Stellar evolution models with an experimental wind scheme

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Acknowledgements: Jorick Vink, Ines Brott, Norbert Langer, Raphael Hirschi, Jose Groh, Cyril Georgy

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Motivation

Stellar wind physics

Theory ⟷ Observations

The idea: constraints from stellar evolution

Motivation: overall mass-loss rates

Vink rates are widely adopted in stellar evolution model calculations, however:

- UV (Sundqvist+2011, Bouret+2012, Šurlan+2013)
- IR (Najarro+2011)
- X-ray (Cohen+2013, Leutenegger+2013, Rauw+2015)

diagnostics consistently yield a factor of ~2 **lower rates** than the Vink rates
(summarized by Sundqvist+2013, Puls+2015)

Motivation: behaviour around the bi-stability

Theoretical prediction:

As v_{inf} decreases at a given T_{eff}, $\dot{M}$ increases in response (Pauldrach & Puls 1990). FeIV $\longrightarrow$ FeIII more lines (Vink+1999)

- Increase in $\dot{M}$ is predicted to be a factor of ~ 5-7 (Vink+1999, 2000)
- Jump temperature is recently confirmed at much lower T_{eff} than previously predicted, at ~20 kK and ~9 kK (Petrov+2016)

Observations:

- There is no (or a modest) increase in $\dot{M}$ at the bi-stability (Crowther+2006, Markova & Puls 2008)
- v_{inf} decreases gradually $\rightarrow$ change in $\dot{M}$ should be gradual

Stellar evolution models of massive stars

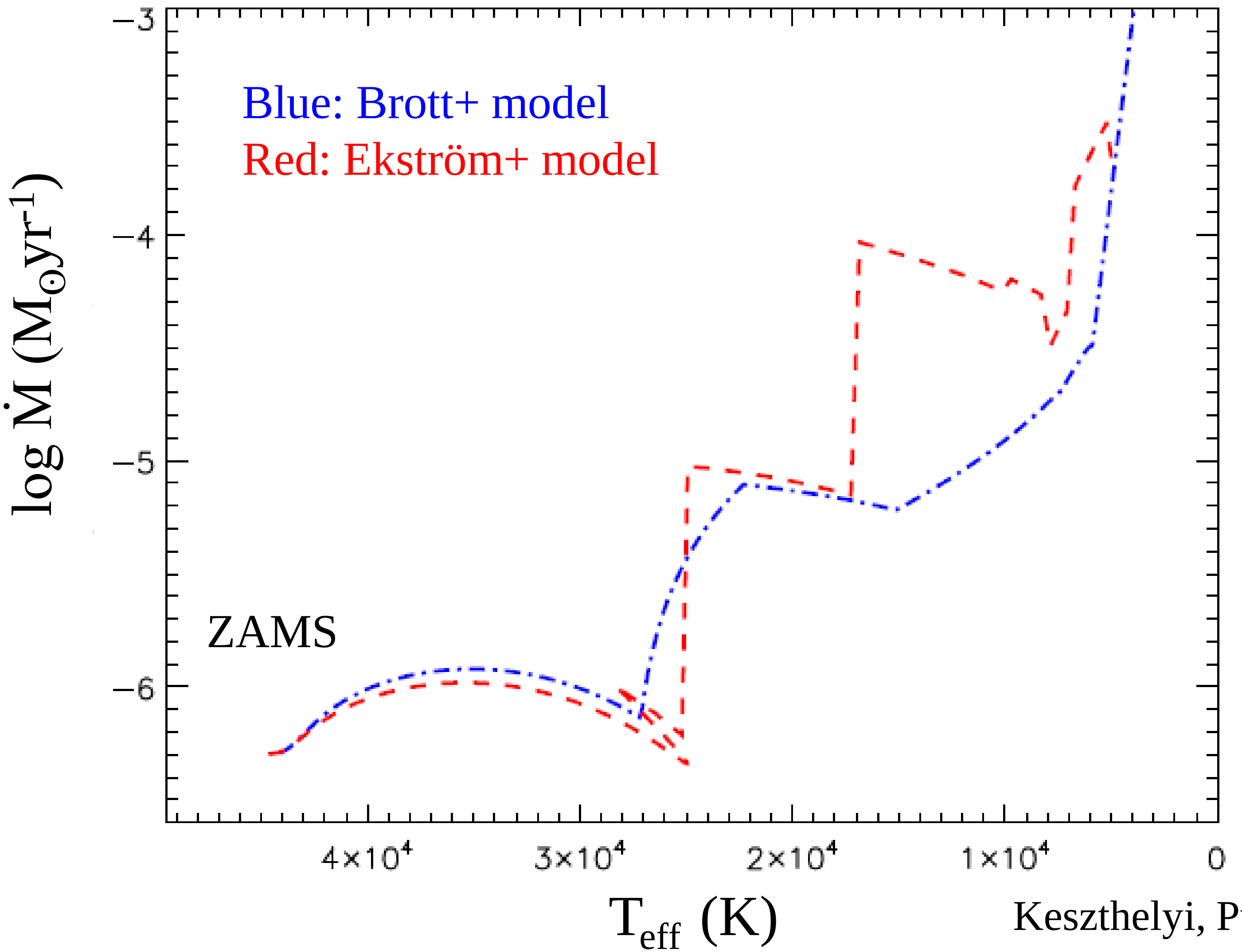
Well-known grids of models by

- Brott et al. 2011 (Bonn group, STERN) &
- Ekström et al. 2012 (Geneva group, GENEC)

adopted the Vink rates. However, ‘modifications’ in mass-loss rates need to be tested.

- Keszthelyi, Puls, Wade 2017 (MESA)

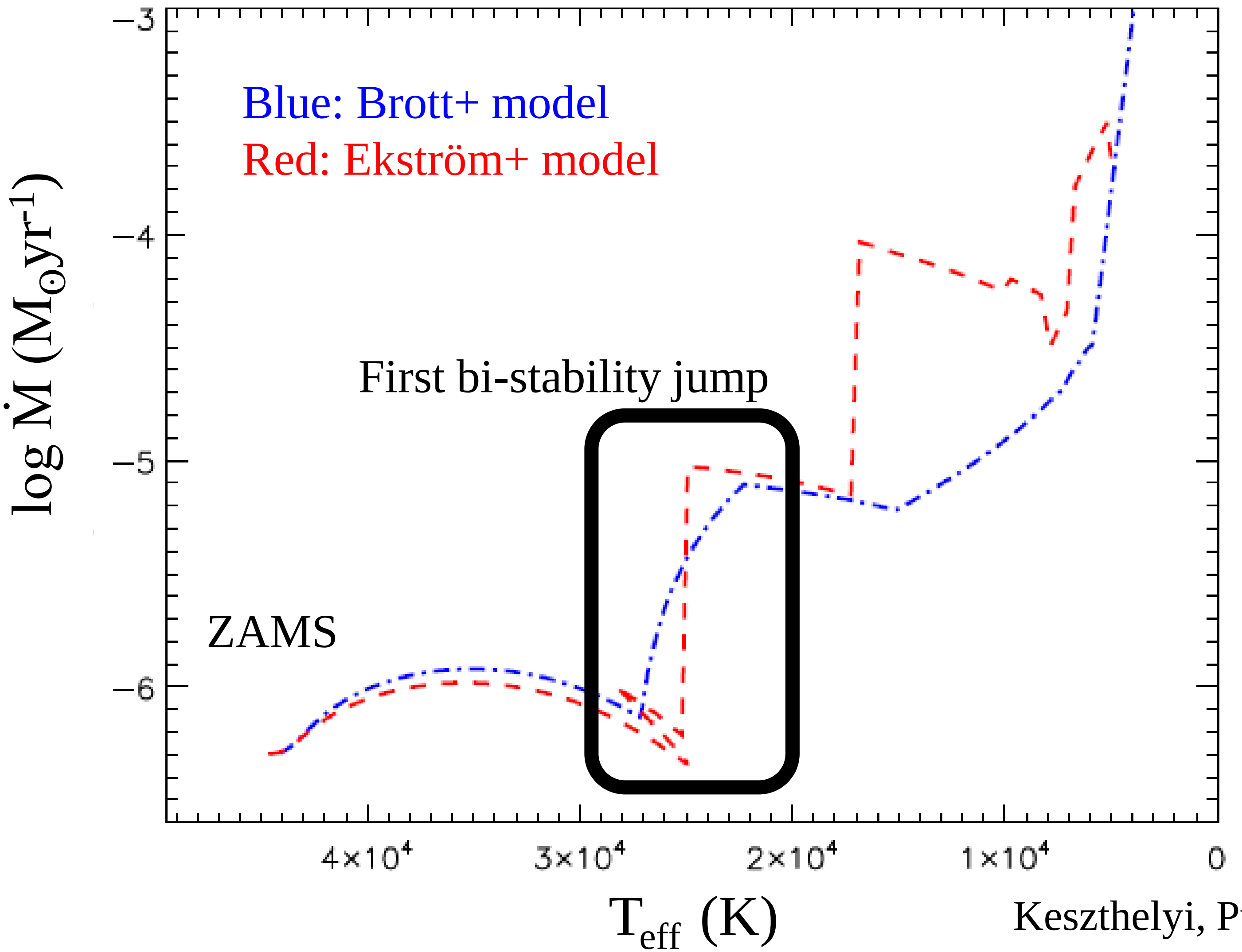
40 $M_\odot$ models
demonstration of the problem



Non-rotating, solar metallicity

Keszthelyi, Puls, Wade 2017

40 $M_\odot$ models



Non-rotating, solar metallicity

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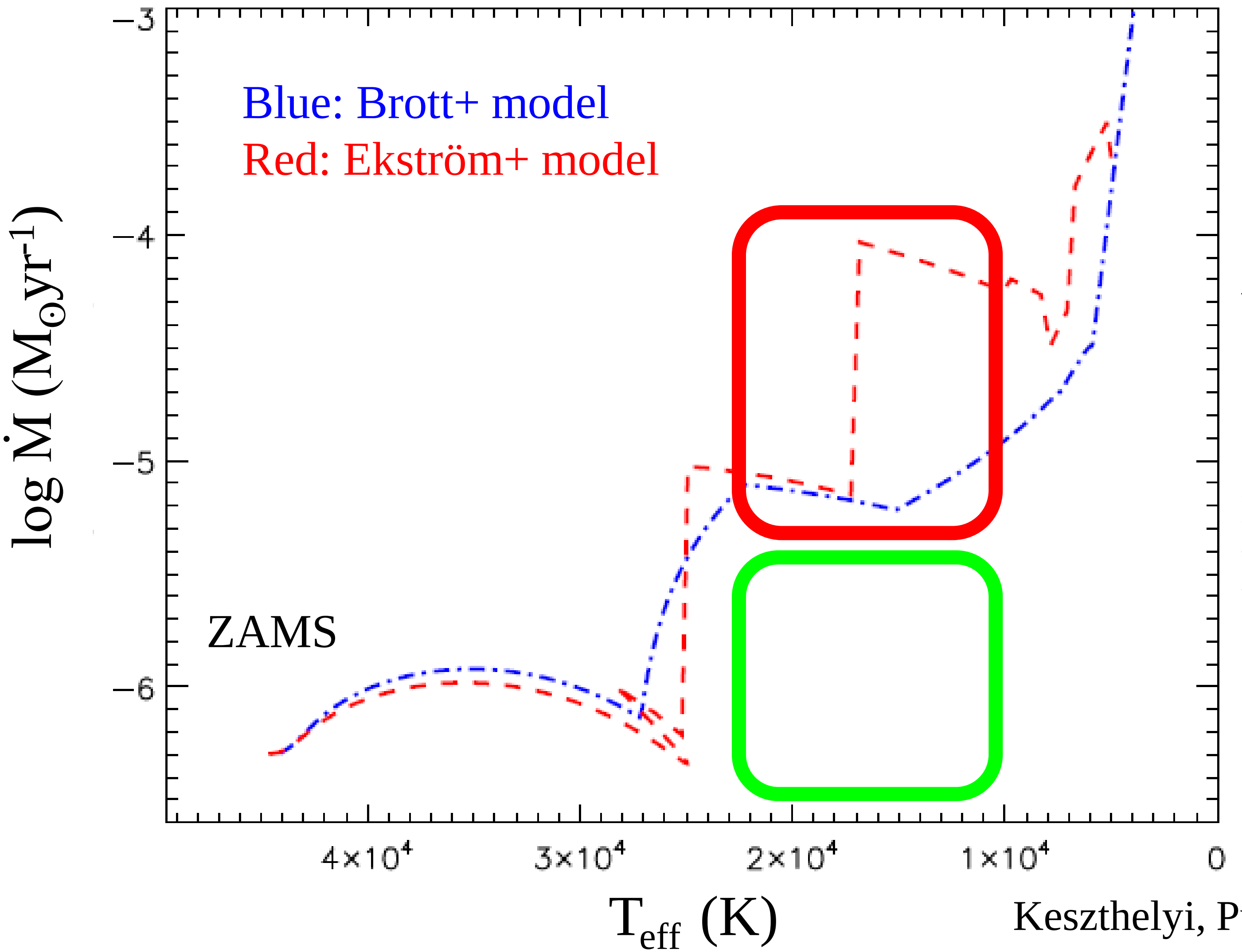
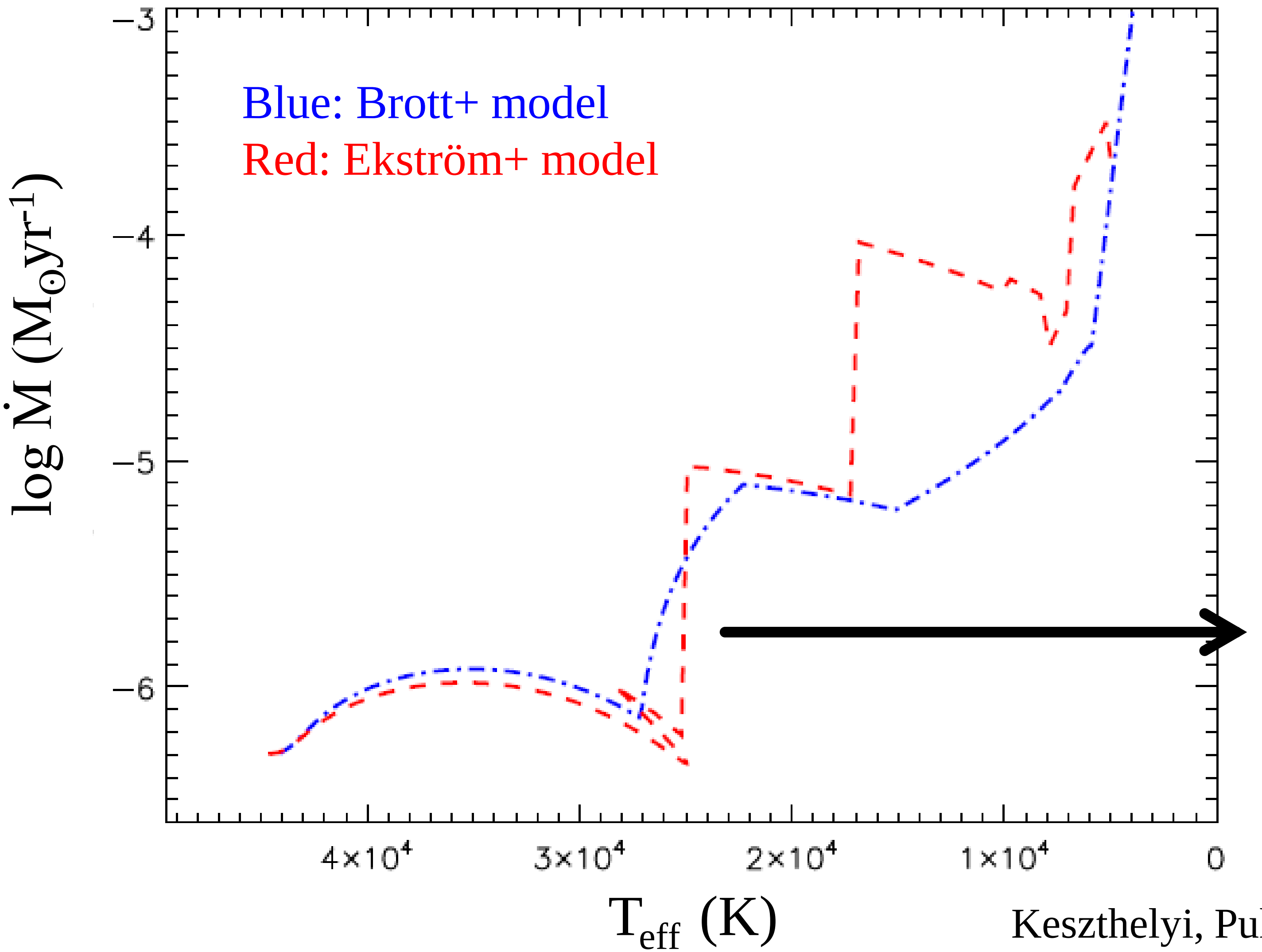
40 $M_\odot$ models: Overall rates



Overall mass-loss rates of typical late BSGs are 1-2 orders of magnitude larger than obtained from diagnostics!

Keszthelyi, Puls, Wade 2017

40 $M_\odot$ models: Jump size



I. Increase in $\dot{M}$ by a factor of 10-15!

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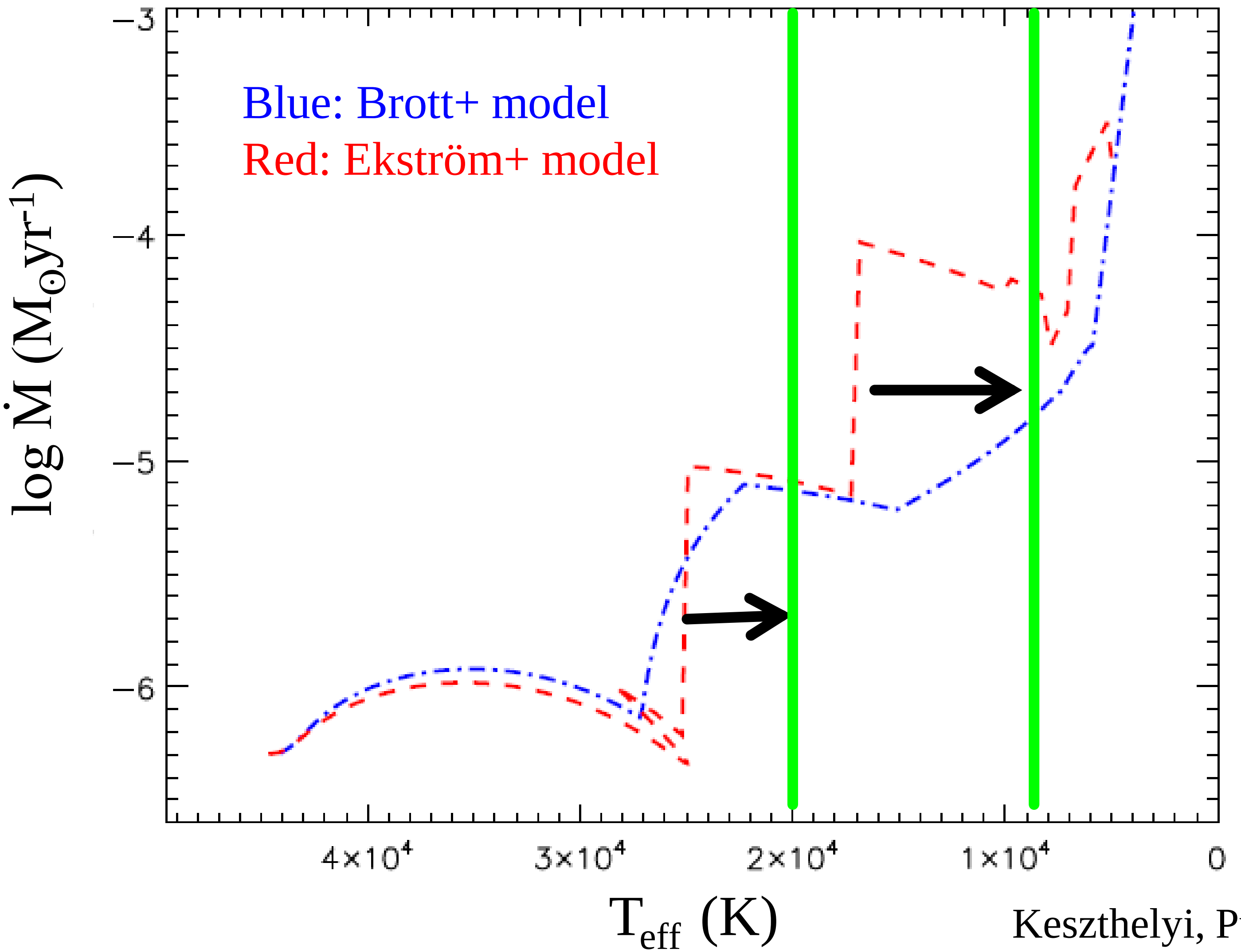
40 $M_\odot$ models: Jump temperature



II.

$T_{\mathrm{eff,\ jump1}}$ at ~25 kK (20 kK)

$T_{\mathrm{eff,\ jump2}}$ at ~17 kK (9 kK)

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An experimental wind routine
based on the Wind-momentum Luminosity Relation (WLR)

WLR: Kudritzki+1995, Puls+1996

$$\dot{M} v_\infty \left(\frac{R}{R_\odot}\right)^{1/2} \propto L^{1/\alpha'}$$

$$\log D_{mom} = x \log L + \log D_0 (T_{eff}, Z)$$

The possibility to include clumping corrected values!

$$\boxed{\log \dot{M} = \log D_{mom} - \log v_\infty - \frac{1}{2} \log\left(\frac{R}{R_\odot}\right)}$$

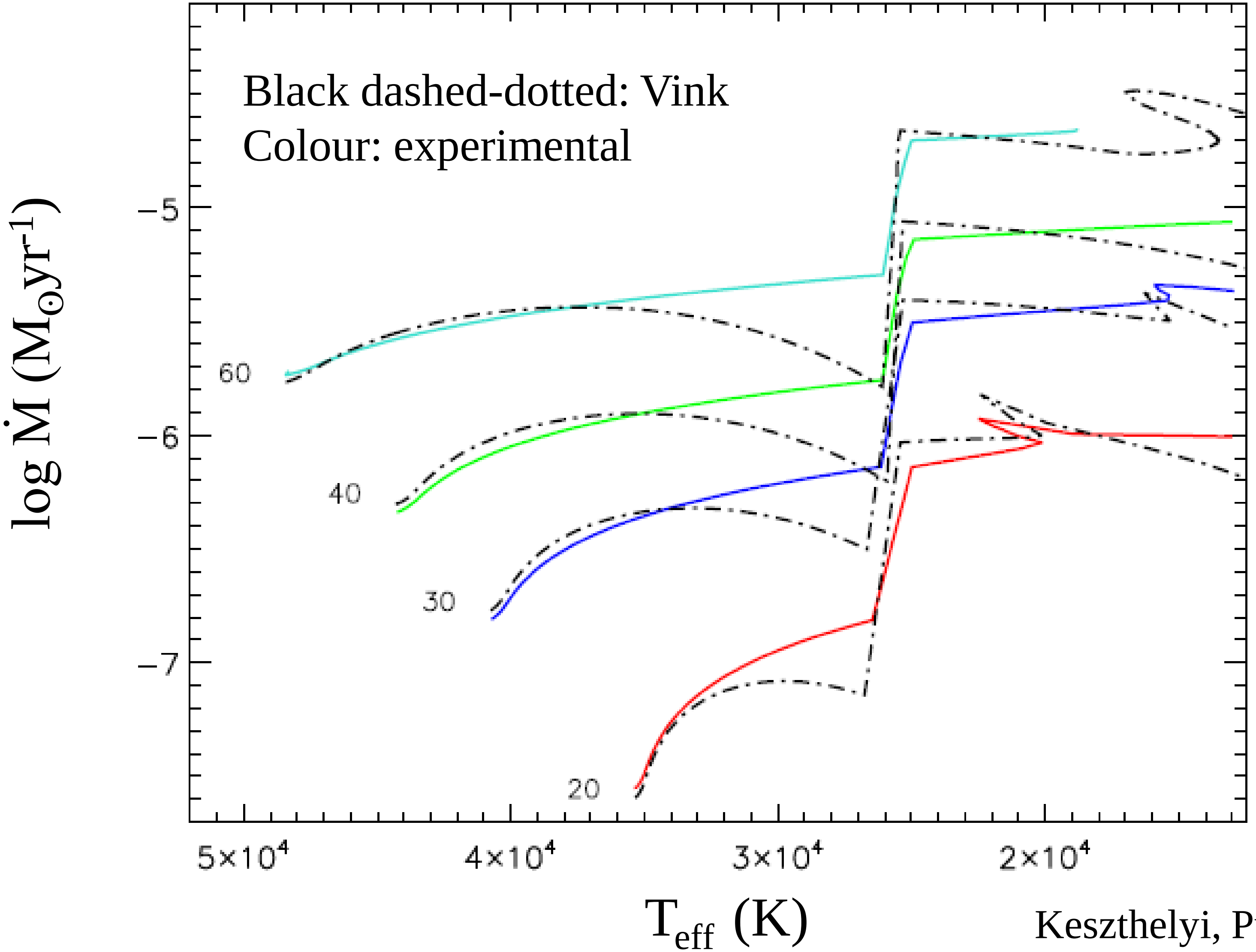
$$\frac{v_\infty}{v_{esc}} = f_{vinf}$$

$\dot{M}$ (final)= f_{scal} $\dot{M}$ (calculated)

$$v_{esc} = \left(2 \frac{GM}{R} (1 - \Gamma_e)\right)^{1/2}$$

The routine is available on the MESA repository website.

MESA model comparison



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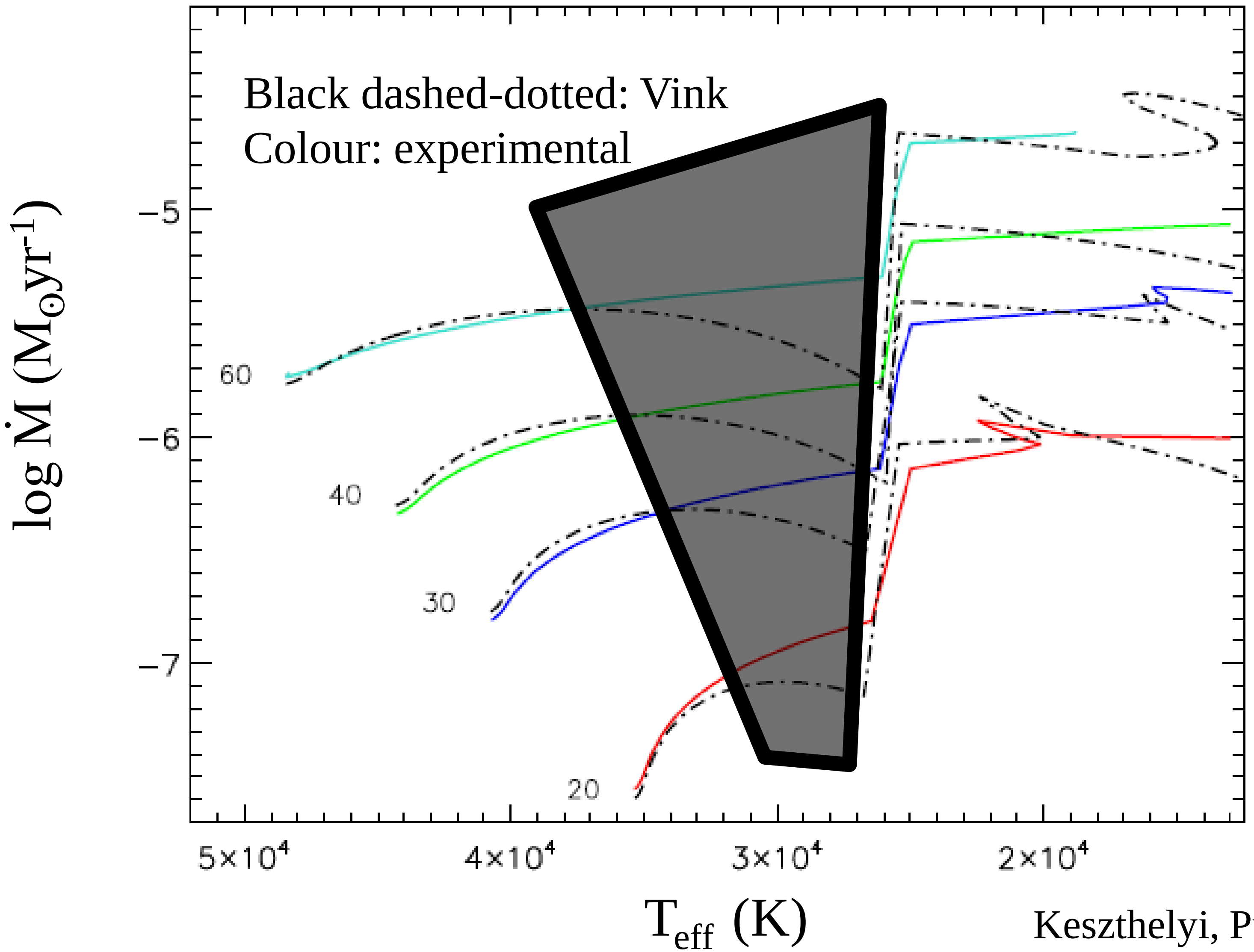
MESA model comparison



Pre bi-stability behaviour (PBB)

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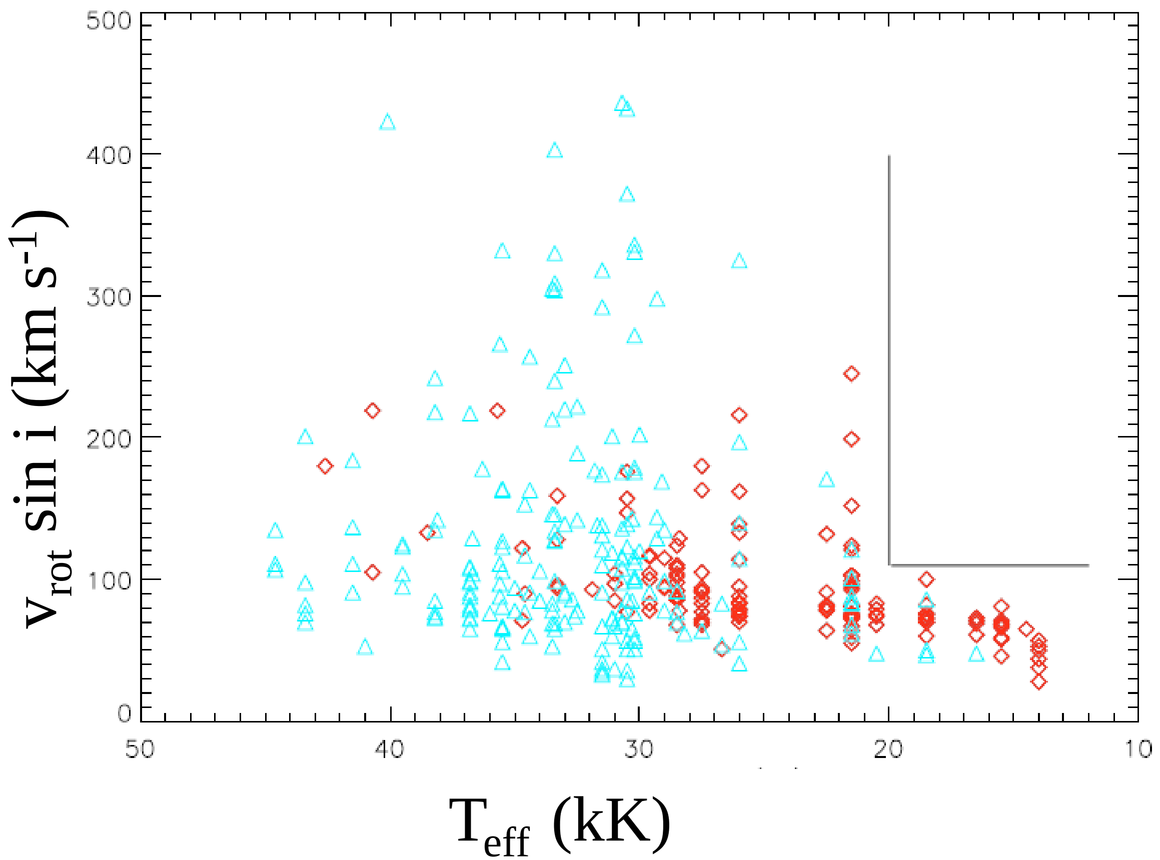
An observational constraint

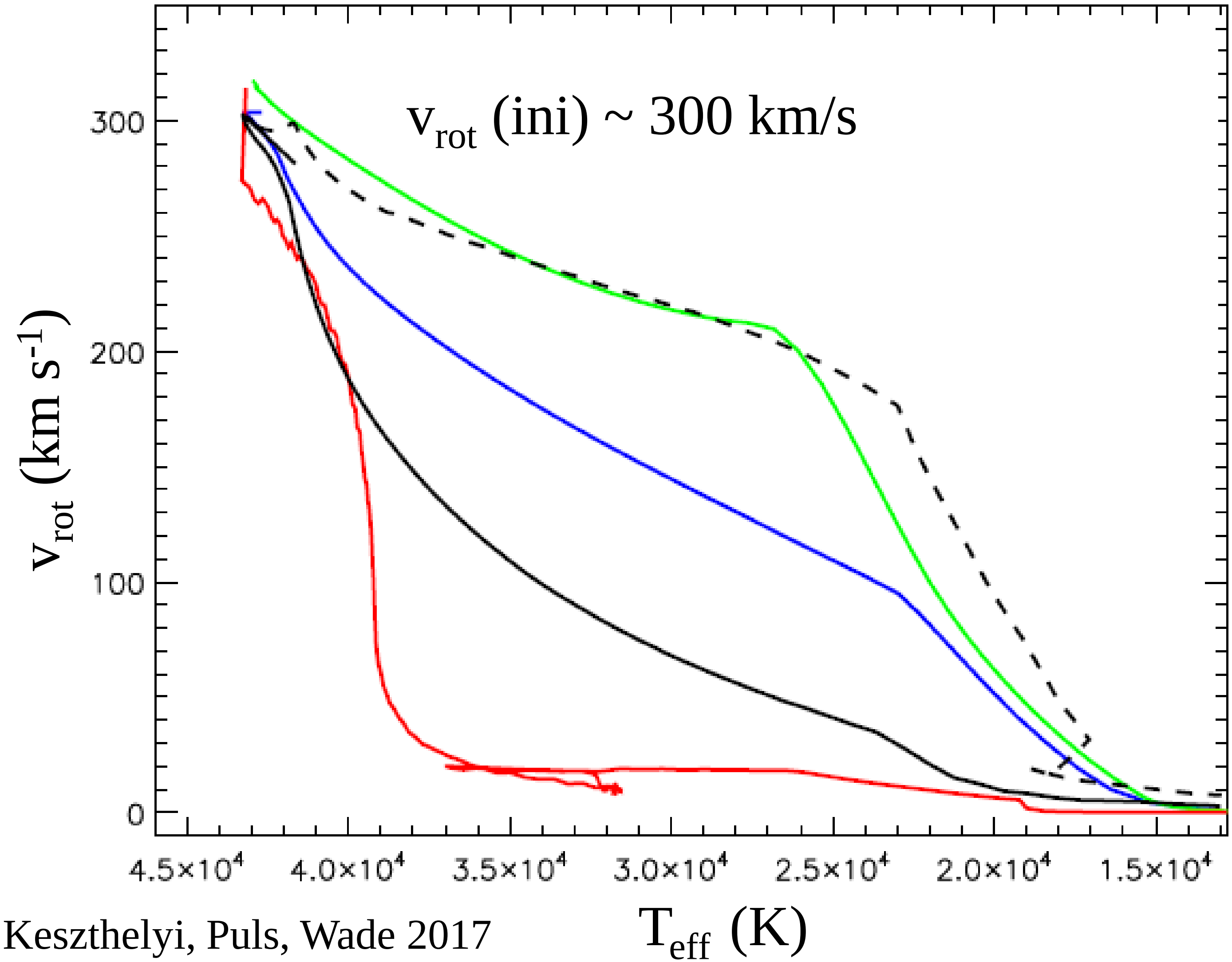
Howarth+1997 sample of Galactic stars



Vink+2010:
If there is a large jump in $\dot{M}$, then this can lead to slowing down the surface rotation via bi-stability braking (BSB).

Note: an alternative solution is to reconsider the initial rotational velocities of O-type stars (Simón-Díaz & Herrero 2014)

40 $M_\odot$ rotating models



Red: Ekström+ model uncoupled config. (differential rotation)

Green: Brott+ model coupled config. (solid body rotation)

Blue: MESA model similar to Brott+ model, f_{scal} = 1.0

Black: f_{scal} =1.0, but uncoupled

Black dashed: f_{scal} = 0.3, uncoupled

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Which models need BSB?

Code	Model	f_{scal}	Internal B field	BSB required for
MESA	MB1	1	yes	$<30\ M_\odot$
	MB2	1	no	$<30\ M_\odot$
	MB3	0.3	no	$<60\ M_\odot$
	MB4	0.3	yes	all models
STERN	Brott+	Vink	yes	all models
GENEC	Ekström+	Vink	no	no model

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- If $\dot{M}$ is reduced, then there is a need for BSB

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- If $\dot{M}$ is correct, then the evaluation of BSB depends on the internal angular momentum transport

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Conclusions

New stellar evolution models need to update their mass-loss routines for hot massive stars:

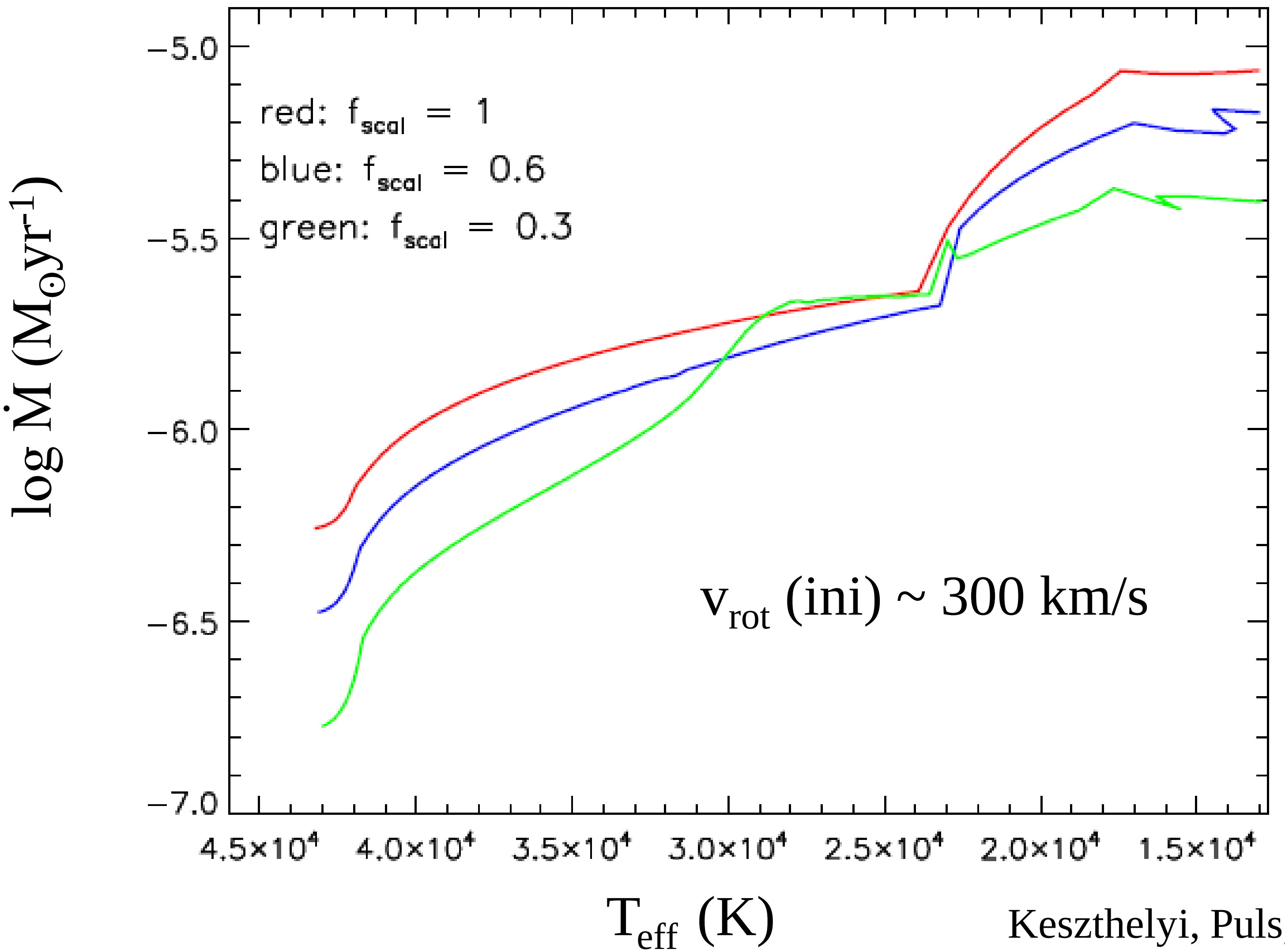
- The position of the jump (20 kK, 9 kK, see Petrov+2016)
- The gradual change in $\dot{M}$ (e.g. Crowther+2006)

A dichotomy in the solution:

- either early $\dot{M}$ is overpredicted, and then there is a need for a large jump at the bi-stability, or
- early $\dot{M}$ is correct, and thus a large jump can be avoided (but model dependent)

Additional slides

40 $M_\odot$ rotating models with an experimental wind scheme



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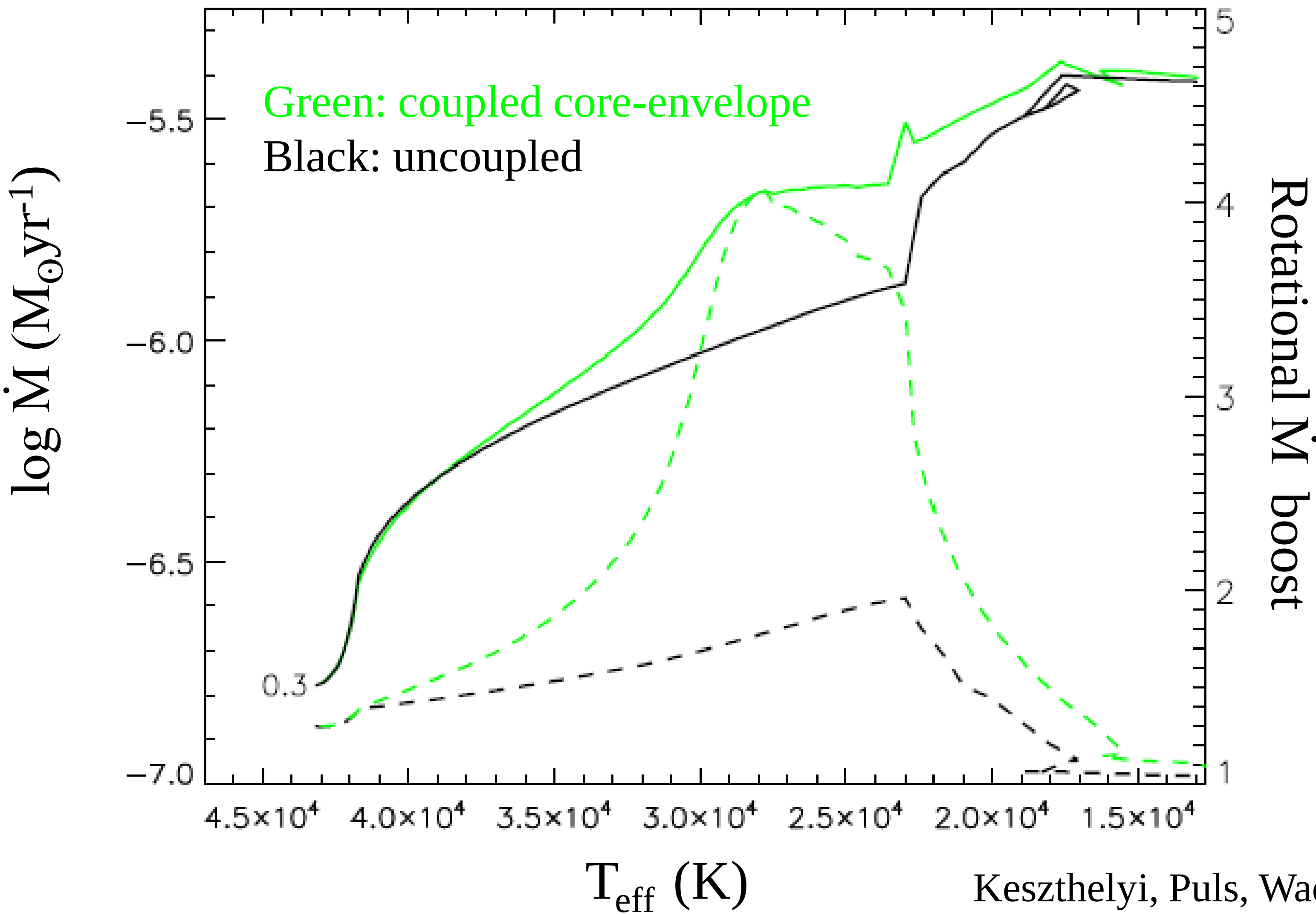
40 $M_\odot$ rotating models with an experimental wind scheme



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An experimental wind routine

based on the Wind-momentum Luminosity Relation (WLR)

$$\boxed{\log \dot{M} = \log D_{mom} - \log v_\infty - \frac{1}{2}\log\left(\frac{R}{R_\odot}\right)}$$

WLR: Kudritzki+1995, Puls+1996

$$\log D_{mom} = x \log L + \log D_0$$

Reference	$x = \frac{1}{\alpha'}$	$\log D_0$
Kudritzki & Puls (2000), OI	1.51	20.69
Vink et al. (2000), OB	1.83	18.68
Repolust et al. (2004), OI, *cl	2.00	17.98
Markova et al. (2004), O, "case D"	1.90	18.58
Martins et al. (2005), O	3.15	10.29
Mokiem et al. (2005), O, early B	1.86	18.71
Mokiem et al. (2005), O, early B, *cl	1.58	20.16
Mokiem et al. (2007b), O, early B	1.84	18.87
Mokiem et al. (2007b), O, early B, *cl	1.56	20.23

The routine is available on the MESA repository website.