Theory of the First Stars: Why are they Massive? What are their Properties?

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1/23/2007

Outline and References

- The Formation of the First Star in the Universe
  - Abel, T., Bryan, and Norman, 2002, Science, 295, 93
- Mass of Population III Stars
  - Nakamura & Umemura, 1999, ApJ, 515, 239
- The Stellar Initial Mass Function in Primordial Galaxies
  - Nakamura & Umemura, 2002, ApJ, 569, 549
- (Formation of the First Stars by Accretion)
  - Omukai & Palla, 2003, ApJ, 589, 677

Misc. Background

- “Population III”
  - less than 1/1000 solar metallicity
- Why should the first stars be larger?
  - Less efficient cooling => larger Jean's mass => larger stars
- When did they form?
  - z~10-100

The Formation of the First Star in the Universe

- The physics should be “simple”:
  - Primordial gas simplifies the chemical and radiative processes
  - No strong magnetic fields
  - No other stars exist to influence the environment

$$e + \mathrm{H} \rightarrow \mathrm{H}^- + h\nu \,, \quad (1)$$

$$\mathrm{H}^- + \mathrm{H} \rightarrow \mathrm{H}_2 + e \,, \quad (2)$$

$$\mathrm{H}^+ + \mathrm{H} \rightarrow \mathrm{H}_2^+ + h\nu \,, \quad (3)$$

$$\mathrm{H}_2^+ + \mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{H}^+ \,. \quad (4)$$

$$3\mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{H} \quad (5)$$

Simulation Setup

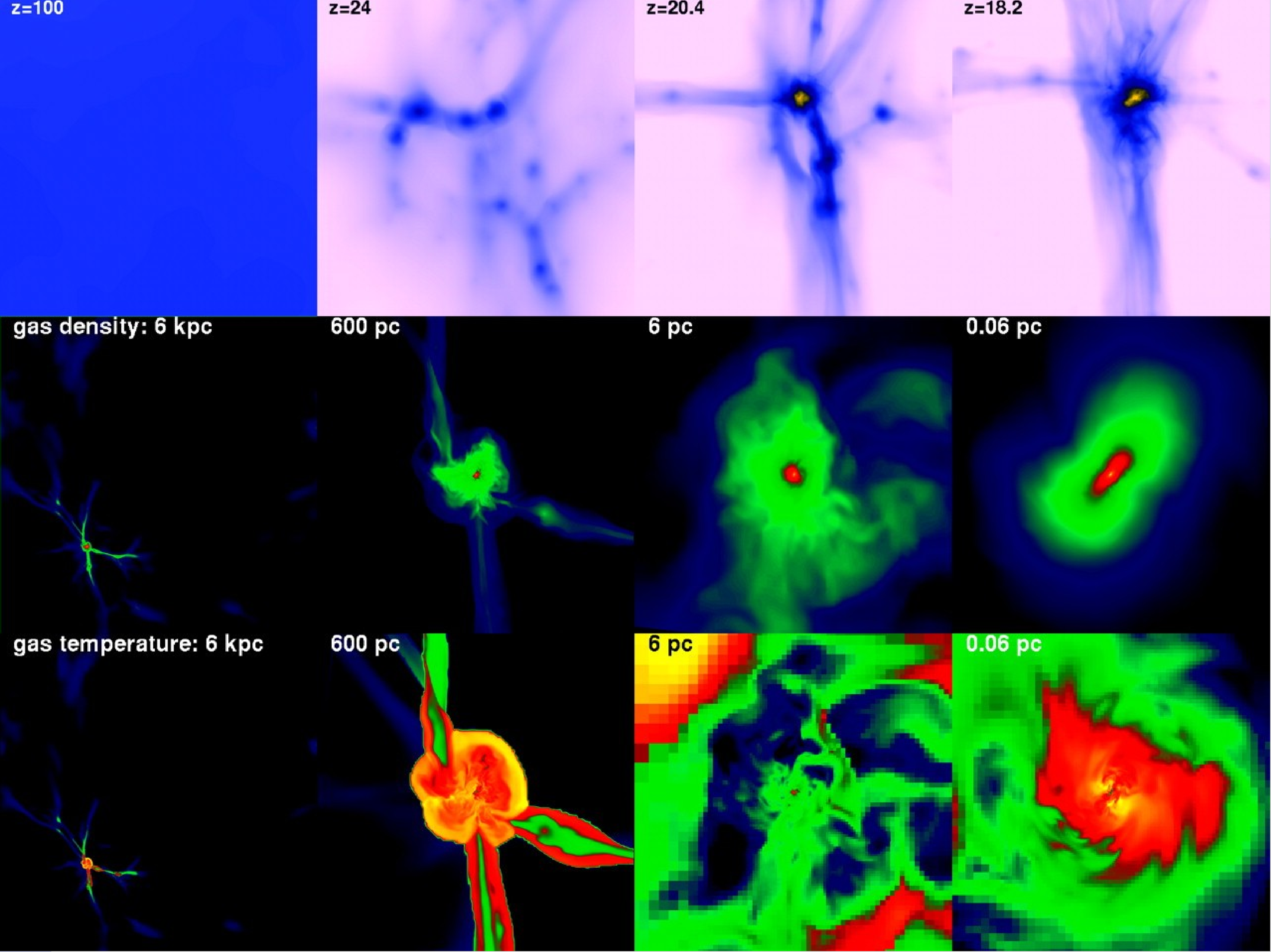
- Use an Eulerian structured AMR cosmological hydrodynamical code
- Initial conditions appropriate for a spatially flat CDM cosmology
  - 6% of the matter density contributed by baryons
  - Zero cosmological constant
  - Hubble constant of 50 km/s/Mpc
- 3D volume 128 kpc on a side (co-moving)
- Periodic boundary conditions

Simulation Setup

- Mass resolution of 1.1 M_{sun} for the dark matter and 0.07 M_{sun} for the gas
- Follow chemistry of H, H^+, H^-, e^-, He, He^+, He^{++}, H_2, and H_2^+
- Also track radiative losses from atomic and molecular line cooling, Compton cooling, and heating of free electrons by the cosmic background radiation (in the optically thin limit)

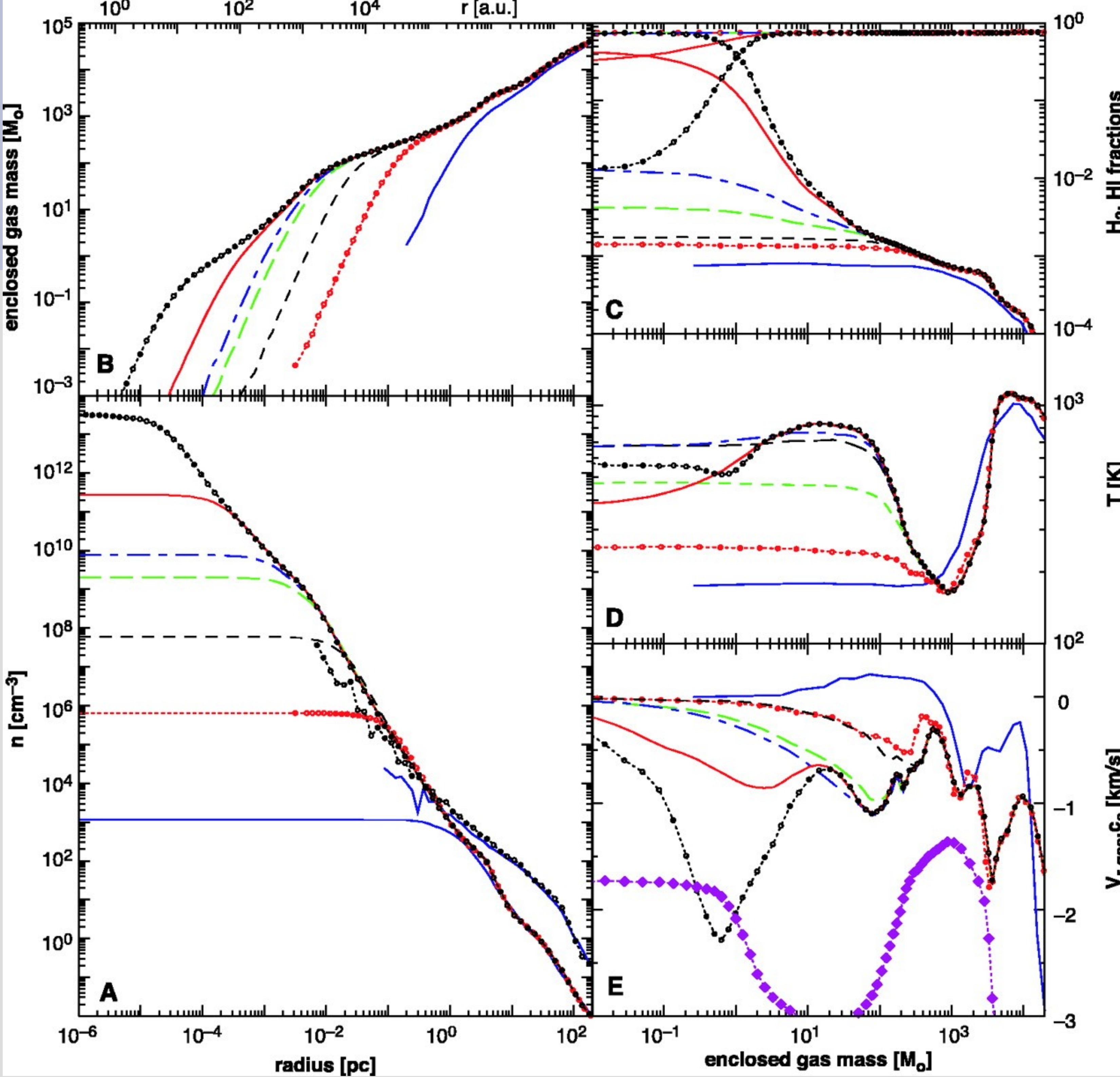
Simulation Setup

- Stop when molecular cooling lines reach an optical depth of 10 at line center
  - Time-dependent radiative line transfer in multiple dimensions is hard

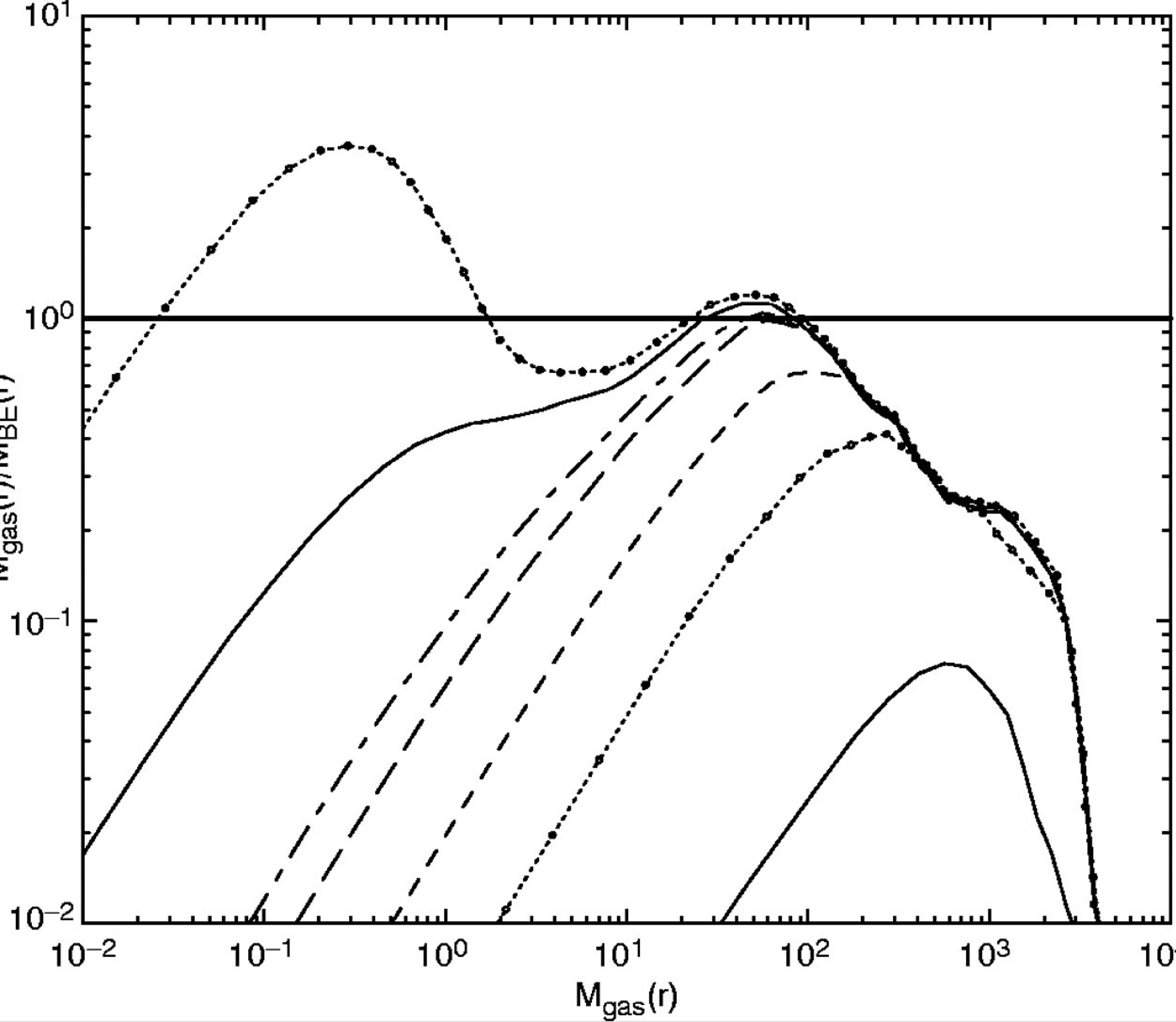

z=100
z=24
z=20.4
z=18.2
gas density: 6 kpc
600 pc
6 pc
0.06 pc
gas temperature: 6 kpc
600 pc
6 pc
0.06 pc

Results: Characteristic Mass Scales

- Four characteristic mass scales:
  - Infall and accretion onto pregalactic halo (7×10^5 M_{sun})
  - Rapid cooling and additional infall (4000 M_{sun})
  - Bonnor and Ebert mass (100 M_{sun})
    - $M_{\rm BE} = 1.18\, M_\odot (c_{\rm s}^4/G^{3/2}) P_{\rm ext}^{-1/2}$ $c_{\rm s}^2 = dP/d\rho = \gamma k_{\rm B} T/\mu m_{\rm H}$
  - Protostar (1 M_{sun})



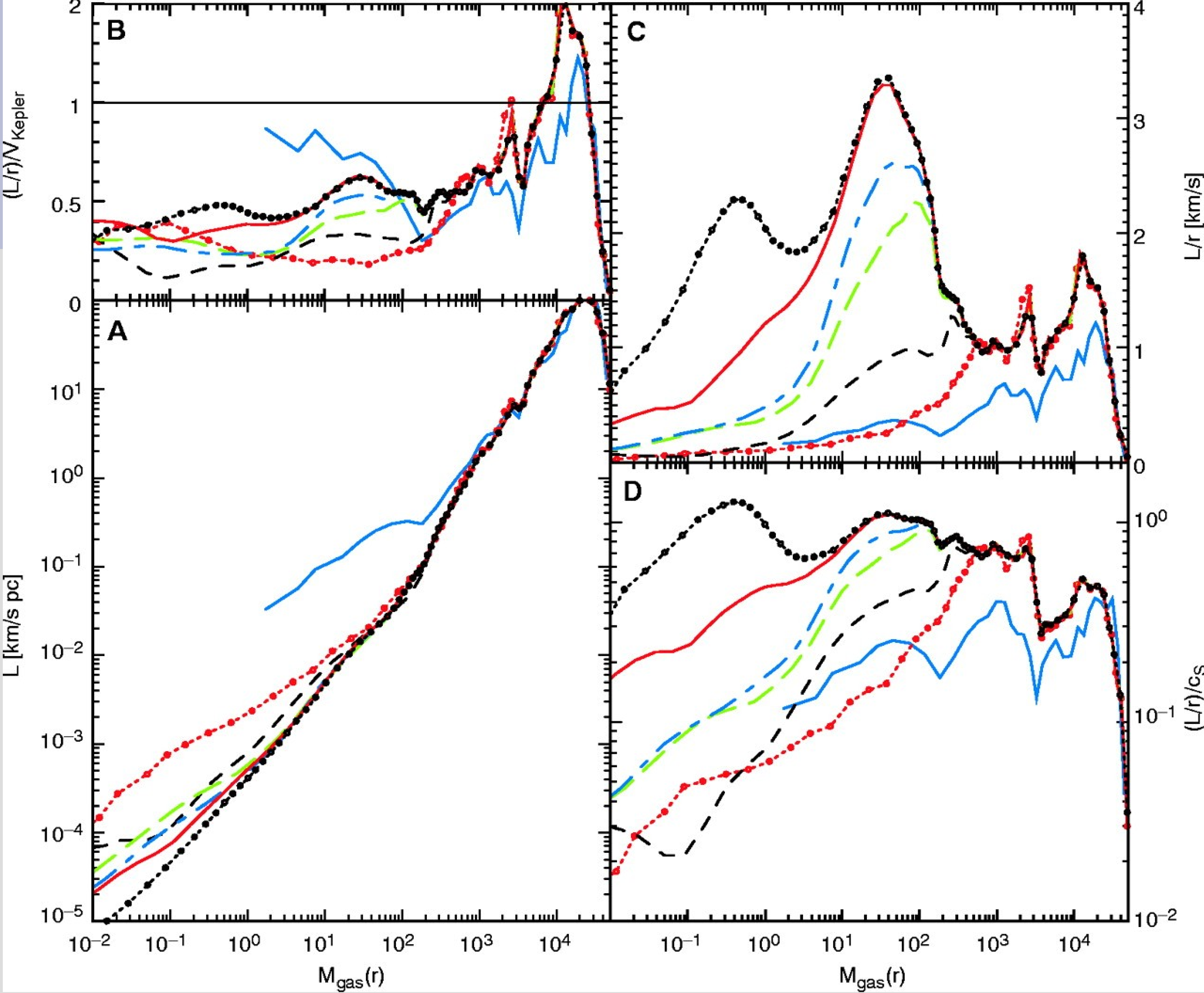
r [a.u.]
10^0
10^2
10^4
enclosed gas mass [M_o]
B
n [cm^{-3}]
A
radius [pc]
H_2, HI fractions
C
T [K]
D
$V_{r,gas}, c_s$ [km/s]
E
enclosed gas mass [M_o]



10^1
10^0
10^{-1}
10^{-2}
$M_{gas}(r)/M_{BE}(r)$
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
10^4
$M_{gas}(r)$

Results: Angular Momentum

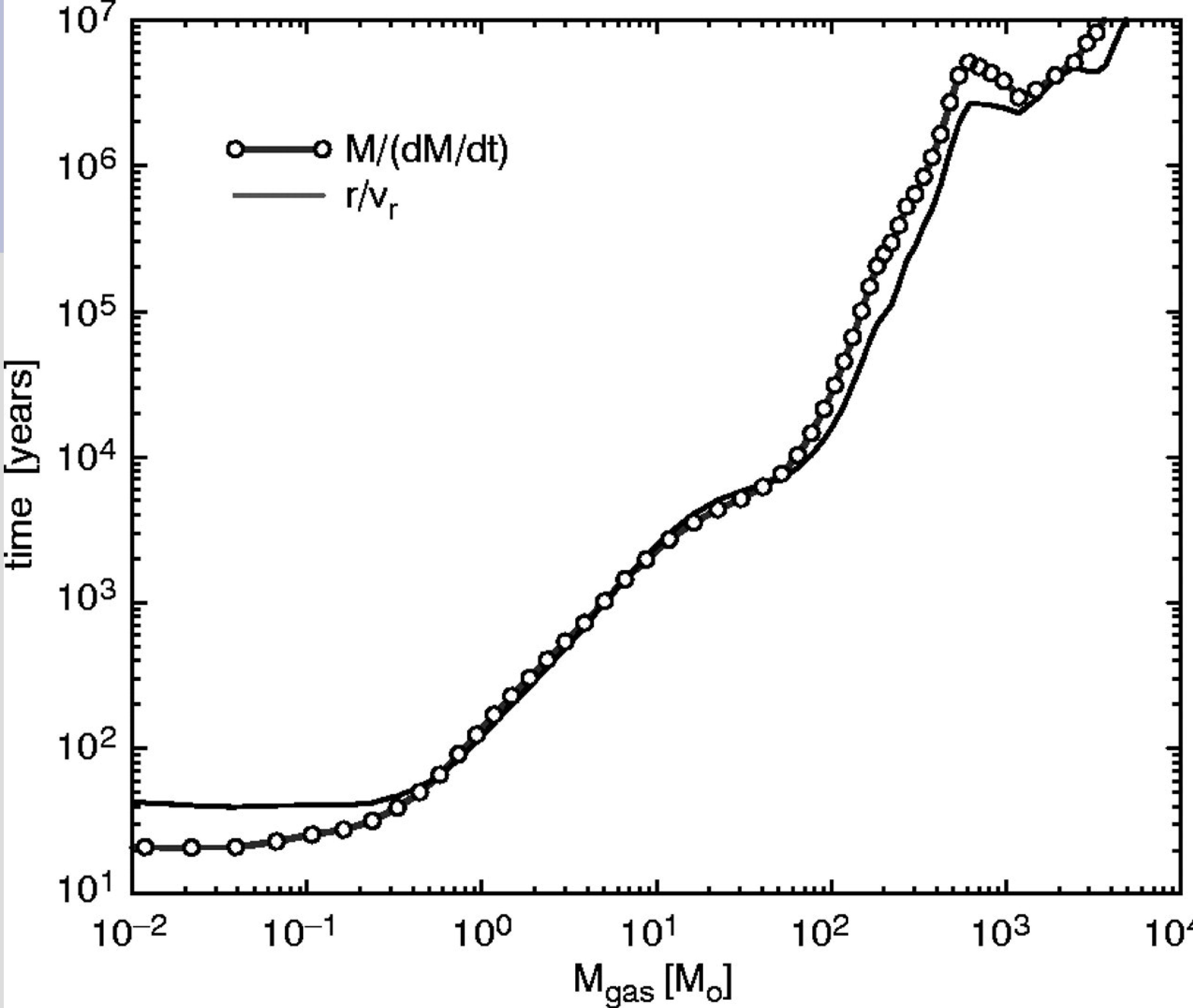
- The collapse is not halted by rotational support for two reasons:
  - The gas starts with little angular momentum
  - Angular momentum is transported
    - Attributed to shock waves during the turbulent collapse
    - Transport is stronger than in present-day star formation due to higher cooling rate



B
C
A
D
(L/r)/V_Kepler
L/r [km/s]
L [km/s pc]
(L/r)/c_S
M_gas(r)
M_gas(r)

Summary: The Formation of the First Star in the Universe

- Pregalactic object forms a single 100 M_{sun} core surrounding a 1 M_{sun} protostar
  - No fragmentation observed
- Final mass of star unclear
  - Estimate 70 M_{sun} after 10^4 yr
  - 600 M_{sun} after 5 Myr
    - BUT a 100 M_{sun} star will supernova within 2 Myr



M/(dM/dt)
r/v_r
time [years]
M_gas [M_o]
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4

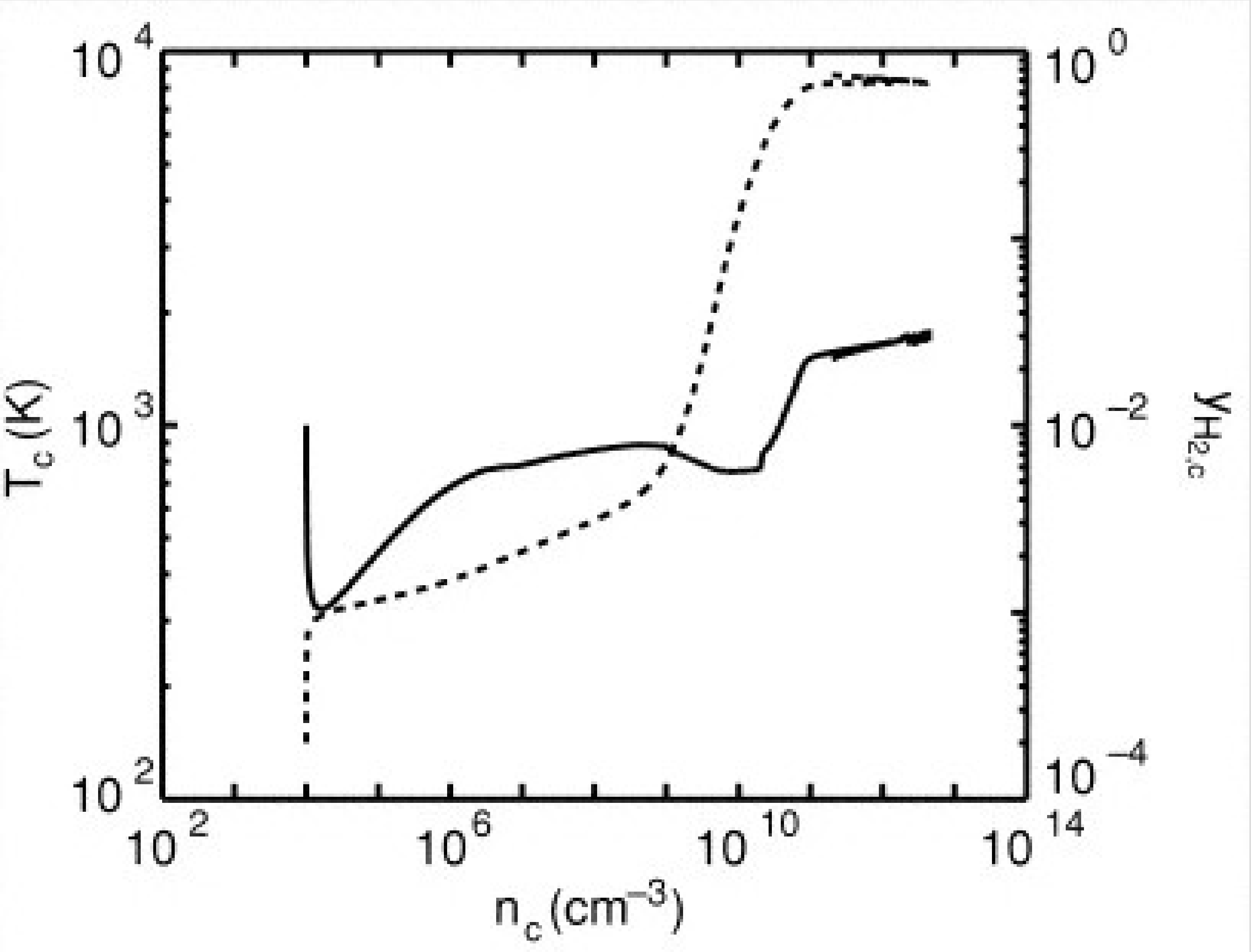
Mass of Population III Stars

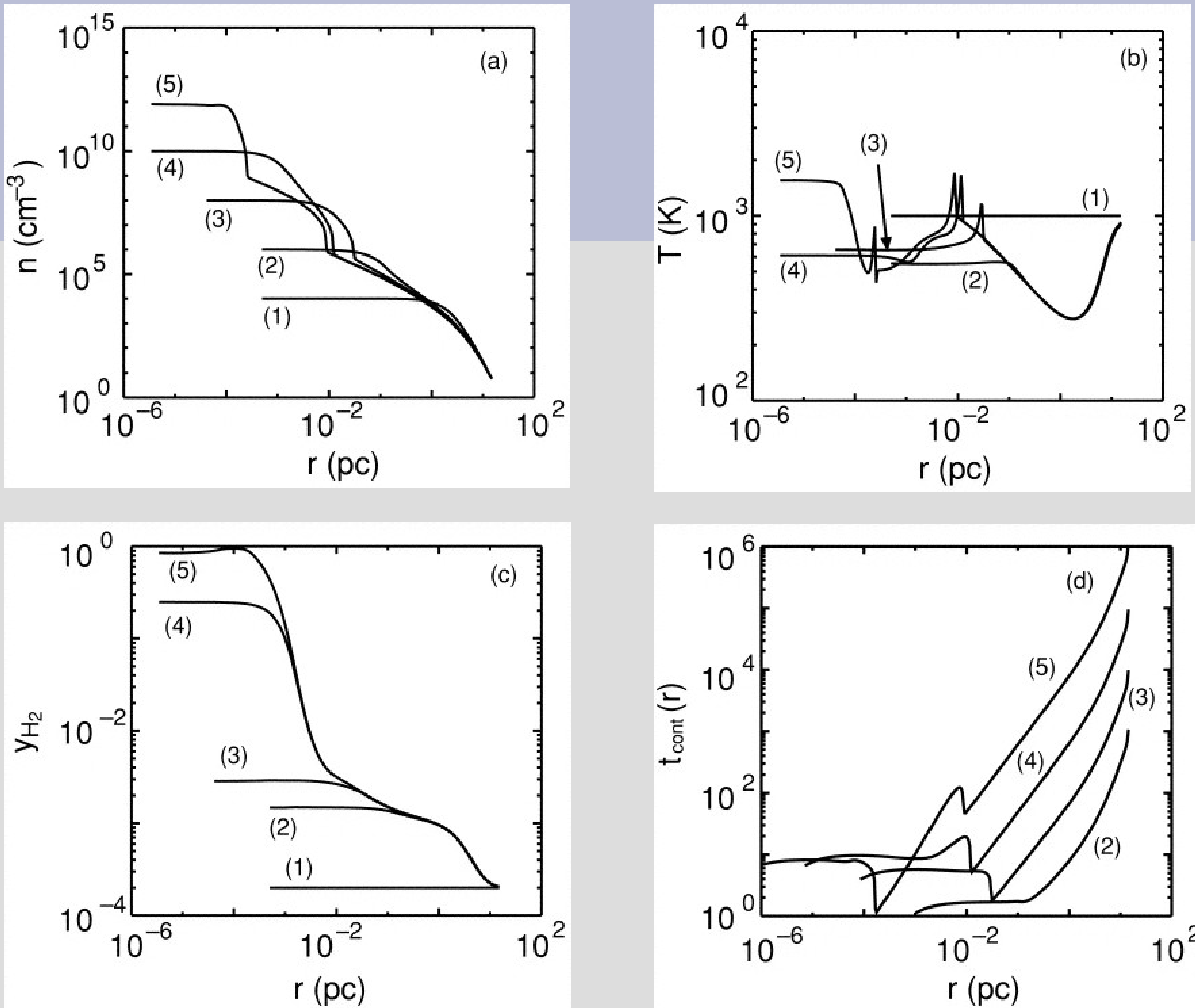
- Model filamentary, axisymmetric, ideal gas cloud
- Include H, H^+, H^-, e^-, He, He^+, He^{++}, H_2, and H_2^+
- Assume cooling from H (at $T \sim 10^4$ K), H_2 (at $T < 10^4$ K), and from chemical reactions
- Follow the 1D hydrodynamics of the system

A Model for a Filamentary Primordial Cloud

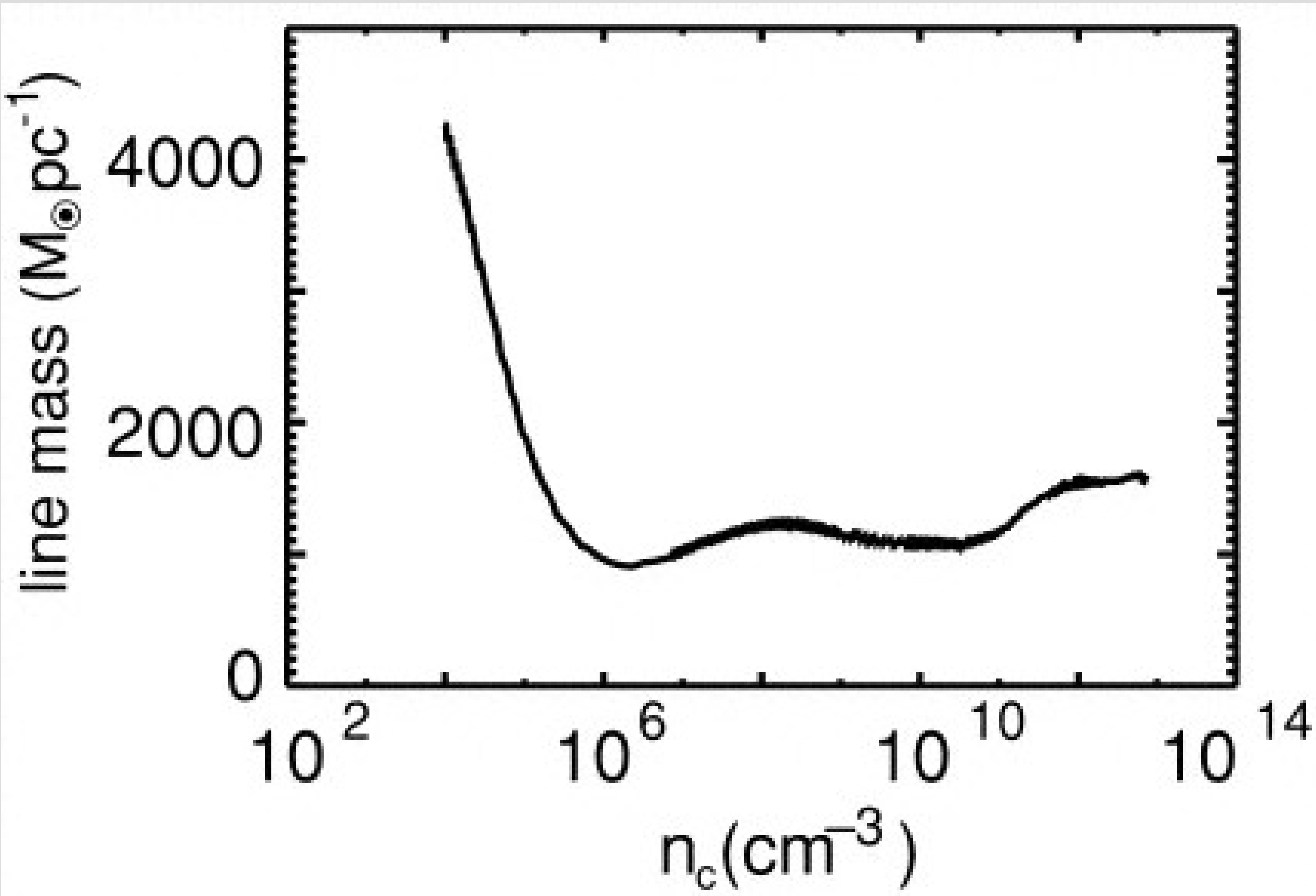
- Initially, gravitational instability of cosmological density perturbations forms a "pancake-like" disk
  - $M \sim 10^{5-7} M_{sun}$
  - $T \sim 200\text{-}1000K$
- Fragments into filamentary clouds
  - Assume filaments are infinitely long cylinders

Numerical Results

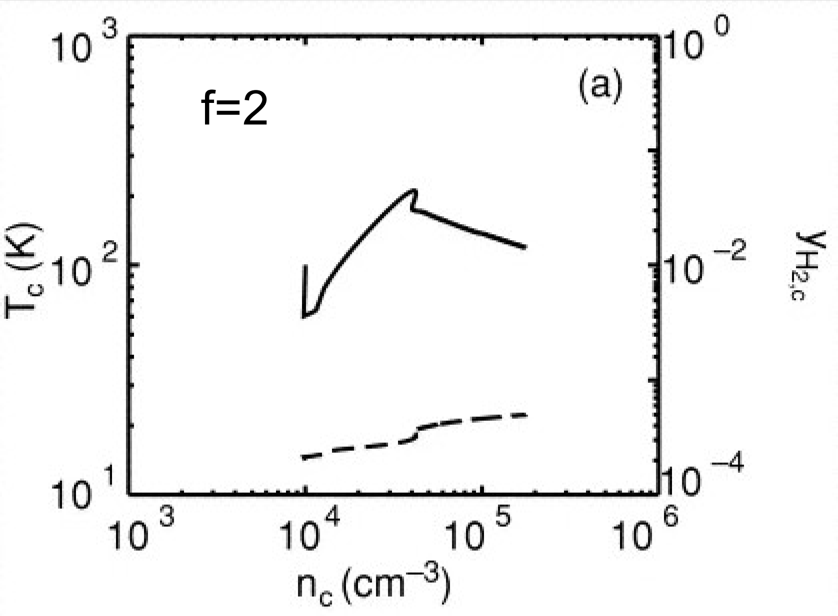


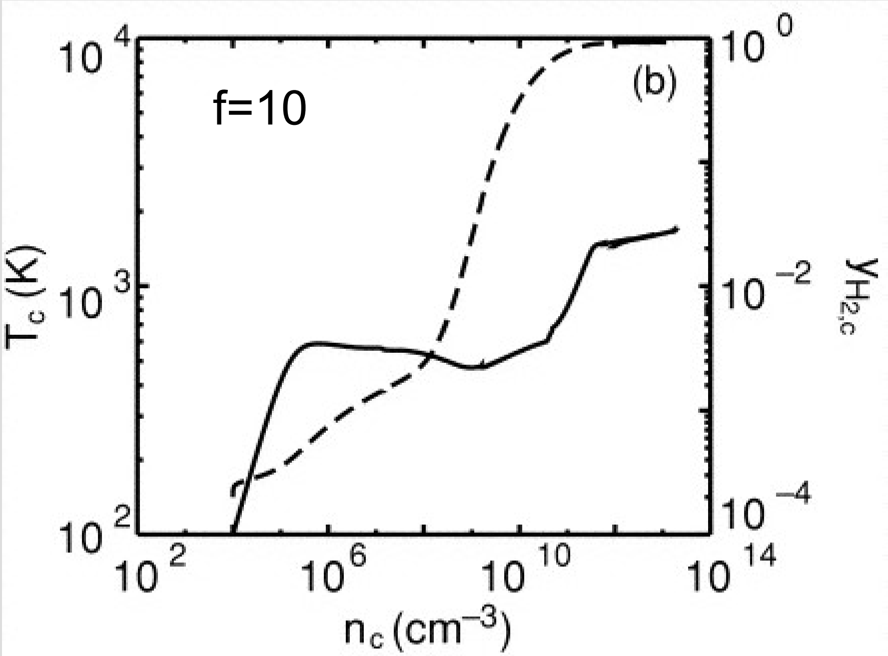

(a)
n (cm^{-3})
r (pc)
(1)
(2)
(3)
(4)
(5)
(b)
T (K)
r (pc)
(1)
(2)
(3)
(4)
(5)
(c)
y_{H_2}
r (pc)
(1)
(2)
(3)
(4)
(5)
(d)
t_{cont} (r)
r (pc)
(2)
(3)
(4)
(5)

Spindle Mass



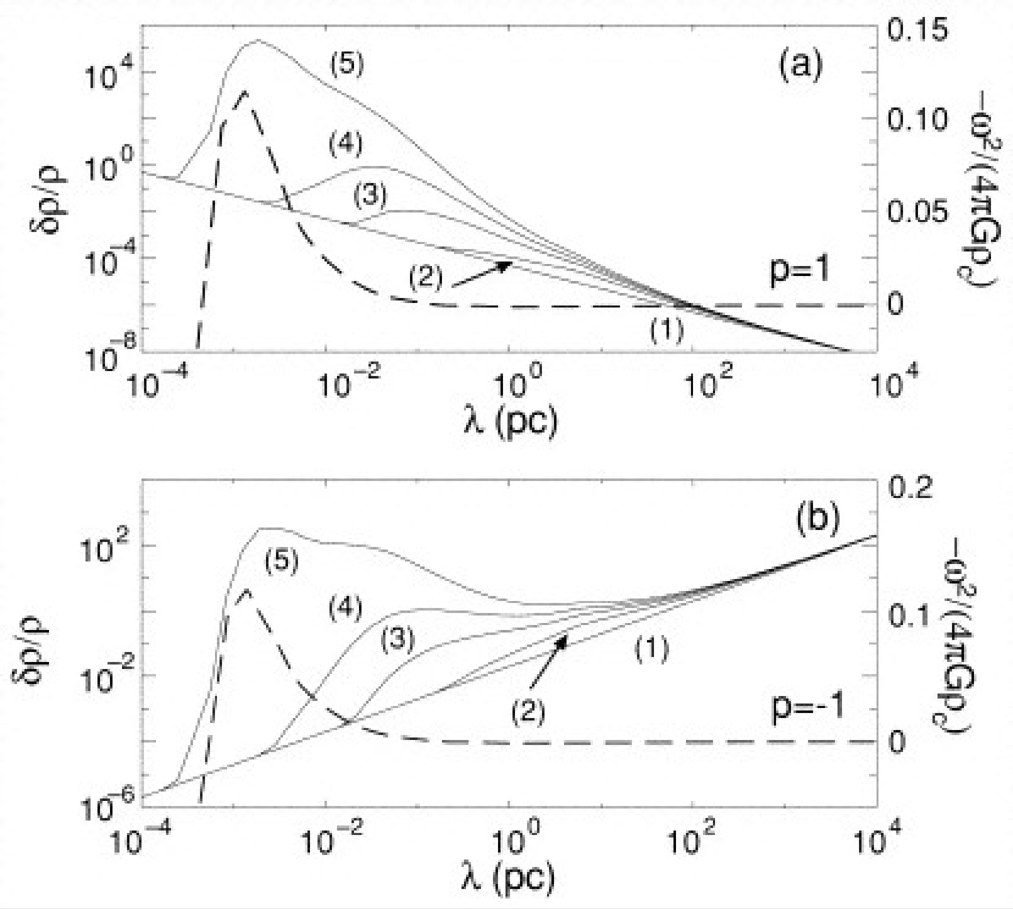
Clouds with Low Initial Temperature (T_0~100 K)





$$\rho = \rho_0 \left(1 + \frac{r^2}{f R_{\rm fil}^2}\right)^{-2}, \qquad (15)$$

Fragmentation of Primordial Gas Clouds



$$\delta\rho(t)/\rho(t) = A \exp\left[ik_z z - \int_0^t i\omega(k_z, t')dt'\right], \qquad (19)$$

$A = A_0(k_z/k_{z,0})^p$

Conclusions: Mass of Population III Stars

- Find that the spindles are unstable against fragmentation
- Based on the size of the fragments, the first stars have a minimum mass of 3 M_{sun}
- Further accretion of the diffuse envelope can increase the mass to a maximum of 16 M_{sun}

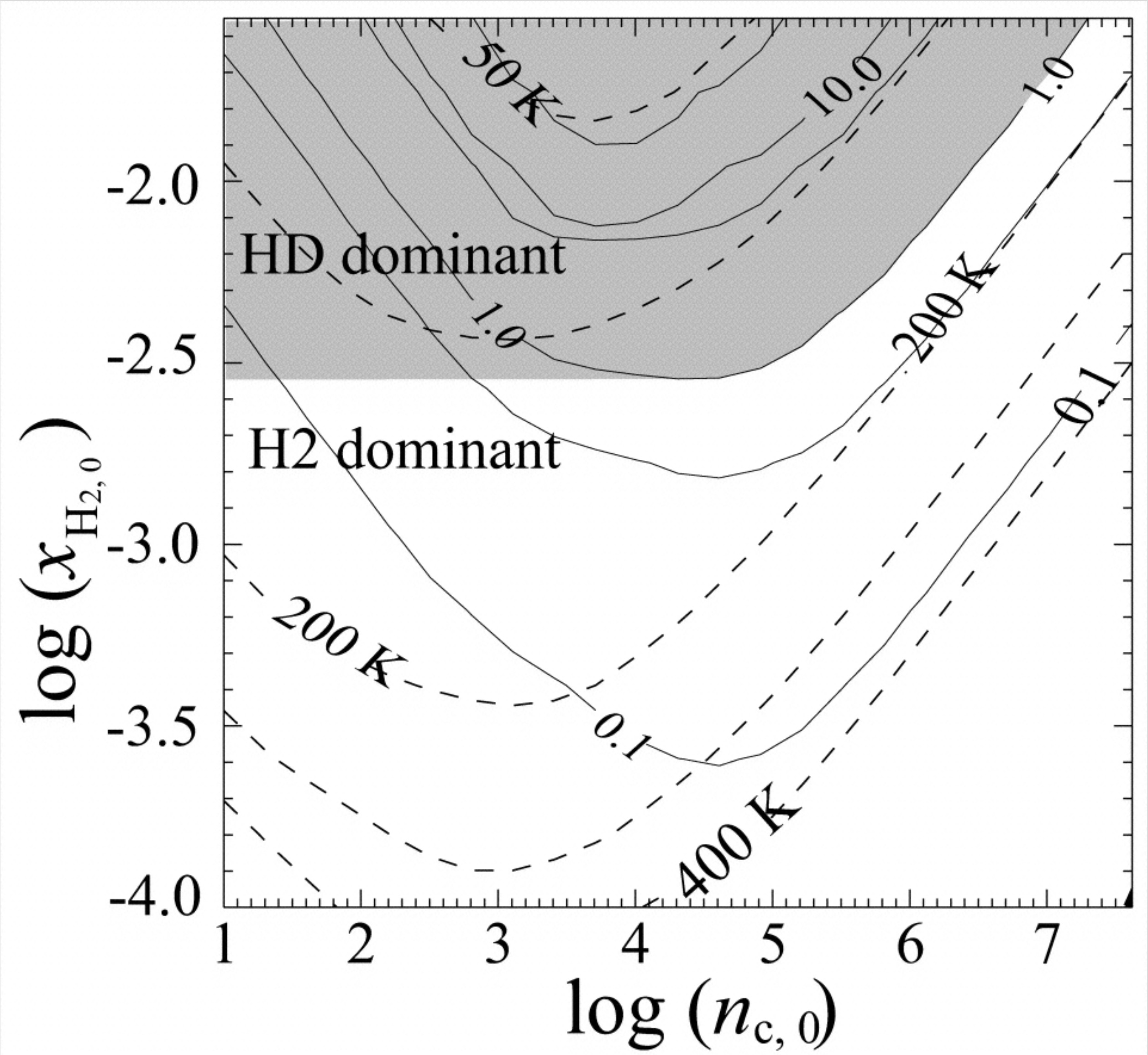
The Stellar Initial Mass Function in Primordial Galaxies

- Include effects of HD cooling
  - Can decrease T<100K*
- Include more species than previous model
  - e, H, H^+, H^-, H_2, H, He, He^+, He^{++}, D, D^+, D^-, HD, and HD^+
- Consider the following thermal processes:
  - H cooling by radiative recombination, collisional ionization, and collisional excitation
  - H_2 line cooling by rotational and vibrational transitions
  - Cooling by H_2 collisional dissociation
  - Heating by H_2 formation
  - HD line cooling by rotational transitions.

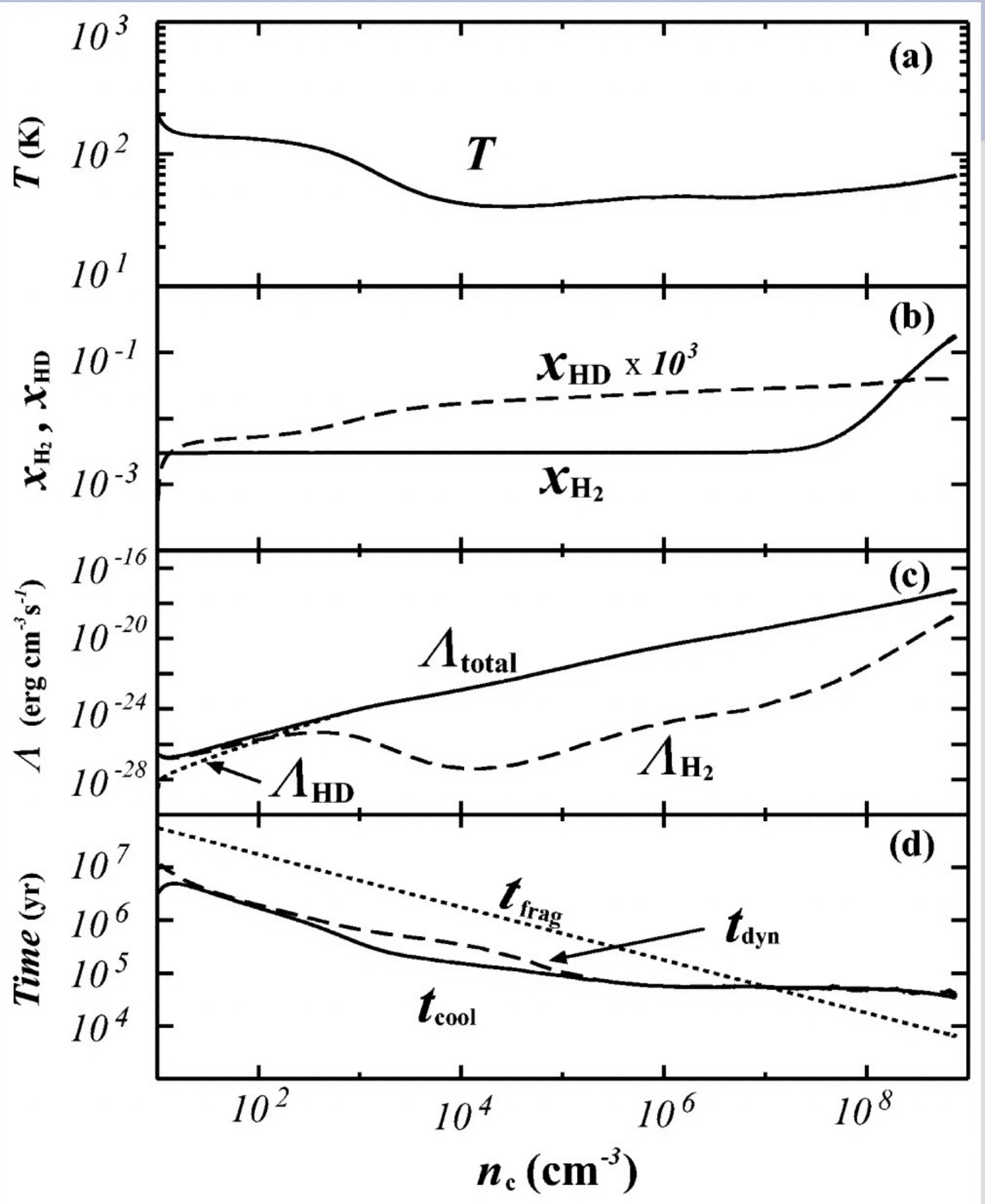
Model

- The system is again an infinitely long cylindrical gas cloud that collapses in the radial direction
- 1-D
- Model parameters are $n_{c,0}$, T_0, f, and $\chi_{H2,0}$

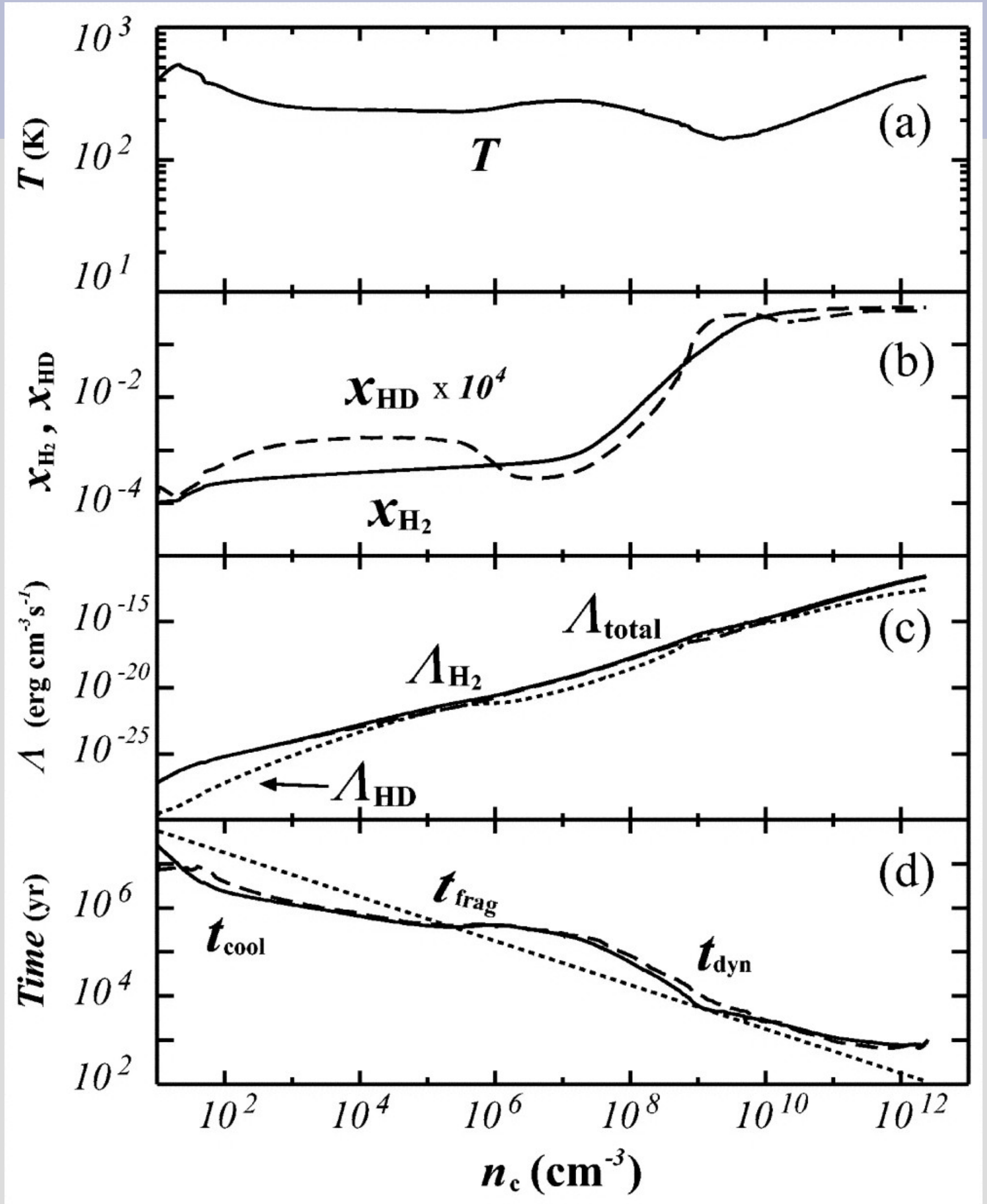
Results: Threshold H_2 Abundance



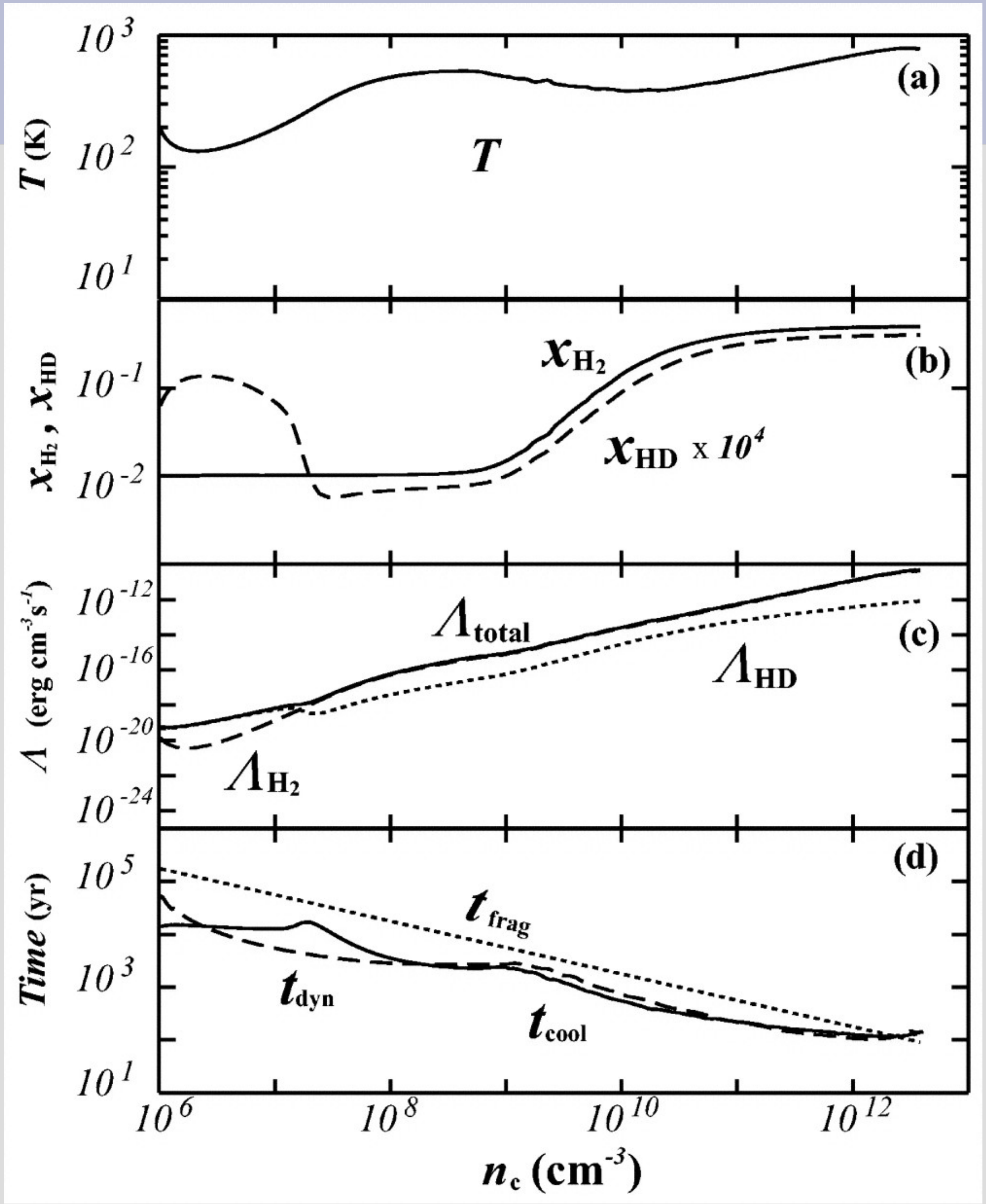
Results: Low-Density Filaments with High H_2 Abundance



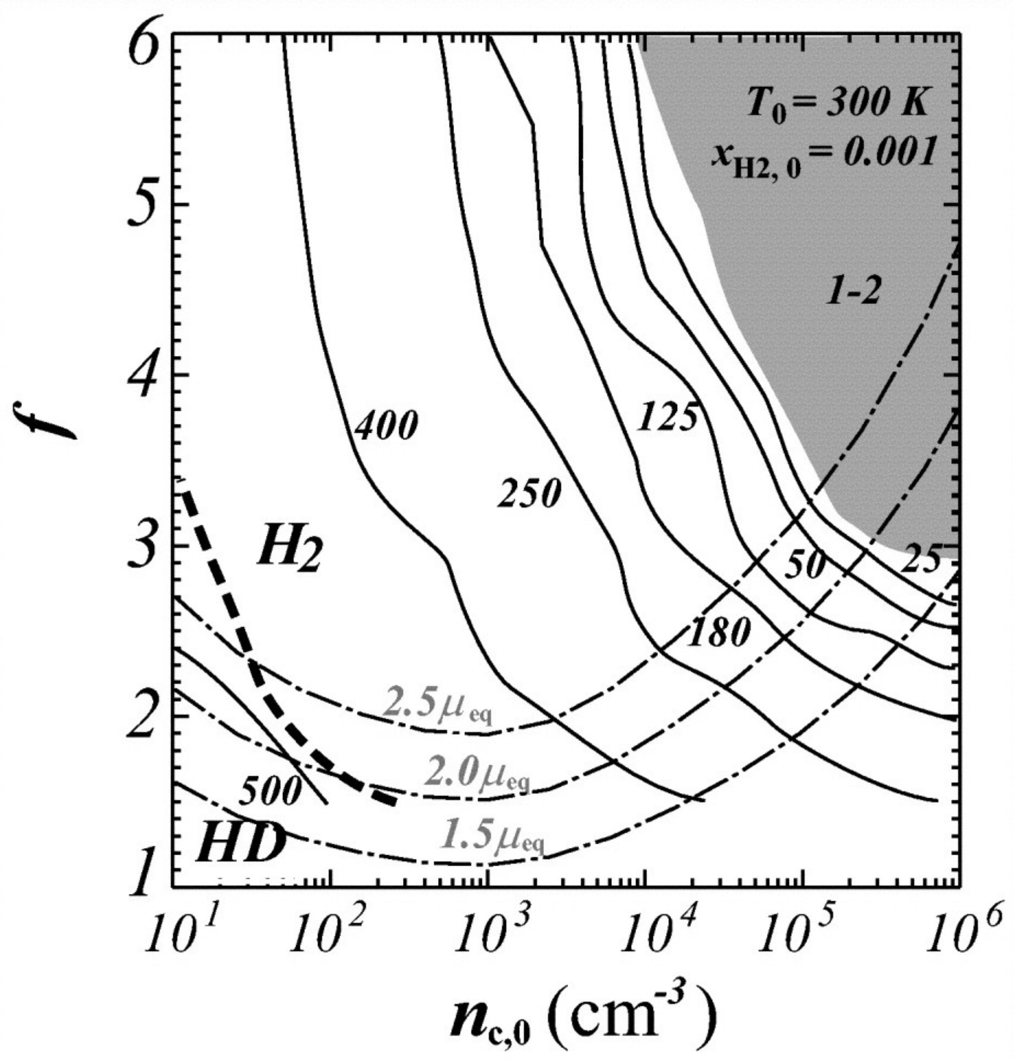
Results:
Low-Density Filaments with Low H_2 Abundances

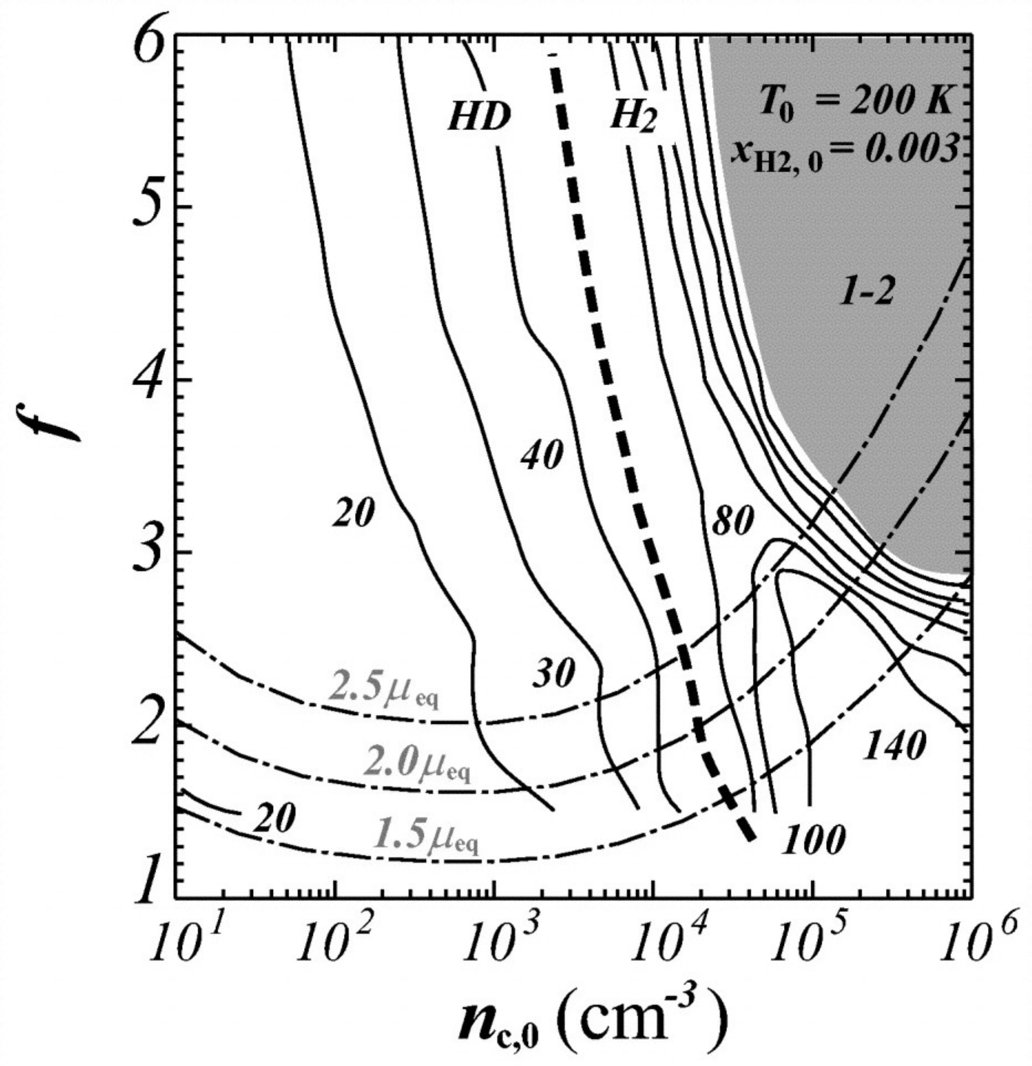


Results: High-Density Filaments



Dependence of the Fragment Mass on the Initial Model Parameters

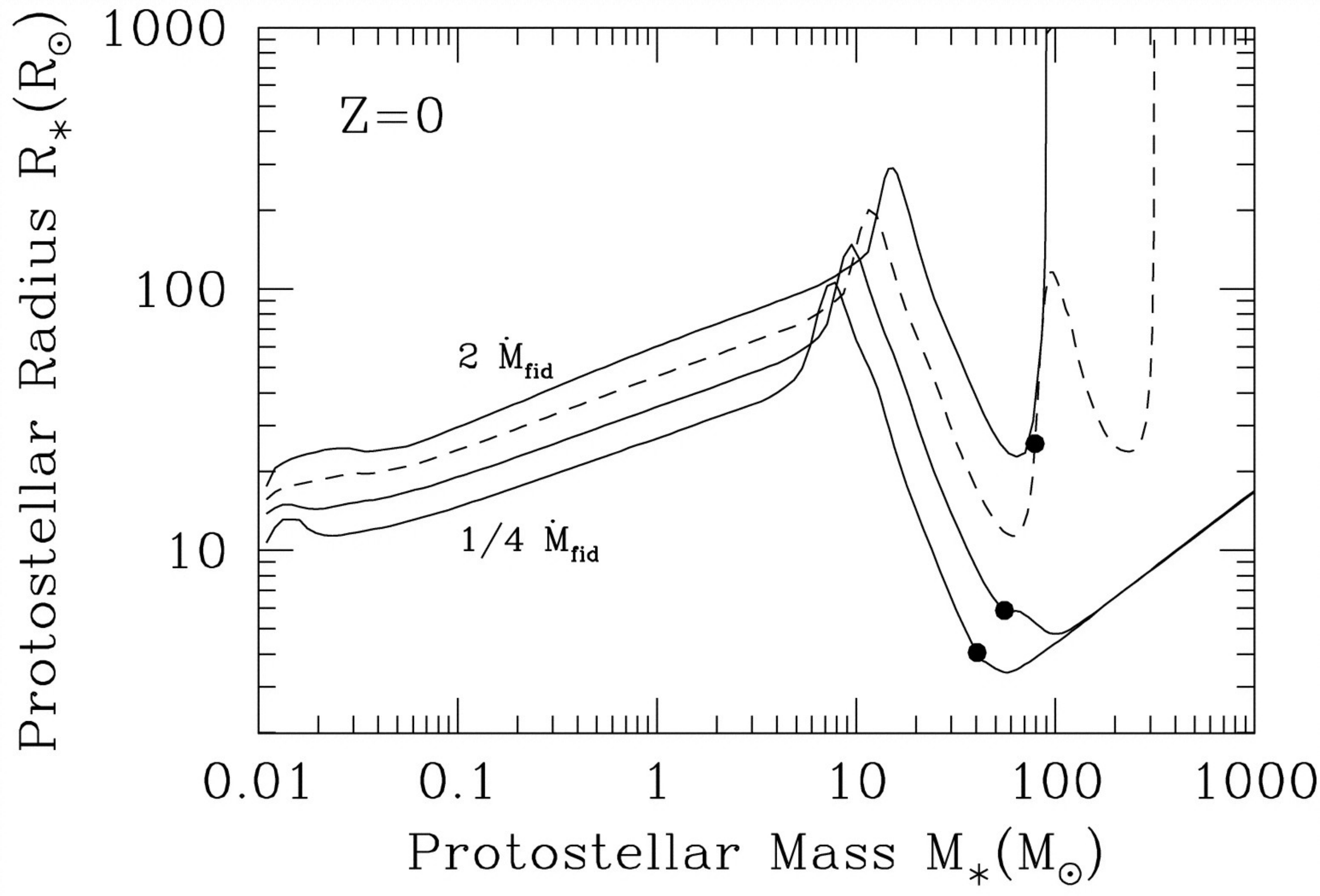


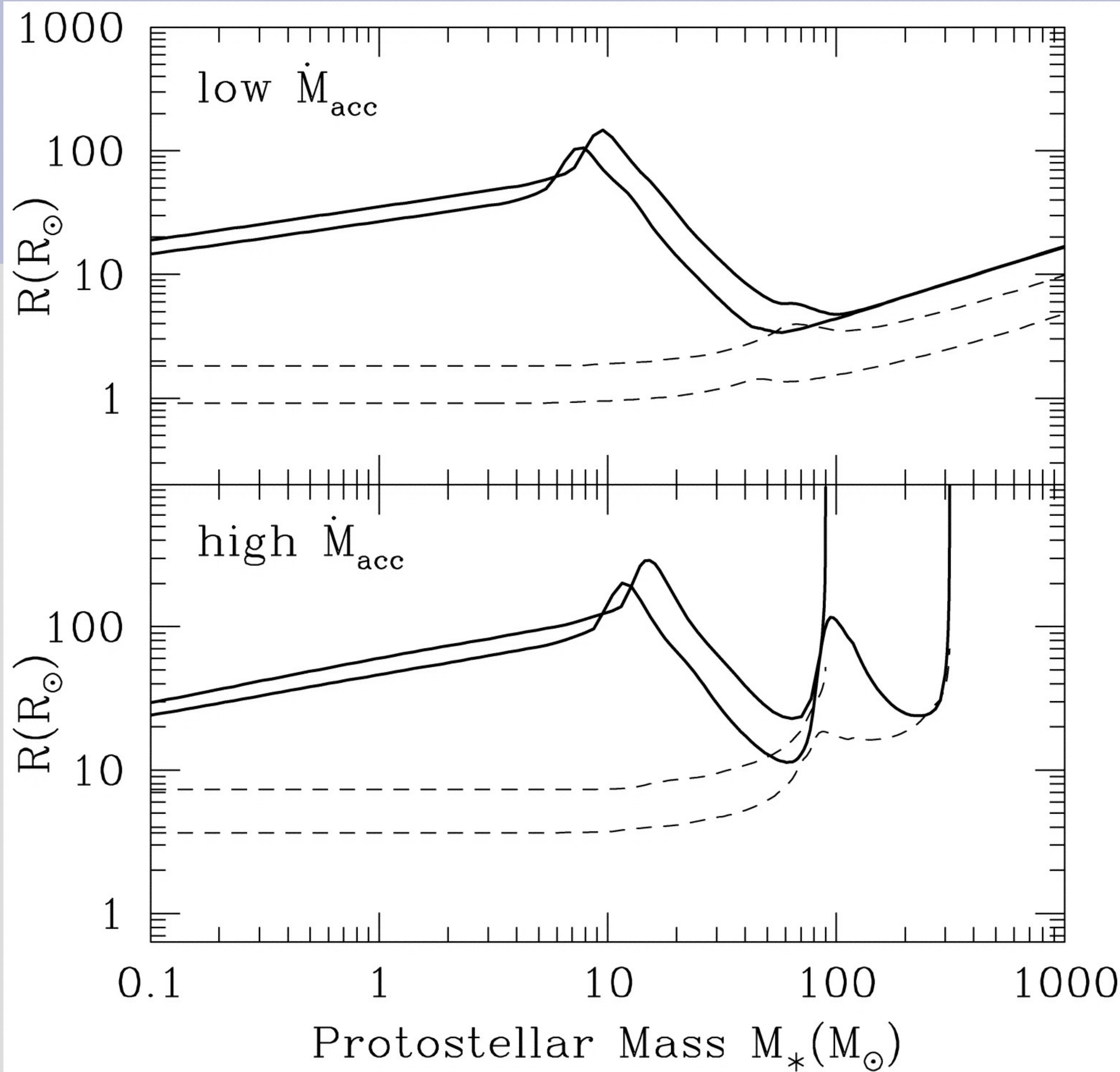


Summary: The Stellar Initial Mass Function in Primordial Galaxies

- Steep boundary in fragment mass near $n_{c,0}=10^4$–10^5 cm^{-3} for f >3, *regardless* of the initial H_2 abundance
  - Implies IMFs in very metal deficient gas are likely to be bimodal
- Minimum mass is few M_{sun} (not sensitive to H_2 abundance)
- Maximum mass is ~100 M_{sun} for $\chi_{H2,0} < 3x10^{-3}$ and ~10 M_{sun} for $\chi_{H2,0} > 3x10^{-3}$

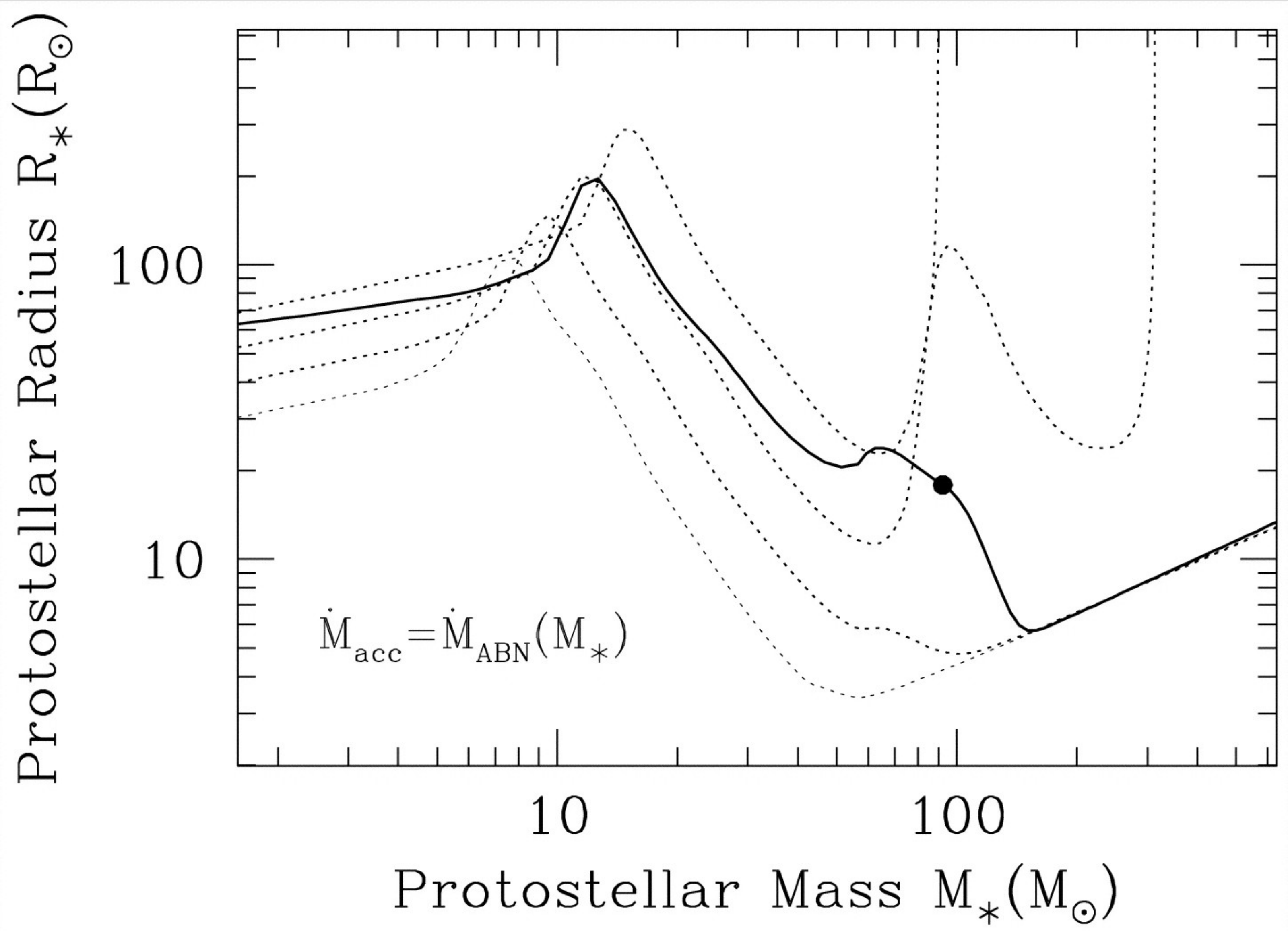
Formation of the First Stars by Accretion





low $\dot{M}_{acc}$
high $\dot{M}_{acc}$
$R(R_\odot)$
$R(R_\odot)$
1000
100
10
1
100
10
1
0.1
1
10
100
1000
Protostellar Mass $M_*(M_\odot)$

Mass-dependent Accretion Rate



Results: Formation of the First Stars by Accretion

- Final mass of star is potentially very large (~600 M_{sun})
- If you assume star supernovas after 3 Myr, then mass is limited to ~500 M_{sun}
- If you also include the likely formation of an H_{II} region, mass is limited to ~460 M_{sun}