PUSHING THE (MASSIVE STAR) ENVELOPE WITH STELLAR ENGINEERING

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MESA Down Under

University of Sydney 2024

OVERVIEW OF THE 3 “MINI”LABS

OVERVIEW OF THE LAB STRUCTURE:

- Minilab 1: The impact of “flux engineering” on the outer stellar structure
- Minilab 2: The impact of mixing length on stellar radius + local and global thermal timescales
- Minilab 3: Mass loss and the transition to stripped-envelope stellar structure

MINILAB 1: FLUX ENGINEERING

WHY ARE MASSIVE STARS HARD?

(PHYSICALLY AND NUMERICALLY)

STARS 101: HYDROSTATIC BALANCE WITH GAS PRESSURE

Let's get down to physics! We start with Hydrostatic Balance:

$$\rightarrow \frac{dP}{dr} = -\rho g, \text{ where } g(r) = \frac{Gm(r)}{r^2}$$

Within the star, m=total mass M, r=radius R, yielding:

$$\frac{P}{R} \sim \rho \frac{GM}{R^2}, \text{combine with ideal gas } P \approx \frac{\rho k_B T}{\mu m_p}$$

Yielding an approximate relation for the central temperature, T_c

$$k_{\mathrm{B}} T_c \approx \frac{GM\mu m_p}{R}$$ so, roughly, $T \propto M/R$

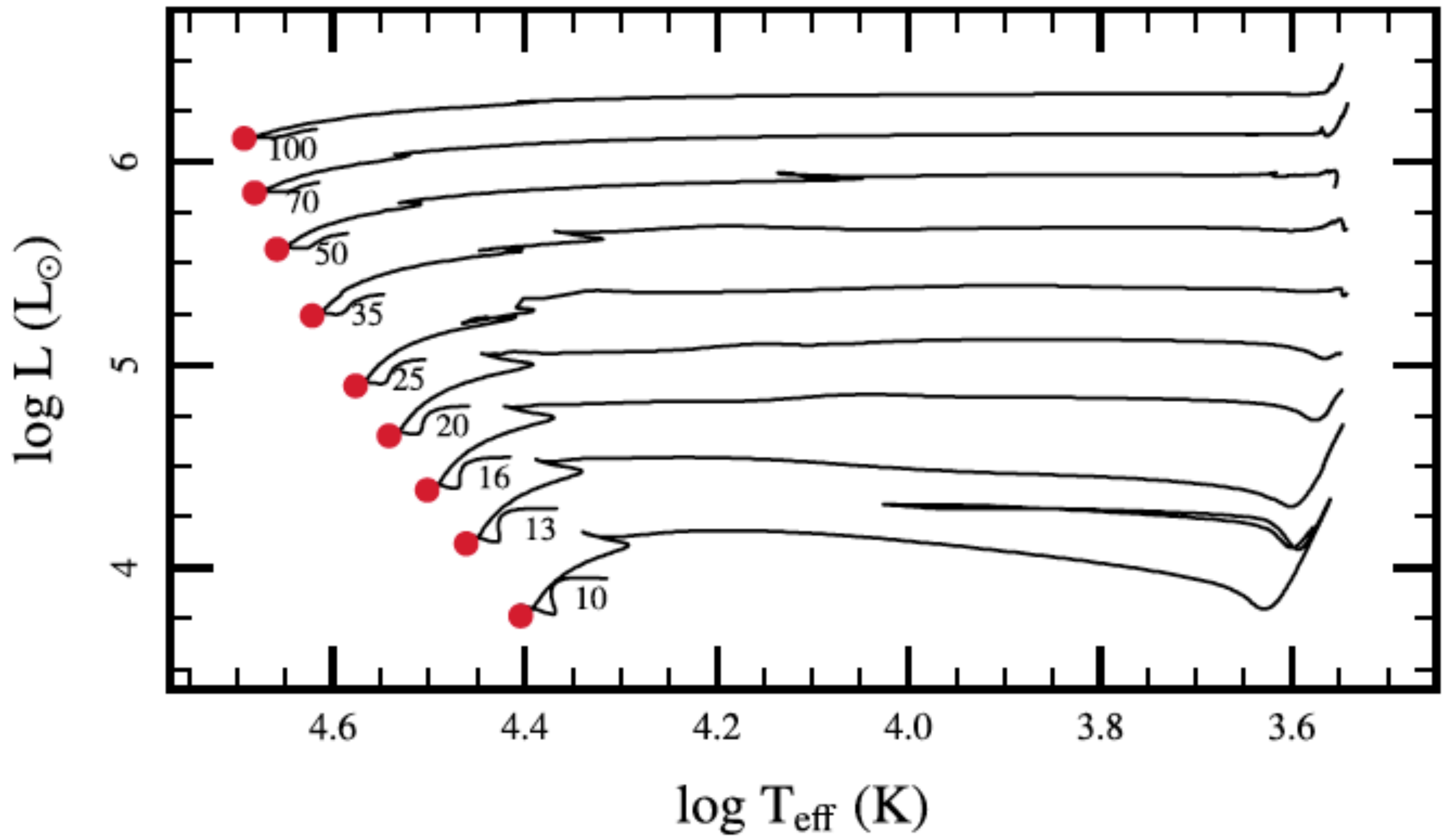
ESTIMATING THE STELLAR LUMINOSITY

Luminosity is determined by heat transport. For the diffusion of photons, we can guess:

$$F = -\frac{c}{3\kappa\rho}\frac{daT^4}{dr}$$

Where the last step assumed that the opacity, κ, is constant and we used the hydrostatic balance relations assuming only ideal gas pressure from the previous slide.

NEARLY CONSTANT L AS R CHANGES, + STRONG MASS DEPENDENCE



Slide from Lars Bildsten's 2019 MESA SS lecture

THE TRANSITION TO RADIATION PRESSURE

Ok, but, was ideal gas pressure (which got us T∝ M/R) an ok assumption?? Let's check:

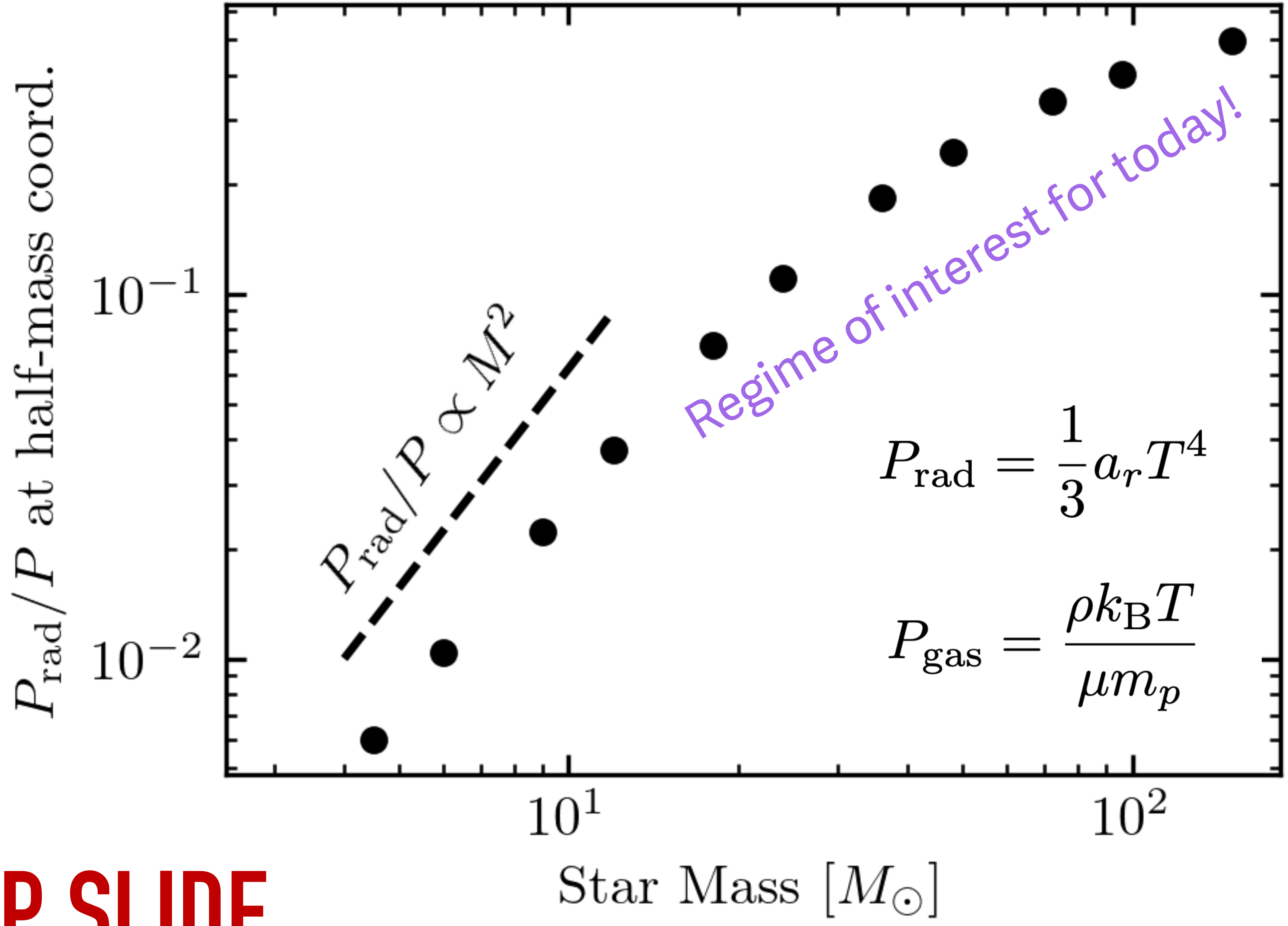
$$\frac{P_{\rm rad}}{P_{\rm gas}} \propto \frac{T^3}{\rho} \approx 10^{-4}\left(\frac{M}{M_c}\right)^2$$

Where the physical mass scale is set by fundamental constants massaged from a_{rad} , k_b, etc:

$$M_c \approx m_p \left(\frac{\hbar c}{G m_p^2}\right)^{3/2} \sim M_\odot$$

A nice example of ``deriving'' the solar mass scale in terms of fundamental constants !!

INCREASING RADIATION PRESSURE IMPORTANCE



BACKUP SLIDE

WHAT HAPPENS TO THE STELLAR LUMINOSITY?

Let's check the extreme limit where radiation pressure dominates. Then, hydrostatic bala

$$P_{\rm rad} = \frac{1}{3} a_r T^4$$

$$\approx a T_c^4$$

Plug

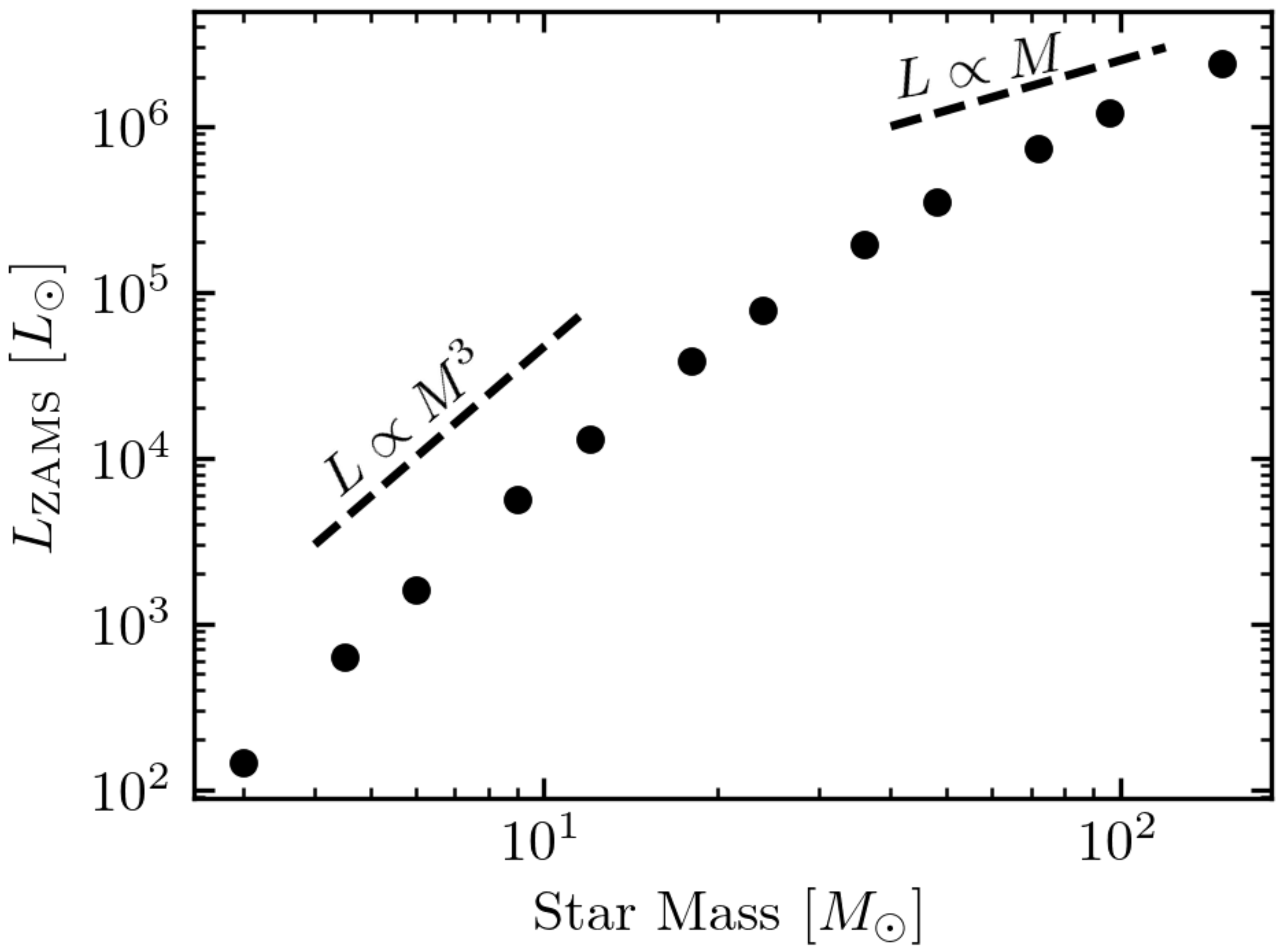
$$P_{\rm gas} = \frac{\rho k_{\rm B} T}{\mu m_p}$$

sion equation and

assu

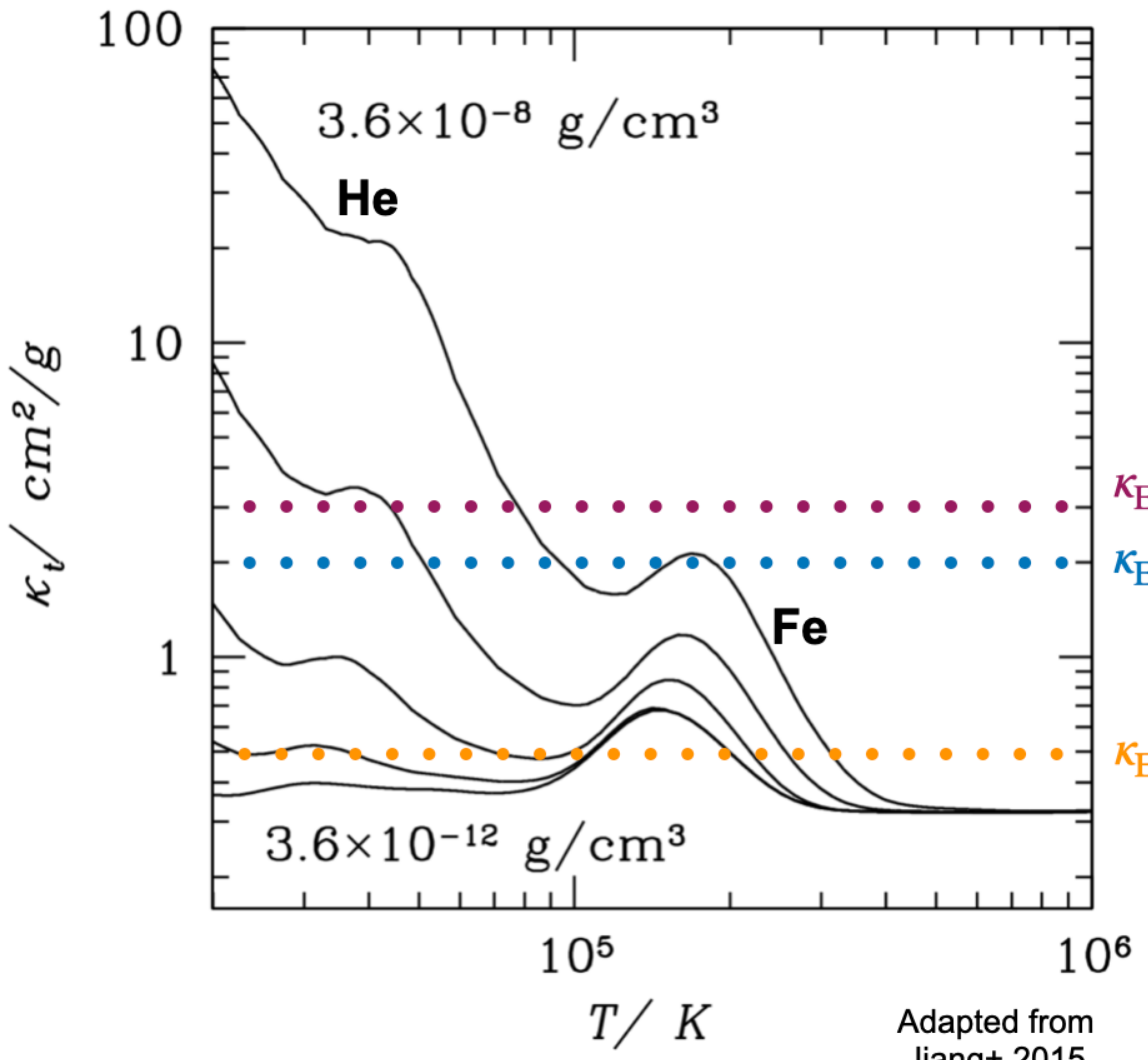
, we recover:

$$L \to L_{\rm Edd} \equiv \frac{4\pi c G M}{\kappa} \approx 3 \times 10^4 L_\odot \left(\frac{M}{M_\odot}\right)$$



CAN WE EXCEED $L_{\rm Edd} \equiv \frac{4\pi c G M}{\kappa}$? LOCALLY, YES!

- If *local* opacity is high, $L_{\rm Edd}$ is *locally* low. Radiation *can't* carry the flux, so we need convection!



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

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

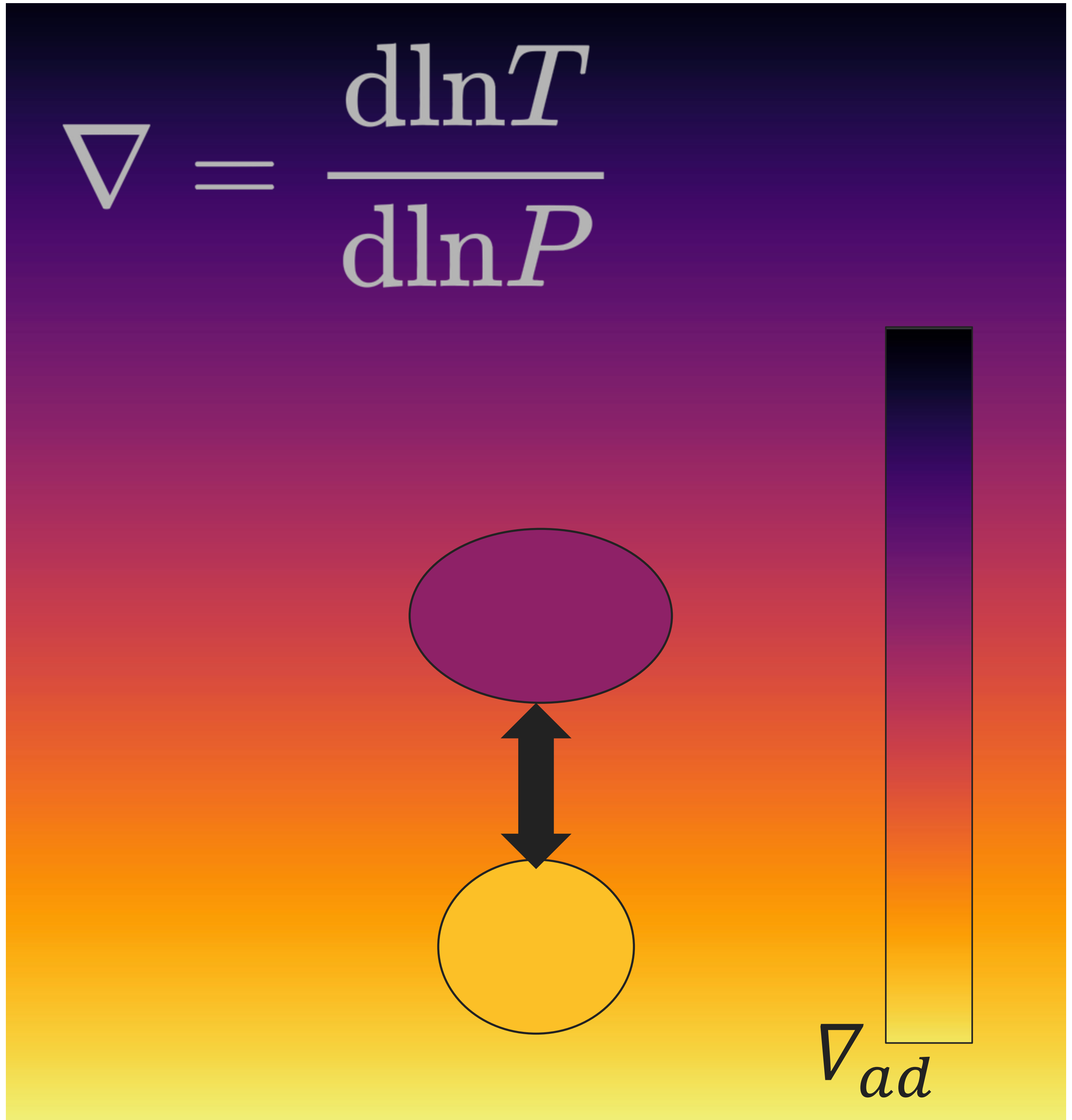
$\kappa_{\rm Edd}$ for $35\,M_\odot$ on mid-MS

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

Adapted from
Jiang+ 2015

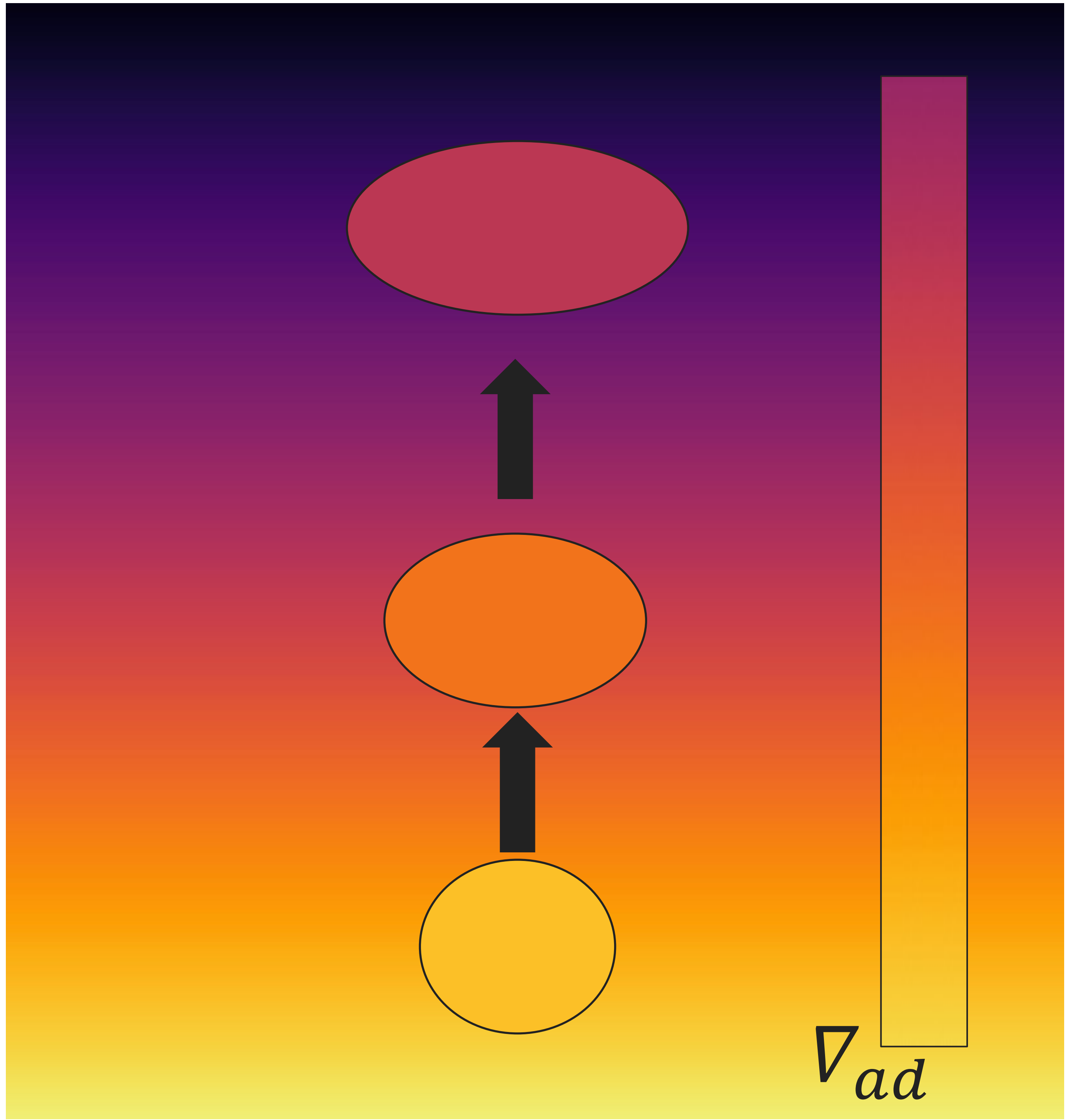
And a slide by William C. Schultz

WHEN AND HOW DOES CONVECTION CARRY FLUX?



Buoyantly Stable

$$\nabla < (\nabla_e \approx \nabla_{ad})$$



Convectively Unstable

$$\nabla > (\nabla_e \approx \nabla_{ad})$$

- Thermodynamic gradients (e.g. dlnT/dlnP) are all tied to the entropy profile, and determine the ability of a fluid parcel to carry heat outwards!

BACKUP SLIDE

BUT... CAN *CONVECTION* CARRY THE FLUX?

- We can write down a convective efficiency:

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

- Where $\gamma >> 1$, convection is *efficient*: a rising plume (eddy)'s temperature obeys the adiabat
- Where $\gamma << 1$, convection is in*efficient*: A plume loses heat (via radiation diffusion) on its way up!
- Radiatively inefficient regions entail large deviations from the adiabat

WHERE DOES THIS TRANSITION HAPPEN?

- In the optically thick limit, we can cast this efficiency γ in terms of the ratio of convective to radiative fluxes

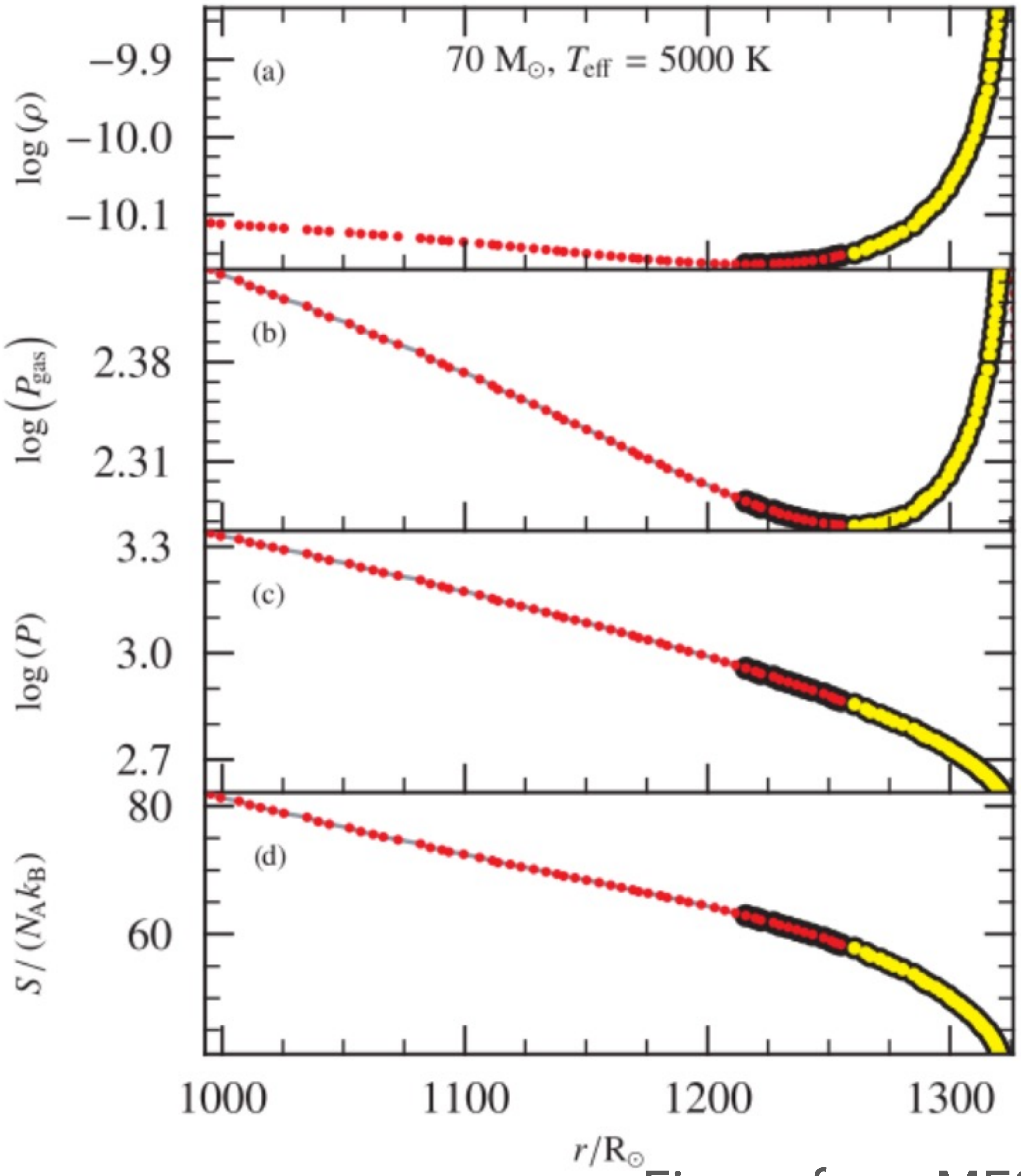
$$\gamma \sim \frac{F_{\rm conv}}{F_{\rm rad}} \sim \frac{(P_{\rm rad} + P_{\rm gas})v_{\rm c}}{P_{\rm rad}\left(\frac{c}{\tau}\right)} \qquad \tau_{\rm crit} \equiv \frac{c}{v_{\rm c}} \frac{P_{\rm rad}}{(P_{\rm rad} + P_{\rm gas})}$$

- So $\gamma \sim \tau / \tau_{\rm crit}$
- If convection occurs where $\tau < \tau_{\rm crit}$, radiative diffusion will carry significant flux
- For the Sun, $\tau_{\rm crit}$ ~ a few. For massive stars, $\tau_{\rm crit} \sim 10^3$ - 10^4

WHEN DOES THAT BECOME A PROBLEM?

- Let's go back to radiative diffusion: $$L_{\rm rad} = -\frac{4\pi r^2 c}{\rho\kappa}\frac{dP_{\rm rad}}{dr},$$
- And combine with Hydrostatic balance: $$\frac{dP}{dr} = -\rho\frac{Gm(r)}{r^2}$$
- We get: $$\frac{dP_{\rm rad}}{dP} = \frac{L_{\rm rad}}{L_{\rm Edd}}.$$
- For P = P_{rad} + P_{gas}, this implies $$\frac{dP_{\rm gas}}{dr} = \left(\frac{dP_{\rm rad}}{dr}\right)\left[\frac{L_{\rm Edd}}{L_{\rm rad}} - 1\right]$$
- Which means that for L_{rad} > L_{edd}, the gas pressure and thereby density profile slope wants to change sign; i.e. form a "density inversion"!

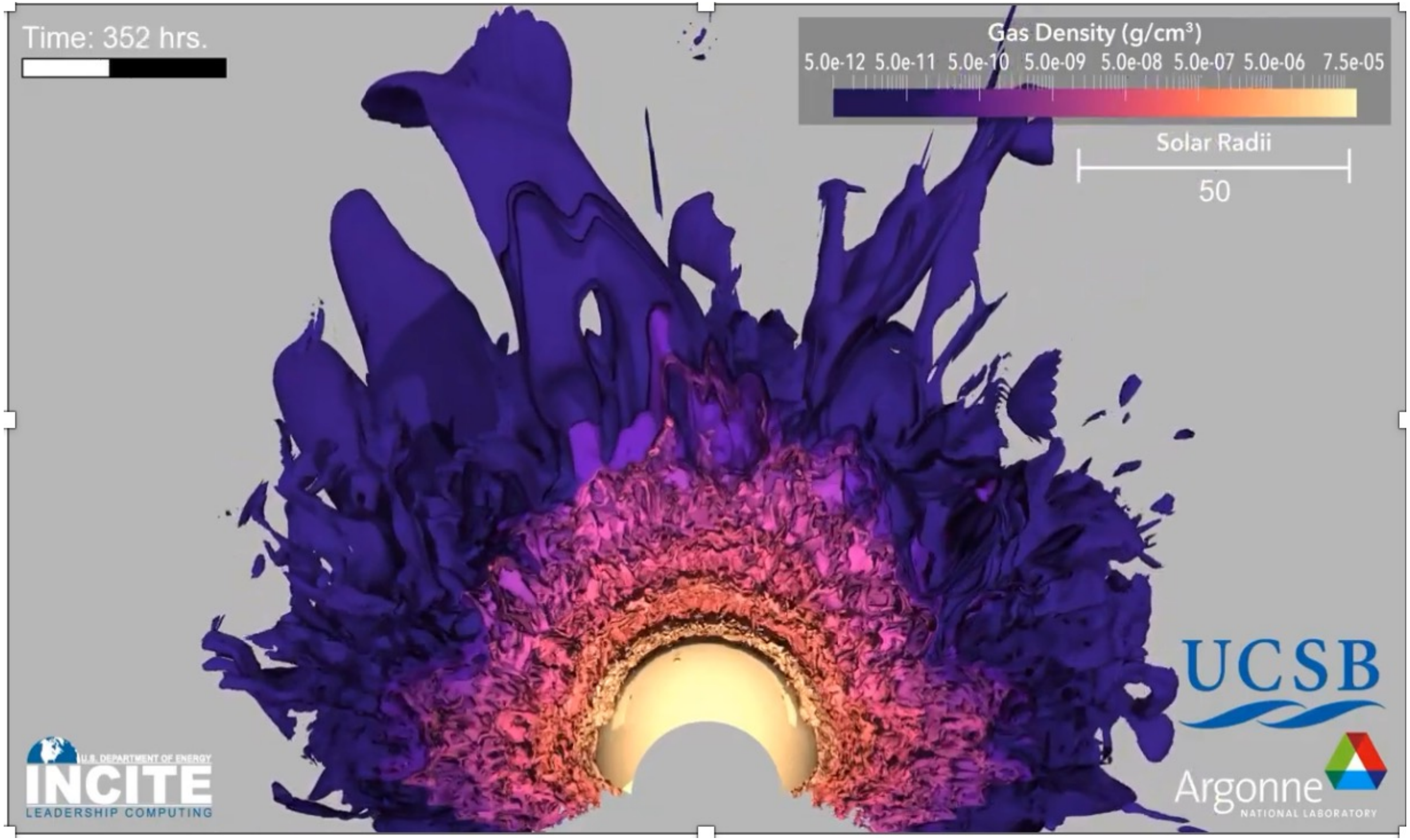
WHAT DOES THIS LOOK LIKE IN 1D?



+ A whole bunch of associated convergence problems

Figure from MESA II Paxton+2013

WHAT HAPPENS IN 3D?



Adapted from Jiang+2018

CAN WE MITIGATE HIGH L_{RAD}/L_{EDD} PROBLEMS?

- ***EVERY CODE THAT ATTEMPTS TO DO MASSIVE STARS HAS SOME ENGINEERING TRICK!*** ***The following is not exhaustive:***

- Bonn (BoOST): No treatment, just envelope inflation (see, e.g., Sanyal et al. 2015)
- STARS / BPASS: non-Lagrangian mesh (see Stancliffe 2006 for an overview) + lower resolution in the outer layers seems to mitigate issues (Eggleton 1973; Eldridge et al. 2017) / Ask Jan …
- FRANEC: remove all the mass outside the location where $L = L_{Edd}$ (see e.g. Limongi & Chieffi 2006)
- GENEC: Strong winds + Use of Density scale height in MLT rather than Pressure scale height (see e.g. Maeder & Meynet 1987)
- Kepler: increase the surface pressure of the star (see e.g. Woosley & Heger 2002, Sukhbold+16) – MESA also has this in Pextra_factor
- PARSEC: limit T gradient so that the density gradient is always negative (see e.g. Chen+2015)

- MESA: adjust thermodynamic gradients so that convection *can* carry the flux: MLT++ (MESA II -- Paxton+2013) and new superad_reduction (MESA VI -- Jermyn+2023)

See also some nice comparisons and discussions Agrawal+2022,23

SUPERAD_REDUCTION

- L_{rad} is too high!
- What if we force convection to carry the flux? Nature finds a way™
- We want to reduce ds/dr ~ 0. We do this by modifying the radiative temperature gradient

$$\nabla_{\rm rad,new} - \nabla_{\rm L} = \frac{\nabla_{\rm rad} - \nabla_{\rm L}}{f_\Gamma}$$

- where

$$f_\Gamma = 1 + \frac{\alpha_1 g(\Gamma_{\rm Edd,exp}/\Gamma_{\rm c} - 1) + \alpha_2 g(\Gamma_{\rm exp}/\Gamma_{\rm inv} - 1)}{\sqrt{\beta}} \times h((\nabla_{\rm exp} - \nabla{\rm L}/\delta_{\rm c})$$

and

$$g(x) \equiv \begin{cases} 0 & x < 0 \\ x^2/2 & 0 < x < 1 \\ x - 1/2 & x > 1 \end{cases}$$

$$h(x) = \begin{cases} 0 & x \leqslant 0 \\ 6x^5 - 15x^4 + 10x^3 & 0 < x \leqslant 1 \\ 1 & x > 1 \end{cases}$$

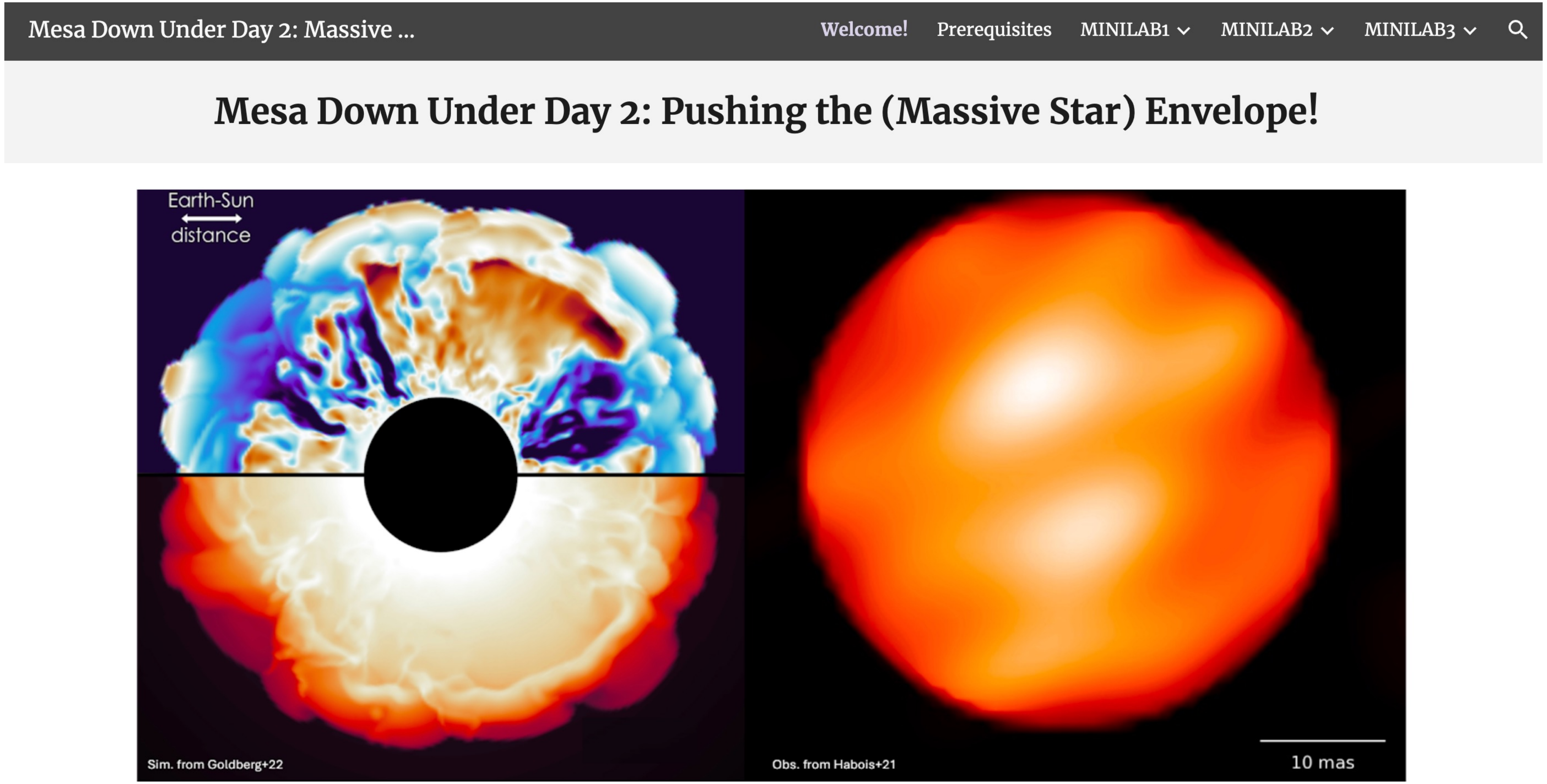
- And $\Gamma_{\rm inv} \equiv 4(1-\beta)/(4-3\beta)$ where $\beta = P_{gas}/P_{total}$
- Many advantages of new implicit superad method: tunable engineering, strictly local, timestep can be large, & more!

NOW IT'S YOUR TURN: HOW DOES STELLAR ENGINEERING AFFECT THE STELLAR STRUCTURE?

HTTPS://SITES.GOOGLE.COM/VIEW/MASSIVE-STARS-MESA-DOWN-UNDER/

Download all lab materials from drive linked in Prerequisites Tab:

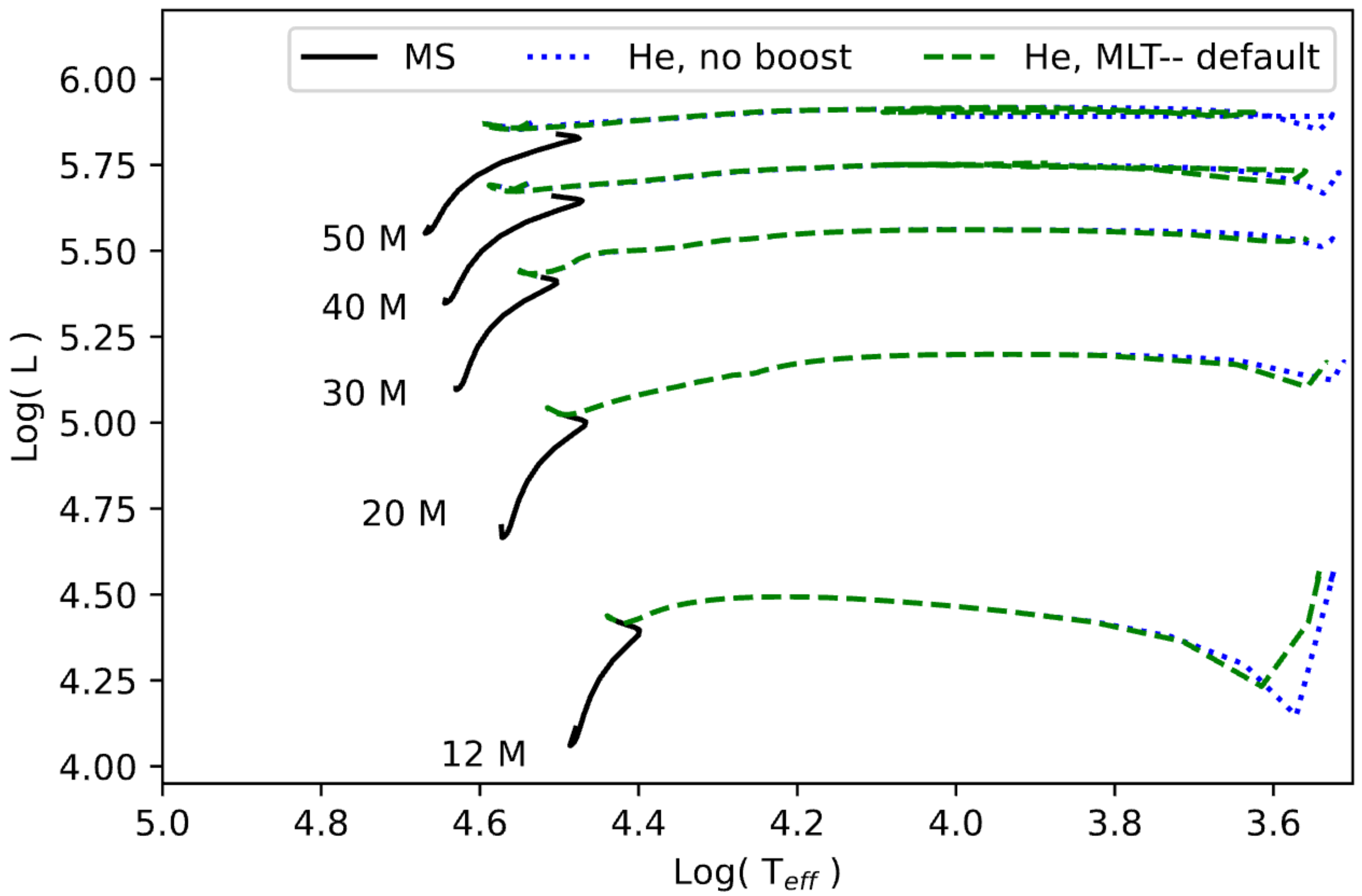
https://sites.google.com/view/massive-stars-mesa-down-under/prerequisites

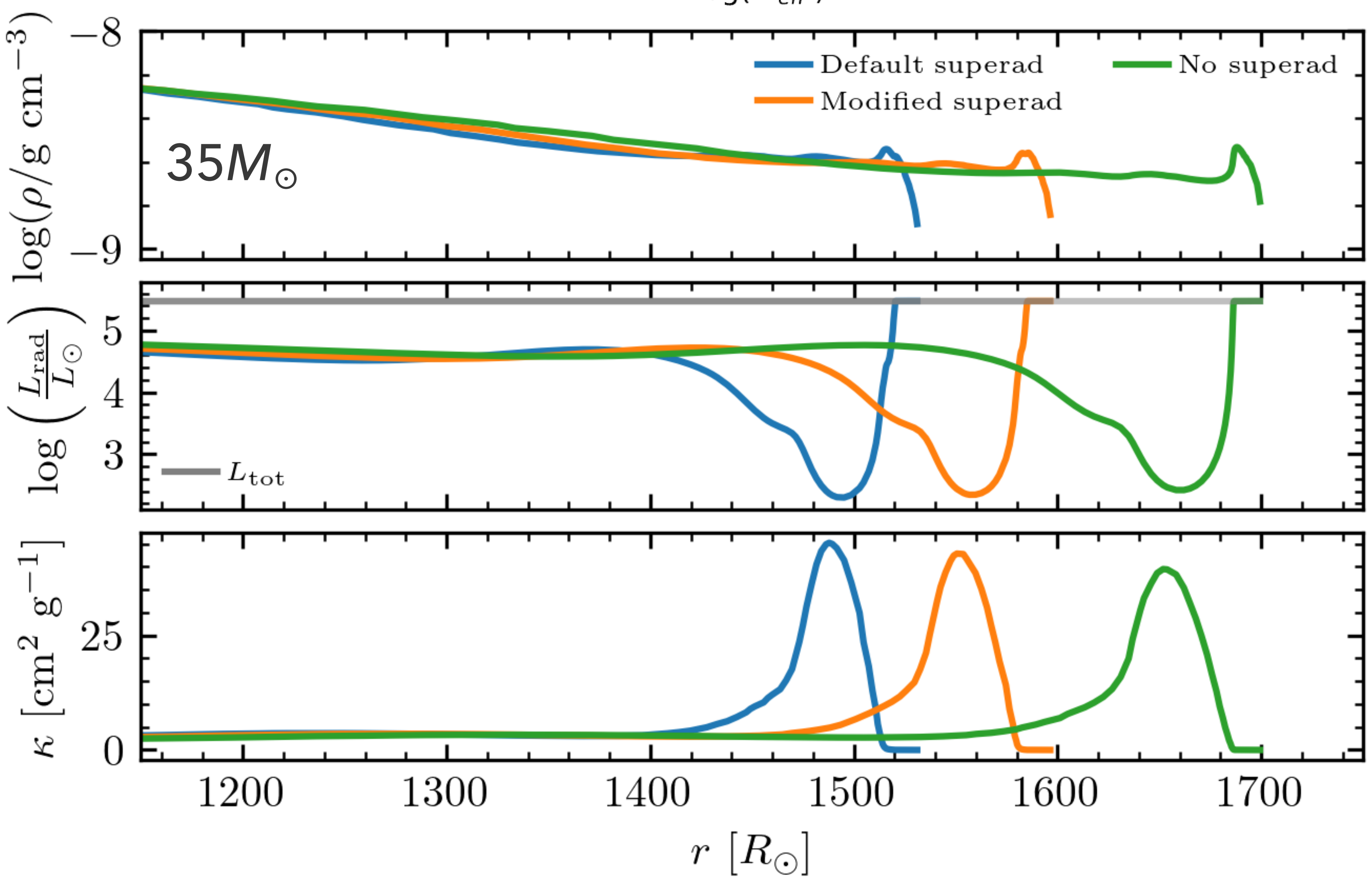


WHAT WE LEARNED

- For lower masses, superad_reduction doesn't do *that* much. At higher masses, it can have a huge impact on the stellar structure and surface temperature

- Increased superad_reduction weakens the density inversion, shifts more flux to convection





LAB 2: MIXING LENGTH THEORY, THE STELLAR RADIUS, AND THE THERMAL TIMESCALE

STELLAR EVOLUTION AFTER CORE HE BURNING

- As the star crosses the Hertzsprung gap, its radius expands rapidly on a thermal time, becoming a Red Supergiant

  Some important questions here, e.g. :

- Just how big does the star get?
  (bigger star = brighter explosion!)
- If the envelope finds itself in contact with a companion's gravitational potential, how much mass can it give, and how fast?

2 IMPORTANT CONCEPTS TO MAKE PROGRESS ON THESE IMPORTANT ?'S:

MIXING LENGTH & THERMAL TIMESCALES

RSG ENVELOPES ARE FULLY CONVECTIVE

CONVECTION ON EARTH

- In the conventional picture of convection: hot, underdense material rises, and cold, overdense material sinks.
- What is the size scale of the flow?

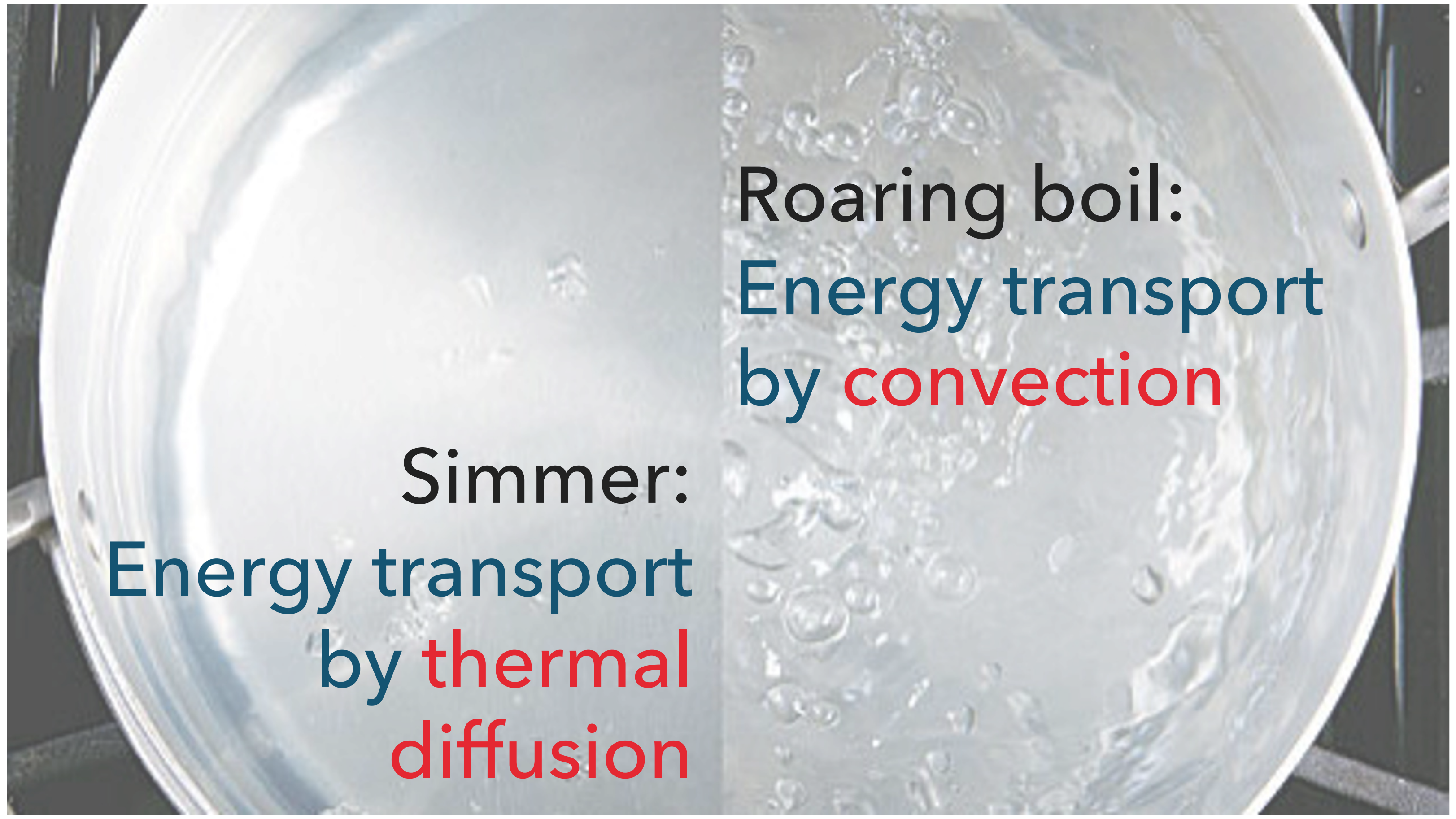
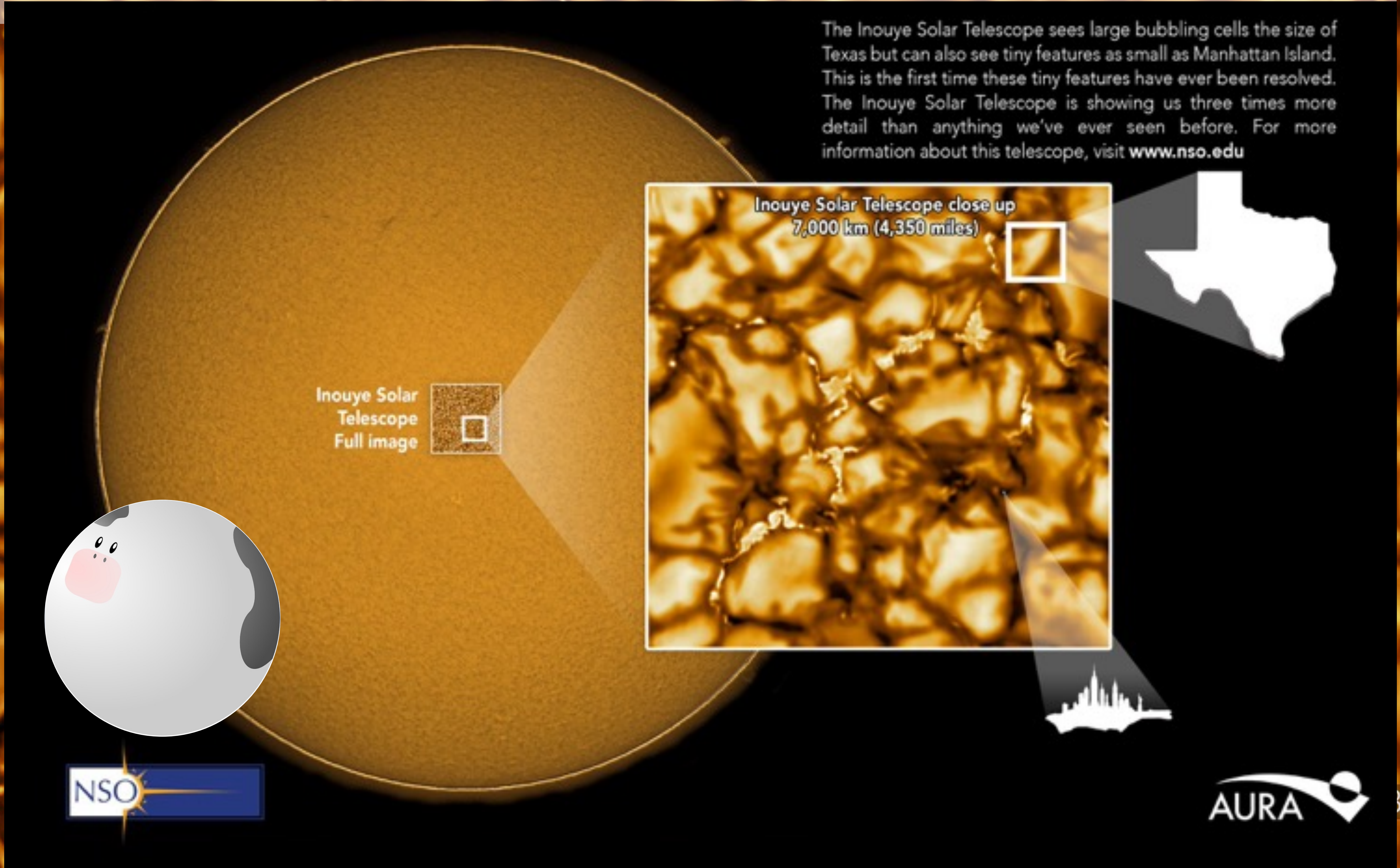


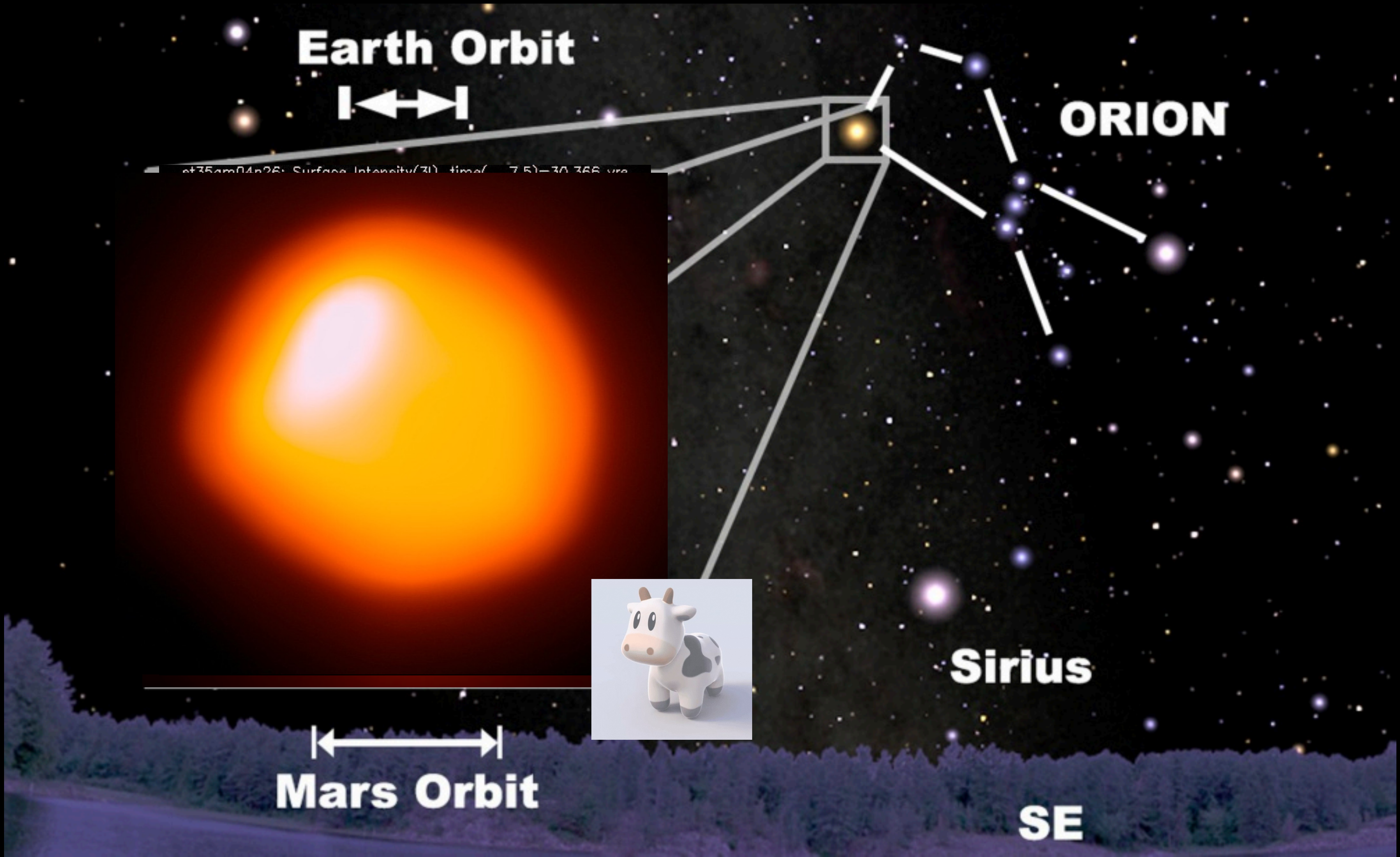
Image courtesy of finecooking.com

CONVECTION IN THE SUN

Data courtesy of DKIST

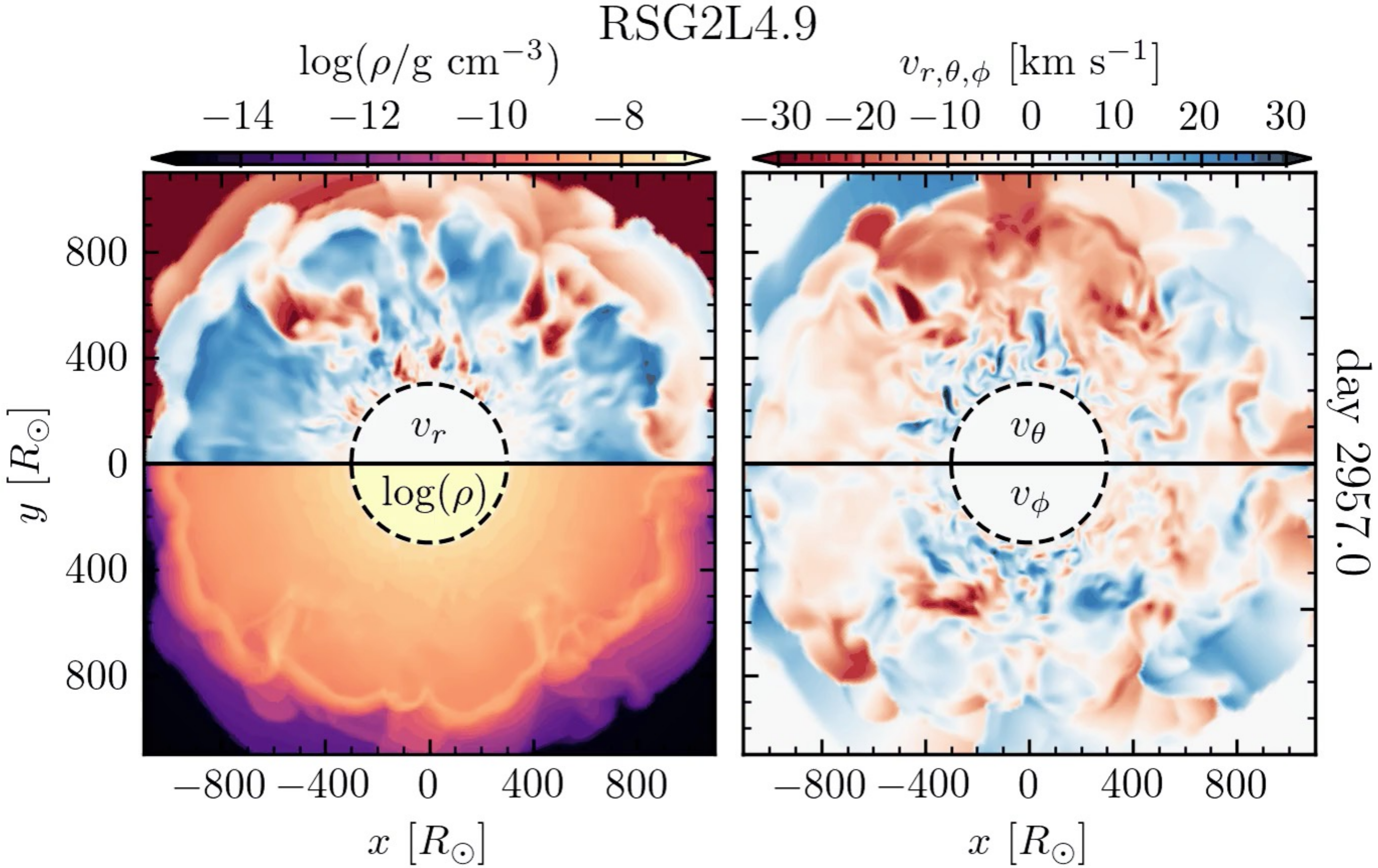


CONVECTION IN A RED SUPERGIANT



CO^{5}BOLD simulations from website of Bernd Freytag; see also Chiavassa+ 2009, 2010a,b, 2011, 2012; Arroyo-Torres+15, Kravchenko +2018; Chiavassa, Kravchenko, & Goldberg 2023

RSG ENVELOPES: LARGE-SCALE, TRANS-SONIC CONVECTION



Adapted from Goldberg et al 2022a

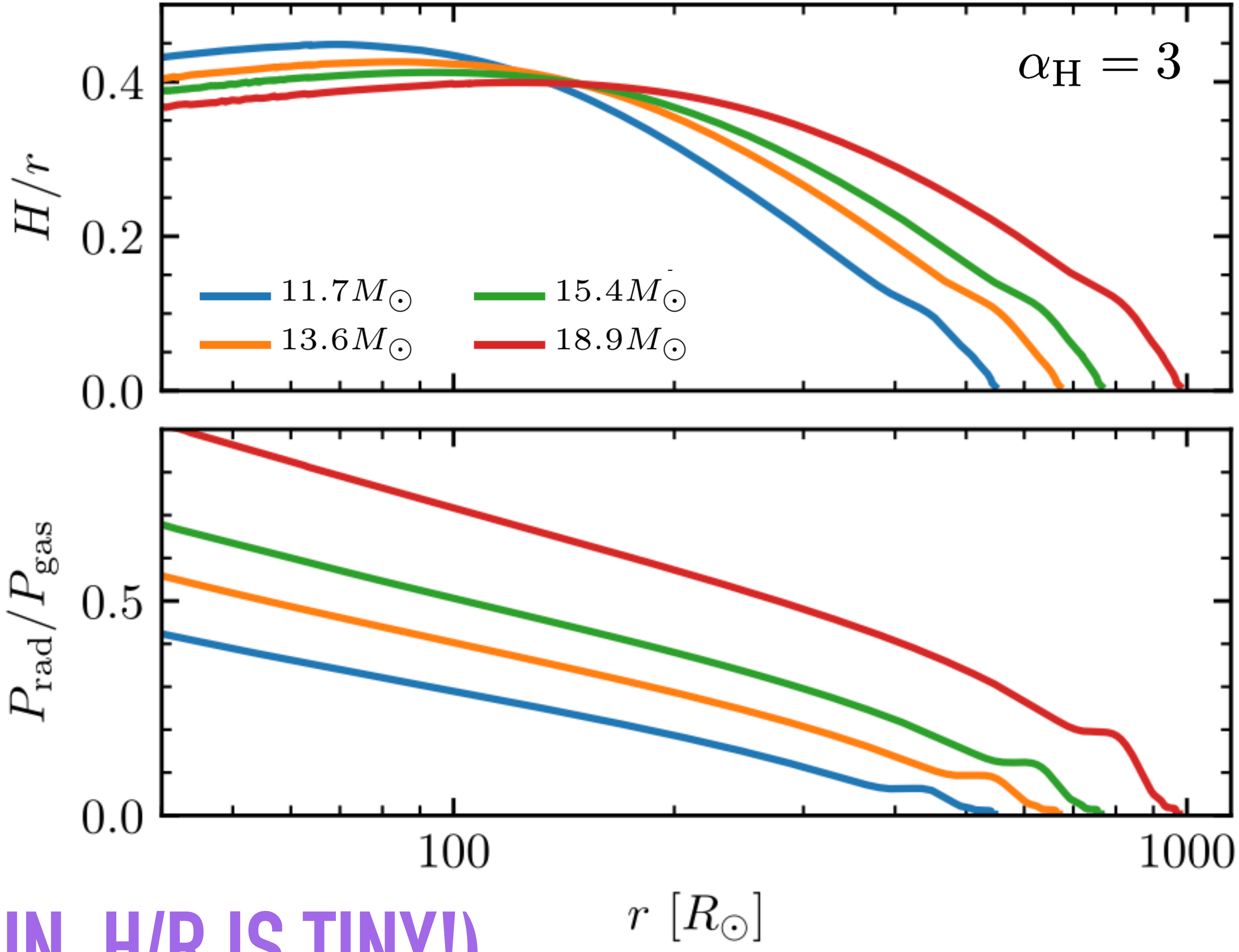
MIXING LENGTH THEORY OF CONVECTION

- The basic picture (Bohm-Vitense 1958) is that a parcel of hot fluid will rise a *mixing length* proportional to the pressure scale height,

$$\ell = \alpha H$$

- In reality, turbulence has eddies and motion at many scales, but you can kind of think of this as the coherence length of a convective plume… Really, it's a characteristic length scale for energy transport!

THIS IS WHY RSG CONVECTION IS SO LARGE-SCALE!



(IN THE SUN, H/R IS TINY!)

Fig adapted from Goldberg et al 2022a

MIXING LENGTH THEORY OF CONVECTION

- In this framework, we can write down a convective velocity as a function of ℓ and the thermodynamic gradients (∇=dlnT/dlnP's, Q=-DlnT/Dlnρ):
- $$v_c^2 = gQ(\nabla - \nabla_e)\frac{\ell^2}{\nu H}$$
- where ν is a geometric factor encoding plume geometry
- The flux from convection can then be calculated

$$F_{\rm conv} = \rho c_P T\sqrt{gQ}\,\frac{\ell^2}{\sqrt{\nu}}H^{-3/2}(\nabla - \nabla_e)^{3/2}$$

- Since $\ell = \alpha H$, α is sometimes discussed as a "convective efficiency" parameter, in that it also scales the flux convection can carry, but this is different than in the radiative sense

FULL MLT SKETCH FROM KIPPENHAHN'S BOOK

- We start with saying the convective flux is the heat contained in a convective parcel traveling at velocity v

$$F_{\mathrm{con}} = \varrho v c_P DT$$

The elements passing at a given moment through a sphere of constant r will have different values of v and DT since they have started their motion at quite different distances, from zero to ℓ_{m}. We assume, therefore, that the "average" element has moved $\ell_{\mathrm{m}}/2$ when passing through the sphere. Then,

$$\begin{aligned} \frac{DT}{T} &= \frac{1}{T}\frac{\partial(DT)}{\partial r}\frac{\ell_{\mathrm{m}}}{2} \\ &= (\nabla - \nabla_{\mathrm{e}})\frac{\ell_{\mathrm{m}}}{2}\frac{1}{H_P}. \qquad (7.4) \end{aligned}$$

BACKUP SLIDE

FULL MLT SKETCH FROM KIPPENHAHN'S BOOK

The density difference [for $DP = D\mu = 0$, see (6.3) and (6.5)] is simply $D\varrho/\varrho = -\delta DT/T$ and the (radial) buoyancy force (per unit mass), $k_r = -g \cdot D\varrho/\varrho$. On average, half of this value may have acted on the element over the whole of its preceding motion ($\ell_m/2$), such that the work done is

$$\frac{1}{2}k_r\frac{\ell_m}{2} = g\delta(\nabla - \nabla_e)\frac{\ell_m^2}{8H_P}. \qquad (7.5)$$

For geometric nu=8

Let us suppose that half of this work goes into the kinetic energy of the element ($v^2/2$ per unit mass), while the other half is transferred to the surroundings, which have to be "pushed aside". Then, we have for the average velocity v of the elements passing our sphere

$$v^2 = g\delta(\nabla - \nabla_e)\frac{\ell_m^2}{8H_P}. \qquad (7.6)$$

- Along with expression for *DT*, plug this into $F_{con} = \varrho v c_P DT$:

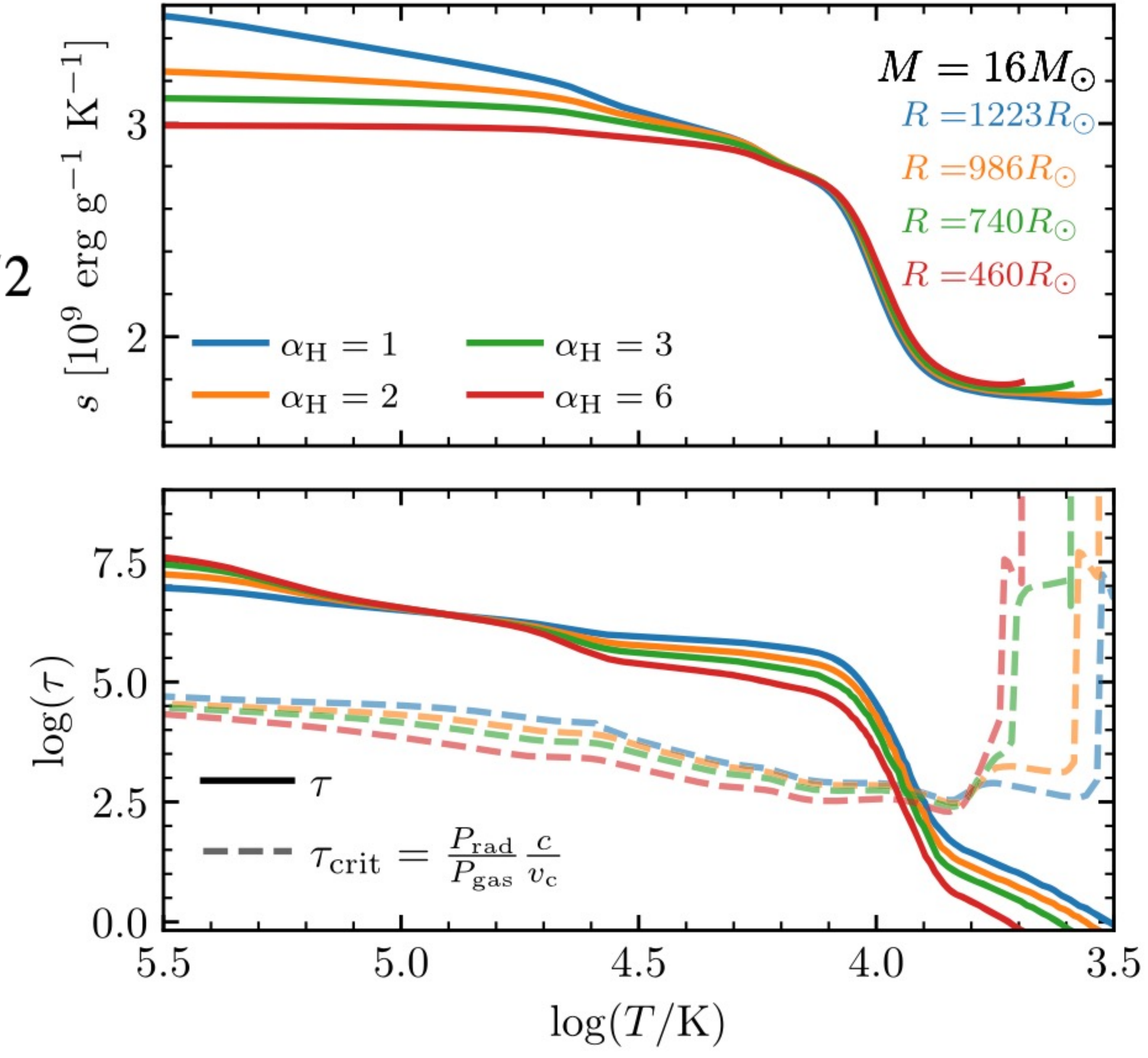
BACKUP SLIDE

$$F_{con} = \varrho c_P T\sqrt{g\delta}\frac{\ell_m^2}{4\sqrt{2}}H_P^{-3/2}(\nabla - \nabla_e)^{3/2}$$

ALPHA MLT AND SUPERADIABATICITY

$$F_{\rm conv} = \rho c_P T \sqrt{gQ}\,\frac{\ell^2}{\sqrt{\nu}} H^{-3/2} (\nabla - \nabla_{\rm e})^{3/2}$$

α ↓ superadiabaticity ↑



ALPHA IS ALSO [CALIBRATED] STELLAR ENGINEERING!

Some examples:

- Calibration to observations from Chun+18
- Calibration to 3D sims from Goldberg+22a

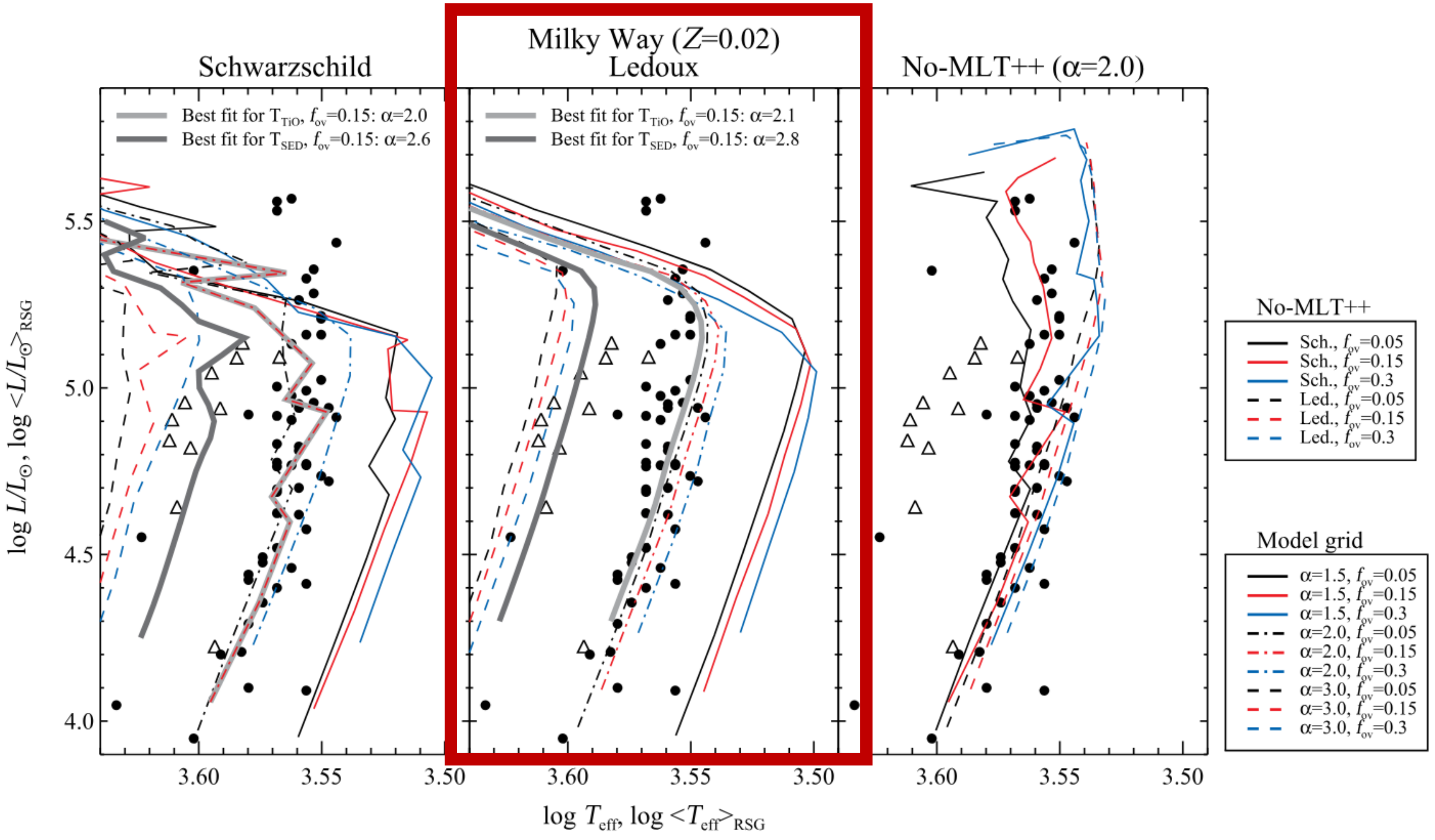
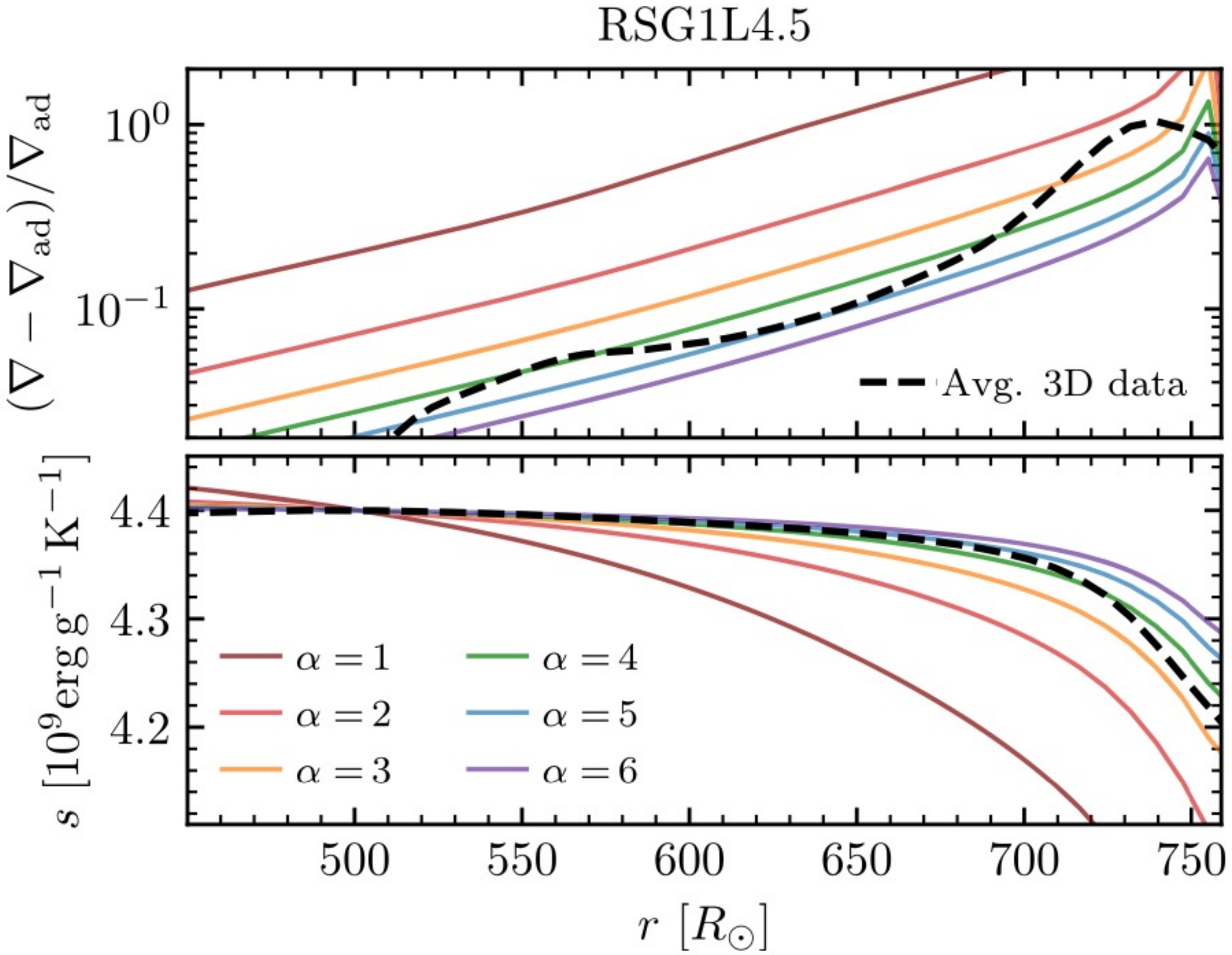


Figure 11. Same as Figure 7, but for solar metallicity ($Z = 0.02$). The results without the MLT++ treatment and with $\alpha = 2.0$ are also plotted in third panel for comparison. The compared Galactic RSG samples are taken from Levesque et al. (2005, TiO temperatures; filled circles) and Gazak et al. (2014, SED temperatures; open triangles).



ABSENT SUCH CALIBRATIONS FOR EVERY INDIVIDUAL STAR, OFTEN THE BEST WE CAN DO IS VARY α AND SEE HOW IT IMPACTS THE STAR

THIS ISN'T JUST A "MESA" THING! NOR JUST MASSIVE STARS!

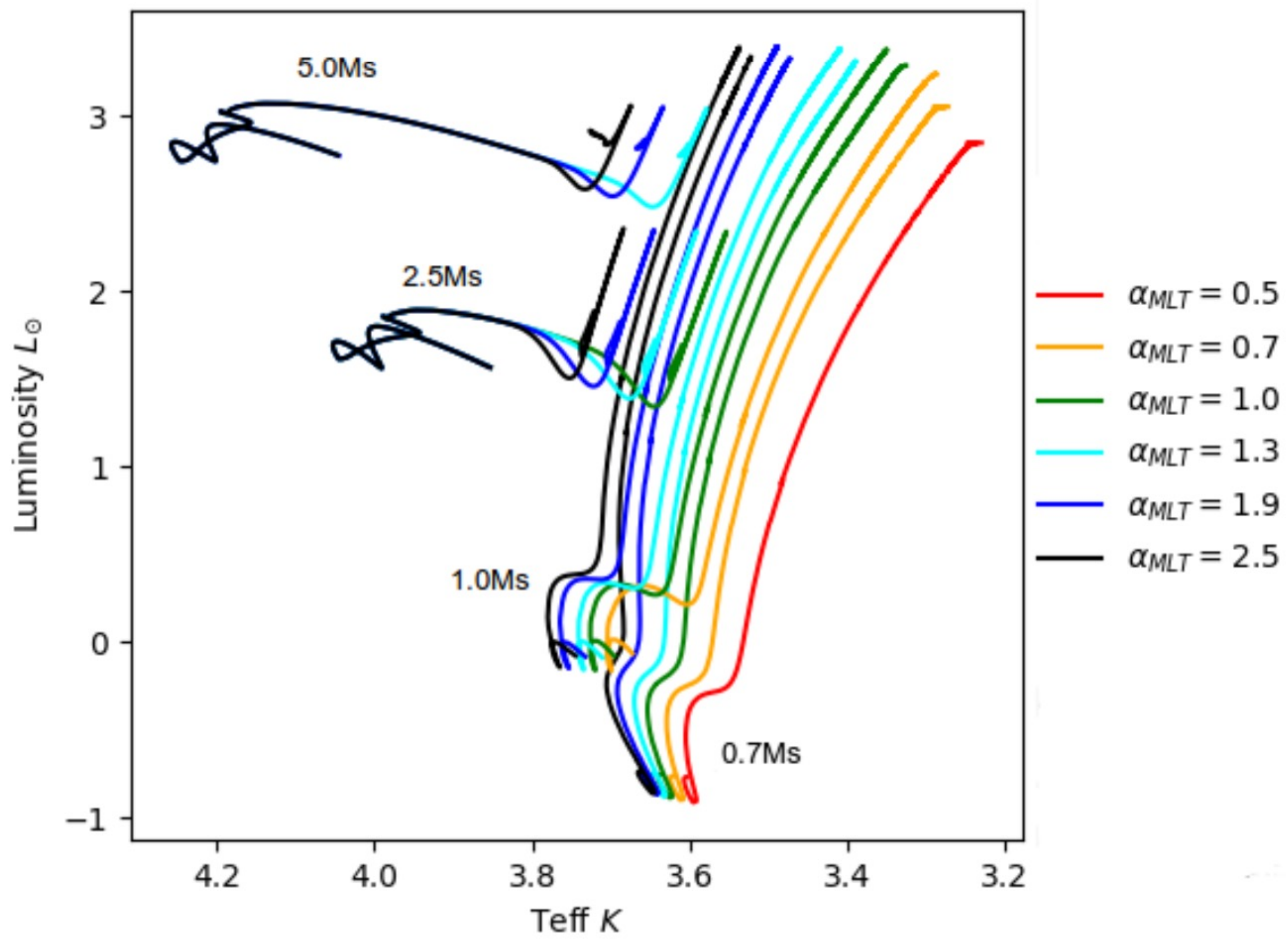


Figure 3. Stellar tracks computed using the Dartmouth Stellar Evolution Program (DSEP) for a range of masses and mixing lengths.

- From Joyce & Tayar 2023 review. α matters when the *envelope* is convective!

ANOTHER IMPORTANT PIECE OF PHYSICS: THERMAL TIMESCALES

- If a star is contracting, how long can it shine?
    - $$t_{KH} = \frac{E_{\text{thermal}}}{L} \approx \frac{|E_{\text{grav}}|}{L} = \frac{GM^2}{2RL}$$
- This is the Kelvin-Helmholtz timescale; ~10^7 years for the Sun
- We can also ask this question locally in a star about how fast it can radiate the energy content contained above that location:
    - $$t_{\text{th}} = \frac{E_{\text{thermal}}(m)}{L} \approx \frac{\int_m^M c_p T \, dm}{L}$$
- The thermal timescale is very relevant for binary mass-transfer, as it mediates how much mass a star can donate and accept!

NOW IT'S YOUR TURN: CHANGING ALPHA? GLOBAL VERSUS LOCAL?

HTTPS://SITES.GOOGLE.COM/VIEW/MASSIVE-STARS-MESA-DOWN-UNDER/

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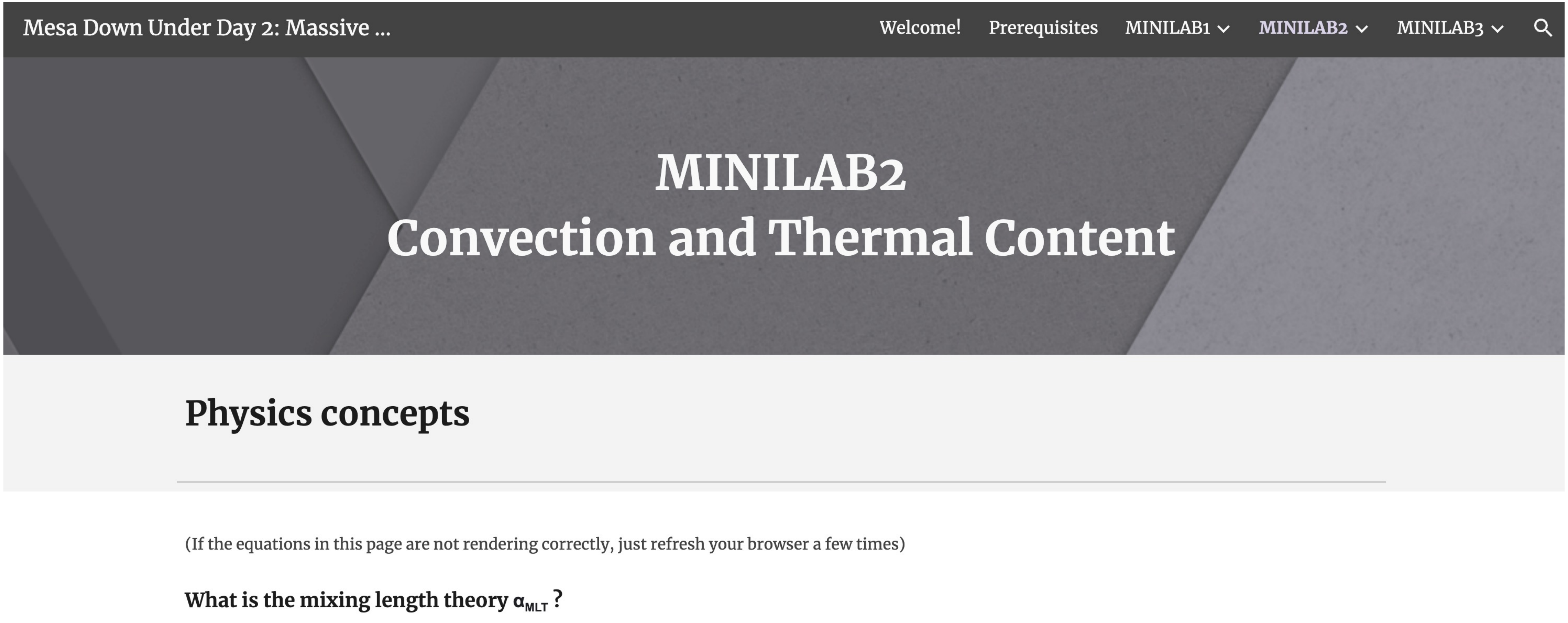
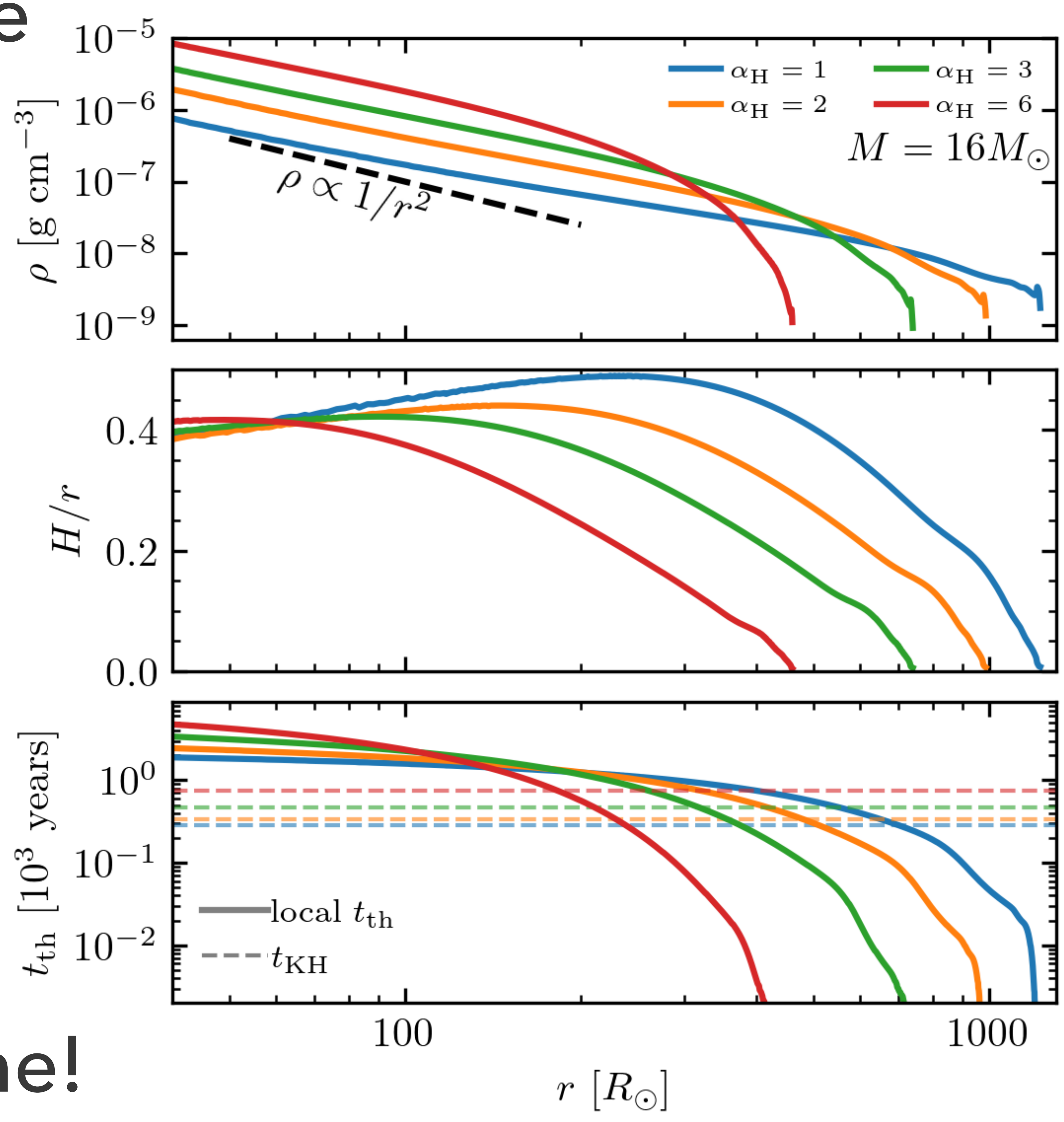


QUESTIONS TO KEEP IN MIND

- How does changing $\alpha_{\rm MLT}$ change the stellar structure?
- In particular, how does varying the mixing length impact the stellar radius and the thermal timescales?
- How big of a difference do you see when comparing the local versus global thermal timescales, compared to the difference in KH timescales for models with different values of $\alpha_{\rm MLT}$?

WHAT WE LEARNED

- For fully convective envelopes in the RSG regime, lower α_{MLT} → larger R
- Local t_{th} ~ orders-of-magnitude variation throughout the envelope, whereas varying alpha varies t_{KH} by ~a factor of 2-3
- For predicting R, T_{eff}? Think about α_{MLT}!
- For binary mass transfer stability? Consider global vs local thermal time!



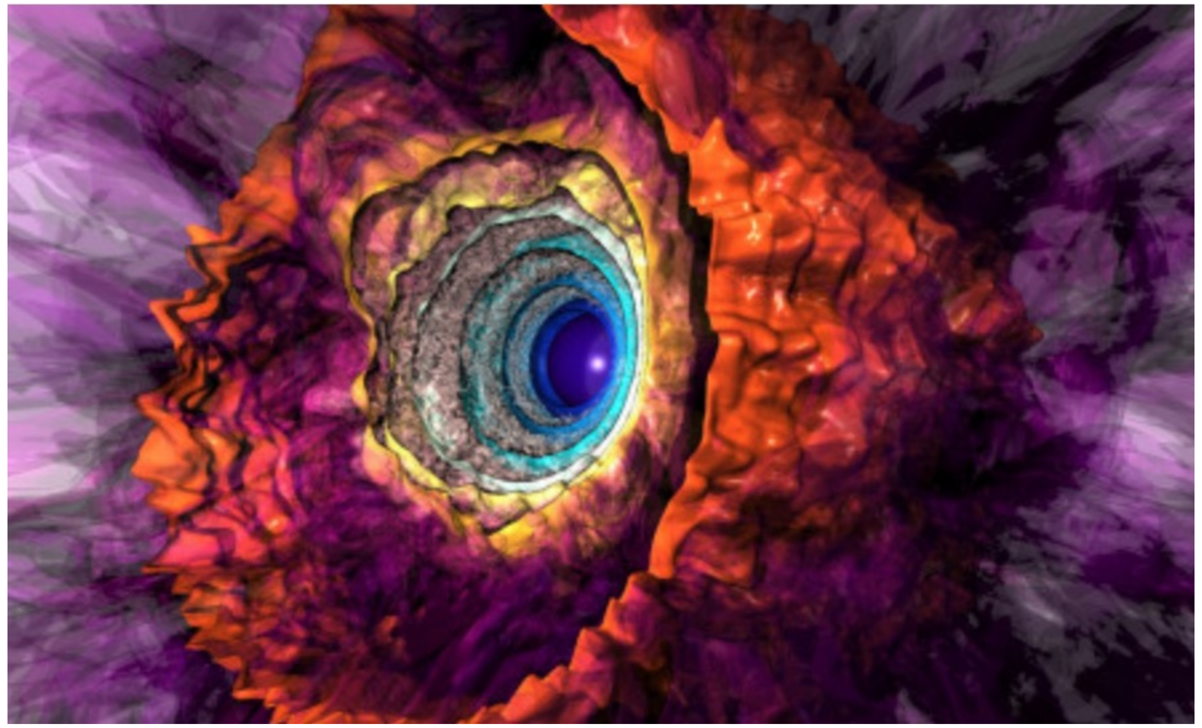
MINILAB 3: ENVELOPE STRUCTURE AS A FUNCTION OF MASS LOSS

AKA…

MINILAB 3: EXPANDING ON BONUS ACTIVITIES FROM MINILABS 1&2

WHY DO (MASSIVE) STARS LOSE MASS?

STELLAR WINDS



ERUPTIVE EVENTS (e.g. LBV Outbursts)

BINARY MASS TRANSFER

AND MANY OTHER UNCERTAIN/CONSTRAINABLE PROCESSES!

HOW IS THIS TYPICALLY CAPTURED IN MESA?

- Various prescriptions for winds are implemented in MESA
- Most common is 'dutch' which interpolates rates in the HR diagram from a number of papers
- You also can implement your wind prescription (and today, you will)
- Rates are a matter of hot debate in the literature!

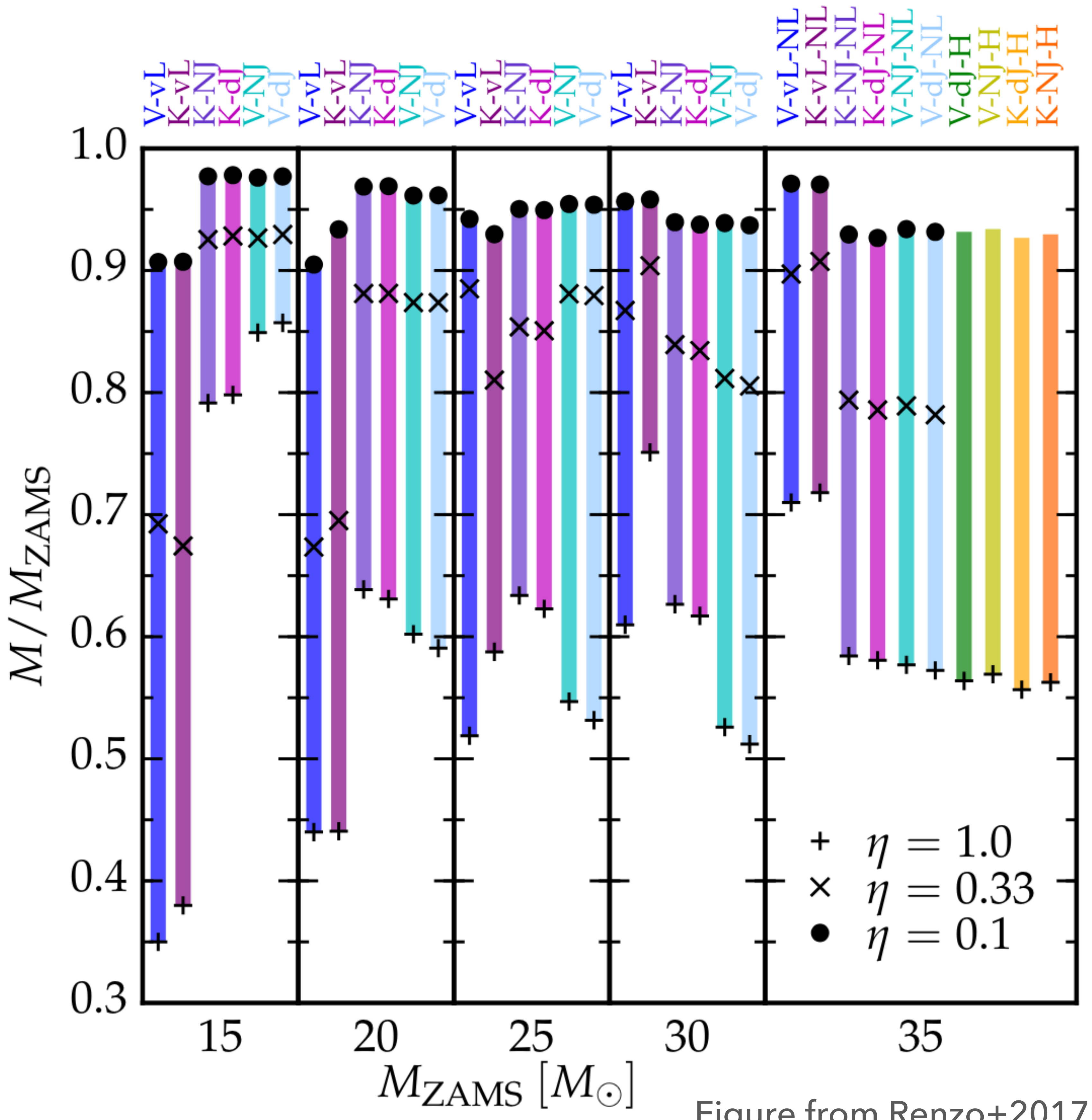


Figure from Renzo+2017

WHAT HAPPENS WHEN MASSIVE STARS LOSE MASS?

Shapes supernova lightcurves

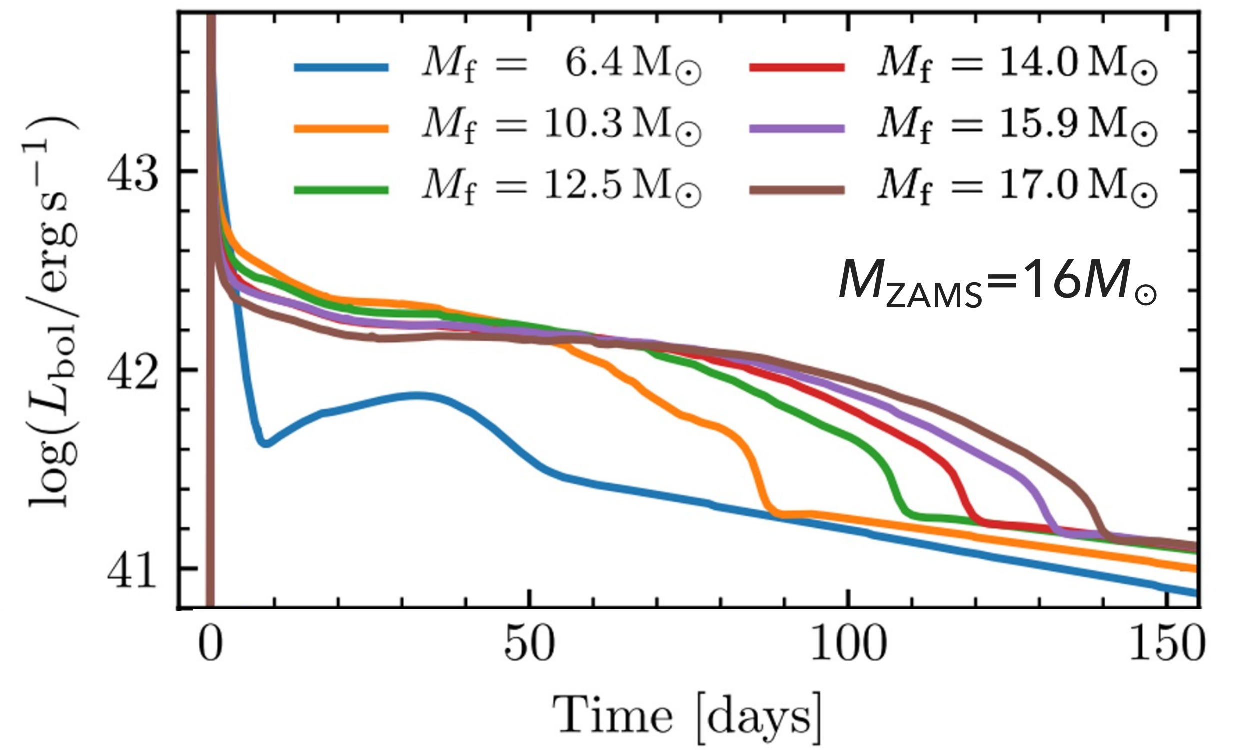
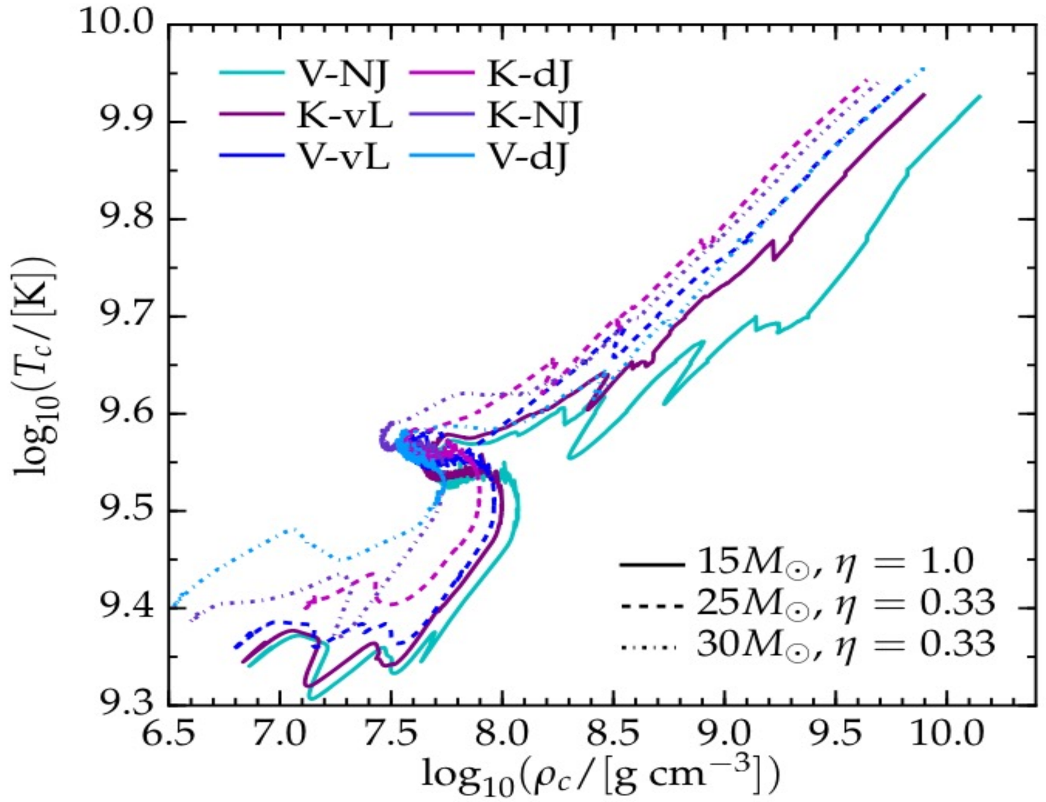
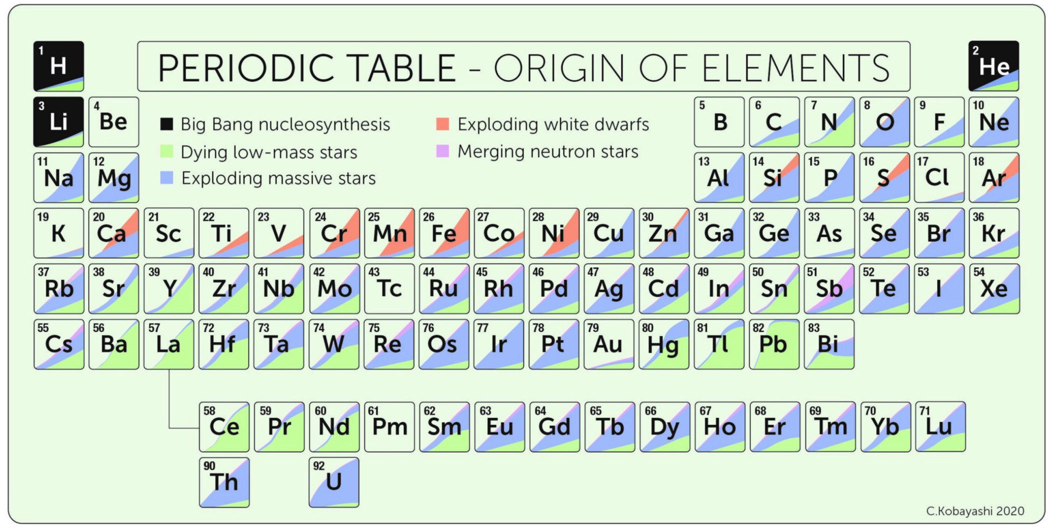


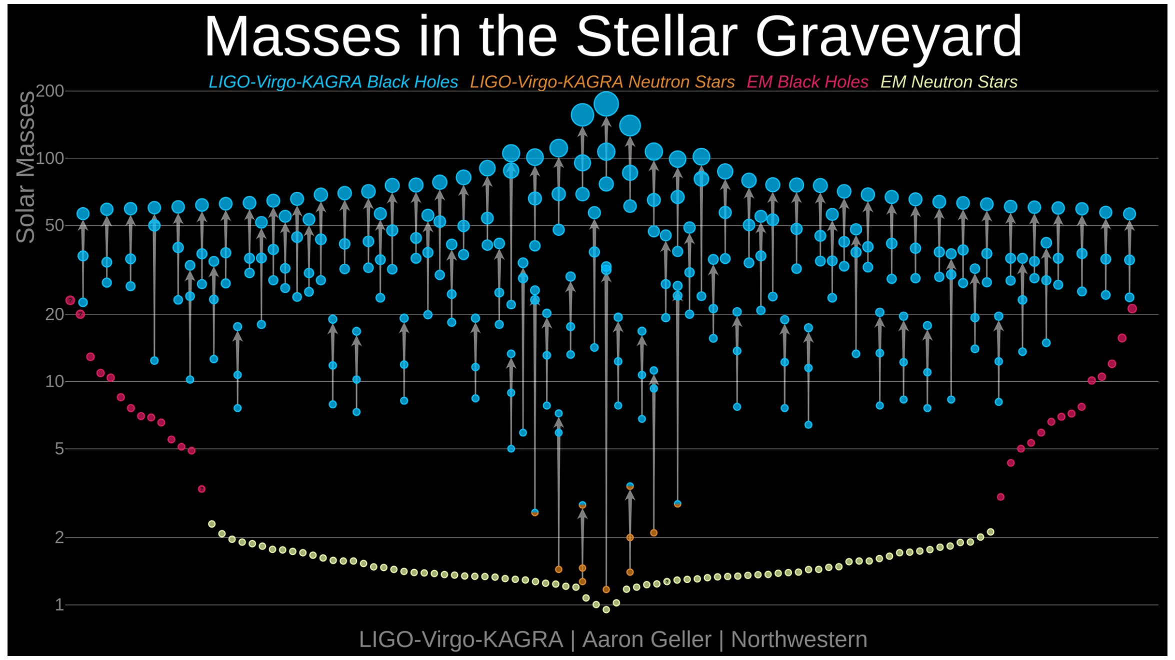
Fig. adapted from MESA IV Paxton+2018



Changes *core* evolution

Fig. from Renzo+2017





Shapes compact object populations through impact on binary evolution

Shapes SN remnant environment

Image: NASA, ESA, CSA, STScI, Danny Milisavljevic, Ilse De Looze, Tea Temim

Stellar Wind Feedback & Galactic Chemical Enrichment

Figs by Kobayashi 2020, NASA

ON WHAT TIMESCALE CAN STARS RESPOND TO MASS LOSS?

- Back to Astrophysics Essentials™ : Hydrostatic balance will be recovered on a *Dynamical Timescale*

  - $$t_{\rm dyn} = \frac{R}{v_{\rm esc}} = \sqrt{\frac{R^3}{2GM}}$$

- And the thermal structure can adjust on a Kelvin-Helmholtz (or Thermal) Timescale (discussed last lab!

  - $$t_{KH} = \frac{E_{\rm thermal}}{L} \approx \frac{|E_{\rm grav}|}{L} = \frac{GM^2}{2RL}$$

ON WHAT TIMESCALE CAN STARS RESPOND TO MASS LOSS?

- Thus, a natural "limiting" mass loss rate for the star to be able to *thermally* adjust to mass loss is
  - $\dot{M}_{\rm KH} \approx \frac{M_{\rm star}}{t_{\rm KH}} = \frac{2RL}{GM}$

$$\approx 6.7 \times 10^{-7} \left(\frac{M}{M_\odot}\right)^{-1} \left(\frac{R}{R_\odot}\right) \left(\frac{L}{L_\odot}\right) M_\odot\,{\rm yr}^{-1}$$

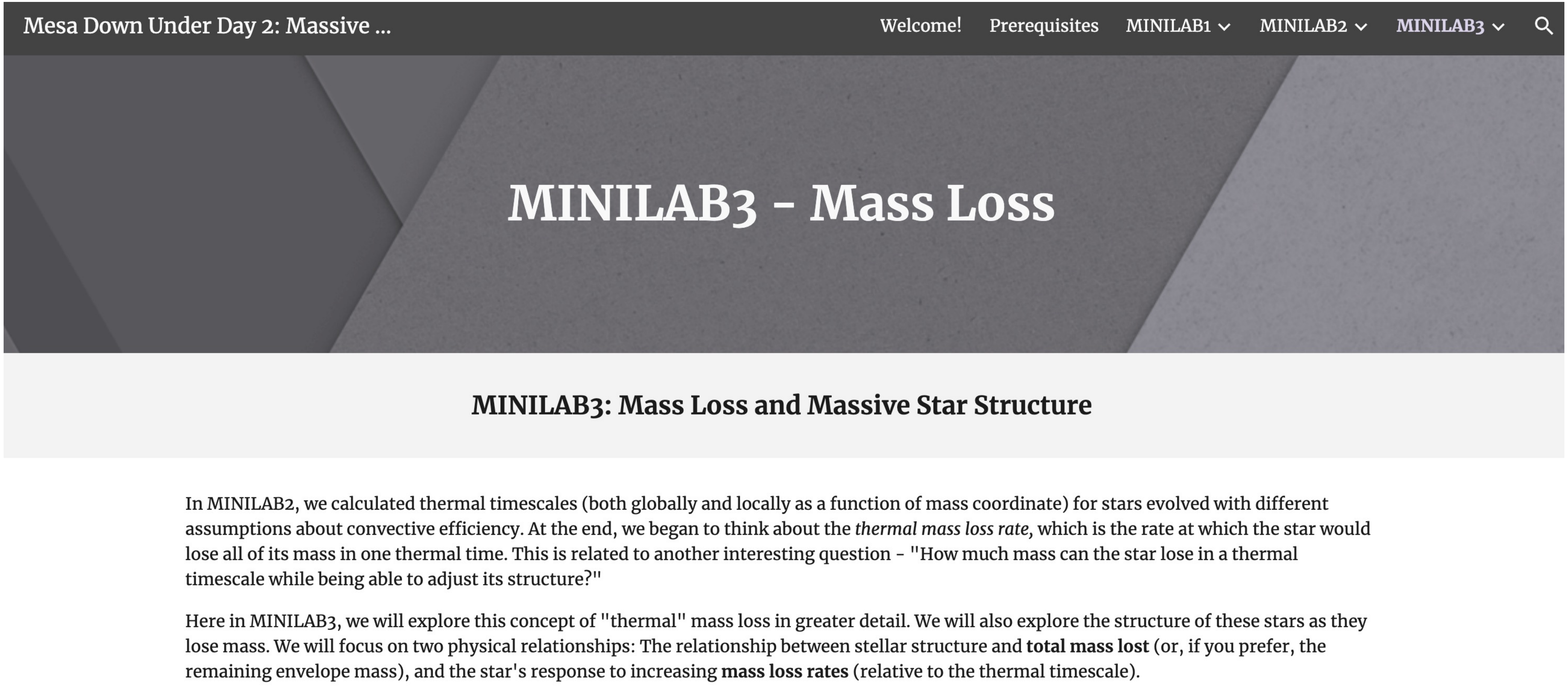
HOW WILL *WE* MAKE THE STARS LOSE MASS?

- In the last lab, we opened src/run_star_extras.f90 and created custom history and profile outputs
- As we learned this morning, run_star_extras can also be a place where you insert your own physics!
- Conveniently, there are hooks for mass loss/mass accretion!
- For arbitrary $\dot{M}$, we can use other_adjust_mdot.
- Since we want to implement a negative $\dot{M}$, i.e. a wind, we can (and will) use the other_wind routine.

HTTPS://SITES.GOOGLE.COM/VIEW/MASSIVE-STARS-MESA-DOWN-UNDER/

Download all lab materials from drive linked in Prerequisites Tab:

https://sites.google.com/view/massive-stars-mesa-down-under/prerequisites



Mesa Down Under Day 2: Massive ... Welcome! Prerequisites MINILAB1 MINILAB2 MINILAB3

MINILAB3 - Mass Loss

MINILAB3: Mass Loss and Massive Star Structure

In MINILAB2, we calculated thermal timescales (both globally and locally as a function of mass coordinate) for stars evolved with different assumptions about convective efficiency. At the end, we began to think about the *thermal mass loss rate,* which is the rate at which the star would lose all of its mass in one thermal time. This is related to another interesting question - "How much mass can the star lose in a thermal timescale while being able to adjust its structure?"

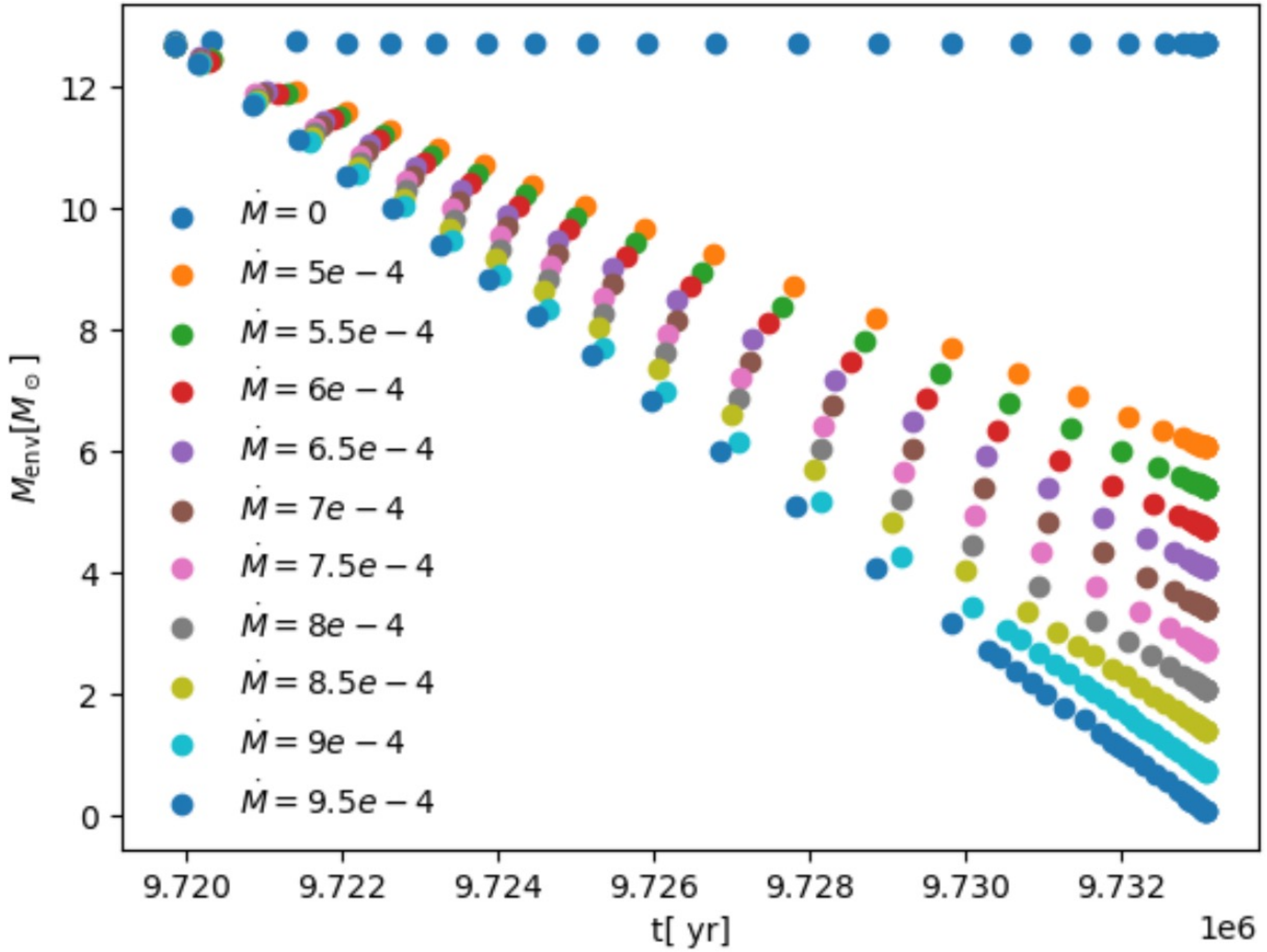
Here in MINILAB3, we will explore this concept of "thermal" mass loss in greater detail. We will also explore the structure of these stars as they lose mass. We will focus on two physical relationships: The relationship between stellar structure and **total mass lost** (or, if you prefer, the remaining envelope mass), and the star's response to increasing **mass loss rates** (relative to the thermal timescale).

QUESTIONS TO KEEP IN MIND

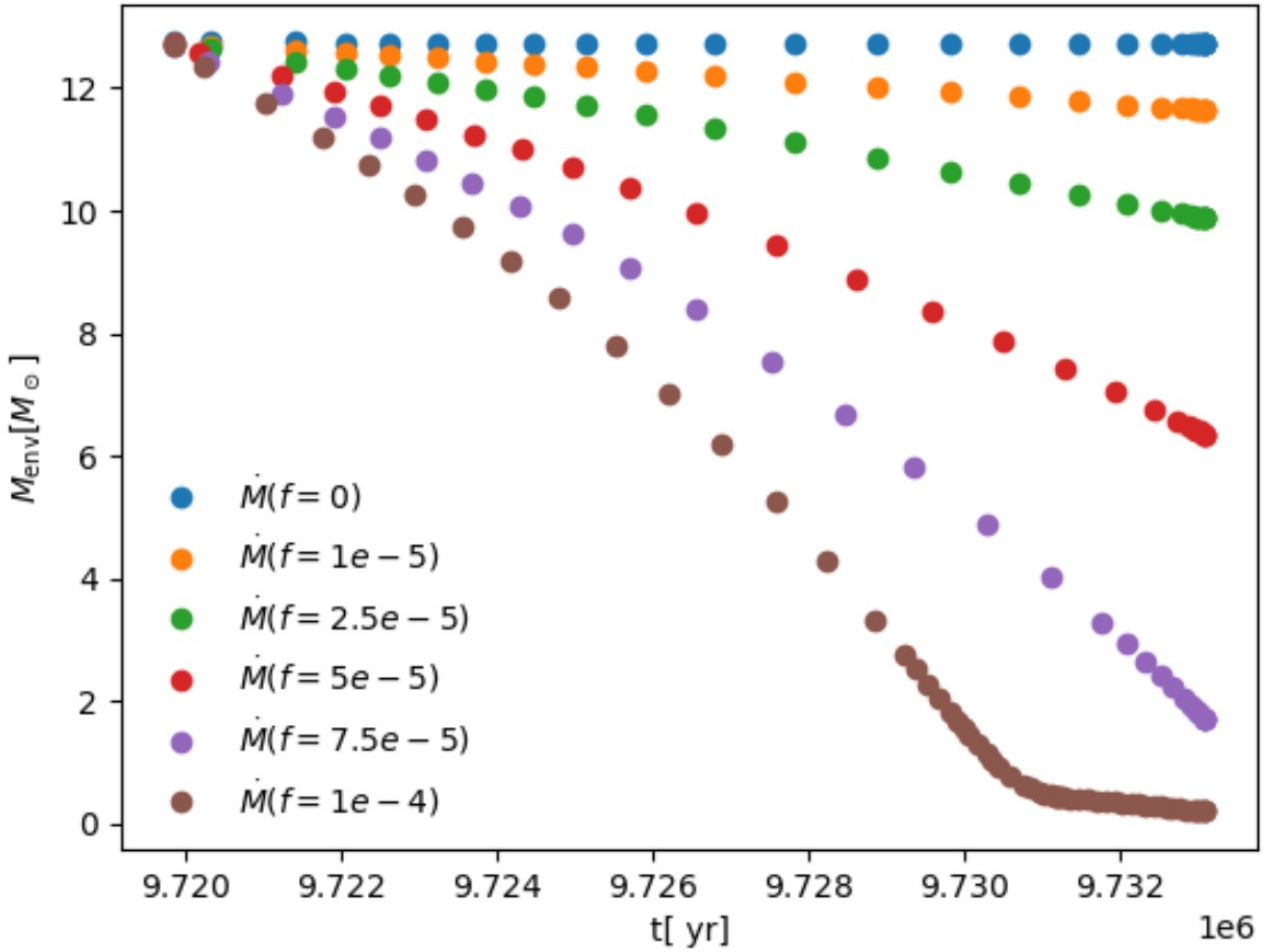
- What happens to the stellar structure with increasing mass lost?
- In particular, how does varying mass loss impact the stellar radius?
- How much does the picture change when the mass loss is not constant, but rather a function of the thermal properties of the stars?

WHAT WE SAW

CONSTANT MASS LOSS



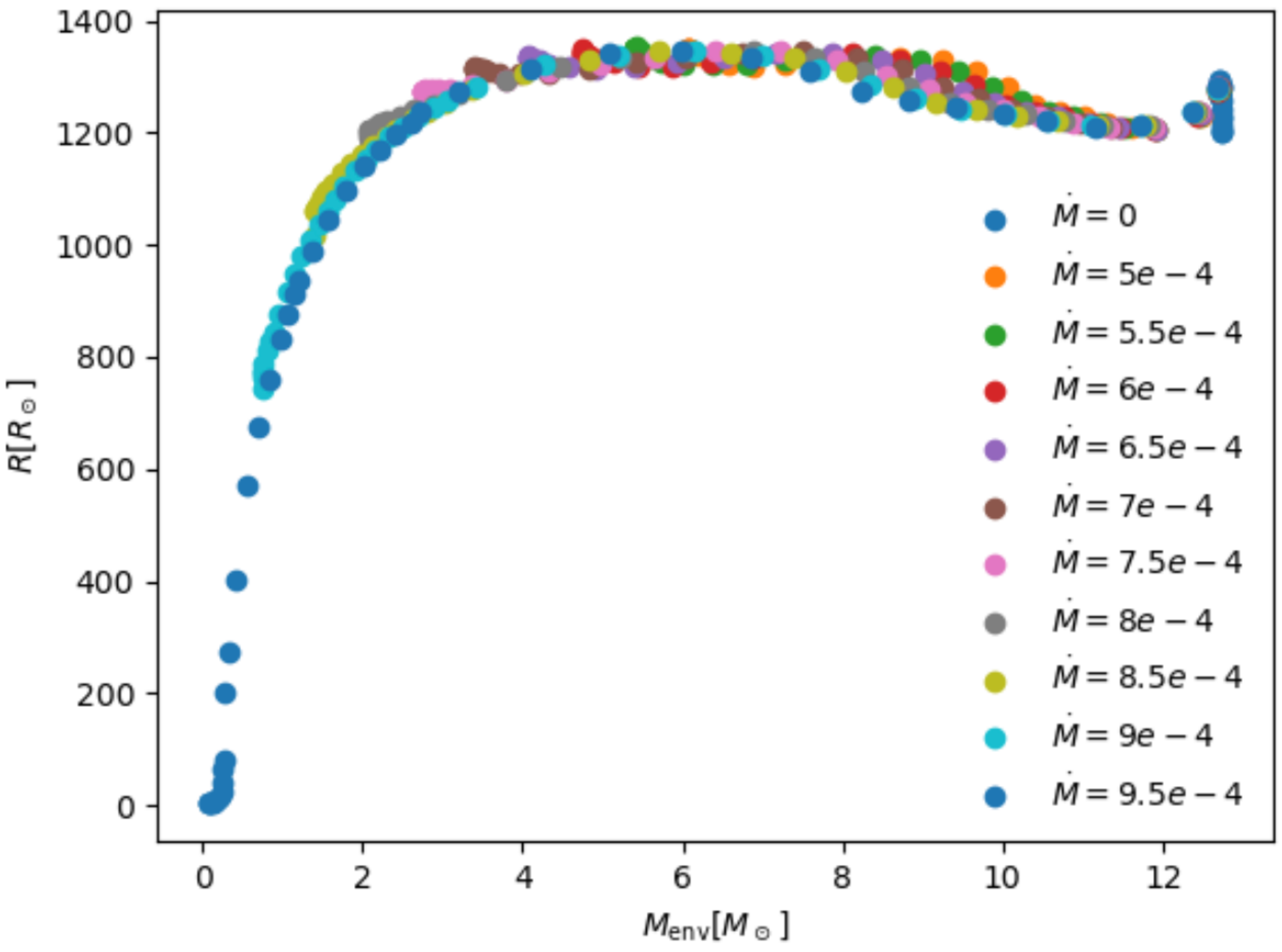
SUB-KH MASS LOSS



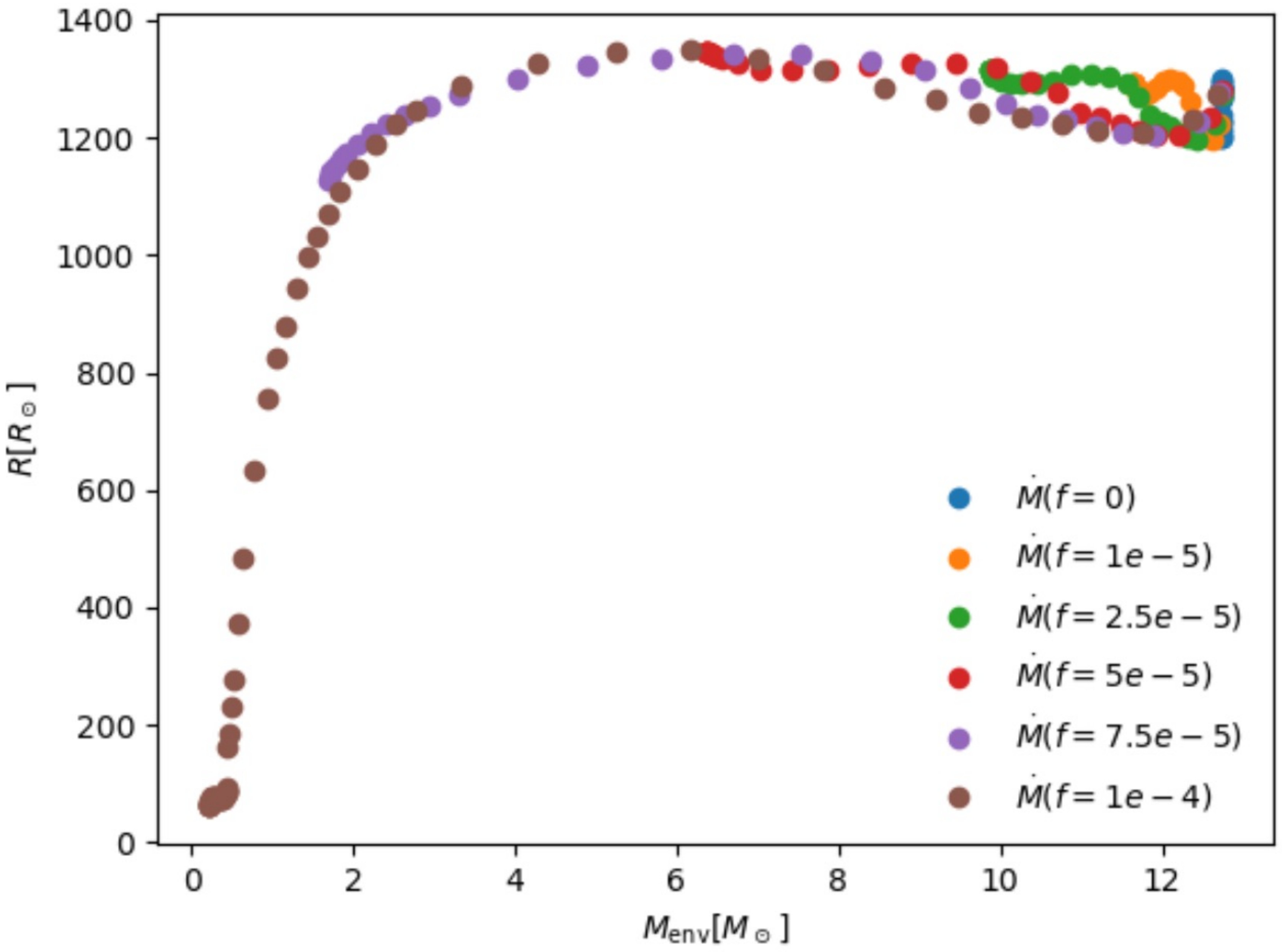
$M_{ZAMS}=20M_\odot$

ENVELOPE MASS DETERMINES THE RADIUS

CONSTANT MASS LOSS

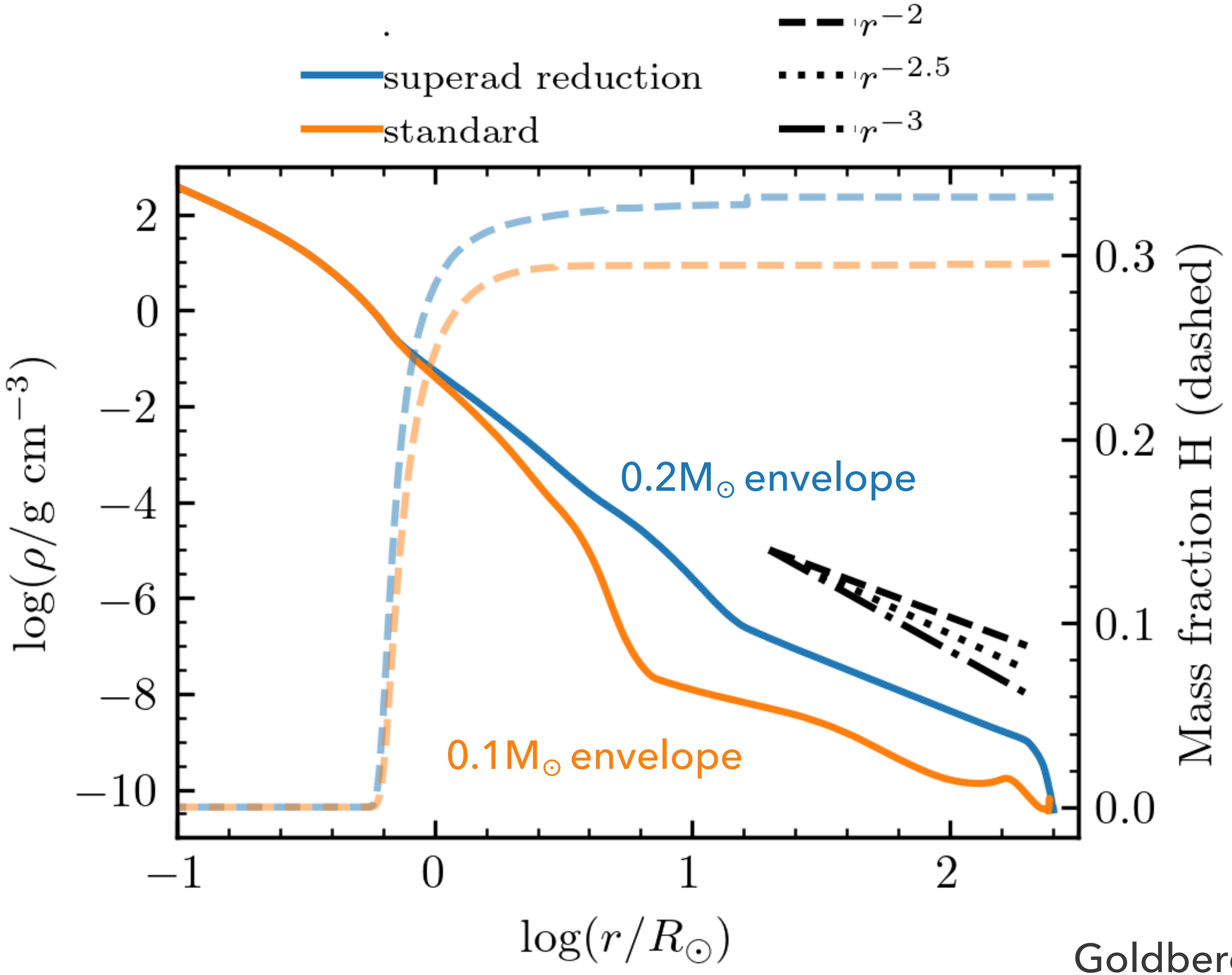


SUB-KH MASS LOSS



$M_{ZAMS} = 20 M_\odot$

REMEMBER: STELLAR ENGINEERING SHAPES THE ENVELOPE



Goldberg et al (in prep)

RECAP AND IMPLICATIONS

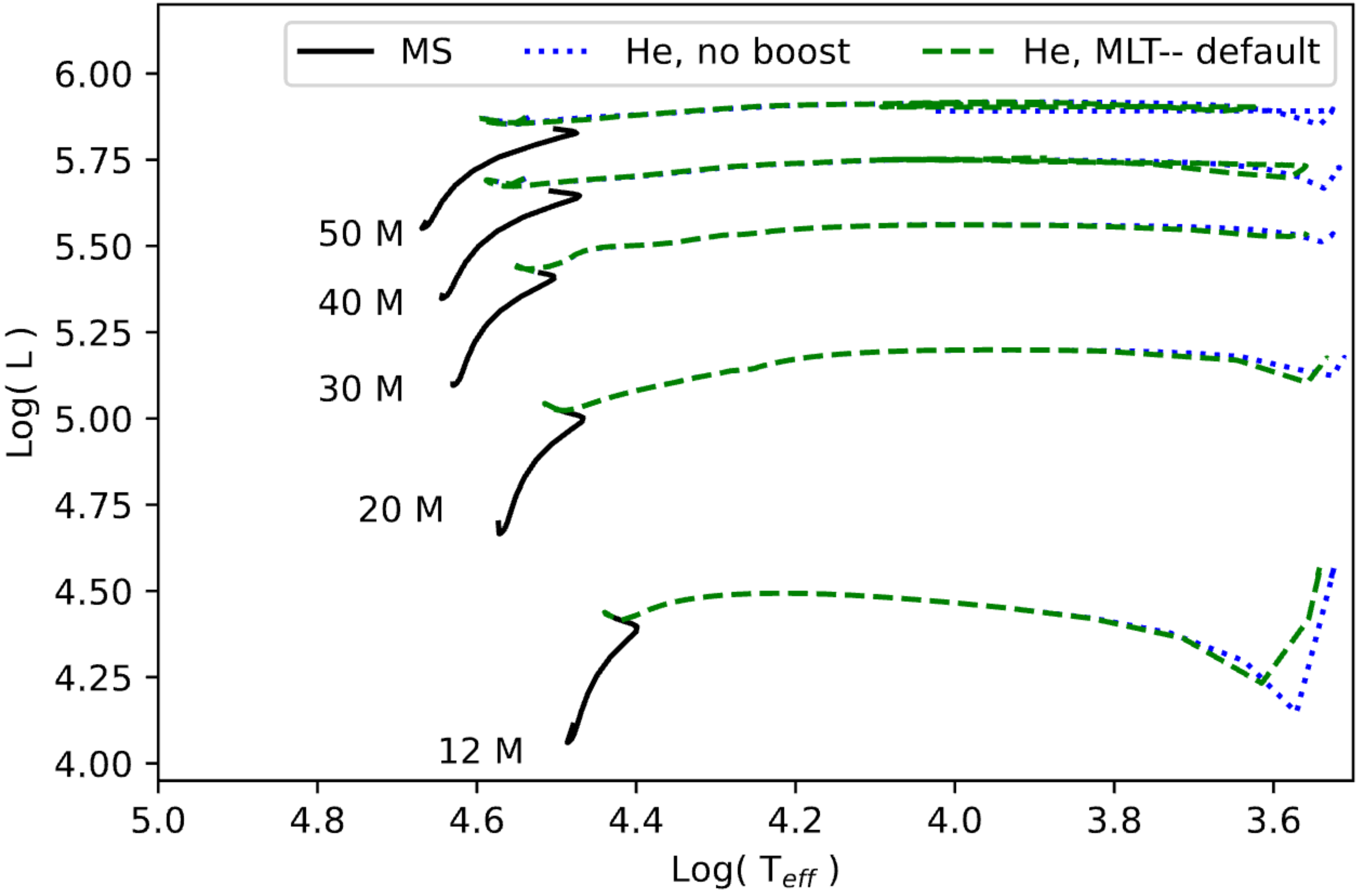
Wednesday, 19 June 2024, recapping labs from Day 2 (Tuesday)

REMINDER: YESTERDAY'S LAB STRUCTURE

- Minilab 1: The impact of "flux engineering" on the outer stellar structure
- Minilab 2: The impact of mixing length on stellar radius + local and global thermal timescales
- Minilab 3: Mass loss and the transition to stripped-envelope stellar structure

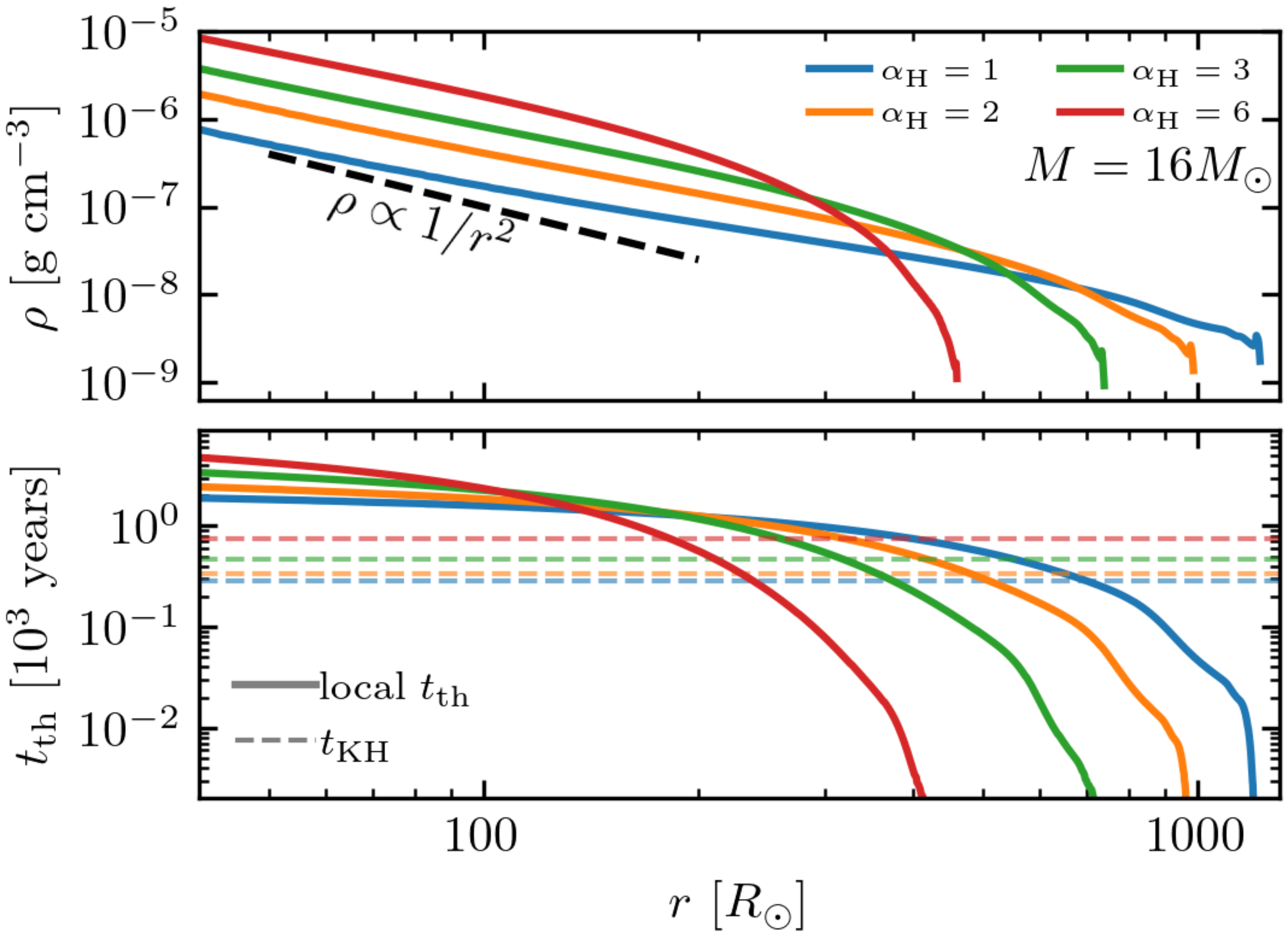
WHAT WE LEARNED (MINILAB1)

- Massive stars are very luminous!
- When they locally exceed the Eddington limit, we need to engineer a way to keep the star from trying to blow itself apart and crash the timestep.
- This impacts HR diagrams & surface properties!



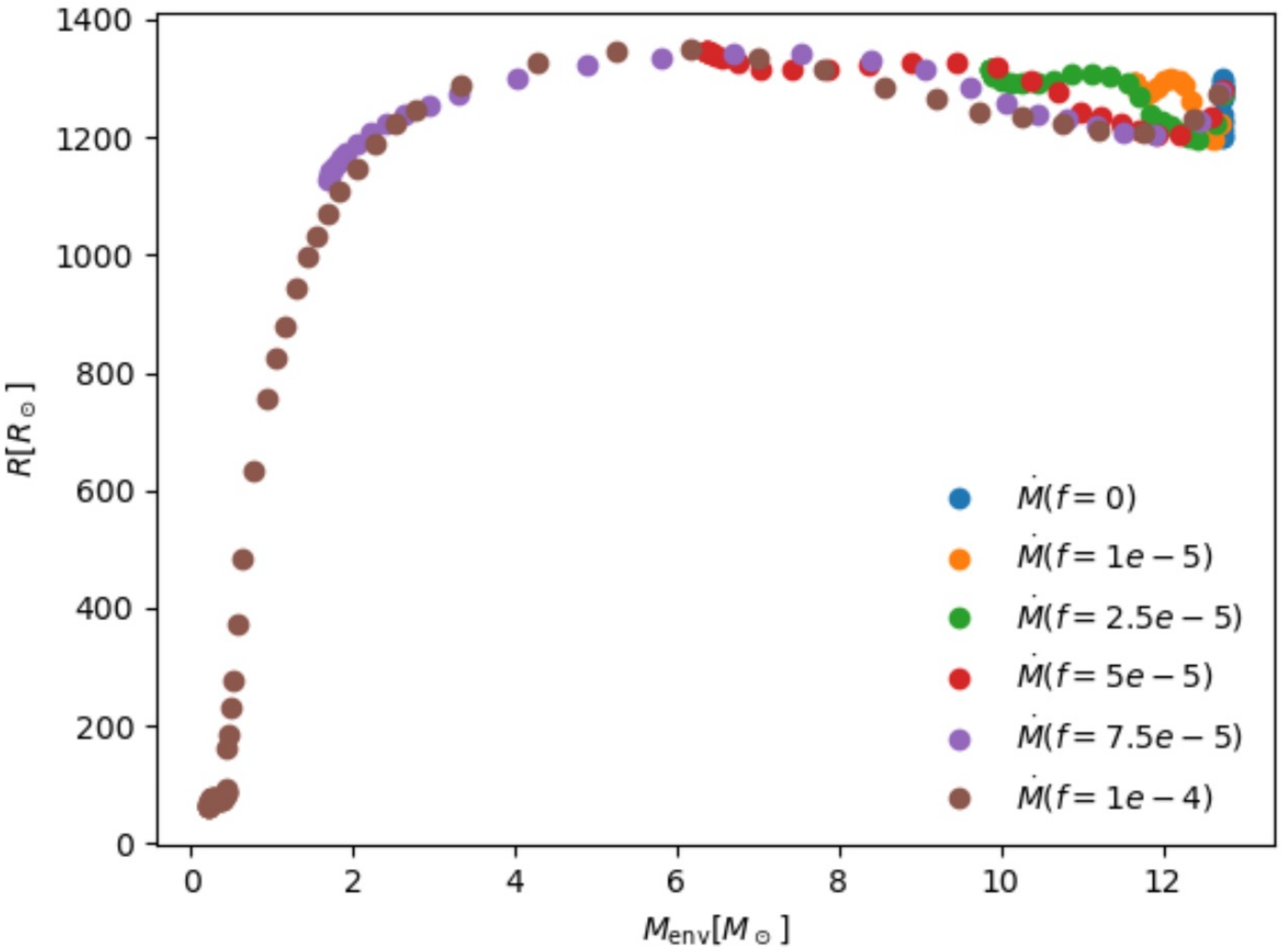
WHAT WE LEARNED (MINILAB2)

- Evolved massive star envelopes are convective (if sufficiently massive)! Thus, your assumed mixing length impacts the stellar radius.
- The radius then is factored into t_{KH}= (stay tuned for Thursday and Friday's labs!) – but reminder that the *local* thermal time varies even more!



WHAT WE LEARNED (MINILAB3)

- The mass-loss rate impacts the envelope mass (perhaps duh)!
- If the envelope mass is sufficiently small, the star can't support such a large convective envelope!
- This leads to an even wider variety of envelope structures / stellar radii



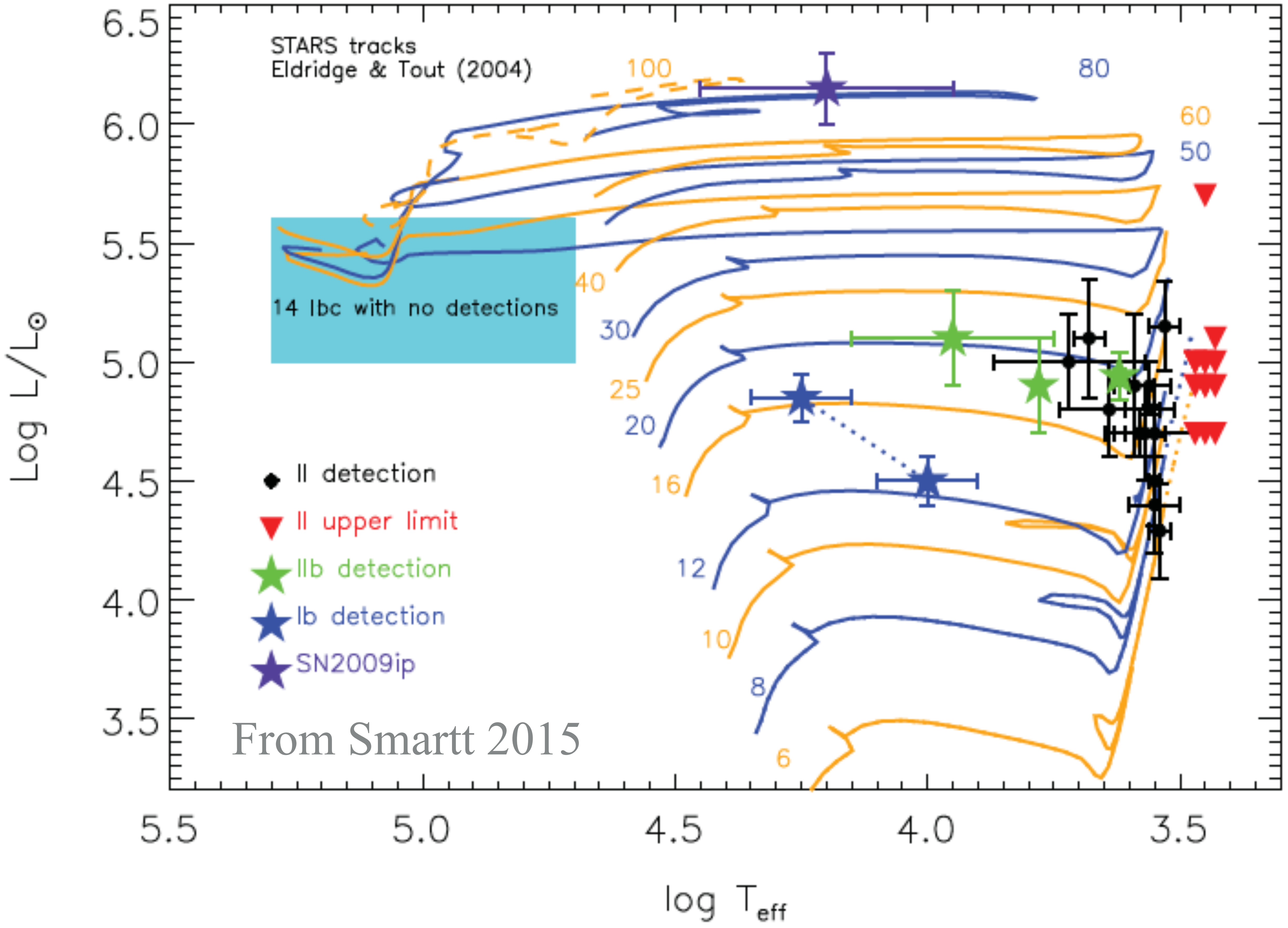
WHY DOES THIS MATTER?

CONNECTIONS TO SUPERNOVAE:

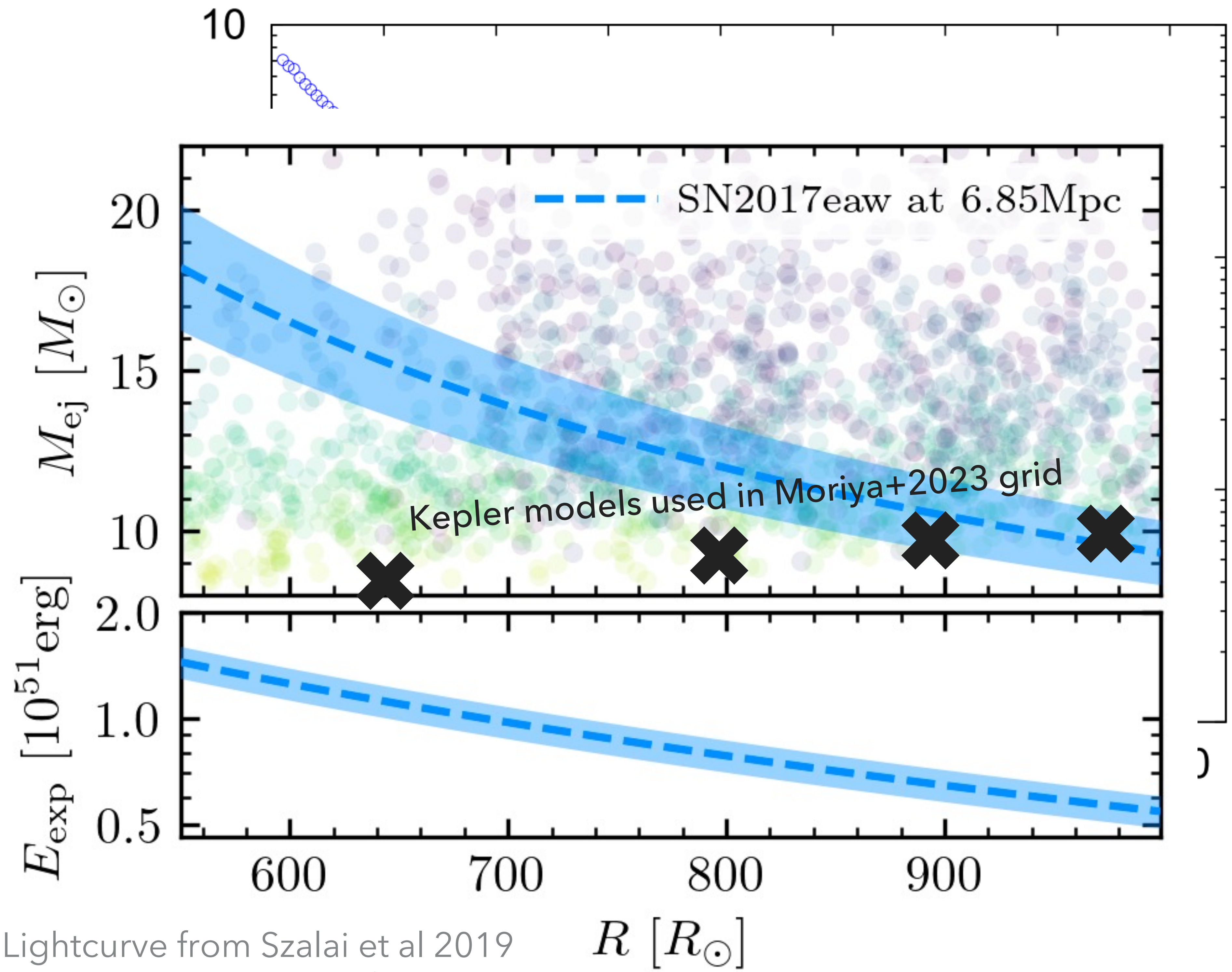
CORE PROPERTIES DETERMINE EXPLOSION ENERGY, REMNANT

ENVELOPE PROPERTIES DETERMINE STELLAR OBSERVABLES AND SUPERNOVA EMISSION

SN PROGENITORS IN NEARBY GALAXIES: COOL SUPERGIANTS



THE IMPORTANCE OF THE STELLAR RADIUS (LAB2)



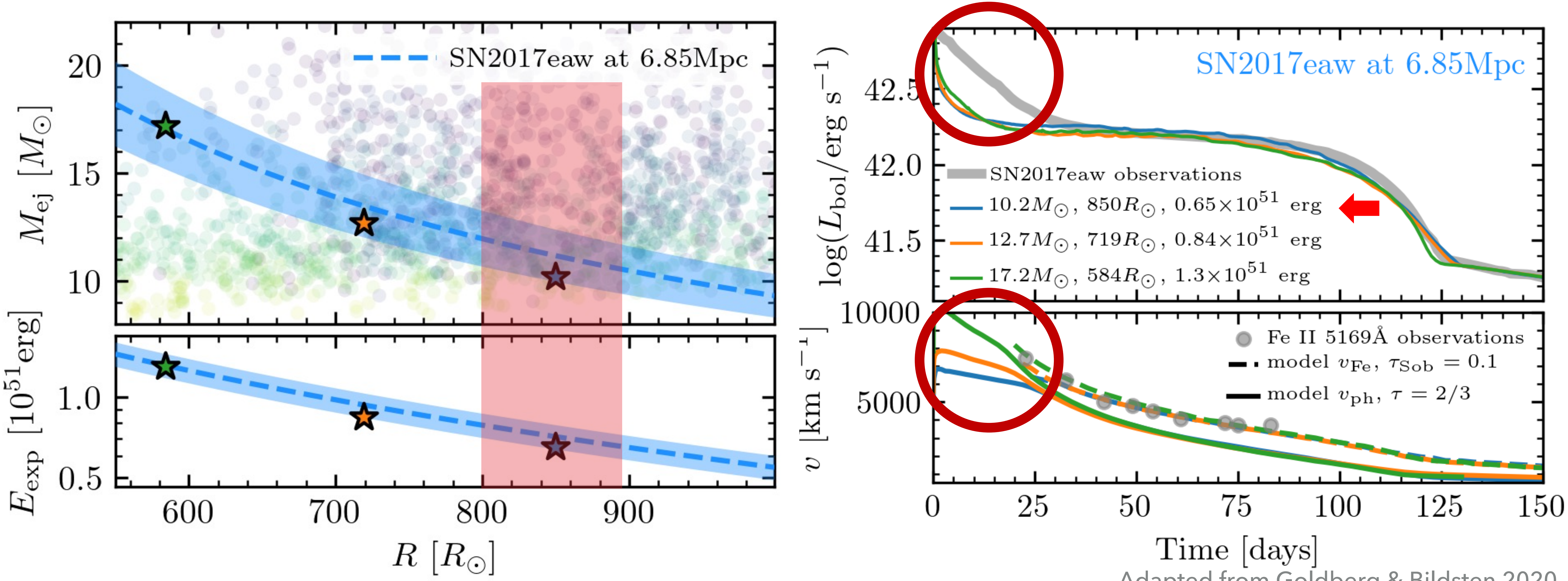
Lightcurve from Szalai et al 2019
Using scaling relations from Goldberg+2019

- Given supernova properties, semi-analytic scaling laws & modeling yield *families* of M_{ej} and E_{exp} as a function of R
- How well do we theoretically constrain M_{ej} vs R?
- If we fit observations and recover R, is that real, or an artifact of our grid?

EXTRACTING EXPLOSION PROPERTIES FROM LIGHTCURVES

- Plateau velocity is a standard candle w/ Luminosity; does *not* identify a unique solution!

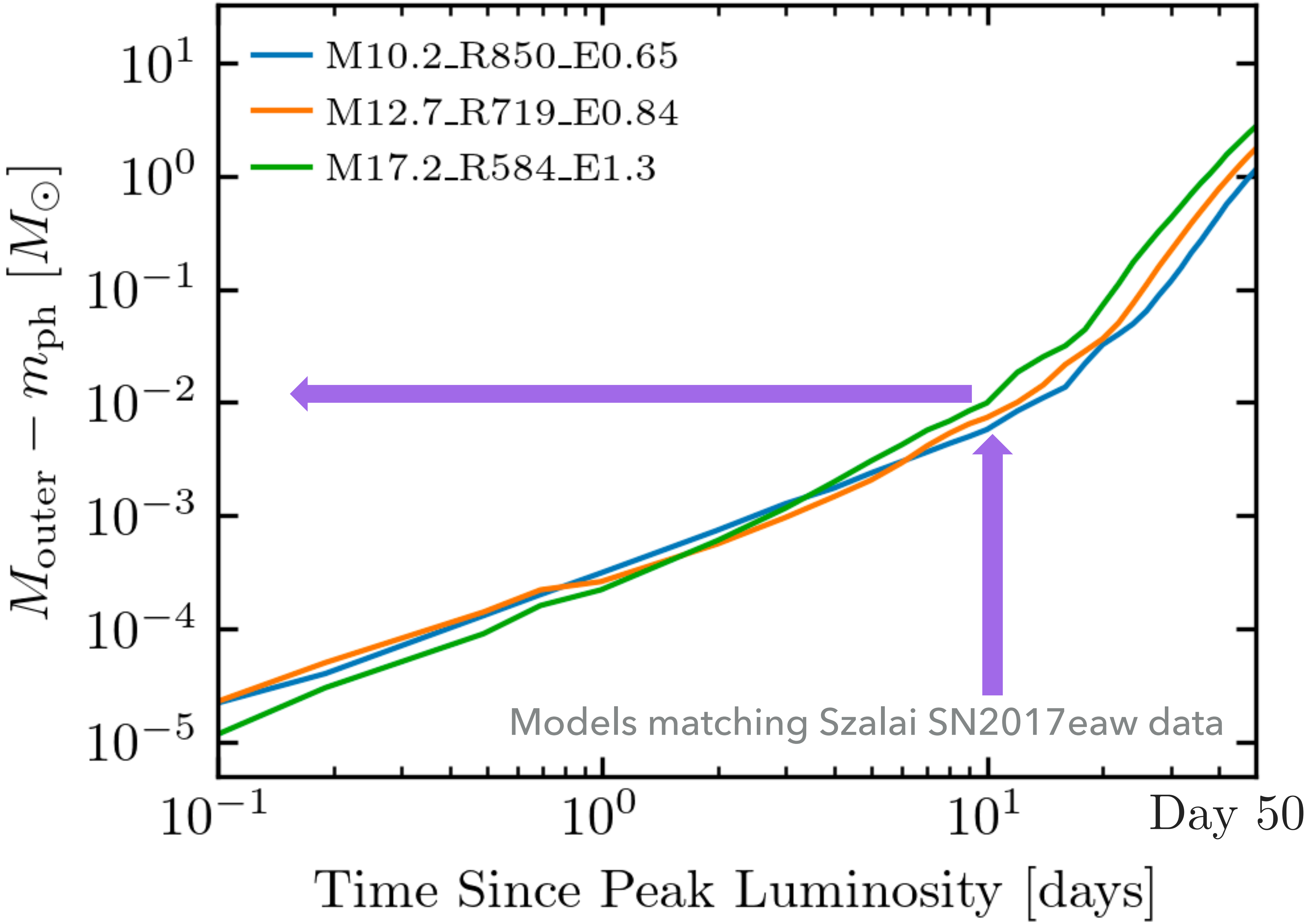
But given a progenitor R, E_{exp} & M_{ej} can be inferred



Adapted from Goldberg & Bildsten 2020

WHAT TO MAKE OF EARLY-TIME EMISSION?

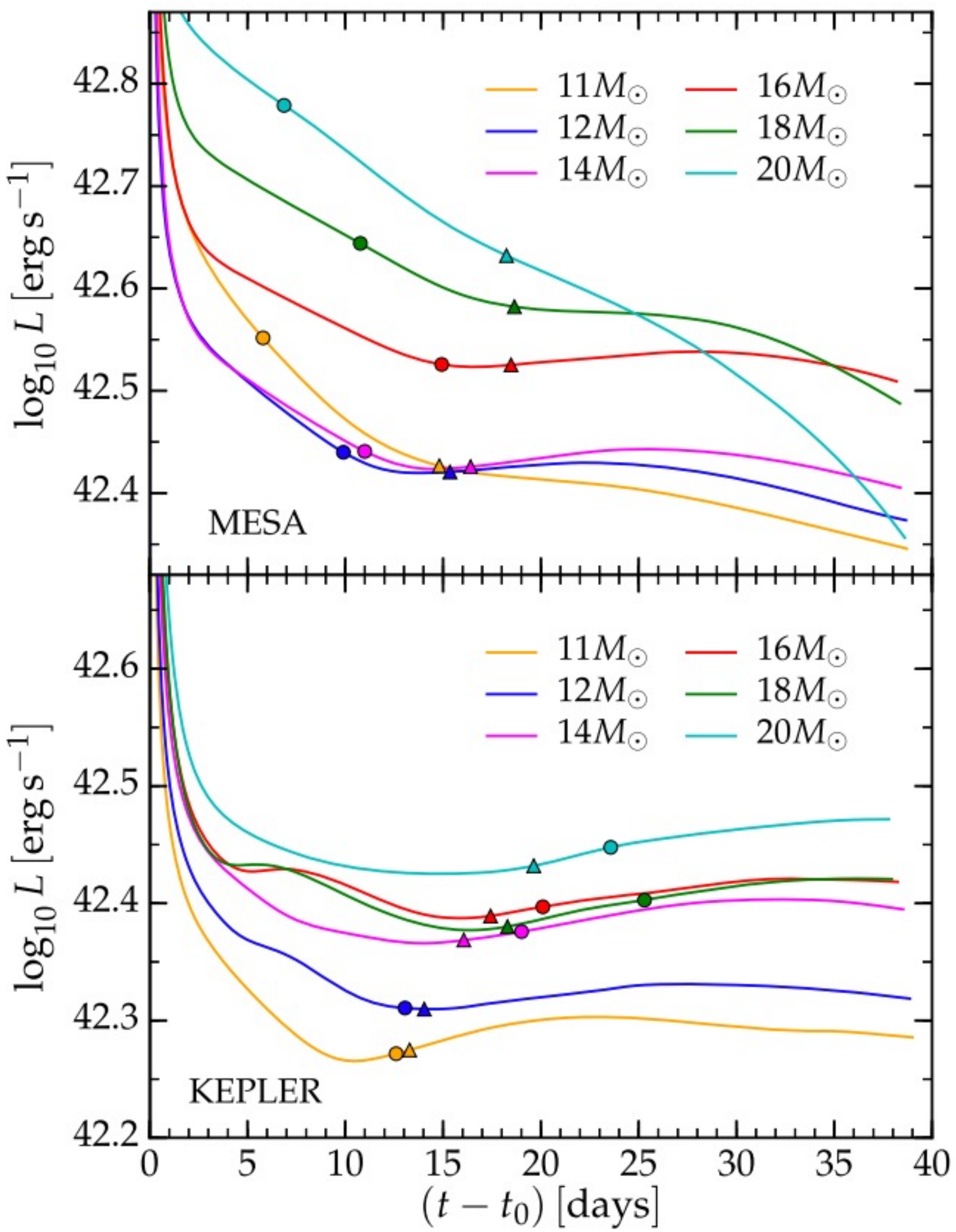
- First ~20 days of the SN = shock-cooling of the outermost ~**0.01-0.1$M_\odot$**
- **What does the star look like there?**

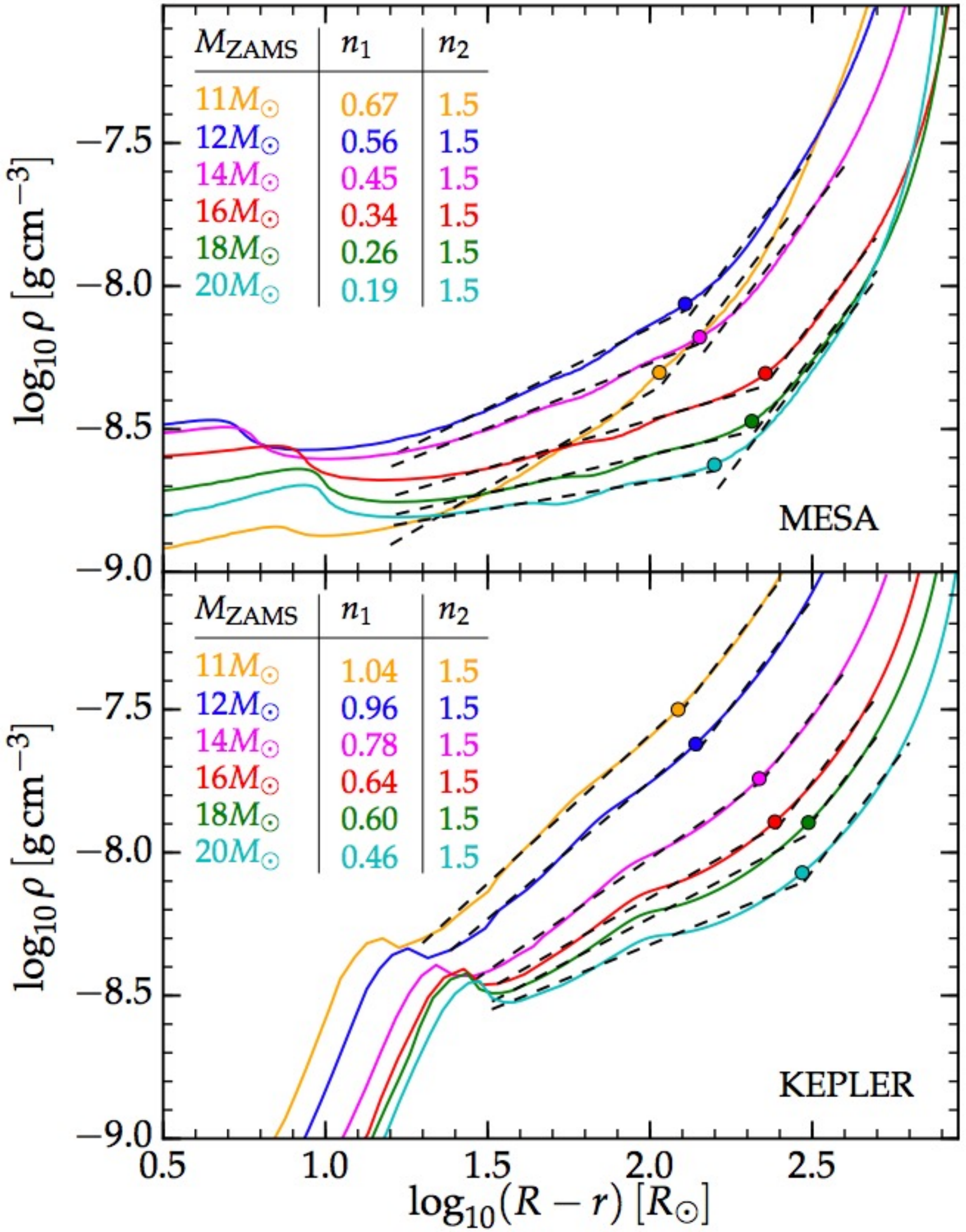


EARLY-TIME SN SENSITIVE TO "SURFACE" & SURROUNDINGS (LAB1)

Figures from Morozova+16

- Outer density profile varies w/ different physical and "engineering" assumptions
- This directly impacts early lightcurve predictions!





MASS LOSS (& BINARITY) LEAD TO A CONTINUUM OF TYPE II SNE (LAB3)

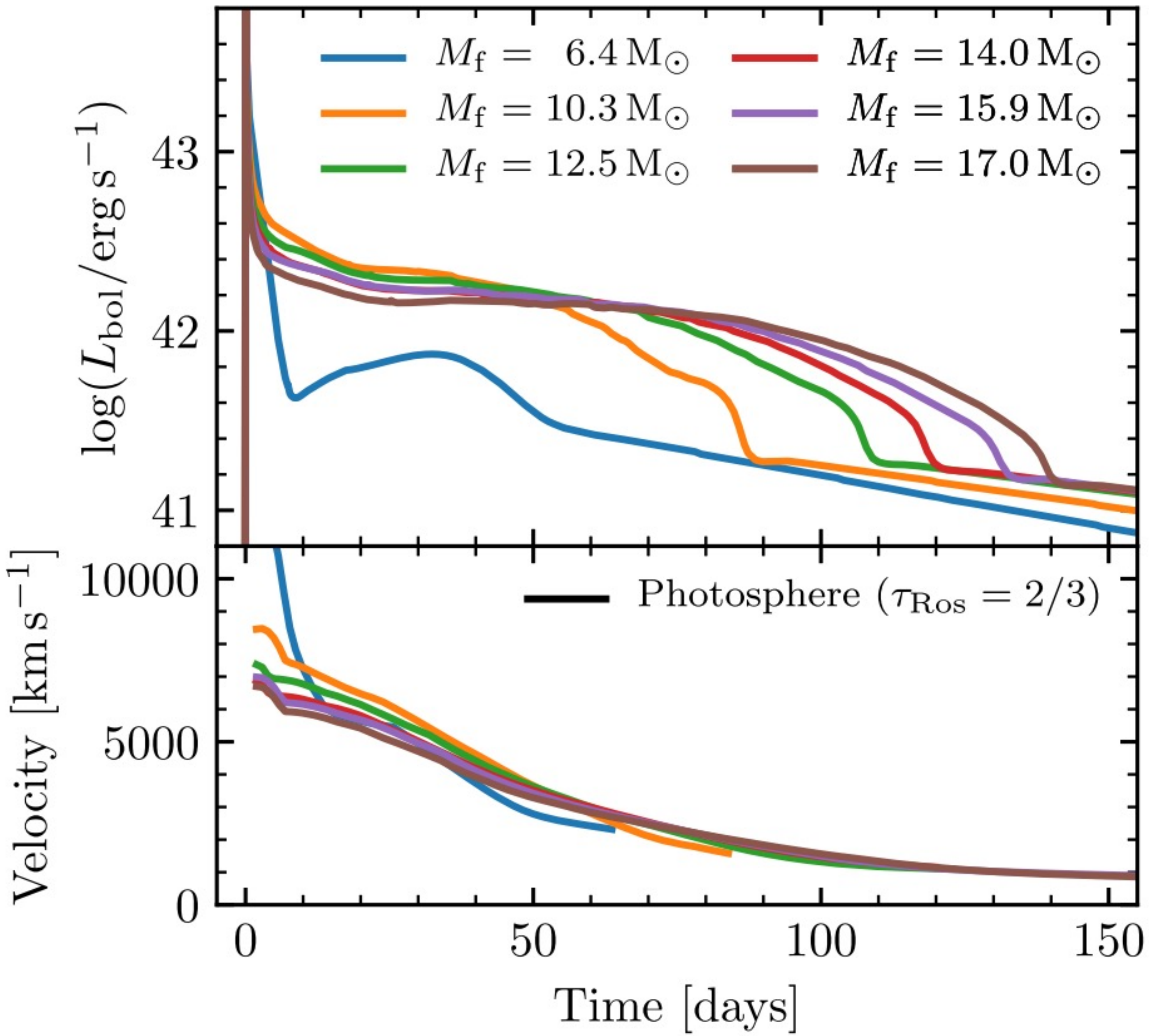


Figure from MESA IV Paxton et al 2018.

See also, e.g., Arnett 1996, Heger+2003, Bayless+15, Morozova+15, Eldridge+2019, Hiramatsu+21, Ercolino+24, Dessart+24 & others & discussions & references therein

WHEN DOING STELLAR PHYSICS, KEEP IN MIND YOUR CHOICES IN “STELLAR ENGINEERING”

THANK YOU!!!

QUESTIONS?

COMMENTS?

THOUGHTS?

CONCERNS?

VIBES?