Composition and Stellar Structure in TDEs using FLASH+MESA

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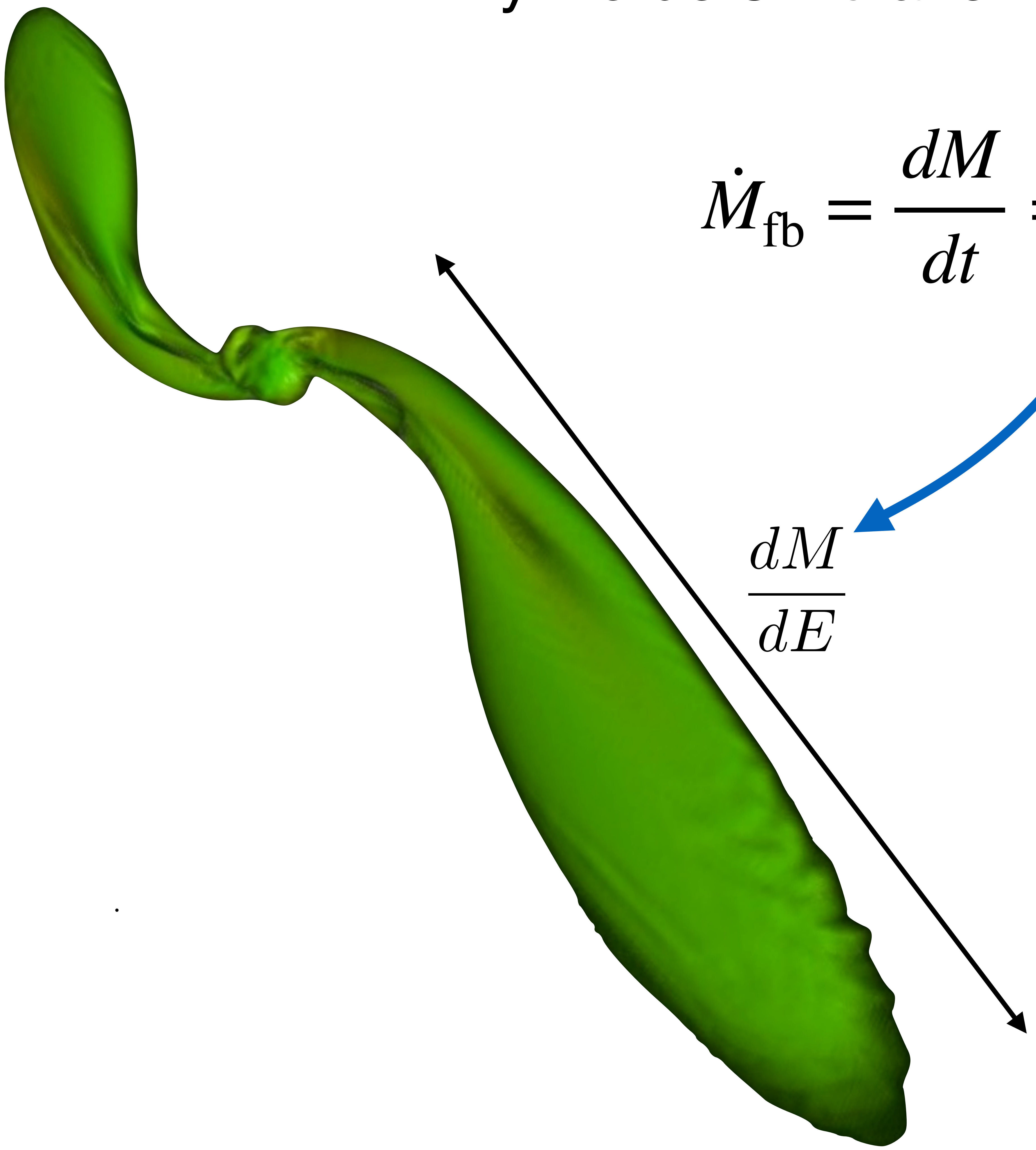
Why we do simulations to determine the fallback rate



$$\dot{M}_{\rm fb} = \frac{dM}{dt} = \frac{dM}{dE}\frac{dE}{dt}$$ = rate of return of material to pericenter.

$$\frac{dM}{dE}$$

$$\frac{dE}{dt} = \frac{1}{3}(2\pi GM)^{2/3}\ t^{-5/3}$$

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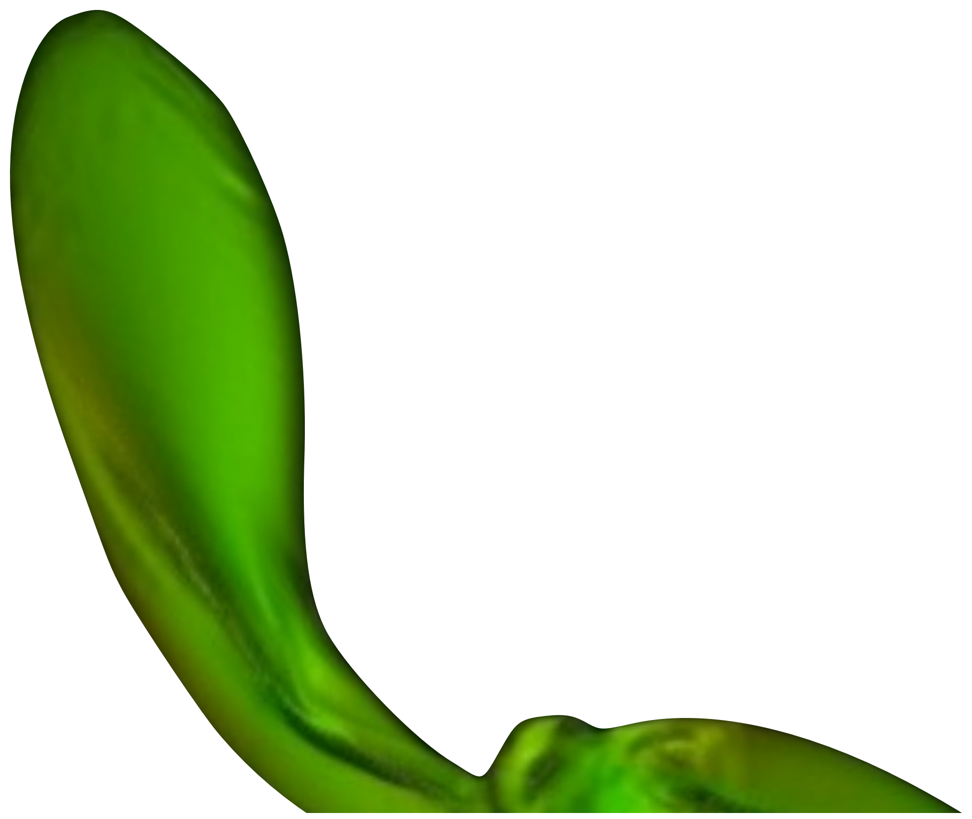

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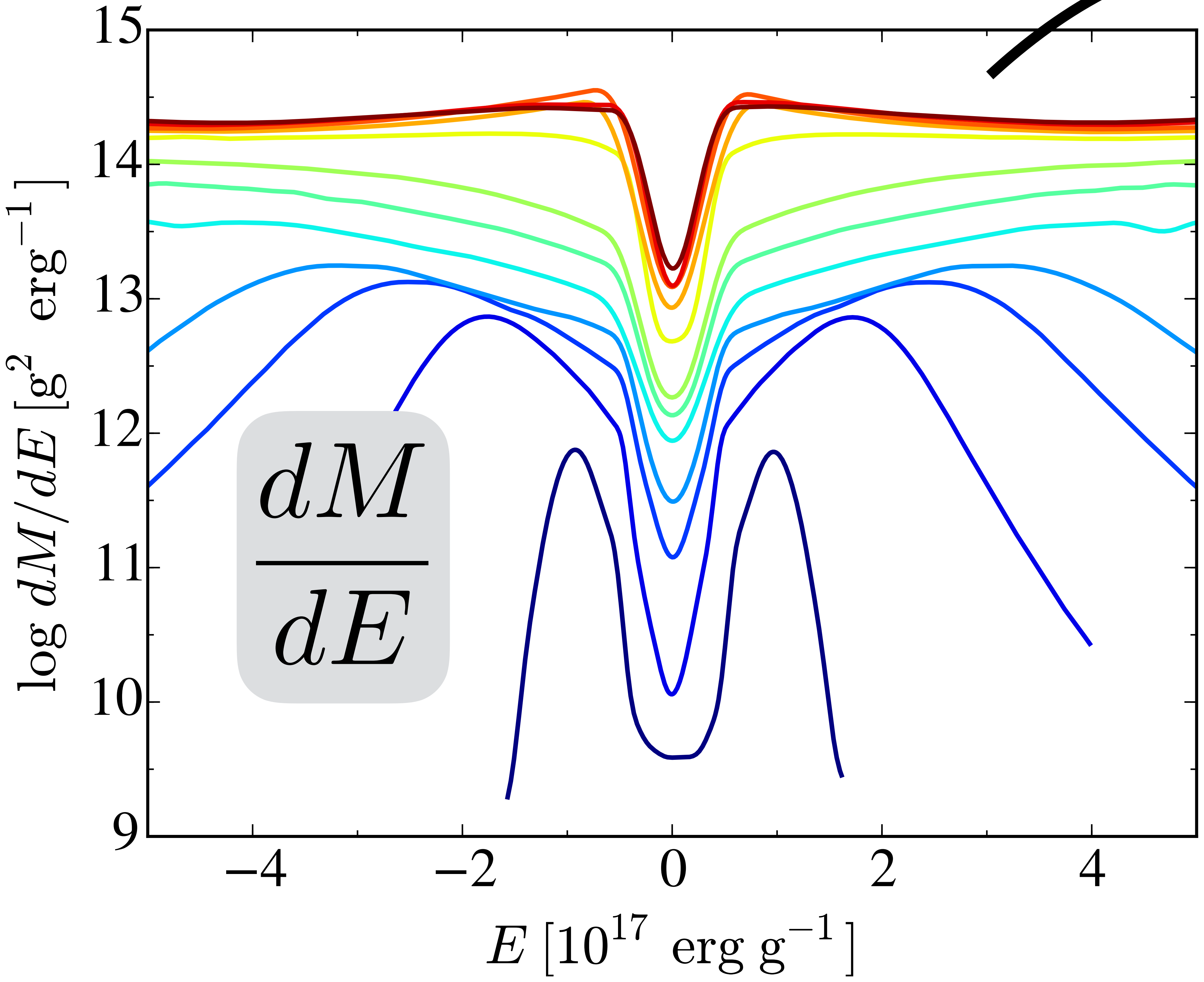
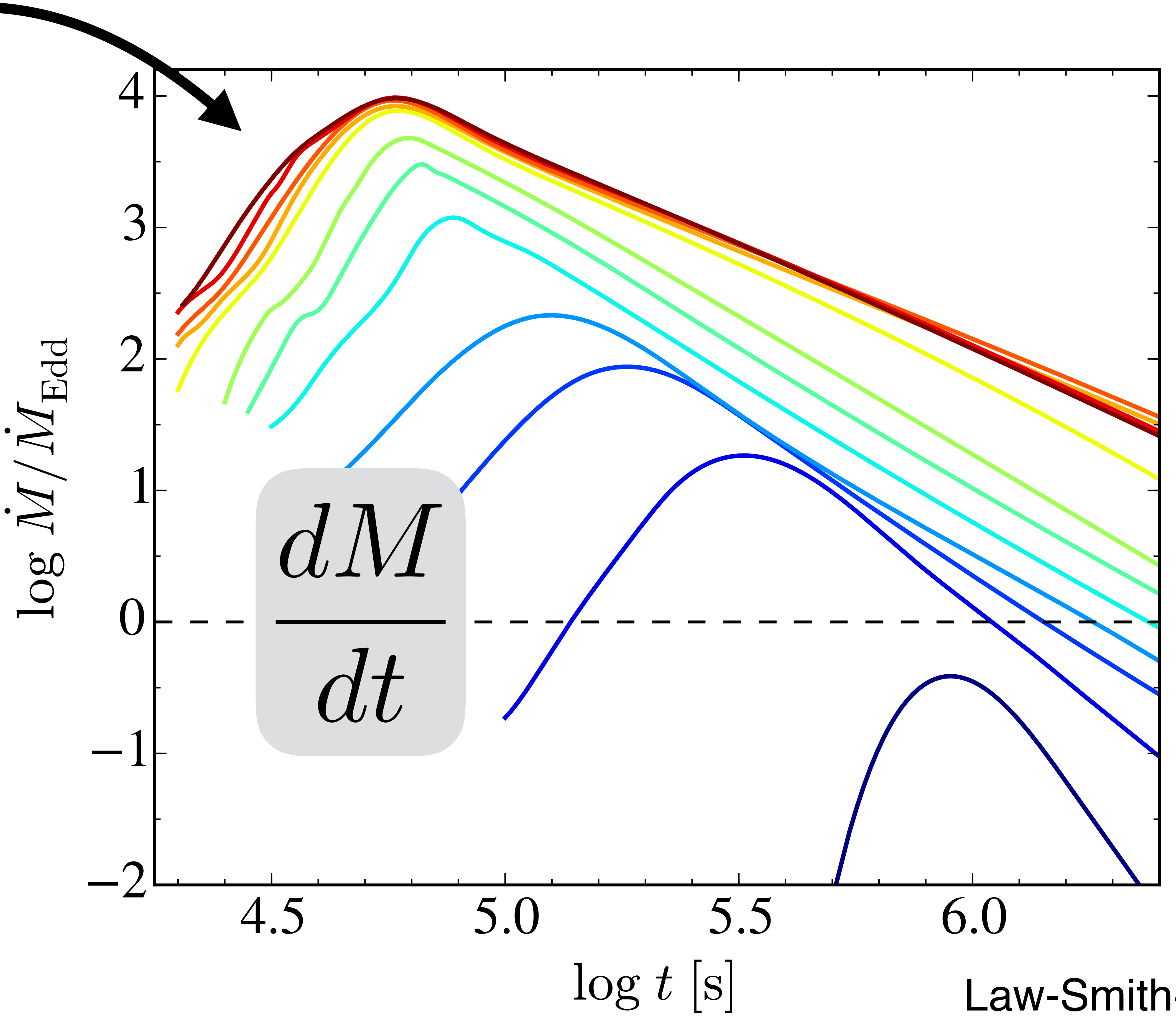
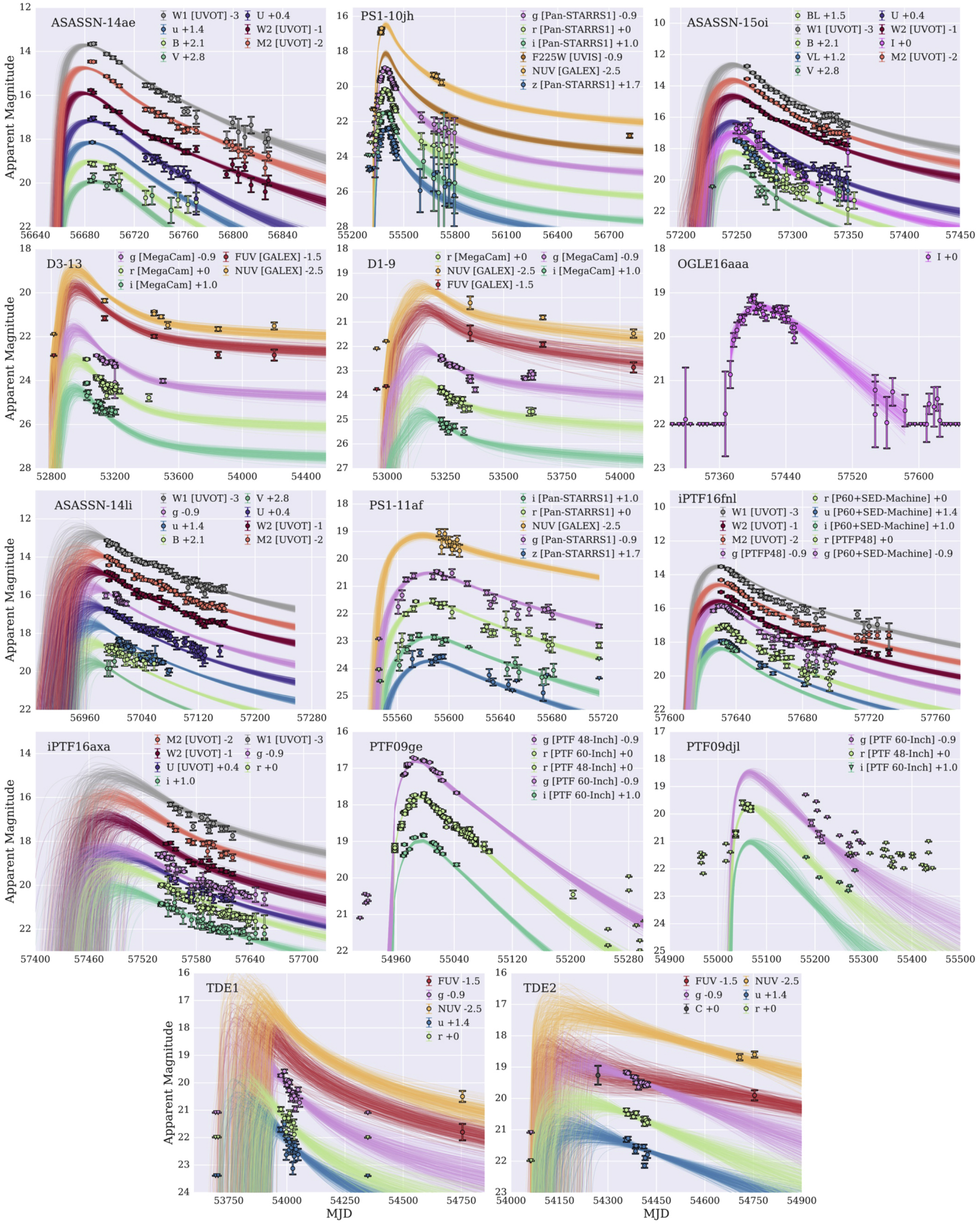
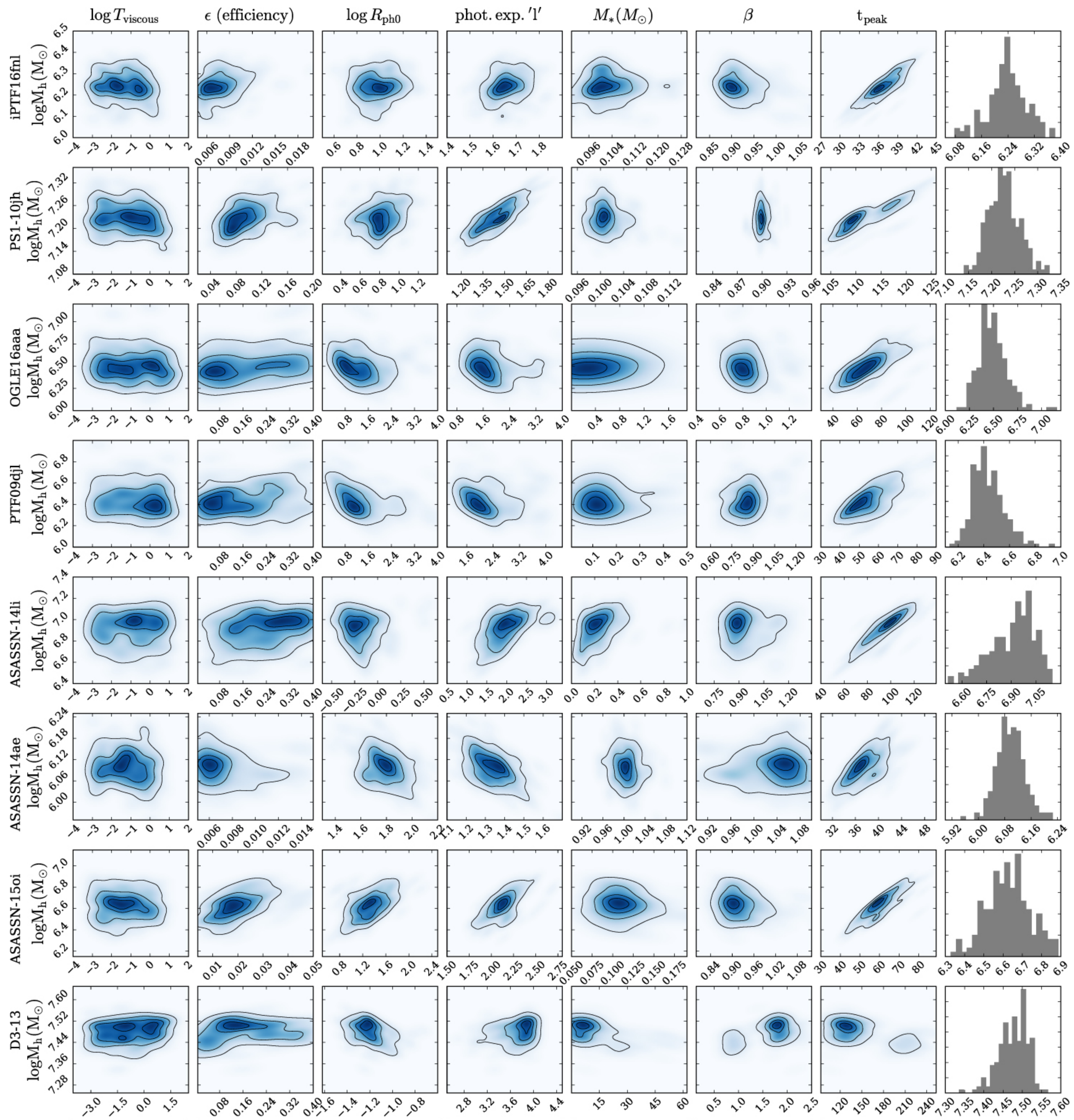




Law-Smith+ 2017b

Can constrain $M_{\rm BH}$ and other properties from well-sampled observations





Mockler+ 2019

FLASH+MESA

- **Setup**
  - Build stars in MESA
    (1D stellar evolution code)
  - Calculate their disruption in FLASH
    (3D adaptive-mesh / grid / Eulerian hydrodynamics code; Newtonian)
- **Features:**
  - Accurate stellar structures
  - Composition: track 49 elements
  - Extended Helmholtz EOS

- **Goals (some more long-term than others)**:
  - Determine parameters from a given TDE observation: BH mass, spin, stellar mass, age, efficiency, etc. Break degeneracies in fitting.
  - Tie composition directly to spectra!
  - Probe nuclear stellar populations, dynamical mechanisms in galactic centers.
  - Tie to QBS/E+As. What kind of star? Related to SFH?
  - Help understand other parts of basic TDE theory, e.g. emission mechanism(s).

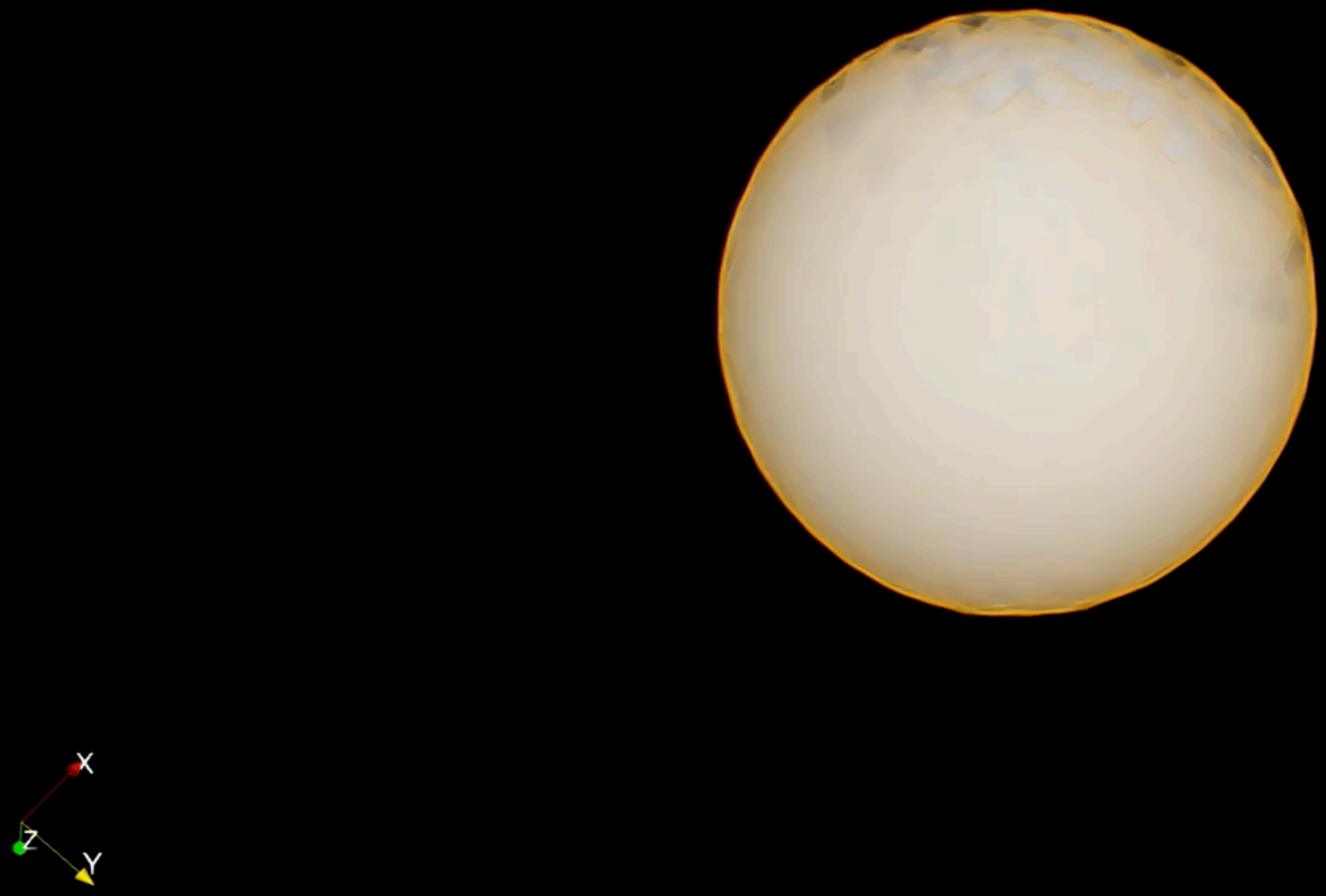
$M_{\rm BH} = 10^6 M_\odot;\; M_* = 1 M_\odot;\; R_\odot \approx 1.3 R_\odot;\; \text{age}_* = \text{TAMS};\; \beta = 1$

code: FLASH

rest frame of star; zoomed in (not full box)

vis.: temperature volume rendering

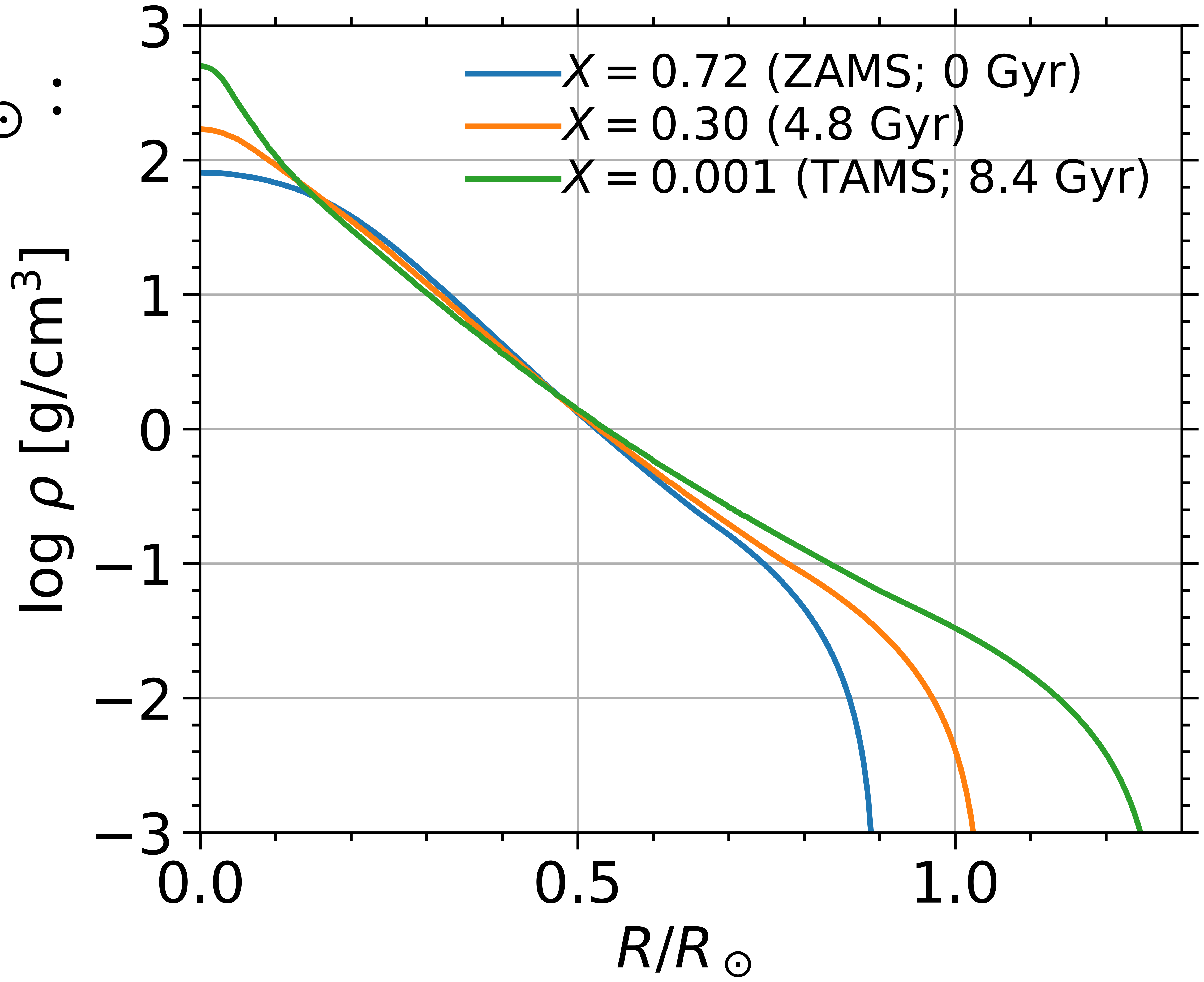
vis. time: $t - t_{\rm p} \approx -3 t_{\rm dyn} \rightarrow +10 t_{\rm dyn}$

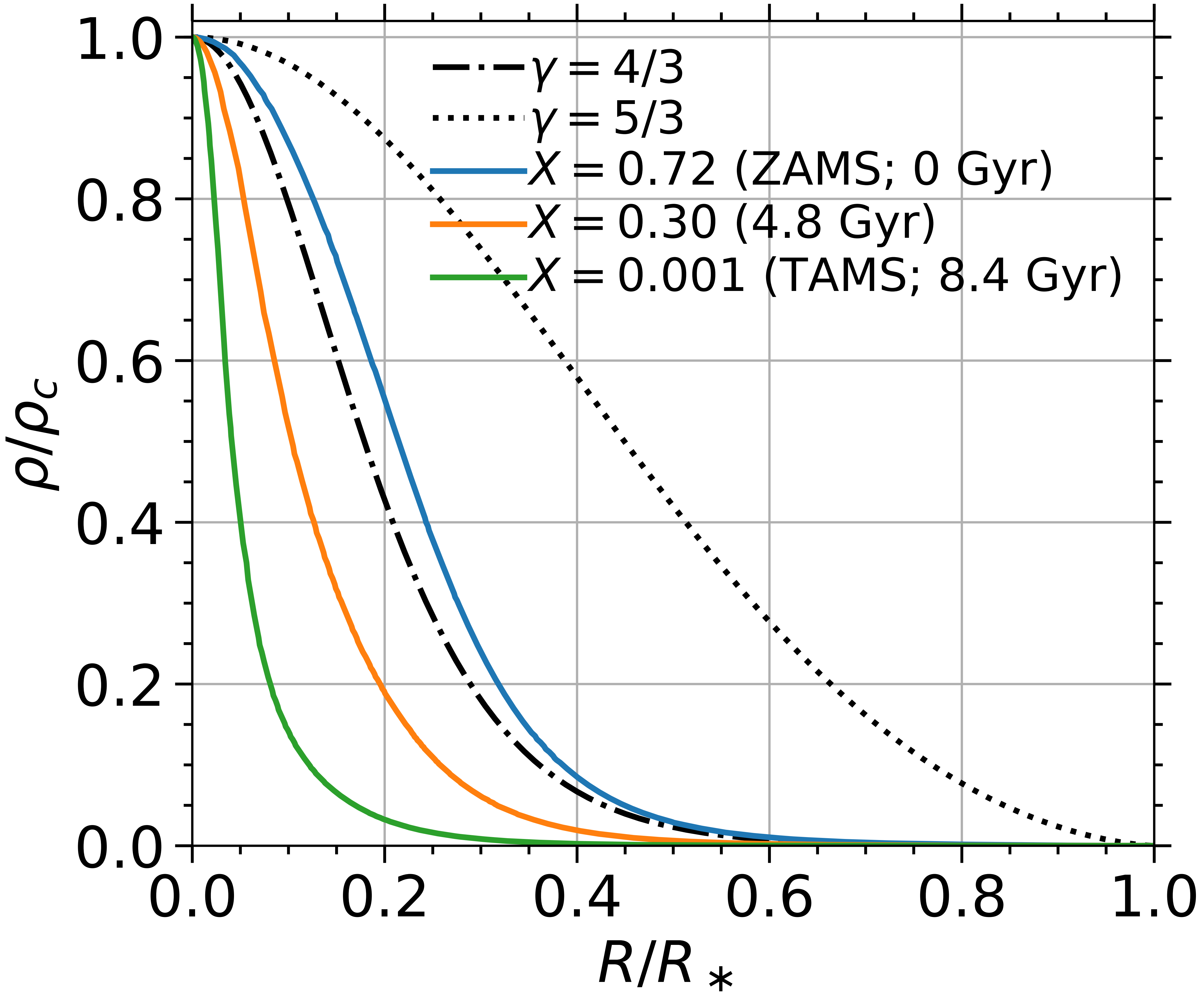


simulation from Law-Smith+ 2019, vis. credit: Nick Leaf / NVIDIA

Stellar structure: depends on mass and age

$1M_\odot$:





Central density increases by 6X, radius increases by 1.4X. ($3M_\odot$: radius increases by 1.8X)

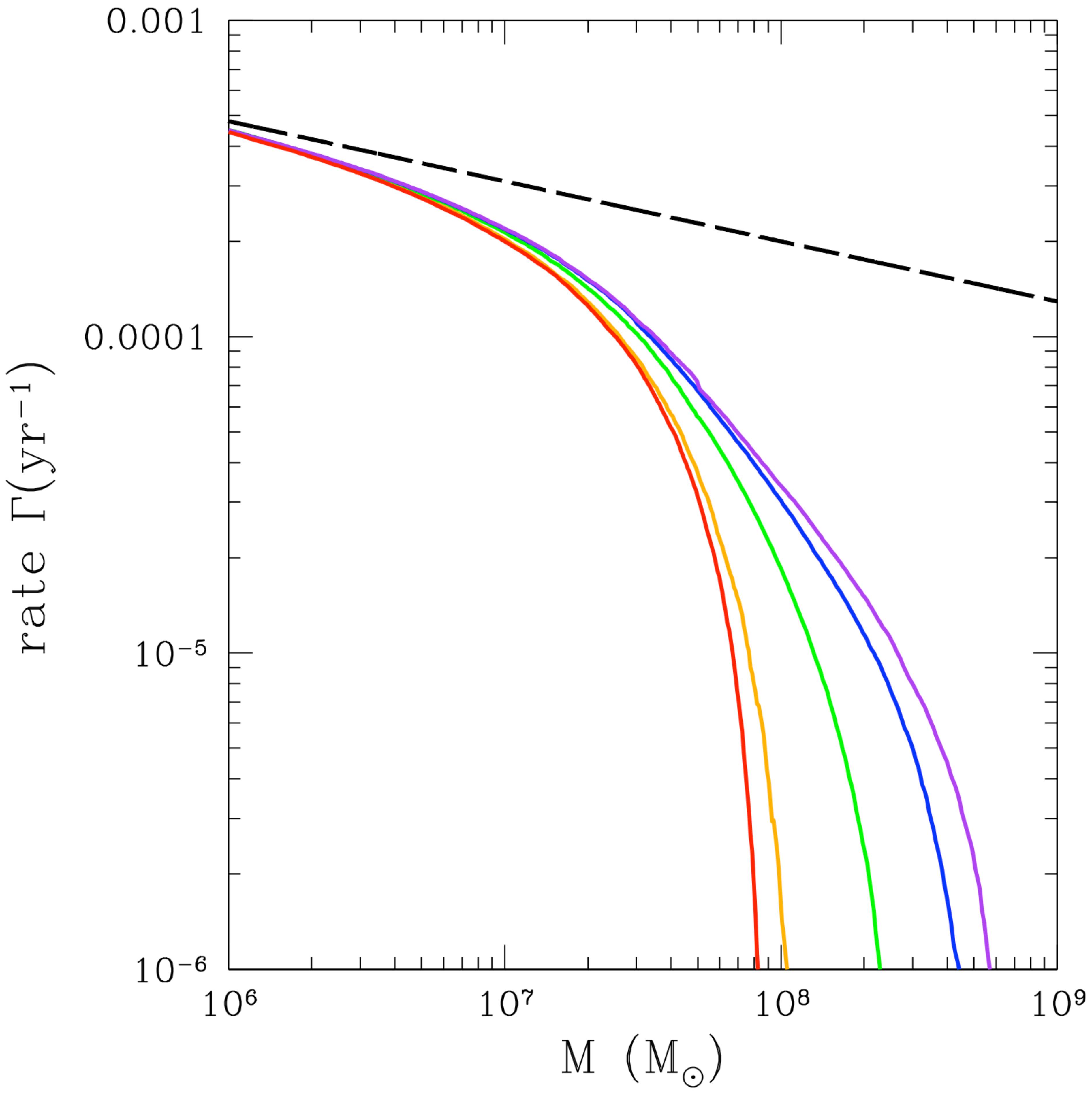
Polytrope is not a particularly good match for most ages.

Law-Smith+ 2019

Uncertainty on $M_{\mathrm{BH,max}}$ from stellar evolution ~~ uncertainty from BH spin

- The maximum BH mass for tidal disruption increases by a factor of ~2 from stellar radius changes due to MS evolution; this is equivalent to varying BH spin from 0 to 0.75 (e.g. Fig. 1 of Kesden 2012).

- BH spin determines the cutoff of the TDE rate as a function of BH mass (e.g. Fig. 4 of Kesden 2012).



Kesden 2012

Stellar structure and susceptibility

full disruption

grazing encounter

All panels same $t - t_{\rm p} \approx +3t_{\rm dyn}$

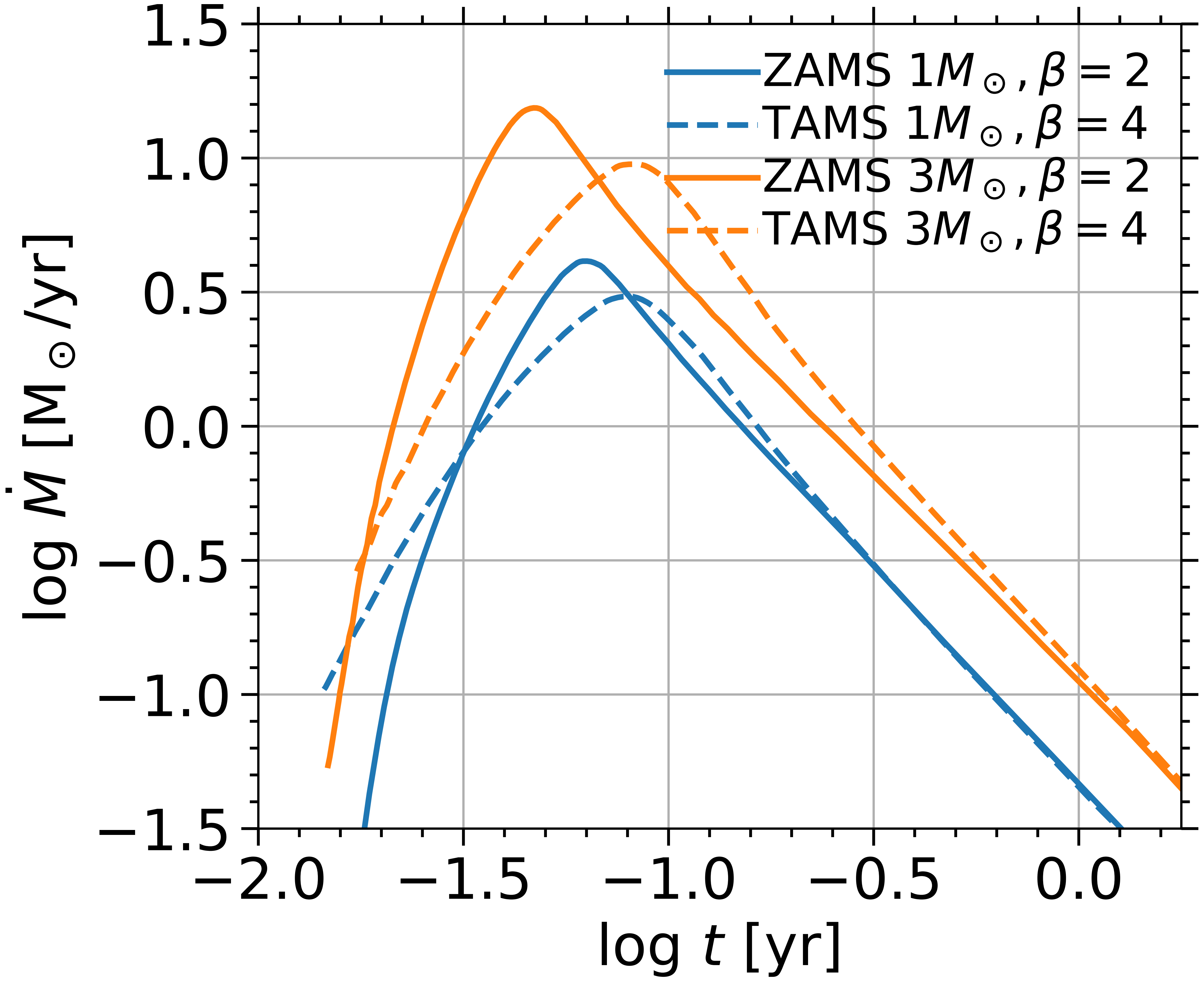
Law-Smith+ 2019

Shape of mass fallback rate curve varies with stellar age

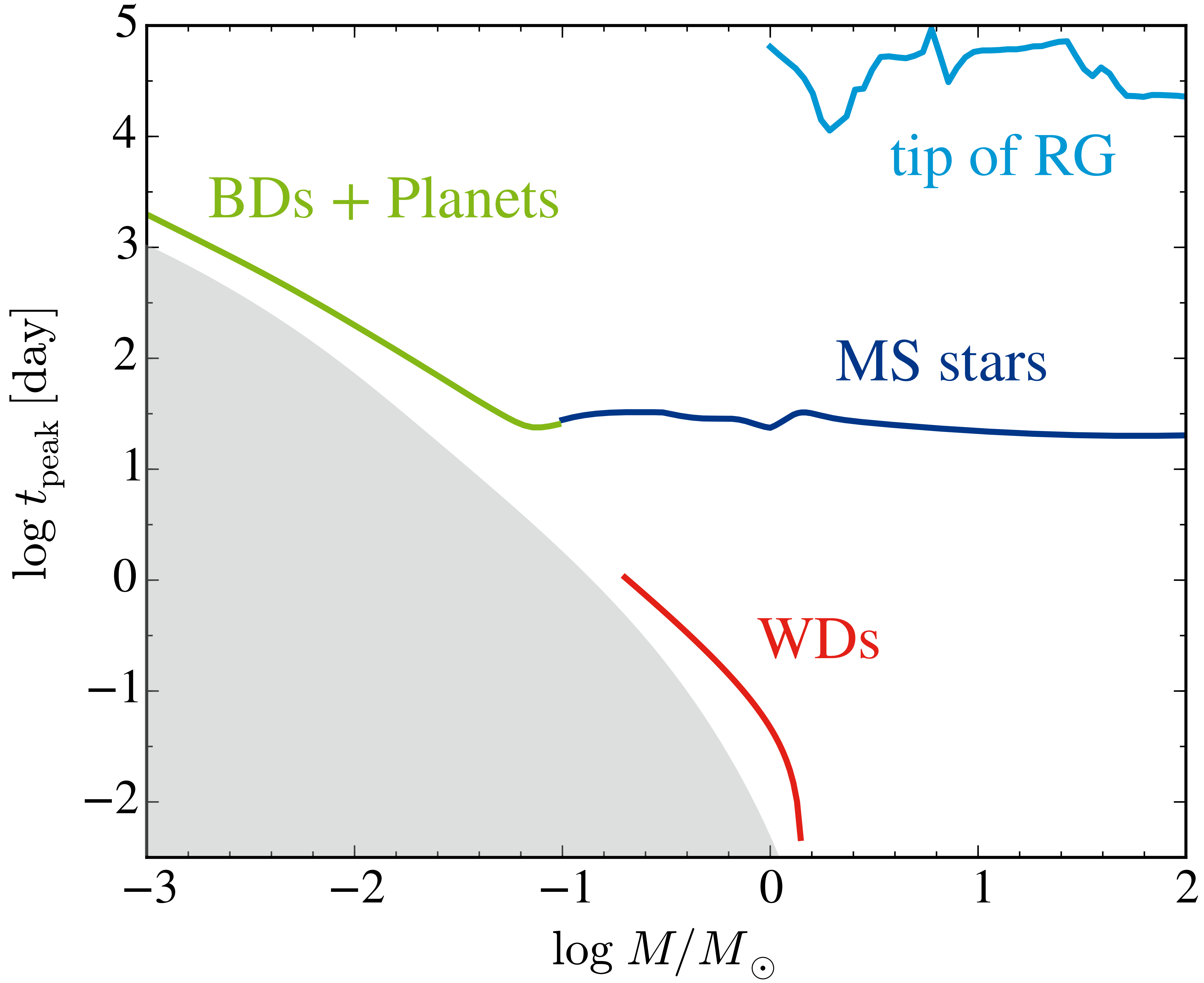
- Different shapes from Guillochon & Ramirez-Ruiz 2013
- $t_{\rm peak}$ increases with stellar age
- $\dot{M}_{\rm peak}$ decreases with stellar age

Law-Smith+ 2019

Example of a stellar mass dependence result:
peak fallback time depends ~weakly on stellar mass

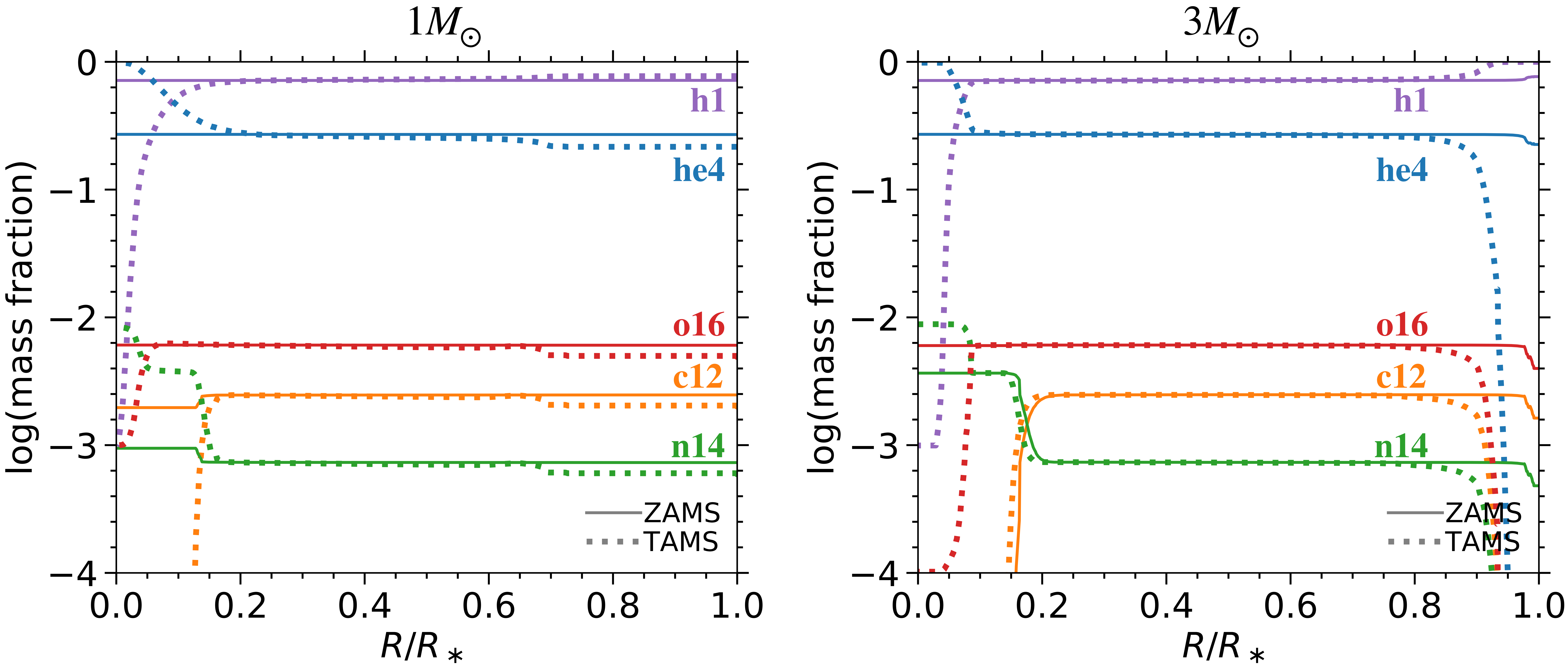


Law-Smith+ 2019



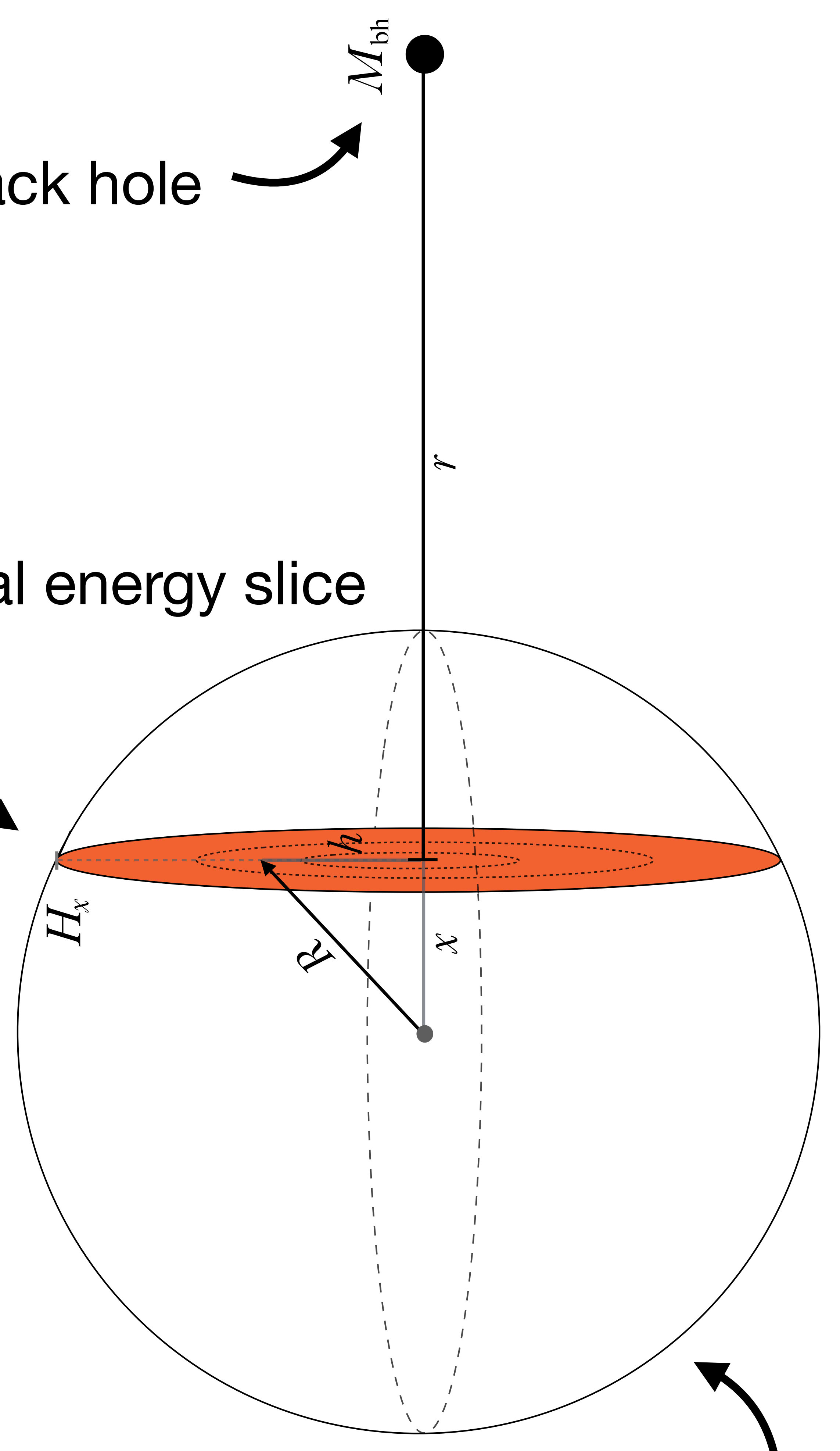
Law-Smith+ in prep.

Composition depends on stellar mass and age. MESA profiles (= i.c.'s):

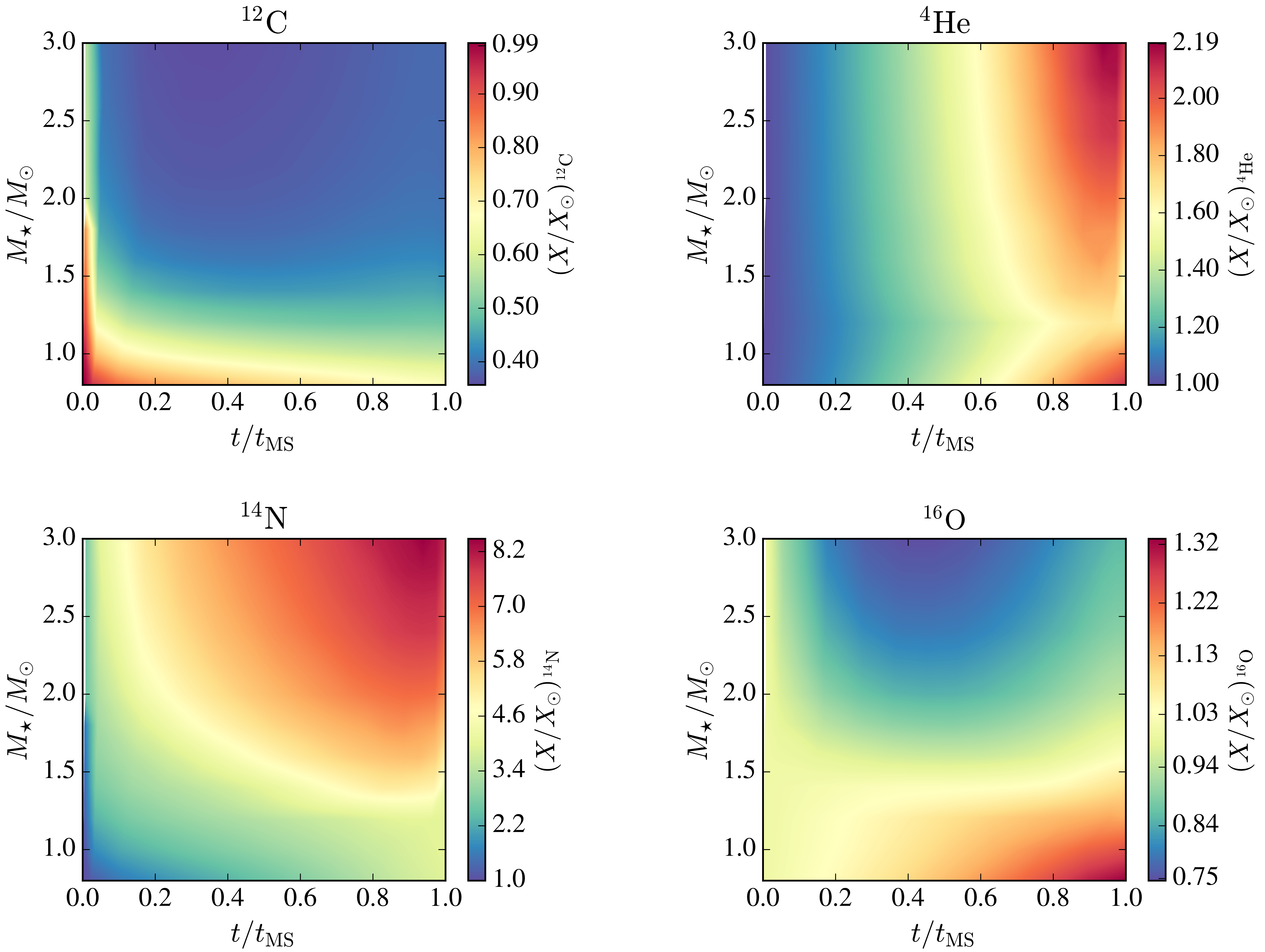


Law-Smith+ 2019

Predictions from analytic framework: fallback composition as fn. of age, mass

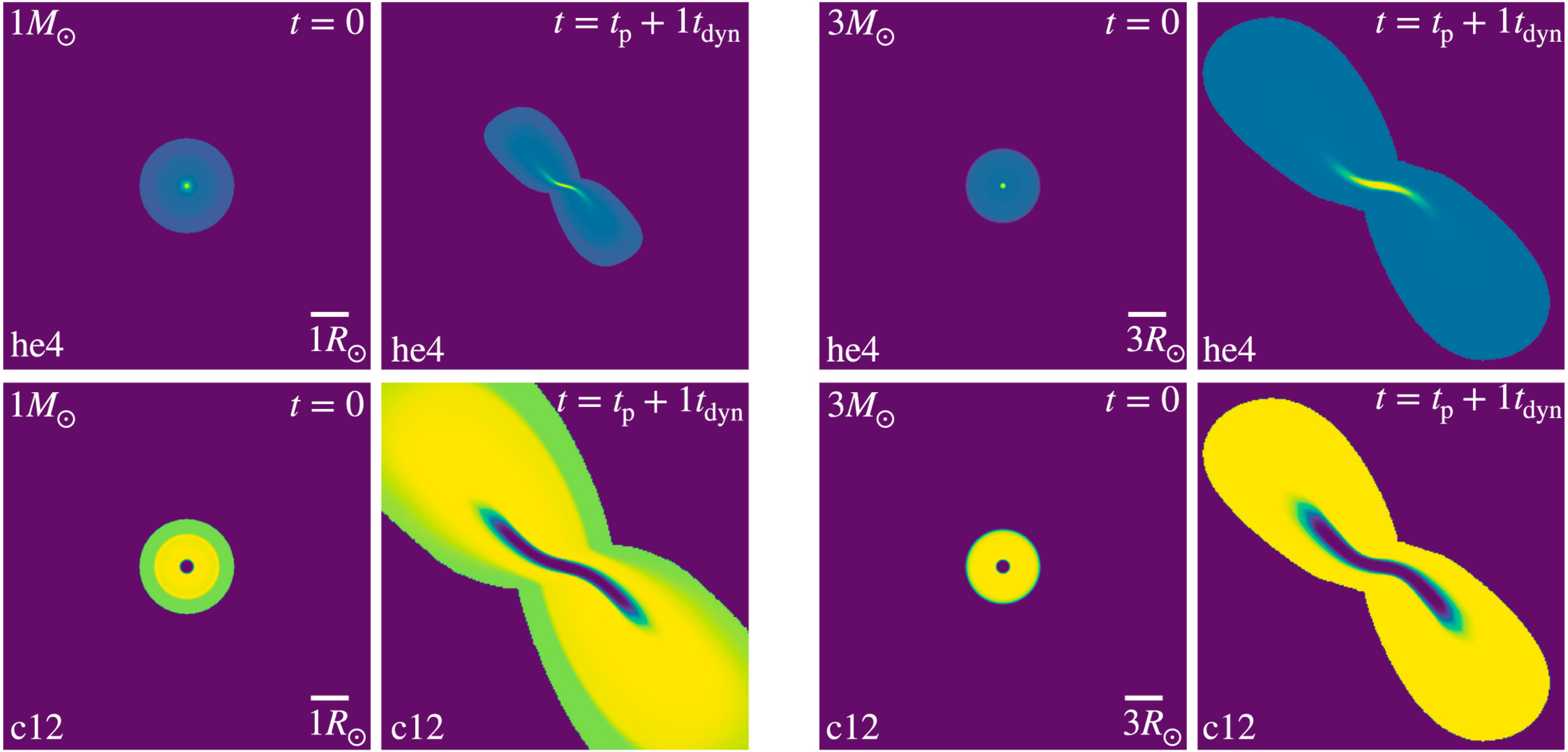


Lodato+ 2009



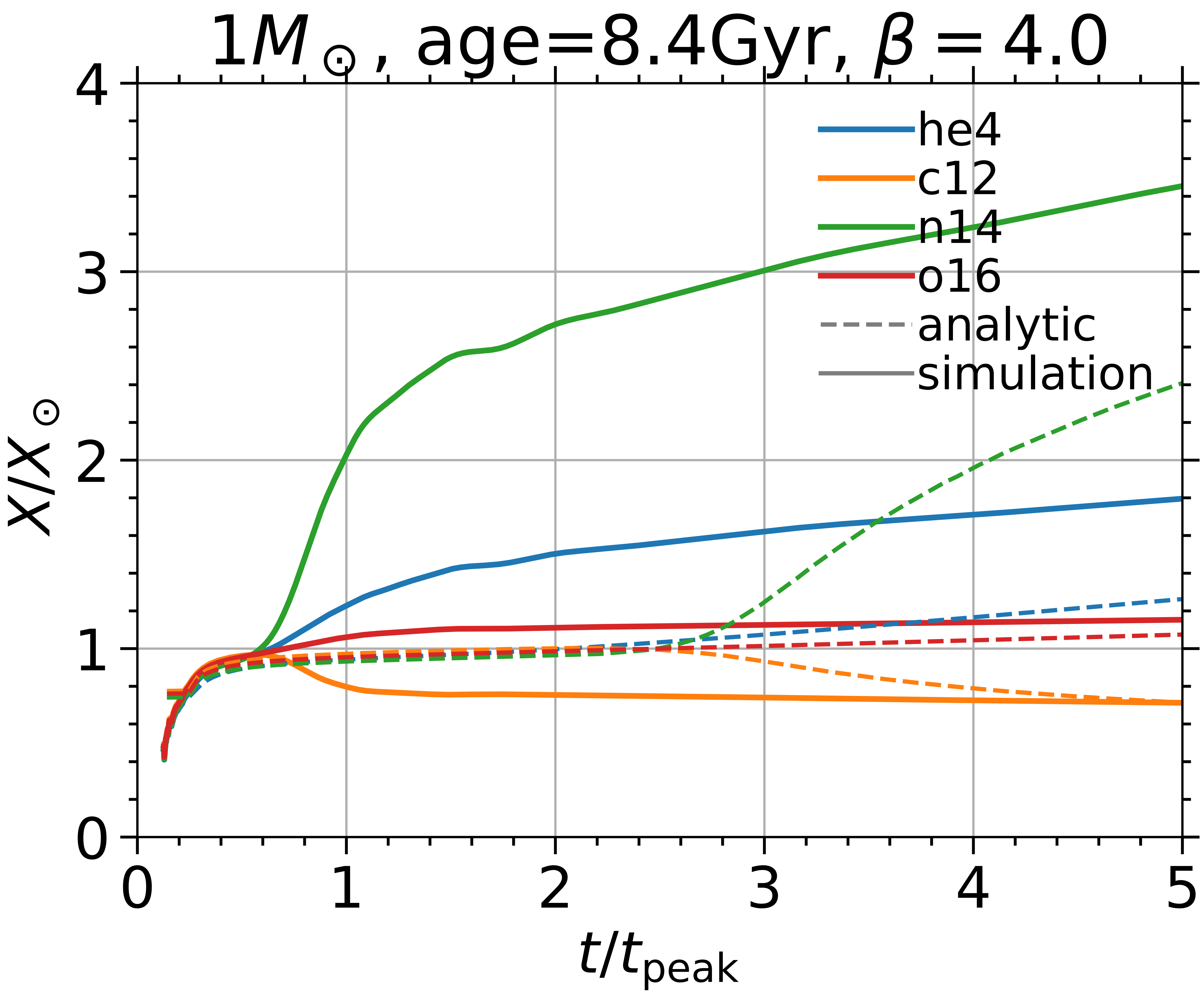
Gallegos-Garcia, Law-Smith, & Ramirez Ruiz 2018

Composition (hydro): strong mixing/rotation during disruption



Law-Smith+ 2019

Composition: abundance anomalies at peak



Most striking results:

- N, He enhanced before/at peak
- C depleted before/at peak

$$\frac{X}{X_\odot} = \frac{\dot{M}_X/\dot{M}_{\rm H}}{M_X/M_{\rm H,\odot}}$$

Law-Smith+ 2019

Composition: abundance anomalies at peak; indicator of stellar mass

- Compositional anomalies in N, He, C, (O) can occur before the peak timescale for disruptions of MS stars.
- More massive stars generally show stronger anomalies at earlier times. (Note different y-axis scales.)

Law-Smith+ 2019

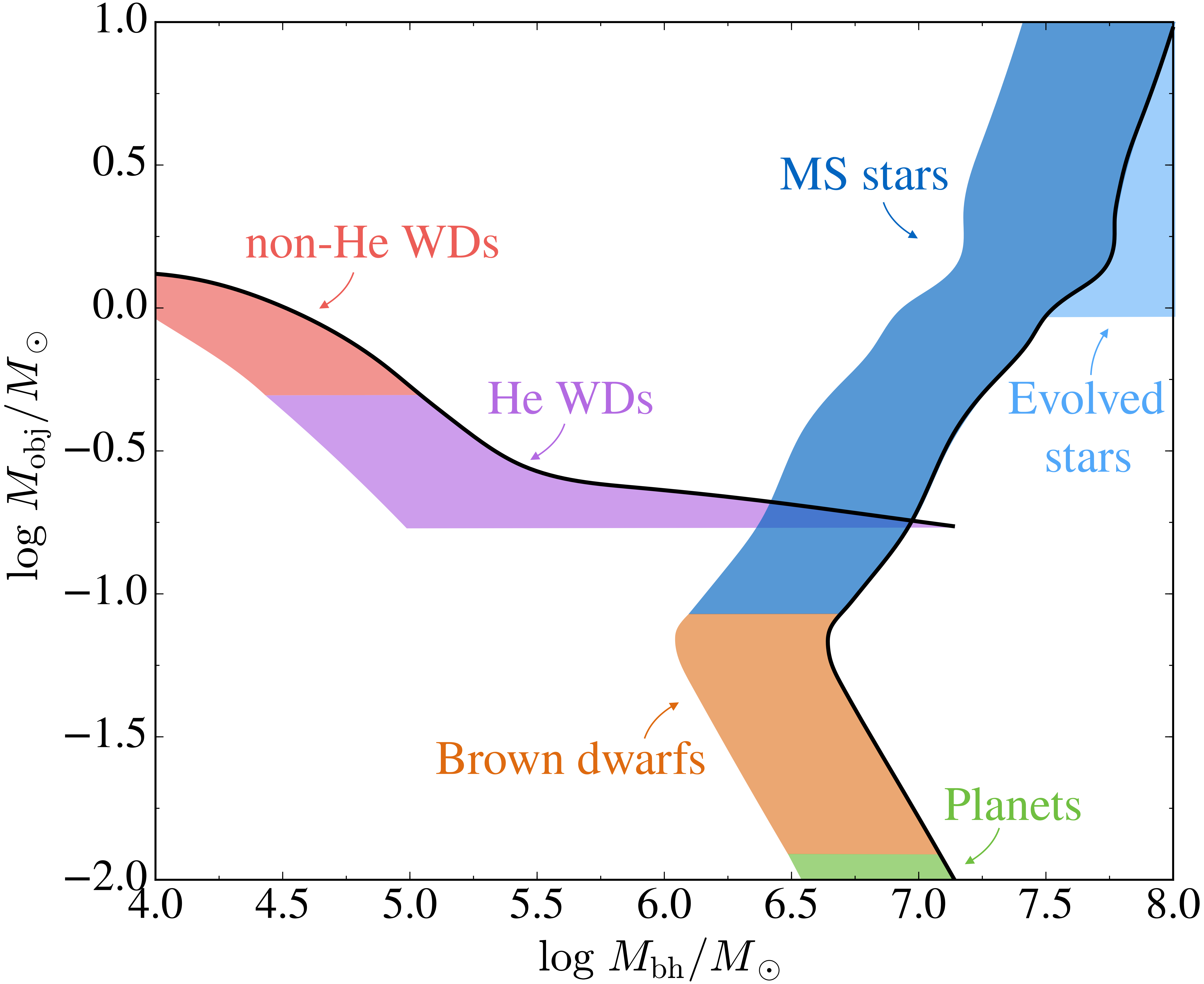
Full grid will be publicly available

- **Grid**:
  - Stellar mass: $0.3 \text{ to } 3M_\odot$.
  - Stellar age: ZAMS to TAMS.
  - Impact parameter β: $\Delta M/M_\star \approx 0.01 \text{ to } 1$
- **Results**:
  - $\dot{M}_{\rm fb}$ vs. time
  - $X/X_\odot$ (composition of fallback material) vs. time
  - $\dot{M}_{\rm peak}$, $t_{\rm peak}$, $\Delta M/M_\star$, $n(t)$, n_∞

Big goal: (light curves + $\dot{M}$ from accurate stellar structures) + (spectra + $X/X_\odot$ + radiative transfer) to better constrain almost everything! (= star, BH, efficiency, emission mechanism, etc.)

Law-Smith+ in prep.

Different objects probe different BHs: the tidal disruption “menu”



Using M-R relationships and estimate of maximum BH mass for observable tidal disruption ($\beta \geq 1$, non-spinning BH; maximally spinning BH increases this by factor of 8):

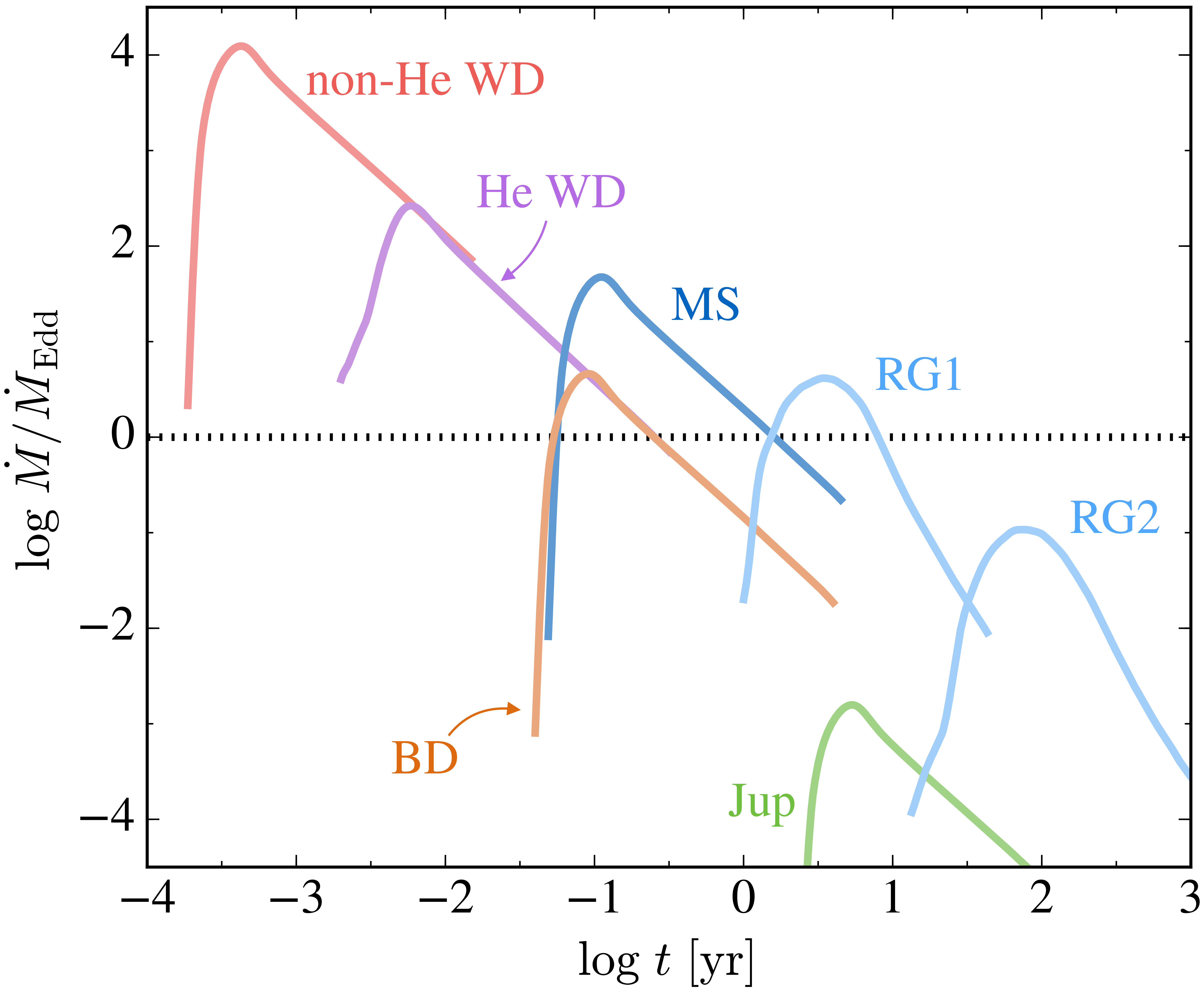
$$M_{\rm BH} \leq \frac{R_\star^{3/2}}{M_\star^{1/2}} \left(\frac{c^2}{4G} \right)^{3/2} \propto \rho_\star^{-1/2}.$$

^This is RHS bounds of each region.

LHS bounds are given using a simple “prompt circularization condition”: $r_{\rm p} < 10 r_{\rm g}$. Observable TDEs are certainly possible to the left of each region.

Law-Smith+ 2017b

Fallback rates for characteristic objects, scaled to $M_{\rm BH} = 10^6 M_\odot$ for comparison



Law-Smith+ 2017b


$M_{\rm BH} = 10^3 M_\odot;\ M_\star = 1 M_\odot;\ R_\odot \approx 1.3 R_\odot;\ {\rm age}_\star = {\rm TAMS};\ \beta = 5$
code: FLASH
vis.: density volume rendering
simulation from Law-Smith+ in prep., vis. credit: Nick Leaf / NVIDIA

Conclusions

- **Fallback-rate hydro simulations with realistic stellar structures and compositions (tracking 49 elements):** build stars in MESA and tidally dirupt in FLASH with a Helmholtz EOS.

- Shape of mass fallback curves different from Guillochon & Ramirez-Ruiz 2013.

- $t_{\rm peak}$ increases with stellar age and $\dot{M}_{\rm peak}$ decreases with stellar age, and these effects diminish with increasing β.

- **Compositional anomalies in N, He, C, O (and others) can occur before the peak of the mass fallback rate for disruptions of MS stars.**

- More massive stars can show stronger abundance anomalies at earlier times.

- Full grid will be publicly available.