Nitrogen and Fluorine production in the early Universe

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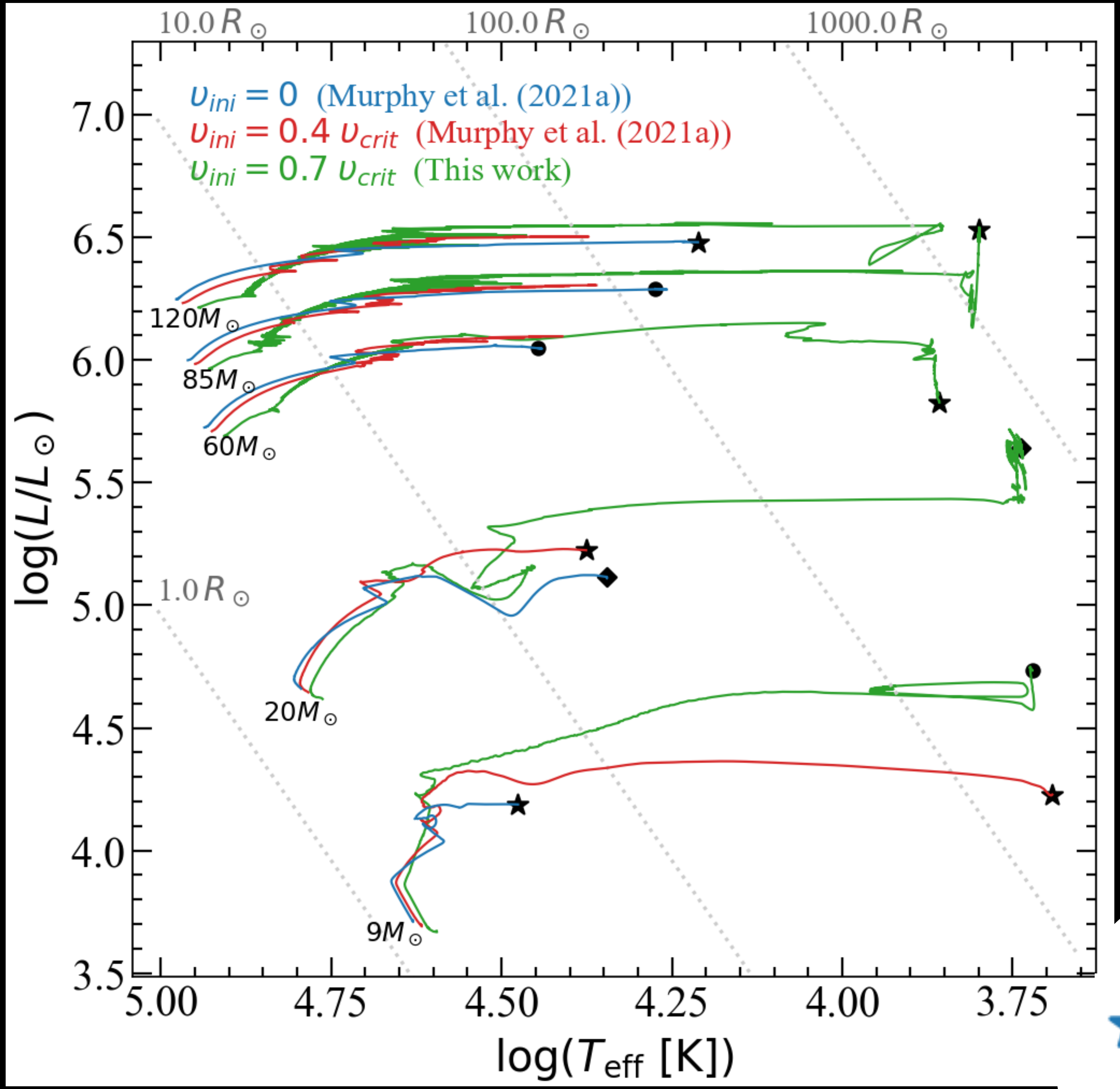
Population III stars

What are the Pop III stars and why are they interesting objects?

- The first generation of stars, formed from the metal-free gas produced in the Big Bang ⇒ Zero-metallicity,
- Formed at redshifts $z \sim 20 - 35$,
  (e.g. Abel et al. 2002, Bromm et al. 2002)
- Massive stars,
  (e.g. Bromm et al. 2002)
- Governed the early chemical evolution of galaxies,
- Contributed to the reionization,
  (e.g. Murphy et al. 2021b, Sibony et al. (2022)
- High rotation.
  (e.g. Stacy et al. 2013)

The rapidly rotating grid



Tsiatsiou et al. (2024)

★ End of He-b

● After He-b

GENEC stellar evolution code

Initial composition: X=0.7516, Y=0.2484, Z=0

Reaction rates: NACRE database

$$D_{shear} = \frac{K}{\frac{\varphi}{\delta}\nabla_\mu + (\nabla_{ad} - \nabla_{rad})} \times \frac{H_p}{g\delta}\left[f_{energ}\left(\frac{9\pi}{32}\Omega\frac{d\ln\Omega}{d\ln r}\right)^2 - (\nabla' - \nabla)\right]$$

Maeder (1997)

$$D_{eff} = \frac{1}{30}\frac{\left|rU(r)\right|^2}{D_h}$$

Chaboyer & Zahn (1992)

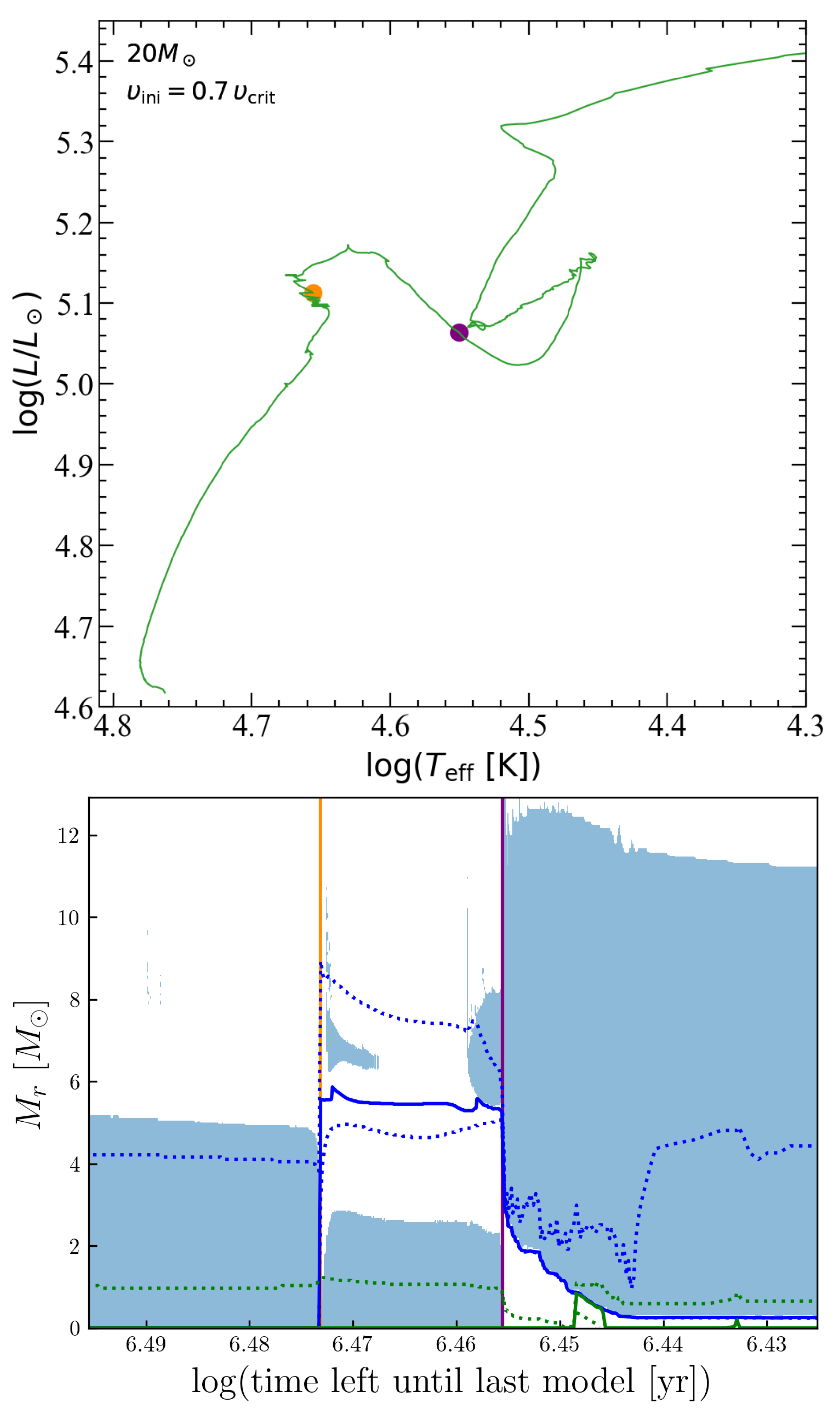
Convective zones: Schwarzschild criterion

Overshoot parameter $d_{\rm over}/H_{\rm p} = 0.1$

Impact of fast rotation on primordial stars

CNO shell boost

- During He-burning, C is injected to the H-burning shell.
- N will be produced in the H-burning shell.
- The mixing induces a huge boost of nuclear energy (It may changes the evolution and nucleosynthesis of the star)
- It may produce a very extended intermediate convective zone attached to the H-burning shell.

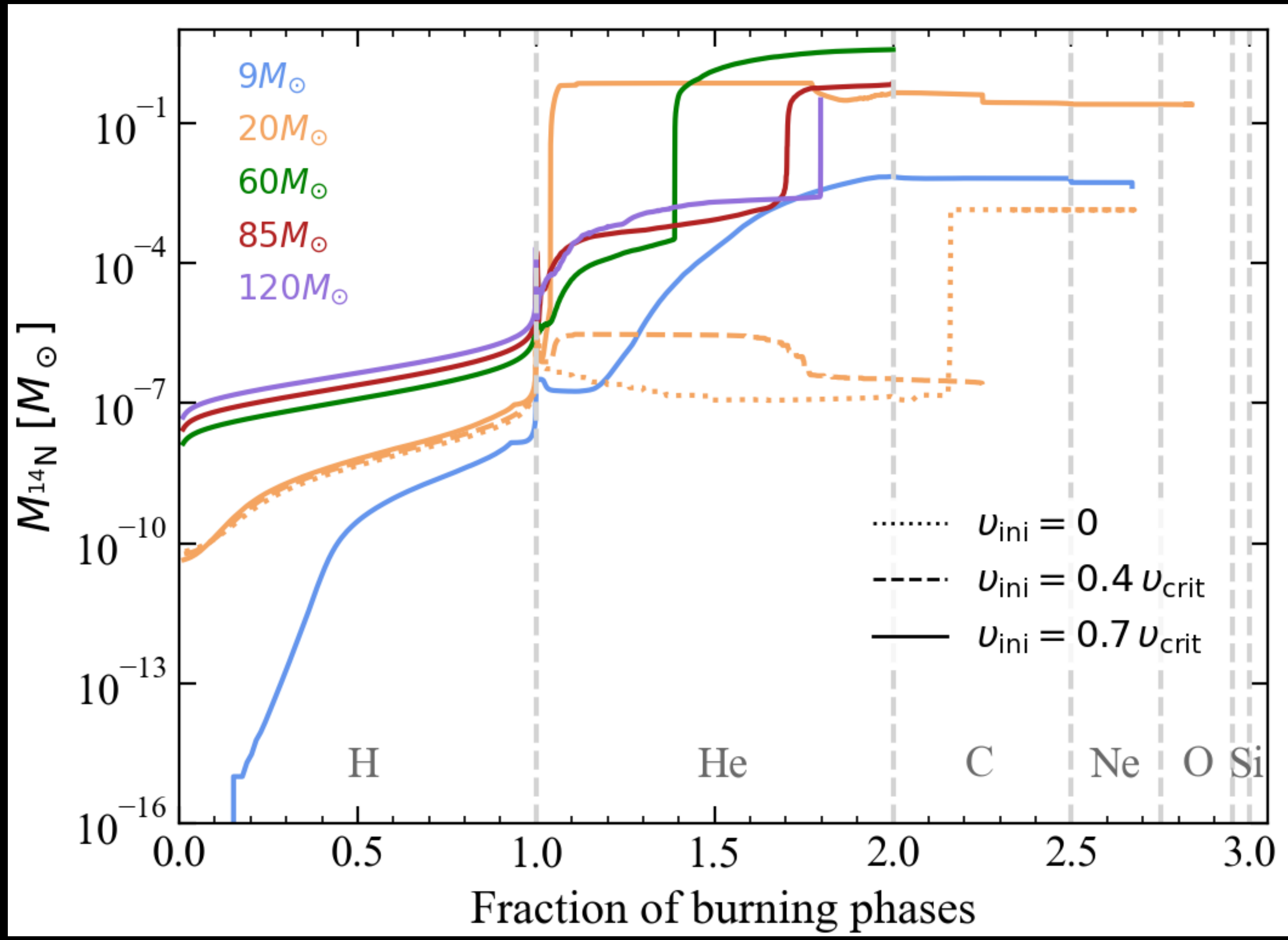


Primary nitrogen ⟶
produced by hydrogen and helium,
and not pre-existing CNO elements

Tsiatsiou et al. (2024)

Primary nitrogen production in Population III models

CNO shell boost ⟶
important role in the primary N-production



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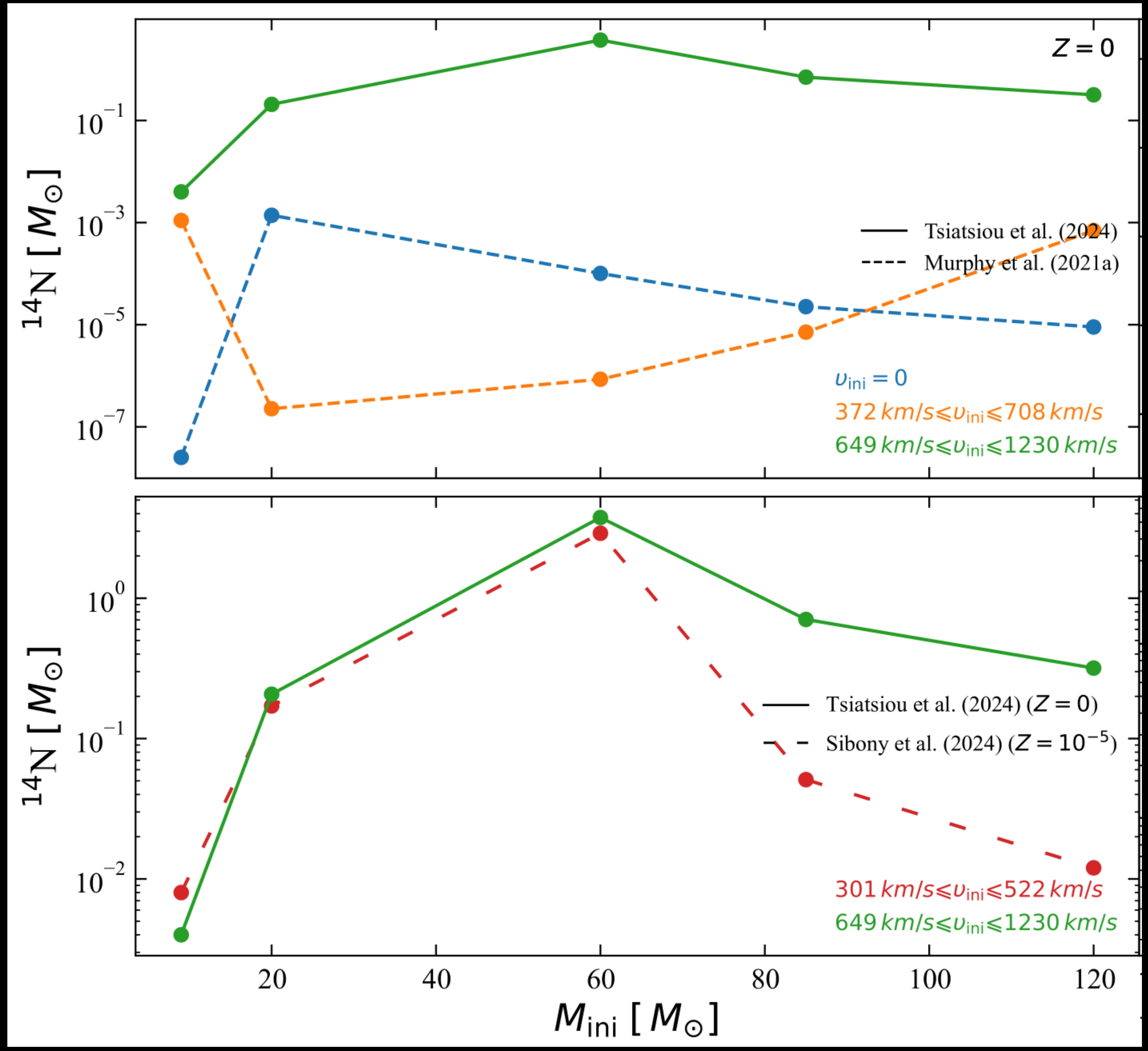
$$M_{^{14}\mathrm{N}} = \int_0^{M_{tot}(t)} X^{14}(M_r, t)\,\mathrm{d}M_r$$



Tsiatsiou et al. (2024)

- Remnant mass and final fate from: *Farmer et al. (2019)*, *Patton & Sukhbold (2020)*.

Can rapidly rotating massive Population III stars be possible sources of extreme N-emitters in high-redshift galaxies?

Rapidly rotating massive Population III stars as possible sources of extreme N-emitters in high-redshift galaxies

- GN-z11 at $z = 10.6$ *(Oesch et al. 2016)*, and CEERS-1019 at $z = 8.6782$ *(Finkelstein et al. 2017)*.
    - N/O abundance ratio of GN-z11 exceeding four times solar *(Cameron et al. 2023)*.
    - CEERS-1019 emission lines suggest advanced chemical processes for a galaxy of its era *(Tang et al. 2023)*.
      N-emitter *(Marques-Chaves et al. 2023)*.
- MSs, VMSs, and SMSs could play a significant role in the chemistry of these galaxies *(Woods et al. 2020)*.

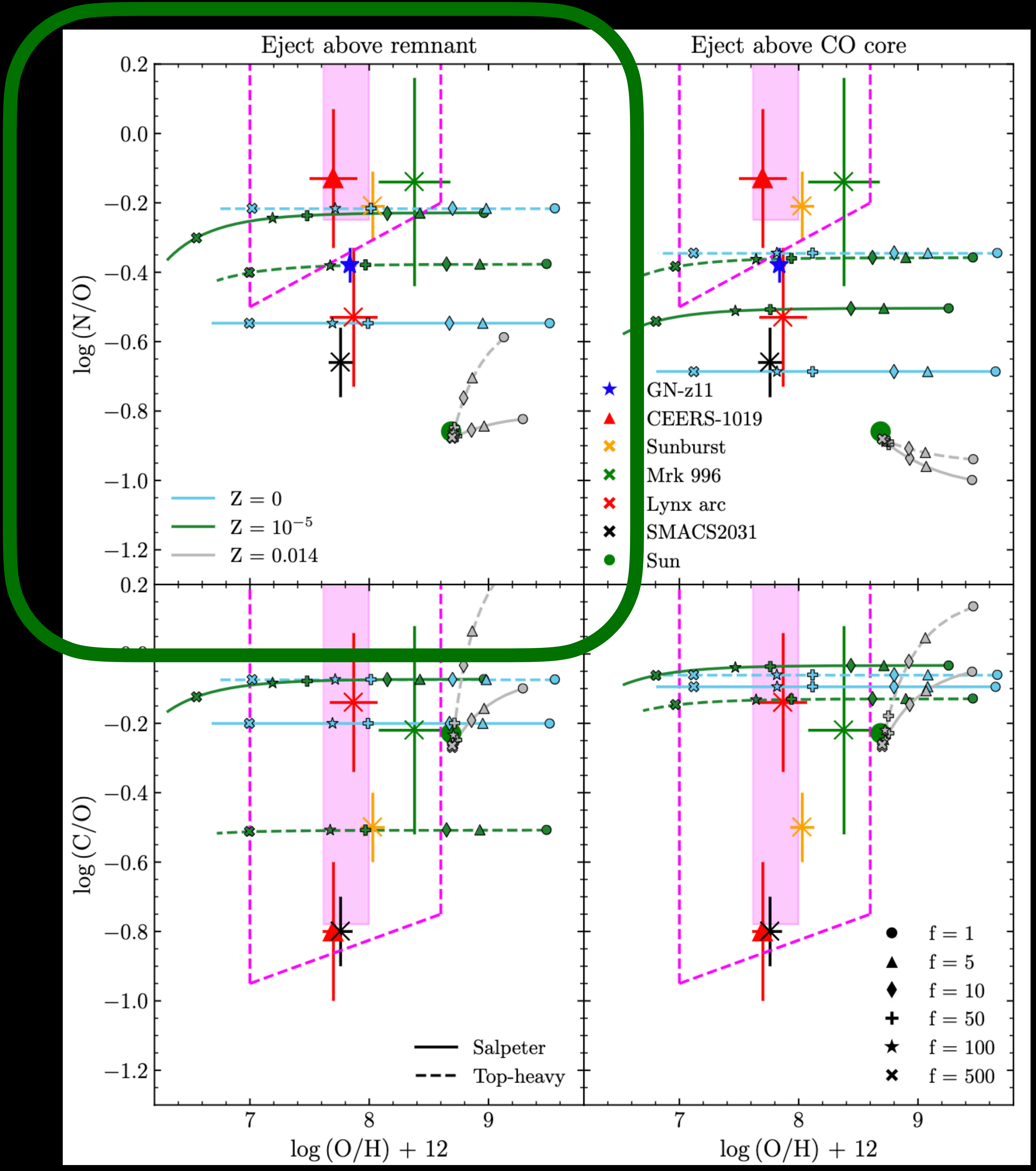
Rapidly rotating massive Population III stars as possible sources of extreme N-enrichment in high-redshift galaxies

N/O abundance ratios

- Enrichment of the surrounding IMS though mass loss.
- Mass-loss episodes prior to the star's death, and/or at the end of evolution.
- Mass-cut = Remnant mass (*Farmer et al. (2019); Patton & Sukhbold (2020)*).
- Generation of populations of stars following an IMF where each population corresponds to a given metallicity.
- Dilution of the ejecta into the ISM.

- Power-law IMFs: $dN/dM_{\text{ini}} \sim M_{\text{ini}}^{\alpha}$
  Salpeter (α = –2.35)
  Top-heavy (α = –1)

- Pink dashed lines and shaded regions show results and lower bounds from observations, from *Marques-Chaves et al. (2024)*.

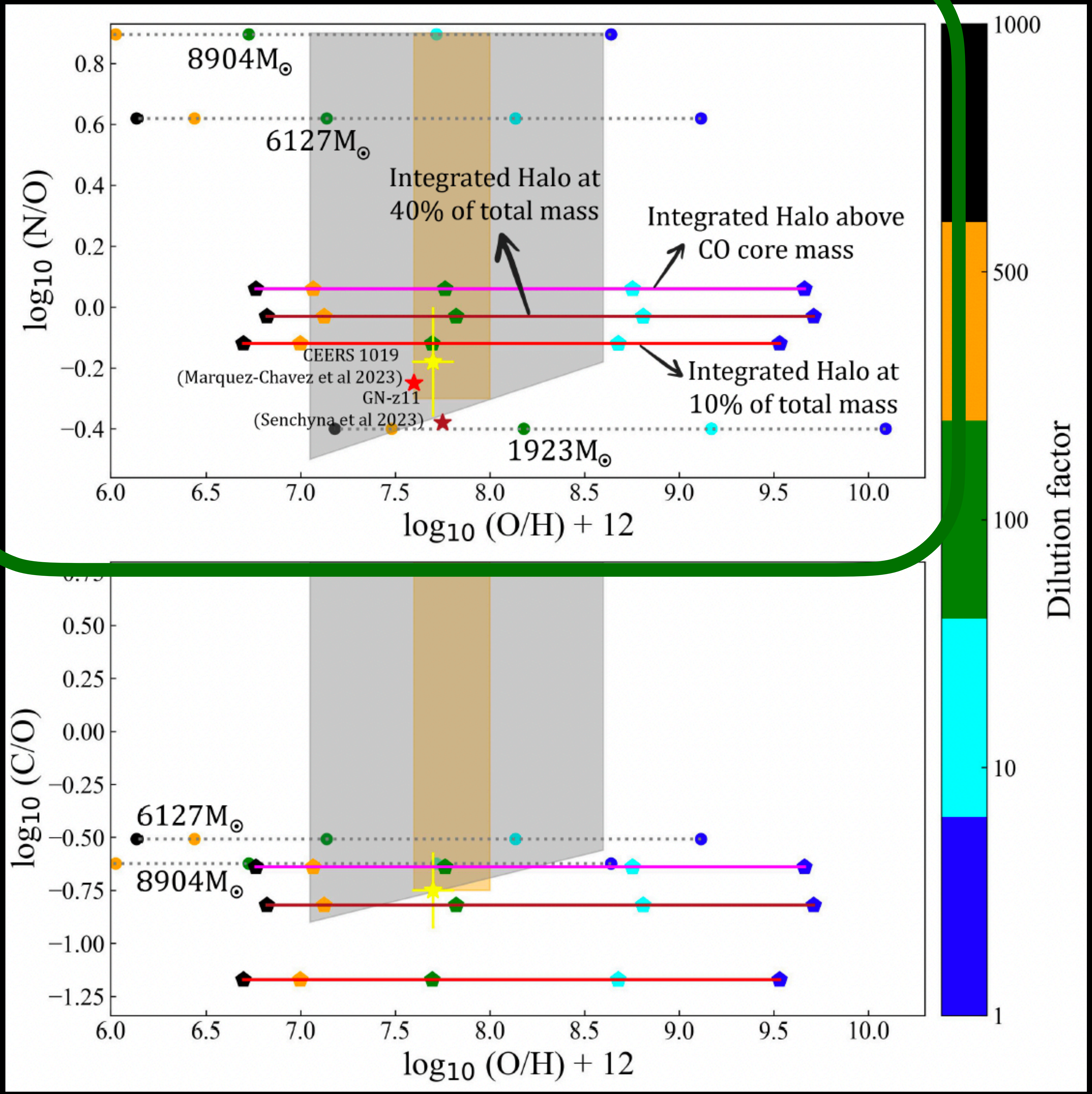


Nandal, Sibony & Tsiatsiou (2024)

Impact of Extremely Massive Stars of extreme N-enrichment in high-redshift galaxies

N/O abundance ratios

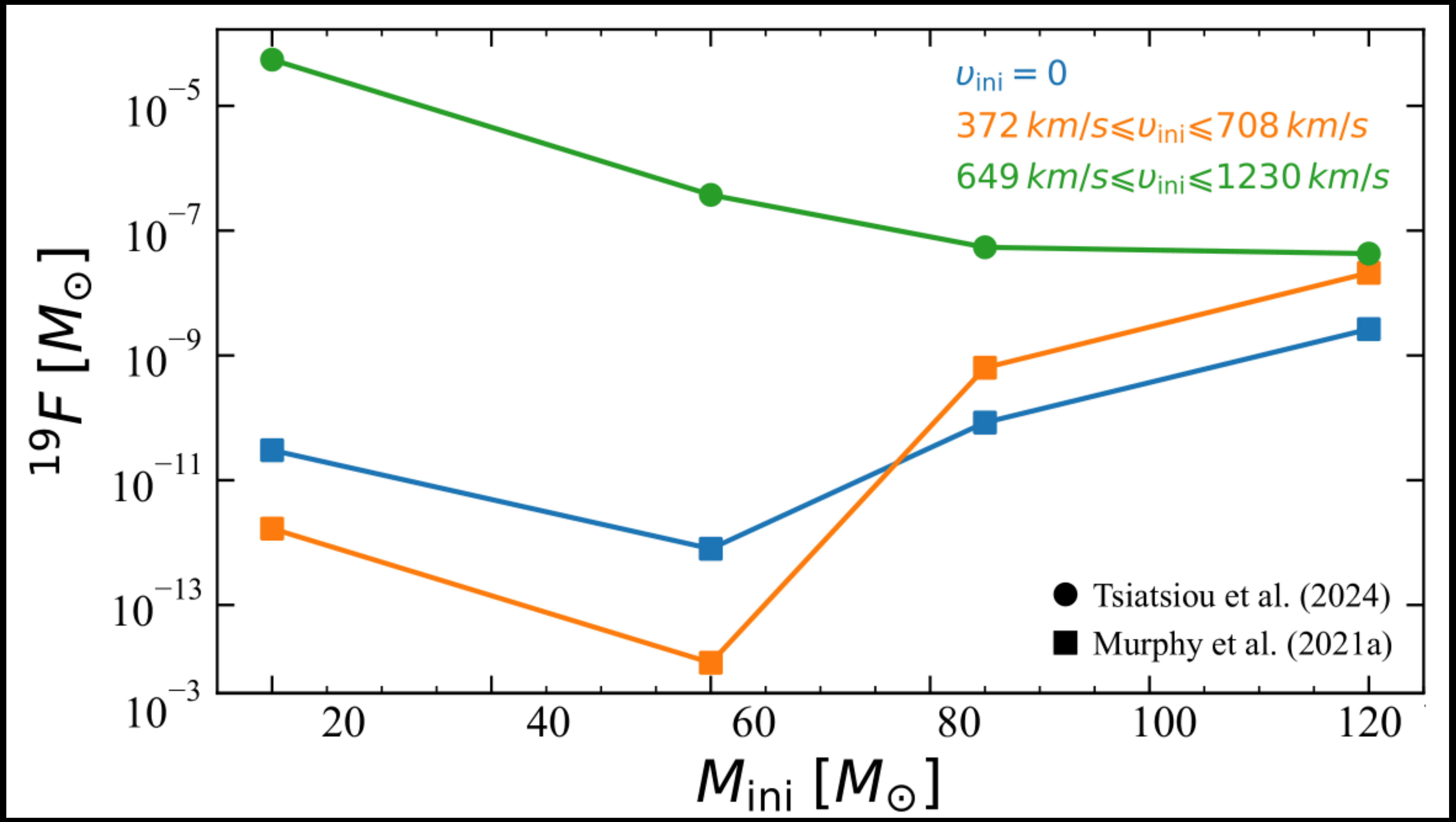
- Pop III stars for $1000\,M_{\odot} \leqslant M_{\mathrm{ini}} \leqslant 9000\,M_{\odot}$.
- Enrichment of the surrounding IMS though mass loss.
- Stars lose their mass at or after the core He-burning phase.
- Ejection Scenarios:
  1. Mass-cut = 10% of the total stellar mass
  2. Mass-cut = 40% of the total stellar mass
  3. Mass-cut = all the stellar mass above CO core.
- Dilution of the ejecta into the ISM.
- The coloured shades regions represent results for the abundances of GN-z11 by *Cameron et al. (2023)*.



Nandal et al. (2024)

Fluorine enrichment in the early Universe

Fluorine stellar yields



Tsiatsiou et al. (to be submitted)

Conclusions

- Enhanced production of primary N for rapidly rotating Pop III models compared to those with lower initial rotations.
- The apparition of the extended intermediate convective zone induced by the injection by diffusion/convection of C and O produced in the He-burning region into the H-burning shell may have a dramatic impact on the structure and the evolution of the star.
- The production of primary N is similar to rapidly rotating Pop III models and the moderately rotating models with $Z = 10^{-5}$.
- Rapidly rotating massive Population III stars & EMS (for individual stars with $1900\,M_\odot \leqslant M_{\rm ini} \leqslant 8900\,M_\odot$) are essential for explaining high N/O ratios, for observations as GN-z11 and CEERS-1019.
- Rapidly rotating Population III stars significantly contributed to early F enrichment, highlighting their critical role in the chemical evolution of the early universe.

Thank you for your attention!