Sonic Horizon and Sub-sonic structure of Wolf-Rayet stars

Constraints on the mass-loss rates of WNE stars

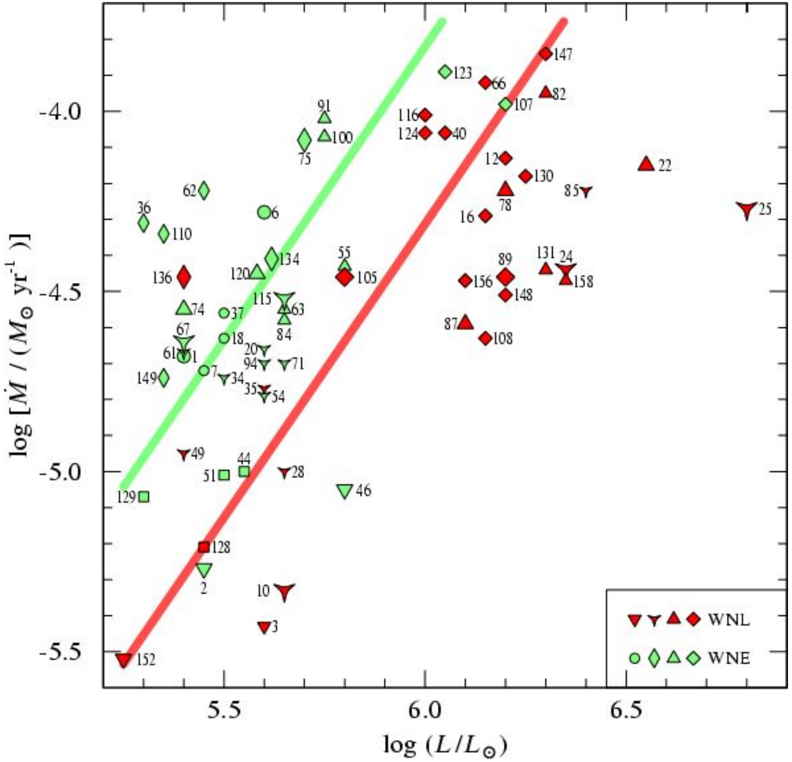
Argelander-Institut für Astronomie

Luca Grassitelli

N.Langer, N.J.Grin, J.Mackey, J.M.Bestenlehner, G.Graefener

UNIVERSITÄT BONN

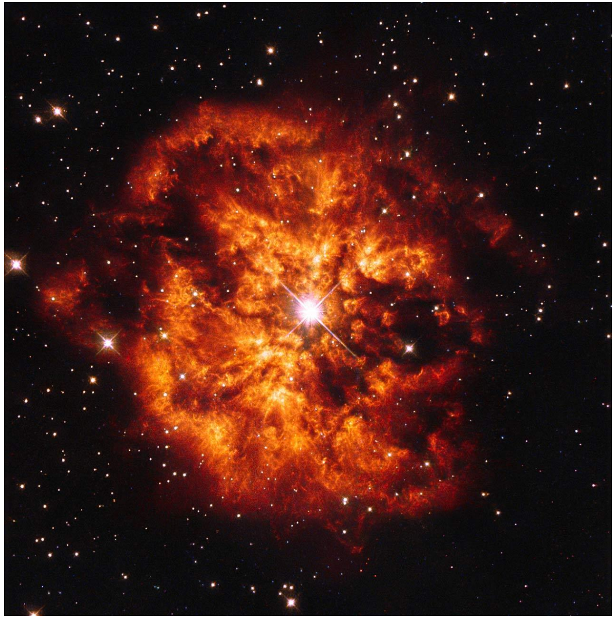
Wolf-Rayet Phase:



Empirical mass-loss rates Vs luminosity for the Galactic WN stars.
Red: WNL stars, Green: WNE stars. *Hamann et al.2006*

- **spectra dominated by broad emission lines of He, C, N, O**
- **dense, optically thick stellar winds due to the high mass-loss rates**
- **naked cores in the final phases of the evolution of massive stars**

- enrich the interstellar medium
- SNe and GRBs progenitors
- physics of stellar winds



Hubble image shows the nebula M1-67 around the Wolf-Rayet star WR 124

WR radius problem:

Radii estimated via spectroscopy and wind models

(adopting a beta-velocity law)

≠

Radii stellar structure models

(hydrostatic with plane parallel atmosphere)

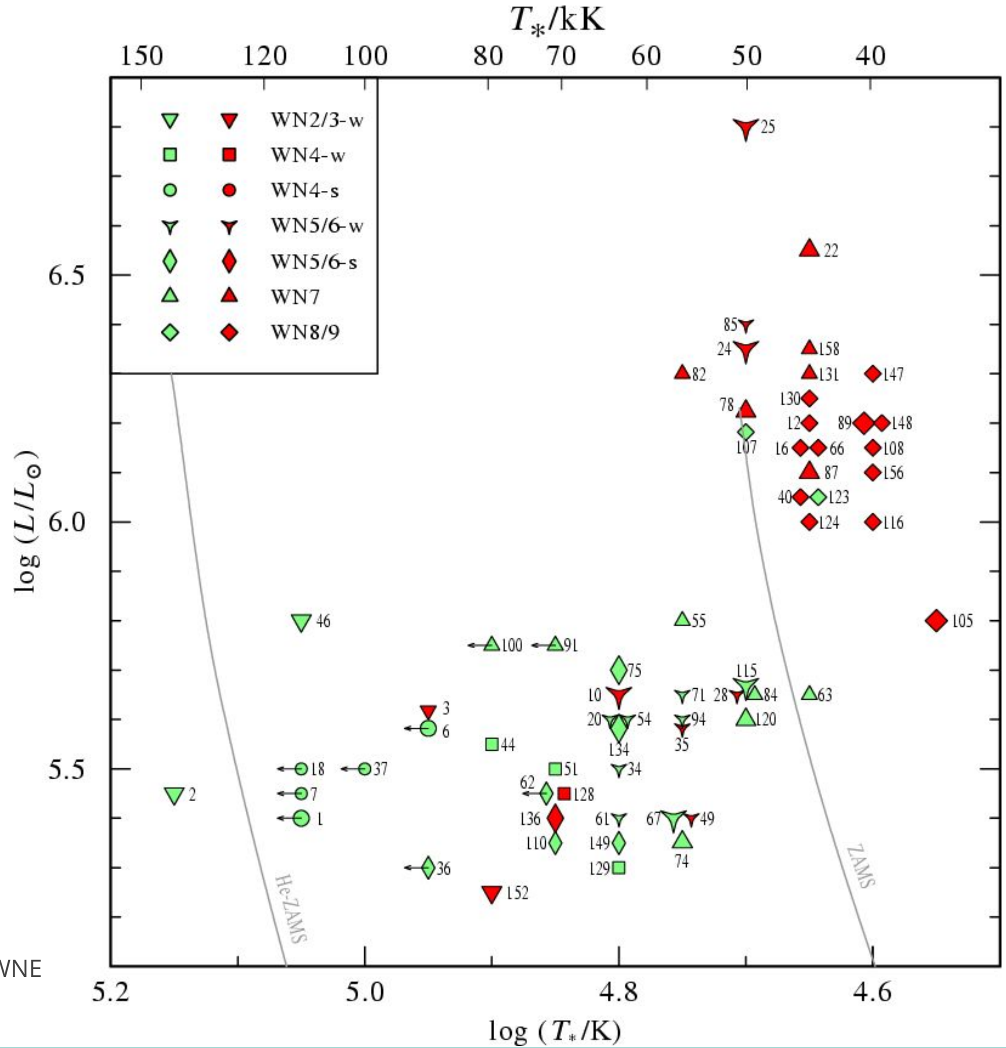


Figure: HR diagram with the WNL and WNE stars (T* temp. at τ=20). *Hamann et al.2006*

Dynamics of a steady-state stellar winds

$$\frac{1}{v}\frac{dv}{dr} = -\left(g - g_{rad} - 2\frac{c_s^2}{r} + \frac{dc_s^2}{dr}\right) / (v^2 - c_s^2)$$

critical point: $v = c_s$

Radiation driven winds:

$$g_{rad} \gg 2\frac{c_s^2}{r} - \frac{dc_s^2}{dr}$$

$$\frac{d\kappa}{dr} > 0$$ at the sonic point

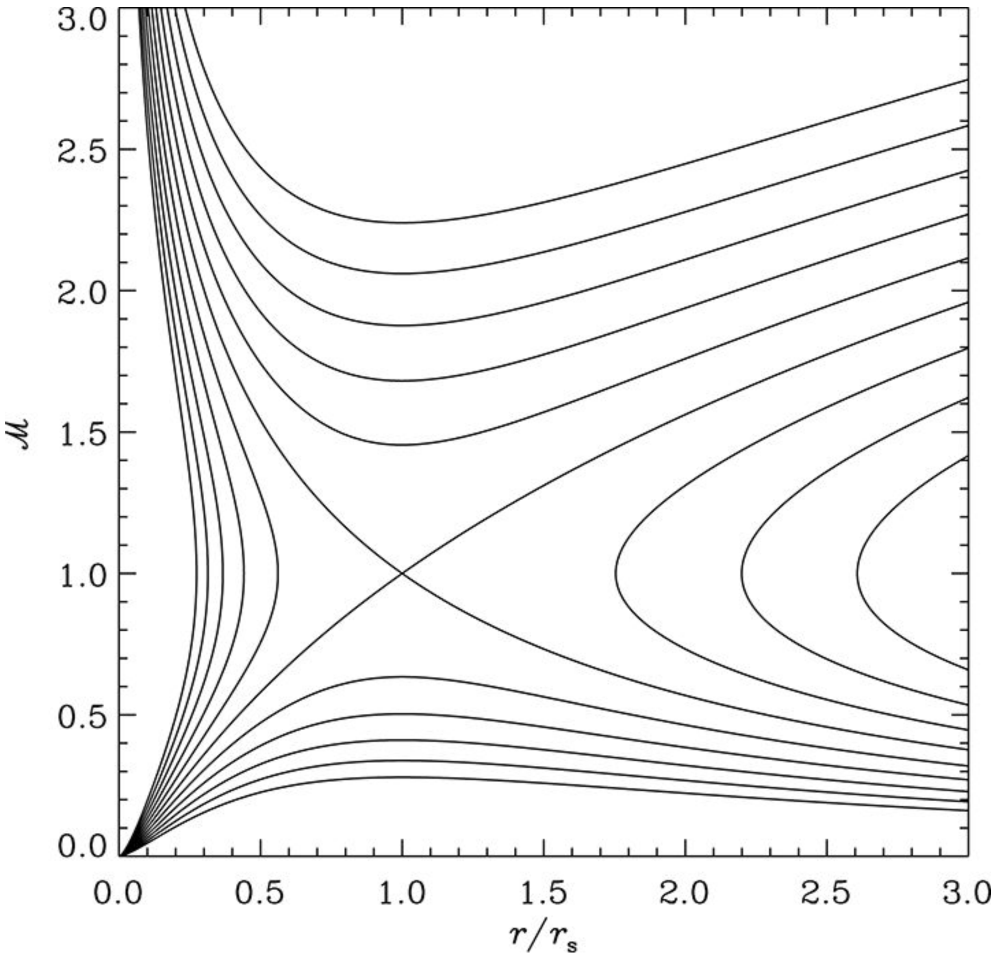


Figure: Solution curves for a stellar wind or accretion flow. X -type critical point at the sonic radius. *Ogilvie 2016*

HORIZON

$$v > c_s$$

+

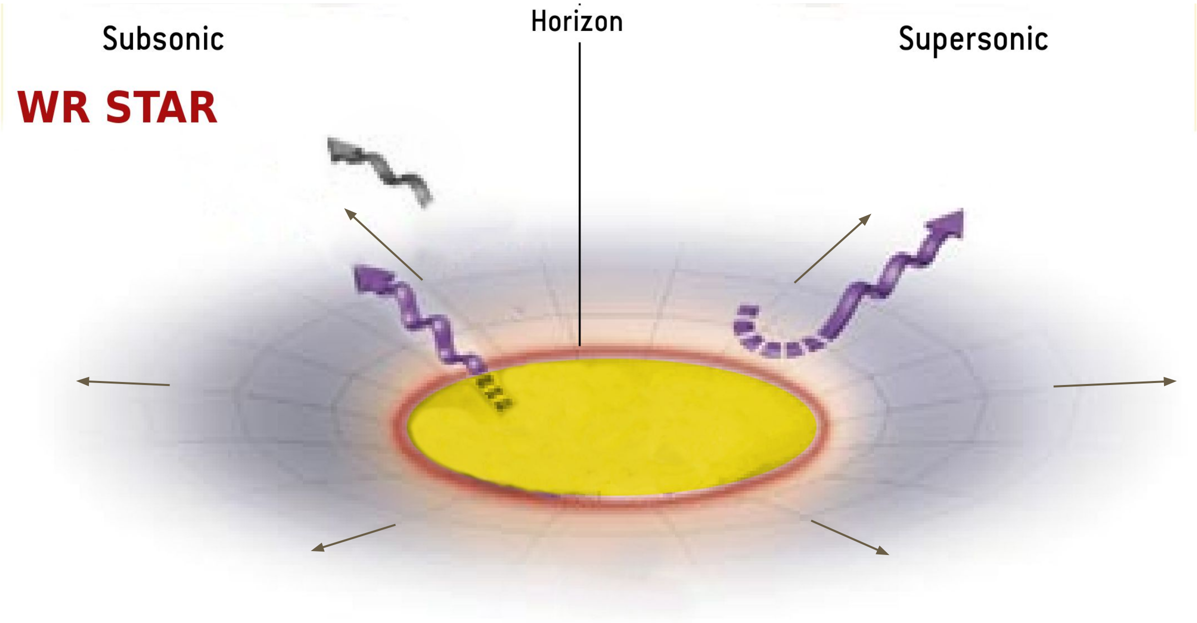
$$\lambda < H_p$$

$$\tau > 1$$

↓

Diffusion approximation ⇒ Properties of the radiation field can be described LOCALLY

The subsonic flow becomes a zone of silence



BEC: Lagrangian 1D stellar evolution code

$$\left(\frac{\partial m}{\partial r}\right)_t = 4\pi r^2 \rho$$

$$\left(\frac{\partial r}{\partial t}\right)_m = \upsilon$$

$$\left(\frac{\partial L}{\partial m}\right)_t = \epsilon_N - \epsilon_g - \epsilon_\nu$$

$$\left(\frac{\partial T}{\partial m}\right)_t = -\frac{Gm}{4\pi r^4}\frac{T}{P}\nabla\left(1 + \frac{r^2}{Gm}\frac{\partial \upsilon}{\partial t}\right)_m$$

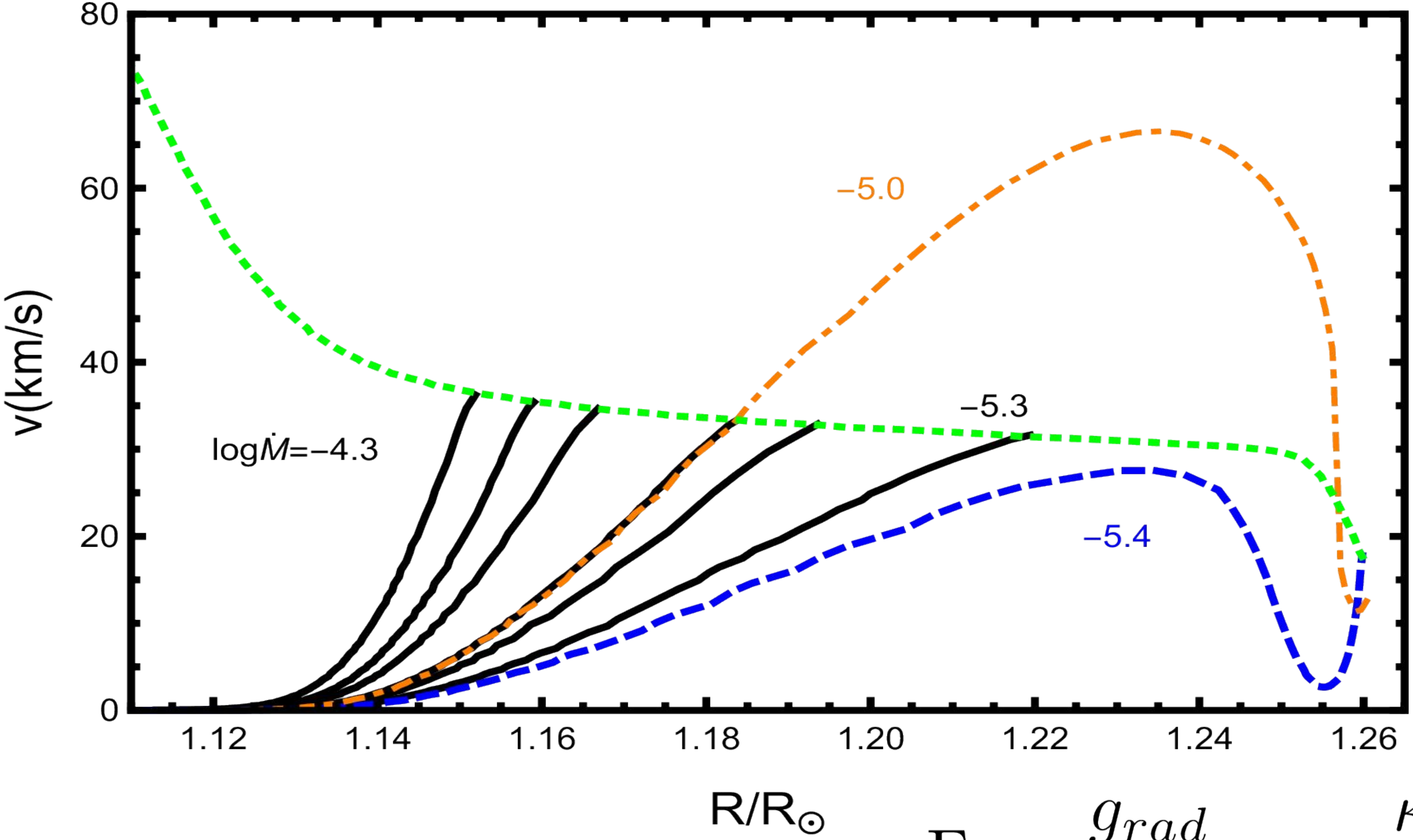
$$\left(\frac{a}{4\pi r^2}\right)_t = \frac{Gm}{4\pi r^4} + \frac{\partial P}{\partial m}$$

Surface boundary conditions

$$\dot{M} = 4\pi r^2 \rho \upsilon$$

$$\upsilon = \sqrt{\frac{k_B T}{\mu m_H}} = c_s$$

Massive Galactic Helium star models: 15 M⊙



Black: Fe-bump, Blue: He-bump, Orange: plane-parallel atmosphere.
Green: isothermal sound speed.

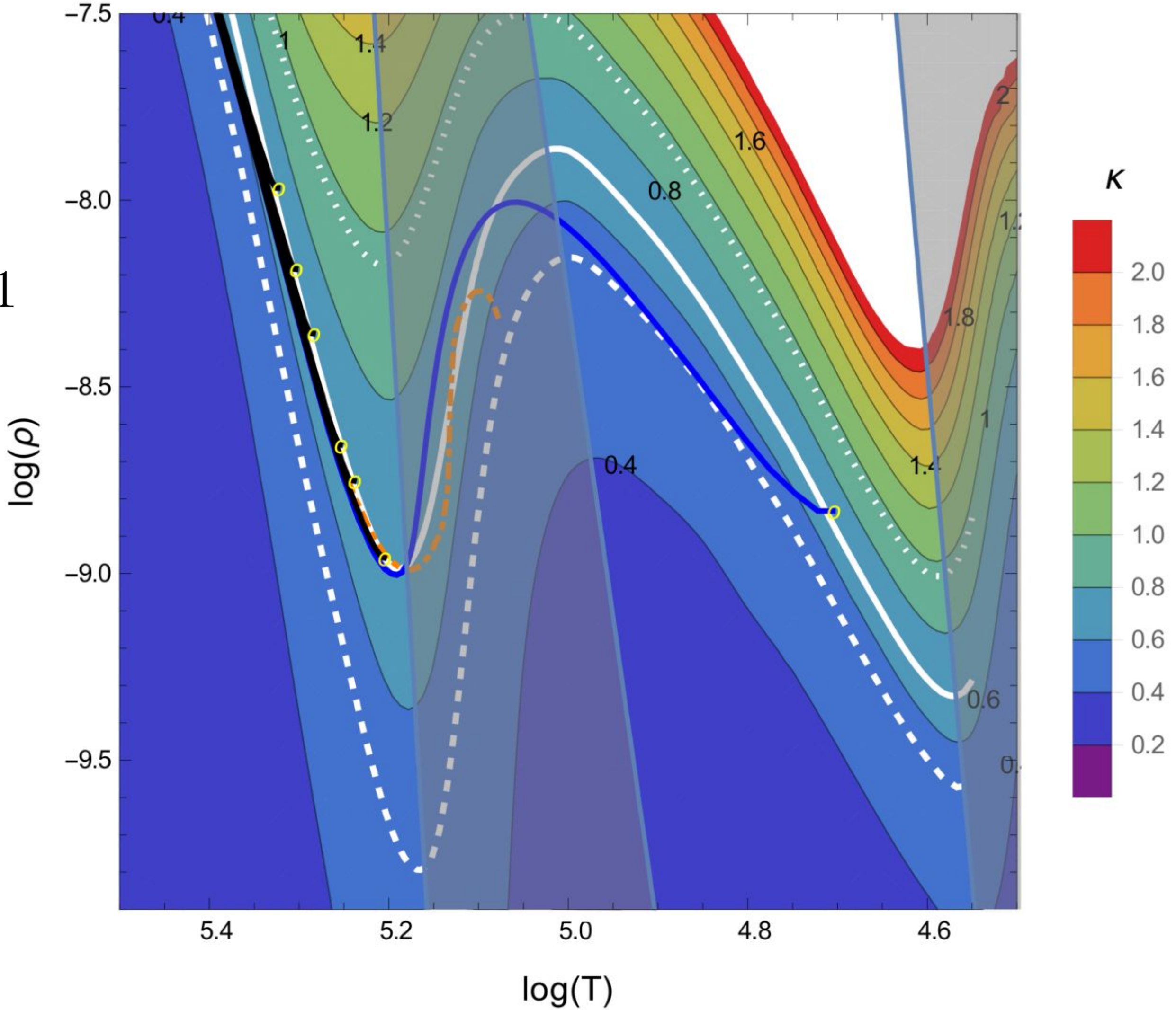
$$\Gamma := \frac{g_{rad}}{g} = \frac{\kappa L}{4\pi c G M} \cong 1$$

log(ρ)-log(T)-κ plane

for

$$\Gamma = \frac{\kappa}{4\pi c G}\frac{L}{M} = 1$$

$$\kappa_{edd} = 4\pi c G \frac{M}{L}$$



Sonic HR-diagram

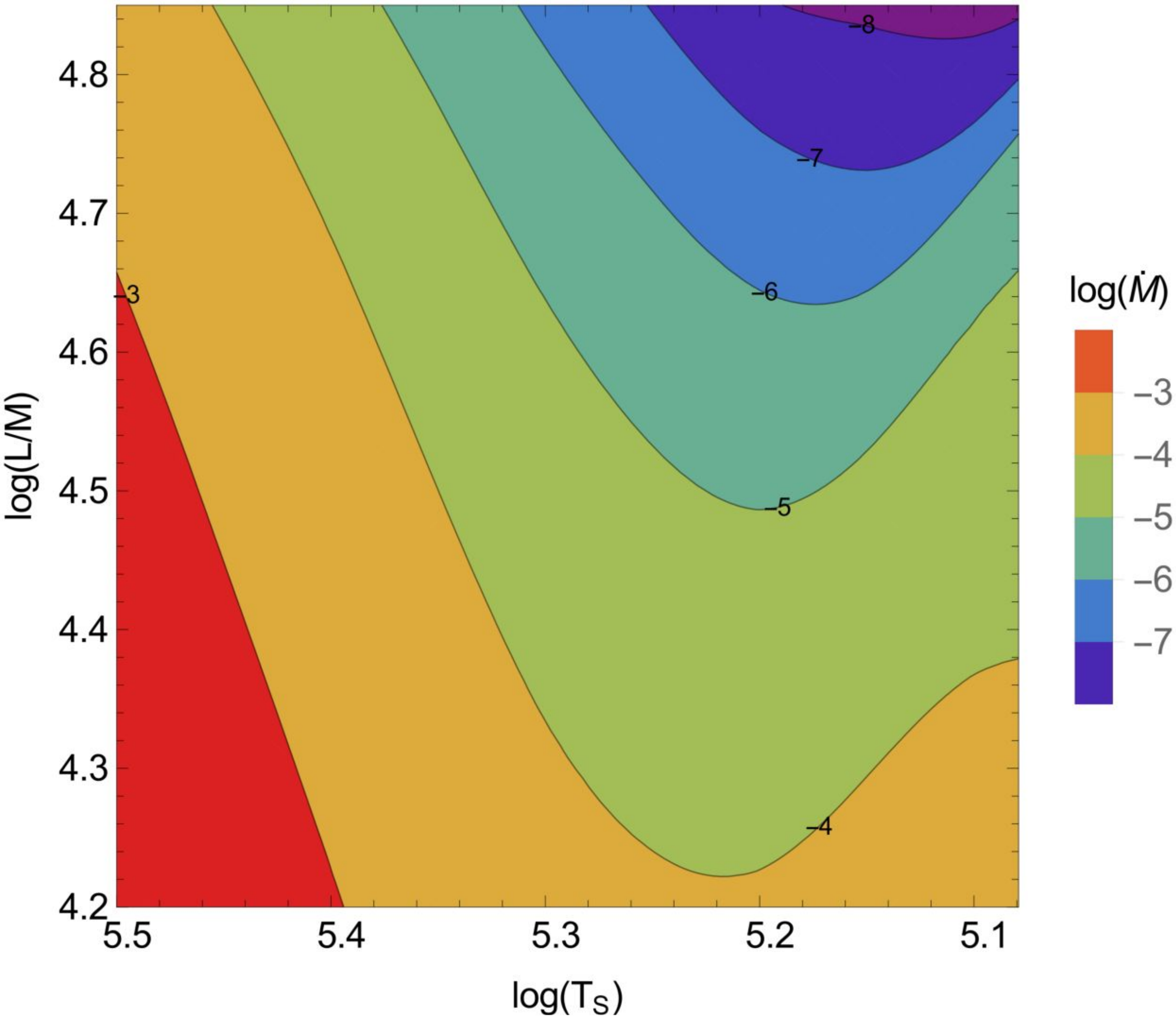
$$T \quad \& \quad \rho \Rightarrow \quad \kappa$$

$$T \quad \& \quad \kappa \Rightarrow \quad \rho$$

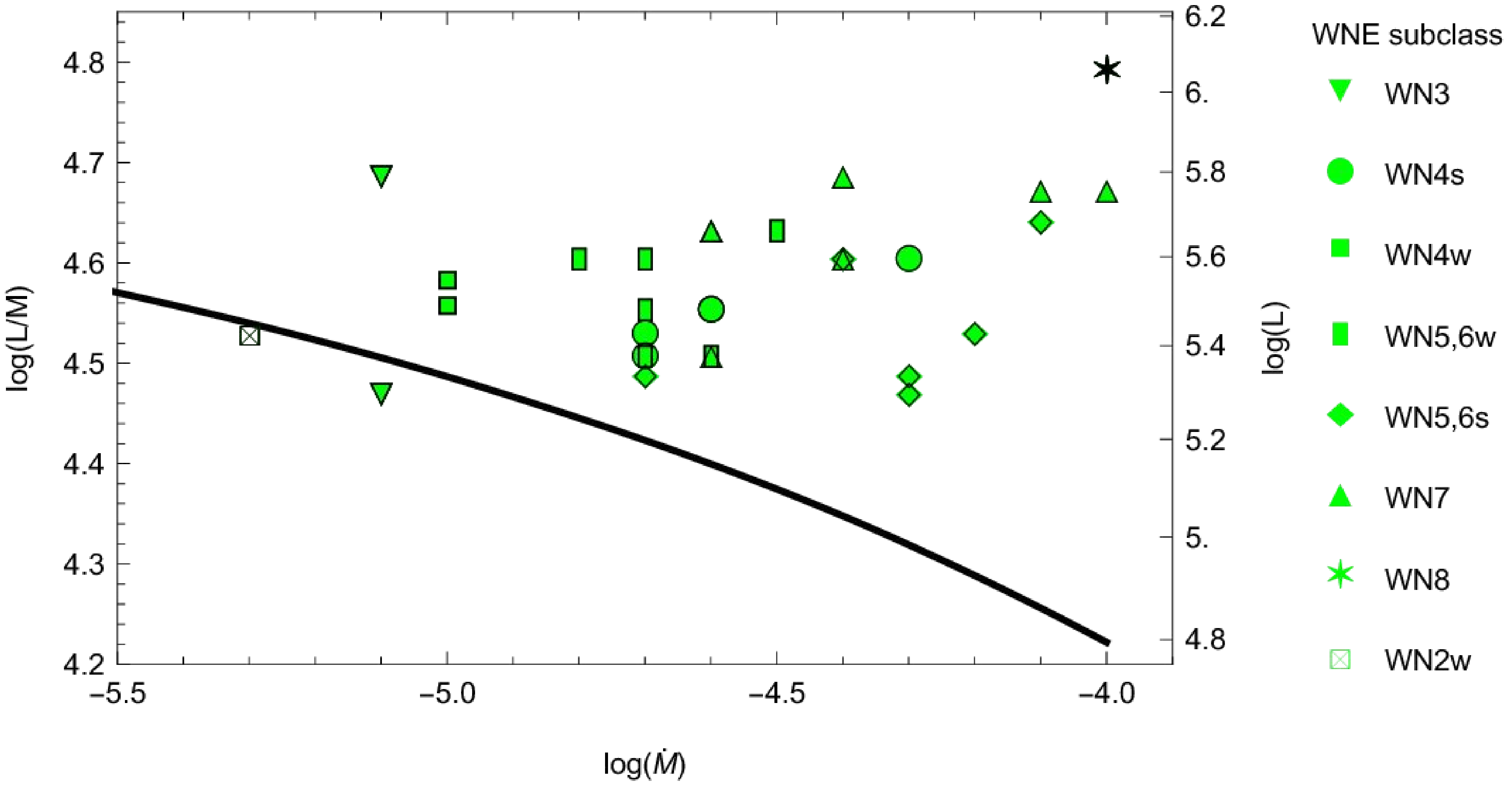
at the Sonic point:

$$T_s \quad \& \quad \frac{L}{M} \Rightarrow \quad \rho\, c_s \times 4\pi R_s^2 = \dot{M}$$

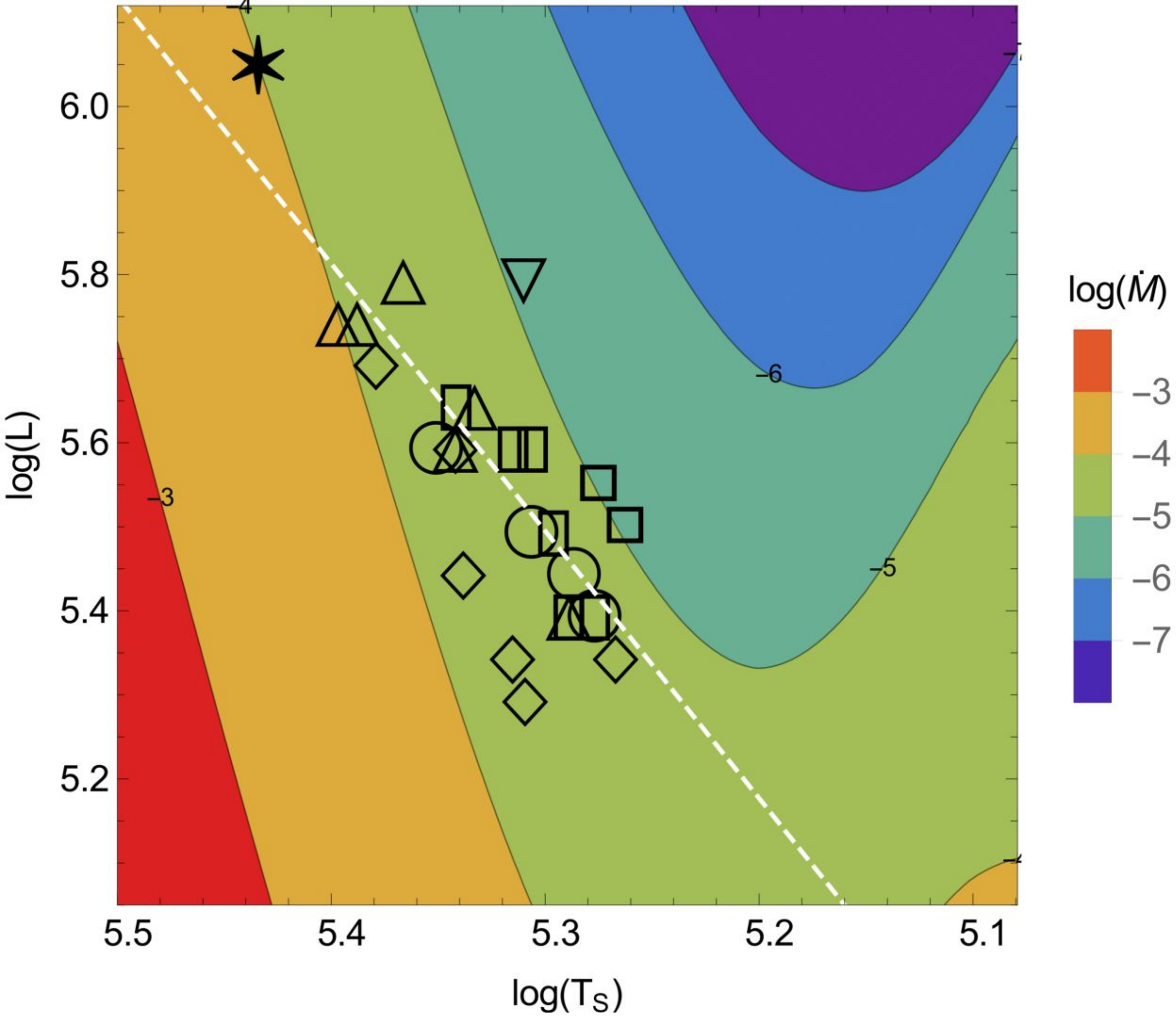
Sonic HR-diagram



Minimum mass-loss rate



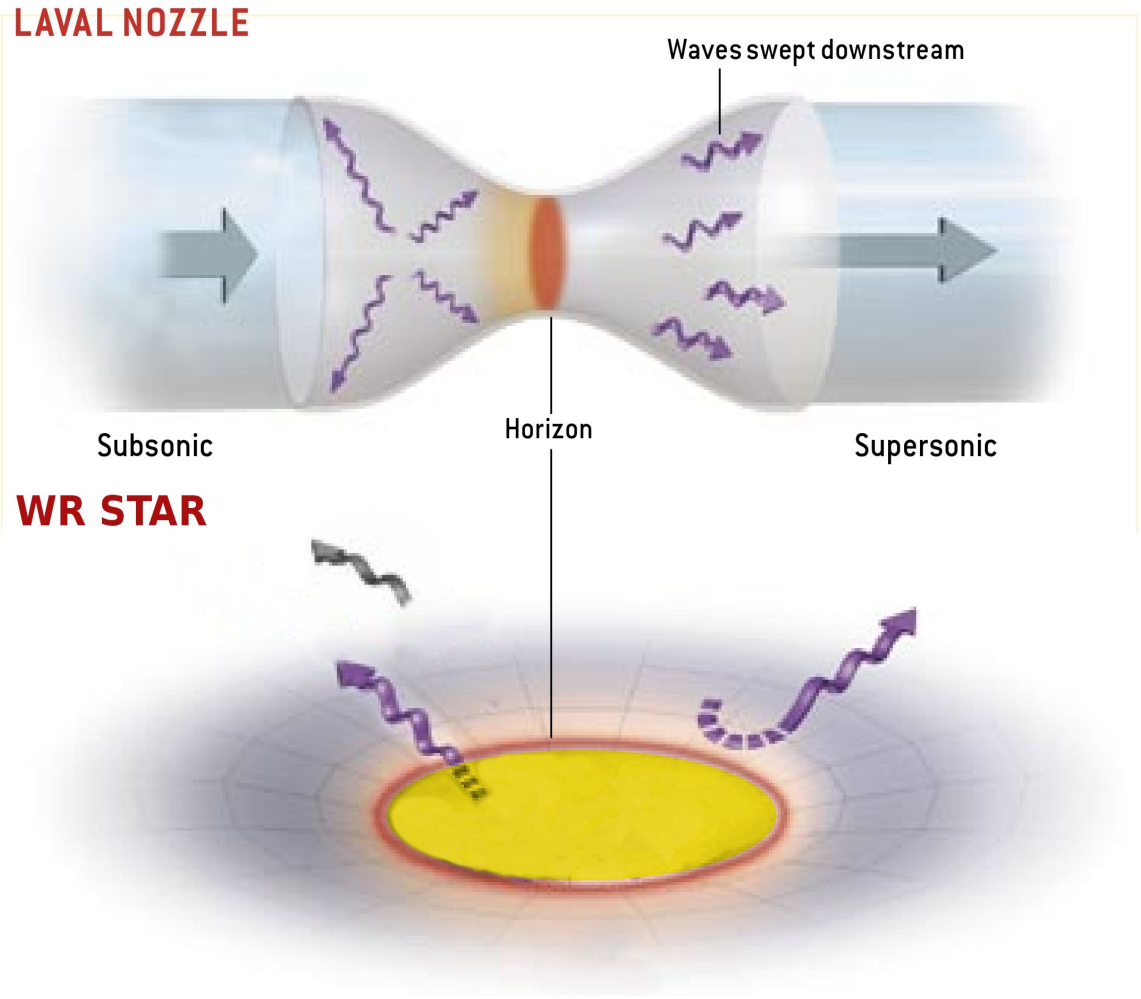
Sonic HR diagram



Conclusions

- ❑ Sonic Horizon ⇒ treat the subsonic structure and the optically thick wind separately
- ❑ Bifurcation Fe-bump and He-bump solutions
- ❑ Proximity of the sonic point to the Edd.limit ⇒ Sonic HR diagram
- ❑ Observed WNEs lie above the minimum Fe mass-loss rate ⇒ Flows driven by Fe bump
- ❑ WNE compact, ~ $1R_\odot$ & 200kK, and our models can serve as inner boundary for atmosphere codes

WR radius problem ⟶ WR wind dynamics problem (stagnation?multiple crit.points?)


LAVAL NOZZLE
Waves swept downstream
Subsonic
Horizon
Supersonic
WR STAR