Primordial molecules and magnetic fields

Daniele Galli, Francesco Palla, Raffaella Schneider
Osservatorio Astrofisico di Arcetri

Dominik Schleicher
Leiden Observatory, ESO

ISSI MODULO meeting, Bern, 10-12 March 2010

A (very) short history

- Saslaw & Zipoy (1967): H_2 formation through H_2^+ at redshift $z \sim 10^3$, → $H_2 \sim 10^{-6}$

- Peebles & Dicke (1968): H_2 formation through H^- at lower z → formation of globular clusters

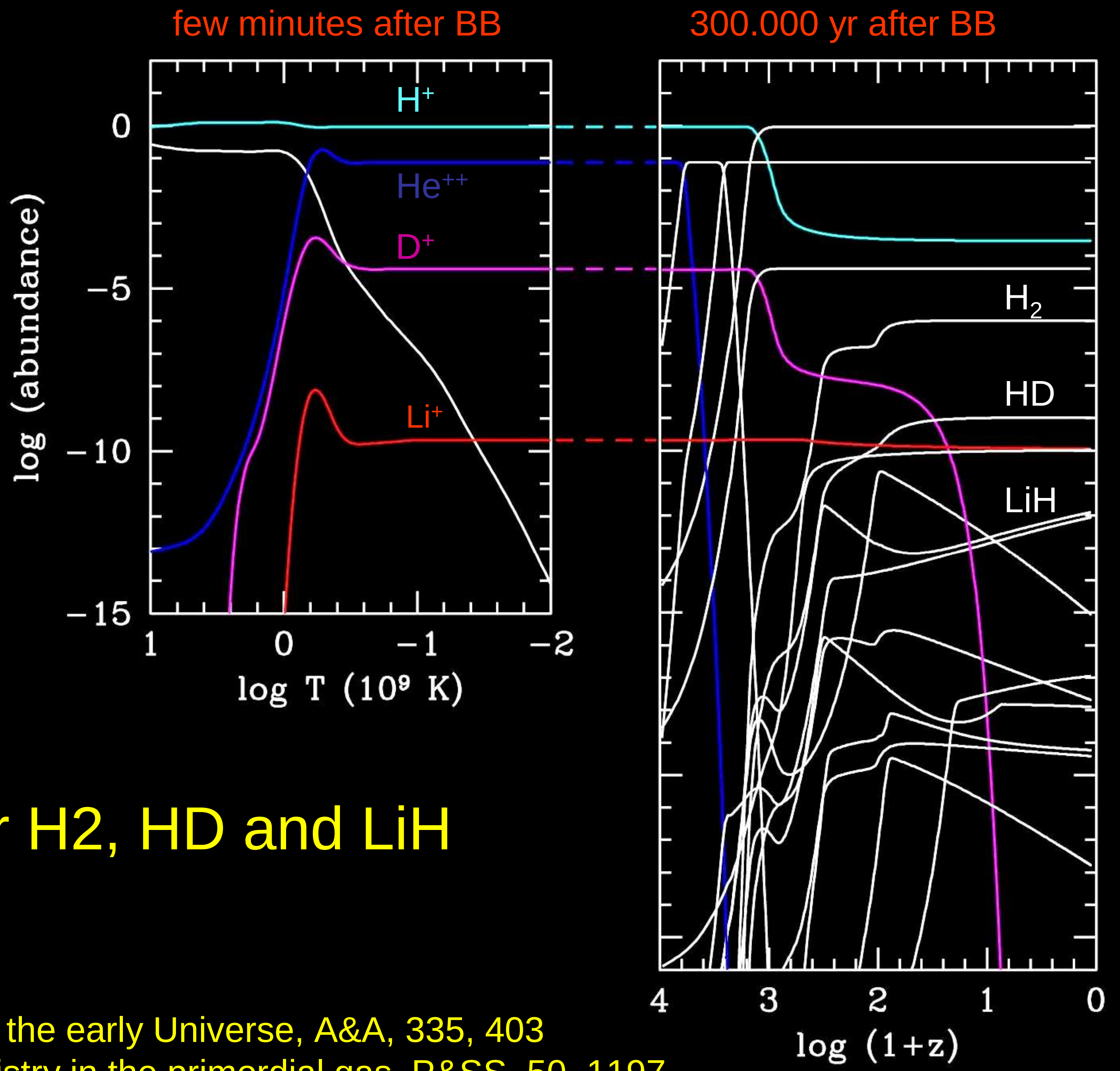
- Hirasawa, Takeda, Hutchins, Silk, Carlberg (1970s): chemical and dynamical evolution of primordial clouds
- → poor cooling, high T, top-heavy IMF of first stars

- Palla, Salpeter & Stahler (1983): 3-body reactions

- Lepp & Shull (1984): formation of H2, HD, LiH, HeH^+ → beginning of the chemistry of the early universe: $H_2 \sim 10^{-6}$ - HD $\sim 10^{-10}$ - LiH $\sim 10^{-12}$ - $HeH^+ < 10^{-13}$

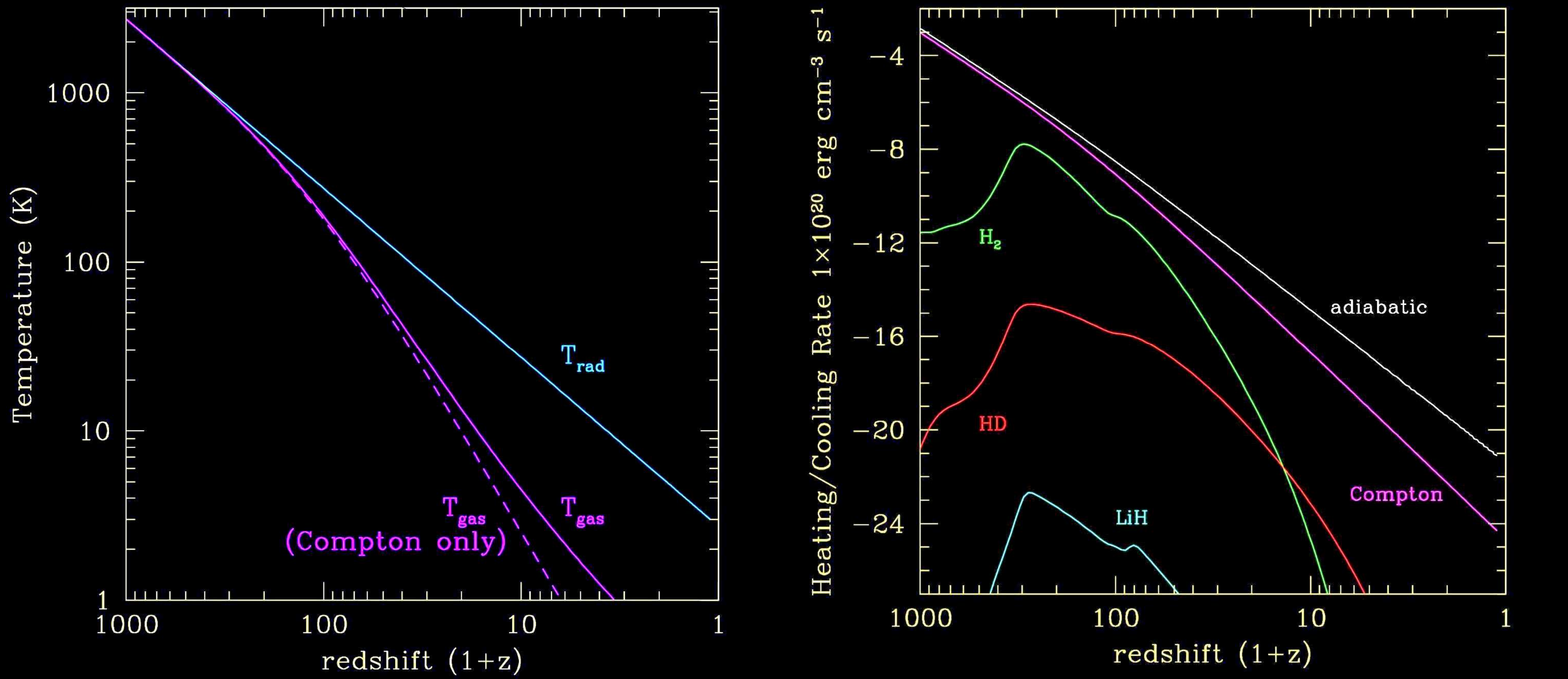
From nuclei to molecules (GP98)

- 21 species
- 22 reactions for H
- 24 reactions for D
- 15 reactions for He
- 26 reactions for Li
- Cooling functions for H2, HD and LiH



- Galli & Palla (1998) The chemistry of the early Universe, A&A, 335, 403
- Galli & Palla (2002) Deuterium chemistry in the primordial gas, P&SS, 50, 1197

Temperature of matter and radiation



Once Compton heating becomes less than expansion cooling, radiation and matter cool adiabatically T_{rad} ~(1+z) T_{gas} ~ $(1+z)^2$

H_2-chemistry

H_2^+ channel

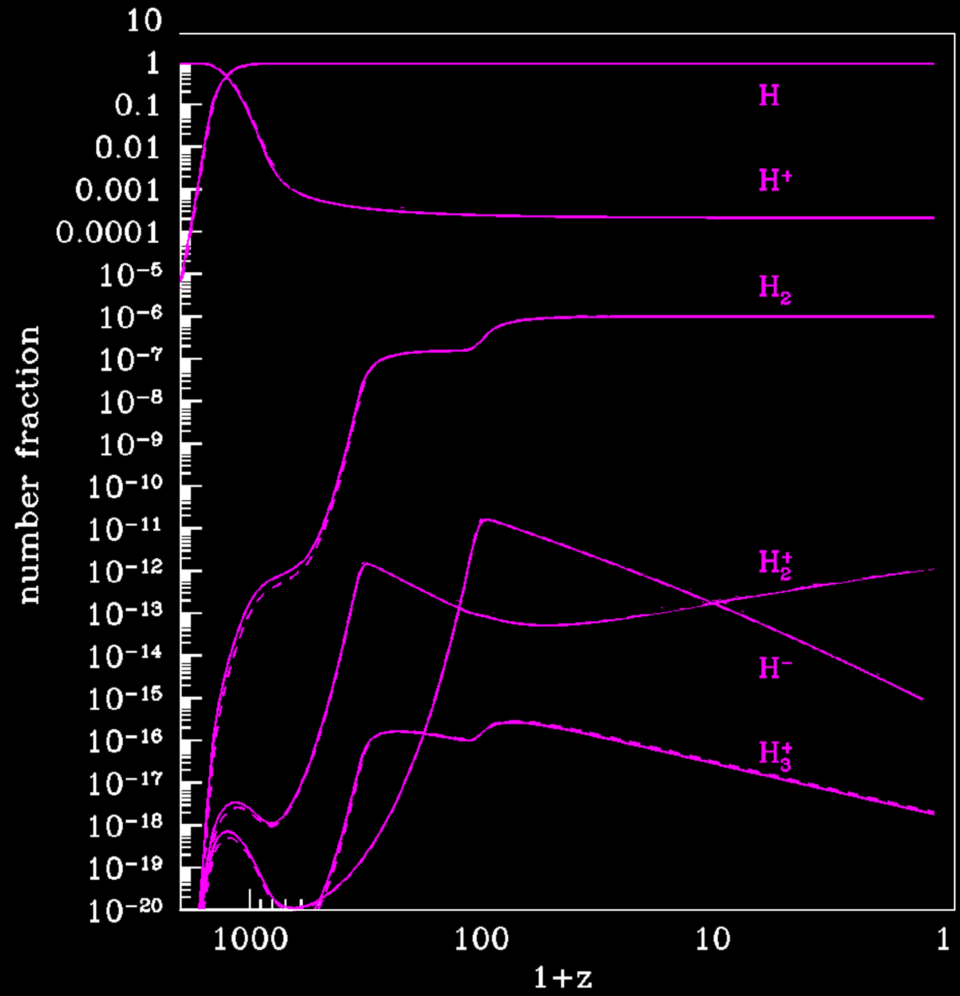
$H + H^+ \rightarrow H_2^+ + \gamma$

$H_2^+ + H \rightarrow H_2 + H^+$

H^- channel

$H + e^- \rightarrow H^- + \gamma$

$H^- + H \rightarrow H_2 + e^-$



Direct radiative association forbidden, H_2 has no dipole moment (not the case for HD and LiH)

HD-chemistry

Formation:

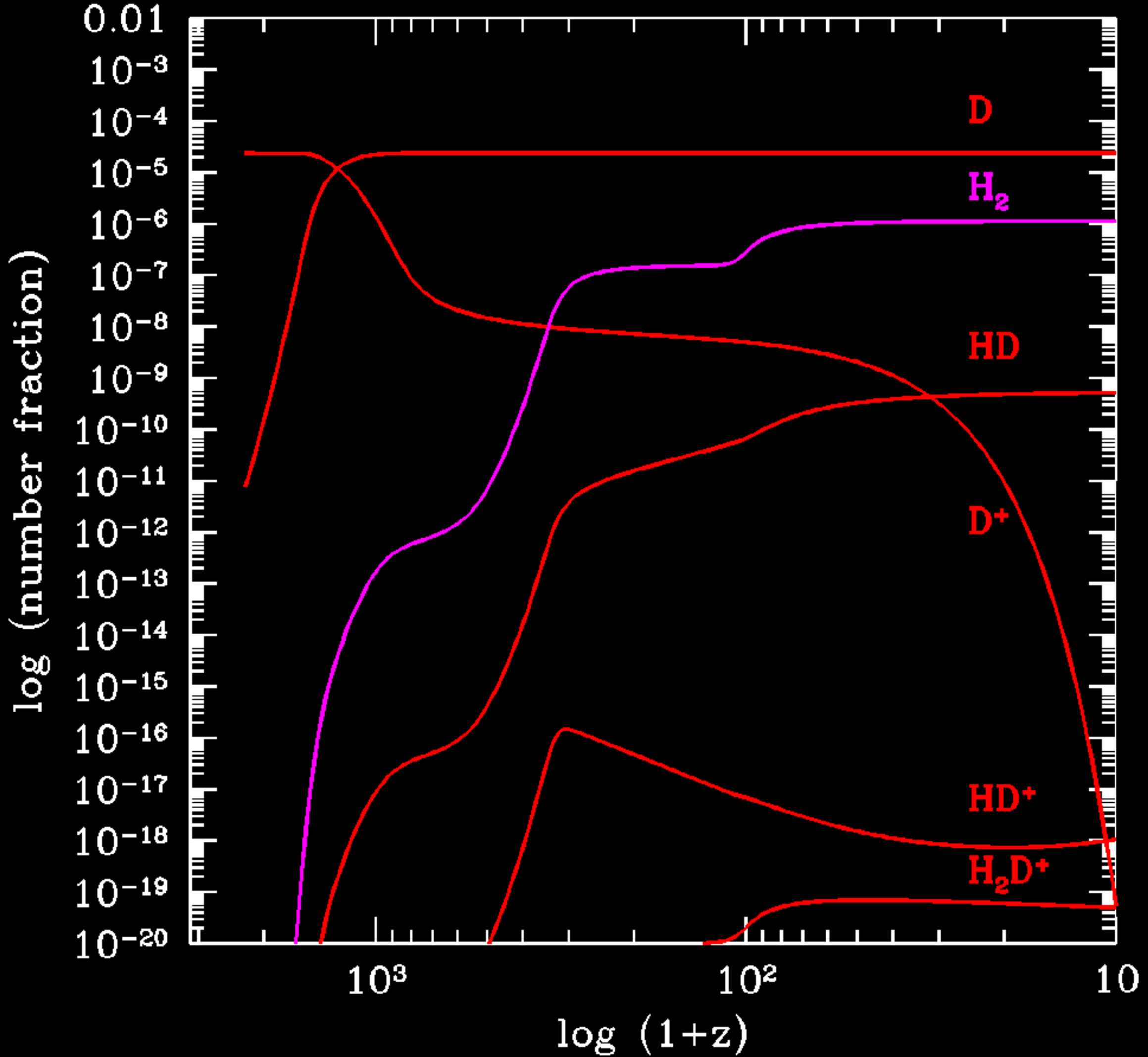
$D^+ + H_2 \rightarrow H^+ + HD$

Destruction:

$HD + H^+ \rightarrow D^+ + H_2$

but at low T

$D^+ + H \rightarrow D + H^+$



HeH^+-chemistry

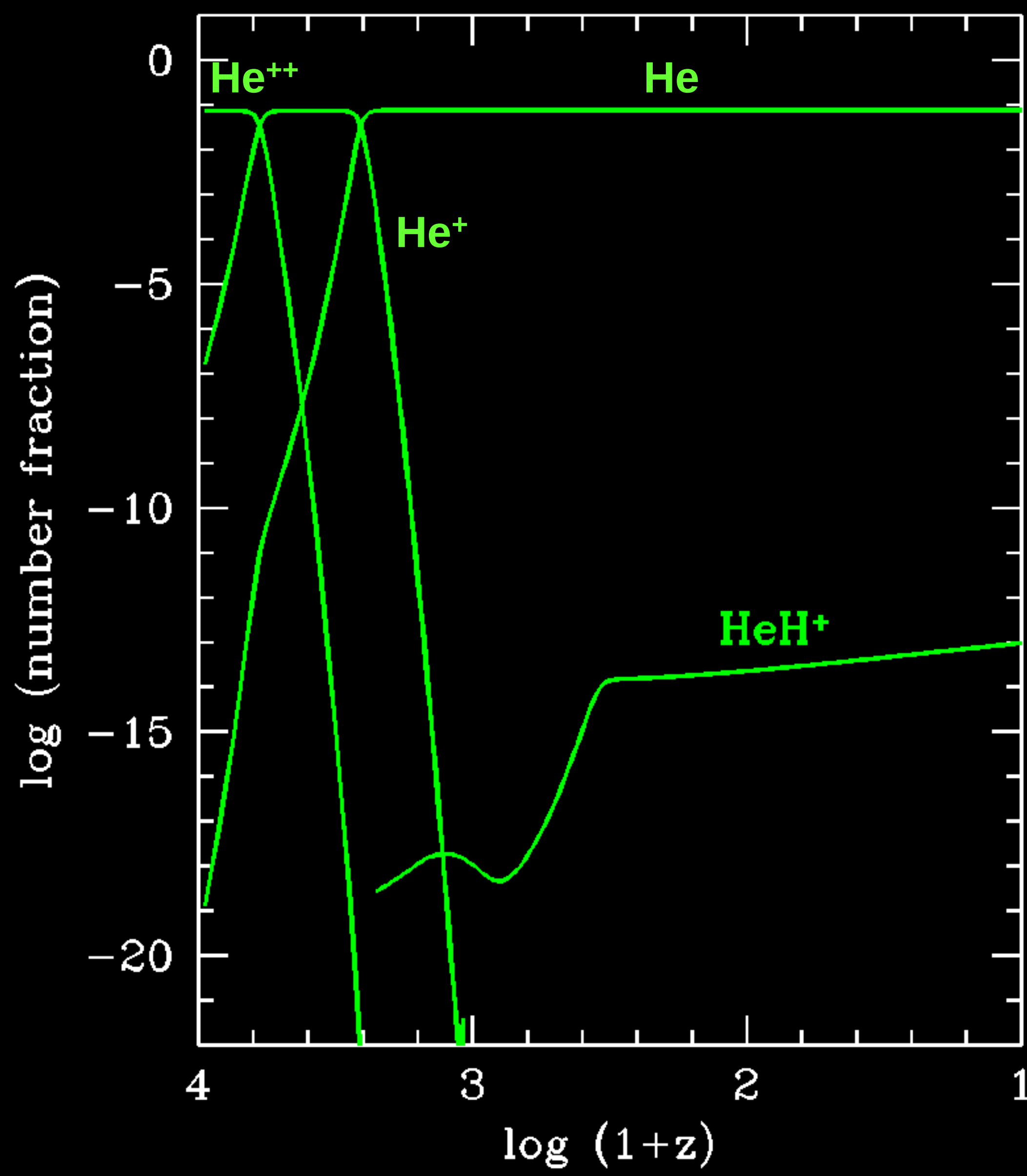
Formation:

$He + H^+ \rightarrow HeH^+ + \gamma$

Destruction:

$HeH^+ + H \rightarrow He + H_2^+$

$HeH^+ + \gamma \rightarrow He + H^+$



LiH-chemistry

Formation:

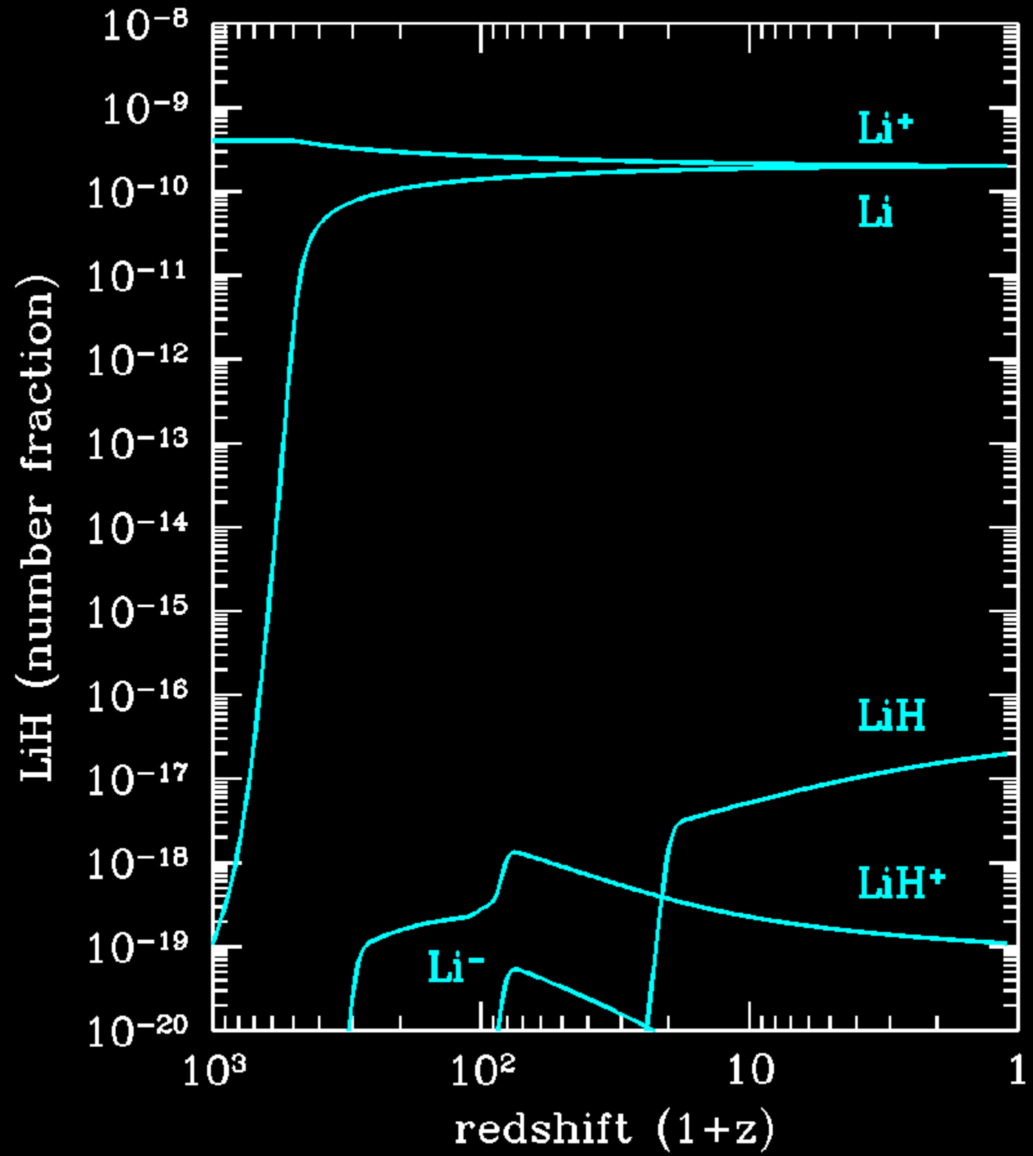
Li + H → LiH + γ

Li^- + H → LiH + e^-

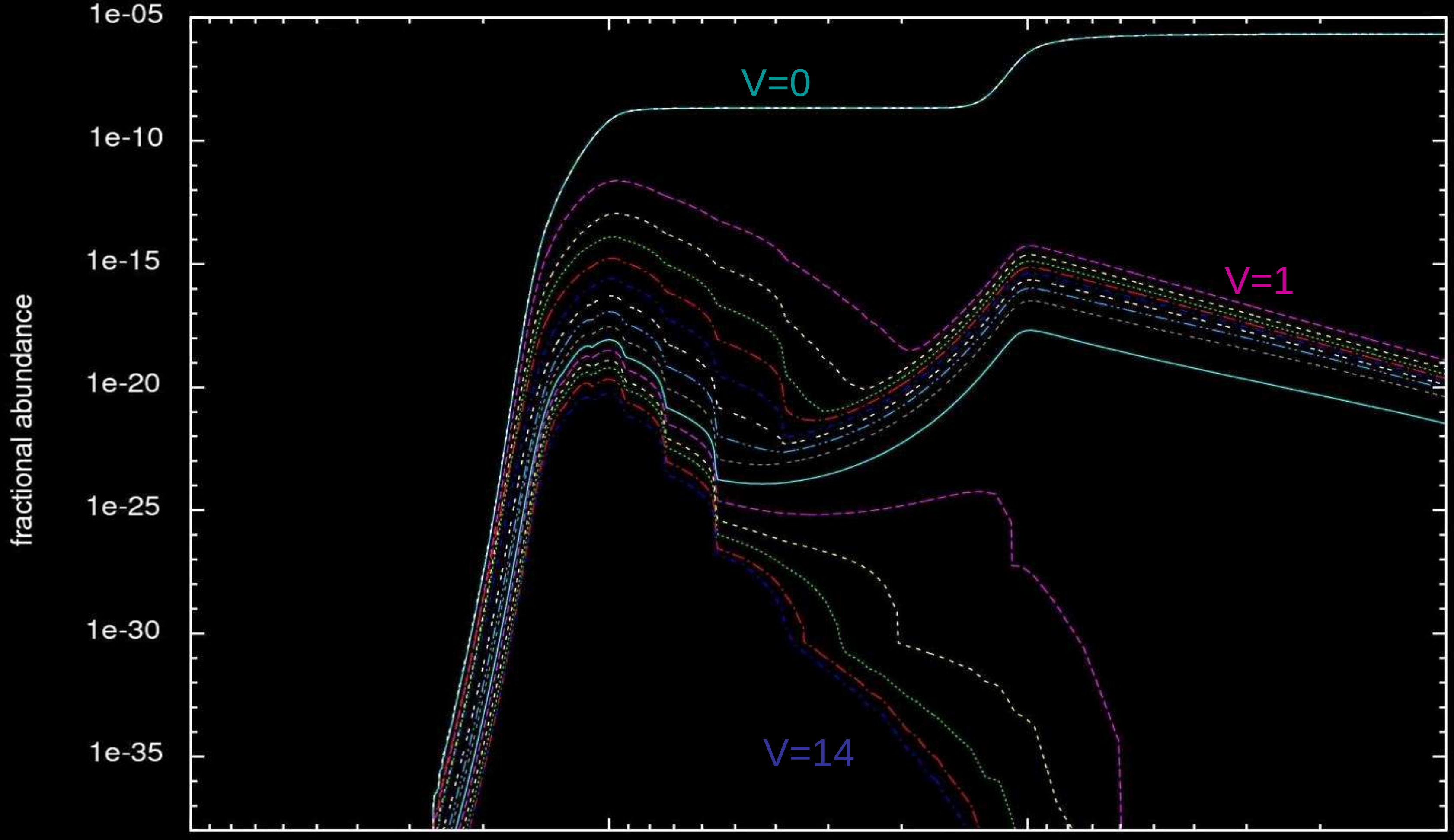
Destruction:

LiH + γ → Li + H

LiH + H → Li + H_2



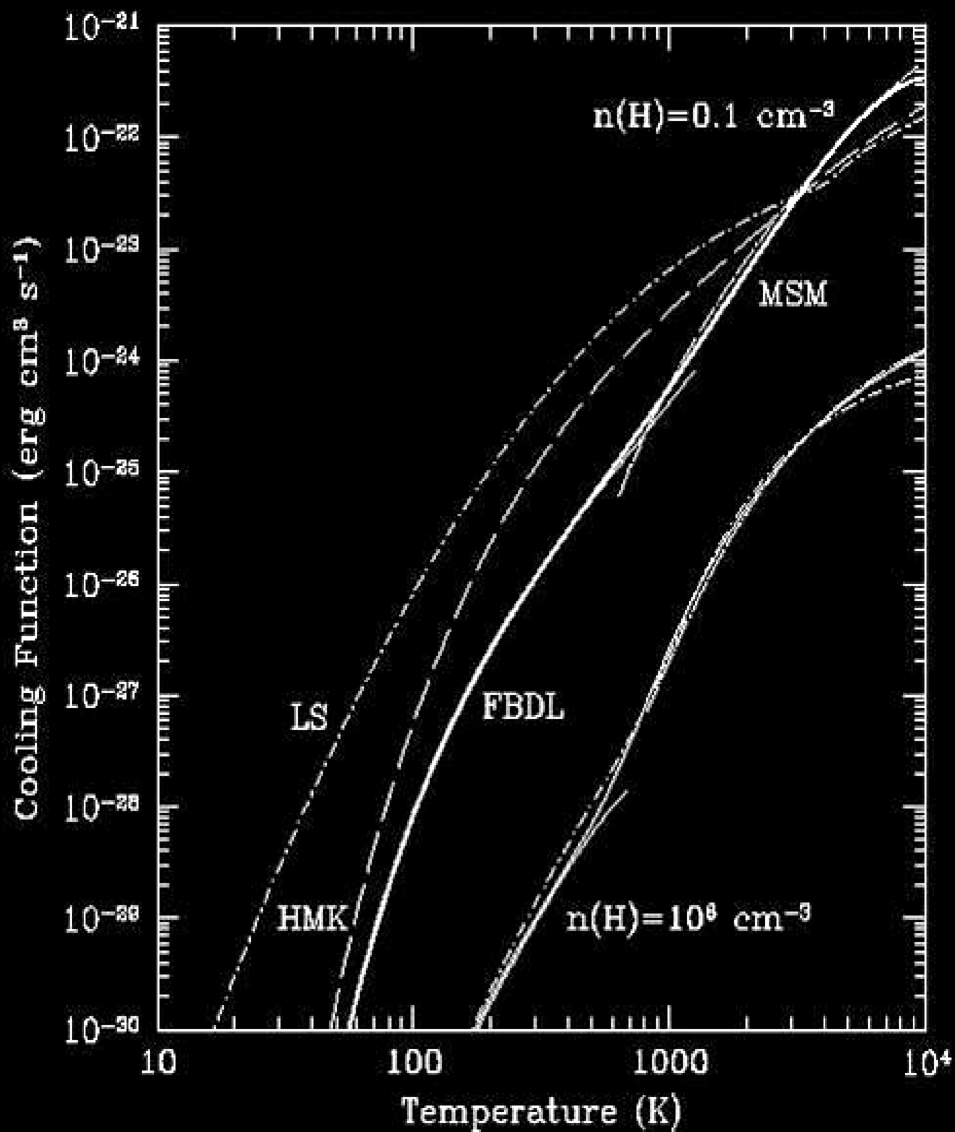
H_2 vibrationally resolved



C M. Coppola (2010), PhD Thesis

H_2 cooling

- Low-T low-n rates for H_2-H coll. exc. highly sensitive to adopted H_3 potential surface
- GP98: coll. coeff. from Forrey et al. (1997) for T < 600 K, Mandy & Martin (1993) T > 600 K
- New set of H_2-H coll. coeff. (Wrathmall & Flower 2007)
- Also coll. coeff. H_2-H_2 (Flower 2000) and H_2-He (Flower et al. 1998, Balakrishnan et al. 1999)



- Today: new improved H_2 cooling rate (Glover & Abel 2008)

GP98 “improved”

- Improved chemical network: ENZO code + GP98 + additional/revised reactions (→ new database)

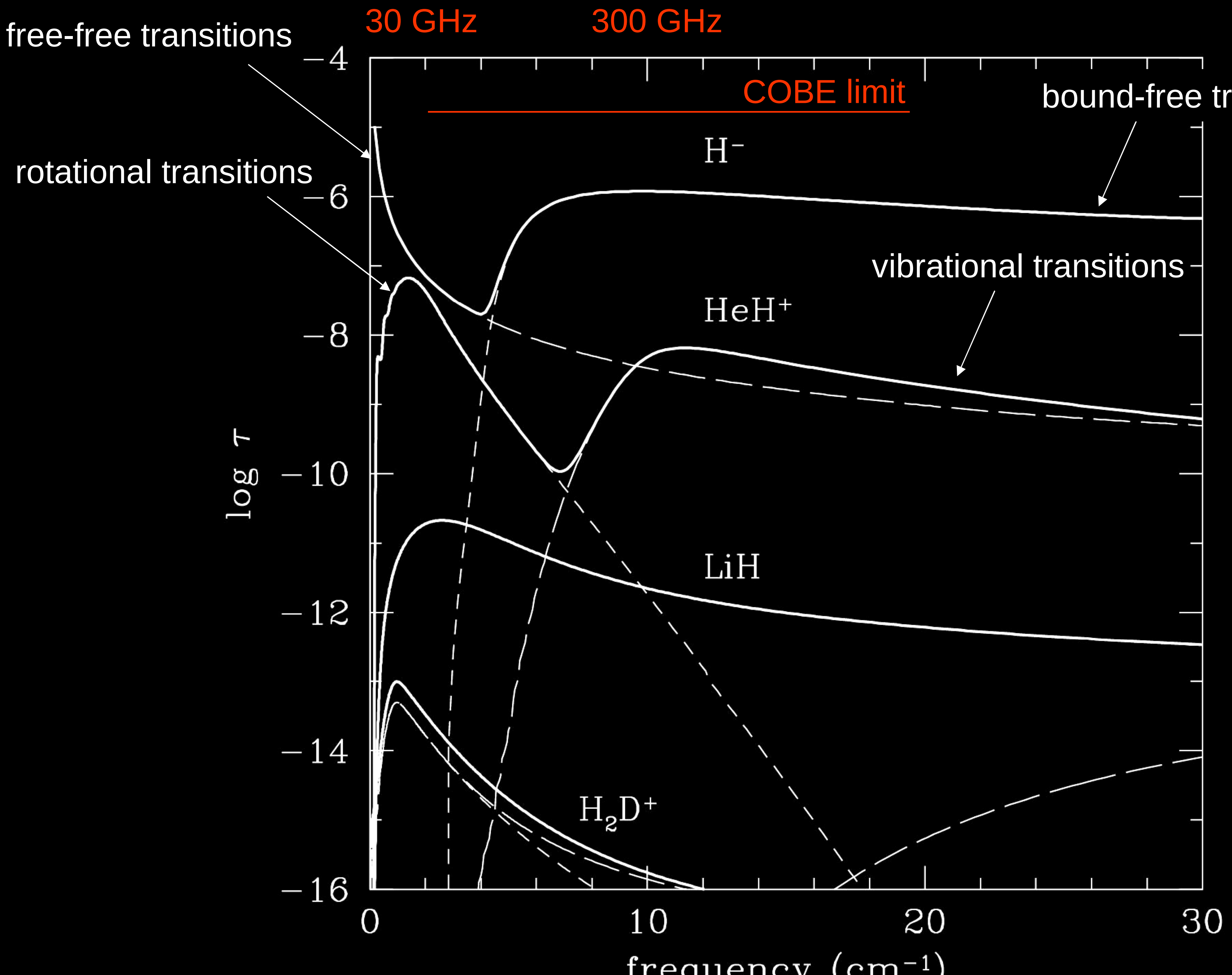
- Improved cosmological recombination: RECFAST

- Improved cooling rates:
  - H_2: Glover & Abel (2008)
  - HD: Flower et al. (2000), Lipovka et al. (2005)

- Optical depth due to line absorption, photoionization and photodissociation

Schleicher et al. (2008)

Optical depth of the primordial Universe



Dust and metals

Today in the Galaxy: $Z_{MW} \approx 0.02$, $D_{MW} = \rho_{dust}/\rho_{gas} \approx 0.01$

• H_2 formation: gas-phase dominates over dust-catalyzed if

$$D < \frac{0.02}{1 + f_{rad,H^-}} D_{MW}$$

(Glover 2003), assuming HMK rate for H_2 formation on dust grains (but ask Stéphanie, Paola).

• H_2 and HD dominate cooling over dust and metal lines radiation if

$$Z < 10^{-5} - 10^{-3}\, Z_\odot$$

(but ask Raffaella et al.). A single massive PopIII SN can produce $Z \approx 10^{-2}\, Z_\odot$! (Greif et al. 2007)

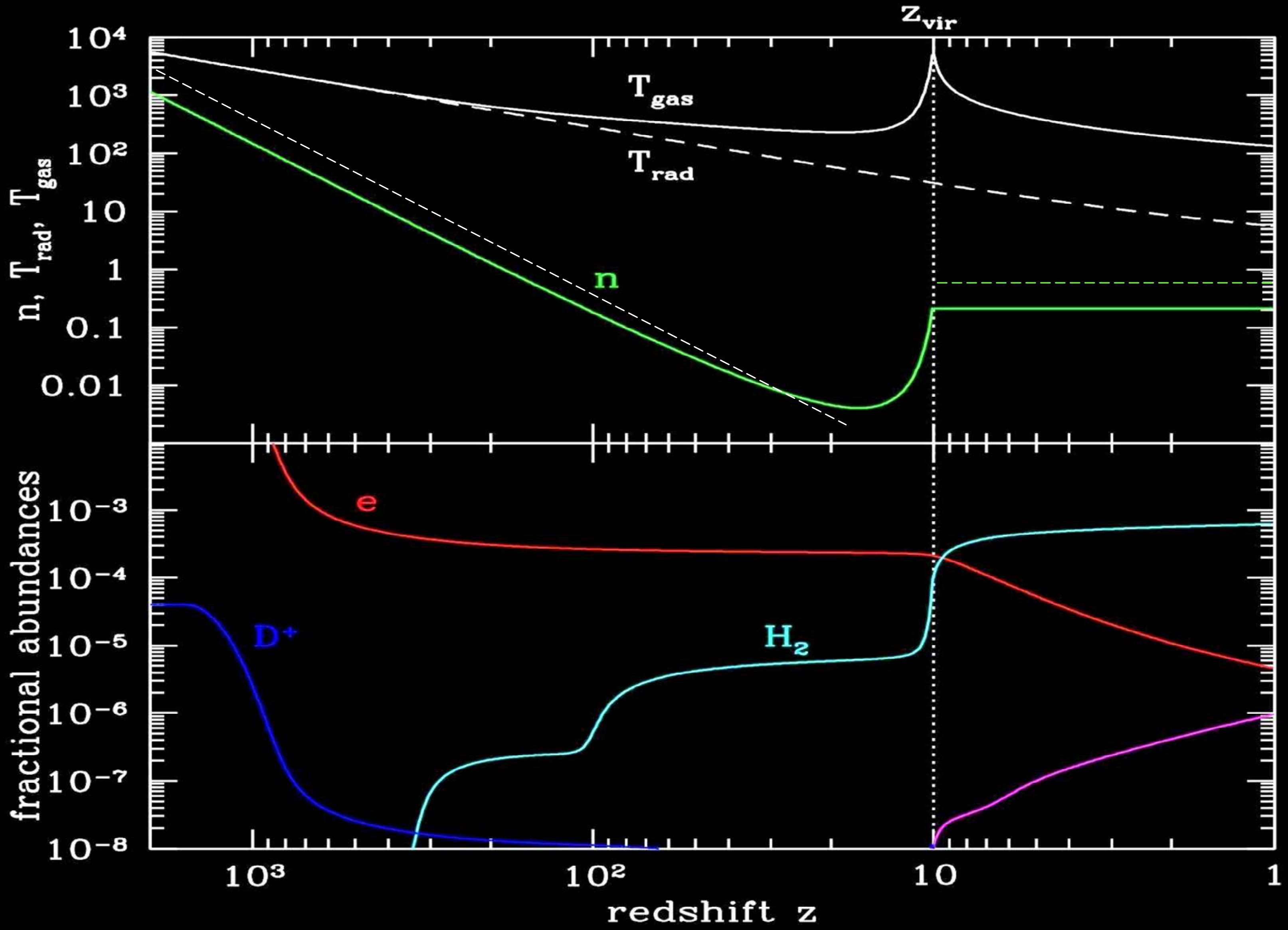
The cosmic scenario

• Standard CDM model: small objects form first and then merge to form larger systems (Blumenthal et al. 1984)

• Primordial gas clouds accumulate in dark-matter "minihaloes" with $M \approx 10^6 M_\odot$ formed at $z \approx 20\text{-}30$ (Bromm et al. 2002)

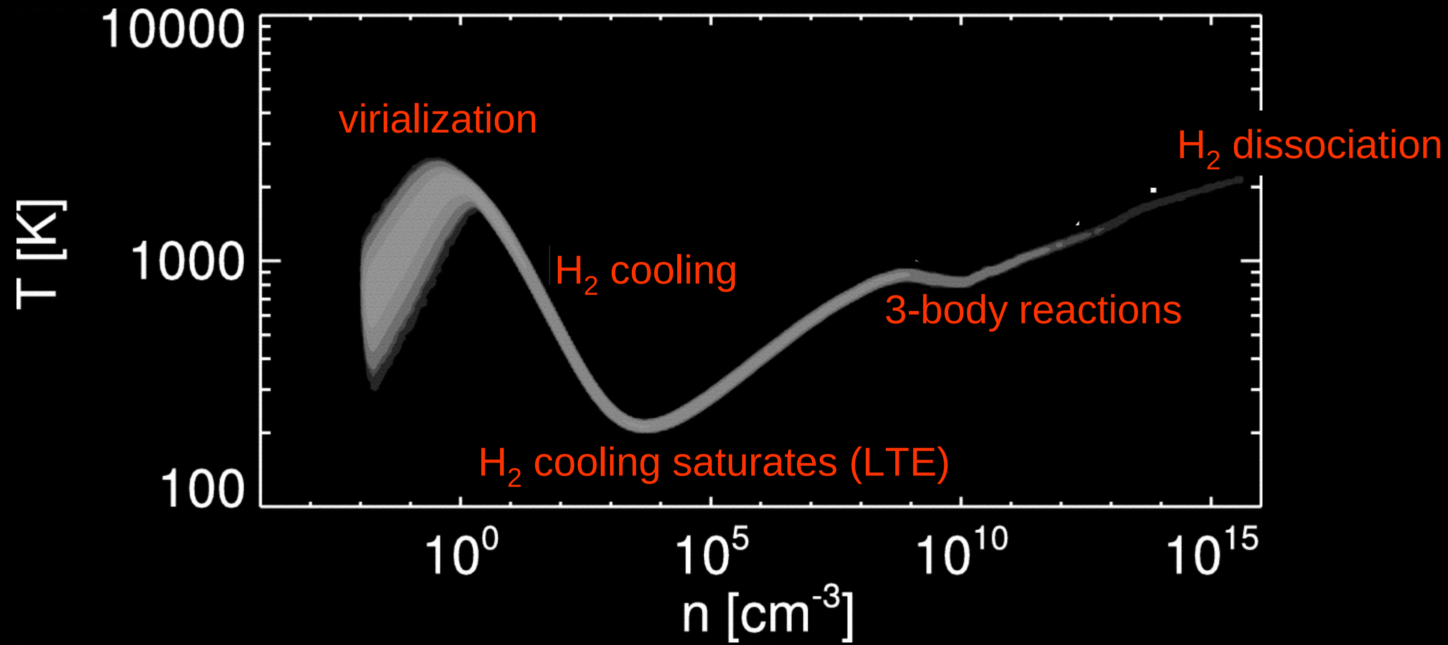
• When sufficient mass is accumulated ($M_{cloud} > M_J$) the cloud can collapse. The subsequent evolution, and the fragmentation mass-scale, depend on the thermodynamics of the gas (Tegmark et al. 1997)

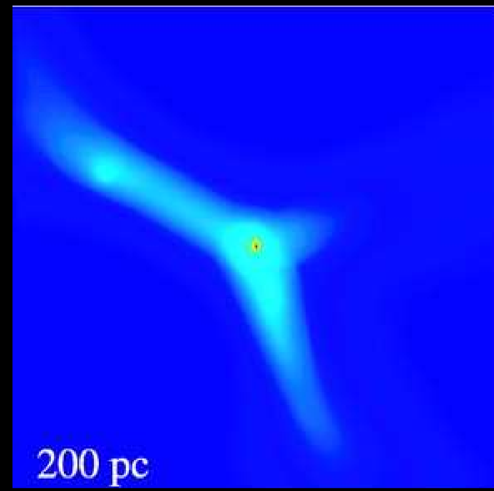
Evolution of an overdense region: I. Semi-analytical model

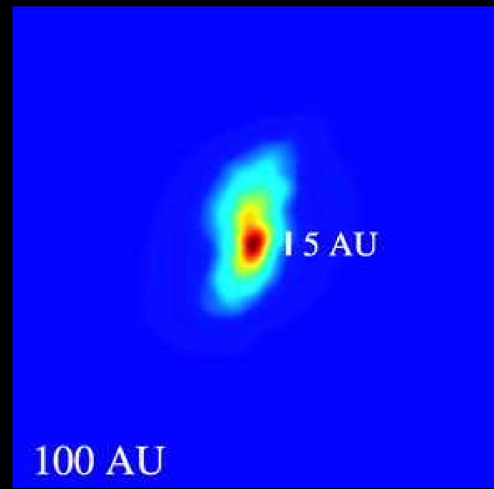


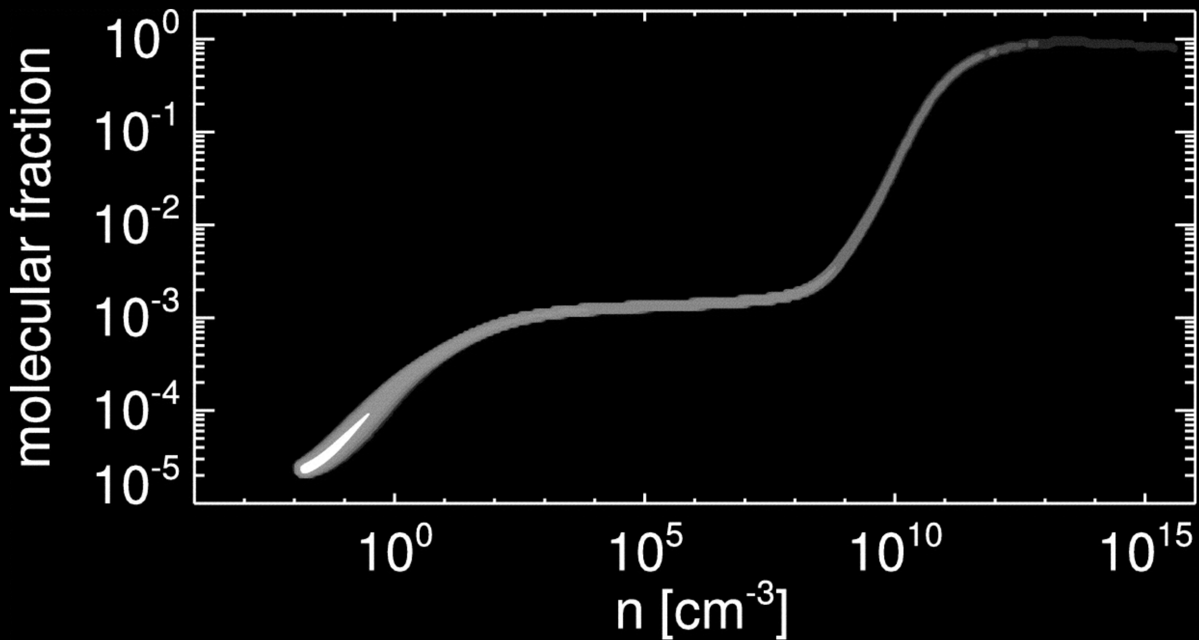
Tegmark et al. (1997), GP02

Evolution of an overdense region: II. Numerical simulation









Yoshida et al. (2006)

Magnetic fields at high-redshift

- Highly speculative (= few data, many theories)
- Inferred from Faraday rotation measure of polarized quasars up to $z \approx 2$ (Bernet et al. 2008)
- Zeeman effect detected in a galaxy at $z=0.692$ (84 μG, Wolfe et al. 2008). Note $B_{MW} \approx 6$ μG (Heiles & Troland 2005)
- B in galaxies: dynamo generated (Parker 1979) or fossil (Kulsrud 1999)?

Magnetogenesis

- post-recombination: ejected by Pop III stars (Rees 2005)
- radiation era: photon drag on electrons (Harrison 1973)
- cosmological phase-transitions: electroweak, QCD, GUT (Hogan 1983)
- inflation (Turner & Widrow 1988)

Effects of B field on cosmic evolution

- Formation of first stars with B = 0 well understood (Abel et al. 2002; Bromm & Larson 2004). Critical mass:

$$M_J \sim (T^3/\rho)^{1/2}$$

- With B ≠ 0 different dynamics: enhanced stability, magnetic braking, MRI instability, magnetocentrifugal launching of jets. Critical mass:

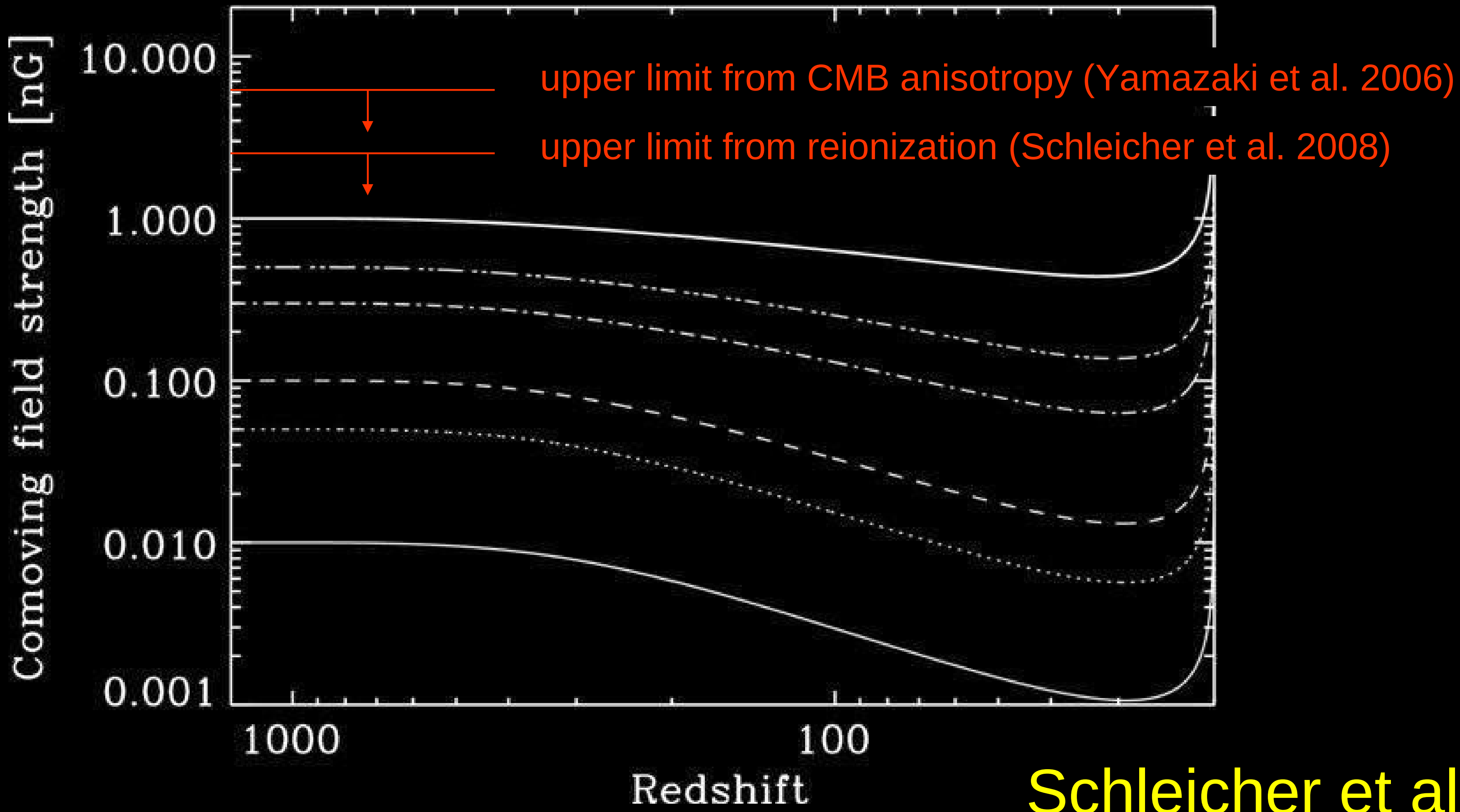
$$M_B \sim B\, R^2$$

- B also affects primordial chemistry and thermal evolution. Ambipolar diffusion heating:

$$L_{AD} \approx \frac{\eta_{AD}}{4\pi} \frac{B^2}{L_B^2}$$

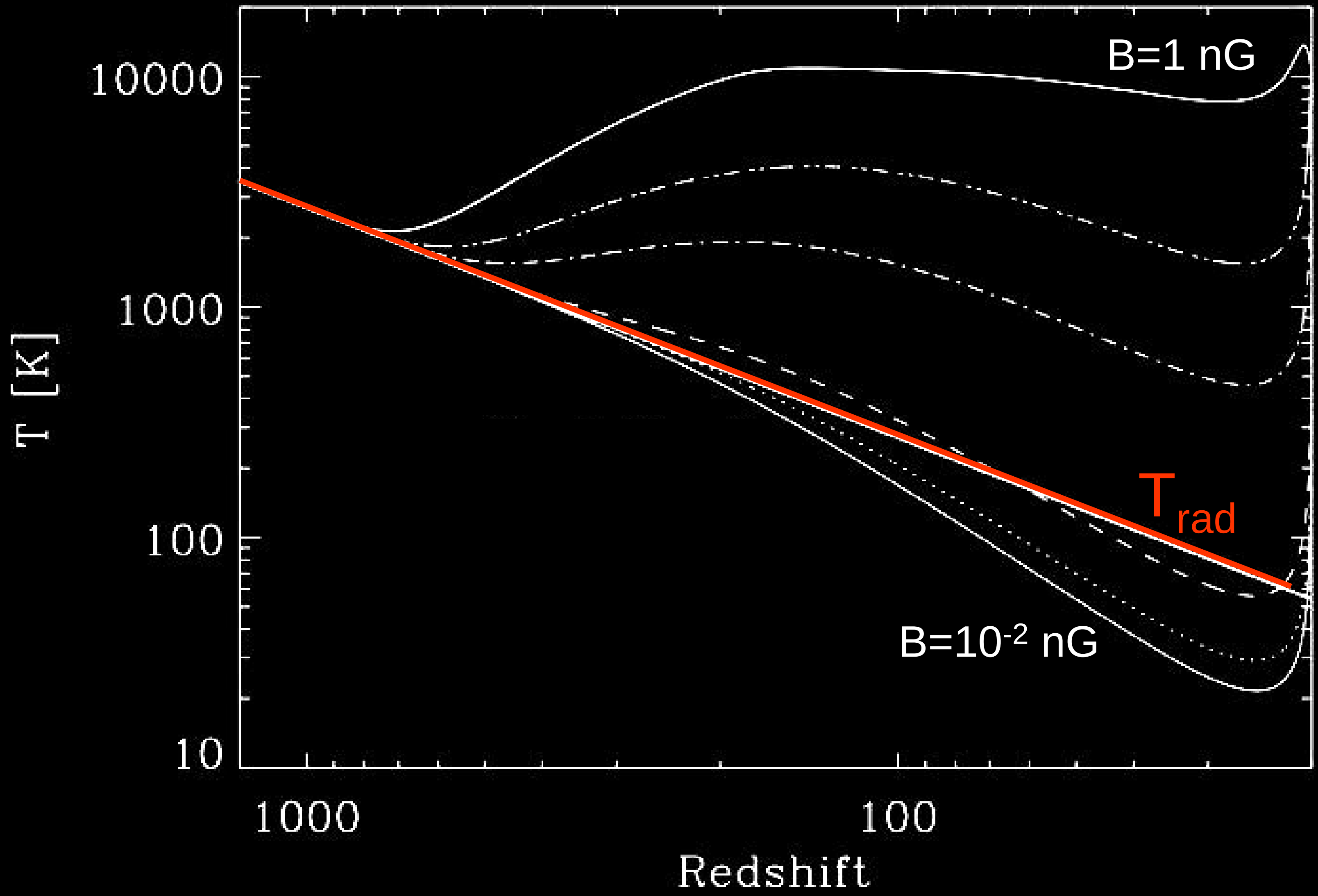
Evolution of B

- Comoving field strength: $B_0 = Ba^2 = \frac{B}{(1+z)^2}$



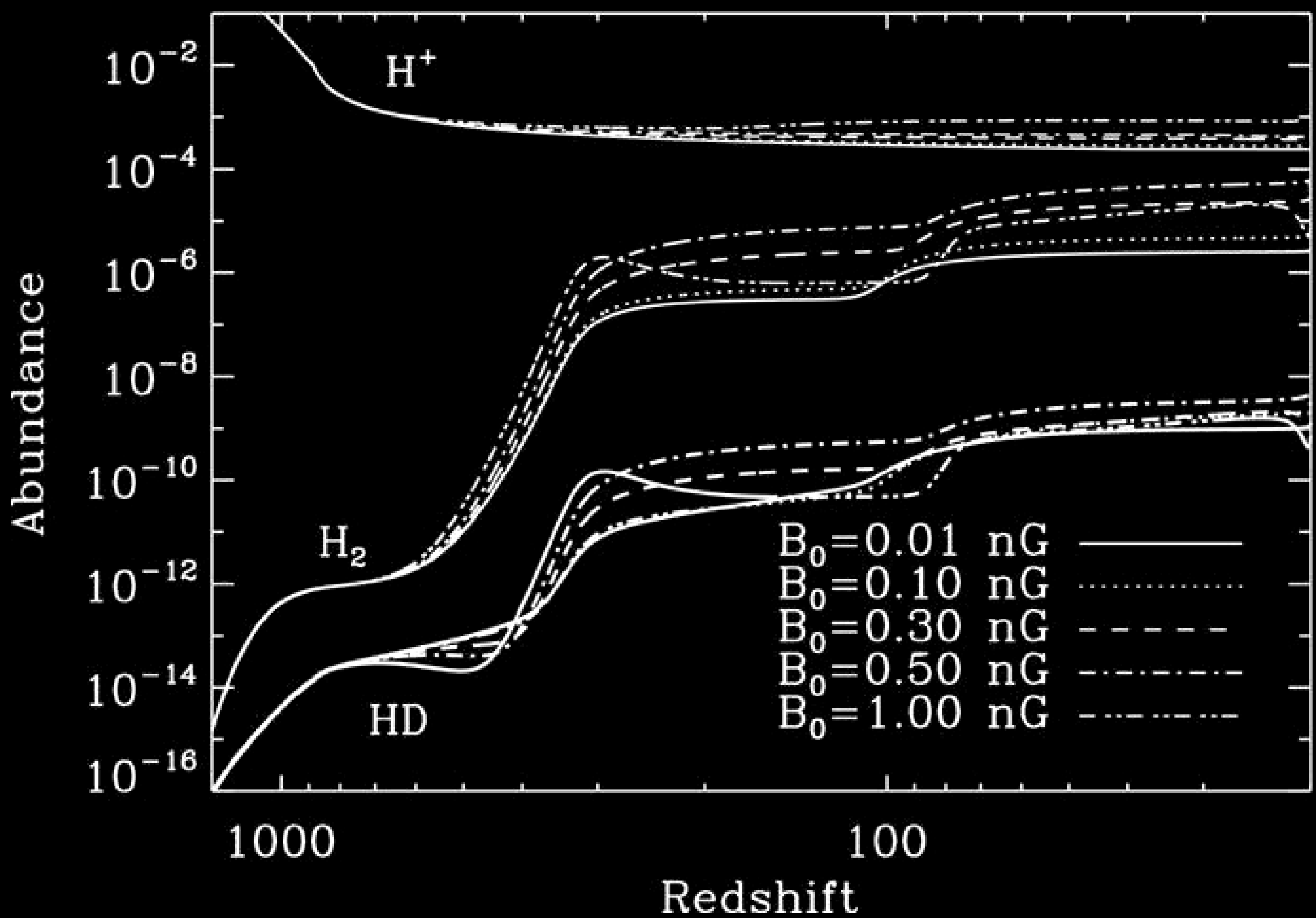
Schleicher et al. (2009)

Evolution of gas temperature with B



Schleicher et al. (2009)

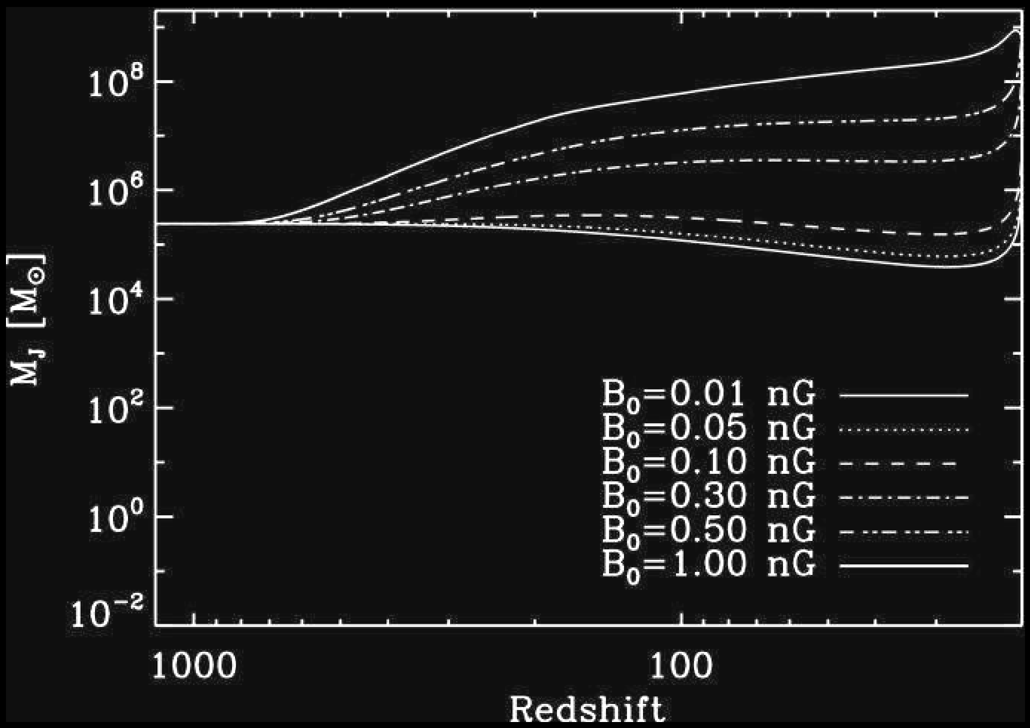
Effects of B on chemistry



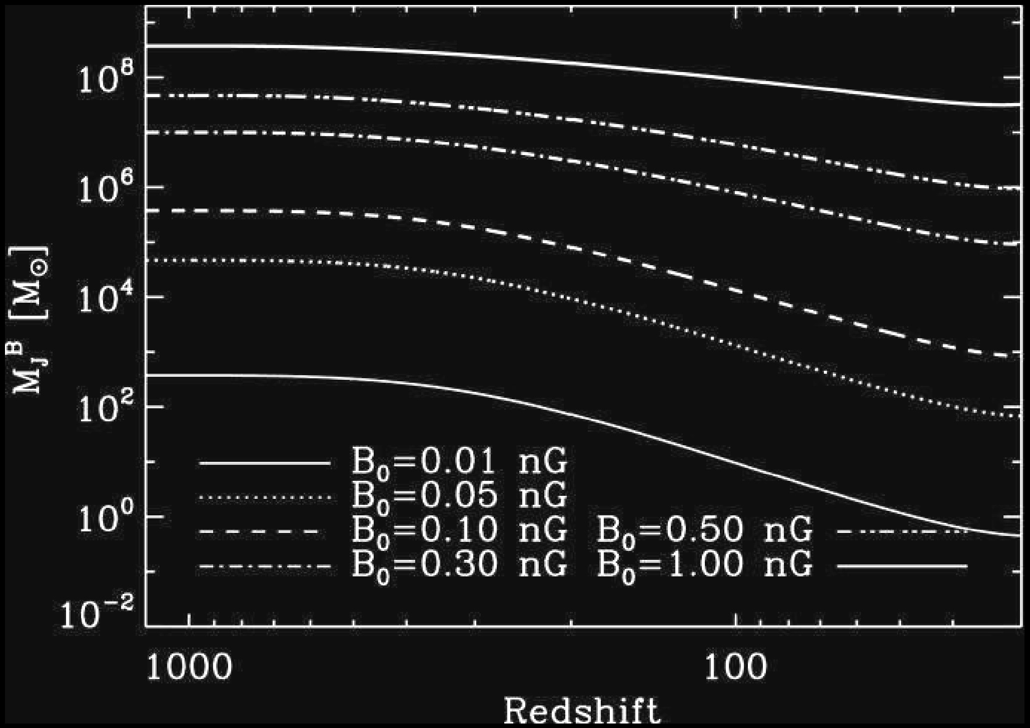
Schleicher et al. (2009)

Effects of B on dynamics

Thermal Jeans mass

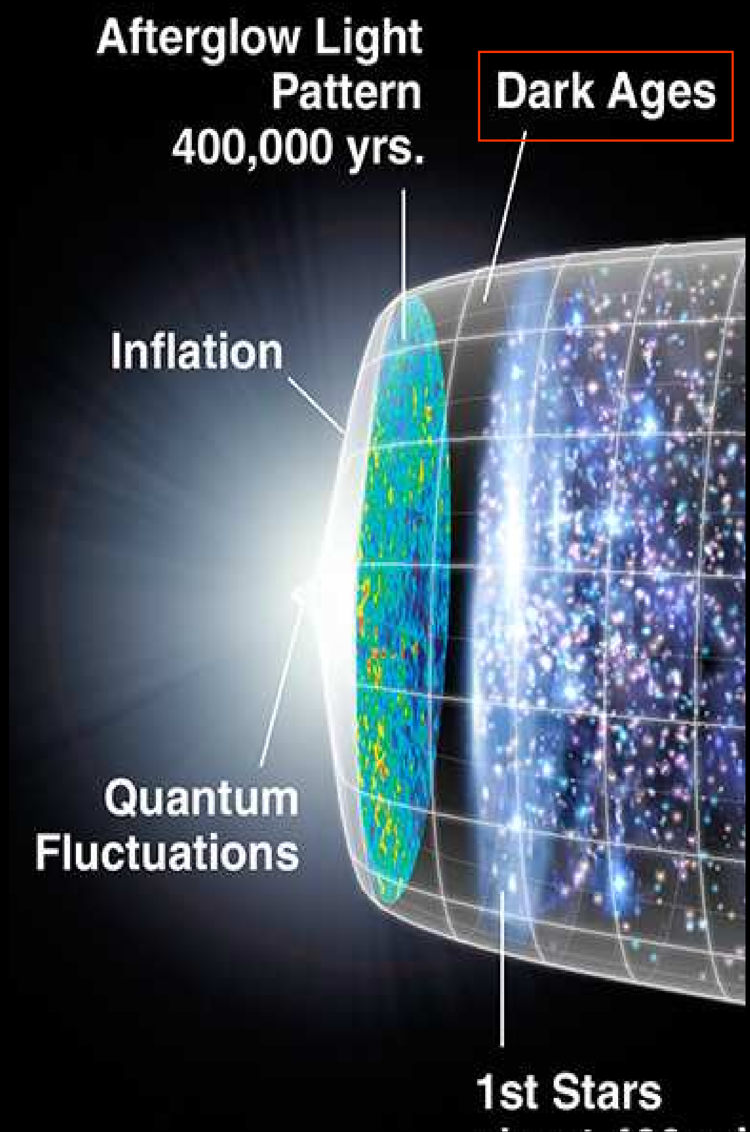


Magnetic critical mass



For B_0 > 0.5 nG the critical mass is larger than M_J !

Conclusions



- Primordial molecules: formed in the Dark Ages, control the thermodynamics of metal-free gas and the formation of the first stars.
- Spectral signatures in the CBR still below sensitivity (but Planck, Herschel).
- Magnetic fields control present-day star formation. Their role for PopIII star formation is largely unexplored.