The Burst Mode of Accretion in Primordial Star Formation

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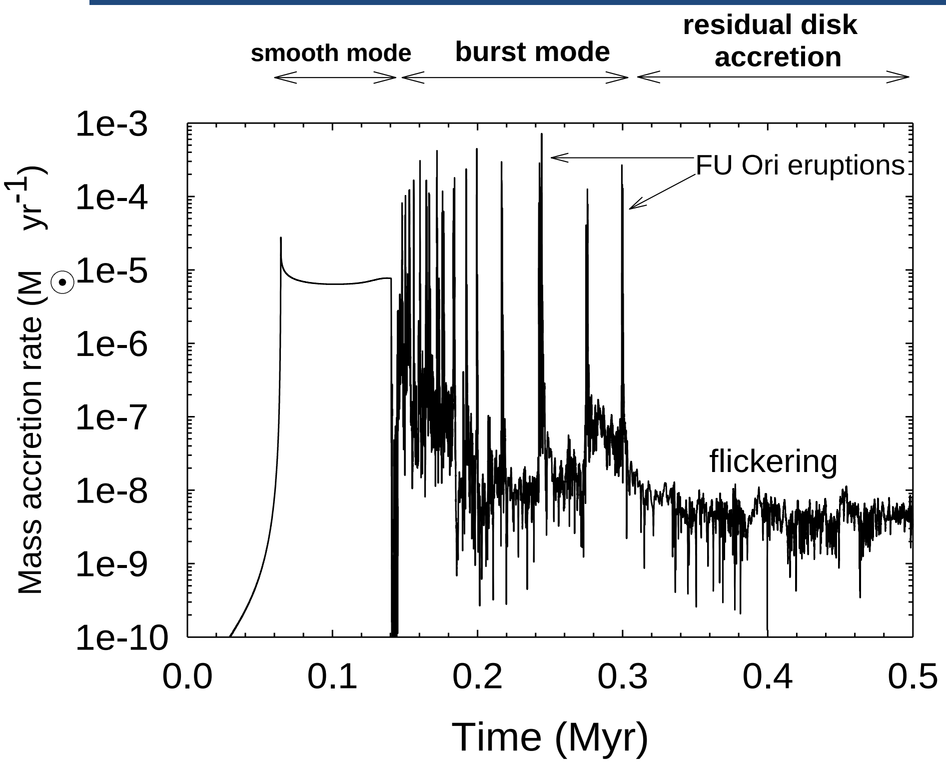
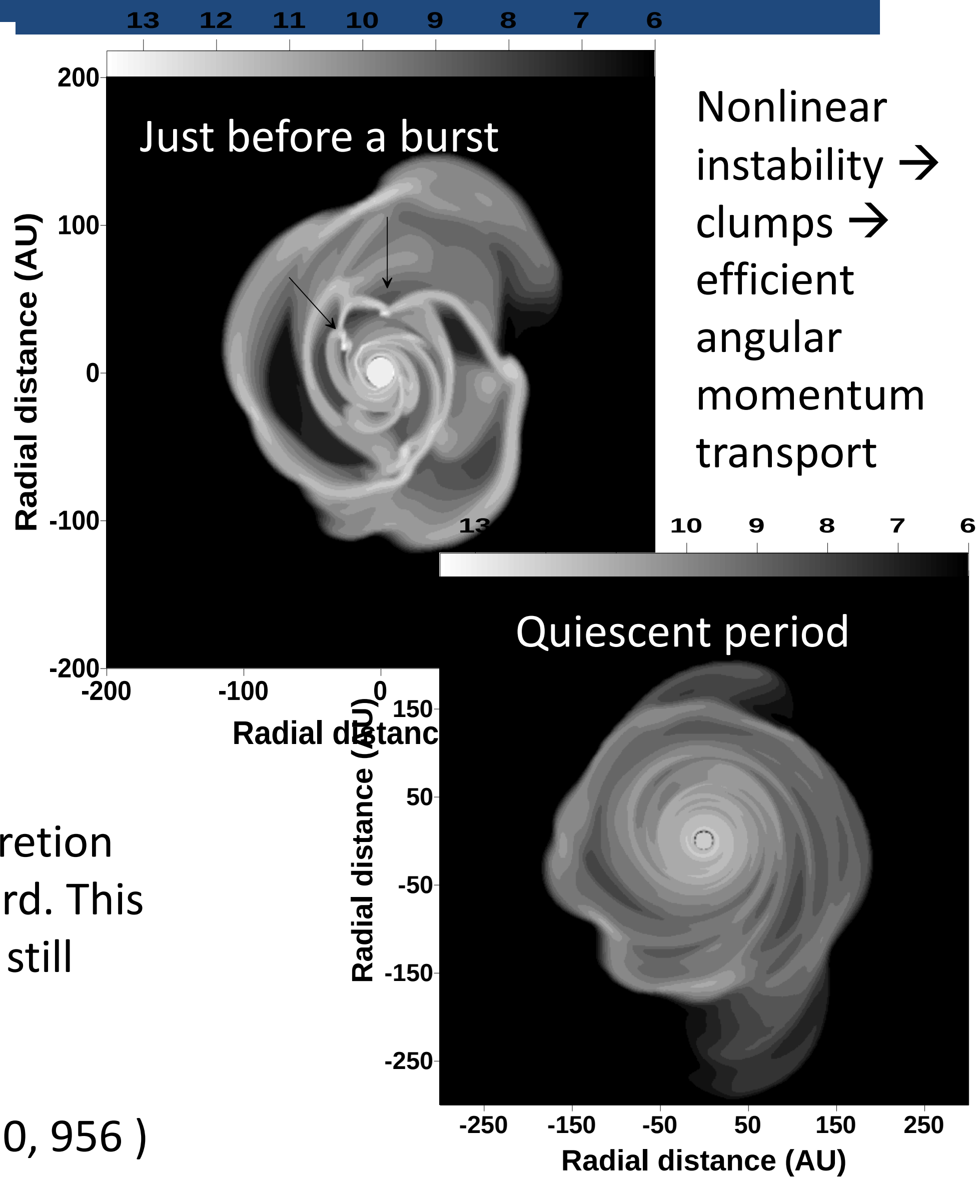
Key Results for Early Accretion Phase





Nonlinear instability → clumps → efficient angular momentum transport

Bursts of accretion occur during the early accretion phase, as clumps are formed and driven inward. This is followed by a more quiescent phase that is still characterized by flickering accretion.

Vorobyov & Basu (2006, ApJ, 650, 956)

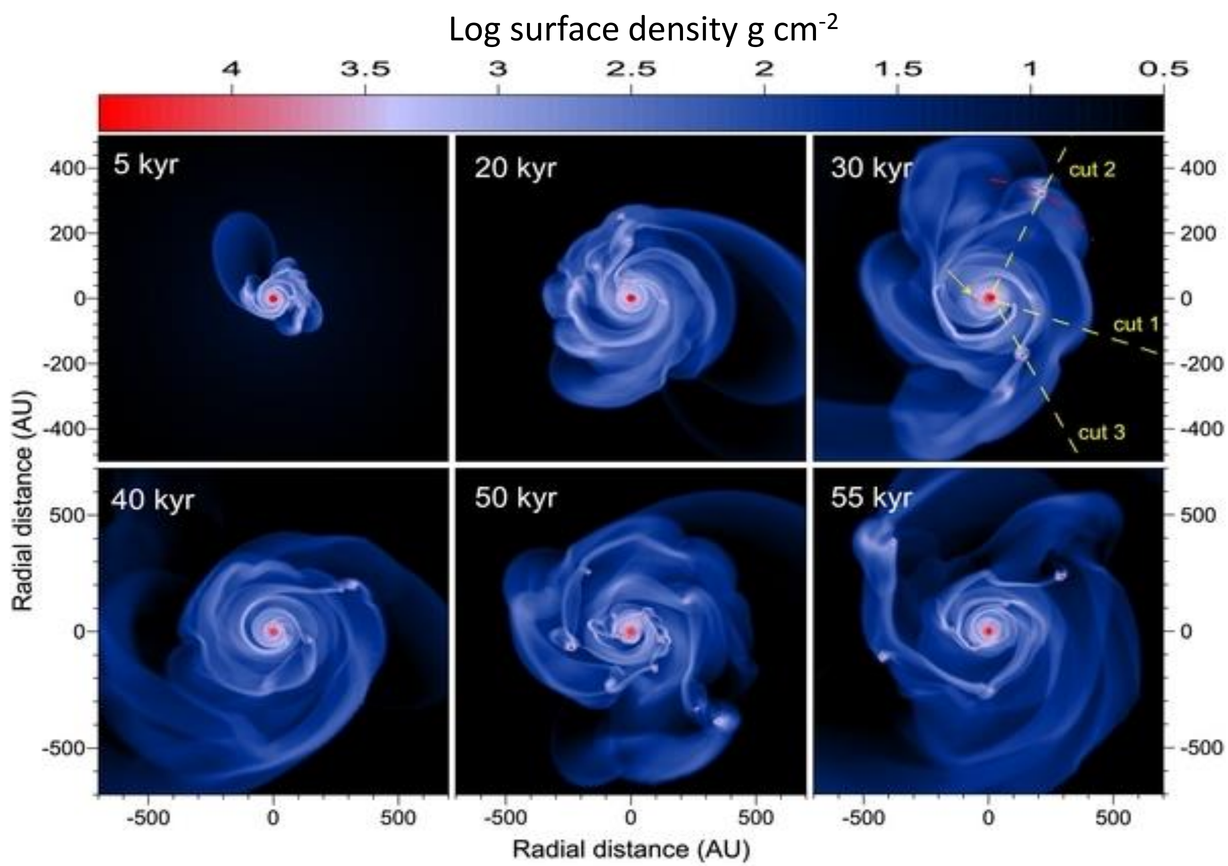
Model Individual Star-Forming Cores

- Thin-disk approximation (vertical hydrostatic equilibrium at all times) and use of central ~ 10 AU sink cell are the critical elements that allow a calculation of long-term evolution
- Solve hydrodynamic equations with a barotropic eqn of state
- Disk formation followed self-consistently from collapse of gas clump. Accretion rate from clump to disk and disk to star emerge self-consistently
- Radiative feedback effects not included. Hence stop calculation at about 40 kyr (M = 40 M_{sun}) , when radiative feedback can become dominant (Tan & McKee 2004, Hosokawa et al. 2011)

Mass Accretion in Massive Pop III disk

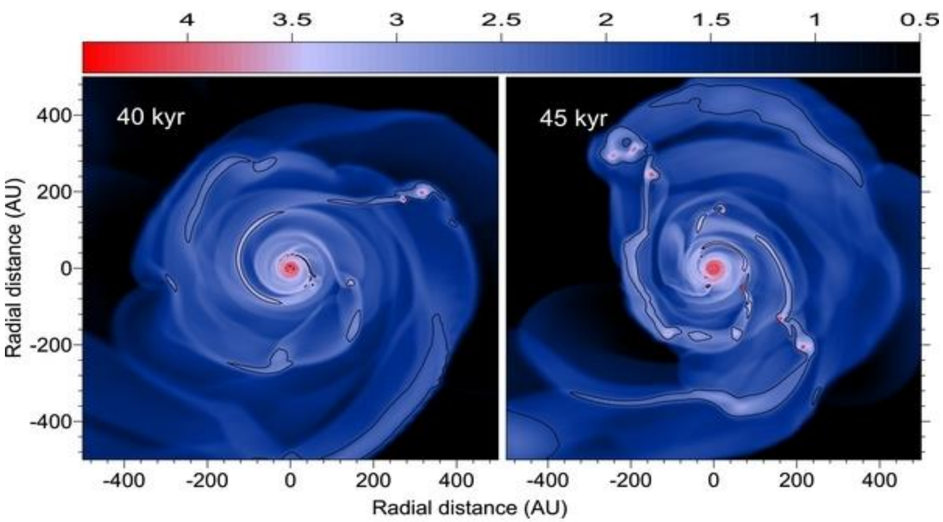
Collapse of primordial gas clumps of mass ~ 300 M_{sun} and T ~ 300 K.

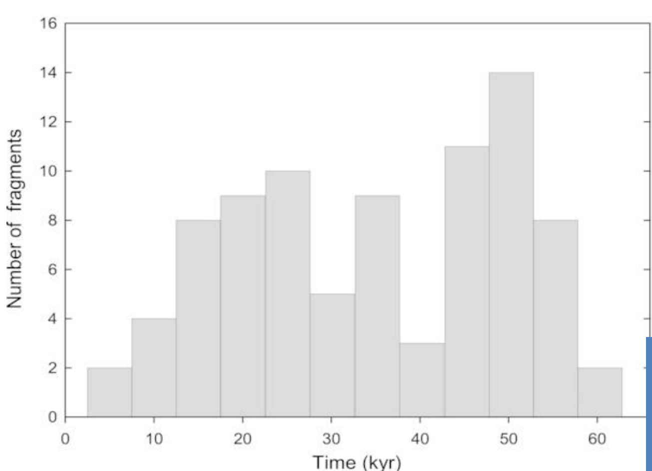
Follow early phase, first ~ 40 kyr, of star-disk evolution, before effects of ionizing radiation from star becomes dominant effect (Hosokawa et al. 2011).

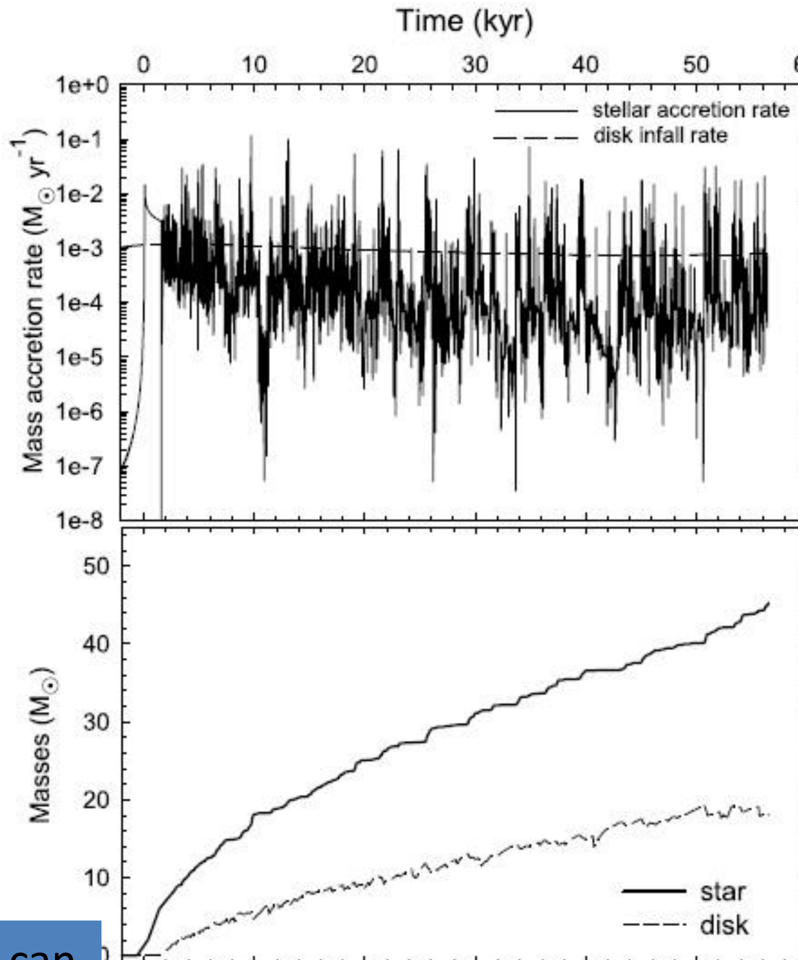


Vorobyov, DeSouza, & Basu (2013, ApJ, 768, 131)

Mass Accretion in Massive Pop III disk



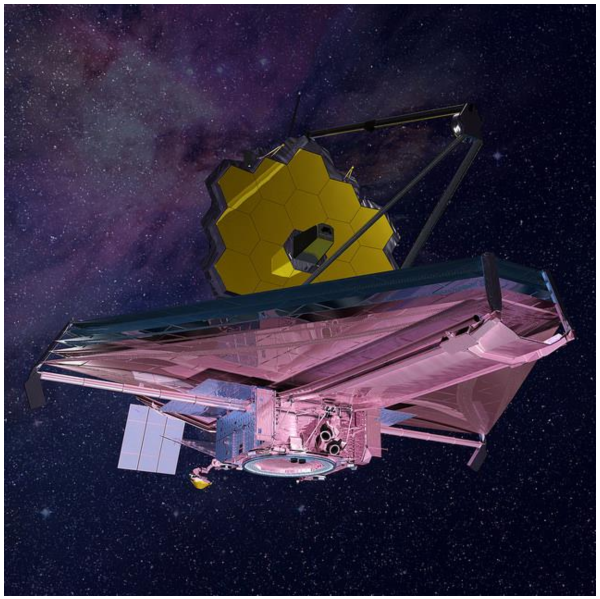




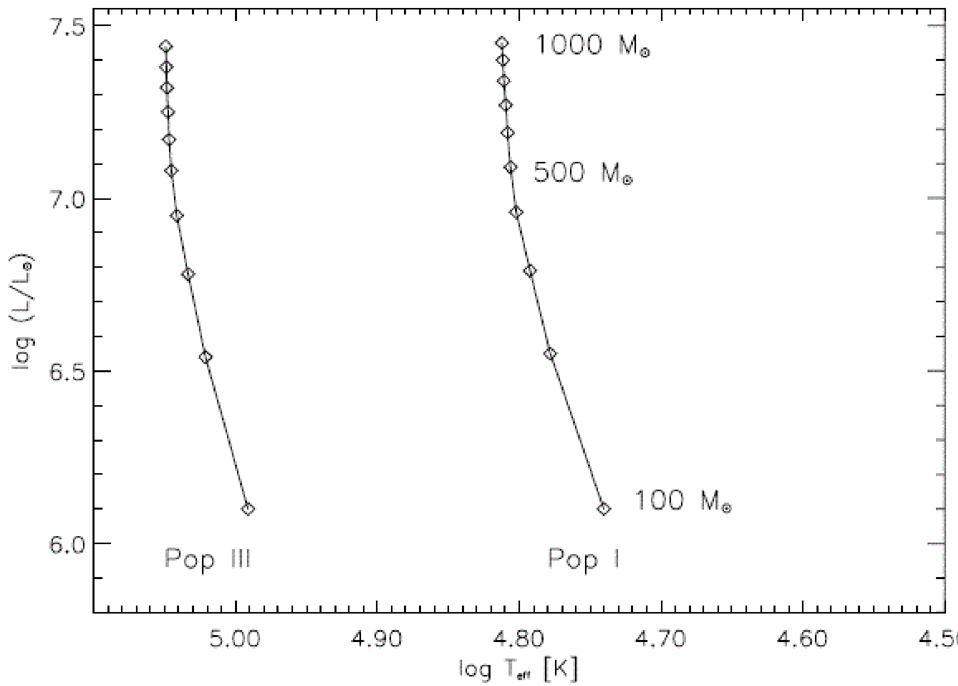
Luminous bursts can occupy ~ 30% of accretion history

Vorobyov, DeSouza, & Basu (2013)

Observability of Pop III stars



BROMM, KUDRITZKI, & LOEB (2001)



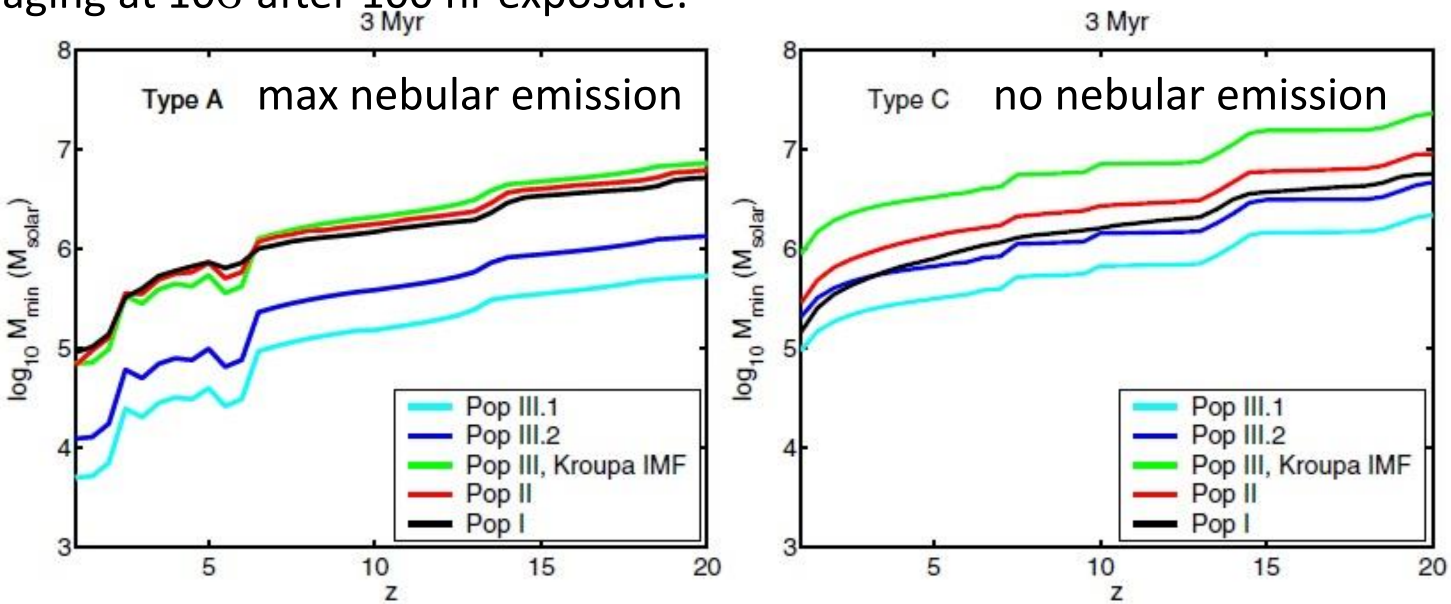
Will JWST observe them?

$$L \simeq L_{Edd} = \frac{4\pi c G m_p}{\sigma_T} M_* \propto M_*$$

Rydberg et al. (2013) and earlier Bromm et al. (2001) conclude that isolated Pop III stars of ~ 300 M_{sun} not visible by JWST at *z* ~ 10-30.

Detectability of Pop III stars

Zackrisson et al. (2011) – minimum detectable mass with JWST UDF , broadband imaging at 10σ after 100 hr exposure.



$$L \simeq L_{Edd} \simeq 3\times10^{6}\left(\frac{M}{100M_{sun}}\right)L_{sun}$$

Predict detectability of ~ 10^5 M_{sun} of massive Pop III stars at *z* = 10. Corresponds to luminosity ~ 10^9 L_{sun}.

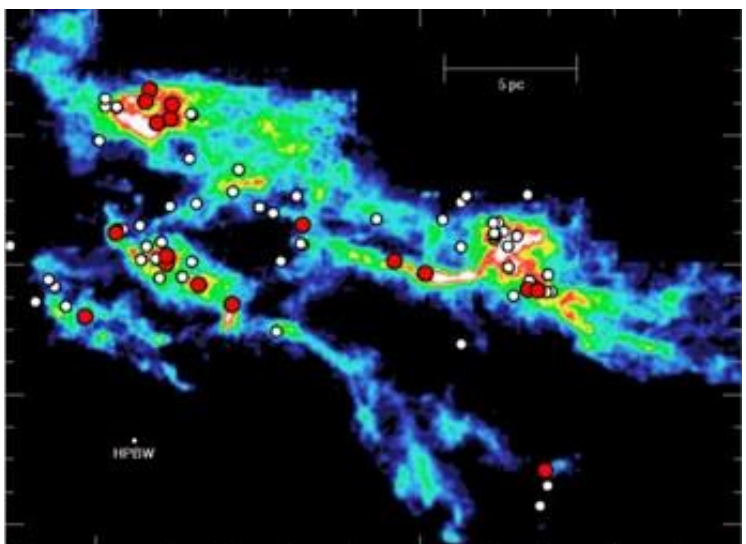
Do Pop III stars form in isolation?

Pop I stars certainly do not! Molecular clouds fragment into complex structures leading to weak to strong star clusters.

$$M_J \ll M_{cloud}$$ in Pop I star formation

Pleiades star cluster

Also $\langle M_* \rangle \ll M_J$



Taurus Molecular Cloud
Onishi et al. (2002)

Clusters of Pop III stars

In standard ΛCDM scenario, dark mater minihalos of mass ~ 10^5 - 10^6 M_{sun} form at z ~ 20-50 and are the precursors of Pop III stars. For ~10% gas mass to dark matter ratio,

$$M_{gas} \approx 10^4 - 10^5 M_{sun}$$

$$M_J \simeq 400 M_\odot \left(\frac{T}{300K} \right)^{3/2} \left(\frac{n}{10^5 \text{ cm}^{-3}} \right)^{-1/2}$$

Jeans mass of primordial gas

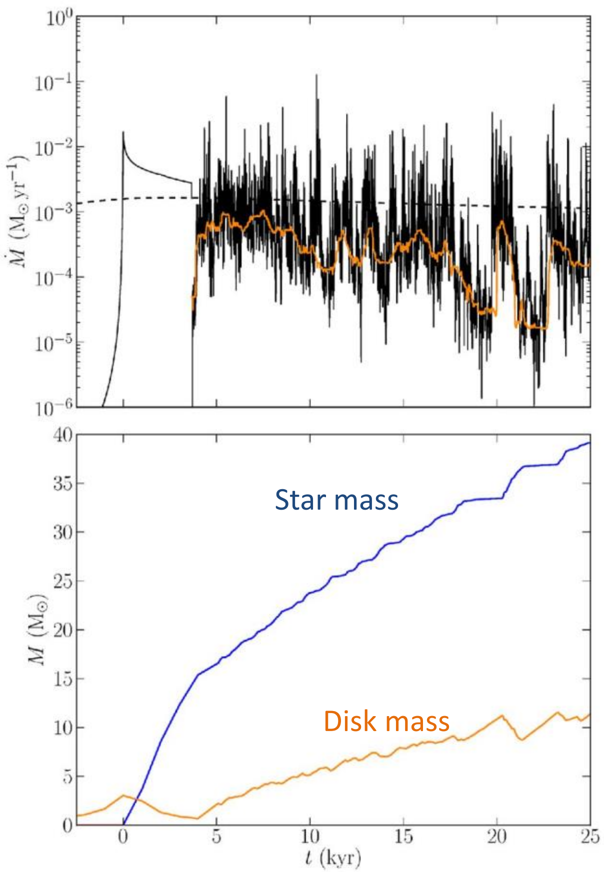
Clusters of size ~10 – 20 seem entirely possible.

Luminosity Evolution

Key point: ~ 30% of time spent in a burst mode; only ~ 10% for present-day models.

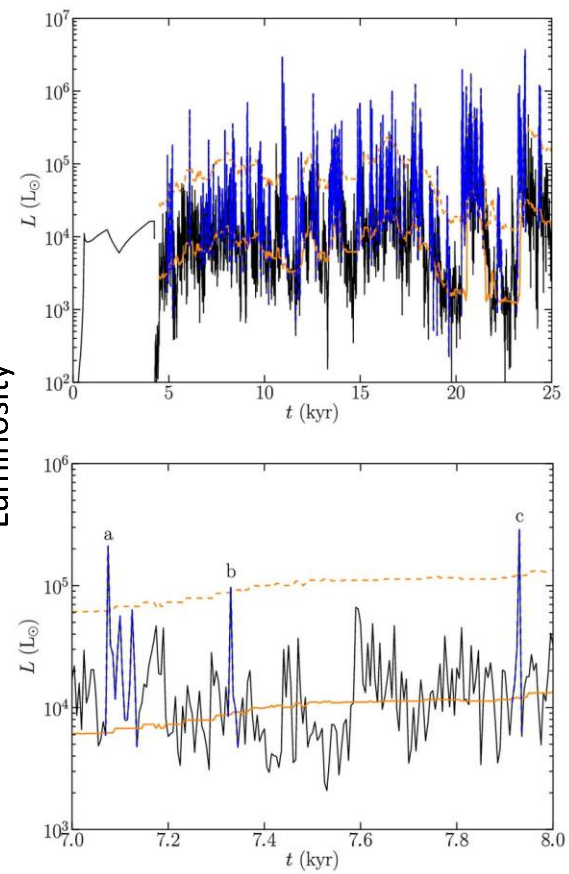
Mass accretion rate

Mass



Mean burst duration ~ 100 yr

Luminosity



Orange lines are 1 kyr time average value; dashed orange is 10x average

Zoom in on a 1 kyr window

DeSouza & Basu (2015, MNRAS, 450, 295)

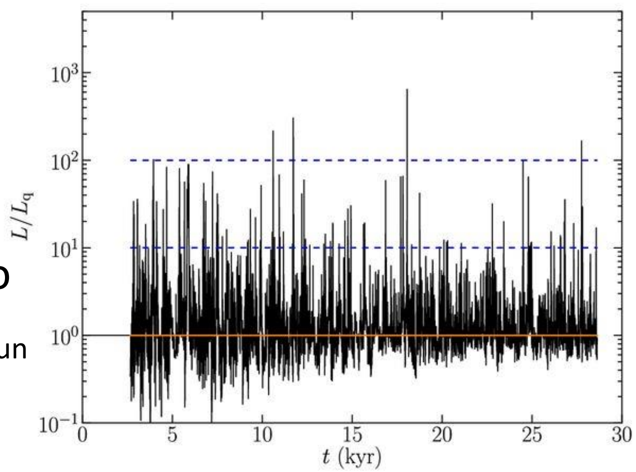
Cluster Luminosity functions

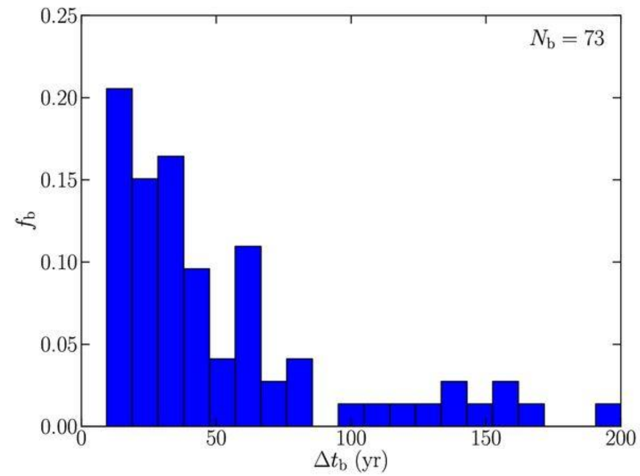
- Combine simulation results for *N* independently evolving cloud core models
- Choose a uniform random distribution of start times
- Choose a lognormal distribution of rotational energies
- Follow evolution until first star in cluster reaches 40 M_{sun}

Cluster Luminosity Evolution

Combined
N=16

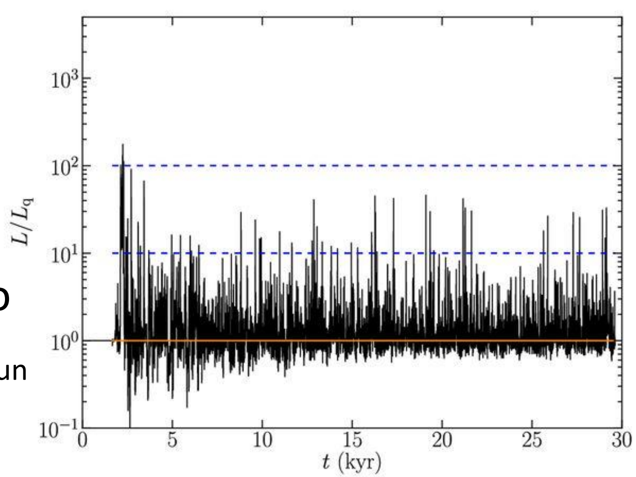
Normalized to
$L_q = 4 \times 10^5 L_{sun}$

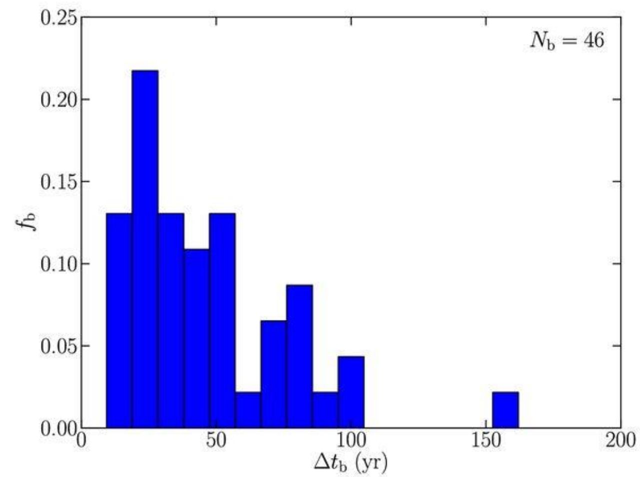




Combined
N=128

Normalized to
$L_q = 4 \times 10^6 L_{sun}$





Fractional amount of time spent in bursts of different durations
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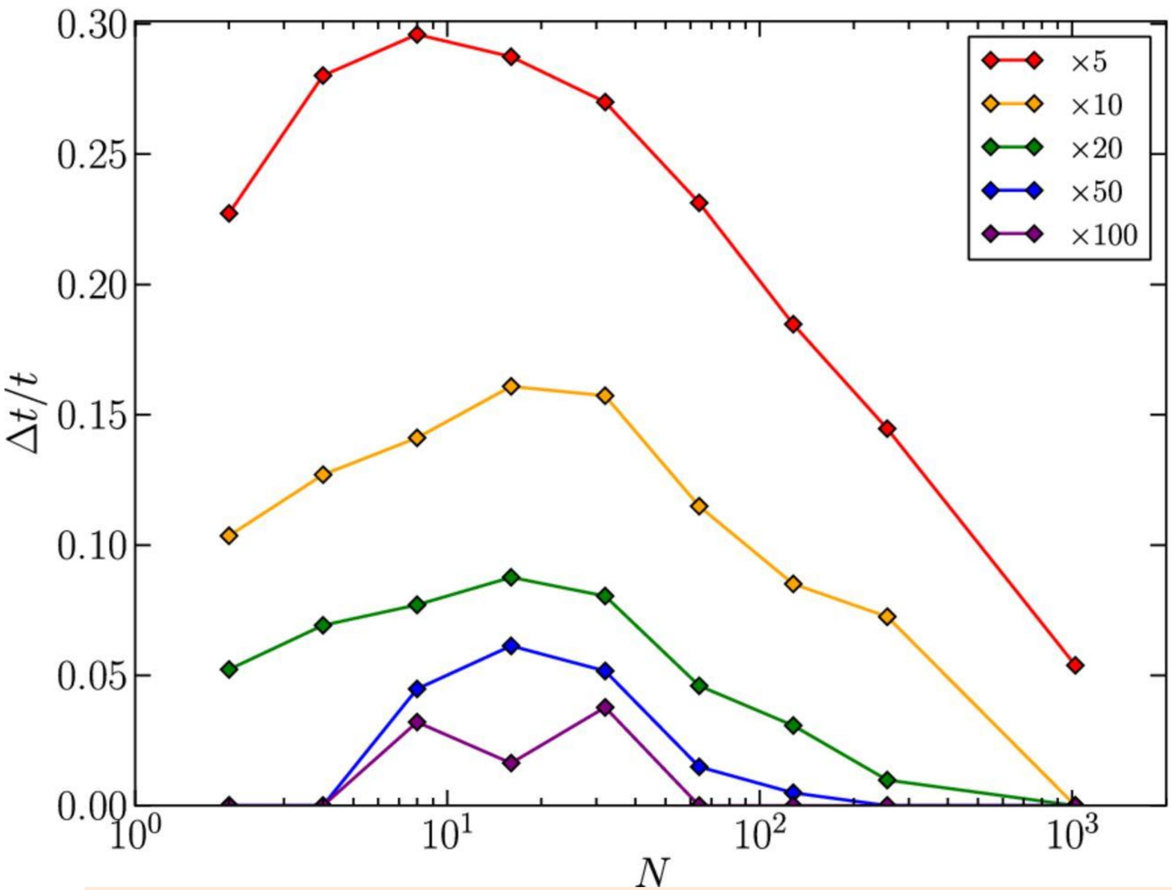
DeSouza & Basu (2015, MNRAS, 450, 295)

Fractional Time at Elevated Luminosity

As cluster members *N* increases, probability of overlapping bursts increases but mean luminosity keeps increasing too.



Fraction of first 40 kyr at elevated luminosity a factor of 5, 10, 20, 50, or 100 above the mean value.

Peak effect for small clusters of size 10-20.
15% of time spent at 10x mean luminosity.

DeSouza & Basu (2015)

SMBH Formation in Early Universe

doi:10.1038/nature14241

An ultraluminous quasar with a twelve-billion-solar-mass black hole at redshift 6.30

Xue-Bing Wu[1,2], Feige Wang[1,2], Xiaohui Fan[2,3], Weimin Yi[4,5,6], Wenwen Zuo[7], Fuyan Bian[8], Linhua Jiang[2], Ian D. McGreer[3], Ran Wang[2], Jinyi Yang[1,2], Qian Yang[1,2], David Thompson[9] & Yuri Beletsky[10]

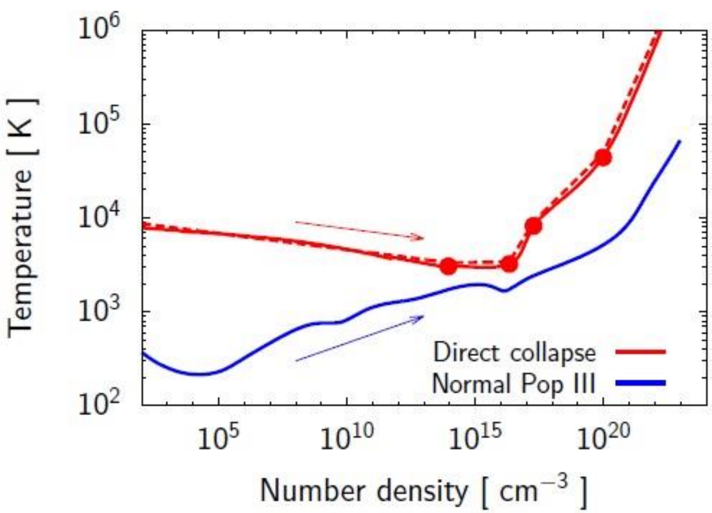
"The existence of such black holes when the Universe was less than one billion years old presents substantial challenges to theories of the formation and growth of black holes and the coevolution of black holes and galaxies."

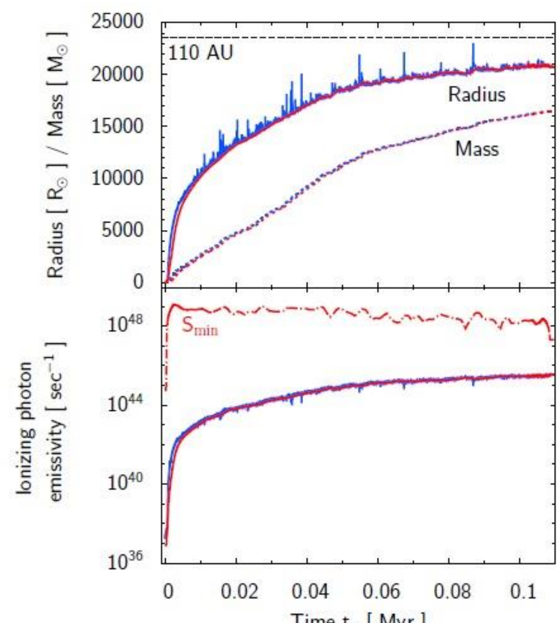
There is a renewed interest in supermassive first stars, ~ 10^5 M_{sun} as progenitors of supermassive 10^9-10^{10} M_{sun} black holes seen at *z* ~ 6-7 (e.g., Wu et al. 2015, Mortlock et al. 2011)

Direct Collapse of Atomic Cooling Halo

Suggested by Bromm & Loeb (2003) as primordial gas clouds in which H_2 has been dissociated by Lyman-Werner radiation. Temperature ~ 10^4 K in these atomic cooling halos, and Jeans mass ~ 10^5 M_{sun} .

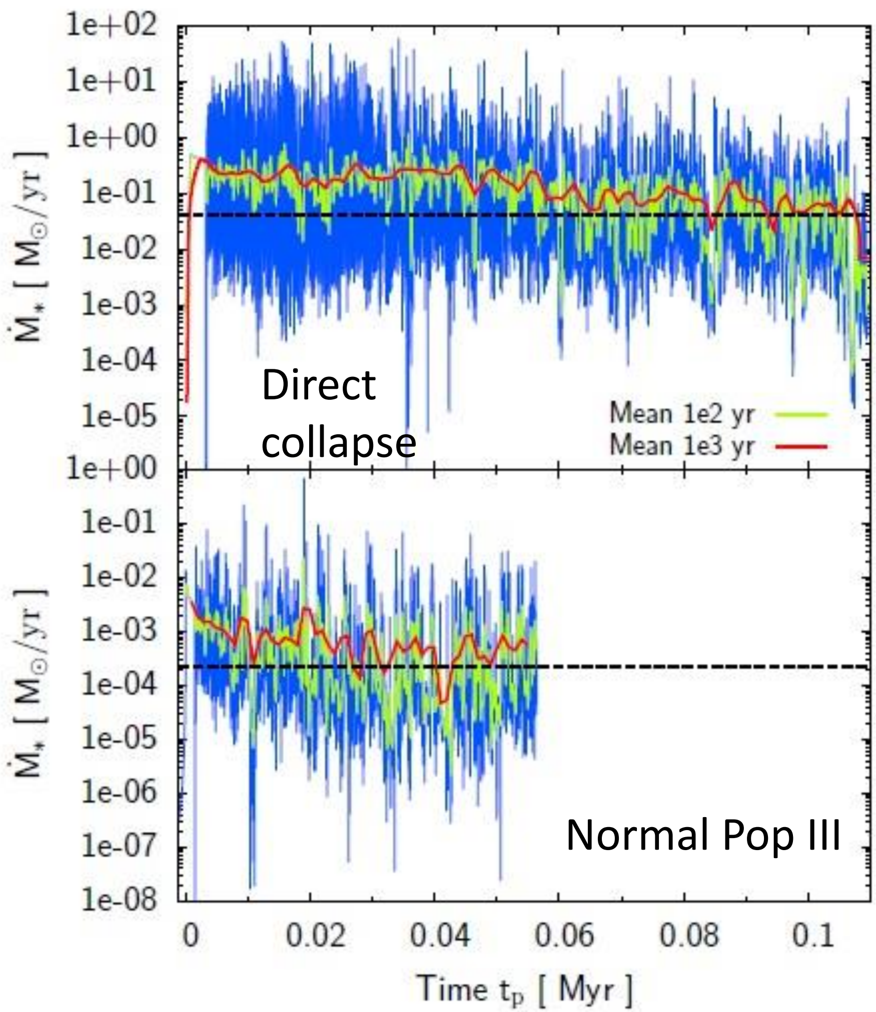
Accretion at high rates ~ c^3/G ~ 10^{-1} $M_{sun}yr^{-1}$ may monotonically inflate star with increasing stellar mass, causing it to remain at a low T_{eff} = 5000 K. At this low effective temperature, very few ionizing photons are emitted by the star.

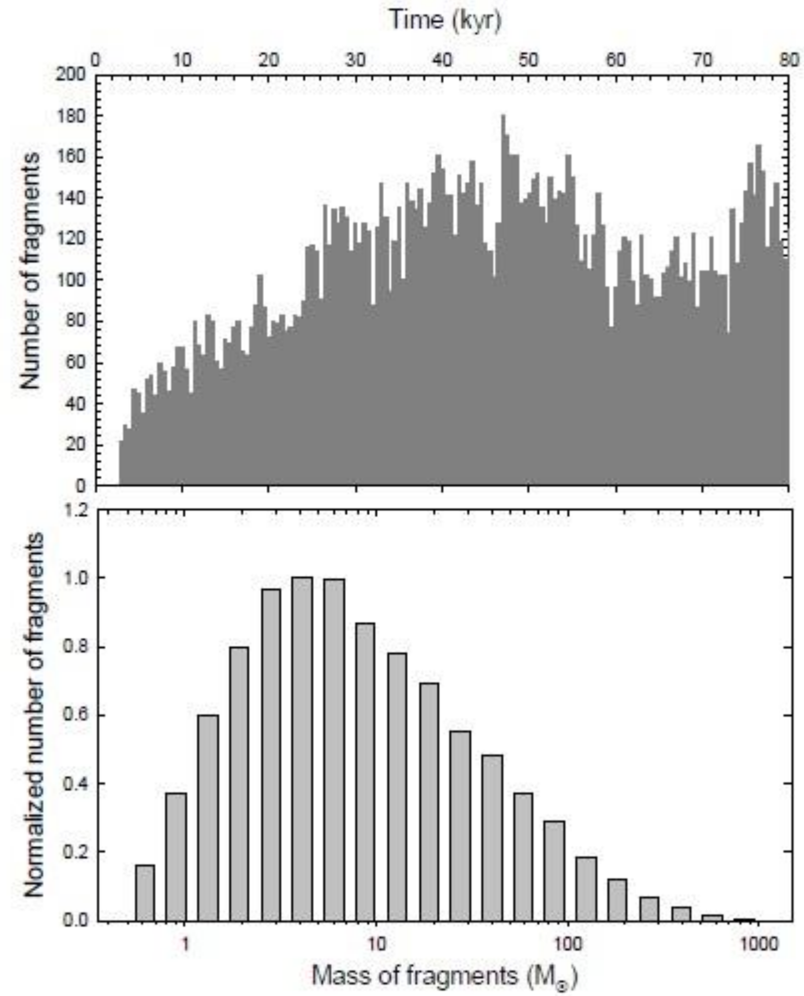




Sakurai, Vorobyov, Hosokawa, Yoshida, Omukai, & Yorke (2016)

Long-term Vigorous Episodic Accretion in Atomic Cooling Halos





Sakurai et al. (2016)

Conclusions

- Burst mode is more intense in primordial star formation than in present day. Up to ~30% of time spent in elevated accretion state
- Small (10-20) clusters of moderately high mass (~ 40 M_{sun}) Pop III stars can be transiently more luminous than a single very high mass (~ 300 M_{sun}) Pop III star
- Large photospheric radii in exotic scenarios (e.g., collapse of 10^4 K atomic cooling halo) can allow continuing episodic accretion without UV/HII region feedback