TITANS OF THE EARLY UNIVERSE

The origin of the first supermassive black holes

Tyrone E. Woods
Monash Centre for Astrophysics

July 18, 2018

With Alex Heger, Ralf Klessen, Lionel Haemmerle,
and Daniel J. Whalen

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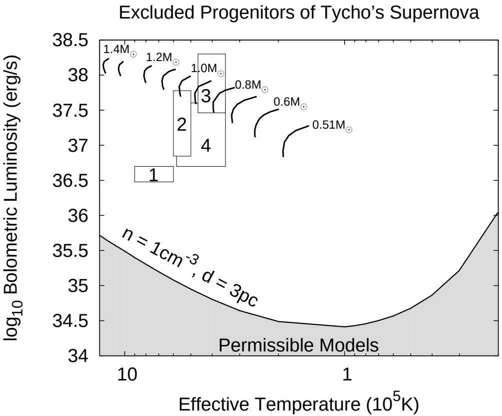
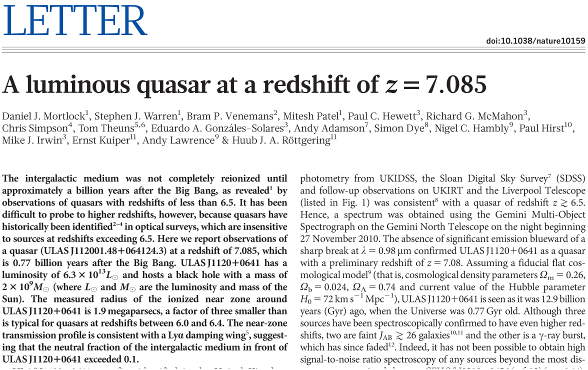
No hot and luminous progenitor for most Type Ia supernovae

Woods, Ghavamian, Badenes, and Gilfanov, *Nature Astronomy*, 2017

See also, e.g., Woods & Gilfanov 2013, 2014, 2016 Johansson, Woods et al., 2014, 2016



The Origin of High-redshift Quasars



LETTER

doi:10.1038/nature10159

A luminous quasar at a redshift of $z = 7.085$

Daniel J. Mortlock[1], Stephen J. Warren[1], Bram P. Venemans[2], Mitesh Patel[1], Paul C. Hewett[3], Richard G. McMahon[3], Chris Simpson[4], Tom Theuns[5,6], Eduardo A. Gonzáles-Solares[3], Andy Adamson[7], Simon Dye[8], Nigel C. Hambly[9], Paul Hirst[10], Mike J. Irwin[3], Ernst Kuiper[11], Andy Lawrence[9] & Huub J. A. Röttgering[11]

The intergalactic medium was not completely reionized until approximately a billion years after the Big Bang, as revealed[1] by observations of quasars with redshifts of less than 6.5. It has been difficult to probe to higher redshifts, however, because quasars have historically been identified[2–4] in optical surveys, which are insensitive to sources at redshifts exceeding 6.5. Here we report observations of a quasar (ULAS J112001.48+064124.3) at a redshift of 7.085, which is 0.77 billion years after the Big Bang. ULAS J1120+0641 has a luminosity of $6.3 \times 10^{13} L_\odot$ and hosts a black hole with a mass of $2 \times 10^9 M_\odot$ (where $L_\odot$ and $M_\odot$ are the luminosity and mass of the Sun). The measured radius of the ionized near zone around ULAS J1120+0641 is 1.9 megaparsecs, a factor of three smaller than is typical for quasars at redshifts between 6.0 and 6.4. The near-zone transmission profile is consistent with a Lyα damping wing[5], suggesting that the neutral fraction of the intergalactic medium in front of ULAS J1120+0641 exceeded 0.1.

photometry from UKIDSS, the Sloan Digital Sky Survey[7] (SDSS) and follow-up observations on UKIRT and the Liverpool Telescope (listed in Fig. 1) was consistent[8] with a quasar of redshift $z \gtrsim 6.5$. Hence, a spectrum was obtained using the Gemini Multi-Object Spectrograph on the Gemini North Telescope on the night beginning 27 November 2010. The absence of significant emission blueward of a sharp break at $\lambda = 0.98\,\mu\mathrm{m}$ confirmed ULAS J1120+0641 as a quasar with a preliminary redshift of $z = 7.08$. Assuming a fiducial flat cosmological model[9] (that is, cosmological density parameters $\Omega_\mathrm{m} = 0.26$, $\Omega_\mathrm{b} = 0.024$, $\Omega_\Lambda = 0.74$ and current value of the Hubble parameter $H_0 = 72\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$), ULAS J1120+0641 is seen as it was 12.9 billion years (Gyr) ago, when the Universe was 0.77 Gyr old. Although three sources have been spectroscopically confirmed to have even higher redshifts, two are faint $J_\mathrm{AB} \gtrsim 26$ galaxies[10,11] and the other is a γ-ray burst, which has since faded[12]. Indeed, it has not been possible to obtain high signal-to-noise ratio spectroscopy of any sources beyond the most dis-

The Origin of High-redshift Quasars

- Truly massive (10^9–$10^{10} M_\odot$) quasars have been observed at redshift ∼7 (e.g., Mortlock+ 2011, Wu+ 2015).
- This is hard to explain:

$$t_{\rm growth} \sim 0.1 \log_{10}\left(\frac{M_{\rm BH}}{M_{\rm seed}}\right) {\rm Gyr}$$

- **Especially** given pop III black holes “born starving” (Alvarez, Wise, & Abel 2009)

The Origin of High-redshift Quasars

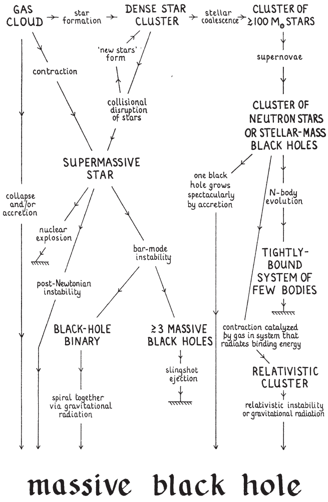
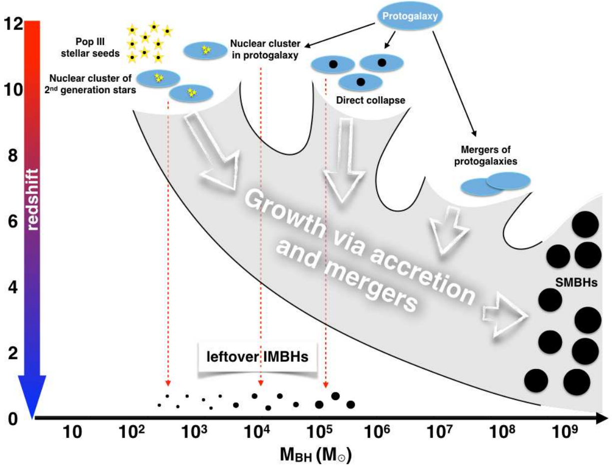


Figure 1 Schematic diagram [reproduced from Rees (106)] showing possible routes for runaway evolution in active galactic nuclei.

The Origin of High-redshift Quasars



See review by Mar Mezcua, 2017

Supermassive Stars – a little history

- How massive is supermassive? 10^4–$10^6 M_\odot$
- Initially hypothesized candidate for quasars
- Assumed to be formed "all at once" (monolithically)
- Strongly radiation-dominated ($\beta = \frac{P_\mathrm{gas}}{P_\mathrm{tot}} << 1$):
    - $\mathrm{P} \propto \rho^{\frac{4}{3}} \rightarrow$ polytrope, with index $\mathrm{n} = 3$
    - Local adiabatic index $\Gamma = 1 + \frac{1}{n} \approx \frac{4}{3} + \frac{\beta}{6}$

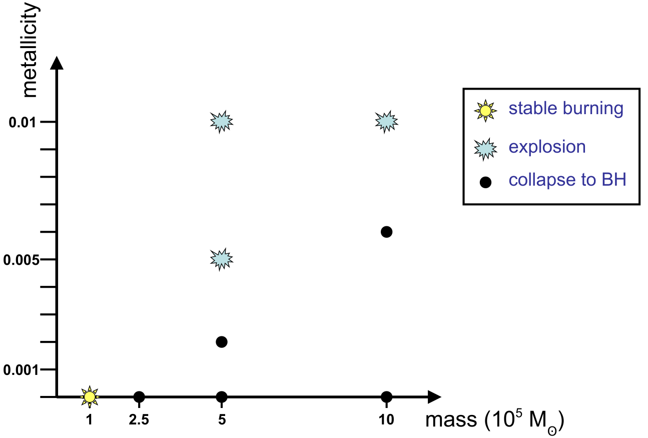
Supermassive Stars – a little history

- Objects with $\Gamma \approx 4/3$ are "trembling on the verge of instability" (Fowler 1964)
- Very small perturbation can trigger collapse!
- Chandrasekhar (1964) and others showed that there is a general relativistic correction to the critical pressure support needed: $\Gamma \approx 4/3 + 1.12\frac{2GM}{Rc^2}$
- Criterion for instability: $\frac{\beta}{6} < 1.12\frac{2GM}{Rc^2}$
- $\beta \propto M^{-\frac{1}{2}}$ for $\beta << 1 \rightarrow \sim 10^5$–$10^6 M_\odot$ stars will quickly collapse!

KEPLER Stellar Evolution Code

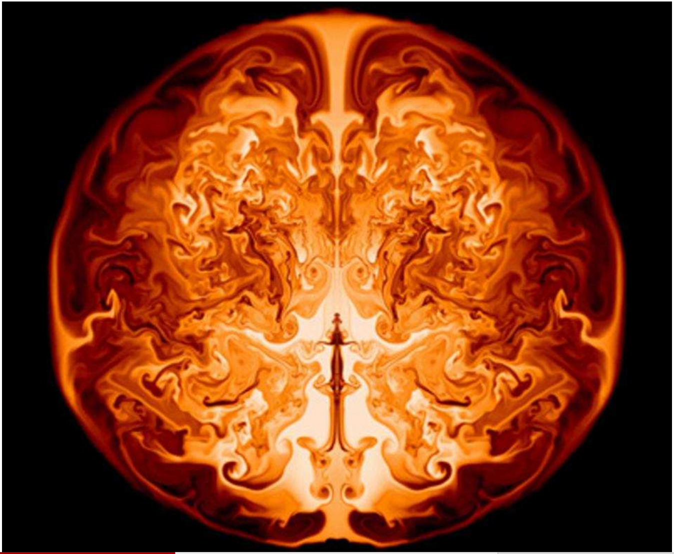
- implicit Lagrangian hydrodynamics and stellar evolution (Weaver, Zimmerman, and Woosley 1978)
- solve conservation equations for mass, energy, and momentum in spherical symmetry
- equation of state allowing for general mixture of radiation, ions, and electrons of arbitrary degeneracy and relativity, as well as pair production
- include post-Newtonian correction to the acceleration due to gravity (e.g., Fuller+ 1986)

Monolithic Supermassive Stars

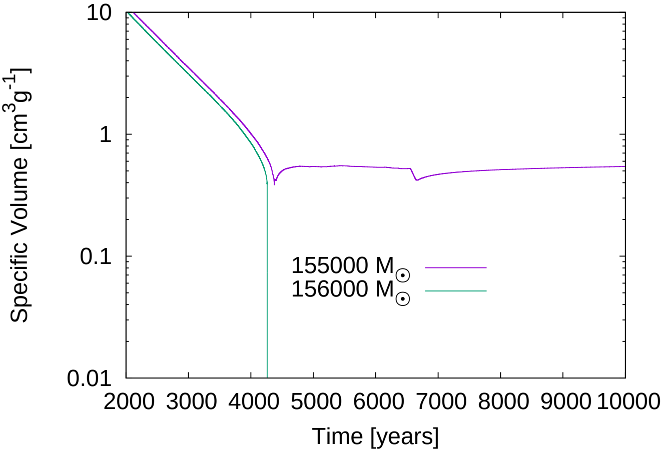


(after Fuller, Woosley, & Weaver 1986)

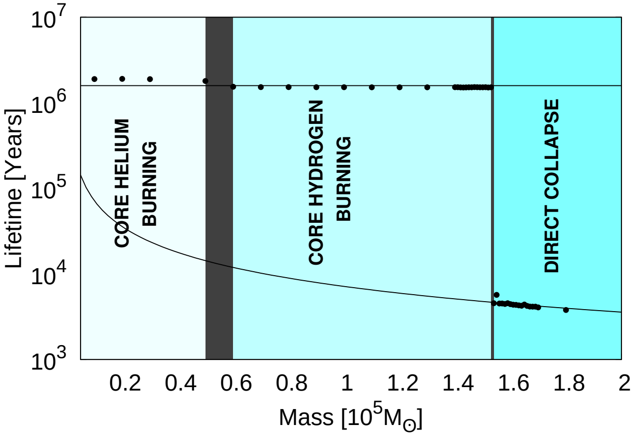
Monolithic Supermassive Stars



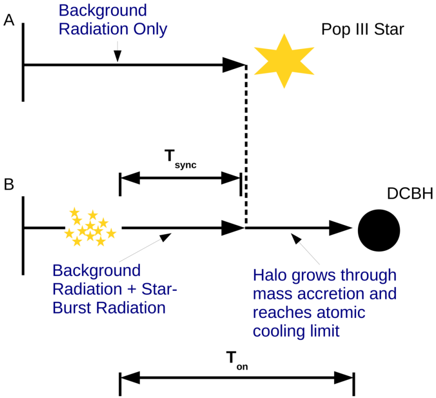
Supermassive Stars



Supermassive Stars



How do you actually make a supermassive star?



Option 1: Regan+, *Nature Astro*, 2017

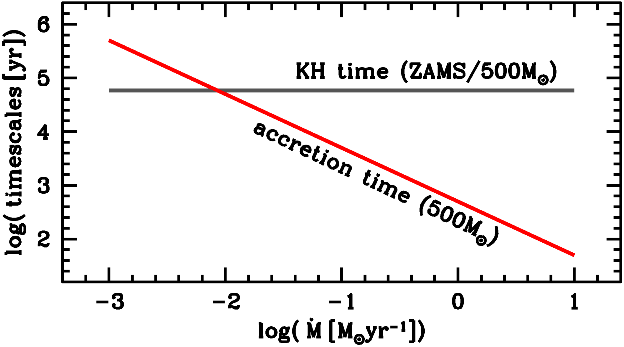
How do you actually make a supermassive star?

- Option 2: high baryonic streaming velocities (Tanaka & Li 2014; Schauer et al., 2017; Hirano et al., 2017). Essentially an atomically-cooled halo with an assist?
- Option 3: really massive infall rates possible in high-z galaxy mergers? (Maier et al 2015)
- Option 4: Coalesence of a dense stellar cluster? (problems, see Latif et al., 2016)

Initial Conditions

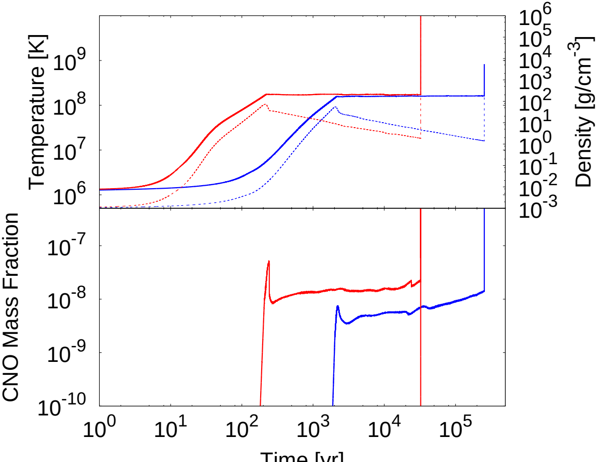
- Begin with a $10M_{\odot}$, $n = 3$ polytrope with a central density of 10^{-3}gcm^{-3} → a somewhat "puffy" protostar.
- Primordial composition, including deuterium and lithium.
- Consider accretion rates in the range 0.01 – 10 $M_{\odot}$/yr, typical of atomically-cooled haloes

Accreting Supermassive Stars Don't Know how to Relax!



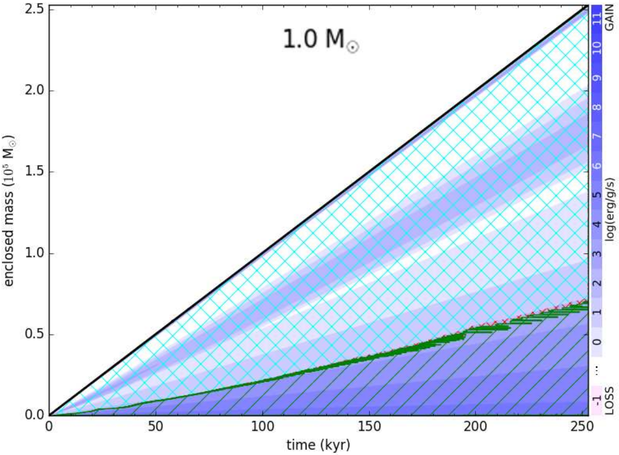
Haemmerle, Woods, et al. (2017)

The Onset of Nuclear-burning



Blue – $1 M_\odot/\text{yr}$ Red – $10\ M_\odot/\text{yr}$

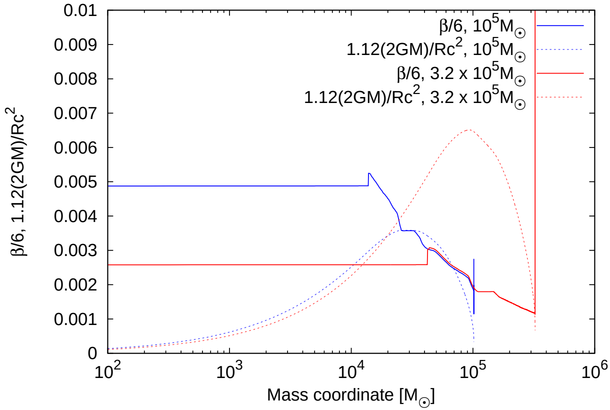
A Representative Case: $1M_\odot/\mathrm{yr}$



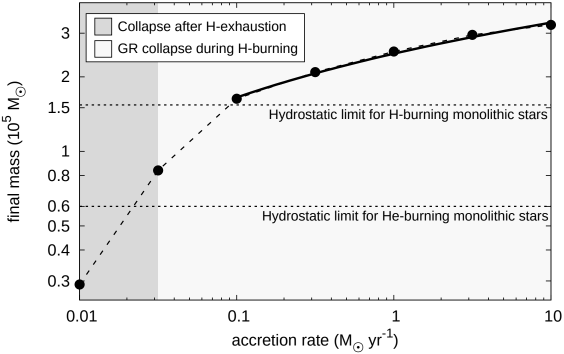
Reminder: criterion for onset of instability

- Recall the Chandrasekhar general relativistic instability for supermassive stars:
  - P $\propto \rho^{\frac{4}{3}} \rightarrow$ polytrope, with index n = 3
  - Local adiabatic index $\Gamma = 1 + \frac{1}{n} \approx \frac{4}{3} + \frac{\beta}{6}$
  - Chandrasekhar (1964) and others showed that there is a general relativistic correction to the critical pressure support needed: $\Gamma \approx 4/3 + 1.12\frac{2GM}{Rc^2}$
  - Polytropic criterion for instability: $\frac{\beta}{6} < 1.12\frac{2GM}{Rc^2}$

When does collapse set in?



The Most Massive Stars that Ever Lived!?



$$M_{\mathrm{SMS,final}} \approx \left[0.83 \log_{10}\left(\frac{\dot{M}}{M_\odot\,\mathrm{yr}^{-1}}\right) + 2.48\right] \times 10^5\,M_\odot$$

The Most Massive Stars that Ever Lived!?

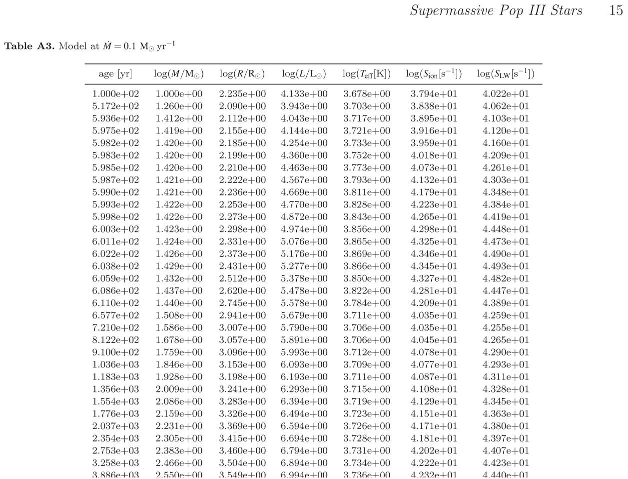
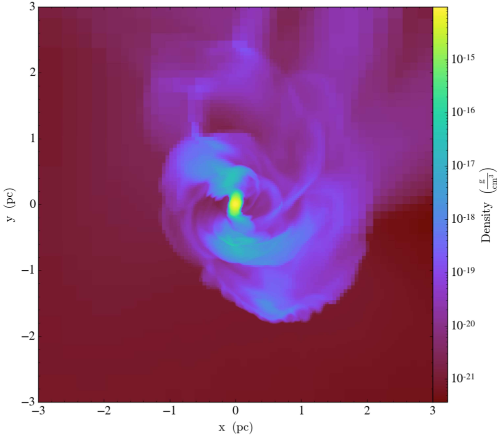


Table A3. Model at $\dot{M} = 0.1\ \mathrm{M_\odot\ yr^{-1}}$

age [yr]	$\log(M/\mathrm{M_\odot})$	$\log(R/\mathrm{R_\odot})$	$\log(L/\mathrm{L_\odot})$	$\log(T_\mathrm{eff}[\mathrm{K}])$	$\log(S_\mathrm{ion}[\mathrm{s^{-1}}])$	$\log(S_\mathrm{LW}[\mathrm{s^{-1}}])$
1.000e+02	1.000e+00	2.235e+00	4.133e+00	3.678e+00	3.794e+01	4.022e+01
5.172e+02	1.260e+00	2.090e+00	3.943e+00	3.703e+00	3.838e+01	4.062e+01
5.936e+02	1.412e+00	2.112e+00	4.043e+00	3.717e+00	3.895e+01	4.103e+01
5.975e+02	1.419e+00	2.155e+00	4.144e+00	3.721e+00	3.916e+01	4.120e+01
5.982e+02	1.420e+00	2.185e+00	4.254e+00	3.733e+00	3.959e+01	4.160e+01
5.983e+02	1.420e+00	2.199e+00	4.360e+00	3.752e+00	4.018e+01	4.209e+01
5.985e+02	1.420e+00	2.210e+00	4.463e+00	3.773e+00	4.073e+01	4.261e+01
5.987e+02	1.421e+00	2.222e+00	4.567e+00	3.793e+00	4.132e+01	4.303e+01
5.990e+02	1.421e+00	2.236e+00	4.669e+00	3.811e+00	4.179e+01	4.348e+01
5.993e+02	1.422e+00	2.253e+00	4.770e+00	3.828e+00	4.223e+01	4.384e+01
5.998e+02	1.422e+00	2.273e+00	4.872e+00	3.843e+00	4.265e+01	4.419e+01
6.003e+02	1.423e+00	2.298e+00	4.974e+00	3.856e+00	4.298e+01	4.448e+01
6.011e+02	1.424e+00	2.331e+00	5.076e+00	3.865e+00	4.325e+01	4.473e+01
6.022e+02	1.426e+00	2.373e+00	5.176e+00	3.869e+00	4.346e+01	4.490e+01
6.038e+02	1.429e+00	2.431e+00	5.277e+00	3.866e+00	4.345e+01	4.493e+01
6.059e+02	1.432e+00	2.512e+00	5.378e+00	3.850e+00	4.327e+01	4.482e+01
6.086e+02	1.437e+00	2.620e+00	5.478e+00	3.822e+00	4.281e+01	4.447e+01
6.110e+02	1.440e+00	2.745e+00	5.578e+00	3.784e+00	4.209e+01	4.389e+01
6.577e+02	1.508e+00	2.941e+00	5.679e+00	3.711e+00	4.035e+01	4.259e+01
7.210e+02	1.586e+00	3.007e+00	5.790e+00	3.706e+00	4.035e+01	4.255e+01
8.122e+02	1.678e+00	3.057e+00	5.891e+00	3.706e+00	4.045e+01	4.265e+01
9.100e+02	1.759e+00	3.096e+00	5.993e+00	3.712e+00	4.078e+01	4.290e+01
1.036e+03	1.846e+00	3.153e+00	6.093e+00	3.709e+00	4.077e+01	4.293e+01
1.183e+03	1.928e+00	3.198e+00	6.193e+00	3.711e+00	4.087e+01	4.311e+01
1.356e+03	2.009e+00	3.241e+00	6.293e+00	3.715e+00	4.108e+01	4.328e+01
1.554e+03	2.086e+00	3.283e+00	6.394e+00	3.719e+00	4.129e+01	4.345e+01
1.776e+03	2.159e+00	3.326e+00	6.494e+00	3.723e+00	4.151e+01	4.363e+01
2.037e+03	2.231e+00	3.369e+00	6.594e+00	3.726e+00	4.171e+01	4.380e+01
2.354e+03	2.305e+00	3.415e+00	6.694e+00	3.728e+00	4.181e+01	4.397e+01
2.753e+03	2.383e+00	3.460e+00	6.794e+00	3.731e+00	4.202e+01	4.407e+01
3.258e+03	2.466e+00	3.504e+00	6.894e+00	3.734e+00	4.222e+01	4.423e+01
3.886e+03	2.550e+00	3.549e+00	6.994e+00	3.736e+00	4.232e+01	4.440e+01

Accreting Supermassive Stars with "realistic" accretion rates



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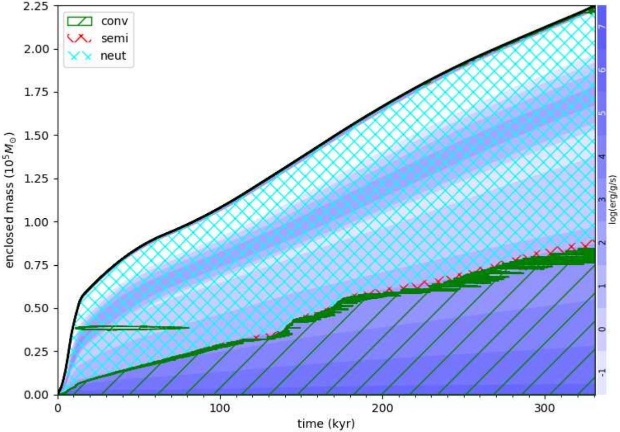
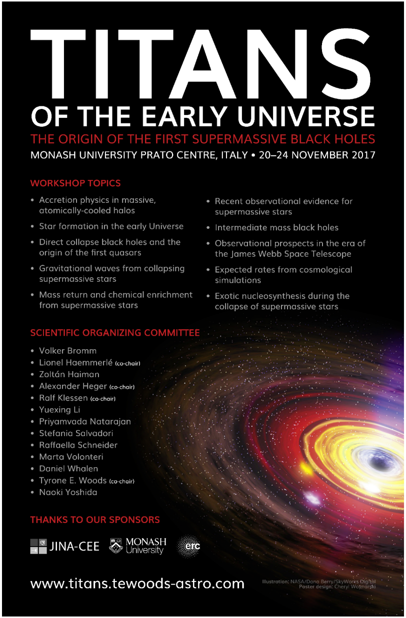


Rotating Supermassive Stars

- ΩΓ-limit: known problem from “normal” Pop I massive star evolution
- $\frac{v_{\mathrm{crit},1}^2}{R_{\mathrm{eq}}} = \frac{GM}{R_{\mathrm{eq}}^2} \rightarrow v_{\mathrm{crit},1} = \sqrt{\frac{GM}{R_{\mathrm{eq}}}}$
- $v_{\mathrm{crit},2}^2 = 2\pi G\overline{\rho}(1-\Gamma_{\mathrm{Edd}})R_{\mathrm{eq}}^2$

Rotating Supermassive Stars

- Haemmerle et al., 2017, submitted: Supermassive stars have to be slow rotators ($v_{surf} < 10-20\% v_{crit,1}$).
- Supermassive star formation by accretion requires mechanisms efficient enough to remove most (≈99%) of the angular momentum from the accretion disc.
- Need to get rid of a lot of angular momentum somehow! Spiral arms in the disk? Magnetic braking?



TITANS

OF THE EARLY UNIVERSE

THE ORIGIN OF THE FIRST SUPERMASSIVE BLACK HOLES

MONASH UNIVERSITY PRATO CENTRE, ITALY • 20–24 NOVEMBER 2017

WORKSHOP TOPICS

- Accretion physics in massive, atomically-cooled halos
- Star formation in the early Universe
- Direct collapse black holes and the origin of the first quasars
- Gravitational waves from collapsing supermassive stars
- Mass return and chemical enrichment from supermassive stars
- Recent observational evidence for supermassive stars
- Intermediate mass black holes
- Observational prospects in the era of the James Webb Space Telescope
- Expected rates from cosmological simulations
- Exotic nucleosynthesis during the collapse of supermassive stars

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Conclusions

- Supermassive protostars accreting $\gtrsim 0.1 M_{\odot}/\mathrm{yr}$ collapse due to the GR while H-burning
- Final fate of (non-rotating) supermassive stars depends in a reliable way on accretion rate (variable rates qualitatively similar)
- Rotation rates of supermassive stars strongly constrained
- Even for non-rotating case, n=3 polytrope poorly predicts moment of collapse... including when applied only to the core.

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KEPLER Stellar Evolution Code

$$\frac{dv}{dt} = 4\pi r^2 \frac{\partial P}{\partial m_r} - \frac{G_{\mathrm{rel}} m_r}{r^2} + \frac{4\pi}{r} \frac{\partial Q}{\partial m_r}$$

$$\frac{du}{dt} = -4\pi P \frac{\partial}{\partial m_r}(v r^2) + 4\pi Q \frac{\partial}{\partial m_r}\left(\frac{v}{r}\right) - \frac{\partial L}{\partial m_r} + \epsilon$$

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