The CSM of massive stars

Norbert Langer (Bonn University)

Envelope inflation

The stellar Eddington limit

acceleration through photon momentum balances gravity

$$\frac{\kappa F}{c} = g$$

$$\Rightarrow \boxed{L_{\mathrm{Edd}} = \frac{4\pi c G}{\kappa} M}$$

$$\Gamma = L/L_{\mathrm{Edd}}$$

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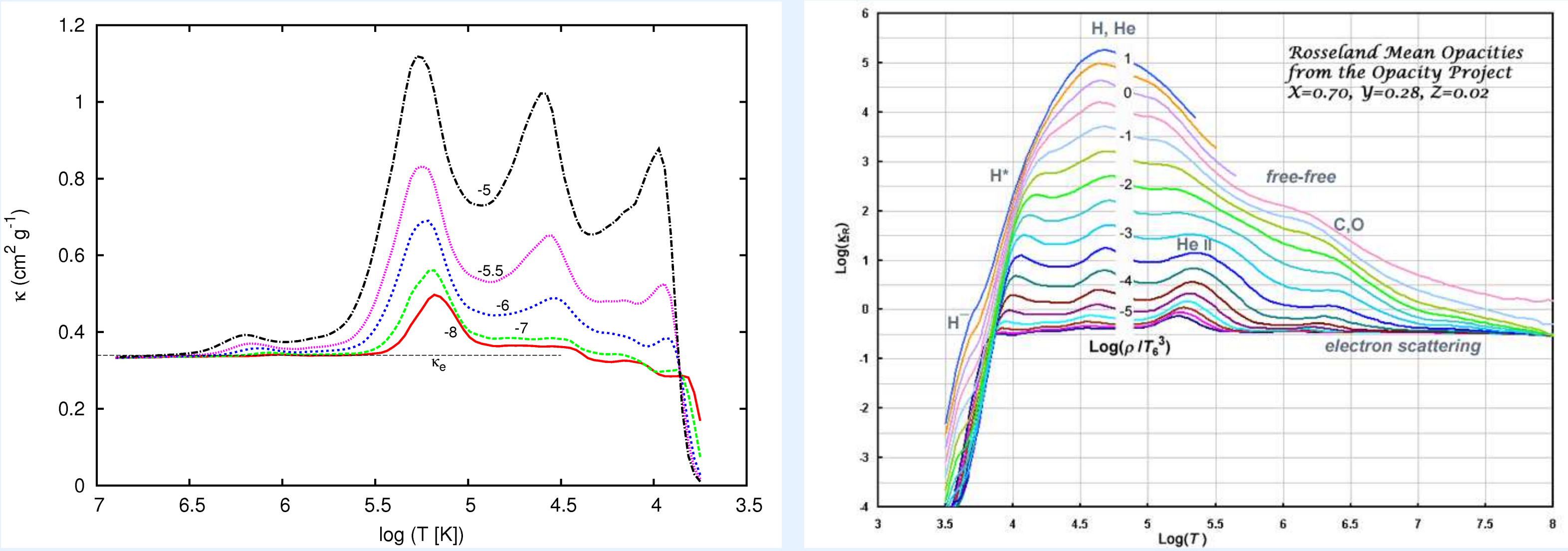
$L > L_{\rm Edd} \Rightarrow$?

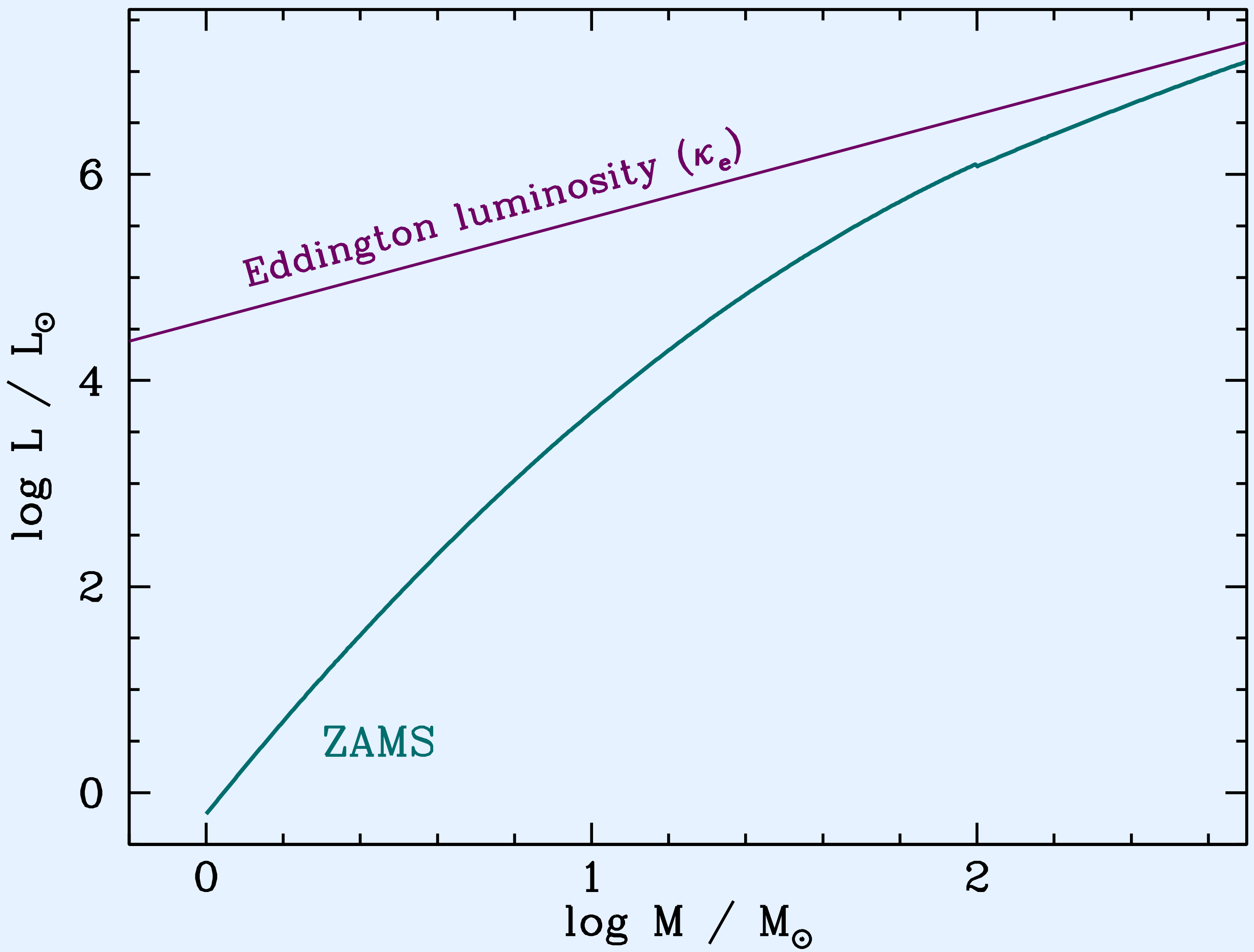
Opacity

complete opacity: e^{-}-scattering + ff + bf + bb + . . .

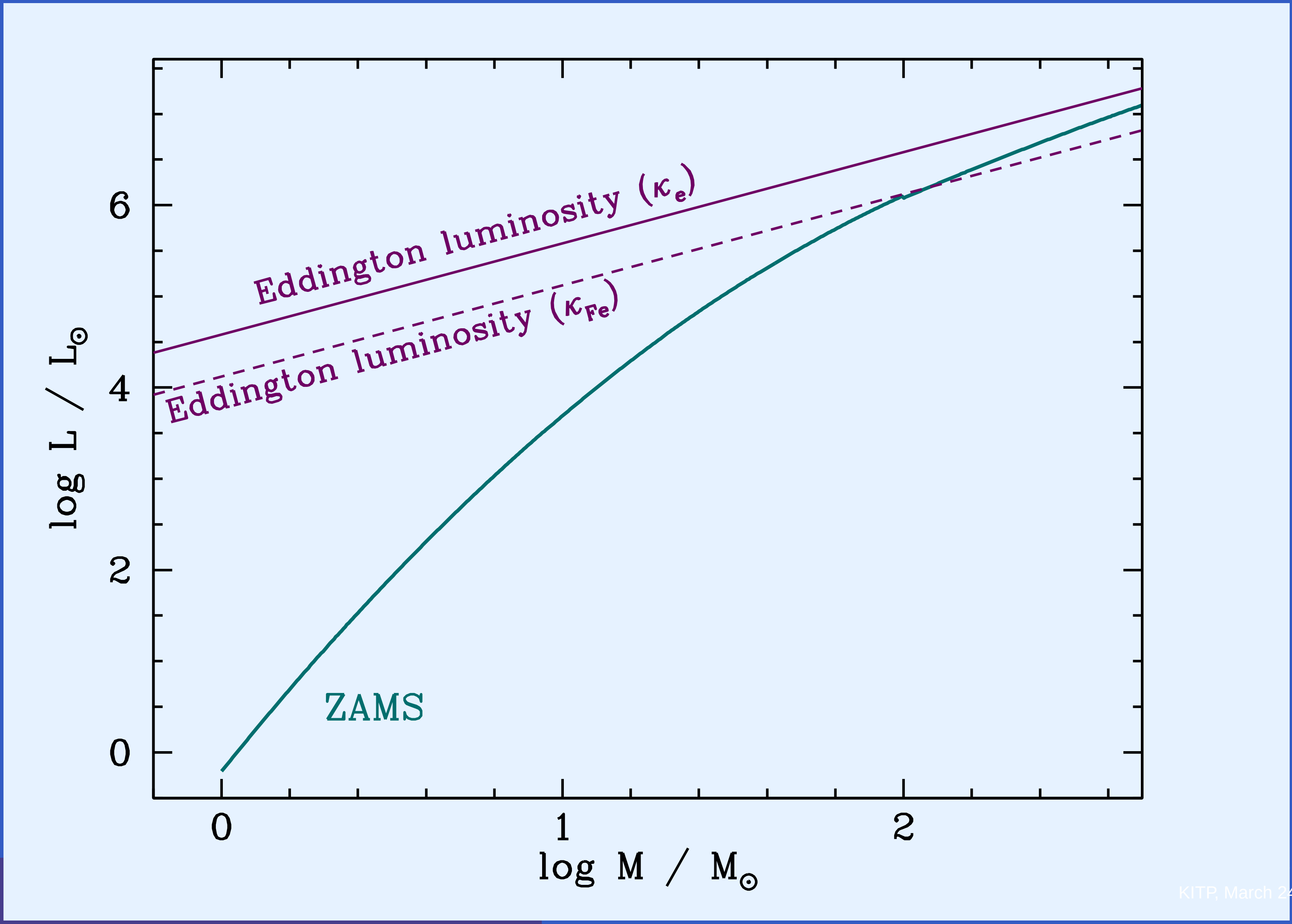


- massive/hot stars: $\kappa_{\rm Fe} \simeq 2\kappa_{\rm e}$
- low mass/cool stars: $\kappa_{\rm H} \simeq 1000\kappa_{\rm e}$
- atomic opacity increases with density

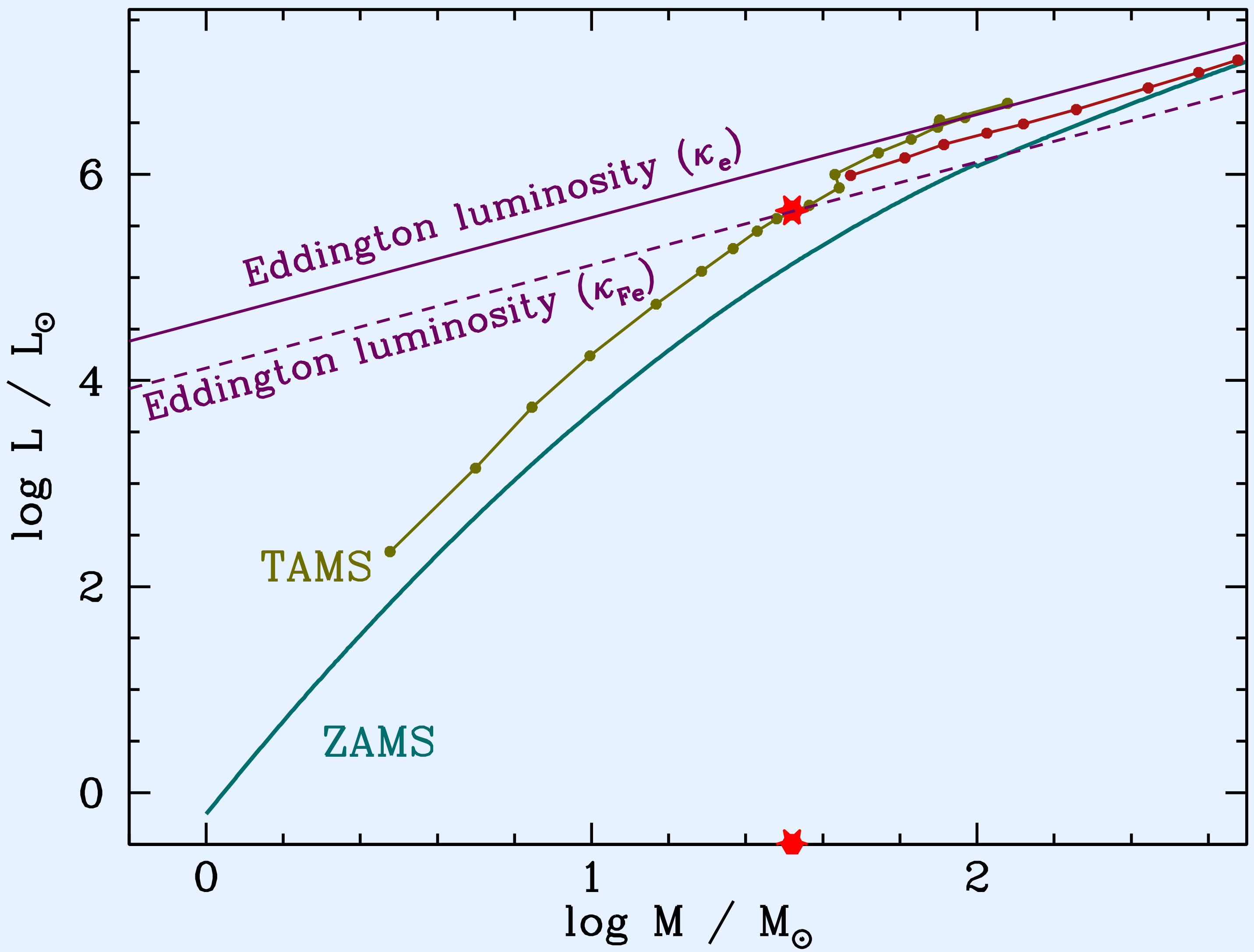
$M - L_{\mathrm{Eddington}}$ relation



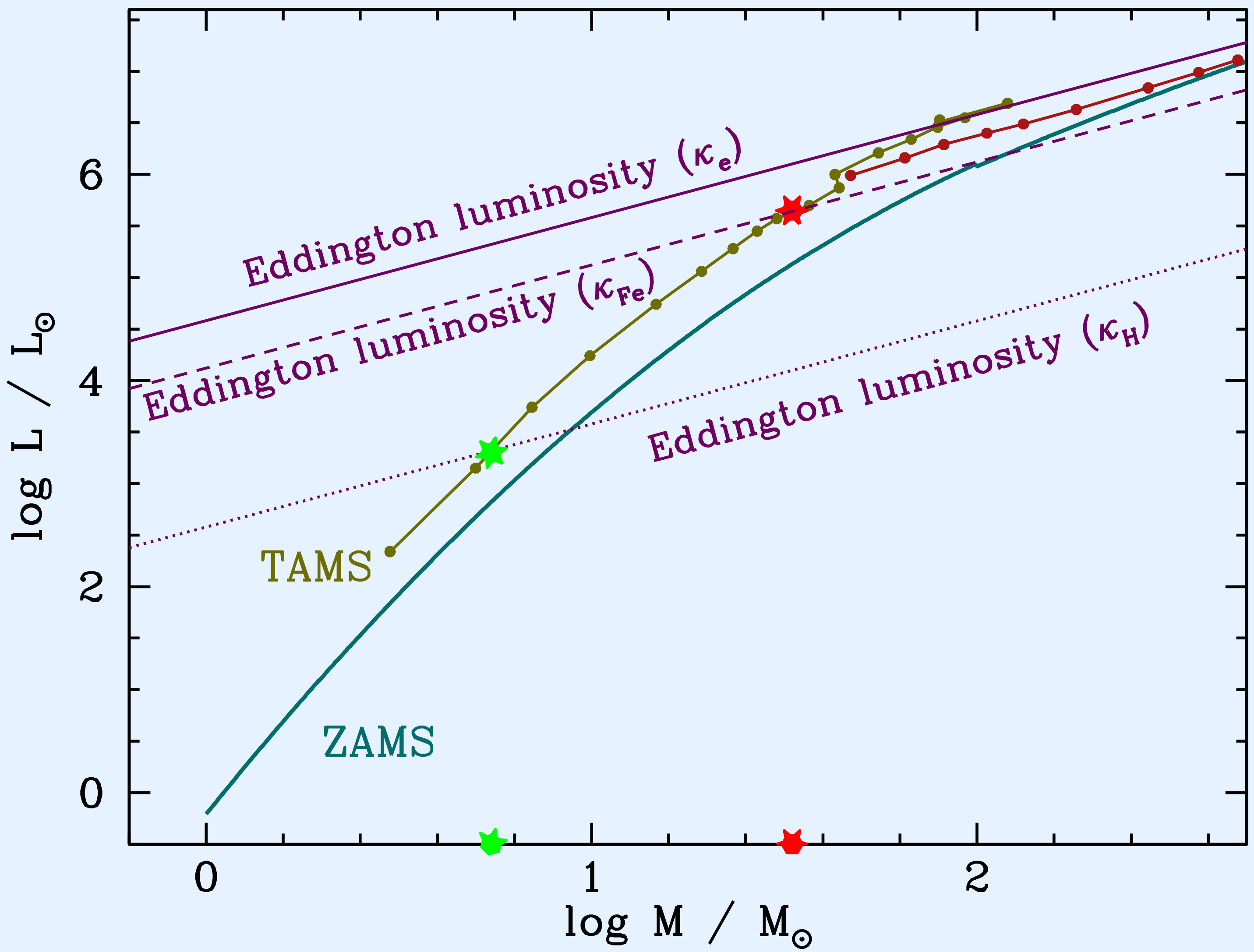
$M - L_{\mathrm{Eddington}}$ relation



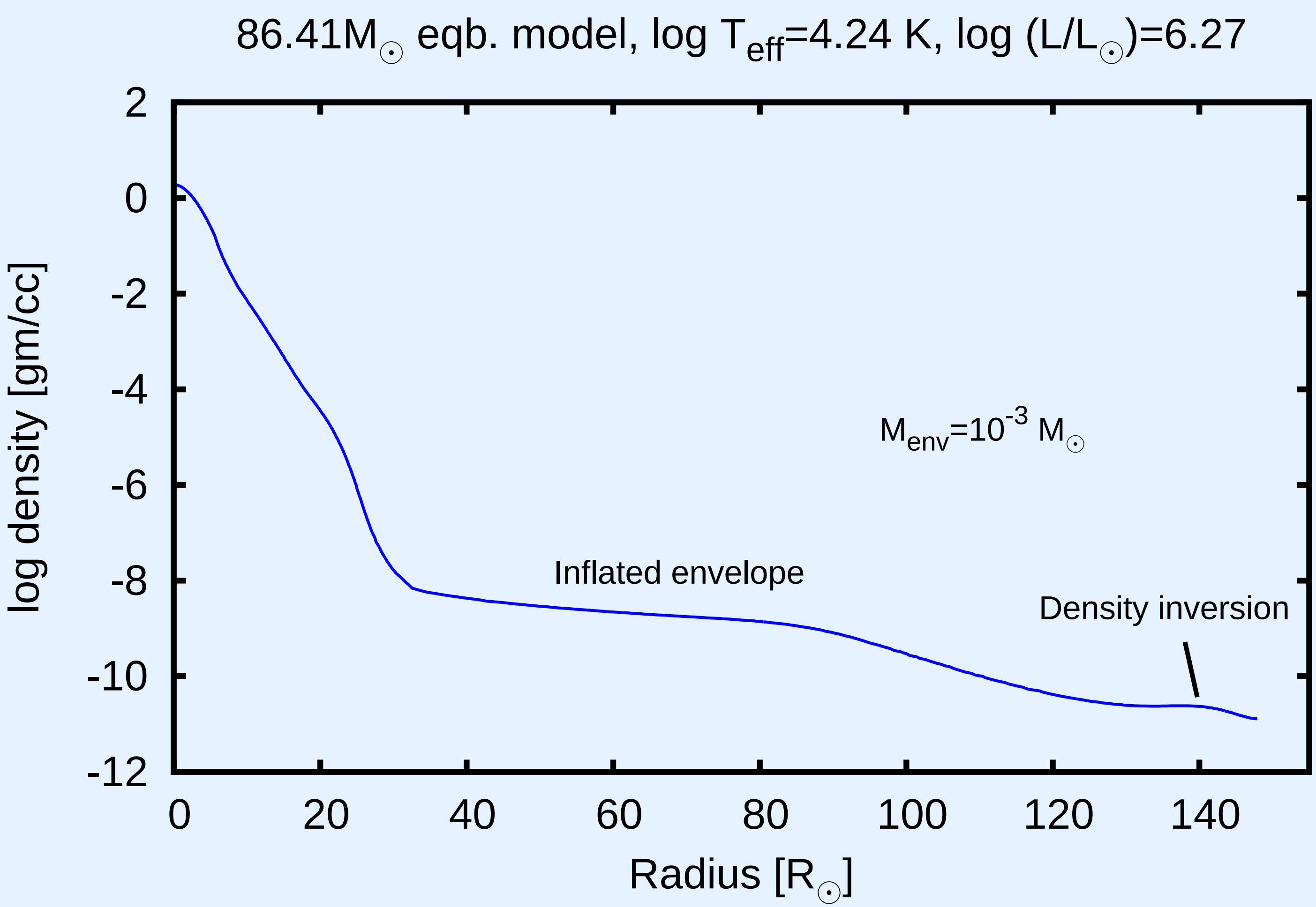
$M - L_{\rm Eddington}$ relation



$M - L_{\text{Eddington}}$ relation



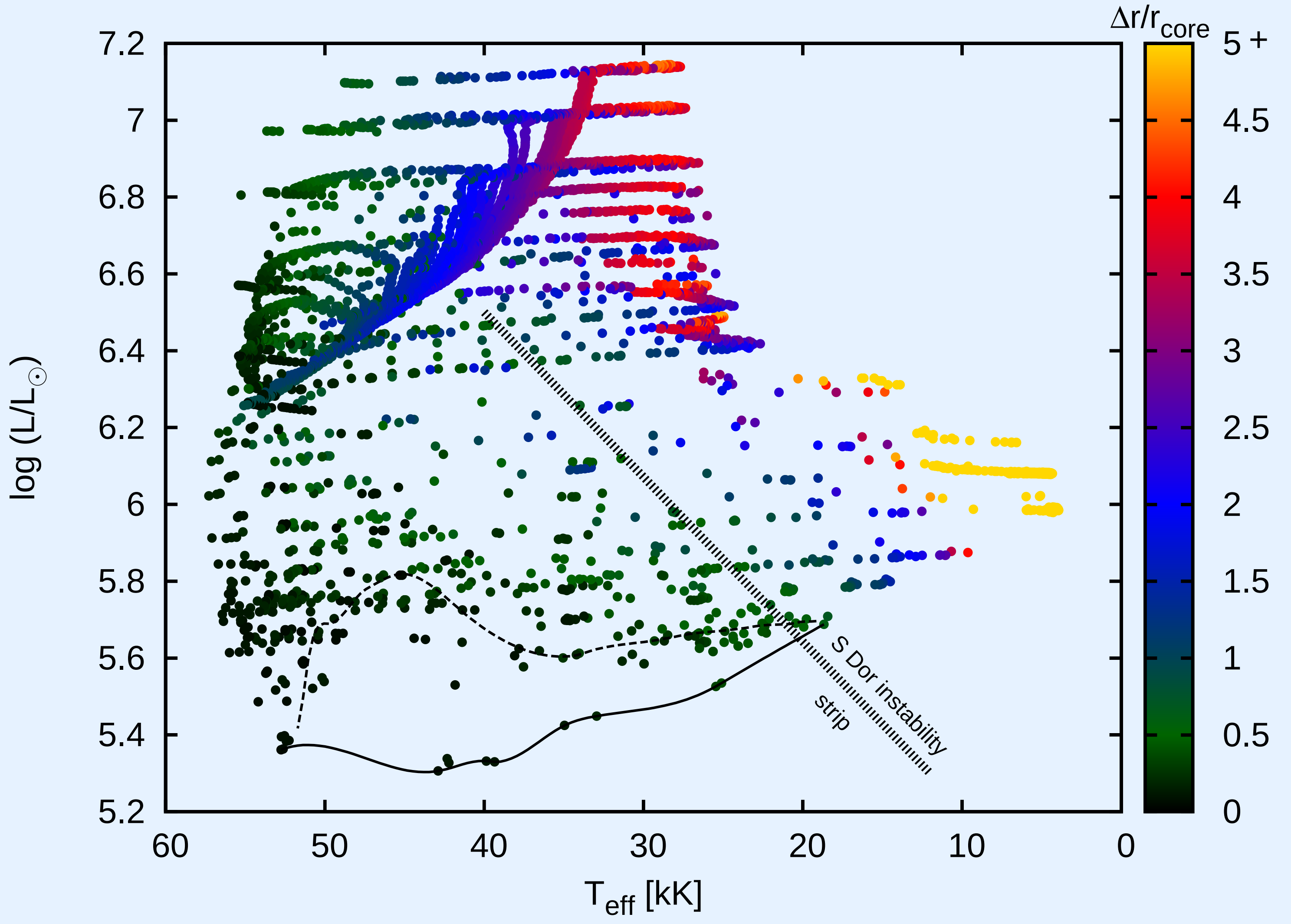
Inflation: 1D



Sanyal et al. 2015

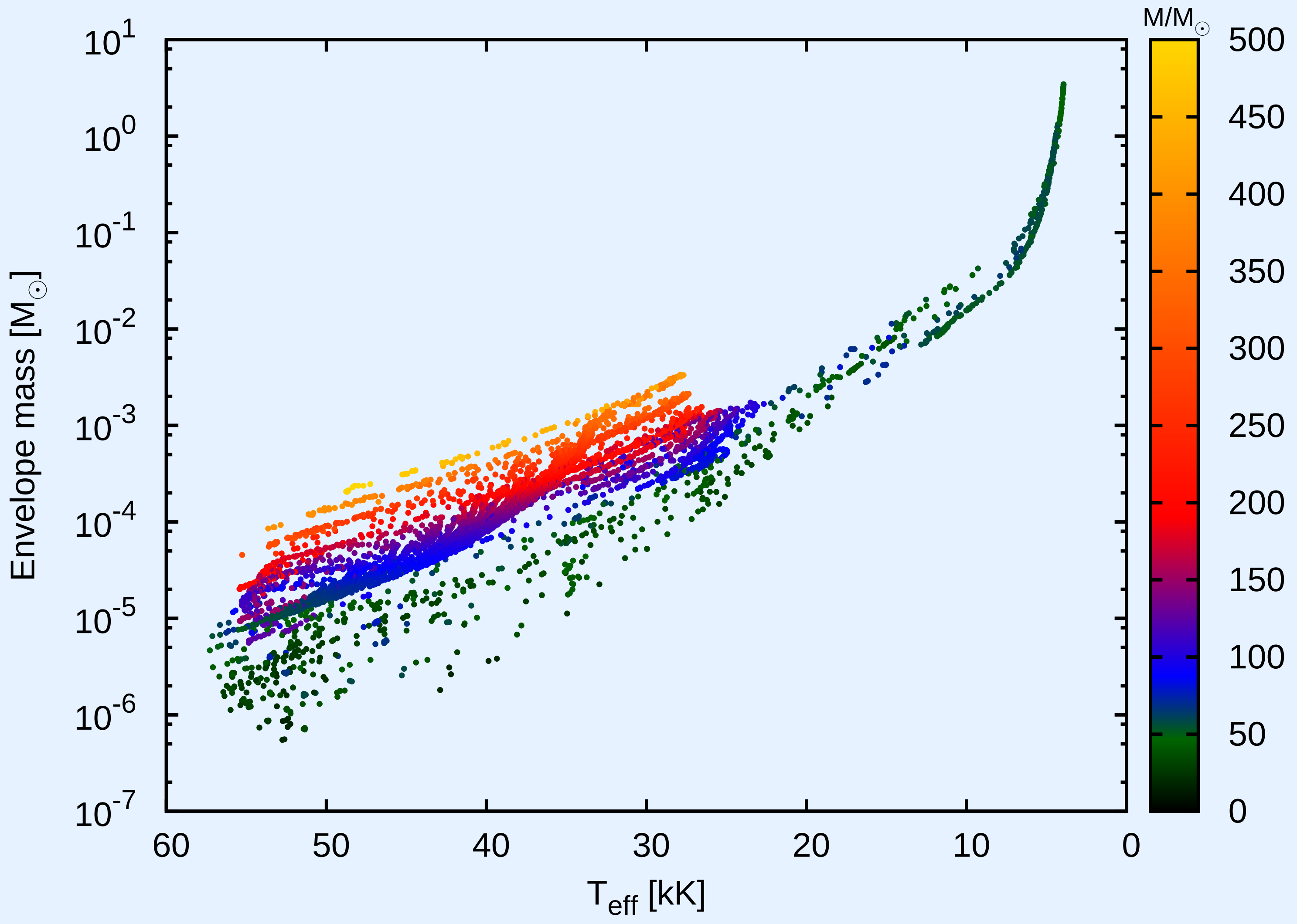
3D $\Rightarrow$ Jiang, Cantiello, et al. 2016, 2017

Eddington-limit → Inflation



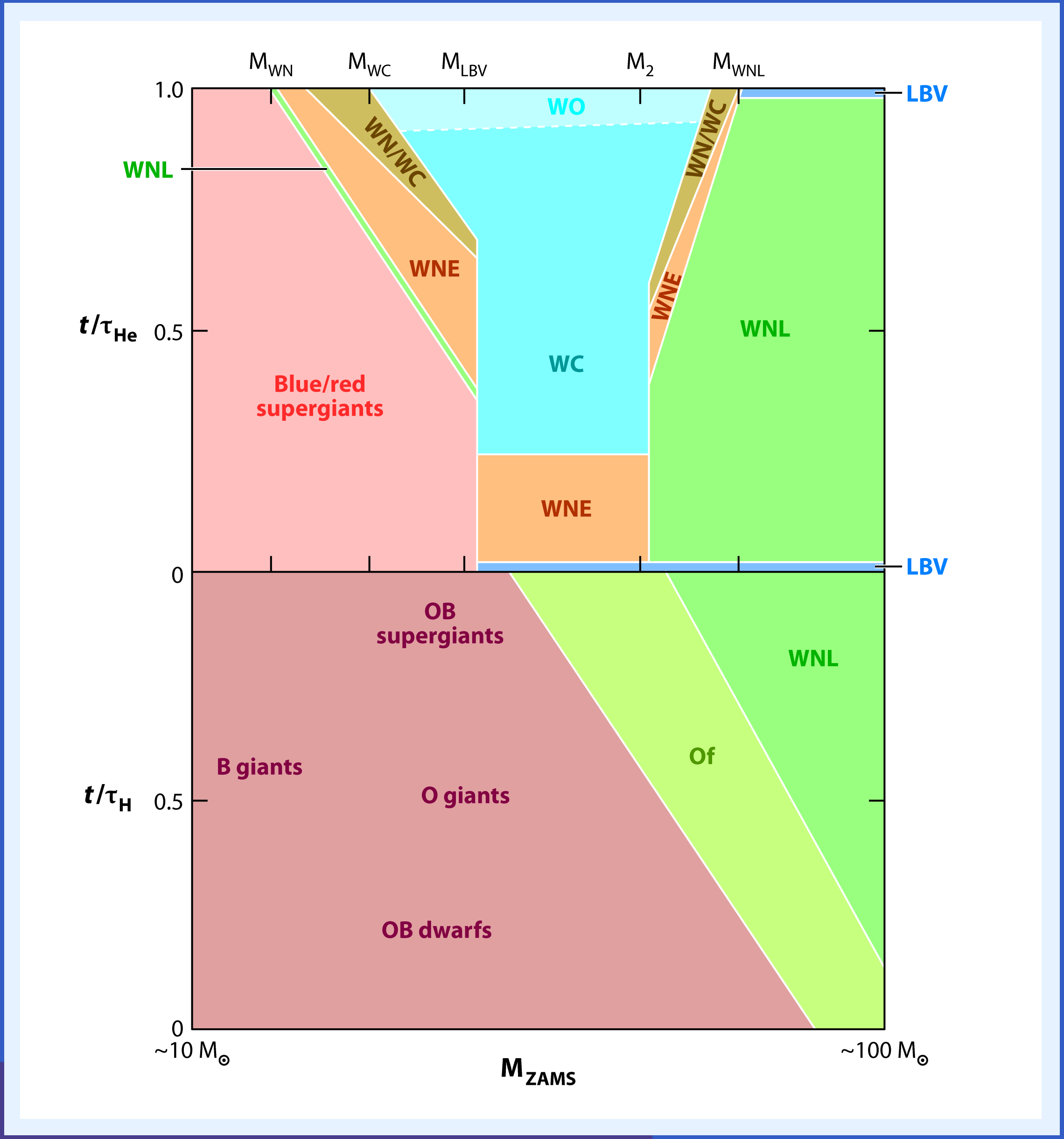
Sanyal et al. 2015

inflated envelope masses



Sanyal 2015

Fast evolution → loss of envelope!?

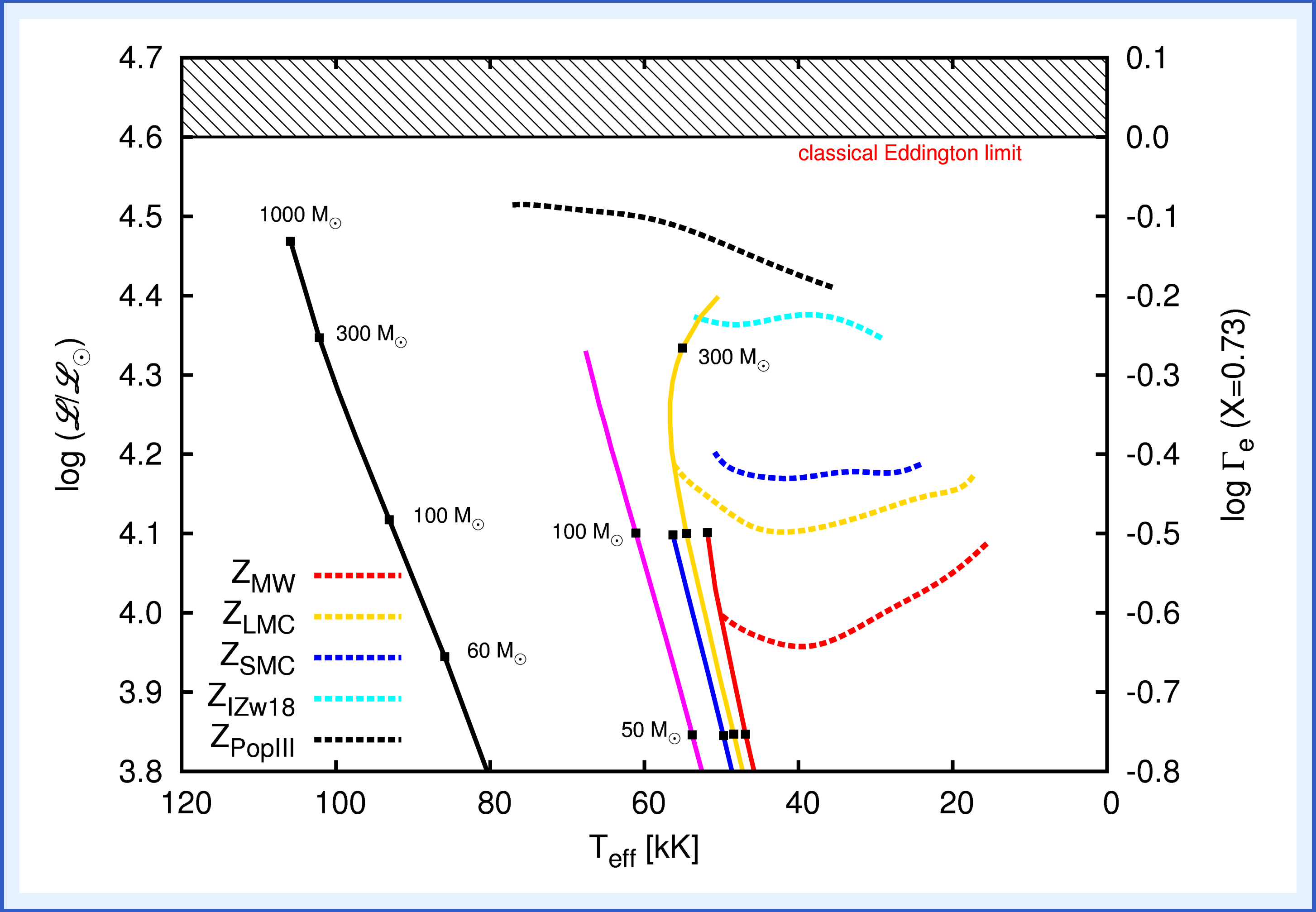


Langer 2012, ARAA

LBV eruptions...

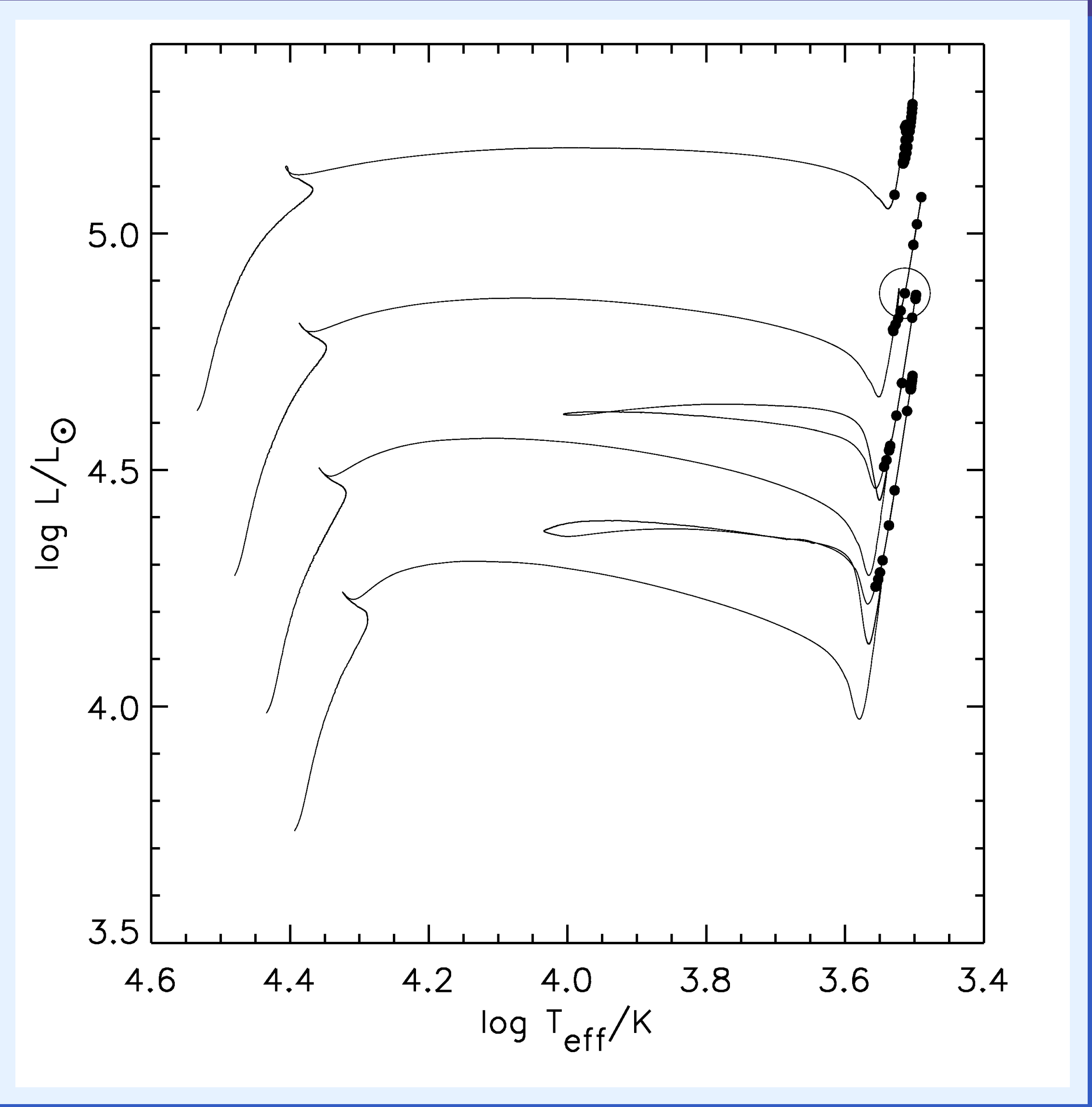
- ... do NOT happen for all stars at the Eddington limit!
- ... might happen when stars at the Eddington limit are driven out of TE:
- $\rightarrow$ ... after core H-exhaustion
  needed to explain the LBVs we see Vink et al. 2007
- $\rightarrow$ ... after core He-exhaustion:
  needed to explain pre-SN LBVs Smith et al. 2012
- ... do or don't require binarity! Smith $\leftrightarrow$ Humphreys
  η Carinae, HR Carinae Rivinius et al. 2015, ...
- ... are helped by rotation? ($\rightarrow$ SG B[e]?)

Inflation: metallicity dependance



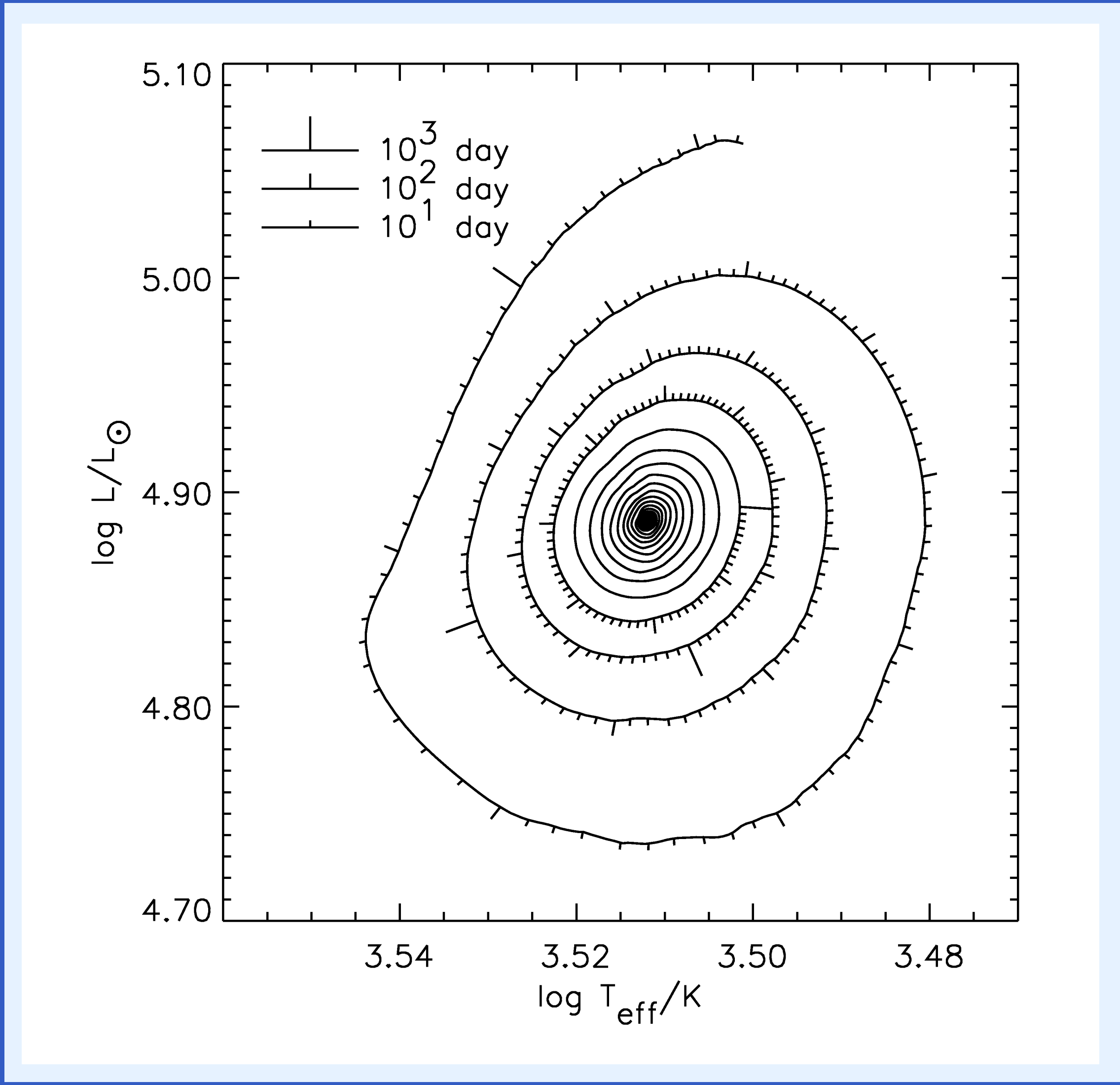
Sanyal et al. 2017

Post-MS: Red Supergiants



Heger et al. 1997

Fast evolution → loss of envelope?

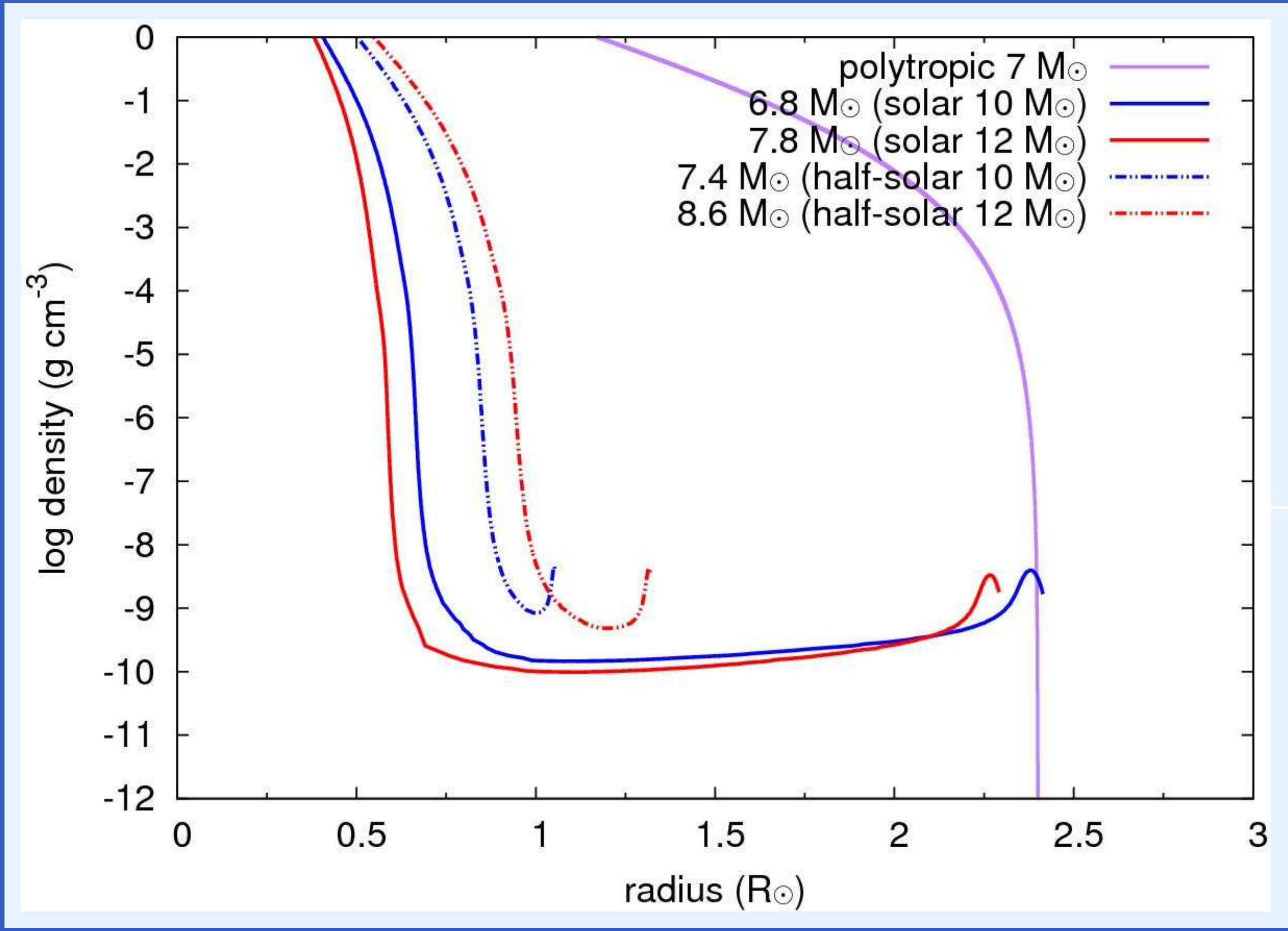


Heger et al. 1997

Pulsations → mass loss at high L/M

- Heger et al. 1997
  → consistent periods and growth rates with linear theory
  → extreme mass loss before SN explosion?
- Yoon & Cantiello 2010
  → superwind may turn off
  → shell formation
- Moriya & Langer 2015
  → works also in Pop III RSG
  → included damping of pulsations due to mass loss

Post-MS: WR SN progenitors



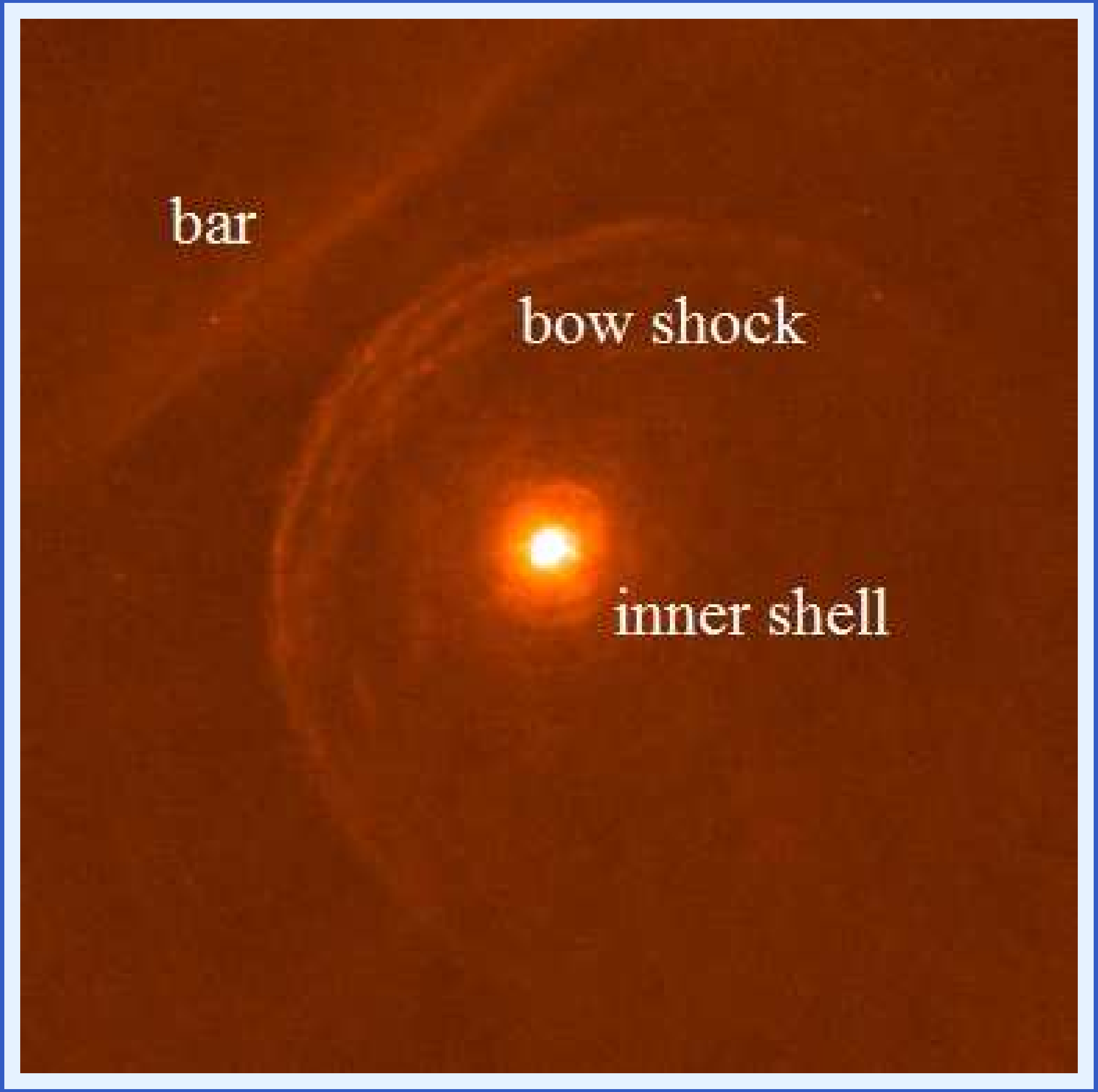
→ SN 2008D

Moriya et al. 2015

?

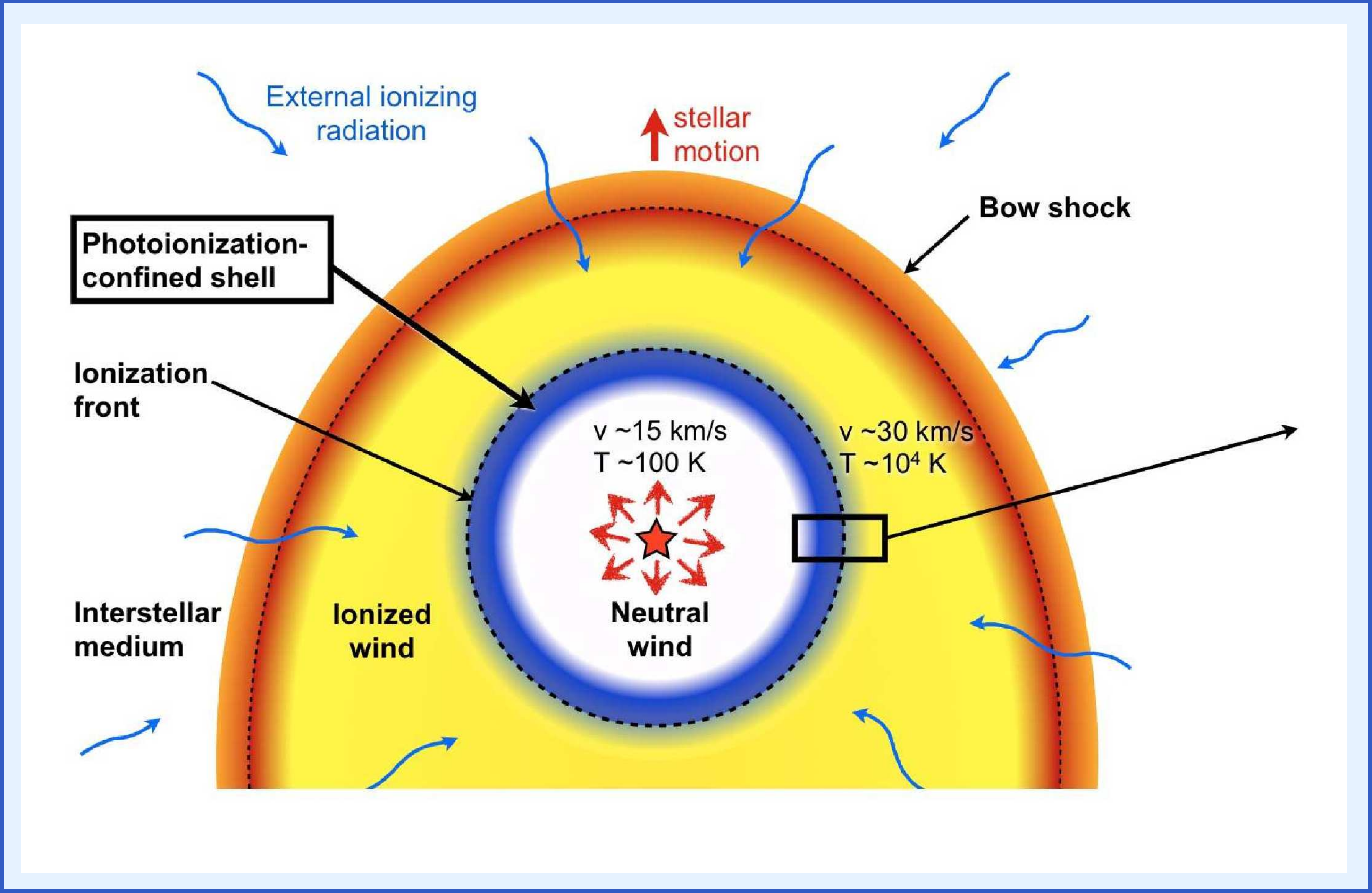
Ionisation Confined Shells

Betelgeuse



V. Gvaramadze, $\rightarrow$ ESA/Herschel/PACS/L. Decin

Ionisation Confined Shells



Mackey et al., 2014, Nature

Betelgeuse's ICS

Le Bertre et al. 2012, MNRAS 422, 3433

- detected in 21 cm, neutral hydrogen
- observed shell mass: $0.09\,\mathrm{M}_\odot$
- shell observed to be stationary
- observed shell radius: $3\,10^{17}$ cm

- inferred photo-ionising flux: $F \simeq 2\,10^7$ cm^{-2}s^{-1}
- inferred stationary shell mass: $\sim 1\,\mathrm{M}_\odot$ (1D)

ICS: analytic theory

$$R_{\rm ICS} = 5\,10^{16}{\rm cm}\ \ \dot{M}_{-4}^{2/3} F_{13}^{-1/3}$$

$$M_{\rm ICS} = 9\,{\rm M}_\odot\ \ \dot{M}_{-4}^{5/3} F_{13}^{-1/3}$$

$$\Rightarrow$$

$$R_{\rm ICS} : 3\,10^{15} \ldots 10^{18}{\rm cm}$$

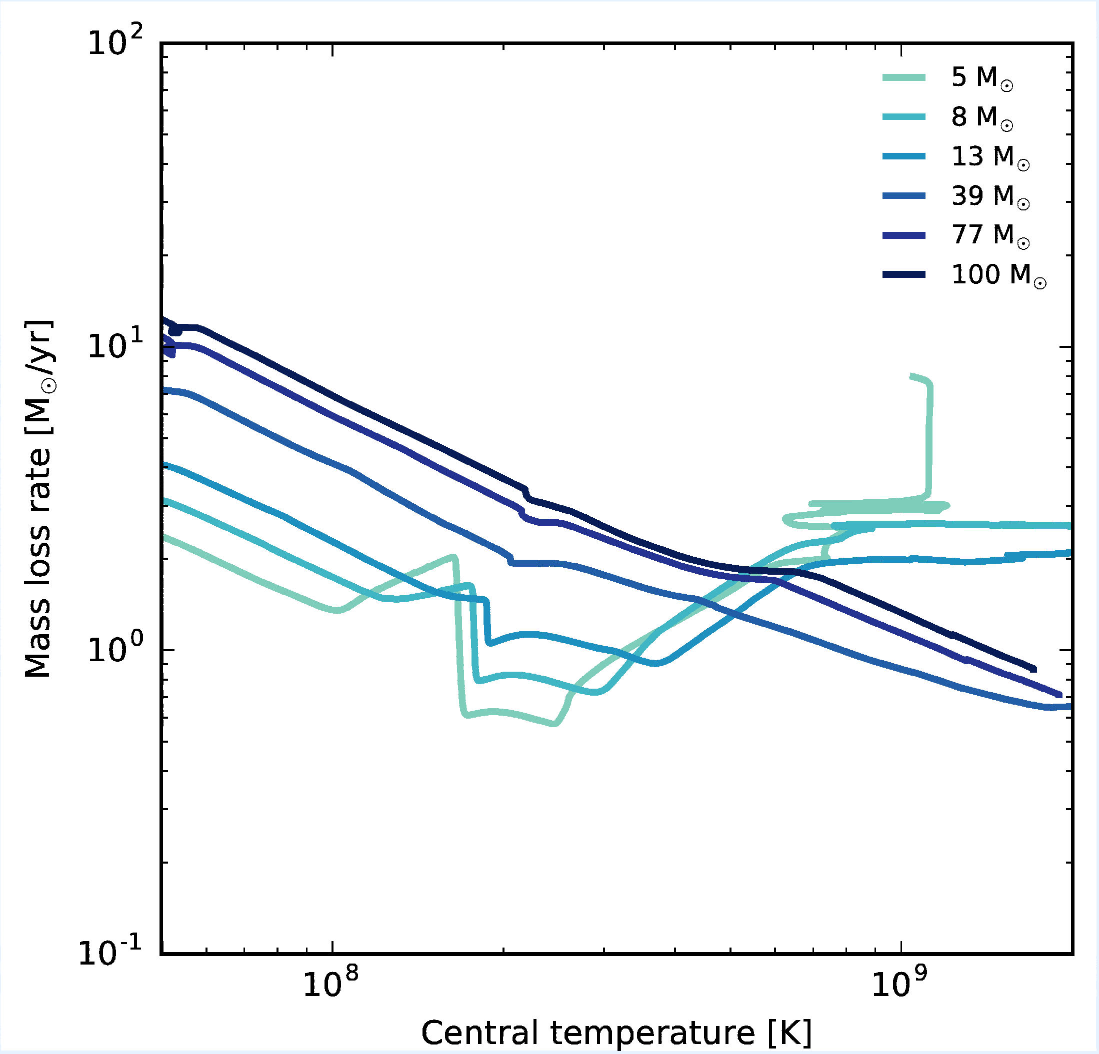
$$M_{\rm ICS} : 0.03 \ldots 10\,{\rm M}_\odot$$

$\Rightarrow$ appliable to SN IIn and SLSN-II !?

Rapidly spinning WR stars

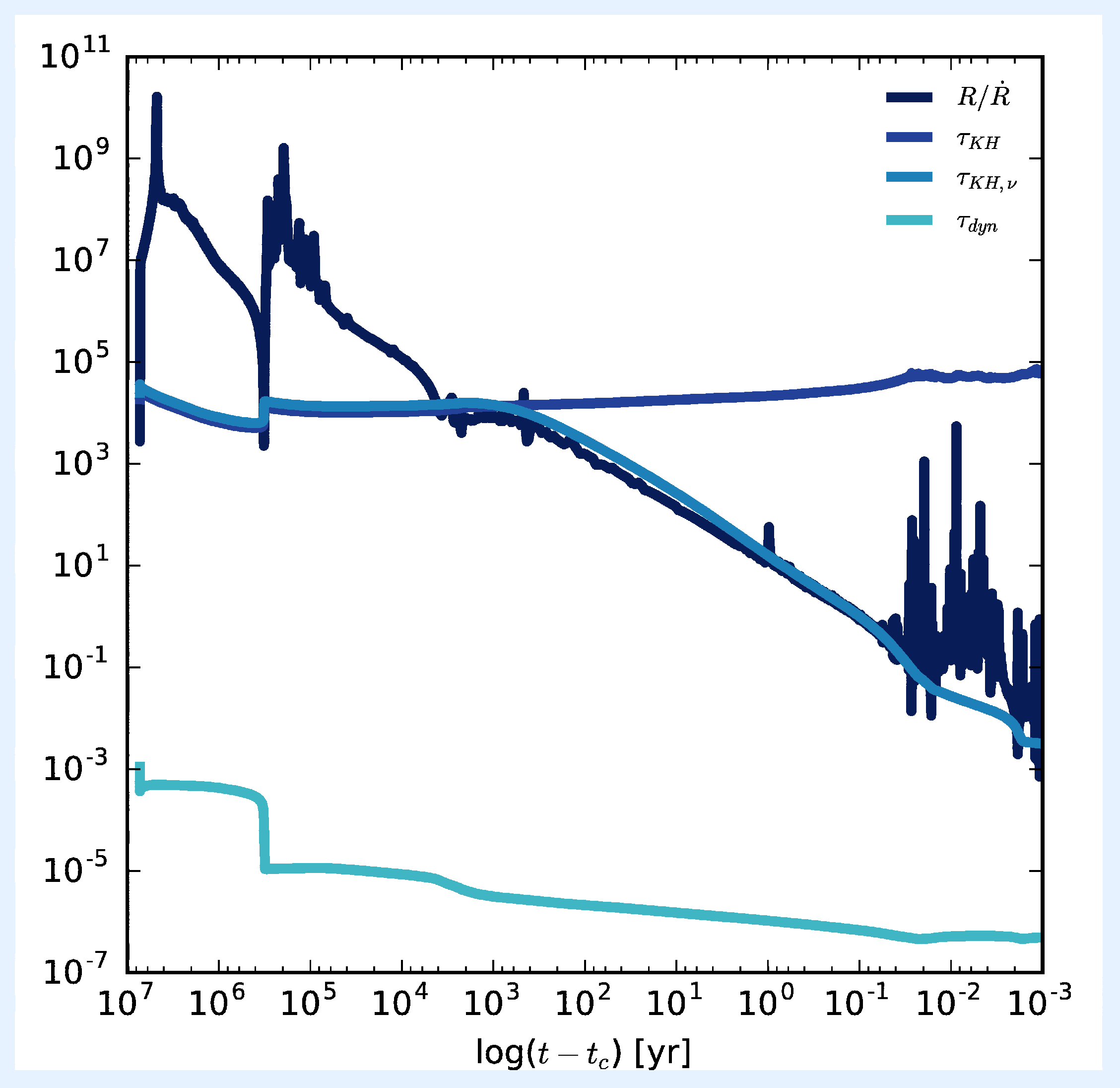
$\rightarrow$ GRB-SNe; SLSN-I

late radius evolution of WR stars



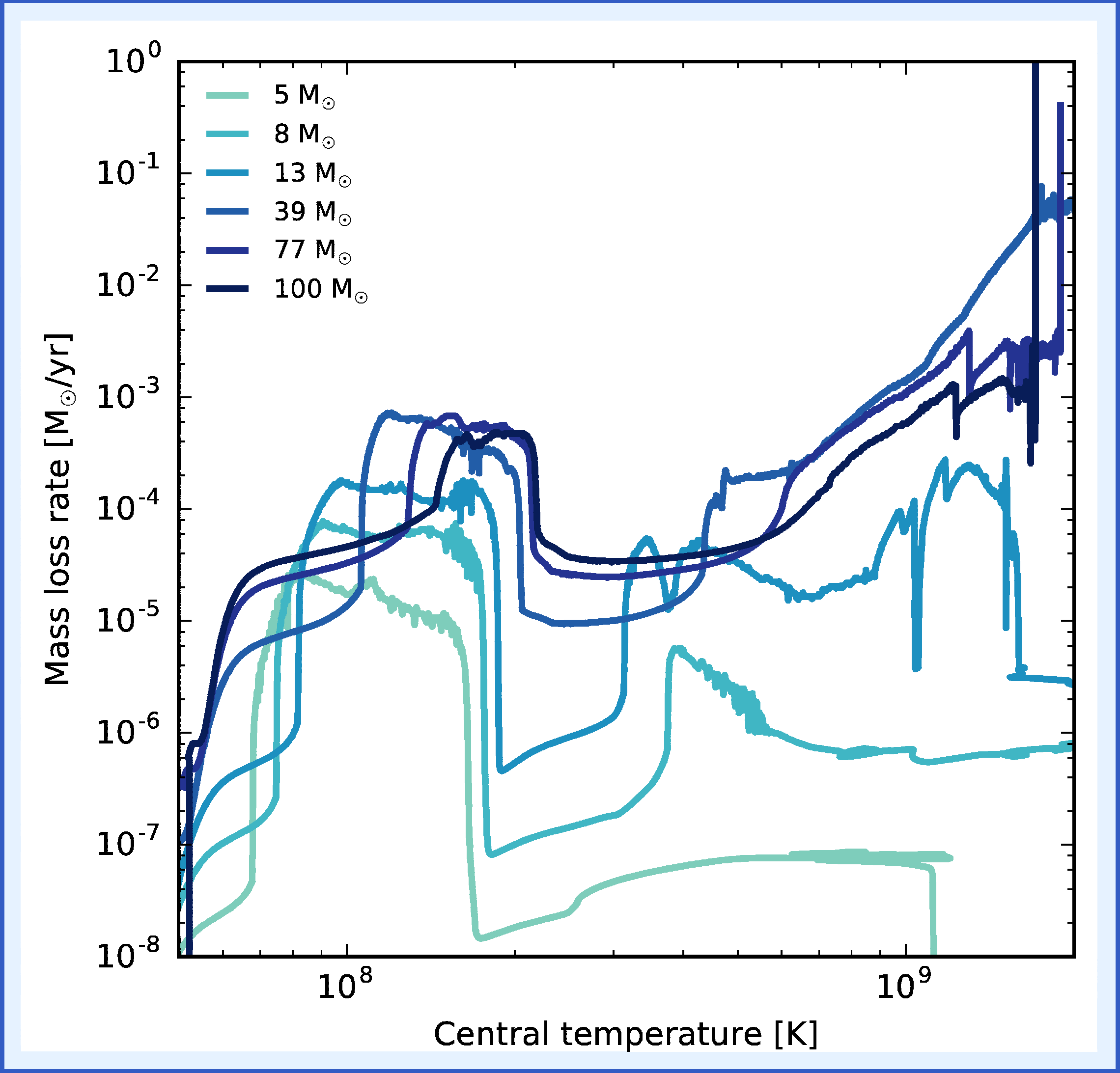
David Ramon Aguilera Dena et al., in prep.

neutrino-accelerated contraction



David Ramon Aguilera Dena et al., in prep.

spin-up induced mass loss



David Ramon Aguilera Dena et al., in prep.

WRs fling off matter

In GRB-SNe and SLSNe I:

- observations: no helium: SNe Ic
  $\Rightarrow$ no “mirror effect” $\Rightarrow$ late contraction
- favored models (magnetar/collapsar): very rapid rotation
  $\Rightarrow$ will reach critical rotation during late contraction
- neutrino-induced speed-up of contraction
  $\Rightarrow$ dramatic mass loss increase
  $\Rightarrow$ independant of previous progenitor evolution

More ways for late-time CSM

- wind-wind bubbles
  when a fast wind follows a slow wind: wind shells
- bow shocks
  10% of the massive stars are runaway stars
- binary mass transfer after core He-exhaustion
  “mirror effect” $\Rightarrow$ late expansion!
  $\Rightarrow$ mass donor explodes during (non-conservative) mass transfer

at core collpse:

stationary dense CSM at core collapse:

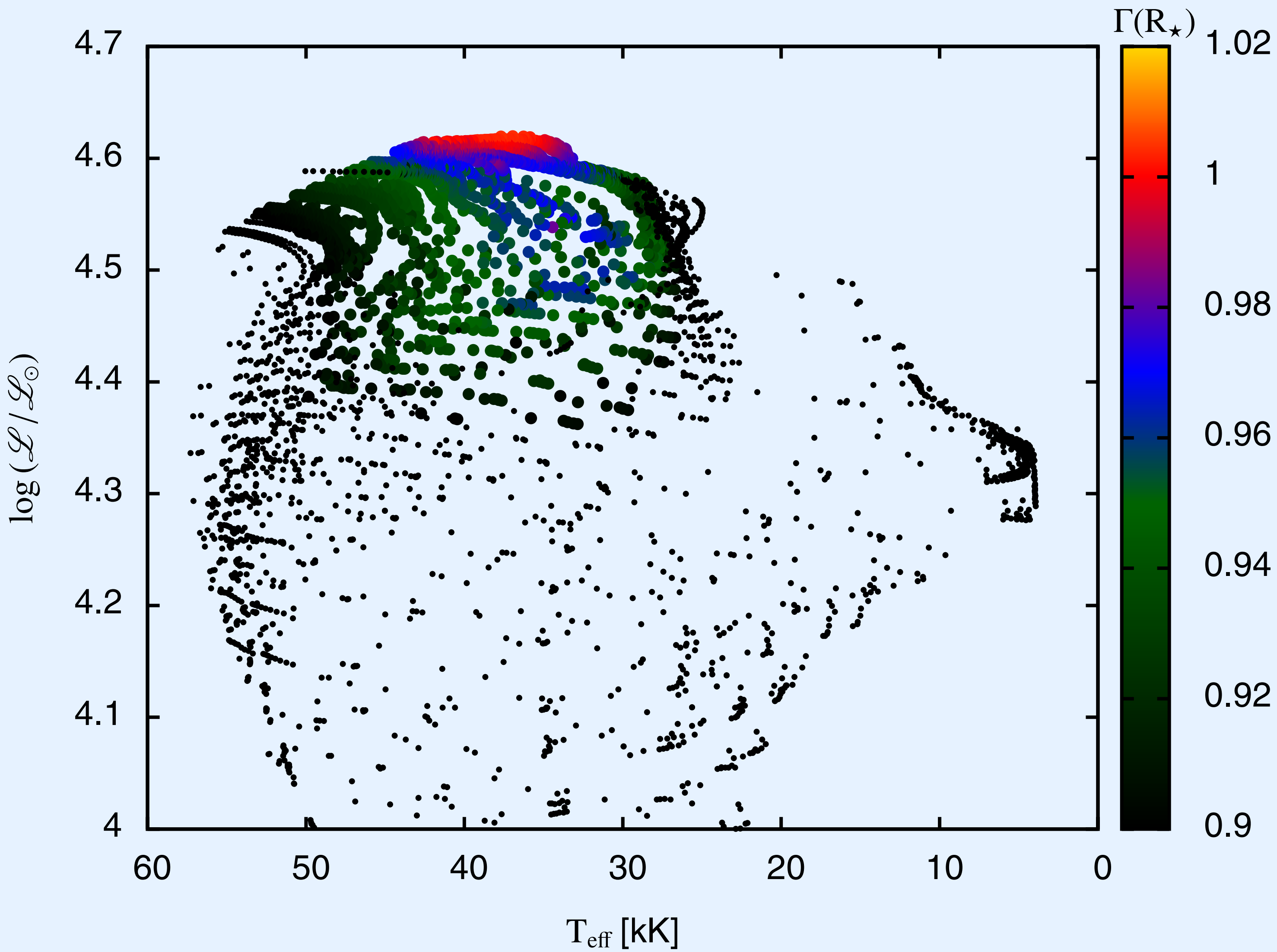
- SN progenitor is inflated
- RSG progenitor is externaly ionised
- SN progenitor is runaway star / exposed to moving ISM

expanding dense CSM at core collapse:

- late evolution $\rightarrow$ increase in L/M $\rightarrow$ envelope loss
- GRB-SNe, SLSN-I: late spin-up
- binaries: late mass transfer / CEE

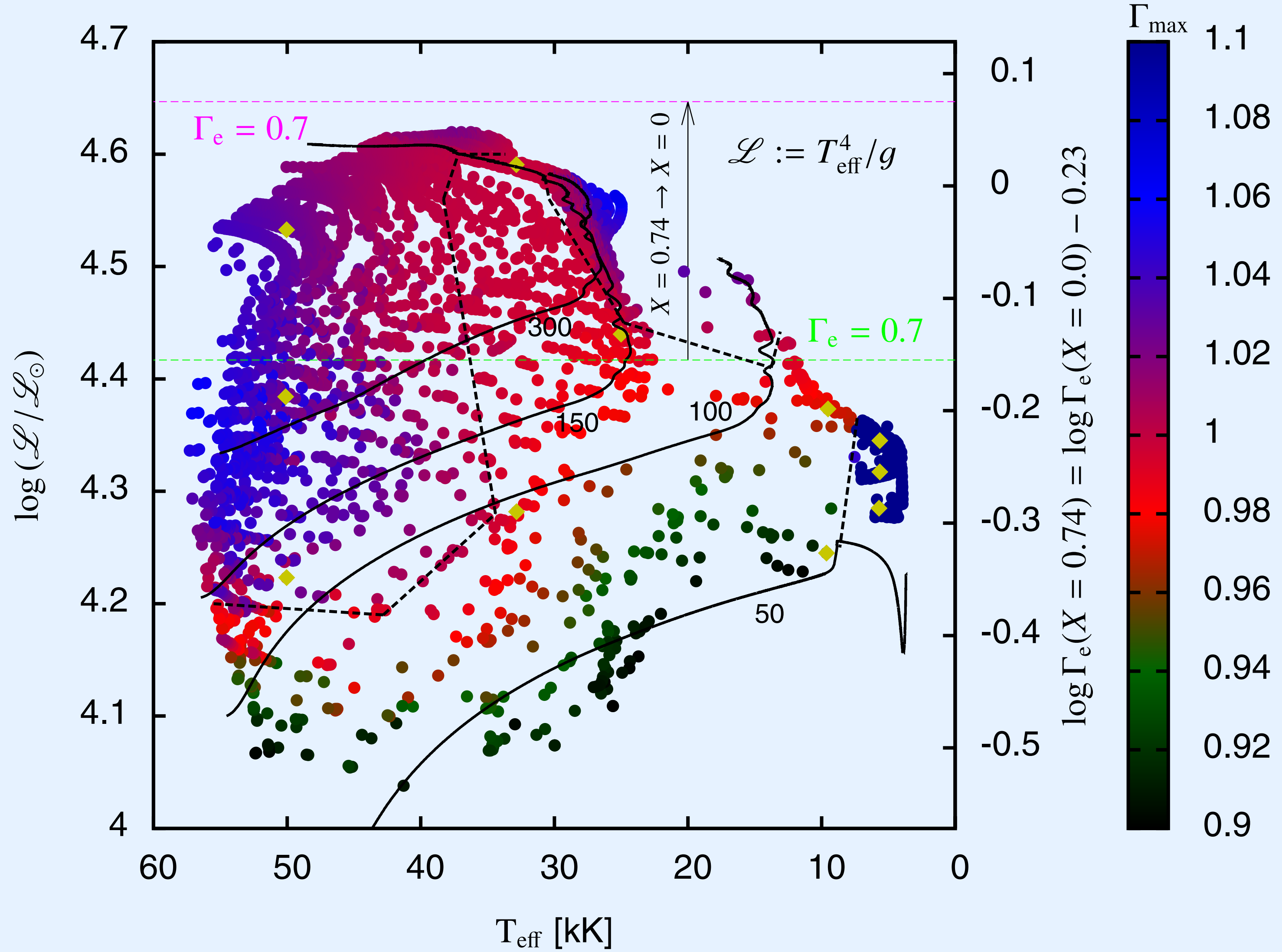
Some of this combines well with:
pulsational pair instability $\Rightarrow$ Woosley
wave driven mass loss $\Rightarrow$ Quataert, Fuller
super-Eddington winds $\Rightarrow$ Owocki

Surface Eddington factors



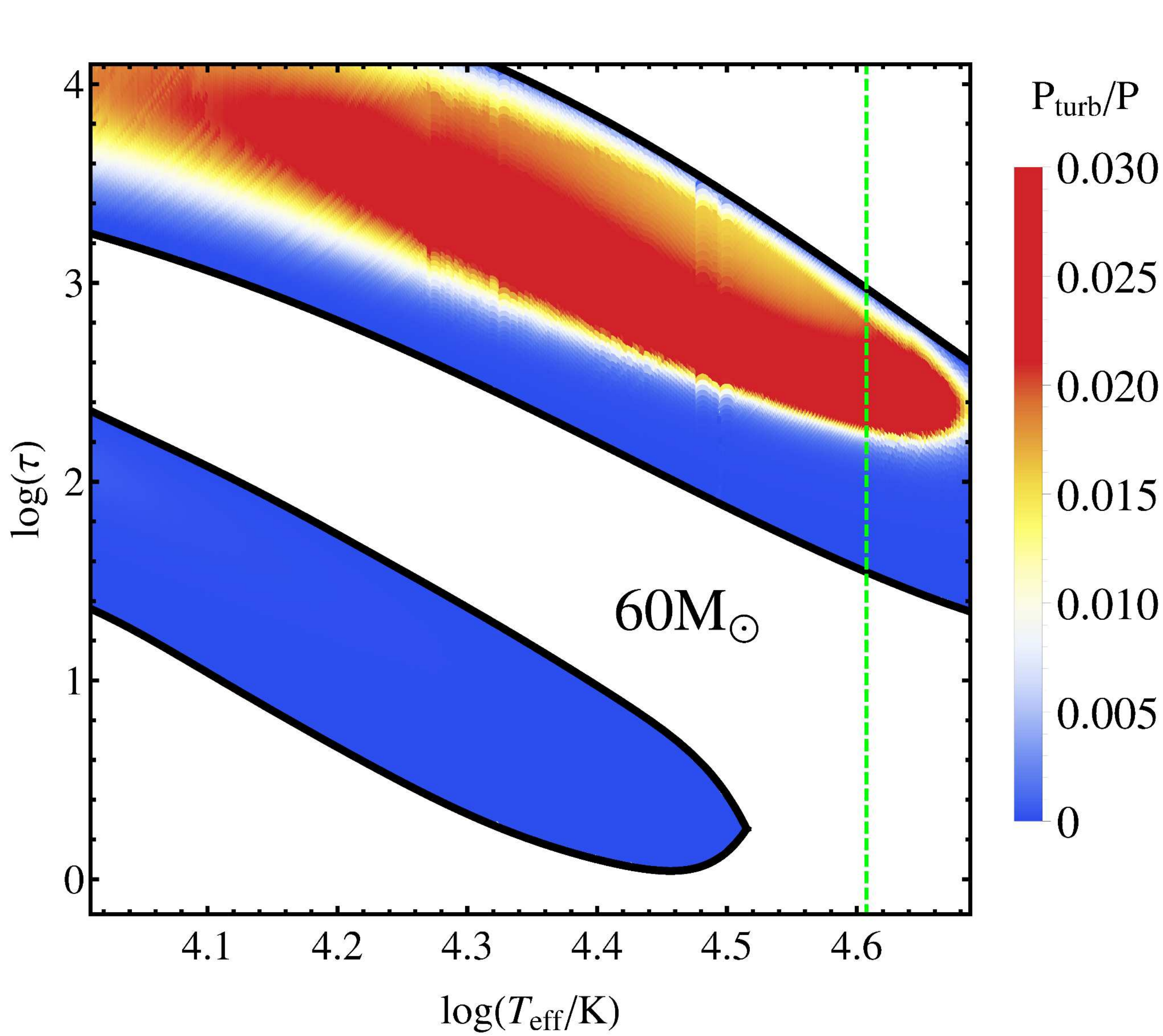
Sanyal et al. 2015

Sub-surface Eddington factors

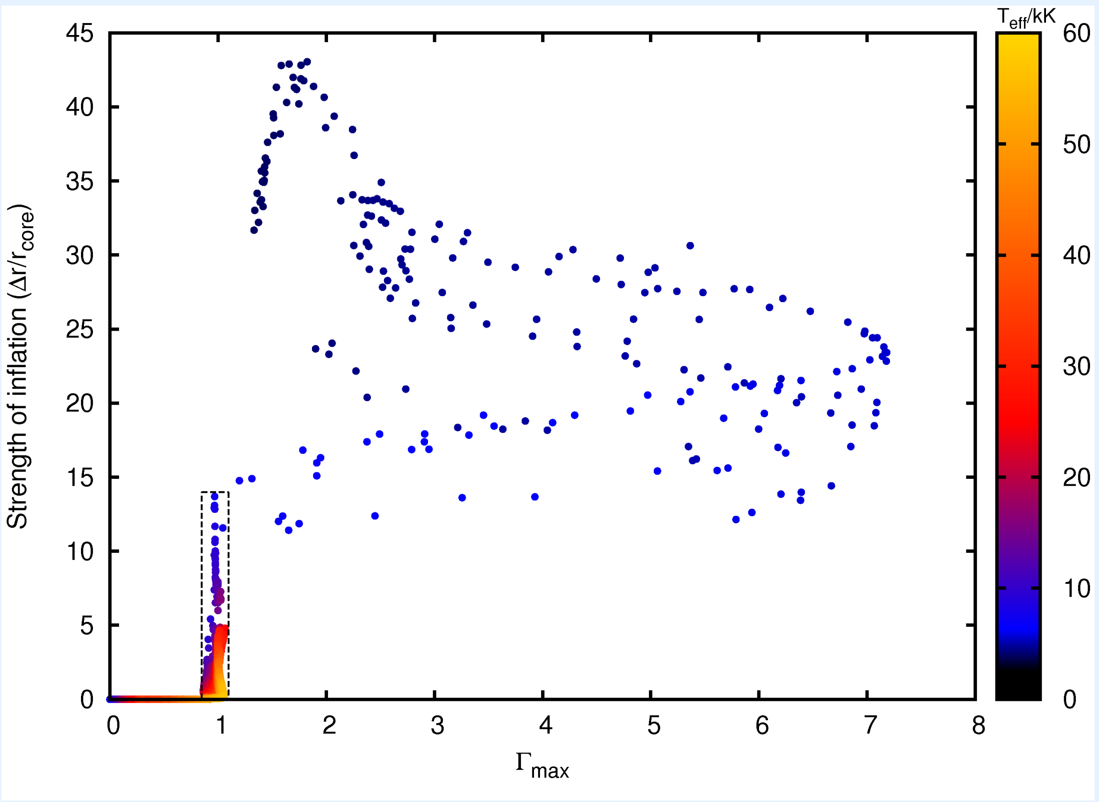


Sanyal et al. 2015

Turbulent pressure: 60 $M_\odot$ model

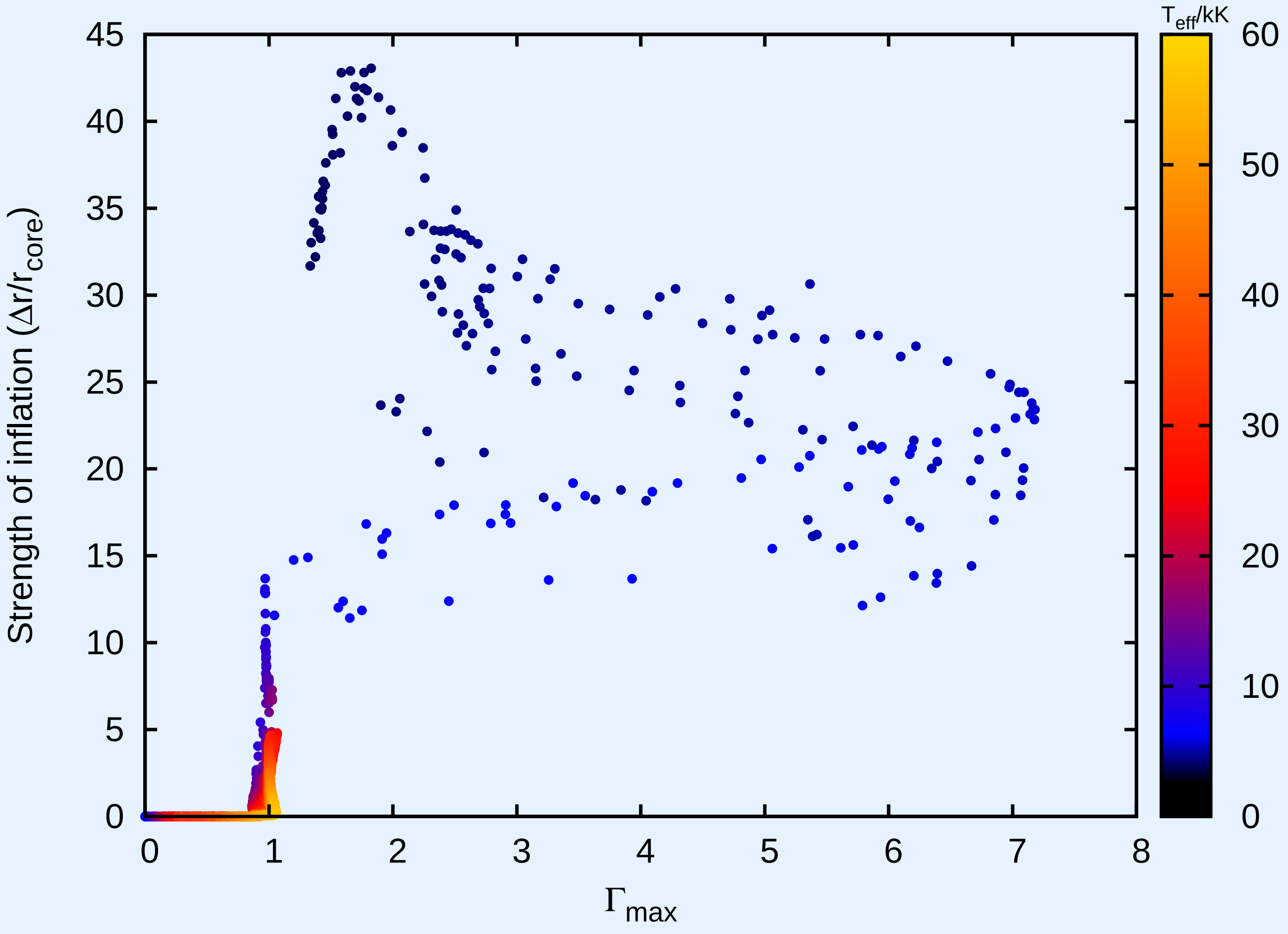


Eddington-limit → Inflation



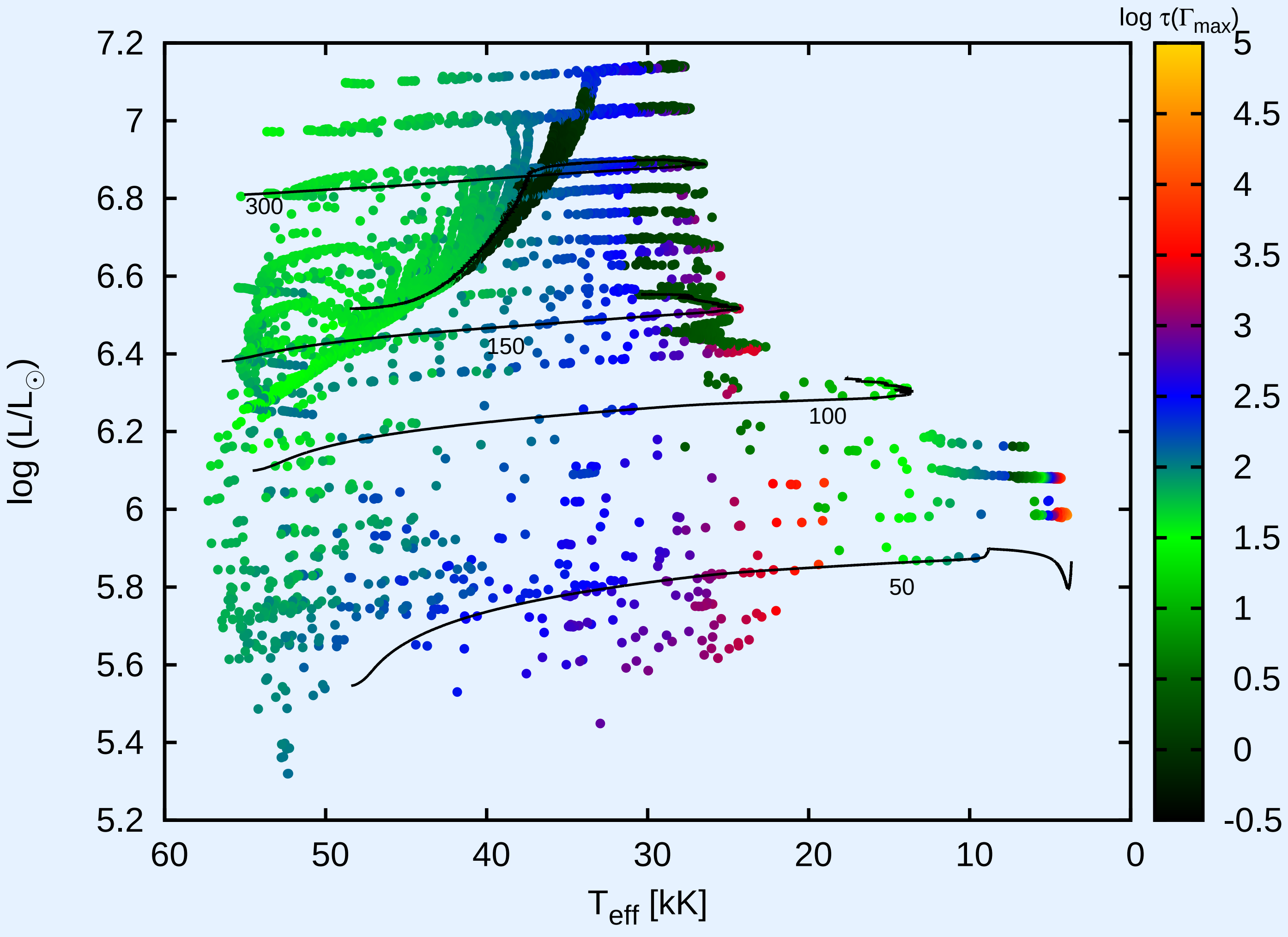
Sanyal et al. 2015

Inflation (Gamma)



Sanyal et al., 2015

Tau (Gamma-max)



Sanyal et al., 2015