

# **Improving models of pulsating stars**

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## **Feedback between models and observations**

- ▶ we want to model and understand our observations with pulsation codes
- ▶ we want to use observations to constrain/develop our pulsation codes

## **Overview**

- ▶ Tools we have (1D)
- ▶ Tools being developed (2D, 3D)
- ▶ Observations we want to model
- ▶ Improvements to 1D tools

## 1D nonlinear pulsation codes:

### Radiative models

- e.g., Stellingwerf (1975)

$$\frac{dU}{dt} = -\frac{1}{\rho} \nabla(p) - \nabla\phi$$

$$\frac{de}{dt} + p \frac{dV}{dt} = -\frac{1}{\rho} \nabla(F_r)$$

### Convective models

- Stellingwerf (1982)  
Bono & Stellingwerf (1992)
- Kuhfuß (1986)  
Feuchtinger (1999)  
Kolláth et al. (1998)  
Smolec & Moskalik (2008)

$$\frac{dU}{dt} = -\frac{1}{\rho} \nabla(p + p_t) + U_q - \nabla\phi$$

$$\frac{de}{dt} + p \frac{dV}{dt} = -\frac{1}{\rho} \nabla(F_r + F_c) - (S - D - D_r)$$

$$\frac{de_t}{dt} + p_t \frac{dV}{dt} = -\frac{1}{\rho} \nabla F_t + E_q + (S - D - D_r)$$

## Reliability of 1D convective models

Origin: Reynolds averaging

- ▶  $x = \langle x \rangle + x'$
- ▶ continuity, momentum and thermal energy equations decomposed into mean and fluctuating part
- ▶ equation for turbulent energy  $e_t = \langle w'^2/2 \rangle$

Approximations and closure relations

- ▶ e.g. down gradient approximations,  $F_c \propto \nabla s$ ,  $F_t \propto \nabla e_t$

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$e_t$  turbulent energy

$S$  source function  $\alpha\alpha_s T p Q e_t^{1/2} \mathcal{Y} / H_p$

$D$  turbulent dissipation  $(\alpha_d/\alpha)(e_t^{3/2}/H_p)$

$D_r$  radiative cooling  $D_r = 4\sigma\gamma_r^2/\alpha^2(T^3 V^2 e_t)/(c_p \kappa H_p^2)$

$p_t$  turbulent pressure  $\alpha_p \rho e_t$

$E_q, U_q$  eddy-viscous terms  $-(4/3)\alpha\alpha_\nu H_p e_t^{1/2} R \frac{\partial(U/R)}{\partial R}$

$F_c$  convective flux  $\alpha\alpha_c \rho T c_p e_t^{1/2} \mathcal{Y}$

$F_t$  turbulent flux  $-\alpha_t \alpha \rho H_p e_t^{1/2} \frac{\partial e_t}{\partial R}$

8 free parameters!

$F_c \propto \mathcal{Y}, S \propto \mathcal{Y}, \mathcal{Y} = \nabla - \nabla_a$

## Reliability of 1D convective models

Ambiguities: source term (buoyant driving/damping)

$$S \propto e_t^{1/2} \mathcal{Y}$$

or

Kuhfuß (1986)

$$S \propto e_t \text{sgn}(\mathcal{Y}) \sqrt{|\mathcal{Y}|}$$

Stellingwerf (1982)

no DM solutions

Smolec & Moskalik (2008,2010)

no DM solutions

G. Bono, private comm.

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$$S \propto e_t^{1/2} \mathcal{Y}_+$$

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DM pulsation

e.g., Kolláth et al. (1998,2002)

negative  
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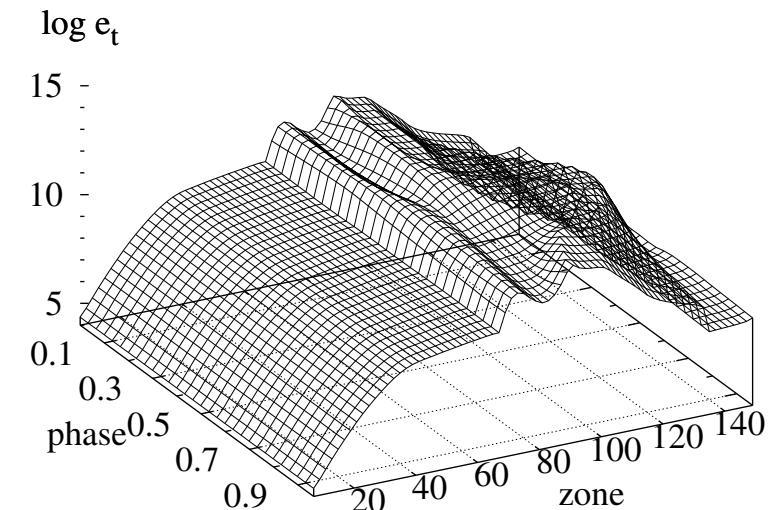
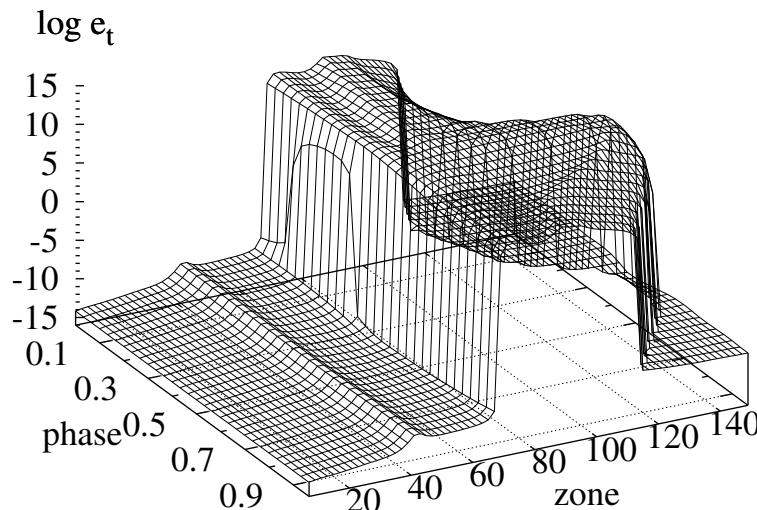
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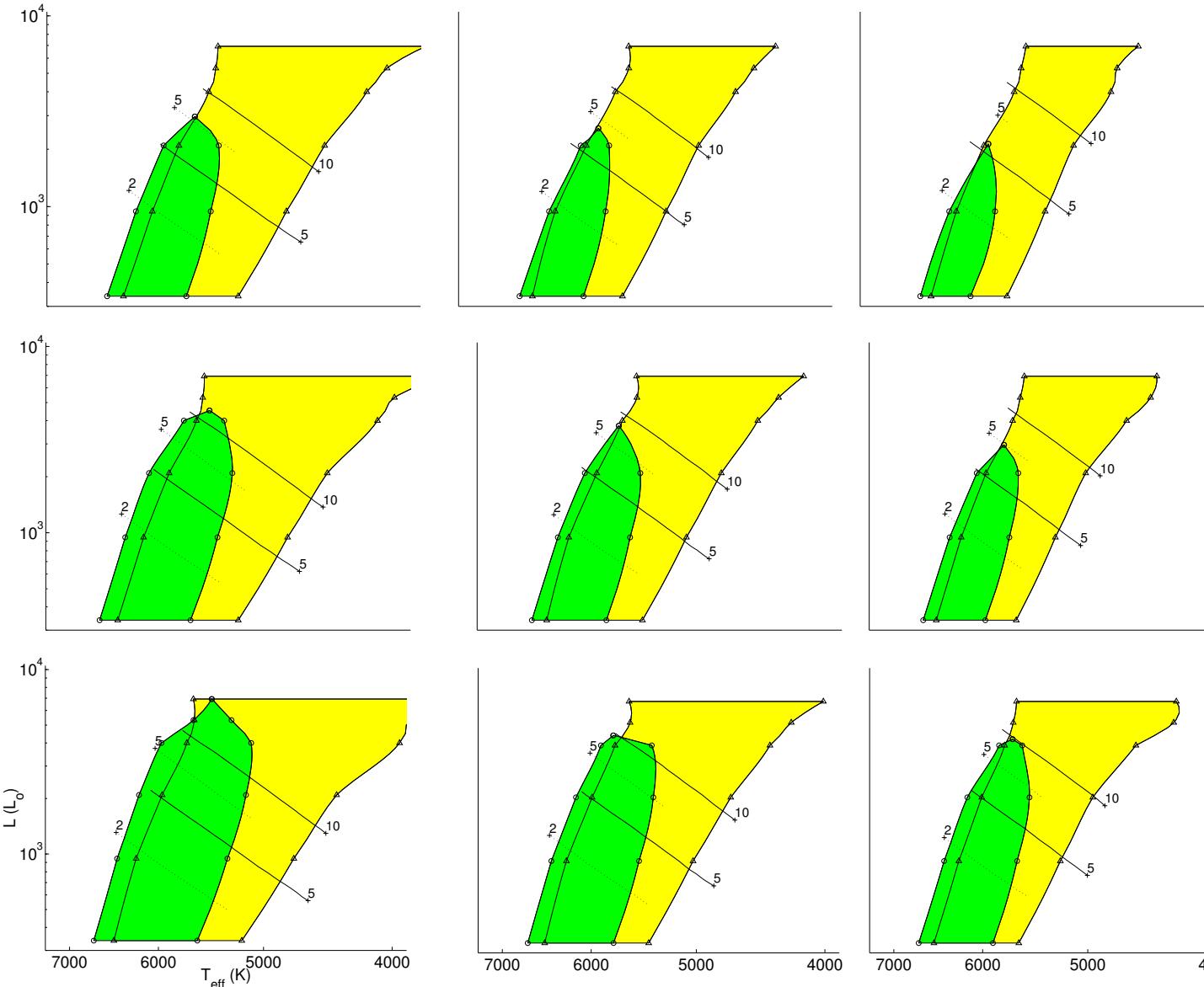
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## Reliability of 1D convective models

### Degeneracies between convective parameters



Yecko et al. (2011)  
 $\alpha_\nu$  (vert.),  $\alpha$  horiz.)

at non-linear level de-  
 generacy for  $\alpha$ ,  $\alpha_\nu$  and  
 p-factor in setting the  
 pulsation amplitude

## Successes of 1D modelling:

- ★ modelling of dynamical phenomena
  - ▶ amplitude saturation in single periodic variables
  - ▶ bump progressions in F and 1O Cepheids
  - ▶ period doubling phenomena in population II Cepheids
  - ▶ low-order Fourier parameter progressions for Cepheids & RR Lyrae stars of different stellar systems (still with some deficiencies)
- ★ modelling and understanding of individual objects
  - ▶ light/radial velocity curves of singly-periodic Cepheids and RR Lyrae stars (e.g. Marconi et al. 2013 – cep227, summary in Marconi 2009, Baranowski et al. 2009 – v440 Per)
  - ▶ the BEP (+explanation for *bump* on the radial velocity curve (Pietrzynski et al. 2012, Smolec et al. 2013)
  - ▶ OGLE-BLG-T2CEP-279 first BL Her star with period doubling (Soszynski et al. 2011, Smolec et al. 2012)

## Challenges for 1D modelling

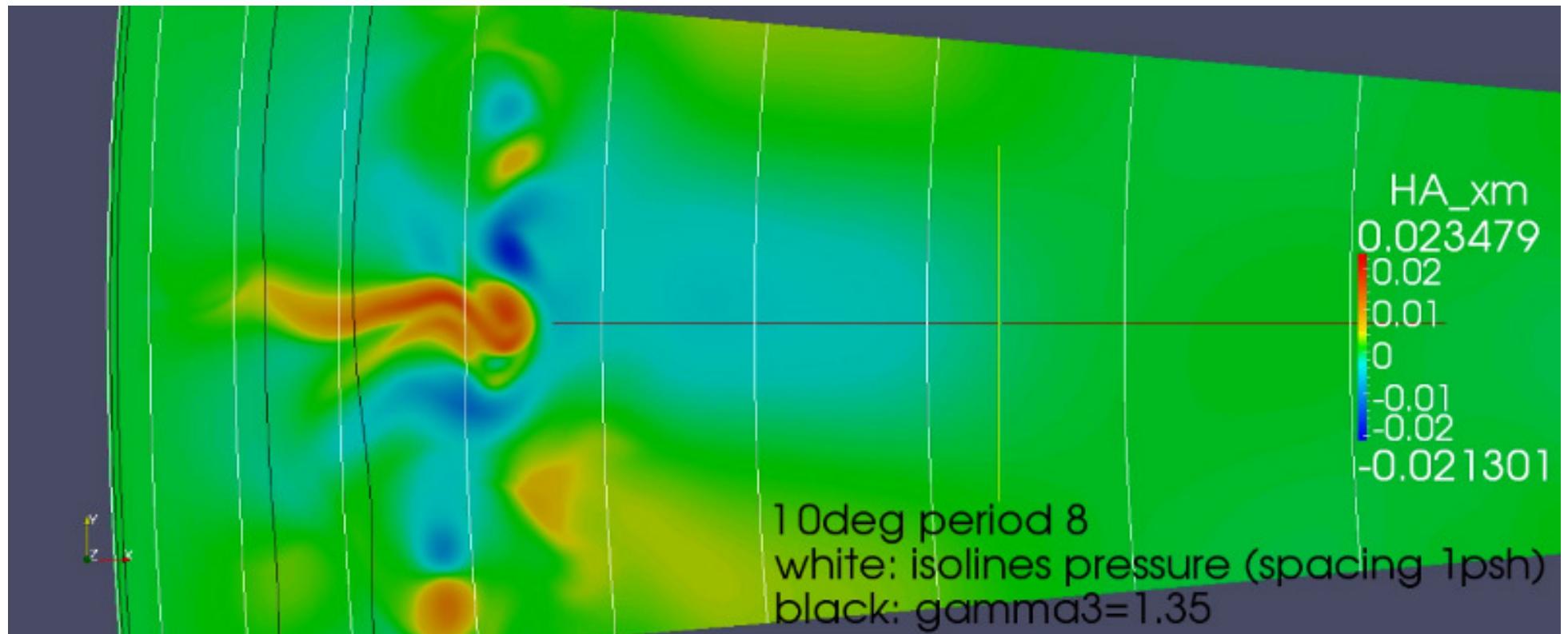
- ★ double- (multi-) periodic pulsation
  - ▶ the issue of negative buoyancy
  - ▶ can observations/3D TC models indicate the necessary dissipation mechanism?
- ★ Blazhko effect
  - ▶ models associated with radial mode resonances (*strange* or trapped surface modes)
  - ▶ models associated with atmosphere dynamics
  - ▶ require careful modelling of the outer atmospheric layers

## **2D/3D pulsation hydrocodes:**

- ★ several simulations for main-sequence/giant stars, e.g.,
  - Stein & Nordlund (1989, 1998), Nordlund et al. (2009)
  - Meakin & Arnett (2007), Arnett, Meakin & Young (2009)
  - Trampedach et al. (2007, 2010)
  - 3D models used to improve the MLT (e.g., Arnett, Meakin & Young 2010)
- ★ 2D/3D modelling of large amplitude pulsations – a challenging problem
  - Early work: Deupree (1977)
  - Gastine & Dintrans (2011)
  - ANTARES (Muthsam et al. 2010)
  - SPHERLS (Geroux & Deupree 2011)

## **ANTARES (Muthsam, et al. 2010):**

- ★ **A Numerical Tool for Astrophysical RESearch**
- ★ time-dependent compressible hydrodynamics, RHD, 1D–3D
- ★ realistic microphysics (OPAL EOS, opacities)
- ★ high-resolution simulation of solar granulation (Muthsam et al. 2007)
- ★ 2D Cepheid models (5125K, 5500K)
- no progress for the last two years (cf. Wroclaw and Granada meetings)

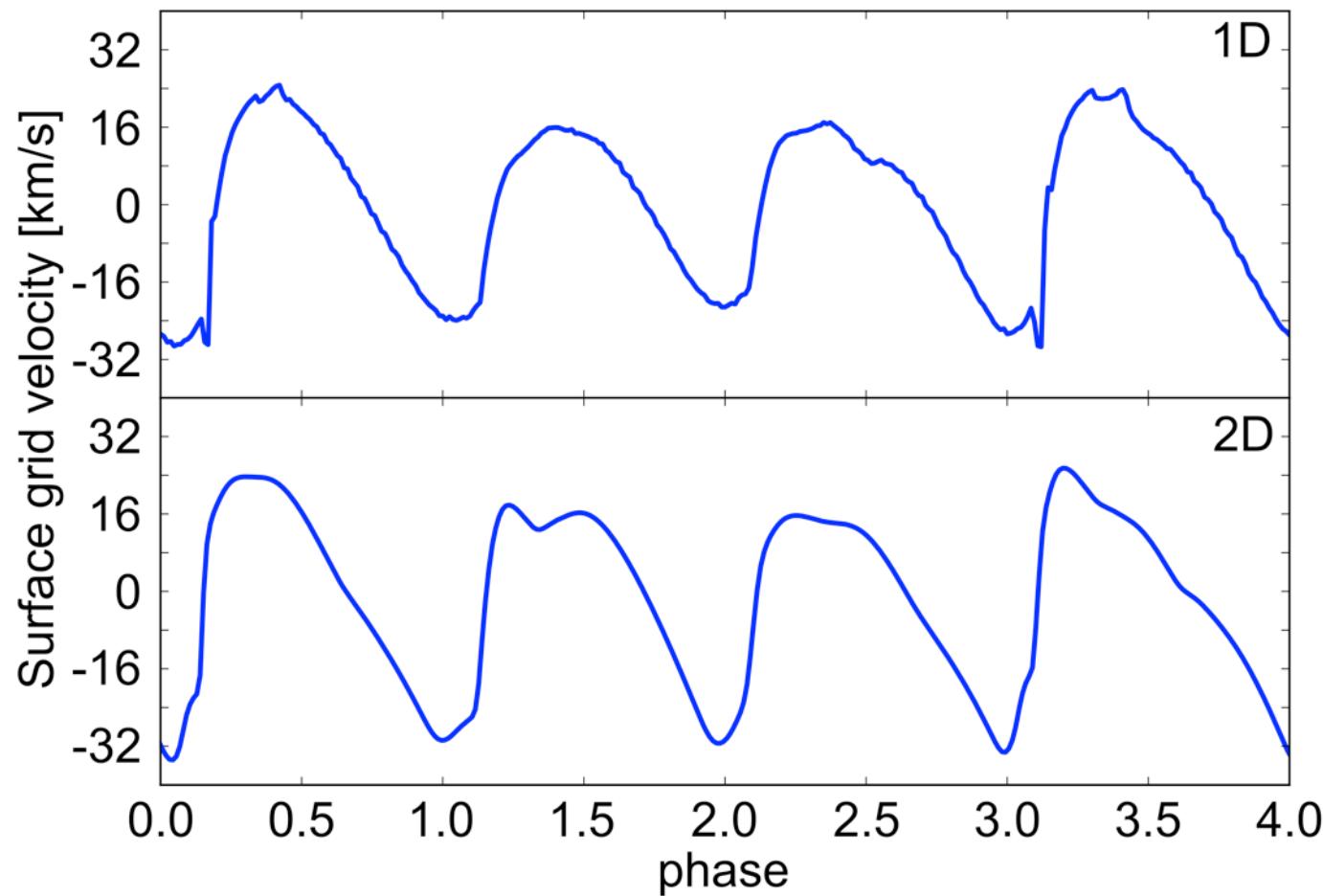
**ANTARES (Muthsam, et al. 2010):**

(Muthsam, Mundprecht)

- overshooting estimate – up to  $1 H_p$

## **SPHERLS (Geroux & Deupree 2011, 2013):**

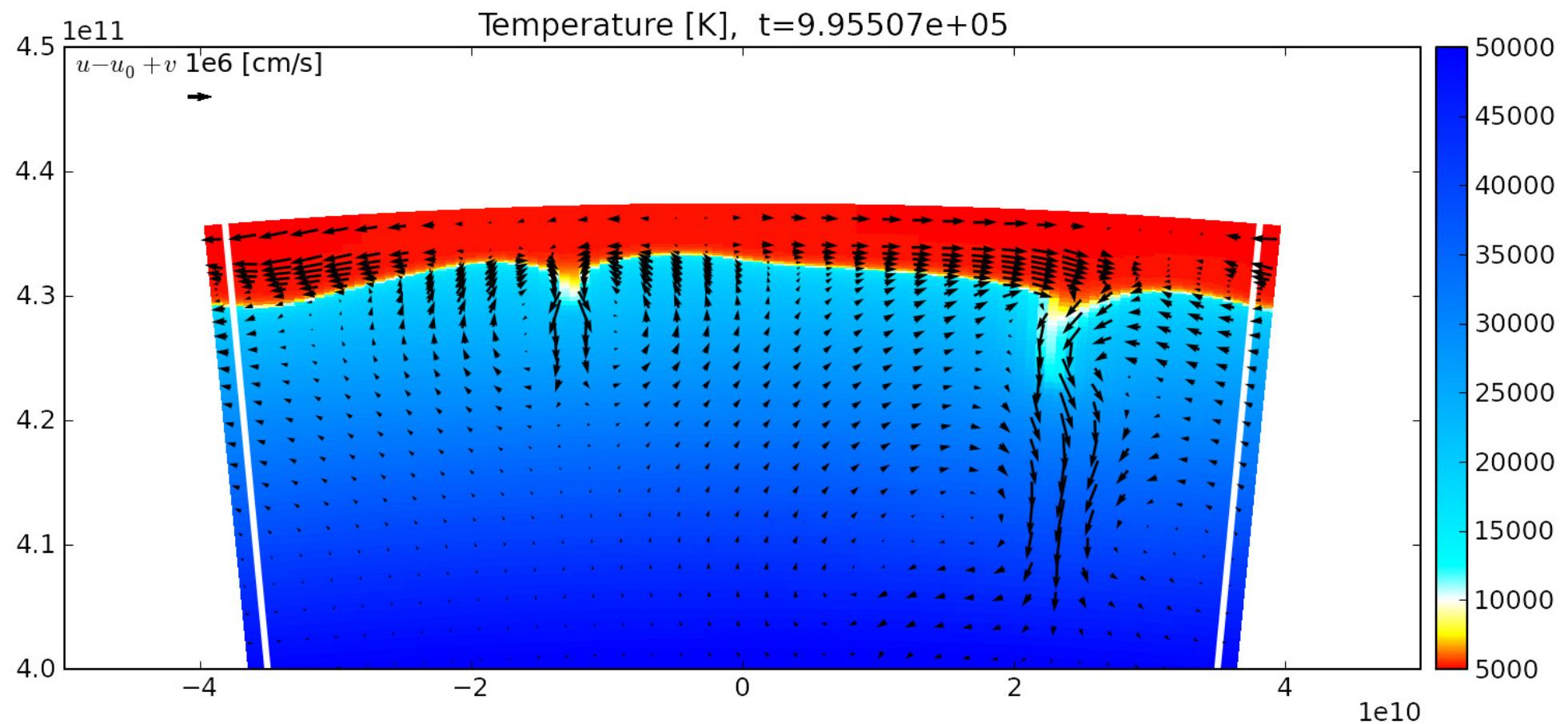
- ▶ Stellar Pulsation with a Horizontal Eulerian, Radial Lagrangian Scheme
- ▶ 1D, 2D (working) and 3D code
- ▶ realistic EOS and opacities
- ▶ radiation in the diffusion approximation
- ▶ full amplitude pulsation for few models

**SPHERLS (Geroux & Deupree 2011, 2013):**

6500K

Geroux (2011)

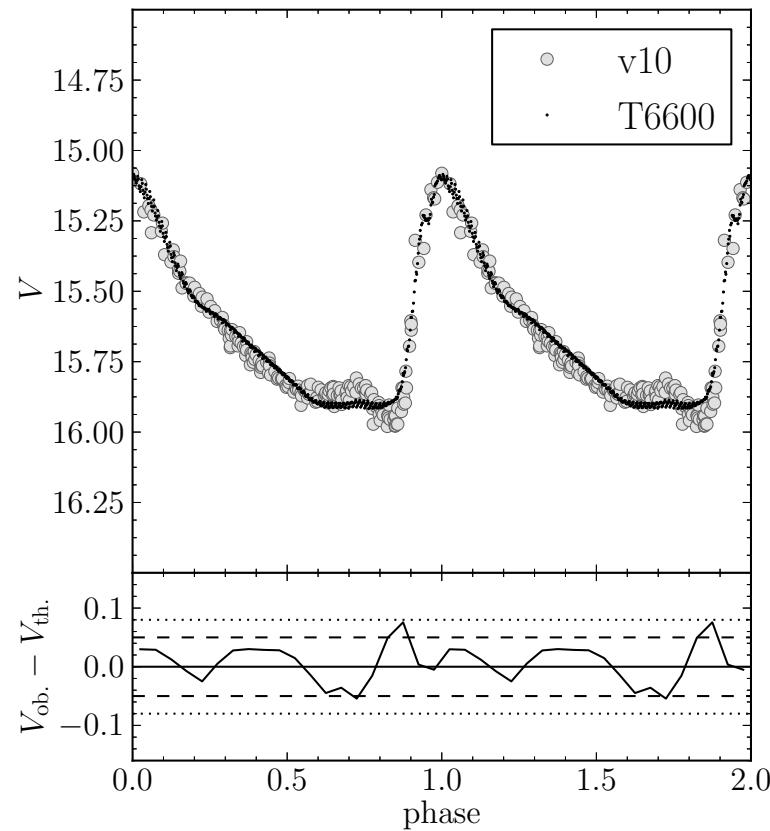
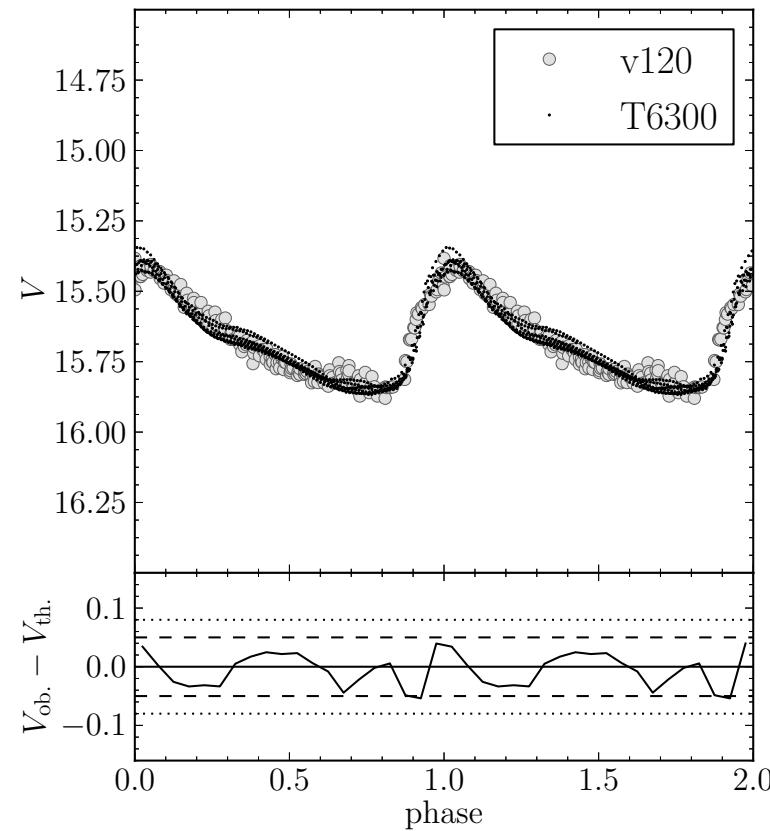
## SPHERLS (Geroux & Deupree 2011, 2013):



Geroux (2011)

- phase dependent overshooting; estimates  $0.25\text{--}0.5 H_p$

## SPHERLS (Geroux & Deupree 2011, 2013):



- comparisons with observation

## **2D/3D pulsation hydrocodes – summary**

- ▶ we need at least 5-10 years before these models are tested and realistic enough (deep enough, with appropriate space/time resolution, etc.)
  - ▶ even then computation of large model surveys may be difficult
  - ▶ understanding of results will arise from analysis of simpler models (AEs, 1D models)

## **Improvements to 1D tools**

- ★ 1D codes often have (based on Warsaw codes)
  - ▶ fixed Lagrangian grid
  - ▶ simple diffusion/Eddington approximation for radiative transfer
  - ▶ coarse resolution of the outer atmosphere layers
  - ▶ colours as postprocessing of bolometric curves through quasi-static approximation with static atmosphere models
  - ▶ are radiative (A. Fokin code with detailed treatment of the atmosphere)

## Improvements to 1D tools

- ▶ Determination of p-factor allows to remove some degeneracy in model solutions
- ▶ together with accurate physical parameters from analysis of eclipsing binaries ( $M$ ,  $L$ ,  $T_{\text{eff}}$ ,  $Z$ ) constraints on convective parameters are now possible

## Improvements to Warsaw codes

- ▶ relaxation technique (fast convergence to limit cycle + stability information) – *debugging phase*
- ▶ detailed treatment of the atmosphere (dynamic grid+RHD) – PhD student needed
  - ▶ atmosphere dynamics from observations (velocity gradients in the atmosphere)
  - ▶ Blazhko effect