The First Hydrides

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The Hydride Toolbox
Paris, 12-15 December 2016

A. Loeb (2006)

Francesco Palla
(1954-2016)

Francesco's Legacy

Star Formation in Space and Time

International Conference
June 5-9 2017
Istituto degli Innocenti
Firenze Italy

SOC chairs: Steve Stahler & Hans Zinnecker

PRIMORDIAL STAR FORMATION: THE ROLE OF MOLECULAR HYDROGEN

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AND

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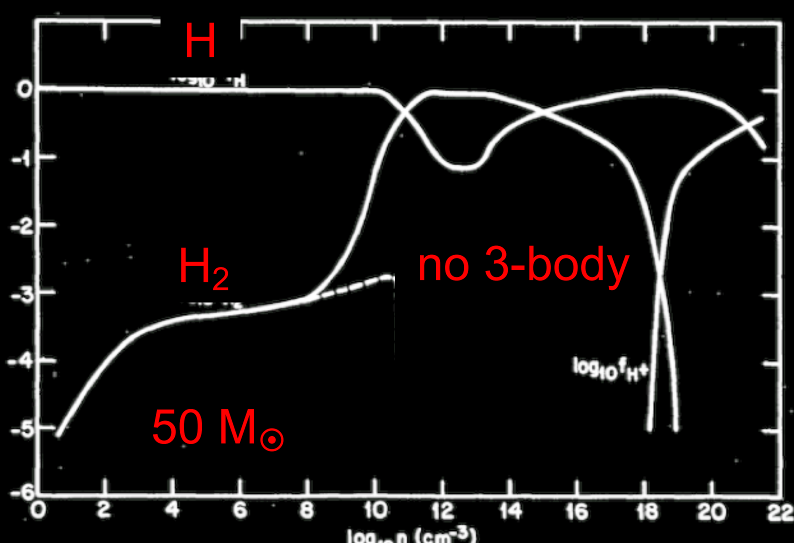
Received 1982 July 12; accepted 1983 January 27

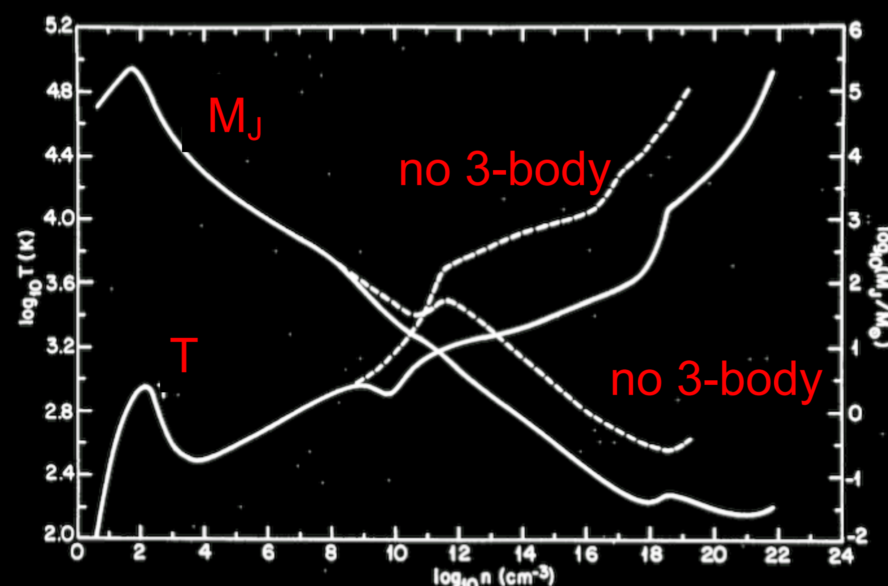
$$\frac{d\rho}{dt}=\frac{\rho}{t_{ff}}, \quad t_{ff}\equiv[3\pi/(32G\rho)]^{1/2}.$$

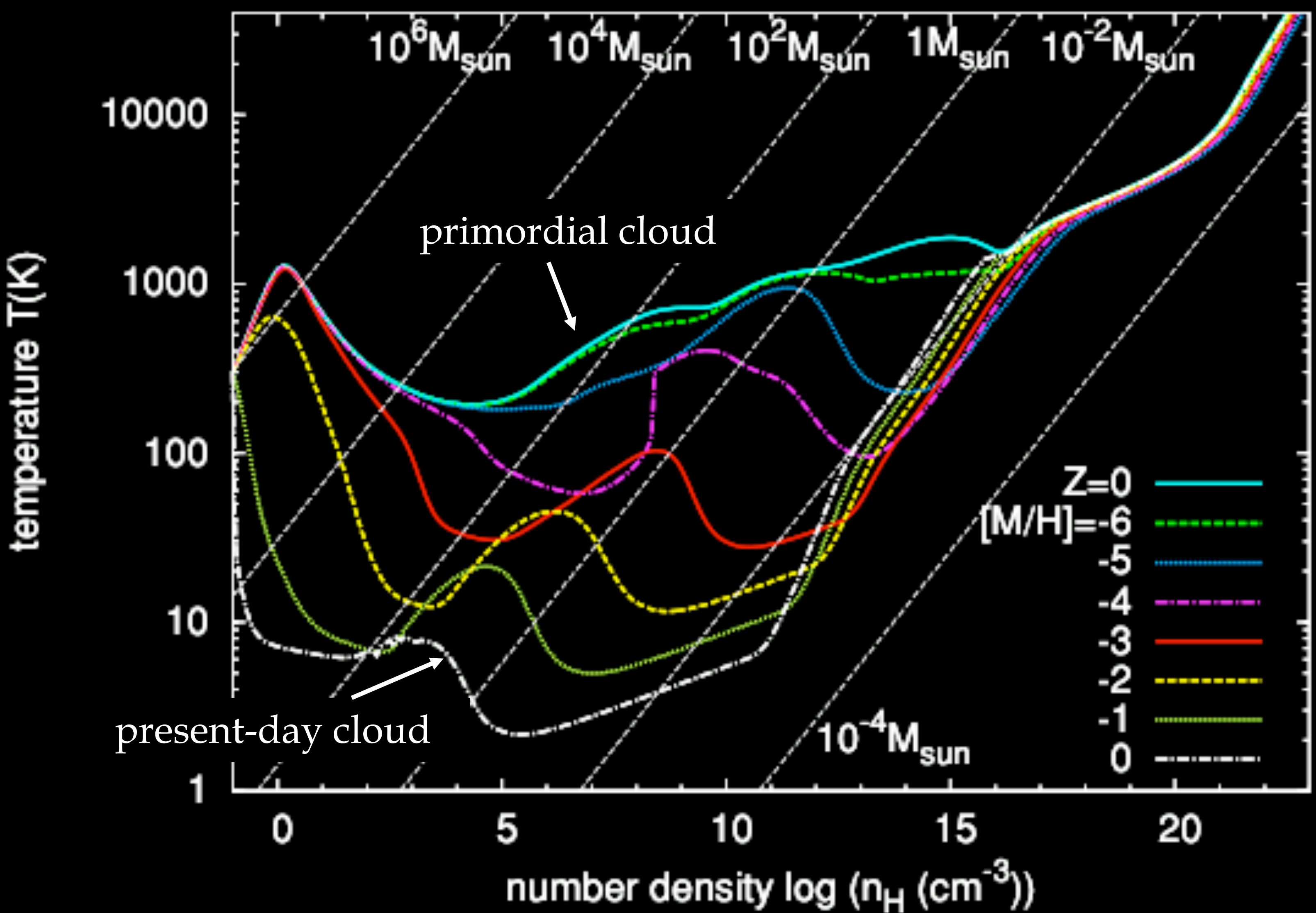
$$\frac{d\varepsilon}{dt}=\frac{P}{\rho^2}\left(\frac{1}{t_{ff}}\right)-\Lambda.$$

$$H+H+H\rightarrow H_2+H,$$

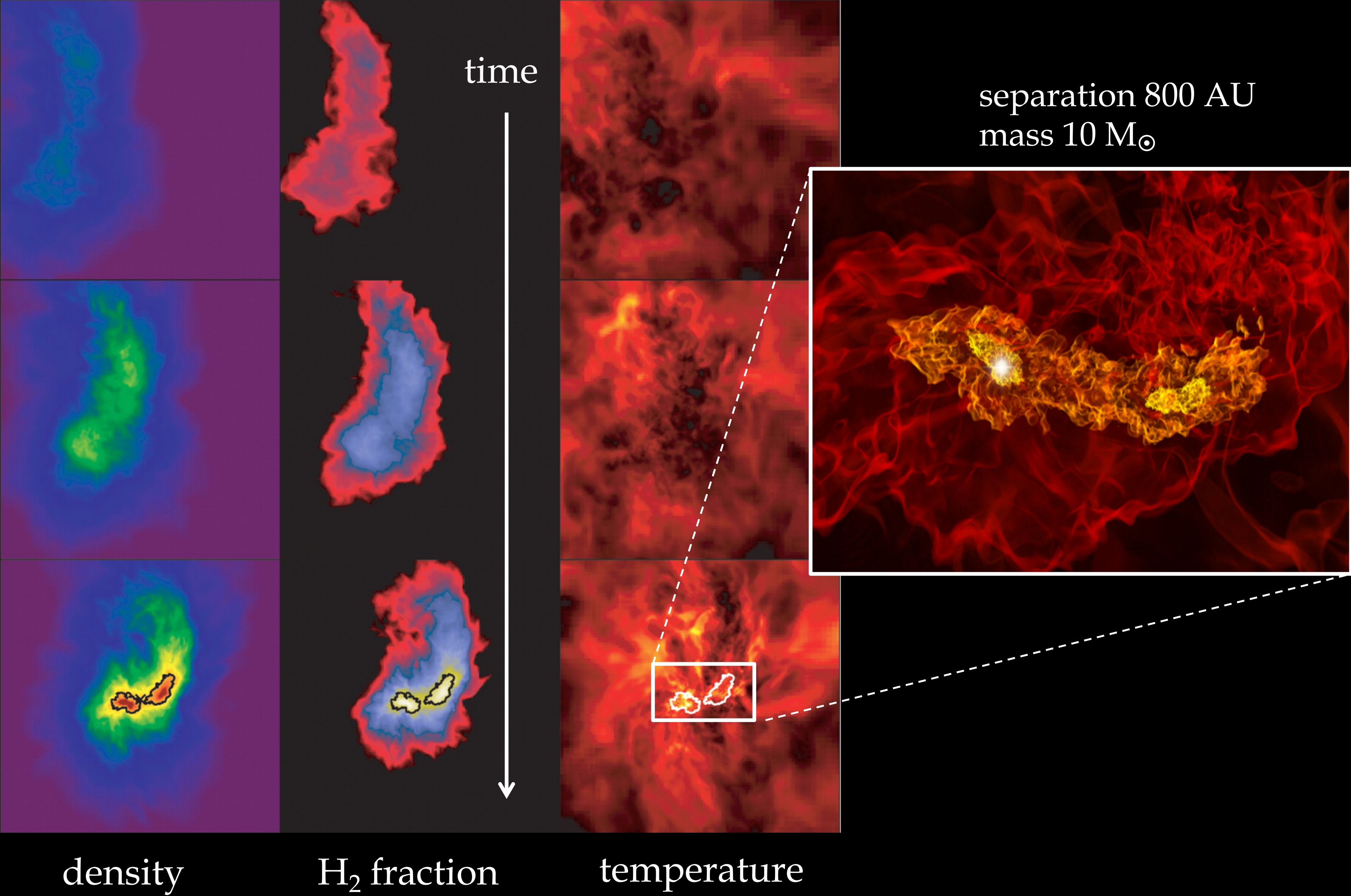
$$H+H+H_2\rightarrow H_2+H_2$$







Omukai et al. (2010)



Turk et al. (2009)

The Dawn of the Hydrides

The Early Universe: a hostile environment for chemistry:

- rapid expansion (low density and temperature)
- strong radiation field (CMB + H, He recombination photons)
- chemically poor (H=0.924, He=0.076, D=$2x10^{-5}$, Li=$4x10^{-10}$)
- no solid particles (catalyzers)

→ few molecules, mostly hydrides

The first hydrides are formed after recombination (z<1000):

- Hydrogen subsystem: H_2, H_2^+, H_3^+, H^-
- Deuterium " ": HD, HD^+, H_2D^+
- Helium " ": HeH^+
- Lithium " ": LiH, LiH^+

- In non-standard Big Bang nucleosynthesis, possible formation of CH, NH, OH, HF (Puy et al. 2007, Vonlanthen et al. 2009)

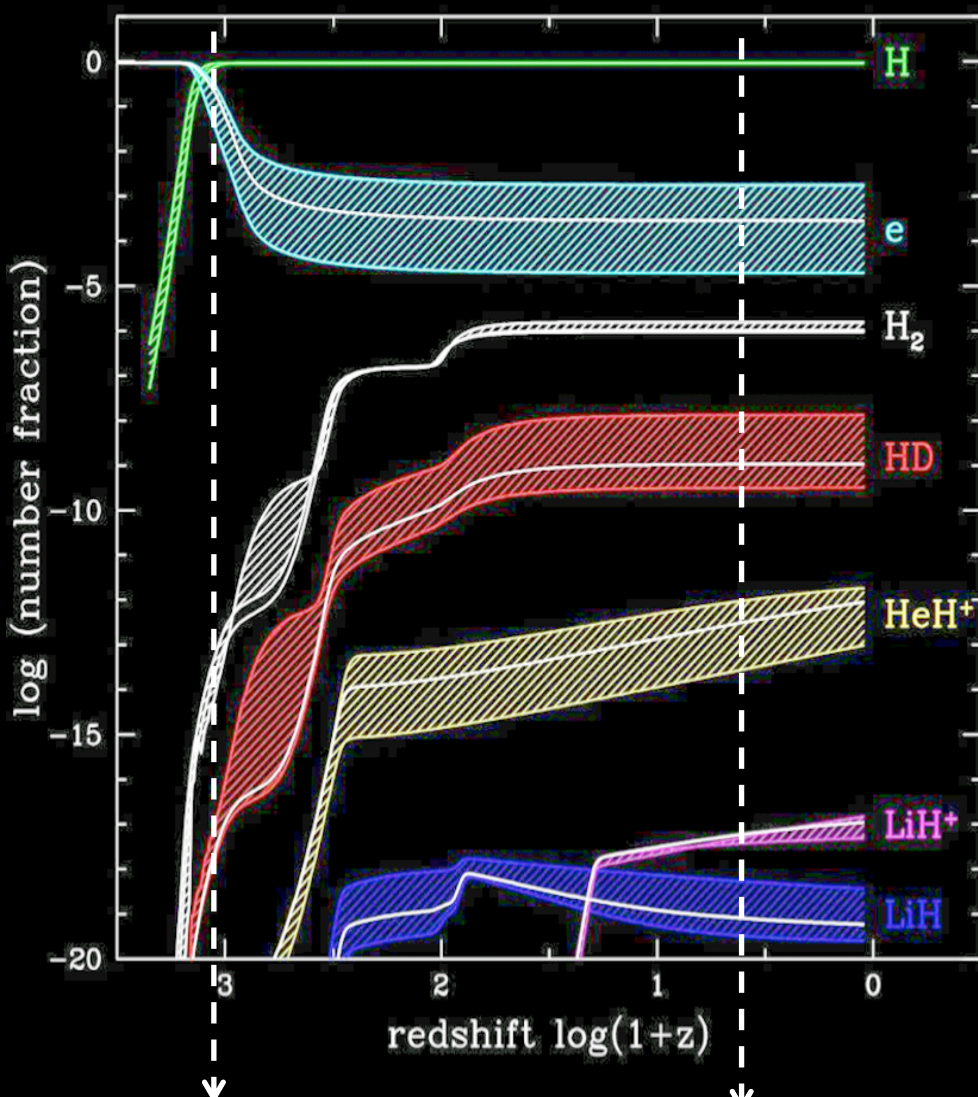
Few species, relatively small chemical network:

- Lepp & Shull (1983) ~ 25 reaction, ~ 10 species
- Galli & Palla (1998) ~ 90 reactions, ~ 20 species
- Gay et al. (2011) ~ 250 reactions, ~ 30 species

Why are the first hydrides important?

- Theoretical models: control the thermodynamics of metal-free gas determining the mass of the first stars (well established)
- Observations: produce spectral/spatial signatures in the CMB that may allow to observationally probe the Dark Ages (challenging)

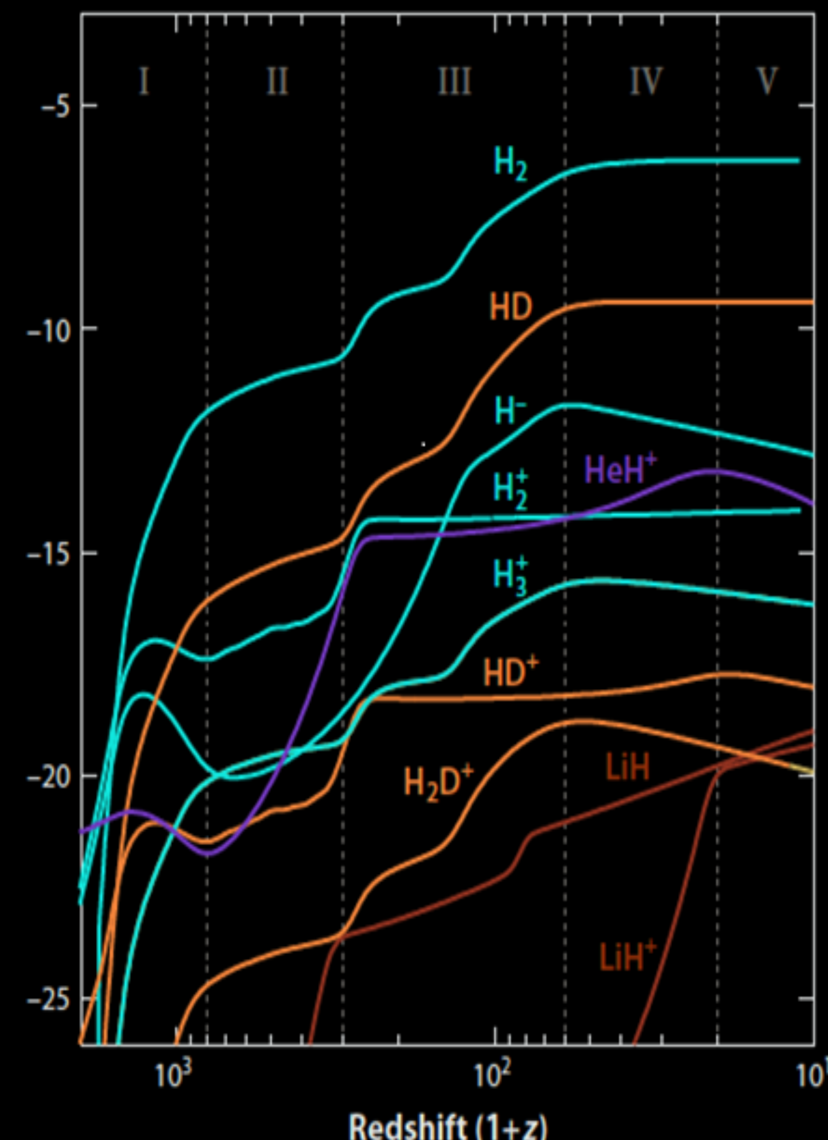
Galli & Palla (1998)



400,000 yr after BB

400 Myr after BB

Galli & Palla (2013)



Helium chemistry

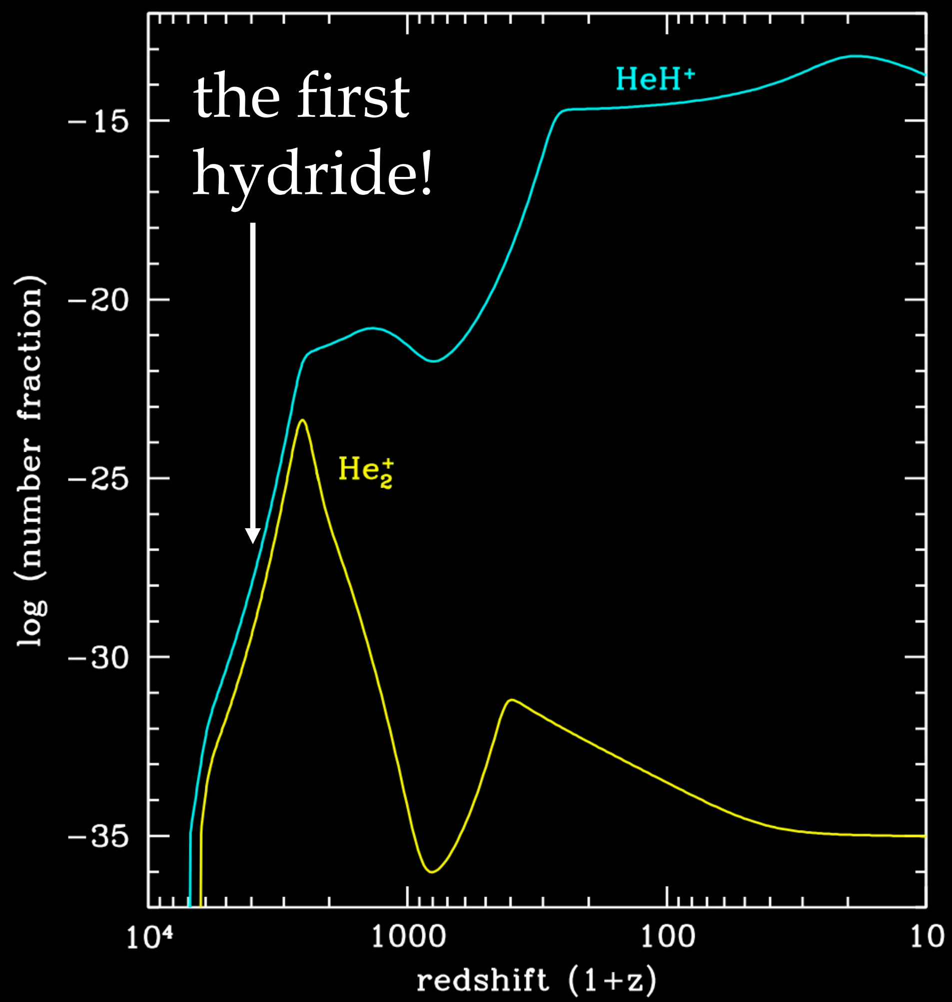
Formation:

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

Destruction:

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

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



Galli & Palla (1998), Bovino et al. (2011)

1. Molecular Hydrogen H_2

- Cooling agent
- Crucial ingredient in collapse models

Hydrogen chemistry

H_2^+ channel

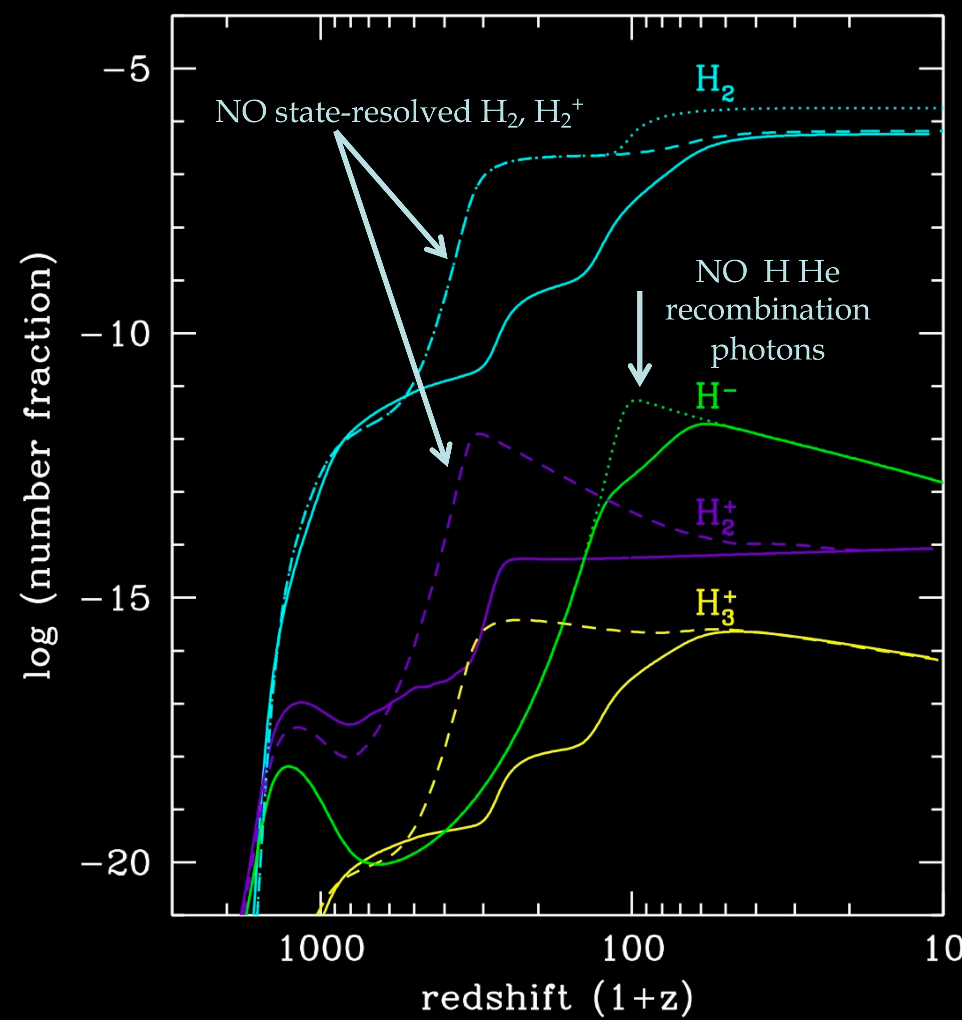
$H + H^+ \rightarrow H_2^+ + \gamma$

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

H^- channel

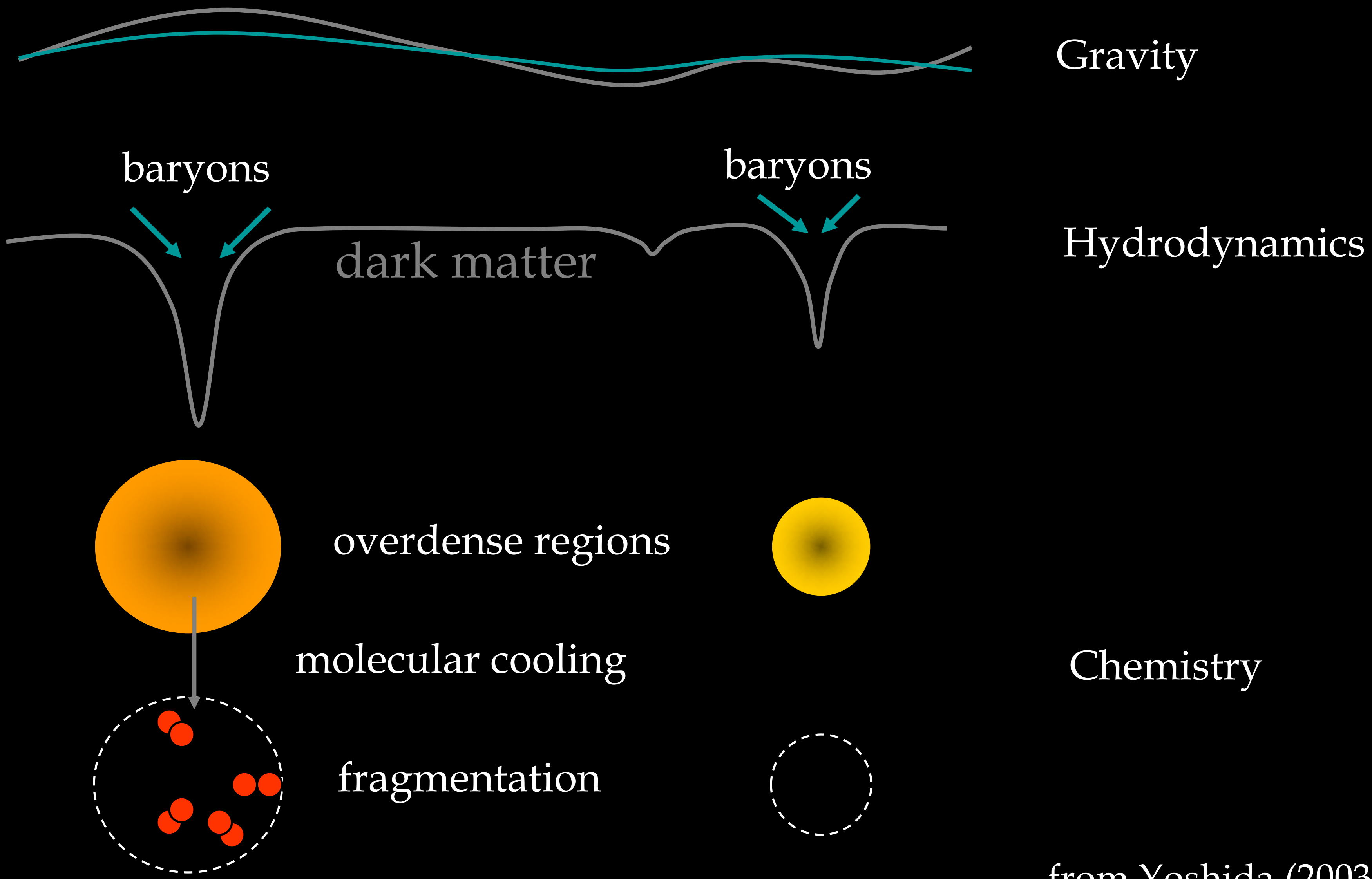
$H + e^- \rightarrow H^- + \gamma$

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



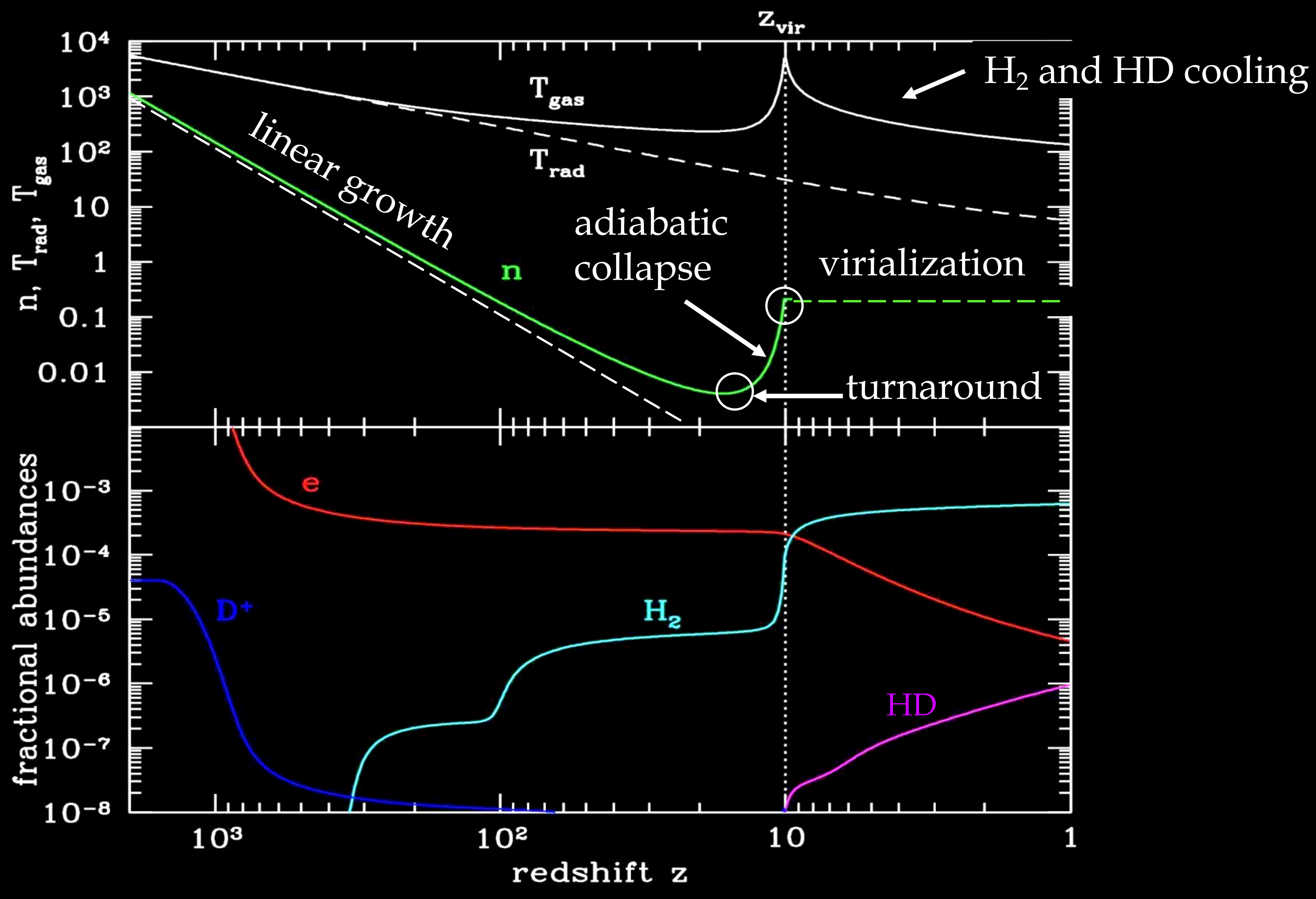
Galli & Palla (1998), Coppola et al. (2011, 2012, 2013)

Schematic picture of primordial star formation



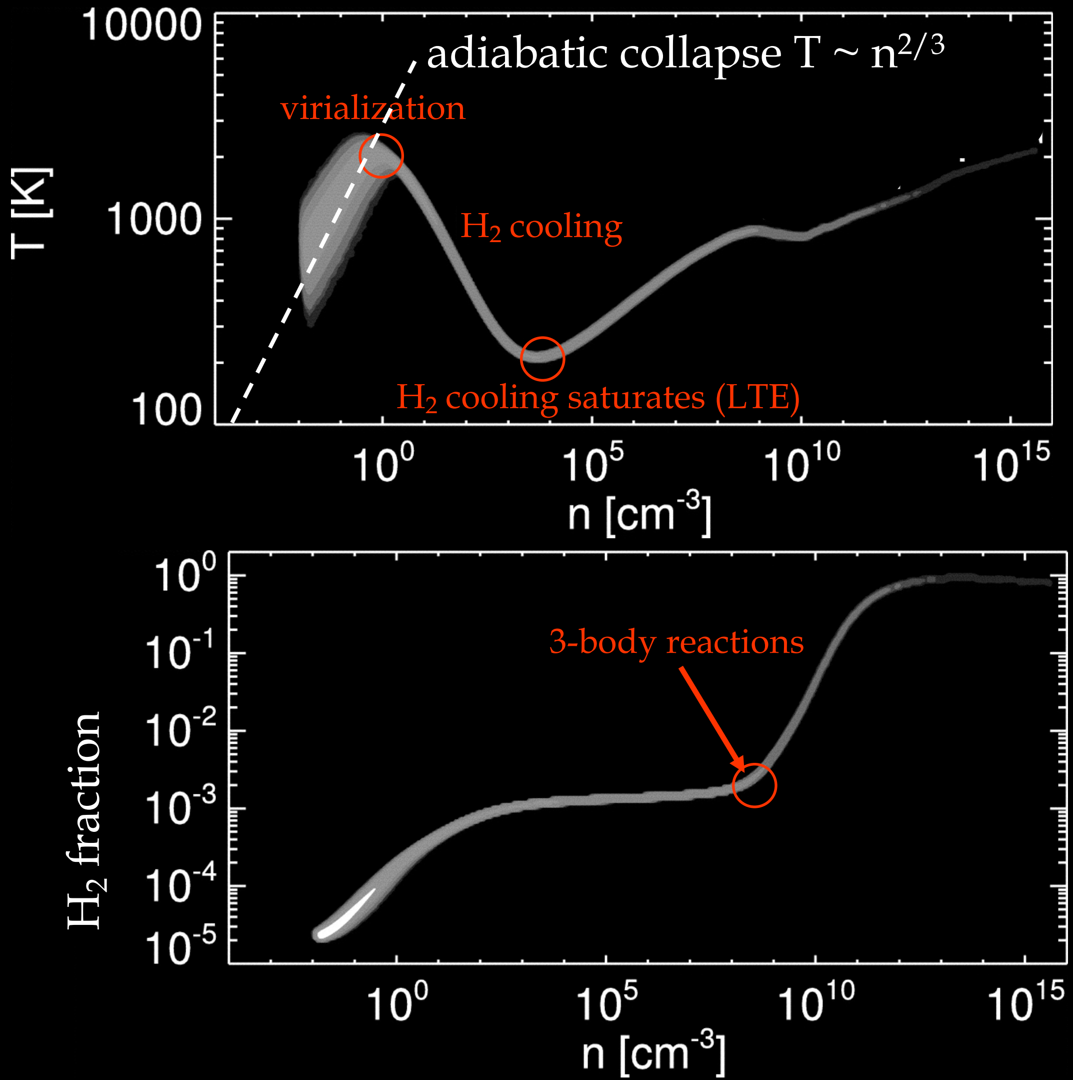
from Yoshida (2003)

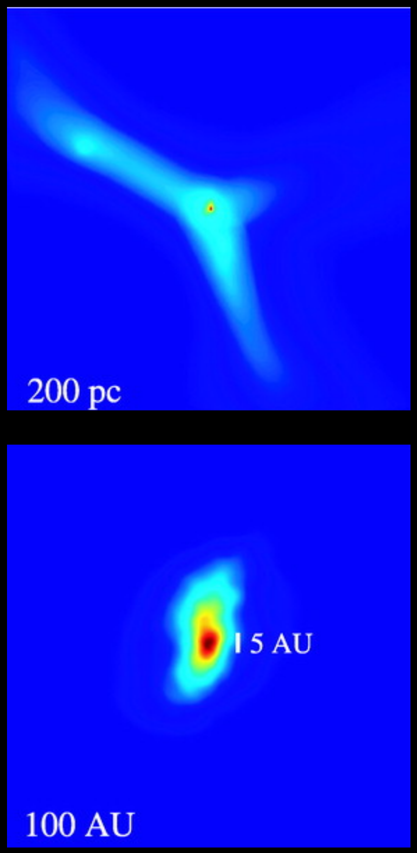
Evolution of an overdense region



Tegmark et al. (1997), Galli & Palla (2002)

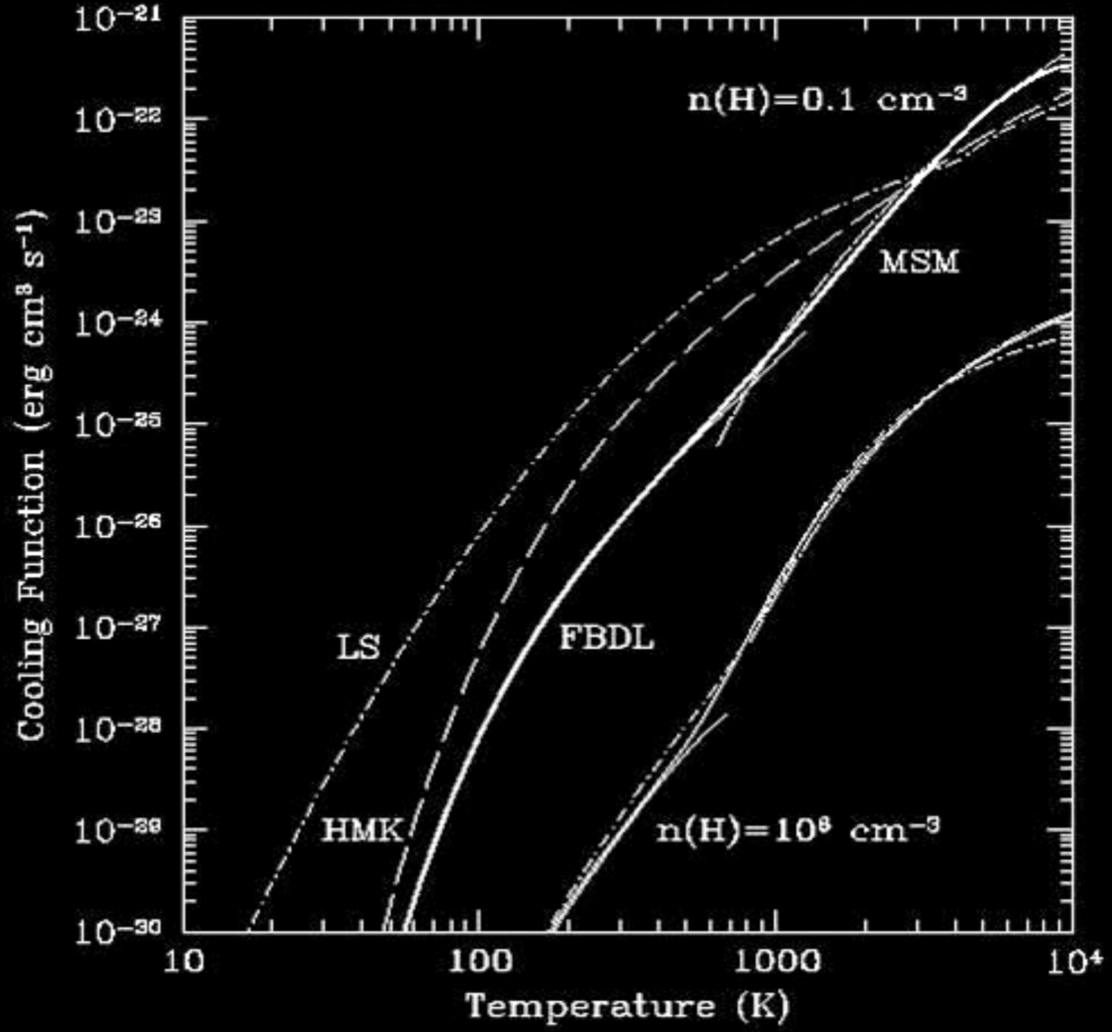
first-star formation





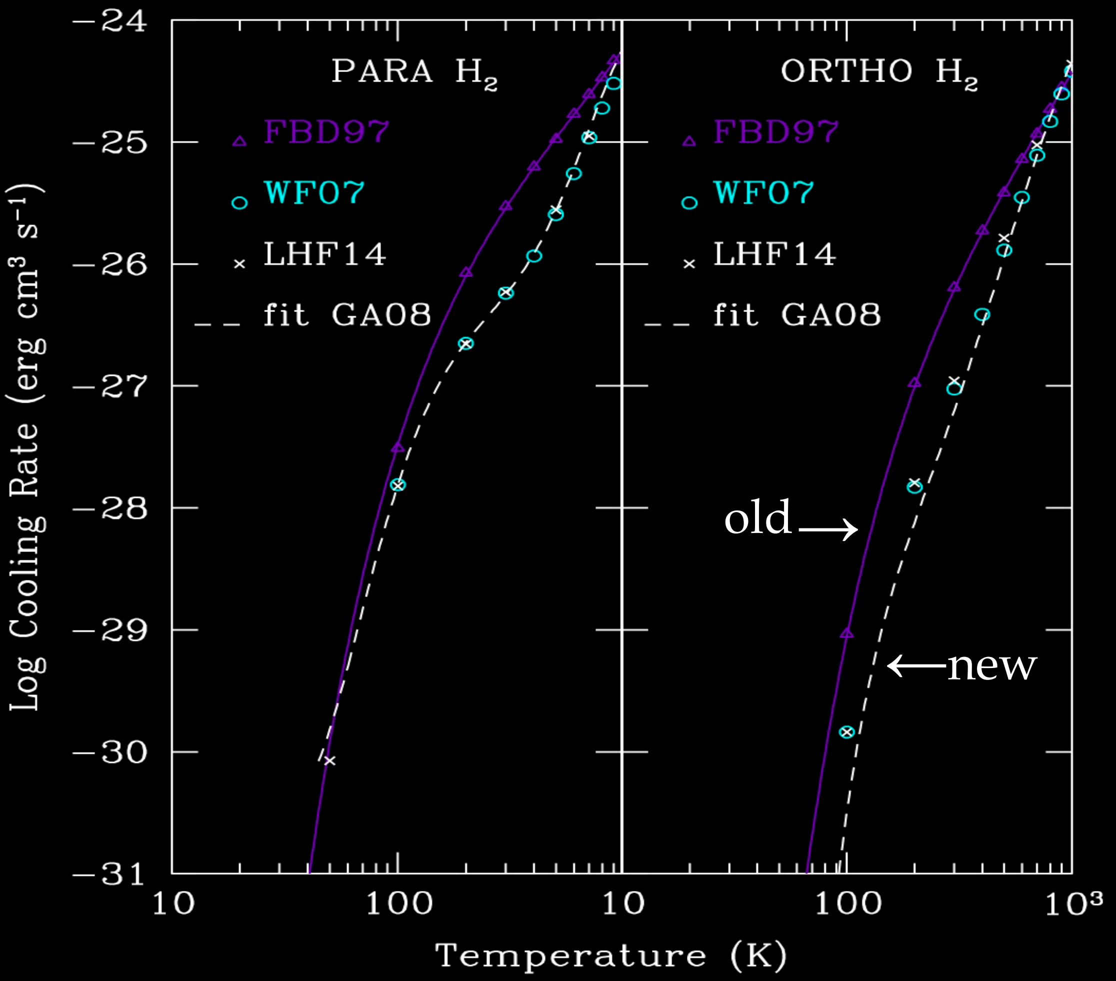
Yoshida et al. (2006)

H-H_2 cooling rate



Galli & Palla (1998)

Low-density H-H_2 cooling rate, present status



- Forrey, Balakrishnan, Dalgarno & Lepp (1997) → GP98 H-H_2 cooling rate
- Wrathmall, Gusdorf & Flower (2007) → GA08 H-H_2 cooling rate
- Lique, Honvault & Faure (2012, 2014)

2. Hydrogen Deuteride HD

- Cooling agent
- Important for cooling of post-shock gas

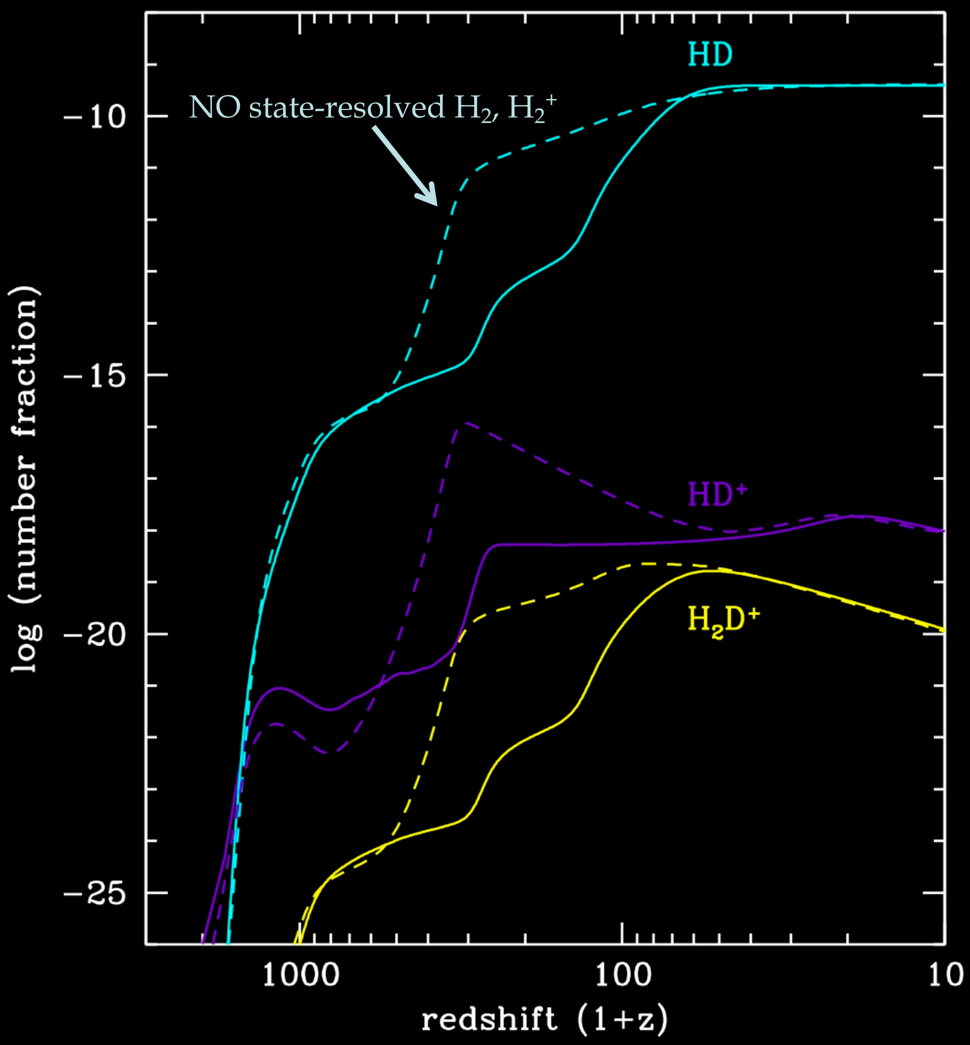
Deuterium chemistry

Formation of HD:

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

Destruction of HD:

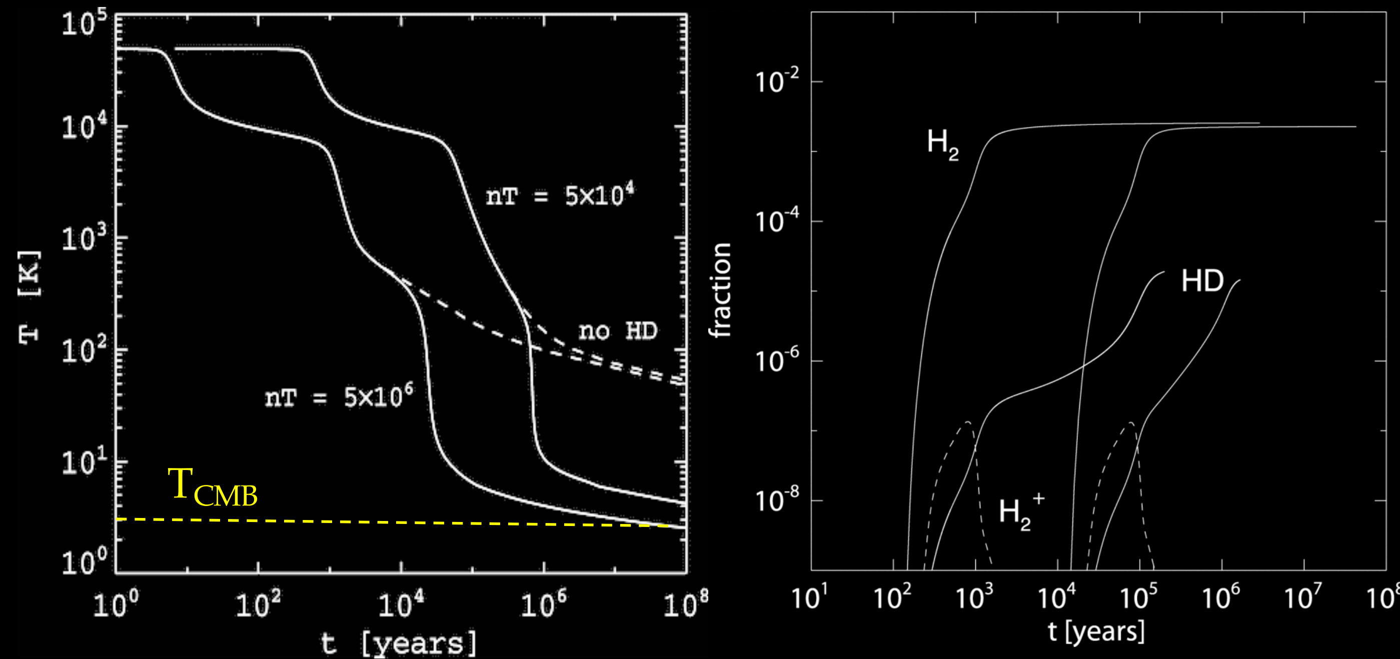
$HD + H^+ \rightarrow D^+ + H_2$



Stancil et al. (1998), Galli & Palla (2002), Coppola et al. (2011, 2012, 2013)

- H_2 cooling: ΔE (J=2-0)= 510 K, ΔE (J=3-1)=845 K → $T_{gas} \sim$ 100 K
- HD cooling: ΔE (J=1-0) = 128 K → $T_{gas} \sim$ 10 K

→ HD line cooling allows strongly shocked primordial gas to cool <u>to the temperature of the CMB</u> (the minimum value attainable)



Johnson & Bromm (2006), Yoshida et al. (2007), McGreer & Bryan (2008), Glover & Abel (2008)

- HD cooling functions computed by:

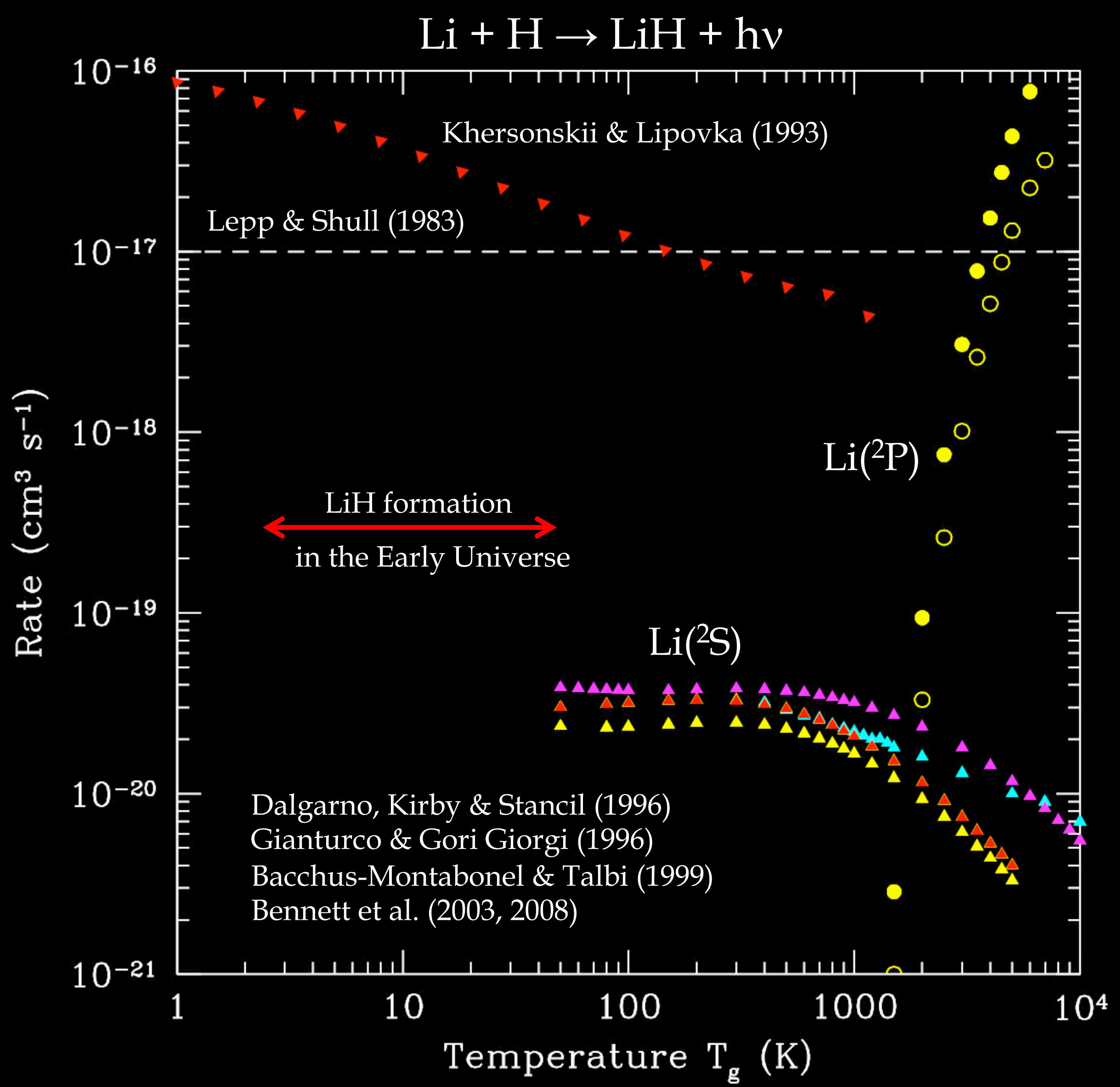
Roueff & Flower (1999), Flower et al. (2000), Lipovka et al. (2005), Coppola et al. (2011) [LTE]

3. Lithium Hydride LiH

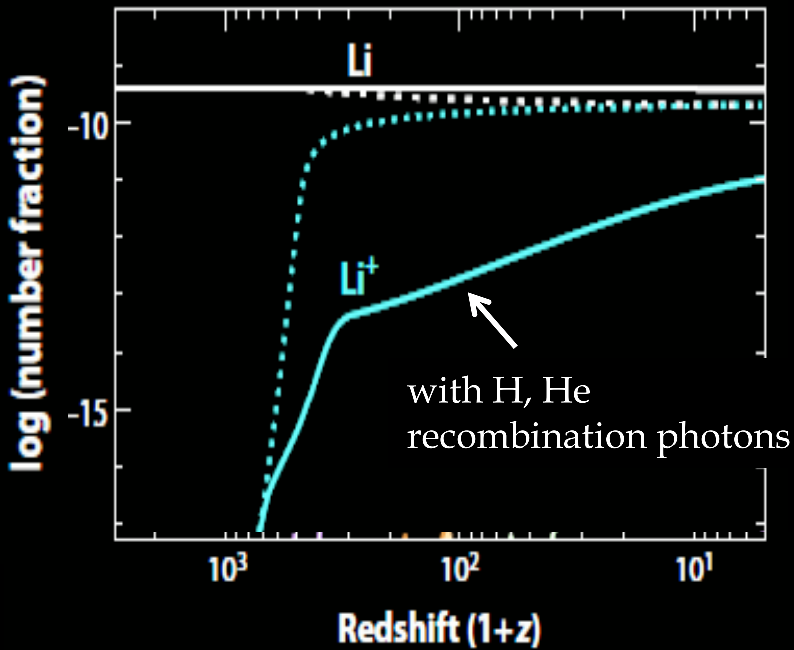
- The highest dipole moment
- But primordial Li $\approx 10^{-10}$

Rise and Fall of Primordial LiH

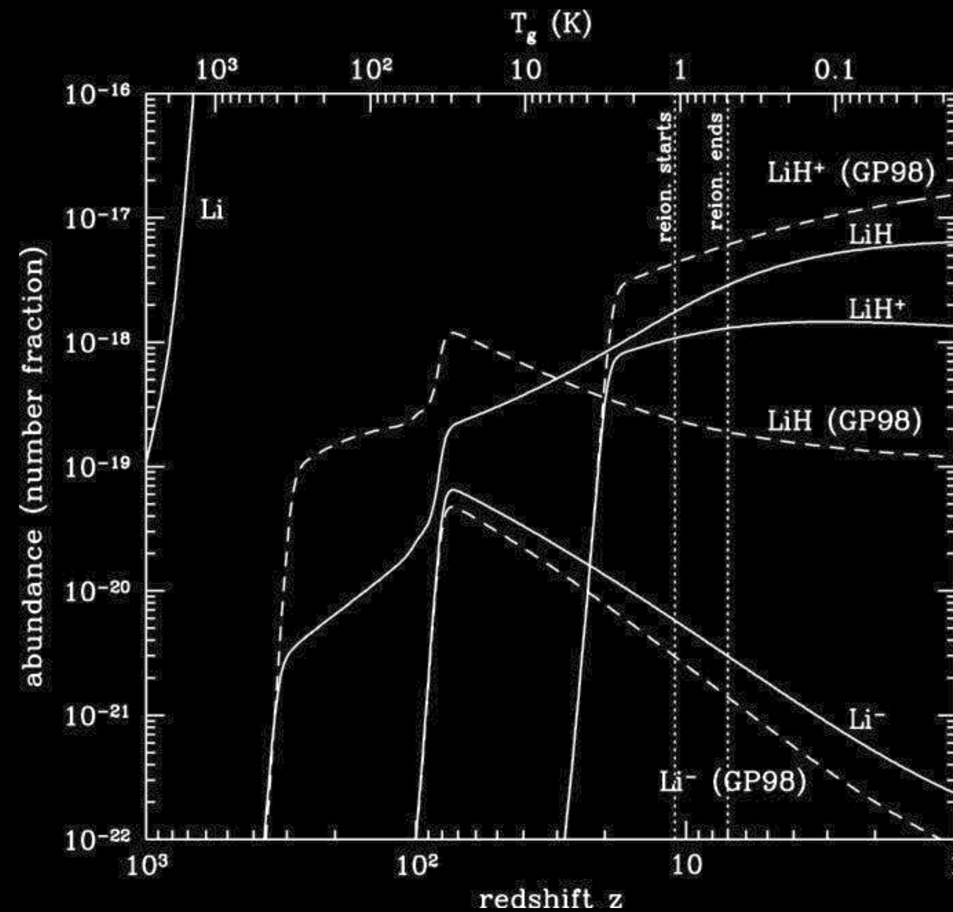
- LiH $\approx 10^{-12} - 10^{-11}$ (Lepp & Shull 1983)
- LiH $\approx 10^{-14} - 10^{-13}$ (Palla, Galli & Silk 1995)
- LiH $\approx 10^{-19}$ (Galli & Palla 1998)
- LiH $\approx 10^{-17}$ (Bovino et al. 2011)


Li + H → LiH + hν
Khersonskii & Lipovka (1993)
Lepp & Shull (1983)
Li(2P)
LiH formation
in the Early Universe
Li(2S)
Dalgarno, Kirby & Stancil (1996)
Gianturco & Gori Giorgi (1996)
Bacchus-Montabonel & Talbi (1999)
Bennett et al. (2003, 2008)
Rate (cm3 s−1)
Temperature Tg (K)
10−16
10−17
10−18
10−19
10−20
10−21
1
10
100
1000
104

incomplete Li recombination



Switzer & Hirata (2005)
Hirata & Padmanabhan (2006)



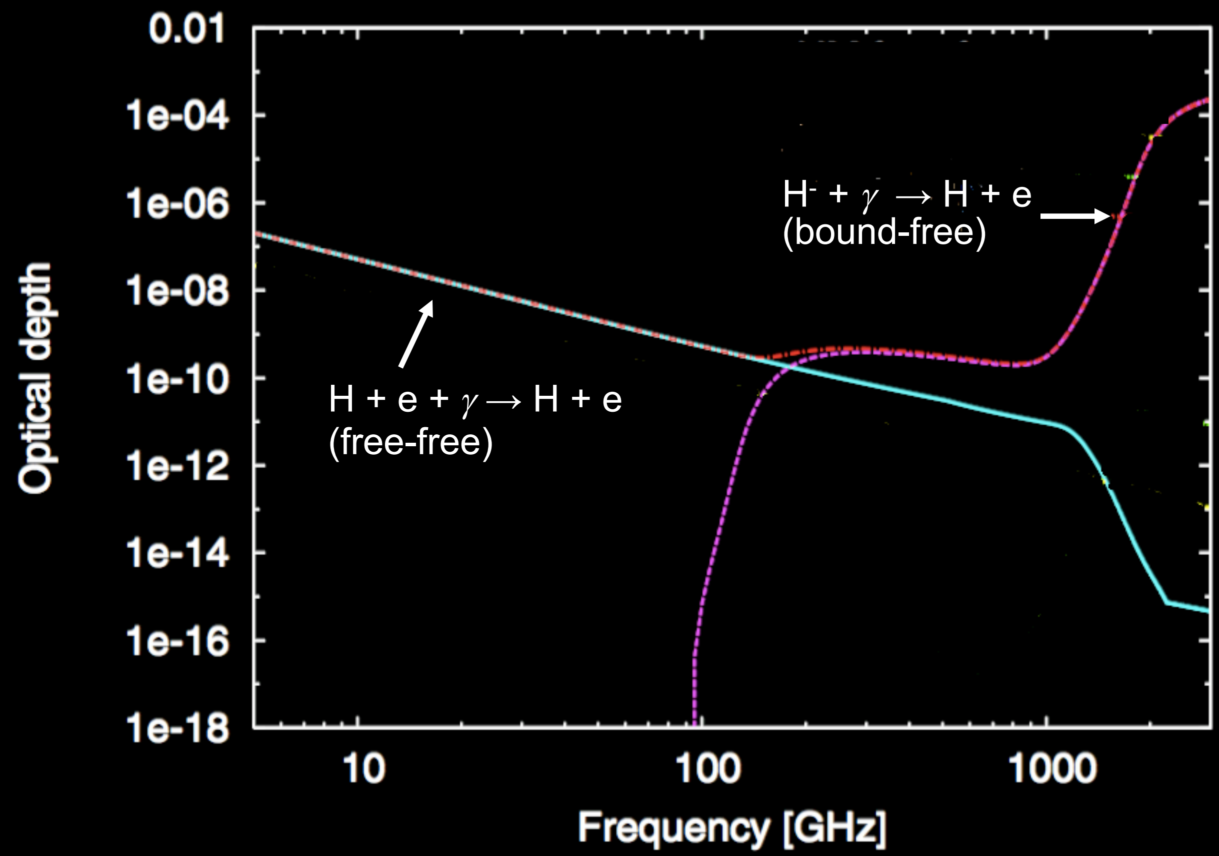
Bovino et al. (2011)

4. Hydride Ion H^-

- Optical depth of the Universe

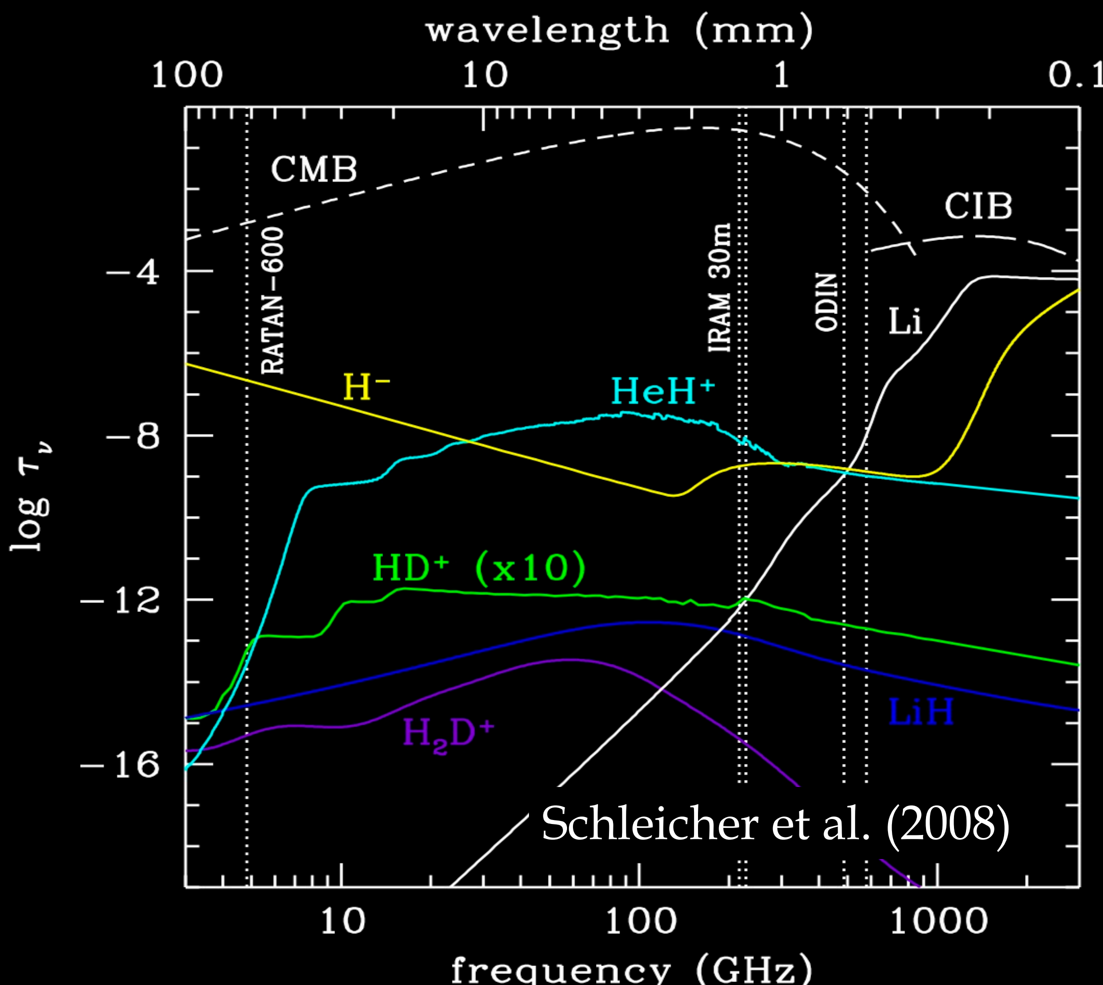

WMAP
PLANCK
LOFAR
SKA
τ (H⁻, HeH⁺, LiH, HD⁺,…)
optical depth of the Dark Ages
CMB
z~1000
400,000 yr after BB
First stars
z~10
400 Myr after BB
Reionization
completed
z~7

Redshift integrated optical depth of H^-



Black (2006), Schleicher et al. (2008)

Redshift-integrated optical depth



- IRAM 220 GHz (de Bernardis et al. 1993)
- RATAN-600 6.2 cm (Gosachinkij et al. 2002)
- ODIN 500 GHz (Persson et al. 2010)

Molecular signals from the Dark Ages

- The first hydrides induce spectral/spatial features in absorption or emission against the CMB. Effects of order ~ τ

(Dubrovich 1977, Zeldovich 1978, Maoli et al. 1994, 1996, Puy et al. 2002)

- Phase of expansion
  spectral distortions (absorption)

- Phase of linear growth :
  spatial anisotropies (resonant scattering)

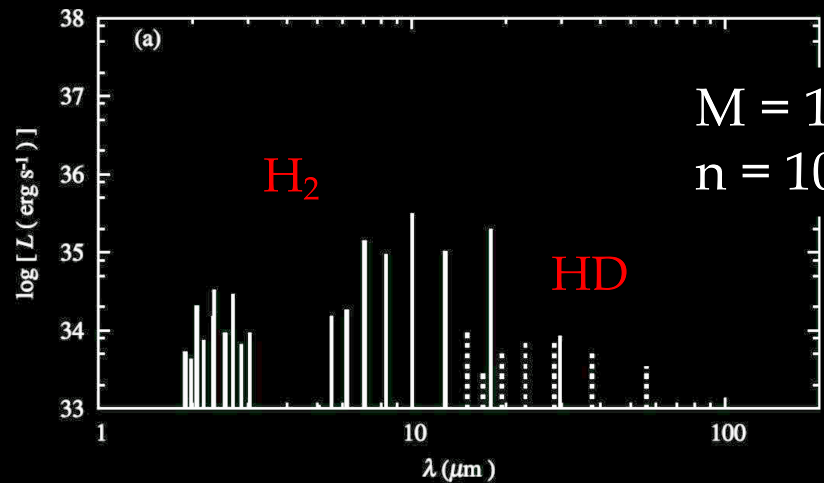
- Phase of gravitational collapse:
  line emission

Current limits:

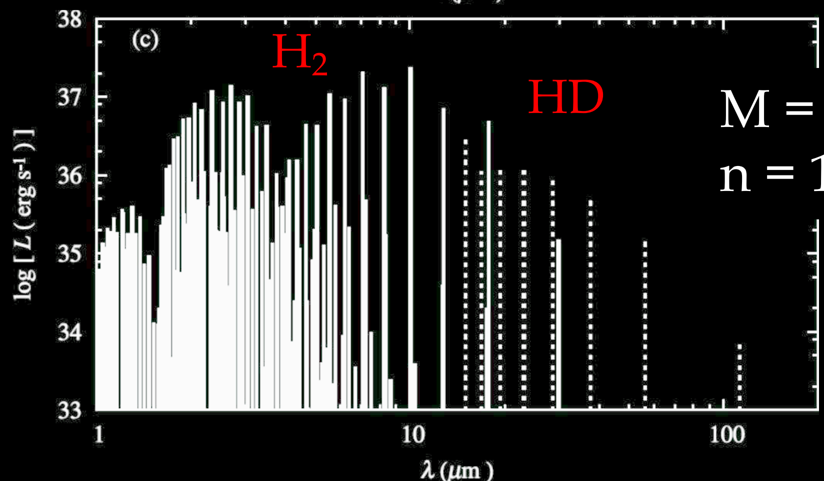
- $\Delta T_r/T_r$ (spectral) $\approx 10^{-4}$ (COBE)
- $\Delta T_r/T_r$ (spatial) $\approx 10^{-6}$ (WMAP, PLANCK)

Future improvement by 3-4 orders of magnitude (PIXIE, PRISM)

H_2 and HD emission from primordial clouds



M = 10^5 M$_\odot$
n = 10^2 cm^{-3} T = 400 K f(H_2) = 10^{-4}



M = 10^5 M$_\odot$
n = 10^6 cm^{-3} T = 400 K f(H_2) = 10^{-3}

Kamaya & Silk (2002, 2003)
Mizusawa, Omukai & Nishi (2005)
K. Walker, PhD Thesis (2016)

Single star formation event not detectable. Protogalactic cloud with SFR ≈ 10^3-10^4 M$_\odot$ yr^{-1} detectable by JWST if z < 10. If z>20 ALMA?

Conclusions:

The role of the first hydrides

• H_2 and HD (and possibly H_3^+) control the cooling of metal-free gas and determine the mass of the first stars.

• H^-, HeH^+ (and Li) dominate the optical depth of the Dark Ages.

• LiH plays a marginal role (if Li ≈ 10^{-10}).

• Detection of the first hydrides would provide a powerful tool to constrain the evolution of the Universe from z ≈ 1000 to z ≈ 10.

The Dawn of Chemistry

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