

Evolución del Universo y evolución estelar



Joan Alcaide Núñez – Junio 2024

Preparación Universitaria DSB



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2. Universo: evolución

3. Universo: Fondo Cósmico de Microondas (CMB)

4. Estrellas: formación y evolución

5. Galaxias: grupo local

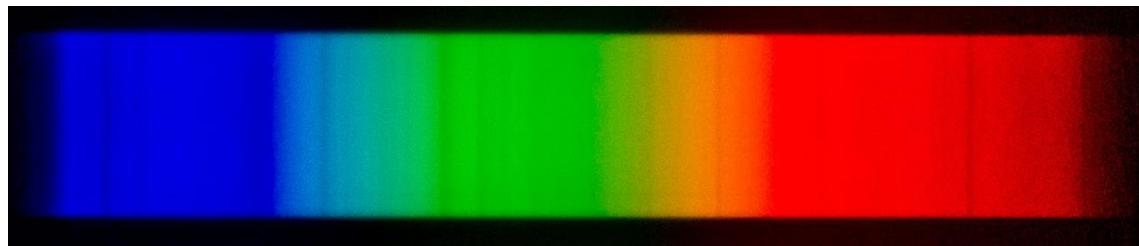
6. Objetos masivos: estrellas de neutrones y agujeros negros

1. Universo: expansión

¿Qué modelo de Universo?



Constante de Hubble



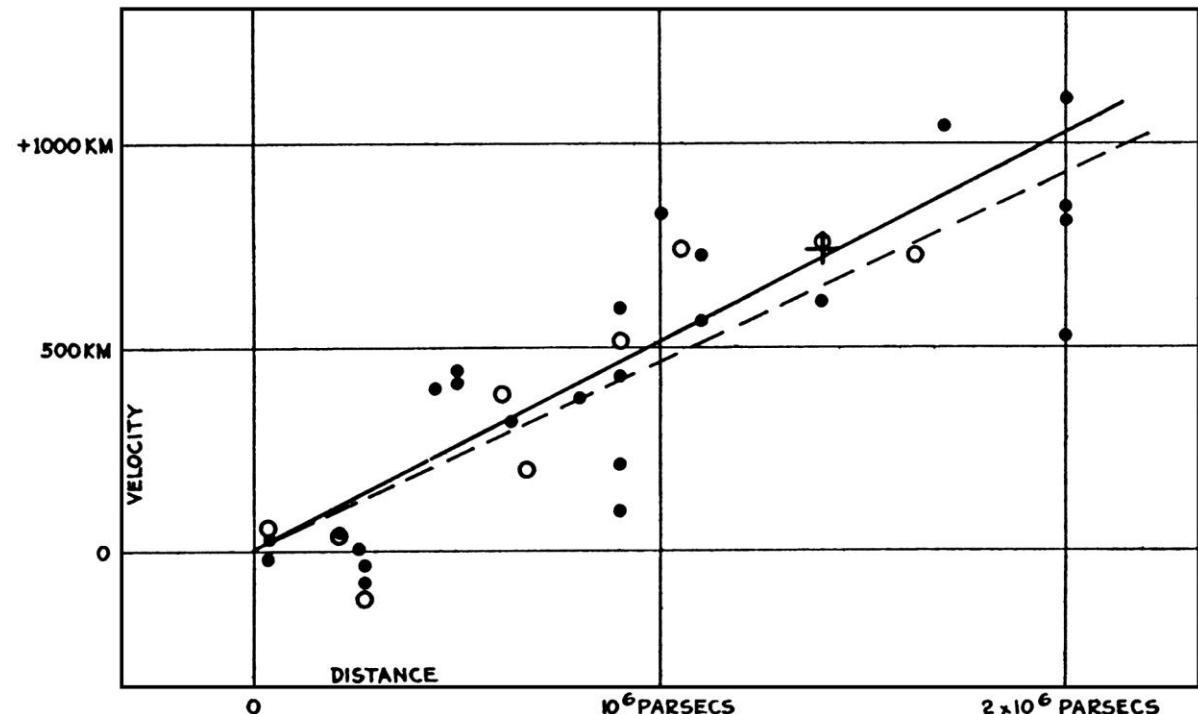
Crédito: JiC 2023

Redshift

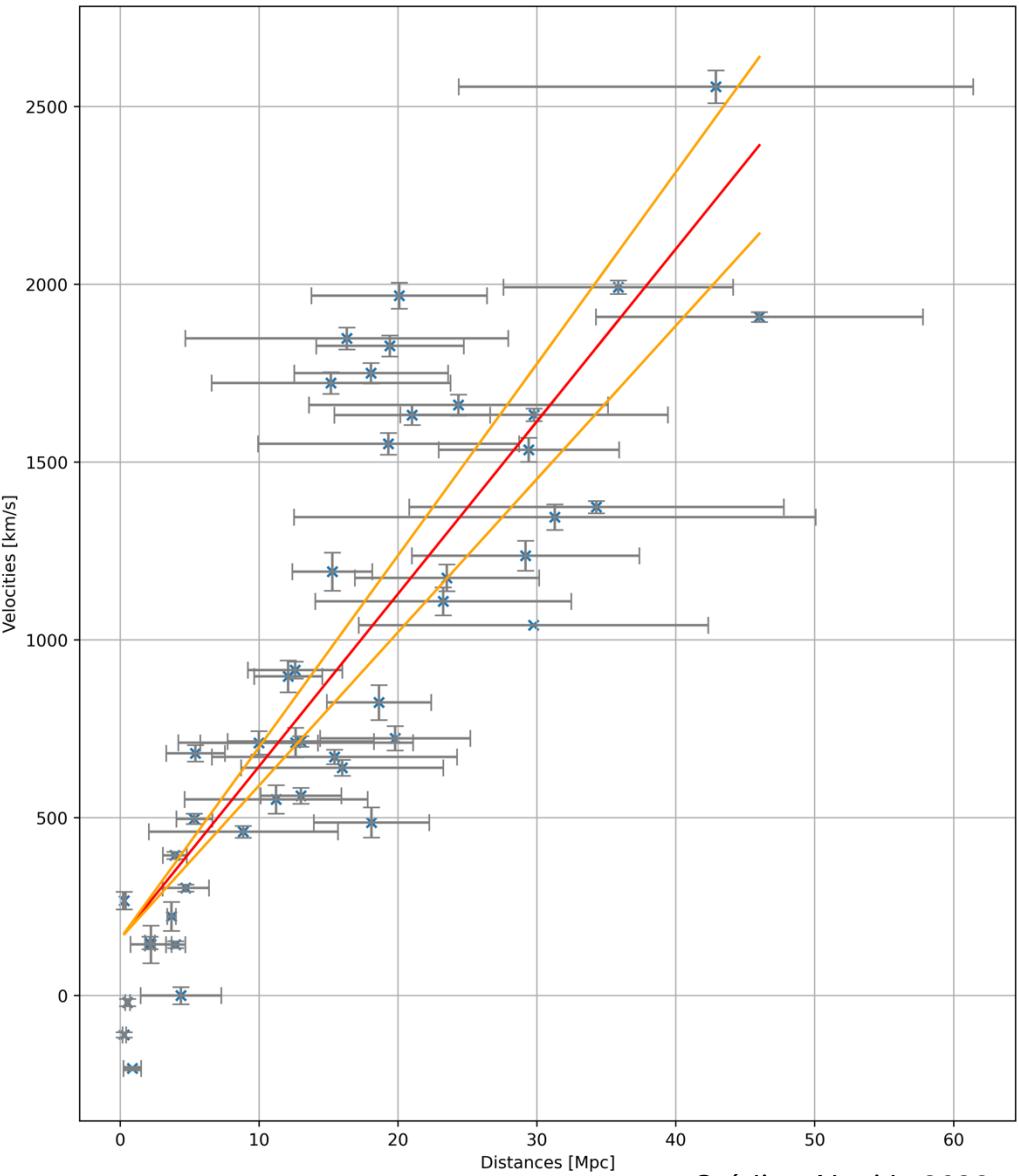
$$v = zc = \frac{\lambda_{ob} - \lambda_{em}}{\lambda_{em}} \cdot c$$

Constante de Hubble

$$v = H_0 d$$



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



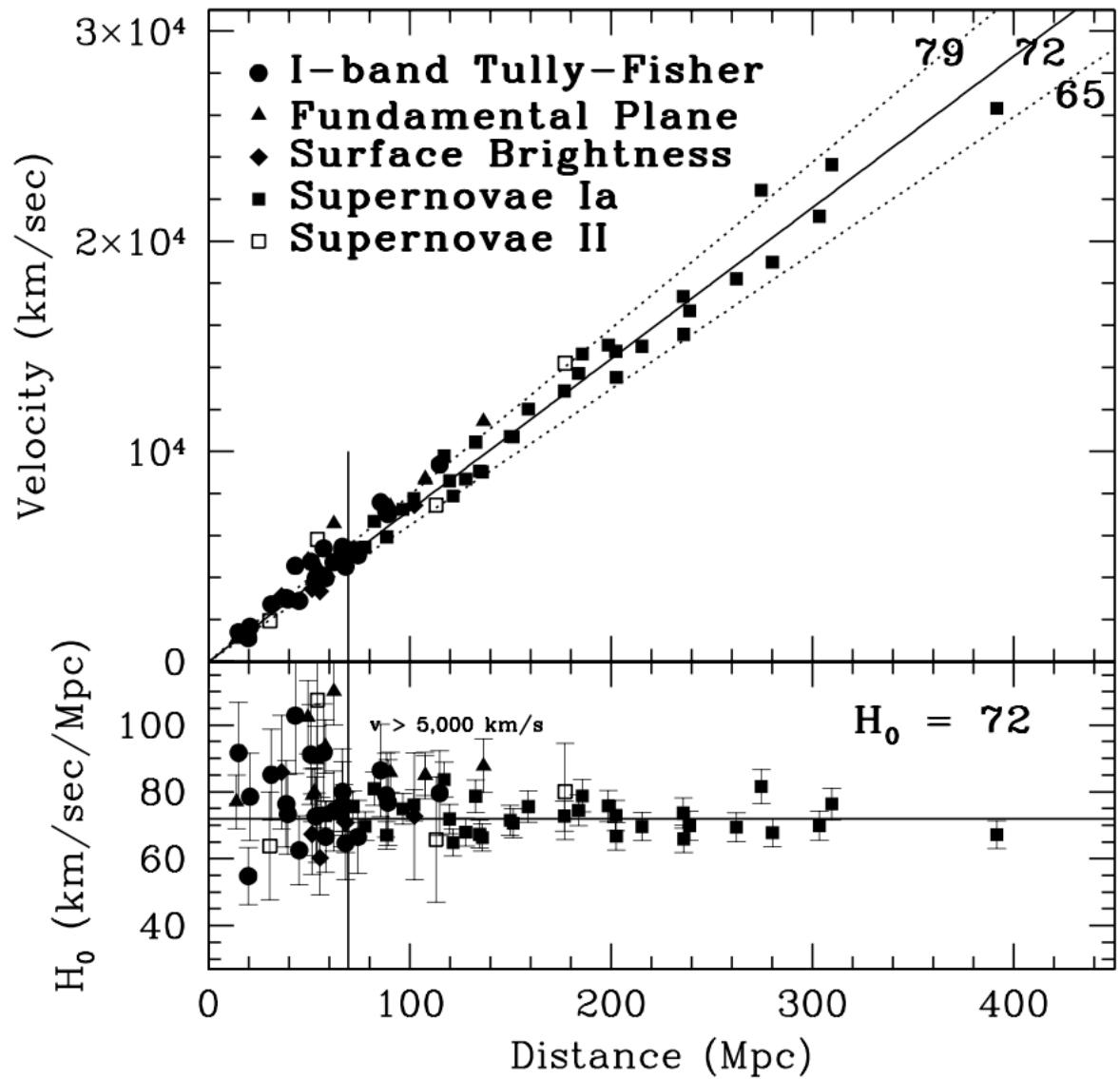
Crédito: Alcaide 2023

Constante de Hubble

$$v = H_0 d$$

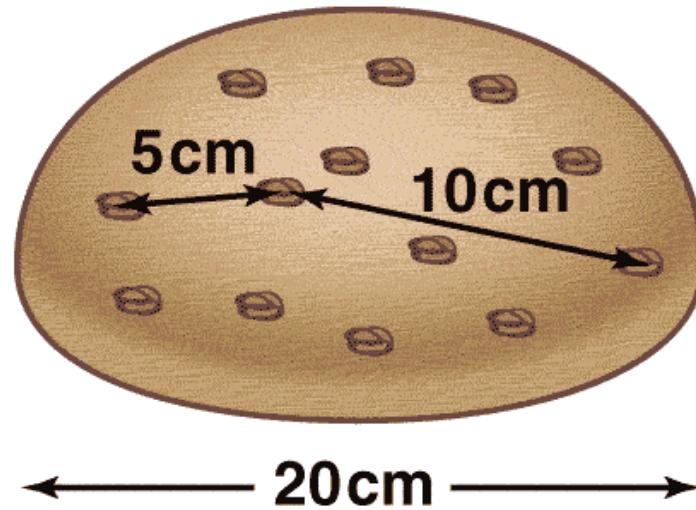
$$H_0 = 72 \pm 8 \text{ } km\text{s}^{-1}\text{Mpc}^{-1}$$

(Freedman et al. 2001, HST Key Project)



Crédito: Freedman et al. 2001

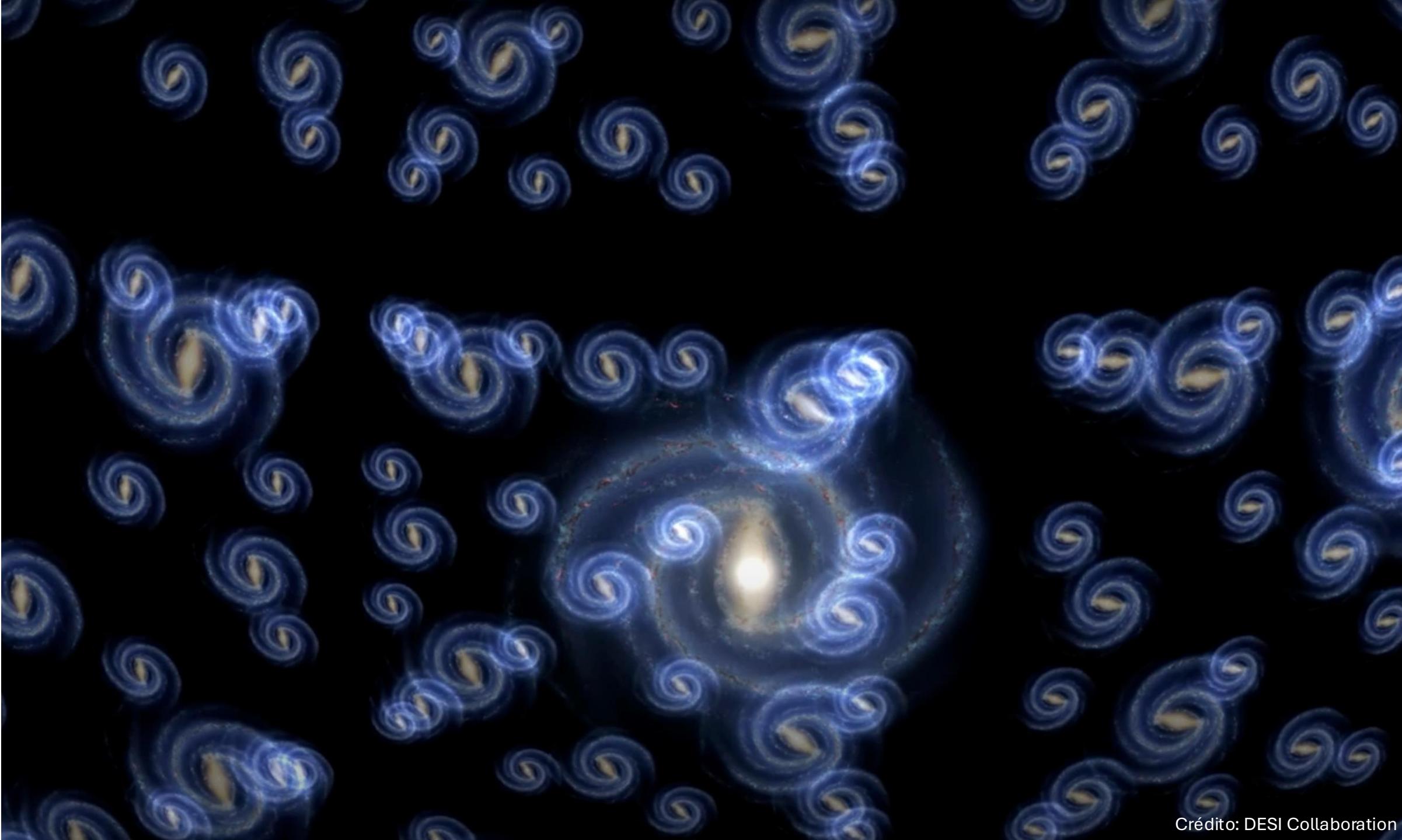
Redshift es proporcional a la distancia



MAP990404

Crédito: NASA (WMAP)

Video



Crédito: DESI Collaboration

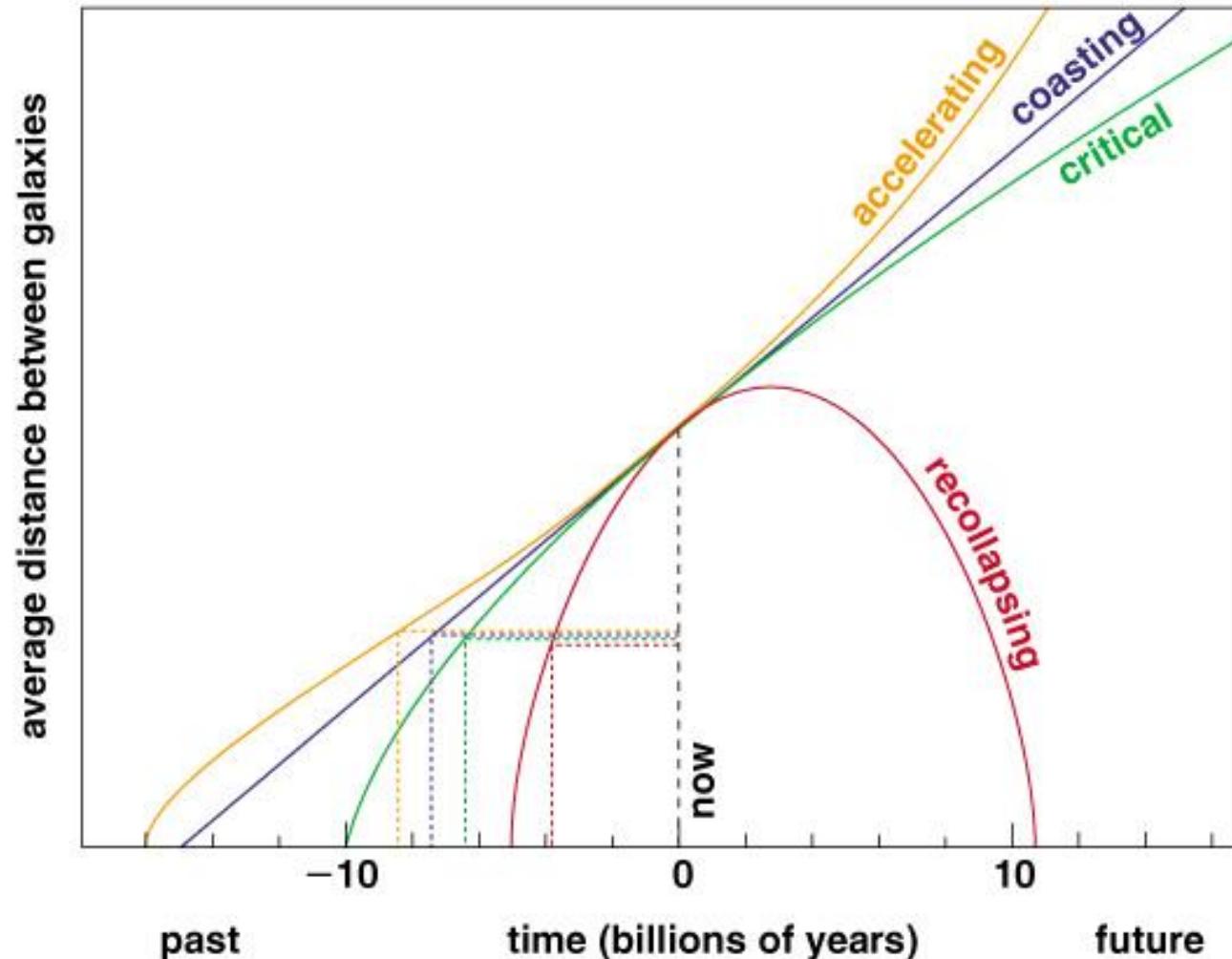
Ecuaciones de Friedman

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2}$$

$$\dot{H} + H^2 = \frac{\ddot{a}}{a} = -\frac{4\pi G}{3} \left(\rho + \frac{3p}{c^2} \right)$$

$$\frac{H^2}{H_0^2} = \Omega_{0,R} a^{-4} + \Omega_{0,M} a^{-3} + \Omega_{0,k} a^{-2} + \Omega_{0,\Lambda}$$

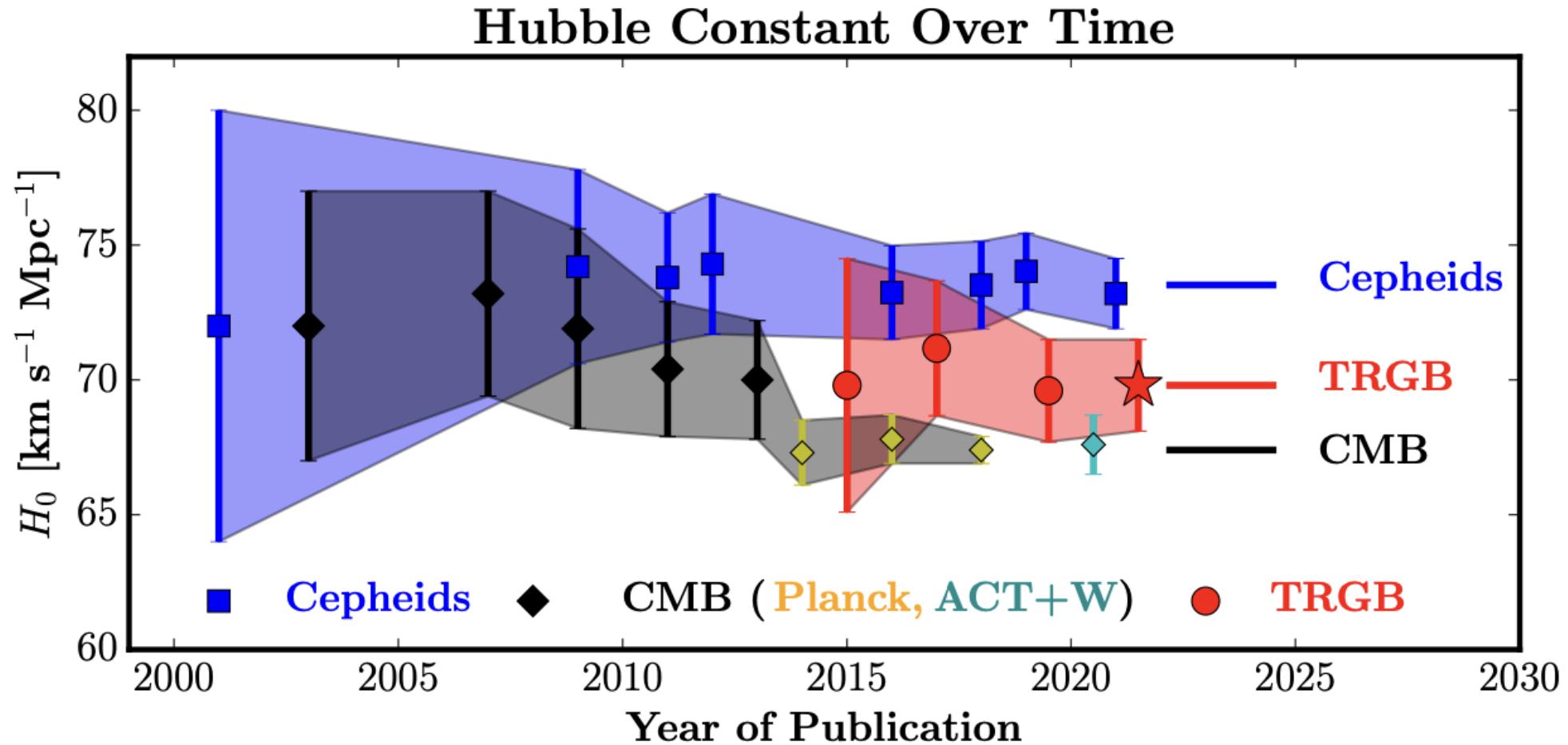
Expansión acelerada (Energía oscura)



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Crédito: University Massachussets (Amherst)

Crisis de la Cosmología

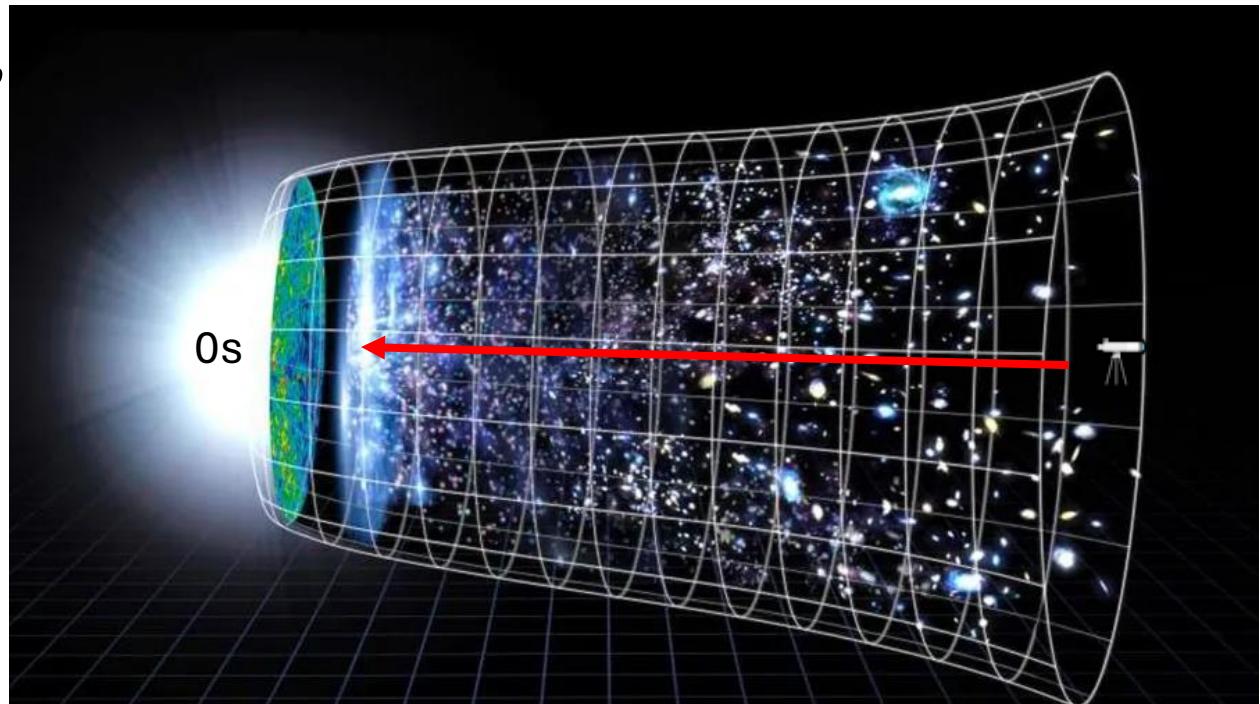


Crédito: Freedman 2021

2. Universo: evolución

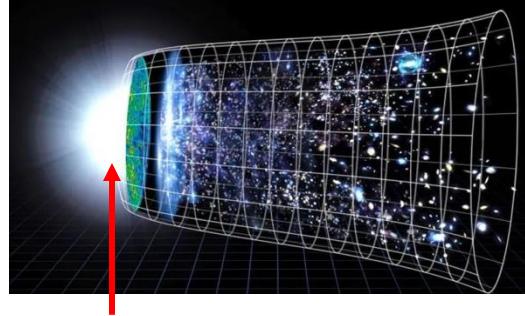
Edad del Universo

- $t_{Universo} = \frac{1}{H_0}$
- 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

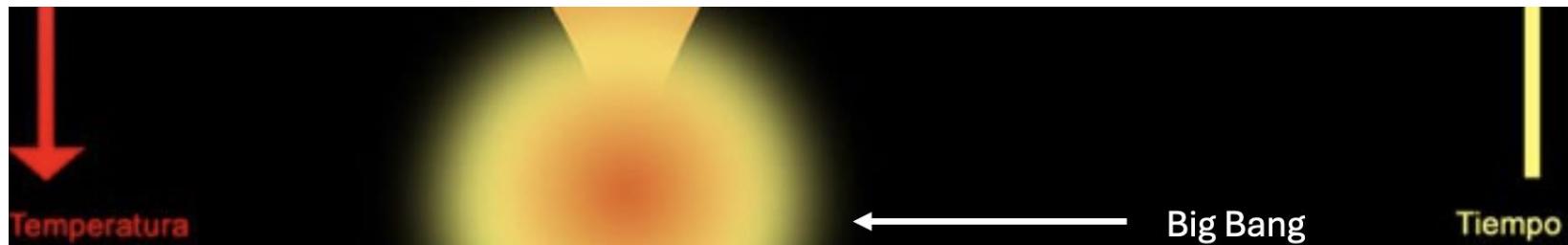


Crédito: MIT Technology Review

Escala de Planck

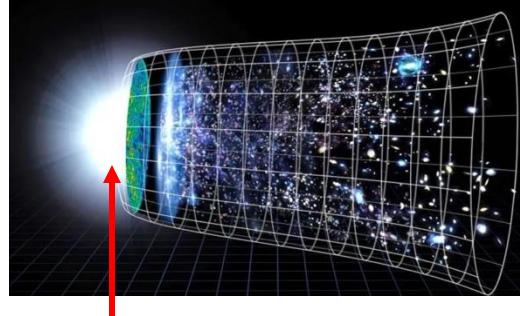


- Unidades mínimas: $10^{-44}s, 10^{-35}m$
- Máxima densidad y temperatura
- Nada está definido → Espacio y tiempo diluidos
- Vacío cuántico

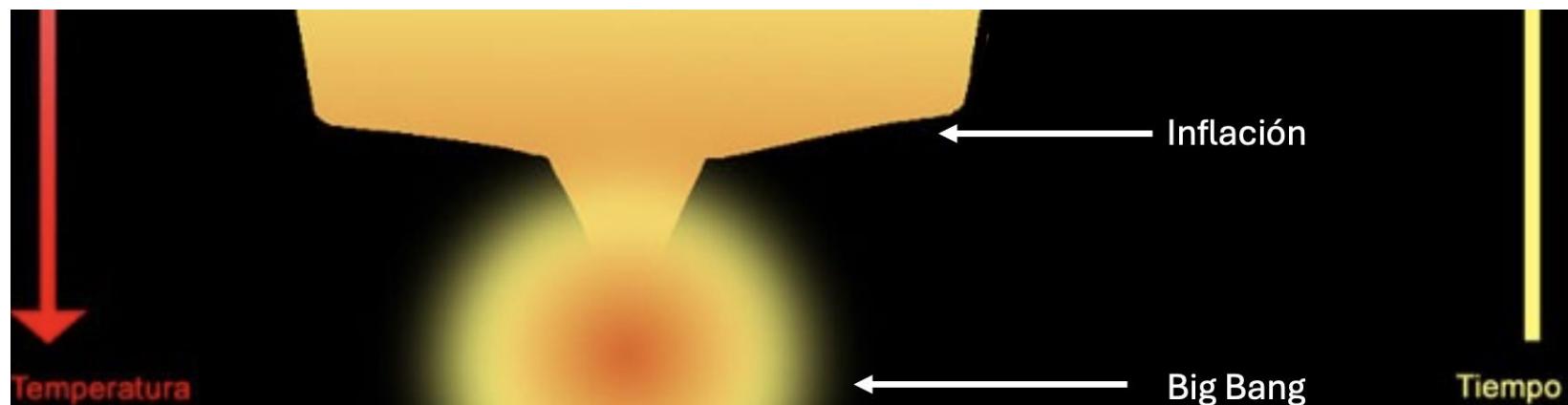


Crédito: IAC

Inflación - El Bang del Big Bang

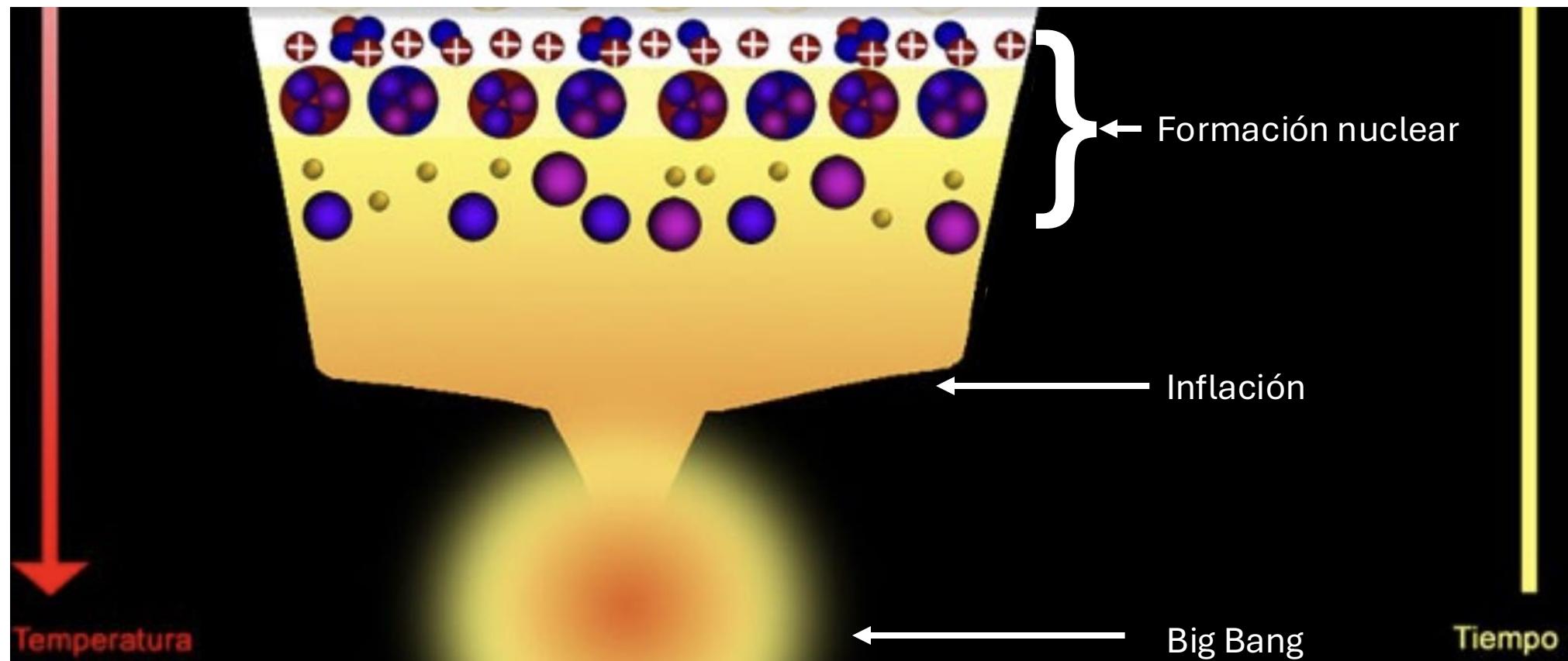
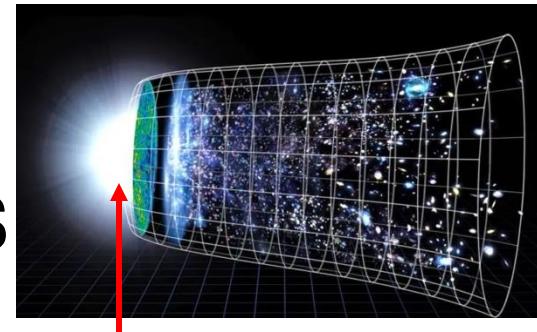


- Fluctuación cuántica
- Crecimiento exponencial: 10^{-13} cm a 2 cm
- Origen de la isotropía del Universo



Crédito: IAC

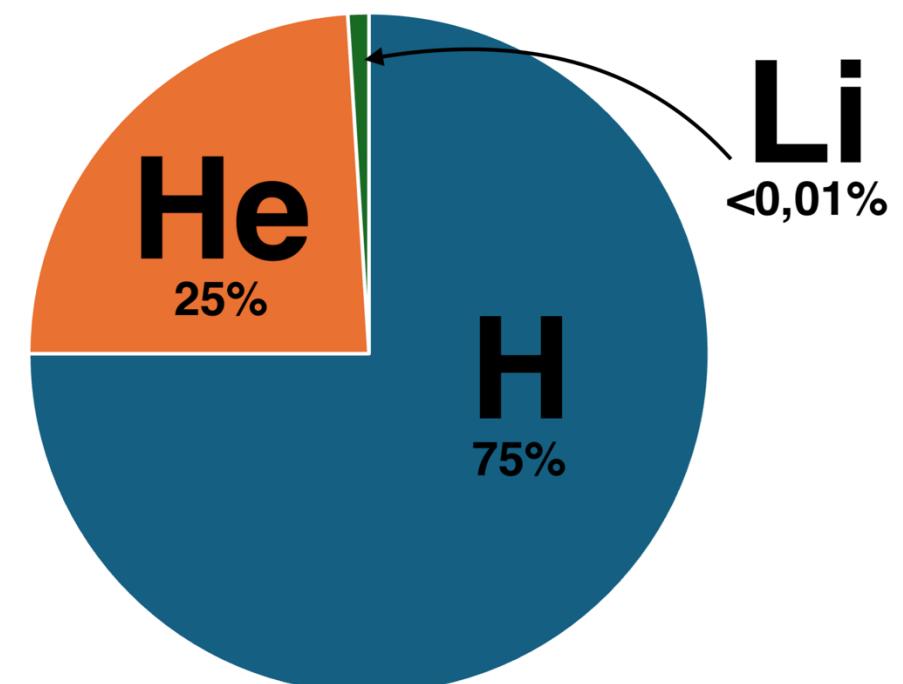
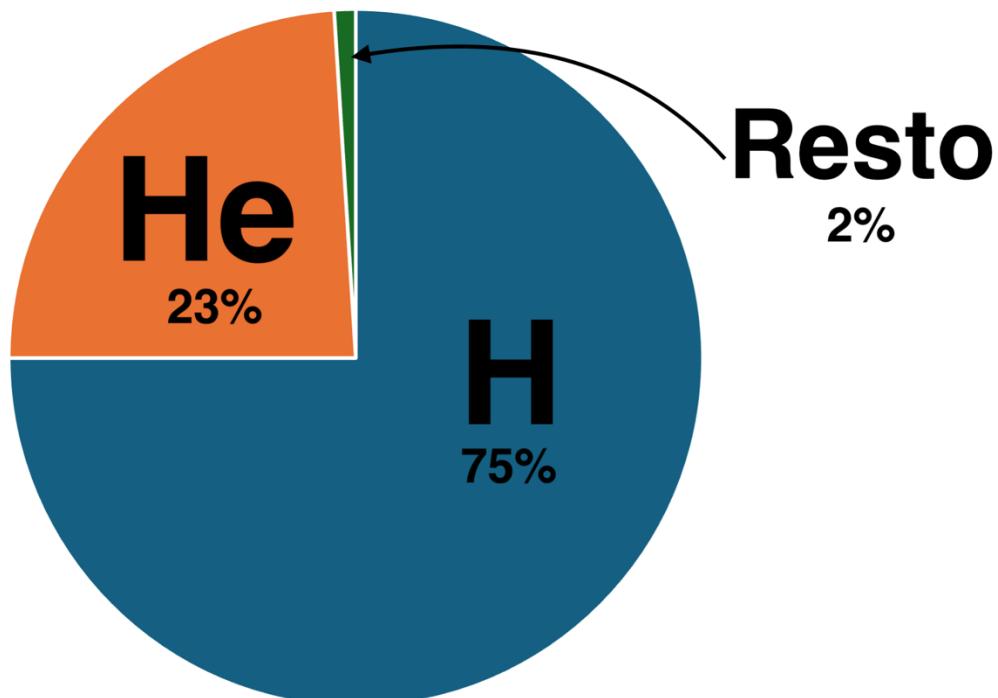
$10^{-12}s - 180s$: Formación de núcleos

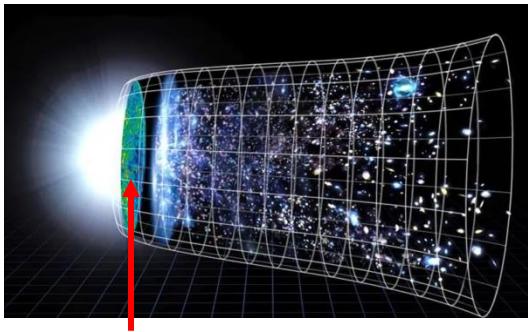


Crédito: IAC

Composición del Universo en $t = 180s$

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

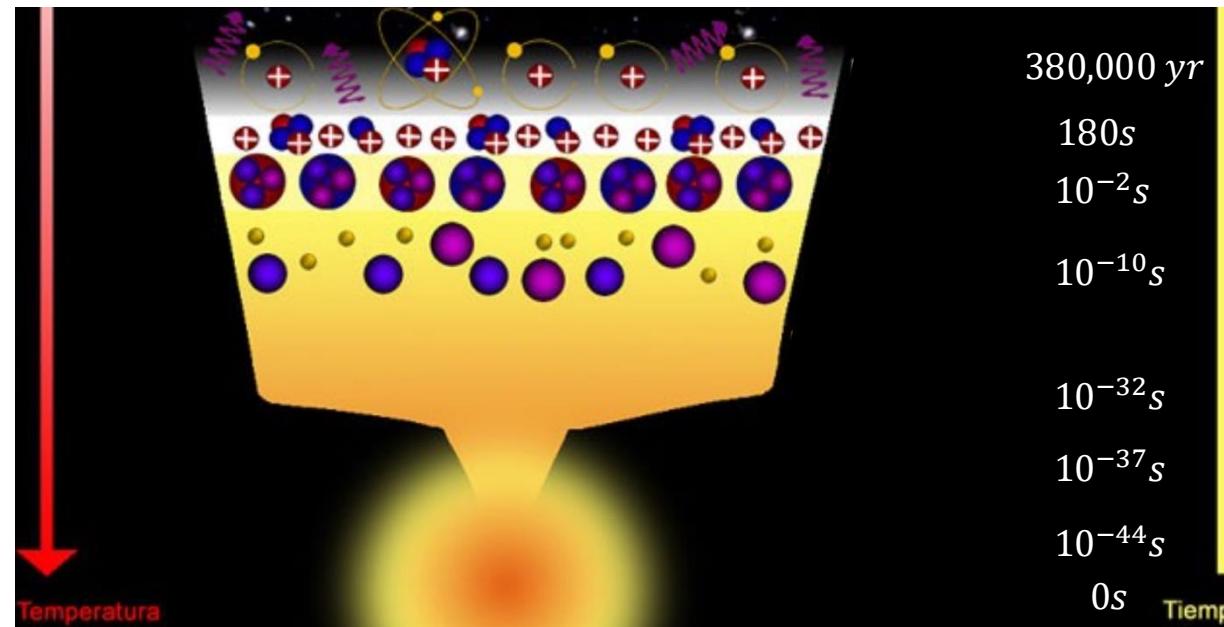




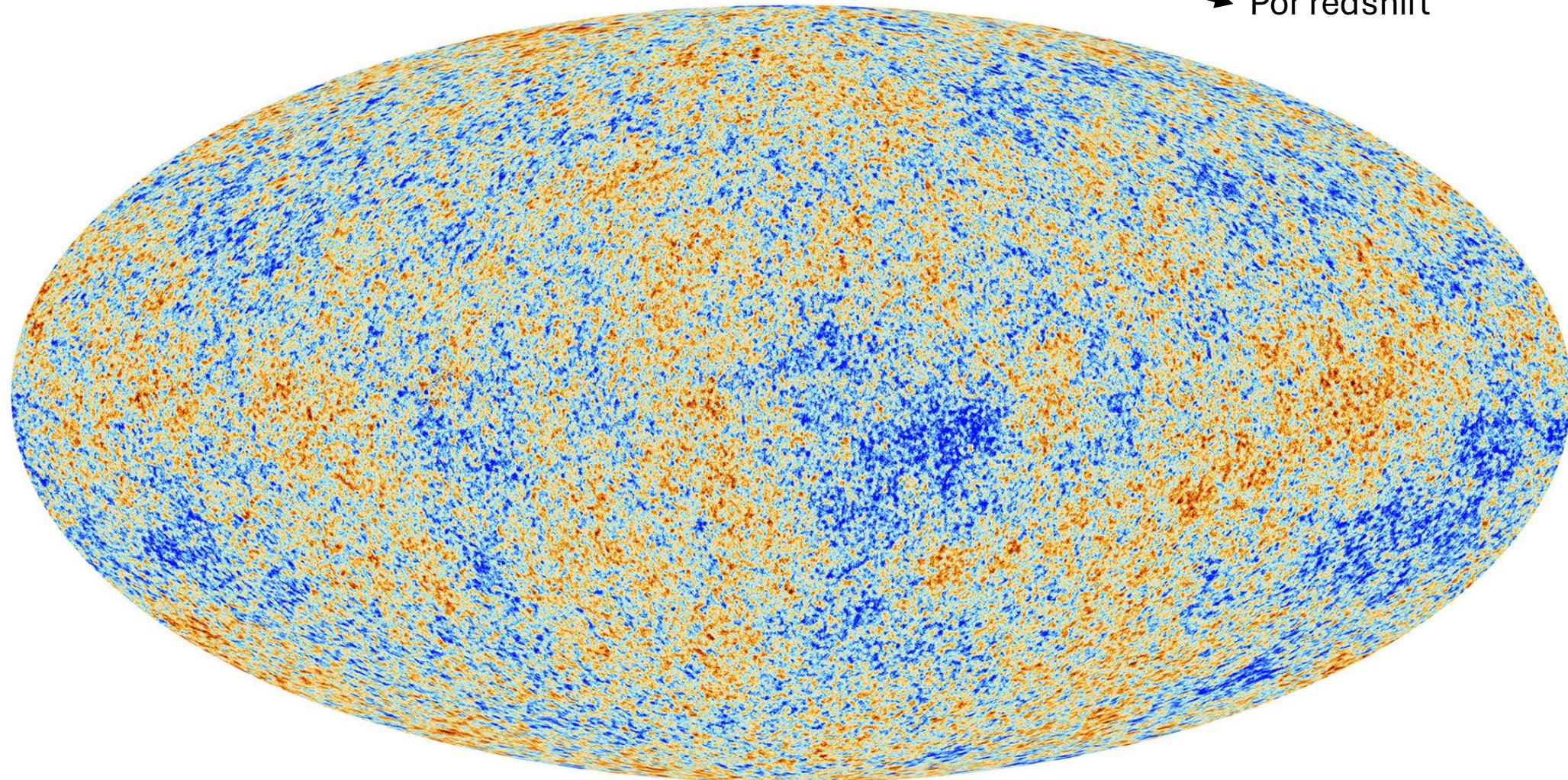
3. Universo: CMB

Fondo Cómico 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

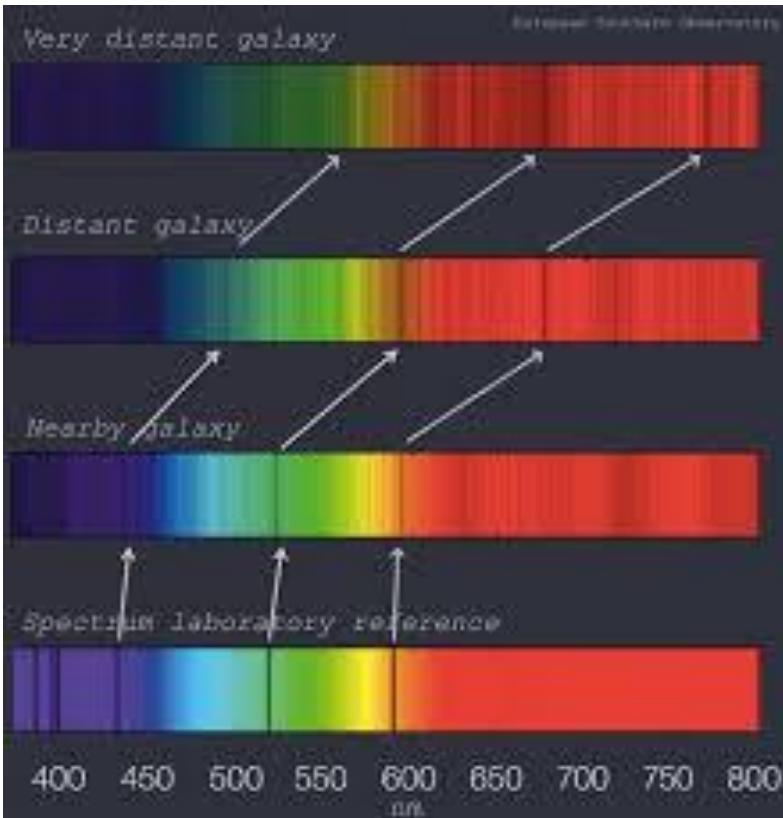


Fondo Cómico de Microondas (CMB)



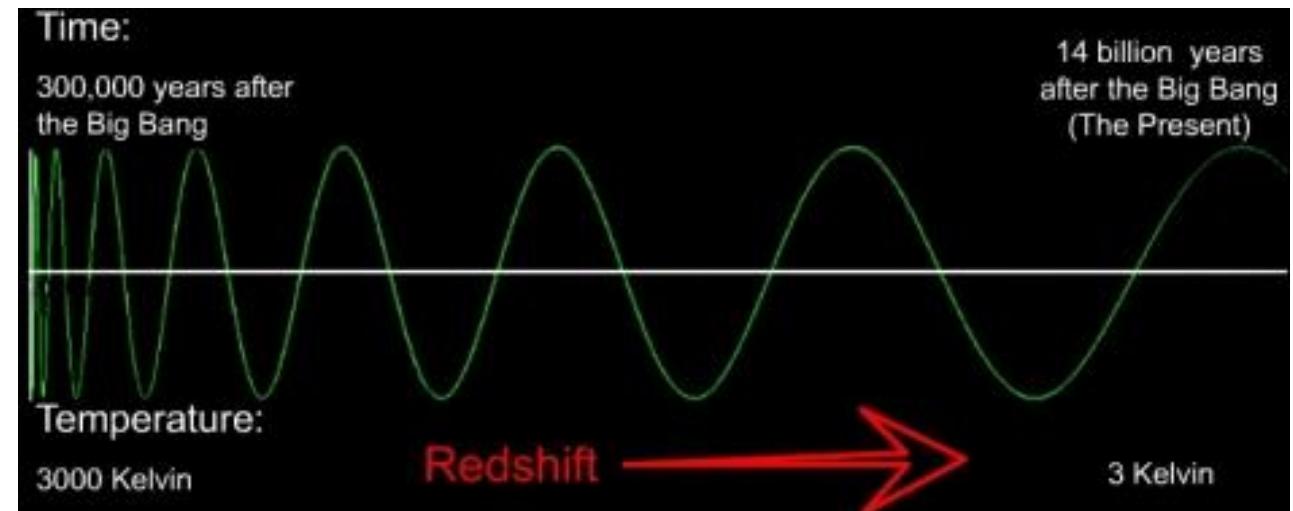
Crédito: ESA

Fondo Cómico de Microondas (CMB)



Crédito ESO

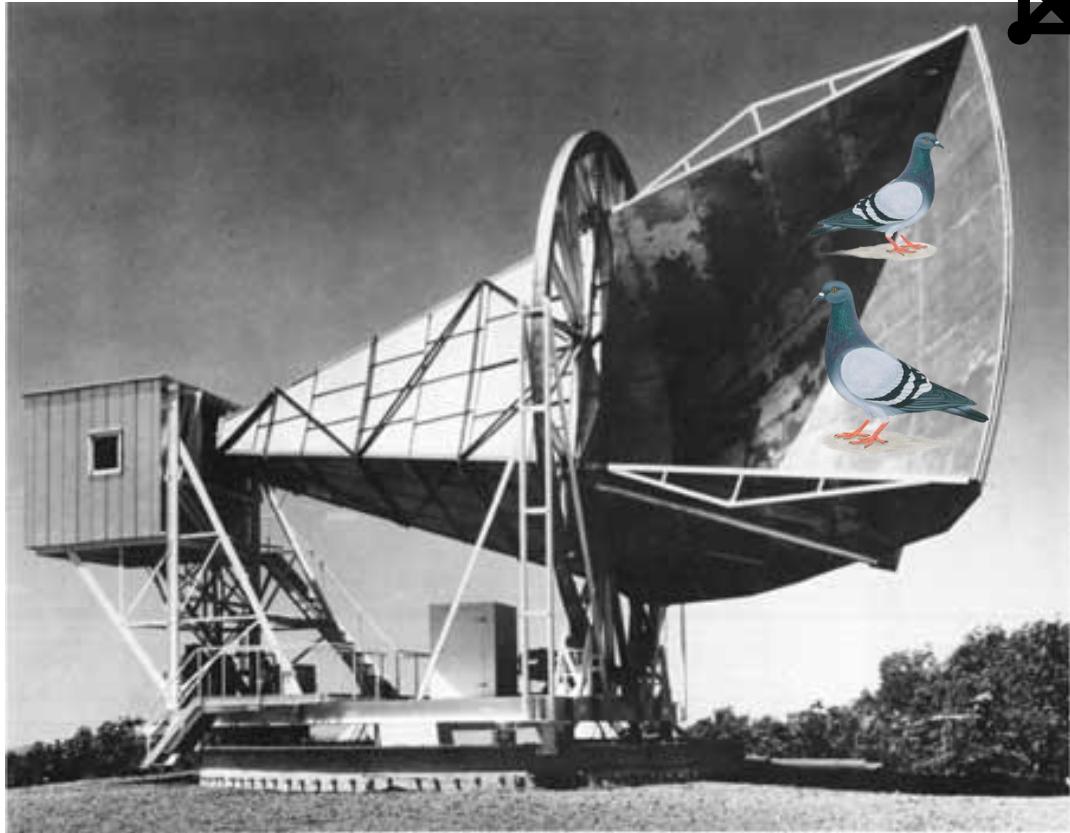
Por redshift



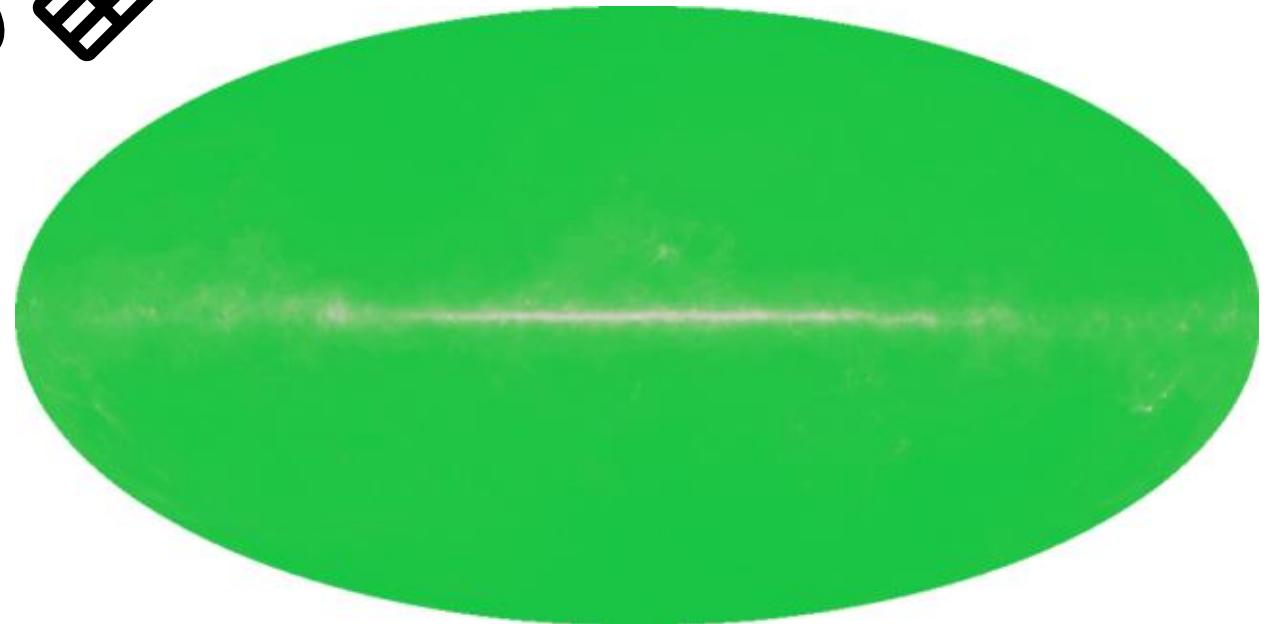
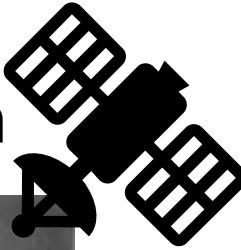
Crédito: The Universe Adventure

Descubrimiento

- Arno Penzias y Robert Wilson



Crédito: National Park Service | Celebrate Urban Birds



Crédito: Penzias & Wilson 1965, NASA

Descubrimiento

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

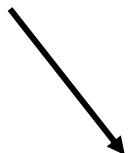
Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our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

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

COSMIC BLACK-BODY RADIATION*

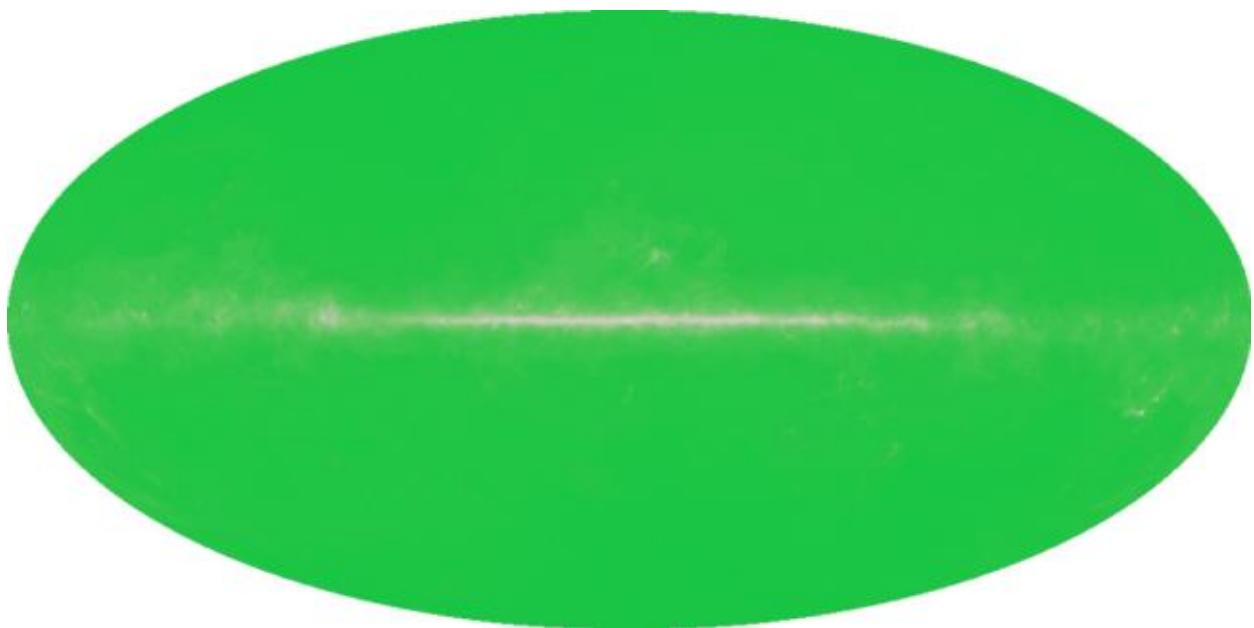
One of the basic problems of cosmology is the singularity characteristic of the familiar cosmological solutions of Einstein's field equations. Also puzzling is the presence of matter in excess over antimatter in the universe, for baryons and leptons are thought to be conserved. Thus, in the framework 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-

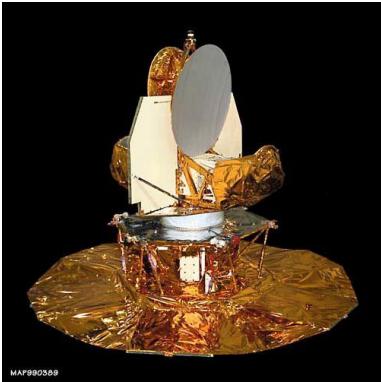


Crédito: Penzias & Wilson 1965, NASA

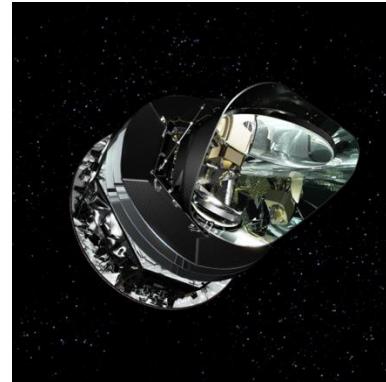
Otras mediciones del CMB



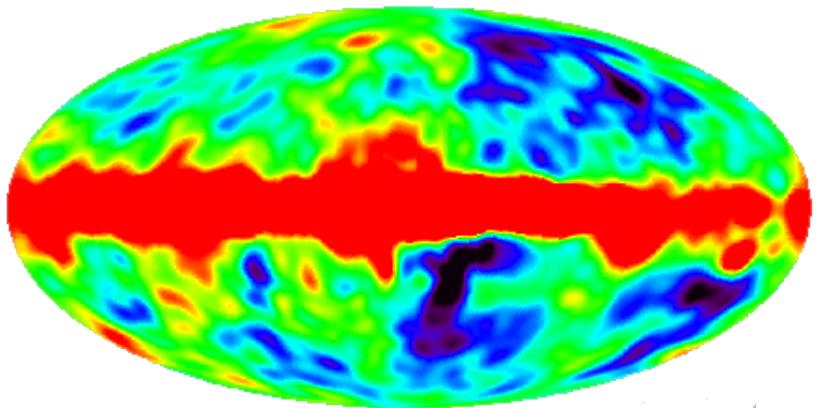
Crédito: NASA Science



Crédito: NASA

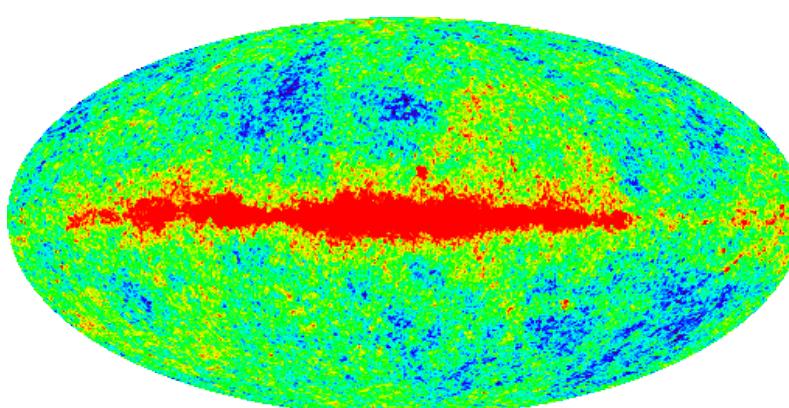


Crédito: ESA



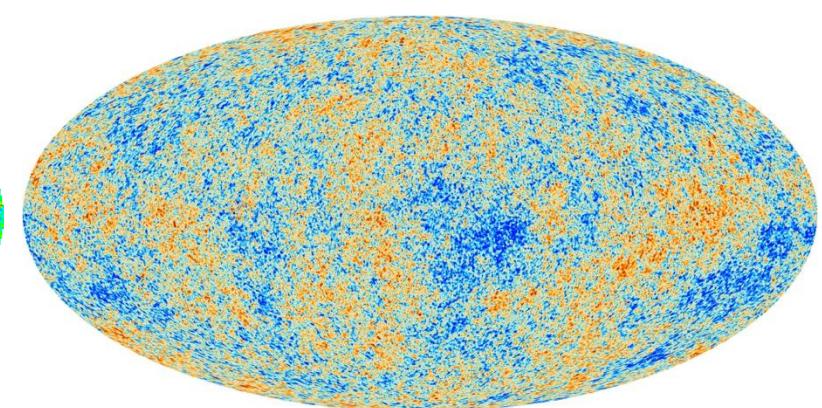
Crédito: CMB Introduction

COBE



Crédito: NASA

WMAP



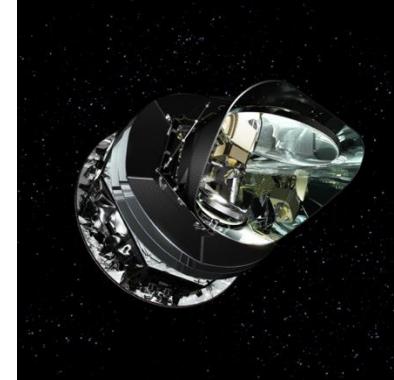
Crédito: ESA

Planck

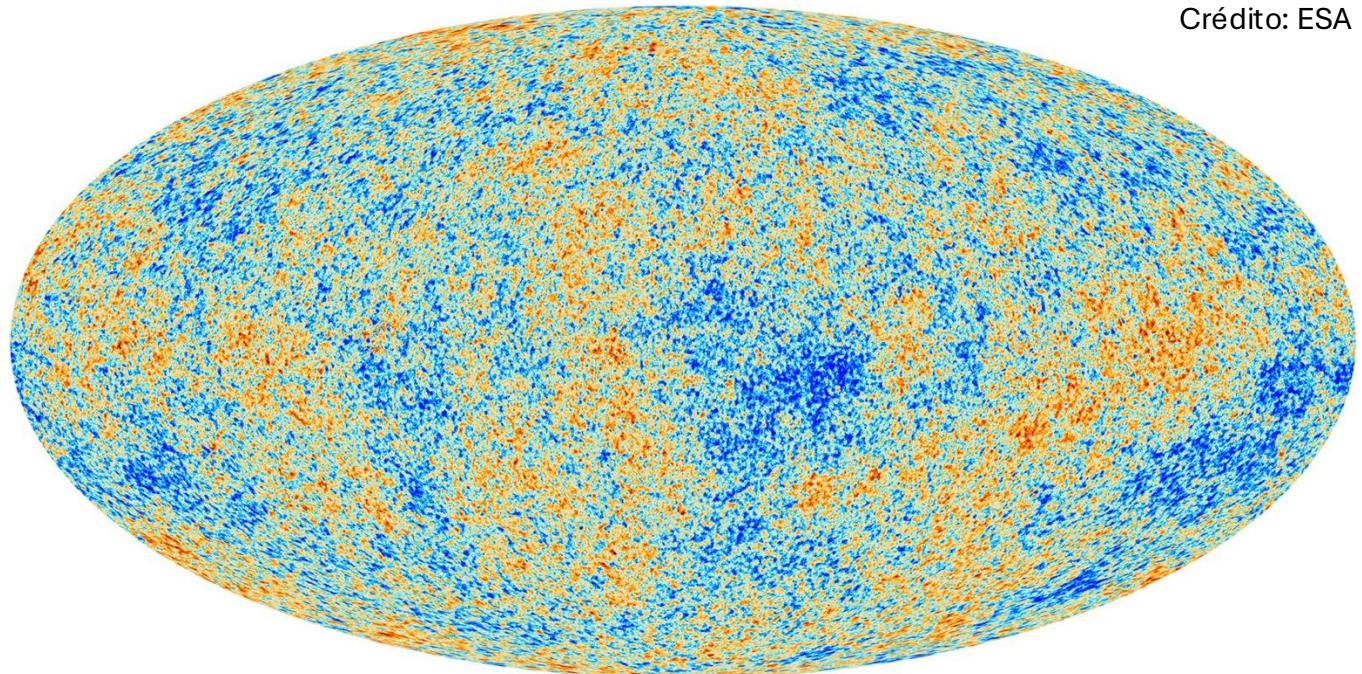
Otras mediciones del CMB

- Radiación no homogénea
- Universo anisotrópico (μK)
- Predicción de la Teoría del Big Bang

Planck



Crédito: ESA

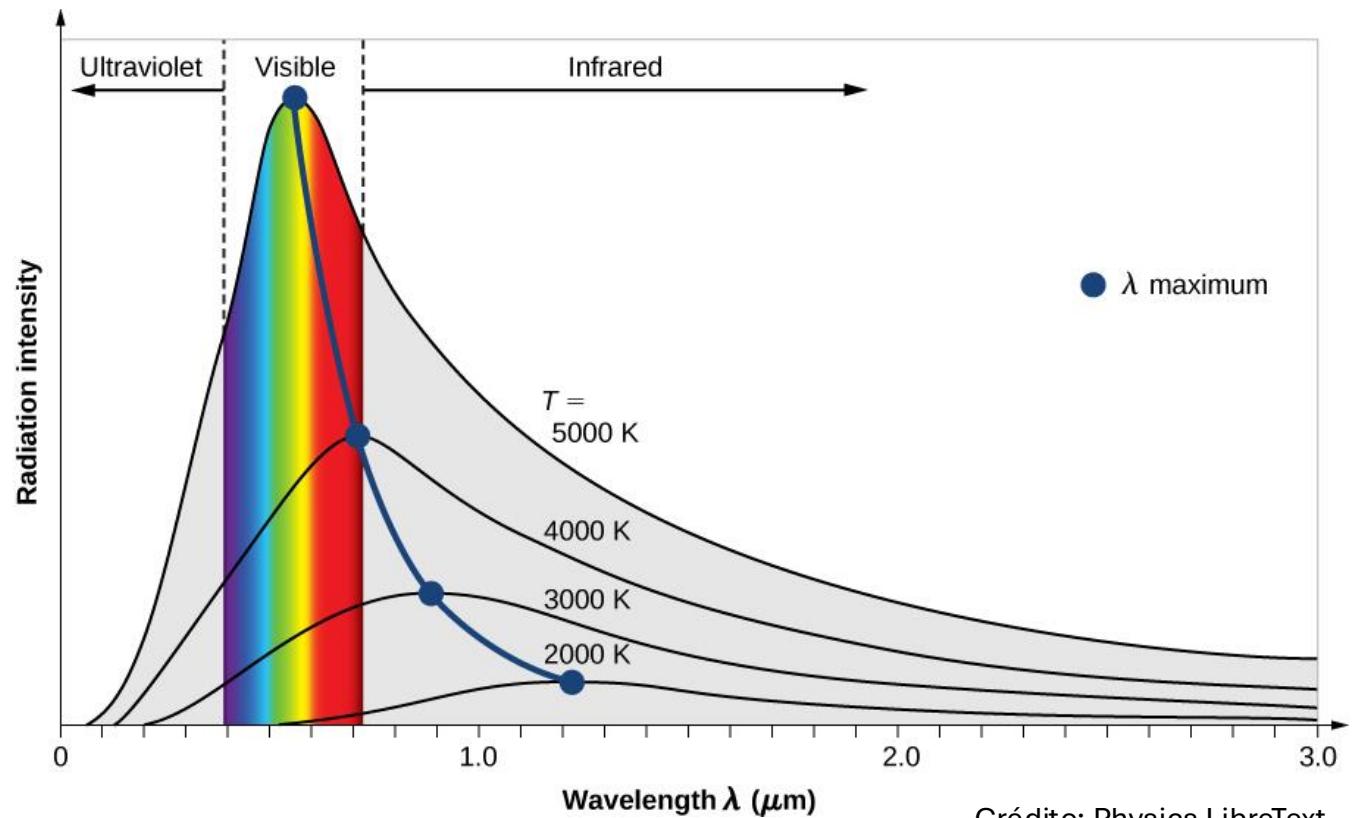


Crédito: ESA

Radiación de Cuerpo negro

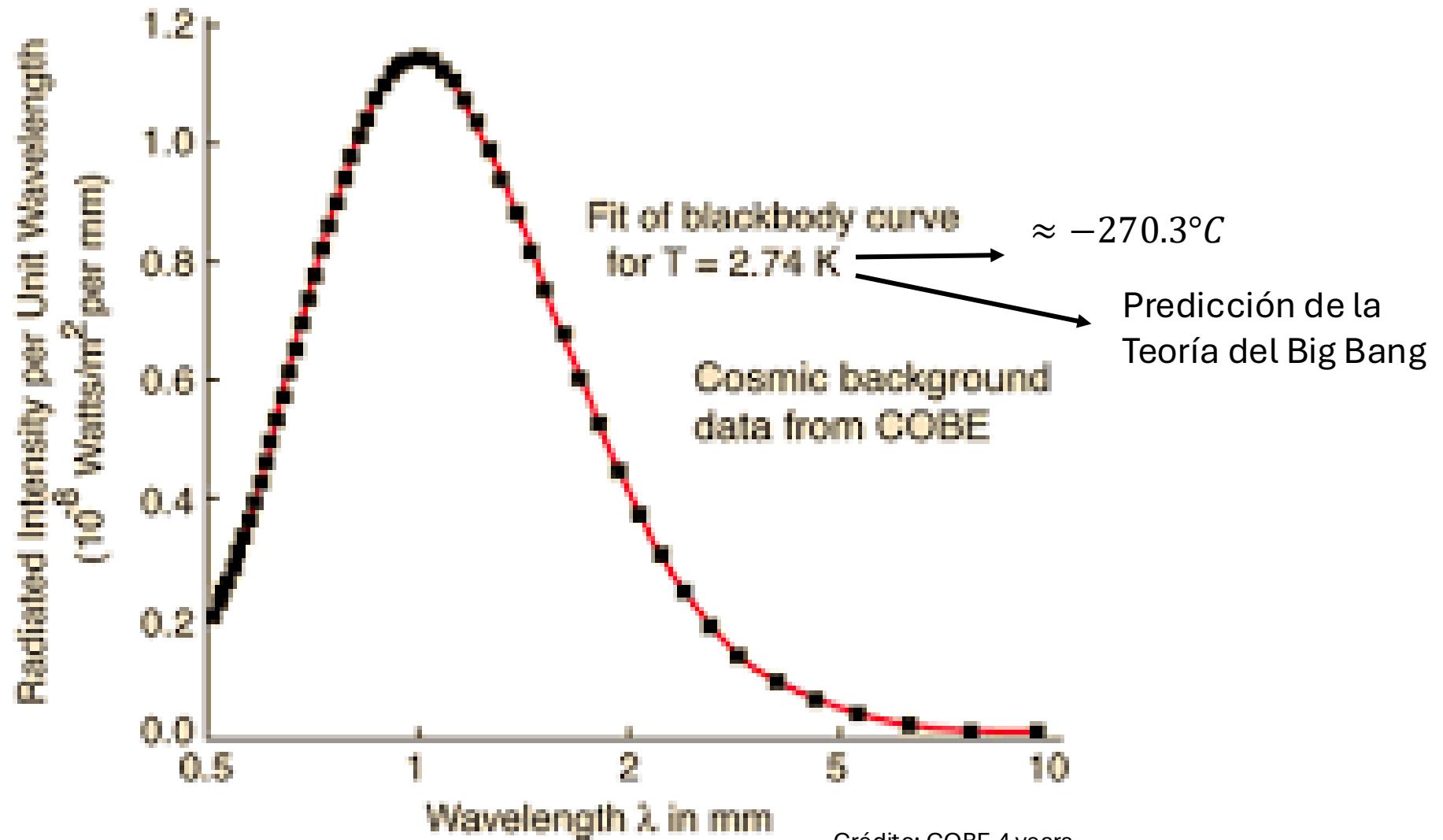
- Cualquier cuerpo con temperatura emite radiación electromagnética
- Relación entre temperatura y emisión por longitud de onda

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



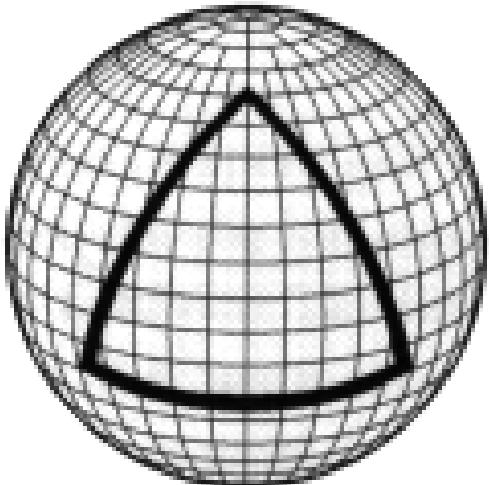
Crédito: Physics LibreText

Temperatura del Universo

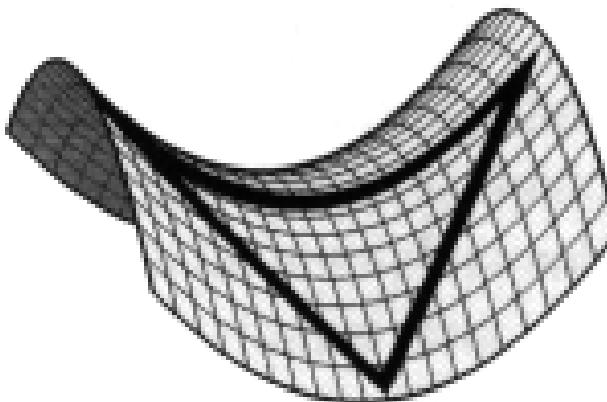


Geometría del Universo

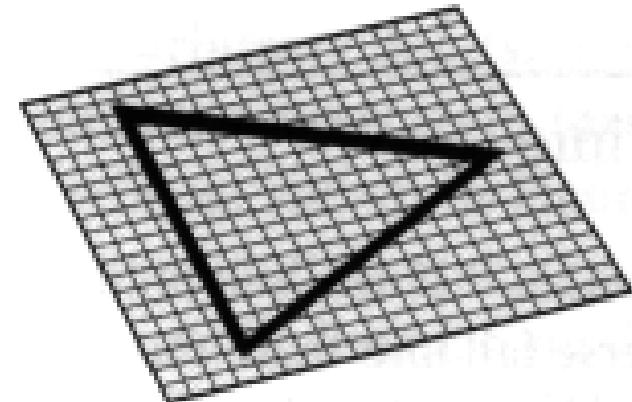
- Expansión indefinida
- Densidad baja
- Expansión finita, Big Crunch
- Densidad baja
- Se expande infinitamente
- Velocidad de expansión depende de la energía oscura



Positive Curvature

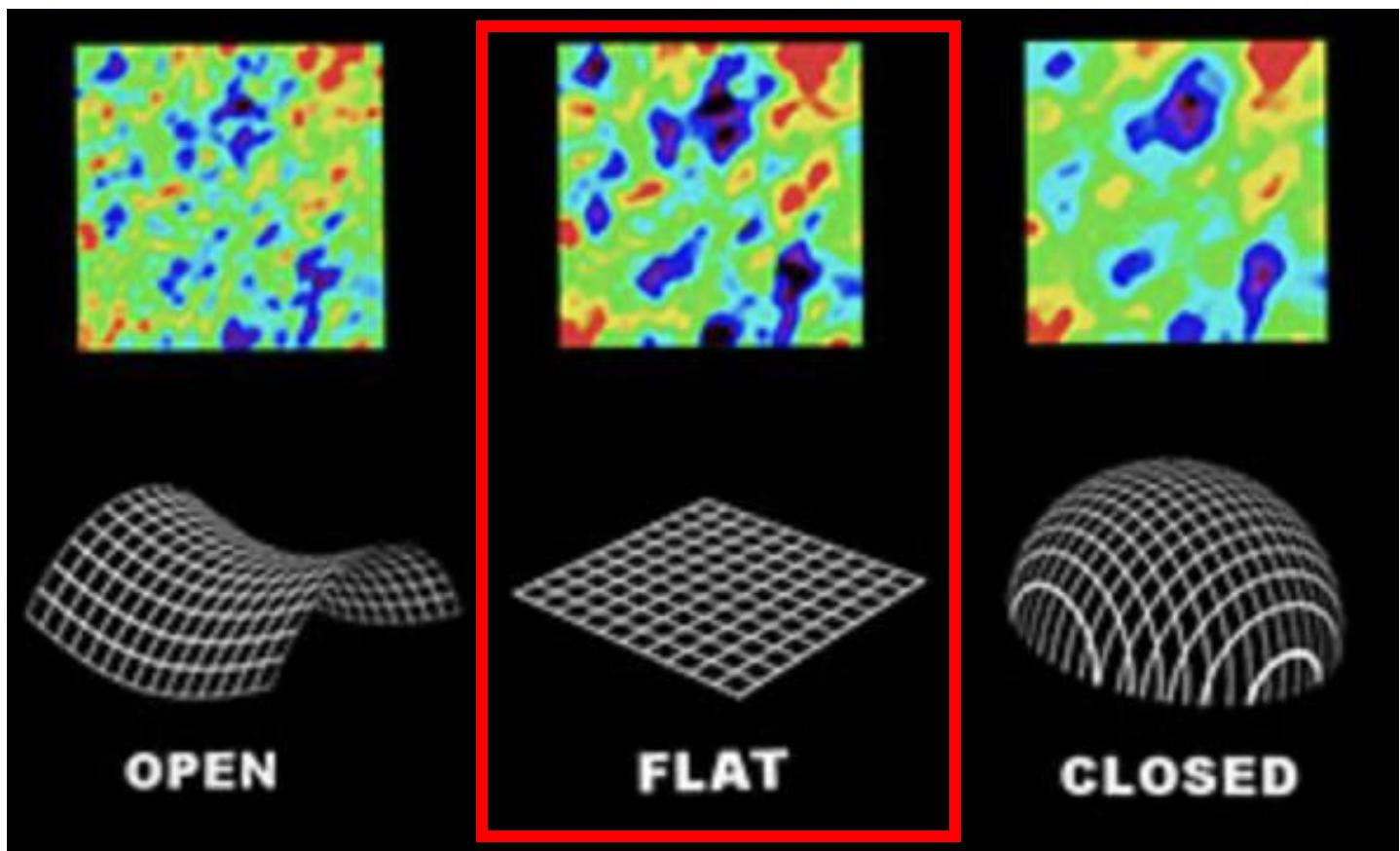
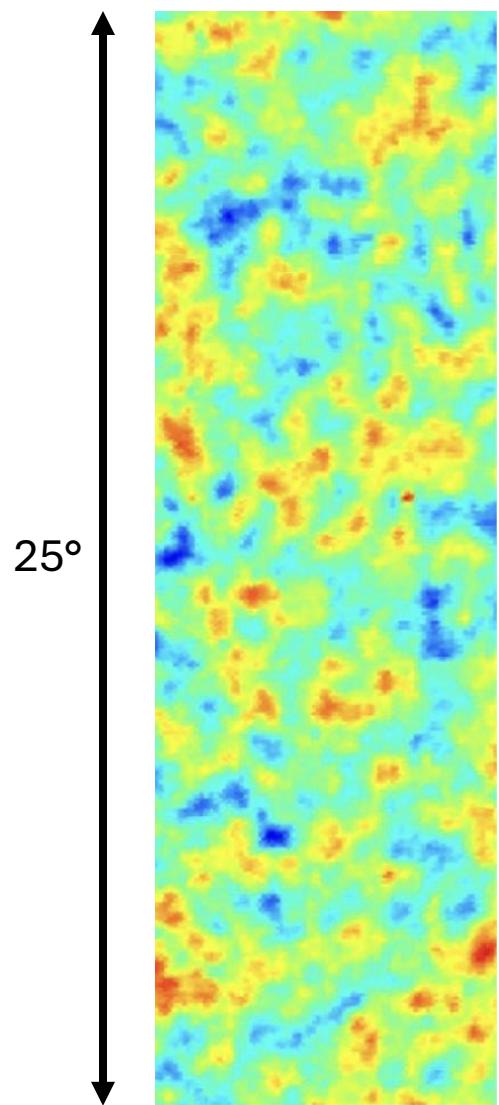


Negative Curvature



Flat Curvature

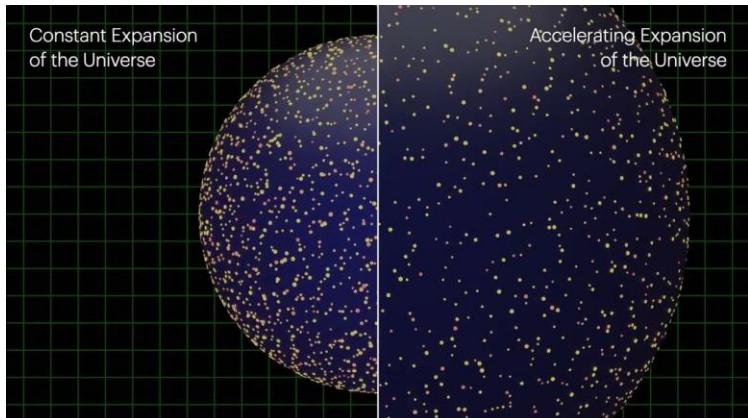
Geometría del Universo



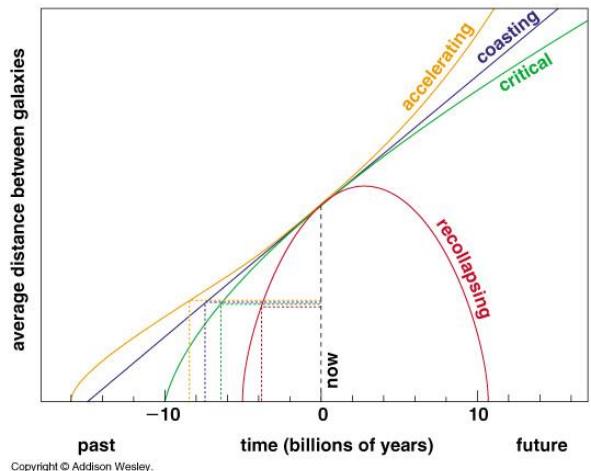
Crédito: Physics LibreText

Crédito: WMAP - NASA

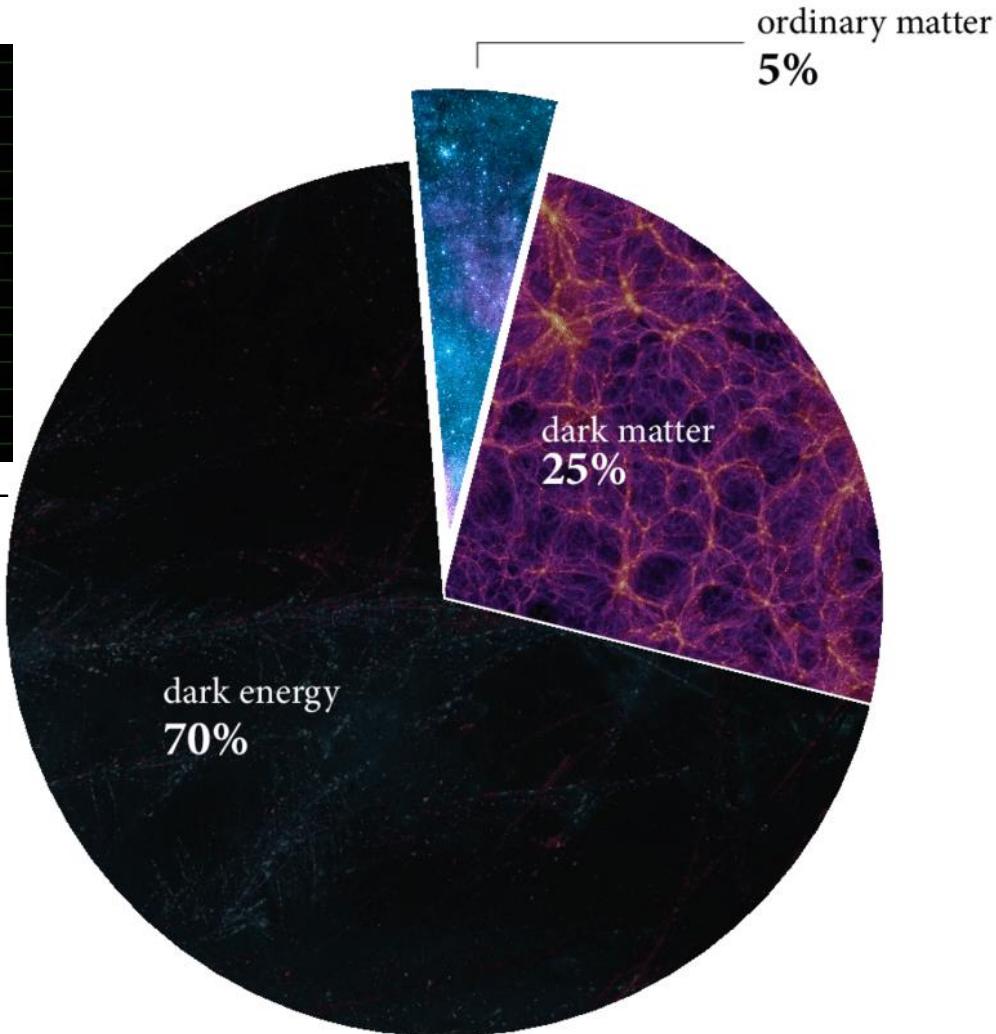
Composición del Universo



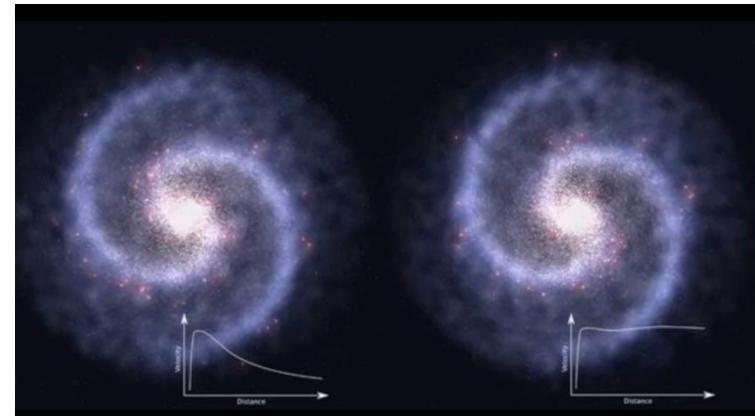
Crédito: NASA, JPL



Crédito: U. Mass Amherst



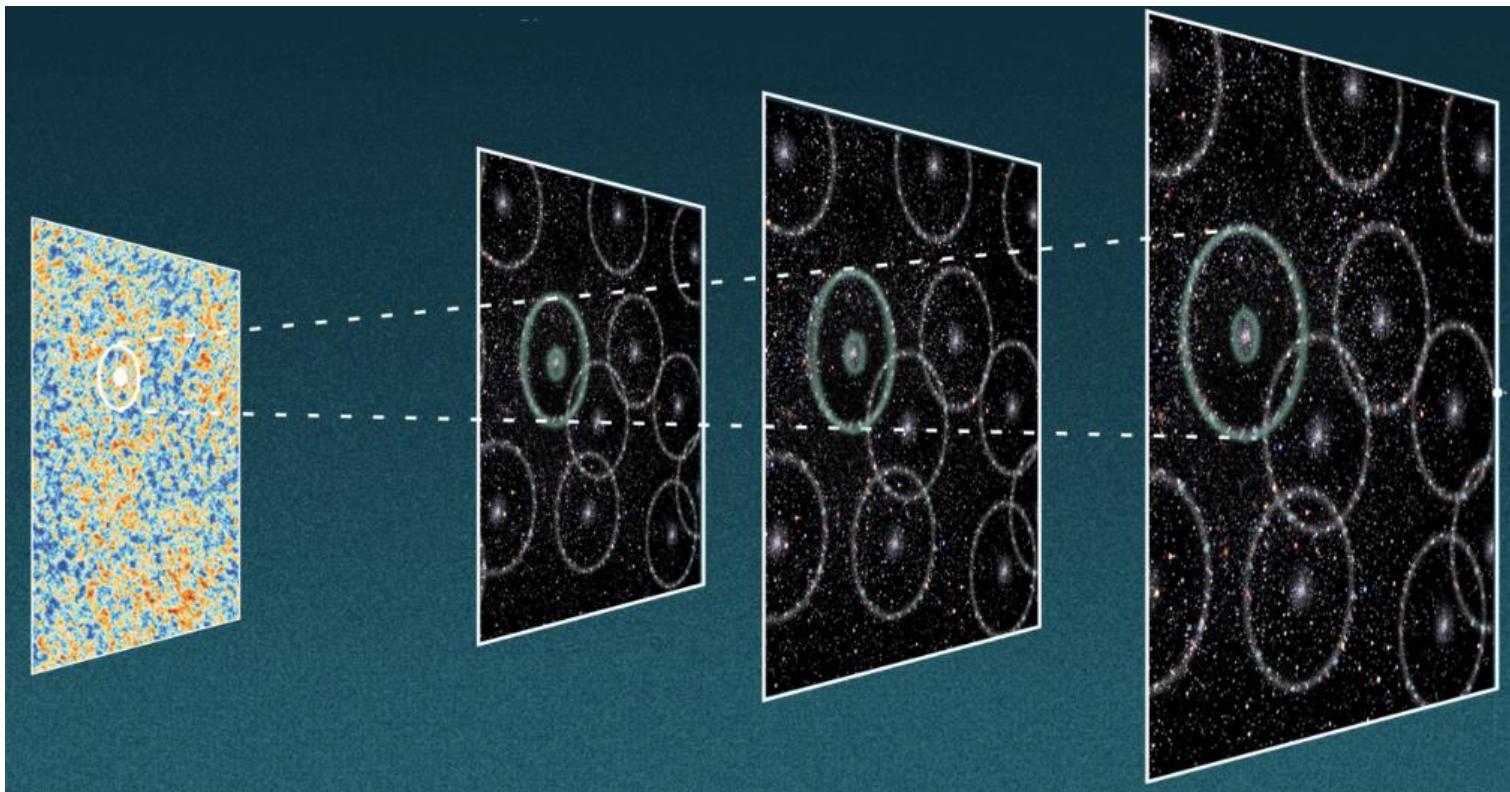
Crédito: Wolz 2022 (doi: 10.15488/12103)



Crédito: Wikipedia

Constante de Hubble (BAO)

- Baryonic Acoustic Oscillations: ‘standard rulers’



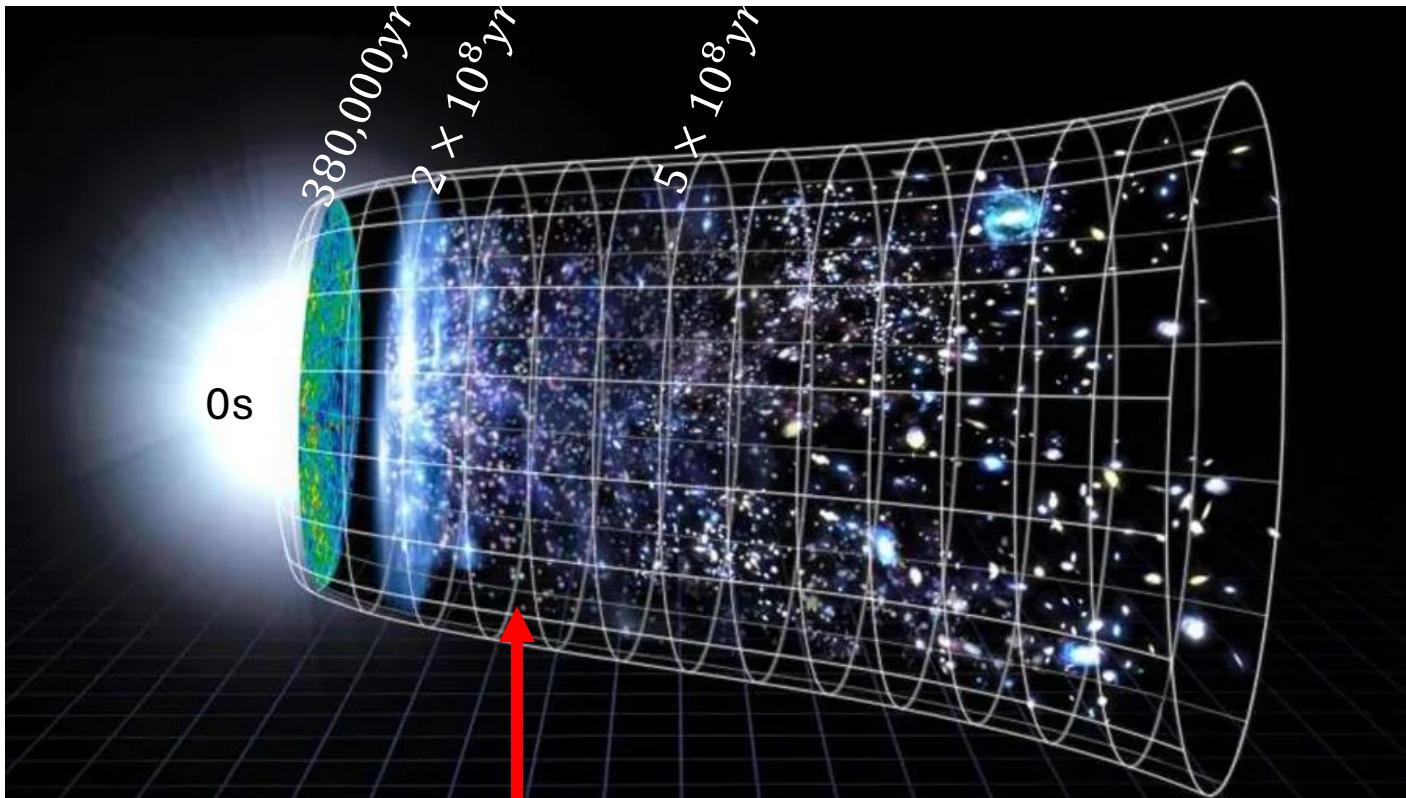
Crédito: ESA EUCLID

$$H_0 \approx 67.4 \pm 0.5 \text{ km s}^{-1}\text{Mpc}^{-1}$$

(Aghanim et al. 2020, Planck Collaboration)

4. Estrellas: formación y evolución

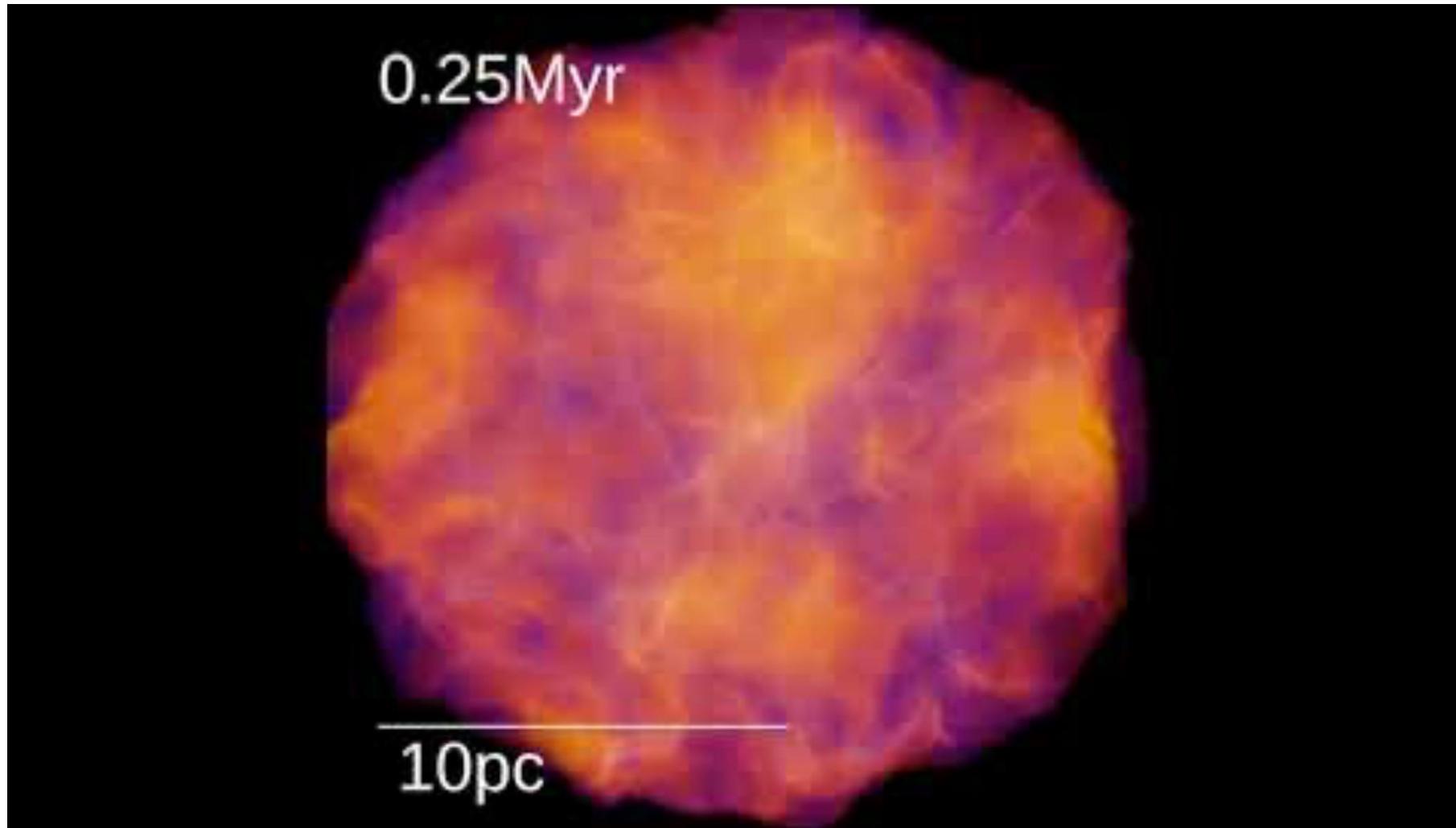
300-500 millones años: Primeras estrellas



Crédito: MIT Technology Review

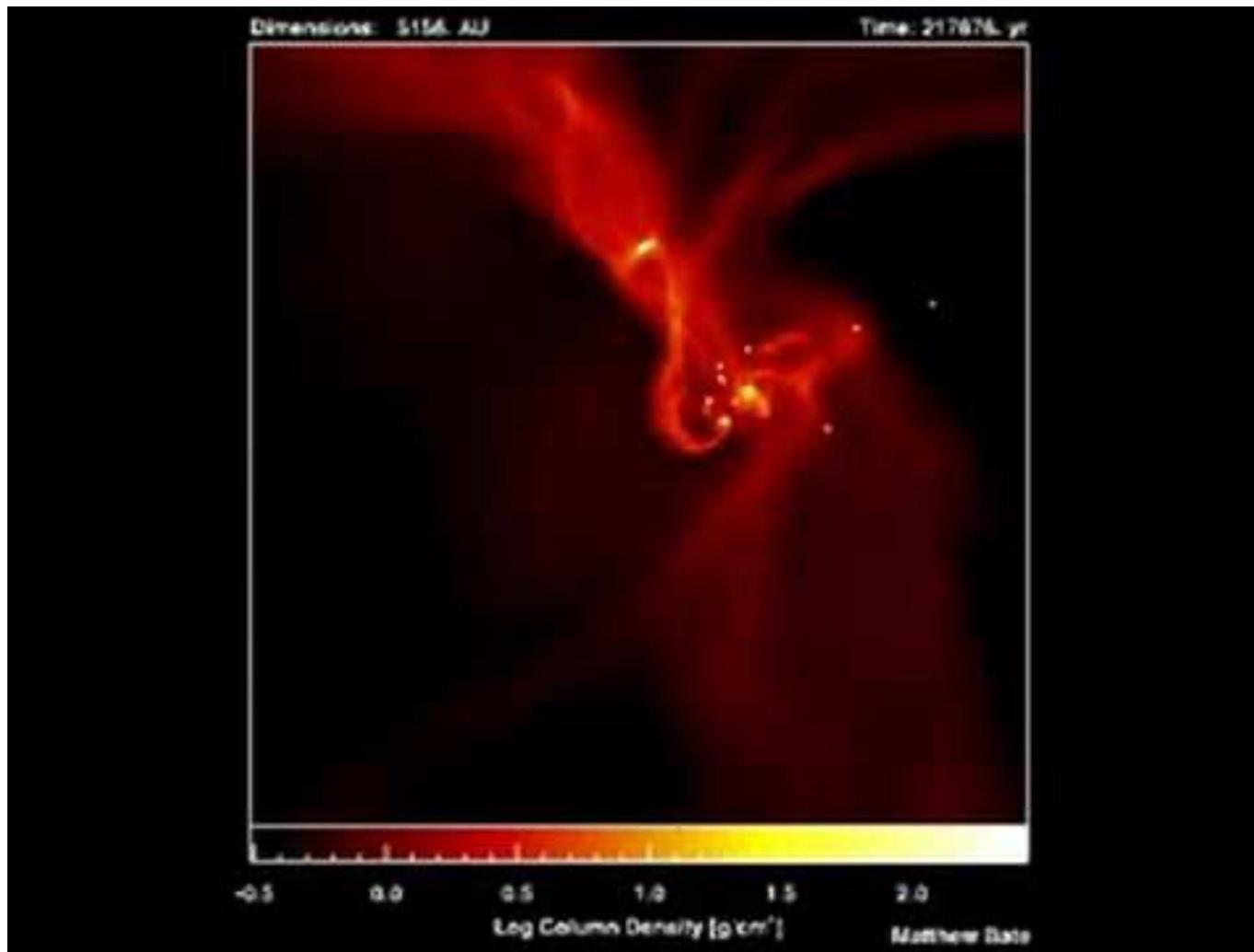
- Distribución de materia (BM + DM) no es uniforme
- ‘Grumos’ de gravedad atraen y acumulan masa
- Nubes de gas masivas colapsan
- Con suficiente presión → fusión!

Formación estelar



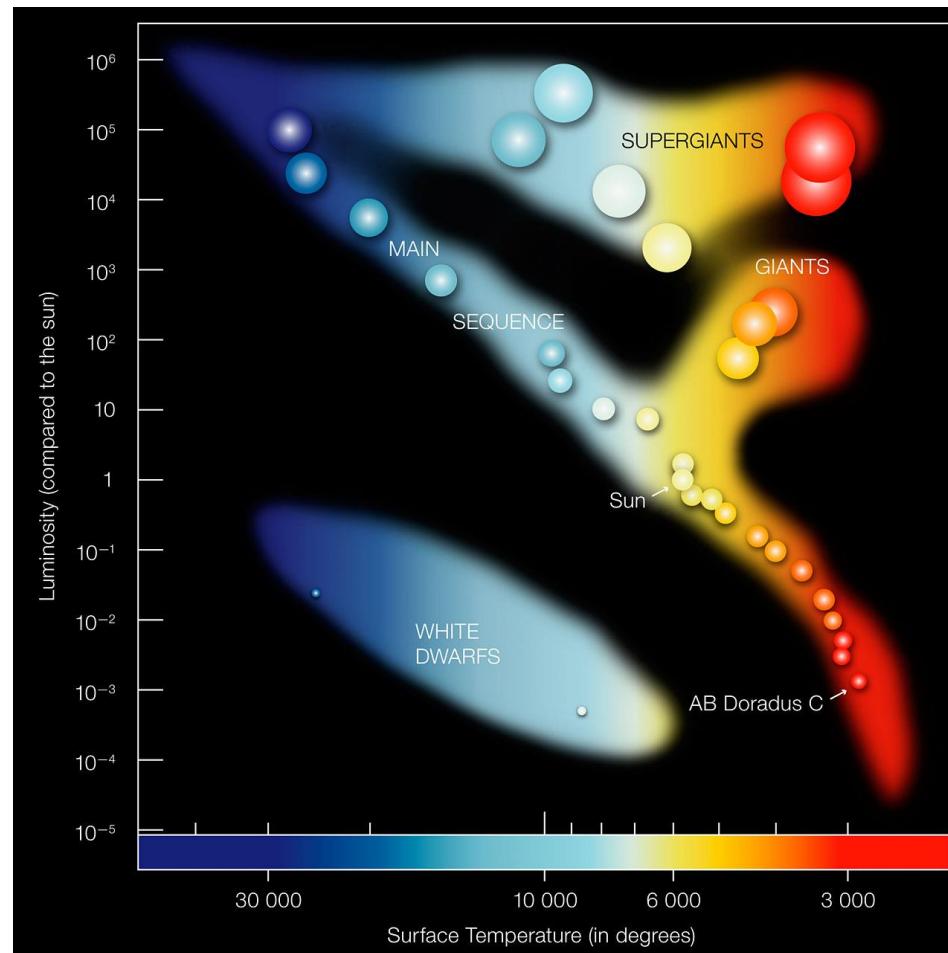
Crédito: STARFORGE

Formación estelar

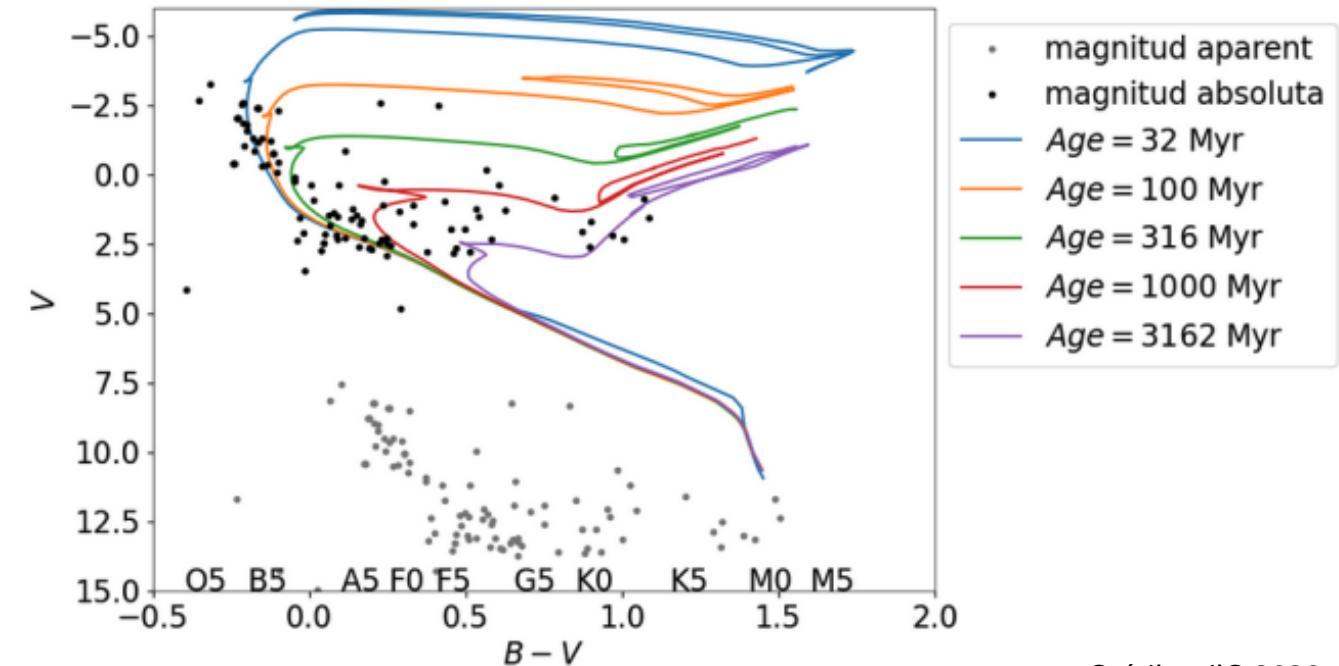


Crédito: Bate et al. 2008

Diagrama HR (Hertzsprung-Russell)



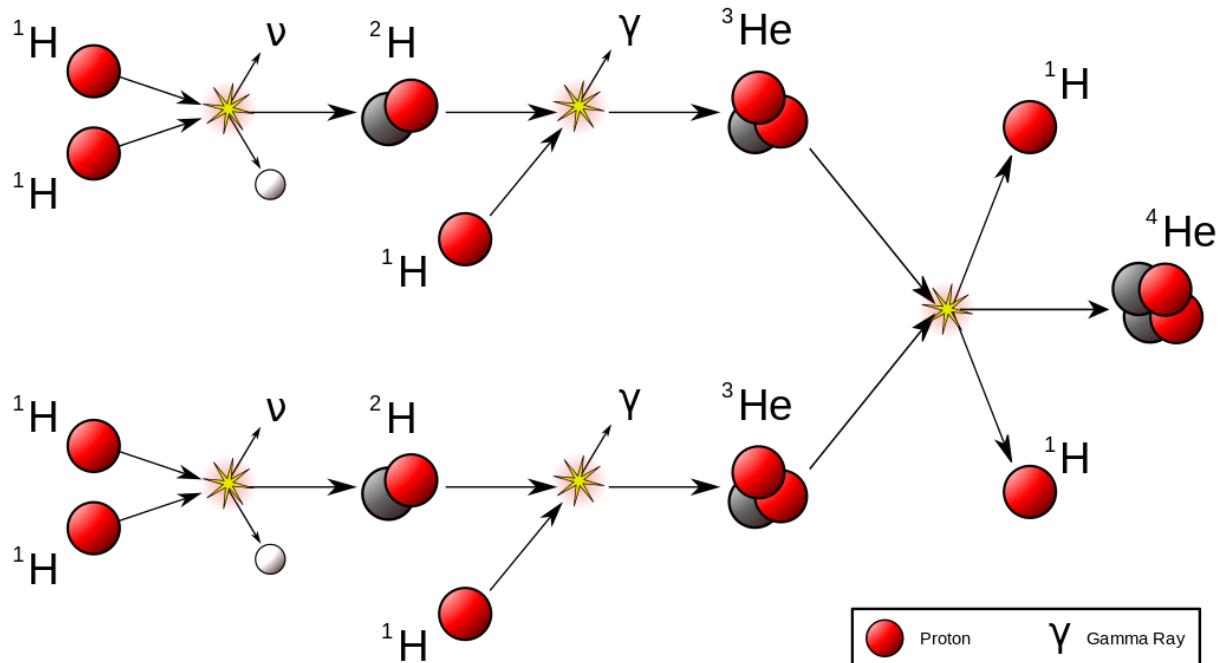
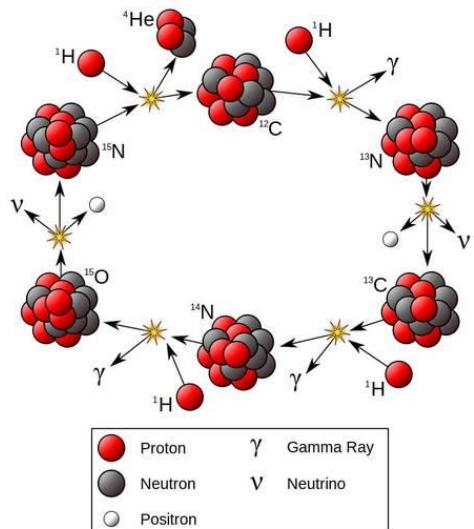
Crédito: ESO



Crédito: JiC 2023

Energía de las estrellas

- Fusión termonuclear
- Otros procesos:
 - PP chain
 - CNO Cycle
 - Triple- α

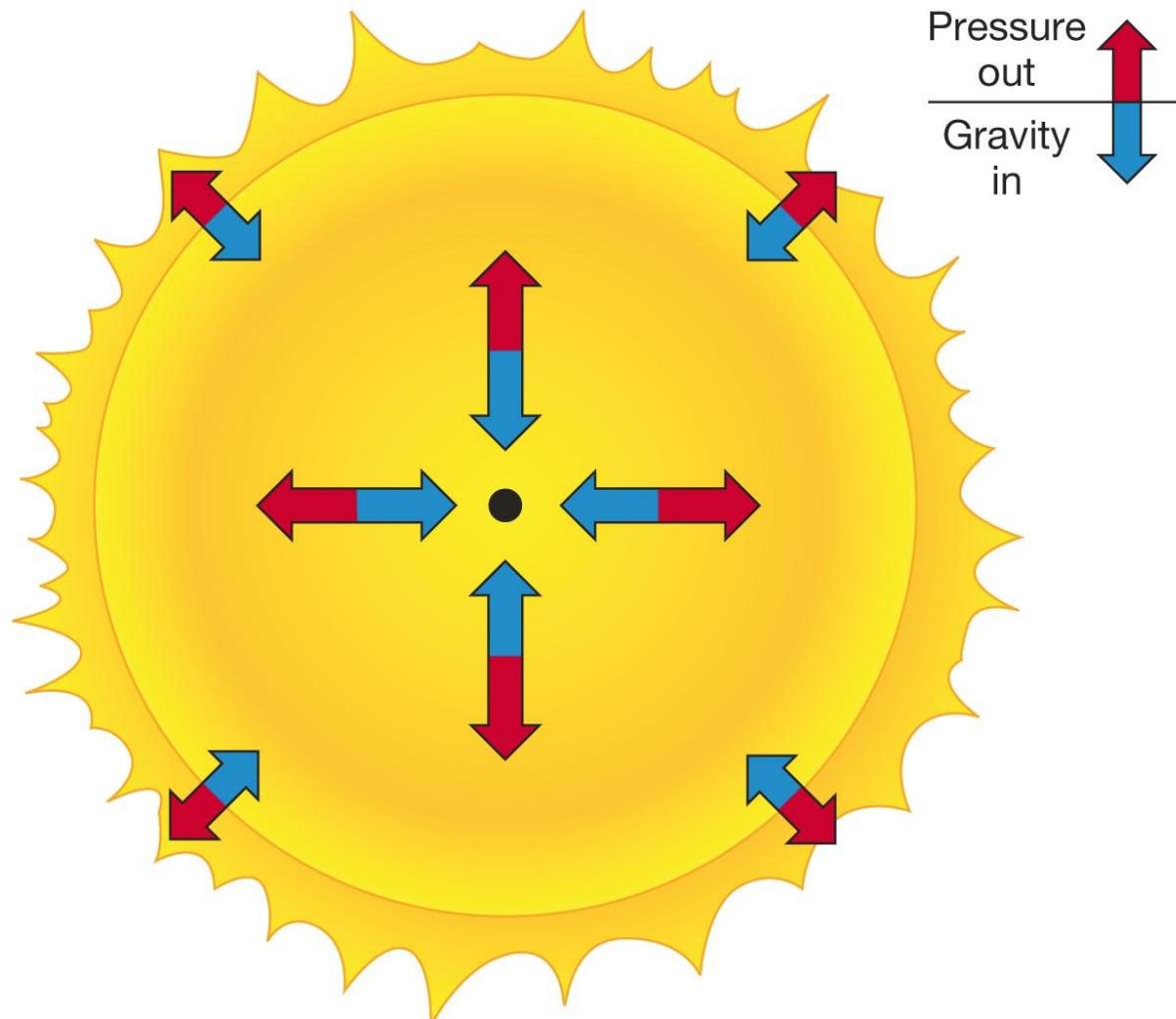


Legend:

- Proton: Red sphere
- Neutron: Grey sphere
- Positron: Open circle
- Gamma Ray: Curved arrow
- Neutrino: Curved arrow with a dot

Crédito: EUROFusion

Un ejercicio de equilibrio (hidrostático)



Evolución estelar

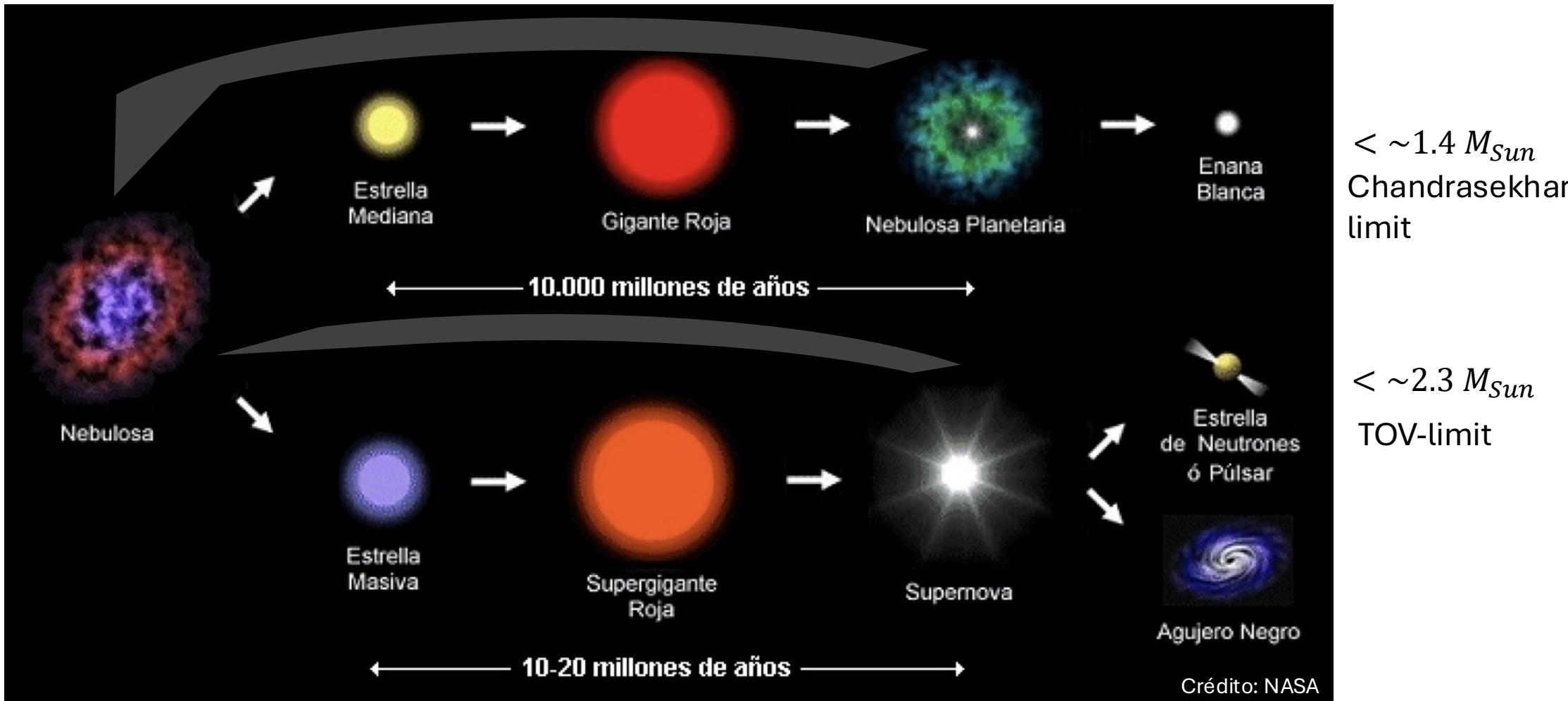
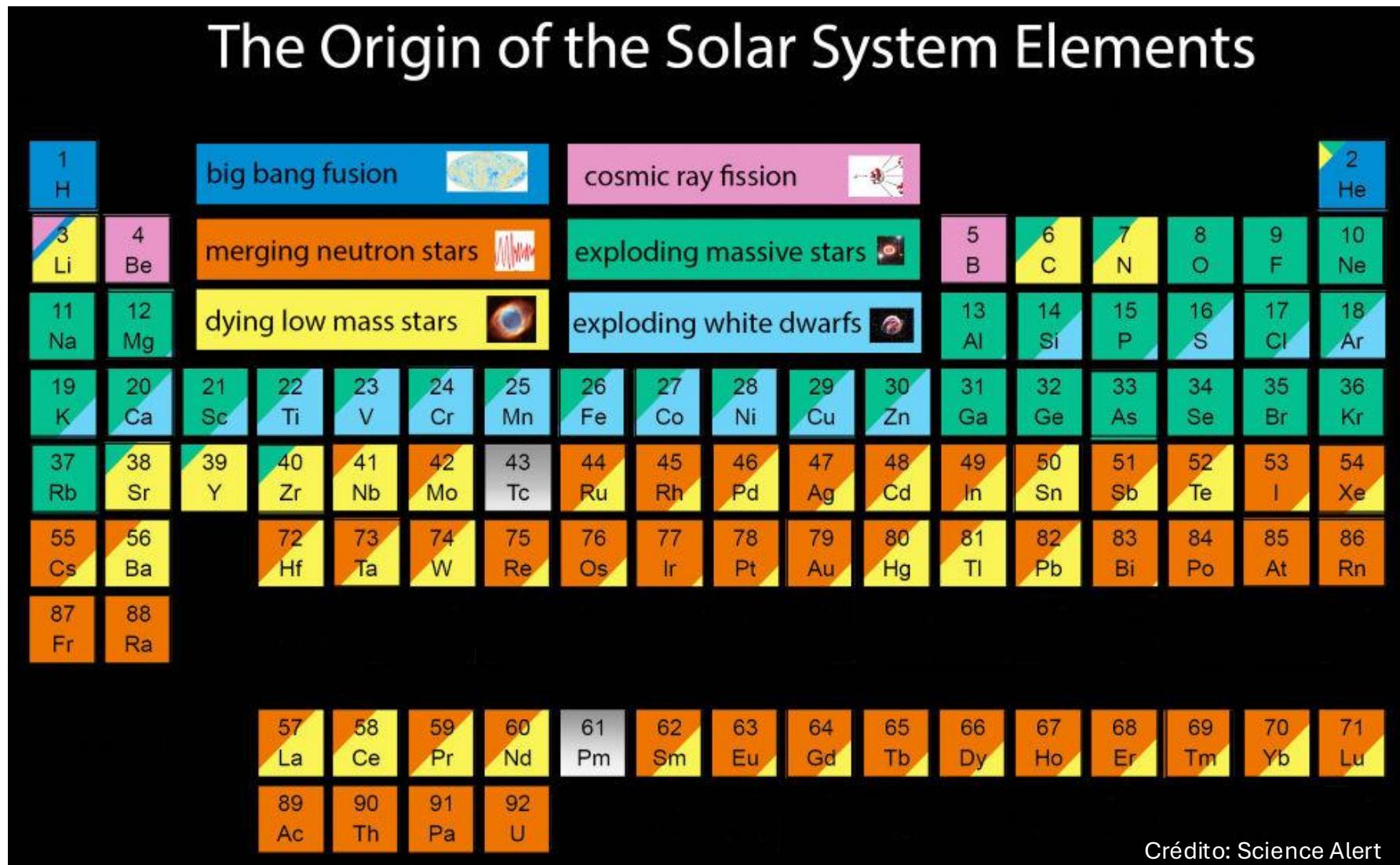


Tabla de los elementos según creación



Poblaciones de estrellas

- Metalicidad = Presencia de elementos más pesados que He

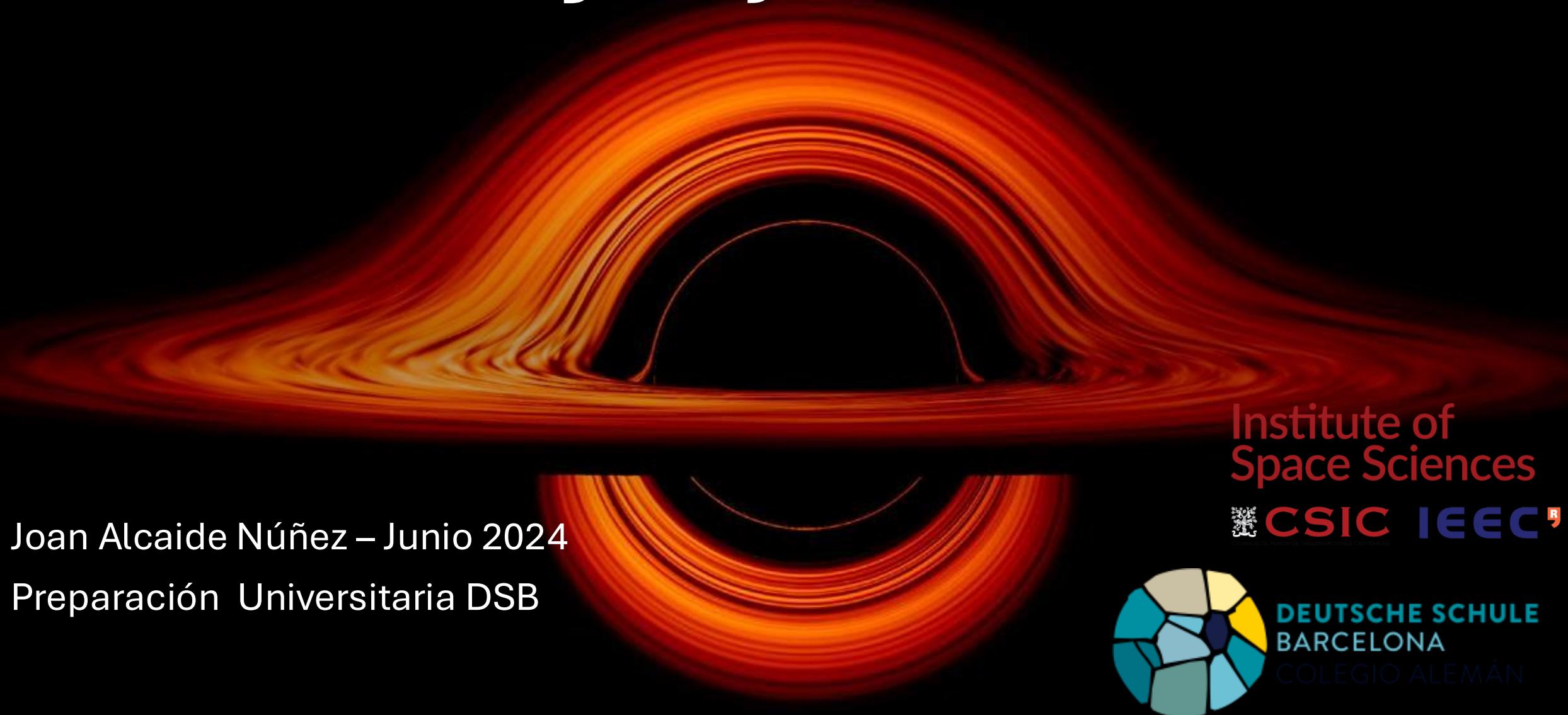
Población	Edad	Metalicidad
III	Primeras estrellas	Muy baja
II	Estrellas viejas	Baja
I	Estrellas Recientes	Alta

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



Crédito: NatGeo

Galaxias y objetos masivos



Joan Alcaide Núñez – Junio 2024

Preparación Universitaria DSB

Institute of
Space Sciences

CSIC IEEC^R



Índice

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2. Universo: evolución 

3. Universo: Fondo Cómico de Microondas (CMB) 

4. Estrellas: formación y evolución 

5. Galaxias: grupo local

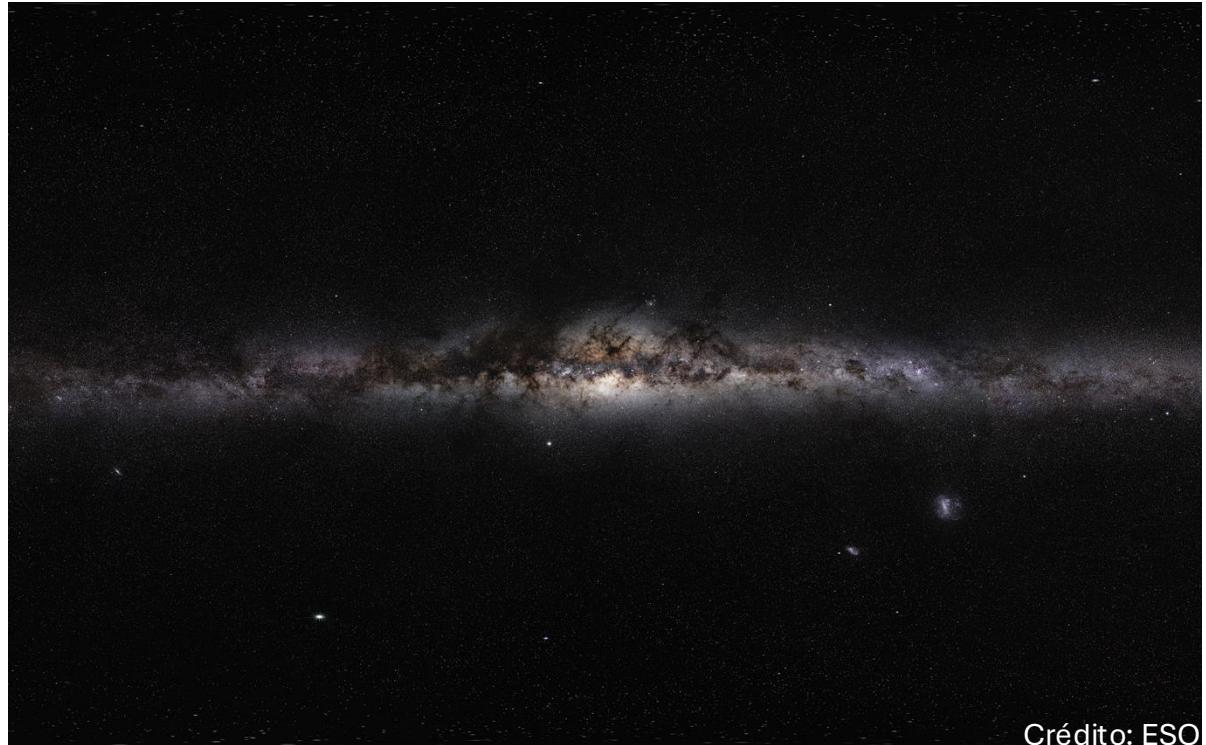
6. Objetos masivos: estrellas de neutrones y agujeros negros

5. Galaxias: grupo local

Nuestra casa: la vía láctea

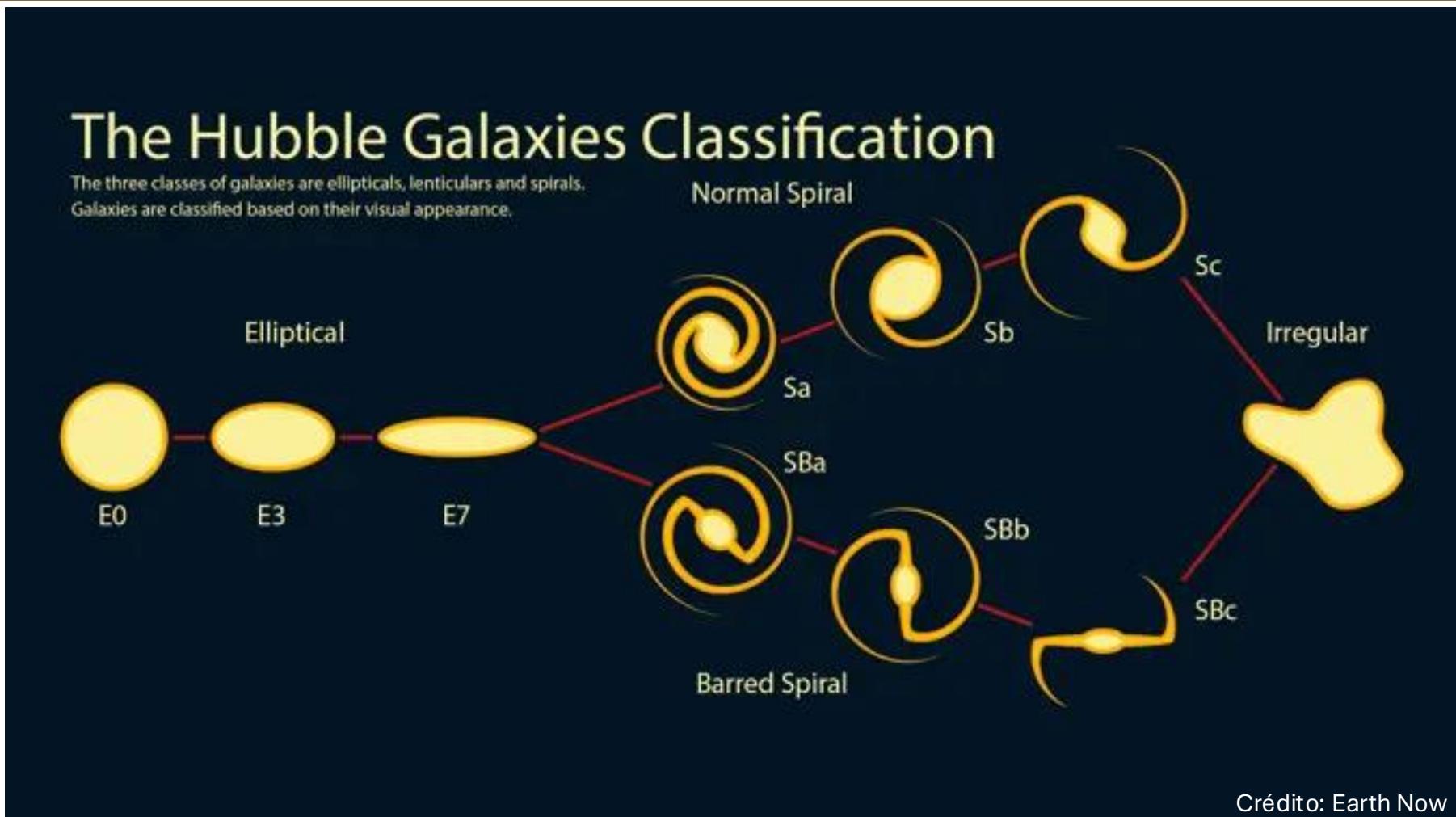


Crédito: AAS Nova



Crédito: ESO

Tipos de galáxias: clasificación de Hubble



Ejemplos

M87 - elíptica



Crédito: ESO

M83 - Barospiráral



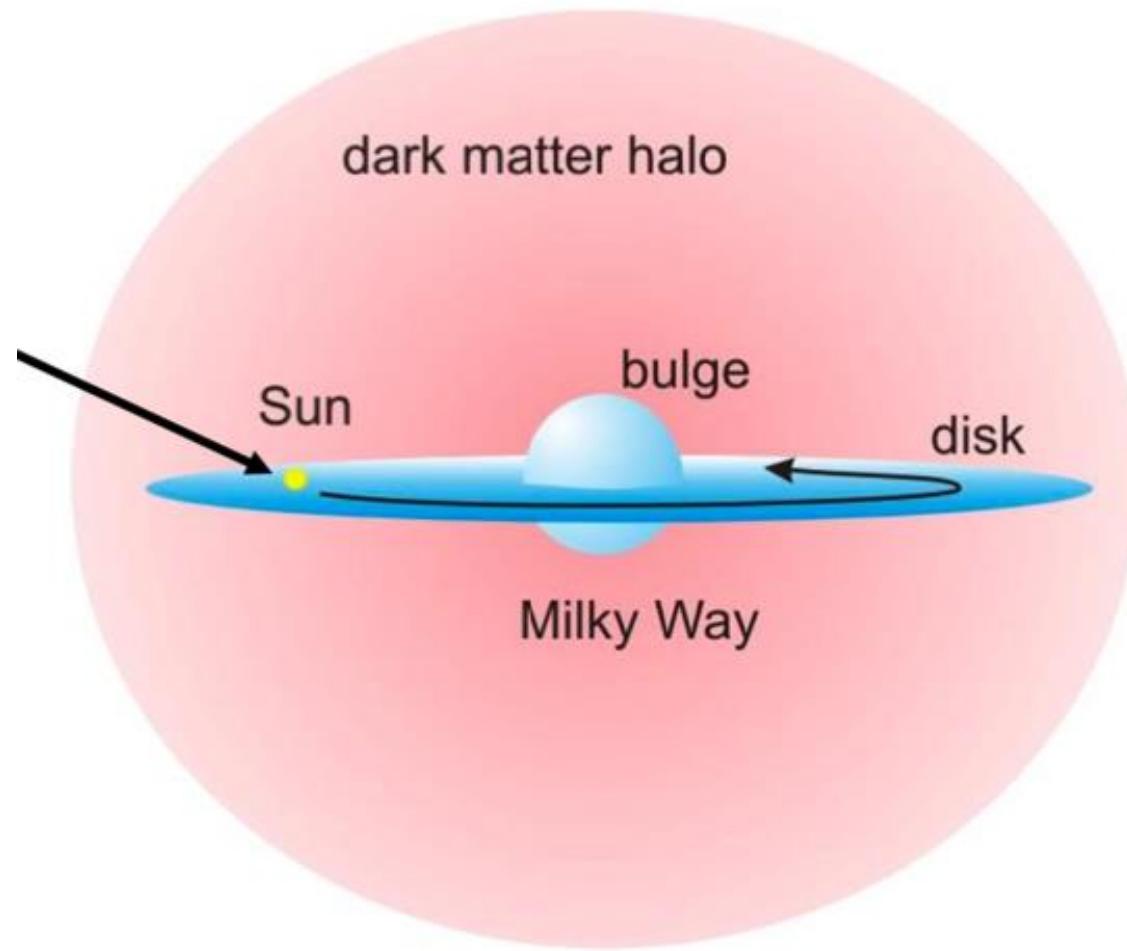
Crédito: ESO

M74 - espiral



Crédito: ESO

Anatomía galáctica



Crédito: Imperial College London

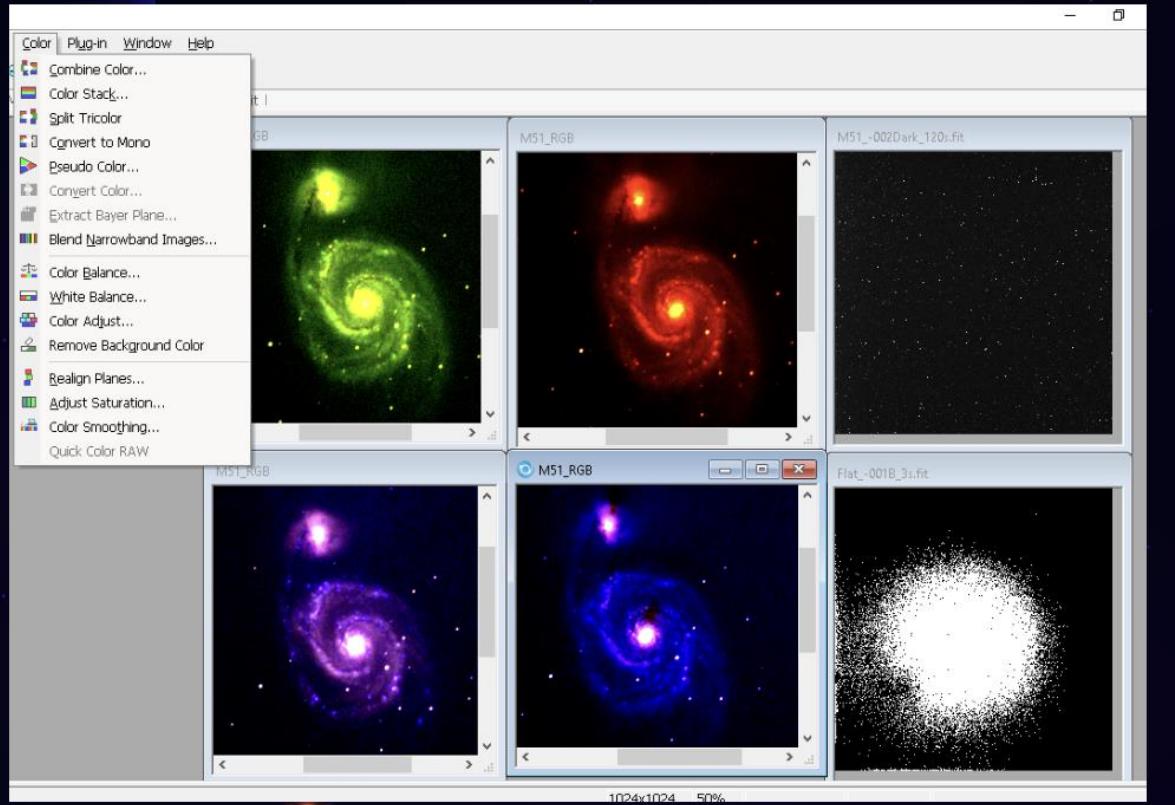


Anatomía galáctica

Crédito: Hubblesite

Colorines

Filtres, calibració i alineació



M51: galàxia remolí

Crèdit: JIC 2023

Crédito: JIC 2023

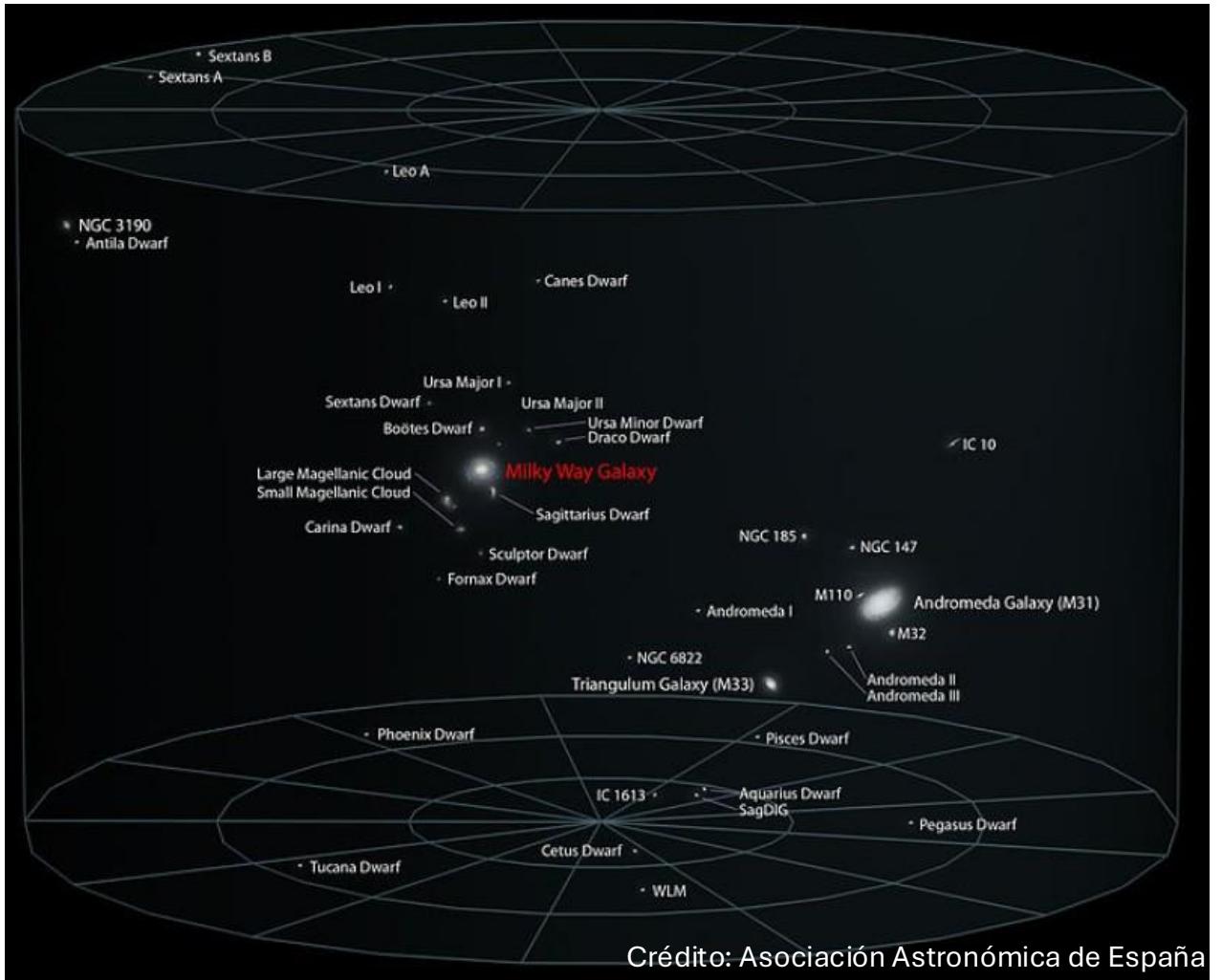
Galaxias satélites (más importantes)



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 (5×10^6 ly)

Andrómeda (M31)



Crédito: ESA/Hubble

Triangulum (M33)

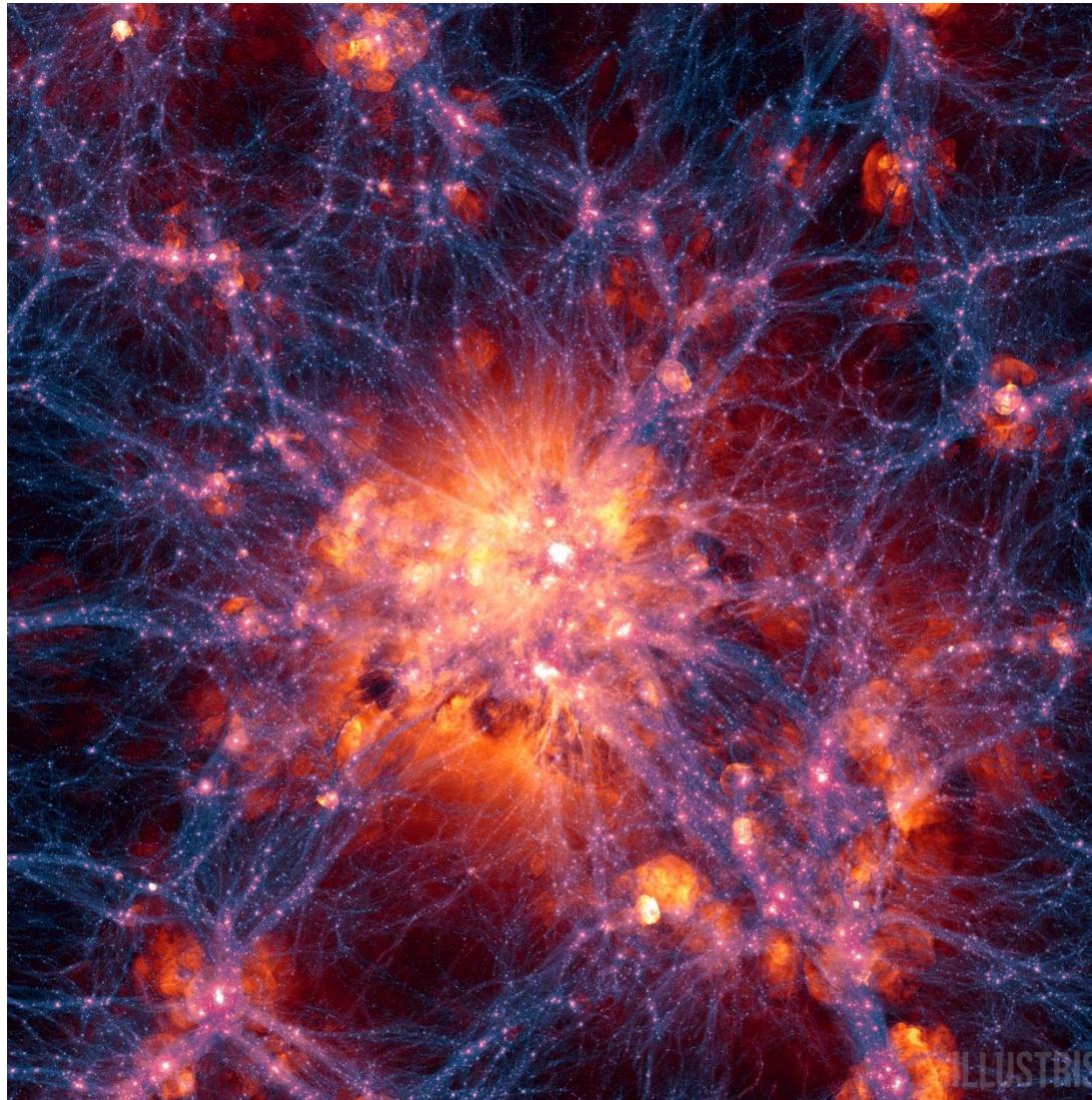


Crédito: ESO

Nuestro lugar en el Universo

- Simulación

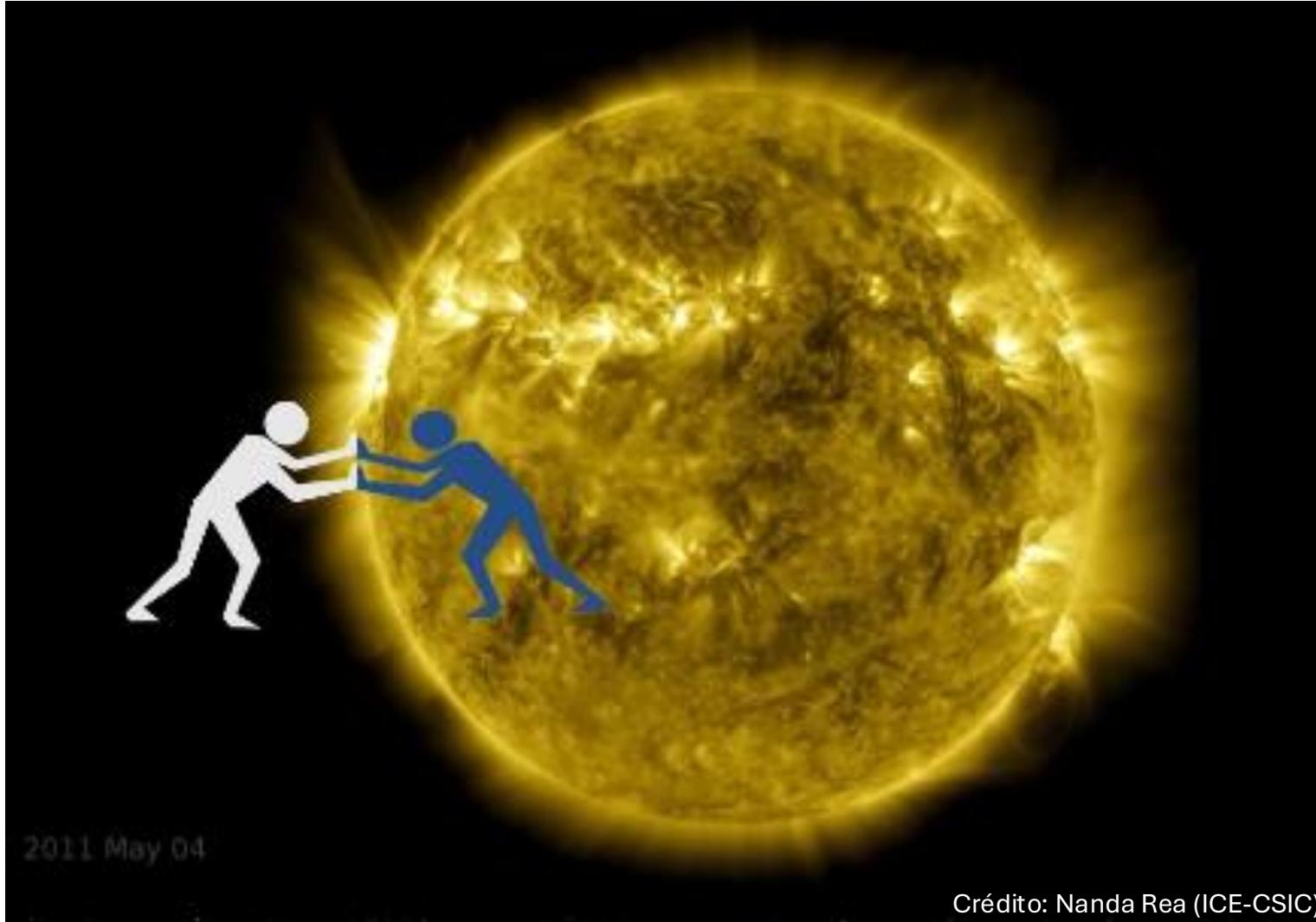
Distribución de la materia



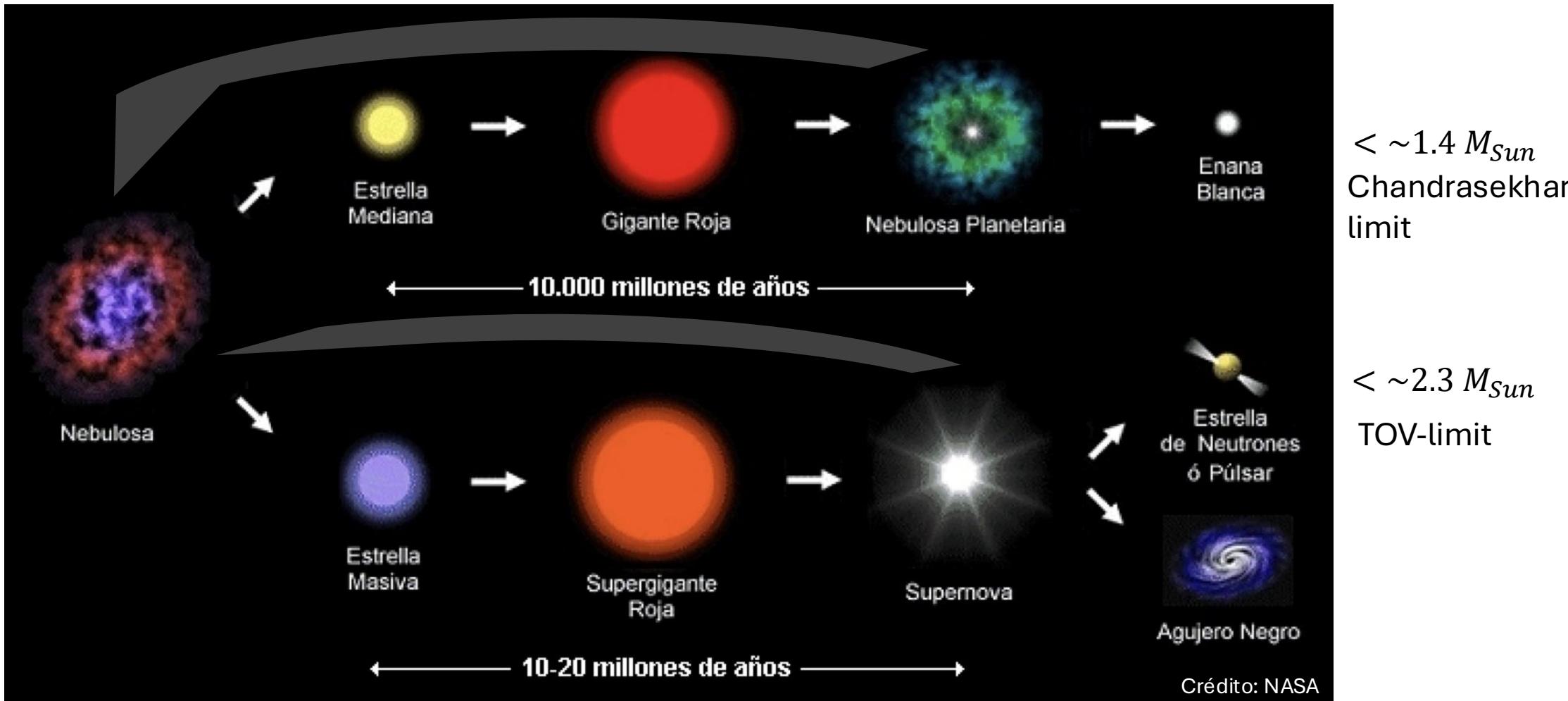
Crédito: Illustris Project (simulation)

6. Objetos masivos

Repaso estrellas



Repaso evolución estelar

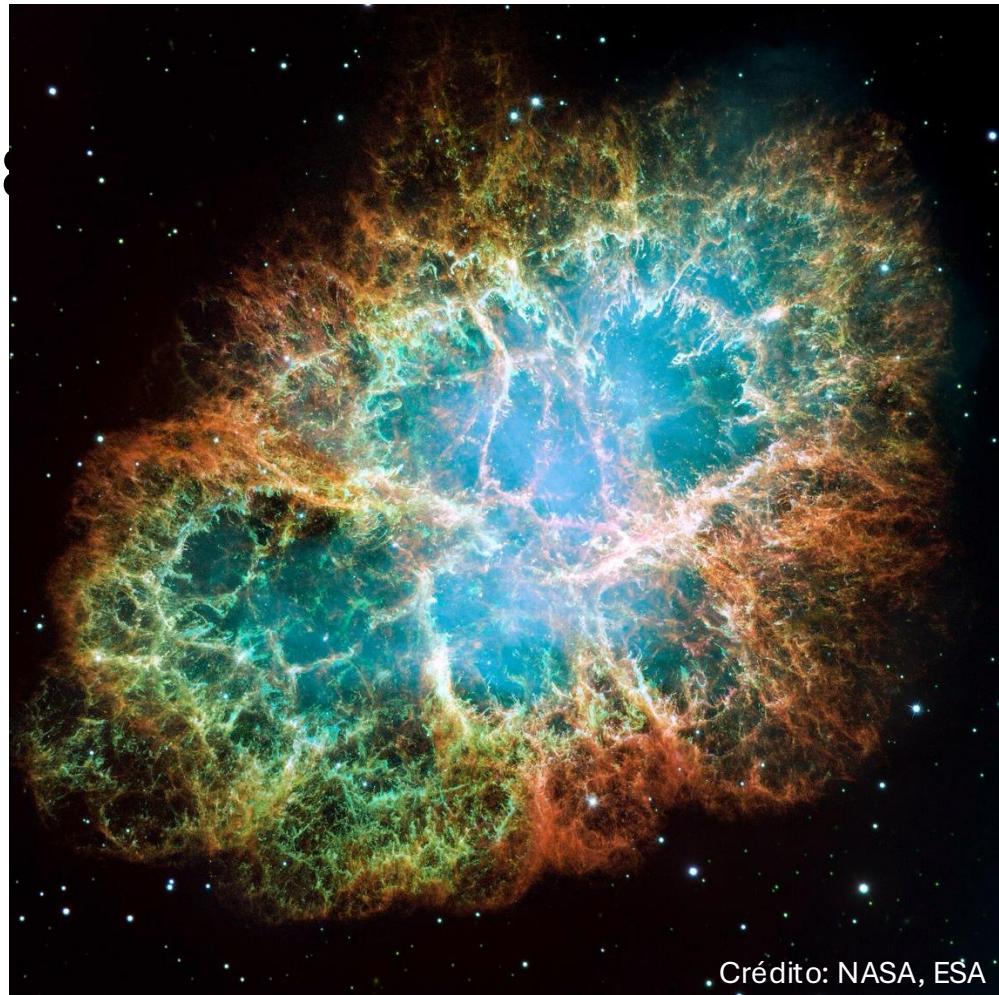


Supernova

- Remanente de las estrellas entre 8 y 20 veces masivas
- Explosión de Supernova



Crédito: Nanda Rea



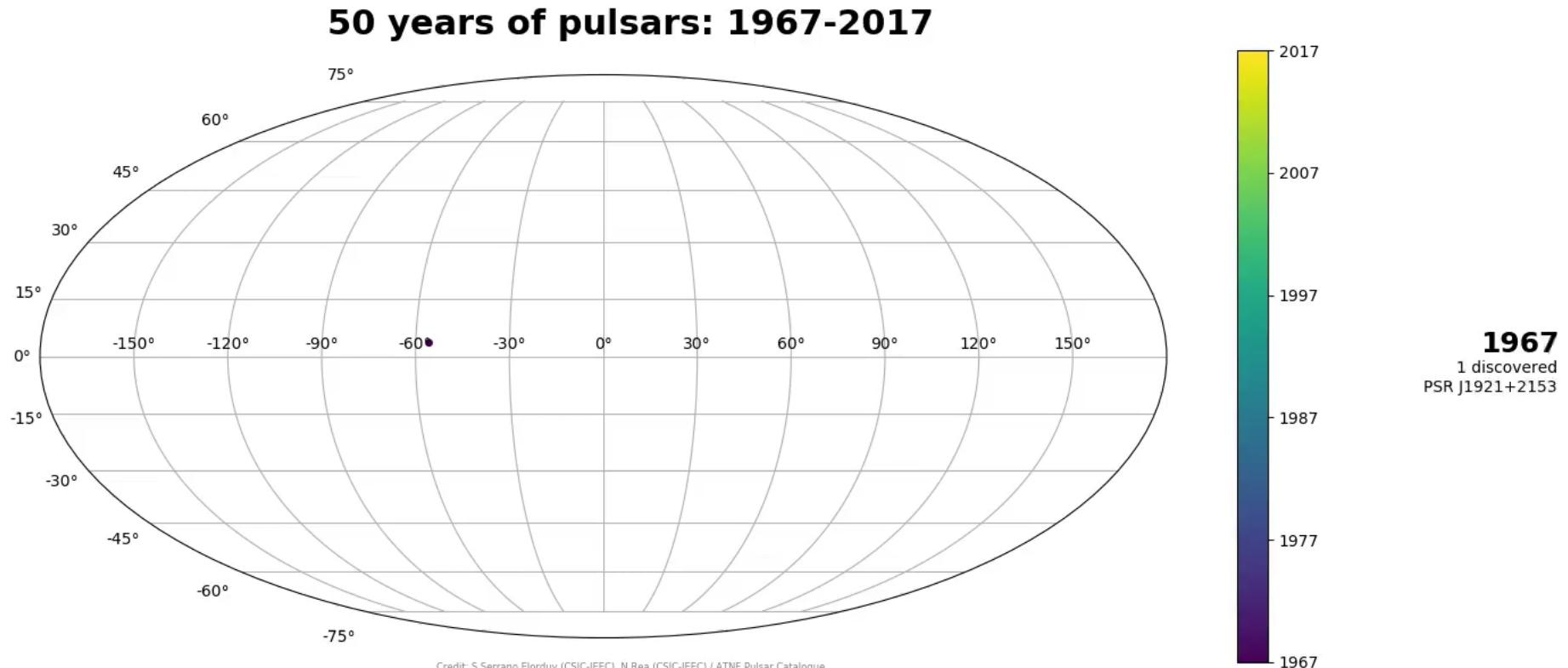
Crédito: NASA, ESA

Estrellas de neutrones

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



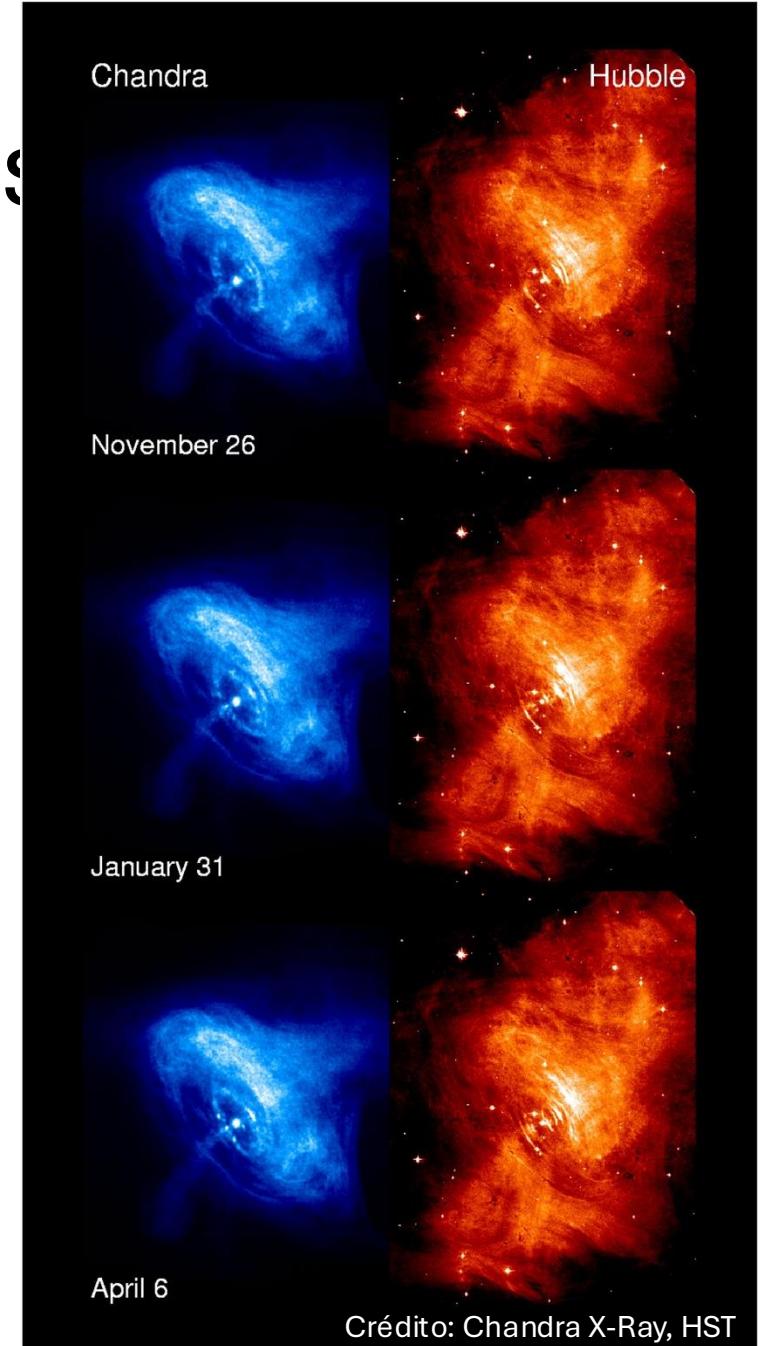
¿Cuántos púlsares hay?



Crédito: Nanda Rea

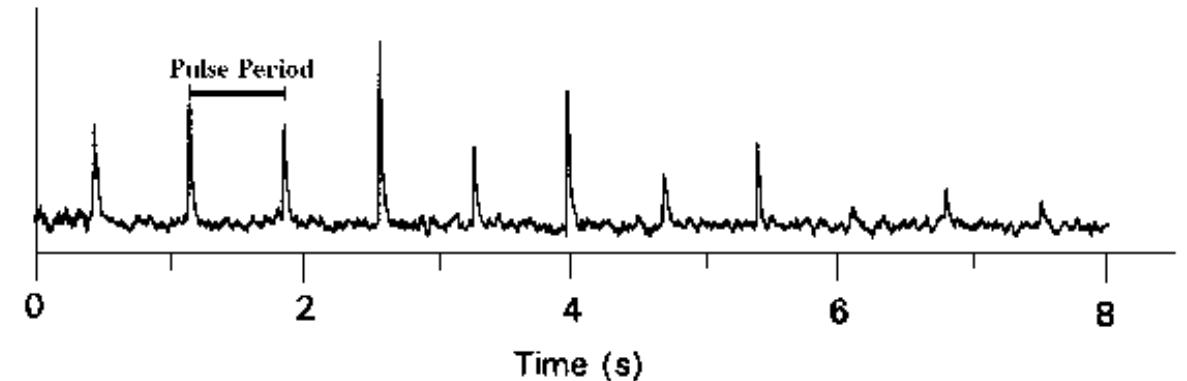
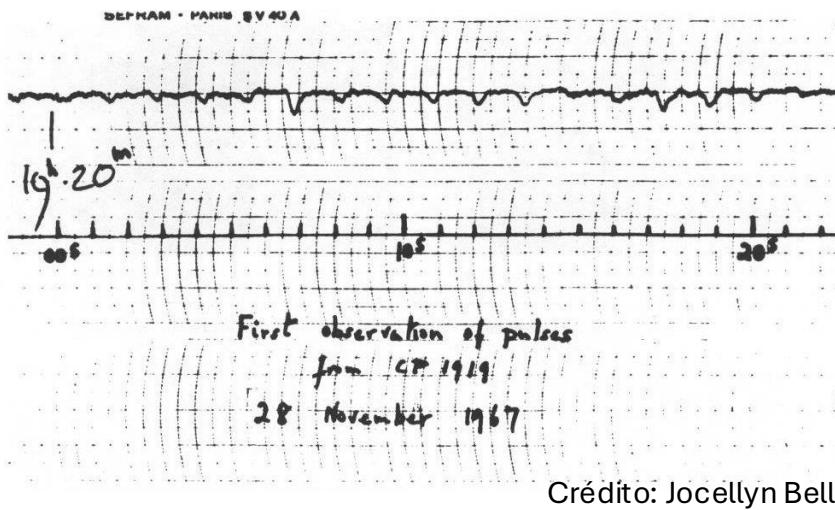
Características de los púlsares

- 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: Australia Telescope National Facility

Música con púlsares



Crédito: Astrophil

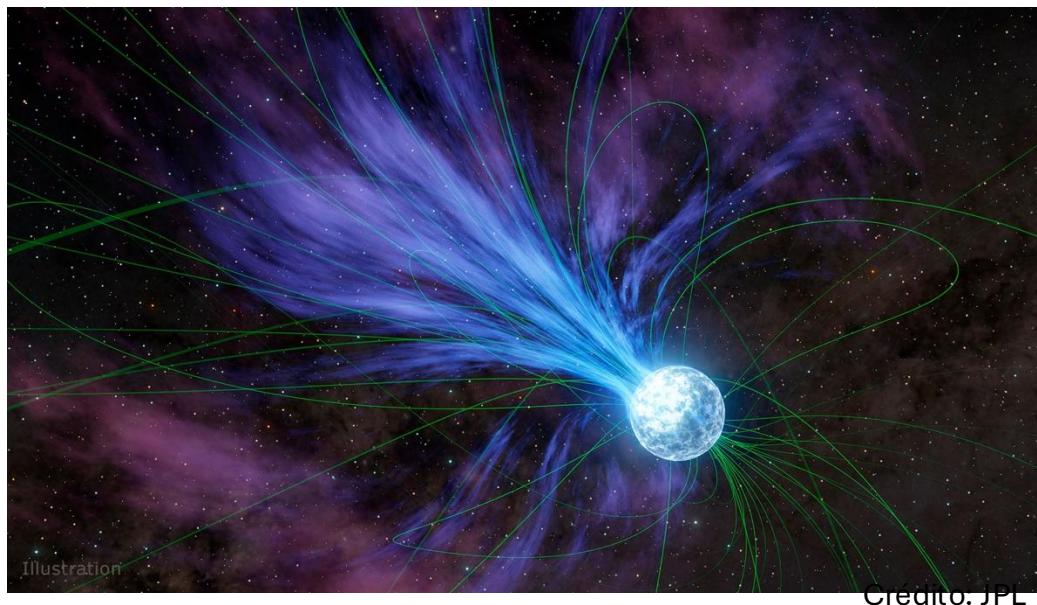
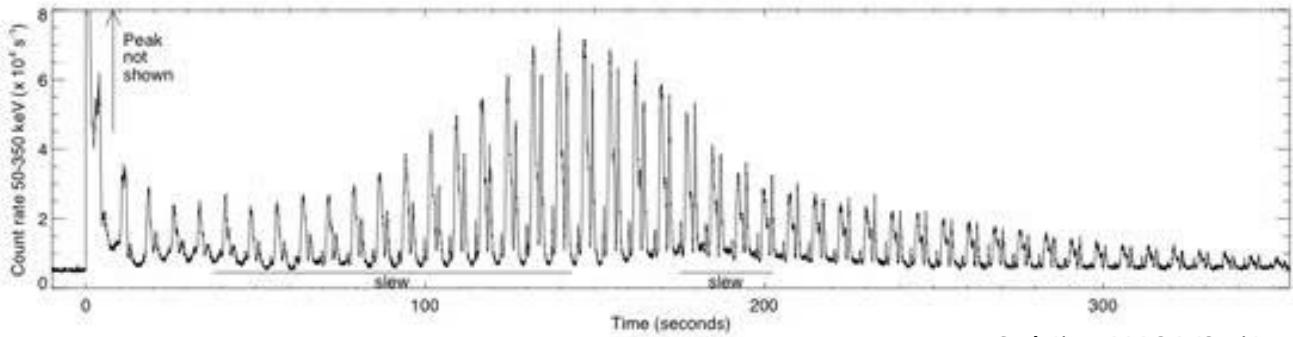
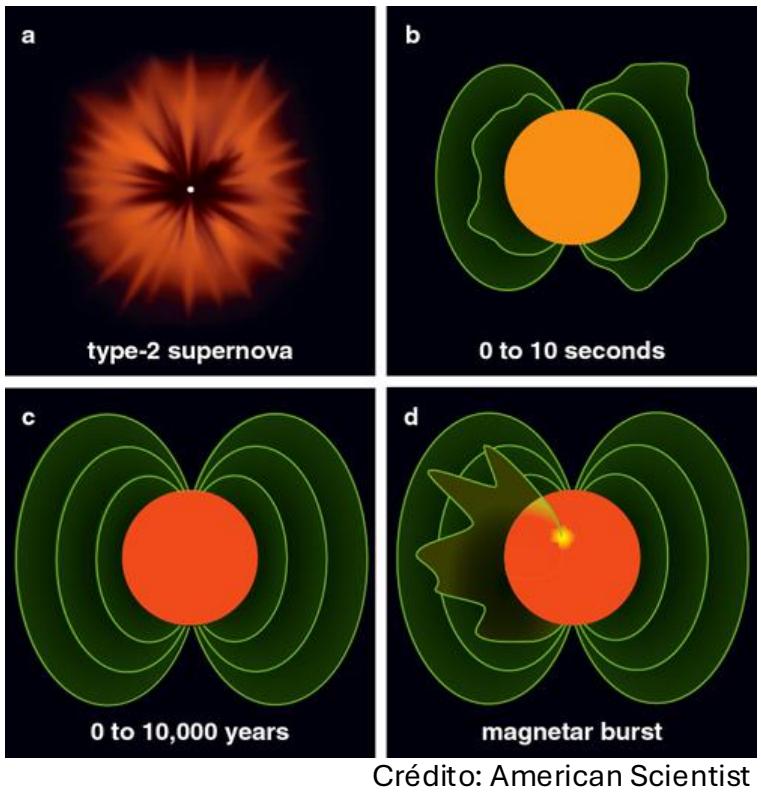
Récords de los púlsares

- Cuerpo celeste más denso conocido ($p = 10^{25}$ atmosferas terrestres)
- Cuerpo celeste con mayor velocidad de rotación (1.39595467 ms)
- Círculo más redondo conocido: órbita de PSR J1909-3744 (5 μm)
- 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%)

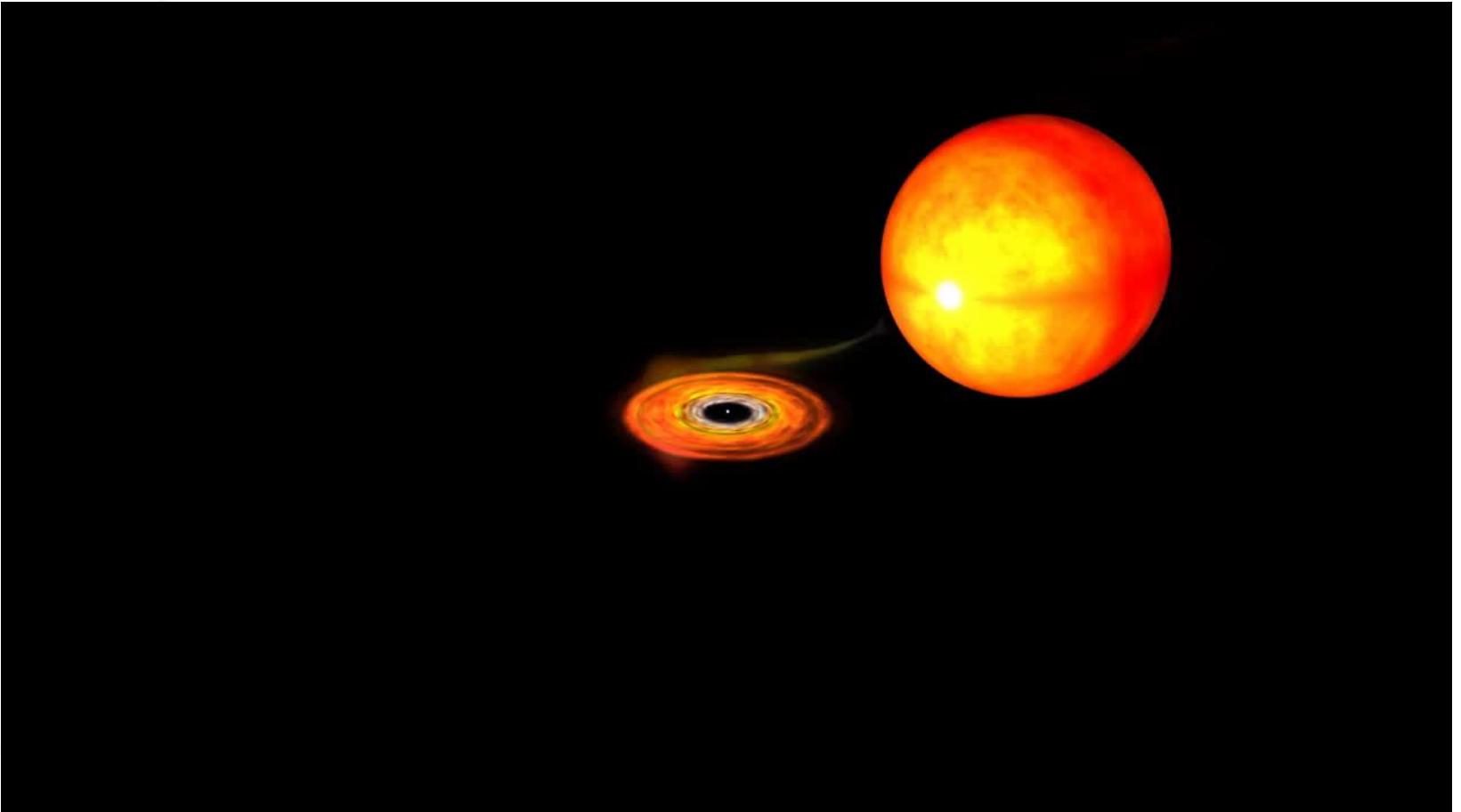
Récords de los púlsares

- 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

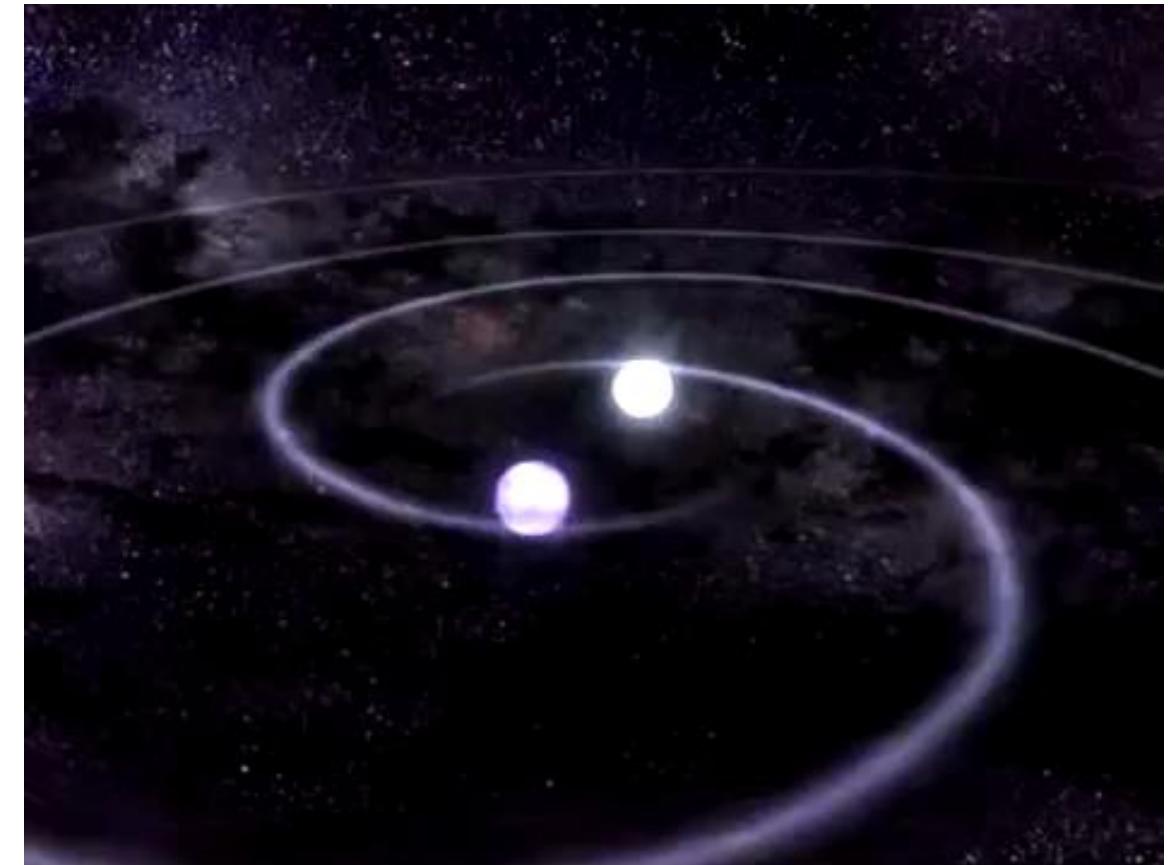
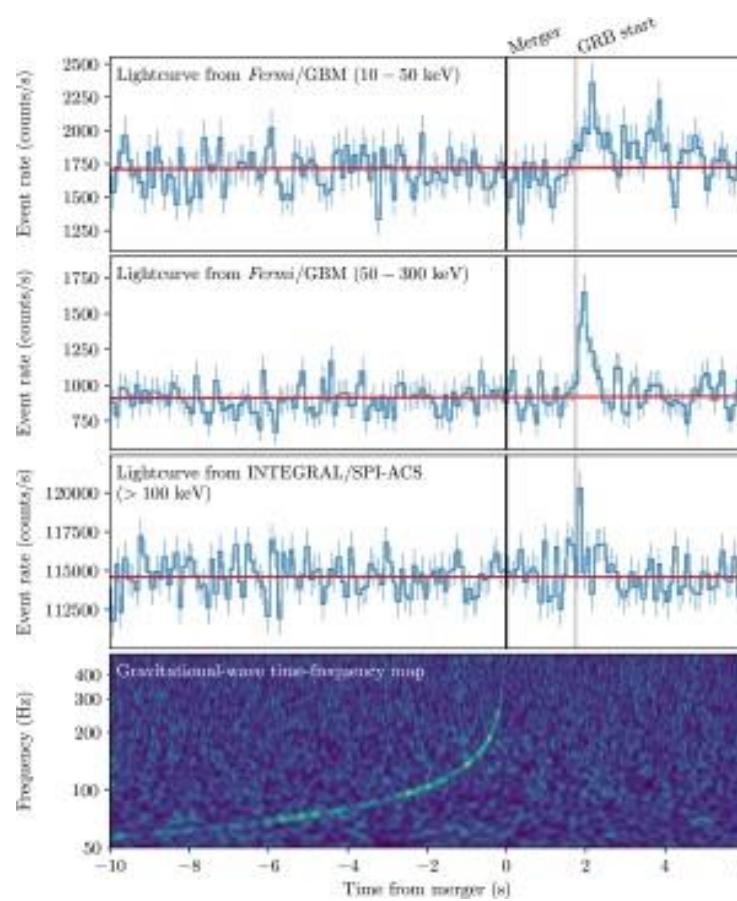


Púlsares en sistemas binarios



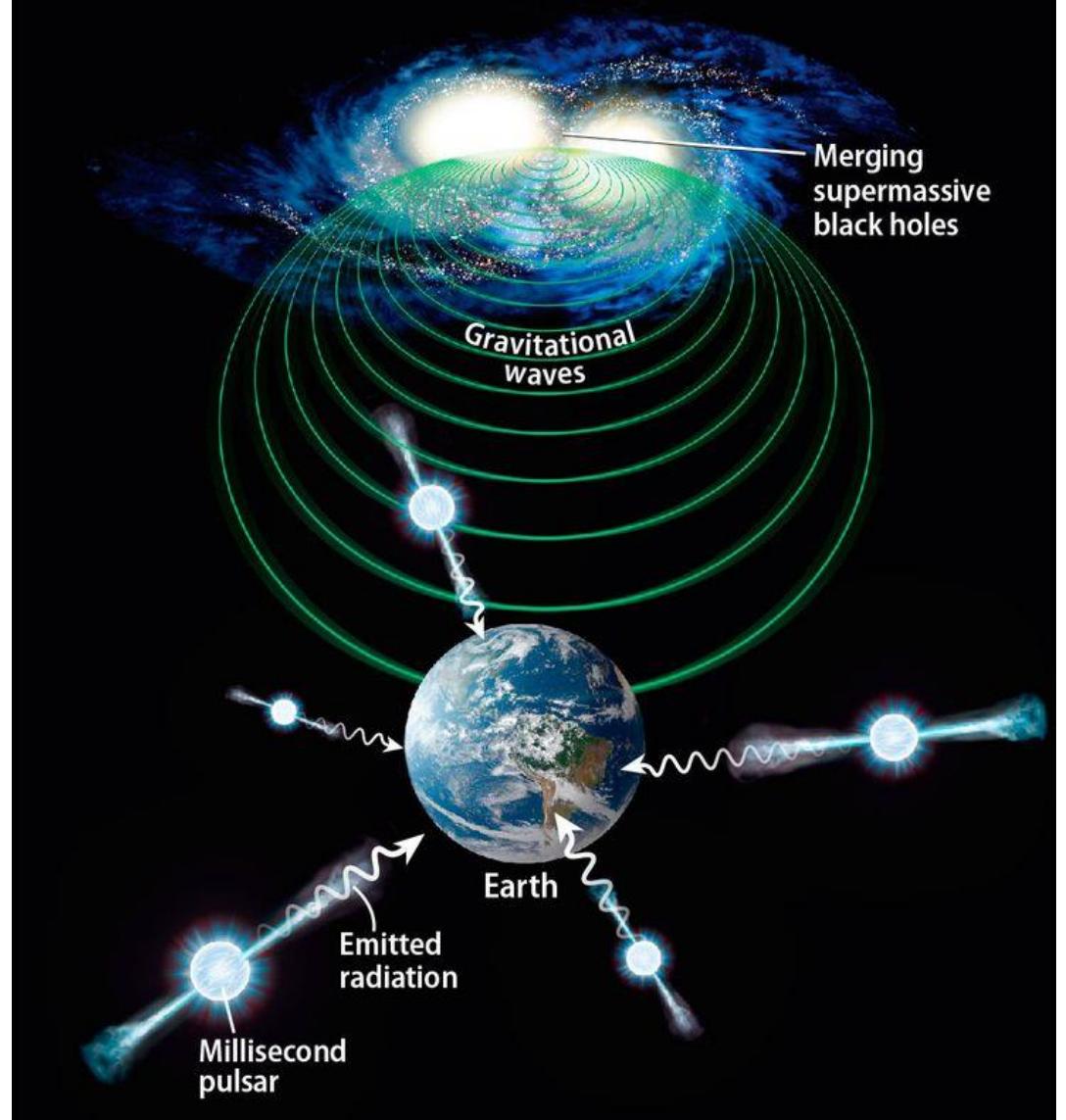
Crédito: Nanda Rea

Colisiones de estrellas de neutrones



Crédito: LIGO & VIRGO Collaboration 2017

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

GROSSMAYR

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 ~ 4 nHz, and another at ~ 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

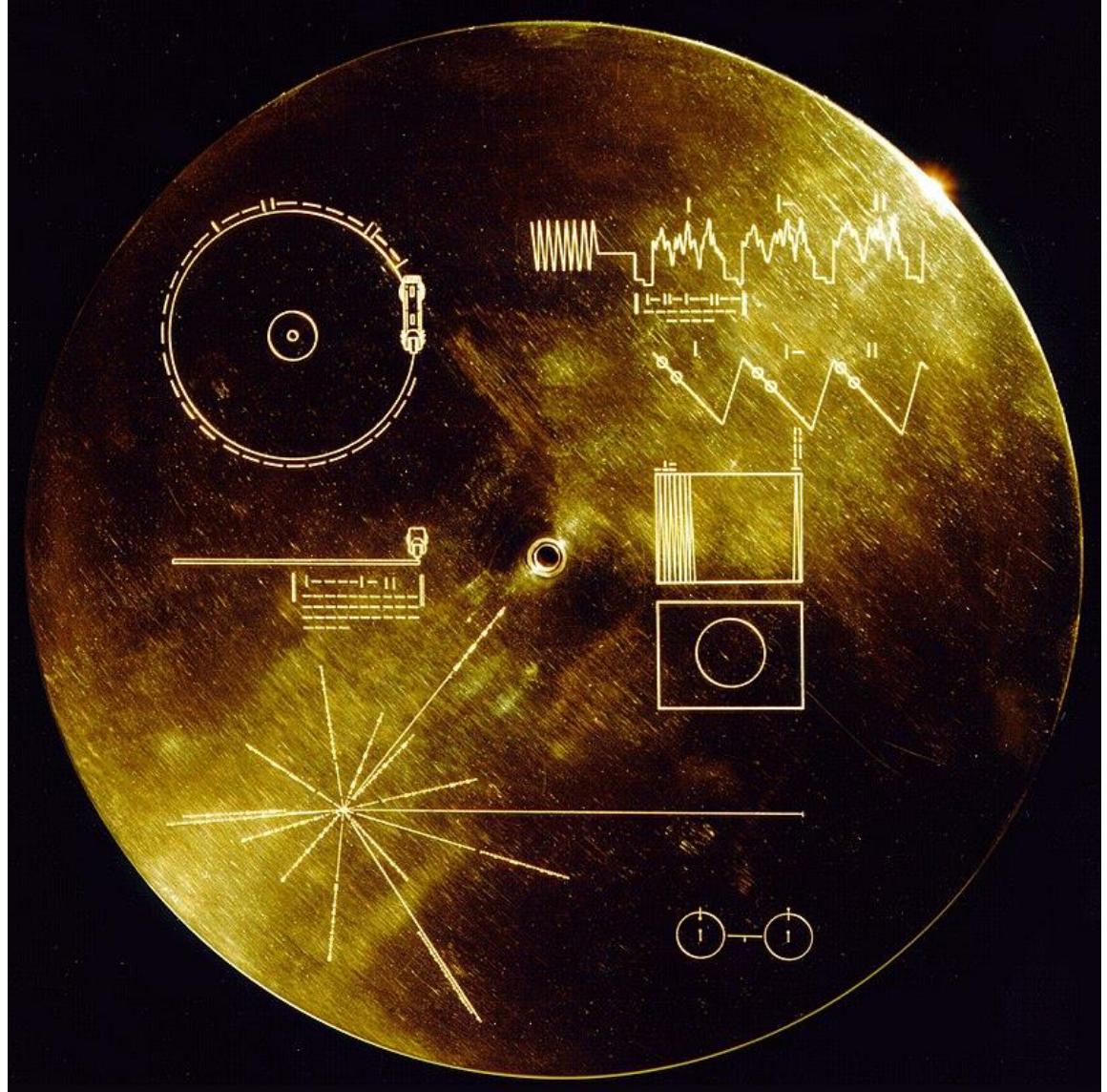
Crédito: NANOGrav Collaboration

DOI: 10.3847/2041-8213/acda9a

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

Demás con púlsares

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



Crédito: Voyager, NASA

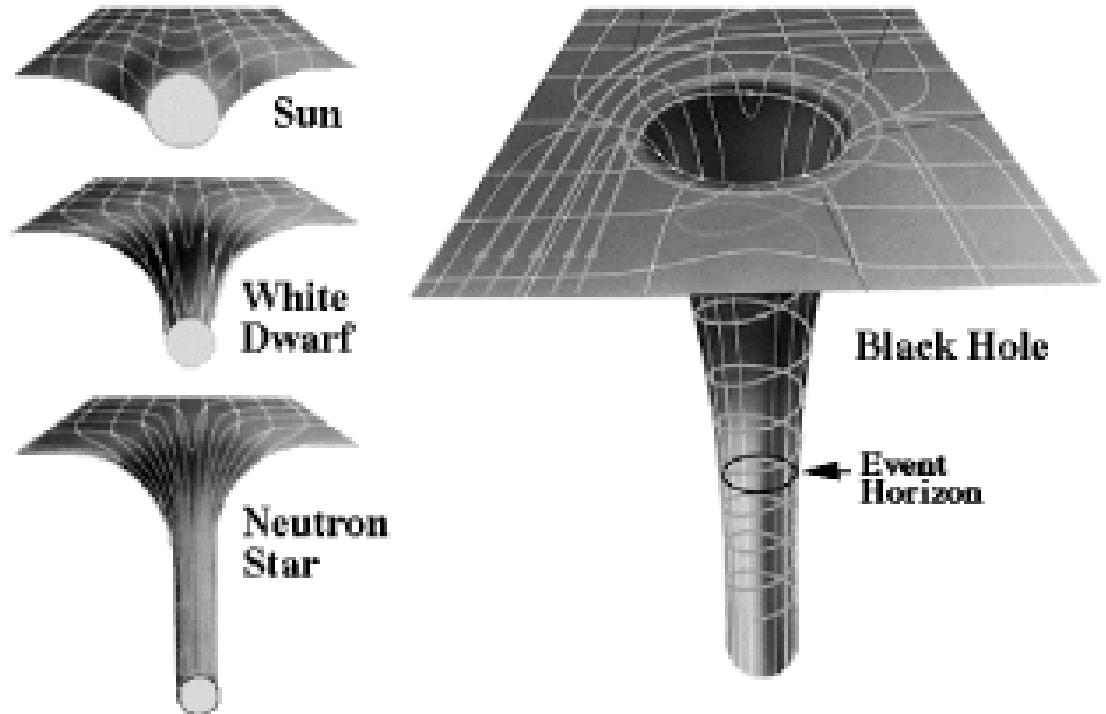
Remanente estelar cuando $M > 25 M_{Sun}$?

**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



Crédito: NASA

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

PBH - primordiales

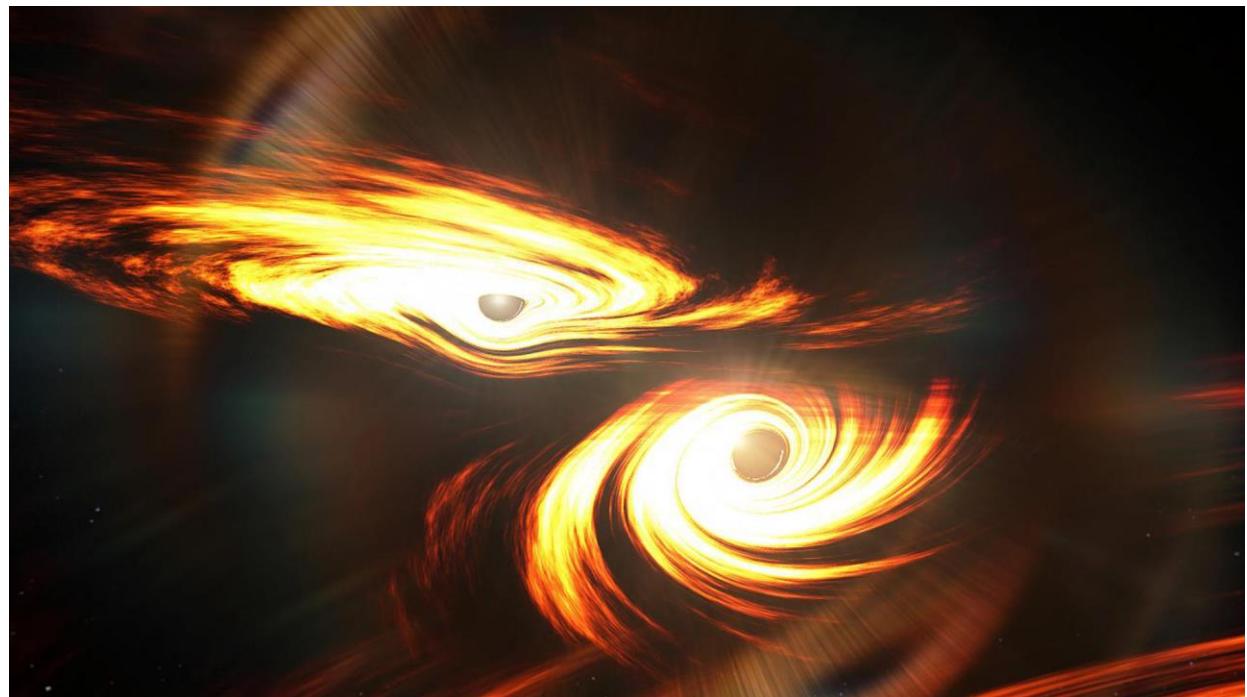
- Tamaño de un átomo
- Massa de una montaña
- No se han observado



Crédito: Astronomy Now

IMBH – intermediate-mass?

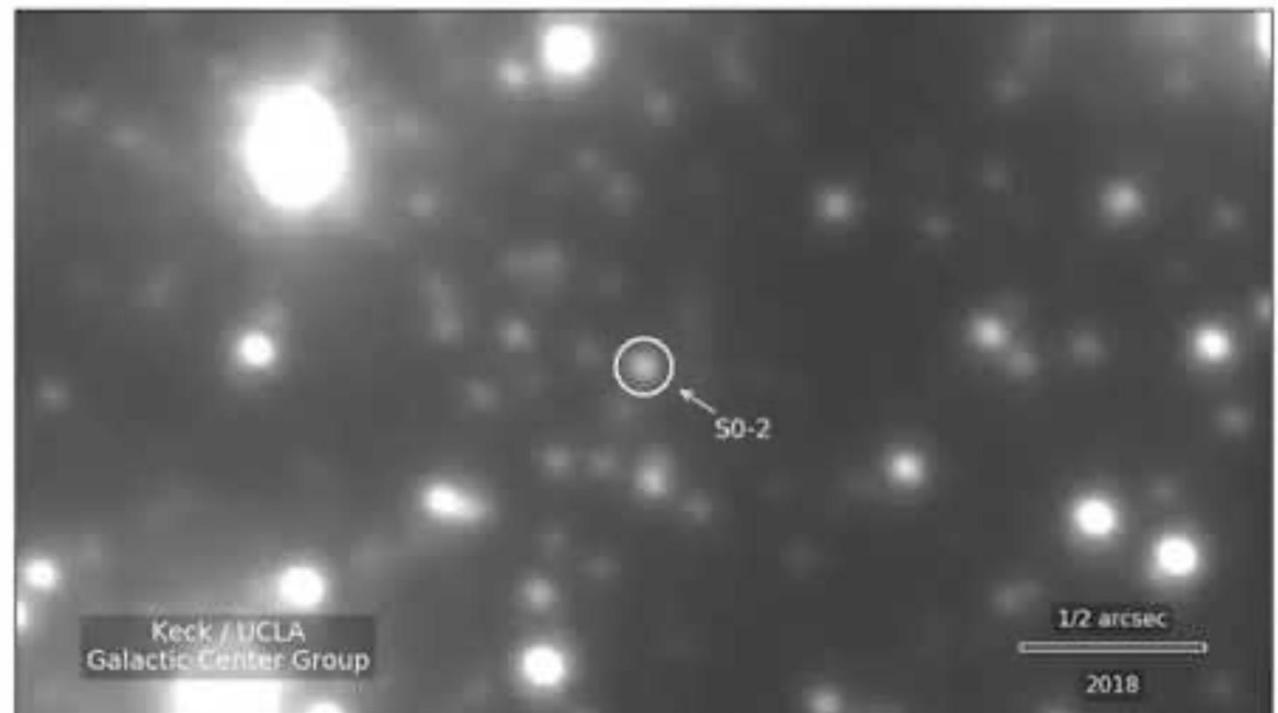
- Candidatos sin clasificación: +300 (via GW o AGN)
- En galaxias enanas?
- Universo temprano?
- Podrían ser las semillas de los SMBHs?



Crédito: Sci News

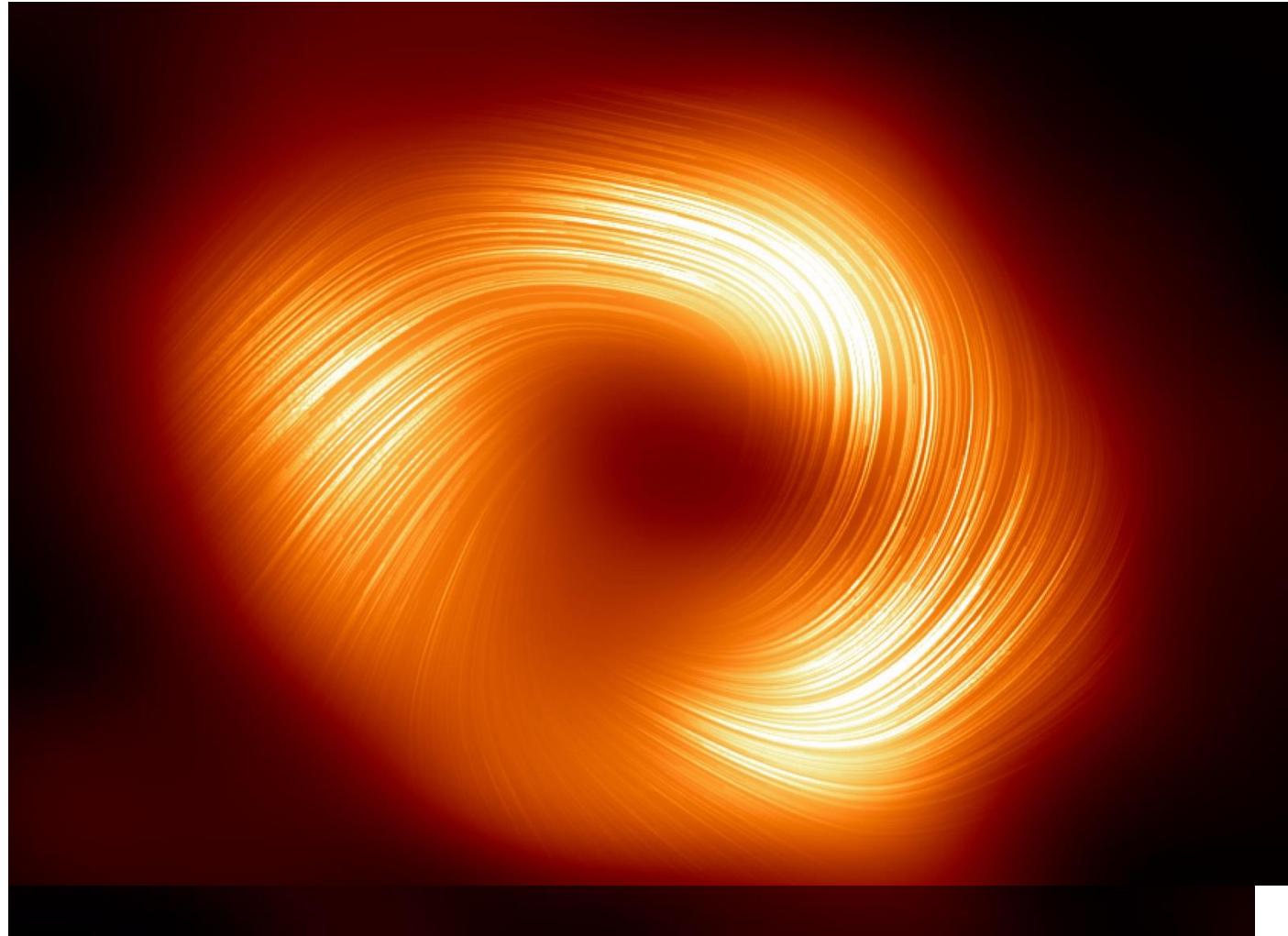
SMBH - Supermasivos

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



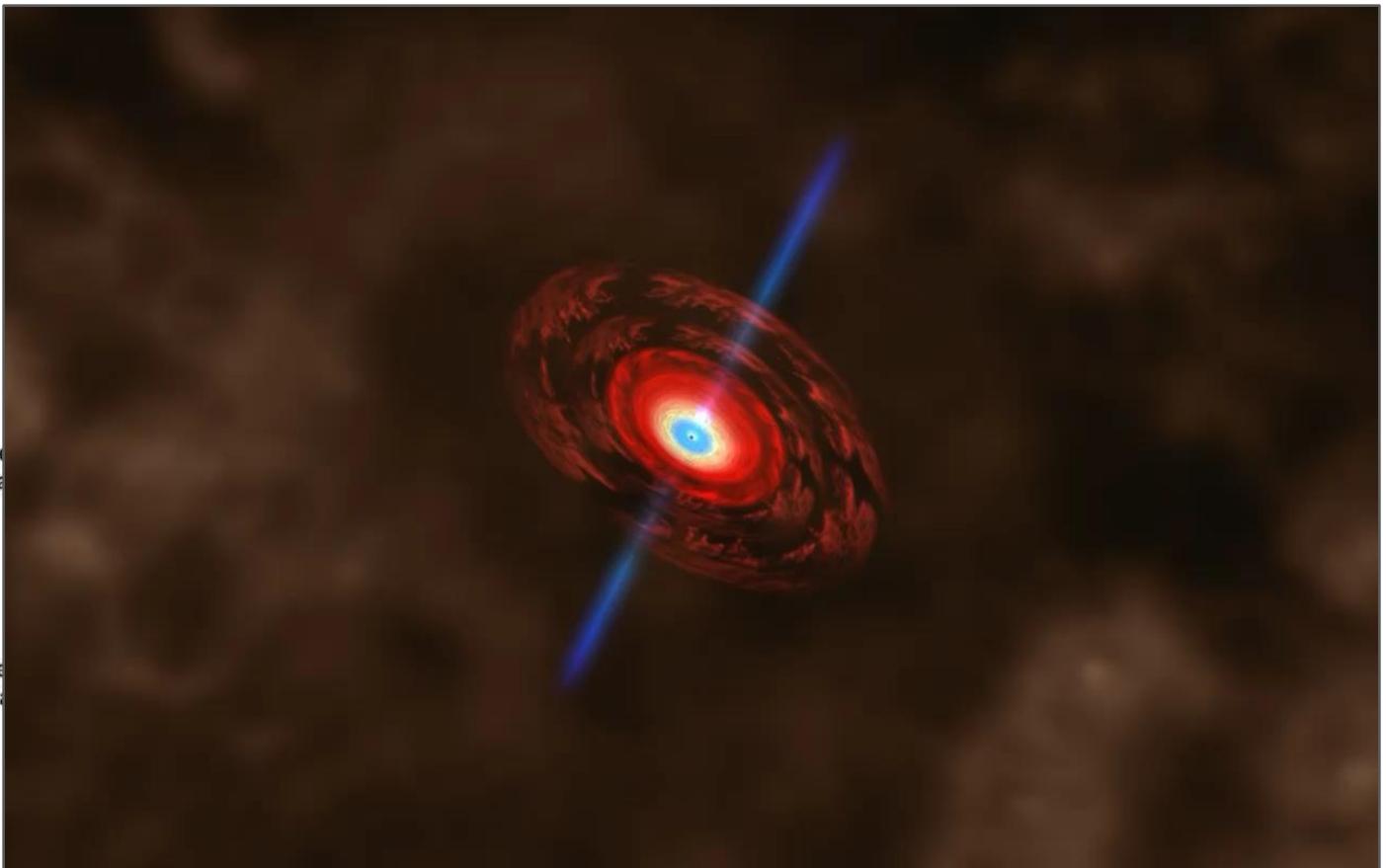
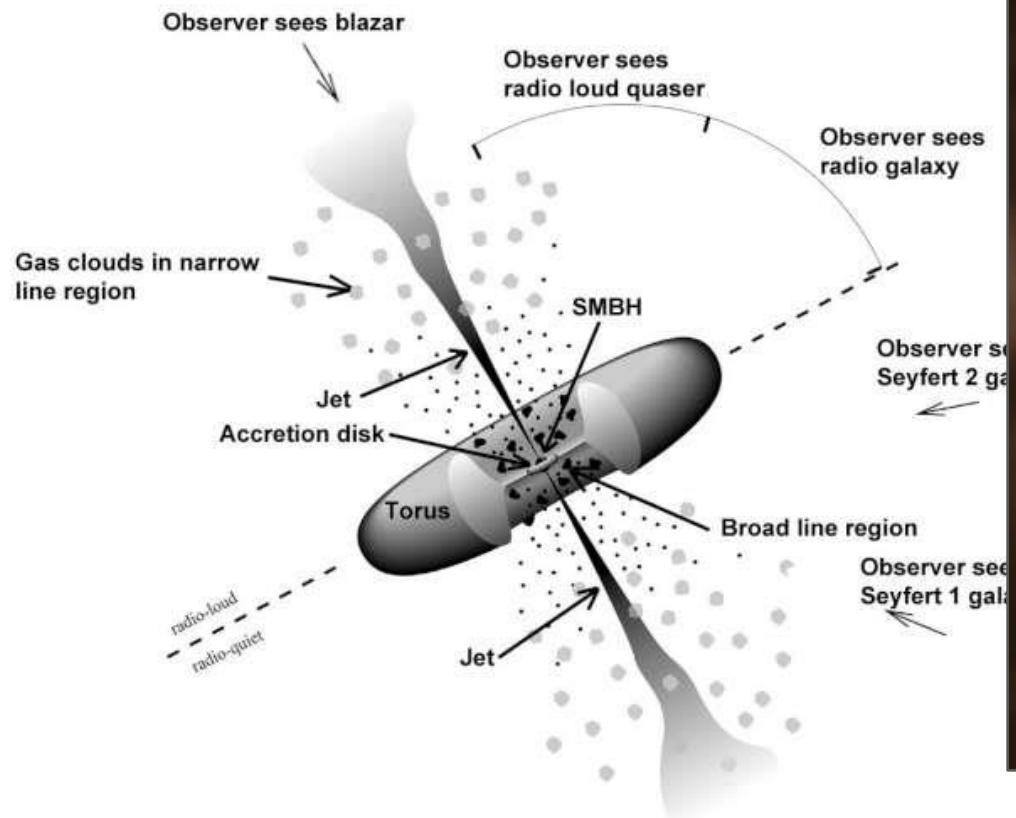
Crédito: Keck/UCLA

SMBH – Sagittarius A*



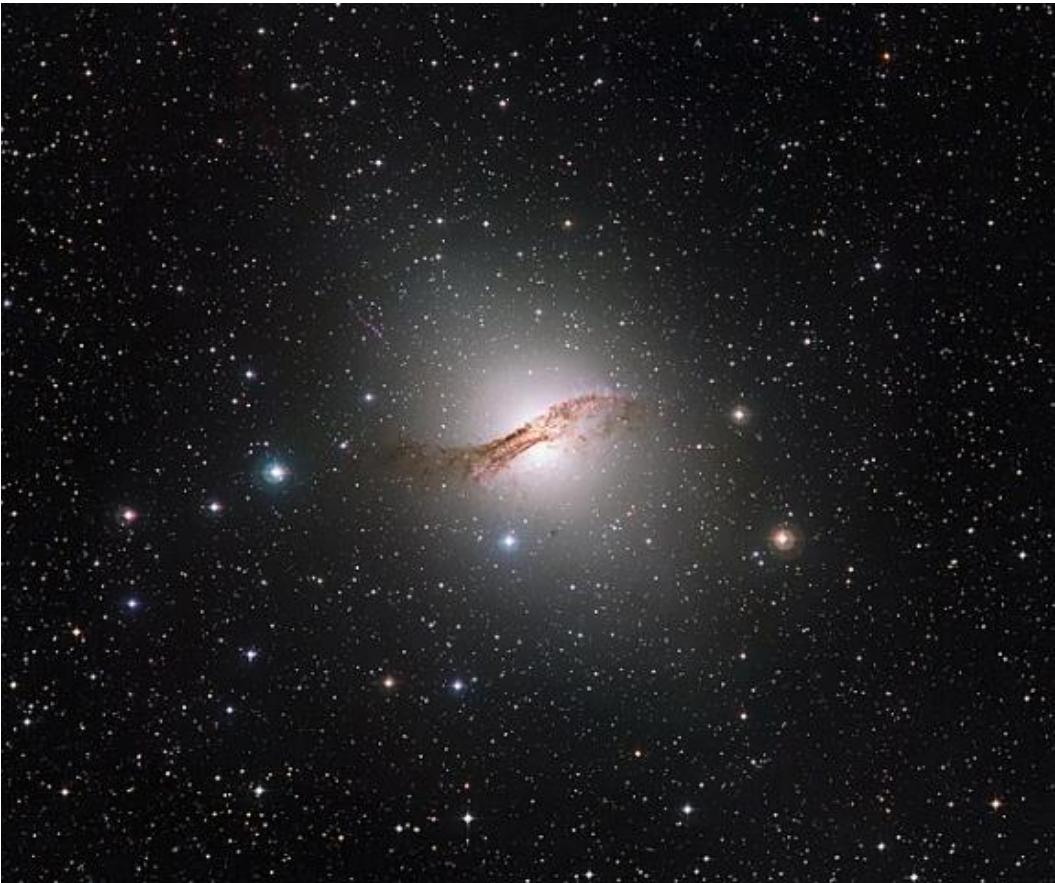
Crédito: EHT

AGNs - activos

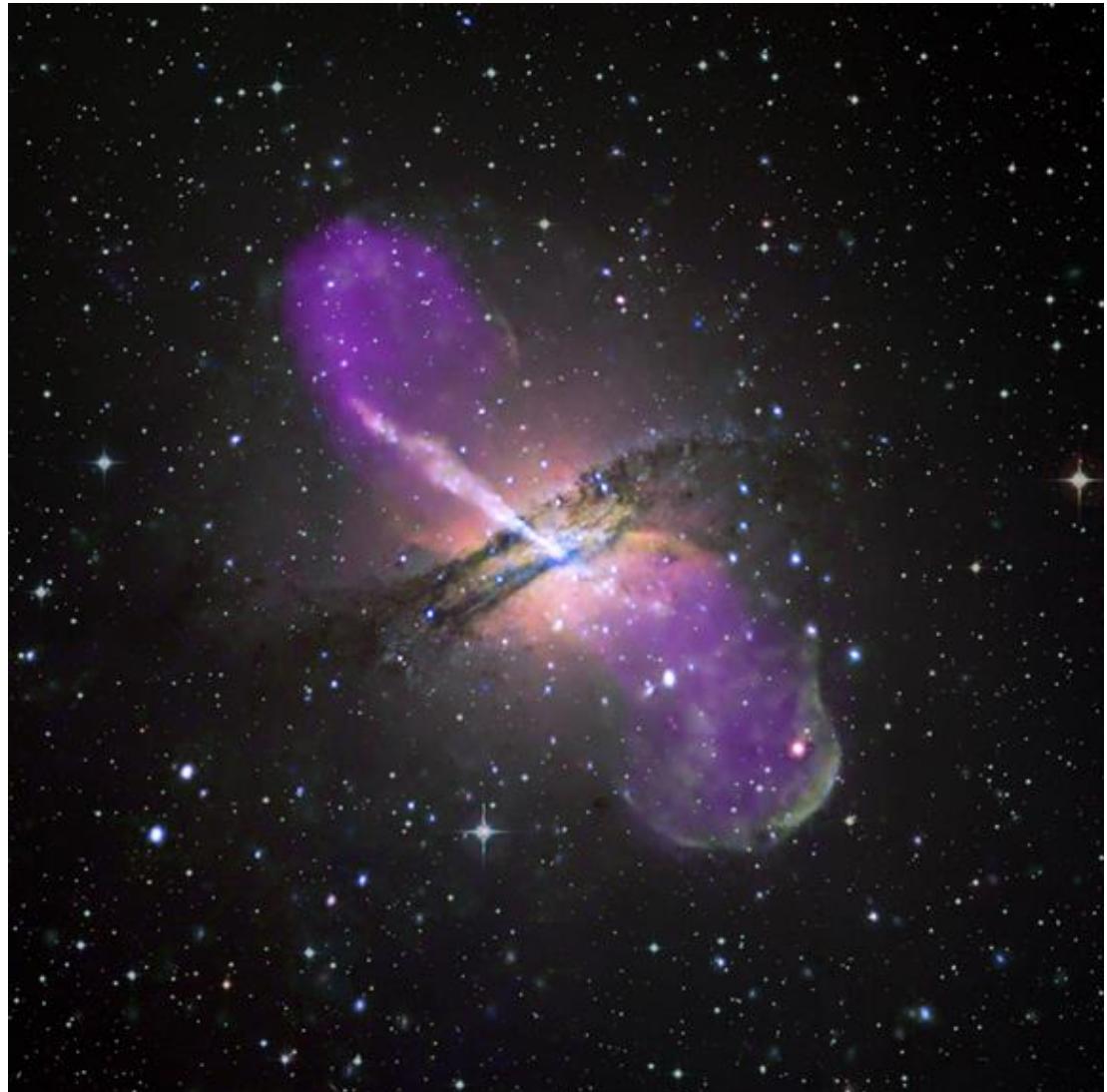


Crédito: Nanda Rea

Centaurus A - AGN

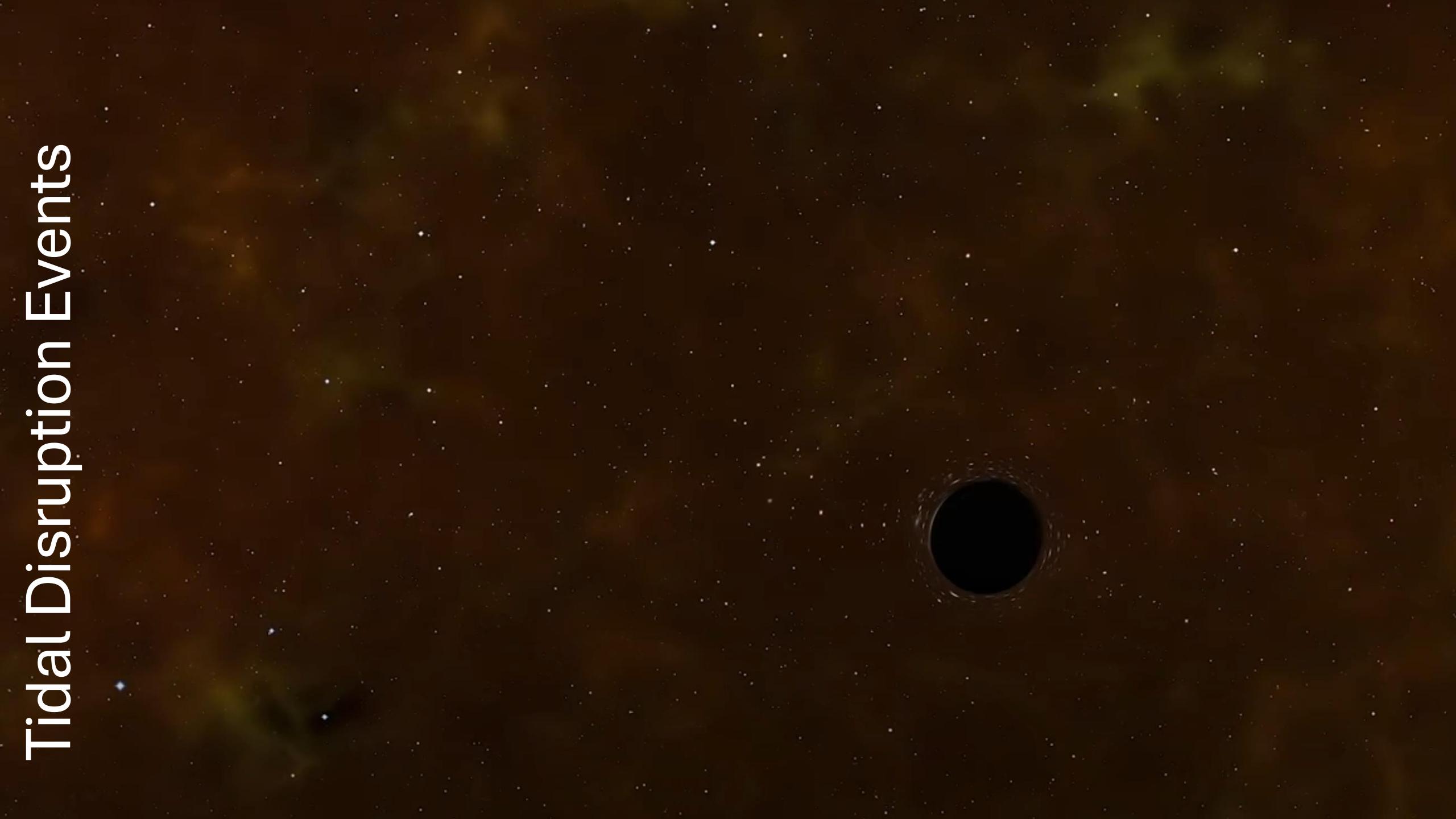


Crédito: ESA Hubble



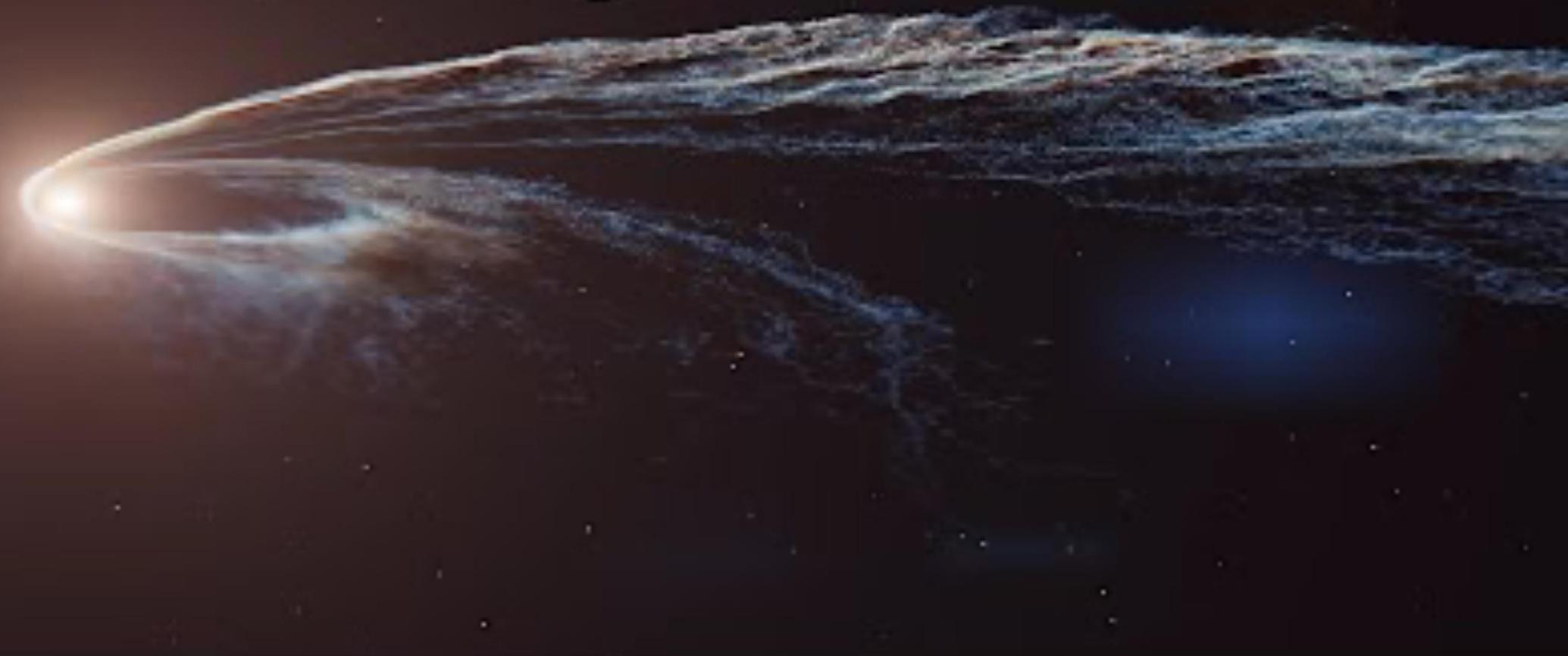
Crédito: Chandra X-Ray

Tidal Disruption Events



Tidal Disruption Events

Black Hole Tidal Disruption Event

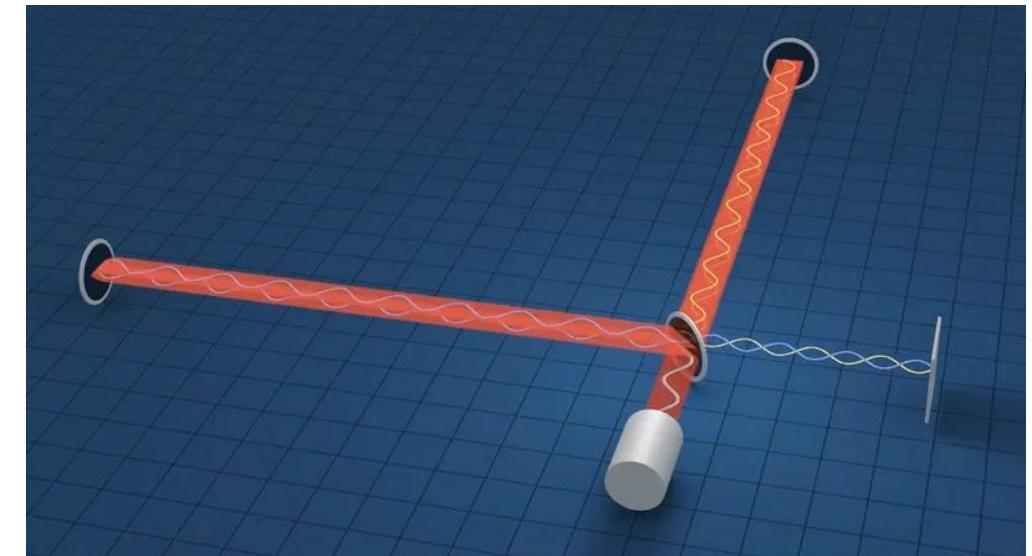


Colisiones de BH – Ondas Gravitacionales

- 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

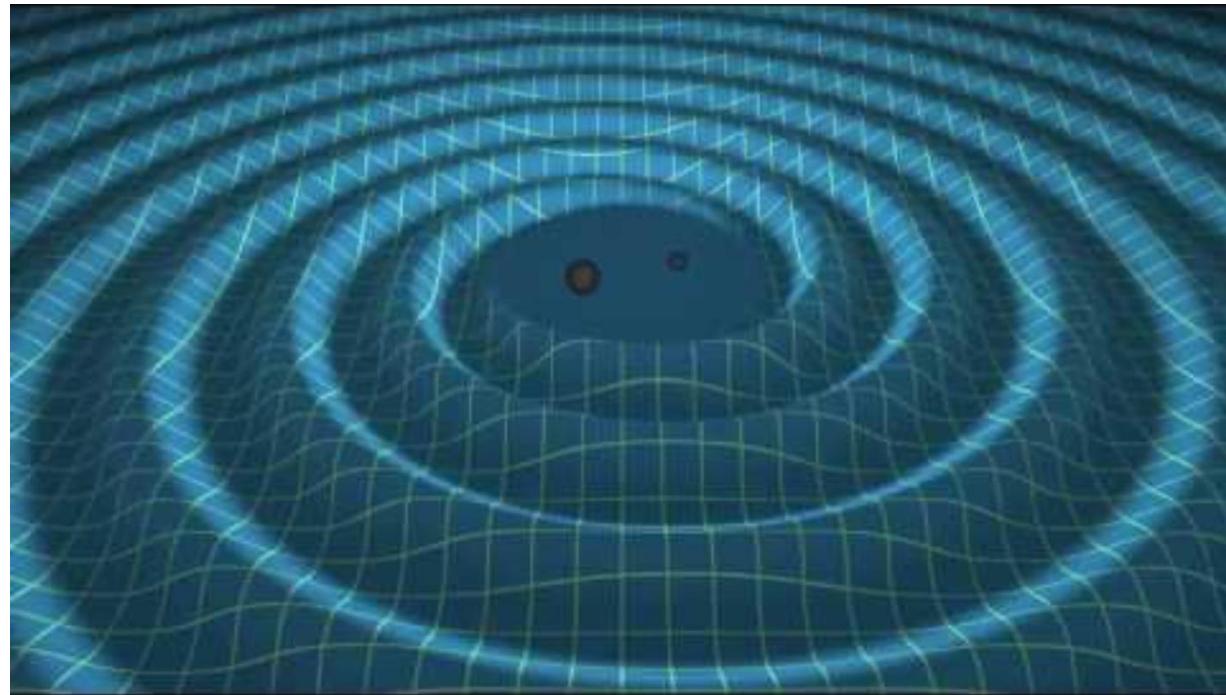


Crédito: LIGO Caltech, MIT



Crédito: LIGO Collaboration

Colisiones de BH



¿Preguntas?