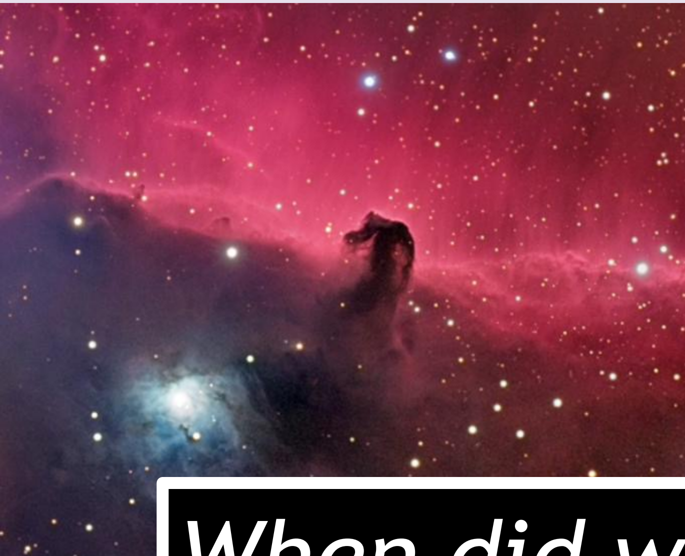
Water in the Early Universe

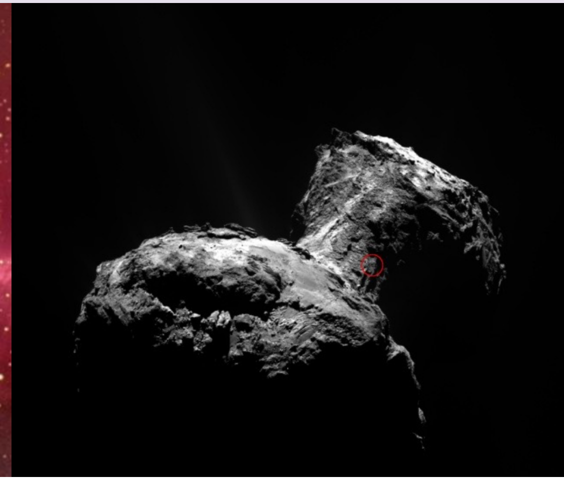
Shmuel Bialy – Tel Aviv University

Bialy, Sternberg & Loeb (2015; ApJ 804 L29)

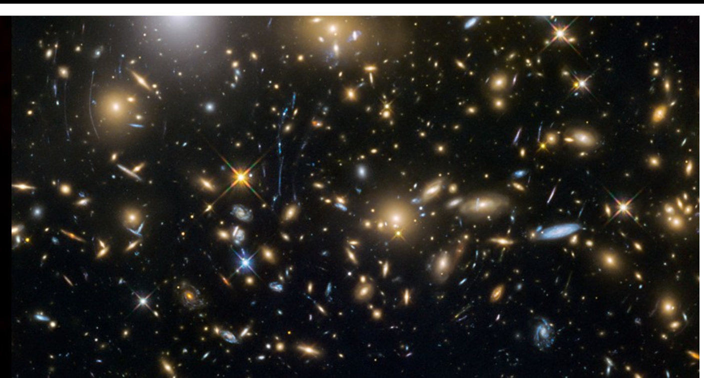
Bialy & Sternberg (2015; MNRAS 450 4424)

Water in the Galaxy





When did water first form in the universe?



The problem in forming early water

In the early universe

(era of first metal enrichment, z~10):

1) Metallicity (Z) was low
   Less O → low H_2O formation rates
2) Low metallicity → low dust abundaces

→ No shielding of far-UV dissociating radiation

On the other hand:

Low metallicity → Less cooling

→ Higher temperatures

→ Efficient warm chemistry

Who wins?

Outline

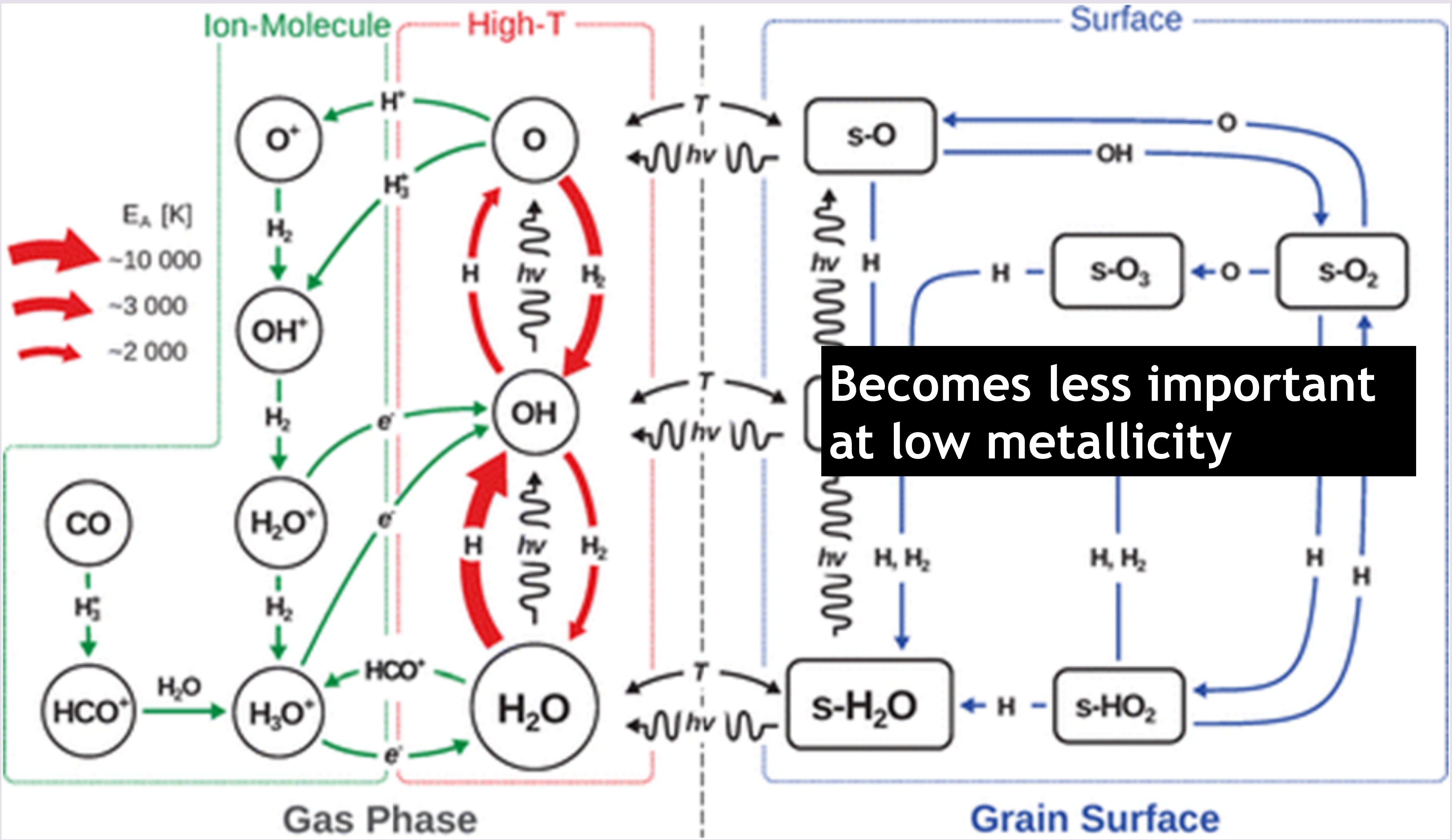
1) Theory: Chemistry

2) Model and Basic parameters

3) Results

4) Summary

Water Chemistry

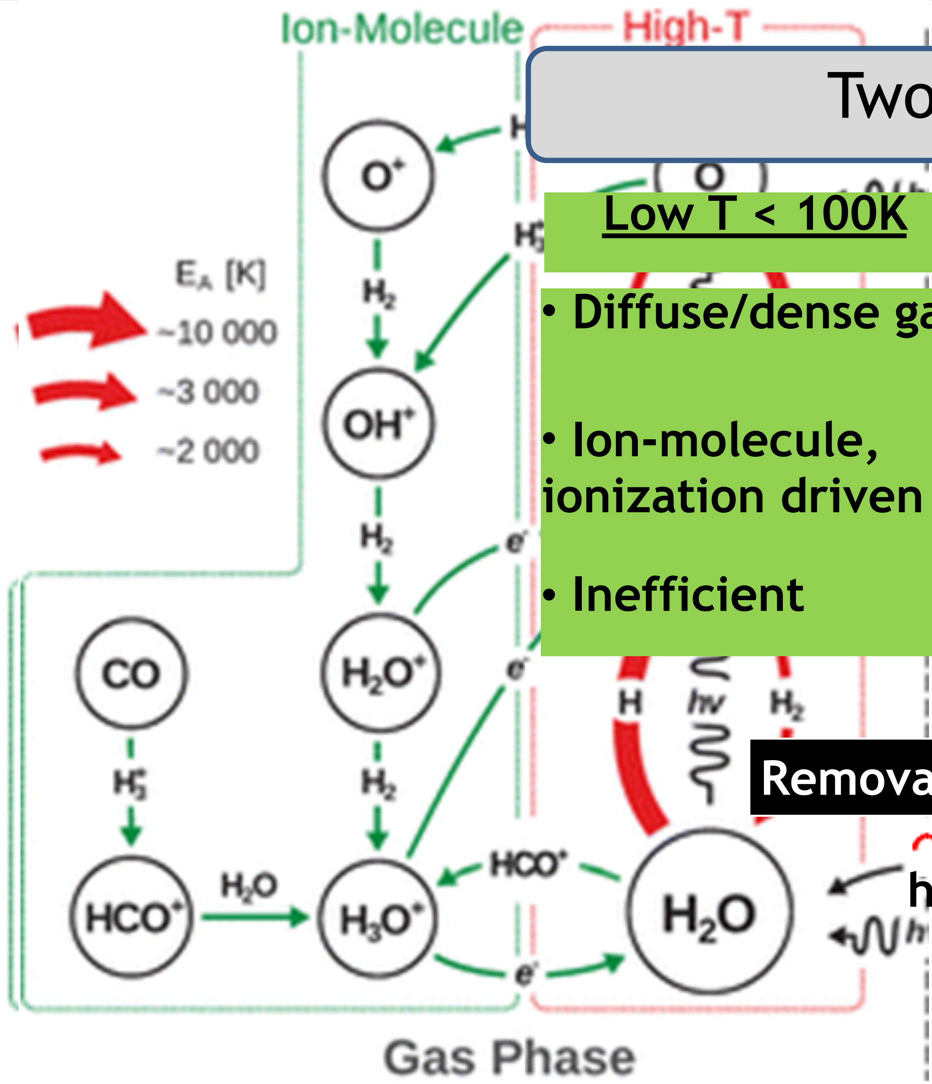


Becomes less important at low metallicity

van Dishoeck, Herbst & Neufeld (2015)

Water Chemistry (Gas phase)

- Theory
- Model
- Results



Two Regimes

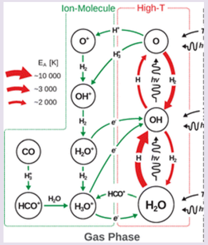
Low T < 100K	**High T > 200K**
• Diffuse/dense gas	•Shocked/warm gas
• Ion-molecule, ionization driven	•Neutral-neutral reactions
• Inefficient	• Efficient

Removal: Photodissociation

hν > 6 eV

van Dishoeck, Herbst & Neufeld

Model



- Gas-phase chemical network (+H_2 formation on dust)

  74 species, ~1000 reactions

- far-UV photodissociation (destroy H_2O and OH)

- Dust-absorption and H_2 self-shielding

- Cosmic-ray/X-ray ionization (drive the ion-mol. chemistry)

→ Species abundances as functions of

T	Z'	I_{UV}/n	ζ /n
Temperature	Metallicity	UV intensity to density	Ionization rate to density

Results

Early universe = decreasing metallicity (Z')

→ Species abundances as functions of

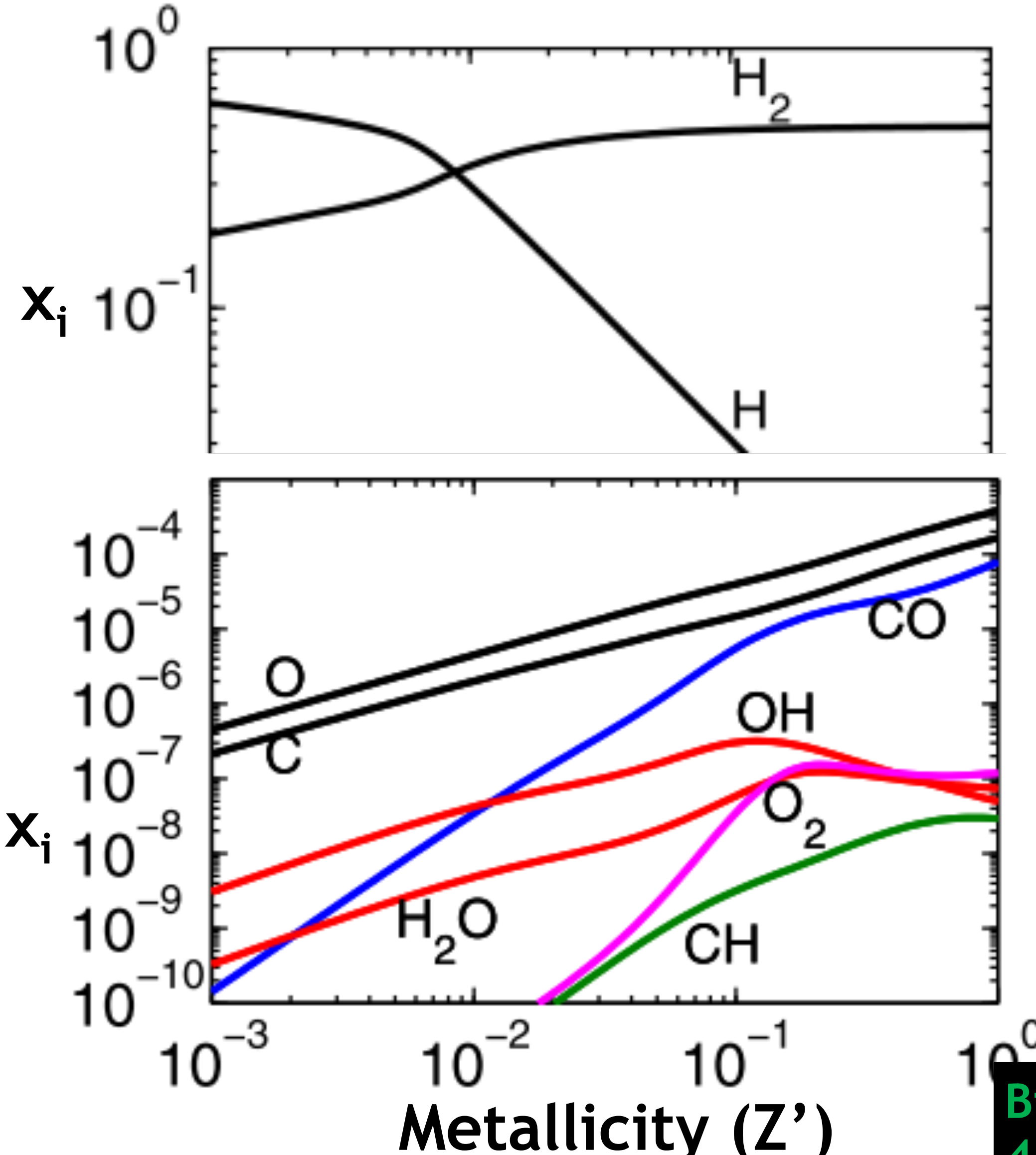
- **T** — Temperature
- **Z'** — Metallicity
- **I_{UV}/n** — UV intensity to density
- **ζ/n** — Ionization rate to density

Results 1:

Low T regime (ion-molecule chemistry)

- T=100K
- I_{UV}=1

$$\frac{\zeta}{n} = \frac{10^{-16}\ s^{-1}}{10^{3}\ cm^{-3}}$$



- H_2 formation - dust and gas
- H_2 removal – cosmic rays
- Low Z' – $H_2 \rightarrow H$

At low Z

- **OH, CH, H_2O ~ Z**
- **O_2, CO ~ Z^2**

Bialy & Sternberg (2015; MNRAS 450 4424)

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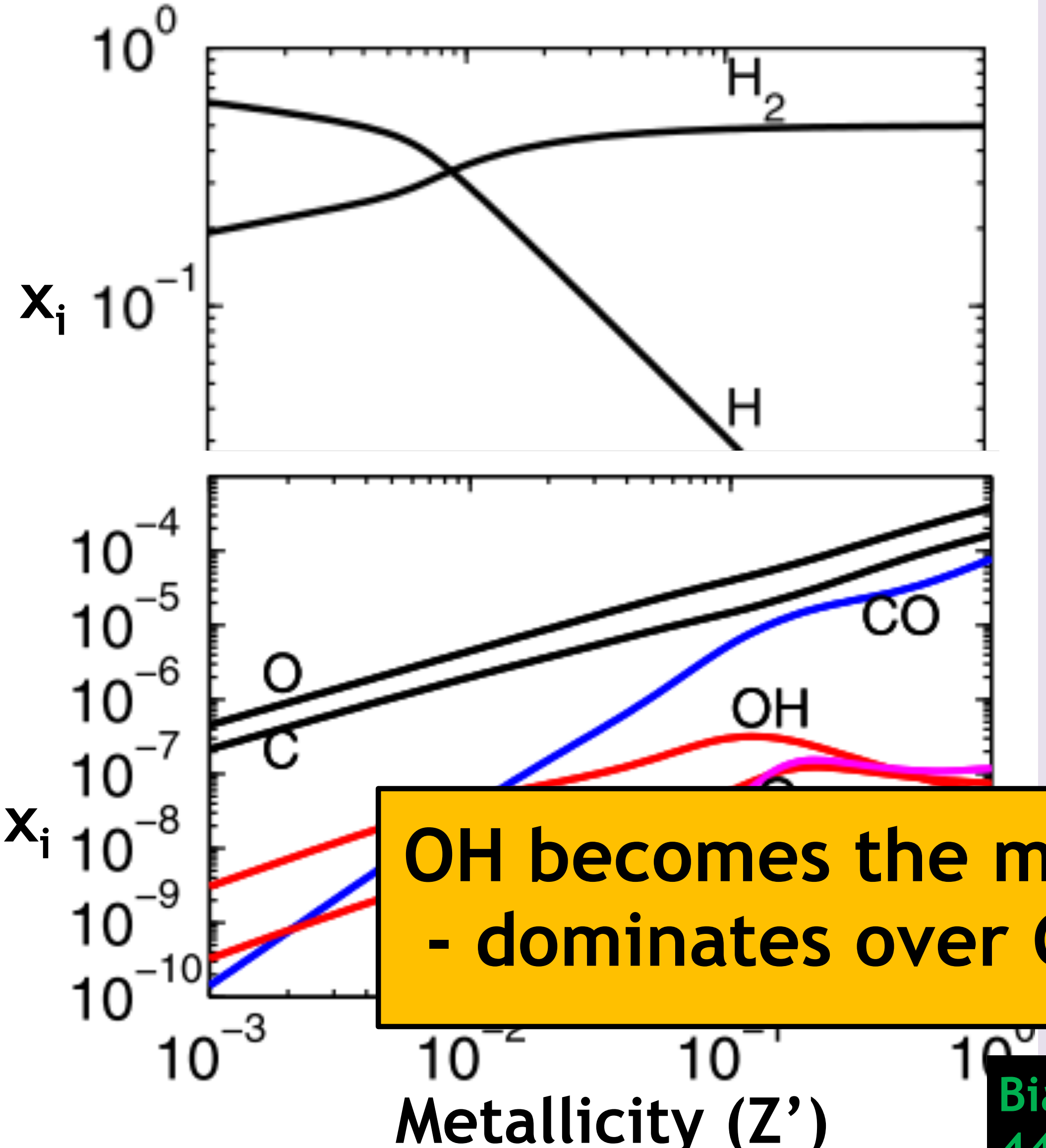

- H_2 formation - dust and gas
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At low Z

- OH, CH, H_2O ~ Z

OH becomes the most abundant molecule - dominates over CO!

Bialy & Sternberg (2015; MNRAS 450 4424)

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6 s^{-1}

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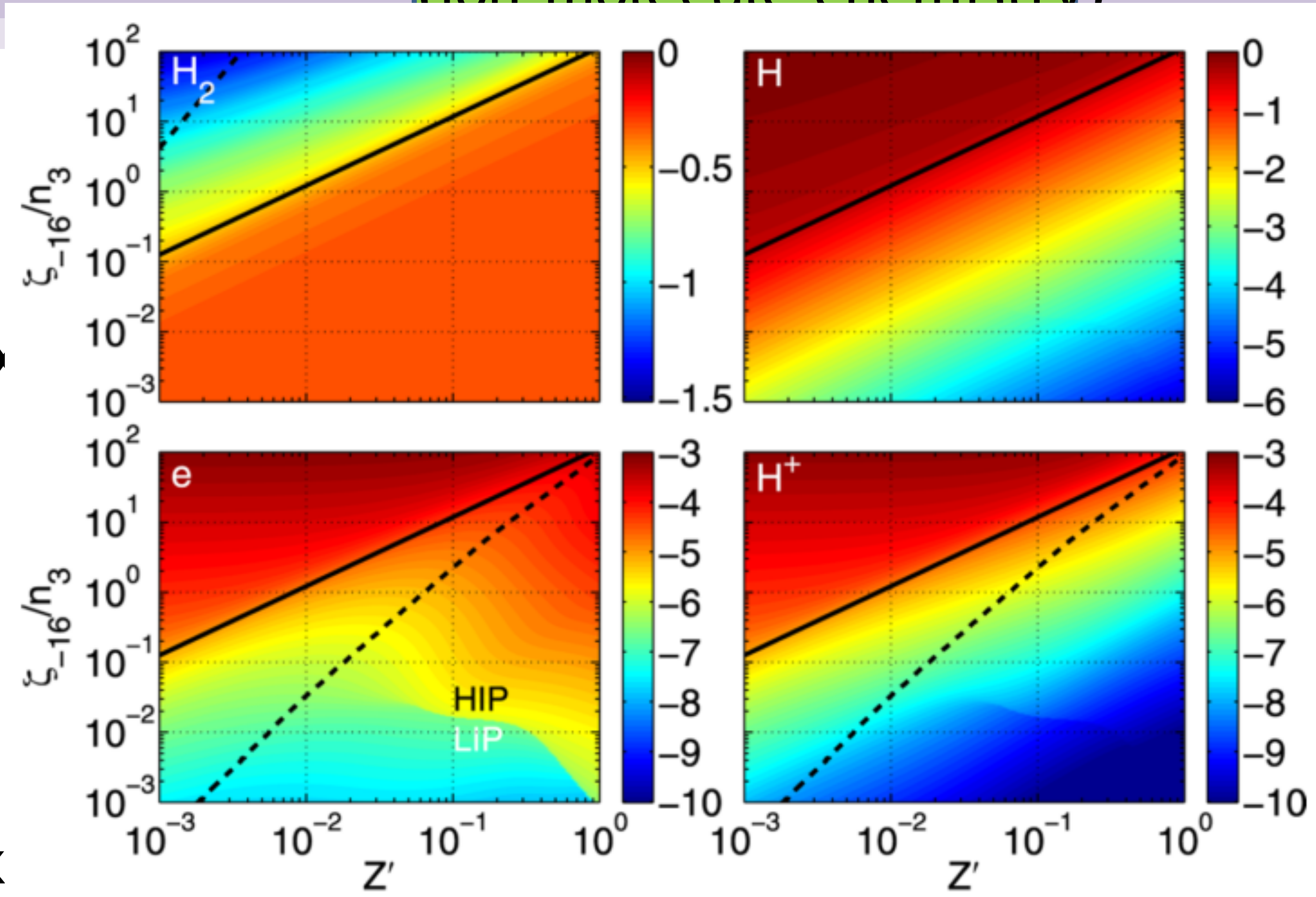
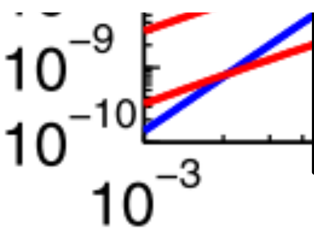


n - dust and gas

– cosmic rays

→ H

H_2O ~ Z



ant molecule

- dominates over CO!

Metallicity (Z')

Bialy & Sternberg (2015; MNRAS 450 4424)

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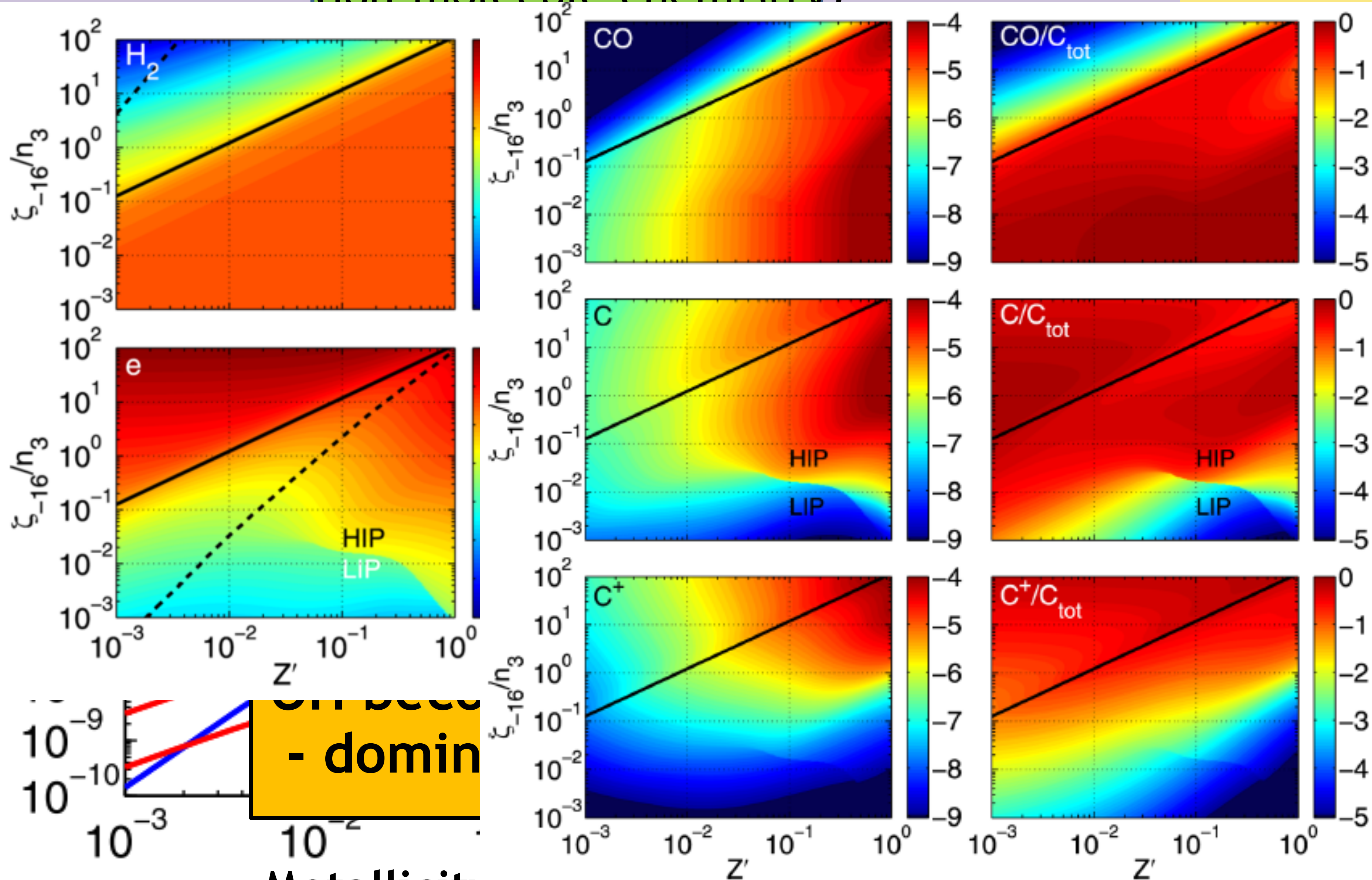

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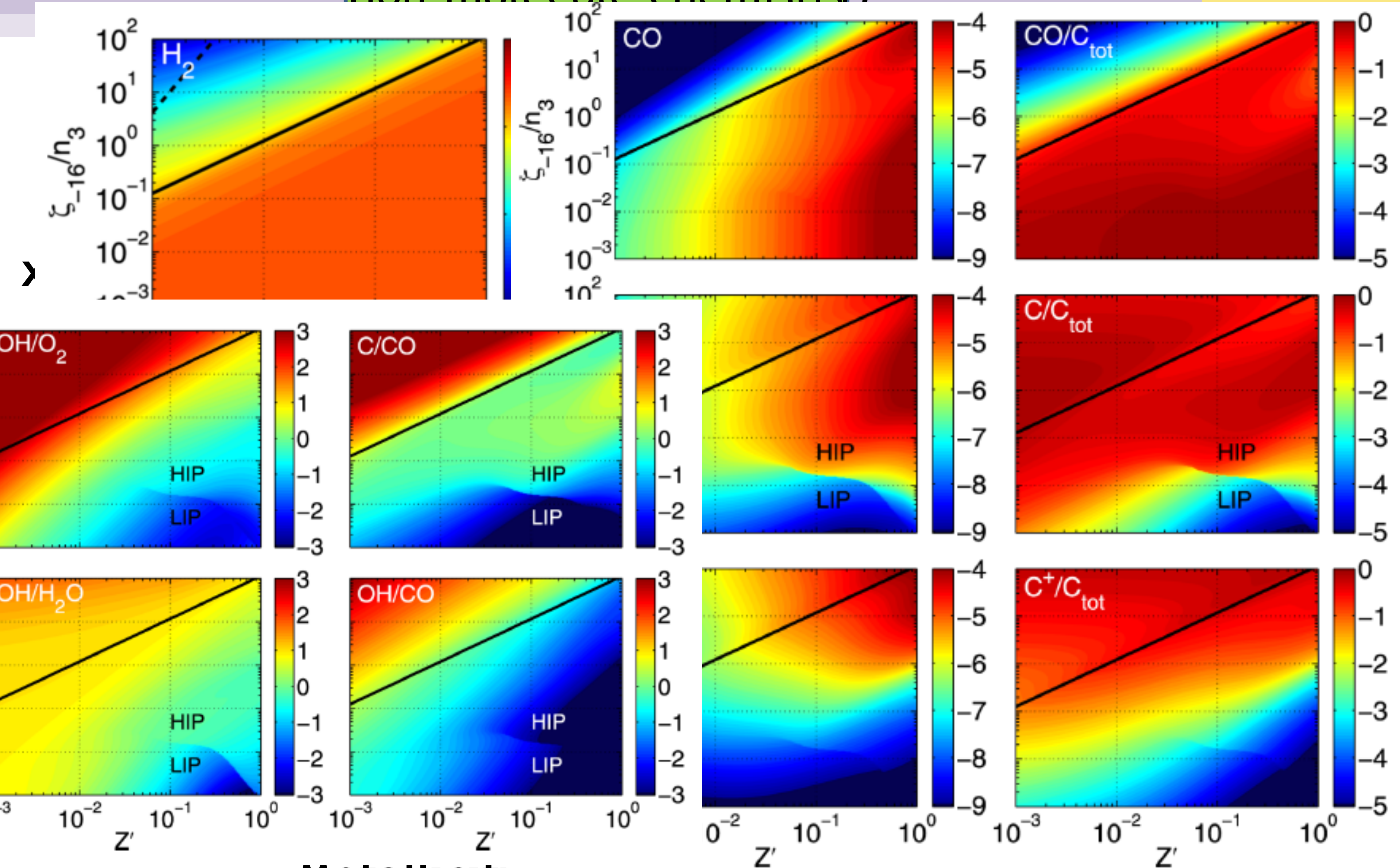

Metallicity (Z')

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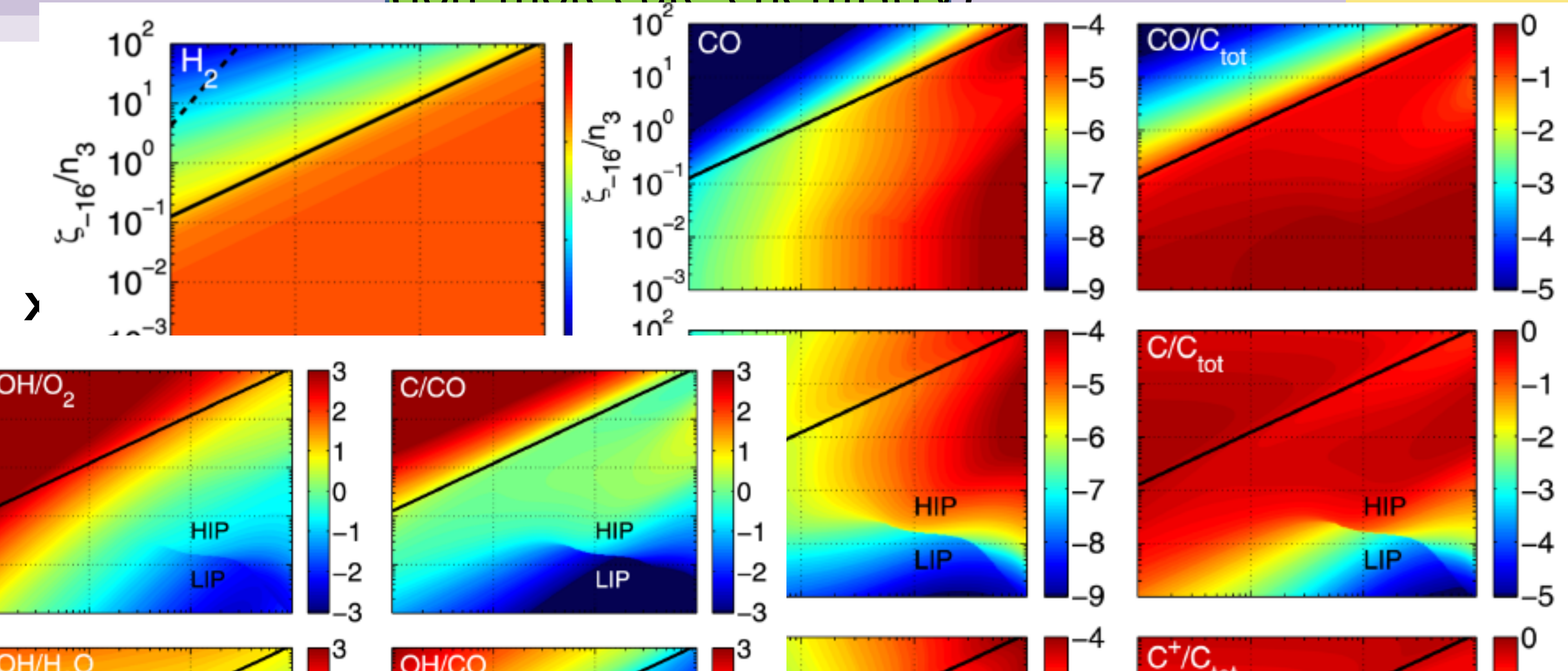

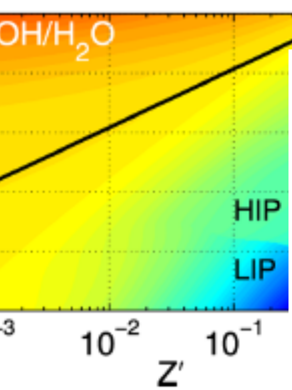

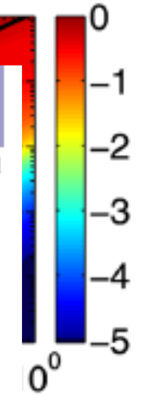

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MNRAS **450**, 4424–4445 (2015) doi:10.1093/mnras/stv851

CO/H_2, C/CO, OH/CO, and OH/O_2 in dense interstellar gas: from high ionization to low metallicity

Shmuel Bialy★ and Amiel Sternberg

Raymond and Beverly Sackler School of Physics & Astronomy, Tel Aviv University, Ramat Aviv 69978, Israel

Low → High T regimes

T	Z'	I_{UV}/n	ζ /n
Temperature	Metallicity	UV intensity to density	Ionization rate to density

How does $x(H_2O)$ depends on temperature?

* Low Z systems are typically warmer because of less efficient cooling

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Low → High T regimes

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T — Temperature

Z' — Metallicity

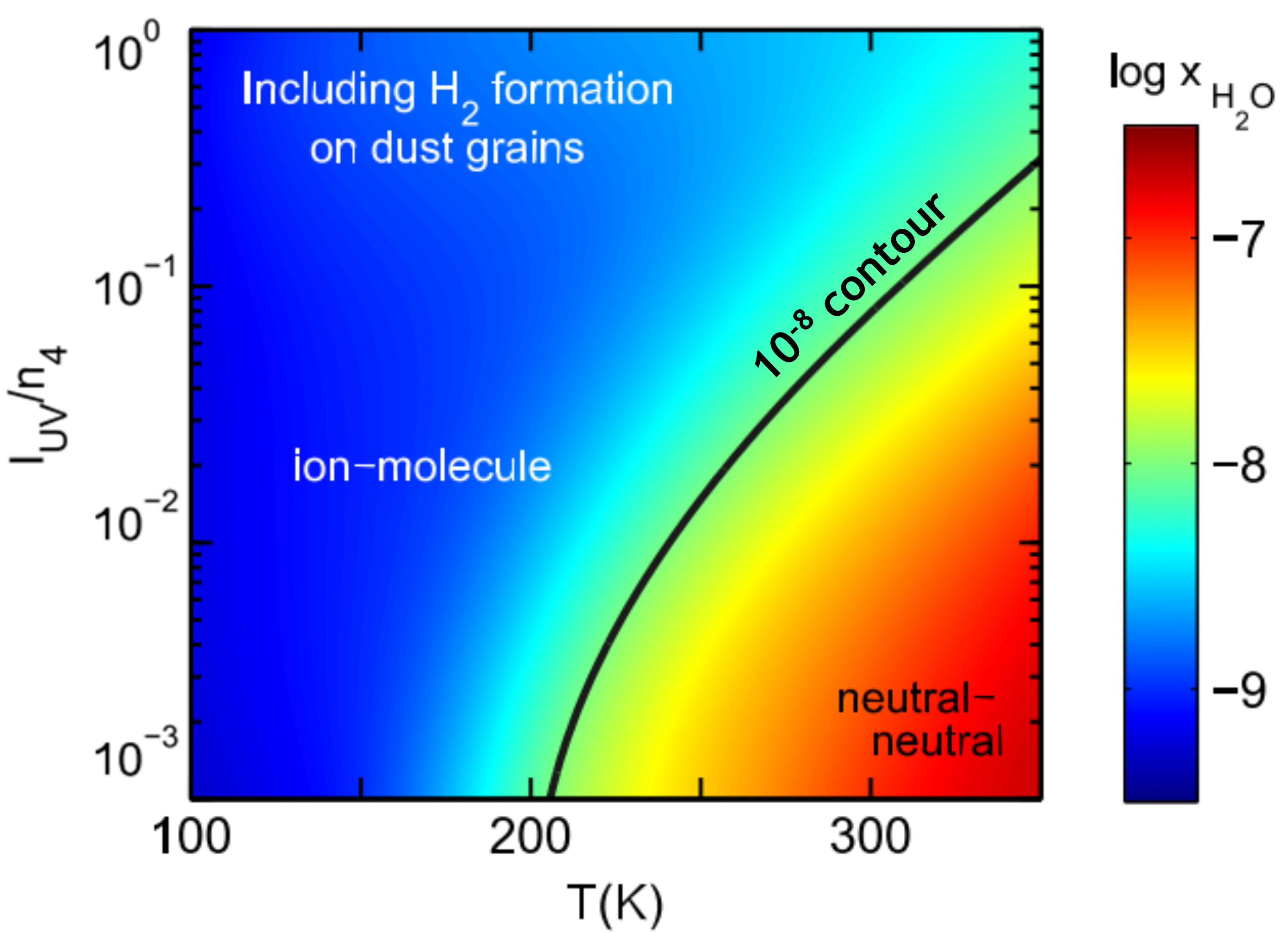
I_{UV}/n — UV intensity to density

ζ /n — Ionization rate to density

Results 2: Low → High T regimes

$Z'=10^{-3}$

- Theory
- Model
- Results



Bialy, Sternberg & Loeb (2015; ApJ 804 L24)

Results 2:

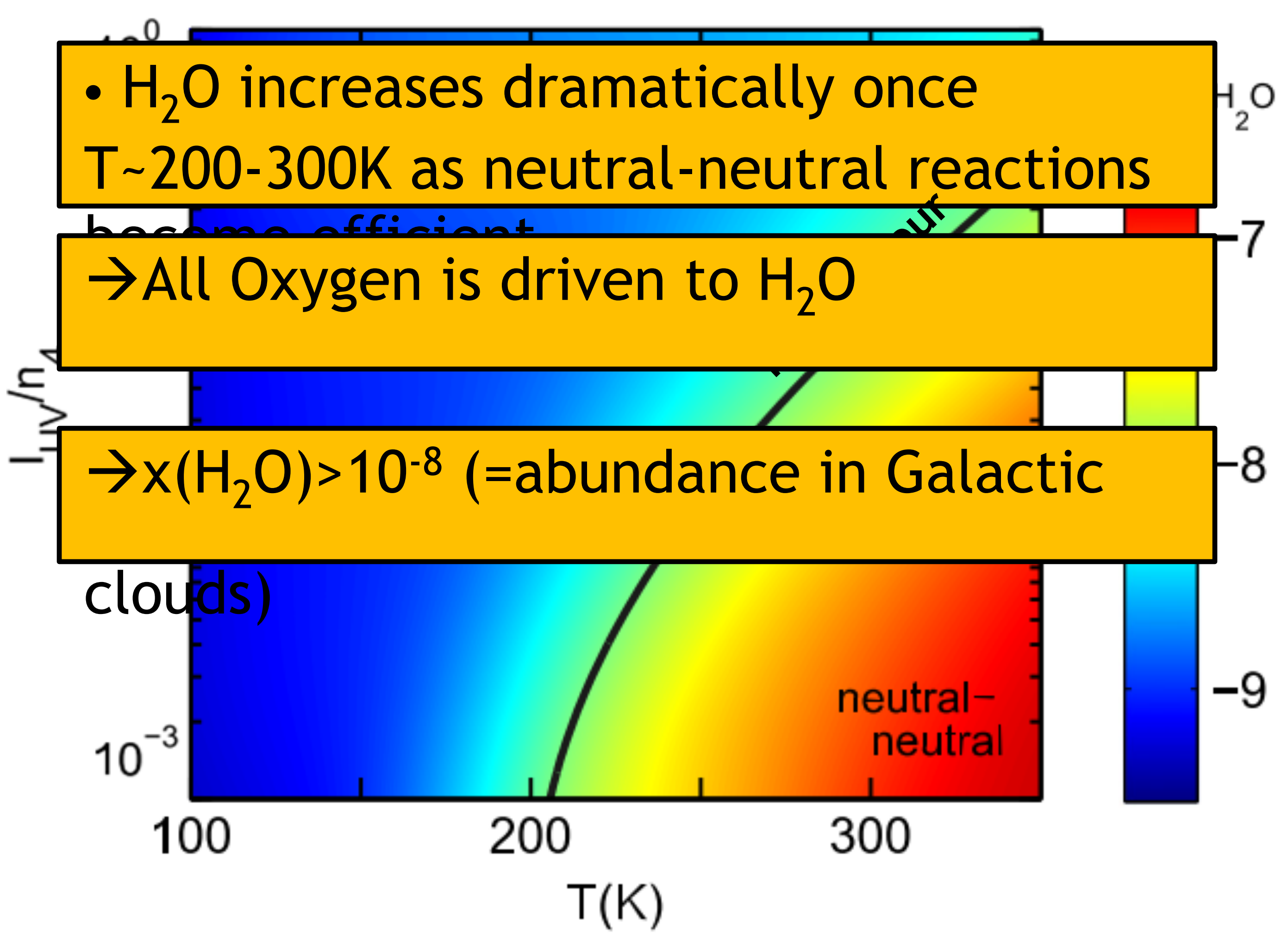
Low → High T regimes

$Z' = 10^{-3}$

- H_2O increases dramatically once T~200-300K as neutral-neutral reactions become efficient

→All Oxygen is driven to H_2O

→$x(H_2O) > 10^{-8}$ (=abundance in Galactic clouds)



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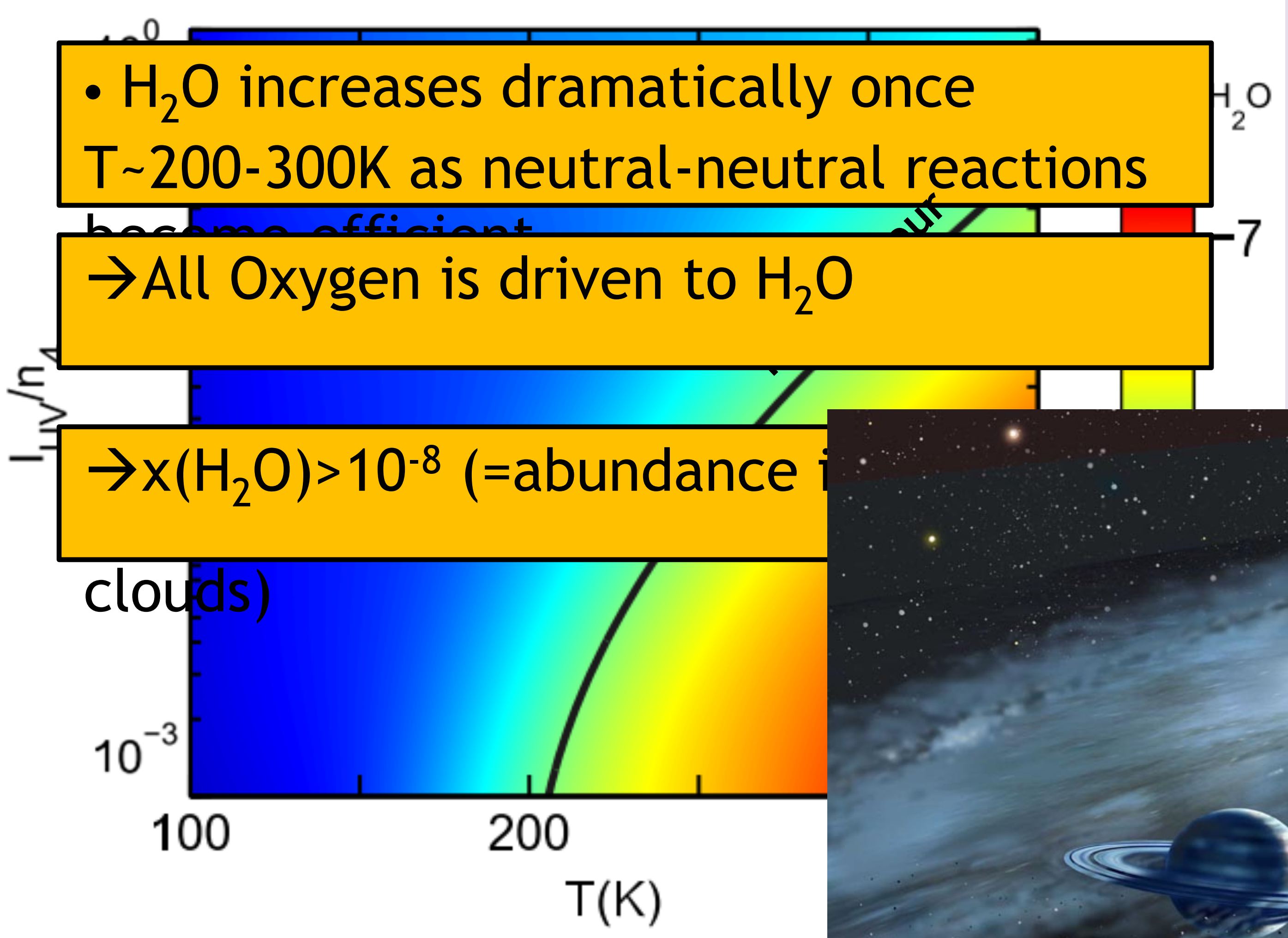
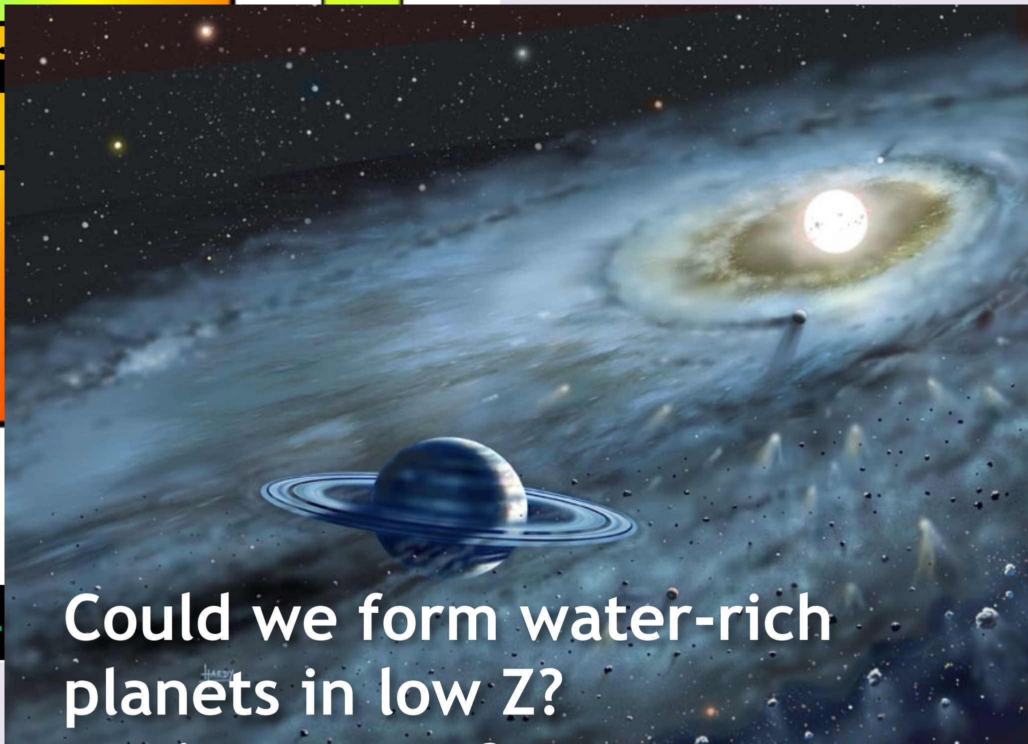


- H_2O increases dramatically once T~200-300K as neutral-neutral reactions become efficient

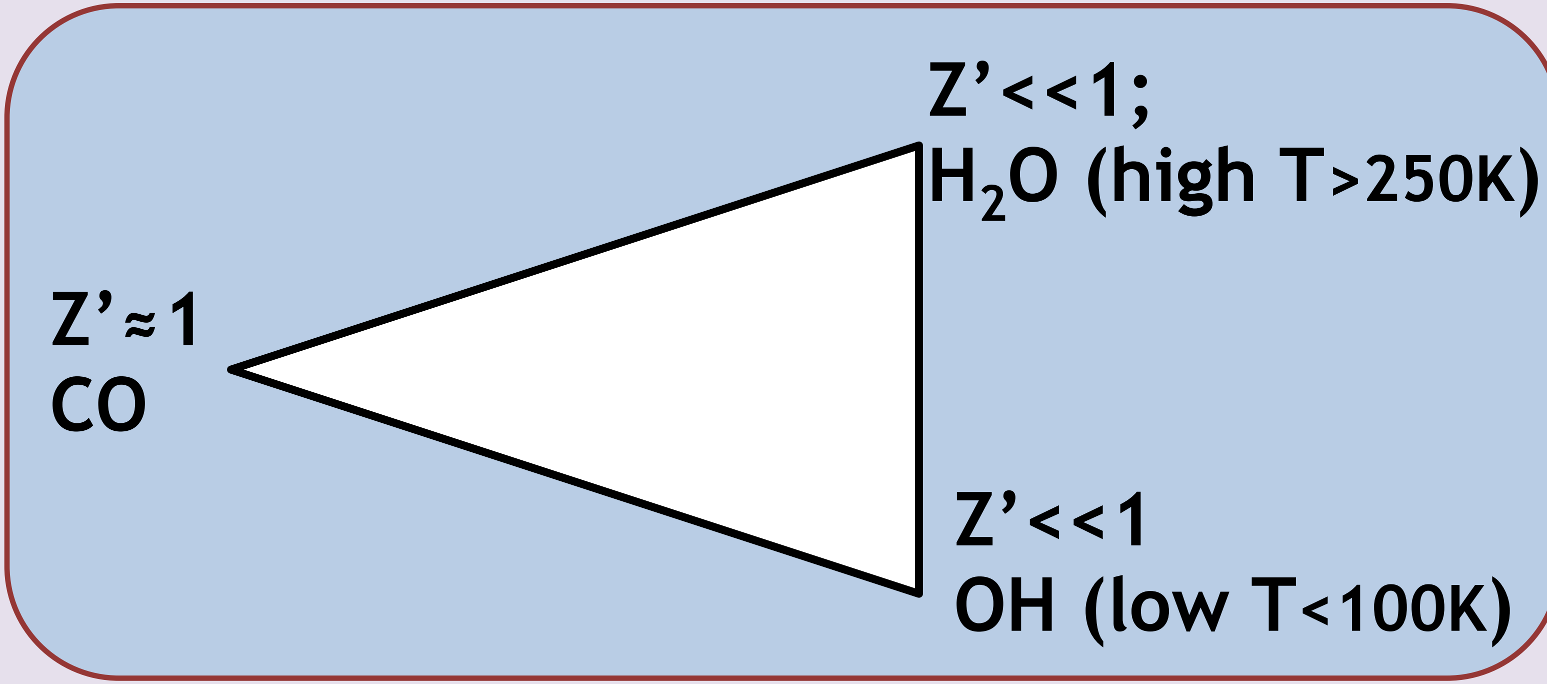
→All Oxygen is driven to H_2O

→$x(H_2O)>10^{-8}$ (=abundance i… clouds)

Bialy, Sternberg & Loeb (2015; ApJ 804



Summary



The efficient H_2O formation at high T (>200K), compensates for the lack of metals and dust in low Z gas, and water can form at high abundances (>10^{-8})

Bialy & Sternberg (2015; MNRAS 450 4424)

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