Extreme Life and Death of Very Massive Stars

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Massive Stars – Broad Astrophysical Influence

Observationally

- Very luminous (visible at large distances)
- Trace star formation

R. Gendler

Evolution

- Main agents in chemical evolution of elements
- Inject energy into env.
- Produce ionizing radiation

NASA, ESA

Death

- Energetic transients (CCSNe, GRBs, PISN)
- Chemical Yields
- Live fast (~few Myr)

Pair Instability

The final **He core** determines the explosion mechanism and remnant properties (Heger, 2003)

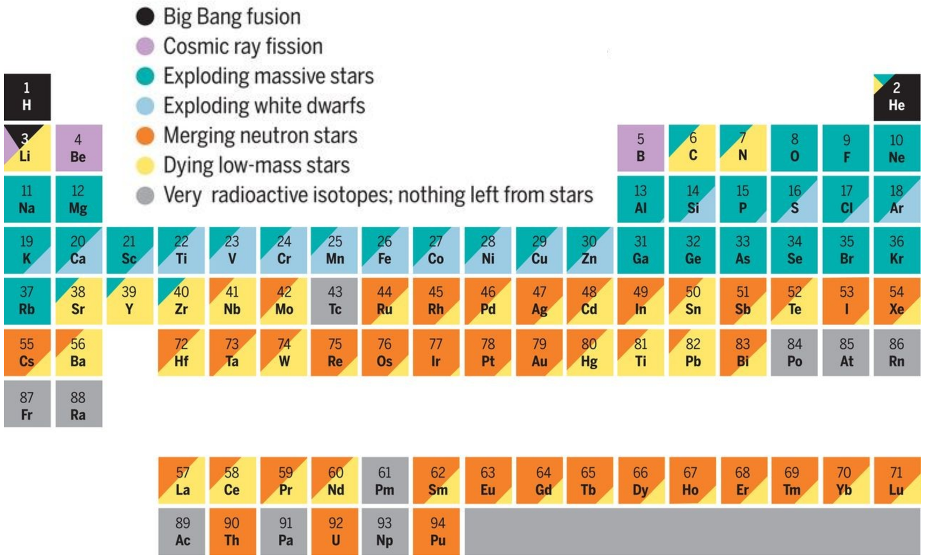
$M_{\text{He Core}} \gtrsim 30\ M_\odot$: $\gamma \rightarrow e^- - e^+$ pair production, lowers $\mathbf{\Gamma}_1 < 4/3$ (**instability**)

Pulsational Pair Instability (PPI)
- $M_{\text{He Core}}$: ~ 35 – 64 $M_\odot$
- Mass ejection

Pair Instability SN (PISN)
- $M_{\text{He Core}}$: 65 – 135 $M_\odot$
- No Remnant

Direct collapse to BH
- $M_{\text{He Core}}$: > 135$M_\odot$
- BH Remnant

Massive Pop III PISN Leave a Unique Nucleosynthetic Signature



- Observations of EMPGs show high (~solar) Fe/O but normal (low metallicity) N/O ratios *(Goswami et al. 2022)*

→ **PISN effects needed from VMS** to reproduce high Fe/O

Model Description

PAdova and TRieste Stellar Evolution Code (PARSEC)

Evolves single, isolated, nonrotating* stars from the pre main sequence, solving for structure and composition (Bressan et al., 2012, Costa et al.,+19, Nguyen et al., +22)

Publicly available to download from: http://stev.oapd.inaf.it/PARSEC/

New Parsec Tracks

Extending PARSEC tracks: *finer* grids of **massive** Pop I, II, & III stars to study their evolution, yields, and death

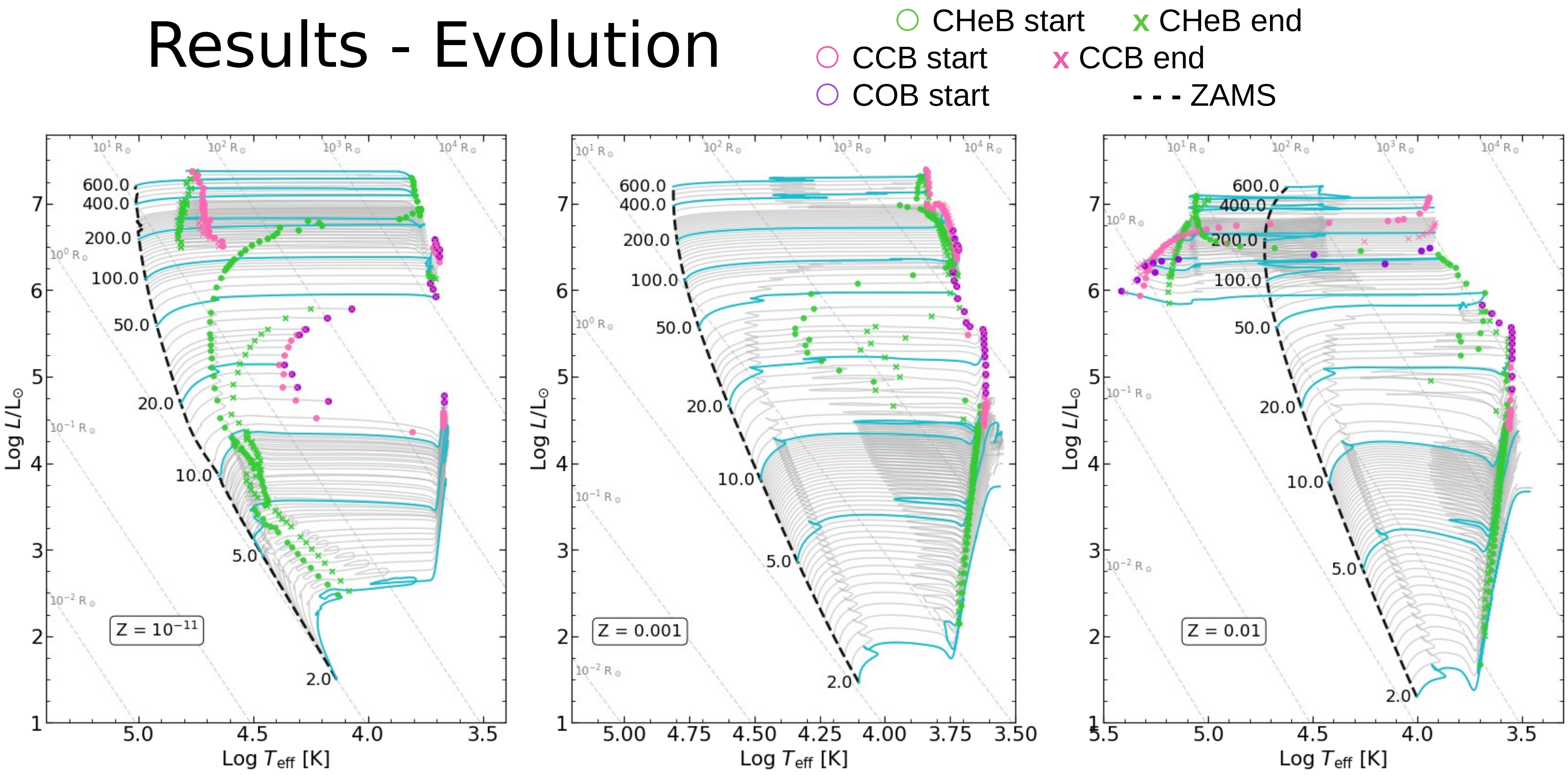
(Costa, Shepherd et al., in prep.)

+ 15 initial metallicities: 10^{-11} – 0.03 Z

+ 87 initial masses: 2 – 600 $M_\odot$

+ Rotating sets (New!)

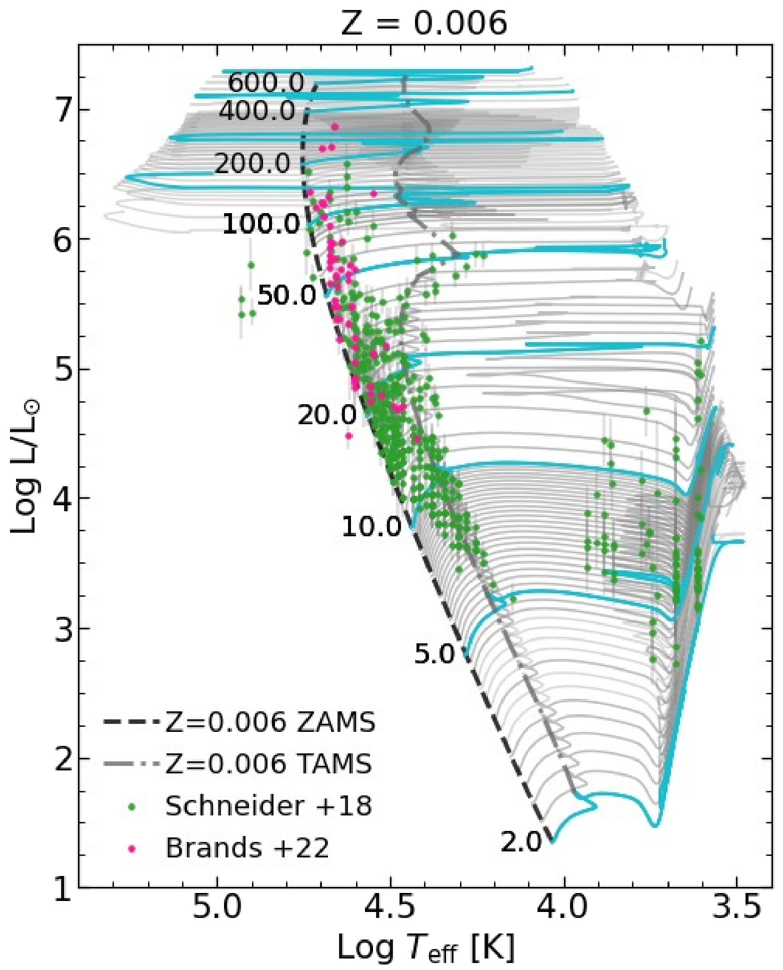
Results - Evolution



Pop III

Pop II

Pop I



Results – Comparison with Observations

Data: Tarantula Nebula (LMC)

Single stars from R136 star cluster

- Schneider, et al., 2018
- Brands, et al., 2022

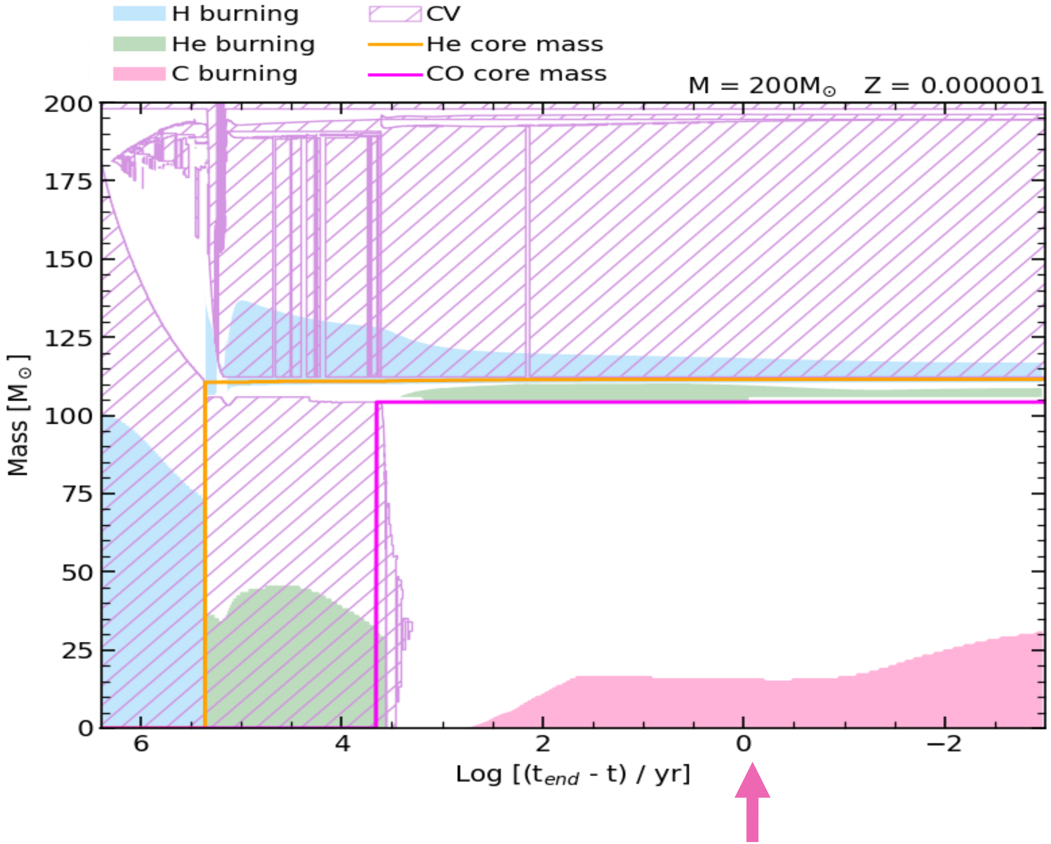
PARSEC Model

HRD of our models for Z = 0.006 (~0.5 $Z_\odot$)

→ Have structure, ages, chemical abundances, stellar type, etc. during whole evolution

Preliminary (but exciting) results!

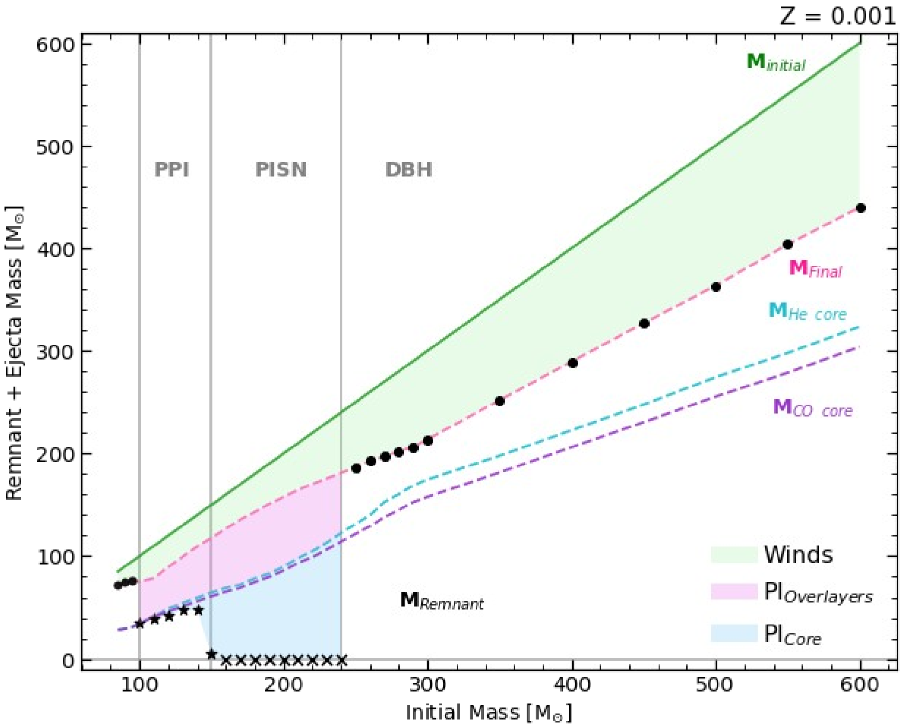
Final Structure



Time when $\langle \Gamma_1 \rangle = 4/3 + 0.01$

Results – Fate

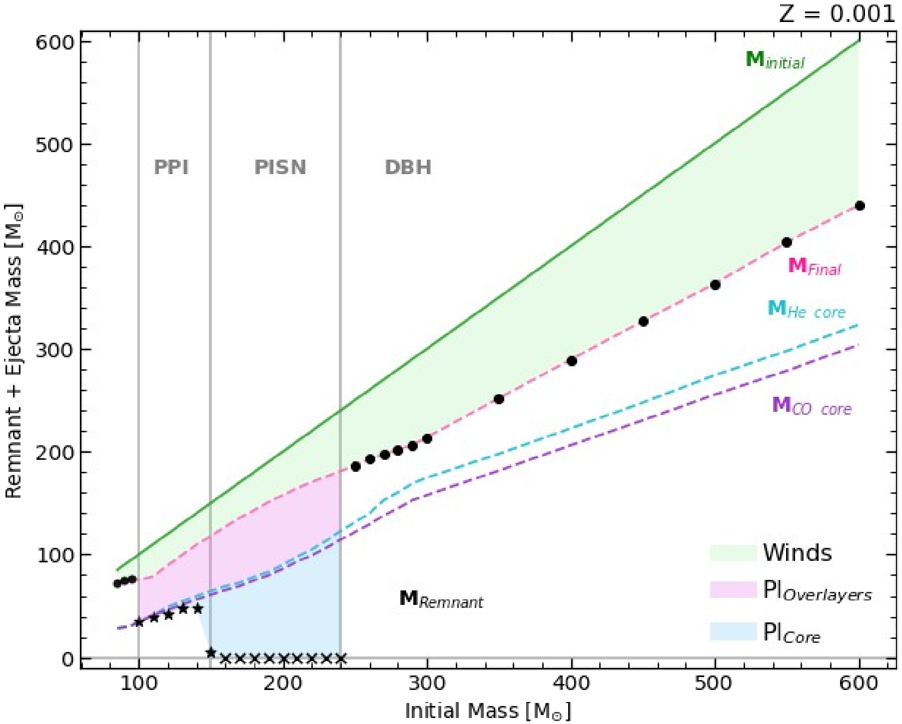
$M_{initial}$ $M_{pre\text{-}SN}$ $M_{He\ core}$ $M_{CO\ core}$



Final fates predicted from Heger & Woosley 2002, Woosley 2017

Results – Fate

$M_{initial}$ $M_{pre\text{-}SN}$ $M_{He\ core}$ $M_{CO\ core}$



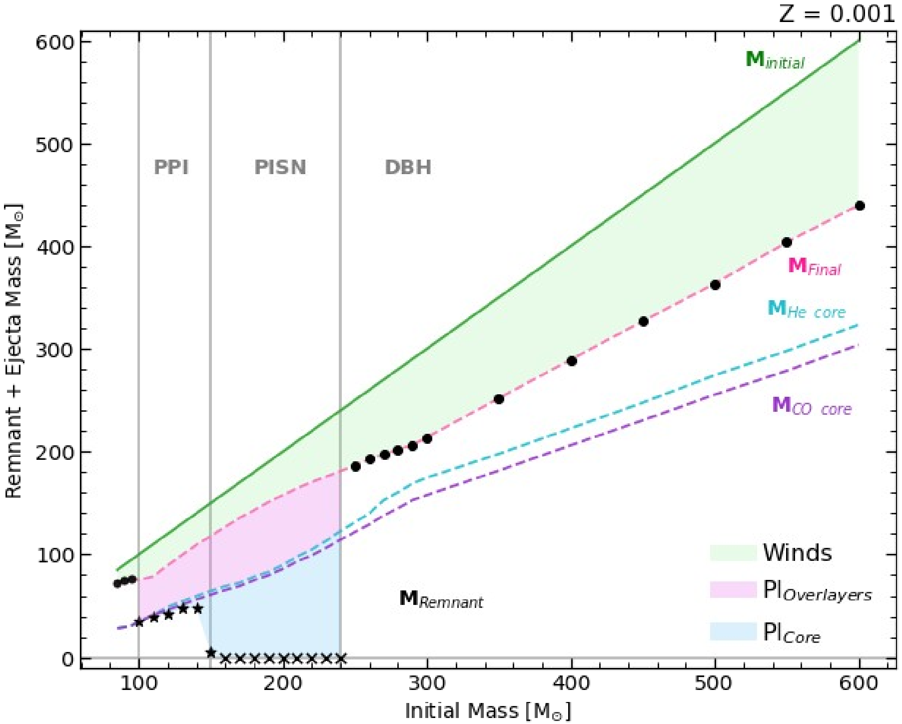
Evolutionary Ejecta (winds):

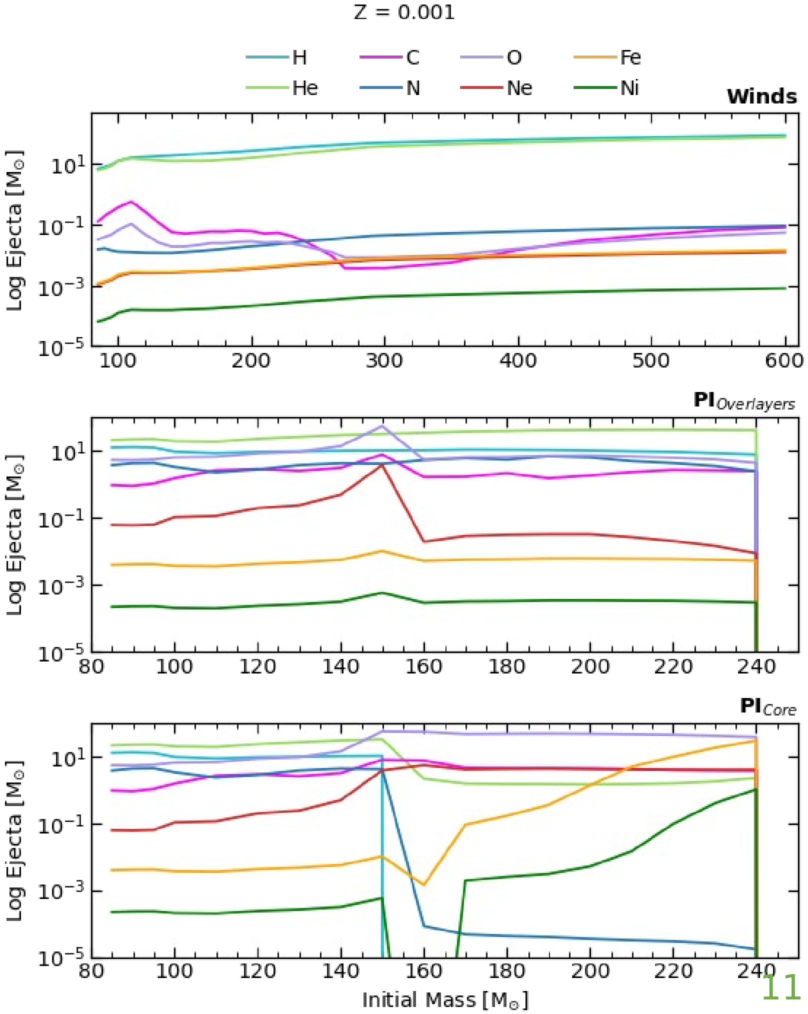
- PARSEC follows elements and main isotopes (C,N,O,Ne, Mg, Na, ..) up to Fe
- Determine instability regions

Explosive Ejecta:

- PI ejecta are computed with explosive models
- 100+ elements & isotopes from H – Ge (Heger & Woosley 2002)

Results – Fate & Yields

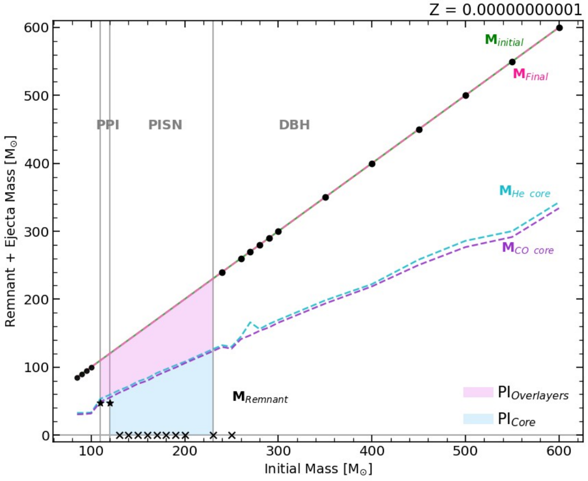




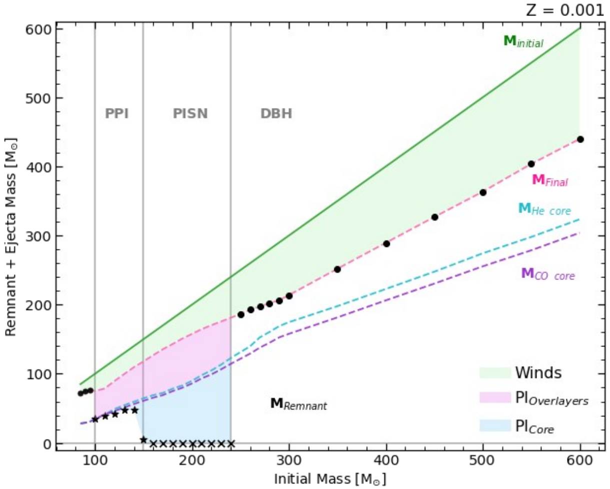
Results – Fate Across Populations

$M_{initial}$ $M_{pre\text{-}SN}$ $M_{He\ core}$ $M_{CO\ core}$

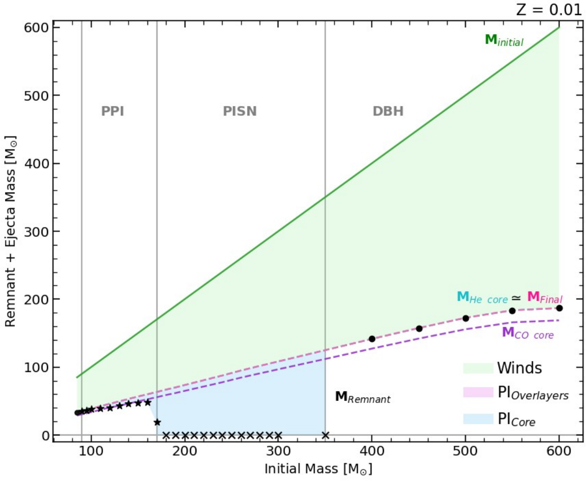
Fate: ● BH ★ PPI × PISN



Pop III



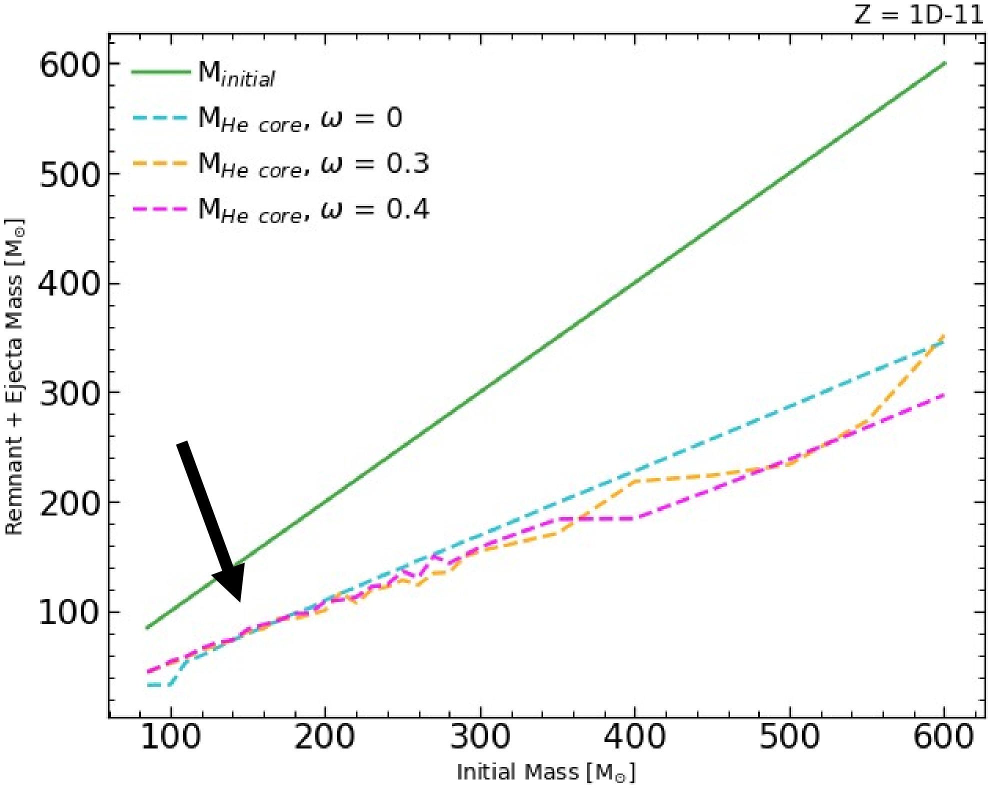
Pop II



Pop I

Predictions of final fates based on Heger & Woosley 2002, Woosley 2017

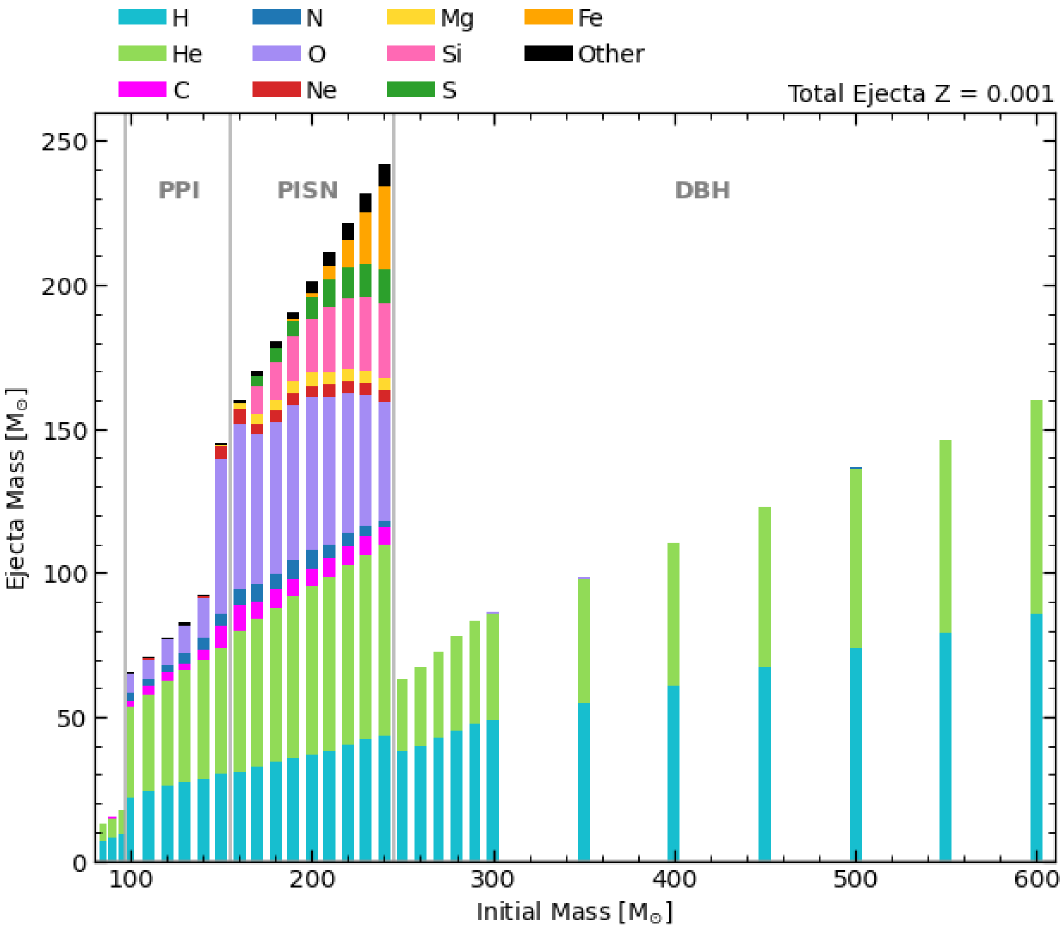
Rotating Stars

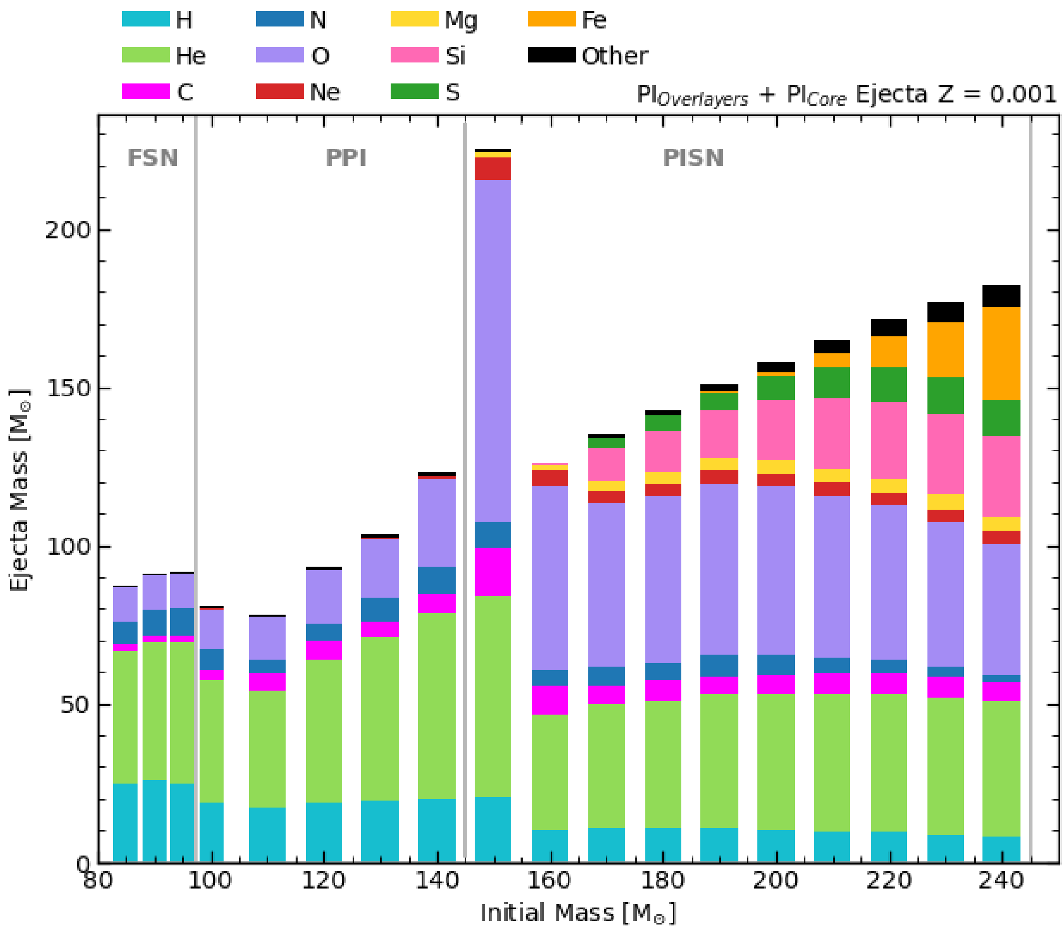


- Rotating sets computed for Pop III, ω = 0.3 and ω = 0.4
- Final He core masses are expected to be larger in rotating stars than in nonrotating sets

(True, but up to a point)

- Rotating stars above a certain mass ($\sim 170 M_\odot$) all experience a dredge up, decreasing the core mass


H
N
Mg
Fe
He
O
Si
Other
C
Ne
S
Total Ejecta Z = 0.001
PPI
PISN
DBH
Ejecta Mass [M⊙]
Initial Mass [M⊙]
0
50
100
150
200
250
100
200
300
400
500
600



Total Explosive Ejecta

Yields ejected via PISN are rich in **Oxygen**, **Silicon**, and **Iron**

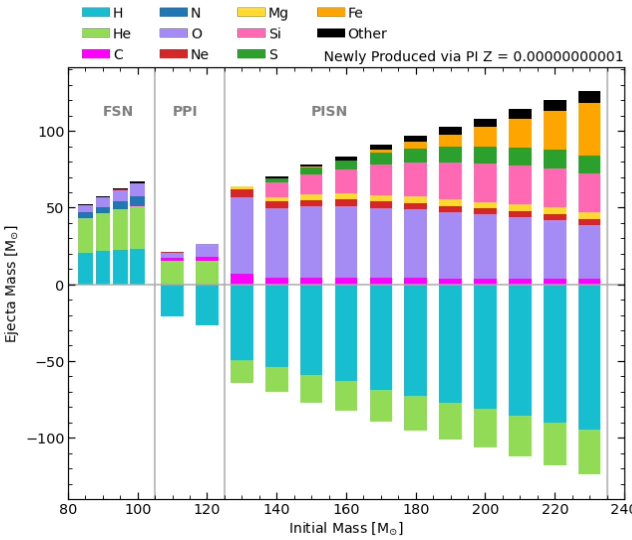
Using **Iron / Oxygen** ratios can help to determine if PPISN/PISN have occurred (Goswami et al., 2021, Bressan et al., 2022)

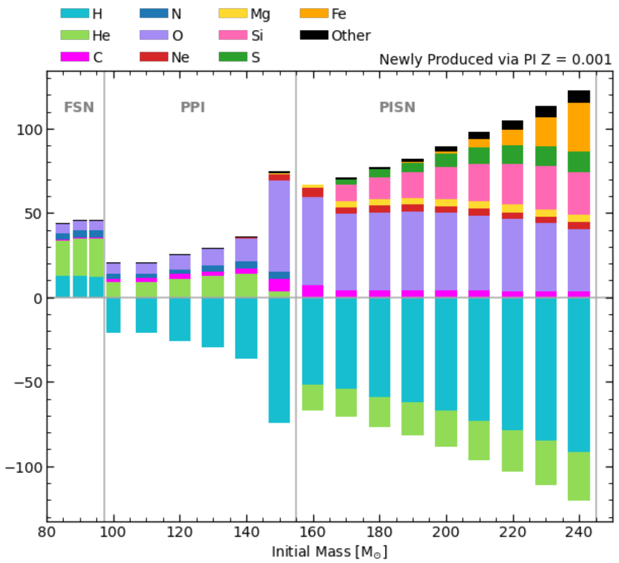
New Ejecta (PI_{Core})

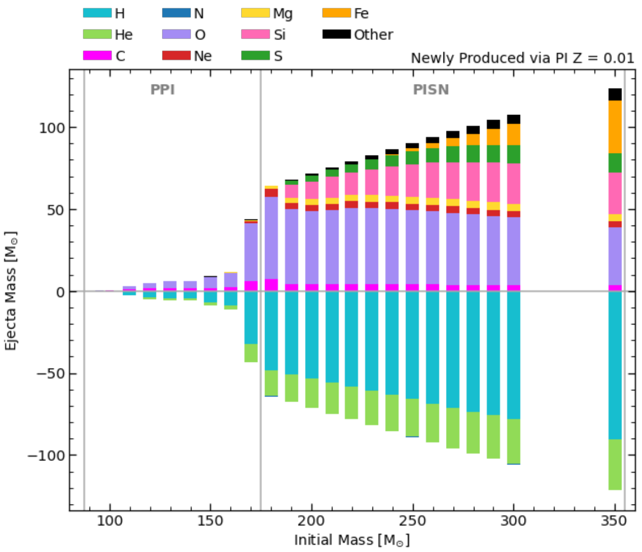
H C O Mg S

He N Ne Si Fe

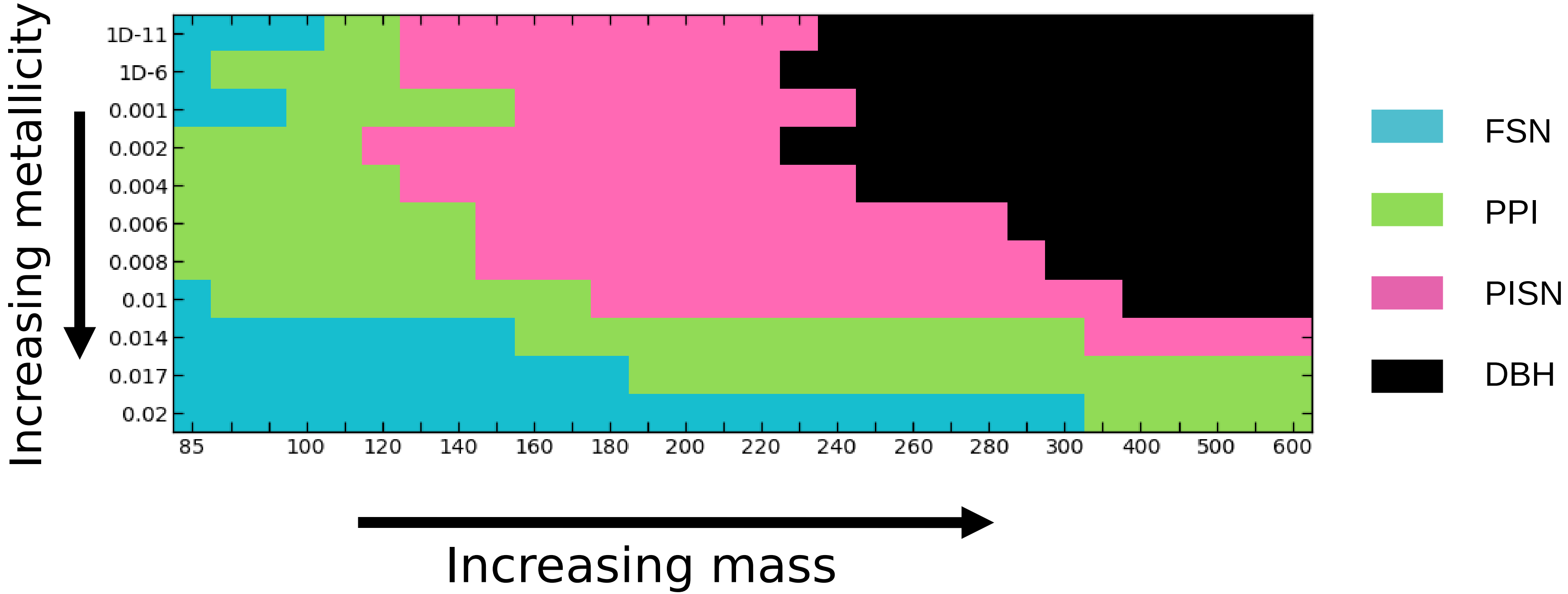
Sum isotopes from ^{3}He - ^{60}ZN







Increasing Z → Shifts Final Fates



Conclusions & Future work

Results

- Computed a large, complete, and consistent set of massive star models
- Investigated how initial mass and metallicity affect the stellar evolution, yields, remnant type and properties
  - Included rotation and calculated ionizing photon counts

Next:

- Releasing the tracks and calculations to the community
  - Can be implemented in chemical enrichment models of galaxies
- Compute yields for rotating tracks
- Compare with observations – investigate ratios indicative of PI events

Thank you for your attention!

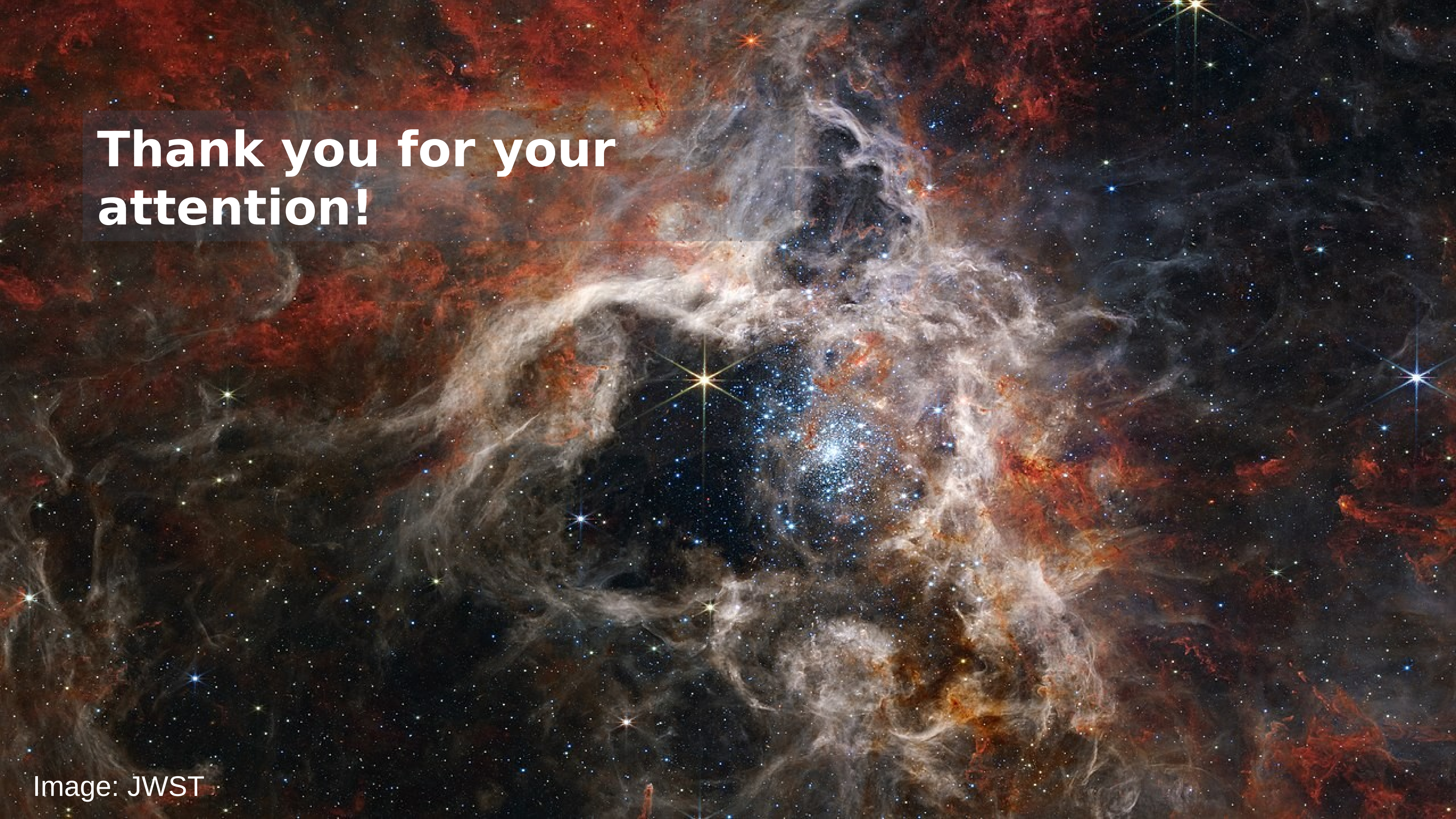


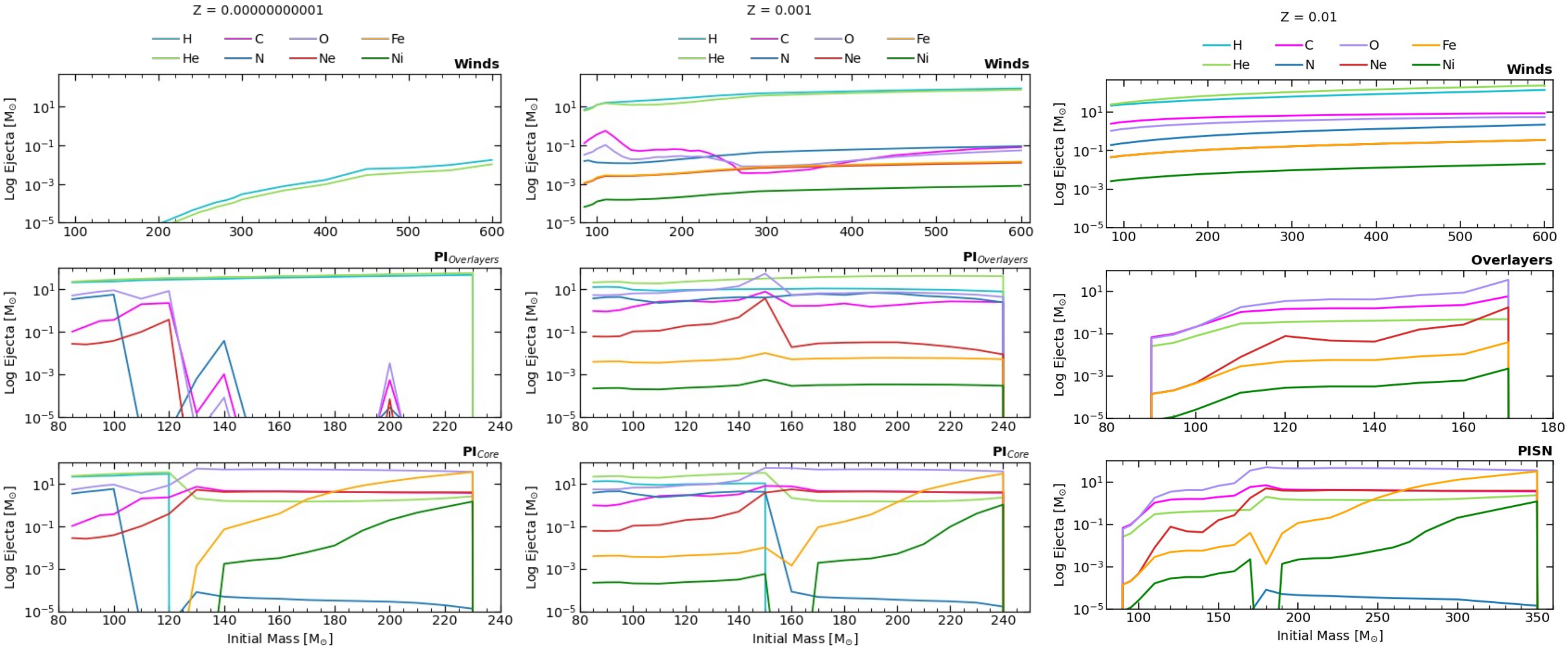
Image: JWST

Backup Slides

Just in case

Yield Components Across Populations

:

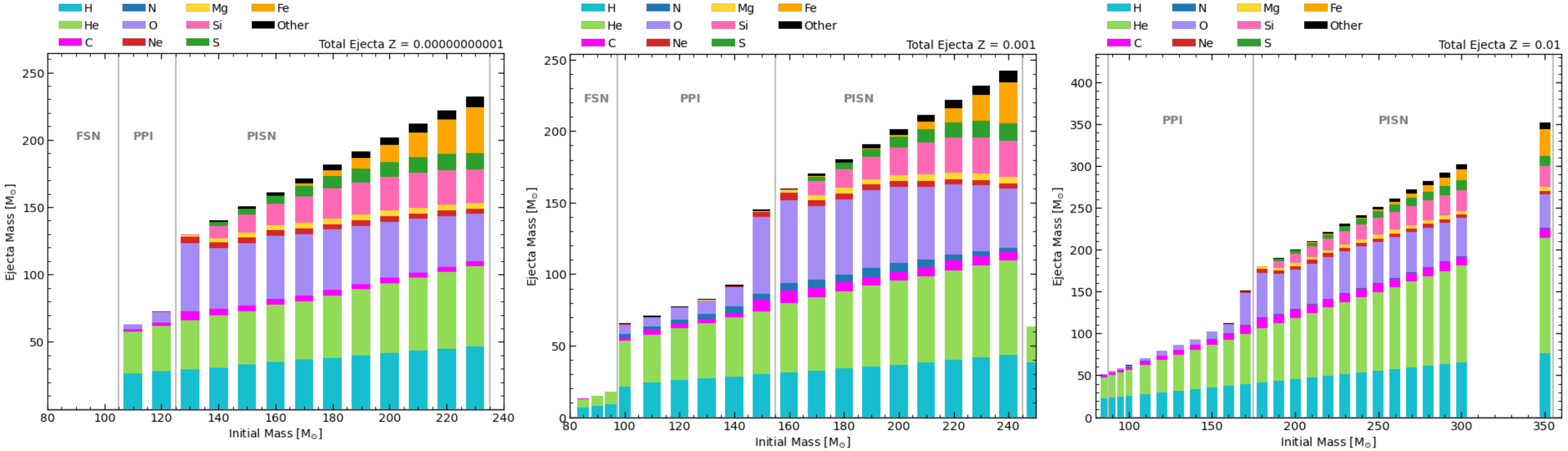


Total Ejecta Yields for Increasing Z

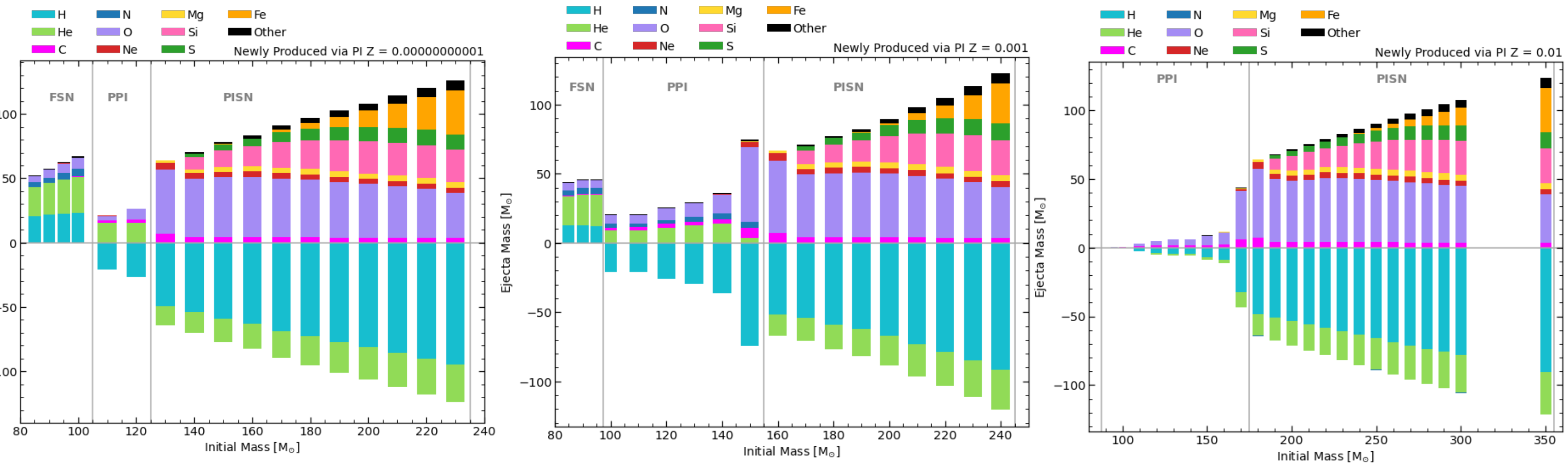
H C O Mg S

He N Ne Si Fe

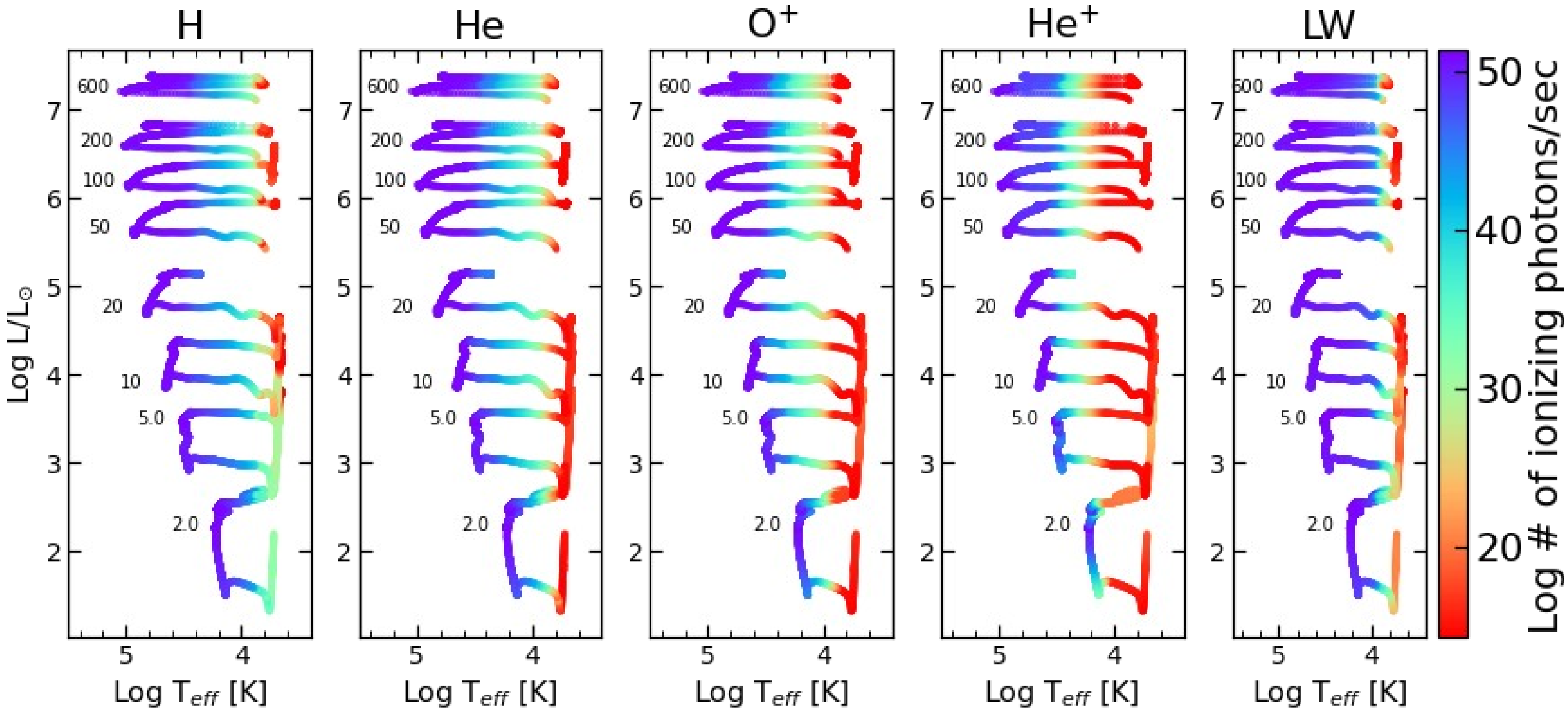
Sum isotopes from ^{3}He - ^{60}ZN



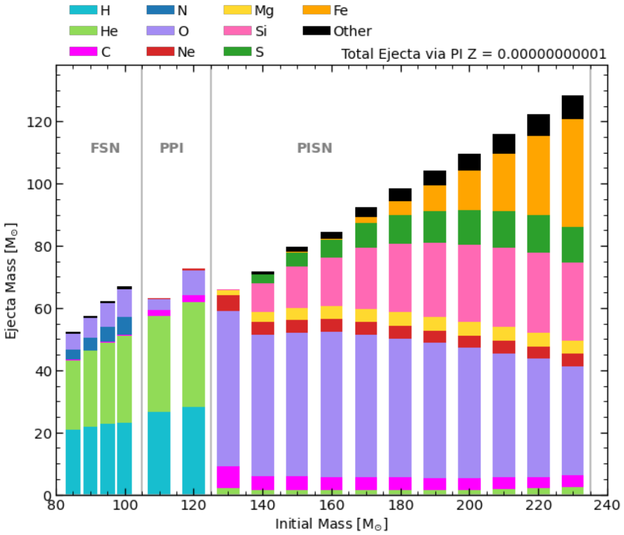
Newly Produced via PISN

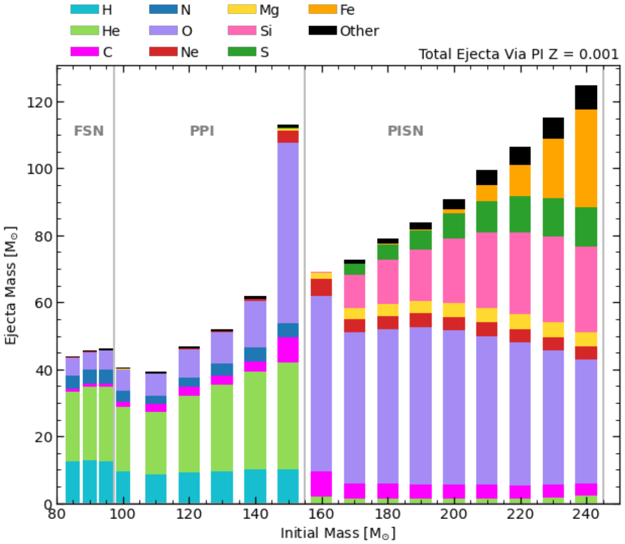


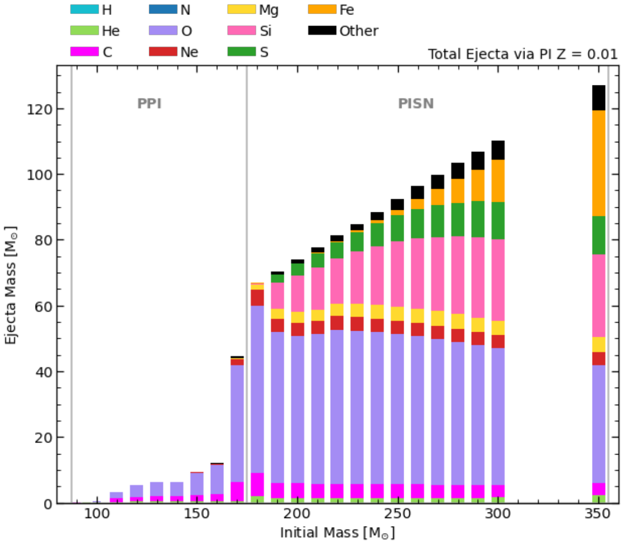
Ionizing Photons



Total ejected via PI







Stability Against PI

- Stability determined using the average adiabatic index over the whole star

$$\langle \Gamma_1 \rangle = \frac{\int_0^M \frac{\Gamma_1 P}{\rho} dm}{\int_0^M \frac{P}{\rho} dm}$$

- Star is dynamically stable if $\langle \mathbf{\Gamma_1} \rangle > 4/3$ (Stothers et al.1999)
- To be conservative:

$$\langle \mathbf{\Gamma_1} \rangle < 4/3 + 0.01 \Rightarrow \text{instability}$$

Yields calculation

Winds $E_j^{winds}(M_i) = \int_0^{\tau_c} \dot{M}(M_i,t) X_j^s(t) dt$

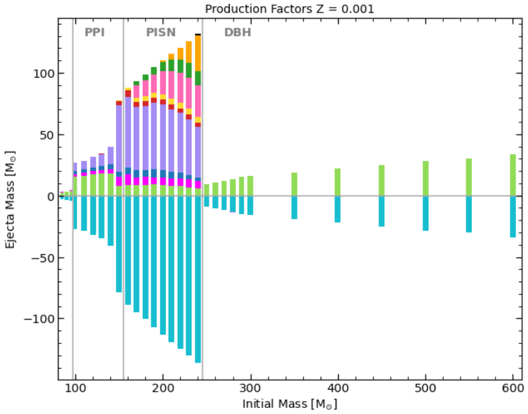
Mass of newly formed elemer $M_{im} = \int_0^{\tau_m} \dot{M}_{lost} \cdot [X_{fin}(i) - X_{orig}(i)] dt$

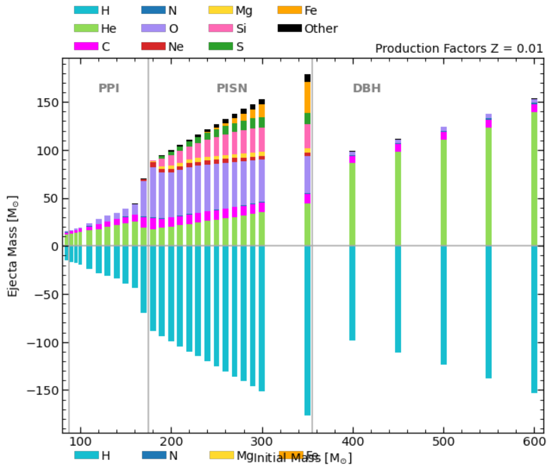
Stellar yield $p_{im} = M_{im}/m_\star$

Total stellar mass ejecte $M_{imo} = X_{orig}(i) \cdot M_{lost}$

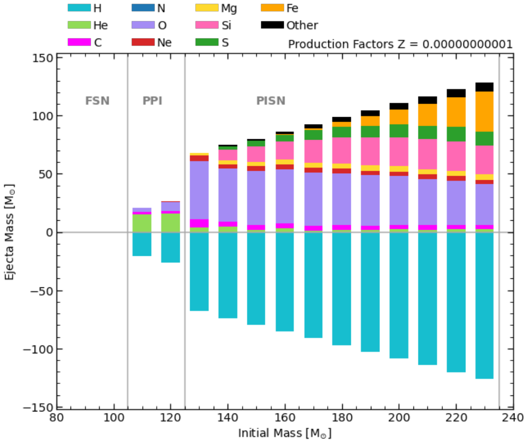
Production factors

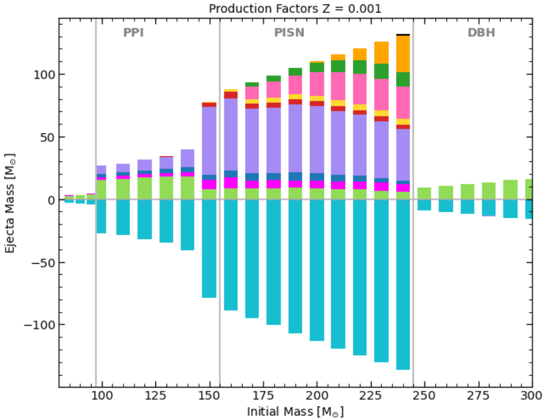
All stars

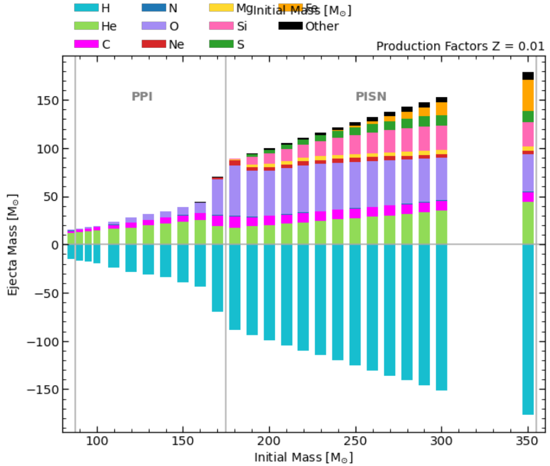




PI stars



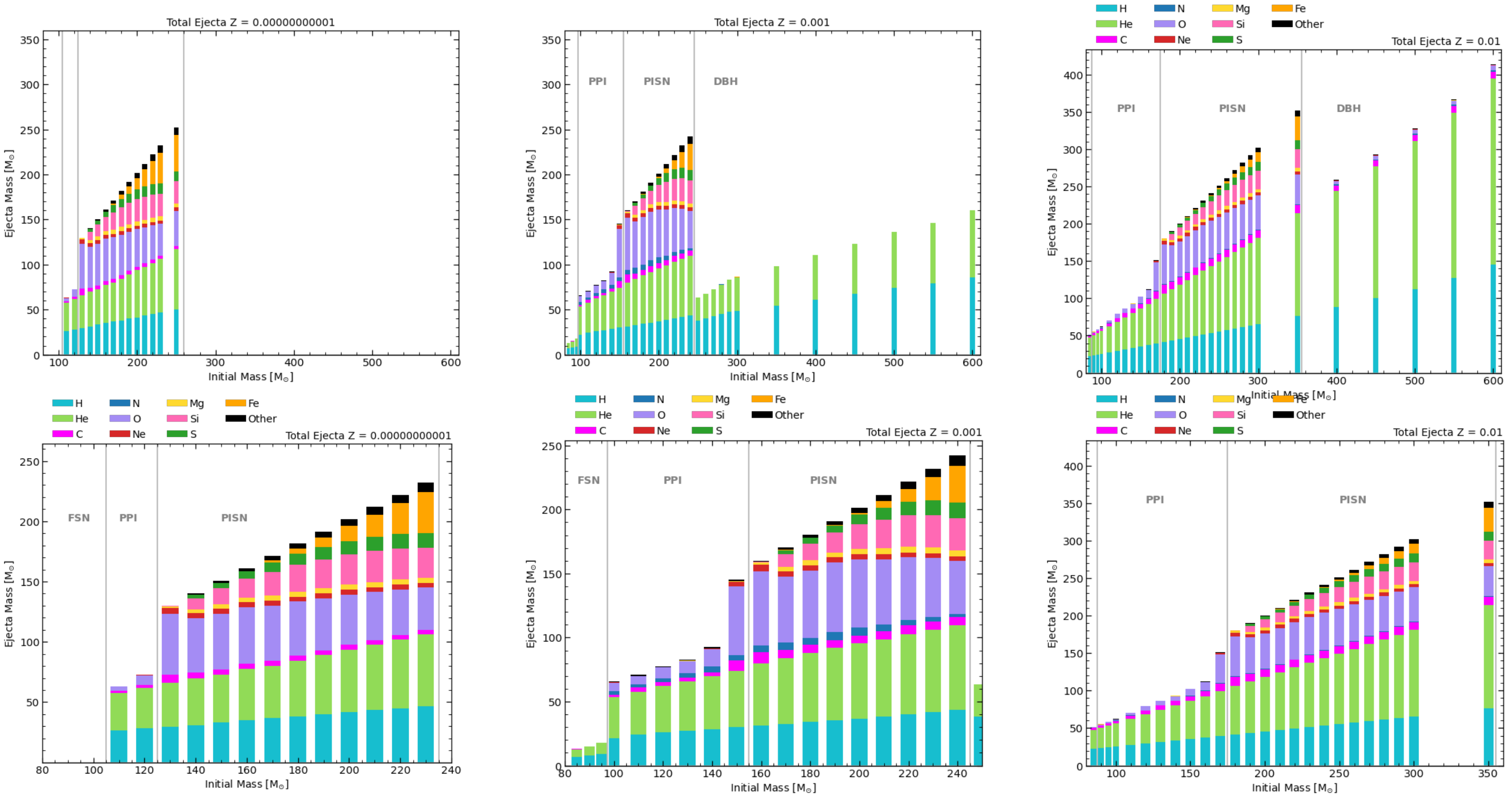


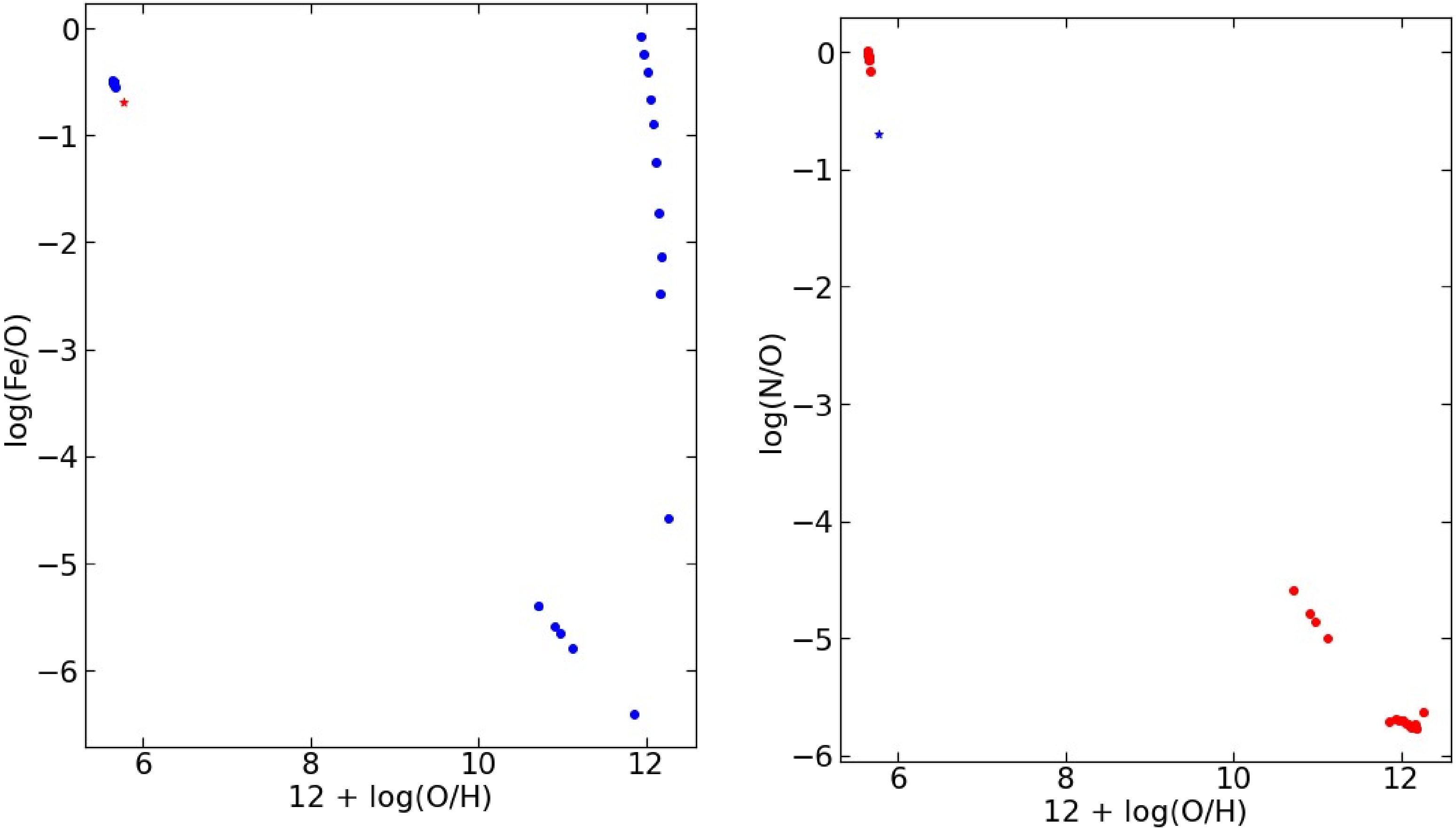


Total Ejecta

All stars

PI stars





0
−1
−2
−3
−4
−5
−6
log(Fe/O)
6
8
10
12
12 + log(O/H)
0
−1
−2
−3
−4
−5
−6
log(N/O)
6
8
10
12
12 + log(O/H)