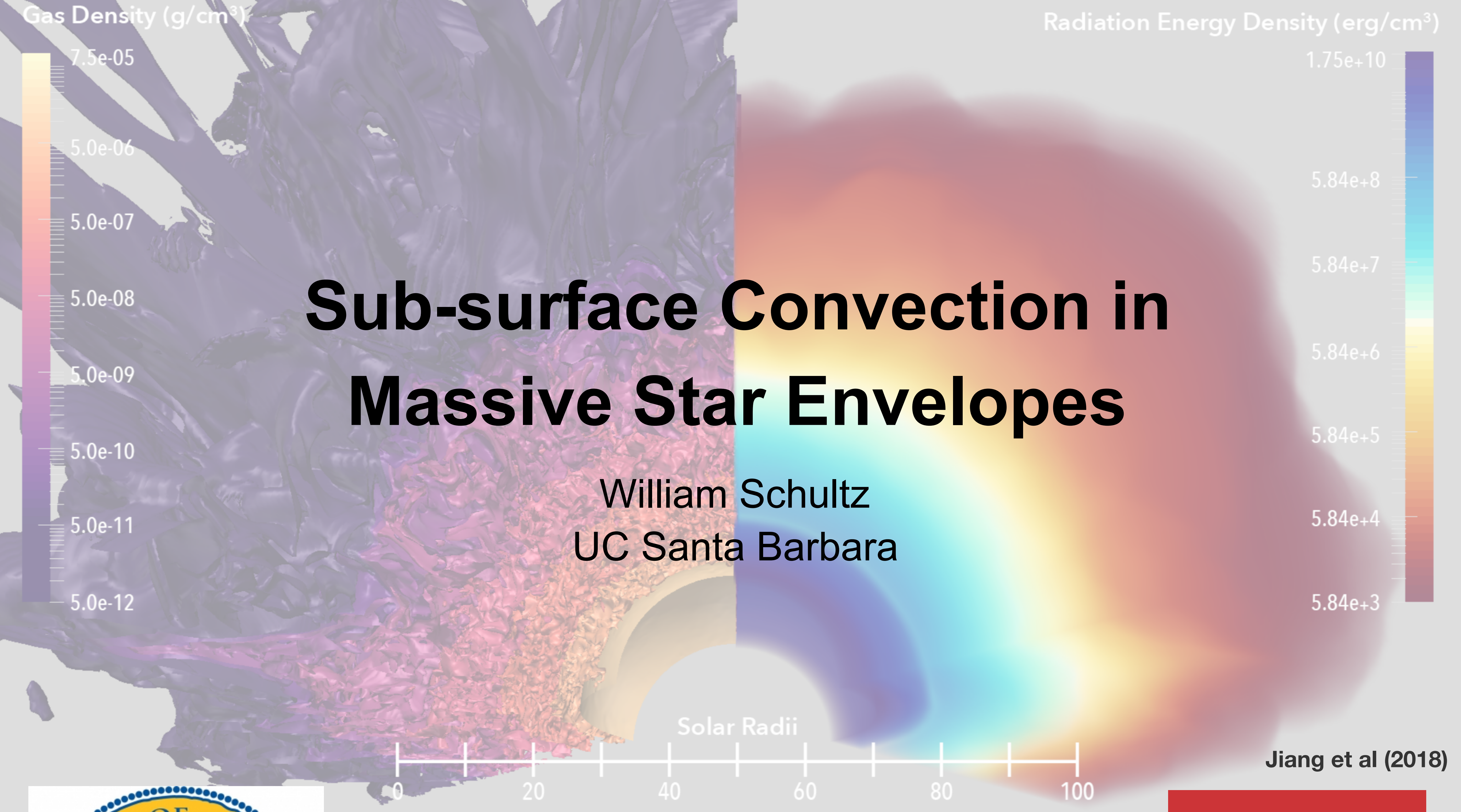


Sub-surface Convection in Massive Star Envelopes

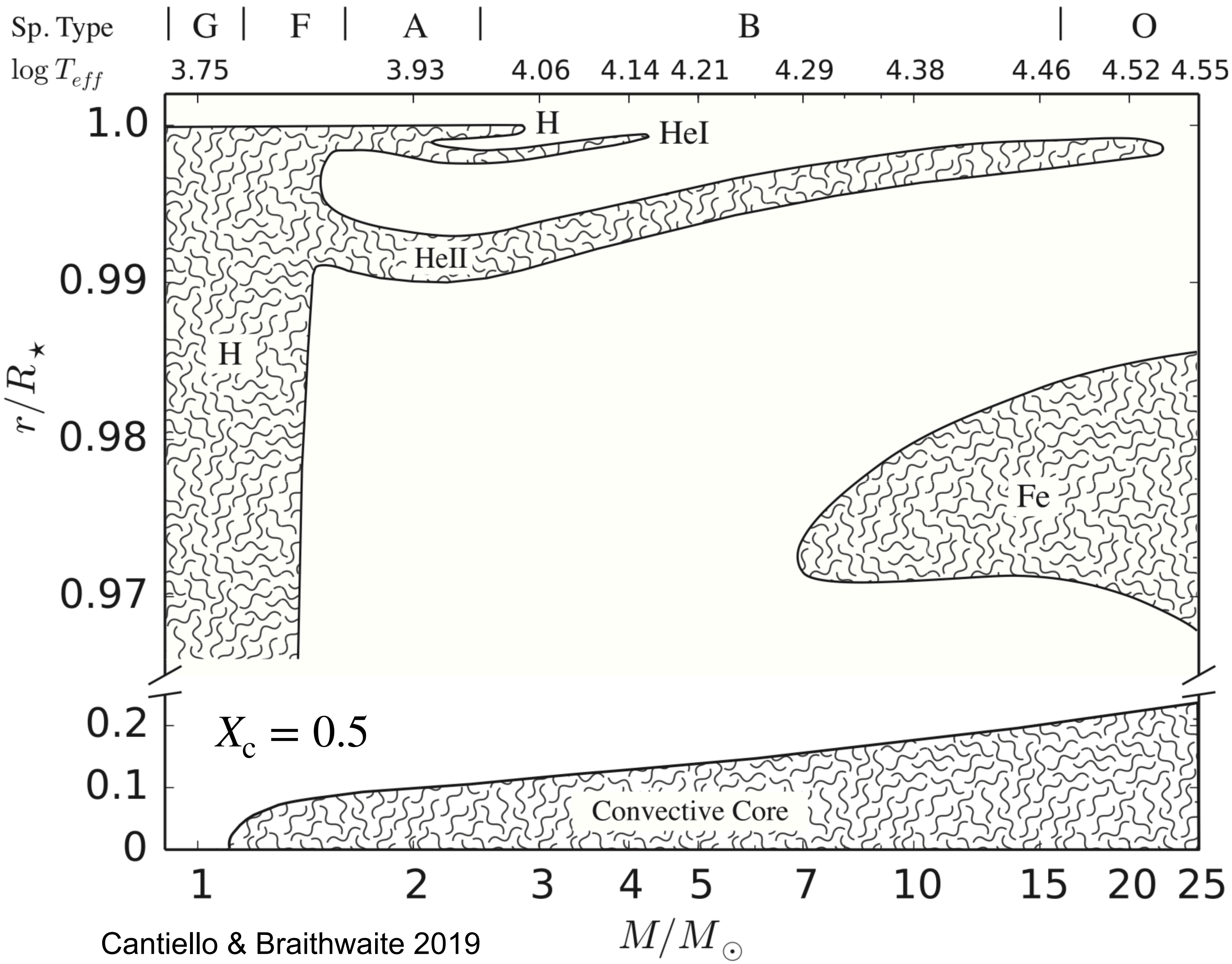
William Schultz
UC Santa Barbara

Jiang et al (2018)

In collaboration with Lars Bildsten and Yan-Fei Jiang
TranStar21 Program @ KITP
December 16th 2021

UC SANTA BARBARA
Kavli Institute for Theoretical Physics

Sub-Surface Convection Zones in HRD



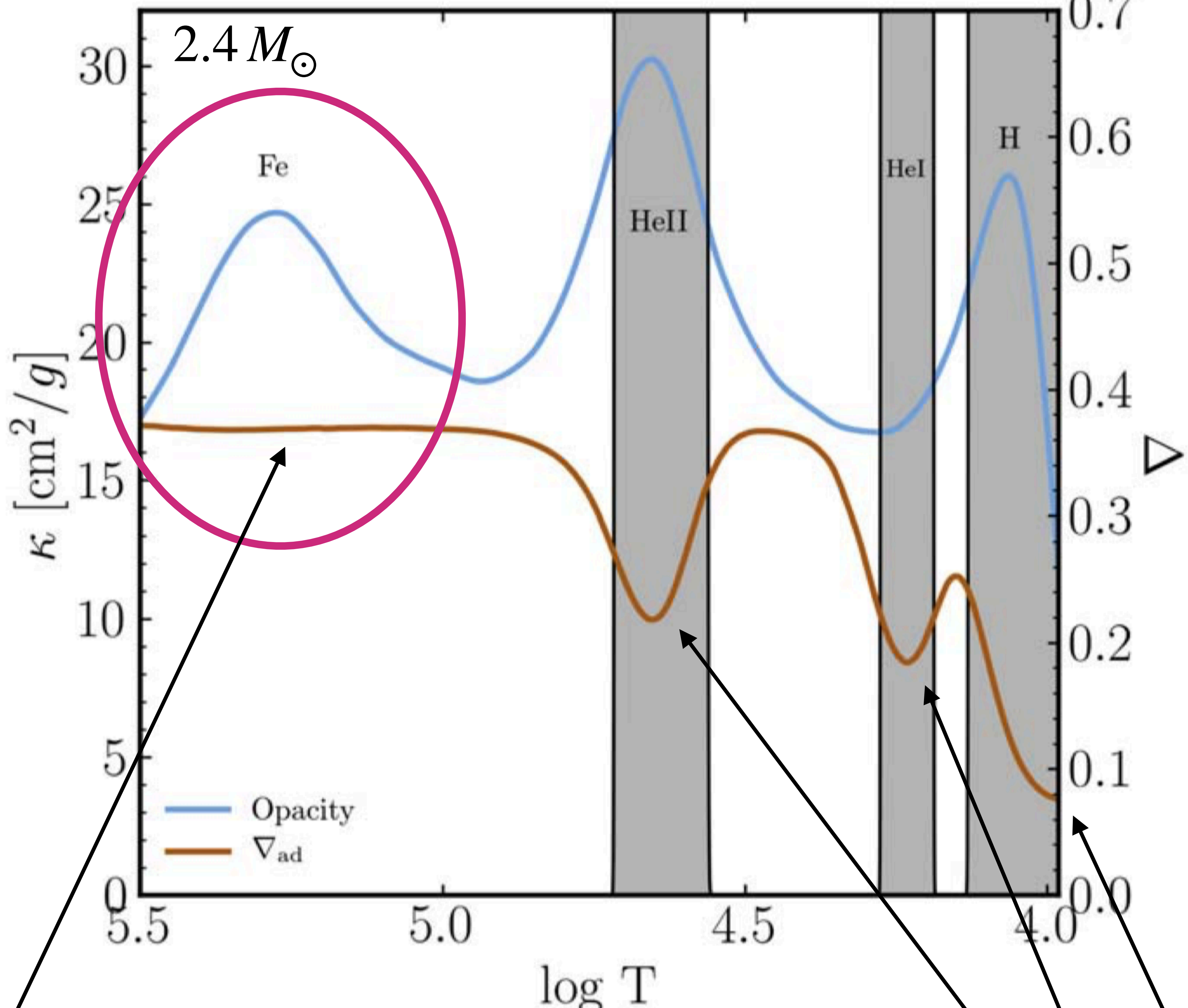
Cantiello & Braithwaite 2019

Sub-surface convection zones ubiquitous in massive stars

“Sub-surface” is very close to the surface. Maybe too close …

Causes of Sub-Surface Convection Zones

Cantiello & Braithwaite 2019

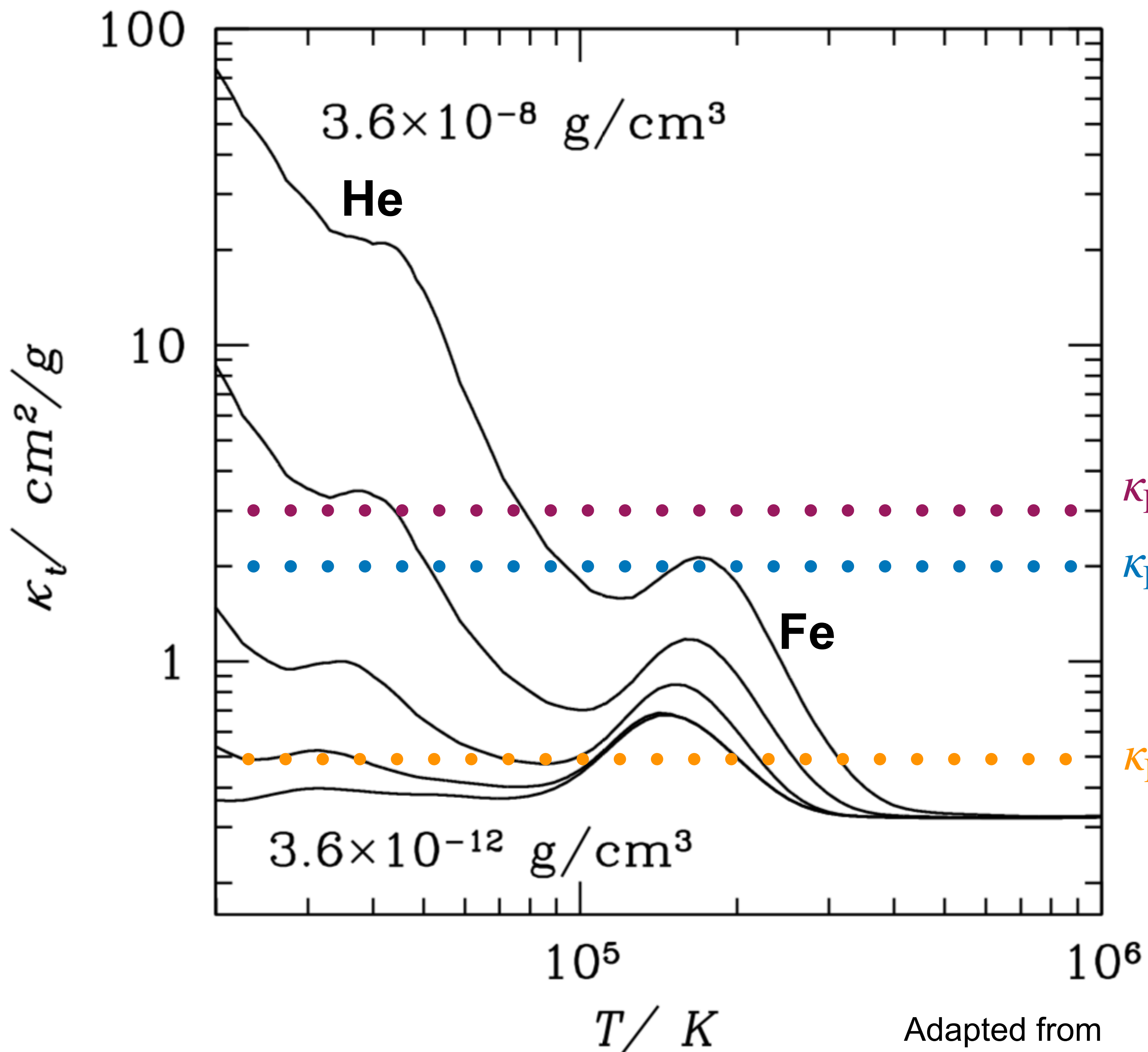


Need $L \sim L_{\rm Edd}$ to excite convection

$(M \gtrsim 10\,M_\odot)$

Partial ionization reduces $\nabla_{\rm ad}$

Convection Excited by Opacity Peaks



$\kappa_{\rm Edd}$ **for** $35\,M_\odot$ **at ZAMS**

$\kappa_{\rm Edd}$ **for** $35\,M_\odot$ **on mid-MS**

$\kappa_{\rm Edd}$ **for** $80\,M_\odot$ **in HG**

Adapted from Jiang+ 2015

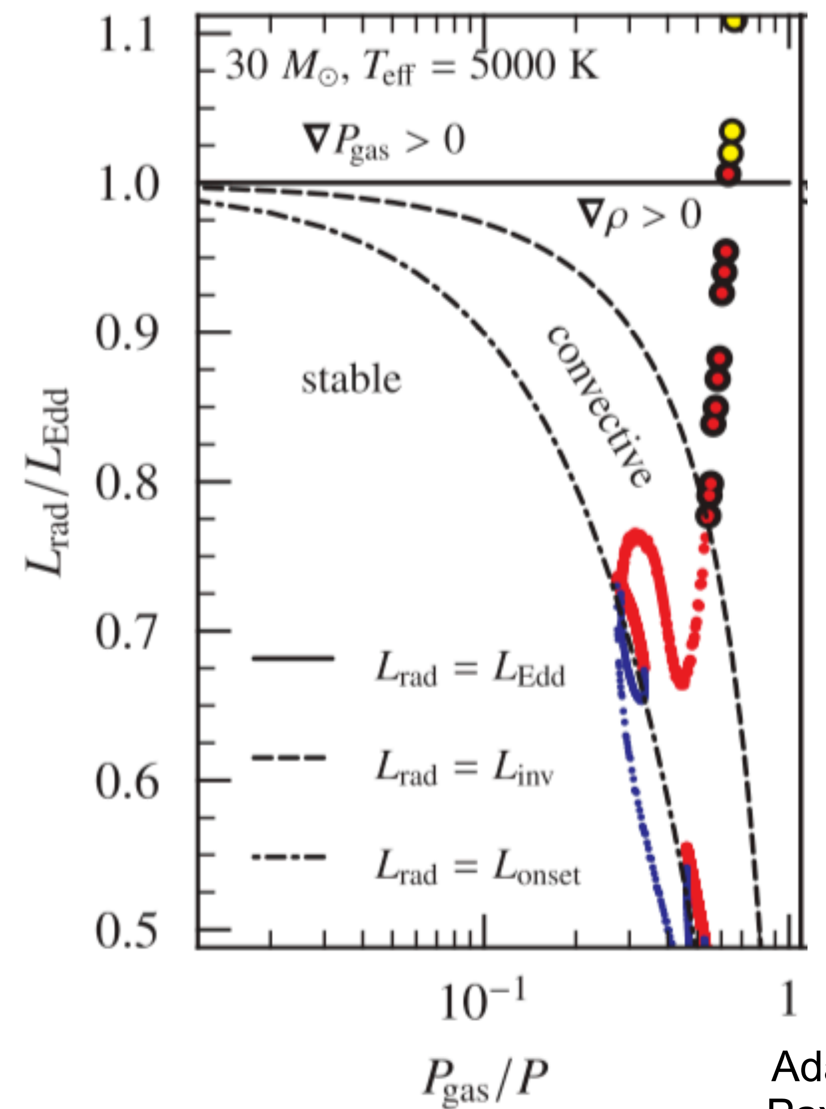
$$\kappa_{\rm Edd} \equiv \frac{4\pi GMc}{L}$$

Density Inversions in 1D Models

With sufficient Eddington ratio

- Convection excited
- Density inversions form
- Gas pressure inversions can form

MLT++ was designed to reduce/ eliminate density inversions



Adapted from Paxton+ 2013

Started 3D exploration using Athena++

Jiang+ 2015	Jiang+ 2017	Jiang+ 2018	Schultz+ 2020	Schultz+ in press
Plane parallel RHD	Plane parallel M+RHD	1/4 star LBV RHD	Exploring LBV models	Narrow Box MS RHD

Convective Efficiency γ

From ∇

$$\gamma \equiv \frac{\nabla - \nabla_{\rm eddy}}{\nabla_{\rm eddy} - \nabla_{\rm ad}} \qquad \nabla \equiv \frac{d \ln T}{d \ln P}$$

$\gamma \gg 1$ **convection is efficient**

$\gamma \ll 1$ **convection is inefficient**

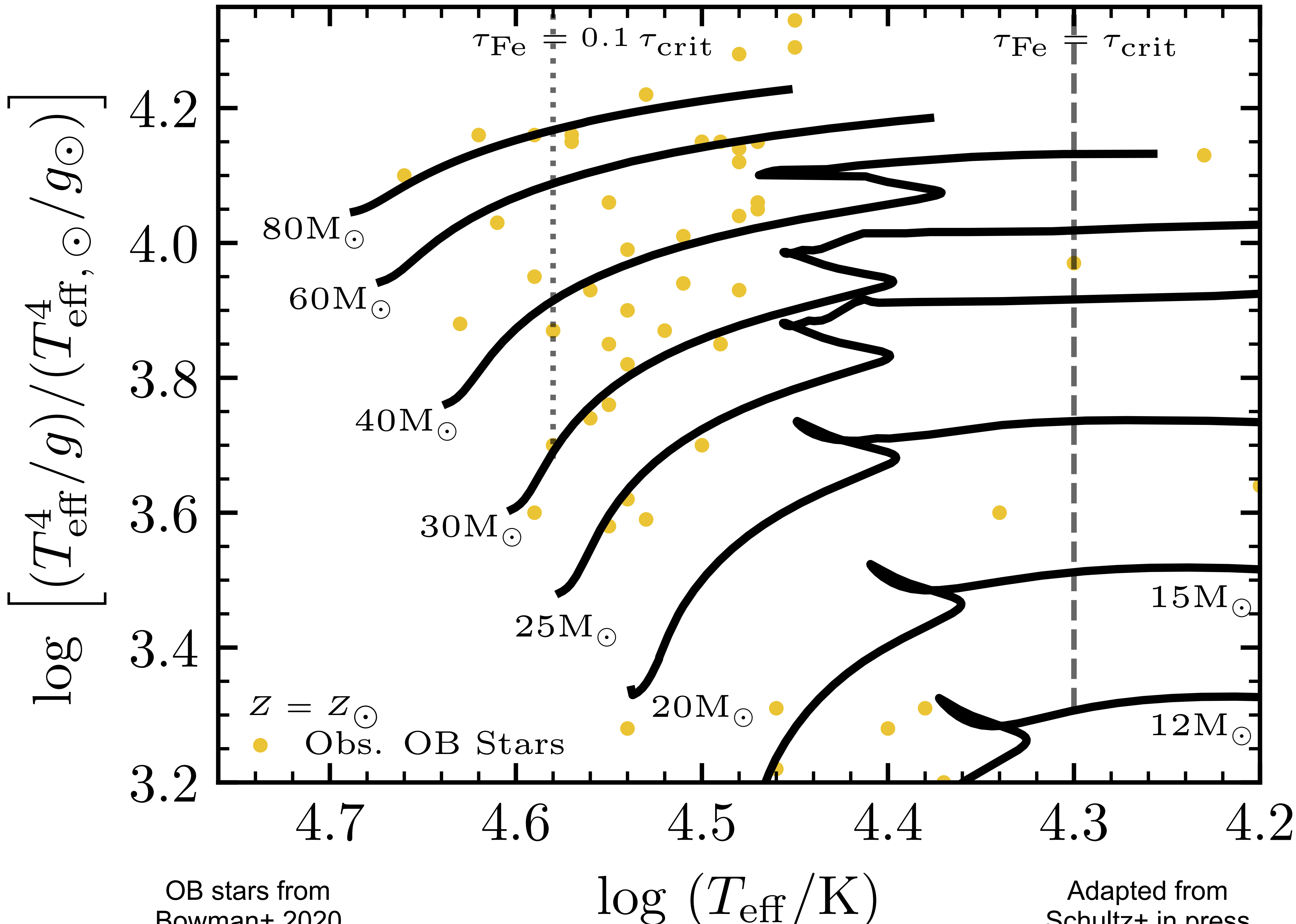
In optically thick limit

$$\gamma \sim \frac{F_{\rm conv}}{F_{\rm rad}} \sim \frac{(P_{\rm rad} + P_{\rm gas})v_{\rm c}}{P_{\rm rad}\left(\frac{c}{\tau}\right)} \qquad \tau_{\rm crit} \equiv \frac{c}{v_{\rm c}} \frac{P_{\rm rad}}{(P_{\rm rad} + P_{\rm gas})}$$

If convection occurs at $\tau < \tau_{\rm crit}$, expect inefficiencies due to radiative losses

For massive stars, $\tau_{\rm crit} \sim 10^3 - 10^4$

τ_{crit} Across the High L sHRD



OB stars from Bowman+ 2020

MESA models from Cantiello+ 2021

Adapted from Schultz+ in press

3D Rad-Hydro Modeling using Athena++

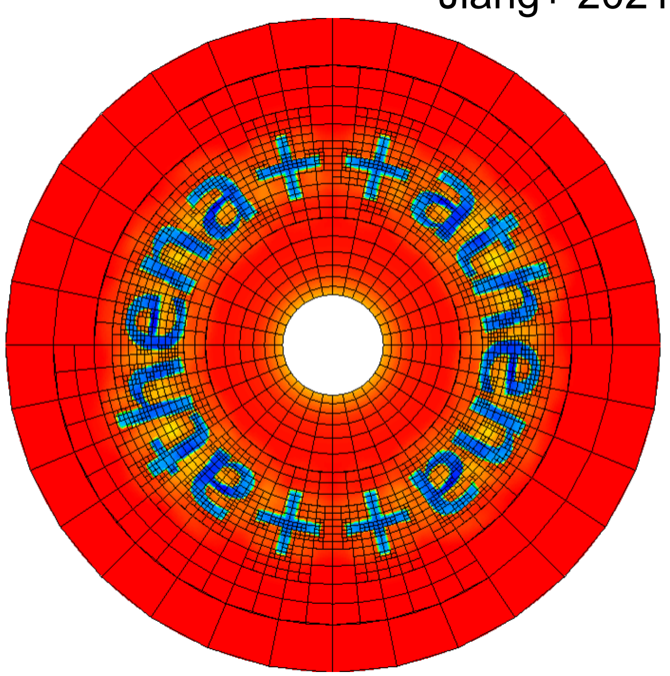
Modeling Method

- Initializing Models
  - Use MESA to get $T, \rho, L, M_{\mathrm{in}}$
  - Take T, ρ at iron opacity peak, integrate to find radiative only model
  - Use radiative solution as initial condition and integrate 3D model with L, M_{in} from MESA
- Solve full time-dependent radiation transport equation implicitly

See Jiang+ 2021

  - Using ~100 angles per cell
  - Calculates specific intensity $\longrightarrow T_{\mathrm{rad}}, E_{\mathrm{rad}}, F_{\mathrm{rad}}$
    - Our models are mostly in LTE
- Dimensionless fluid numbers (e.g. Re, Pe) not explicitly specified

Jiang+ 2012
Davis+ 2012
Jiang+ 2021

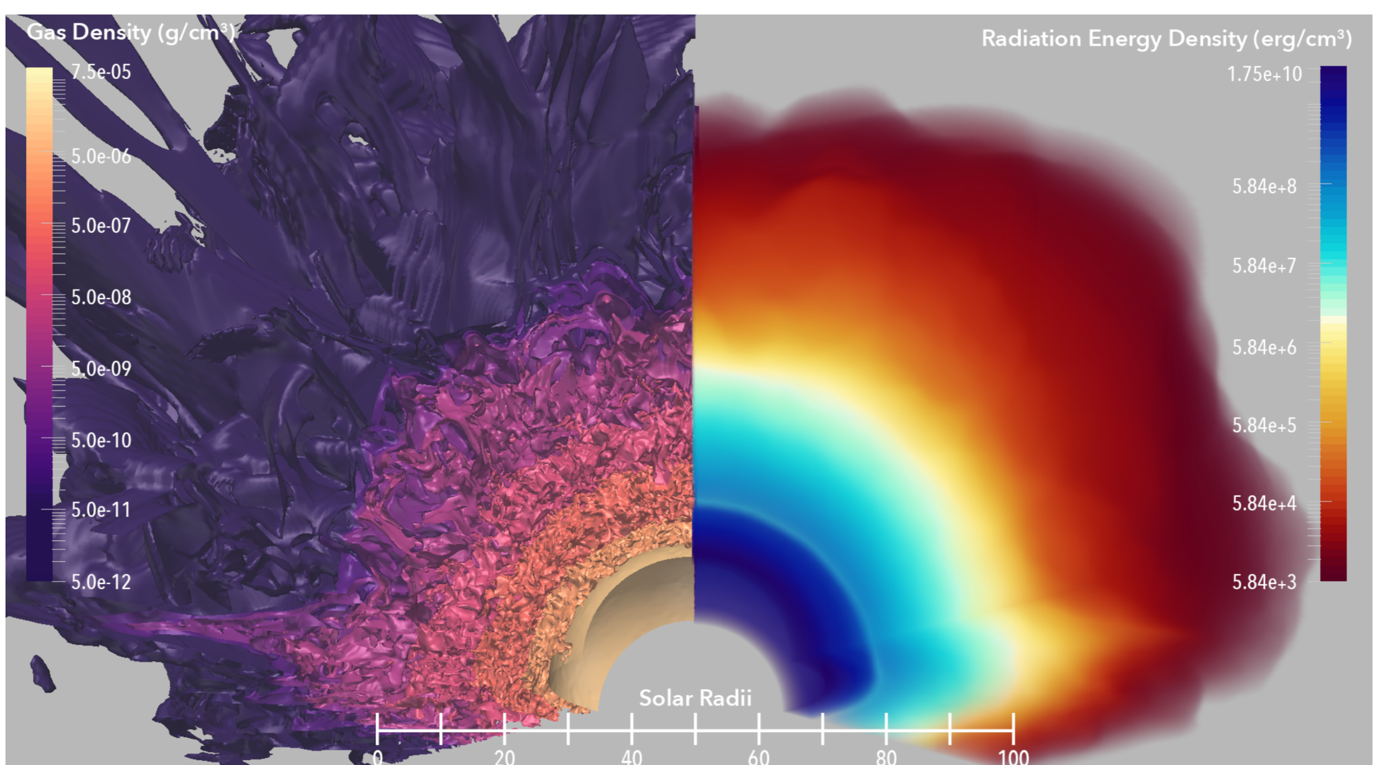


Checking Assumption/Limitations

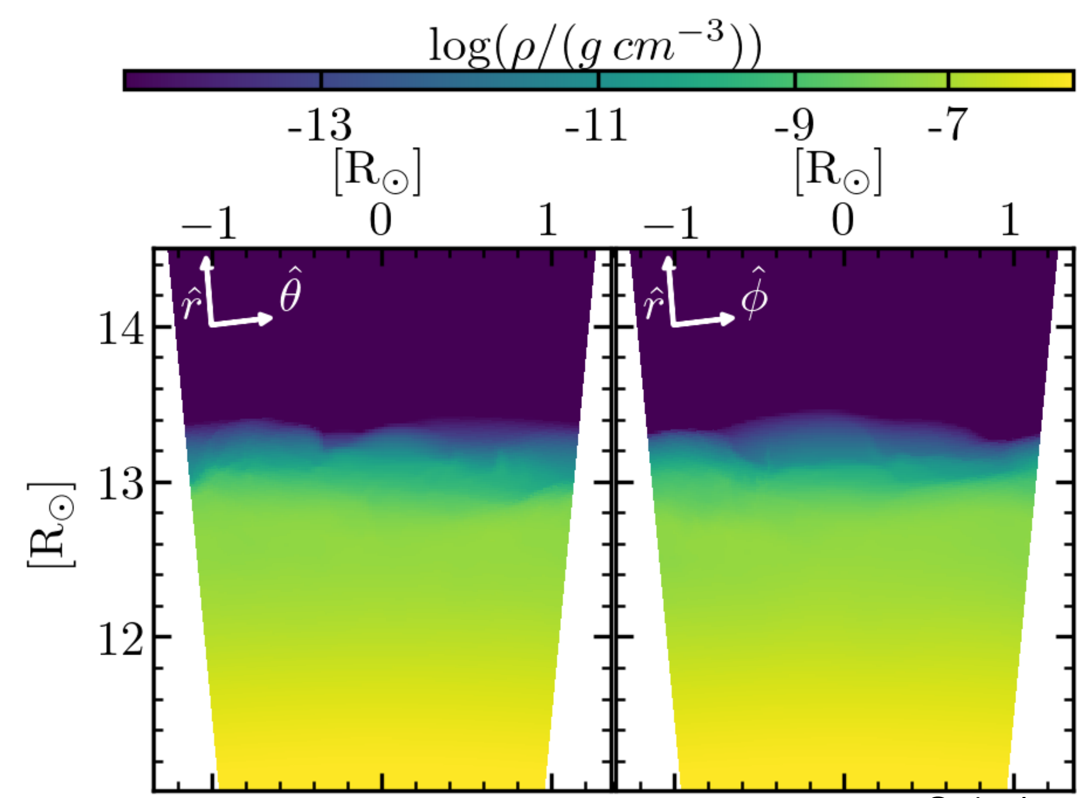
- Constant μ
  - Good for FeCZ, less so at surface/HeCZ ✓*
- Gravitational acceleration $\propto r^2$
  - $M_{\rm env}/M_{\rm star} < 0.2\,\%$ ✓
- Solar Metallicity ✓
  - Also running lower metallicity models
- Gray OPAL opacity
  - Good in optically thick ✓*
  - LDI is important in optically thin region
- No magnetic field
  - FeCZ damped in high B field ✓
    - Requires >10kG field in CZ
- No rotation
  - Rotation period $\gg$ eddy turnover time in FeCZ ✓
    - (~3 days $\gg$ ~1 hour for $35\,M_\odot$ mid-MS)

Two Classes of 3D Models

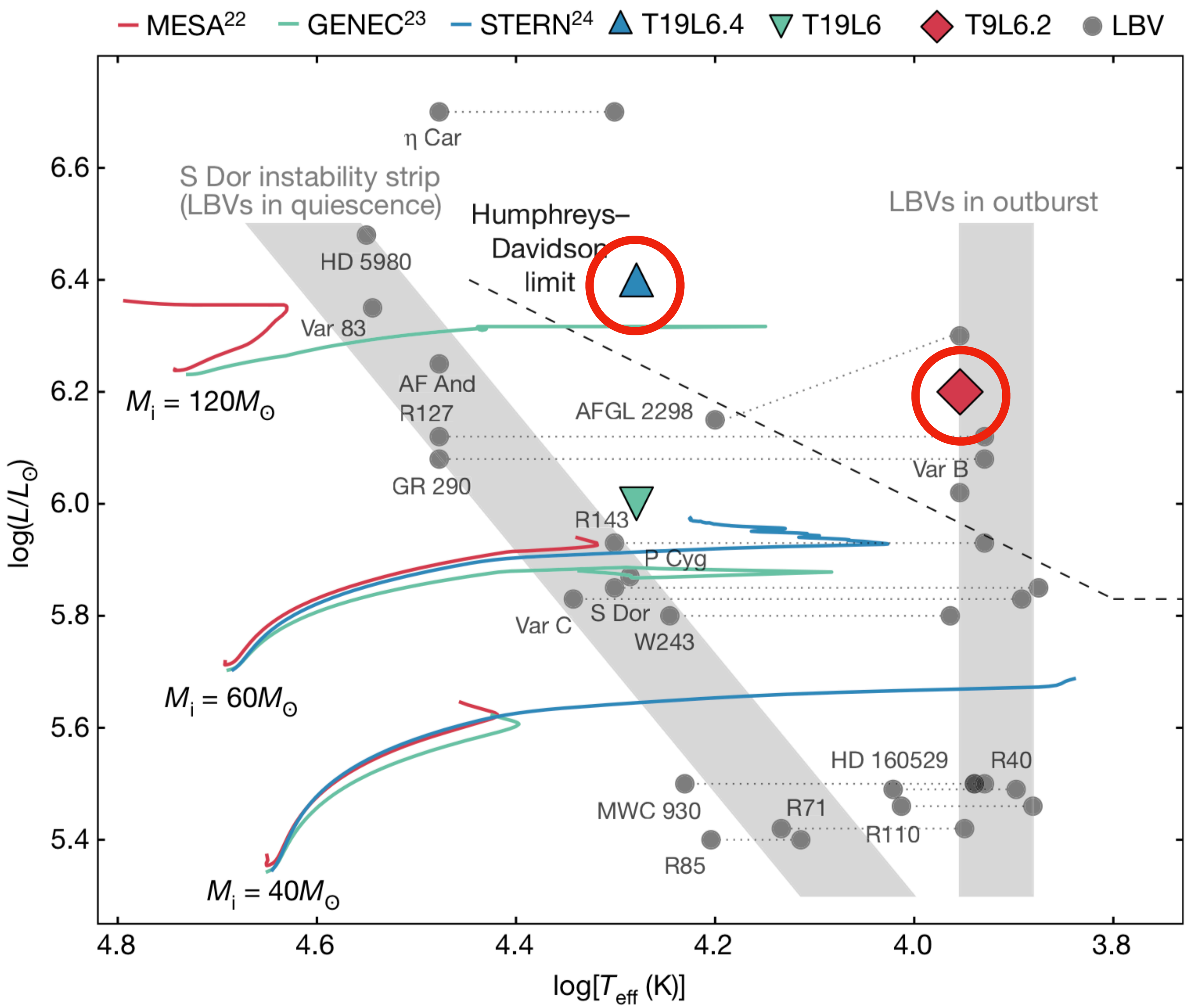
Global	Box
Jiang+ 2018 Schultz+ 2020	Schultz+ in press
$\phi : 0 \rightarrow \pi$	$\phi : -\pi/20 \rightarrow \pi/20$
$\theta : -\pi/4 \rightarrow \pi/4$	$\theta : -\pi/20 \rightarrow \pi/20$
$\Delta r_{\rm box}/R_{\rm star} \sim 1$	$\Delta r_{\rm box}/R_{\rm star} \sim 0.3$
Resolution: (512, 256, 512) (r, θ, ϕ)	Resolution: (265, 256, 256) (r, θ, ϕ)
$\sim 10^8$ CPU hours	$\sim 10^6$ CPU hours



Jiang+ 2018



Global Models



Jiang+ 2018

T19L6.4
80 solar masses
~100 solar radii

$$\tau_{\rm Fe} \approx 3\tau_{\rm crit}$$

T9L6.2
56 solar masses
~300 solar radii

$$\tau_{\rm Fe} \approx 10\tau_{\rm crit}$$

Table 1: Properties of the 3D Stellar Models

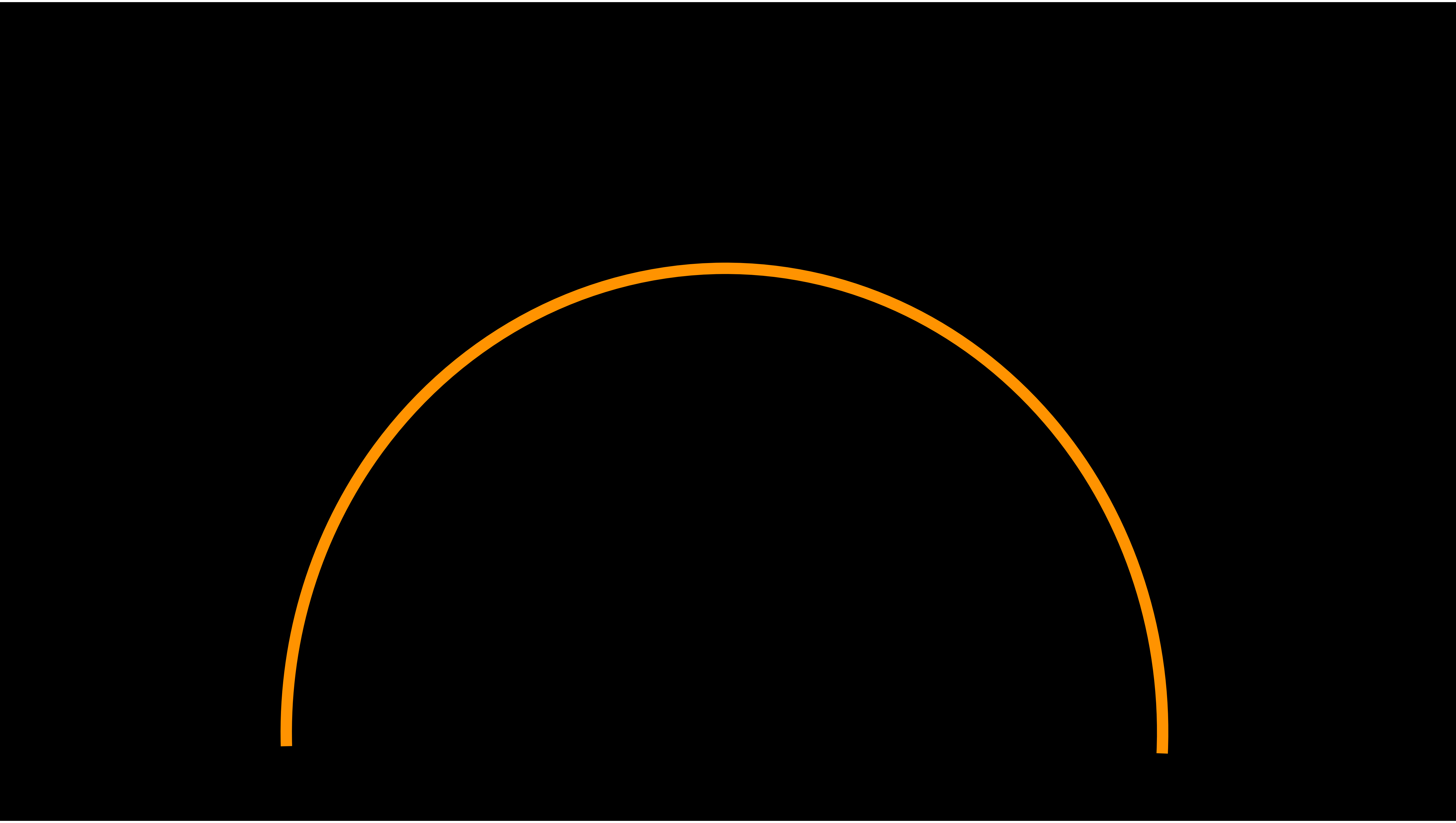
Name	$M_{\rm core}$ ($M_\odot$)	$M_{\rm env}$ ($M_\odot$)	$T_{\rm eff}$ (10^3 K)	L ($\log(L/L_\odot)$)	$L_{\rm Edd}$ [1] ($\log(L/L_\odot)$)	$r_{\rm base}$ ($R_\odot$)	$r_{\rm max}$ ($R_\odot$)	$r_{\rm ph}$ [2] ($R_\odot$)	$r_{\rm Fe}$ ($R_\odot$)	$\tau_{\rm Fe}$	Z ($Z_\odot$)
T9L6.2	56	0.13	9	6.20	6.26	35.0	809.8	353.3	80.3	28,000	1
T19L6.4	80	0.011	19	6.40	6.42	16.3	335.5	99.0	44.0	5,400	1

[1] For an assumed electron scattering opacity.

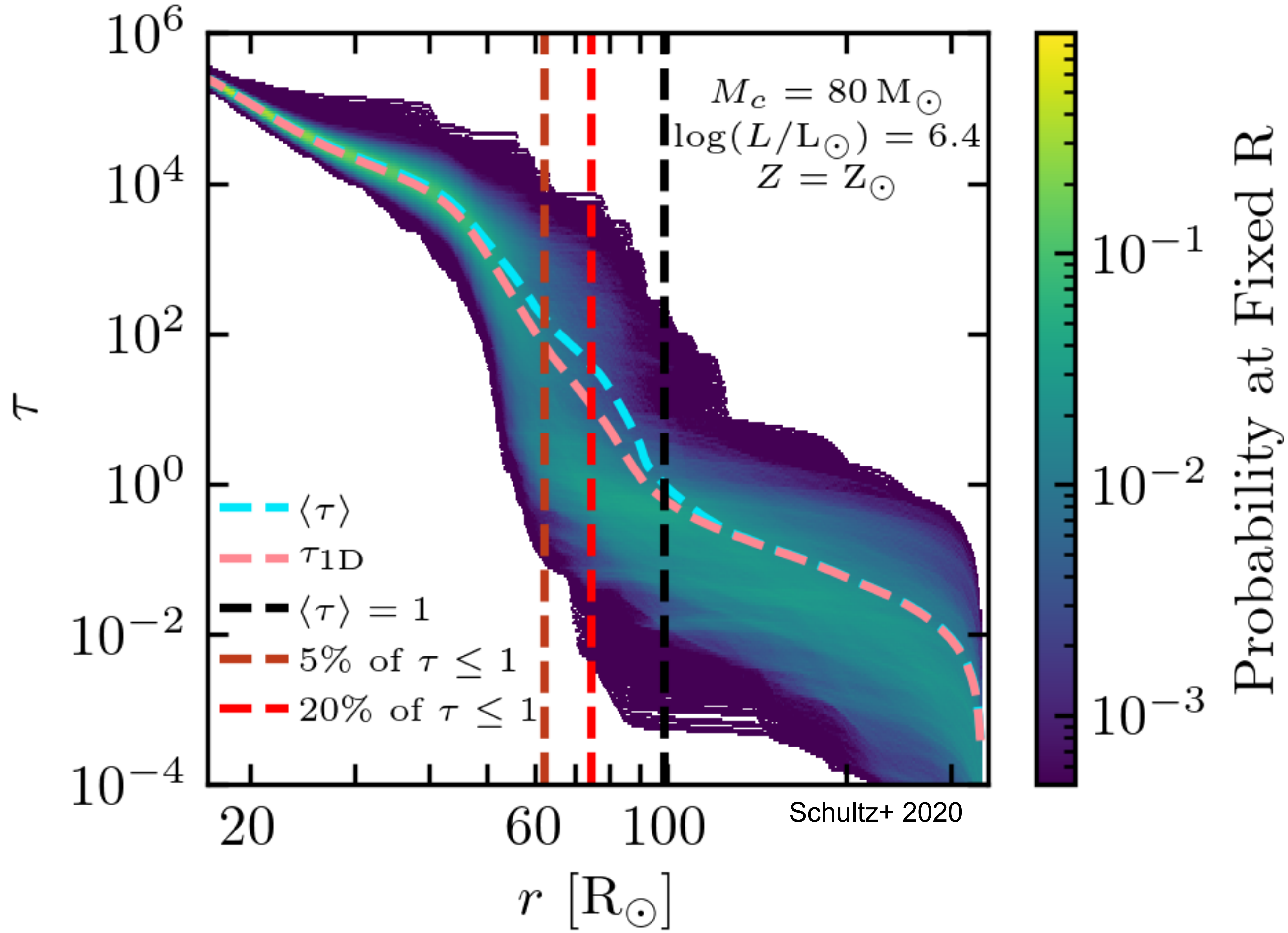
[2] The photosphere radii specified are where $\langle\tau(r_{\rm ph})\rangle = 1$.

Modified from
Schultz+ 2020

T19L6.4



T19L6.4: Optical Depth Profile

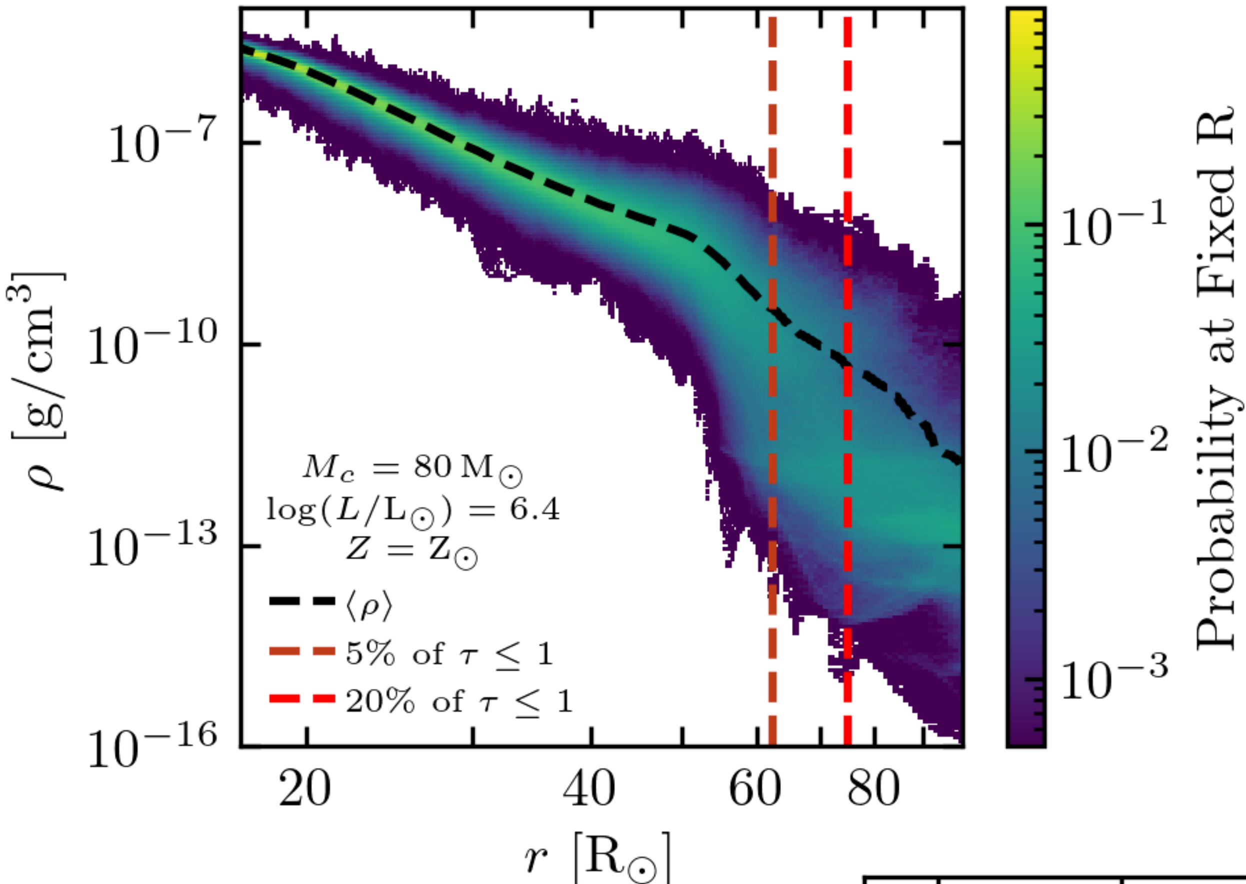


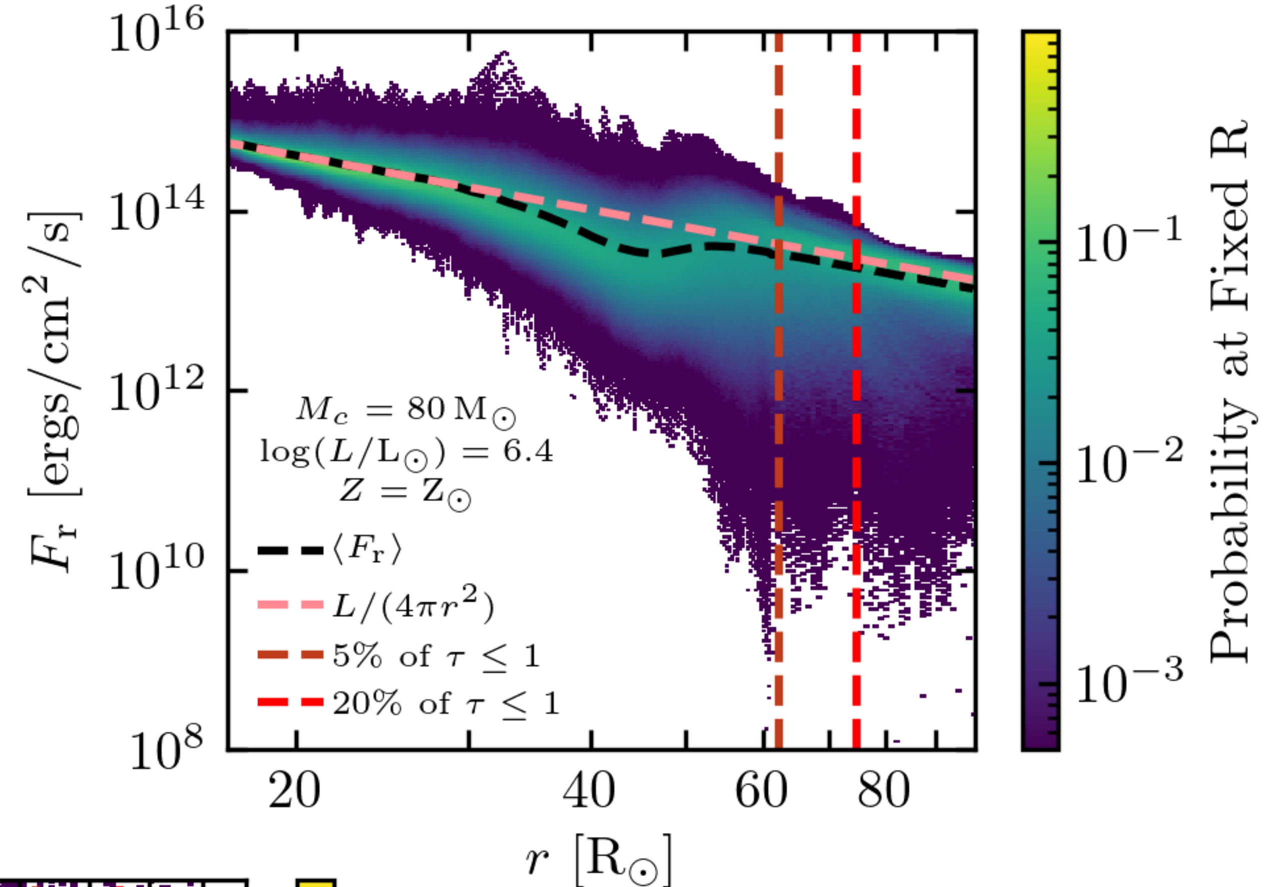
Schultz+ 2020

$$\tau_{1\mathrm{D}}(r) = \int_r^{r_{max}} \langle\kappa(r')\rangle\langle\rho(r')\rangle dr'$$

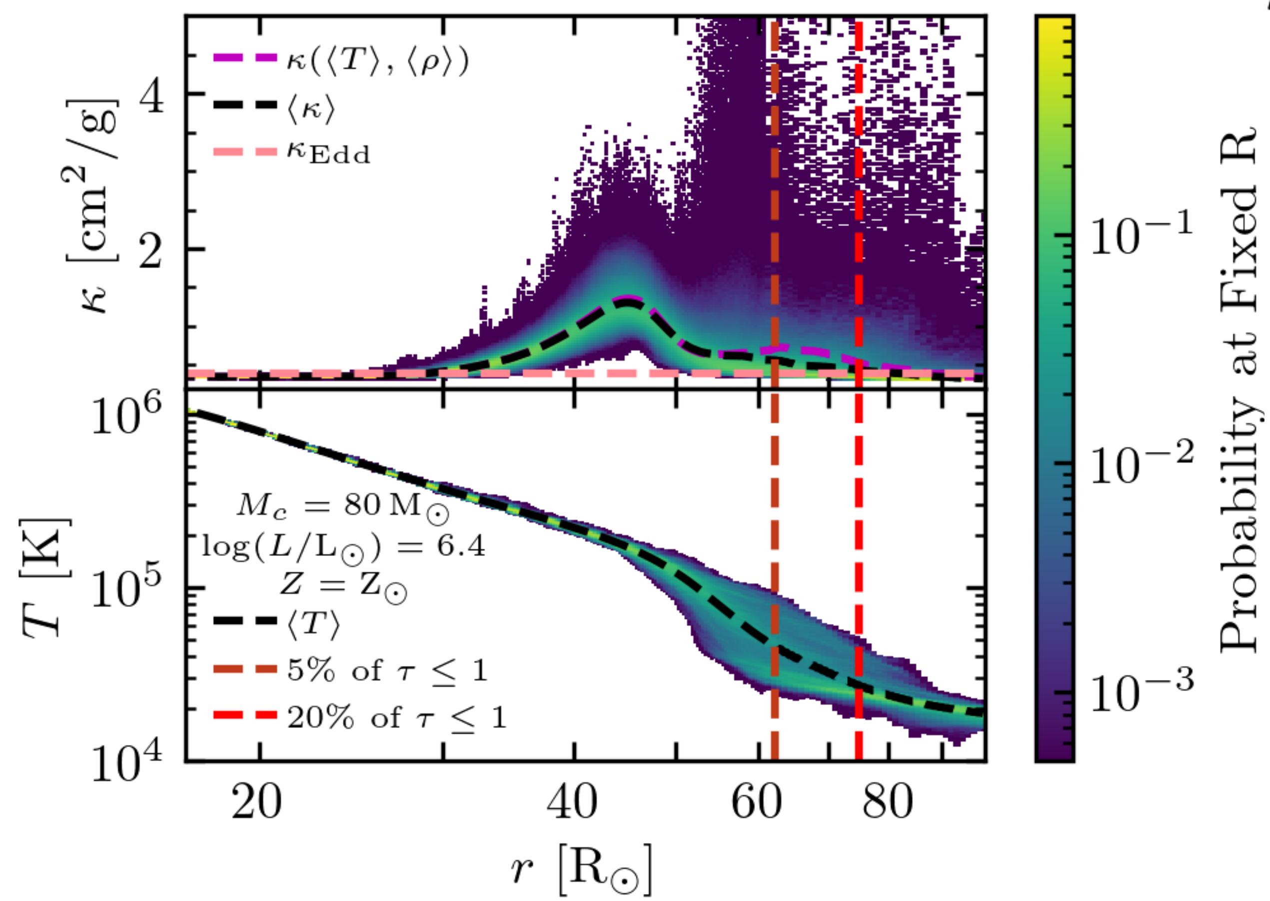
$*\,\tau$ is calculated along radial lines of sight only

T19L6.4: Spatial Variability





$$\kappa_{\mathrm{Edd}} = \frac{4\pi G M_c c}{L}$$



Schultz+ 2020

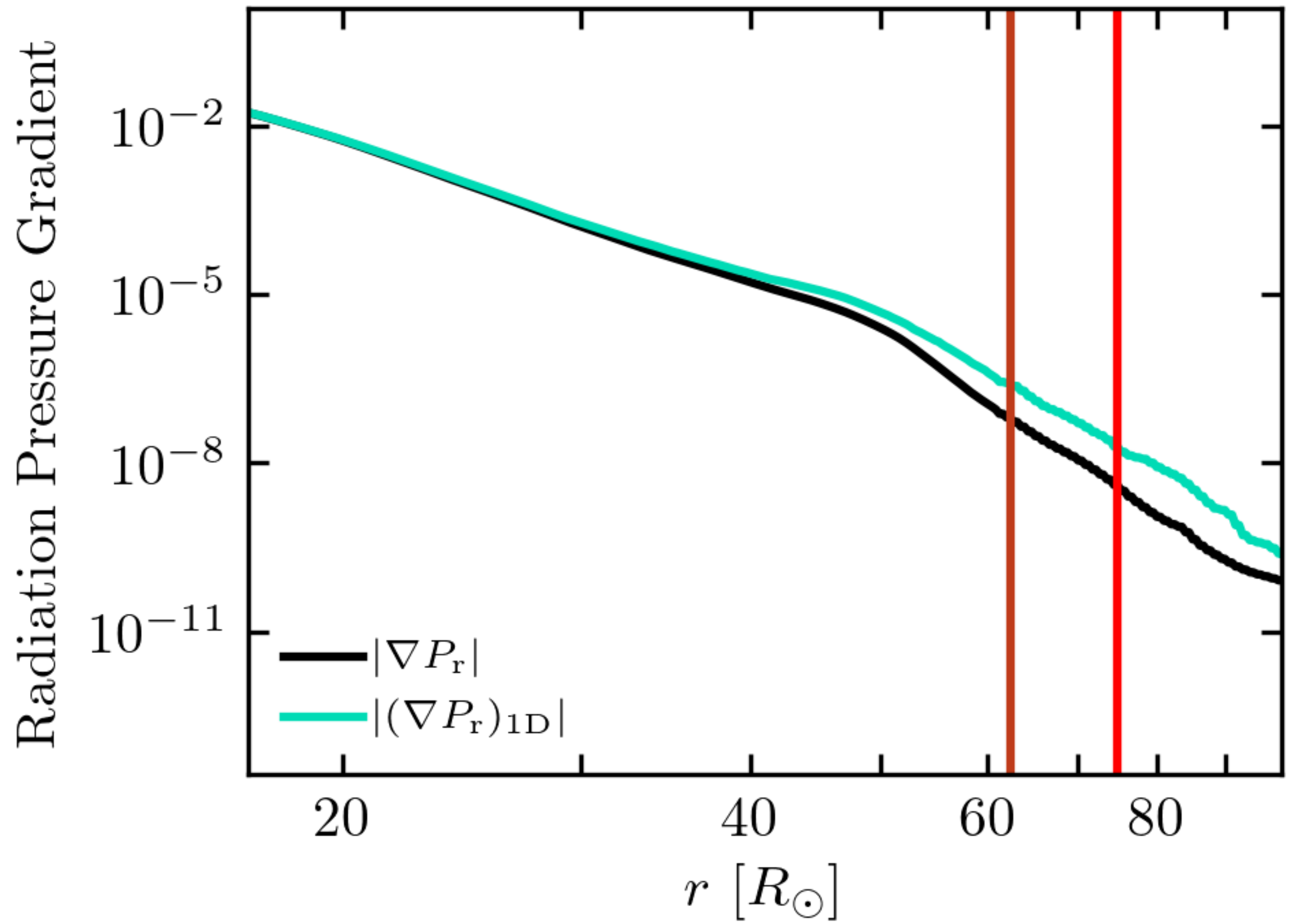
Correlations Impact ∇P_r

$$\nabla P_r = \frac{-1}{c}\langle \kappa F_r \rho \rangle$$

$$(\nabla P_r)_{1D} = \frac{-1}{c}\langle \kappa \rangle \langle F_r \rangle \langle \rho \rangle$$

From spatial variability,

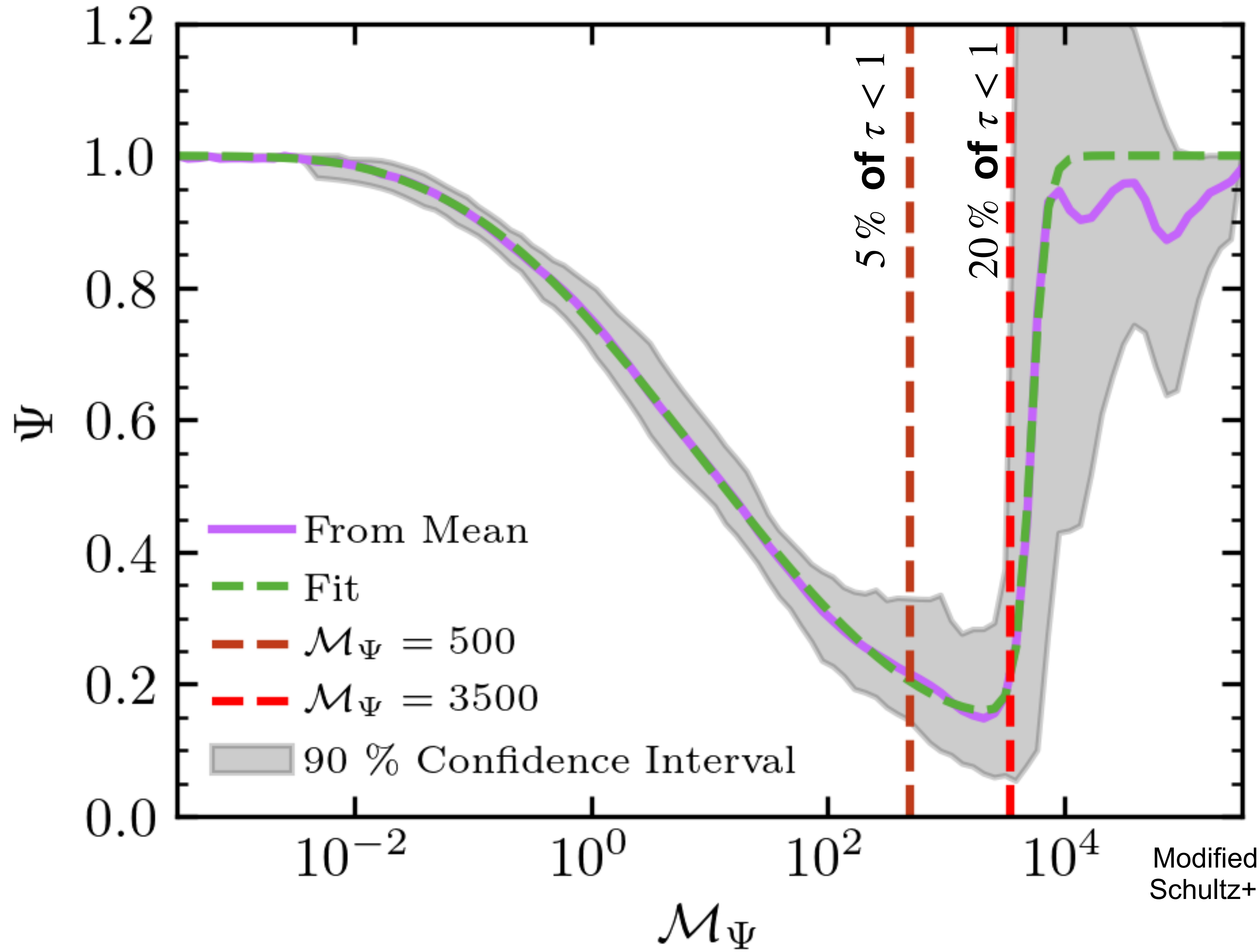
$$\nabla P_r \approx \frac{-1}{c}\langle \kappa \rangle \langle F_r \rho \rangle$$



Define a quantity Ψ such that $\nabla P_r \approx (\nabla P_r)_{1D}\Psi$

$$\Psi \equiv \frac{\langle F_r \rho \rangle}{\langle F_r \rangle \langle \rho \rangle}$$

Ψ in T19L6.4 and T9L6.2



Modified from Schultz+ 2020

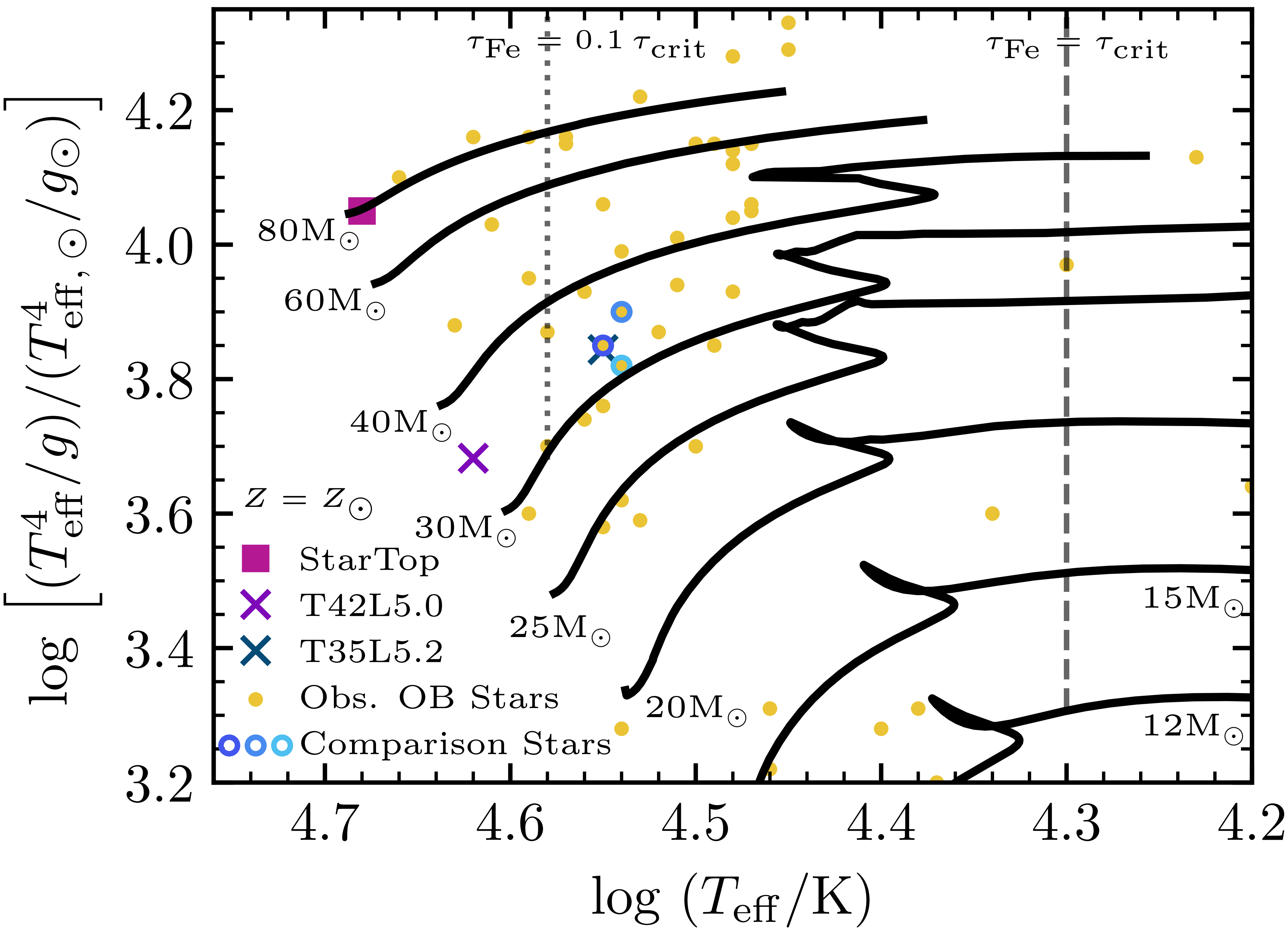
$\mathscr{M}_\Psi = f(L, T, r)$ **is analogous to radius**

See Owocki & Sundqvist 2018 and references there-in for more on porosity

- **Porosity is important near the surface of massive stars**
- **Decreased pressure support counteracted by turbulent pressure**

Box Models

Schultz+ in press



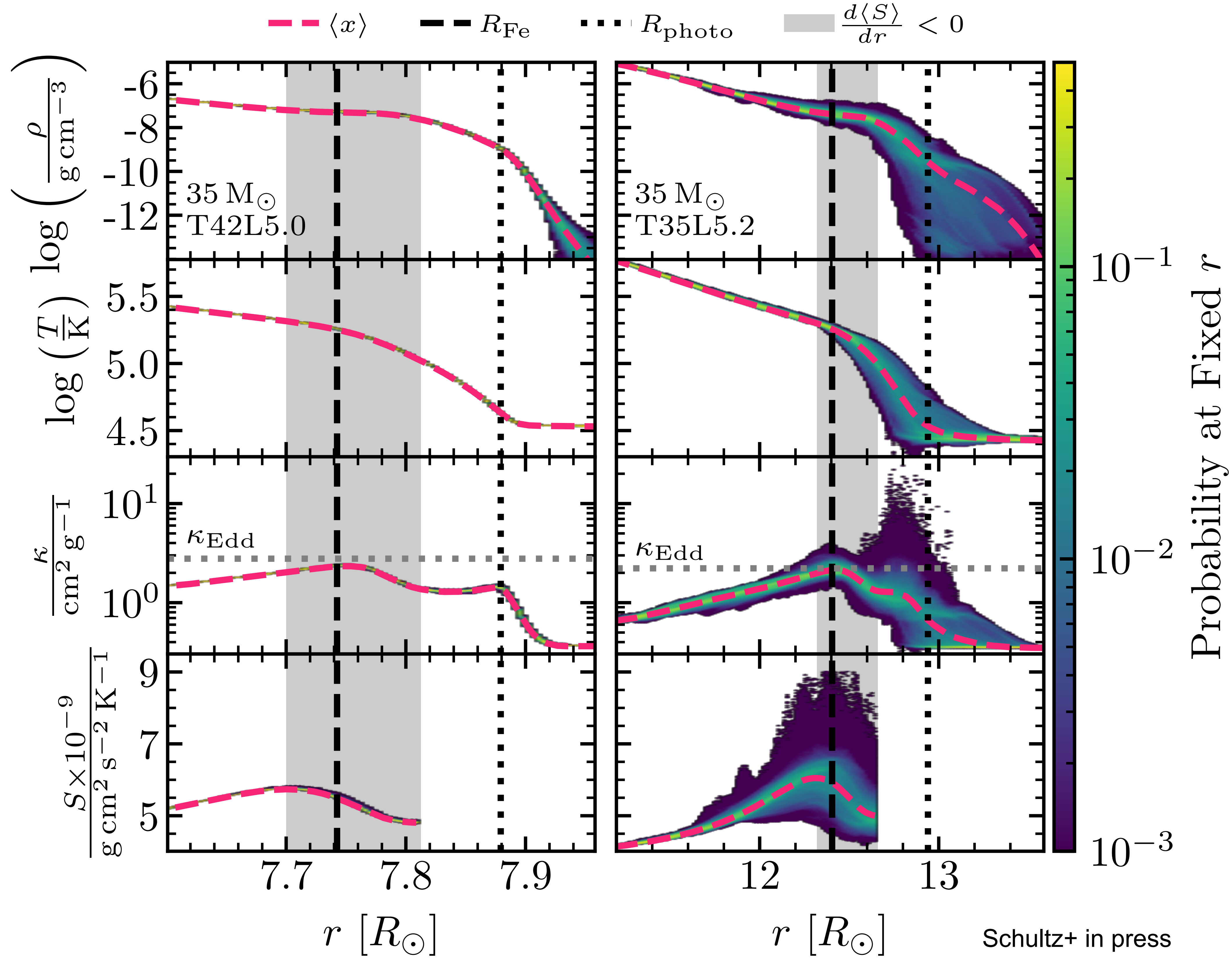
T42L5.0 (ZAMS)
35 solar masses
~8 solar radii

$\tau_{\rm Fe} \approx 0.01\tau_{\rm crit}$

T35L5.2 (mid-MS)
35 solar masses
~13 solar radii

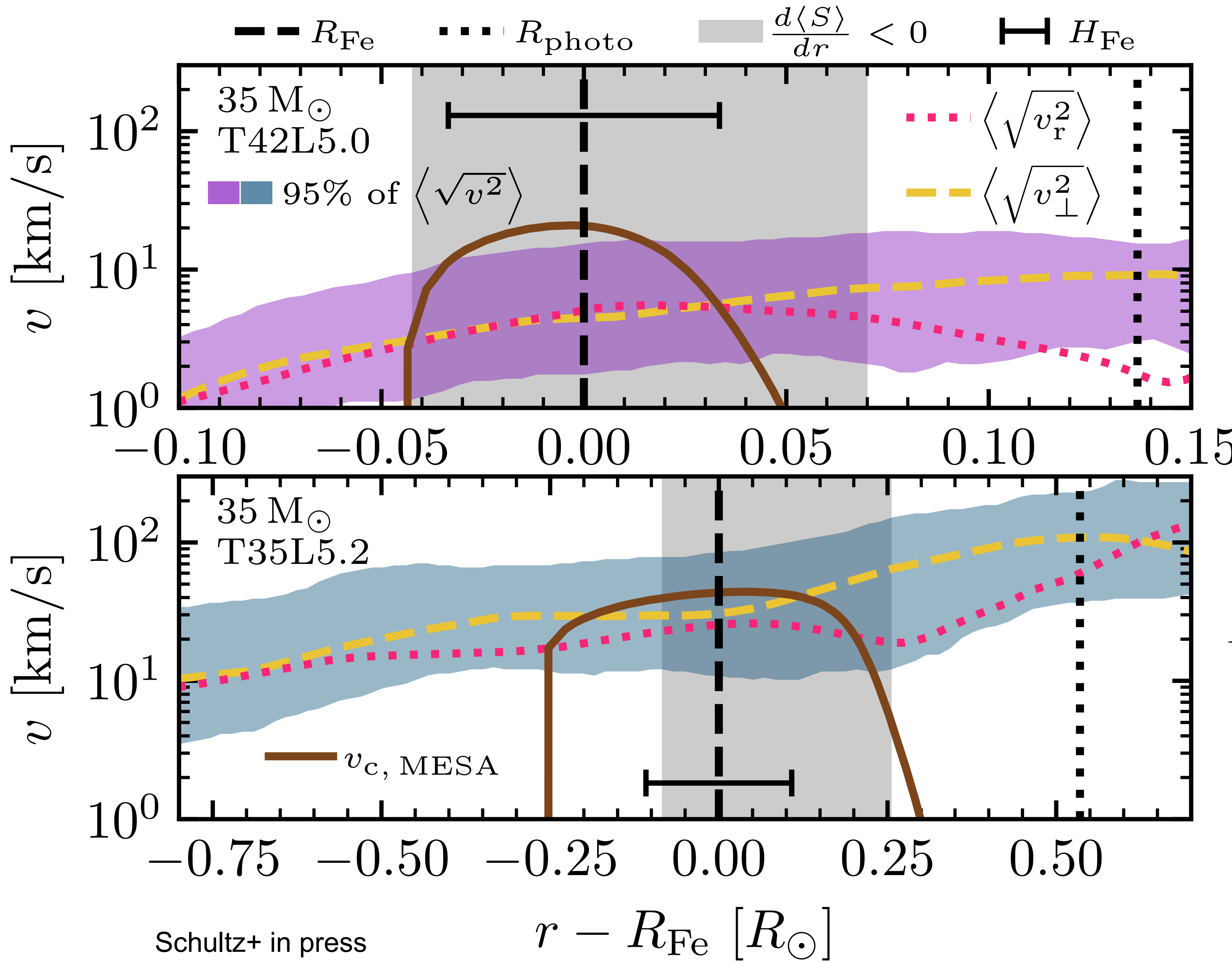
$\tau_{\rm Fe} \approx 0.2\tau_{\rm crit}$

Top Model Spatial Variability



Schultz+ in press

O Star Turbulent Surface Velocities



35 $M_\odot$ **ZAMS**

$v_{\rm surf} \approx 10\,{\rm km\,s^{-1}}$

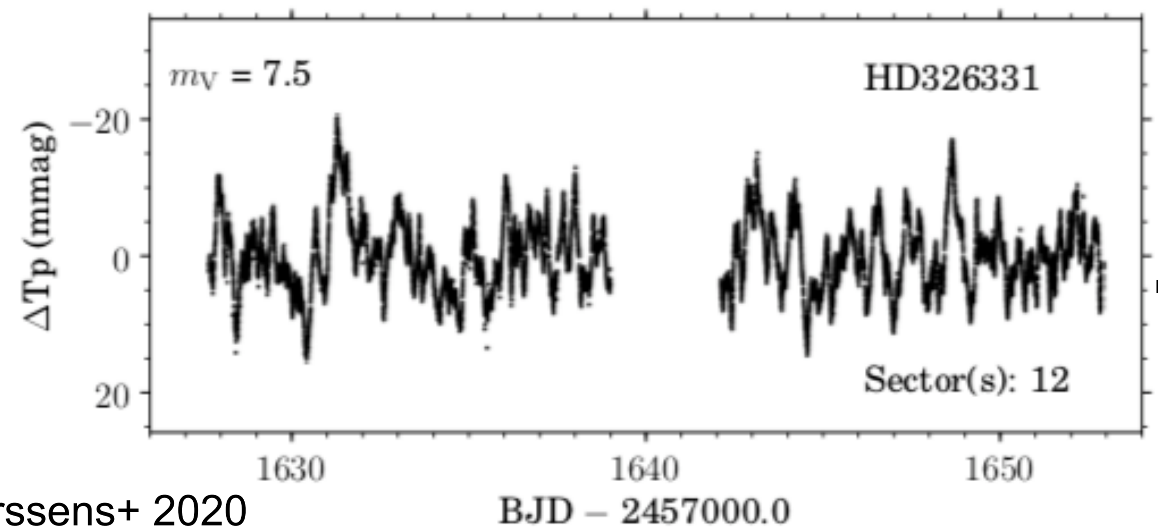
35 $M_\odot$ **mid-MS**

$v_{\rm surf} \approx 100\,{\rm km\,s^{-1}}$

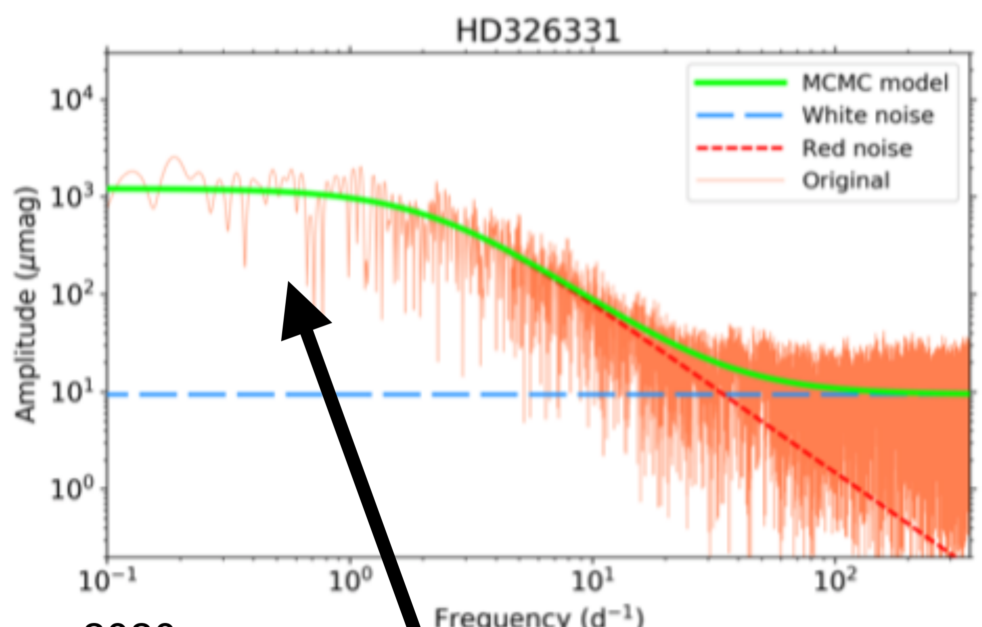
Schultz+ in press

- Velocities not confined sub-surface convection zone in 3D
- Convective fluxes carry small amount of energy

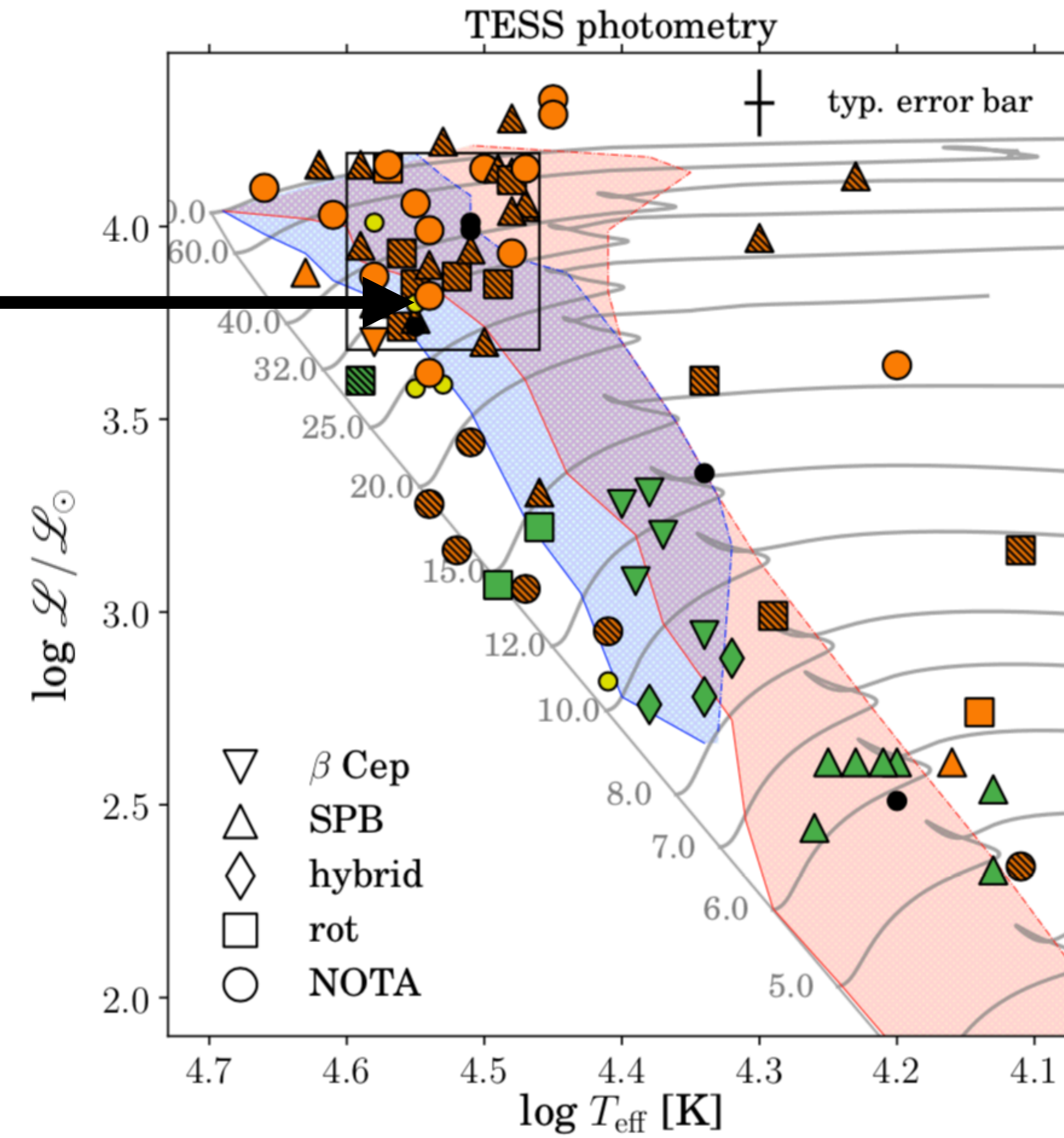
TESS Characterizations of Massive Stars



Burssens+ 2020



Bowman+ 2020

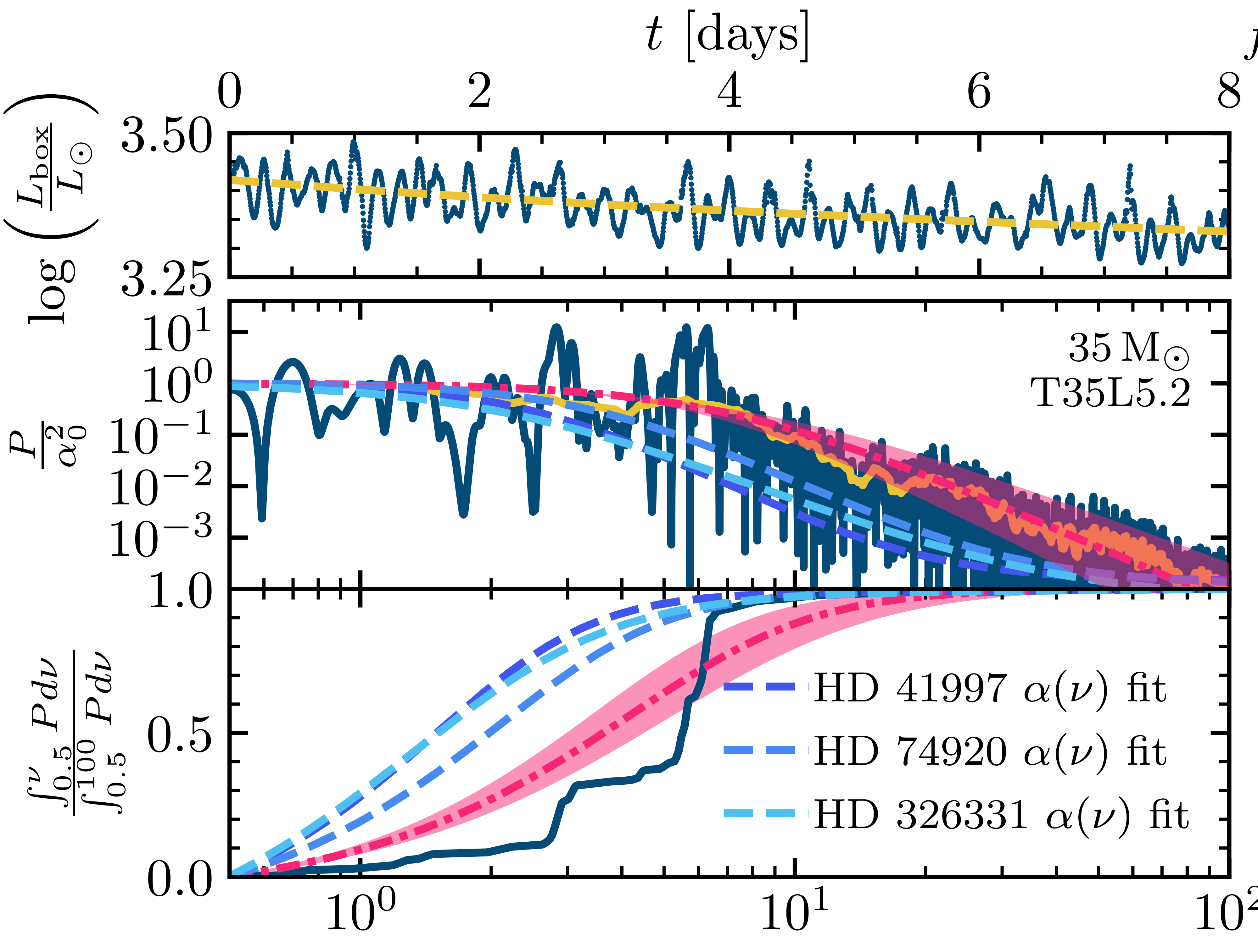


Burssens+ 2020

Stochastic Low-Frequency Variability: 3 possible causes

1. Internal gravity waves — e.g. Aerts+ 2009, Simón-Días & Herrero 2010, 2014, 2017, Edelmann+ 2019, Bowman+ 2020
2. Near surface convective zones — e.g. Lecoanet & Quataert 2013, Grassitelli+ 2015, Cantiello+ 2021, Schultz + in press
3. Wind interactions — e.g. Moffat+ 2008, David-Uraz+ 2017, Aerts+ 2018, Simón-Díaz+ 2018, Krticka & Feldmeier 2018,

Stochastic Low-Frequency Variability



Schultz+ in press

$$f(\nu) = \frac{\alpha_0}{\left(1 + \left(\frac{\nu}{\nu_{\mathrm{char}}}\right)^{\gamma}\right)}$$

Model:

$\alpha_0 \approx 0.23\,\%$

$\alpha_{0,\mathrm{full\ star}} \approx 0.03 - 0.2\,\%$

$\nu_{\mathrm{char}} \approx 7$ **days**$^{-1}$

$\gamma \approx 1.9$

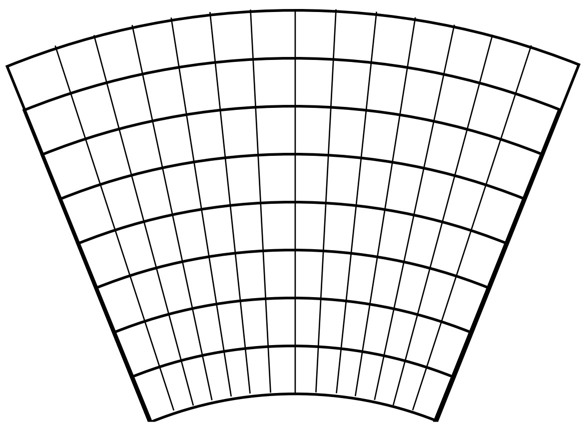
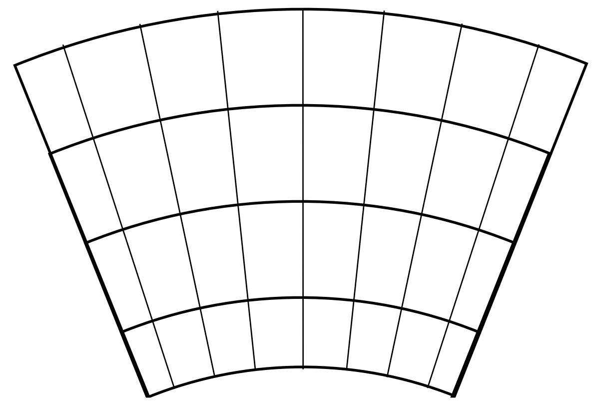
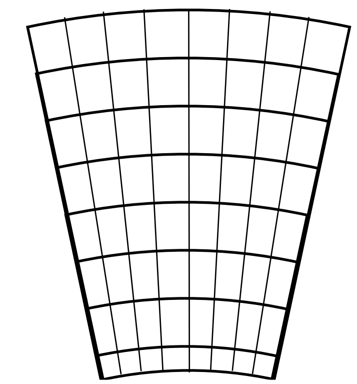
Observations:

$\alpha_{0,\mathrm{full\ star}} \approx 0.03 - 0.1\,\%$

$\nu_{\mathrm{char}} \approx 2.2 - 3.7$ **days**$^{-1}$

$\gamma \approx 1.7 - 2.3$

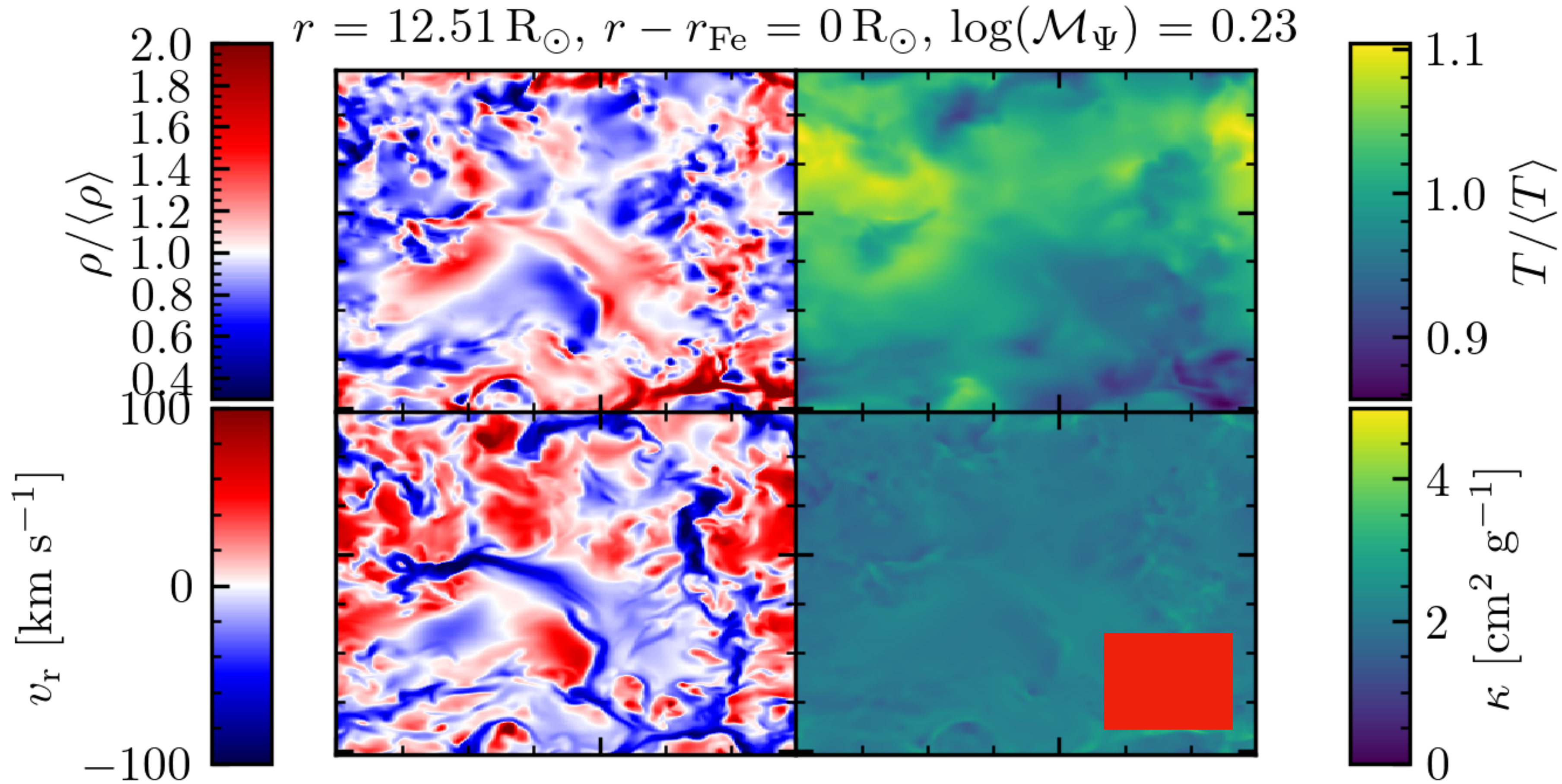
Brief Resolution Study

T35L5.2	Lower Resolution	Smaller Box
		

	Lower Resolution	Smaller Box
$v_{\rm surf}$ **characteristics**	✓	✓
QPO frequencies	✓	✗ (✓)

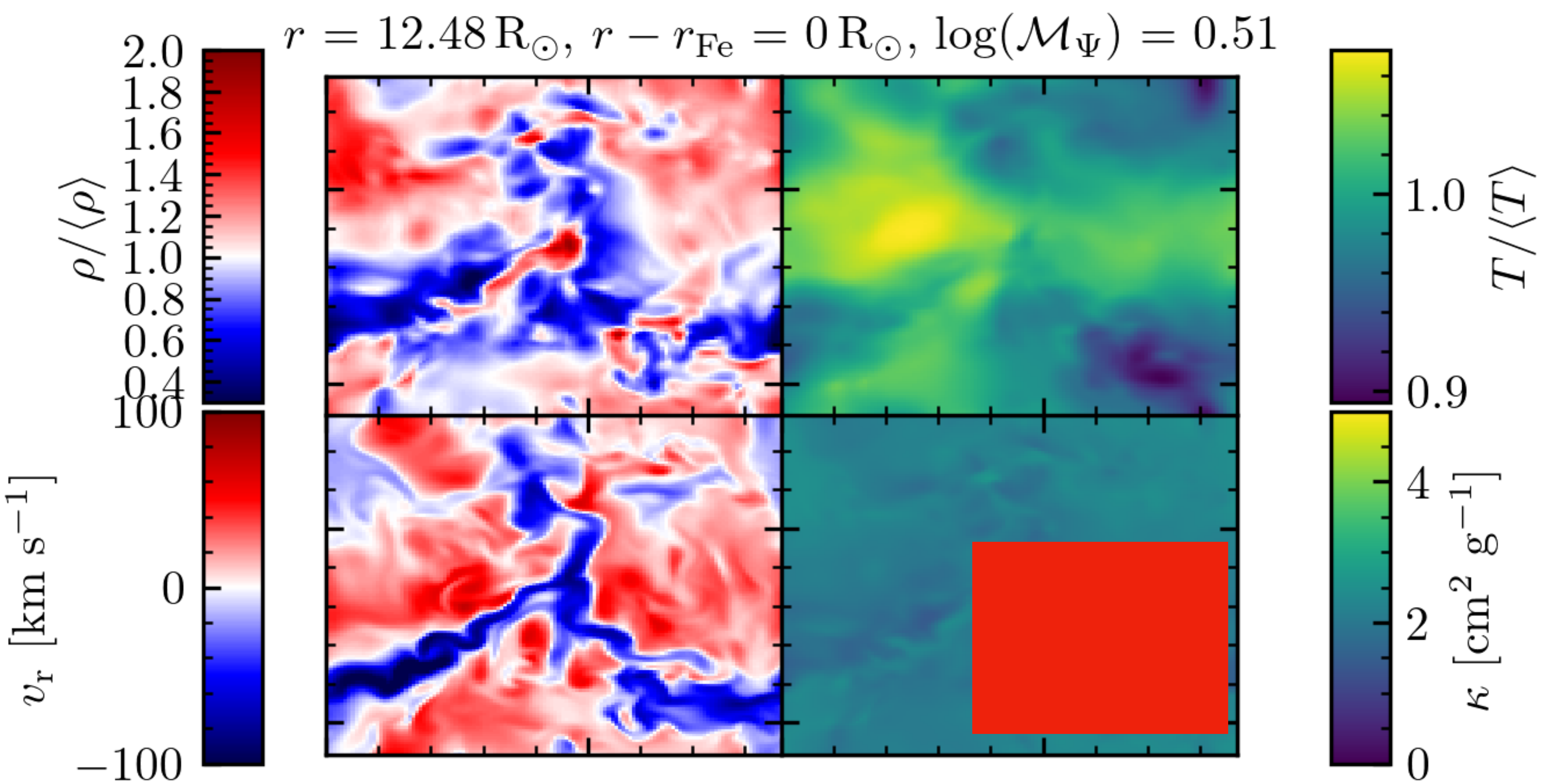
T35L5.2	Lower Resolution	Smaller Box
$\alpha_0 \approx 0.23\,\%$	$\alpha_0 \approx 0.25\,\%$	$\alpha_0 \approx 0.16\,\%$
$\nu_{\rm char} \approx 7\,{\rm days}^{-1}$	$\nu_{\rm char} \approx 7\,{\rm days}^{-1}$	$\nu_{\rm char} \approx 10\,{\rm days}^{-1}$
$\gamma \approx 1.9$	$\gamma \approx 1.9$	$\gamma \approx 1.9$

Model Cross-Sections



T35L5.2

Many plumes
Can be extrapolated to full star



Smaller Box

Few plumes
Plumes are correlated so cannot extrapolate

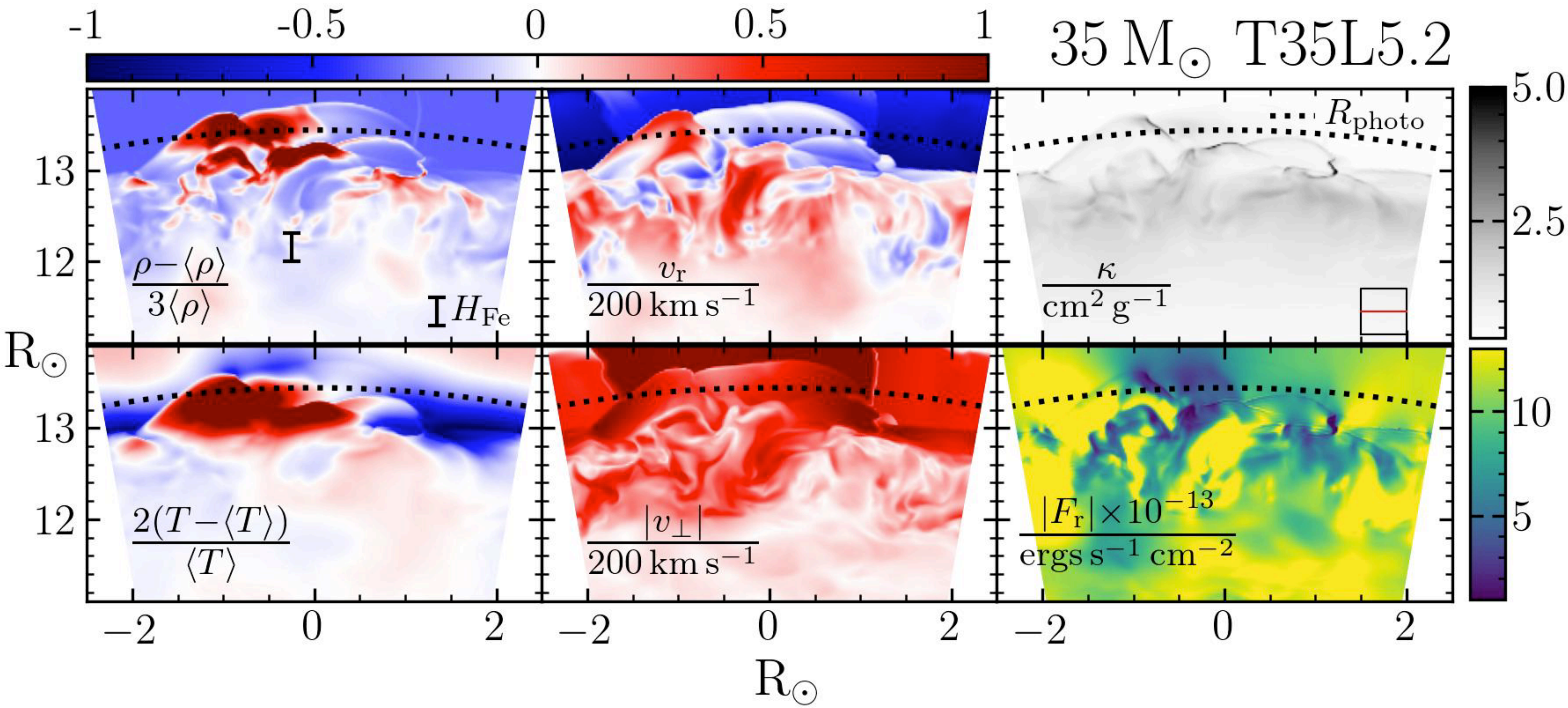
Main Takeaways

- Porosity/clumping is important at the surface of massive stars
- Turbulent motion from near-surface CZs persists to the surface of massive stars at $|v_{\rm surf}| \sim 100\,{\rm km\,s^{-1}}$
- Near-surface CZs can induce SLFV resembling recent TESS observations

Future Outlook

- More models running
  - Mid-MS $35\,{\rm M_\odot}$ with lower metallicity
  - $13\,{\rm M_\odot}$ TAMS model
- Investigate line effects in opacity
- How would turbulent pressure affect 1D model evolution?

Thank you!



35 M⊙ T35L5.2
-1
-0.5
0
0.5
1
5.0
2.5
10
5
$R_{\rm photo}$
$\frac{\rho-\langle\rho\rangle}{3\langle\rho\rangle}$
$H_{\rm Fe}$
$\frac{v_{\rm r}}{200\,{\rm km\,s^{-1}}}$
$\frac{\kappa}{{\rm cm^2\,g^{-1}}}$
$\frac{2(T-\langle T\rangle)}{\langle T\rangle}$
$\frac{|v_\perp|}{200\,{\rm km\,s^{-1}}}$
$\frac{|F_{\rm r}|\times10^{-13}}{{\rm ergs\,s^{-1}\,cm^{-2}}}$
13
12
$R_\odot$
−2
0
2
$R_\odot$

Backup

Choosing Model Independent Variable

For radiation pressure dominated system, we chose

$$F_{\mathrm{c,\,Rad\,dominant}} = (E_{\mathrm{r}})\, v_{\mathrm{c}}$$

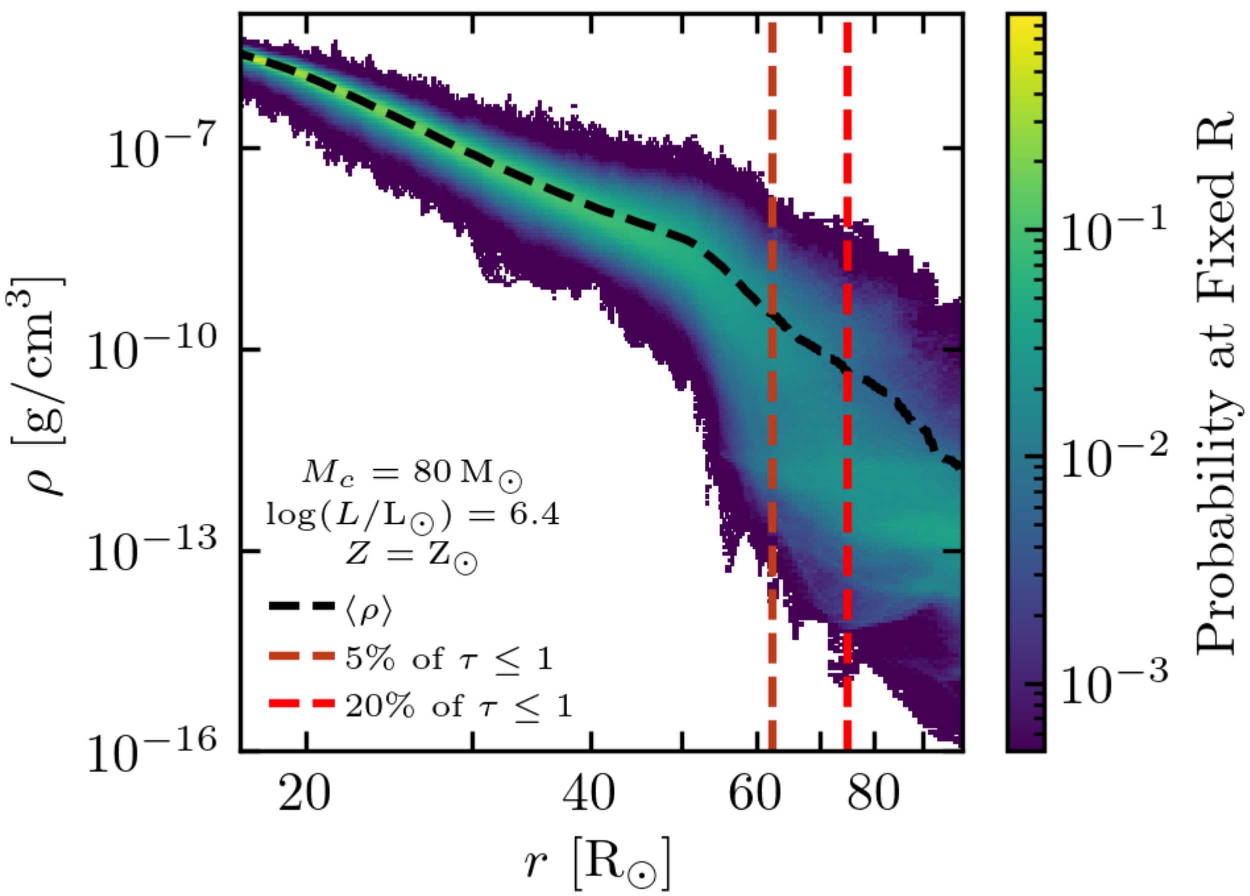
We then choose the velocity needed for this flux to carry the entire luminosity

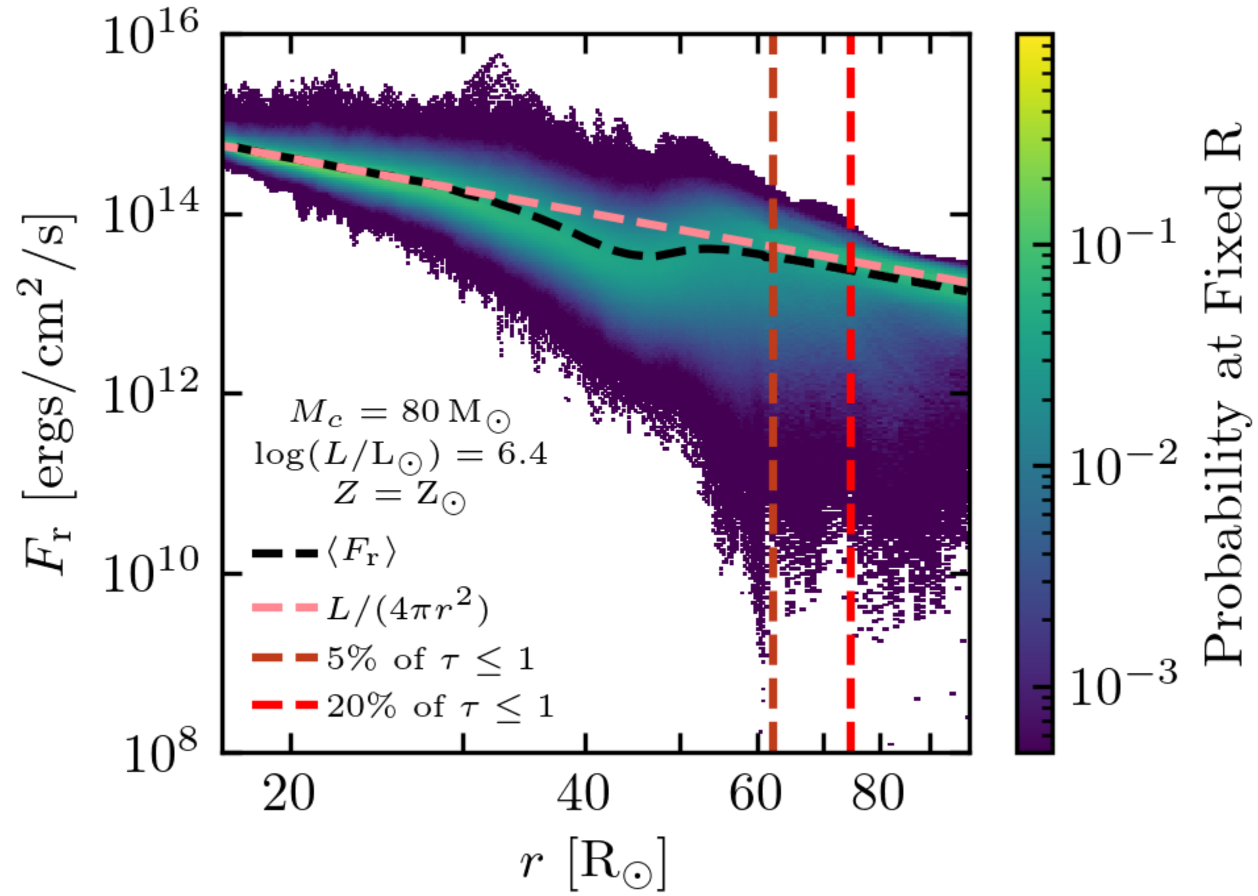
$$\frac{L}{4\pi r^2} \equiv E_{\mathrm{r}} v_{\mathrm{L}} \text{ or } v_{\mathrm{L}} \equiv \frac{L}{4\pi r^2 E_{\mathrm{r}}} = \frac{L}{4\pi r^2 a T^4}$$

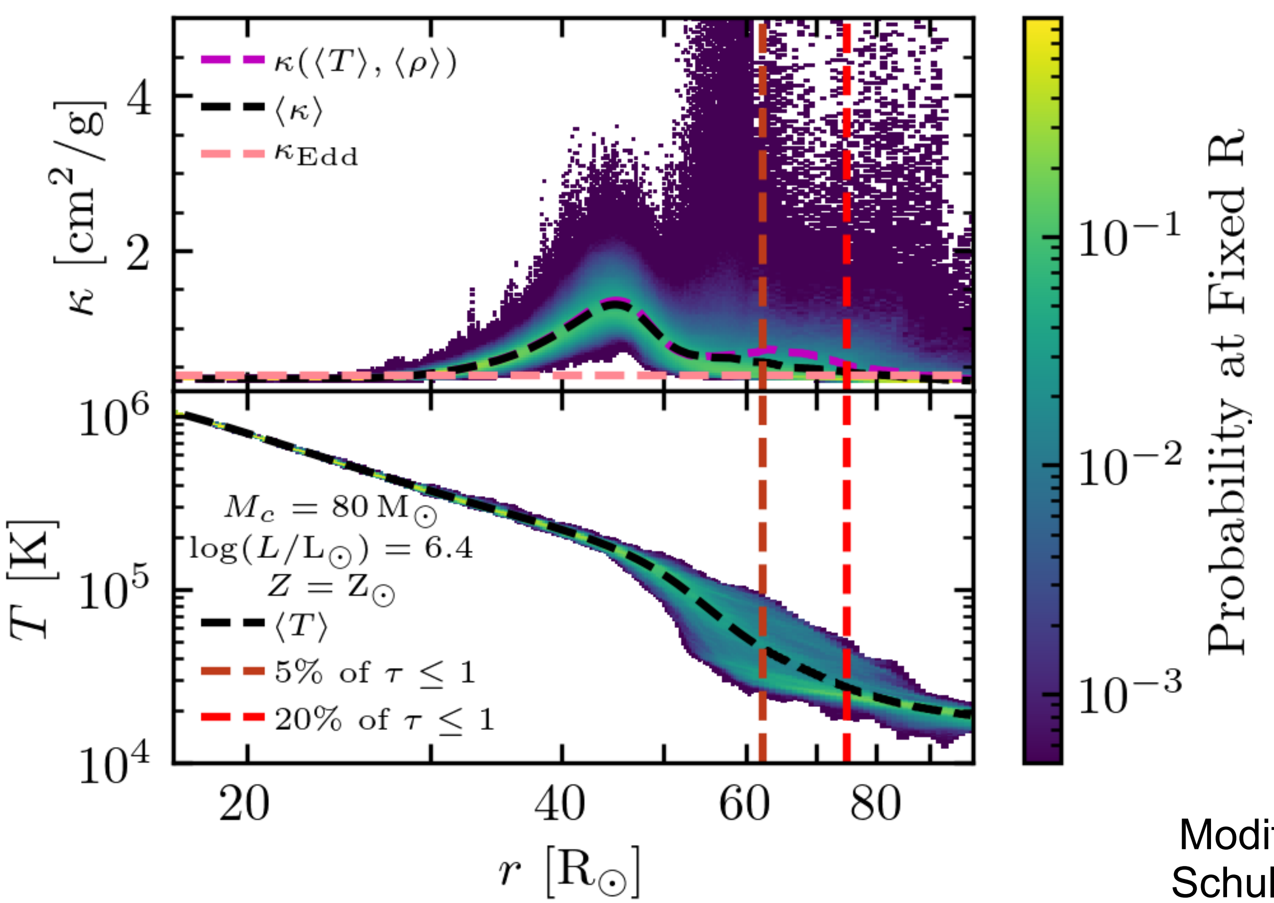
Dividing by the isothermal gas sound speed, we arrive at a pseudo-Mach number

$$\mathscr{M}_{\Psi}(r) \equiv \frac{v_{\mathrm{L}}(r)}{\sqrt{\frac{k_{\mathrm{B}} T(r)}{\mu m_{\mathrm{p}}}}} = \frac{L}{4\pi r^2 a T^{4.5}(r)} \left(\frac{\mu m_{\mathrm{p}}}{k_{\mathrm{B}}}\right)^{1/2}$$

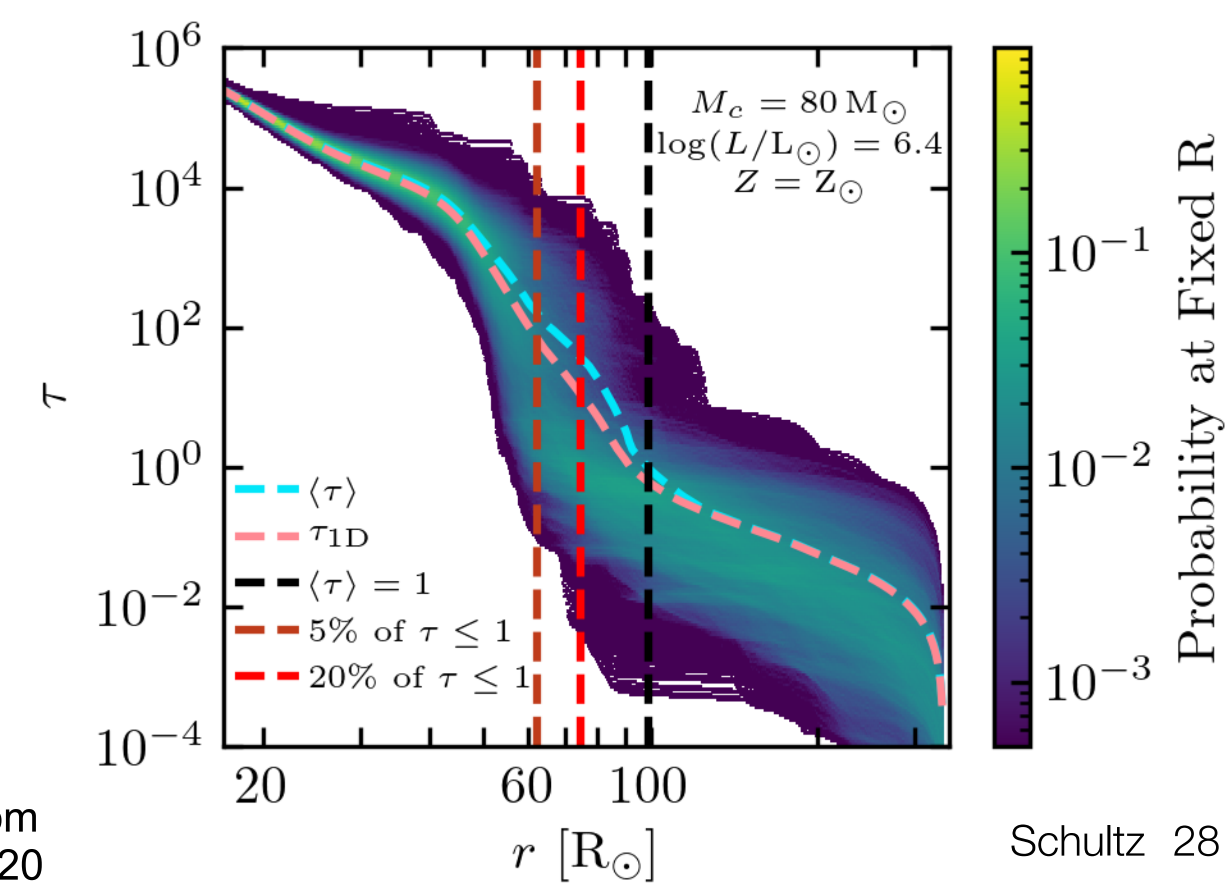
Are There Correlations?



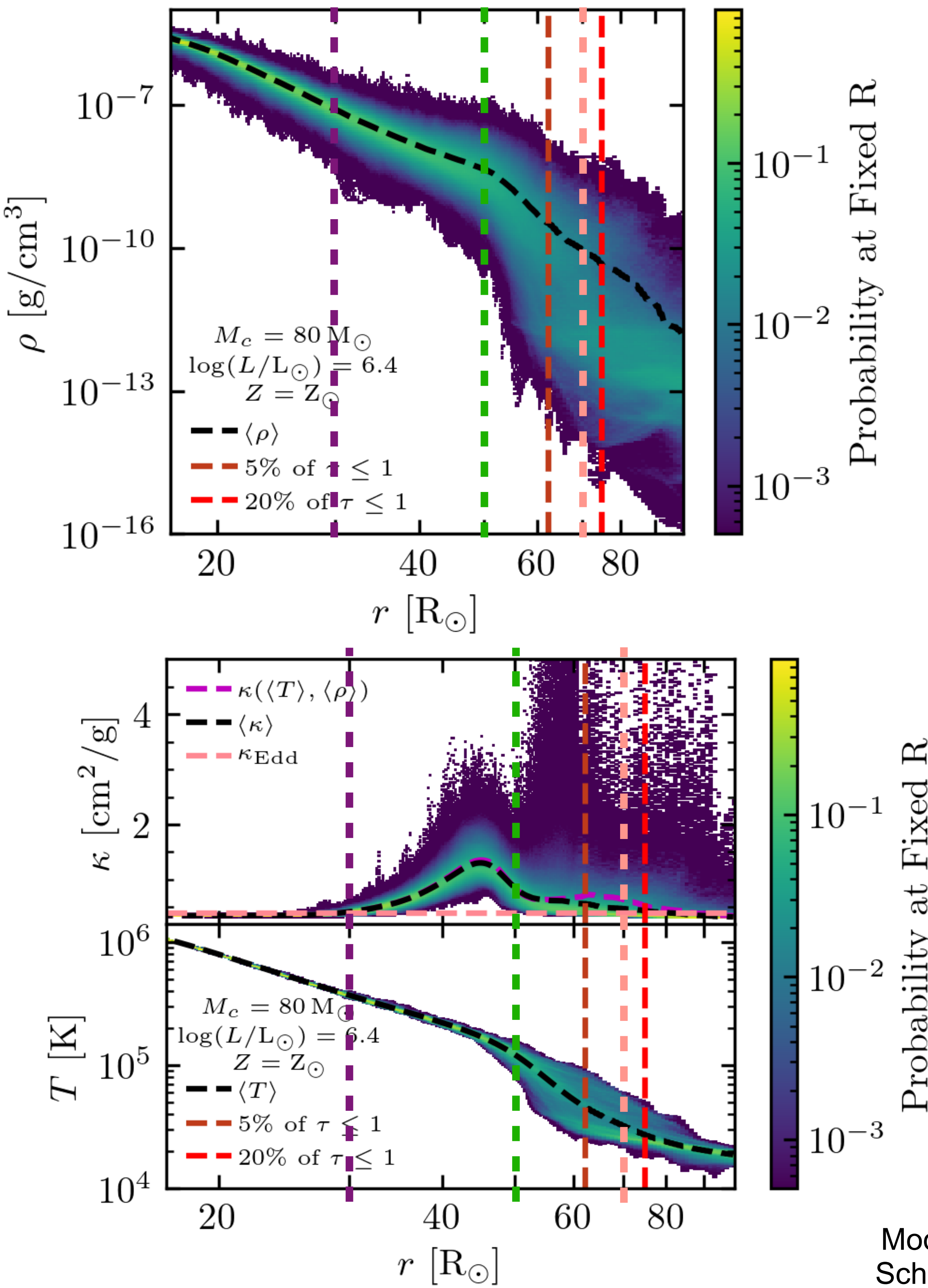




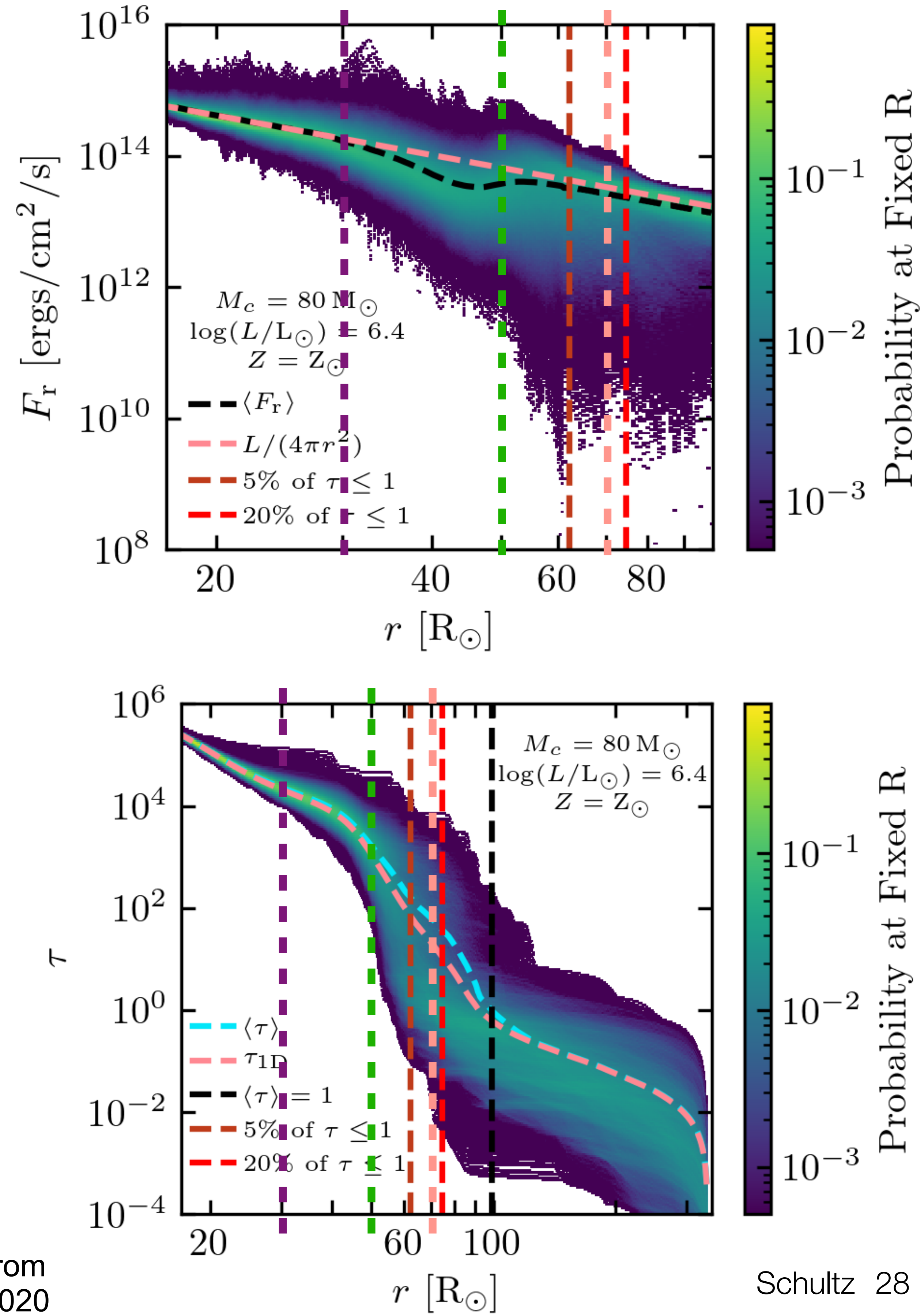
Modified from Schultz+ 2020



Are There Correlations?

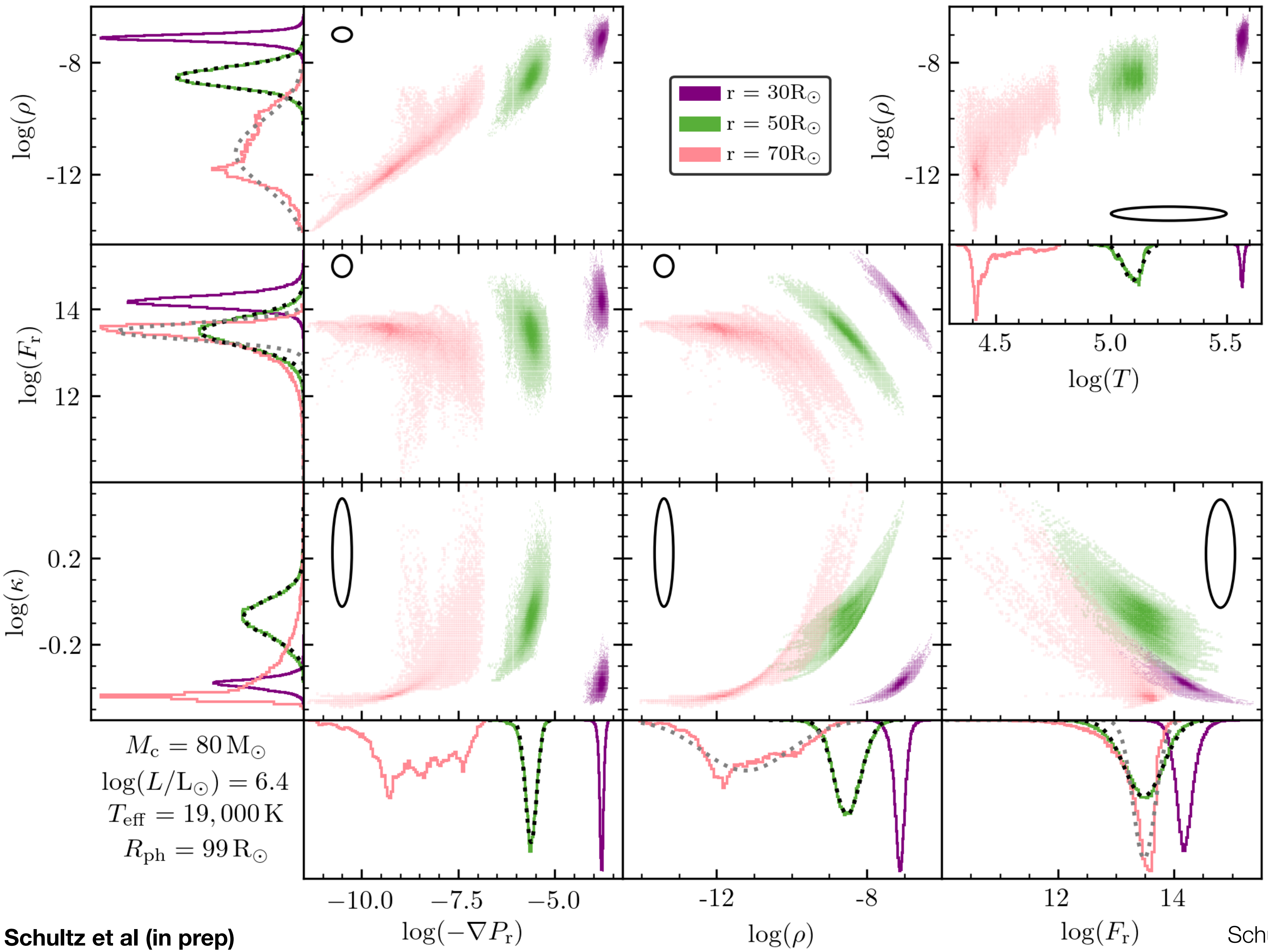


Modified from Schultz+ 2020



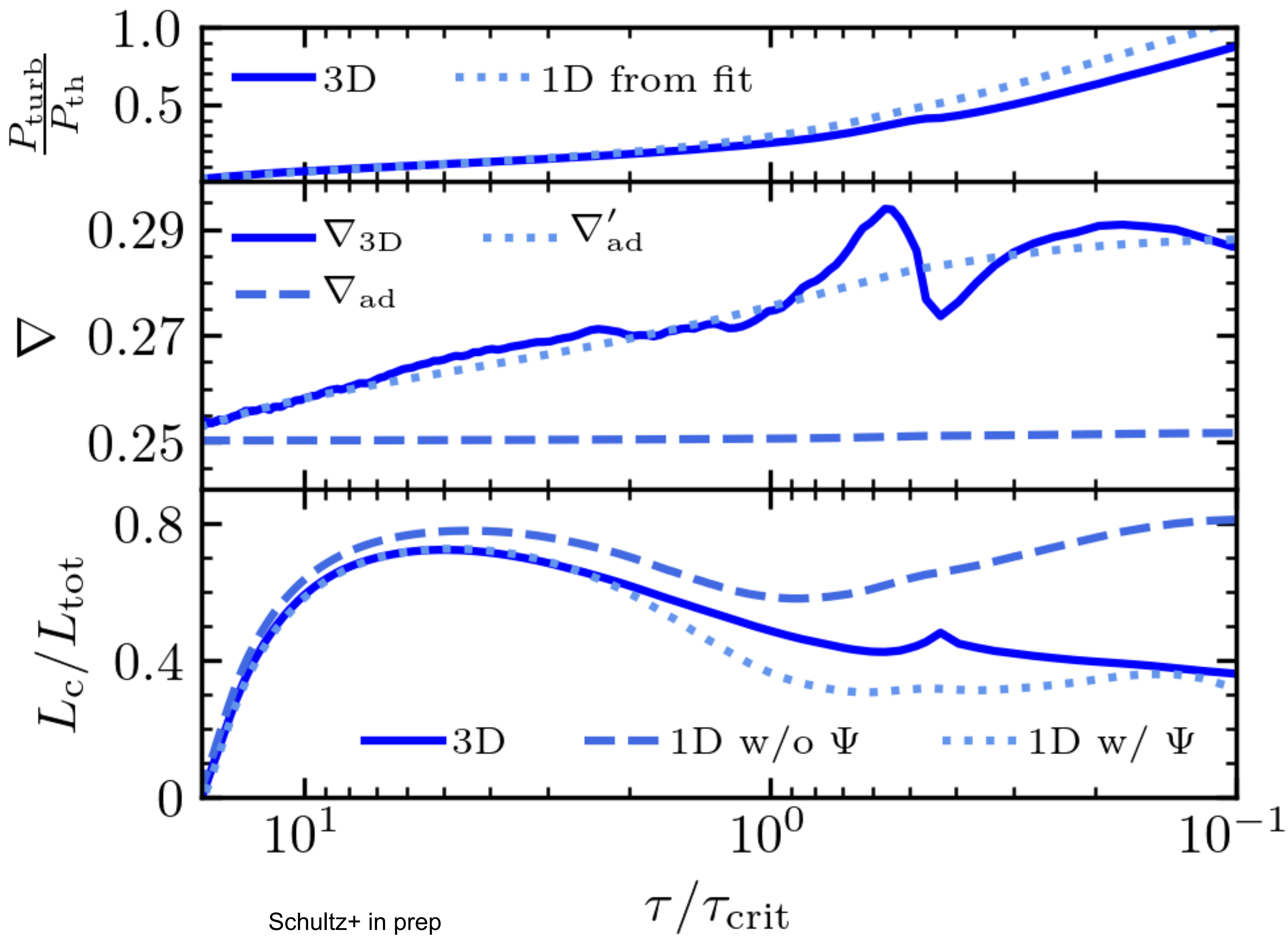
Correlations

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma_{\ln(x)}} \exp\left(-\frac{(\ln(x) - \langle \ln(x) \rangle)^2}{2\sigma^2_{\ln(x)}}\right)$$



Schultz et al (in prep)

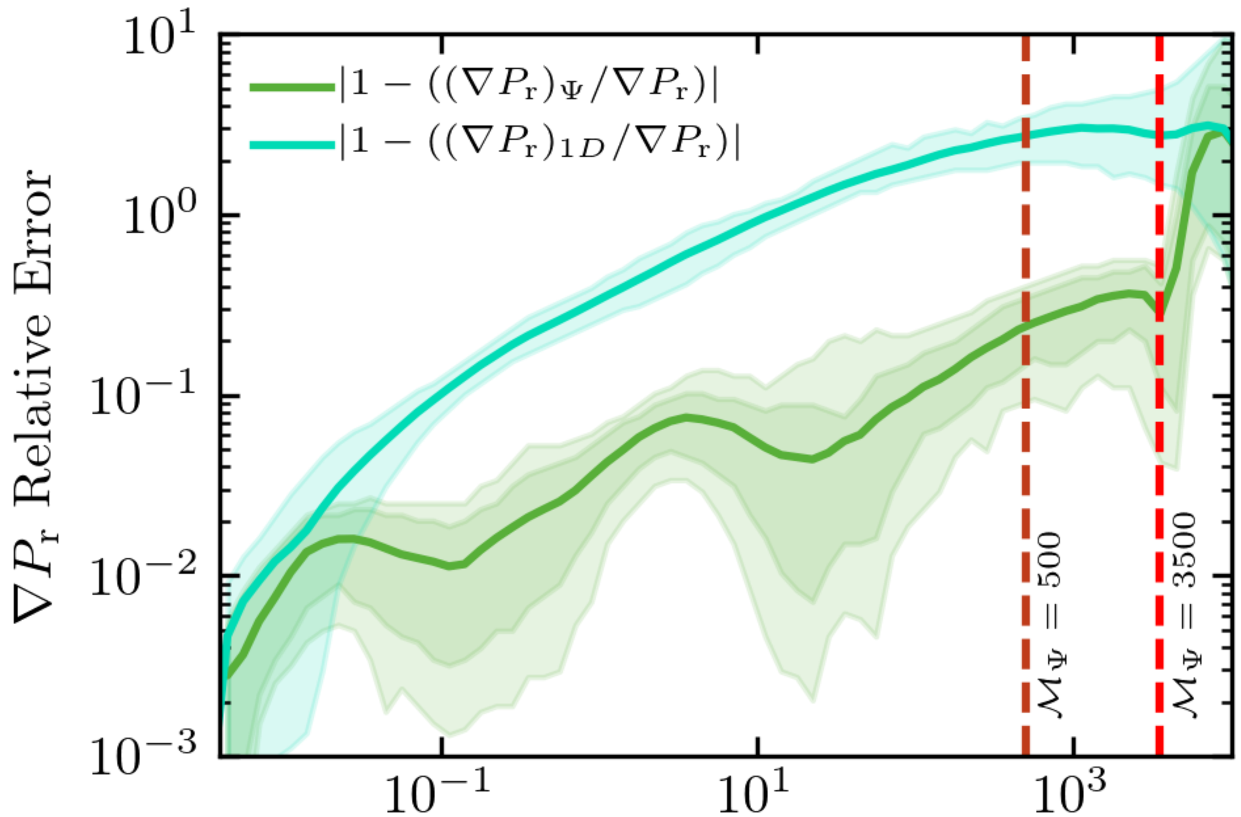
Turbulent pressure in grad



Schultz+ in prep

Global Models Shed Light on Turbulent Convection

Turbulence reduces radiation pressure gradient

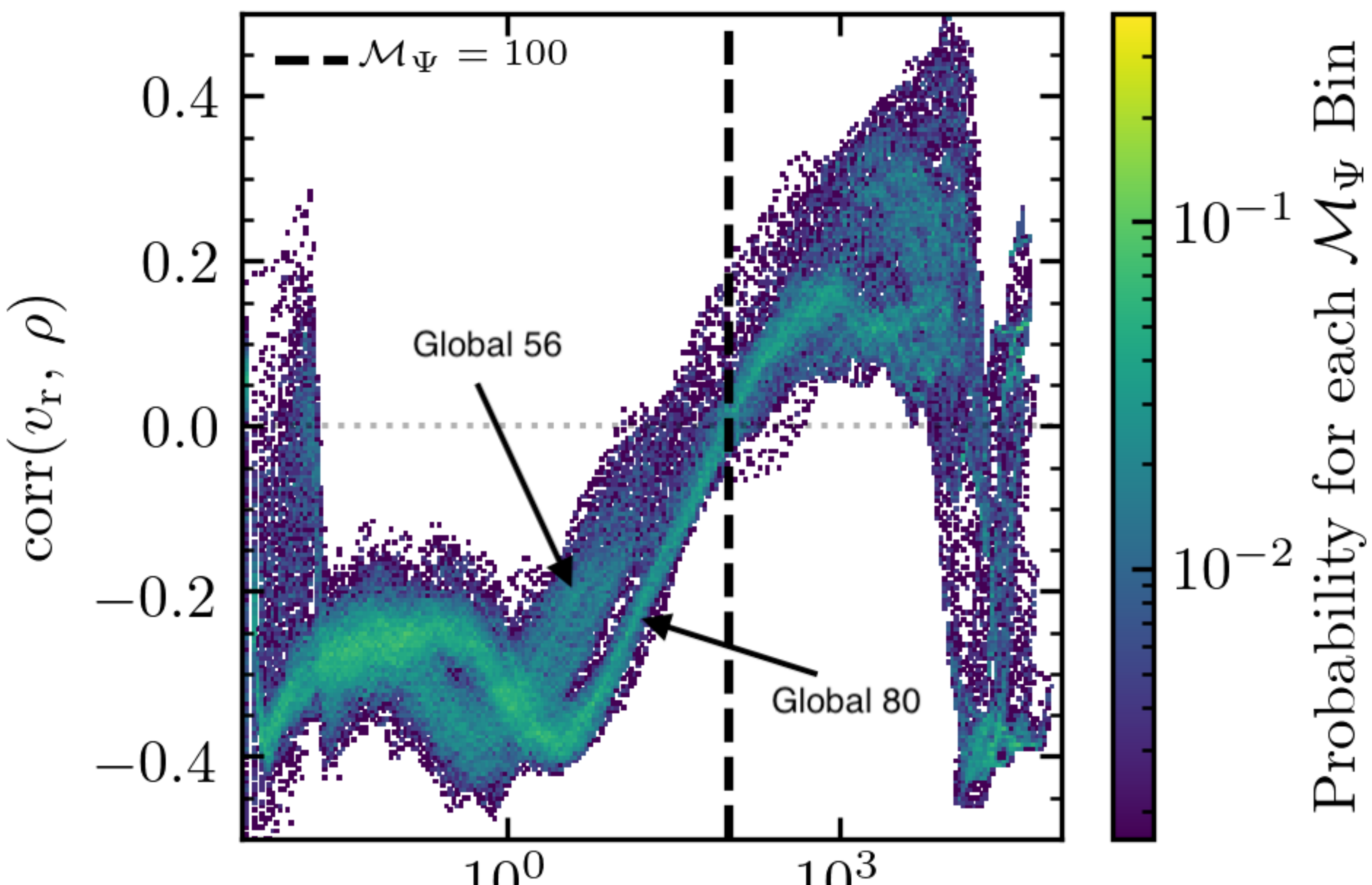


Stellar interior $\mathcal{M}_\Psi$ Surface

Schultz, Bildsten, Jiang (2020)

Two types of turbulence

MLT-like failed wind-like



Stellar interior $\mathcal{M}_\Psi$ Surface

Schultz et al (in prep)