

# Evolución del Universo y evolución estelar

Joan Alcaide Núñez – Junio 2024

Preparación Universitaria DSB



**DEUTSCHE SCHULE**  
BARCELONA  
COLEGIO ALEMÁN

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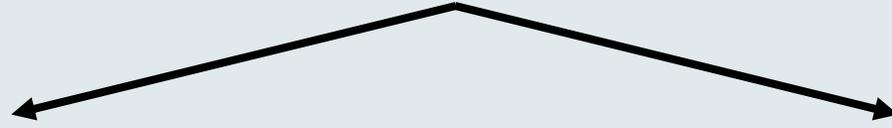
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6. Objetos masivos: estrellas de neutrones y agujeros negros

# 1. Universo: expansión

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# ¿Qué modelo de Universo?



## **Big Bang Model**

- Evolucionario
- Tiempo finito

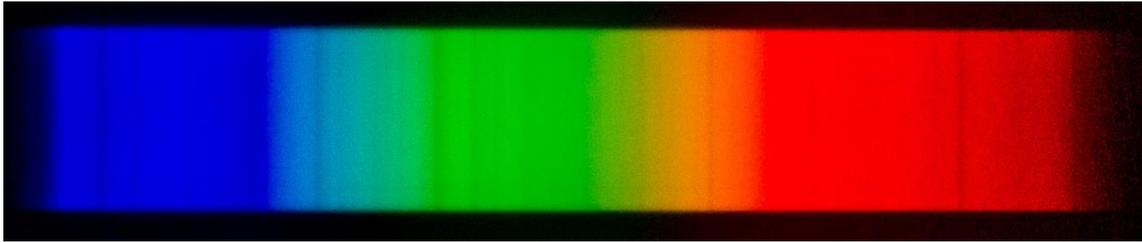
## **Steady State Model**

- Estático
- Tiempo infinito (eterno)



**EXPANSIÓN DEL UNIVERSO**

# Constante de Hubble



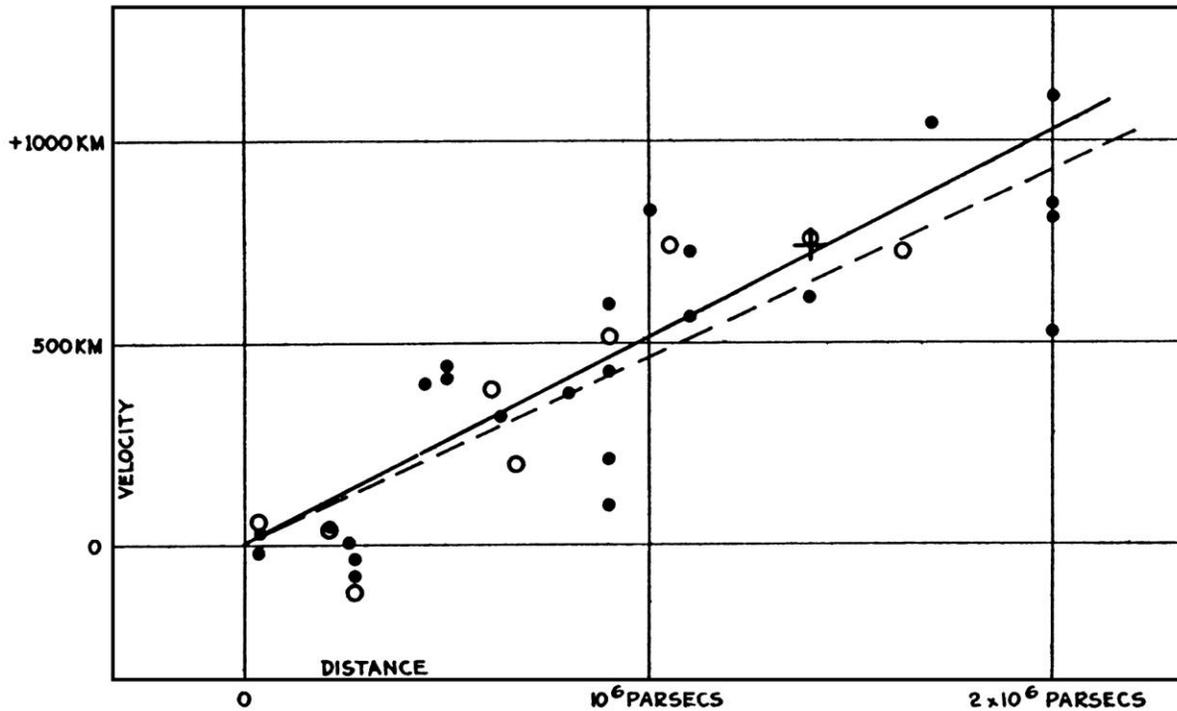
Crédito: JiC 2023

Redshift

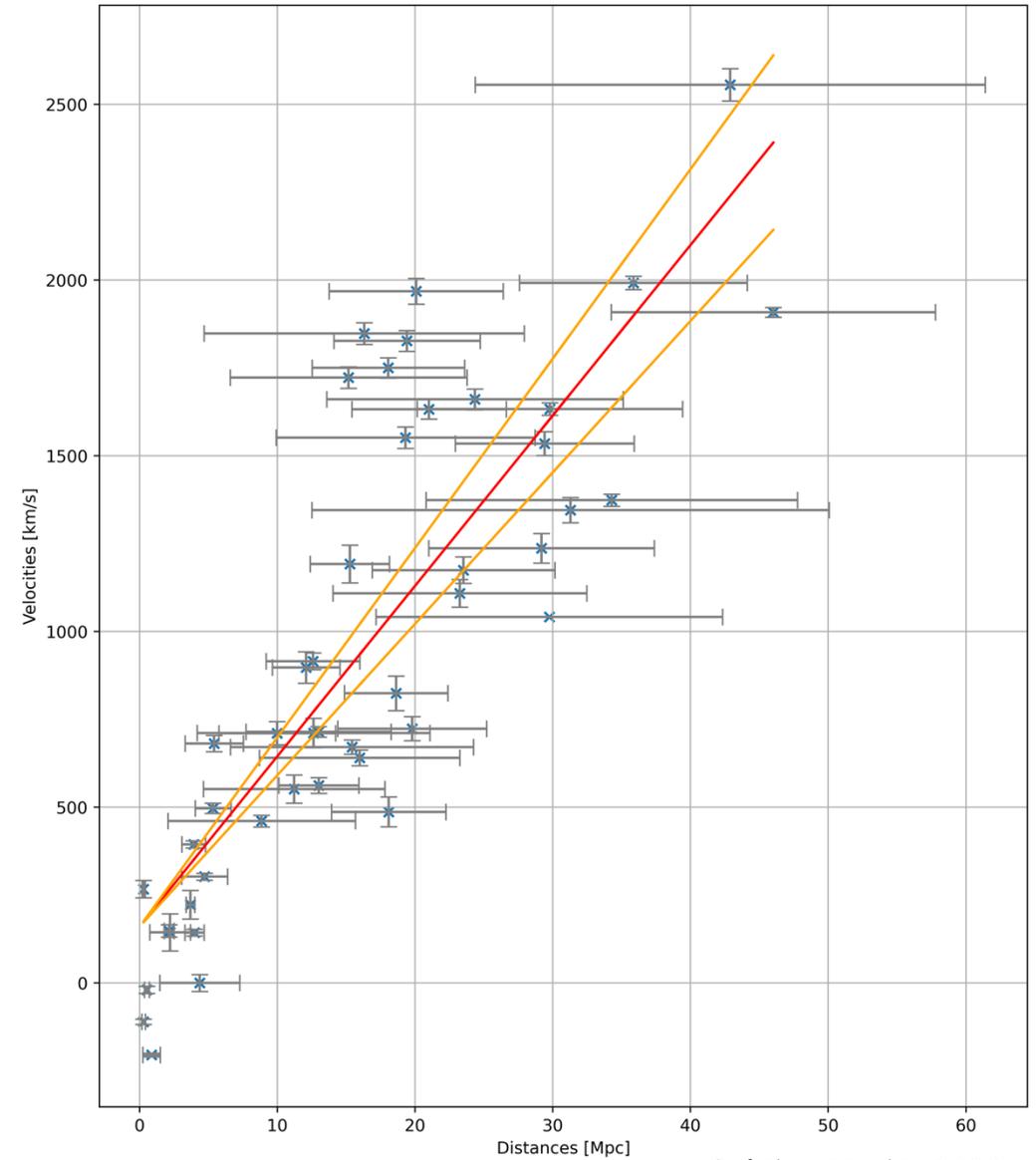
$$v = zc = \frac{\lambda_{ob} - \lambda_{em}}{\lambda_{em}} \cdot c$$

# Constante de Hubble

$$v = H_0 d$$



Crédito: Hubble 1929 (doi: 10.1073/pnas.15.3.168)



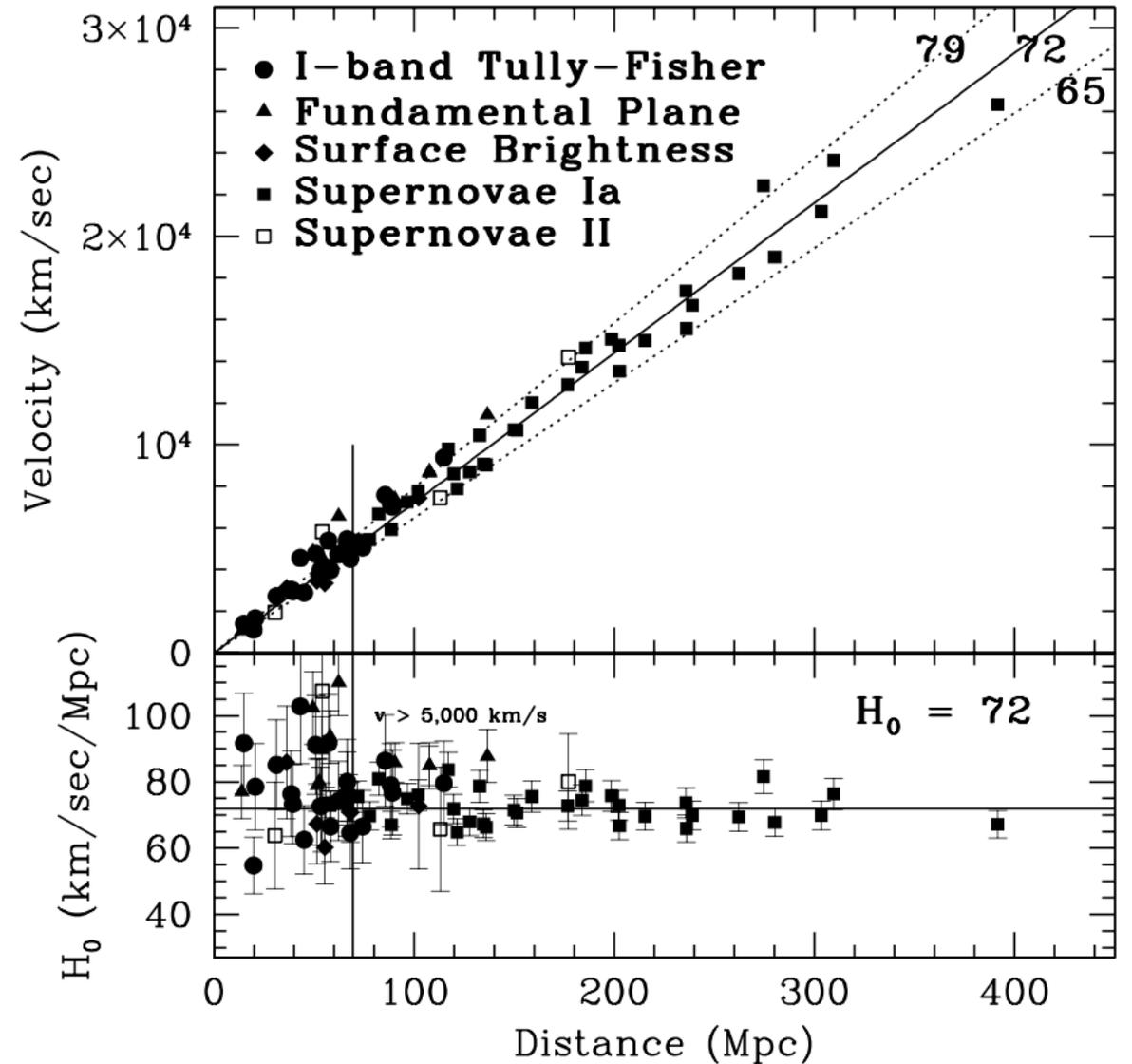
Crédito: Alcaide 2023

# Constante de Hubble

$$v = H_0 d$$

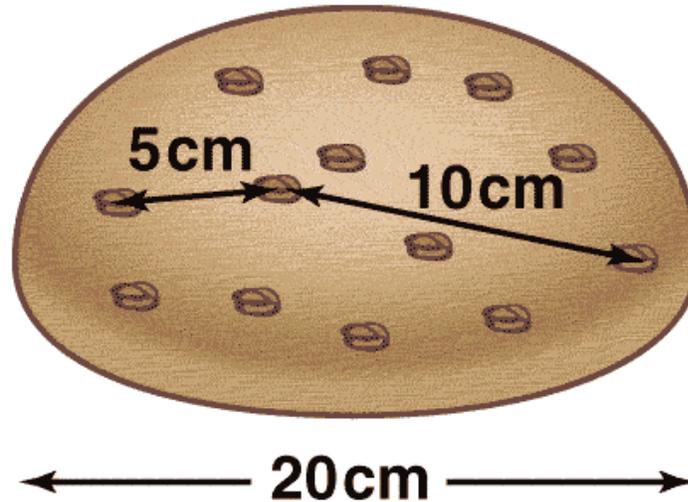
$$H_0 = 72 \pm 8 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

(Freedman et al. 2001, HST Key Project)

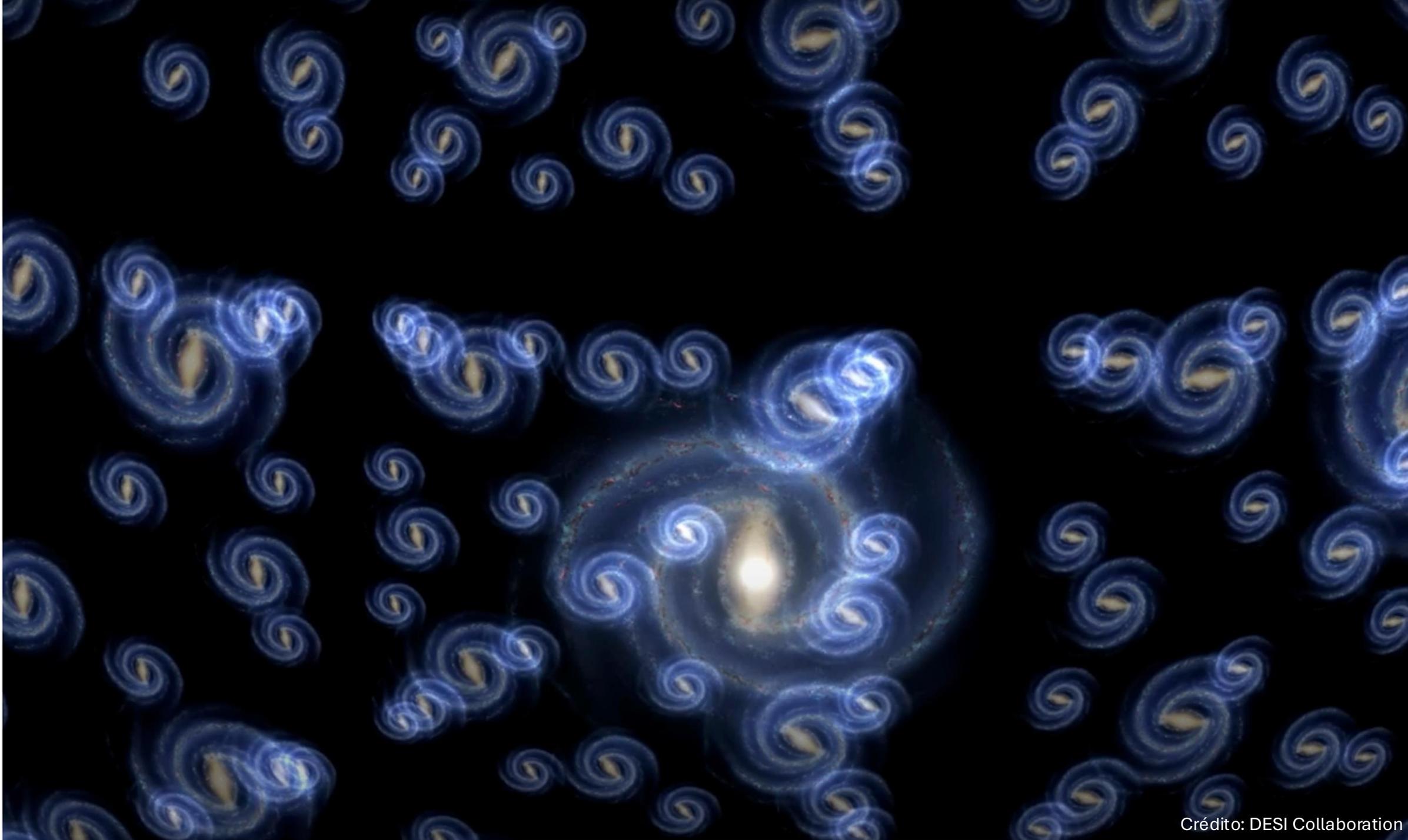


Crédito: Freedman et al. 2001

# Redshift es **proporcional** a la distancia



Video

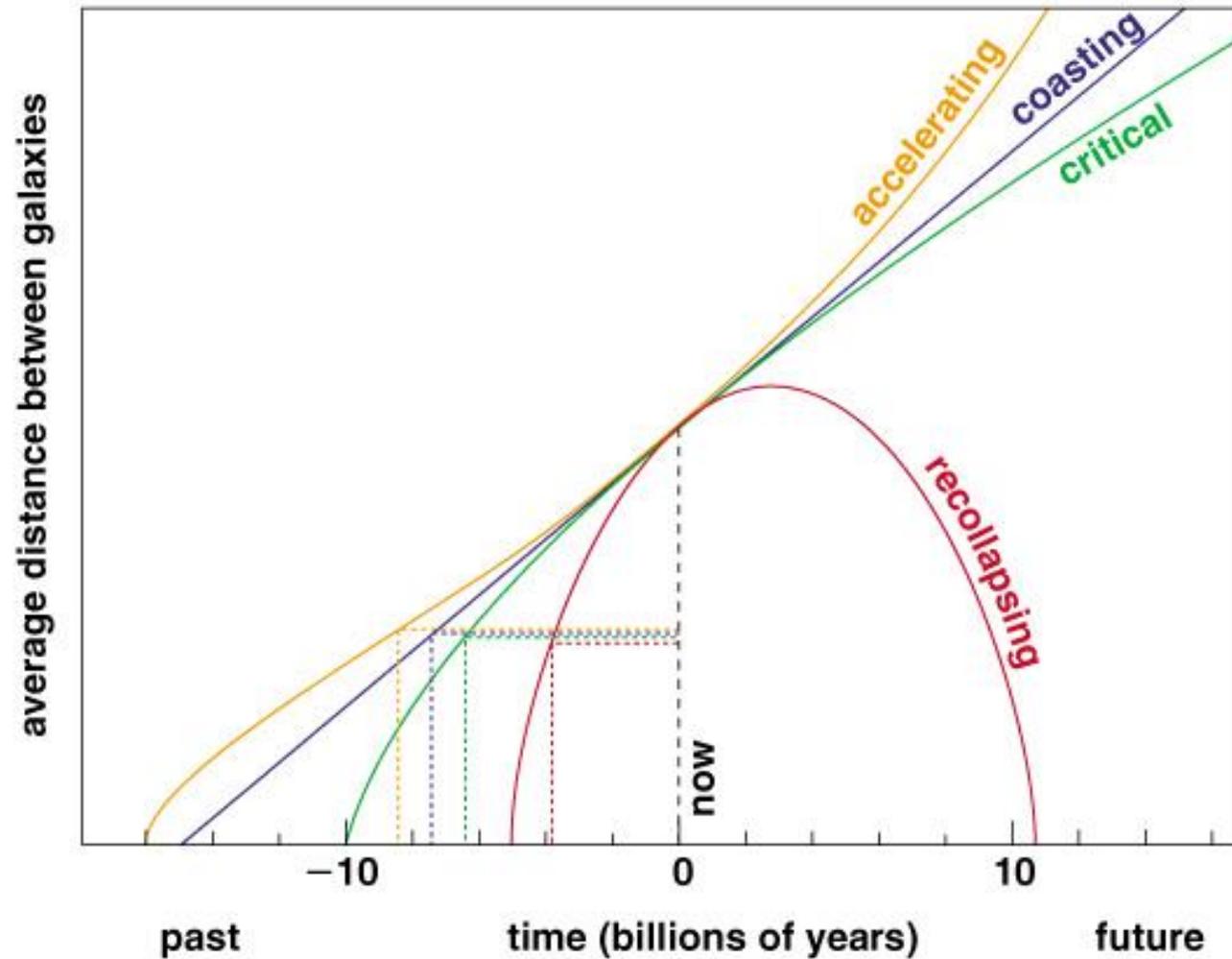


Crédito: DESI Collaboration

# Ecuaciones de Friedman

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2}$$
$$\dot{H} + H^2 = \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)$$
$$\frac{H^2}{H_0^2} = \Omega_{0,R}a^{-4} + \Omega_{0,M}a^{-3} + \Omega_{0,k}a^{-2} + \Omega_{0,\Lambda}$$

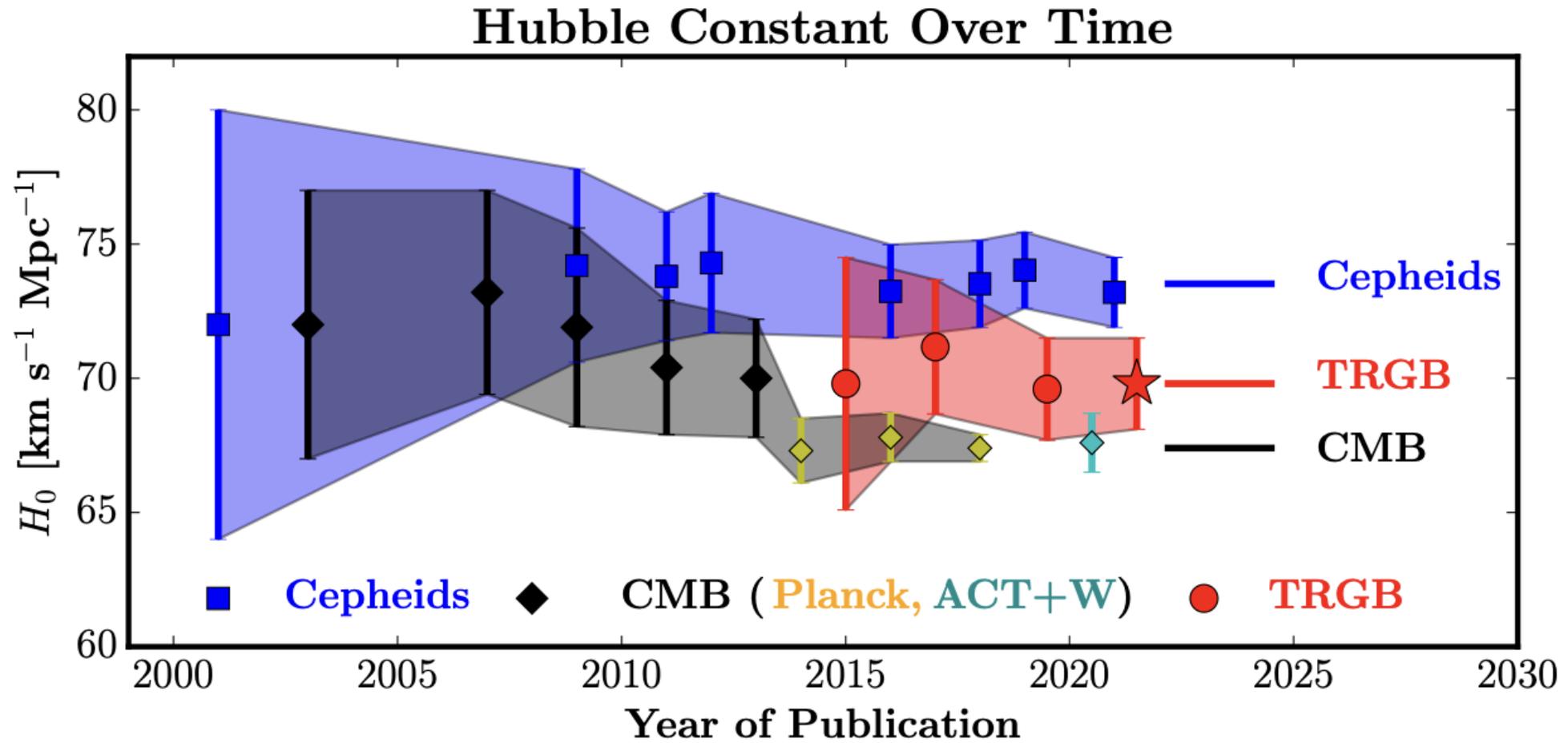
# Expansión acelerada (Energía oscura)



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Crédito: University Massachusets (Amherst)

# Crisis de la Cosmología

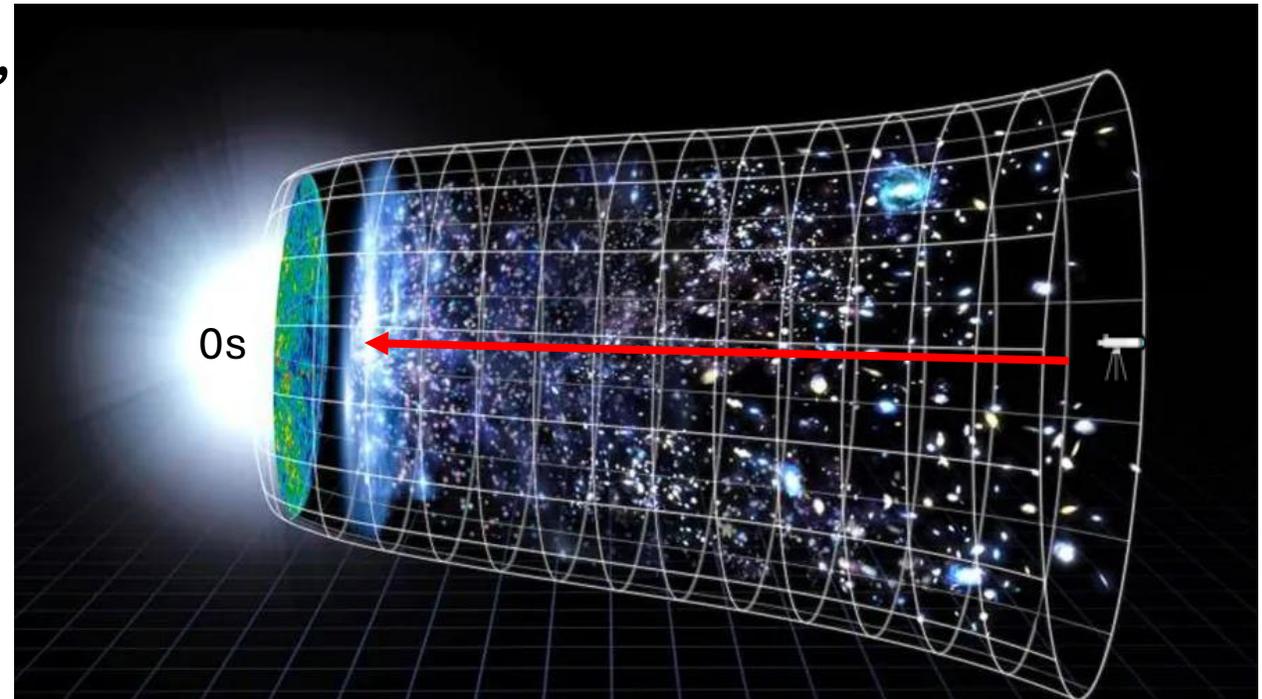


# 2. Universo: evolución

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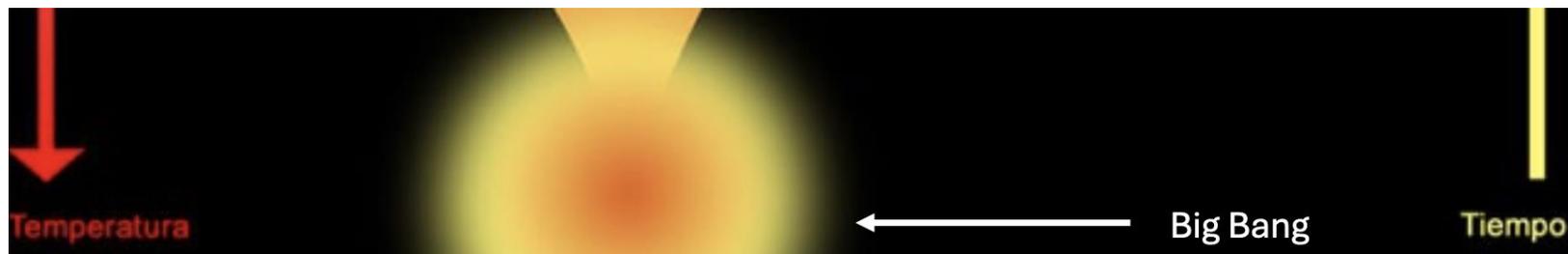
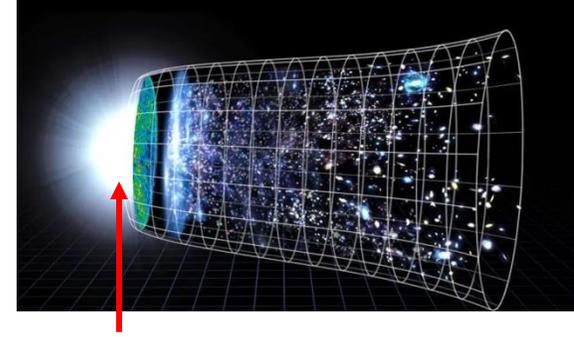
# Edad del Universo

- $t_{\text{Universo}} = \frac{1}{H_0}$
- Con  $H_0 \approx 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , entonces  $t = 13,800 \text{ Gyr}$
- Cuando más lejos observamos, más atrás en el tiempo vemos
  - $c$  es finita

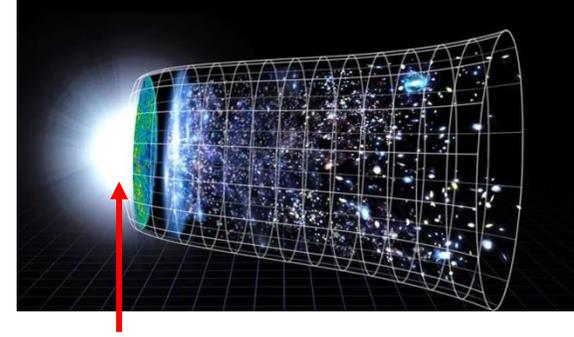


# Escala de Planck

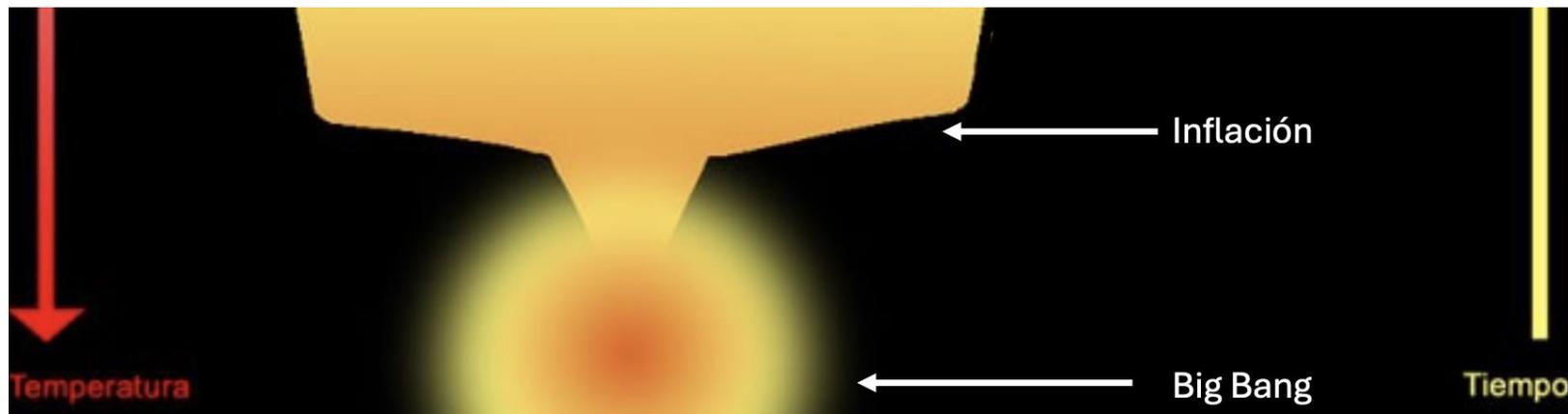
- Unidades mínimas:  $10^{-44} s$ ,  $10^{-35} m$
- Máxima densidad y temperatura
- Nada está definido → Espacio y tiempo diluidos
- Vacío cuántico



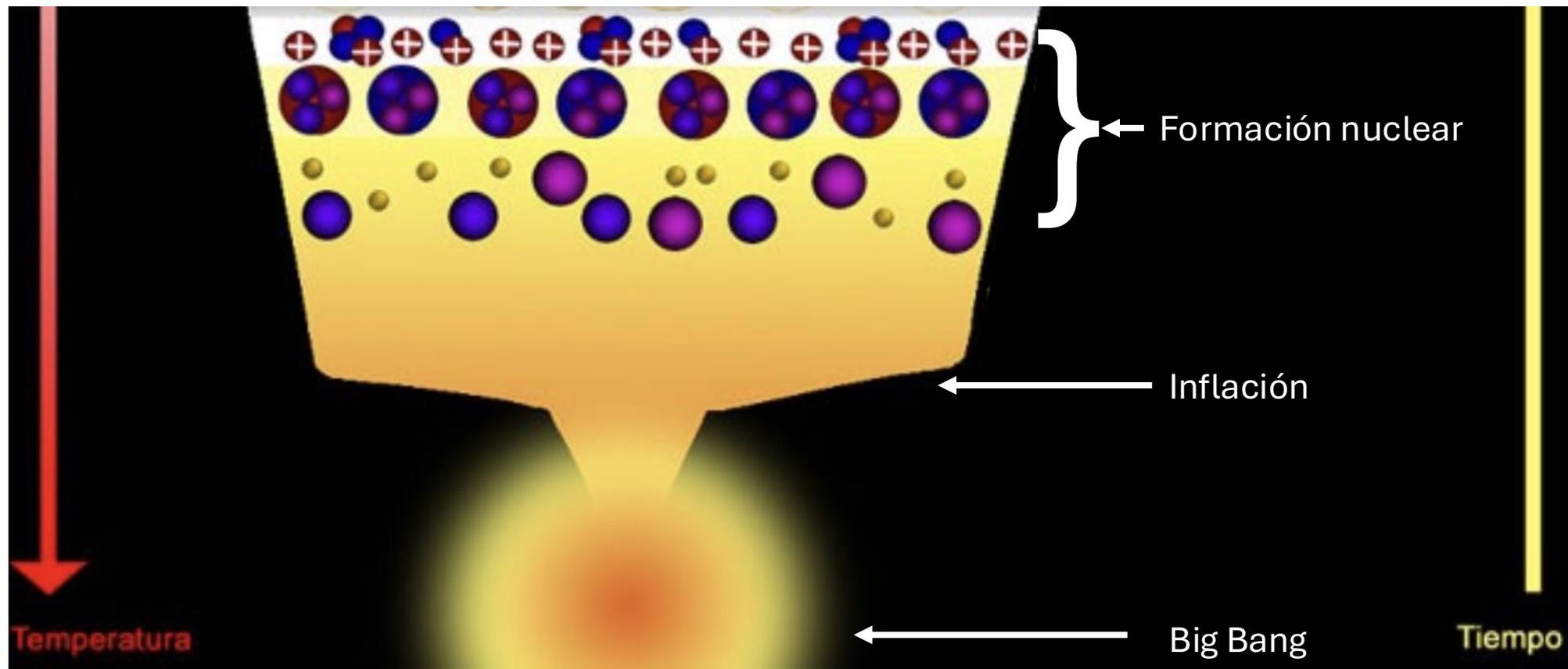
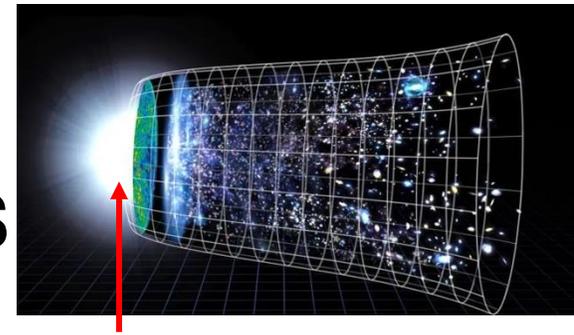
# Inflación - El Bang del Big Bang



- Fluctuación cuántica
- Crecimiento exponencial:  $10^{-13} \text{ cm}$  a  $2 \text{ cm}$
- Origen de la isotropía del Universo

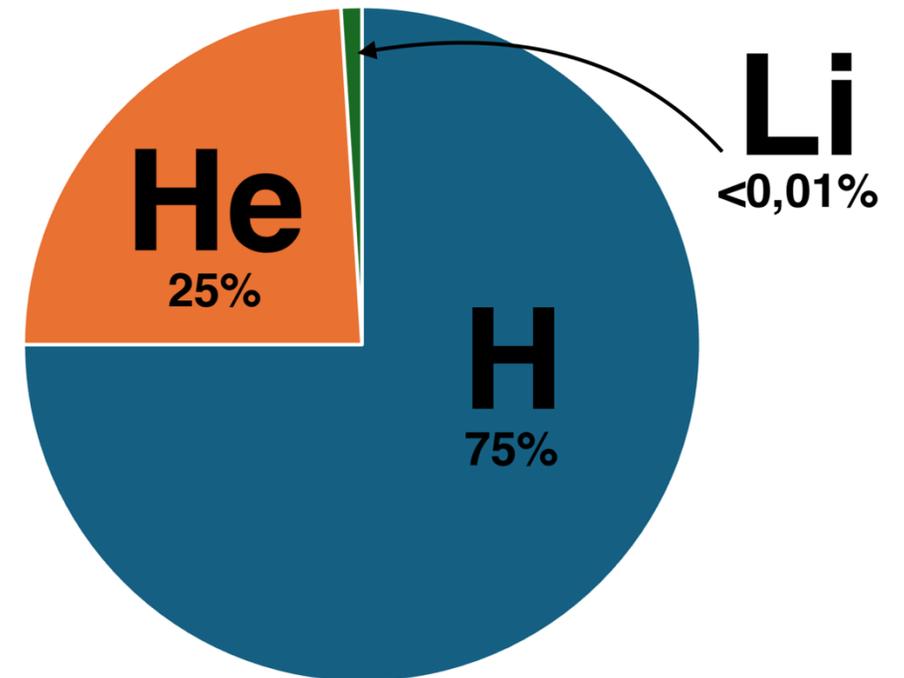
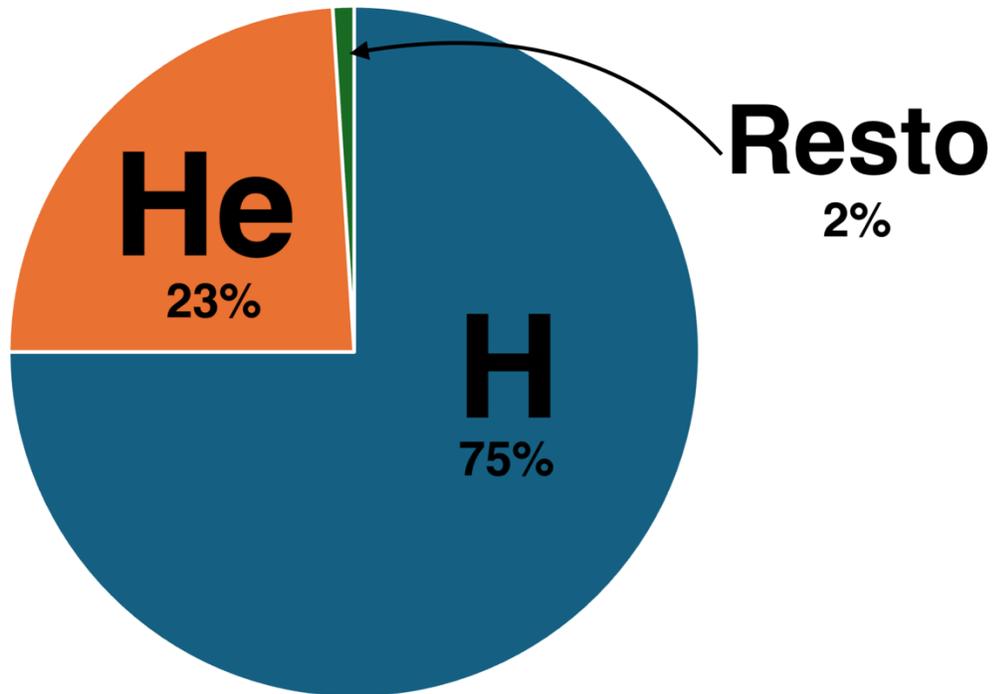


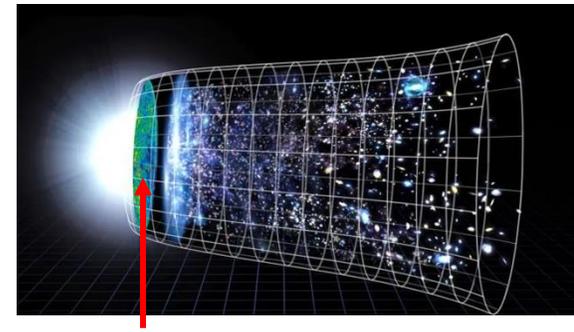
$10^{-12}s - 180s$ : Formación de núcleos



# Composición del Universo en $t = 180s$

$$T = 10^{32}K \rightarrow 3 \times 10^8K$$



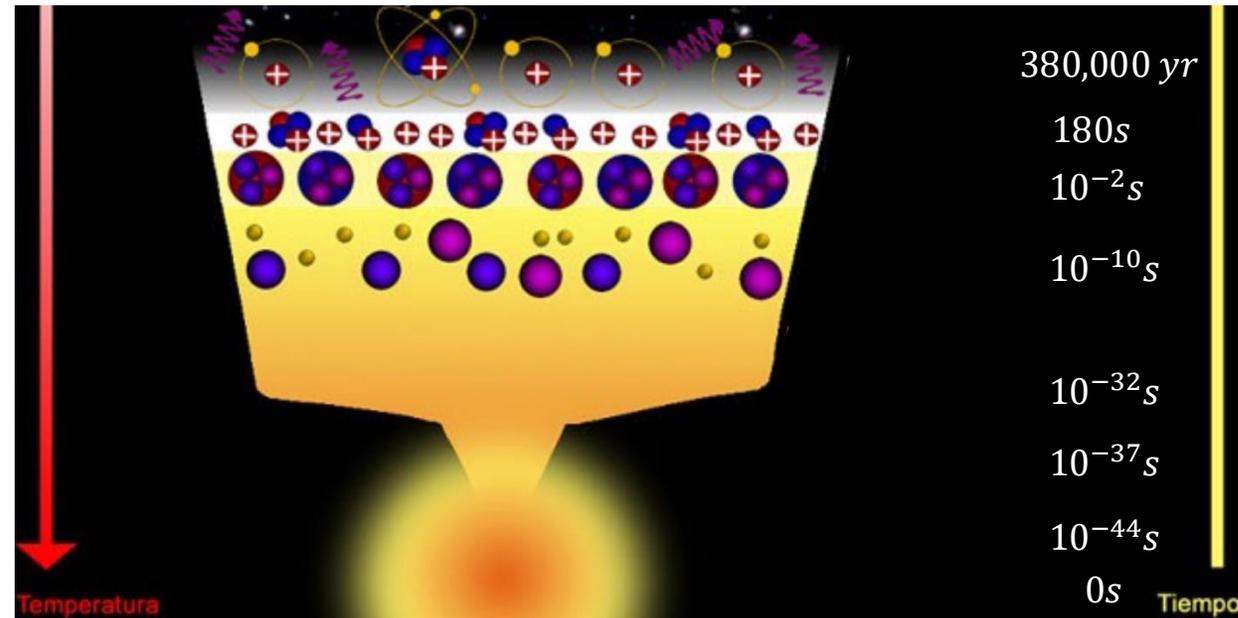


# 3. Universo: CMB

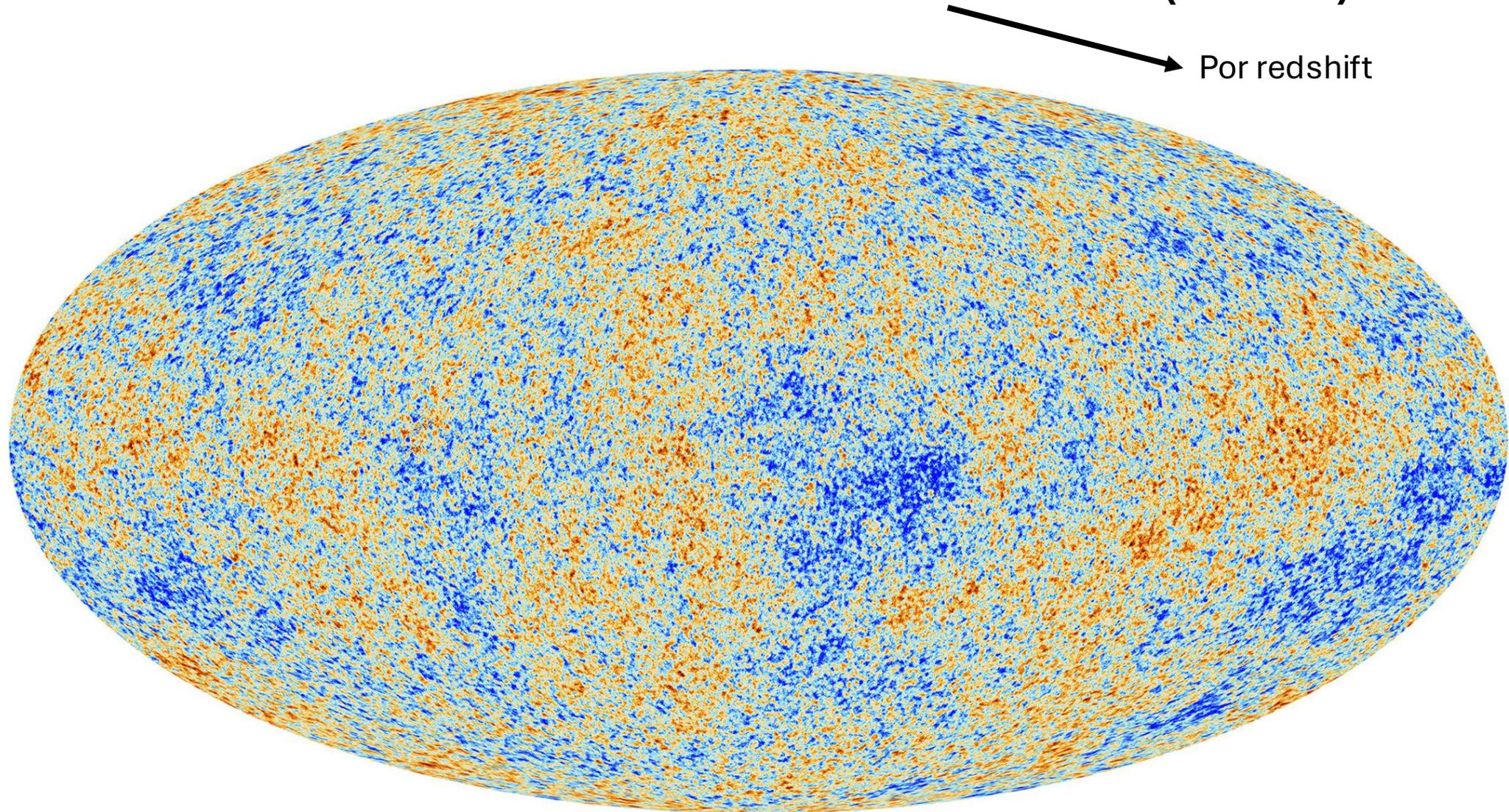
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# Fondo Cósmico de Microondas (CMB)

- Emisión 380,000 años después del Big Bang
- Temperatura baja de 3,000  $K$
- Electrones y fotones son libres (Reducción Compton scattering)
- **Fotones pueden moverse libremente → liberación de radiación**
- El universo se hizo transparente

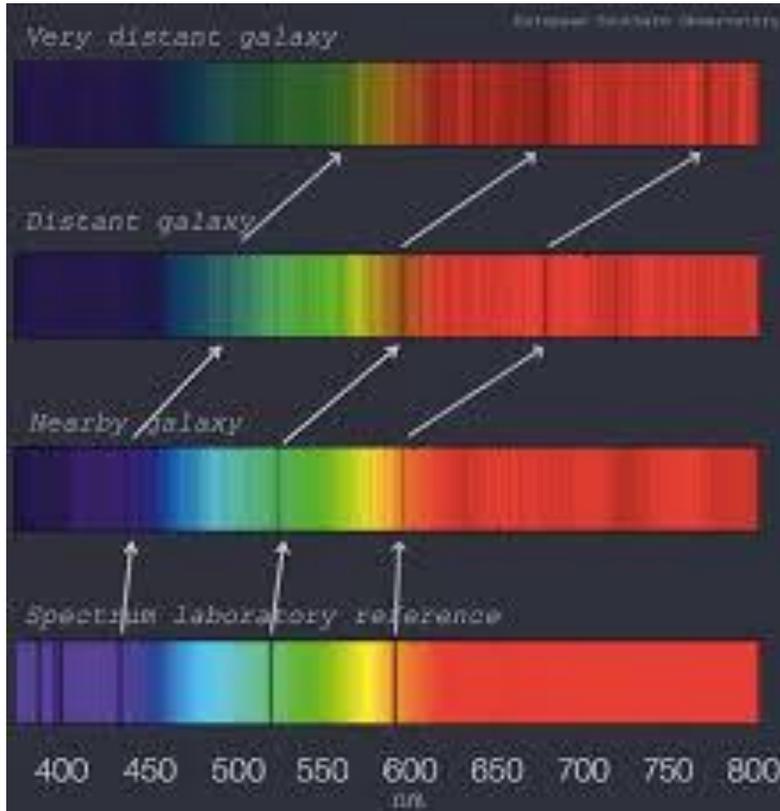


# Fondo Cósmico de Microondas (CMB)

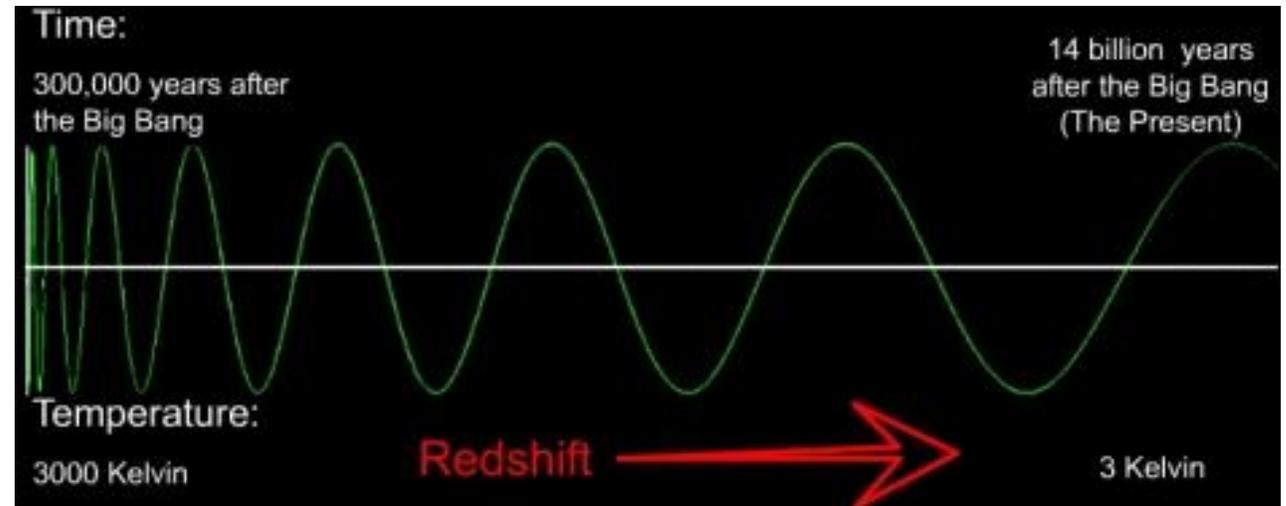


# Fondo Cósmico de Microondas (CMB)

Por redshift



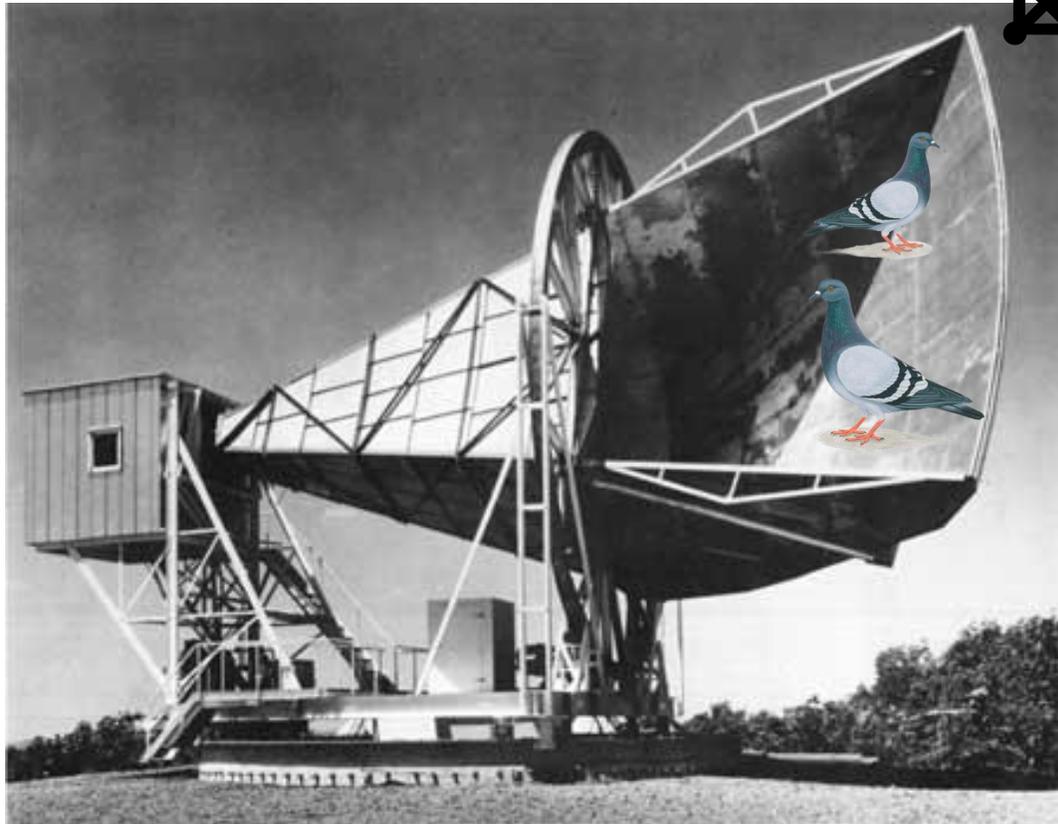
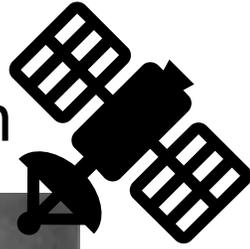
Crédito ESO



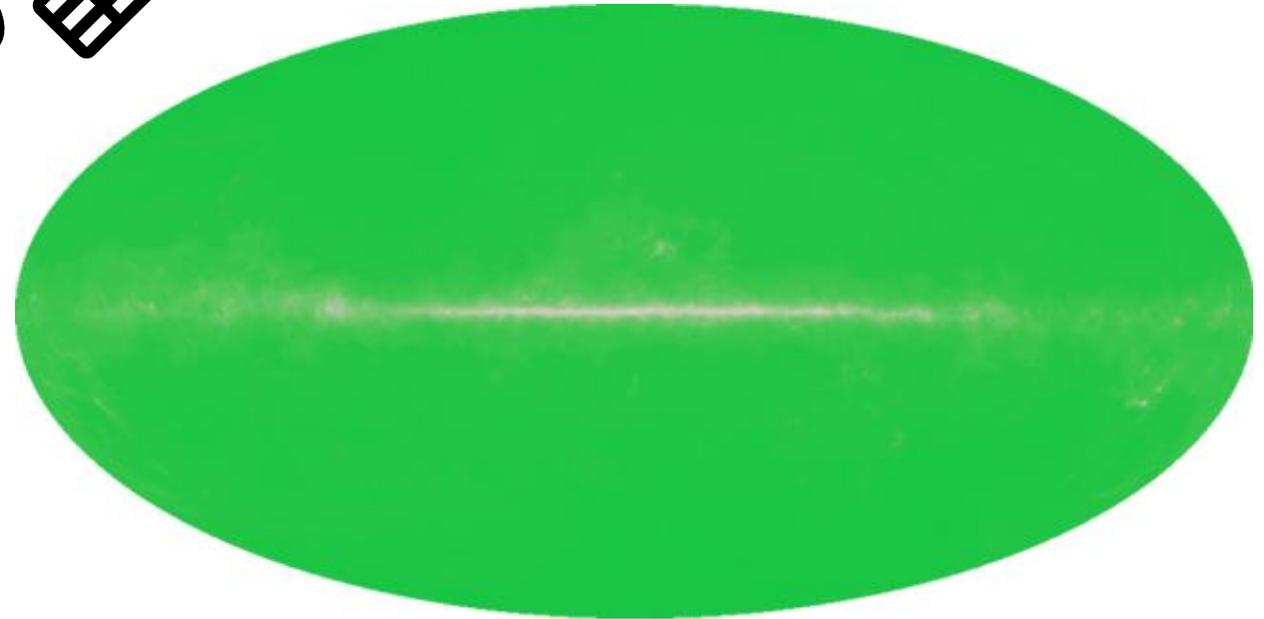
Crédito: The Universe Adventure

# Descubrimiento

- Arno Penzias y Robert Wilson



Crédito: National Park Service | Celebrate Urban Birds



Crédito: Penzias & Wilson 1965, NASA

# Descubrimiento

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## A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

Crédito: Penzias, Wilson 1965 (doi: 10.1086/148307)

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## COSMIC BLACK-BODY RADIATION\*

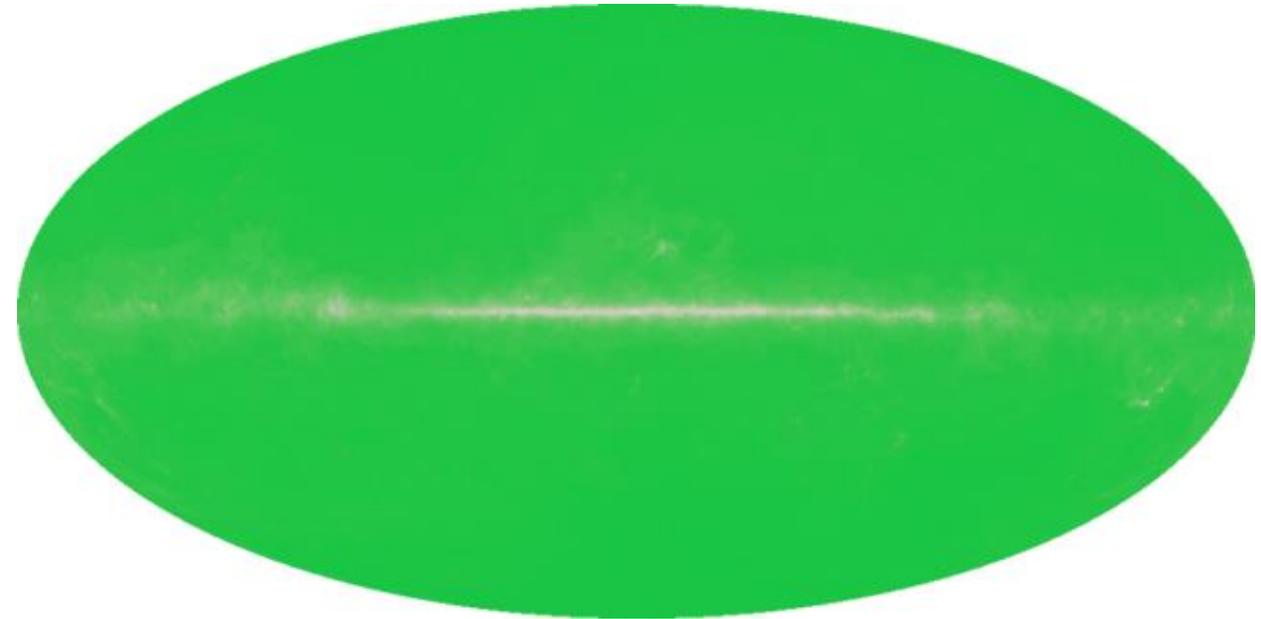
One of the basic problems of cosmology is the singularity characteristic of the familiar cosmological solutions of Einstein's field equations. Also puzzling is the presence of matter in excess over antimatter in the universe, for baryons and leptons are thought to be conserved. Thus, in the framework of conventional theory we cannot understand the origin of matter or of the universe. We can distinguish three main attempts to deal with these problems.

Crédito: Dicke et al. (doi: 10.1086/148306)



## CONCLUSIONS

While all the data are not yet in hand we propose to present here the possible conclusions to be drawn if we tentatively assume that the **measurements of Penzias and Wilson (1965) do indicate black-body radiation at 3.5° K.** We also assume that the universe can be considered to be isotropic and uniform, and that the present energy density in gravi-

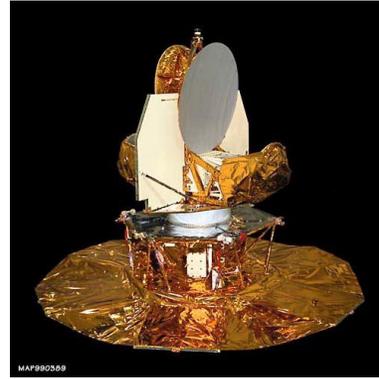


Crédito: Penzias & Wilson 1965, NASA

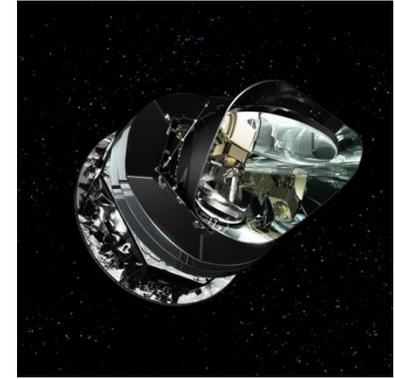
# Otras mediciones del CMB



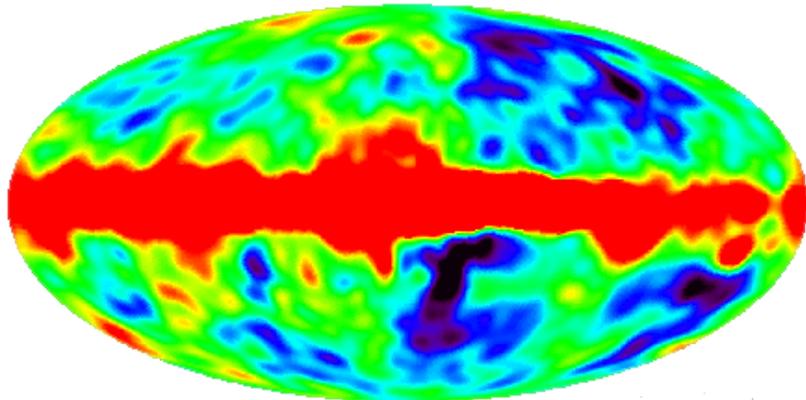
Crédito: NASA Science



Crédito: NASA

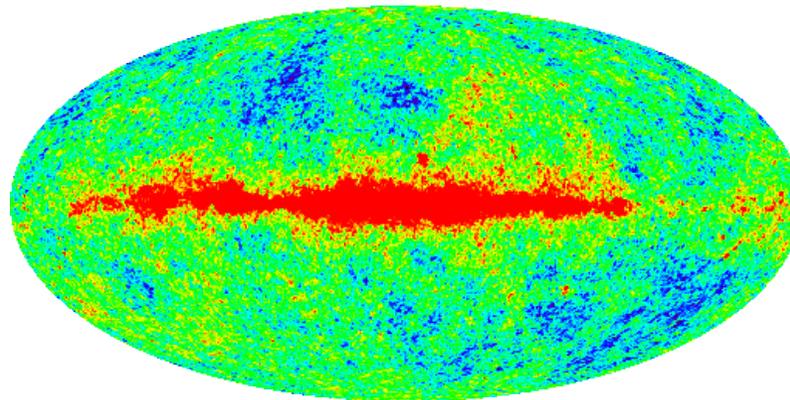


Crédito: ESA



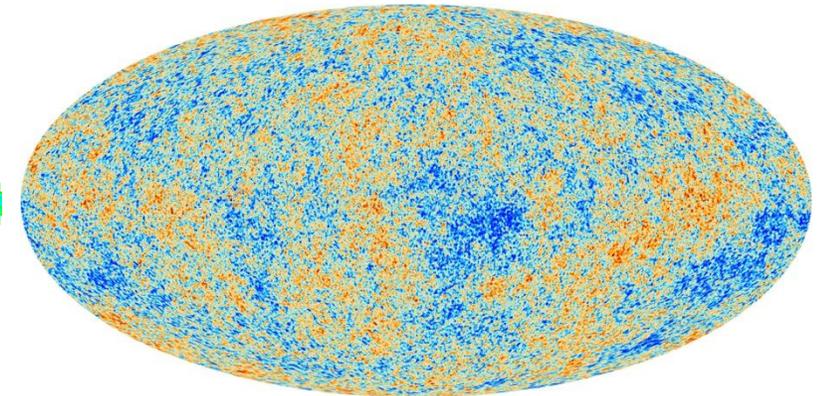
Crédito: CMB Introduction

COBE



Crédito: NASA

WMAP



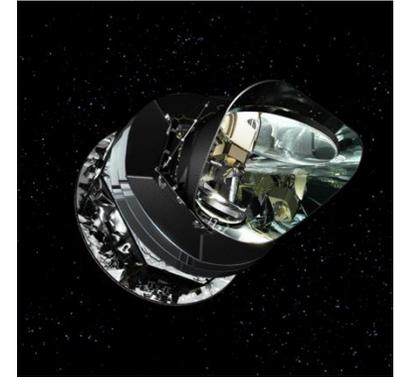
Crédito: ESA

Planck

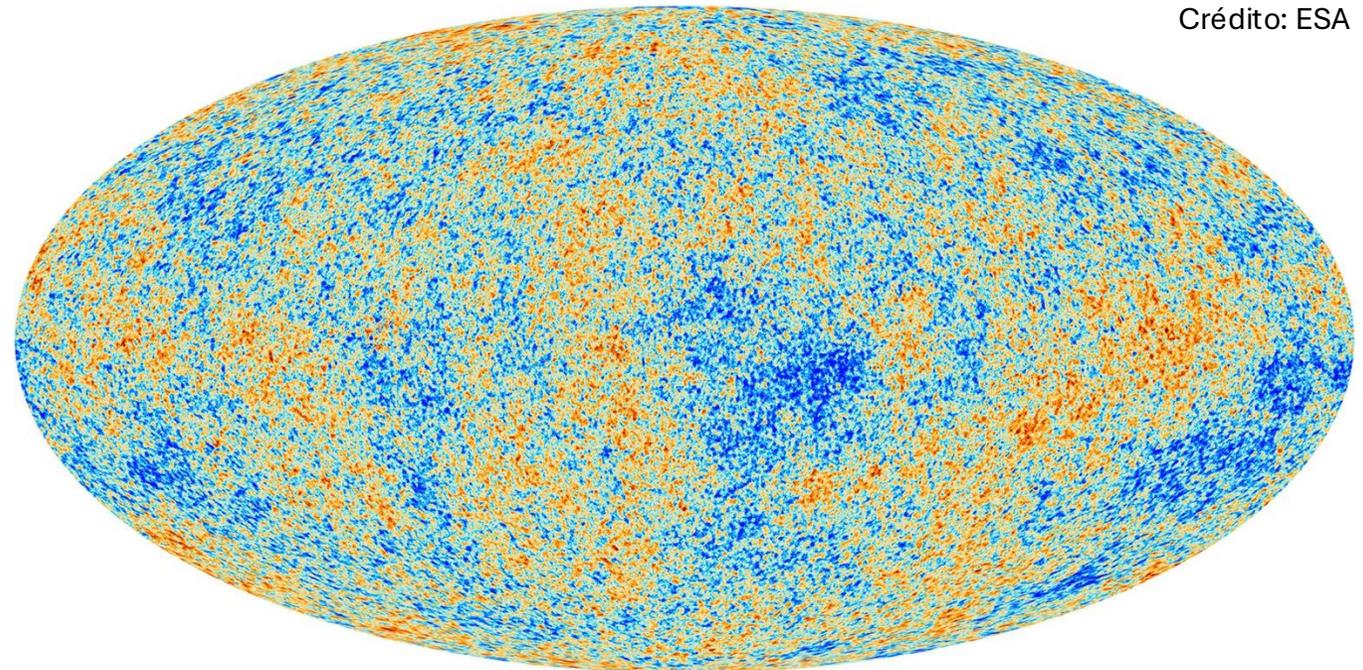
# Otras mediciones del CMB

- Radiación no homogénea
- Universo anisotrópico ( $\mu K$ )
- Predicción de la Teoría del Big Bang

Planck



Crédito: ESA

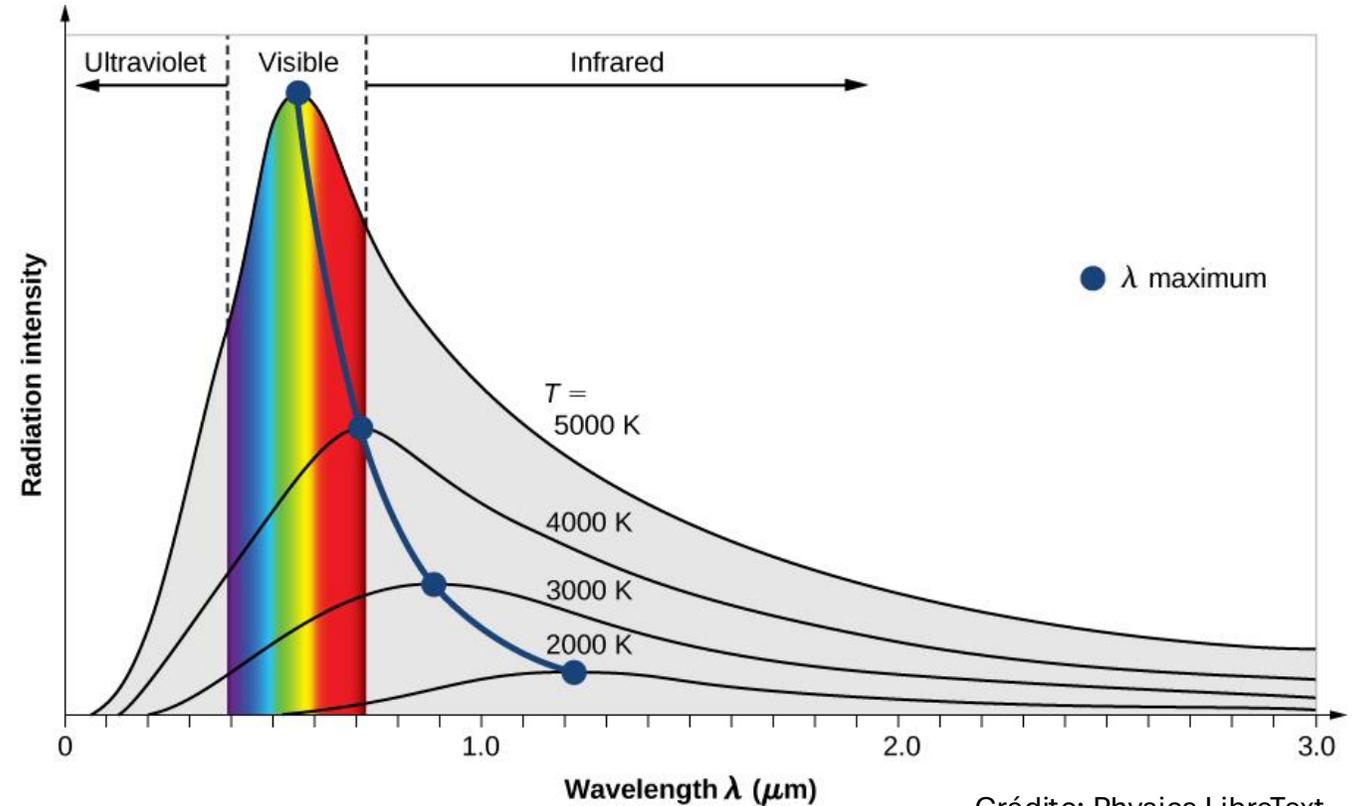


Crédito: ESA

# Radiación de Cuerpo negro

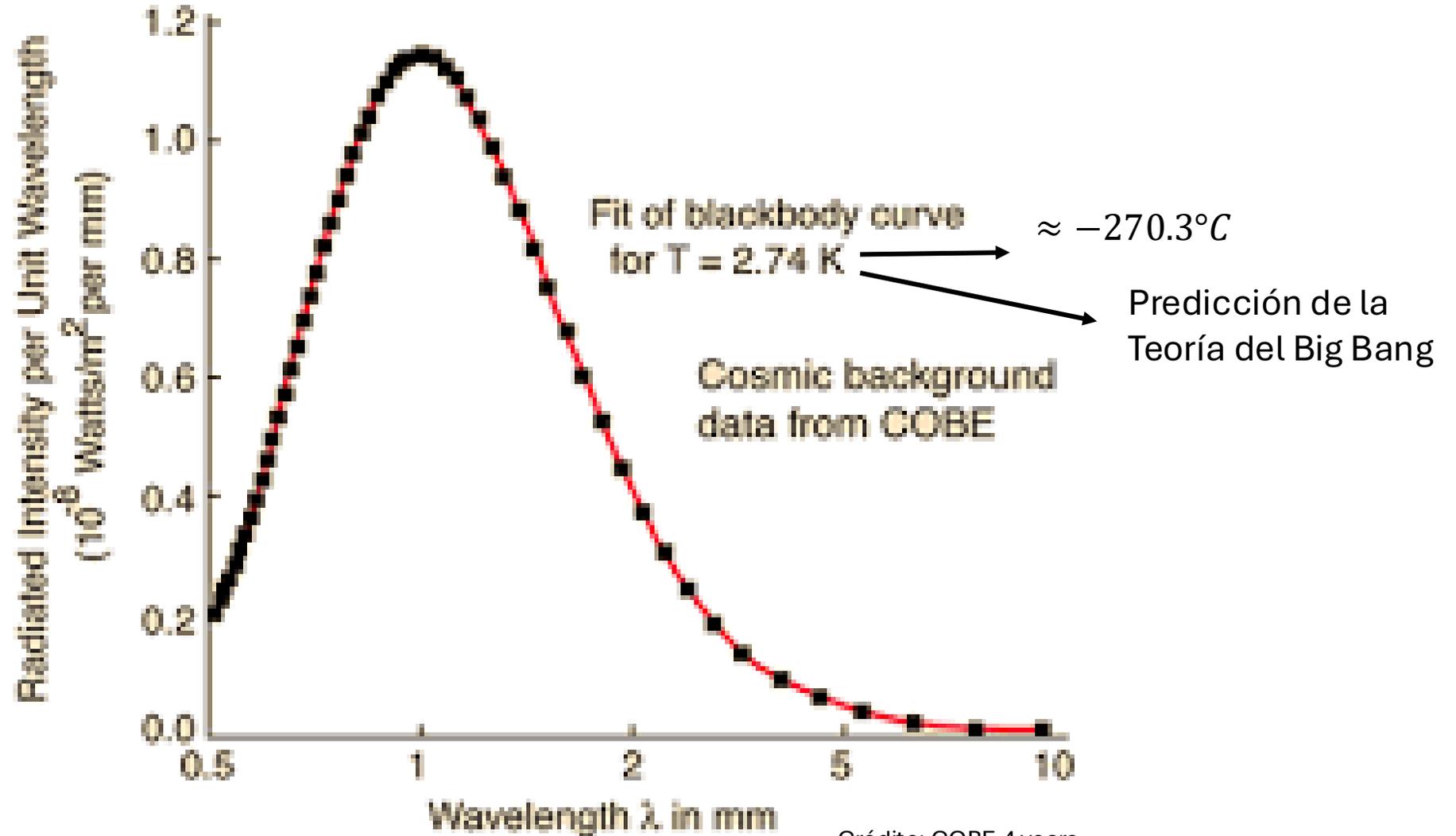
- Cualquier cuerpo con temperatura emite radiación electromagnética
- Relación entre temperatura y emisión por longitud de onda

$$I(\lambda, T) = \frac{8\pi hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda K_B T}} - 1}$$



Crédito: Physics LibreText

# Temperatura del Universo

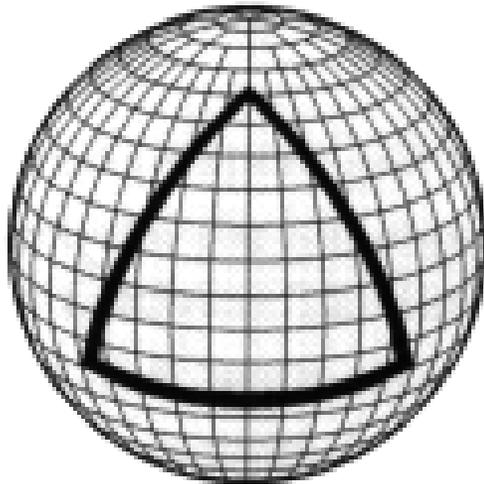


# Geometría del Universo

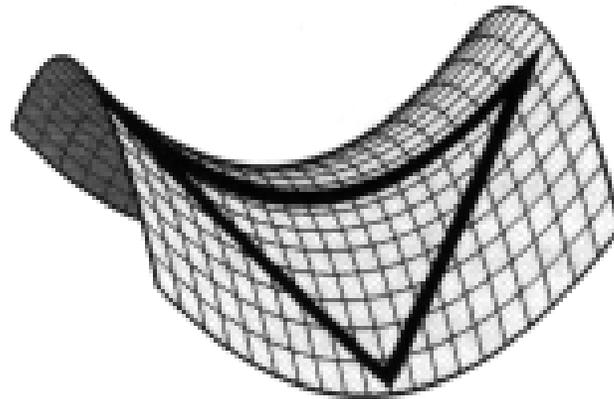
- Expansión indefinida
- Densidad baja

- Expansión finita, Big Crunch
- Densidad baja

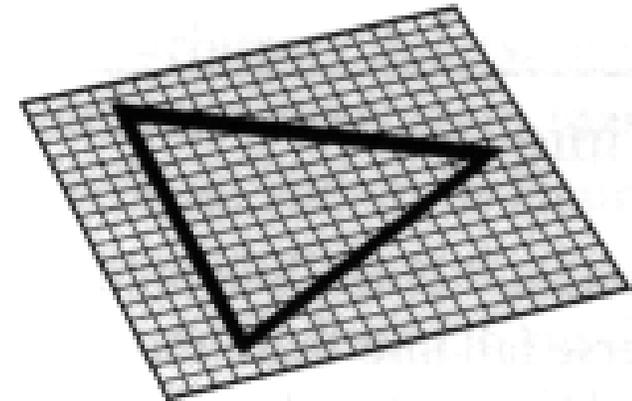
- Se expande infinitamente
- Velocidad de expansión depende de la energía oscura



**Positive Curvature**

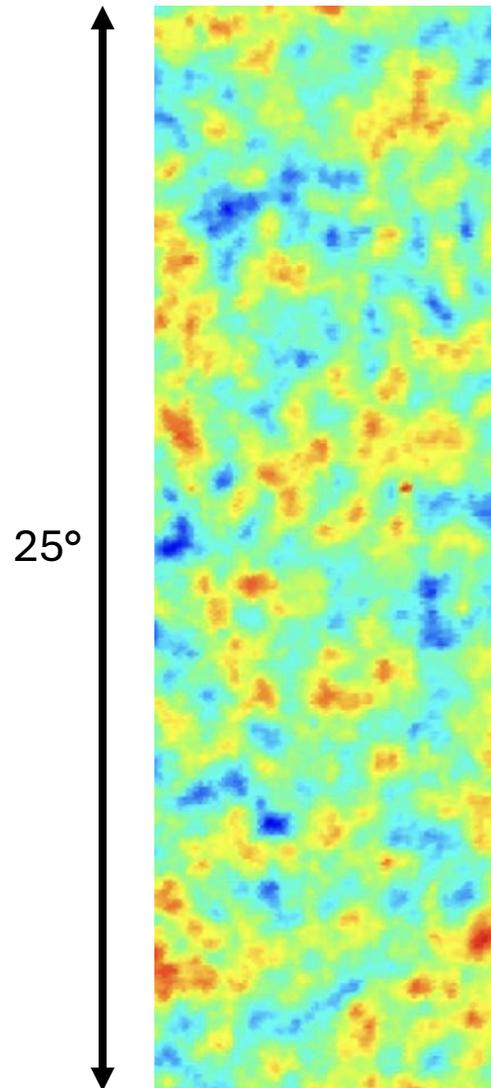


**Negative Curvature**

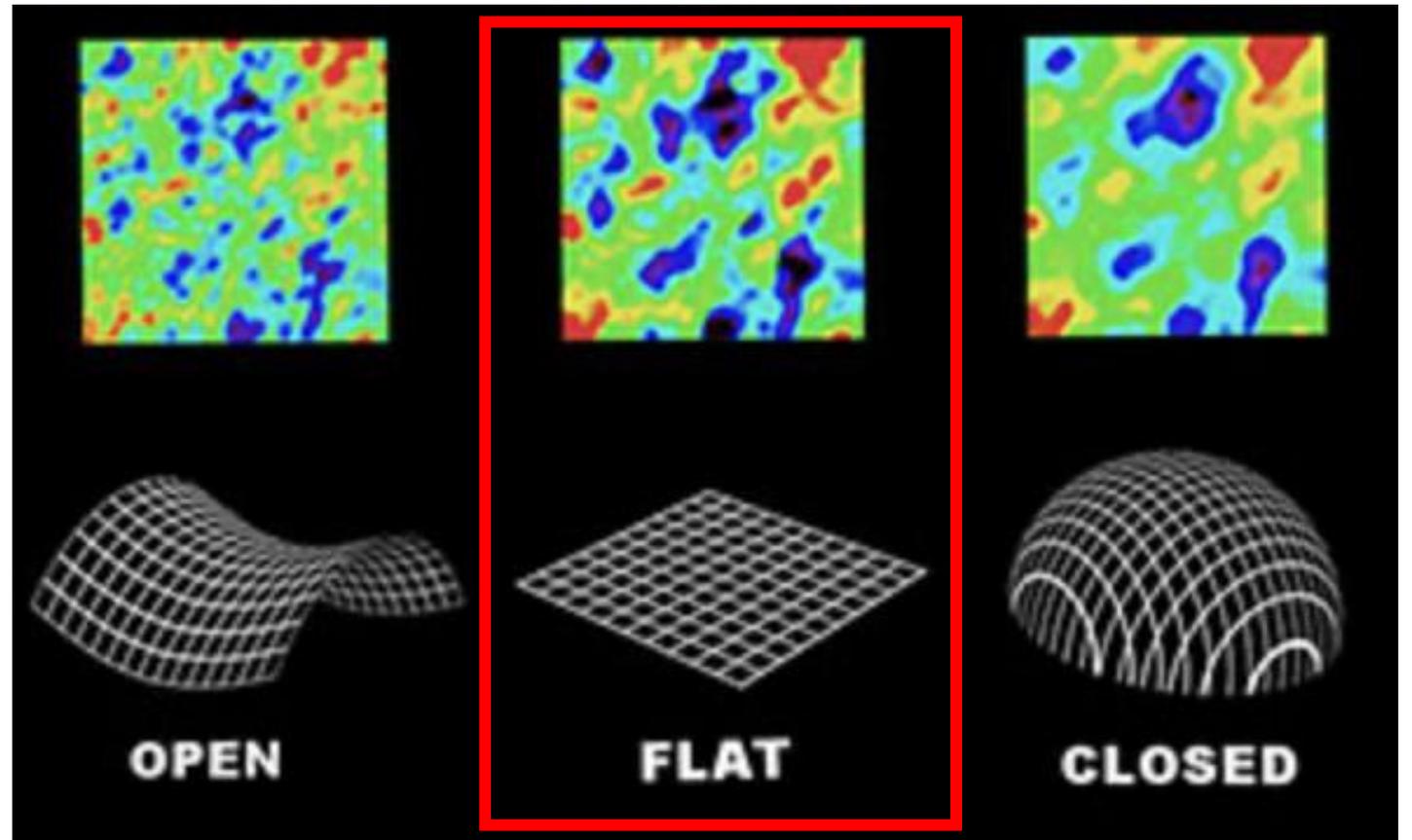


**Flat Curvature**

# Geometría del Universo

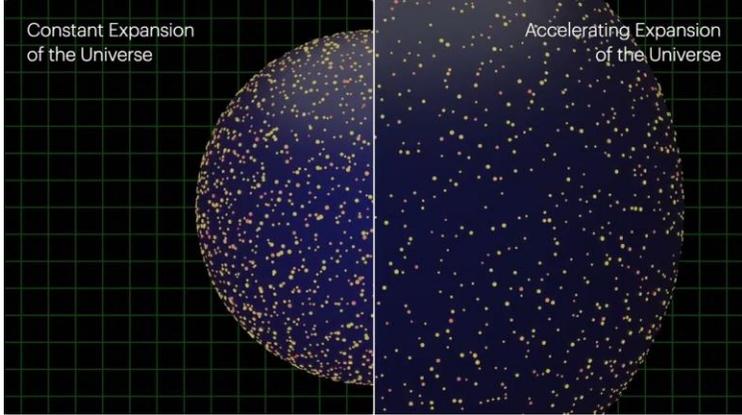


Crédito: Physics LibreText

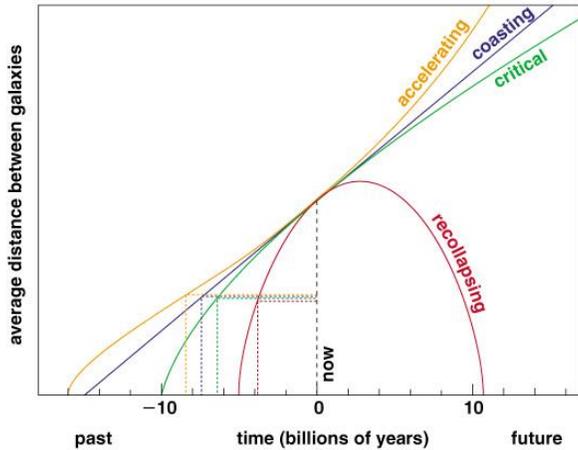


Crédito: WMAP - NASA

# Composición del Universo

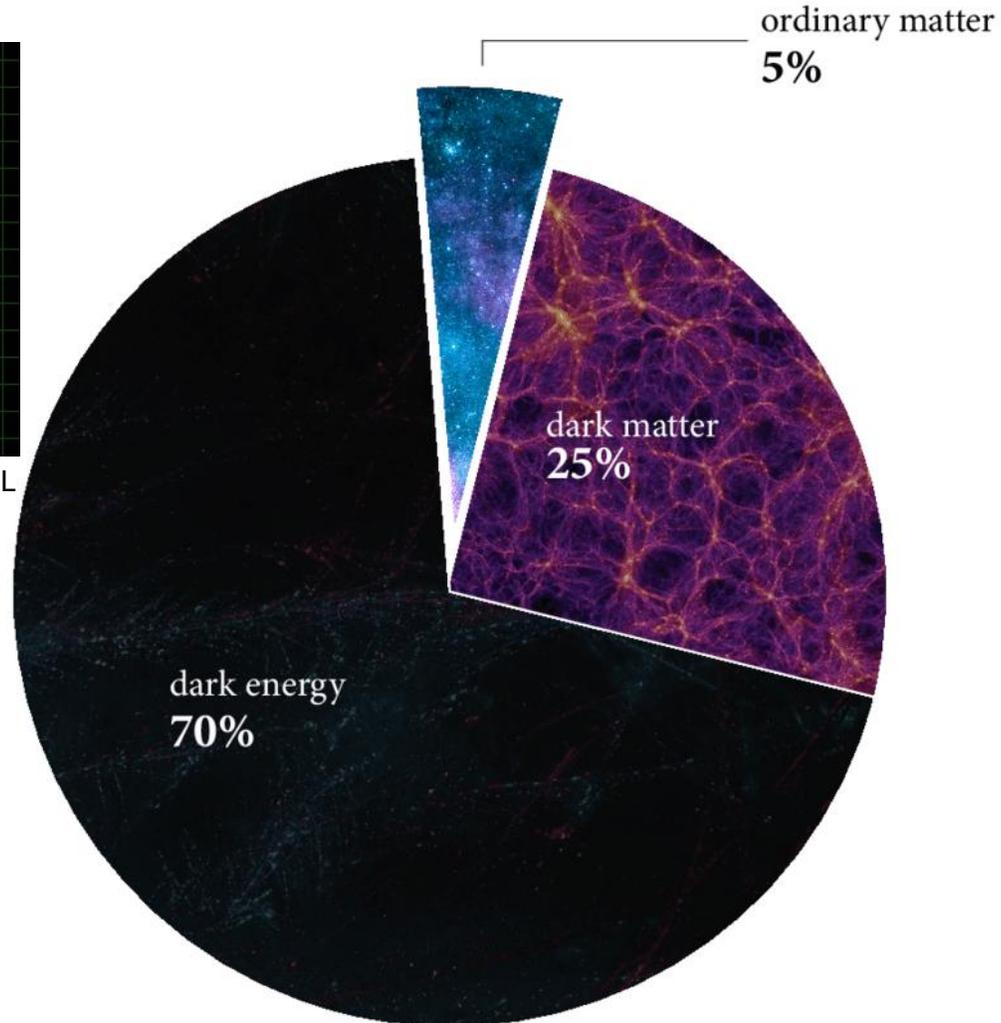


Crédito: NASA, JPL

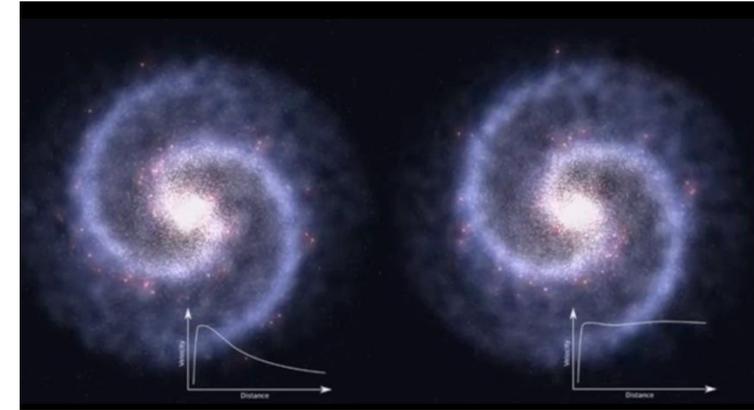


Copyright © Addison Wesley.

Crédito: U. Mass Amherst



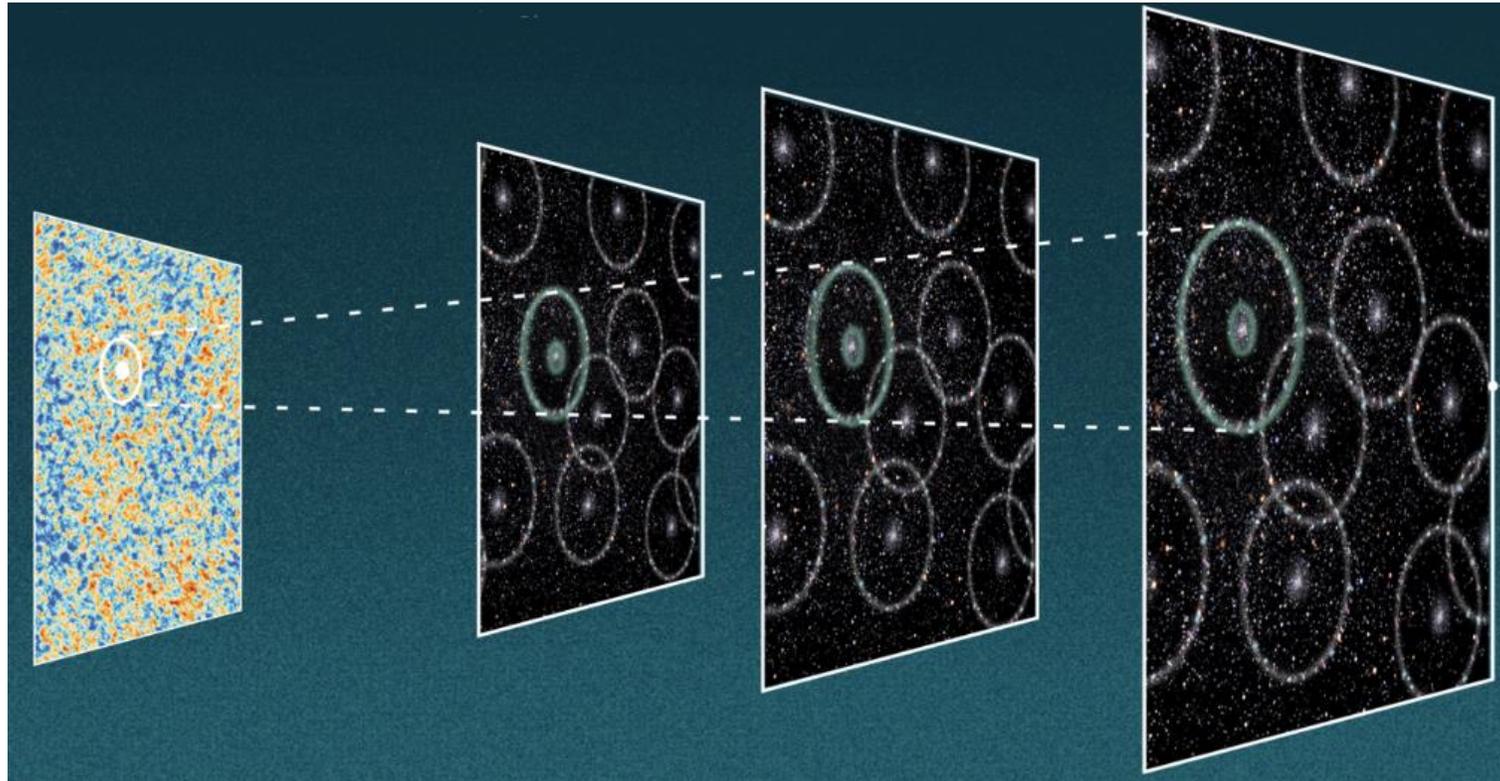
Crédito: Wolz 2022 (doi: 10.15488/12103)



Crédito: Wikipedia

# Constante de Hubble (BAO)

- Baryonic Acoustic Oscillations: ‘standard rulers’



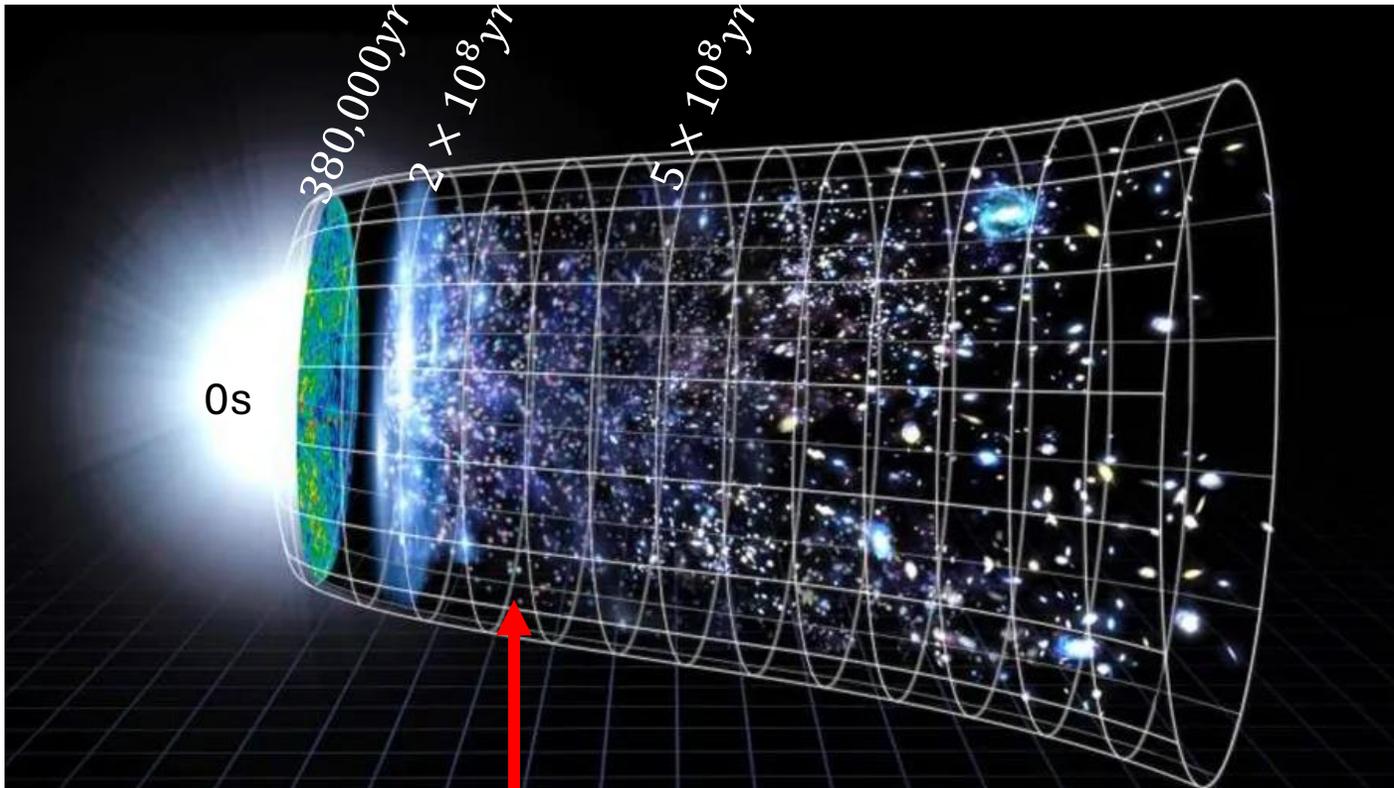
Crédito: ESA EUCLID

$$H_0 \approx 67.4 \pm 0.5 \text{ km s}^{-1} \text{ Mpc}^{-1} \text{ (Aghanim et al. 2020, Planck Collaboration)}$$

# 4. Estrellas: formación y evolución

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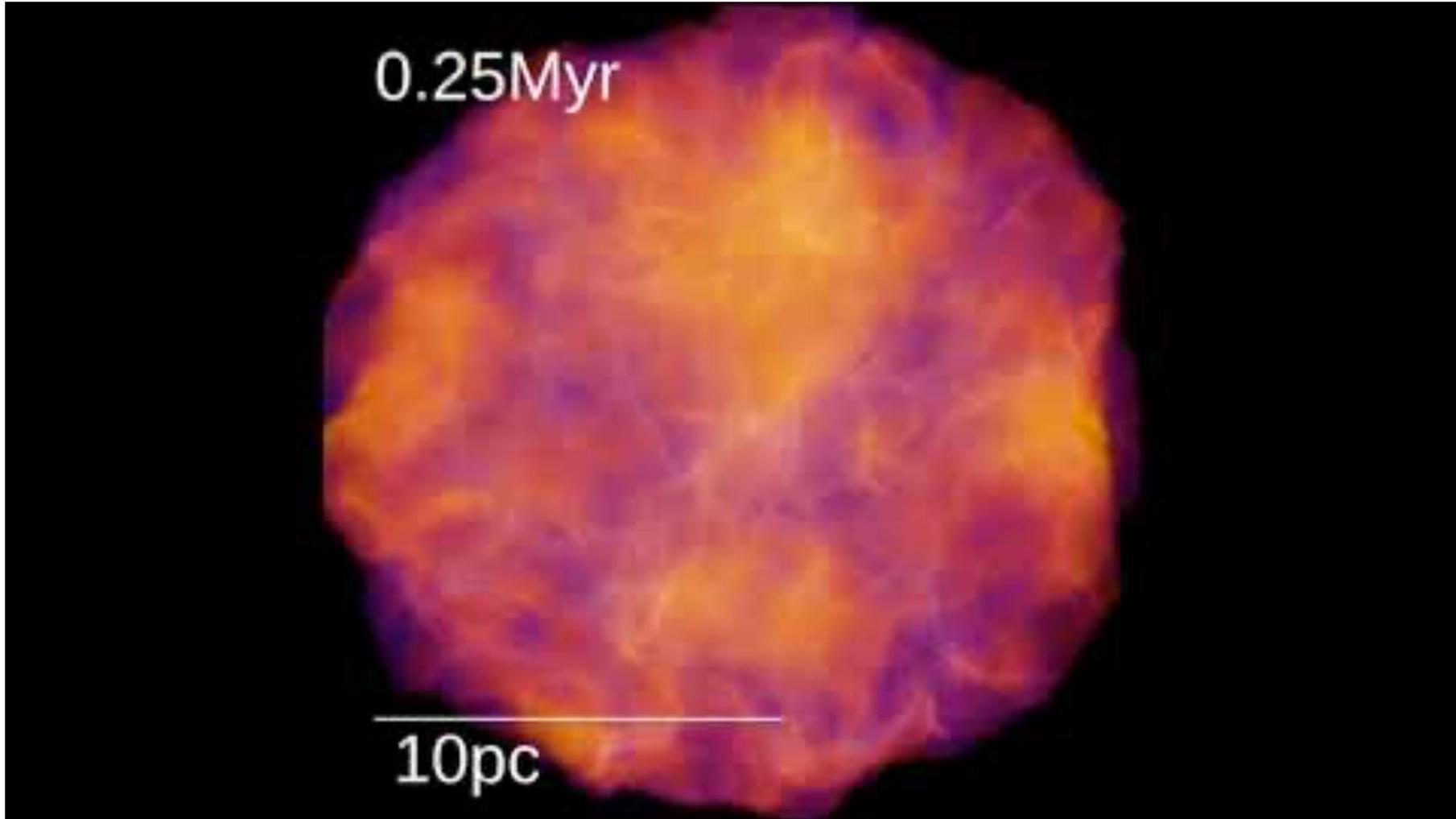
# 300-500 millones años: Primeras estrellas



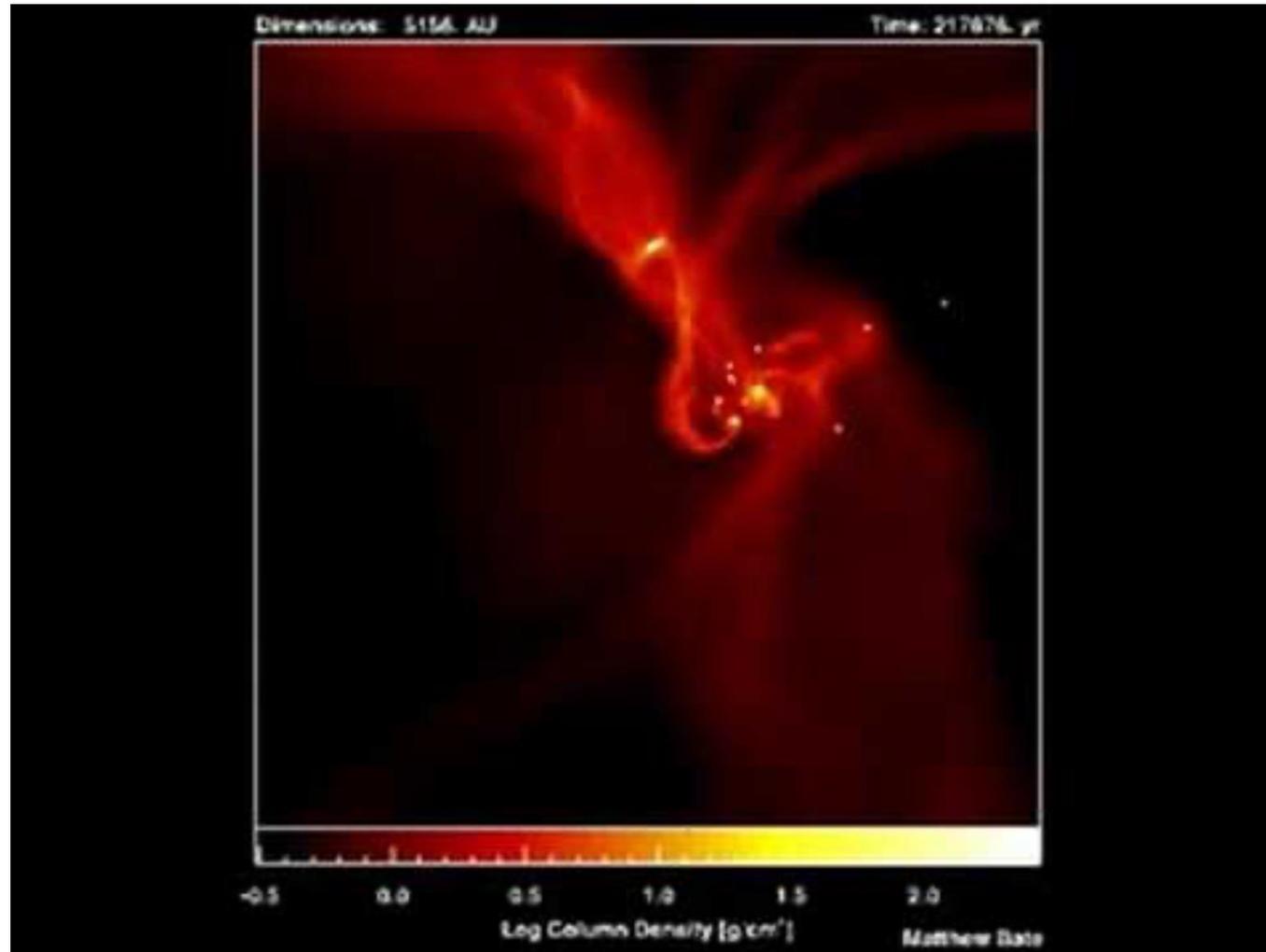
Crédito: MIT Technology Review

- Distribución de materia (BM + DM) no es uniforme
- ‘Grumos’ de gravedad atraen y acumulan masa
- Nubes de gas masivas colapsan
- Con suficiente presión → fusión!

# Formación estelar

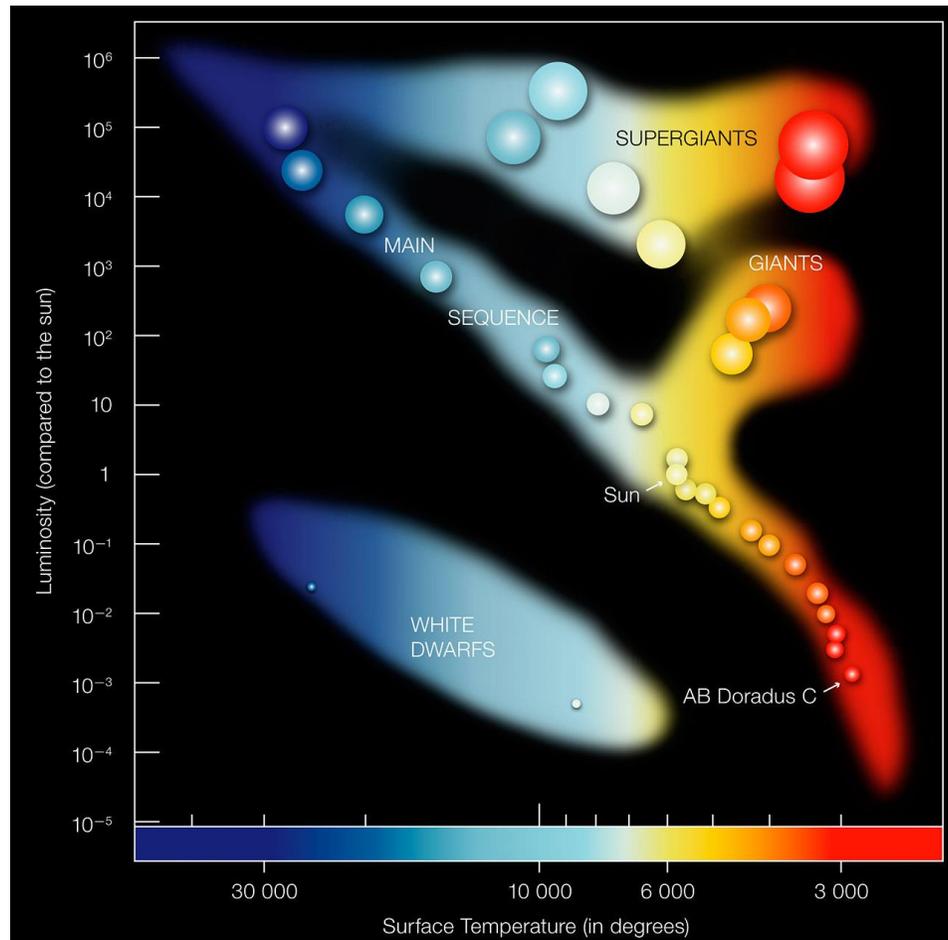


# Formación estelar

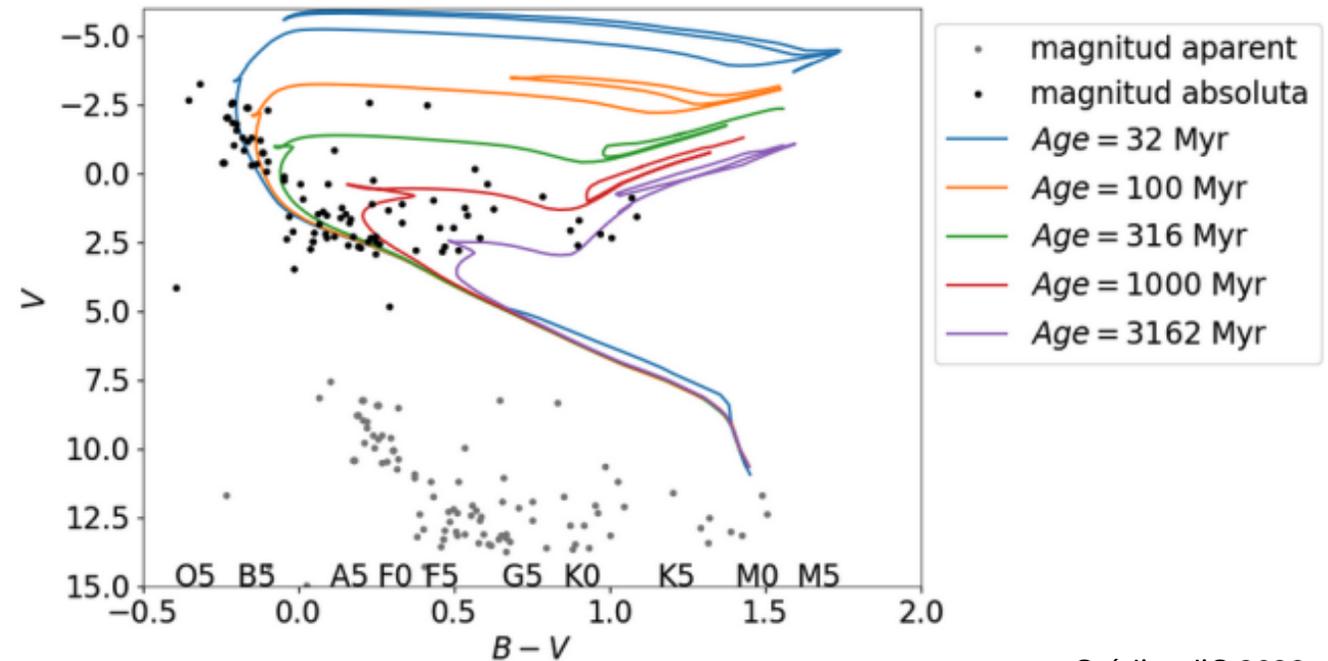


Crédito: Bate et al. 2008

# Diagrama HR (Hertzsprung-Russell)



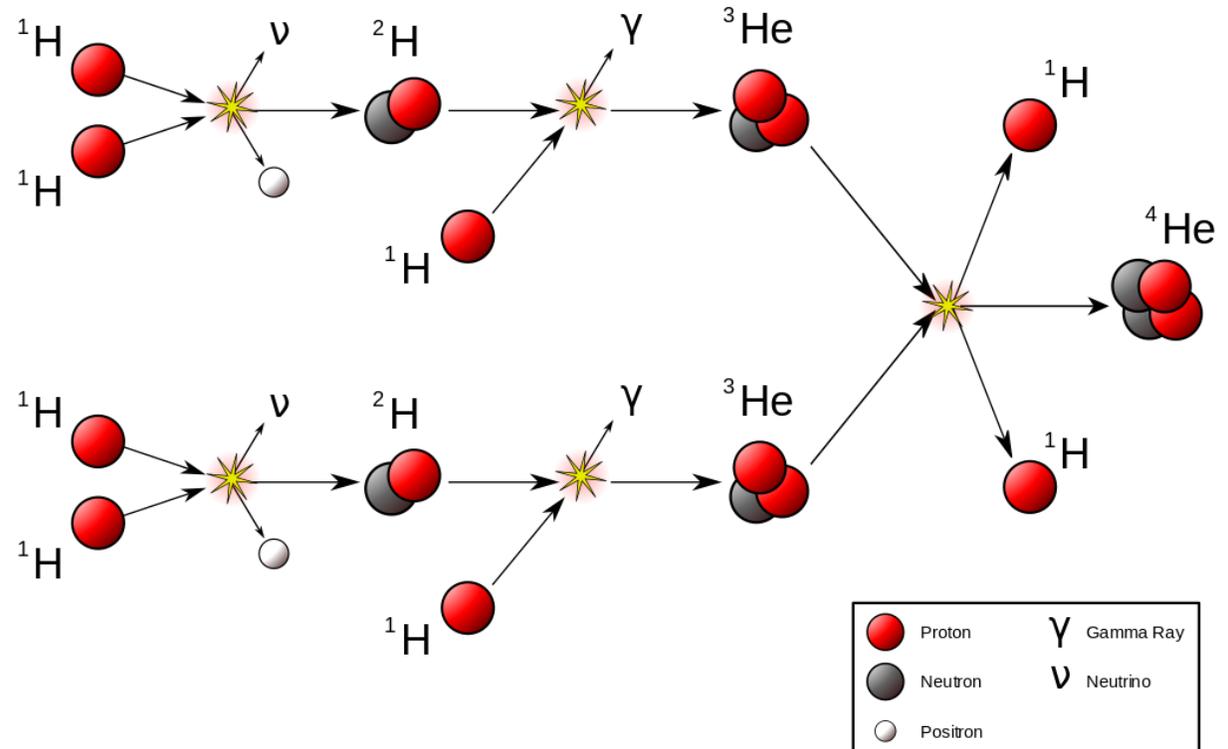
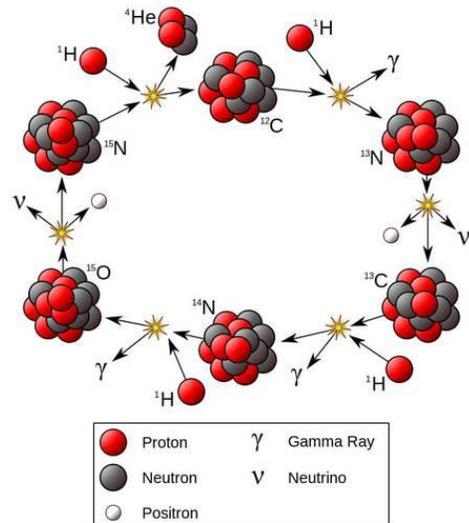
Crédito: ESO



Crédito: JiC 2023

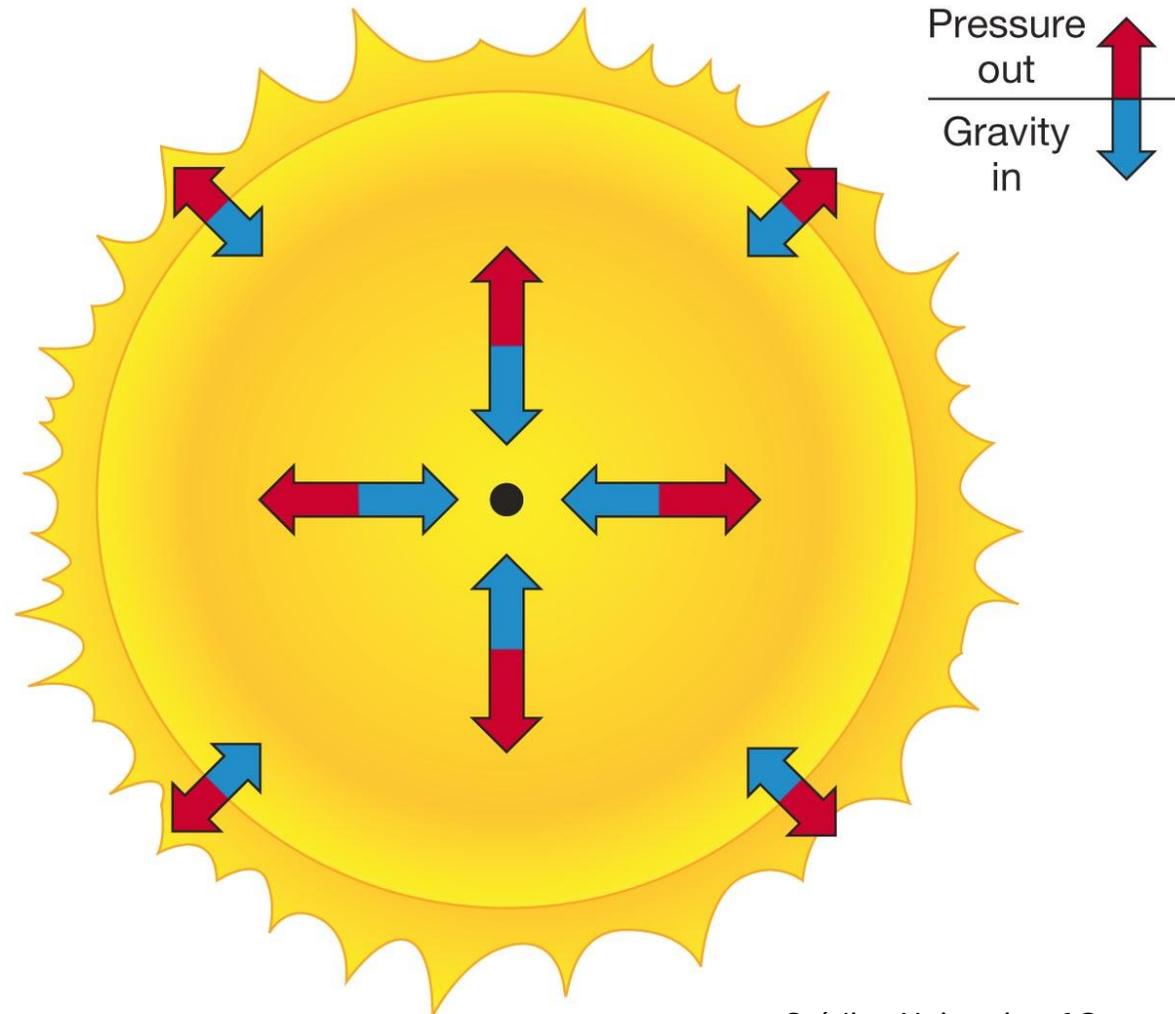
# Energía de las estrellas

- Fusión termonuclear
- Otros procesos:
  - PP chain
  - CNO Cycle
  - Triple- $\alpha$

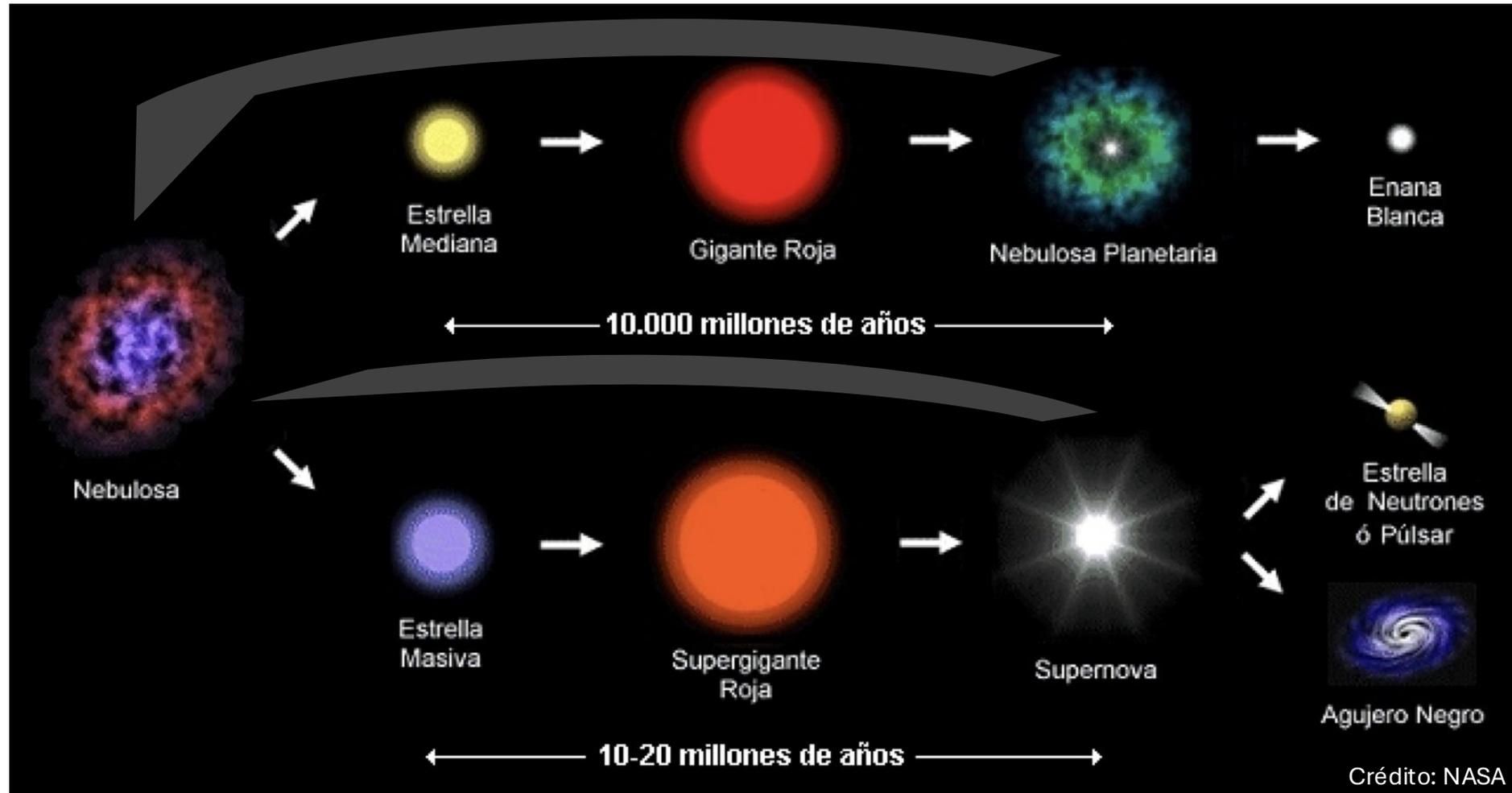


Crédito: EUROFusion

# Un ejercicio de equilibrio (hidrostático)



# Evolución estelar



$< \sim 1.4 M_{Sun}$   
Chandrasekhar  
limit

$< \sim 2.3 M_{Sun}$   
TOV-limit

# Tabla de los elementos según creación

**The Origin of the Solar System Elements**

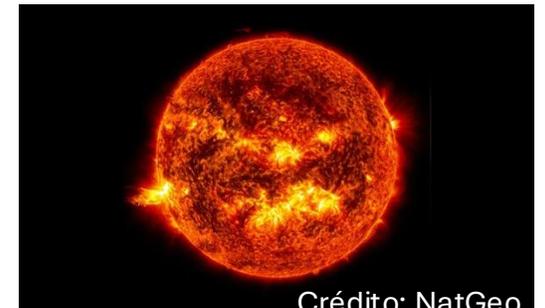
1 H	big bang fusion 					cosmic ray fission 					2 He						
3 Li	4 Be	merging neutron stars 					exploding massive stars 					5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg	dying low mass stars 					exploding white dwarfs 					13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			89 Ac	90 Th	91 Pa	92 U											

# Poblaciones de estrellas

- Metalicidad = Presencia de elementos más pesados que *He*

Población	Edad	Metalicidad
III	Primeras estrellas	Muy baja
II	Estrellas viejas	Baja
I	Estrellas Recientes	Alta

Ej. Sol: 4,500 millones de años, 1.4% metalicidad



# Galaxias y objetos masivos

Joan Alcaide Núñez – Junio 2024

Preparación Universitaria DSB

Institute of  
Space Sciences



DEUTSCHE SCHULE  
BARCELONA  
COLEGIO ALEMÁN

# Índice

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5. Galaxias: grupo local

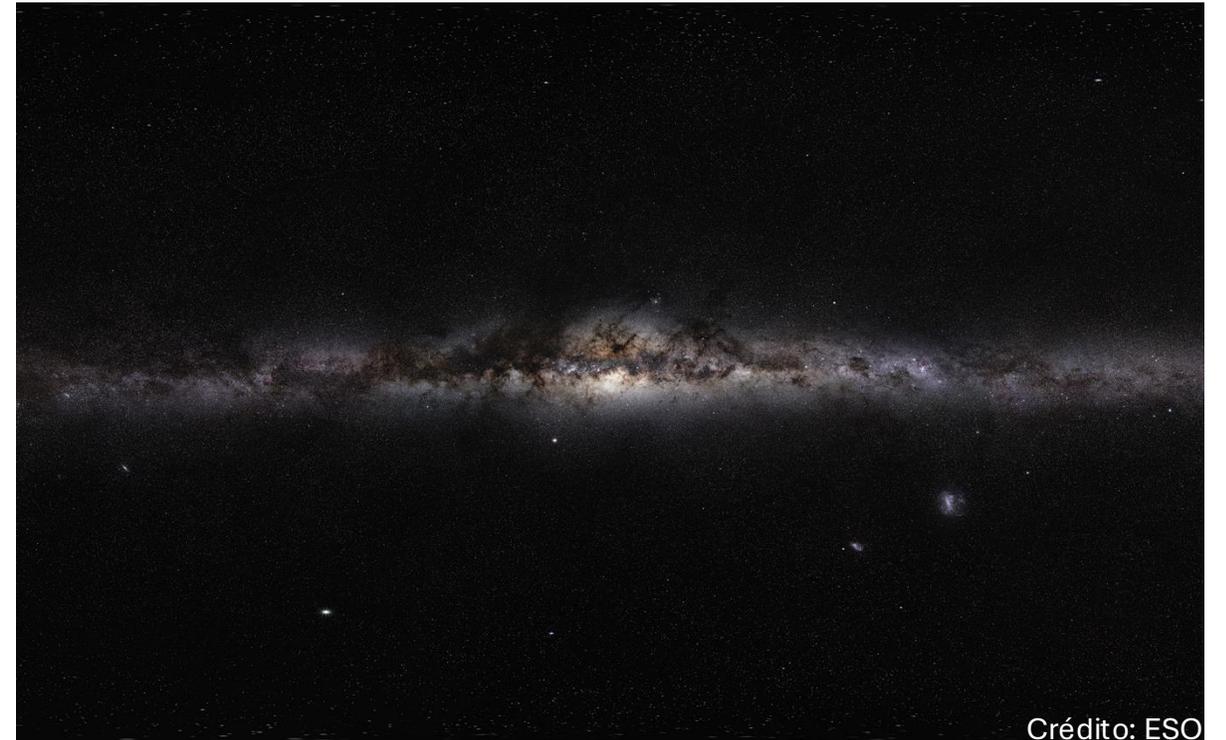
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6. Objetos masivos: estrellas de neutrones y agujeros negros

# 5. Galaxias: grupo local

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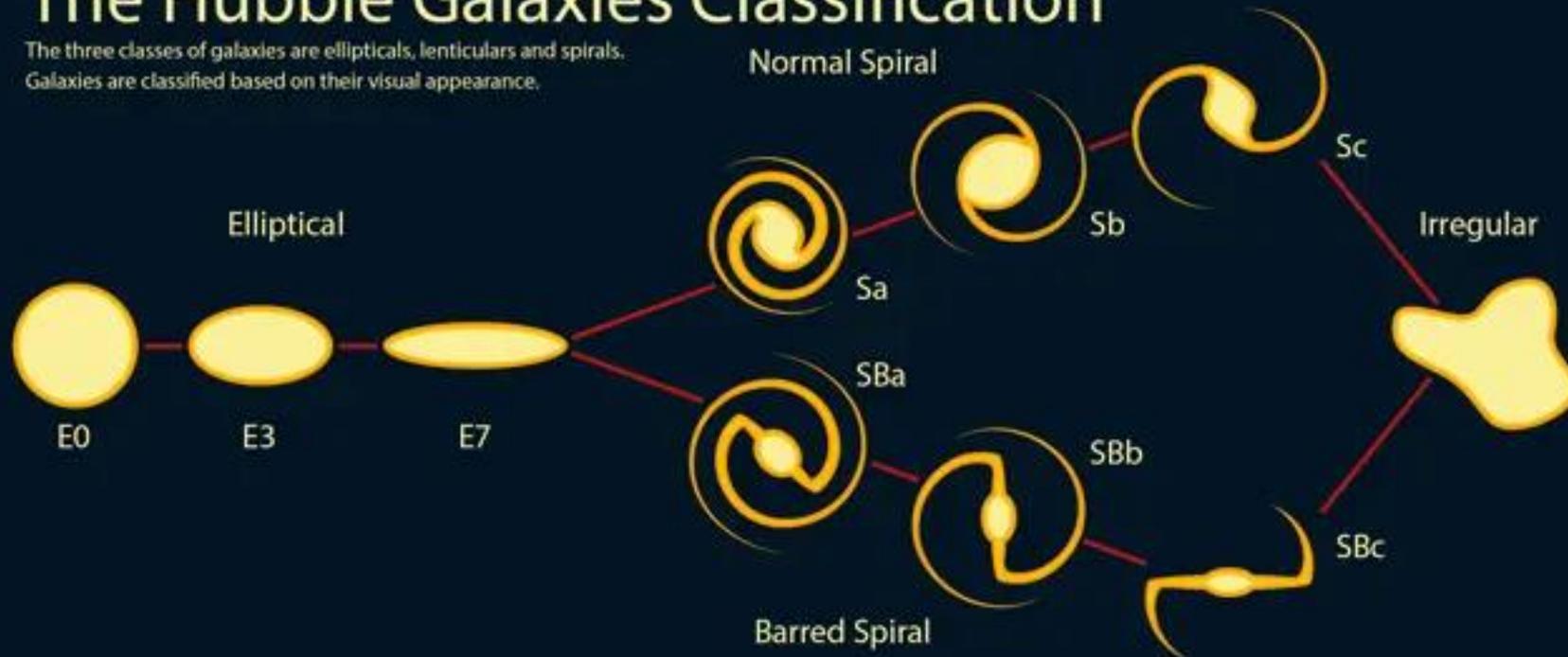
# Nuestra casa: la vía láctea



# Tipos de galáxias: clasificación de Hubble

## The Hubble Galaxies Classification

The three classes of galaxies are ellipticals, lenticulars and spirals.  
Galaxies are classified based on their visual appearance.



Crédito: Earth Now

# Ejemplos

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M87 - elíptica



Crédito: ESO

M81 - Barro espiral



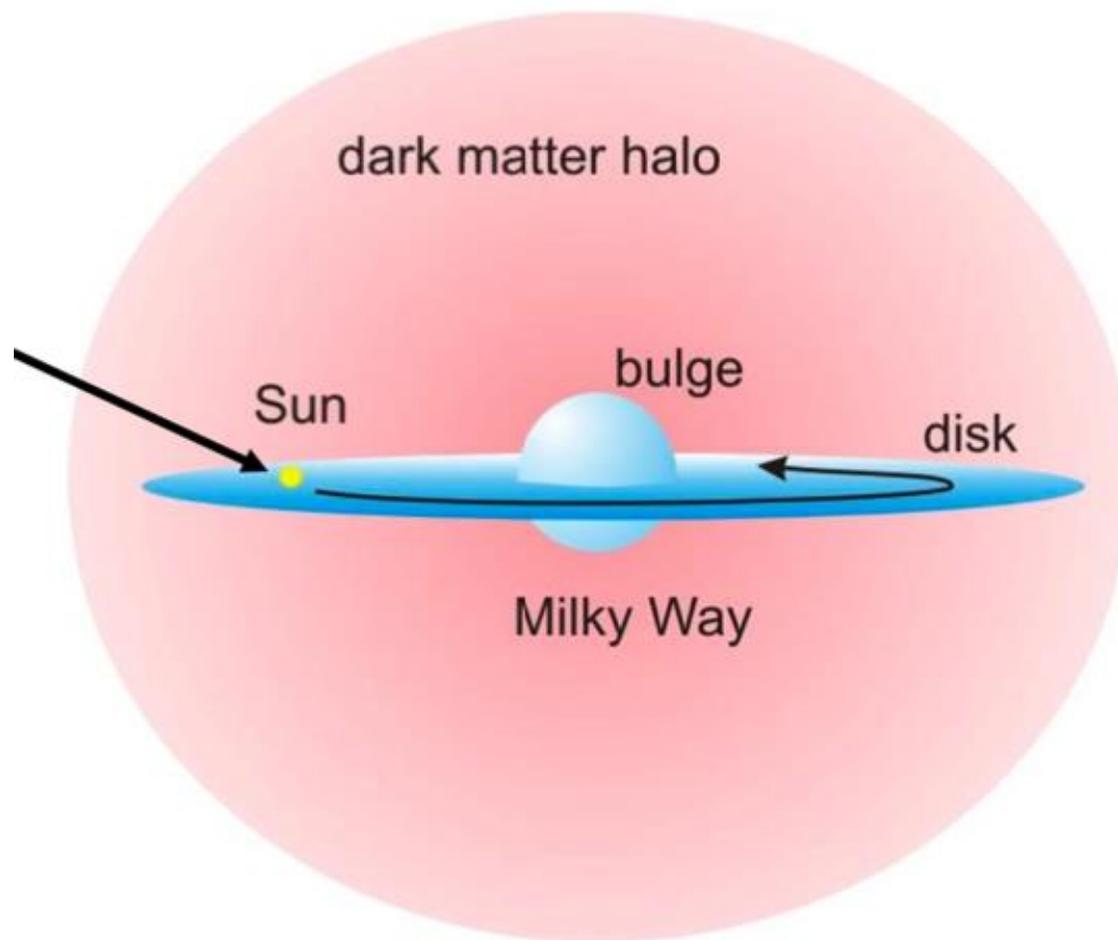
Crédito: ESO

M74 - espiral



Crédito: ESO

# Anatomía galáctica

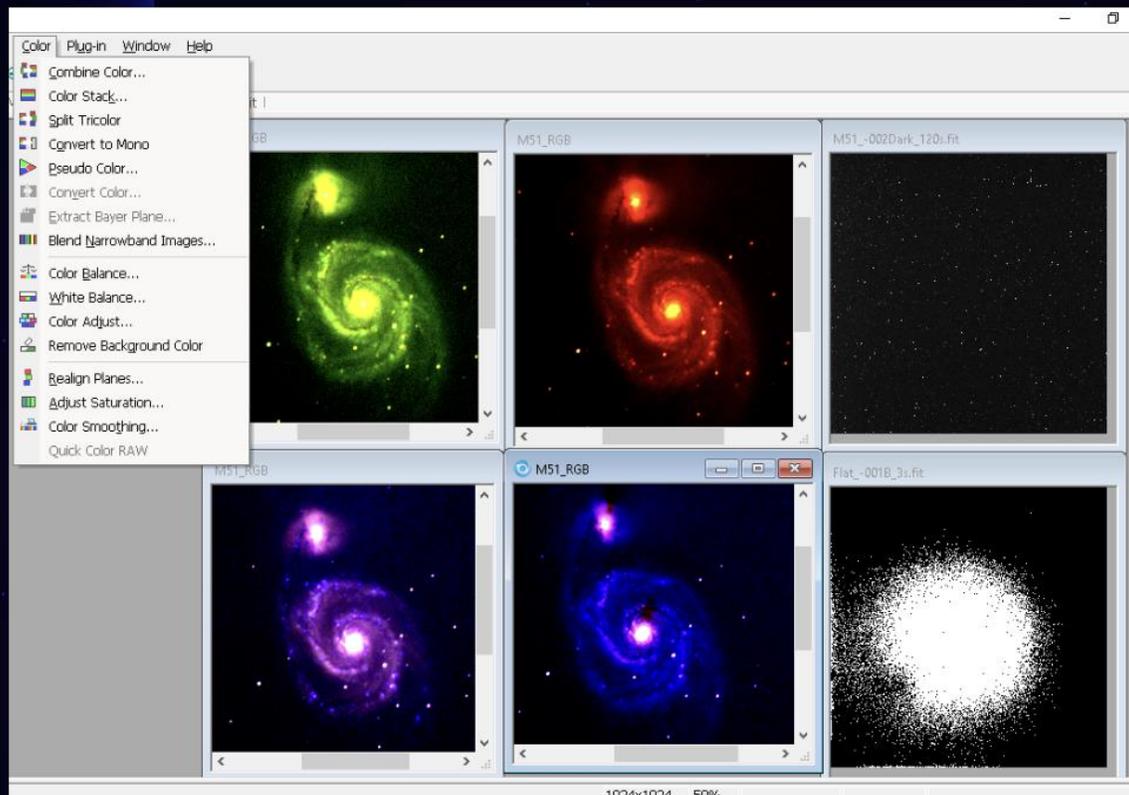




# Anatomía galáctica

# Colorines

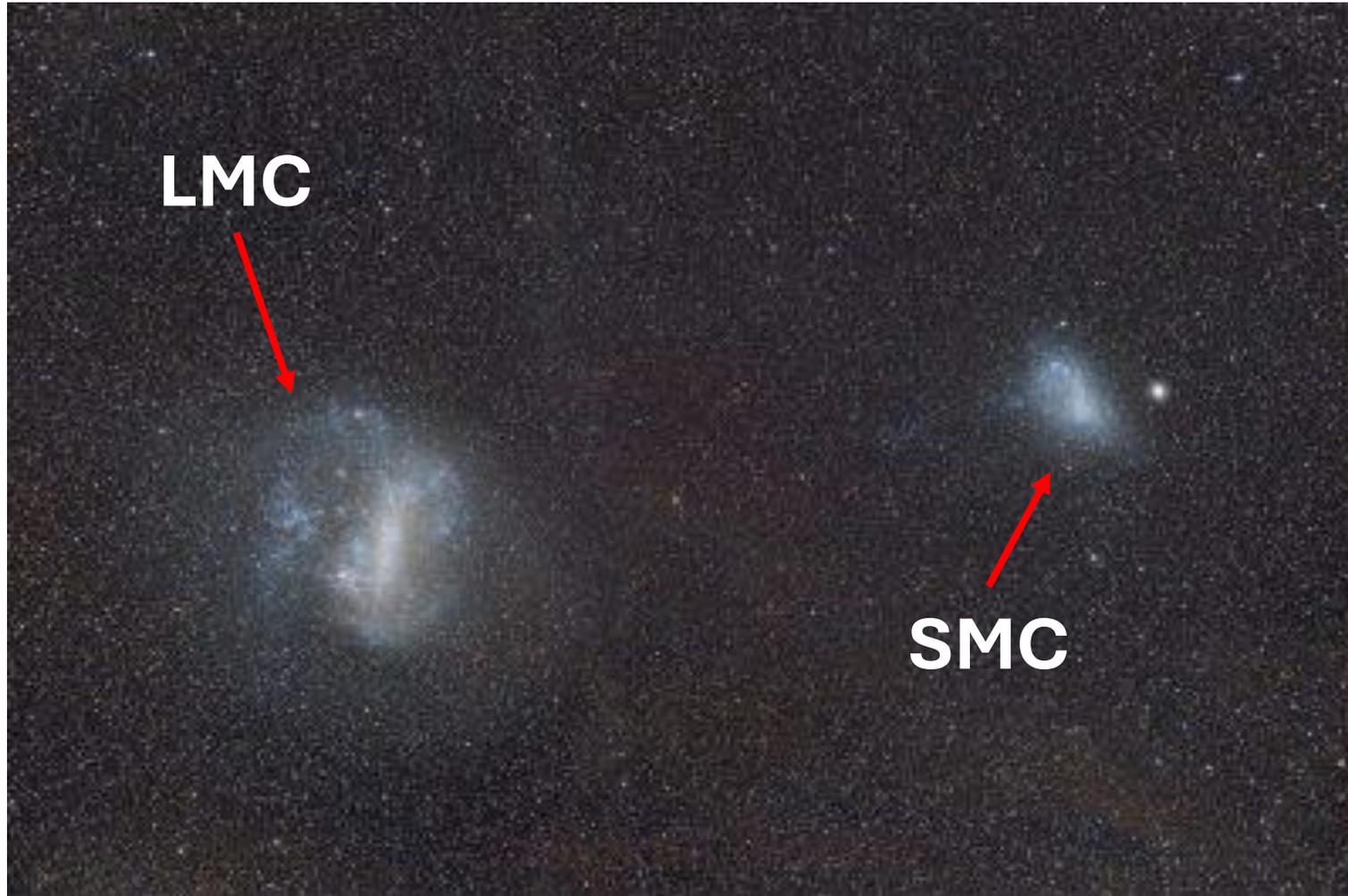
## Filtres, calibració i alineació



M51: galàxia remolí

Crèdit: JiC 2023

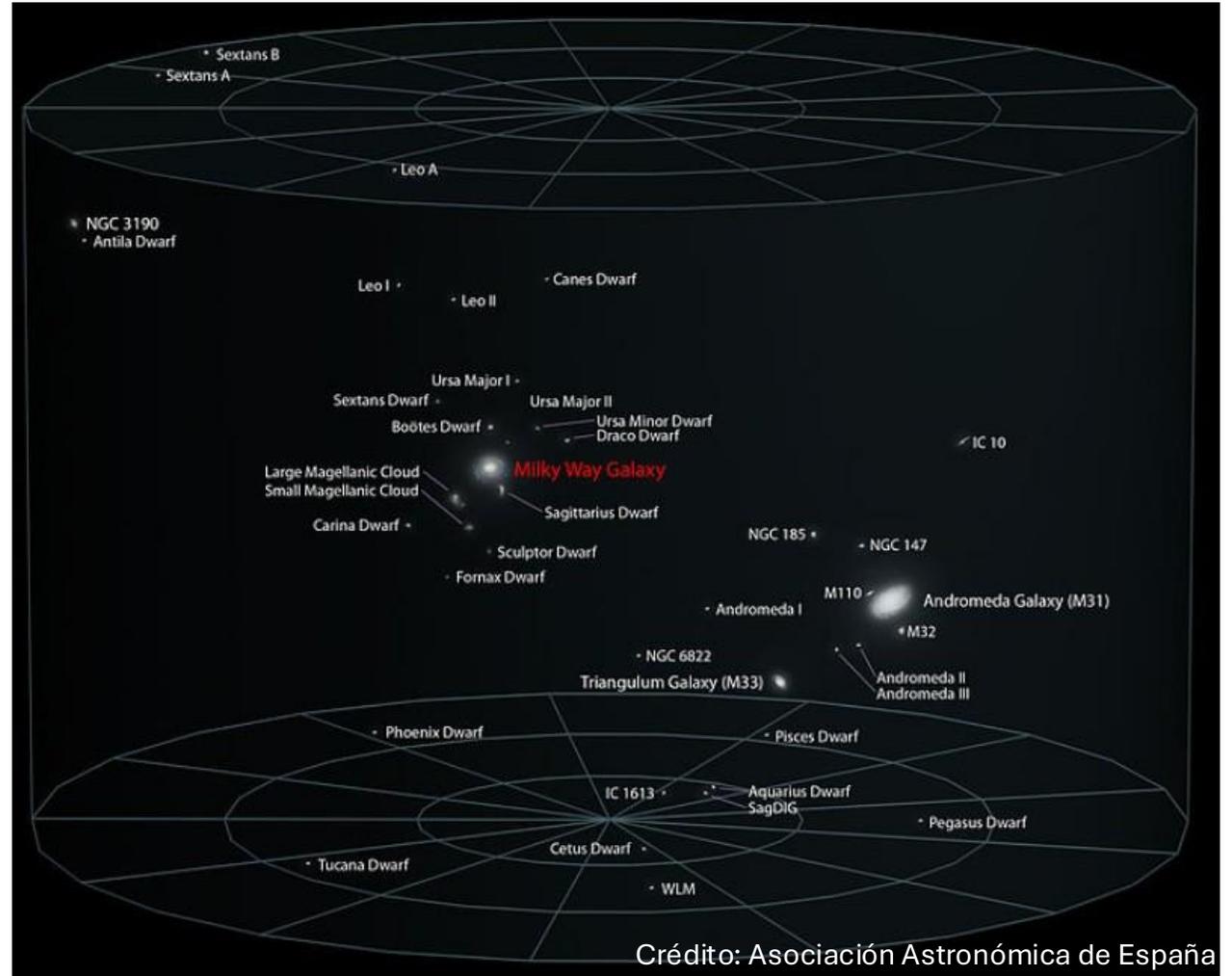
# Galaxias satélites (más importantes)



Crédito: Earth Sky

# Definición grupo local

- Conjunto de galaxias en el que se encuentra la Vía Láctea
- Abarca 5 millones de años luz
- Dominado por tres galaxias espirales
- Alrededor de 36 galaxias



# Grupo local de galaxias ( $5 \times 10^6$ ly)

Andrómeda (M31)



Crédito: ESA/Hubble

Triangulum (M33)

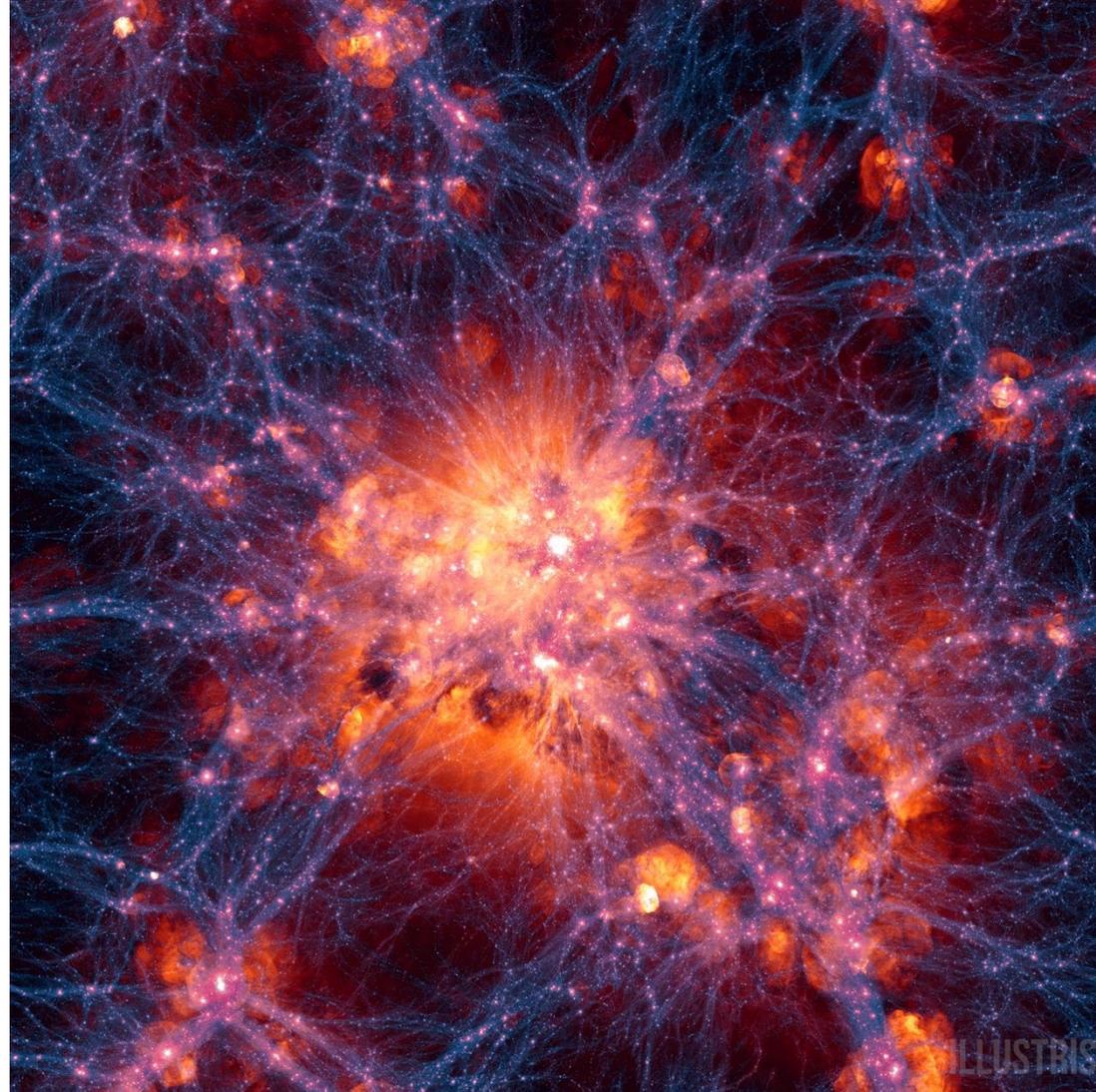


Crédito: ESO

# Nuestro lugar en el Universo

- [Simulación](#)

# Distribución de la materia

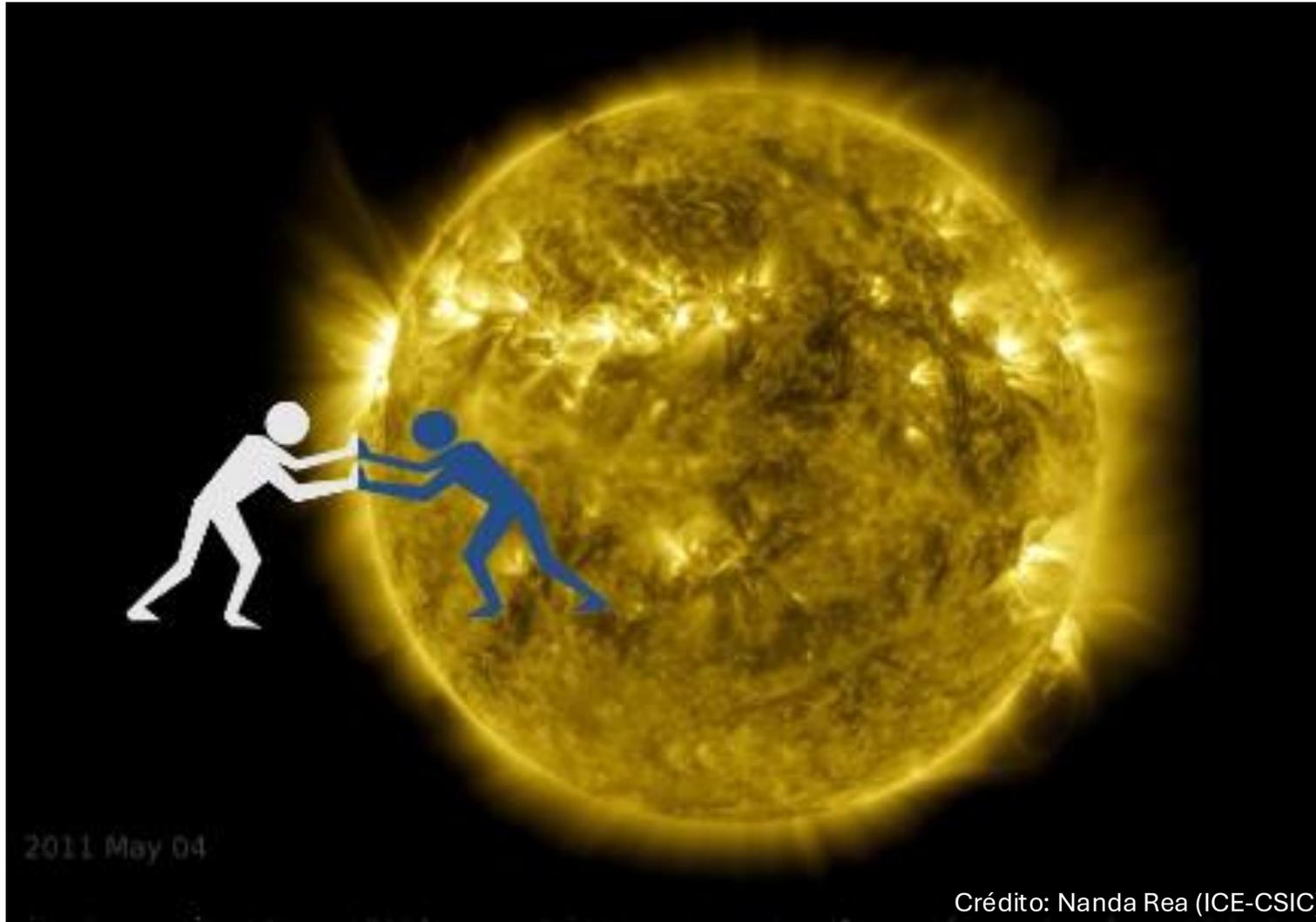


Crédito: Illustris Project (simulation)

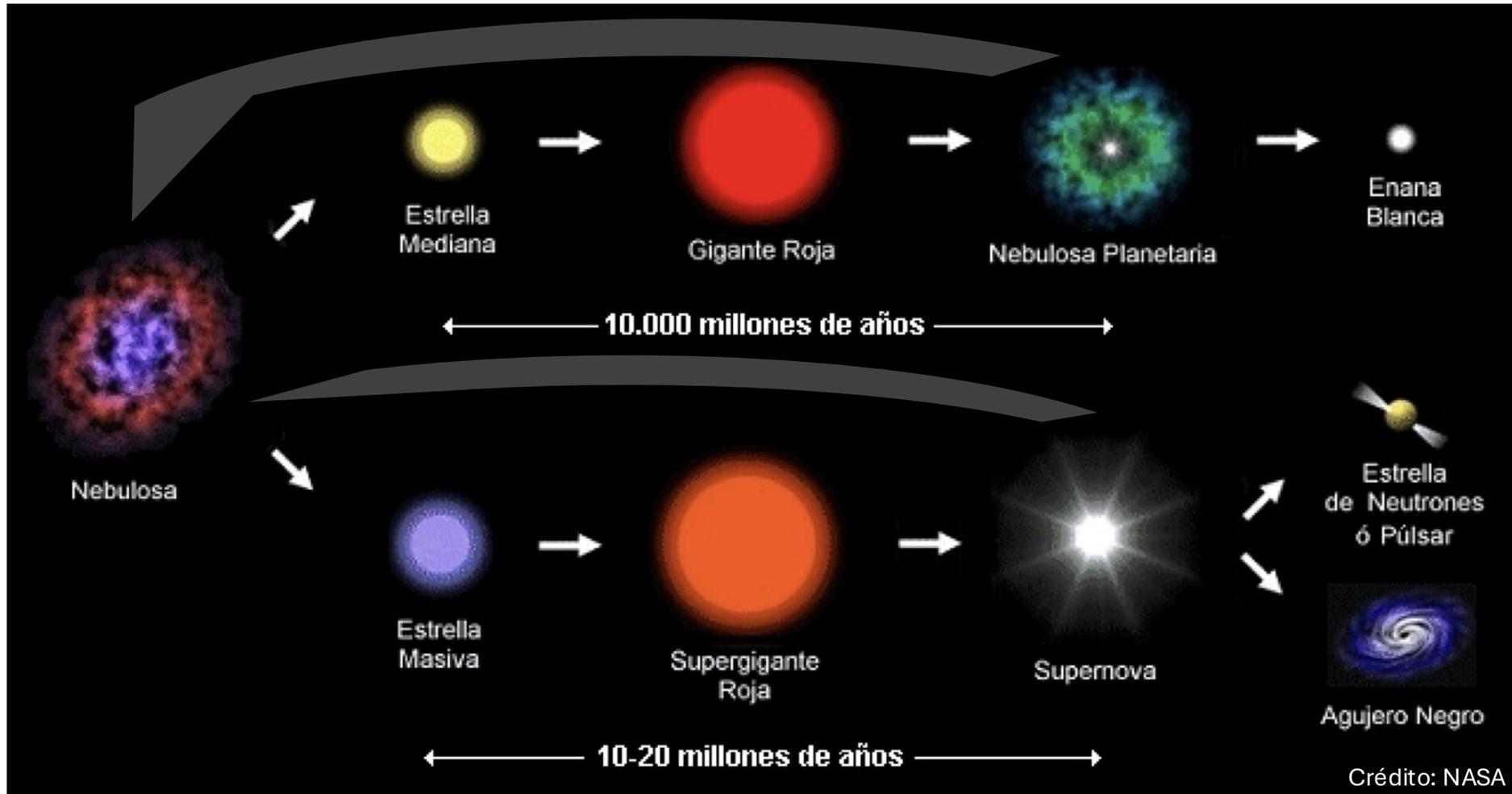
# 6. Objetos masivos

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# Repaso estrellas



# Repaso evolución estelar



$< \sim 1.4 M_{Sun}$   
Chandrasekhar  
limit

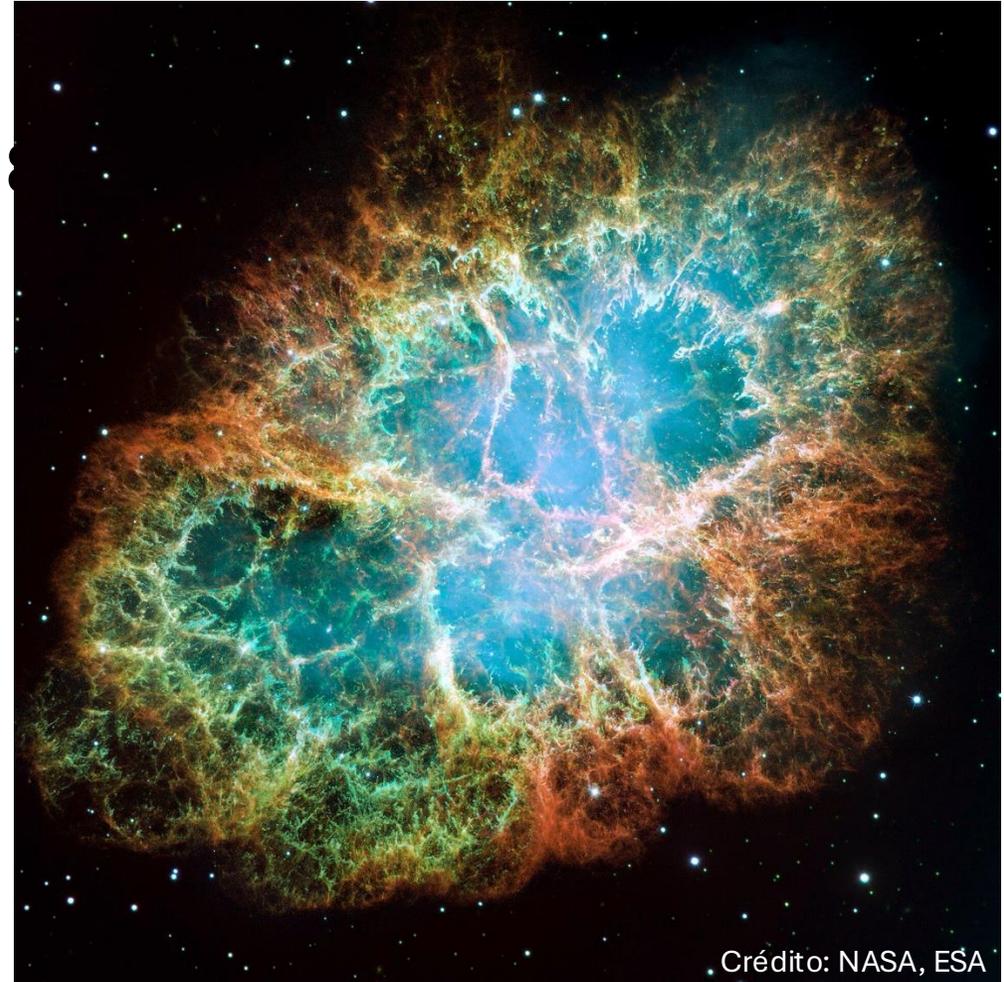
$< \sim 2.3 M_{Sun}$   
TOV-limit

# Supernova

- Remanente de las estrellas entre 8 y 100 veces más masivas que el Sol
- Explosión de Supernova



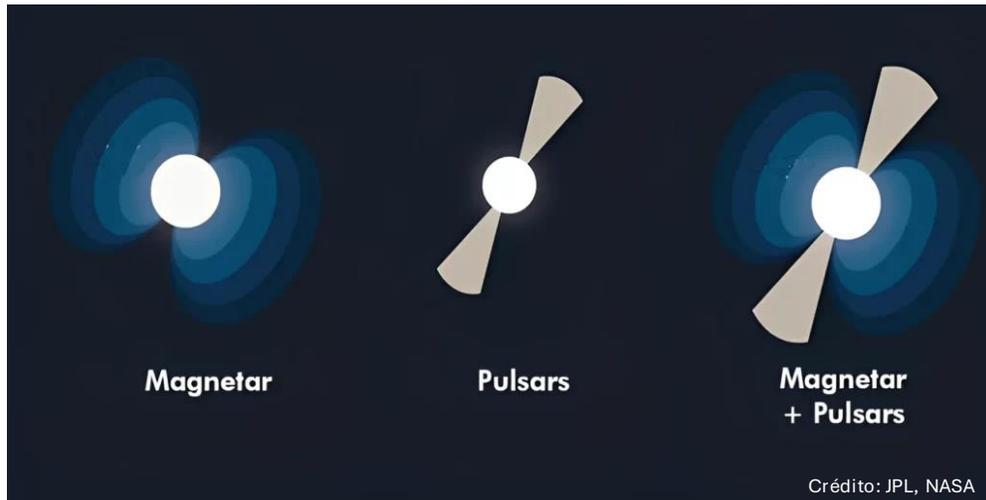
Crédito: Nanda Rea



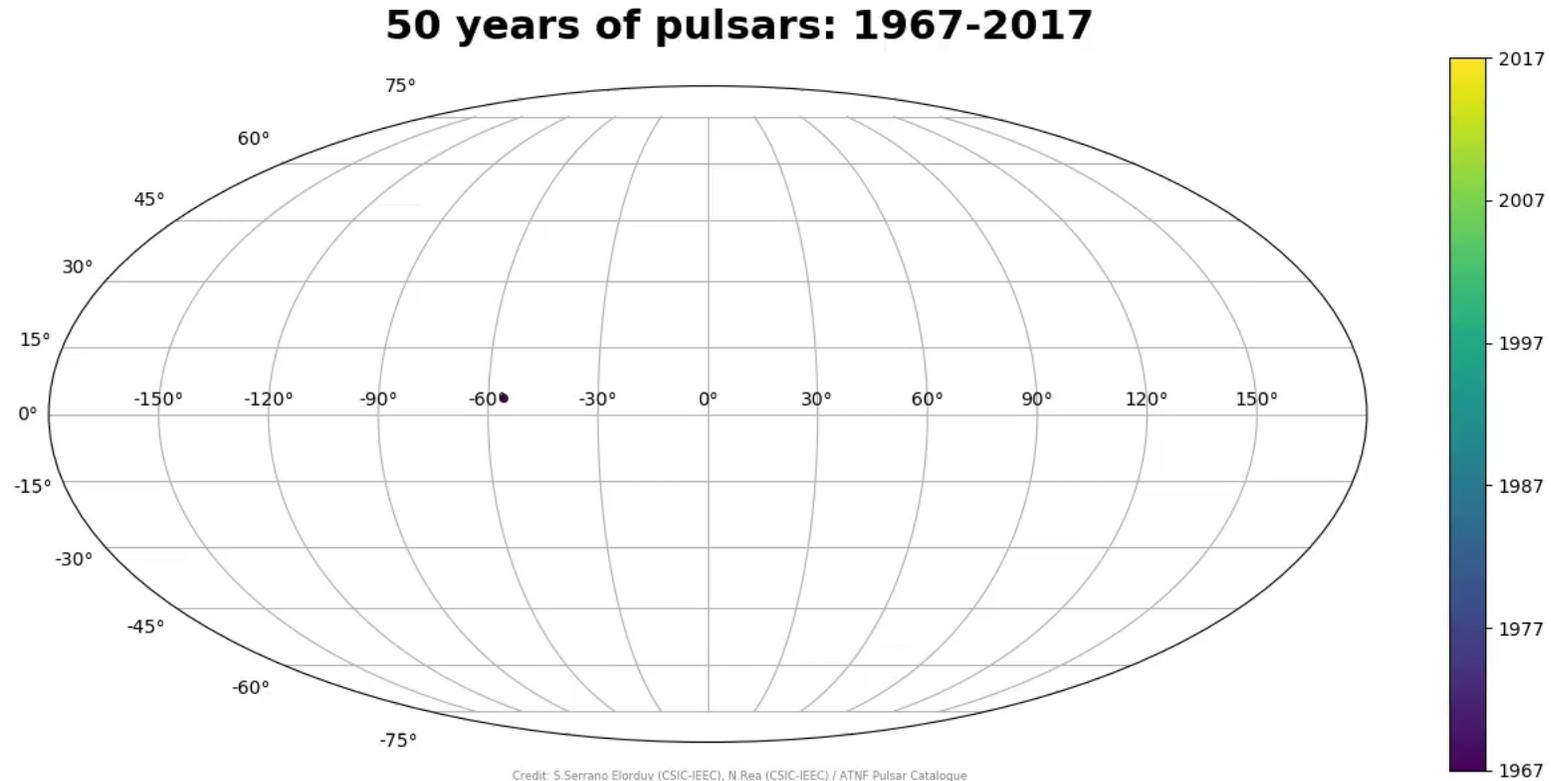
Crédito: NASA, ESA

# Estrellas de neutrones

- Densidad muy alta:  $1 M_{Sun}$  en  $10km \varnothing$



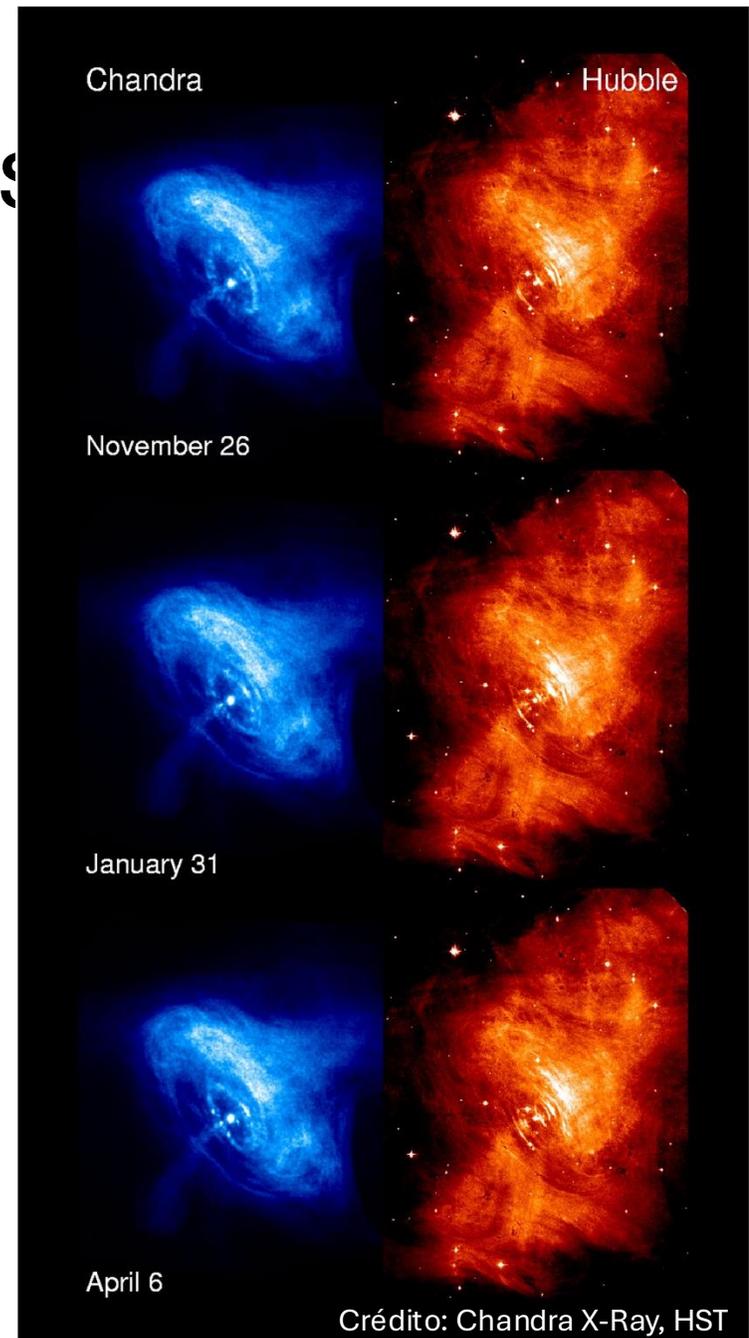
# ¿Cuántos púlsares hay?



Crédito: Nanda Rea

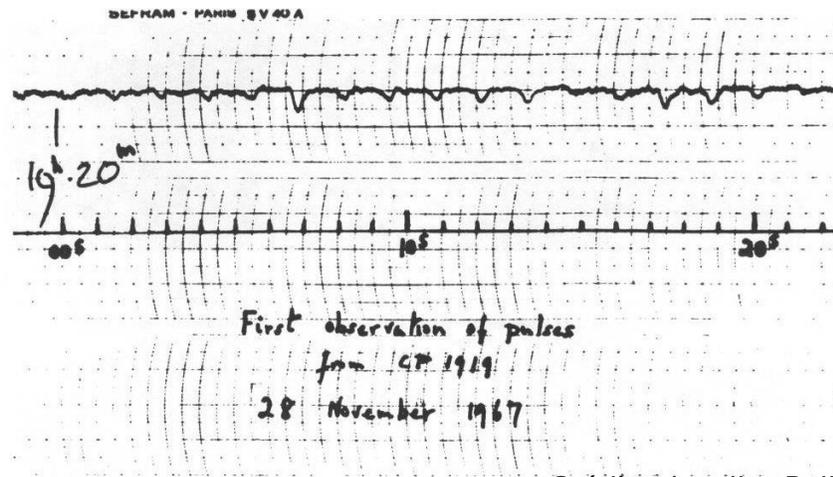
# Características de los púlsares

- Viento de púlsares
- Relojes más precisos
- Púlsares para medir distancias
  - Dispersion Measure, Pulsar Timing Arrays, ...

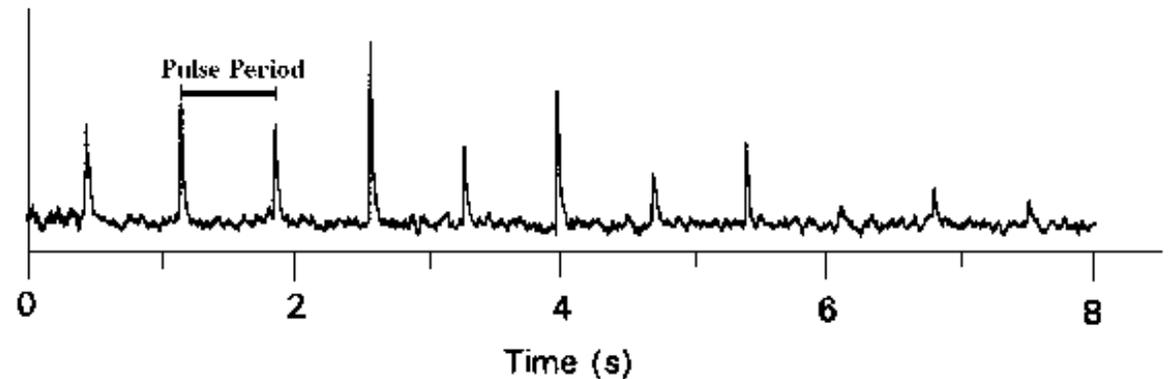


# Características de los púlsares

- Viento de púlsares
- Relojes más precisos
- Púlsares para medir distancias (DM, PTA)



Crédito: Jocellyn Bell



Crédito: Australia Telescope National Facility

# Música con púlsares 📡



Crédito: Astrophil

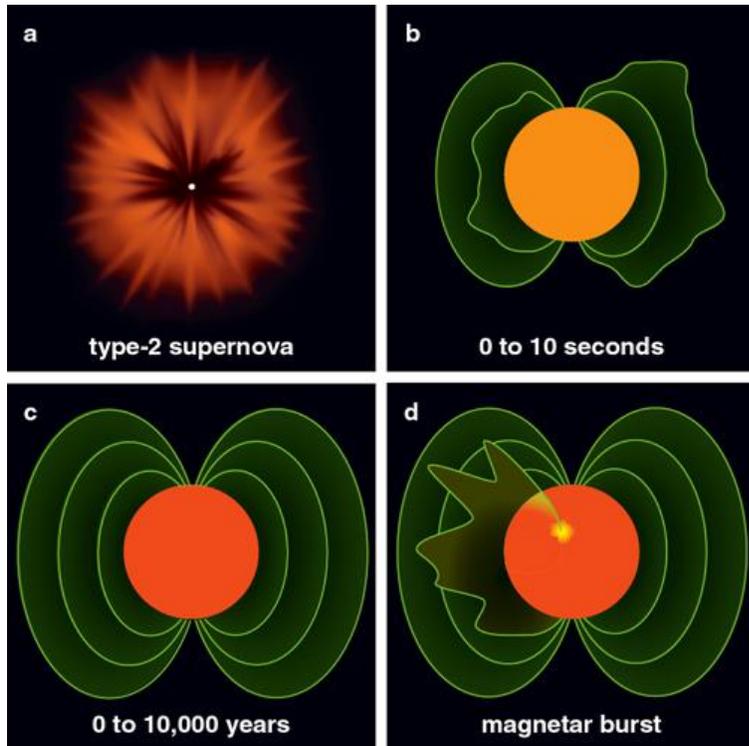
# Récords de los púlsares

- Cuerpo celeste más denso conocido ( $\rho = 10^{25}$  atmosferas terrestres)
- Cuerpo celeste con mayor velocidad de rotación ( $1.39595467$  ms)
- Círculo más redondo conocido: órbita de PSR J1909-3744 ( $5 \mu\text{m}$ )
- Reloj con mayor precisión más estable
- Objetos más magnéticos conocidos (SGR 1806-20:  $2 \times 10^{15} G$ )
- Prueba de la relatividad general más precisa (en sistemas binarios: 0.05%)

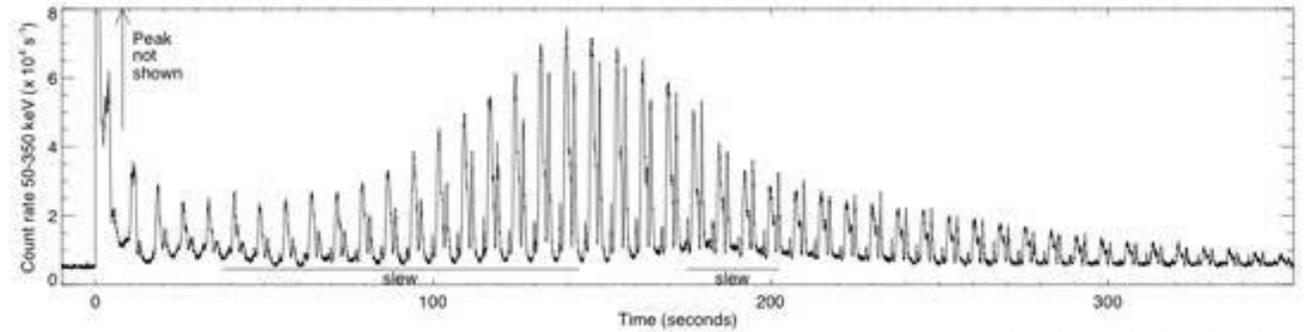
# Récords de los púlsares

- Detector de ondas gravitacionales más económico (PTA)
- Sistema más económico de pesar los planetas del sistema solar
- Futuro sistema de GPS en el espacio (reloj + posición precisas)

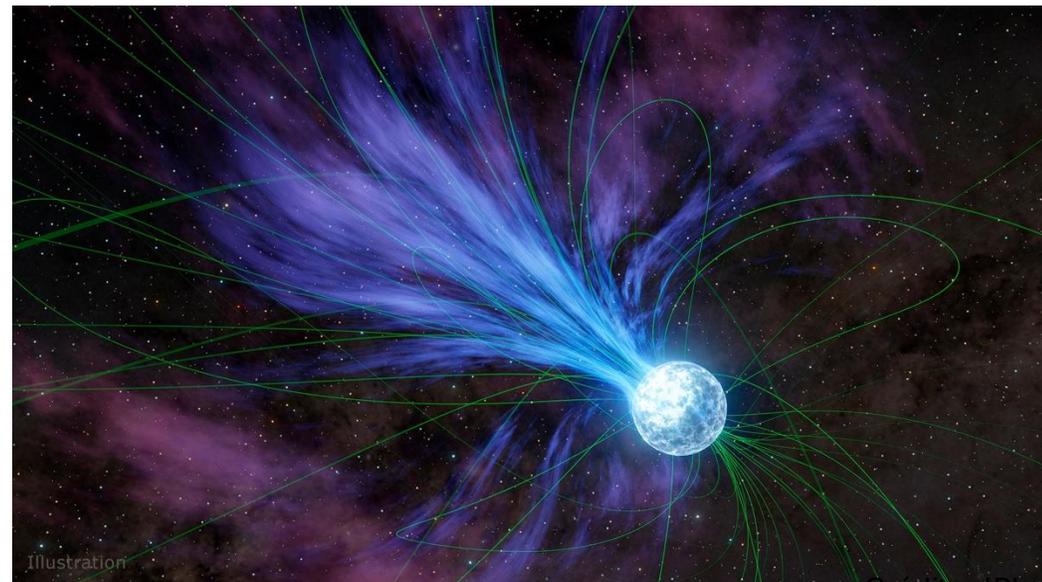
# Campo magnético de magnetares



Crédito: American Scientist

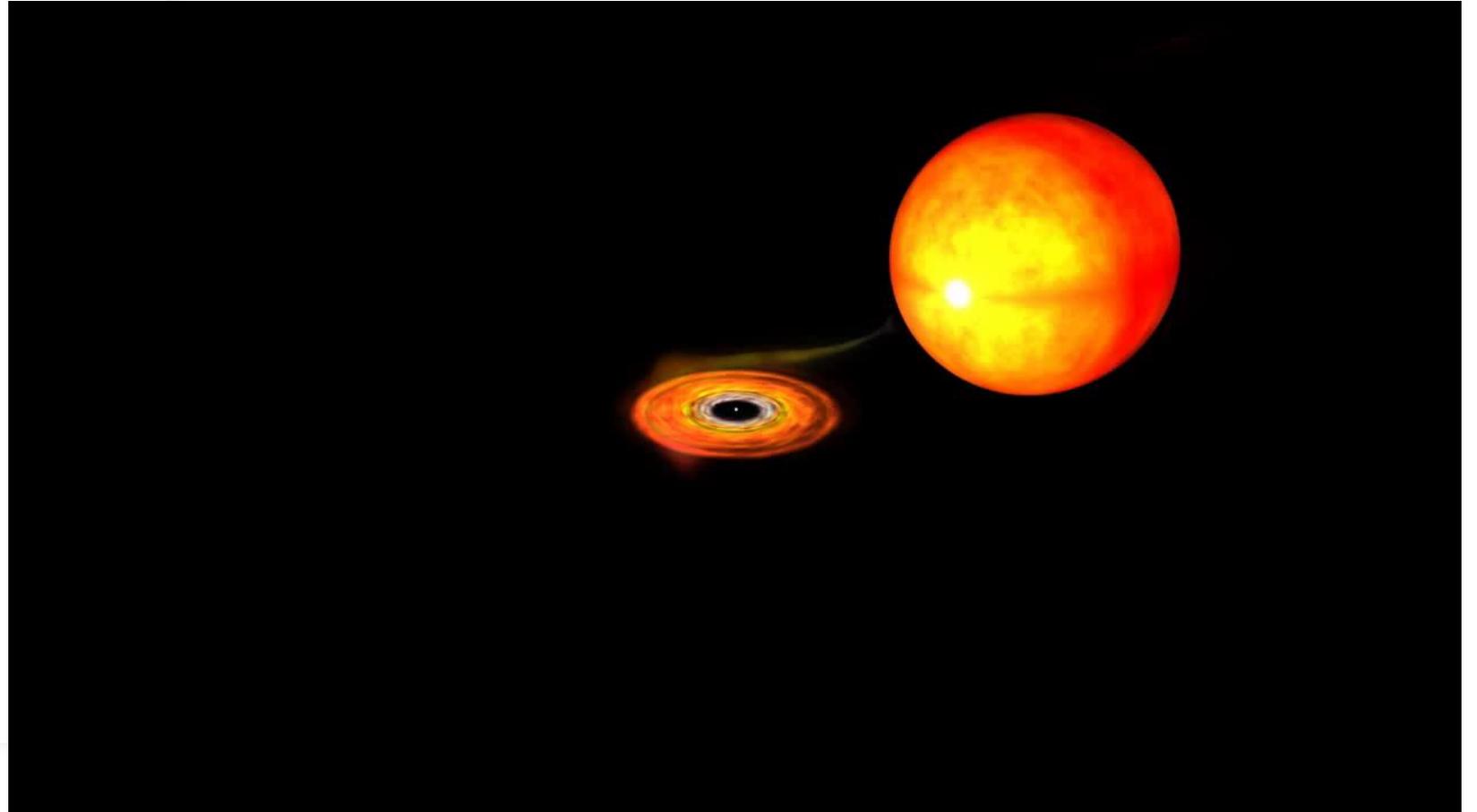


Crédito: NASA/Swift



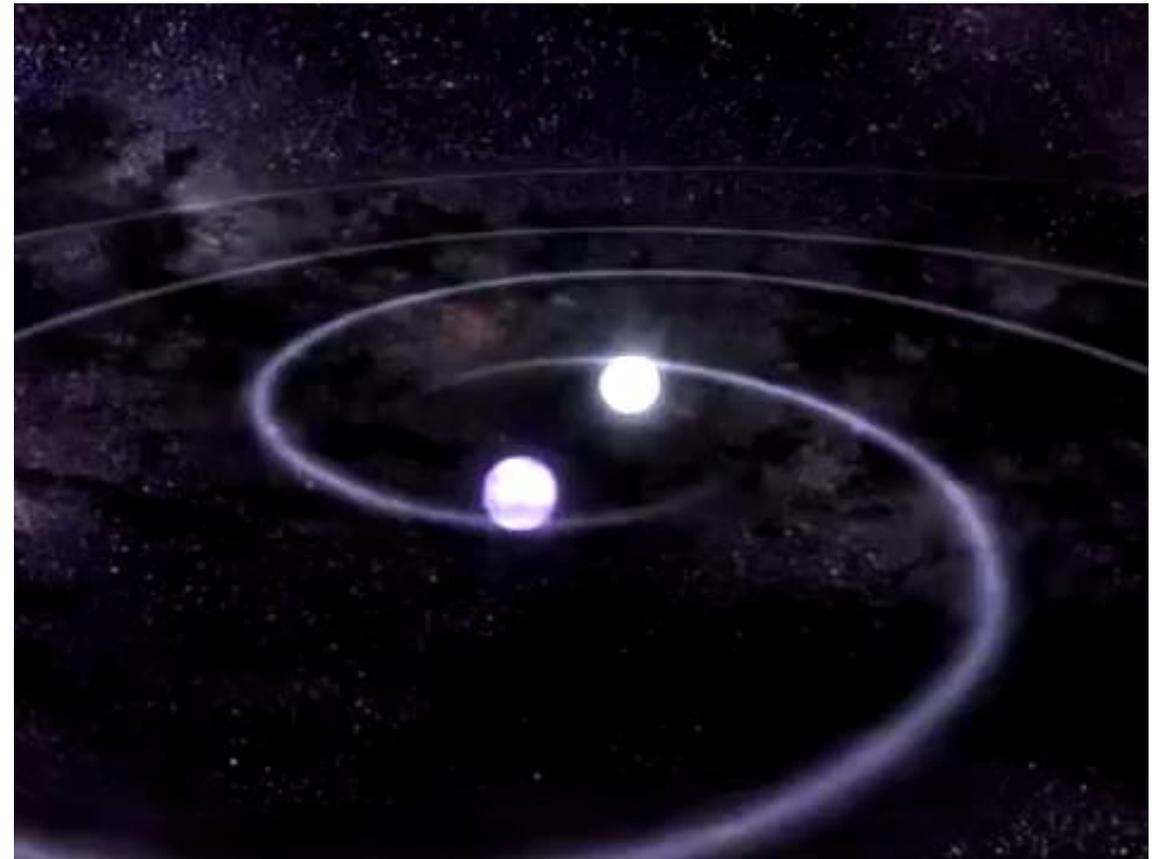
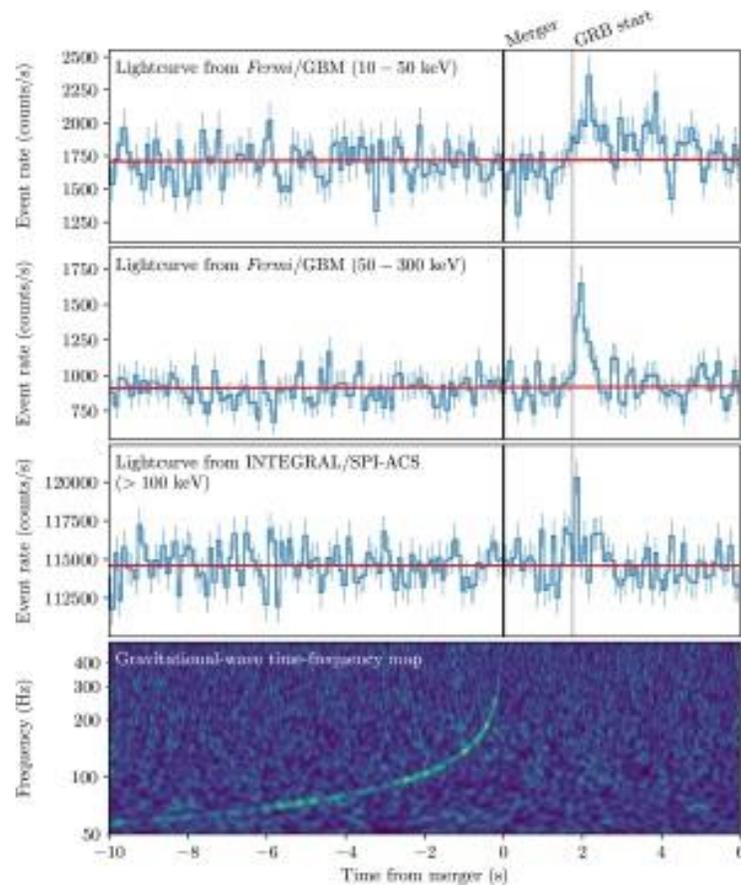
Crédito: JPL

# Púlsares en sistemas binarios

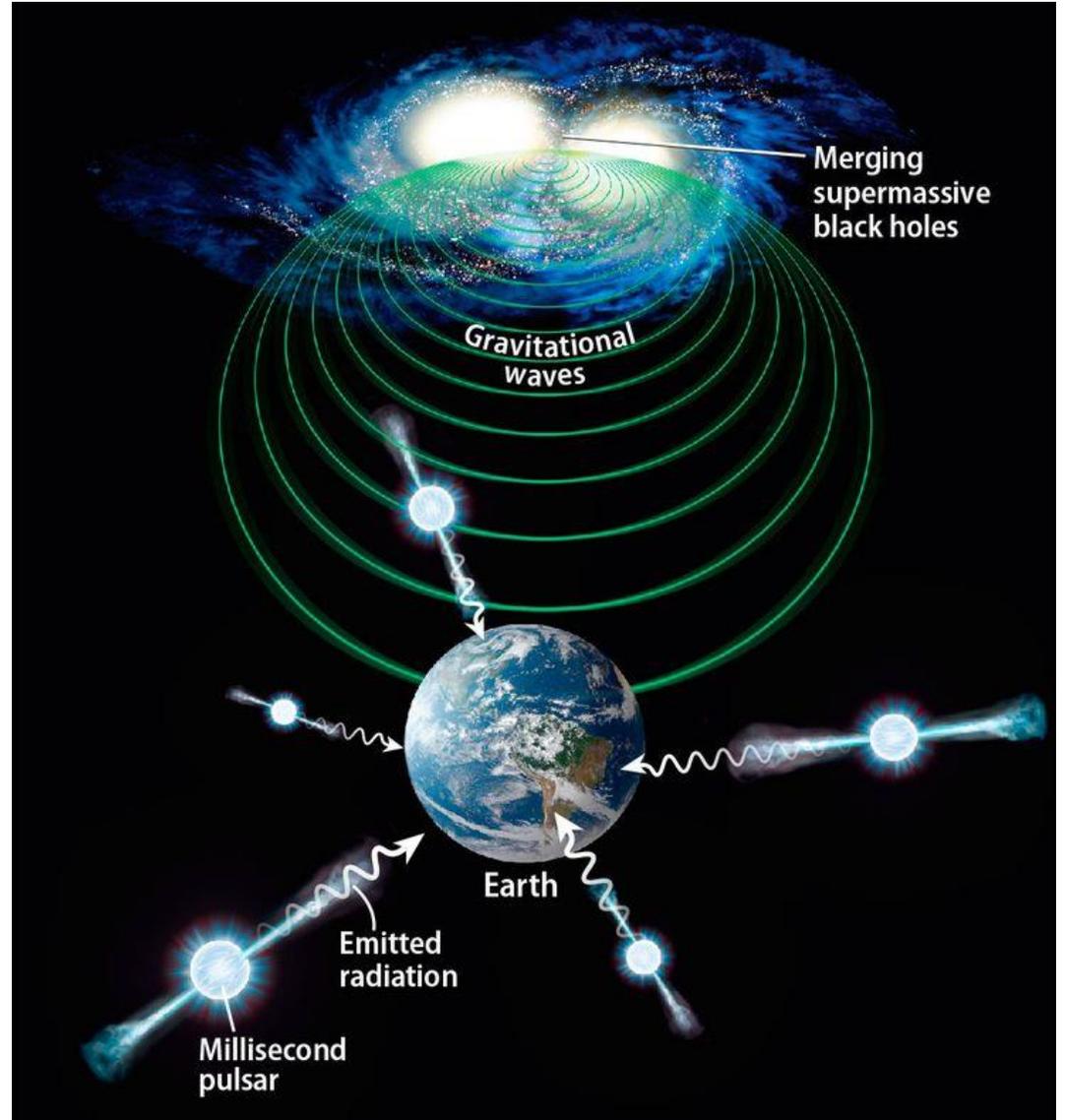


Crédito: Nanda Rea

# Colisiones de estrellas de neutrones



# Púlsares como detectores de GW (PTA)



Crédito: Nanda Rea

# NANOGrav, Julio 2023

The NANOGrav 15 yr Data Set: Observations and Timing of 68 Millisecond Pulsars <sup>CROSSMIA</sup>

## Abstract

We present observations and timing analyses of 68 millisecond pulsars (MSPs) comprising the 15 yr data set of the North American Nanohertz Observatory for Gravitational Waves (NANOGrav). **NANOGrav is a pulsar timing array (PTA) experiment that is sensitive to low-frequency gravitational waves (GWs).** This is NANOGrav's fifth public data release, including both "narrowband" and "wideband" time-of-arrival (TOA) measurements and corresponding pulsar timing models. We have added 21 MSPs and extended our timing baselines by 3 yr, now spanning nearly 16 yr for some of our sources. The data were collected using the Arecibo Observatory, the Green Bank Telescope, and the Very Large Array between frequencies of 327 MHz and 3 GHz, with most sources observed approximately monthly. A number of notable methodological and procedural changes were made compared to our previous data sets. These improve the overall quality of the TOA data set and are part of the transition to new pulsar timing and PTA analysis software packages. For the first time, our data products are accompanied by a full suite of software to reproduce data reduction, analysis, and results. Our timing models include a variety of newly detected astrometric and binary pulsar parameters, including several significant improvements to pulsar mass constraints. We find that the time series of 23 pulsars contain detectable levels of red noise, 10 of which are new measurements. **In this data set, we find evidence for a stochastic GW background.**

*Unified Astronomy Thesaurus concepts:* Millisecond pulsars (1062); Pulsar timing method (1305); Time series analysis (1916); Pulsars (1306); Gravitational waves (678)

Crédito: NANOGrav Collaboration  
DOI: 10.3847/2041-8213/ace18a

LIGO+VIRGO: km  
NANOGrav: ly

The NANOGrav 15-year Data Set: Bayesian Limits on Gravitational Waves from Individual Supermassive Black Hole Binaries

## ABSTRACT

Evidence for a **low-frequency stochastic gravitational wave background has recently been reported based on analyses of pulsar timing array data.** The most likely source of such a background is a **population of supermassive black hole binaries**, the loudest of which may be individually detected in these datasets. Here we present the search for individual supermassive black hole binaries in the NANOGrav 15-year dataset. We introduce several new techniques, which enhance the efficiency and modeling accuracy of the analysis. The search uncovered weak evidence for two candidate signals, one with a gravitational-wave frequency of  $\sim 4$  nHz, and another at  $\sim 170$  nHz. The significance of the low-frequency candidate was greatly diminished when Hellings-Downs correlations were included in the background model. The high-frequency candidate was discounted due to the lack of a plausible host galaxy, the unlikely astrophysical prior odds of finding such a source, and since most of its support comes from a single pulsar with a commensurate binary period. Finding no compelling evidence for signals from individual binary systems, we place upper limits on the strain amplitude of gravitational

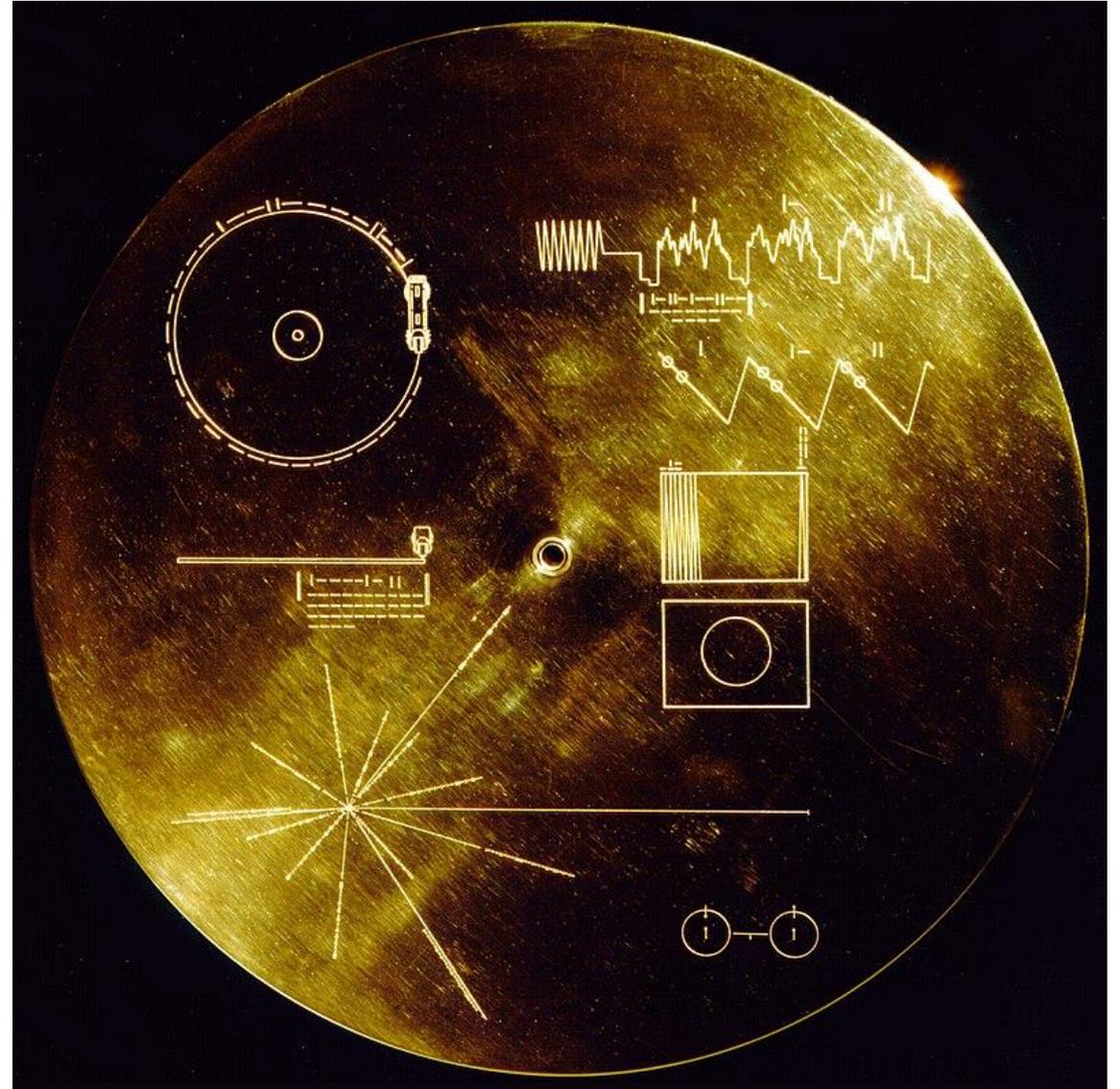
Crédito: NANOGrav Collaboration  
DOI: 10.3847/2041-8213/acda9a

Low frequencies  $\Leftrightarrow$  high wavelength  $\rightarrow$  less energy = smaller mass

# Demás con púlsares

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- Púlsares en sistemas binarios (o triples)
  - NS-NS o NS-WD o NS-RG, ...
- Púlsares con planetes
- Navegación en rayos x
- ...



Crédito: Voyager, NASA

Remanente estelar cuando  $M > 25 M_{Sun}$ ?

Remanente estelar  
cuando  $M >$   
 $25 M_{Sun}$ ?

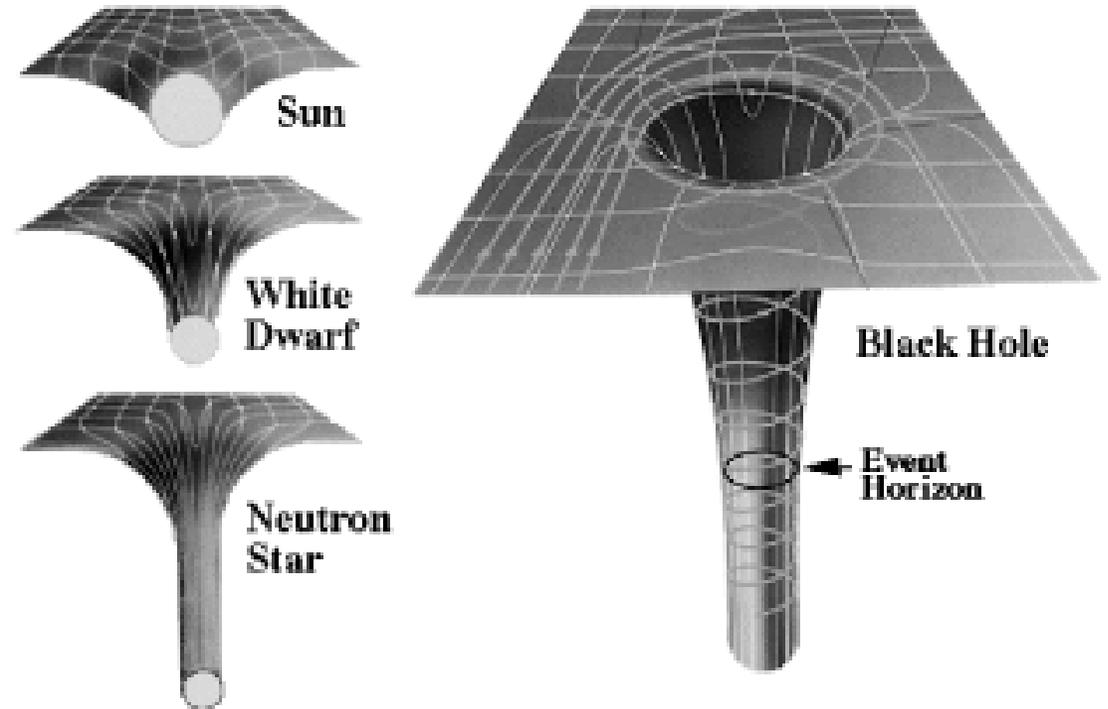


# Agujeros negros (BH)

---

- Región del espacio-tiempo
- Singularidad del espacio-tiempo (según GR)
  - Espacio y tiempo no están definidos
- Velocidad de escape  $> c$

$$R_S = \frac{2GM}{c^2}$$



Crédito: NASA

# PBH - primordiales

- Tamaño de un átomo
- Massa de una montaña
- No se han observado



# IMBH – interediate-mass?

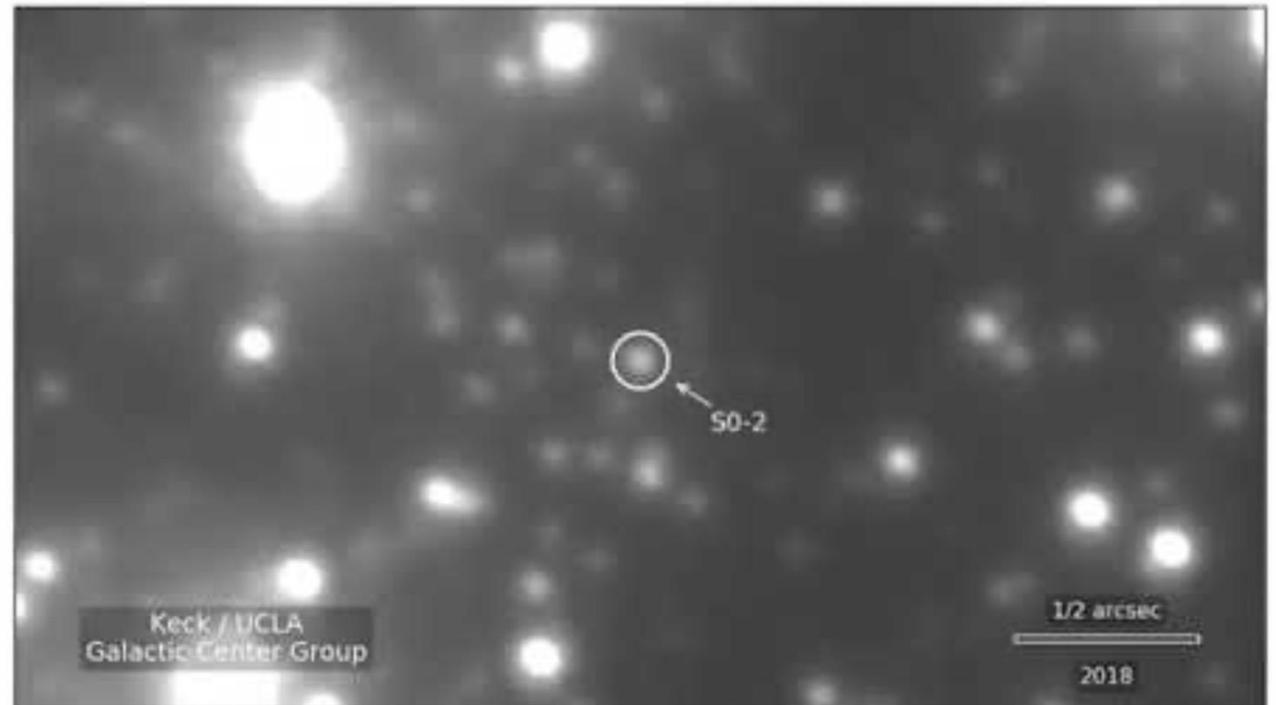
- Candidatos sin clasificación: +300 (via GW o AGN)
- En galaxias enanas?
- Universo temprano?
- Podrían ser las semillas de los SMBHs?



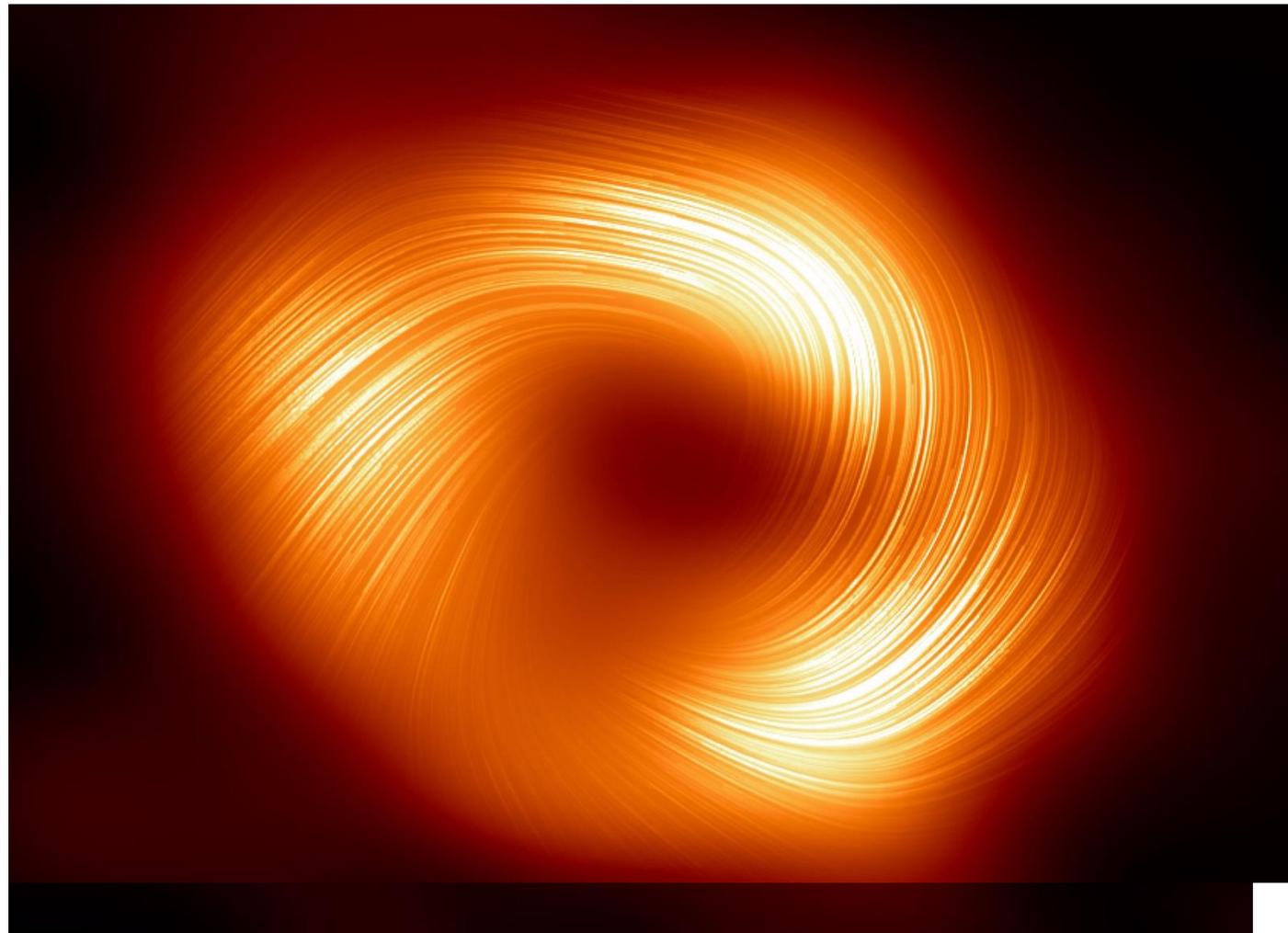
Crédito: Sci News

# SMBH - Supermasivos

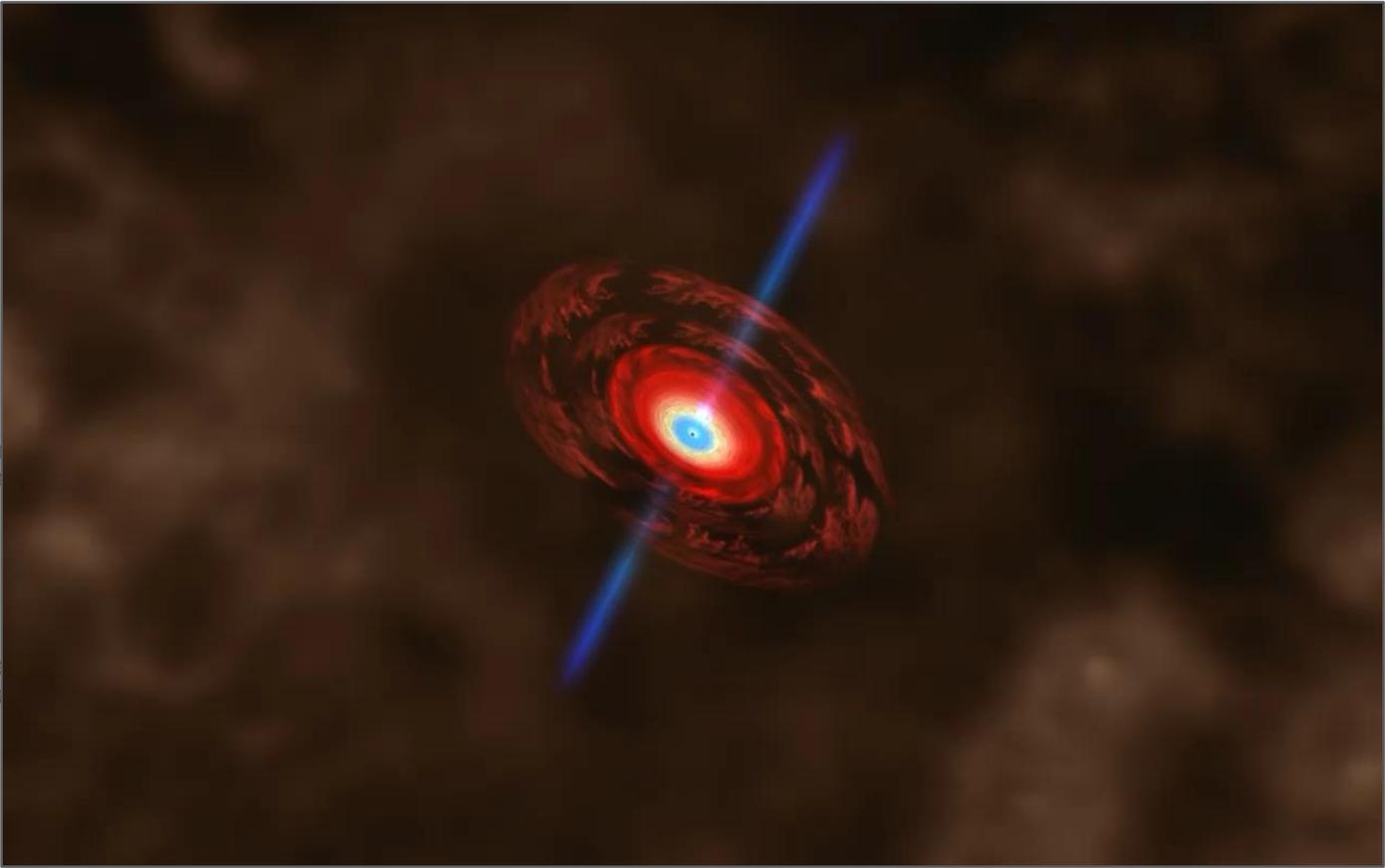
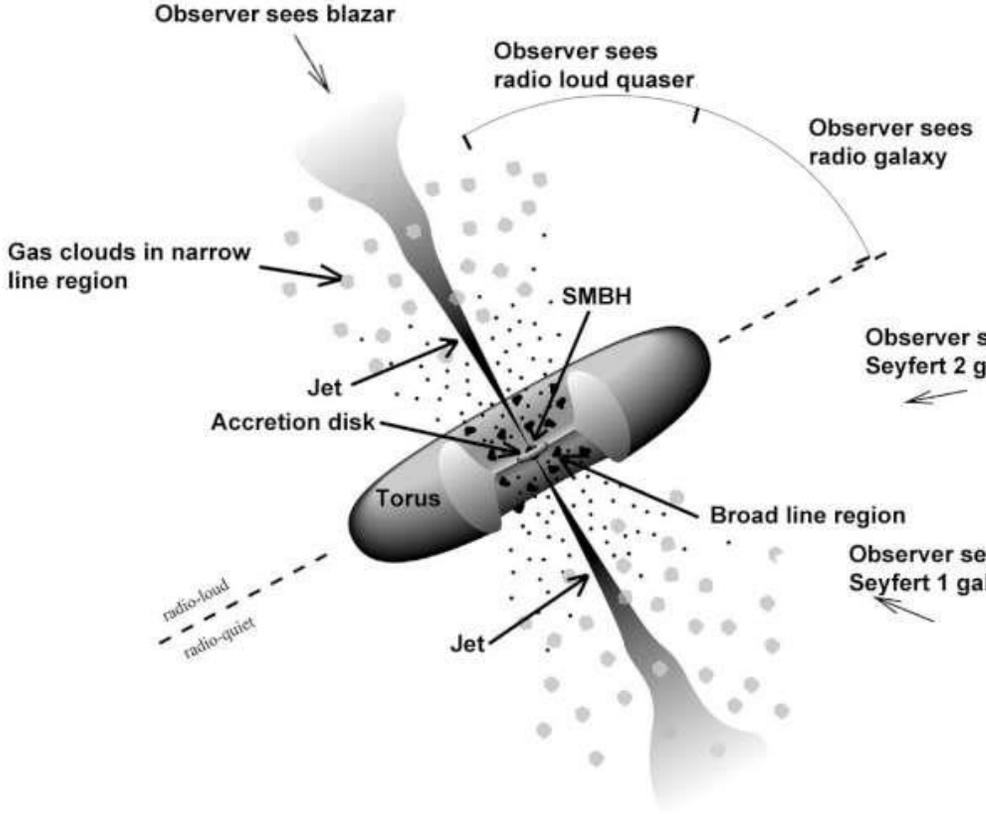
- Agujeros Negros Super Masivos
- Uno en el centro de cada galaxia
- Primero detección indirecta



# SMBH – Sagittarius A\*

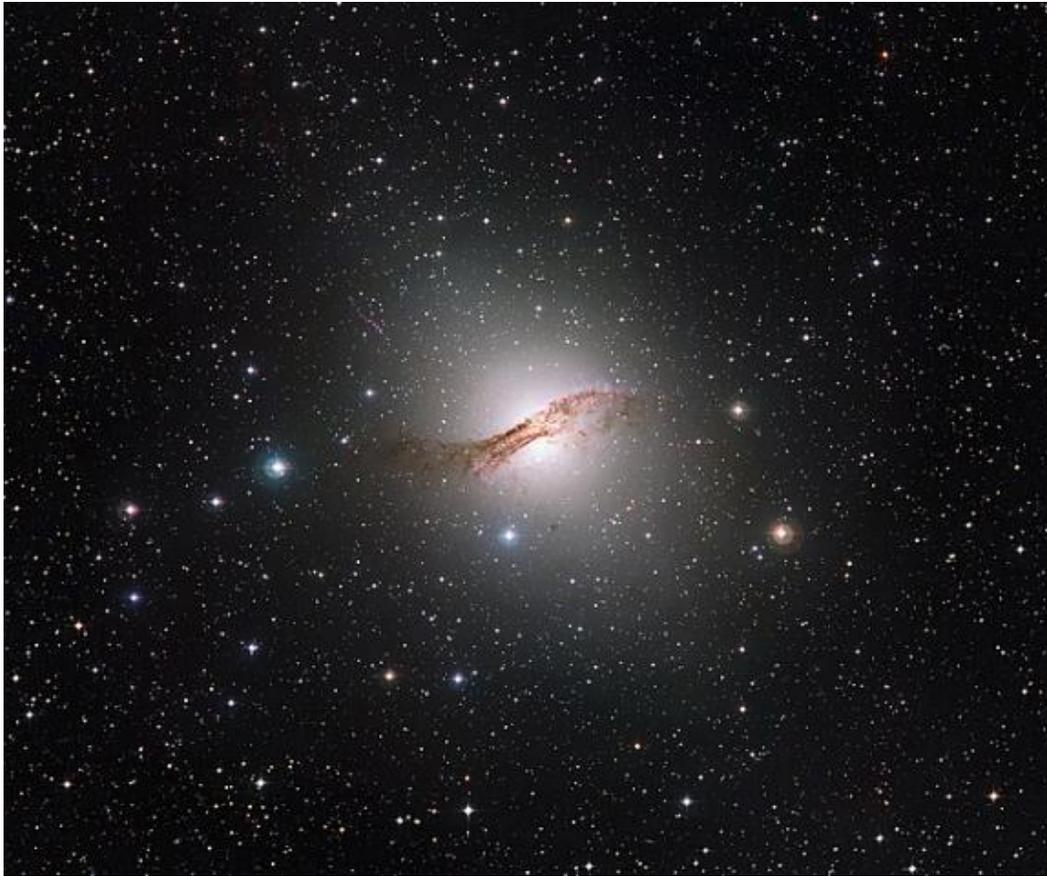


# AGNs - activos

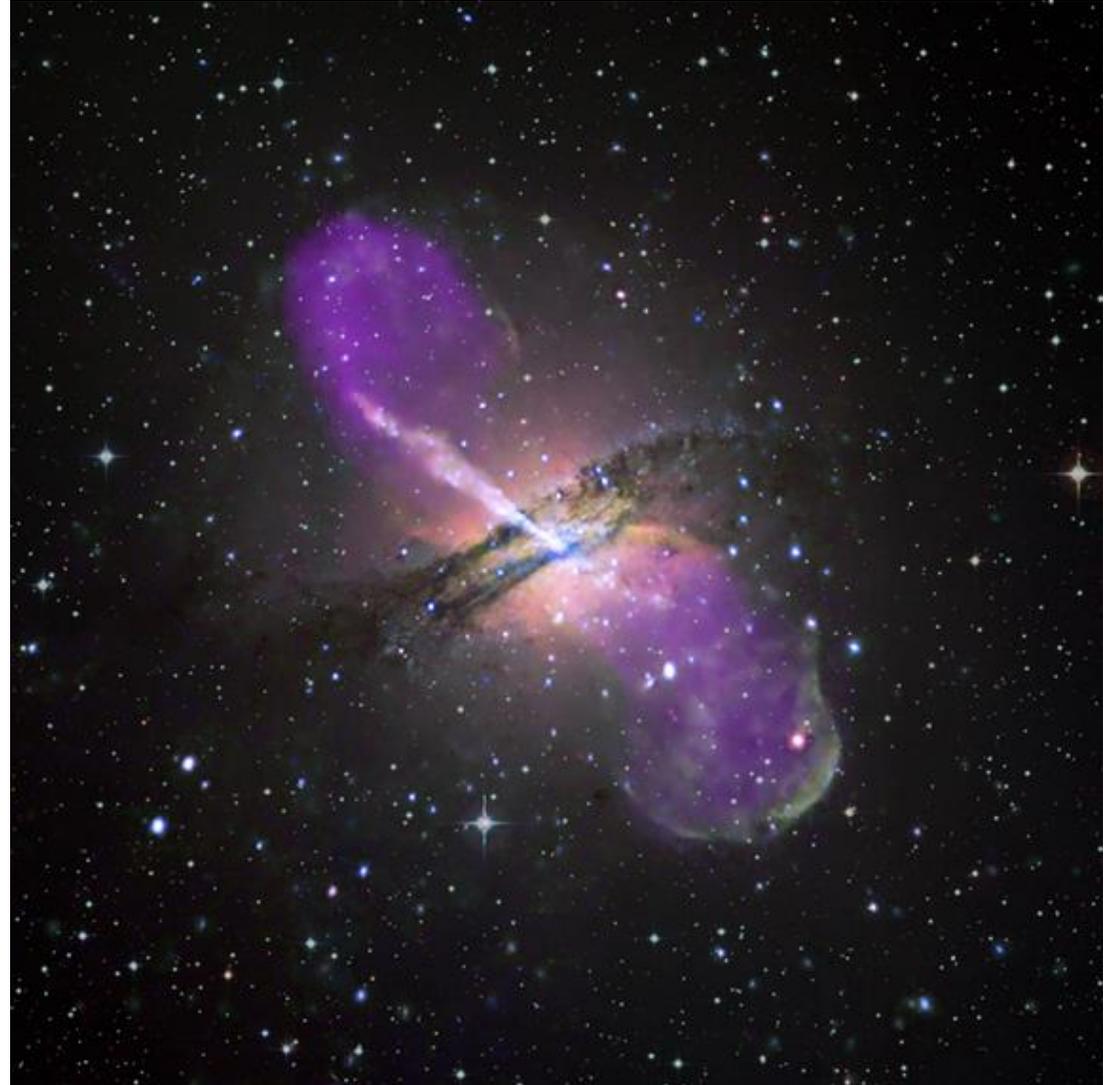


Crédito: Nanda Rea

# Centaurus A - AGN



Crédito: ESA Hubble



Crédito: Chandra X-Ray

# Tidal Disruption Events



Tidal Disruption Events

# Black Hole Tidal Disruption Event

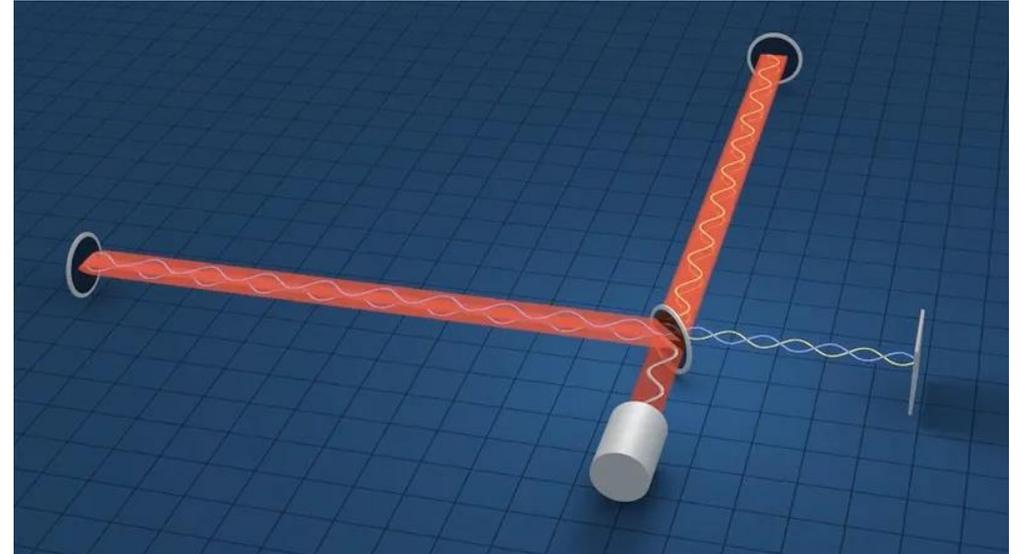


# Colisiones de BH – Ondas Gravitacionales

- Ondas que se propagan por el espacio-tiempo
- Propagación a la velocidad de la luz
- Causa: gravedad de la colisión de dos BH o NS
- Energía proviene de la pérdida de masa en la colisión

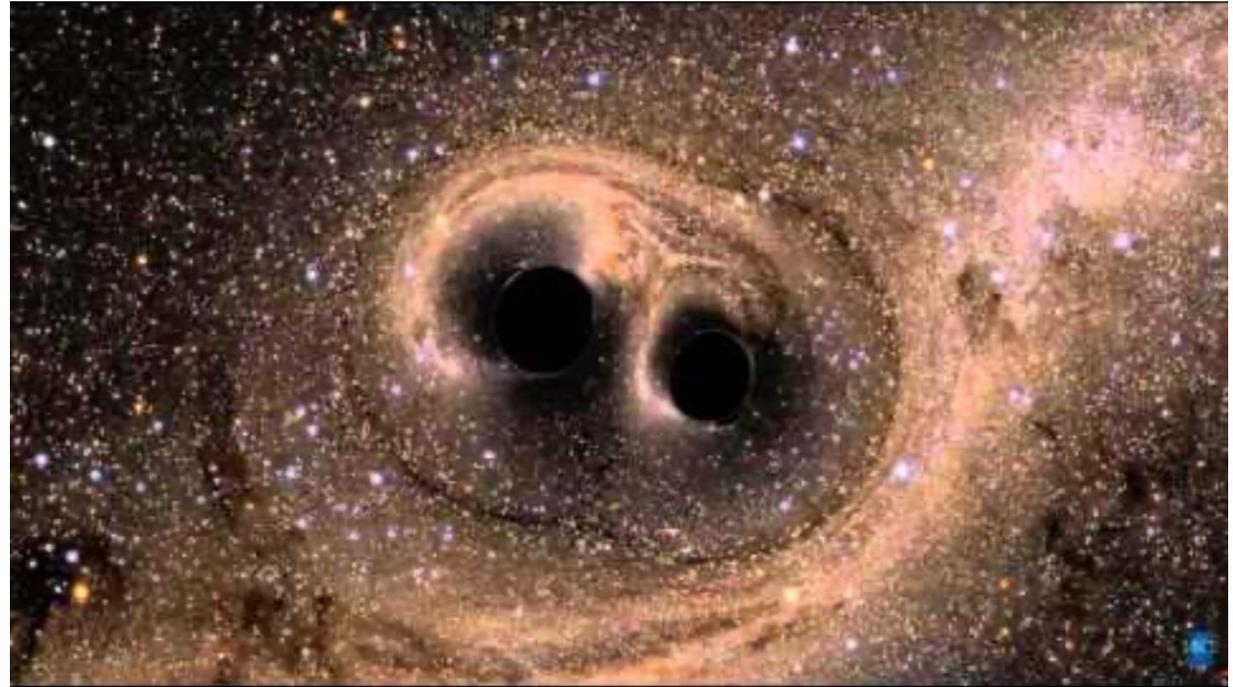
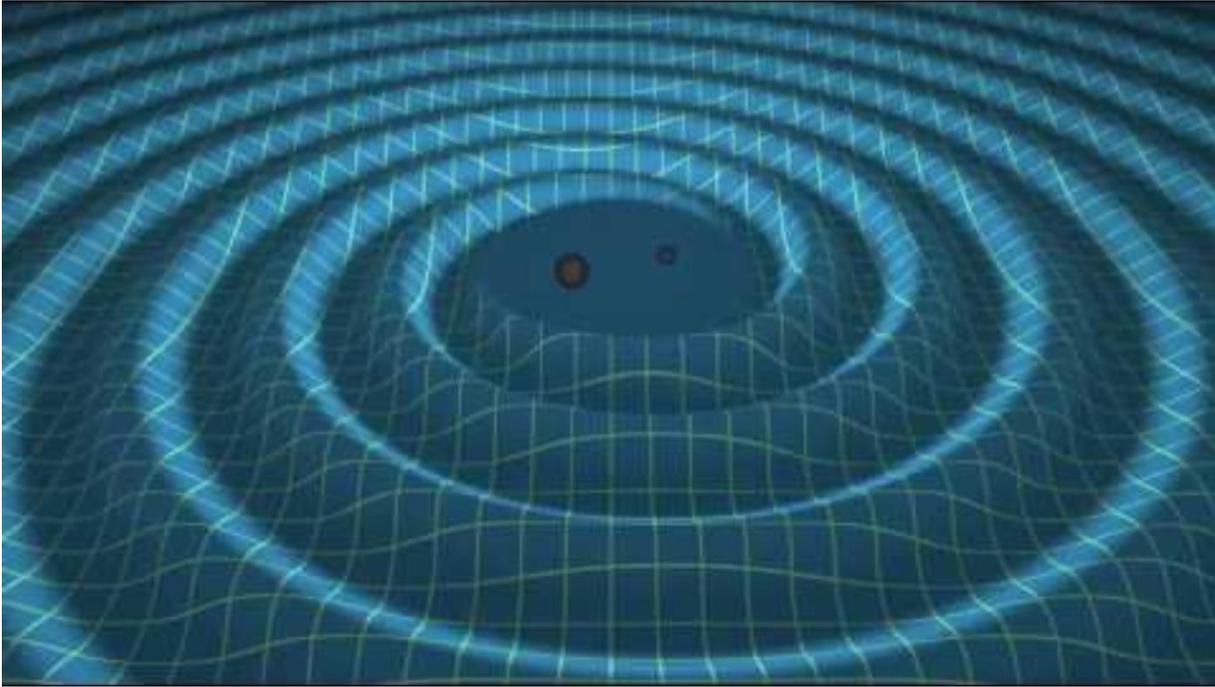


Crédito: LIGO Caltech, MIT



Crédito: LIGO Collaboration

# Colisiones de BH



¿Preguntas?

