# Convective overshooting in stars with MUSIC

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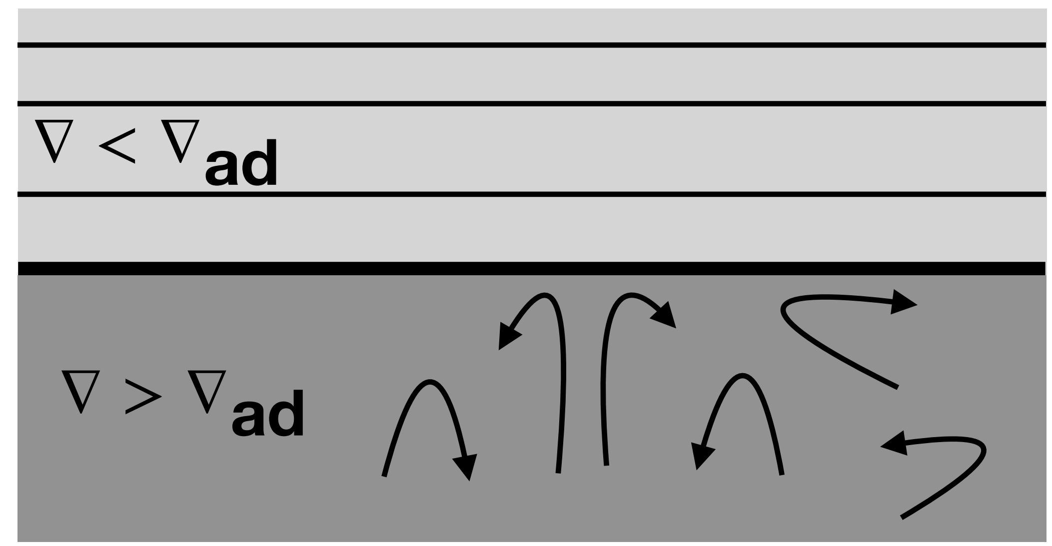
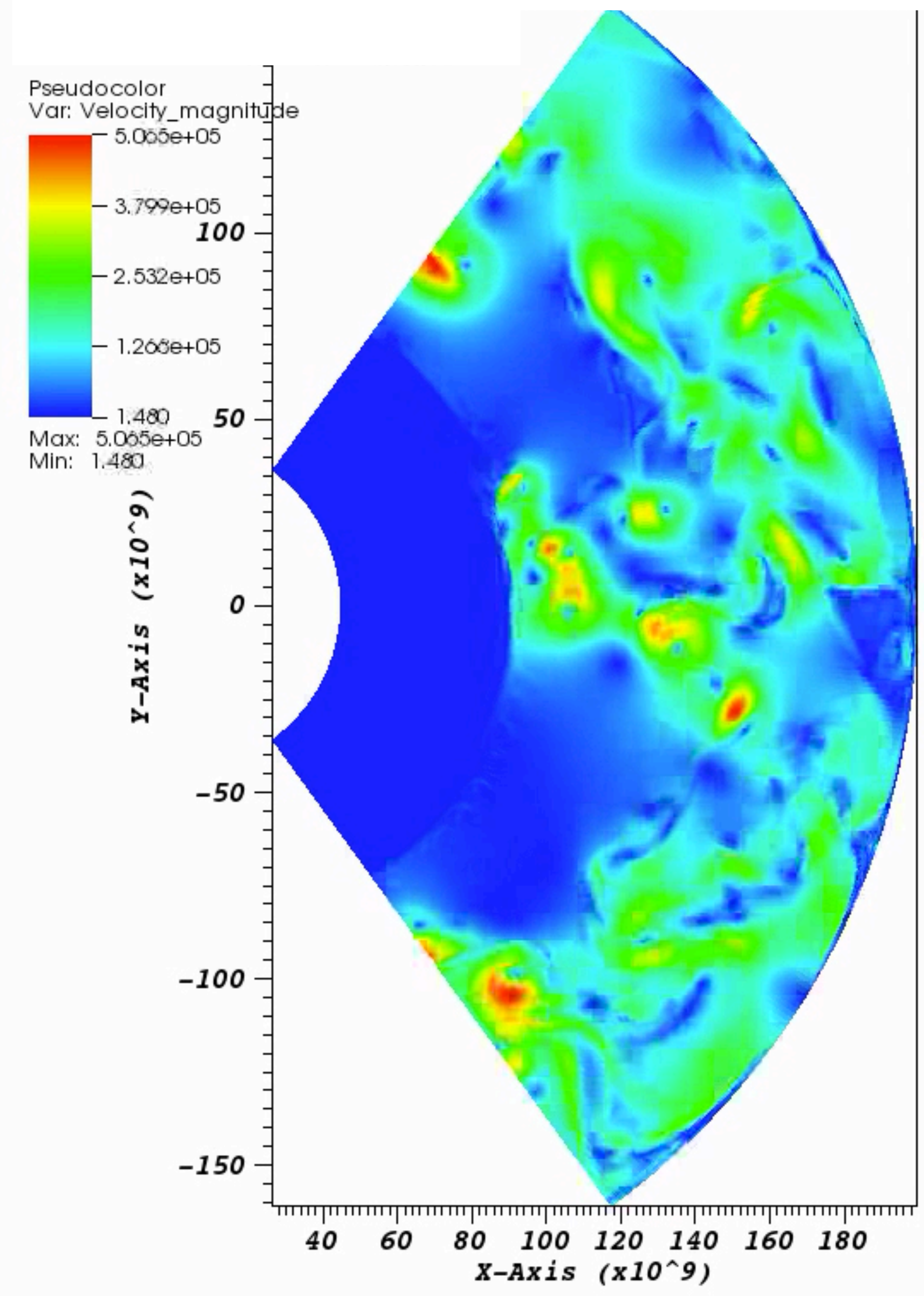
# Convective overshooting

- Two layers of fluid: one is stably stratified, the other isn't
- Vigorous convection
- Inertia drags convection across the Schwarzschild boundary, $\nabla = \nabla_{\mathbf{ad}}$
- Results:
  - Wave excitation
  - Enhanced mixing (of temperature, angular momentum, material)
  - …



# Convective overshooting in stars

- Blamed for long standing problems in stellar evolution
  - Chemical mixing (*Li* depletion in PMS)
    *Castro et al 2016*
  - Transport of angular momentum
    *Roxburgh 1965; Shaviv & Salpeter 1973; Schmitt et al 1984, etc…*
- Interpretation of helioseismology data
  *Christensen-Dalsgaard et al 2011*



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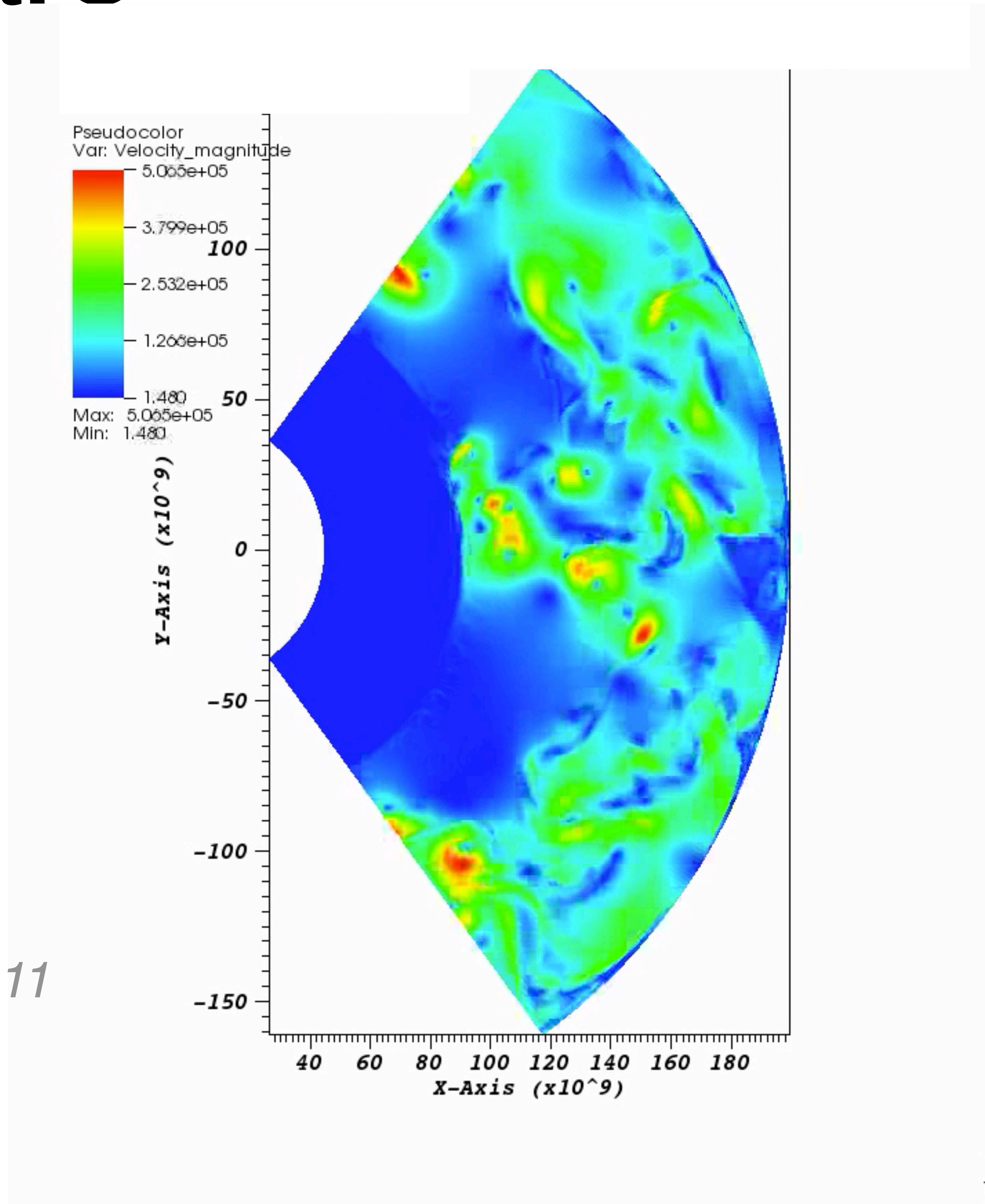

# MUSIC

## MUltidimensional Stellar Implicit Code

- Compressible Euler equations

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{u})$$

$$\frac{\partial (\rho e)}{\partial t} = -\nabla \cdot (\rho e \mathbf{u}) - p \nabla \cdot \mathbf{u} + \nabla \cdot (\chi \nabla T)$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} = -\nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) - \nabla p + \rho \mathbf{g}$$

$$\chi = \frac{16 \sigma T^3}{3 \kappa \rho}$$

- Realistic EoS & opacity
  (Lyon code; MESA; OPAL)

  *(Baraffe et al., Paxton et al.,*
  *Opacity Project at Livermore)*

- Prescribed gravity

*Viallet et al. 2011, 2013, 2016*
*Geroux et al. 2016*
*Pratt et al. 2016*
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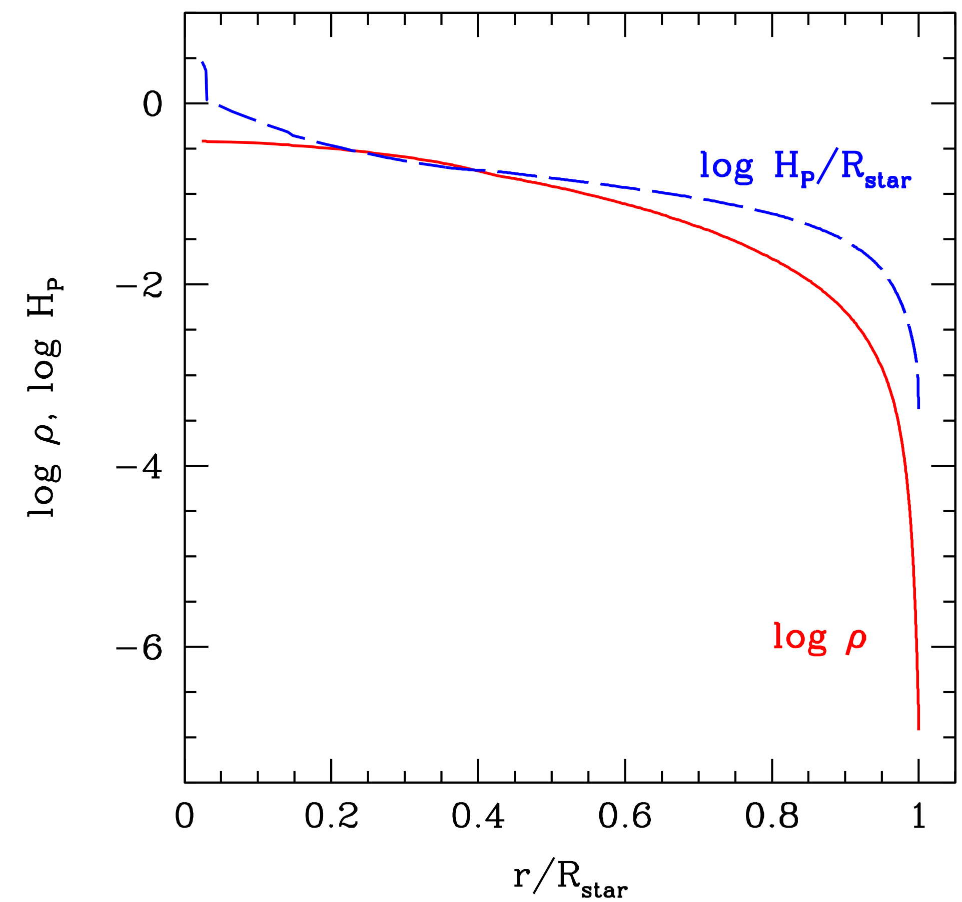
- Fully compressible: $M_s \in (10^{-6}, 10^{-1})$

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- Time-implicit

➡ Solar time scales:

- $\tau_{\rm dyn} \sim (R^3/GM)^{1/2} \sim 30$ min
- $\tau_{\rm conv} \sim v_{\rm rms}/H_p \sim 6$ days
- $\tau_{\rm thermal} \sim GM^2/(RL) \sim 2\times10^7$ yr

*Viallet et al. 2011, 2013, 2016*
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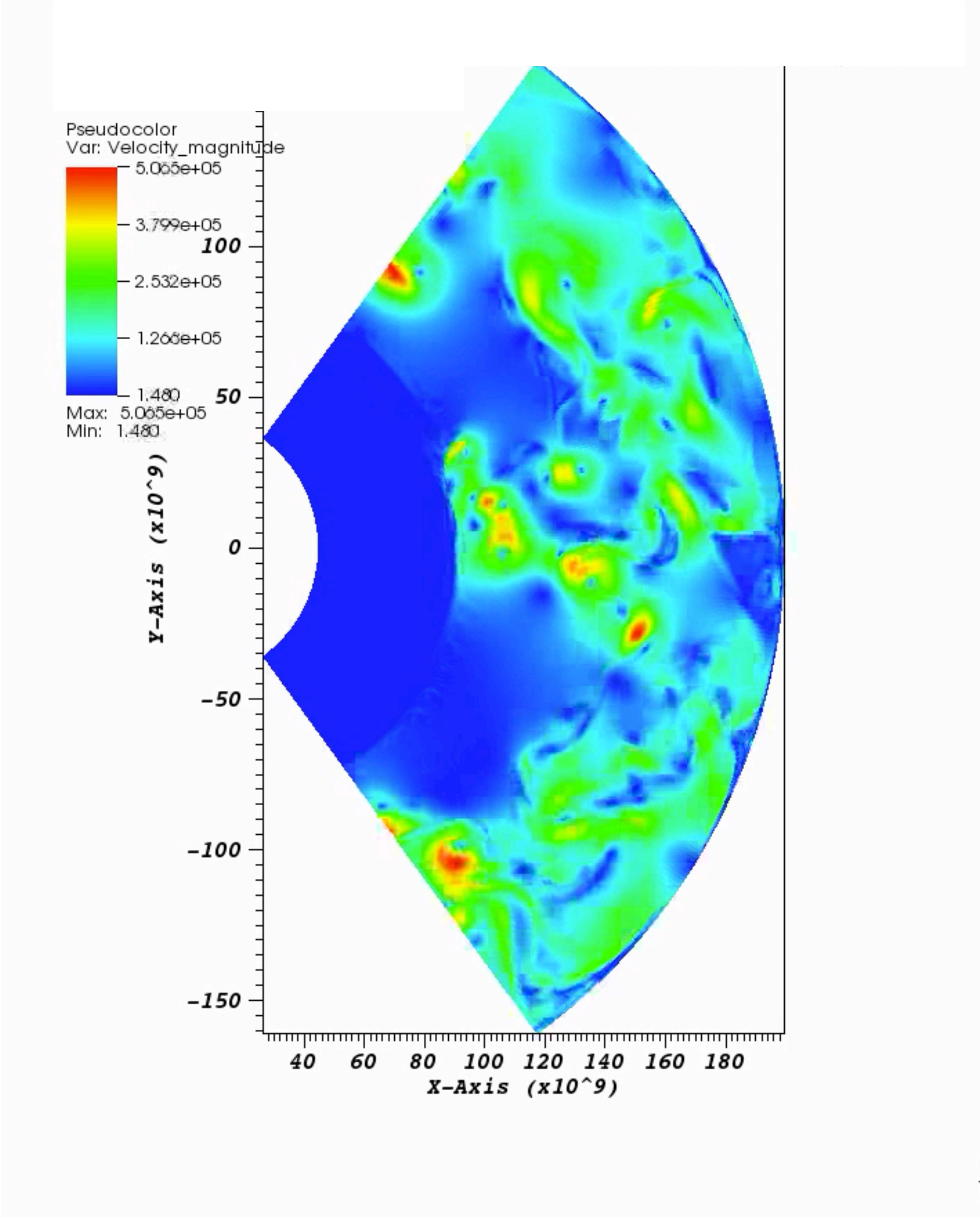
- Prescribed gravity

- Fully compressible: $M_s \in (10^{-6}, 10^{-1})$
- Time-implicit
- Finite-volume staggered-grid
- IC from 1D stellar evolution model
- Spherical and Cartesian geometry (2d & 3d)

*Viallet et al. 2011, 2013, 2016*
*Geroux et al. 2016*
*Pratt et al. 2016*
*Goffrey et al. 2017*

# Solar simulations

- Initial conditions (reference state) current Sun model
  - $L = L_\odot, Z = Z_\odot, M = M_\odot$
  - EoS from MESA
  - NO rotation
  - NO magnetic fields
- Evolve over 100s of $\tau_{\rm conv}$
- Effect of the domain



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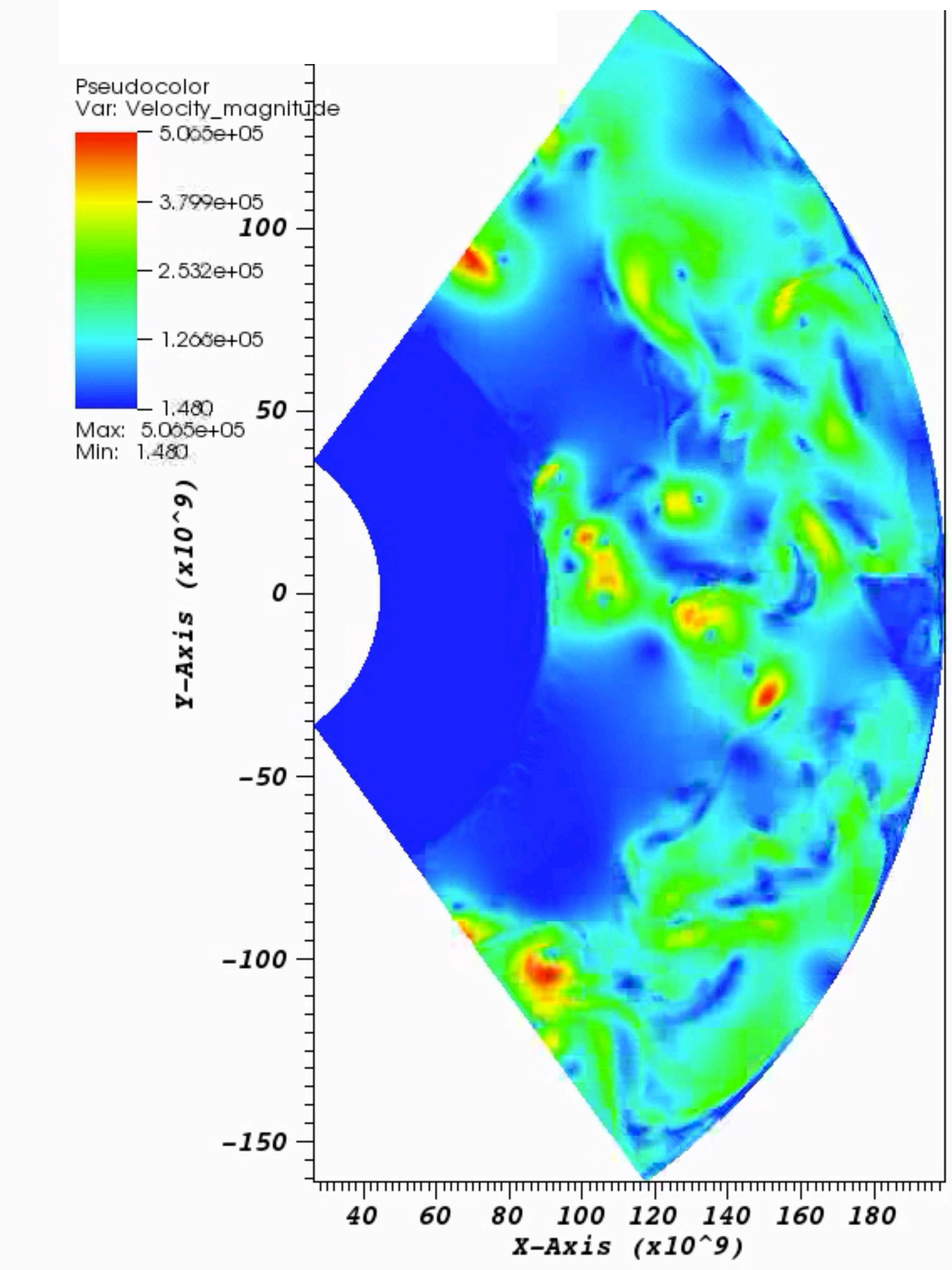
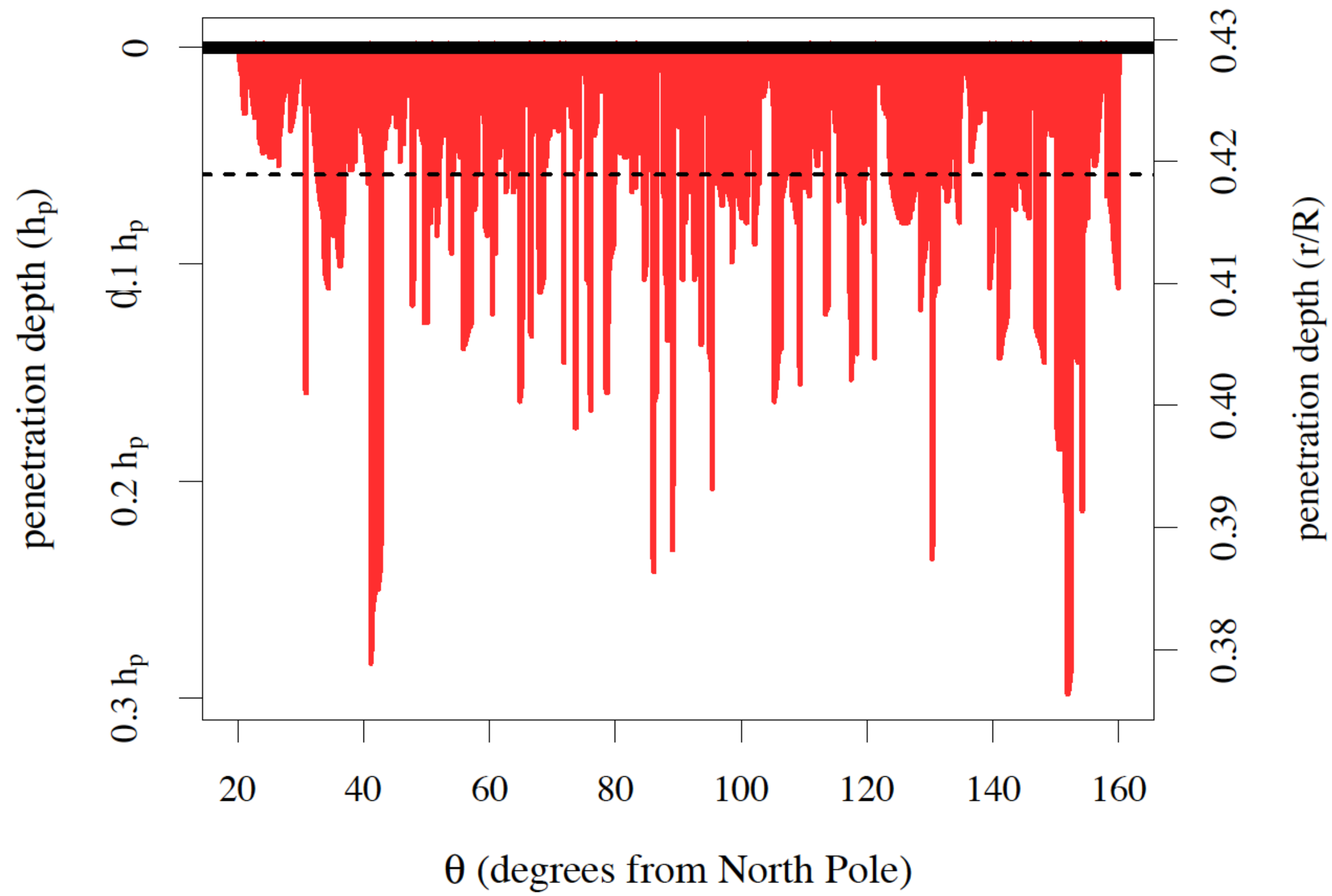


# Statistics of overshooting

- Overshooting depth is typically taken as a horizontal and time average over e.g. K.E. flux
- BUT data is highly non-Gaussian in space and in time




(Pratt et al., 2016, 2017)

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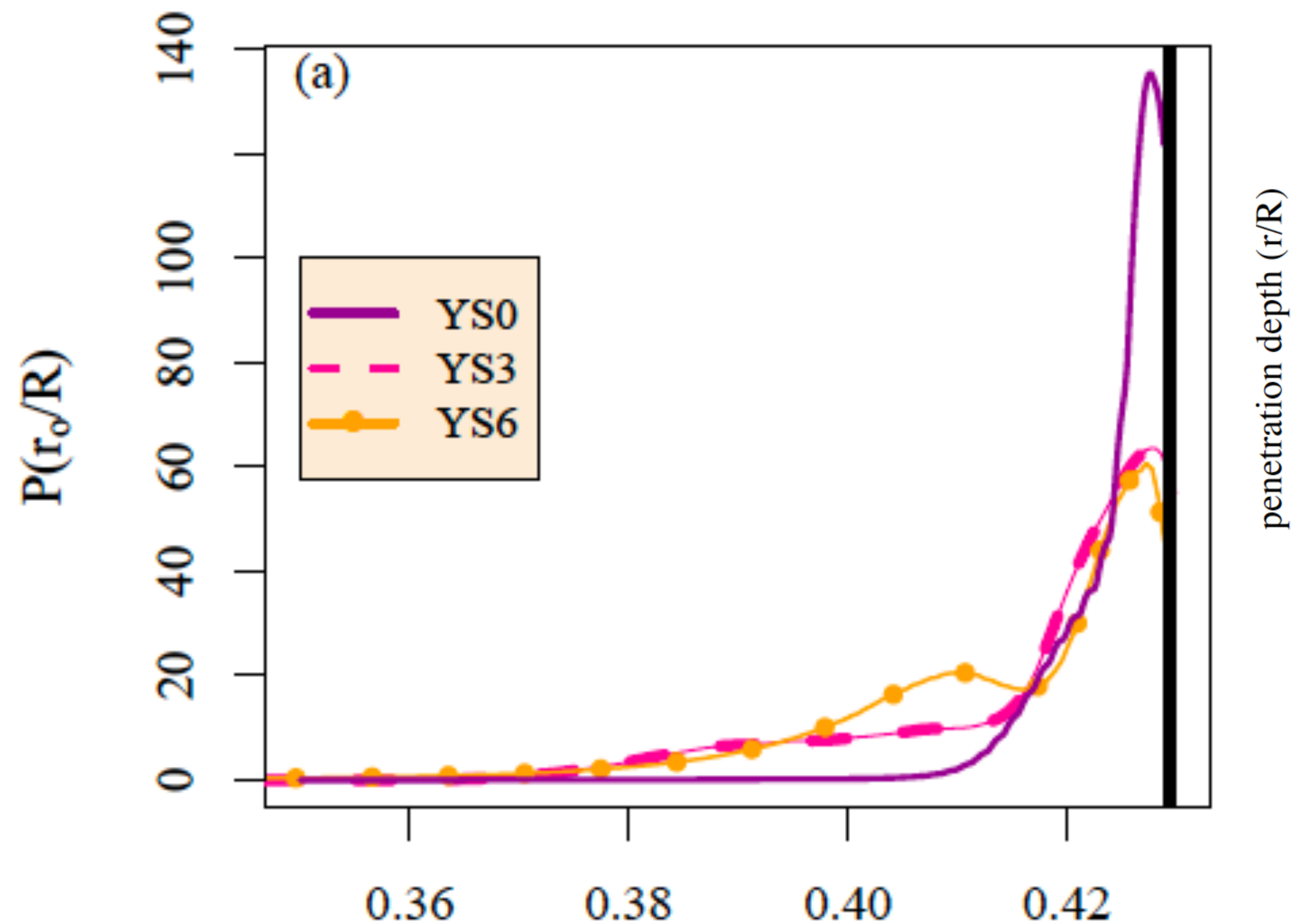
- Good fit by a Gumbel distribution

$$F(r) = exp\left[-exp\left(-\frac{x-\mu}{\lambda}\right)\right]$$

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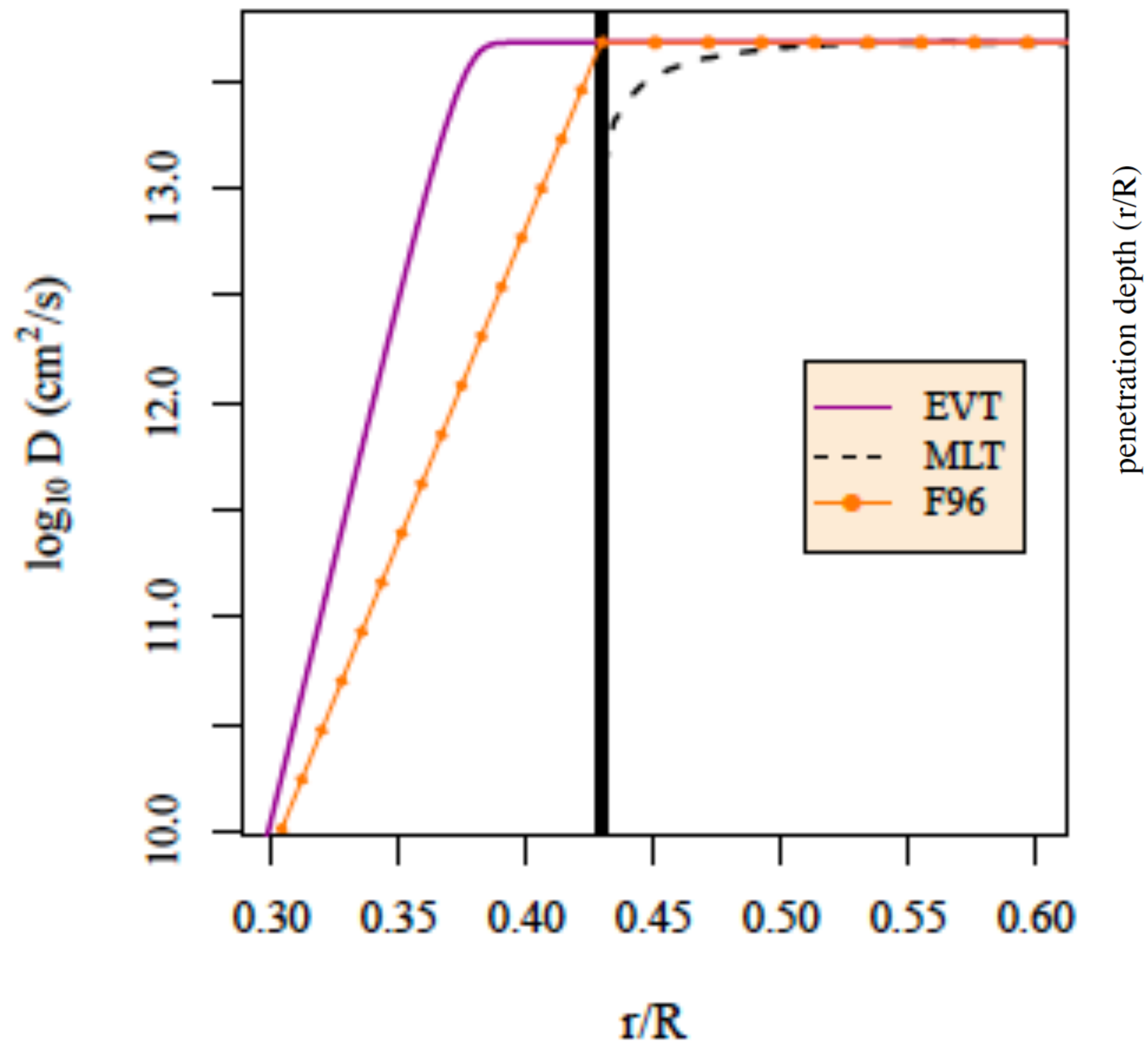
$$F(r) = exp\left[-exp\left(-\frac{x-\mu}{\lambda}\right)\right]$$

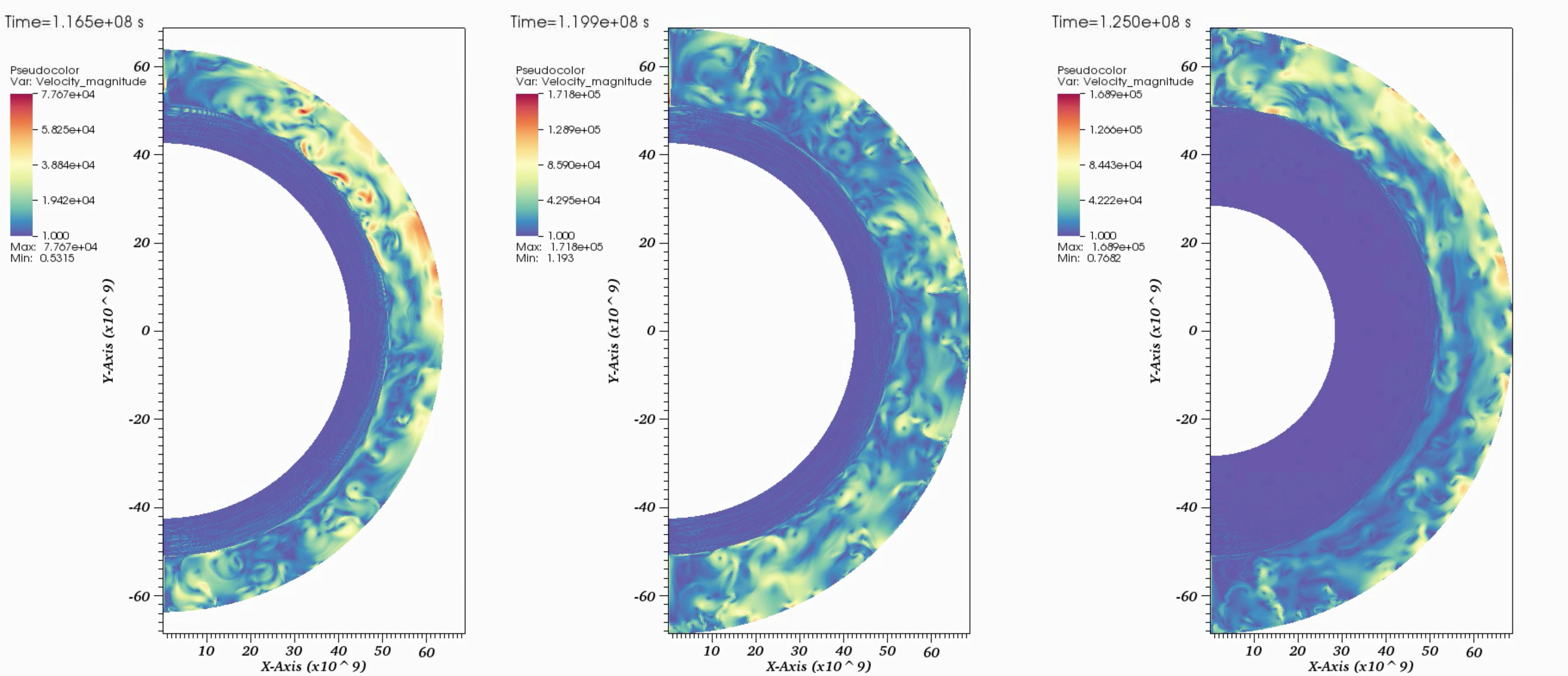
- Applied to Li depletion in PMS




(Baraffe et al. 2017, Pratt et al., 2016, 2017)

# Dependence on the domain

**velocity magnitude**




**$r/R_\odot \in [0.6, 0.9]$** **$r/R_\odot \in [0.6, 0.97]$** **$r/R_\odot \in [0.4, 0.97]$**

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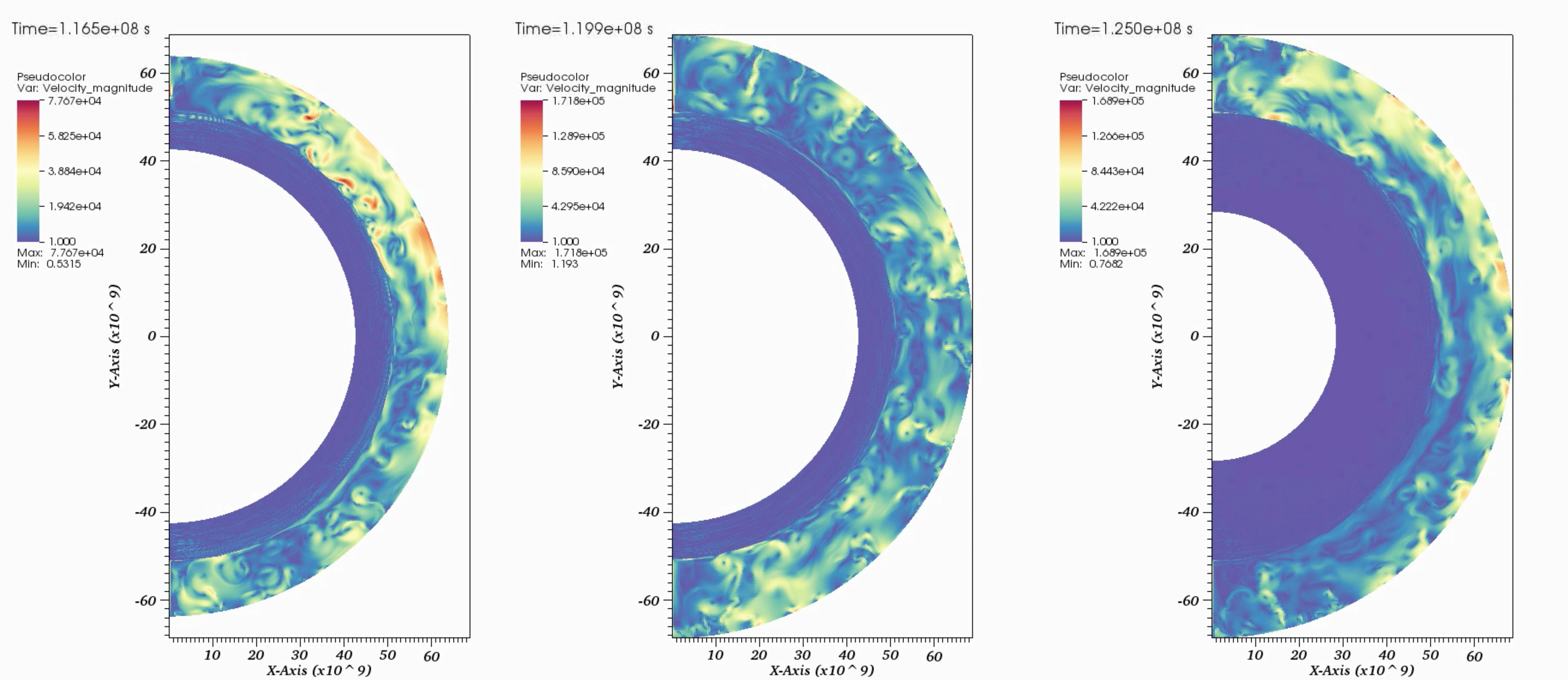
**velocity magnitude**

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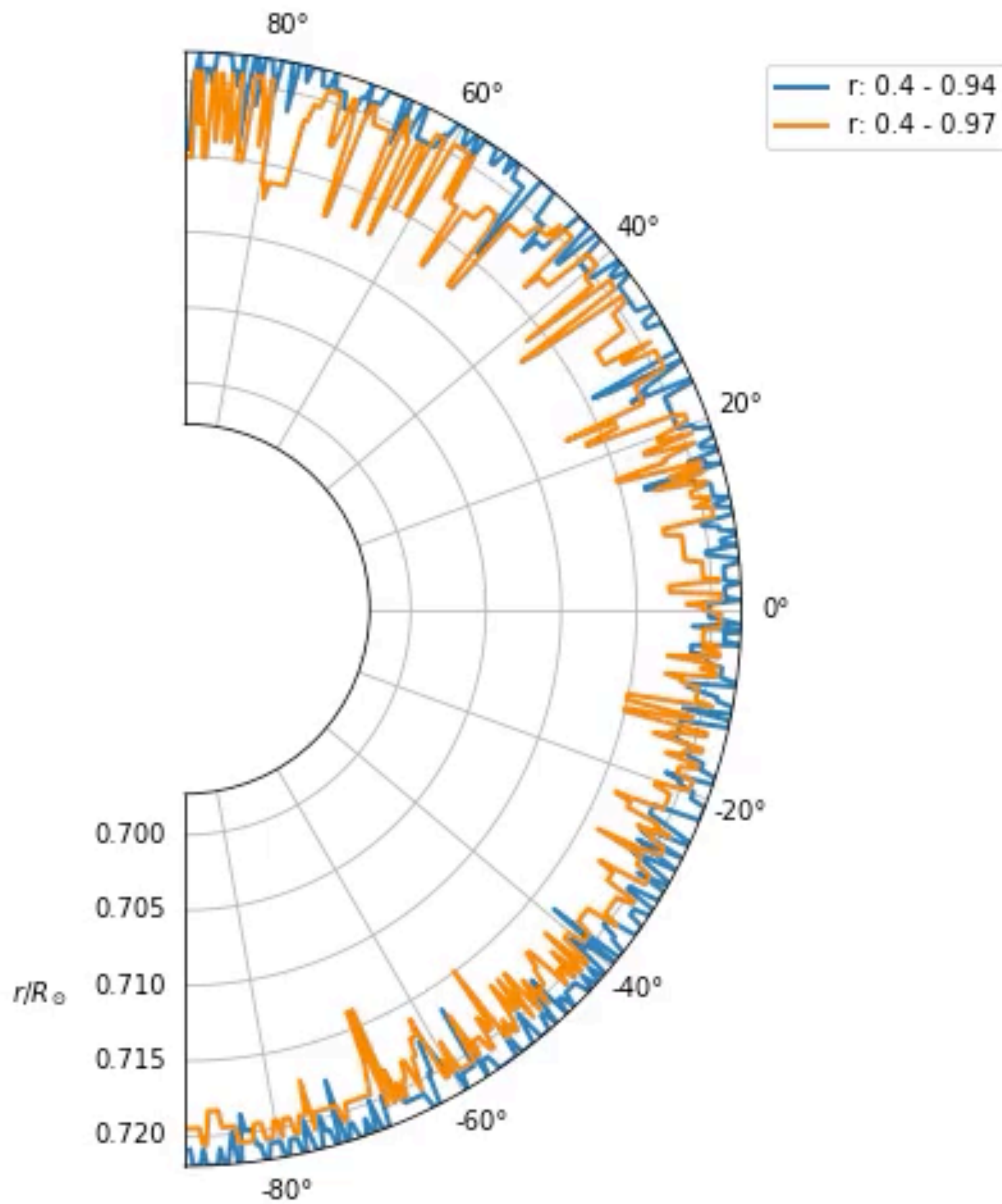
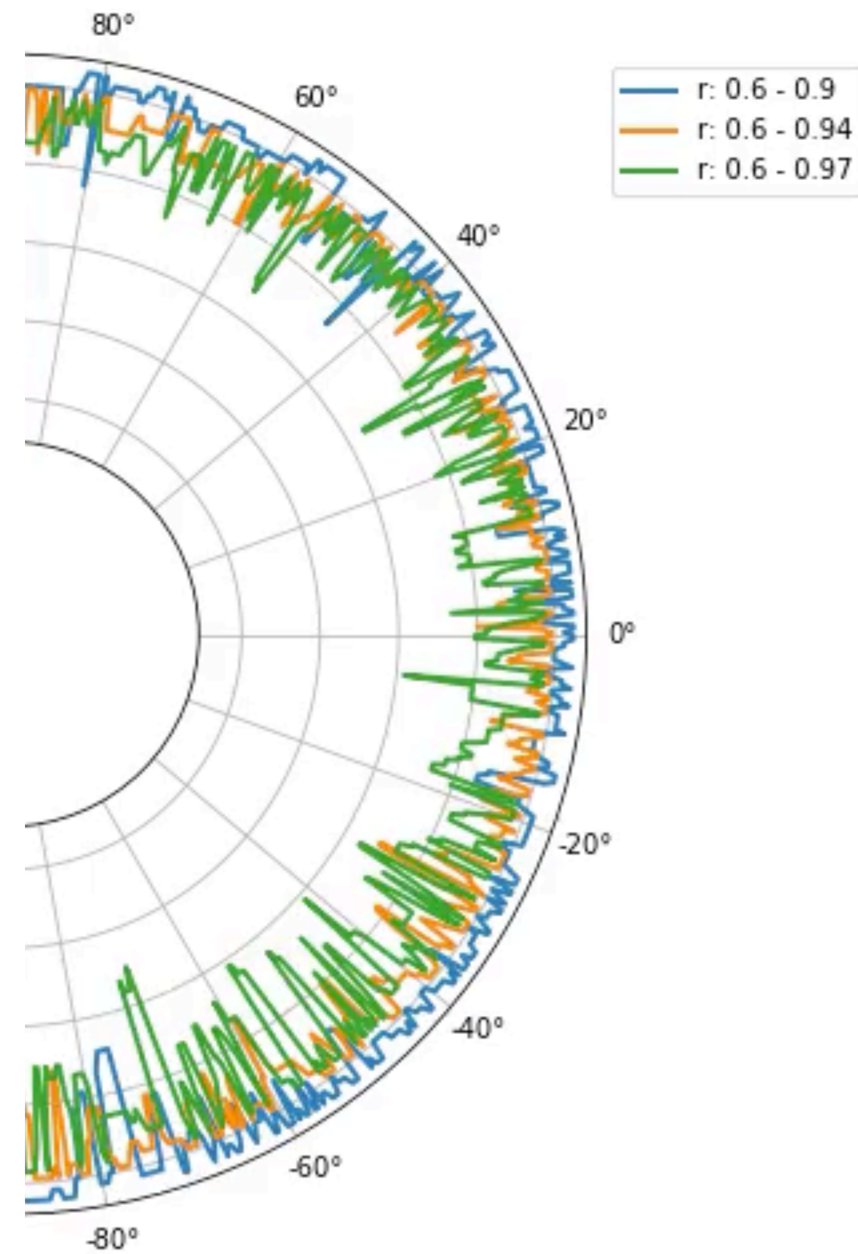
# Overshooting evolution

**Radial K.E. flux** $= \langle u_r(\rho \mathbf{u}^2/2)\rangle_\theta$




**$r_{min}$ = 0.4** **$r_{min}$ = 0.6**

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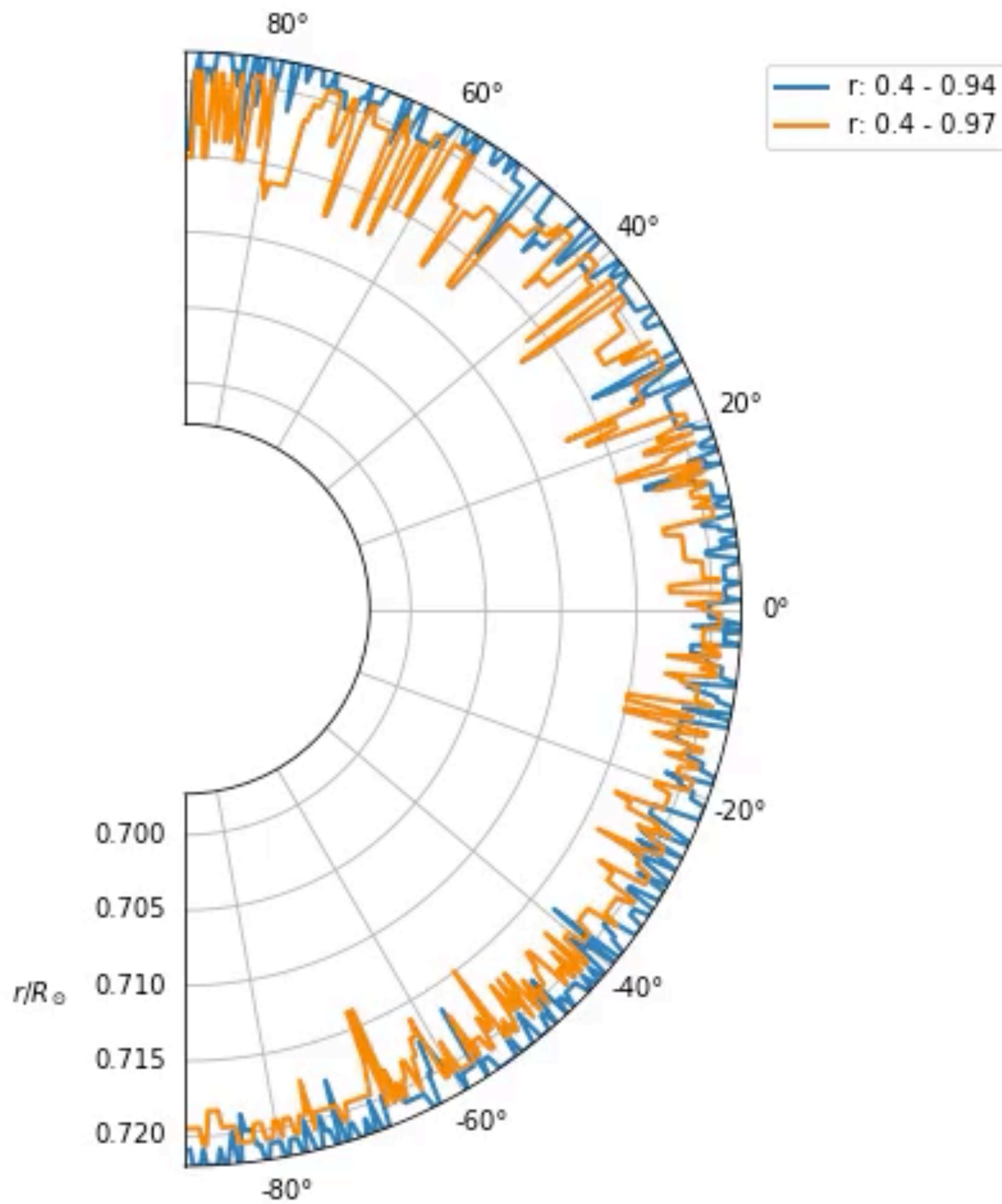


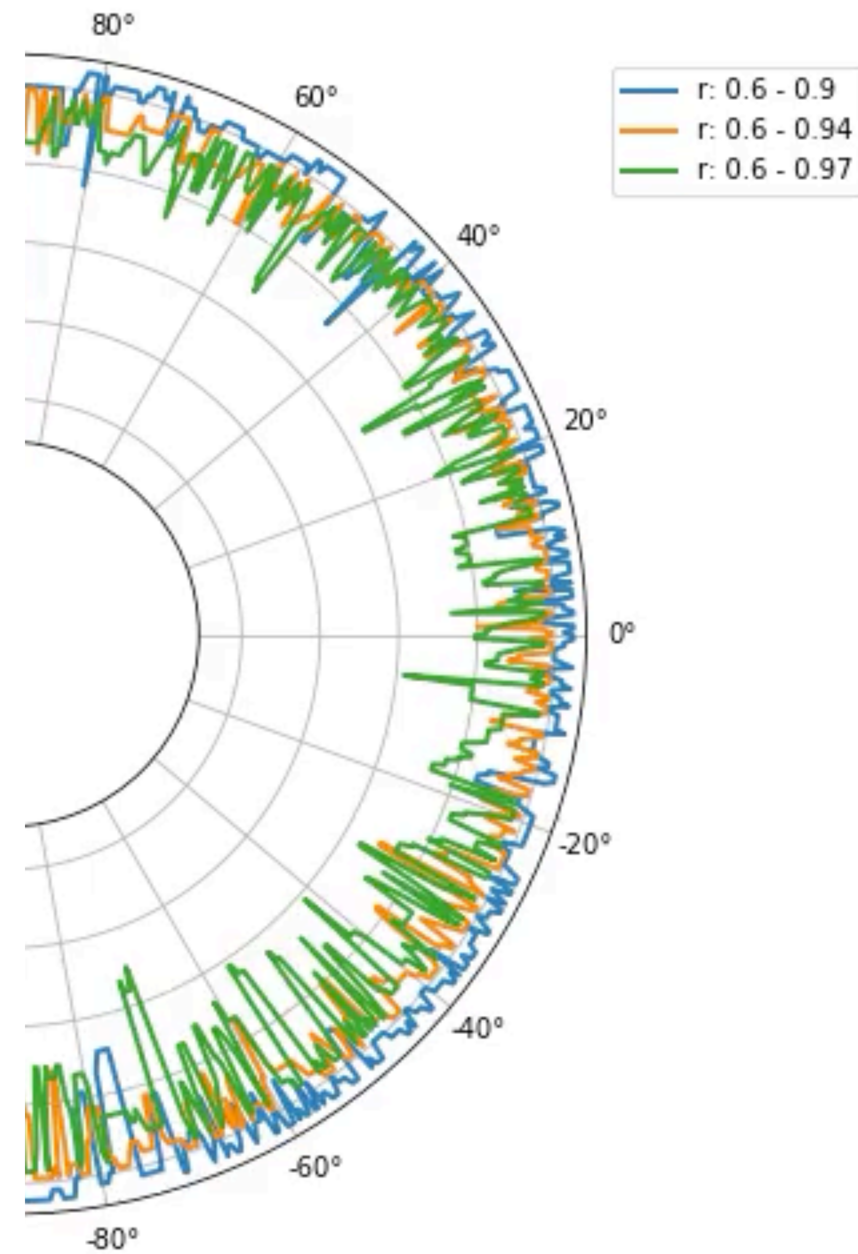


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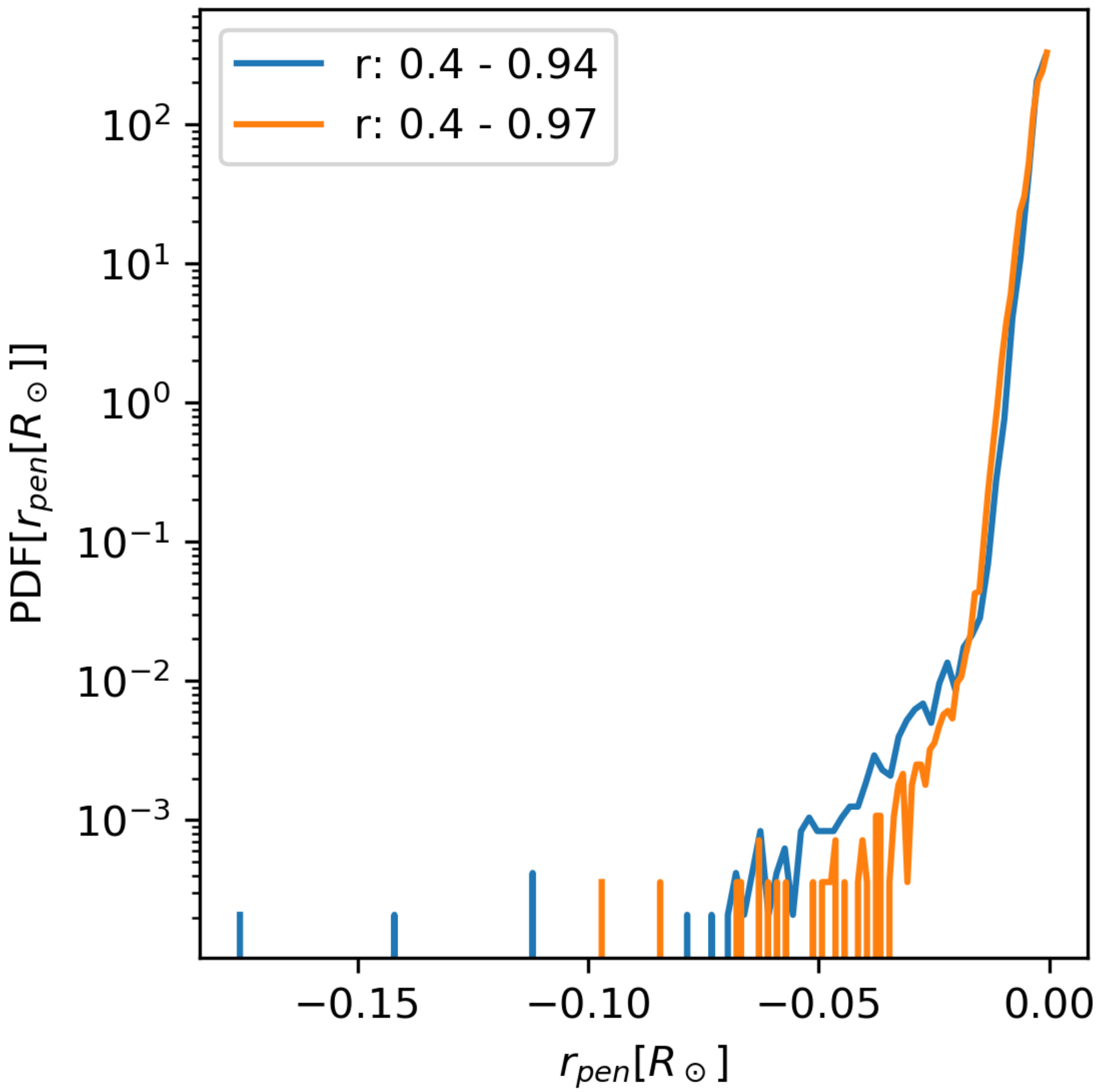


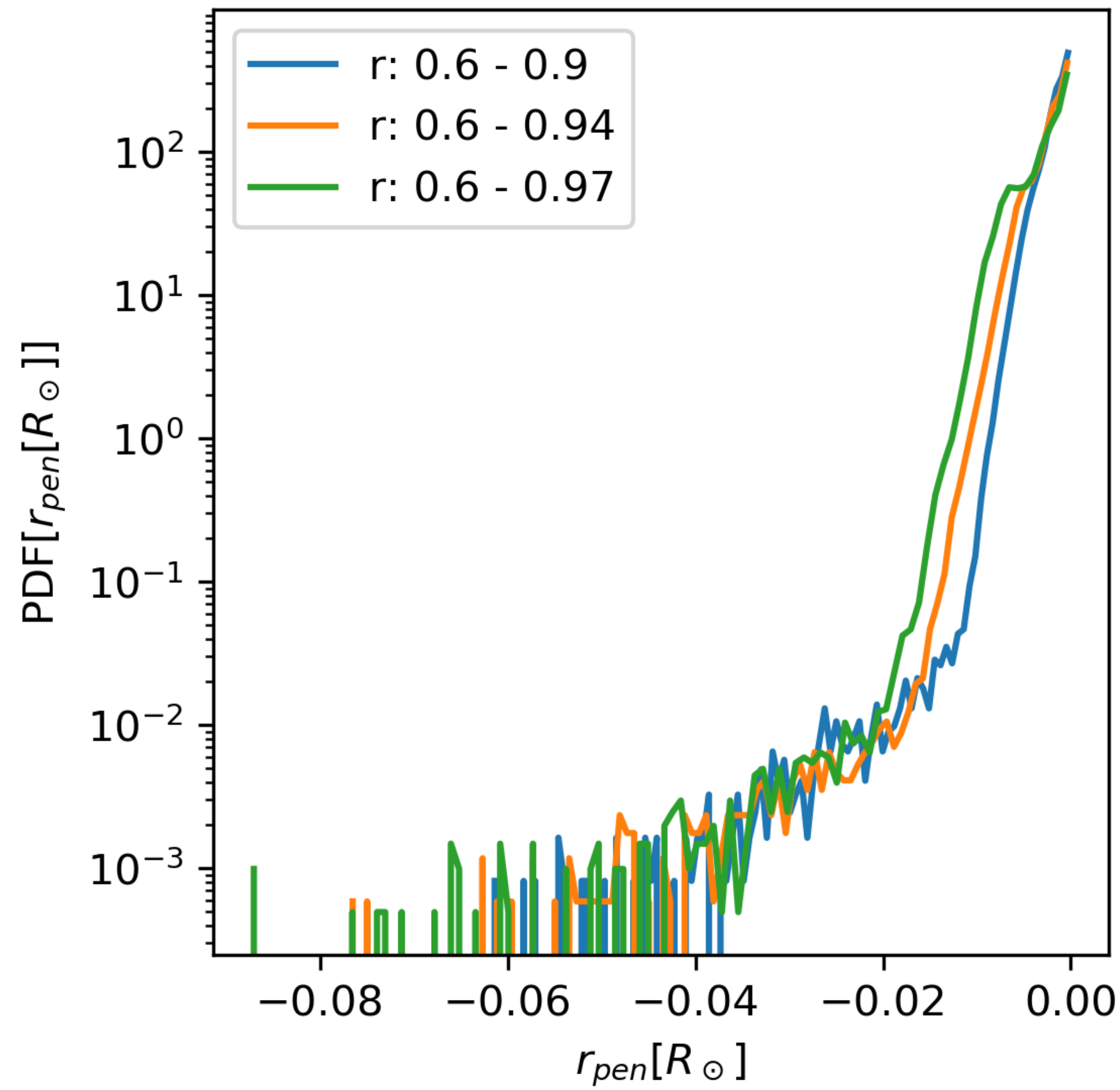


**$H_p$ ~ 0.08 $R_\odot$**

# Summary and outlook

- Convective overshooting in stellar interiors
- MUSIC — fully compressible, time-implicit ILES, with realistic microphysics on a spherical grid
- Effects of convective overshooting depend on high-order statistics
- Convective penetration for a wide range of stellar masses with and without rotation (envelopes and cores)
- Under development:
  - Magnetic fields (with constraint transport)
  - Explicit viscosity/diffusivity
  - Online tracer particles