# NEW $^{12}C+^{12}C$ NUCLEAR REACTION RATES: IMPACT ON STELLAR EVOLUTION

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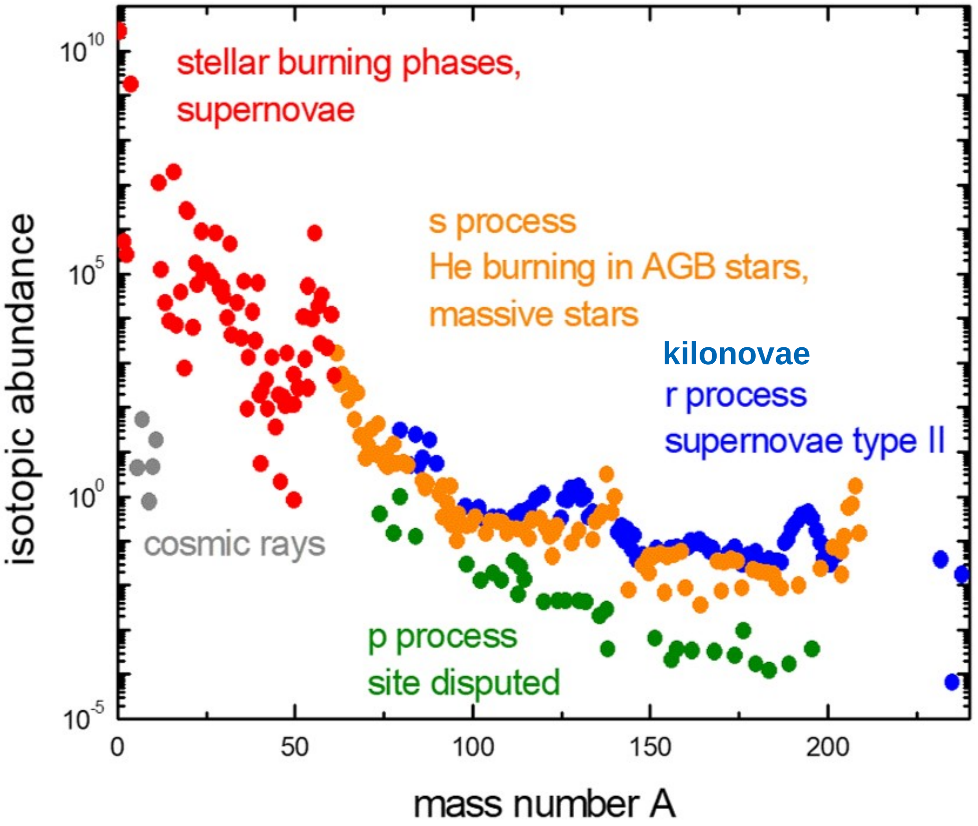
for the STELLA collaboration

# Isotopic abundance and stellar nucleosynthesis

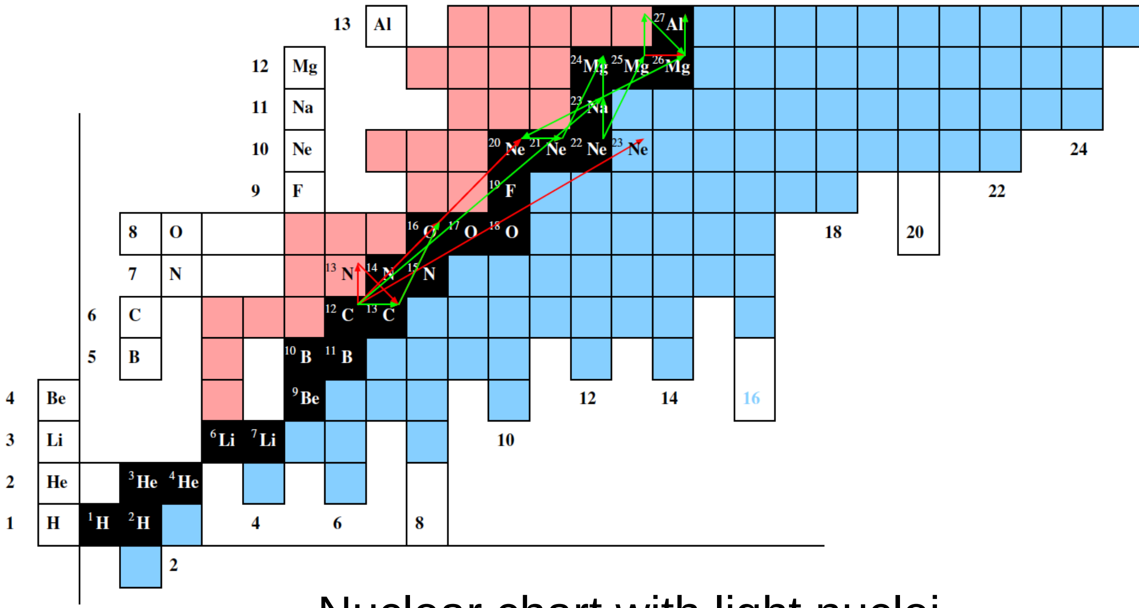
- Origin of chemical elements => **nucleosynthesis**

Isotopic abundance of chemical elements in the Universe



# Isotopic abundance and stellar nucleosynthesis

- Origin of chemical elements => **nucleosynthesis**
- C-burning phase
  - “**key phase**” of stellar evolution
  - $^{12}$C + $^{12}$C => fusion of heavy-ions, neutrons seed generation




Nuclear chart with light nuclei
(from Chieffi *et al.*, APJ **502**, 1998)

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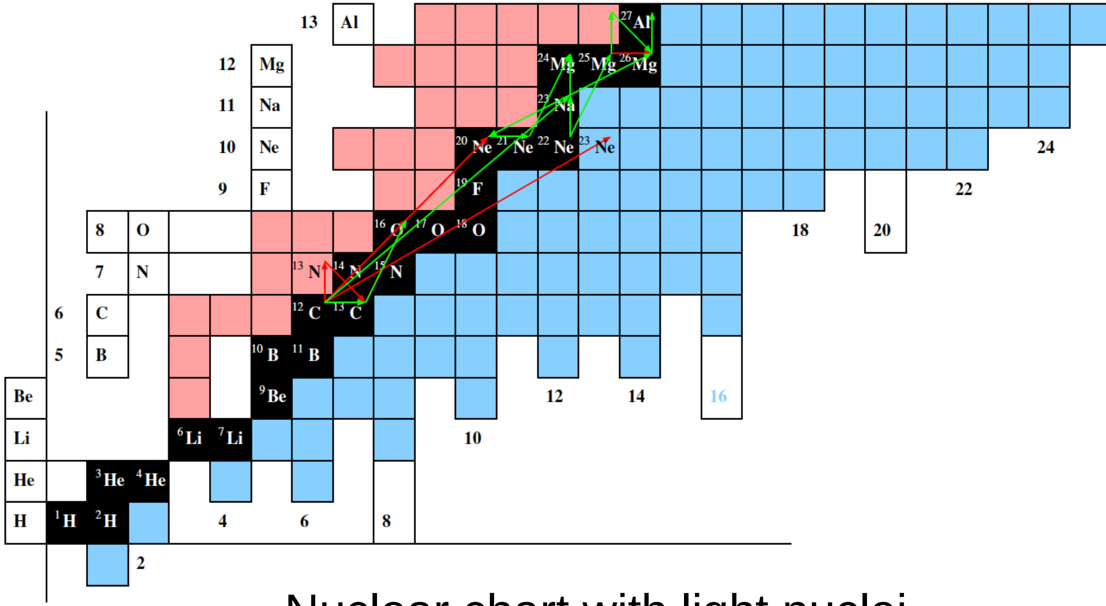
- **Reaction rates**

$$r = N_x N_y \langle\sigma v\rangle (1+\delta_{xy})^{-1} \longrightarrow r = N_A \langle\sigma v\rangle$$

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

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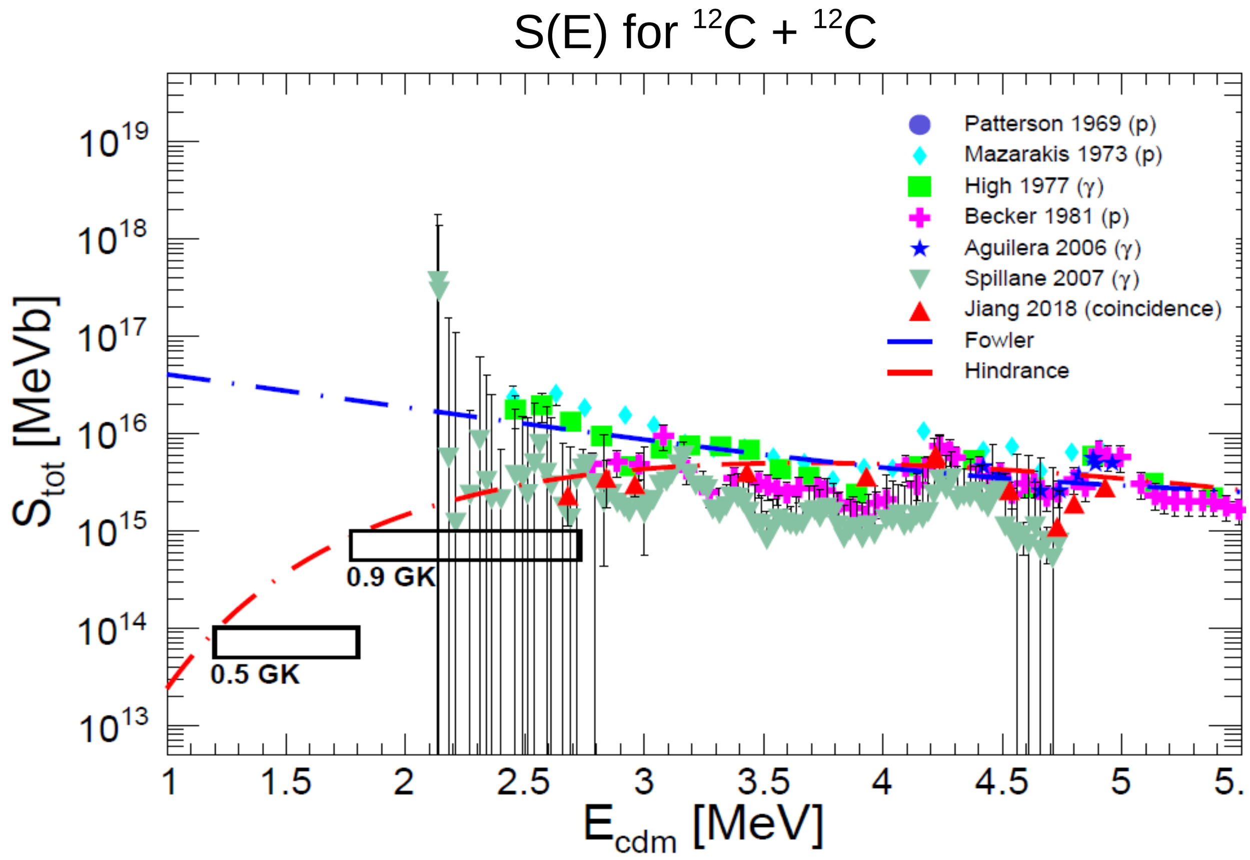
# $^{12}C + ^{12}C$ fusion reaction




- Investigation of **fusion hindrance** and **resonances**

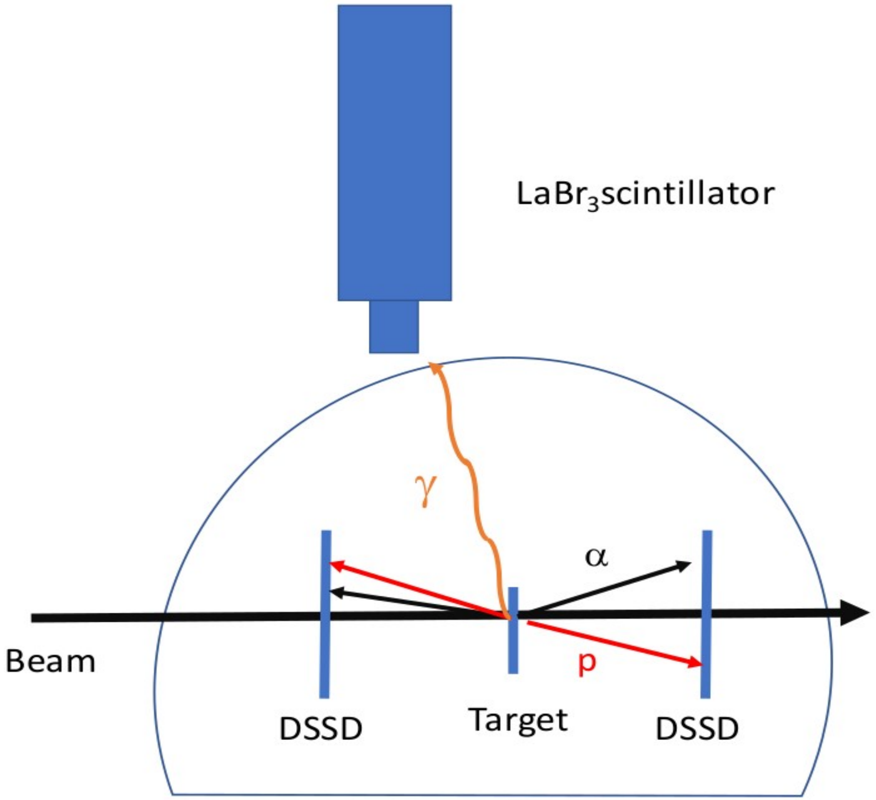
(Fruet *et al*. PRL **124**, 2020)

- At low energies => order of magnitude between theoretical models
- **Experimental challenges**
  - Small cross sections (~pb)
  - Background
- Jiang et al. => **coincidence method**

(Jiang *et al*., NIMA **682**, 2012)

# Coincidence method with STELLA

- Background => **coincidences**
  - Simultaneous measurements of light particles and associated gamma rays




Scheme of the reaction chamber

# Coincidence method with STELLA

- Background => **coincidences**
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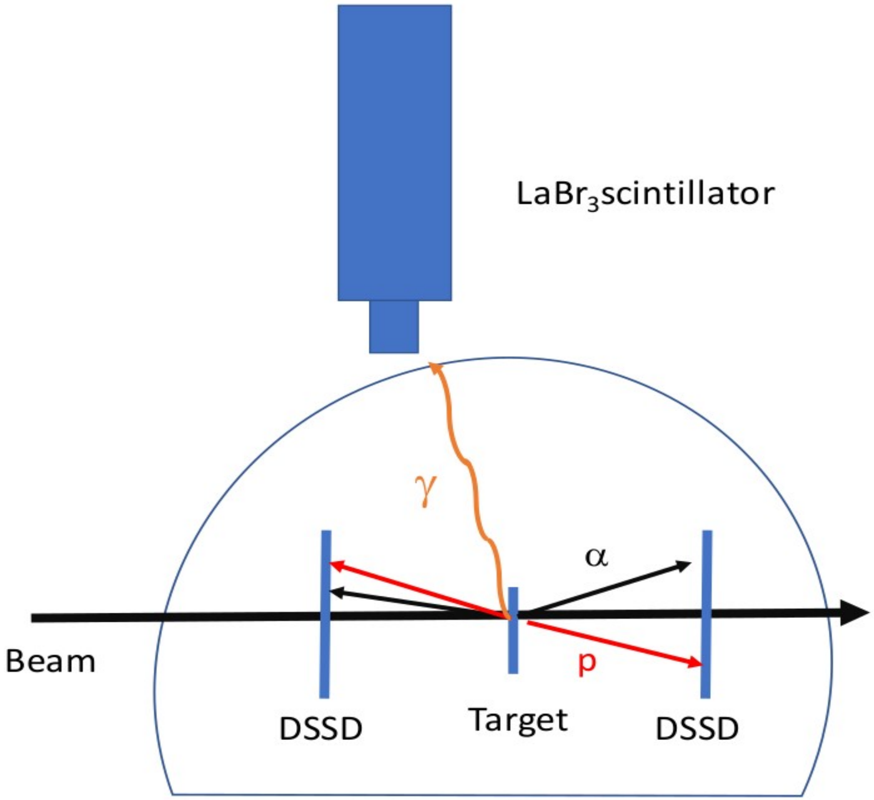
- **STELLA mobile station (STELar LAboratory)**

(Heine *et al.*, NIMA **903,** 2018)

  - Andromede facility (IJCLab, Orsay France) => I = 1-10 pµA
  - Thin rotating targets (180 - 350 nm, 1000 rpm)
  - $LaBr_3$(Ce) scintillators FATIMA (FAst TIMing Array)
  - Annular charged-particle silicon detectors (high granularity and nanoseconds timing)
  - High vacuum ($10^{-8}$ mbar)

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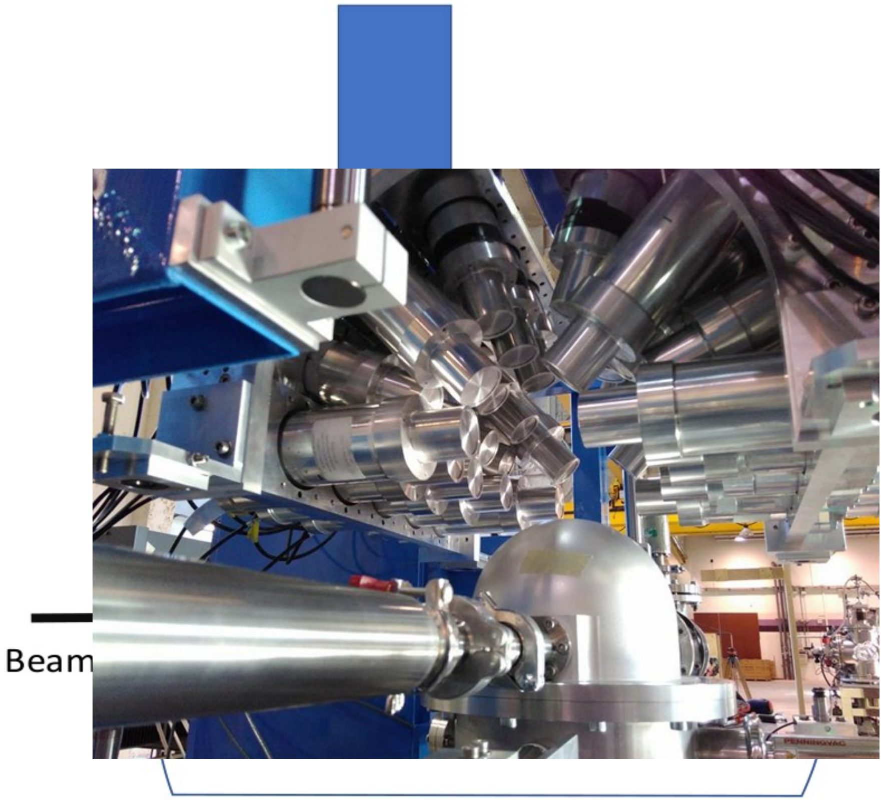


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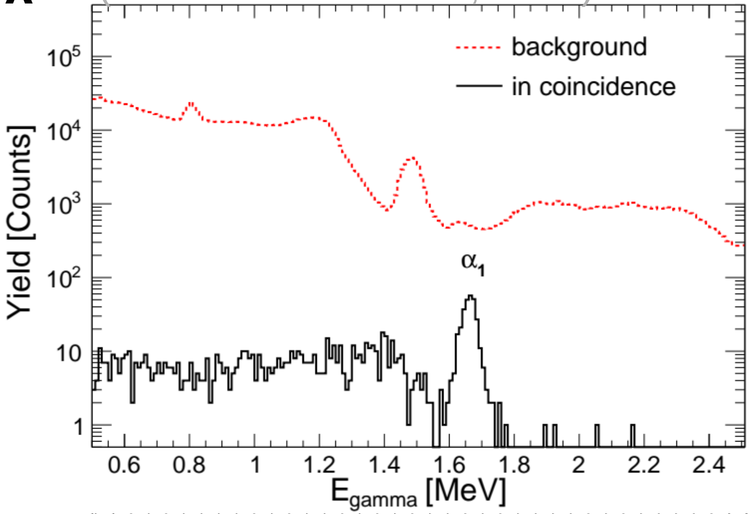
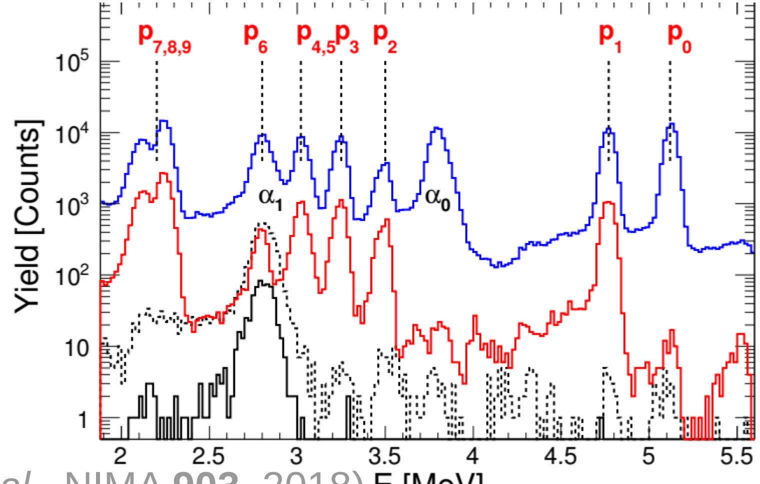
**=> Direct measurement at low energies**

(Fruet *et al.* PRL **124**, 2020)

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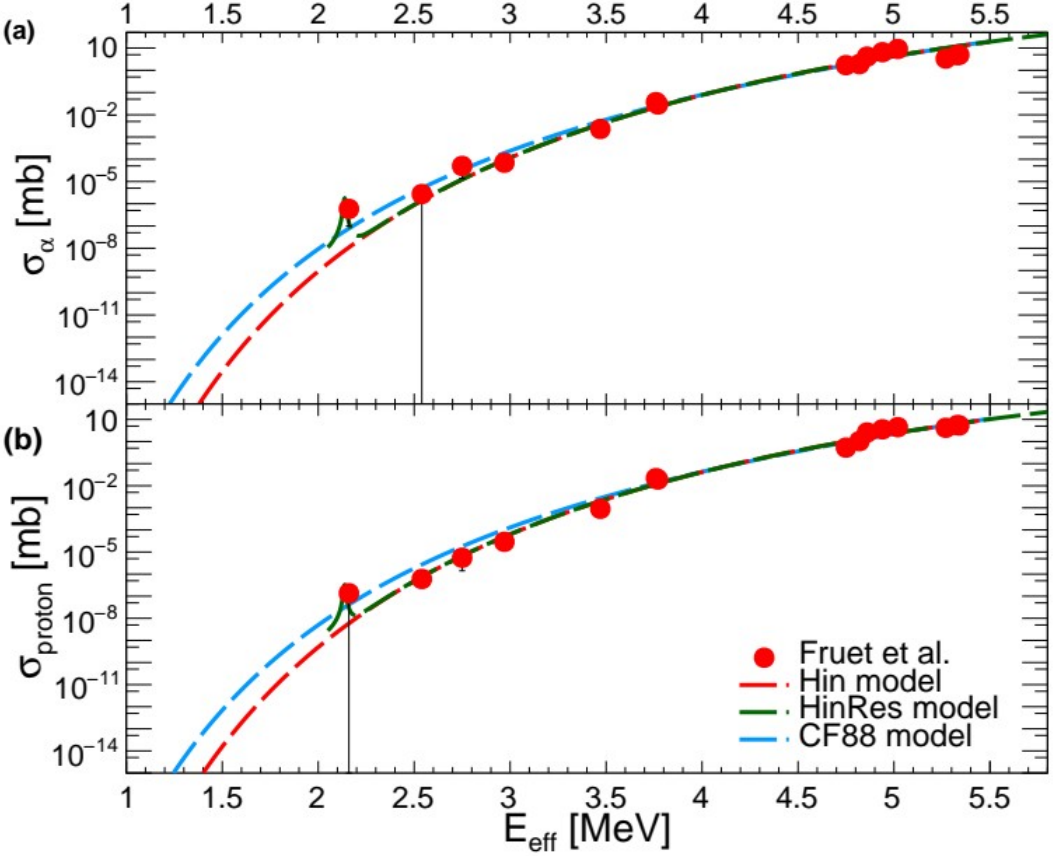
# Excitation functions

Cross section for $^{12}C + ^{12}C$




- Cross sections measured by STELLA for $E_{com}$ = 5,4 – 2,1 MeV

  (Fruet *et al.*, PRL **124**, 2020)

- Hindrance model adapted from Jiang *et al.*

  (Jiang *et al.*, PRC **75**, 2007)

- Resonance at $E_{com}$ = 2.14 MeV proposed by Spillane *et al.*

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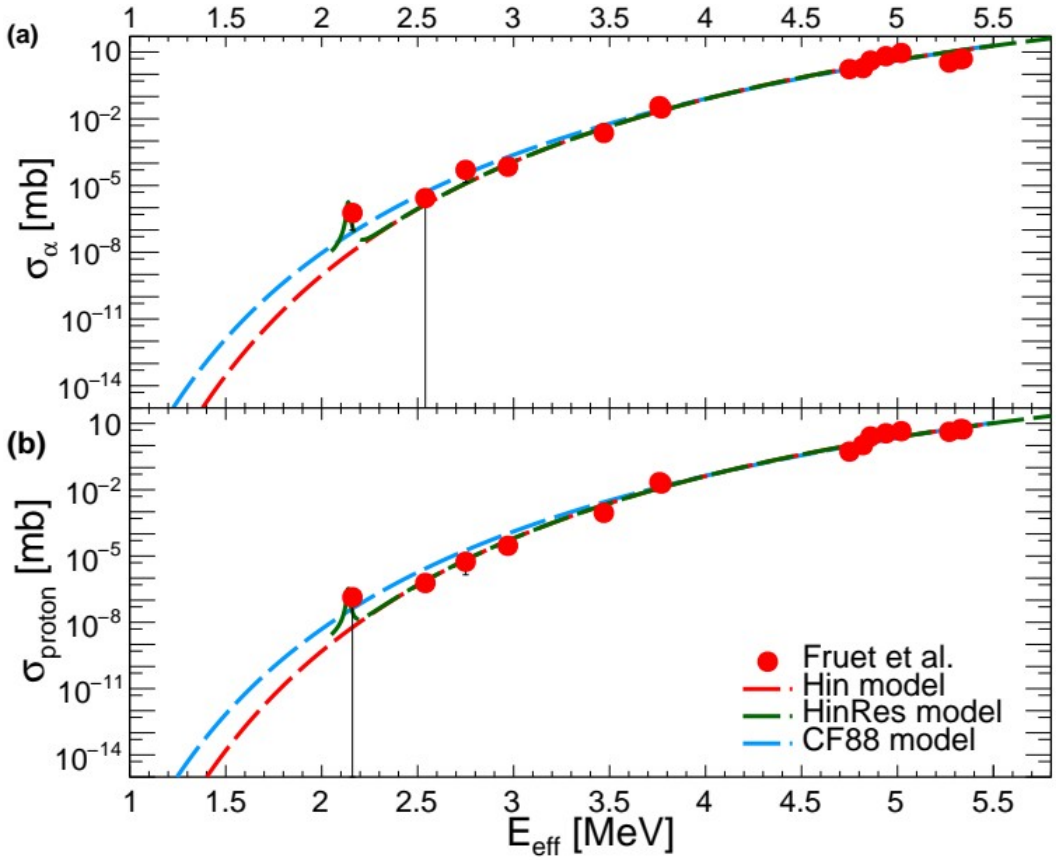


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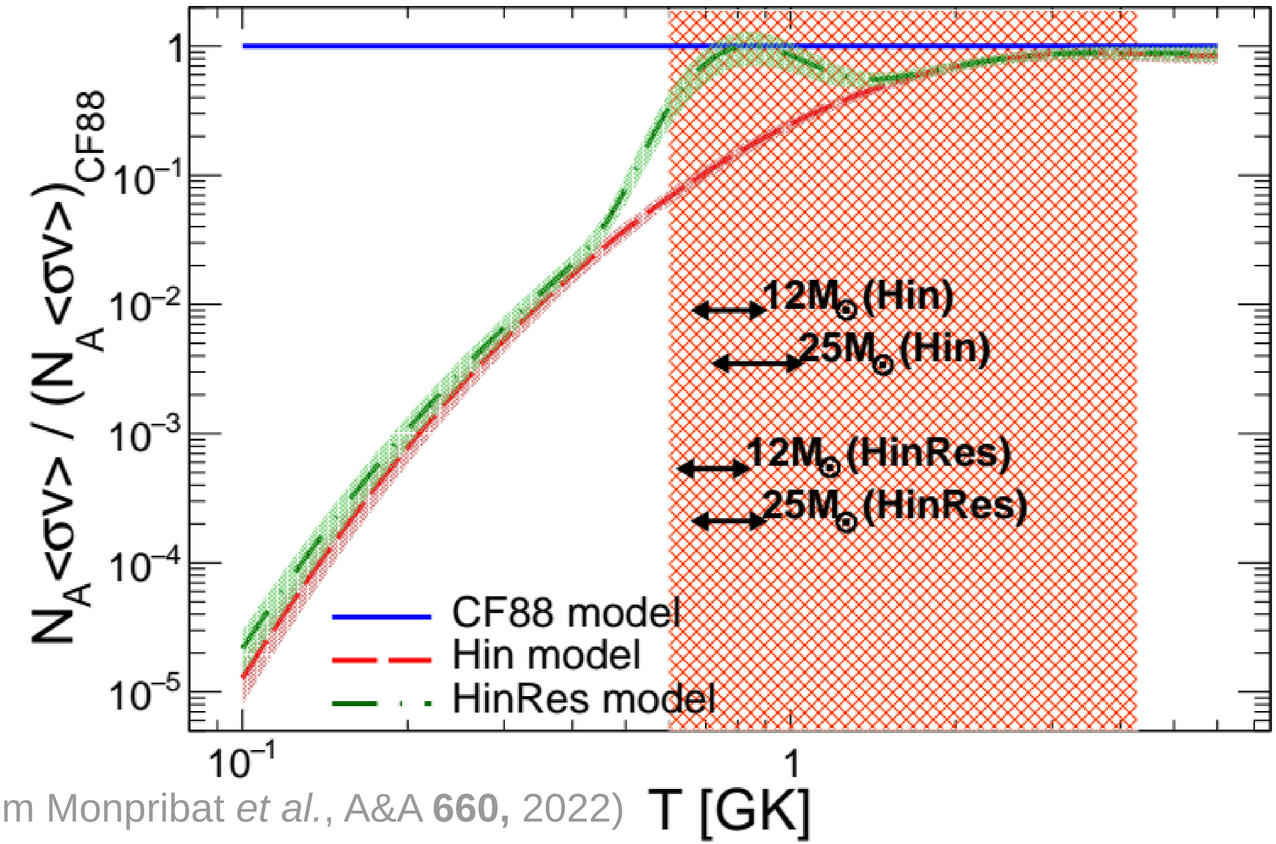
- Simultaneous fit for α and proton channels
- **Parameters consistent** with those from Jiang *et al.*
- **Compatibility between hindrance resonance model and STELLA measurements**

# Reaction rates

- Different approaches for hindrance and hindrance + resonance models
- Estimation **STELLA sensitivity**
  - Temperature range where no extrapolations are required
  - Reached temperature : T = 0,6 GK
- Relative uncertainties
  - Hin : 15 %
  - HinRes : 31 %
- **C-burning phases in the sensitivity zone**

Reaction rates for $^{12}C + ^{12}C$




(from Monpribat *et al.*, A&A **660,** 2022)

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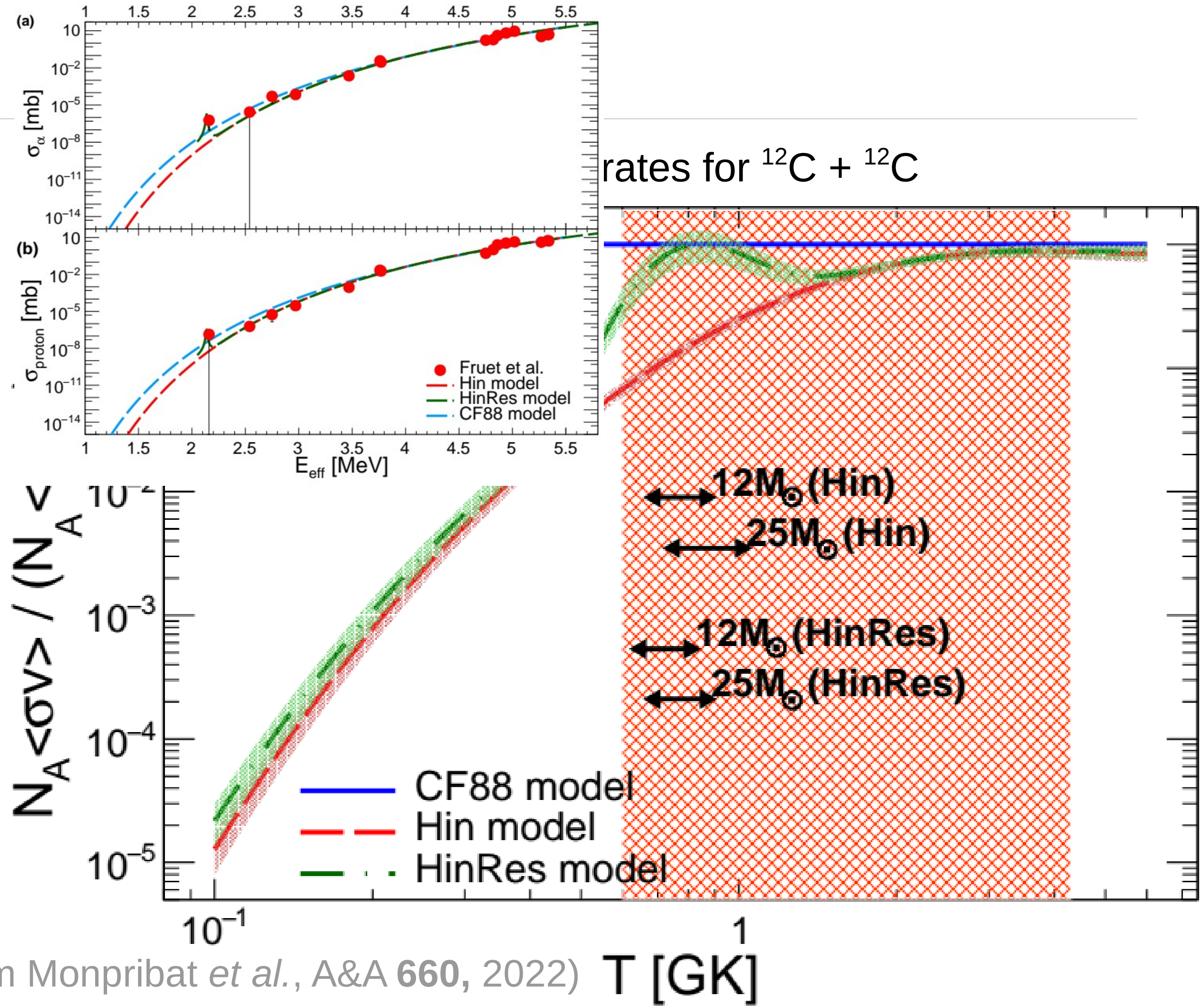



(from Monpribat *et al.*, A&A **660,** 2022)

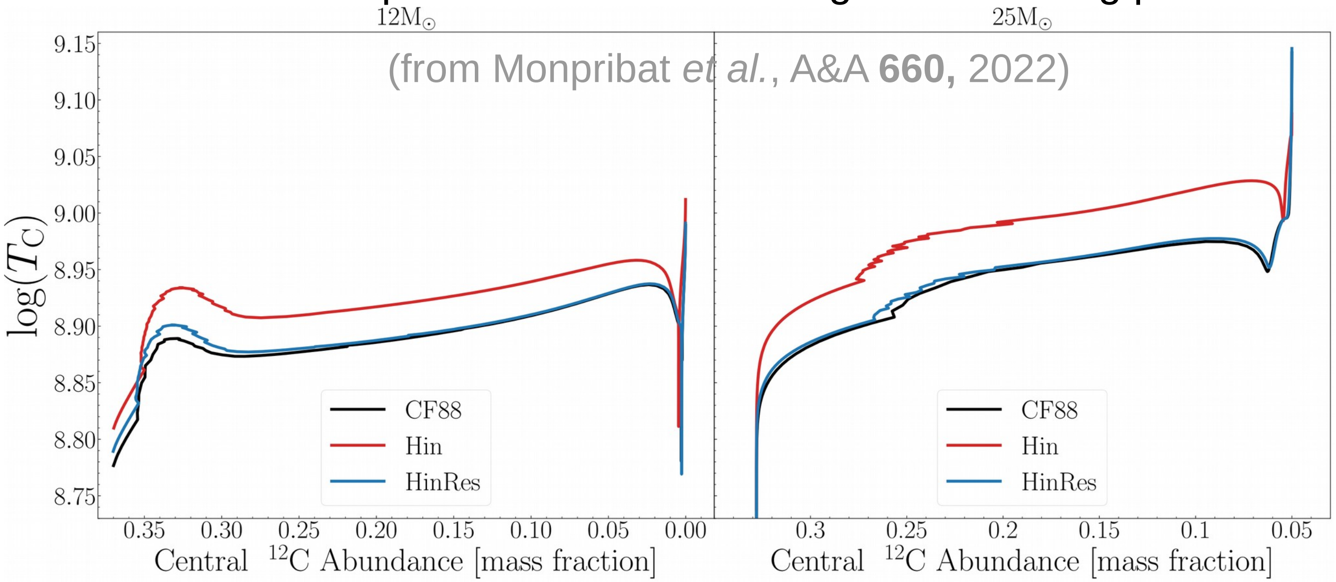
# Impact on stellar evolution: GENEC

- The **Geneva stellar evolution code**

(Eggenberger *et al.*, Astro. & Space Science **316**, 2008)

  - Two stellar models: 12 and 25 $M_\odot$, no rotation, $Z_\odot$
- Evolution followed until the end of C-burning phase

Central temperature evolution during the C-burning phase

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- **Fusion temperature for hindrance model: 10% higher => C-burning phase lifetime divides by 2**
- Hindrance + resonance and CF88 similar

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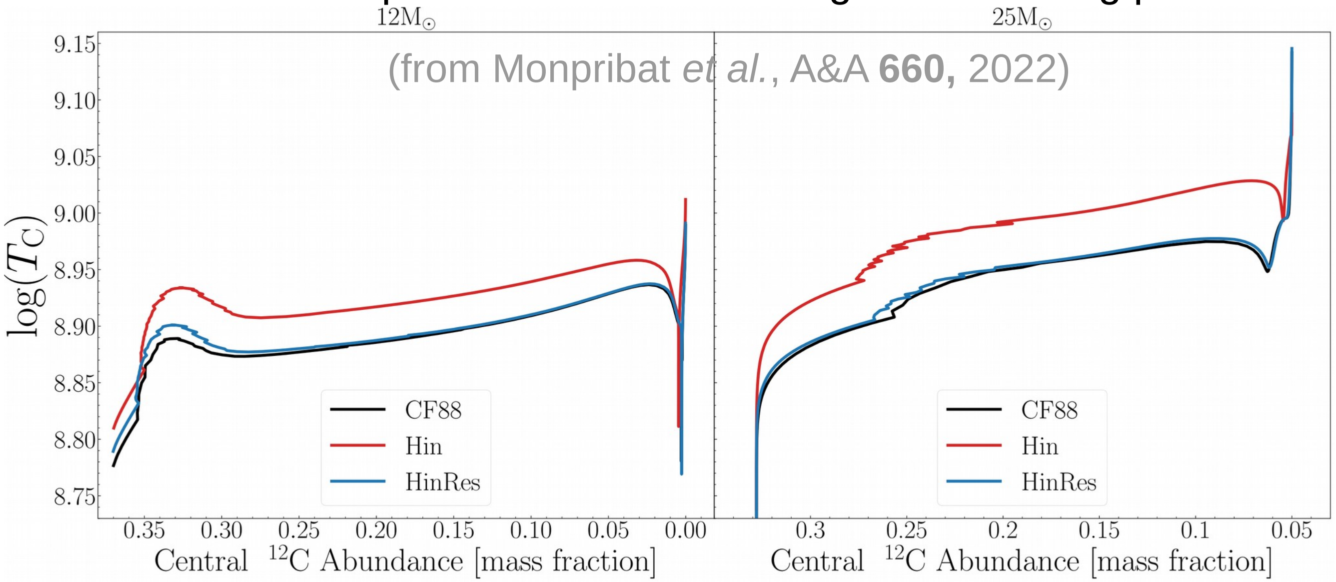
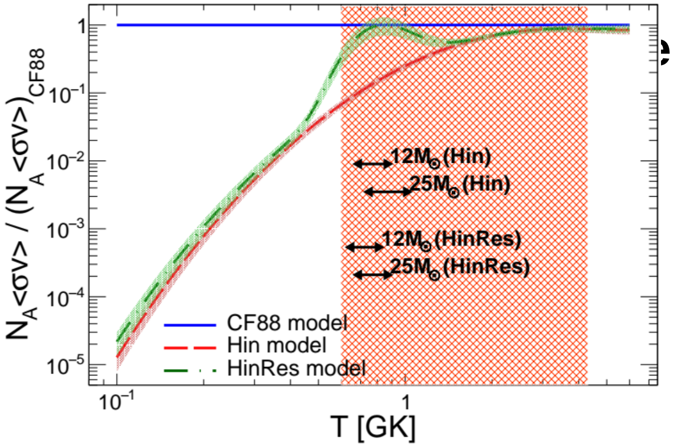


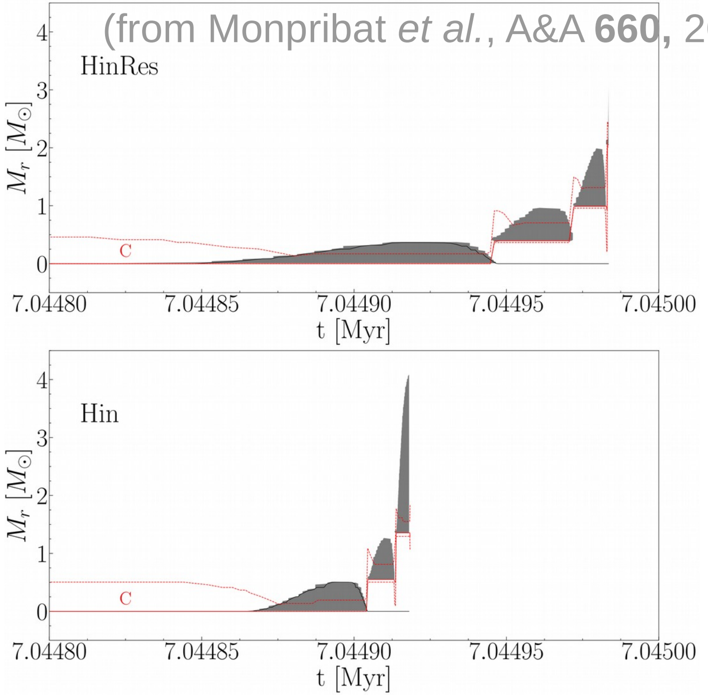

- **Fusion temperature for hindrance model: 10%**



# Impact on stellar evolution: GENEC

- **C-burning regions => evolve in the same way**
- Hindrance => convective zone much extended
- No differences for 12 $M_{\odot}$ model

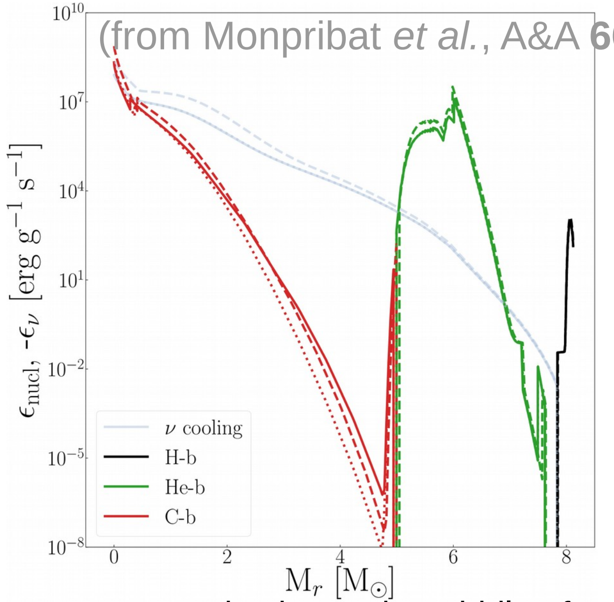
(from Monpribat *et al.*, A&A **660,** 2022)




Kippenhahn diagram for the center of 25 $M_{\odot}$ models during the end of C-burning phase

- C-burning phase => longest phase with large neutrino emissions
- **Difference in C-burning phase lifetime** => may have impacts on core collapse and remnant nature

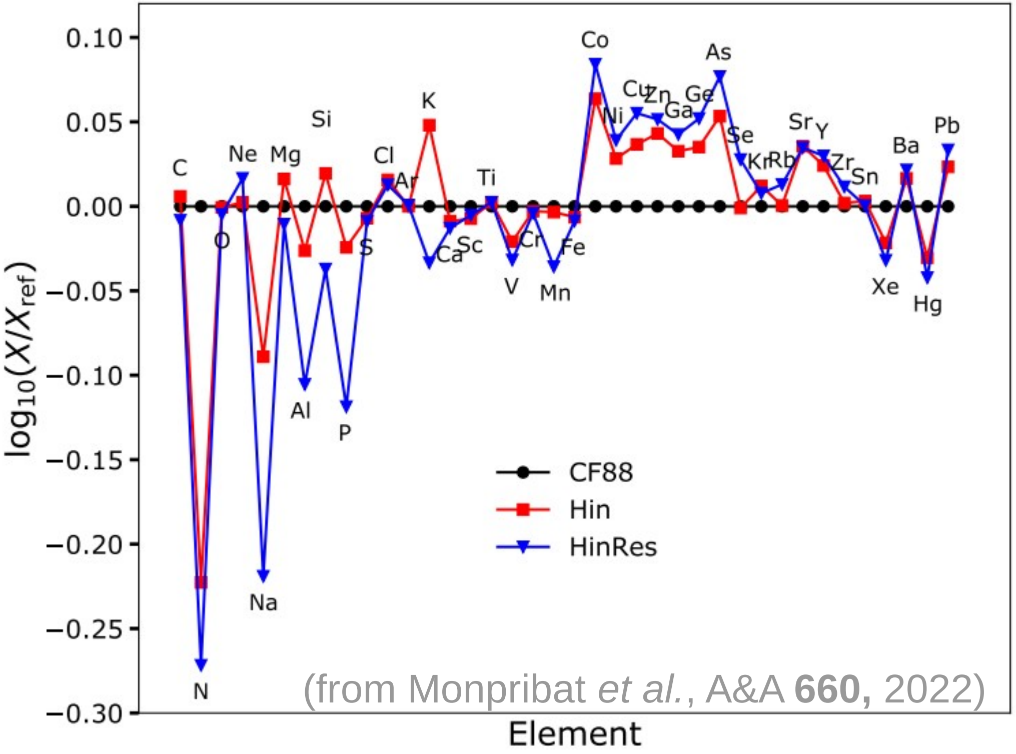
(from Monpribat *et al.*, A&A **660,** 2022)




Energy production at the middle of C-burning for 25 $M_{\odot}$ models

# Impact on detailed nucleosynthesis

- “**One layer-model**” => monitoring the evolution of 1454 isotopes
  (Choplin *et al.*, A&A **593**, 2016)
- Stellar model: 25 $M_\odot$ with GENEC
- Final abundances
  - Na, Al and P
  - Small changes for heavier elements
- **Possible impact on nucleosynthesis**



(from Monpribat *et al.*, A&A **660,** 2022)

Abundances obtained at the end of the C-burning phase normalized on the final abundance of CF88 rate

# Conclusion

- Determination of new nuclear reaction rates from STELLA data
  - Excitation functions according to two scenarios: hindrance and hindrance + resonance
  - Hindrance and hindrance + resonance reactions rates lower than CF88 one
  - STELLA sensitivity covers the C-burning regions of stellar evolution models used in this work
- Impact on stellar evolution:
  - Moderate impact on the C-burning phase
  - Simulations of the following burning phases required
  - New measurements needed to more constrain the scenarios

**=> New reaction rates ready to be implemented** (tabulated version available: Monpribat *et al.*, A&A **660,** 2022)

# Acknowledgements

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And thank you for your attention

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