Some open questions on the physics of (massive) stars

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Rolf Kudritzki (IfA, USA)
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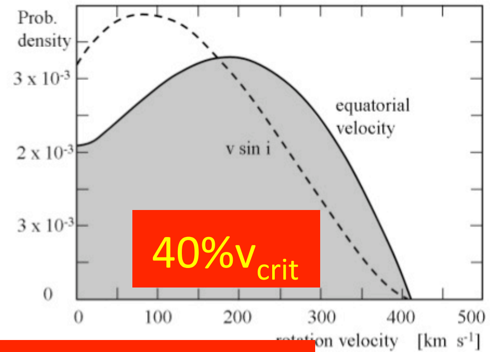
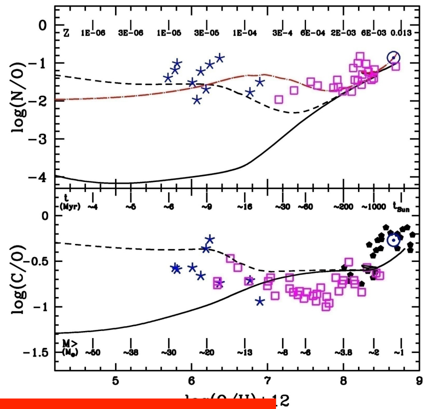
A few Challenges in massive star evolution

ROTATION



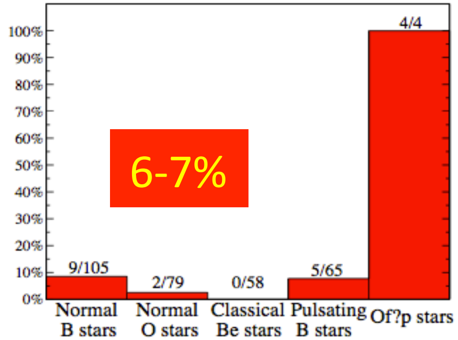
40%v_{crit}

Huang and Gies 2008



Chiappini et al 2009

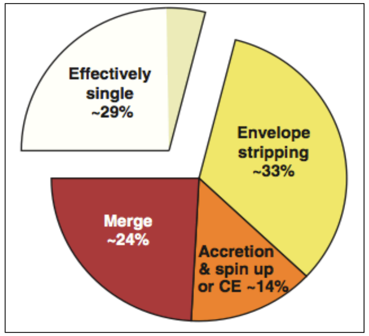
MAGNETIC FIELD



6-7%

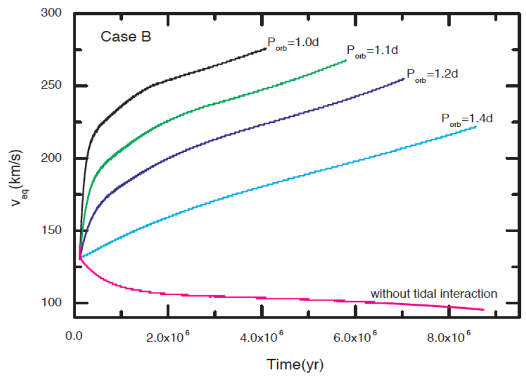
Wade et al. 2014

MULTIPLICITY



50-70%

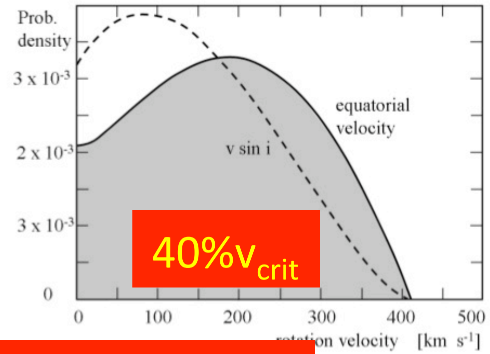
Sana et al. 2012



Song et al. 2013

A few Challenges in massive star evolution

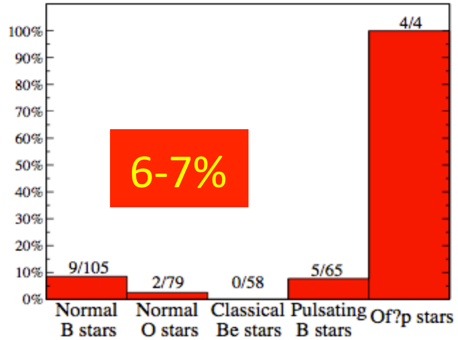
ROTATION



$40\%v_{crit}$

Huang and Gies 2008

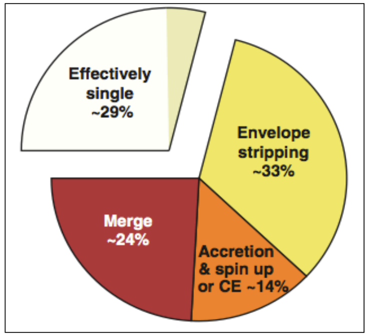
MAGNETIC FIELD



6-7%

Wade et al. 2014

MULTIPLICITY



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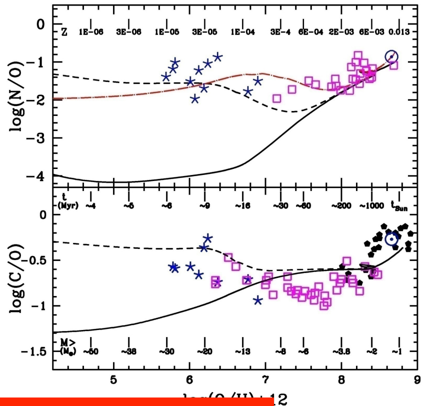

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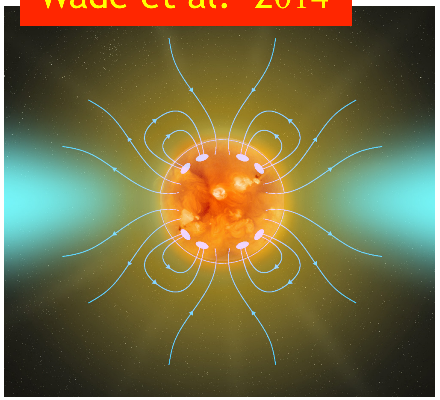
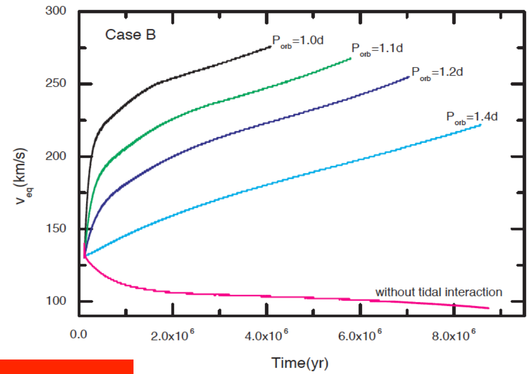




Song et al. 2013

What is the origin of these distributions

How do these distributions vary with metallicity?

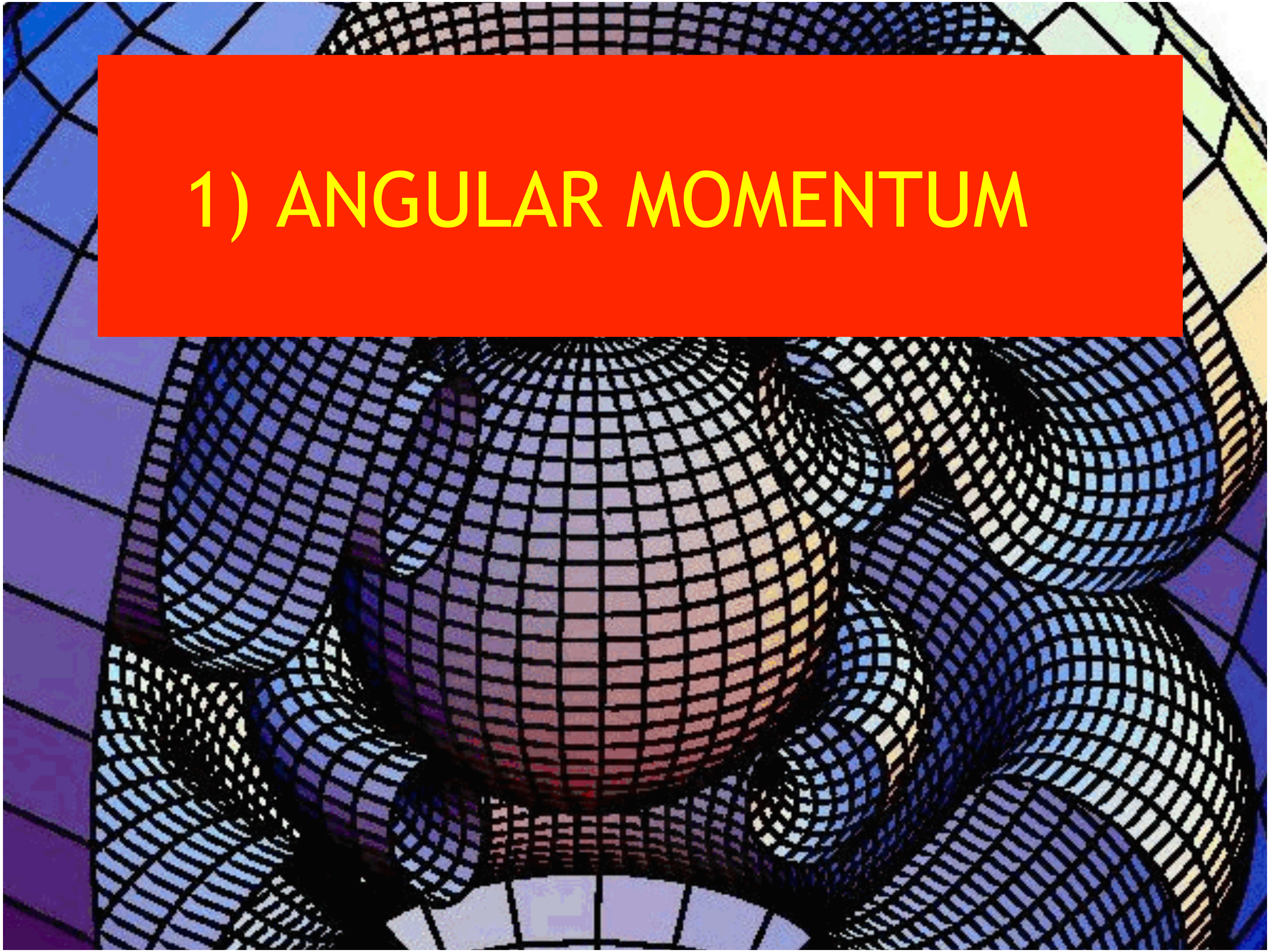
How do these distributions vary with the environment? (e.g. stellar density)

What are the impacts on the interior?

TWO TOPICS

- ANGULAR MOMENTUM
- BLUE SUPERGIANTS

1) ANGULAR MOMENTUM



TRANSPORT PROCESSES INDUCED BY ROTATION

What is needed : An energy reservoir

A process which extracts energy from this reservoir for producing a movement

Two types of energy reservoir

1) Excess energy in differential rotation

Gradient of Ω needed

The process is viscosity

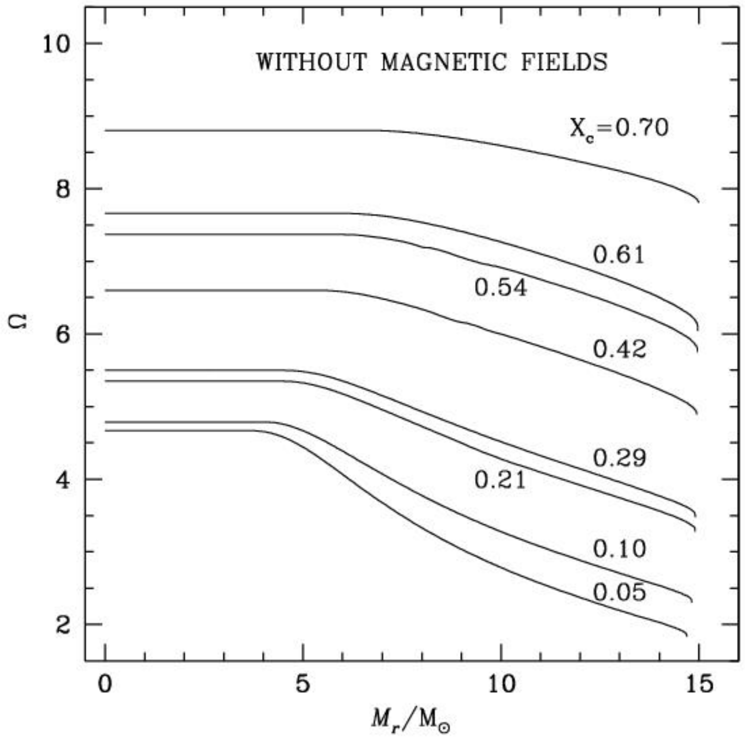
2) Thermal energy

Ω needed

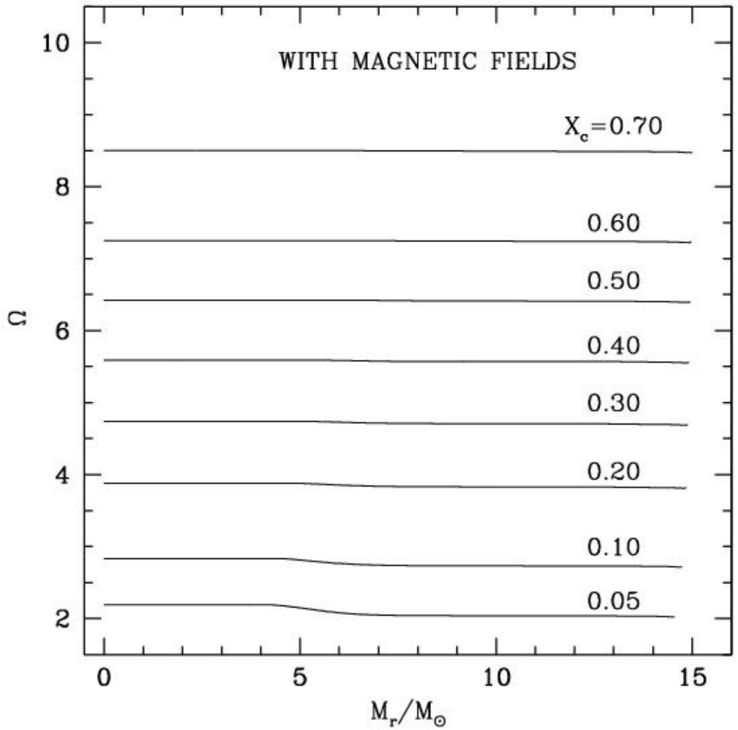
The process is meridional circulation

THE TWO FAMILIES OF ROTATING STELLAR EVOLUTION MODELS

MIXING IS SHEAR DRIVEN



MIXING IS DRIVEN BY MERIDIONAL CURRENTS



Mixing efficiency increases
with rotation, initial masses, decreasing metallicity in both cases

SHEAR DRIVEN MIXING

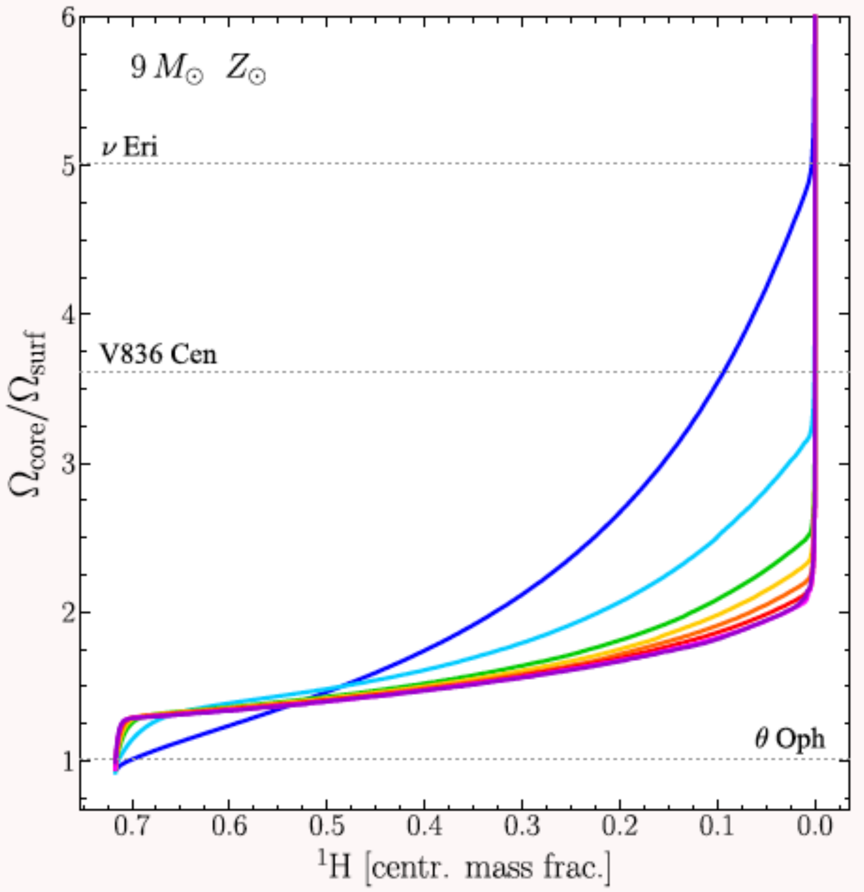
MERIDIONAL CURRENTS DRIVEN MIXING

Internal rotation

Radial gradients

Uniform rotation

Models from Georgy+ 2013b, obs. values from Aerts 2008



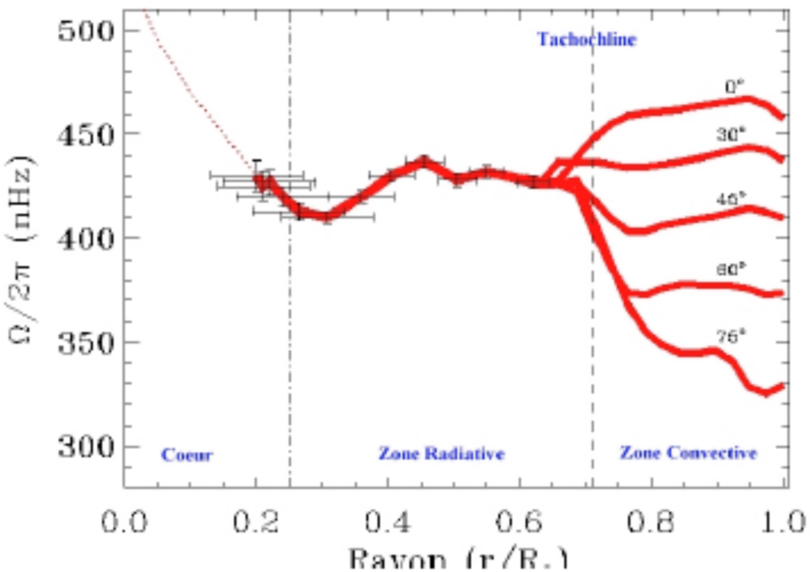
Aerts 2008, Goupil 2011

star	$\Omega_{core}/\Omega_{env}$
ν Eri	~ 5
V836 Cen	3.6
θ Oph	~ 1
12 Lac	1.8 – 5

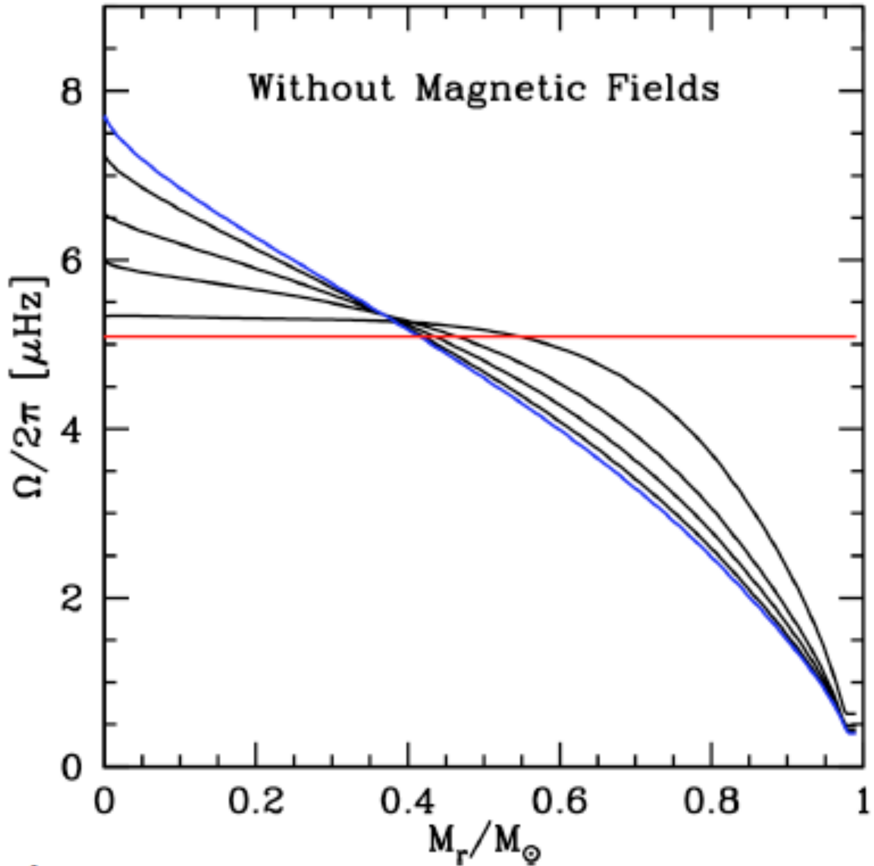
The solar rotation profile

- Helioseismic measurements
  - Rotational splittings:

$$\delta\omega_{n\ell m} = m\beta_{n\ell}\int_0^R K_{n\ell}(r)\Omega(r)\mathrm{d}r$$



Garcia et al. 2007

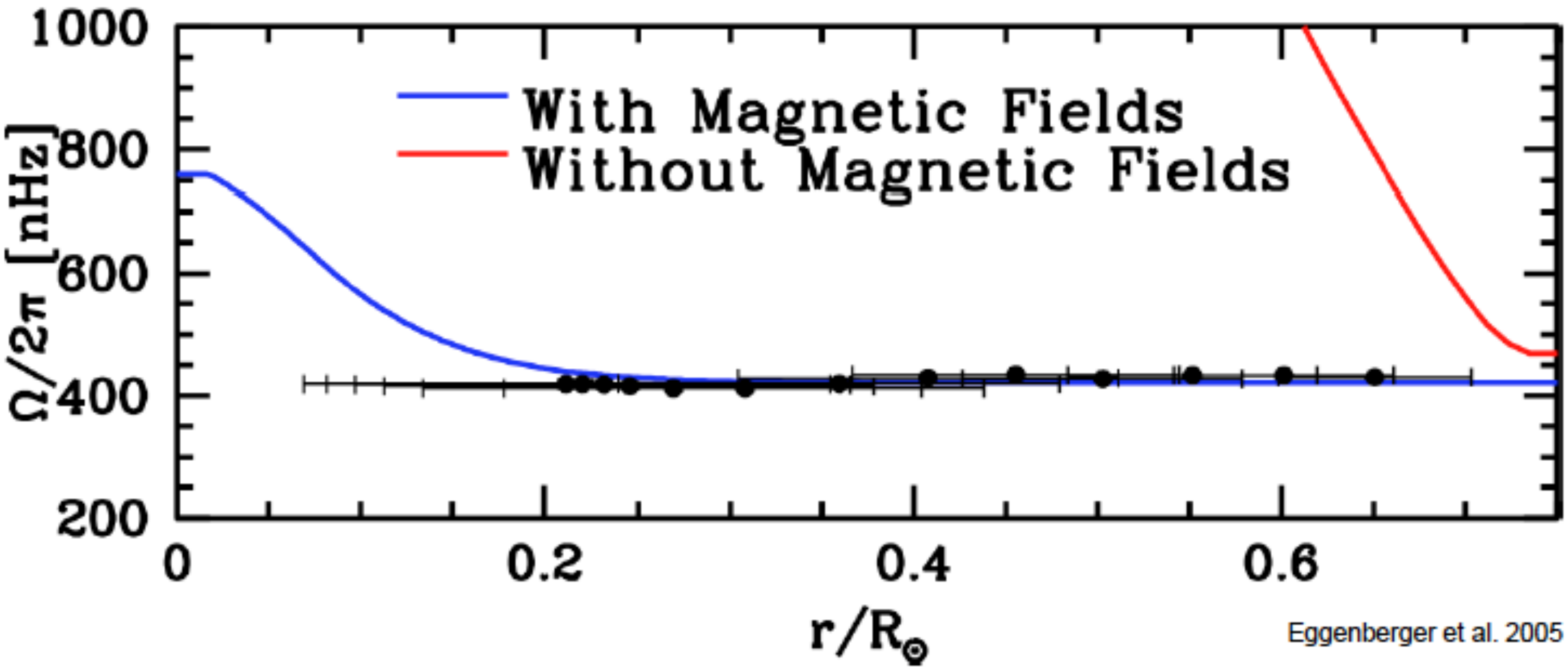


  - Problem with shellular rotation

Pinsonneault et al. 1989; Chaboyer et al. 1995; Talon et al. 1997; Eggenberger et al. 2005; Turck-Chièze et al. 2010

The solar rotation profile

- Effects of magnetic fields



$$\rho \frac{\mathrm{d}}{\mathrm{d}t}\left[r^2\Omega\right] = \frac{1}{5r^2}\frac{\partial}{\partial r}\left[\rho r^4 \Omega U\right] + \frac{1}{r^2}\frac{\partial}{\partial r}\left[\rho (D_{\mathrm{shear}} + \nu_{\mathrm{magn}}) r^4 \frac{\partial \Omega}{\partial r}\right]$$

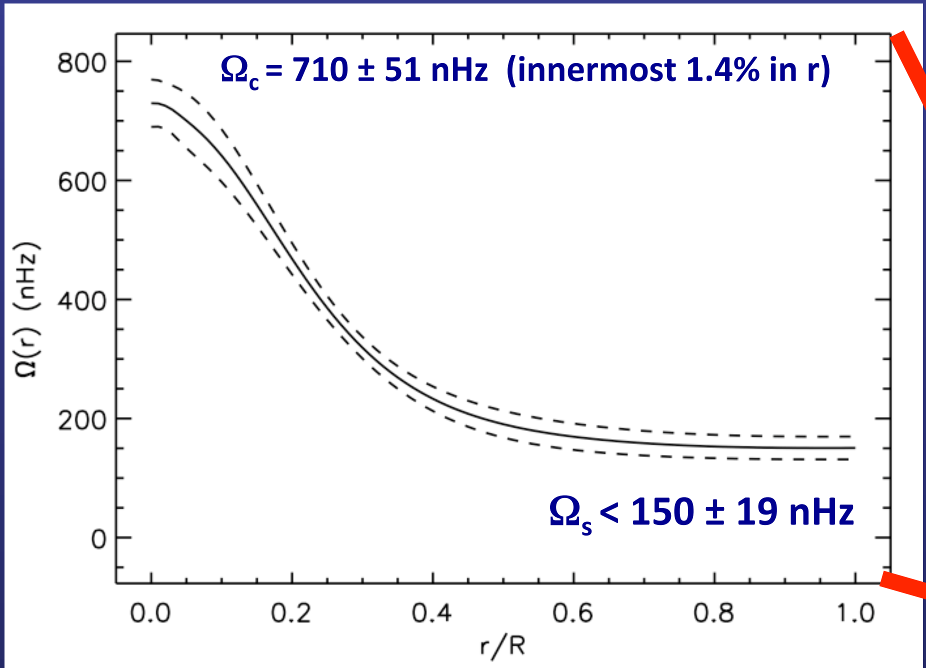
Asteroseismology of red giants

Mixed modes in the red giant KIC 7341231 (0.84 M_{sol}, [Fe/H]=-1)

- Rotational splittings for 18 modes (Deheuvels et al. 2012)→Inversion of the rotation profile:

OBSERVATION

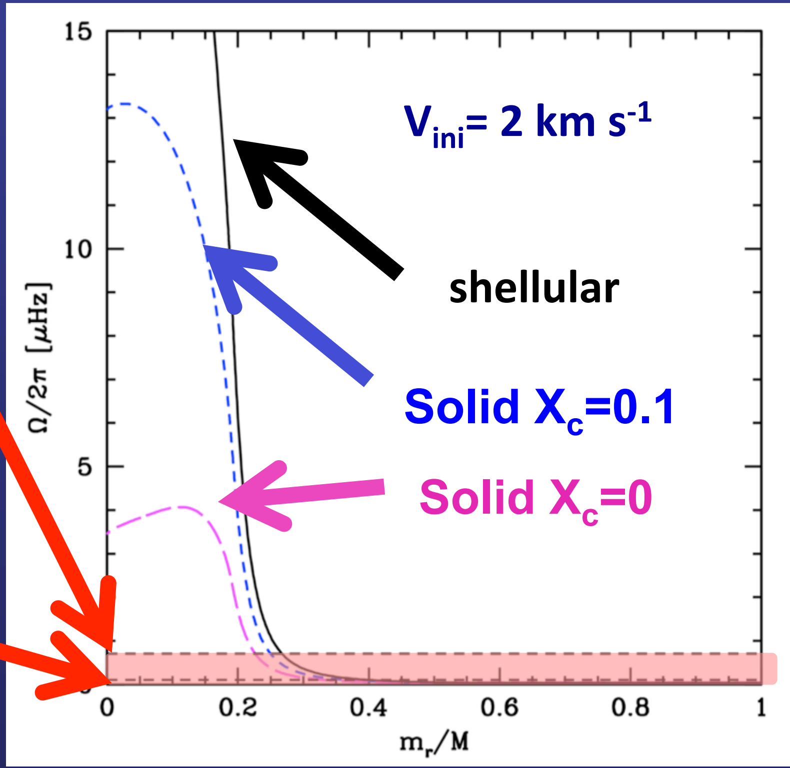
Nano Hertz



Deheuvels et al. 2012

MODELS

Micro Hertz



Ceillier et al. 2013

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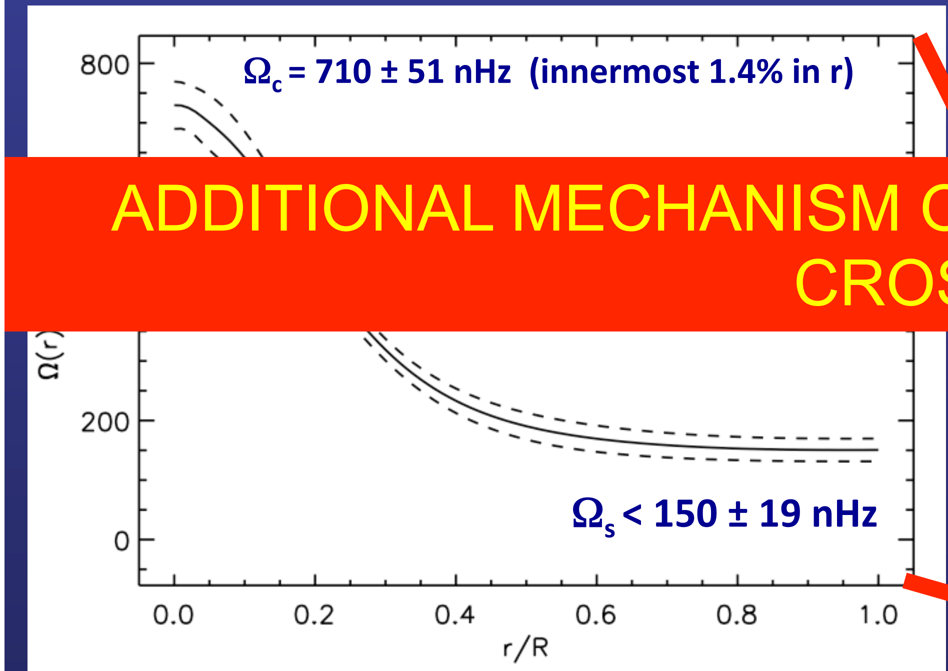
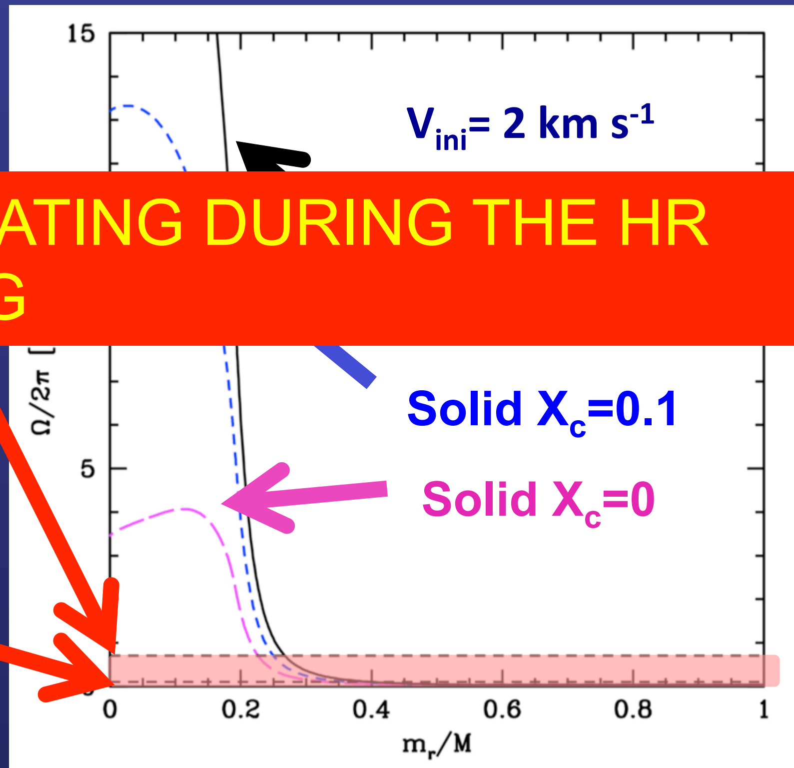
OBSERVATION **MODELS**

Nano Hertz



Deheuvels et al. 2012

Micro Hertz



Ceillier et al. 2013

ADDITIONAL MECHANISM OPERATING DURING THE HR CROSSING

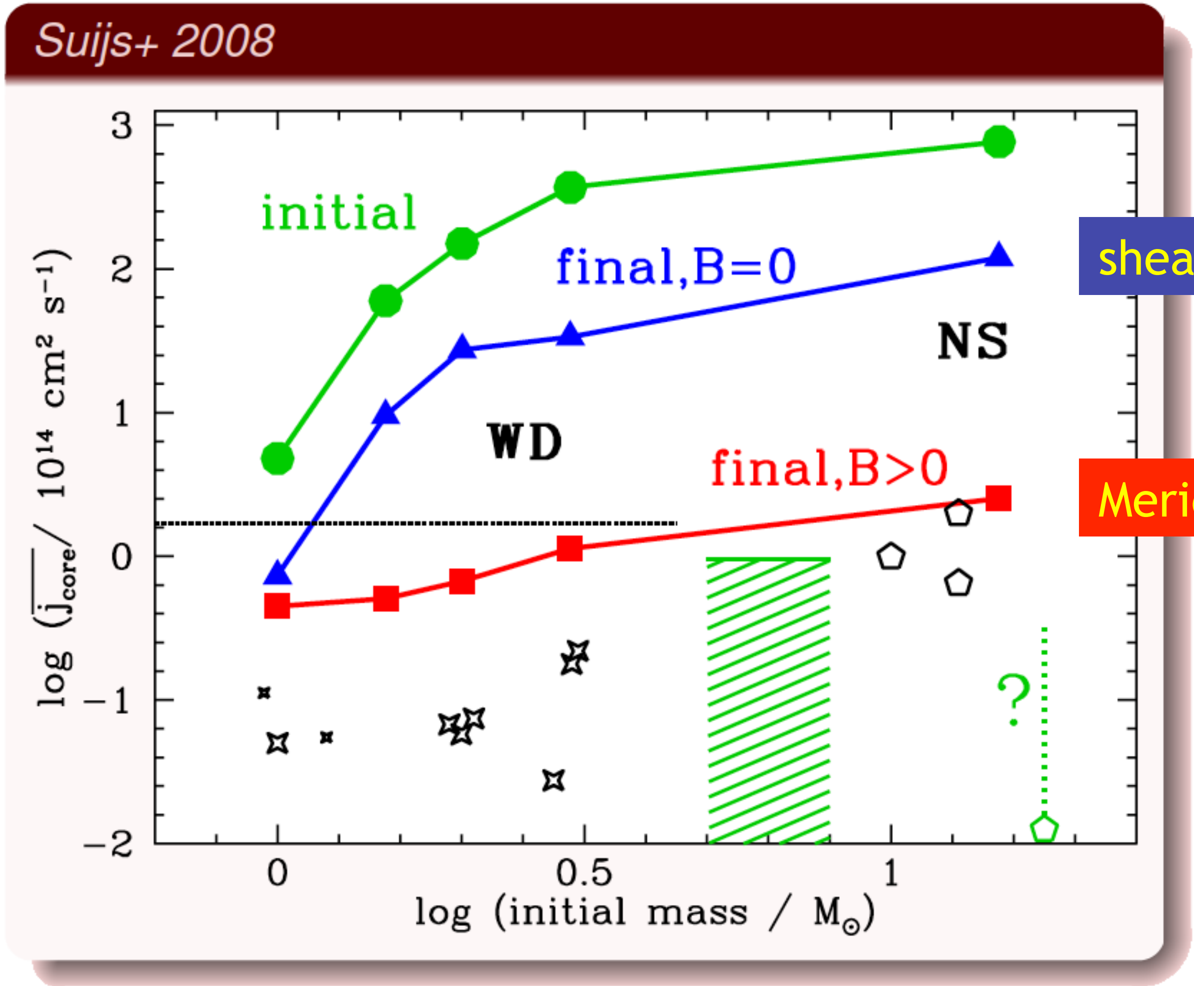
Angular momentum in the remnant

SHEAR DRIVEN MIXING

Too high

MERIDIONAL CURRENTS DRIVEN MIXING

Still too high but
Less than in shear mixing models

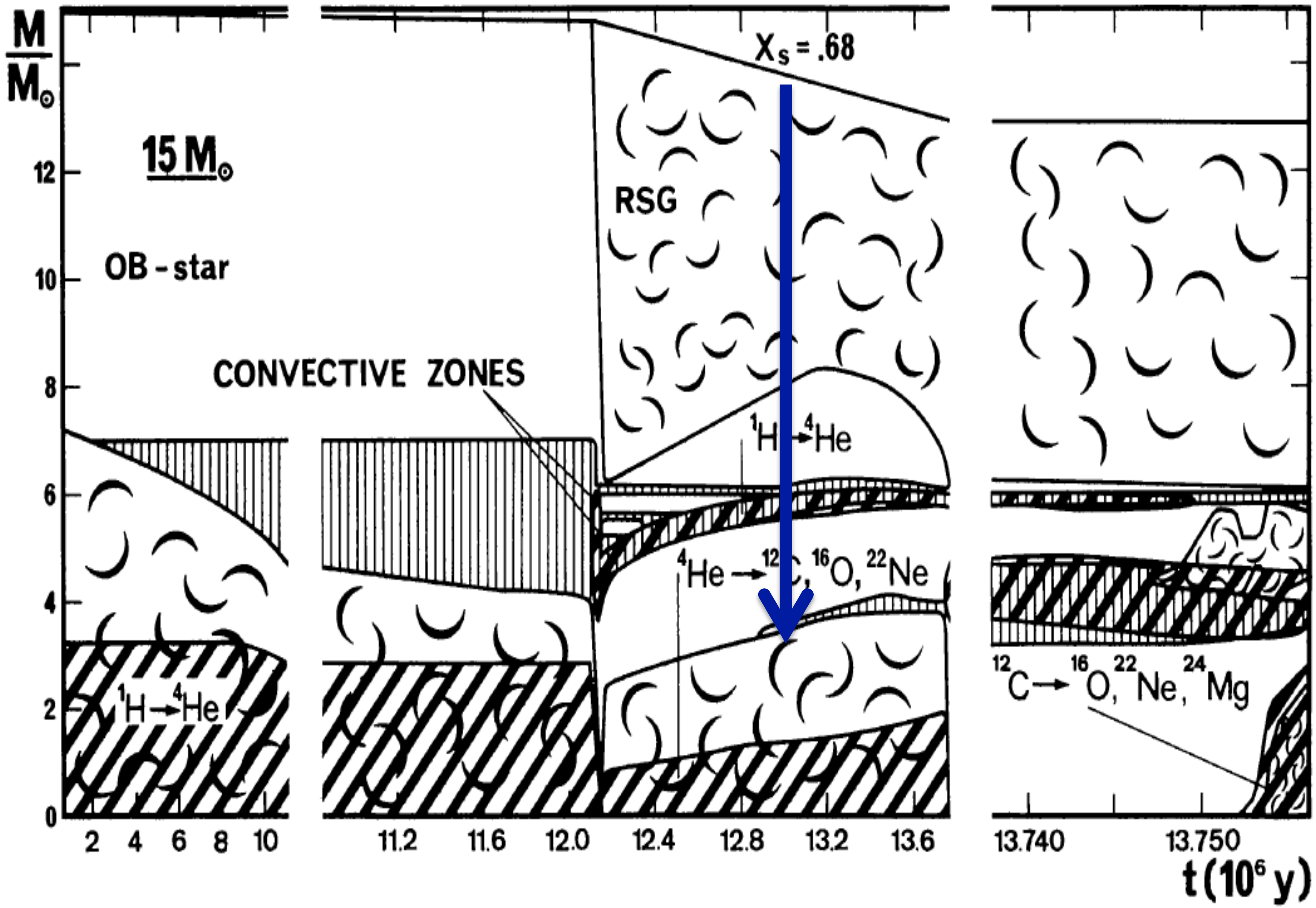


shear

Meridional currents

Magnetic coupling between the core and the intermediate radiative zone

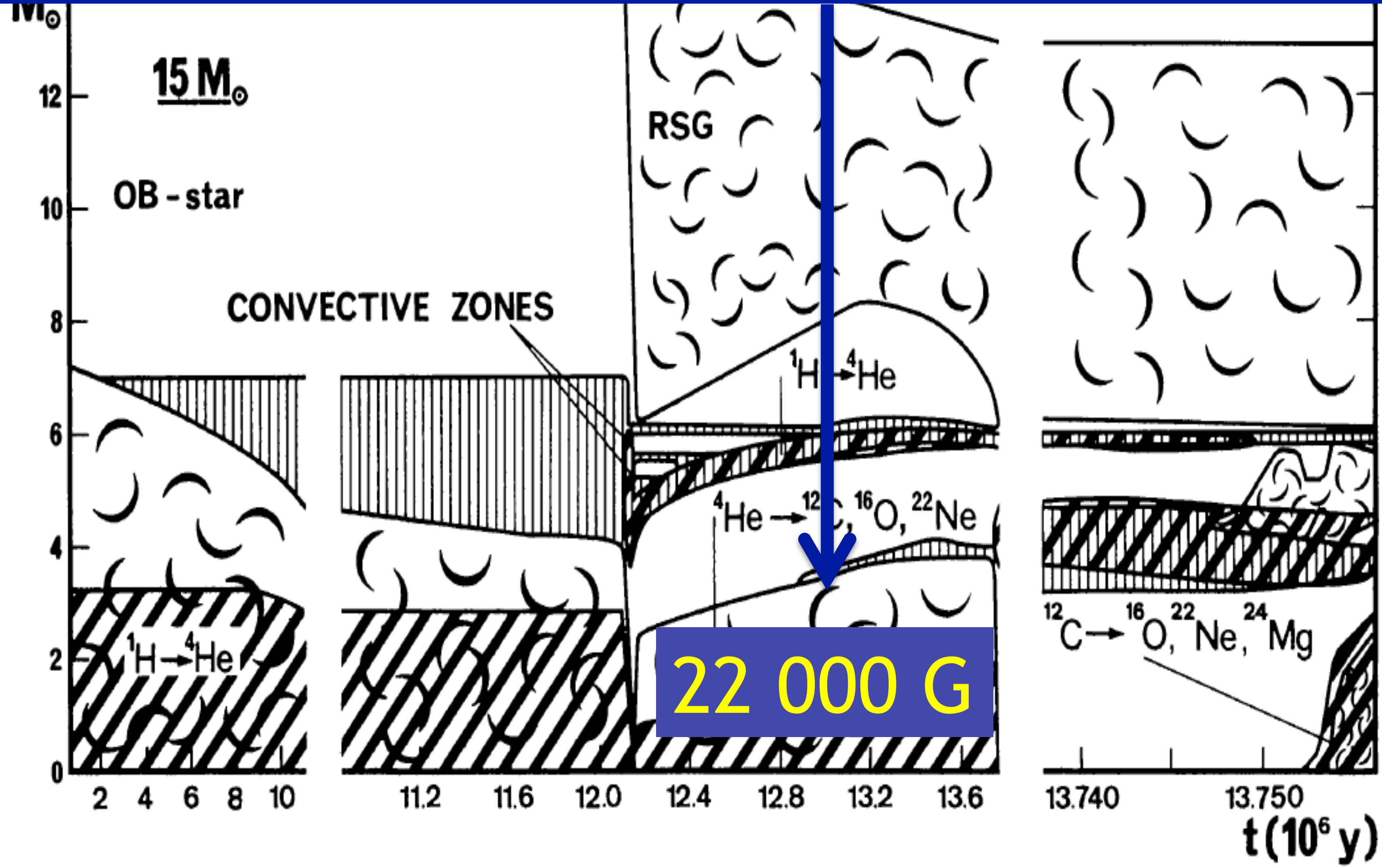
Maeder and Meynet (2014)



Magnetic coupling between the core and the intermediate radiative zone

Maeder and Meynet (2014)

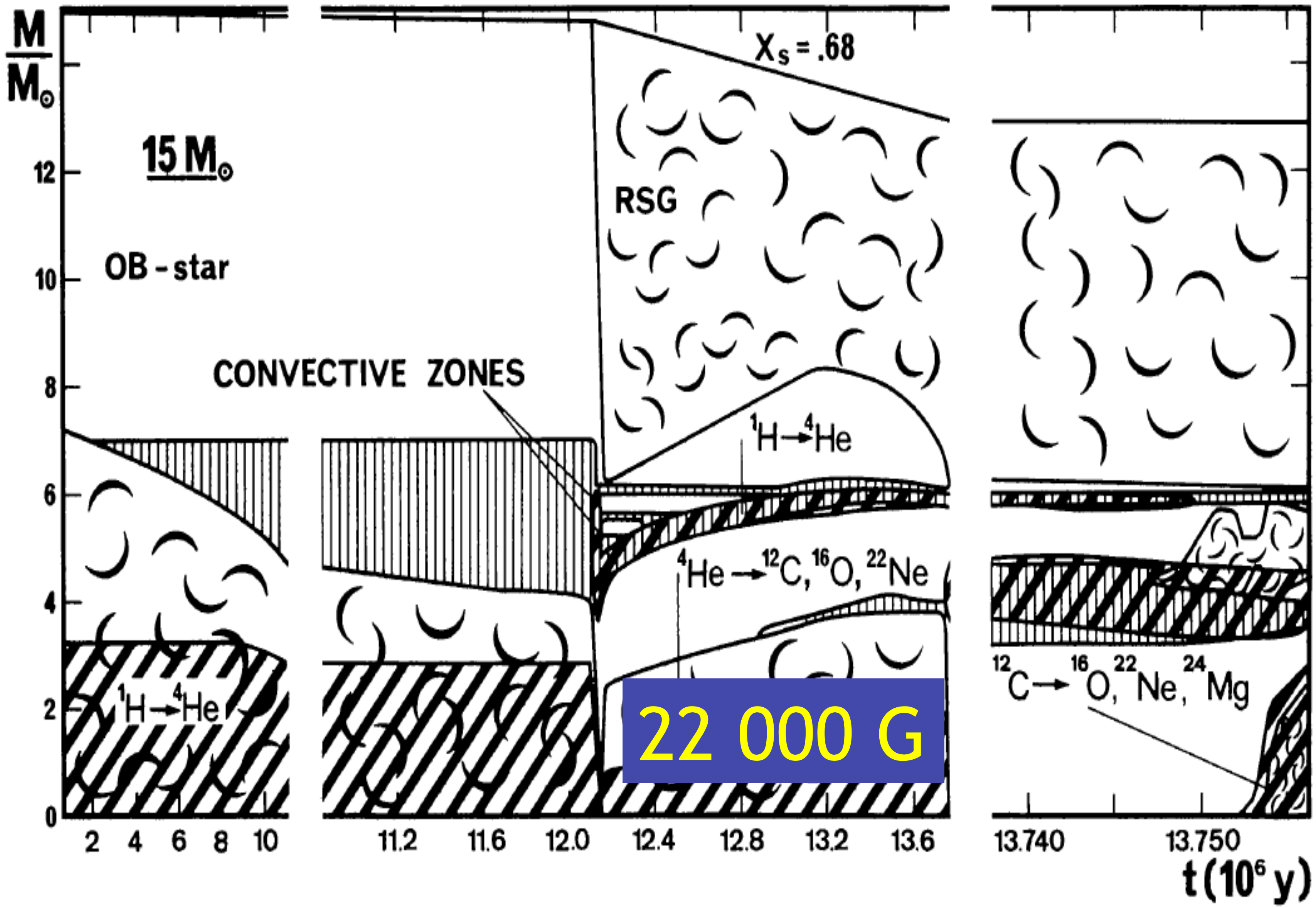
Pulsar→ 10^{12} G, flux conservation→B_c~22 000 G in core at mid He-burning phase



Magnetic coupling between the core and the intermediate radiative zone

Maeder and Meynet (2014)

CAN THIS CORE MAGNETIC FIELD COUPLE THE CORE WITH THE BASE OF THE OUTER CONVECTIVE ENVELOPE?



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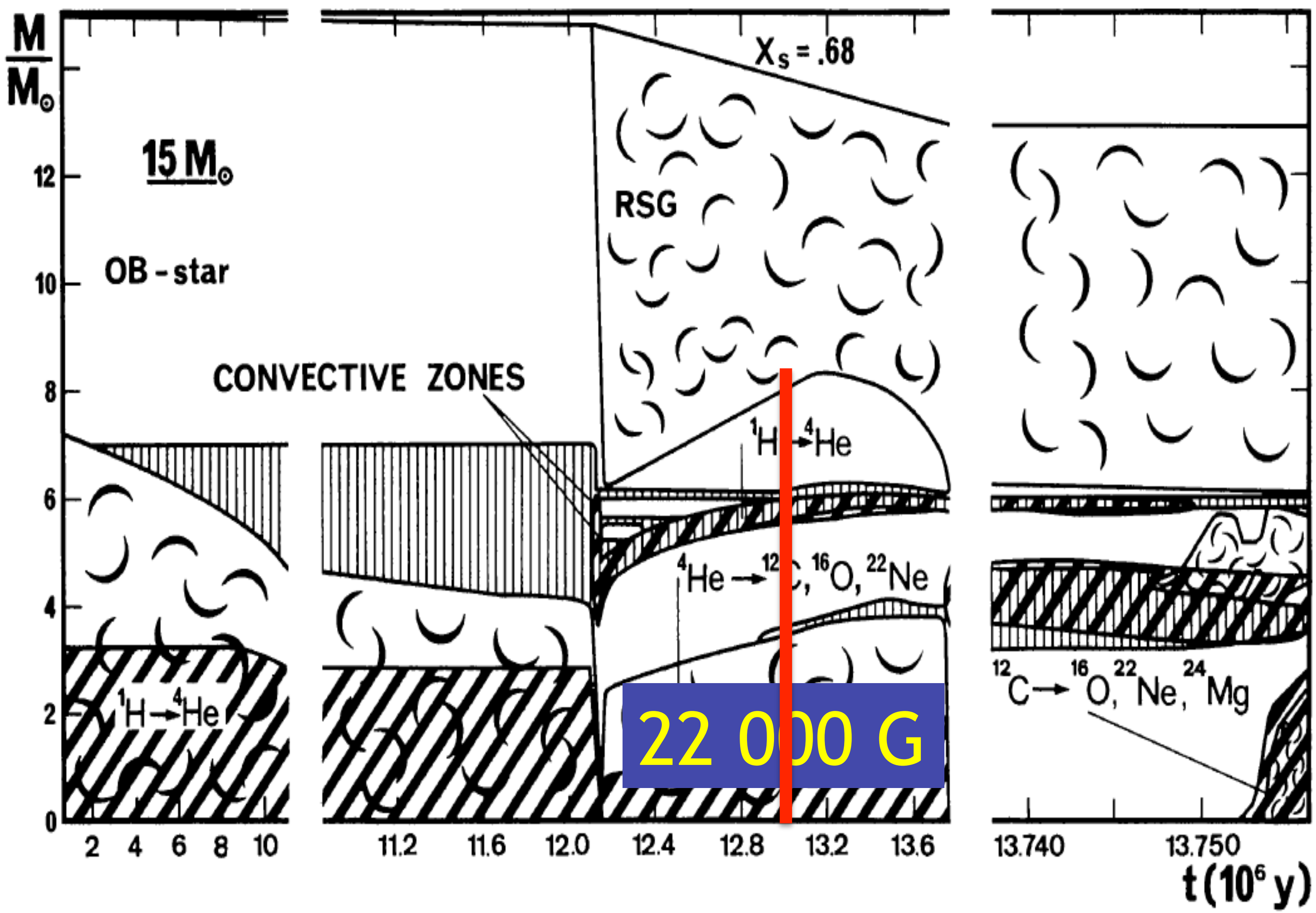


$$B(r) = B_c \left(\frac{R_c}{r}\right)^n$$

n=2 for radial field
n=3 for dipolar field

Coupling with base of the CZ

$$u_B(r) = \frac{B^2(r)}{8\pi} \quad \text{and} \quad u_{\rm conv} = \frac{1}{2}\,\varrho\, v^2_{\rm conv}$$

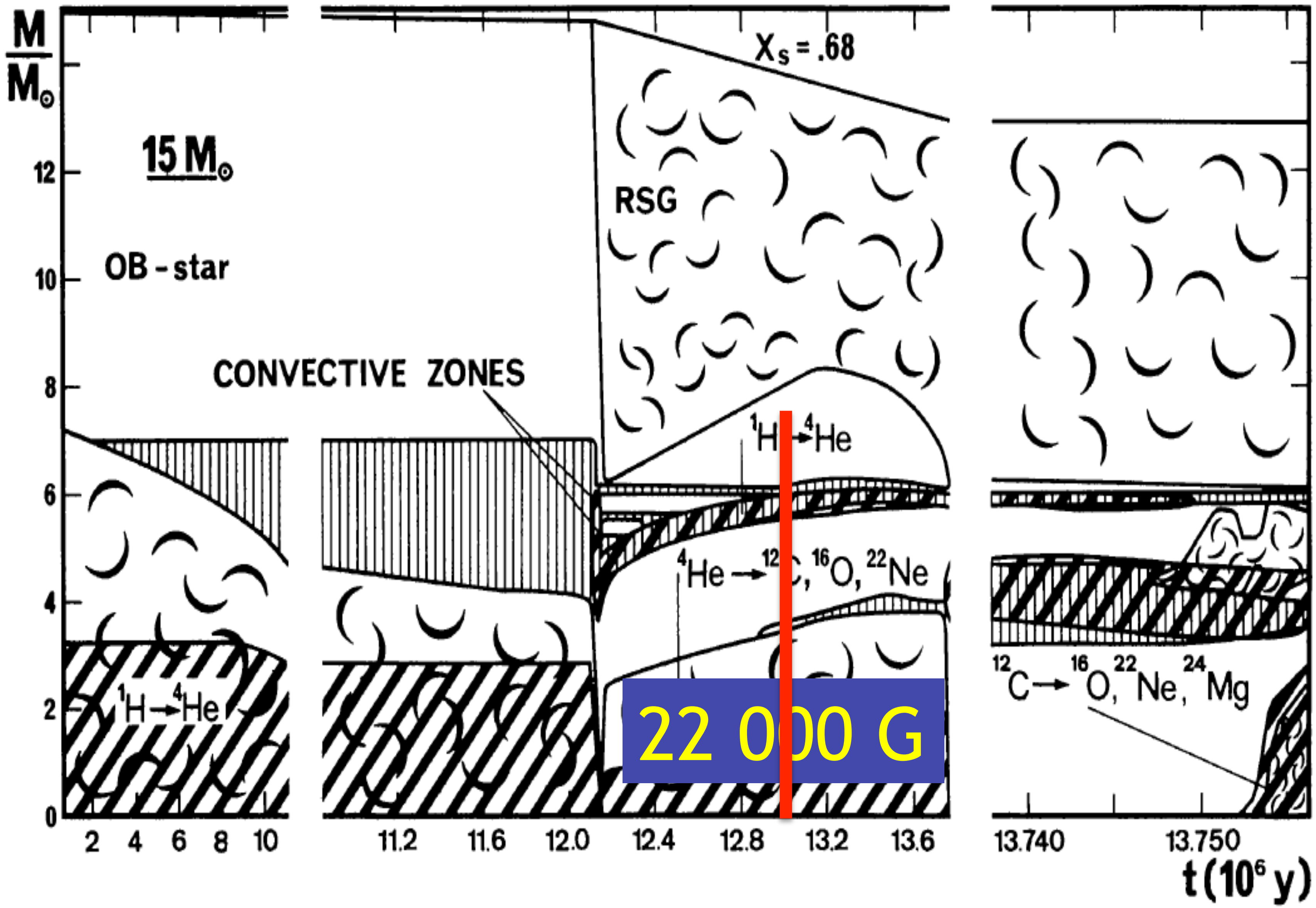
n=2	n=3
$B_c \sim 10^8$ G	$B_c \sim 10^{11}$ G

Available : 2.2 10^4 G → coupling very unlikely

Magnetic coupling between the core and the intermediate radiative zone

Maeder and Meynet (2014)

CAN THIS CORE MAGNETIC FIELD COUPLE THE CORE WITH THE INTERMEDIATE RADIATIVE ZONE?



$$B(r) = B_c \left(\frac{R_c}{r} \right)^n$$

n=2 for radial field
n=3 for dipolar field

Coupling with the intermediate radiative zone

$$u_B(r) = \frac{B^2(r)}{8\pi} \quad \text{and} \quad u_{\mathrm{h}} = \frac{1}{2} \varrho \frac{D_{\mathrm{h}}^2}{r^2}$$

n=2 | n=3

$B_c \sim 5$ G | $B_c \sim 870$ G

Available : 2.2 10^4 G → coupling possible
But what are the timescales?

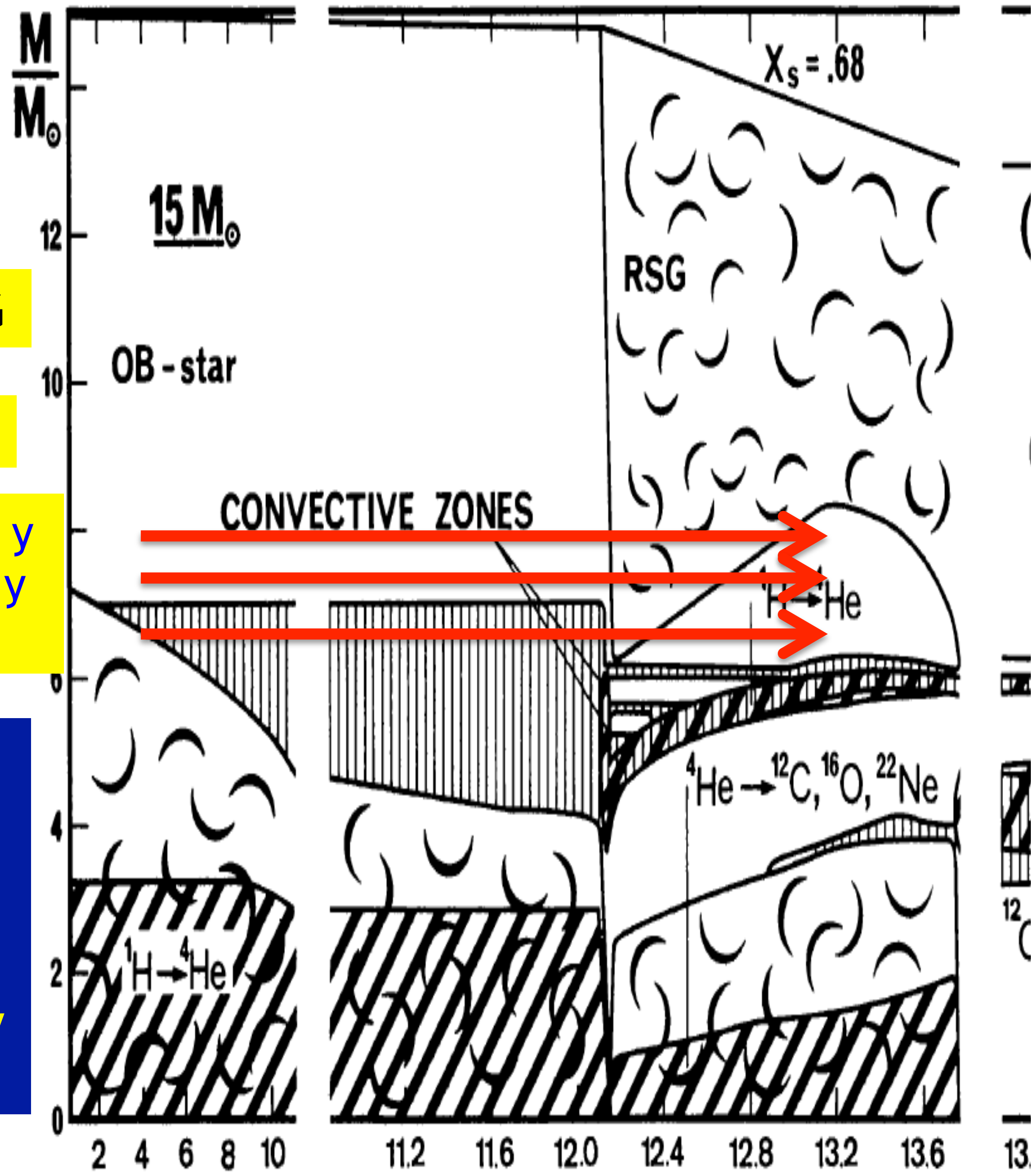
Timescales: Ω/ω_A^2 for B_c=22000 G

	n=2	n=3
Outer radi	3.3 10^5 y.	6.1 10^9 y
Mid radi	5.38 10^4 y.	4.9 10^6 y
Edge core	2000 y.	2000y

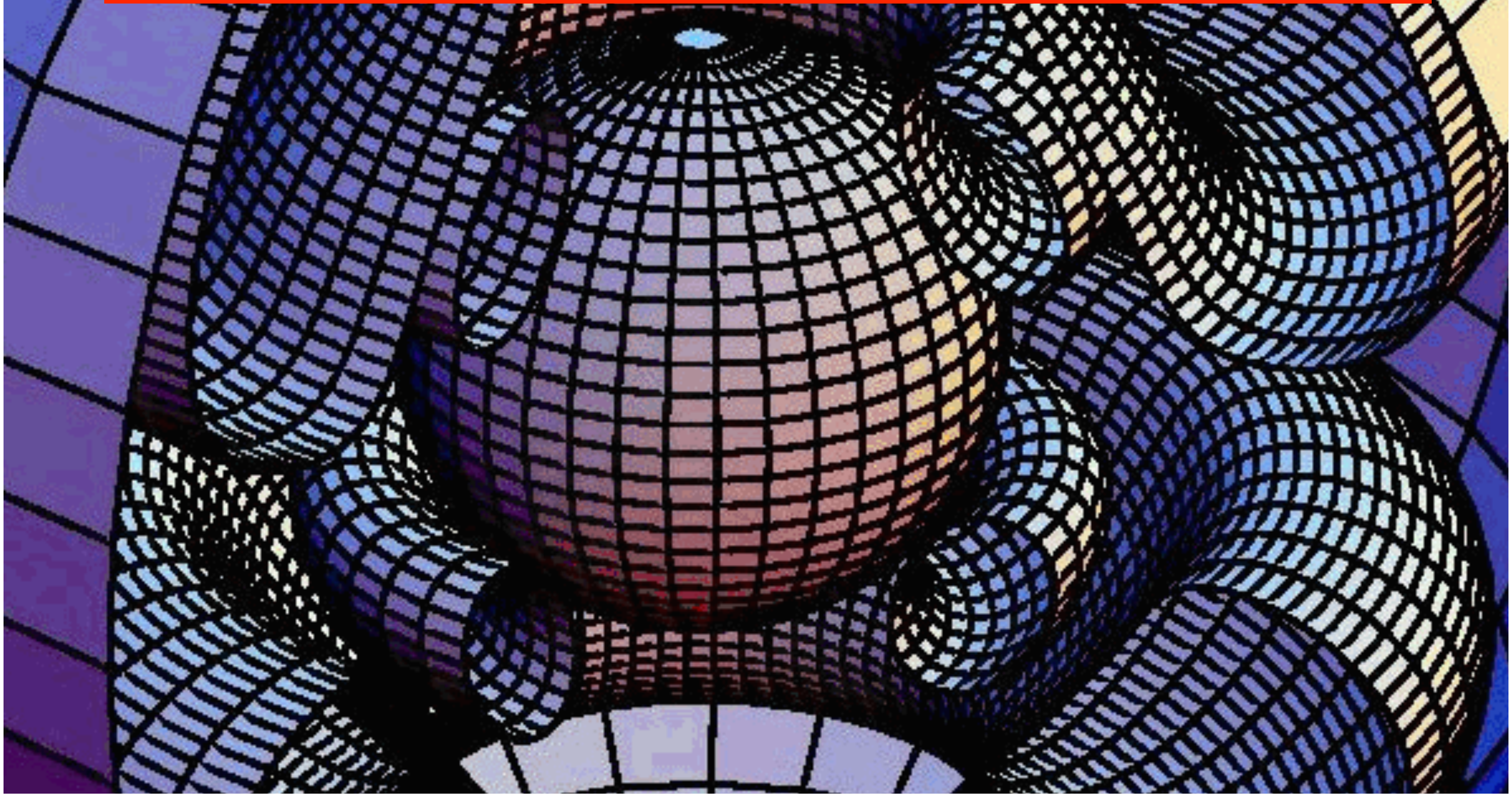
Available

Duration crossing HRD 10^5 y
TOO SHORT FOR COUPLING

Duration core He-burning 1.5 10^6 y
OK FOR COUPLING IN CASE n=2



2) BLUE SUPERGIANTS SUCCESSES AND CHALLENGES



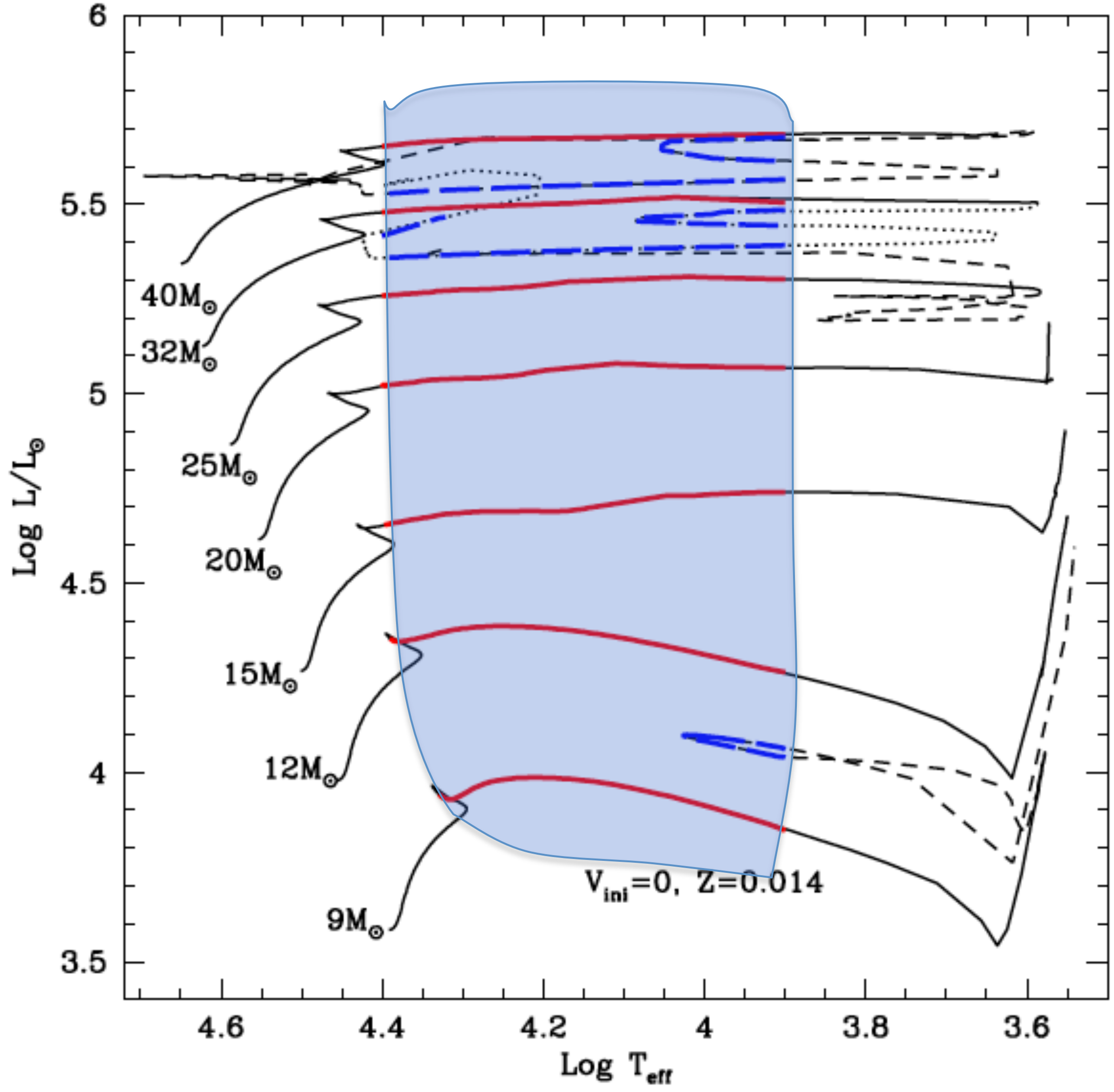
BLUE SUPERGIANTS

$10\text{-}40\ M_{sol}$

$T_{eff} \sim 8000\text{-}20000$ K

$M_V \sim -9.5$ mag

AS BRIGHT AS
A Globular Cluster
OR
A DWARF GALAXY



SPECTROSCOPY→ intrinsic energy distribution
→ reddening and metallicity

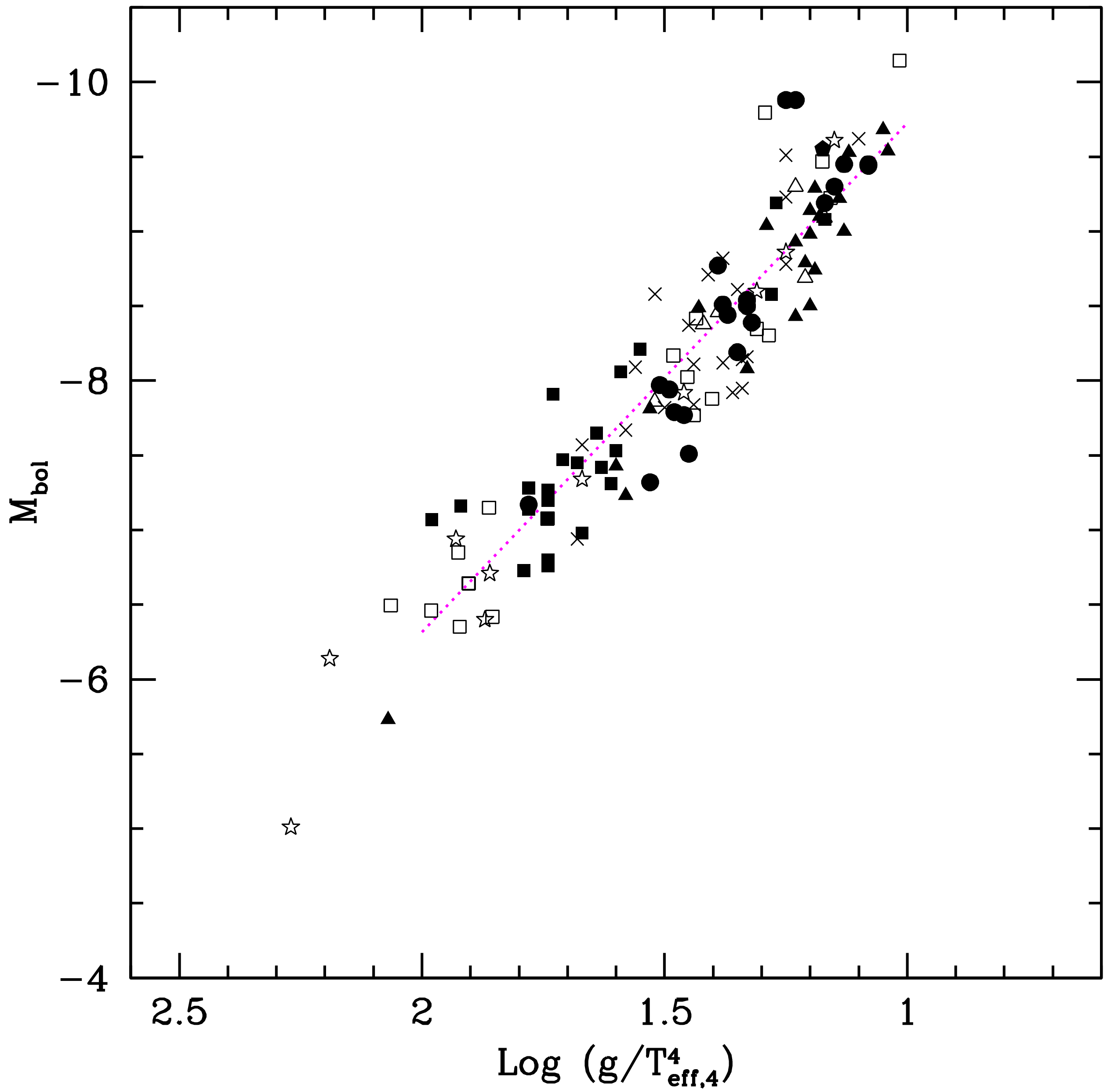
AGE BETWEEN 5 and 13 millions years
→ not too much concentrated in their birth region, smaller crowding effects than for O-type stars

Short lifetimes→ little chance to have two (non resolved) stars which spectroscopically would appear as a single blue supergiants

Blue Supergiants
As standard candles

Kudritzki et al. 2003

Kudritzki et al. 2008ab
Urbaneja et al. 2008
U et al. 2009
Kudritzki et al. 2012
Kudritzki et al. 2013
Kudritzki et al. 2014
Hosek et al. 2014



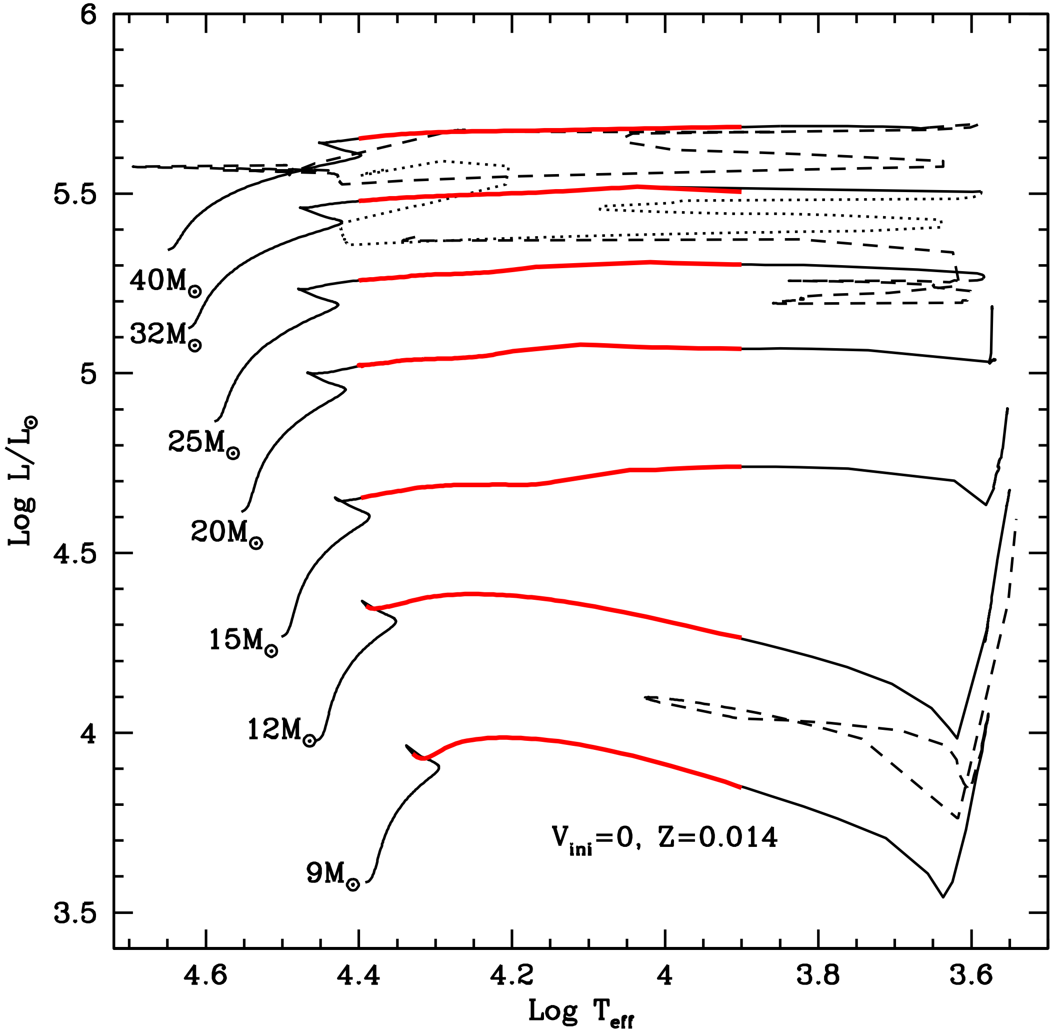
WHY DO WE HAVE SUCH A WELL DEFINED RELATION?

IF THE BLUE SUPERGIANTS FOLLOW A MASS-LUMINOSITY RELATION OF THE TYPE

$$\log L = \alpha * \log M + b$$

$$M_{bol} = 2.5\frac{\alpha}{\alpha - 1}\left[\log\frac{g}{T_{\mathrm{eff},4}^4} - 16\right] - 2.5\frac{\alpha}{\alpha - 1}\left[\log(4\pi\sigma G) + \log\frac{M_\odot}{L_\odot}\right] + 2.5\frac{b}{\alpha - 1} + 4.75.$$

GROUP 1 BSG= BSG HAVING DIRECTLY EVOLVED FROM THE MS



FOR A GIVEN MASS

L~cst

Actual mass~cst

http://obswww.unige.ch/Recherche/evoldb/index/

STELLAR
EVOLUTION

Members
Research
Database
Publications

SYCLIST
SYnthetic CLusters
Isochrones &
Stellar Tracks

Comments? Suggestions?
Bug to report?
contact us!

Geneva stellar models: interactive tools

Home > Database > Interactive tools

Welcome to the interactive webpage for the Geneva stellar models

Through this portal, you'll access several tools designed for the Geneva stellar models provided by the SYCLIST code. We propose the following services:

- **Isochrone calculation**

  Compute a single isochrone of the desired age,
  or a sequence of isochrones giving the age range and the time steps.

- **Interpolation of a new model:**

  Create a new model by interpolating between existing tracks.
  Choose the mass, rotation rate and metallicity and obtain the corresponding model track.

- **Request the computation of a synthetic cluster:**

  fill the form for the cluster's settings and the data will be emailed to you soon.

Please select one of the following modes:

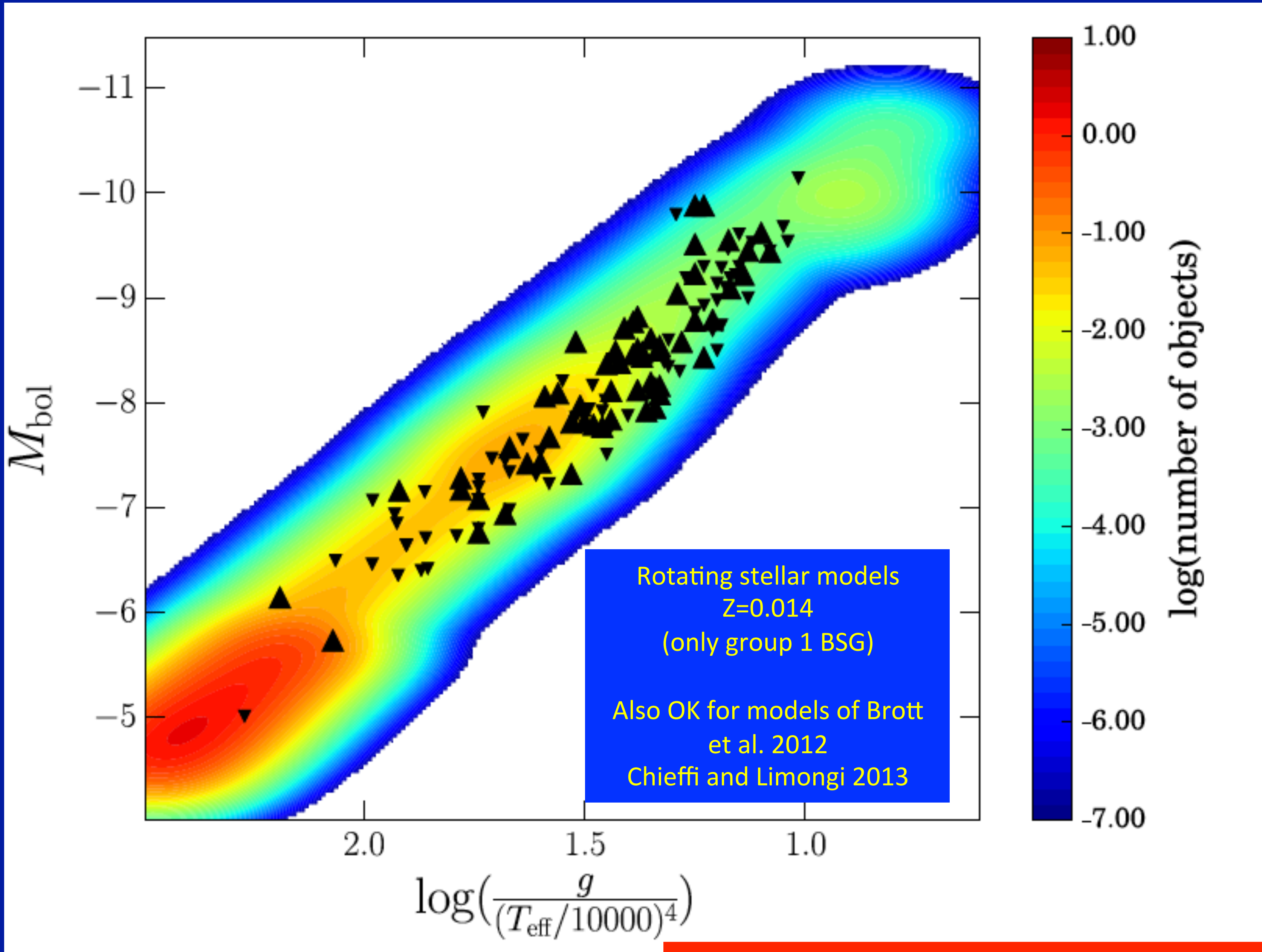
Compute an isochrone

Submit

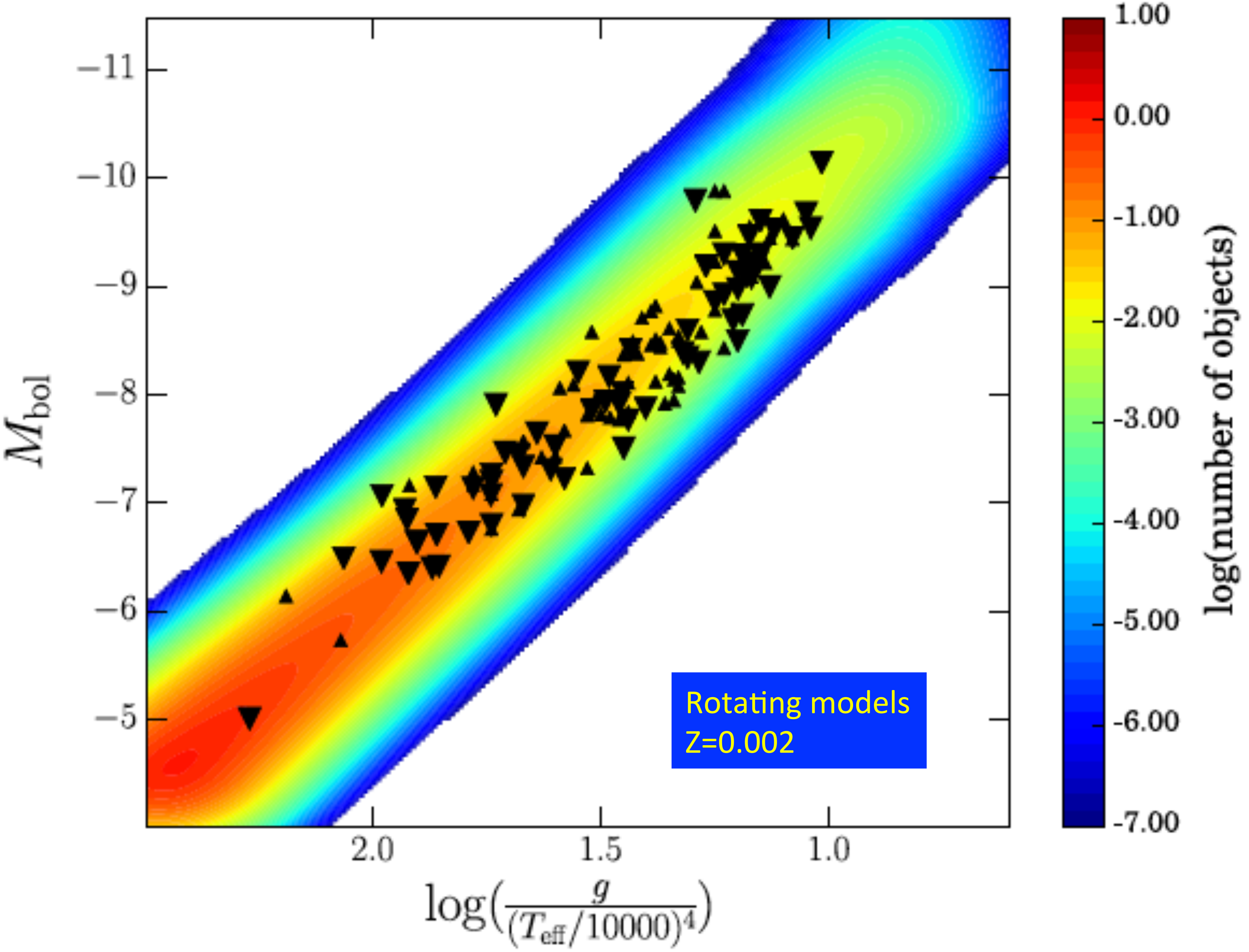
Output files formats | Site Map | admin

Site created with dj by C. Georgy & S. Ekström - Last update: March 31, 2015 at 16:32

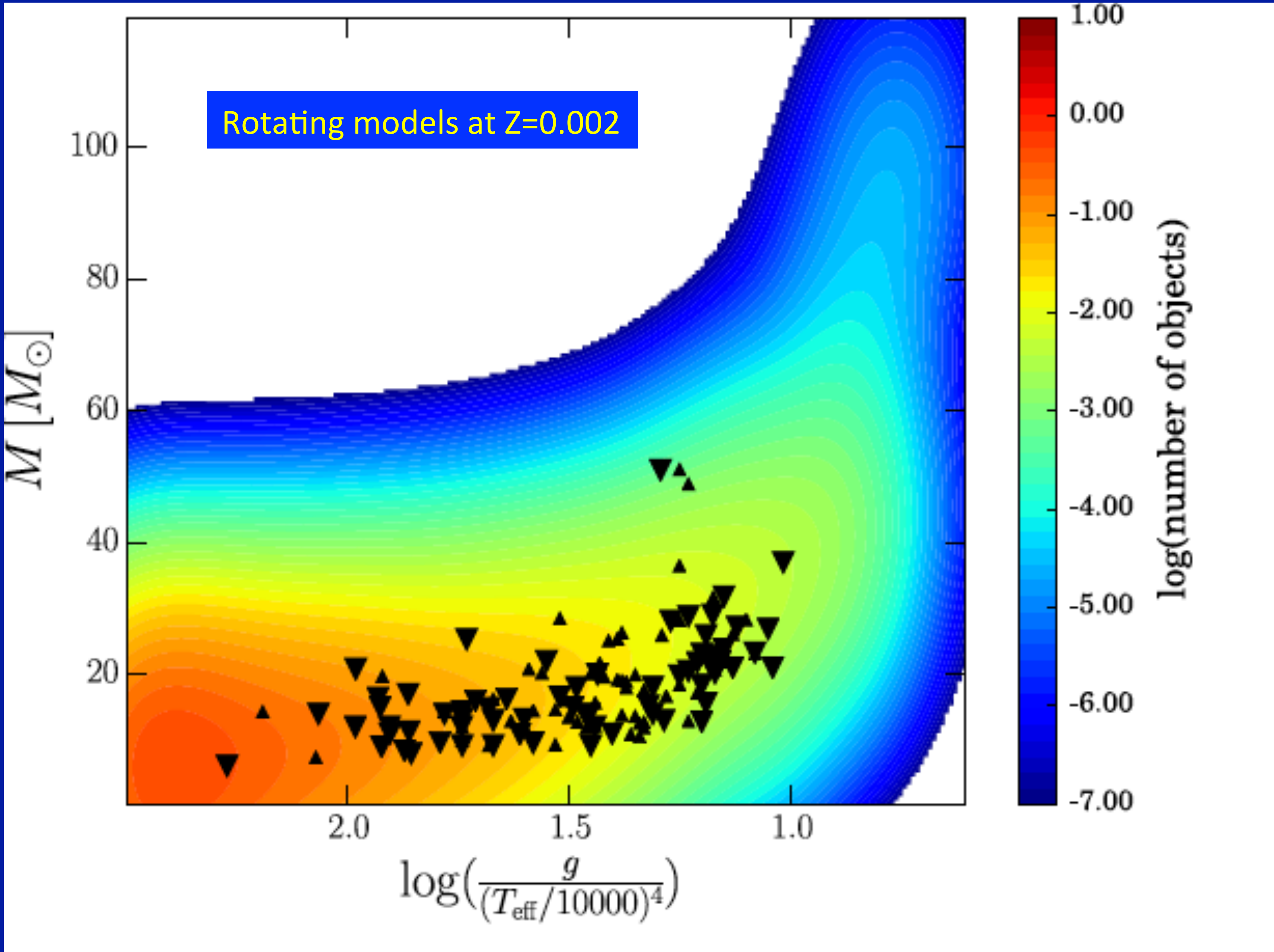
USING SYCLIST → PROBABILITY DENSITY (cst SFR)



Meynet, Kudritzki, Georgy, A& A, in press



M_{bol}
−11
−10
−9
−8
−7
−6
−5
2.0
1.5
1.0
$\log(\frac{g}{(T_{eff}/10000)^4})$
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
log(number of objects)
Rotating models
Z=0.002

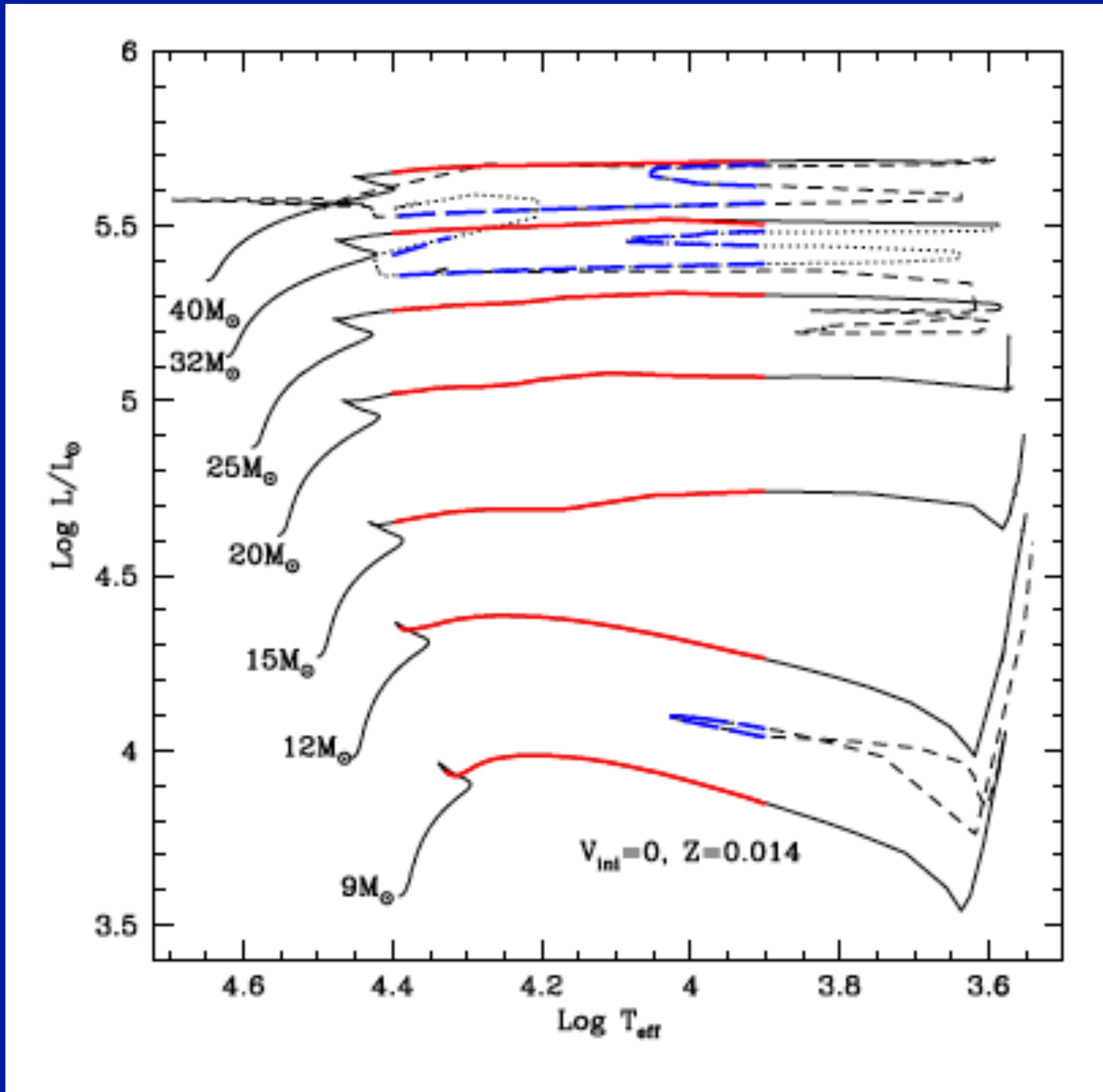


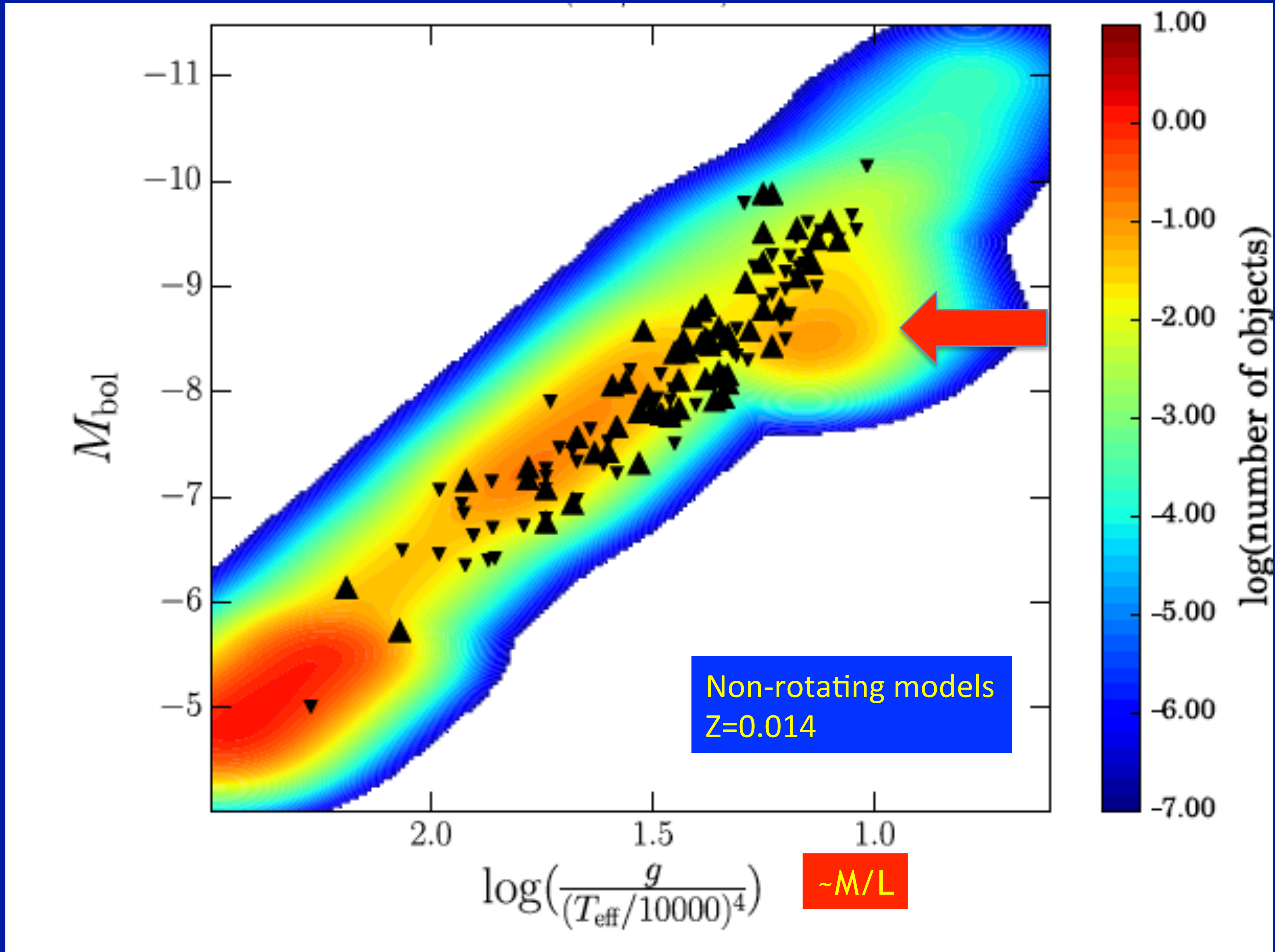
Rotating models at Z=0.002
100
80
60
40
20
$M\ [M_\odot]$
2.0
1.5
1.0
$\log(\frac{g}{(T_{\rm eff}/10000)^4})$
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
log(number of objects)


THUS→ GOOD AGREEMENTS
BUT HERE ONLY GROUP 1 BSG
WHAT DOES HAPPEN WHEN
POST RSG BSG APPEAR?

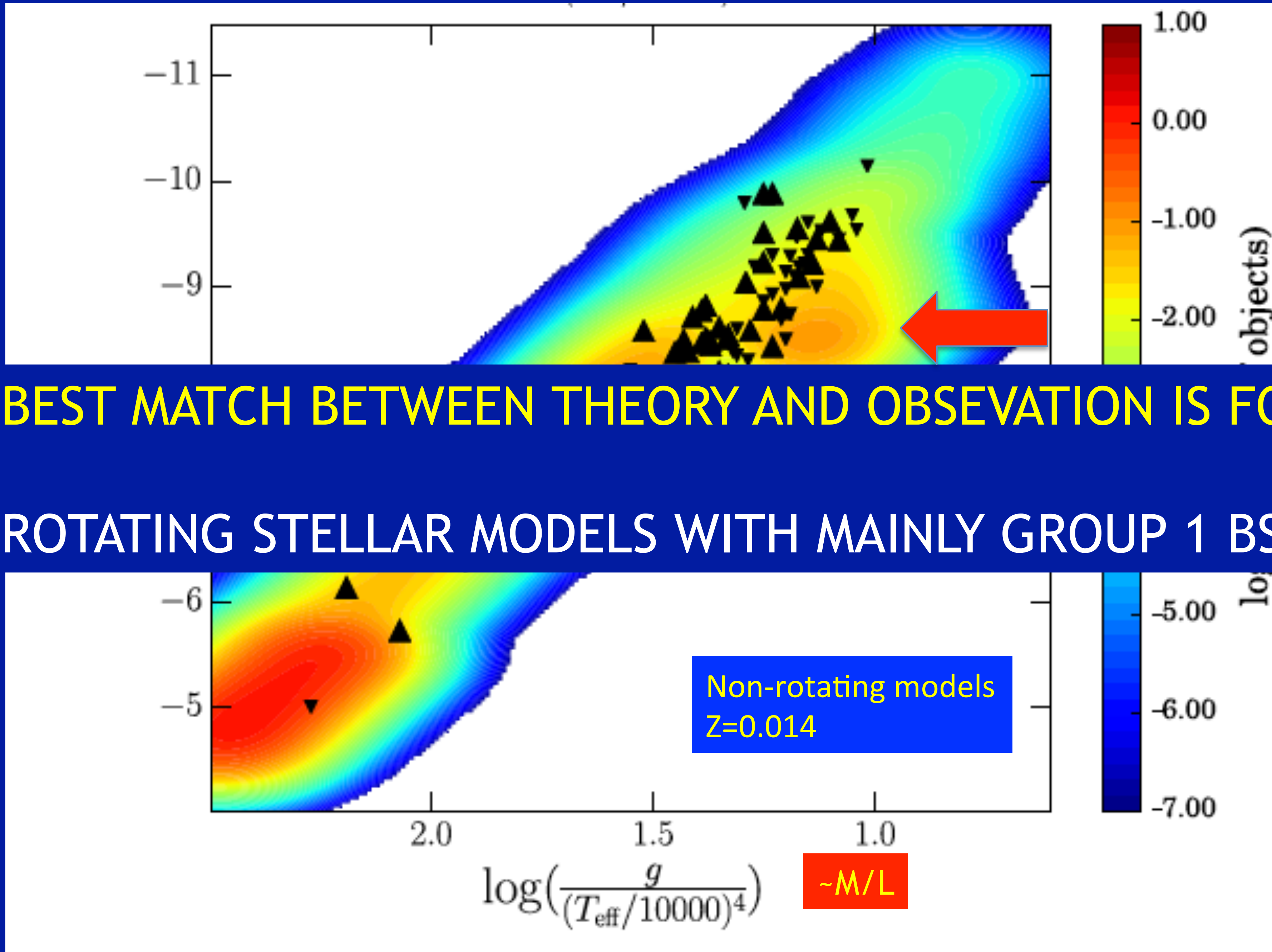
GROUP 2 BSG= POST RED SUPERGIANT BSG

WHERE WOULD BE THESE STARS IN THE FWGL?





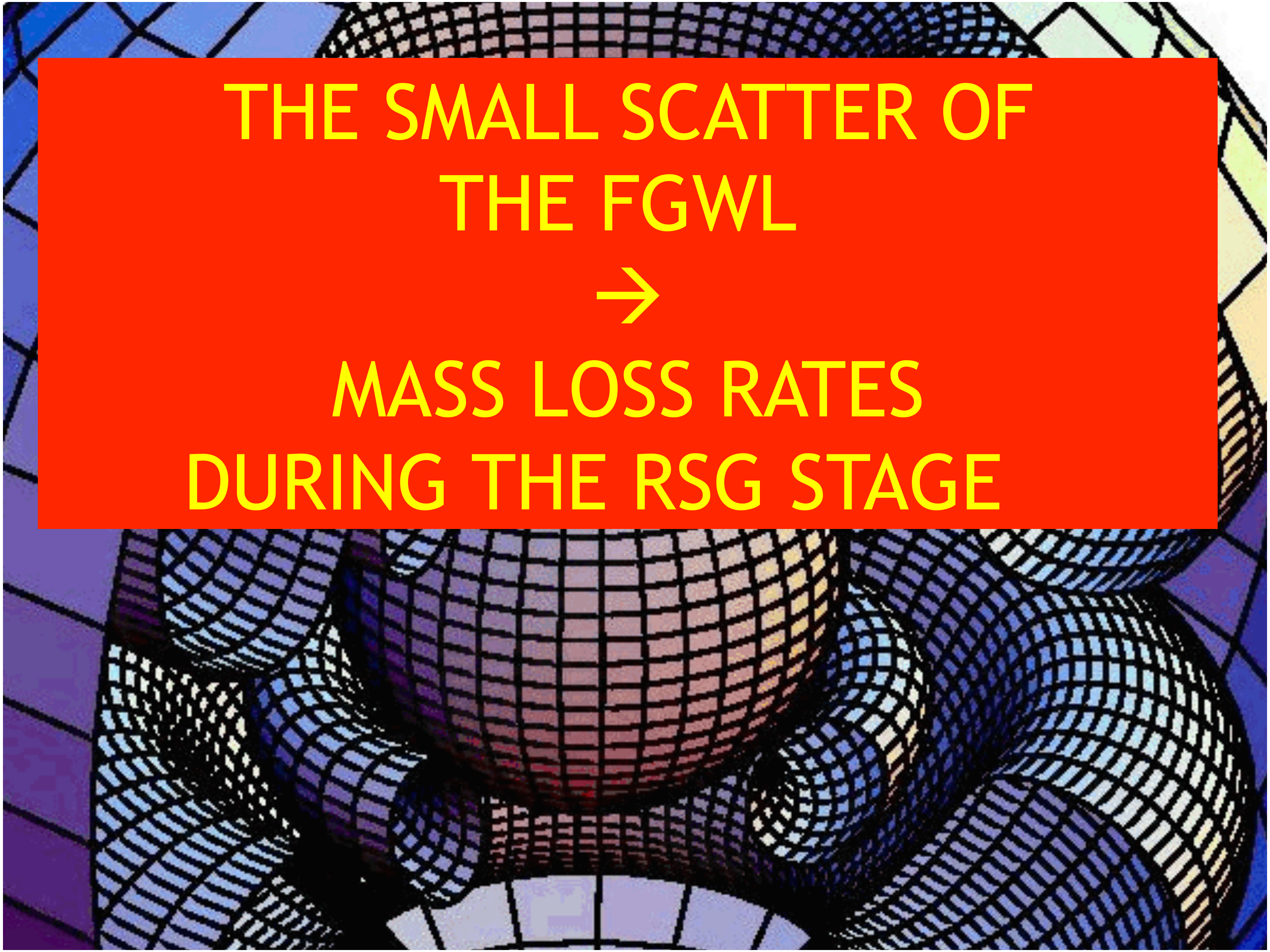
−11
−10
−9
−8
−7
−6
−5
2.0
1.5
1.0
M_{bol}
$\log(\frac{g}{(T_{eff}/10000)^4})$
~M/L
Non-rotating models
Z=0.014
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
log(number of objects)

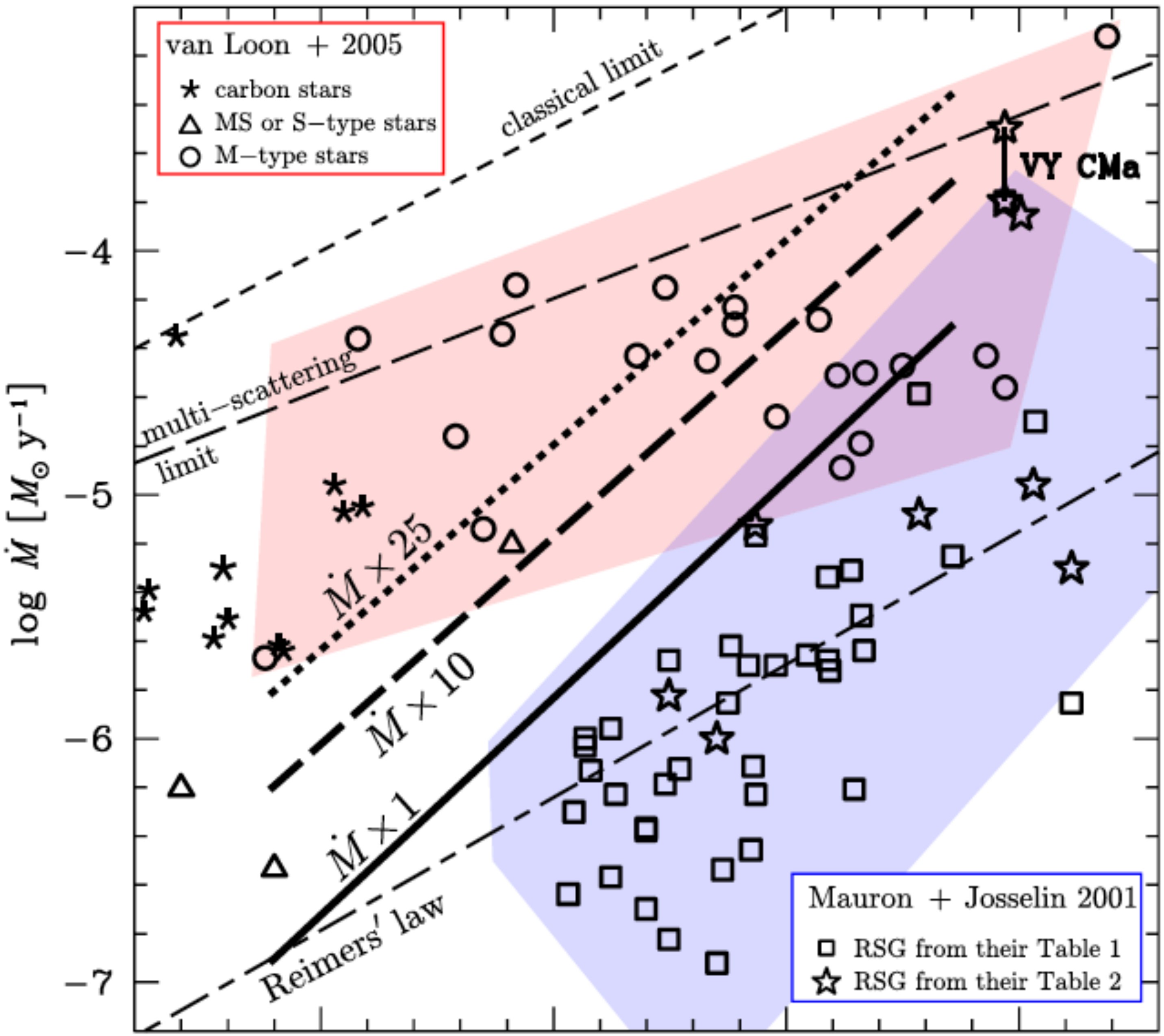


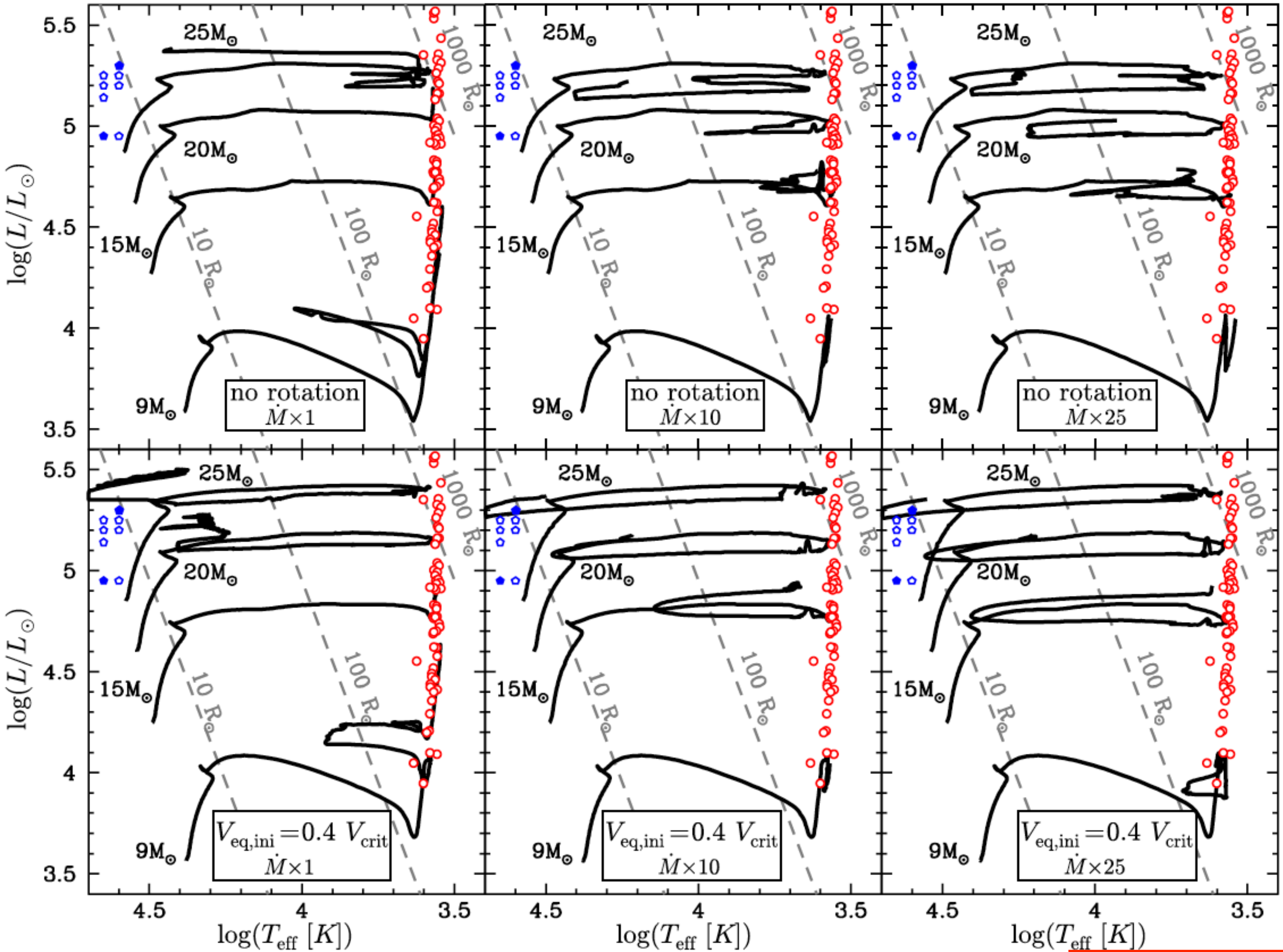
BEST MATCH BETWEEN THEORY AND OBSEVATION IS FOR

ROTATING STELLAR MODELS WITH MAINLY GROUP 1 BSG

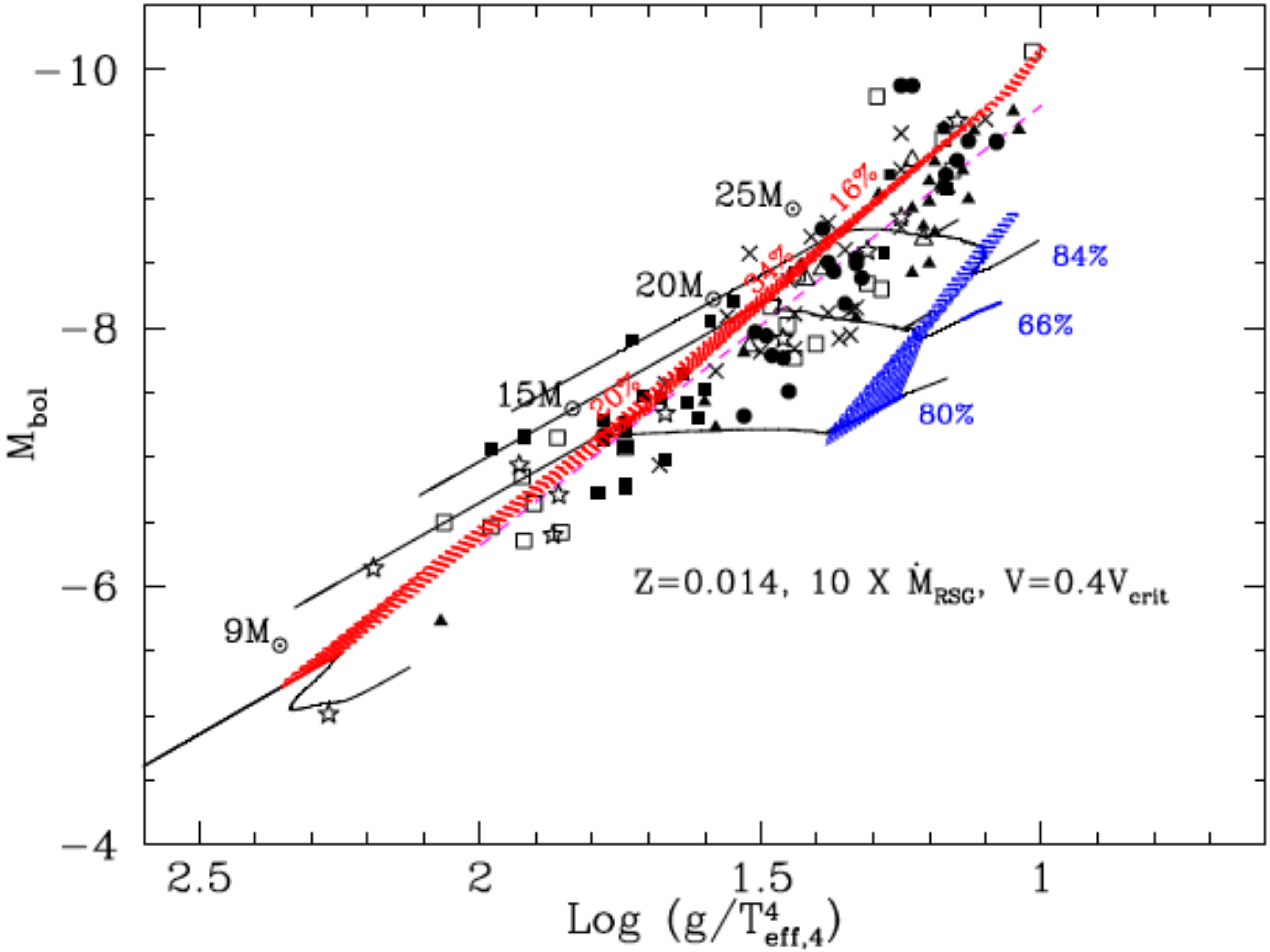
THE SMALL SCATTER OF THE FGWL → MASS LOSS RATES DURING THE RSG STAGE



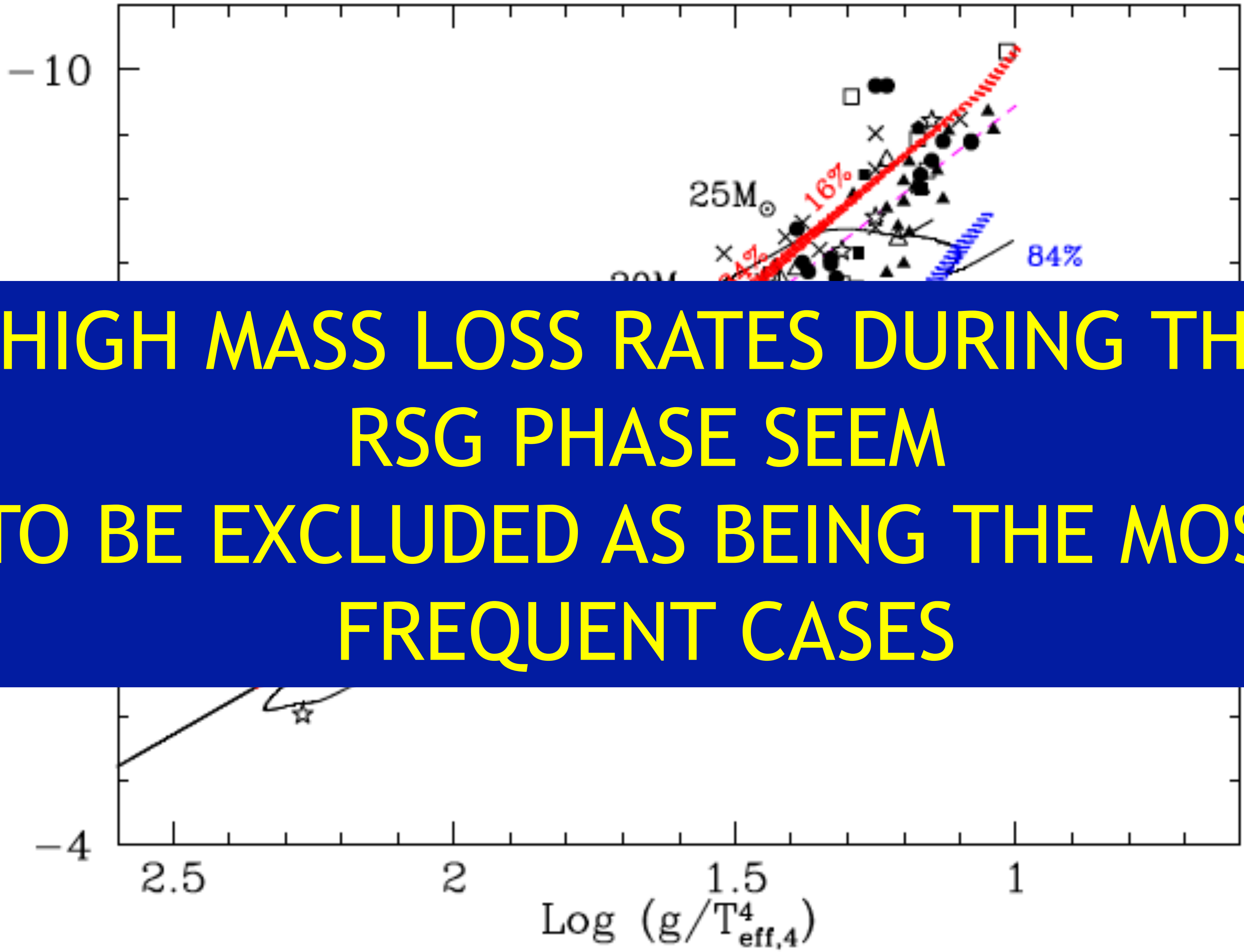

van Loon + 2005
carbon stars
MS or S−type stars
M−type stars
classical limit
multi−scattering limit
VY CMa
$\dot{M} \times 25$
$\dot{M} \times 10$
$\dot{M} \times 1$
Reimers' law
Mauron + Josselin 2001
RSG from their Table 1
RSG from their Table 2
log $\dot{M}$ [$M_\odot$ y^{-1}]
log $L/L_\odot$
−4
−5
−6
−7
4
4.5
5
5.5



Meynet et al. 2014



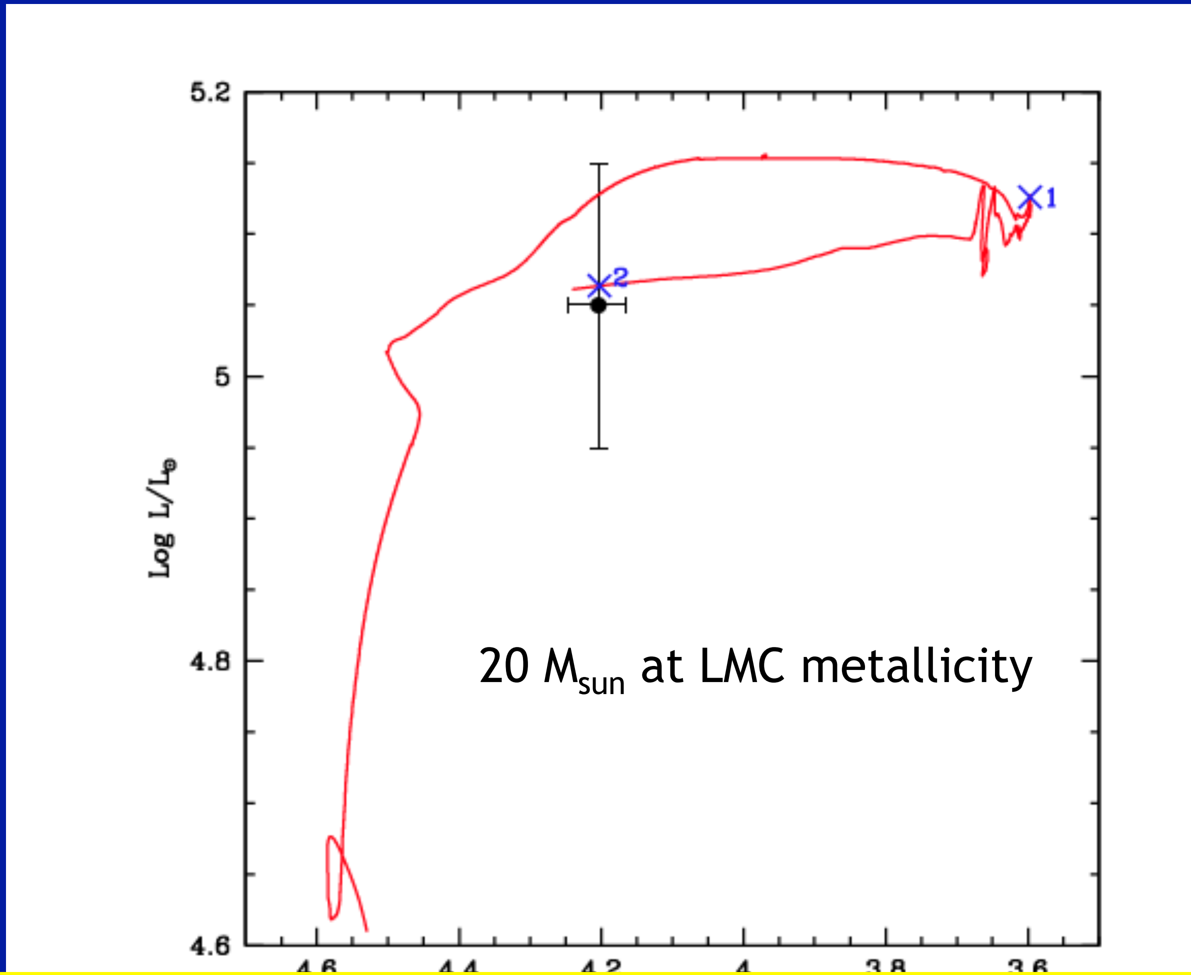
Z=0.014, 10 X $\dot{M}_{RSG}$, V=0.4V_{crit}
M_{bol}
Log $(g/T^4_{eff,4})$
25M☉
20M☉
15M☉
9M☉
16%
34%
20%
84%
66%
80%
−10
−8
−6
−4
2.5
2
1.5
1



HIGH MASS LOSS RATES DURING THE RSG PHASE SEEM
TO BE EXCLUDED AS BEING THE MOST FREQUENT CASES

THE CASE OF THE PROGENITOR OF THE SN 1987A

Kinematics of the nebulosity→ matter ejected rougly 10^4 y. before explosion
Meaburn et al. 1995; Crotts and Haethcote 2000



STAR EVOLVED TO THE BLUE AT THE VERY END OF ITS EVOLUTION
(RED→ BLUE SG MAY BE TRIGGERED BY A RLOF IN A CLOSE BINARY)
AT THE VERY END OF THE RSG PHASE

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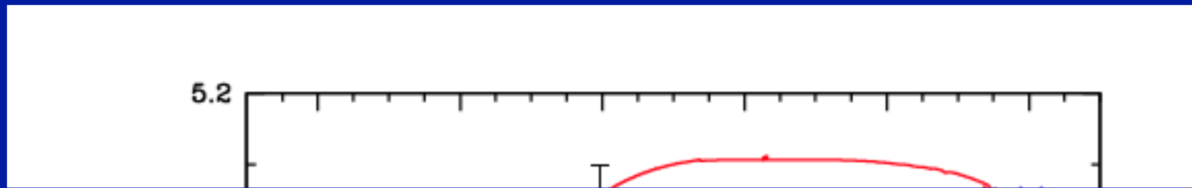
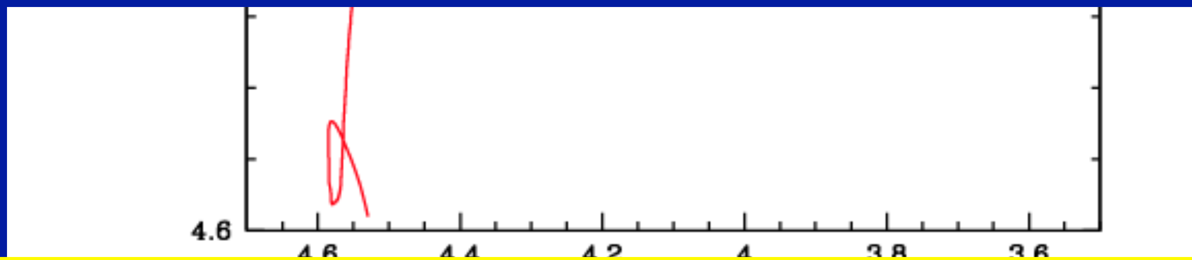


HIGH MASS LOSS RATES TRIGGERED BY MASS TRANSFER AT THE VERY END OF THE RSG PHASE
MAY PRODUCE SHORT LIVED BSG

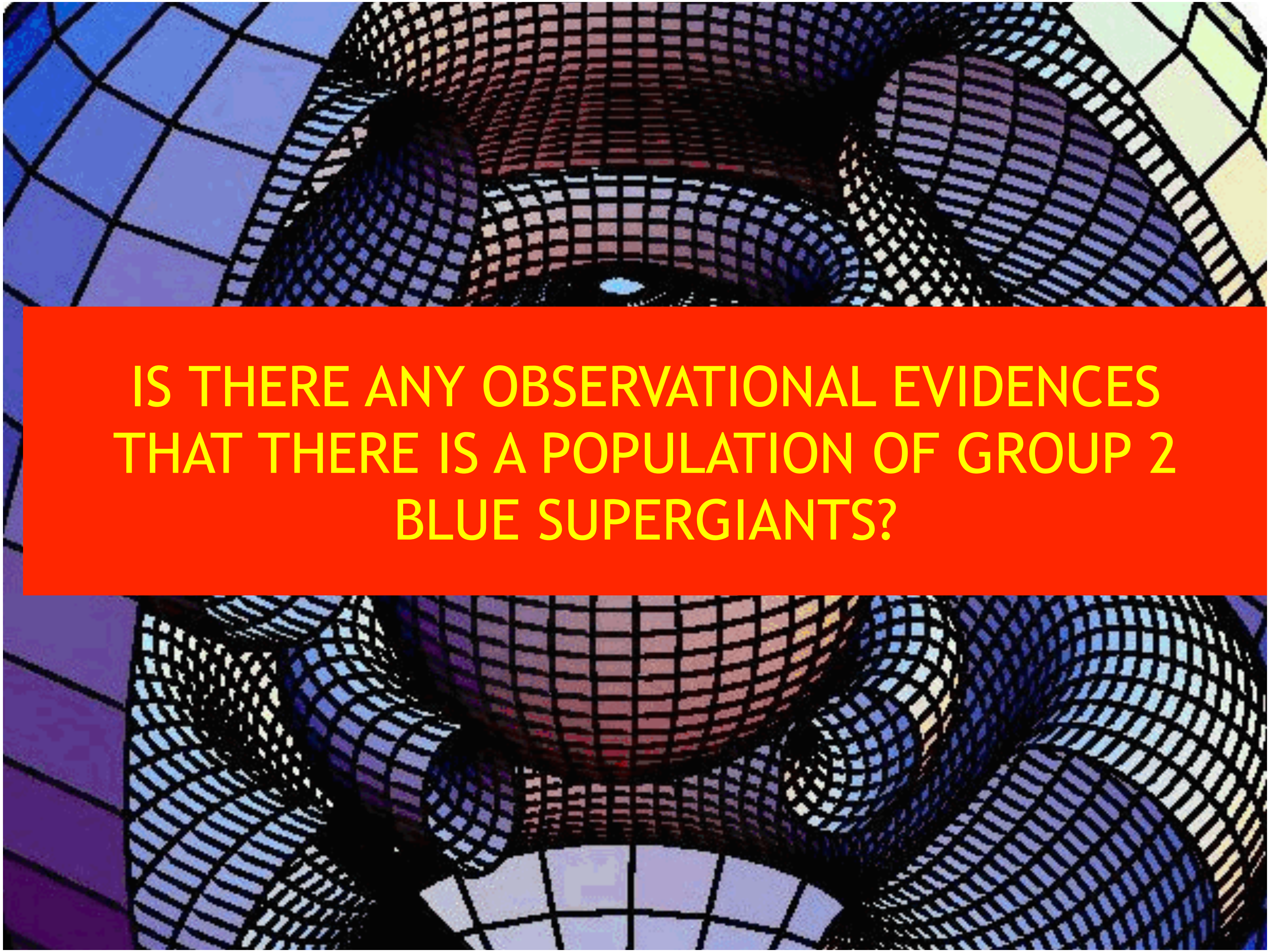


STAR EVOLVED TO THE BLUE AT THE VERY END OF ITS EVOLUTION
(RED→ BLUE SG MAY BE TRIGGERED BY A RLOF IN A CLOSE BINARY)
AT THE VERY END OF THE RSG PHASE

ANY STRONG MASS LOSSES SEEMS TO BE EXCLUDED DUE EITHER TO STELLAR WINDS OR MASS TRANSFER

→ PRODUCE TOO LARGE SCATTER OF THE FGWLR

ONE EXCEPTION → VERY STRONG MASS LOSS AT THE VERY END OF THE EVOLUTION

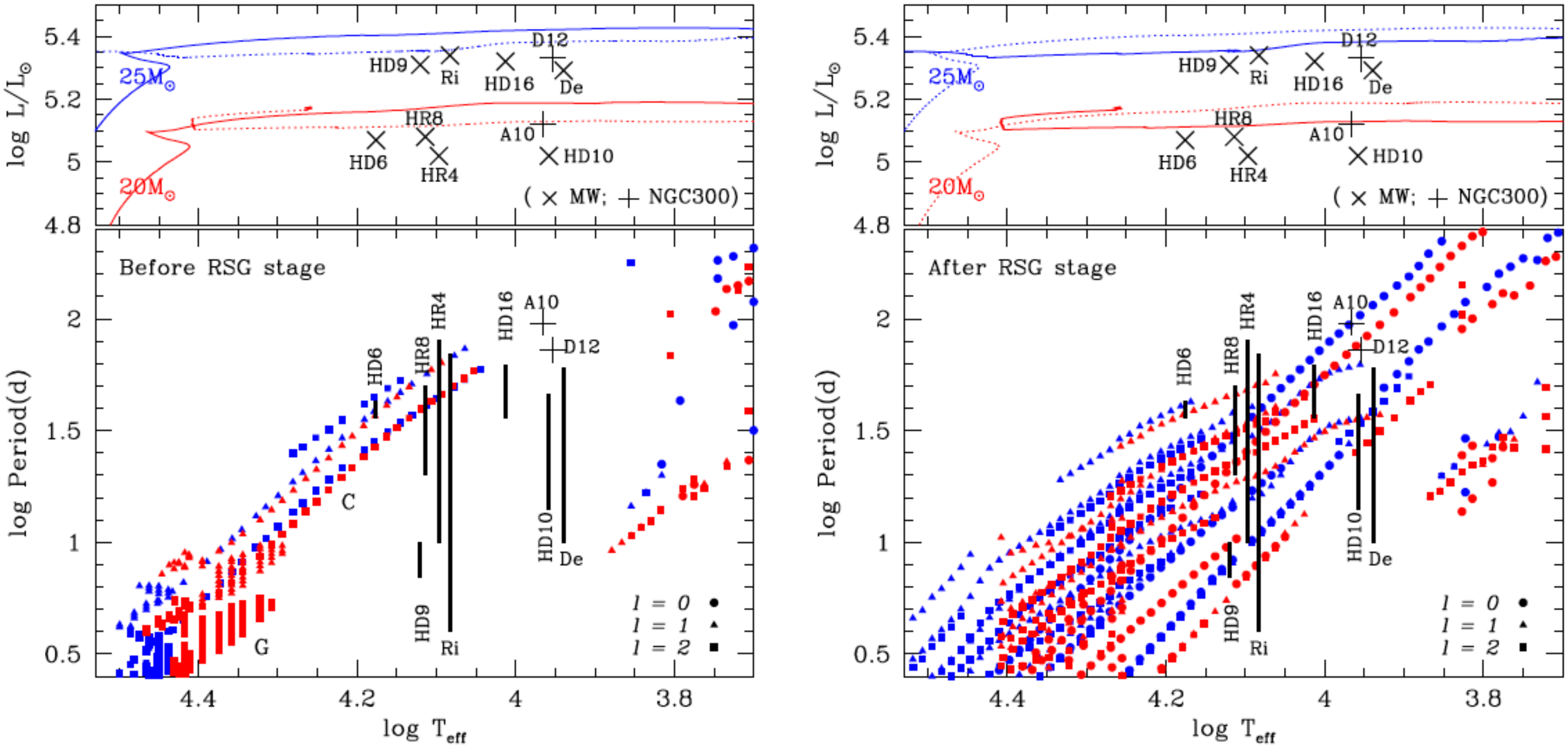


IS THERE ANY OBSERVATIONAL EVIDENCES THAT THERE IS A POPULATION OF GROUP 2 BLUE SUPERGIANTS?

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **433**, 1246–1257 (2013) doi:10.1093/mnras/stt796
Advance Access publication 2013 June 8

Evolution of blue supergiants and α Cygni variables: puzzling CNO surface abundances

Saio et al 2013



IN ADDITION TO PULSATION PROPERTIES
SURFACE ABUDANCES
SURFACE GRAVITIES
SHOULD BE CONSISTENT WITH A POST RED SUPERGIANT STAGE

SURFACE ABUNDANCES

Table 2. The surface H abundance and ratios of CNO elements for BSG models at $\log T_{\rm eff} = 4.0$

	BSG before RGB			BSG after RGB		
$M_{\rm i}$	$X_{\rm H}$	N/C	N/O	$X_{\rm H}$	N/C	N/O
14 (rot)	0.70	2.27	0.517	0.44	38.0	2.41
20 (rot)	0.68	2.46	0.609	0.42	39.7	2.94
25 (rot)	0.64	3.23	0.877	0.35	60.4	4.22

The initial values are N/C≡ $X_{\rm N}/X_{\rm C}$ = 0.289 and N/O≡ $X_{\rm N}/X_{\rm O}$ = 0.115, where $X_{\rm i}$ means mass fraction of element i.

Rigel N/C=2.0 N/O=0.46
Deneb N/C=3.4 N/O= 0.65

CNO-PUZZLE !

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRASL 439, L6–L10 (2014) doi:10.1093/mnrasl/slt16
Advance Access publication 2013 December 30

The puzzle of the CNO abundances of α Cygni variables resolved by the Ledoux criterion

Georgy et al. 2014

Table 1. Surface chemical ratio in the 'Schwarzschild' and 'Ledoux' models of a rotating 25 $M_\odot$ when the surface $\log(T_{eff}) = 4.0$ during the second crossing of the HRD, as well as the observed values for Rigel and Deneb (Przybilla et al. 2010).

Model/star	N/C	N/O	X_{He}
'Schwarzschild' (model)	57.86	4.17	0.635
'Ledoux' (model)	6.97	1.61	0.458
Rigel (observation)	2.0	0.46	0.32
Deneb (observation)	3.4	0.65	0.37

LEDOUX CRITERION FOR CONVECTION FAVORED.

BUT IS IT COMPATIBLE WITH THE SMALL SCATTER OF THE FGLR?

CONCLUSIONS

PRESENT ROTATING MODELS LIKELY STILL
MISS SOME EFFICIENT TRANSPORT MECHANISM
FOR THE ANGULAR MOMENTUM

AN INTERESTING GLOBAL CONSTRAINT ON STELLAR MODELS
→ THE SMALL OBSERVED SCATTER OF THE FGLR

SMALL SCATTER WELL REPRODUCED BY ROTATING MODELS
WITH NO OR ONLY VERY FEW GROUP 2 BSG

CONTINUOUS HIGH MASS LOSS RATES DURING
THE RSG PHASE IS NOT THE RULE

HOWEVER GROUP 2 BSG SEEMS TO EXIST→ WOULD
CORRESPOND TO ALPHA CYGNI VARIABLES.
HOW TO EXPLAIN THE PROPERTIES OF THESE STARS REMAINS
TO BE INVESTIGATED