Mass loss recipes over stellar evolution

International Summer School
Stellar Winds and Outflows

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Physics of Extreme Massive Stars

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01

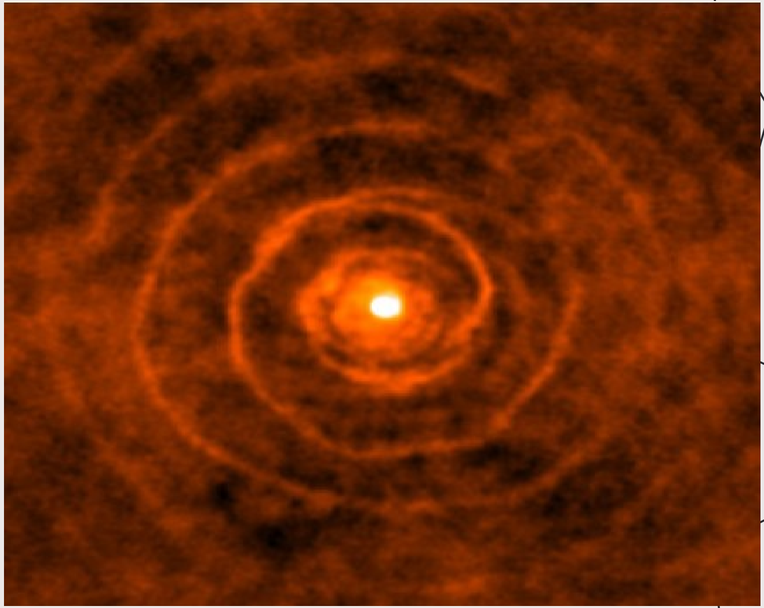
Introduction

Mass loss process gain relevance at different evolutionary stages

- Sun mass loss=10^(-14)Msun/year (via solar winds)
- **Highest mass loss** are known for very massive stars (M>50 Msun) and intermediate mass (~5 Msun) at very late evolutionary stages

Nuclear process which provide part of the radiation lost from stellar surface, imply a conversion from matter to energy and **leads to a reduction of the stellar mass, too.**

Stellar winds results from the **interaction** of the **photons** emitted from the photosphere with **atoms, molecules or dust grain** in the atmosphere → Complicated **radiation-hydrodynamic problem** that may depends in addition on chemical process.



Winds from **very cool stars** depend on the coupling of radiation to dust grains. Their formation process strongly depends on the **temperature and density** in their atmosphere and might be subject of regular variations due to stellar pulsations. **High mass loss rates are often related to pulsations in extended stellar envelopes.**

- **Full theoretical model** for any stellar wind **is not available**

- **Information** about stellar mass loss still results from **observations**

↓

Empirical mass loss formulations are used in stellar evolution models.

They all have been obtained from observations of some **class of stars** and therefore **differ from each other.**
None of them if very accurate but it suffice to have the **correct order of magnitude** of mass loss and its **dependence on the global properties** of the star.

- Mass loss in stellar evolution models

Radiative mass loss

Supra-Eddington mass loss

Mechanical mass loss

- # Mechanical mass loss:

The mass per unit of time lost equatorially when the **surface velocity** of the star reaches the **critical velocity**.

The mechanical mass loss is determined by the **angular momentum** that needs to be lost to ensure that the surface velocity remains **subcritical**.

• Supra-Eddington mass loss

Eddington limit ($\Gamma = 1$): point at which a star's luminosity is so strong that the radiation force balances gravity

Eddington luminosity is the maximum luminosity a star can achieve when there is **balance** between the **force of radiation** acting outward and the **gravitational force** acting inward.

For some massive stars models (>15Msun) in the RSG phase some external layers of the envelope might exceed the Eddington luminosity L_Edd = 4πcGM/κ, due to a peak in the **opacity** that lead to **lower L_Edd** → to increase artificially the mass loss rate (in Geneva models: by a factor of 3 whenever L>5*L_Edd)

• Radiative mass loss:

Recipes

- Vink et al. (2001)
- de Jager et al. (1988)
- Reimers (1977)
- Sylvester et al. (1998)& van Loon et al. (1999)
- Nugis & Lamers (2000)

Correction for rotating models:

$$\dot{M}(\Omega) = F_\Omega \dot{M}(\Omega = 0) = F_\Omega \dot{M}_{\rm rad}$$

$$F_\Omega = \frac{(1-\Gamma)^{\frac{1}{\alpha}-1}}{\left[1 - \frac{\Omega^2}{2\pi G \rho_{\rm m}} - \Gamma\right]^{\frac{1}{\alpha}-1}}$$

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

02

mass loss recipes

Vink et al (2001)

- They studied the mass loss in **early O & B type of stars**
- In the relevant spectral range in which **early-type of stars** emit most of their radiation, **H & He** have only few lines & **metal lines** are responsible for the line driving.
- Mdot=f(Z) for 1/100<Z/Zsun<10.
- They took into account momentum transfer of radiation to gas in a way that allows **photons interact with ions** more than once. (**multiple scattering**)

Vink et al (2001)

- Castor et al. 1975, predicted a power-law without the effect of ”multiple scattering”

$$\dot{M} \propto Z^m$$

- But such pure power-law dependence of **$\dot{M}$ on Z over the entire parameters space is questionable**, due to the presence of one or more **“bi-stability” jumps**.
- The ionization equilibrium depends on Temperature and Density-→ the **position of this bi-stability jump might be shifted as function of Z**.
- From theory and observations: vinf/vesc jumps from 2.6 at the hot side of the jump to 1.3 to the cool side.

Vink et al (2001)

- Monte Carlo simulations to **follow the fate** of a large number of **photons** through the wind and calculates the **radiative acceleration of the wind material.**

- Non-LTE approximation for the model of extended atmospheres with ISA-WIND code.

- For each Z, they calculated $\dot{M}$ for 12 temperatures between 12500K and 50000K

- $X = 1 - Y - Z.$ $Y = Y_p + \left(\frac{\Delta Y}{\Delta Z}\right) Z$ With Yp=0.24 and DY/DZ=3

Vink et al (2001)

- 3 different values of the Eddington factor to explore the dependency for different L and M.

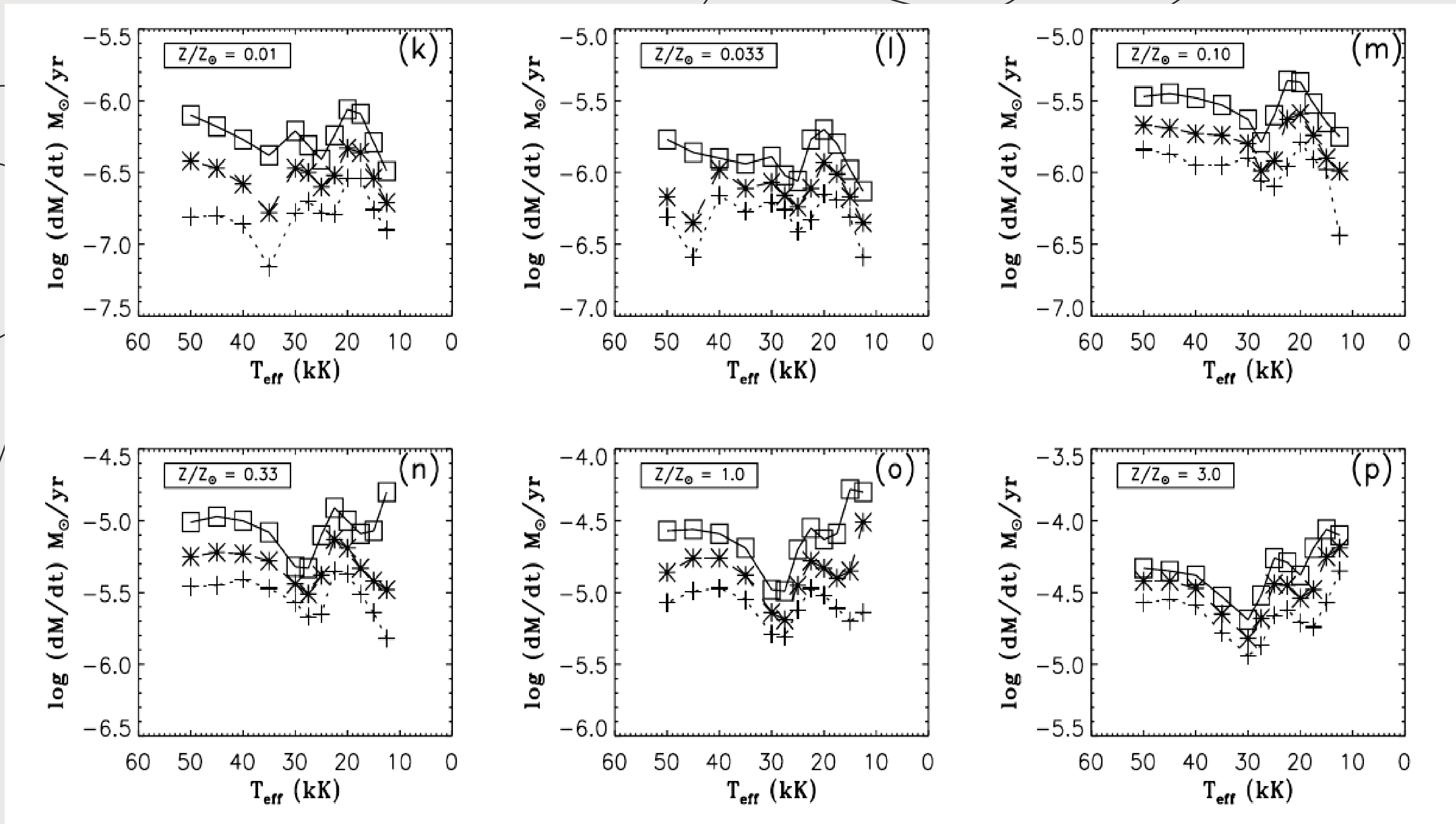
$$\Gamma_e = \frac{L\sigma_e}{4\pi cGM} = 7.66\ 10^{-5}\sigma_e \left(\frac{L}{L_\odot}\right)\left(\frac{M}{M_\odot}\right)^{-1}$$

- electron scattering cross-section per unit of mass

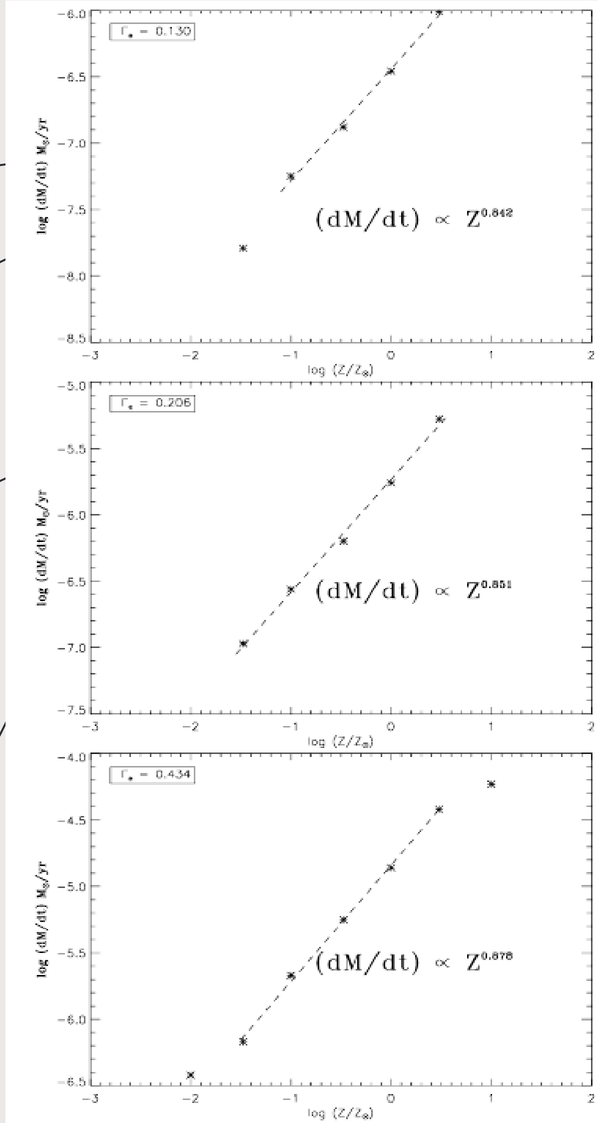
- Different values for the ratio of the terminal velocity over the scape velocity

- And considered a betha-type velocity law for the accelerating part of the wind

$$v(r) = v_\infty \left(1 - \frac{R_*}{r}\right)^\beta$$



(k)
Z/Z⊙ = 0.01
(l)
Z/Z⊙ = 0.033
(m)
Z/Z⊙ = 0.10
(n)
Z/Z⊙ = 0.33
(o)
Z/Z⊙ = 1.0
(p)
Z/Z⊙ = 3.0
log (dM/dt) M⊙/yr
Teff (kK)



$$
\begin{aligned}
\log \dot{M} = & - 6.697\ (\pm 0.061) \\
& + 2.194\ (\pm 0.021)\ \log(L_*/10^5) \\
& - 1.313\ (\pm 0.046)\ \log(M_*/30) \\
& - 1.226\ (\pm 0.037)\ \log\left(\frac{v_\infty/v_{\rm esc}}{2.0}\right) \\
& + 0.933\ (\pm 0.064)\ \log(T_{\rm eff}/40\,000) \\
& - 10.92\ (\pm 0.90)\ \{\log(T_{\rm eff}/40\,000)\}^2 \\
& + 0.85\ (\pm 0.10)\ \log(Z/Z_\odot)
\end{aligned}
$$

for $27\,500 < T_{\rm eff} \leq 50\,000$ K

$$
\begin{aligned}
\log \dot{M} = & - 6.688\ (\pm 0.080) \\
& + 2.210\ (\pm 0.031)\ \log(L_*/10^5) \\
& - 1.339\ (\pm 0.068)\ \log(M_*/30) \\
& - 1.601\ (\pm 0.055)\ \log\left(\frac{v_\infty/v_{\rm esc}}{2.0}\right) \\
& + 1.07\ (\pm 0.10)\ \log(T_{\rm eff}/20\,000) \\
& + 0.85\ (\pm 0.10)\ \log(Z/Z_\odot)
\end{aligned}
$$

for $12\,500 \leq T_{\rm eff} \leq 22\,500$ K

de Jager et al (1988)

- They performed an **statistical analysis** of the mass loss in 271 star of **spectral types O through M**
- Until then the recipes depended on **M, g and R** which cannot be **directly observed**. Their recipe depends on **T_eff and L** → the knowledge of M, g, R may be essential for understanding the **mechanism** which produce the mass loss.
- The $\dot{M}$ depends on the terminal velocity and **v_inf** can be different for stars **with the same T_eff, L, and M** (when the radiation is not the main agent for driving winds.

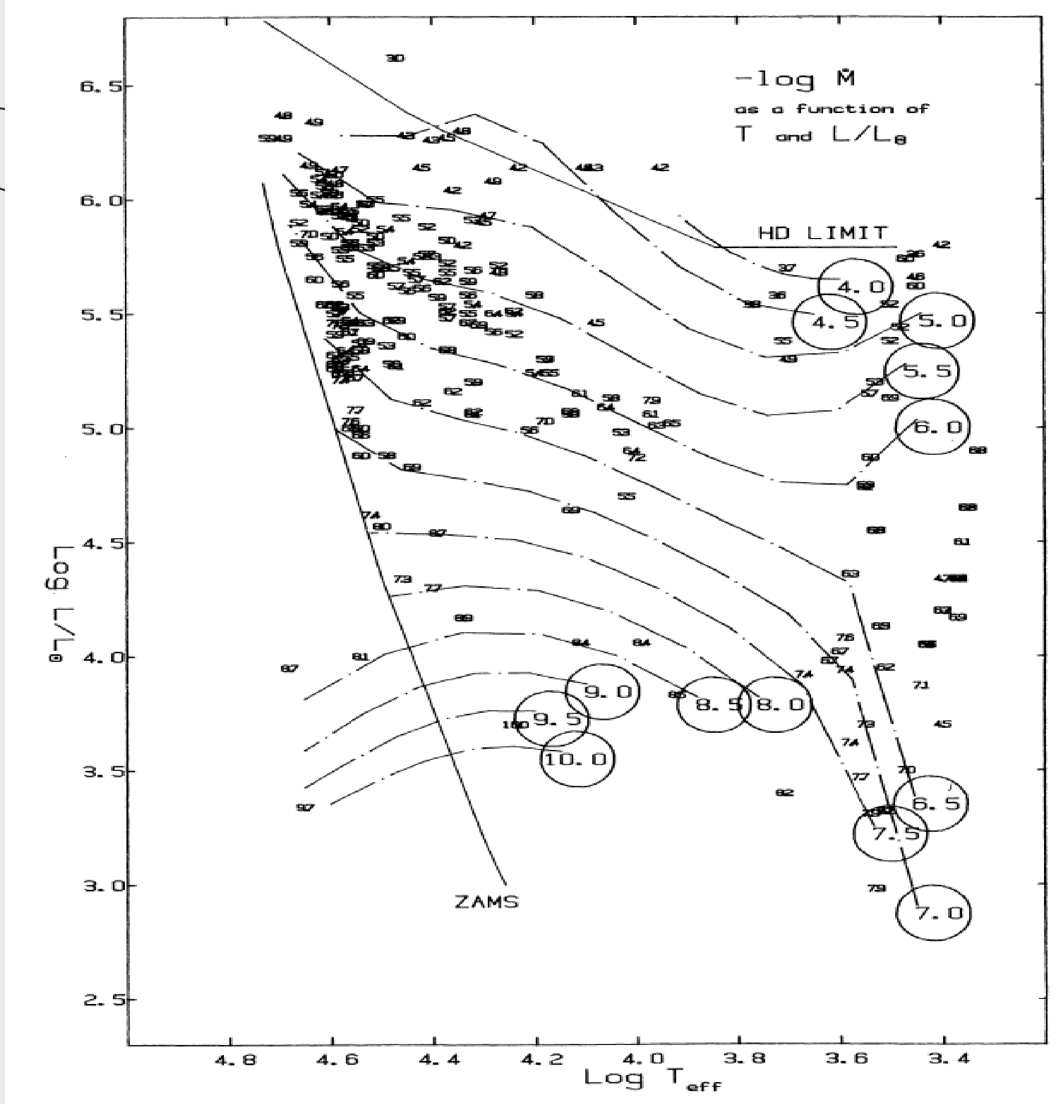
de Jager et al (1988)

- They compile **6 different methods** to derive the mass loss of these stars in the literature (including from the UV spectra, from H_alpha, from the infrared)
- They calculate **an average** for the values of $\dot{M}$ obtained with the same methods but different dataset.
- They adopted the **T_eff and L** as **the average from individual measurement** and the **statistical relation** between **spectral type and luminosity class+T_eff and L**

$$-\log(-\dot{M}) = \sum_{n=0}^{N} \sum_{\substack{i=0 \\ j=n-i}}^{i=n} a_{ij}\, T_i(\log T_{\rm eff}) \times T_j\left(\log\left(\frac{L}{L_\odot}\right)\right)$$

At first order:

$$\log_{10}(-\dot{M}) = 1.769\,\log_{10}(L/L_\odot) - 1.676\,\log_{10}(T_{\rm eff}/[\mathrm{K}]) - 8.158$$



Nieuwenhuijzen & de Jager et al (1990)

- Improvement over de Jager et al (1988) → they used **the same data sample** with similar methods but includes the dependency of the mass loss on the **total stellar mass.**

- They also translate the **temperature dependency into a radius** dependence.

- They used different **evolutionary models** to obtain the masses → their algorithm depends **on the evolutionary tracks** and how they were created (i.e.different mixing theories)

Nieuwenhuijzen & de Jager et al (1990)

- Also, stars at **different evolutionary stages** can pass through the **same point in the HR with different masses** → they derived a 'average expected mass' taking into account:

$$t^{(d)} \stackrel{\text{def}}{=} \frac{\delta t}{\sqrt{[\delta \log_{10}(T_{\text{eff}}/[\text{K}])]^2 + [\delta \log_{10}(L/L_{\odot})]^2}}$$

- Time for a star to travel over the distance (δ T, δ L)

- Resulting :

$$\log_{10}(-\dot{M}) = -14.02 + 1.24 \log_{10}(L/L_{\odot}) + 0.16 \log_{10}(M/M_{\odot}) + 0.81 \log_{10}(R/R_{\odot}) \ .$$

Van Loon et al. (2005)

- Empirically determined on the basis of observations of **oxygen rich AGB and RSG in the Large Magallanic Claud**.
- AGB and RSG have very **extended and cool envelopes** where dust grains might form through sublimation→ they based their analysis in **dust -driven wind model.**
- **Photons from radiation** transfer momentum to these grains, **pushing them away**. Gas grain drag the gas with them through collisional coupling.

Van Loon et al. (2005)

- They fit the observed IR spectra to synthetic spectra obtained with simple model of gas/dust mixture using T_eff and L as variable.

$$\log_{10}(-\dot{M}) = -5.65(15) + 1.05(14)\log_{10}(L/10^4 L_\odot) + \\ -6.3(1.2)\log_{10}(T_{\rm eff}/3\,500\,{\rm K}) \quad ,$$

- Limitations: **high uncertainty of the dust grain properties** (mass fraction, opacity, when they form, etc)

Nugis & Lamers (2000)

- Only for WR stars. The amount of **He** their atmospheres **affects their temperature** and therefore the ionization fraction and the level population of all other atoms and ions.

- The wind mass loss rate of these stars **depends strongly on their chemical composition.**

- They considered a relevant sample of observed galactic WR stars. → 1 set: with **mass and distance known** (also L) (binaries, open cluster)

  → 2 set: with **unknown** intrinsic **luminosity**

Nugis & Lamers (2000)

- They derived an **empirical bolomentric** correction for set 1.
- They used a **theoretical Mass-Luminosity relation** to infer the luminosity of set 2 and the corrected it by the bolomentric correction.

$$\log_{10}(-\dot{M}) = -11.0 + 1.29(14)\log_{10}(L/L_{\odot}) + 1.73(42)\log_{10}(Y) + 0.47(09)\log_{10}(Z) \ ,$$

- **WR winds are strong and optically think** → **the radius is a function of the wavelength** → It cannot be expressed in terms of **R or T_eff** (no Stefan-Boltzmann law).

Kudritzki et al (1989)

- Based on an **analytic solution** for stationary, isothermal, spherically-symmetric and without viscosity **gas flow** with no magnetic fields and no rotation.

- To find an analytic solution the assumed a solve “$\beta - 1\mathrm{aw}$” for the velocity field:

$$v(r) = v_{\infty}\left(1 - \frac{R}{r}\right)^{\beta}$$

- Common assumption close to numerical solutions ($\beta = 1$)

- They **do not treat dynamically** the system, but rather assume a velocity structure.

Kudritzki et al (1989)

- Free parameters

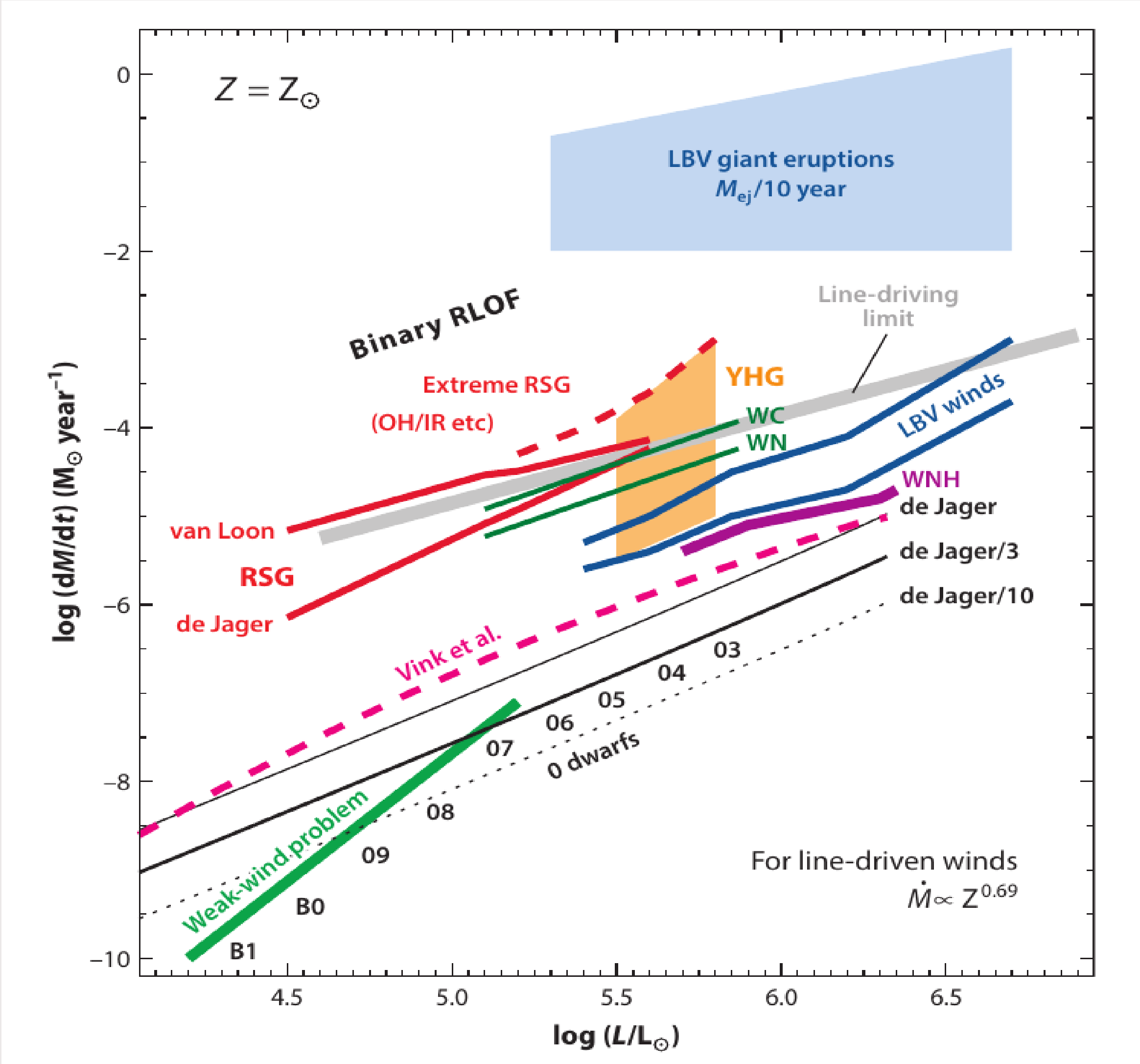
$$\dot{M} \equiv \dot{M}(\alpha, \delta, k, M, L, v_{th}) = \tilde{D}(\alpha, \delta, v) \left(\frac{\sigma_{\mathrm{Th}} k L}{4\pi c} \right)^{1/(\alpha-\delta)} \times \times \left(\frac{4\pi\alpha}{\sigma_{\mathrm{Th}} v_{\mathrm{th}}} \right)^{\alpha/(\alpha-\delta)} \left(\frac{1-\alpha}{GM(1-\Gamma)} \right)^{(1-\alpha)/(\alpha-\delta)} ,$$

- Thermal velocity of protons
- Eddington ratio = L/L_Edd

- **Caveats**: the ‘free parameters’ are not constant but rather depends on the **optical depth**. Practically, **they are calibrated on ξ Pupis.**

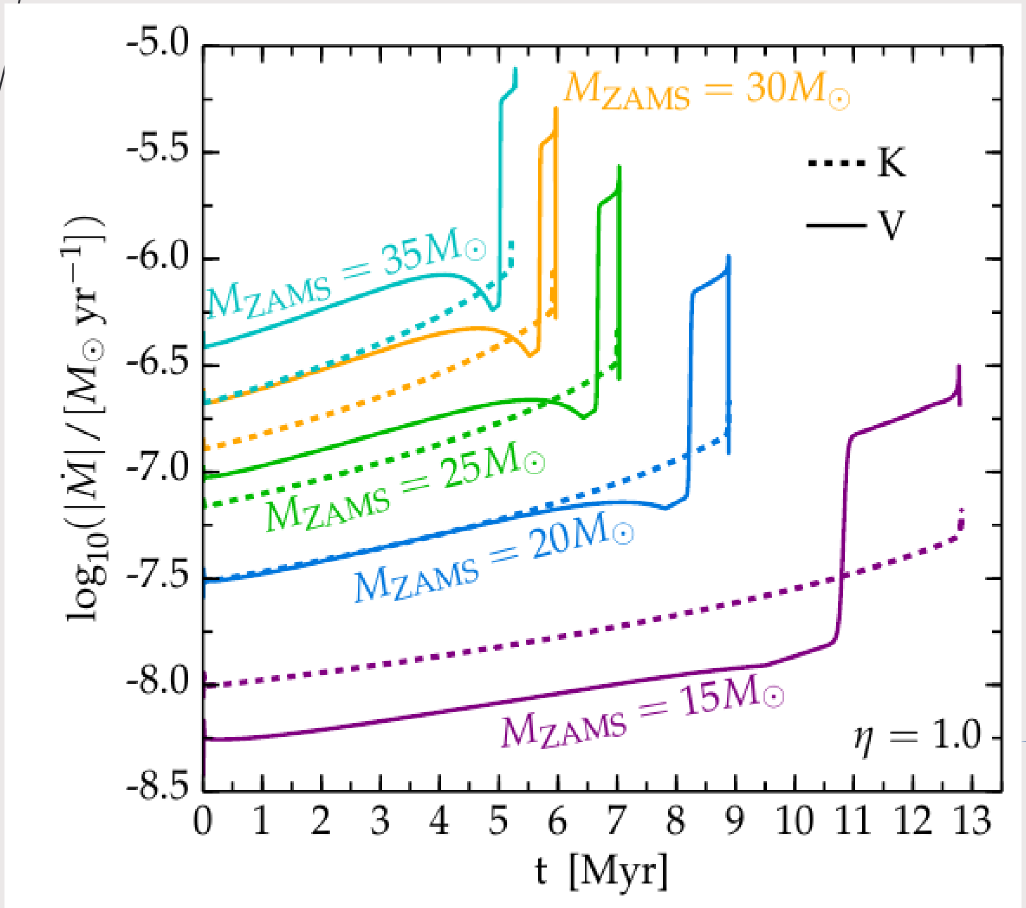
03

Summary



$Z = Z_\odot$
LBV giant eruptions
M_{ej}/10 year
Binary RLOF
Line-driving limit
Extreme RSG
(OH/IR etc)
YHG
WC
WN
LBV winds
WNH
de Jager
de Jager/3
de Jager/10
van Loon
RSG
de Jager
Vink et al.
03
04
05
06
07
0 dwarfs
08
09
B0
B1
Weak-wind problem
For line-driven winds
$\dot{M} \propto Z^{0.69}$
log (dM/dt) ($M_\odot$ year^{-1})
log ($L/L_\odot$)
0
−2
−4
−6
−8
−10
4.5
5.0
5.5
6.0
6.5

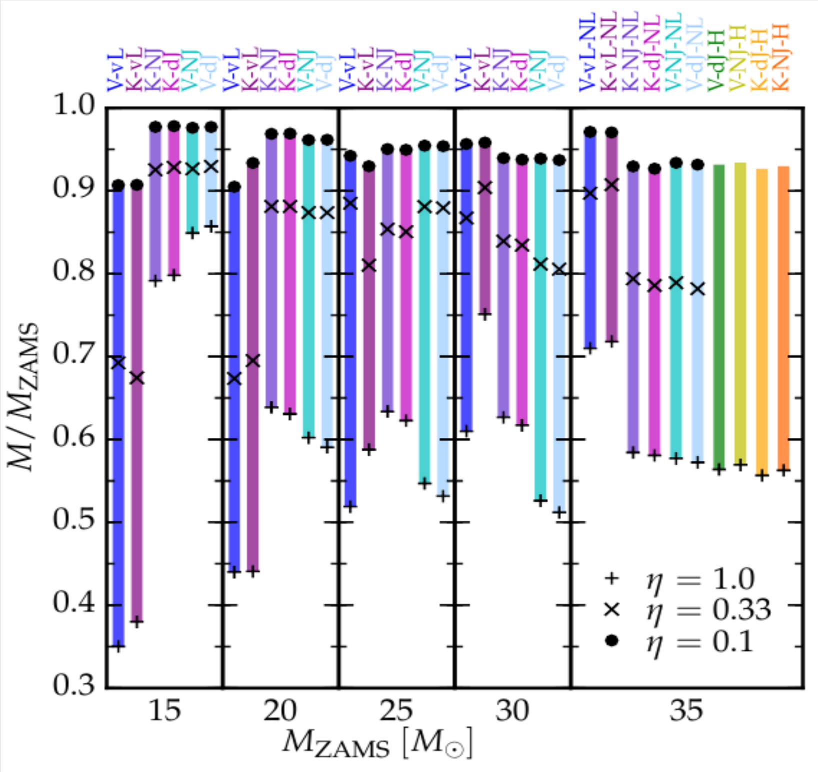
- Comparison between Vink and Kudritzki

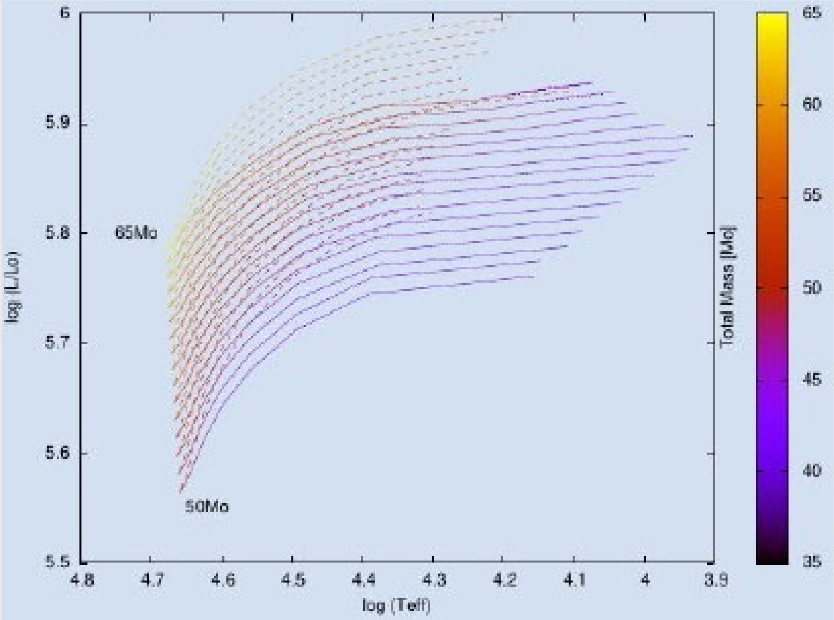


- The rapid rise in the solid curves is due to the inclusion of the bistability jump.

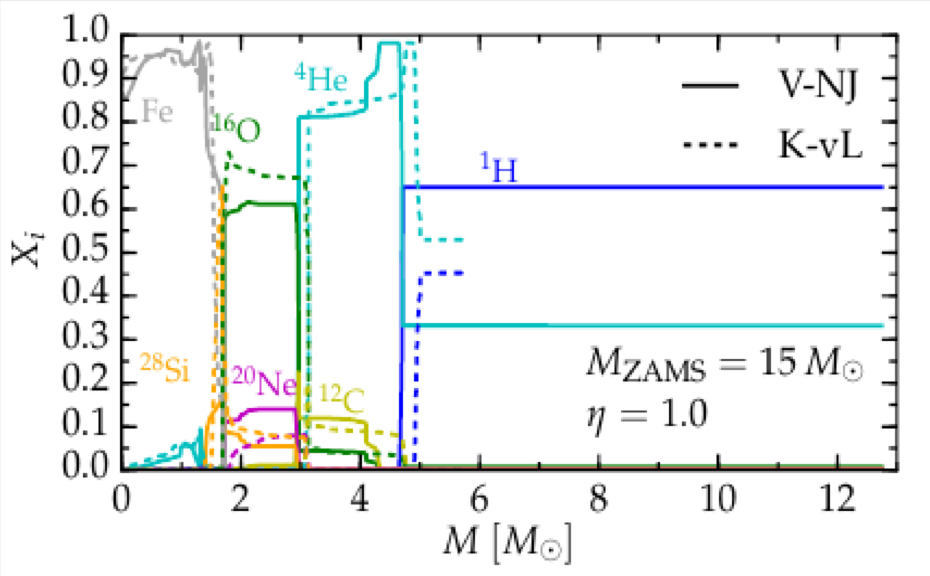
  - Parameter to modify the wind efficiency, to take into account the effect of clumping, for example.

- Efficiency parameter





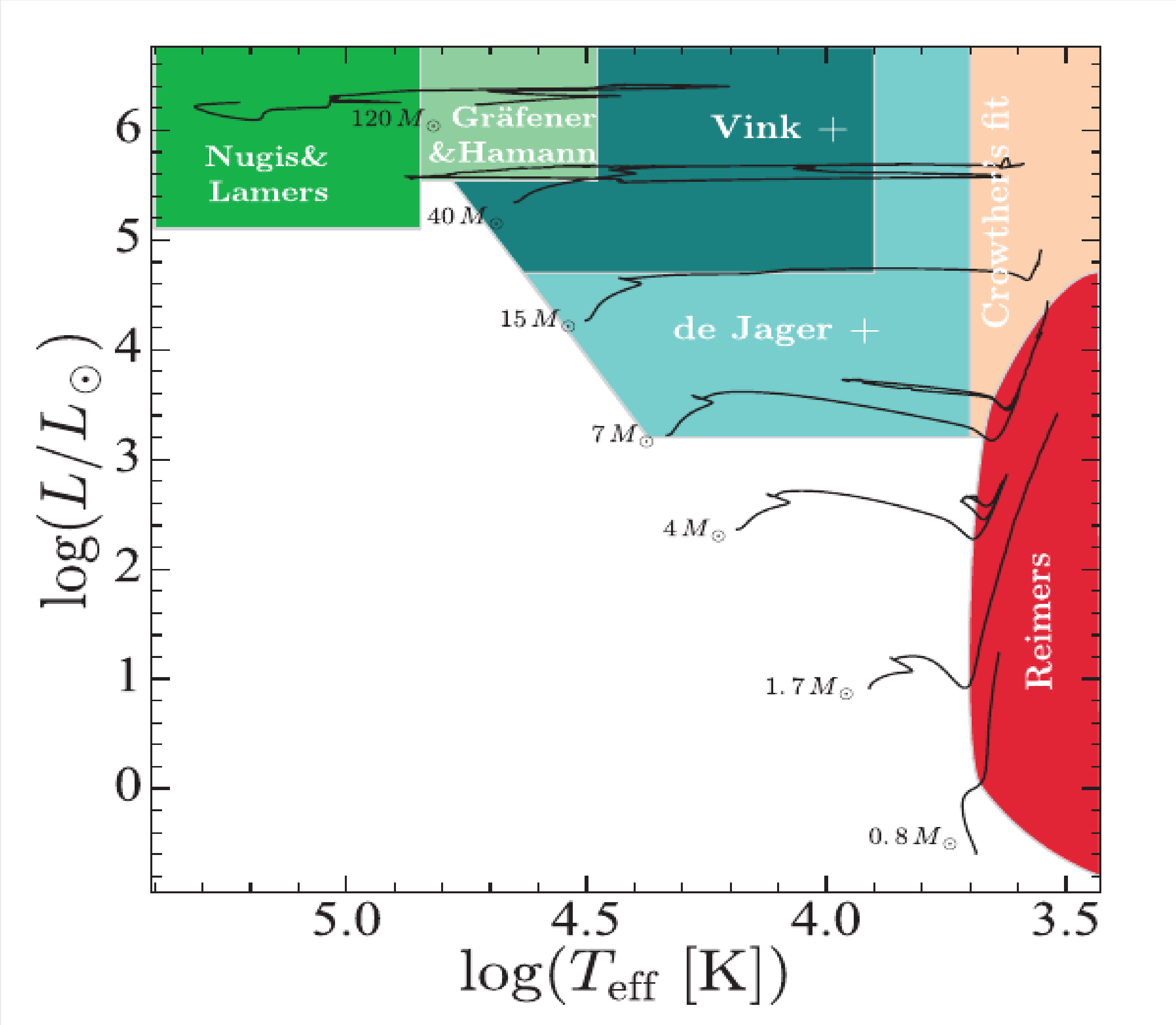
- Results by different recipes applied over the evolution



- Chemical profile for a pre-SN at the onset of the core collapse

- An initial 15Msun star can reach the onset of the core collapse as a He rich 6 Msun or as a 12 Msun H rich star

- It directly affect the enrichment of the interstellar medium.


Nugis&
Lamers
Gräfener
&Hamann
Vink +
Crowther's fit
de Jager +
Reimers
120 $M_\odot$
40 $M_\odot$
15 $M_\odot$
7 $M_\odot$
4 $M_\odot$
1.7 $M_\odot$
0.8 $M_\odot$
$\log(L/L_\odot)$
$\log(T_{\rm eff}$ [K])
6
5
4
3
2
1
0
5.0
4.5
4.0
3.5

- On main sequence:
  - Stars with mass below 7 Msun → constant mass
  - Above 7 Msun → Radiative mass-loss rate is adopted from Vink et al. (2001)
- For red (super) giants:
  - Stars up to 12 Msun → Reimers(1975,1977)
  - for stars of 15 Msun and above → de Jager et al. (1988) constant mass **(for log(Teff)>3.7)** & linear fit to the data from Sylvester et al (1998) & van Loon et al. (1999)
  - **(for log(Teff)<3.7)**

- For Wolf-Rayet:

- Evolved stars with M>20-30Msun, 35000<Teff<50000 → Nugis & Lamers (2000), or Grafener & Hamann (2008) in its small domain.

- When Mdot (Grafener & Hamann (2008))< Mdot (Vink et al. (2001)) → Vink recipe is used.

- Nugis & Lamers (2000) and Grafener & Hamann (2008) mass loss rates account for some clumping effects (Muijres et al (2011) making them 2 or 3 times lower the normal rates.

• Caveats

- There remain **substantial issues in understanding the physics of wind driving**, **magnetic field and angular momentum** loss and is challenging to understand how these corresponds to observational diagnosis.

- Usually, **mass loss rates** needs to be **reduced** by a factor of 2(3) compared with rates derived **observationally** (like those of de Jager & Nieuwenhuijzen) → is like replace mass loss rates at Z=Zsun by currently used mass loss rates for Z=0.37(0.2) Zsun

- There is a high level of uncertainties in the most important phases of mass loss for massive stars → • This isn't good!

• What can we do?

- DON'T PANIC!

- We have a firm understanding of stellar winds of **hot O-type** of stars relevant for most of their lives **on the H-burning MS phase**

- To place more emphasis on **matching individual observed stars** with well-constrained physical parameter, instead of matching statistics of massive-stars populations which are **contaminated by binaries.**

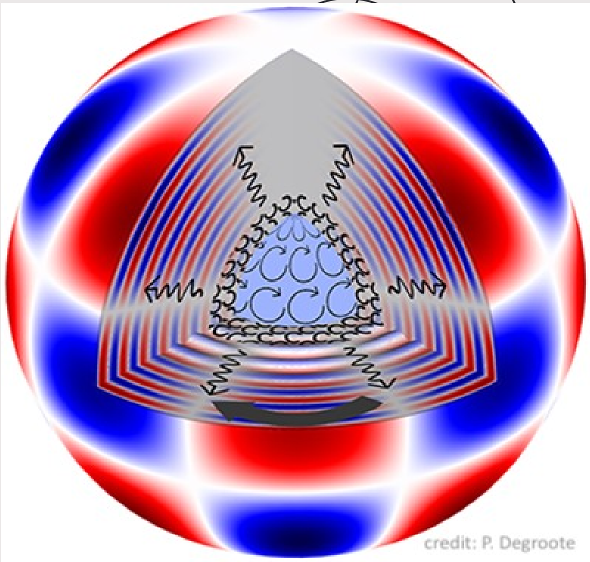
- To use stellar evolution codes as **"toy models"** to investigate the final outcome for a wide range of mass loss including episodic mass loss

04

Oscillations

Stellar oscillations

- Pulsations can facilitate the mass loss in massive stars.
- In classical pulsators, pulsations are usually excited by the k-mechanism.
- Modes known to facilitate mass loss are driven mainly by **instabilities of non-thermal origin** and can be interpreted in term of **mechanical quantities** only.



Stellar oscillations

- Adiabatic equations

$$\frac{\delta\rho}{\rho} = -\vec{\nabla}.\delta\vec{r},$$

$$T\frac{\partial\delta s}{\partial t} = \delta\left(\epsilon - \frac{\mathrm{d}L}{\mathrm{d}m}\right)$$

$$\frac{\partial^2\delta\vec{r}}{\partial t^2} = -\vec{\nabla}\psi' - \frac{\vec{\nabla}P'}{\rho} + \frac{\rho'}{\rho}\vec{\nabla}\psi,$$

$$\frac{\delta P}{P} = \Gamma_1\frac{\delta\rho}{\rho} + \frac{\rho}{P}(\Gamma_3 - 1)T\delta s$$

$$\nabla^2\psi' = 4\pi G\rho'$$

$$x\frac{\mathrm{d}y_1}{\mathrm{d}x} = \left(\frac{V}{\Gamma_1} - 1 - \ell\right)y_1 + \left(\frac{\ell(\ell+1)}{c_1\omega^2} - \frac{V}{\Gamma_1}\right)y_2 + \frac{\ell(\ell+1)}{c_1\omega^2}y_3 + \upsilon_T y_5,$$

$$x\frac{\mathrm{d}y_2}{\mathrm{d}x} = \left(c_1\omega^2 - A^*\right)y_1 + \left(A^* + 3 - U - \ell\right)y_2 - y_4 + \upsilon_T y_5,$$

$$x\frac{\mathrm{d}y_3}{\mathrm{d}x} = (3 - U - \ell)\,y_3 + y_4,$$

$$x\frac{\mathrm{d}y_4}{\mathrm{d}x} = UA^* y_1 + U\frac{V}{\Gamma_1}y_2 + \ell(\ell+1)y_3 + (2 - U - \ell)y_4 - \upsilon_T U y_5,$$

$$x\frac{\mathrm{d}y_5}{\mathrm{d}x} = V\left[\nabla_{\mathrm{ad}}(U - c_1\omega^2) - 4(\nabla_{\mathrm{ad}} - \nabla) + c_{\mathrm{dif}}\right]y_1 + V\left[\frac{\ell(\ell+1)}{c_1\omega^2}(\nabla_{\mathrm{ad}} - \nabla) - c_{\mathrm{dif}}\right]y_2$$
$$+ V\left[\frac{\ell(\ell+1)}{c_1\omega^2}(\nabla_{\mathrm{ad}} - \nabla)\right]y_3 + V\nabla_{\mathrm{ad}}y_4 + \left[V\nabla(4 - \kappa_S) + 2 - \ell\right]y_5 - \frac{V\nabla}{c_{\mathrm{rad}}}y_6,$$

$$x\frac{\mathrm{d}y_6}{\mathrm{d}x} = \left[\ell(\ell+1)c_{\mathrm{rad}}\left(\frac{\nabla_{\mathrm{ad}}}{\nabla} - 1\right) - Vc_{\epsilon,\mathrm{ad}}\right]y_1 + \left[Vc_{\epsilon,\mathrm{ad}} - \ell(\ell+1)c_{\mathrm{rad}}\left(\frac{\nabla_{\mathrm{ad}}}{\nabla} - \frac{3 + \partial c_{\mathrm{rad}}}{c_1\omega^2}\right)\right]y_2$$
$$+ \left[\ell(\ell+1)c_{\mathrm{rad}}\frac{3 + \partial c_{\mathrm{rad}}}{c_1\omega^2}\right]y_3 + \left[c_{\epsilon,S} - \frac{\ell(\ell+1)c_{\mathrm{rad}}}{\nabla V} + \mathrm{i}\omega c_{\mathrm{thm}}\right]y_5 - (\ell+1)y_6.$$

- Non-adiabatic equations

Stellar oscillations

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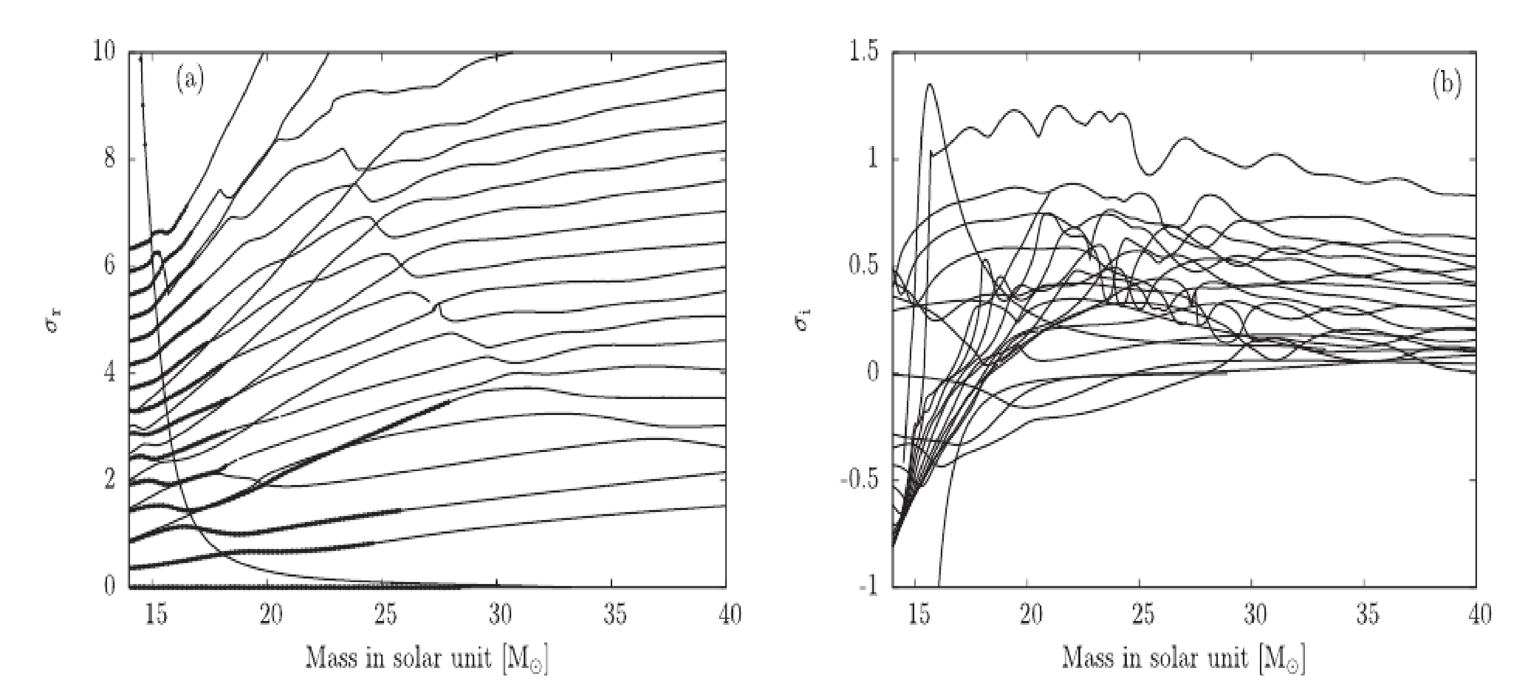

Stellar oscillations

- Caveats:

- It is not possible to quantify the mass lost by stellar oscillations

- There is no open source code capable of **following these modes through a non-linear stability analysis.**

Thanks!

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