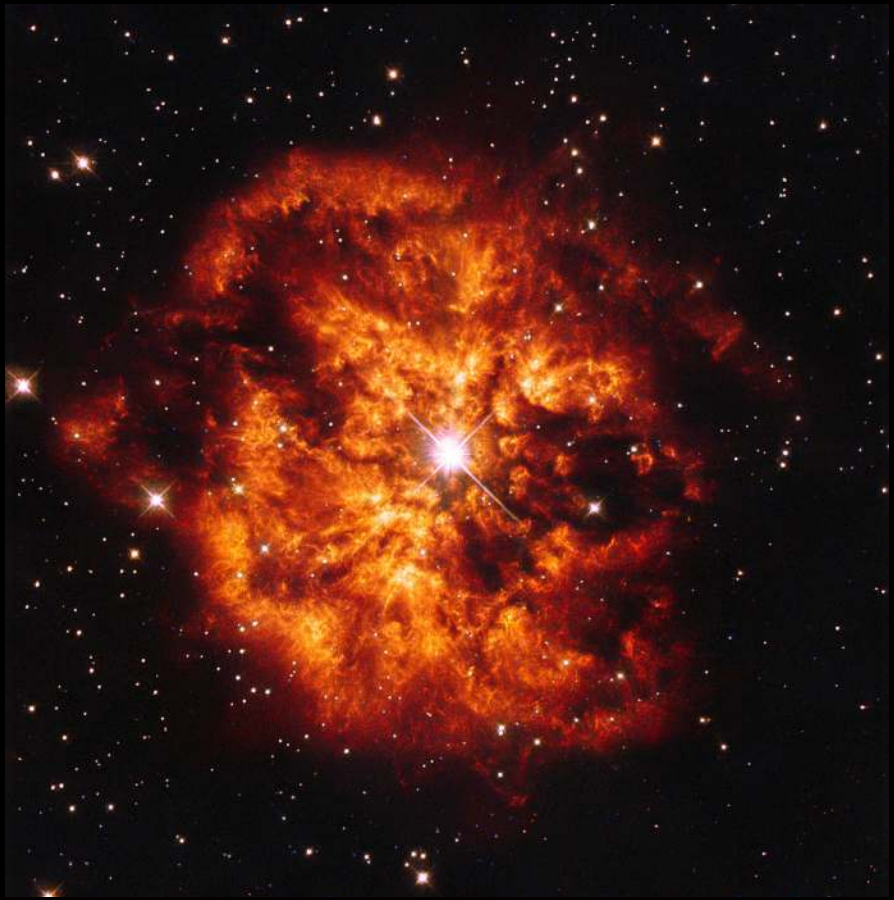
Nested dust shells around the Wolf–Rayet binary WR 140 observed with JWST

(Lau et al. 2022)

Credit: NASA/ESA/CSA/STScI/JPL-Caltech

Ryan Hazlett

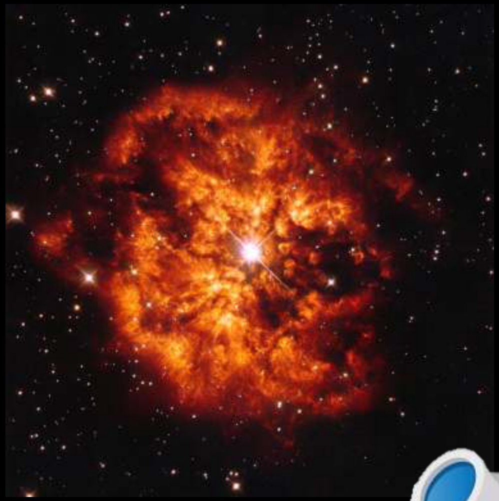
Observing Wolf-Rayet Stars

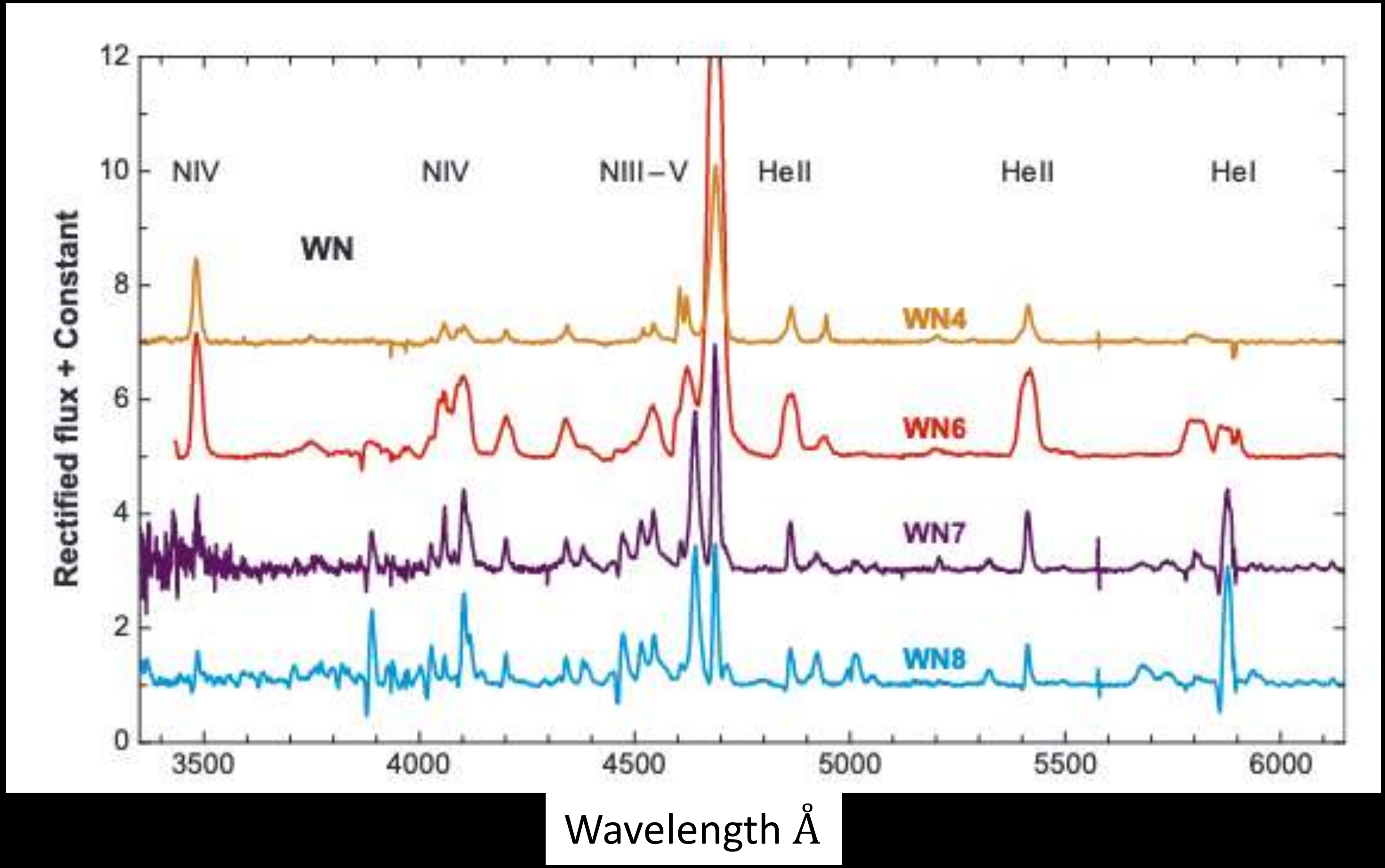


HST image of WR 124

Credit: ESA/Hubble & NASA

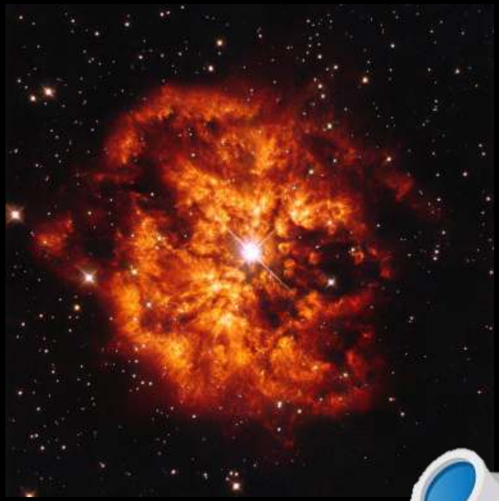
Strong Broad Emission Lines in Spectra

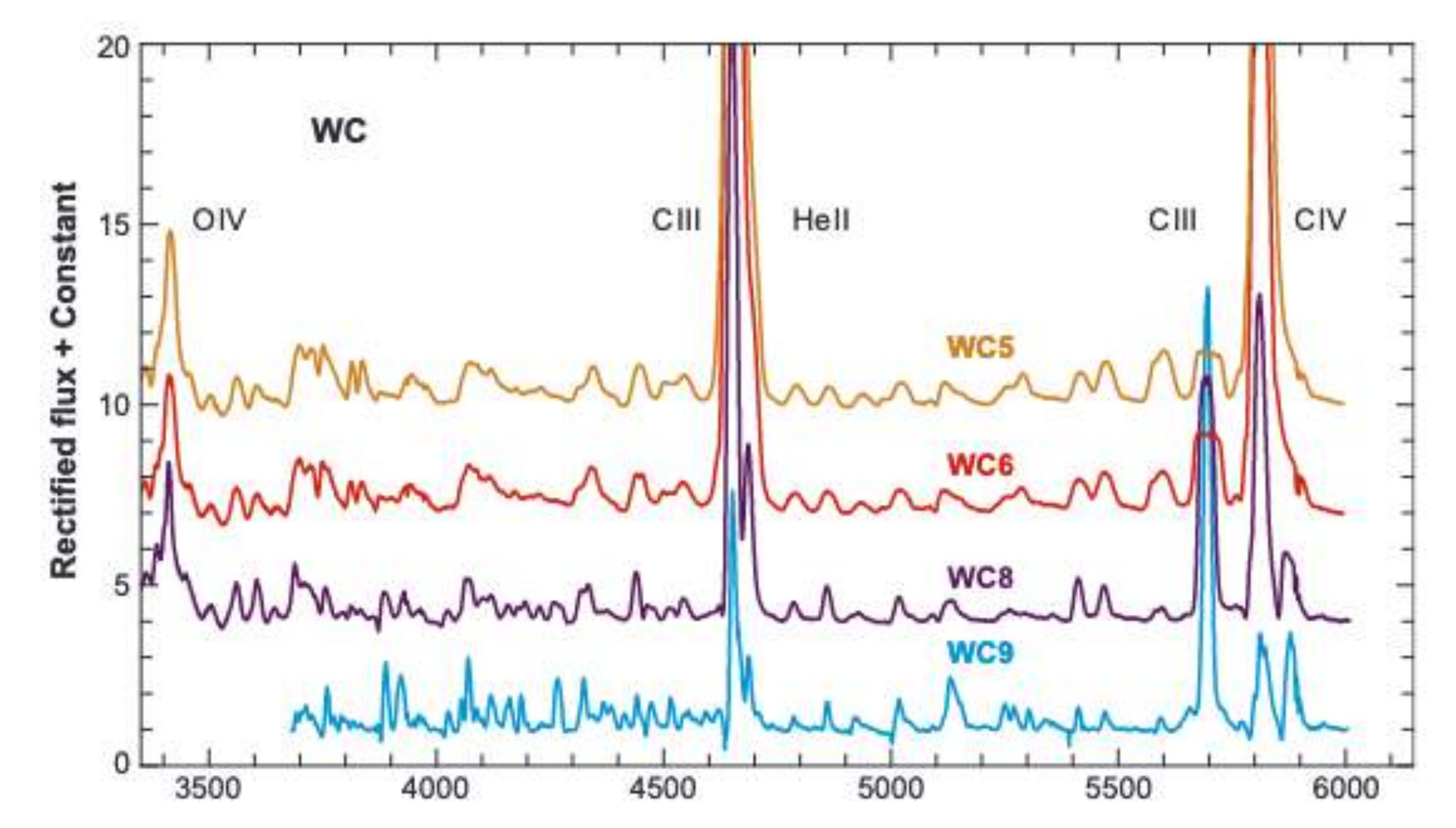




(Crowther 2007)

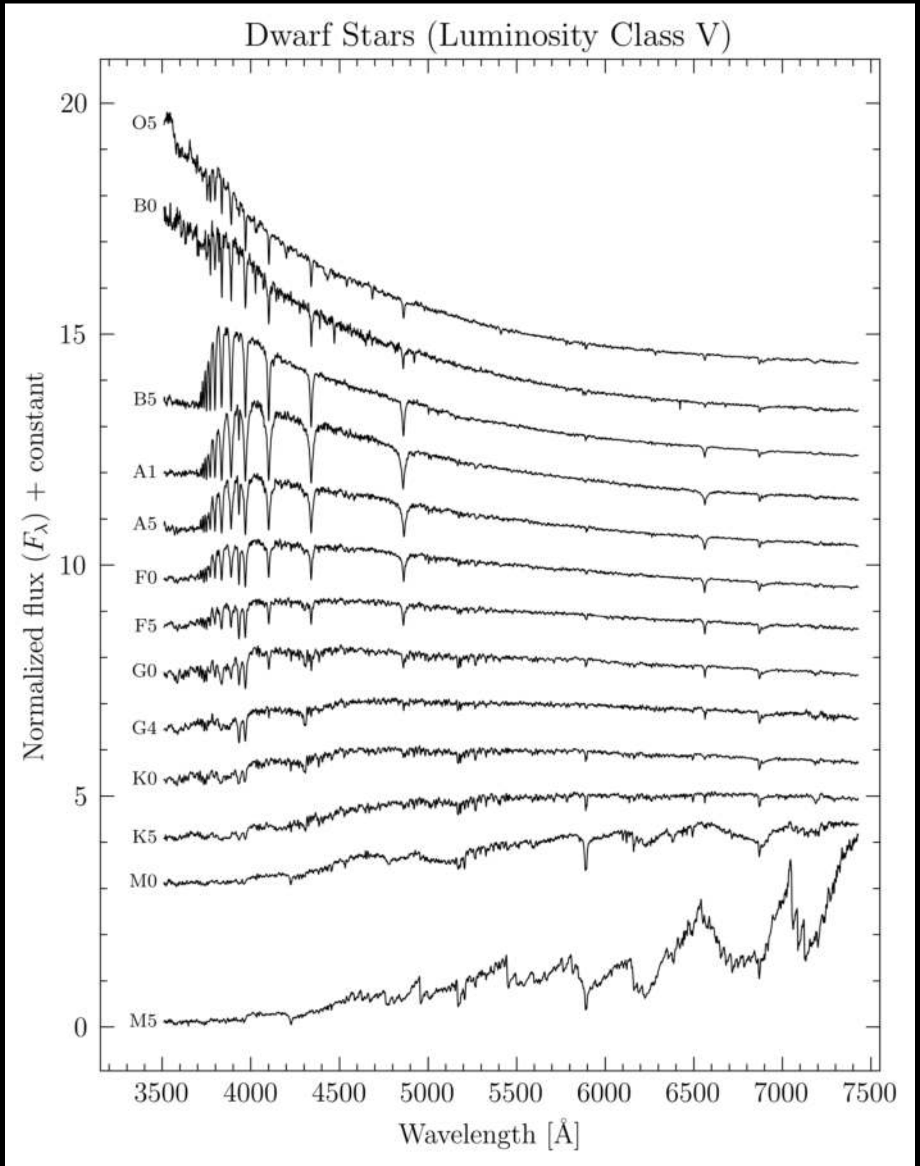
Strong Broad Emission Lines in Spectra



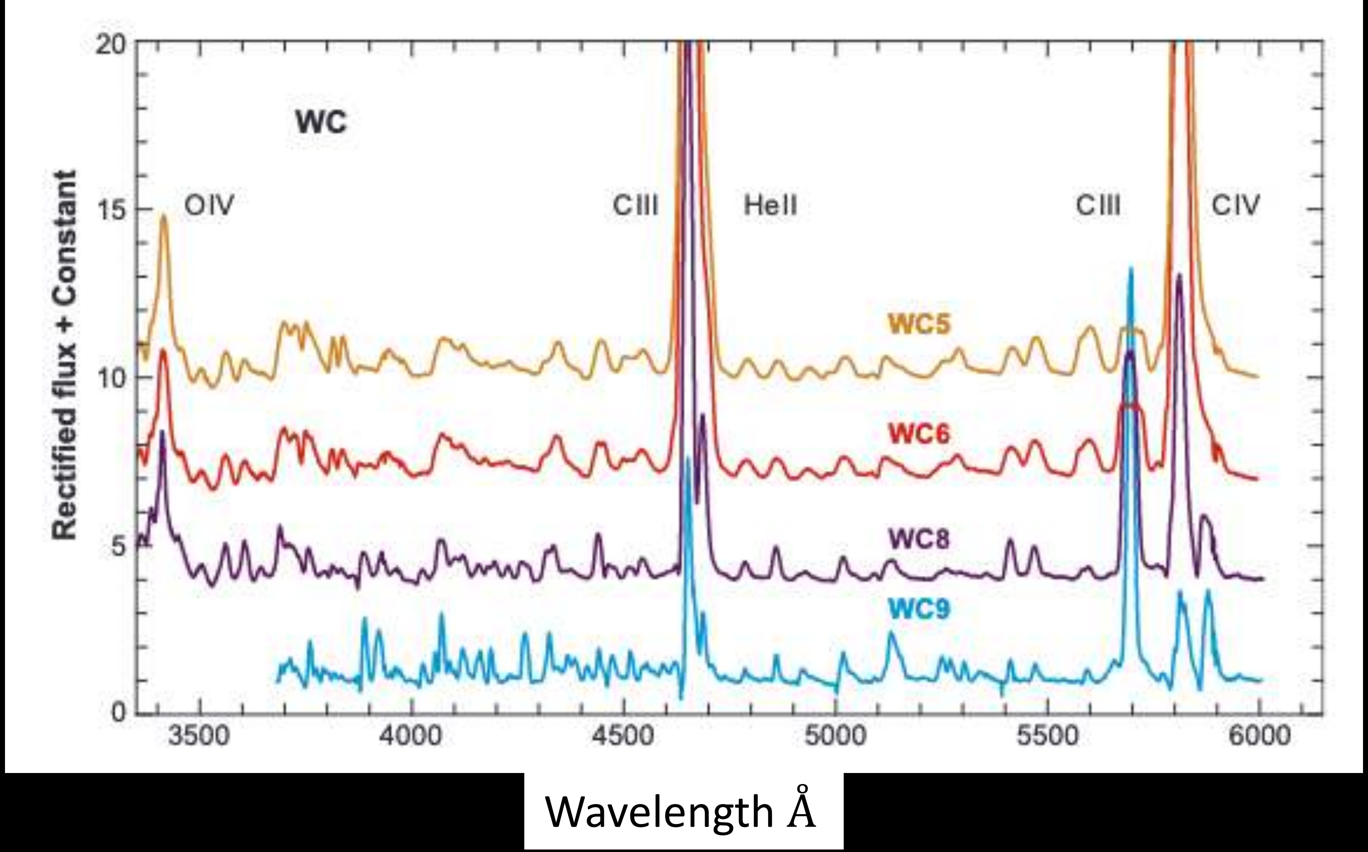


Wavelength Å

(Crowther 2007)

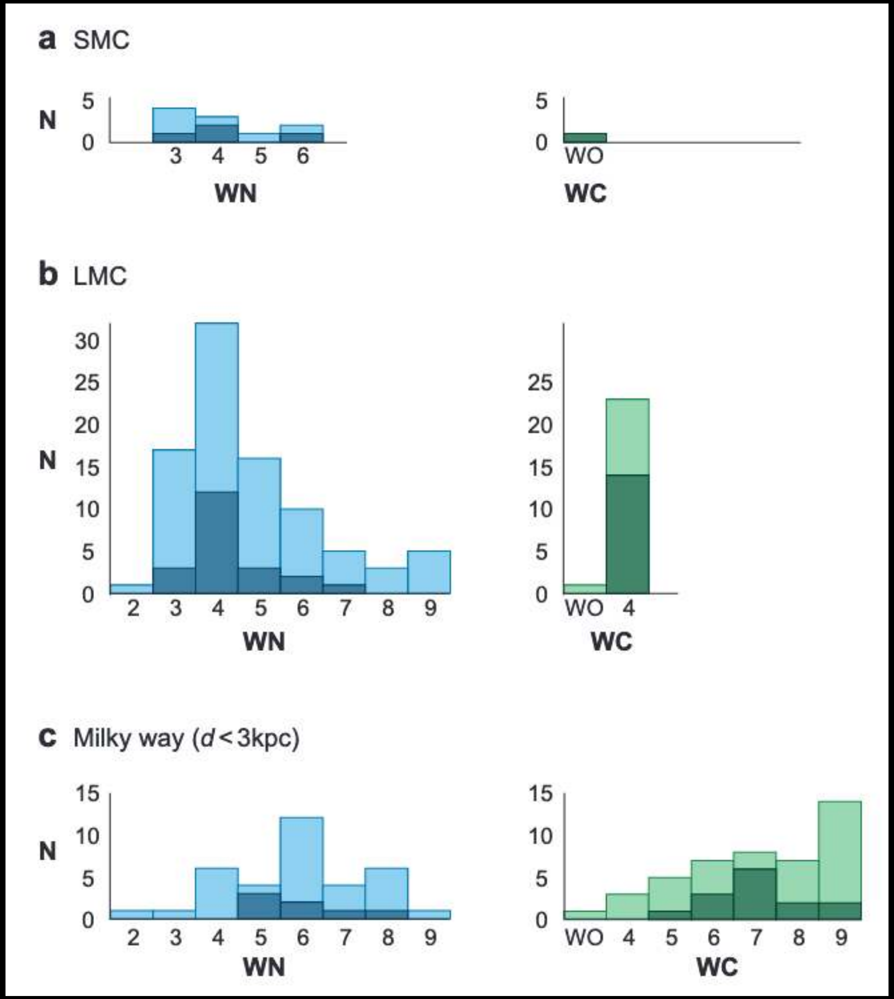


(Jacoby et al. 1984)



(Crowther 2007)

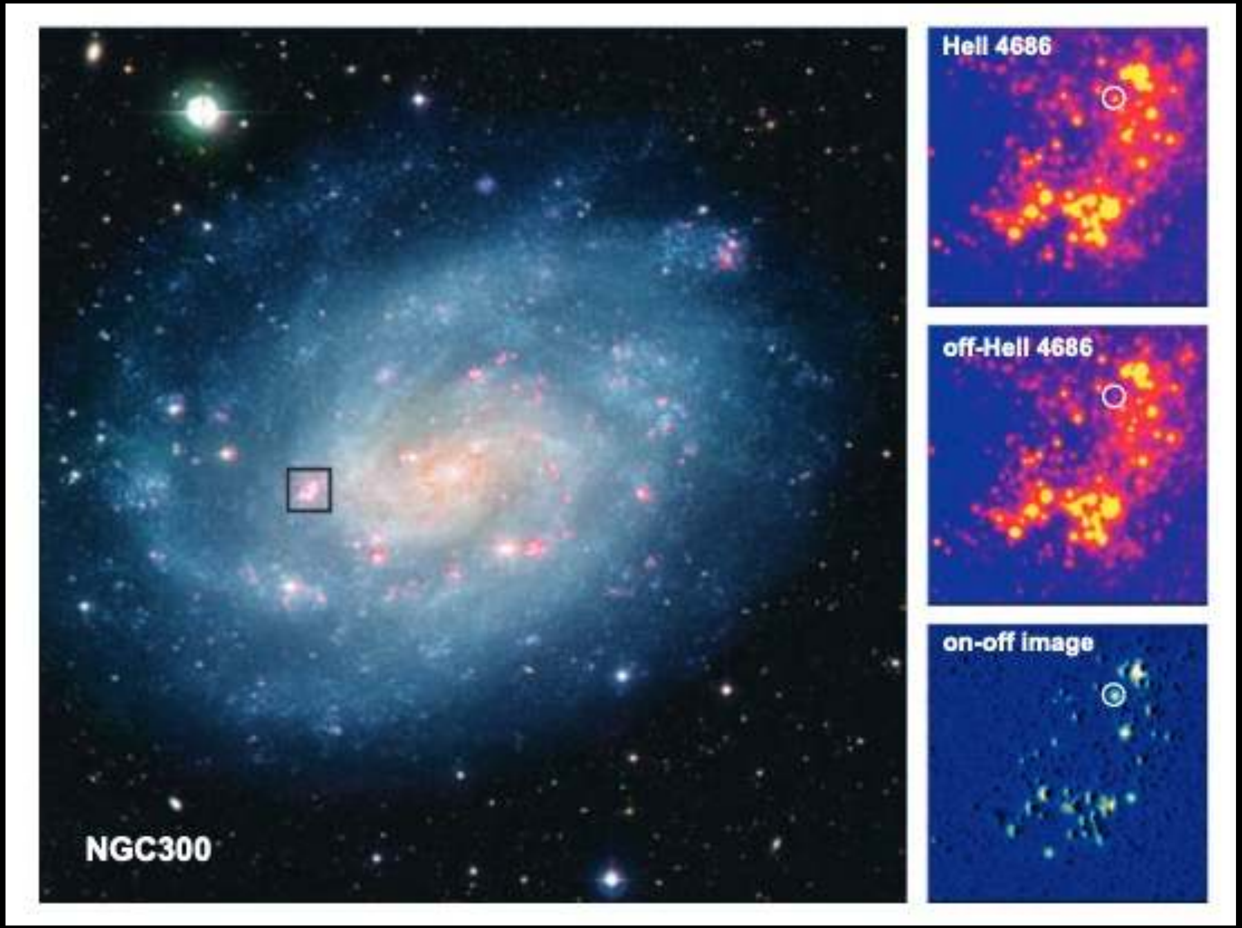
Wolf-Rayet Stars are Rare



(Crowther 2007)

- WR binaries are shaded
- Individual WR stars can't be resolved in distant galaxies
- Is there a dependence on metallicity?

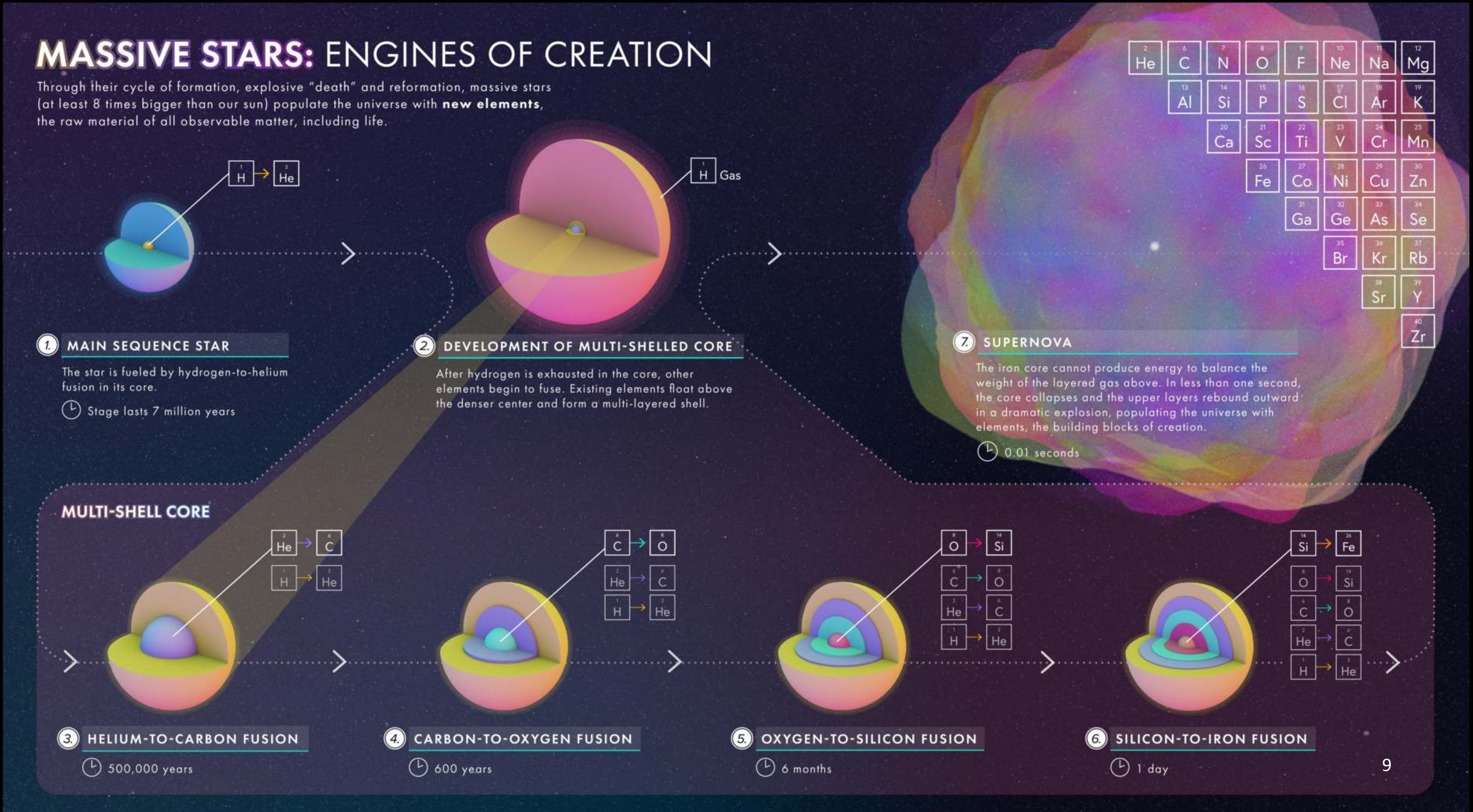
Identifying WR Stars using He II



(Schild et al. 2003)

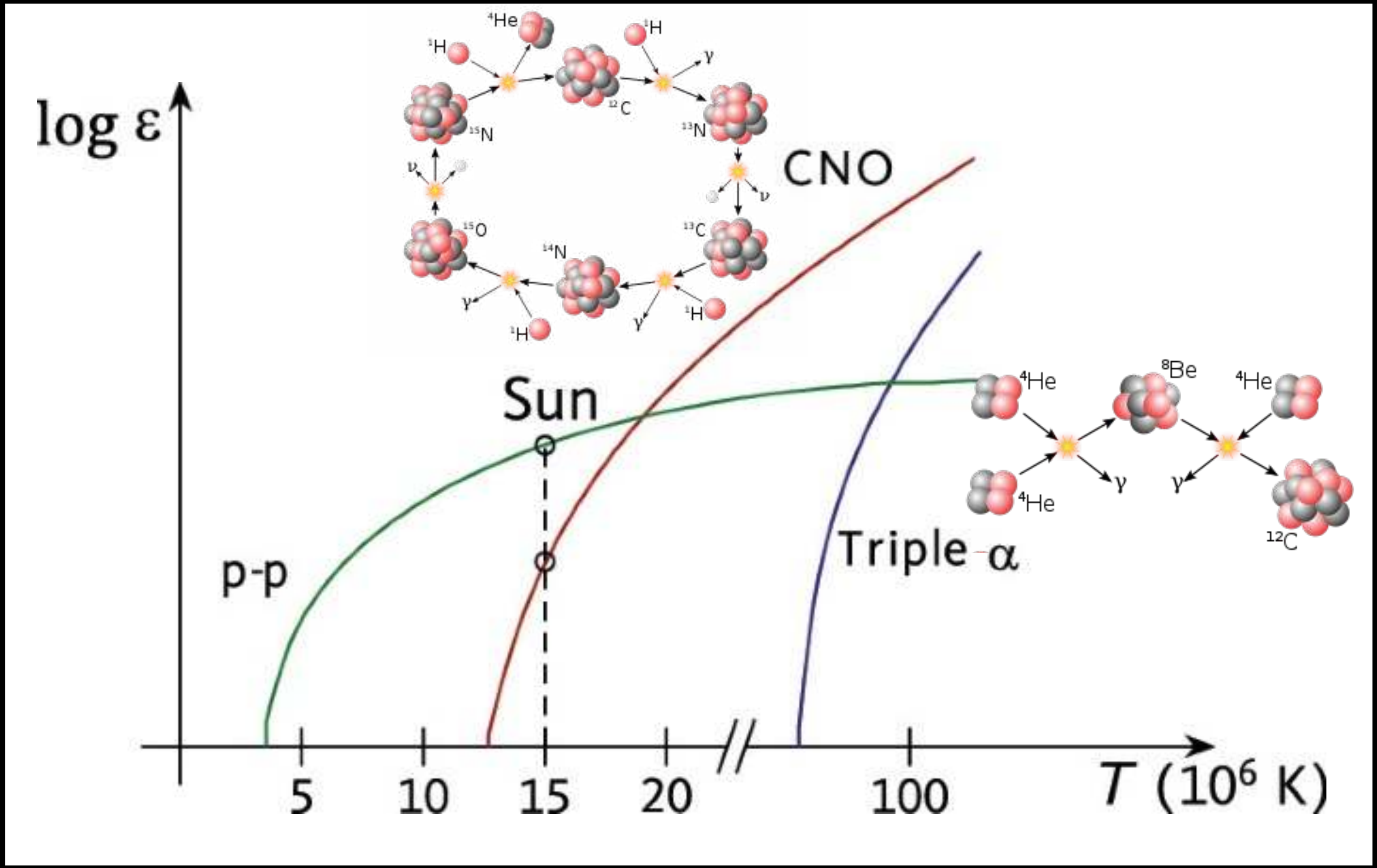
- Narrow-band image obtained with ESO VLT/FORS2
- WR emission can be confused for Population III signatures (Katz et al. 2022)

Evolution from the Main Sequence to a Wolf-Rayet star?



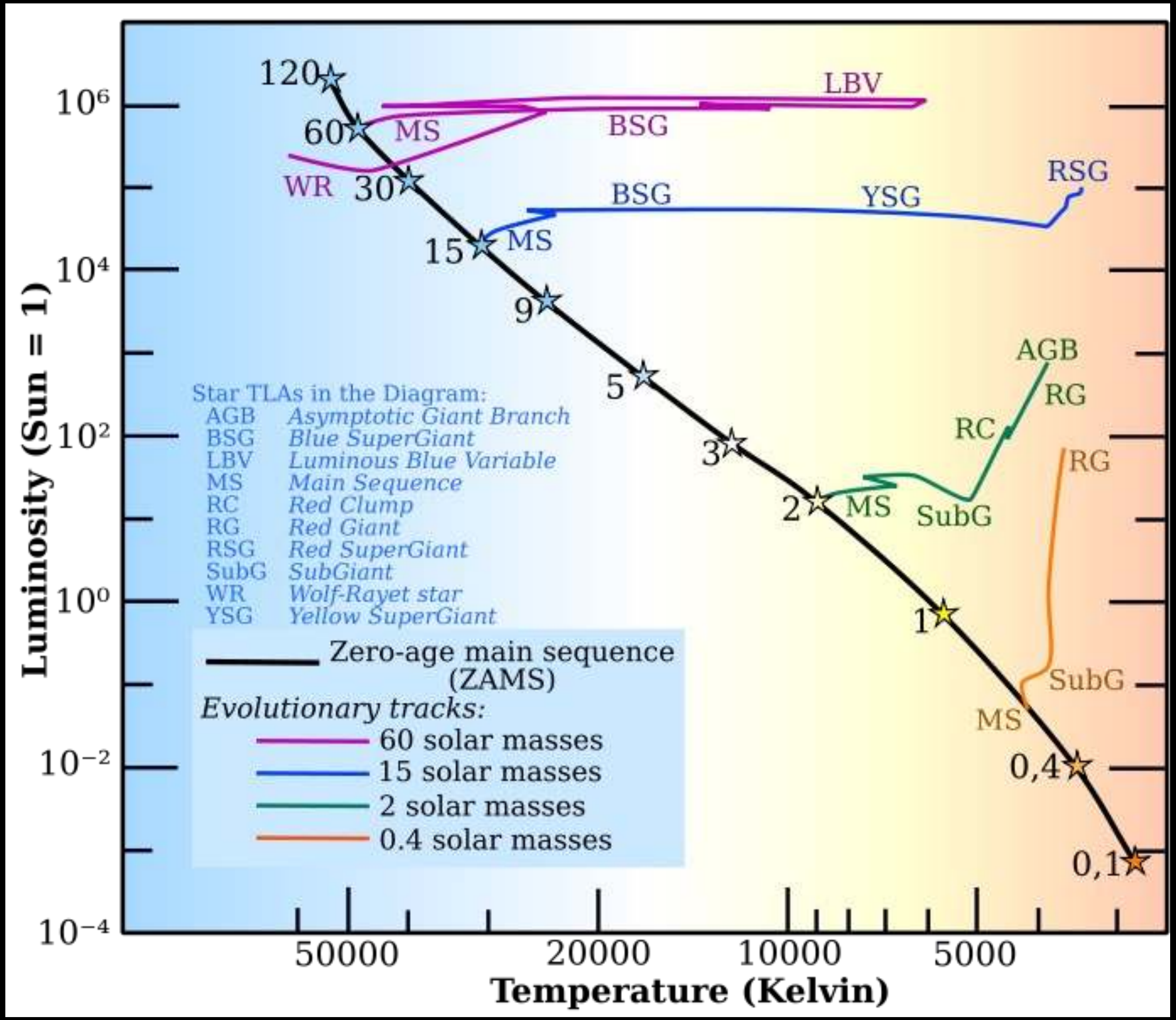
Credit: NASA, ESA, and L. Hustak (STScI)

High Energy Output and Strong Winds



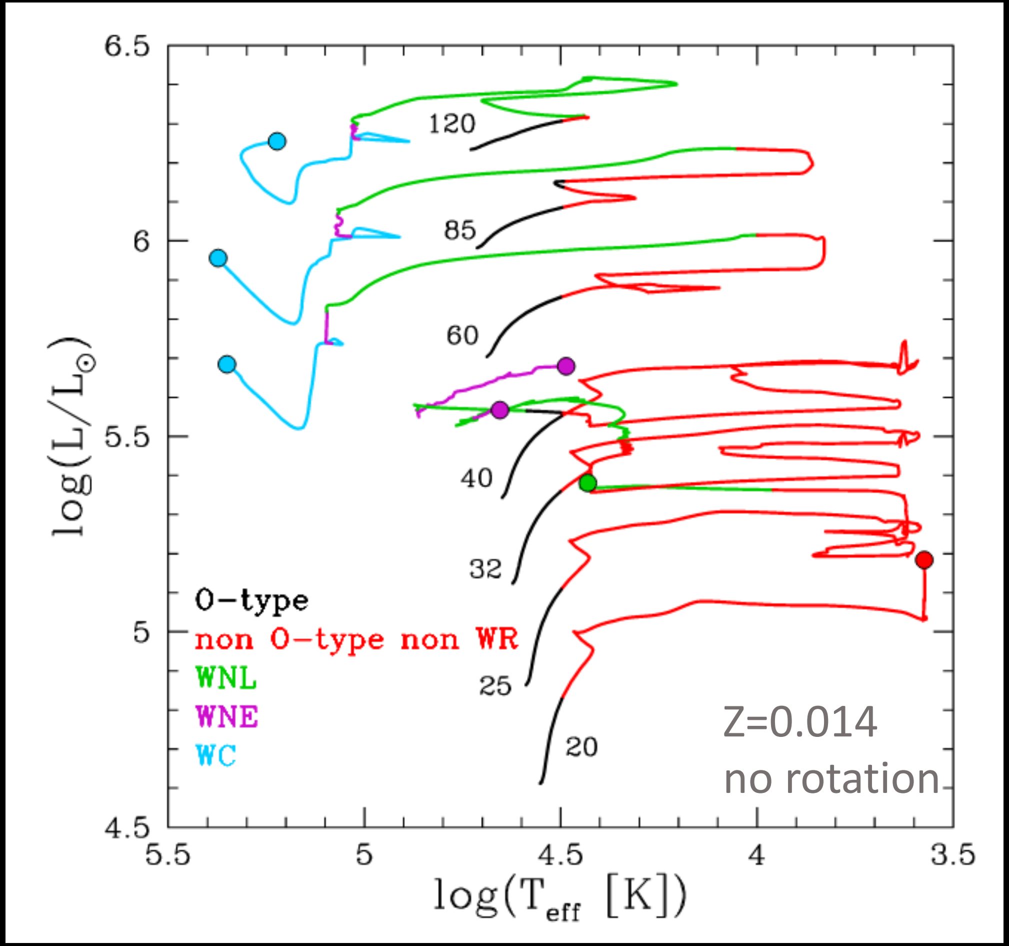
- High radiation pressure from burning shells
- CNO cycle products transported into the envelope
- Envelope blown away over a WR phase
- Significant mass loss before supernova

Quickly Approaching Death, the WR Stage

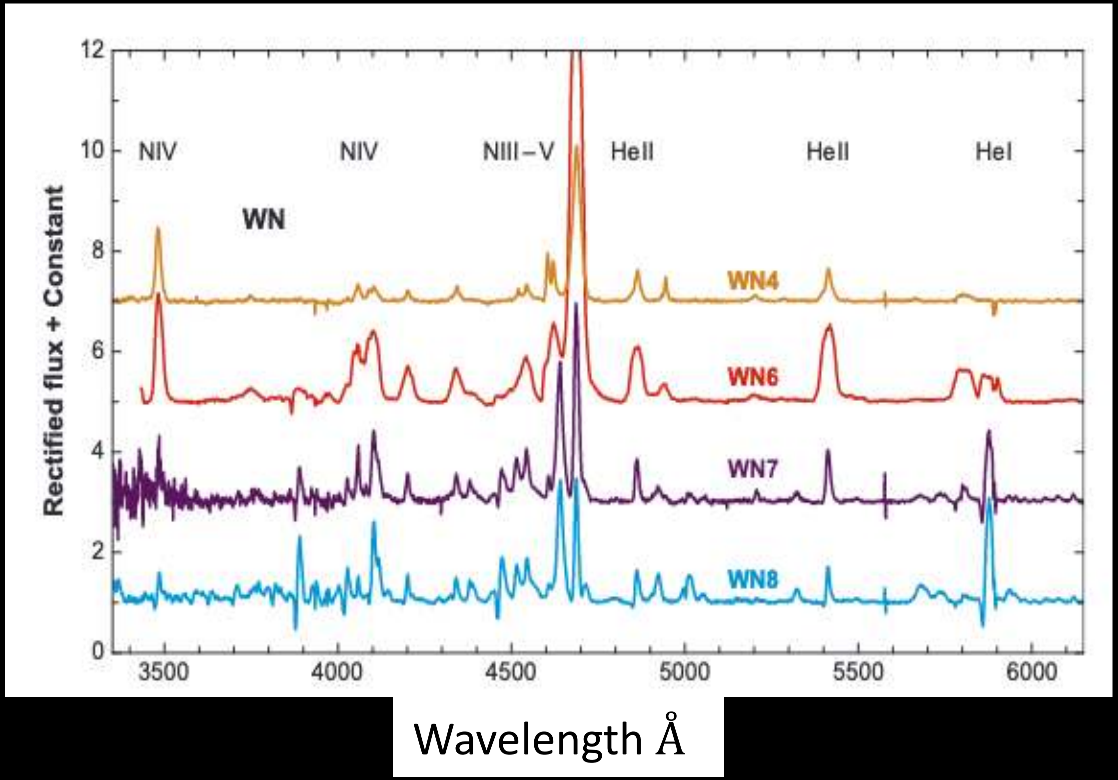


- High radiation pressure produces fast winds $> 1000\ km\ s^{-1}$
- Winds blow off outer envelope exposing inner shells
- Very high temperatures $10^5 - 10^6 K$
- Chemically enriches nearby ISM

WR Evolution on HR Diagram

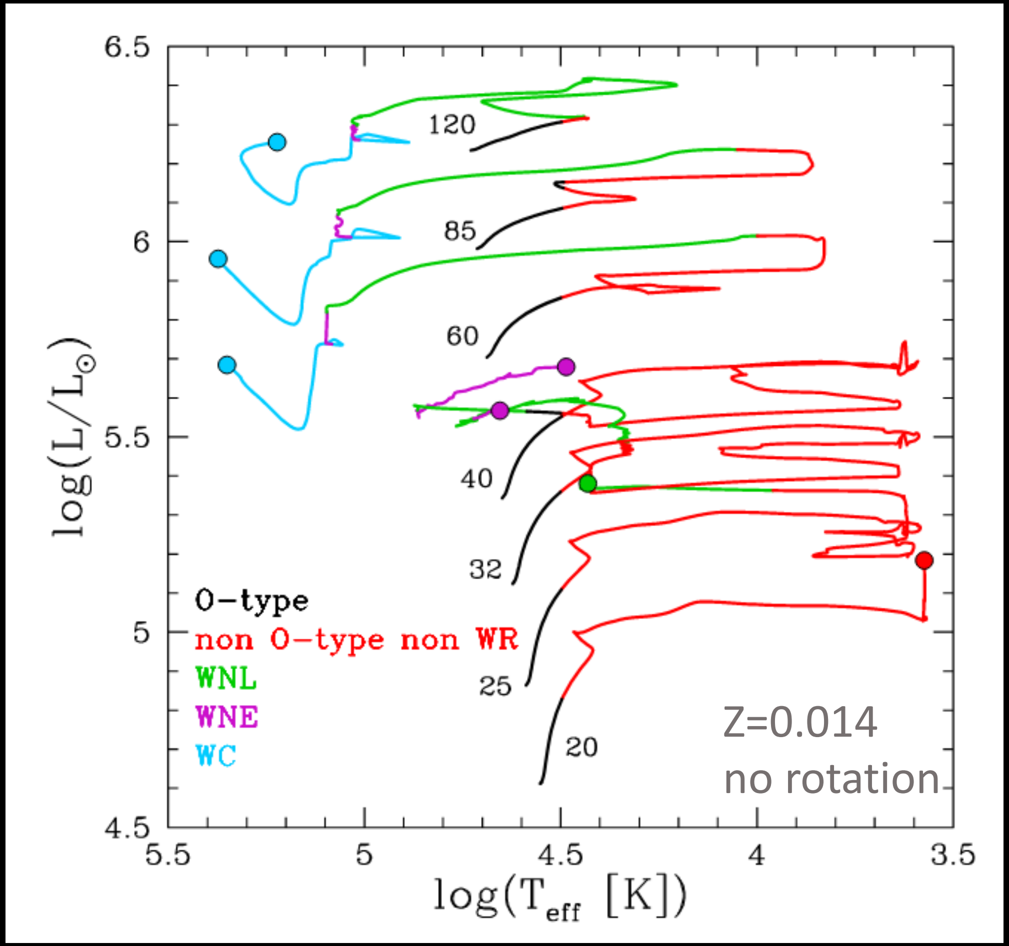


(Georgy et al. 2018)

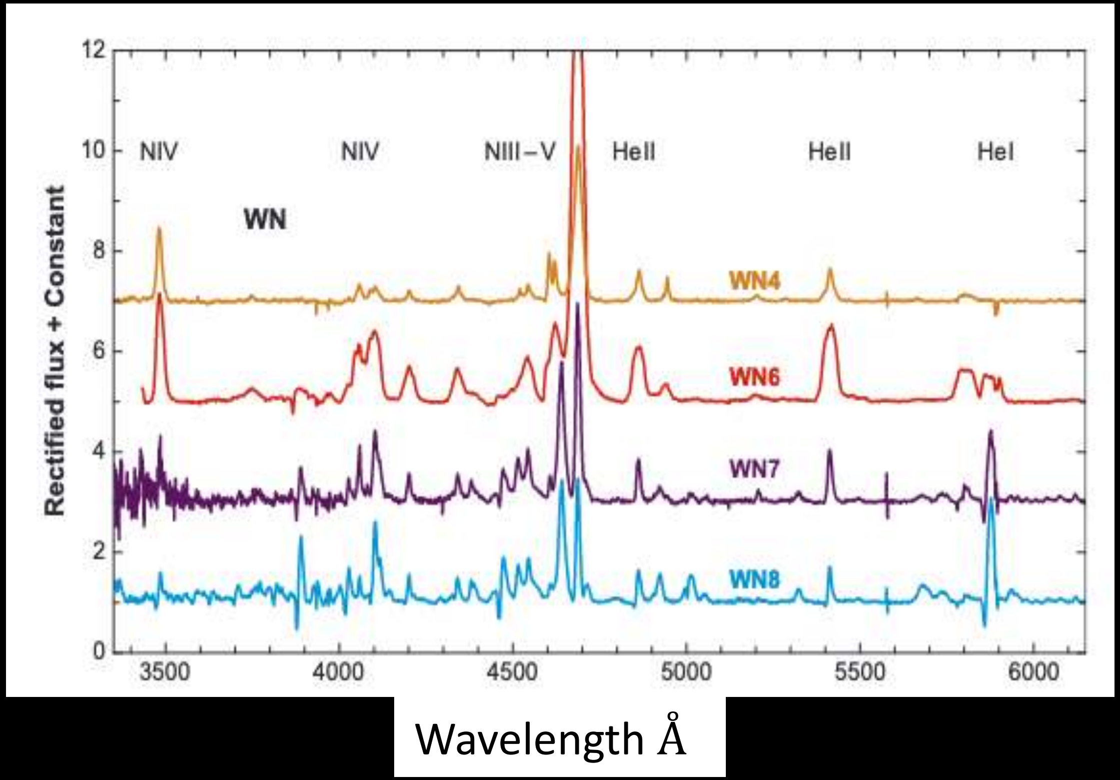


WNL: Hydrogen burning shell around helium core blowing off inert envelope

WR Evolution on HR Diagram

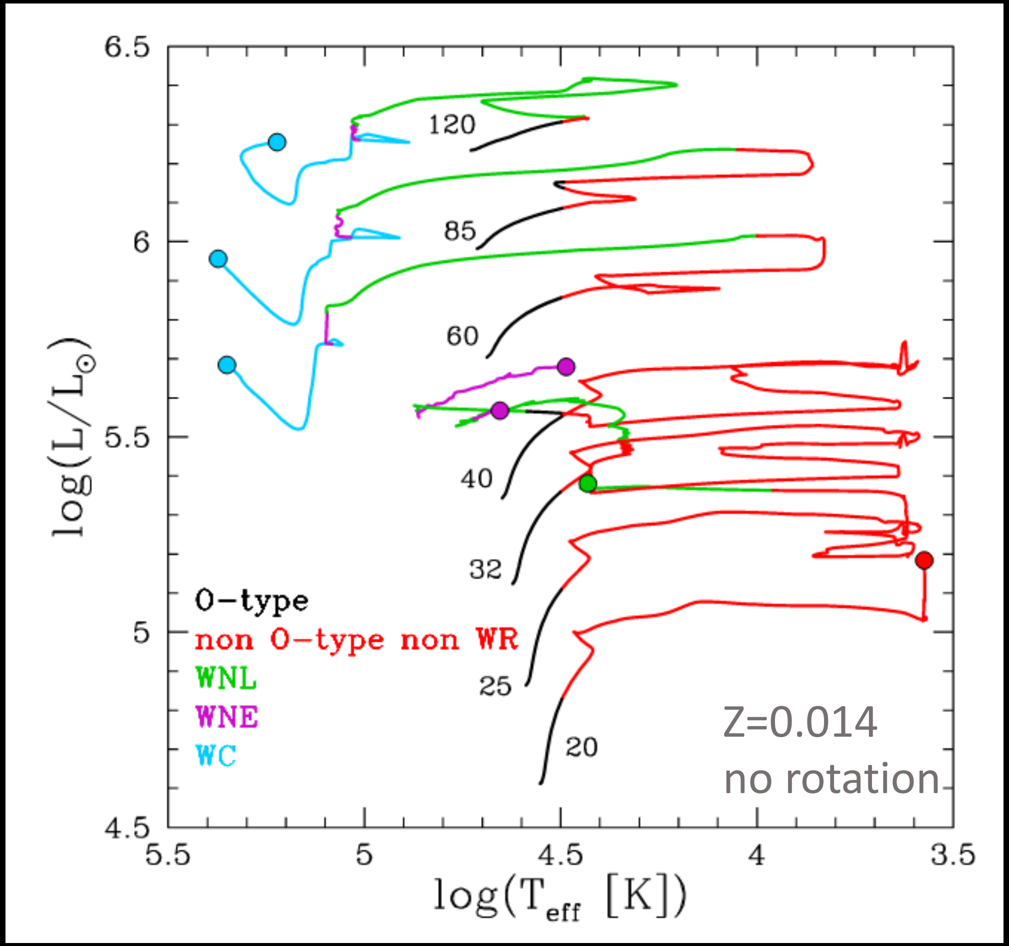


(Georgy et al. 2018)

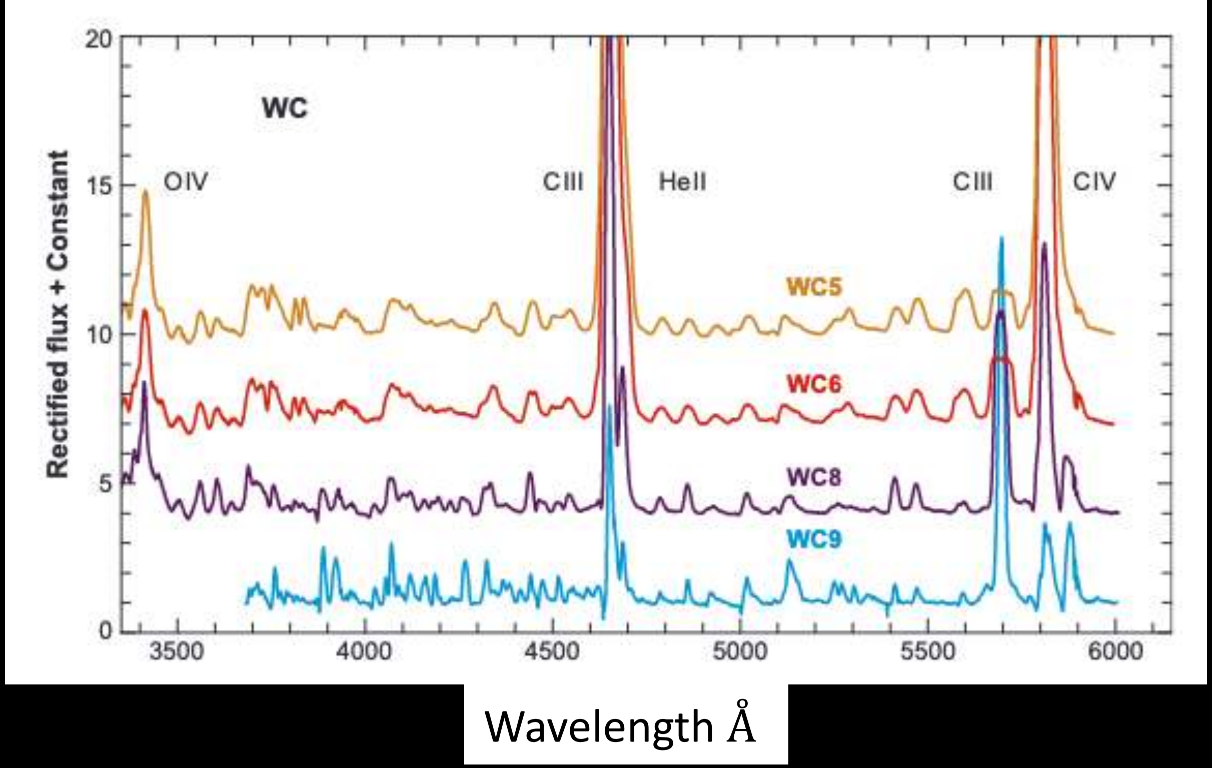


WNE: Hydrogen in envelope mostly blown off

WR Evolution on HR Diagram

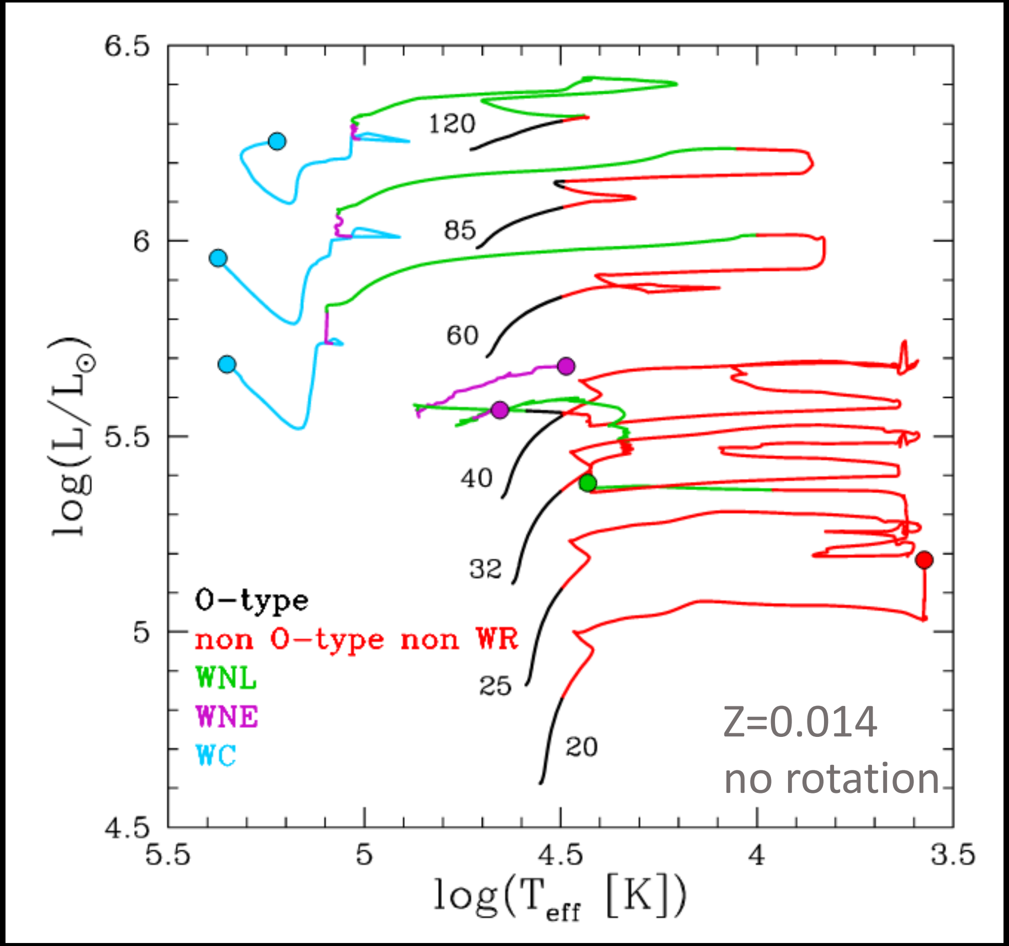


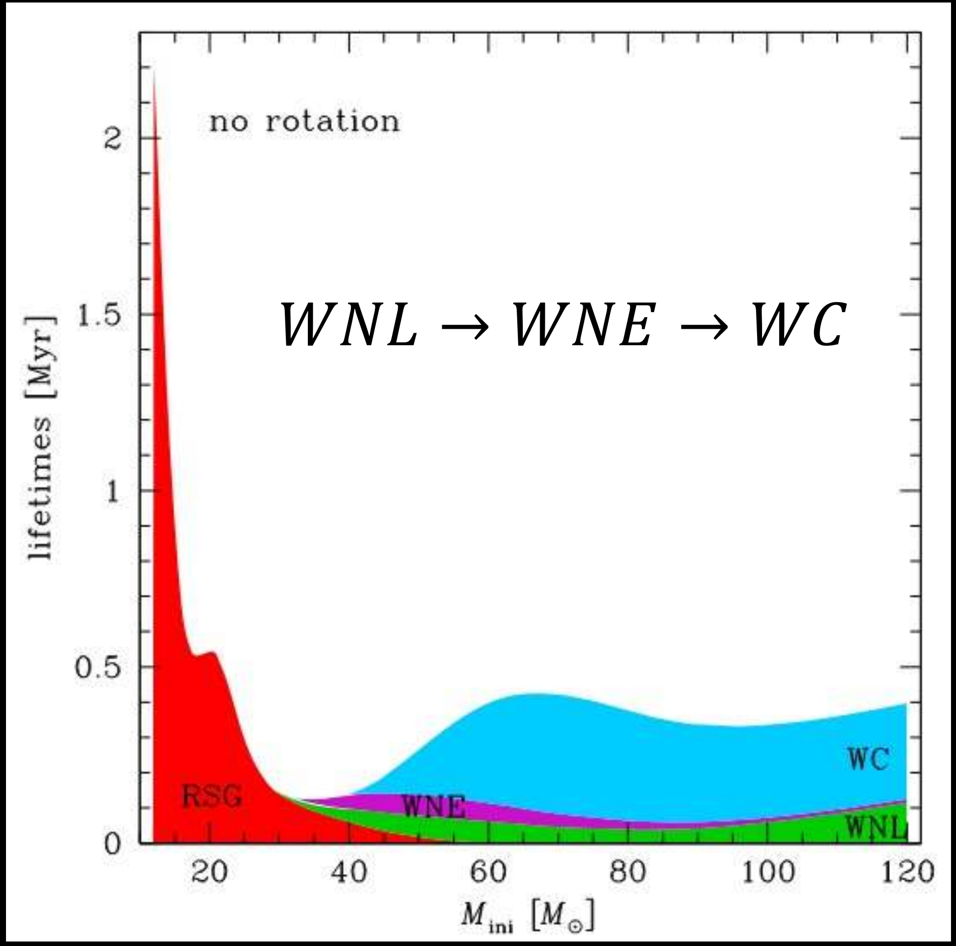
(Georgy et al. 2018)



WC: More carbon in envelope than nitrogen, significant mass loss

WR Evolution on HR Diagram



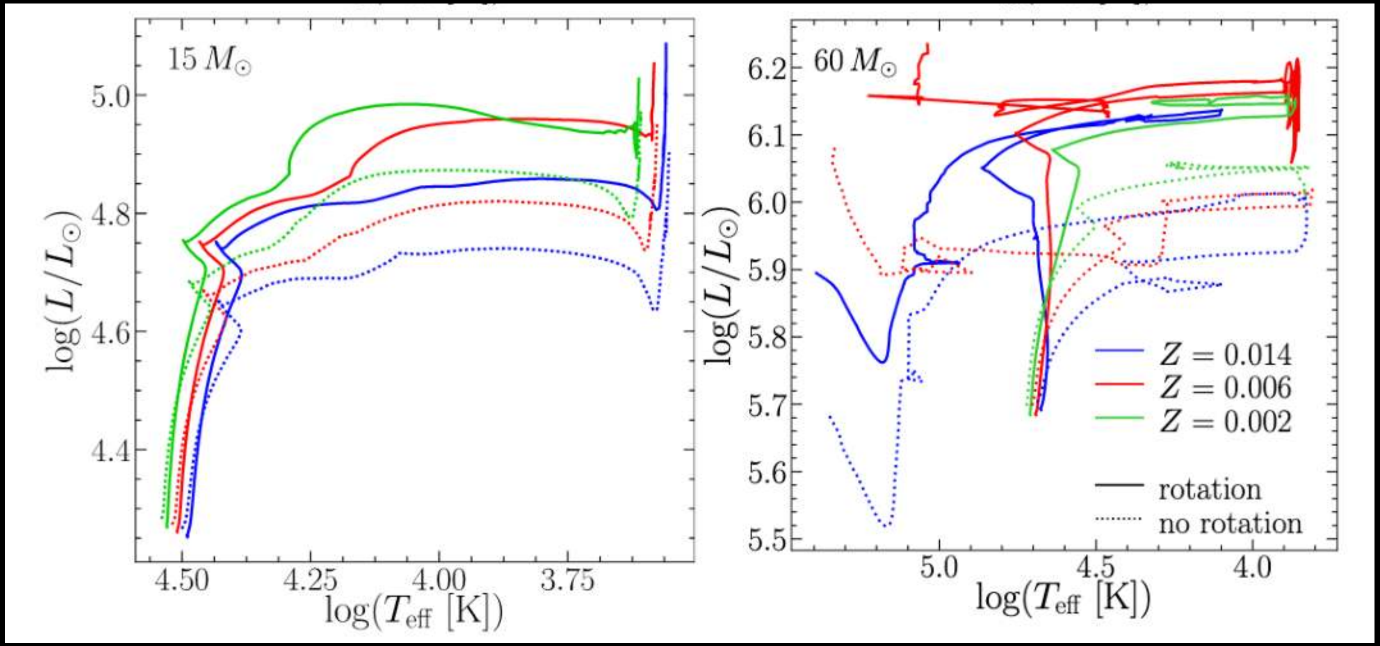


(Georgy et al. 2018)

What Influences WR Star Evolution?

1. Metallicity
2. Rotation
3. Mass Loss Rate

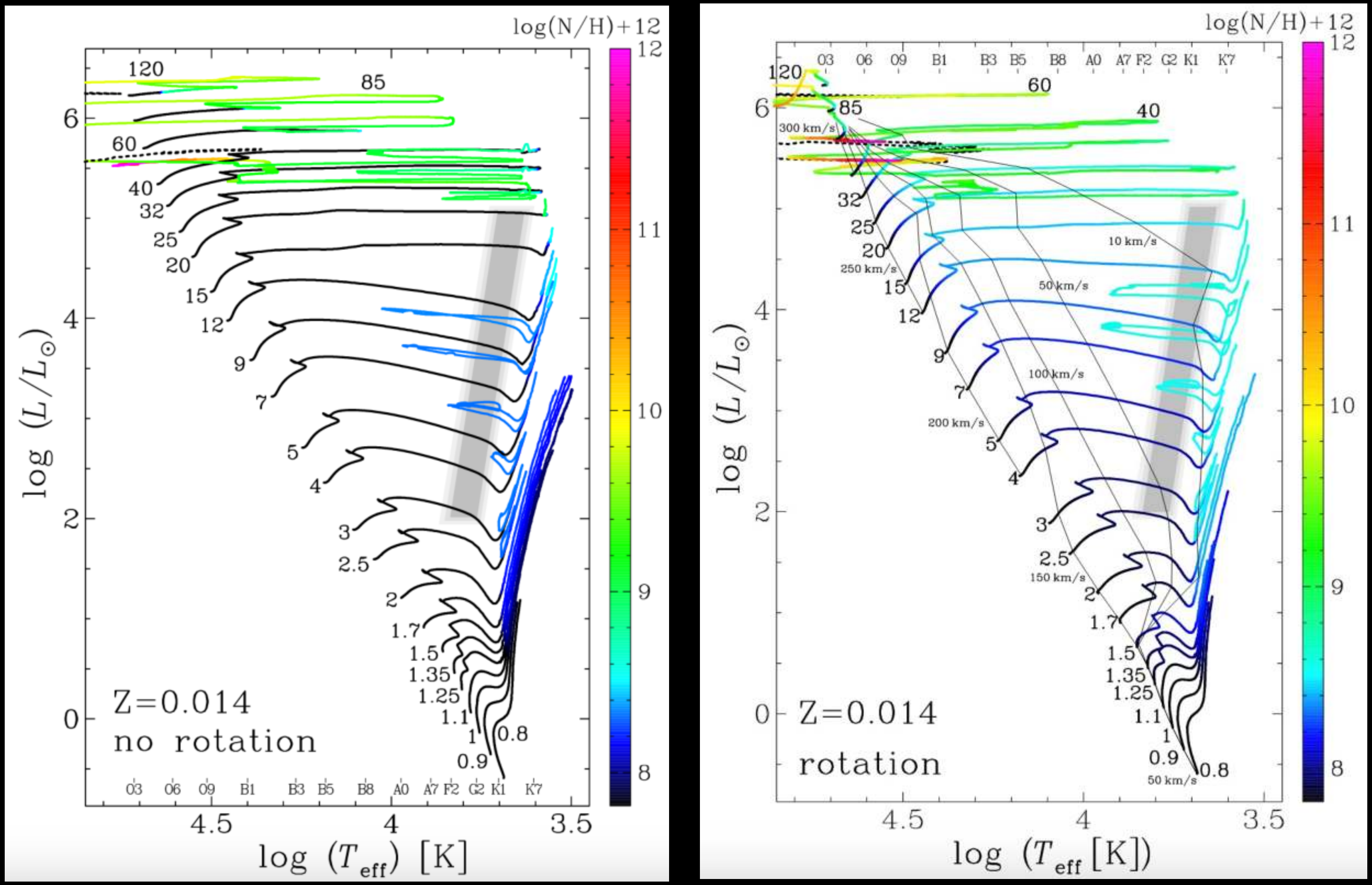
Low Metallicity and WR Evolution



(Eggenberger et al. 2022)

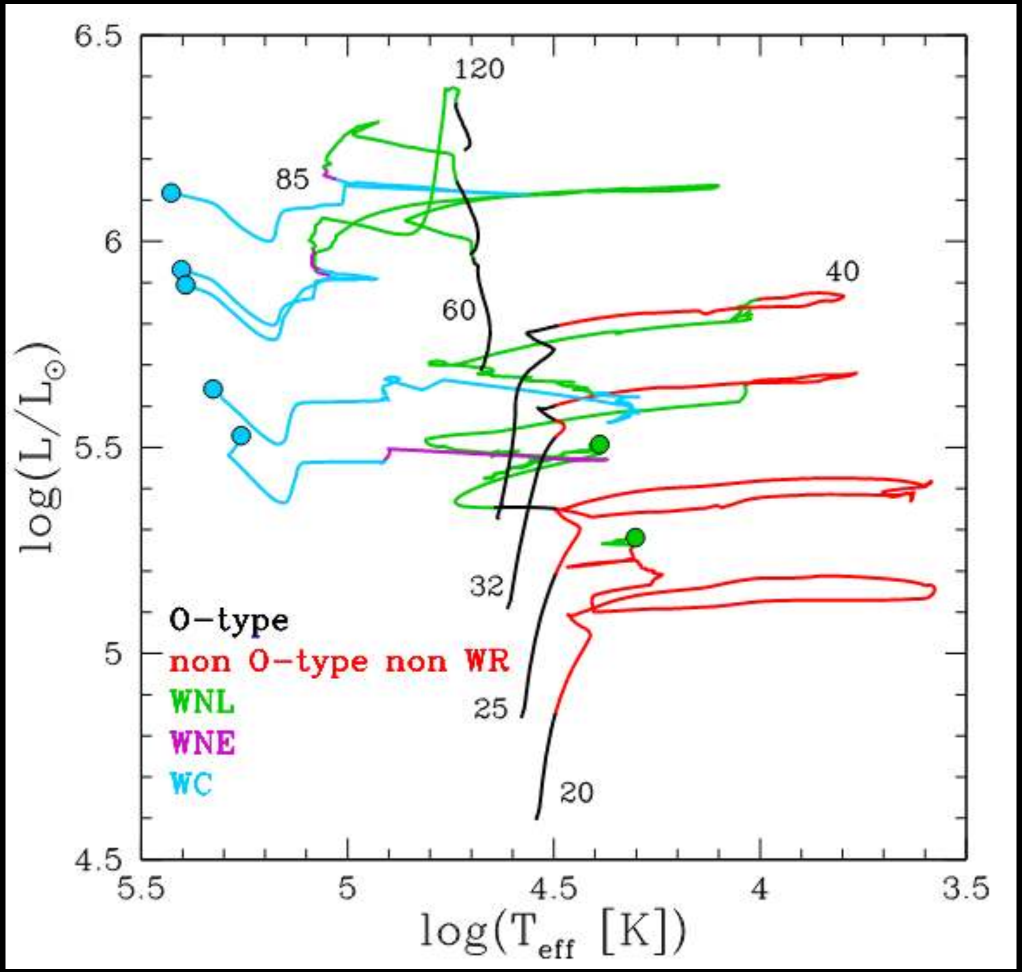
- Lower metallicity:
  - Shifts the tracks hotter and more luminous
  - Weaker mass losses by stellar winds due to lower opacities.
  - Increase He core burning time

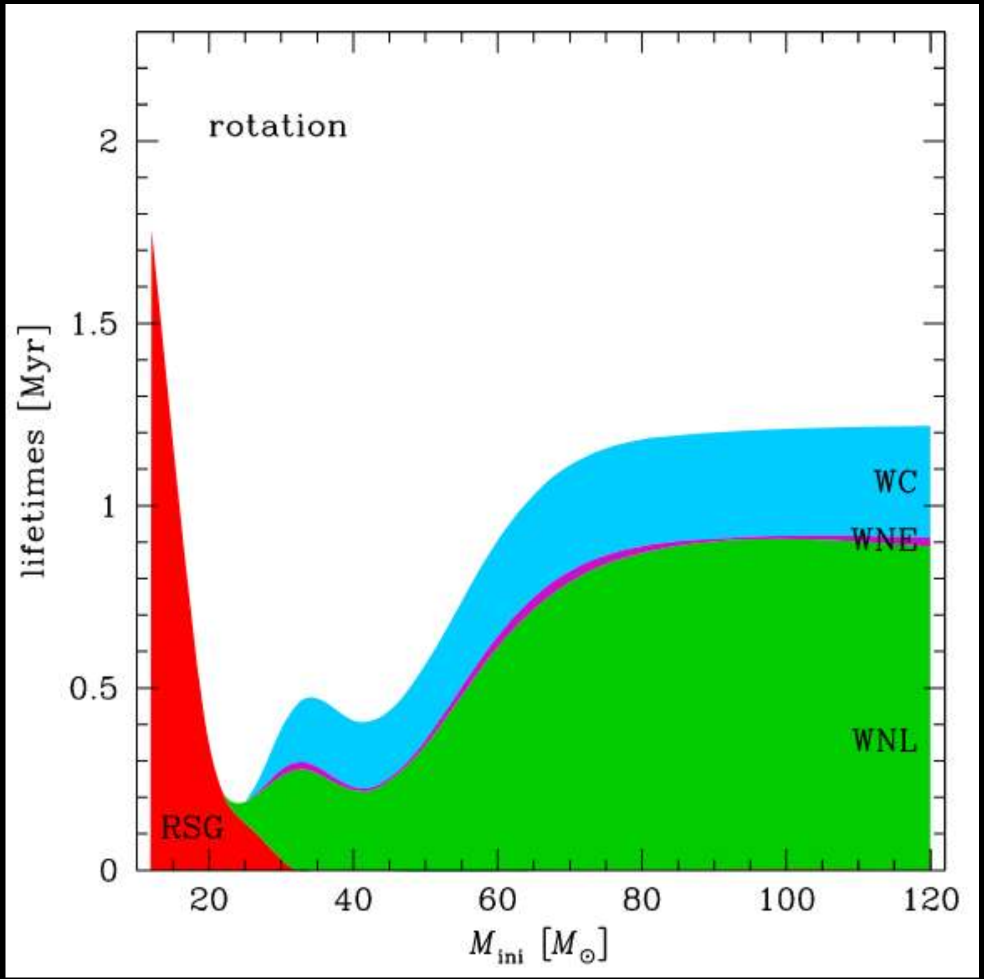
CNO Cycle Nitrogen Mixed to the Surface



(Ekstrom et al. 2012)

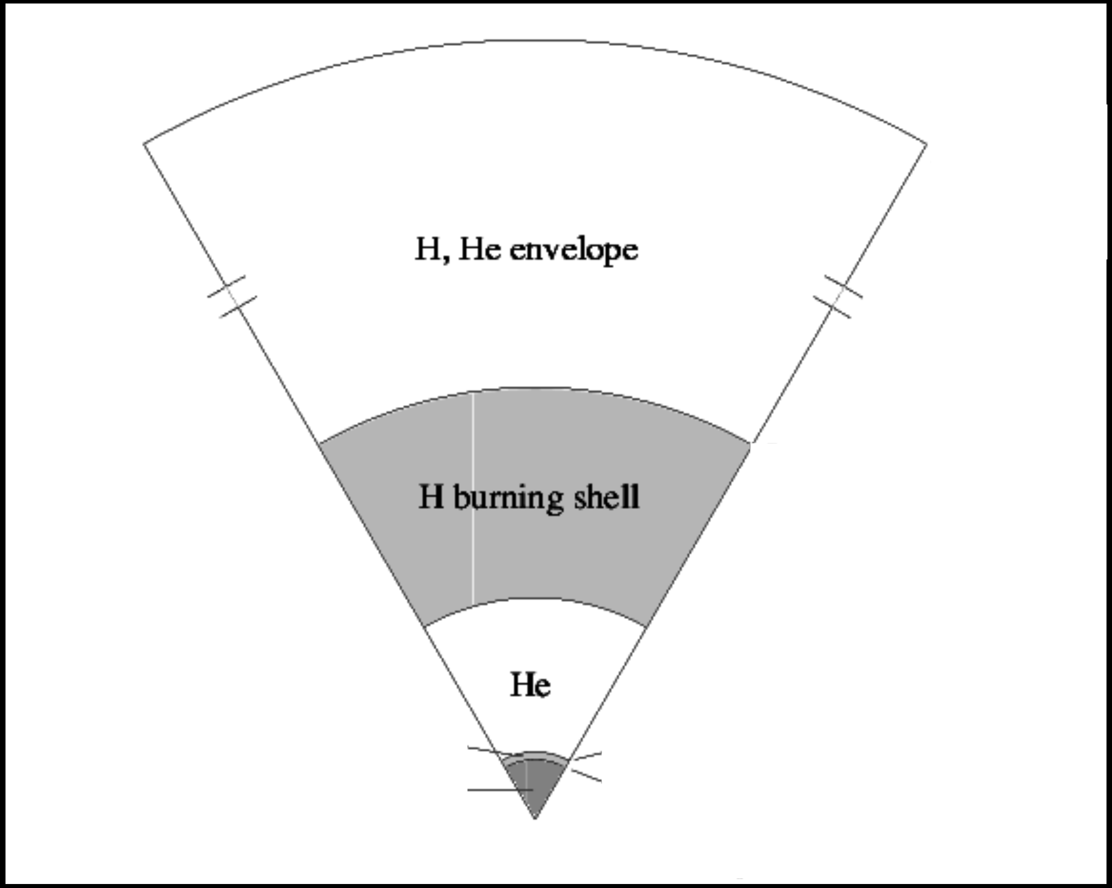
Rotation Lengthens WR Stage





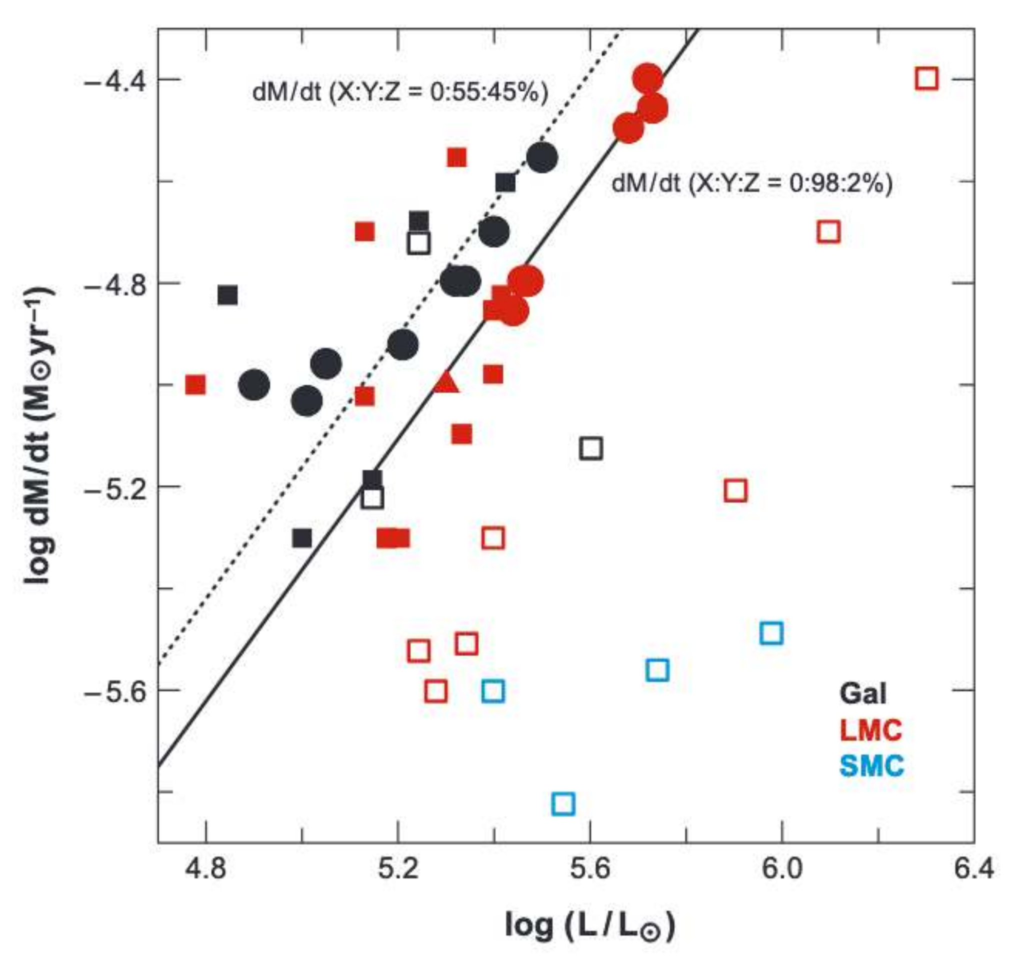
(Georgy et al. 2018)

Impact of Rotational Mixing



- How mixed are the H and He layers?
- Mixing prolongs hydrogen shell burning phase
- Takes longer to reach helium core burning

Metallicity Dependent Winds?



(Crowther 2007)

- ■ WN3-6
- ● WC5-9

Not Filled: Has Surface H

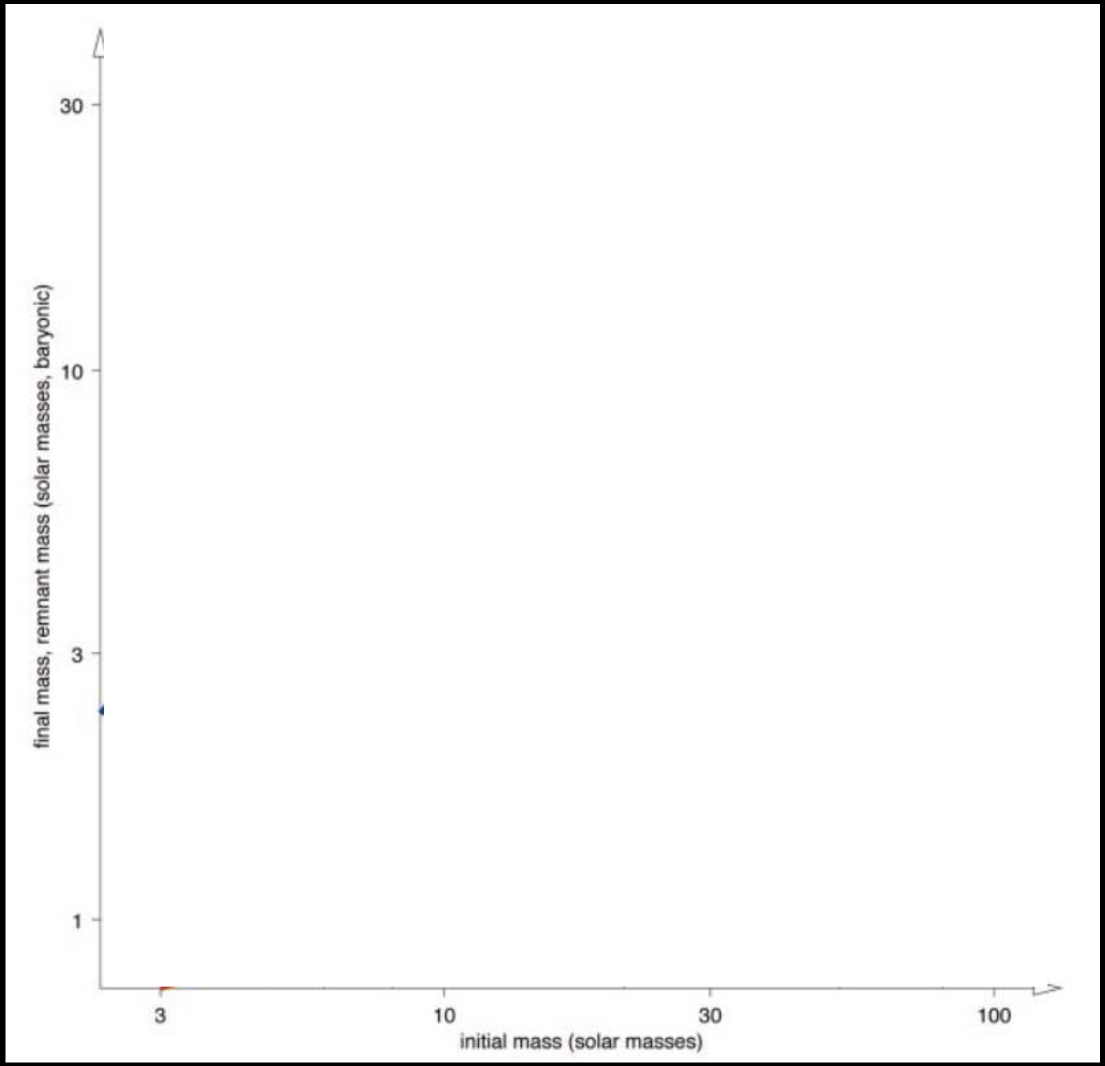
Filled: No Surface H

Milky Way and LMC: $0.5 - 1\ Z_{\odot}$

SMC: $0.125\ Z_{\odot}$

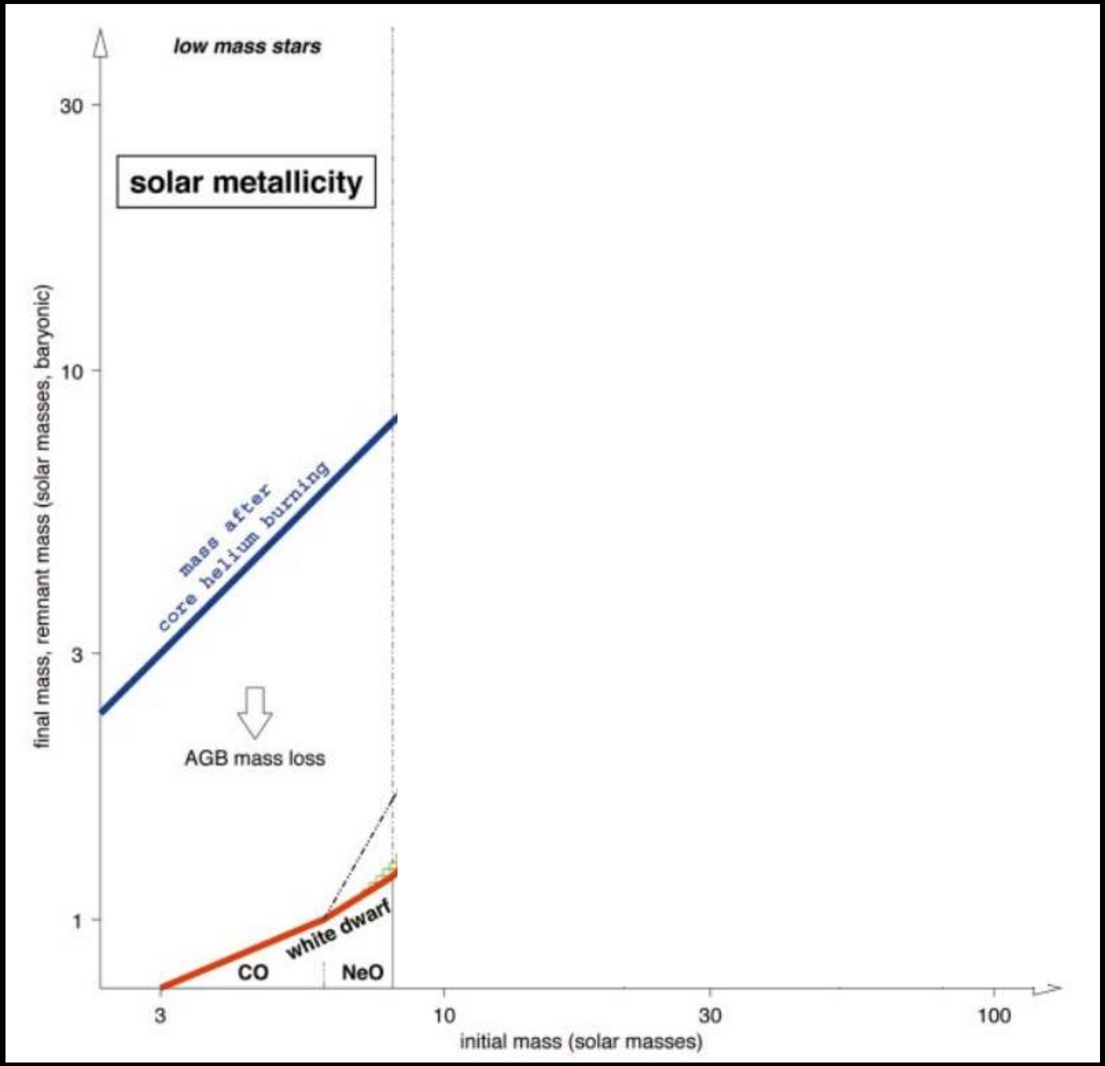
Note: Mass-loss estimates are obtained from near-IR He lines

Most Initial Mass Lost in Winds



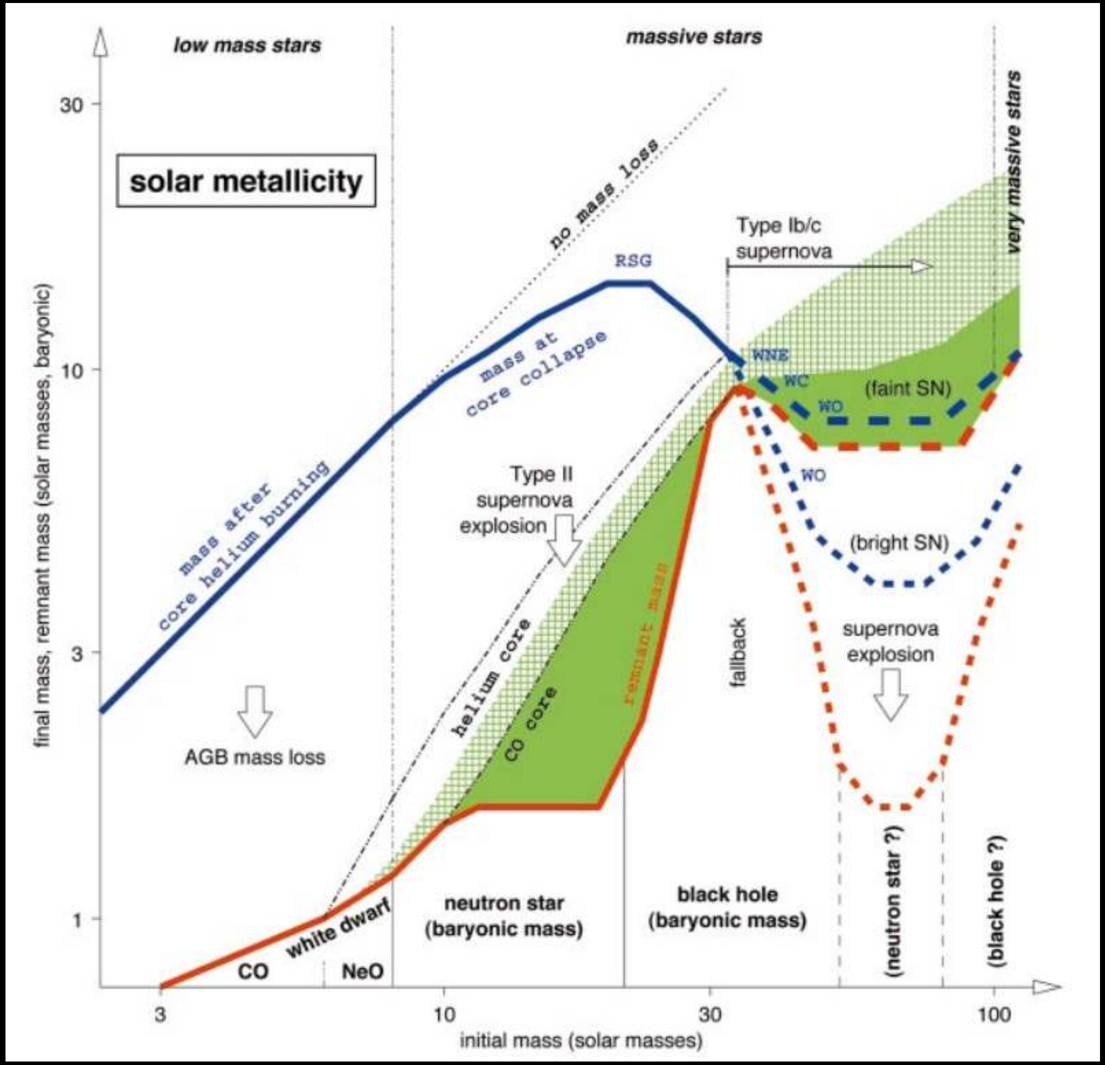
(Woolsey et al. 2002)

Most Initial Mass Lost in Winds



(Woolsey et al. 2002)

Most Initial Mass Lost in Winds



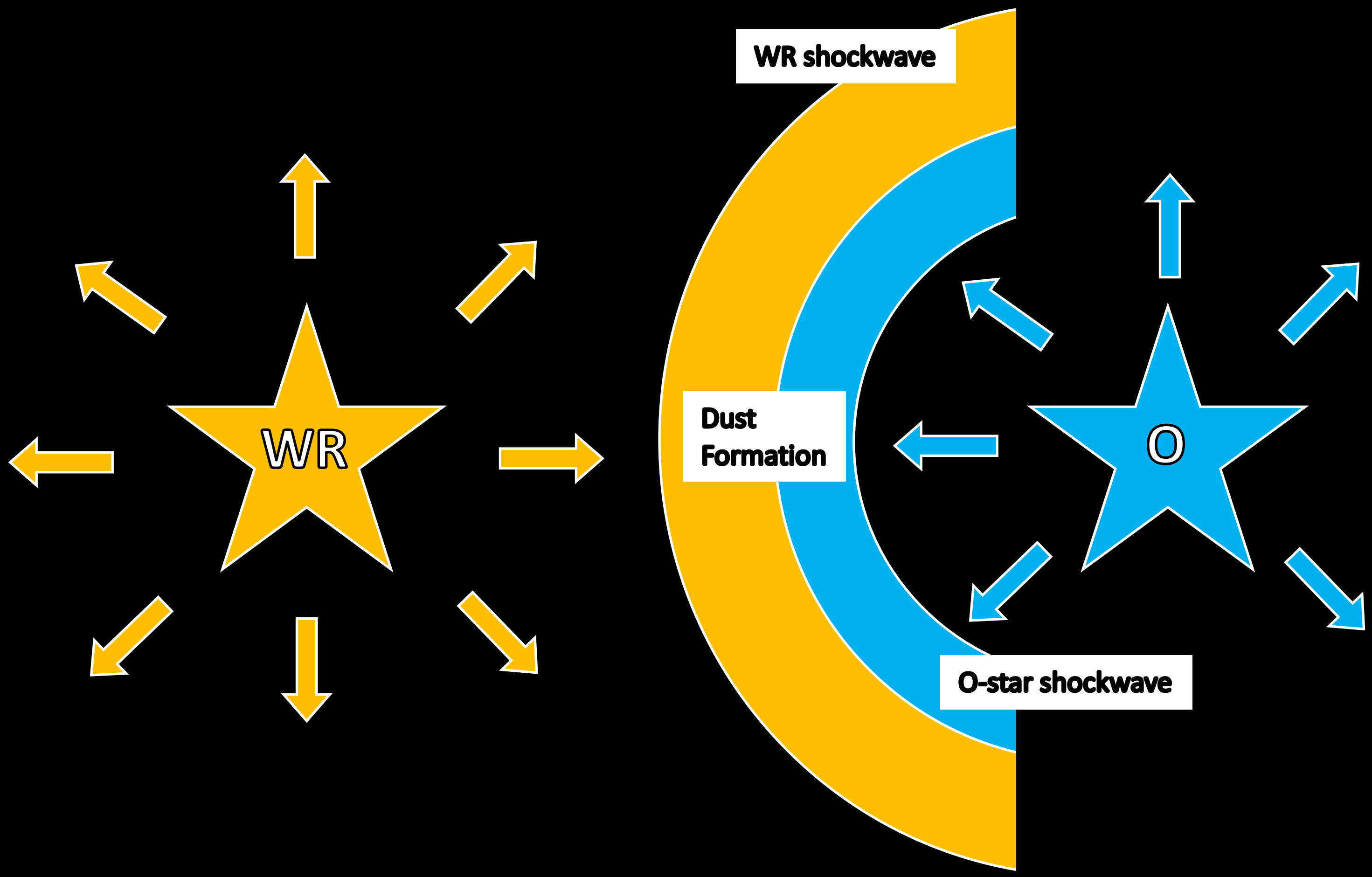
(Woolsey et al. 2002)

What happens when a Wolf-Rayet Star is in a Binary System?

(Lau et al. 2022)

Credit: NASA/ESA/CSA/STScl/JPL-Caltech

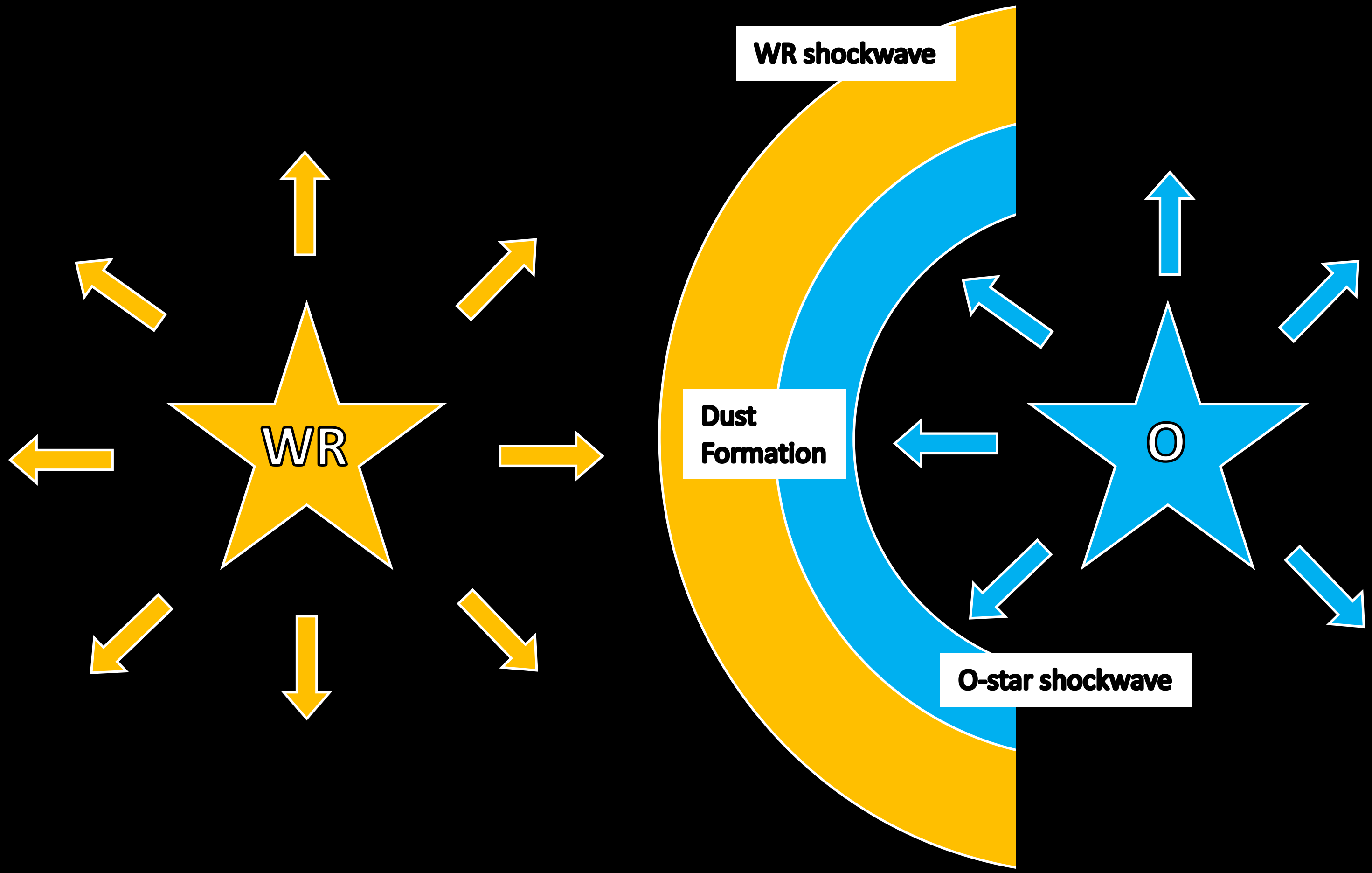
WR 140 Stellar Wind Collision



- WC7 in highly eccentric 8-year orbit around an O-star
- Dense stellar wind from WR star

Adapted from (Usov 1991)

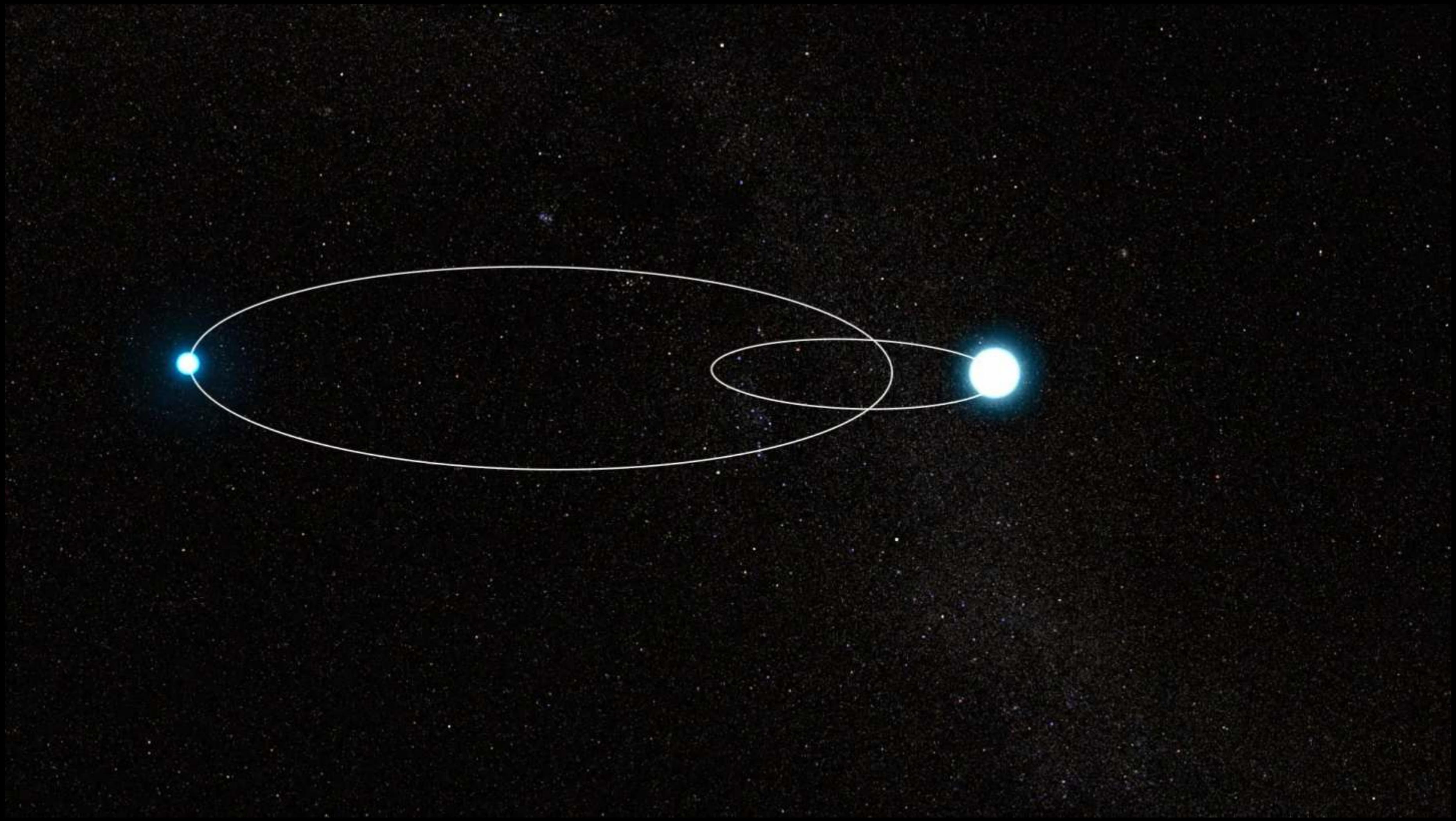
WR 140 Stellar Wind Collision



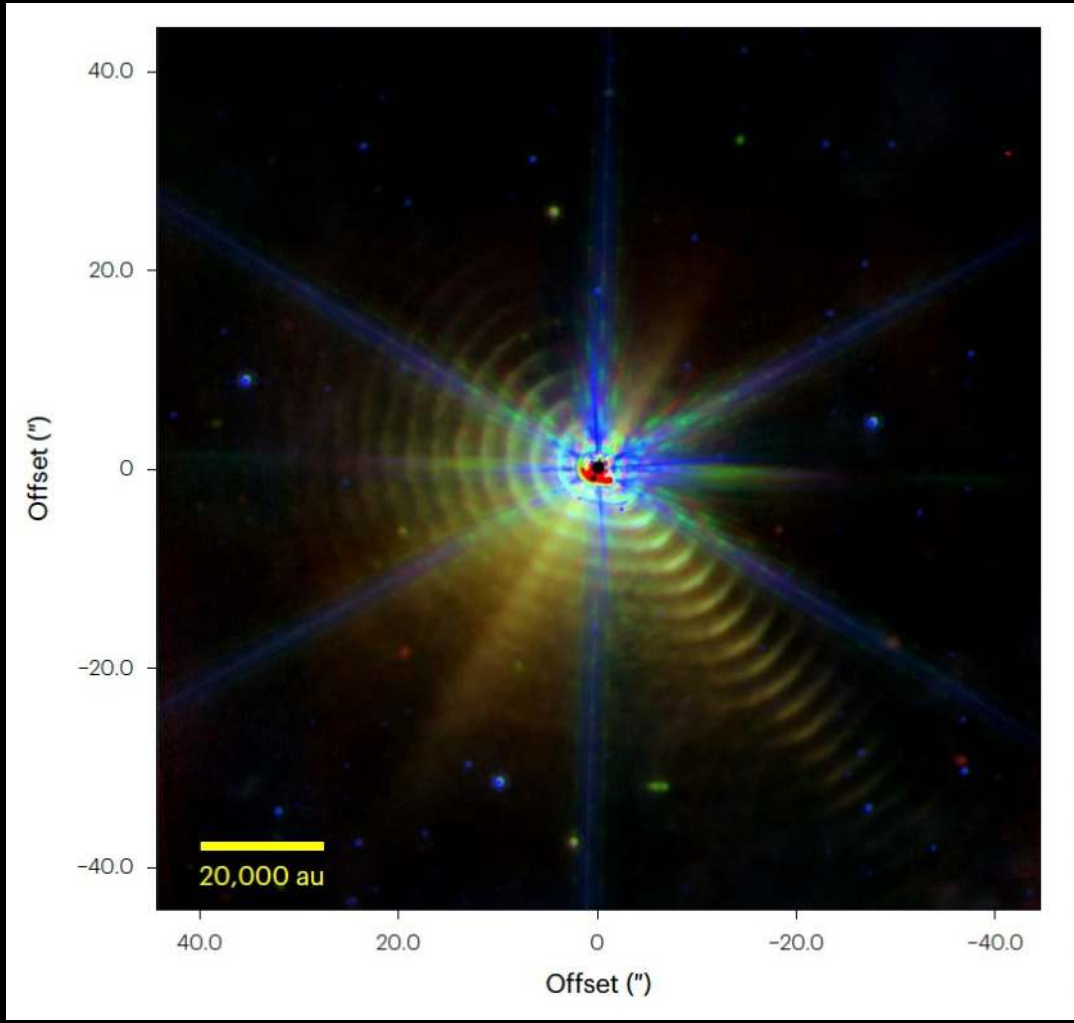
- WC7 in highly eccentric 8-year orbit around an O-star
- Dense stellar wind from WR star
- O-star stellar wind slows WR wind considerably at closest approach
- Dust forms in shock compressed wind

Adapted from (Usov 1991)

Dust Condensing in Wind Collisions



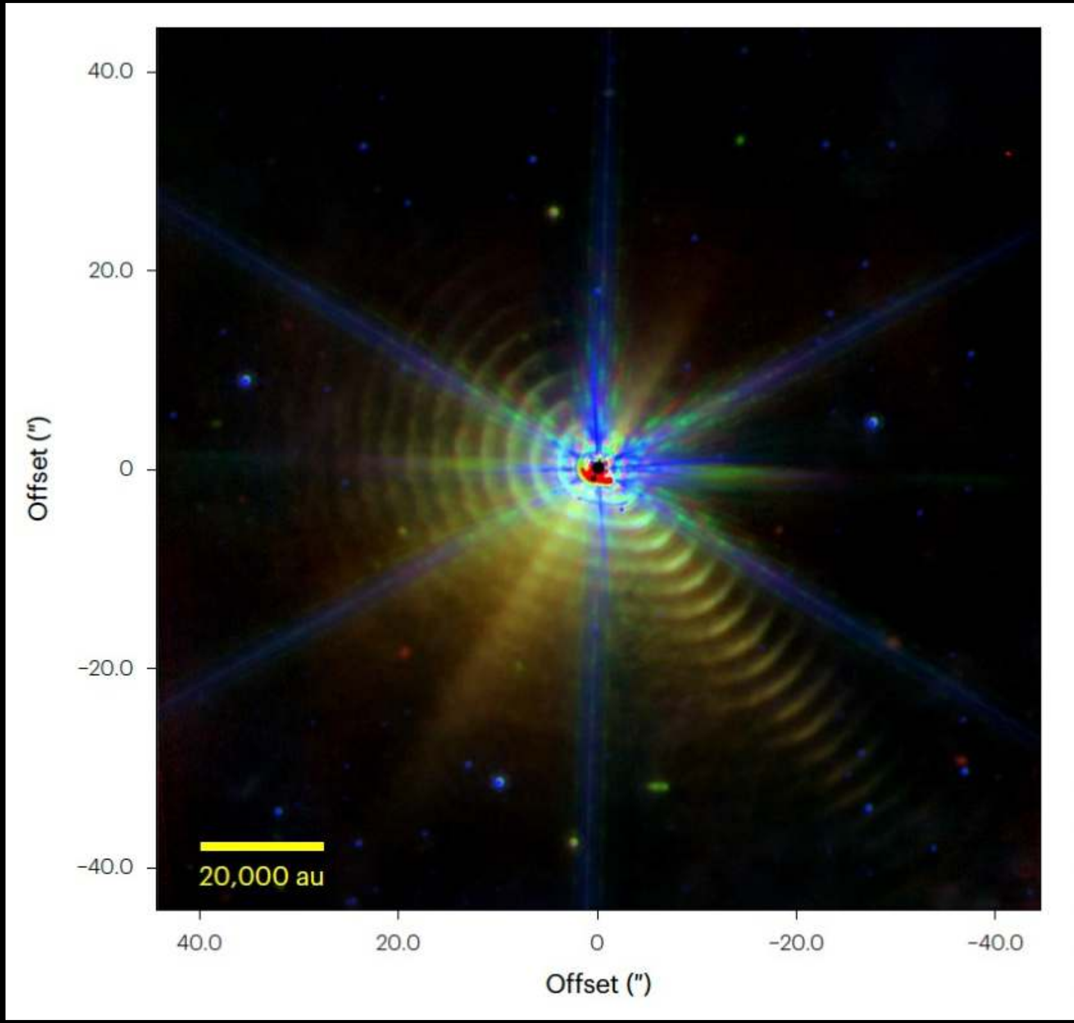
MIRI Observations of WR 140



(Lau et al. 2022)

- F770W, F1500W and F2100W filters correspond to blue, green and red

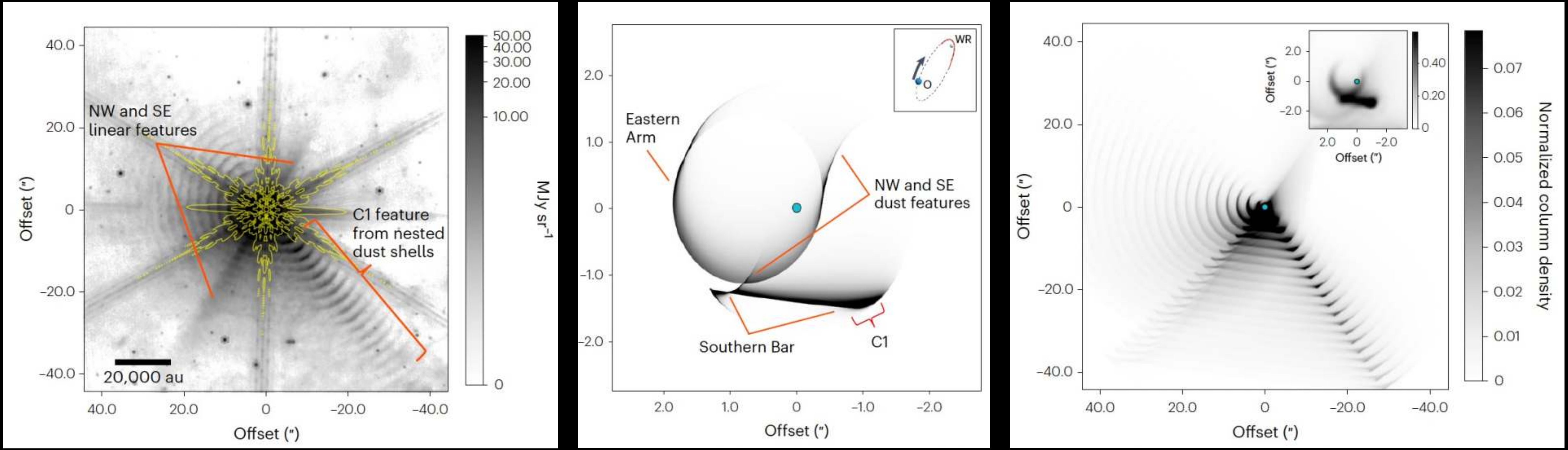
MIRI Observations of WR 140



(Lau et al. 2022)

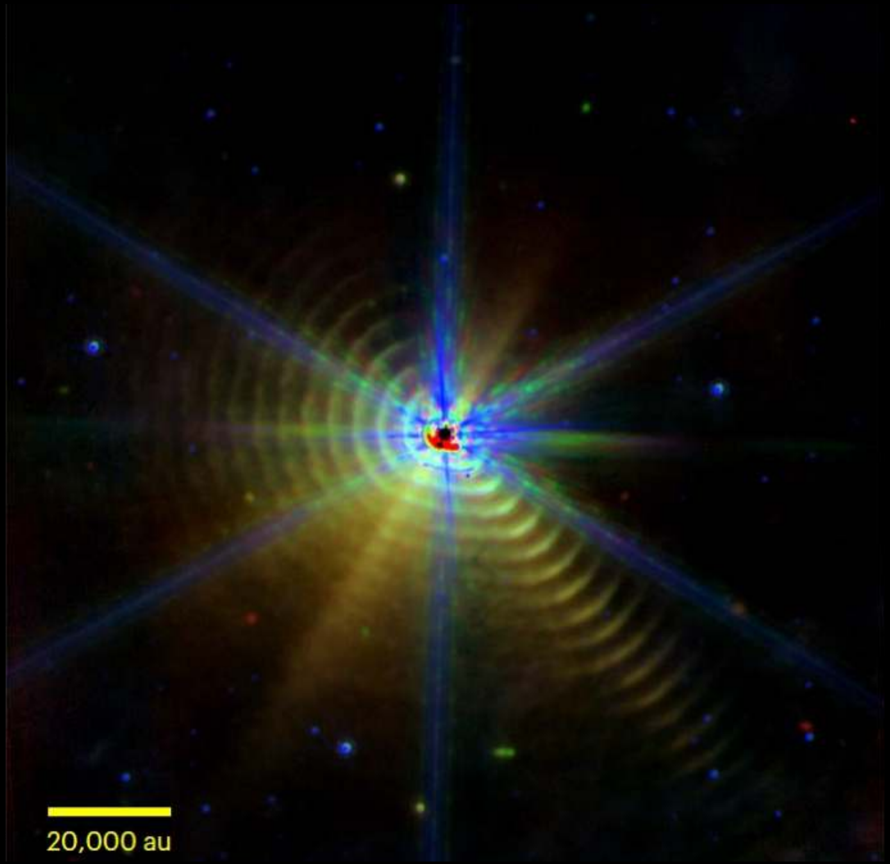
- F770W, F1500W and F2100W filters correspond to blue, green and red
- Evenly spaced dust shells exceeding 70,000 AU
- Eight symmetric diffraction spikes from detector saturation

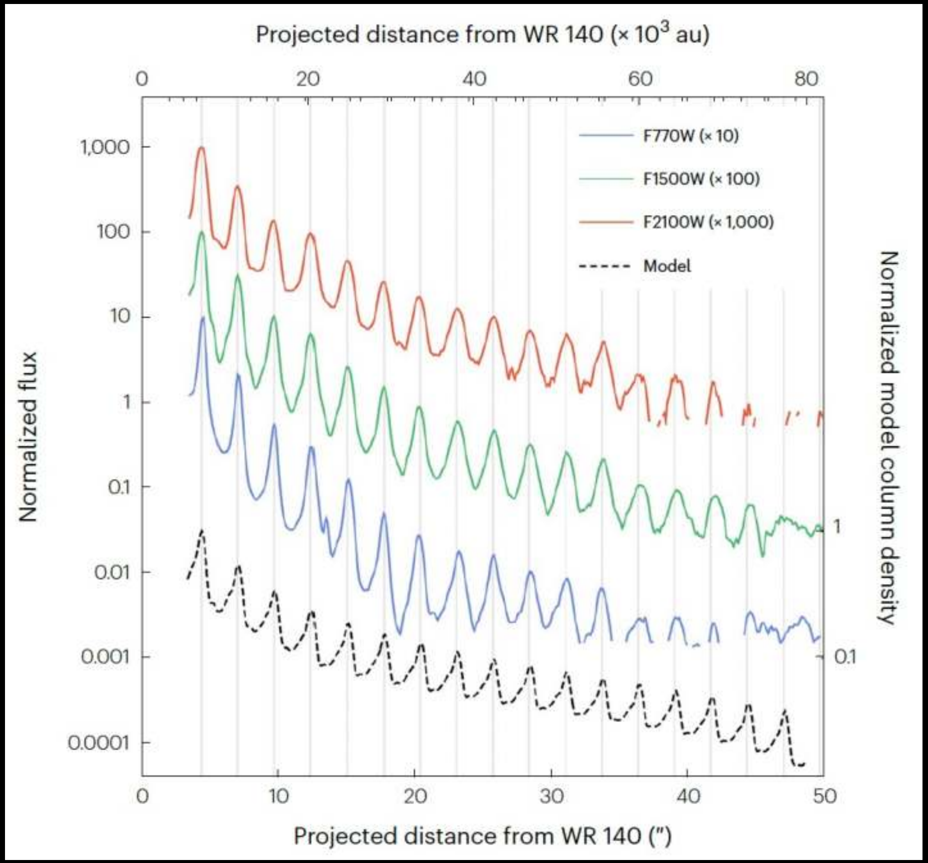
Shell Dust Model an Excellent Match



(Lau et al. 2022)

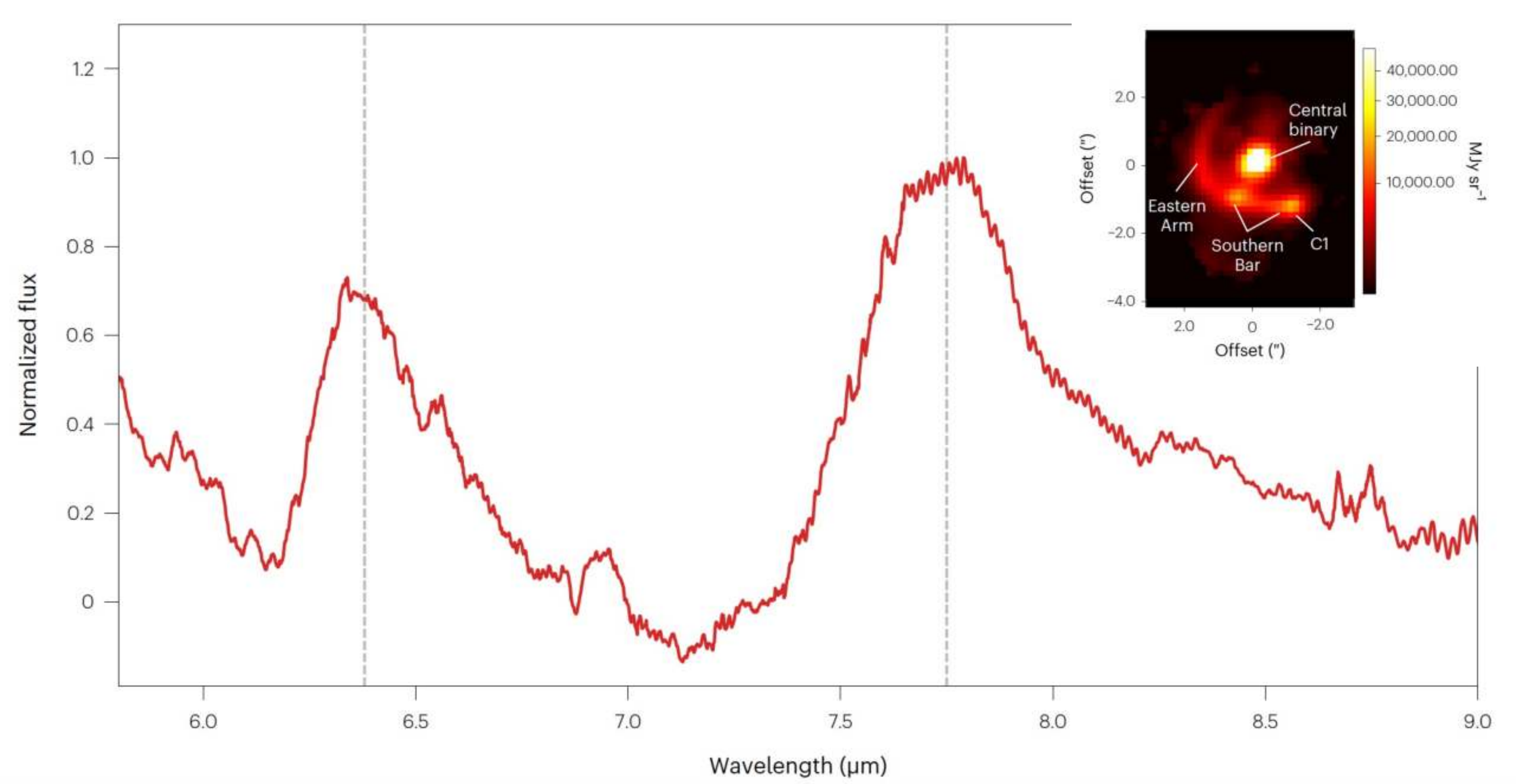
Dust Shells Expanding at Constant Velocity





Takeaway: Dust formed by WR 140 can survive its harsh circumstellar environment and probably enriches the surrounding ISM

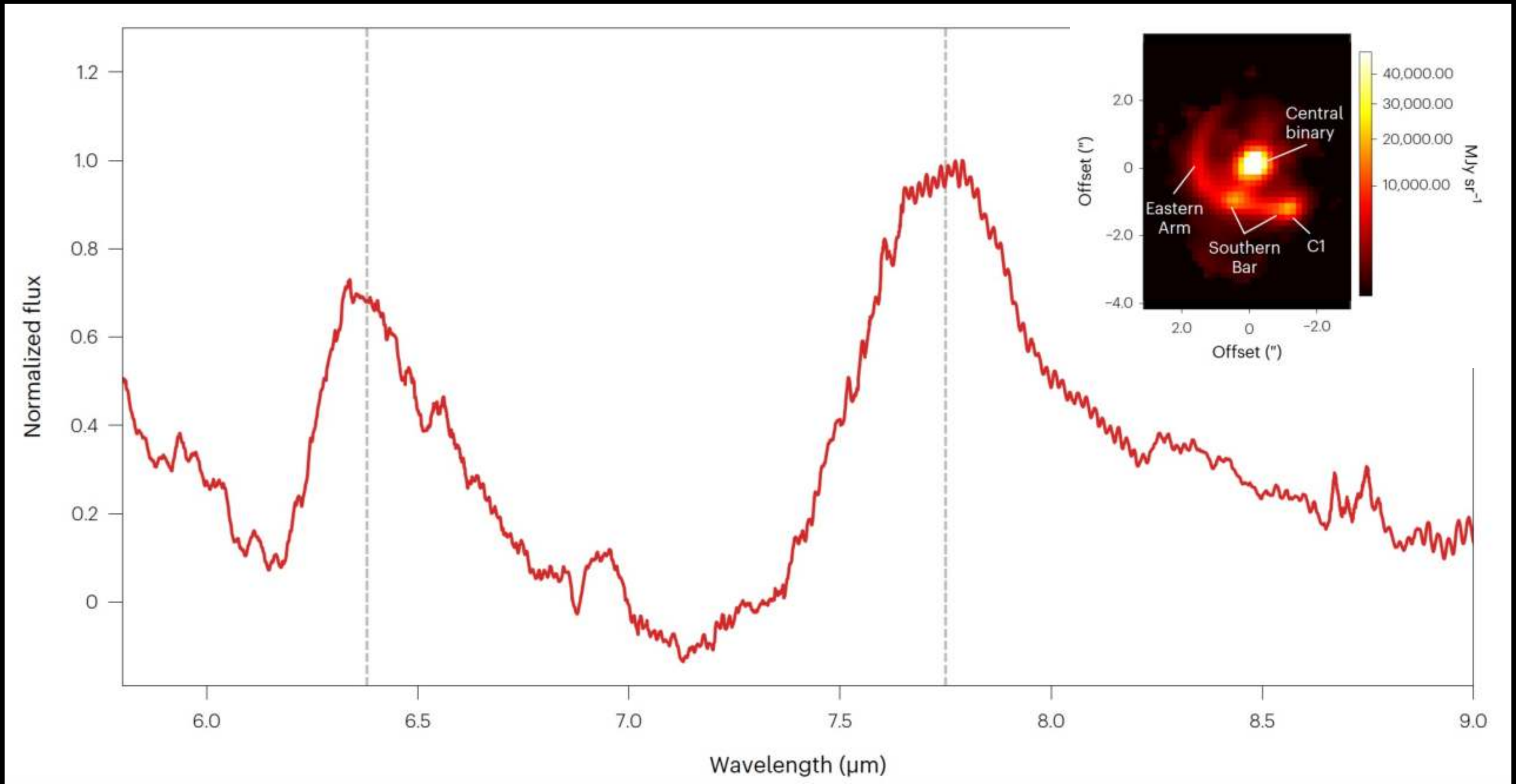
MIRI MRS Dust and PAH Detections



(Lau et al. 2022)

- 7.7 μm feature: aromatic C–C stretching modes in PAHs

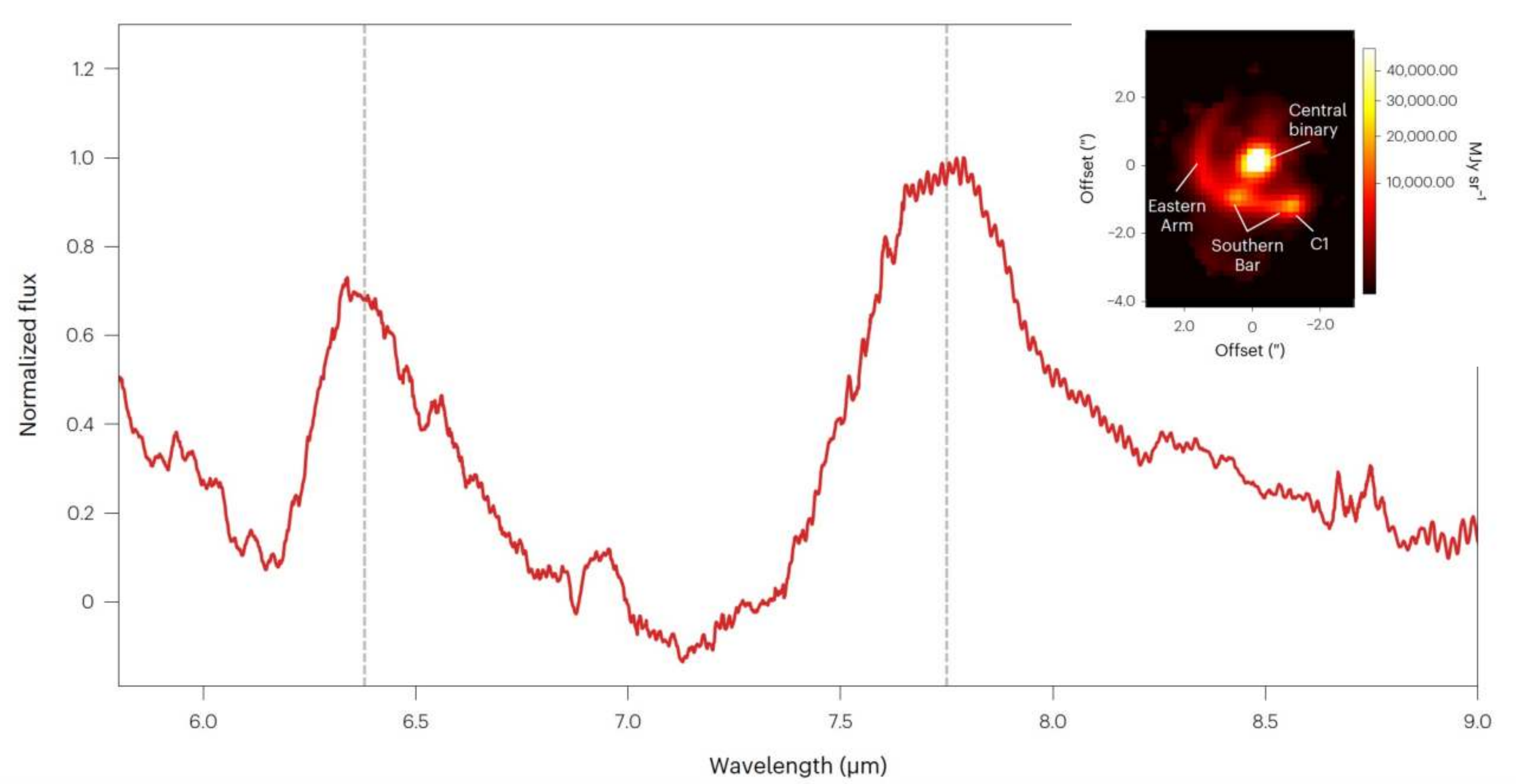
MIRI MRS Dust and PAH Detections



(Lau et al. 2022)

- 7.7 μm feature: aromatic C–C stretching modes in PAHs
- 6.4 μm feature: large carbonaceous molecules or small, H-free grains

MIRI MRS Dust and PAH Detections



(Lau et al. 2022)

- 7.7 μm feature: aromatic C–C stretching modes in PAHs
- 6.4 μm feature: large carbonaceous molecules or small, H-free grains
- WR binaries could contribute significantly to dust production

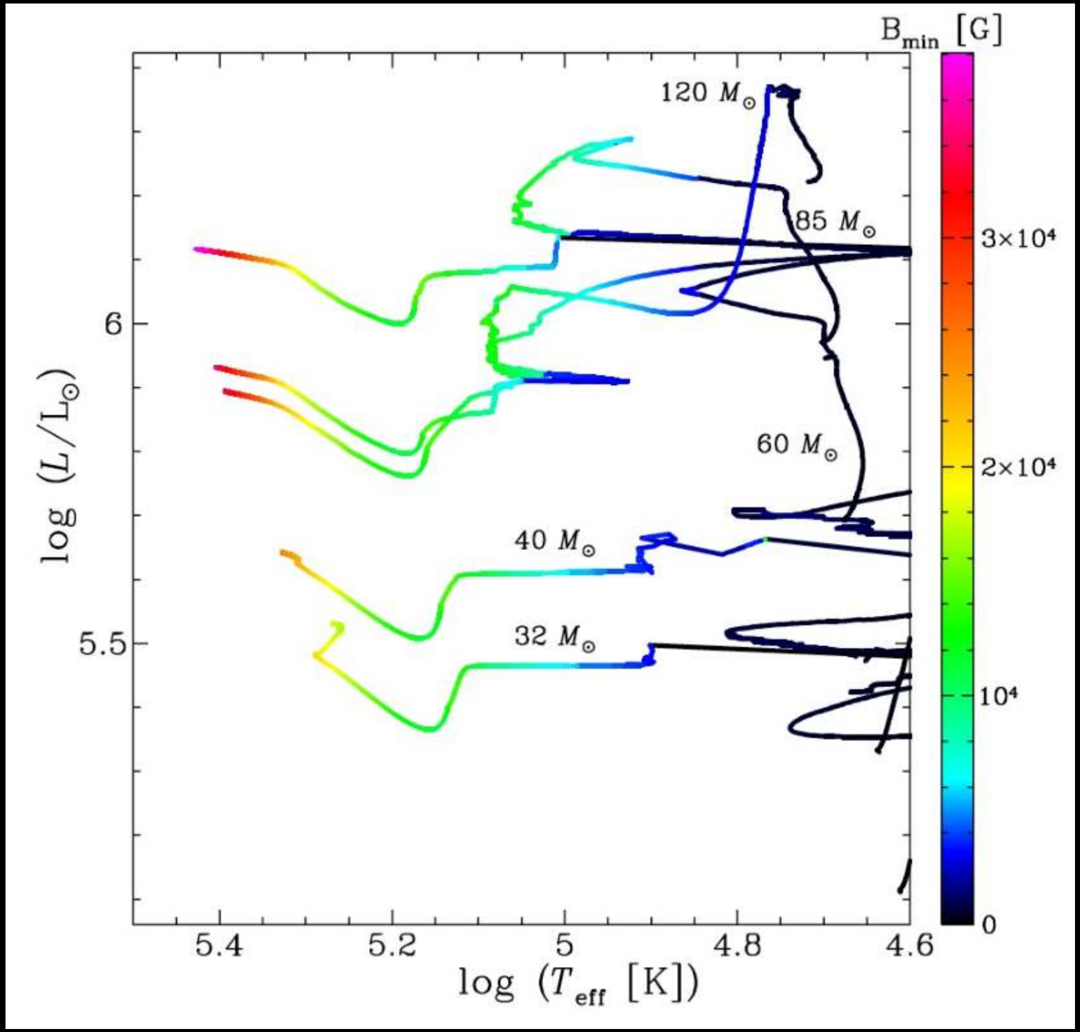
Takeaway

- Current understanding of Wolf-Rayet stars is the product of decades of observational/theoretical work.
- Previously impossible observations of metal enriched winds and dust formation from WR stars can be performed by JWST
- Dust-forming WC binaries could be an early and dominant source of organic compounds and carbonaceous dust in the ISM

References

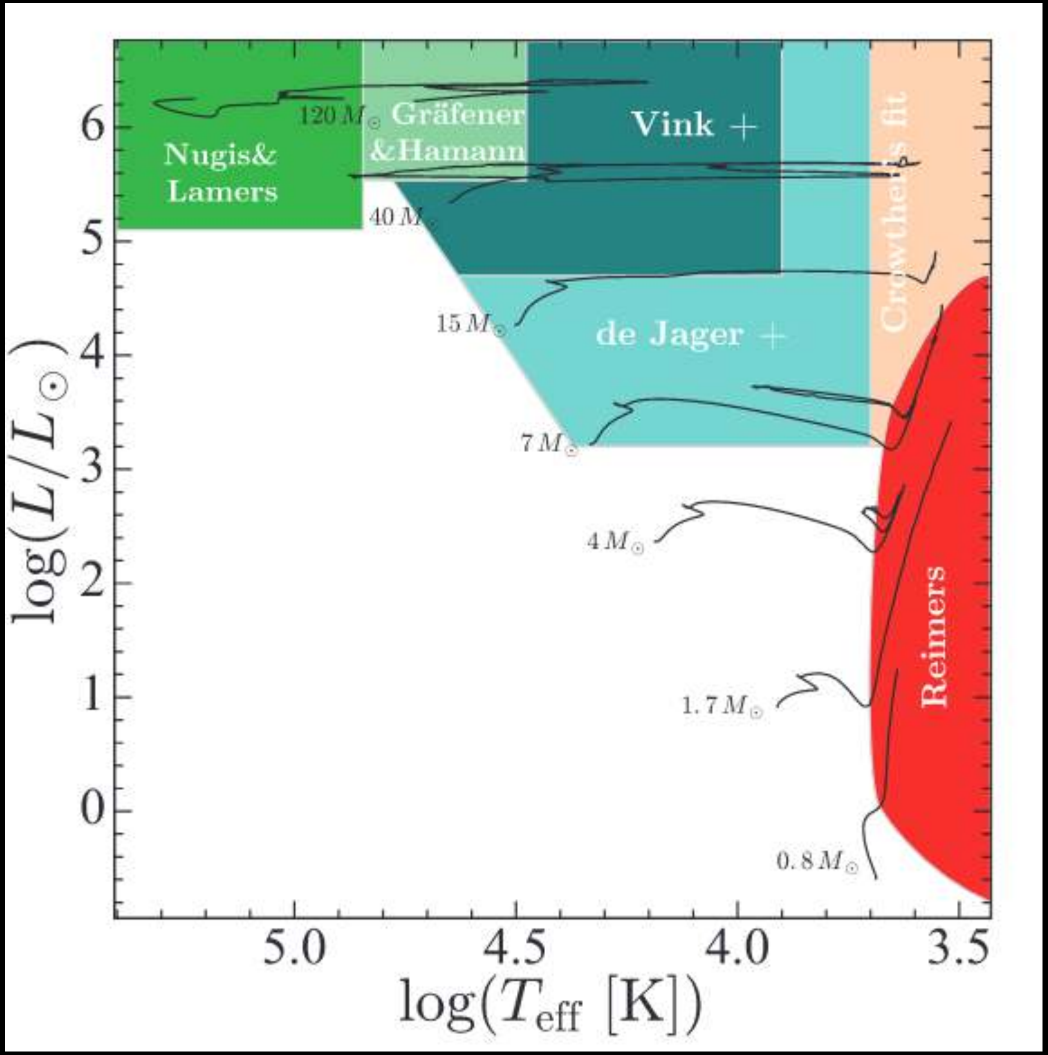
- Crowther, P. A. 2007, ARA&A, 45, 177, doi: 10.1146/annurev.astro.45.051806.110615
- Eggenberger, P., Ekstr¨om, S., Georgy, C., et al. 2021, A&A, 652, A137, doi: 10.1051/0004-6361/202141222
- Ekstr¨om, S., Georgy, C., Eggenberger, P., et al. 2012, A&A, 537, A146, doi: 10.1051/0004-6361/201117751
- Georgy, C., Ekstr¨om, S., Meynet, G., et al. 2012, A&A, 542, A29, doi: 10.1051/0004-6361/201118340
- Han, Y., Tuthill, P. G., Lau, R. M., & Soulain, A. 2022, Nature, 610, 269, doi: 10.1038/s41586-022-05155-5
- Katz, H., Kimm, T., Ellis, R. S., Devriendt, J., & Slyz, A. 2022, arXiv e-prints, arXiv:2207.04751, doi: 10.48550/arXiv.2207.04751
- Lau, R. M., Eldridge, J. J., Hankins, M. J., et al. 2020, ApJ, 898, 74, doi: 10.3847/1538-4357/ab9cb5
- Lau, R. M., Hankins, M. J., Han, Y., et al. 2022, Nature Astronomy, 6, 1308, doi: 10.1038/s41550-022-01812-x
- Marchenko, S. V., & Moffat, A. F. J. 2017, MNRAS, 468, 2416, doi: 10.1093/mnras/stx563
- Usov, V. V. 1991, MNRAS, 252, 49, doi: 10.1093/mnras/252.1.49
- Woosley, S. E., Heger, A., & Weaver, T. A. 2002, Rev. Mod. Phys., 74, 1015, doi: 10.1103/RevModPhys.74.1015

Rotation Rates Consistent with Pulsars?



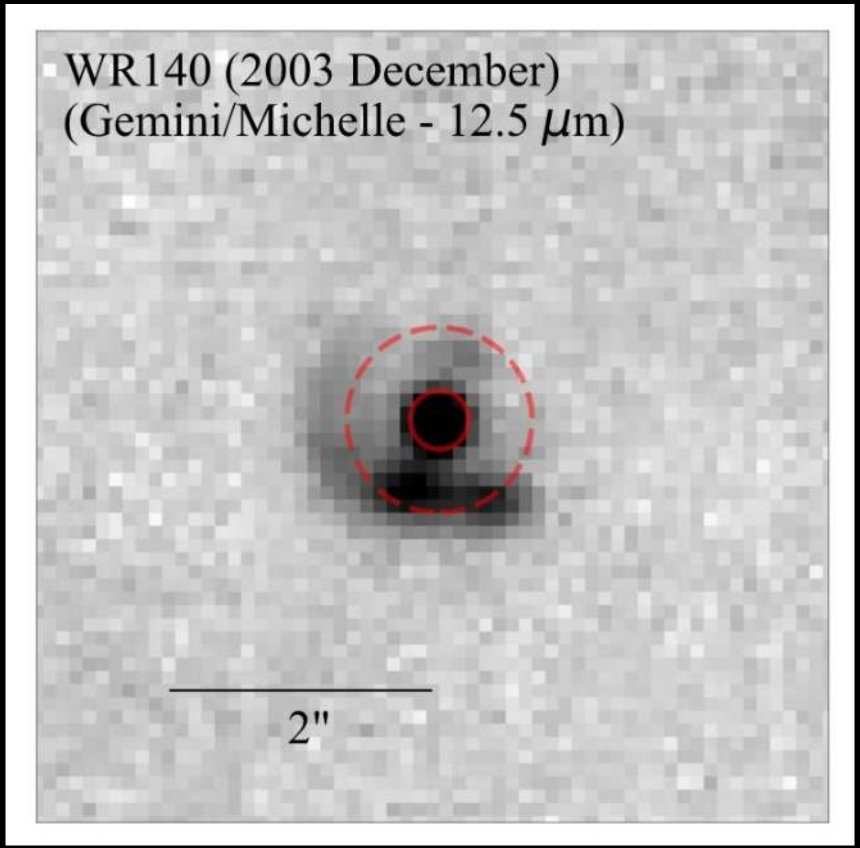
(Georgy et al. 2018)

Mass Loss Prescriptions

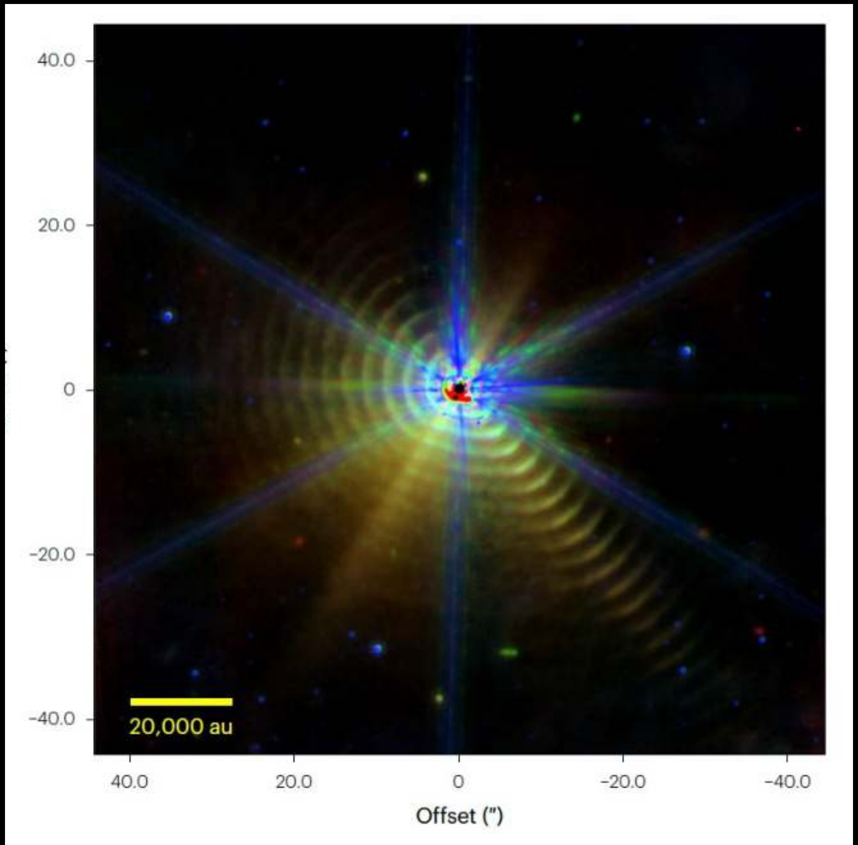


(Eggenberger et al. 2021)

Prior Sensitivity Limitations

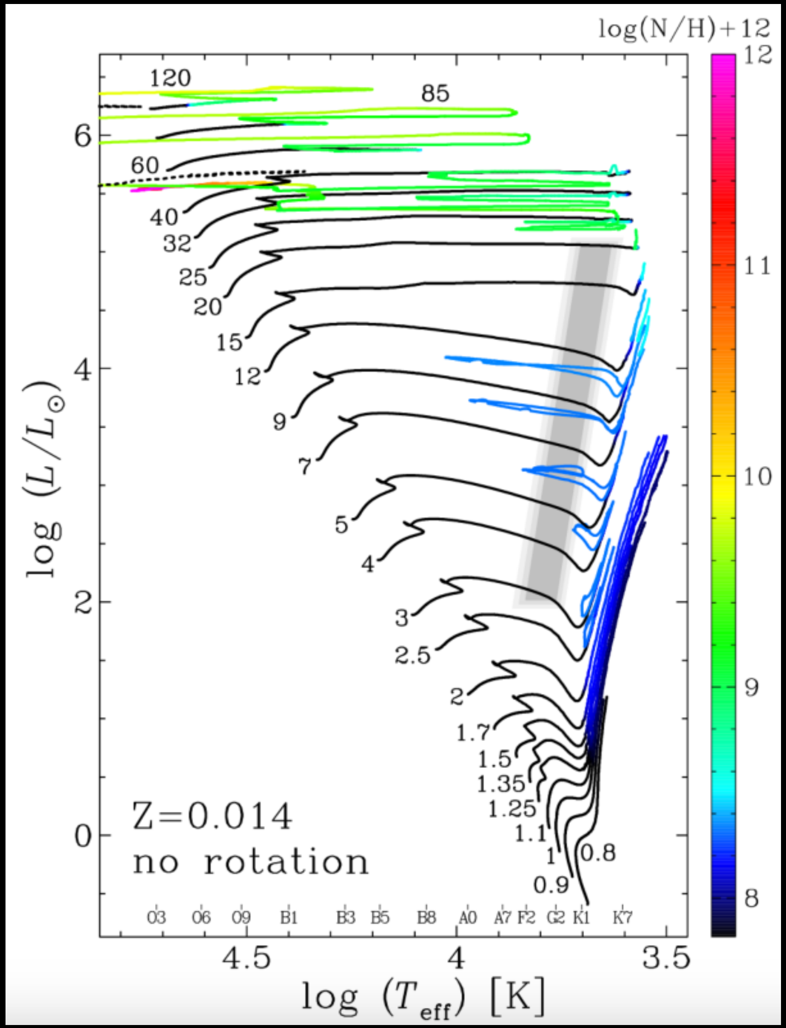


(Williams et al. 2009a)

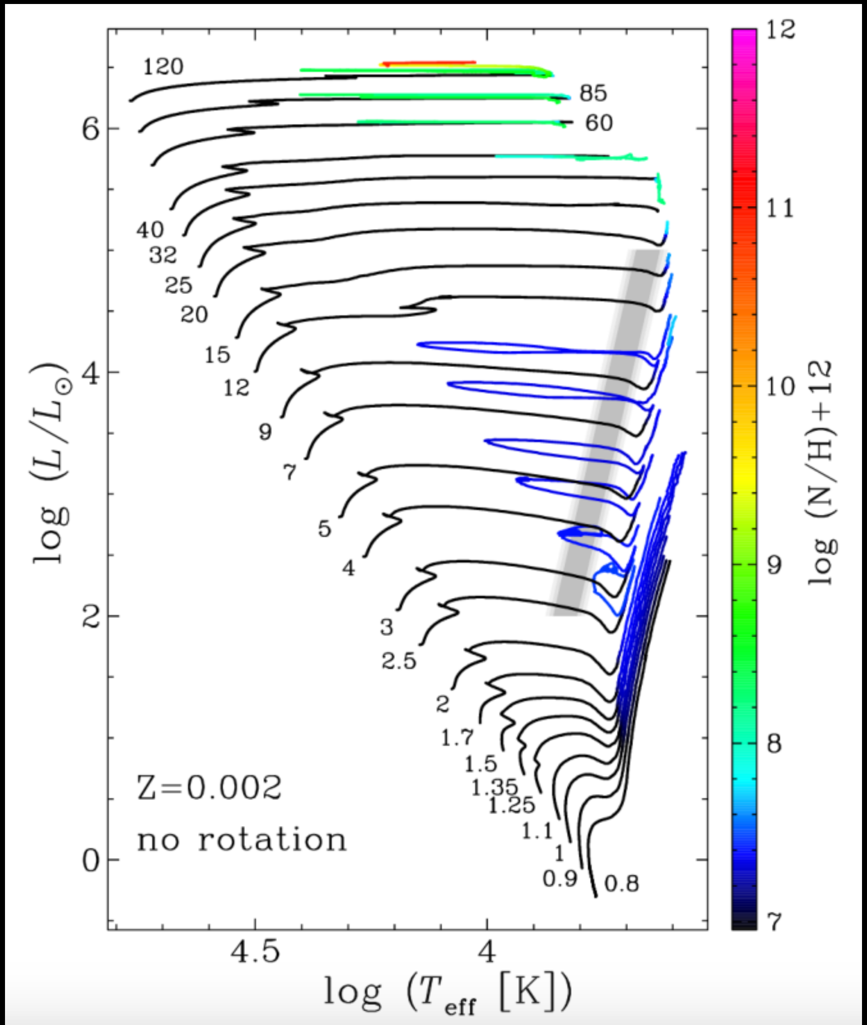


(Lau et al. 2022)

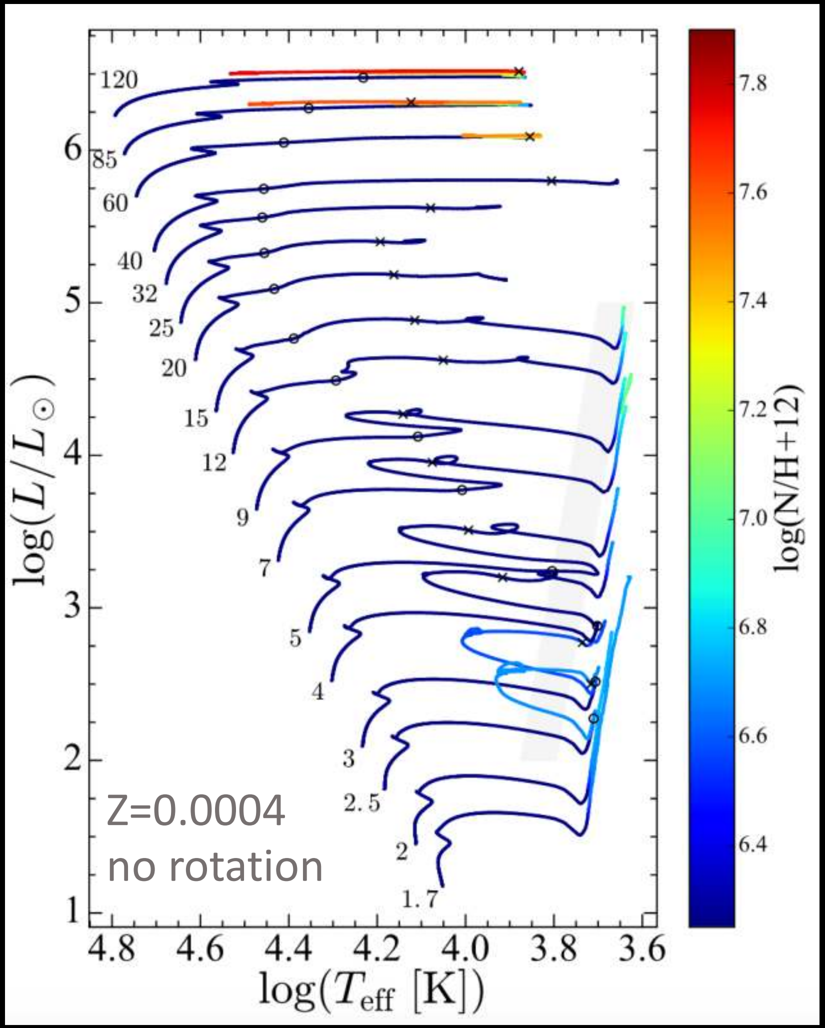
Focus on Surface Nitrogen Abundance



(Ekstrom et al. 2012)

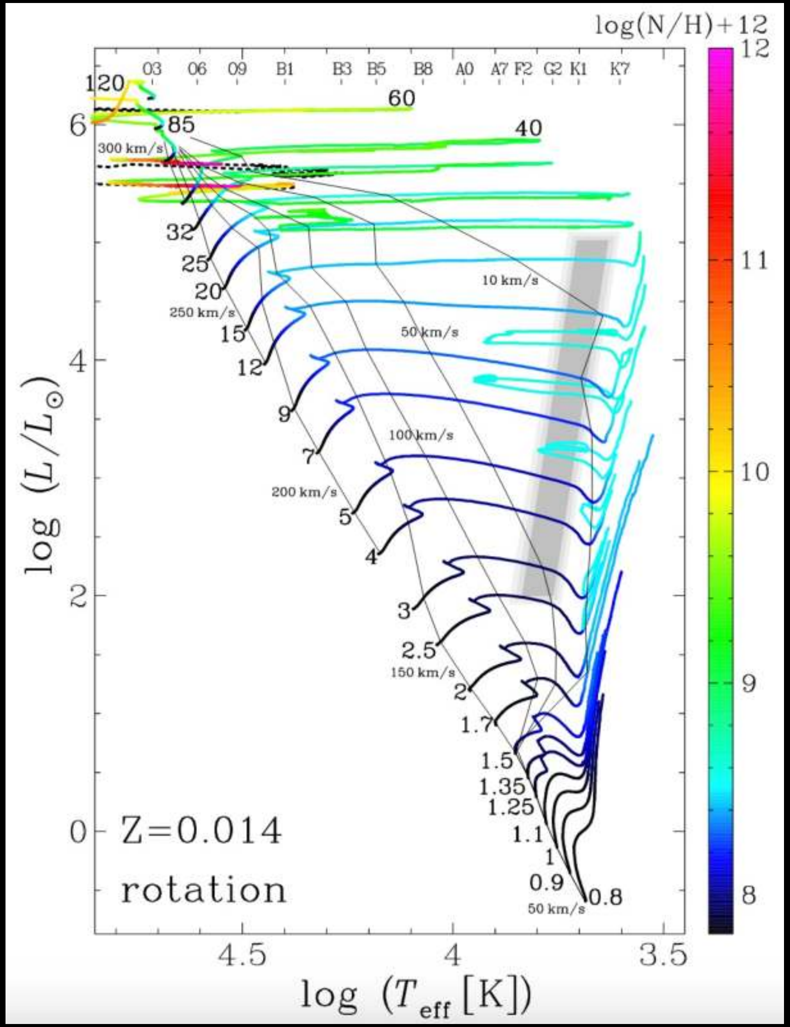


(Georgy et al. 2013)

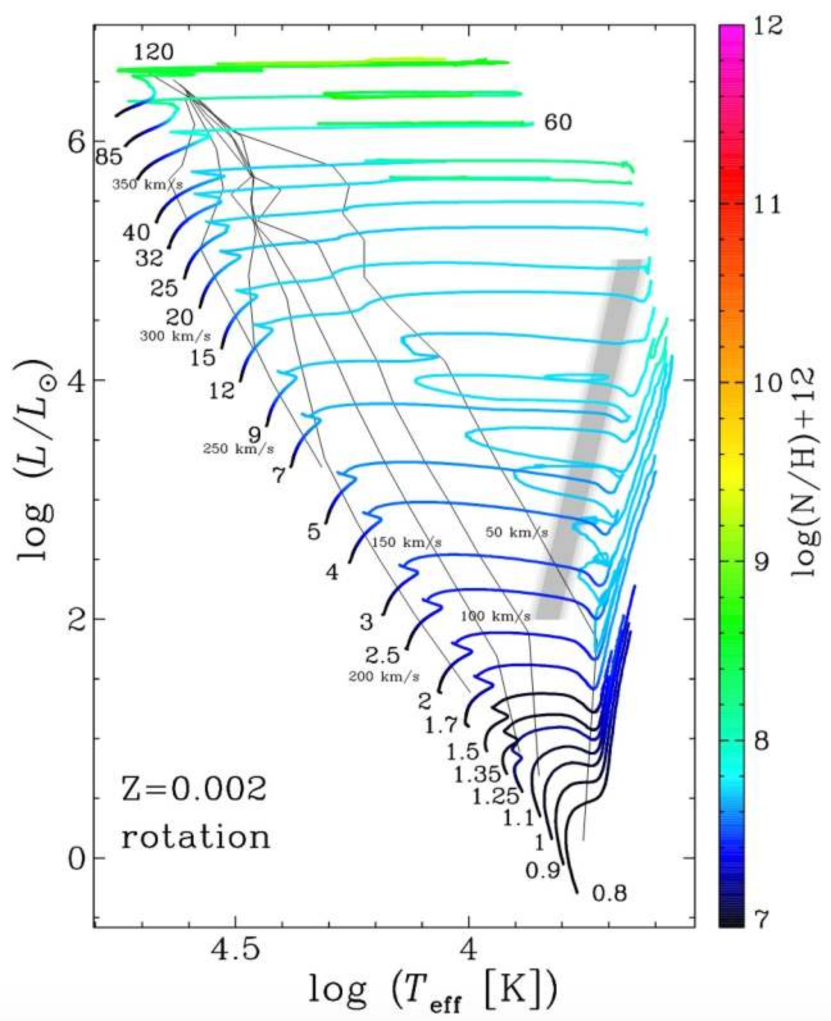


(Groh et al. 2019)

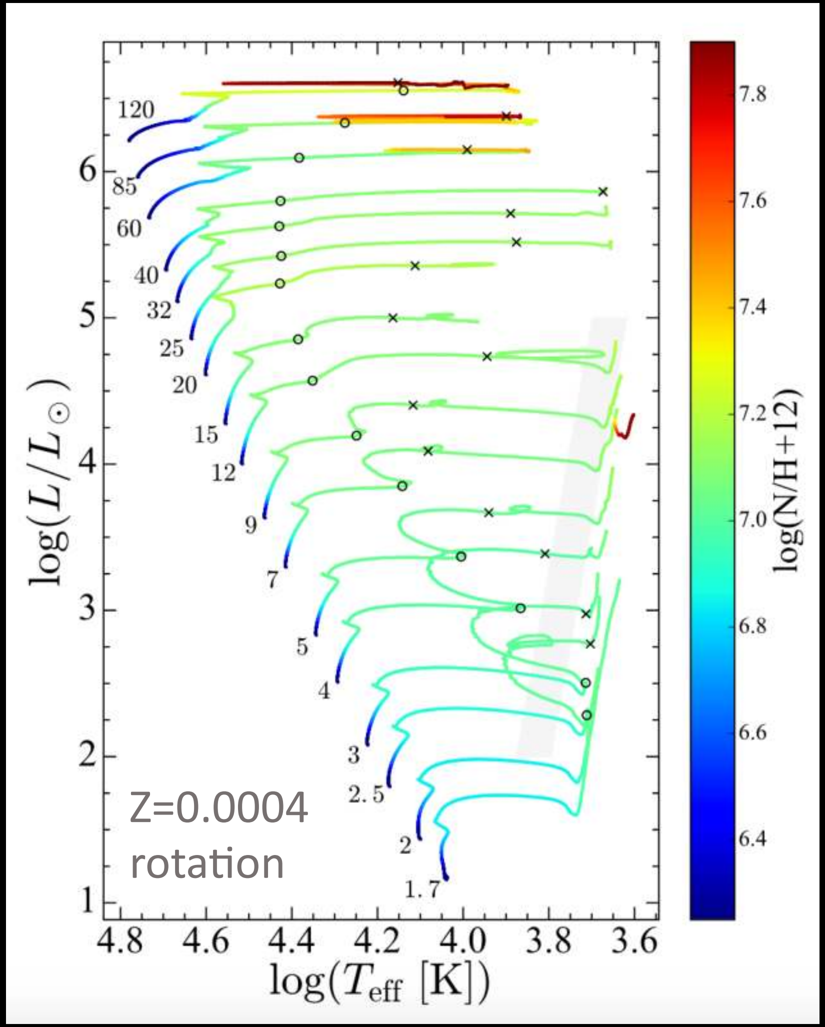
Surface Nitrogen Higher if Rotating



(Ekstrom et al. 2012)



(Georgy et al. 2013)



(Groh et al. 2019)