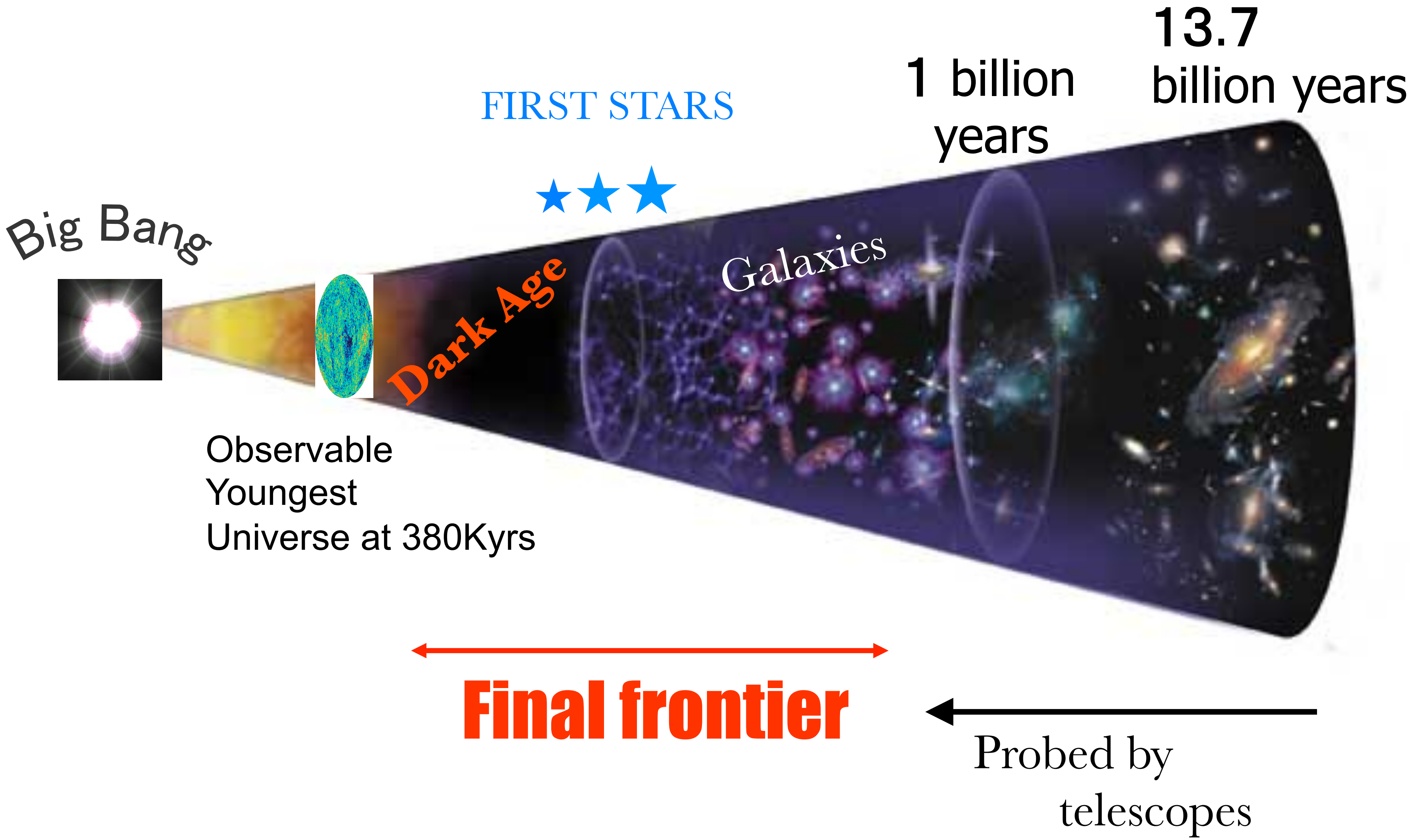
ICEPPシンポジウム 平成24年2月20日

講義3
宇宙暗黒時代

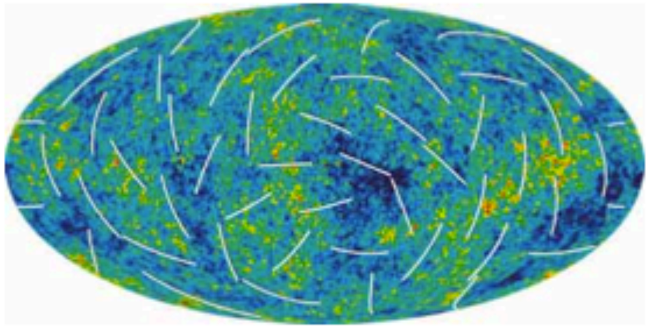
IPMRS Summer School “The First Stars and Cosmic Reionization”

Contents

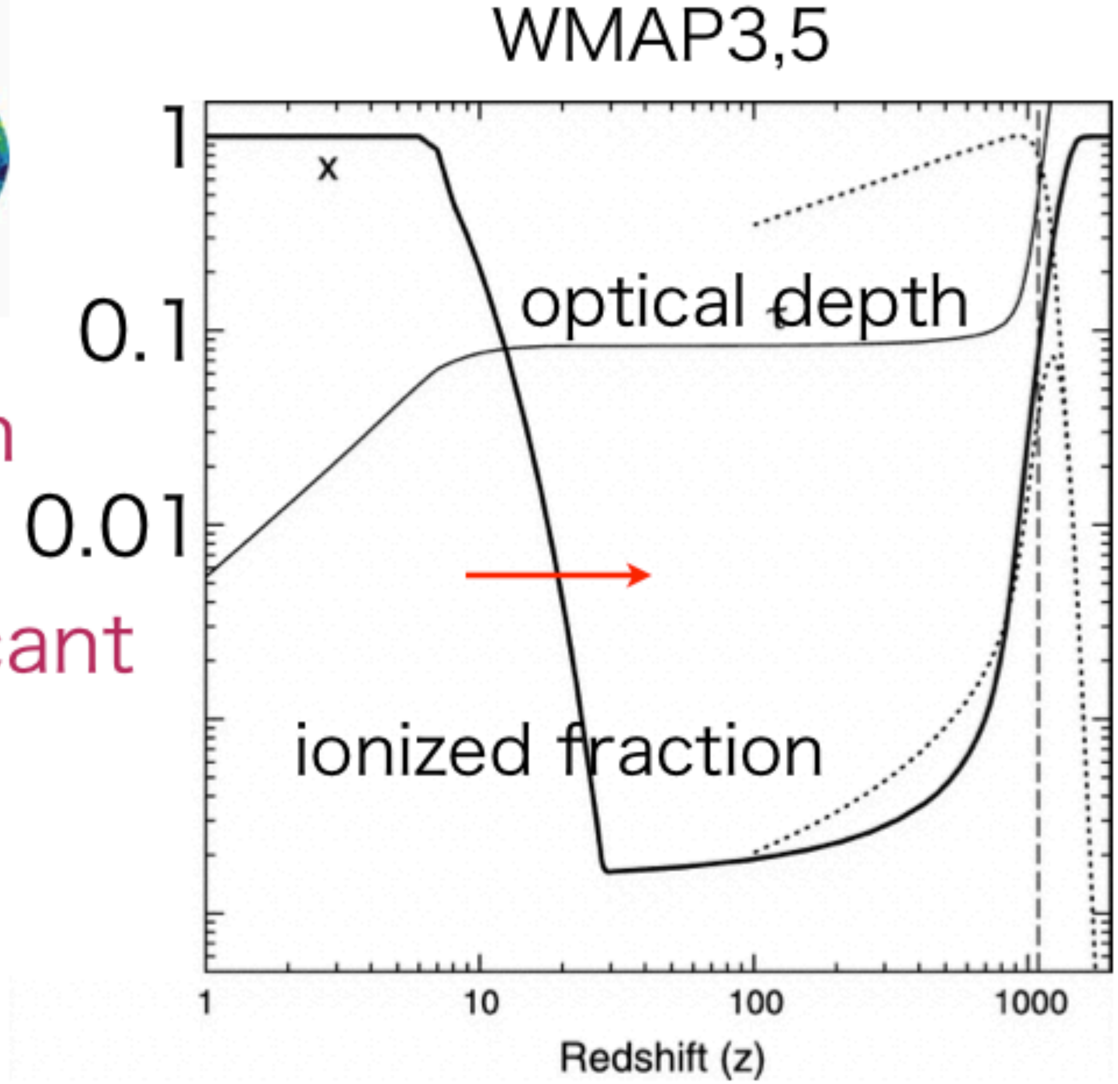
Brief History of the Universe



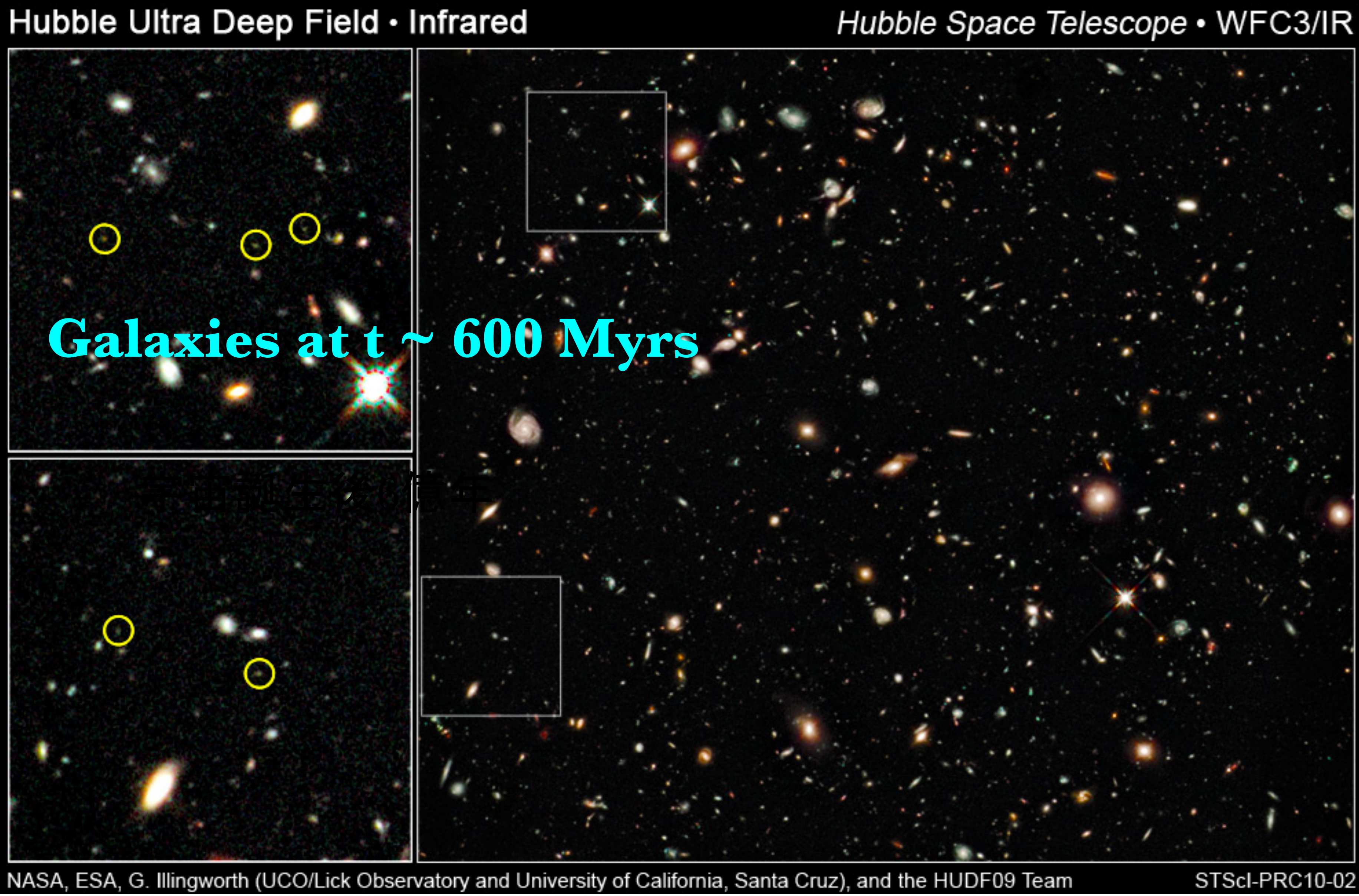
STAR FORMATION AT HIGH-z



CMB polarization measurement suggests significant star-formation at z > 10

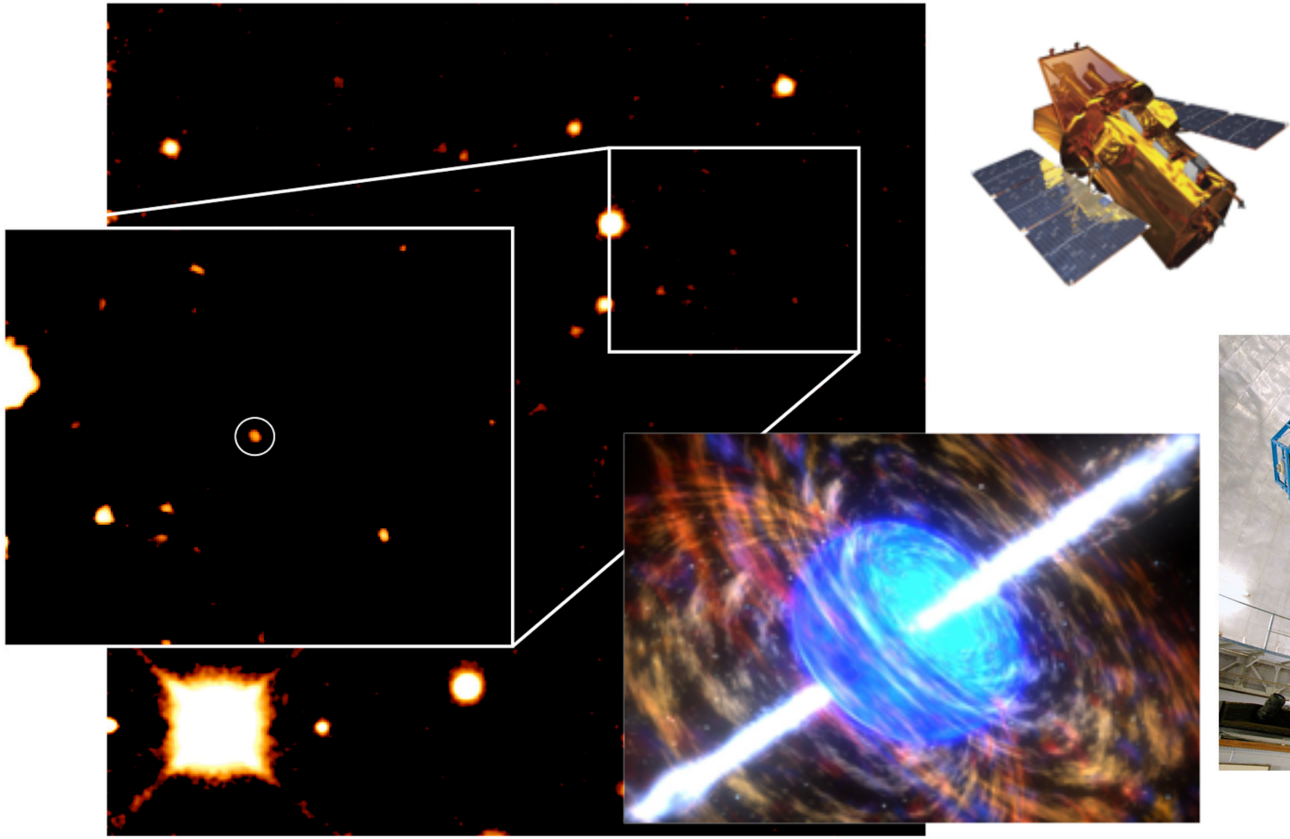


MOST DISTANT GALAXIES



Galaxies at t ~ 600 Myrs

First explosion



OAO-ISLE J band

国立天文台 岡山天体物理観測所

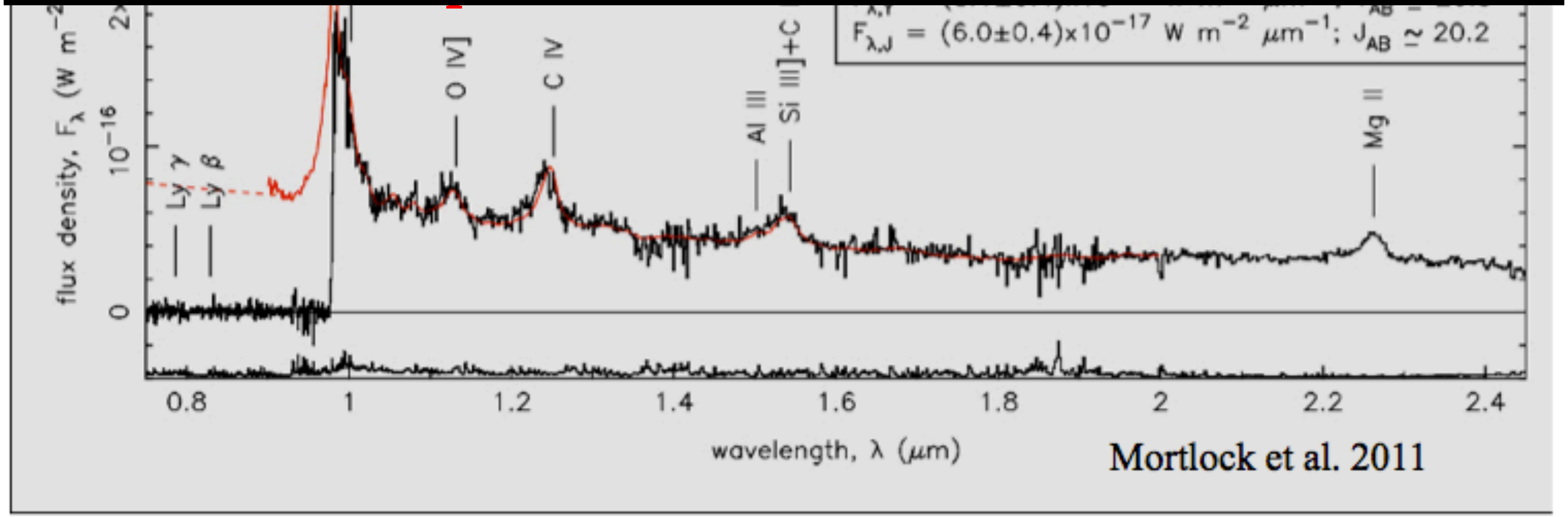
Death of a massive star
600 million years after the Big Bang!!!

2 billion times heavier than the sun

A Young but Big! Blackhole

The age of the Universe ~ 770 million years

How did the first blackholes form and grow ?
Where were the heavy elements synthesized ?

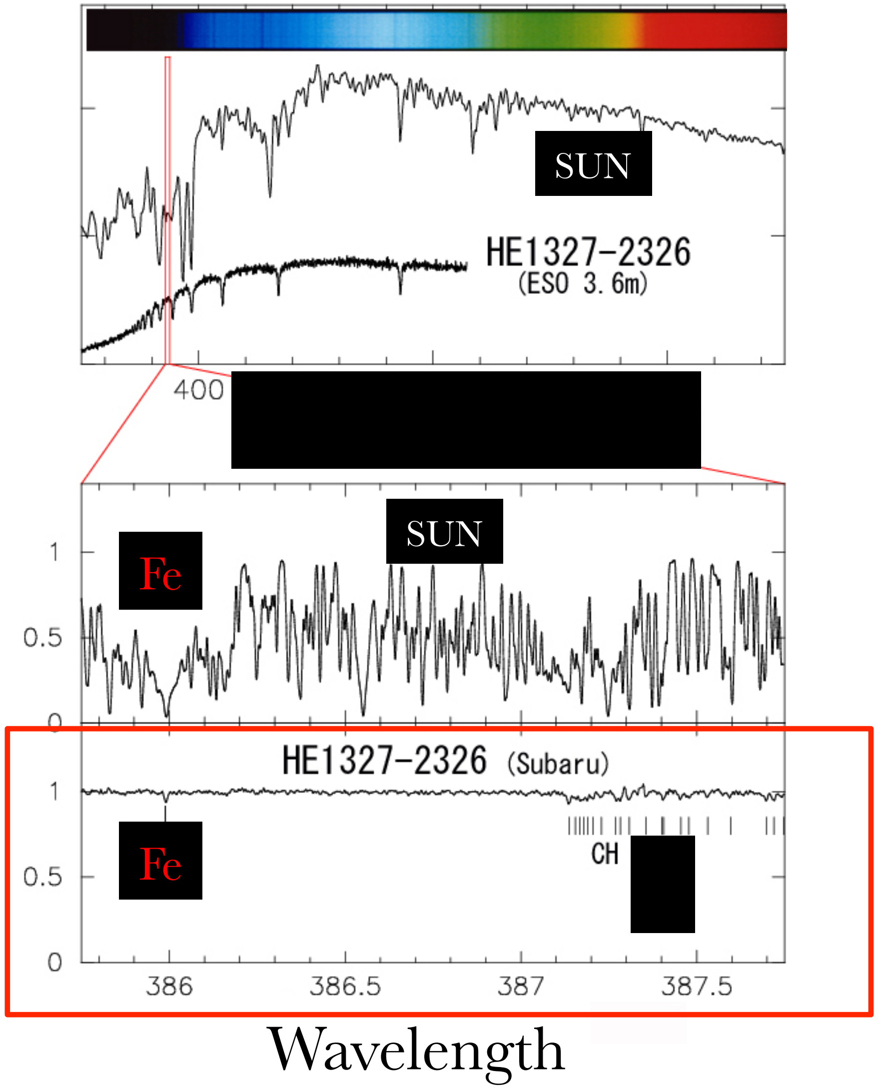


Mortlock et al. 2011

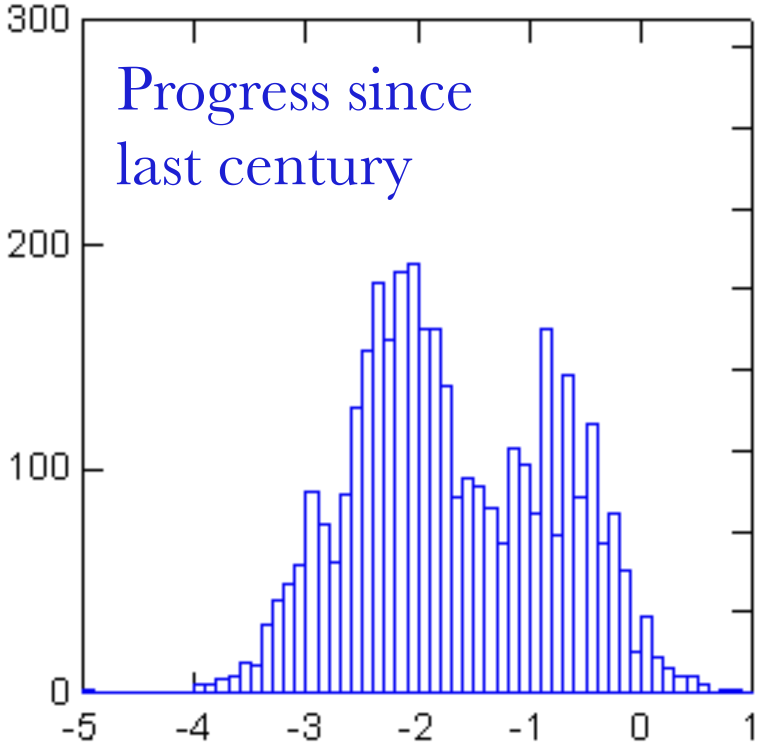
STELLAR RELICS IN THE BACKYARD

Subaru telescope observation

The star contains…no iron!!

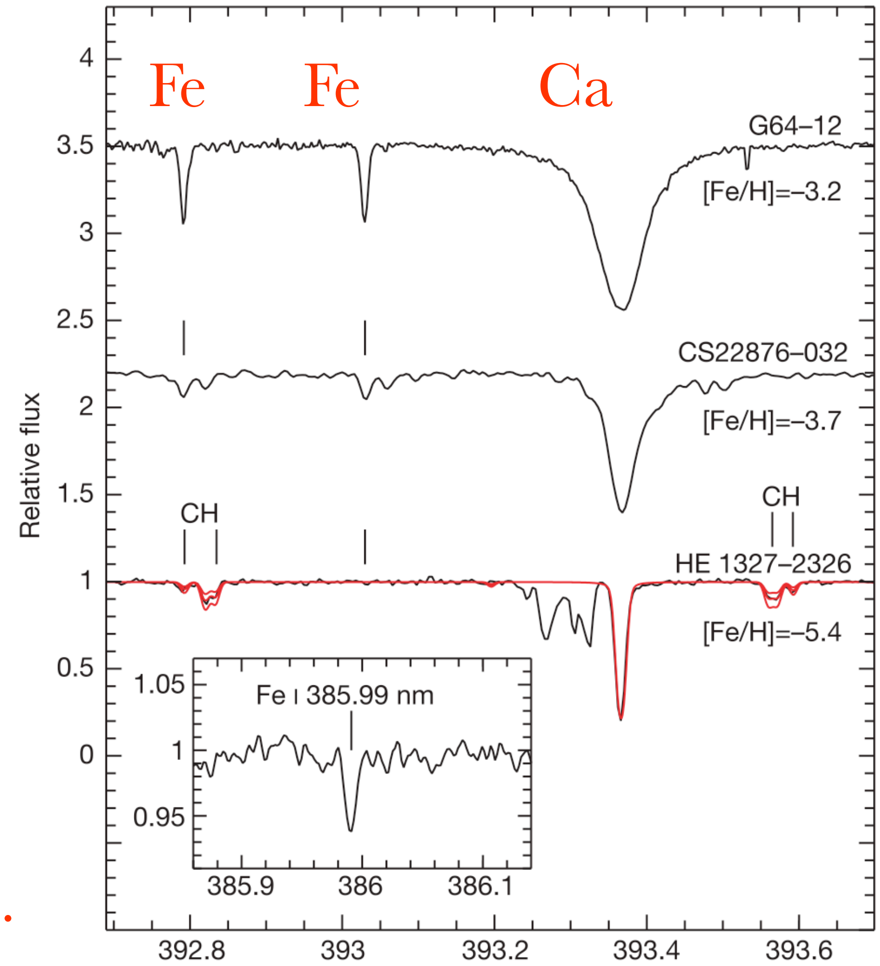


SURVIVING EARLY GENERATION STARS



The star HE1327 contains
iron only 1/300,000 of the sun.

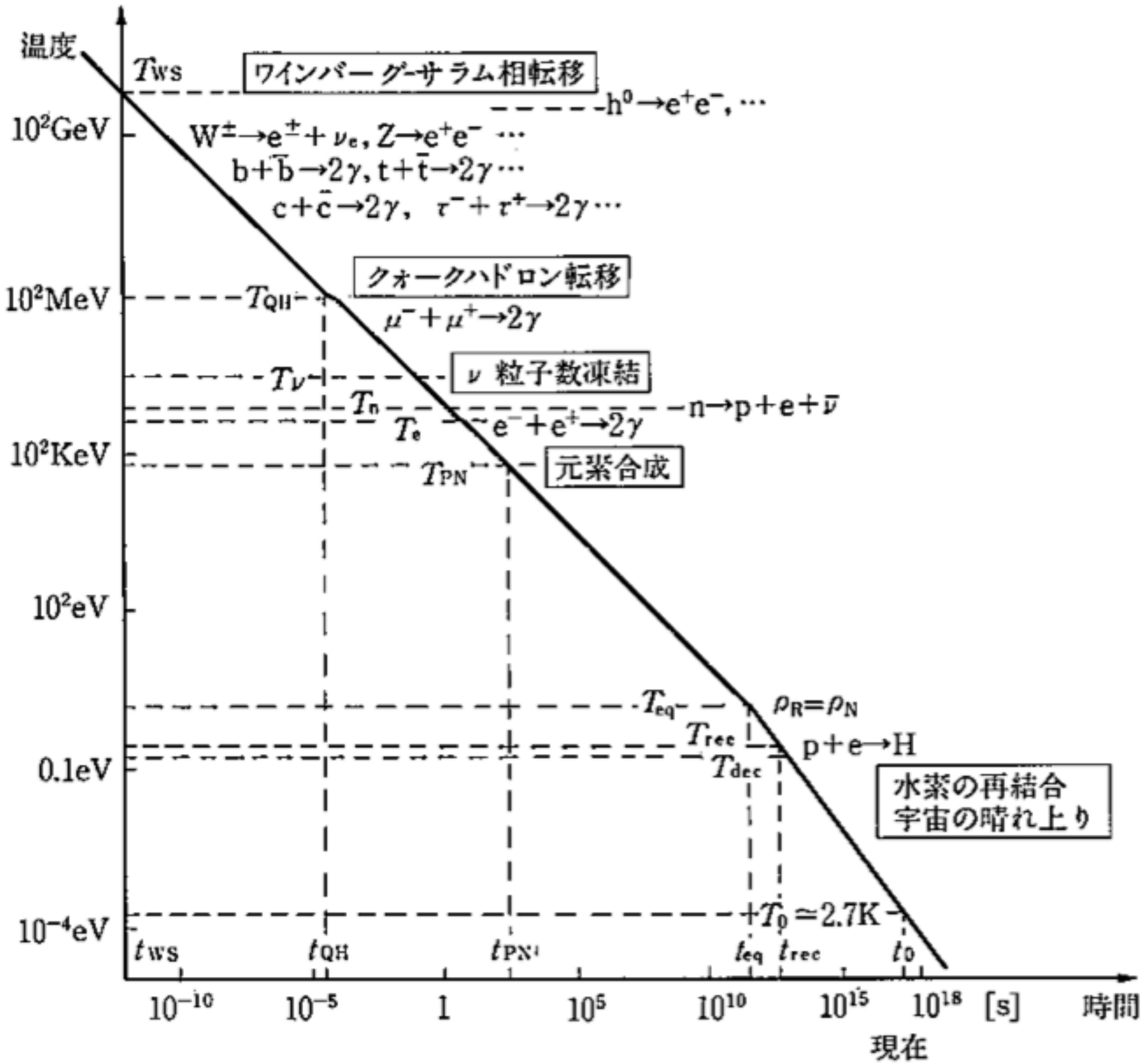
Almost no iron!!



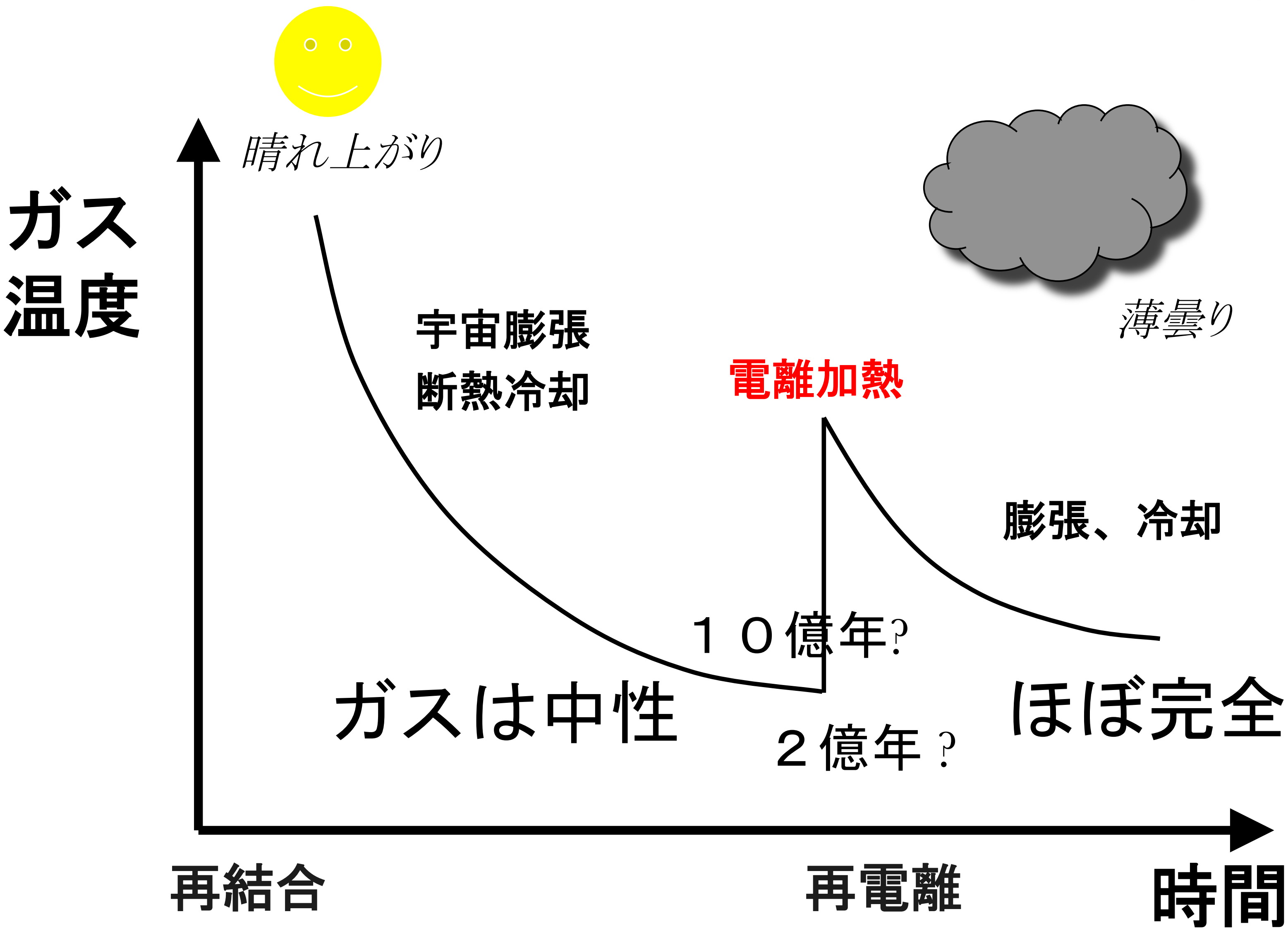
Wavelength

Cosmic Reionization

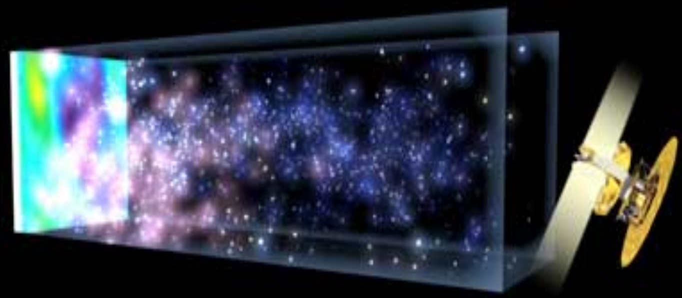
Thermal history

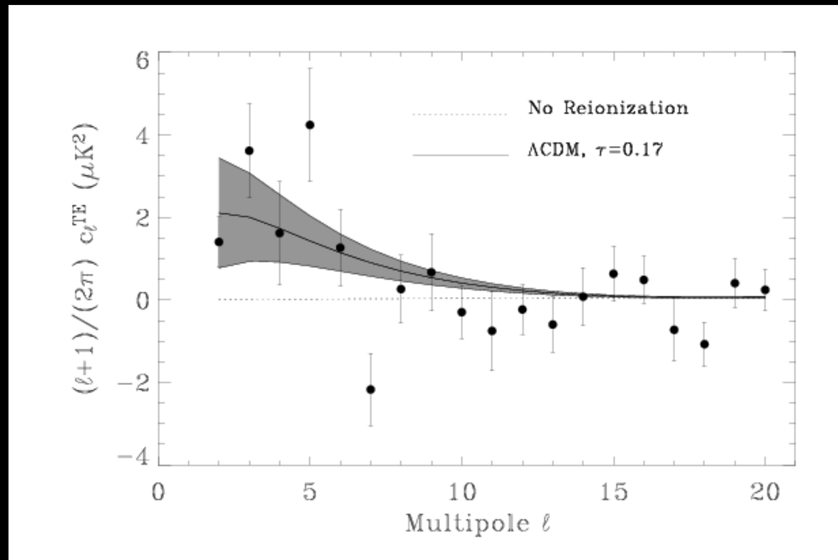


ビッグバンの後、晴れのち曇り

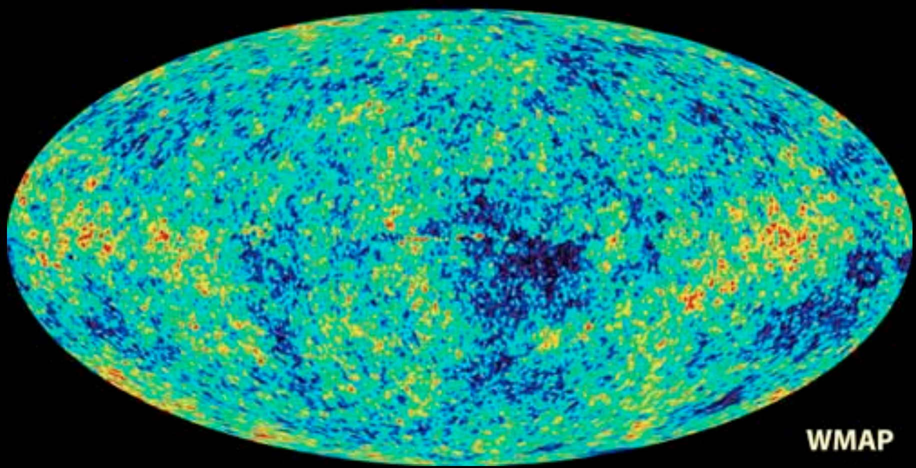


WMAP results





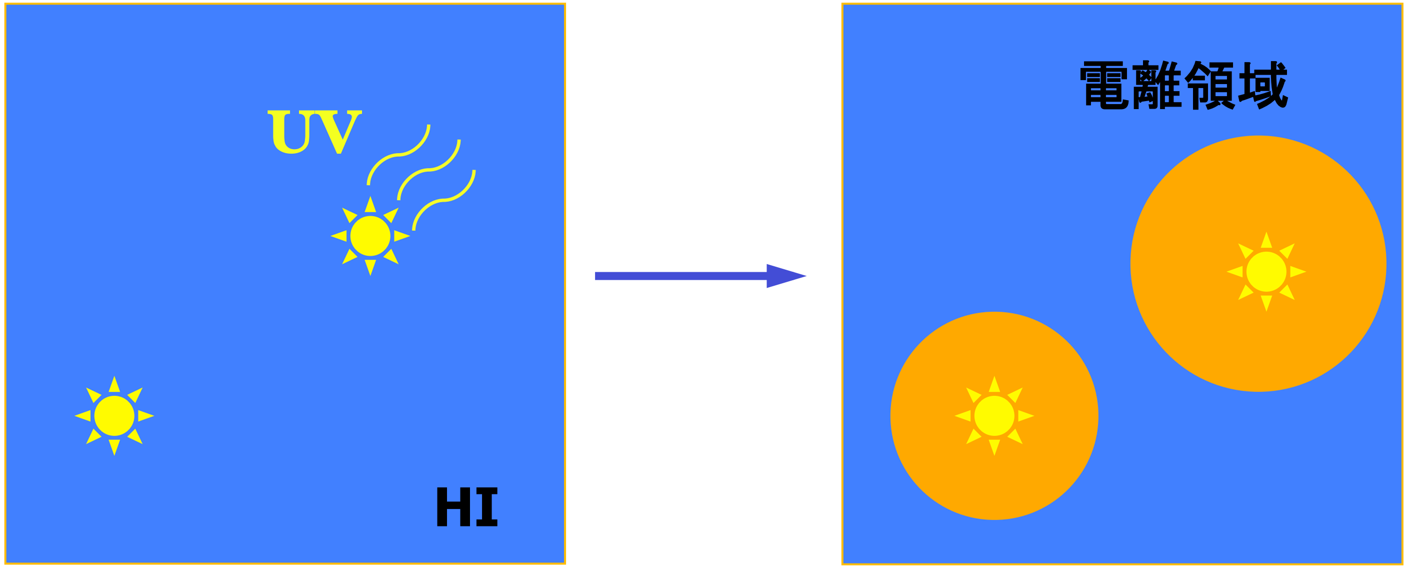
大規模な偏光パターン

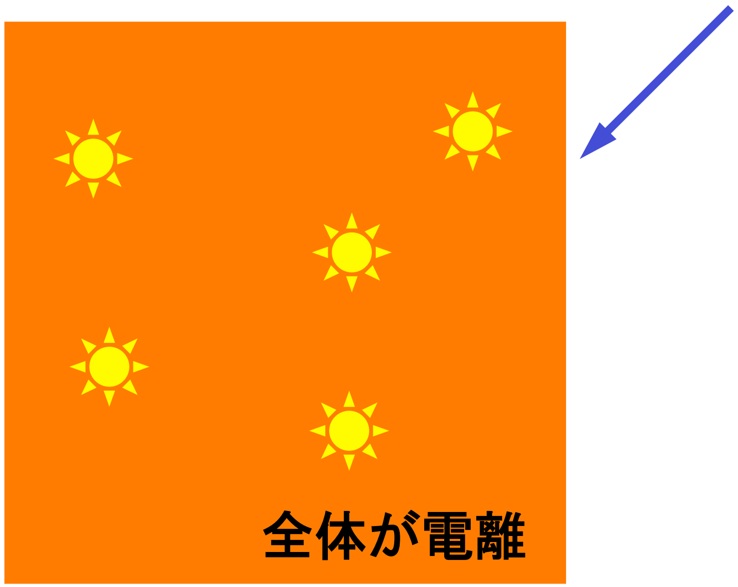


早期再電離

（～4億年）

宇宙再電離

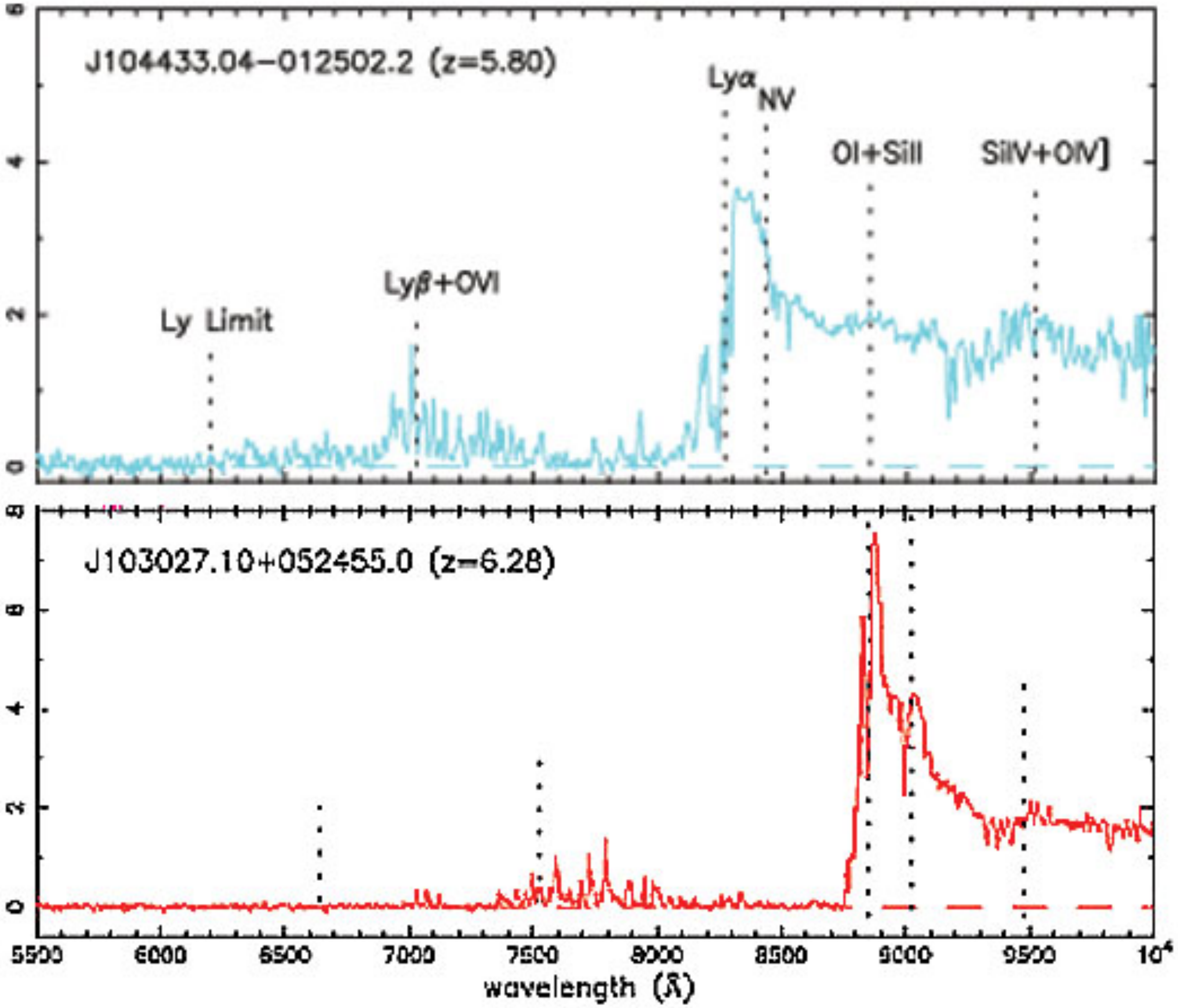




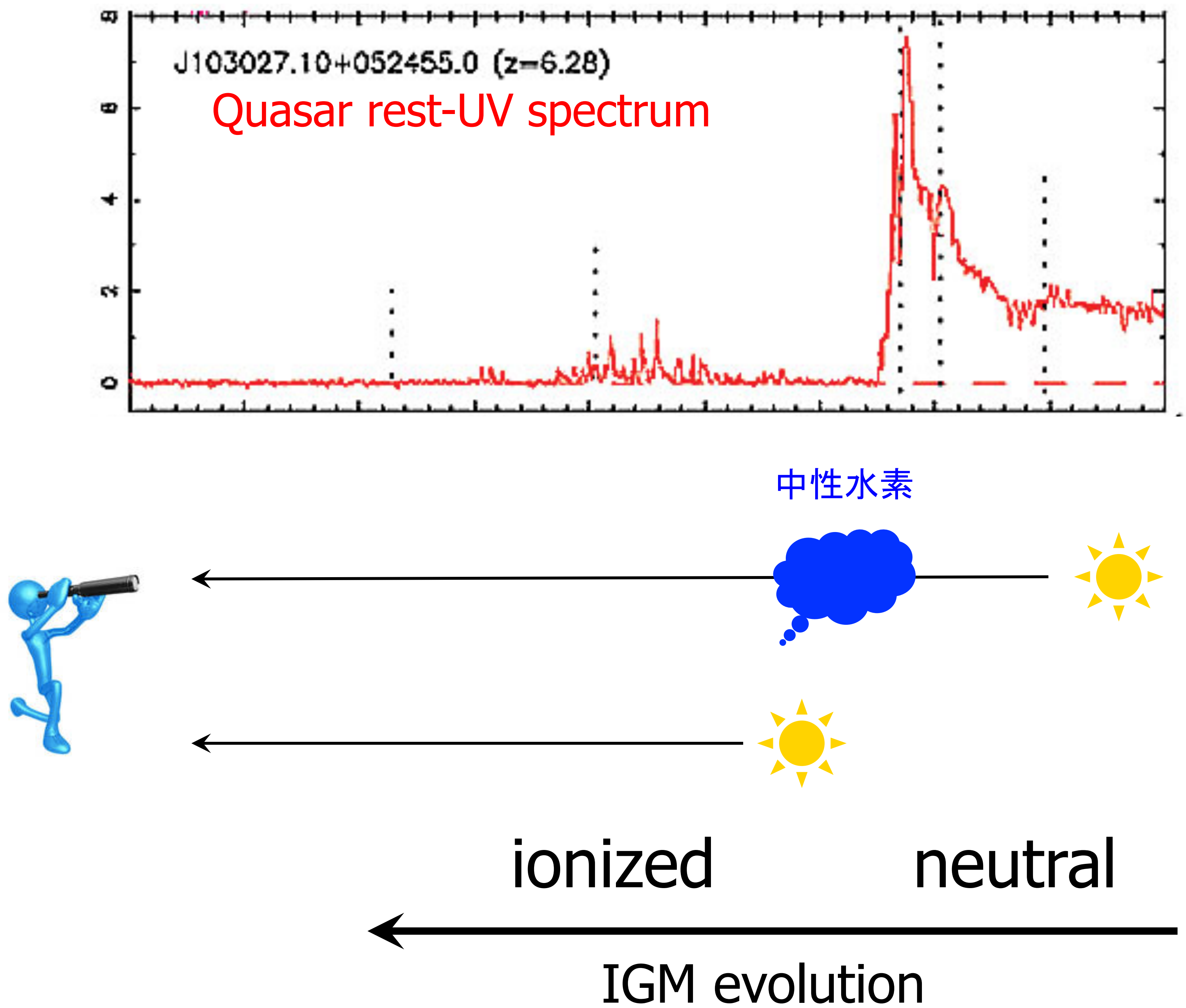
UV photons

$$H + \gamma = H^{+} + e^{-}$$

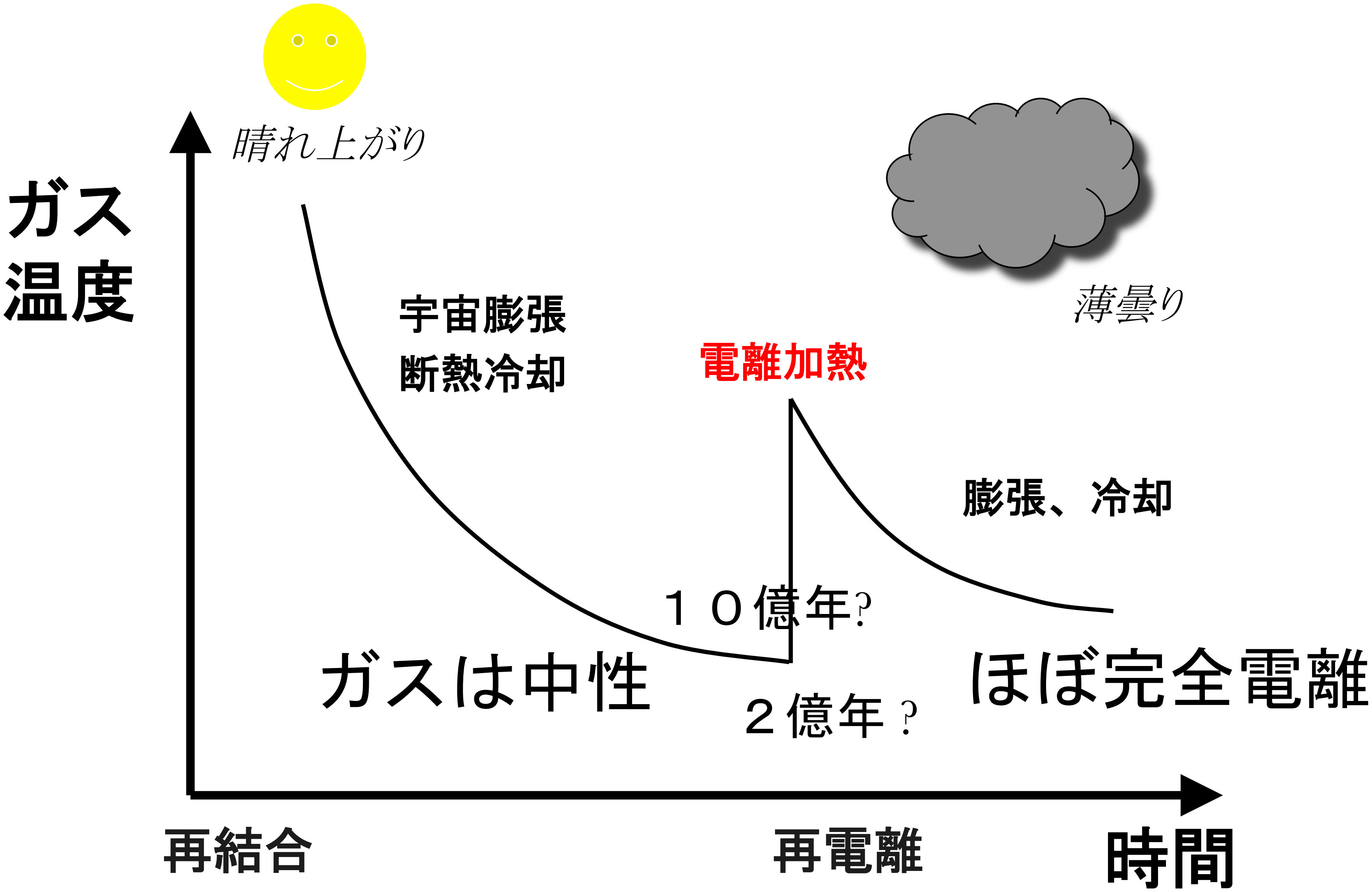
Hydrogen Reionization and Gunn-Peterson Trough



Transmission shortward (blue side) of Lyman-a completely suppressed - “a trough”.


J103027.10+052455.0 (z=6.28)
Quasar rest-UV spectrum
中性水素
ionized
neutral
IGM evolution

ビッグバンの後、晴れのち曇り

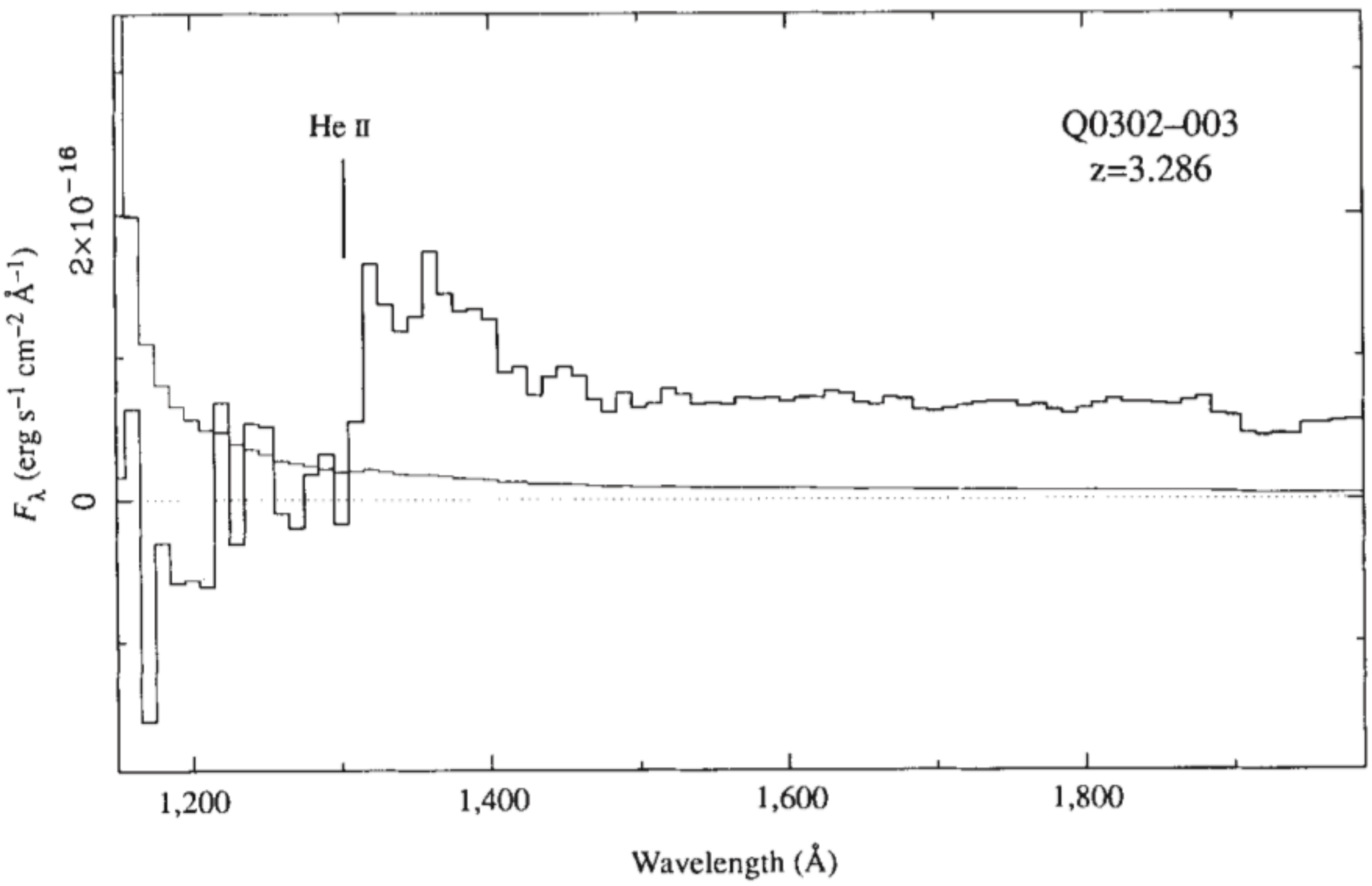


Hydrogen Reionization

$$\mathrm{H} + \gamma \rightarrow \mathrm{p} + \mathrm{e}$$

The ionization potential of an H atom is 13.598 eV. Photons more energetic than this can *photo-ionize* hydrogen.
The residual energy is carried out by detached electrons, which eventually heat up the gas (IGM). Suppose that 1eV per ionization (per H atom) is deposited as heat; this is sufficient to raise the gas temperature to ~ 10000 K.

HeII Gunn-Peterson Trough



Detection of intergalactic ionized helium absorption in a high-redshift quasar

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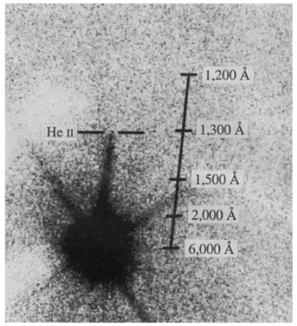
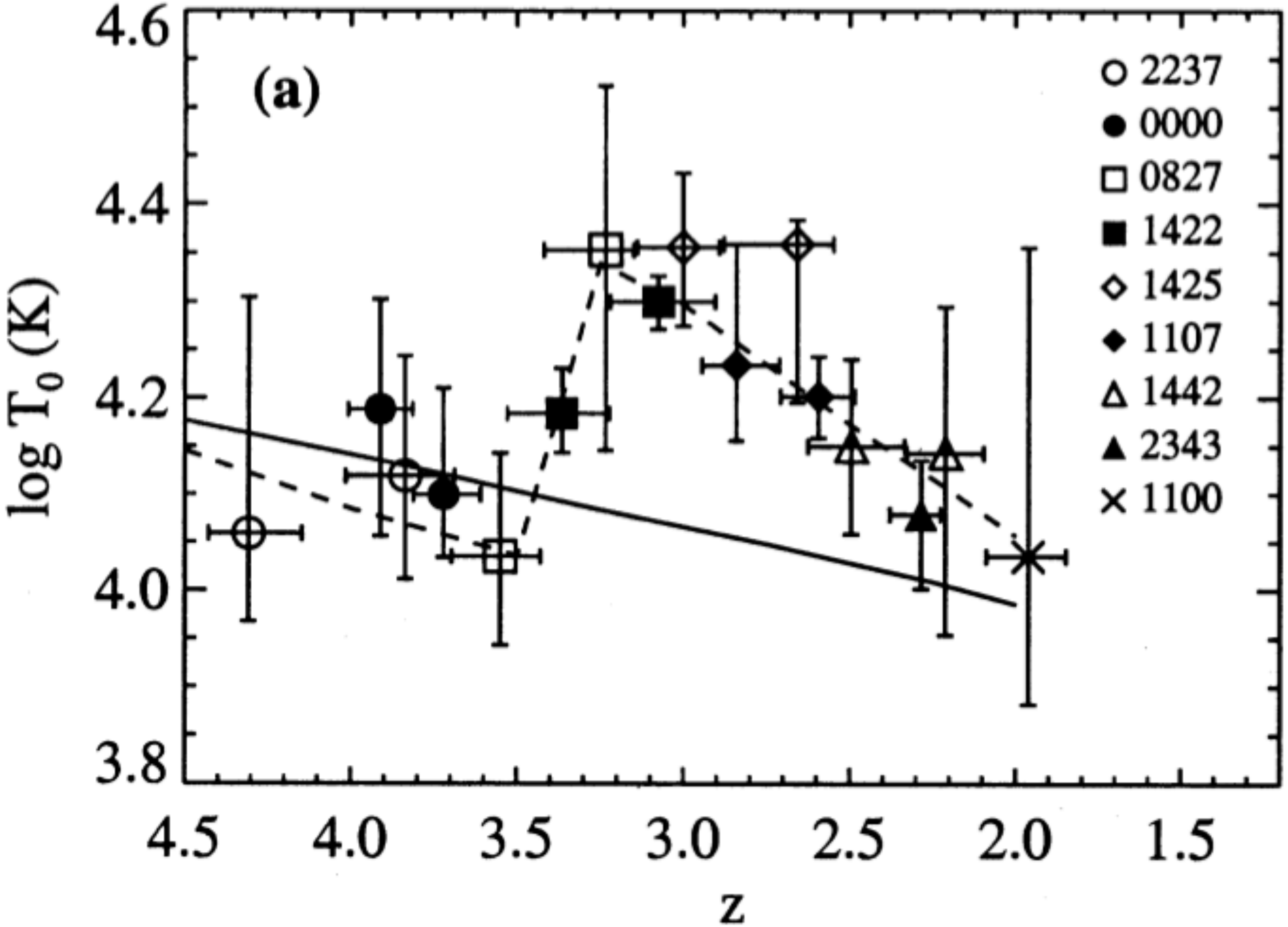
[*] Astrophysics Division, Space Science Department of ESA, ESTEC, 2200 AG Noordwijk, The Netherlands
[†] Royal Greenwich Observatory, Madingley Road, Cambridge CB3 0EZ, UK
[‡] Laboratoire d'Astronomie Spatiale du CNRS, Traverse du Siphon, Les Trois Lucs, 13012 Marseille, France
[§] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, Maryland 21218, USA

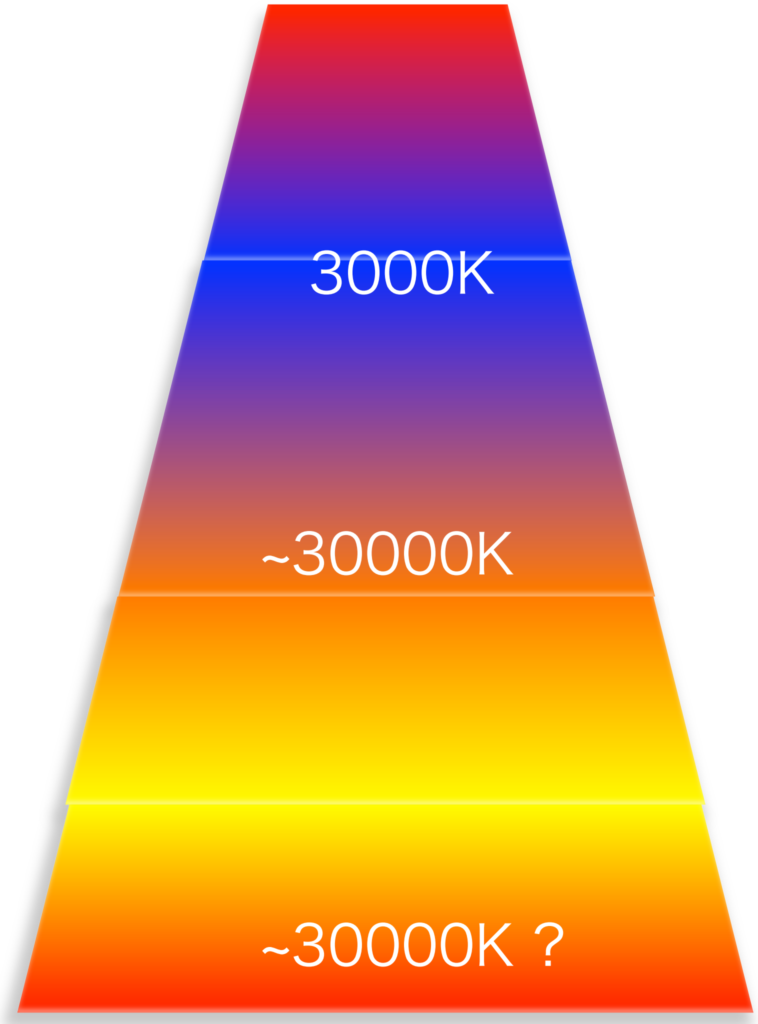


Observations obtained with the recently refurbished Hubble Space Telescope reveal strong absorption arising from singly ionized helium along the line of sight to a high-redshift quasar. The strength of the absorption suggests that it may arise in a diffuse ionized intergalactic medium. The detection also confirms that substantial amounts of helium existed in the early Universe, as predicted by Big Bang nucleosynthesis theory.

HeII reionization



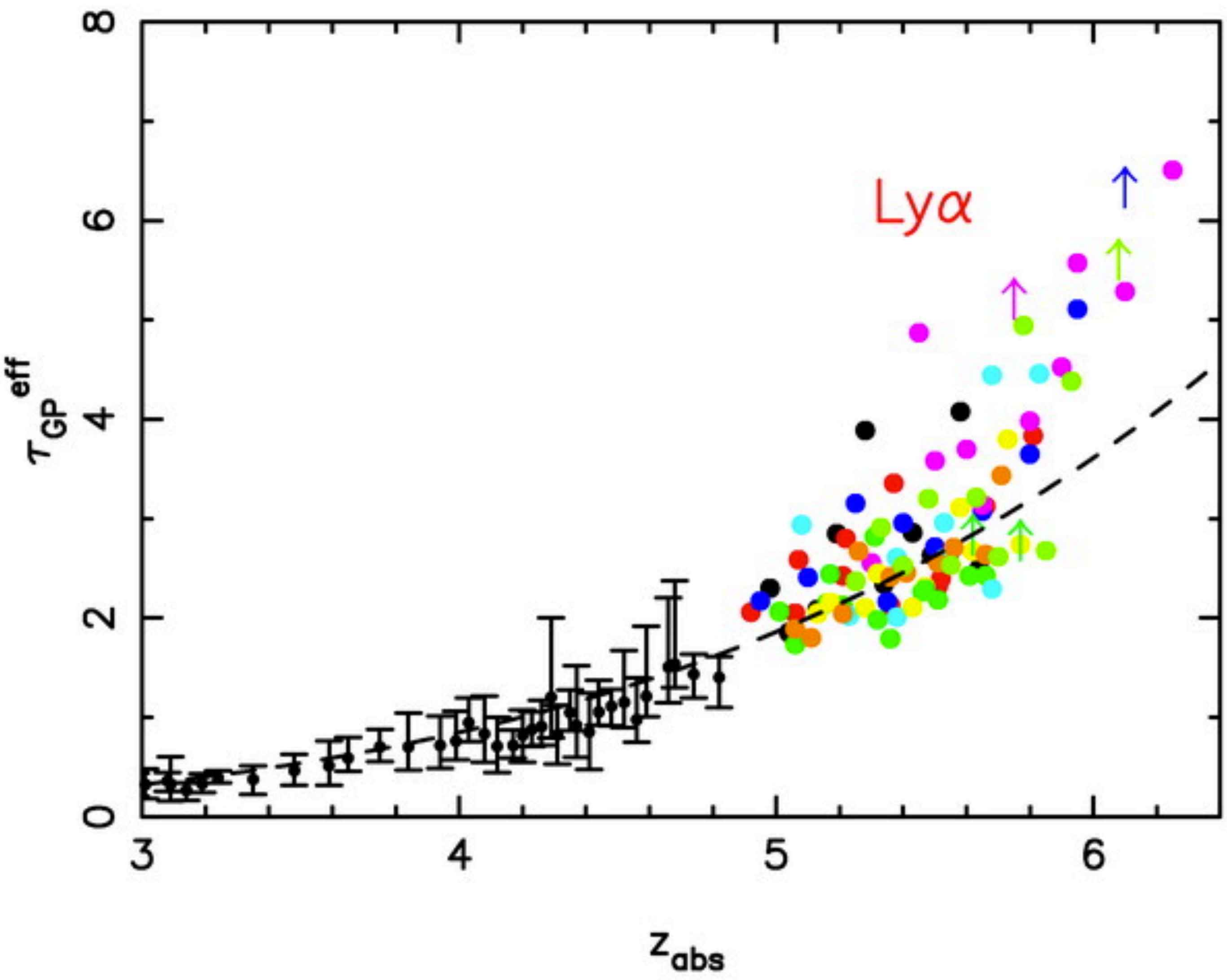
Thermal history of the Universe
- structure formation view -



Star/Galaxy formation

Quasar formation

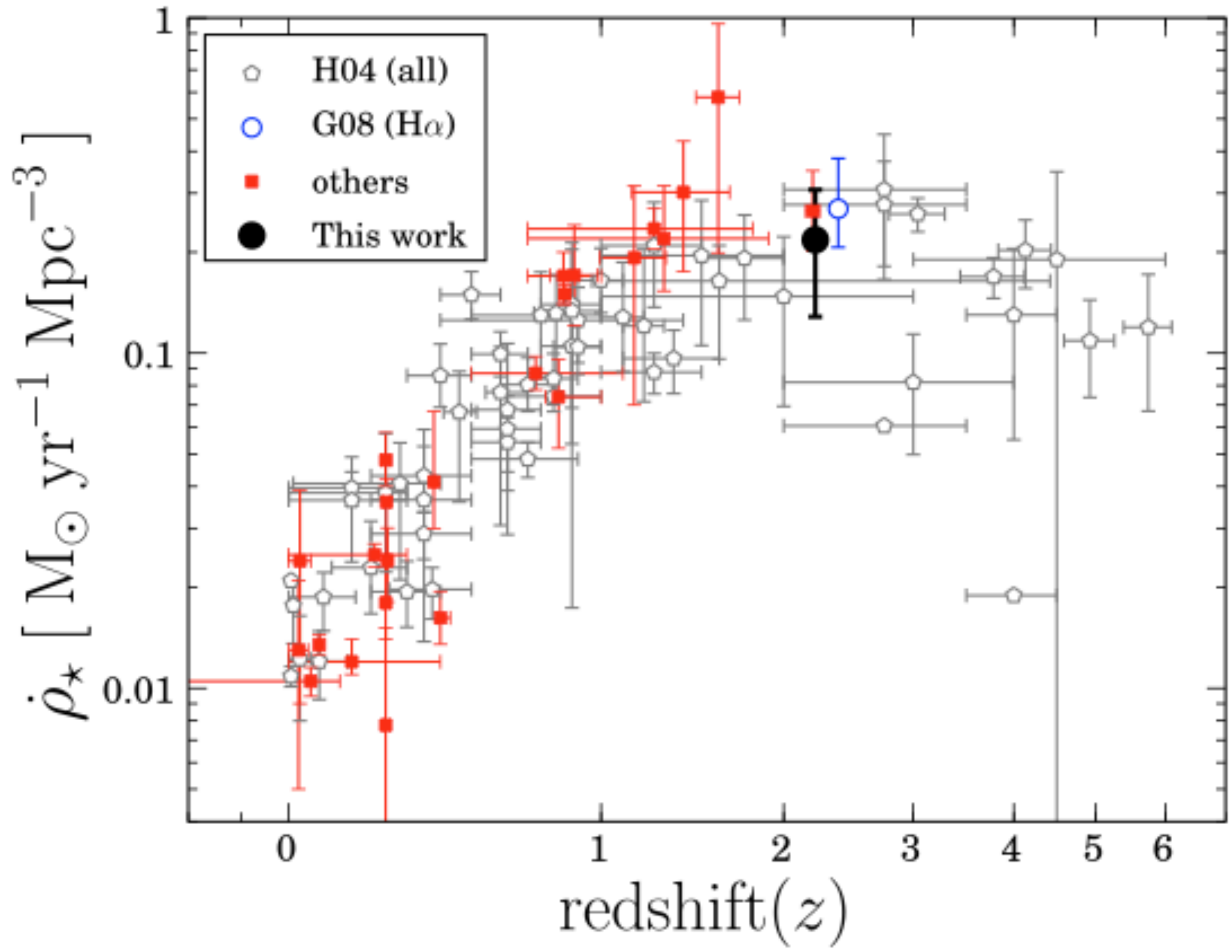
IGM almost fully ionized at z<6



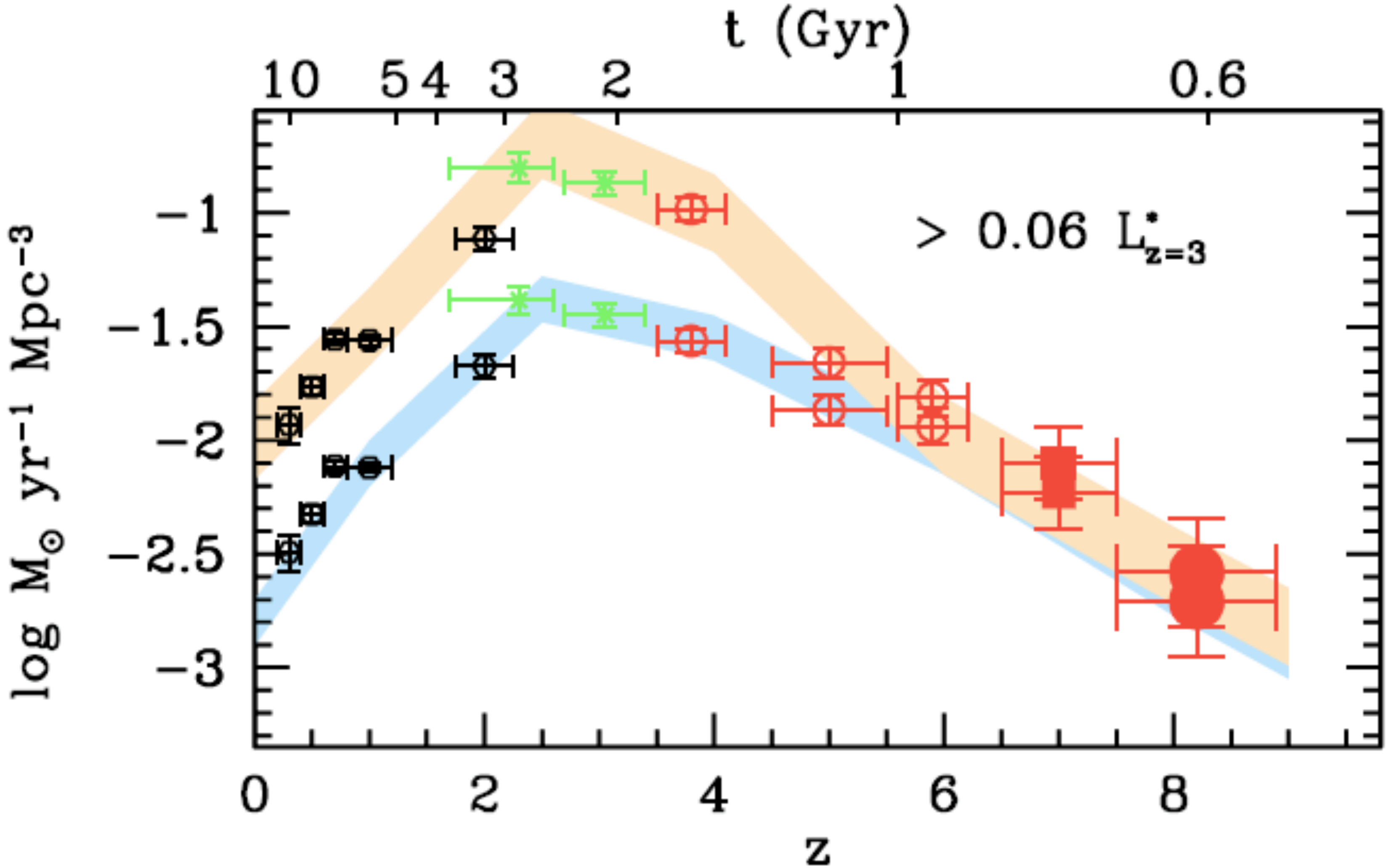
Quiz 3: 宇宙再電離

1メガパーセク(324万光年）立方あたり
10^{67} 個の水素原子が存在する。
　20太陽質量の種族I星は平均しておよそ
8×10^{47} 個 / 秒 の紫外光を放出する。
宇宙にある水素全てを電離するには
このような星がいくつ生まれなくては
ならないか。

Cosmic Star Formation History

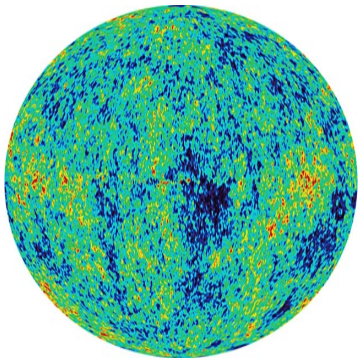


Cosmic Star Formation History

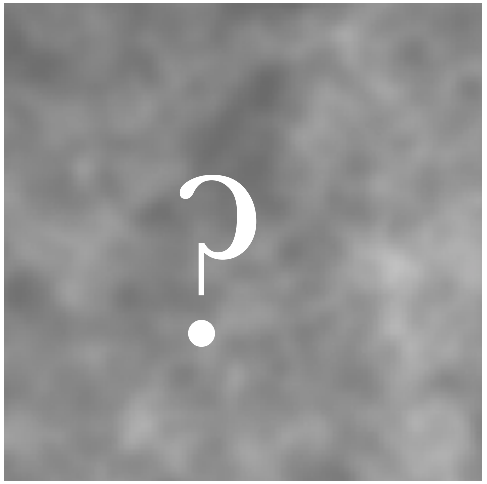


Star formation in the early universe

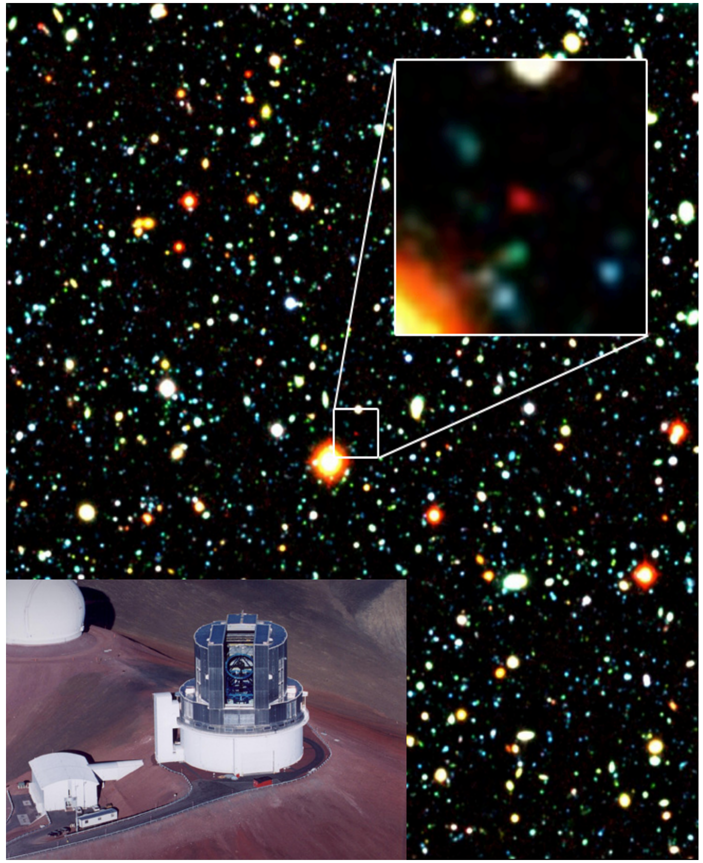
Known, Unknown, Known



Baby Universe
~ 380 Kyrs



Dark Ages
~ a million years ?



Farthest galaxy
~ 6
00 Myrs

In the beginning, there was a sea
oif light elements and dark matter…
And some ripples.

Primordial gas chemistry

e, H, H+, H−, H2, H2+, He, He+, He++ D, D+, D−, HD, HD+

Composition: 76% H, 24% He、10^{-5} D、little Li

- Collisional ionization, recombination
- Formation of molecules (H_2, HD, H_3^+, H_2^+, HD^+, HeH)
- Photoionization, photo-dissociation
- Radiative cooling

  collisional excitation, collisional ionization, recombination, Bbremsstrahlung, compton cooling, CMB heating

~ 50-70 reactions

Chemical reactions and rates

$H + e \rightarrow H^{+} + 2e$	$k_1 = \exp[-32.71396786 + 13.536556(\ln T_e) - 5.7$
	$+ 0.0348255977(\ln T_e)^5 - 0.00263197617(\ln$
$H^{+} + e \rightarrow H + h\nu$	$k_2 = \exp[-28.6130338 - 0.72411256 \ln T_e - 0.02$
	$+ 4.98910892 \times 10^{-6}(\ln T_e)^6 + 5.75561414 \times$
$He + e \rightarrow He^{+} + 2e$	$k_3 = \exp[-44.09864886 + 23.91596563 \ln T_e - 10$
	$+ 0.0679539123(\ln T_e)^5 - 0.00500905610(\ln$
$He^{+} + e \rightarrow He + h\nu$	$k_{4r} = 3.925 \times 10^{-13} T_e^{-0.6353}$, $k_{4d} = 1.544 \times 10^{-9} T_e^{-1}$
$He^{+} + e \rightarrow He^{++} + 2e$	$k_5 = \exp[-68.71040990 + 43.93347633 \ln T_e - 18$
	$+ 0.08113042(\ln T_e)^5 - 0.00532402063(\ln T_e)$
$He^{++} + e \rightarrow He^{+} + h\nu$	$k_6 = 2 \times k_2(T_e/4)$
$H + e \rightarrow H^{-} + h\nu$	$k_7 = 1.4 \times 10^{-18} T^{0.928} \exp(-T/16200)$
$H^{-} + H \rightarrow H_2 + e$	$k_8 = 4.0 \times 10^{-9} T^{-0.17}$
$H + H^{+} \rightarrow H_2^{+} + h\nu$	$k_9 = \mathrm{dex}[-19.38 - 1.523 \log T + 1.118(\log T)^2 -$
$H_2^{+} + H \rightarrow H_2^{*} + H^{+}$	$k_{10} = 6.0 \times 10^{-10}$

Above is just a partial list.

Stars are formed…

in a cold, dense, molecular gas cloud.

Gravity alone does not make it. Gravitational collapse compresses and heats the gas.

We need a mechanism to cool a gas cloud.

Radiative cooling removes the excess energy (i.e., lower the gas pressure) and makes it possible for the gas to cool and condense.

Radiative cooling operates *only* if there are coolants.

How did all this happen in the early universe ?

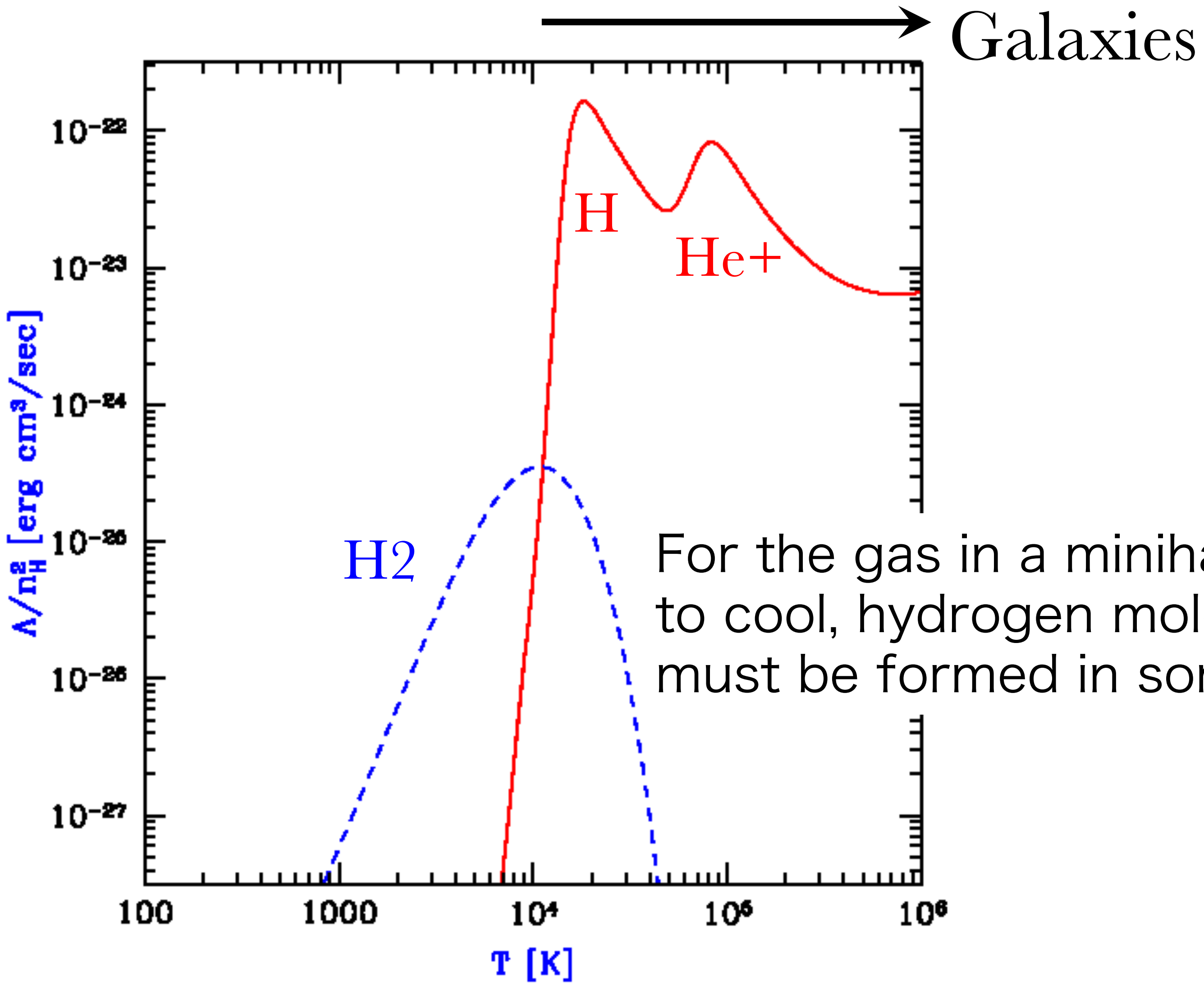
In the present-day universe...

Interstellar gas can cool by, e.g.,

* Metallic ions such as Fe, Si, O
* Molecules such as CO, OH
* Dust thermal emission

None of these coolants existed in the early universe.

Primordial cooling function



For the gas in a minihalo to cool, hydrogen molecules must be formed in some way.

H2 Formation : Gas phase reactions

Photo-attachment

$$\mathrm{H} + \mathrm{e} \rightarrow \mathrm{H}^{-} + h\nu$$

H_2 formation

$$\mathrm{H}^{-} + \mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{e}$$

Slow reactions, using residual electrons as a catalyst.

Effective at T > 1000 K (M ~ 10^5 Msun)

Molecular fraction reaches ~ 0.001

H2 Formation : Gas phase reactions

Photo-attachment

$$\mathrm{H} + \mathrm{e} \rightarrow \mathrm{H}^- + h\nu$$

H_2 formation

$$\mathrm{H}^- + \mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{e}$$

Slow reactions, using residual electrons as a catalyst.

Effective at T > 1000 K (M ~ 10^5 Msun)

Molecular fraction reaches ~ 0.001

A brief History

Late 60's) Pregalactic clouds, molecular hydrogen

Matsuda-Sato-Takeda, Yoneyama, Saslaw & Zipoy

Peebles & Dicke (globular cluster)

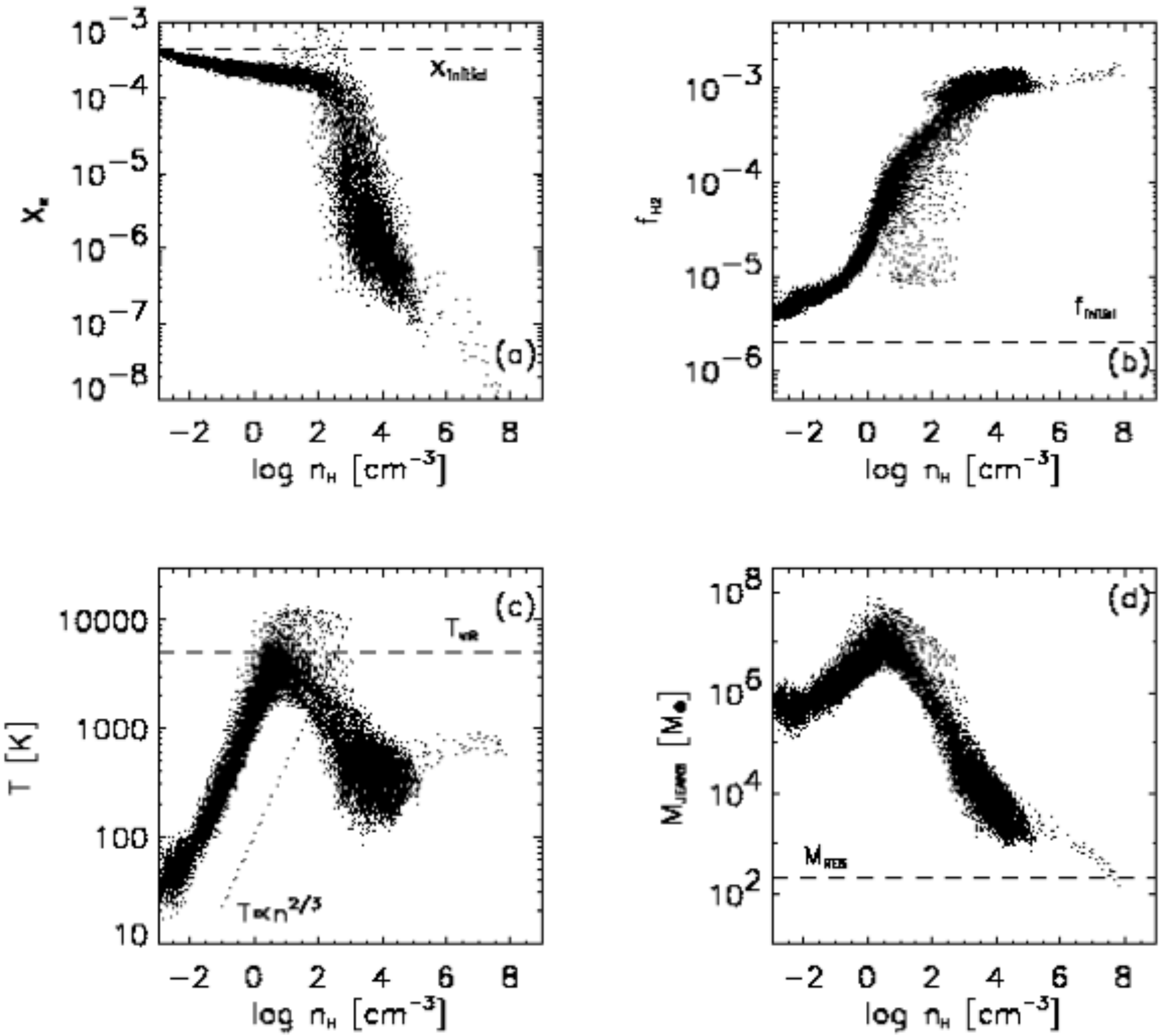
Early 80's) Primordial star formation, fragmentation

Palla-Stahler-Salpeter, Yoshii, Silk, Couchman & Rees (DM)

2000-) Protostar formation, cosmological simulations

Omukai-Nishi, Ripamonti-Ferrara+, Bromm+, Abel+

Primordial gas cloud



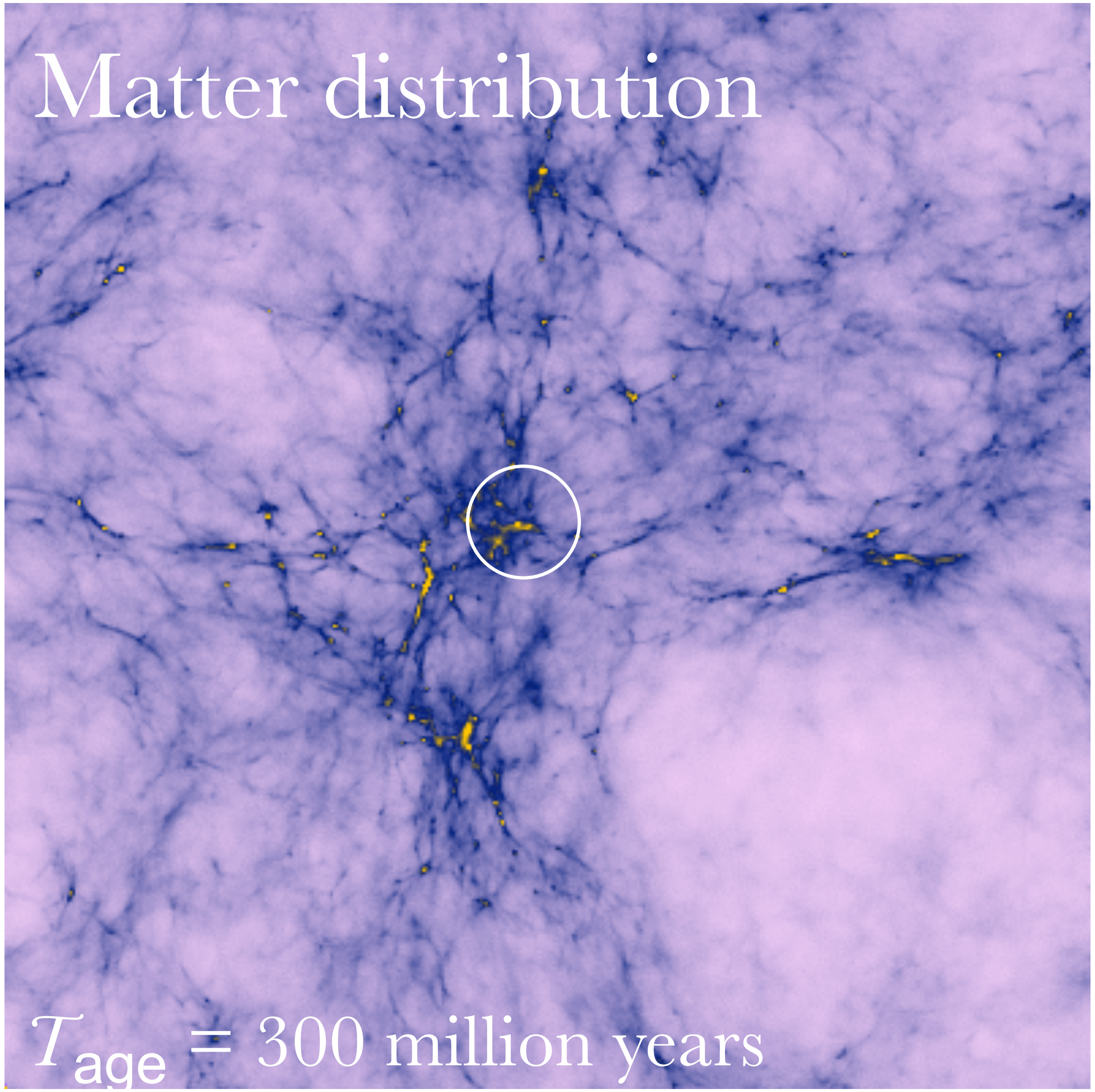
Bromm, Coppi, Larson 2002

Physical properties of H2 molecules connected to thermal evolution.

ΔE (J=2 → 0) ~ 512 K sets the minimum temperature.

Non-LTE cooling to LTE cooling "loitering".

Cosmological First Objects

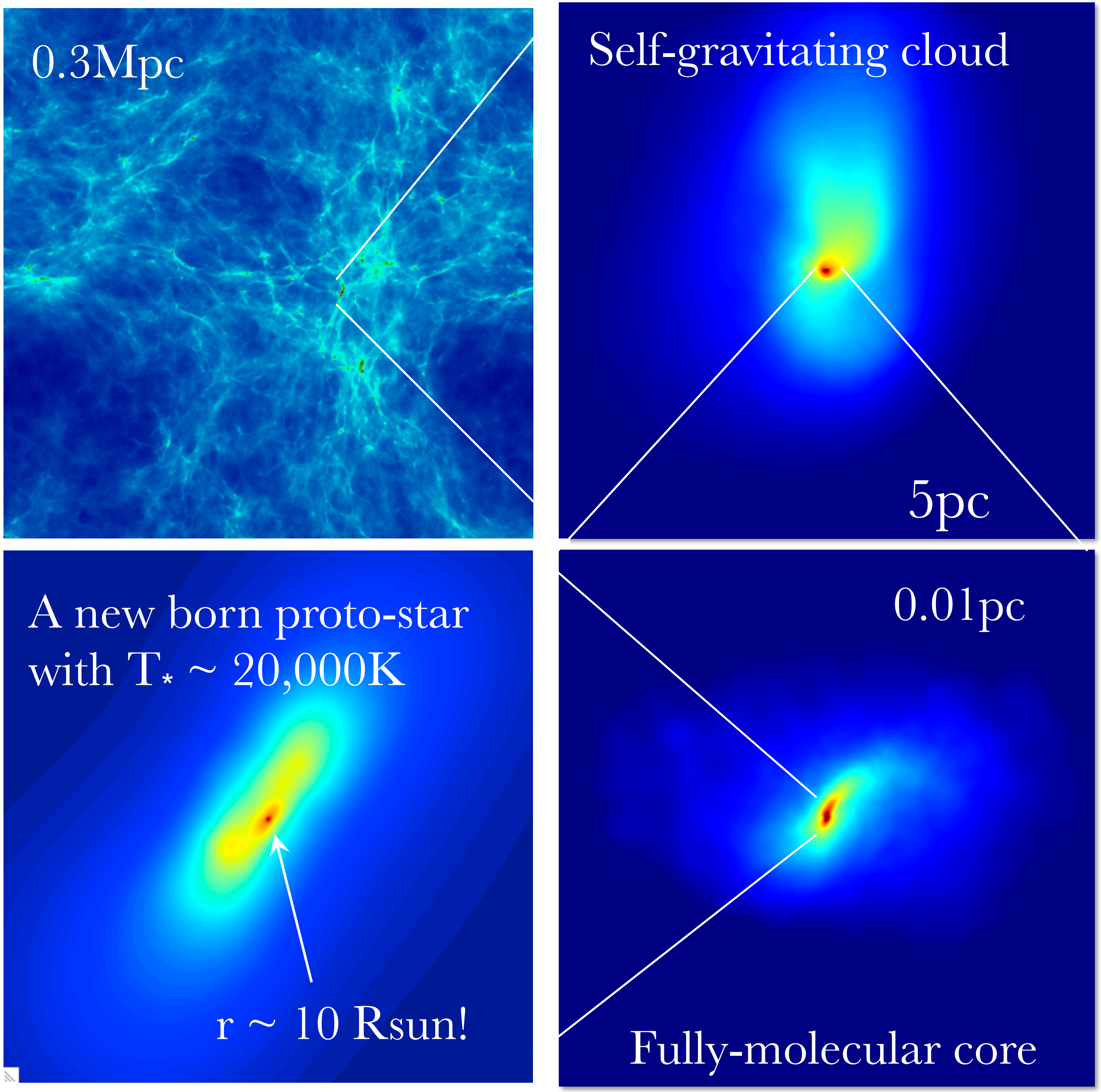


Web-like structure
in the early universe.

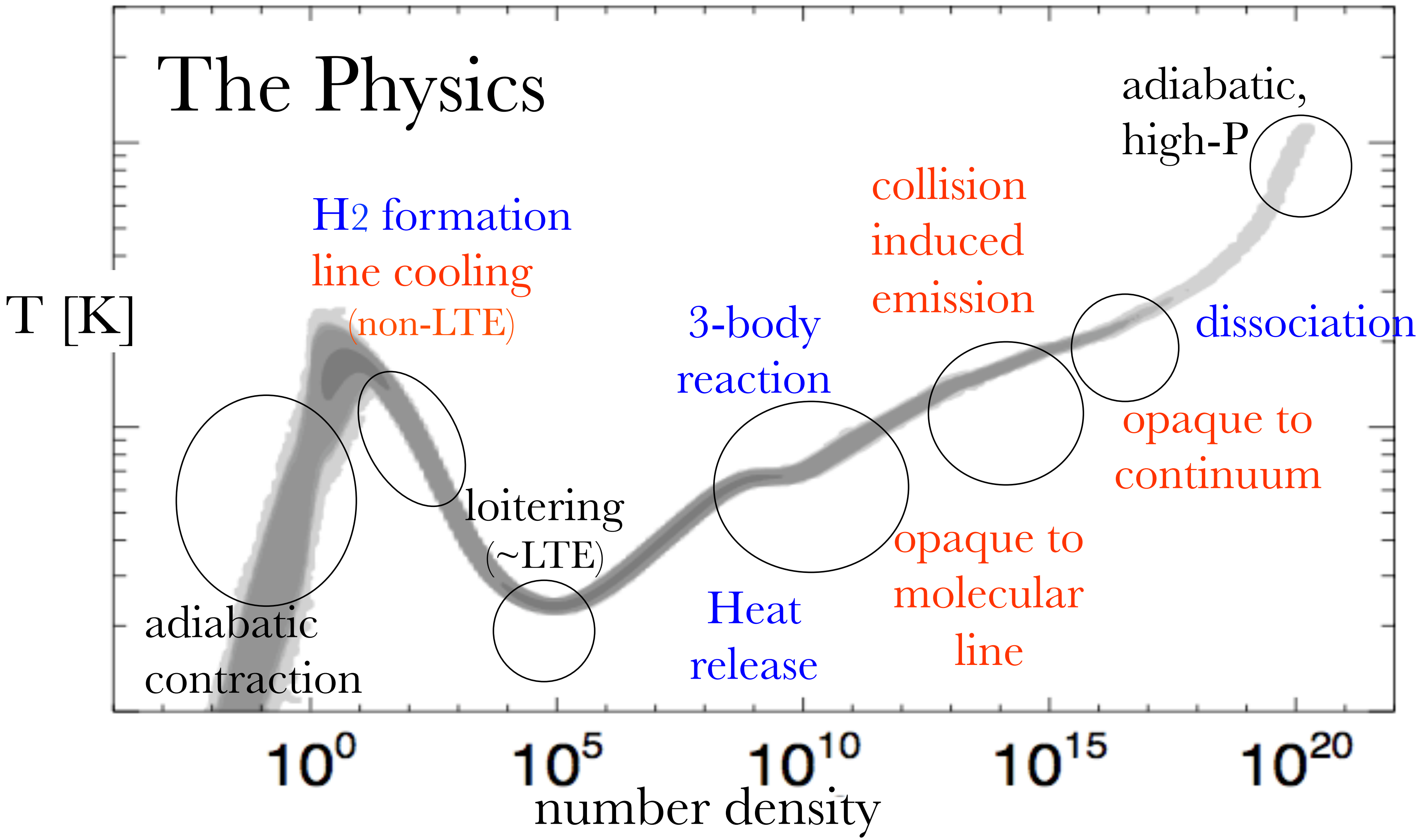
Halo mass
~ 1,000,000 Msun

Gas clouds
are ~ 1000 Msun.

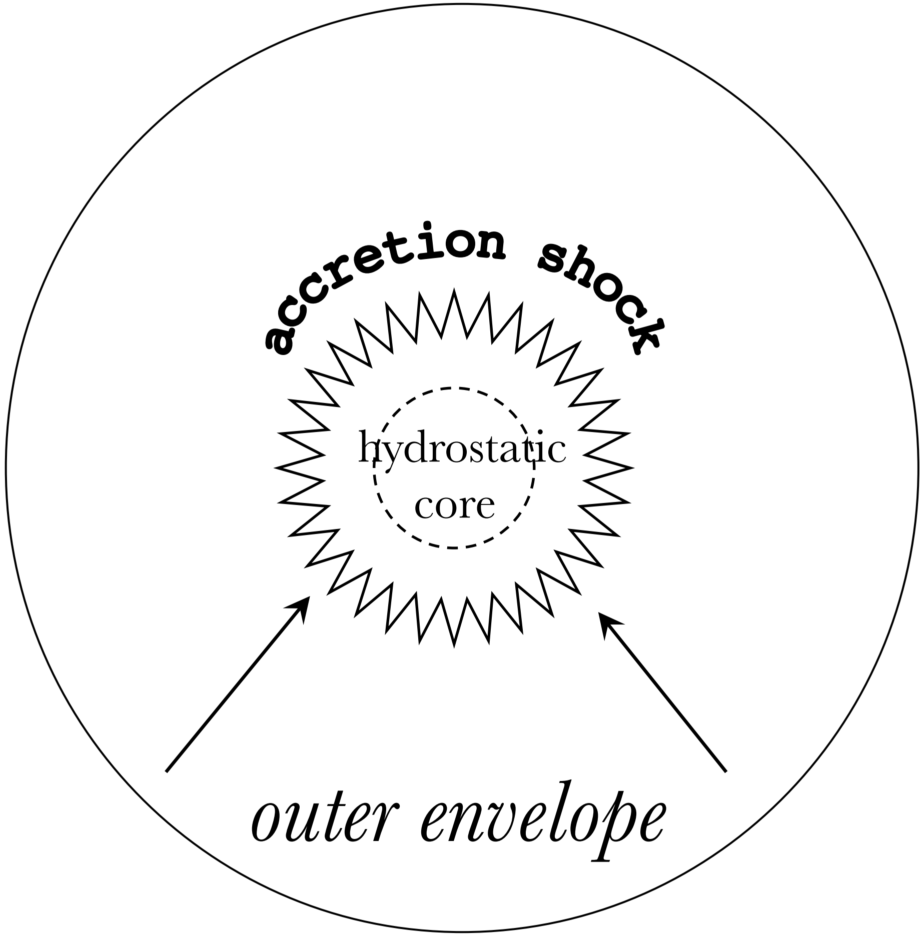
Strongly clustered.


0.3Mpc
Self-gravitating cloud
5pc
A new born proto-star
with T* ~ 20,000K
r ~ 10 Rsun!
0.01pc
Fully-molecular core

THERMAL EVOLUTION OF A PRE-STELLAR GAS



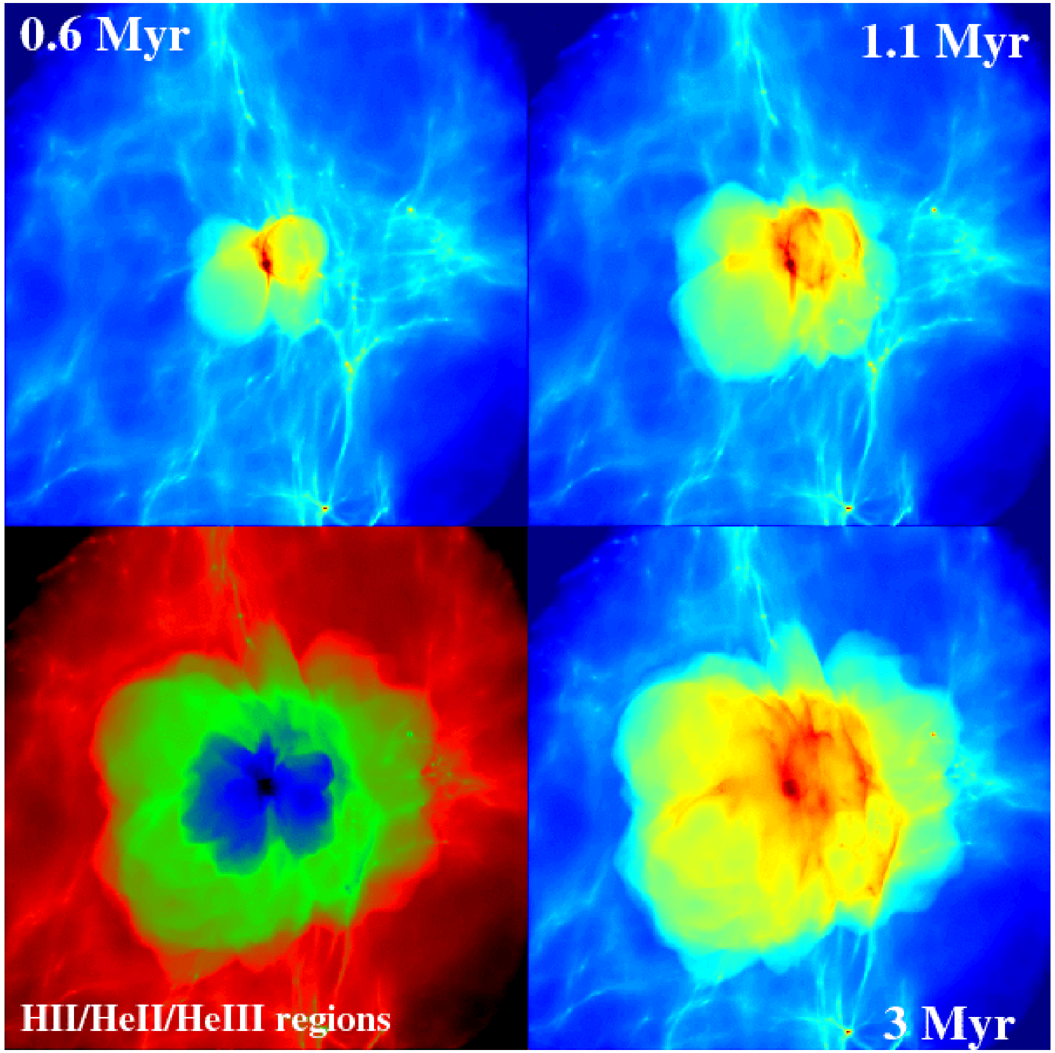
Protostellar evolution



The hot gas is accreted onto the central proto star.

The star grow rapidly to become very large.

ファーストライト



質量が太陽の数十倍だと明るさは十万倍以上。

エネルギーの高い紫外線を放出し、周辺ガスを電離

図　明るい黄色の部分は中心星により暖められたガス

References (textbooks)

Peter Coles and Francesco Lucchin

Cosmology (Wiley)

Abraham Loeb, *How did the first stars and galaxies form ?* (Princeton University Press)

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The Astronomy Revolution (Taylor & Francis)

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B. Ciardi and A. Ferrara
Space Science Reviews (2005)