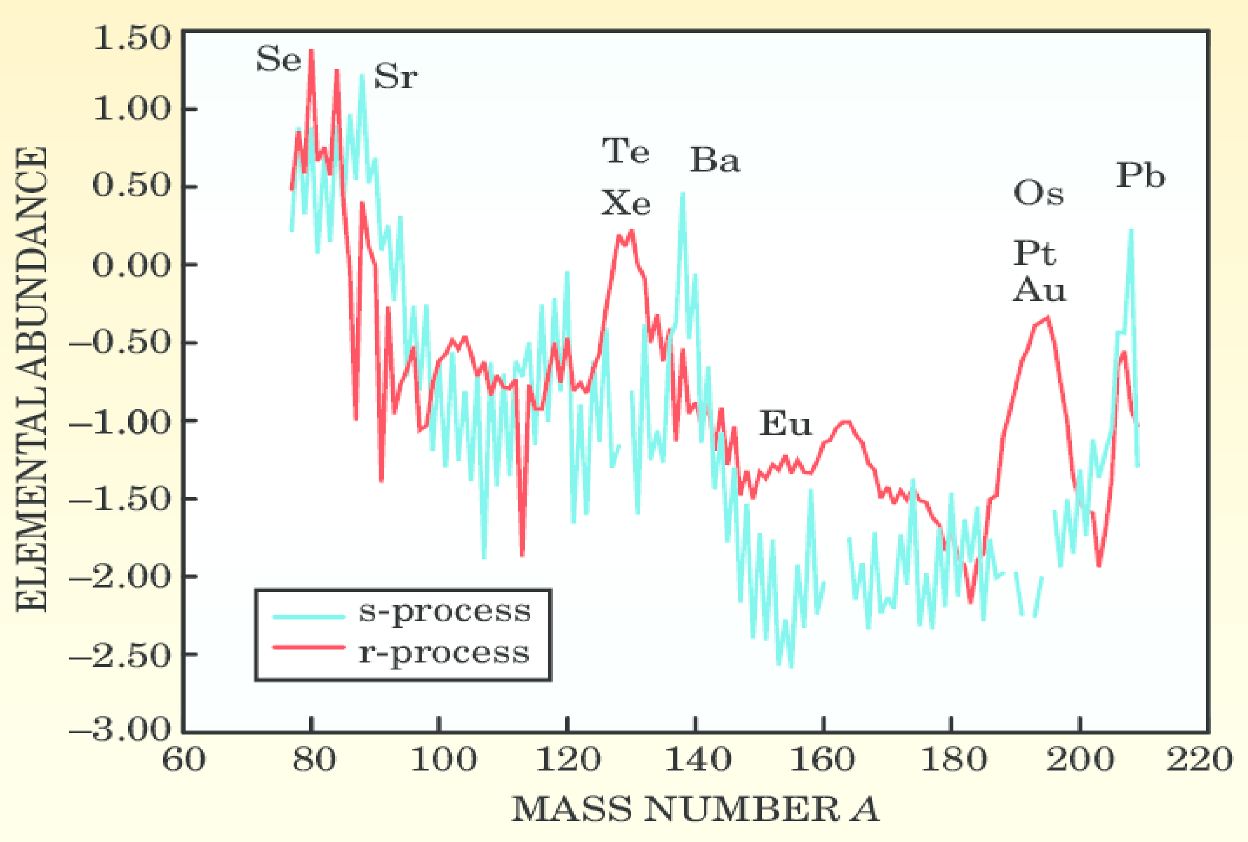

Crab nebula, M1

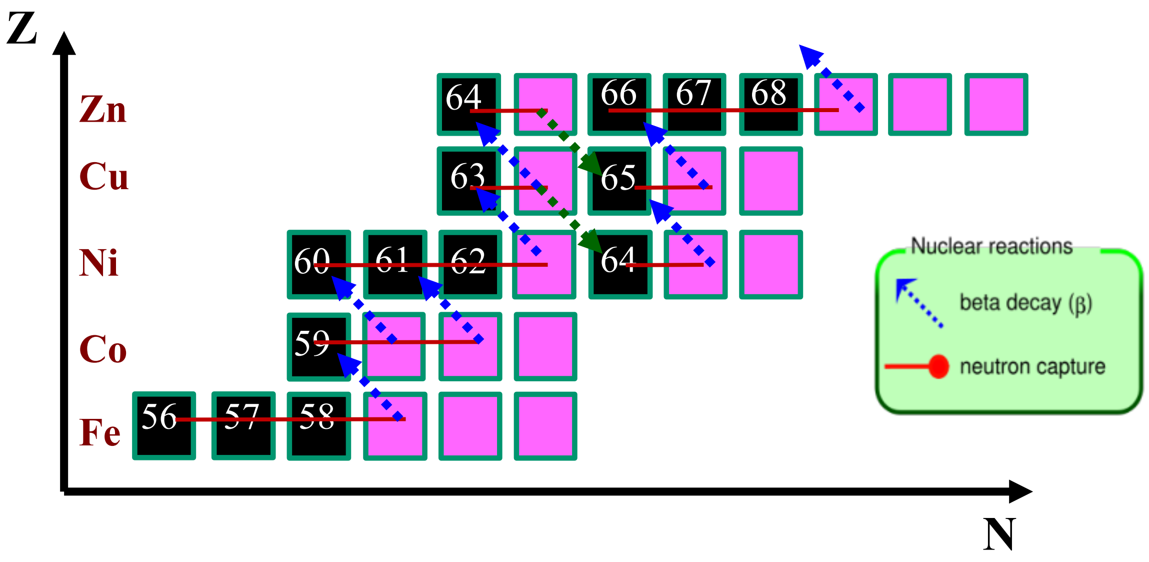
s-process

s-process (s = slow neutron capture process)

$\tau_\beta << \tau_n \quad \Leftrightarrow N_n \sim 10^8 - 10^{11}$ n/cm^3

→ production of half of the abundance of heavy elements

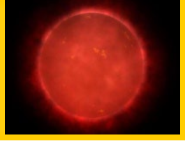




➢ **Main** component
→ production of 90<A<209 elements in low-mass AGB stars 1-4 $M_\odot$ (T~0.1 GK)

➢ **Weak** component
→ production of 56<A<90 elements in intermediate-mass AGB star (T~0.3 GK) & **massive stars** (T~0.2-1GK)

s-process in rotating metal-poor massive stars



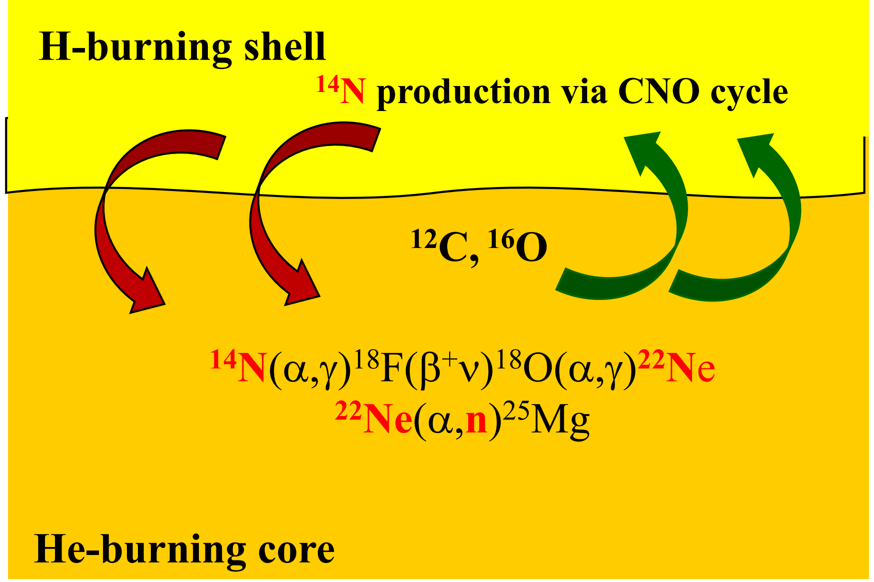
Weak s-process → **56<A<90** in **massive stars** M>**8M**$_\odot$

- End of core He burning (T ~3·10^8 K, N$_n$ =**10^6** cm^{-3}) ⟶ **Main neutron source: ^{22}Ne(α,n)^{25}Mg**

  → Starting with ^{14}N in the He core: ^{14}N(α,γ)^{18}F(β$^+$ν)^{18}O(α,γ)^{22}Ne ⟶ ^{22}Ne(α,n)^{25}Mg

- **^{22}Ne(α,n)^{25}Mg** reactivated during C-shell burning @ T~1 GK → N$_n$ =**10^{11}** cm^{-3}

- **Metal-poor massive stars** ([Fe/H] <-1)→ negligible *s*-process production (low ^{22}Ne & Fe seed abundance)
- With fast rotation induced mixing ⟶ ^{22}Ne production in He core strongly enhanced **Nishimura+16, Choplin+18**



↳ large production of *s*-elements between Strontium & Barium 90<A<140

- Enhanced weak s-process (es-process) **Frischknecht+16**

→ Important impact on chemical enrichment in early galaxies.

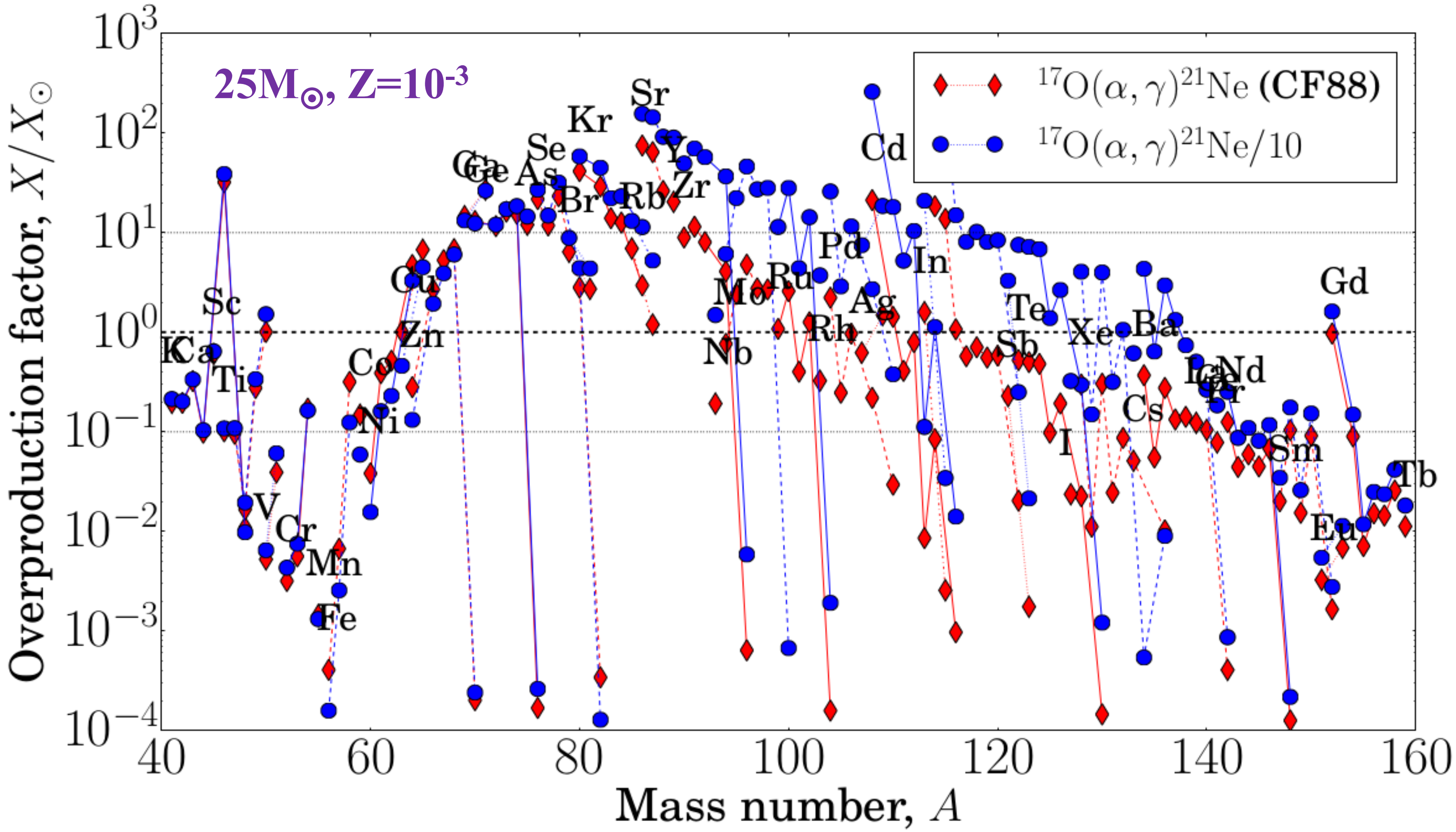
→ Source of heavy elements such as Barium in early universe? **Barbuy+14**

s-process in rotating metal-poor massive stars

But the final abundances of the enhanced weak *s*-process strongly depends on:

$^{16}O(n,\gamma)^{17}O$ neutron poison effect & **$^{17}O(\alpha,n)/^{17}O(\alpha,\gamma)$** reaction rate ratio

→ neutron recycling efficiency



Nishimura+MNRAS-2017

Calculation with $^{17}O(\alpha,n)^{20}Ne$ Nacre adopted rate & $^{17}O(\alpha,\gamma)^{22}Ne$ CF88 rate

From nuclear physics to abundances

Nuclear physics Experiments & theory
(**cross-sections, resonance parameters**, , masses, β-decays,…)

Reaction rate

Astrophysics Modelling & nucleosynthesis (reaction network)

Abundances

Observations

Abundances

$$\langle \sigma v \rangle = \left(\frac{8}{\pi \mu} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E) E e^{-E/kT} dE$$

- Can sometimes be measured directly but mostly @ higher energy

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Reaction rate → **Astrophysics Modelling & nucleosynthesis (reaction network)** → **Abundances**

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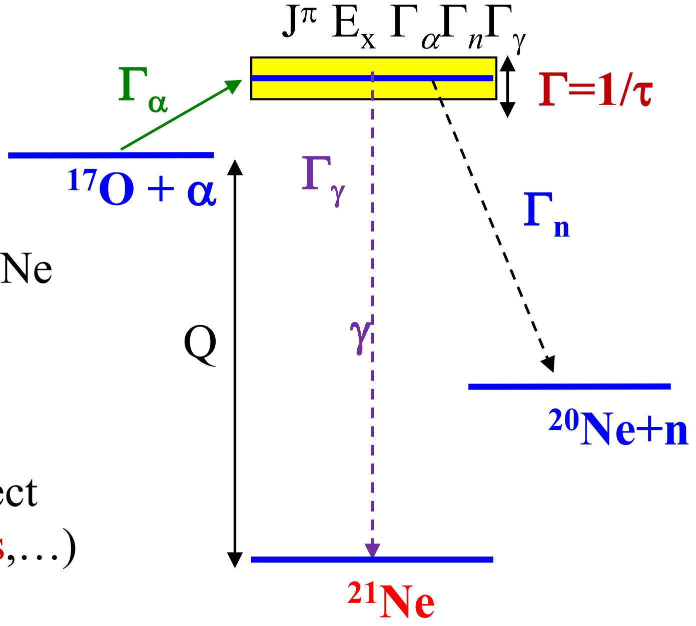
- For narrow resonance cases :

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

$$\rightarrow (\omega\gamma)_R = \frac{2J_c + 1}{(2J_A + 1)\cdot(2J_x + 1)} \frac{\Gamma_x \Gamma_y}{\Gamma_{tot}}$$

$A = {}^{17}O$, $C = {}^{21}Ne$
$x = \alpha$
$y = n, \gamma$



- $E_R = E_x - Q$ is the resonance energy
- Γ_x, Γ_y are the partial decay widths
- J_A, J_C J_x : total angular momentum of the nuclei A,C & x

Can be determined from indirect measurements (transfer reactions,…)

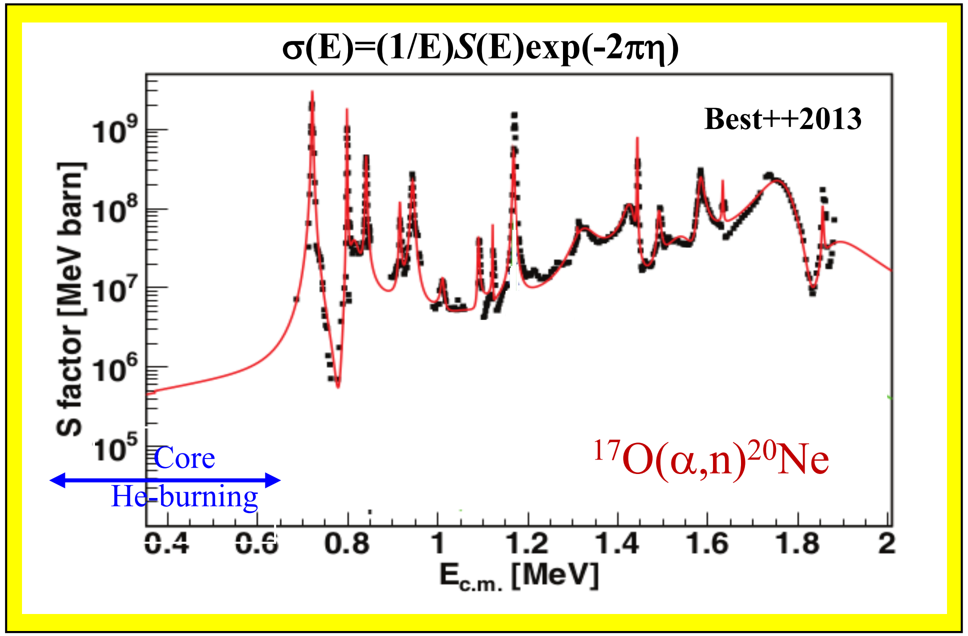
Present status on $^{17}O(\alpha,n)^{20}Ne$ and $^{17}O(\alpha,\gamma)^{21}Ne$

- Core He burning: T ~0.2-0.3 GK → $E_{c.m}$~ **0.297-0.646 MeV** → E_x=7.64-8.00 in ^{21}Ne
- Shell Carbon burning: T~1 GK→ $E_{c.m}$~ 0.783-1.5 MeV→ E_x=8.13-8.85 in ^{21}Ne

$^{17}O(\alpha,n)^{20}Ne$ & $^{17}O(\alpha,\gamma)^{21}Ne$ direct measurements:

- **Denker++1994, Best++2013**
- **Best++2011, Taggart++2019**
- **Williams++2022**

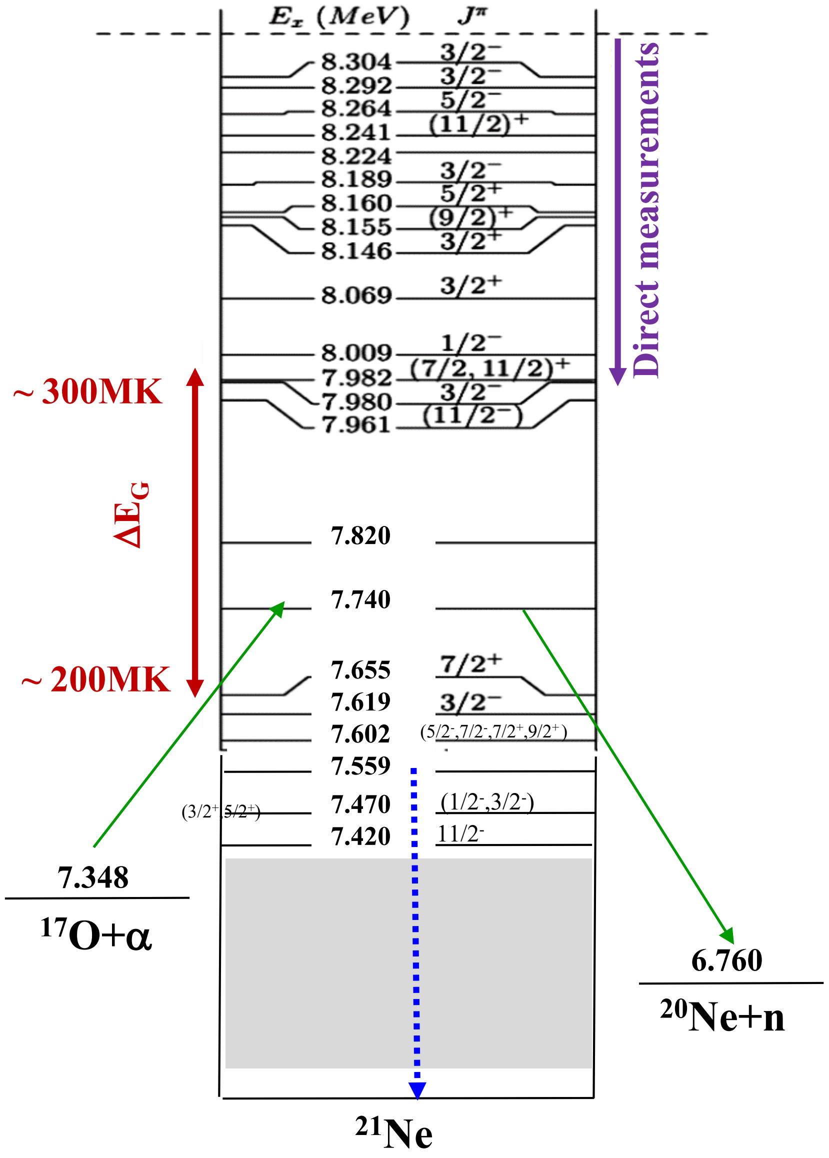
No direct measurements @
Core He burning energies ($E_{c.m}$ <0.630 MeV)



→ few hundreds keV << $E_{Coulomb}$

→ σ(E) very weak (≤ 100 pb)

→ Neutron & γ detection: large background



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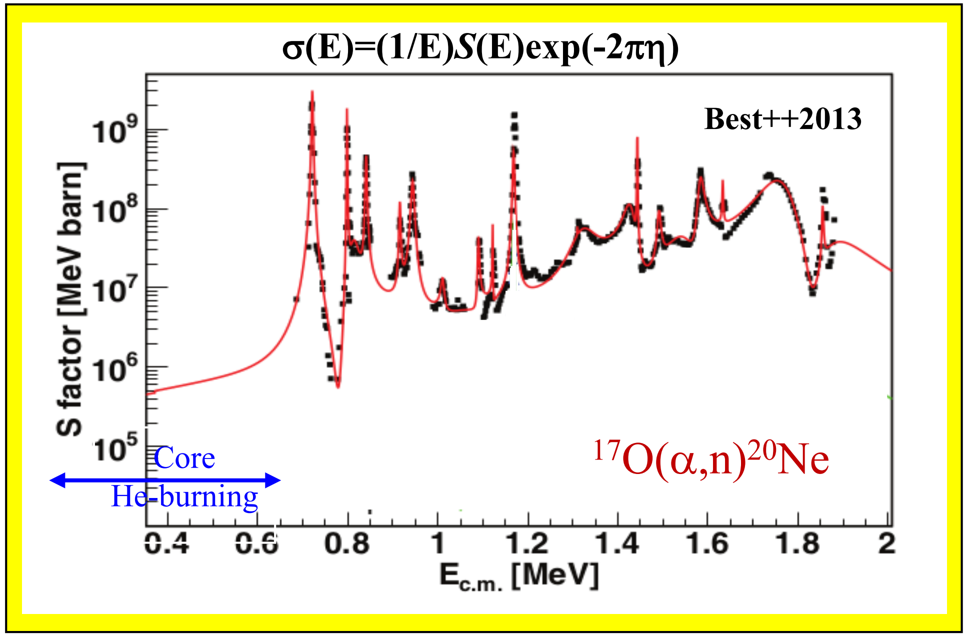
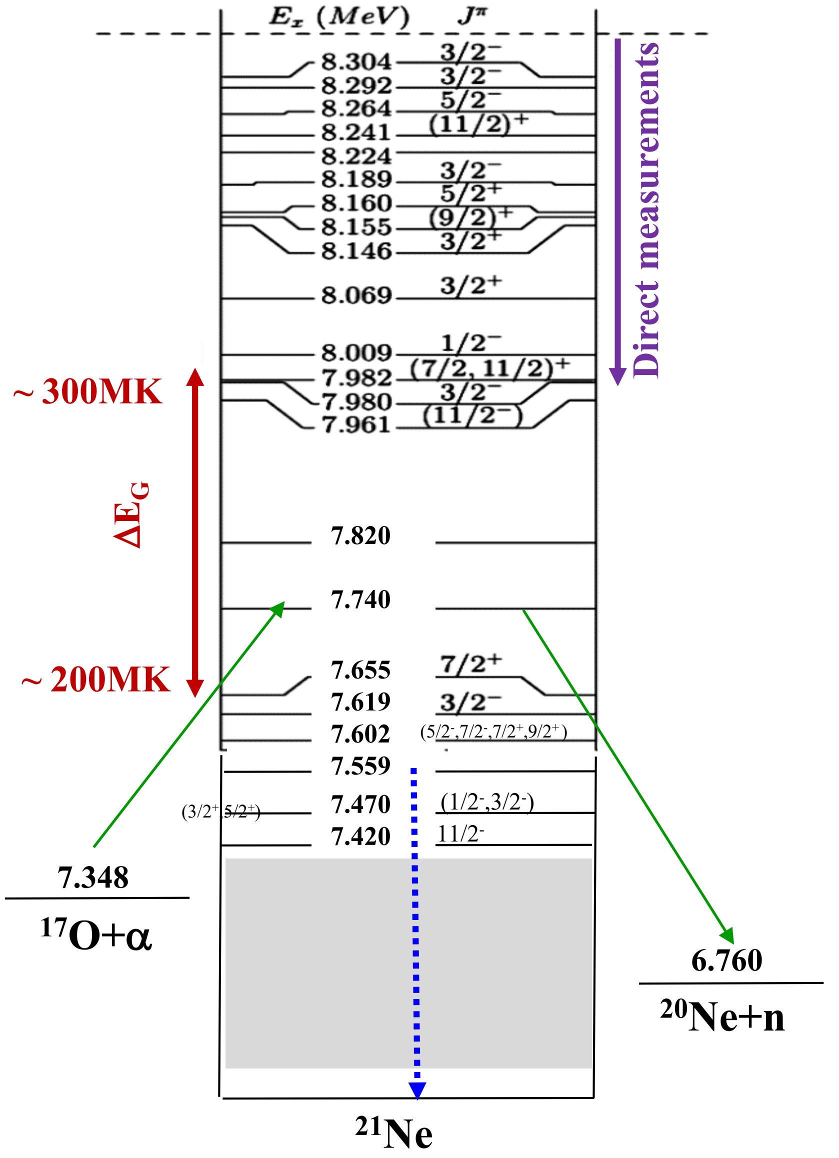


What about Spectroscopy of ^{21}Ne?

→ Known E_x

→ Unknown or poorly known Γ_α, Γ_n, $\Gamma_\gamma/\Gamma_{tot}$

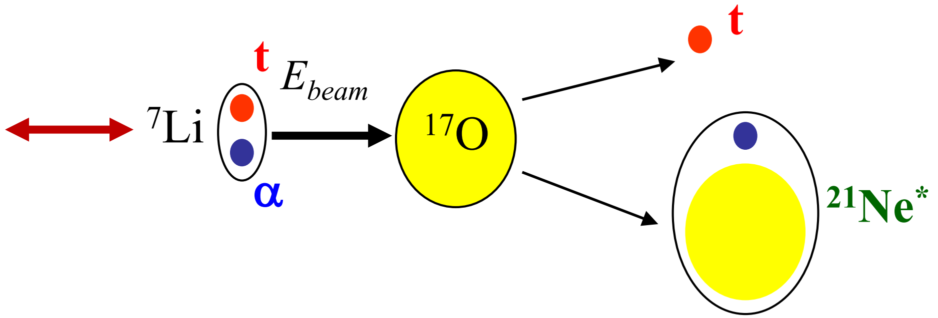
→ Few have spin-parity assignments J^π



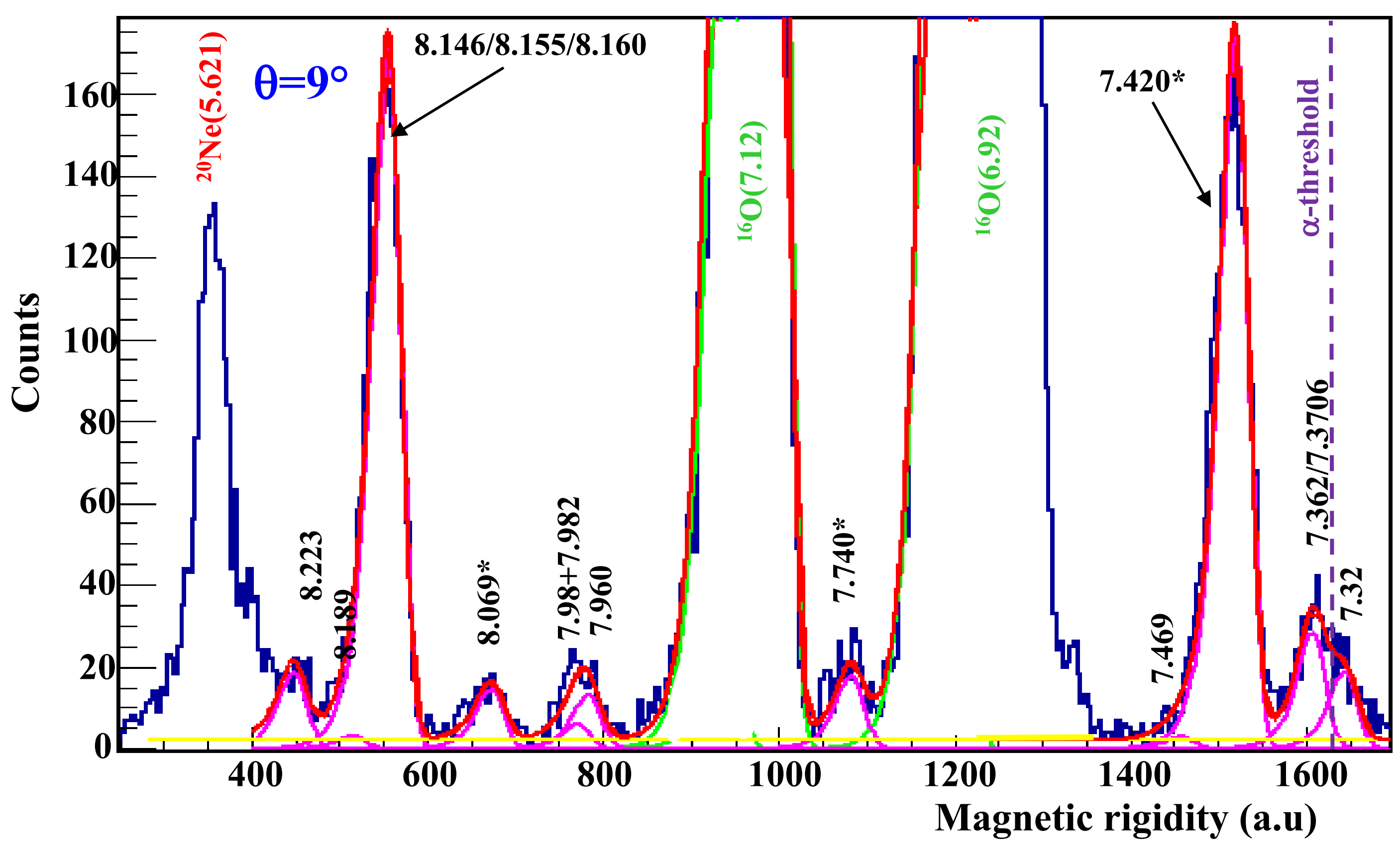
- Neutron transfer reaction → S_n→ Γ_n **Frost-Schenk++MNRAS2022**
- α-transfer reaction → S_α→ Γ_α (present work/MLL-exp)

Study of ^{21}Ne states via $^{17}O(^{7}Li,t)^{21}Ne$ α-transfer reaction

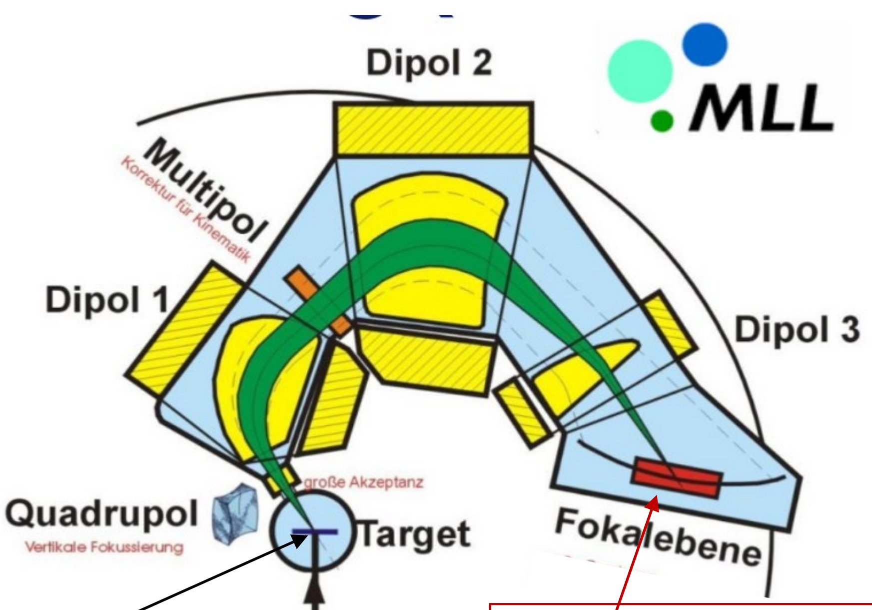
$\alpha + ^{17}O \longrightarrow ^{21}Ne^{*}$ → $^{21}Ne + \gamma$ / $^{20}Ne + n$



Region of interest



Q3D spectrometer



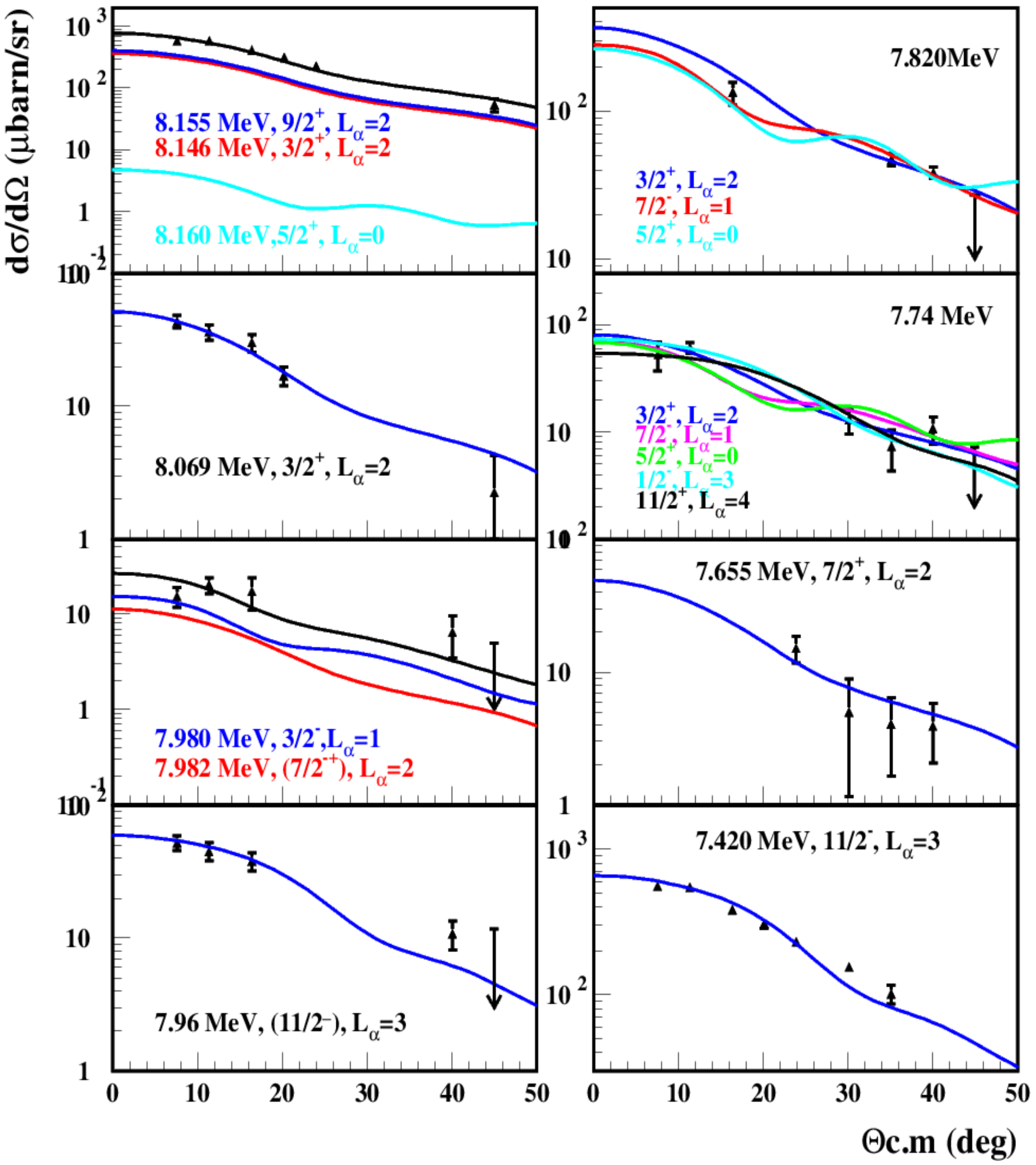
$W^{17}O_3$ enriched @ 35% on ^{nat}C

^{7}Li beam
E=28 MeV
I=100 nAe

- 2 proportional gas counters: **Pos, ΔE_1, ΔE_2**
- plastic scintillator: **E**

Experimental energy resolution (FWHM) : ~ 30 keV (6°) - 71 keV (36°)

FR-DWBA calculations



- From the normalisation of the DWBA (Distorded Wave Born Approximation) calculations (FRESCO code) to the data → Spectroscopic factor

$$\left.\frac{d\sigma}{d\Omega}\right|_{exp} = C^2 S'_\alpha\, S_\alpha \left.\frac{d\sigma}{d\Omega}\right|_{FR-DWBA}$$

$S'_\alpha = \langle {}^7Li\,|t\otimes\alpha\rangle = 1$ **Kubo et al PRC 1978)**

$S_\alpha = \langle {}^{21}Ne^*\,|{}^{17}O\otimes\alpha\rangle$

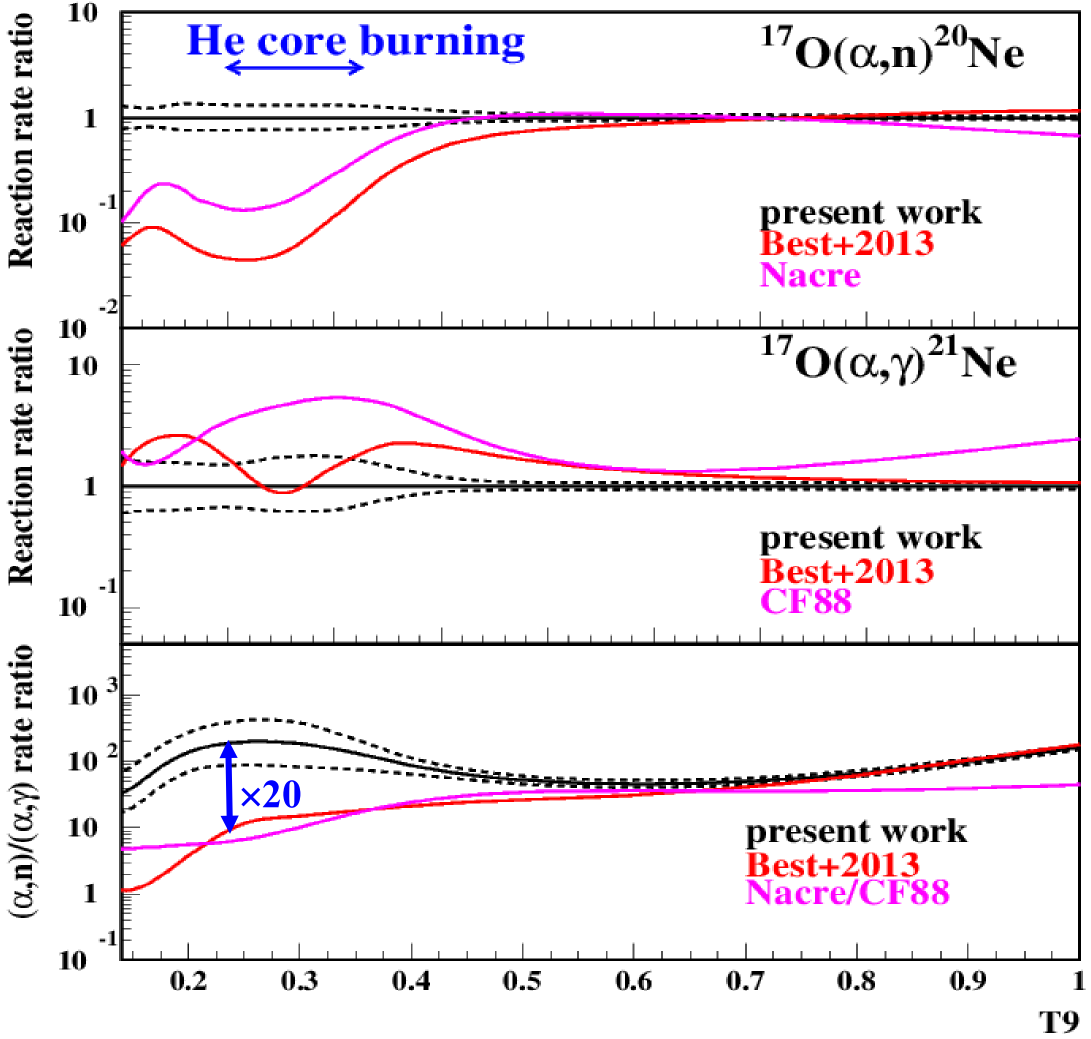
$$S_\alpha \rightarrow \Gamma_\alpha = 2P_l \frac{\hbar^2 R}{2\mu} S_\alpha |\phi(R)|^2$$

P_l = Coulomb & centrifugal penetrability factor
φ(R) radial part of the $\alpha + {}^{17}O$ wave function

- Γ_α uncertainty: 3- 40% (stat), **35%** (optical potentials)

$^{17}O(\alpha,n)$ & $^{17}O(\alpha,\gamma)$ new reaction rates & impact on the s-process in low Z massive stars

Reaction rates calculations:



→ **Better neutron efficiency recycling** with a factor of about **20** with the **present rates** than Best+2013 rates

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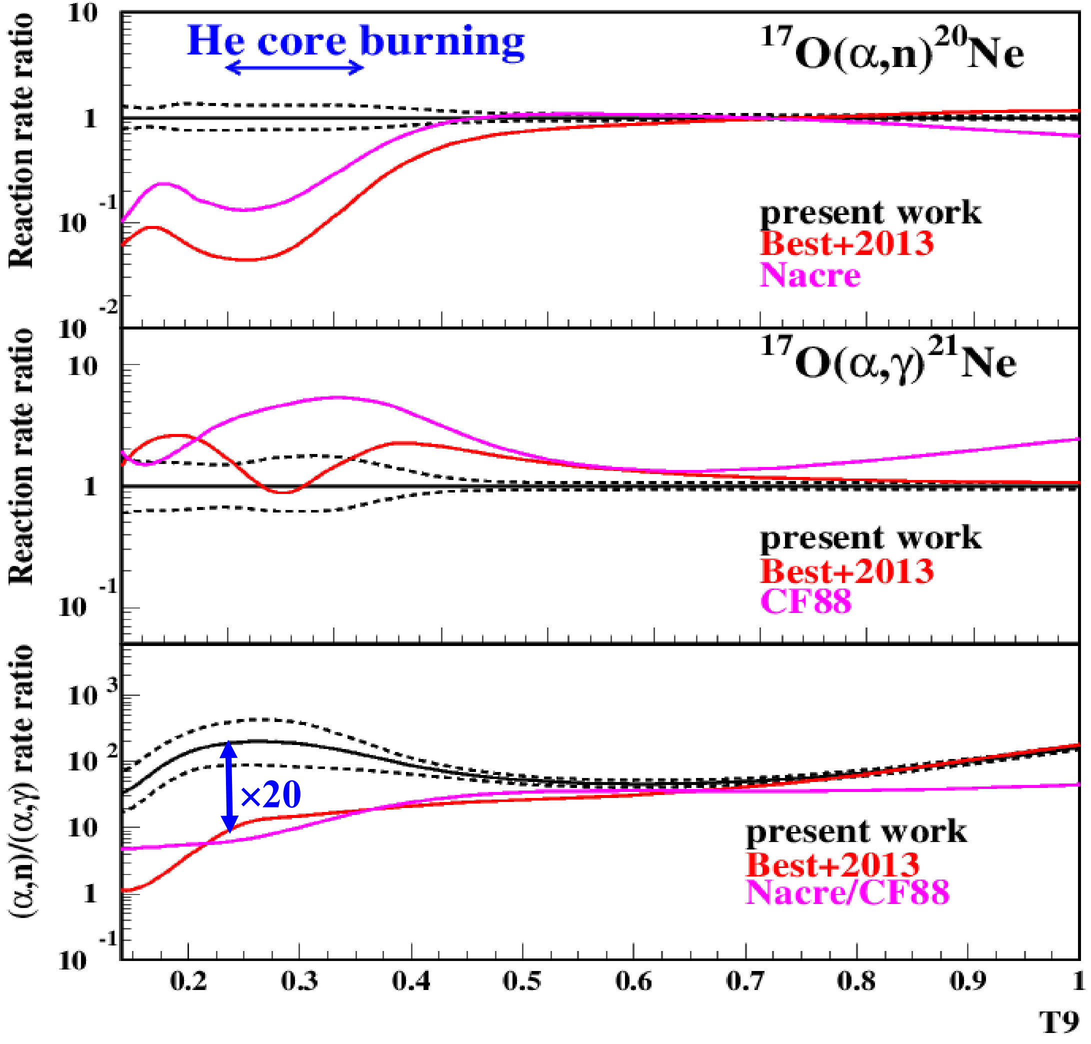

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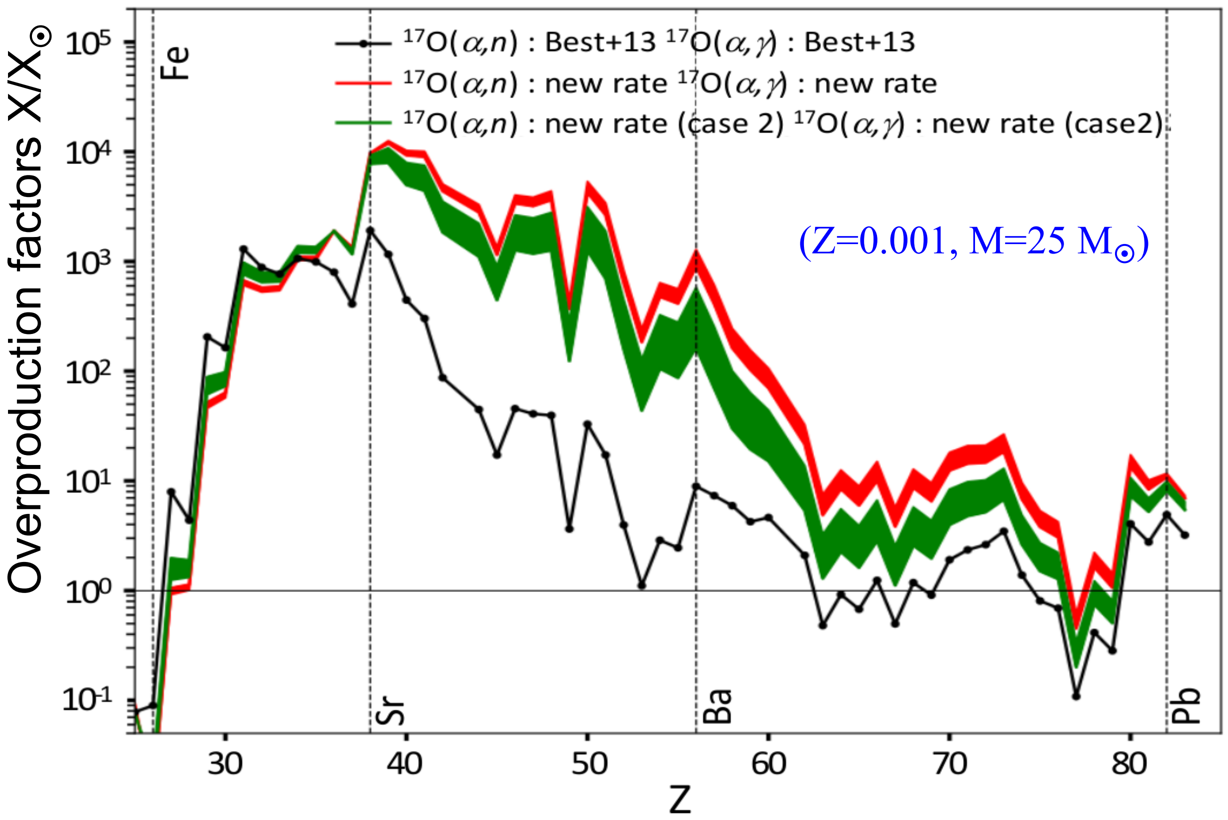
Nucleosynthesis calculations:



F. H et al., Phys Rev Lett 132, 182701 (2024)

→**Large enhancement** (>30 (>20 dex)) of elements 40 < Z < 60 with the present **new rates** in comparison to previous rates

→ **Two order** of magnitude (**~×30 (case2)**) on **Barium** : largest effect

→ In line with the observation of an enhanced s-process in CEMP-s(Carbon Enhanced Metal poor) stars **Hansen+2016**

Participants

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THANK YOU
FOR
YOUR ATTENTION