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The Evolution of Supermassive Pop III stars

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references: **Haemmerlé**, Woods, Klessen, Heger, Whalen 2017 arXiv:1705.09301
Woods, Heger, Whalen, **Haemmerlé**, Klessen 2017 ApJ 842 L6

SuperMassive Stars (SMS): progenitors of high redshift quasars?

- $M > 10^4\ M_{sun}$: radiation dominated, General Relativistic (GR) effects
  (Hoyle & Fowler 1963, Hoyle et al. 1964, Chandrasekhar 1964)

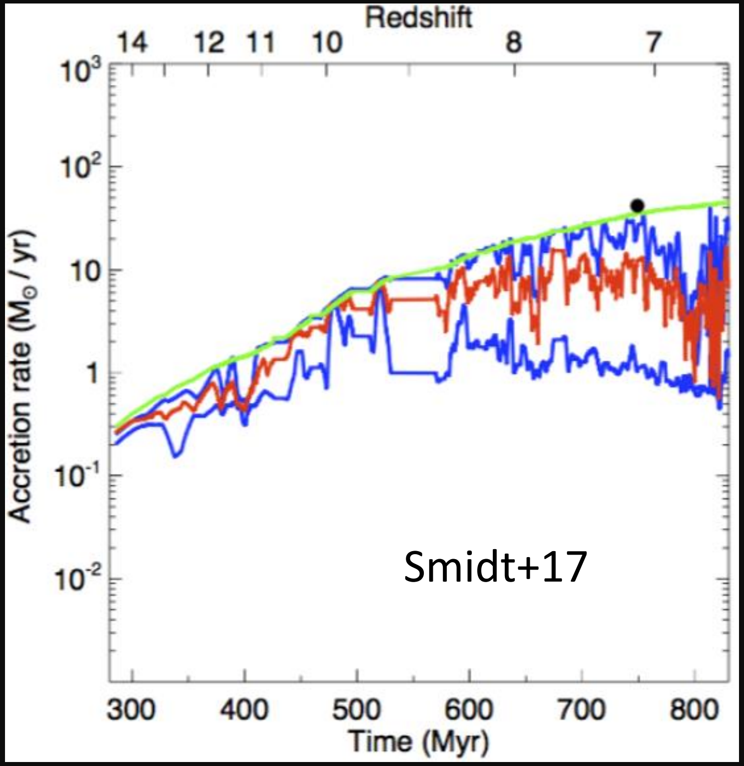
- Quasars $z \approx 7$: ULAS J1120+0641 ($M = 2\times10^9\ M_{sun}$, $z = 7.1$, Mortlock+11)
  SDSS J010013.02+280225.8 ($M = 1.2\times10^{10}\ M_{sun}$, $z = 6.3$, Wu+15)
  => **$dM/dt \approx 1\ M_{sun}\ yr^{-1}$**

- Direct Collapse scenario:

External Lyman-Werner (LW) radiation field dissociates H_2. => no molecular cooling
=> $T \approx 10^4$ K
=> Jeans mass $\approx 10^7\ M_{sun}$

=> **One central stellar object forms by accretion at high rate (0.1-10 $M_{sun}\ yr^{-1}$).**

In agreement with hydrodynamical simulations of primordial halos (e.g. Latif+13, Smidt+17).



BUT: **The ionising feedback has to remain weak!**

SuperMassive Stars (SMS): general properties

- radiation dominated: => $\beta := P_{gas}/P_{tot} << 1$ => $\Gamma_1 \approx 4/3$

  => **The star is *trembling on the verge of instability* (Fowler 1964).**

- GR effects: Post-Newtonian correction to hydrostatic equilibrium

$$G_{\mathrm{rel}} = G\left(1 + \frac{P}{\rho c^2} + \frac{2GM_r}{rc^2} + \frac{4\pi P r^3}{M_r c^2}\right)$$

(Fuller, Woosley & Weaver 1986)

- Chandrasekhar (1964): GR stability criterion for **polytropes**

  - 1st order GR correction to Γ_{crit}: $$\Gamma_{\mathrm{crit}} = \frac{4}{3} + K\,\frac{2GM_r}{r c^2}$$

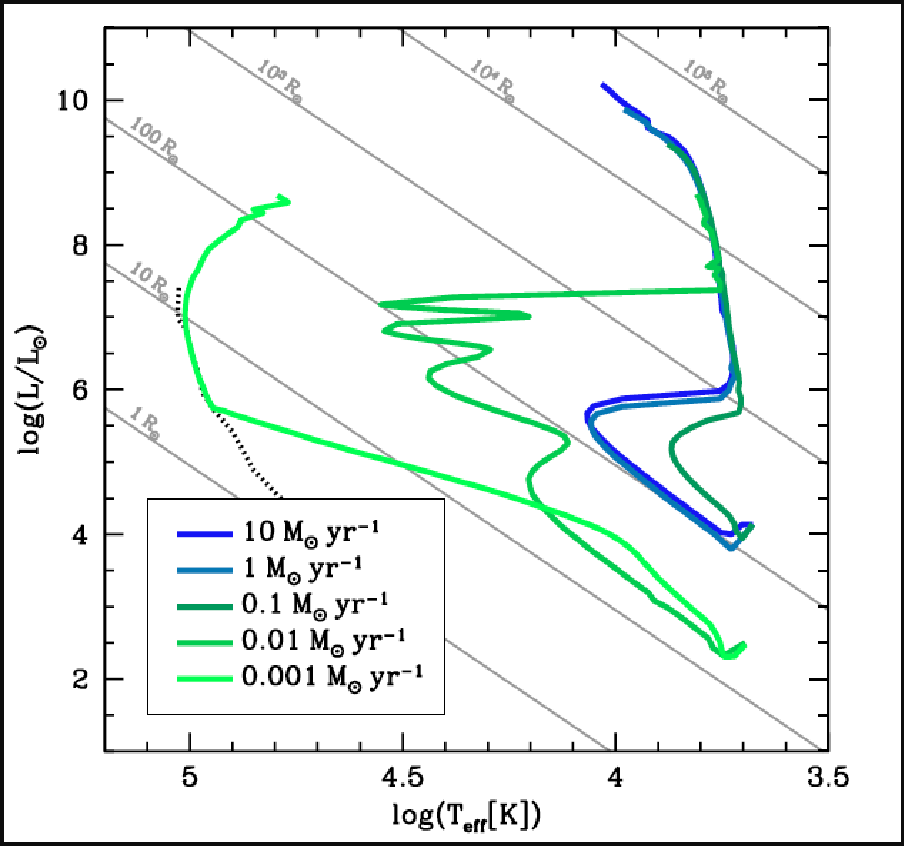
  - 1st order "gas" correction for Γ: $$\Gamma = \frac{4}{3} + \frac{\beta}{6}$$

=> **The star is GR stable only if:** $$\frac{\beta}{6} > K\,\frac{2GM_r}{r c^2}$$ *...pulsational instability!*

(R > Schwarzschild radius)

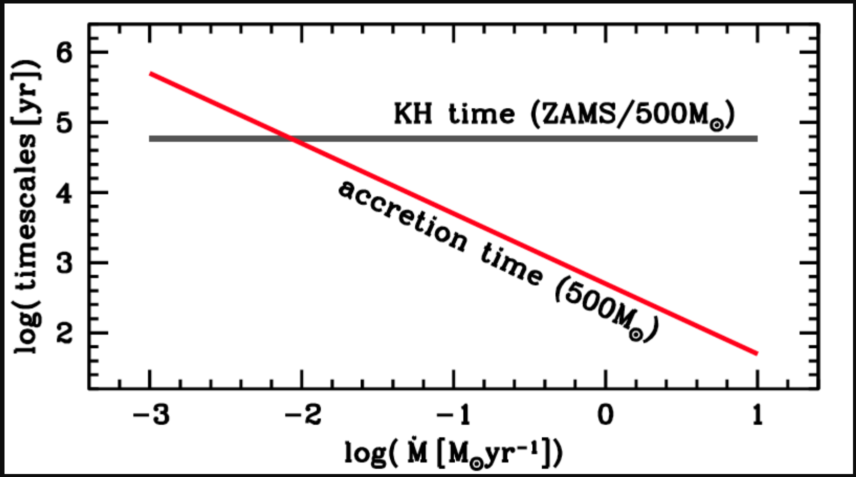
Models of accreting PopIII protostars:

- **GENEVA**: 1D hydrostatic stellar evolution code
- accretion of mass: 0.001-10 M_{sun} yr^{-1}, towards the highest mass-range $>10^5 M_{sun}$
- accretion of entropy: cold disc accretion, lower limit
- convection: mixing-length theory, Schwarzschild criterion, no overshooting
- GR effects: post-Newtonian correction to hydrostatic equilibrium



Results: 2 asymptotic regimes

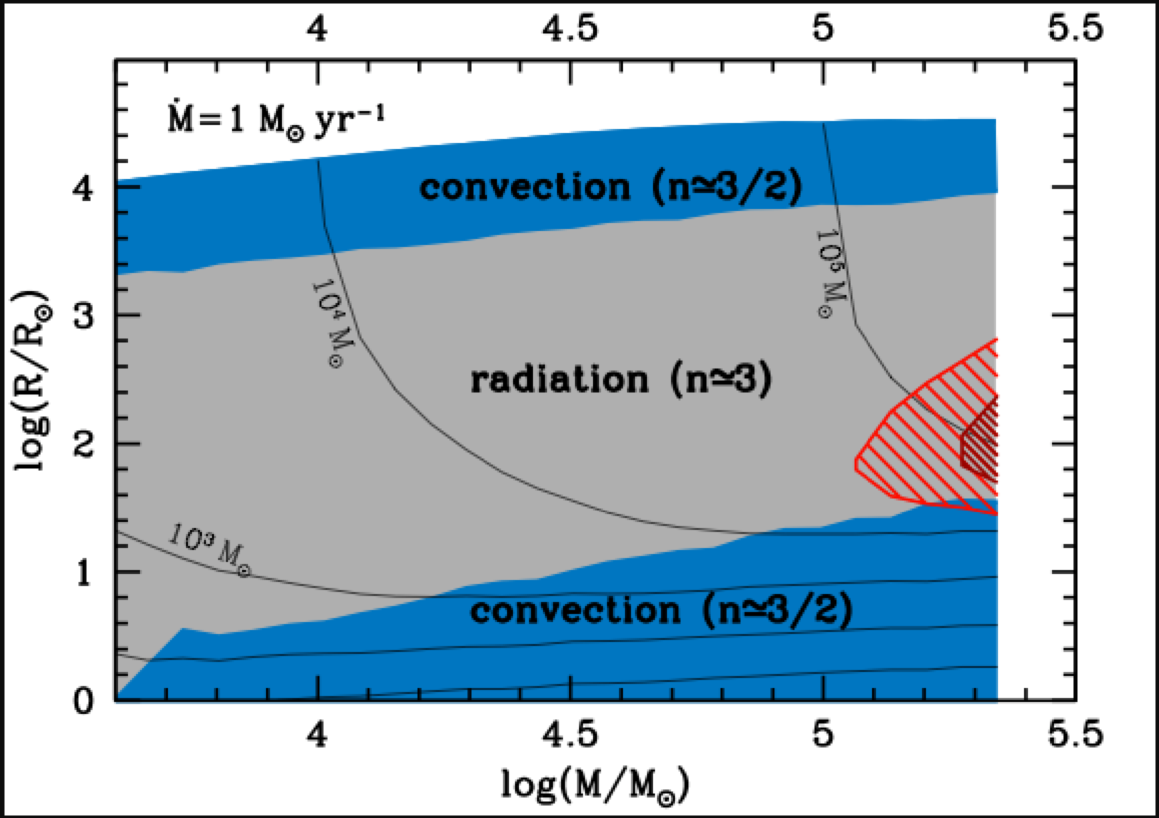
- low dM/dt : accretion time > KH time
  => compact blue -> ZAMS
- high dM/dt : accretion time < KH time
  => puffed red -> Hayashi limit



GR instability & final masses:

Structure in the SMS range:
- **convective** core (H-burning)
- intermediate **radiative** region
- **convective** envelope (Hayashi line)

$\dot{M} =$	0.1	1	10	$\mathrm{M_\odot\,yr^{-1}}$
$M_3 =$		1.16	2.61	$\times 10^5\,\mathrm{M_\odot}$
$M_{3/2} =$		1.88	3.60	$\times 10^5\,\mathrm{M_\odot}$
$M_{\mathrm{fin}} =$	0.70	2.29	5.43	$\times 10^5\,\mathrm{M_\odot}$



Polytropic criterion for GR stability:

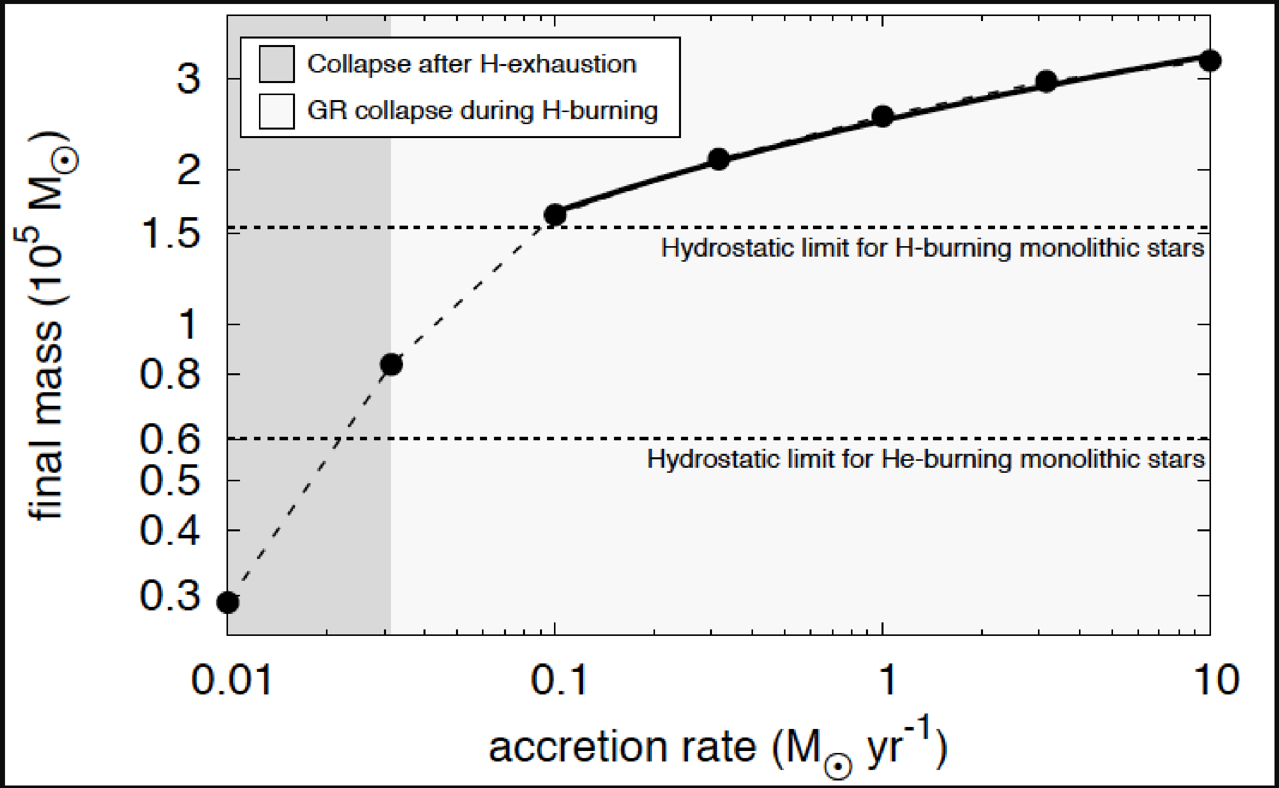
$$\frac{\beta}{6} > K\,\frac{2GM_r}{r\,c^2}$$

Radiation: n≈3 => K=1.12

Convection: n≈1.5 => K=0.64

KEPLER code:

- 1D **hydrodynamical** stellar evolution code
- accretion of entropy: cold disc accretion **+ advection term**
- convection: mixing-length theory, **Ledoux criterion + overshooting**
- GR effects: post-Newtonian correction to hydrostatic equilibrium



Woods, Heger, Whalen, **Haemmerlé**, Klessen 2017 ApJ 842 L6

...the most massive stars that ever existed?

CONCLUSIONS:

Supermassive Pop III stars accreting at rates > 0.01 $M_{sun}yr^{-1}$ evolve along the Hayashi line.

They keep a weak ionising feedback until they collapse into a black hole, supporting the direct collapse scenario.

The mass at collapse depends on the accretion rate (the higher is the rate, the larger is the final mass), but remains in the same order of magnitude ($1\text{-}5\times10^5 M_{sun}$) for rates 0.1 – 10 $M_{sun}yr^{-1}$.

Since we do not expect accretion rates > 10 $M_{sun}yr^{-1}$, these objects might be the most massive stars ever formed in our Universe.

We provide **numerical tables** of the surface properties of supermassive Pop III stars accreting at various rates:
Haemmerlé, Woods, Klessen, Heger, Whalen 2017 **arXiv:1705.09301**