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Progenitors of LGRBs: Are single stars enough?

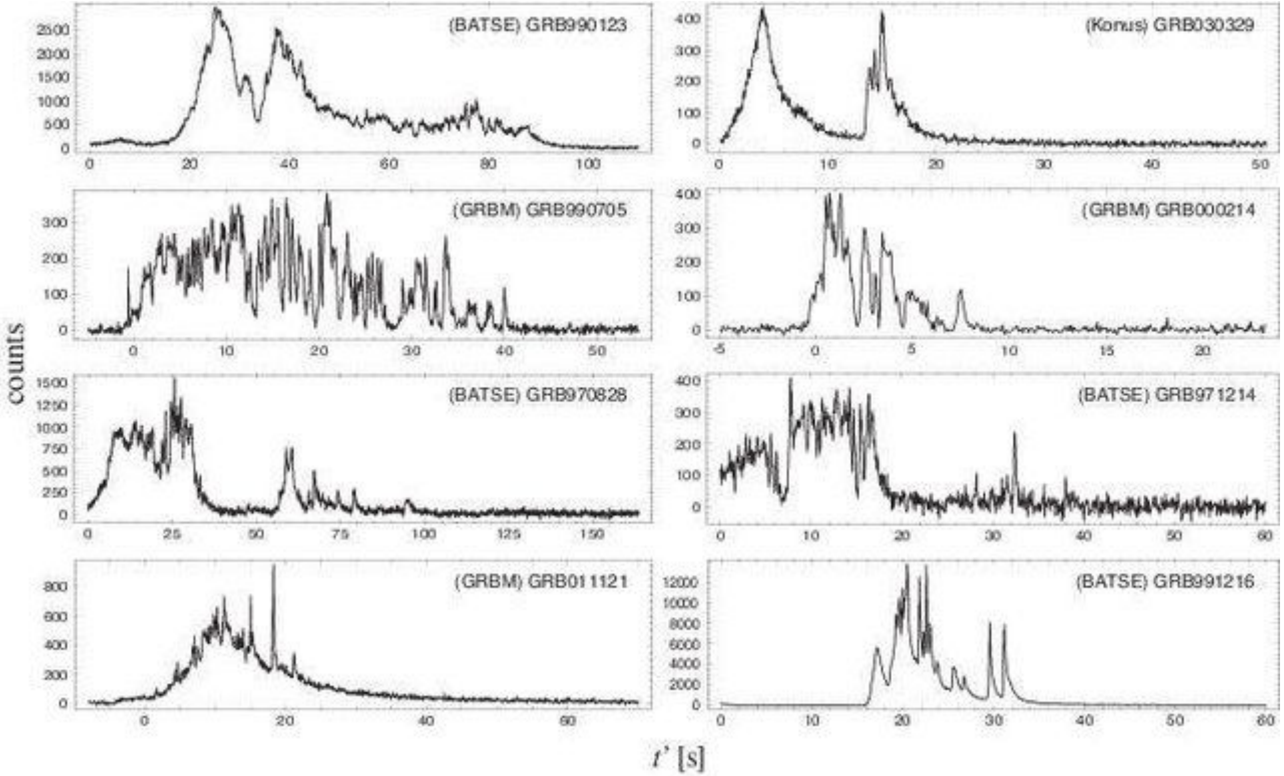
***Rafia Sarwar* [1], *Dorottya S zécsi* [1], *Koushik Sen* [1], *Poojan Agrawal* [2], *and Hanno Stinshoff* [1]**

[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
18th September 2024
VLT-FLAMES TaranTula Survey Meeting,
European Space Agency Centre, Madrid, Spain

Figure Credit: NASA

What is a gamma ray burst...



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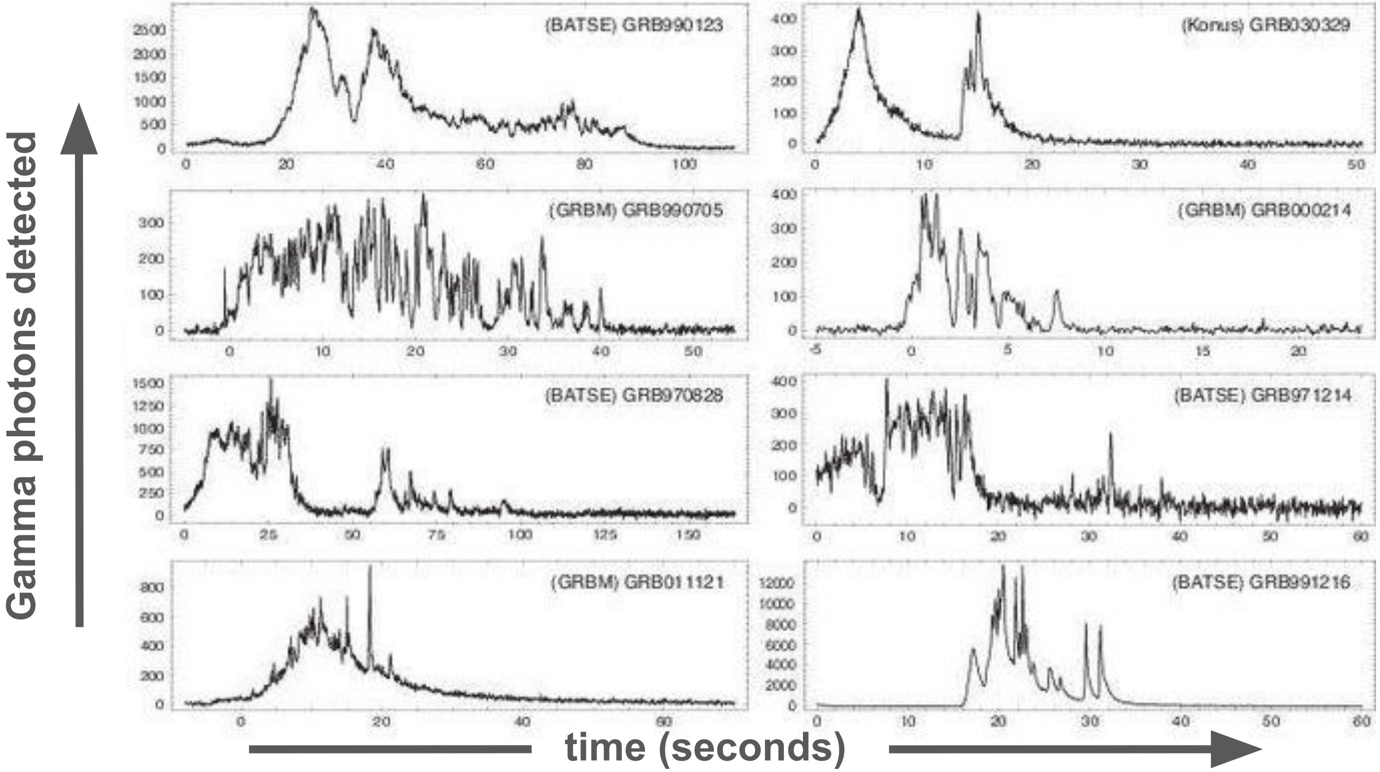
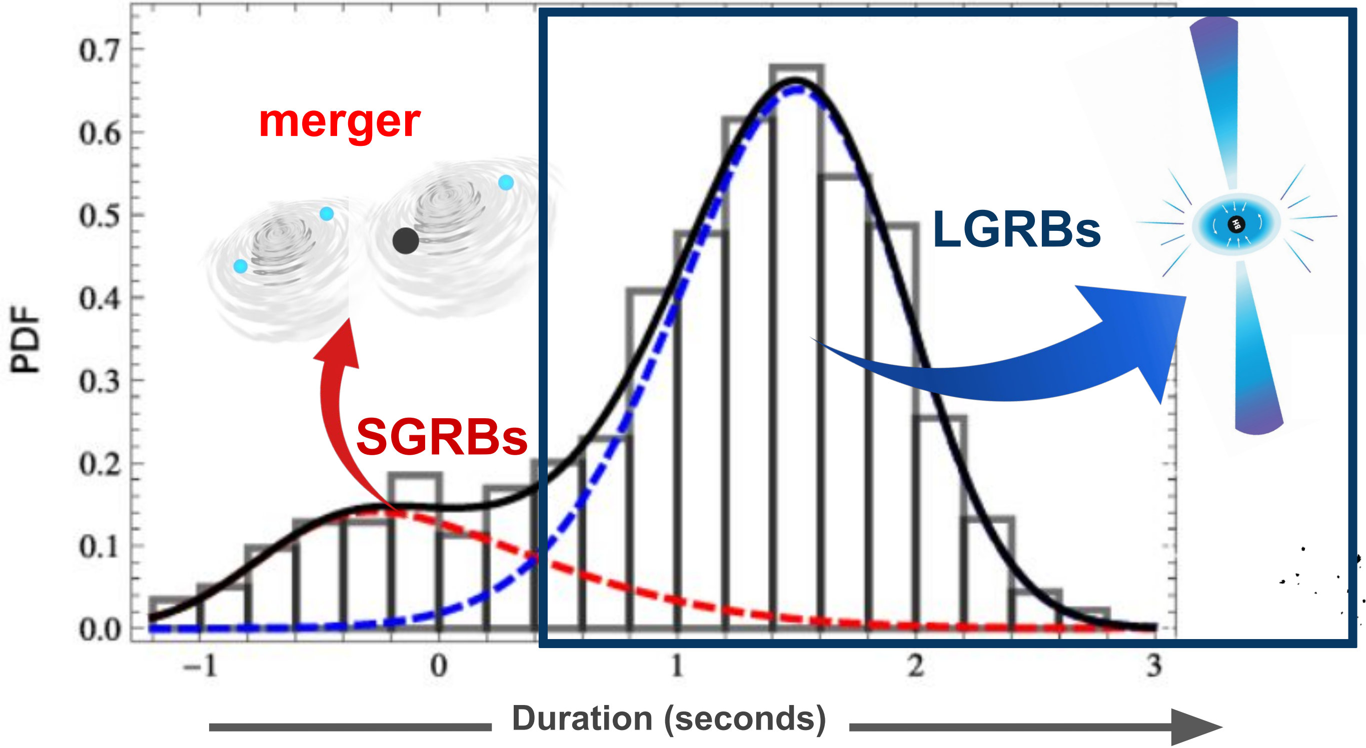
What is a gamma ray burst...



Rafia Sarwar
18th September 2024

What is a gamma ray burst...



Mariusz Tarnopolski (2016)

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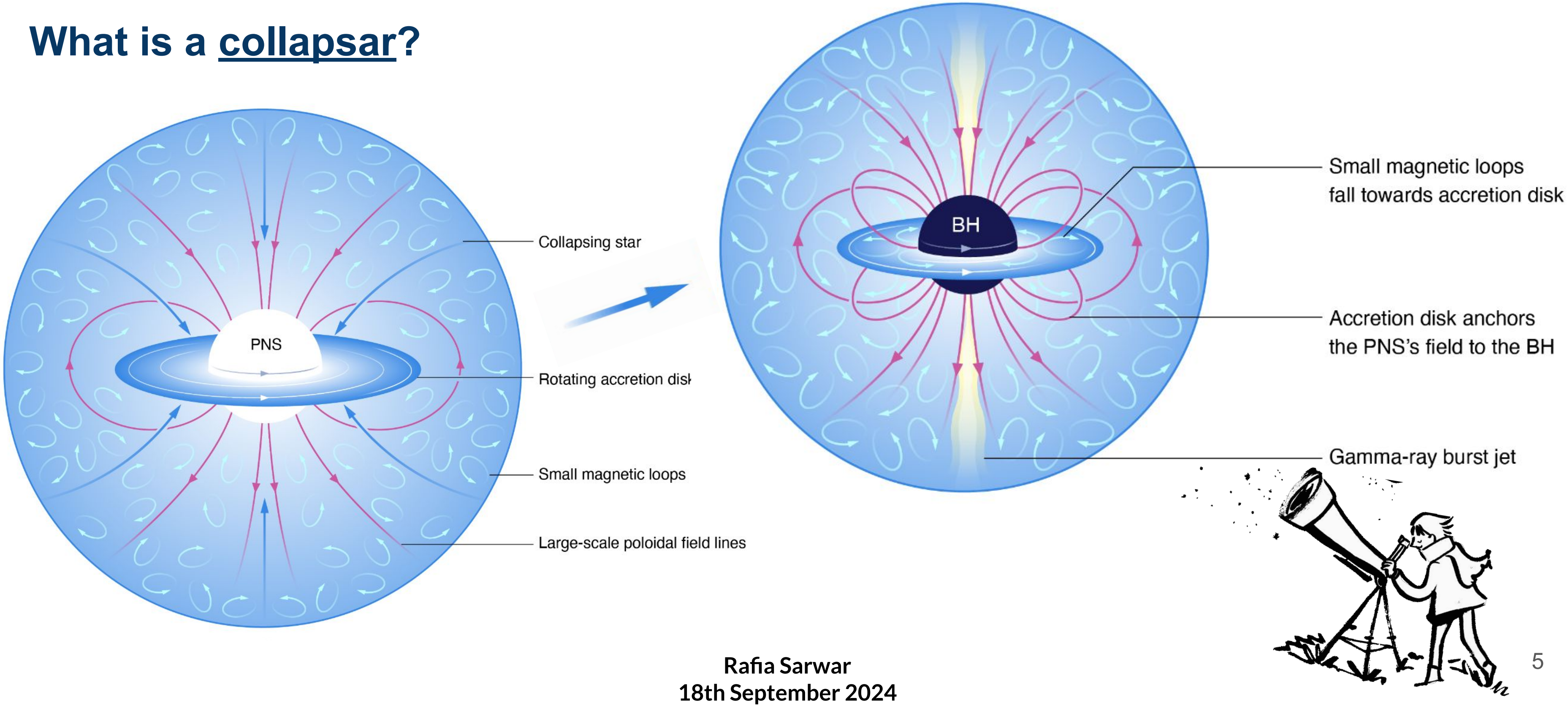
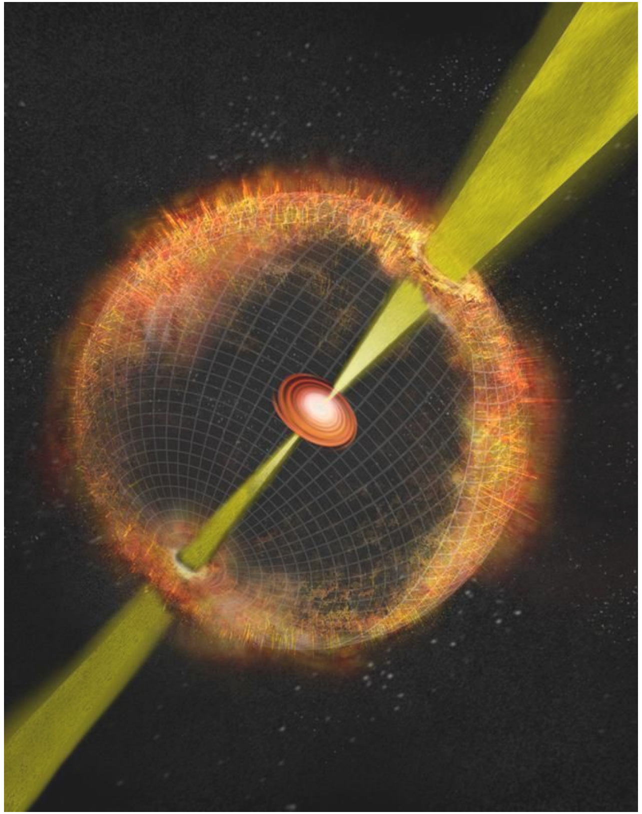
How can we produce a LGRB?

What is a collapsar?



Conditions for a collapsar



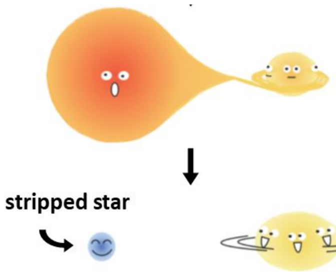
3 conditions for collapsars

- Iron core
- Fast rotation
- no or tiny envelope

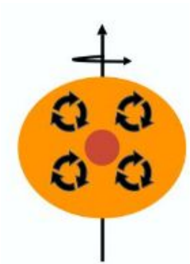
➔ We need a spinning naked helium star!

Spinning naked Helium star

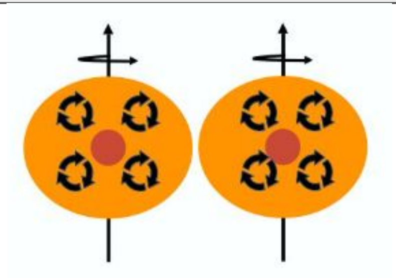
Classic Wolf-Rayet star?



Wolf-Rayet star from a binary?



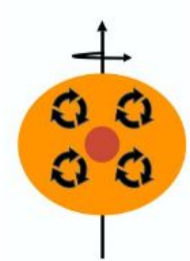
Chemically homogeneous evolution



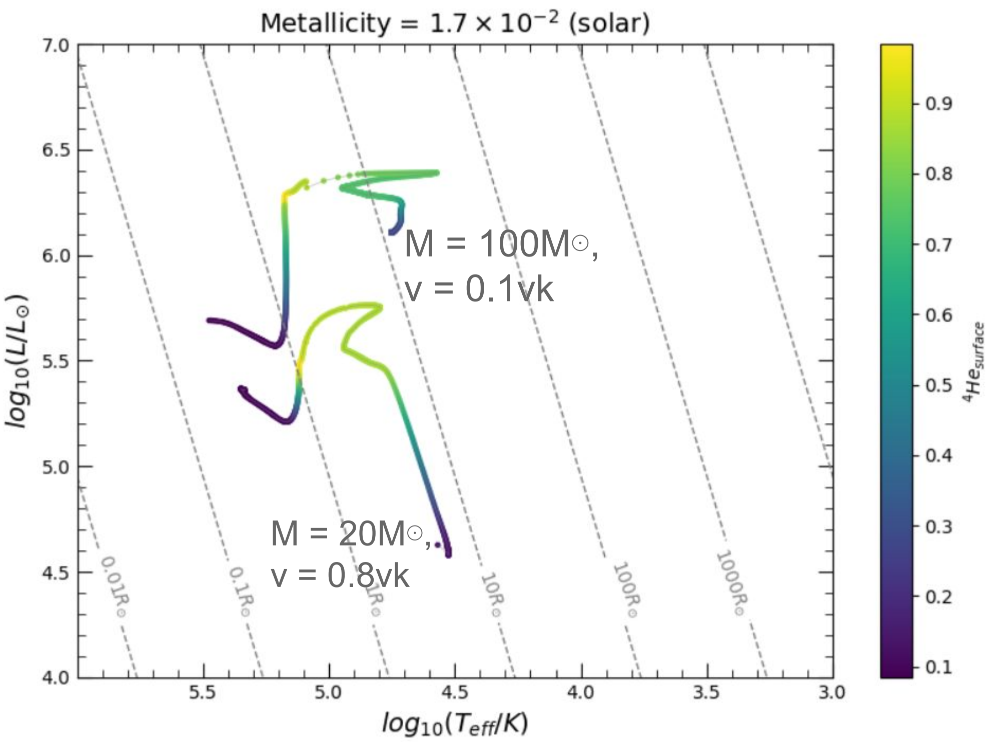
CHE binary

Spinning naked Helium star

Classic Wolf-Rayet star?



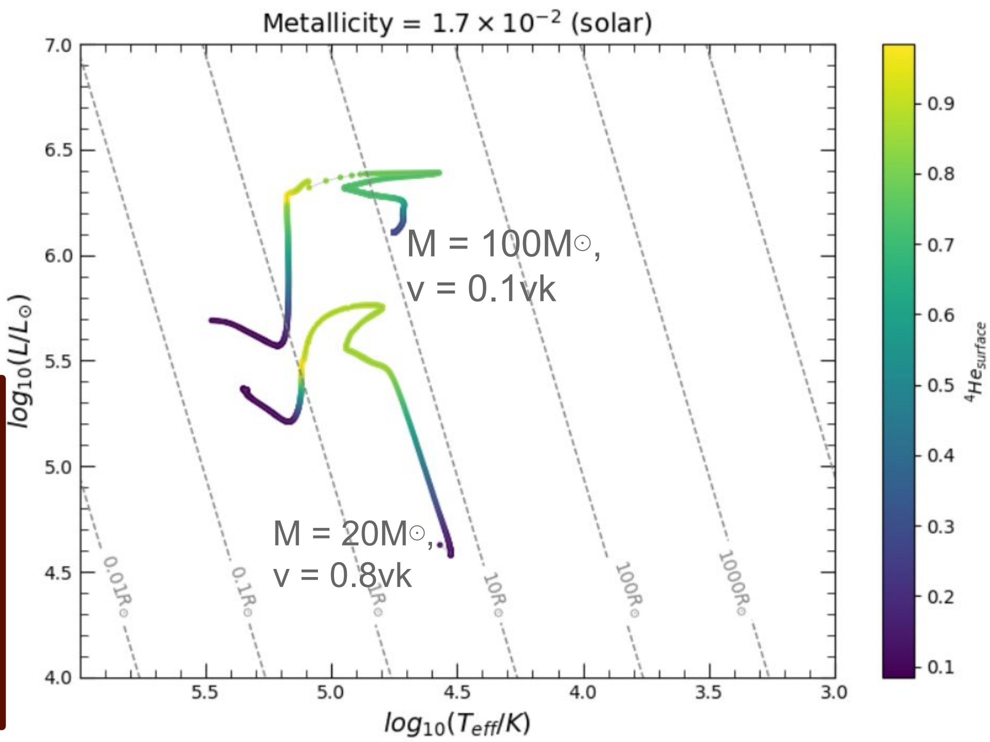
Chemically homogeneous evolution



Spinning naked Helium star

Classic Wolf-Rayet star?

Chemically homogeneous evolution



Observational data

GRBOX : Gamma-Ray Burst Online Index

[about] [help] [report errors/bugs] v 0.7

filter by year:
[2018] [2017] [2016] [2015] [2014] [2013] [2012] [2011] [2010] [2009] [2008] [2007] [2006] [2005] [2004] [2003] [2002] [2001] [2000] [1999] [1998] [1997] [older] [all]

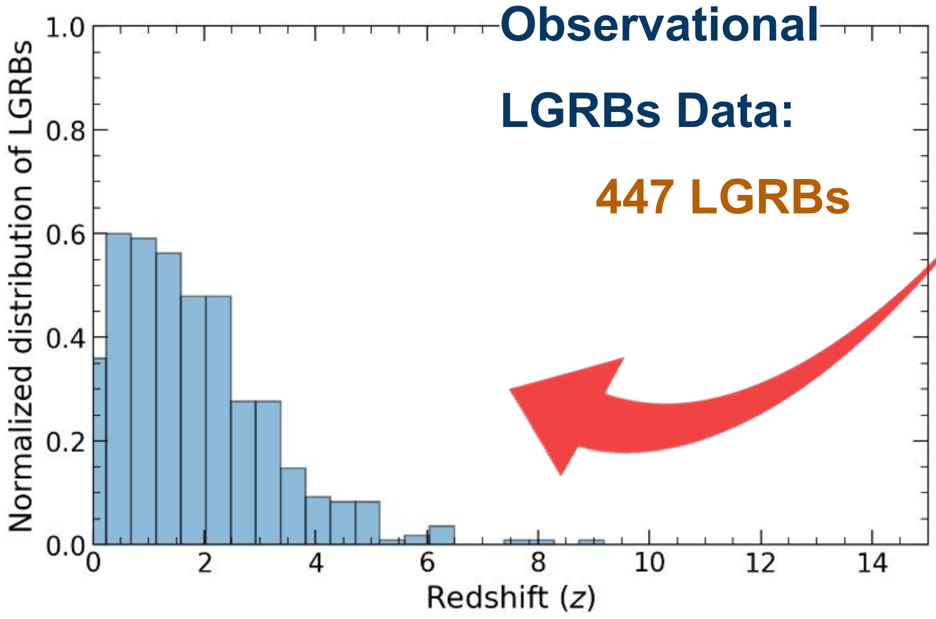
GRB	T90	comments	RA	Dec	z	Greiner X	O	R	refs
180325A	94.1	Very luminous, reddened afterglow with 2175-A dust bump. Optical observations during main burst peak.	10:29:42.7	+24:27:49.3	2.04				
180324A	7.2	Possible very weak afterglow	05:06:06.37	+56:42:51.5					
180316A	87	Bright early afterglow.	17:41:42.94	+00:44:54.0					
180314B	73	Some follow-up, no deep limits.	19:51:32.80	+23:37:26.6					
180314A	51.2	Bright UV/optical afterglow; well-observed.	06:37:03.7	-24:29:45.8	1.445				
180311A	23	No ground follow-up.	00:13:33.05	-54:29:29.2					
180305A	12.5	LAT burst with X-ray/optical afterglow.	03:18:28.33	+32:06:36.2					
180224A	10.9	Bright early OT but little further follow-up.	13:30:44.057	+38:04:44.55		y			
180210A	40	Fermi/LAT burst with afterglow.	00:07:22.02	+18:33:09.9					
180205A	15.5	Bright burst; very bright afterglow. Extensive observations	08:27:16.74	+11:32:30.9	1.409	y			

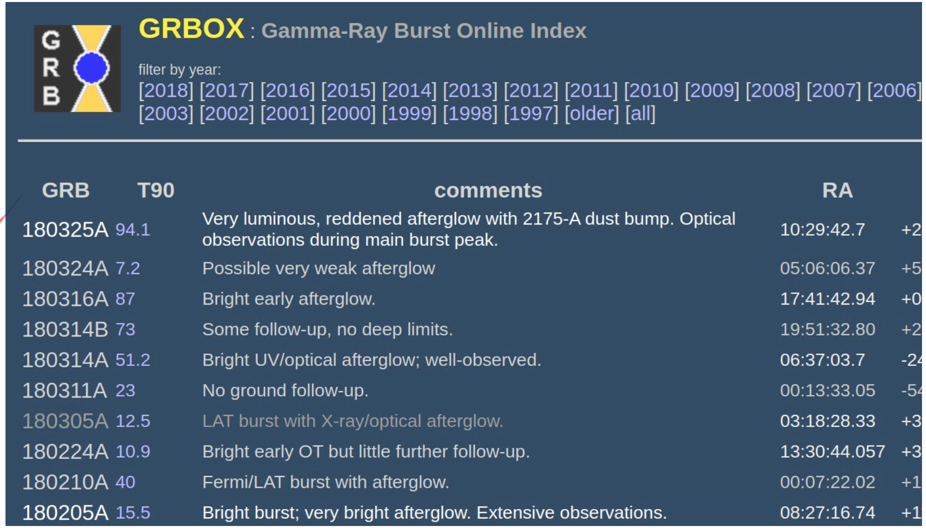
https://sites.astro.caltech.edu/grbox/grbox.php?starttime=700101&endtime=181231

Motivation

Observational LGRBs Data:

447 LGRBs





GRBOX : Gamma-Ray Burst Online Index

filter by year:
[2018] [2017] [2016] [2015] [2014] [2013] [2012] [2011] [2010] [2009] [2008] [2007] [2006]
[2003] [2002] [2001] [2000] [1999] [1998] [1997] [older] [all]

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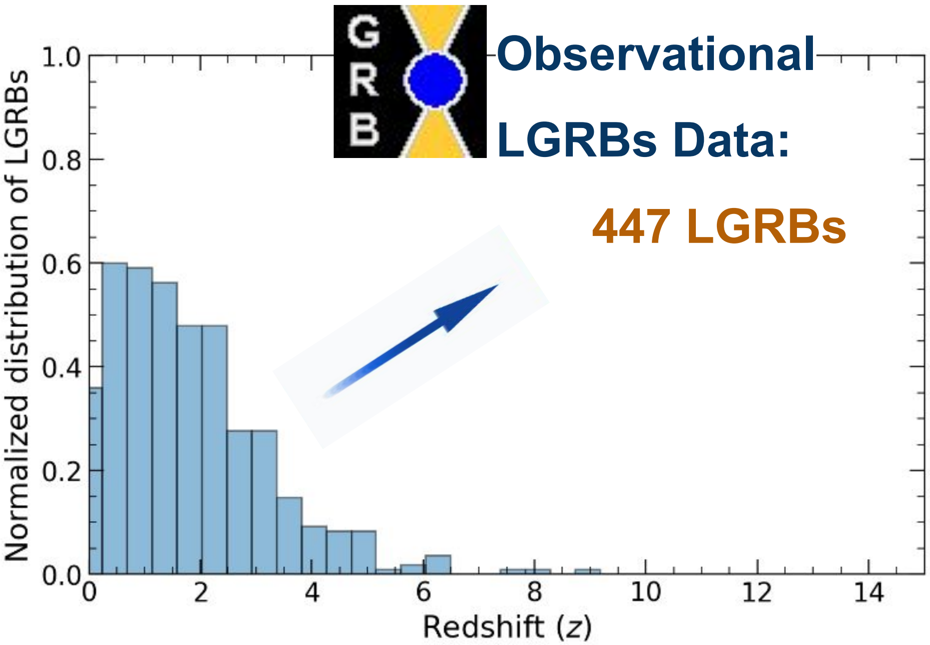
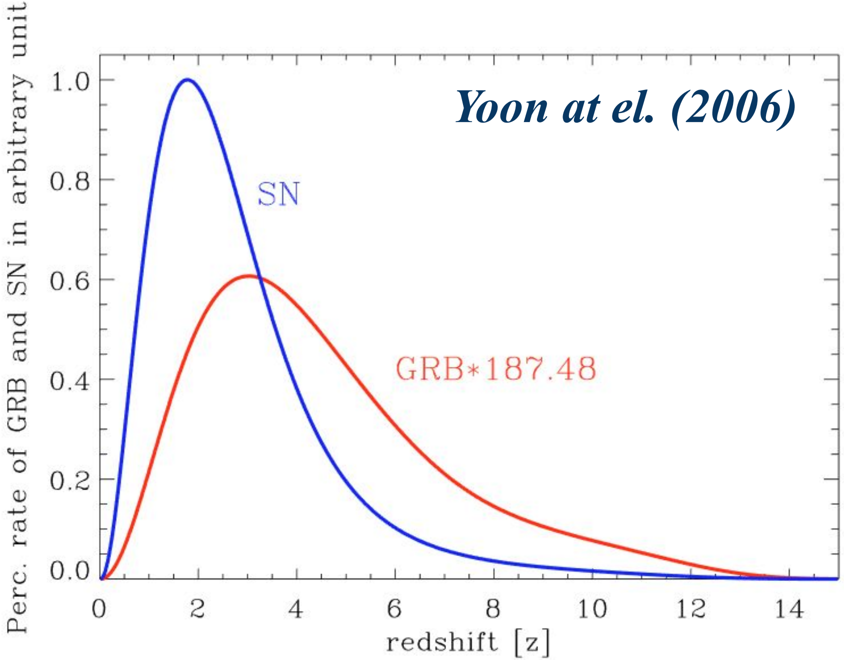
180224A	10.9	Bright early OT but little further follow-up.	13:30:44.057	+3
180210A	40	Fermi/LAT burst with afterglow.	00:07:22.02	+1
180205A	15.5	Bright burst; very bright afterglow. Extensive observations.	08:27:16.74	+1

https://sites.astro.caltech.edu/grbox/grbox.php?starttime=700101&endtime=181231

Motivation





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Market of stellar evolution codes

TWIN

MESA

GENeva stellar Evolution Code

PARSEC

Padova

BINSTAR

Bonn code

GARching Stellar Evolution Code

Yale Rotation Evolution Code

FRANEC

Darthmouth Stellar Evolution Code

STERN

Code Liègeois d'Evolution Stellaire

STAREVOL

Code de Montpellier-Montréal

Lyon Evolutonary code

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Model parameters

Initial masses	**10M⊙**	**20M⊙**	**30M⊙**	**40M⊙**	**50M⊙**	**60M⊙**	**70M⊙**	**80M⊙**	**90M⊙**	**100M⊙**

Metallicities	**0.017 (solar)**	**0.01**	**0.004 (LMC)**	**0.002 (SMC)**	**0.001**	**0.0001**	**0.00001**

Initial velocity	**0.1vk**	**0.2vk**	**0.3vk**	**0.4vk**	**0.5vk**	**0.6vk**	**0.7vk**	**0.8vk**

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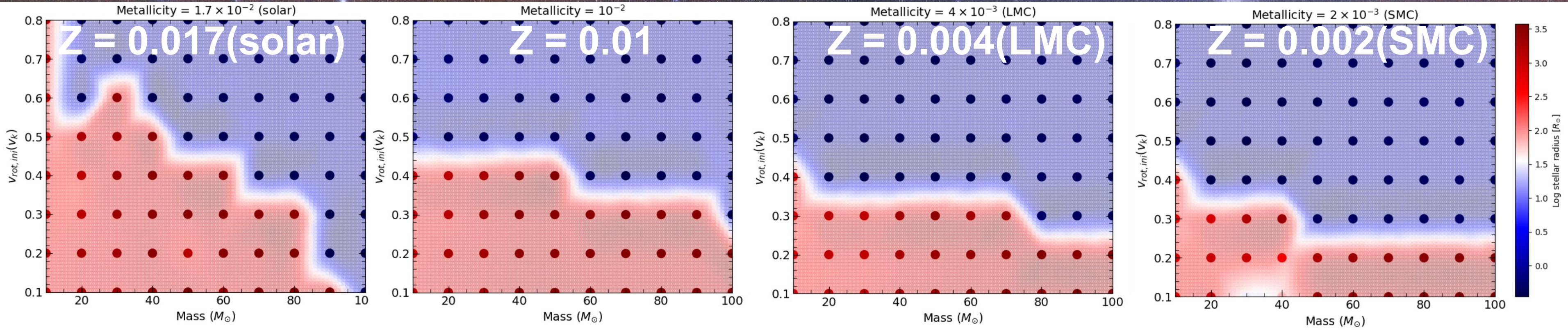
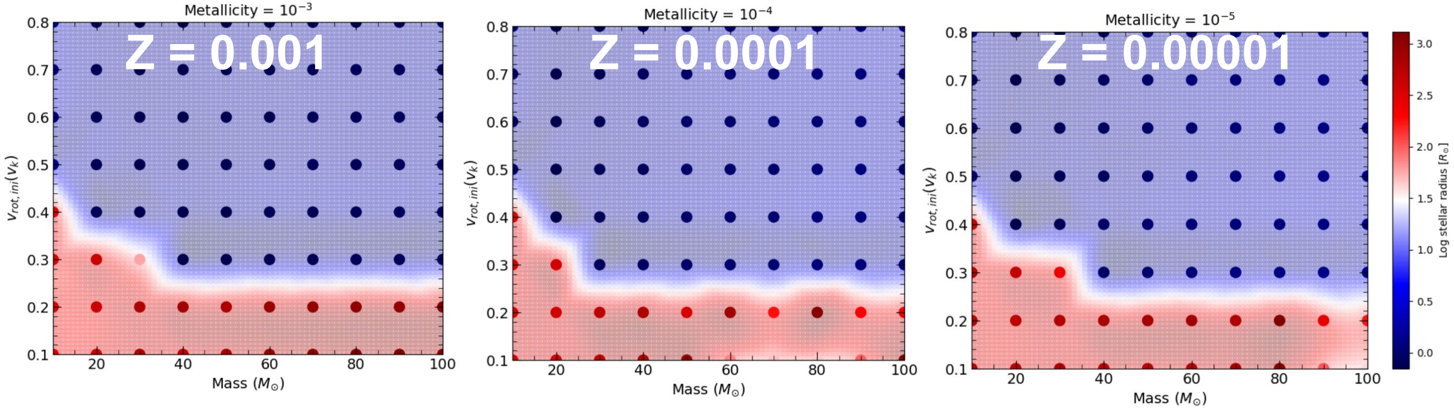
Evolution of massive stars





R. Sarwar et al. (2024)
In preparation

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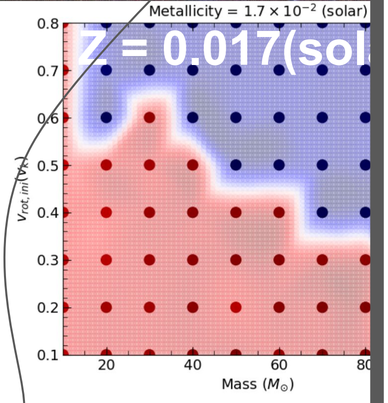
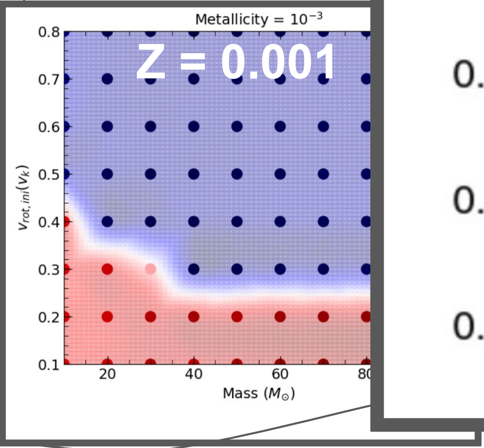
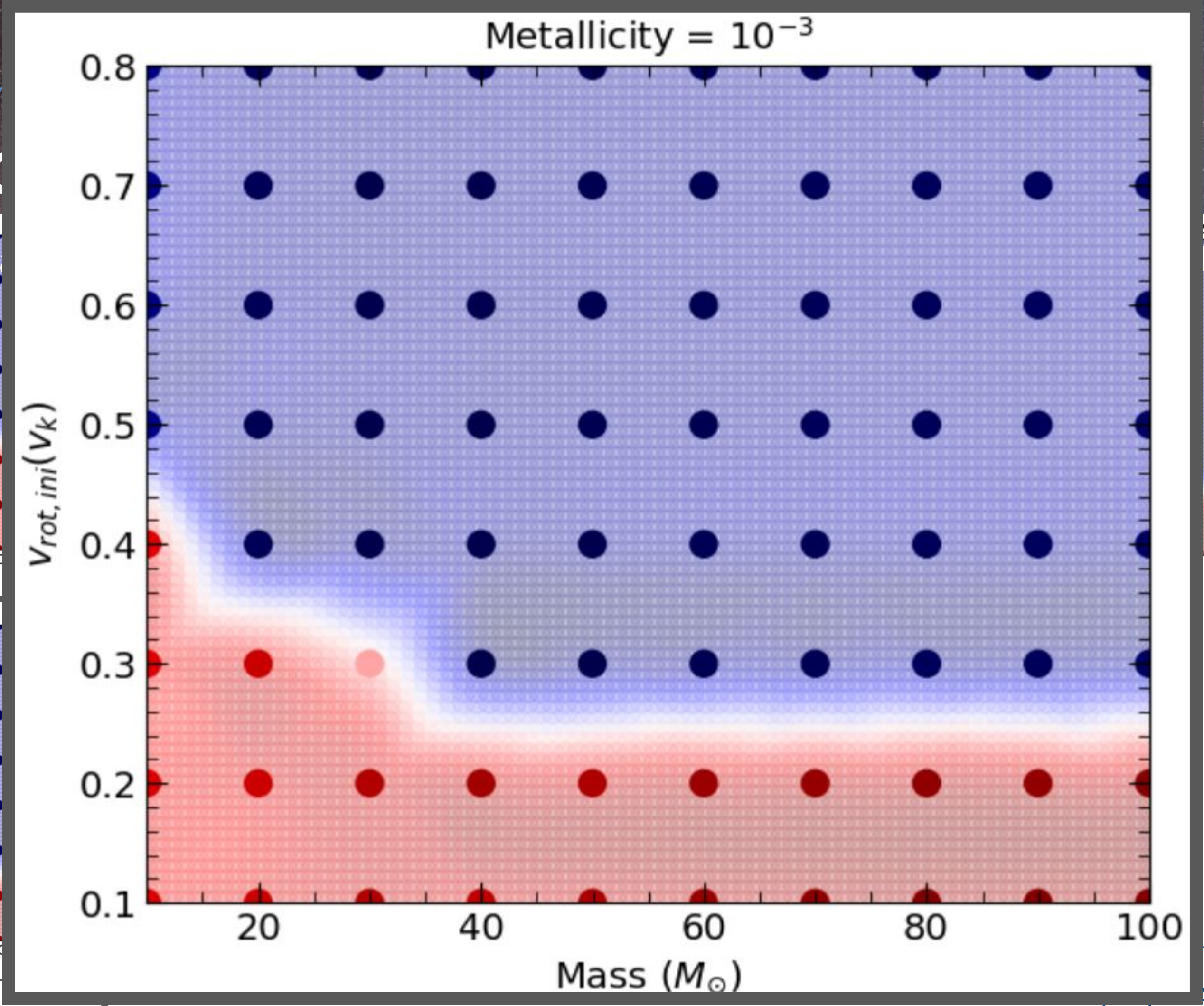
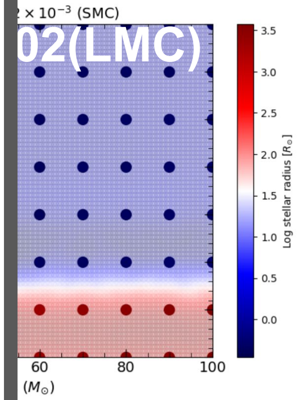
Evolutio…







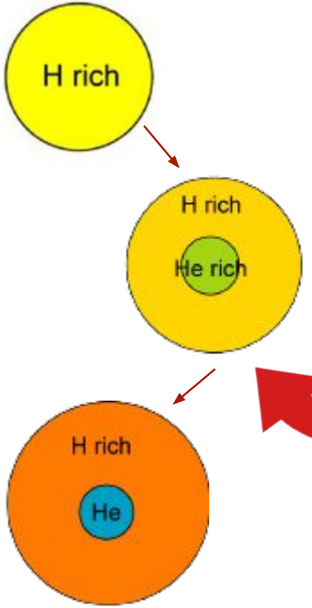


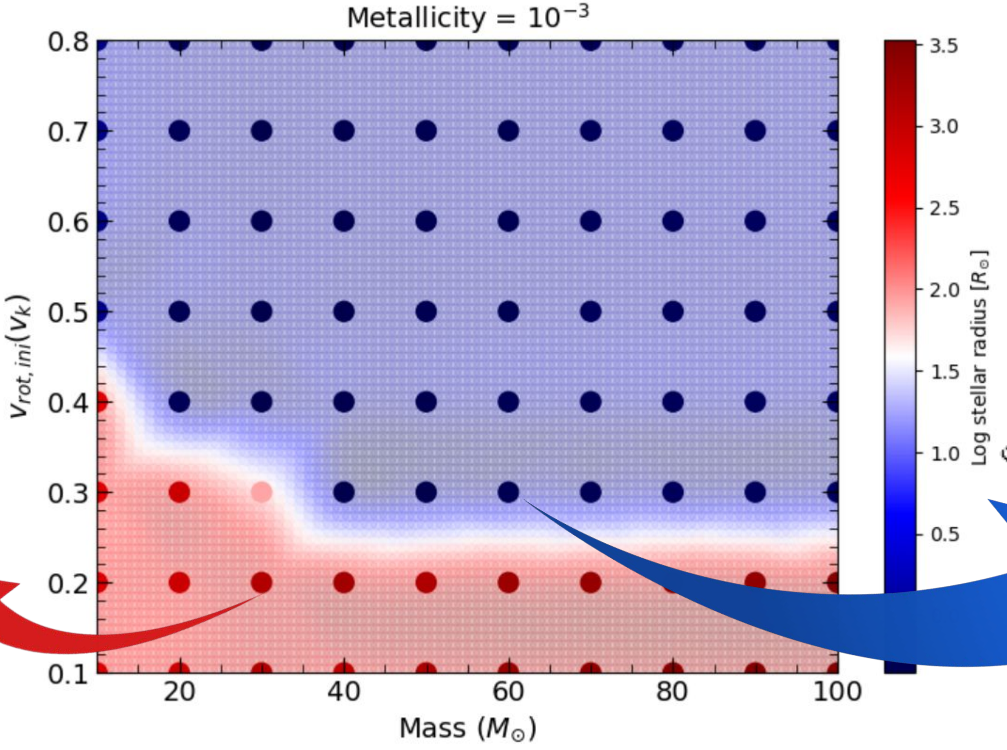
et al. (2024)
ation

Evolution of massive stars

Slowly rotating:

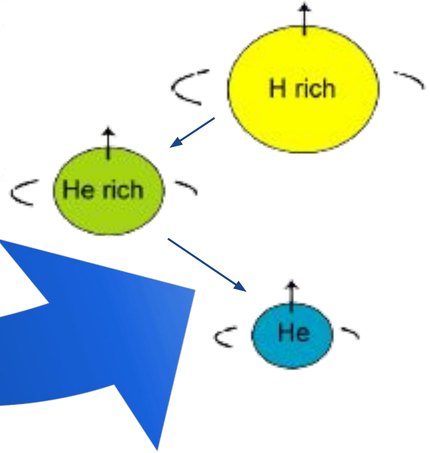
- classical core-envelope
- red-supergiant





Rapidly rotating massive stars:

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



R. Sarwar et al. (2024)
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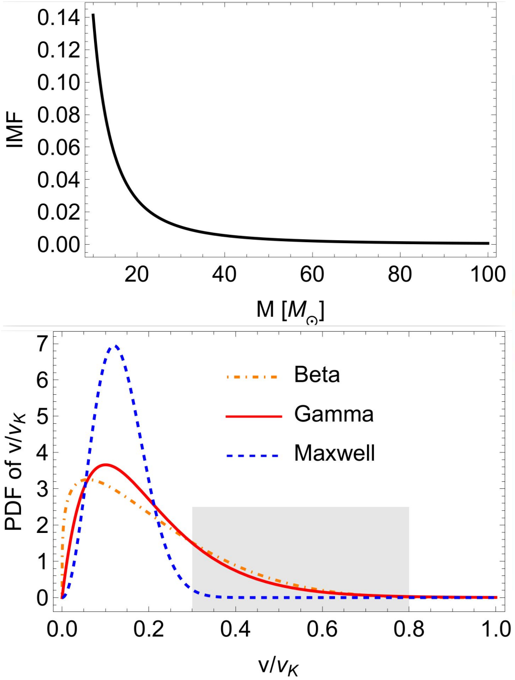
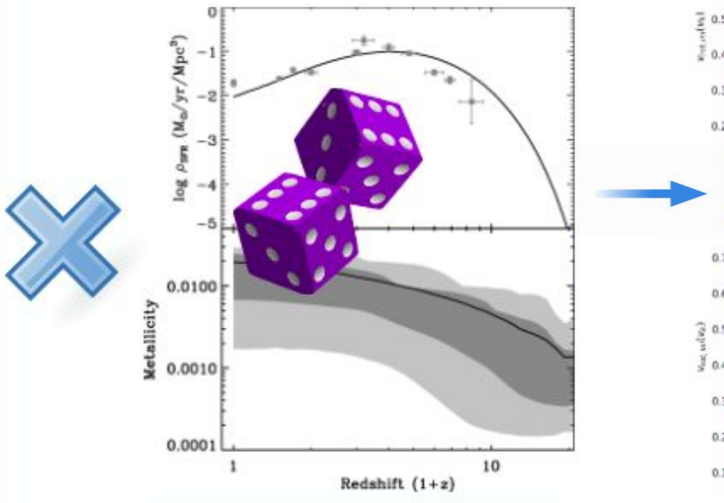
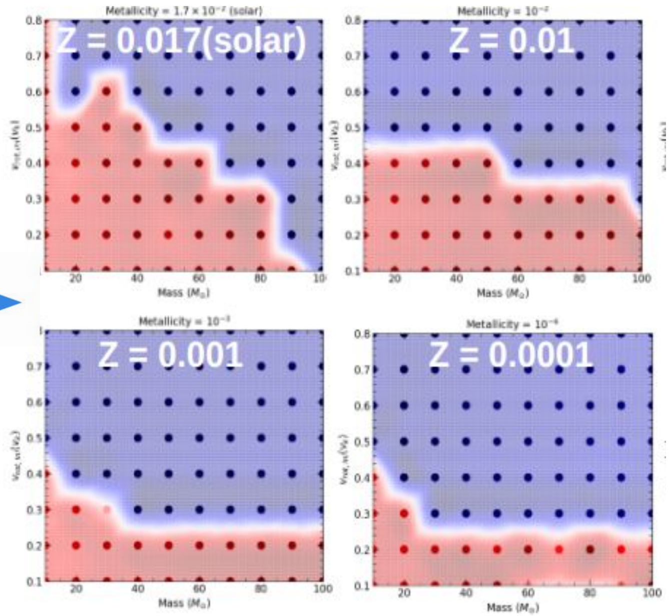
Population synthesis

Initial mass function (IMF) + Rotational velocity distribution



Star formation rate (SFR) + Cosmic metallicity density distribution





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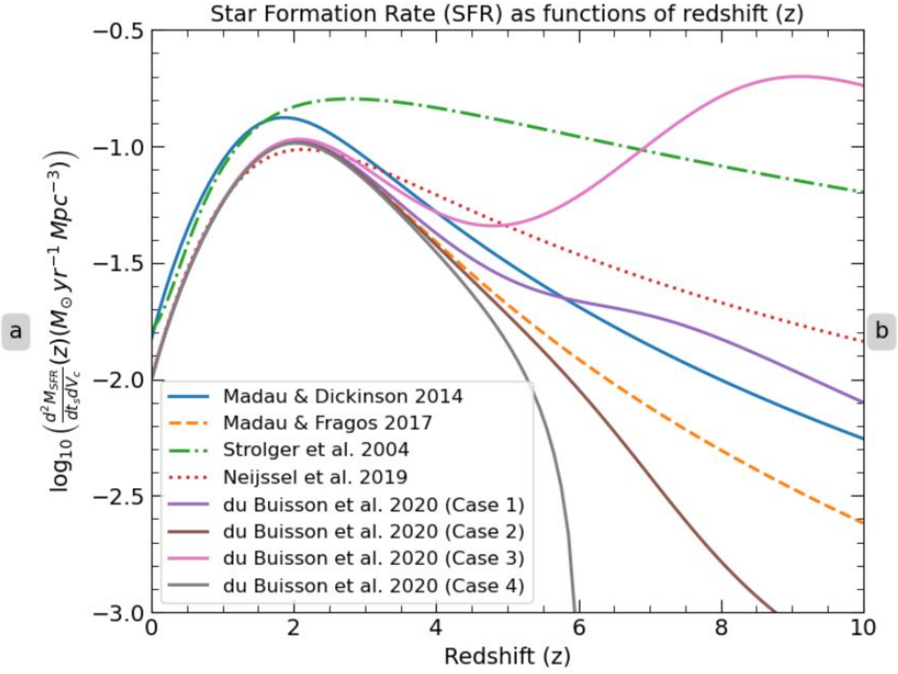
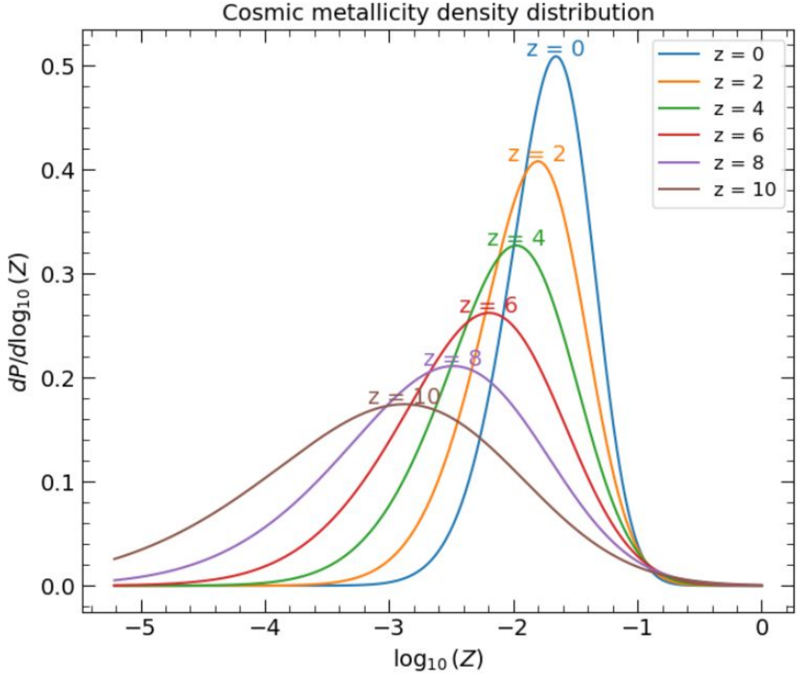
Cosmic star formation rate and metallicity distribution



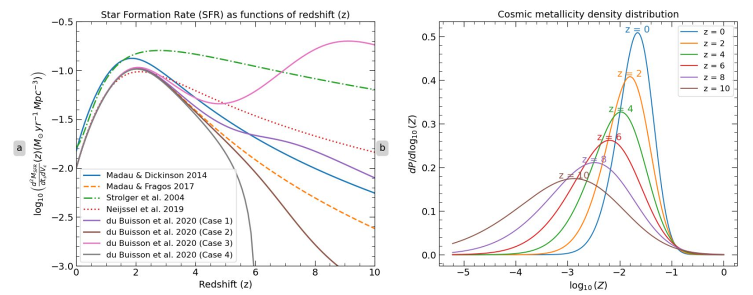


$$\mathrm{SFRD}(z) = \frac{d^2M_{\mathrm{SFR}}}{dtdV_c}(z) = a\frac{(1+z)^b}{1+[(1+z)/c]^d}$$

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

L.A.C. van Son et al. (2023)

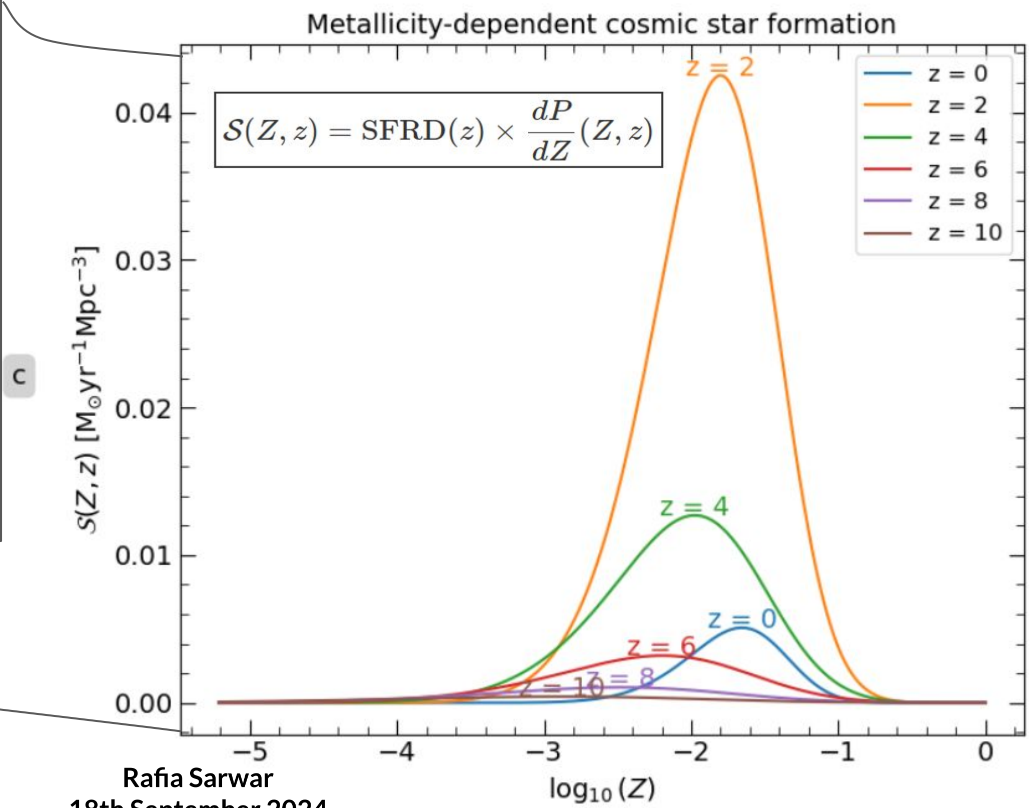
Metallicity-dependent cosmic star formation



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

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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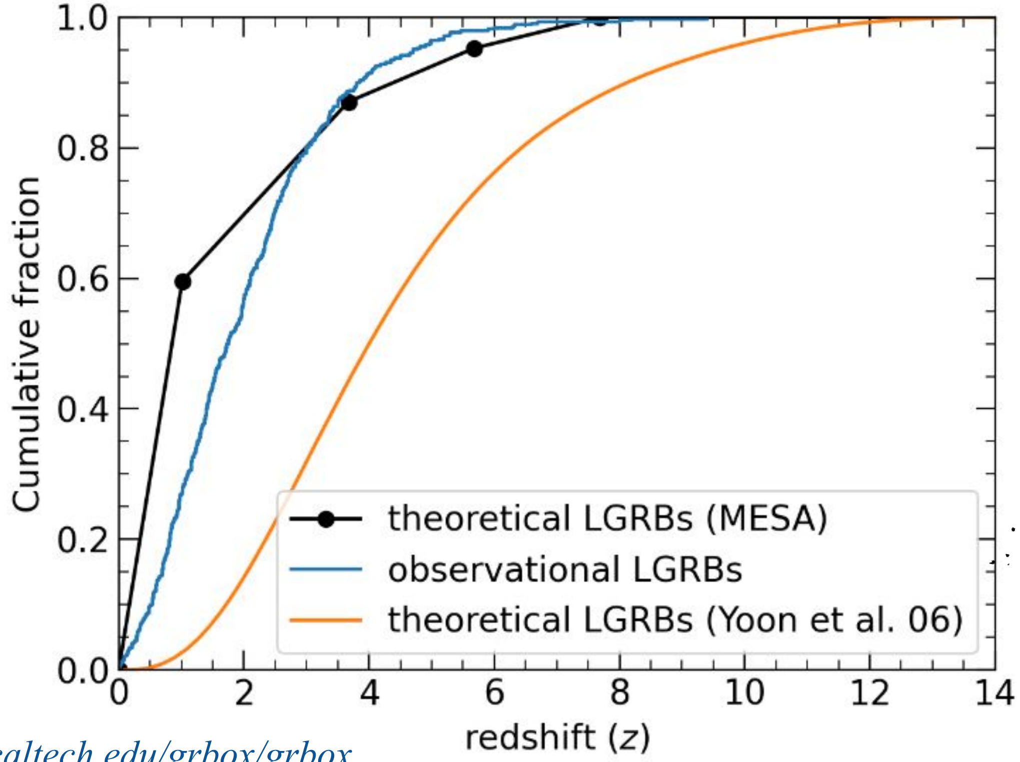
Single star models vs observation



R. Sarwar et al. (2024)
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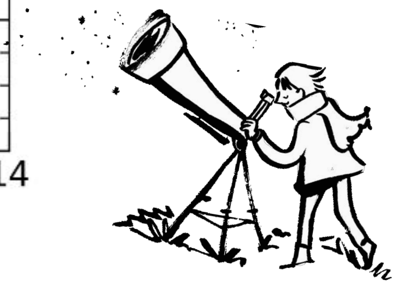
https://sites.astro.caltech.edu/grbox/grbox.php?starttime=700101&endtime=181231



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Further steps

- Use different SFR distributions and see which one matches the best with observations
- Excluding PPISNe from stellar models (simulating PPISNe phase – not part of models)
- Look into observational biases (collaboration Dr. Christina Thöne)
- Compare with the literature
- Binary models
- Reproducing the duration histogram ($\longrightarrow$ next slide)

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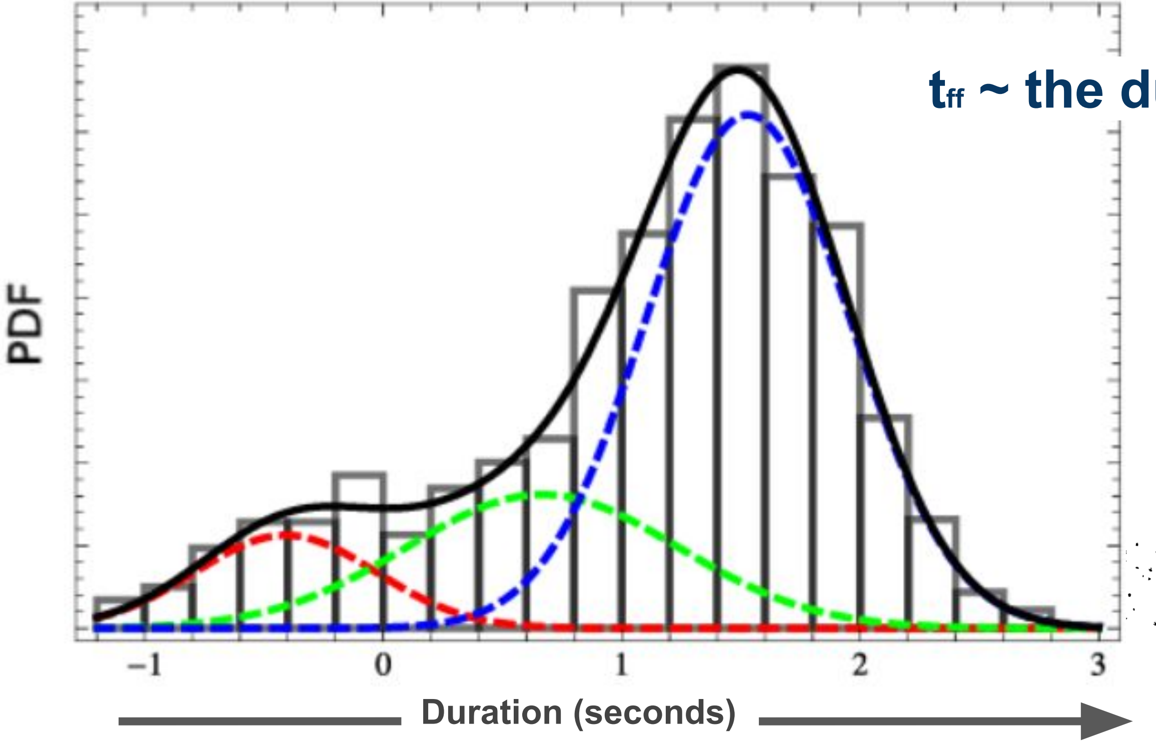
Reproducing the skewed duration distribution



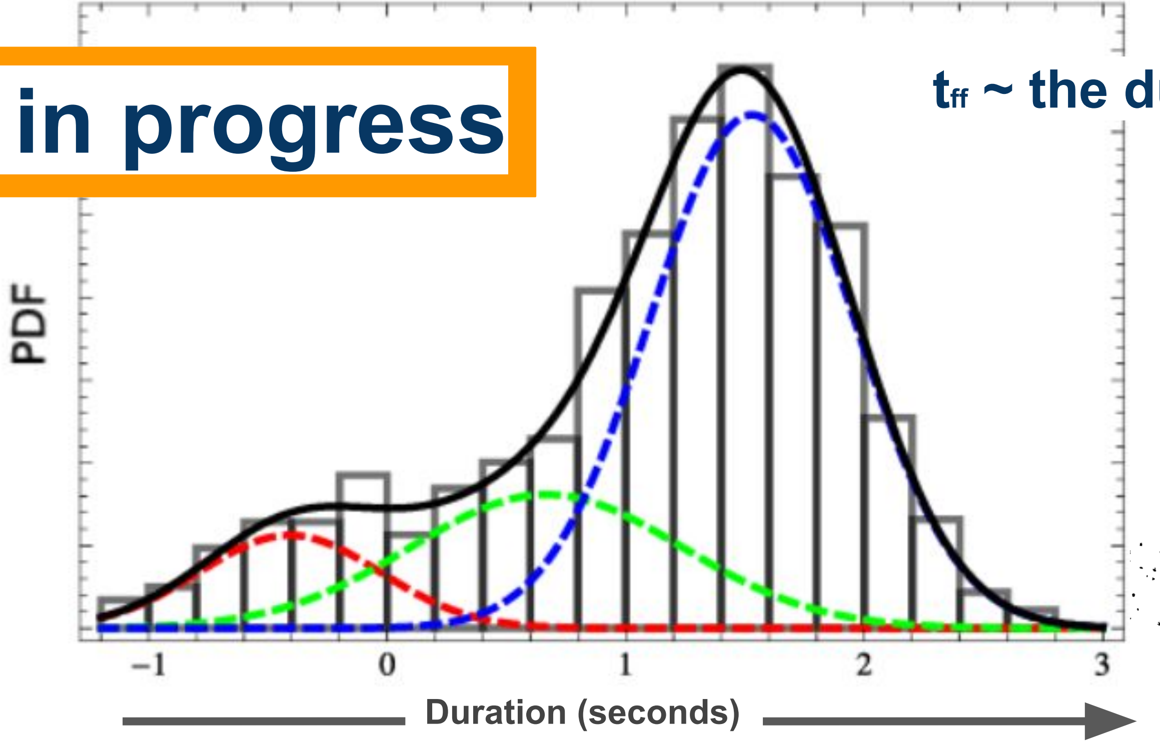
t_{ff} ~ the duration

Mariusz Tarnopolski (2016)

Reproducing the skewed duration distribution

Work in progress

t_{ff} ~ the duration



Mariusz Tarnopolski (2016)

Take home message

Updated theoretical models fit the observations better than Yoon's 2006

- **Wind mass loss prescriptions**
- **Extended initial mass range to 100$M_\odot$ (instead of 60$M_\odot$)**
- **Updated star formation rates**
- **Cosmic metallicity distribution**

Take home message

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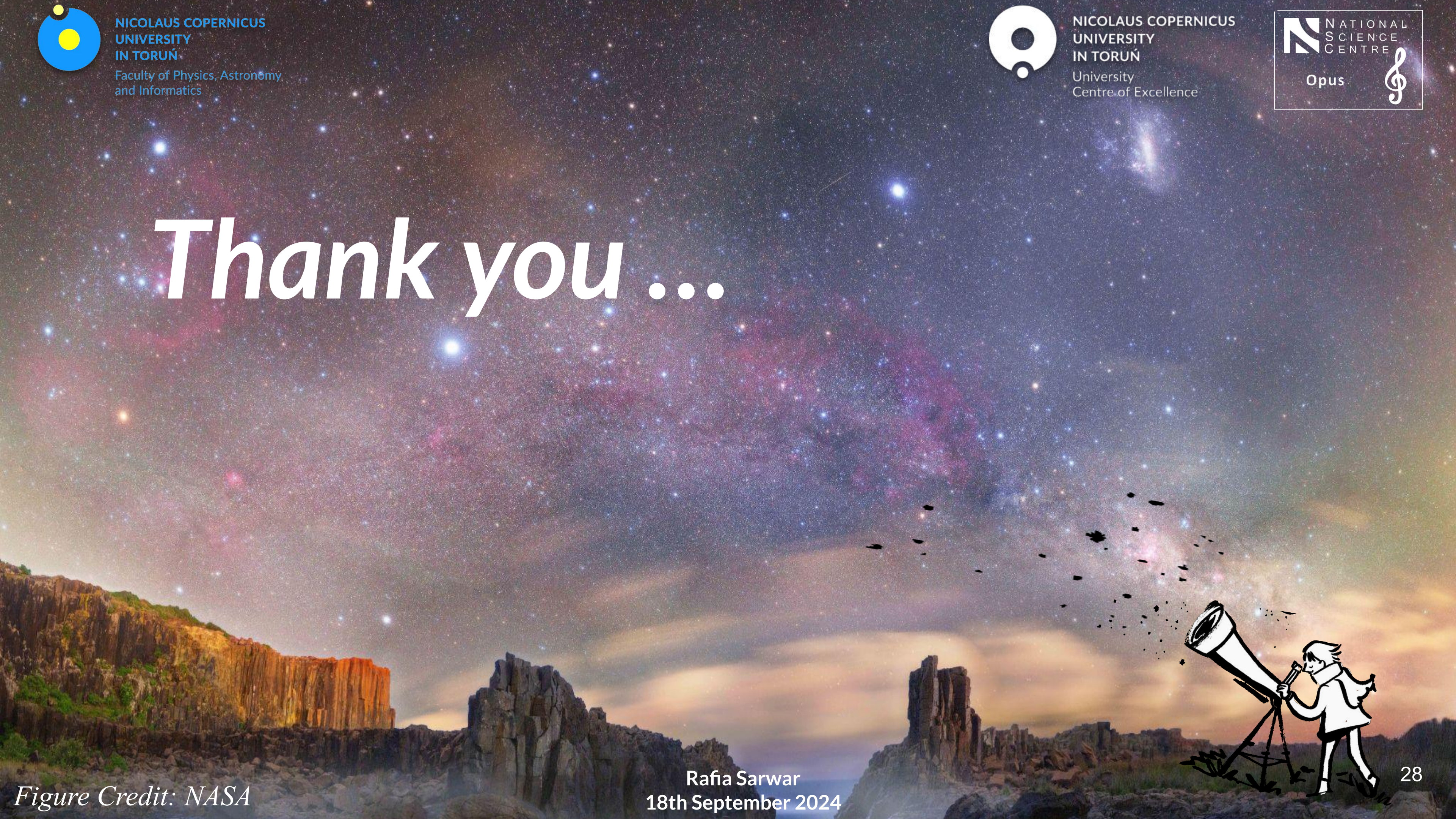

Thank you ...

Figure Credit: NASA

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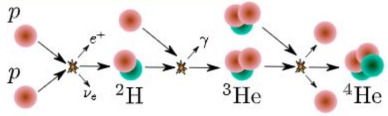
Mass Loss by stellar winds

The choice of wind mass loss recipe depends on the temperature $T_{\rm eff}$ and surface hydrogen mass fraction $X_{\rm s}$. For hot stars ($T_{\rm eff} > 25\,\rm kK$) that are hydrogen rich ($X_{\rm s} > 0.7$) we adopted the prescription of Vink et al. (2001). For hot hydrogen-poor stars ($X_{\rm s} < 0.4$) we used the wind of Hamann et al. (1995) divided by ten. We linearly interpolated between the predicted log $\dot{M}$ given by both prescriptions in case $0.4 < X_{\rm s} < 0.7$. For cold stars ($T_{\rm eff} \lesssim 25\,\rm kK$) we used the prescription from Nieuwenhuijzen & de Jager (1990) in case it predicts a mass loss rate higher than Vink et al. (2001). Due to its high opacity, iron is the main driver of stellar winds. We scaled all winds to the iron abundance rather than the metallicity Z. The stellar winds thus scale as $\dot{M} \propto (X_{\rm Fe}/X_{\rm Fe,\odot})^{0.85}$, where the factor 0.85 is the metallicity dependence found by Vink et al. (2001). Here, $X_{\rm Fe,\odot} = 0.00124$ (Grevesse et al. 1996).

A. Schootemeijer et al. (2019)

Nuclear burning

PP-I chain

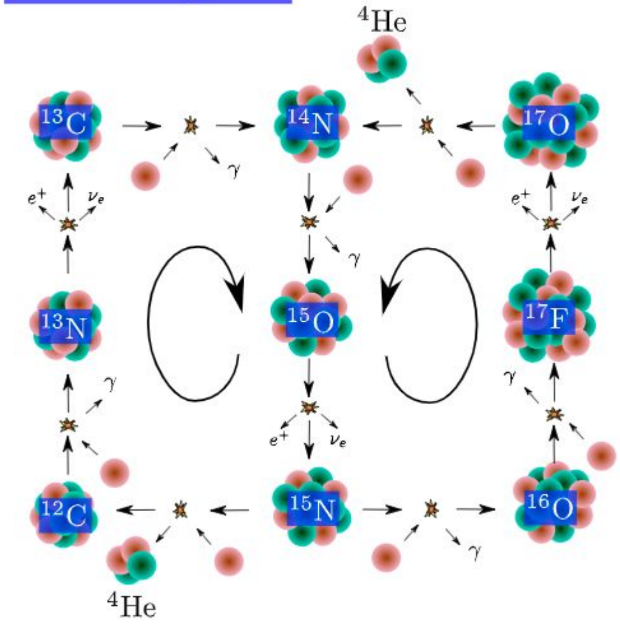


$$p + p \rightarrow {}^2H + e^+ + \nu_e \quad \text{(twice)}$$

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

$$^3He + {}^3He \rightarrow {}^4He + p + p$$

CNO cycle



$$^{12}C + p \rightarrow {}^{13}N + \gamma$$

$$^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$$

$$^{13}C + p \rightarrow {}^{14}N + \gamma$$

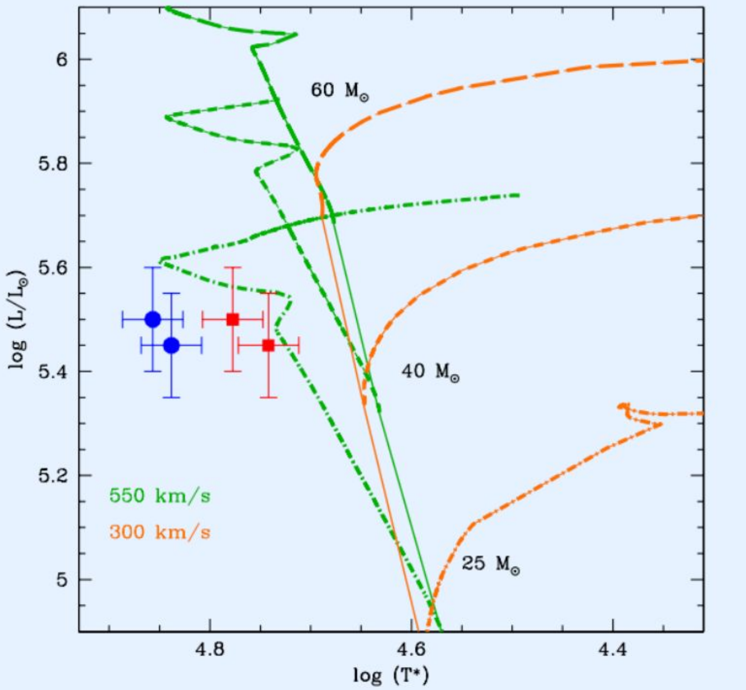
$$^{14}N + p \rightarrow {}^{15}O + \gamma$$

$$^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$$

$$^{15}N + p \rightarrow {}^{12}C + {}^4He$$

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

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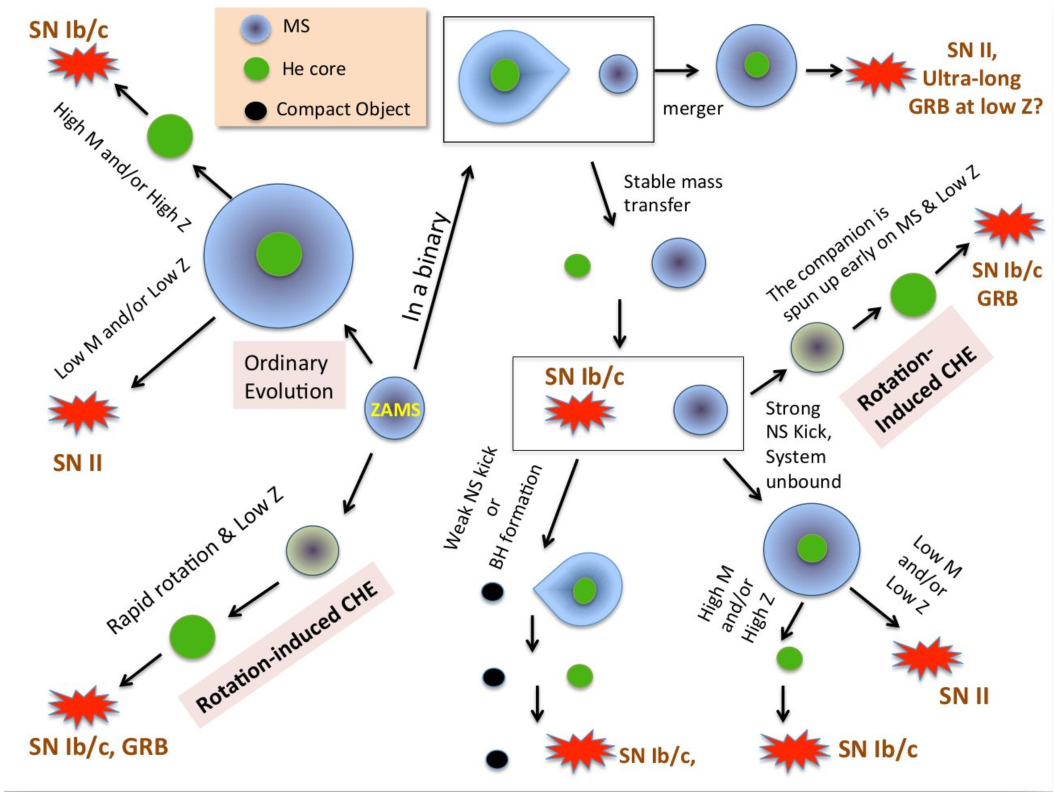
Fate of rapidly rotating massive stars



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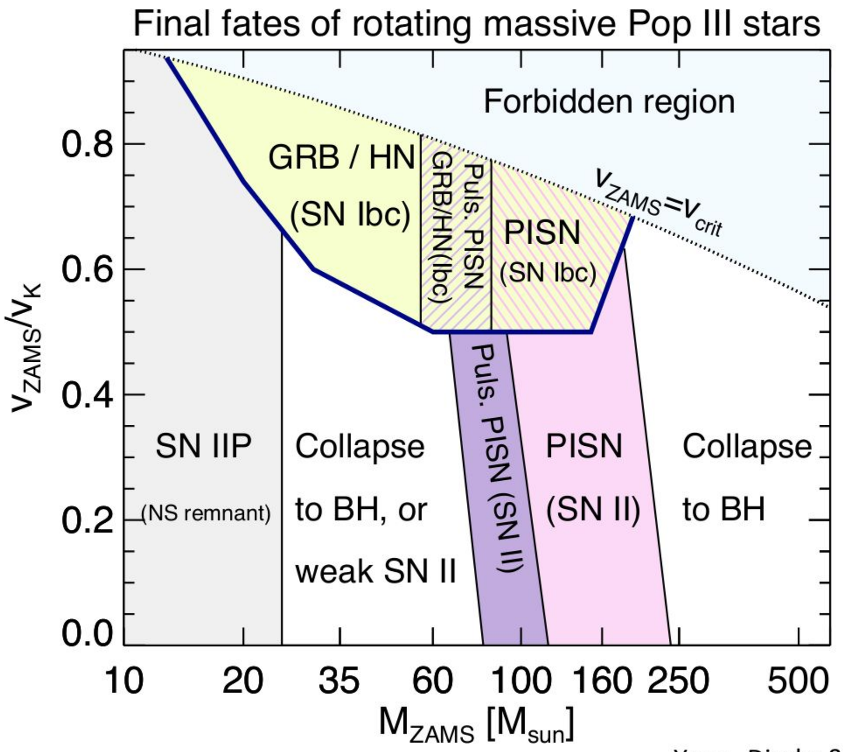
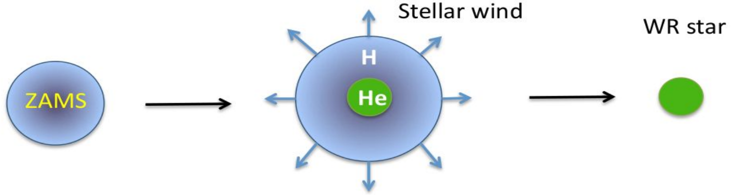


Yoon, Dierks & Langer 2012

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!**

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

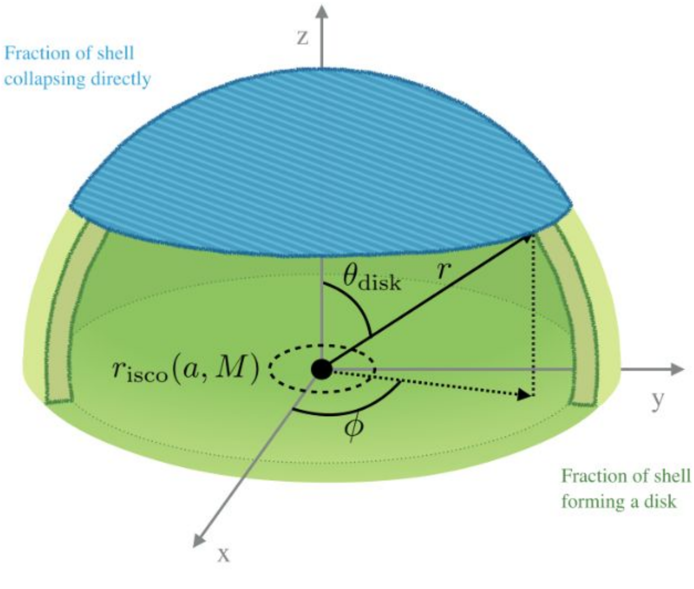
$$r_{\rm isco} = 3 + z_2 \pm [(3 - z_1)(3 + z_1 + 2z_2)]^{1/2}$$

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

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

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)

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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

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