# Pre-SN Evolution of Massive Star

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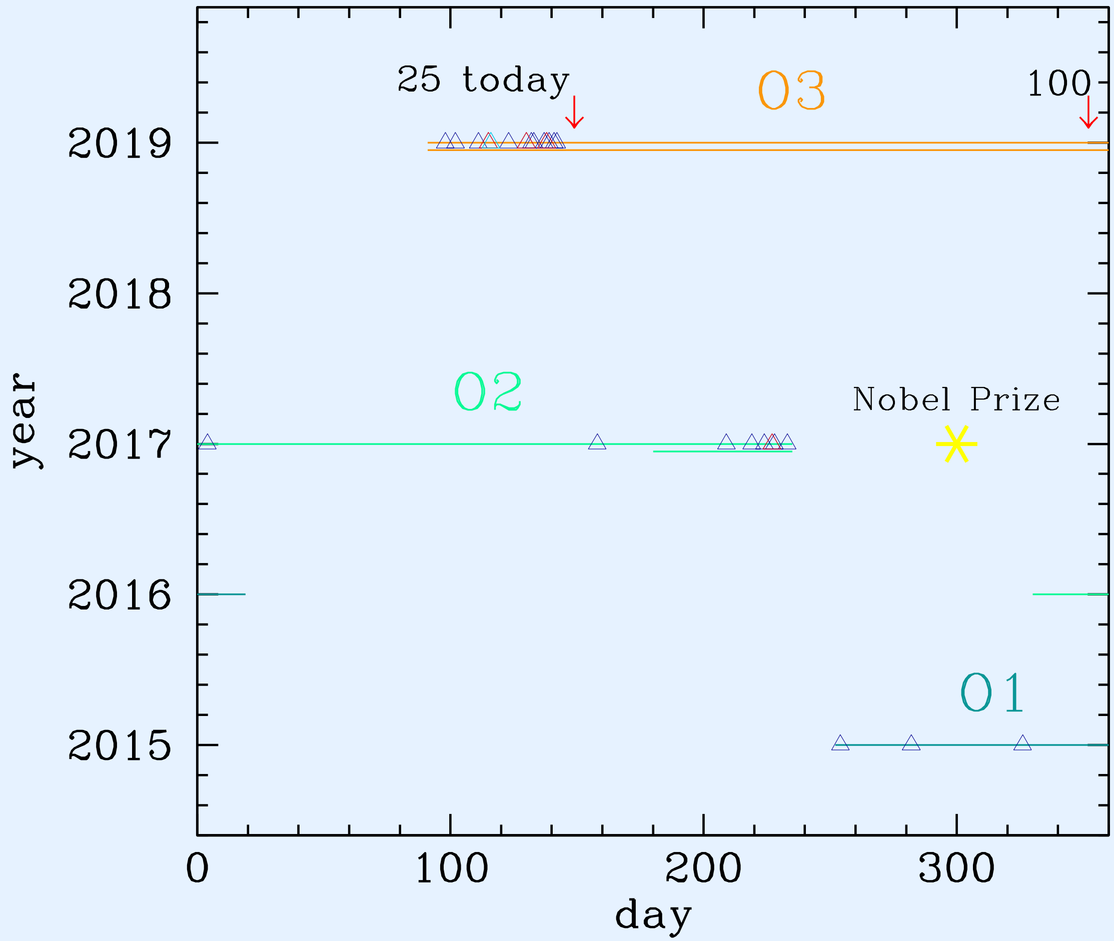
# GW events




https://gracedb.ligo.org/latest/

# mass $\uparrow \longrightarrow$ our ignorance $\Uparrow$

G stars

- low chance to be binary product
- $\dot{M} \simeq 0$
- high internal stability $(\beta = 1)$
- B fields ubiquitous

O stars

- high chance to be binary product
- self-evaporate
- at verge of instability $(\beta \to 0)$
- B fields sporadic

massive stars are so relevant

- SNe, GRBs, NSs, BHs
- determine state of ISM
- dominate chemical evolution

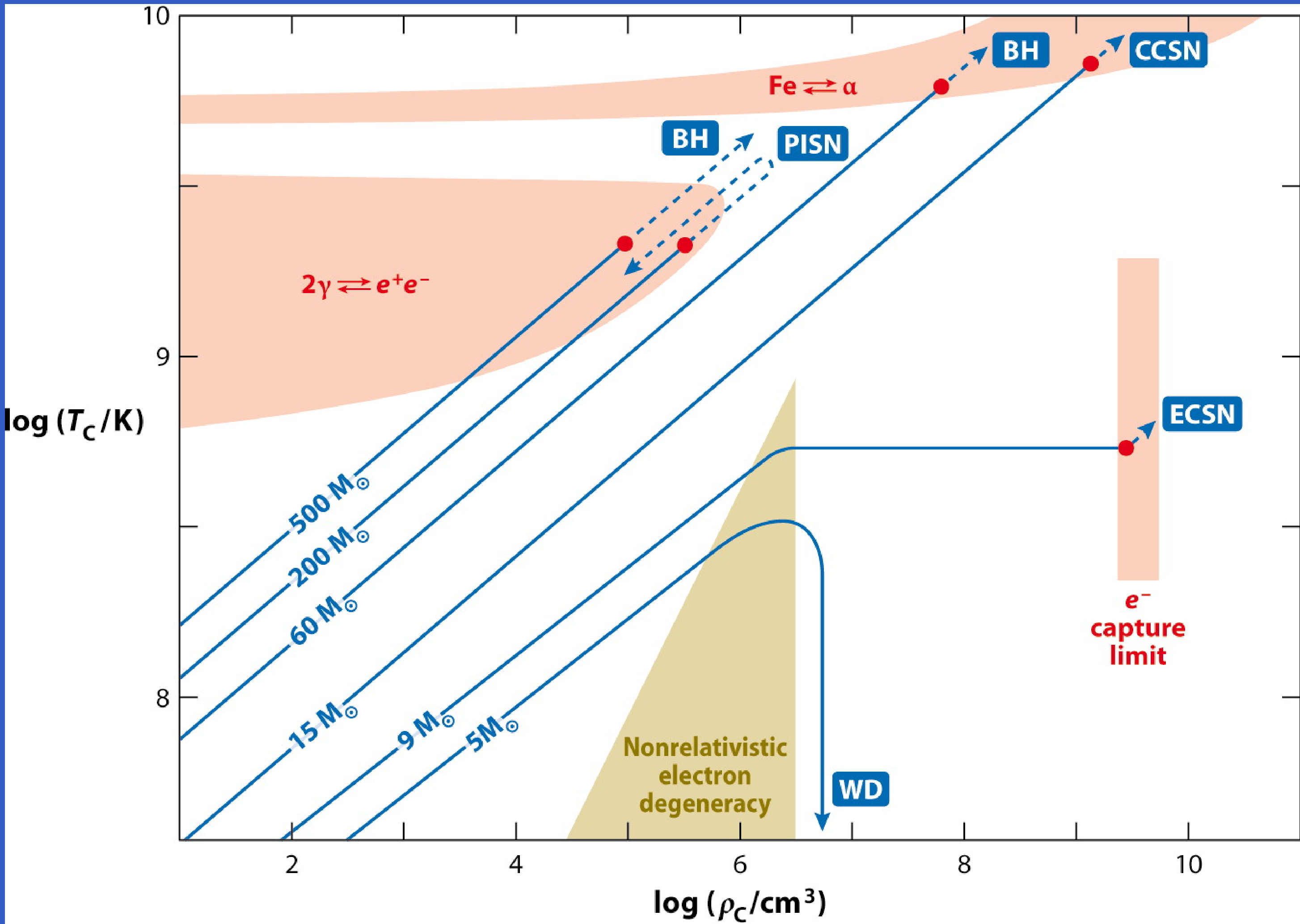
# The stellar mass determines the fate

$\frac{1}{\rho}\frac{P}{R} \sim \frac{M}{R^2}$ hydrostatic eq.
and $P \sim \rho T$ ideal gas
and $T = const.$ burning temperature

$\Rightarrow$

$$\rho \sim \frac{1}{M^2}$$

# The stellar mass determines the fate

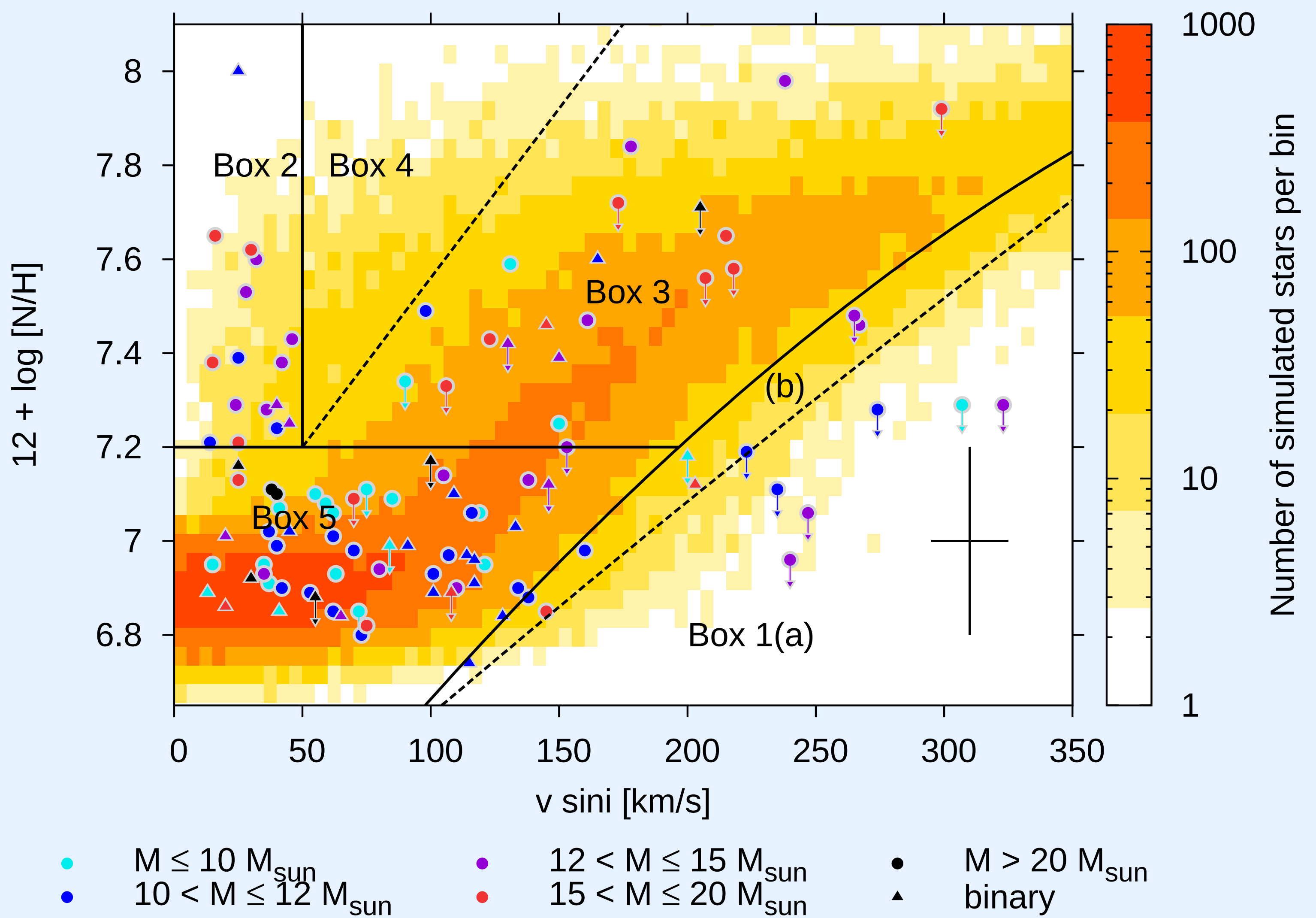



NL 2012, ARAA

# Massive star $\neq$ Massive star

- metallicity
- rotation
- binarity
- magnetic fields
- “ordinary” evolution ($< 30\%$)

# The Hunter diagram: early B stars




Brott+ 2011

# Metallicity & the Eddington limit

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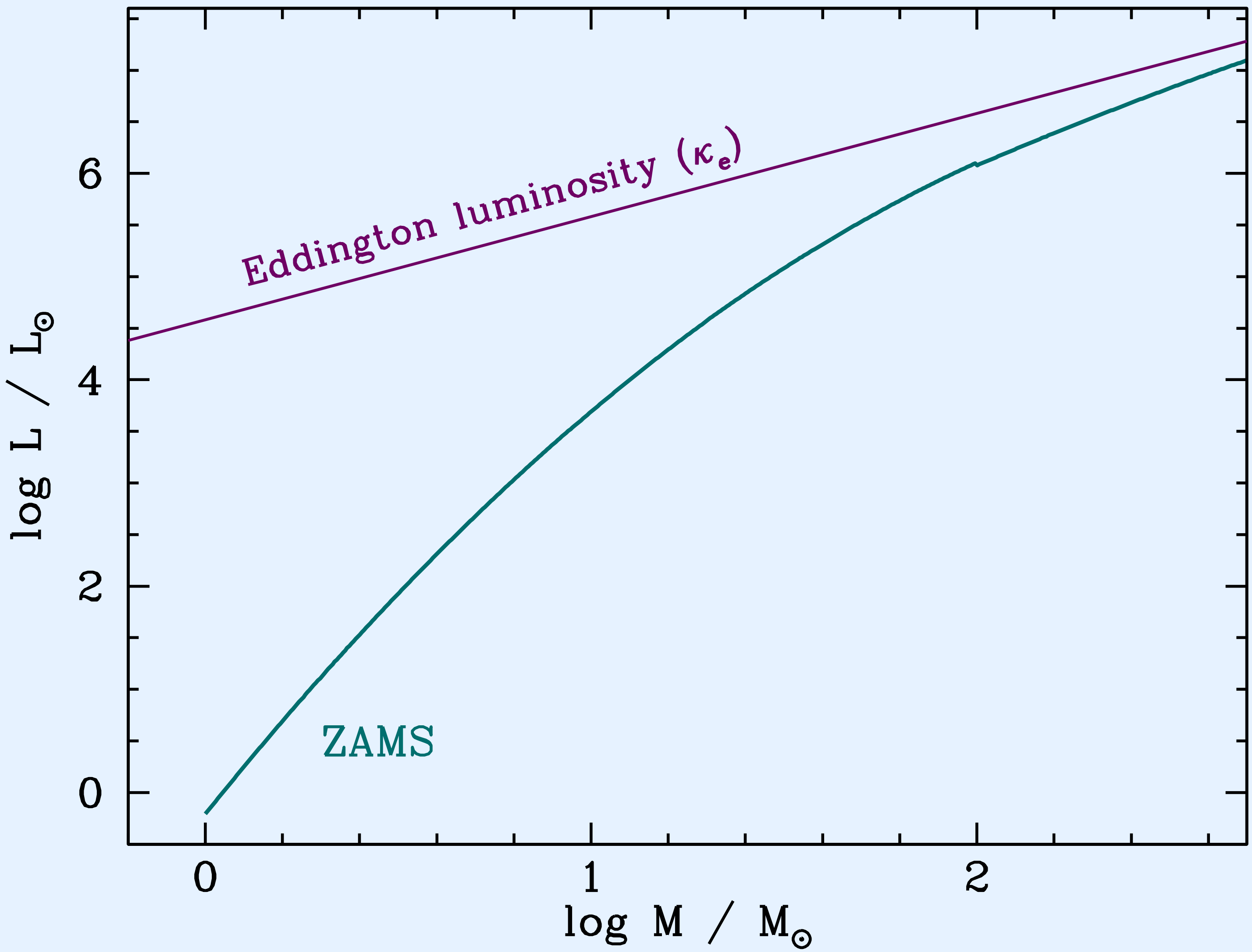
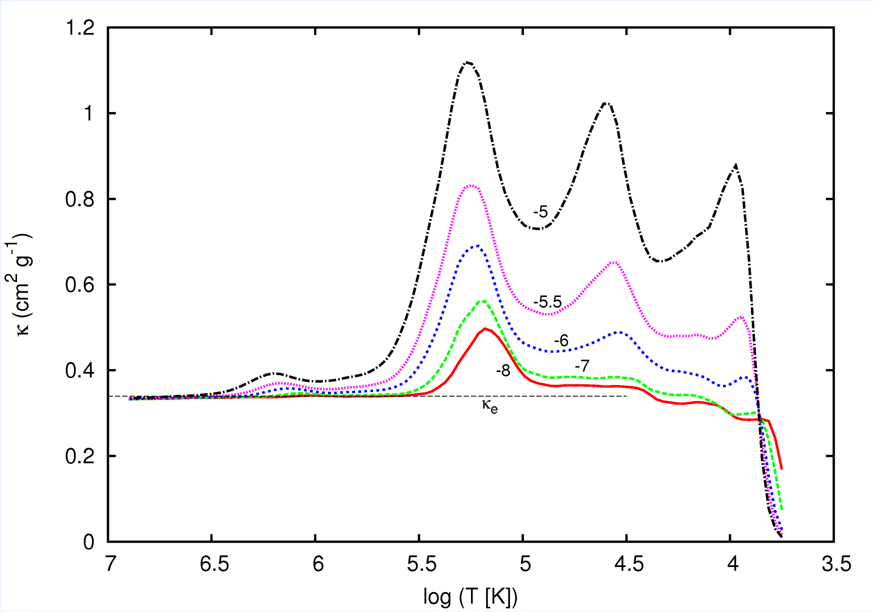


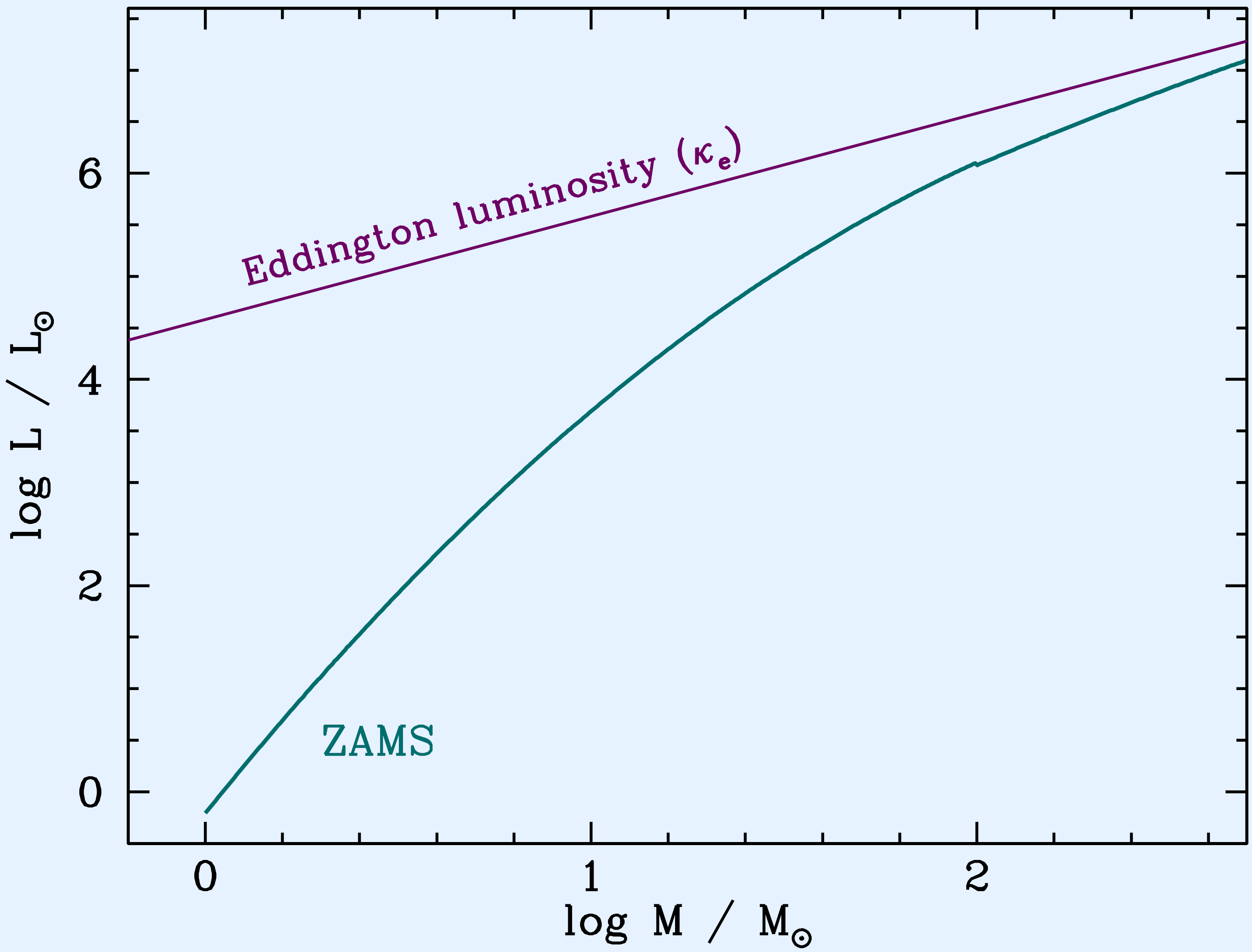
# complete opacity

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




- massive stars: $\kappa_{\rm Fe} \simeq 2\kappa_{\rm e}$
- opacity increases with density

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



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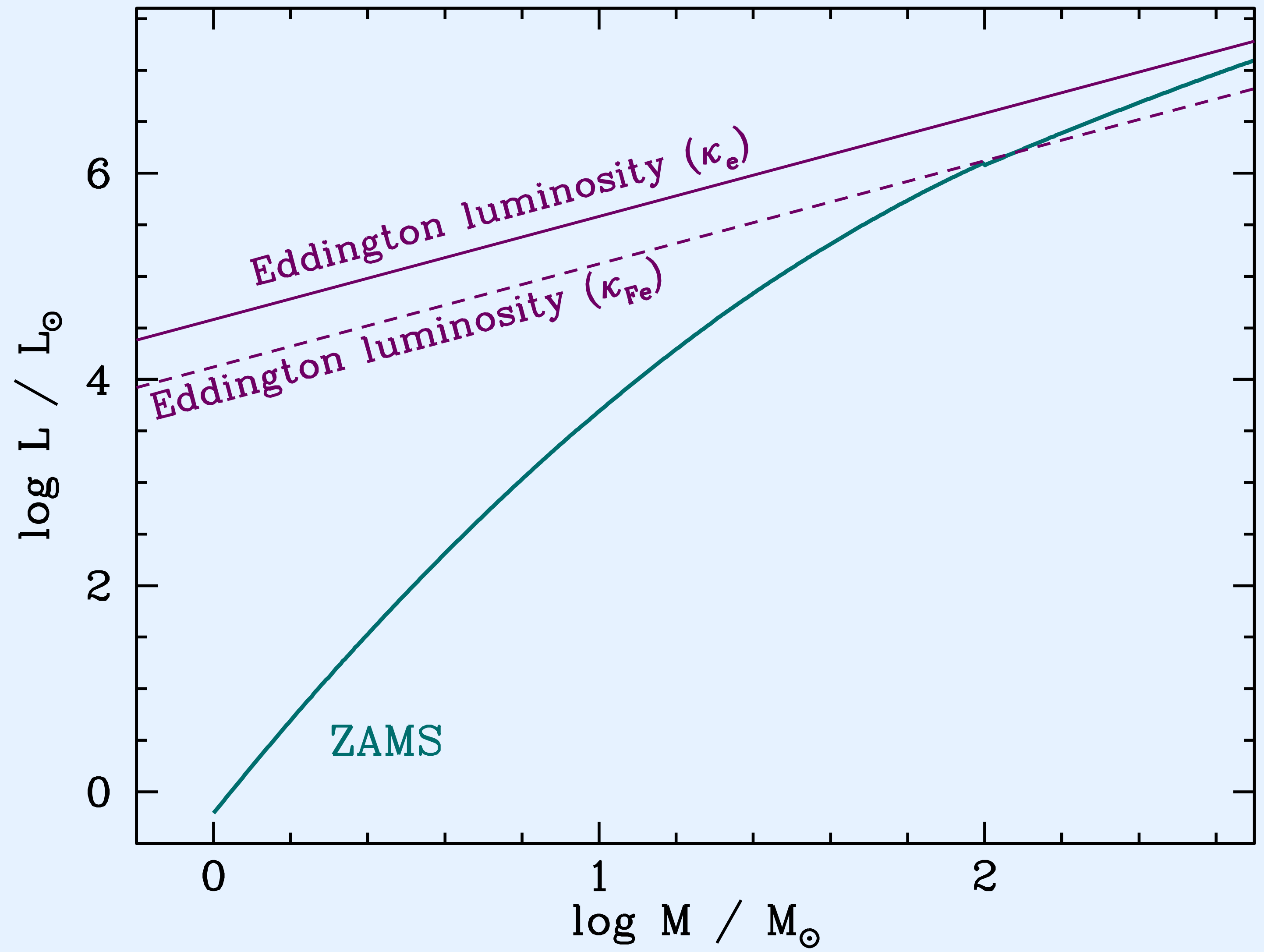
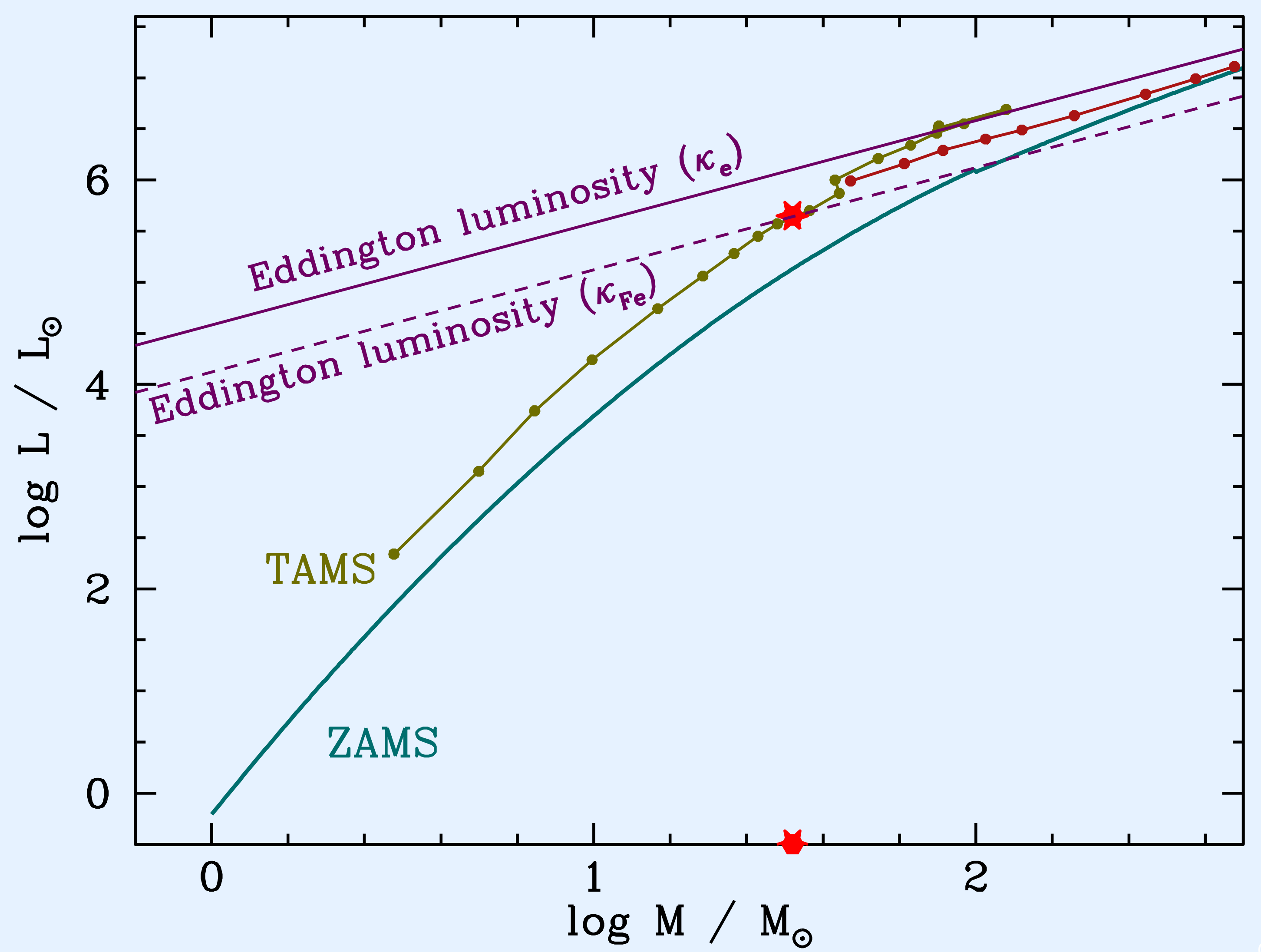
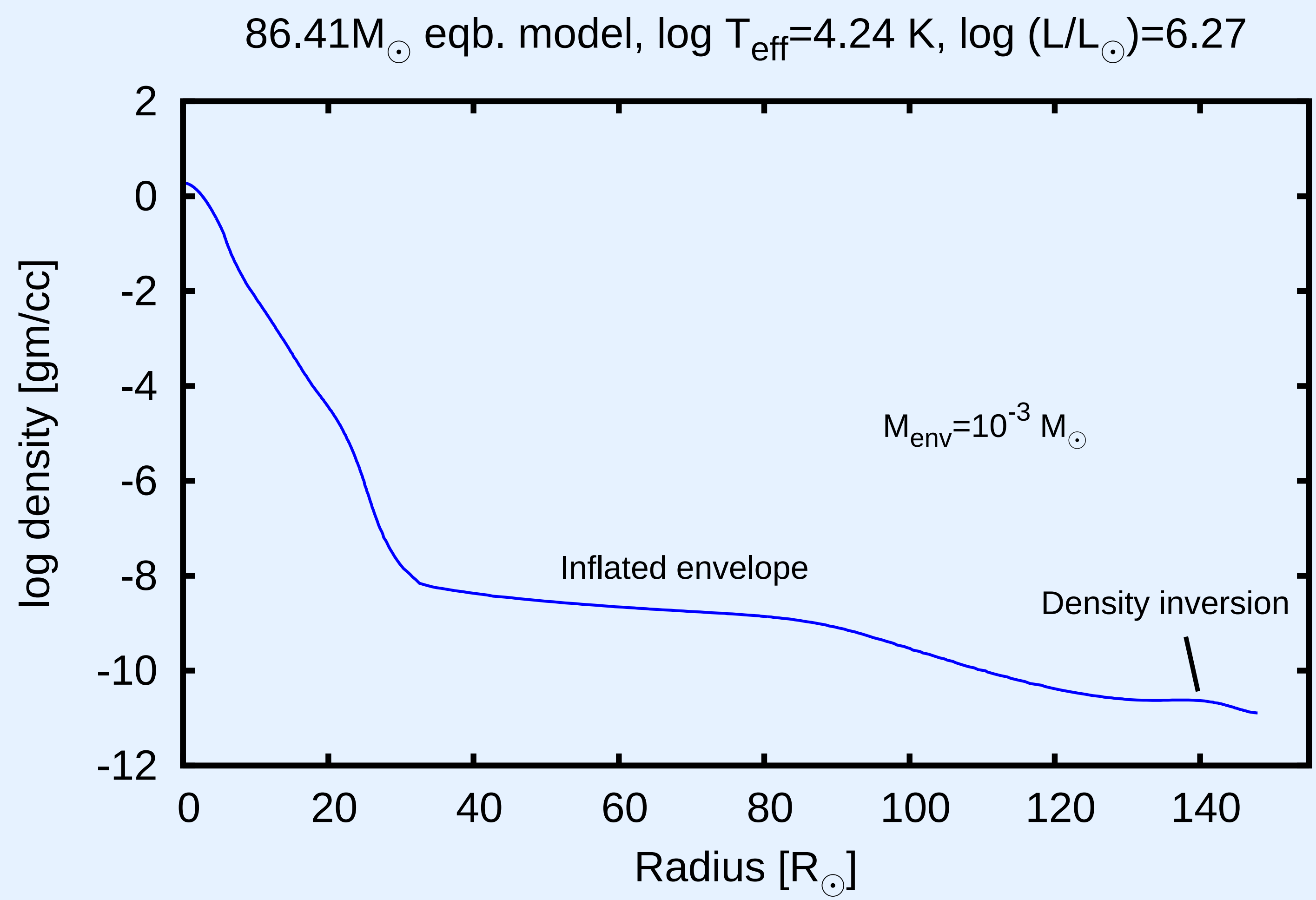


# $M - L_{\mathrm{Eddington}}$ relation

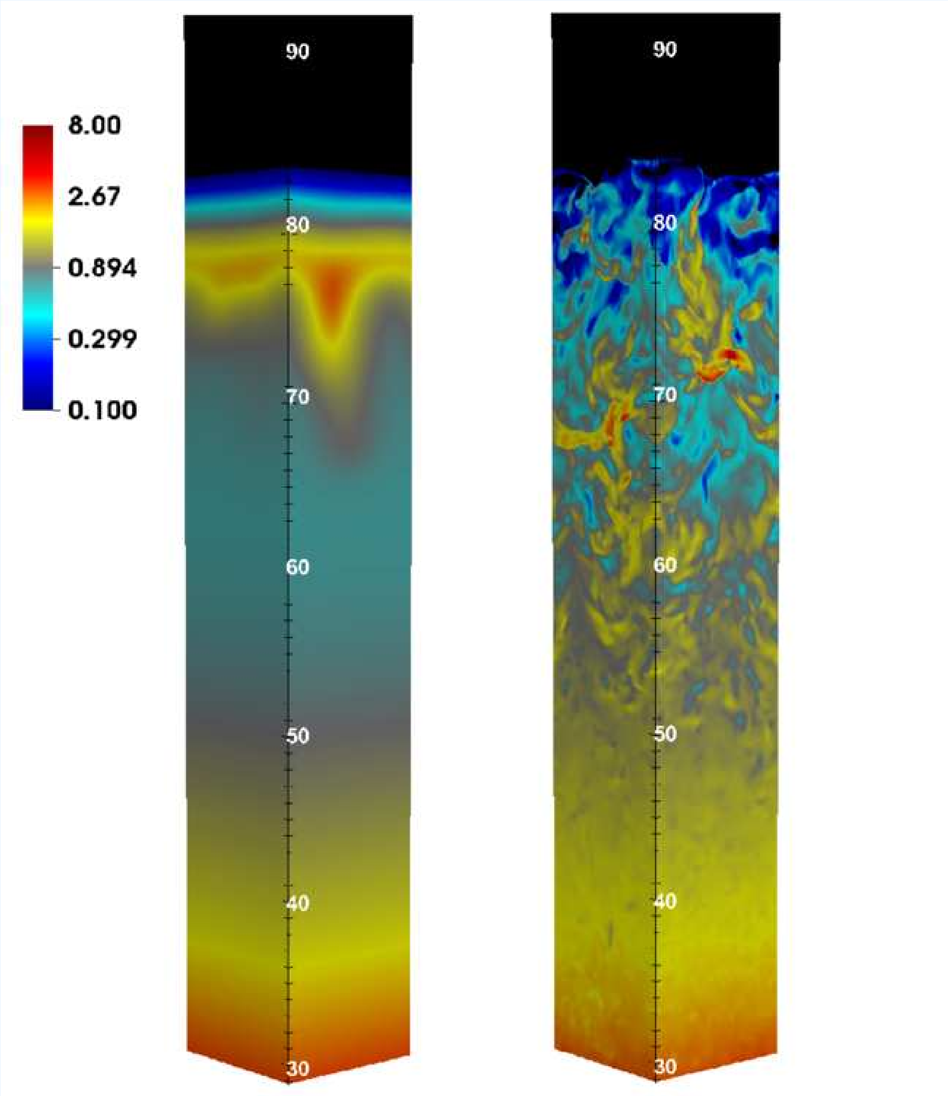


# Inflation: 1D



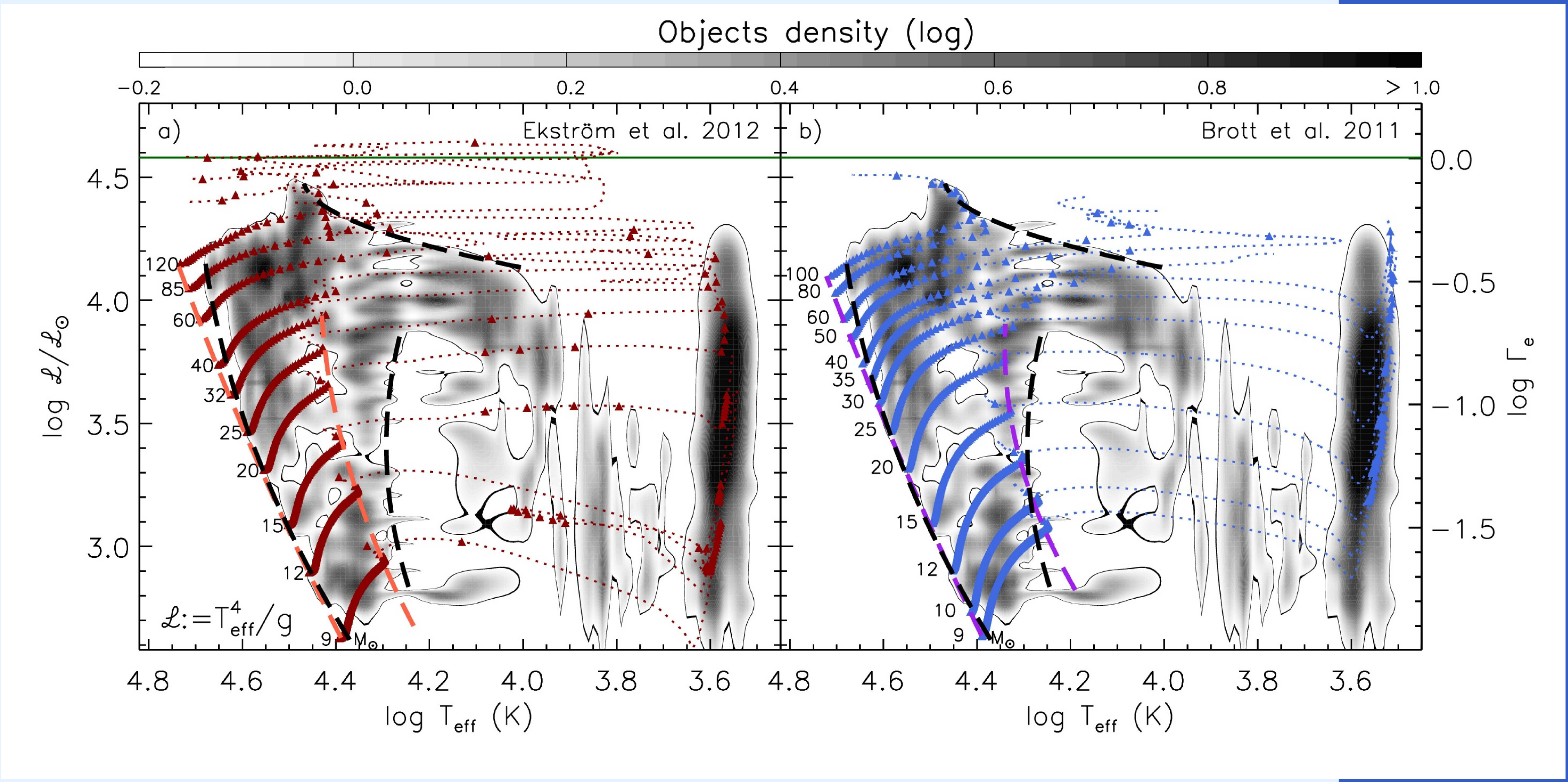

Sanyal et al. 2015

# Inflation: 3D




Jiang et al. 2016

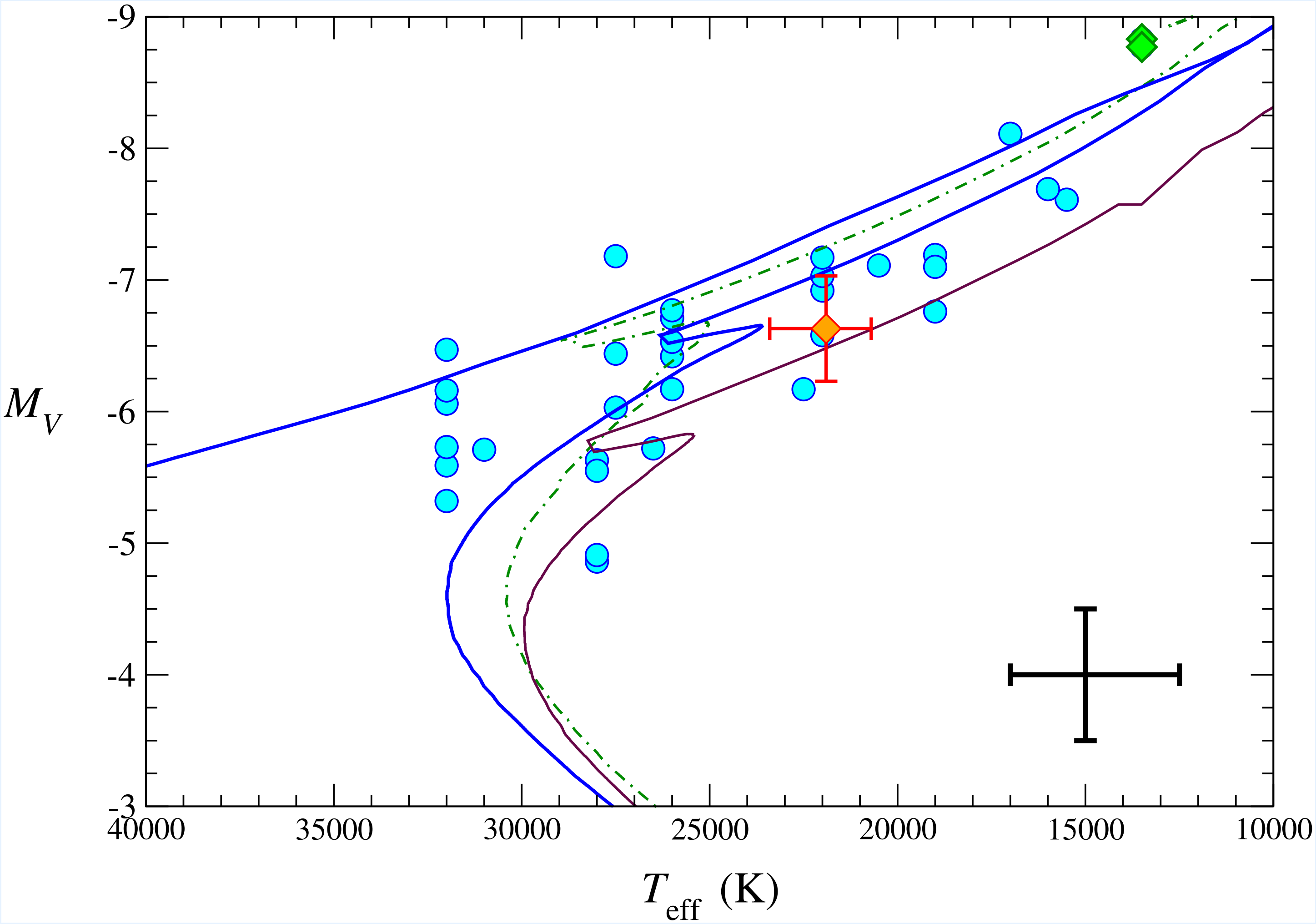
# The Galactic sHRD




600 stars: distance- and reddening-independent

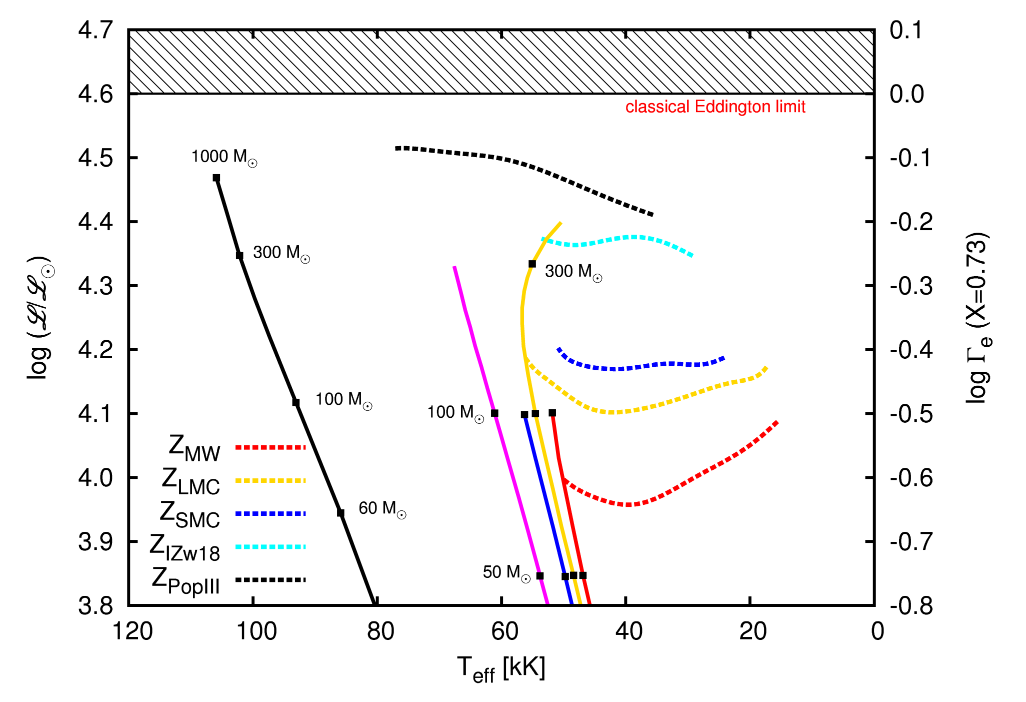
Castro et al. 2014

# CMD of Westerlund 1




Clark et al. 2014

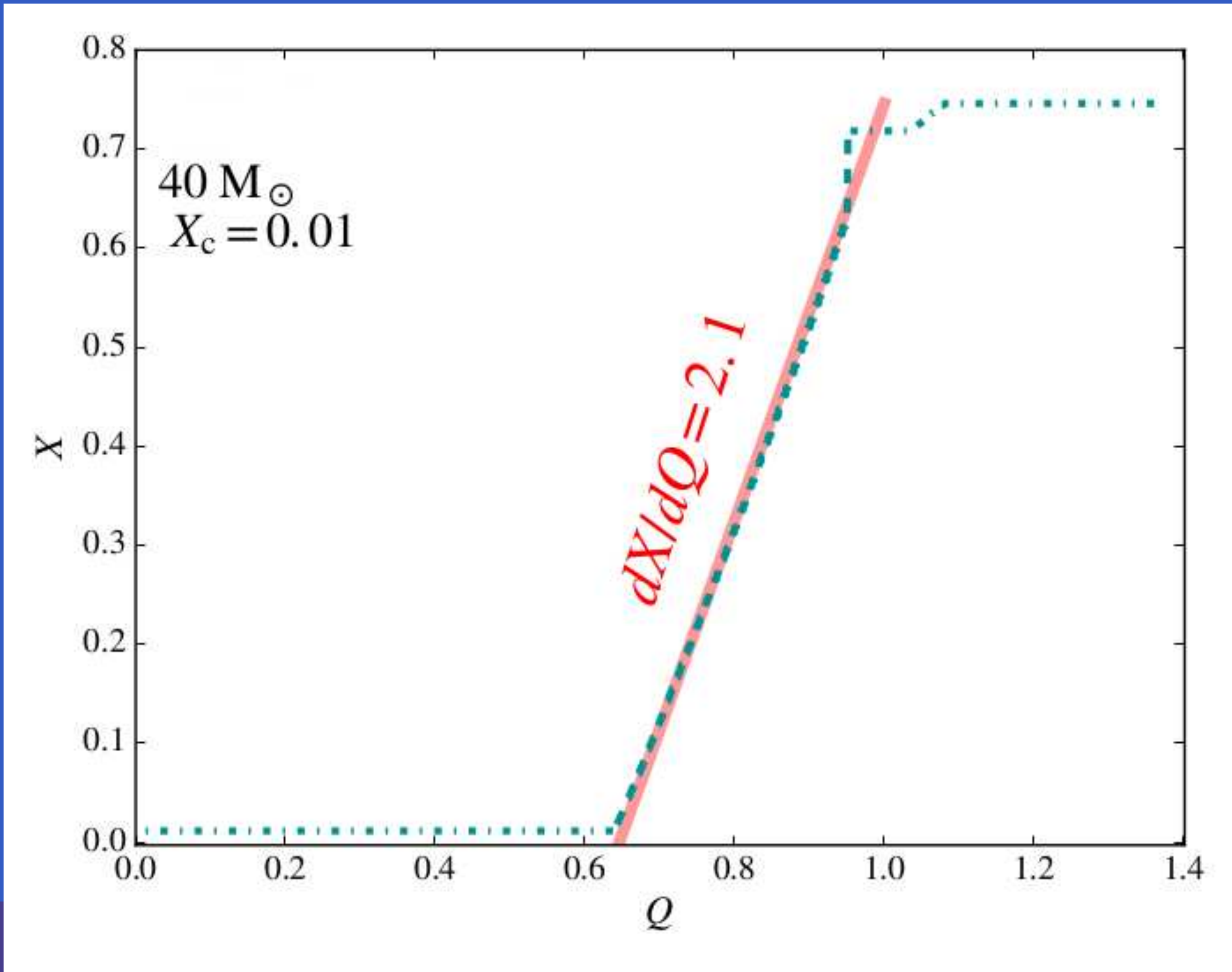
# Inflation as f(Z)



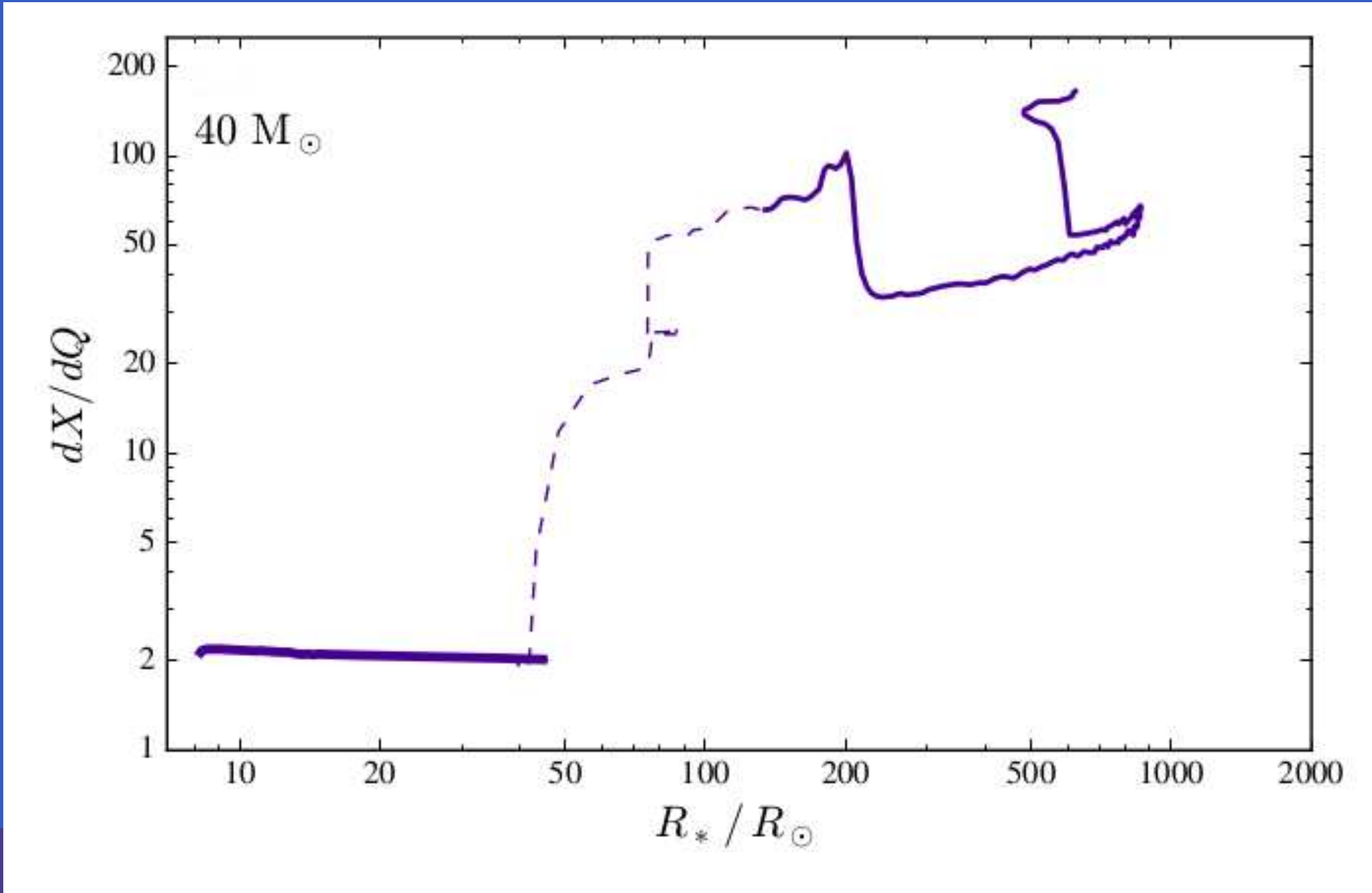

Sanyal et al. 2017

# Chemical gradients

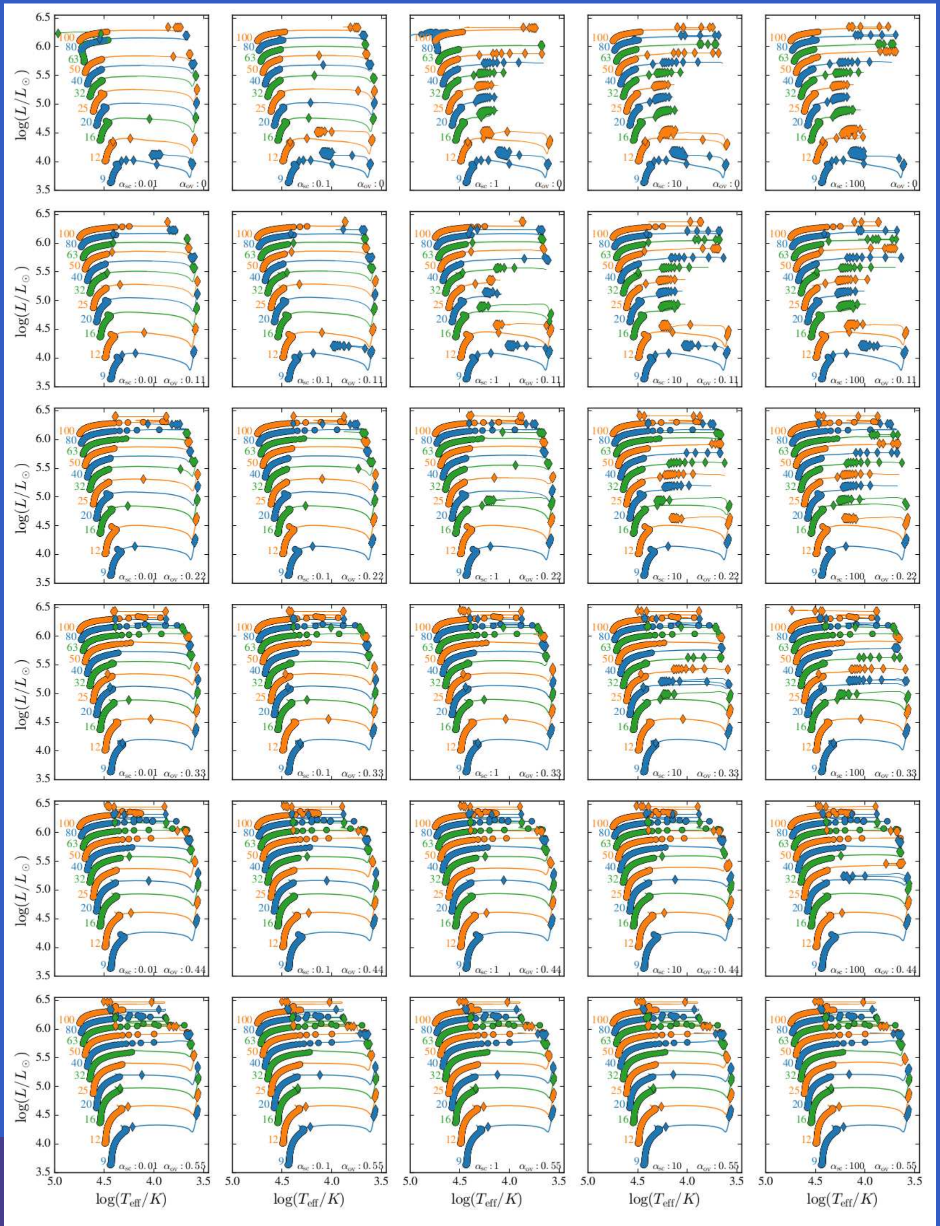
# From core H-burning: $dX/dq \simeq 2$



# post-H-burning: $dX/dq \uparrow$



# SMC supergiants: H-gradient



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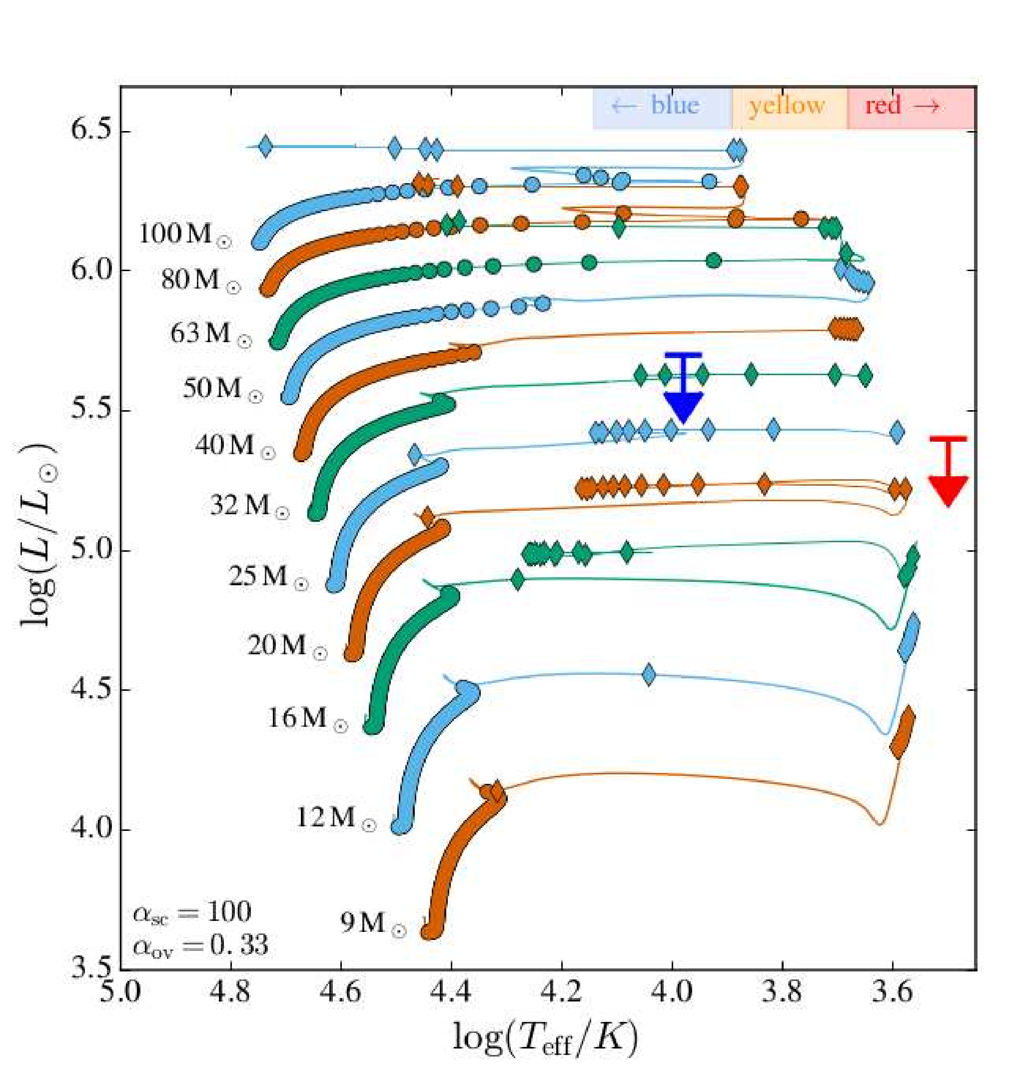
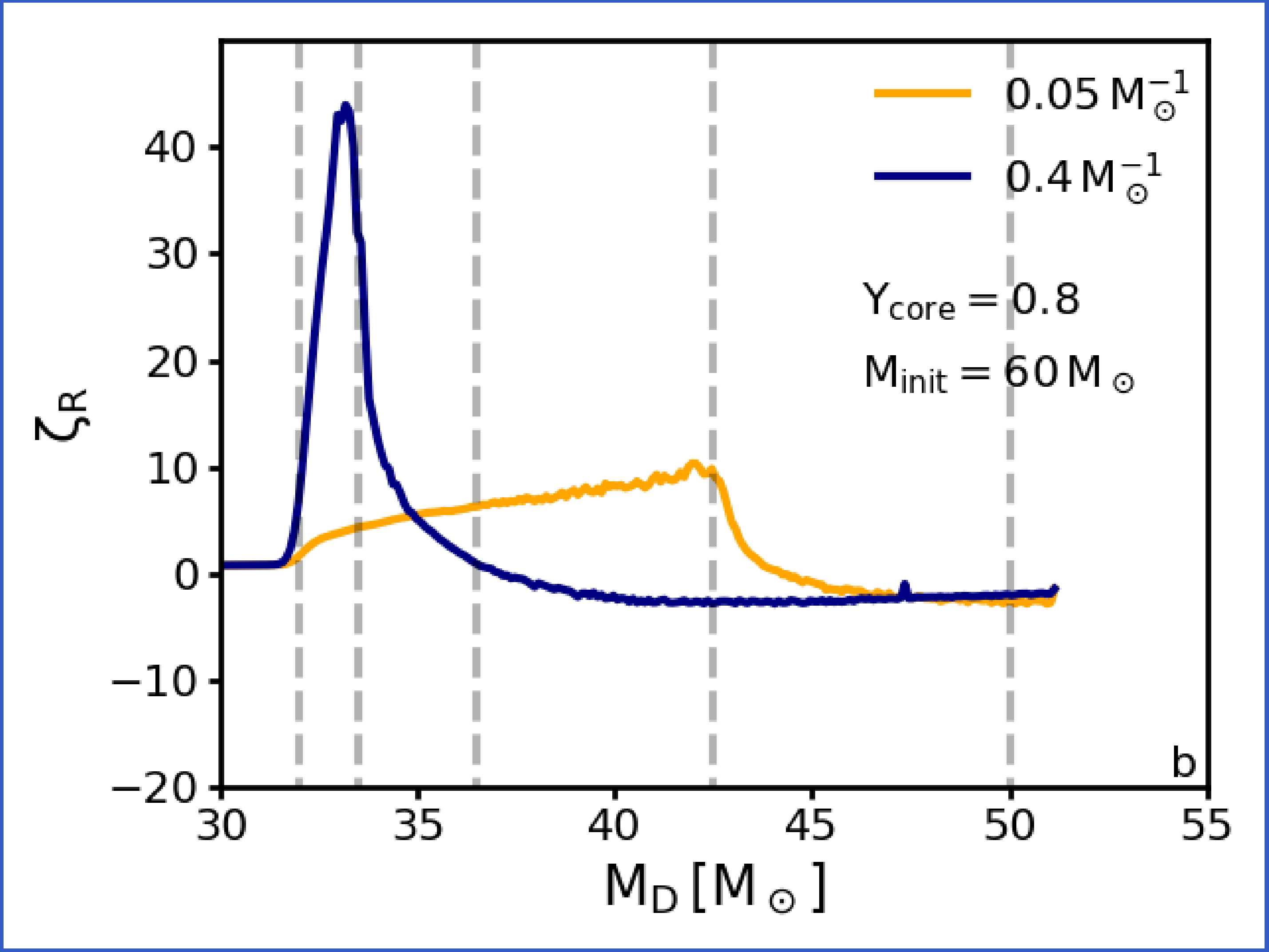



Schootemeijer+ 2019

# Supergiant-HMXBs: H-gradient




Quast+ 2019

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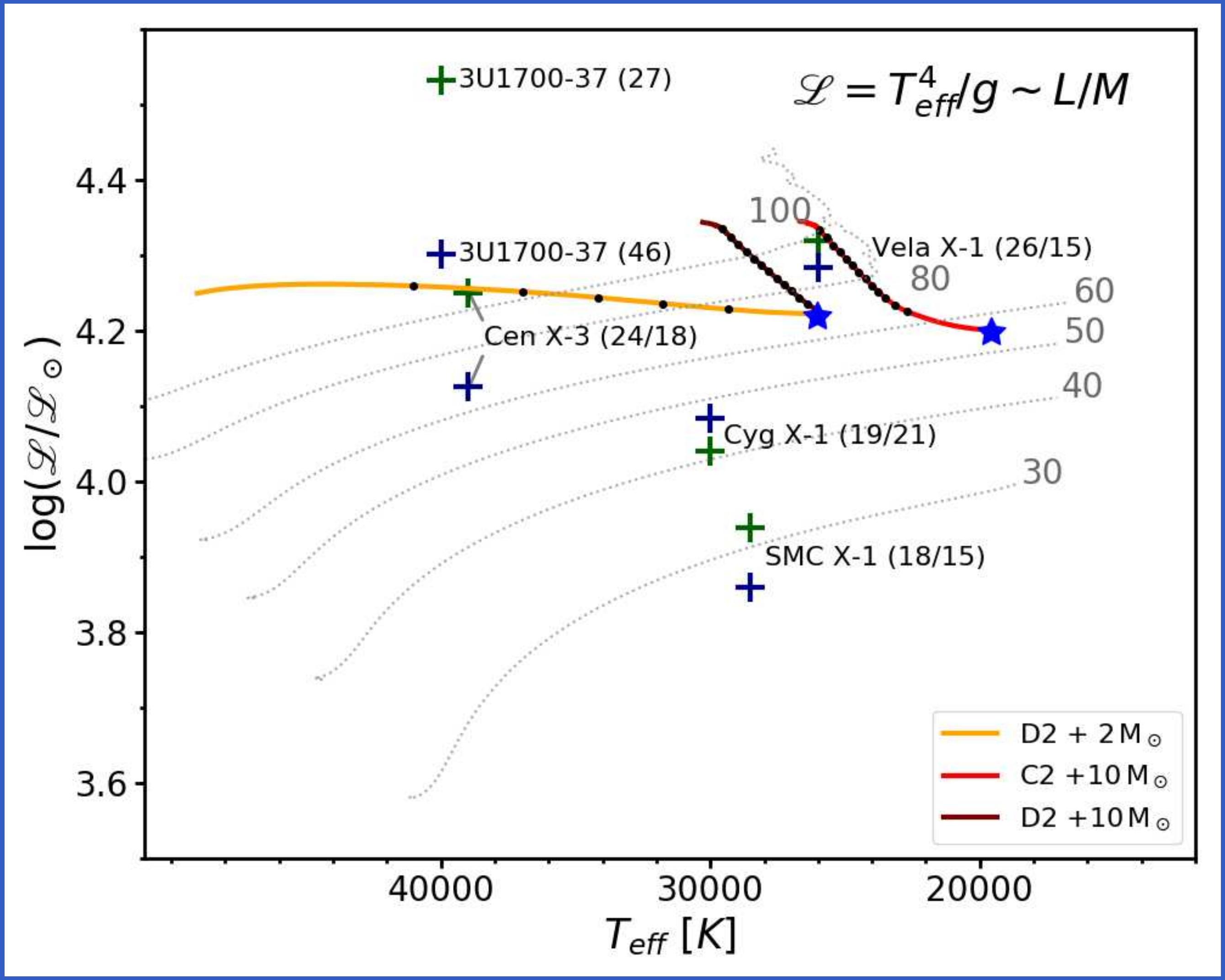
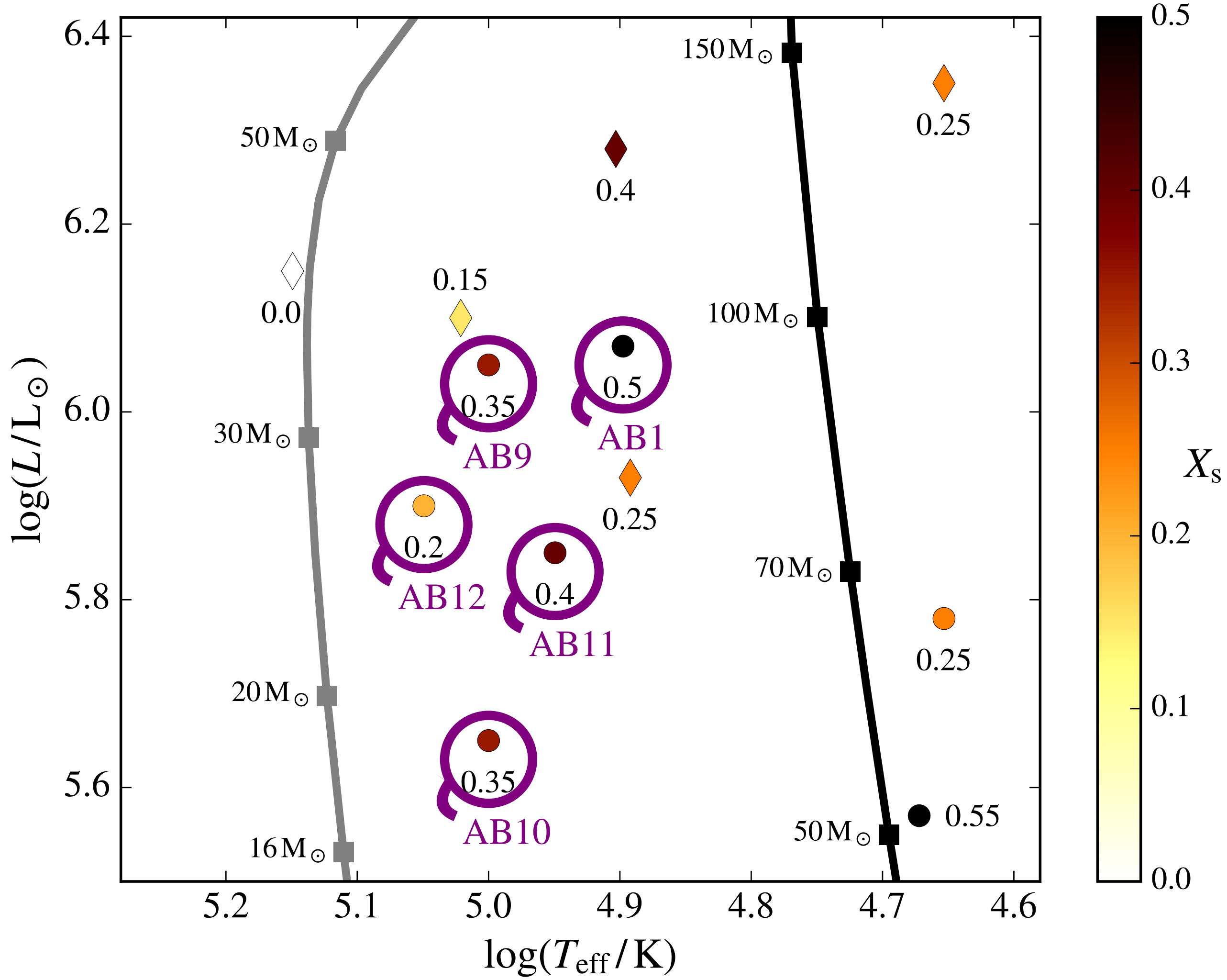


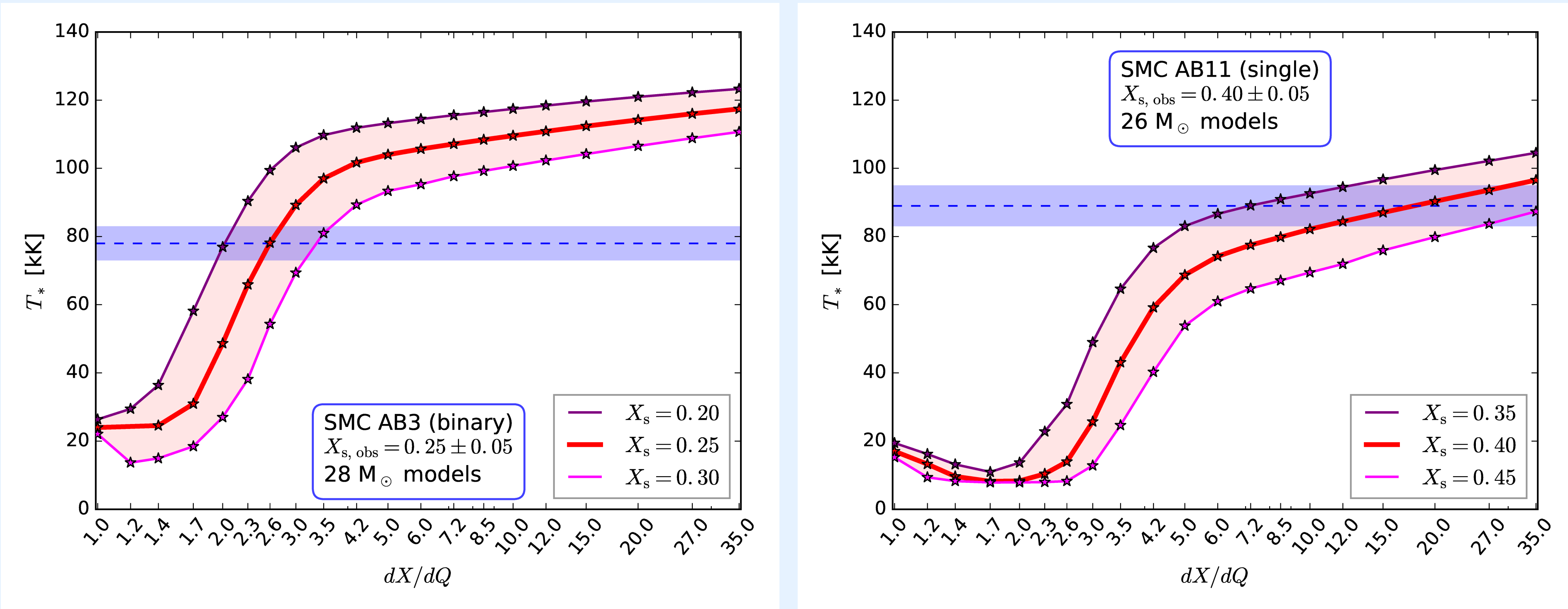

Quast+ 2019

# SMC WR stars




Schootemeijer+ 2018

# SMC WR stars: H-gradient




Schootemeijer+ 2018

# Quasi-chemically homogeneous evolution

# long-duration GRBs (collapsars)

- massive core ⇒ black hole
- compact size ⇒ $\frac{R_*}{c} \simeq \tau_{engine}$
- rapid rotation ⇒ centrifugal barrier
  ⇒ $j \simeq 10^{16}\,\mathrm{cm^2 s^{-1}}$

Woosley 1993

# Chemically homogeneous evolution

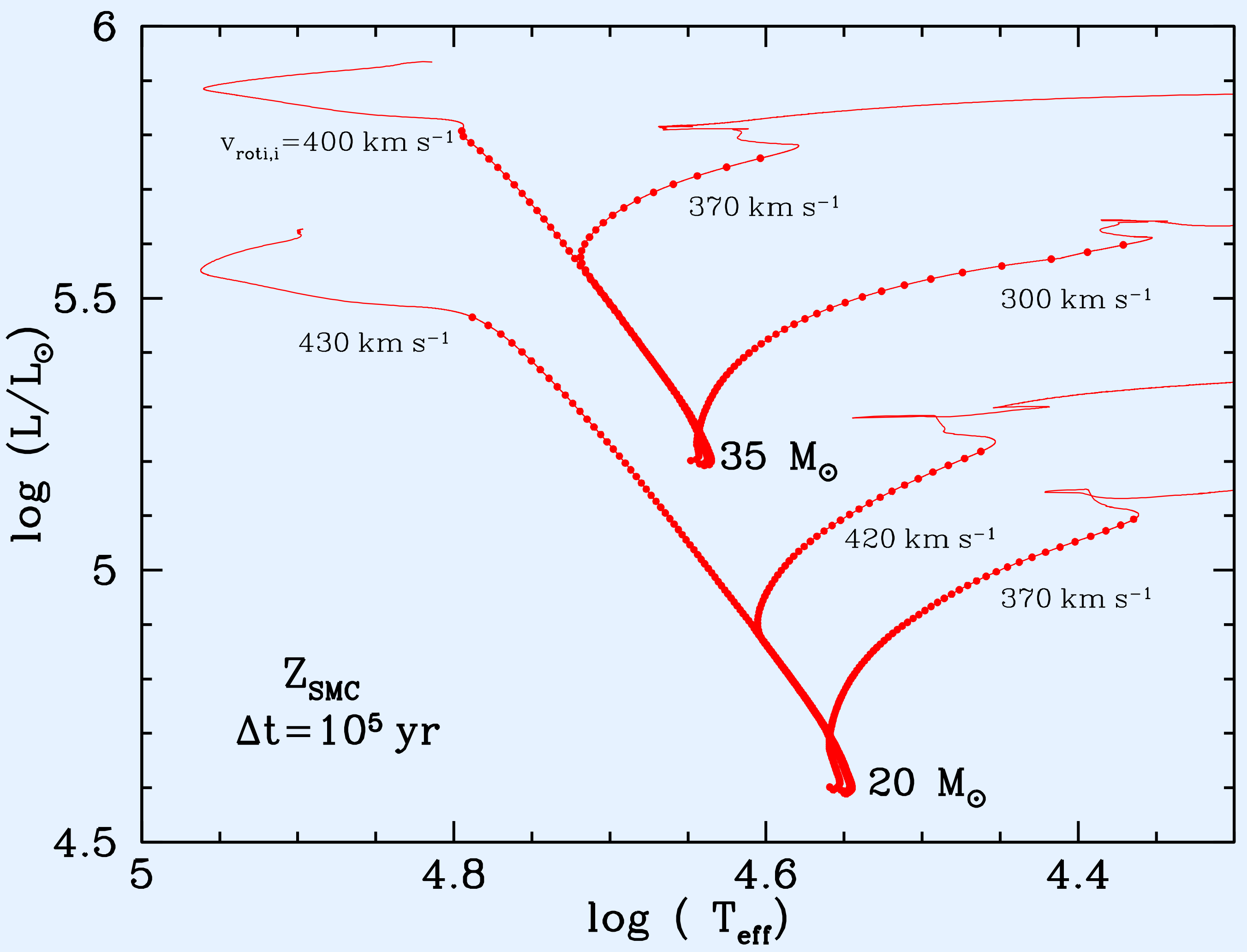
$v_{rot} \uparrow \Rightarrow$ internal mixing timescale $\tau_{\rm mix} \downarrow$

For $M > 10\,{\rm M}_\odot$:

$\tau_{\rm mix} \simeq \tau_{\rm nuc} \Rightarrow$ Chem. homogeneous evolution

Maeder 1987; Yoon & Langer 2005; Woosley & Heger 2006

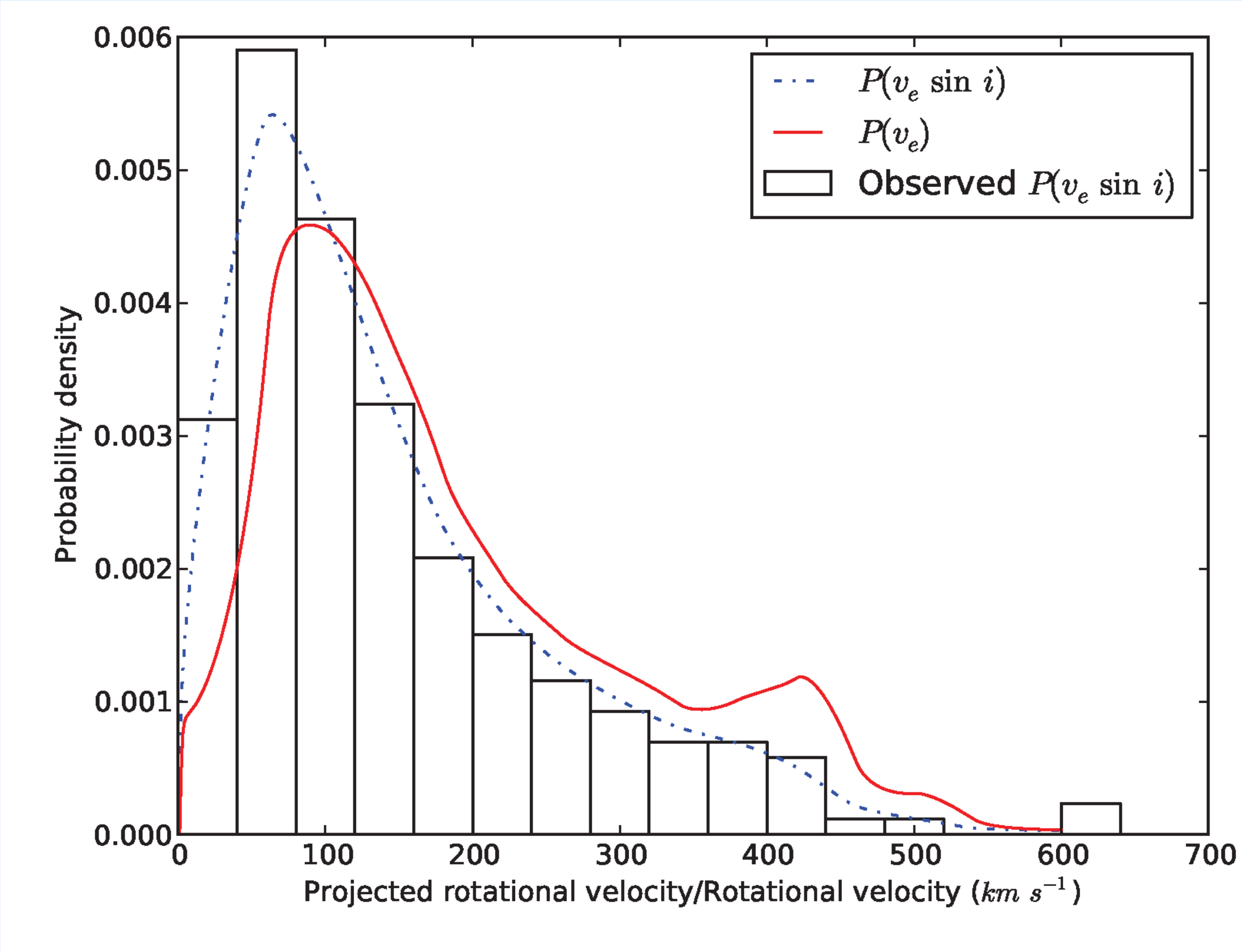
# Chemically homogeneous evolution




Brott et al. 2011

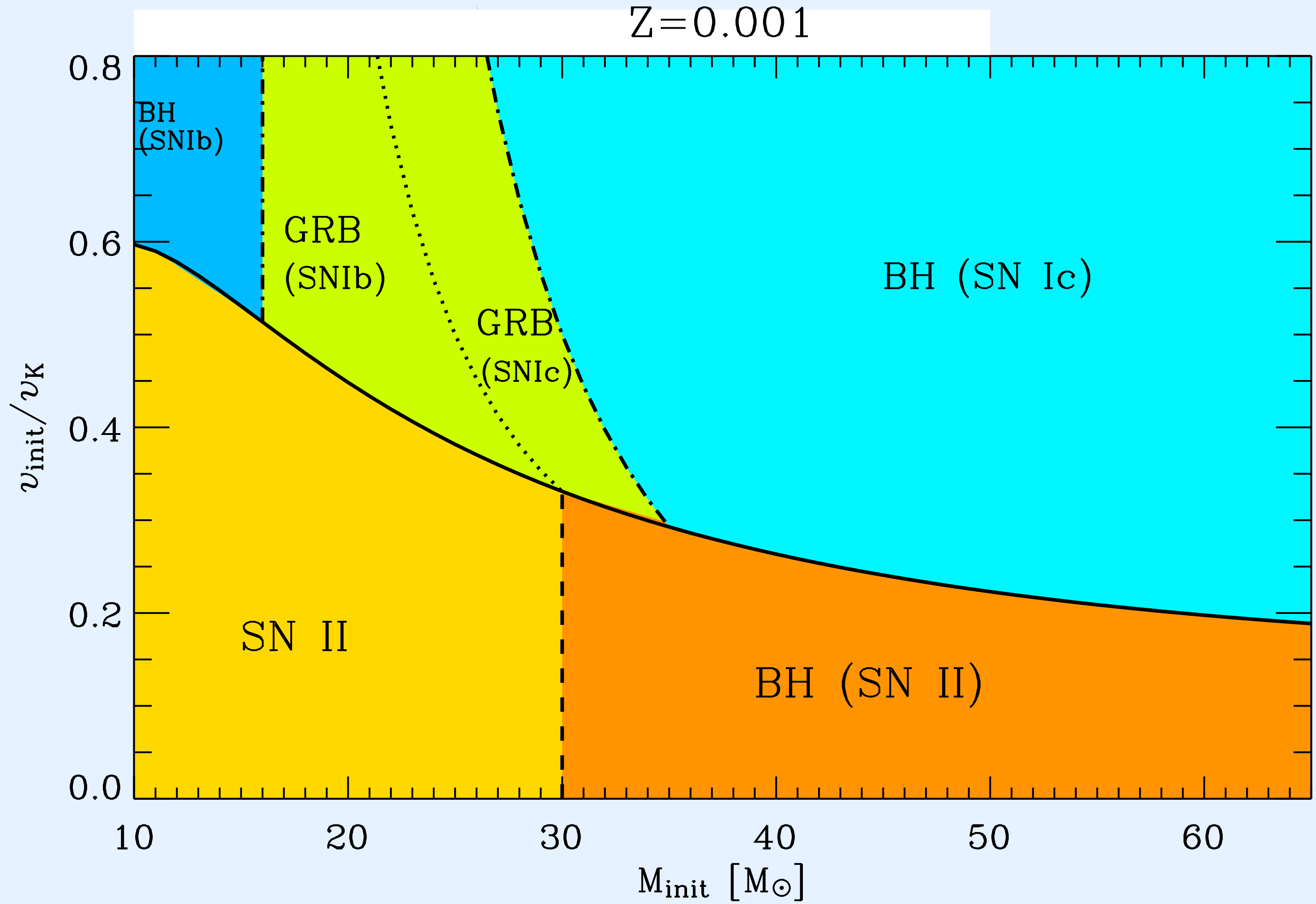
# CHE: how frequent?

$\Rightarrow$ single star are slowly rotating



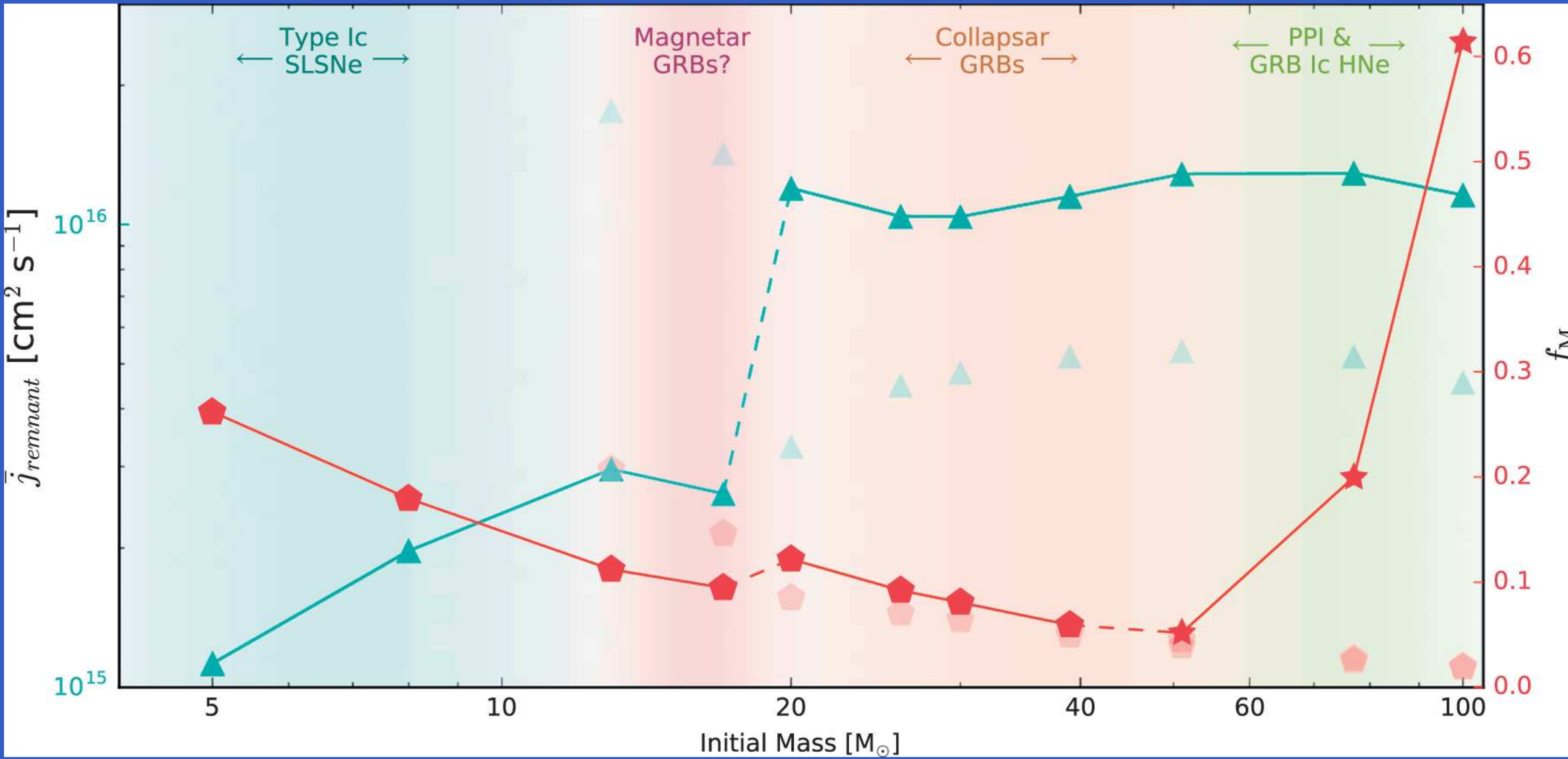

Ramirez Agudelo, Simon Diaz, Sana, et al. 2013, A&A, 560, A29

# lGRB progenitors at $Z=10^{-3}$



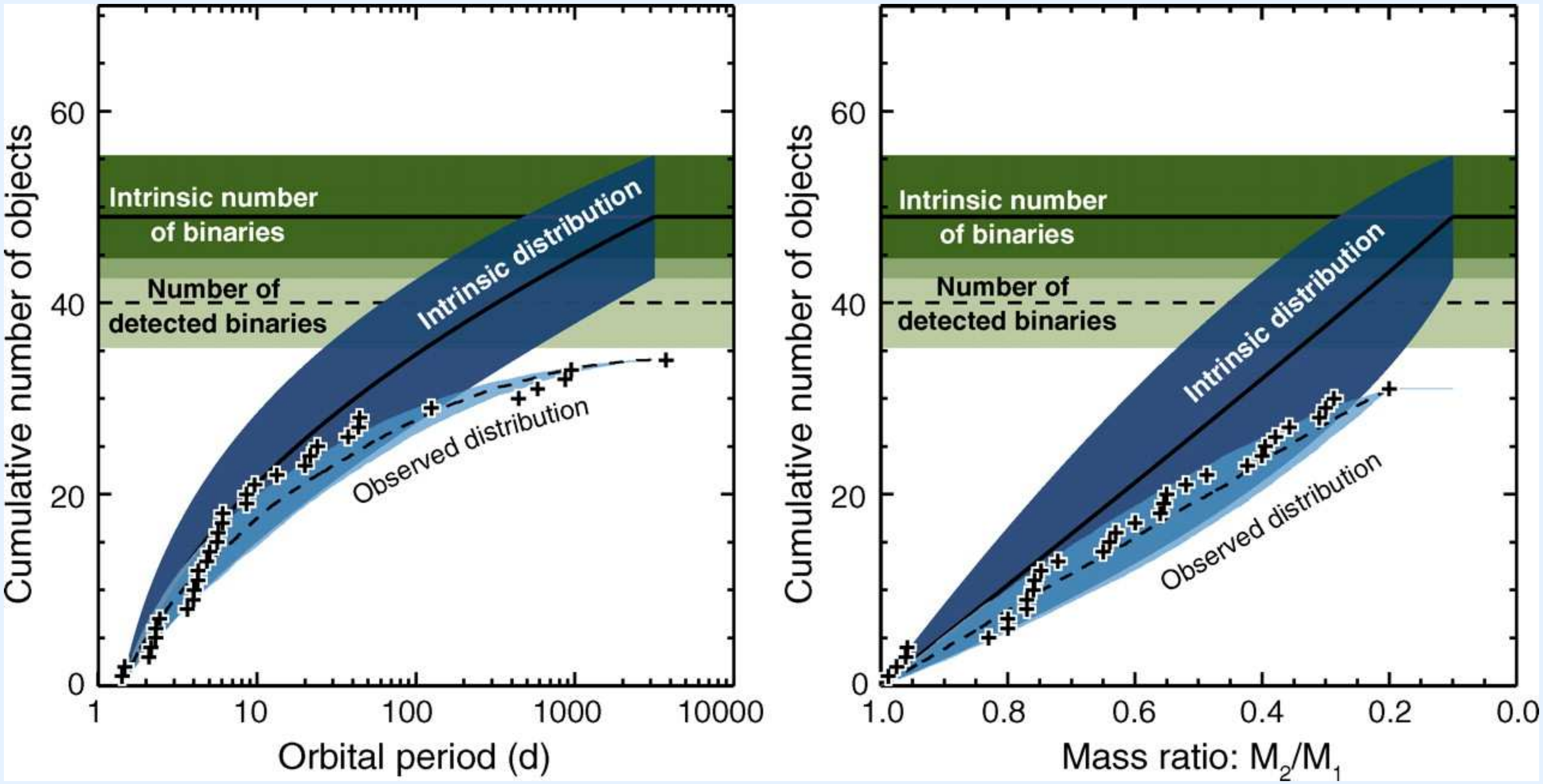

Yoon et al. 2006

# sCHE: SLSNe & lGRBs



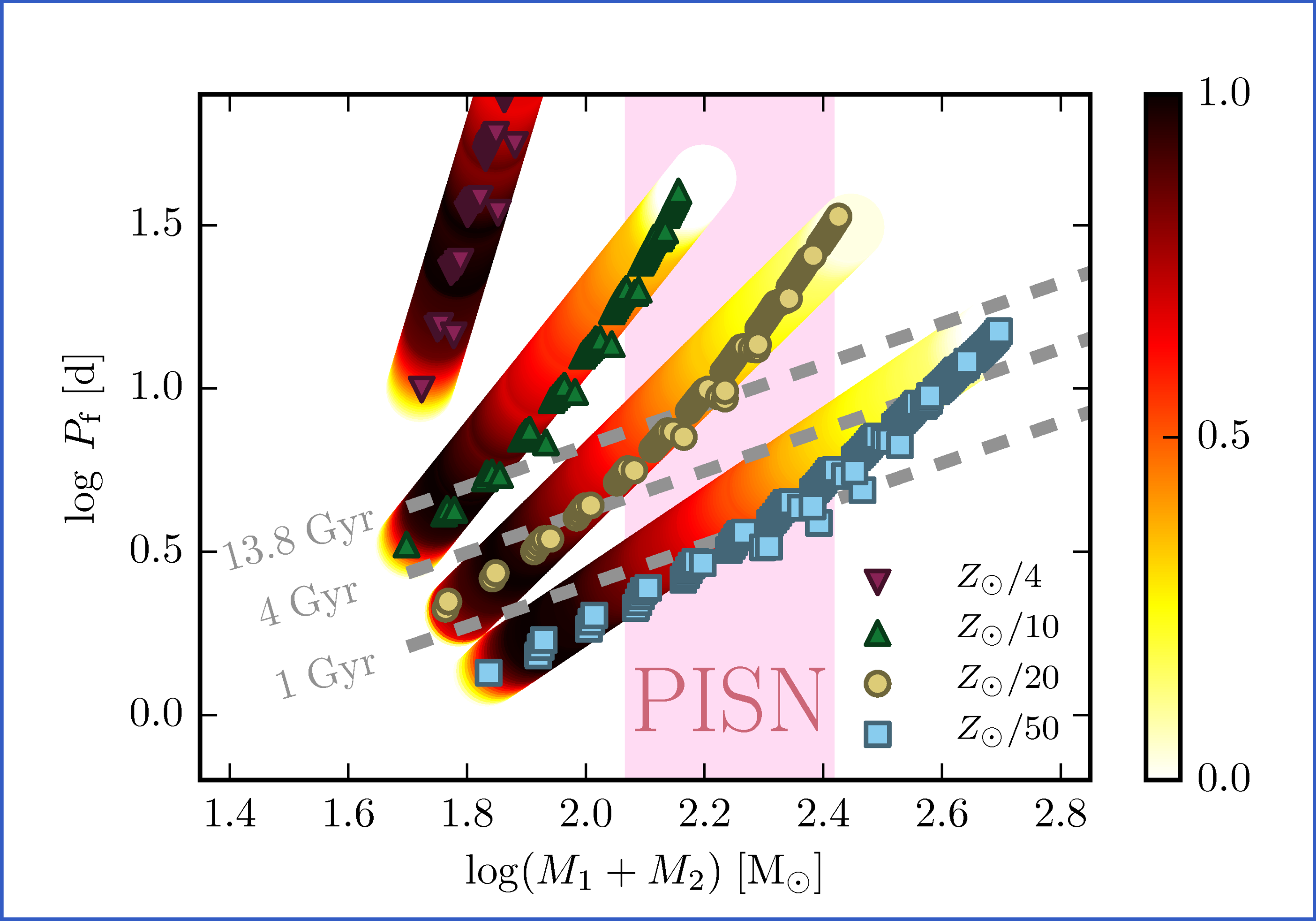

Aguilera Dena+ 2018: see his talk

# Binaries!



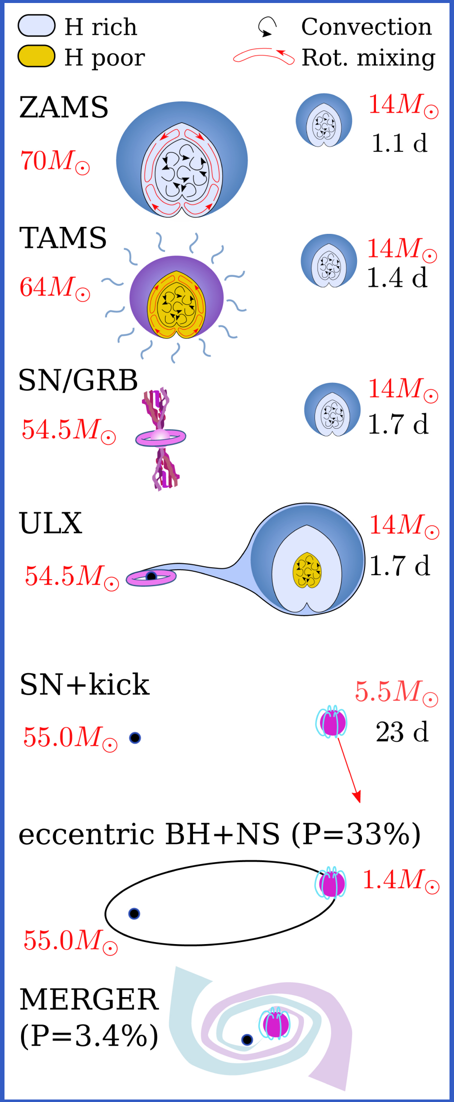

Sana et al., Science, 2012

# Forming BH+BH merger




Marchant+ 2016

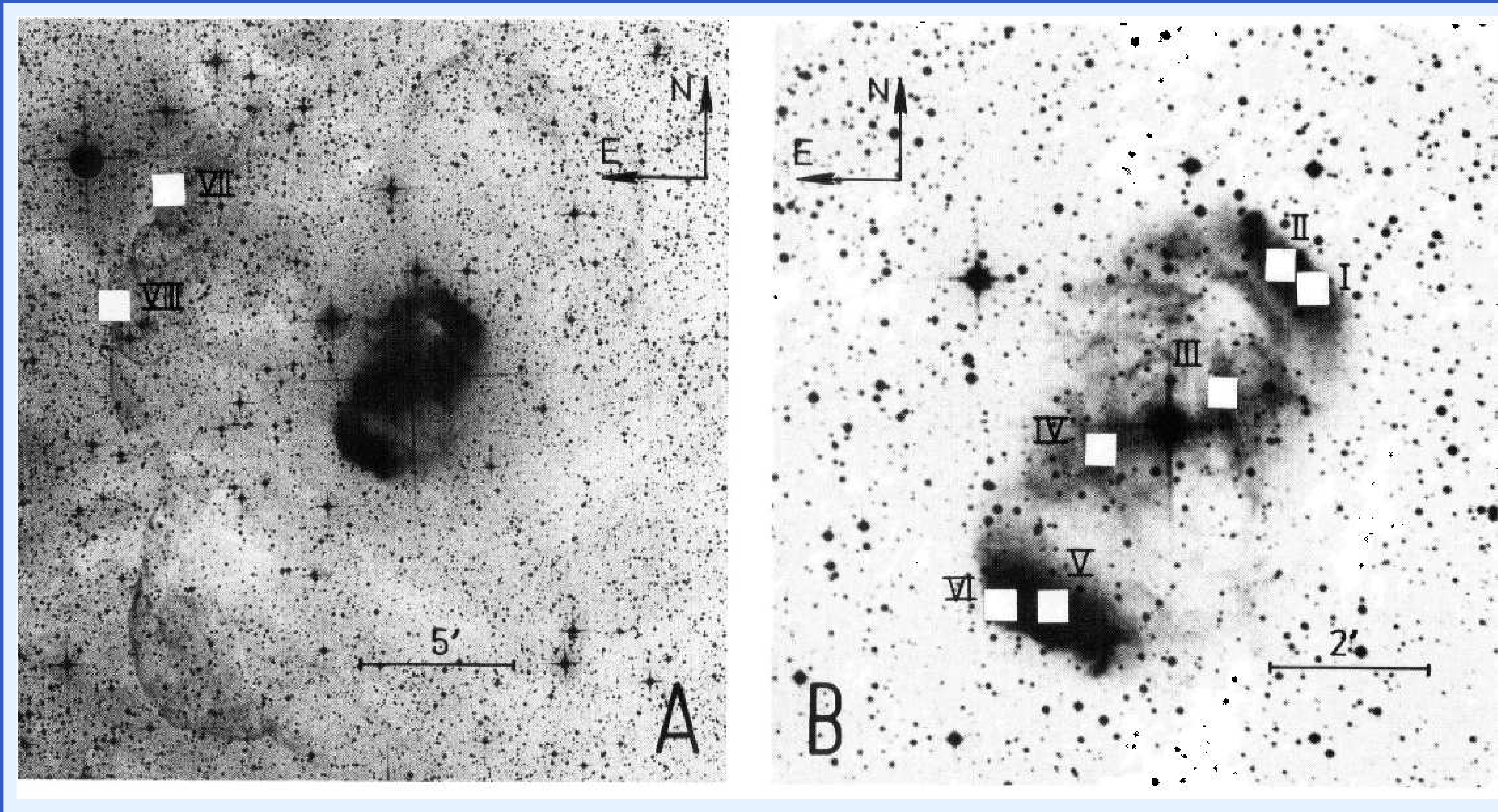
# Forming the brightest ULXs




Marchant+ 2017

# Magnetic stars

# HD 148937 O6.5f?p: a smoking gun?

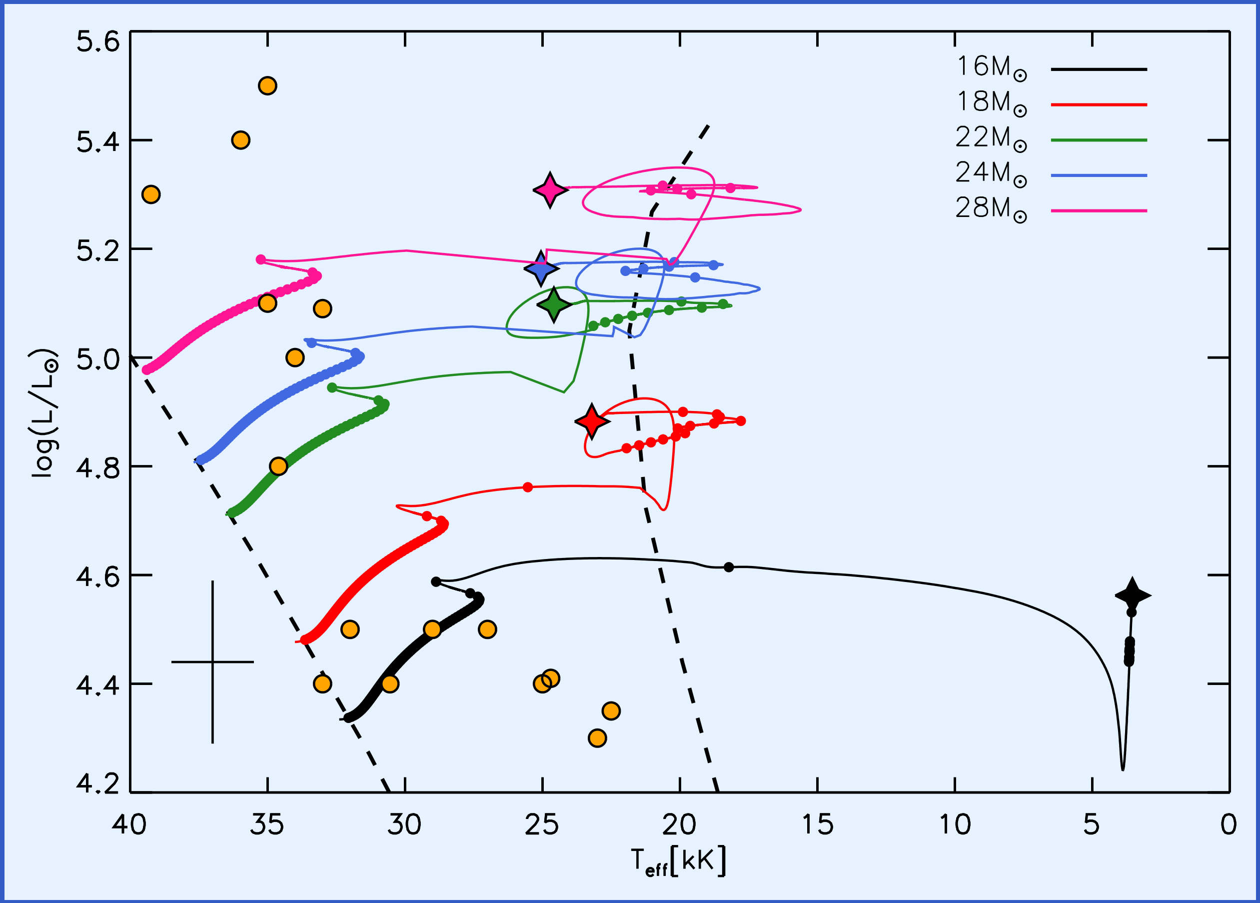



Leitherer & Chavarria-K. 1987

# Merger products

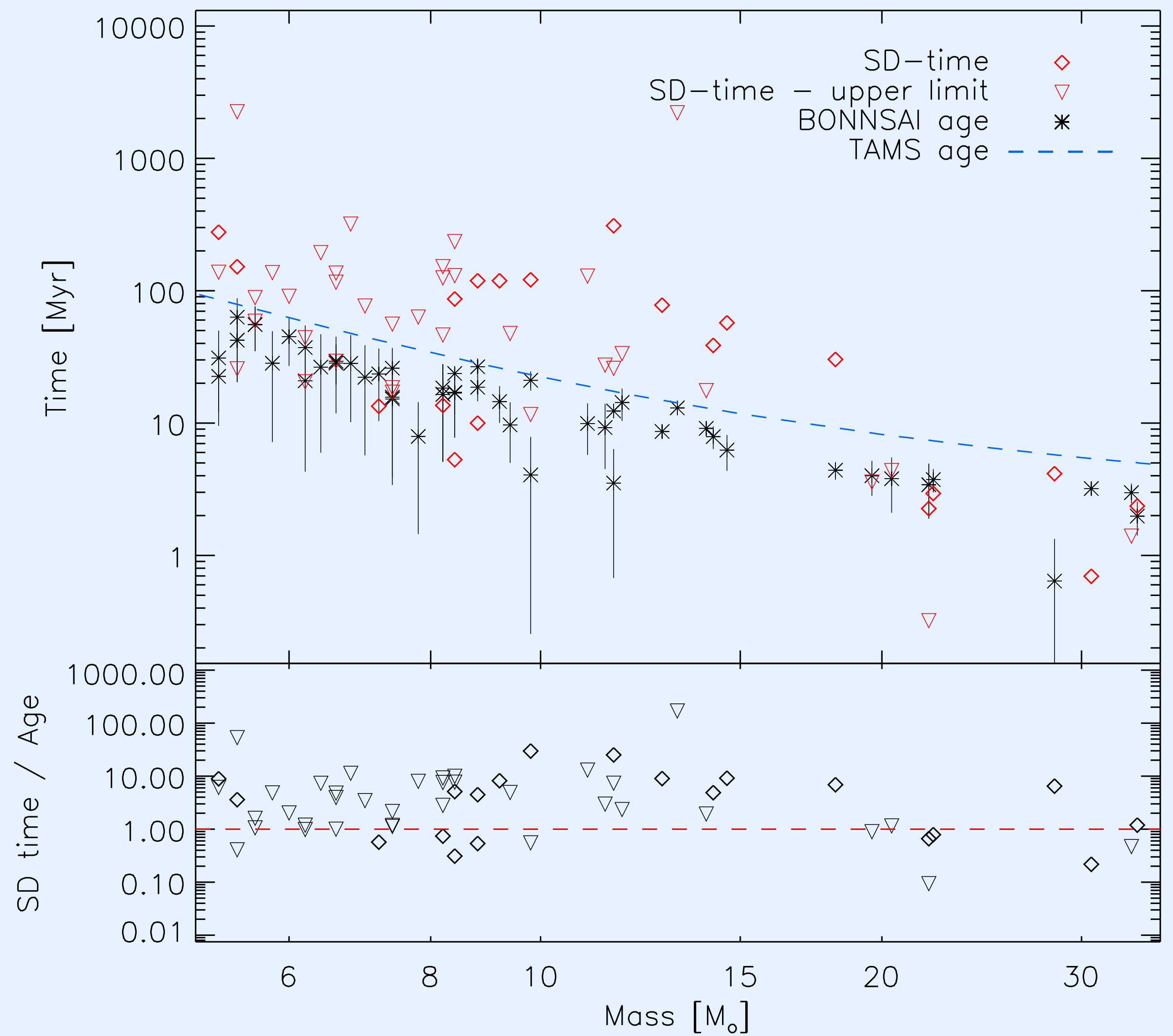
MS merger: blue stragglers

post-MS merger: blue supergiant



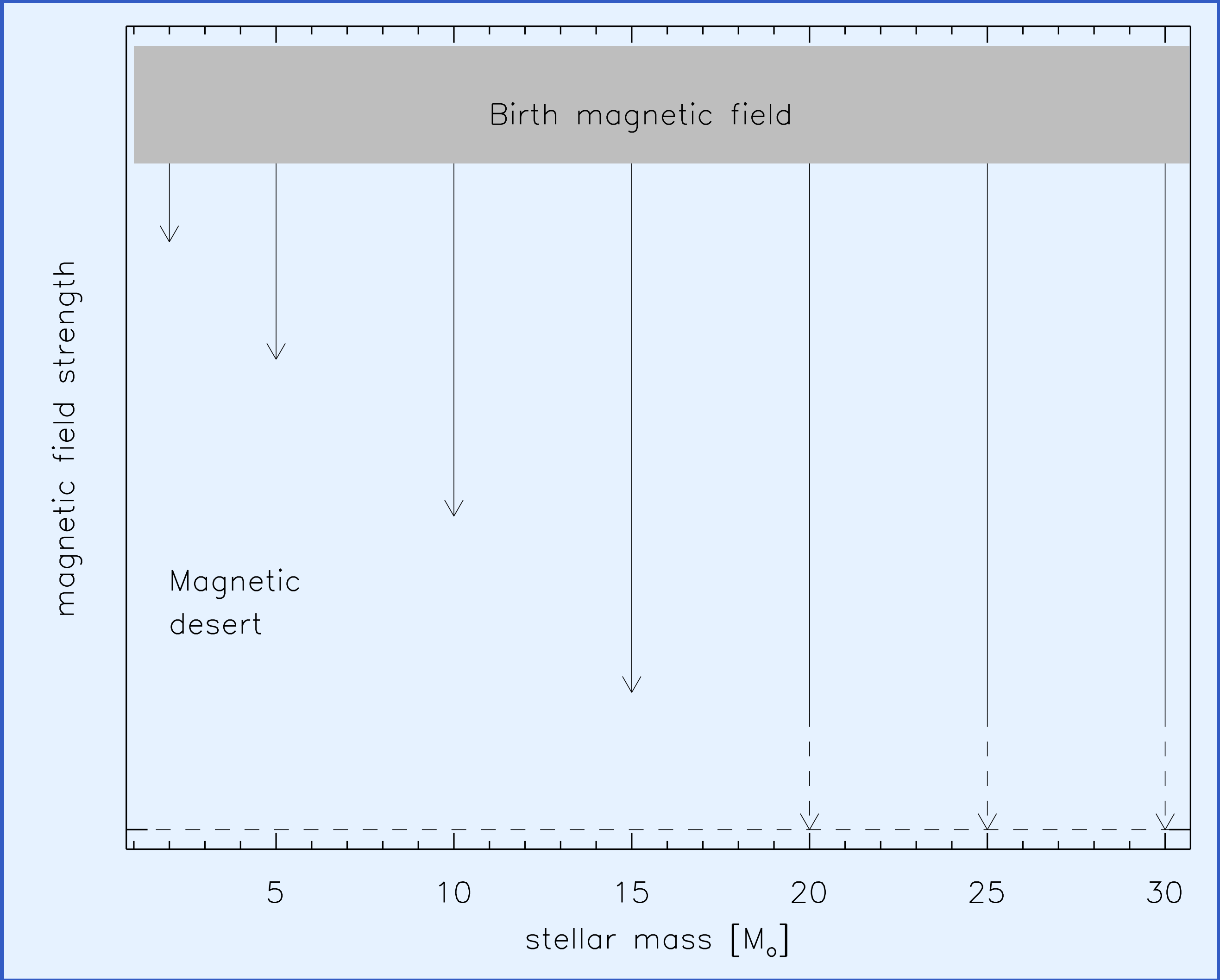

Petermann+ 2015

# B-field decay




Fossati+ 2016

# B-field decay: mass dependent




Fossati+ 2016

# Advanced evolution

Can stable large scale fields prevail?

- intermediate mass stars:
  magnetic Herbig AeBe (10%) $\rightarrow$ Ap/Bp star (10%) $\rightarrow$ magnetic WD (10%)
- massive stars:
  magnetic OB (10%) $\rightarrow$ magnetar (10% ?)

flux conservation: B-fields scale within uncertain-ties

# Thank you for your interest!