# My chemistry with Francesco

Daniele Galli

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# Arcetri Observatory, circa 2003

# It all started 30 years ago…

- June 21 –July 26, 1987, Whistler, British Columbia, Canada
  "Galactic and Extragalactic Star Formation" (organized by Ralph Pudritz)

Riccardo

me

Francesco
"Master Chef"

# From Francesco's 1987 review talk "Primordial Star Formation"

1. The search for zero-metal stars. Deficit of metal-poor stars? No star found with $Z \leq 10^{-4}\ Z_{\odot}$. *See talks by R. Schneider, P. Molaro, …*

2. Chemistry in the early Universe. Main chemical routes to $H_2$ and HD well established (Lepp & Shull 1984). Abundances: $H_2 = 10^{-6}$, $HD = 10^{-10}$, $LiH = 10^{-12}$. Large variations depending on adopted cosmological model; uncertainties in the $H_2$ cooling rate.

3. The evolution of collapsing gas clouds. Critical metallicity: for $Z > 10^{-3}\ Z_{\odot}$, heavy element cooling ($T = 10\text{-}30$ K, normal MCs), for $Z < 10^{-4}\ Z_{\odot}$, $H_2$ cooling ($T = 500\text{-}10^3$ K). *See talks by V. Bromm, K. Omukai, S. Glover, …*

4. From clouds to stars. Stahler, Palla & Salpeter (1986a, protostar phase), Stahler, Palla & Salpeter (1986b, PMS phase). *See talks by D. Schleicher, T. Hosokawa…*

# The Palla-Salpeter-Stahler trilogy (1983-1986)

THE ASTROPHYSICAL JOURNAL, **271**:632–641 1983 August 15


## PRIMORDIAL STAR FORMATION: THE ROLE OF MOLECULAR HYDROGEN

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*Received 1982 July 12; accepted 1983 January 27*

THE ASTROPHYSICAL JOURNAL, **302**:590–605, 1986 M


## PRIMORDIAL STELLAR EVOLUTION: THE PROTOSTAR PHASE

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## PRIMORDIAL STELLAR EVOLUTION: THE PRE–MAIN-SEQUENCE PHASE

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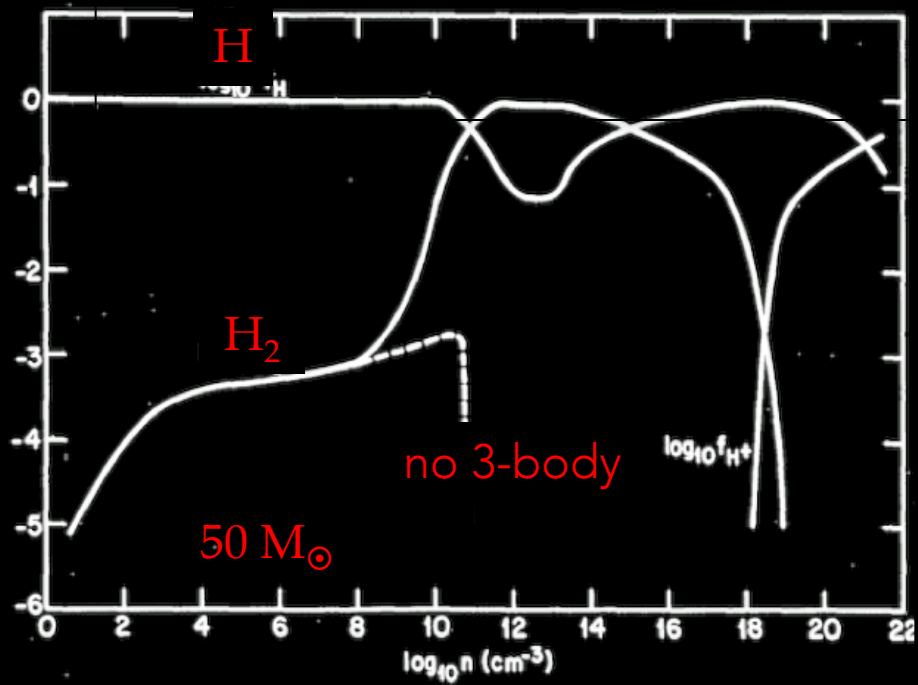
*Received 1986 February 18; accepted 1986 March 7*

# Pressure-free collapse of a primordial cloud

$$\frac{d\rho}{dt} = \frac{\rho}{t_{ff}},$$

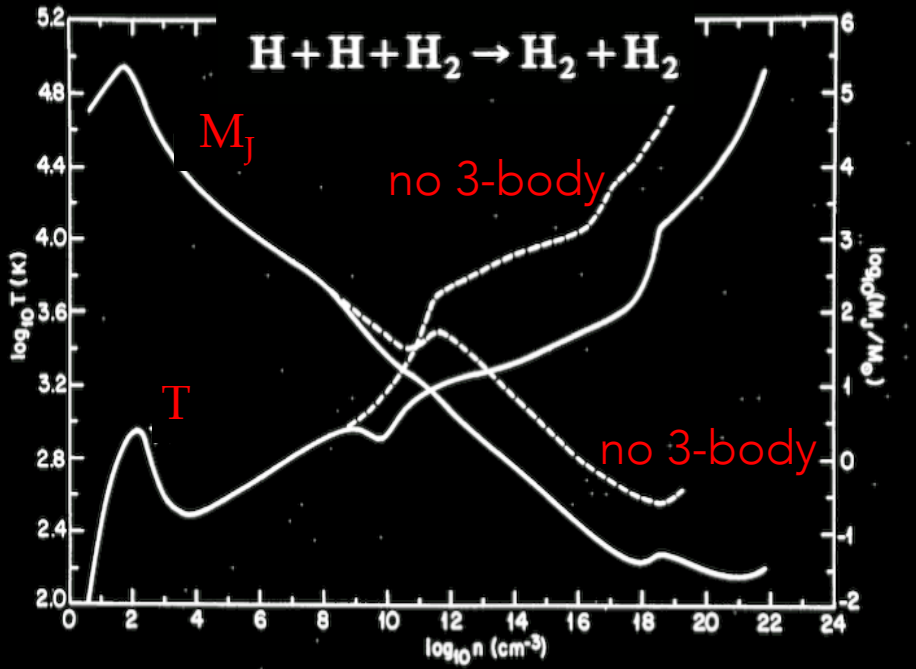
$$\frac{d\varepsilon}{dt} = \frac{P}{\rho^2}\left(\frac{1}{t_{ff}}\right) - \Lambda.$$




importance of 3-body reactions!

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

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




Palla, Salpeter & Stahler (1983), Omukai (2000)

## Situation in the late 80's-early '90s:

- Tension between SBBN and observed abundances of light elements
- Search for CMB fluctuations (found by COBE in 1992)
- Emergence of ΛCDM model with $\Omega_m \approx 0.3$ and $\Omega_\Lambda \approx 0.7$ in 1998

## Our "program":

1. Understand the Galactic evolution of D, $^3$He and Li ("baryometers") to derive their primordial abundances and constrain the baryon-to-photon ratio $\eta \propto \Omega_b h^2$.

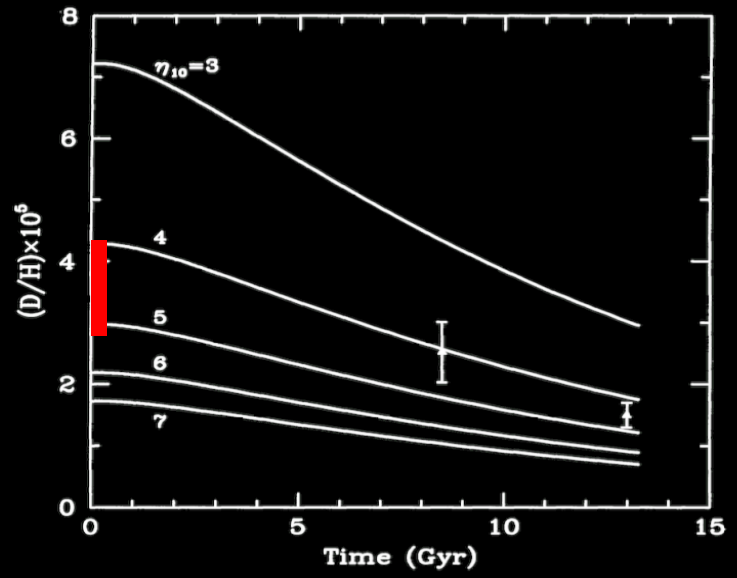
2. Provide a "standard" chemical network for a $Z=0$ gas. Few species (~ 30), small chemical network (~200 reactions). Cooling rates.

3. Use this network in simple semi-analytical collapse models to determine the mass of the first stars.

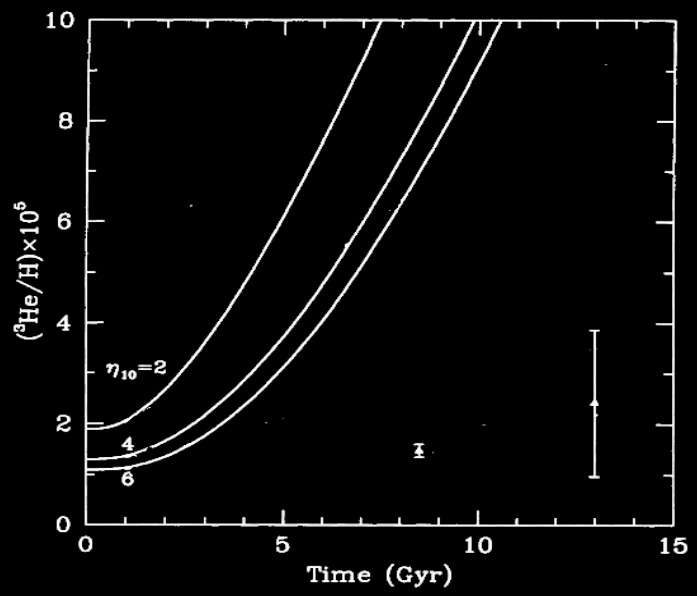
# Determining the baryon density parameter $\Omega_b h^2$

$\Omega_b h^2 = (1.6 \pm 0.1) \times 10^{-2}$ from the abundances of light elements (Galli, Palla et al. 1995)

Deuterium

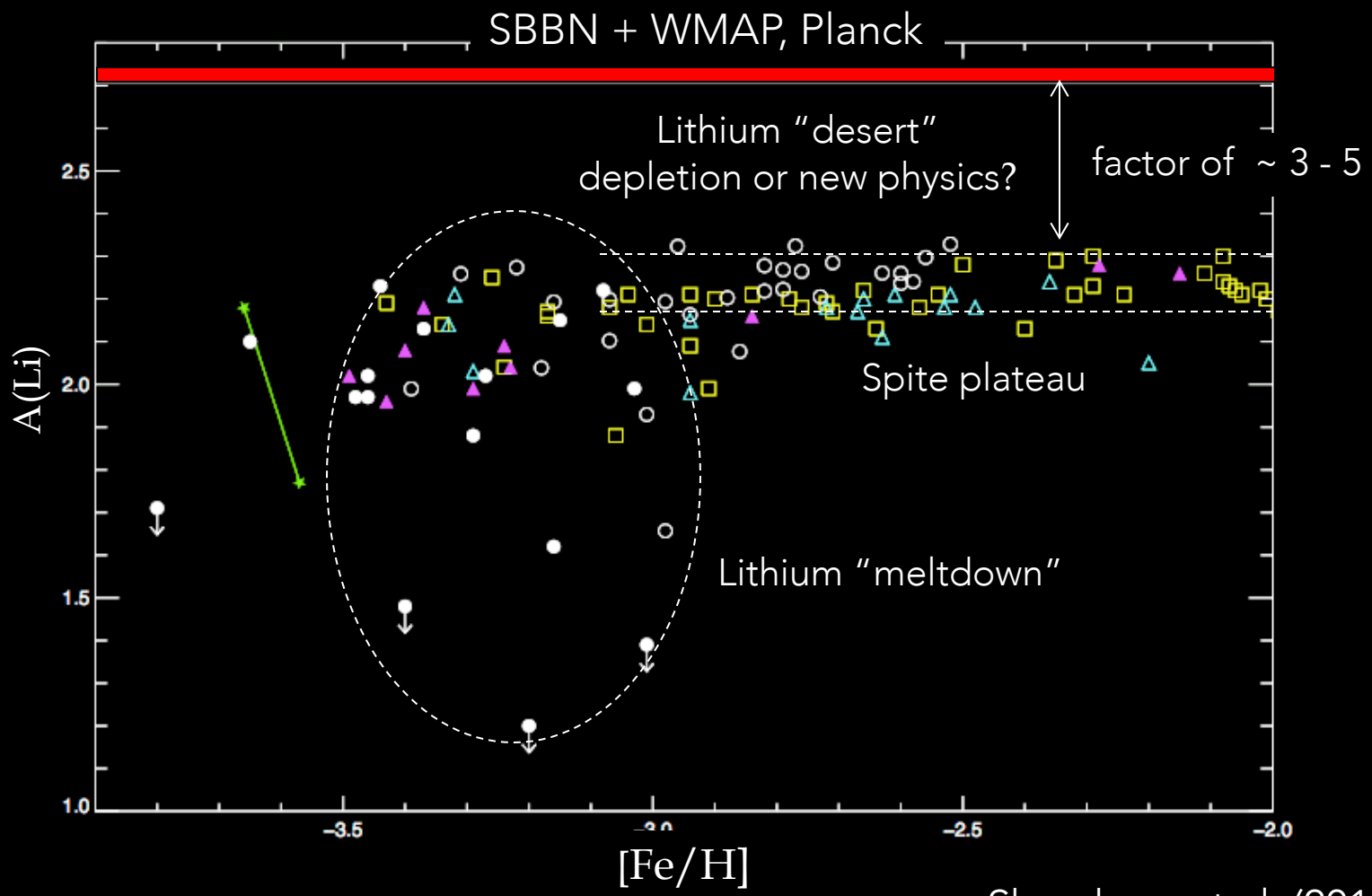



$^3$Helium




$\Omega_b h^2 = (2.22 \pm 0.03) \times 10^{-2}$ from the CMB (WMAP 2003)
$\Omega_b h^2 = (2.23 \pm 0.01) \times 10^{-2}$ from the CMB (Planck 2013)

# Lithium is still a problem




Sbordone et al. (2012)

# The Dawn of Chemistry

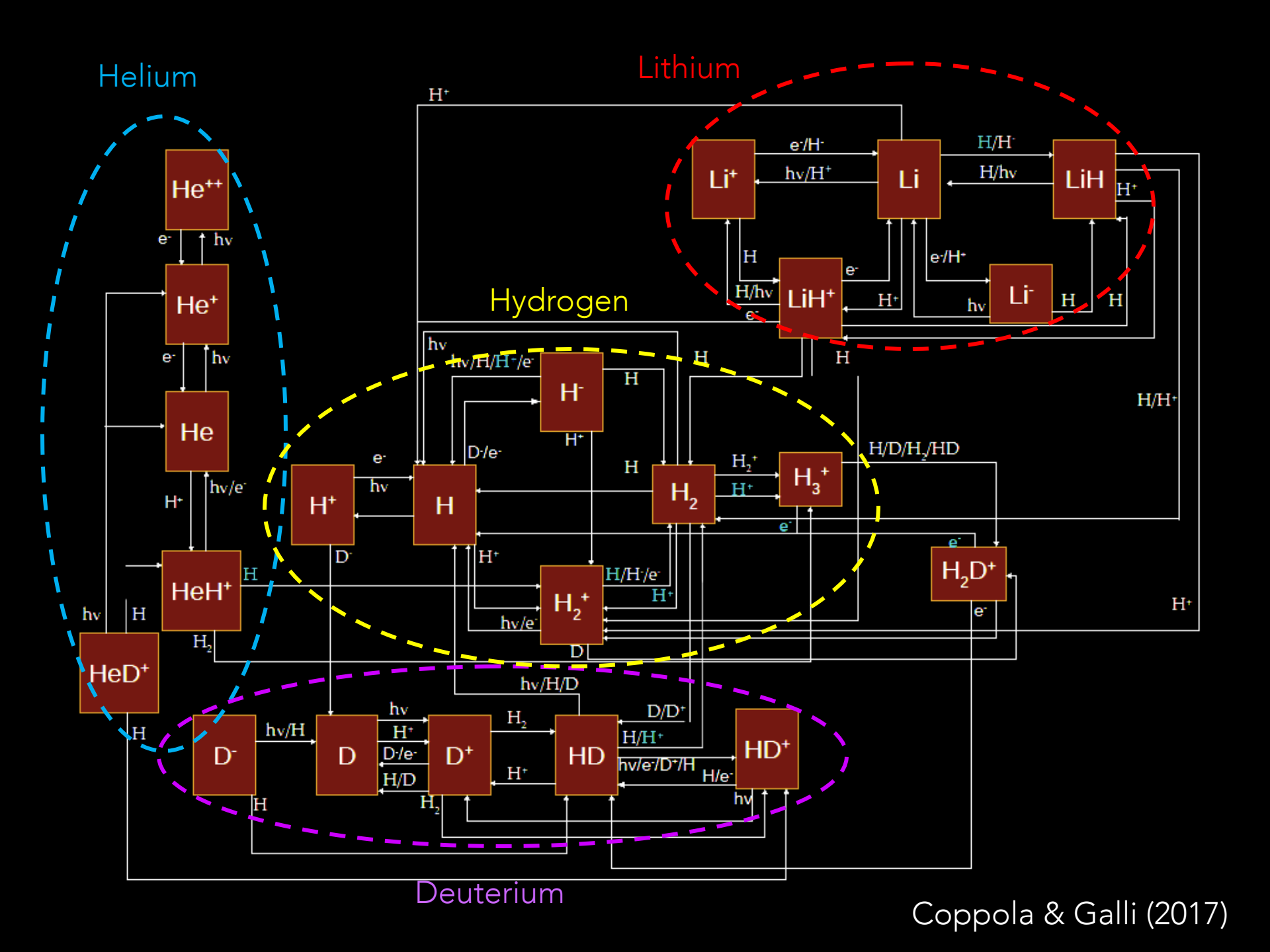
The Early Universe: a hostile environment for chemistry:

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

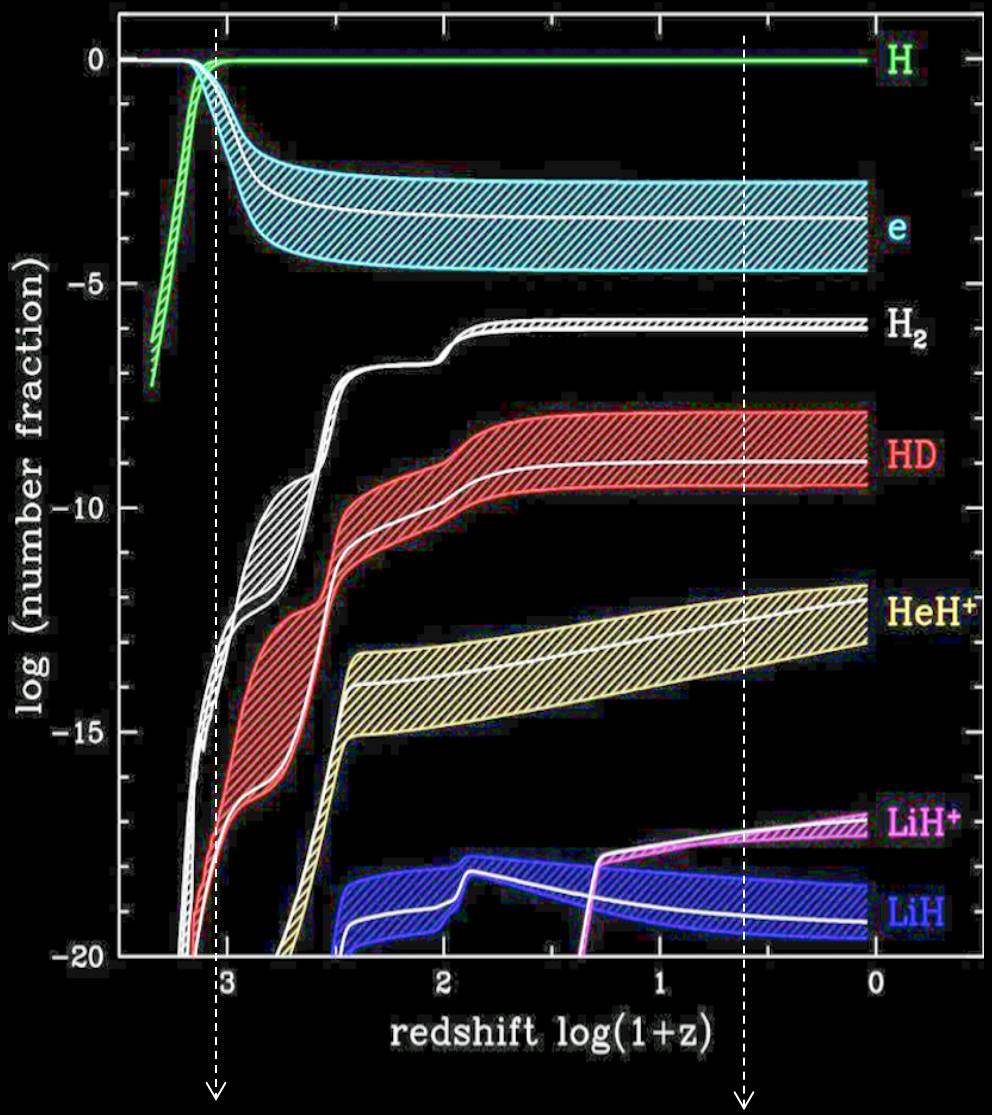
→ few molecules, mostly hydrides

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, $LiH^+$


Helium
Lithium
Hydrogen
Deuterium
He++
He+
He
HeH+
HeD+
Li+
Li
LiH
LiH+
Li-
H+
H
H-
H2
H2+
H3+
H2D+
D-
D
D+
HD
HD+
e-/H-
H/H-
hv/H+
H/hv
e-/H+
H/H+
H/D/H2/HD
hv/H/H-/e-
D-/e-
H/H-/e-
hv/e-
hv/H/D
D/D+
H/H+
hv/H
H/D
H/e-
hv/e-/D+/H
Coppola & Galli (2017)

Galli & Palla (1998)




400,000 yr after BB

400 Myr after BB

# The Dawn of Chemistry

Daniele Galli and Francesco Palla

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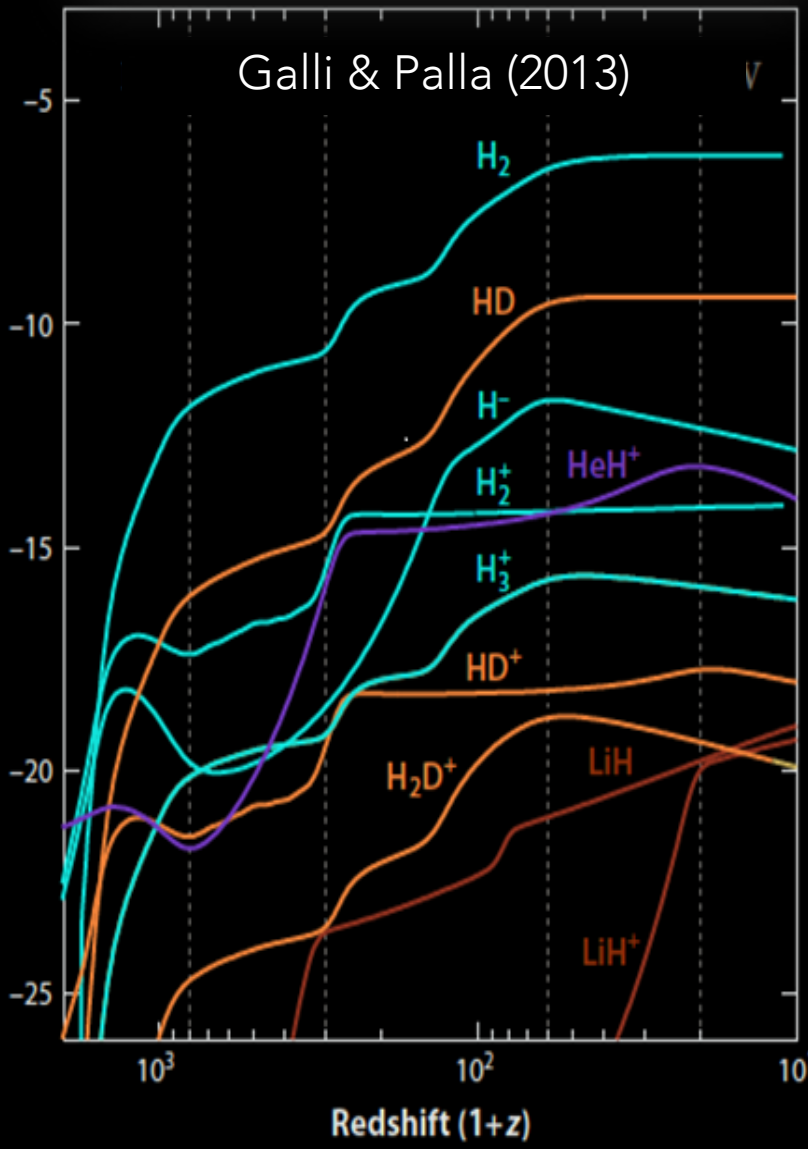
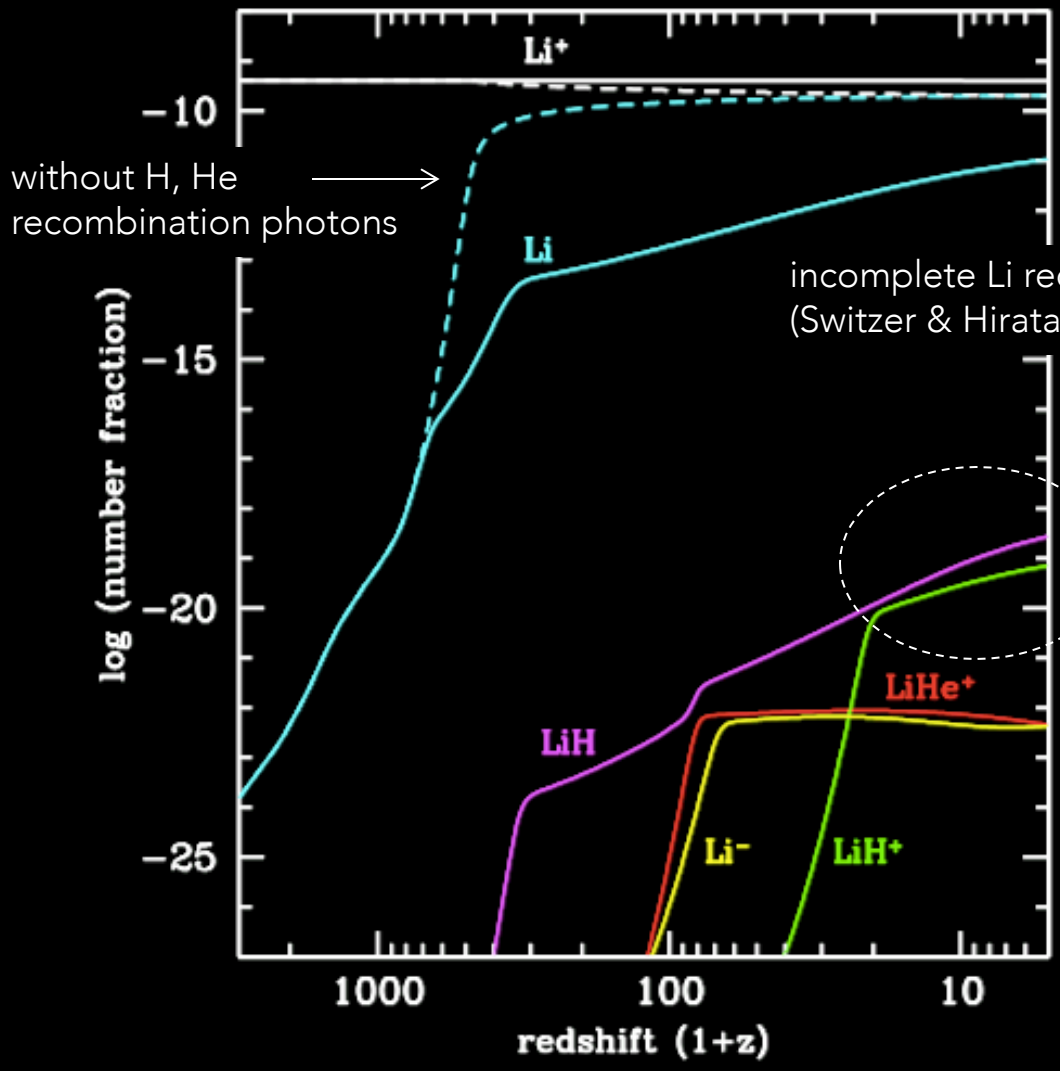
Galli & Palla (2013)

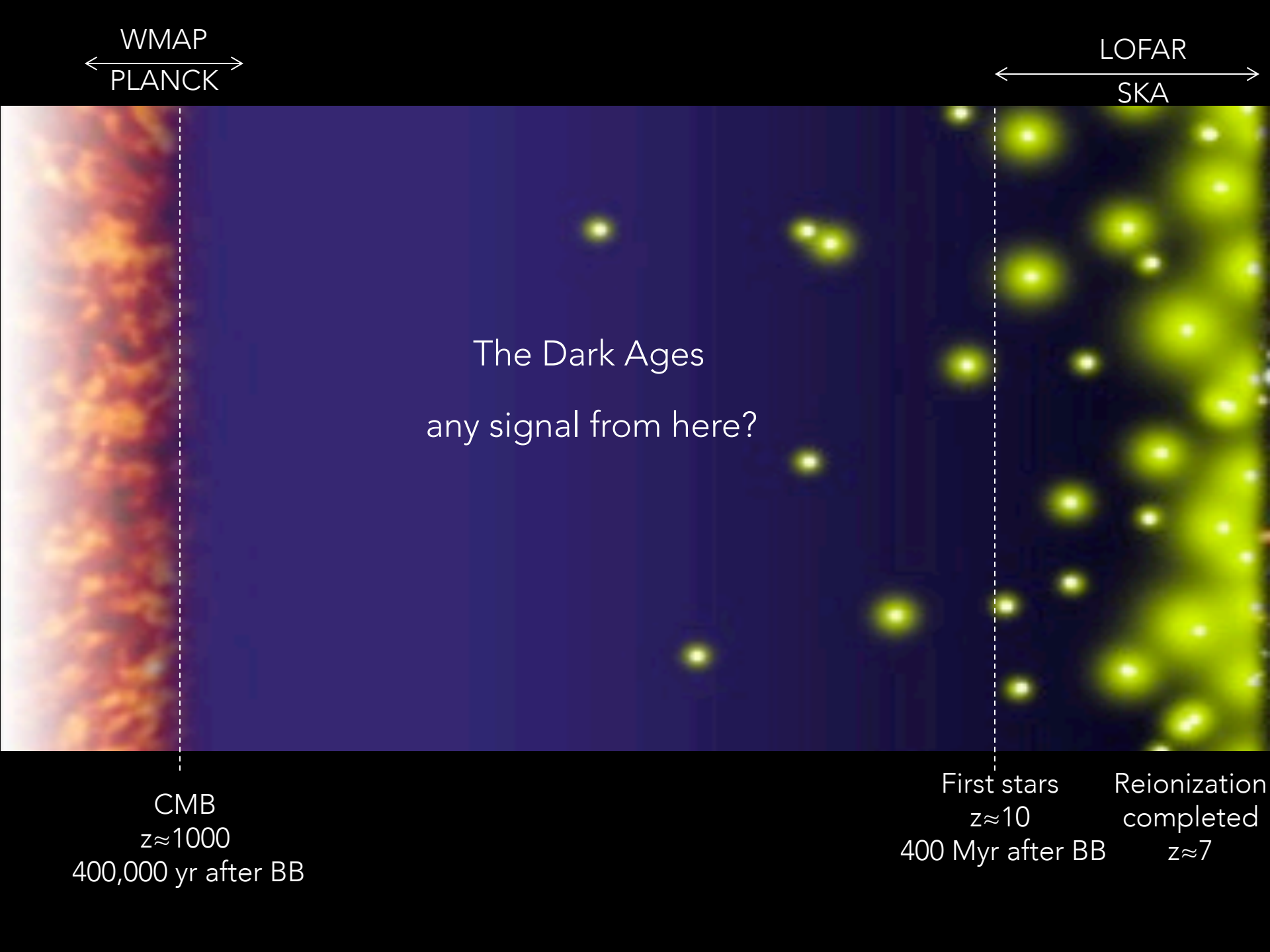


# The demise of Lithium Hydride

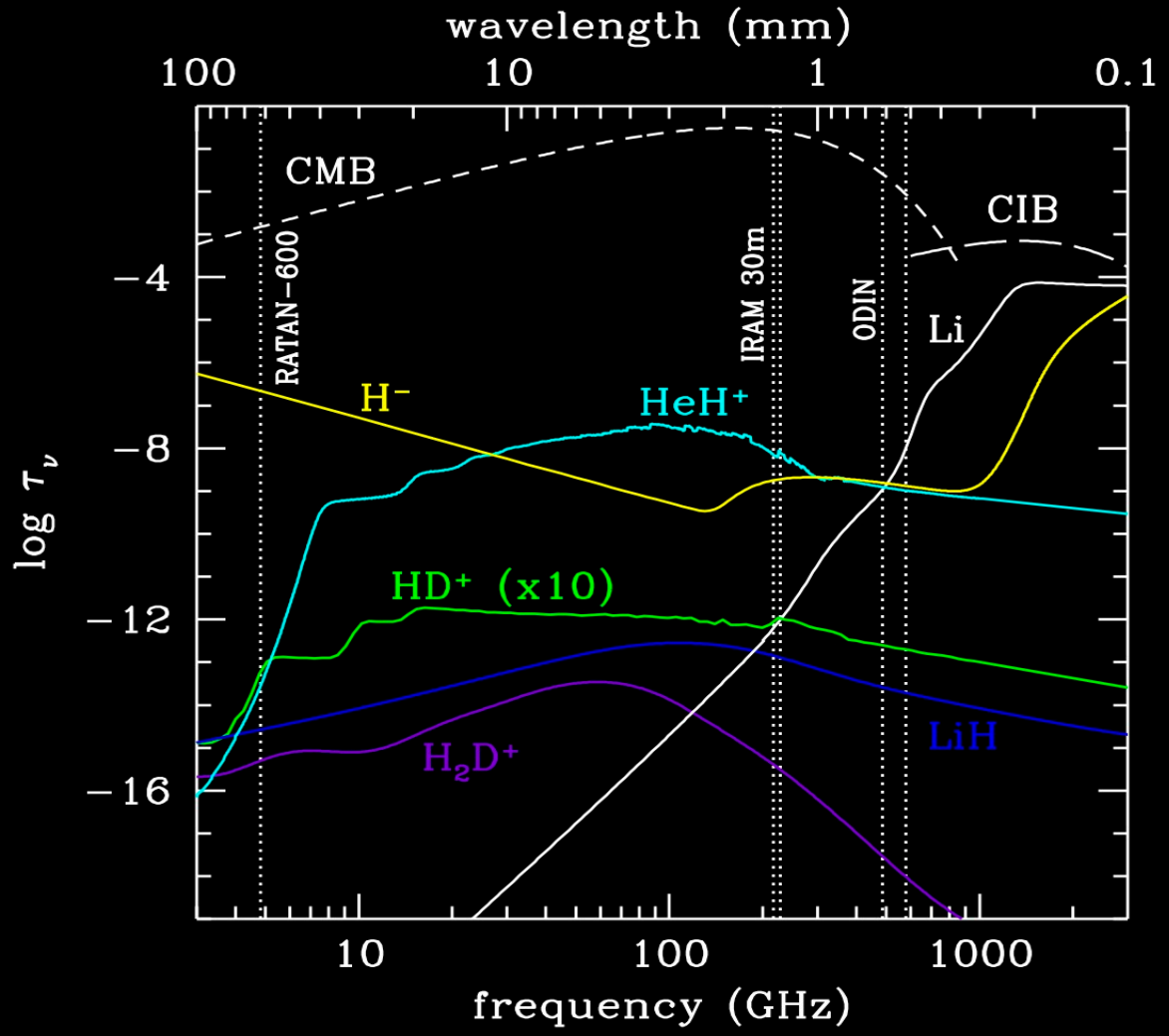



$LiH/H \approx 10^{-18}$
too low to have
any effect

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

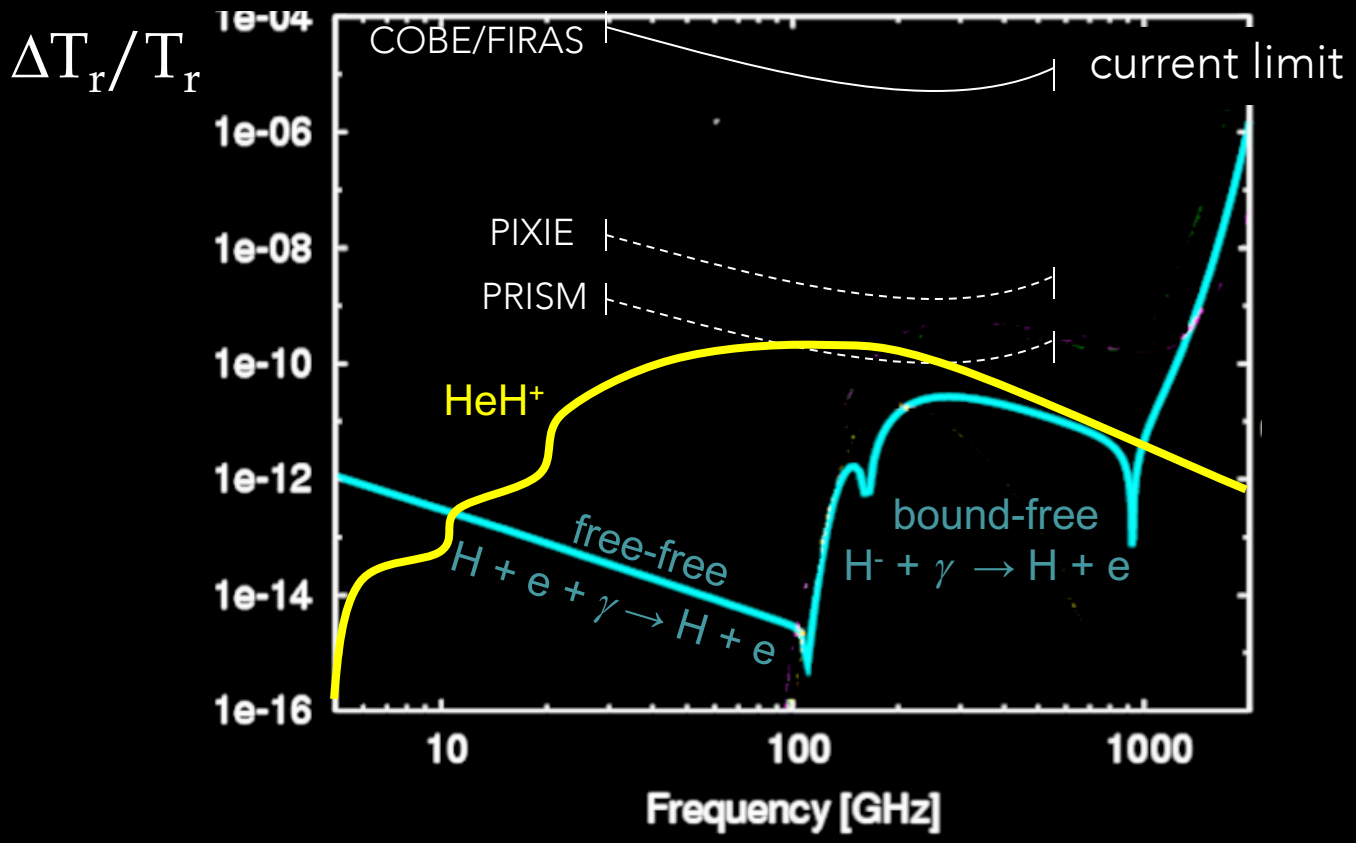

WMAP
PLANCK
LOFAR
SKA
The Dark Ages
any signal from here?
CMB
z≈1000
400,000 yr after BB
First stars
z≈10
400 Myr after BB
Reionization
completed
z≈7

# Redshift-integrated optical depth of the Dark Ages



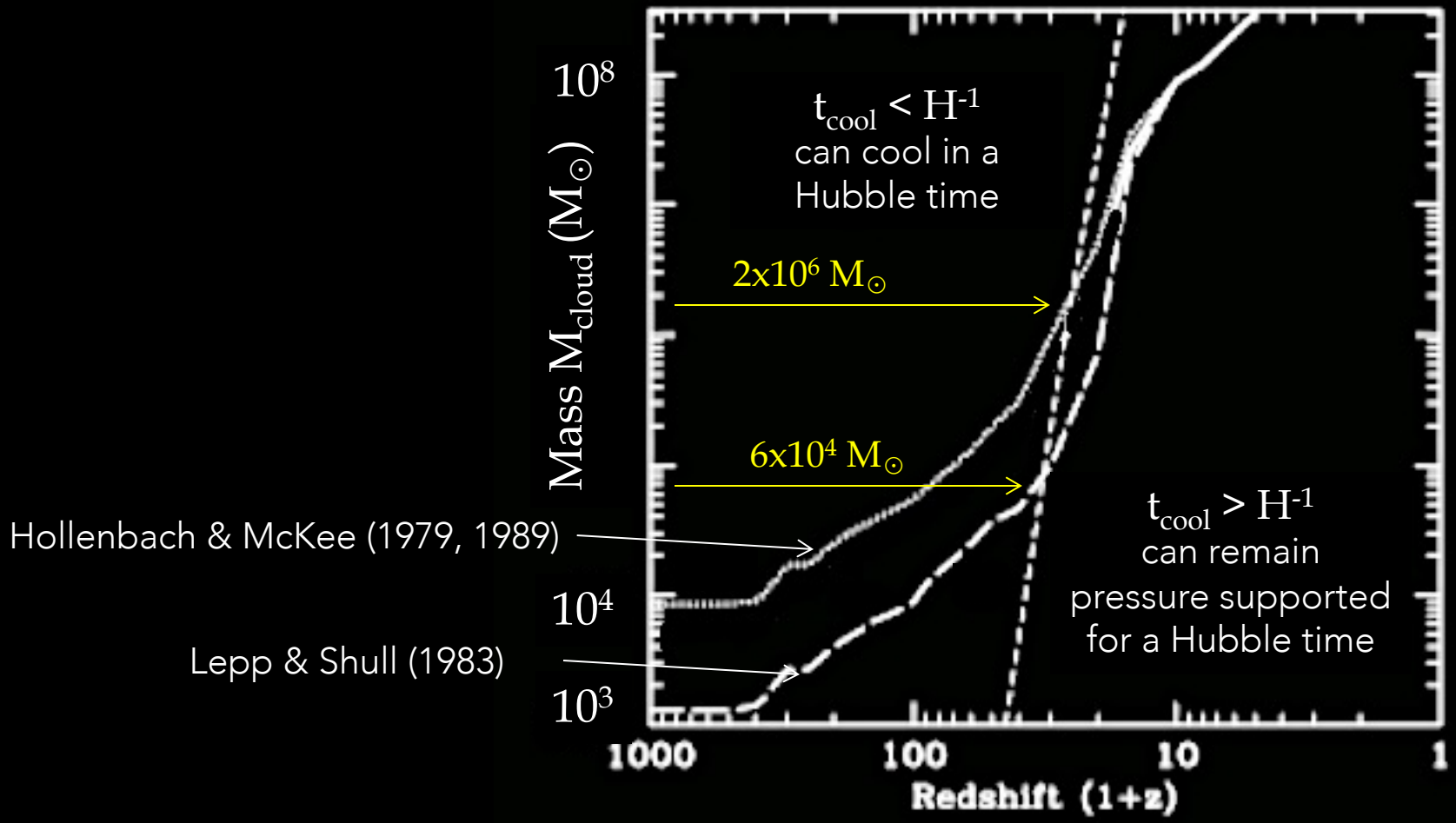

Schleicher, Galli, Palla et al. (2008)

# Spectral distortions in the CMB: deviations from a pure black-body spectrum



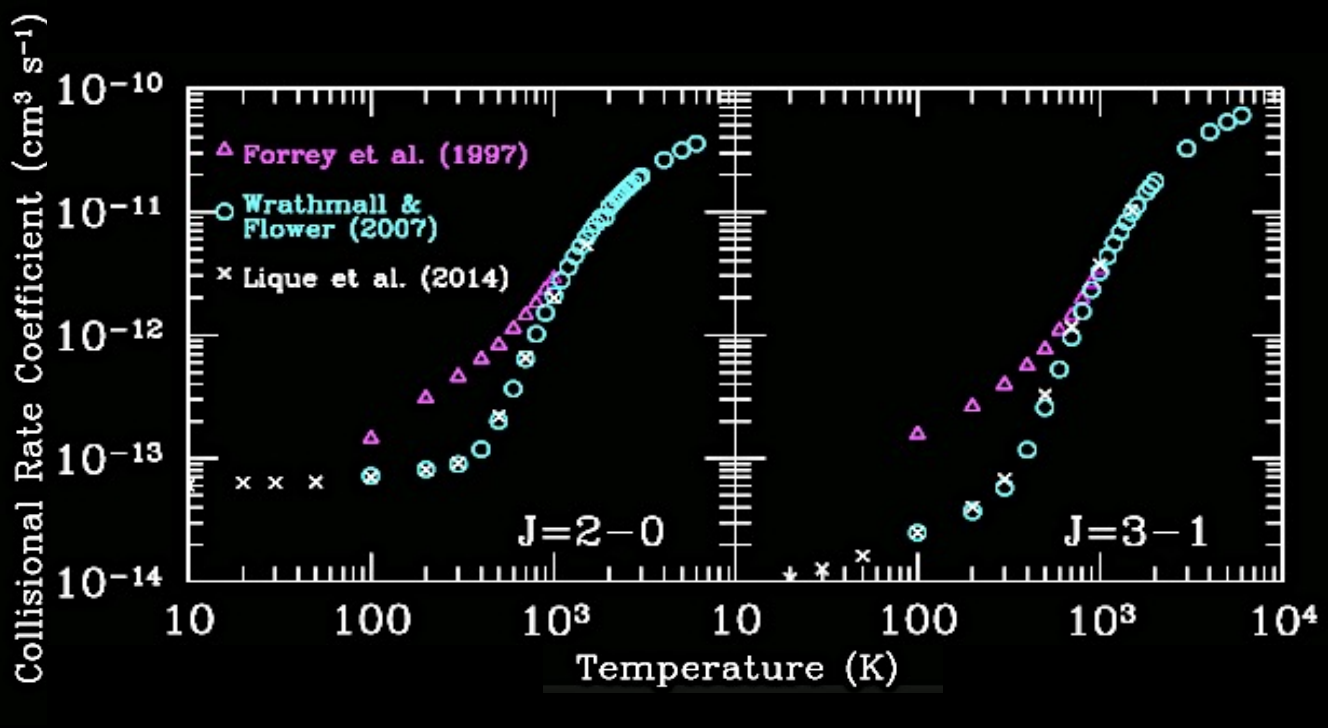

Schleicher, Galli, Palla et al. (2008)

# Effect of $H_2$ cooling on the minimum mass needed to collapse



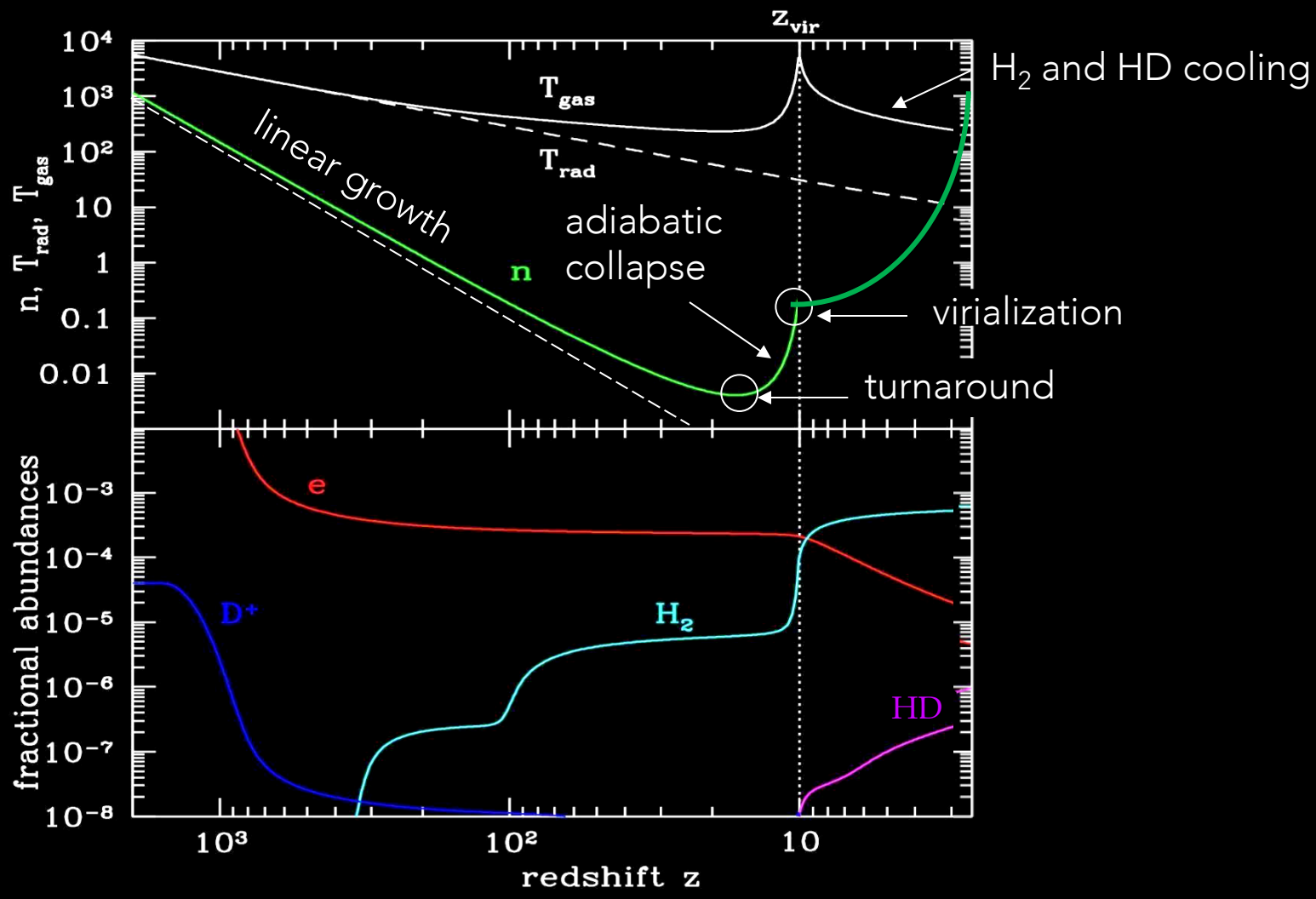

Tegmark et al. (1997)

- Galli & Palla (1998) cooling rate based on Forrey et al. (1997)
- supersed by Glover & Abel (2008) cooling rate based on Wrathmall & Flower (2007)




- The most recent calculations of collisional rate coefficients (Lique et al. 2012, 2104) confirm and extend Wrathmall & Flower (2007)

# Evolution of an overdense region



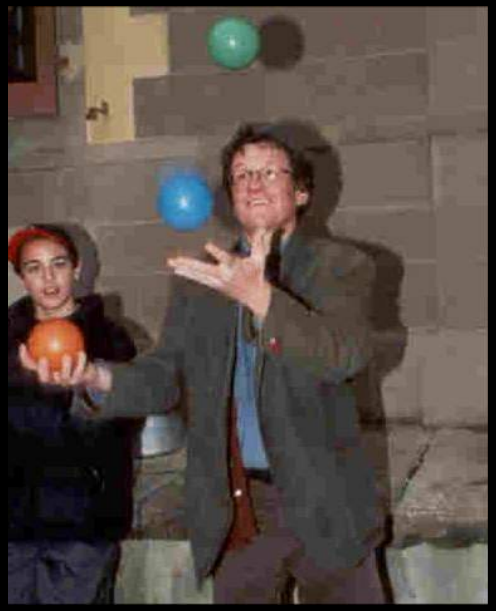

Tegmark et al. (1997), Galli & Palla (2002)

My chemistry with Francesco:

- the pleasure of following one's curiosity
- the pleasure of sharing knowledge with others

We met (and collaborated with) several bright young "students", in order of appearance:

- Raffaella Schneider
- Kazu Omukai
- Dominik Schleicher
- Stefano Bovino
- Tommaso Grassi
- Carla Coppola



Bottom line: it was great fun

Francesco: UNA BELLA PERSONA