



Universidad Nacional de Río Negro

Int. Partículas, Astrofísica & Cosmología - 2019

- **Unidad** 04 – El Big Bang
- **Clase** UO4 C01
- **Fecha** 19 Nov 2019
- **Cont** Universo en expansión
- **Cátedra** Asorey



Contenidos: un viaje en el tiempo

HOW DID OUR UNIVERSE BEGIN?

In the 13.8 billion years ago entire visible universe was stained in an unimaginably dense point, a billionth size of a nuclear particle—before it has expanded—a fighting gravity all the way.

Infation
In less than a nanosecond a massive energy field inflates space by a factor of a thousand times. It fills it with a soup of subatomic particles called quarks.

Age: 10^{-3} milliseconds
Size: Infinitesimal to golf ball

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

Age: 10^{-2} milliseconds
Size: 0.1-million present size

First nucle
As the universe continues to cool, the first hydrogen atoms arise. A third particles block .01 to 200 1-billionth its size

Age: $.01$ milliseconds
Size: Present size

First atoms, first light
As electrons begin orbiting nuclei, creating atoms, the glow from their infall becomes visible. This light is as far back as our instruments can see.

Age: $.0009$ years
Size: .0009 present size

The "dark ages"
For 300 million years this continues. As the universe continues to cool, the first stars form galaxies and stars. Dense gas clouds collapse under their own gravity, forming stars again. Clumps of dark matter that will become galaxies glow brightest.

Age: $.0009$ to $.300$ million years
Size: .0009 to 0.1 present size

Gravity wins: first stars
Dense gas clouds collapse under their own gravity, forming stars again. The culprit: dark energy. Its nature: unclear.

Age: $.300$ to $.380$ million years
Size: 0.1 present size

Antigravity wins
After being slowed for billions of years, dark energy's antigravity wins again. The culprit: dark energy. Its nature: unclear.

Age: $.380$ to $.77$ 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: $.77$ to 13.8 billion years
Size: Present size

Unidad 4
El Big Bang
Allá lejos y hace tiempo

COSMIC QUESTIONS

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 showed 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?

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 space that counters gravity, providing an explanation for observations that the expansion of space is accelerating.

The Universe

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

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

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.

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

The Unknown Edge
For what we can't see, the possible shapes are many.

Sphere
Saddle
Flat

Unidad 2
Astrofísica
Cálido y frío

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 density 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.

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 1
Partículas 1
todo es relativo

By through the universe on our digital edition

LONDON PHOTOS: ANDREW STEPHEN; FERNE GEMMELL/REDFERNS; ART MONTAGNA/DESIGN SOURCE: CHARLES BENNETT, JOHN HESTER, ANDREW LAMBERT, UNIVERSITY OF COLORADO; ANDREW LAMBERT, NATIONAL GEOGRAPHIC SOCIETY



Relatividad general

- Charlamos sobre la relatividad general y la curvatura del espacio tiempo



- Entonces....

¿Cuál es la fuerza más fuerte de la Naturaleza?



- Entonces....

**¿Cuál es la fuerza más fuerte de la
Naturaleza?**

Gravedad



A gran escala....

- ... la expansión del Universo compensa la gravedad
- ¿Qué pasará a escalas más pequeñas?
- Las inhomogeneidades grumos se agrupan y crecen
- Se necesita más tiempo para formar grumos más grandes

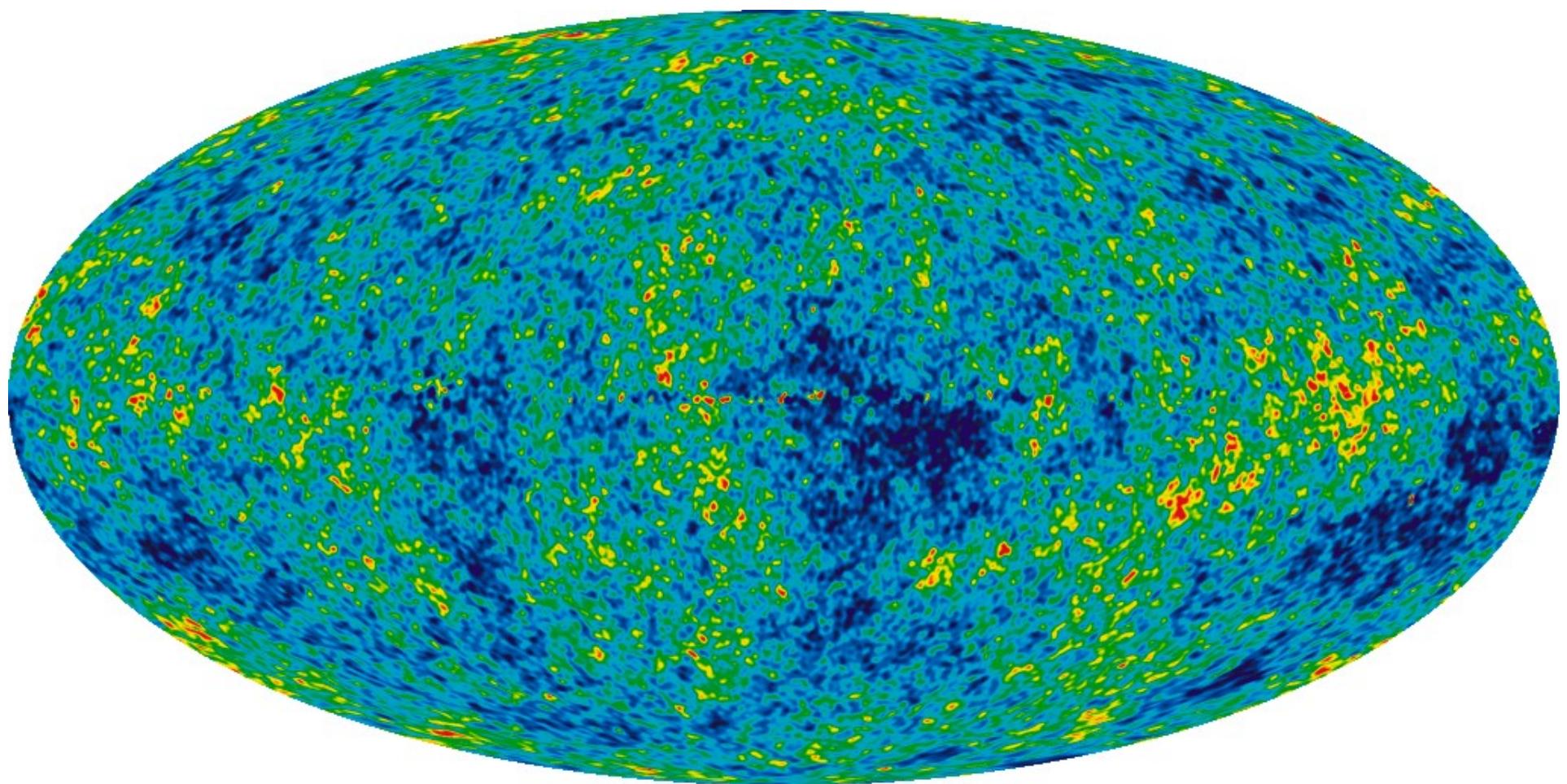


Nestun, con grumos

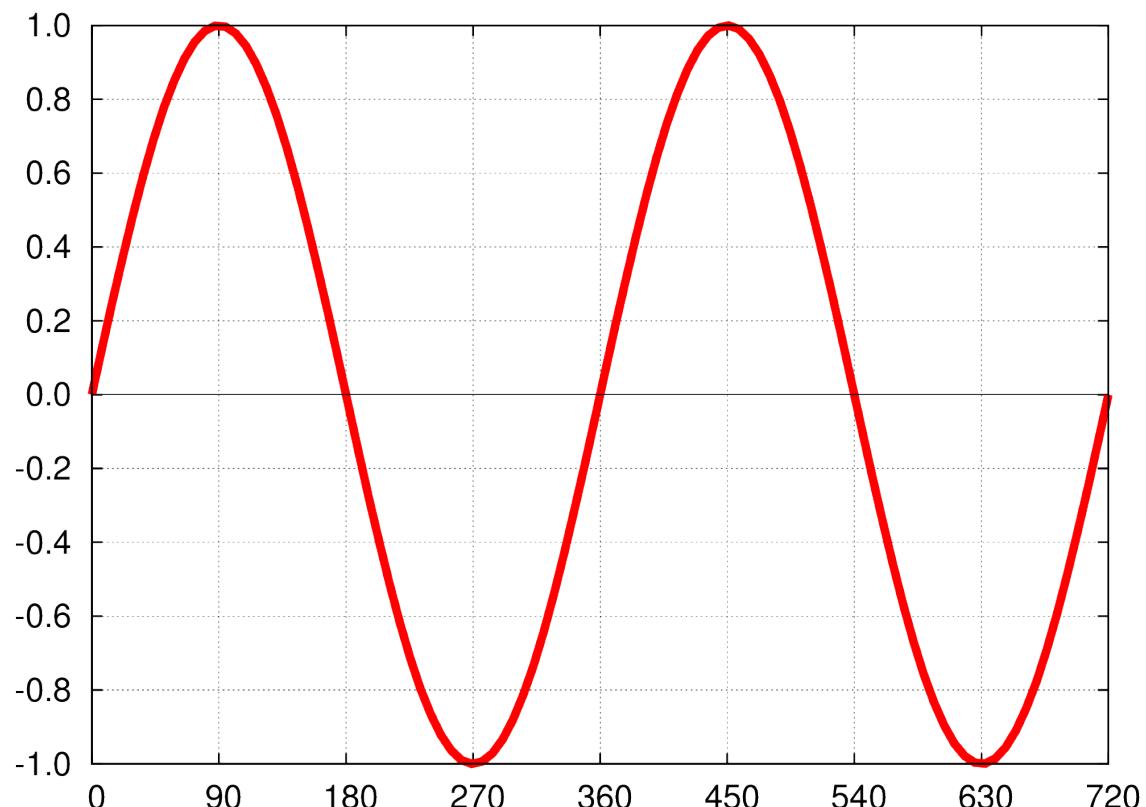




A las escalas más grandes...



Propiedades de una onda



- λ : longitud de onda
 - f: frecuencia
 - $c = \lambda \times f$
 - Ondas EM (luz):
 - $E = h f = h c / \lambda$
- $c = 3 \times 10^8 \text{ m/s}$
- $h = 6.6261 \times 10^{-34} \text{ Js}$



Efecto Doppler

“Es el cambio aparente en la frecuencia de una onda causado por el movimiento relativo entre la fuente de las ondas y el observador”

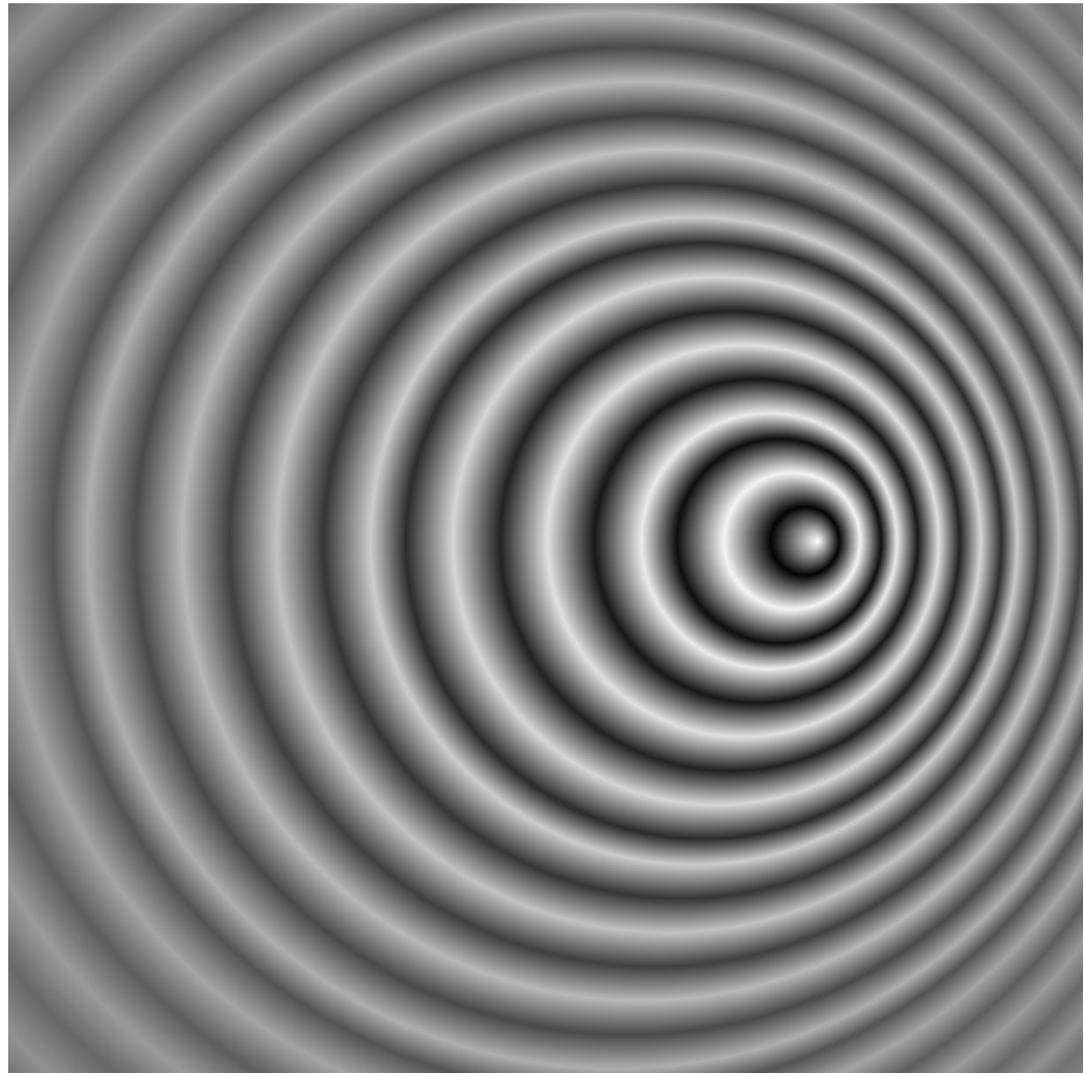
Dr. Sheldon Cooper





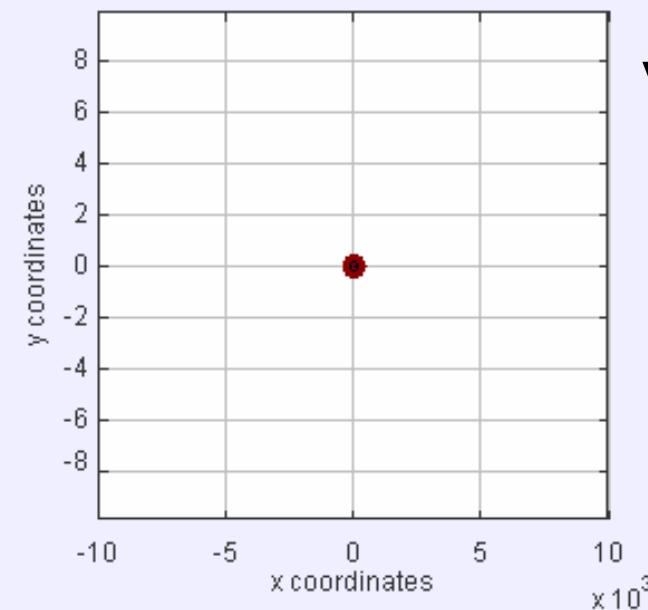
Efecto Doppler en la luz

- Pensar en el lanzamiento de pelotas a frecuencia constante
- El efecto doppler es un fenómeno ondulatorio



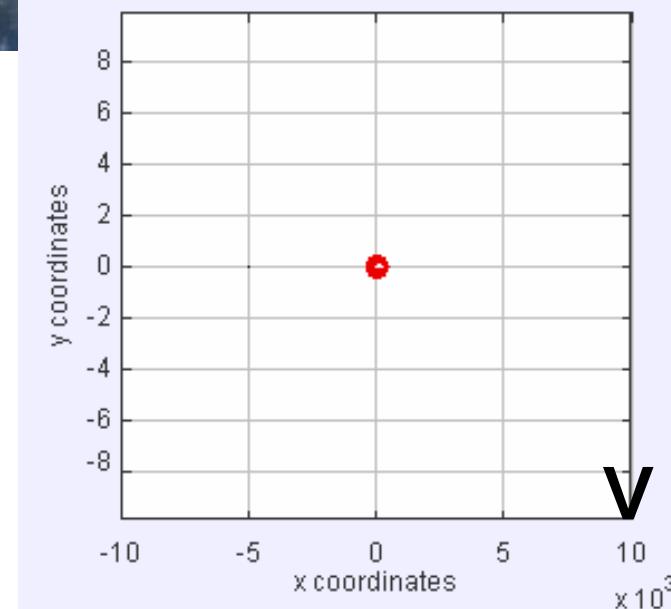
Efecto Doppler

$\times 10^3$ Doppler Effect Model in 1D [Doppler Effect]



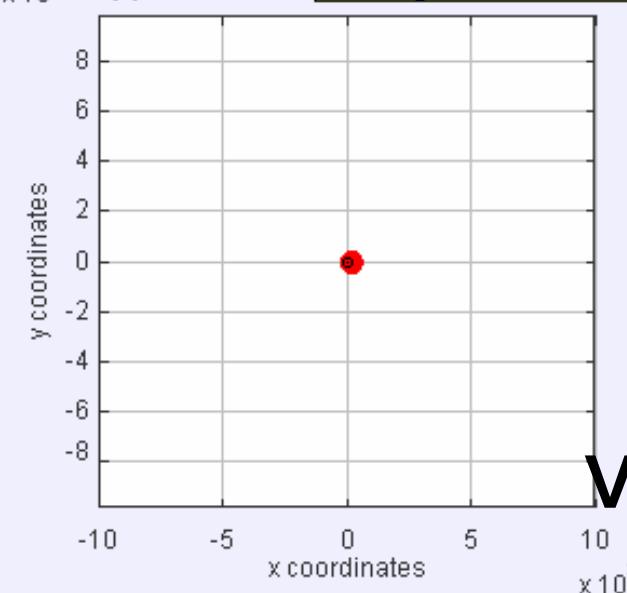
$$v = 0$$

$\times 10^3$ Doppler Effect Model in 1D [Doppler Effect]



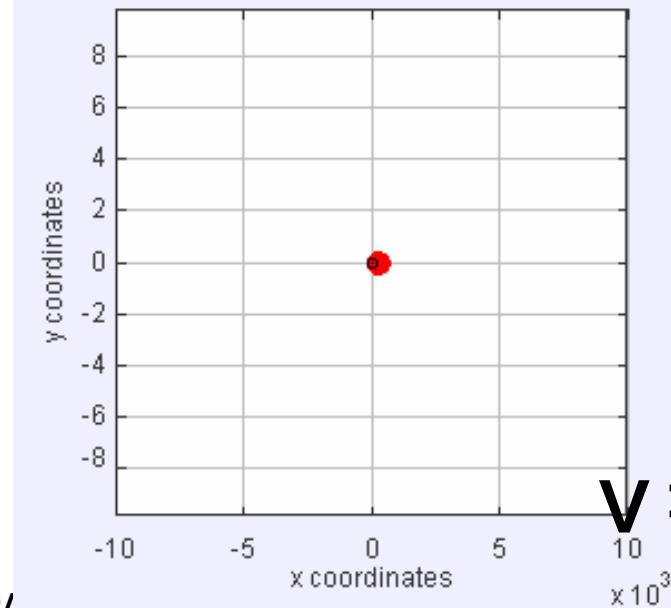
$$v = 0,7 v_s$$

$\times 10^3$ Doppler Effect Model [Breaking the sound barrier]



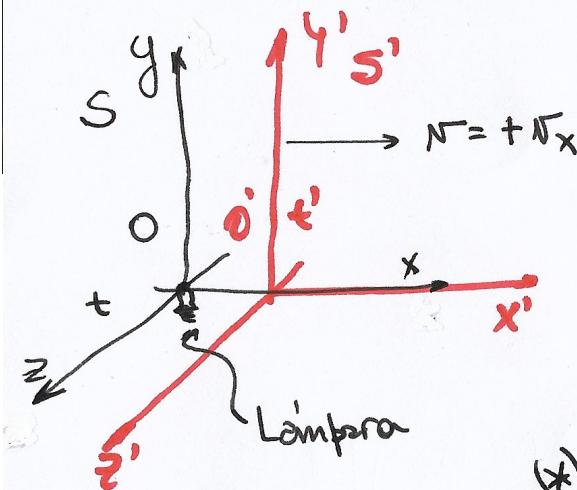
$$v = 1 v_s$$

$\times 10^3$ Doppler Effect Model in 1D [Supersonic]



$$v = 1,4 v_s$$

Sean dos observadores en sistemas S y S':



Vínculos:

$$at=t'=0; \theta=0'$$

En ese momento, la lámpara emite un pulso de luz con N ondas



Doppler relativista

En el frame S, el observador O recibe pulso cuando $t=t_0=0$ y

(*) Finaliza a $t=t_f$. Luego, la frecuencia emitida es

$$f_0 = N/t_f - t_0 \Rightarrow f_0 = N/t_f$$

Definimos los eventos: 1: el frente del pulso alcanza O' (visto desde O). x_1, t_1

2: el final del pulso alcanza O' (visto desde O). x_2, t_2

Evento 1: visto en S, ocurre a $t_1=0; x_1=0$

Evento 2: visto en S, el pulso alcanza el Observador O', jefe con $N < C$

\Rightarrow El frente del pulso está en $x_{fp} = Ct; x_{O'} = Nt$

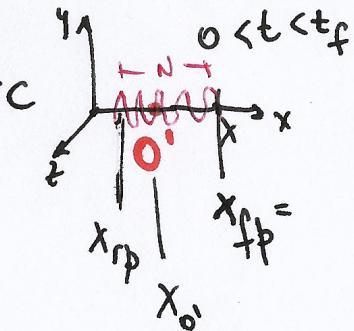
y lo retaguardia del pulso en $x_{rp} = 0$ a $t=t_f$ (ver *)

Cuando $t=t_2 \Rightarrow x_{rp} = x_{O'} \Rightarrow x_{rp} = C(t_2 - t_f)$

y podemos $x_{O'} = Nt_2$

Luego el evento 2 ocurre cuando $x_{O'} = x_{rp}$

la retaguardia
es el tiempo desde que estaba en
el origen hasta que alcanzó al Obs. O'



$$\Rightarrow x_0' = x_{rp} \Rightarrow Nt_2 = c(t_2 - t_f) \Rightarrow t_2 = \frac{ct_f}{(c-N)}$$

Doppler relativista

$$\Rightarrow \text{Evento 1: } x_1=0, t_1=0 ; \text{ Evento 2: } x_2=Nt_2, t_2=\frac{ct_f}{(c-N)}$$

Las T.L. $x'=N(x_2-Nt)$ y $t'=\gamma(t-Nx/c^2)$

$$\Rightarrow \text{Evento 1: } x_1'=0 \quad (x_1=0, t_1=0) \quad y \quad t_1'=0.$$

$$\text{Evento 2: } x_2'=\gamma(Nt_2-Nt)=0 \quad y \quad t_2'=\gamma\left(t_2-\frac{N^2}{c^2}t_2\right)=t_2\gamma(1-\beta^2)=\frac{t_2\gamma}{\gamma^2}=\frac{t_2}{\gamma}$$

$$\Rightarrow x_2'=0 \quad y \quad t_2'=t_2/\gamma$$

Luego, recordando $t_2=\frac{ct_f}{(c-N)}$ $\Rightarrow t_2'=\frac{ct_f}{(c-N)\gamma}=\frac{ct_f}{\gamma(1-\beta)\gamma}=\frac{ct_f}{(1-\beta)}\sqrt{\frac{1-\beta^2}{1+\beta}}=t_f\sqrt{\frac{1-\beta}{1+\beta}}\sqrt{\frac{1-\beta^2}{1+\beta}}$

$$\Rightarrow t_2' = t_f \sqrt{\frac{1-\beta}{1+\beta}}$$

¿Qué frecuencia observa O' ? Ve tener N ondas en un tiempo $\Delta t'=t_2'-t_1'=t_2'$ \Rightarrow

$$f_0' = N/\Delta t' = \frac{N}{t_f} \sqrt{\frac{1-\beta}{1+\beta}} \Rightarrow f_0' = f_0 \sqrt{\frac{1-\beta}{1+\beta}}$$

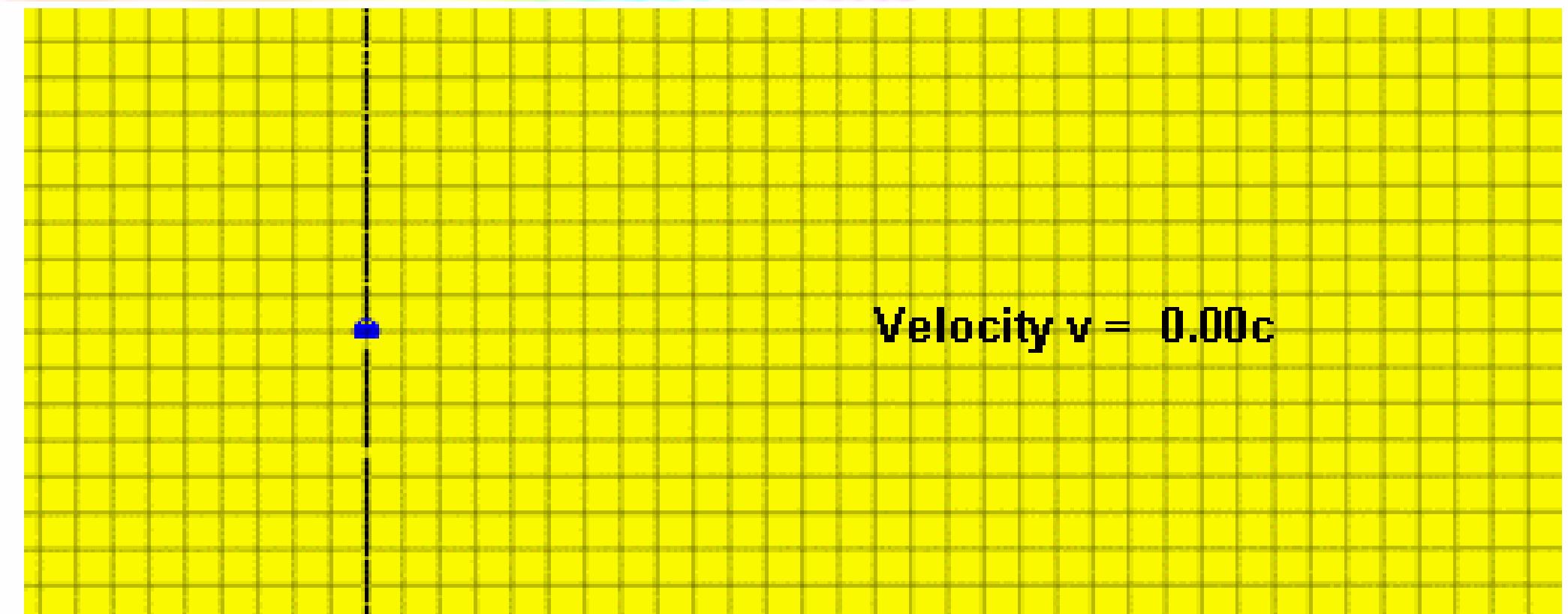
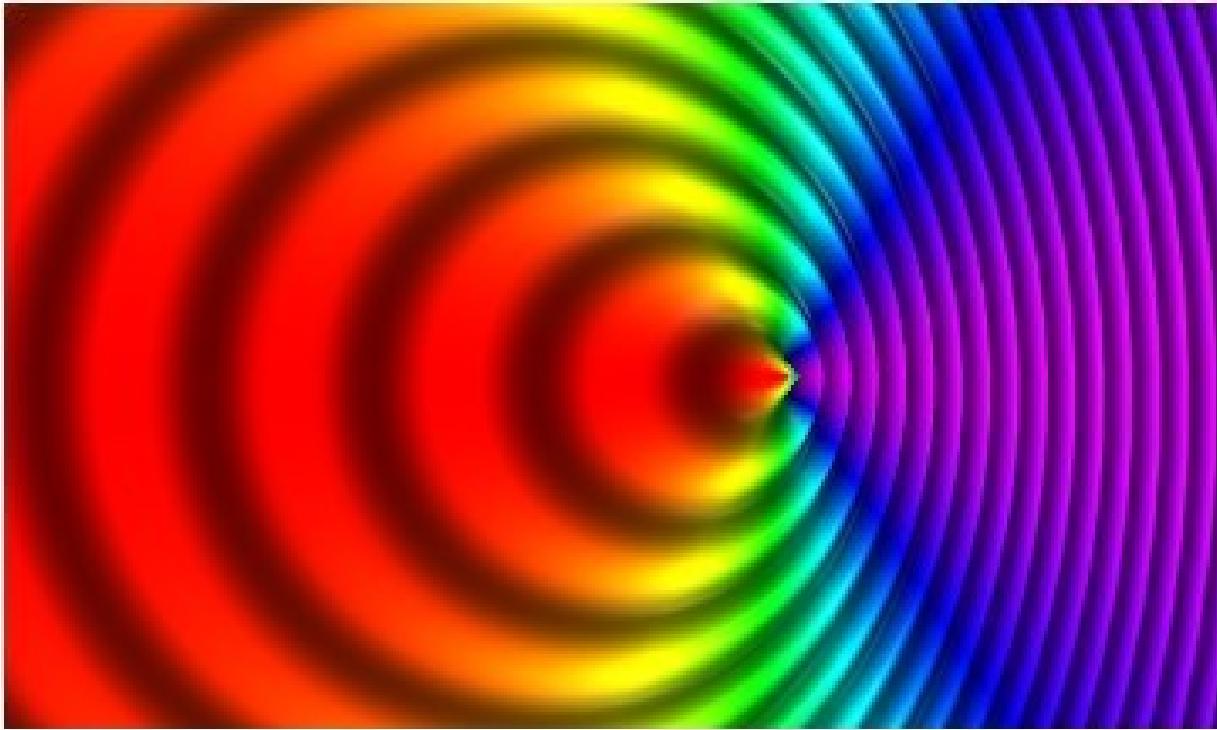
$$\frac{1-\beta}{1+\beta} < 1 \Rightarrow f_0' < f_0$$

Comienza el rojo
Si se alejan

Si se acercan $\Rightarrow \beta \rightarrow -\beta$ (ya que $N=-Nx$) \Rightarrow

$$f_0' = f_0 \sqrt{\frac{1+\beta}{1-\beta}}$$

Comienza el azul
(freno y obs. se acercan).



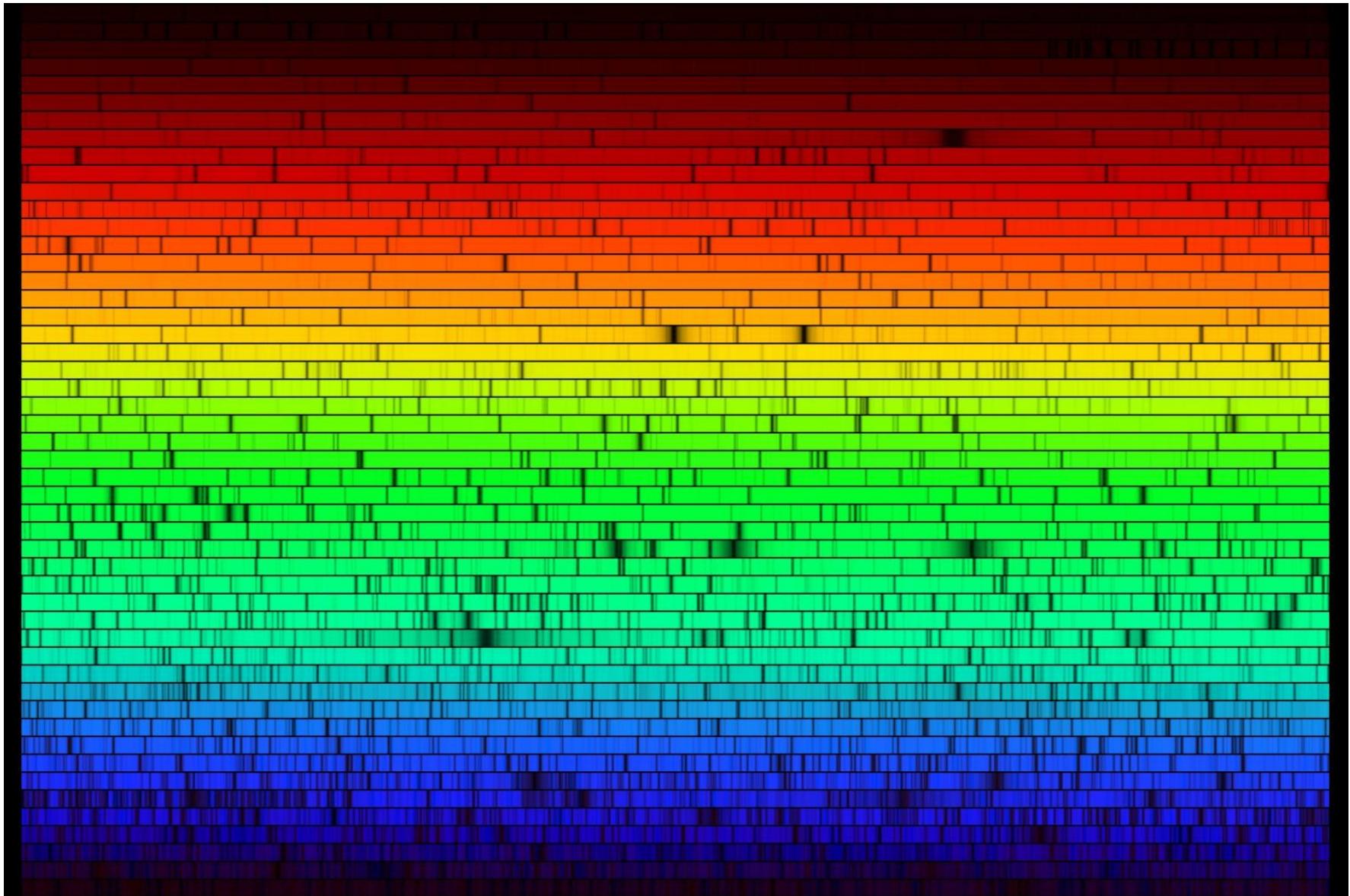
Mirando al Sol con un buen prisma

The Dark Side of the Moon

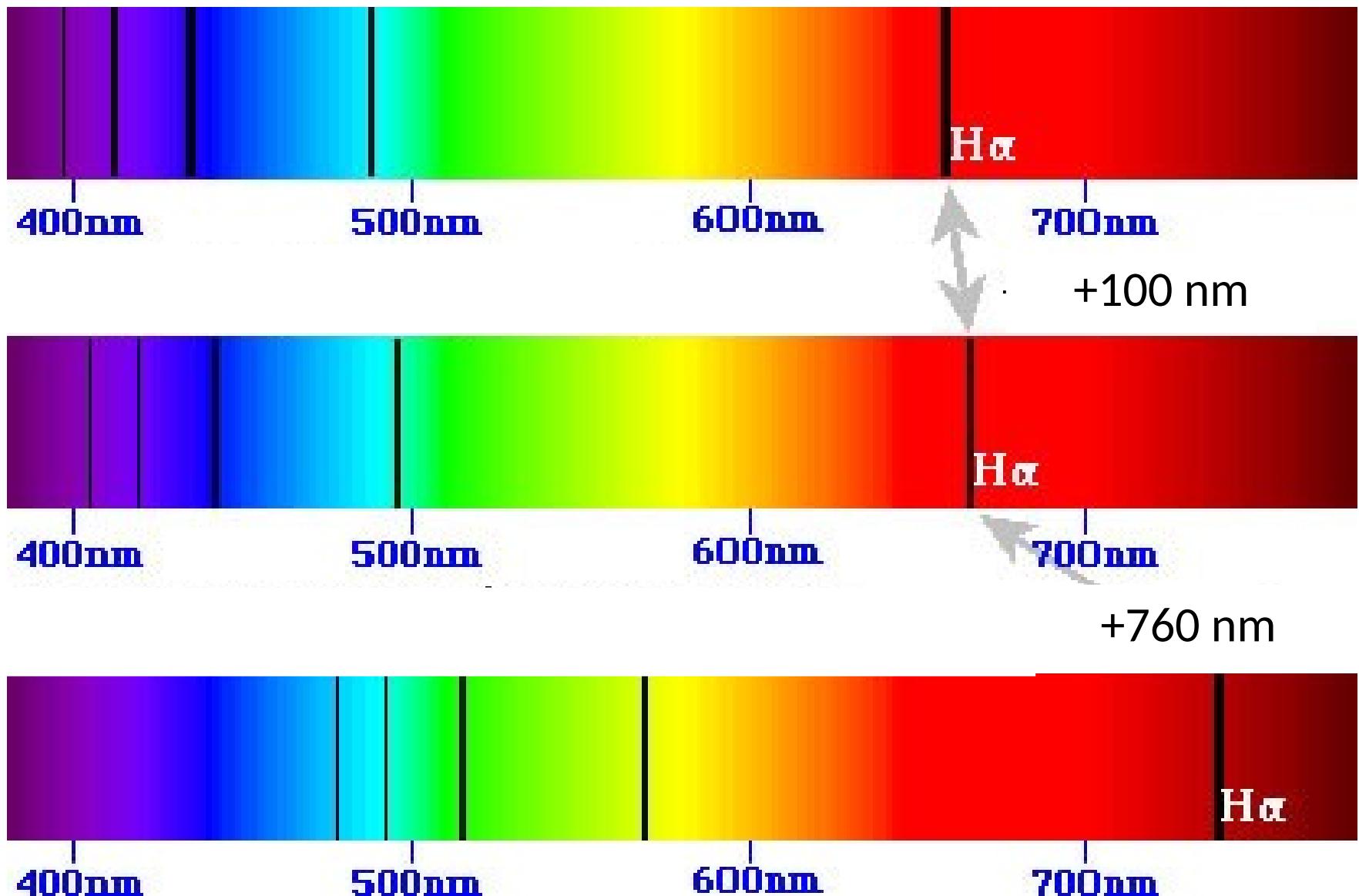
Breathe, breathe in the air. Don't be afraid to face.
Ticking away the moments that make up a dull day.
Money, get away. Get a good job with good pay to
us, and them. And after all we're only ordinary men
The lunatic is on the grass. Remembering games we
All that you touch. All that you see. All that you



Mirando al Sol con un buen prisma



Doppler en la luz



Corrimiento al rojo

$$\frac{f_o}{f_e} = \sqrt{\frac{1-\beta}{1+\beta}} < 1 \rightarrow f_o < f_e, \text{ y } f\lambda = c \Rightarrow f_o = \frac{c}{\lambda_o}, \text{ y lo mismo para } \lambda_e$$

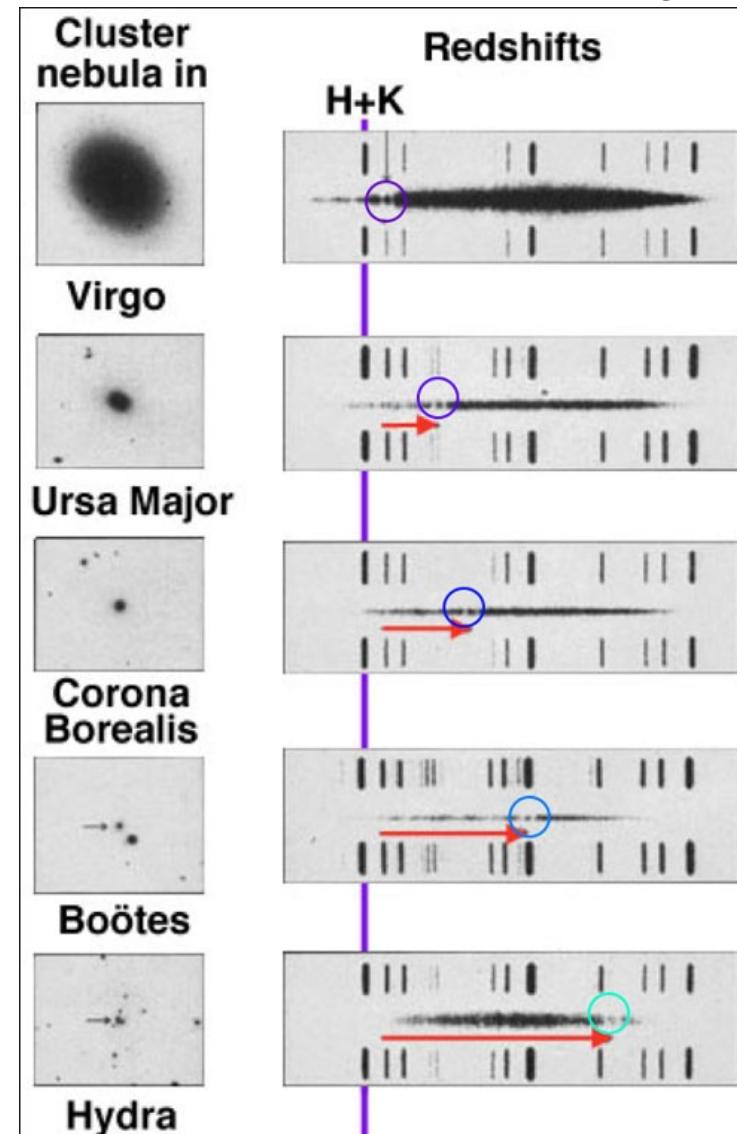
$$\frac{\lambda_o}{\lambda_e} = \sqrt{\frac{1+\beta}{1-\beta}} > 1 \rightarrow \lambda_o > \lambda_e$$

$$\text{Def. } z \equiv \frac{\lambda_o - \lambda_e}{\lambda_e} \Rightarrow 1+z = \frac{\lambda_o}{\lambda_e} = \sqrt{\frac{1+\beta}{1-\beta}}$$

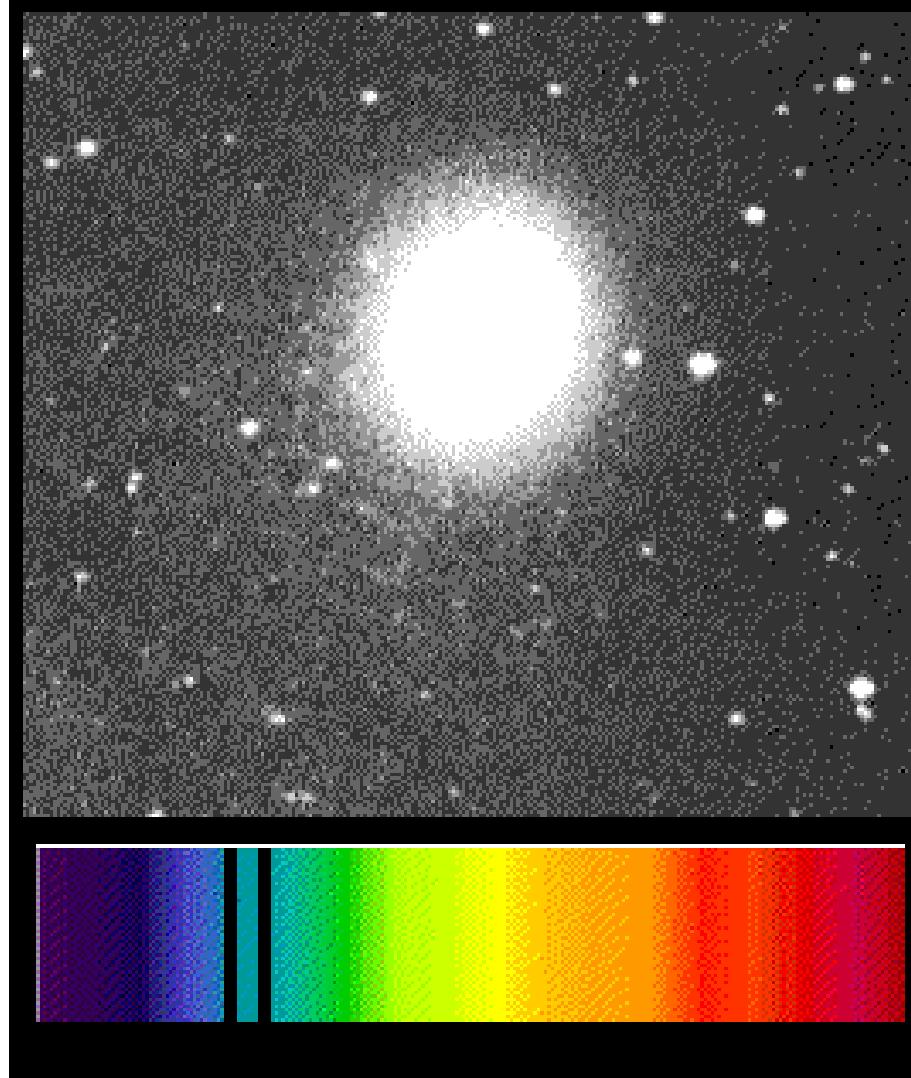
z es el corrimiento al rojo.

Se puede probar que si $v \ll c$

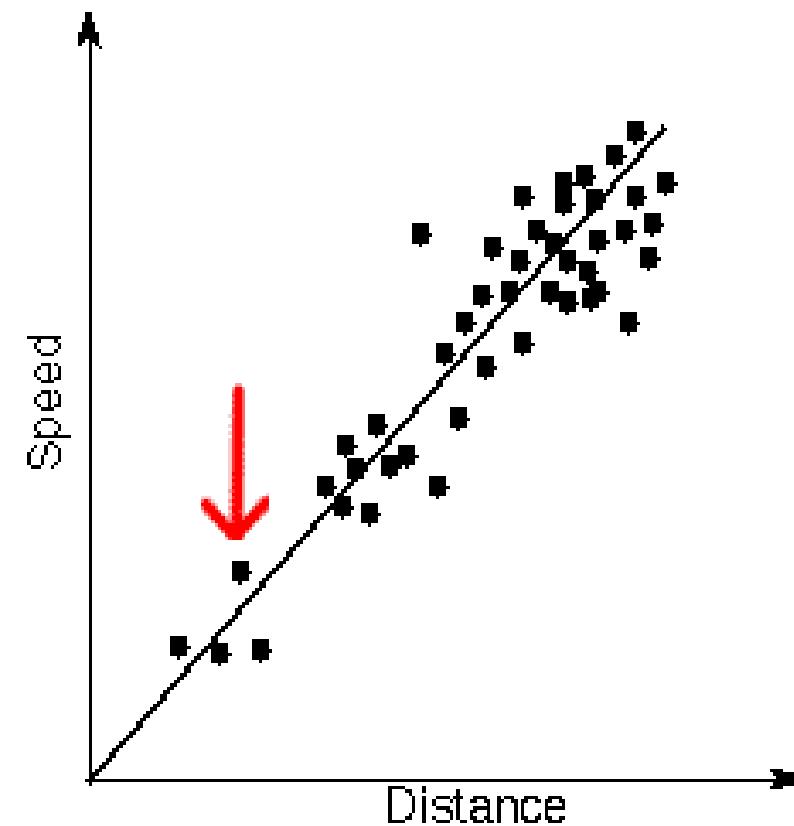
$$z \approx \beta$$



El Universo se expande



Hubble Law
recession speed = $H_0 \times$ distance



$$V = H_0 \times d$$

Nov 19, 2019

$$H_0 = 67 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

H. Asorey - IPAC 2019

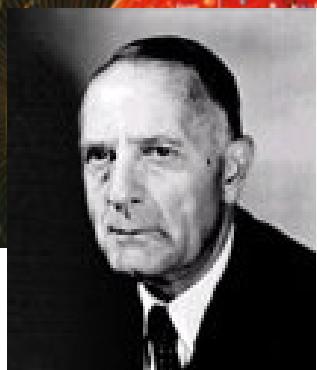


¿y más allá del “rojo”? Encuentre las diferencias

HST, infrarrojo

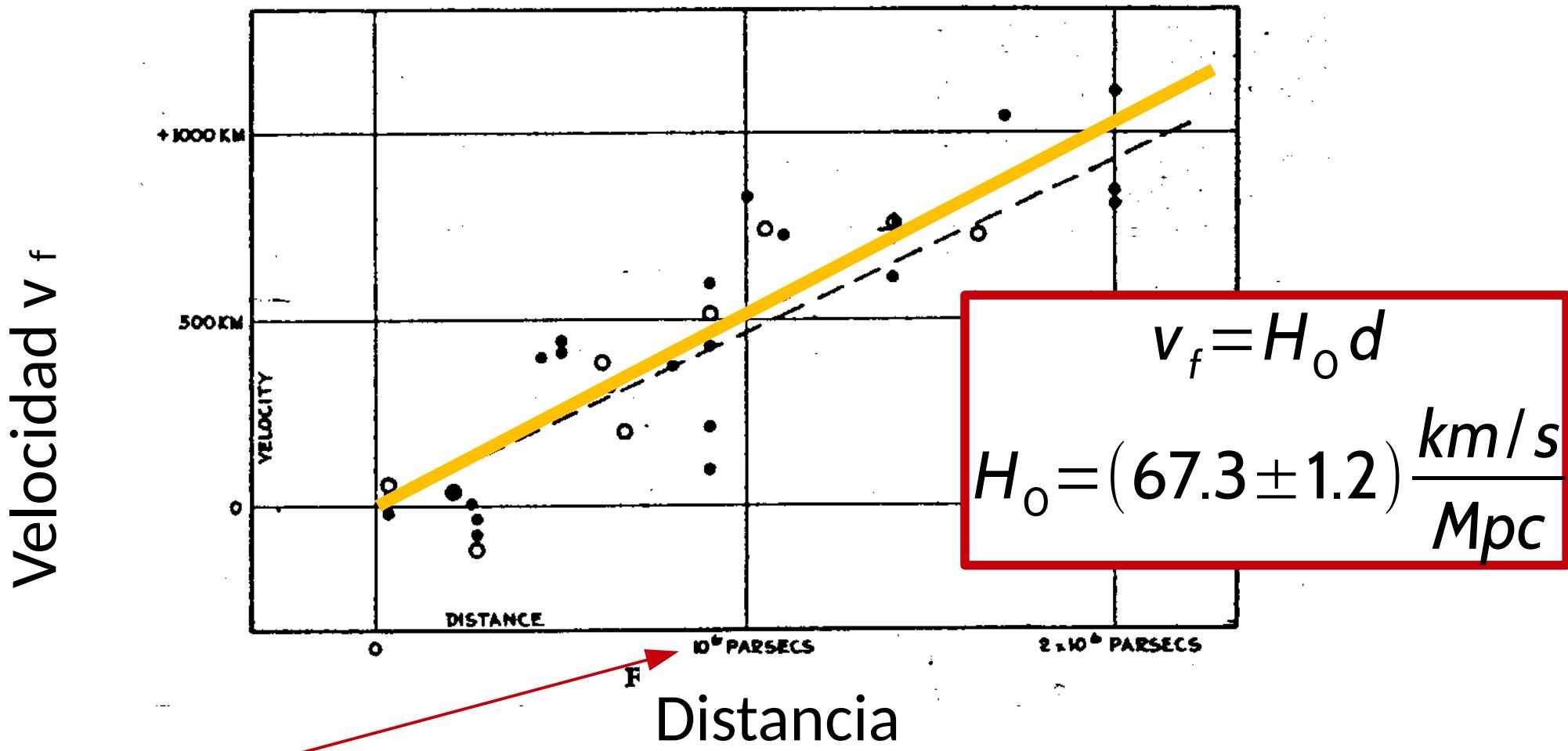
HST, visible





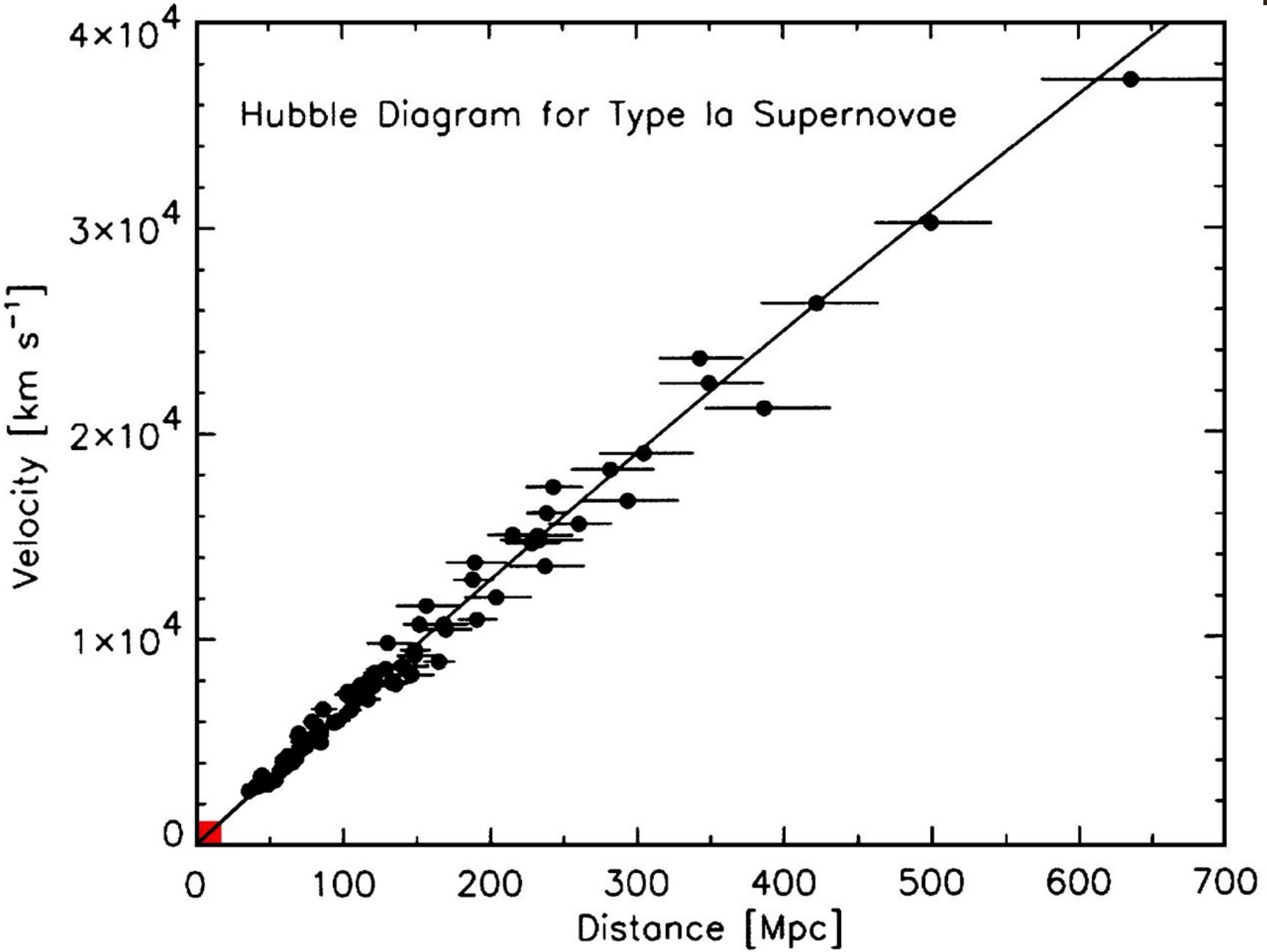
Ley de Hubble: el Universo se expande

Un objeto situado a 1 Mpc de la Tierra se aleja a una velocidad de 67 km/s



$$10^6 \text{ parsecs} = 1 \text{ Mpc (megaparsec)} = 3.085 \times 10^{22} \text{ m}$$

Ley de Hubble en Siglo XXI





¿De qué manera?





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



Horizontes en el Universo

- Radio de Hubble: distancia a la cual la velocidad de expansión es igual a c

$$r_H(t) = \frac{c}{H(t)}$$

- Horizonte cosmológico: la distancia que se propagó la luz desde el inicio del Universo. Como el universo se expande, esto no es “simplemente” 13.8×10^9 años luz

Hoy es 14.4 Gpc = 46.9 Gal



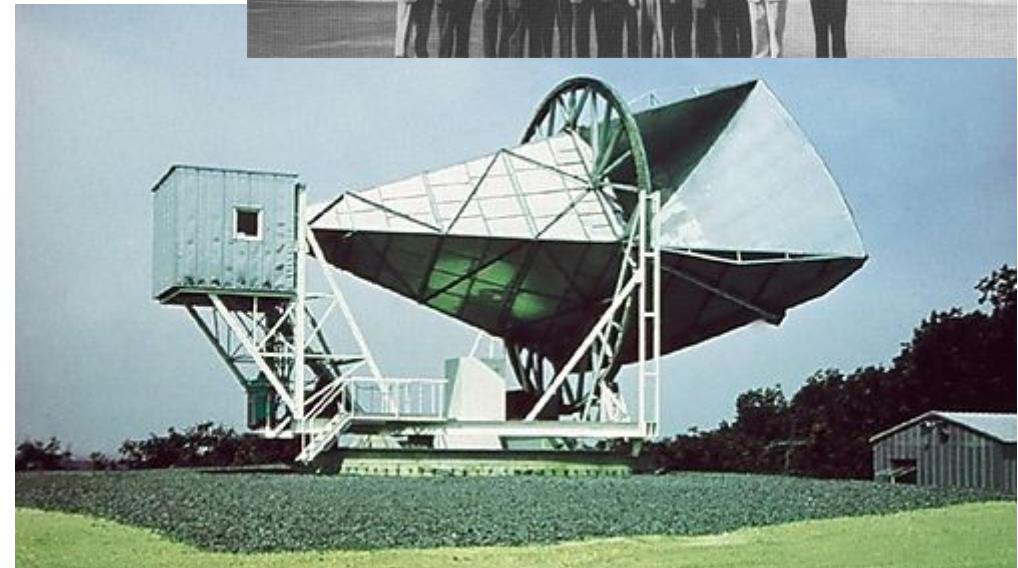
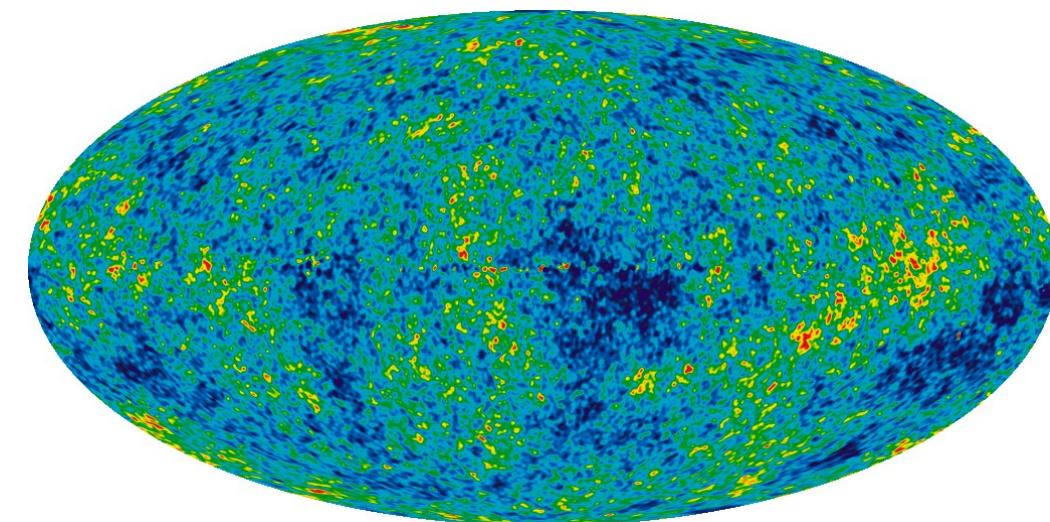
Pero si el Universo está en expansión....

- ... siempre lo estuvo?
- Estado estacionario
 - Creación continua de materia (hidrógeno)
$$1 \frac{M_{\odot}}{Mpc^3}$$
 - Universo homogéneo e isótropo
- generación inicial
 - Principio cosmológico: las propiedades del Universo son las mismas para todos los observadores
 - Altas temperaturas y densidades
 - Expansión y enfriamiento

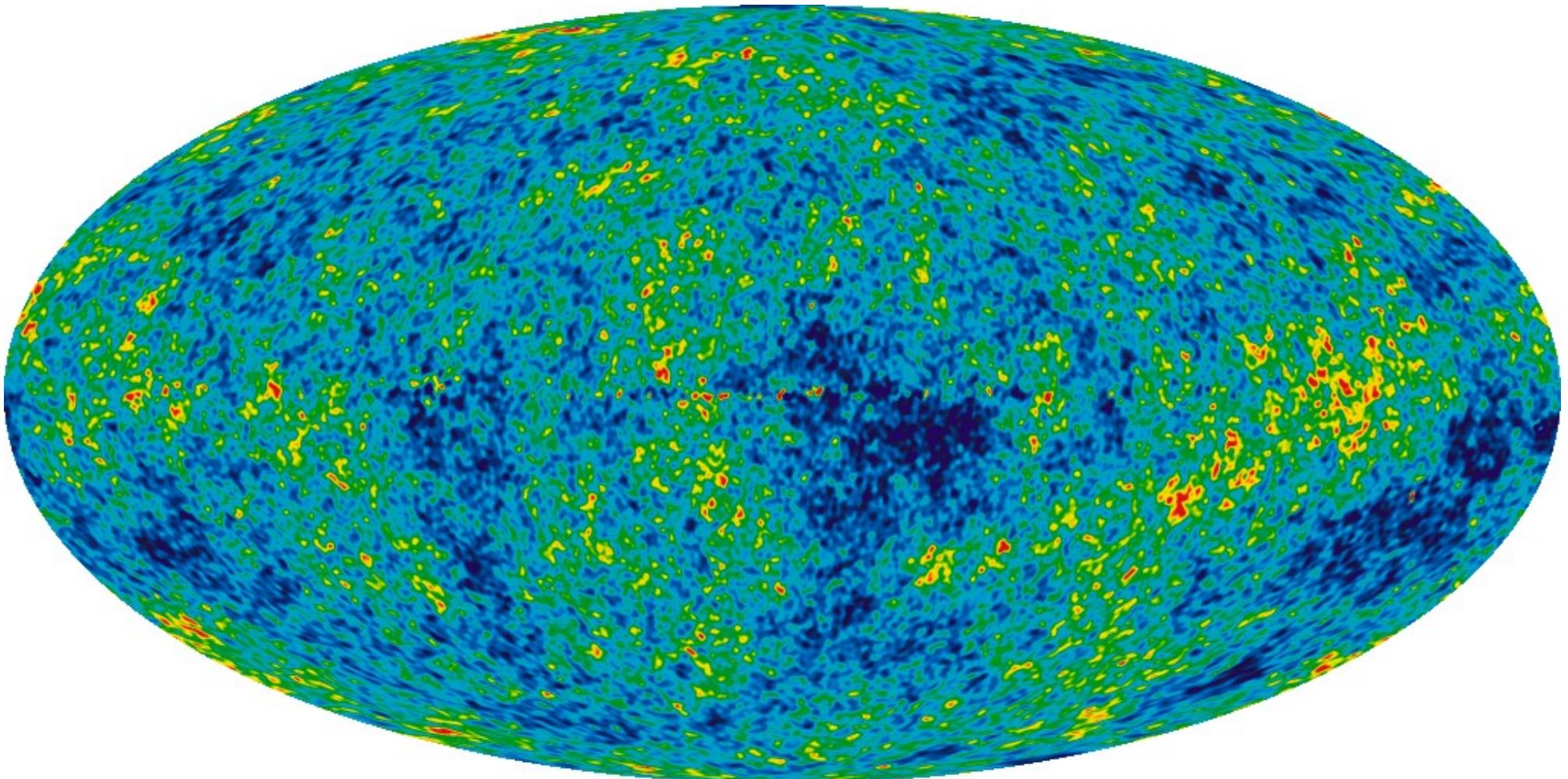


The Big Bang Theory

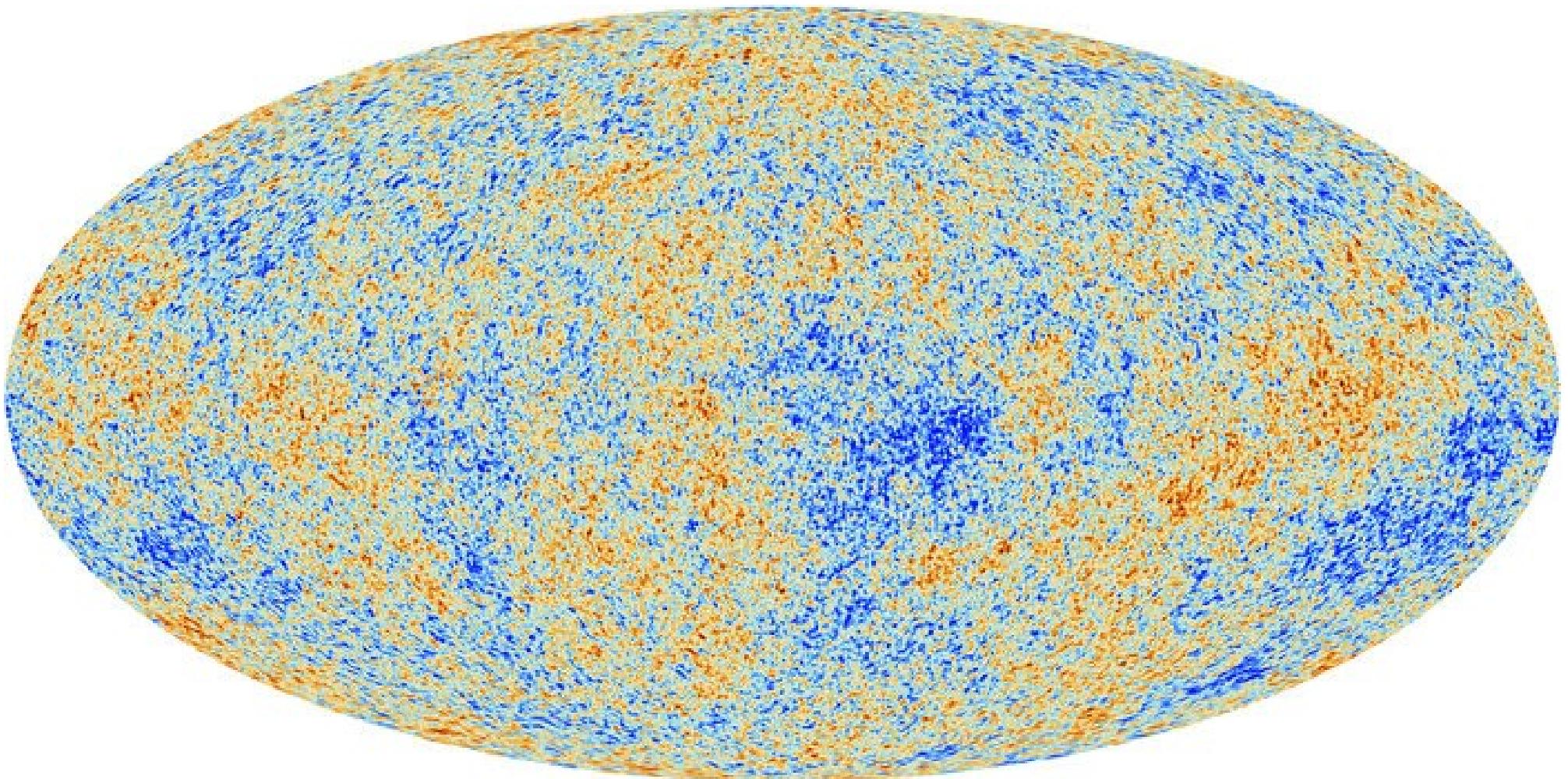
- Alpher & (Bethe) & Gamow → Paper alfabético
- Penzias & Wilson (1965)
- $\lambda=7.35$ cm
- ¿Energía? ¿Temperatura?



Radiación de fondo de microondas

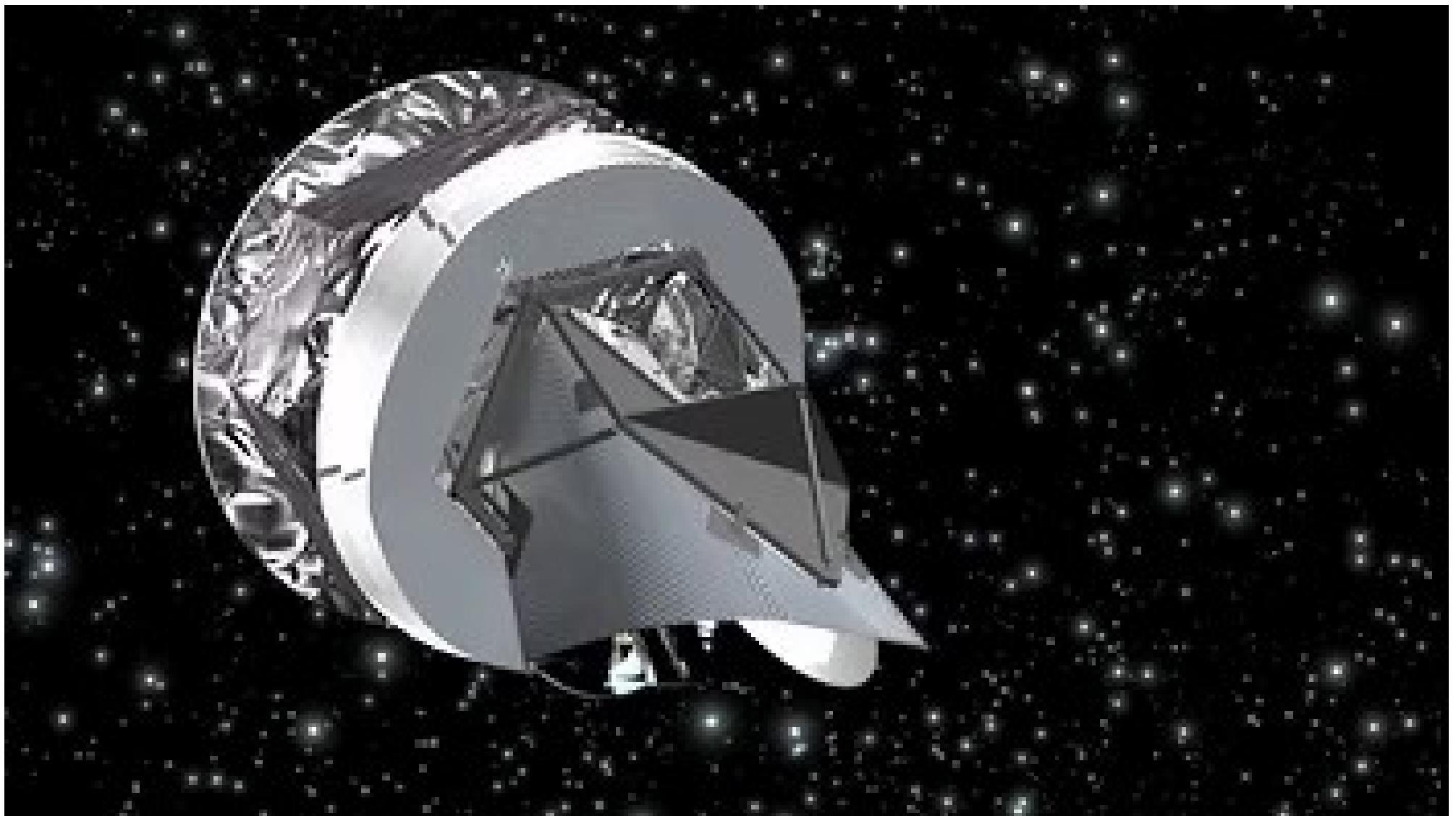


Radiación de fondo de microondas





Así se construye



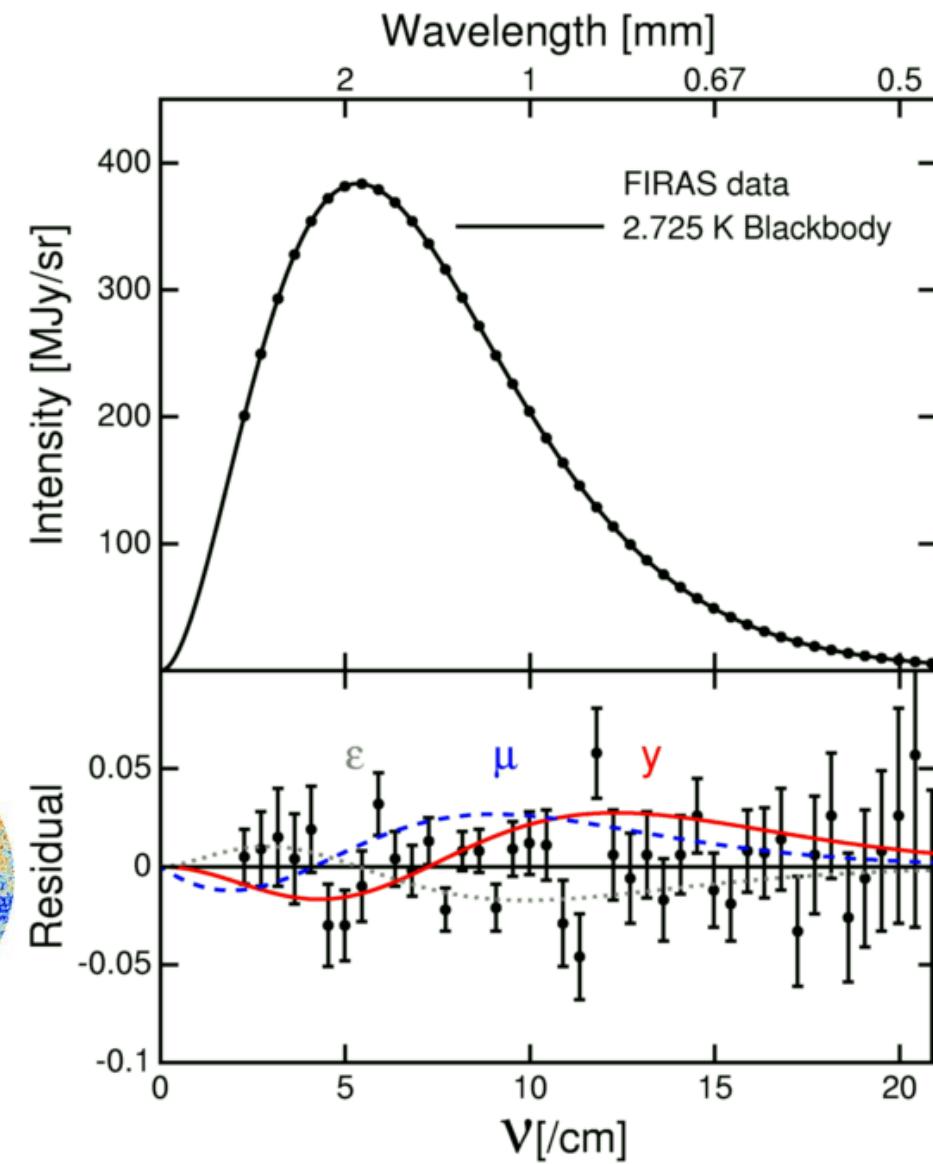
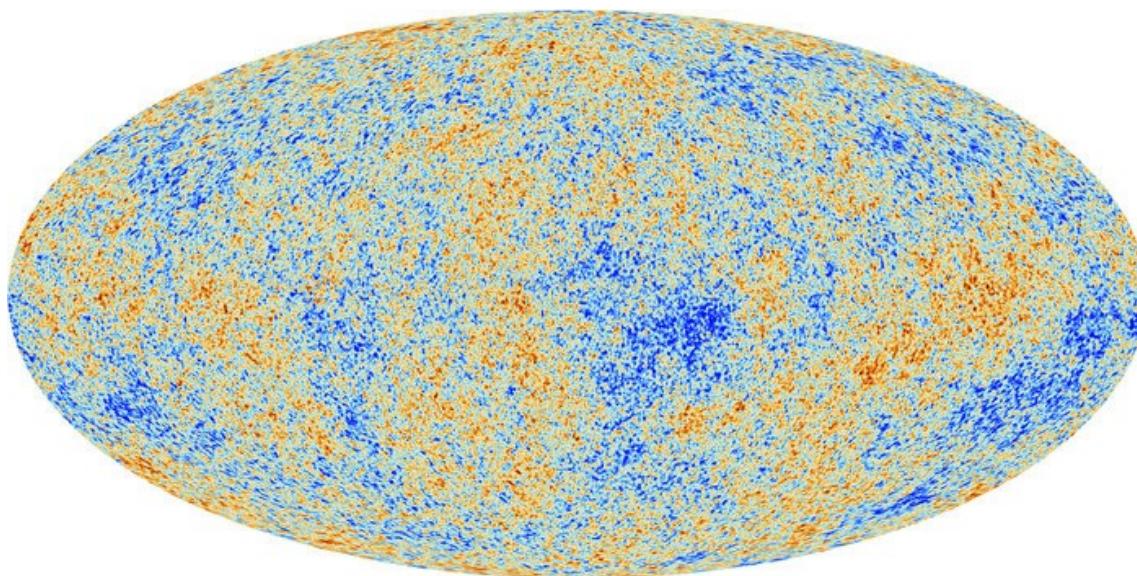
Radiación de fondo de microondas

- Radiación de cuerpo negro:

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

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

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



¿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?

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

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

Densidad crítica

La velocidad de expansión para un objetos en d es

$$N = H_0 d$$

Sia una estrella de radio R . Luego la superficie se aleja del centro

con velocidad $N = H_0 R$

¿Podrá escaparse de la atracción del centro del universo?

$$r_E = \sqrt{\frac{2GM}{R}}$$

Si la estrella tiene densidad ρ y volumen $V \Rightarrow \rho = M/V \Rightarrow$

$$M = \rho \frac{4}{3} \pi R^3 \Rightarrow N_E^2 = \frac{2G}{R} \rho \frac{4}{3} \pi R^3 \Rightarrow \rho = \frac{3 N_E^2}{8\pi G R^2}$$

Reemplazando $N_E^2 = H_0^2 R^2 \Rightarrow$

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

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

Densidad
crítica



Midiendo...

- Defino: $\Omega = \rho / \rho_c$

$$\Omega_i \equiv \frac{\rho_i}{\rho_c}$$
$$\Omega_{\text{tot}} = \sum_i \Omega_i$$

- Ahora mido el contenido de materia del Universo, y obtengo:

$$\Omega = 1.00 \pm 0.01$$

<https://arxiv.org/pdf/1807.06209.pdf>



¡Entendimos el Universo!





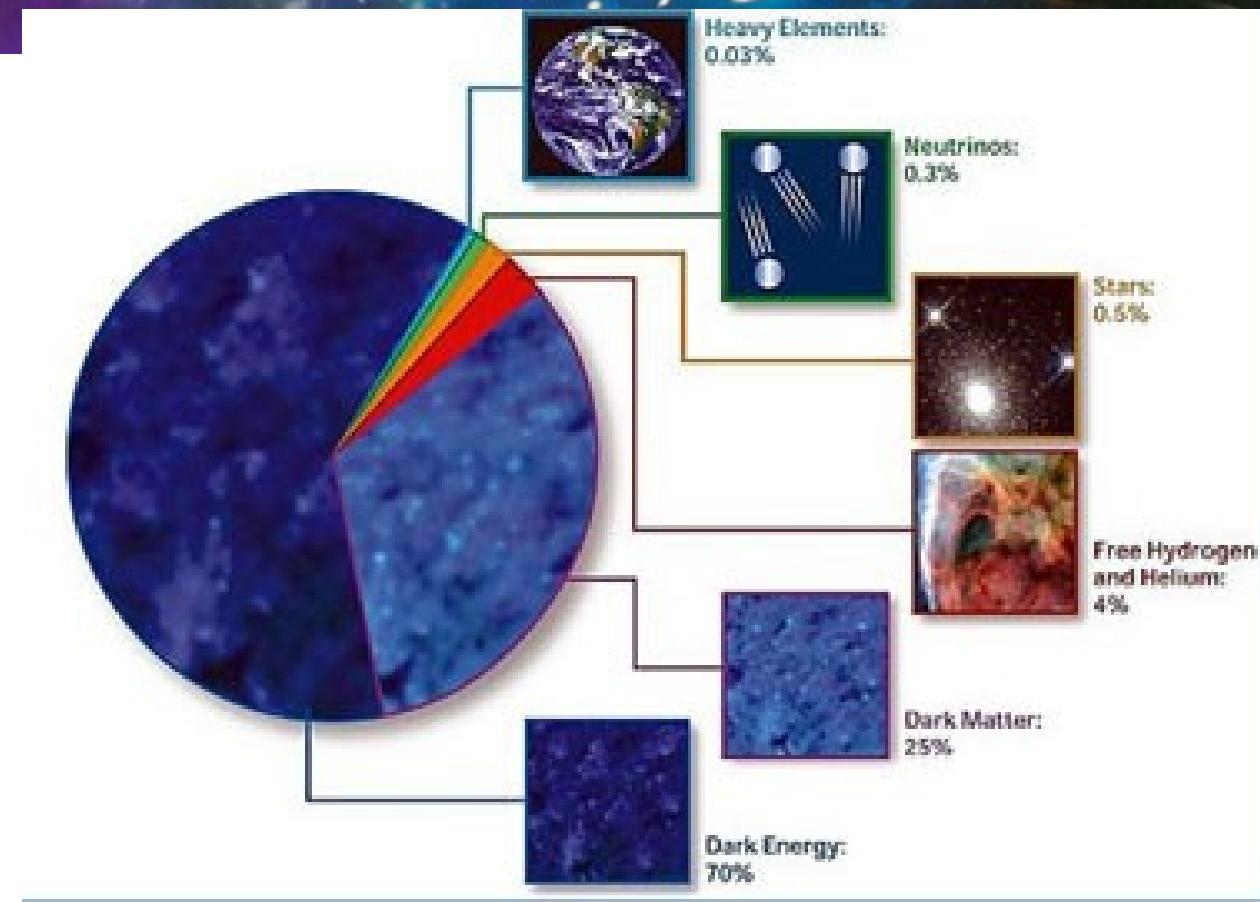
Alto, ¿cómo lo medimos...?

- La distribución de materia y energía del Universo, ¿es uniforme?
- ¿Cuánta materia y cuanta energía?
- ¿Qué otros factores debemos tener en cuenta?

Contenido de materia energía del Universo

- Cómo se compone:

- $\Omega_k = 10^{-5}$
- $\Omega_\gamma = 0.002$
- $\Omega_m = 0.0486 \pm 0.001$



- Total esperado: $\Omega = 0.0488$
- Total medido: $\Omega = 1 \rightarrow$ problemas

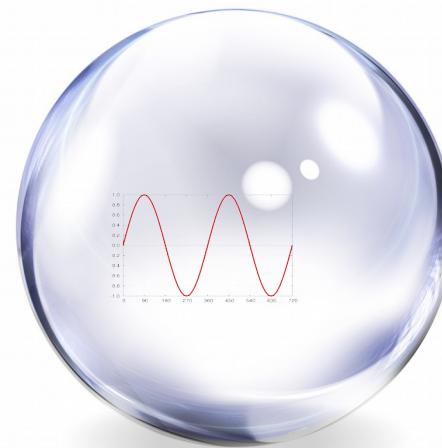


Materia y energía en la expansión

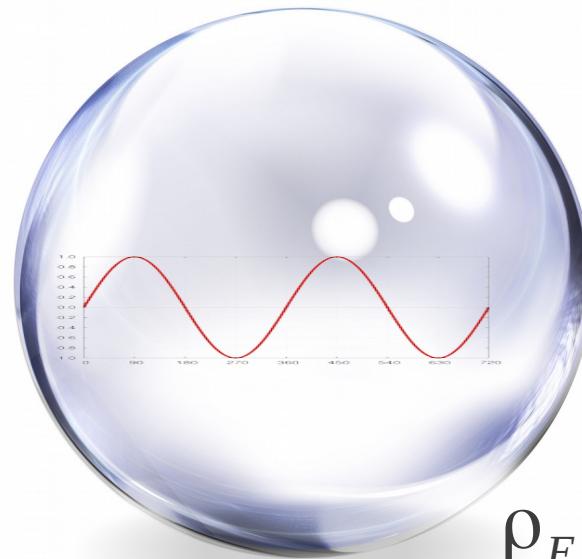
$$E=mc^2$$



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



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

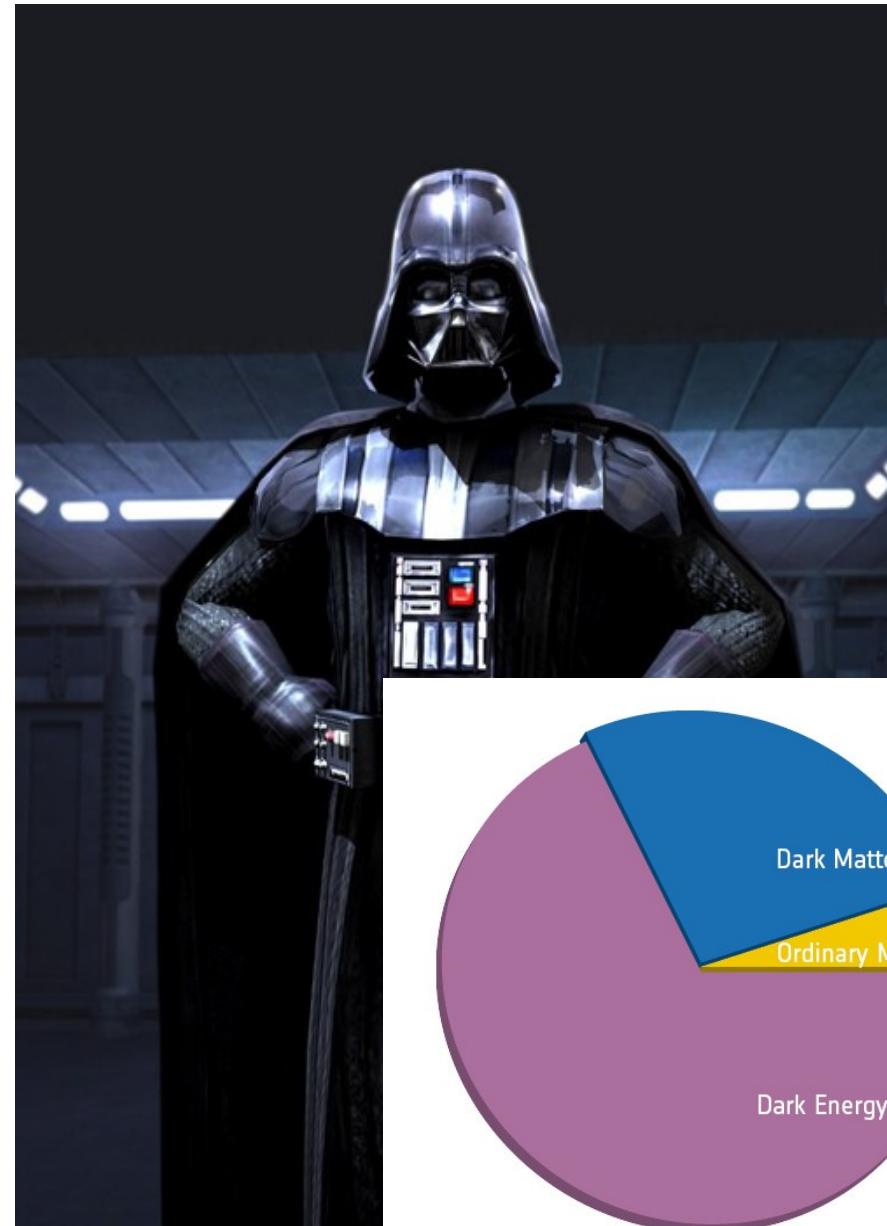


$$\rho_M \sim 1/R^3$$

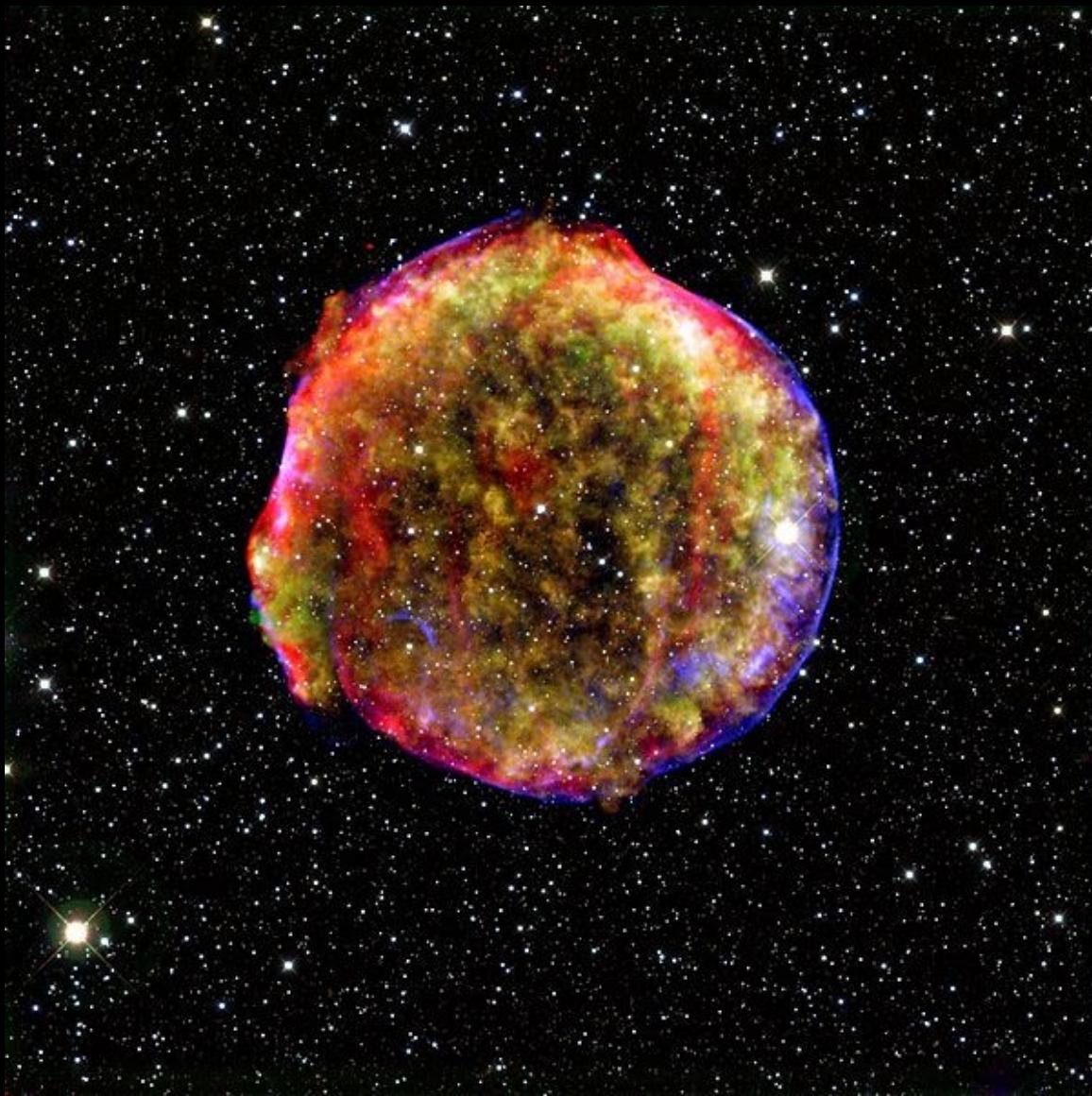
Contenido de materia energía del Universo

- Cómo se compone:

- $\Omega_k = 0.001\%$
- $\Omega_\gamma = 0.2\%$
- $\Omega_m = (4.86+-0.001)\%$
- $\Omega_M = (25.89+-0.0057)\%$
- $\Omega_{mat}=\Omega_m+\Omega_M= 30.89\%$
- $\Omega_\Lambda=(68.3+-0.0062)\%$



Supernovas Ia

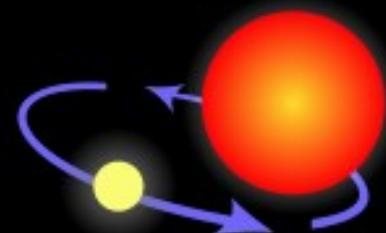


The progenitor of a Type Ia supernova

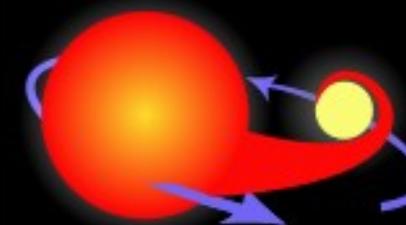
“Velas estándares”



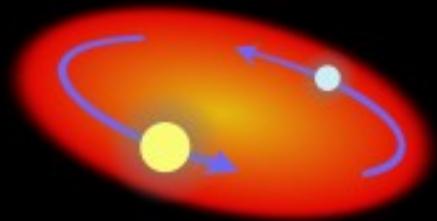
Two normal stars are in a binary pair.



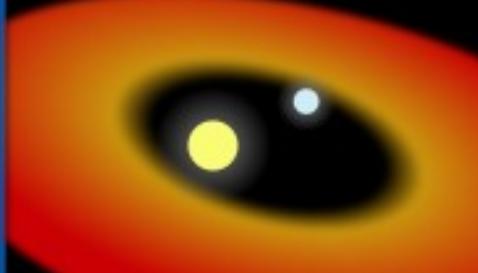
The more massive star becomes a giant...



...which spills gas onto the secondary star, causing it to expand and become engulfed.



The secondary, lighter star and the core of the giant star spiral toward within a common envelope.



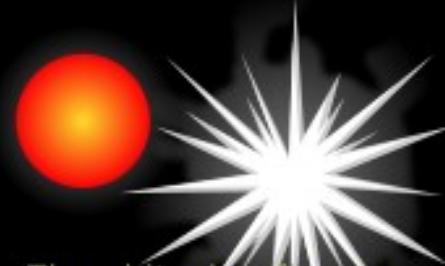
The common envelope is ejected, while the separation between the core and the secondary star decreases.



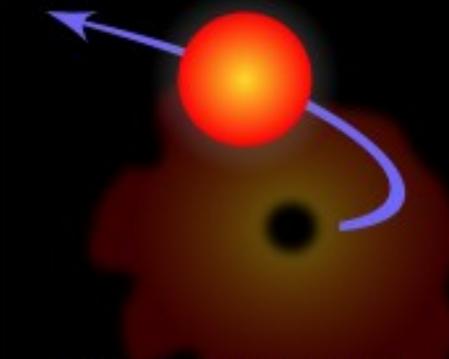
The remaining core of the giant collapses and becomes a white dwarf.



The aging companion star starts swelling, spilling gas onto the white dwarf.

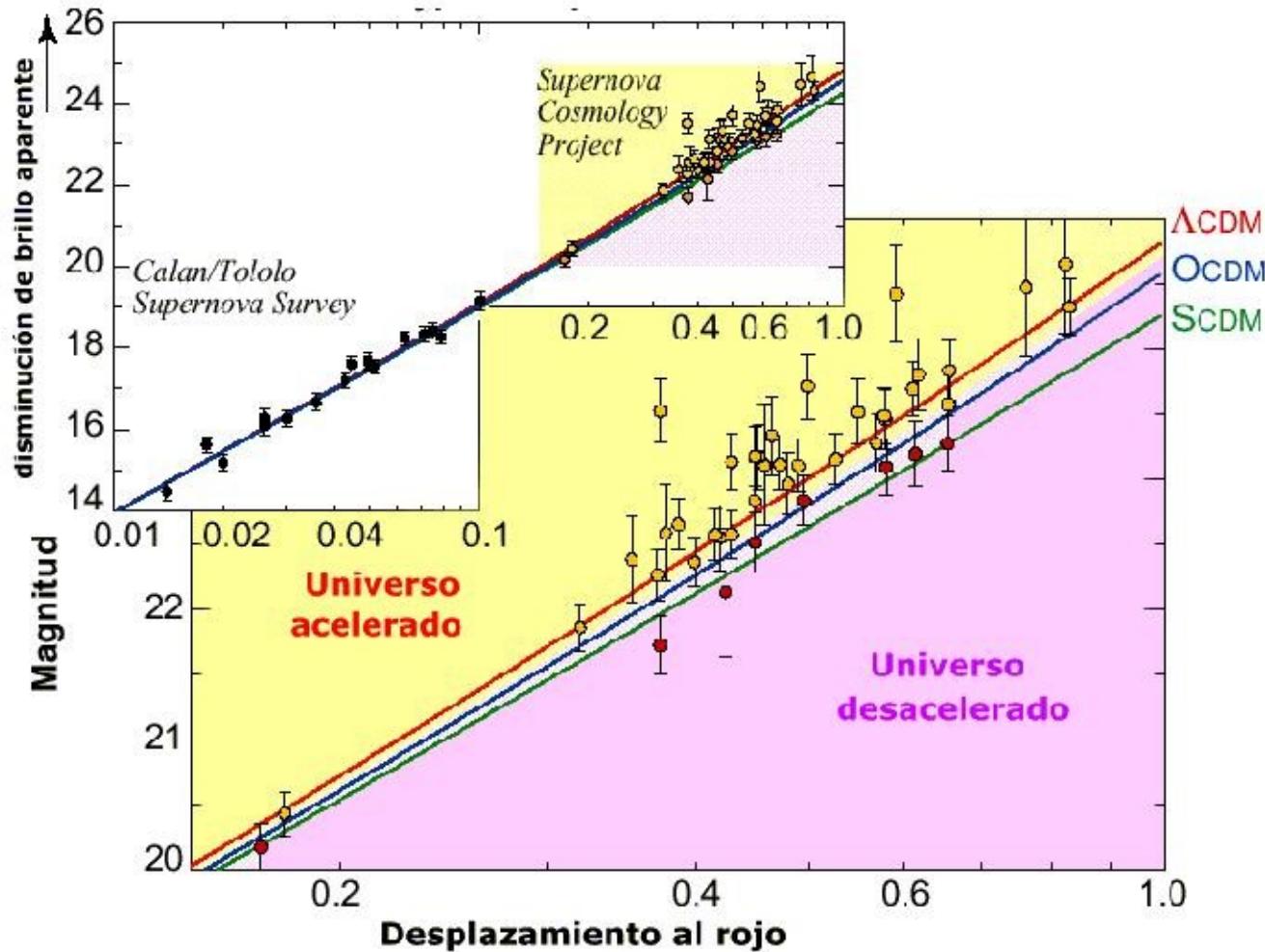


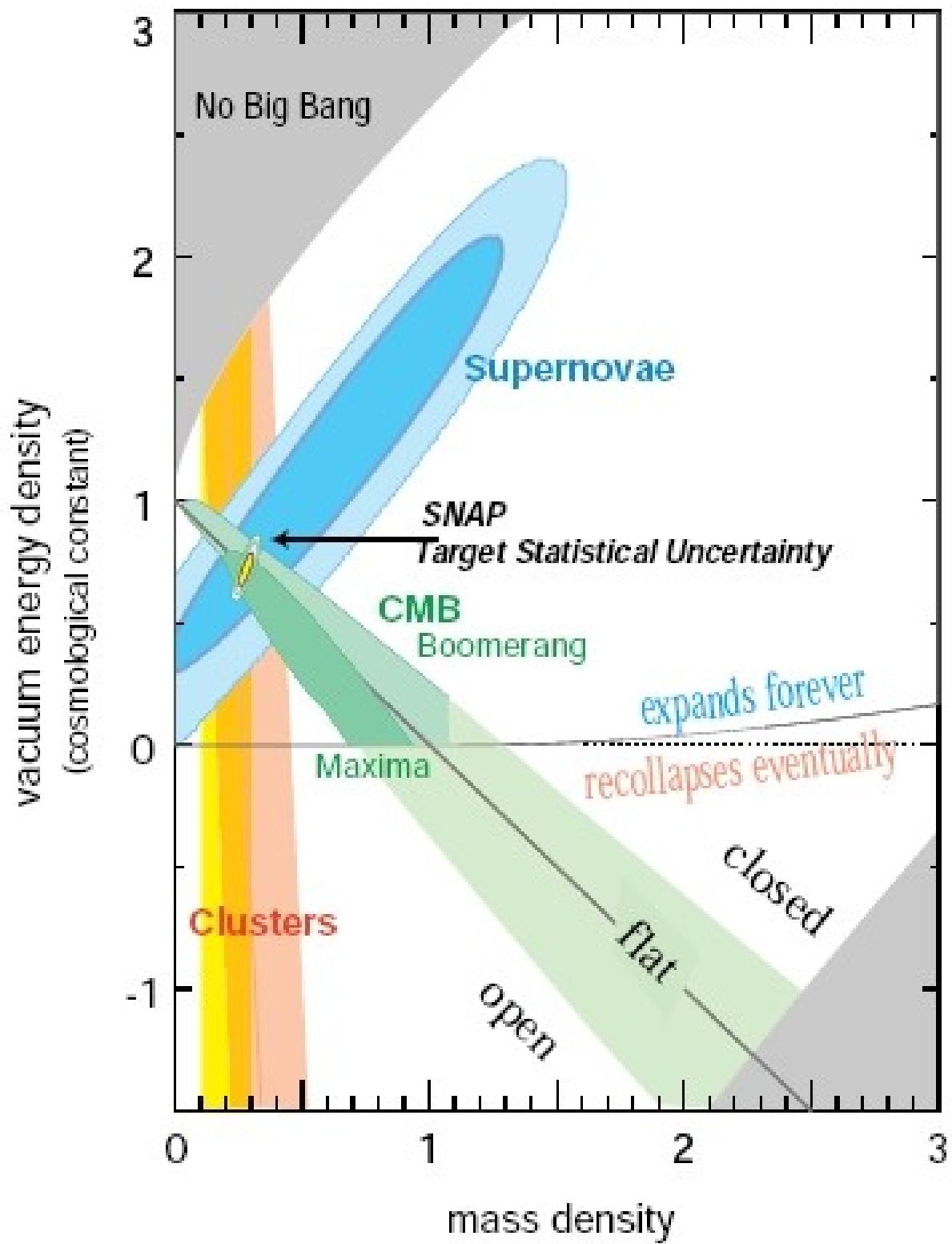
The white dwarf's mass increases until it reaches a critical mass and explodes...



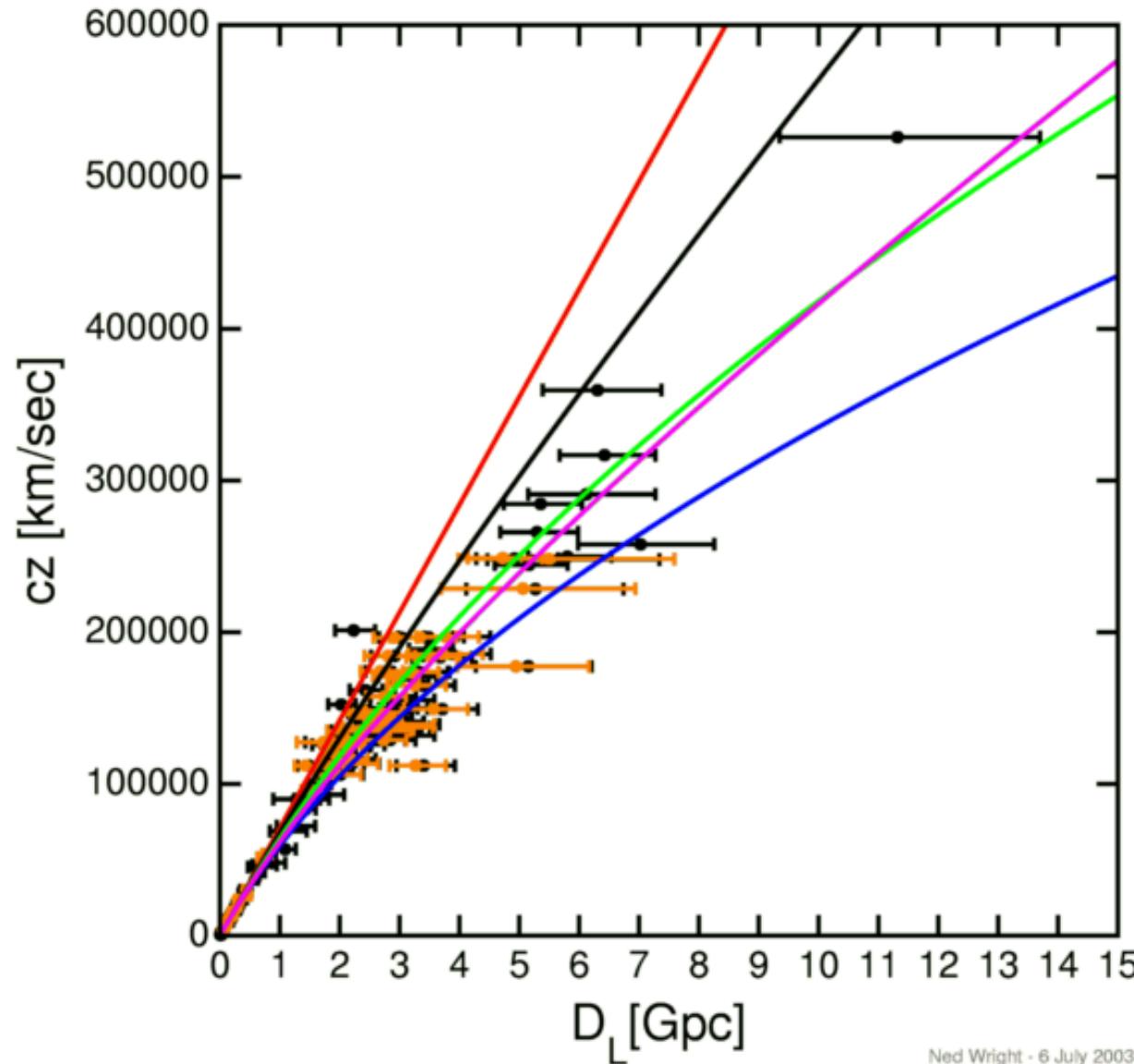
...causing the companion star to be ejected away.

Expansión acelerada





El nuevo diagrama de Hubble



Ned Wright - 6 July 2003

Lo que viene...



→ COSMIC HISTORY

esa

