

# Historia Termica Del Universo

Jueves 20 Agosto

# Results from last lecture

Dark matter       $\omega_m = 0 \iff \rho_m(a) = \rho_{m,0} \times a^{-3}$

Radiation  
cosmological  
constant       $\omega_R = 1/3 \iff \rho_R(a) = \rho_{R,0} \times a^{-4}$

$\omega_\Lambda = -1 \iff \rho_\Lambda(a) = Cte$

Radiation era       $\omega_R = 1/3 \Rightarrow a(t) \propto t^{1/2}$

Matter era       $\omega_m = 0 \Rightarrow a(t) \propto t^{2/3}$

cosmological  
constant       $\frac{\dot{a}}{a} = \sqrt{\frac{8\pi G \rho_\Lambda}{3}} \Rightarrow a(t) \propto \exp^{\sqrt{\frac{8\pi G \rho_\Lambda}{3}} t}$

# Distances

$$\chi(z_{emis}) = \frac{c}{H_0} \int_0^{z_{emis}} \frac{dz}{\sqrt{\Omega_{M,0}(1+z)^3 + \Omega_{R,0}(1+z)^4 + \Omega_\Lambda}}$$

$$D_L = \chi(1+z)$$

$$D_A = \frac{\chi}{(1+z)}$$

# Outline today's lecture

- Comovil Horizon definition.
- Universe Geometry and Energetic content.
- Universe homogeneous and Distance estimates.
- **Thermic history of the Universe.**

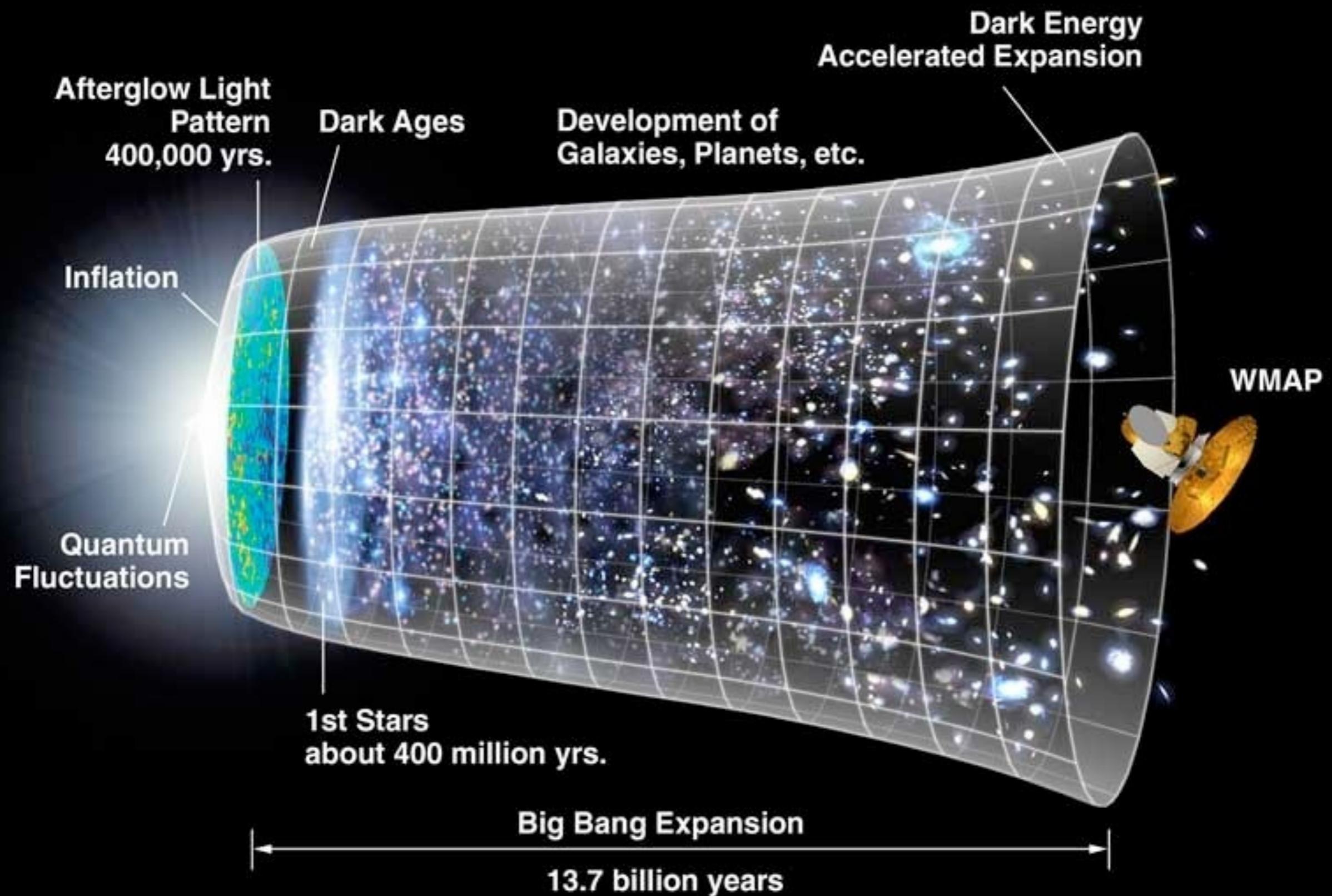
# Comoving Horizon

Distancia que un foton viaja en ausencia de interacciones desde un t=0

$$\eta \equiv \int_0^t \frac{dt'}{a(t')}$$

Ninguna información puede viajar mas rapido que esta distancia

Regiones alejadas mas de esta distancia no pueden estar casualmente conectadas.



# Time Since Big Bang

# Major Events Since Big Bang

present

Era of Galaxies

1 billion years

Era of Atoms

500,000 years

Era of Nuclei

3 minutes

Era of Nucleosynthesis

0.001 seconds

Particle Era

$10^{-10}$  seconds

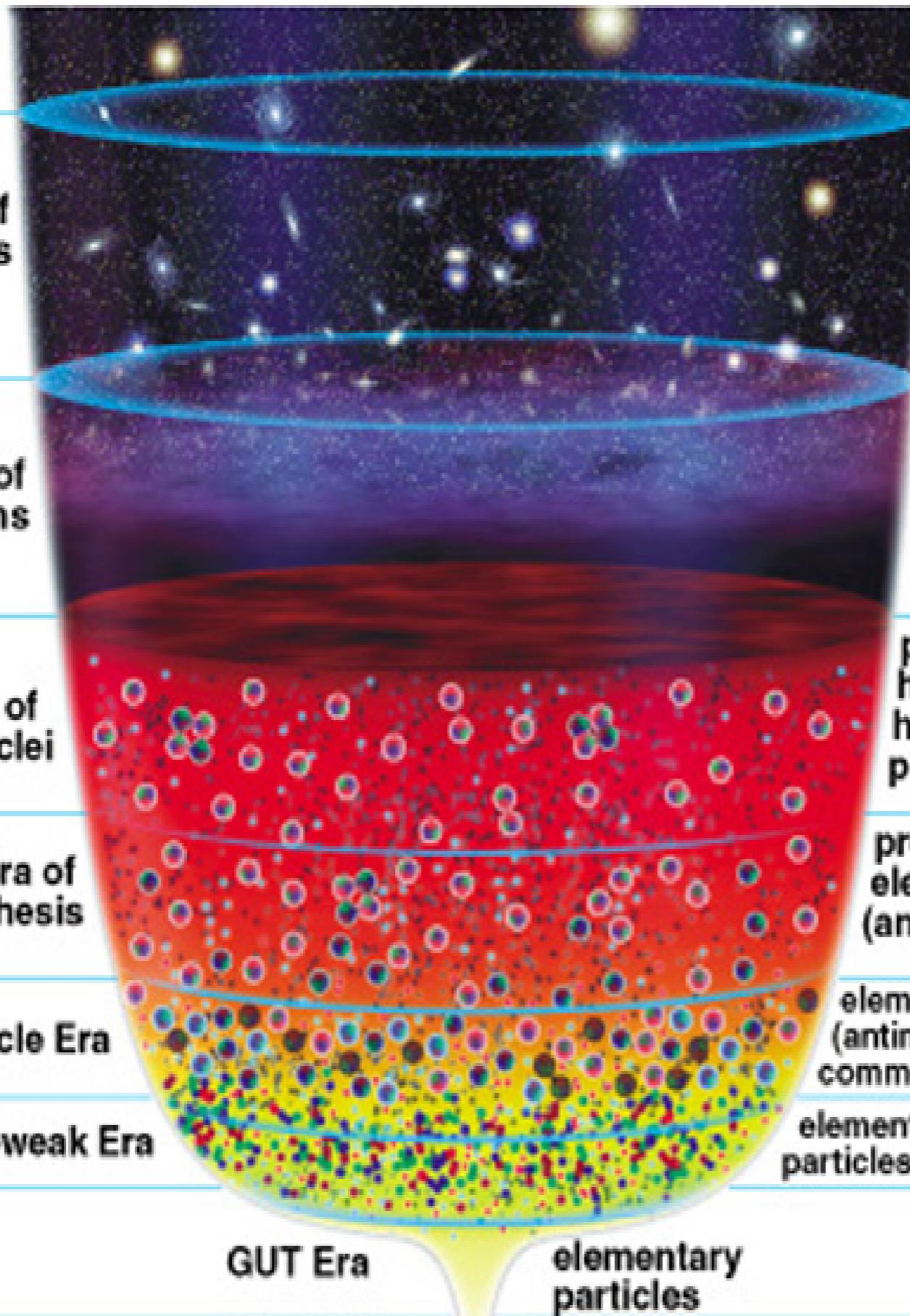
Electroweak Era

$10^{-36}$  seconds

GUT Era

$10^{-43}$  seconds

Planck Era



stars,  
galaxies  
and clusters  
(made of  
atoms and  
plasma)

atoms and  
plasma  
(stars  
begin  
to form)

plasma of  
hydrogen and  
helium nuclei  
plus electrons

protons, neutrons,  
electrons, neutrinos  
(antimatter rare)

elementary particles  
(antimatter  
common)  
elementary  
particles

elementary  
particles

????

Humans  
observe  
the cosmos.

First galaxies  
form.

Atoms form;  
photons fly free  
and become  
microwave  
background.

Fusion ceases;  
normal matter is  
75% hydrogen,  
25% helium, by  
mass.

Matter annihilates  
antimatter.

Electromagnetic and weak  
forces become distinct.

Strong force becomes  
distinct, perhaps  
causing inflation of  
universe.

# Big Bang

- Modelo del Big Bang describe el inicio del Universo como denso y caliente.
- La expansión del Universo implica su enfriamiento.
- A ciertas temperaturas, ocurren eventos particulares (transiciones de fase)

Inicio  
 $T_{PLANCK}$

# Inflación

- Periodo de expansión acelerado en el universo temprano.
- Fluctuaciones cuánticas microscópicas se vuelven macroscópicas.
- Las perturbaciones serán las semillas de las estructuras.

**$10^{-33}$  s**

# Inflación

- Resuelve muchos problemas del modelo
  - Platonitud del Universo
  - Problema de Horizonte
  - Generación de Perturbaciones a escalas macroscópicas

# Fisica de Particulas

- De la desintegracion del foton surgen todas las partículas del modelo estandar (quarks, leptones y bosones).

Las tres generaciones de la Materia (Fermiones)			
	I	II	III
masa →	3 MeV	1.24 GeV	172.5 GeV
carga →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
nombre →	u up	c charm	t top
	<b>u</b>	<b>c</b>	<b>t</b>
	6 MeV	95 MeV	4.2 GeV
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	d down	s strange	b bottom
	<b>d</b>	<b>s</b>	<b>b</b>
	106 MeV	<0.19 MeV	<18.2 MeV
	-1	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	e electron	$\nu_\mu$ muon neutrino	$\nu_T$ tau neutrino
	<b>e</b>	<b><math>\nu_\mu</math></b>	<b><math>\nu_T</math></b>
	0.511 MeV	106 MeV	1.78 GeV
	-1	-1	-1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	$\mu$ muon	T tau	T tau
	<b><math>\mu</math></b>	<b>T</b>	<b>T</b>
	80.4 GeV	90.2 GeV	0
	$\pm 1$	0	1
	$W^\pm$ fuerza débil	Z fuerza débil	<b>Z</b> fuerza débil
	<b><math>W^\pm</math></b>	<b>Z</b>	<b>Z</b>

$10^{-4}$  s

Bariones

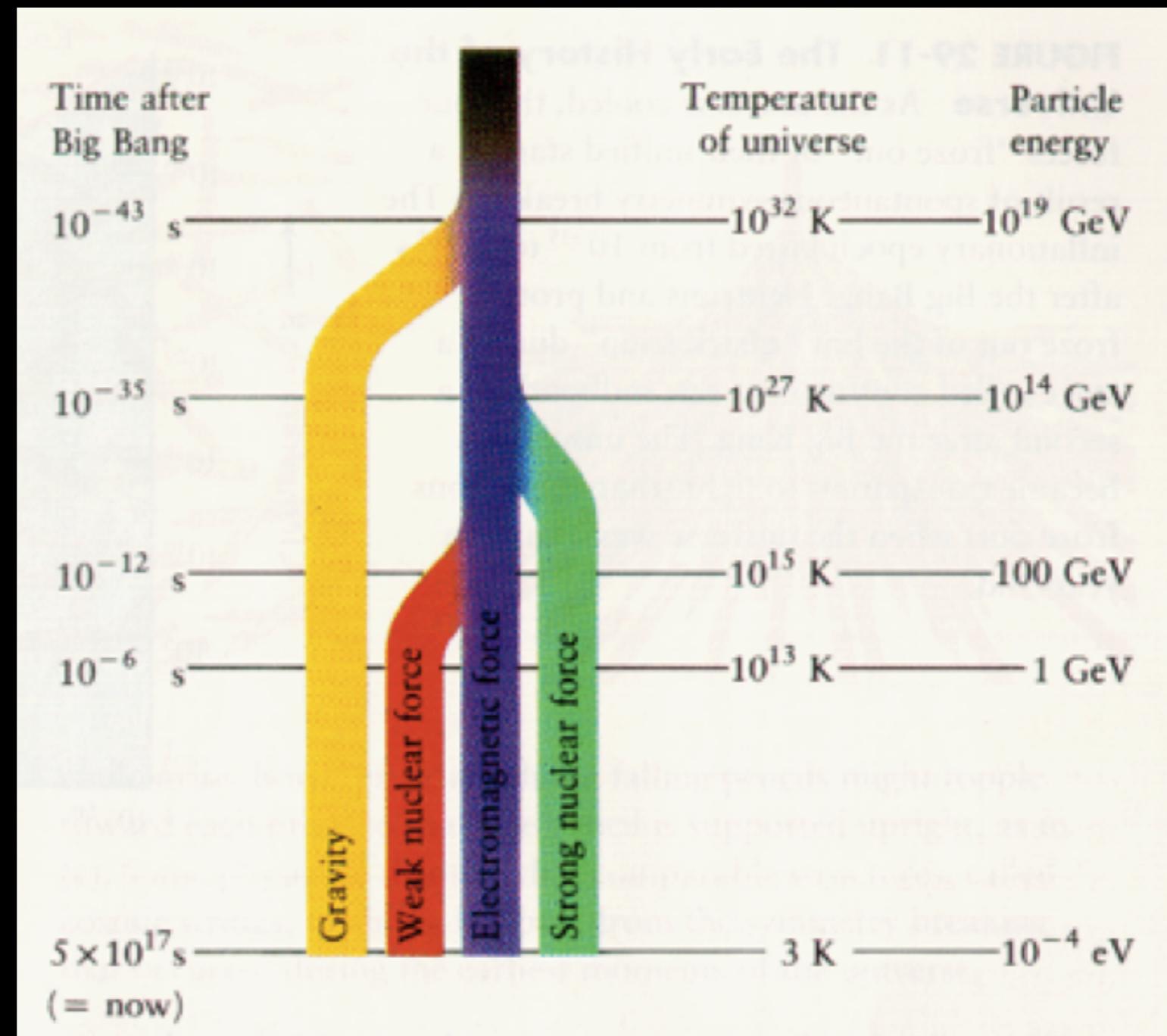
Desaparicion de antihadrones

$10^{-6}$  s

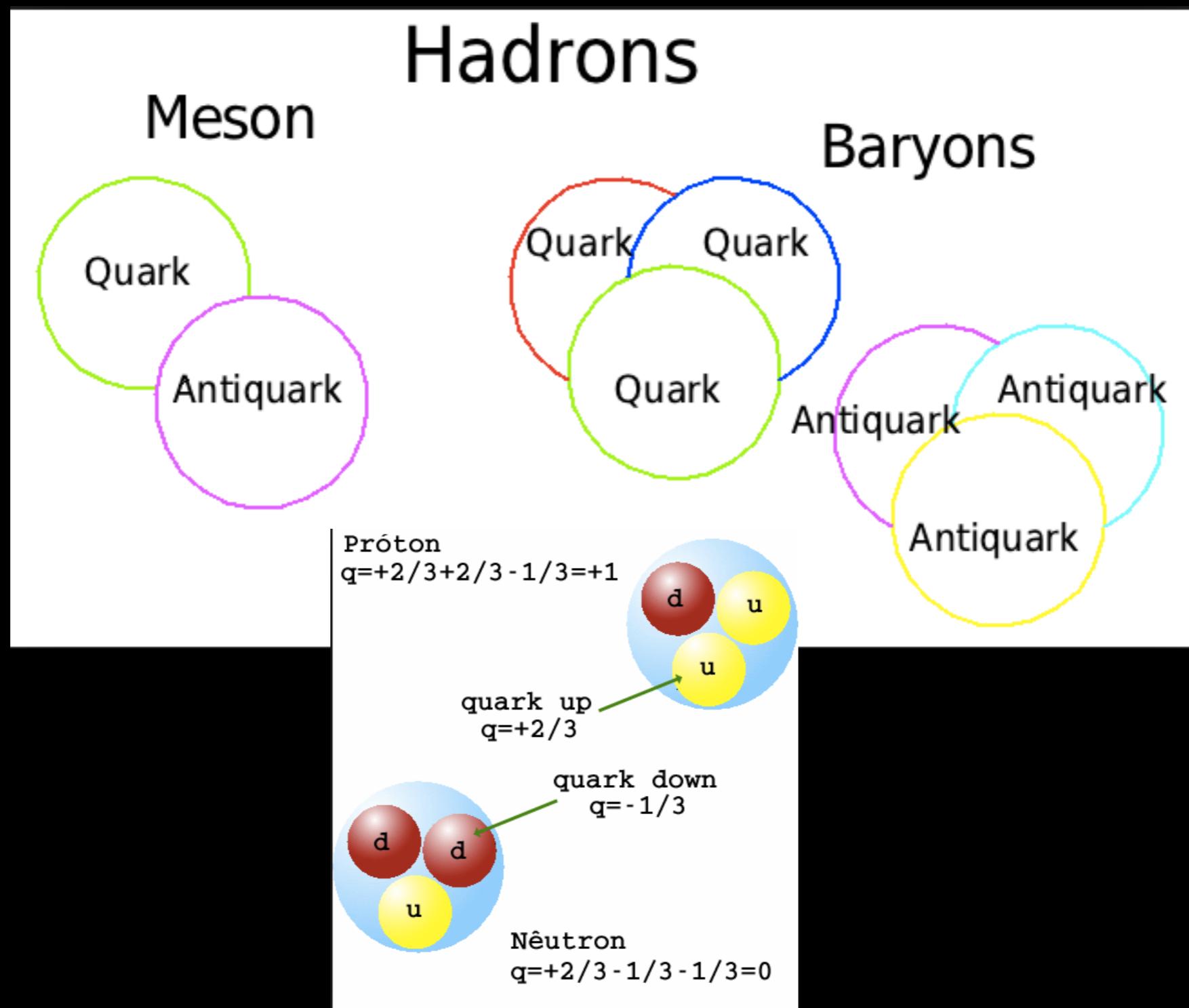
Quarks y Leptones

Confinamiento de Quarks

$10^{-33}$  s



# Formación de Hadrones



# Nucleosintesis Primordial

- La energia de protones y neutrones disminuye haciendo posible la producción de deuterio ( $H_2$ ) via fusion nuclear
- A partir del deuterio elementos mas pesados se forman:  $^3H$ ,  $^3He$ ,  $^4He$ ,  $^6Li$   $^7Li$ ,  $^7Be$   $^8Be$

10,000 a

Nucleos

3 min

Neutrones, electrones protones

Nucleosintesis  
Primordial

$10^{-4}$  s

Bariones

$10^{-6}$  s

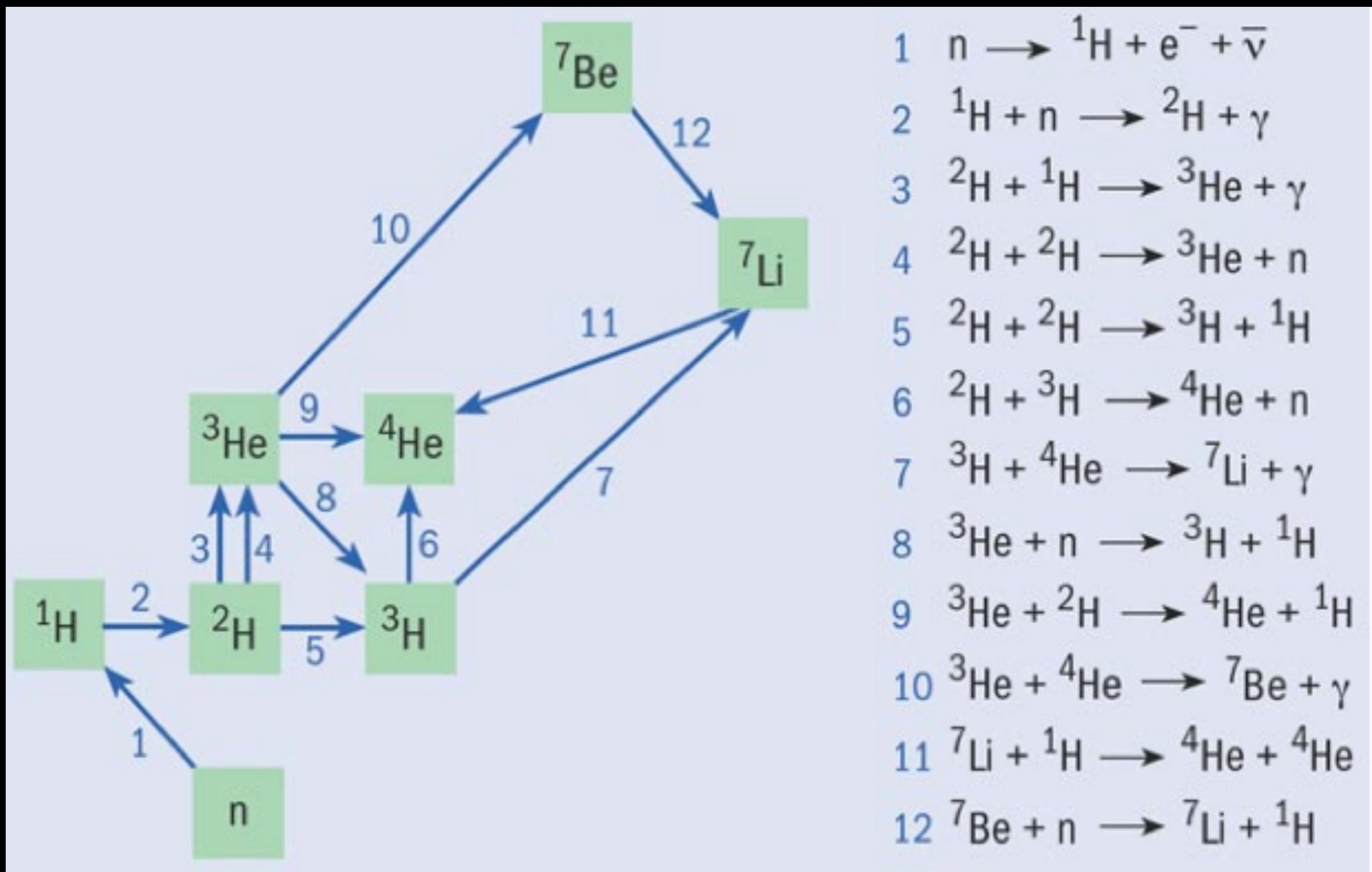
Quarks y Leptones

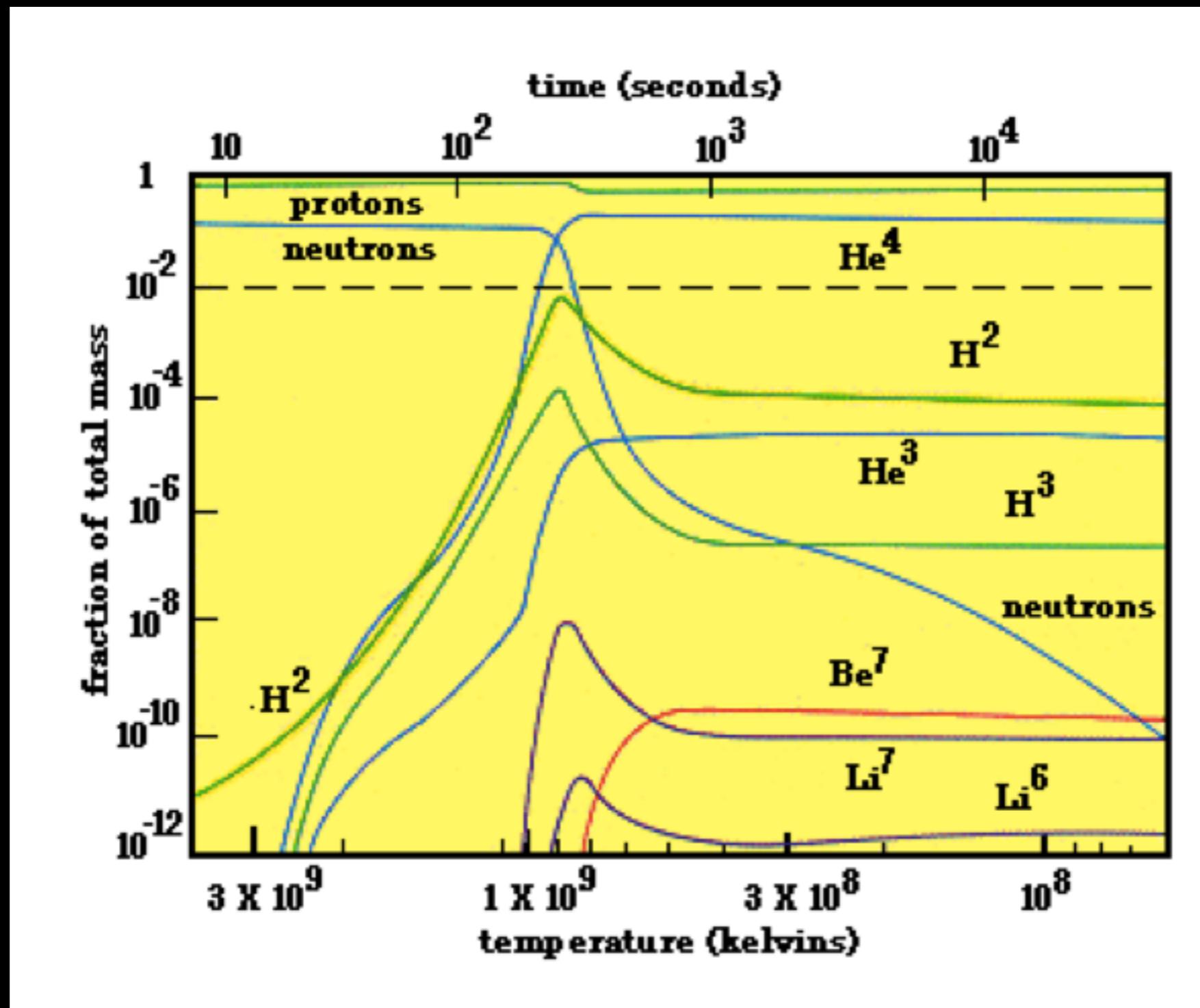
$10^{-33}$  s

<b>T &gt;&gt; 1 MeV</b>	Thermodynamic equilibrium between all the components of the universe ; Universes dominated by radiation ; $\frac{\#neutrons}{\#protons} \sim 1$ Photodissociation prevents any complex nuclei to form.
<b>1&gt;T&gt;0.7Mev</b>	Weak interaction cannot maintain equilibrium between all particles; neutrons decouple: “neutron freeze-out”: $\frac{\#neutrons}{\#protons} \sim \frac{1}{6}$ . Free neutrons decay into protons; atomic nuclei stay at thermodynamic equilibrium. Freeze-out temperature $T_f$ .
<b>0.7&gt;T&gt;0.05Mev</b>	Nuclear thermodynamic equilibrium cannot be maintained. Electron-positron annihilation has heated the photon bath. Atomic nuclei form through 2-body collisions: $p + n \rightarrow D + \gamma$ (only one way because radiation density is low enough).

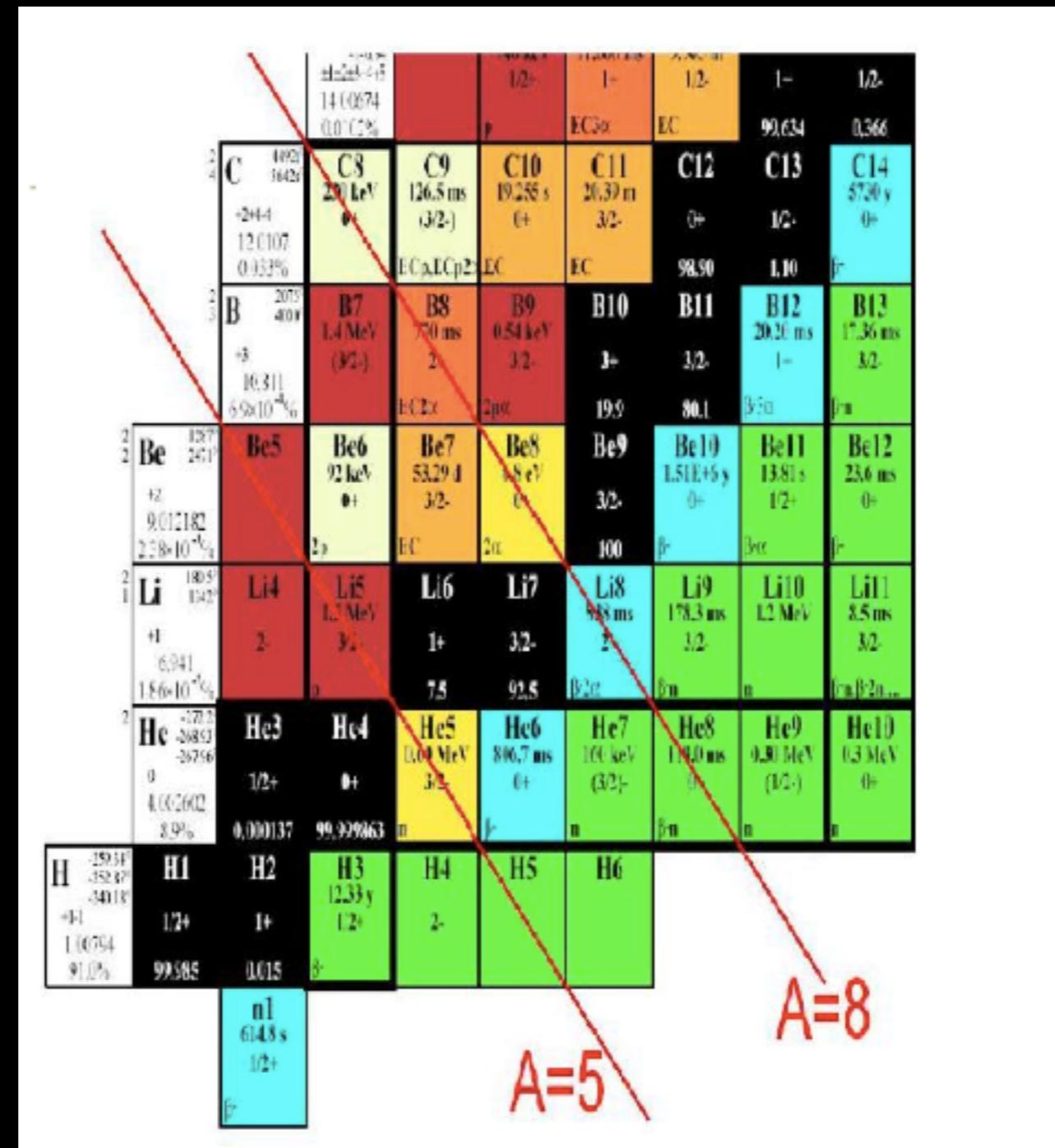
Table 2: Thermal evolution of the universe

# Nucleosíntesis Primordial



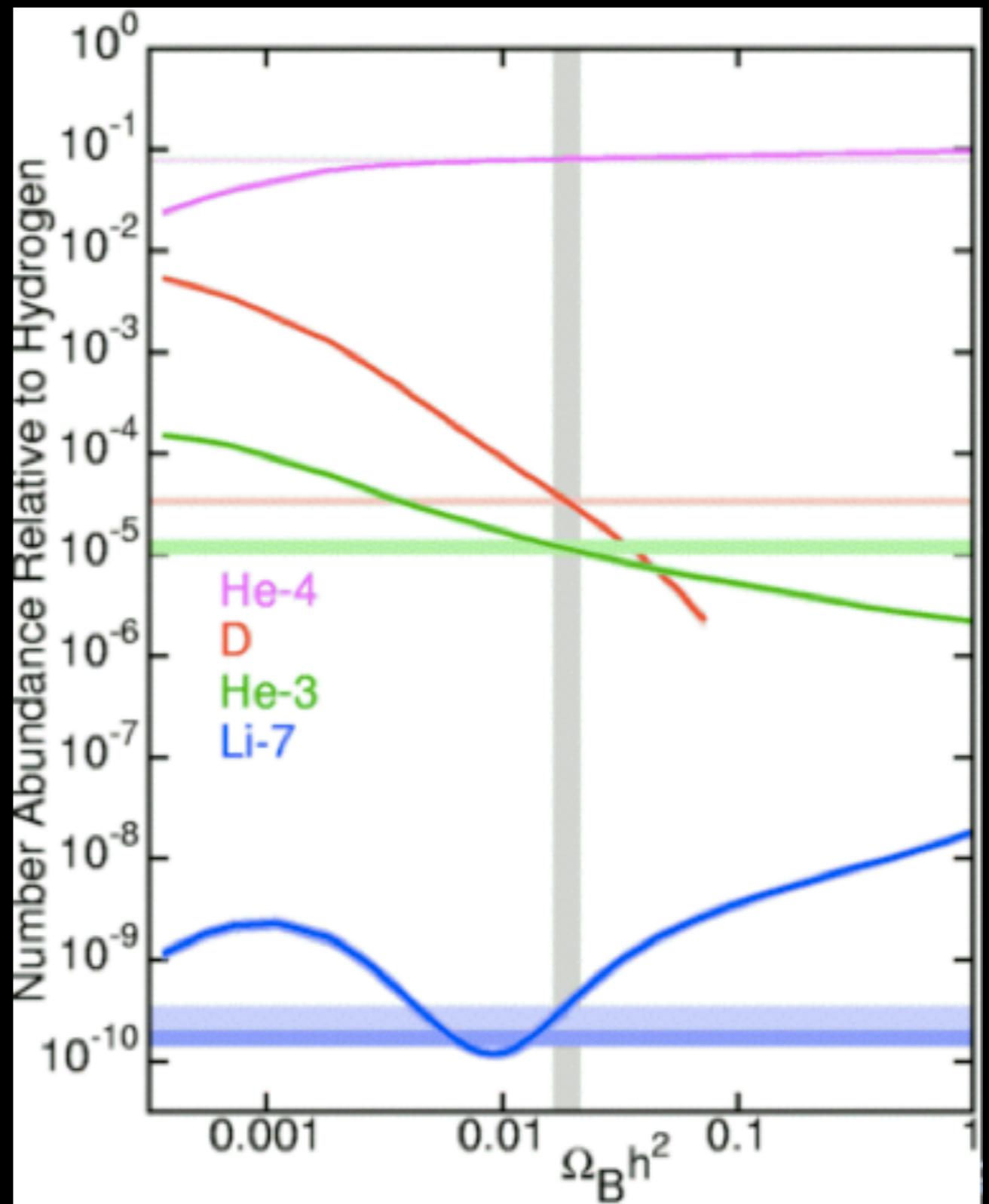


	$^2H$	$^3H$	$^3He$	$^4He$
$B_A (MeV)$	2.22	6.92	7.72	28.3
$T_A (MeV)$	0.066	0.1	0.11	0.28



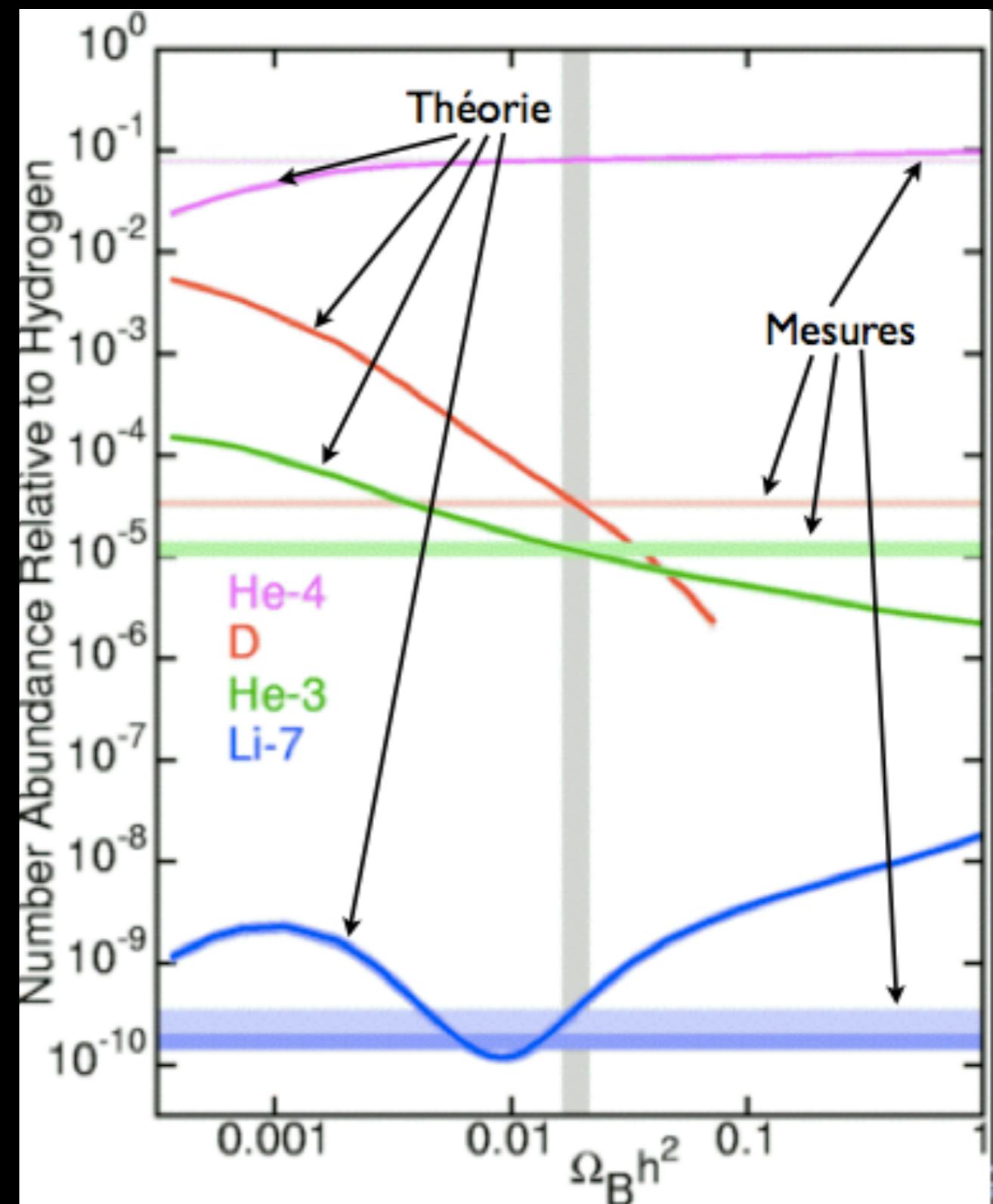
# Nucleosíntesis Primordial

- A partir del minuto  $\sim 20$  el universo es demasiado frío para continuar la fusión nuclear, ya no existen más neutrones libres.
- Las abundancias primordiales están casi fijas (salvo las especies radioactivas que se desintegran  $^3\text{H}$ ,  $^7\text{Be}$ ,  $^8\text{Be}$ )



# Nucleosíntesis Primordial

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- **Remarcable correspondencia de la teoría con las observaciones !**



# Nucleosintesis Primordial

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10,000 a

Igualdad materia-radiacion

Nucleos

3 min

Neutrones, electrones protones

Nucleosintesis Primordial

$10^{-4}$  s

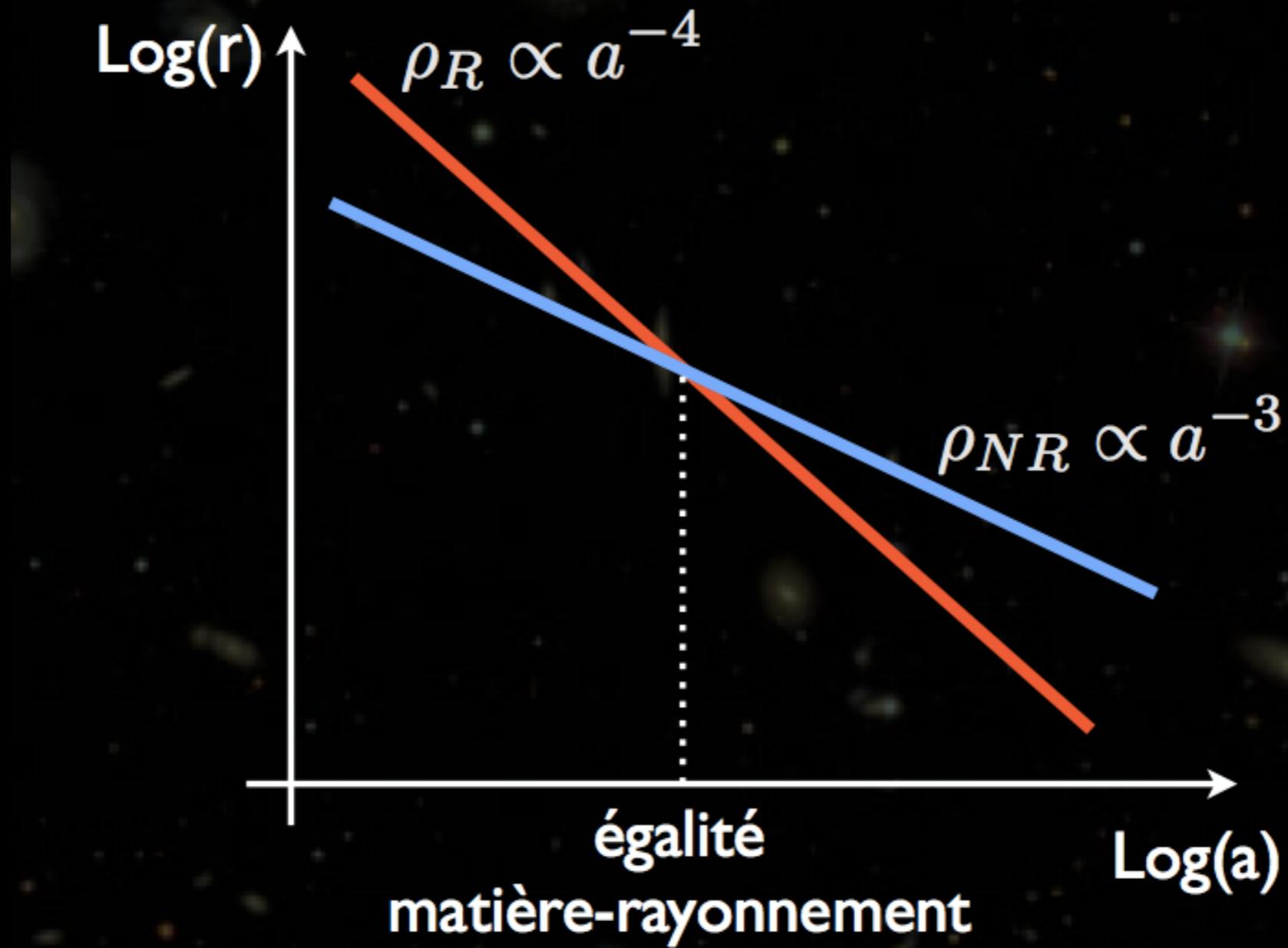
Bariones

$10^{-6}$  s

Quarks y Leptones

$10^{-33}$  s

# Igualdad Materia-Radiación



# calcul de $z_{\text{eq}}$

- **Radiation:**

$$\rho_R \propto a^{-4}$$

$$\Omega_R = \frac{8\pi G \rho_R}{3H^2}$$

- **Matière:**

$$\rho_{NR} \propto a^{-3}$$

$$\Omega_{NR} = \frac{8\pi G \rho_{NR}}{3H^2}$$

$$\Rightarrow \frac{\Omega_R}{\Omega_{NR}} = \frac{\rho_R}{\rho_{NR}} = \frac{\Omega_{R,0} \times (1+z)^4}{\Omega_{NR,0} \times (1+z)^3} = \frac{\Omega_{R,0}}{\Omega_{NR,0}} \times (1+z)$$

★ Photons : le CMB est un corps noir à 2.725 K

- Densité d'énergie par la loi de Stefan

$$\rho_{\gamma,0} c^2 = 4\sigma T^4 / c \text{ J.m}^{-3}$$
$$\sigma = 5.67 \times 10^{-8} \text{ M.m}^{-2}.\text{K}^{-4}$$

$$\rho_{\gamma,0} c^2 = \frac{4 \times 5.67 \times 10^{-8} \times 2.725^4}{3 \times 10^8} \text{ J}$$
$$= 4.17 \times 10^{14} \text{ J.m}^{-3}$$

$$\rho_{\gamma,0} = 4.64 \times 10^{-31} \text{ kg.m}^{-3}$$

$$\Omega_{\gamma,0} = \frac{8\pi G \rho_{\gamma,0}}{3H_0^2} = 2.47 h^{-2} \times 10^{-5}$$

# calcul de $z_{eq}$

- ★ Neutrinos: contribution de ~70% supplémentaire
- ★ donc pour le rayonnement:  $\Omega_{R,0} \simeq 4.2 h^{-2} \times 10^{-5}$

$$(1 + z_{eq}) = \frac{\Omega_{NR,0}}{\Omega_{R,0}}$$
$$= \frac{h^2 \times \Omega_{m,0}}{4.2 \times 10^{-5}}$$

$$z_{eq} = 23800 \times h^2 \times \Omega_{m,0}$$
$$z_{eq} \simeq 3600$$

# Desacoplamiento de radiación y báriones

- Emisión del Fondo Difuso Cosmológico, 3000 K a  $z=1000$ , medido hoy a 3K, fotografía del universo a  $z=1000$ .

380,000 a

Última Difusión  
Desacoplamiento  
radiación-materia

Materia no relativista

10,000 a

Núcleos

3 min

Neutrinos, electrones protones

$10^{-4}$  s

Bariones

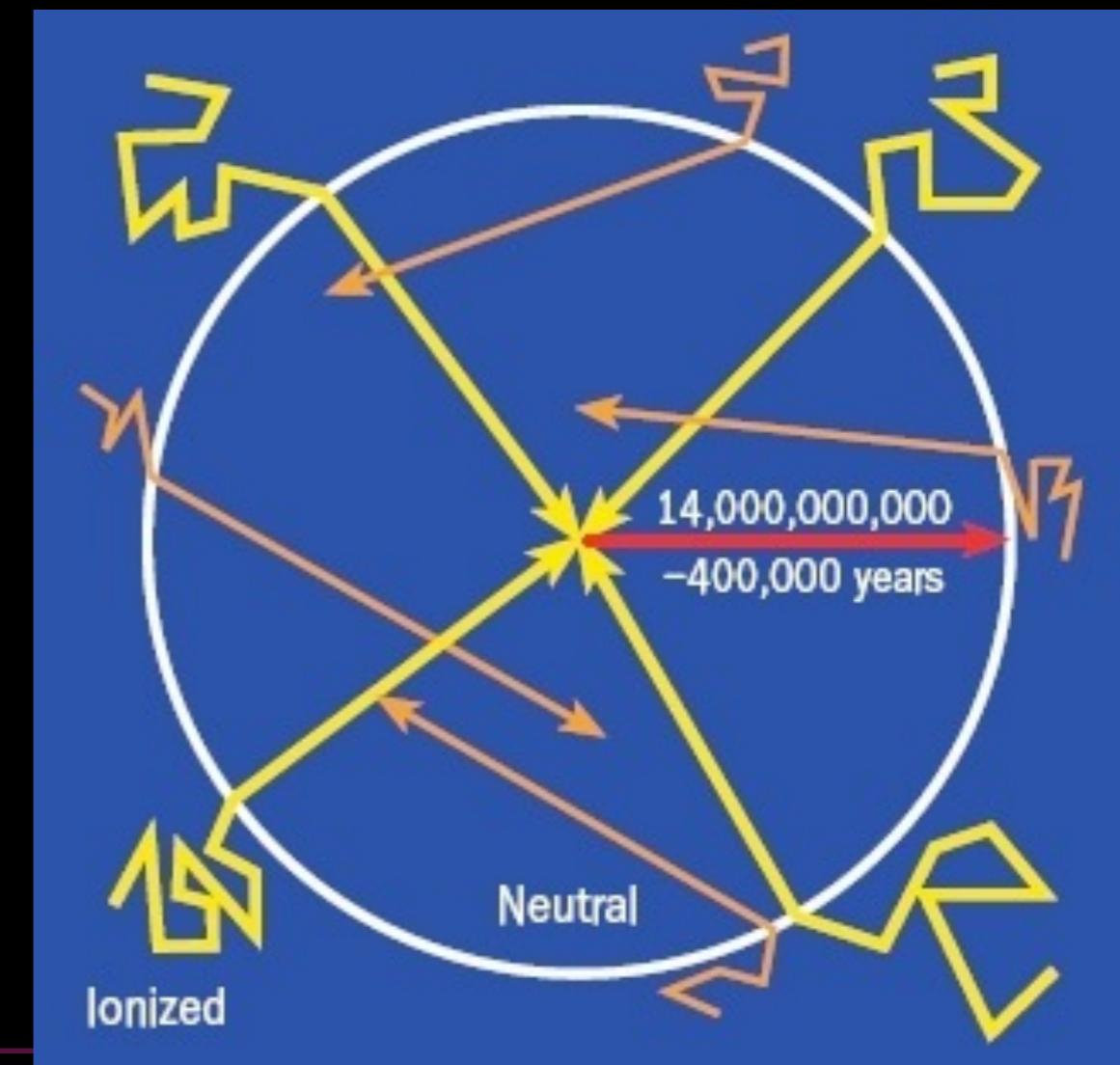
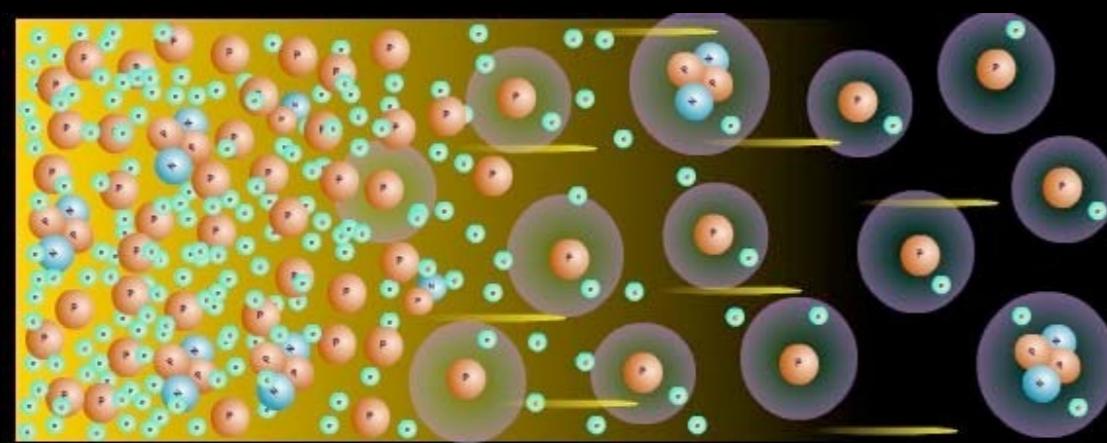
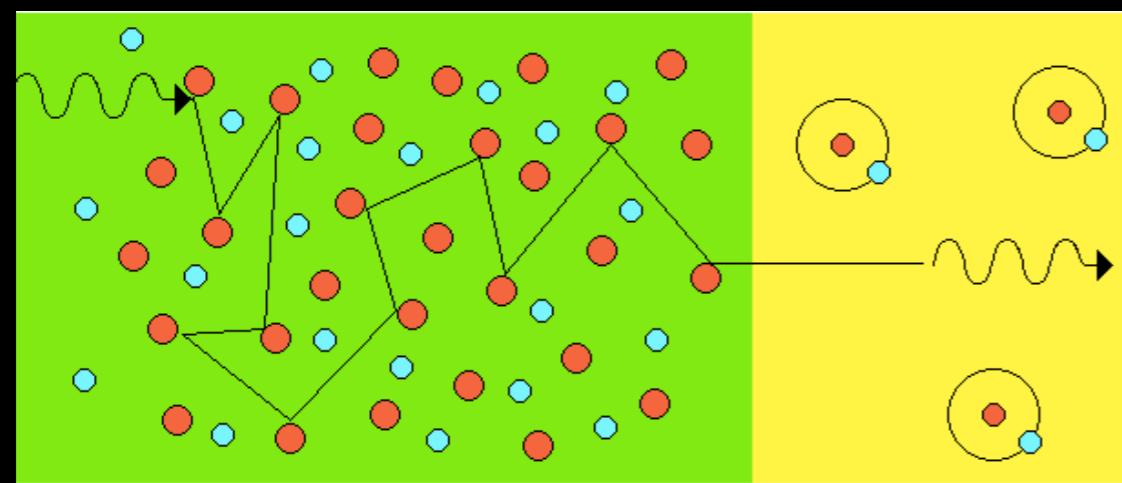
$10^{-6}$  s

Quarks y Leptones

$10^{-33}$  s

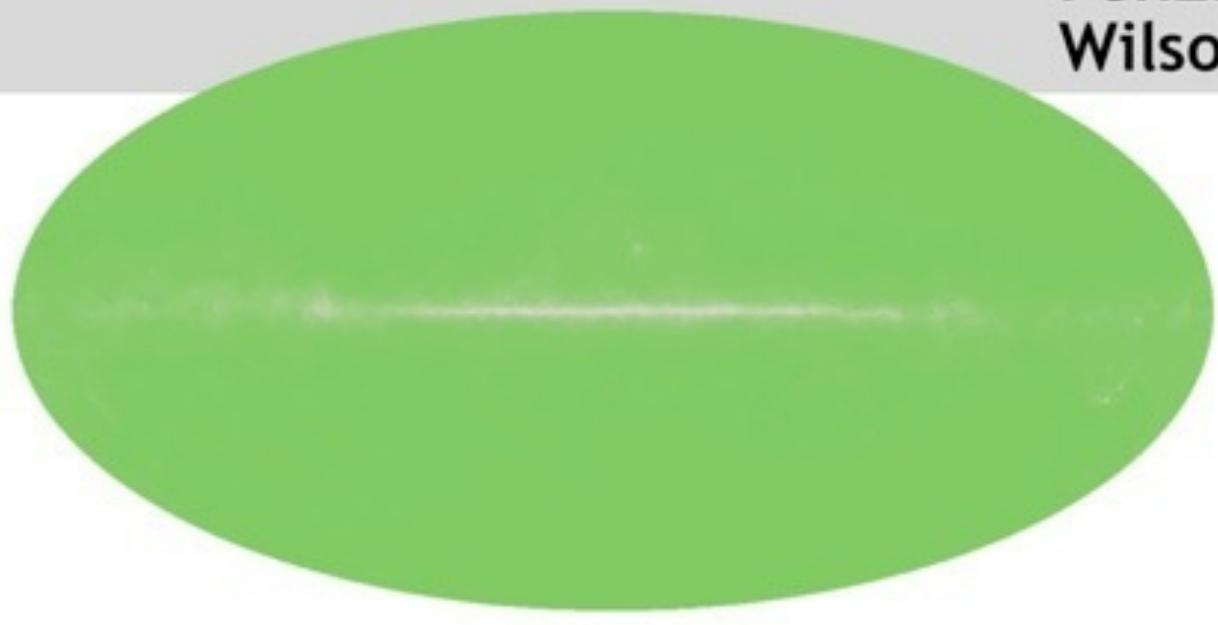
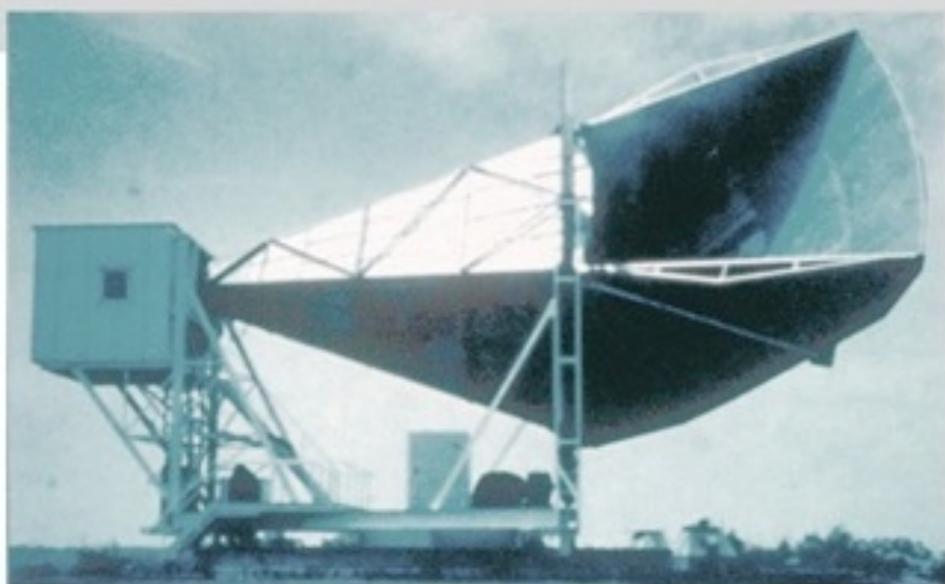
# Desacoplamiento de radiación y bariones

- Interacciones Continuas, trayectoria libre medias de fotones pequeñas, el universo es opaco
- Temperatura disminuye  $T < 13.6 \text{ eV} - 3000 \text{ K}$ , electrones y nucleos forman atomos, fotones no interactuan mas, el universo se vuelve transparente



# Temperatura Homogénea

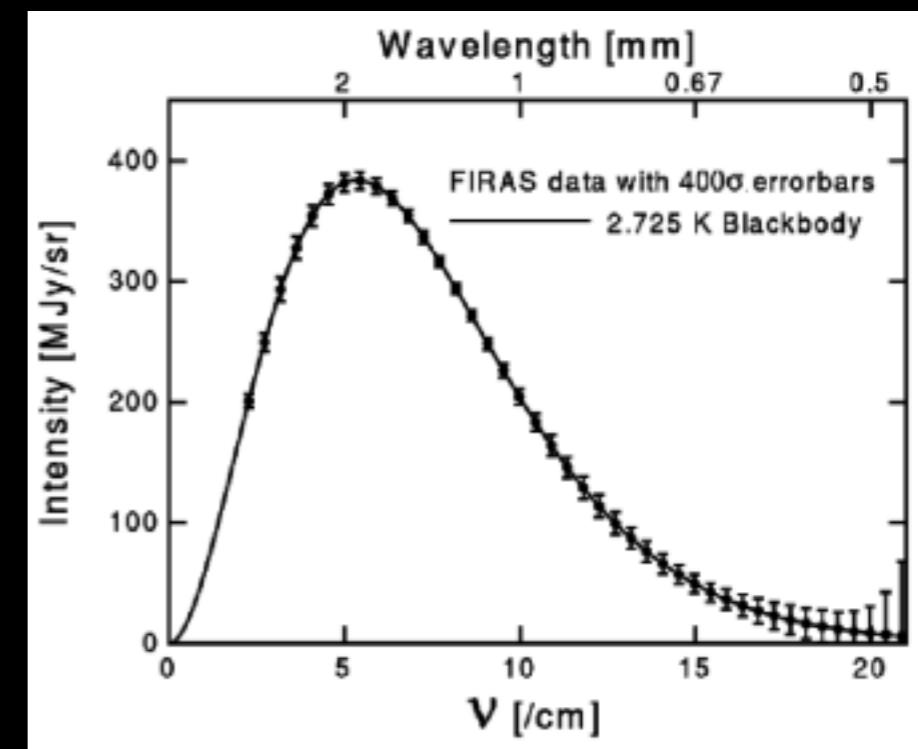
1965



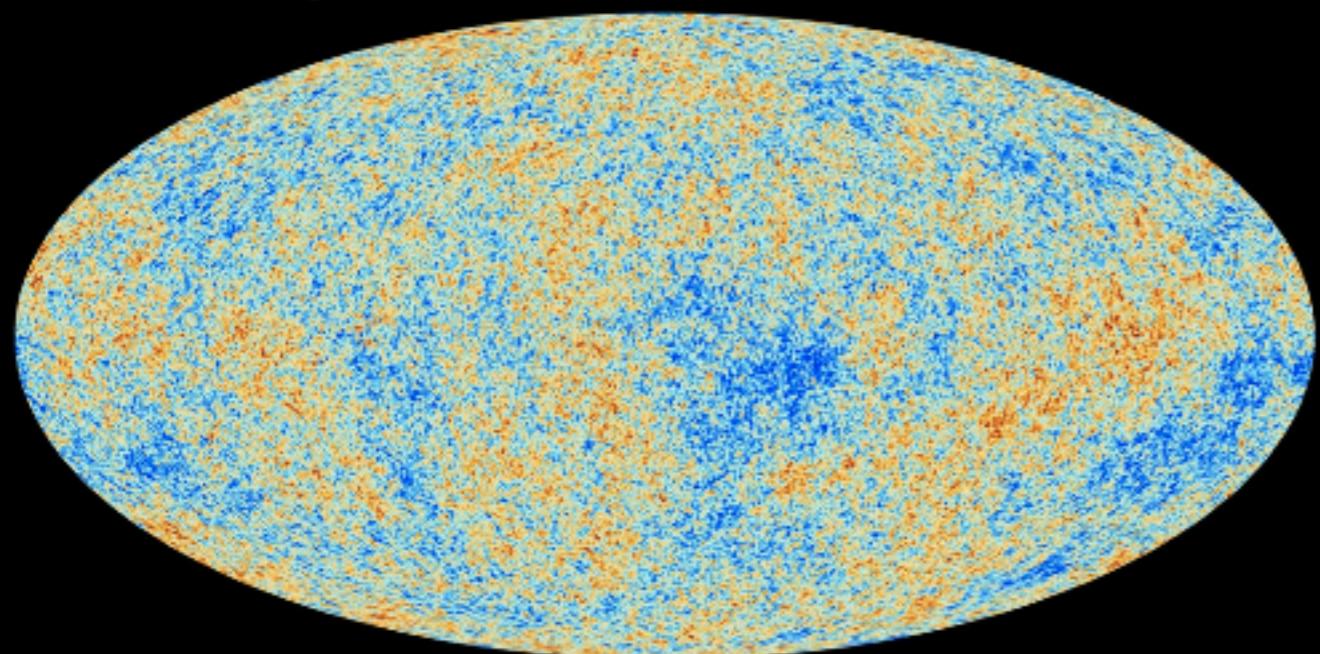
Penzias and  
Wilson

# Cosmic Microwave Background Radiación Penzias and Wilson

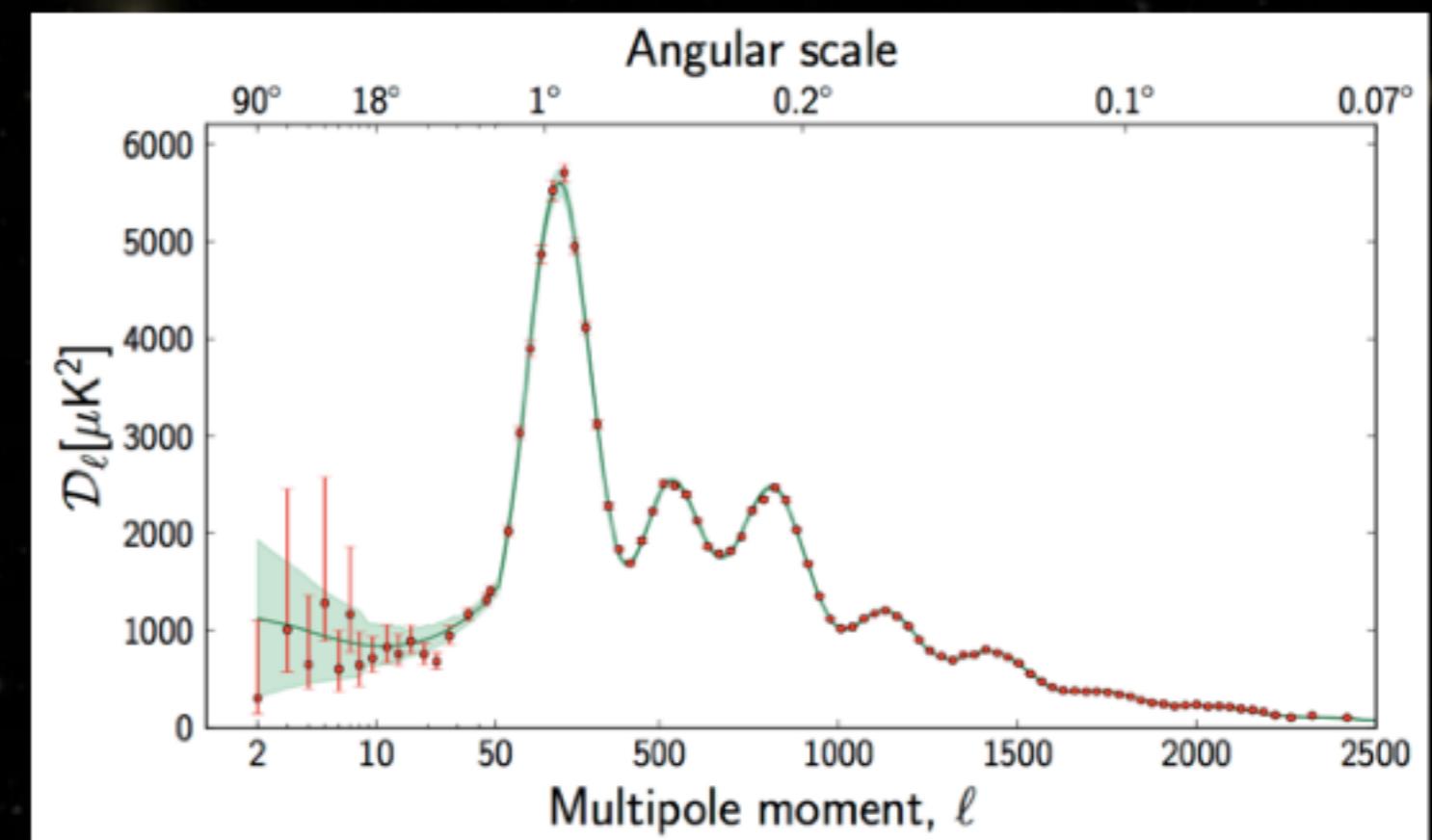
- Radiación Isotrópica
- Cuerpo Negro Perfecto,  $a \sim 3K$
- Equivalente a 3000K a  $z=1100$
- radiación emitida 400,000 después del Big Bang

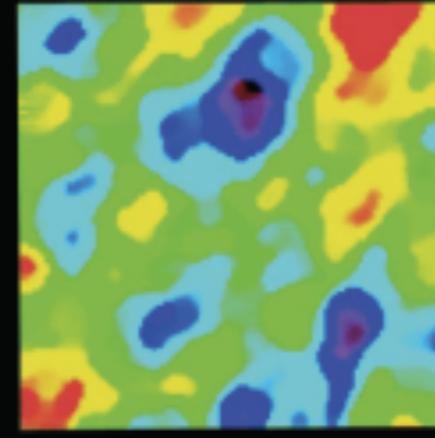
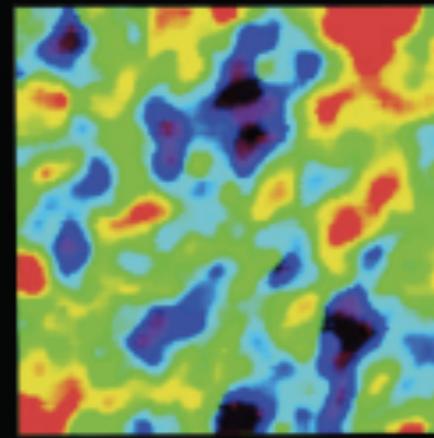
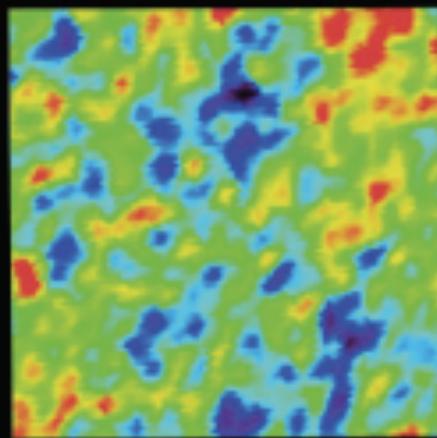


# Explicación Pizarrón



*Amplitude des  
fluctuations en fonction  
de leur taille angulaire :  
Spectre de Puissance*



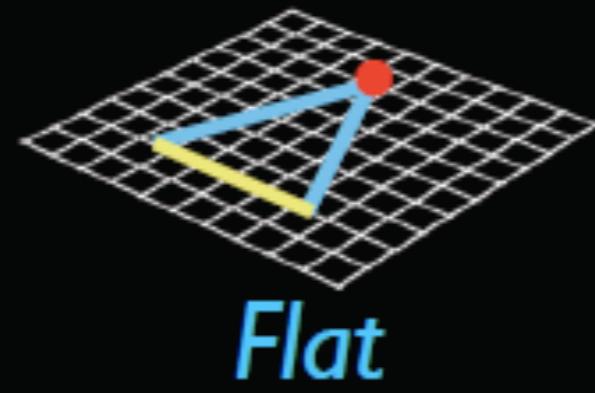


*The physical size of the fluctuations is the horizon size at the last scattering surface.*

$$\Omega < 1 \Rightarrow \theta_c < 1^\circ \quad \Omega = 1 \Rightarrow \theta_c \simeq 1^\circ \quad \Omega > 1 \Rightarrow \theta_c > 1^\circ$$



*Open*



*Flat*



*Closed*

*The geometry of the Universe determines the angular size of the fluctuations.*

$$\Omega \equiv \frac{\text{Energy in the Universe}}{\text{Energy required for flatness}} = 1.005 \pm 0.007 \text{ today}$$

# Universo “Obscuro”

## Universo Neutro

Formacion de estructura por colapso gravitacional en las sobredensidades de materia oscura

380,000 a

- Era oscura,  $z=1,000-15$ , se forma la estructura

10,000 a

## Nucleos

3 min

## Neutrones, electrones protones

$10^{-4}$  s

## Bariones

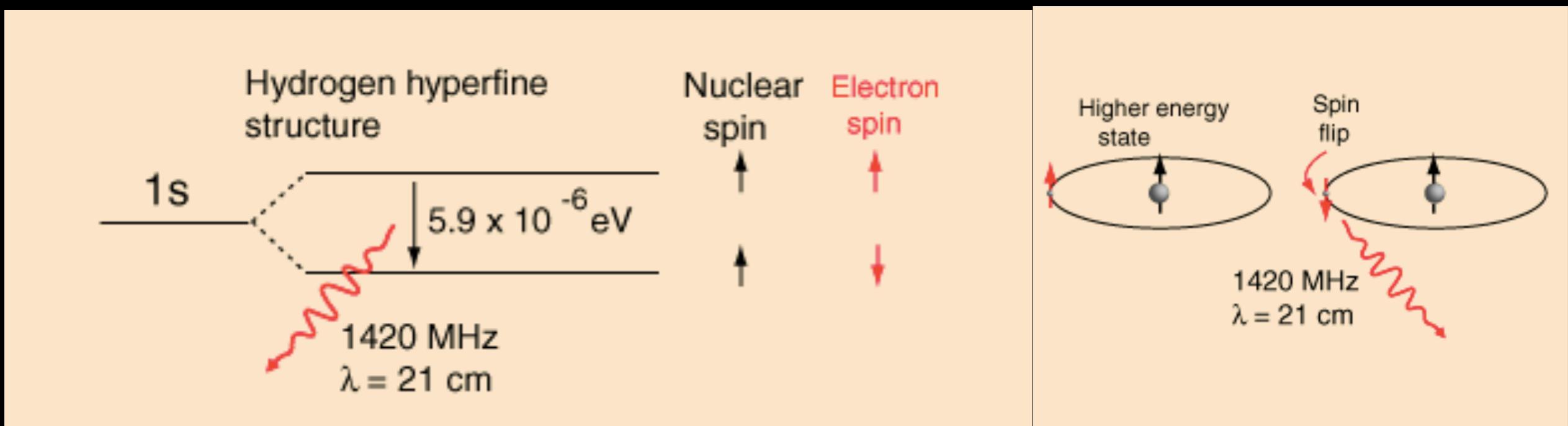
$10^{-6}$  s

## Quarks y Leptones

$10^{-33}$  s

# Universo Obscuro

# 21-cms

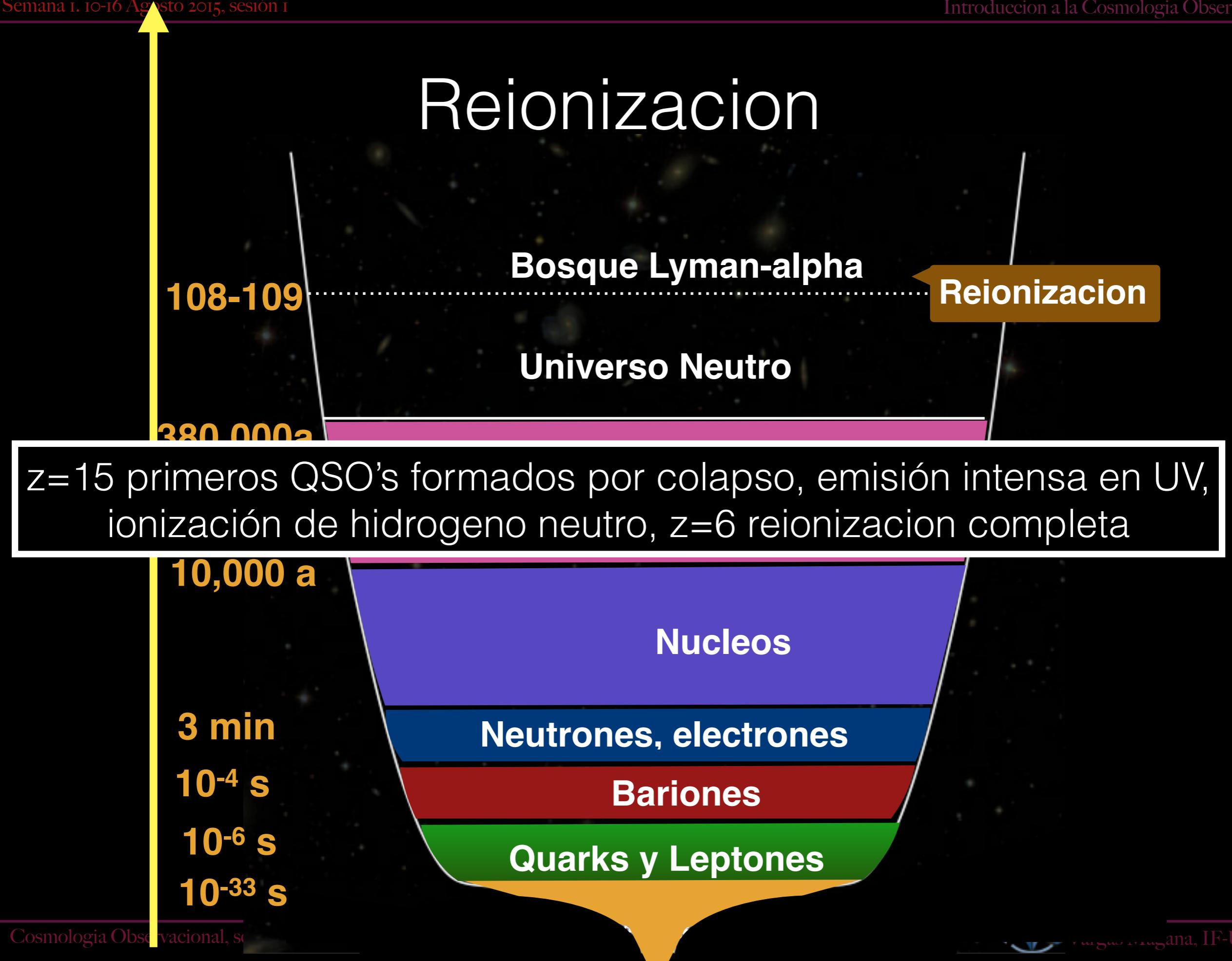


Esta radiación de hidrógeno a 1420 MHz viene de la transición entre los dos niveles 1s del estado fundamental del hidrógeno, ligeramente divididos por la interacción entre el espín del electrón y el espín nuclear.

# Formación de estructura

# N-body Simulations

- Expanding  $U$ 
  - All calculations carried out in co-moving coordinates
- Only gravity as significant force
  - Limits smallest scale that is valid in the model as it ignores pressure effects
  - It is a model of cold dark matter only (no interactions, no thermal velocities)
  - Work in Newtonian limit – particles are non-relativistic
- Can model  $U$  as few massive particles each representing about  $10^{15}$  solar masses
  - Treat particles as average density over a finite volume (not point particles)
- Periodic Boundary Conditions
  - Assumes  $U$  is on large scales basically the same everywhere
  - limits largest scale that can be seen in the model

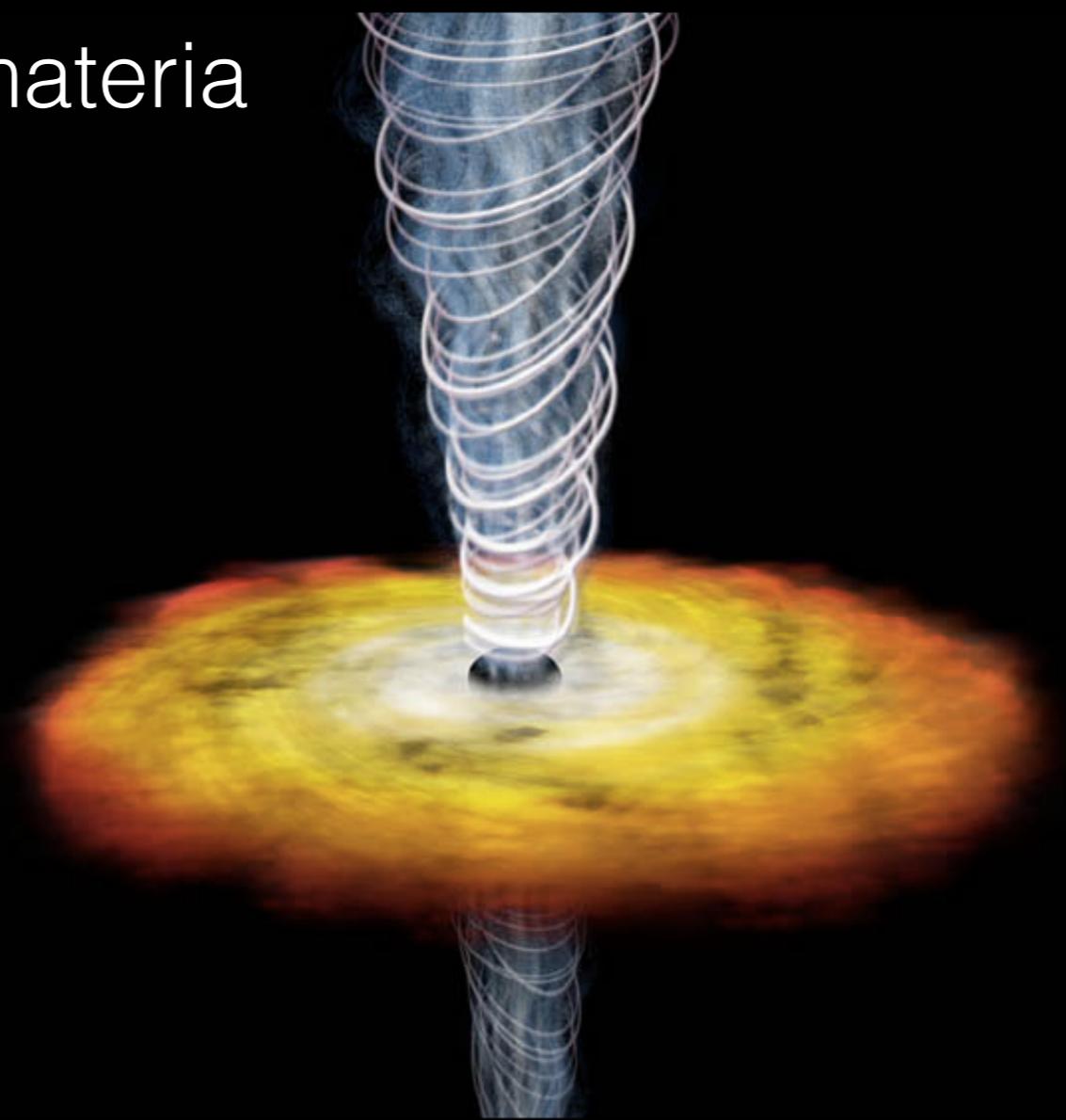


# Reionización(video)



# Quasares y Hoyos Negros

Hoyo Negro que acreta materia



# Quasar spectra

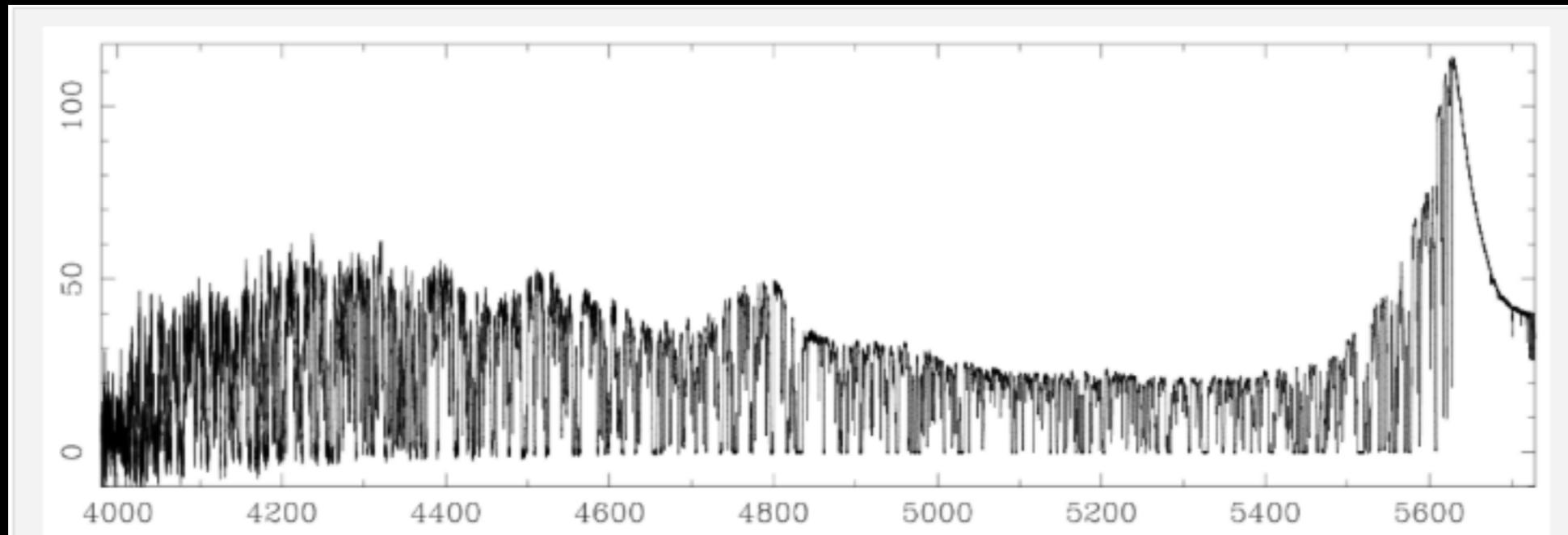
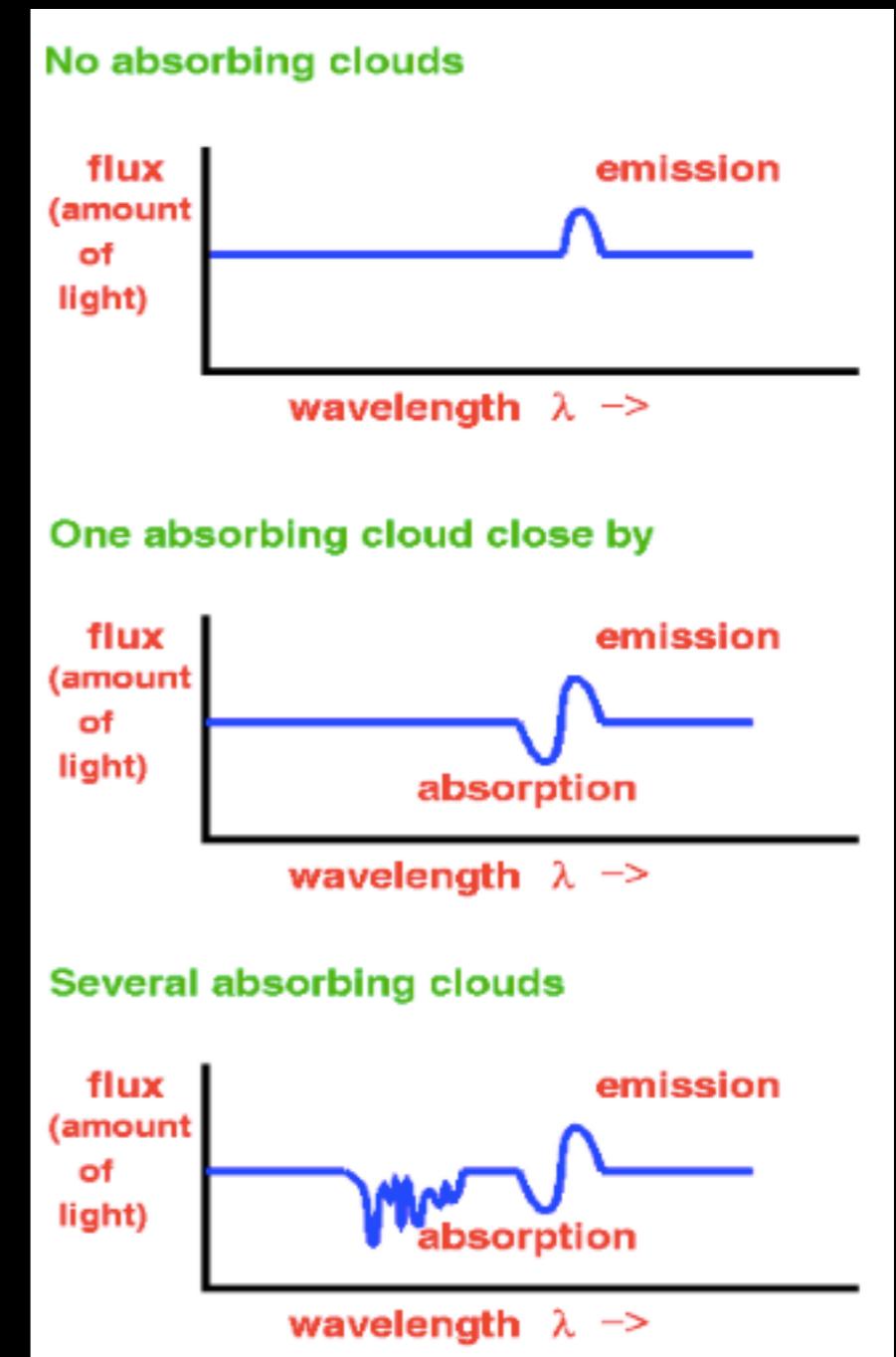
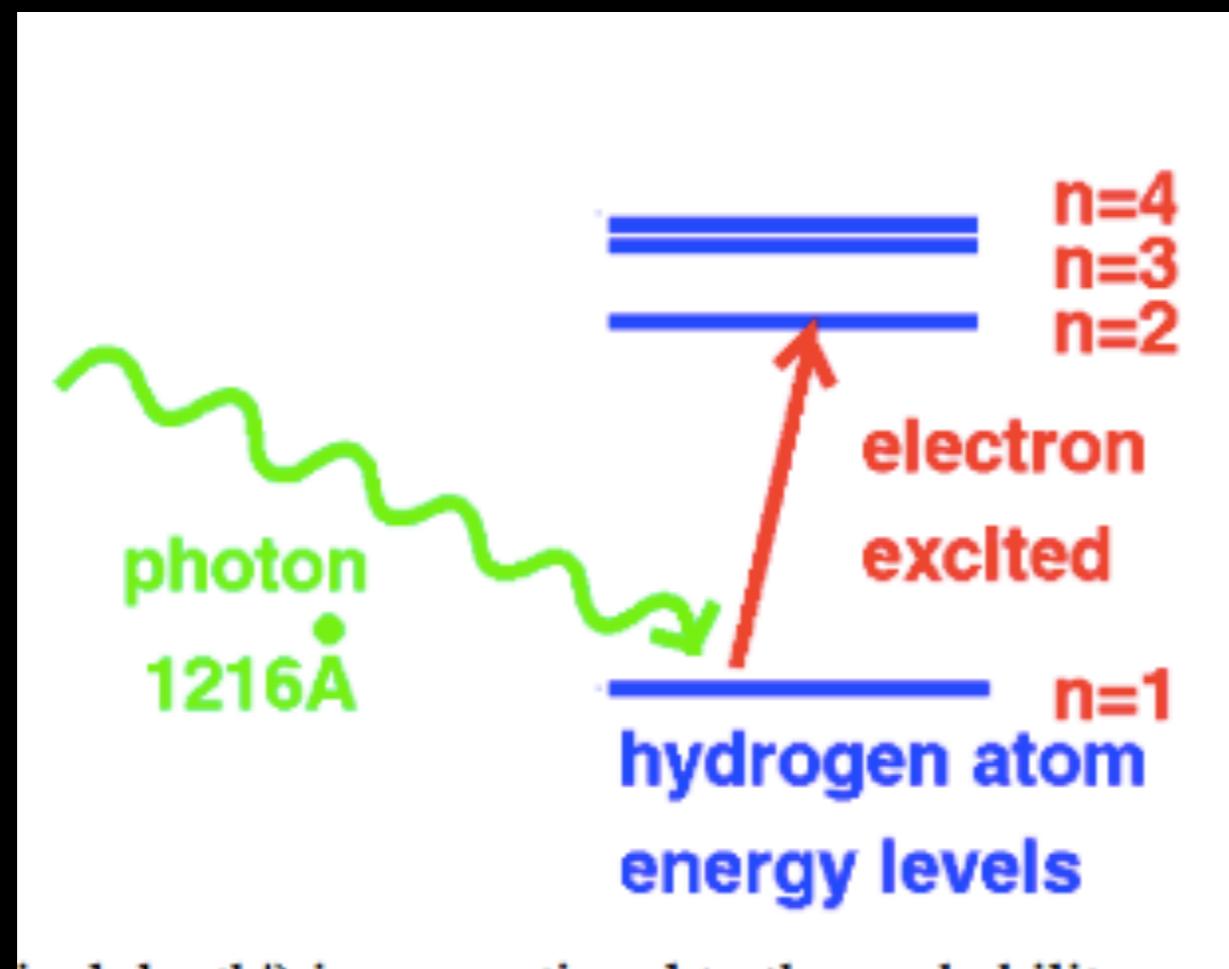
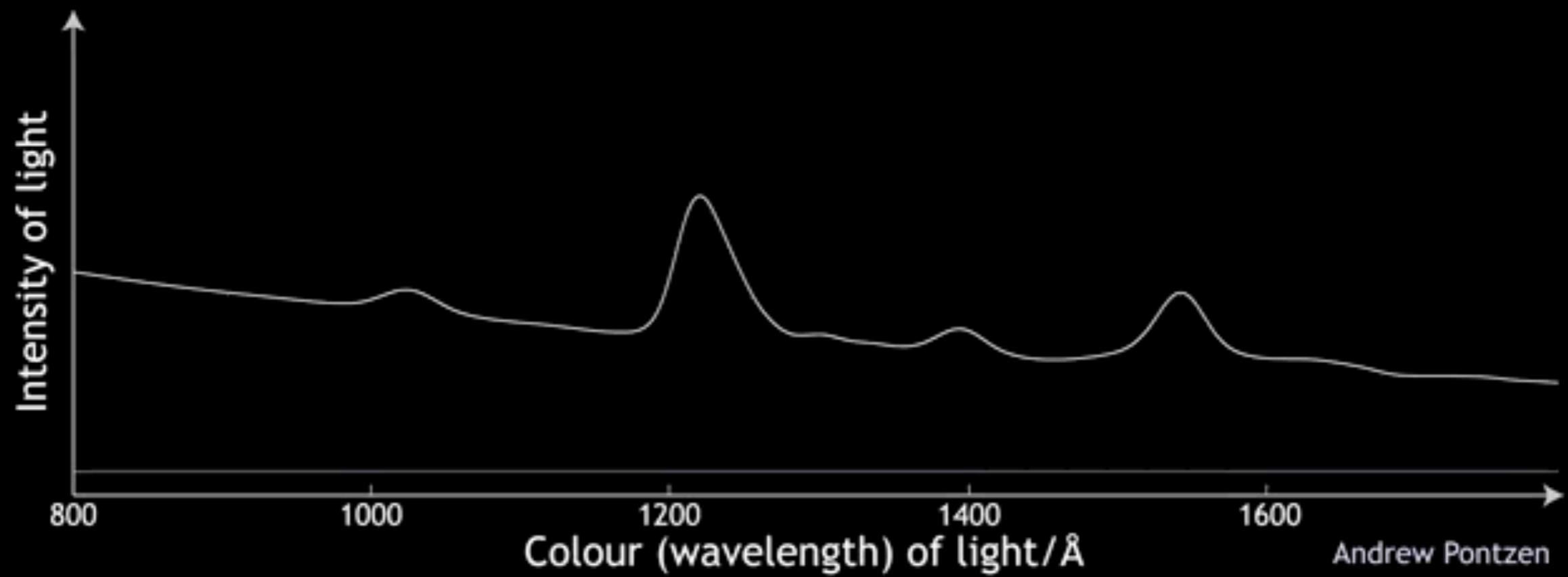
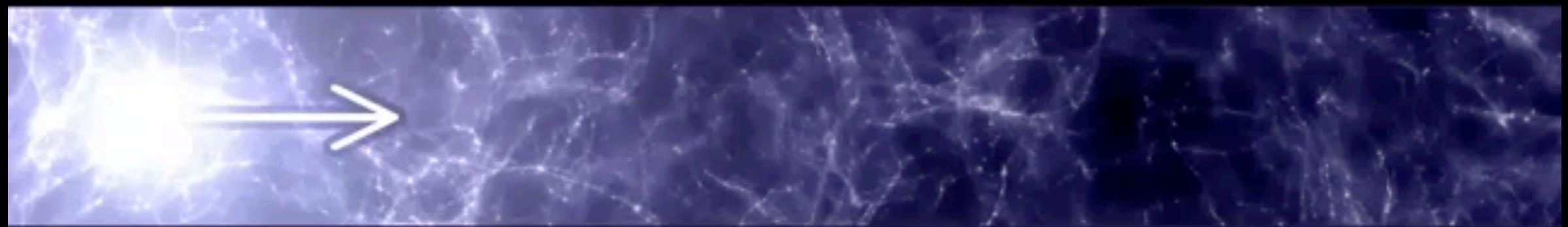


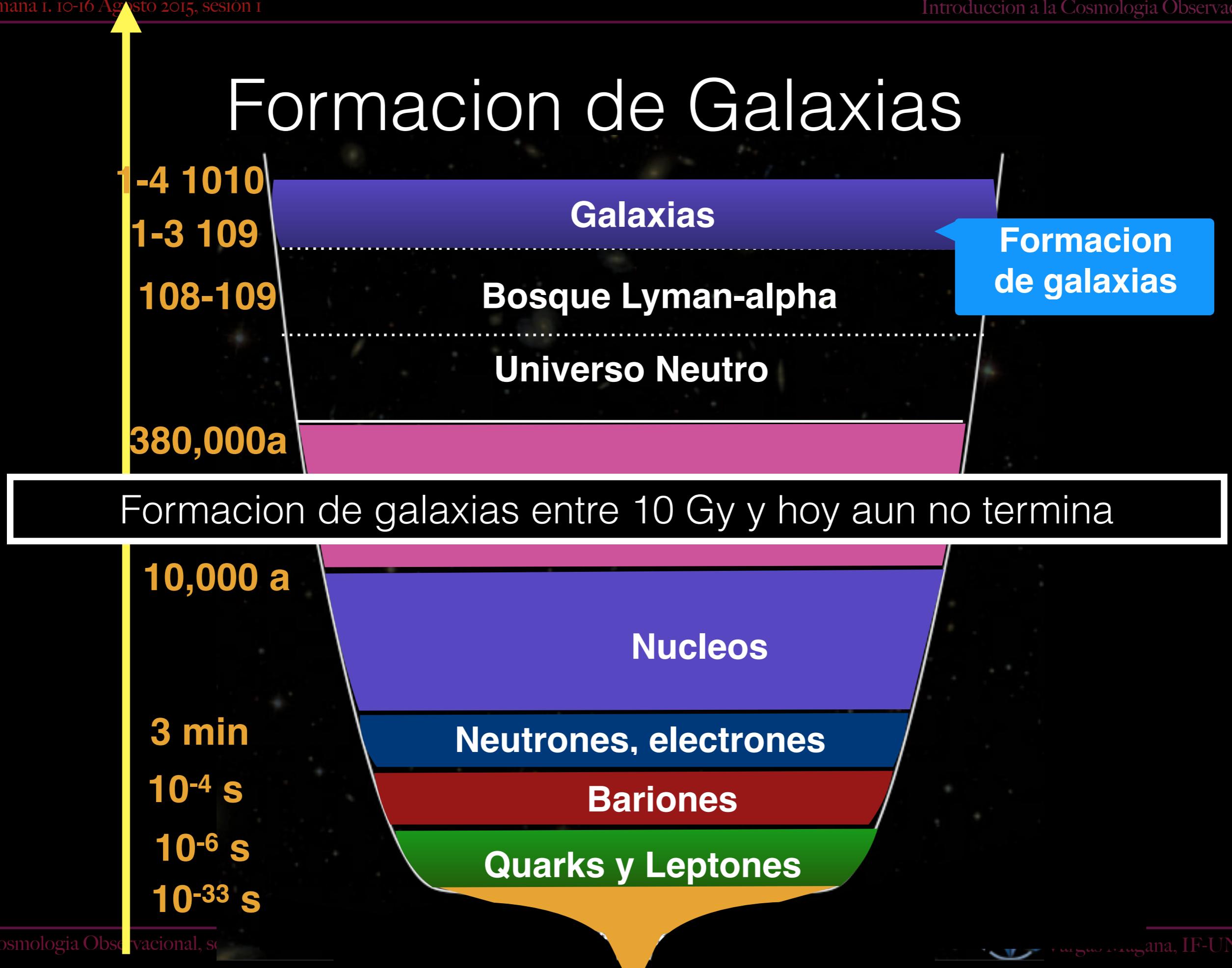
Figure 1: The Lyman Alpha absorption line forest. The broad emission feature at the right of the plot is the Lyman alpha intrinsic to the quasar, while the dense series of absorption lines to the left are from the intervening neutral hydrogen at lower redshifts. Figure from Rauch 1998: <http://arxiv.org/abs/astro-ph/9806286>

# Lyman Alpha

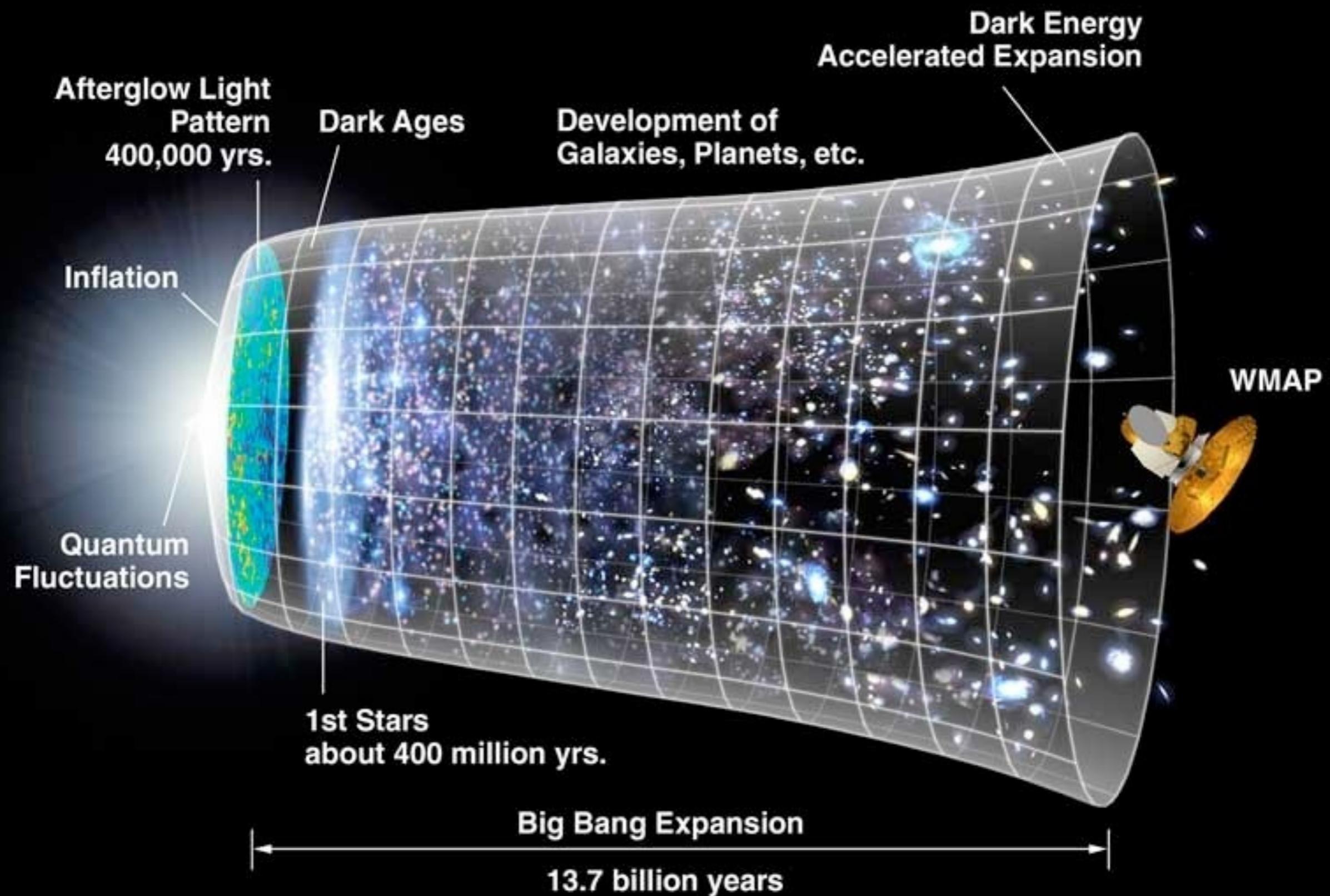


# Foret Lyman Alpha(video)





# Galaxy Formation(video)



Referencia Basica. Semana 1.  
An Introduction to Modern Cosmology, Andrew Liddle.  
Modern Cosmology, Scott Dodelson.