大質量放出を伴う初代星からの対不安定型超新星

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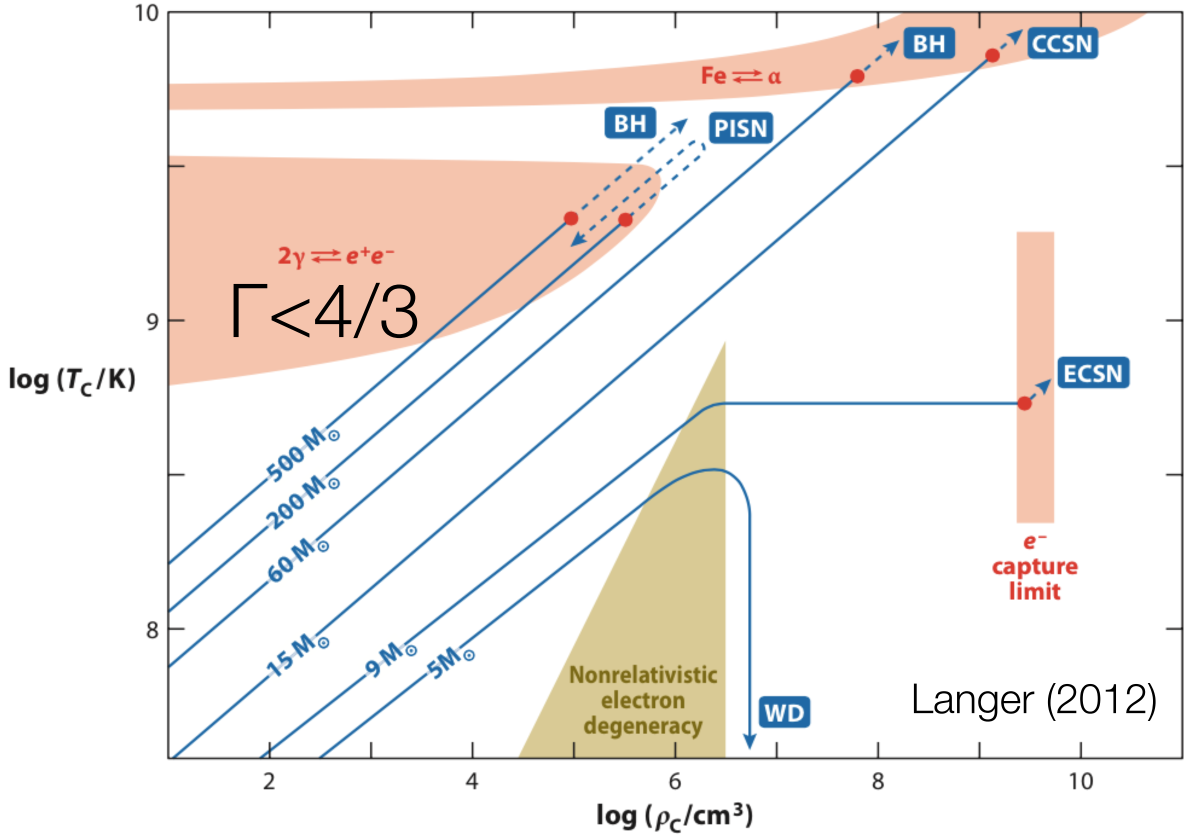
Pair-instability supernovae (PISNe)

- thermonuclear explosions of very massive stars
  - He core mass between ~ 60 Msun and ~ 130 Msun
    - ZAMS mass between ~ 150 Msun and ~ 250 Msun
      - when there are little mass loss and rotation



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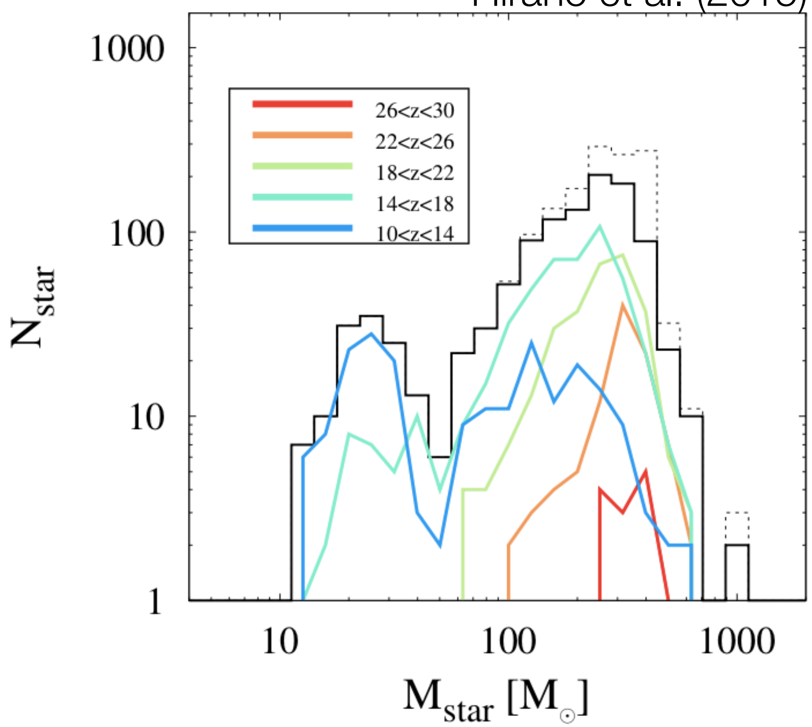
- PISNe prefer metal-poor environment
    - small radiation-driven mass loss
      - rapid rotation
    - first stars
    - first IMF may be top-heavy

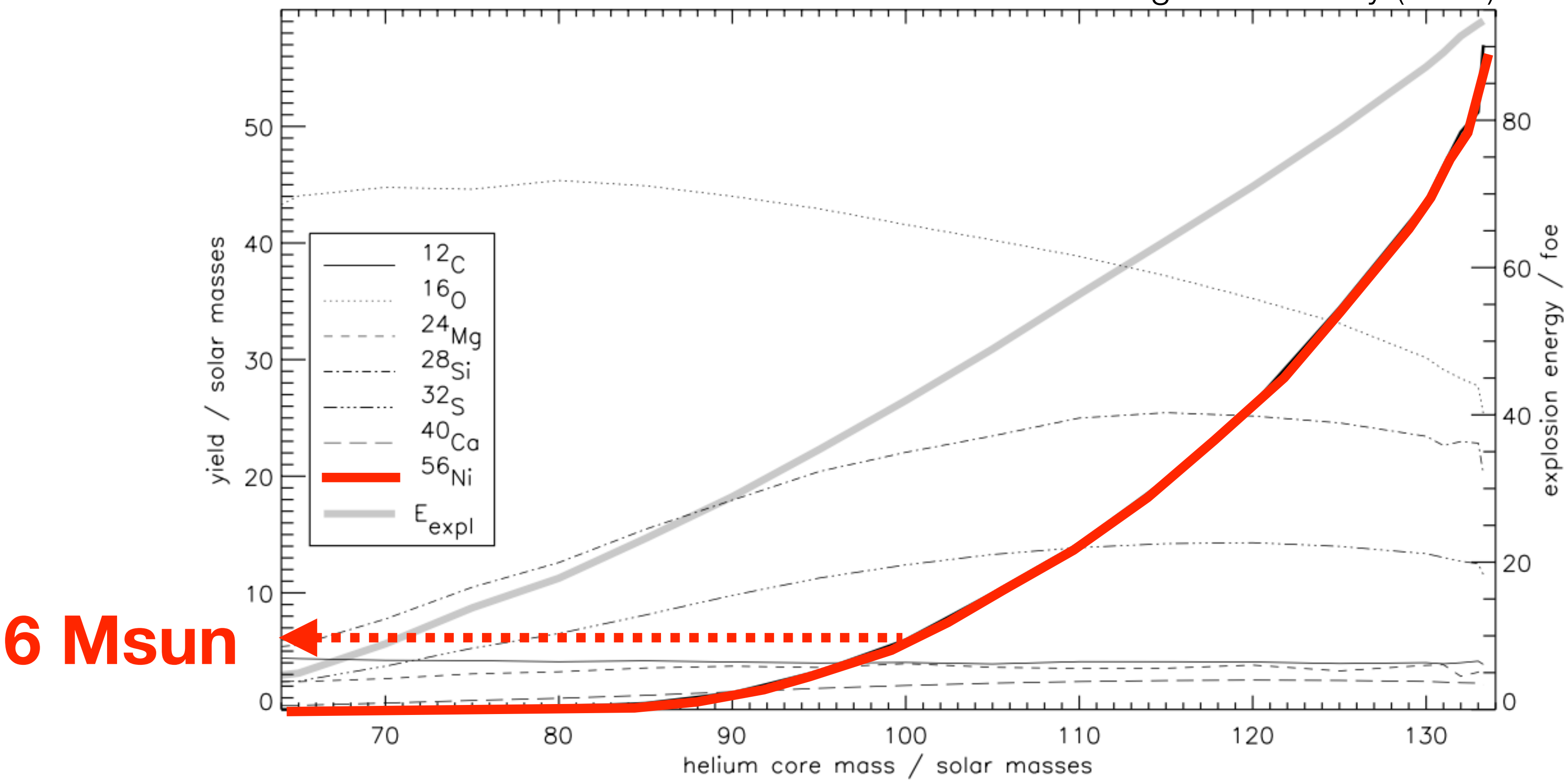
Hirano et al. (2015)



Pair-instability supernovae (PISNe)

- large amount of **56Ni** can be produced (but not necessarily!)
  - nuclear decay of 56Ni → 56Co → 56Fe makes SNe bright
  - typical core-collapse SNe: ~ 0.05 - 0.1 Msun

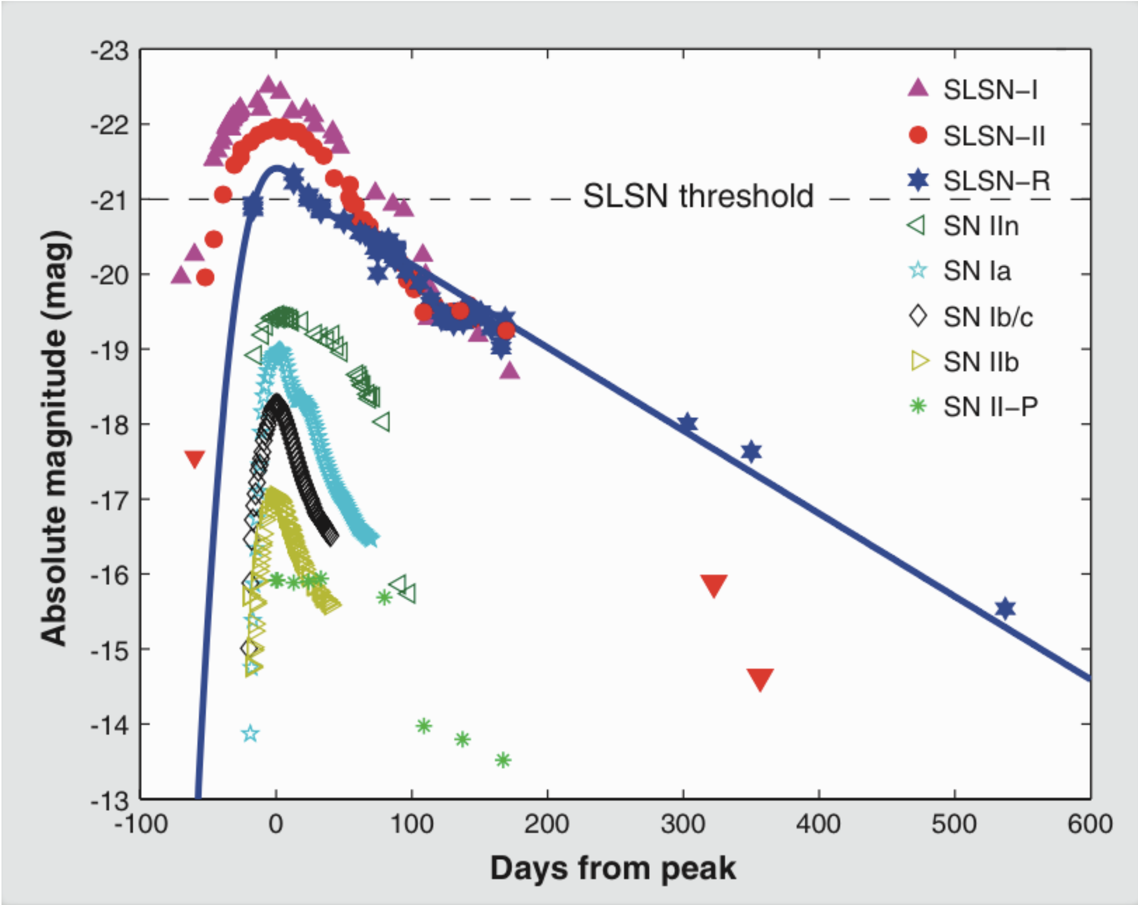
Heger & Woosley (2002)



Pair-instability supernovae (PISNe)

- large amount of 56Ni production: very luminous
  - related to superluminous SNe (SLSNe)?
  - no conclusive SLSNe observed yet

Gal-Yam (2012)



Pair-instability supernovae: summary

- thermonuclear explosions of very massive stars
  - He core mass needs to be between ~ 60 Msun and ~ 130 Msun
    - ZAMS mass corresponds to ~ 150 Msun - ~ 250 Msun
  - progenitors should have small mass-loss rates
    - presumed to appear at low metallicity environment
    - especially first stars
- some of them produce large amount of 56Ni: very luminous
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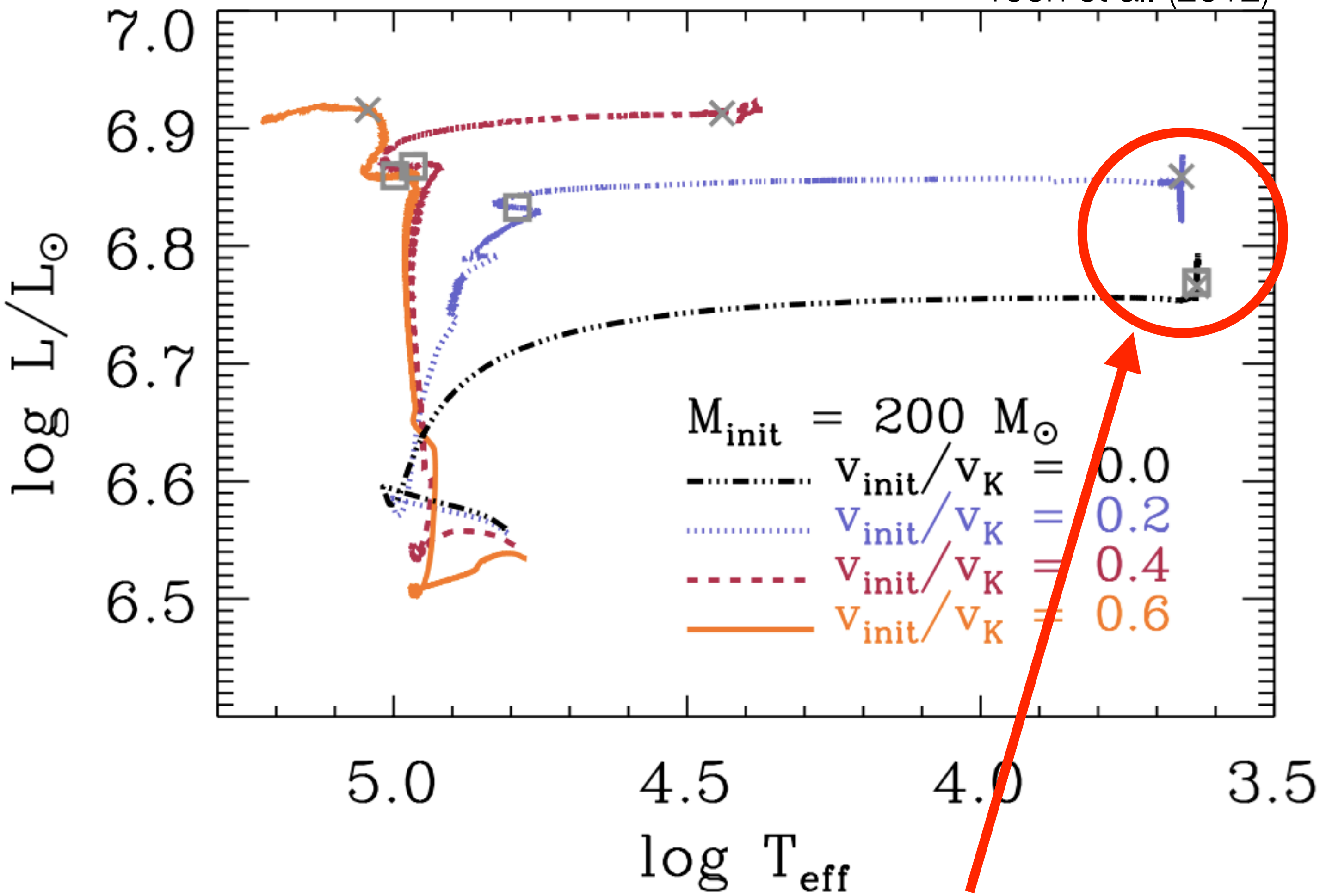
PISN progenitors do not have mass loss at all?

- evolution of zero-metallicity PISN progenitors in HR diagram

Yoon et al. (2012)

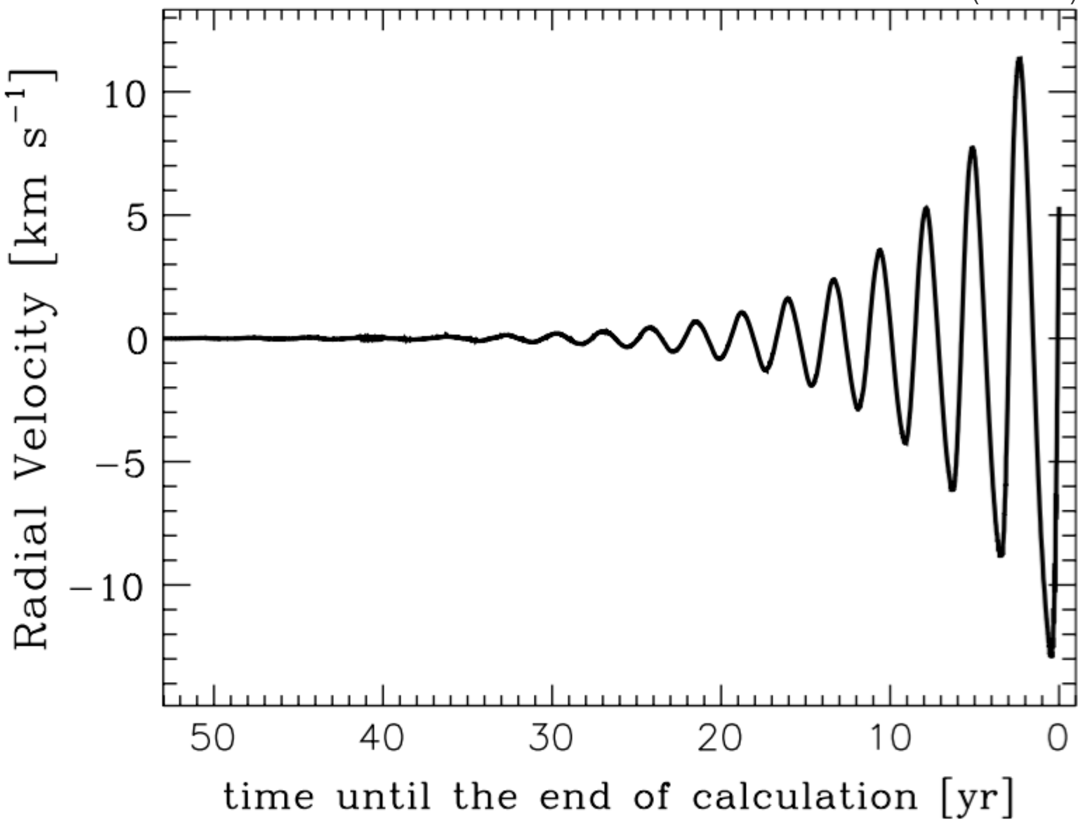


PISN progenitors evolve to red supergiants (RSGs)

Luminous RSGs: pulsationally unstable stars!

- RSGs with large L/M-ratio are pulsationally unstable
  - due to the kappa-mechanism activated near the surface
  - leading to mass loss (Heger et al. 1997, Yoon & Cantiello 2010)

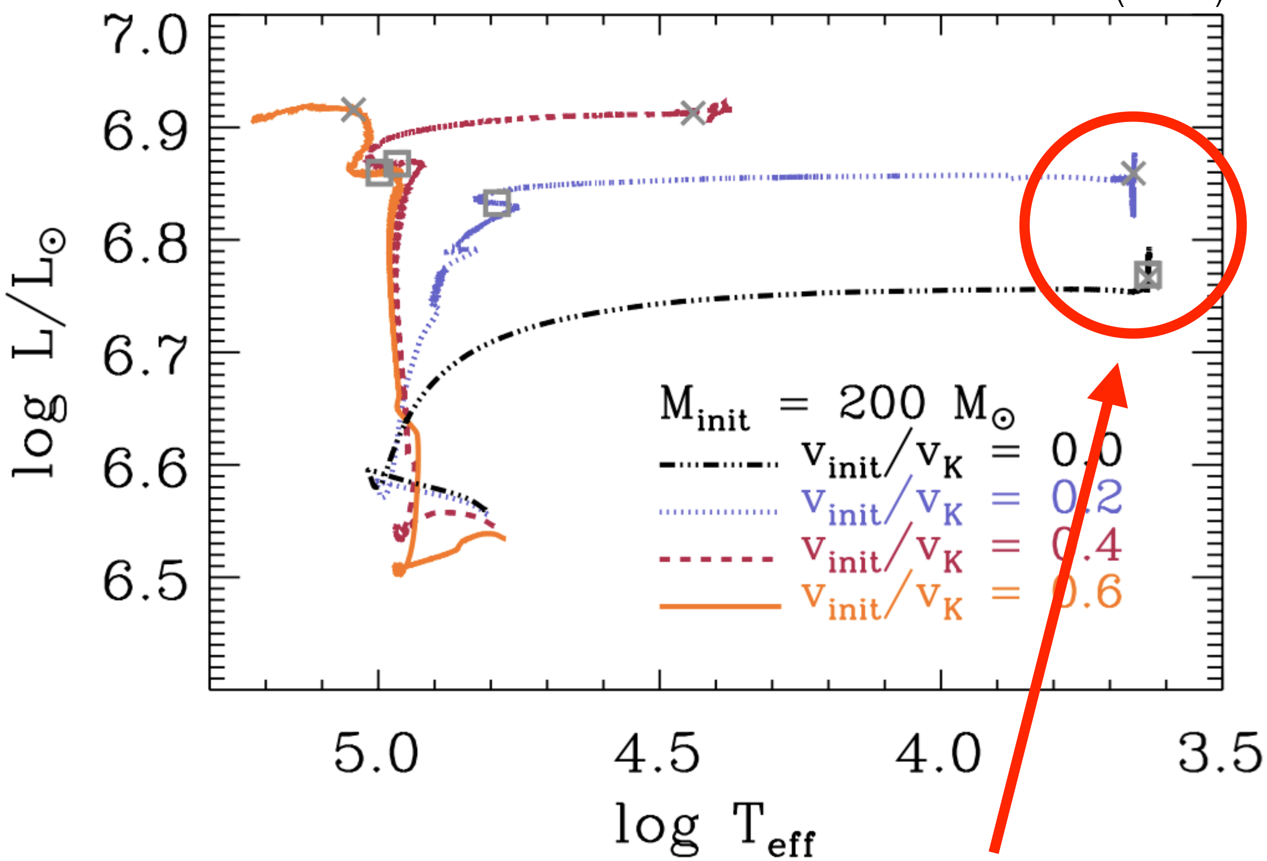
Yoon & Cantiello (2010)



Pulsations in RSG PISN progenitors?

- do RSG PISN progenitors suffer from pulsational mass loss?
  - if they do, how does it affect them?

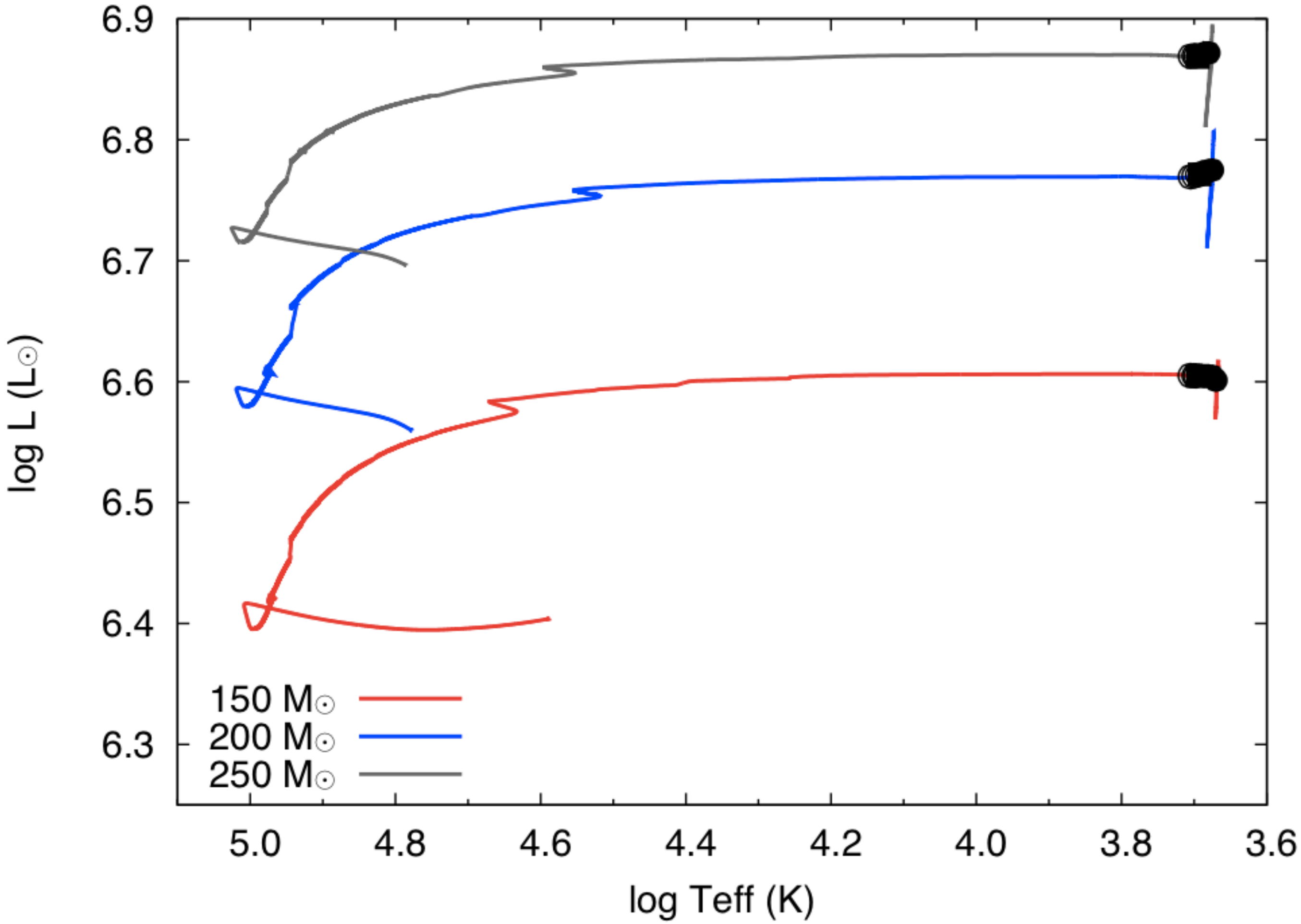
Yoon et al. (2012)



PISN progenitors evolve to red supergiants (RSGs)

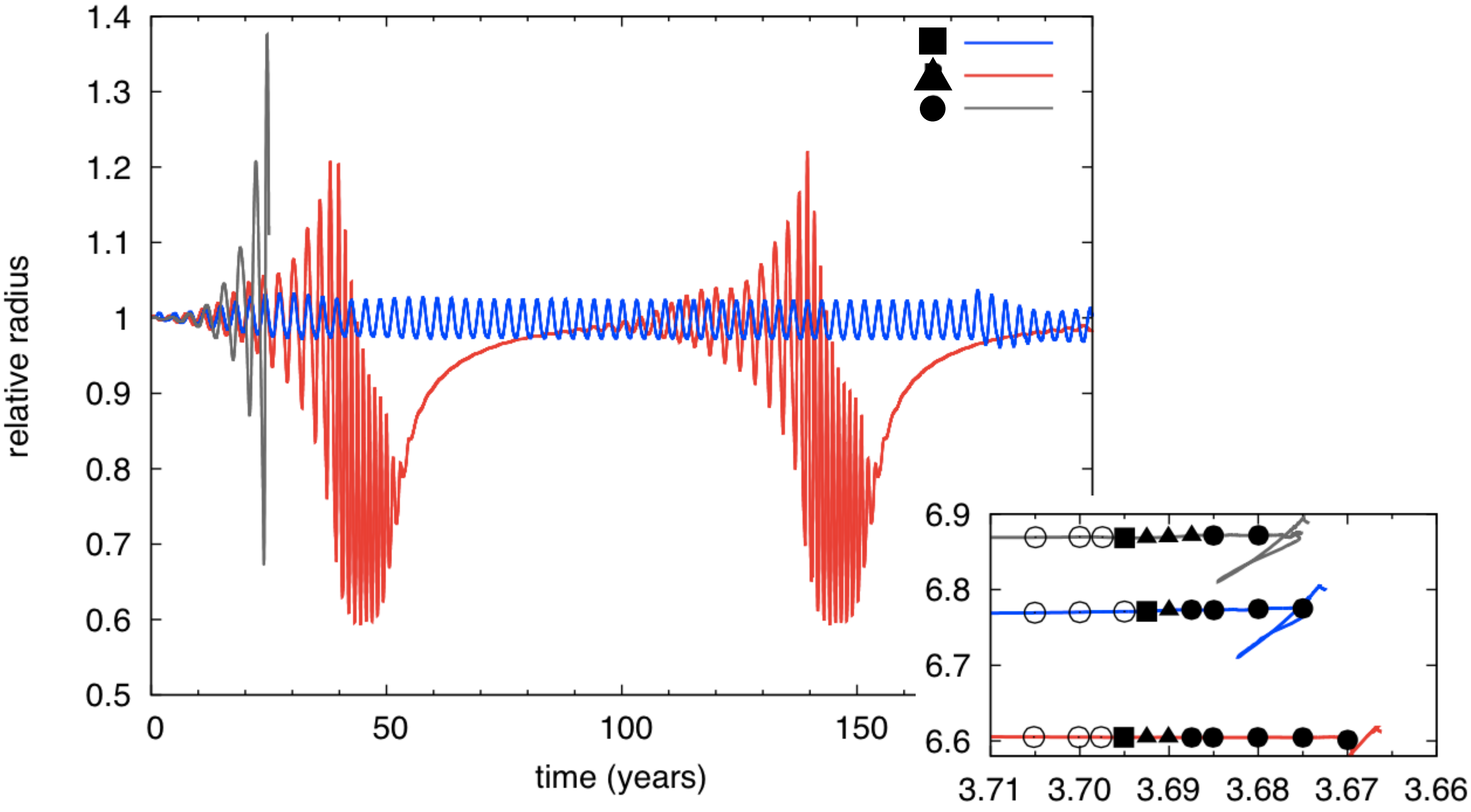
Zero-metallicity non-rotating PISN progenitors

- MESA (Paxton et al. 2011, 2013, 2015)

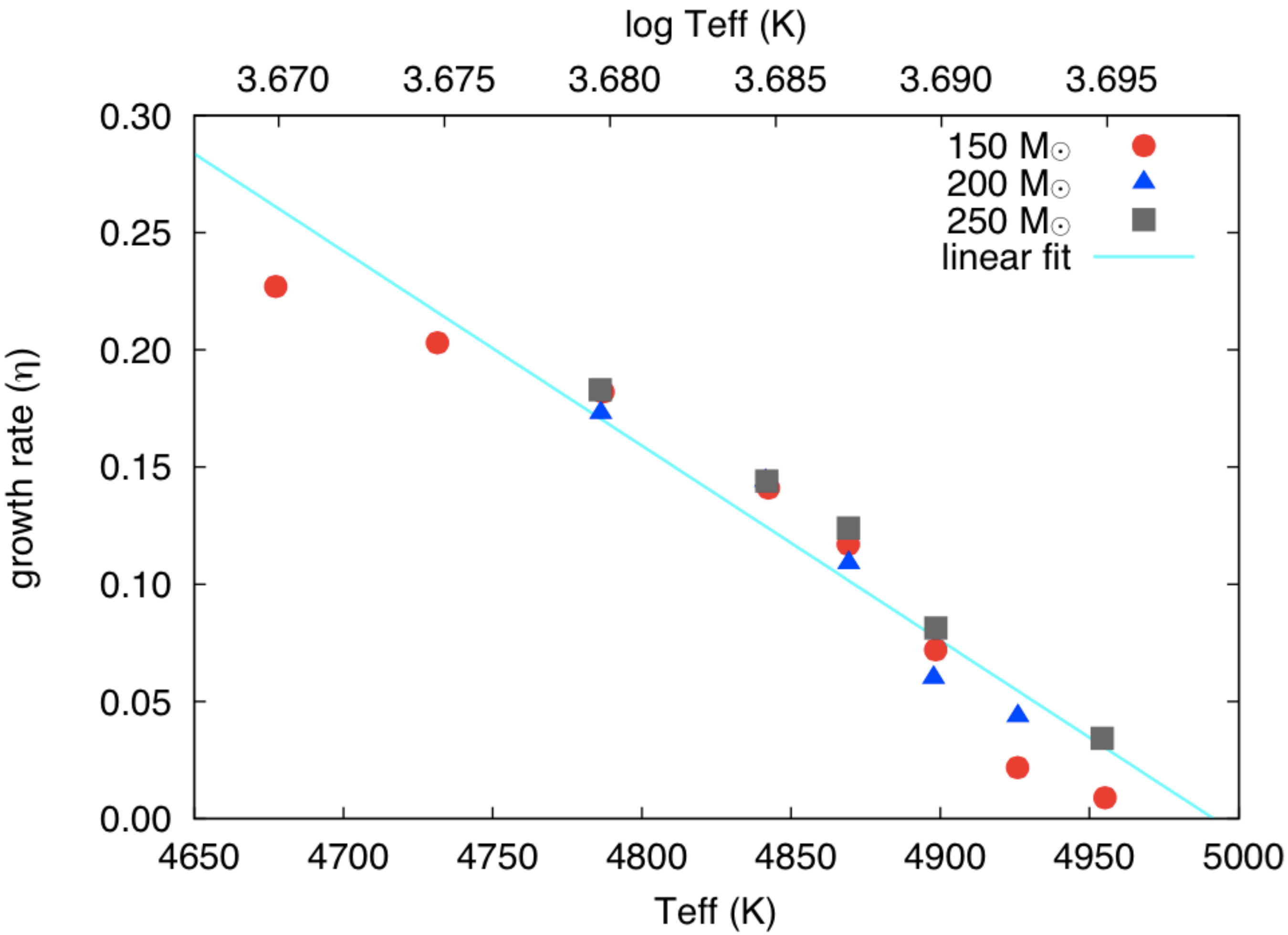


Pulsations of PISN progenitors during RSGs

- Follow evolution with very small time steps (dt <1e-3 year)



Pulsations of PISN progenitors during RSGs



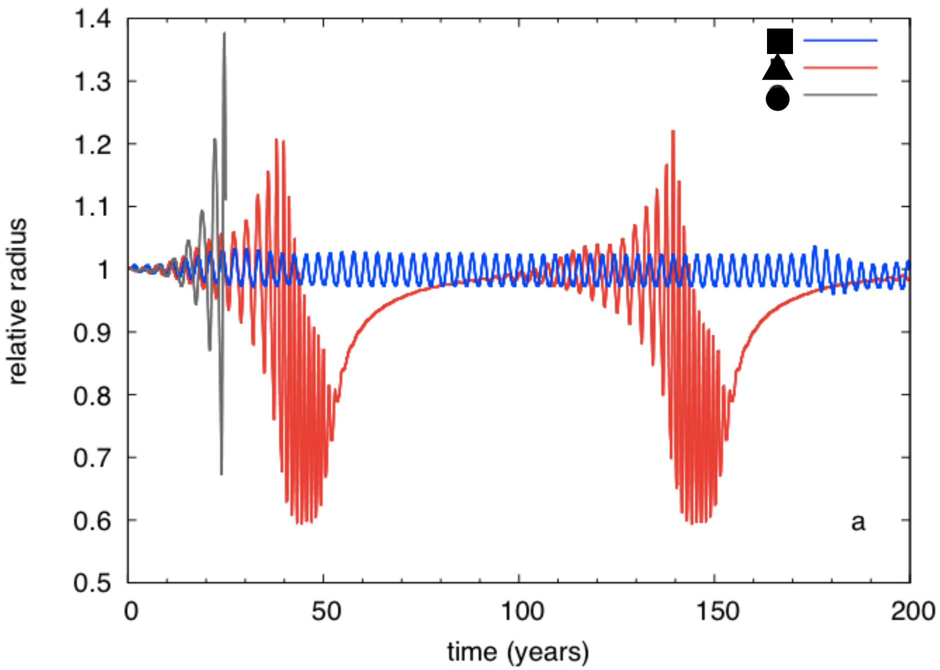
unstable when Teff < ~5000 K

$$\eta = (-8.30 \pm 0.59) \times 10^{-4} T_{\rm eff} + (4.15 \pm 0.29)$$

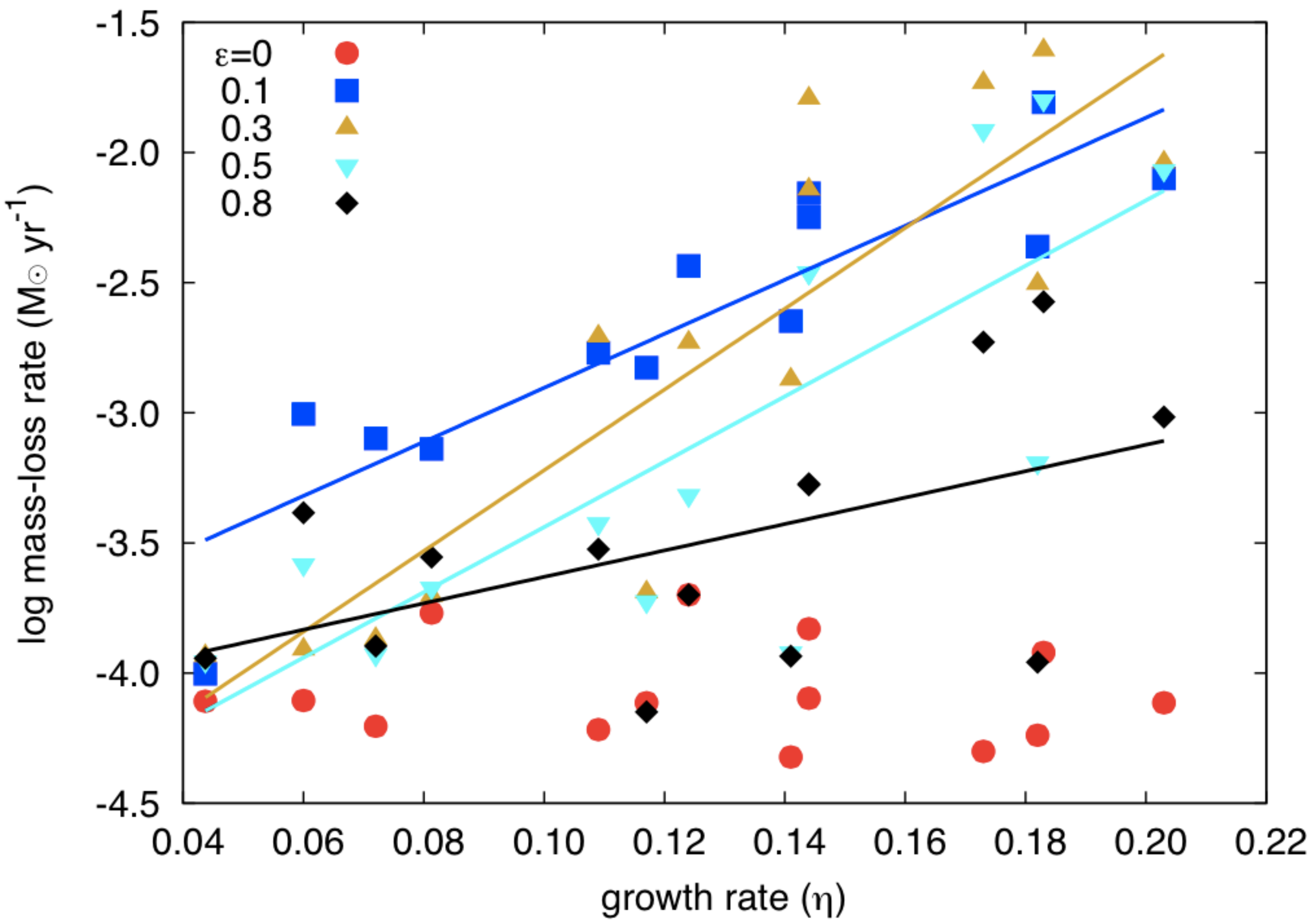
Relating pulsations to mass loss

$$\varepsilon \Delta E_{\mathrm{kin}} = \frac{1}{2} \dot{M}_{\mathrm{kin}} v_{\mathrm{esc}}^2 \Delta t$$

ε : conversion efficiency



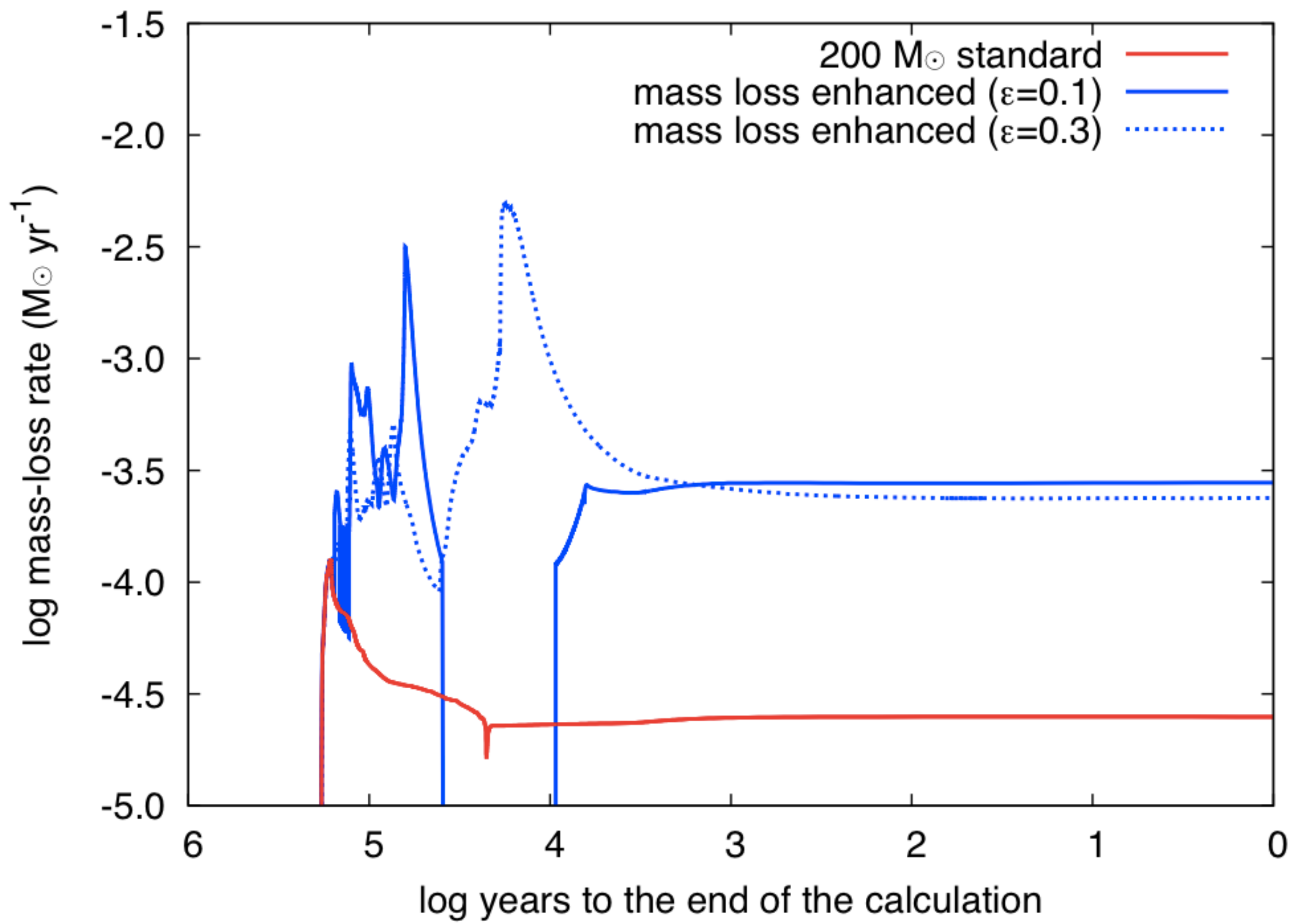
Pulsation-induced mass-loss rates



$$\log_{10} \dot{M}_{\rm kin} = \begin{cases} (10.38 \pm 1.58)\eta - (3.94 \pm 0.21) & (\varepsilon = 0.1), \\ (15.51 \pm 2.92)\eta - (4.77 \pm 0.33) & (\varepsilon = 0.3), \\ (12.55 \pm 2.88)\eta - (4.69 \pm 0.39) & (\varepsilon = 0.5), \\ (5.08 \pm 2.87)\eta - (4.14 \pm 0.33) & (\varepsilon = 0.8), \end{cases}$$

Effect of pulsation-driven mass loss on evolution

- mass-loss history



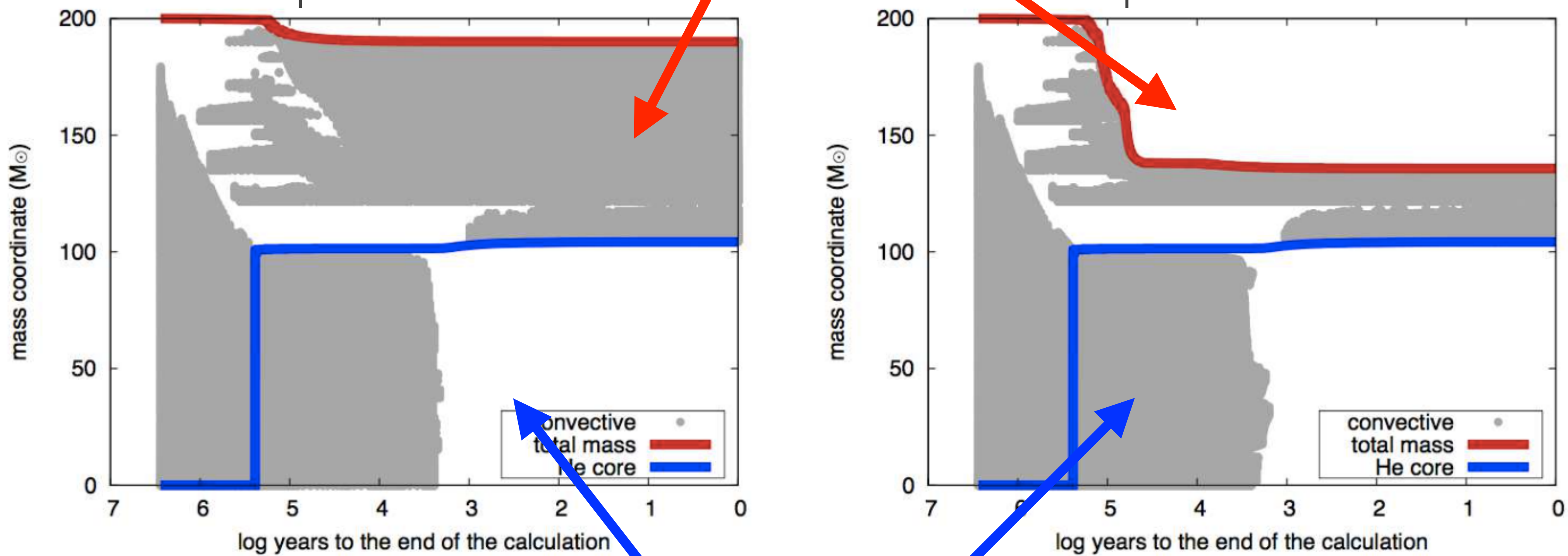
Effect of pulsation-driven mass loss on evolution

- Kippenhahn diagram

only surface H-rich layers are lost

w/o puls. mass loss

w/ puls. mass loss

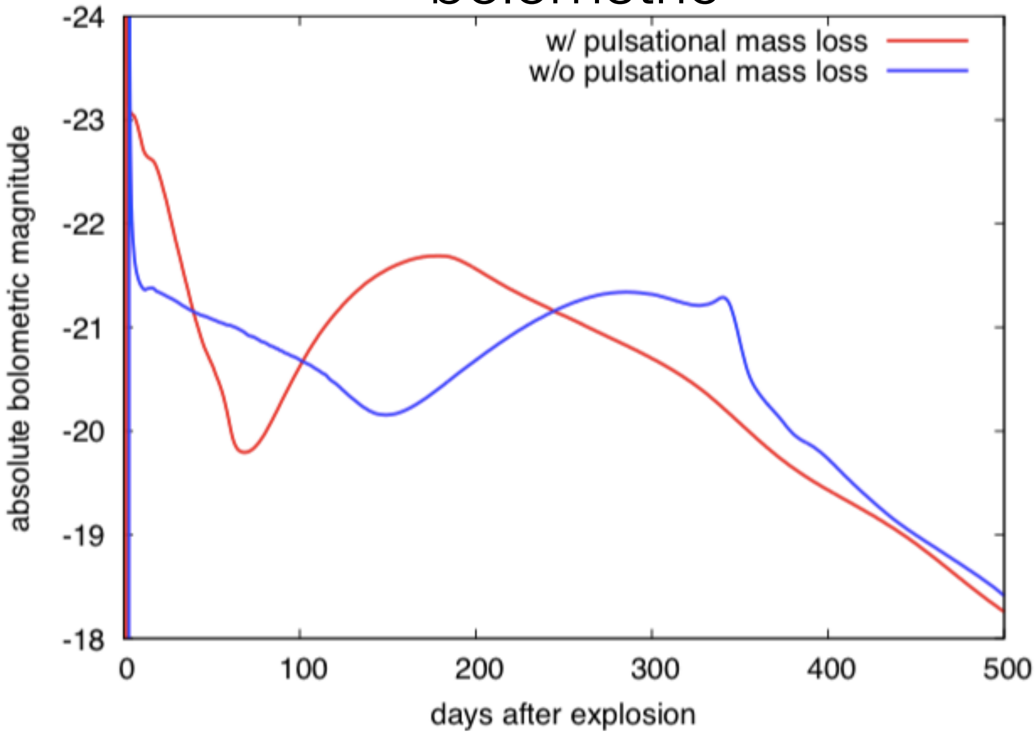


He-core mass is unaltered!

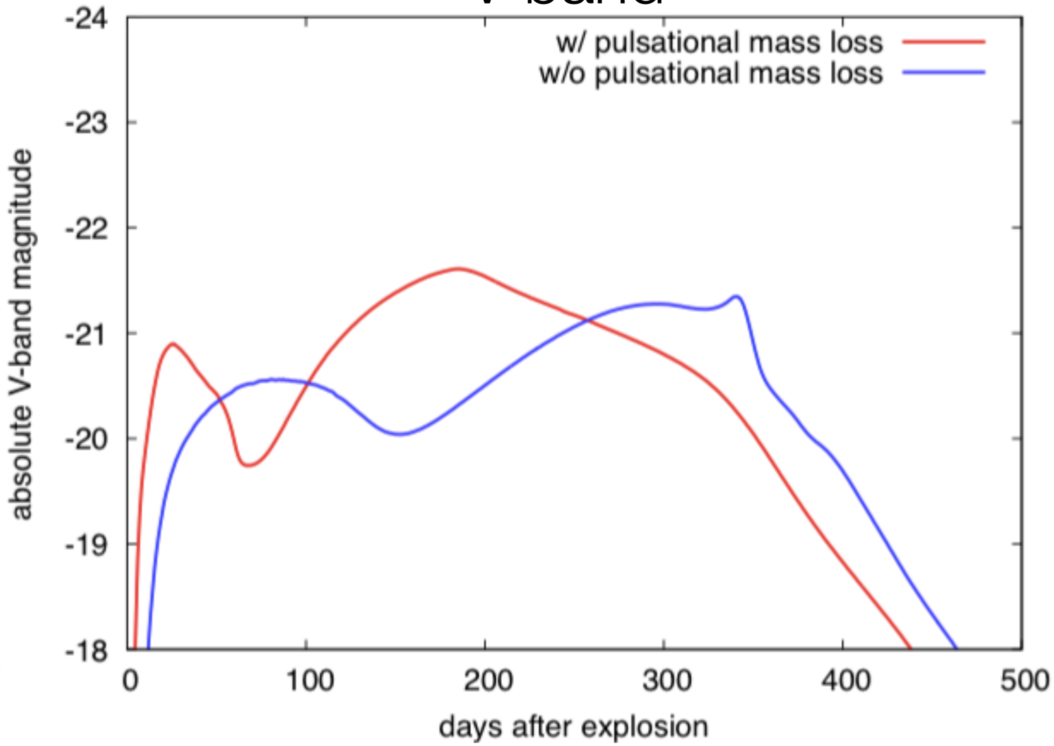
Effect on PISN properties: preliminary LCs

- 250 Msun model with and without pulsation-driven mass loss
  - w/o: Mtot=236 Msun, Mcore=125 Msun, Menv=111 Msun
  - w/ (ε=0.1 model): Mtot=164 Msun, Mcore=124 Msun, Menv=40 Msun
    - 56Ni mass = 35 Msun

bolometric



V band



Conclusions

- Metal-free PISN progenitors can experience large mass loss
  - H-rich envelope during RSG evolution becomes unstable
  - pulsation can drive large mass loss
  - mass-loss rates become very high even in metal-free progenitors
  - PISN progenitors still explode as PISNe
- PISNe
  - progenitors are less massive than previously thought
    - different light curve evolution
  - dense CSM can be created by surface pulsational mass loss
  - PISN + dense CSM = Type IIn SNe (can be very luminous)