ESAC Science Faculty Seminar
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Modeling hot star atmospheres: The current and the next generation

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Introduction: Hot, Massive Stars

- Massive: $M_{\text{init}} > 8 M_{\odot}$

Orion Belt (Credit: ESO/ESA/NASA)

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  → high surface brightness
  → strong UV flux

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Unofficial motto:
"Live fast, die young"

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Introduction: Mass Loss via Stellar Winds

Massive stars show a **strong matter outflow**, called *stellar wind*

- Mass loss up to $1 \ldots 10\,M_\odot$ in $10\,000\,\mathrm{yr}$
- Wind velocities up to ≈ 5000 km/s

Hot stars:
Outflow is driven by strong radiation

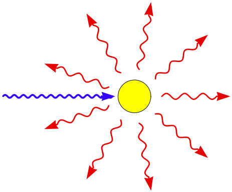
Huge influence on environment:

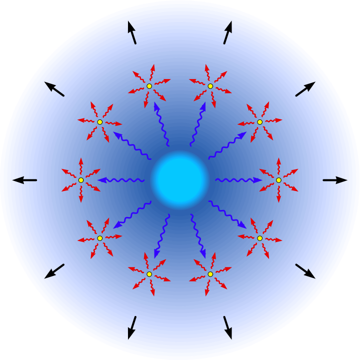
- chemical enrichment
- kinetic energy injection
- ionizing radiation

The "Bubble Nebula" NGC 7635
(Credit: Russell Croman)

Introduction: Line-driven Winds

- Each photon carries momentum $\frac{h\nu}{c}$
- Momentum transfer from photons to metal ions by line absorption



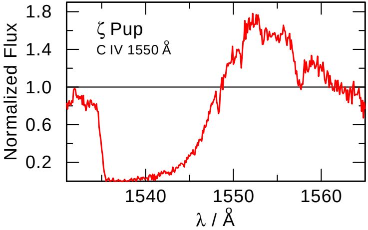


- Absorptions mainly from radial directions but isotropic re-emission
  $\Rightarrow$ Radial net outflow

Spectral appearance

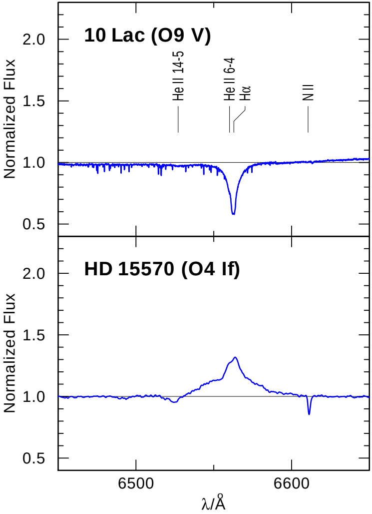
Spectral signatures of mass-loss:

UV: P Cygni Profiles

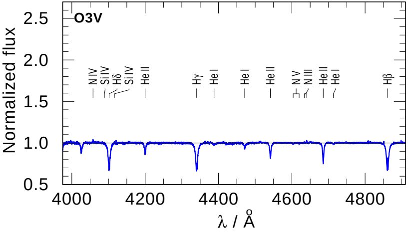


Optical:

- low $\dot{M}$: absorption lines
  $\hookrightarrow$ decently affected by wind
- high $\dot{M}$: emission lines
  $\hookrightarrow$ strongly affected by wind



Line-driven wind regimes: From OB up to Wolf-Rayet



O and B Stars

- optical spectrum has mostly absorption lines
- relatively narrow lines
- mass loss rates up to $\approx 5 \times 10^{-6}$

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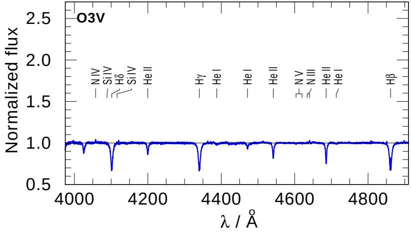

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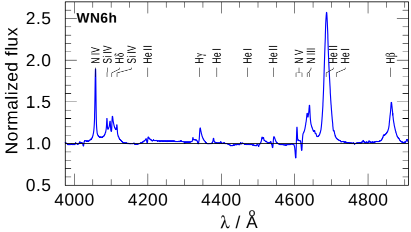


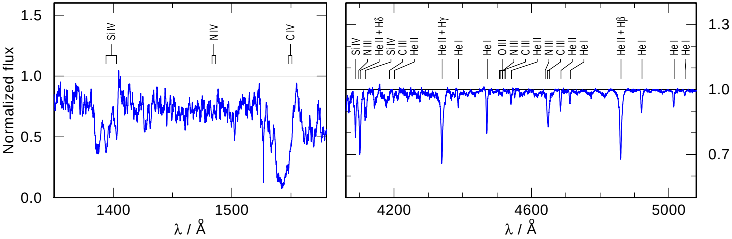
WR Stars

- optical spectrum dominated by emission lines $\rightarrow$ dense wind
- strong lines, huge emission peaks
- mass loss rates up to $\approx 5 \times 10^{-5}$

Why study stellar atmospheres?

Why we should care about stellar atmospheres:

- The stellar atmosphere is all we really see from the star
- Its spectrum is (usually) the only information we get
  $\Rightarrow$ understand the spectrum to understand the star



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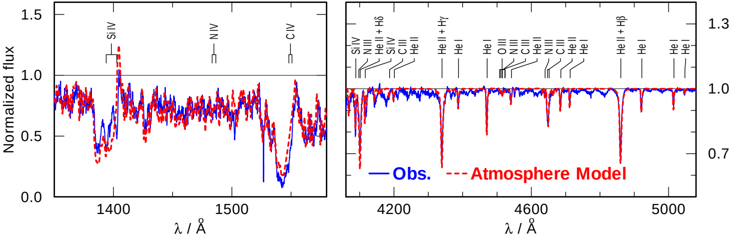
- Only a proper modeling of the atmosphere can reproduce the emergent spectrum



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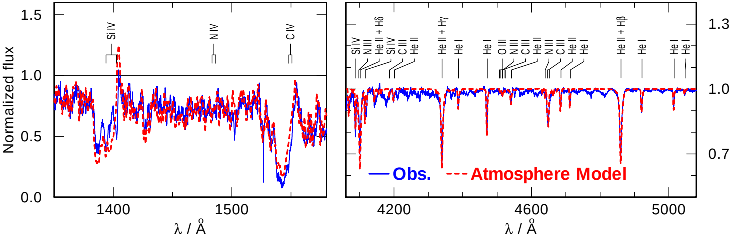

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- stellar and wind parameters (T_{eff}, $\log g$, L, v_∞, $\dot{M}$ ...)

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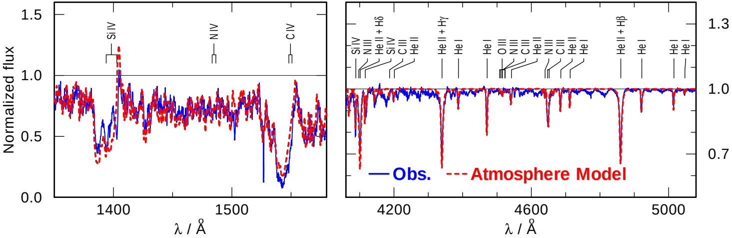

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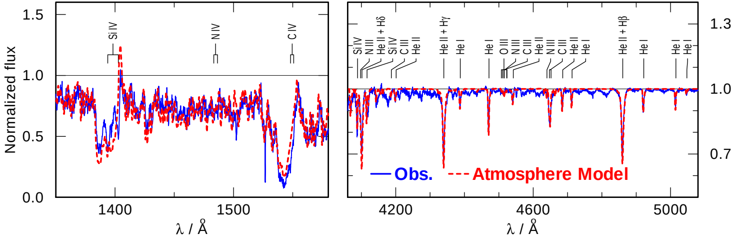

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- insights on stellar feedback ($\dot{M}$, ionizing photons, etc.)

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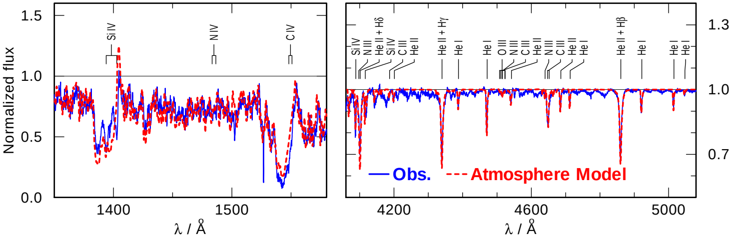

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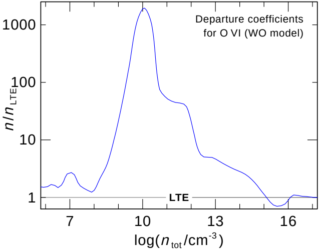
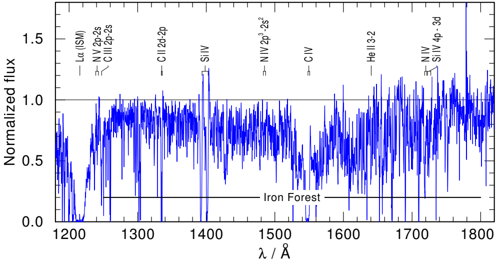
⇒ Stellar atmosphere models are the basis for a plethora of applications

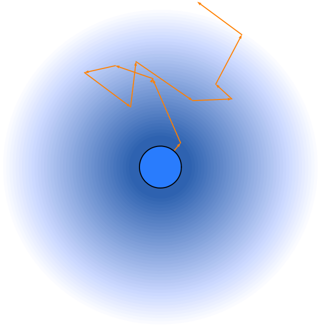
Modeling stellar atmospheres

What has to be included?

- Extreme non-LTE situation
- Multiple scattering in an expanding atmosphere (avoid CAK limitations)
- Model atoms for H, He, C, N, Fe, etc.
- Accounting for millions of lines for iron group elements ("blanketing")







The complexity of non-LTE stellar atmosphere modeling

Radiation Transfer

Symbolically: linear mapping Λ

$$\mathbf{J} = \mathbf{\Lambda}\,\mathbf{S}(\vec{n})$$

radiation field — source function — population numbers

→ Coupling in space

Rate Equations (Statistical Equilibrium)

Set of linear eqns. at each spacial point

$$\vec{n} \cdot \mathbf{P}(\mathbf{J}) = [0, ..., 0, 1]$$

pop. numbers (at 1 depth point) — transition rates

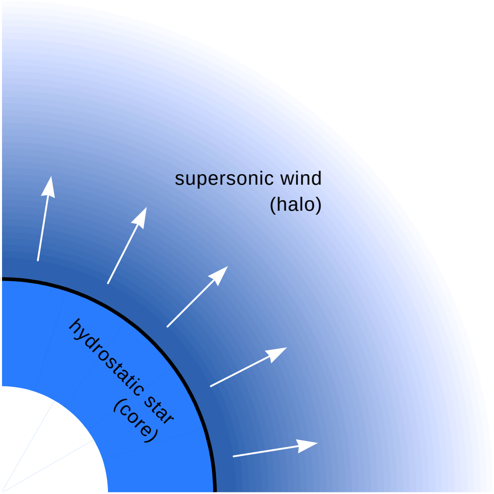
→ Coupling in frequency

Radiative transition rates:
Frequency integrals

$$R_{lu} = \int \frac{4\pi}{h\nu}\,\sigma_{lu}(\nu)\,J_\nu\,\mathrm{d}\nu$$

→ **high-dimensional, non-linear, fully coupled in space and frequency**

Modeling two regimes



Two different regimes must be taken into account

- hydrostatic regime
- wind regime

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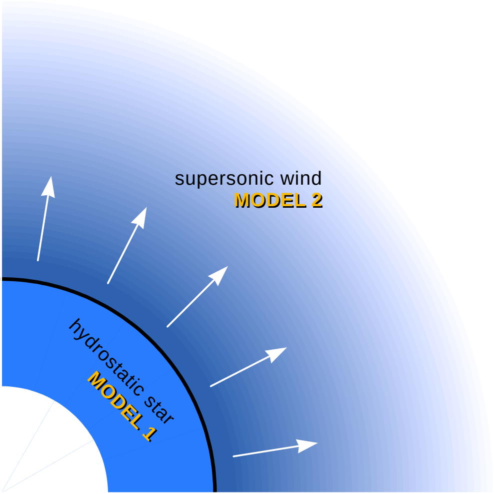

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Traditional core-halo approach: Two separate models

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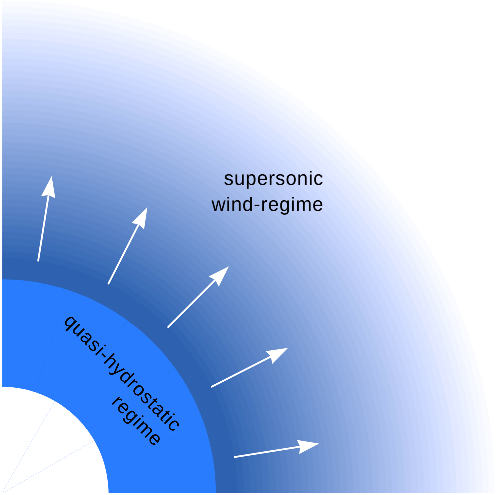

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Modern approach, since $\approx$ 1990s:
Unified model atmospheres
(e.g. Hamann & Schmutz 1987, Gabler et al. 1989)

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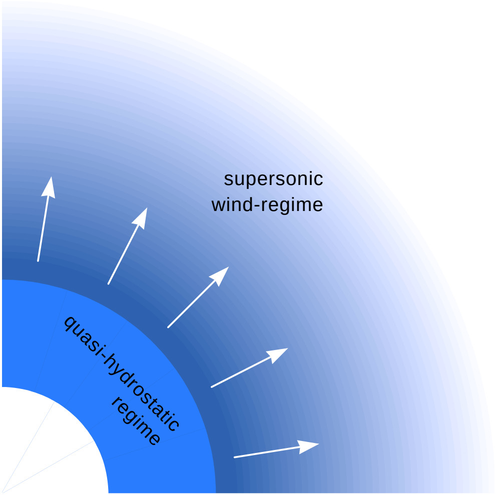

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Unified models require an accurate description of the radiation pressure:
⇒ use **Monte Carlo** (MC) or **Comoving Frame** (CMF)

Comoving frame radiative transfer: The benefits

CAK - Approximate description of a_{rad} using parameters (α, ...)

$$a_{\text{rad}} = a_{\text{thom}} + a_{\text{lines}} + \cancel{a_{\text{true}}}\text{ cont}$$

$$= \Gamma_e \cdot g(r) \left[1 + \mathcal{C} \left(\frac{r^2 v}{\dot{M}} \frac{\mathrm{d}v}{\mathrm{d}r} \right)^{\alpha} \right]$$

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- allows fast calculation based on only a few parameters
- neglects continuum contribution
- neglects multiple scattering $\rightarrow$ breakdown for thick winds

Comoving frame radiative transfer: The benefits

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$$\begin{aligned} a_{\text{rad}} &= a_{\text{thom}} + a_{\text{lines}} + a_{\text{\sout{true} cont}} \\ &= \Gamma_e \cdot g(r) \left[1 + \mathcal{C} \left(\frac{r^2 v}{\dot{M}} \frac{\mathrm{d}v}{\mathrm{d}r} \right)^{\alpha} \right] \end{aligned}$$

CMF radiative transfer - exact evaluation of the acceleration integral:

$$a_{\text{rad}}(r) = \frac{4\pi}{c} \frac{1}{\rho(r)} \int_0^\infty \kappa_\nu(r) H_\nu(r) \mathrm{d}\nu$$

- implicitly includes various effects (e.g. multiple scattering)
- works for all line-driven winds (WR, O, B, LBV, sdO, [WR], ...)
- detailed approach $\rightarrow$ significant calculation time

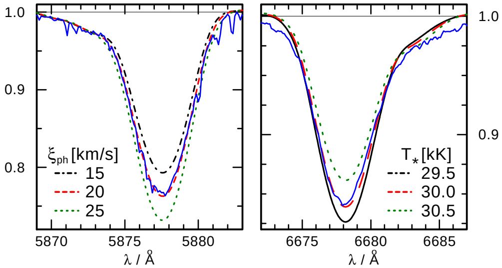
Quasi-Hydrostatic Regime

Another layer of complexity:

Hydrodynamically-consistent description of the quasi-hydrostatic regime

→ essential for a proper analysis of OB-stars

→ affects spectrum if quasi-static photosphere is visible
(O, B, "cool" and/or "thin" WR winds)



Model requirement:

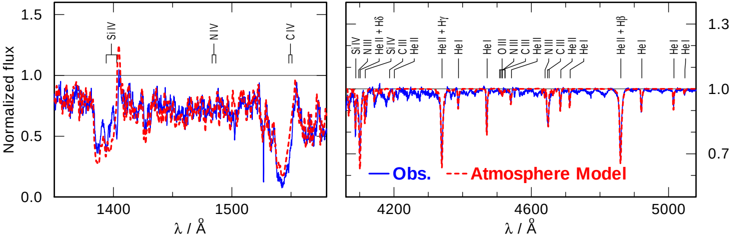
stratification in the subsonic part must fulfill the hydrostatic equation (e.g. Sander et al., 2015)

left figures from Shenar et al. (2014):

absorption line diagnostic examples

CMF model atmospheres: State of the art

The current state of the art:



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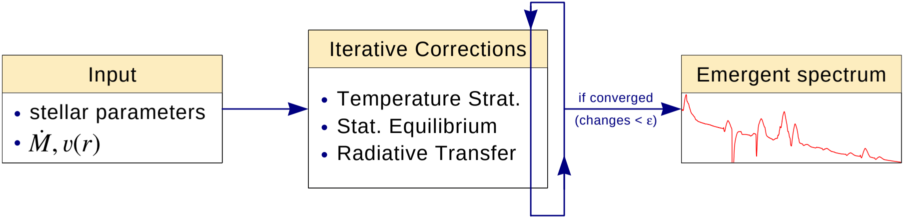

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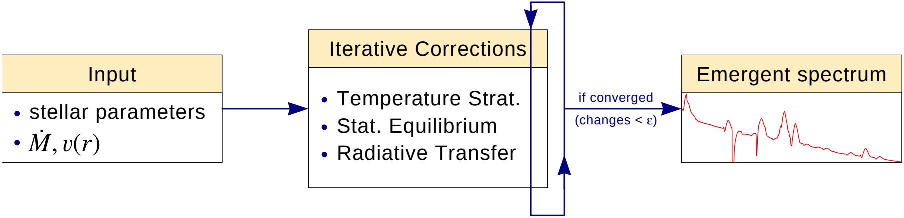

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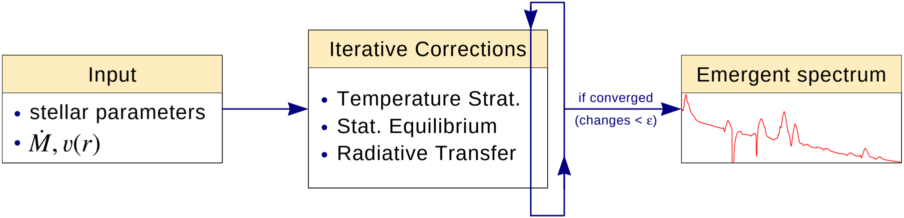

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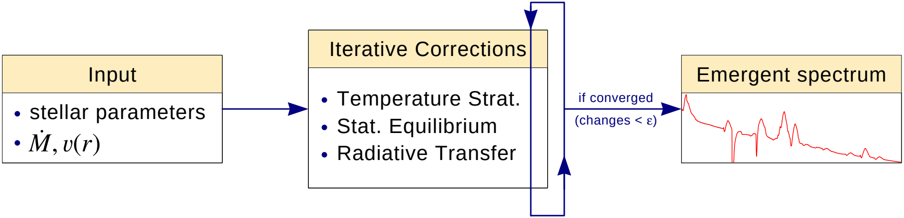

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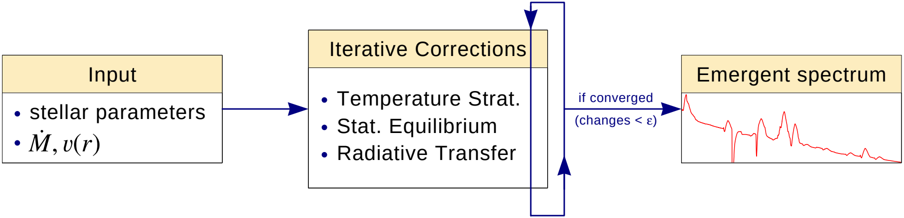

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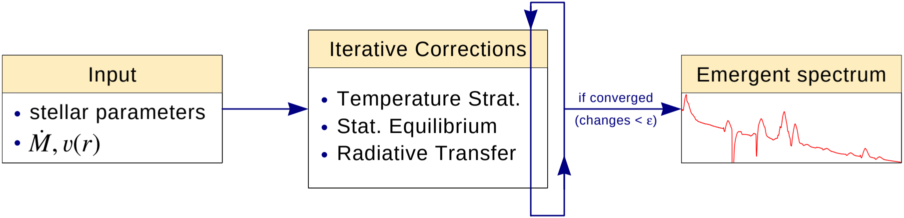

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- Approximate treatment for density inhomogeneities ("clumping")

The PoWR Code

PoWR

Potsdam **W**olf-**R**ayet Star Model Code for expanding stellar atmospheres

→ **detailed model atmospheres for hot stars**

Online model grids: `www.astro.physik.uni-potsdam.de/PoWR/`

For each model the website provides:

- Spectral energy distribution
- High-resolution line spectrum for various bands
- Atmosphere stratification
- Photometric colors and ionizing fluxes

plus extensive preview features for all spectra

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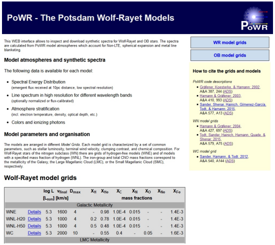

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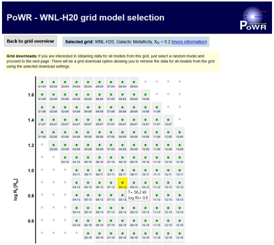
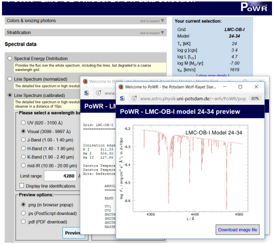


Preview & Download:



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Unified model atmosphere: *Accurate physics throughout the atmosphere!*

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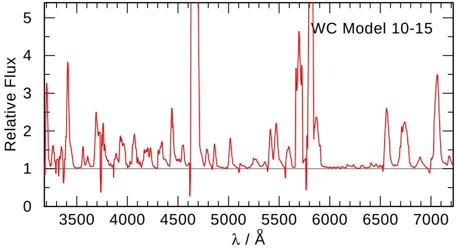

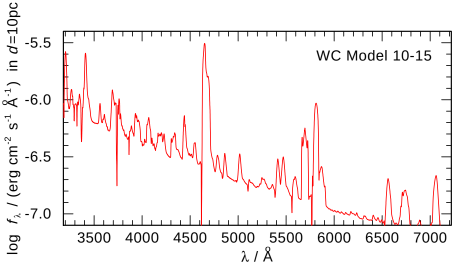

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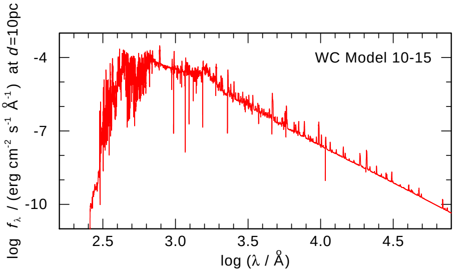

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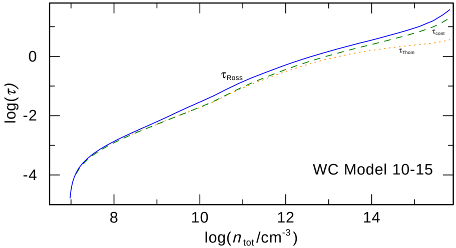

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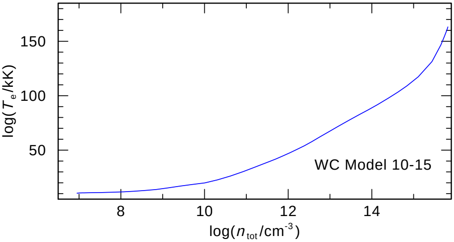

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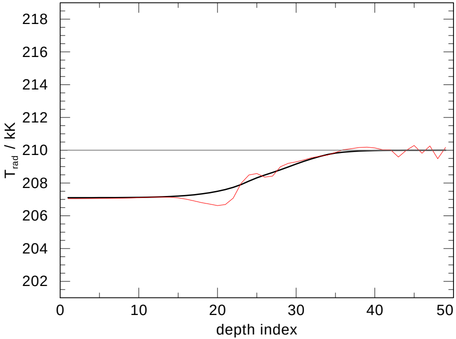

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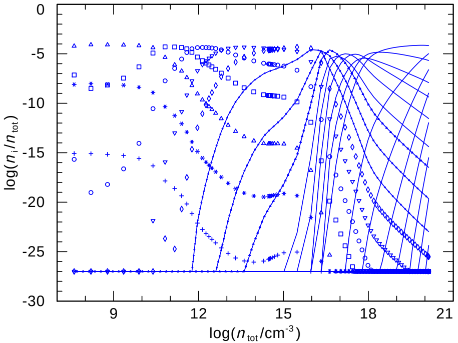

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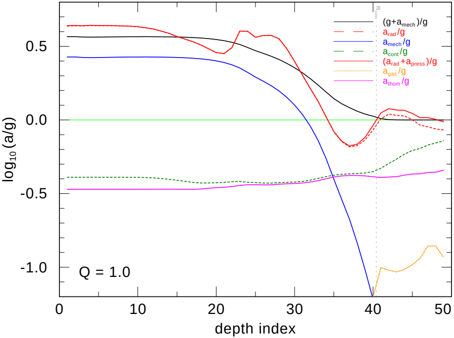
- Ionisation stratification
- Detailed acceleration balance



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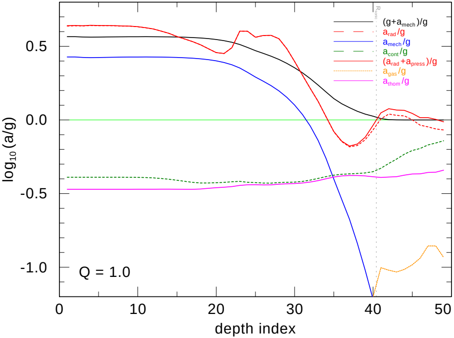
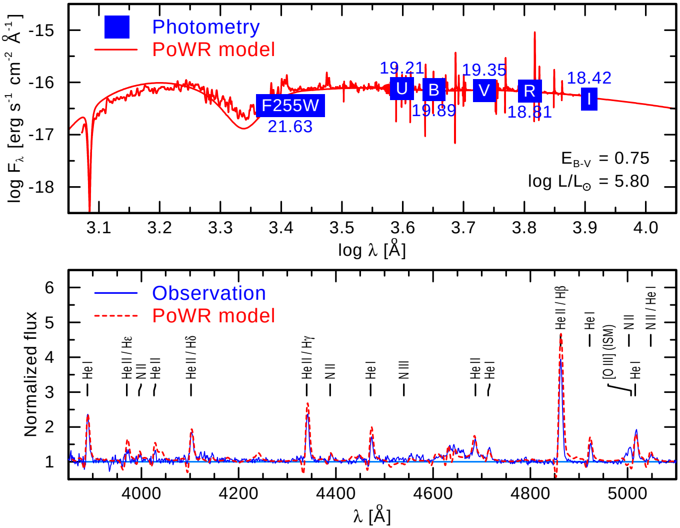


⇒ Stratification details can provide input for various follow-up research!

Application examples

Obtaining stellar and wind parameters by reproducing observations:



Example from Sander et al. (2014)

M31WR 148 (WN10)

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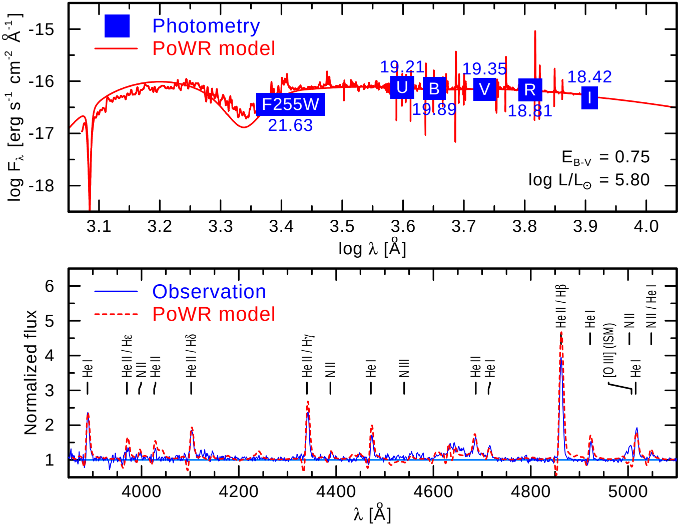

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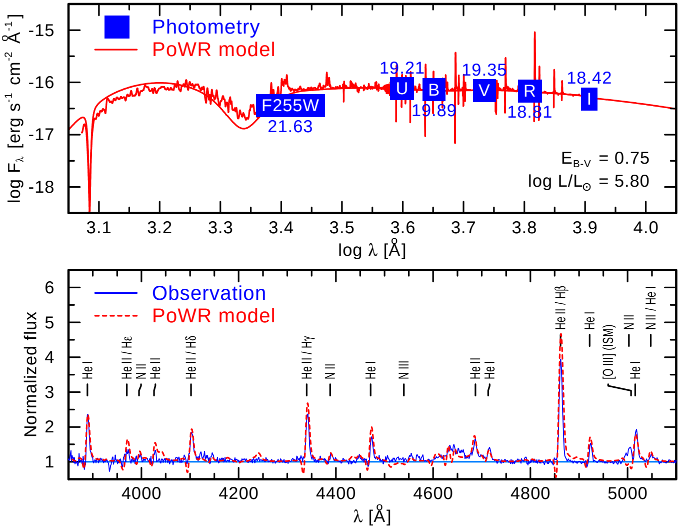

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T_*,

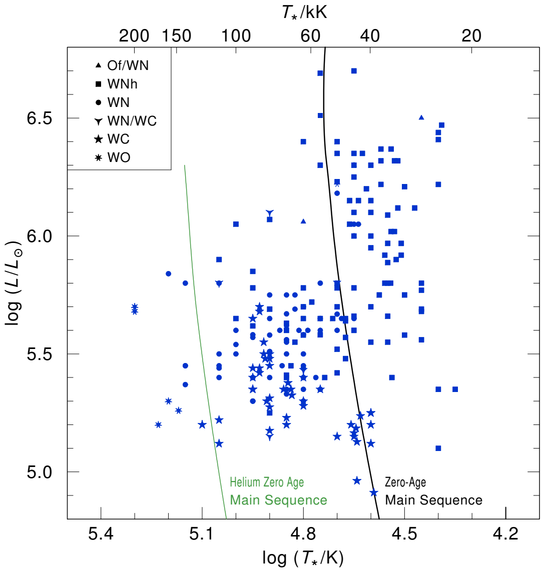
log L,

log $\dot{M}$,

...

⇒ HRD position

Example: WR Hertzsprung-Russell Diagram



In the last decade a growing number of WR stars have been analyzed with stellar atmosphere codes:

combined HRD from MW, LMC, SMC, & M31

Sources:

- Crowther et al. (2002),
- Hamann et al. (2006),
- Barniske et al. (2008),
- Martins et al. (2008),
- Liermann et al. (2010)
- Sander et al. (2012),
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- Tramper et al. (2015)

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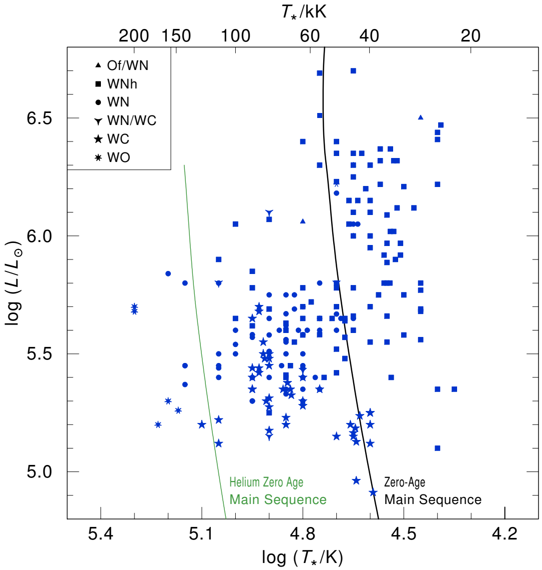


Over 250 different Wolf-Rayet stars analyzed in total

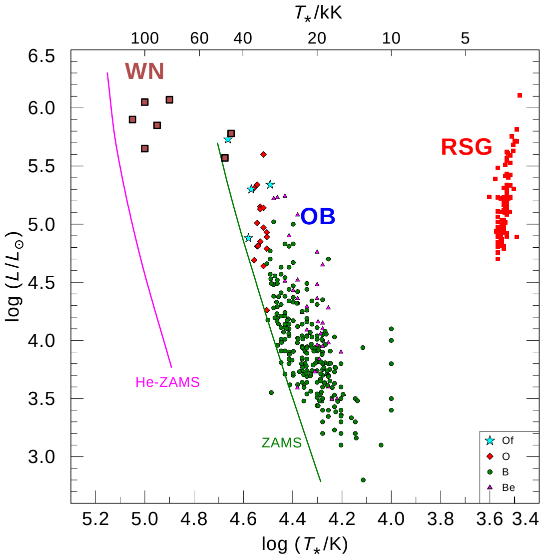
HRD contains (apperantly) single stars only

Always: log $L/L_\odot > 4.9$

No hydrogen-free WR at log $L/L_\odot > 6.0$

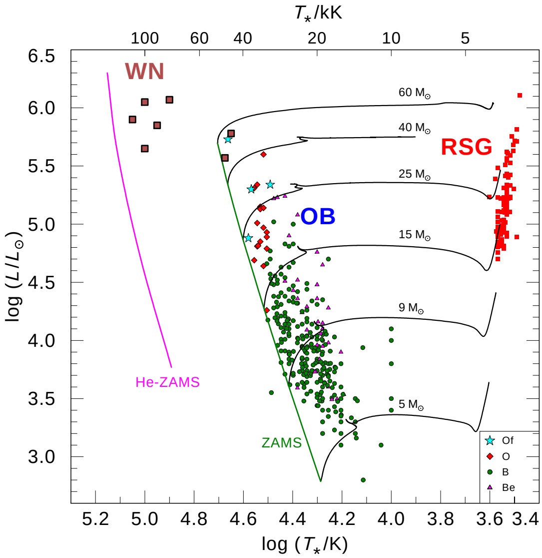
(Attention: This does not include [WR] aka CSPN!)

Example: Massive stars in the SMC



Comparison of empirical results with stellar evolution models

Sources:
WNs: Hainich et al. (2015)
RSGs: Massey & Olsen (2003)
OBs: Ramachandran et al. (in prep)



Comparison of empirical results with stellar evolution models
→ often yields interesting insights on multiple fields

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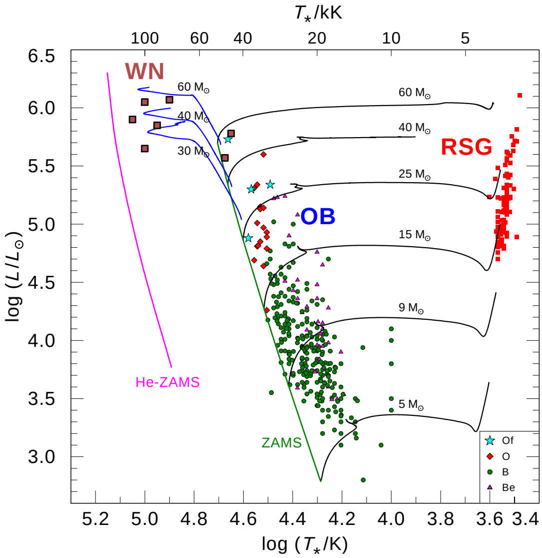

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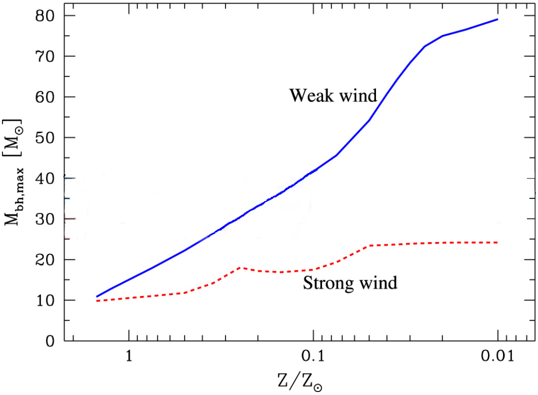
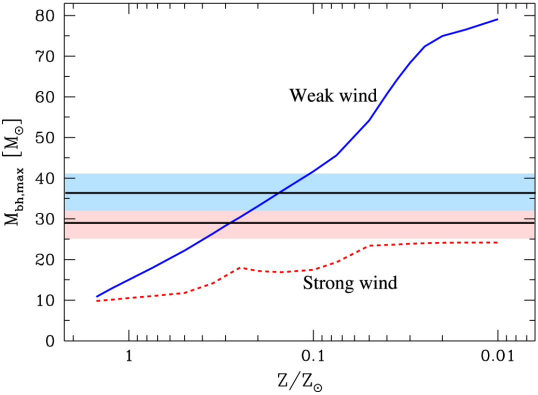
Predict spectral appearances



Application example:
Gravitational Wave Progenitors
How do they look like?

Figure adapted from Abbott et al. (2016)

Predict spectral appearances



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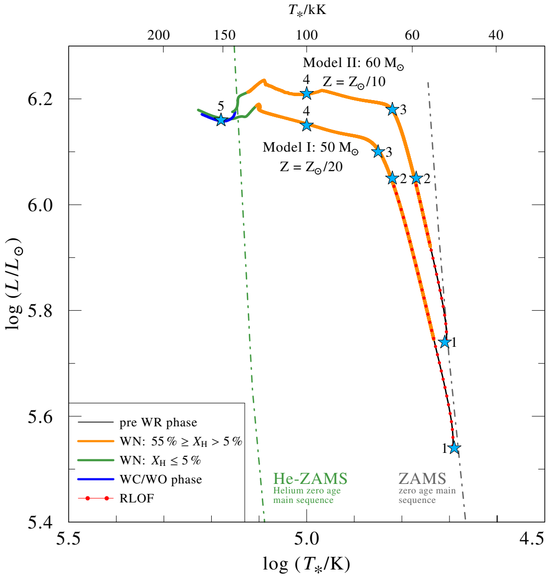

Application example:
Gravitational Wave Progenitors
How do they look like?

- Calculate models for predicted tracks

GW progenitor tracks from Marchant et al. (2016)

Predict spectral appearances

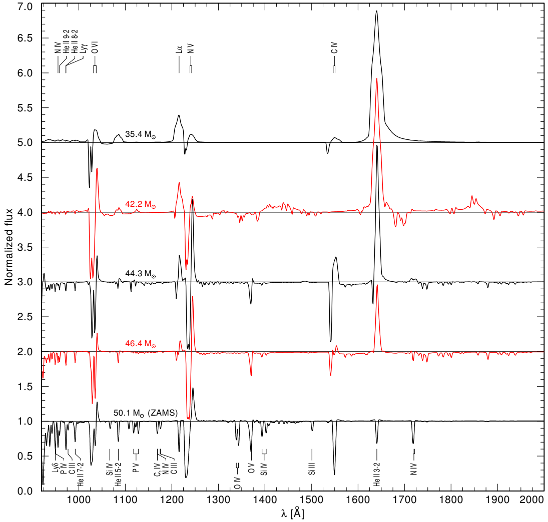

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Figure from Hainich et al. (2017, in prep)

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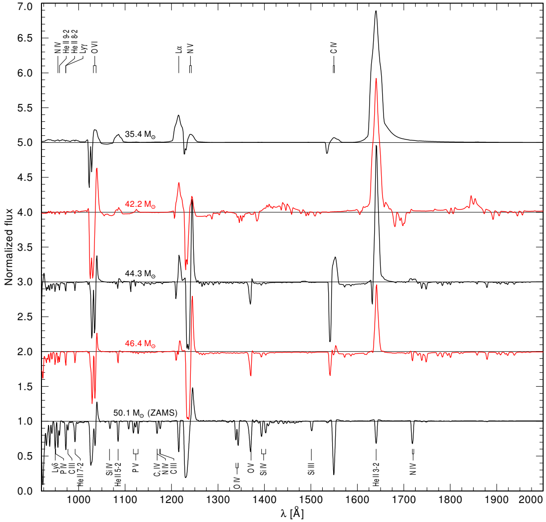

Application example:
Gravitational Wave Progenitors
How do they look like?

- Calculate models for predicted tracks
- Obtain observational parameters
- Consistency checks between atmosphere and evolution models
  ↪ improve evolutionary calculations

Figure from Hainich et al. (2017, in prep)

The next generation of atmosphere models

The next step

Use models for more then measurements:

Gain predictive power for mass-loss rates!

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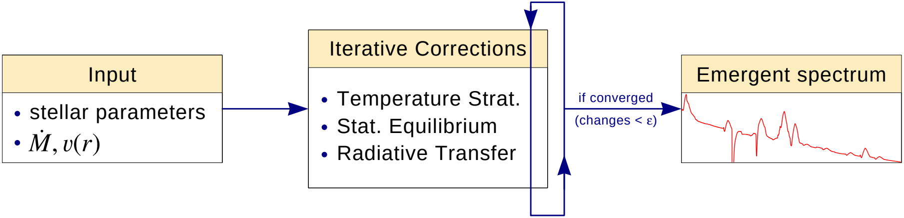

The next generation of atmosphere models

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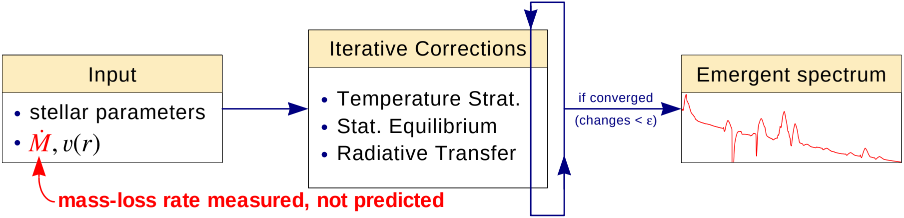


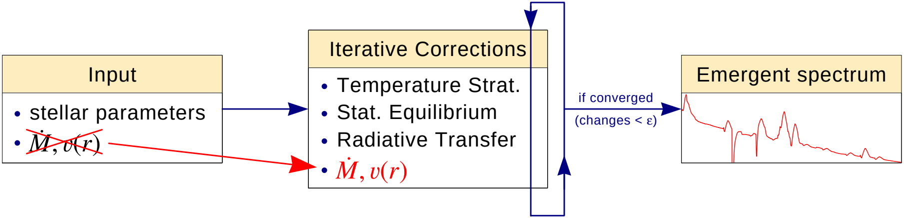
⇒ excellent for obtaining empirical parameters, but lacks predictive power

The next generation of atmosphere models

The next step

Use models for more then measurements:

Gain predictive power for mass-loss rates!



⇒ $v(r)$ and $\dot{M}$ need to be calculated consistently

Radiation Transfer
Symbolically: linear mapping Λ

$$\mathbf{J} = \mathbf{\Lambda}\,\mathbf{S}(\vec{n})$$

radiation field, source function, population numbers

→ Coupling in space

Rate Equations (Statistical Equilibrium)
Set of linear eqns. at each spacial point

$$\vec{n} \cdot \mathbf{P}(\mathbf{J}) = [0, ..., 0, 1]$$

pop. numbers (at 1 depth point), transition rates

→ Coupling in frequency

Radiative transition rates:
Frequency integrals

$$R_{lu} = \int \frac{4\pi}{h\nu}\,\sigma_{lu}(\nu)\,J_\nu\,\mathrm{d}\nu$$

→ **high-dimensional, non-linear, fully coupled in space and frequency**

The complexity of non-LTE stellar atmosphere modeling

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$\mathbf{J} =$ ... $., 0, 1]$

radiation field

$v(r)$ and $\dot{M}$ assumed,
not self-consistent

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→ Coupling in frequency

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→ add hydrodynamics

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The complexity of non-LTE stellar atmosphere modeling

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Symb.: lin. mapping Λ

$$\mathbf{J} = \mathbf{\Lambda}\mathbf{S}(\vec{n}, v)$$

radiation field — source func. — pop. numb.

→ Coupling in space

Hydrodynamics
non-lin. differential eqn.

$$\frac{\mathrm{d}v}{\mathrm{d}r} = -\frac{g}{v}\frac{\tilde{\mathcal{F}}(\mathbf{J}, \vec{n})}{\tilde{\mathcal{G}}(v, \vec{n})}$$

velocity gradient — velocity field

→ Adjustment of $\dot{M}$

Rate Eqns. (Stat. Eq.)
Linear eqn. set / point

$$\vec{n} \cdot \mathbf{P}(\mathbf{J}) = \vec{b}$$

pop. numbers (at 1 depth point) — transition rates

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Hydrodynamics: Theoretical consequences

The hydro*dynamic* equation:

$$v\left(1-\frac{a_{\mathrm{s}}^2}{v^2}\right)\frac{\mathrm{d}v}{\mathrm{d}r}=a_{\mathrm{rad}}(r)-g(r)+2\frac{a_{\mathrm{s}}^2}{r}-\frac{\mathrm{d}a_{\mathrm{s}}^2}{\mathrm{d}r}$$

In contrast to the hydrostatic equation, this equation has a **critical point** (here at $v=a$, i.e. the sonic point)

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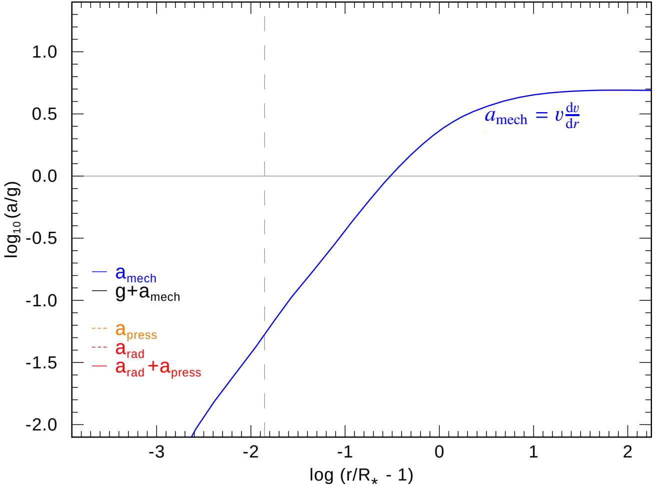
$\hookrightarrow$ **consistent models gain predictive power**

Consistent implementation of hydrodynamics:

- $v(r)$ via integration of the hydrodynamic equation
- iterative adjustment of $\dot{M}$

Excursion: Depth-dependent acceleration

Acceleration contributions in an expanding stellar atmosphere:



standard atmosphere model with prescribed $v(r)$ and $\dot{M}$

Excursion: Depth-dependent acceleration

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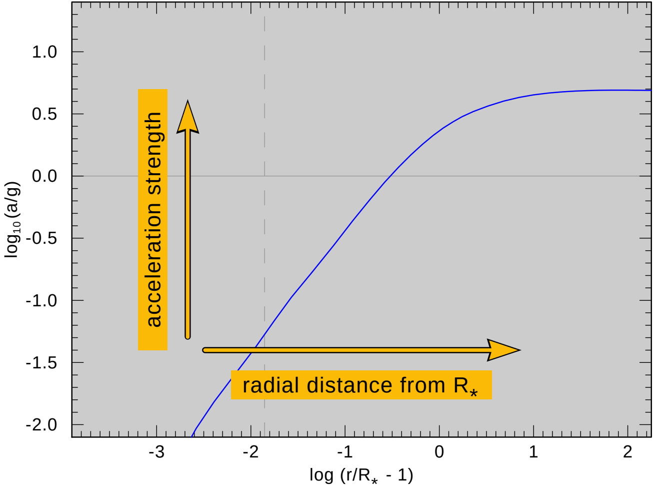

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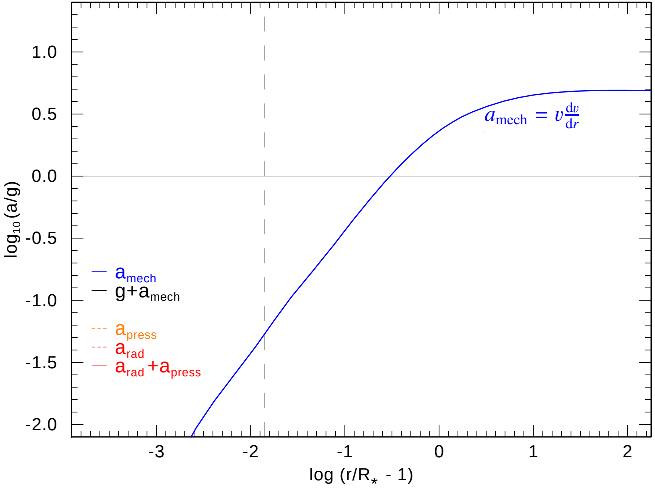

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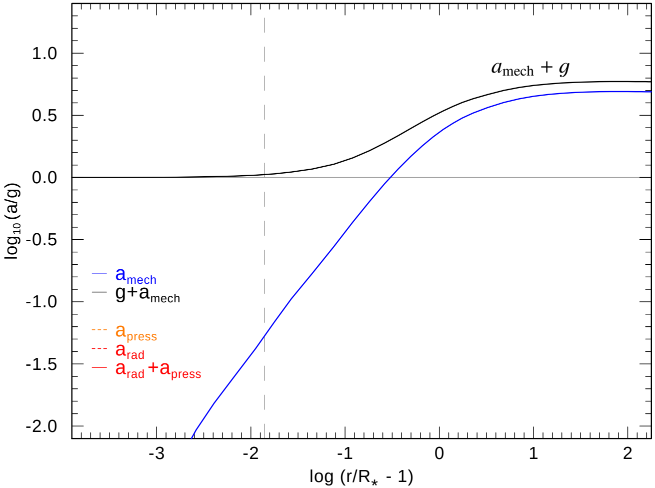
Hydrodynamic equation: $a_{\text{mech}} + g = a_{\text{rad}} + a_{\text{press}}$



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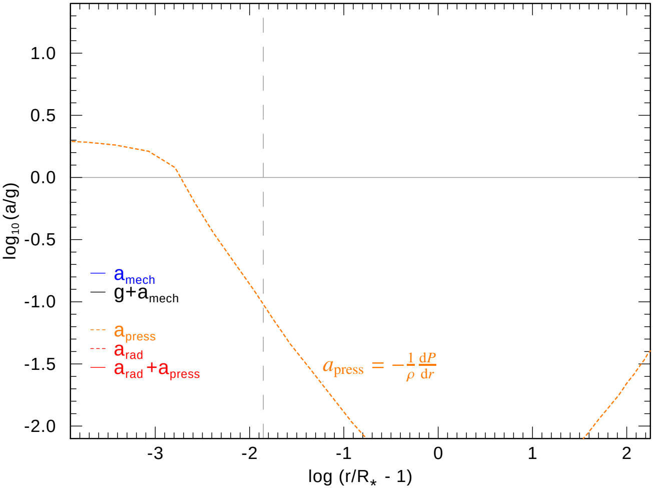

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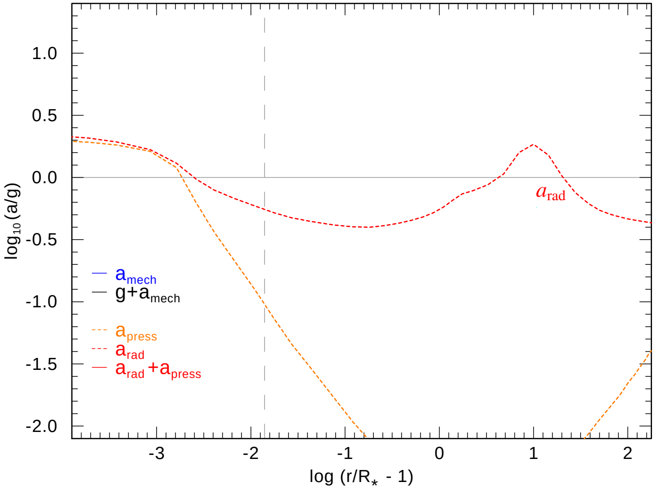

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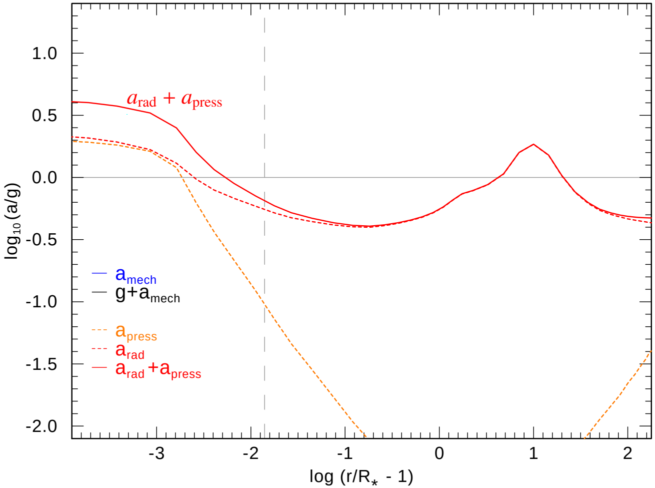

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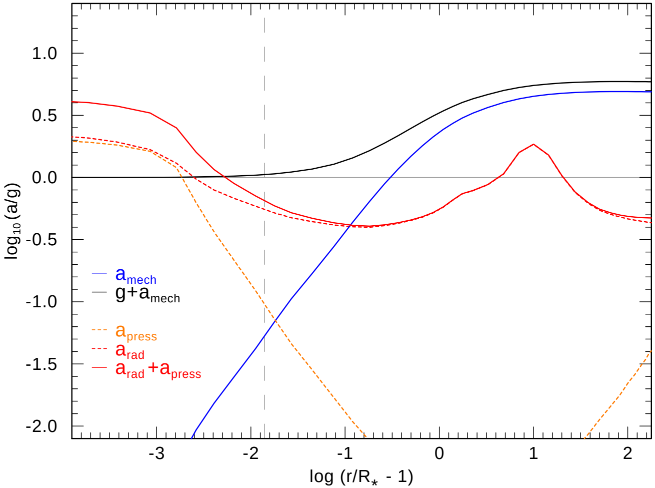

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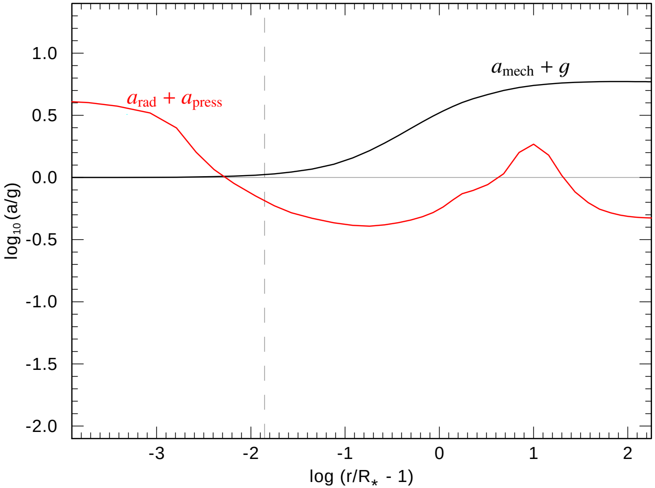

standard atmosphere model with prescribed $v(r)$ and $\dot{M}$

hydrodynamic equation not fulfilled

Excursion: Depth-dependent acceleration

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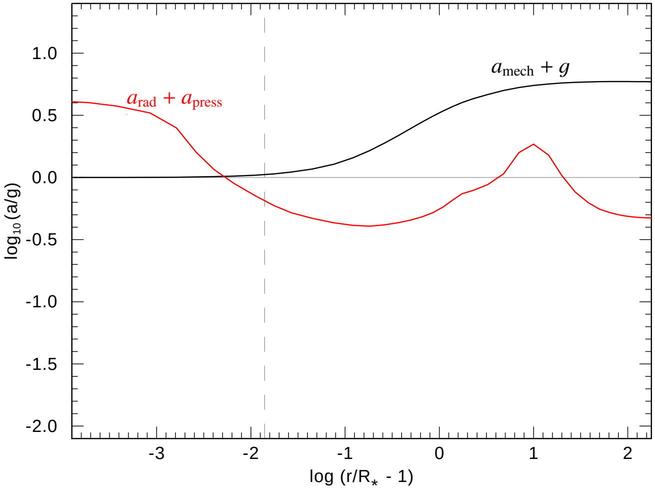


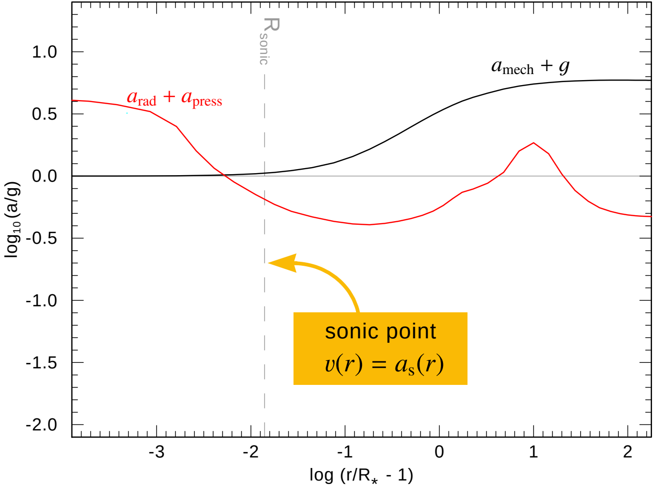
standard atmosphere model with prescribed $v(r)$ and $\dot{M}$

hydrodynamic equation not fulfilled

$\Rightarrow$ adjust a_{mech}

Excursion: Depth-dependent acceleration

Remember the two different regimes in the stellar atmosphere:



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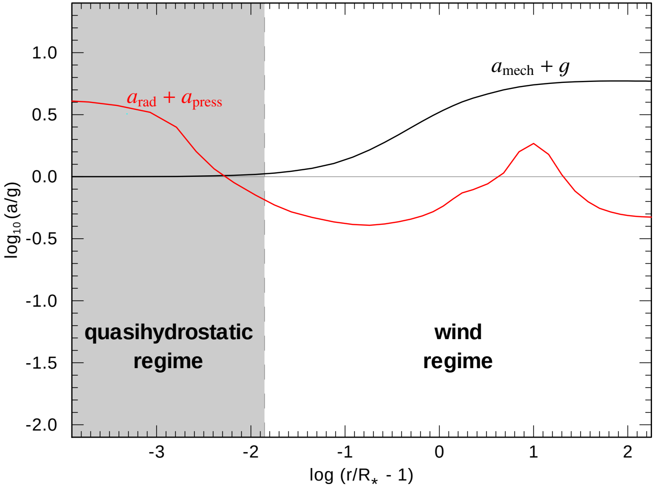
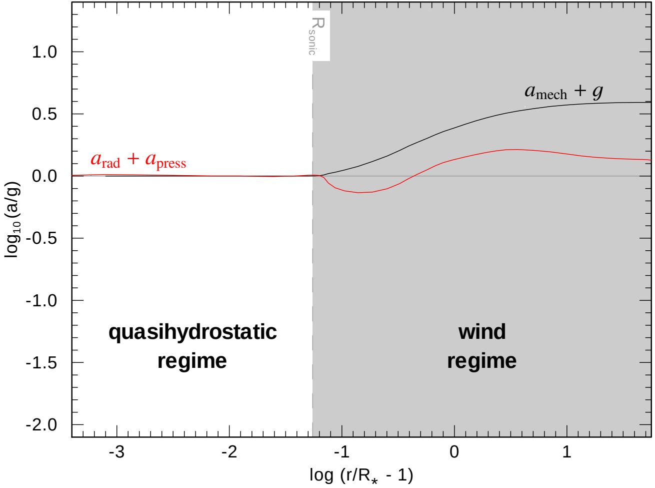


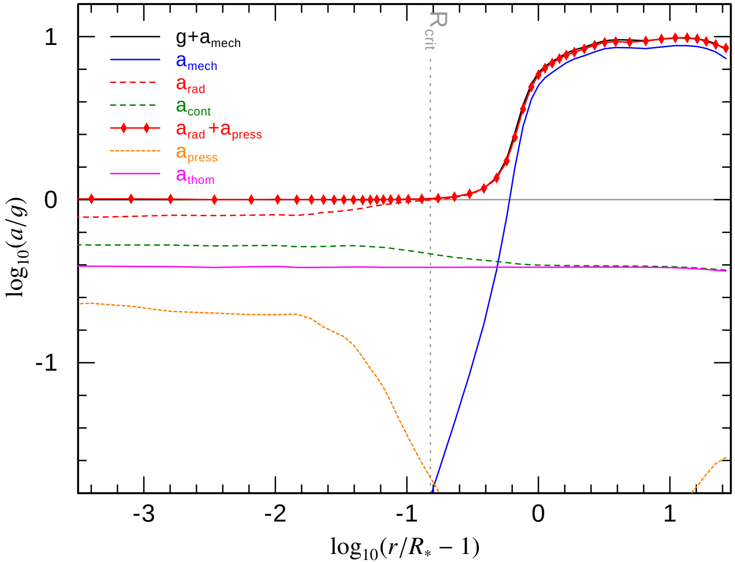
Excursion: Depth-dependent acceleration

Quasi-hydrostatic regime already consistent in newer models



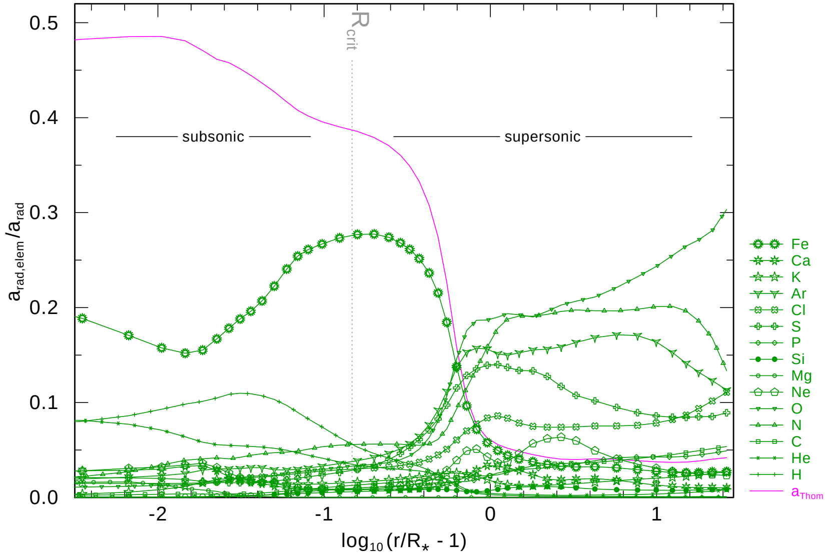
Results: Force balance

Locally consistent acceleration balance: Sander et al. (2017)



Results: Driving details

Contributions to the radiative acceleration:



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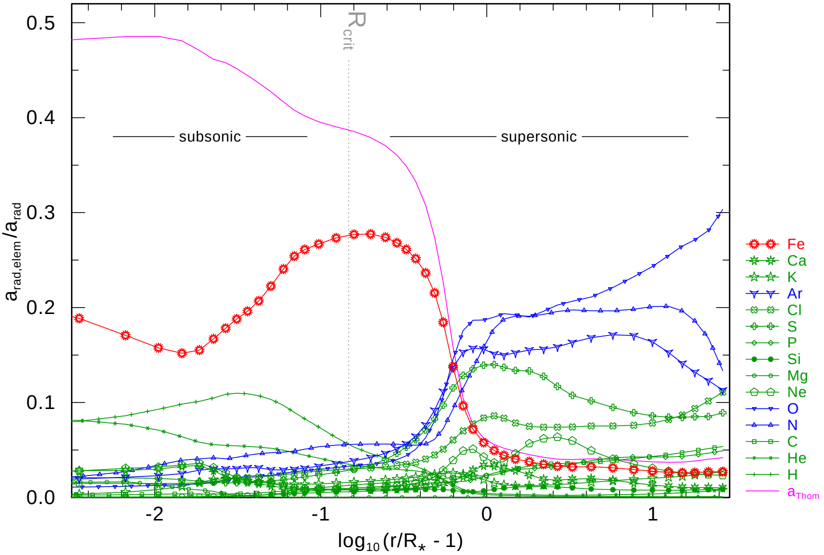
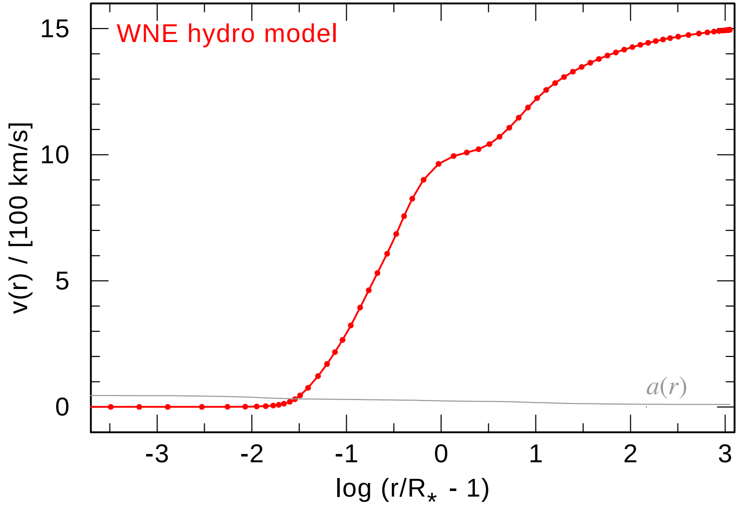


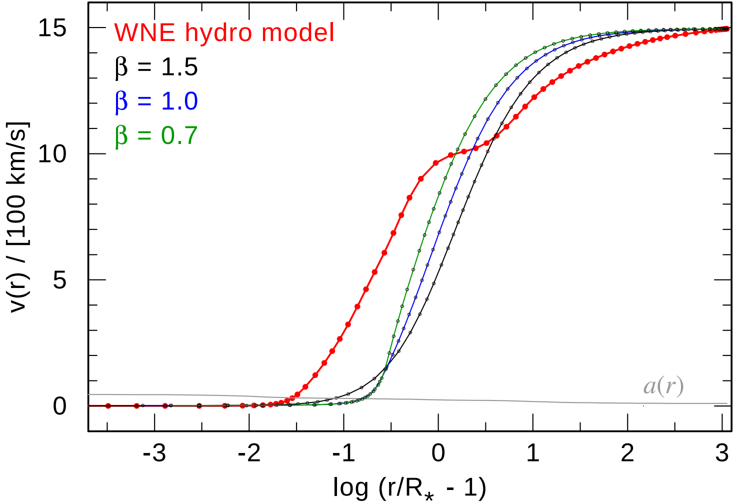
Results: Velocity field

WNE model: hydrodynamically consistent



Results: Velocity field

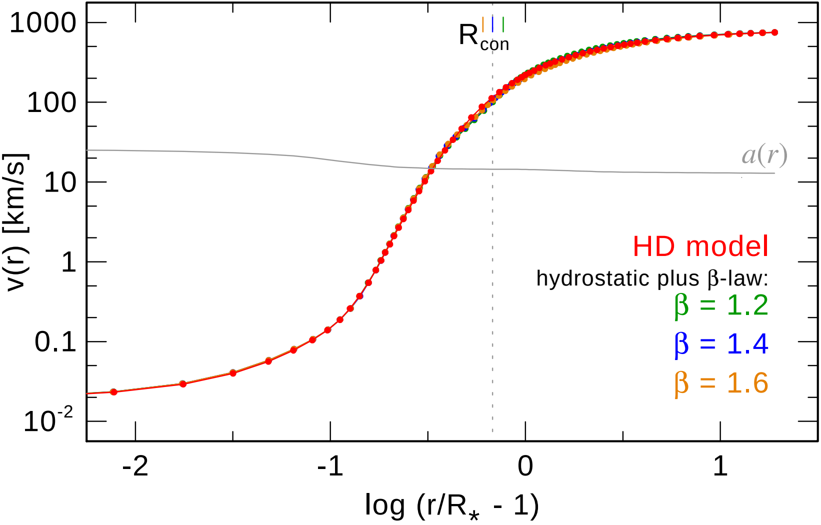
WNE model: hydrodynamically consistent vs. beta-law $v(r) = v_\infty \left(1 - \frac{1}{r}\right)^\beta$



⇒ very different velocity law than classically assumed

Results: Velocity field

Sanity check with B star model: can be approximated with standard β-law



Summary & Conclusions

The current and the next generation of atmosphere models:

- extensive applicability
  - → O, B, Of/WN, LBVs, WRs, CSPN, etc.
  - → from the first stars up to $Z > Z_\odot$
- reliable stellar and wind parameters for a wide range of T_{eff}, v_∞ and $\dot{M}$
- *new, sophisticated method to include hydrodynamics*
  - → predictive power for $\dot{M}$
  - → detailed approach with cross-checks due to local consistence + emergent spectrum

"Thor's Helmet" around WR 7
(Credit: SSRO & PROMPT/UNC)

Results:

- HD scheme usable for various spectral types
- new Zeta Pup "benchmark" model
- basis for detailed insights into wind driving of hot stars