

The Spins of Stellar Remnants

From white dwarfs to gamma-ray bursts

Norbert Langer (Utrecht University)

with thanks to:

- Alexander Heger (Los Alamos)
- Colin Norman (Baltimore)
- Jelena Petrovic (Nijmegen)
- Maarten Suijs (Utrecht)
- Stan Woosley (Santa Cruz)
- Sung-Chul Yoon (Amsterdam)

Reasons to look at the spin

- WD spins/ NS, pulsar spins / BH spins
- long gamma-ray bursts \leftrightarrow collapsars
- supernova asymmetries
- Be stars, Be X-ray binaries
- LBVs (AGBs) & their nebulae
- rotation affects stellar evolution

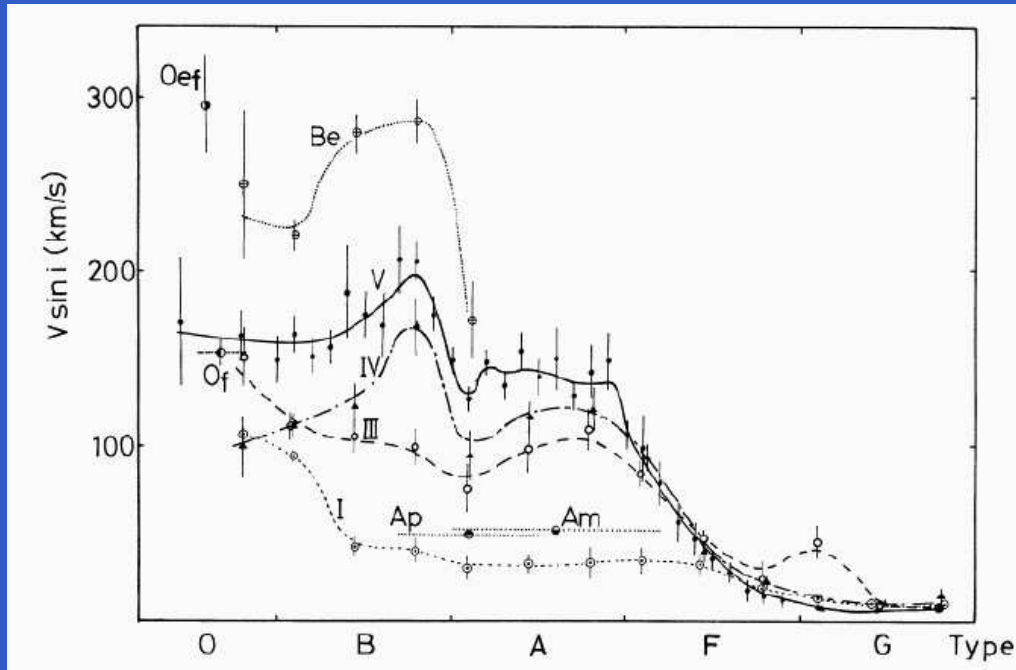
Tool: stellar evolution code

- centrifugal force: averages on isobars (Kippenhahn and Thomas '78)
- rotationally induced transport (Heger, Langer and Woosley '00; Yoon and Langer '04)
- dissipation of rotational energy (Yoon '04)
- magnetic torques (Spruit '02)

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- dissipation of rotational energy (Yoon '04)
- magnetic torques (Spruit '02)
- rotationally supported mass loss (Ω -limit, Langer '98)
- mass and ang. momentum transfer (Wellstein & Langer '99)
- tidal spin-orbit coupling (Wellstein '01)

Observations: Main Sequence Rotation



Fukuda 1982

specific angular momentum:

● $M < 1.2 M_{\odot}:$

$$j \simeq 10^{16} \text{ cm}^2 \text{ s}^{-1}$$

$$v_{\text{rot}} \ll v_{\text{crit}}$$

● $M > 1.2 M_{\odot}:$

$$j \simeq 10^{18} \text{ cm}^2 \text{ s}^{-1}$$

$$v_{\text{rot}} \simeq v_{\text{crit}}$$

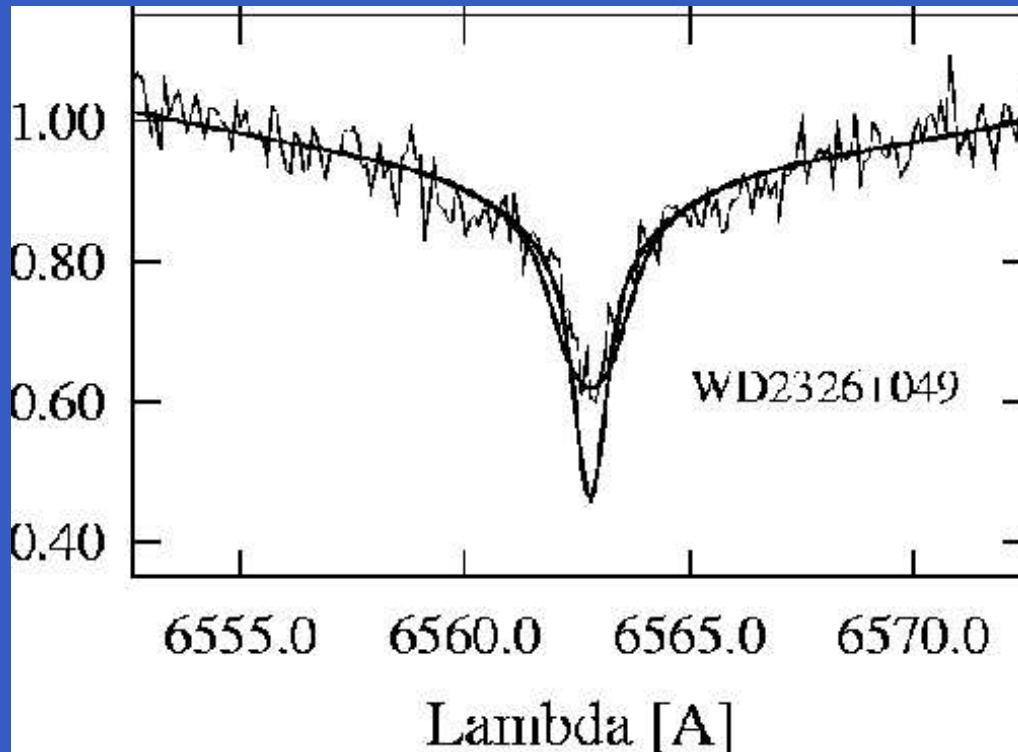
Observations ...

| object | $j / \text{cm}^2 \text{s}^{-1}$ | P or v_{rot} |
|-----------------------|---------------------------------|---|
| MS $M < 1.2M_{\odot}$ | 10^{16} | $v_{\text{rot}} \simeq 2 \text{ km s}^{-1}$ |
| MS $M > 1.2M_{\odot}$ | 10^{18} | $v_{\text{rot}} \simeq 200 \text{ km s}^{-1}$ |
| young pulsars | $10^{13} \dots 10^{14}$ | $P = 10 \dots 100 \text{ ms}$ |
| isol. WDs | $< 10^{14}$ | $v_{\text{rot}} < 20 \text{ km s}^{-1}$ |
| accr. WDs (CVs) | $\dots 10^{16}$ | $\dots 1000 \text{ km s}^{-1}$ |
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| MSP | $\sim 10^{16}$ | |
| long GRB | $> 3 \cdot 10^{16}$ | |

White Dwarf Rotation



Koester et al. 1998

specific angular momentum:

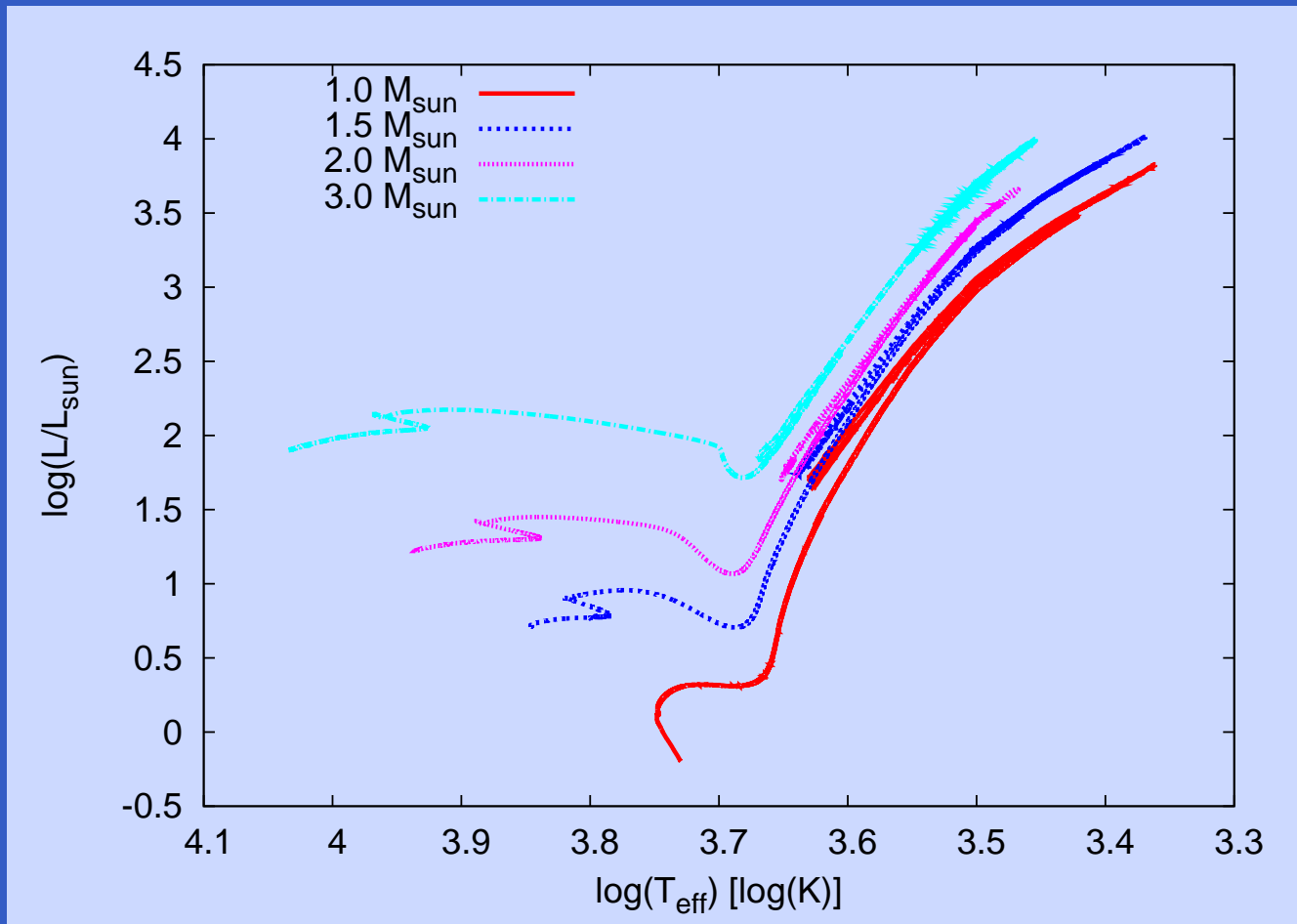
● Koester et al.
(1998)

● Berger et al.
(2005)

$$\Rightarrow j_{WD} < 10^{14} \text{ cm}^2 \text{ s}^{-1}$$

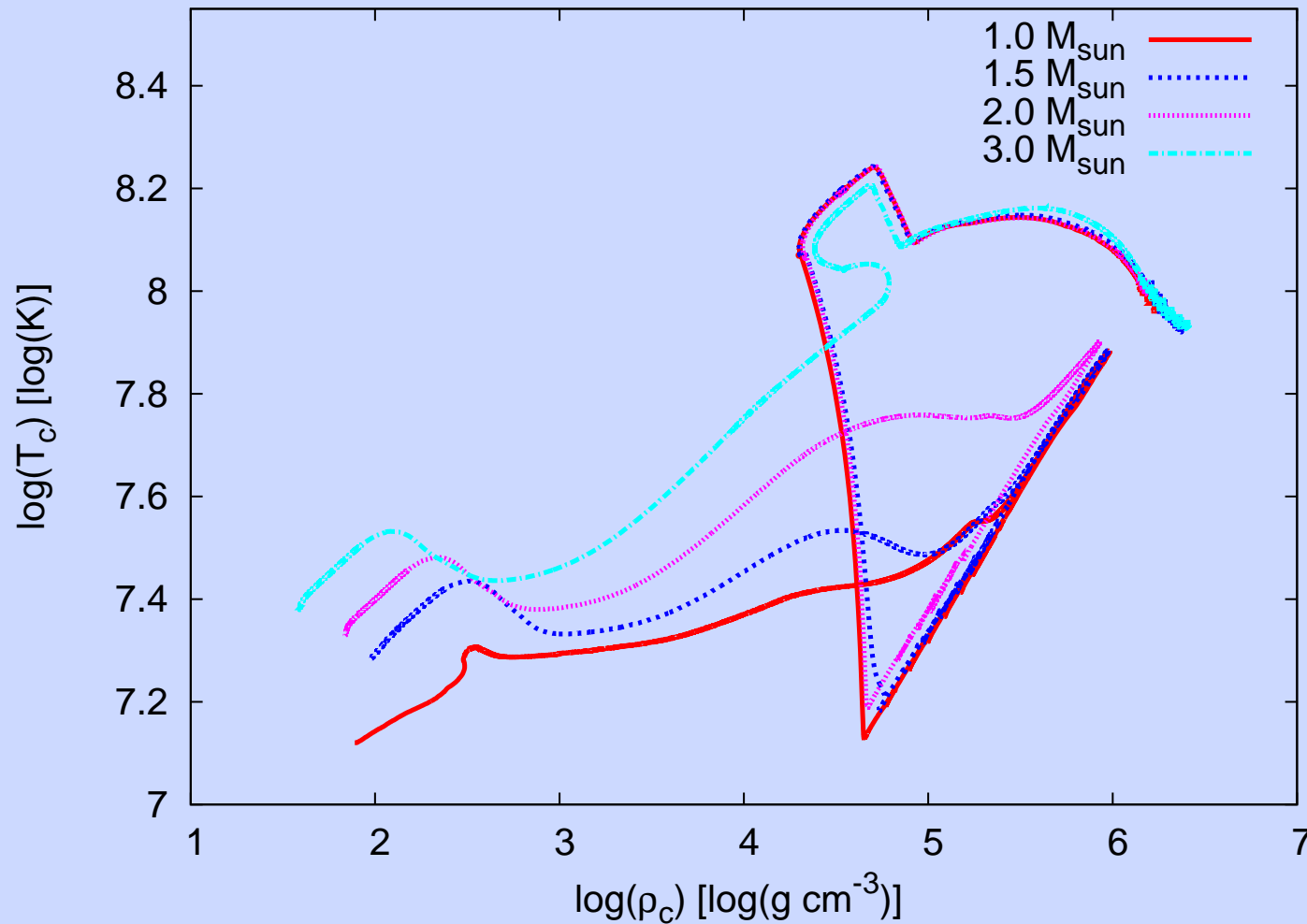
Low mass single stars: HR diagram

... on the computer:

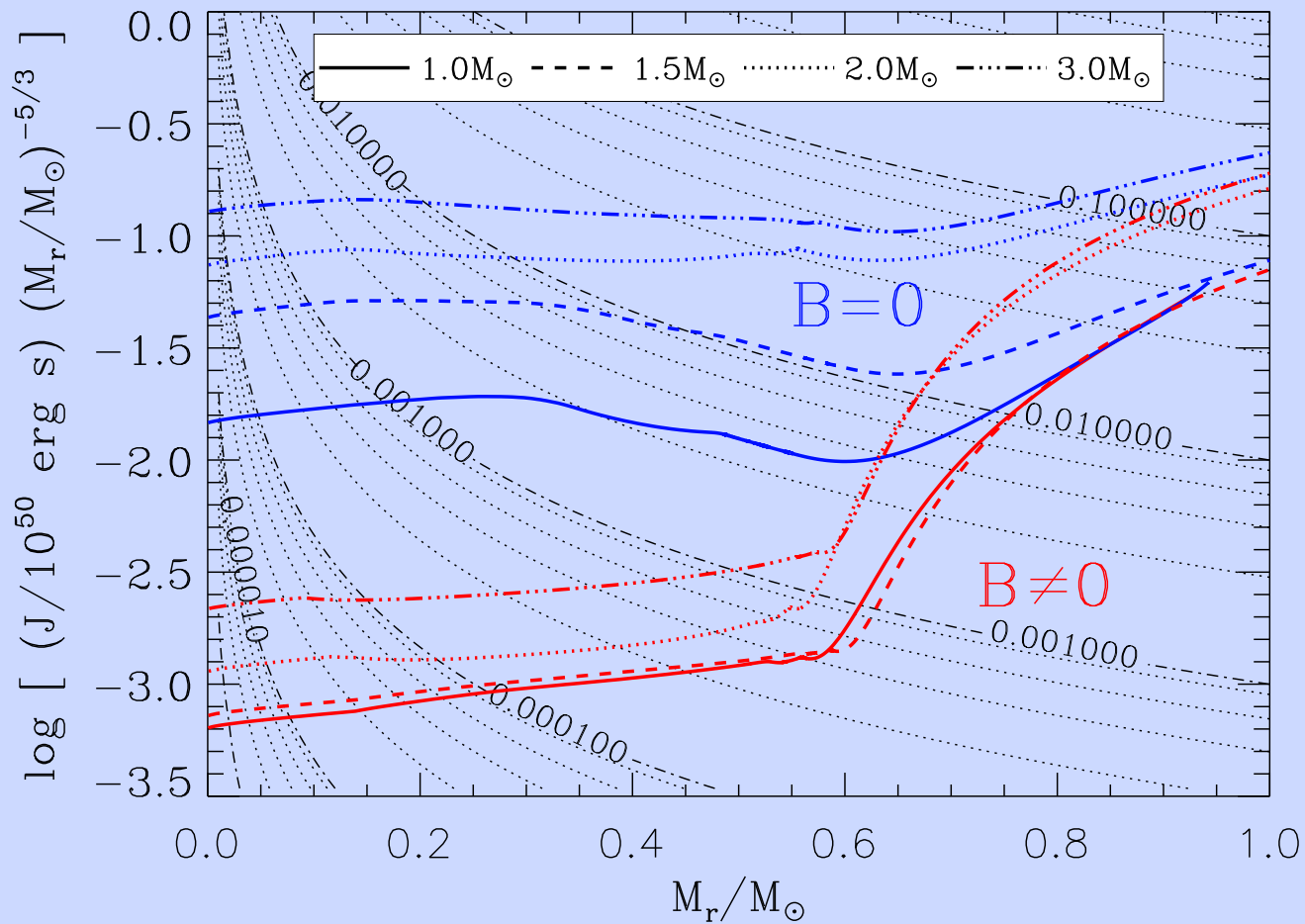


Suijs et al. 2006, A&A, to be submitted

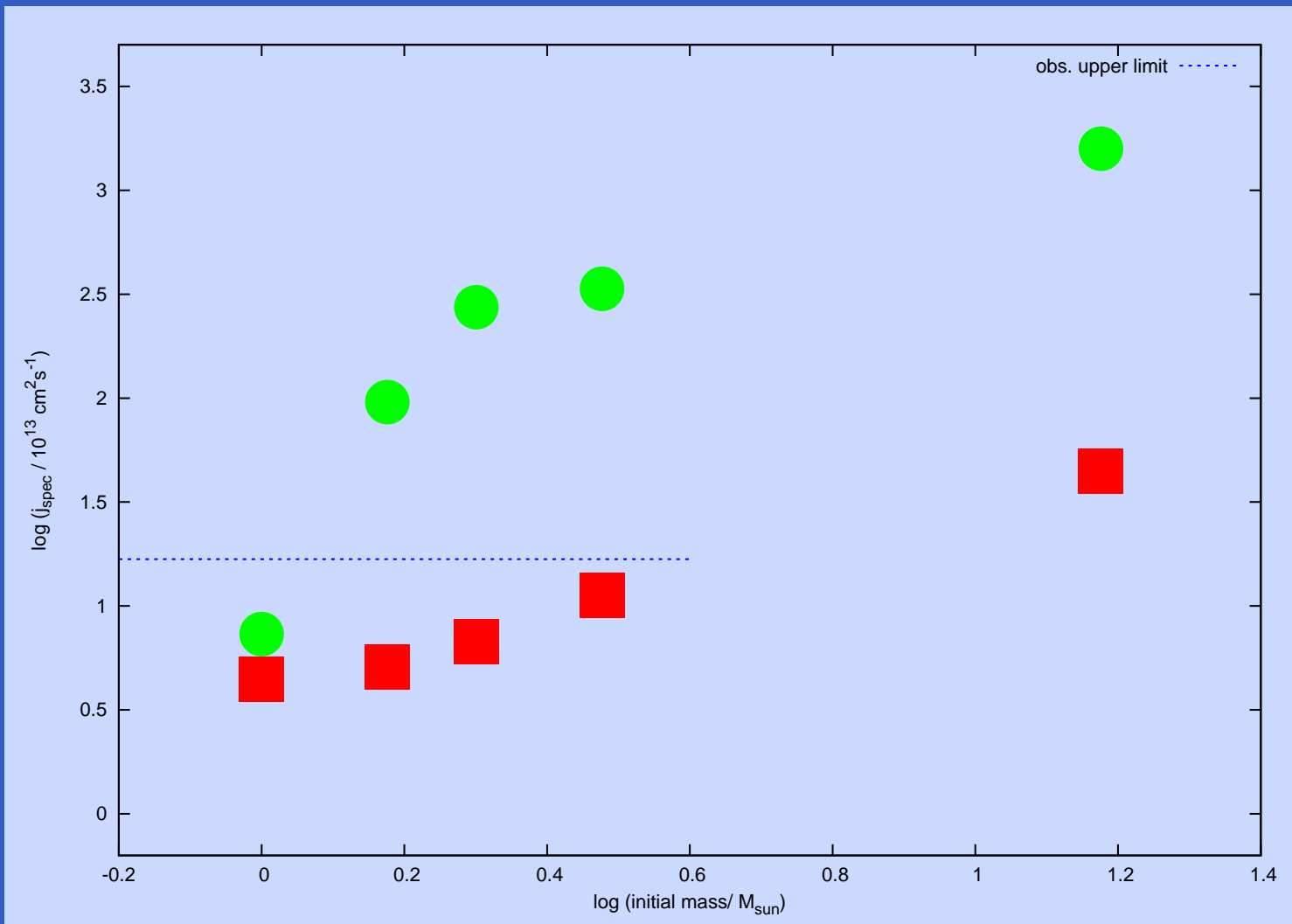
Low mass single stars: $T_c - \rho_c$ diagram



Low mass single stars: HR diagram

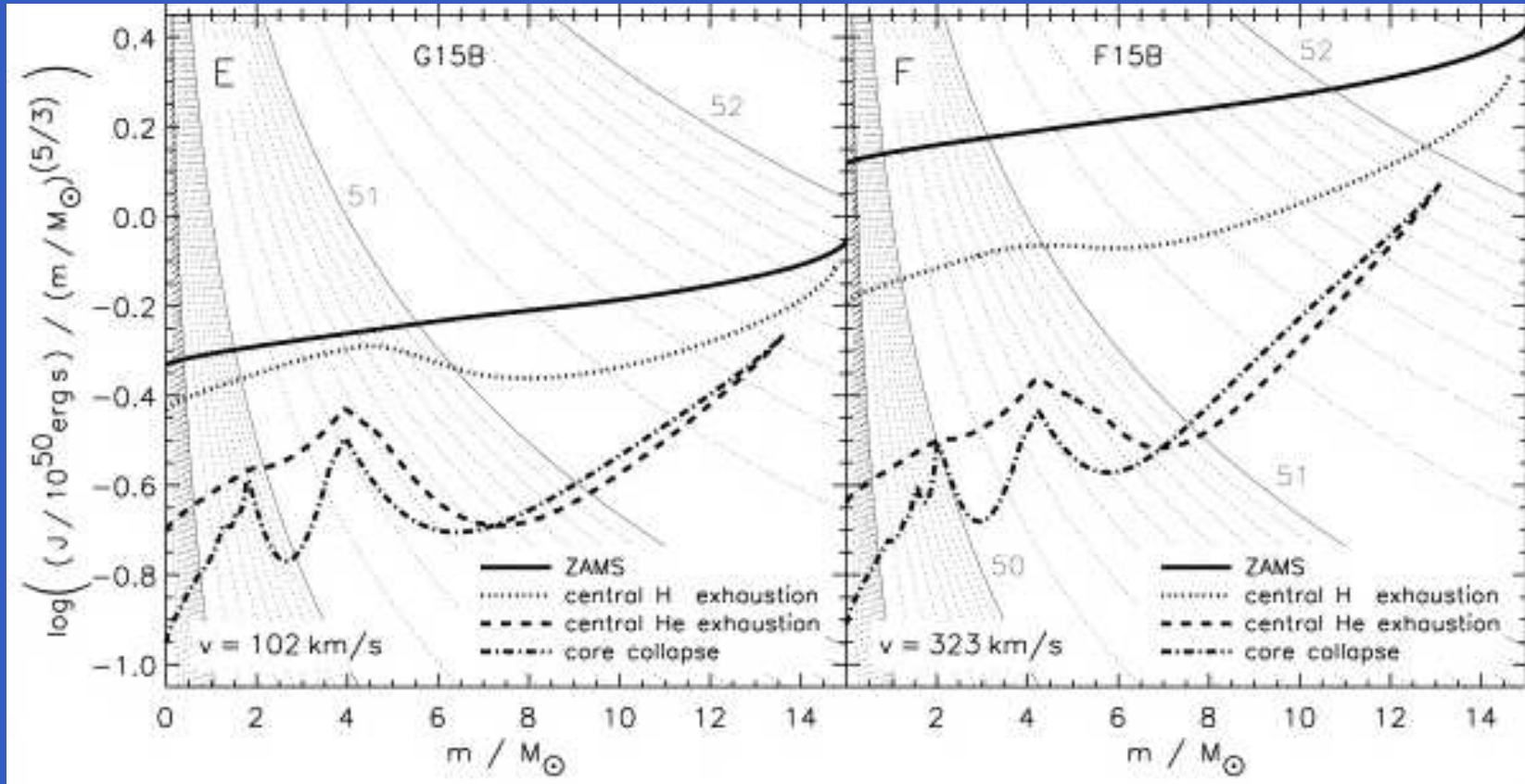


Low mass single stars: HR diagram



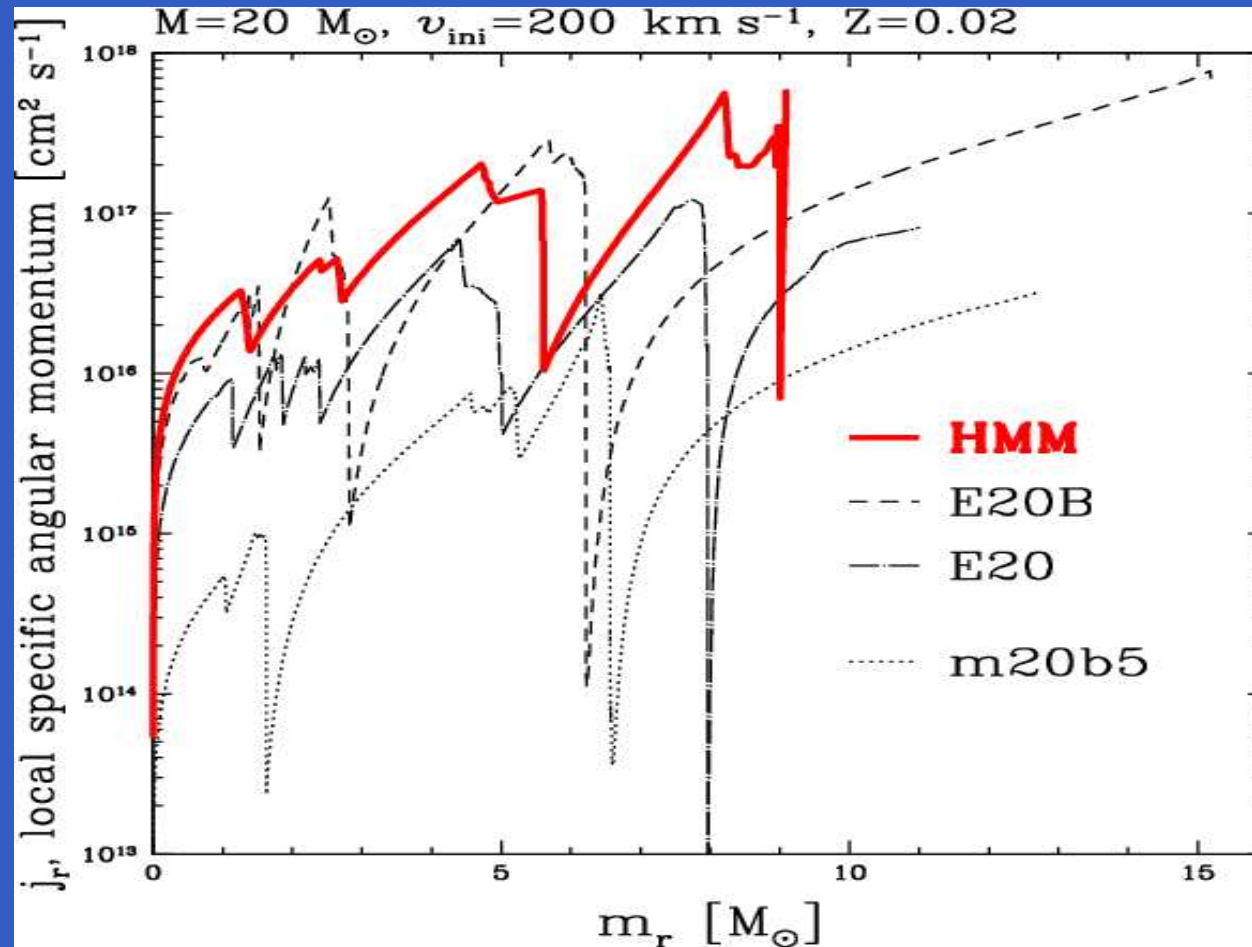
Suijs et al. 2006, A&A, to be submitted

Massive stars: Z_{\odot}



Heger, Langer & Woosley, 2000; Hirschi, Meynet & Maeder 2005

Angular momentum: effect of B-fields



Heger et al. 2000, 2005; Hirschi et al. 2005

Predicted NS birth spins

$B = 0$

| M M_{\odot} | $\dot{j}_{\text{Fe-core}}$ $10^{15} \text{ cm}^2 \text{ s}^{-1}$ |
|--------------------|---|
| 10 | 7.9 |
| 20 | 6.3 |
| 25 | 3.1 |

Heger, Langer & Woosley 2000

$B \neq 0$

| M M_{\odot} | P ms | $\dot{j}_{\text{Fe-Kern}}$ $10^{15} \text{ cm}^2 \text{ s}^{-1}$ | $B_{\text{Fe-Kern}}$ 10^9 G |
|--------------------|---------|---|--|
| 15 | 7.7 | 0.39 | 5.1 |
| 20 | 5.5 | 0.055 | 4.2 |
| 25 | 4.0 | 0.075 | 3.8 |

Heger, Woosley, Langer & Spruit 2003; Heger,

Woosley & Spruit 2005

Observed spins of young neutron stars

periods (Marshall et al. 1998) and angular momenta of young pulsars (from Heger et al. 2003)

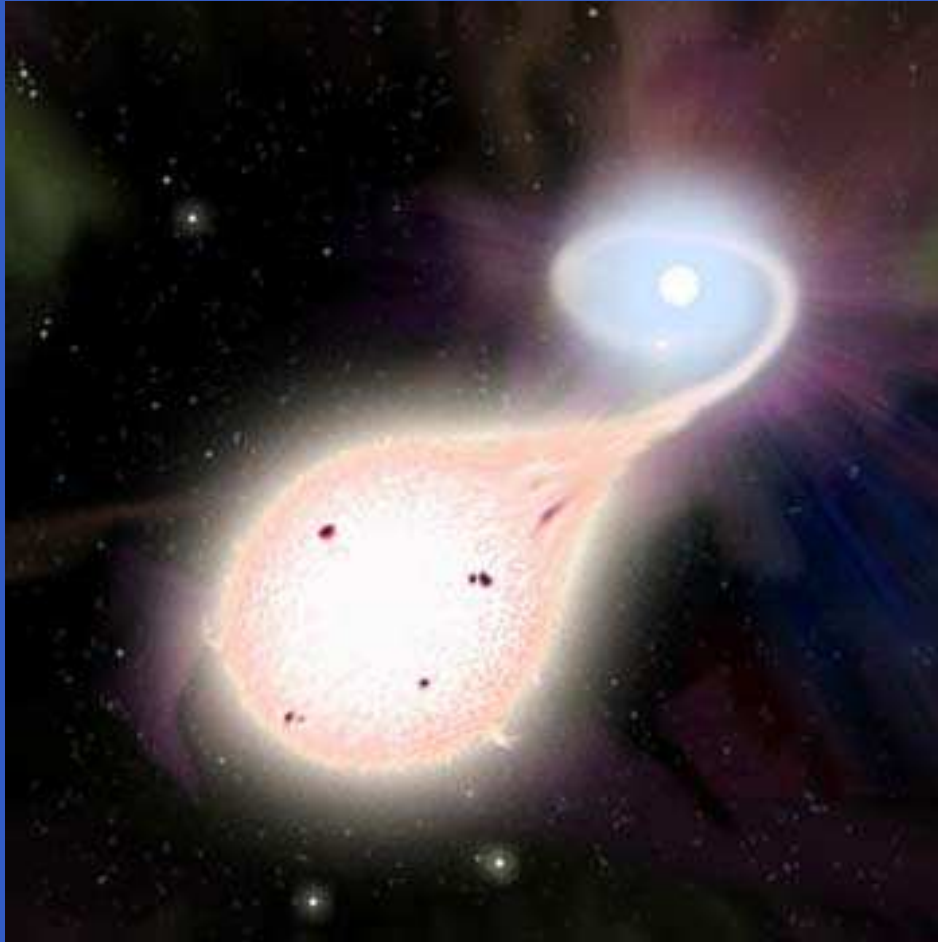
| pulsar | period (ms) | j ($\text{cm}^2 \text{s}^{-1}$) | J (erg s) |
|-----------------------------|----------------|--|----------------------|
| PSR J0537-6910 (N157B, LMC) | 16 | $2.0 \cdot 10^{14}$ | $5.67 \cdot 10^{47}$ |
| PSR B0531+21 (Crab) | 33 | $9.9 \cdot 10^{13}$ | $2.75 \cdot 10^{47}$ |
| PSR B0540-69 (LMC) | 50 | $6.5 \cdot 10^{13}$ | $1.81 \cdot 10^{47}$ |
| PSR B1509-58 | 150 | $2.2 \cdot 10^{13}$ | $6.05 \cdot 10^{46}$ |

Bottom line

- B-fields needed to obtain low WD spins
- B-fields needed to obtain low NS spins
- No rapidly rotating core in single stars at $Z \simeq Z_{\odot}$

How to make long GRBs?

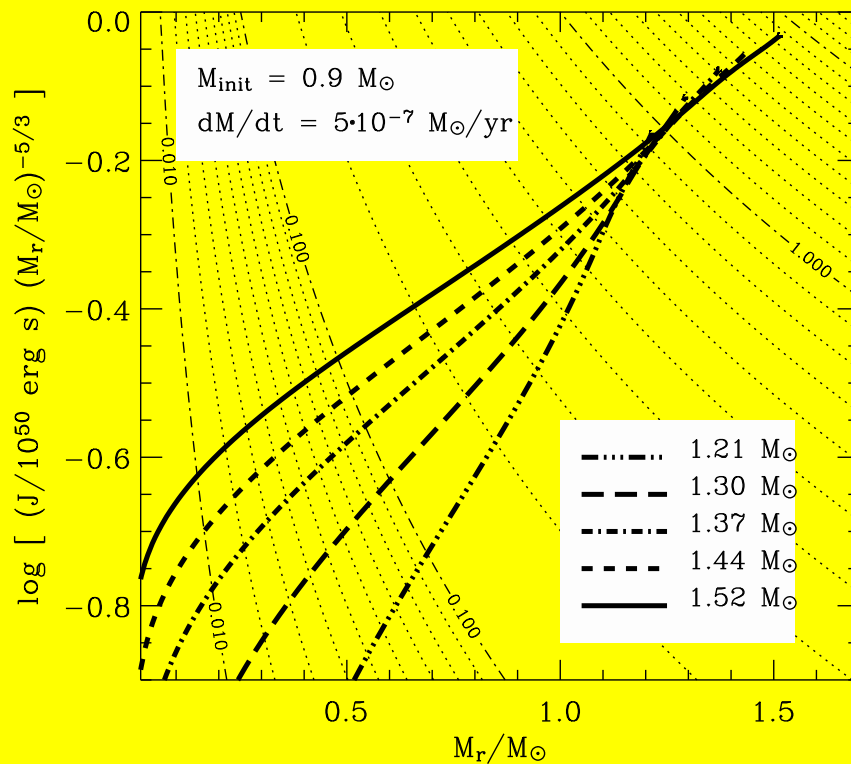
Binary mass transfer



$$\dot{M} \Rightarrow \dot{J}$$

Marufov, 2003

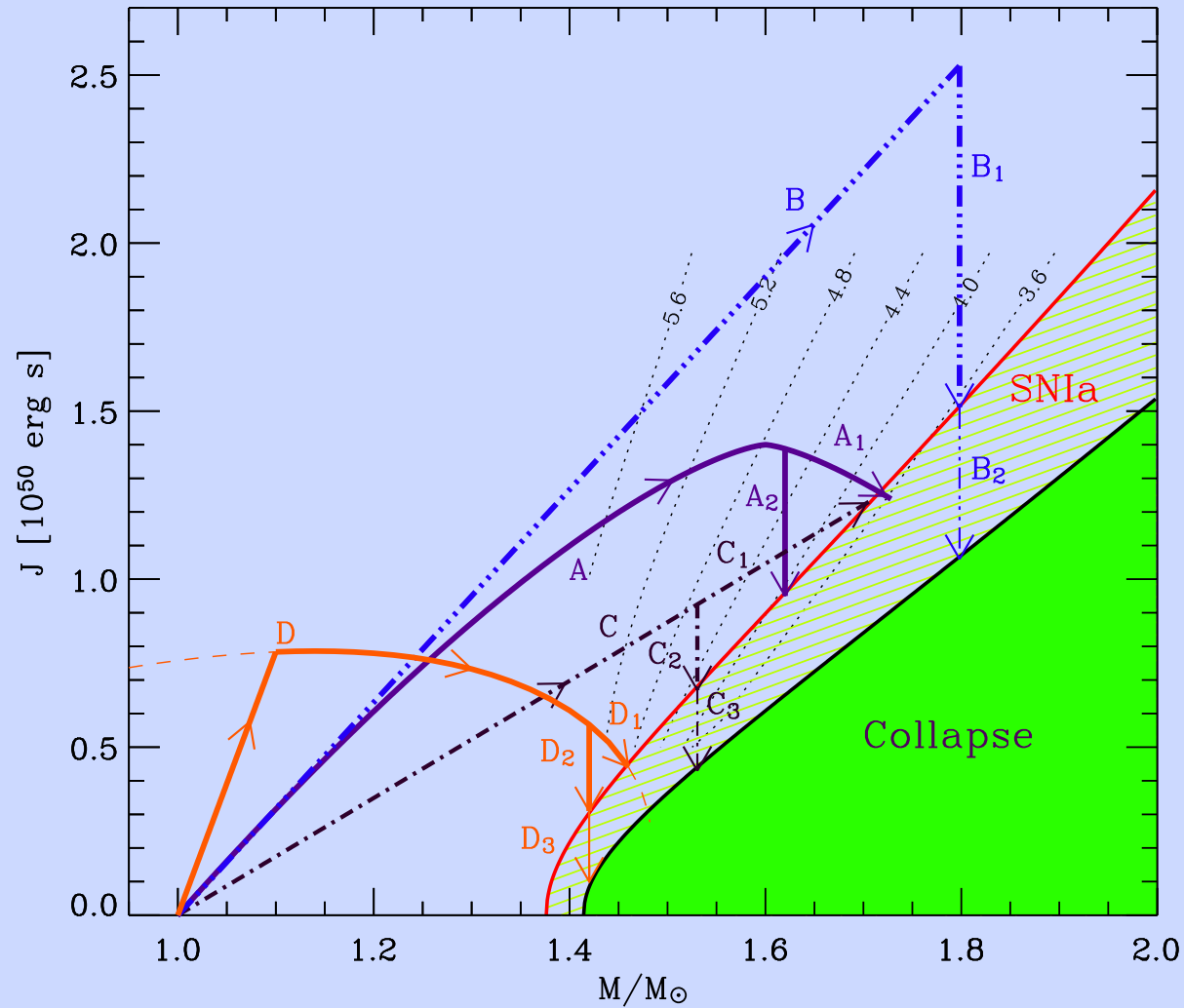
SN Ia progenitors



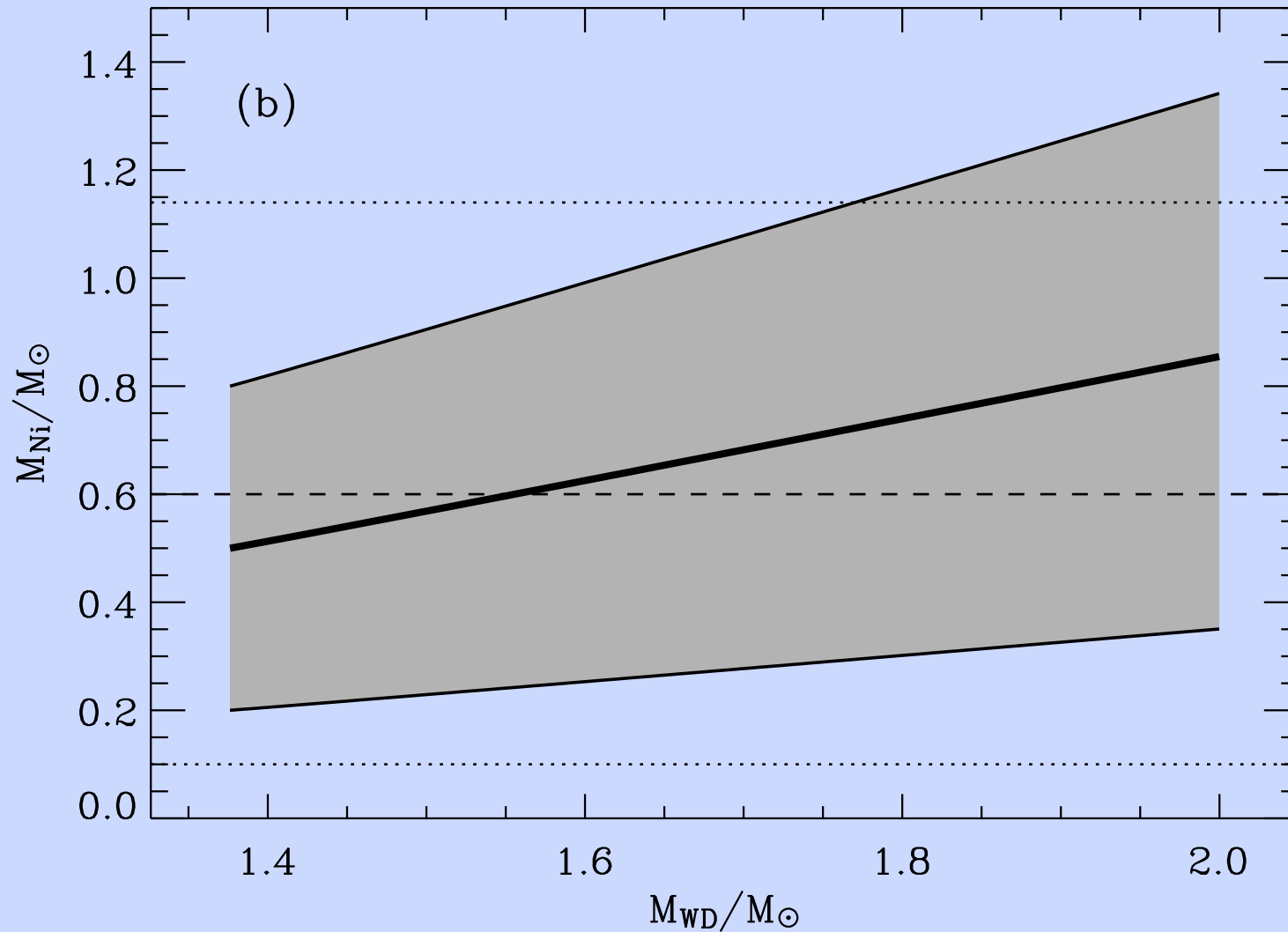
Yoon & Langer, 2004

- WD is spun-up
- increased Chandrasekhar-mass
- → Phillips-relation?

WDs to SN Ia: $M - J$ -coupling

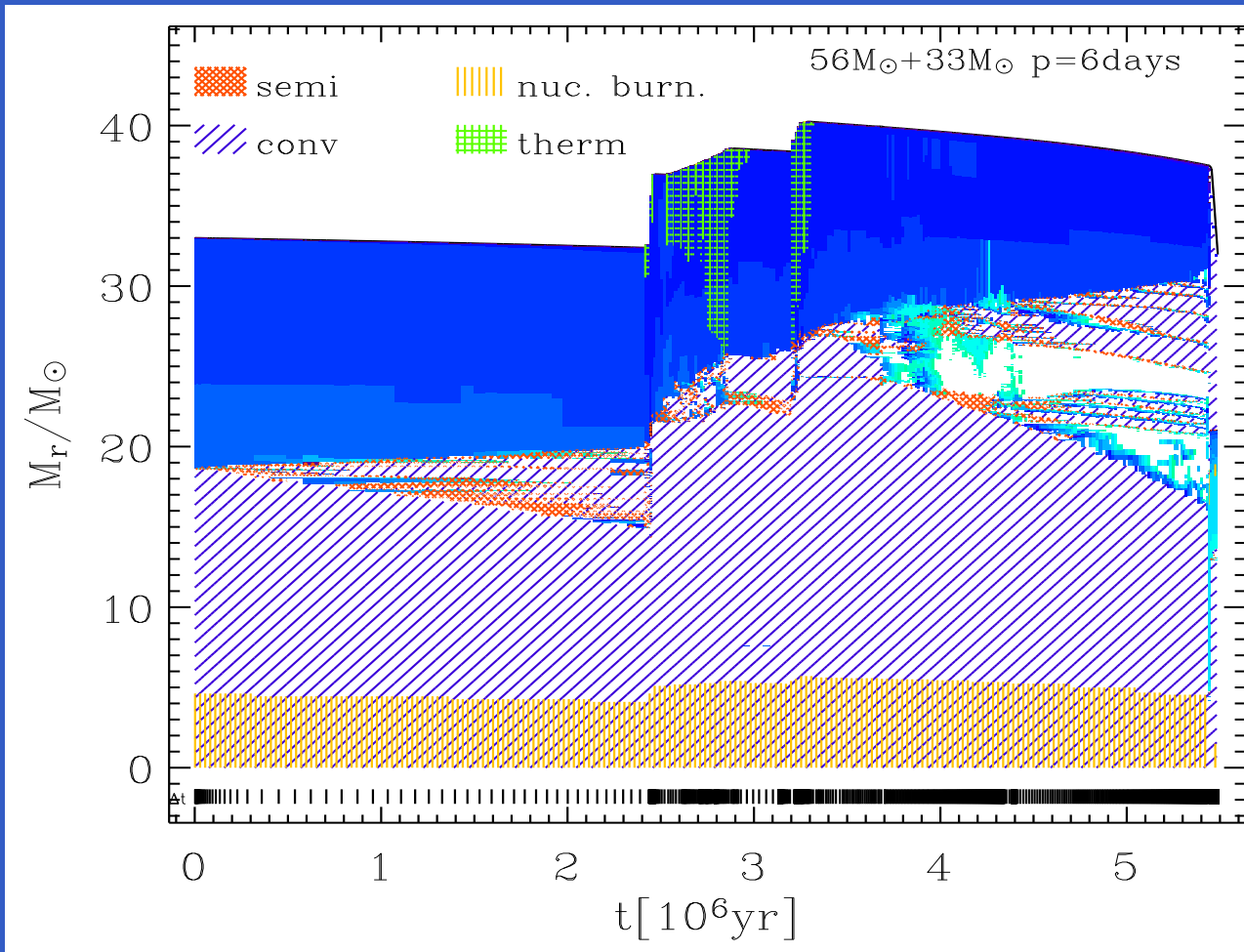


Required nickel masses



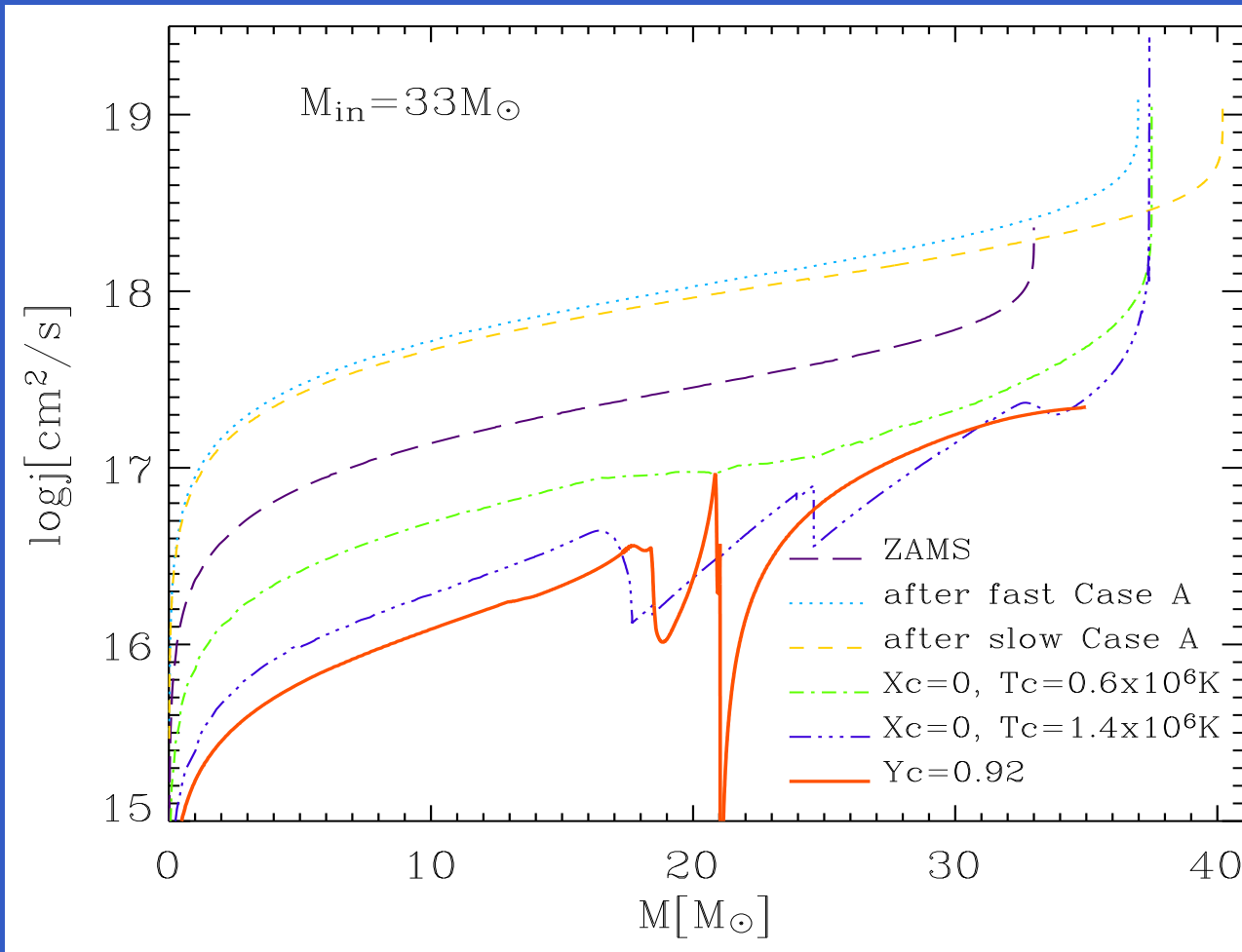
Accretion induced spin-up to GRB ...

Petrovic, Langer, Yoon & Heger 2005, A&A 435, 247



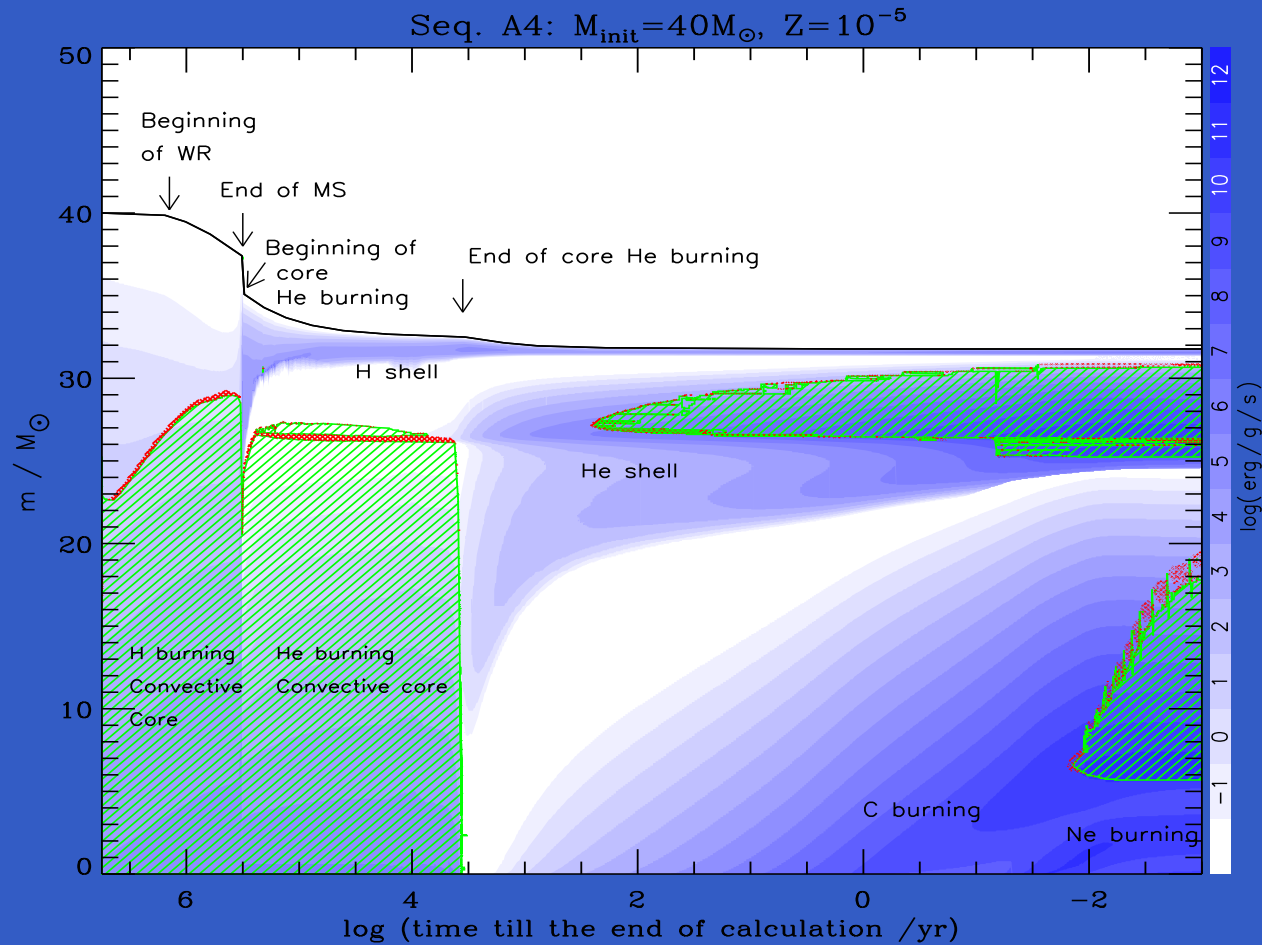
...does not work

Petrovic, Langer, Yoon & Heger 2005, A&A 435, 247



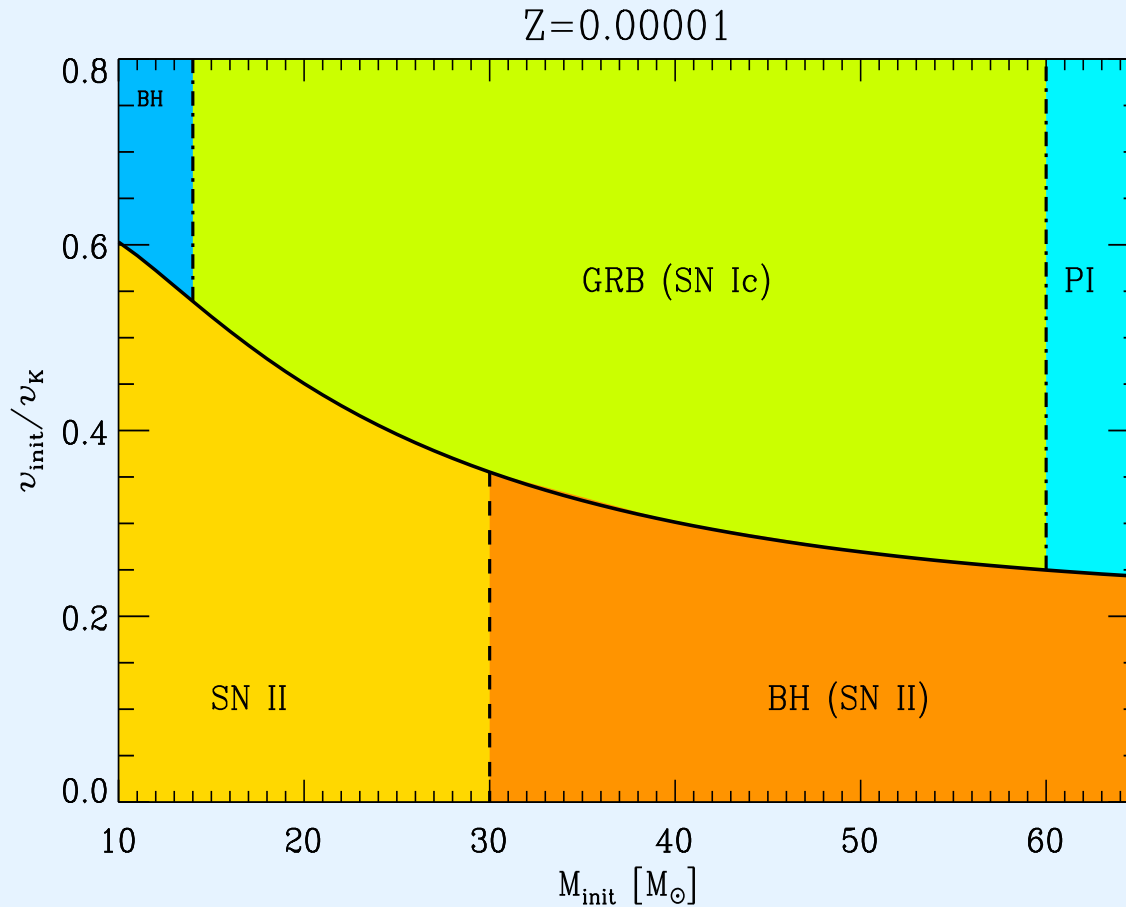
Chem. homogeneous evolution to GRB

Maeder 1987, A&A, 187, 159; Langer 1992, A&A, 265, L17



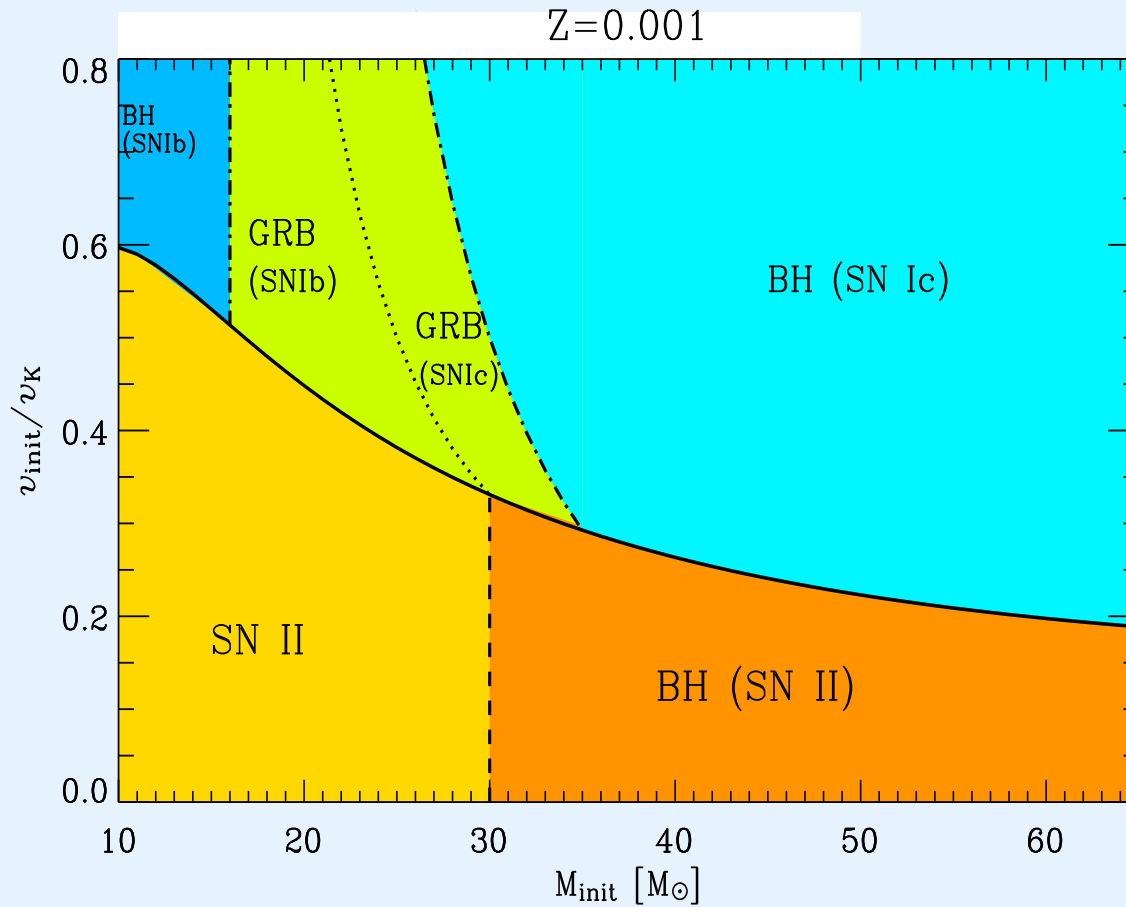
Yoon & Langer, 2005, A&A 443, 643 ; Woosley & Heger, 2006, ApJ 637, 914

Models at $Z=10^{-5}$



Yoon, Langer & Norman, 2006, astro-ph/0606637

Models at $Z=10^{-3}$



Yoon, Langer & Norman, 2006, astro-ph/0606637

Metallicity bias \rightarrow single stars

locally: 1 GRB / 1000 SNe

assume GRBs come from $Z < Z_{\odot}/3$

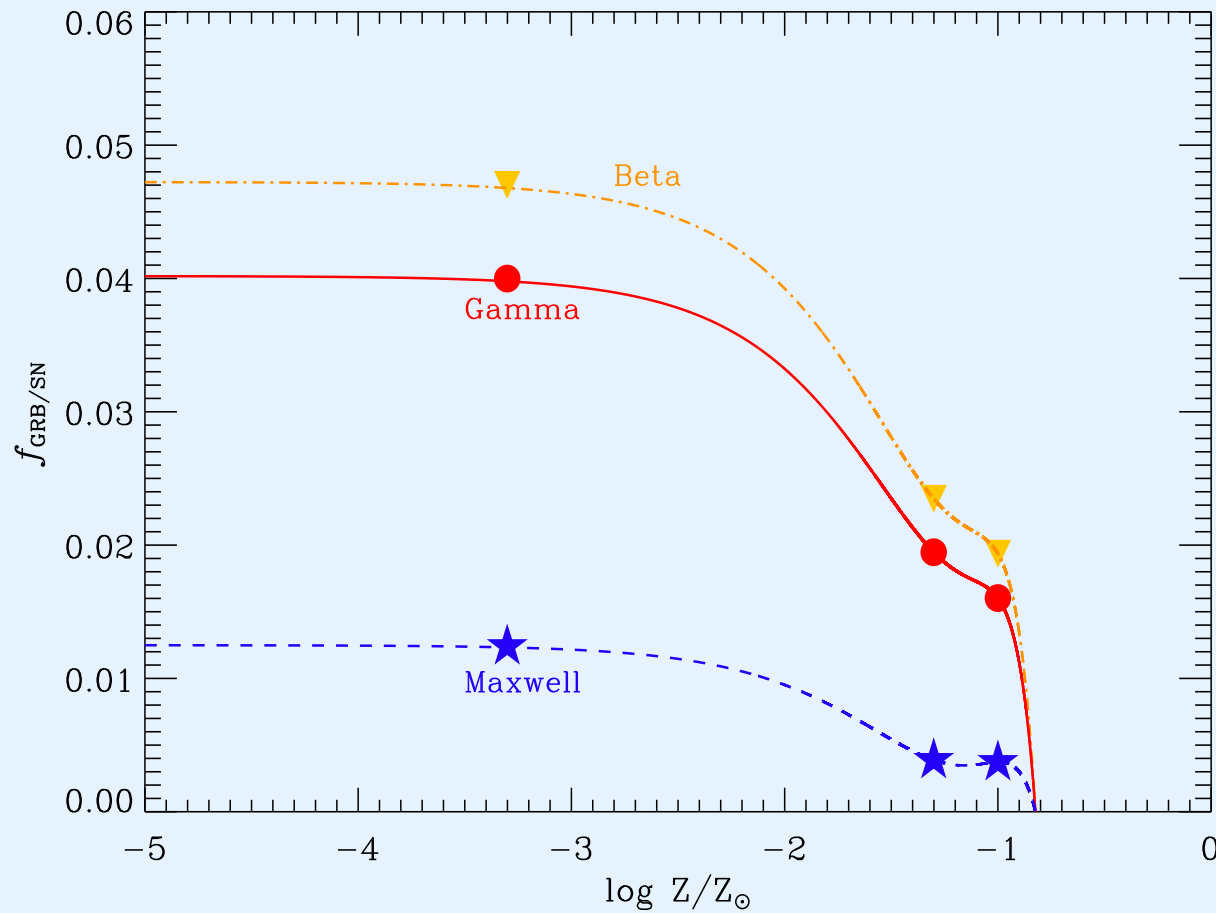
(Fruchter et al. 2006, Wolf & Podsiadlowski 2006)

$$\rightarrow \frac{\#SNe(Z < Z_{\odot}/3)}{\#SNe} \simeq \frac{1}{10} \quad (\text{Langer \& Norman 2006})$$

$$\text{also: } \frac{\#SNe \rightarrow BH}{\#SNe} \simeq \frac{1}{20}$$

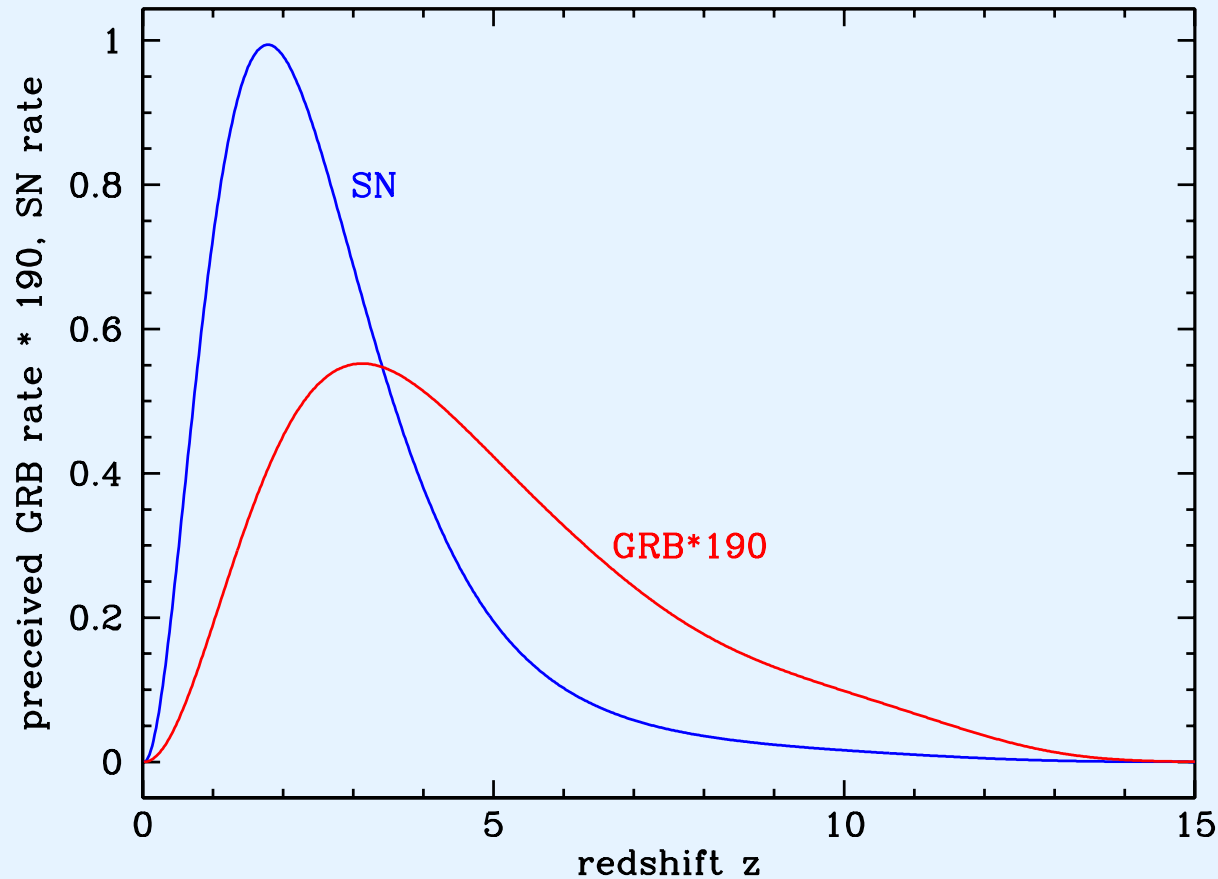
\Rightarrow 1 out of 5 BHs makes a GRB!

Predicted GRB/SN ratio as $f(Z)$



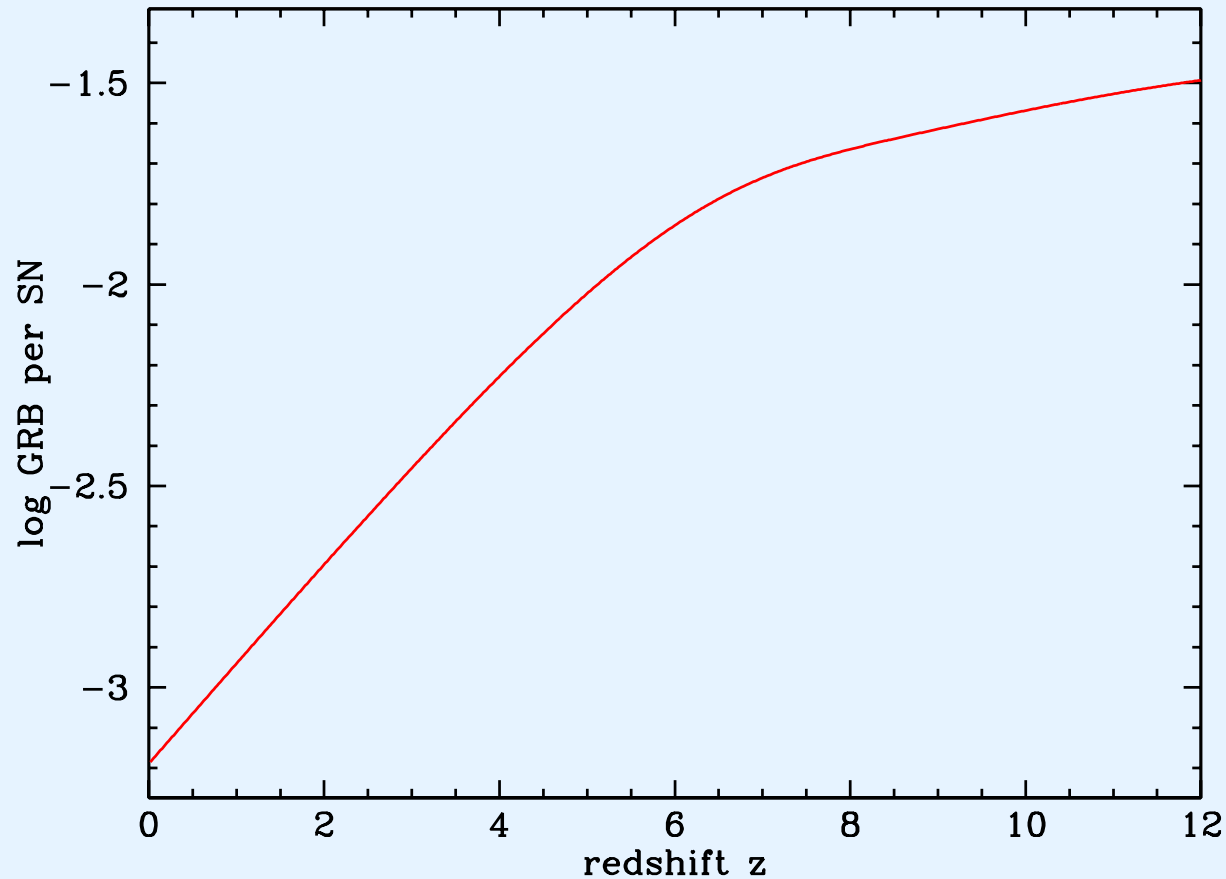
Yoon, Langer & Norman, 2006, astro-ph/0606637

Perceived SN, GRB rates as $f(z)$



Yoon, Langer & Norman, 2006, astro-ph/0606637

GRB/SN ratio as $f(z)$



Yoon, Langer & Norman, 2006, astro-ph/0606637

Summary

- B-fields needed to reproduce spins of compact stars
- $Z = Z_{\odot}$: high core spin needs binary
- SNe Ia from $1.4 \dots 2.0 M_{\odot}$ WDs?
- Chem. homogeneous evolution: GRBs at low Z
- GRB low Z bias \Rightarrow single stars

WR models at low metallicity

Need of **magnetic** core-envelope coupling

Spruit 2002, A&A 381, 923

- obtain low NS spins Heger et al. 2005, ApJ, 626, 350
- obtain low WD spins Suijs et al. 2006, in prep.
- low GRB/hypernova rate van Putten 2004, ApJ, 611, 81

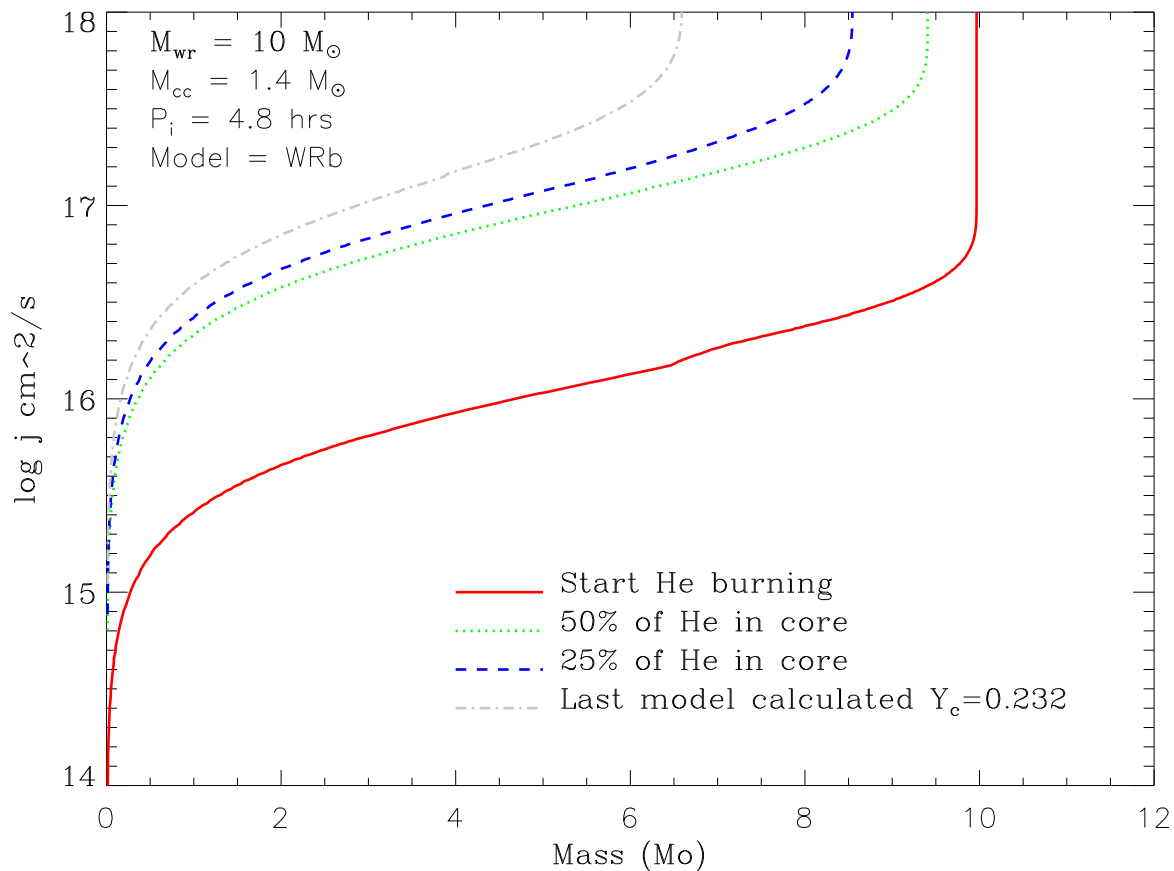
Hirschi et al. 2005, A&A, 443, 581

Problem: any GRB from single stars?

look at binary models...

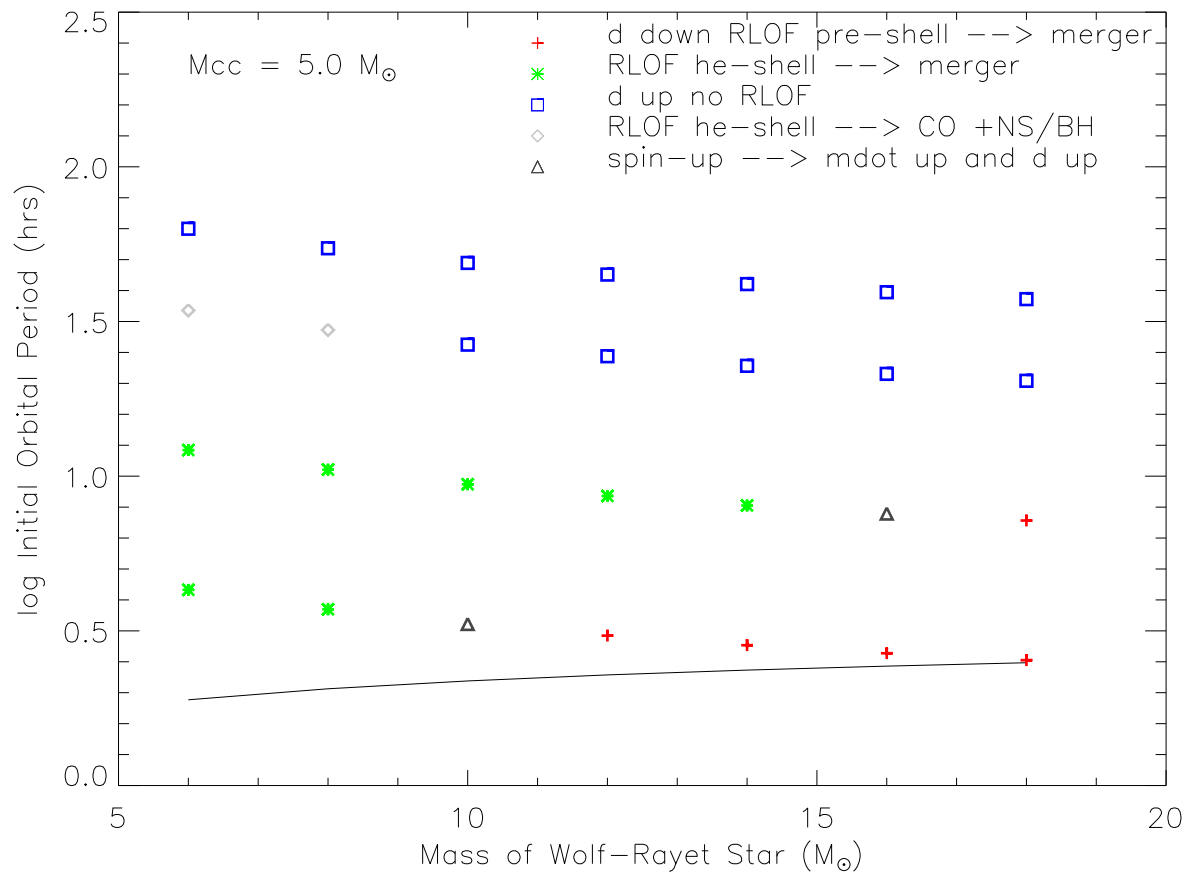
Tidally induced spin-up...

Detmers, Langer & Podsiadlowski, in prep.



...also does not work

Detmers, Langer & Podsiadlowski, in prep.



Other binary scenarios...?

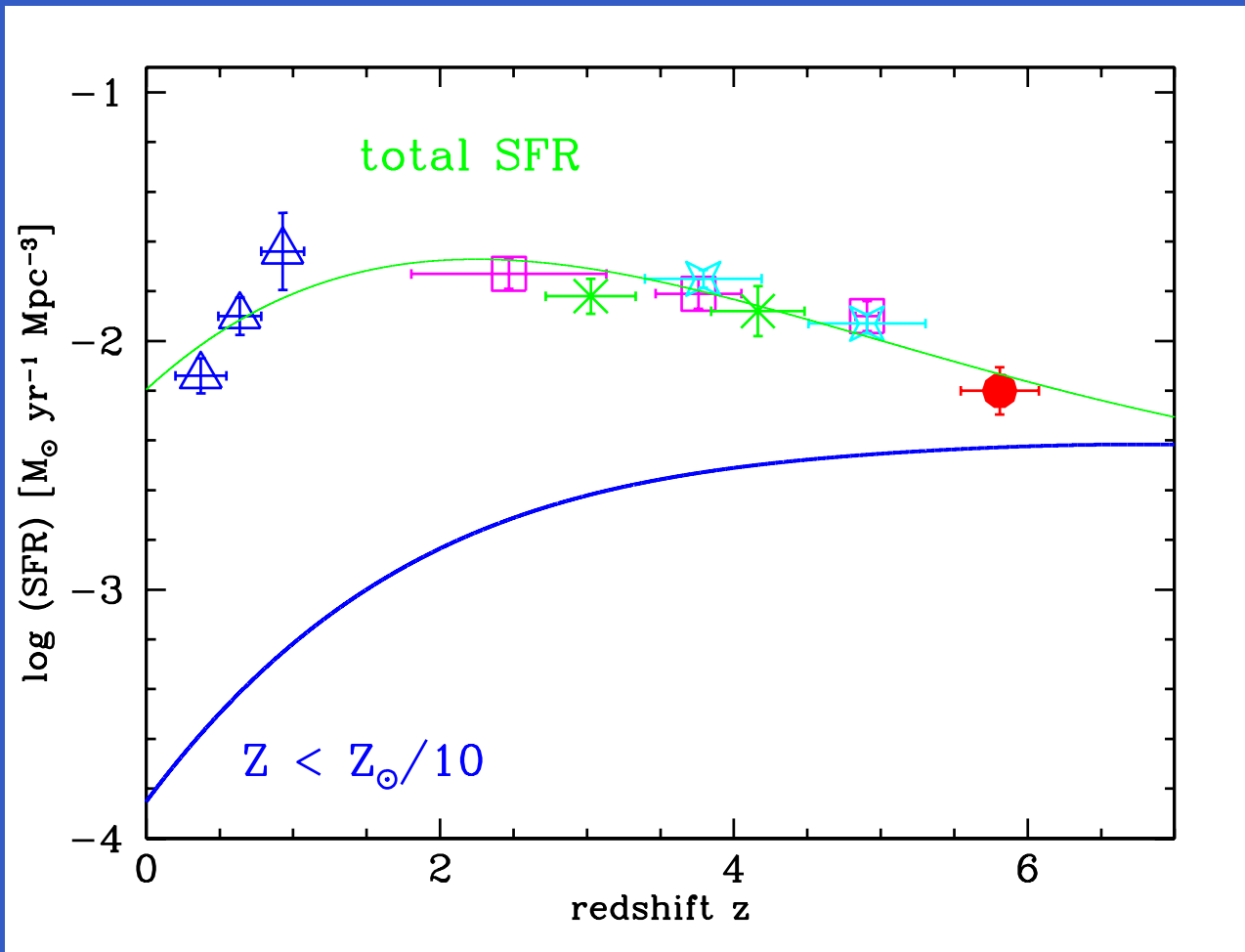
e.g. binary merger

Fryer & Heger 2005, ApJ 623, 302

... possible, but rare

Metallicity bias

Langer & Norman 2006, ApJL 638, L63



Metallicity bias \rightarrow single stars

locally: 1 GRB / 1000 SNe

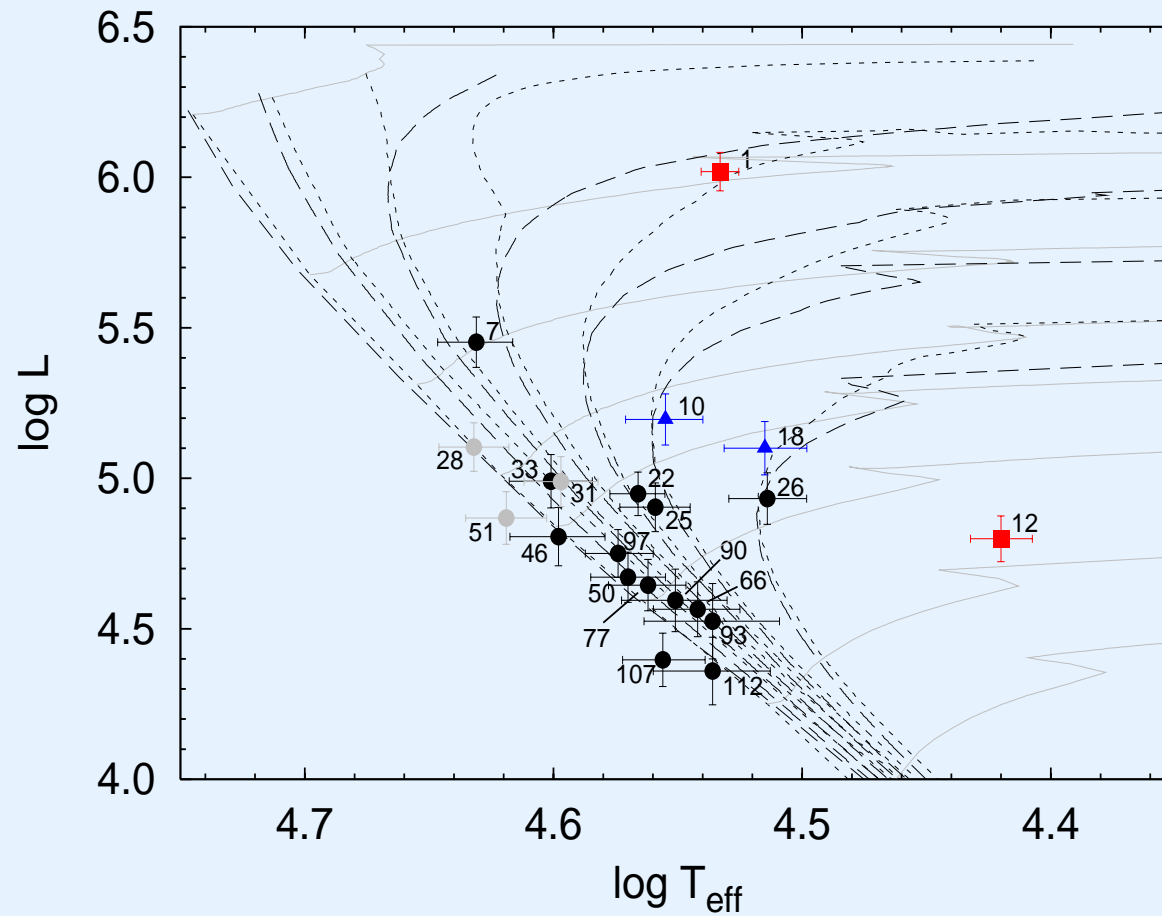
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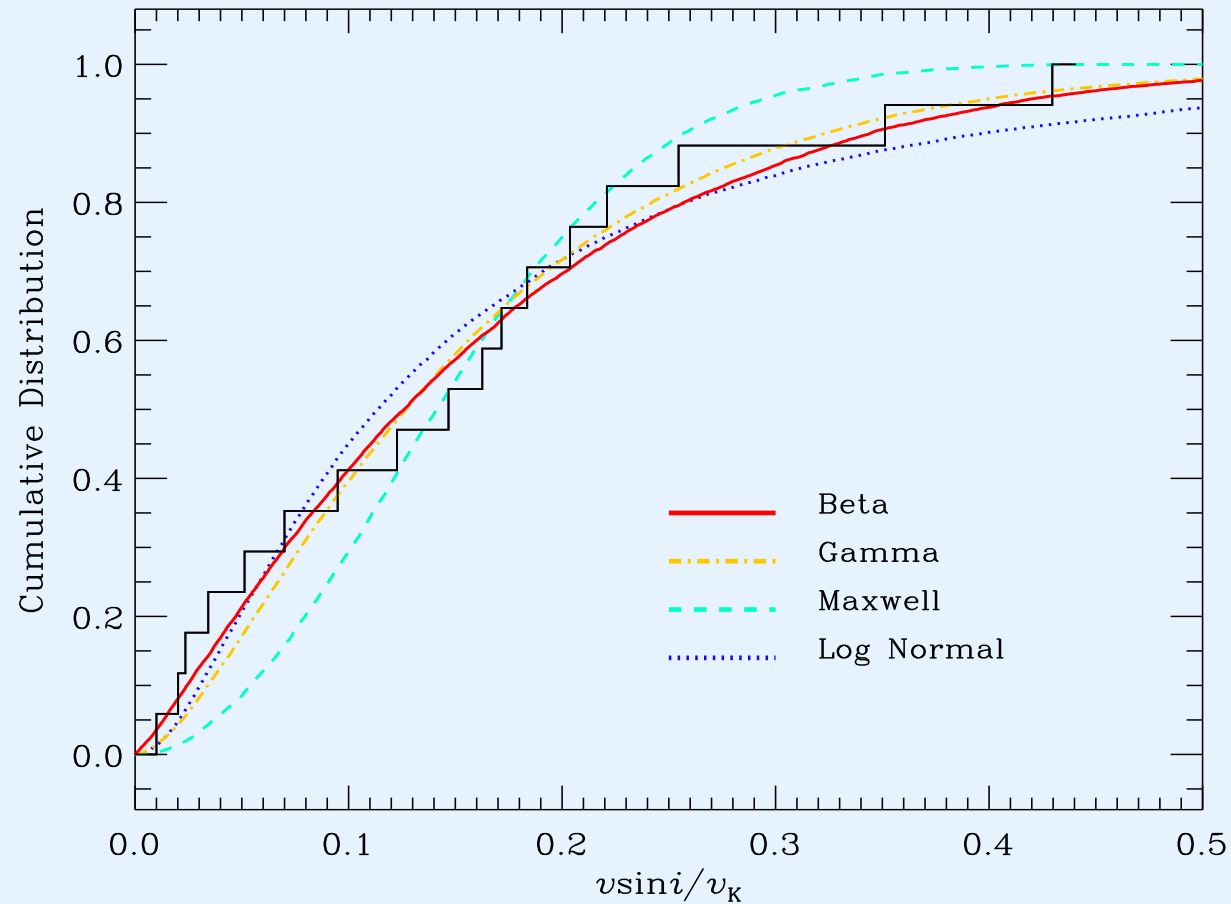
\Rightarrow EVERY BH makes a GRB!

Observations: NGC 346!!



Mokiem et al. 2006, A&A, in press

Rotational velocities? NGC 346!!



Mokiem et al. 2006