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NATIONAL SCIENCE CENTRE
Opus

Progenitors of LGRBs: Single stars <u>are</u> enough!

Rafia Sarwar [1], Dorottya Szécsi [1], Mariusz Tarnopolski [1], Koushik Sen [2], Poojan Agrawal [3], Hanno Stinshoff [1], Christina Thöne [4]

[1] Institute of Astronomy | Faculty of Physics, Astronomy and Informatics, *Nicolaus Copernicus University*, Toruń, Poland.
[2] Steward Observatory, Department of Astronomy, University of Arizona, 933 N Cherry Ave, Tucson, AZ, USA.
[3] Institute of Astronomy, KU Leuven, Celestijnenlaan 200D, B-3001, Leuven, Belgium.
[4] Astronomical Institute of the Czech Academy of Sciences (ASU-CAS), Fricova 298, Ondřejov, 251 65, Czech Republic.

Rafia Sarwar
13th January 2025
Institute of Astronomy | Faculty of Physics
Nicolaus Copernicus University, Toruń, Poland.

Figure Credit: NASA

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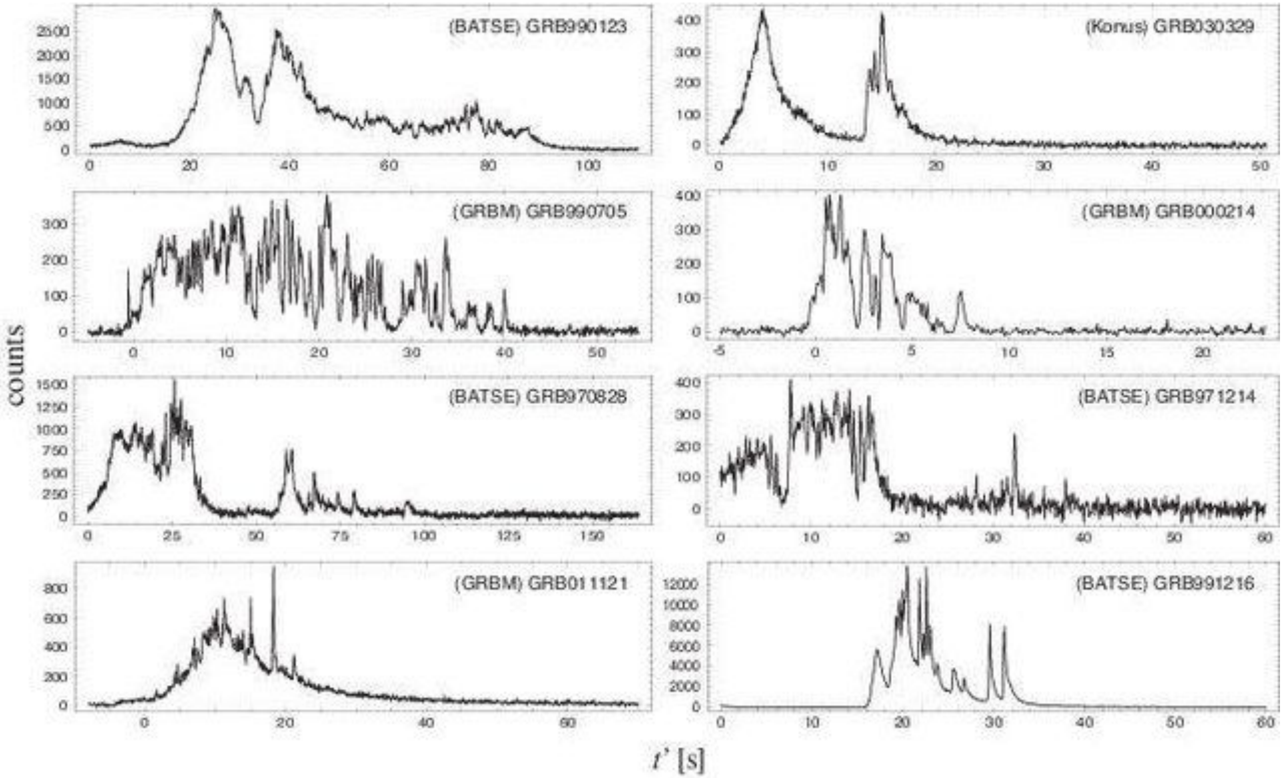
What is a gamma ray burst...



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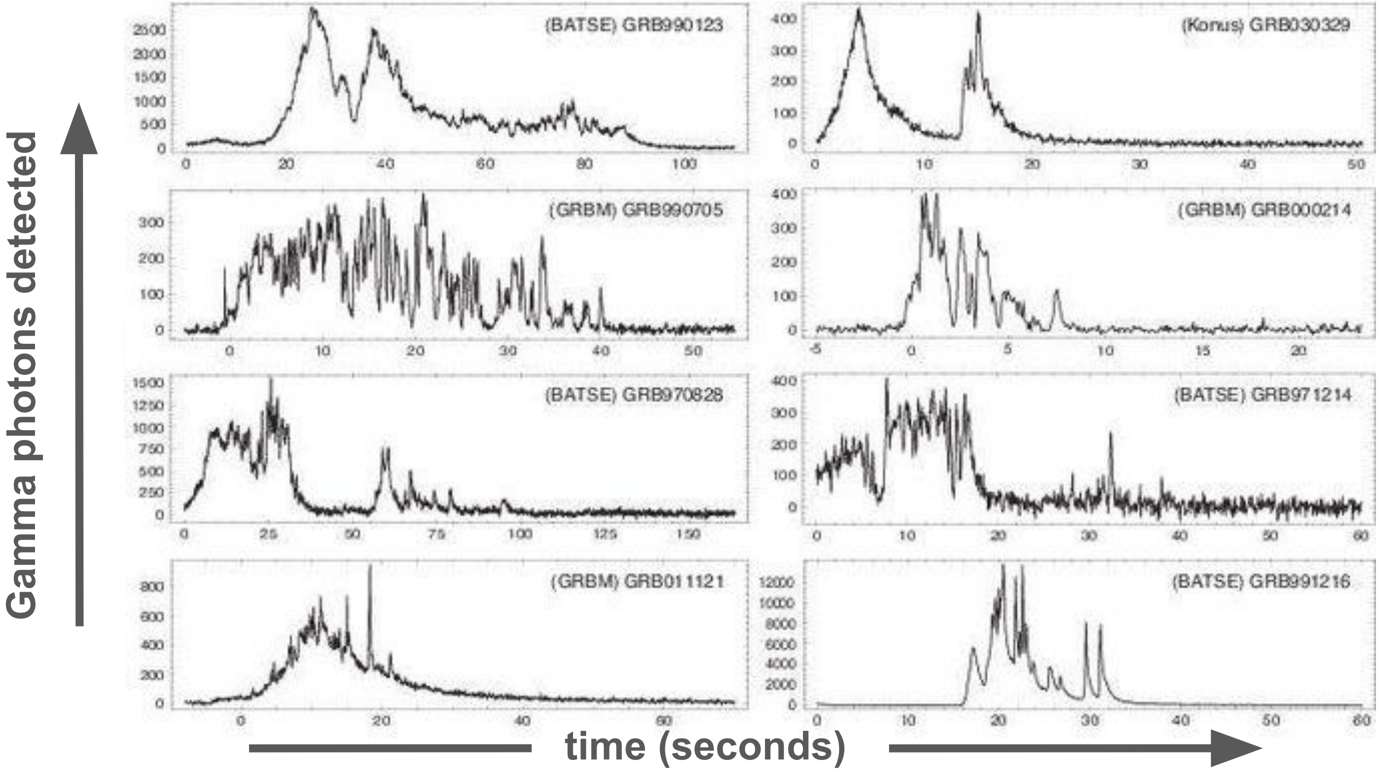

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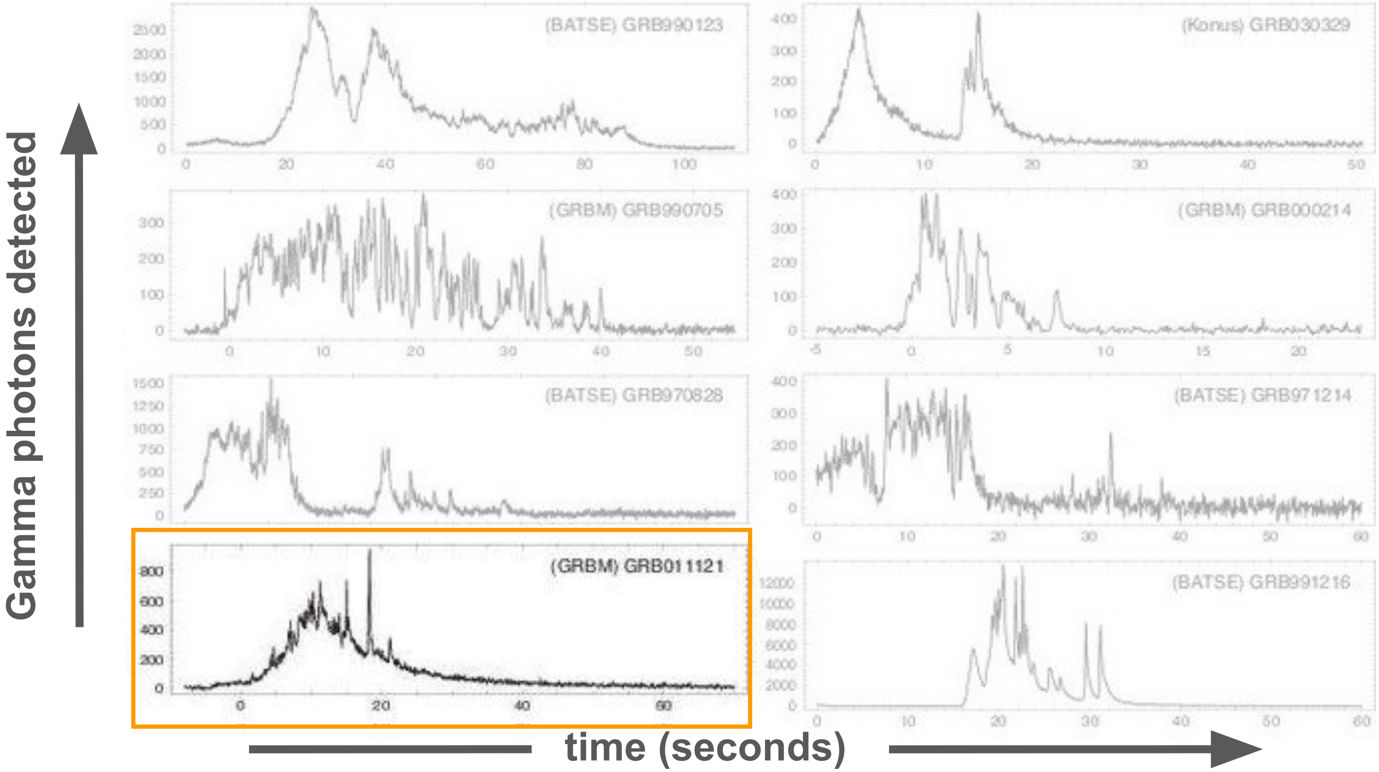

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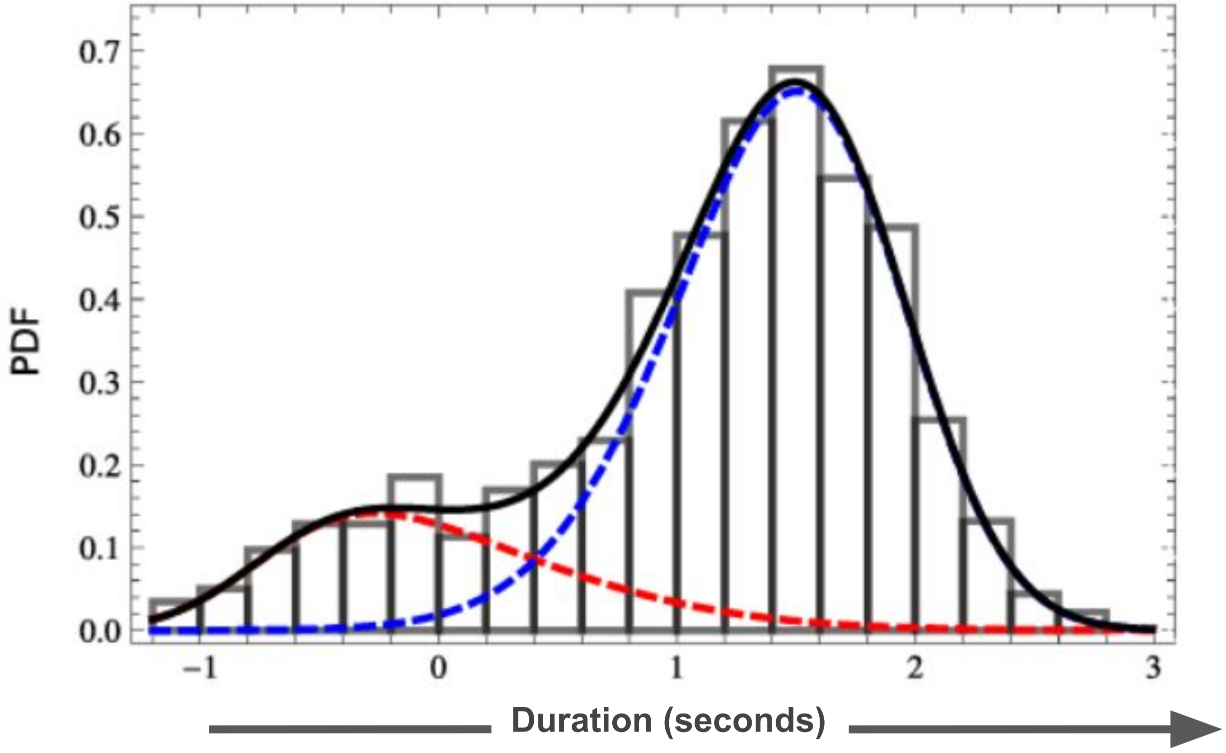
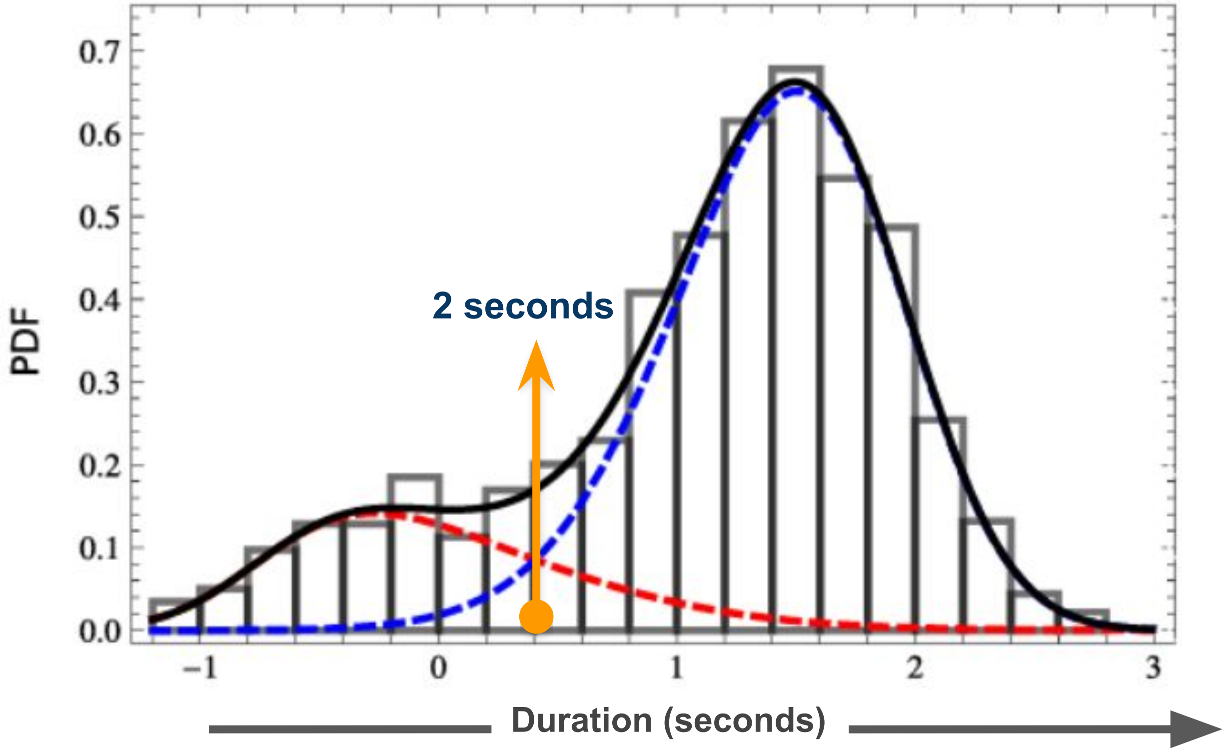


Mariusz Tarnopolski (2016)

What is a gamma ray burst...



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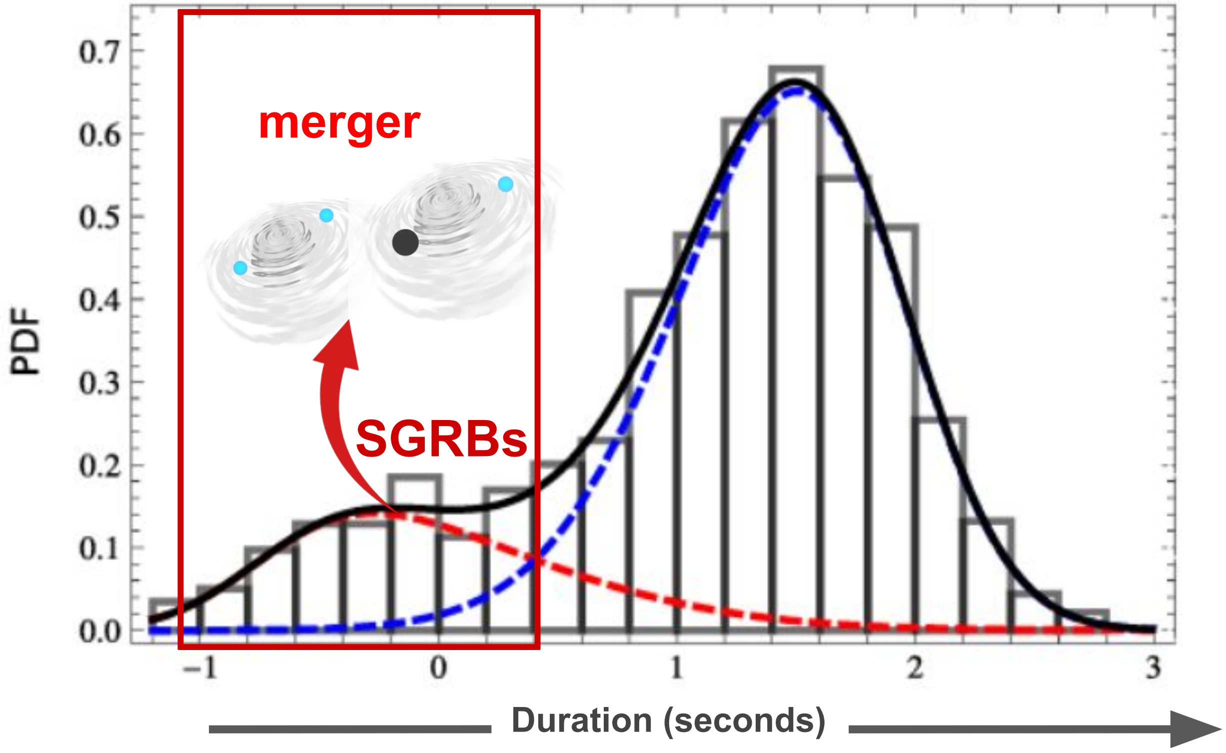

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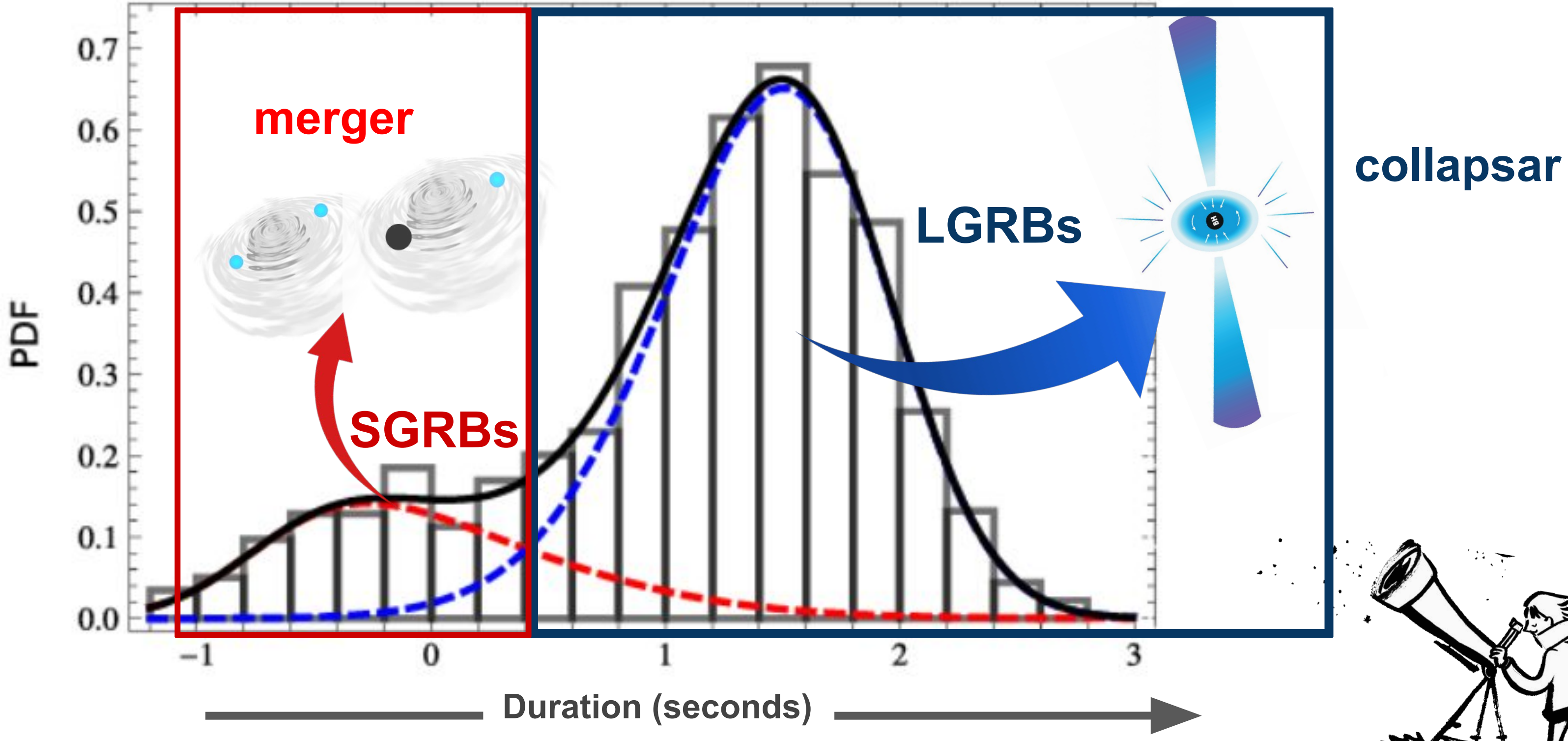

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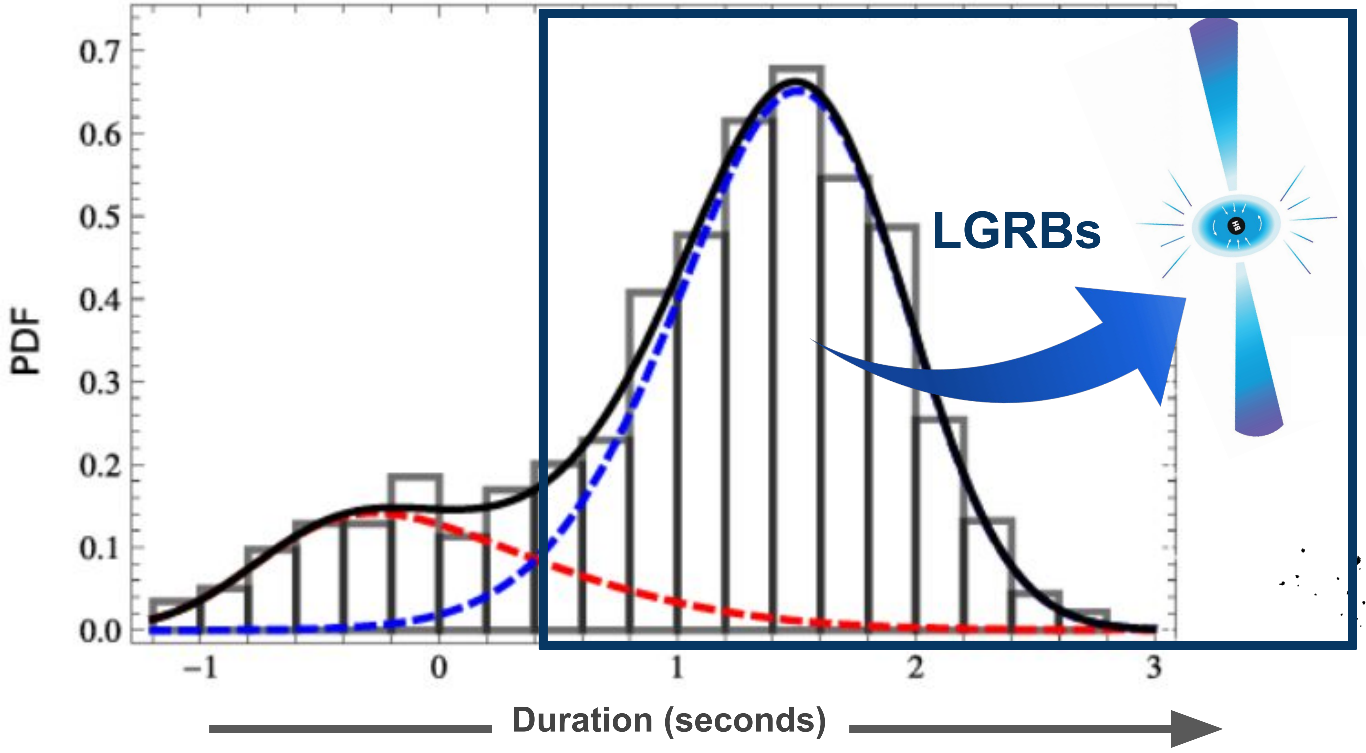


Mariusz Tarnopolski (2016)

How can we produce a LGRB?

What is a collapsar?

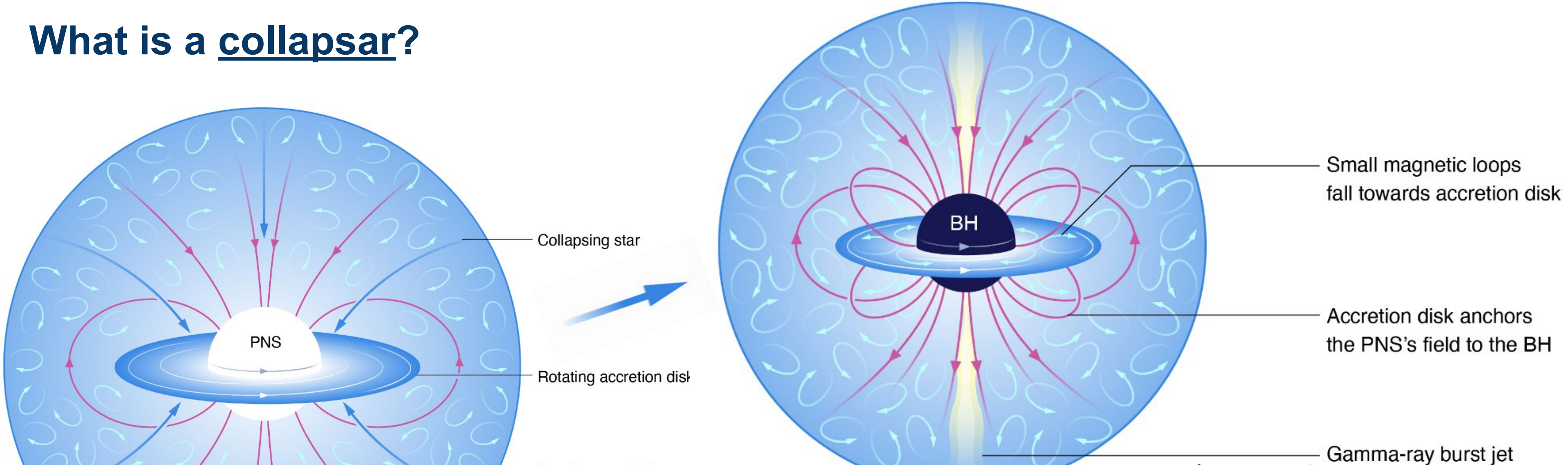
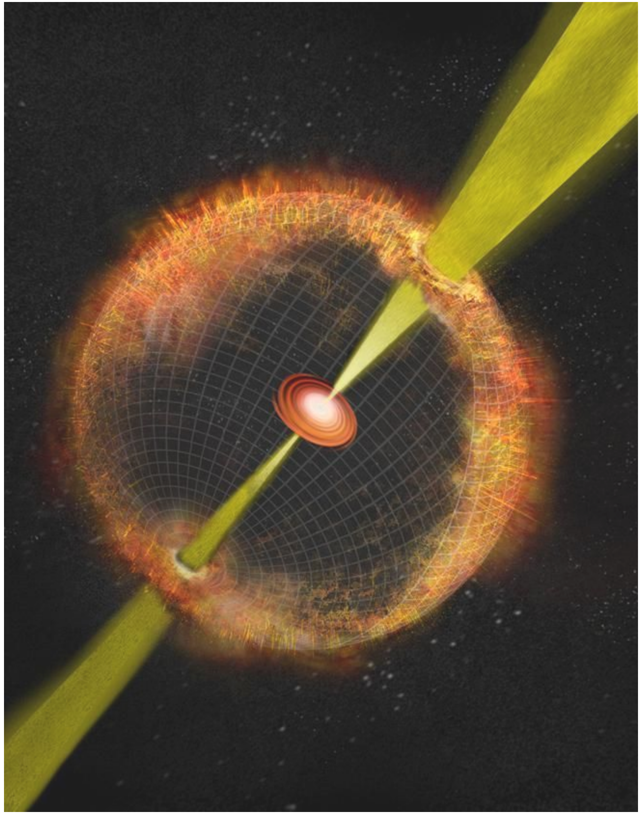


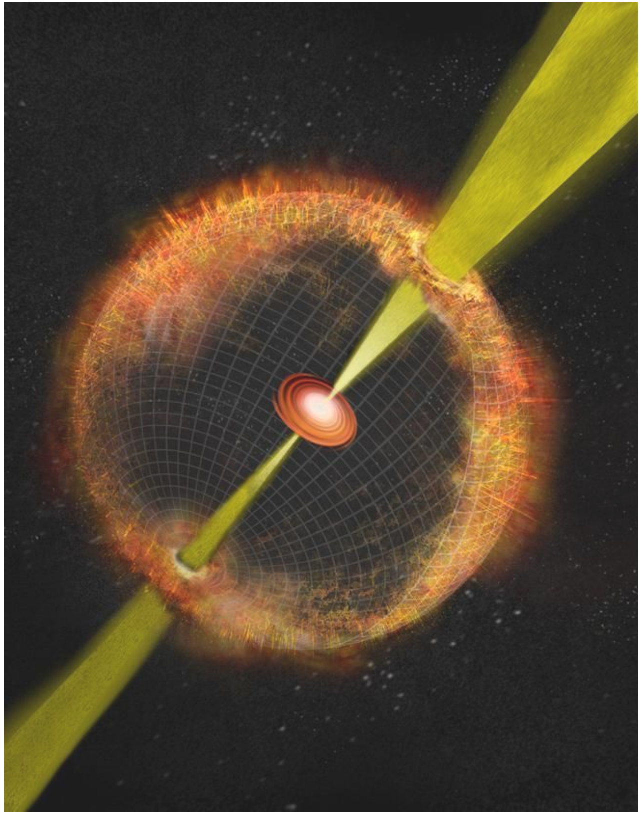
Figure Credit: Ore Gottlieb

Conditions for a collapsar



3 conditions for collapsars

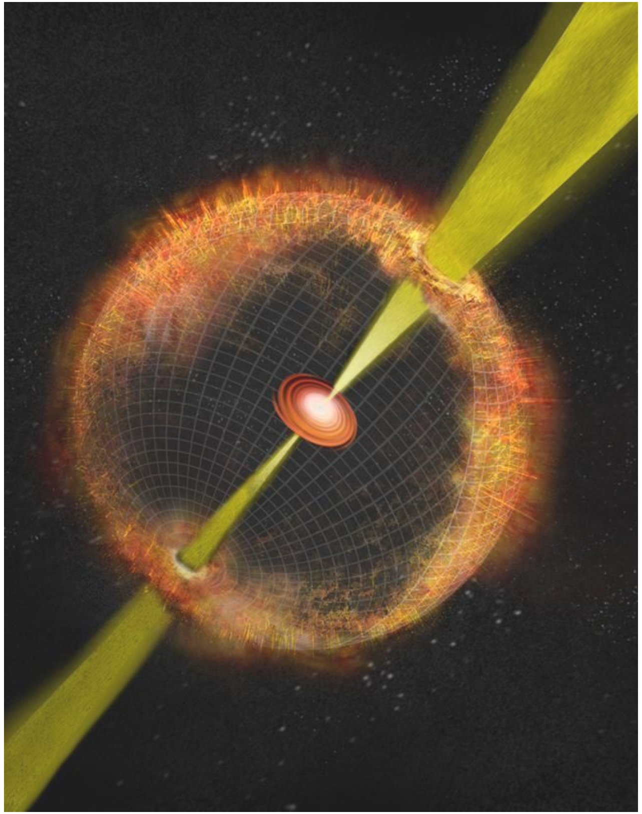
Conditions for a collapsar



3 conditions for collapsars

- Iron core
- Fast rotation
- no or tiny envelope

Conditions for a collapsar



3 conditions for collapsars

- Iron core
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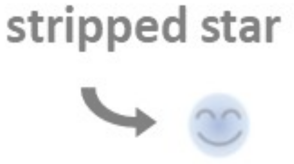
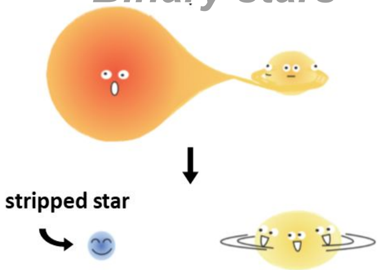
➔ We need a spinning naked helium star!

Spinning naked Helium star

	Single stars	Binary stars
No-rotation	stripped star; Classic Wolf-Rayet star?	
Fast-rotation		

Classic Wolf-Rayet star?

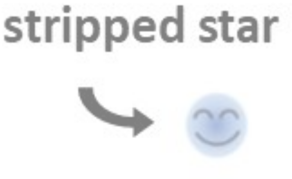
Spinning naked Helium star

	Single stars	*Binary stars*
No-rotation	 Classic Wolf-Rayet star?	 **Wolf-Rayet star from a binary?**
Fast-rotation		

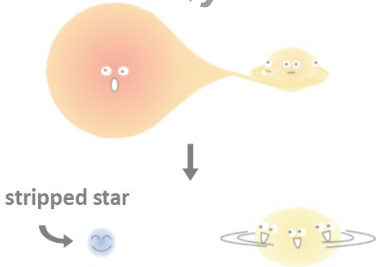
Spinning naked Helium star

Single stars | *Binary stars*

No-rotation

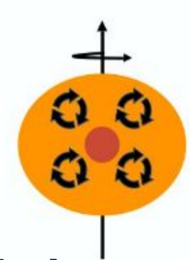


Classic Wolf-Rayet star?



Wolf-Rayet star from a binary?

Fast-rotation

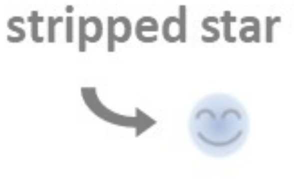


Chemically homogeneous evolution (CHE)

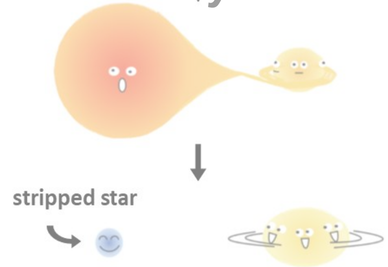
Spinning naked Helium star

Single stars | *Binary stars*

No-rotation

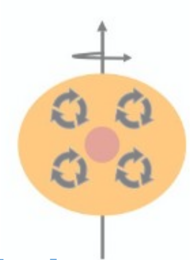


Classic Wolf-Rayet star?

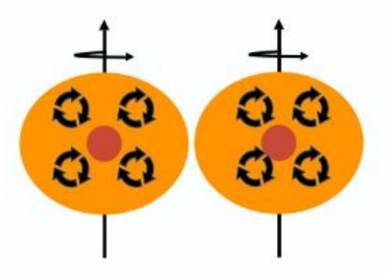


Wolf-Rayet star from a binary?

Fast-rotation



Chemically homogeneous evolution (CHE)



CHE binary

Spinning naked Helium star

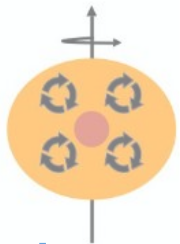
Single stars

No-rotation

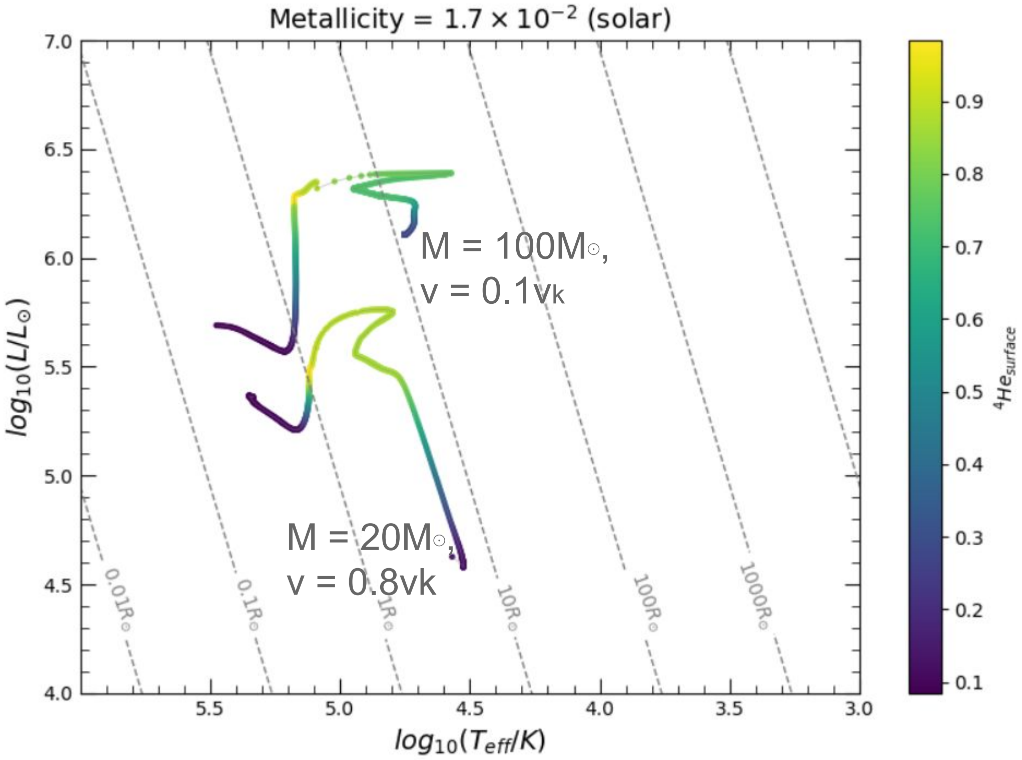
stripped star

Classic Wolf-Rayet star

Fast-rotation



Chemically homogeneous evolution (CHE)



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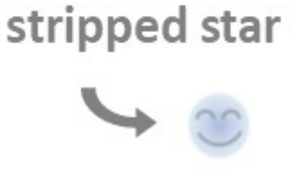
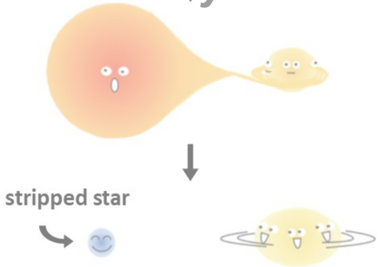
Spinning naked Helium star

Single stars | *Binary stars*

No-rotation

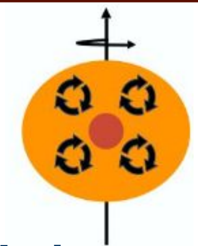


Classic Wolf-Rayet star?

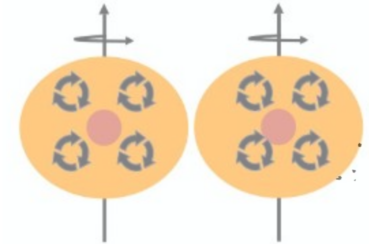


Wolf-Rayet star from a binary?

Fast-rotation



Chemically homogeneous evolution (CHE)



CHE binary

Observational data

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]

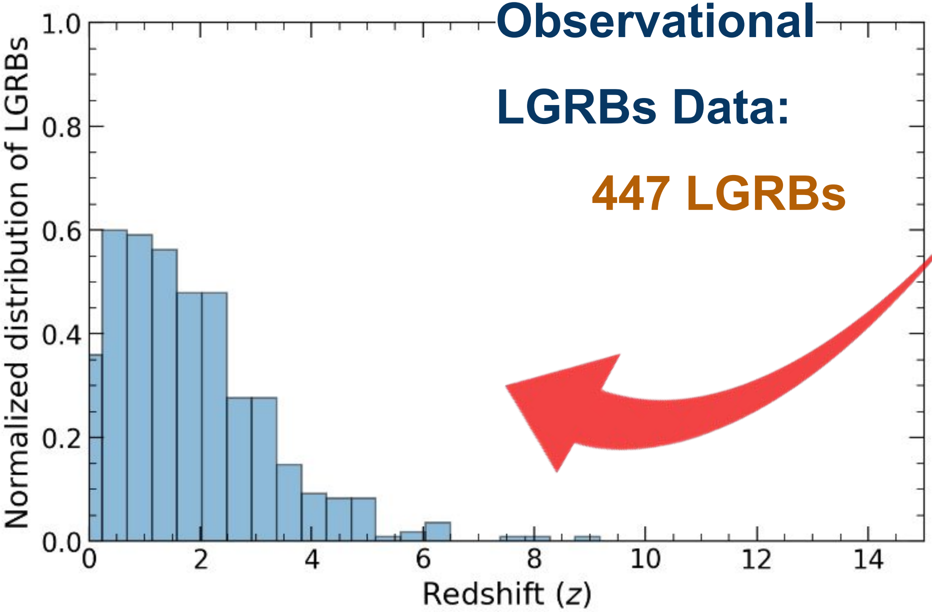
GRB	T90	comments	RA	Dec	z	Greiner X	O	R	refs
180325A	94.1	Very luminous, reddened afterglow with 2175-A dust bump. Optical observations during main burst peak.	10:29:42.7	+24:27:49.3	2.04				
180324A	7.2	Possible very weak afterglow	05:06:06.37	+56:42:51.5					
180316A	87	Bright early afterglow.	17:41:42.94	+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			

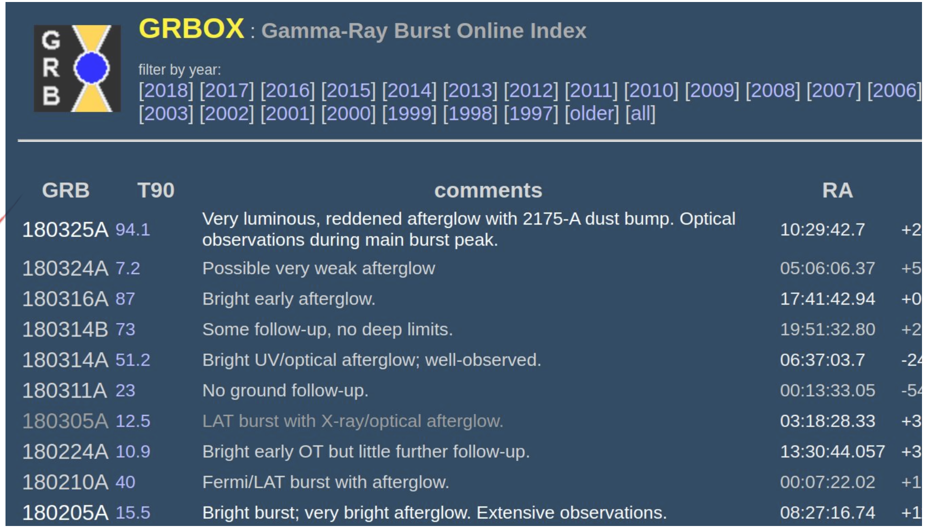
https://sites.astro.caltech.edu/grbox/grbox.php?starttime=700101&endtime=181231

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]

GRB	T90	comments	RA	
180325A	94.1	Very luminous, reddened afterglow with 2175-A dust bump. Optical observations during main burst peak.	10:29:42.7	+2
180324A	7.2	Possible very weak afterglow	05:06:06.37	+5
180316A	87	Bright early afterglow.	17:41:42.94	+0
180314B	73	Some follow-up, no deep limits.	19:51:32.80	+2
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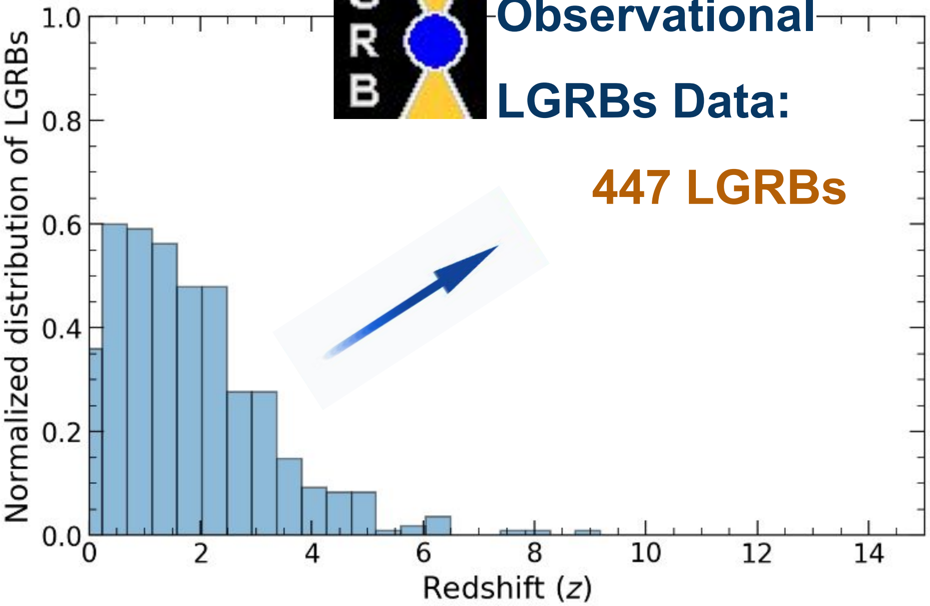
180311A	23	No ground follow-up.	00:13:33.05	-54
180305A	12.5	LAT burst with X-ray/optical afterglow.	03:18:28.33	+3
180224A	10.9	Bright early OT but little further follow-up.	13:30:44.057	+3
180210A	40	Fermi/LAT burst with afterglow.	00:07:22.02	+1
180205A	15.5	Bright burst; very bright afterglow. Extensive observations.	08:27:16.74	+1

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

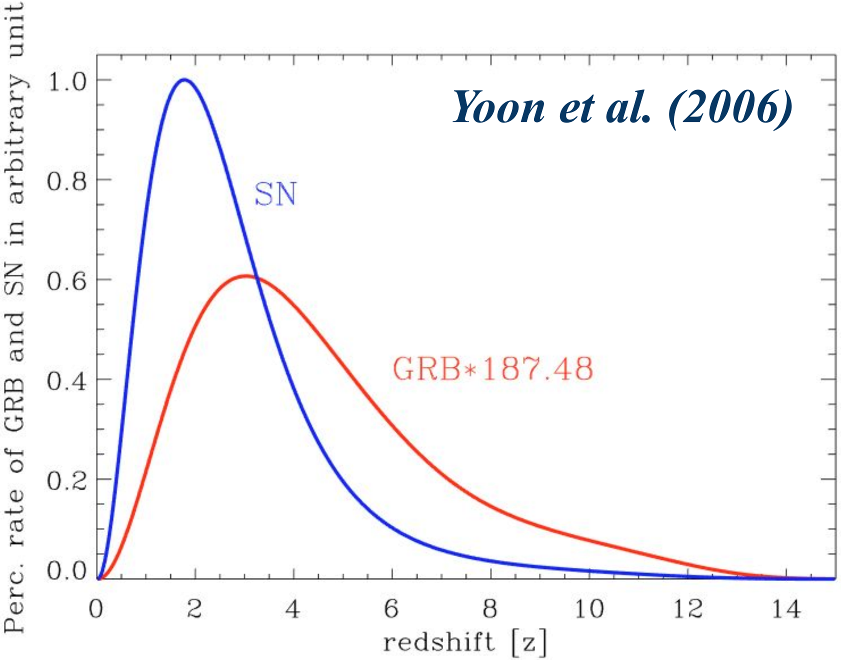
Motivation

Observational LGRBs Data:

447 LGRBs



Yoon et al. (2006)



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

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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STERN

Code Liègeois d'Evolution Stellaire

STAREVOL

Code de Montpellier-Montréal

Lyon Evolutonary code

Model parameters

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

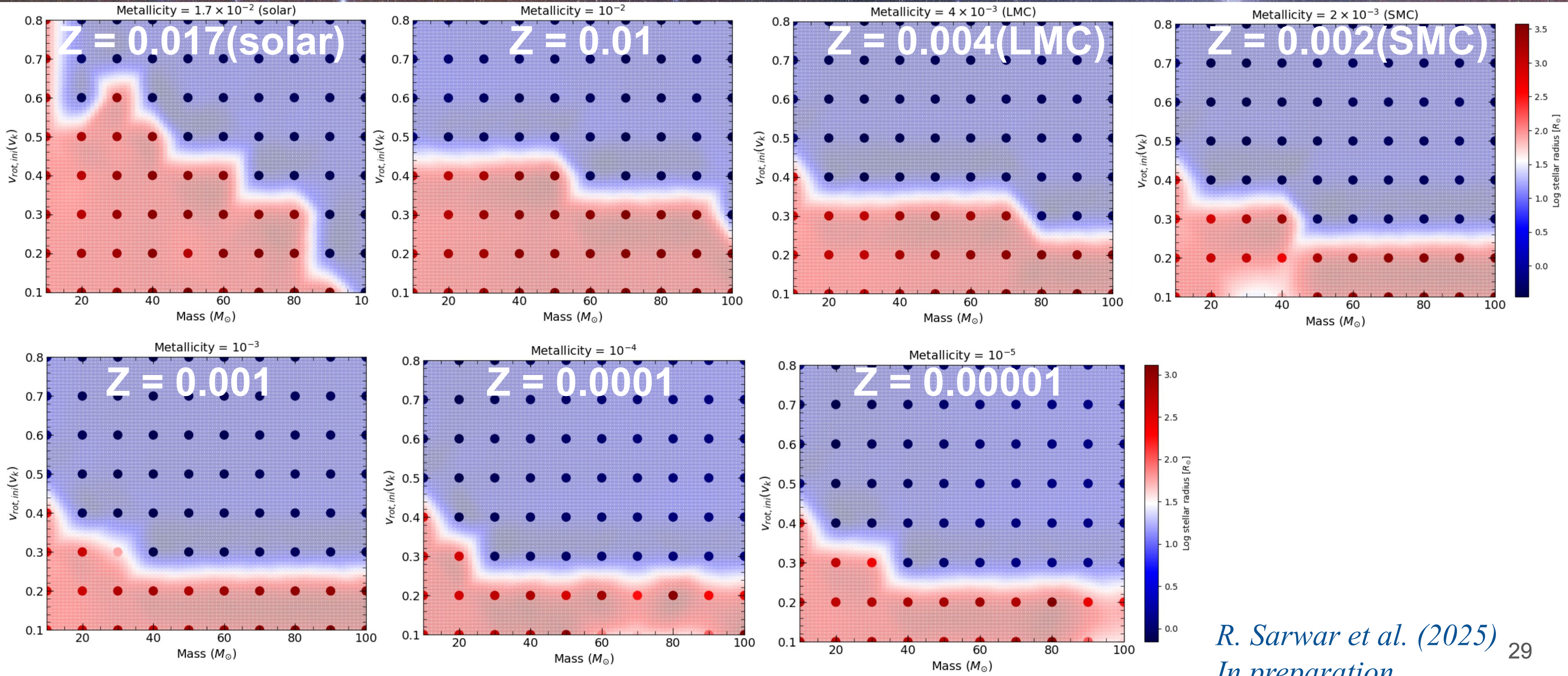
Metallicities	0.017 (solar)	0.01	0.004 (LMC)	0.002 (SMC)	0.001	0.0001	0.00001

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

Results

Rafia Sarwar
13th January 2025

Evolution of massive stars



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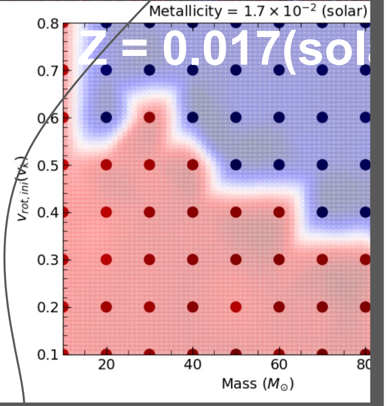

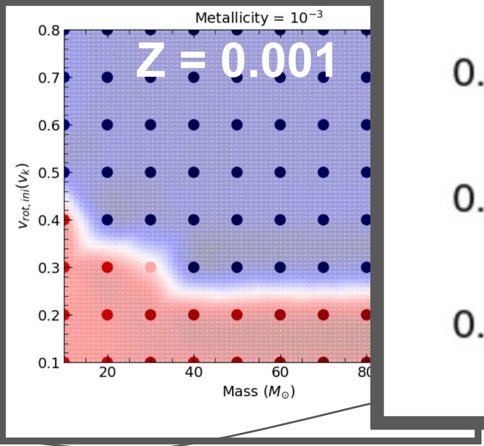

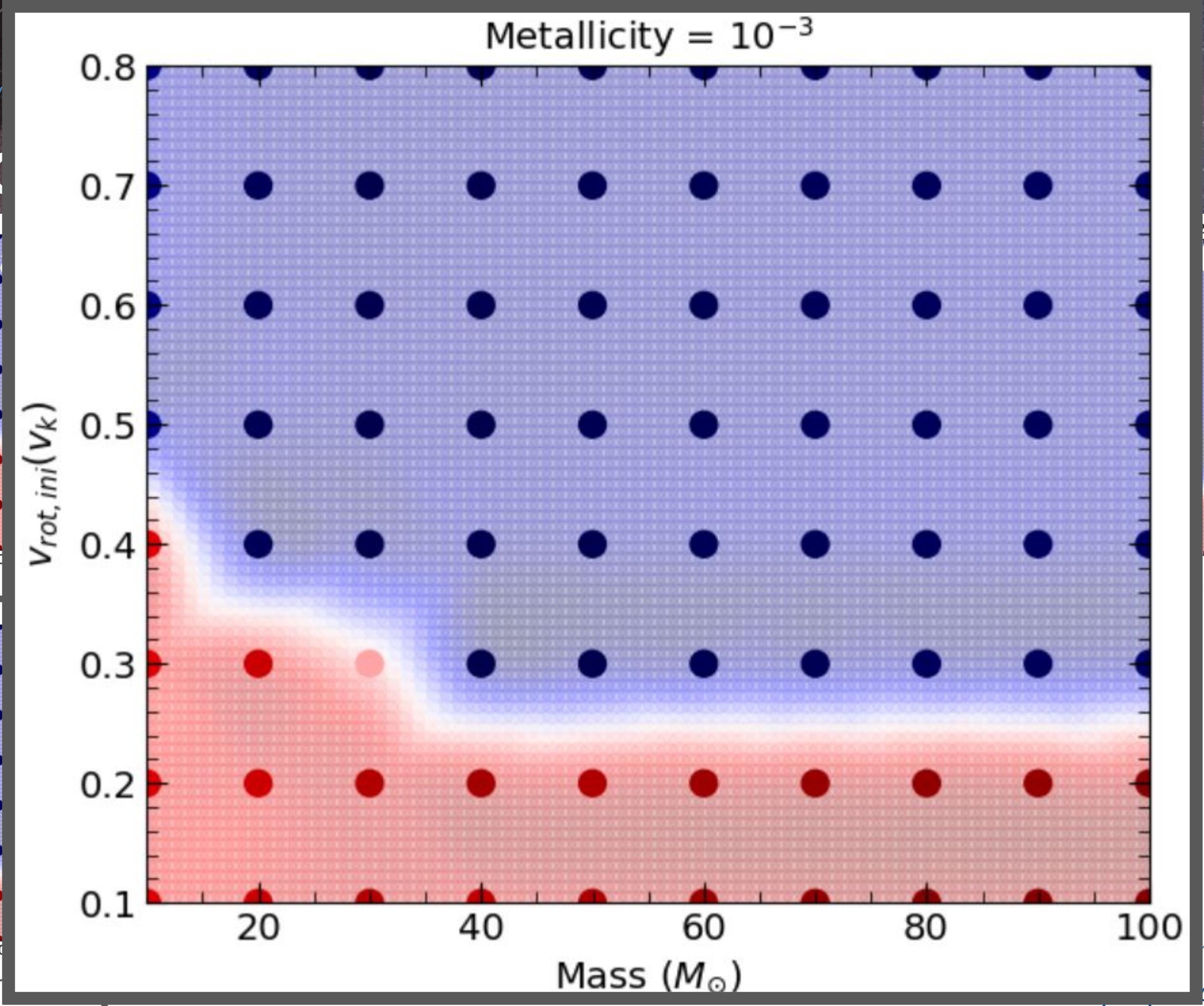

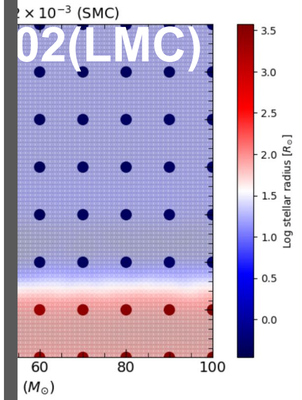

et al. (2025)
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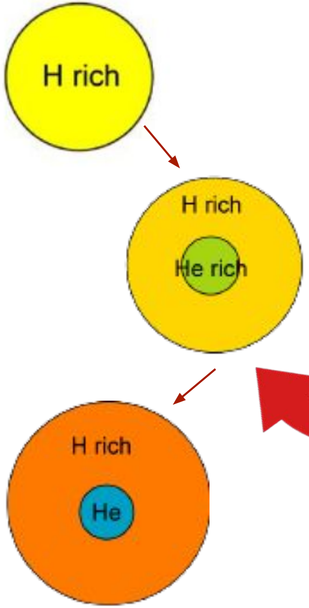
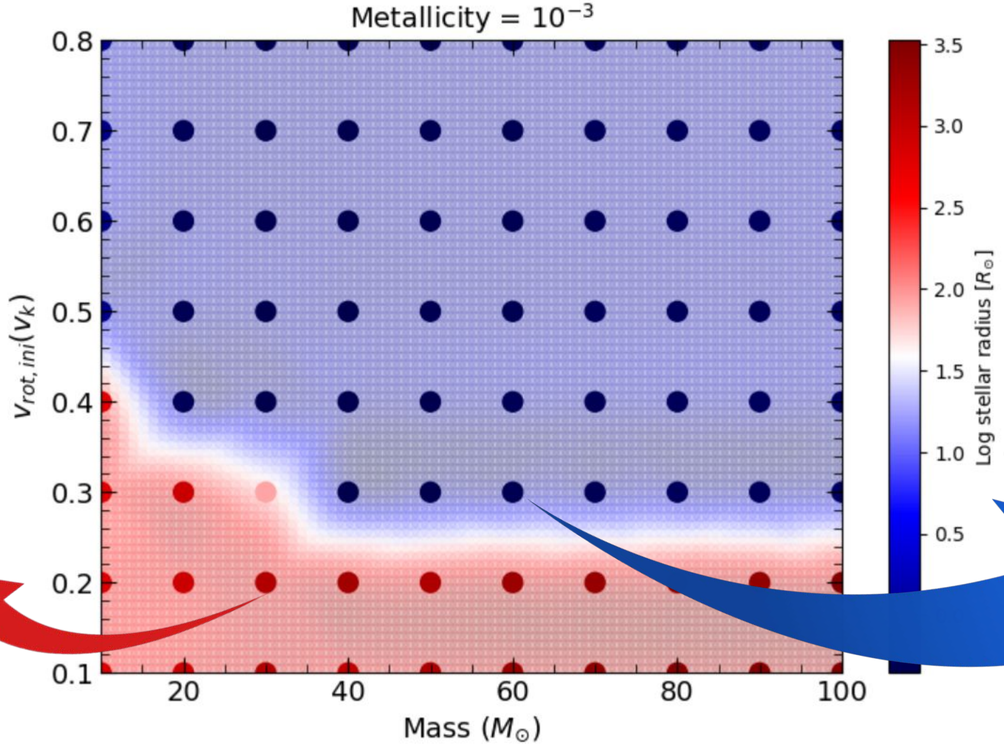
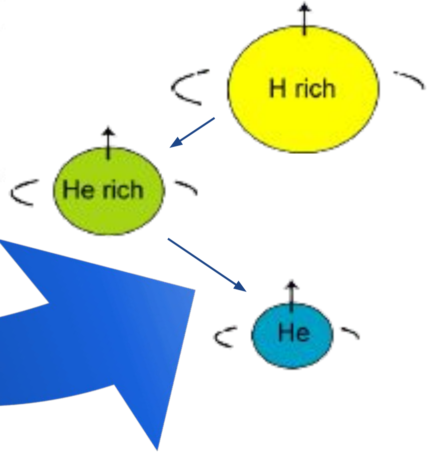
Evolution of massive stars

Slowly rotating:
- classical core-envelope
- red-supergiant





Rapidly rotating massive stars:
- rapid rotationally-induced chemical mixing
- quasi-chemical homogeneity



R. Sarwar et al. (2025)
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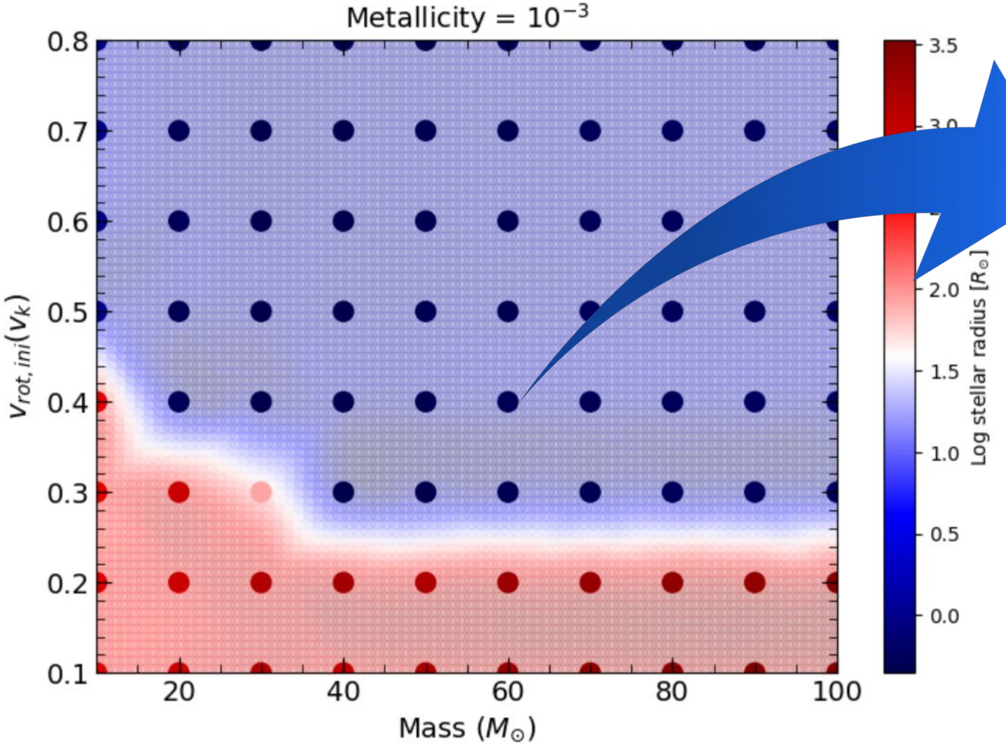
Evolution of massive stars



Conditions for a collapsar:

3 conditions for collapsars

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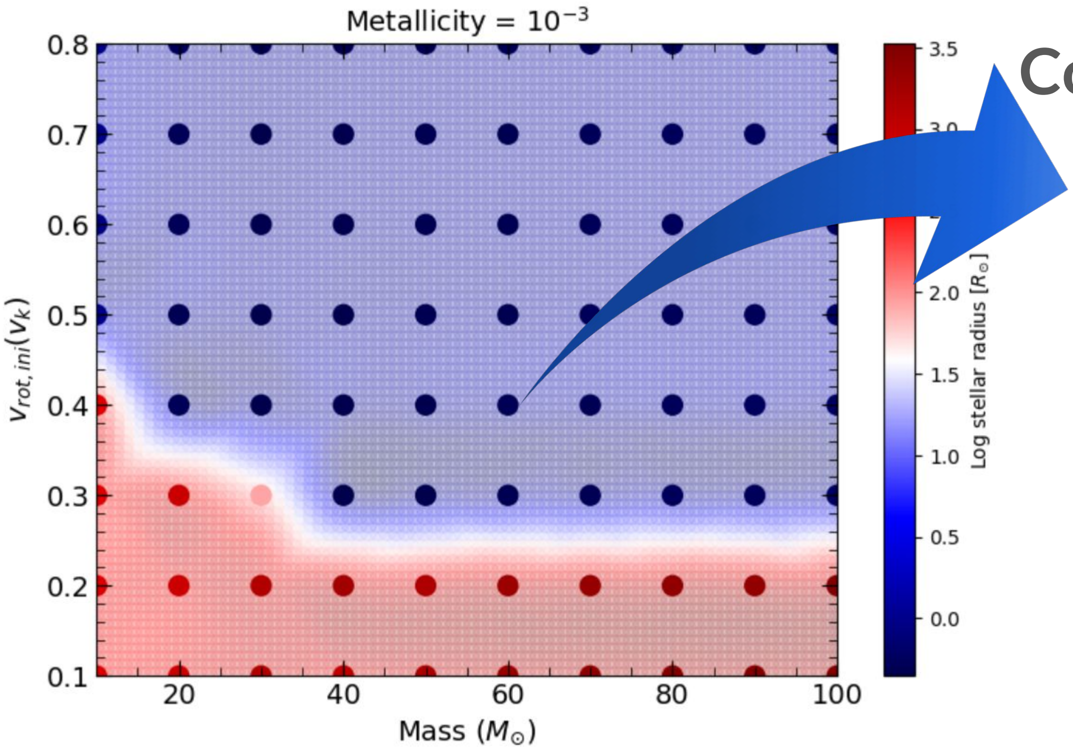
13th January 2025

Evolution of massive stars



Conditions for a collapsar:

3 conditions for collapsars

- **Iron core**

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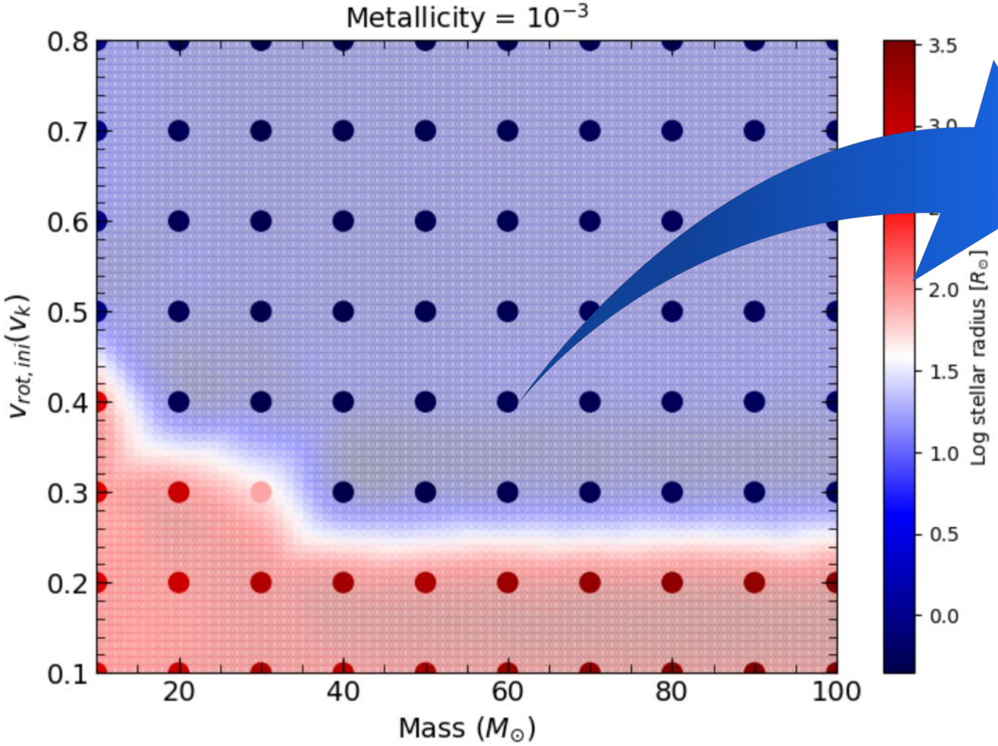
Evolution of massive stars



Conditions for a collapsar:

3 conditions for collapsars

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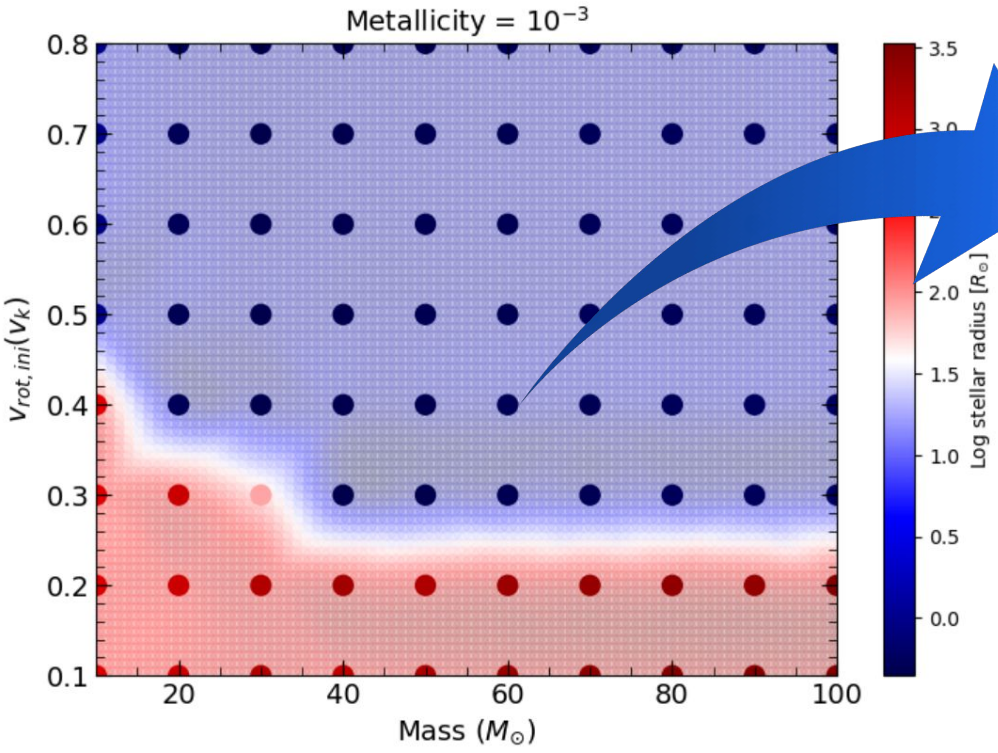
Evolution of massive stars



Conditions for a collapsar:

3 conditions for collapsars

- **Iron core** ✔
- **Fast rotation**

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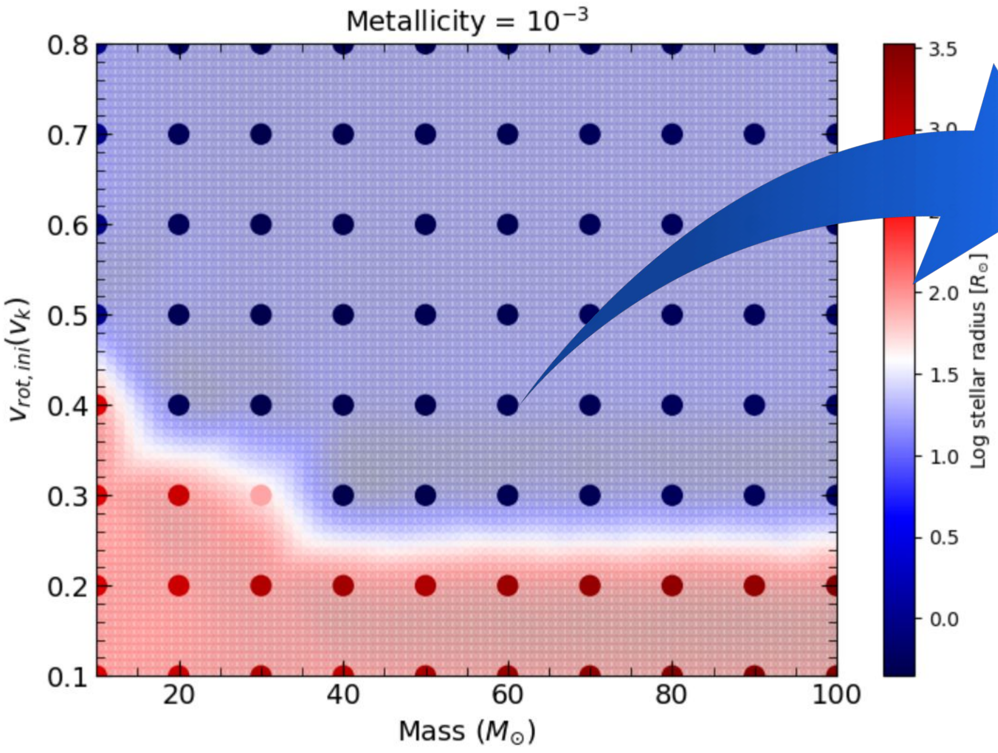
In preparation

Evolution of massive stars



Conditions for a collapsar:

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- **Iron core** ✔
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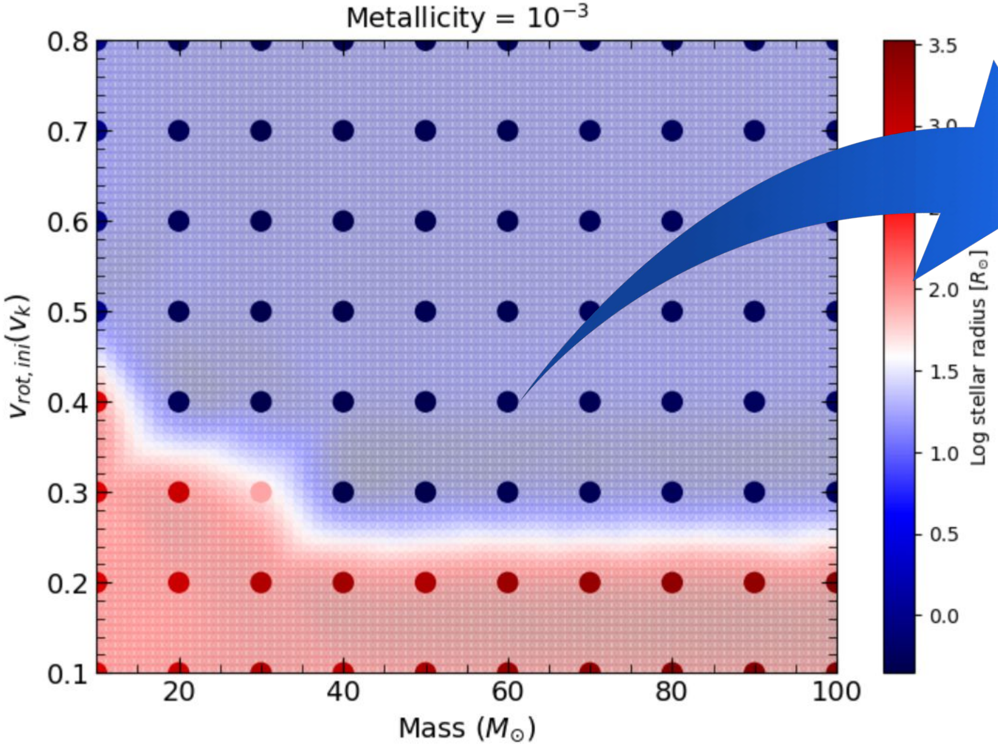


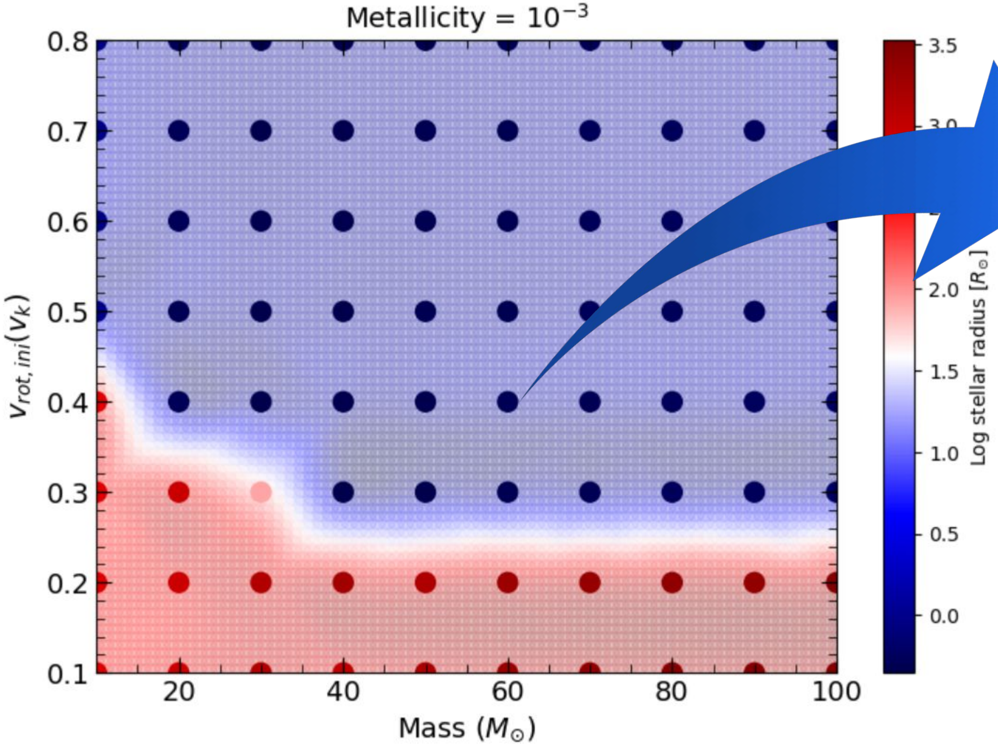
Conditions for a collapsar:

3 conditions for collapsars

- **Iron core** ✔
- **Fast rotation** ✔
- **no or tiny envelope**

R. Sarwar et al. (2025)
In preparation

Evolution of massive stars



Conditions for a collapsar:

3 conditions for collapsars

- Iron core ✔
- Fast rotation ✔
- no or tiny envelope ✔

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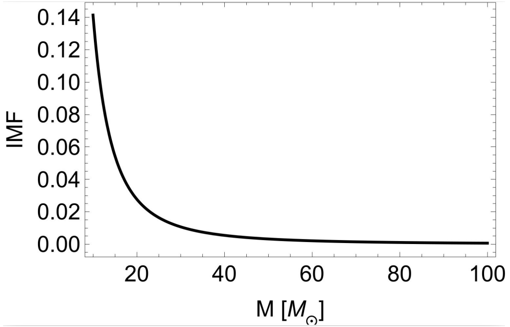
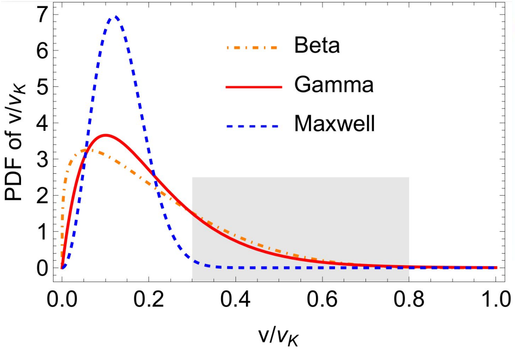
In preparation

Population synthesis

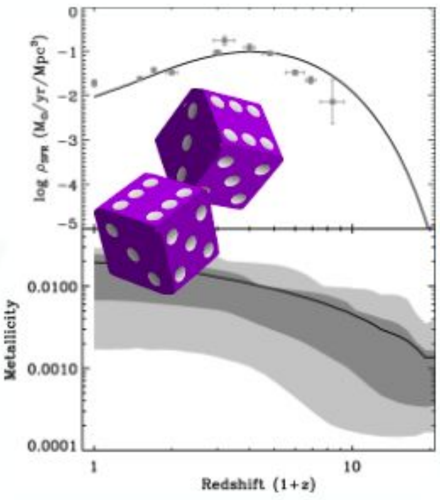
Initial mass function (IMF)
+
Rotational velocity distribution





×

Star formation rate (SFR)
+
Cosmic metallicity density distribution



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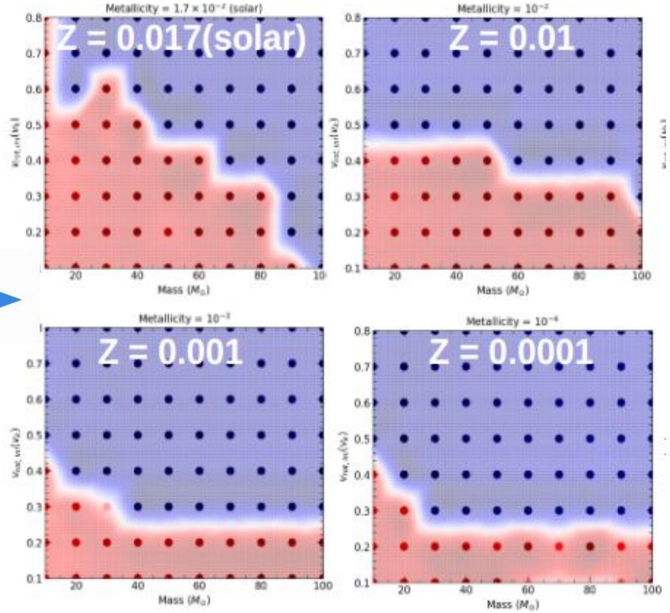
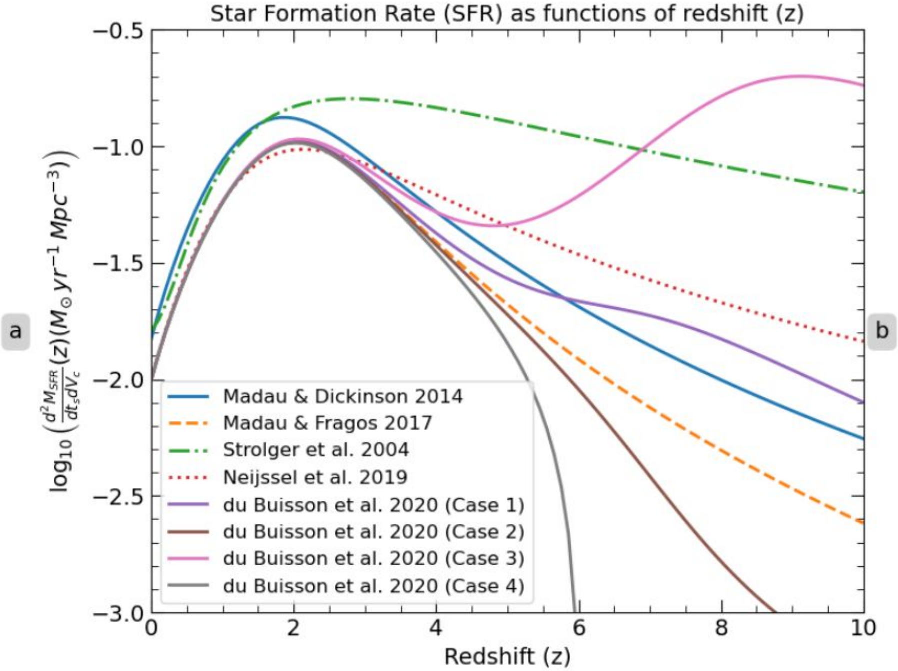
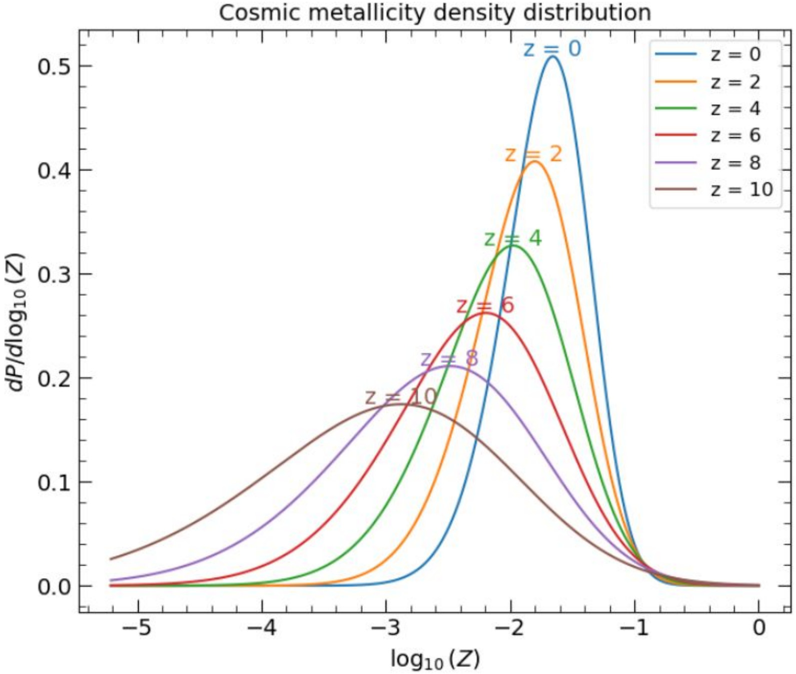


Cosmic star formation rate and metallicity distribution



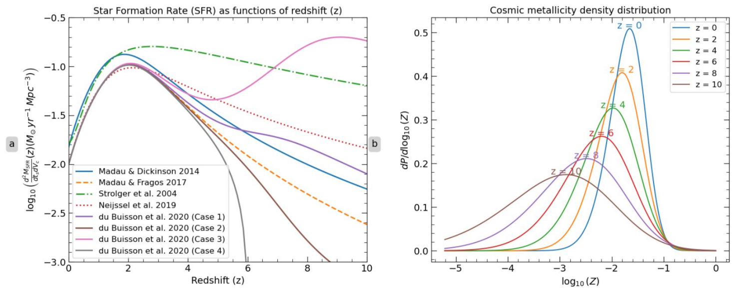


$$\mathrm{SFRD}(z) = \frac{d^2 M_{\mathrm{SFR}}}{dt dV_c}(z) = a\frac{(1+z)^b}{1+[(1+z)/c]^d}$$

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

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

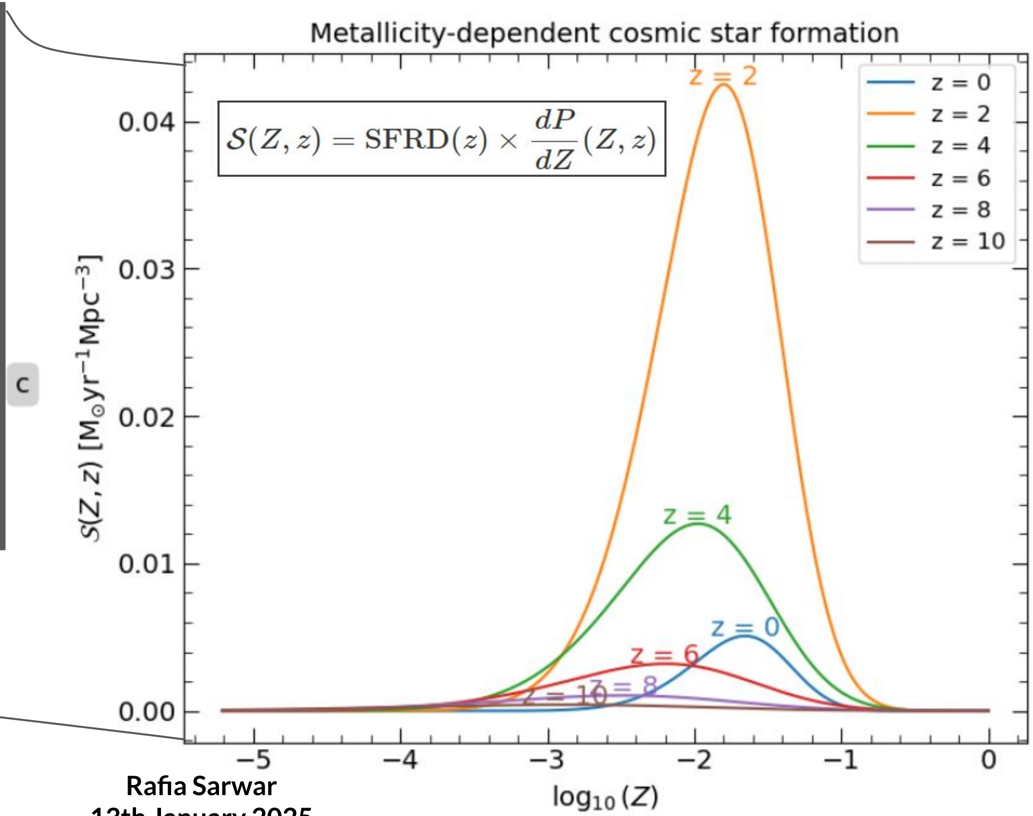
Metallicity-dependent cosmic star formation



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

X

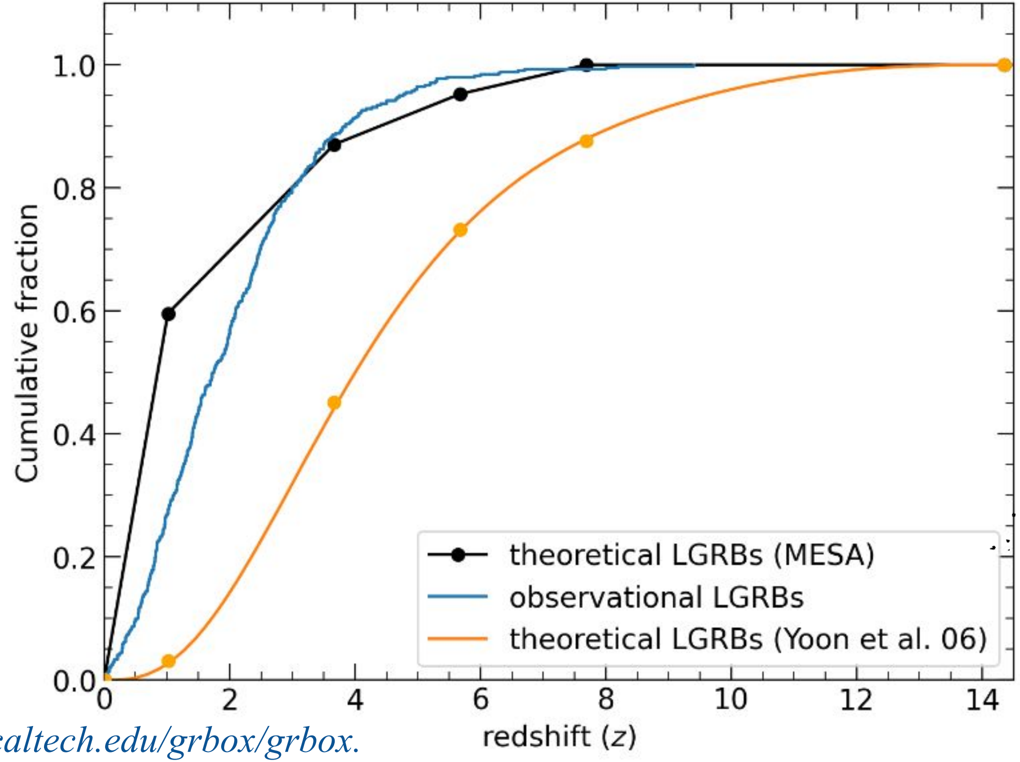
$$\frac{dP}{dZ}(Z,z) = \frac{2}{\omega(z)Z} \times \phi\left(\frac{\ln Z - \xi(z)}{\omega(z)}\right)\Phi\left(\alpha\frac{\ln Z - \xi(z)}{\omega(z)}\right)$$



R. Sarwar et al. (2025)
In preparation

Rafia Sarwar
13th January 2025

Single star models vs observation



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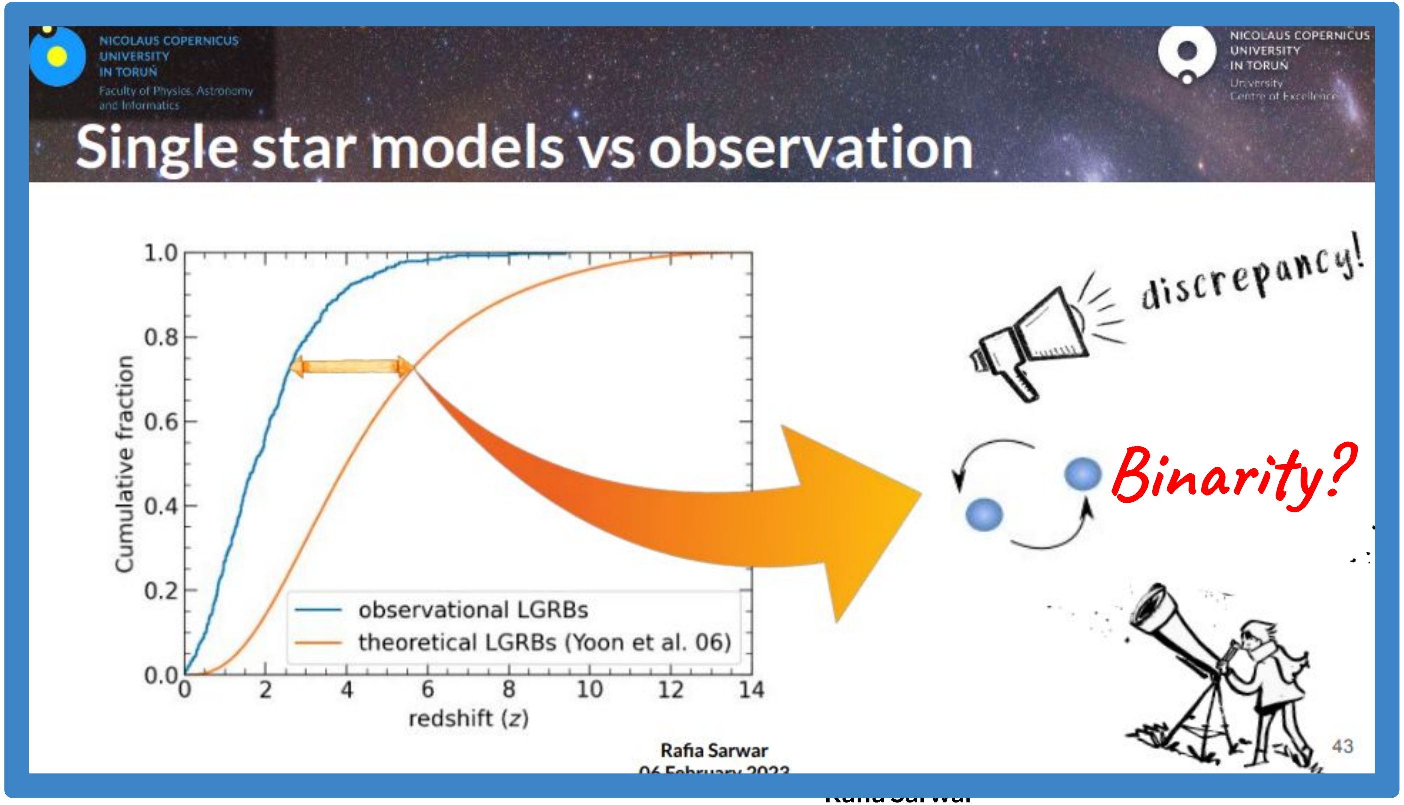
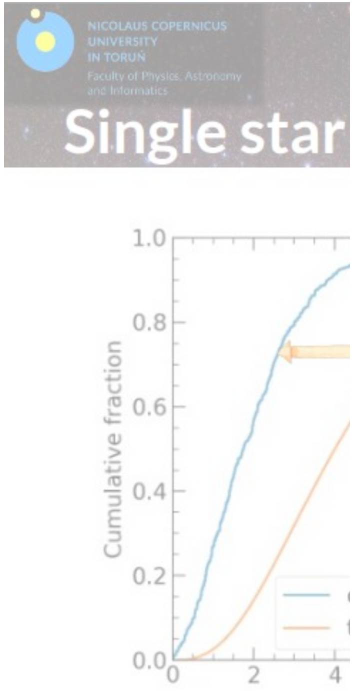
https://sites.astro.caltech.edu/grbox/grbox.php?starttime=700101&endtime=181231

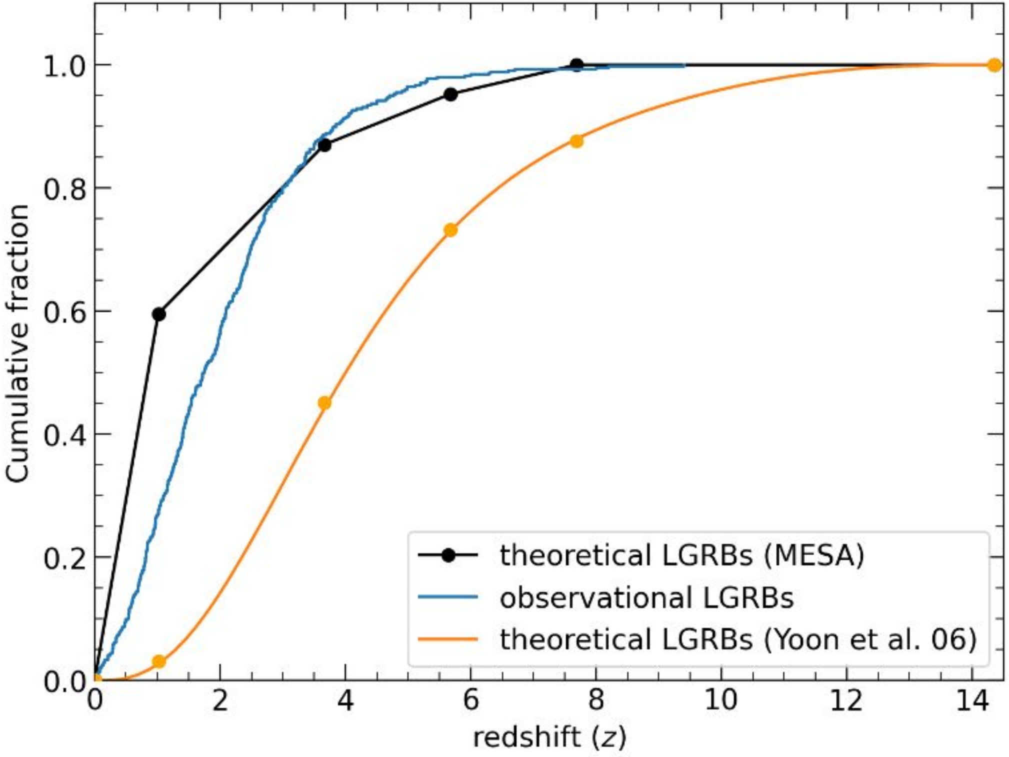
Single star models vs observation



My last talk in Piwnice

Single star models vs observation





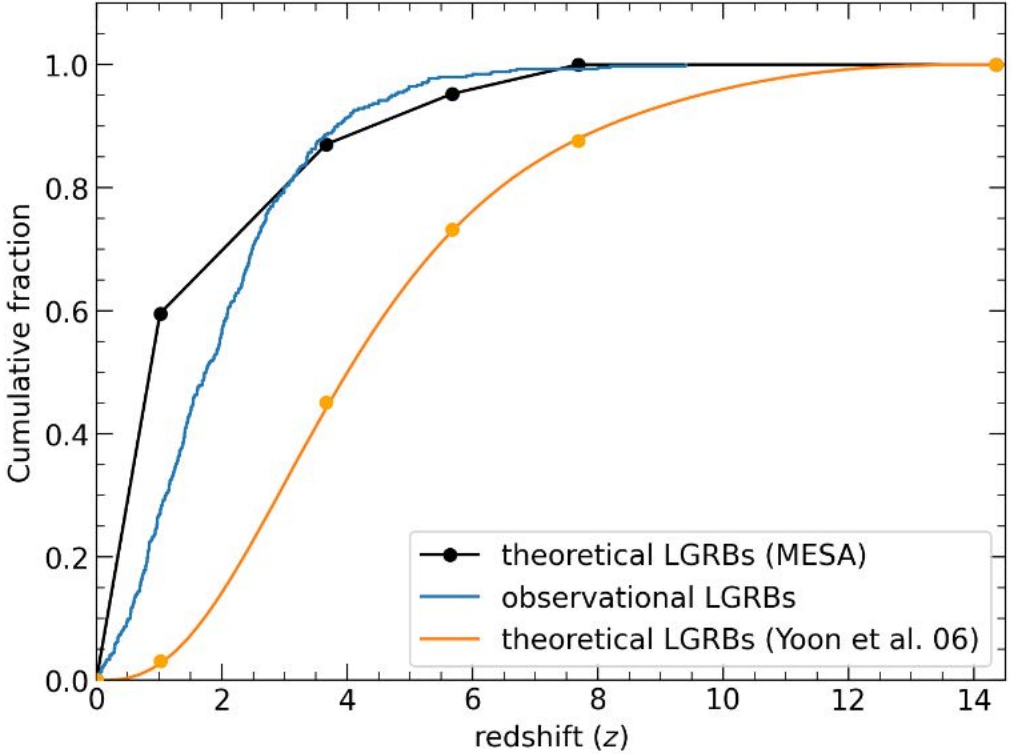
Single stars with up-to-date physics!

R. Sarwar et al. (2025)
In preparation

Single star models vs observation

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

- **Wind mass loss prescriptions**
- **Extended initial mass range to 100M☉ (instead of 60M☉)**
- **Updated star formation rates**
- **Cosmic metallicity distribution**



R. Sarwar et al. (2025)
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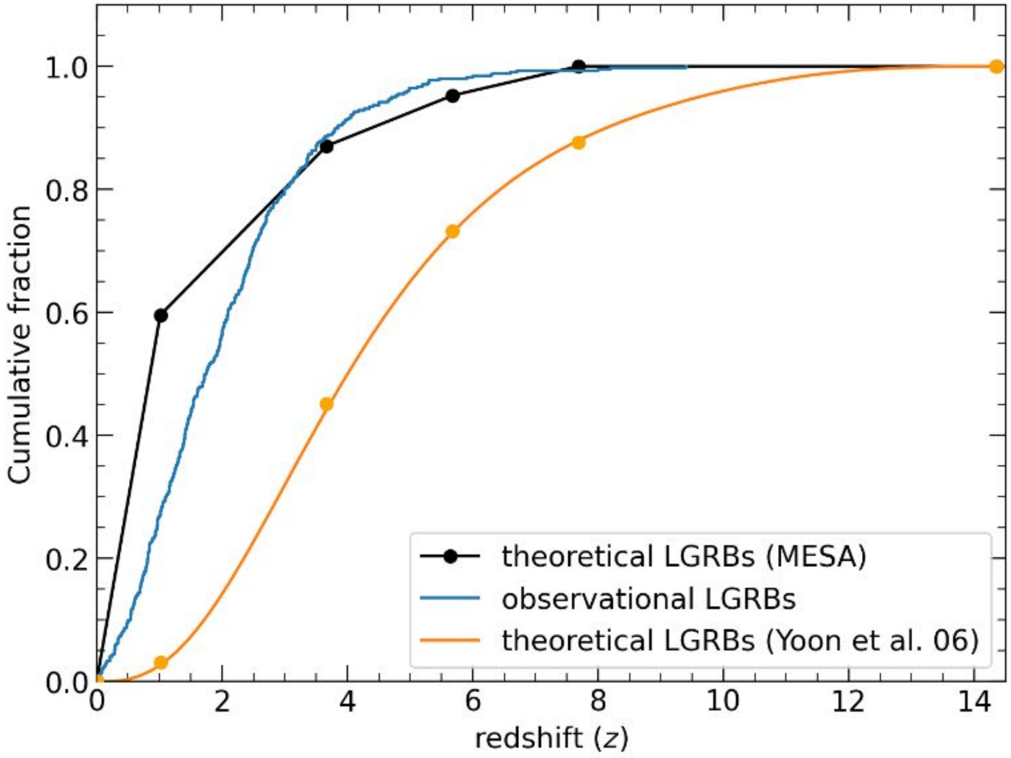

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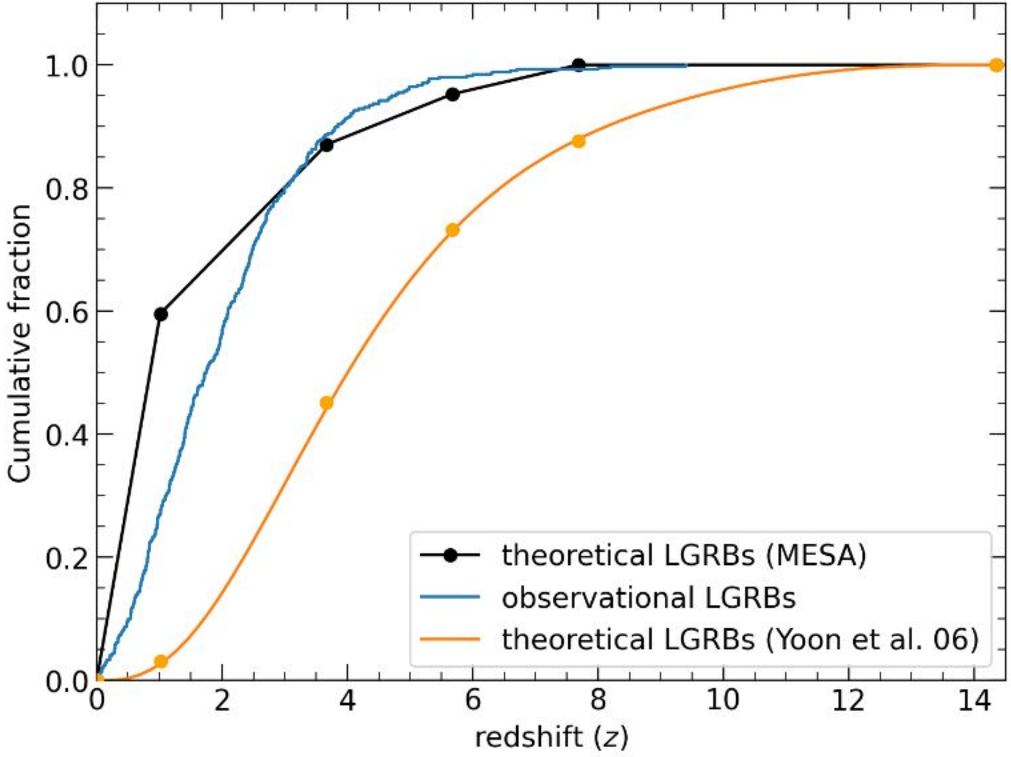
In preparation

Updated wind mass loss prescriptions

$$\log\left(\frac{\dot{M}_{\rm WR}}{M_\odot\ {\rm yr}^{-1}}\right) = -12.95 + 1.5\log L/L_\odot - 2.85X_s \quad (1)$$
$$+0.86\log(Z_{\rm init}/Z_\odot)\ , \quad \text{for} \quad \log L/L_\odot > 4.5,$$
$$= -36.8 + 6.8\log L/L_\odot - 2.85X_s$$
$$+0.86\log(Z_{\rm init}/Z_\odot)\ , \quad \text{for} \quad \log L/L_\odot \leq 4.5.$$

$$\dot{M}^*_{\rm WR} = w_{\rm CNO}\cdot\dot{M}_{\rm WR} \quad (2)$$

$$w_{\rm CNO} = 1 + \max\left(19\frac{Z - Z_{\rm init}}{1 - Z_{\rm init}}, 0\right). \quad (3)$$



R. Sarwar et al. (2025)
In preparation

Publication: in preparation

Progenitors of LGRBs: Are single stars enough?

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Received XYZ; accepted XYZ

ABSTRACT

Stars more massive than $8M_{\odot}$ are ignited by nuclear-burning processes of chemical elements in their interiors until the formation of the carbon-oxygen core that marks the end of their life cycle. The final fate of evolved massive stars is classically linked to energetic and luminous transient sources: long-duration gamma-ray bursts (LGRBs). In this work, I present the revised and expanded single-star models using MESA and new observational comparisons. My study demonstrates the impact of rotation during the evolution of these stars, leading to chemically homogeneous evolution followed by various types of supernova explosions. I also compare these theoretical models with the observed number of LGRBs with known redshifts. The comparison reveals that the updated massive-star physics can explain the observed distribution more fairly than previous studies, primarily due to how mass loss from stellar winds is treated during evolution.

Key words. Stars: Massive stars - chemically homogeneous evolution - long-duration gamma-ray bursts

1. Introduction

In the electromagnetic spectrum, gamma-ray bursts (GRBs) are amidst the most bright and luminous explosive events across the cosmic ages (Atteia et al. 2017). Prompt emissions of GRBs typically cover a spectrum from gamma-rays to X-rays and even optical wavelengths (Gorbovskoy et al. 2016; Vestrand et al. 2014). Observed redshifts (z) of GRBs range from a low of 0.0085 supernovae and LGRBs (Ensman & Woosley 1988; Galama et al. 1998; Bloom et al. 1999, 2002; Hjorth et al. 2003; Heger et al. 2003; Stanek et al. 2003; Woosley & Bloom 2006; Cano et al. 2017). Primarily, the collapsar model by Woosley et al. (1993) is the leading theoretical scenario for explaining LGRBs.

The collapse of massive, core of a fast-spinning massive star collapses due to gravity to form a proto-neutron star (PNS) surrounded by an intensely hot accretion disk. The fast-rotating

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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)
- Binary models (?)
- Reproducing the duration histogram (→ next slide)

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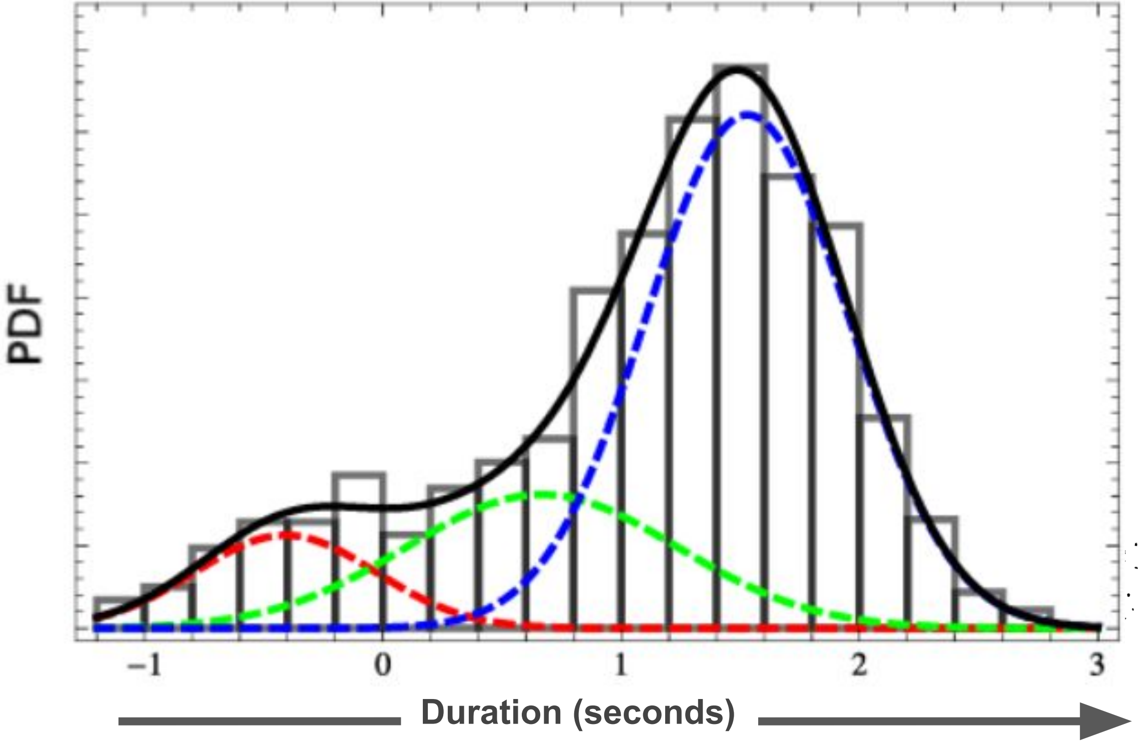
Reproducing the skewed duration distribution



Mariusz Tarnopolski (2016)

Rafia Sarwar
13th January 2025

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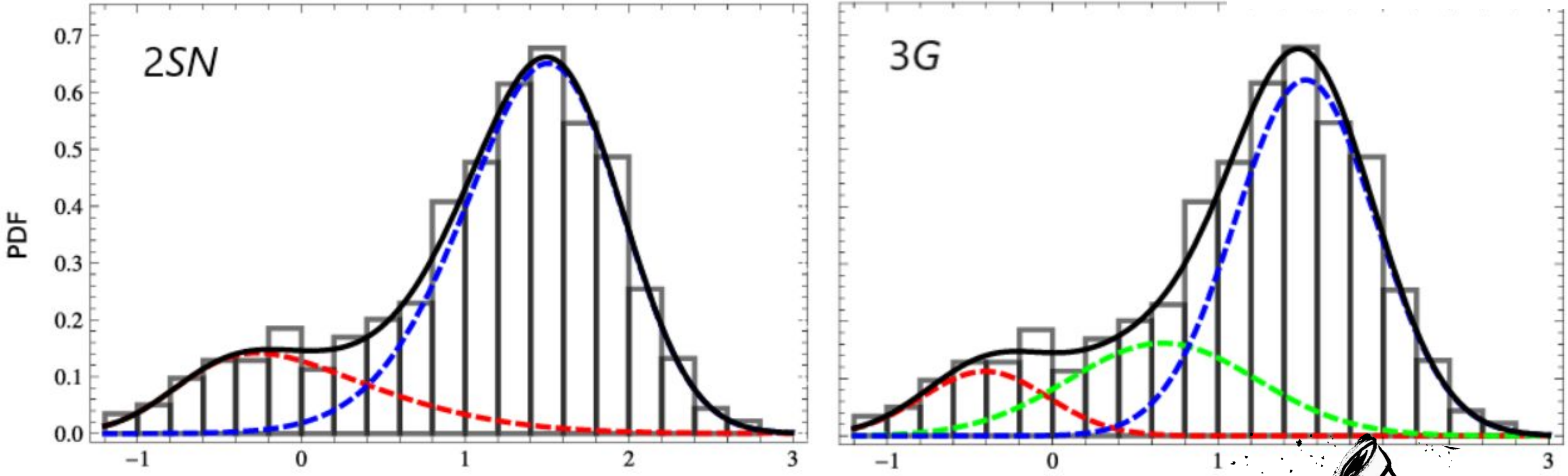
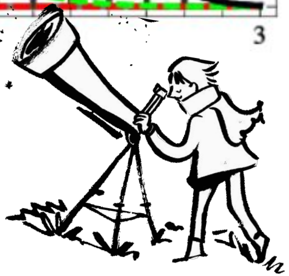
Reproducing the skewed duration distribution

t_{ff} ~ the duration



Duration (seconds)



Mariusz Tarnopolski (2016)

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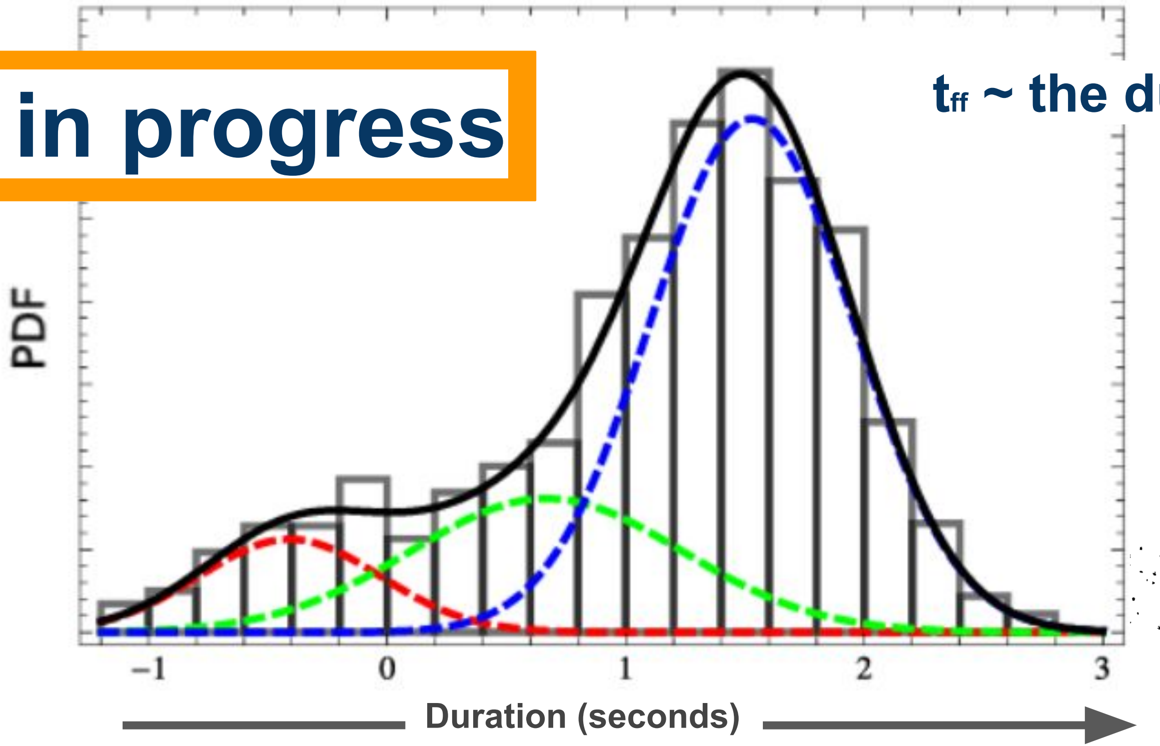
Reproducing the skewed duration distribution

Work in progress

t_{ff} ~ the duration



Mariusz Tarnopolski (2016)

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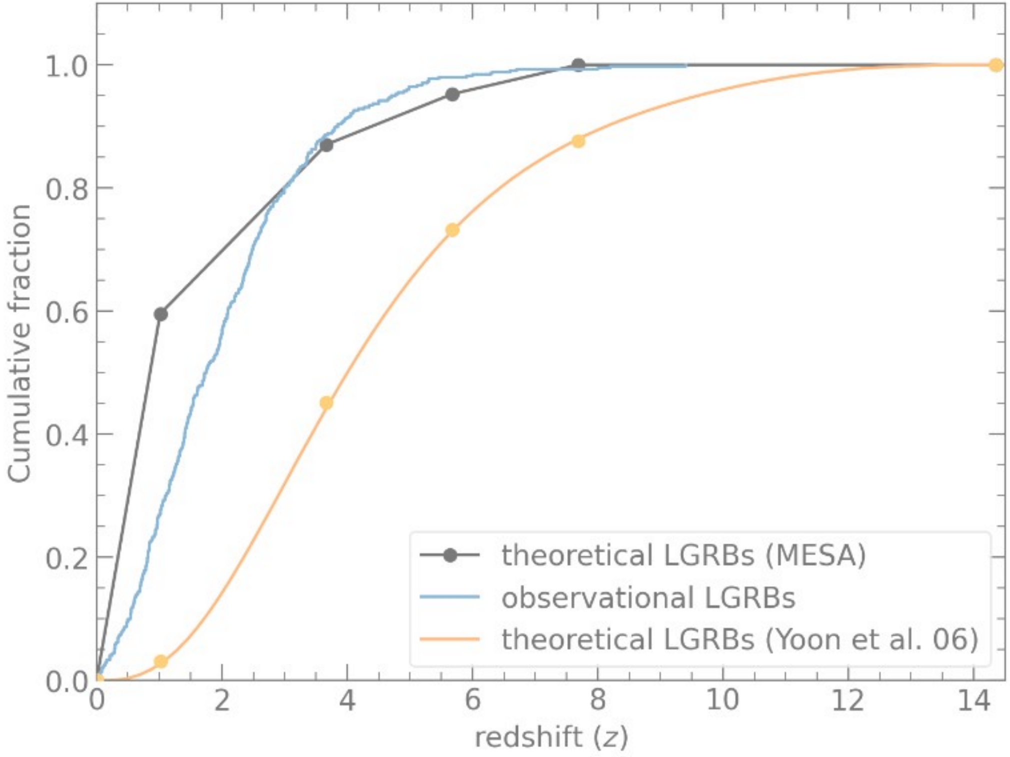
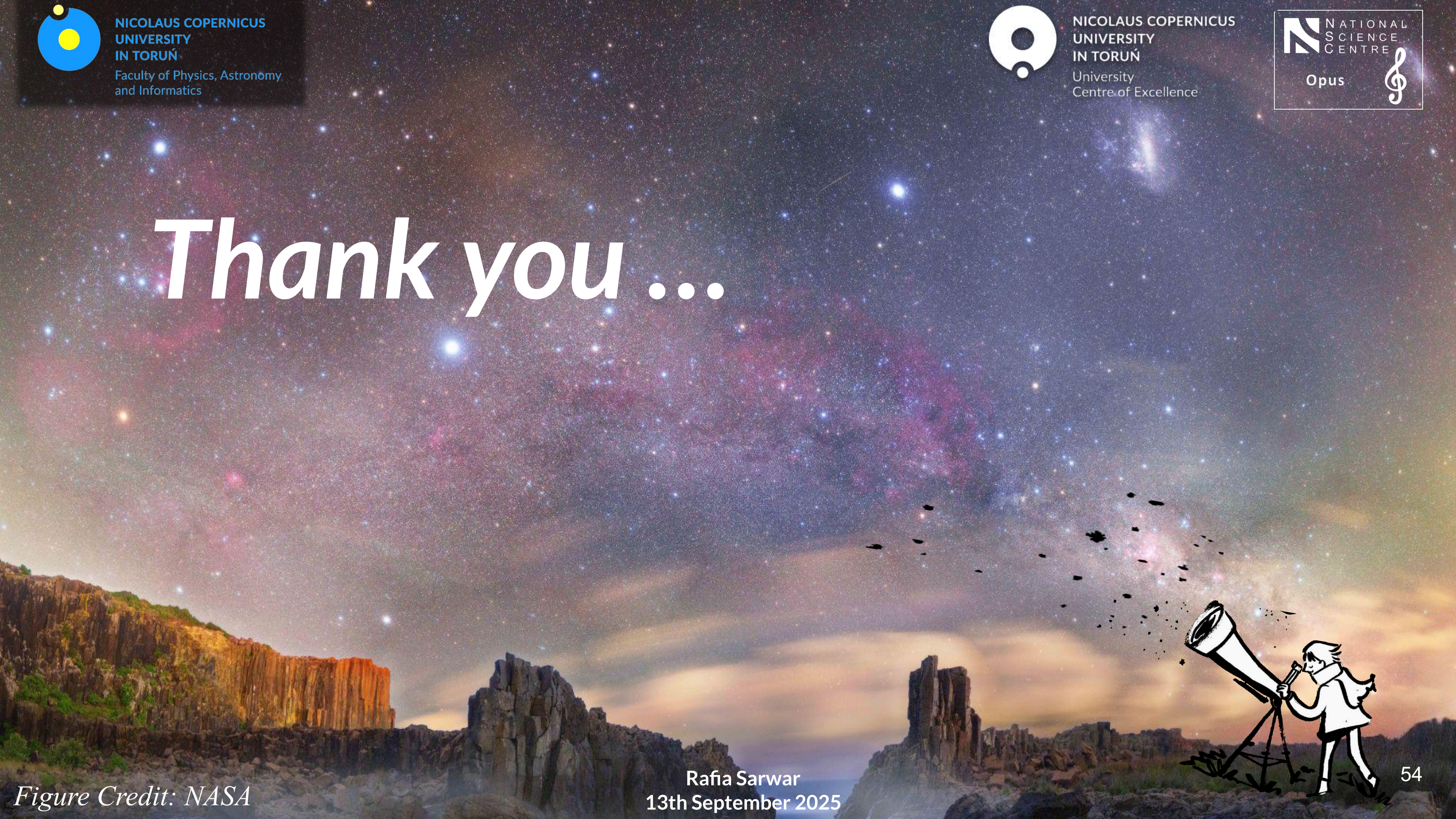
Take home message

Single star models with updated physics fits the observations well.





Thank you ...

Figure Credit: NASA

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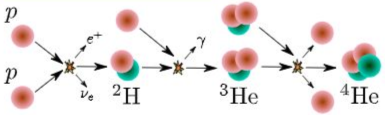
Mass Loss by stellar winds

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

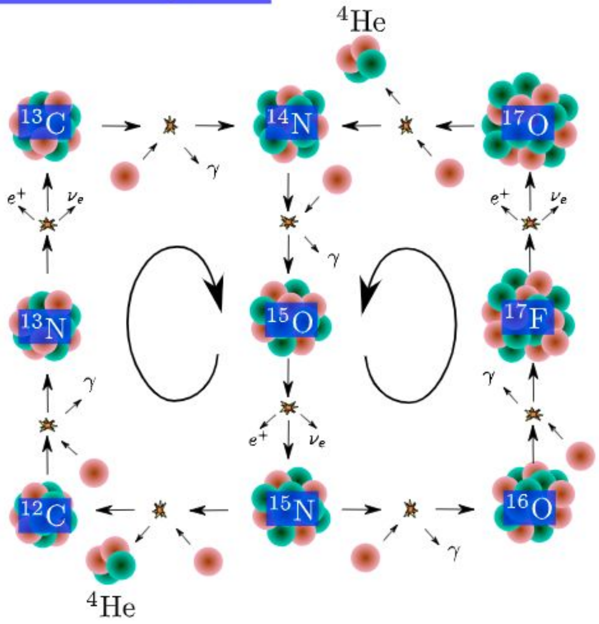


$$p + p \rightarrow {}^2H + e^+ + \nu_e \quad \text{(twice)}$$

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

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

CNO cycle



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

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

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

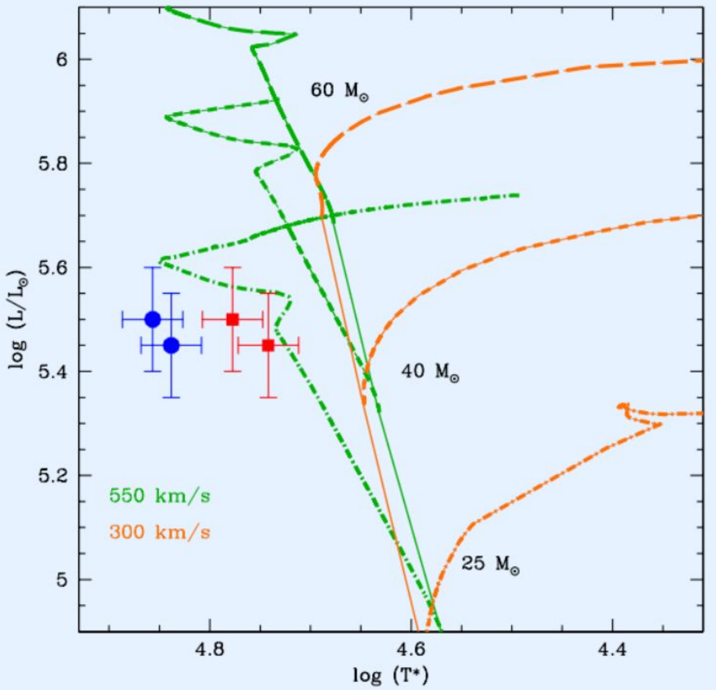
$${}^{14}N + p \rightarrow {}^{15}O + \gamma$$

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

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

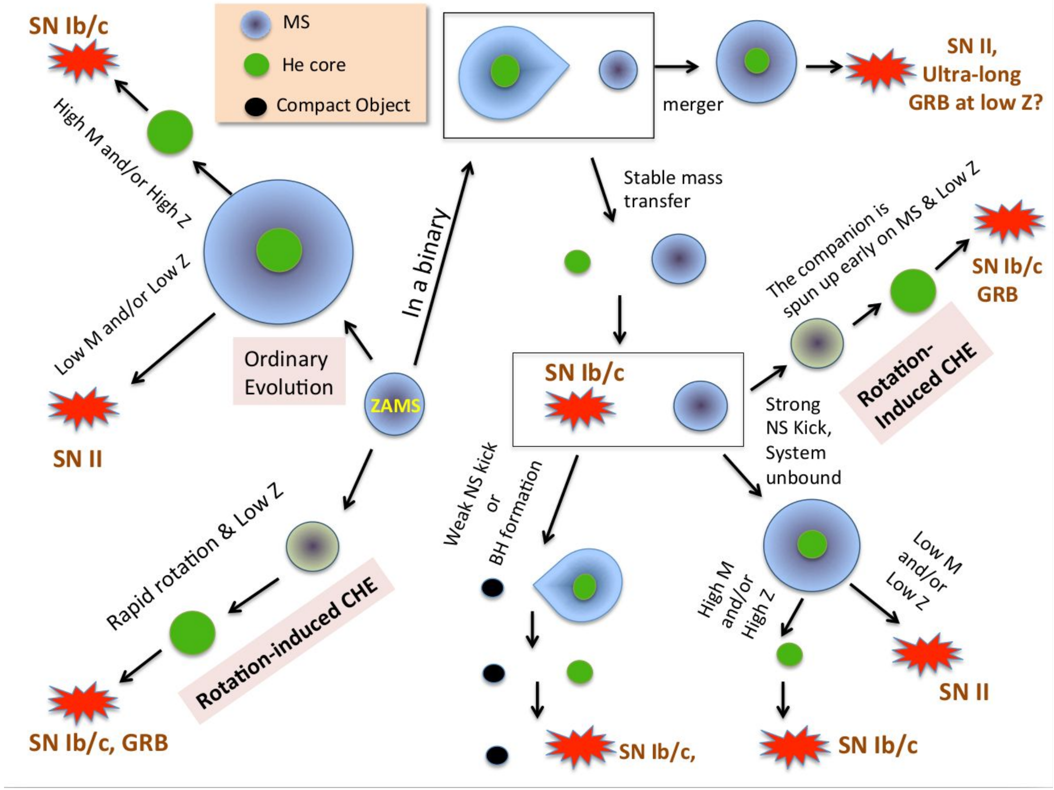
Figure 1.3: Main reactions involved in the proton-proton chain and the CNO cycle. The PP-chain is the main source of energy for low mass stars ($M \lesssim 1.5 M_{\odot}$), while hydrogen burning in more massive stars is dominated by the CNO cycle.

Evidence for CHE stars

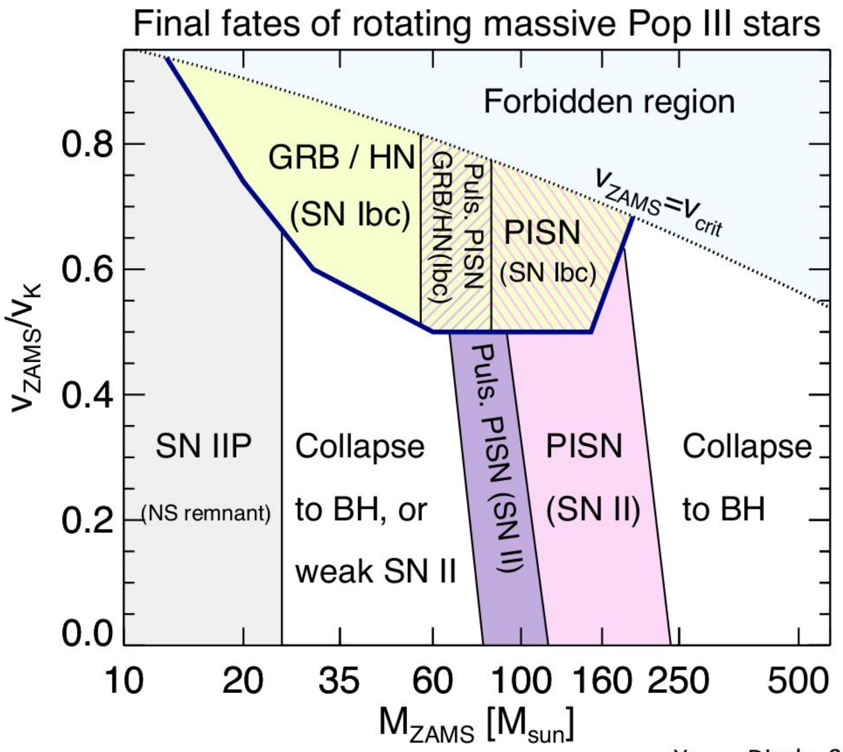


Martins et al. 2013

Fate of rapidly rotating massive stars



Fate of rapidly rotating massive stars



Yoon, Dierks & Langer 2012

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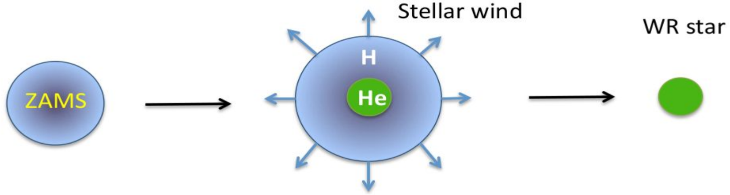
Mass Loss by Winds:
Standard scenario for massive star evolution

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!**

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Specific angular momentum

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

By Bardeen et al. (1972), radius at ISCO, scaled by GMBH/c.c is

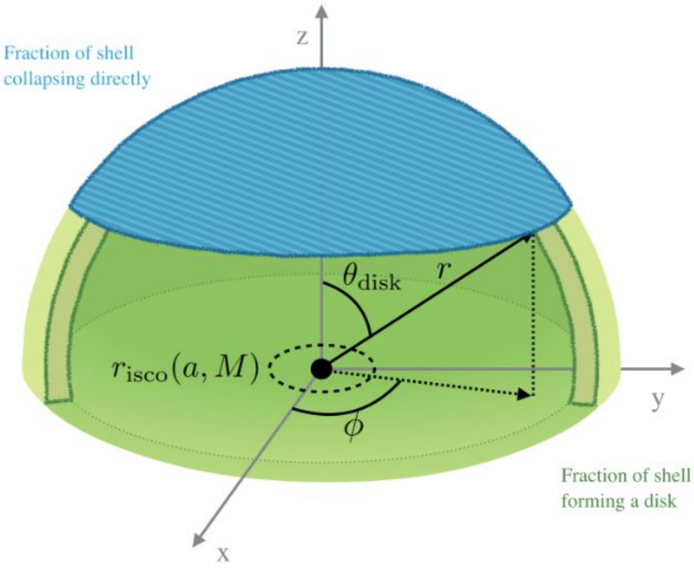
$$r_{\rm isco} = 3 + z_2 \pm [(3 - z_1)(3 + z_1 + 2z_2)]^{1/2}$$

where z1 and z2 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 GMBH/c, can be written as:

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



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

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