01

El Universo Observable

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00 Contenidos

Breve resumen de la cosmología observacional:

- Escalas y distancias, homogeneidad e isotropía a gran escala, el fondo cósmico de microondas, el universo está hecho de partículas, el universo en expansión.

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01 Motivación

Necesitamos conocer las **simetrías del Universo** para elegir la **métrica** (geometría) y el **Tensor Energía-Momento** (contenido de materia/energía) adecuados que **resuelvan las ecuaciones de Einstein** a nivel cosmológico.

Para ello, recurriremos a **evidencias observacionales sobre el Universo**.

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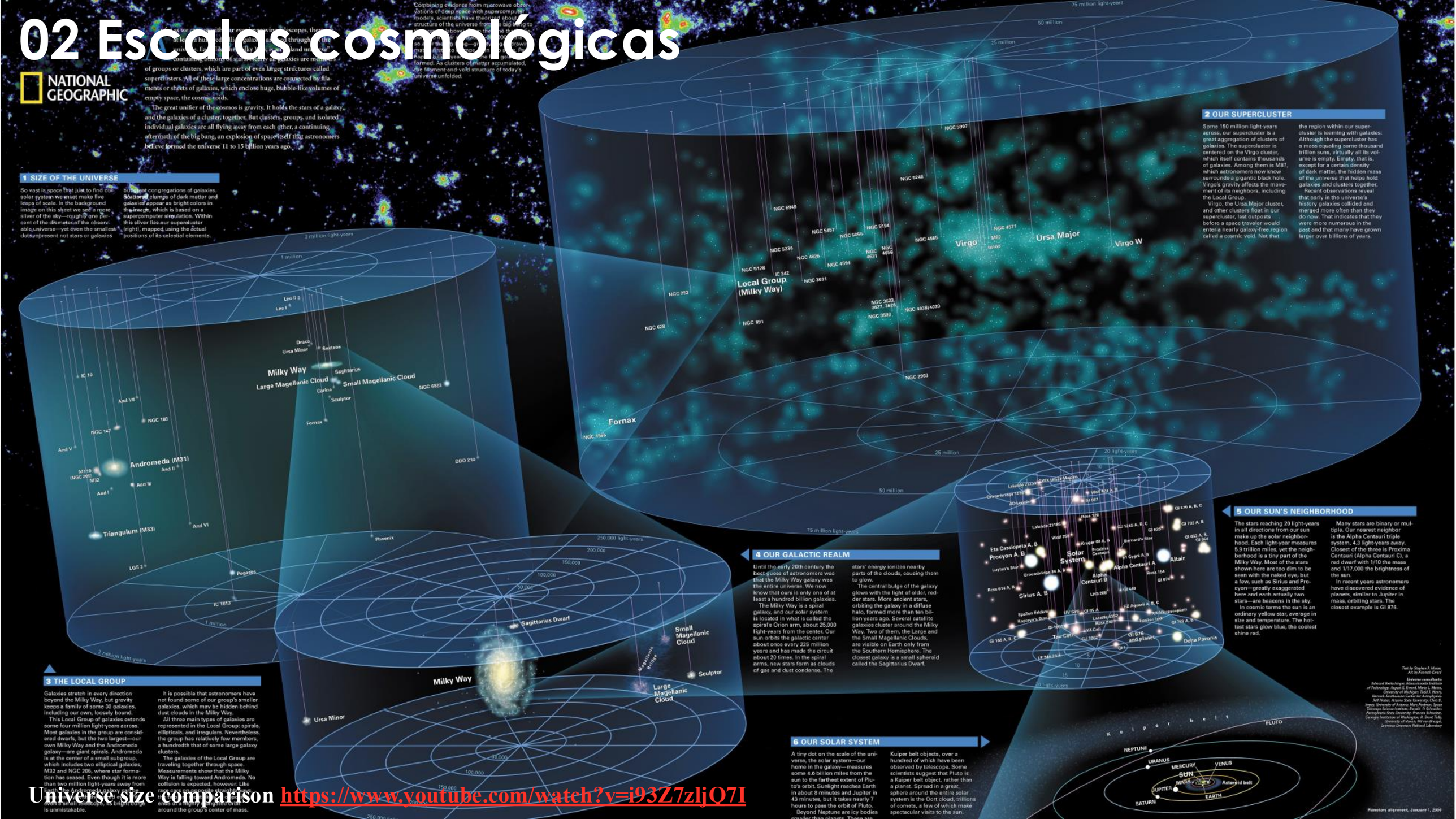
02 Escalas cosmológicas

NATIONAL GEOGRAPHIC

containing billions of stars, nearly all galaxies are members of groups or clusters, which are part of even larger structures called superclusters. All of these large concentrations are connected by filaments or sheets of galaxies, which enclose huge, bubble-like volumes of empty space, the cosmic voids.

The great unifier of the cosmos is gravity. It holds the stars of a galaxy, and the galaxies of a cluster, together. But clusters, groups, and isolated individual galaxies are all flying away from each other, a continuing aftermath of the big bang, an explosion of space itself that astronomers believe formed the universe 11 to 15 billion years ago.

Combining evidence from microwave observations of deep space with supercomputer models, scientists have theorized about structure of the universe from the big bang to the present. Below, the cosmic microwave map [illegible] billion years after the big bang, galaxies formed. As clusters of matter accumulated, the filament-and-void structure of today's universe unfolded.



1 SIZE OF THE UNIVERSE

So vast is space that just to find our solar system we must make five leaps of scale. In the background image on this sheet we see a mere sliver of the sky—roughly one percent of the diameter of the observable universe—yet even the smallest dots represent not stars or galaxies but great congregations of galaxies. Scattered clumps of dark matter and galaxies appear as bright colors in the image, which is based on a supercomputer simulation. Within this sliver lies our supercluster (right), mapped using the actual positions of its celestial elements.

2 OUR SUPERCLUSTER

Some 150 million light-years across, our supercluster is a great aggregation of clusters of galaxies. The supercluster is centered on the Virgo cluster, which itself contains thousands of galaxies. Among them is M87, which astronomers now know surrounds a gigantic black hole. Virgo's gravity affects the movement of its neighbors, including the Local Group.

Virgo, the Ursa Major cluster, and other clusters float in our supercluster, last outposts before a space traveler would enter a nearly galaxy-free region called a cosmic void. Not that the region within our supercluster is teeming with galaxies: Although the supercluster has a mass equaling some thousand trillion suns, virtually all its volume is empty. Empty, that is, except for a certain density of dark matter, the hidden mass of the universe that helps hold galaxies and clusters together.

Recent observations reveal that early in the universe's history galaxies collided and merged more often than they do now. That indicates that they were more numerous in the past and that many have grown larger over billions of years.

3 THE LOCAL GROUP

Galaxies stretch in every direction beyond the Milky Way, but gravity keeps a family of some 30 galaxies, including our own, loosely bound.

This Local Group of galaxies extends some four million light-years across. Most galaxies in the group are considered dwarfs, but the two largest—our own Milky Way and the Andromeda galaxy—are giant spirals. Andromeda is at the center of a small subgroup, which includes two elliptical galaxies, M32 and NGC 205, where star formation has ceased. Even though it is more than two million light-years away from Earth, the Andromeda galaxy can be seen in an all telescope; its bright image is unmistakable.

It is possible that astronomers have not found some of our group's smaller galaxies, which may be hidden behind dust clouds in the Milky Way.

All three main types of galaxies are represented in the Local Group: spirals, ellipticals, and irregulars. Nevertheless, the group has relatively few members, a hundredth that of some large galaxy clusters.

The galaxies of the Local Group are traveling together through space. Measurements show that the Milky Way is falling toward Andromeda. No collision is expected, however. Like race cars on opposite straightaways, ones of a mighty [illegible] orbit around the group's center of mass.

4 OUR GALACTIC REALM

Until the early 20th century the best guess of astronomers was that the Milky Way galaxy was the entire universe. We now know that ours is only one of at least a hundred billion galaxies.

The Milky Way is a spiral galaxy, and our solar system is located in what is called the spiral's Orion arm, about 25,000 light-years from the center. Our sun orbits the galactic center about once every 225 million years and has made the circuit about 20 times. In the spiral arms, new stars form as clouds of gas and dust condense. The stars' energy ionizes nearby parts of the clouds, causing them to glow.

The central bulge of the galaxy glows with the light of older, redder stars. More ancient stars, orbiting the galaxy in a diffuse halo, formed more than ten billion years ago. Several satellite galaxies cluster around the Milky Way. Two of them, the Large and the Small Magellanic Clouds, are visible on Earth only from the Southern Hemisphere. The closest galaxy is a small spheroid called the Sagittarius Dwarf.

5 OUR SUN'S NEIGHBORHOOD

The stars reaching 20 light-years in all directions from our sun make up the solar neighborhood. Each light-year measures 5.9 trillion miles, yet the neighborhood is a tiny part of the Milky Way. Most of the stars shown here are too dim to be seen with the naked eye, but a few, such as Sirius and Procyon—greatly exaggerated here and each actually two stars—are beacons in the sky.

In cosmic terms the sun is an ordinary yellow star, average in size and temperature. The hottest stars glow blue, the coolest shine red.

Many stars are binary or multiple. Our nearest neighbor is the Alpha Centauri triple system, 4.3 light-years away. Closest of the three is Proxima Centauri (Alpha Centauri C), a red dwarf with 1/10 the mass and 1/17,000 the brightness of the sun.

In recent years astronomers have discovered evidence of planets, similar to Jupiter in mass, orbiting stars. The closest example is Gl 876.

6 OUR SOLAR SYSTEM

A tiny dot on the scale of the universe, the solar system—our home in the galaxy—measures some 4.6 billion miles from the sun to the farthest extent of Pluto's orbit. Sunlight reaches Earth in about 8 minutes and Jupiter in 43 minutes, but it takes nearly 7 hours to pass the orbit of Pluto.

Beyond Neptune are icy bodies smaller than planets. There are Kuiper belt objects, over a hundred of which have been observed by telescope. Some scientists suggest that Pluto is a Kuiper belt object, rather than a planet. Spread in a great sphere around the entire solar system is the Oort cloud, trillions of comets, a few of which make spectacular visits to the sun.

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Universe size comparison https://www.youtube.com/watch?v=i93Z7zljQ7I

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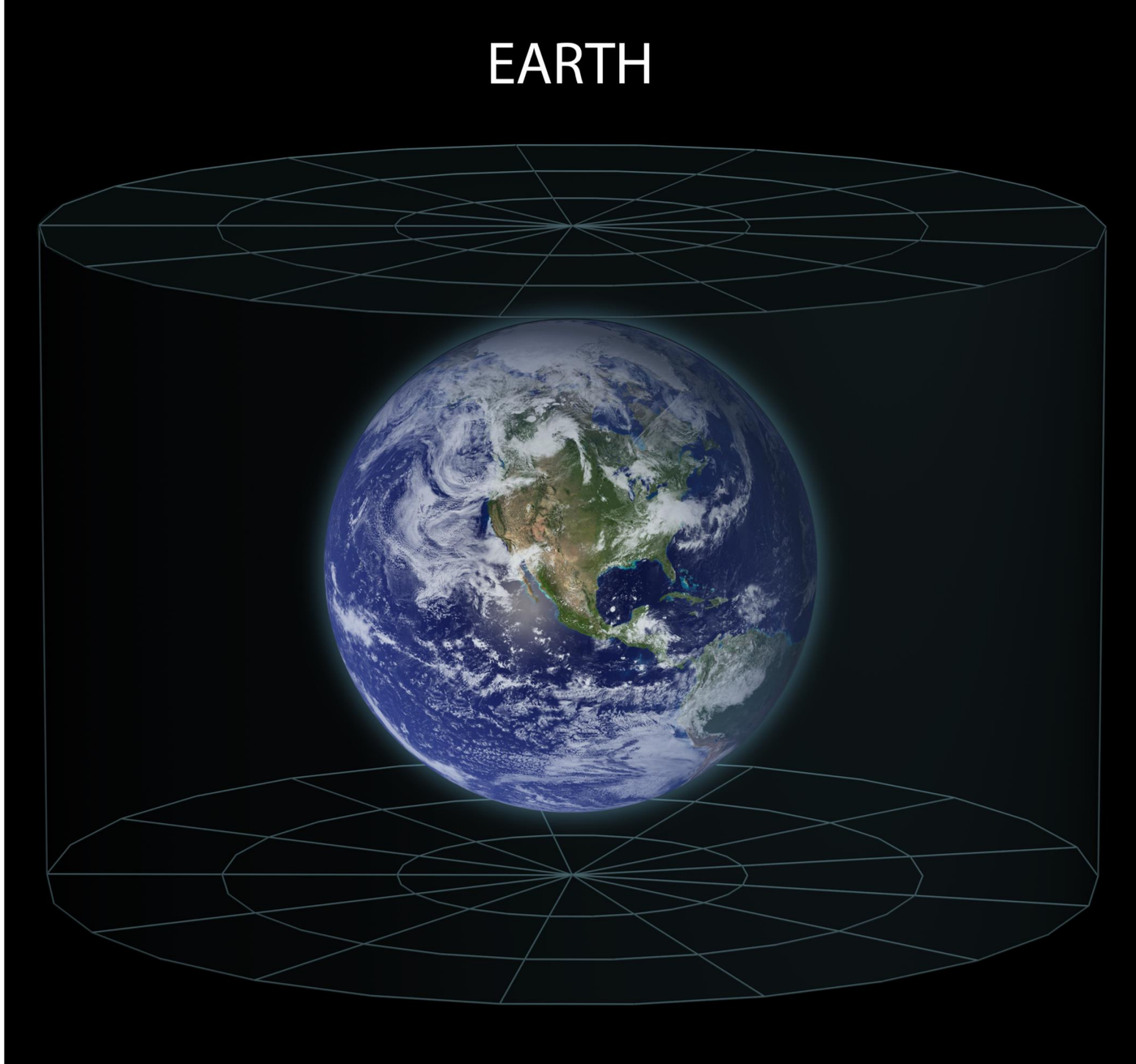
$$R_{Tierra} = 6371 \text{ km}$$



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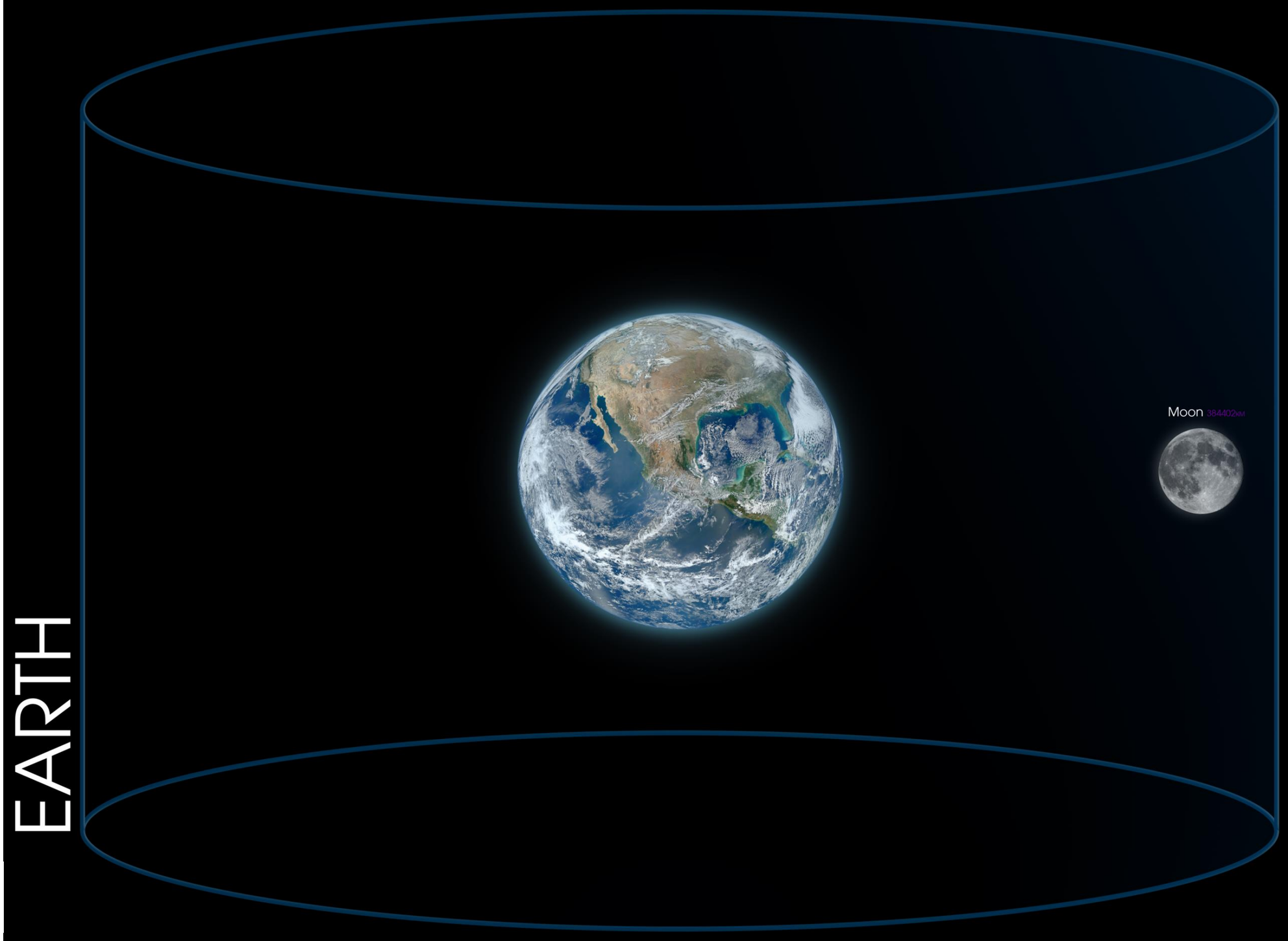
d ~ 384,400 km
~ 1,282 ls



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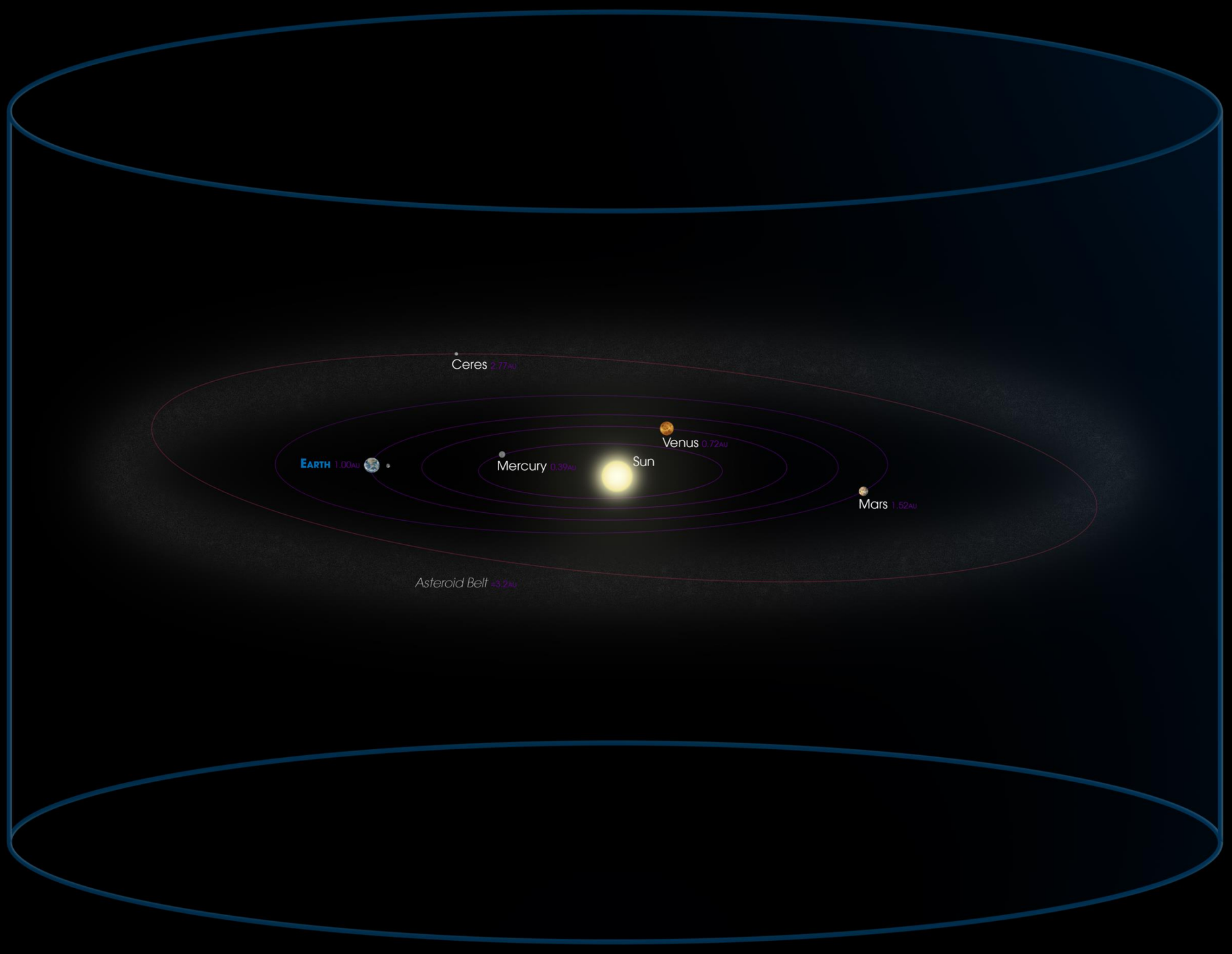
INNER SOLAR SYSTEM

$1\ UA = 150 \cdot 10^6\ km$

$\sim 8\ lm$



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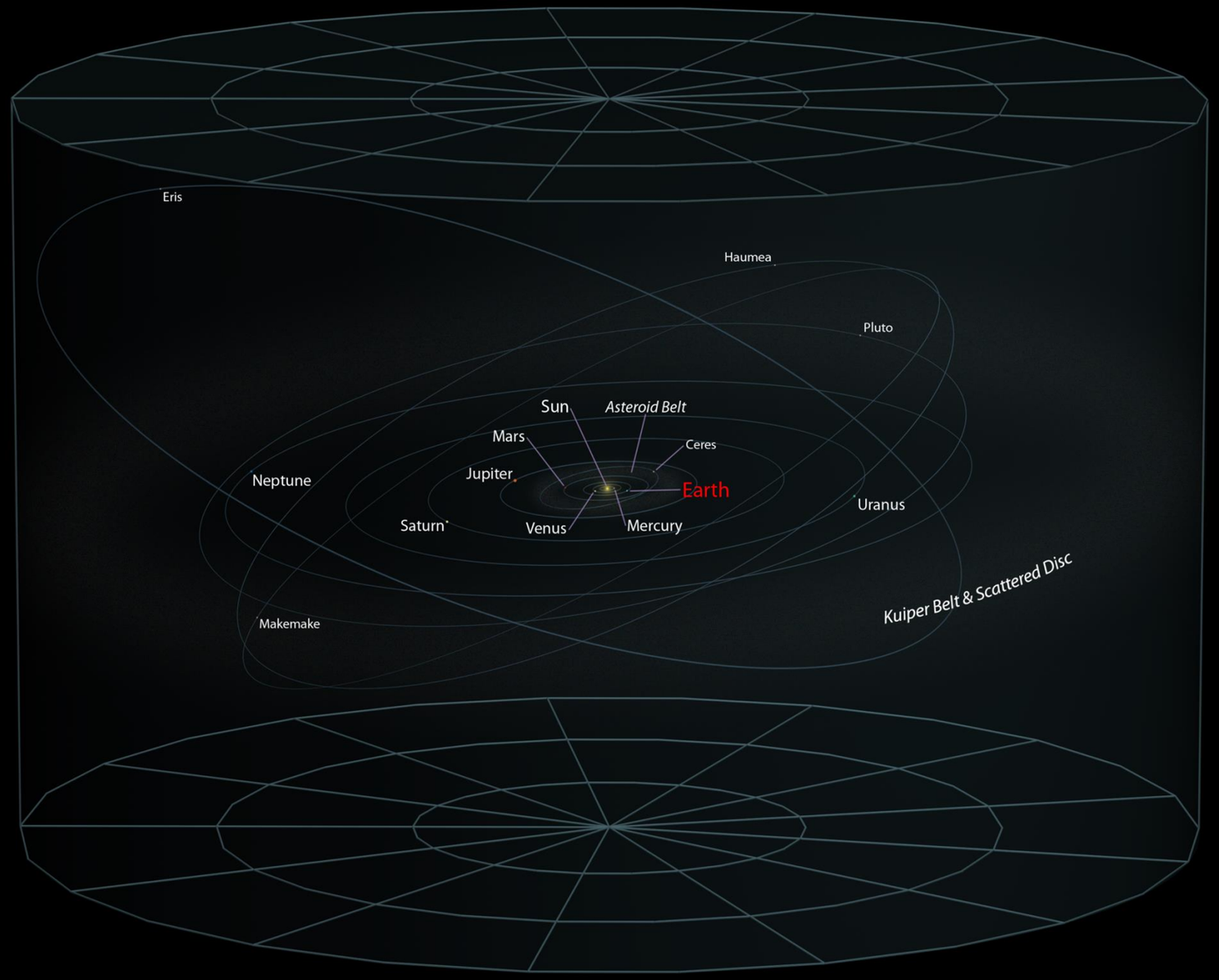
$d_{Neptuno} \sim 30$ UA

$d_{Oort} \sim 2 \cdot 10^3 - 10^5$ UA

SOLAR SYSTEM



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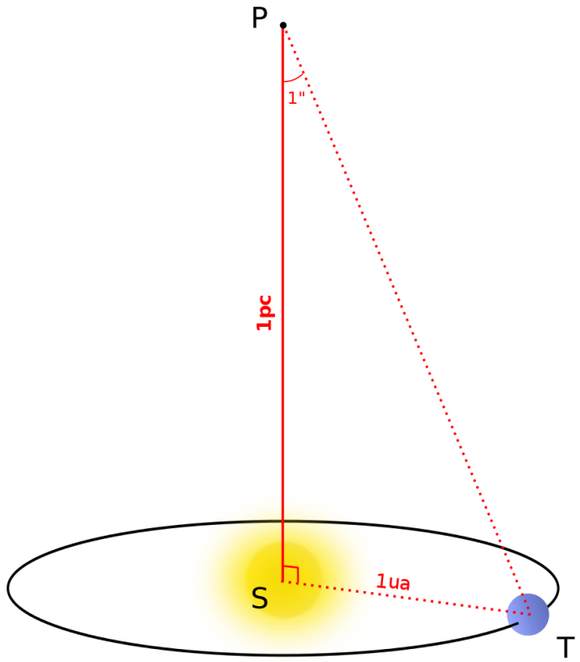
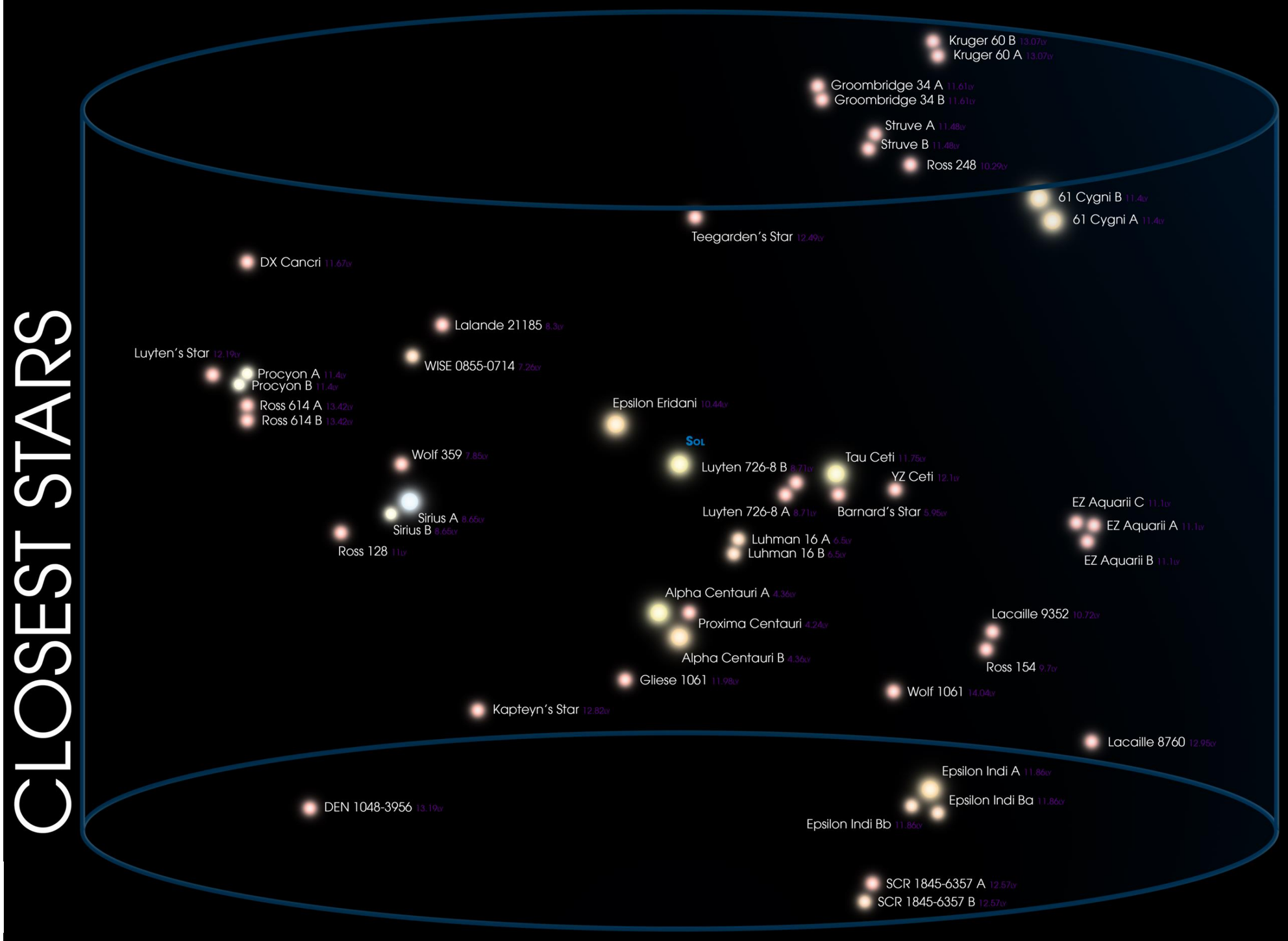
$d_{Sirio} \sim 2{,}64$ pc

1 parsec ~ 3,26 ly

$\sim 3 \cdot 10^{13}$ km





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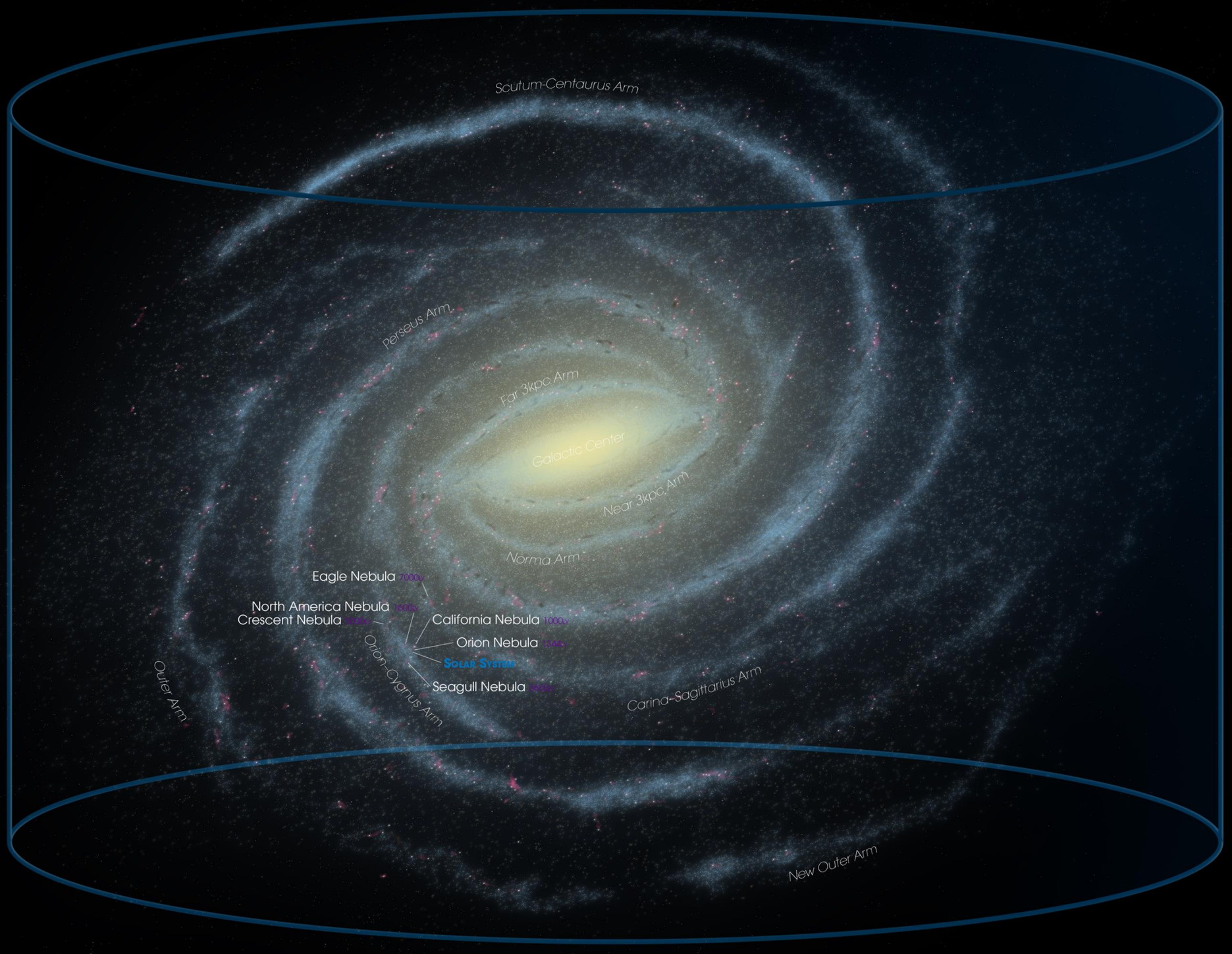
$d_{Orion} \sim 8{,}2$ kpc

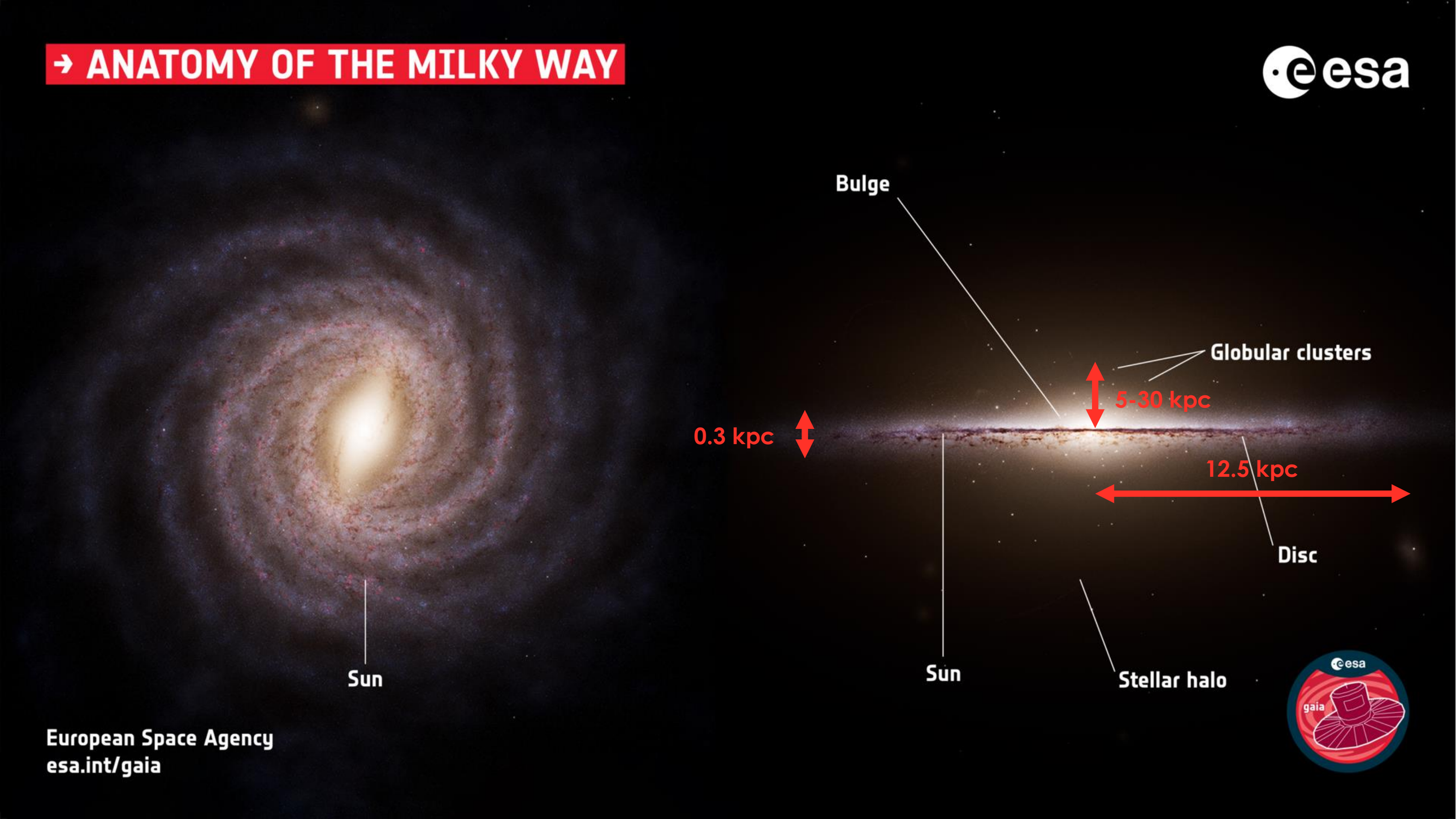
$\tau \sim 2 \cdot 10^8$ yr

$v_r \sim 220$ km/s.

MILKY WAY GALAXY



→ ANATOMY OF THE MILKY WAY



European Space Agency
esa.int/gaia

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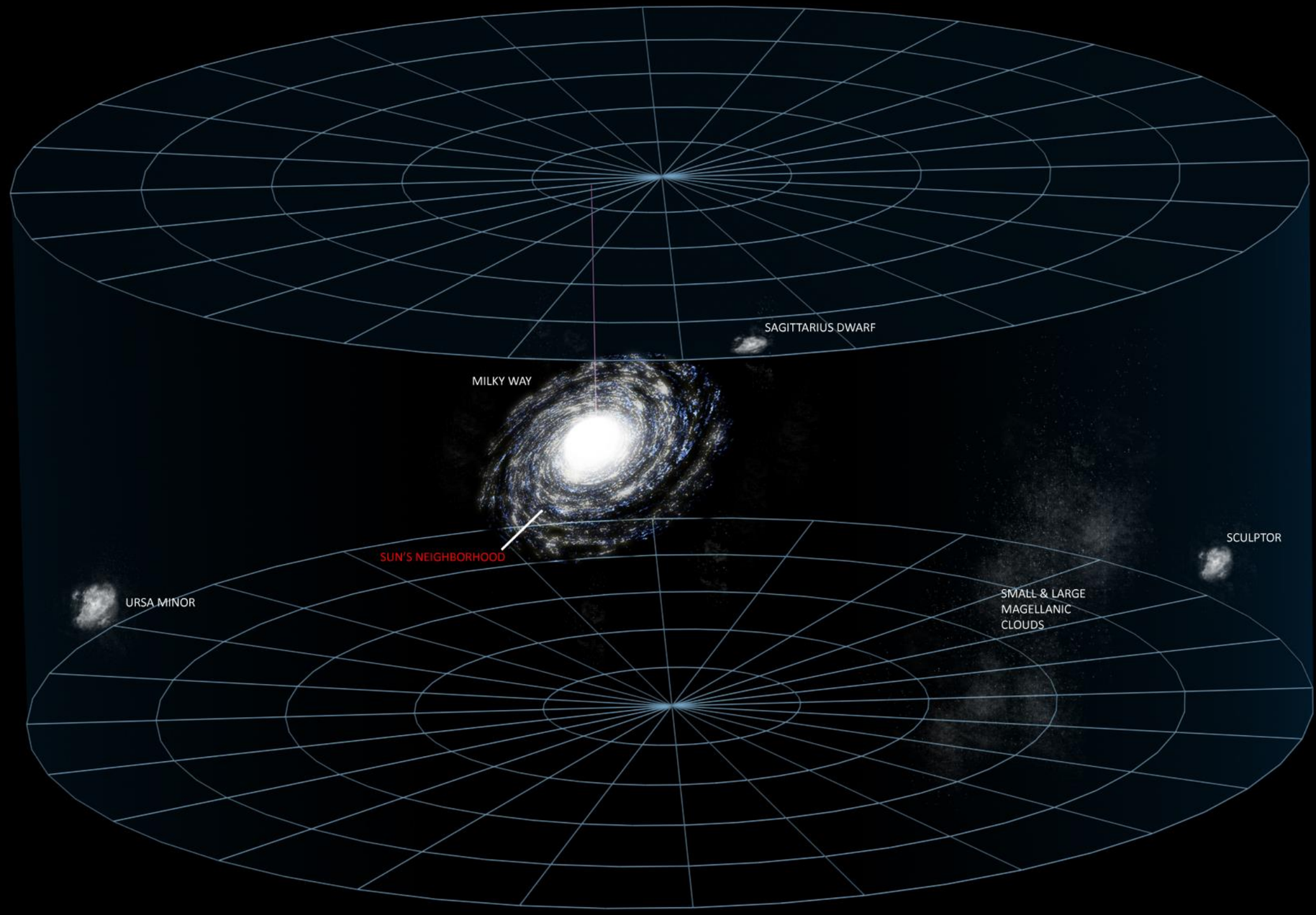
GALACTIC REALM



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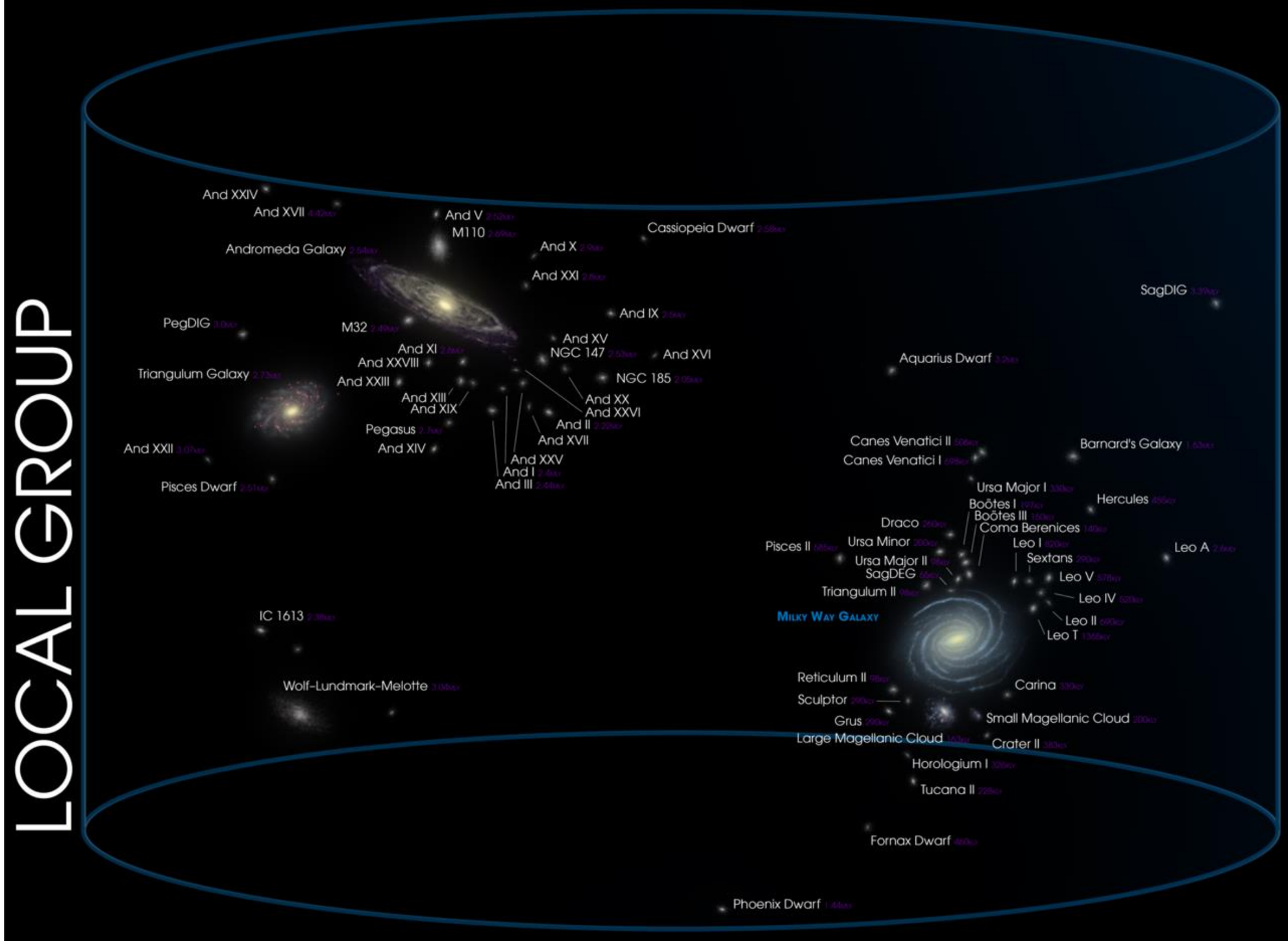
$d_{LMC} \sim 50$ kpc
$d_{M31} \sim 770$ kpc

1 Mpc ~ distancia media entre galaxias



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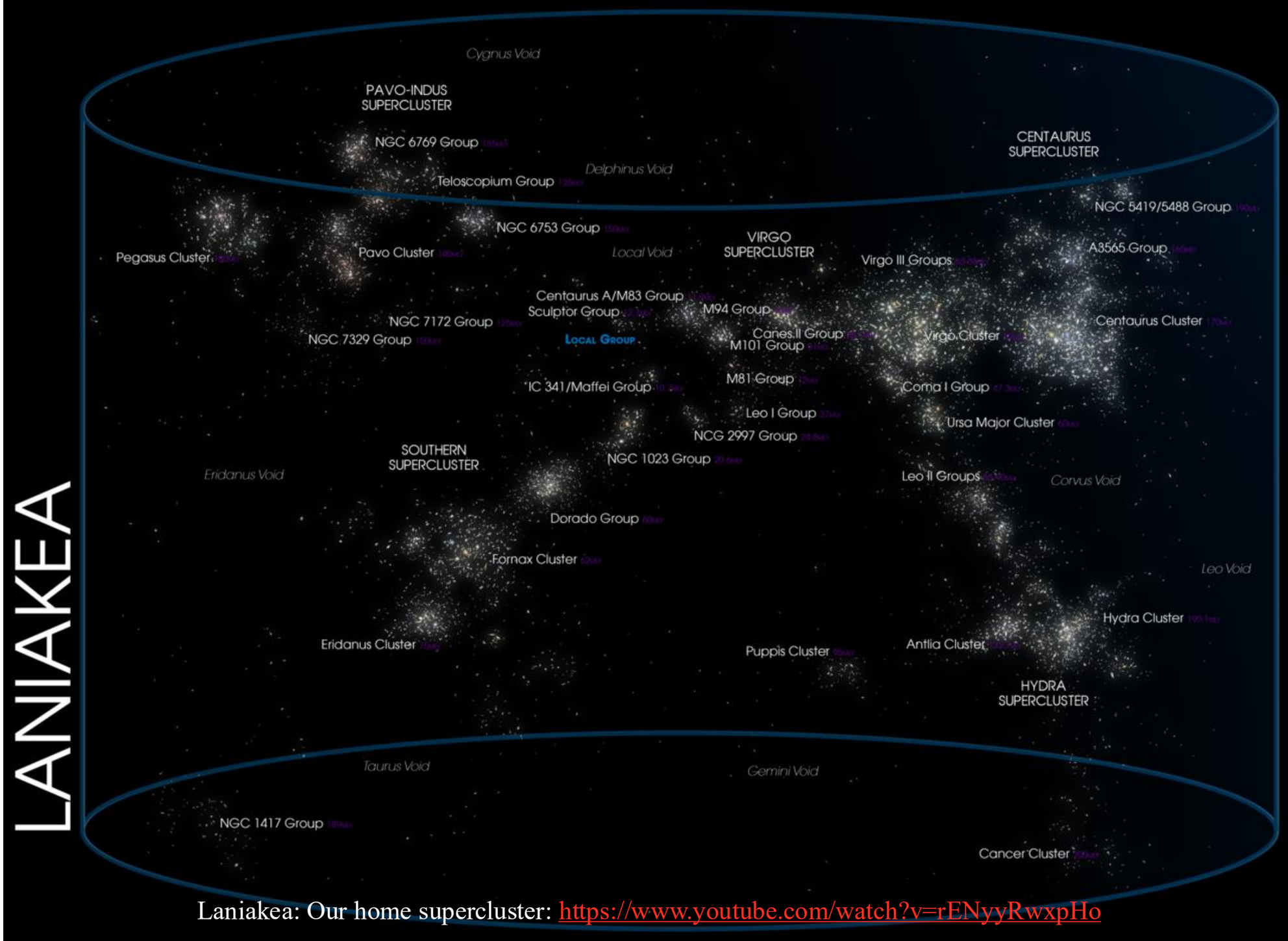

Laniakea: Our home supercluster: https://www.youtube.com/watch?v=rENyyRwxpHo

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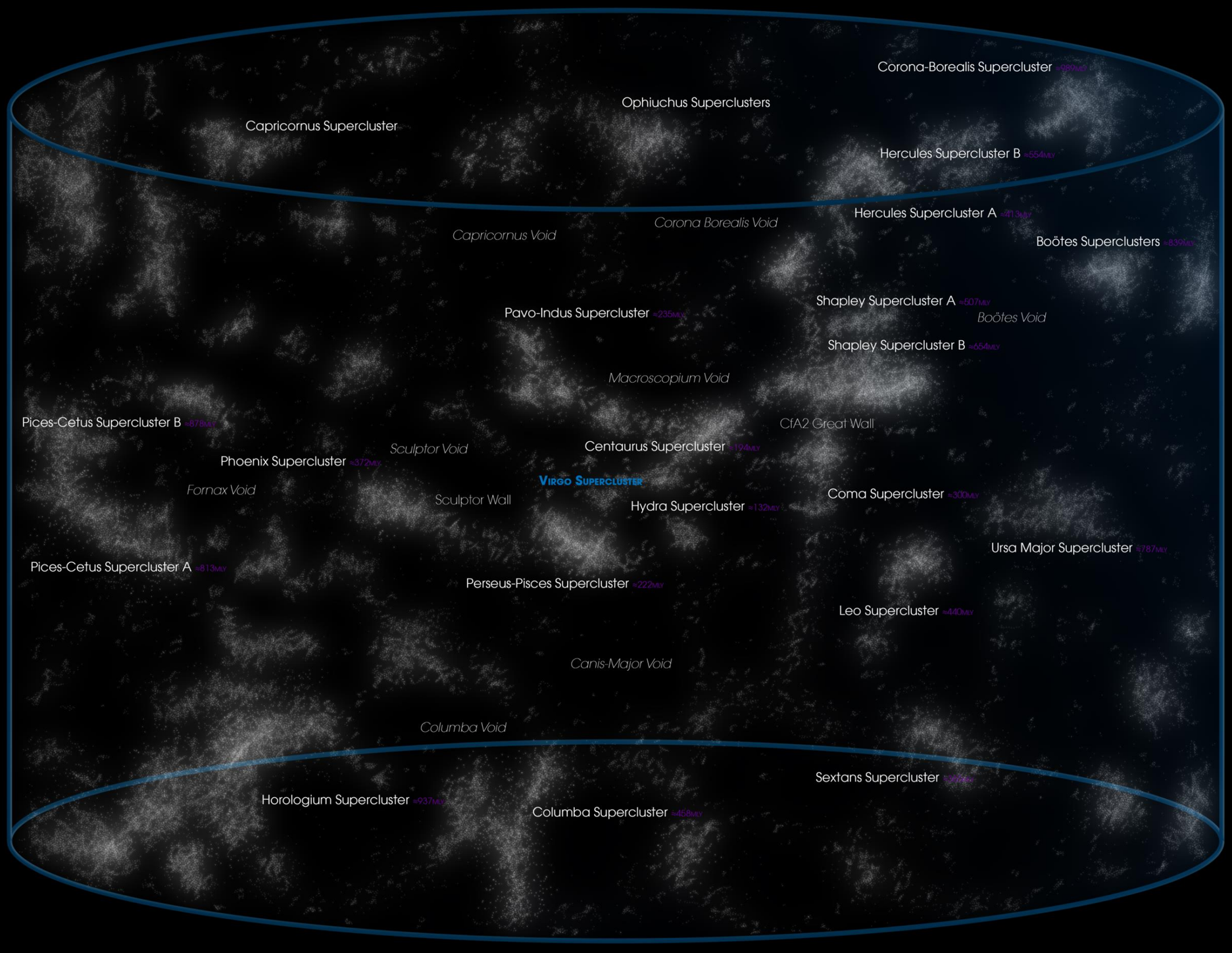
LOCAL SUPERCLUSTERS



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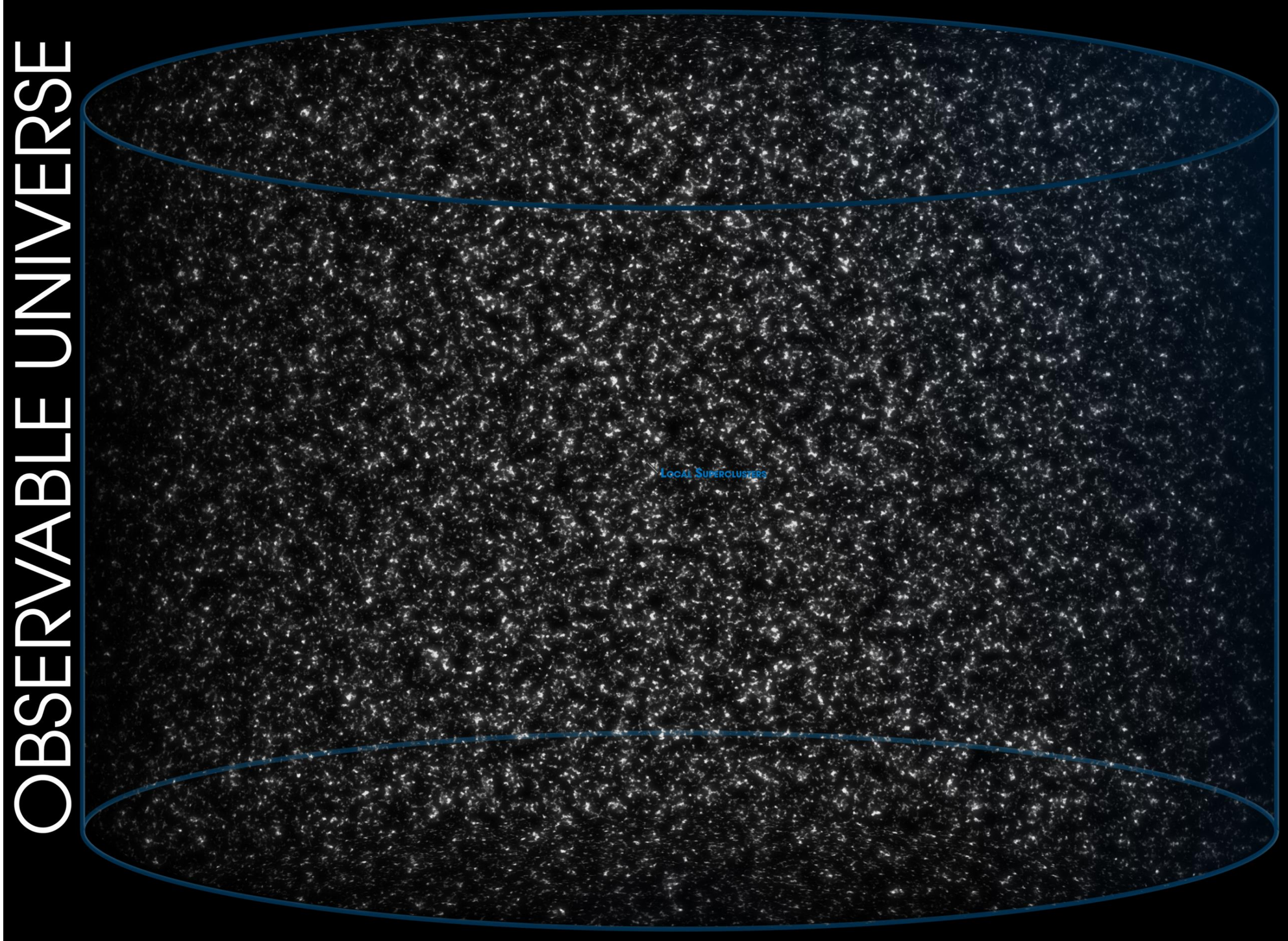
Tamaño ~ 28.5 Gpc
~ $9{,}3 \cdot 10^{10}$ ly



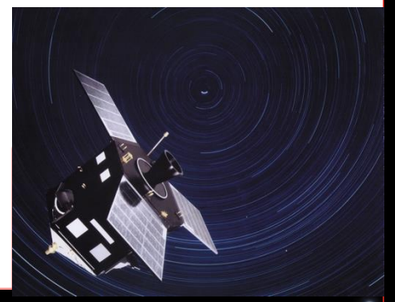
03 Medida de distancias: Paralaje

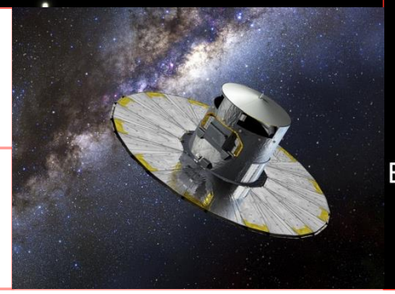
Cronología

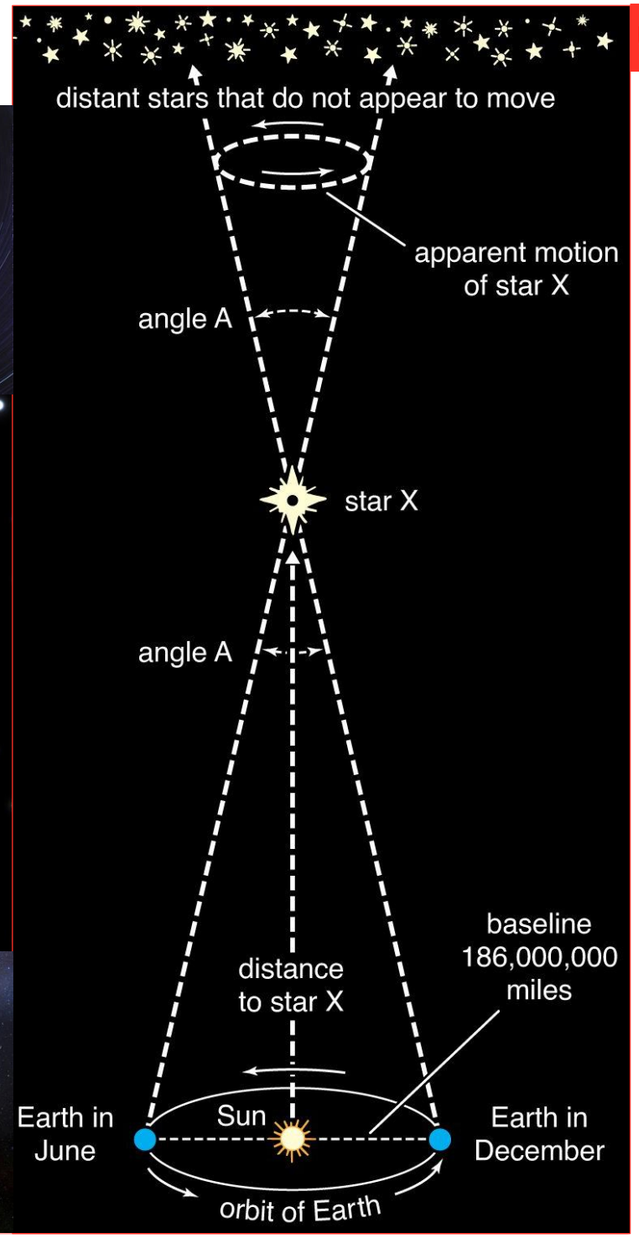
- 1838 Bessel: 61-Cygni (~3pc)
- 1989 Hiparcos: 20.800 estrellas
- 2013 Gaia: 10^{12} estrellas

Características

- Método **geométrico**.
- Exclusivamente válido para estrellas cercanas.
- Método sobre el cual se calibran otros métodos: *The distance ladder*.







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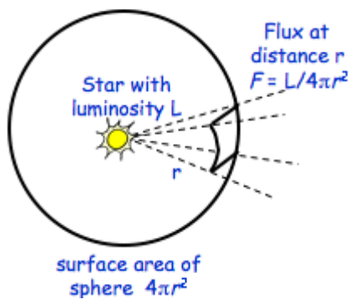
03 Medida de distancias: Cefeidas

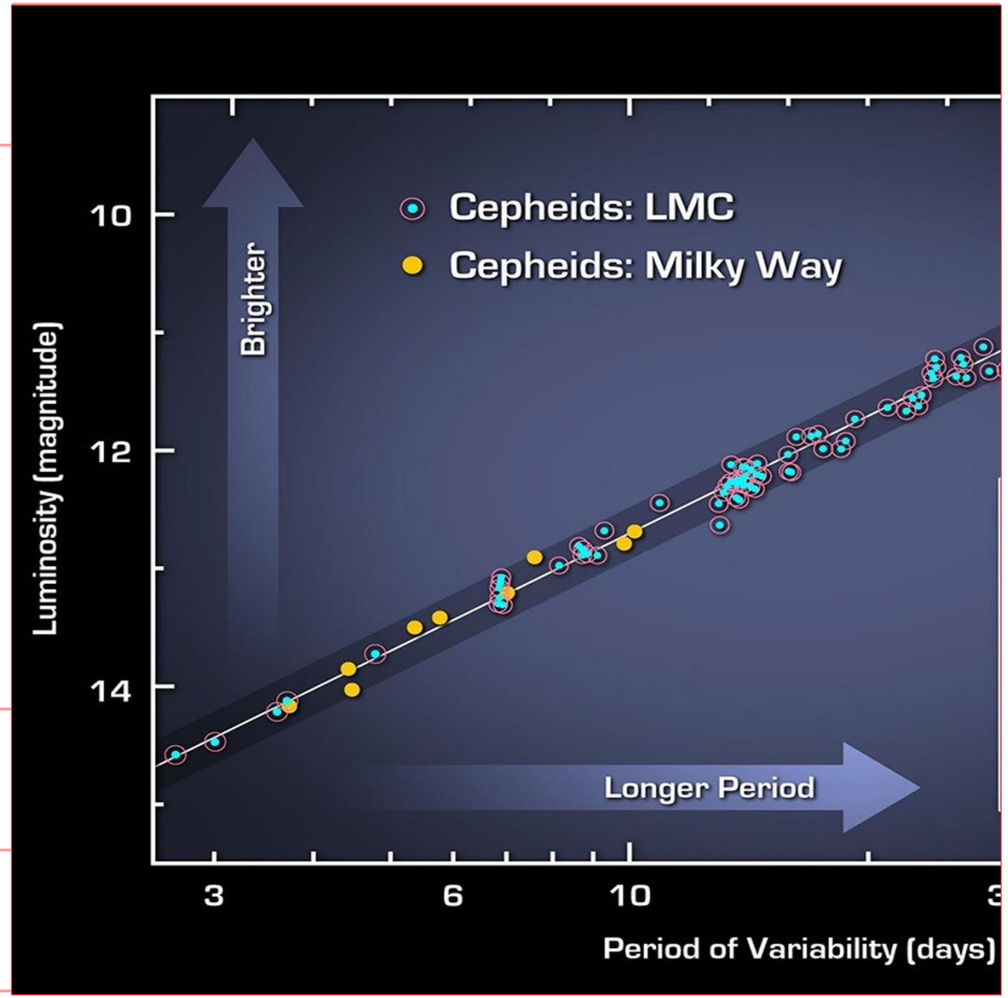
Cronología

- 1910-1997: Luminosidad intrínseca de cúmulos estelares
- 1912 H. Leavitt: Variables Cefeidas
- 1925 E. Hubble: Cefeidas extragalácticas

Características

- Método basado en la **luminosidad intrínseca** de ciertas estrellas.
- Existe una relación entre la variabilidad y la luminosidad de las Cefeidas.
- Las Cefeidas son muy brillantes y permiten el calculo de **distancias más lejanas que mediante paralaje**.





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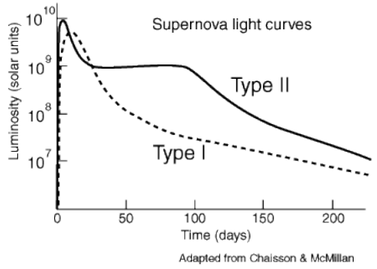
03 Medida de distancias: Supernovas Ia

Cronología

- 1970s: Luminosidad Intrínseca de SNIa

Características

- SNIa pueden ser tan brillantes como la galaxia huésped.
- 1 SNIa/300yr en una galaxia.
- 1 SNIa/yr en un cúmulo estándar de galaxias.
- SNIa son consideradas las **candelas estándar para medir distancias cosmológicas**.



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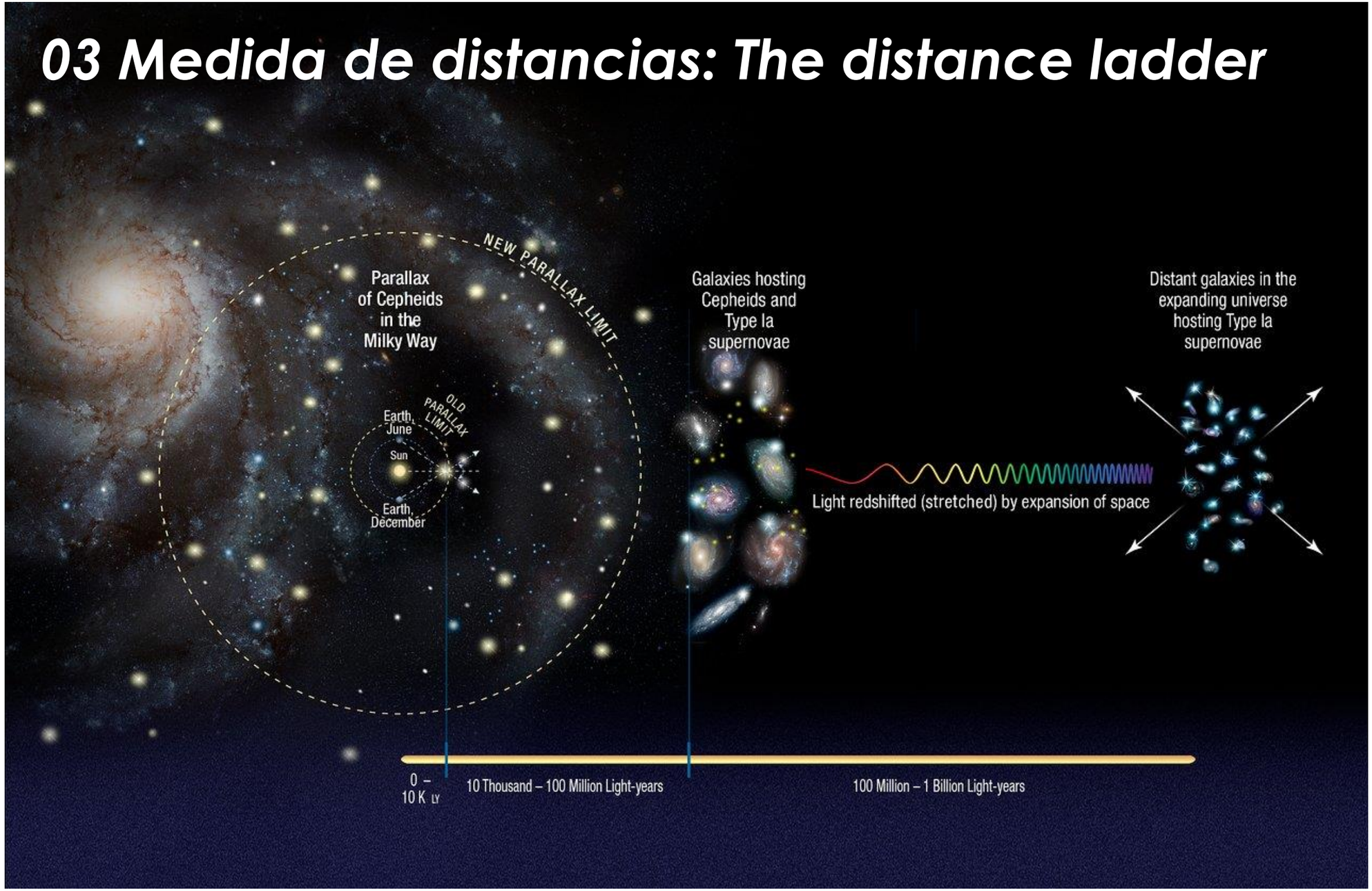
03 Medida de distancias: The distance ladder



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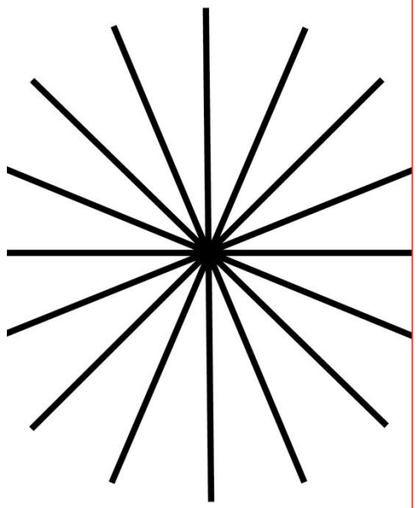
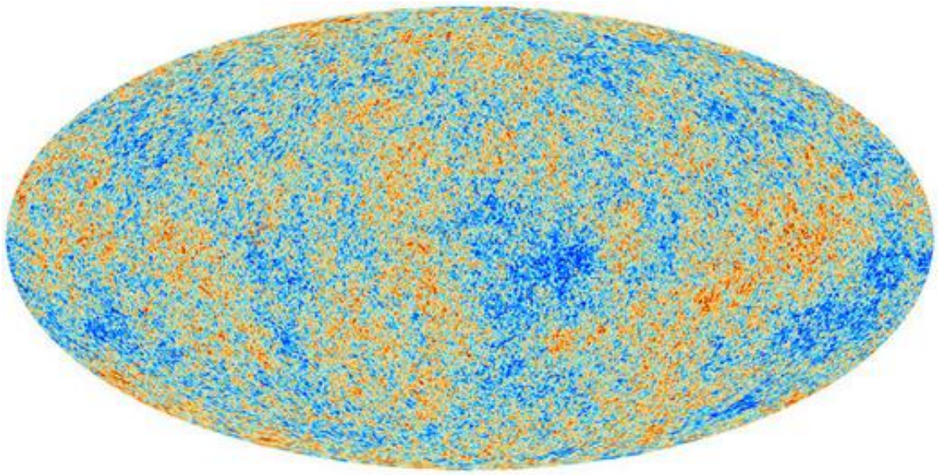
04 El universo es isótropo

- 1965 A. Penzias y R. Wilson descubren accidentalmente el fondo cósmico de microondas (Cosmic Microwave Background, CMB).
- Radiación isótropa de cuerpo negro a T = 2.725 ± 0.001 K
- Procede de la etapa de la recombinación, cuando el Universo tenía 380 Kyrs y una temperatura de 3000K.
- A esa temperatura y densidad, los átomos neutros son estables y la materia se hace "transparente" para la radiación.
- La radiación es altamente isótropa, pero tiene pequeñas anisotropías (e.g. CMB poles)





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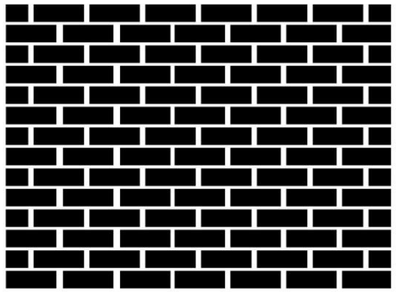
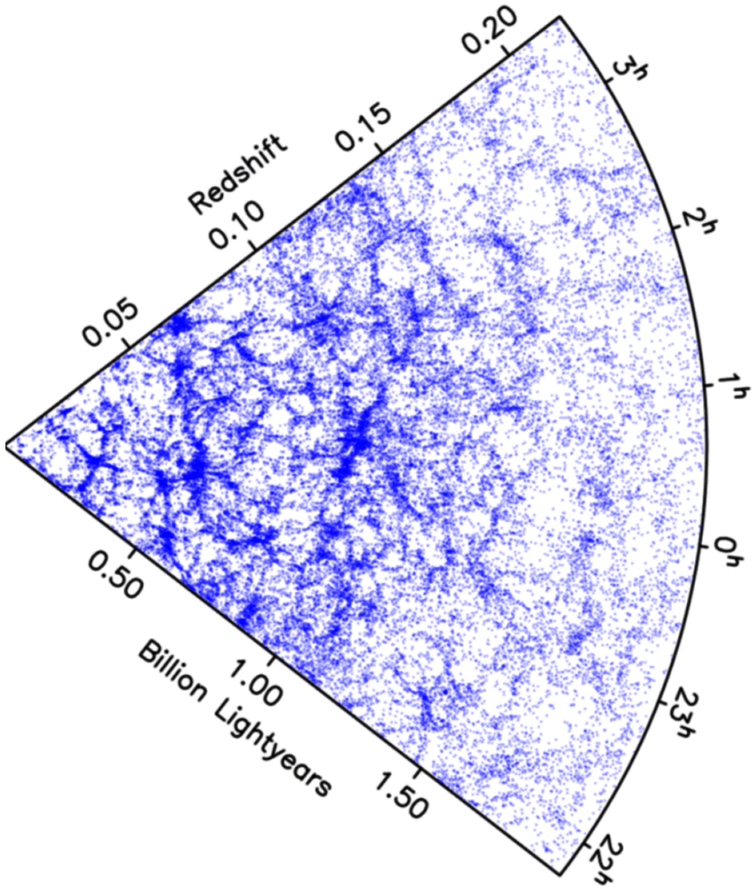
05 El universo es homogéneo

- La isotropía del Universo y abandonar el heliocentrismo a escalas cosmológicas conducen a un Universo homogéneo.
- Muestreos de ~10^5-10^6 galaxias confirman la estructura homogénea a gran escala.
- A pequeña escala aparecen estructuras como filamentos, paredes y vacíos.
- A gran escala la densidad es menor (bias observacional) pero la estructura es claramente homogénea.
- Surveys actuales: SDSS, DESI, Euclid
- Surveys futuros: LSST, SKA.





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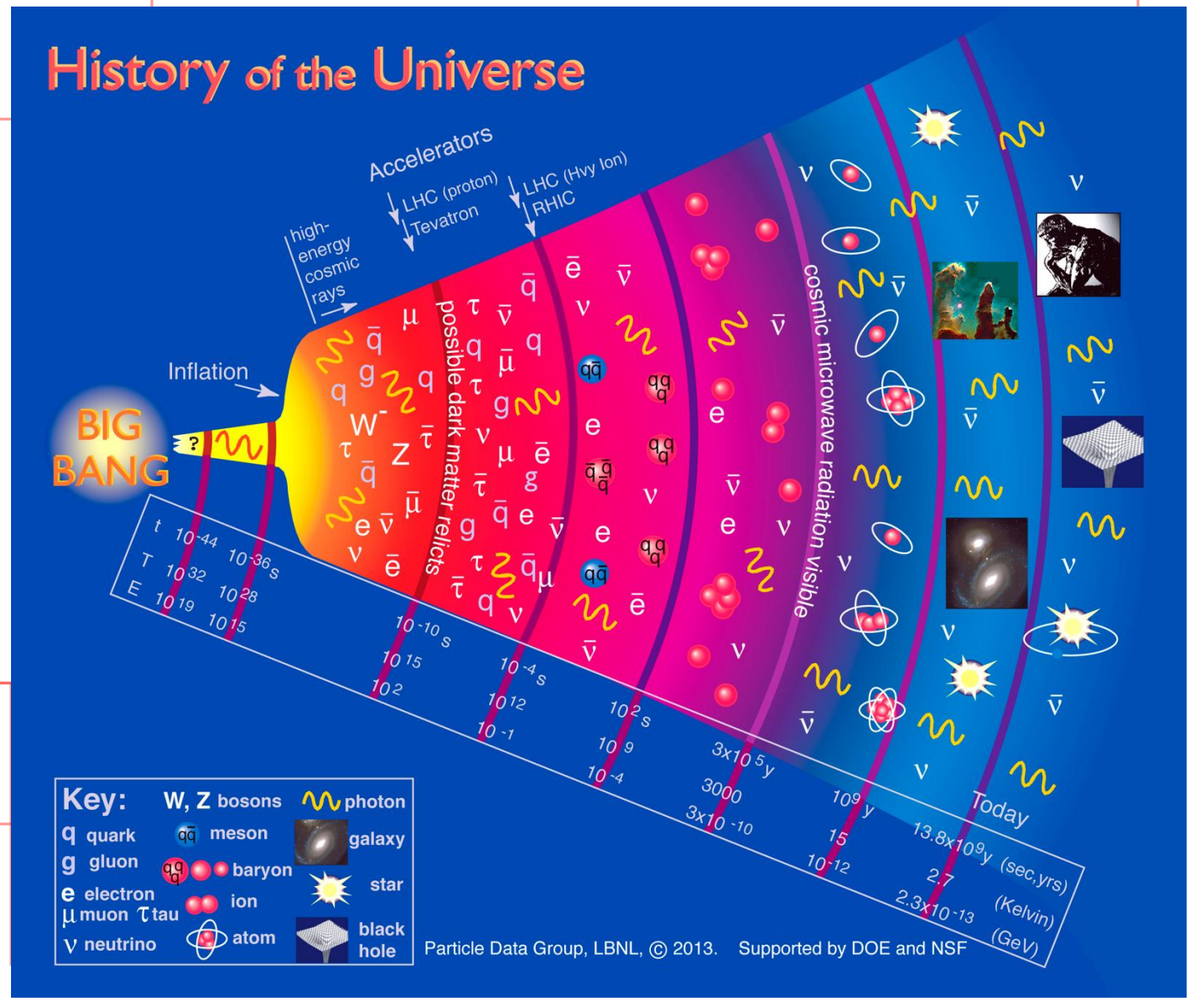
06 Contenido del universo

- El universo primordial era un plasma caliente de **partículas** y **fotones**.
- El camino libre medio de la radiación era muy pequeño, de manera que los fotones y las partículas estaban tan acoplados, que se dice que el **universo** era **opaco**.
- Tres minutos después del Big Bang, se produce la **nucleosíntesis**, que es la formación de los primeros núcleos atómicos ligeros: Deuterio (D=p+n), Helio 3 (D+p), Helio 4 (D+D) y Litio.
- Los **elementos más pesados** se formarán posteriormente **en el interior de las estrellas**.
- Cuando la expansion enfrió el universo suficientemente (< 3000 K), se formaron los átomos y el **universo** se hizo **transparente a la radiación**.



(The Origin of Chemical Elements https://doi.org/10.1103/PhysRev.73.803)

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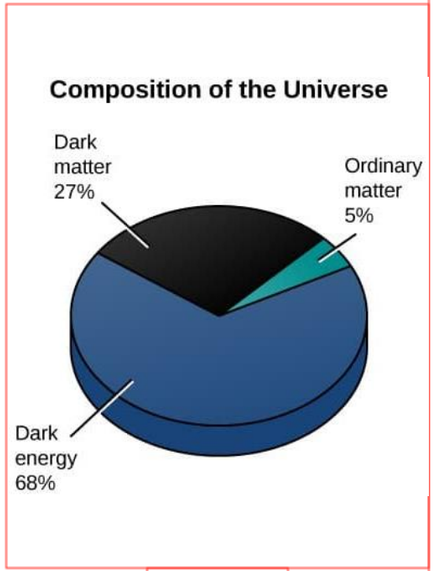
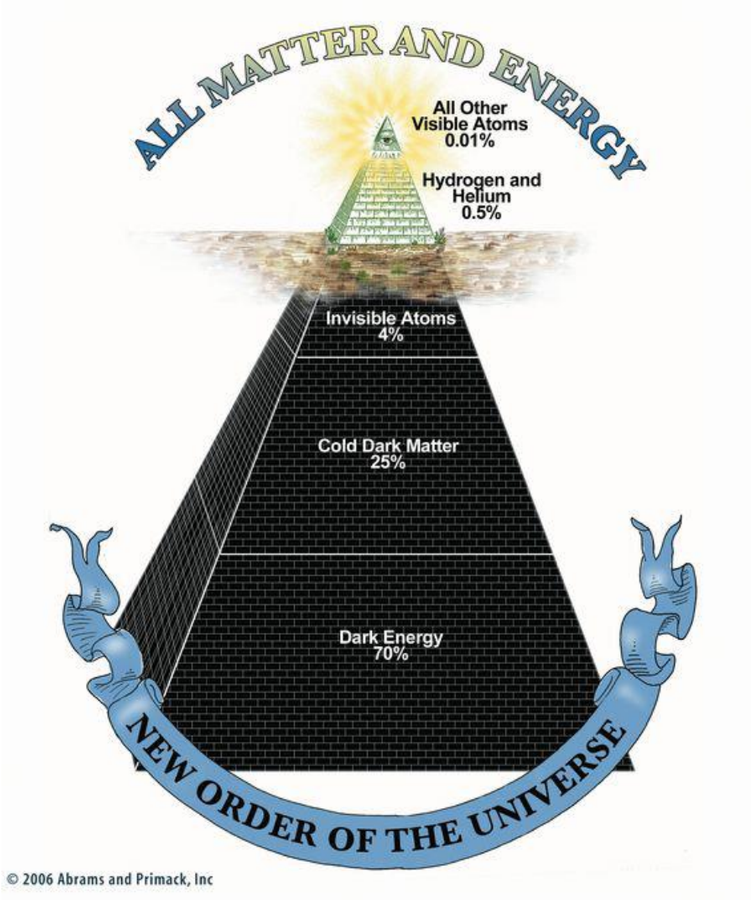
06 Contenido del universo

- Bariones
  - Átomos, protones, neutrones y electrones
  - Típicamente no relativistas
- Radiación
  - Radiación electromagnética
  - CMB
  - Interacciona con los bariones
- Neutrinos (υ_e, υ_μ, υ_τ)
  - Interacciona muy débilmente con la materia
- Materia oscura
  - Explica las curvas de rotación en los halos galácticos.
  - Su naturaleza es una incógnita.





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07 La expansión del universo

Cronología

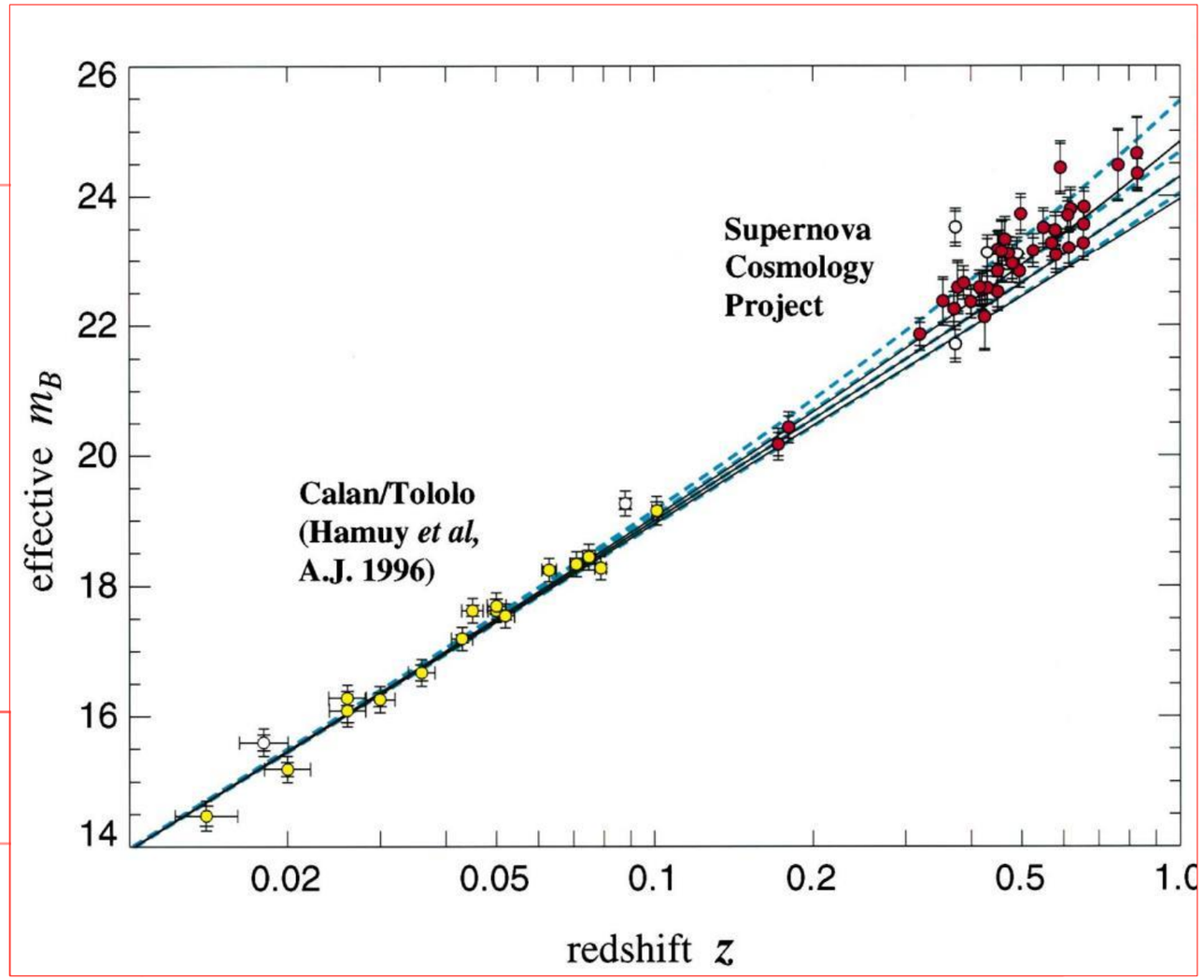
- 1918 Corrimiento al rojo de nebulosas
- 1927 Lemaitre: Las nebulosas son galaxias como la Vía Láctea
- 1929 Hubble: Relación aproximadamente lineal entre distancia y corrimiento al rojo (z, *redshift*).

  $v \sim H_0\, d$, donde $z=v/c$
- 1998 El Universo se expande aceleradamente (SNIa lejanas)
- 2010-2025 Tensión de Hubble

  CMB, $H_0 \sim 67{,}4$ Km/s/Mpc

  Distance Ladder, $H_0 \sim 73\text{-}74$ Km/s/Mpc

  TDCOSMO, $H_0 \sim 71.6$ Km/s/Mpc



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07 La expansión del universo: Corrimiento al rojo

Redshift $$z \equiv \frac{\Delta\lambda}{\lambda}$$

Doppler Redshift $$1 + z = 1 + \frac{v}{c}$$

Relativistic Doppler Redshift $$1 + z = \sqrt{\frac{1+\beta}{1-\beta}}, \quad \beta = \frac{v}{c}$$

Cosmological Redshift $$1 + z = \frac{a(t_o)}{a(t_e)}$$

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07 La expansión del universo: Ley de Hubble

Ley de Hubble $v \approx H_0 \cdot d$

La **constante de Hubble H_0** representa la **tasa de expansión actual del universo ($t = t_0$)**, pero dicha expansión no es constante a lo largo del tiempo.

La **velocidad de recesión v**, que históricamente se obtuvo a través de la medida del corrimiento al rojo z interpretándolo como un efecto Doppler, es en realidad una medida de la expansión cosmológica integrada a lo largo del tiempo. La **distancia d** se interpreta como la distancia propia del objeto evaluada en el **tiempo actual t_0**, aunque observacionalmente se emplean distancias obtenidas a partir de la luminosidad.

Por ello, la ley de Hubble es aproximadamente lineal y útil para redshifts pequeños exclusivamente: en ese régimen H(t) varía poco durante el trayecto de la luz, la distancia cambia poco entre emisión y observación, y la relación Doppler entre z y v es una buena aproximación. Sin embargo, a **redshifts cosmológicos estas aproximaciones dejan de ser válidas**.

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07 La expansión del universo: Edad del universo

$$v \approx H_0 \cdot d \implies \frac{d}{t_0} \approx H_0 \cdot d \implies t_0 = H_0^{-1} \approx 13.8 Gyr$$

Si asumimos como aproximación que la velocidad de recesión se ha mantenido constante, obtenemos una **estimación límite para la edad del universo t_0,** al suponer al suponer que la separación actual entre galaxias cercanas era nula al inicio del Big Bang (es decir, que todas ocupaban el mismo punto en t=0).

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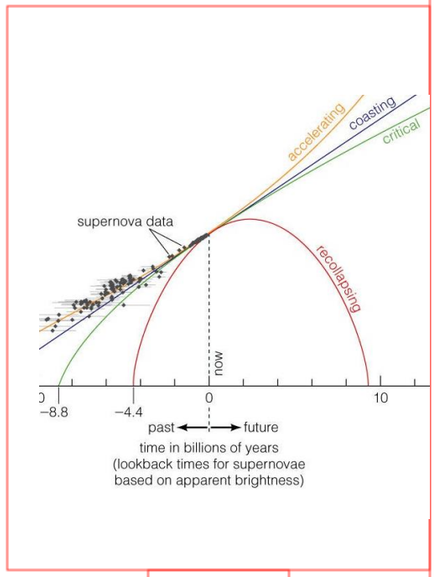
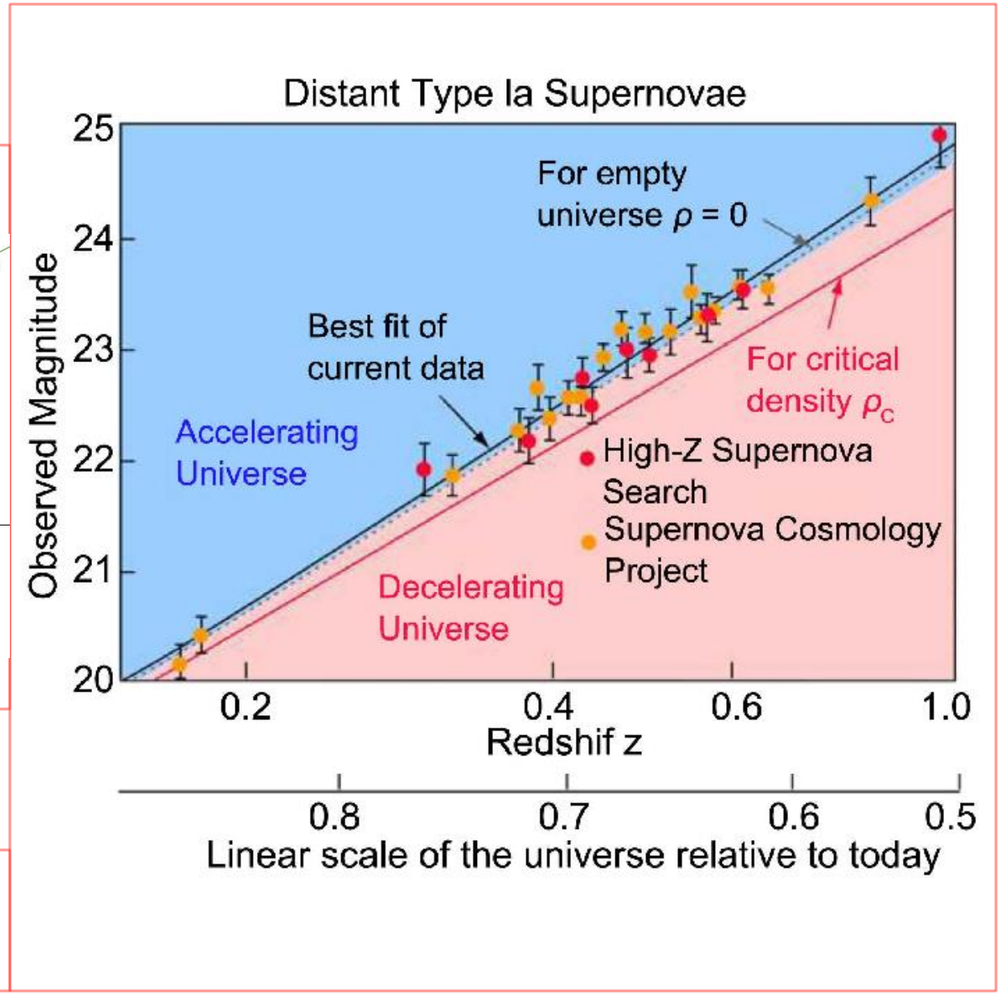
07 La expansión del universo: Expansión acelerada

$$R^{\mu\nu} - \frac{1}{2}g^{\mu\nu}R + \Lambda g^{\mu\nu} = 8\pi G T^{\mu\nu}$$

$$R^{\mu\nu} - \frac{1}{2}g^{\mu\nu}R = 8\pi G(T^{\mu\nu} - \frac{\Lambda}{8\pi G}g^{\mu\nu})$$

$$T^{\mu\nu}_{vac} = -\frac{\Lambda}{8\pi G}g^{\mu\nu} \implies T^{tt}_{vac} = \frac{\Lambda}{8\pi G}$$





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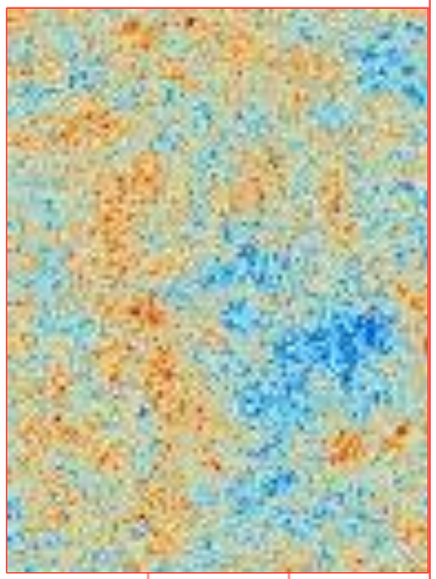
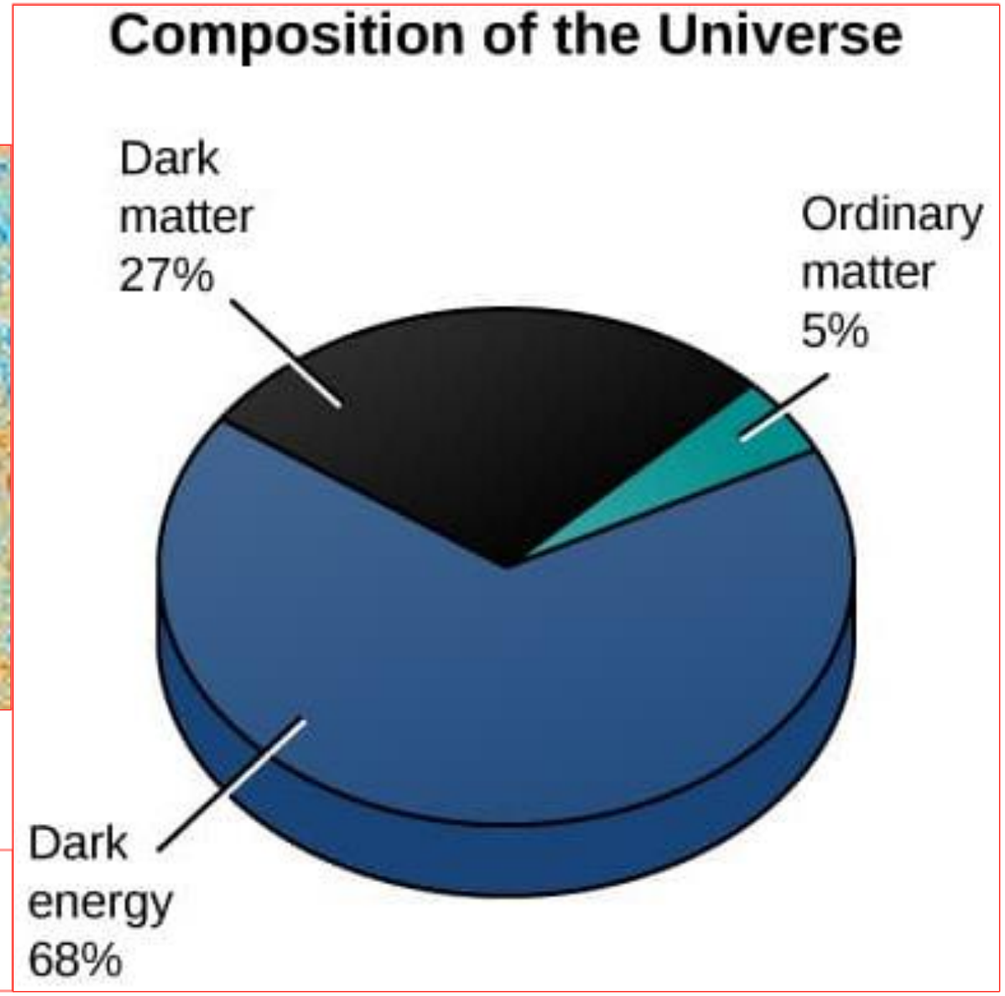
08 El Modelo Cosmológico Estándar Λ-CDM

Descripción matemática y física de un universo que se originó en el **Big Bang** y que se **expande de manera acelerada**.

Ingredientes:

- Universo **homogéneo e isótropo**
- **Materia Bariónica** (quarks, leptones) ~5%
- **Materia Fría** (Cold Dark Matter) ~27% → WIMPs, Axiones
- Constante Cosmológica Λ (**Energía Oscura**) ~68%
- **Radiación cósmica de fondo** (fotones y neutrinos)





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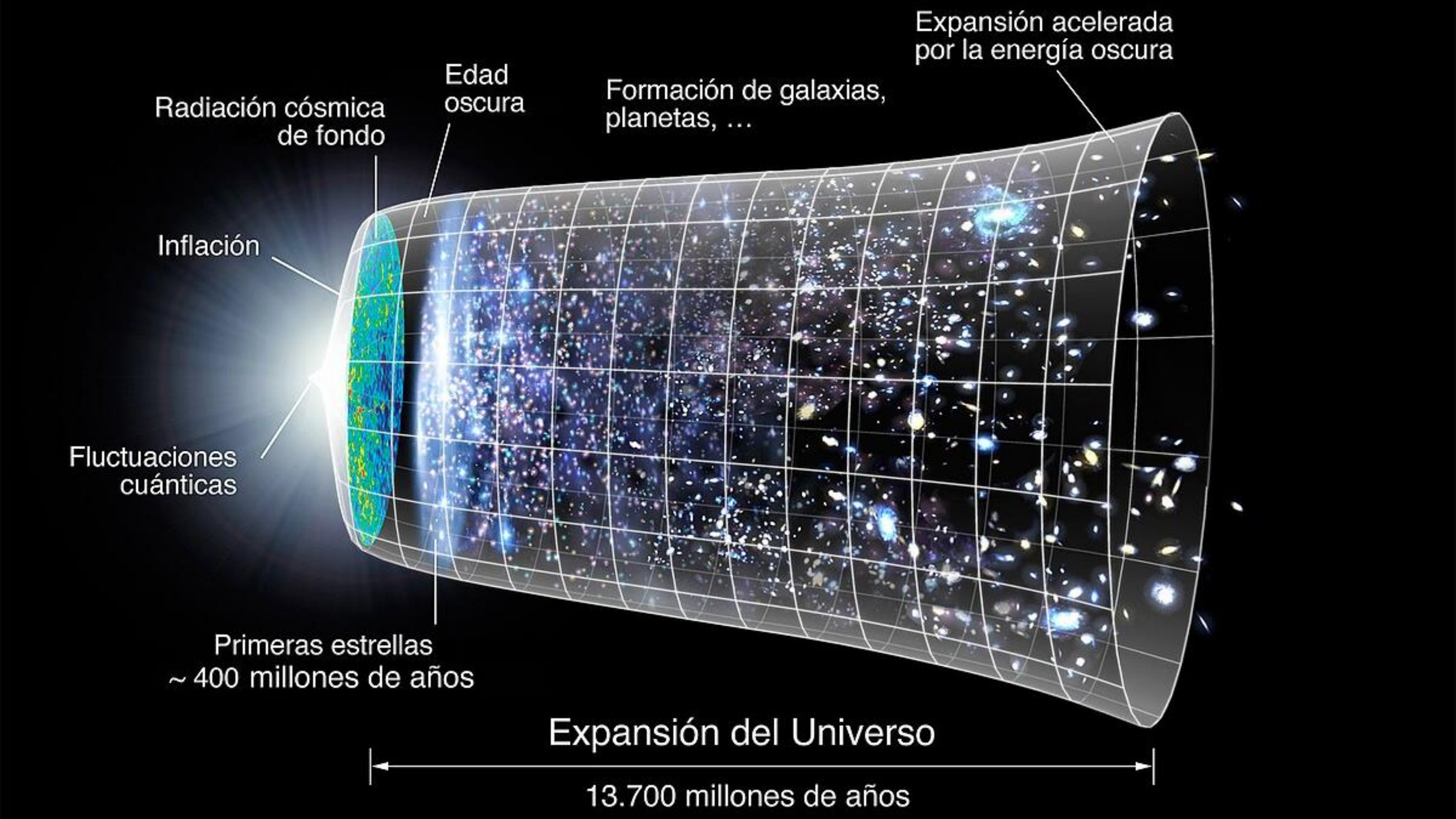
Expansión acelerada
por la energía oscura
Edad
oscura
Formación de galaxias,
planetas, …
Radiación cósmica
de fondo
Inflación
Fluctuaciones
cuánticas
Primeras estrellas
~ 400 millones de años
Expansión del Universo
13.700 millones de años

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Notas

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Ve más allá

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