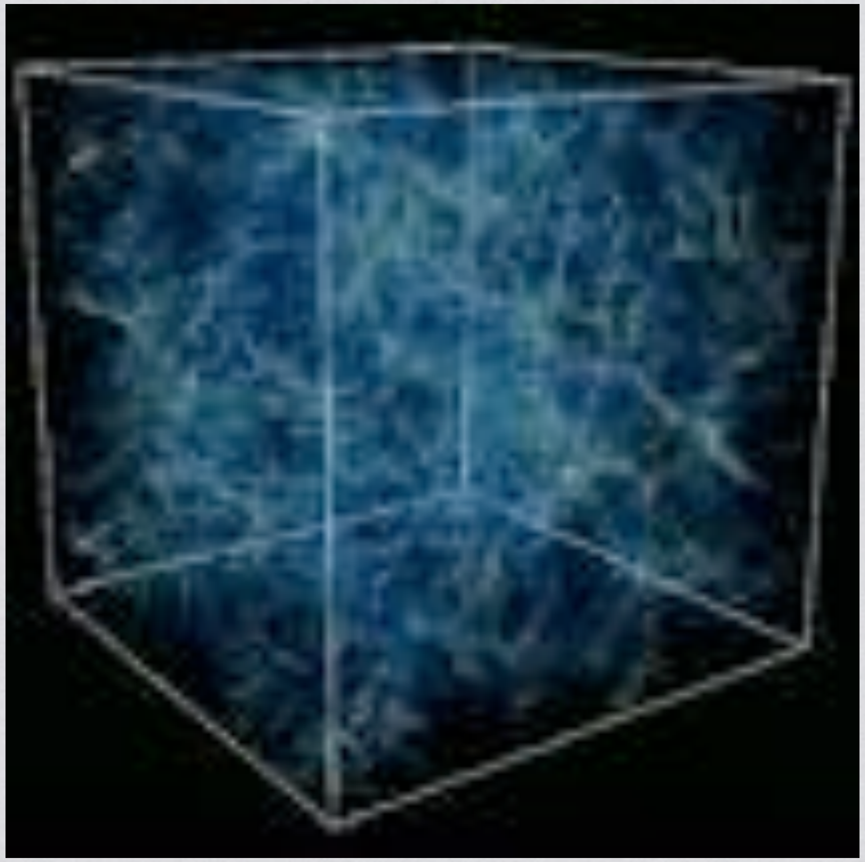
Star Formation

Dark Matter and Baryons

- ★ Gravity (DM) defines large scale structure of the Universe
- ★ Baryons are mostly hitchhiking a ride
- ★ Yet, their physical interactions are far richer
    - ★ "Gastrophysics"

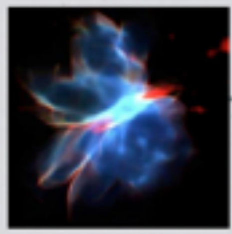


★ How are stars formed?

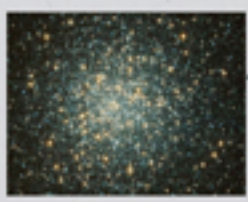
Before starting:

Stellar population classification

- For astronomers: Metals == Chemical elements heavier than Helium



- Population III stars:
  - metal-free, massive (but no direct observations), first stars formed in the universe



- Population II stars:
  - low-metallicity stars (lets say <1% solar), normal mass function (typical mass <Msun), old stars (globular clusters, galactic nuclei)

- Population I stars (like the Sun):
  - high-metallicity, young and hot, normal mass function, found preferentially in spiral arms

Let's start from observations!

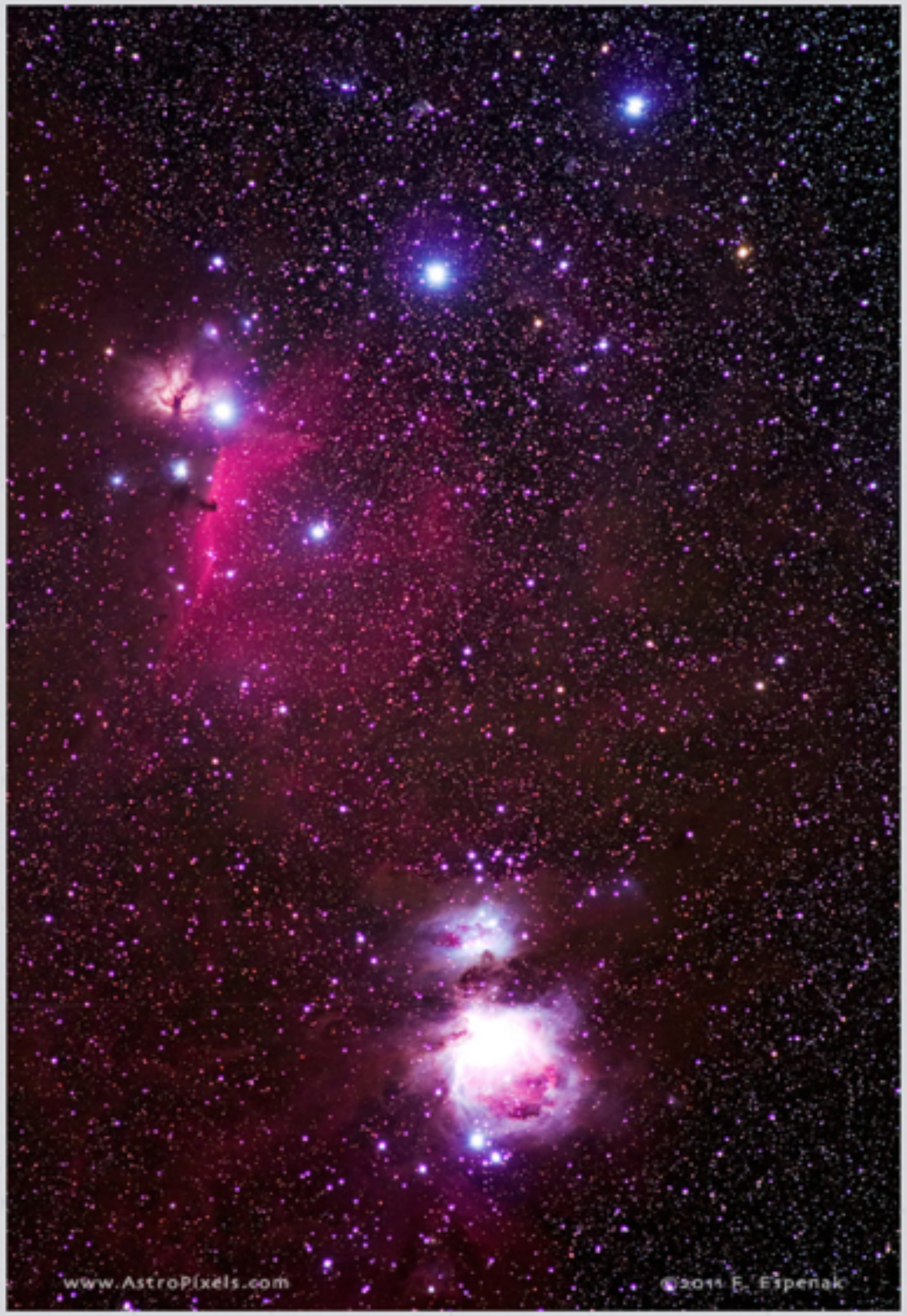
★ Stars form out of cold, dense, dusty molecular gas

★ Figure shows clumpy star formation in spiral arm

★ Gas in arms is compressed, first step toward star formation

Let's start from observations!

- On smaller scales:
  - Giant Molecular Clouds
    - $M \sim 10^6 M_{sun}$; $R \sim 10pc$
      - STAR CLUSTERS
  - Molecular cloud cores
    - $M \sim$ few M_{sun}; $R \sim 0.1pc$
      - STARS



Outline

- ★Basic Physics of star formation
  - ★Jeans Mass
  - ★Cooling
- ★Forming the first stars in dark-matter halos
- ★From the first stars to the first galaxies

Basic physics of star formation

- ★ Star forming regions experience struggle between:
  - ★ Gravity - acts to collapse the cloud
  - ★ Pressure
  - ★ Magnetic fields
  - ★ "Bulk motions"

  } - sources of support preventing collapse

If gravity wins, on what timescale is the collapse happening?

Basic physics of star formation

★ Star forming regions experience struggle between:

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} - sources of support preventing collapse

Collapse is on dynamical gravitational time:

$$t_G \sim \sqrt{\frac{R^3}{2GM}} \sim \frac{1}{\sqrt{G\rho}}$$

The Jeans mass

- ★ What is the minimum mass for collapse?
  - ★ Gravity - acts to collapse the cloud
  - ★ Pressure - prevents collapse

The Jeans mass

★ What is the minimum mass for collapse?

- ★ Gravity - acts to collapse the cloud
- ★ Pressure - prevents collapse

Borderline case is that of hydrostatic equilibrium:

- Gravitational Energy: $E_G \sim -\frac{G\,M\,M}{L}$

=

- Thermal Energy: $E_T \sim N\,k\,T$

For volume of linear size L, N gas molecules of mass m

The Jeans mass/length

★ Gravitational/Thermal energy:

$$\frac{|E_G|}{E_T} \sim \frac{G\,M^2}{L\,N\,k\,T} \sim \frac{G\left(\rho\,L^3\right)m}{L\,k\,T}$$

The Jeans mass/length

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★ Length at which they are equal is Jeans length:

$$\boxed{L_J \sim \left(\frac{k\,T}{G\,\rho\,m}\right)^{1/2}}$$

Jeans mass is then simply ρL_J^3

Timescales (another derivation)

★ Collapse time vs. sound crossing time:

$$t_G = \frac{1}{\sqrt{G\rho}} \qquad t_S = \frac{L}{c_S} \qquad c_s \sim \left(\frac{kT}{m}\right)^{1/2}$$

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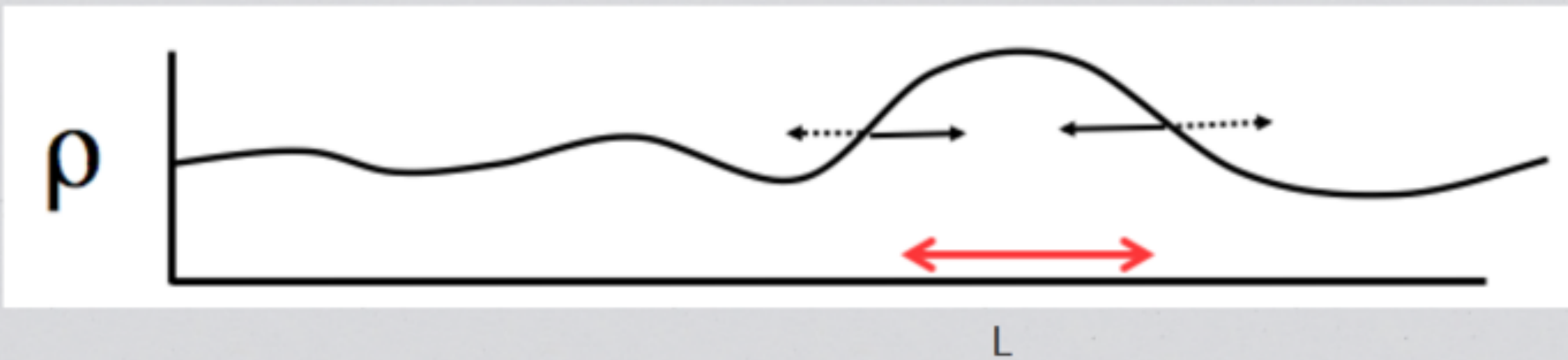
★ Let's take the ratio and see when they are equal:

$$\frac{t_S}{t_G} \sim \frac{L\sqrt{G\rho}}{c_S} \sim L\left(\frac{G\rho m}{kT}\right)^{1/2}$$

Jeans length (again)!

$$\boxed{L_J \sim \frac{c_S}{\sqrt{G\rho}}}$$

The Jeans mass/length

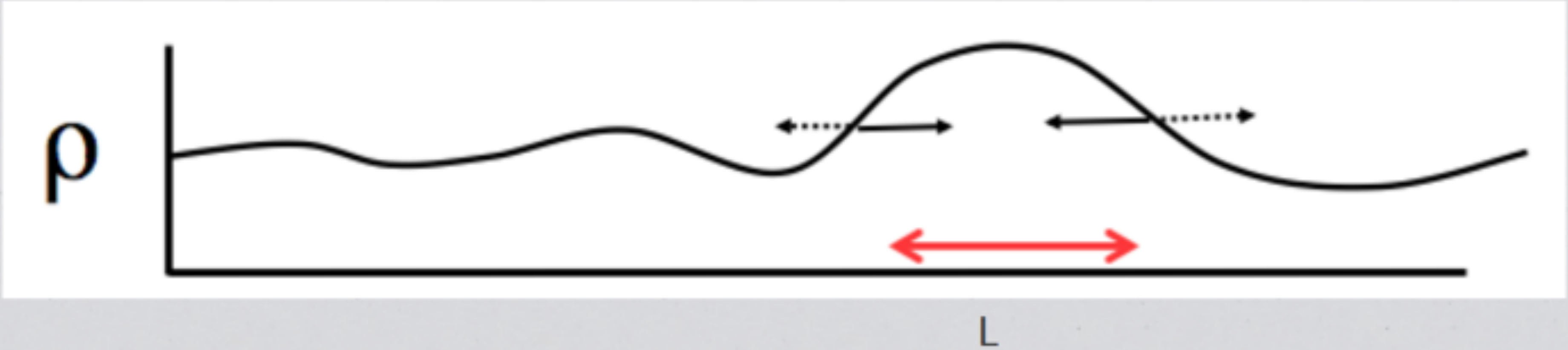


$$L_J \sim \left(\frac{k\,T}{G\,\rho\,m} \right)^{1/2}$$

★ $L > L_J$: gravity wins

★ $L < L_J$: pressure wins

The Jeans mass/length



$$L_J \sim \left(\frac{k\,T}{G\,\rho\,m}\right)^{1/2}$$

★ $L > L_J$: gravity wins

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Why and how cooling is tilting the balance?

A consistency check:

- ★ Lets take molecular clouds in the local Universe:
  - ★ $\rho \sim 10^{-19}$g cm^{-3}
  - ★ T~10K

$M_J \sim 8 \times 10^{32}$ g ~ 0.4 M_{sun}

$R_J \sim 10^4$ AU

- ★ Typical mass and length scales for star formation about right

The importance of cooling

★ How do we get the right conditions for star formation?

★ Gas in the Interstellar Medium is not dense enough

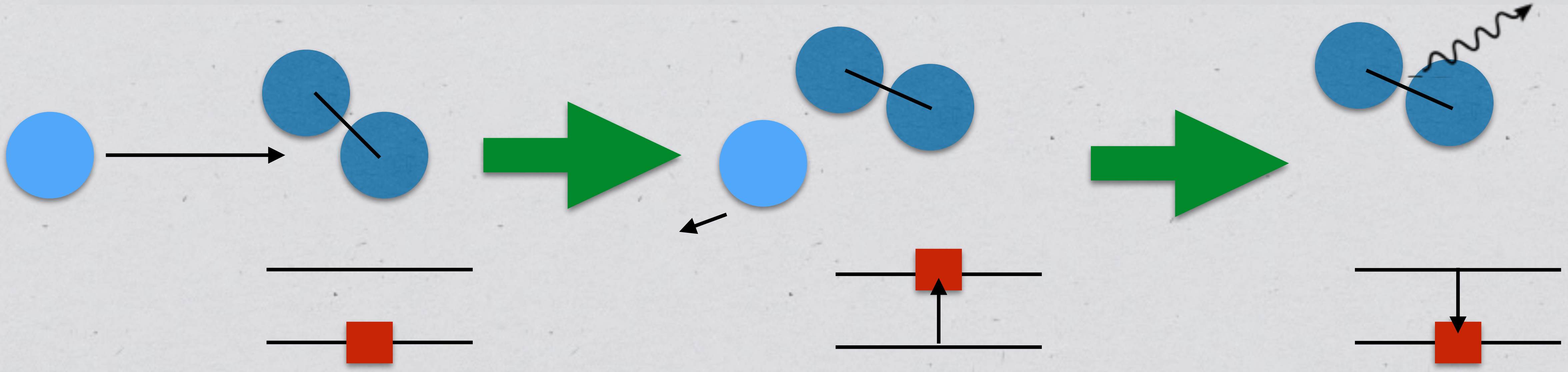
★ Gas after a dark-matter halo virializes is too hot (shock heated to halo T_{vir})

★ How can gas cool?

Radiative cooling

★ Collisions in gas excite atomic/molecular levels

★ Return to ground state by γ emission



★ How do you expect cooling to depend on metallicity of gas?

Radiative cooling and “metals”

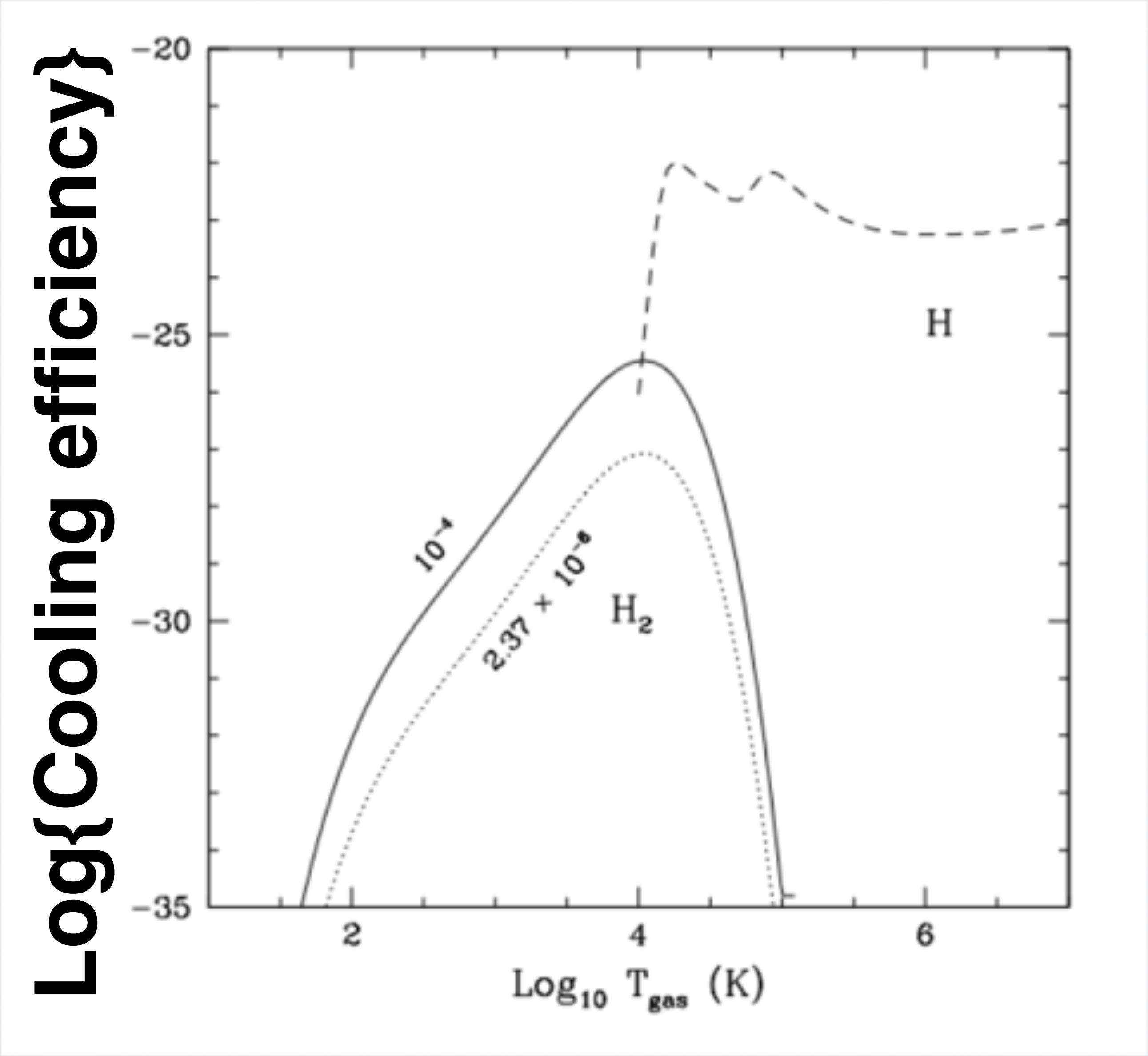
- ★ The more “metals” the more efficient the cooling: many energy levels available

- ★ Simple atoms and molecules are inefficient at radiative cooling
  - ★ Metal-free gas ($Z<10^{-3.5}Z_{Sun}$) hard to cool

- ★ What is your expectation for the Jeans mass in first gas clouds?

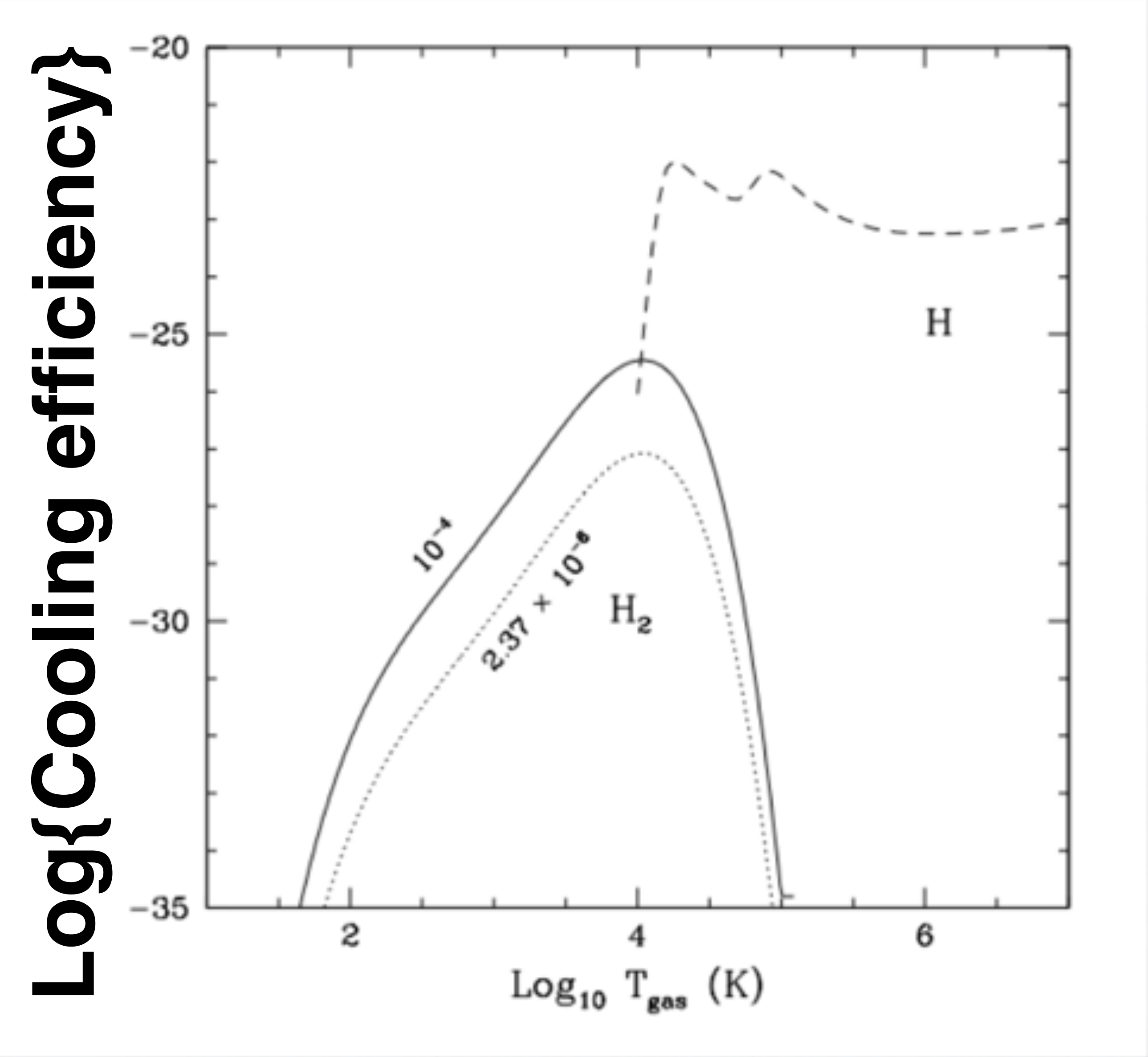
Metal-free gas

- ★ Cooling below $10^{-3.5}$ Z_{sun} relies on Lyα/H_2:
  - ★ Inefficient!
  - ★ But cooling efficiency grows with temperature



Metal-free gas

- ★ Cooling below $10^{-3.5}$ Z_{sun} relies on $Ly\alpha/H_2$:
  - ★ Inefficient!
  - ★ But cooling efficiency grows with temperature
  - ★ WHY?



DM halos and cooling of gas

★ Temperature of gas in DM halos depends on halo mass and redshift

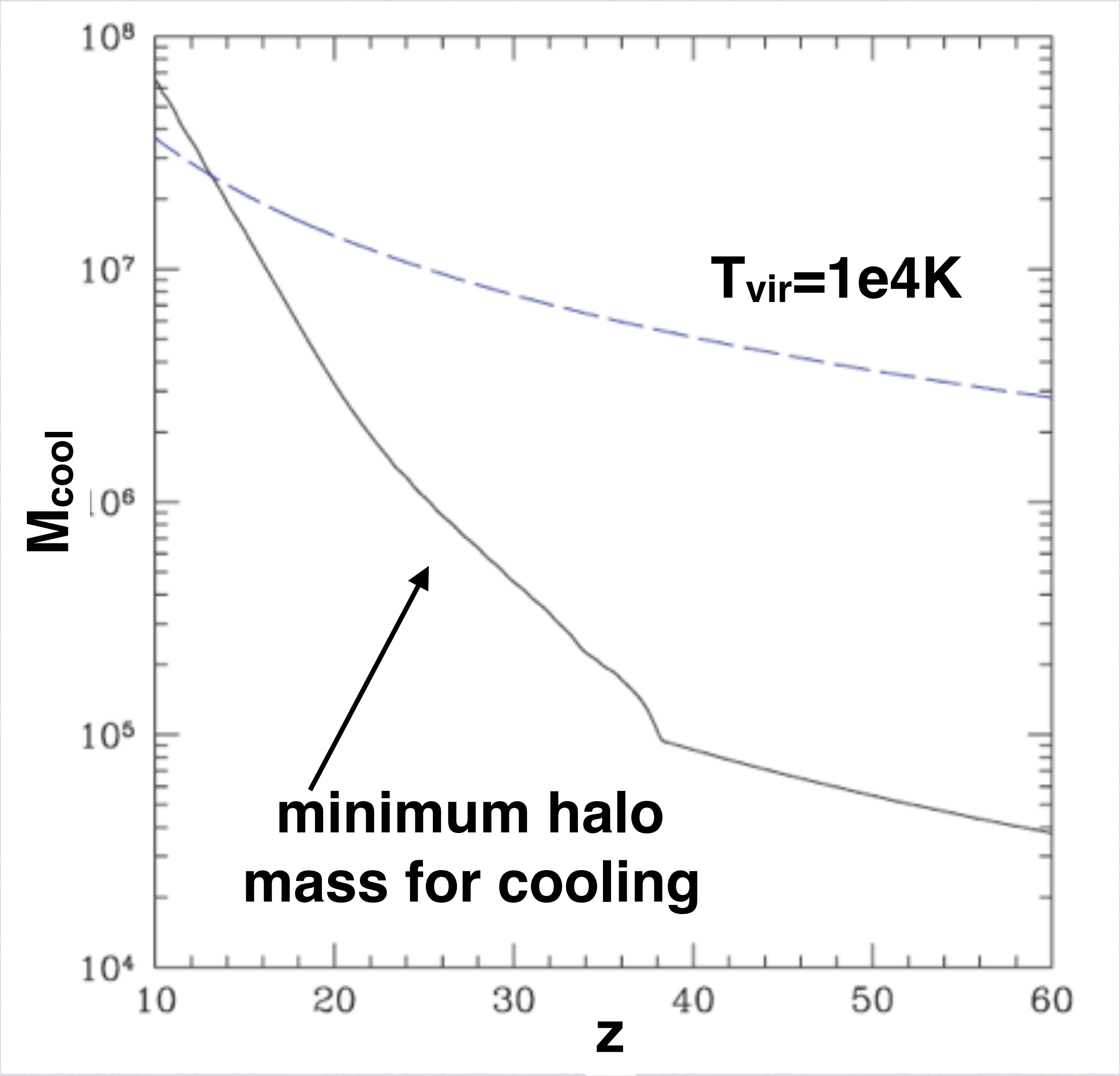
$$T_{\rm vir}(M,z) \simeq 2554\,{\rm K}\left(\frac{M}{10^6\,M_\odot}\right)^{2/3}\left(\frac{1+z}{31}\right).$$

★ There is a minimum halo mass for which cooling is efficient (cooling time less than Hubble time)

$$M_{t_H-{\rm cool}} \simeq 1.54\times10^5\,M_\odot\left(\frac{1+z}{31}\right)^{-2.074}.$$

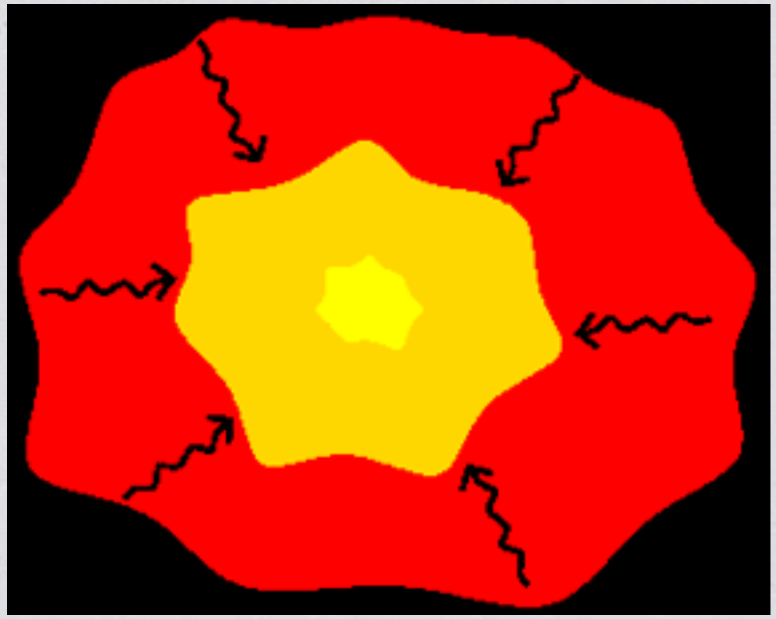
Minimum halo for cooling

- Minimum mass for H_2 cooling increases with redshift: Combination of expansion and radiation

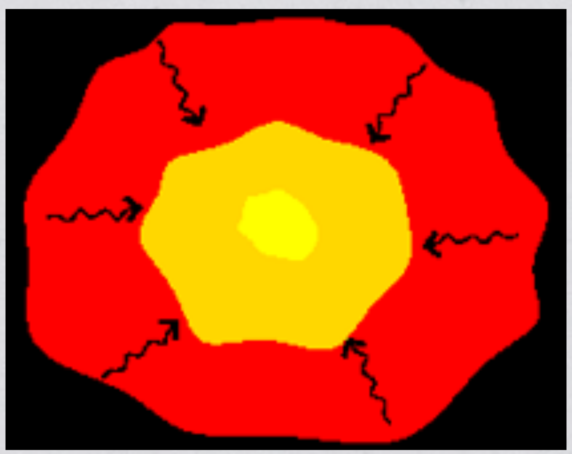


Trenti & Stiavelli (2009)

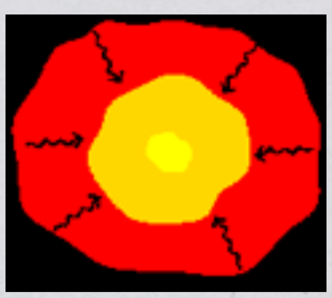
The simple picture



Gas cloud starts to contract



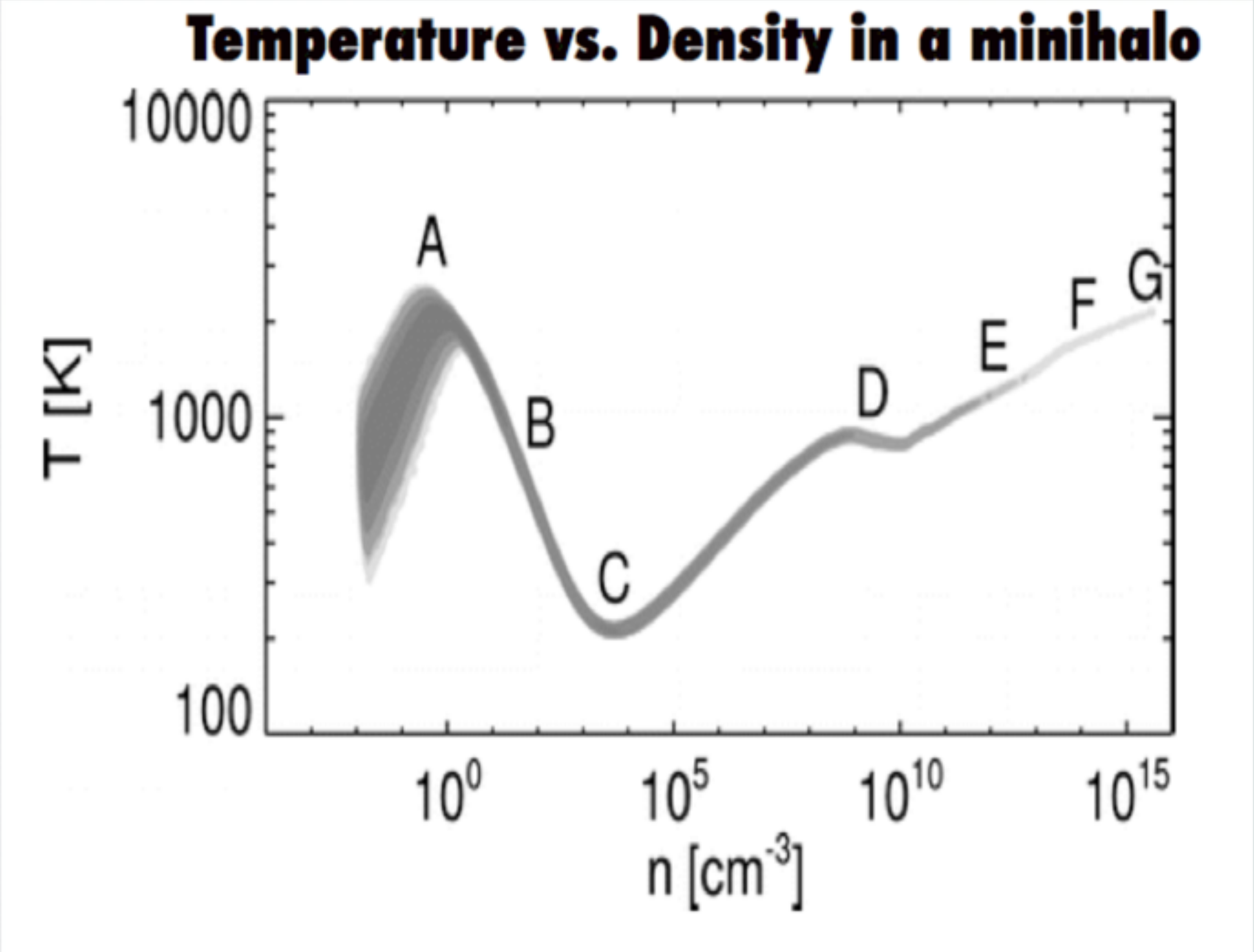
It gets smaller and denser



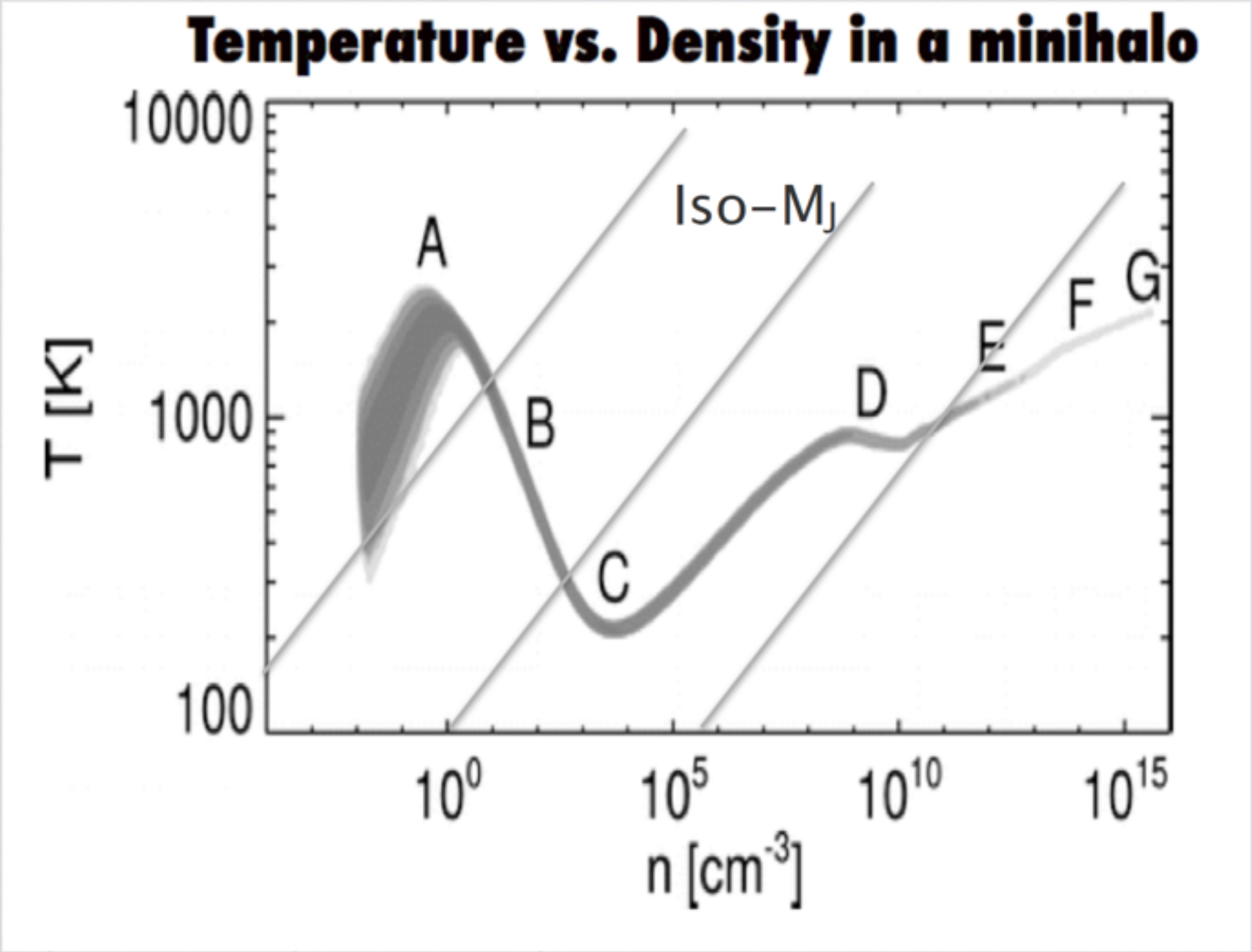
And smaller...

Denser, Hotter until H-fusion begins: A star is born!

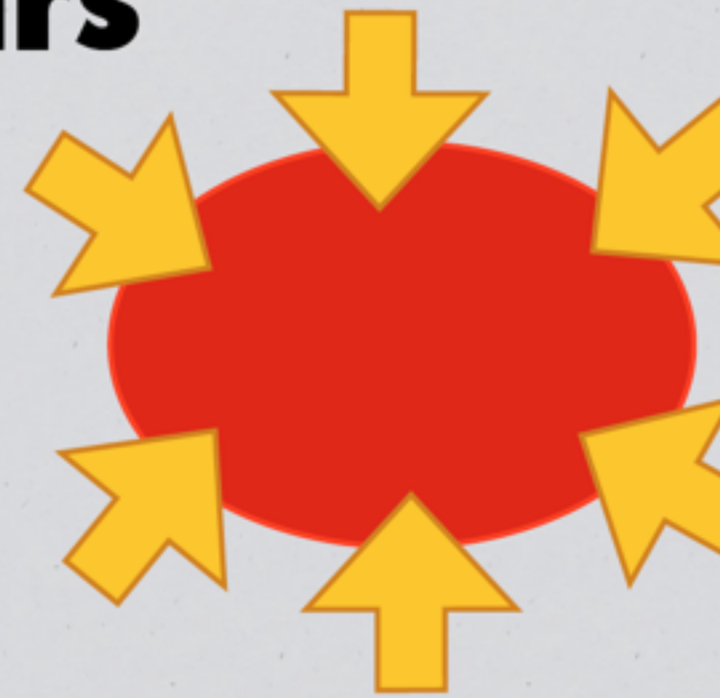
Evolution of a minihalo



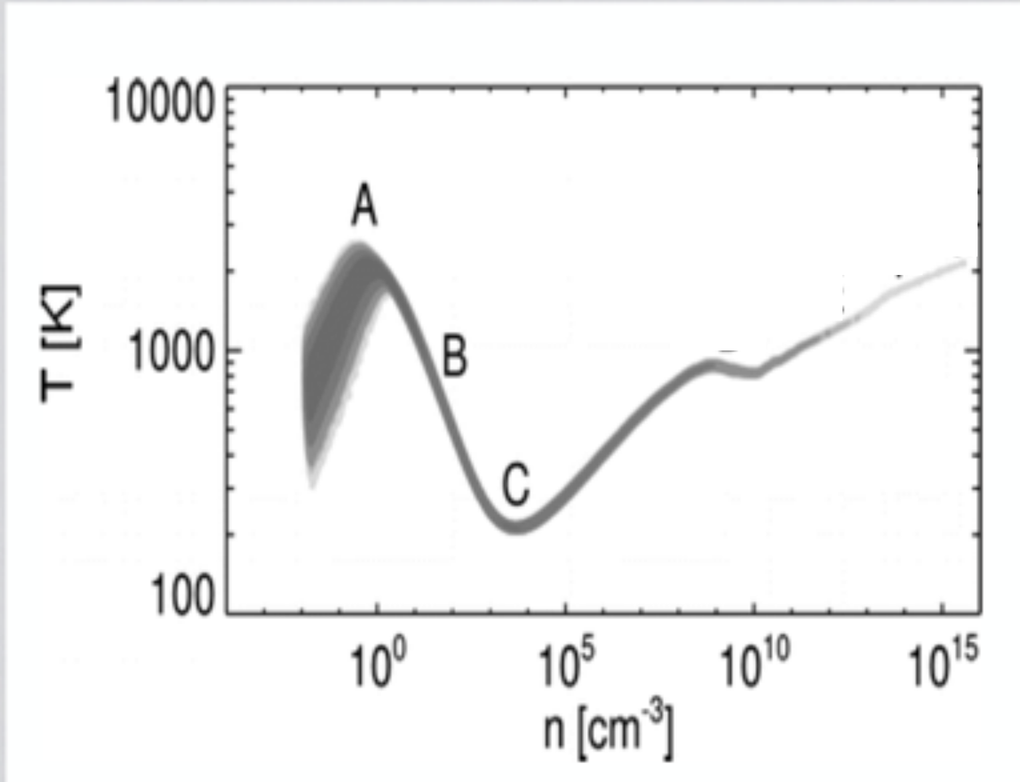
Evolution of a minihalo



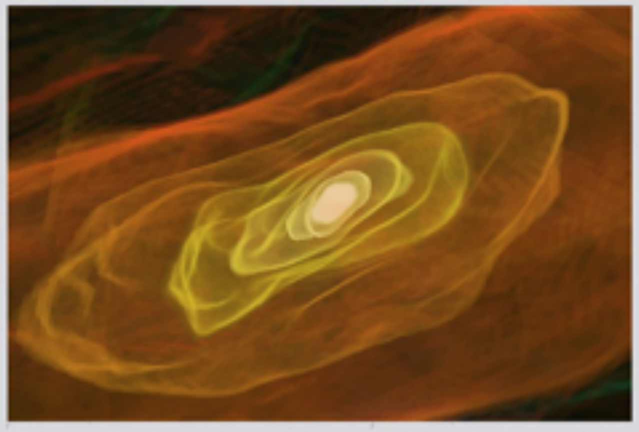
The birth of the first stars



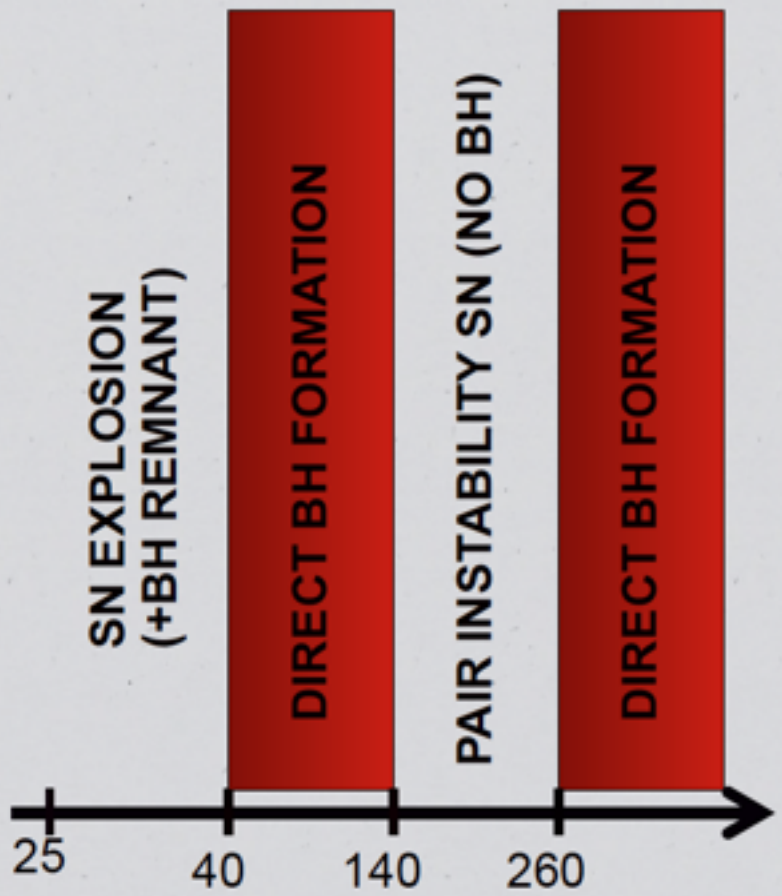
- The minihalo collapses and its gas (hydrogen+helium) reaches equilibrium between gravity and pressure support [A]
- Radiative cooling reduces temperature and rises density [B]
- Critical density for gravitational (Jeans) instability is reached [C]
    - Gravity dominates over pressure
        - Collapse of ~$10^{3\text{-}4}$ M_{sun} of gas



First Star: life & death



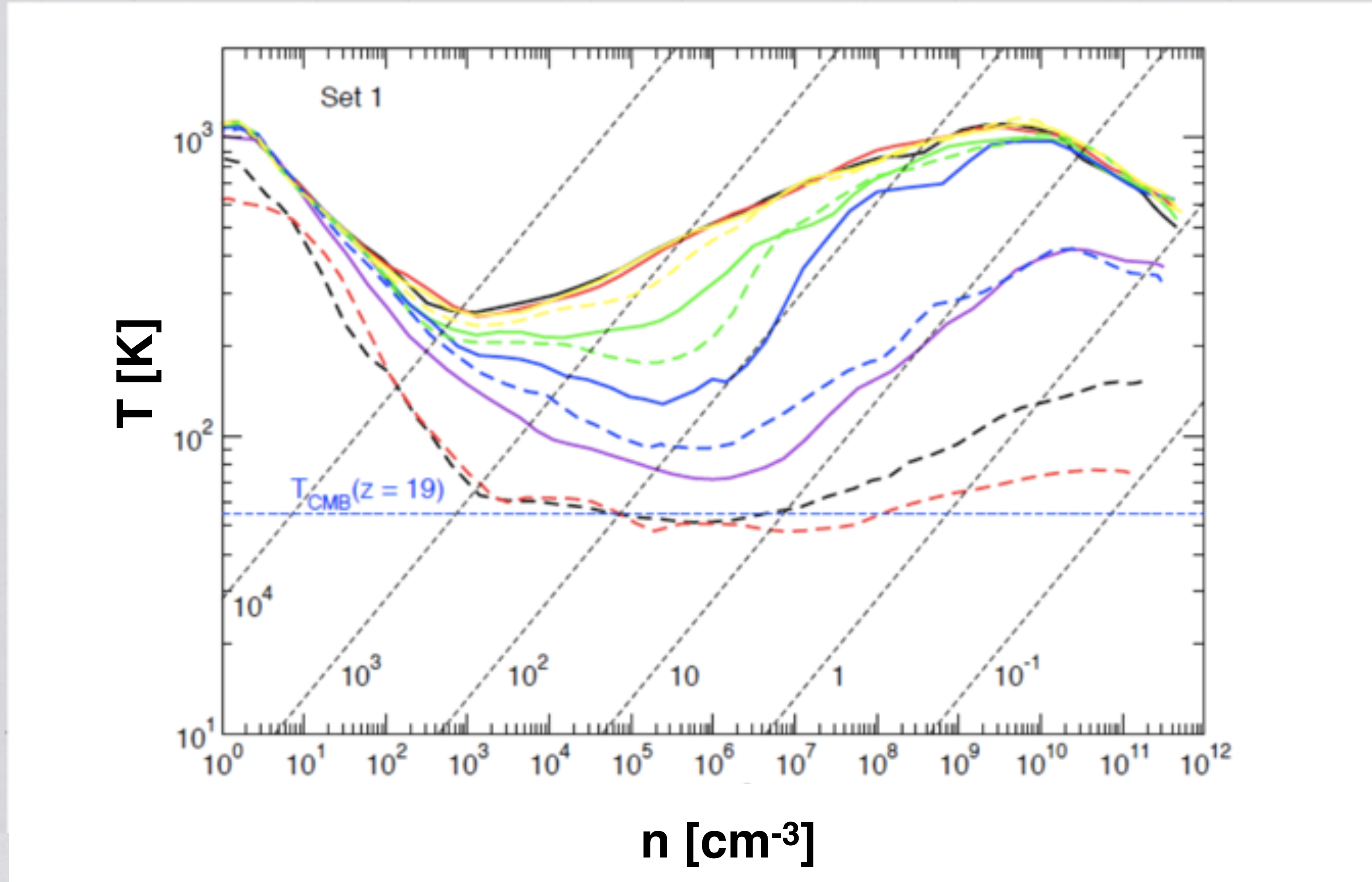
- Simulations predict one (or two) stars per minihalo, with heavy masses [~10-100 M_{sun})]
- Heavy masses imply short lifetimes (a few Myr)
- Supernova explosion can release heavy elements into the interstellar medium
- Or... direct black hole formation, possibly providing the first seeds that later grow into supermassive black holes



from Heger et al. (2003)

Metal cooling: transition to PopII

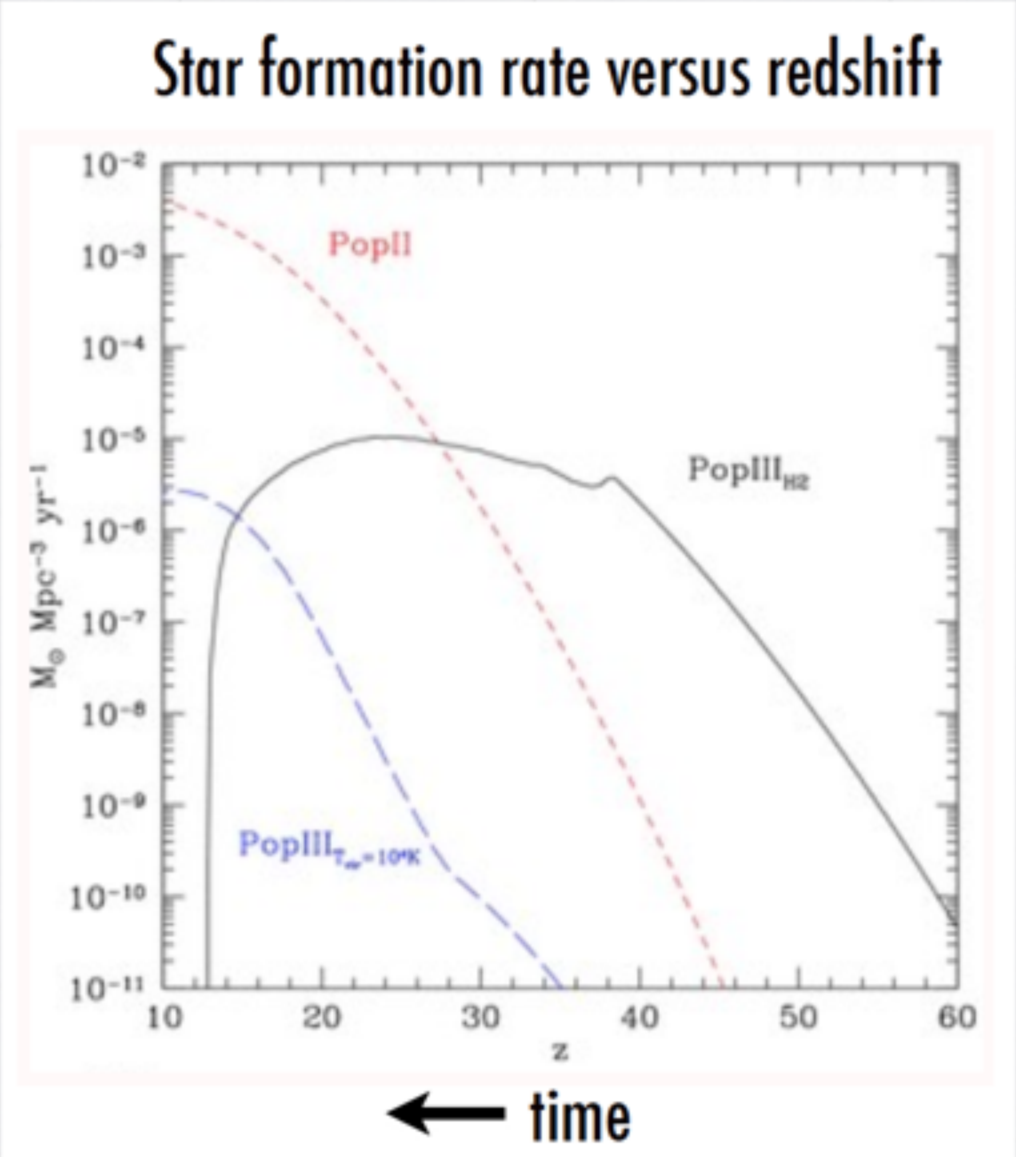
- At $Z \sim 10^{-3.5} Z_{sun}$ Transition from PopIII to PopII



Smith et al. (2009)

Early Star Formation history

- Star formation history evolution:
  - PopIIIs begin forming very early on (z>60, or t<40Myr) in minihalos ($M_h < 10^{5\text{-}6}\ M_{sun}$)
- Radiative feedback self-regulates their formation rate after z~35 (t~80Myr), suppressing cooling of gas in minihalos
- **PopII stars become dominant at z<25 (t>150Myr)**



Trenti & Stiavelli (2009)

Summary

- ★ Addition of gas physics to dark-matter dynamics:
  - ★ How can gas cool and form stars?
- ★ Jeans mass (gravity overcome pressure)
- ★ Cooling in the early Universe
- ★ Formation of first stars (PopIII, metal free)
- ★ Transition to first galaxies (metal enriched)

Suggested readings

★ Tegmark et al. (1997), ApJ, 474, 1

  ★ How small were the first cosmological objects?