The First Stars

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Outline

- Star forming minihalos at high z
- Cooling physics and chemistry
- Gravitational Collapse and formation of protostar
- Magnetic fields
- Accretion and protostar evolution
- Feedback
- Fragmentation?
- Conclusions

Jeans and filter mass

- Gas collapses and cools in dark matter mini-halos
- From linear theory, the minimum mass that a perturbation must have in order to collapse gravitationally is the Jeans mass:

$$M_J = \frac{4\pi}{3}\rho_0 \left(\frac{\lambda_J}{2}\right)^3 \qquad \lambda_J = c_s \sqrt{\frac{\pi}{G\rho_0}}$$

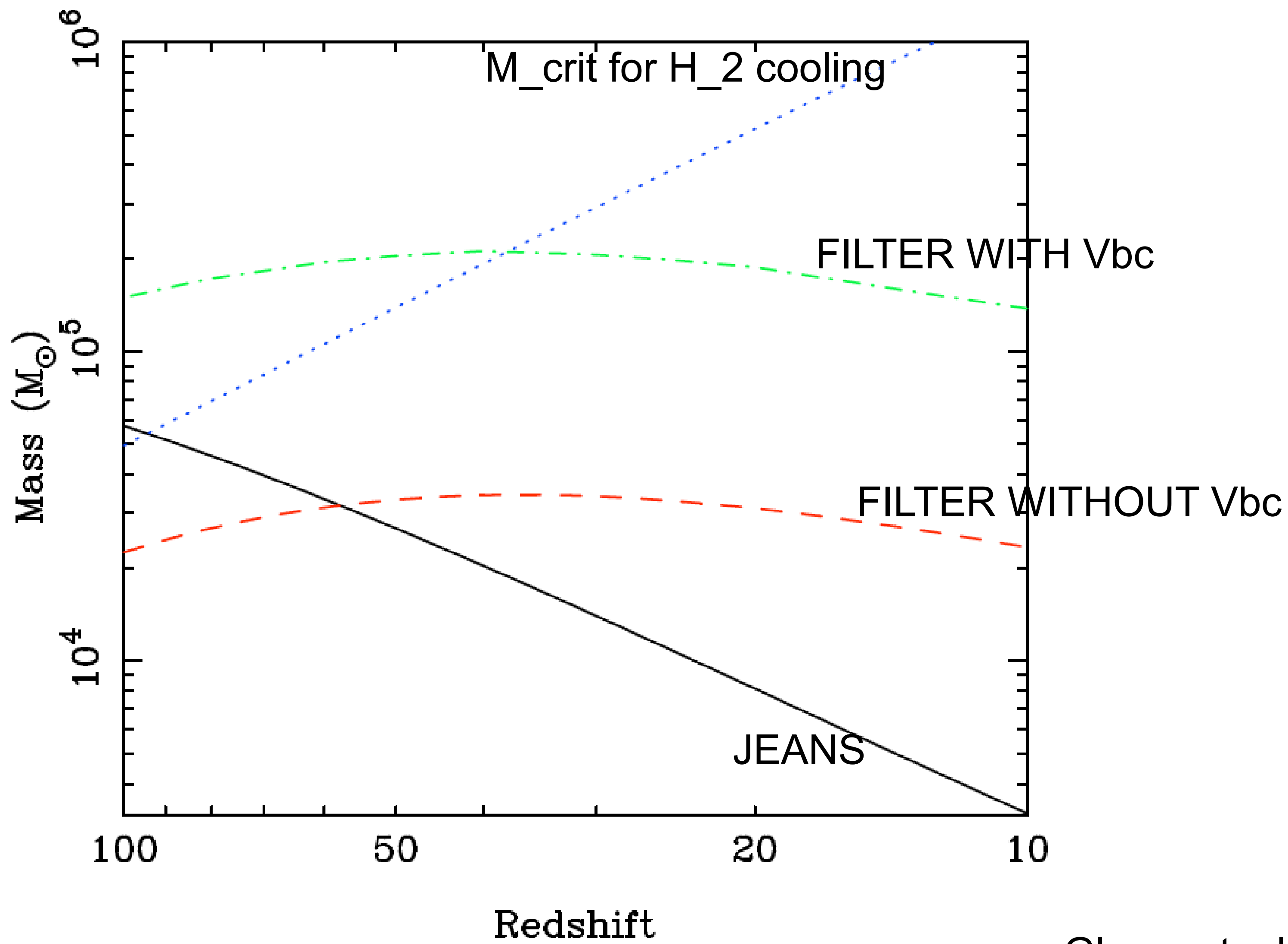
Jeans and filter mass

- But Jeans mass time dependent and changes significantly during the collapse.
- Better analysis gives filtering mass

$$\lambda_F^2 = \frac{3}{1+z} \int_z^\infty \lambda_J^2 \left[1 - \left(\frac{1+z}{1+z'} \right)^{1/2} \right] dz'$$

- Also effect from relative velocities between DM and Gas

Jeans and filter mass



Glover et. al.

Heating and cooling

- Gas falling into the minihalo is shock-heated to

$$T_{\rm vir} = \frac{\mu m_{\rm p} v_{\rm c}^2}{2k} = 1.98 \times 10^4 \left(\frac{\mu}{0.6}\right) \left(\frac{M}{10^8 h^{-1}\,{\rm M}_\odot}\right)^{2/3} \left[\frac{\Omega_m}{\Omega_m(z)} \frac{\Delta_c}{18\pi^2}\right]^{1/3} \left(\frac{1+z}{10}\right) {\rm K}$$

- Can cool to $T \sim 10^4\,{\rm K}$ with atomic H transitions
- After that need molecules:

$$\begin{aligned} {\rm H} + {\rm e}^- &\rightarrow {\rm H}^- + \gamma, \\ {\rm H}^- + {\rm H} &\rightarrow {\rm H}_2 + {\rm e}^-, \end{aligned}$$

- Can reach $T_{\rm min} \sim 150\text{-}200\ {\rm K}$
- Then HD cooling can take over

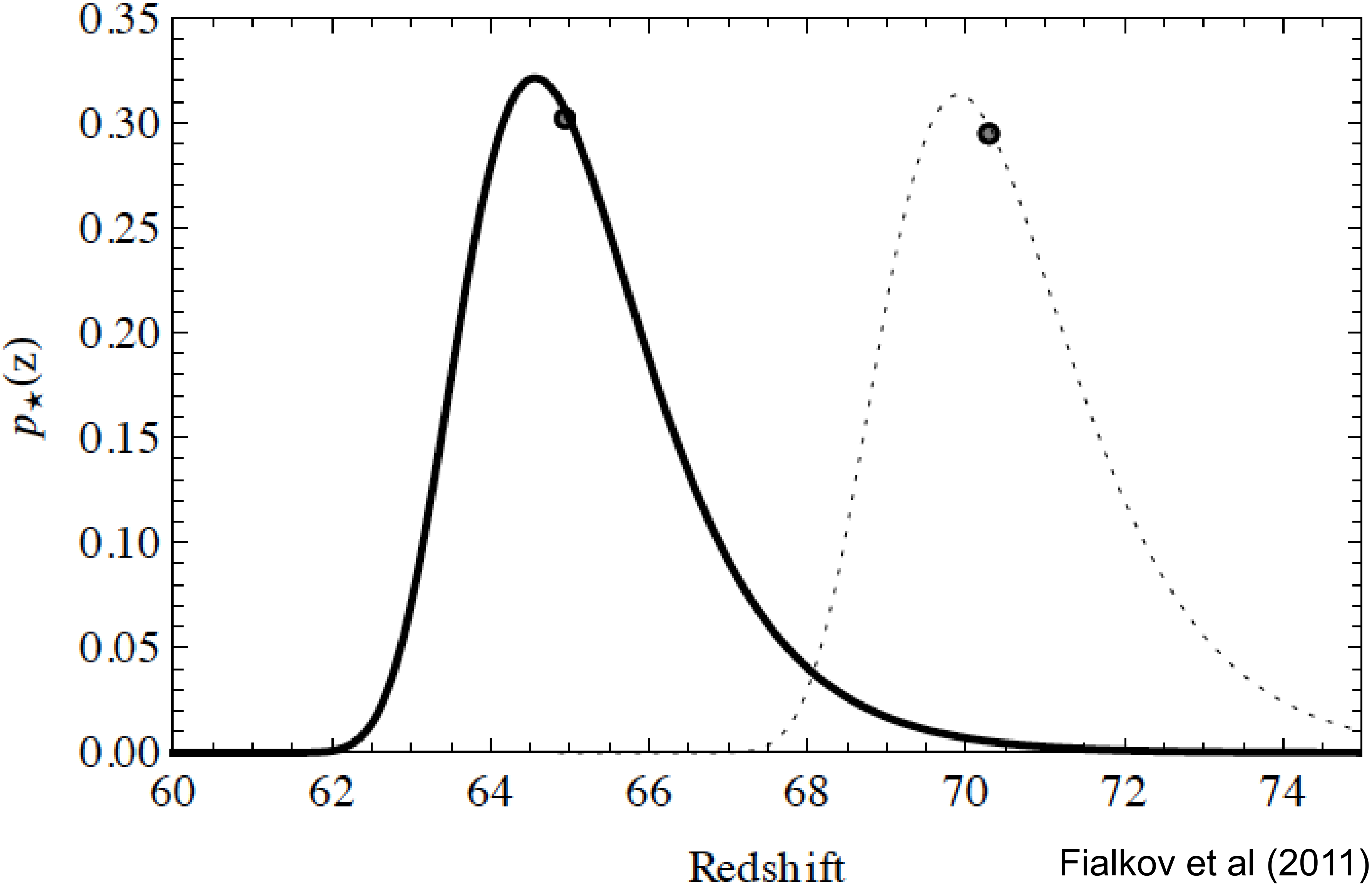
Cooling and collapse

- Rate equations show that can cool in a fraction of Hubble time if T > $T_{\rm crit} \sim 1000$ K
- This gives a minimum mass for cooling

$$M_{\rm crit} \simeq 6 \times 10^5 h^{-1} \left(\frac{\mu}{1.2}\right)^{-3/2} \Omega_m^{-1/2} \left(\frac{1+z}{10}\right)^{-3/2} \mathrm{M}_\odot$$

- Reach Bonnor-Ebert mass and collapse further
- At very high density > 10^8–10^9 cm^{-3} convert most H into H_2 via three-body reaction (exothermic). Temperature increases slightly

When does it happen?

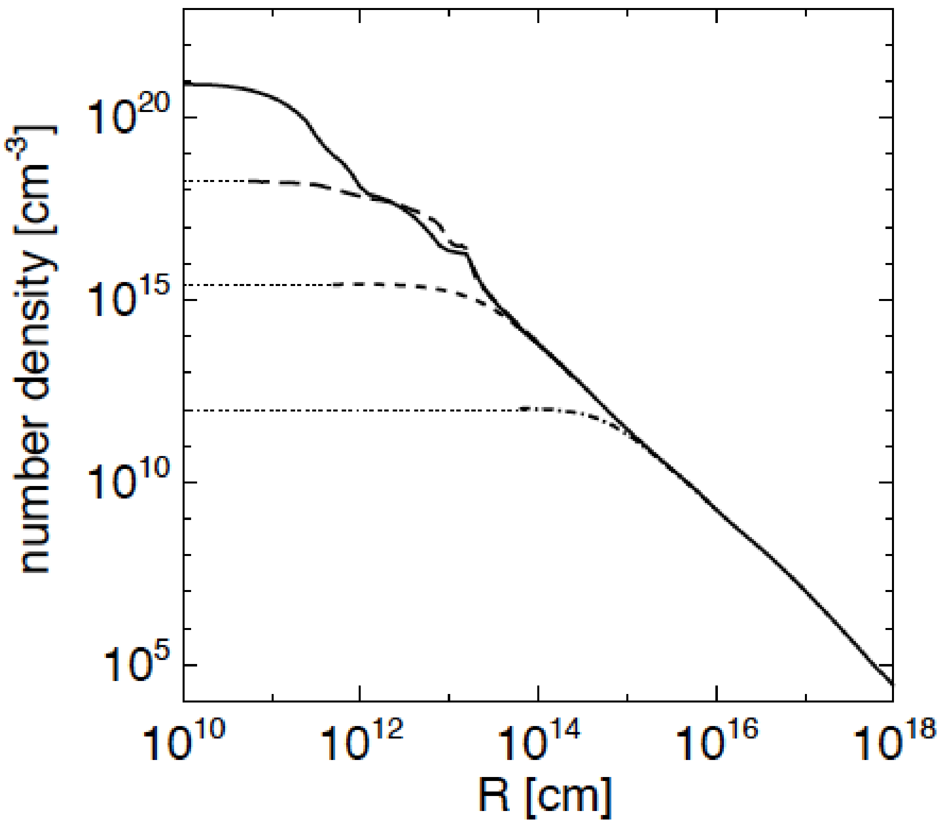


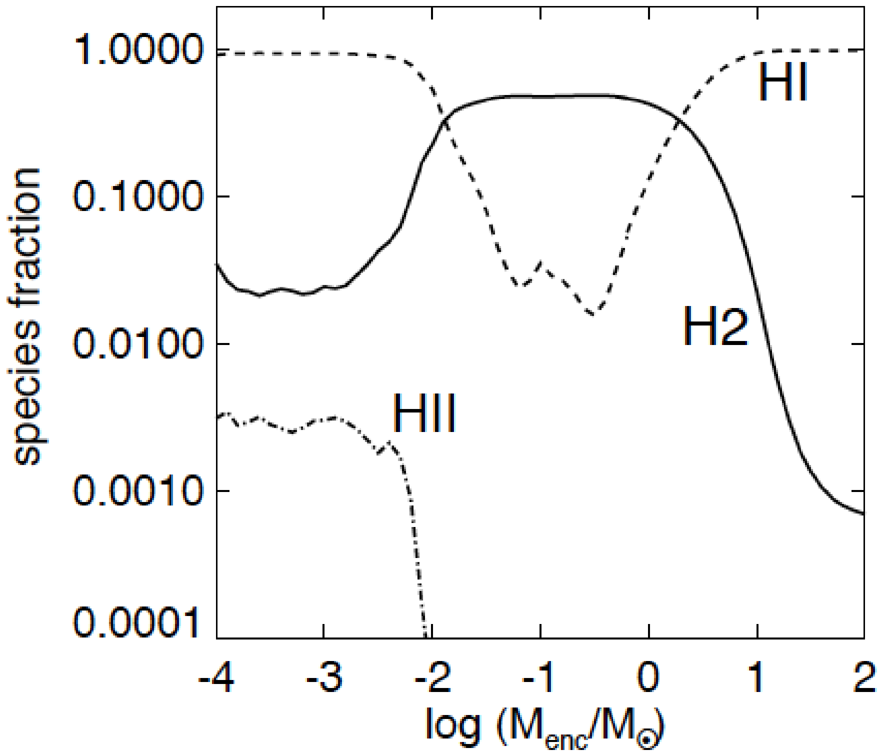
Fialkov et al (2011)

Collapse, and the first protostars

- As density increases, H_2 lines become optically thick
- At $n \sim 10^{14}\ \mathrm{cm}^{-3}$ collision-induced emission
- At $n \sim 10^{16}\ \mathrm{cm}^{-3}$ cool by dissociating H_2.
- Left with a dense core with size ~ $0.1\ \mathrm{AU}$ and mass ~ $0.01\,\mathrm{M}_\odot$ and n ~ $10^{20}\ \mathrm{cm}^{-3}$
- This is a Pop III core!

In summary





Yoshida et al (2008)

Magnetic fields?

- Bounds on primordial magnetic fields give B < 1 nG (comoving)
- If no other generation mechanism, then B is unimportant in formation of primordial stars, even in the case of perfect flux freezing
- Turbulent dynamo could create B large enough to be dynamically important
- Ambipolar diffusion heating can affect the thermal properties of the protostar
- Not clear if this actually happens

Accretion

- Other uncertain period. Simulations are hard because timestep has to satisfy the Courant condition

$$\Delta t \leq \frac{\Delta x}{c_s}$$

- Following the protostar for thousands of years is too computationally expensive (for now!)
- Solutions: semi-analytic modeling, numerical in 1D or use sink particles

Accretion

- Neglect any feedback for now...
- Dimensional analysis:

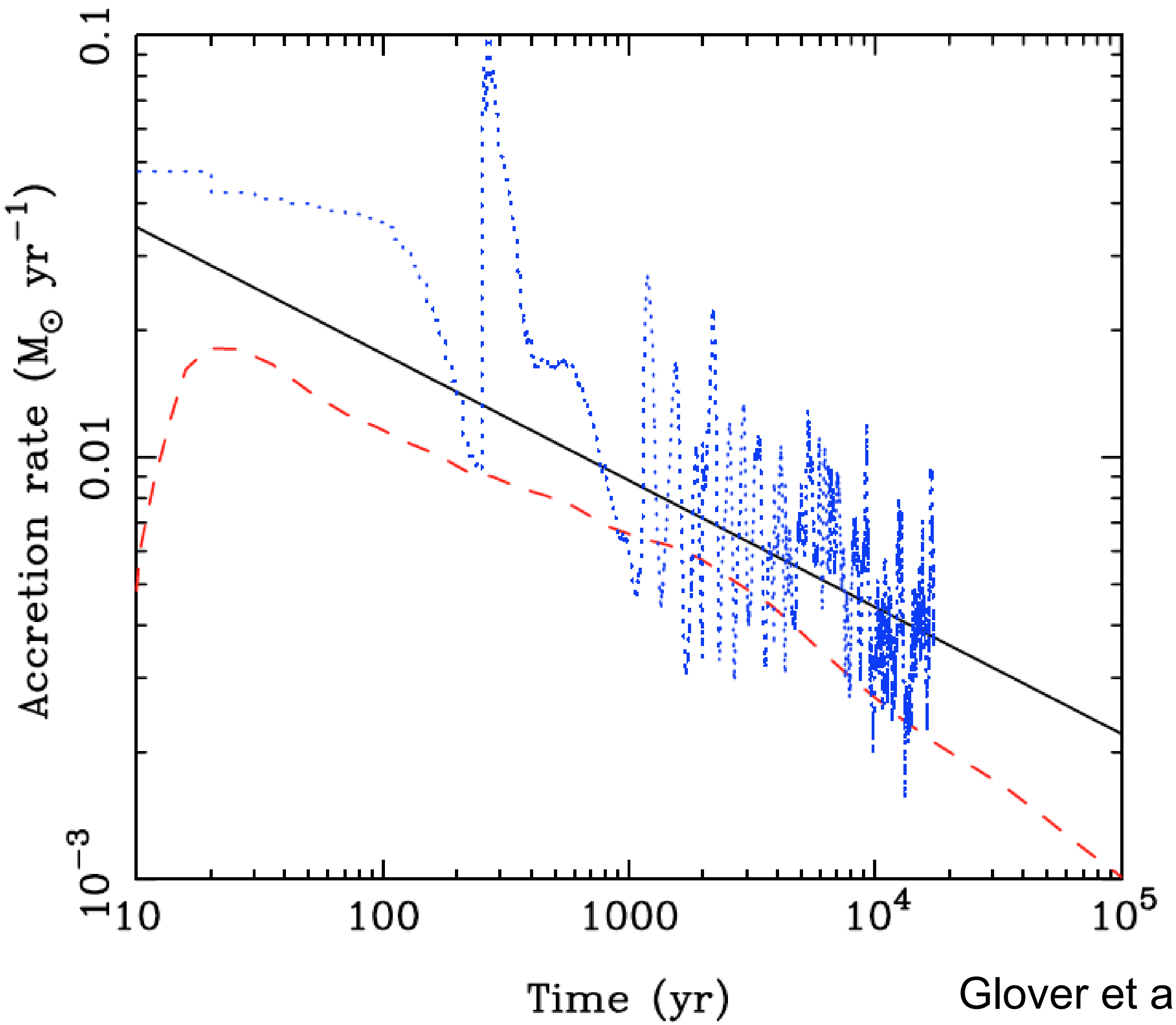
free fall time = $t_{\rm ff} = \sqrt{3\pi/32G\langle\rho\rangle}$

expected accretion rate $\dot{M}_{\rm est} \sim M_{\rm J}\sqrt{G\langle\rho\rangle}$

- Simulations:

$$\dot{M} = 6.0 \times 10^{-2} \left(\frac{t}{1\mathrm{yr}}\right)^{-0.343} \mathrm{M}_\odot\,\mathrm{yr}^{-1}$$

Accretion



Glover et al (2012)

Accretion and initial mass

- If no feedback, expect very massive primordial stars:

$$M_* = 0.1 \left(\frac{t}{1\,\mathrm{yr}} \right)^{0.70} \mathrm{M}_\odot\,\mathrm{yr}^{-1}$$

- After 5 x 10^4 yrs, $M_* \simeq 195\,\mathrm{M}_\odot$
- After 2 x 10^6 yrs, $M_* \simeq 2575\,\mathrm{M}_\odot$
- In practice, fragmentation is probably important and feedback can't be completely ignored. But still expect very massive stars!

Three stages of evolution

- Phase I: relaxation to entropy profile consistent with accretion flow. Lasts until $M_* = 0.1\,\mathrm{M}_\odot$
- Phase II: adiabatic core contraction. The core remains reasonably cold $T_c \sim 10^5\,\mathrm{K}$. Accretion shocks increase entropy in the outer layers. The gas surrounding the shock is optically thick due to H^- opacity. Lasts till $M \sim 1\mathrm{M}_\odot$
- Phase III: homologous core collapse. Luminosity and entropy waves propagating outward.
- Deuterium burning: $t = 1000\,\mathrm{yr}$ $M = 12\,\mathrm{M}_\odot$
- H burning: $t = 1.6 \times 10^4\,\mathrm{yr}$ $M = 80\,\mathrm{M}_\odot$
- Enter ZAMS: $t \sim 10^6\,\mathrm{yr}$.

Mechanical Feedback

- Mechanical feedback: winds play an important role in evolution of Pop I stars, where radiative acceleration driven by metal and ion lines.
- In metal free gas, only contribution from He^+ and free e^-. Maybe weak CNO-driven wind.
- Effects are not very important.

Radiative Feedback

- <u>Radiative feedback</u>: possible mechanisms
- Radiation pressure – likely never large enough
- Photodissociation of H_2 and reduction in cooling rate – not sufficient to halt accretion
- Heating of surrounding gas by radiation. If thermal energy > gravitational binding, can stop accretion
- Escape velocity $v_{esc} \simeq 9.4 \left(\frac{R}{100\,\mathrm{AU}} \right)^{-0.1} \mathrm{km\,s^{-1}}$
- Corresponding to $T \sim 10^4$ K
- Low *photospheric* temperature $T_p \sim 6000$ K for *protostar.* Once on the main sequence, can form HII region with higher T. Still open question whether this can stop accretion

Fragmentation

- Initially was thought that most of the mass of the disk would accrete on the protostar, so would expect very large mass.
- However accretion disk can become unstable and fragment in smaller pieces.
- Dynamics not fully understood. Do you get companions or do they eventually merge?
- Much more on this in future talks!

Conclusions

- First stars form at z ~ 65 in extremely high peaks of density fluctuations.
- Cooling physics and chemistry very different from present day star formation.
- Expect pretty massive stars.
- Lots of poorly understood points, including magnetic fields, the role of fragmentation and feedback etc...

References

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