# 天文学正在发现


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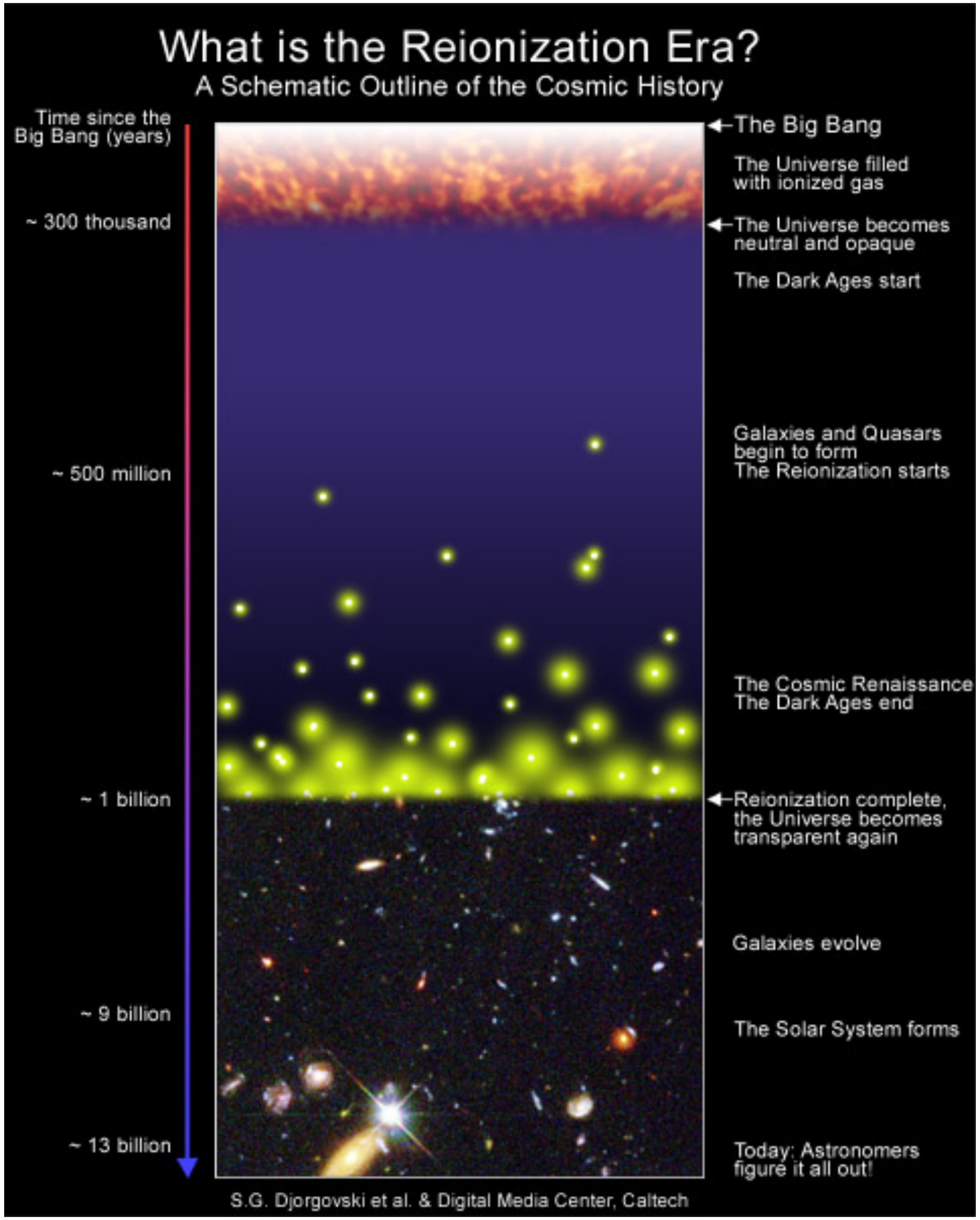
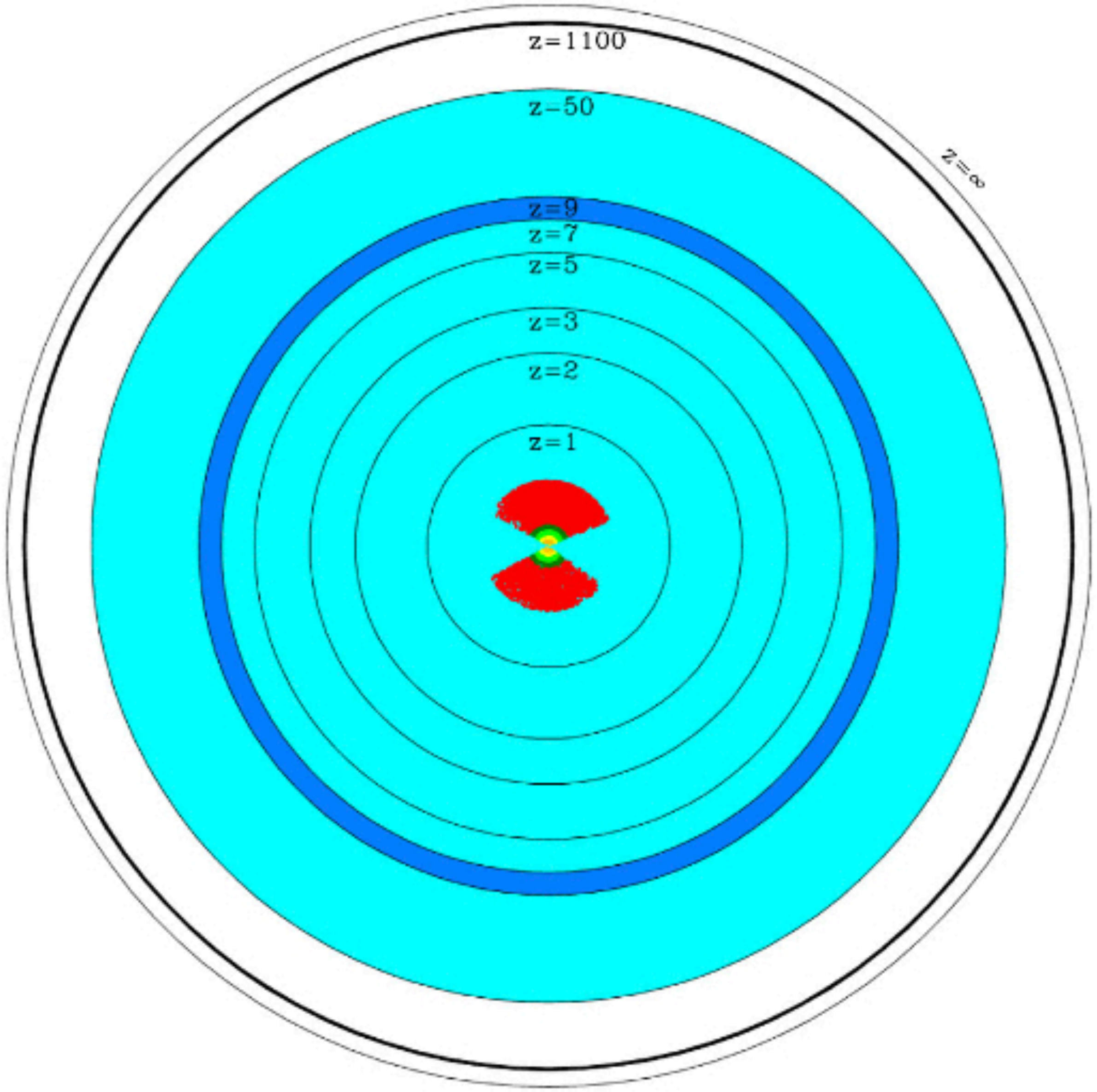
## outline

1. 膨胀宇宙的发现
2. 暗物质的发现
3. 暗能量的发现
4. 宇宙微波背景辐射的发现
5. 中微子的发现
6. 引力波的发现
7. 脉冲星的发现
8. 宇宙第一缕曙光的“发现”

# dark ages

# Cosmic Dark Ages



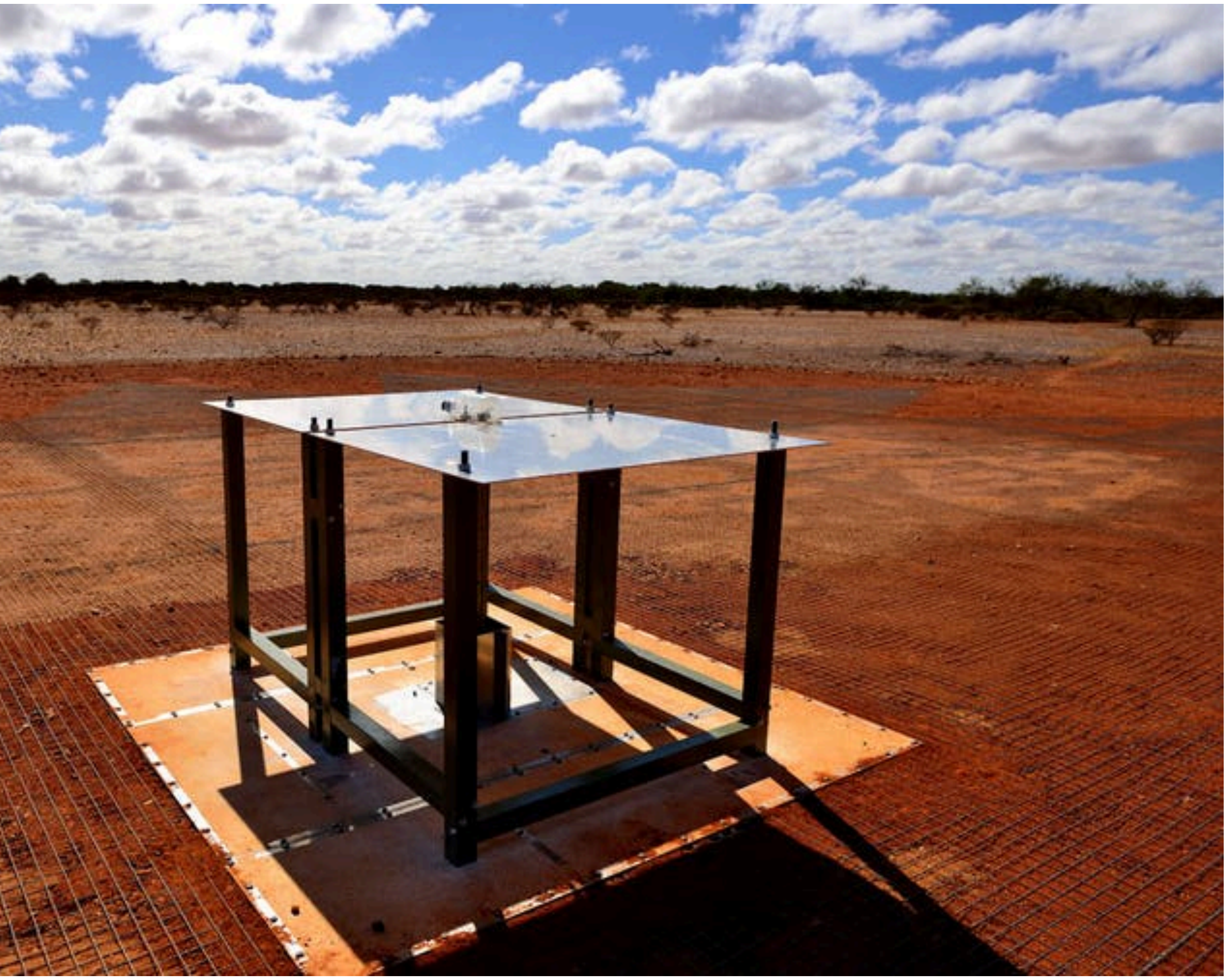
# What does she tell us?

# LETTER

doi:10.1038/nature25792

# An absorption profile centred at 78 megahertz in the sky-averaged spectrum

Judd D. Bowman[1], Alan E. E. Rogers[2], Raul A. Monsalve[1,3,4], Thomas J. Mozdzer



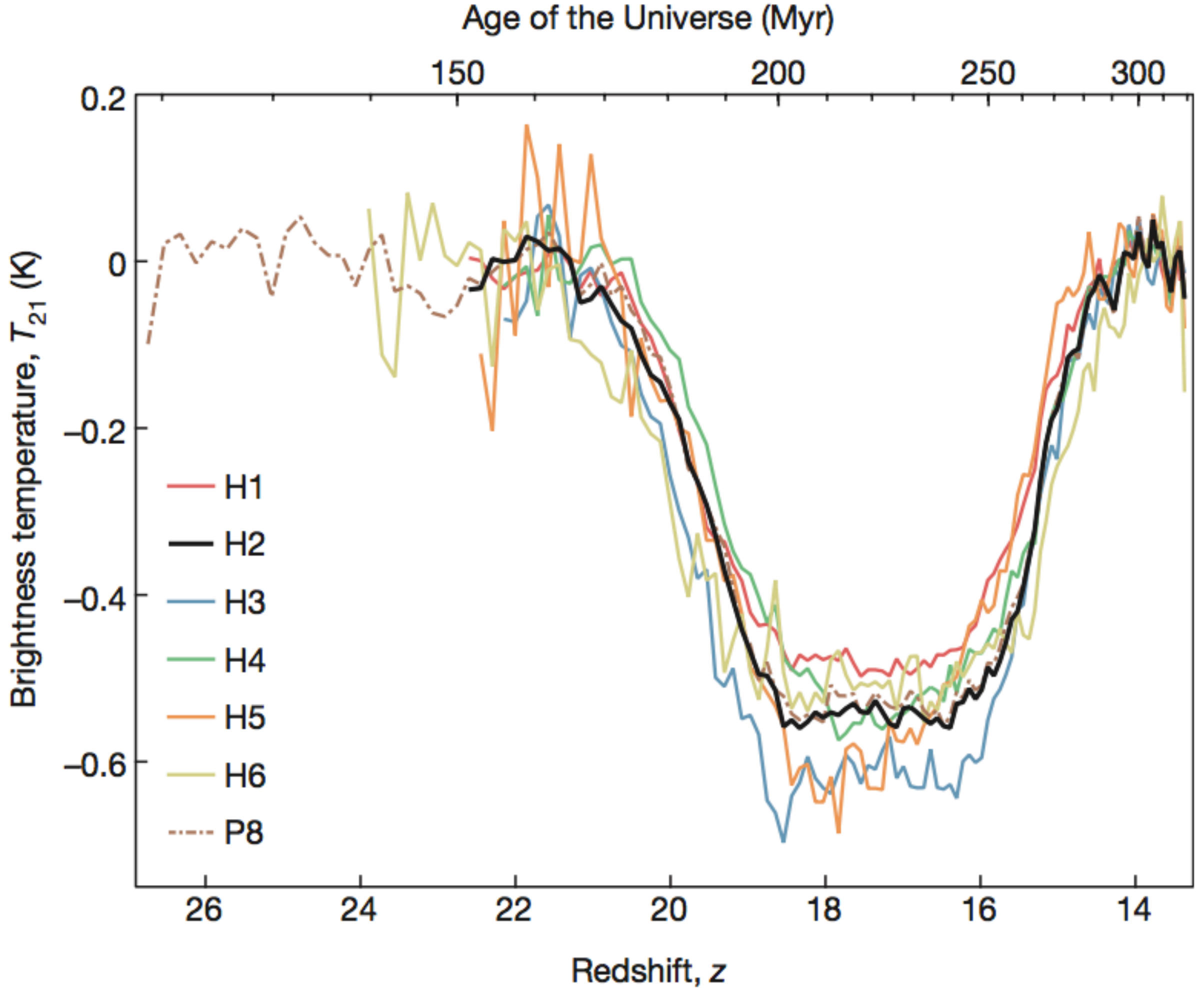
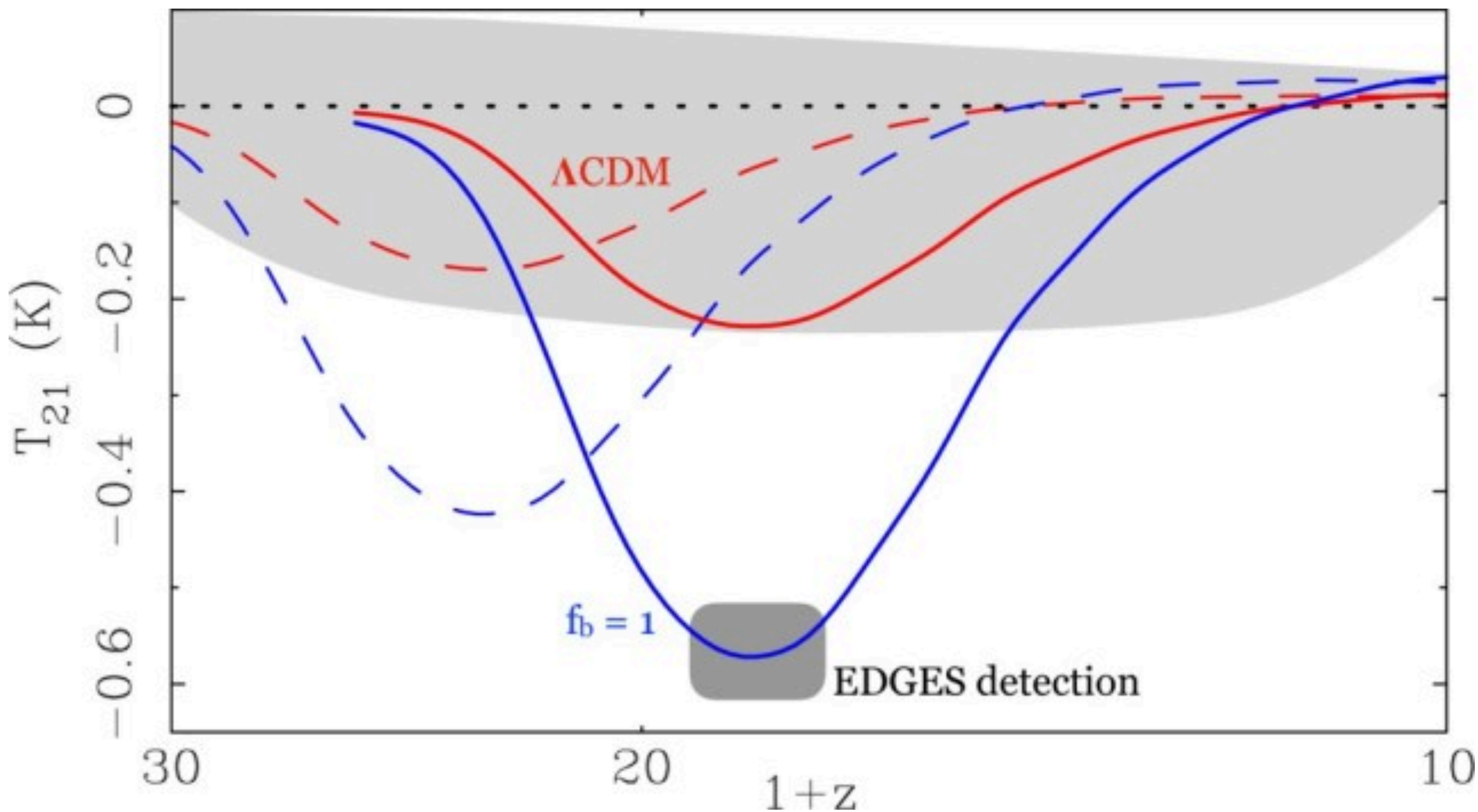
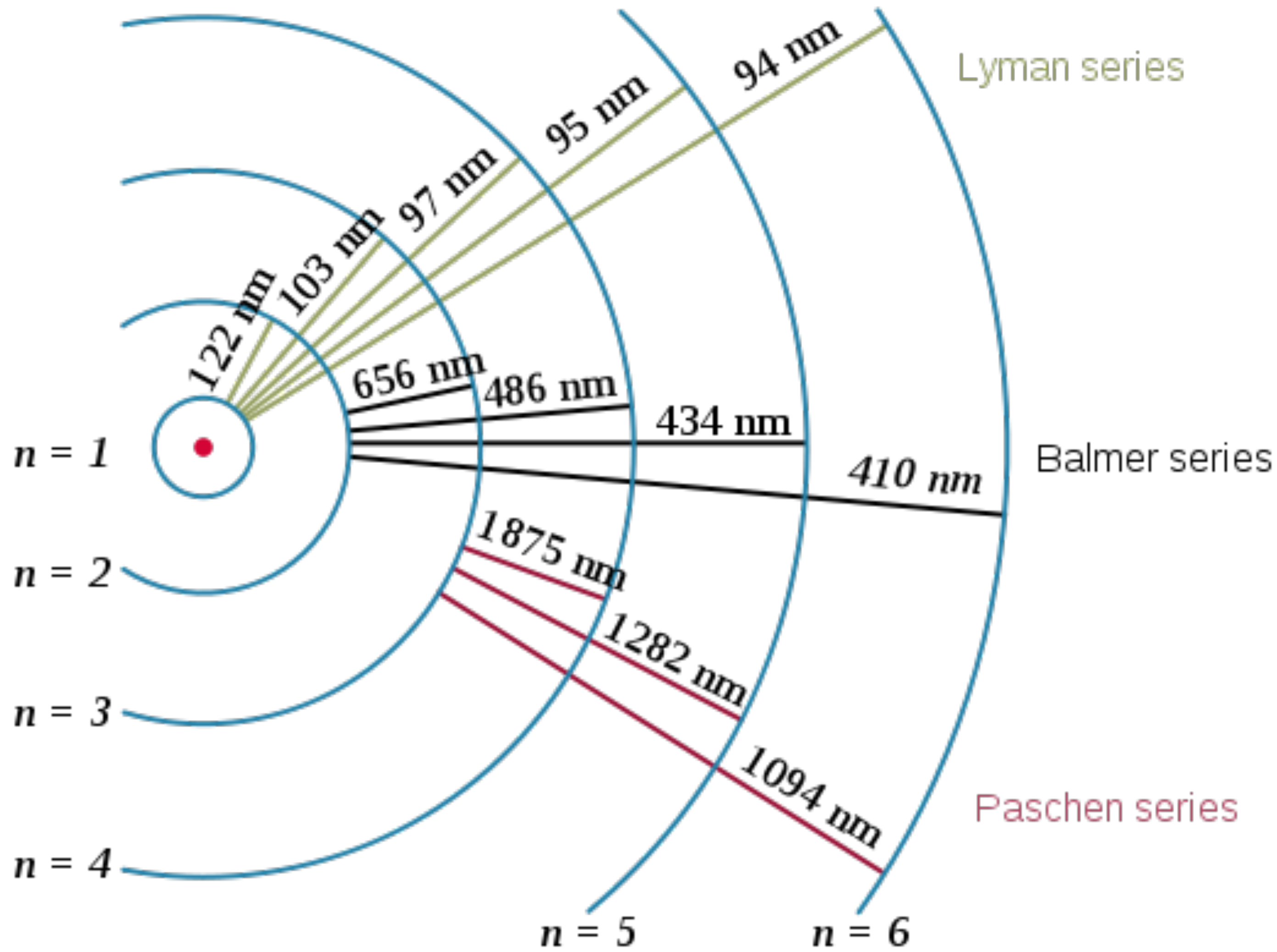



**Figure 2 | Best-fitting 21-cm absorption profiles for each hardware case.** Each profile for the brightness temperature $T_{21}$ is added to its residuals and plotted against the redshift $z$ and the corresponding age of the Universe. The thick black line is the model fit for the hardware and analysis configuration with the highest signal-to-noise ratio (equal to 52; H2; see Methods), processed using 60–99 MHz and a four-term polynomial (see equation (2) in Methods) for the foreground model. The thin solid lines are the best fits from each of the other hardware configurations (H1, H3–H6). The dash-dotted line (P8), which extends to $z > 26$, is reproduced from Fig. 1e and uses the same data as for the thick black line (H2), but a different foreground model and the full frequency band.


CRISIS
OPPORTUNITY


ΛCDM
$f_b = 1$
EDGES detection
$T_{21}$ (K)
0
−0.2
−0.4
−0.6
30
20
10
1+z

# Let us first understand what it is!




$n \to 1$

$n \to 2$

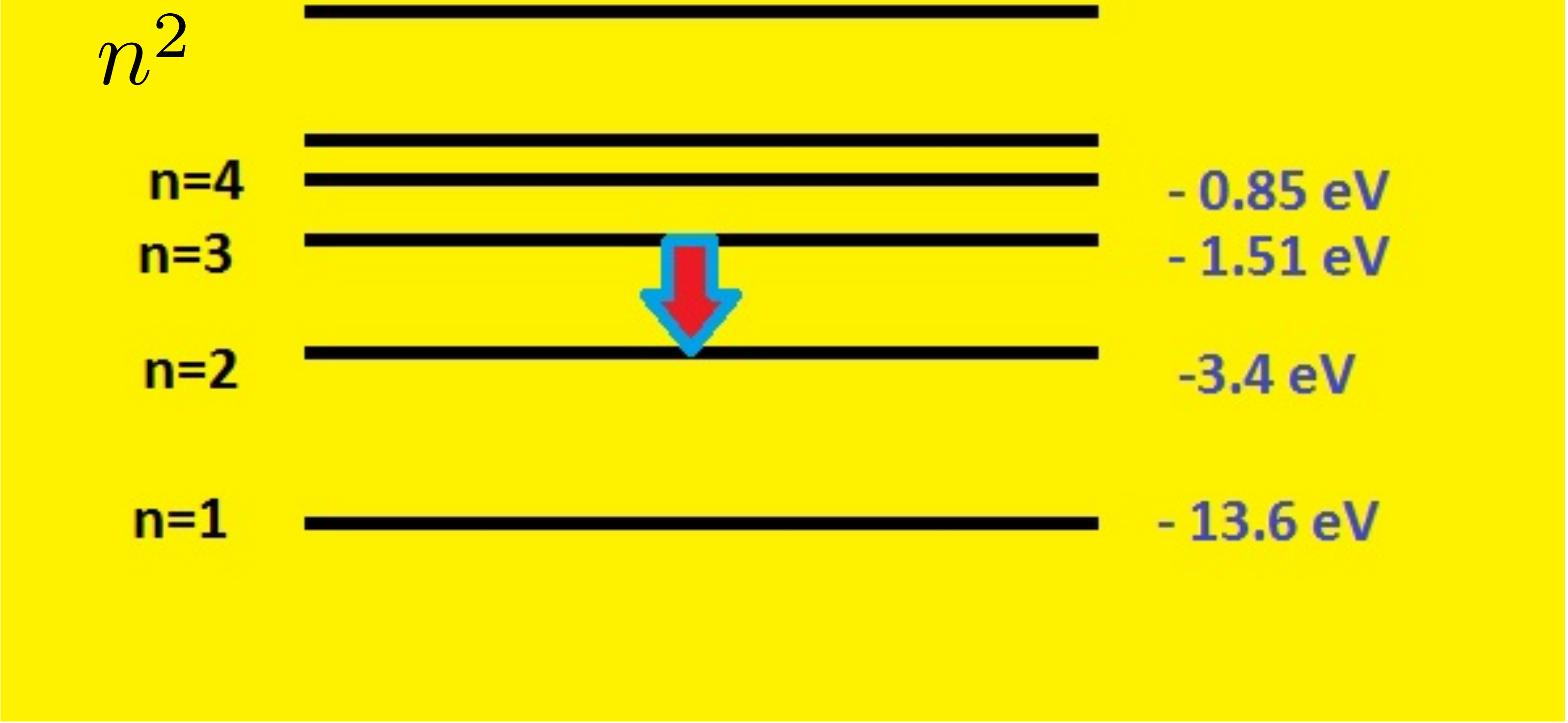
$n \to 3$

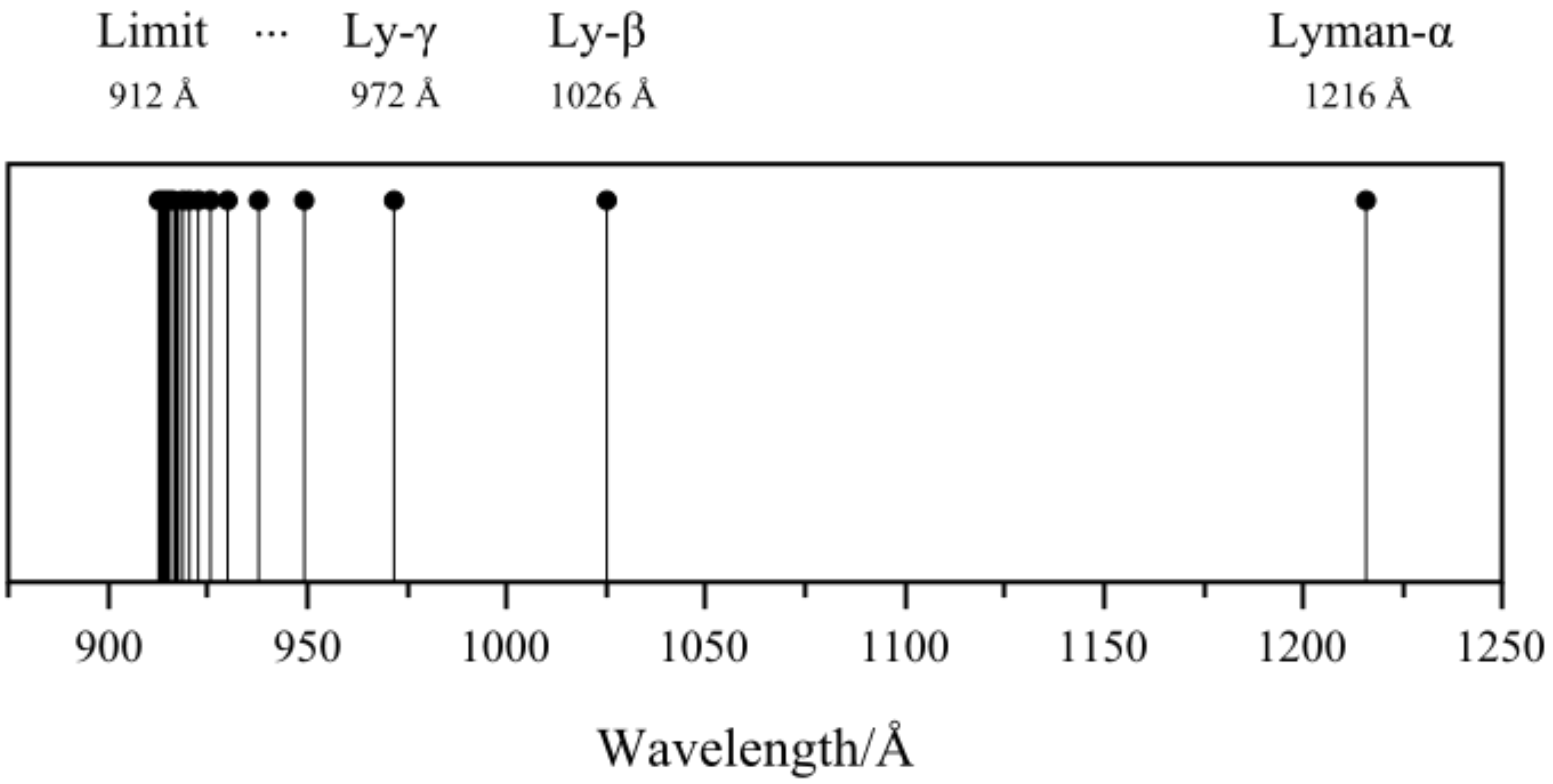
**from *n* = 2 to *n* = 1 is called Lyman-alpha, 3 to 1 is Lyman-beta, 4 to 1 is Lyman-gamma, and so on**

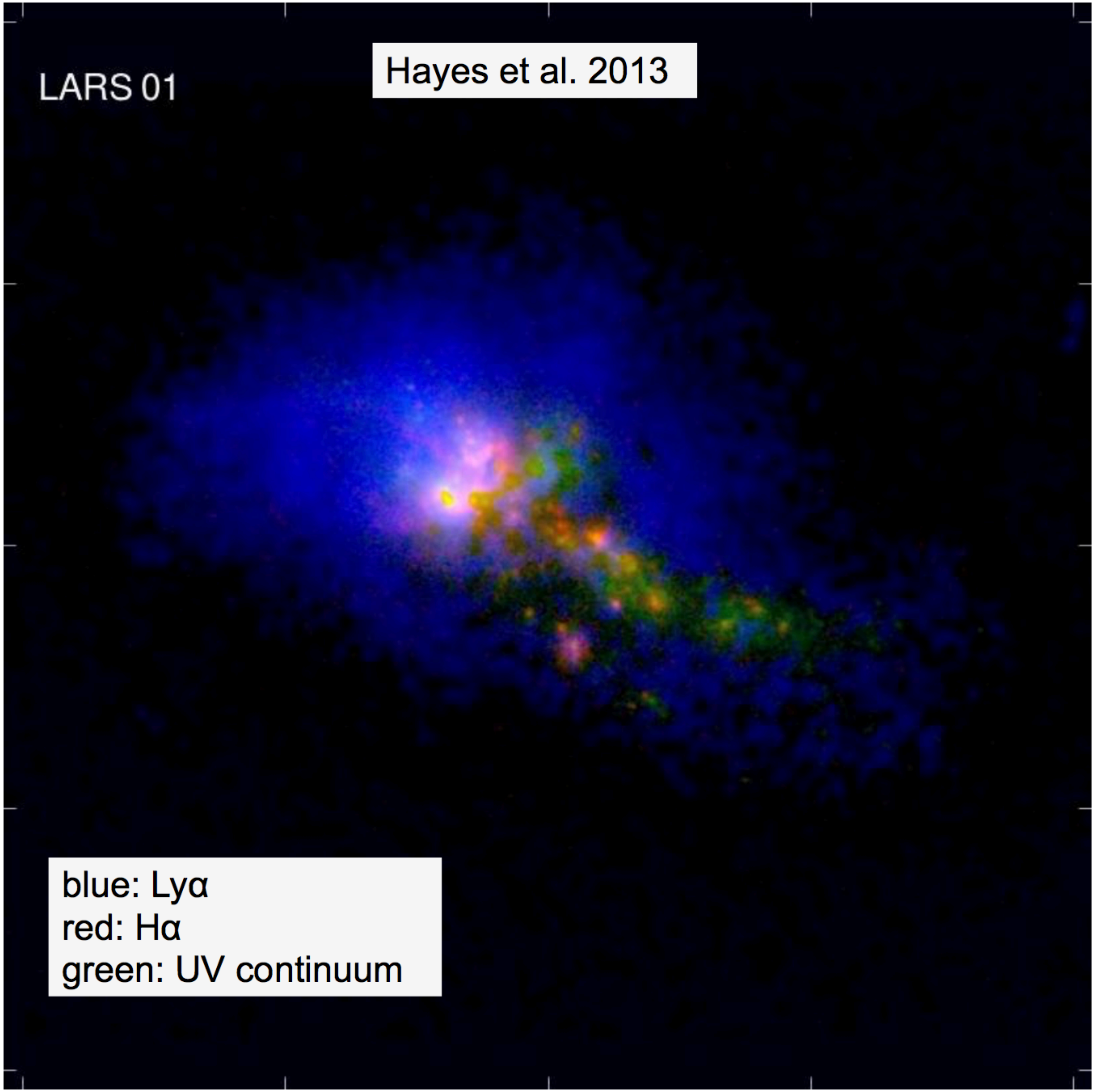
*n* = 3 to *n* = 2 is called H-α, 4 to 2 is H-β, 5 to 2 is H-γ, and 6 to 2 is H-δ

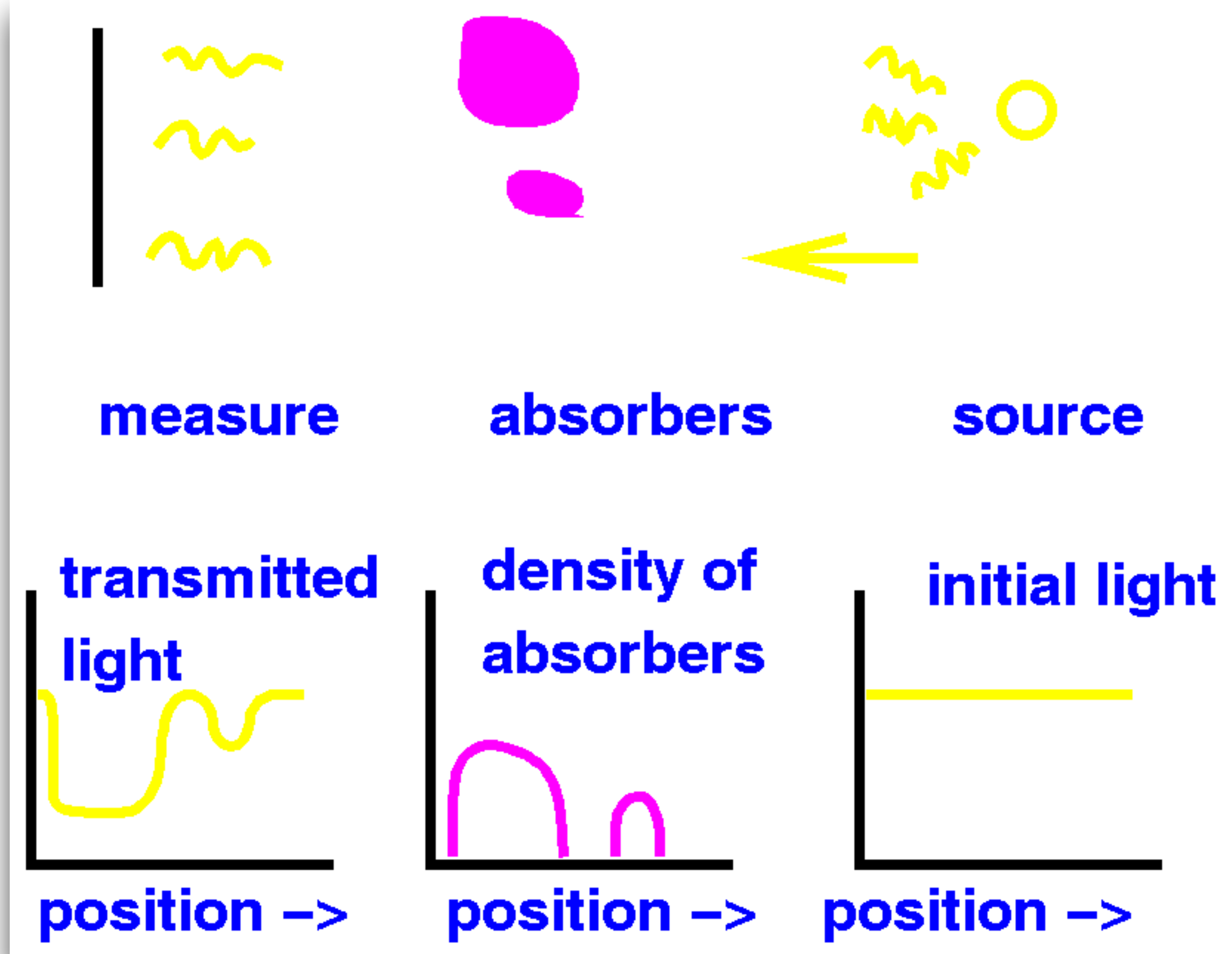
$$E_n = -\frac{13.6[\mathrm{eV}]}{n^2}$$

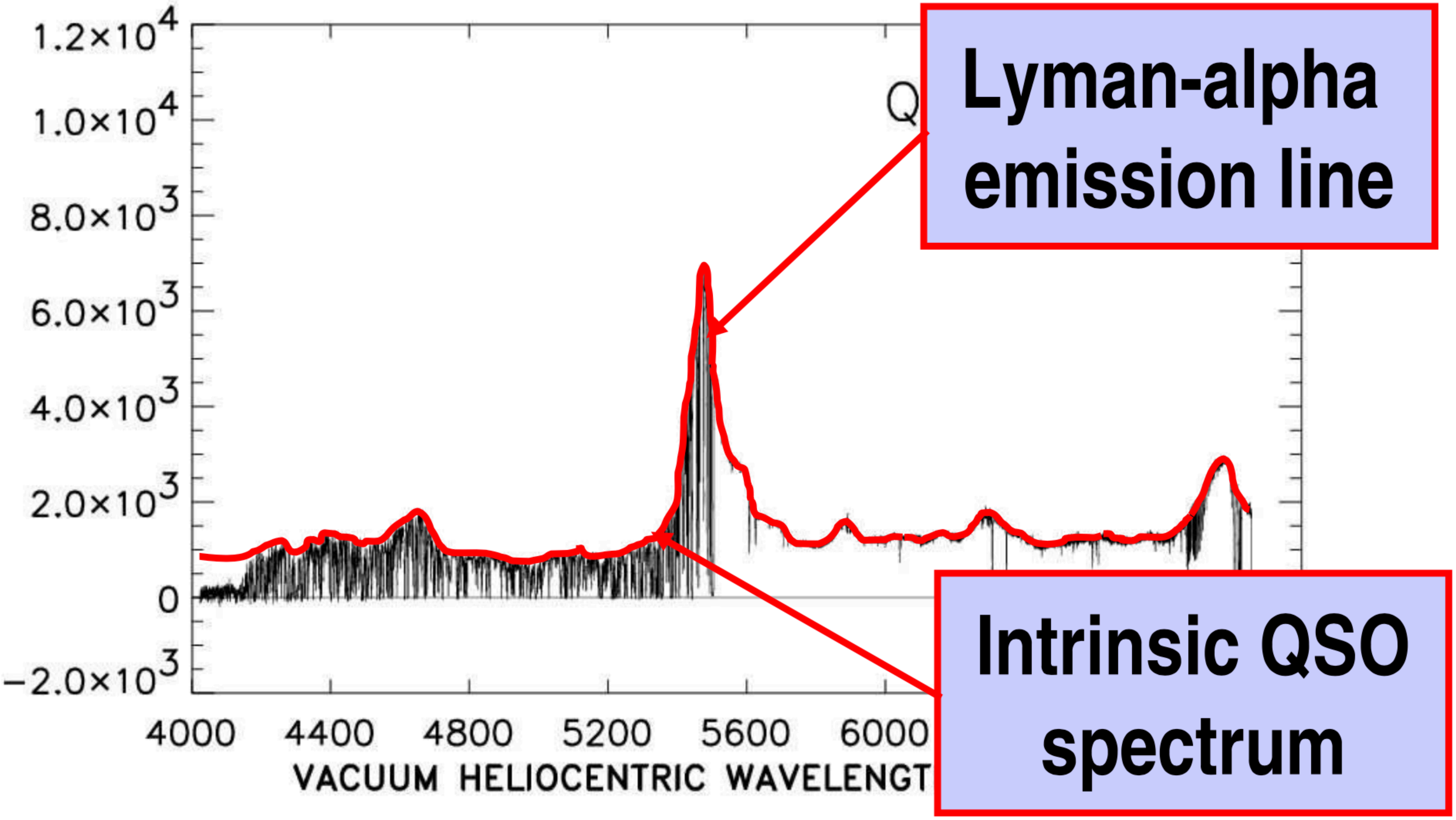
$$\lambda(nm) = \frac{1240}{E[\mathrm{eV}]}$$



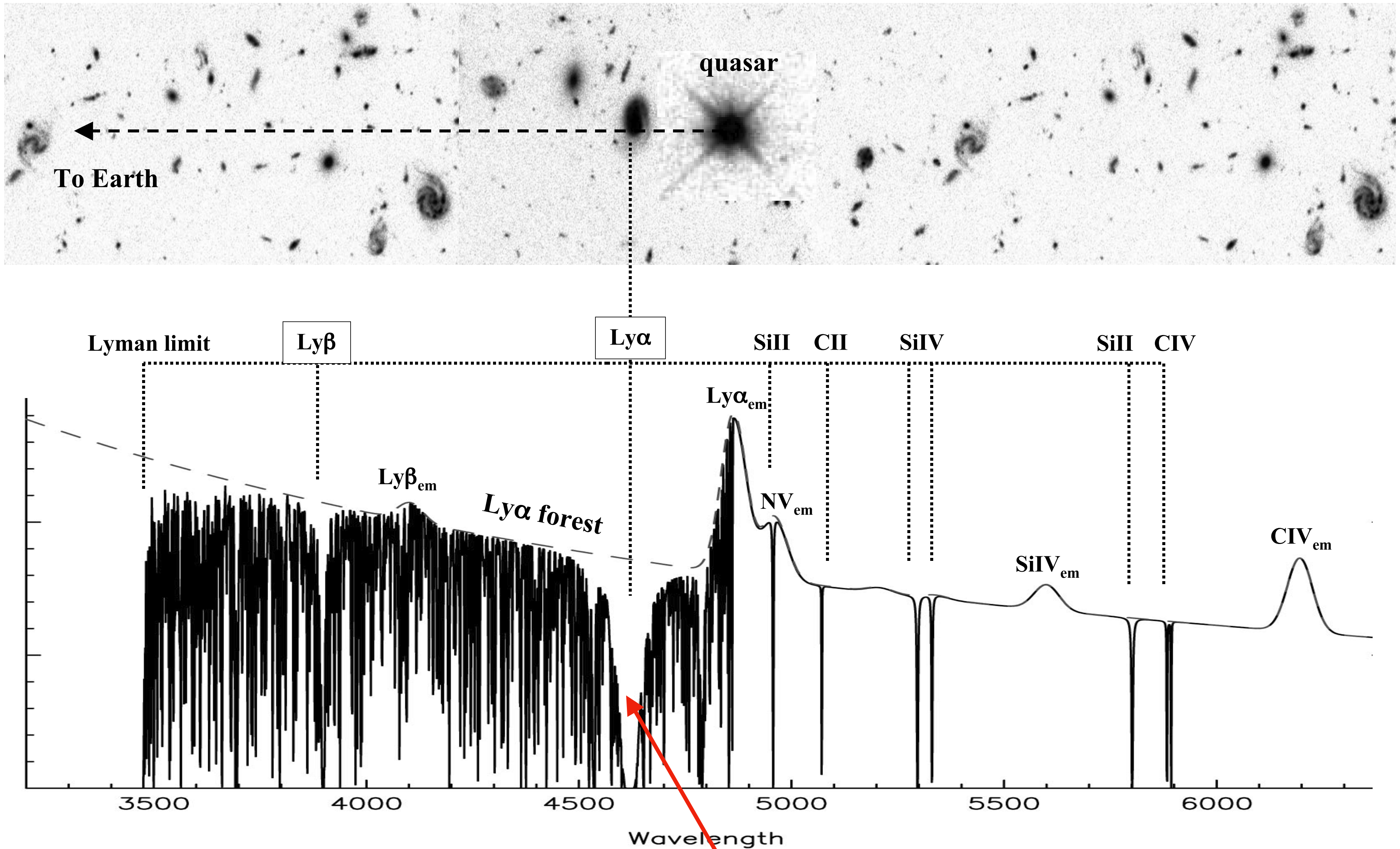




LARS 01
Hayes et al. 2013
blue: Lyα
red: Hα
green: UV continuum


measure
absorbers
source
transmitted light
density of absorbers
initial light
position ->
position ->
position ->



1.2×10^4
1.0×10^4
8.0×10^3
6.0×10^3
4.0×10^3
2.0×10^3
0
−2.0×10^3
4000
4400
4800
5200
5600
6000
VACUUM HELIOCENTRIC WAVELENGT
Q
Lyman-alpha emission line
Intrinsic QSO spectrum




# Lya forest:

– Numerous, weak lines from hydrogen clouds

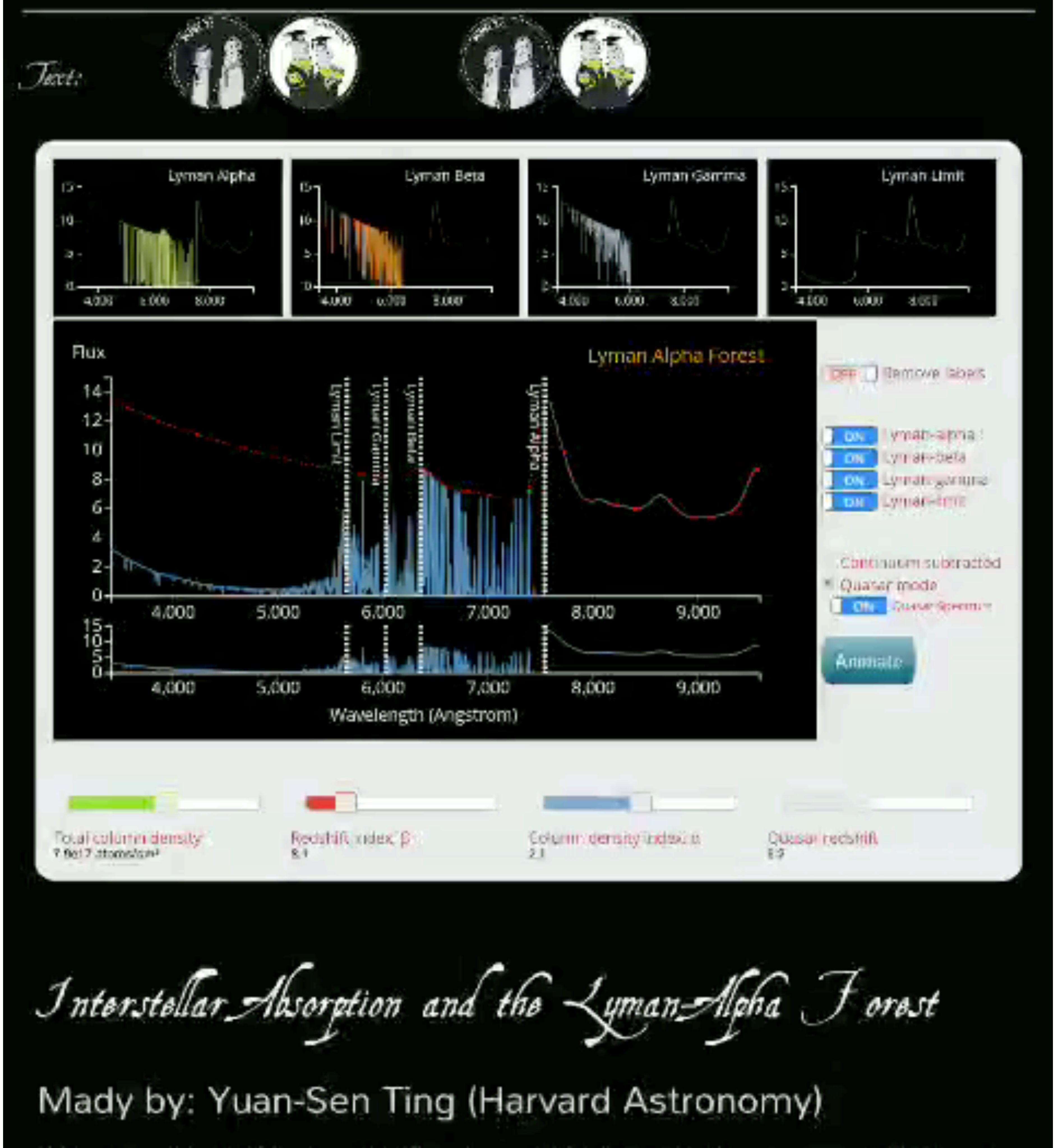
– Lyman alpha clouds are proto-galactic clouds, with low density, they are not galaxies

# “Damped”Lya:

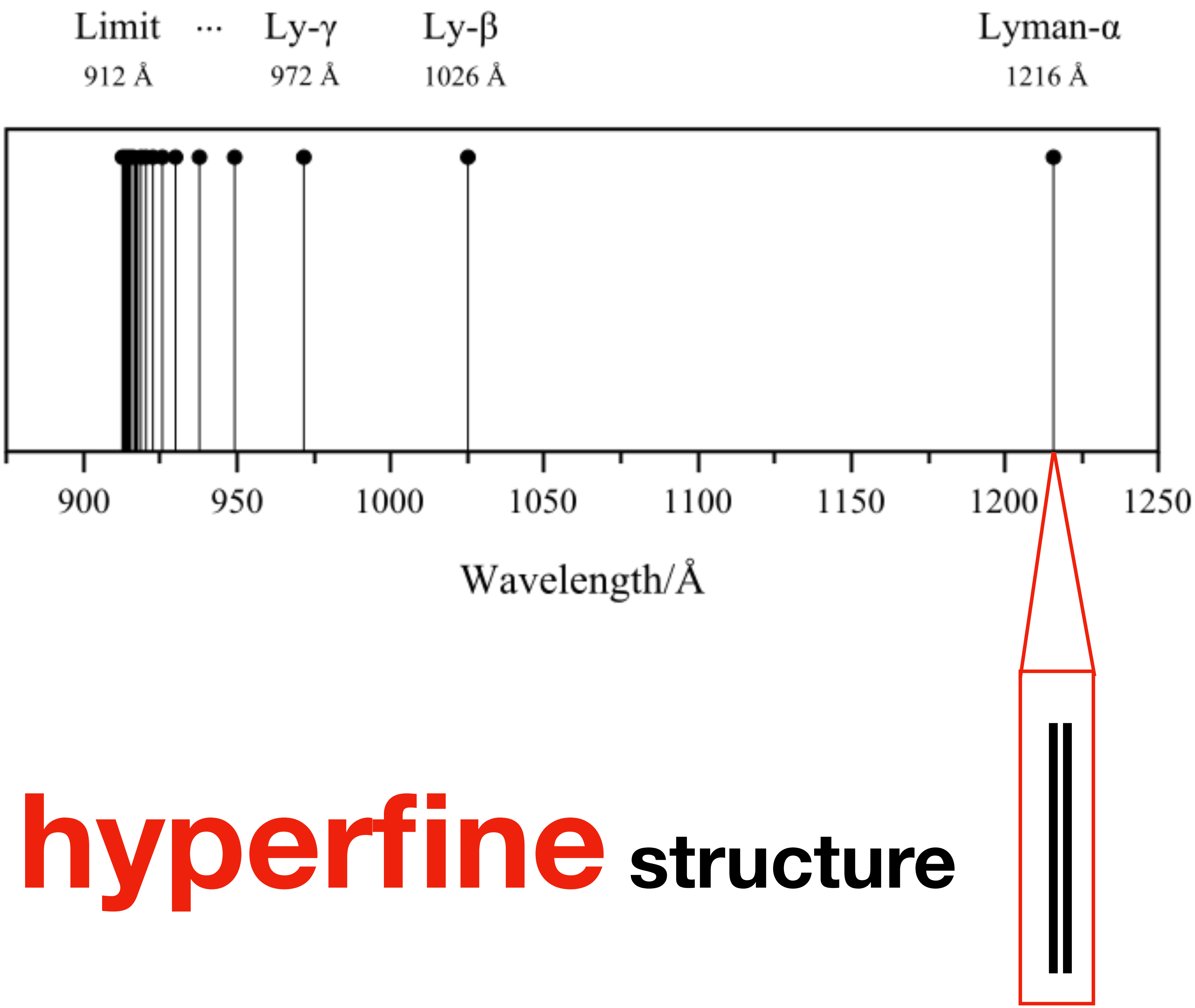
– Rare, strong hydrogen absorption
– Coming from intervening galaxies

– An intervening galaxies often produce both metal and damped Lyman alpha absorptions.

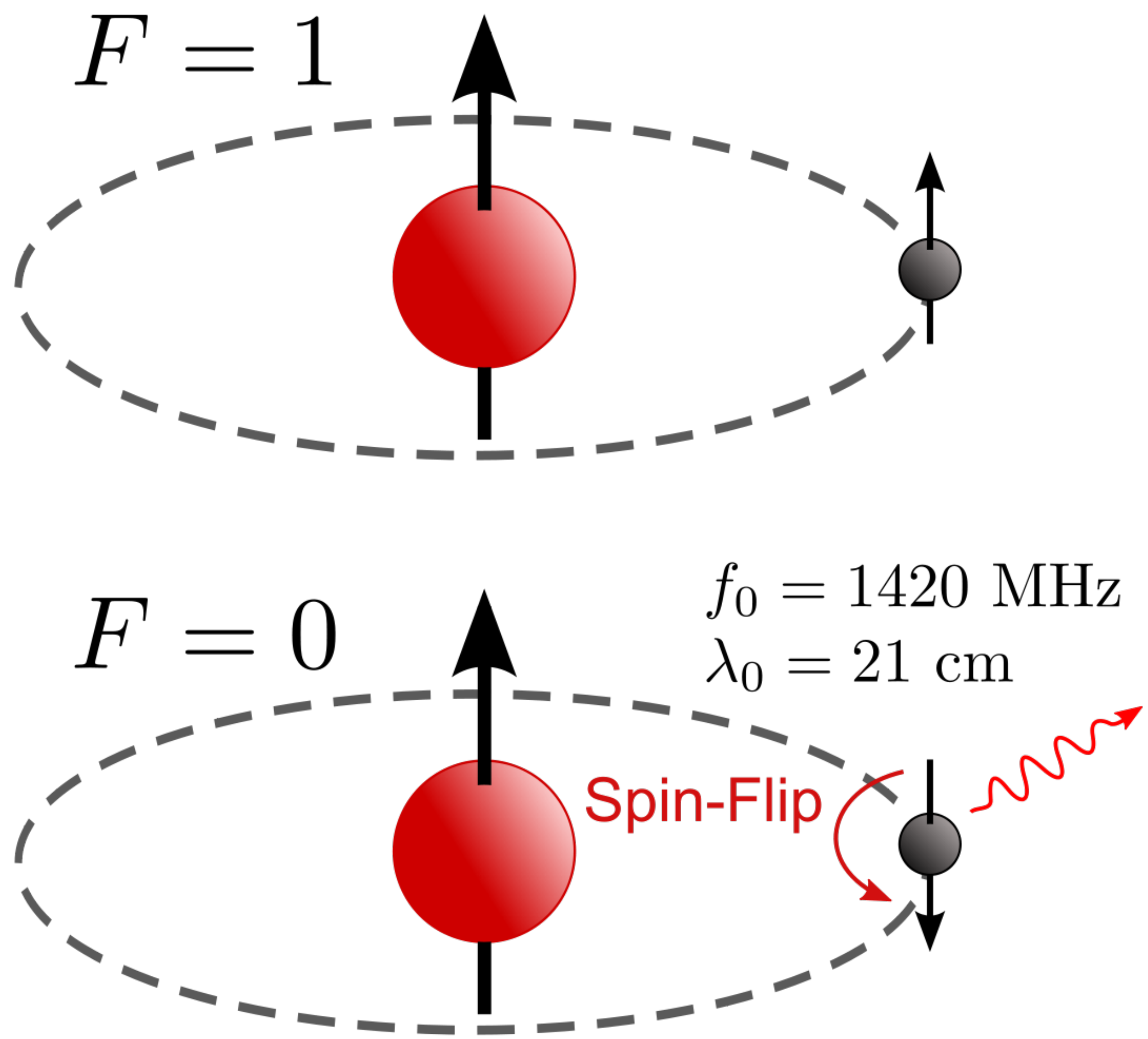
[Credit: Yuan-Sen Ting]

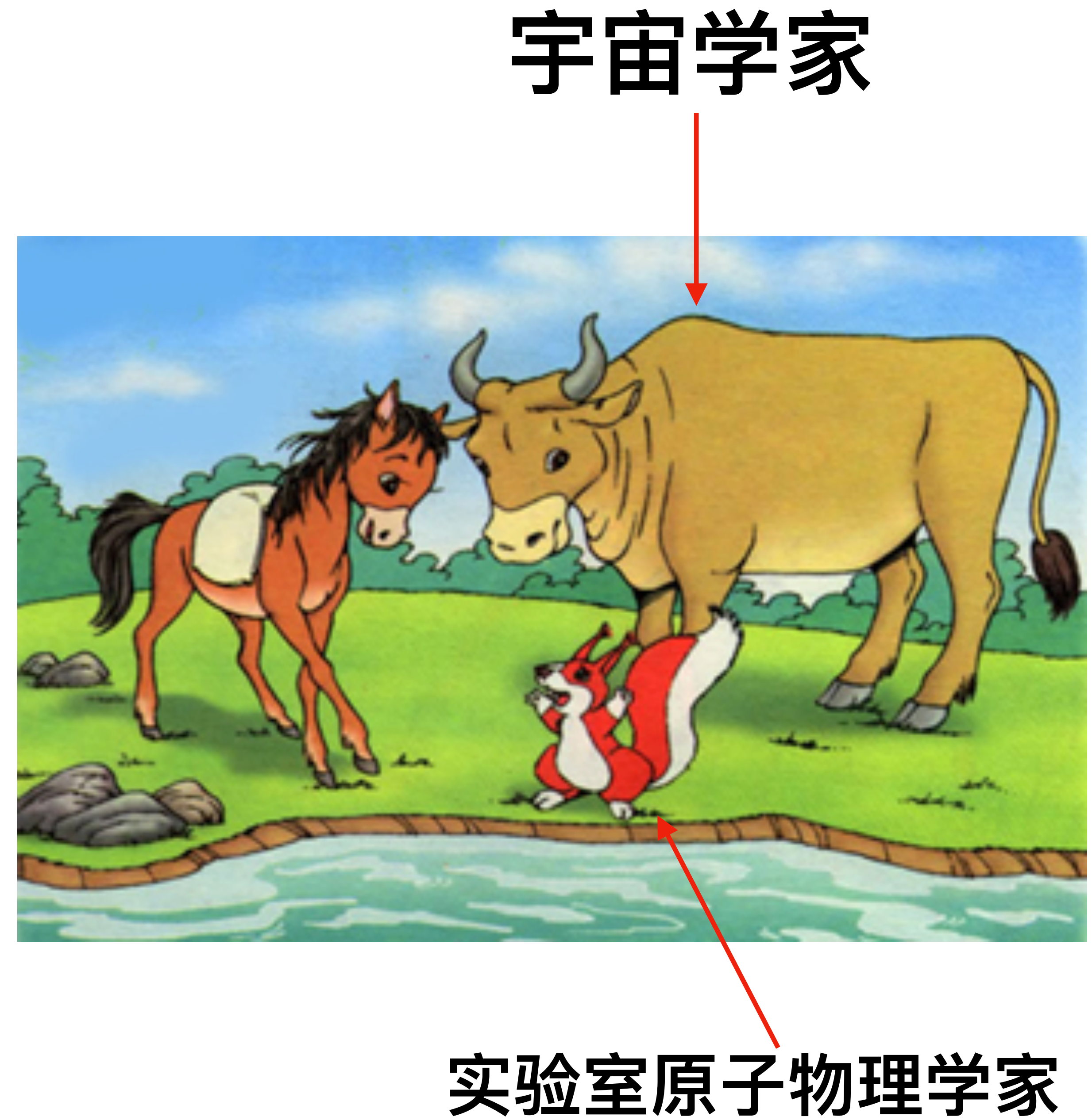


# fine structure




**hyperfine** structure

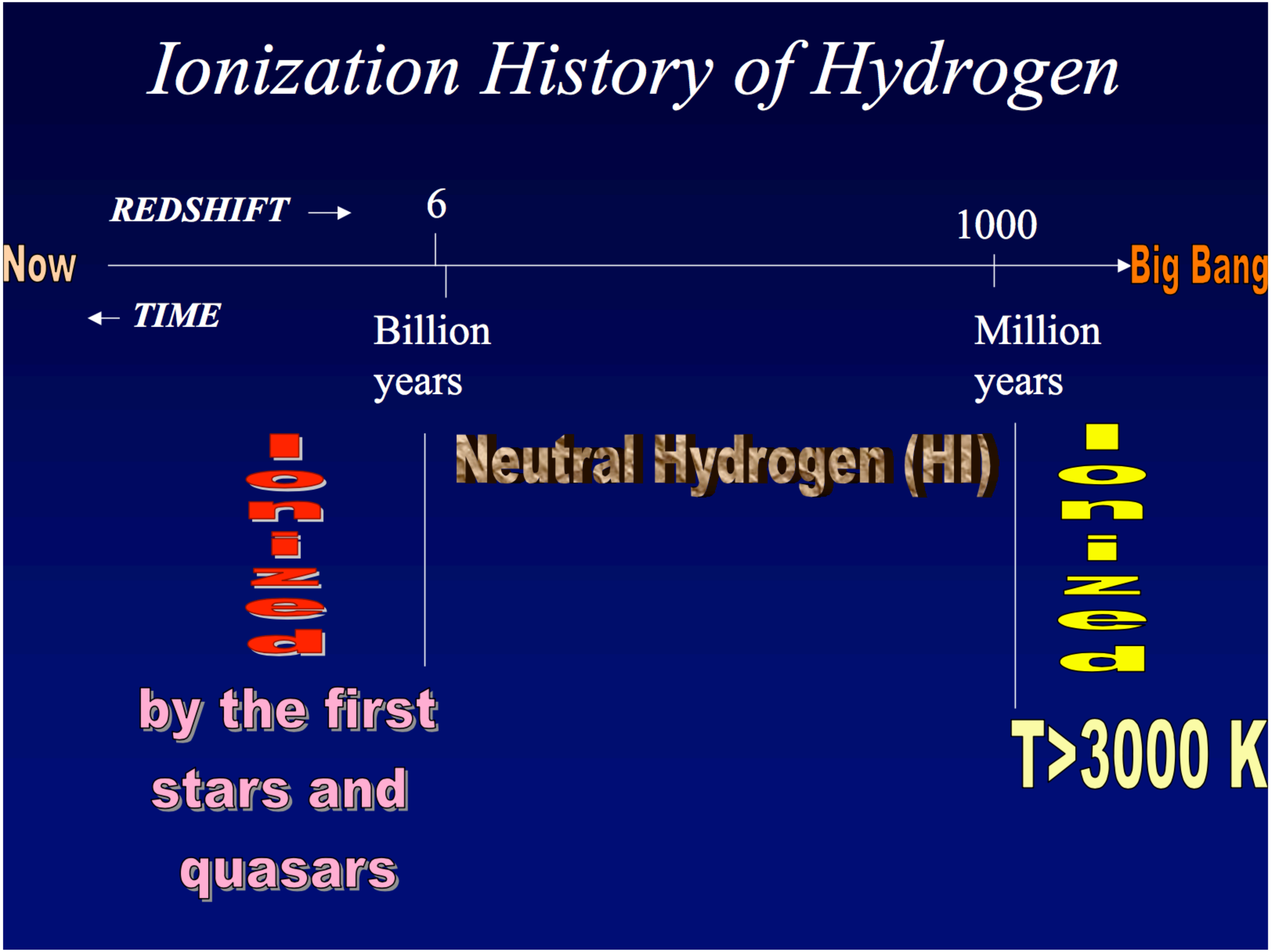


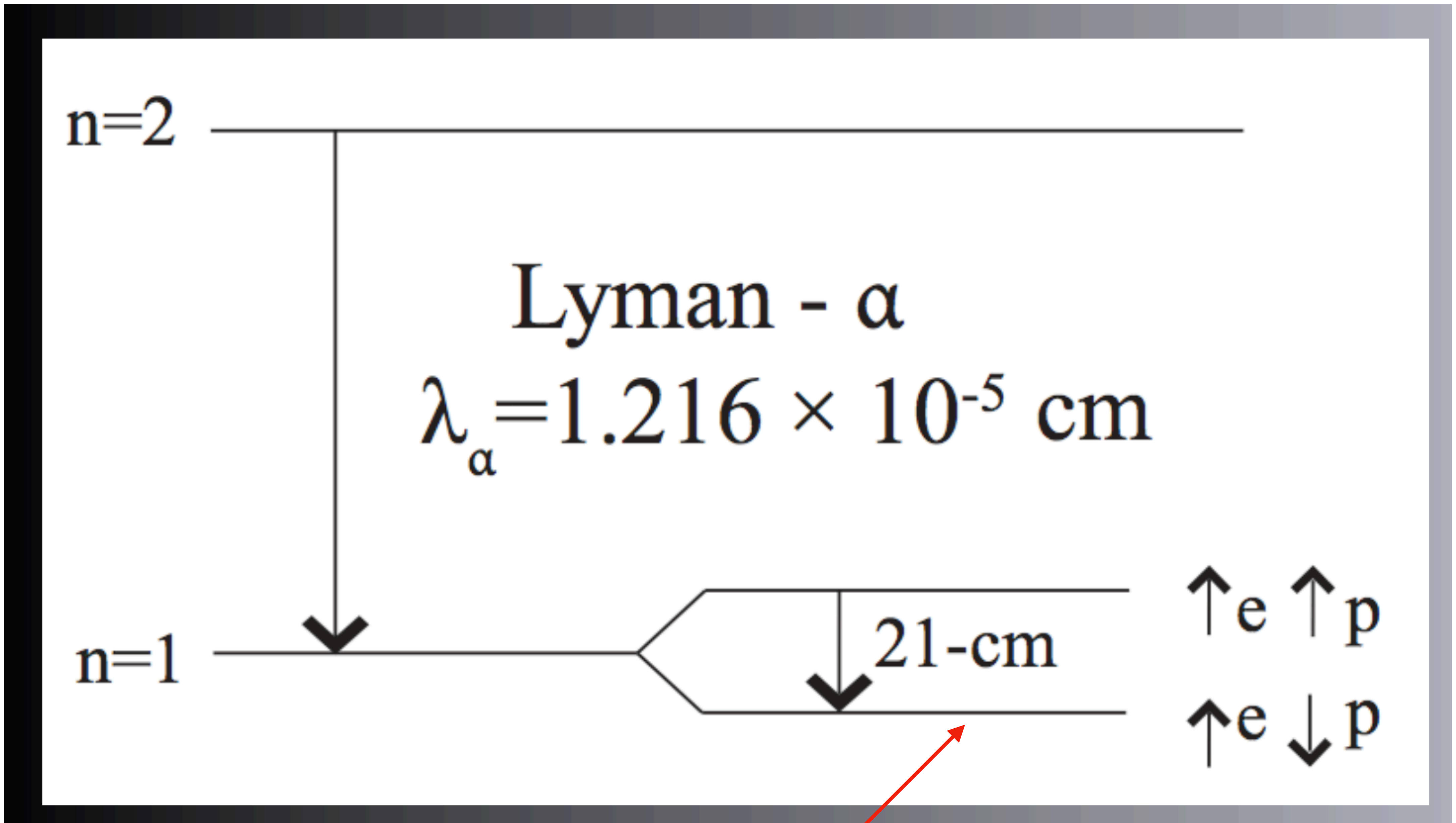




This transition is highly forbidden with an extremely small transition rate of

**$2.9\times10^{-15}$ s$^{-1}$**,

and a mean lifetime of the excited state of around **10 million years**.

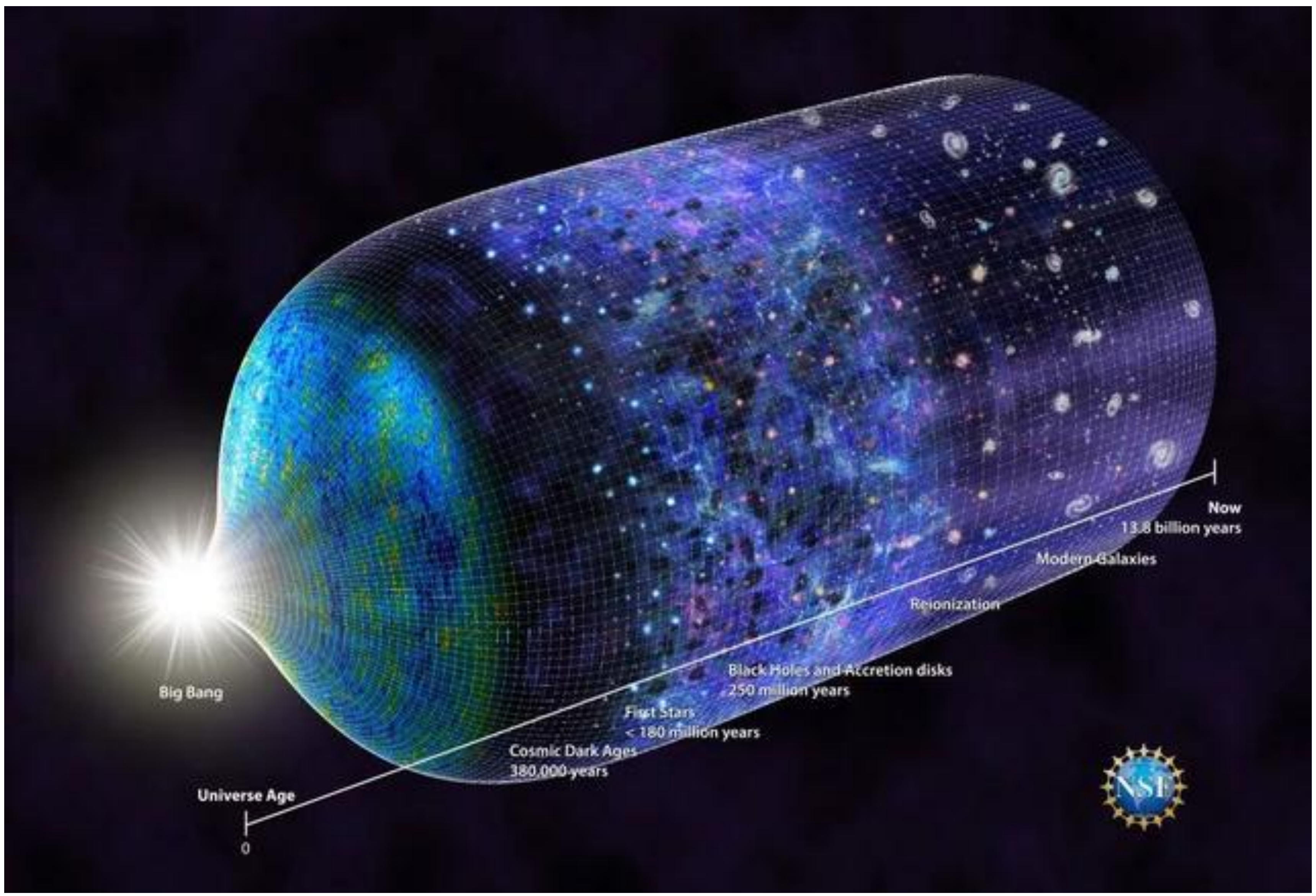

Ionization History of Hydrogen
REDSHIFT →
6
1000
Now
Big Bang
← TIME
Billion years
Million years
Ionized
Neutral Hydrogen (HI)
Ionized
by the first stars and quasars
T>3000 K




**VERY VERY** small mount of energy

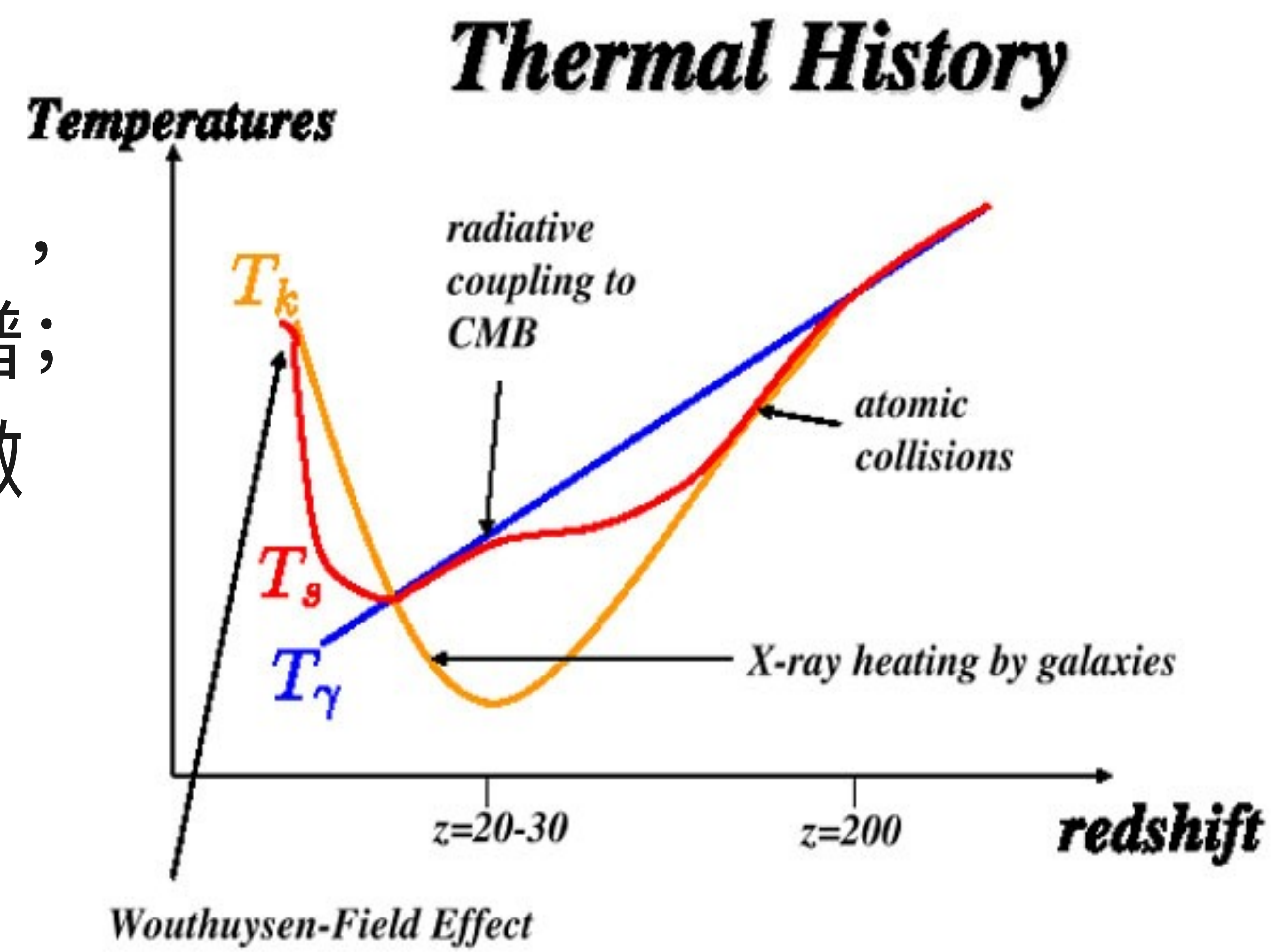
https://zhuanlan.zhihu.com/p/34223993

陈学雷：出人意料的宇宙黎明之冷




国台

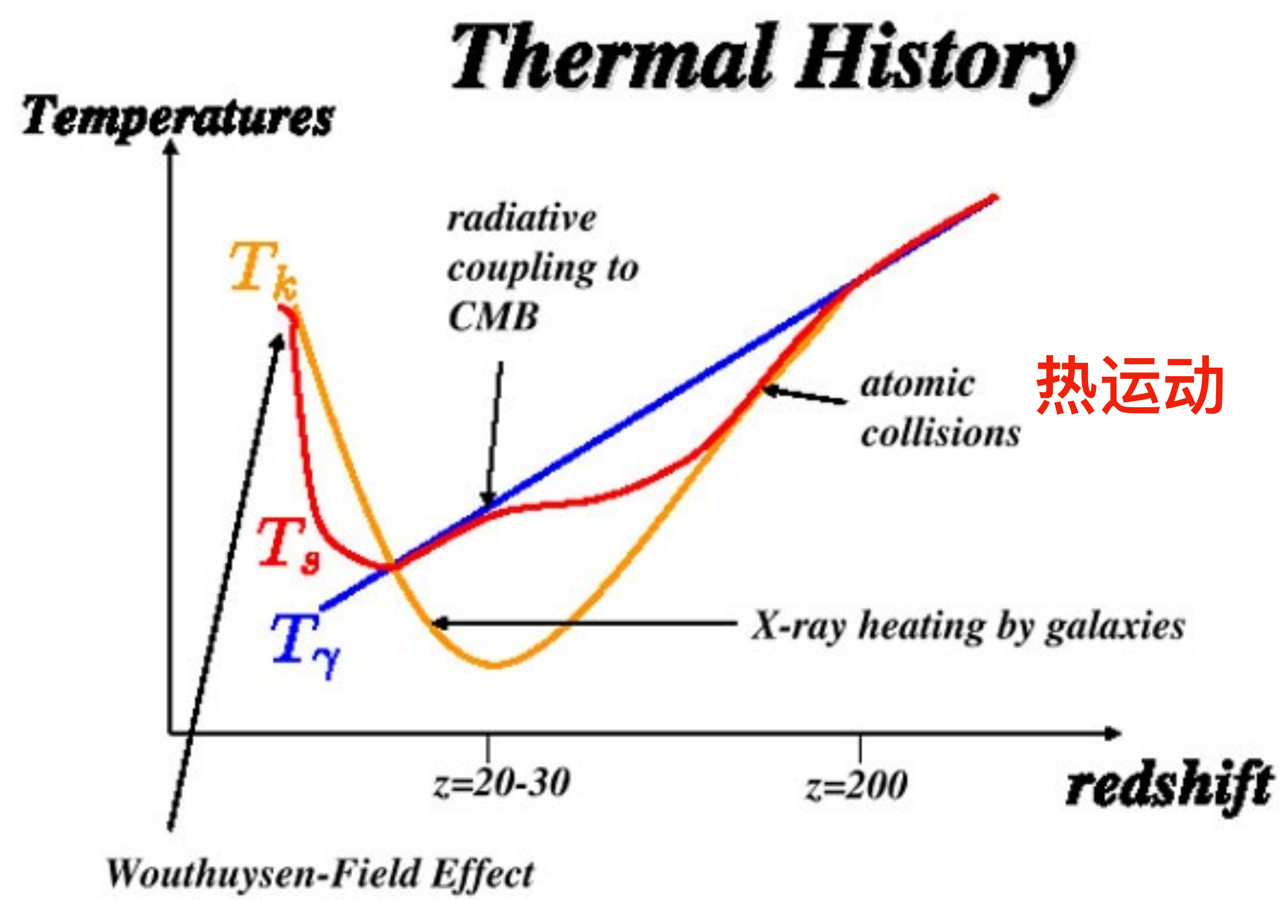
为了描述处在两个能级上的氢原子的相对比例，可以引入“**自旋温度**”的概念：自旋温度越高，在高能级上的氢原子的比例就越大。当自旋温度高于当时的宇宙微波背景辐射温度时（随着宇宙膨胀，宇宙微波背景的温度也在不断变化），总的发射就会超过吸收，产生发射谱；反之，当自旋温度低于当时的宇宙微波背景辐射温度时就产生吸收谱。

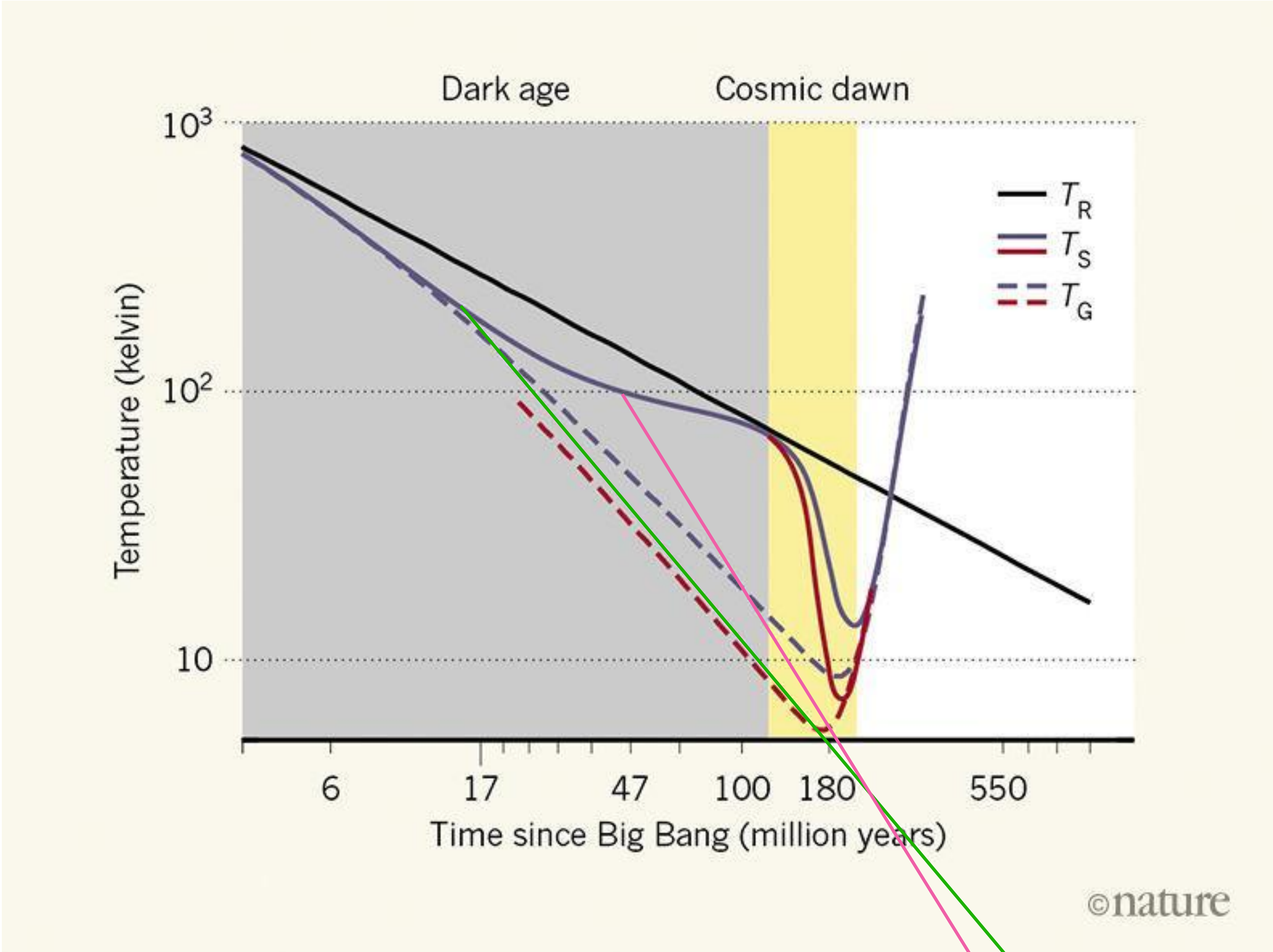



$$T_s \propto \frac{n_{F1}}{n_{F0}}$$

https://zhuanlan.zhihu.com/p/34223993

一方面，原子自旋跃迁和宇宙微波背景辐射的相互作用会使自旋温度趋近宇宙微波背景辐射温度；**另一方面，原子的碰撞、赖曼（Lyman）光子的散射又会使这一温度趋近于原子运动的温度（也就是我们一般所说的气体温度）**，实际的自旋温度是二者的某种平均，夹在二者之间。

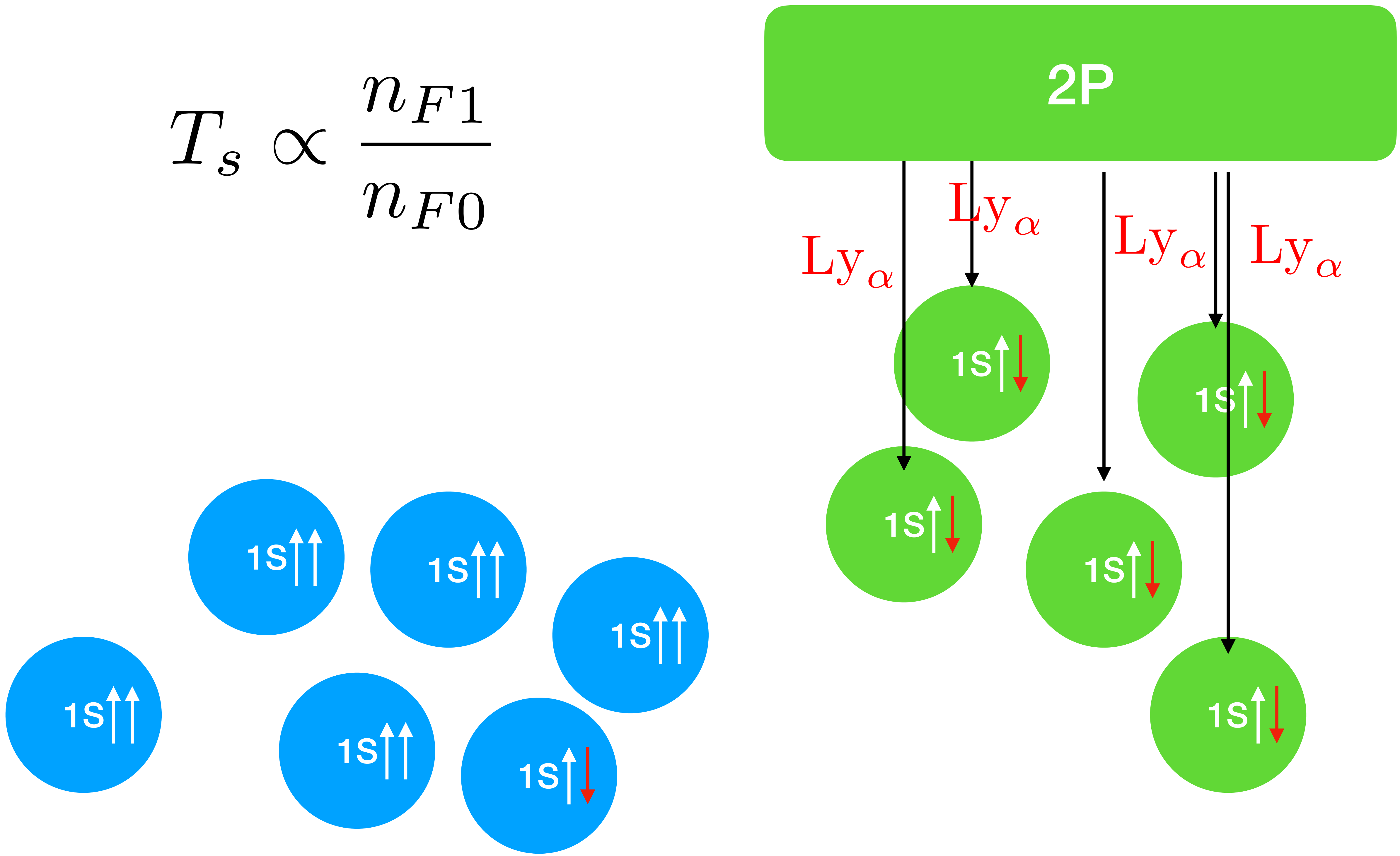



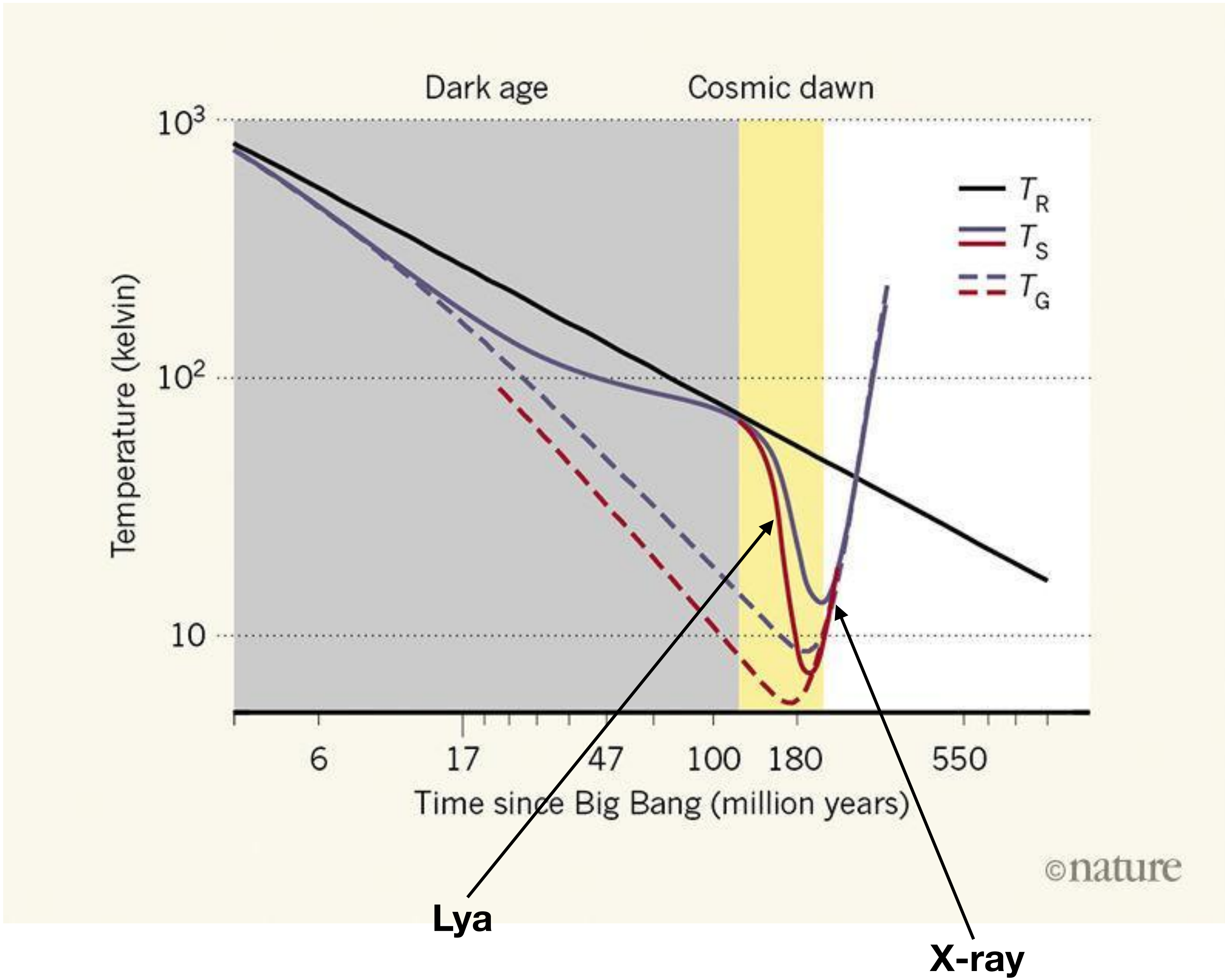



在更早的宇宙**黑暗时代**，也有一个21cm吸收谱，当时宇宙气体的密度还比较高，原子频繁碰撞，因此自旋温度接近气体温度，而宇宙气体的温度低于宇宙微波背景，因此产生21cm吸收谱。但是，随着宇宙膨胀，气体密度降低，原子碰撞不再频繁，这时气体自旋温度接近宇宙微波背景温度，因此在宇宙黎明前21cm信号就消失了。

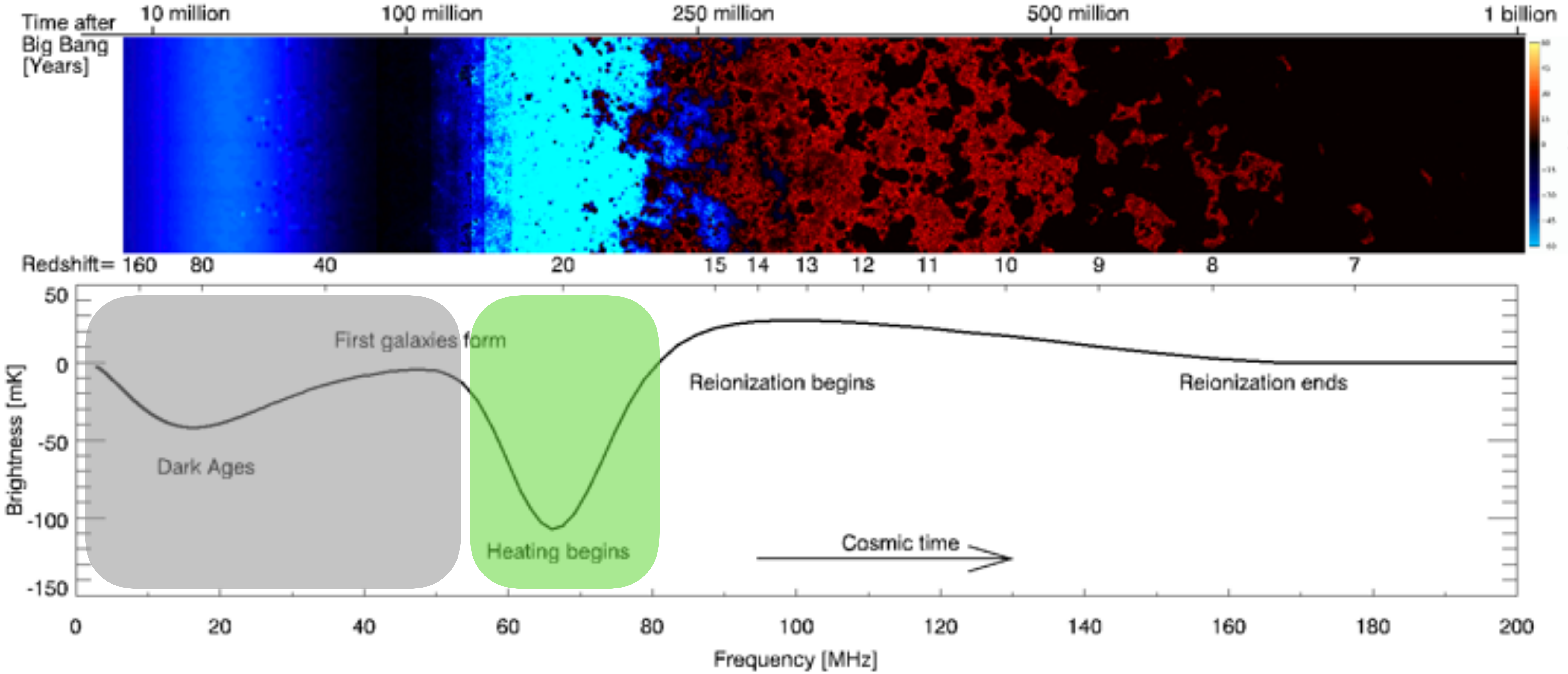
一旦**第一代恒星开始形成**，这些恒星会产生大量的Lyman alpha光子，氢原子与Lyman alpha光子的散射会使它的自旋温度迅速趋近原子运动温度。

$$T_s \propto \frac{n_{F1}}{n_{F0}}$$






**Spin temperature thermalised with gas temperature, so T_G ↗ , T_s ↗**

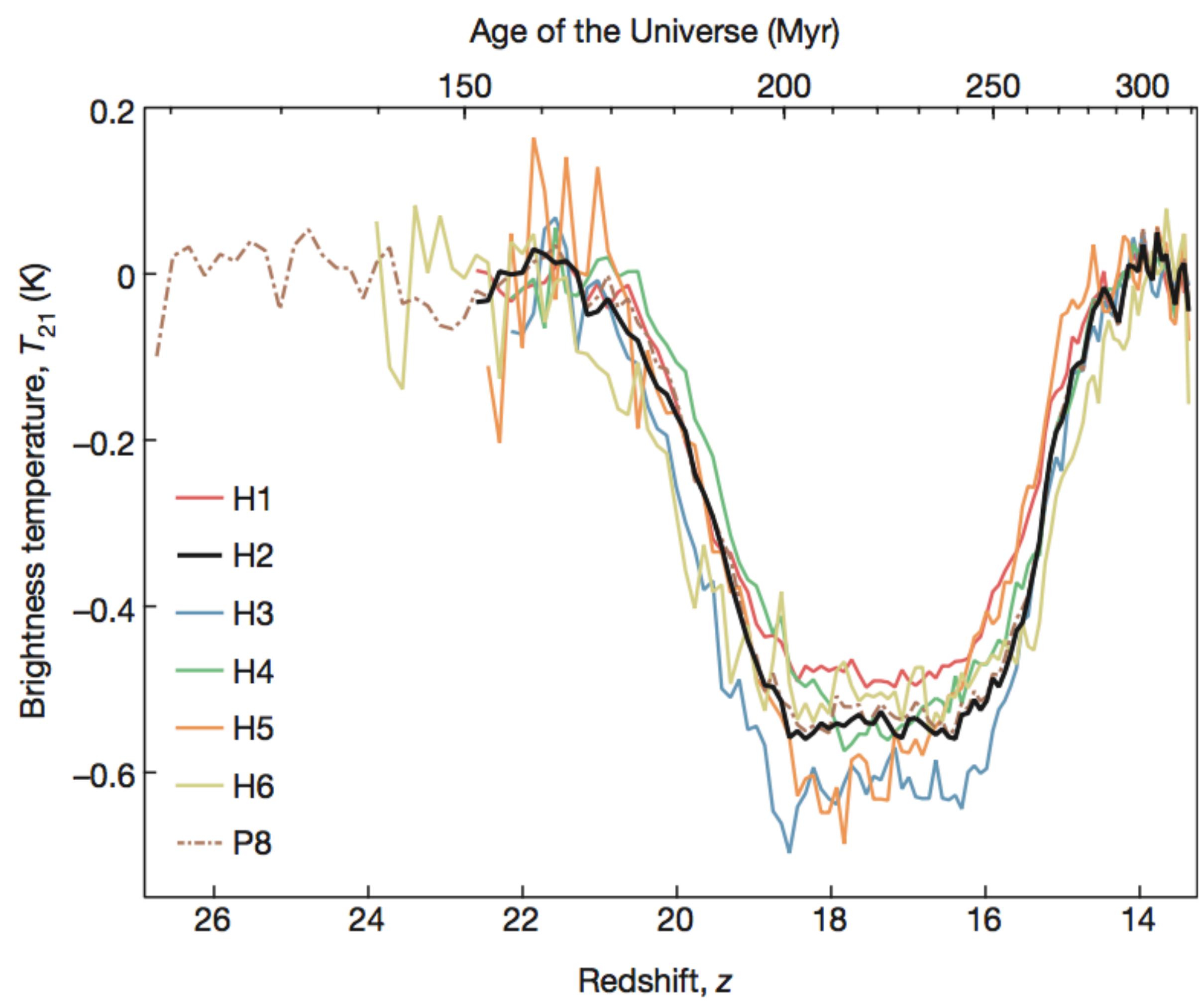


Time after Big Bang [Years]
10 million
100 million
250 million
500 million
1 billion
Redshift= 160
80
40
20
15
14
13
12
11
10
9
8
7
First galaxies form
Reionization begins
Reionization ends
Dark Ages
Heating begins
Cosmic time
Brightness [mK]
50
0
-50
-100
-150
0
20
40
60
80
100
120
140
160
180
200
Frequency [MHz]

# Cosmic Dawn Signal!

1420/60~24

1420/99~14

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**Problem-13: The possible explanation of this anomaly.**

**Problem-14: 综述世界上当前射电天文学现状**