~~Formation of~~ Rapidly rotating massive stars as progenitors of long GRBs

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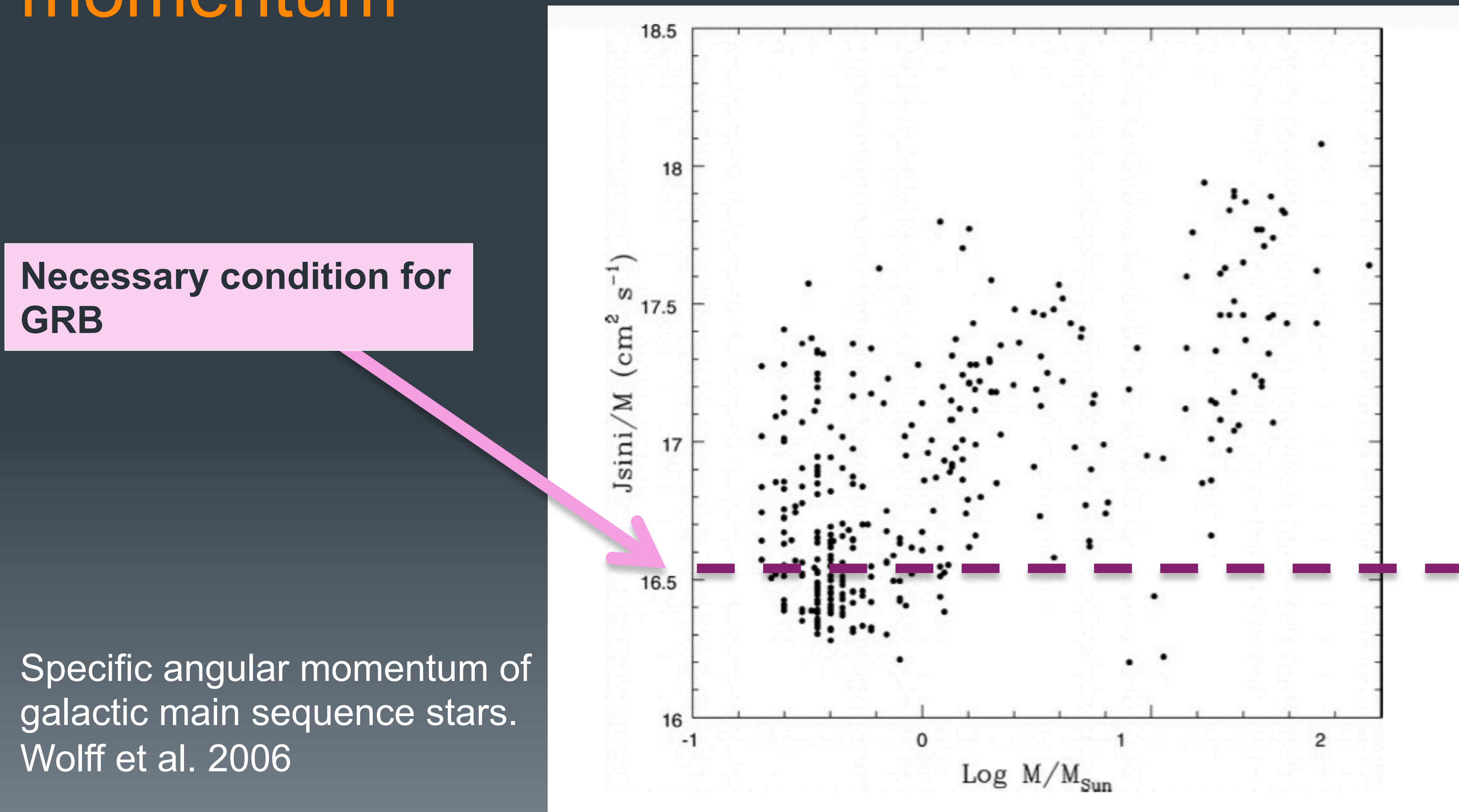
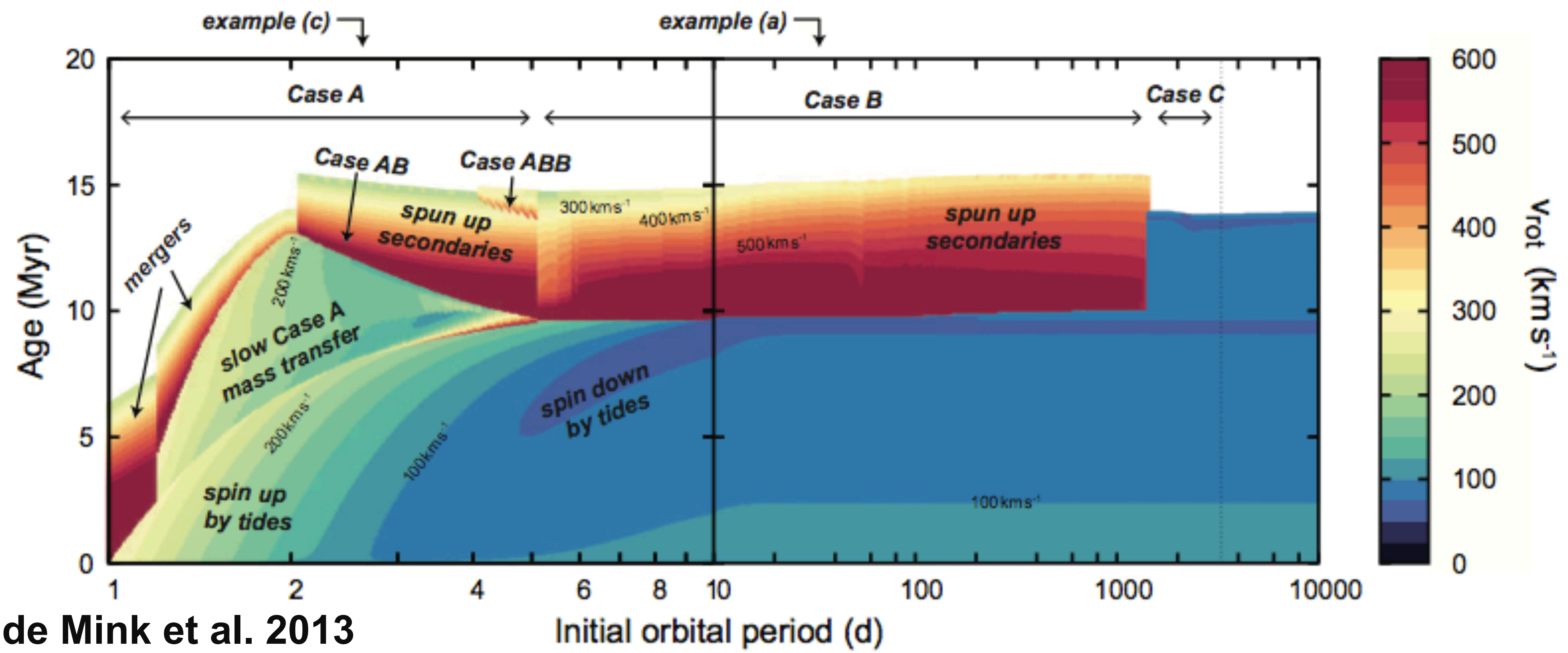
Many massive stars are born with a large amount of angular momentum



Specific angular momentum of galactic main sequence stars. Wolff et al. 2006

There are also many ways to produce rapidly rotating massive stars via binary interactions



de Mink et al. 2013

See also Cantiello et al. 2007, Huang et al. 2010

Which evolutionary paths of rapidly rotating massive stars lead to production of a long GRB?

Unfortunately not much progress in ***theory*** has been made on this question, during the last several years.

In this talk, I will explain why.

Long GRBs and Their Progenitors

- long GRBs associated with SNe Ic
  - Massive helium stars like ordinary SNe Ic progenitors, but ***with some special conditions***
- long GRBs without SN as ociation
  - Mergers of helium sta
  - Massive he
- long GR
  - Blue s
  - Superma

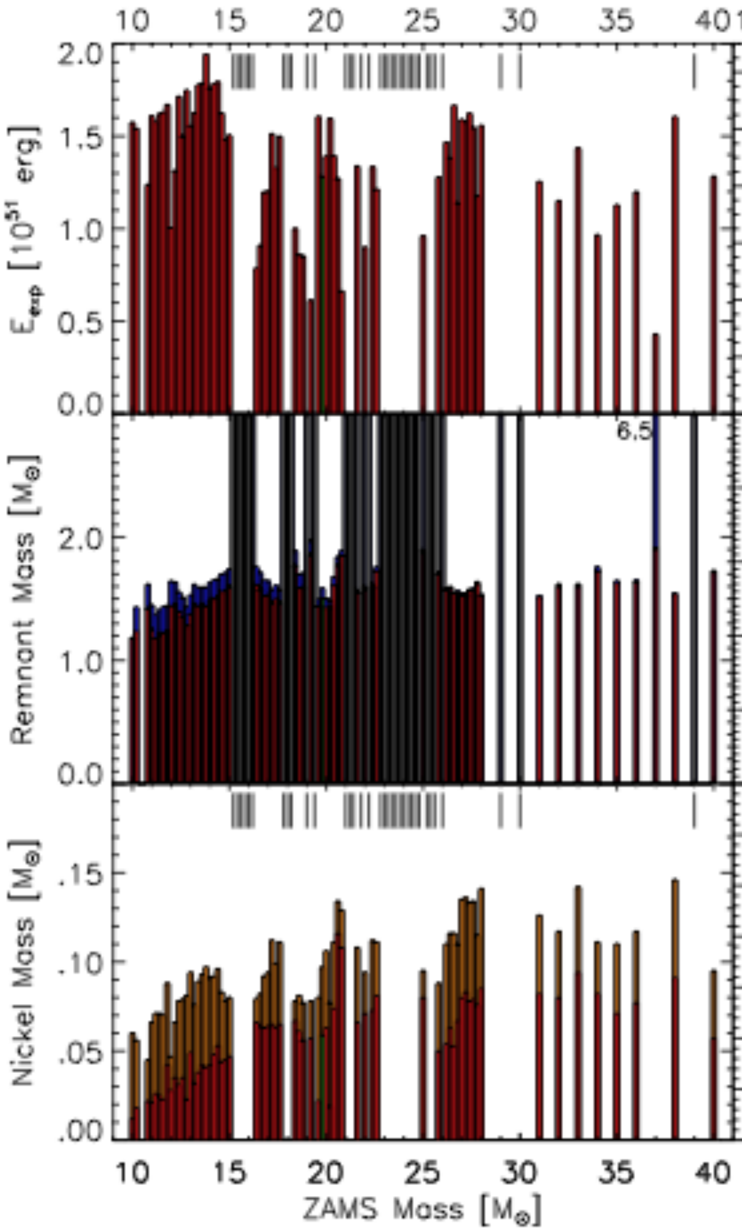
This talk will focus on this.

Q1: According to the collapsar scenario, long GRBs are associated with BHs. But, then, which stars make a BH?

It has been long believed that there is a “mass cut” for BH formation. But is it really so?

Recent studies indicate that the details of the core structure are sometimes equally or more important than the progenitor mass (Ugliano et al 13, Dessart et al. 12, O’Connor & Ott 13). Magnetar-driven explosion could also prohibit formation of a BH (Dessart et al. 08).

Ugliano et al. 2013



The stellar evolution at the final stages is highly non-linear with complicated convection history, and the final stellar structure is not easy to predict robustly.

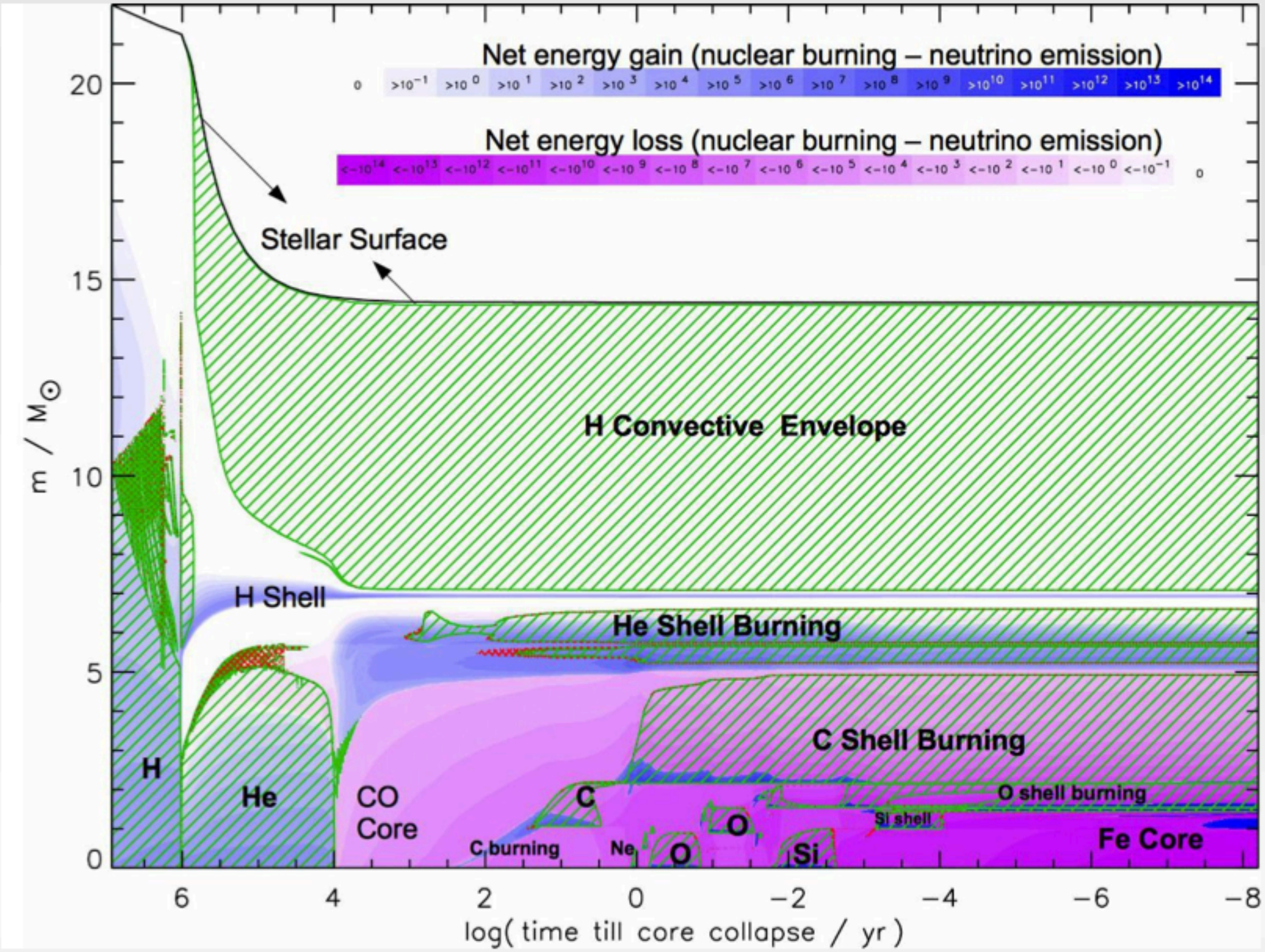


Figure from A. Heger

Q2: Why is there no GRB associated with SN Ib?

So far, all supernovae associated with long GRBs were Type Ic.

Both Type Ib and Ic supernovae originate from hydrogen-deficient massive stars.

First of all, then, what makes SN Ic progenitors different from SN Ib progenitors?

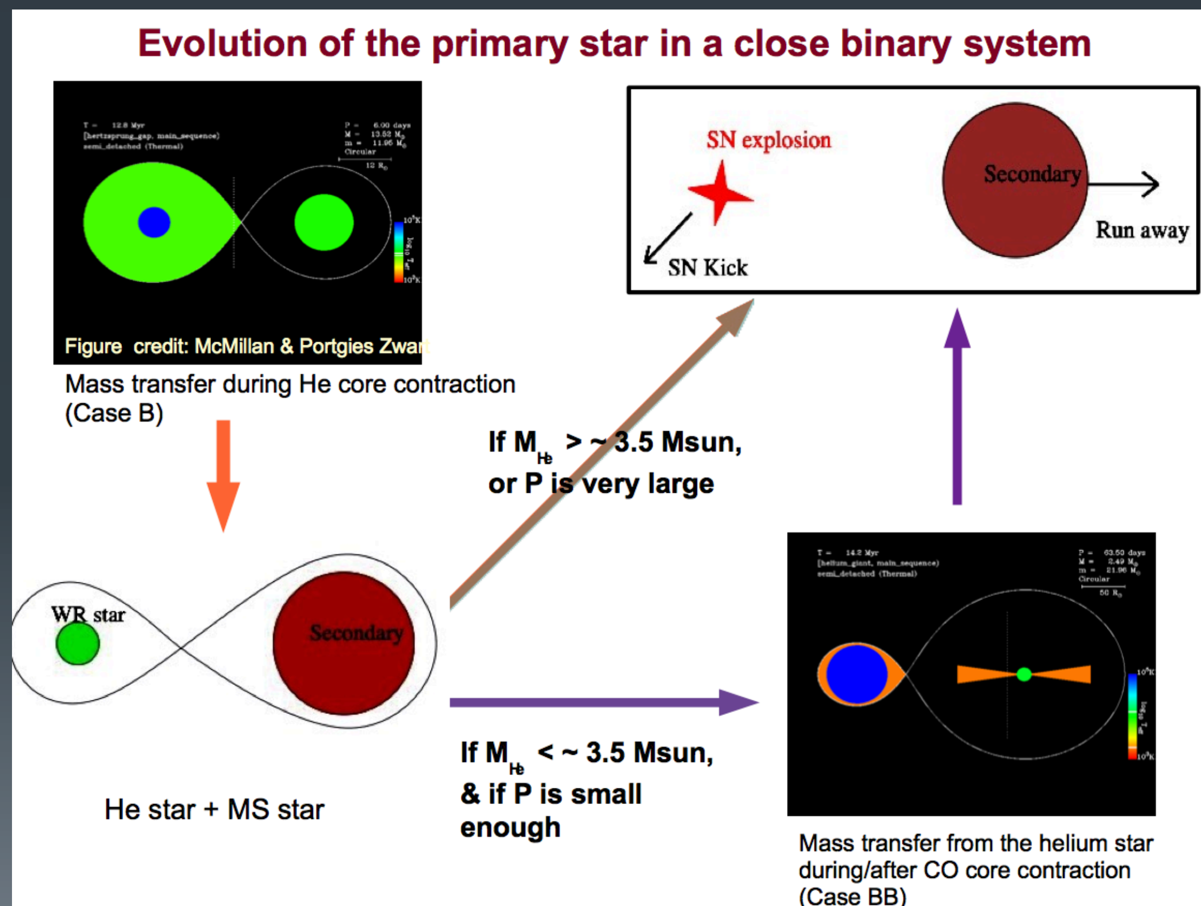
We still do not know.

Evolution of massive stars towards Type Ib/c supernovae

Long GRB is a sub-set of SN Ib/c

Single Stars: Conti Scenario

Binary Stars



What makes SN Ic progenitors different from SN Ib progenitors?

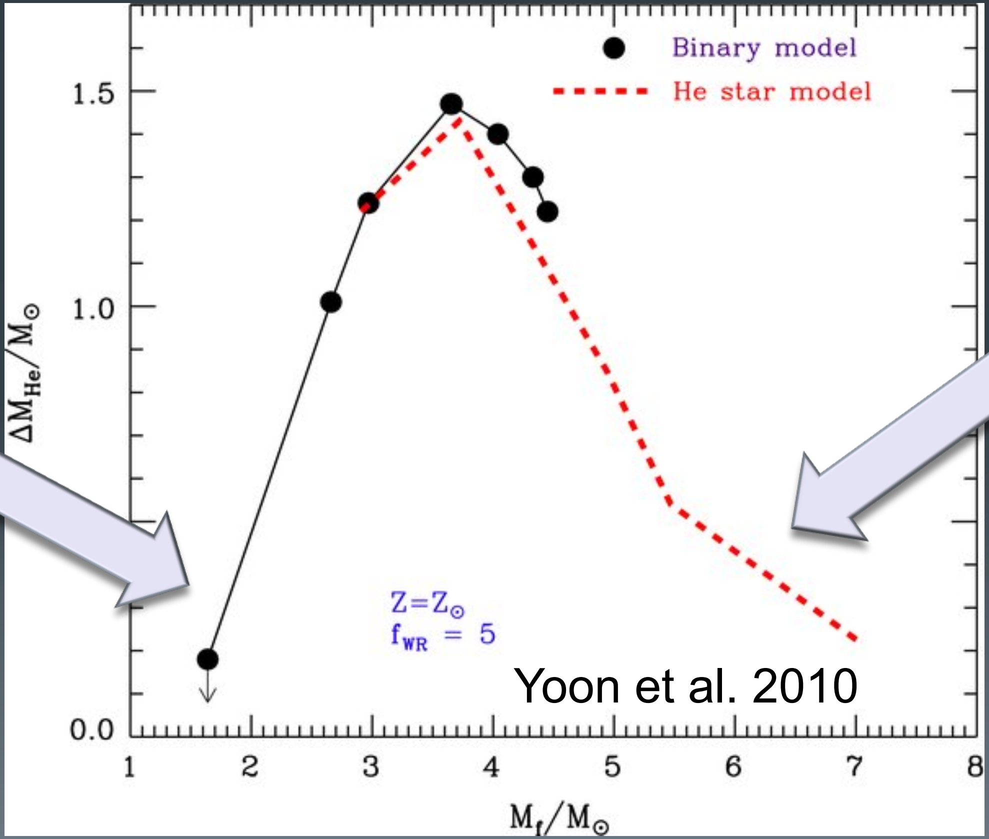
1. Total amount of helium?

   (cf. Hachinger et al. 2009)

Case BB mass transfer for relatively low-mass He stars:

This can make "faint SN Ic", like SN 2005ek.

Cf. Drout et al. 2013, Tauris et al. 2013.

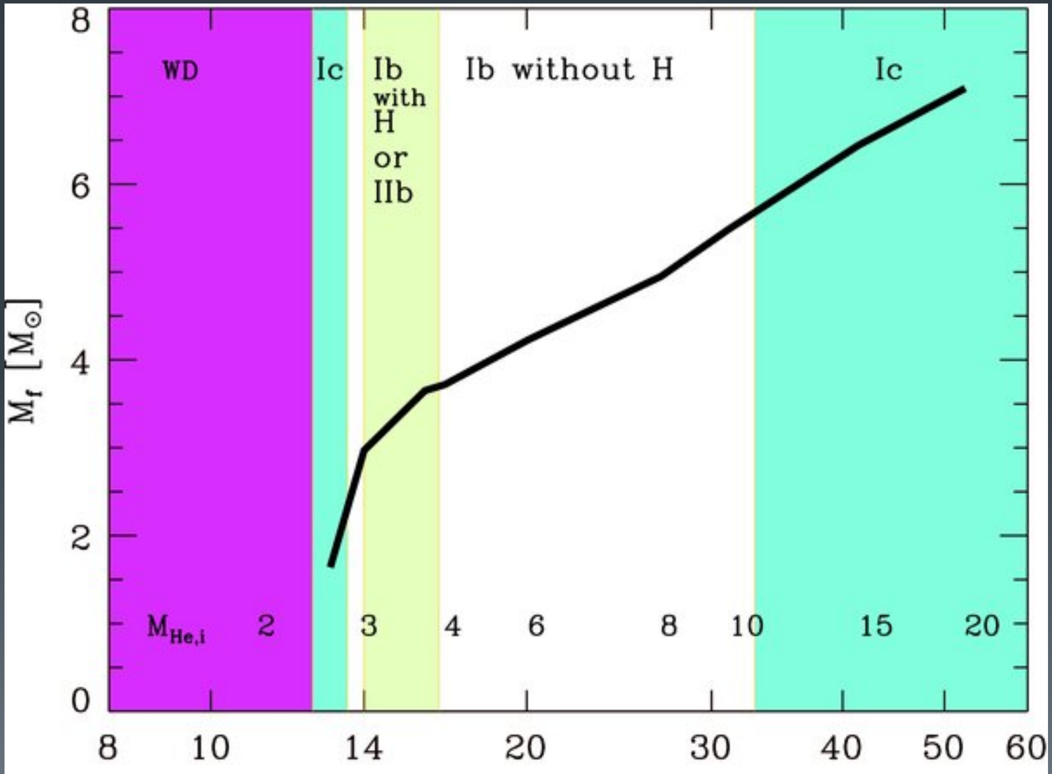


Yoon et al. 2010

WR winds for massive He stars. Stellar evolution models predict more than 0.2 Msun of helium left until the end.

If the total amount of He is the governing factor for distinguishing SN Ic from SN Ib, SNe Ic should have systematically larger ejecta mass than SNe Ib.

But, that's not what we observe (e.g. Drout et al. 2011, ApJ, 741, 97). The typical ejecta mass is about 2 Msun for both Ib and Ic.



Yoon et al. 2010

What makes SN Ic progenitors different from SN Ib progenitors?

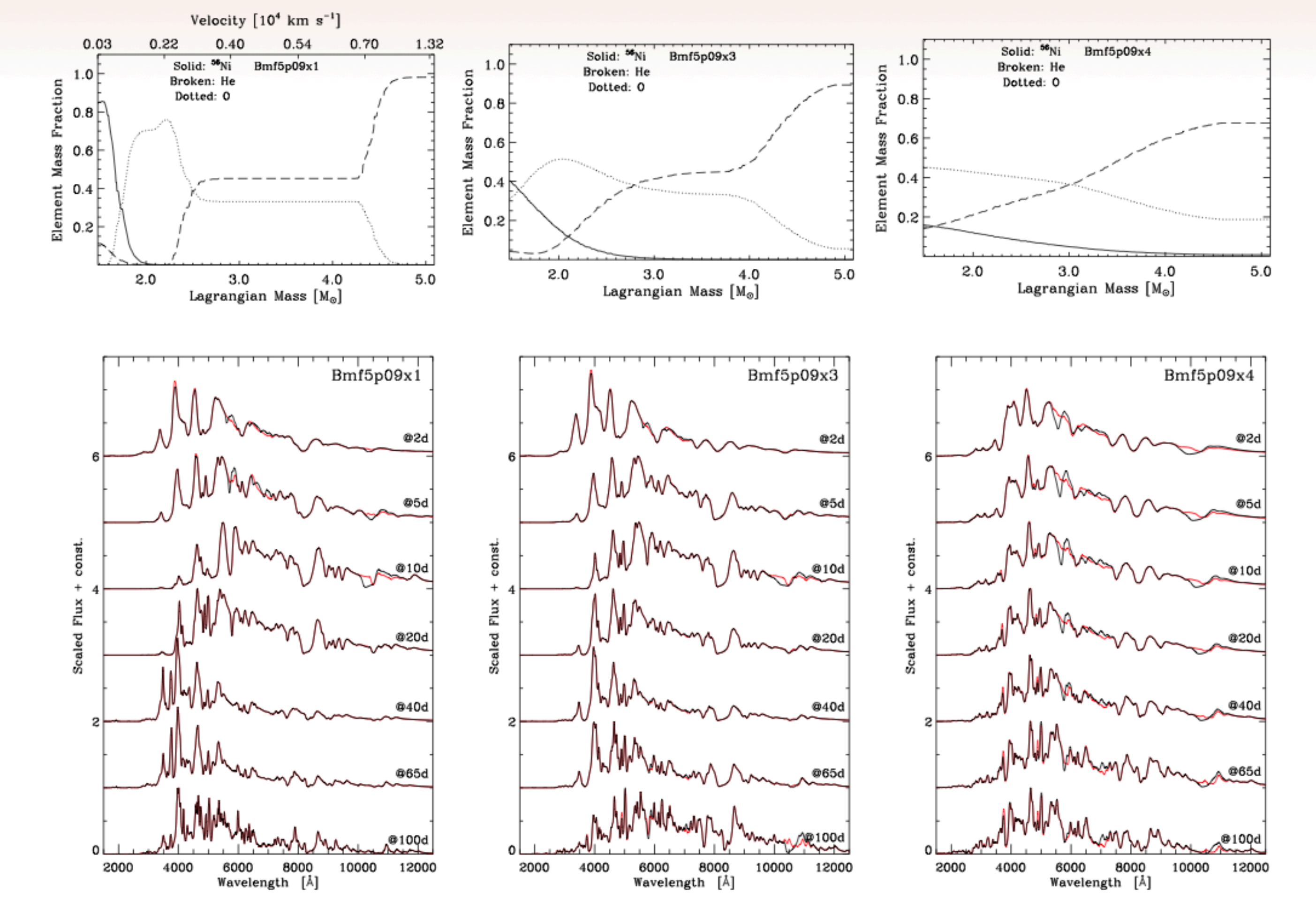
2. Mixing of ^{56}Ni with He?

Dessart et al. 2012

Mixing seems to be critical for He lines.

But which progenitors are more prone to mixing?

See also Hachinger et al. 2009

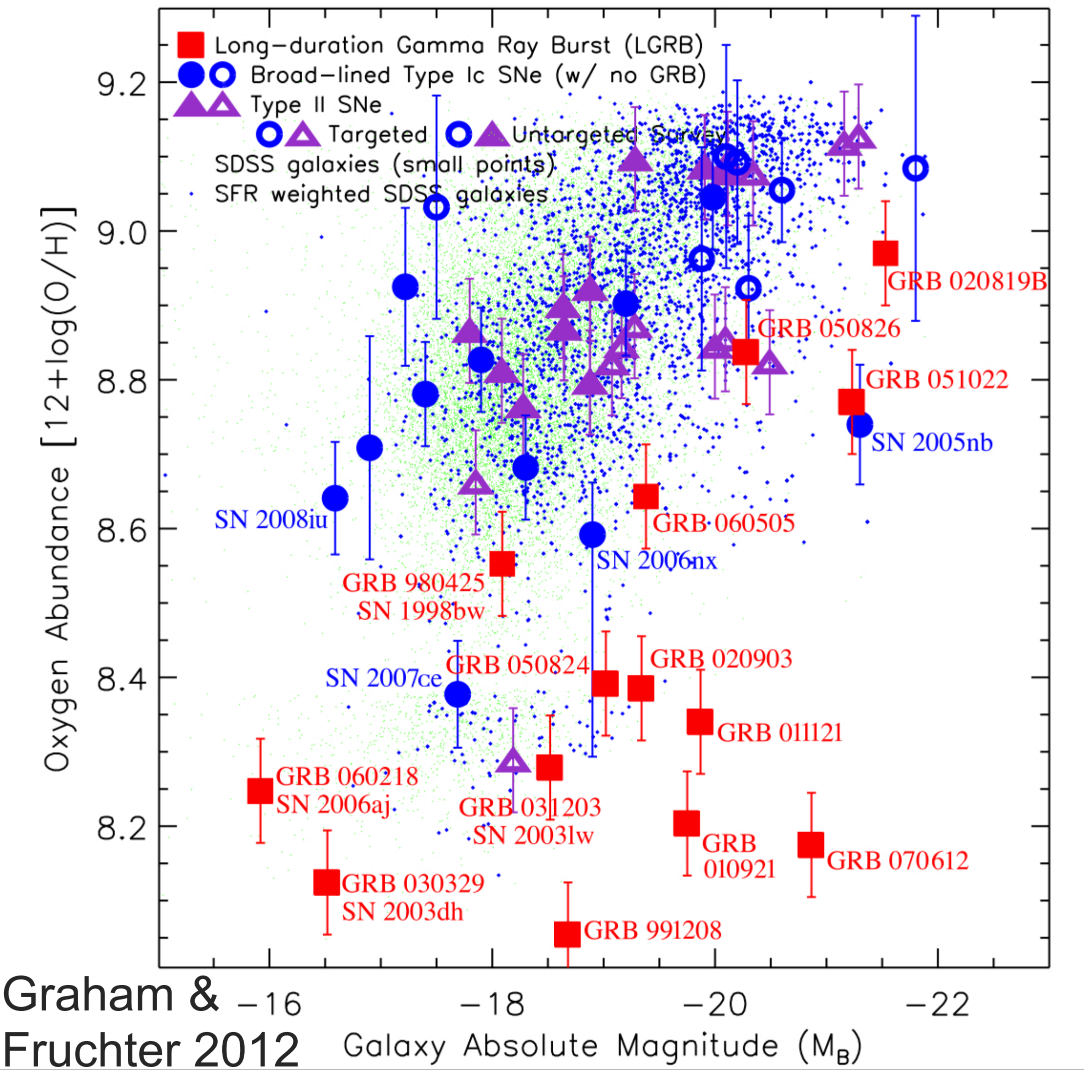


Q3: which stars make broad-lined Ic without GRB?

Clueless!!!! (maybe related to magnetar-driven explosion?)

Observations seem to indicate that their are systematically more massive than ordinary SN Ic.

Would it be related to magnetars? Then, why not broad-lined SN Ib?

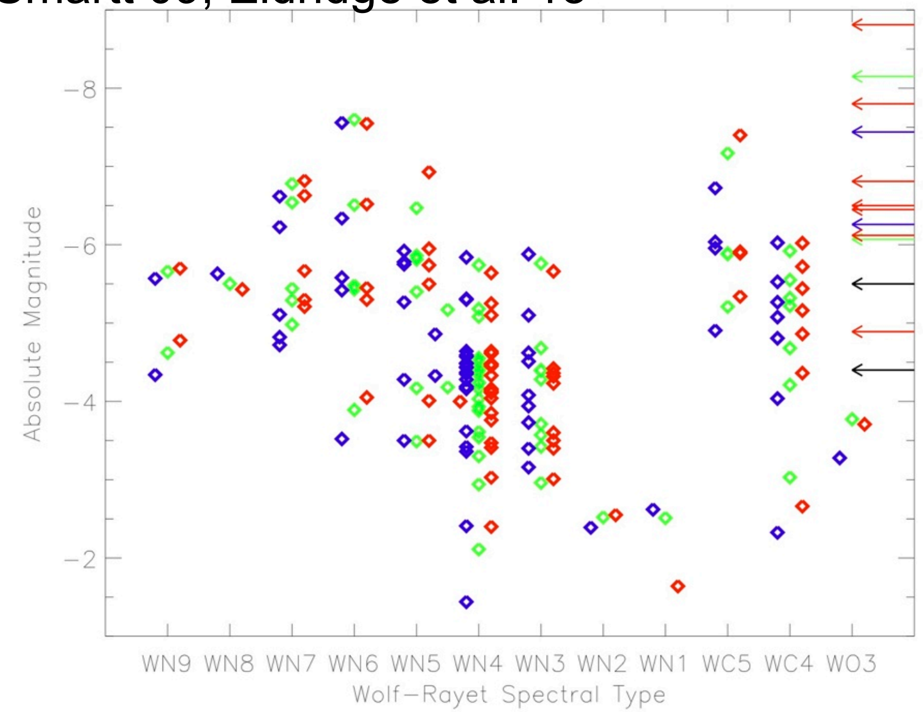


Graham & Fruchter 2012

Q4: Why is it so difficult to directly identify SN Ibc progenitors?

So far, there is no firm direct identification of SN Ibc progenitors in the pre-SN images, unlike SN IIP progenitors. If SN Ibc progenitors look like the observed WR stars, at least a few should have been found in the past surveys (Smartt et al. 2009, Eldridge et al. 2013; but see).

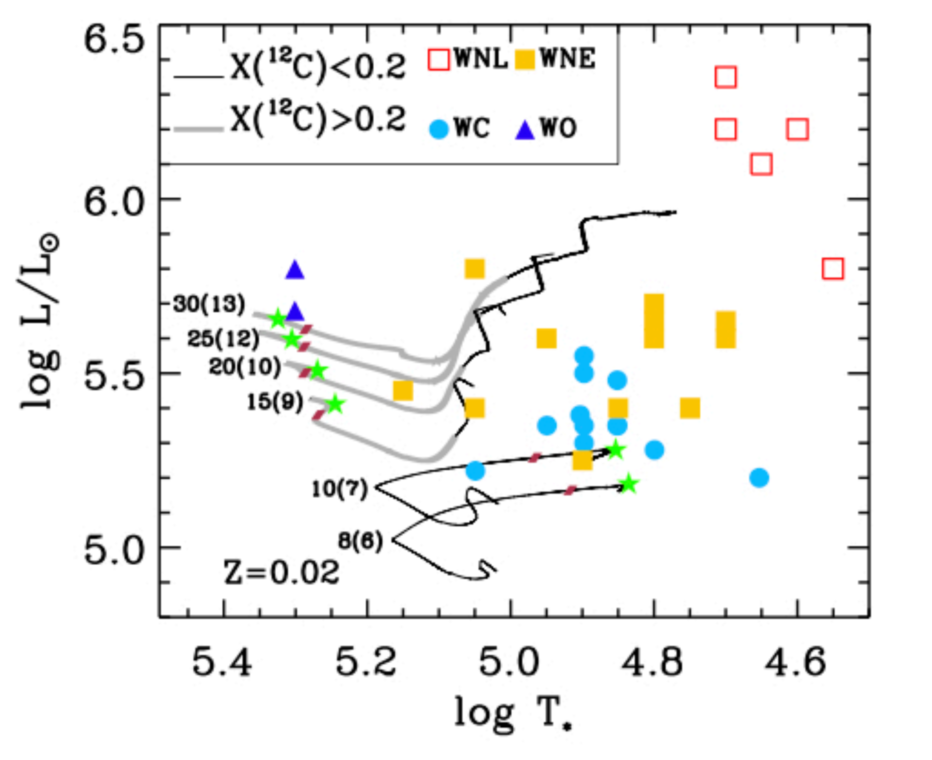
Smartt 09, Eldridge et al. 13

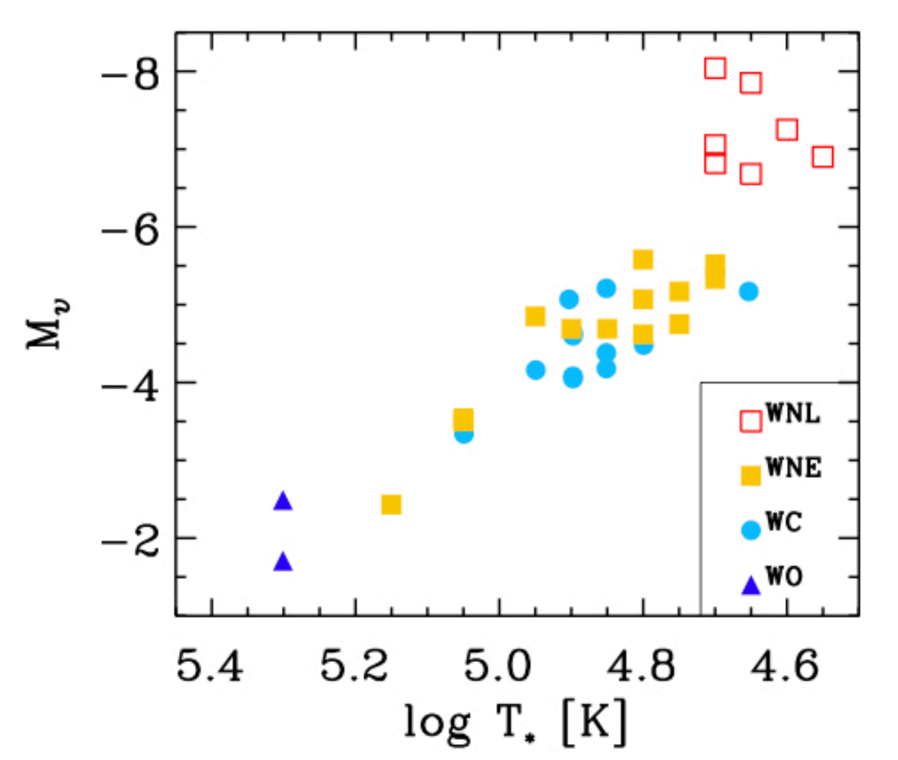


The SN Ibc progenitors at the pre-SN stage may look very different from most of the observed WR stars!

If their final masses are higher than about ~ 8 Msun, they will be very compact, hot, and optically faint like WO stars.

This would also be the case for GRB progenitors.





Yoon et al. 2012

Q5: How can we explain the metallicity dependence of the long GRB event rate?

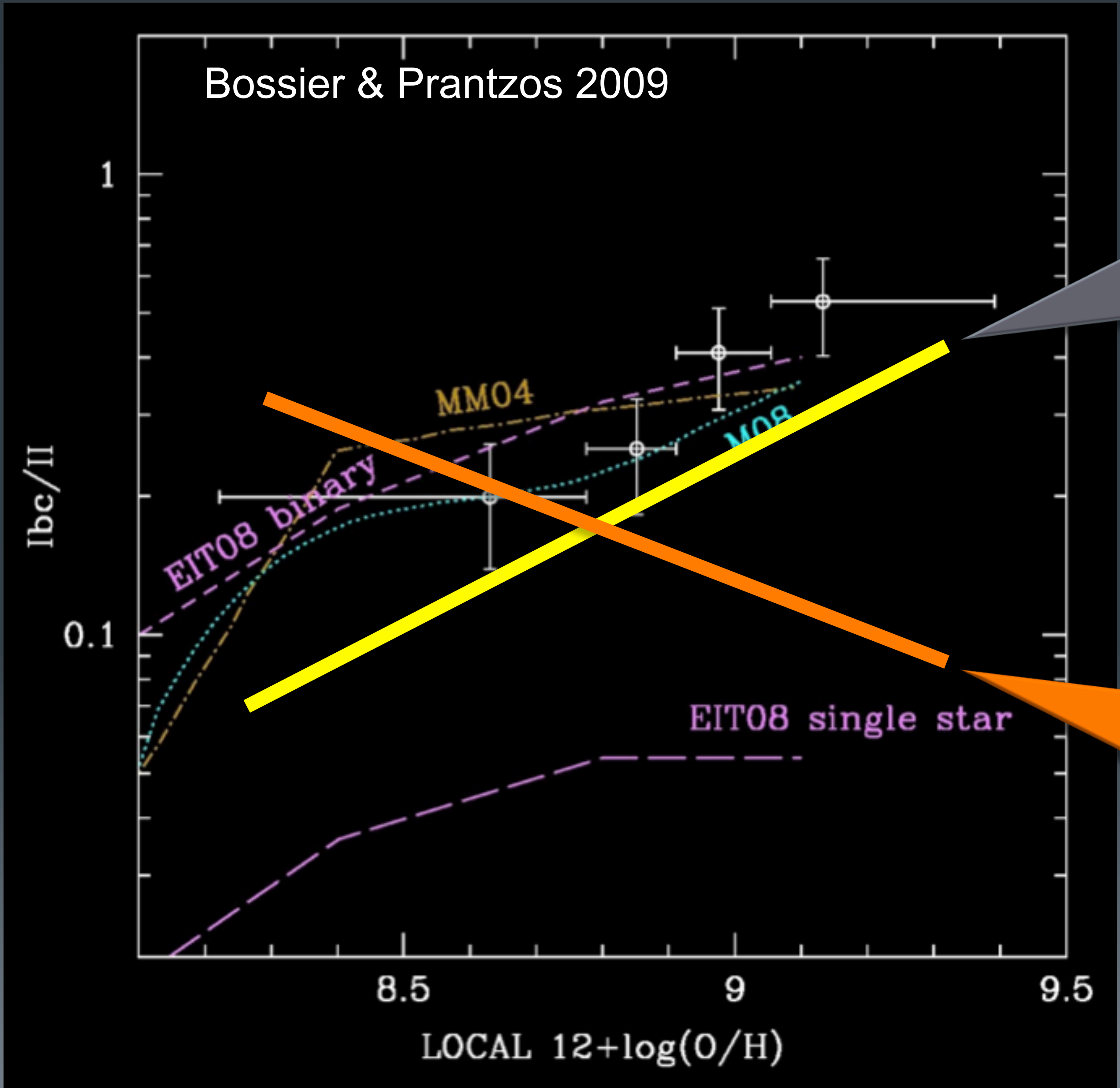
Although it is not conclusive yet, many observations seem to indicate that low-Z is preferred for the production of long GRBs. (e.g., Modjaz et al. 2008, Graham & Fruchter 2012)

Would a low Z be preferred if the amount of angular momentum retained in the progenitor were the key necessary condition for long GRB?

NO! if the core braking is not efficient (non-magnetic stellar evolution models; Heger et al. 2000, Hirschi et al. 2004).

Probably yes, if the core braking is strong (magnetic models), depending on the evolutionary paths you want to consider. (Yoon & Langer 05, Woosley & Heger 06)

Both observation and theory indicate that high-Z is preferred for ordinary SN Ibc



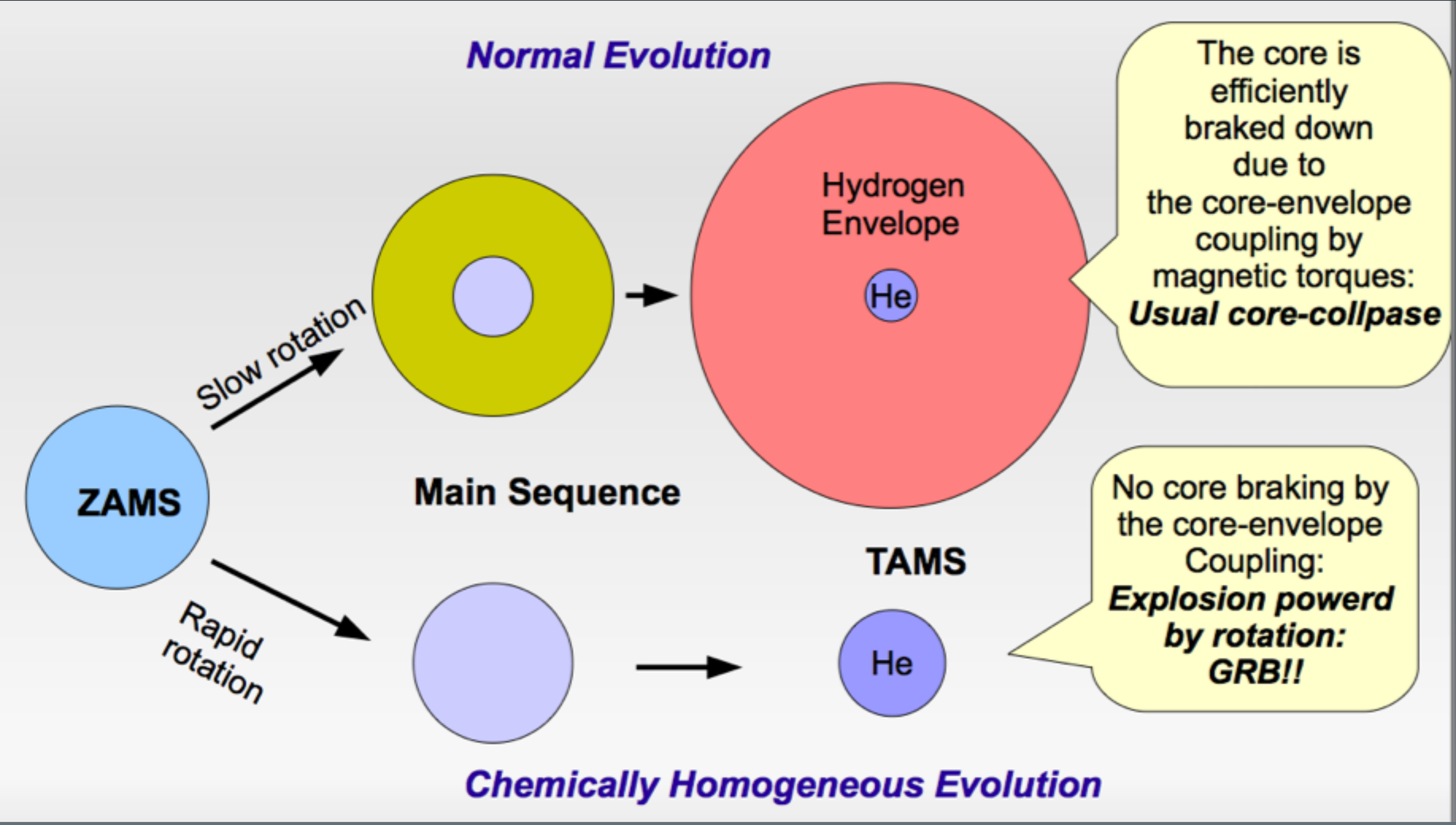
If long GRB is a "random" subset of SN Ibc (as expected from non-magnetic stellar models)

This is what observations seem to indicate.

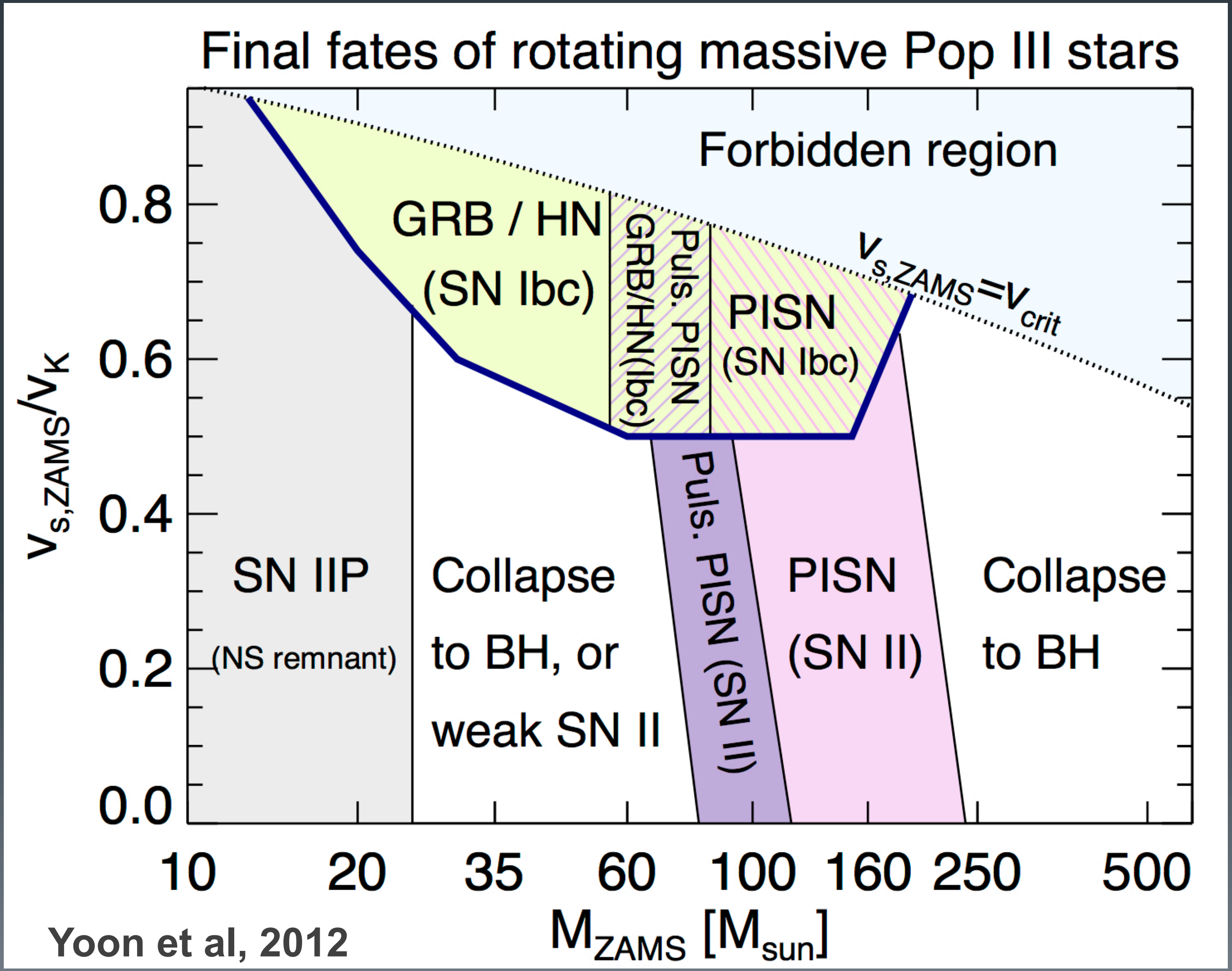
Then, what's special with low-metallicity?

High Metallicity	Low Metallicity
Strong winds resulting from metal lines	Weaker line-driven winds
Unstable for many times	Relatively stable? (cf. Baraffe et al. 2001)
Strong mass loss	Weak mass loss
The evolution of massive stars is dominated by "mass loss"	The evolution of massive stars is dominated by "rotation" (i.e., rotational mixing and centrifugally driven winds)

CHE: chemically homogeneous evolution via rotationally-induced chemical mixing



CHE can lead to formation of massive He stars even at zero-metallicity as GRB progenitors

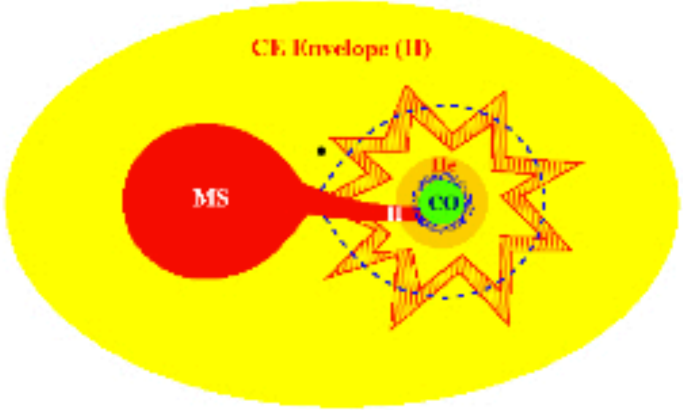


Q6: Can binary systems produce a long GRB?

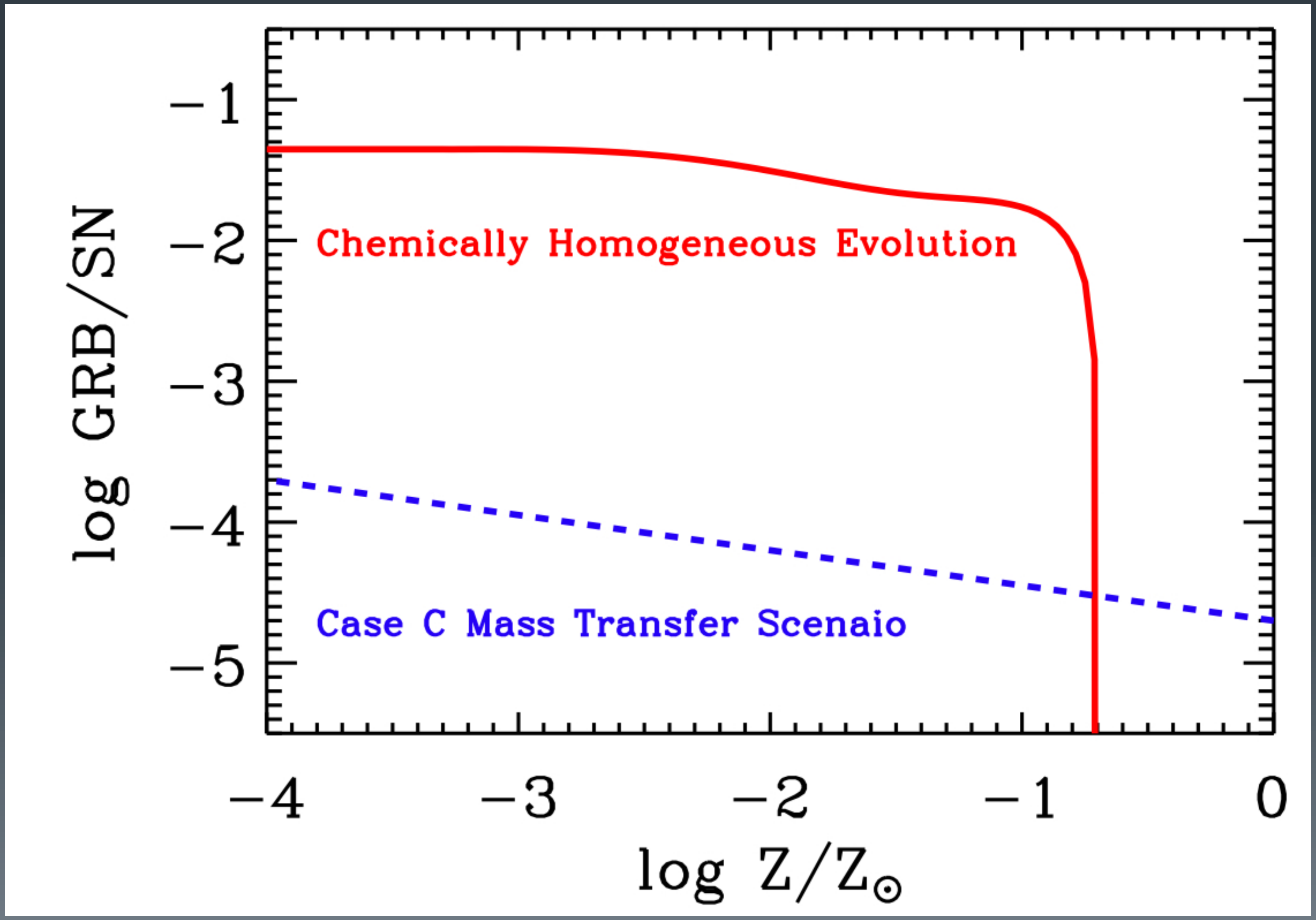
Case-C mass transfer in binary systems with a low mass companion Brown et al. 2000 ; Podsiadlowski et al. 2010

- connection with some low mass X-ray binaries?
- explosive common evenlope ejection with low mass companion (1.0 – 3.0 $M_\odot$) Podsiadlowski et al. 2010
- can occur even at $Z = Z_\odot$

Podsiadlowski et al. 2010



Binary scenarios might explain long GRBs from metal-rich host galaxies. Strong preference for low-metallcity is expected in the CHE scenario.



Summary

The necessary conditions for long GRB progenitors, and related questions.

- ✓ Rapid rotation (***Q: which mechanism is most important for the transport of angular momentum in stars?***)
- ✓ BH formation ***(Q: core should be massive enough???)***
- ✓ No extended hydrogen envelope ***(Q: OK. But then why there's no GRB associated with SN Ib?)***

Are there other important necessary conditions that we are missing? B-fields?