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Progenitors of LGRBs: Are single stars enough?

Rafia Sarwar [1], ***Dorottya Szécsi*** [1], ***Koushik Sen*** [1], ***Poojan Agrawal*** [2], ***and Hanno Stinshoff*** [1]

[1] Institute of Astronomy | Faculty of Physics, Astronomy and Informatics, *Nicolaus Copernicus University*, Toruń, Poland.
[2] Department of Physics and Astronomy, *University of North Carolina*, Chapel Hill, USA.

Rafia Sarwar
30 January 2024
International Conference on Gravitation and Cosmology 2024, Lahore, Pakistan

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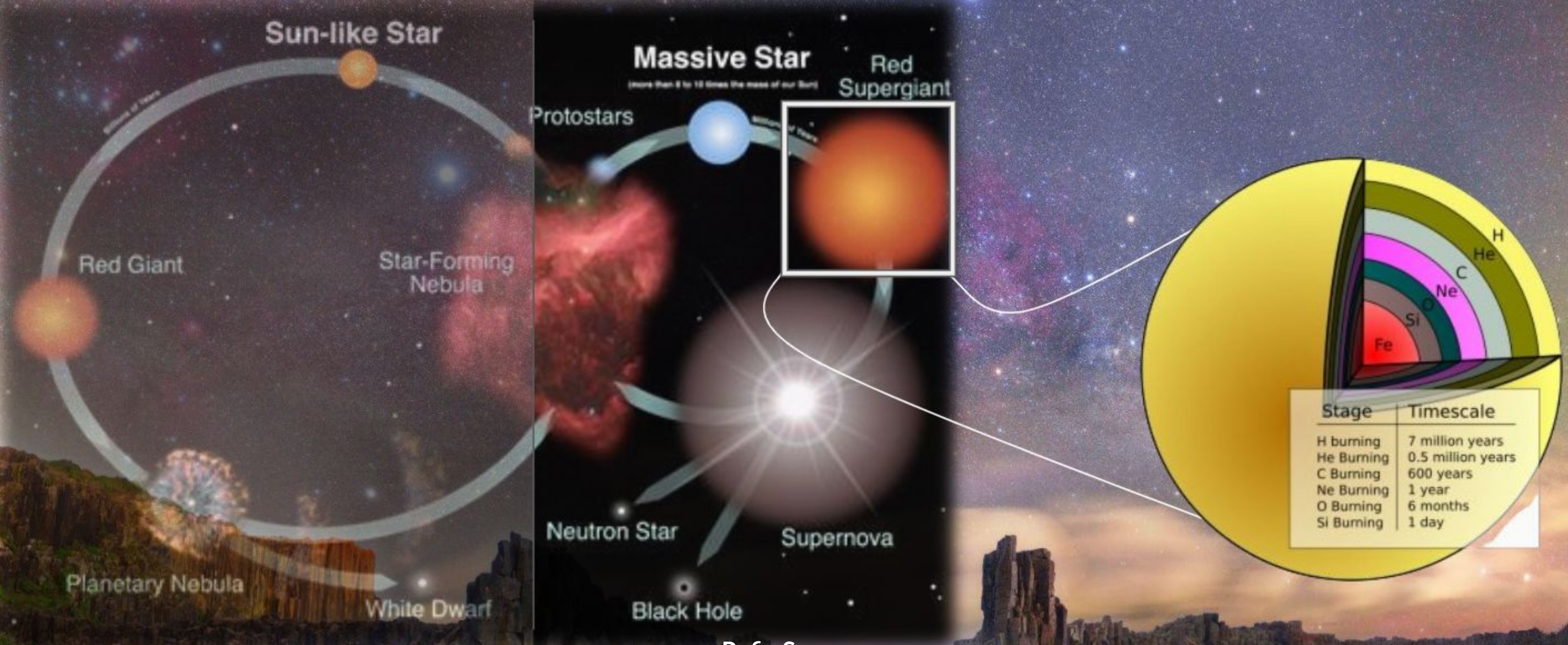
Massive stars



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Why massive stars

Figure Credit: NASA

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Why massive stars

Cosmological impact by the feedback processes

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Why massive stars

Physics of binary stars

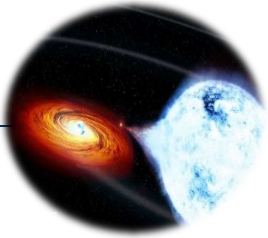

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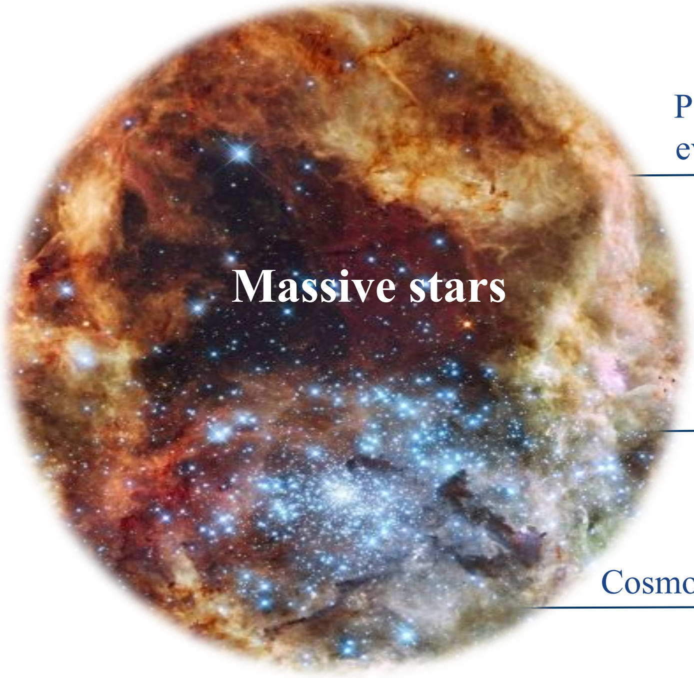
Figure Credit: NASA

Why massive stars



Parents of supernova events & gamma ray bursts

Physics of binary stars

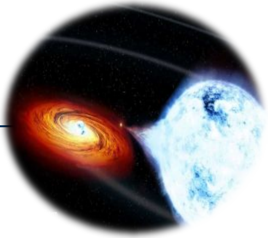


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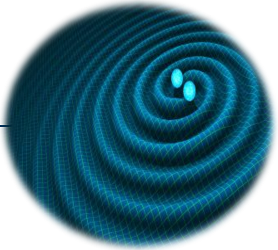
Figure Credit: NASA

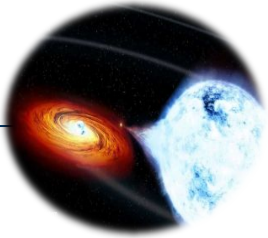
Why massive stars

Binary stars as progenitors of gravitational waves



Parents of supernova events & gamma ray bursts

Physics of binary stars



Cosmological impact by the feedback processes

Figure Credit: NASA

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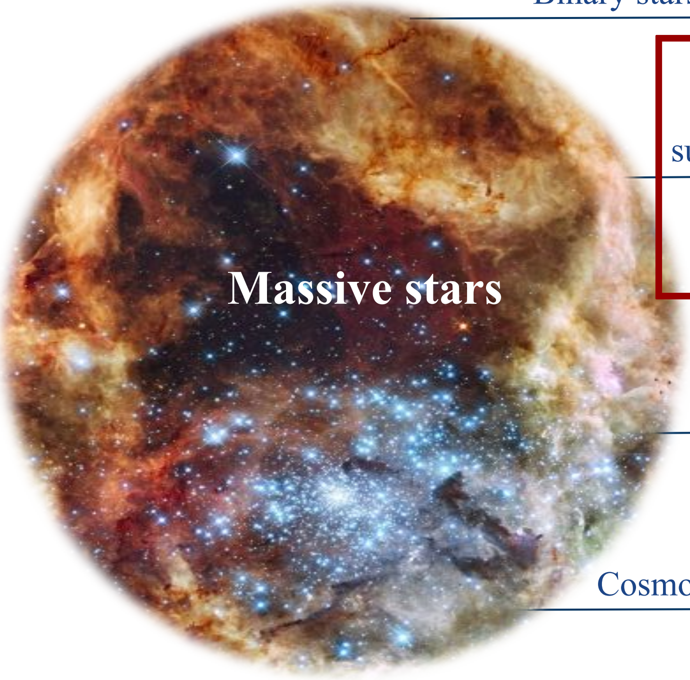
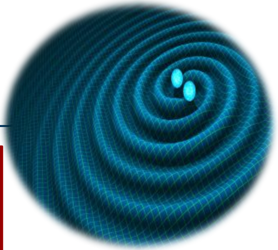
Why massive stars

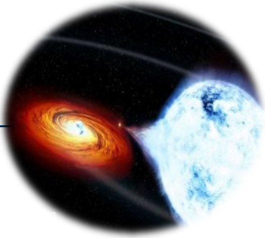


Binary stars as progenitors of gravitational waves



Progenitors of supernova & gamma ray bursts

Physics of binary stars



Cosmological impact by the feedback processes

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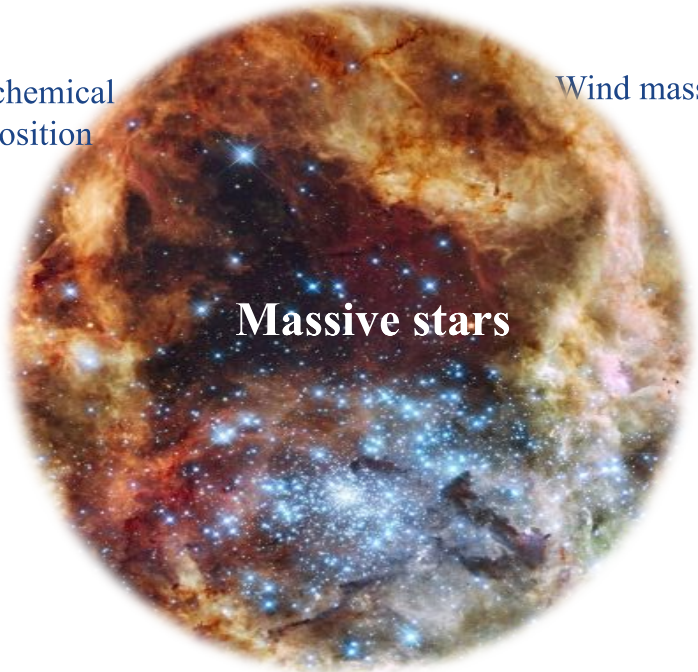
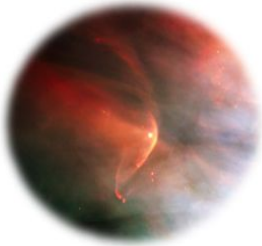
Factors impacting massive stars

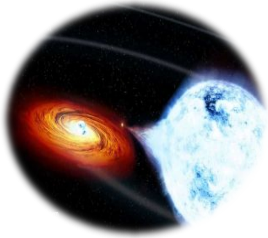
Initial chemical composition



Wind mass loss



Binary interaction



Rotational mixing

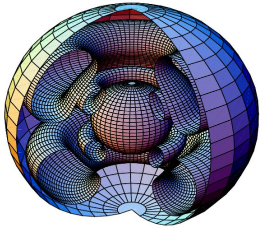


Figure Credit: NASA

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Bifurcation of massive star evolution

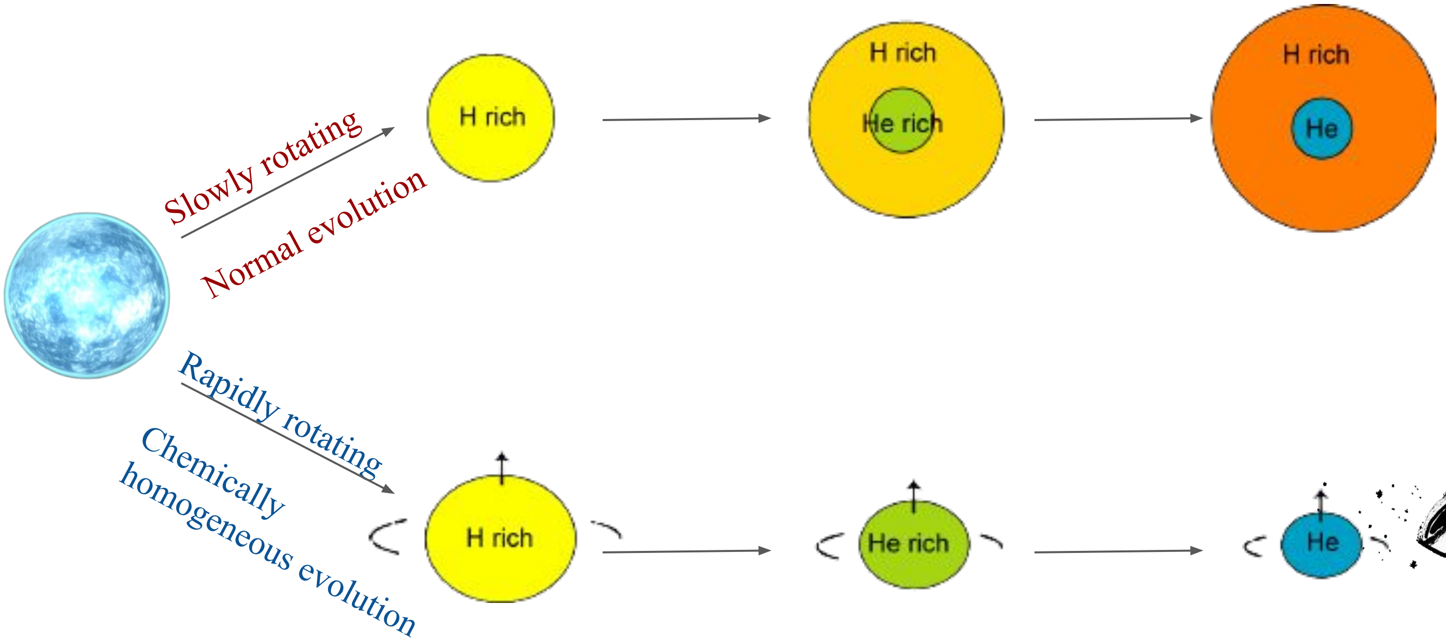


Figure Credit: De Mink et al. (2008)

Market of stellar evolution codes

MESA

Geneva

Bonn …

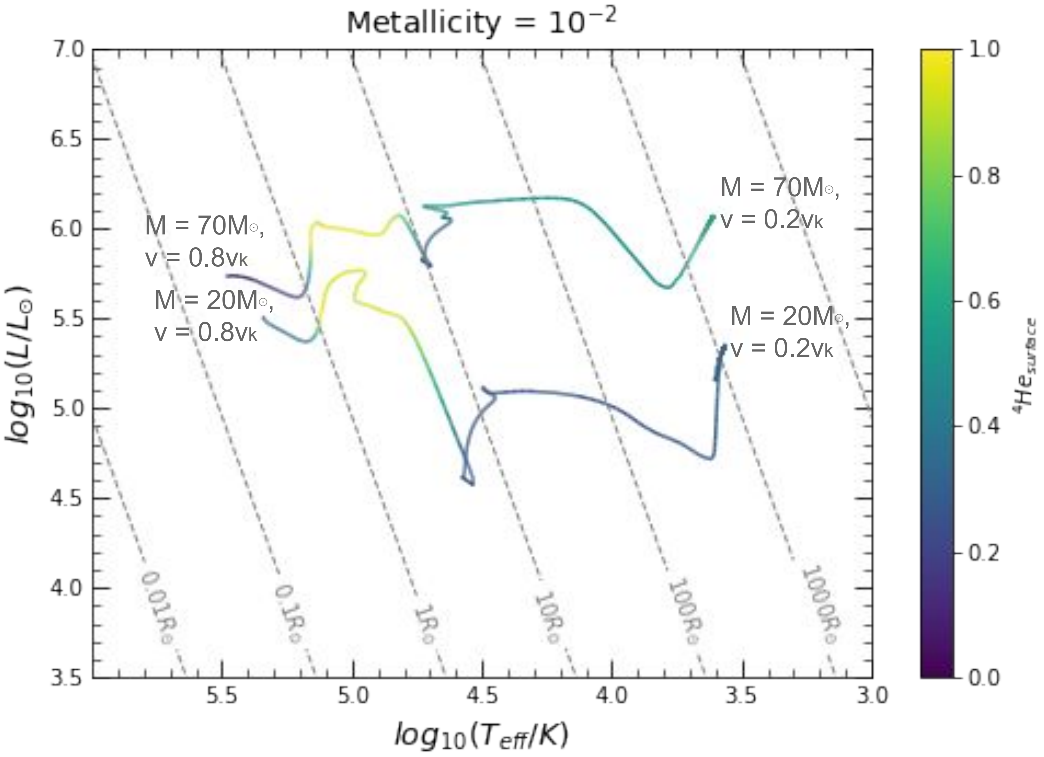
Model parameters

Metallicities	0.01	0.001	0.0001	0.00001

Initial masses	$10M_\odot$	$20M_\odot$	$30M_\odot$	$40M_\odot$	$50M_\odot$	$60M_\odot$	$70M_\odot$	$80M_\odot$	$90M_\odot$	$100M_\odot$

Initial velocity	$0.1v_k$	$0.2v_k$	$0.3v_k$	$0.4v_k$	$0.5v_k$	$0.6v_k$	$0.7v_k$	$0.8v_k$

Evolution of massive stars



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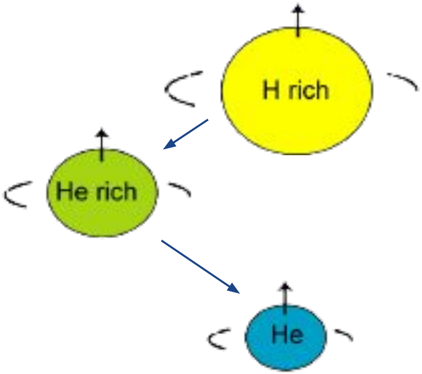
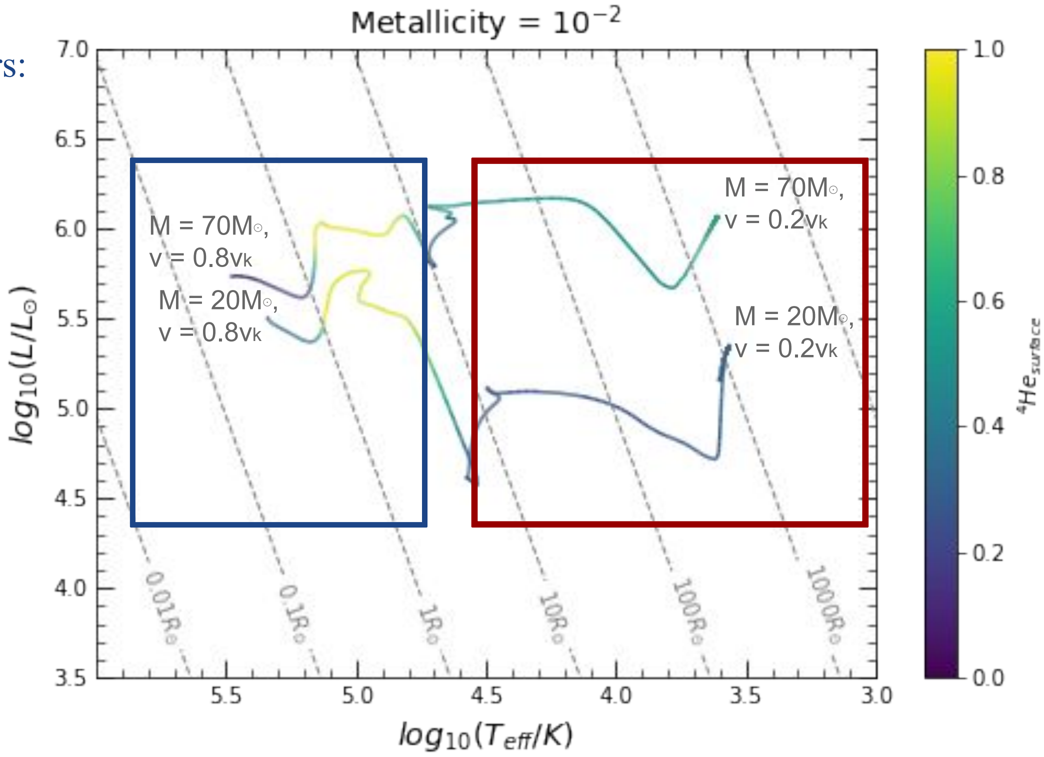
Evolution of massive stars

Rapidly rotating massive stars:

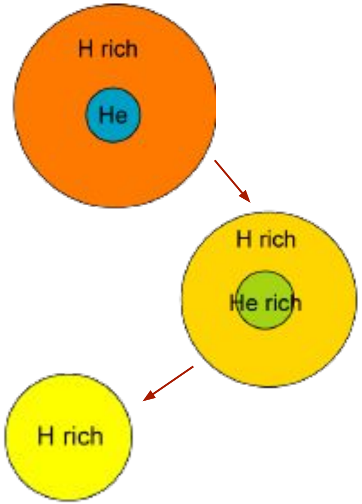
- rapid rotationally-induced chemical mixing
- quasi-chemical homogeneity





Slowly rotating:

- classical core-envelope
- red-supergiant



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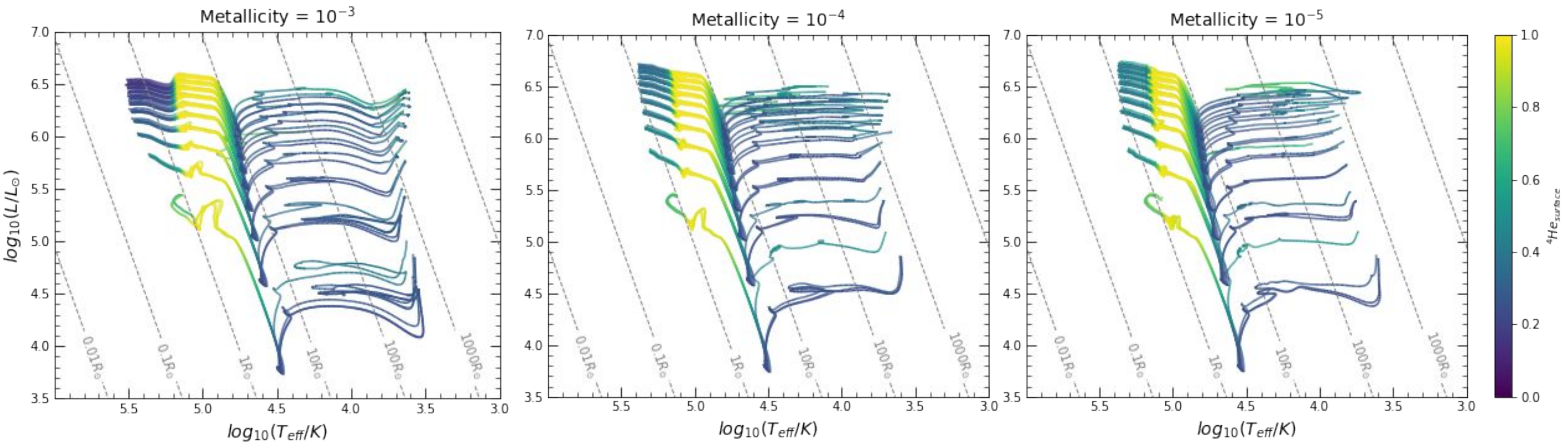
Evolution of massive stars



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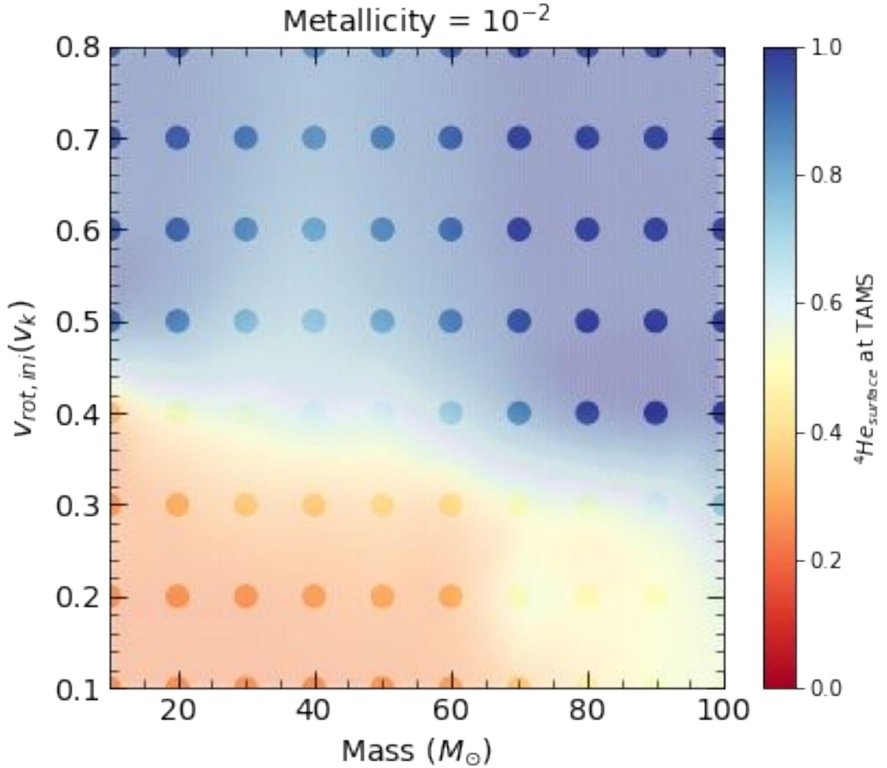
MESA stellar grid



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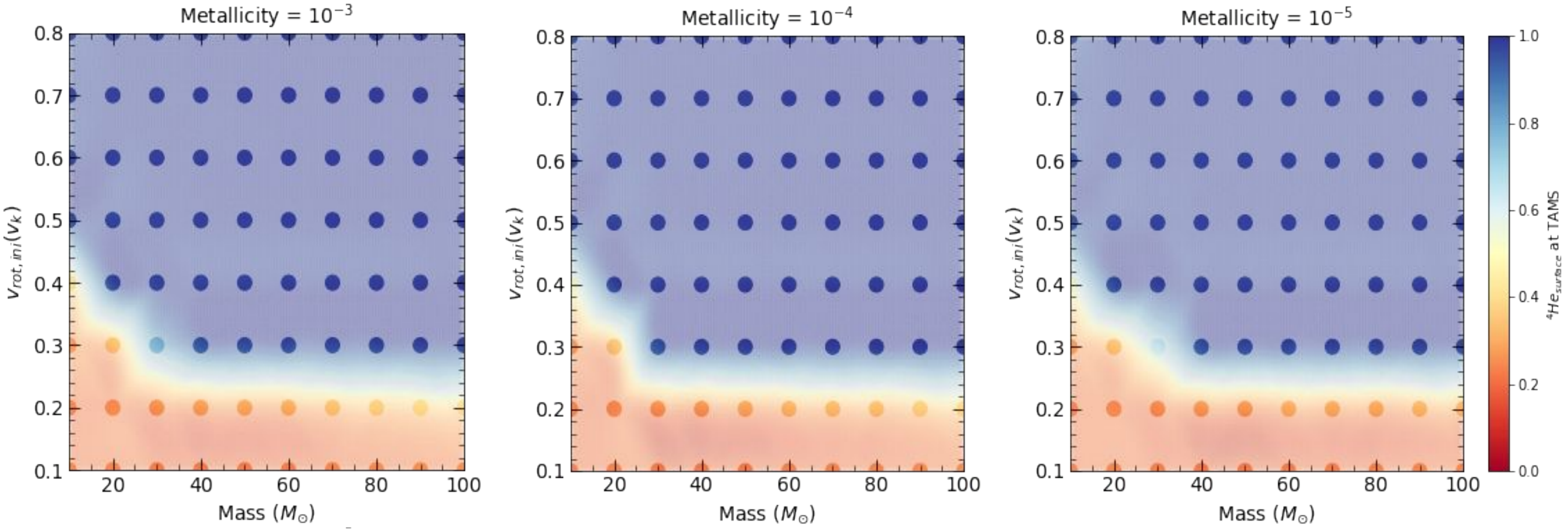
MESA stellar grid



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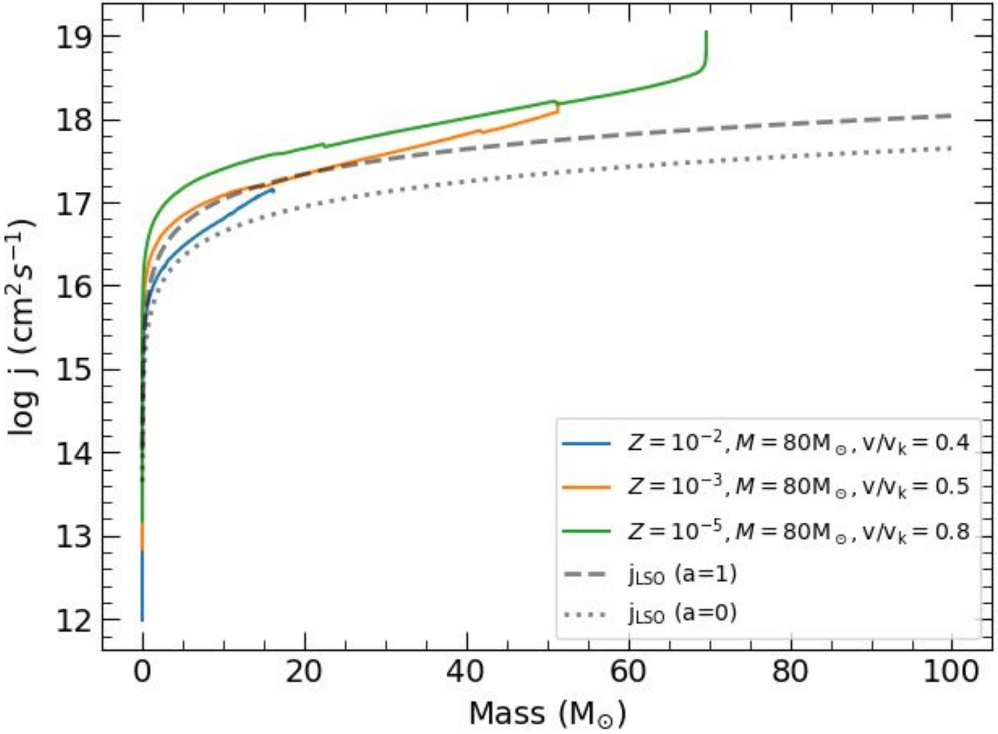
Progenitors of LGRBs



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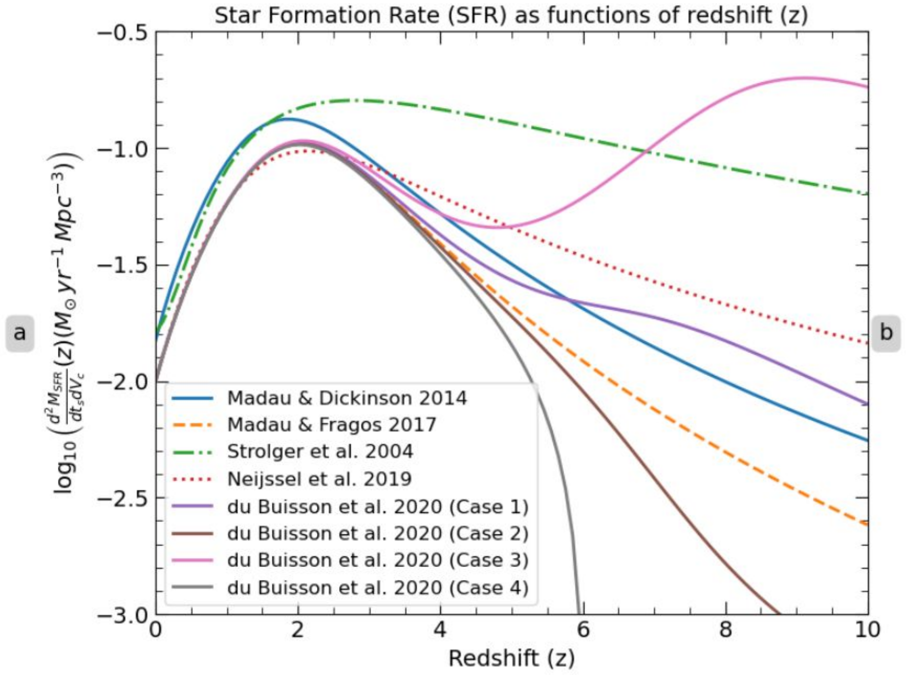
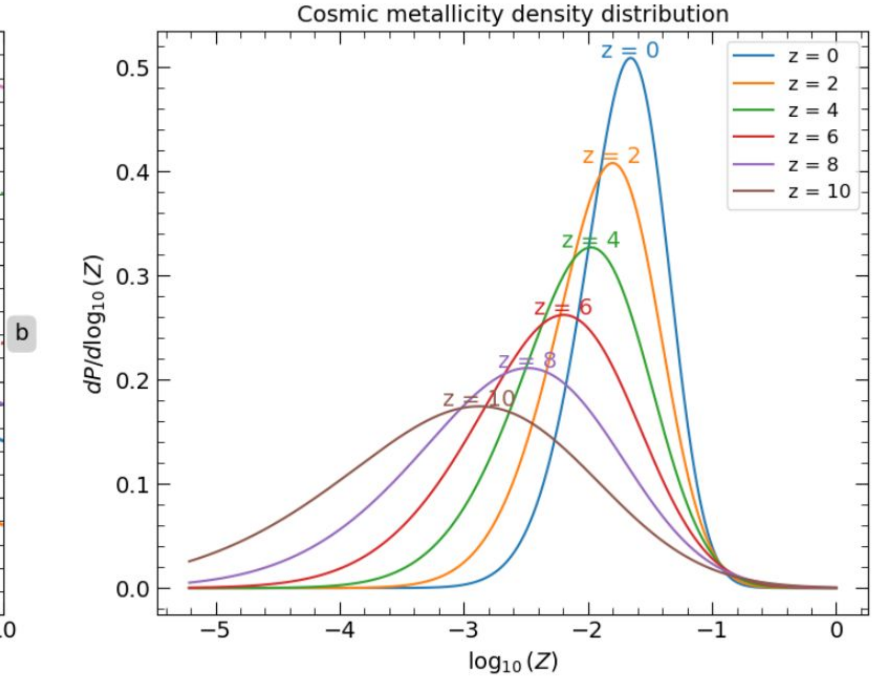
Cosmic star formation rate and metallicity distribution

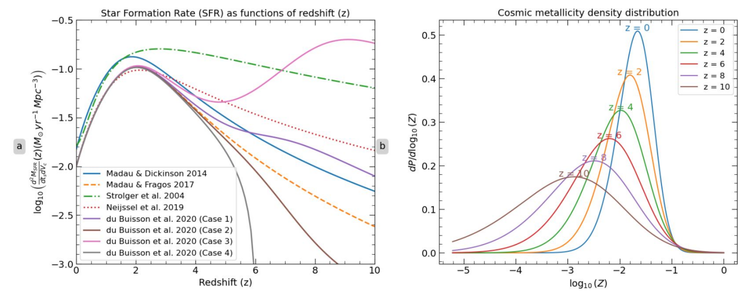


$$\mathrm{SFRD}(z) = \frac{d^2 M_{\mathrm{SFR}}}{dt dV_c}(z) = a\frac{(1+z)^b}{1+[(1+z)/c]^d}$$



$$\frac{dP}{dZ}(Z,z) = \frac{2}{\omega(z)Z} \times \phi\left(\frac{\ln Z - \xi(z)}{\omega(z)}\right)\Phi\left(\alpha\frac{\ln Z - \xi(z)}{\omega(z)}\right)$$

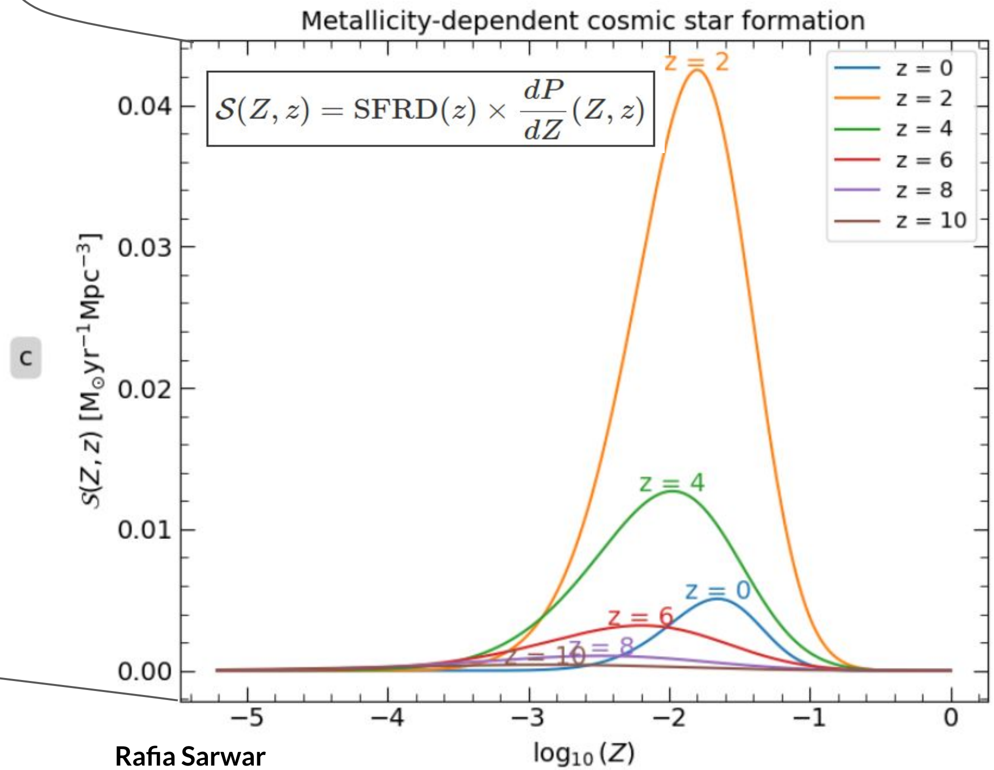
Metallicity-dependent cosmic star formation



$$\mathrm{SFRD}(z) = \frac{d^2 M_{\mathrm{SFR}}}{dt dV_c}(z) = a\frac{(1+z)^b}{1+[(1+z)/c]^d}$$

X

$$\frac{dP}{dZ}(Z,z) = \frac{2}{\omega(z)Z} \times \phi\left(\frac{\ln Z - \xi(z)}{\omega(z)}\right)\Phi\left(\alpha\frac{\ln Z - \xi(z)}{\omega(z)}\right)$$



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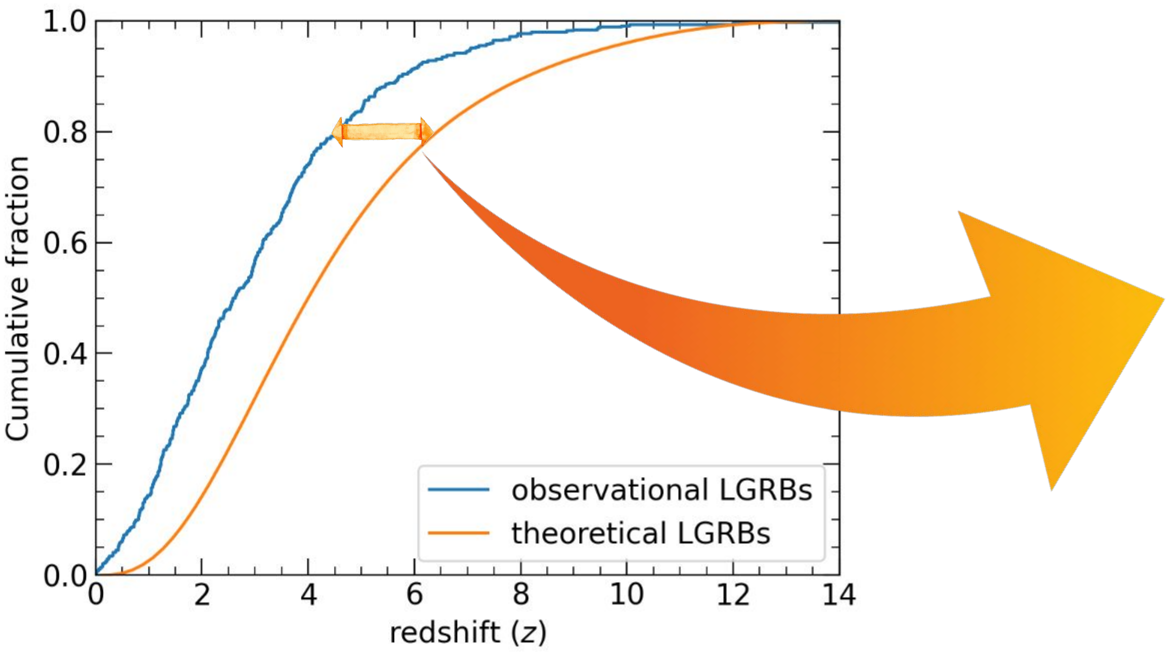
Single star models vs observation



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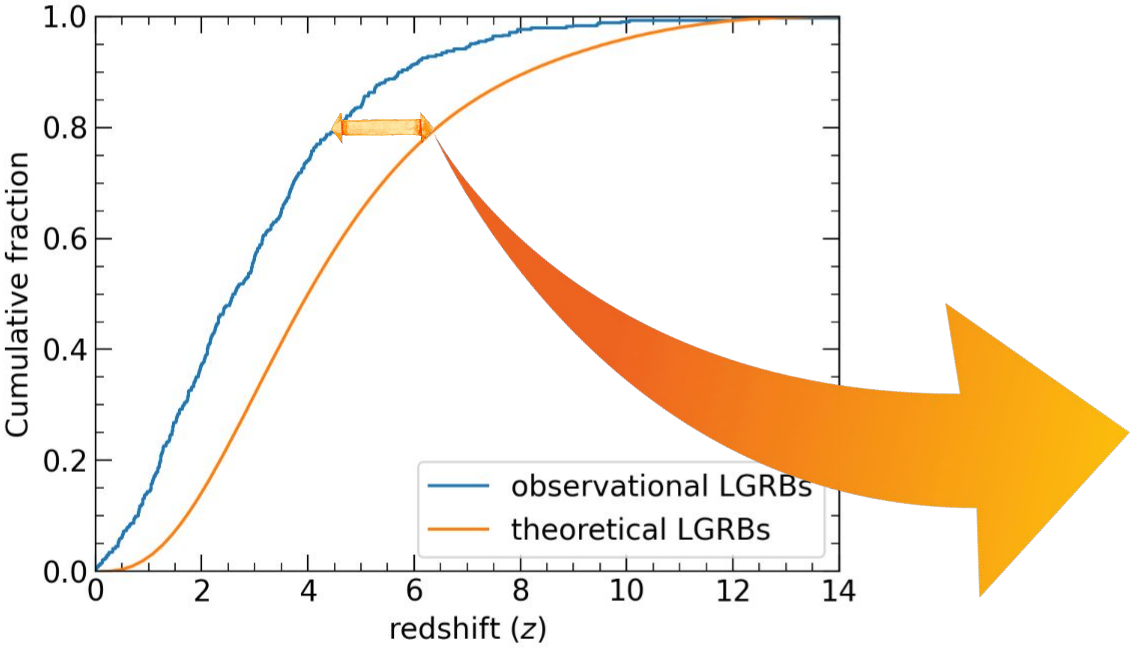

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Chemically homogeneous evolution of massive binary stars

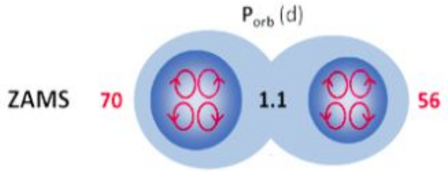

Figure Credit: Pablo Marchant et al. (2016)

Chemically homogeneous evolution of massive binary stars

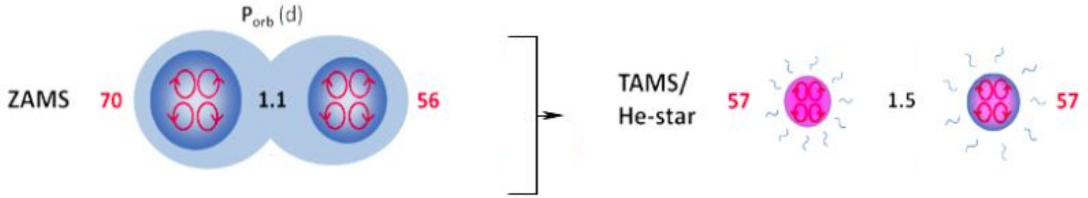

Figure Credit: Pablo Marchant et al. (2016)

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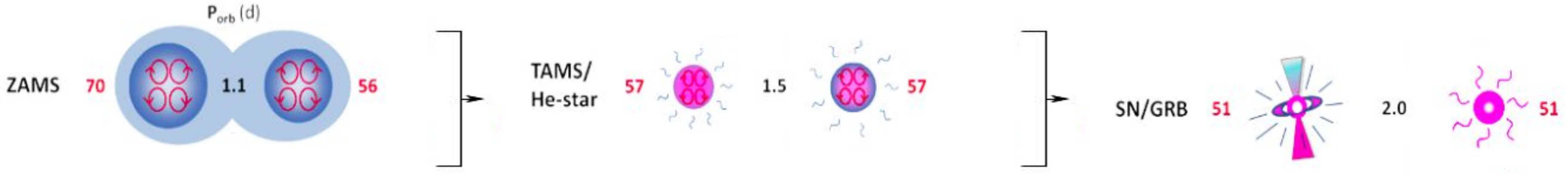

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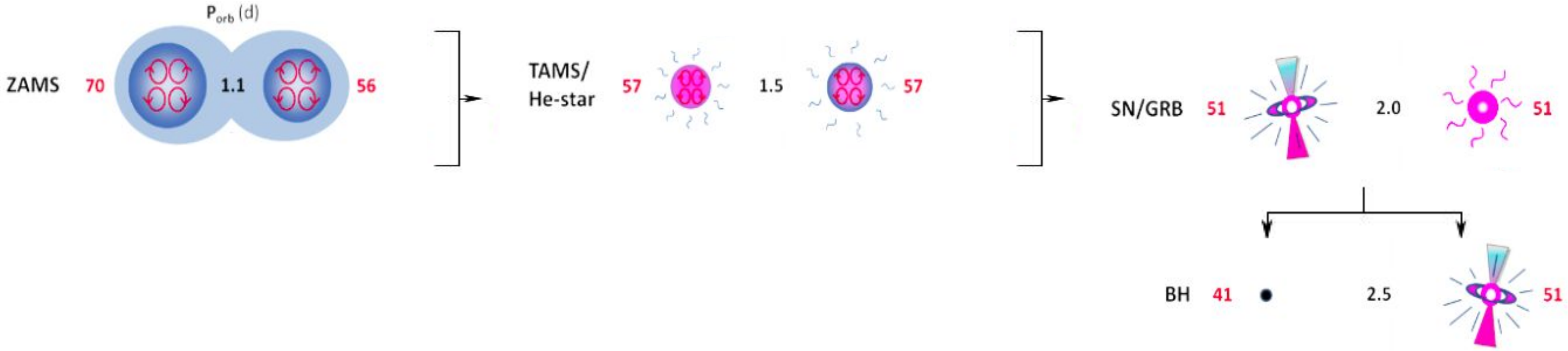

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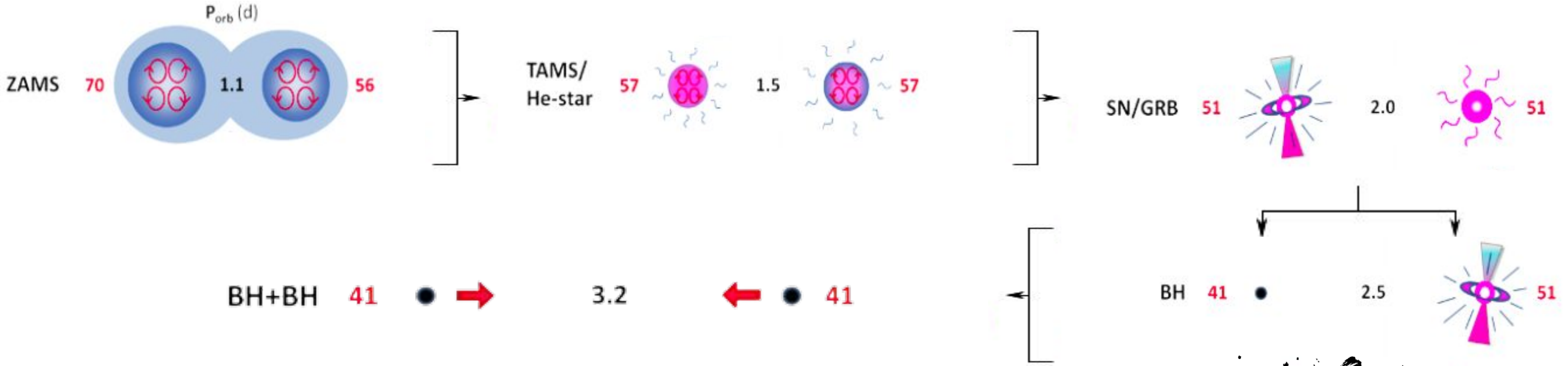

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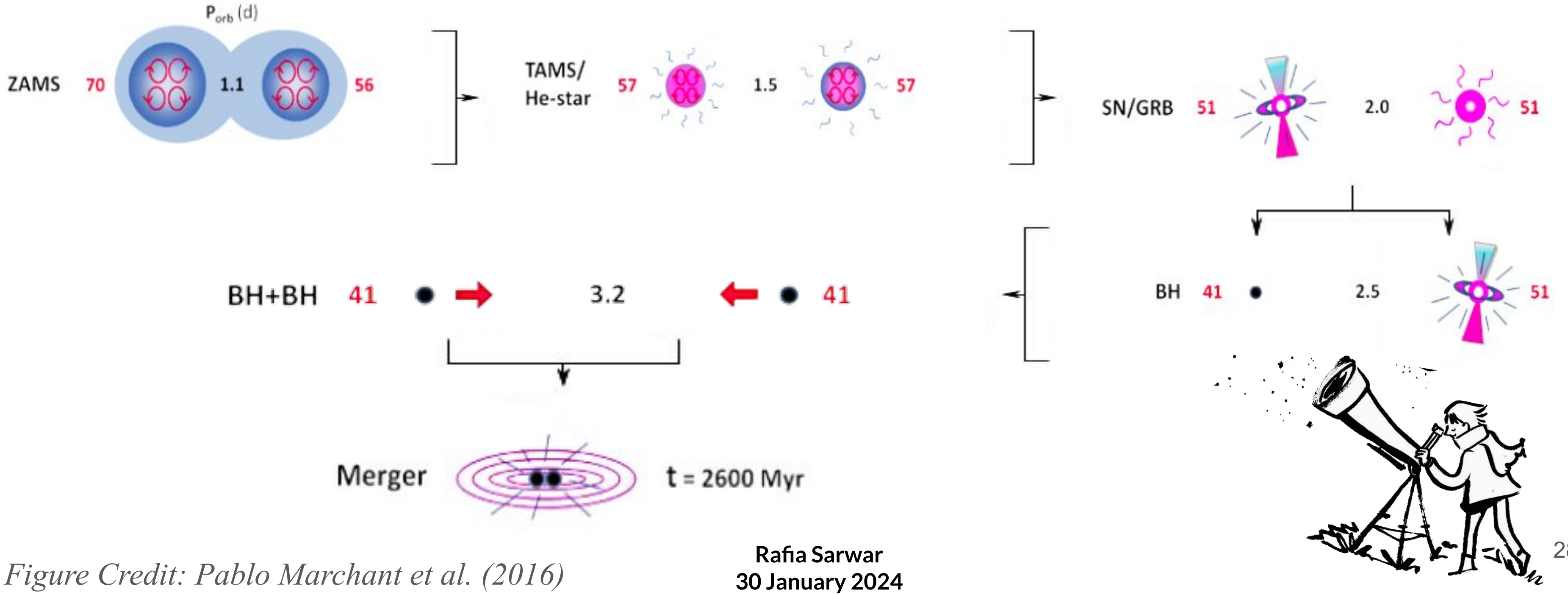

Figure Credit: Pablo Marchant et al. (2016)

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The Gravitational-Wave Transient Catalogue 3 (GWTC-3)

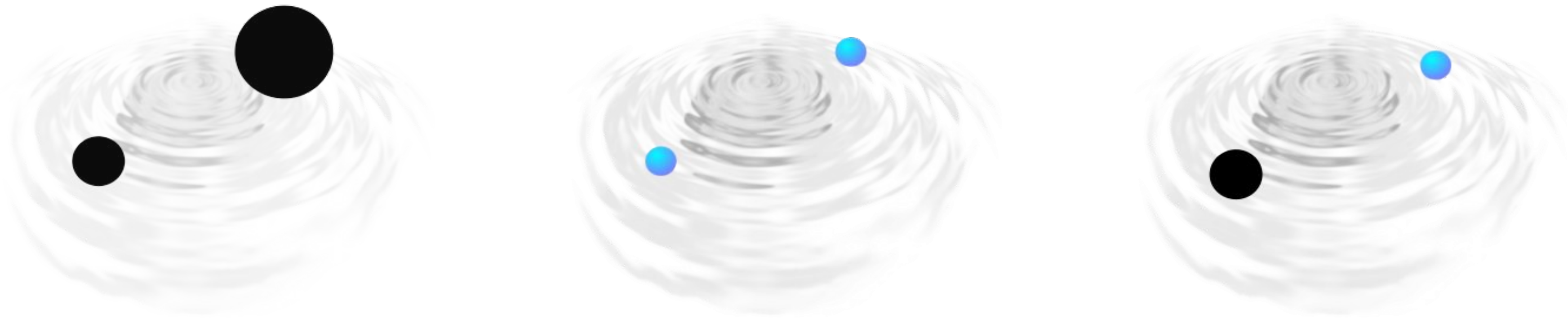

Figure Credit: Tassos Fragos

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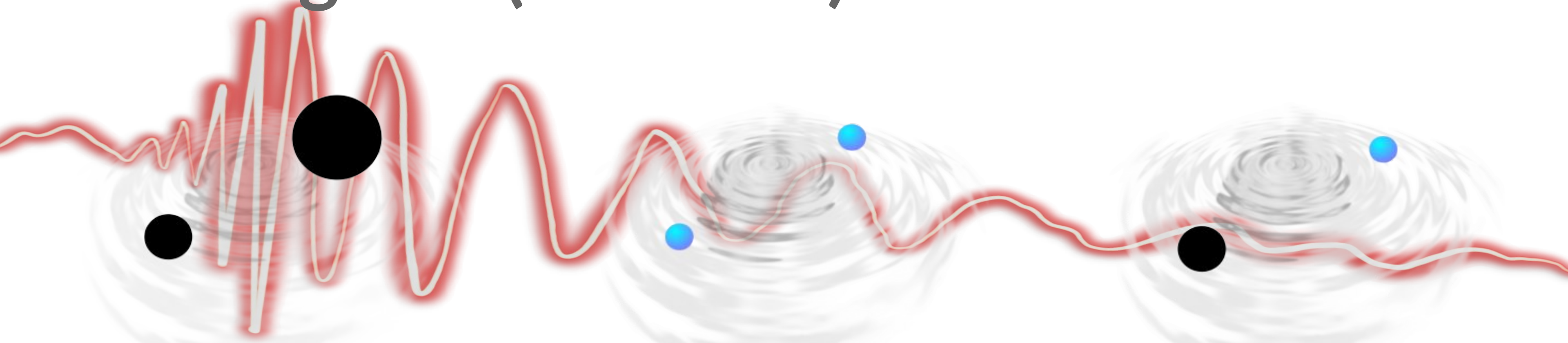

72
Binary black holes

2
Binary neutron star

2-3
Black hole-neutron star

Abbot et al. arXiv:2111.03606 (2021)

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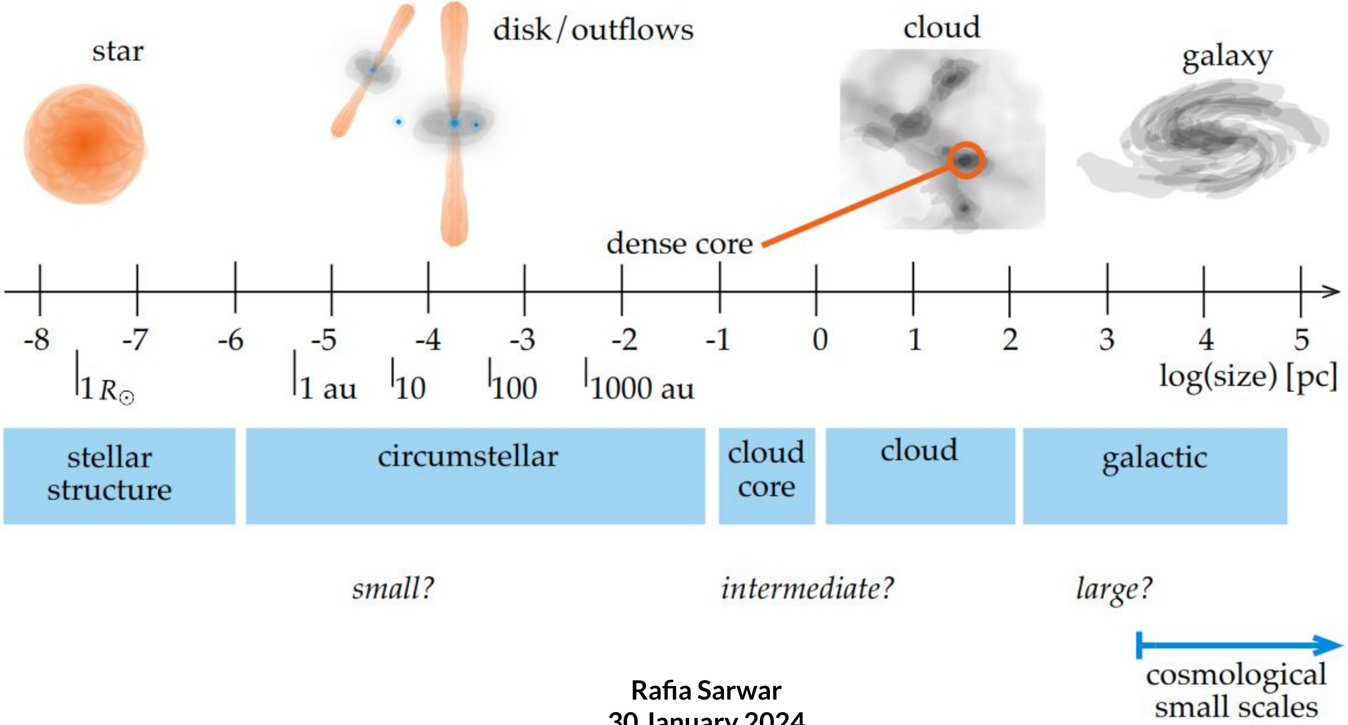
Sizes in the Universe



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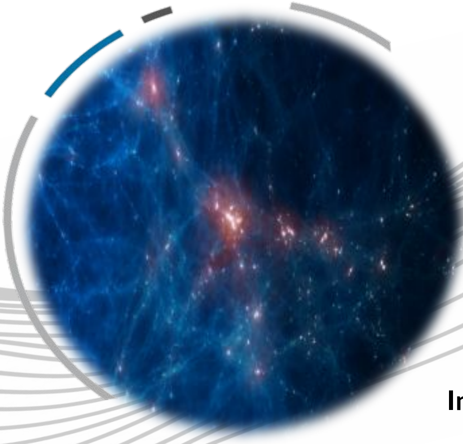
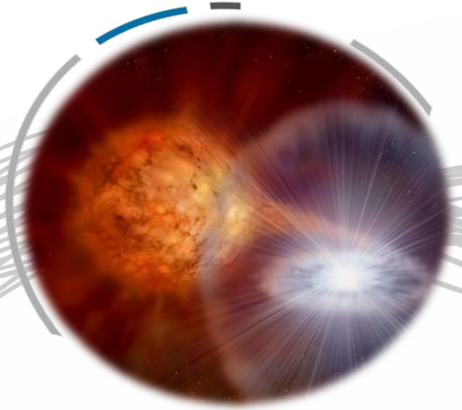
Take home message

Theoretical understanding of the evolution of massive stars and binaries, and their impact on their surrounding environments may be the key to understand early galaxies.





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Thank you …

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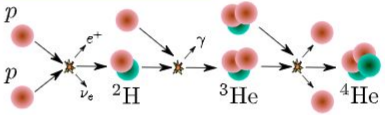
Figure Credit: NASA

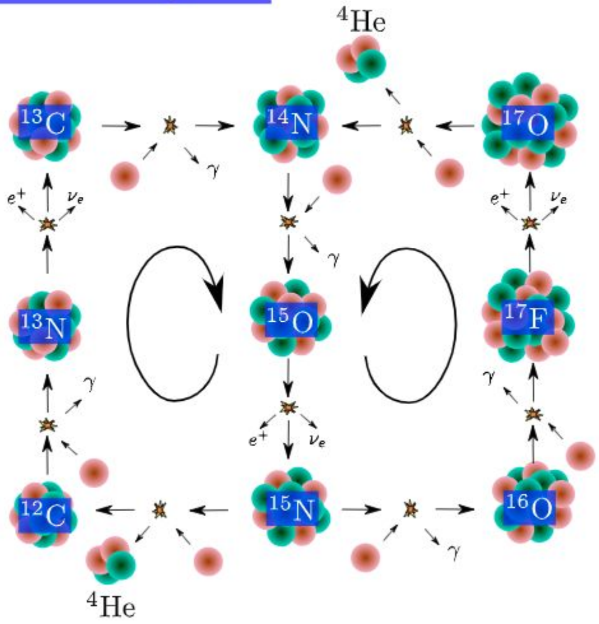
Nuclear burning

PP-I chain



$$p + p \rightarrow {}^2H + e^+ + \nu_e \quad \text{(twice)}$$
$$p + {}^2H \rightarrow {}^3He + \gamma \quad \text{(twice)}$$
$${}^3He + {}^3He \rightarrow {}^4He + p + p$$

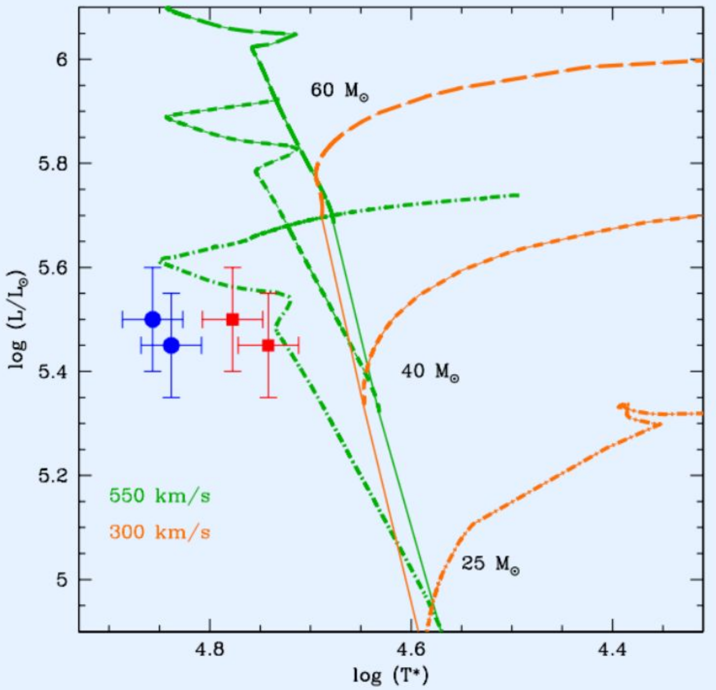
CNO cycle



$${}^{12}C + p \rightarrow {}^{13}N + \gamma$$
$${}^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$$
$${}^{13}C + p \rightarrow {}^{14}N + \gamma$$
$${}^{14}N + p \rightarrow {}^{15}O + \gamma$$
$${}^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$$
$${}^{15}N + p \rightarrow {}^{12}C + {}^4He$$

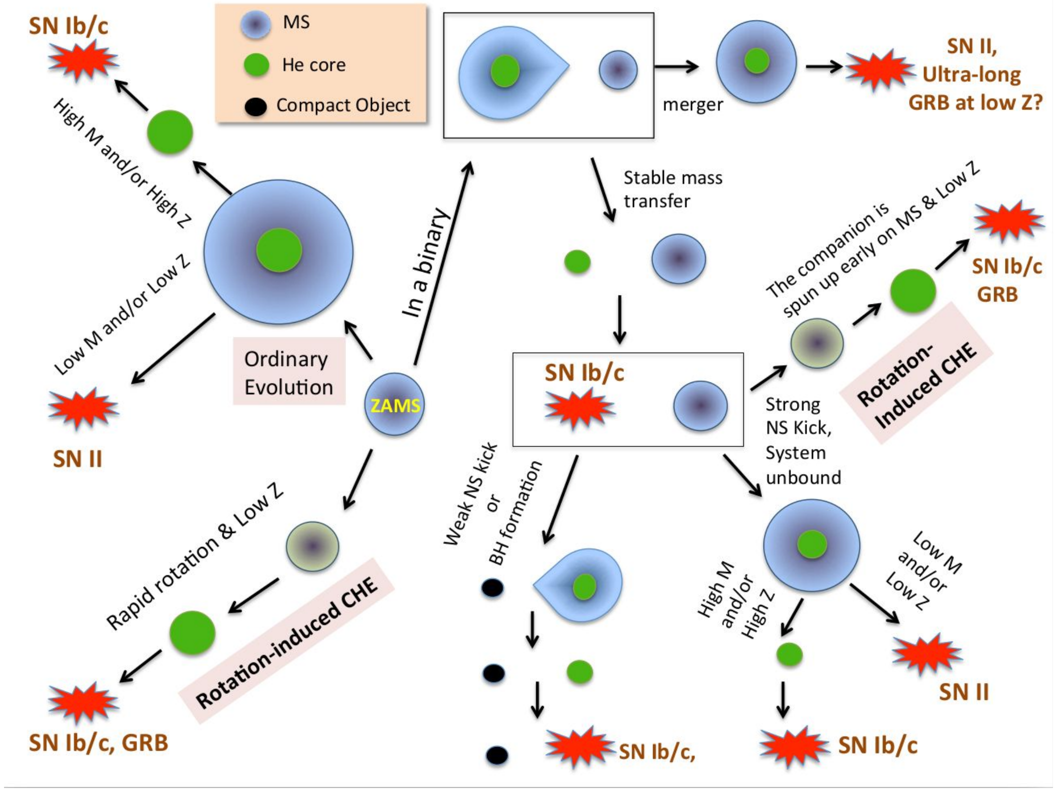
Figure 1.3: Main reactions involved in the proton-proton chain and the CNO cycle. The PP-chain is the main source of energy for low mass stars ($M \lesssim 1.5 M_\odot$), while hydrogen burning in more massive stars is dominated by the CNO cycle.

Evidence for CHE stars

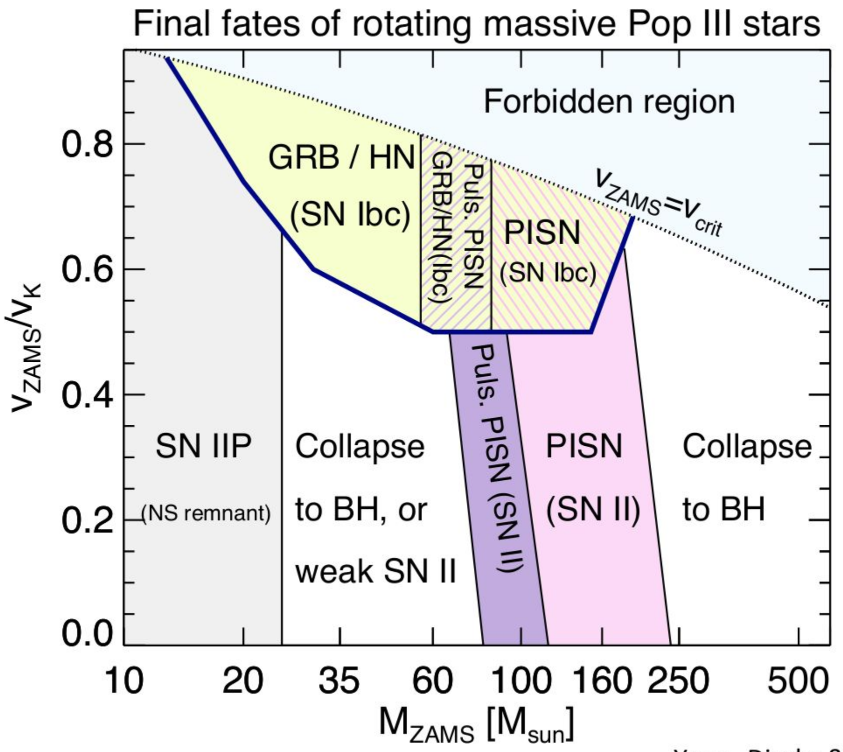


Martins et al. 2013

Fate of rapidly rotating massive stars



Fate of rapidly rotating massive stars



Yoon, Dierks & Langer 2012

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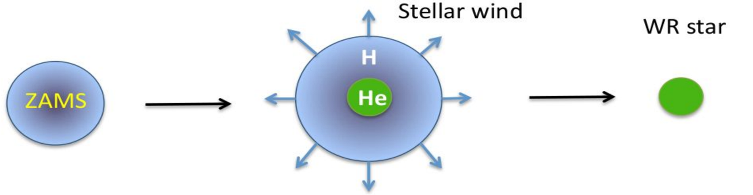
Mass Loss by Winds: Standard scenario for massive star evolution

Mass Loss by Winds:
Standard Scenario for Massive Star Evolution

$$L \propto M^3 \qquad \dot{M}_{\rm wind} \propto L^{1.5} Z^{0.7} \propto M^{4.5} Z^{0.7}$$



WR stars are near the Eddington limit:
- large convective core size
- strong mass loss to remove helium from the envelope.

→ **quasi-chemically homogeneous evolution!**

Mass Loss by stellar winds

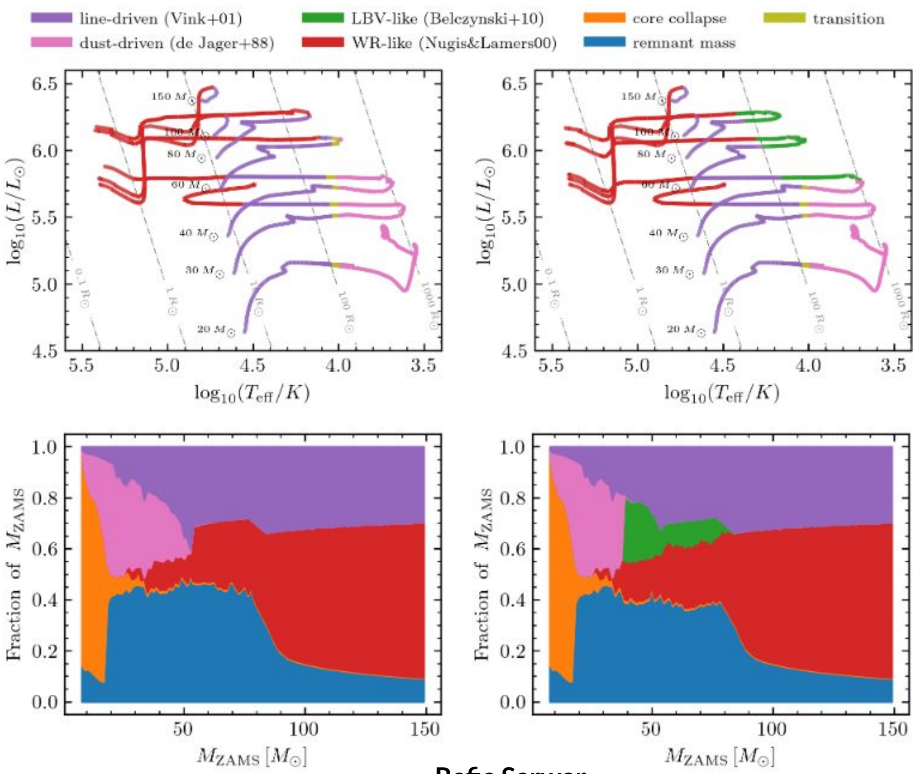


Figure Credit: S. S. Bavera at al. (2023)

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Specific angular momentum

Initial spin of a collapsing star is written as $a_{\rm core} = \frac{J_{\rm core} c}{G M_{\rm core}^2}$

By Bardeen et al. (1972), radius at ISCO, scaled by $GM_{BH}/c.c$ is

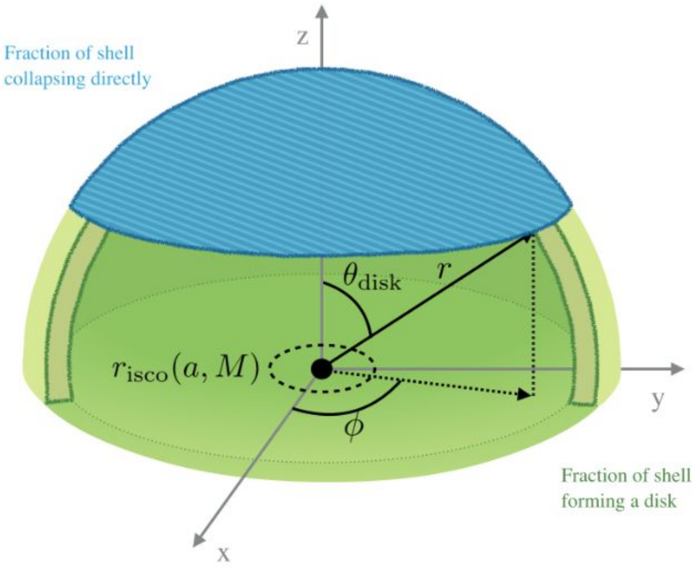
$$r_{\rm isco} = 3 + z_2 \pm [(3 - z_1)(3 + z_1 + 2z_2)]^{1/2}$$

where z_1 and z_2 are determined by the spin according to:

$$z_1 = 1 + (1 - a^2)^{1/3} \left[(1 + a)^{1/3} + (1 - a)^{1/3}\right]$$
$$z_2 = (3a^2 + z_1^2)^{1/2} .$$

The specific angular momentum at ISCO, scaled by GM_{BH}/c, can be written as:

$$j_{\rm isco} = \frac{2}{3^{3/2}} \left[1 + 2(3r_{\rm isco} - 2)^{1/2}\right]$$



ROTATION ALONG Z AXIS

Figure Credit: Batta & Ramirez-Ruiz (2019)

Why do homogeneous stars evolve bluewards

$$R \propto \mu^{2/3} M^{0.81}$$ with homology relation and CNO cycle

$$L \propto \frac{\mu^{7.5} M^{5.5}}{R^{0.5}}$$ with homology relation and Kramer's opacity law

$$\longrightarrow \quad T_{\text{eff}} \propto \mu^{1.5} M^{0.75}$$