# Pulsational Pair-instability Supernovae

Shing-Chi Leung, Ken’ichi Nomoto
Kavli IPMU, The University of Tokyo

with collaborations of
Sergei Blinnikov (ITEP), Ming-Chung Chu (CUHK)

A talk for the Ringberg Workshop on the progenitor-supernova-remnant connection

Gustav Mahler and
Komponierhäuschen (Steinbach am Attersee)

Figures: Wikipedia

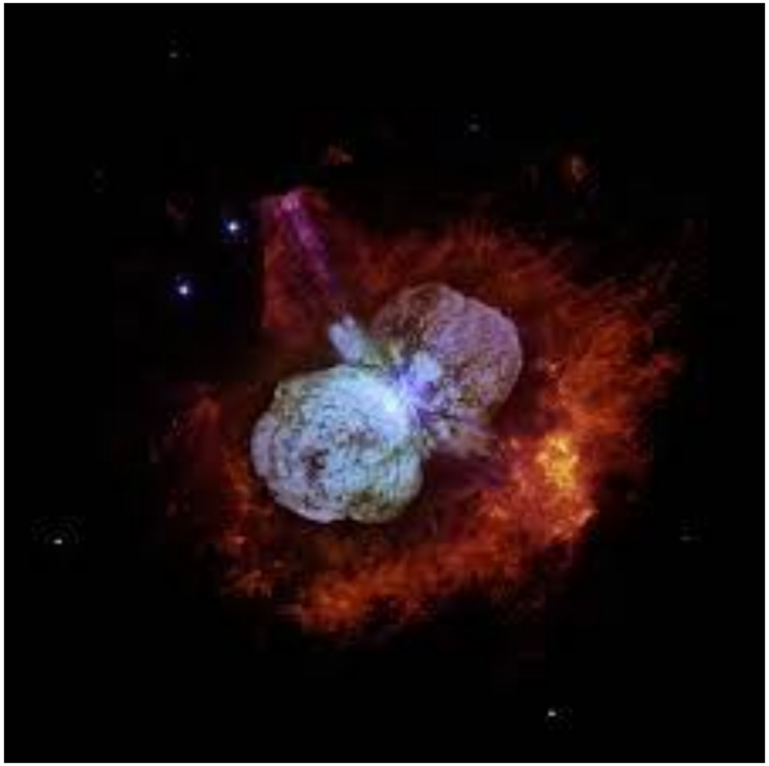
# Background

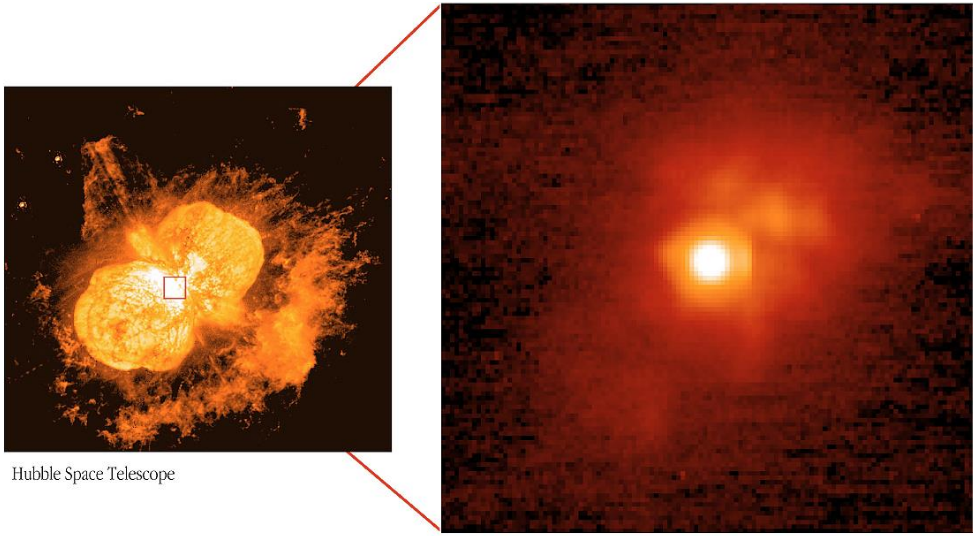
The extreme mass ejection of Eta Carinae has drawn us the attentions to the possibility of pulsational pair-instability supernovae

Initial mass: 100-200 Msun

1837: the Great eruption (10-20 Msun)

1890: the Small eruption (0.1 Msun)





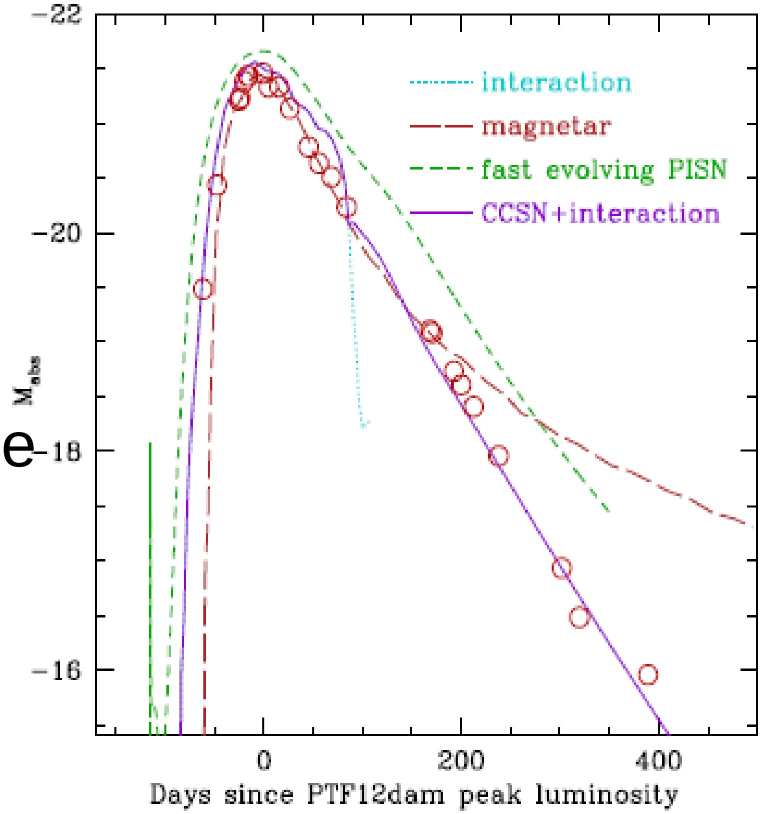
Hubble Space Telescope

VLT YEPUN + NAOS-CONICA

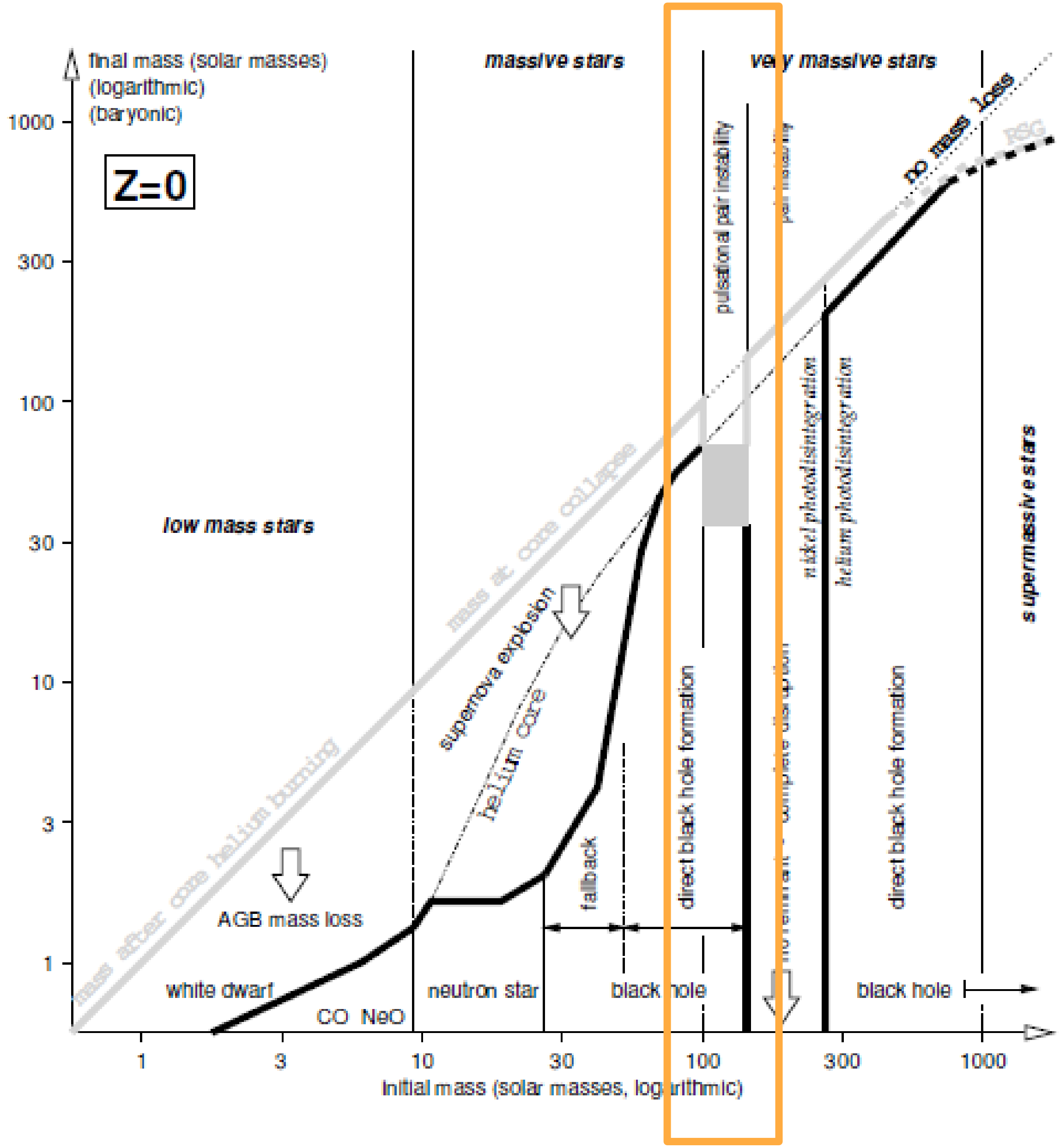
# The puzzle of Eta Carinae

For a massive star with considerable mass loss, what is its evolution before its collapse?

- The mass loss composition as a function of ($M$,$Z$,$\Omega$)
- The interaction of ejected mass
- The pre-collapse configuration
- Prediction of its collapse timing
- Multi-messenger signals



Tolstov et al. (2017)



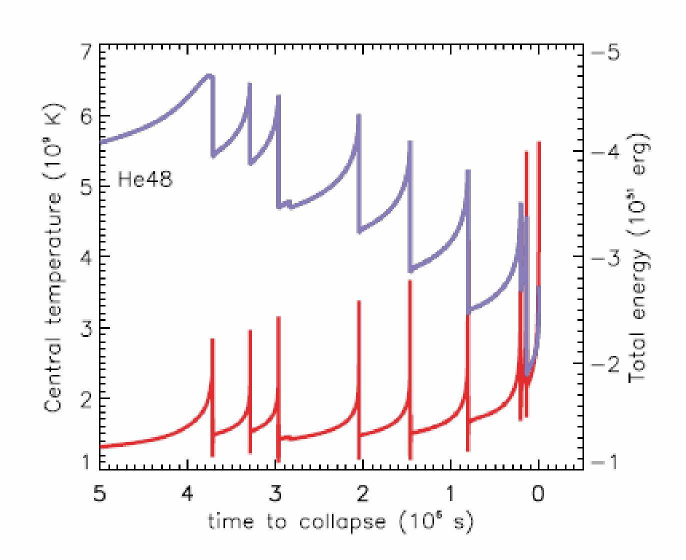
At zero metallicity, stars with a mass 100 – 140 solar mass (or He core from 40 – 64 solar mass) forms the pulsational pair-instability SN

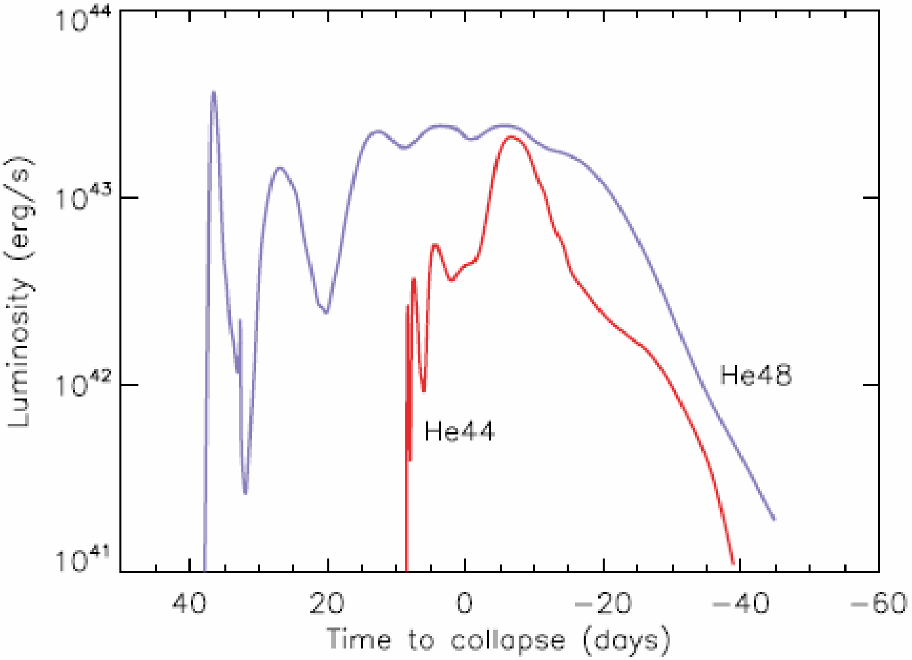
Heger et al. (2003)

# Recent progress (in 1D)

Woosley (2017) has presented the first systematic study of PPISN using the Kepler code, the pulsation history and light curves are studied.

Core from 40 - 64 $M_{sun}$ can exhibit pulsations.





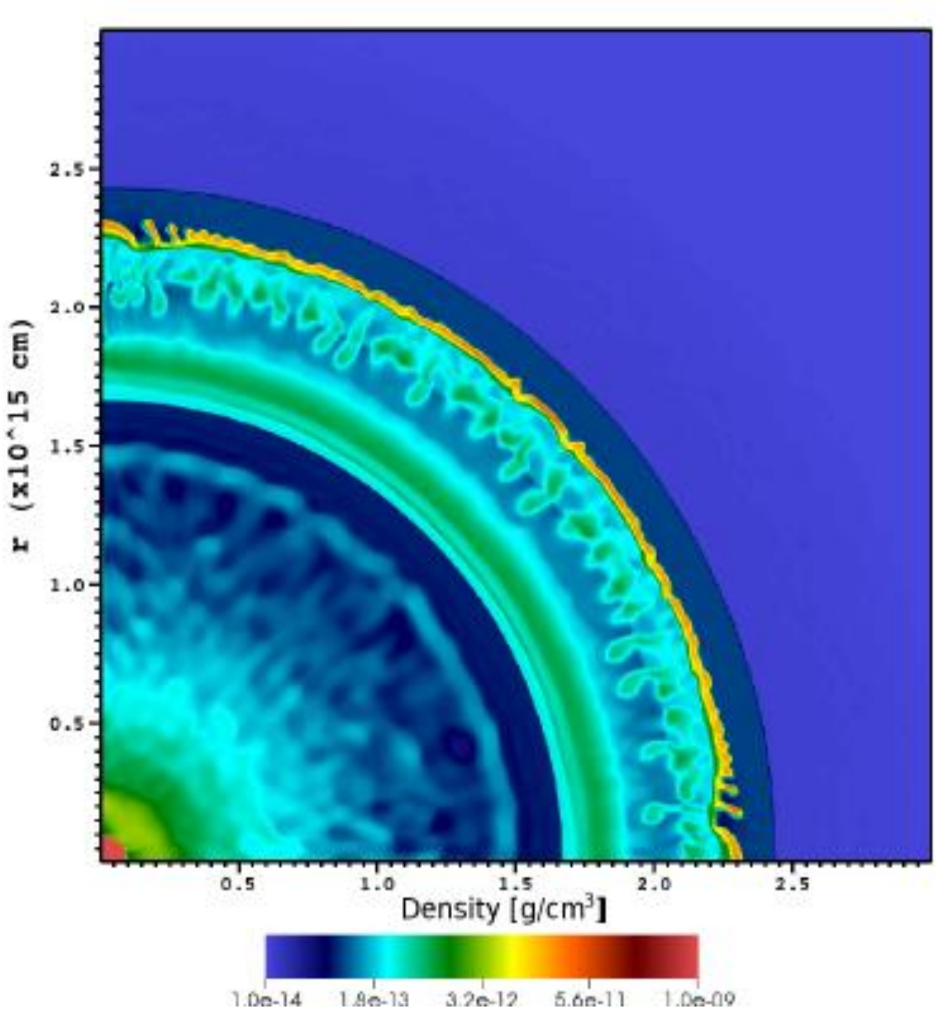
Example of a 48 Msun He-core

# Recent progress (in 2D)

(Chen et al., 2014)

Matching the pre-pulsation model from stellar evolution code to multi-D hydrodynamics code

- RT instabilities in the form of density-fingers



# Method

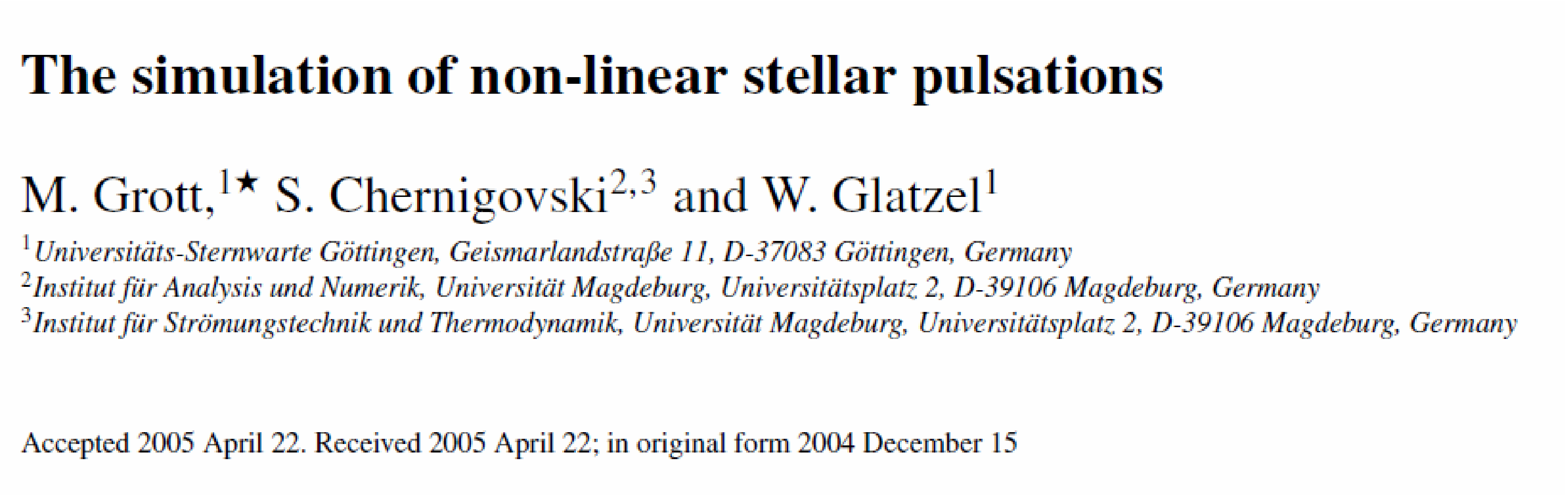
One-dimensional stellar evolution + hydrodynamics code
Modules for Experiment in Stellar Astrophysics

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

MESA

Dynamical prescription

The use of the fully conservative scheme (Grott 2005)



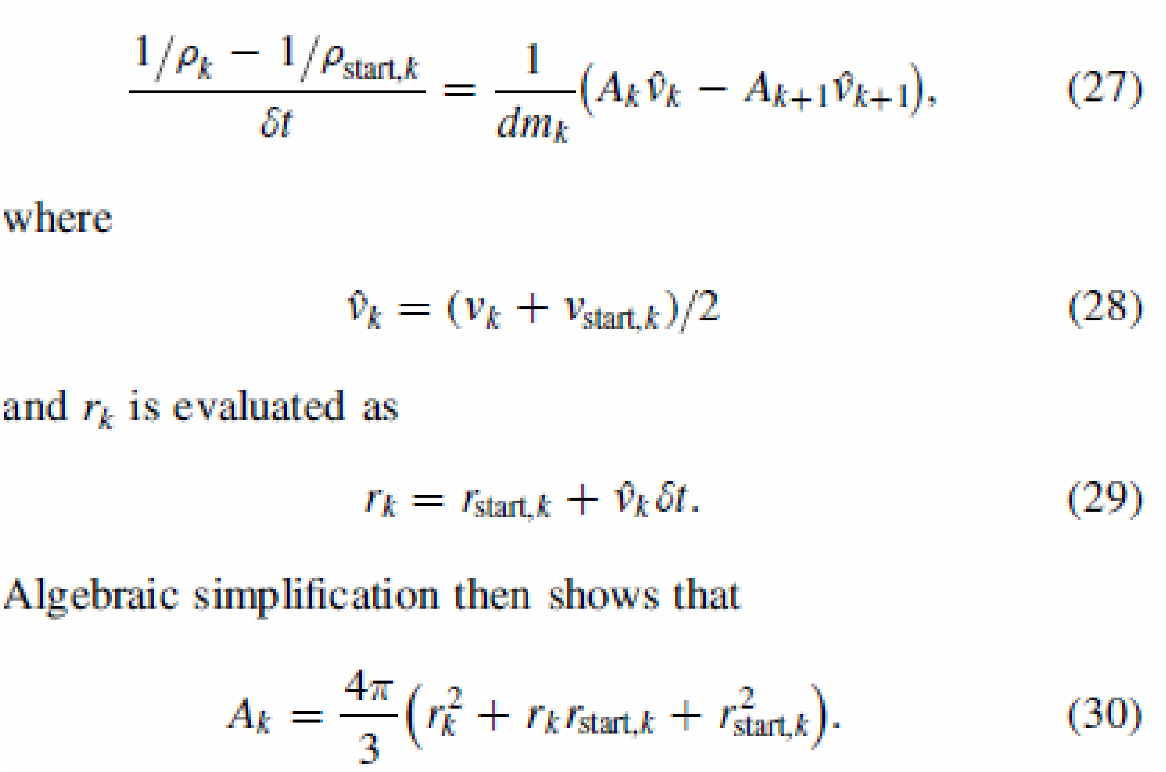
**The simulation of non-linear stellar pulsations**

M. Grott,[1]★ S. Chernigovski[2,3] and W. Glatzel[1]
[1] *Universitäts-Sternwarte Göttingen, Geismarlandstraße 11, D-37083 Göttingen, Germany*
[2] *Institut für Analysis und Numerik, Universität Magdeburg, Universitätsplatz 2, D-39106 Magdeburg, Germany*
[3] *Institut für Strömungstechnik und Thermodynamik, Universität Magdeburg, Universitätsplatz 2, D-39106 Magdeburg, Germany*

Accepted 2005 April 22. Received 2005 April 22; in original form 2004 December 15

# The energy conserving implicit scheme

From Paxton (2015)



$$\frac{1/\rho_k - 1/\rho_{\mathrm{start},k}}{\delta t} = \frac{1}{dm_k}\left(A_k \hat{v}_k - A_{k+1}\hat{v}_{k+1}\right), \tag{27}$$

where

$$\hat{v}_k = (v_k + v_{\mathrm{start},k})/2 \tag{28}$$

and $r_k$ is evaluated as

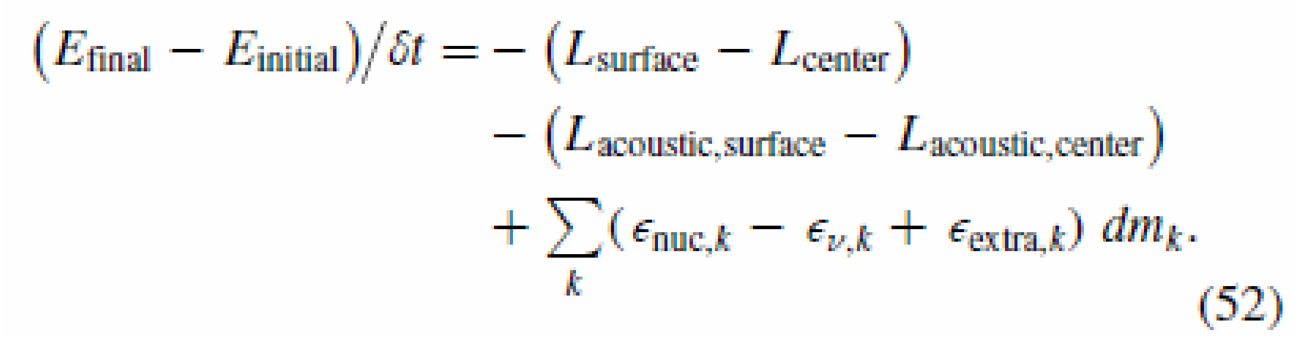
$$r_k = r_{\mathrm{start},k} + \hat{v}_k \delta t. \tag{29}$$

Algebraic simplification then shows that

$$A_k = \frac{4\pi}{3}\left(r_k^2 + r_k r_{\mathrm{start},k} + r_{\mathrm{start},k}^2\right). \tag{30}$$

# Fully energy conservation scheme

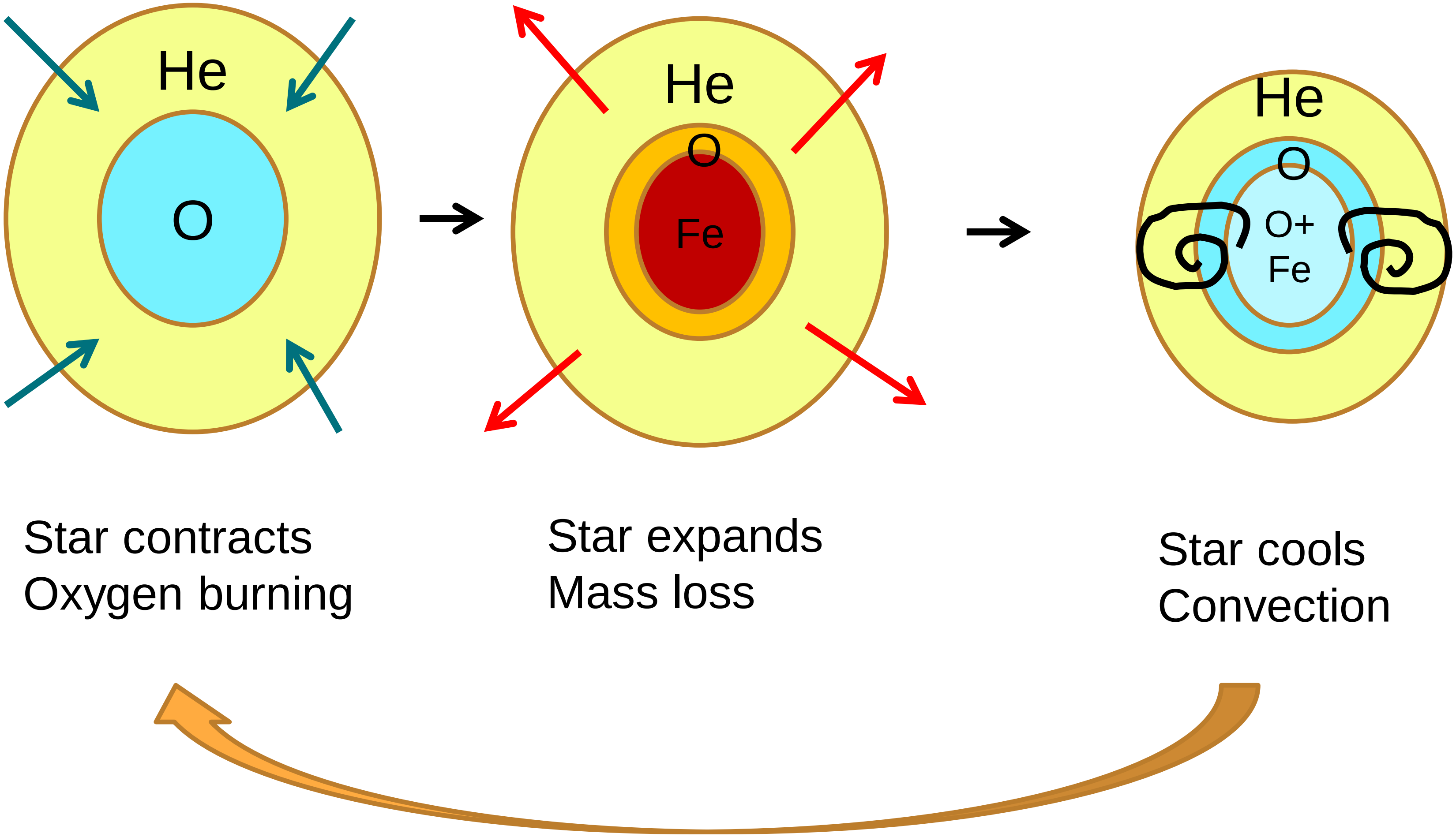
After updating for one step, only the boundary terms and source terms matter



$$\begin{aligned}\left(E_{\rm final} - E_{\rm initial}\right)/\delta t = & -\left(L_{\rm surface} - L_{\rm center}\right) \\ & - \left(L_{\rm acoustic,surface} - L_{\rm acoustic,center}\right) \\ & + \sum_k \left(\epsilon_{{\rm nuc},k} - \epsilon_{\nu,k} + \epsilon_{{\rm extra},k}\right) dm_k . \end{aligned} \tag{52}$$

The algorithm conserves energy naturally, thus guaranteeing that the solution describes the same system as the initial one

# Qualitative Picture of PPISN

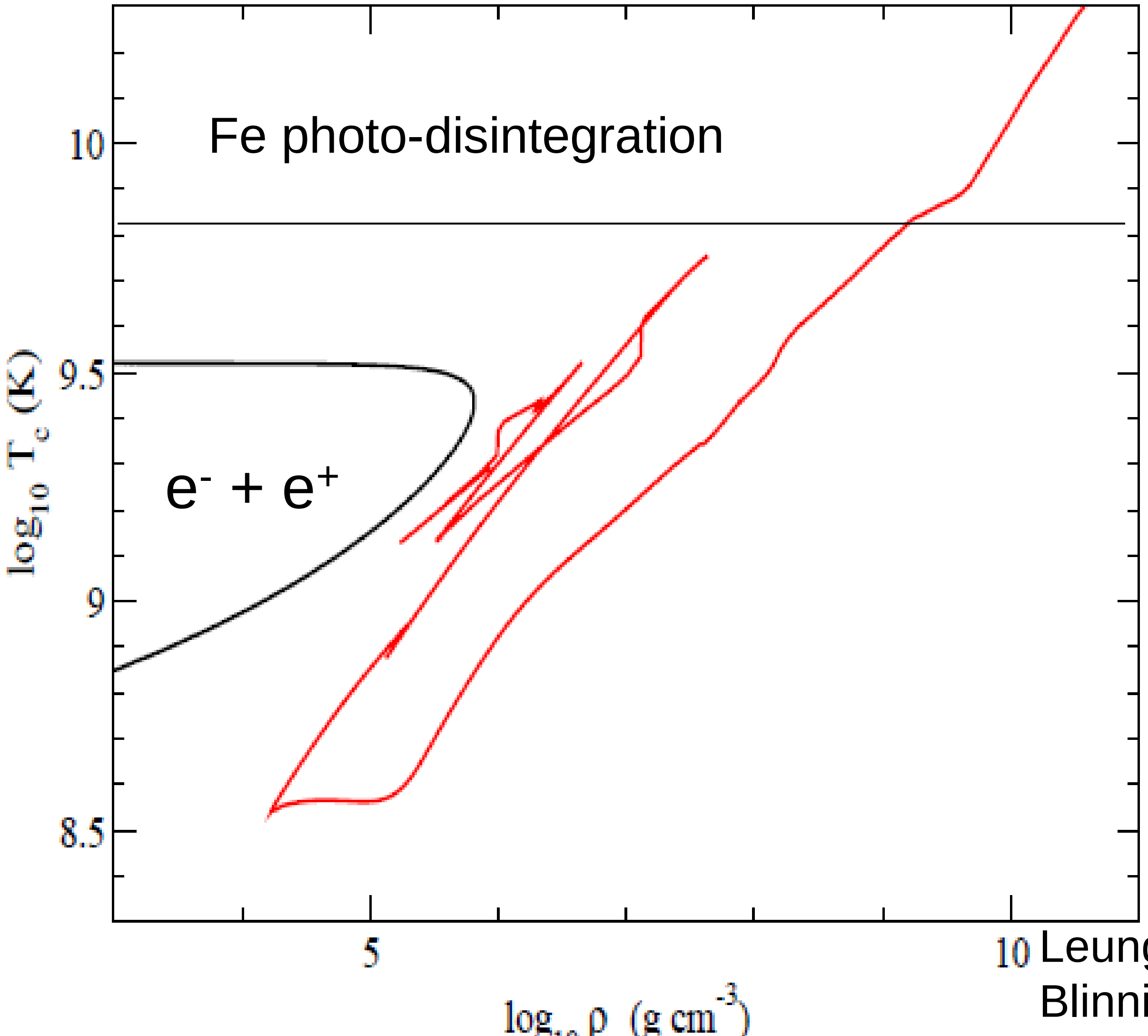


Star contracts
Oxygen burning

Star expands
Mass loss

Star cools
Convection

# Typical thermodynamics (He = 50Msun)

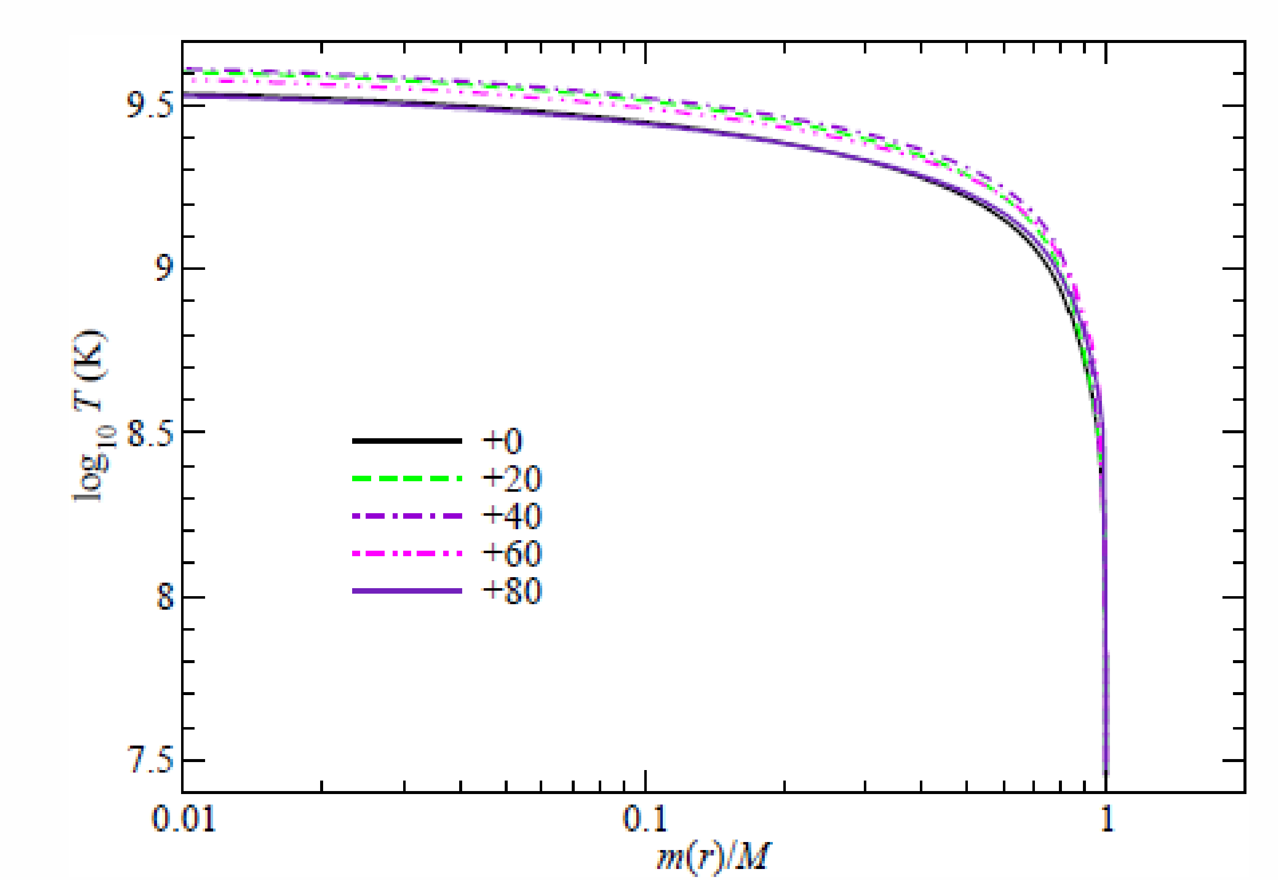


Leung, Nomoto, Chu,
Blinnikov (2017, In preparations)

Leung + (2017, In preparations)

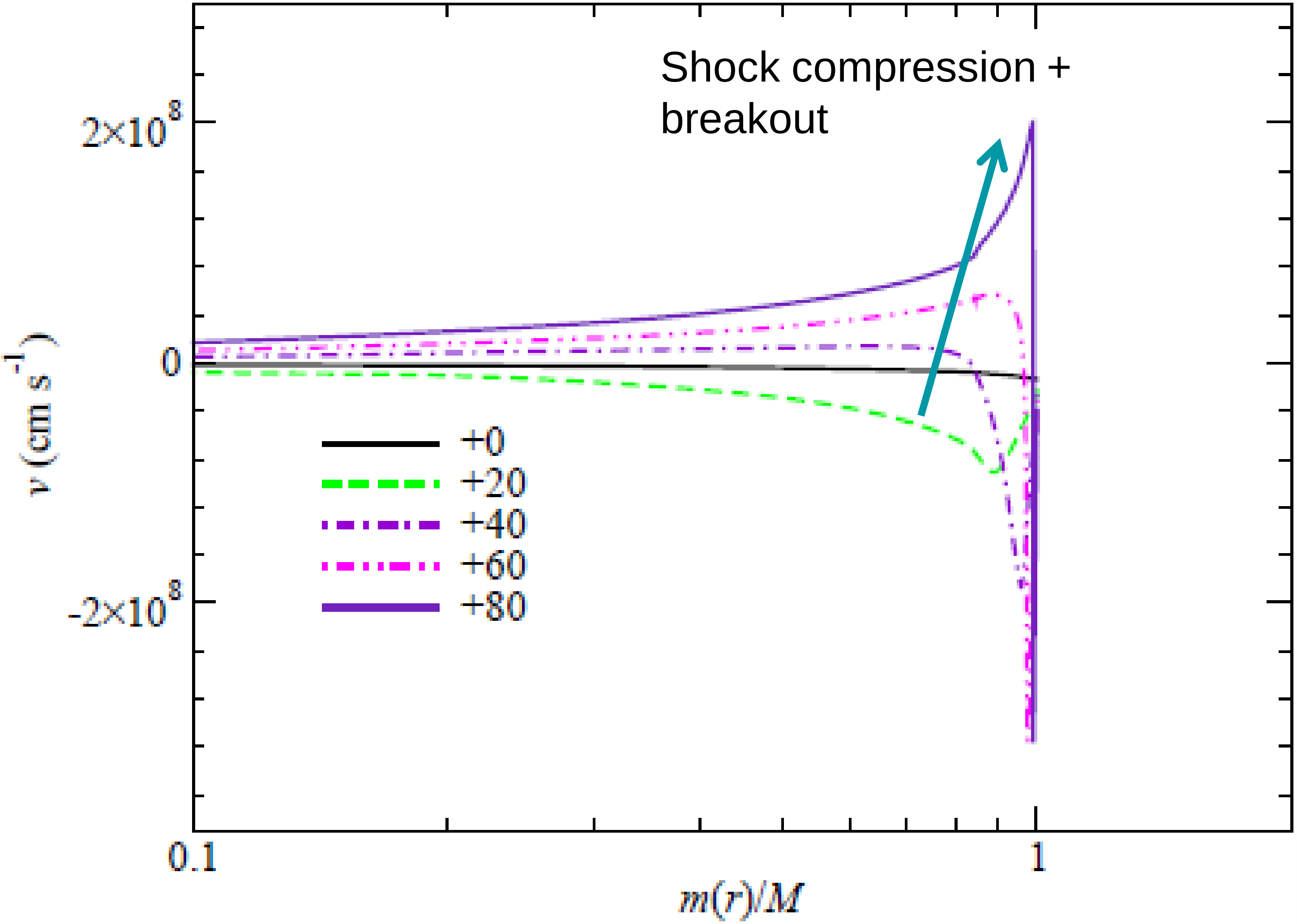
# Hydrodynamics (He60, 1st pulse)

The whole star heats up during contraction



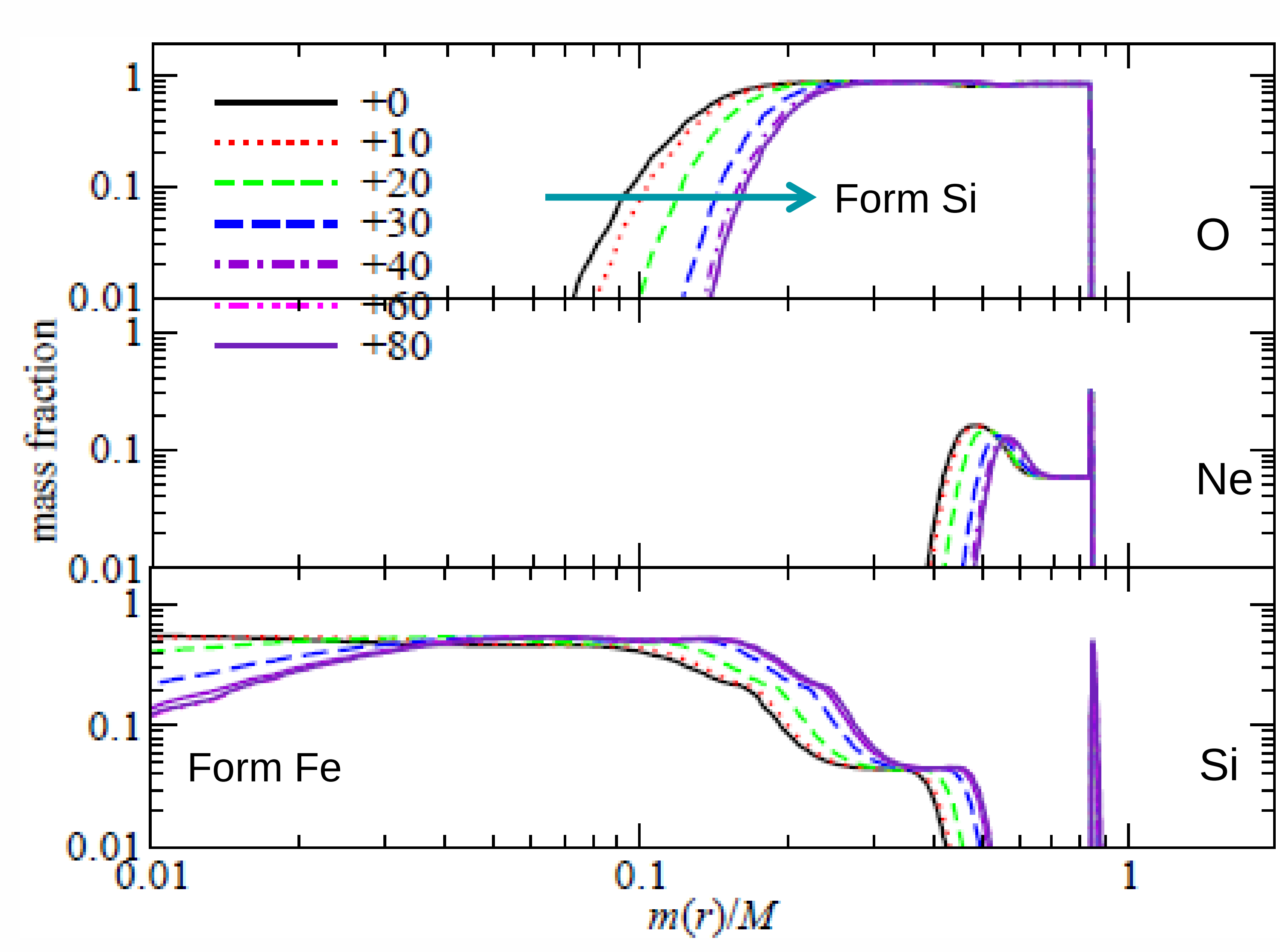
Leung + (2017, In preparations)

# Velocity evolution (He60, 1st pulse)


Shock compression + breakout

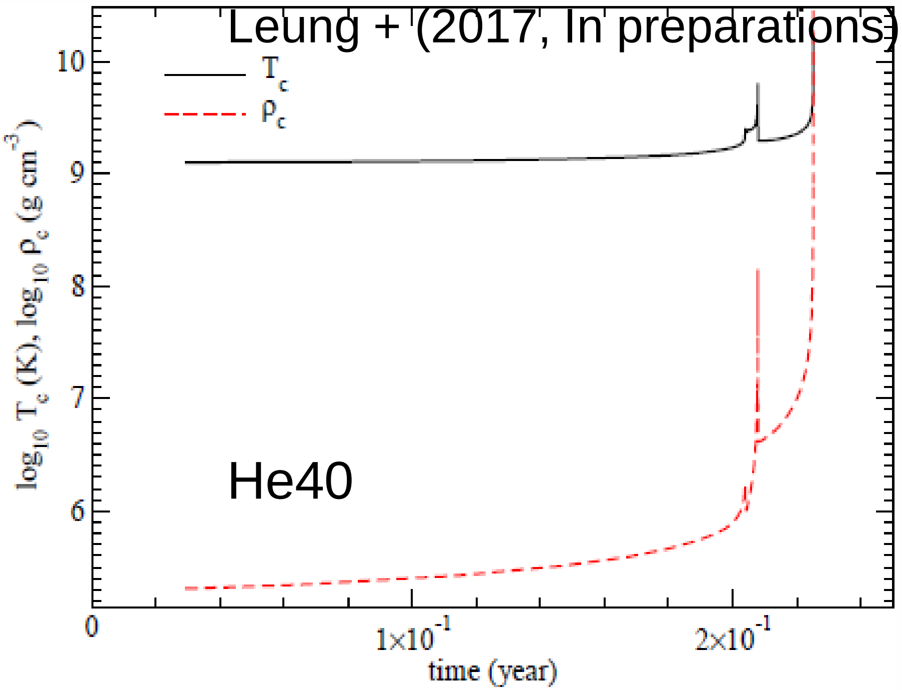
Leung + (2017, In preparations)

# Chemical composition (He60, $1^{st}$ pulse)

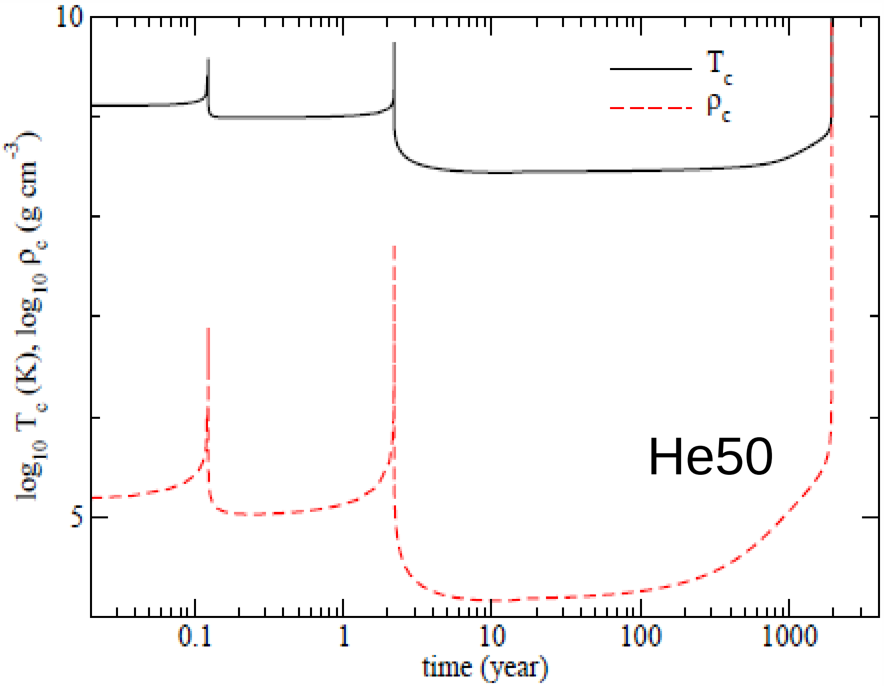


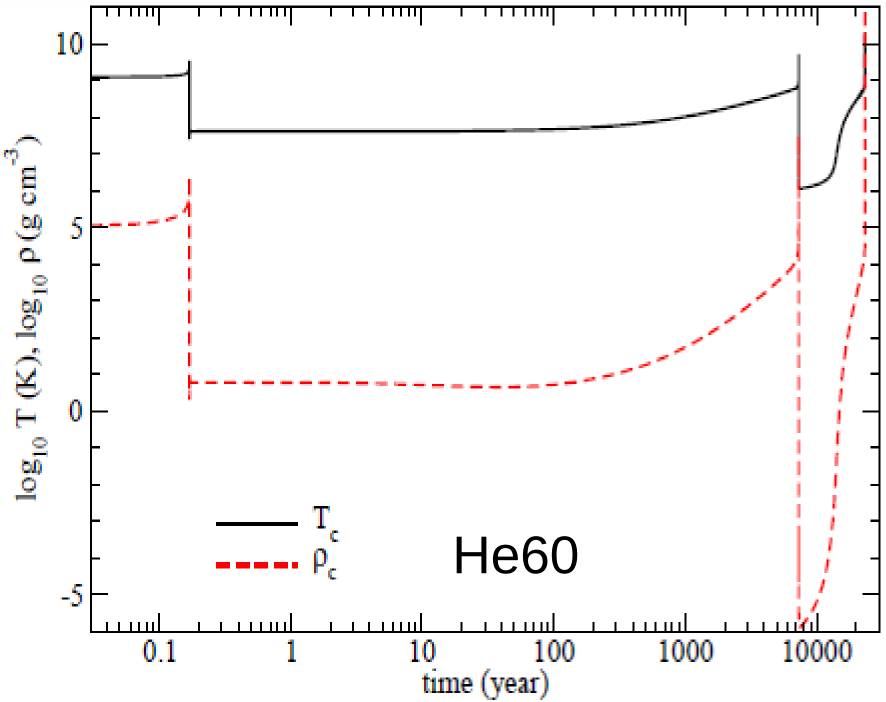
# Pulsation

Central density/tempereature against time for M(He) = 40, 50 and 60 solar mass



Leung + (2017, In preparations)



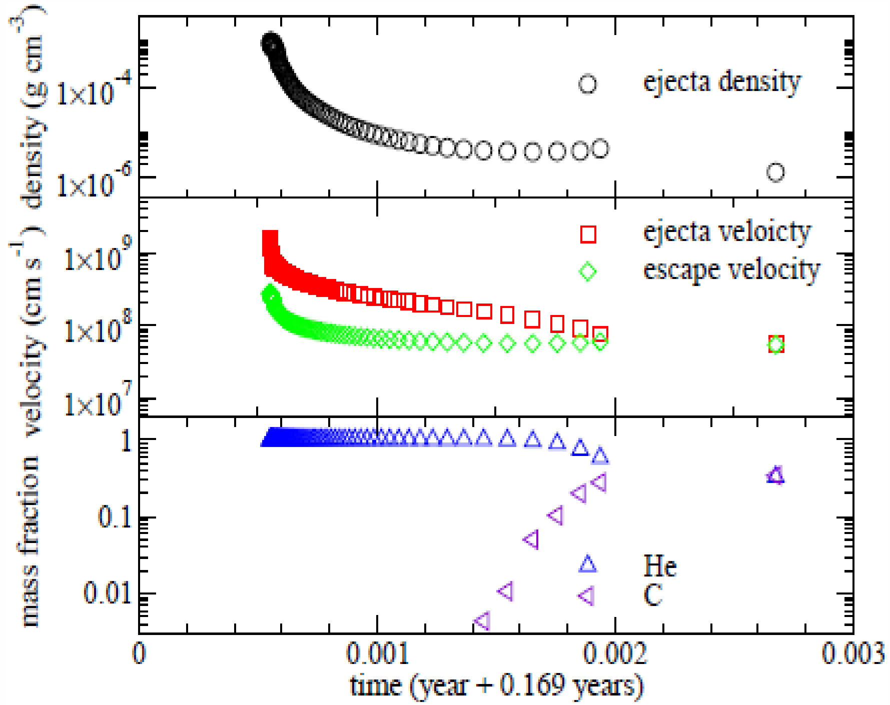


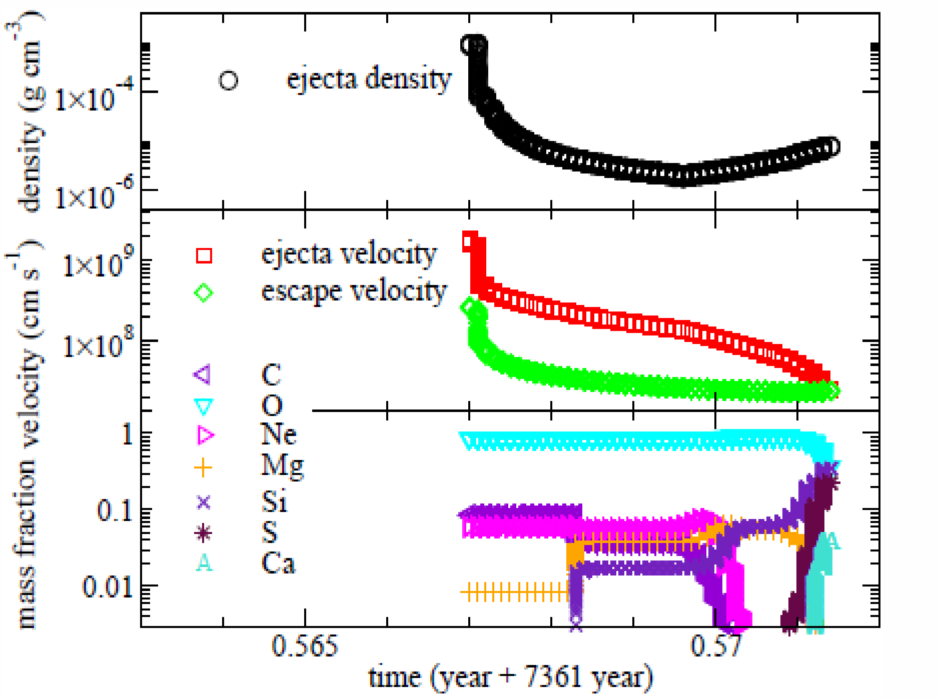
Leung + (2017, In preparations)

# Mass loss history

Let us examine the He60 model and see how the mass loss occurs before its collapse.

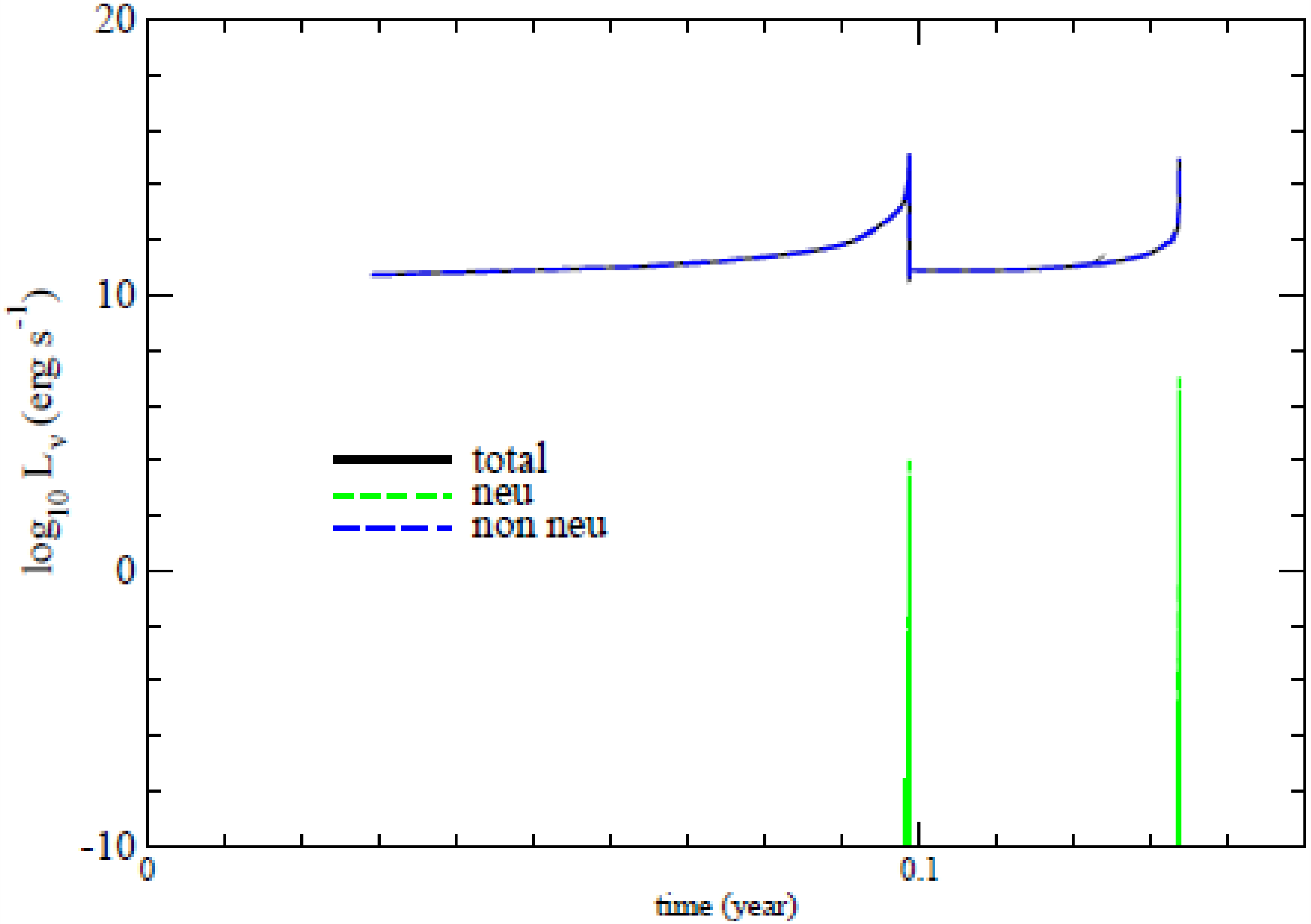
Pulse 1: 10 Msun, Pulse 2: 38 Msun



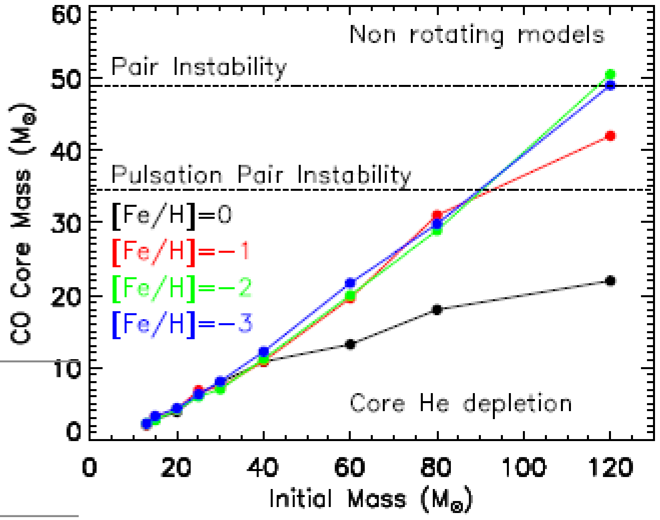


Leung + (2017, In preparations)

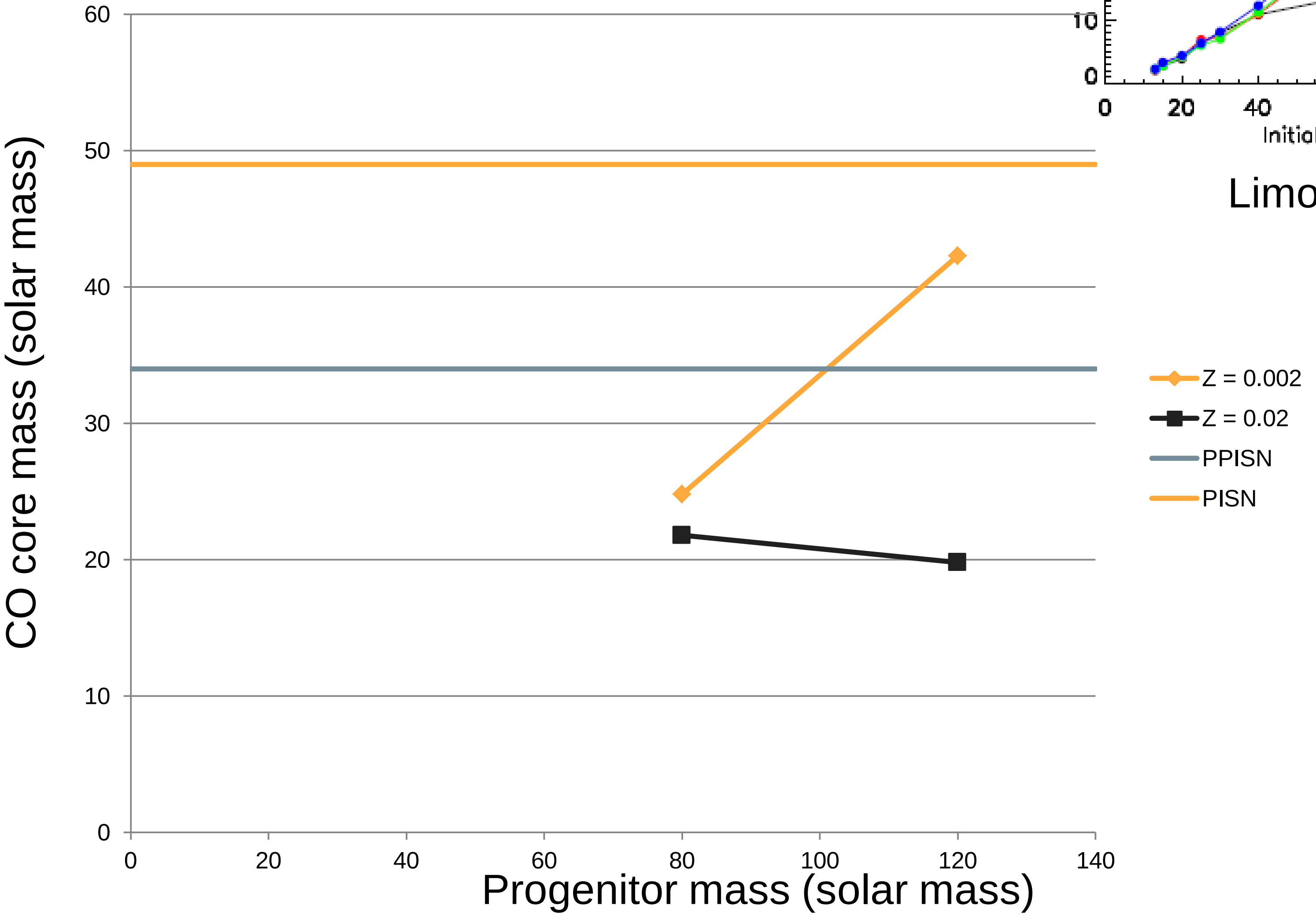
# Neutrino pattern (He40 model)



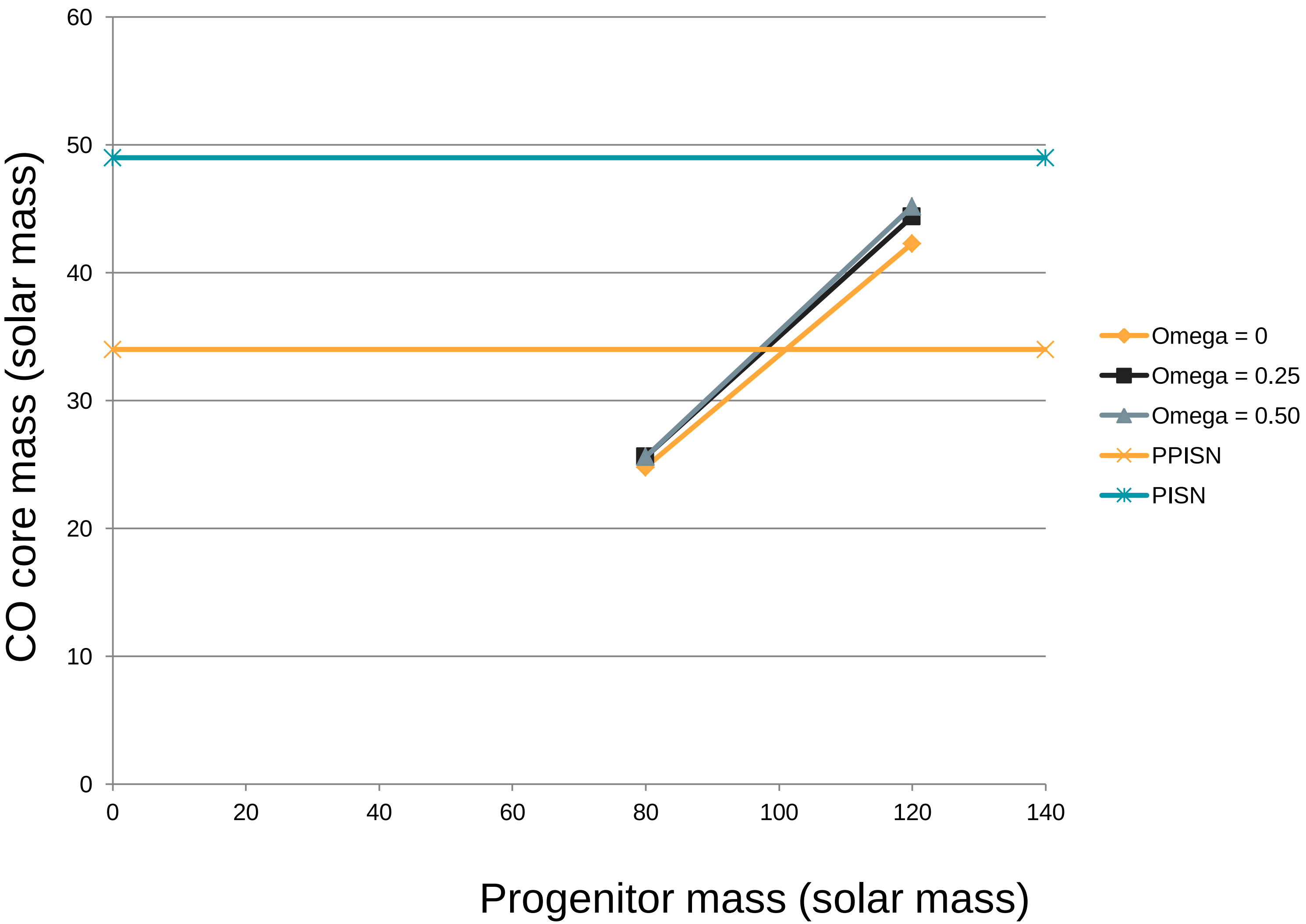
# Effects of metallicity (Omega = 0)



Limongi (2017)



# Effects of rotation (Z = 0.002)



# Conclusion

We have presented progenitor models of pulsational pair instability supernovae (before its collapse) using MESA

- ➢ Thermodynamics and hydrodynamics
- ➢ Mass loss histories
- ➢ Neutrino signals

We examined the effects of

- ➢ Metallicity
- ➢ Rotation

to the progenitor models