

# Universidad Nacional de Río Negro

## Int. Partículas, Astrofísica & Cosmología - 2019

- **Unidad**      04 – El Big Bang
- **Clase**        U04 C02
- **Fecha**        20 Nov 2019
- **Cont**          historia térmica
- **Cátedra**      Asorey



**HOW DID OUR UNIVERSE BEGIN?**

The 13.8 billion years ago entire visible universe was contained in an unimaginably dense point, a billionth the size of a nuclear particle. Then it expanded—defying gravity all the way.

**Inflation**  
In far less than a nanosecond, a repulsive energy field inflates space to visible size and fills it with a soup of subatomic particles called quarks.

**Age:**  $10^{-32}$  milliseconds  
**Size:** Infinitesimal to golf ball

**Early building blocks**  
The universe expands, cools. Quarks clump into protons and neutrons, the building blocks of atomic nuclei. Perhaps dark matter forms.

**First nuclei**  
As the universe cools, the first nuclei of hydrogen and helium form.

**First atoms, first light**  
As electrons begin orbiting nuclei, creating atoms, the glow from our infant universe is unveiled. This light is as far back as our instruments can see.

**The "dark ages"**  
For 300 million years this cosmic background radiation is the only light. Clumps of matter that will become galaxies glow brightest.

**Gravity wins: first stars**  
Dense gas clouds come under their own gravity, clumps of dark matter to event form galaxies and stars. Fusion lights up the stars.

**Antigravity wins**  
After being slowed for billions of years by gravity, cosmic expansion accelerates again. The output, dark energy, its nature, unclear.

**Today**  
The universe continues to expand, becoming ever less dense. As a result, newer stars and galaxies are forming.

**10 billion years**  
.77 percent size

**13.8 billion years**  
Present size

**Our solar system**

**Galaxies**

**Dark energy accelerates**

**HOW WILL IT END?**

Which will win in the end, gravity or antigravity? Is the density of matter enough for gravity to halt or even reverse cosmic expansion, leading to a big crunch? It seems unlikely—especially given the power of dark energy, a kind of antigravity. Perhaps the acceleration in expansion caused by dark energy will trigger a big rip that shreds everything, from galaxies to atoms. If not, the universe may expand for hundreds of billions of years, long after all stars have died.

**Big crunch**  
**Big rip**  
**Infinite expansion**

**Galaxies ripped apart by rapid expansion**

**Unidad 3**  
**Cosmología**  
**No es lo que se ve**  
**Sino lo que se palpa**

**Observable Universe**  
The universe began 13.8 billion years ago. Because it has been expanding ever since, the furthest observable edge is now 47 billion light-years away.

**The Unknown Edge**  
What we can't see possible shapes a sphere, a saddle, or flat.

**WHAT IS THE SHAPE OF OUR UNIVERSE?**

Einstein discovered that a star's gravity curves space around it. But is the whole universe curved? Might space close up on itself like a sphere or curve the other way, opening out like a saddle? By studying cosmic background radiation, scientists have found that the universe is poised between the two: just dense enough with just enough gravity to be almost perfectly flat, at least the part we can see. What lies beyond we can't know.

**WHAT IS OUR UNIVERSE MADE OF?**

Matter, dust, and gas—the stuff we can discern—make up less than 5 percent of the universe. Their gravity can't account for how galaxies hold together. Scientists figure about 24 percent of the universe is a mysterious dark matter—perhaps exotic particles formed right after inflation. The rest is dark energy: an unknown energy field or property of space that counteracts gravity, providing an explanation for observations that the expansion of space is accelerating.

**The Universe**

Component	Percentage
Dark matter	24%
Dark energy	71.5%
Gas	4%
Planets and stars	0.5%

**Unidad 2**  
**Astrofísica**  
**Cálido y frío**

**Unidad 1**  
**Partículas 1**  
**todo es relativo**

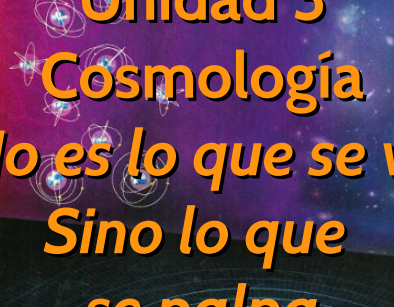
**DO WE LIVE IN A MULTIVERSE?**

What came before the big bang? Maybe other big bangs. The uncertainty principle holds that even the vacuum of space has quantum energy fluctuations. Inflation theory says our universe exploded from such a fluctuation—a random event that, odds are, had happened many times before. Our cosmos may be one in a sea of others just like ours—or nothing like ours. These other cosmos will very likely remain forever inaccessible to observation, their possibilities limited only by our imagination.

**Multiple universes**

**Fly through the universe on our digital edition.**

ILLUSTRATION: JAMES H. HANSEN, UNIVERSITY OF CHICAGO; CHARLES BRANNETT, UNIVERSITY OF CHICAGO; CHARLES BRANNETT, UNIVERSITY OF CHICAGO; CHARLES BRANNETT, UNIVERSITY OF CHICAGO

A presentation slide with a dark blue, starry background. At the top left, the word "Hydrogen" is written in a small, white, sans-serif font. The main title "Unidad 3" is in a large, bold, white sans-serif font. Below it, "Cosmología" is in a large, bold, yellow sans-serif font with a black outline. The phrase "No es lo que se ve" is in a large, bold, yellow sans-serif font with a black outline. Below that, "Sino lo que" is in a large, bold, yellow sans-serif font with a black outline. At the bottom, "se palpa" is in a large, bold, yellow sans-serif font with a black outline. In the bottom right corner, there is a small white icon of a globe and the text "©47 billion" in a small, white, sans-serif font.

Hydrogen

# Unidad 3

## Cosmología

*No es lo que se ve*

*Sino lo que*

*se palpa*

©47 billion

# Unidad 2

## Astrofísica

### Cálido y frío

# Unidad 1

## Partículas 1

*todo es relativo*





# Una torta de chips de chocolate



- La velocidad depende de la distancia entre los chips
- Cada uno piensa que es el “centro del Universo”
- Pero ninguno lo es

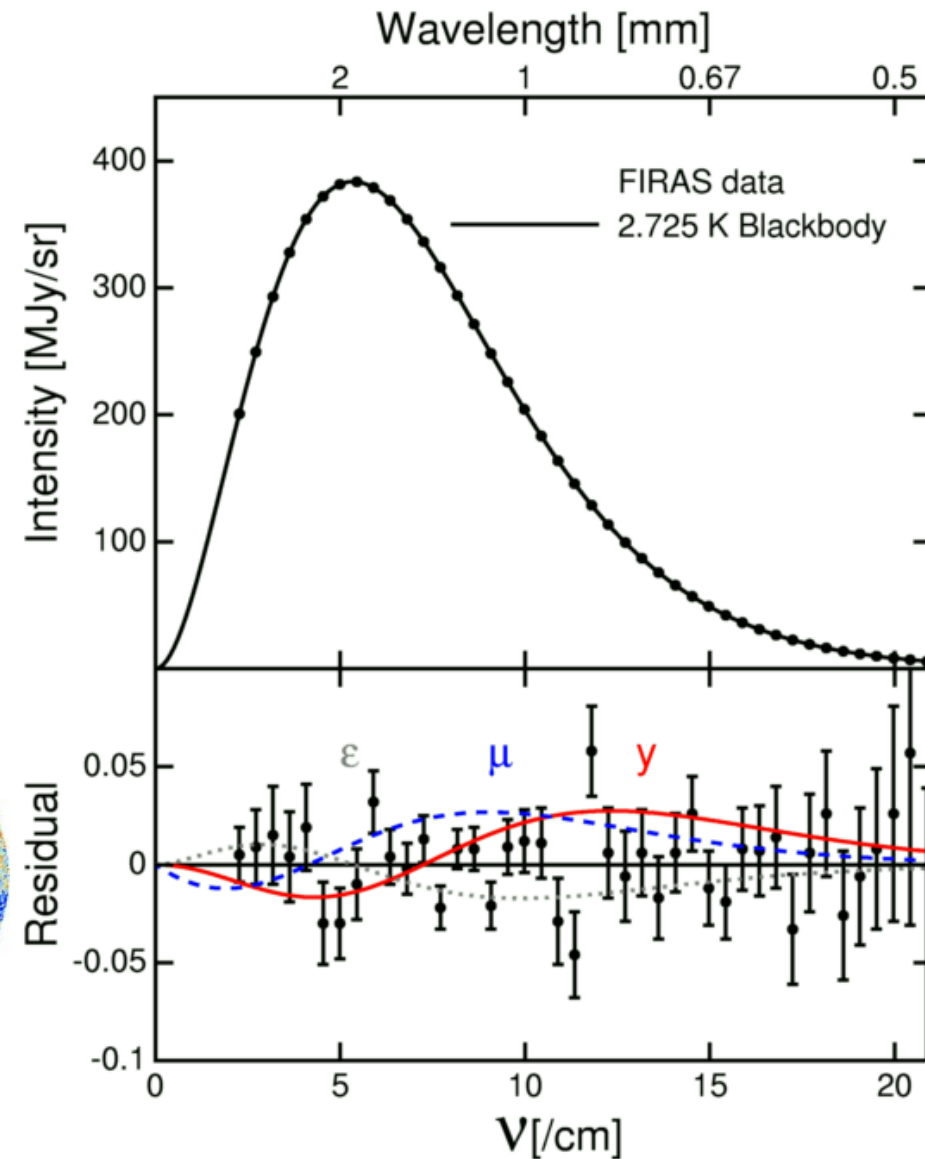
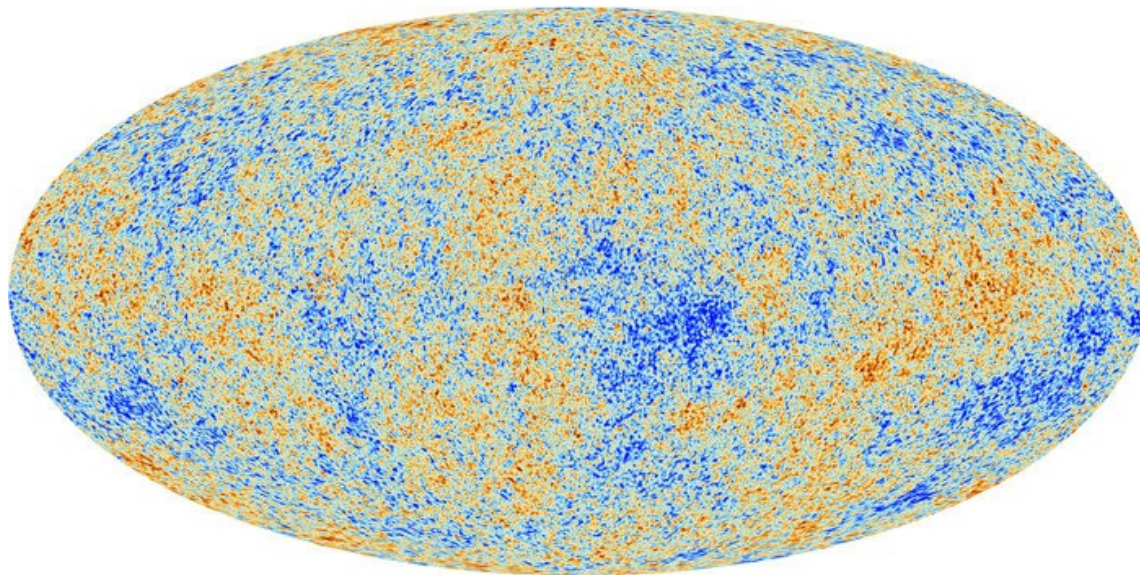
# Radiación de fondo de microondas

- Radiación de cuerpo negro:

$$T = (2.726 \pm 0.0013) \text{ K}$$

$$n_\gamma = 430 \text{ fotones/cm}^3$$

$$\langle E_\gamma/V \rangle = 0.25 \text{ eV/cm}^3$$



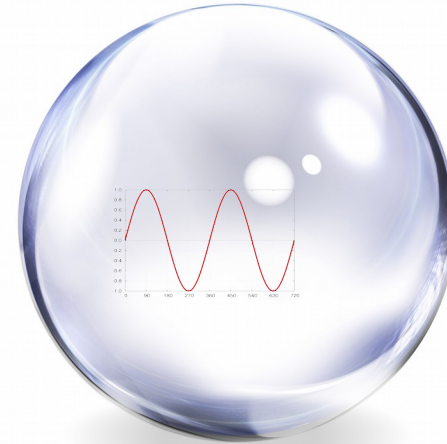


# Materia y energía en la expansión

$$E = mc^2$$



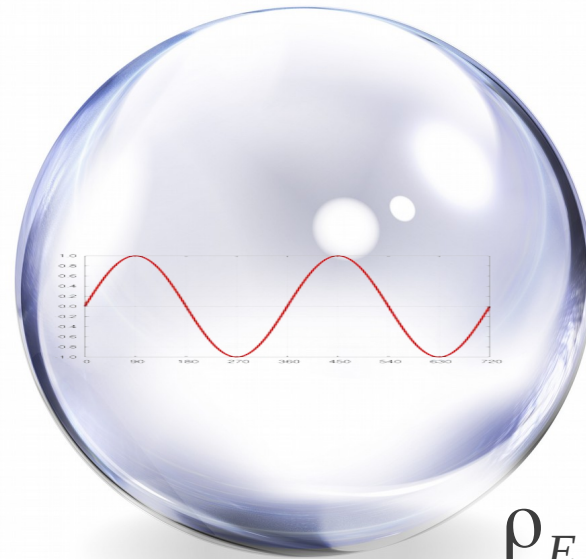
$$E = \frac{hc}{\lambda}$$



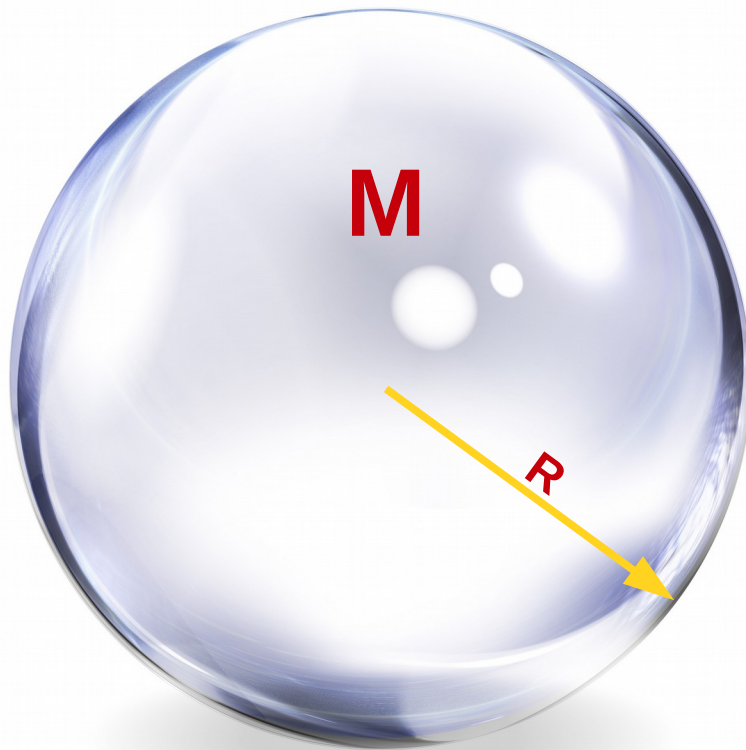
$$\rho_M \sim 1/R^3$$



$$\rho_E \sim (1/R^4)$$



# ¿La gravedad podrá compensar la expansión?



$$\frac{\rho_c}{m_p} = 6 \text{ protones}/m^3$$

- Densidad crítica:  
Densidad para la cual la gravedad detendrá la expansión del Universo
- ¿Cómo podemos calcularla?

$$\rho_c = \frac{3 H_0^2}{8 \pi G}$$

$$\Omega_i \equiv \frac{\rho_i}{\rho_c}$$

A horizontal banner image showing the evolution of the universe from the Big Bang to the present. It starts with a bright yellow/orange sphere on the left, transitions through a red field of particles, a purple field of atoms, and ends with a blue field of galaxies on the right. Arrows indicate the progression of time and space.

# Midiendo...

- Defino:  $\Omega = \rho / \rho_c$
- Ahora mido el contenido de materia del Universo, y obtengo:

$$\Omega = 1.00 \pm 0.01$$



# Contenido de materia energía del Universo

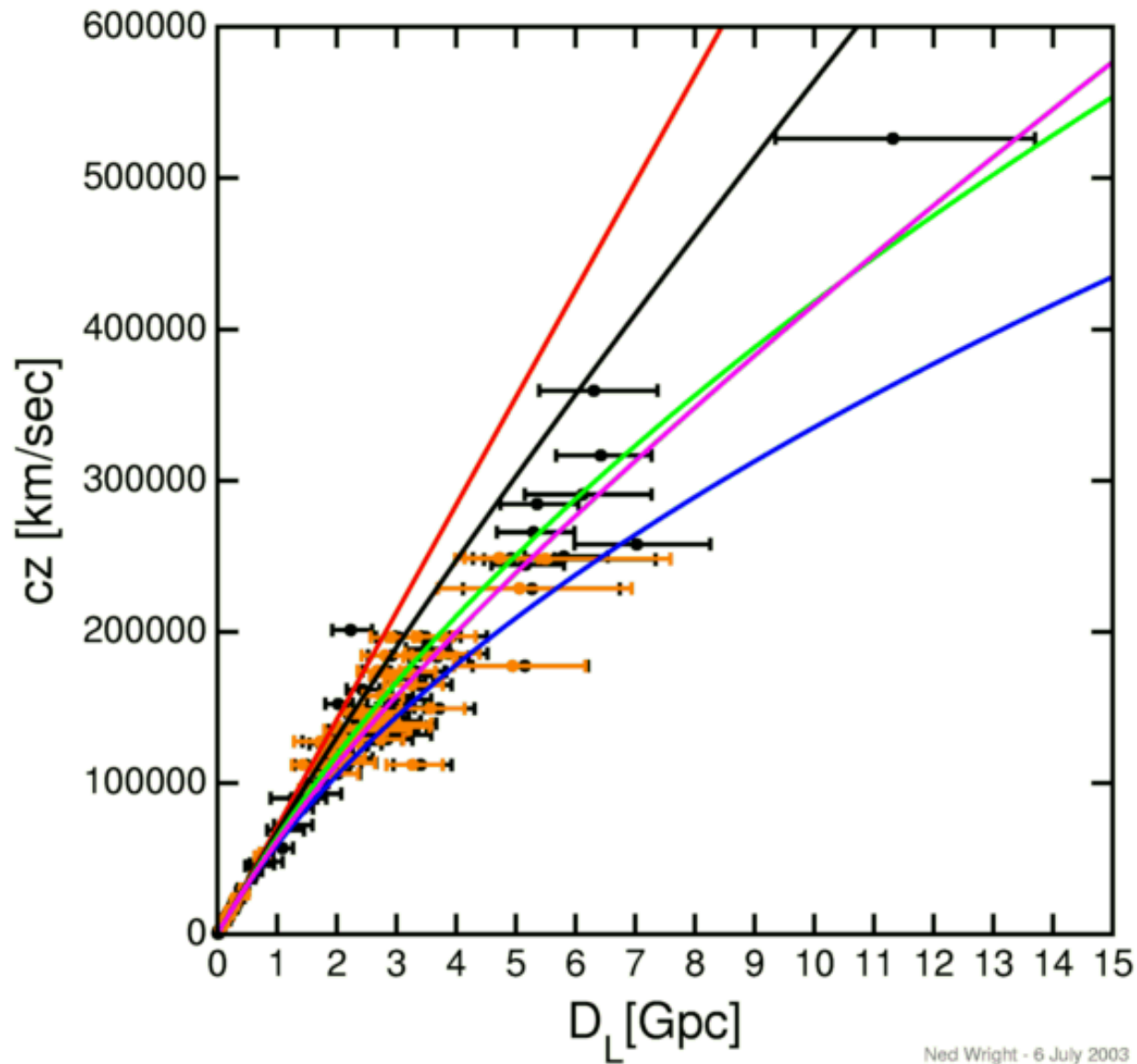
- Cómo se compone:

- $\Omega_k = 0.001\%$
- $\Omega_\gamma = 0.2\%$
- $\Omega_m = 4\%$
- $\Omega_M = 23\%$
- $\Omega_E = 73\%$





# El nuevo diagrama de Hubble





# Historia térmica del Universo

- El tamaño del Universo, define una especie de temperatura, en el sentido de que a menor radio, mayor densidad, más interacciones, mayor energía media
- Recordemos, para un mol ( $n=1$ ) de gas ideal:

$$PV = RT \text{ ó } PV = N_A k_B T \text{ y entonces } R = N_A k_B$$

donde  $k_B$  es Boltzmann y  $N_A$  es Avogadro:

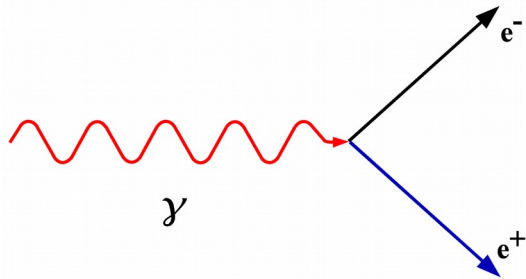
$$k_B = 1.38065 \times 10^{-23} \text{ J/K, ó } k_B = 8.61733 \times 10^{-5} \text{ eV/K}$$

- Y en general  $\langle E \rangle \propto k_B T$



# Historia térmica del Universo

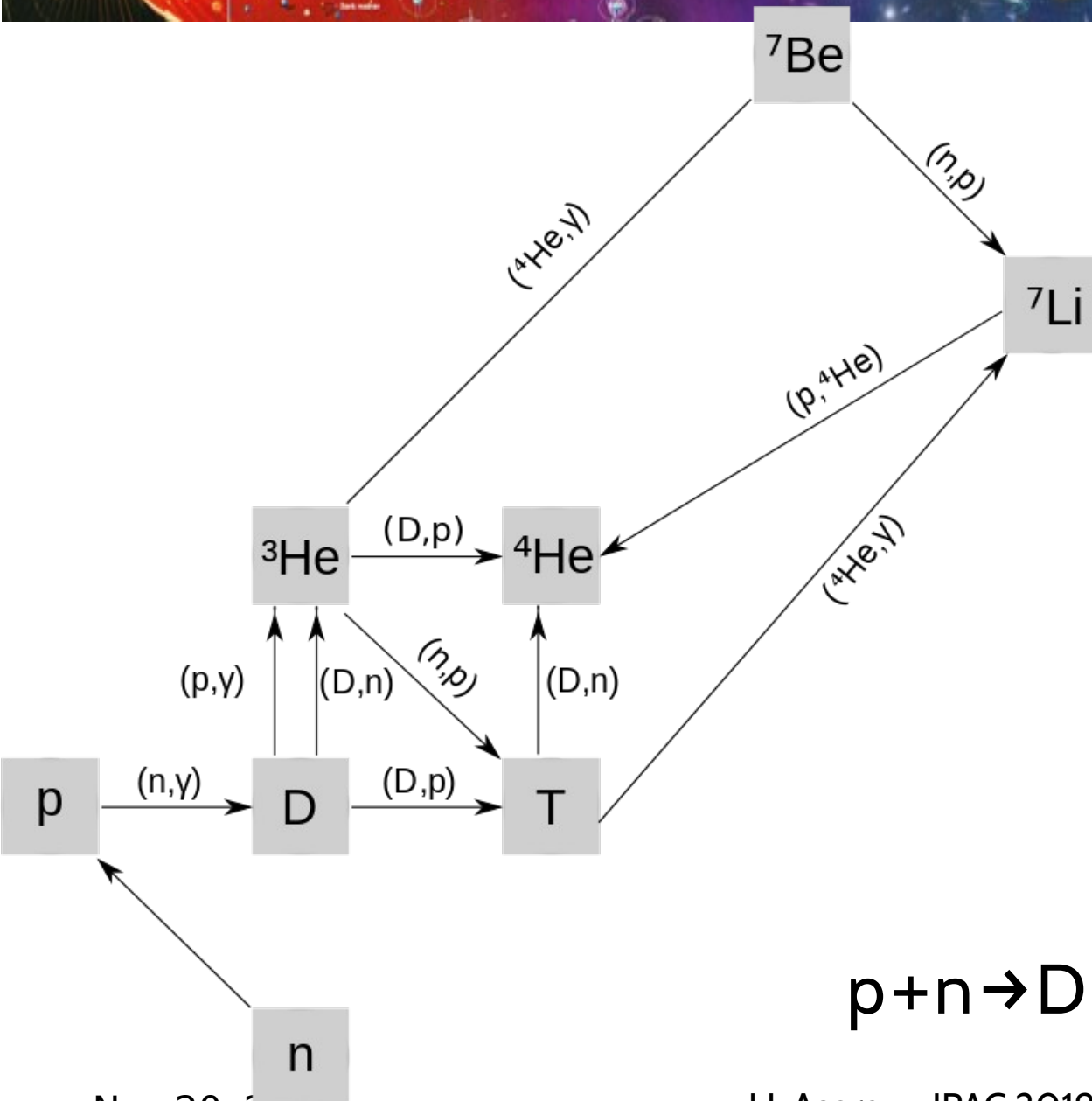
- Pensemos en la producción de pares. Sólo ocurre si



$$E_{\gamma} > 2m_e c^2$$

- Y lo mismo para la aniquilación de pares
- Estos procesos pueden ocurrir si la energía media es tal que hay una población con energías suficientes para que ocurran.
- A medida que el Universo se expande, la energía media disminuye, y por ende la temperatura, y procesos que antes eran posibles, ahora no lo son

# Nucleosíntesis en el big-bang



- Formación de átomos simples
- Principal fuente de hidrógeno y helio
- Los átomos pesados se forman en la nucleosíntesis estelar (supernovas)
- Notación:

$p + n \rightarrow D + \gamma$ , se escribe  $p(n, \gamma)D$





# Recombinación

- Unos 378 kA (kilo años) después del Big Bang ( $z=1100$ ), la temperatura media era de 4000 K, orden  $\sim$  eV
- Notar que 4000 K con un corrimiento de 1100, y si fuera lineal  $4000\text{ K}/1100 \simeq 3.6\text{ K}$  (sin embargo, no es lineal)
- La tasa de formación de átomos simples es alta, y aparecen poblaciones de átomos neutros
- Des-ionización directa es ineficiente  $\rightarrow$  produce un fotón de 13.6eV que reioniza un átomo cercano
- Des-ionización de niveles excitados, decaen a  $n=2$ , y luego
  - Lyman-alpha ( $n=2 \rightarrow n=1$ , UV, 121.6nm)
  - Decaimiento de 2 fotones

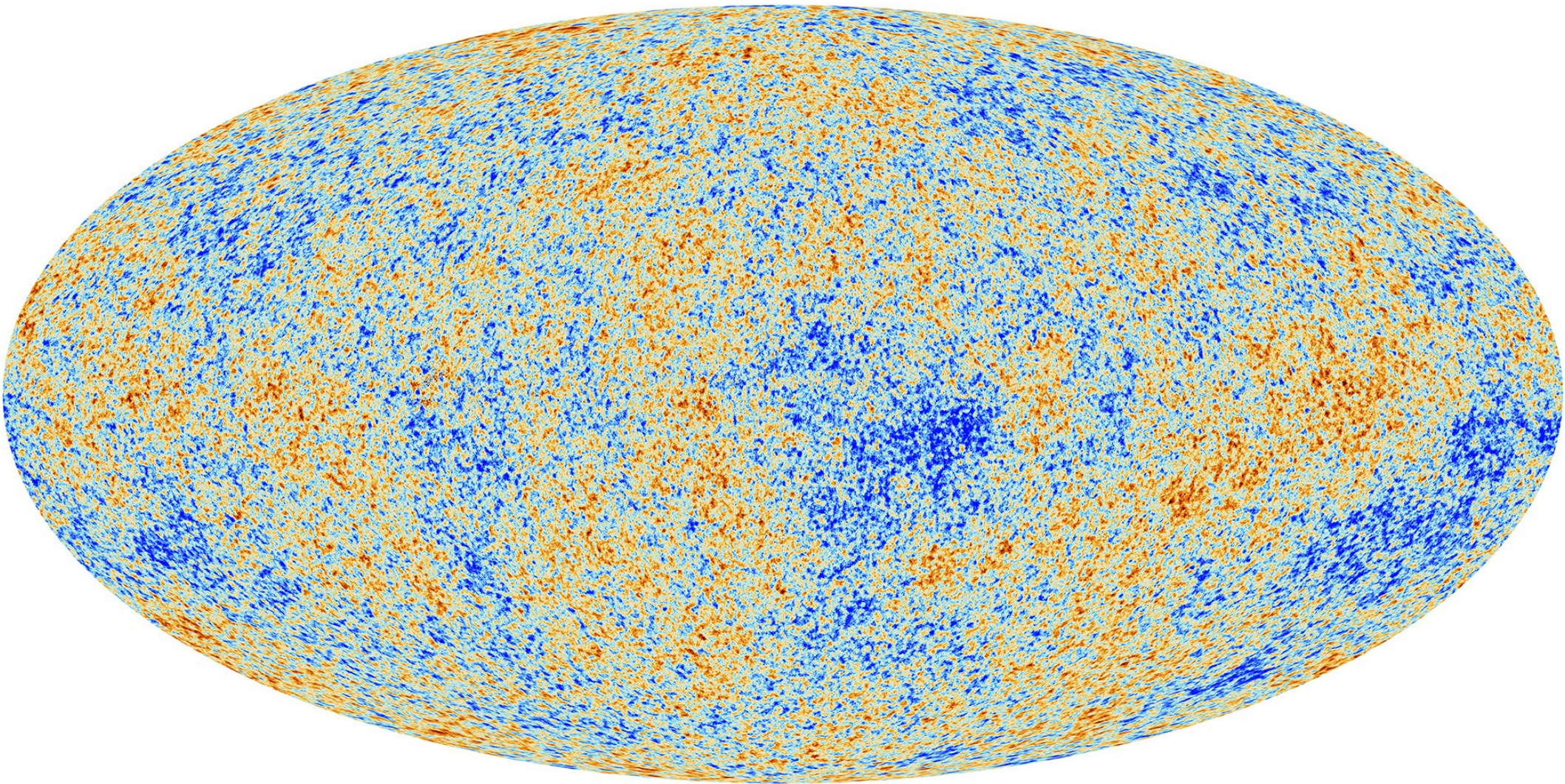
A horizontal banner image. The left side shows a glowing orange sphere with concentric circles and arrows, representing the early universe. The right side shows a dark blue space filled with stars and galaxies, representing the later universe. The text 'Muy poco después de la recombinación' is overlaid in white with a black outline.

# Muy poco después de la recombinación

- Los electrones formaron átomos, y la densidad de electrones cae abruptamente
- La disminución de electrones disminuye la tasa de interacción Compton, y además el Universo se está expandiendo
- El Universo se vuelve transparente, los fotones continúan propagándose hasta hoy, perdiendo energía por la expansión (redshift!)

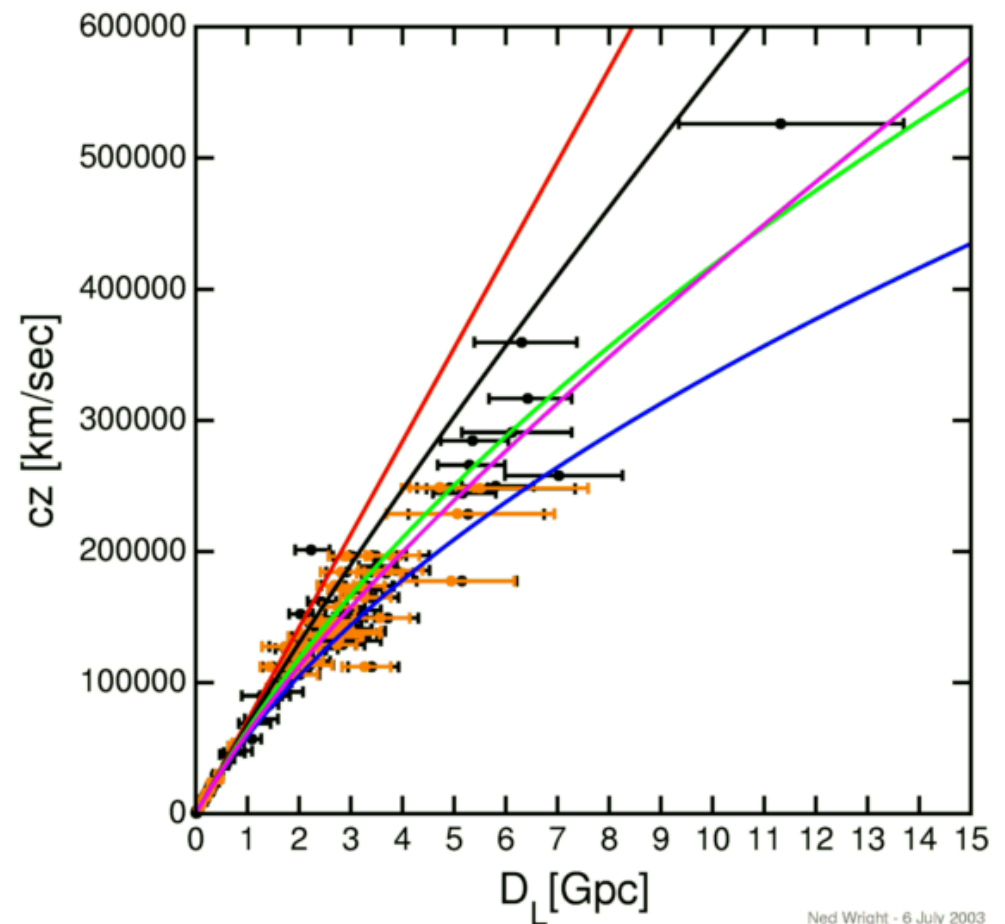
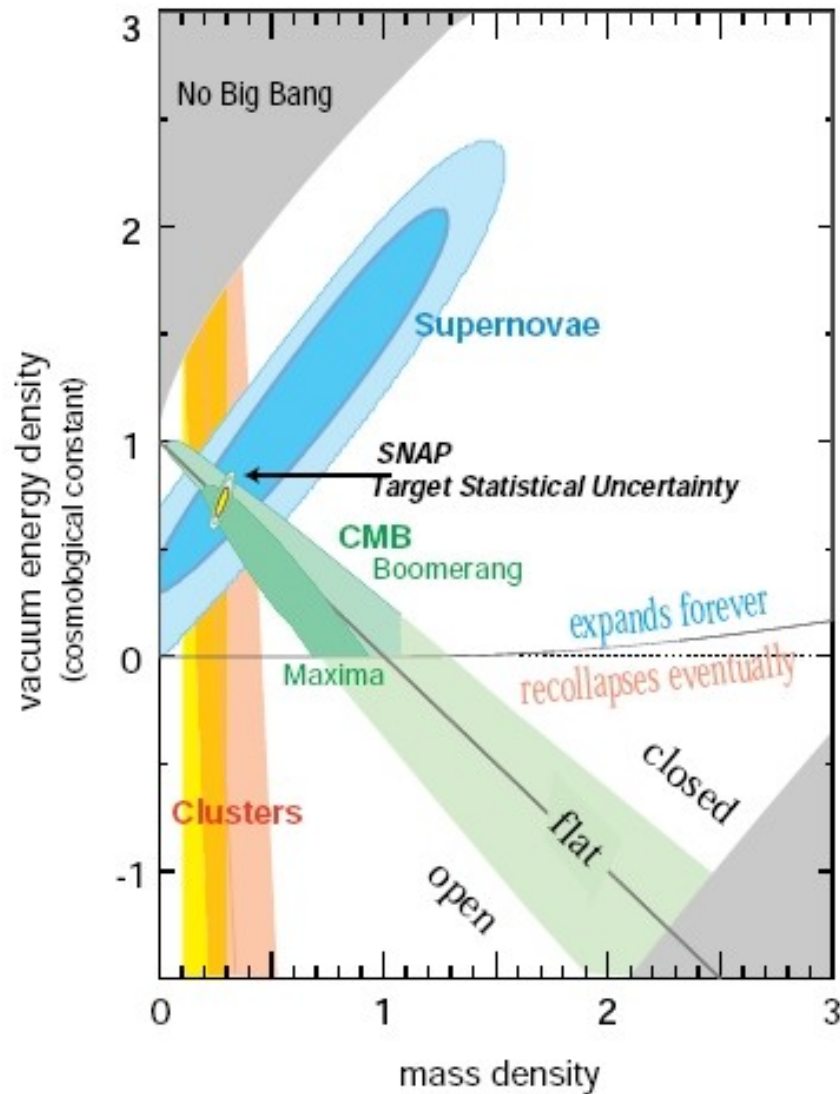


# Una foto del Universo a $z=1100$





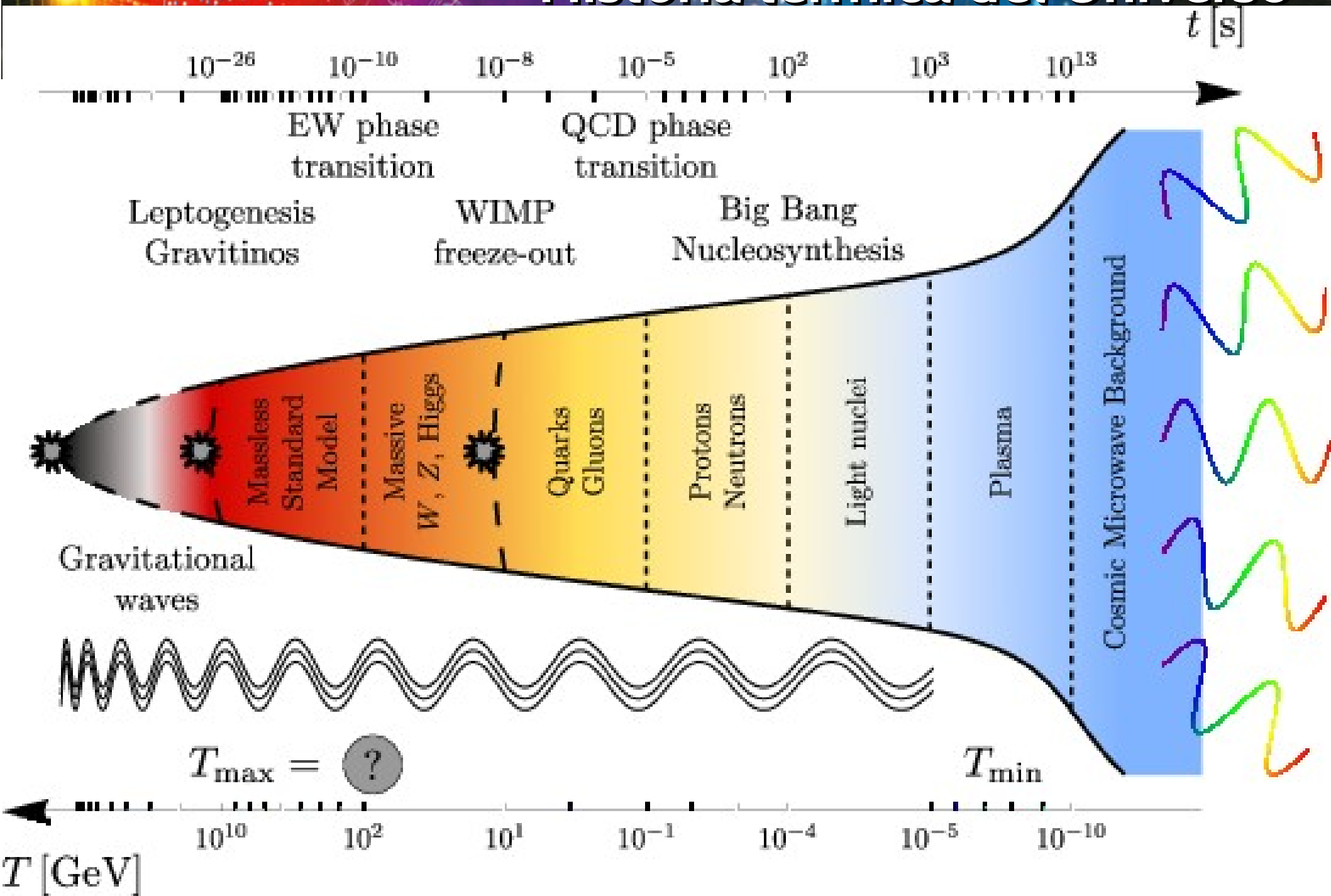
# Modelo cosmológico



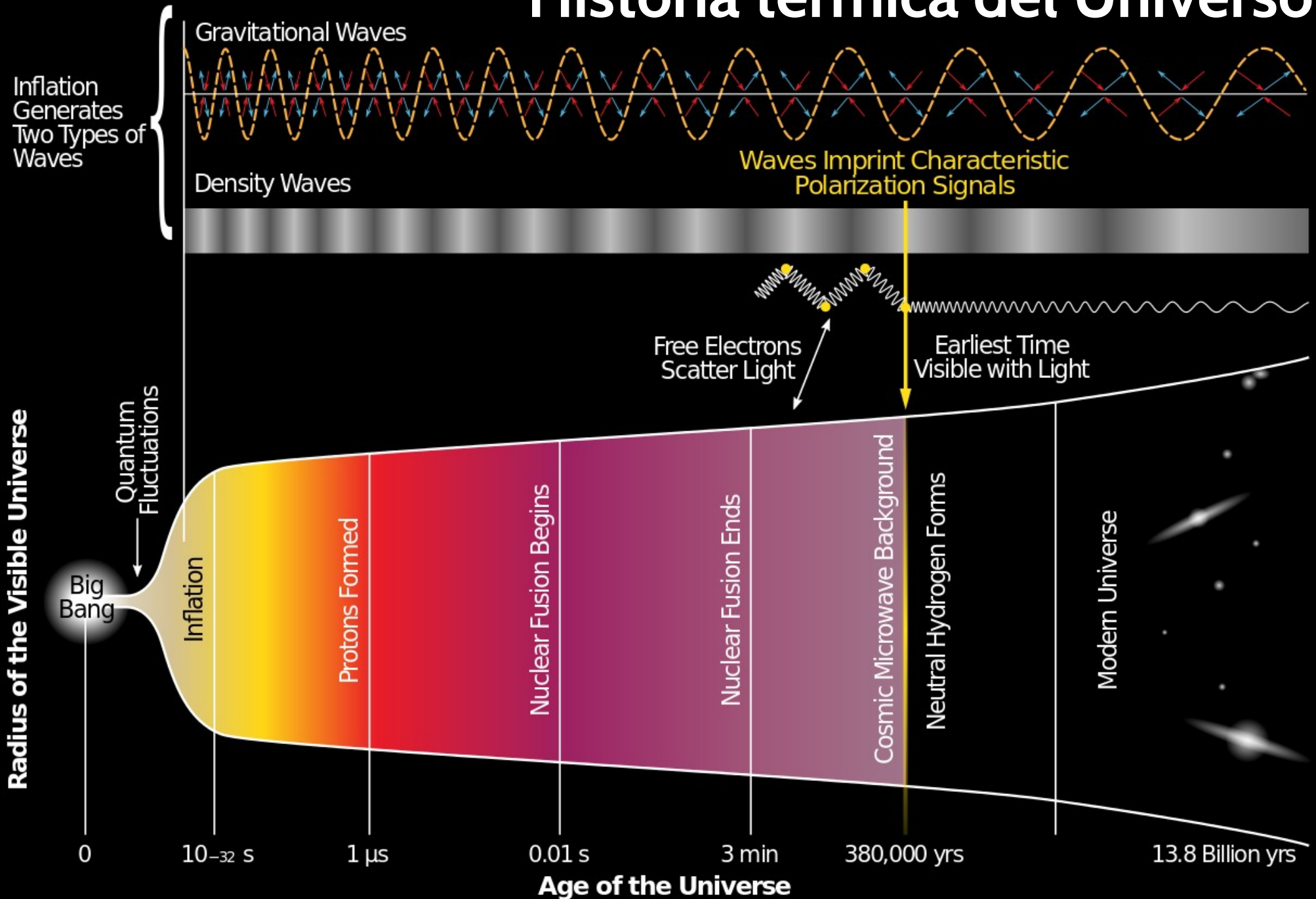
Ned Wright - 6 July 2003



# Historia térmica del Universo



# Historia térmica del Universo



# Historia térmica del Universo

Época	Tiempo	Redshift	Temp.	Descripción
Planck	$<10^{-43}$ s	→ infinito	$>10^{32}$ K	La física actual no es capaz de predecir los sucesos en esta época
Gran Unificación	$<10^{-36}$ s	→ infinito	$>10^{29}$ K	Unificación global de las fuerzas de interacción
Inflación y Electrodébil	$<10^{-36}$ s	→ infinito	$>10^{28}$ K → $10^{22}$ K	Expansión exponencial del Universo (Inflación) por un factor $10^{26}$ . La temperatura baja $10^6$ en $10^{-33}$ s. Se separa la fuerza fuerte de la electrodébil
Quarks	$>10^{-12}$ s	→ infinito	$>10^{12}$ K	QGP (Quark gluon plasma). Aún no hay hadrones, aunque las interacciones ya están separadas
Hadrones	$10^{-6}$ s → 1 s	→ infinito	$10^{10}$ K – $10^9$ K	Se forman los hadrones (bariones y mesones). Protones, neutrones, ...
Leptones	1 s → 10 s	→ infinito	$10^9$ K	Leptones, antileptones y fotones en equilibrio térmico (creación de pares)



# Historia térmica del Universo

Época	Tiempo	Redshift	Temp.	Descripción
Nucleo-síntesis	10 s – 10 <sup>3</sup> s		10 <sup>11</sup> K – 10 <sup>9</sup> K	Se forman los primeros núcleos
Fotones	10 s – 10 <sup>13</sup> s		10 <sup>9</sup> K – 10 <sup>3</sup> K	El universo es un plasma de núcleos, electrones y fotones
<b>Era de Materia</b>	<b>47 kA – 10 GA</b>	<b>3400 – 0.4</b>	<b>10<sup>4</sup> K – 4 K</b>	<b>La densidad de energía total está dominada por los componentes de materia → desaceleración de la expansión</b>
Recombinación	380 kA	01100	4000 K	Se forman los primeros átomos simples al combinarse protones con electrones (H, He, Li) Los fotones dejan de estar en equilibrio térmico, y el universo se vuelve transparente → CMB
Edades oscuras	380 kA – 150 MA	1100 – 20	4000 K – 60 K	Hay átomos pero aún no se forman las primeras estrellas

# Historia térmica del Universo

Época	Tiempo	Redshift	Temp.	Descripción
Era Estelar	150 MA – 100 GA	20 – (-1) (z=0 hoy)	60 K – 0,03 K	Formación de las estrellas de la 3ra población hasta el cese de formación estelar
Reionización	150 MA – 1 GA	20 – 6	60 K – 19 K	La radiación estelar reinoniza la materia
Galaxias	1 GA – 10 GA	6 – 0.4	19 K – 4 K	Se forman las galaxias y empiezan a agruparse en clusters de complejidad creciente
Energía Oscura	> 10 GA	< 0.4	< 4 K	La expansión es dominada por la energía y no la materia. Comienza la expansión acelerada. Se forma el sistema Solar.
Hoy	13.8 GA	0	2.7 K	Usted está aquí
Futuro lejano	> 100 GA	<(-1)	< 0.1 K	El Universo se oscurece más y más a medida se expande aceleradamente. Las estrellas mueren pero se dificulta la formación de nuevas.



# Usted aquí y ahora



## → COSMIC HISTORY



10<sup>-32</sup> seconds

1 second

100 seconds

380 000 years

300–500 million years

Billions of years

13.8 billion years

Beginning  
of the  
Universe



### Inflation

Accelerated expansion  
of the Universe

### Formation of light and matter

### Light and matter are coupled

Dark matter evolves  
independently: it starts  
clumping and forming  
a web of structures

### Light and matter separate

- Protons and electrons  
form atoms
- Light starts travelling  
freely; it will become the  
Cosmic Microwave  
Background (CMB)

### Dark ages

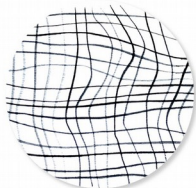
Atoms start feeling  
the gravity of the  
cosmic web of dark  
matter

### First stars

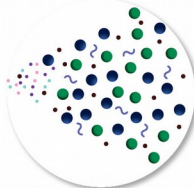
The first stars and  
galaxies form in the  
densest knots of the  
cosmic web

### Galaxy evolution

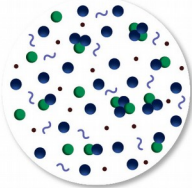
### The present Universe



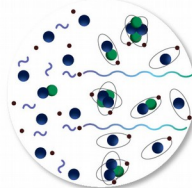
- Tiny fluctuations:  
the seeds of future  
structures
- Gravitational waves?



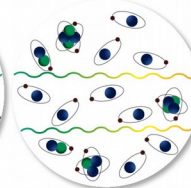
Frequent collisions  
between normal matter  
and light



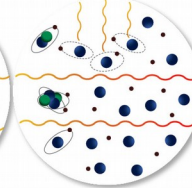
As the Universe expands,  
particles collide less  
frequently



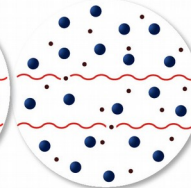
Last scattering of  
light off electrons  
→ **Polarisation**



The Universe is dark as  
stars and galaxies are  
yet to form



Light from first stars and  
galaxies breaks atoms  
apart and "reionises"  
the Universe



Light can interact  
again with electrons  
→ **Polarisation**



## HOW DID OUR UNIVERSE BEGIN?

Some 13.8 billion years ago our entire visible universe was contained in an unimaginably hot, dense point a billionth the size of a nuclear particle. Since then it has expanded—a lot—fighting gravity all the way.

**Inflation**  
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**Age:**  $10^{-32}$  milliseconds  
**Size:** Infinitesimal to golf ball

**Early building blocks**  
The universe expands, cools. Quarks clump into protons and neutrons, the building blocks of atomic nuclei. Perhaps dark matter forms.  
**Age:** 0.1 milliseconds  
**Size:** 0.1-trillionth present size

**First nuclei**  
As the universe continues to cool, the lightest nuclei, of hydrogen and helium, arise. A thick fog of particles blocks all light.  
**Age:** 0.01 to 200 seconds  
**Size:** 1-billionth present size

**First atoms, first light**  
As electrons begin orbiting nuclei, creating atoms, the glow from our infant universe is unveiled. This light is as far back as our instruments can see.  
**Age:** 380,000 years  
**Size:** .0009 present size

**The "dark ages"**  
For 300 million years this cosmic background radiation is the only light. Clumps of matter that will become galaxies glow brightest.  
**Age:** 380,000 to 300 million years  
**Size:** .0009 to 0.1 present size

**Gravity wins: first stars**  
Dense gas clouds collapse under their own gravity—and that of dark matter—to eventually form galaxies and stars. Nuclear fusion lights up the stars.  
**Age:** 300 million years  
**Size:** 0.1 present size

**Antigravity wins**  
After being slowed for billions of years by gravity, cosmic expansion accelerates again. The output: dark energy. Its nature: unclear.  
**Age:** 10 billion years  
**Size:** .77 present size

**Today**  
The universe continues to expand, becoming ever less dense. As a result, fewer new stars and galaxies are forming.  
**Age:** 13.8 billion years  
**Size:** Present size

## HOW WILL IT END?

Which will win in the end, gravity or antigravity? Is the density of matter enough for gravity to halt or even reverse cosmic expansion, leading to a big crunch? It seems unlikely—especially given the power of dark energy, a kind of antigravity. Perhaps the acceleration in expansion caused by dark energy will trigger a big rip that shreds everything, from galaxies to atoms. If not, the universe may expand for hundreds of billions of years, long after all stars have died.



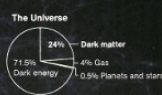
Galaxies ripped apart by rapid expansion

## COSMIC QUESTIONS

In the 20th century the universe became a story—a scientific one. It had always been seen as static and eternal. Then astronomers observed other galaxies flying away from ours, and Einstein's general relativity theory implied space itself was expanding—which meant the universe had once been denser. What had seemed eternal now had a beginning and an end. But what beginning? What end? Those questions are still open.

## WHAT IS OUR UNIVERSE MADE OF?

Stars, dust, and gas—the stuff we can discern—make up less than 5 percent of the universe. Their gravity can't account for how galaxies hold together. Scientists figure about 24 percent of the universe is a mysterious dark matter—perhaps exotic particles formed right after inflation. The rest is dark energy, an unknown energy field or property of space that counteracts gravity, providing an explanation for observations that the expansion of space is accelerating.



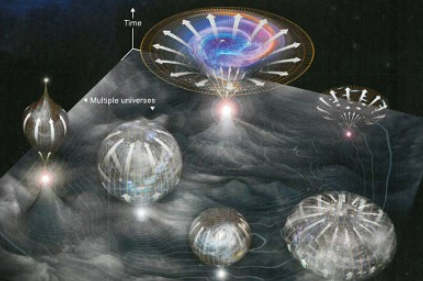
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## DO WE LIVE IN A MULTIVERSE?

What came before the big bang? Maybe other big bangs. The uncertainty principle holds that even the vacuum of space has quantum energy fluctuations. Inflation theory says our universe exploded from such a fluctuation—a random event that, odds are, had happened many times before. Our cosmos may be one in a sea of others just like ours—or nothing like ours. These other cosmos will very likely remain forever inaccessible to observation, their possibilities limited only by our imagination.

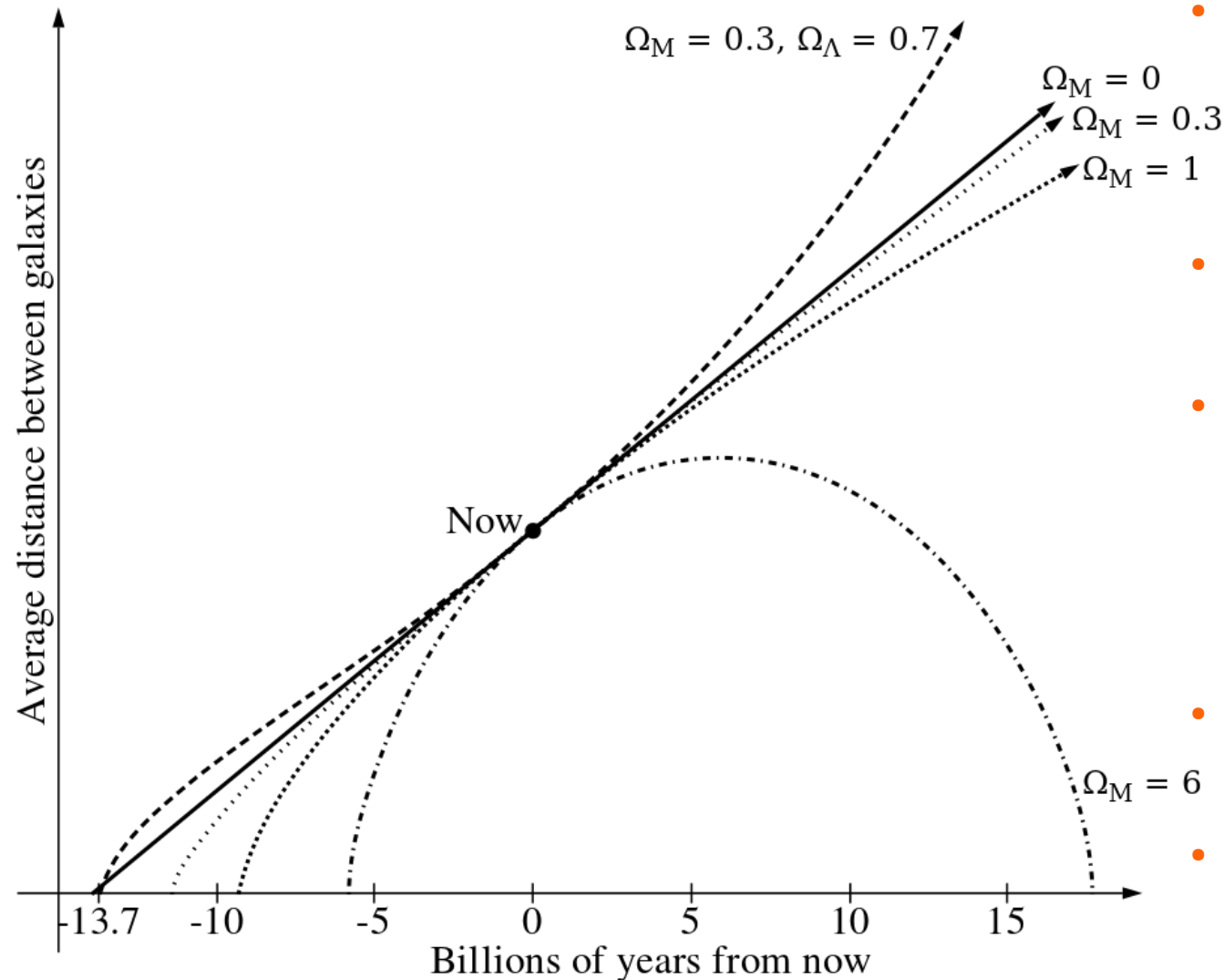


Fly through the universe on our digital edition.  
LAWSON PARKER, HOW STAFF, IANNA GRIFFITHS AND MICHAEL MATHIAS  
SOURCES: CHARLES BRANNETT, JAMES HODGES, UNIVERSITY OF CHICAGO  
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# Historia térmica del Universo

## El futuro



- **Big crunch ( $\Omega > 1$ ):** la gravedad eventualmente domina la expansión hasta el colapso gravitatorio
- **Big Bounce:** big bang luego del big crunch
- **Big Rip:** si la densidad de la energía oscura aumenta, entonces la aceleración es cada vez mayor  $\rightarrow$  ruptura del espacio tiempo
- **Abierto ( $\Omega < 1$ ):** la expansión continúa para siempre
- **Plano ( $\Omega = 1$ ):** la expansión continúa para siempre, pero en forma desacelerada ( $v=0$  a  $t=\infty$ )





*That's all Folks!*