ICTP The Abdus Salam International Centre for Theoretical Physics
Physics Without Frontiers

IAEA

unesco

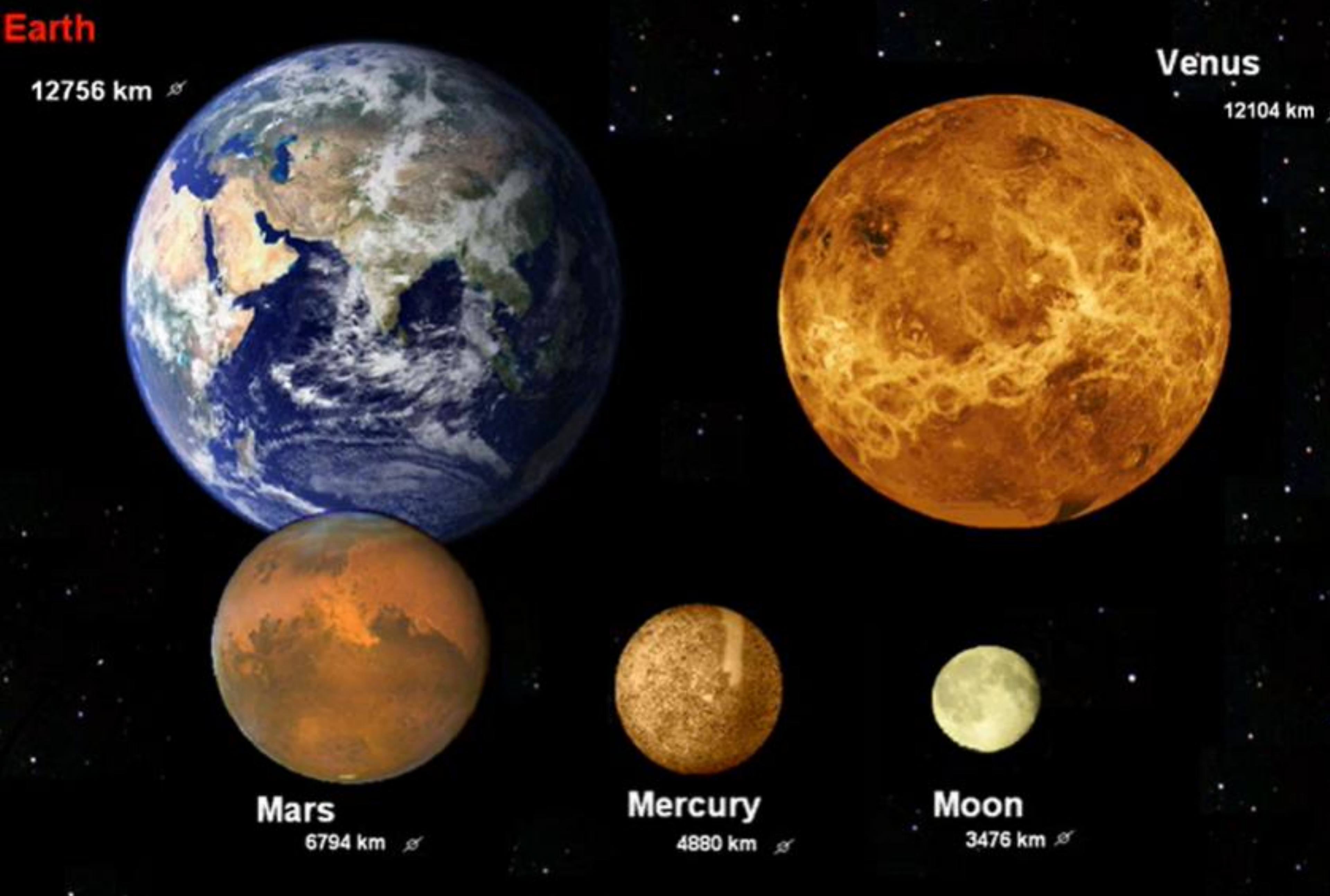
Big Bang, Hubble's Law and Cosmic Microwave Background

Speaker: Suphakorn Chunlen

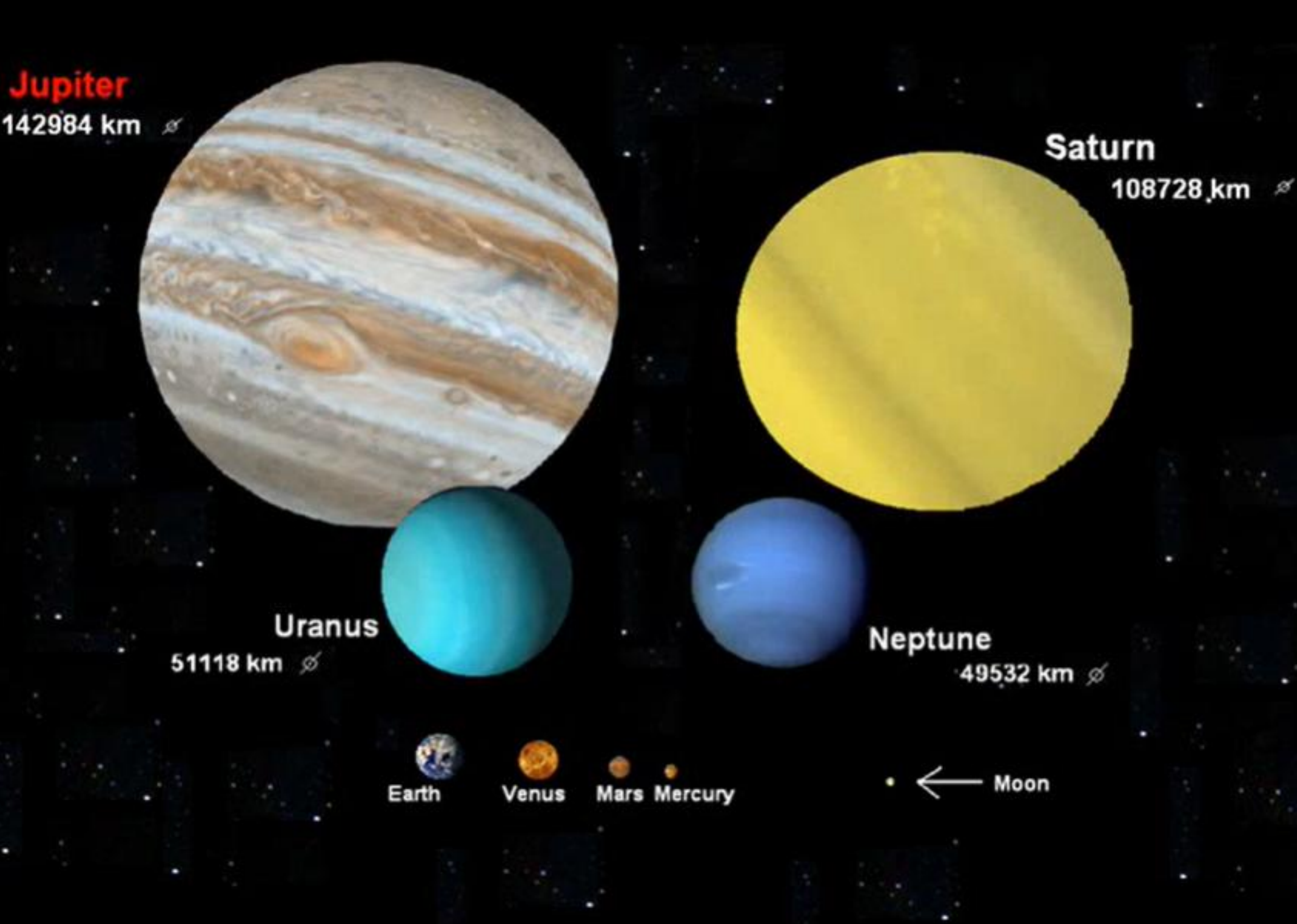
https://upload.wikimedia.org/wikipedia/commons/0/0f/Cosmic_web.jpg?20191213215716

What is Cosmology?

- It is the study of the entire universe, including its origin, evolution, overall structure, and fate.
- It uses physics and observation to answer deep questions about the cosmos:
  - How did the universe begin? (The Big Bang)
  - What is the universe made of? (Dark Matter, Dark Energy, etc)
  - What is its large-scale structure? (Galaxy Clusters, Filaments, etc)
- It uses mathematical models based on the law of physics and tests these models against observational data (e.g., the Cosmic Microwave Background or CMB).



https://www.youtube.com/watch?v=TzHD_5-riGI



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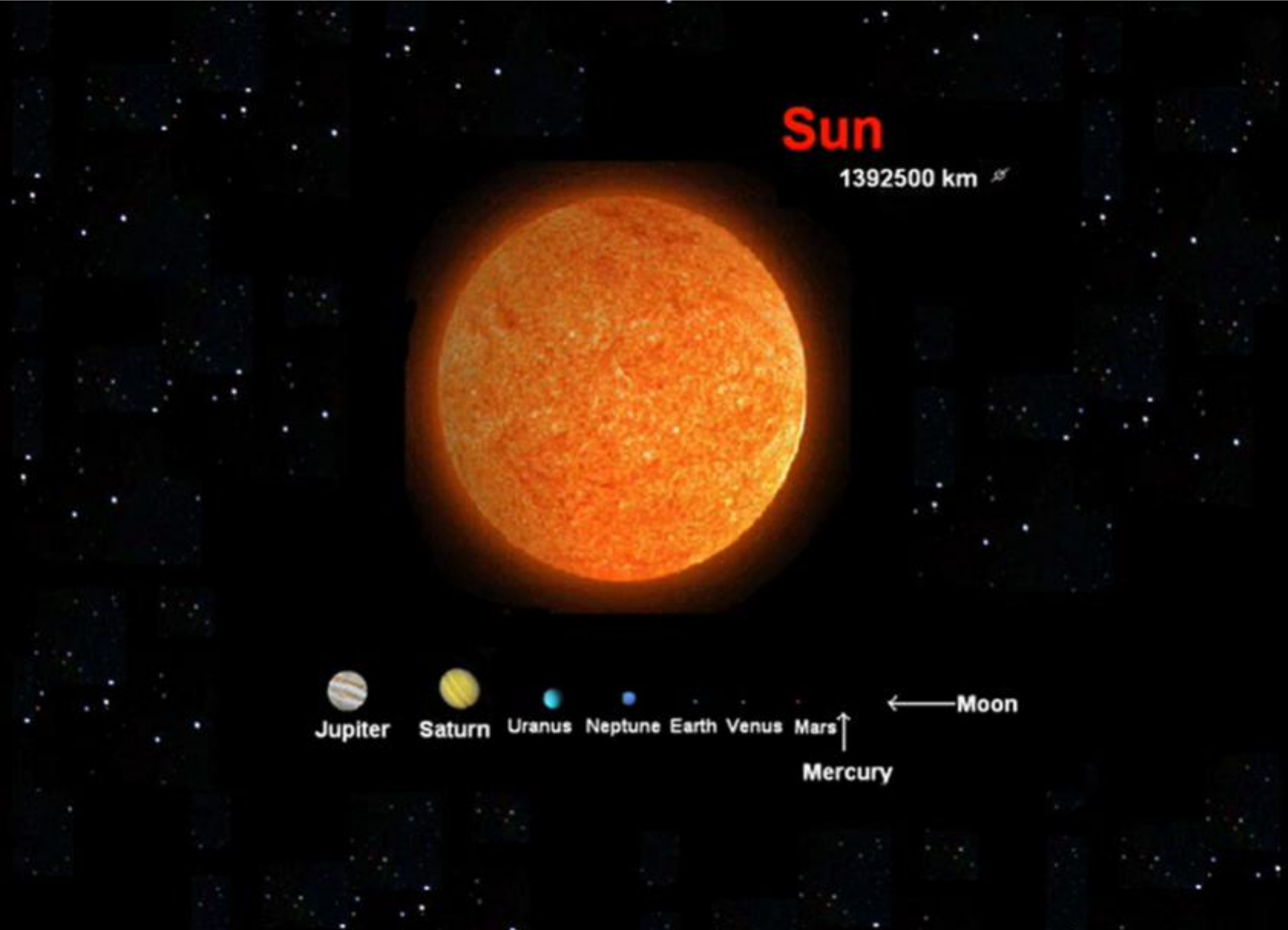

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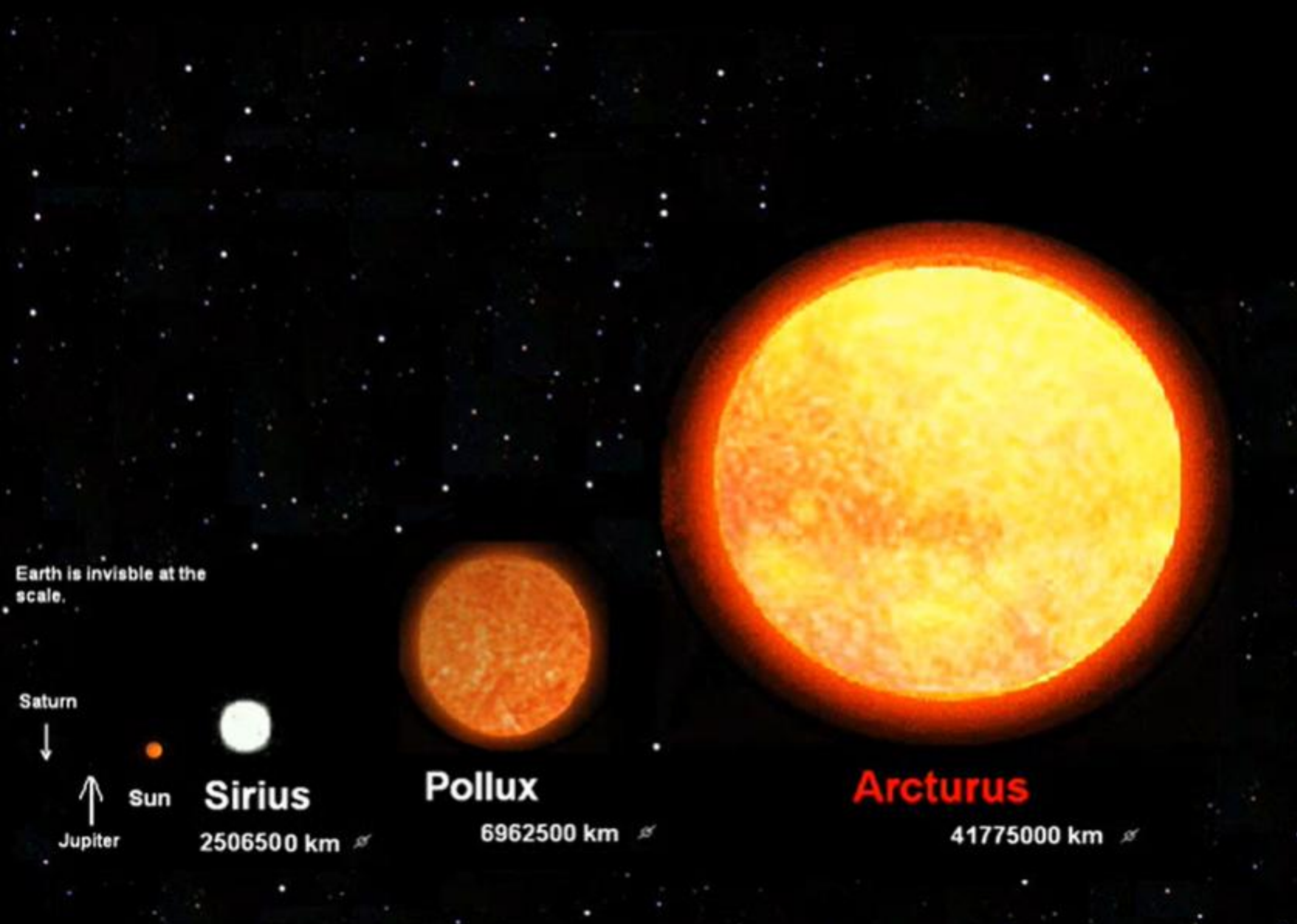

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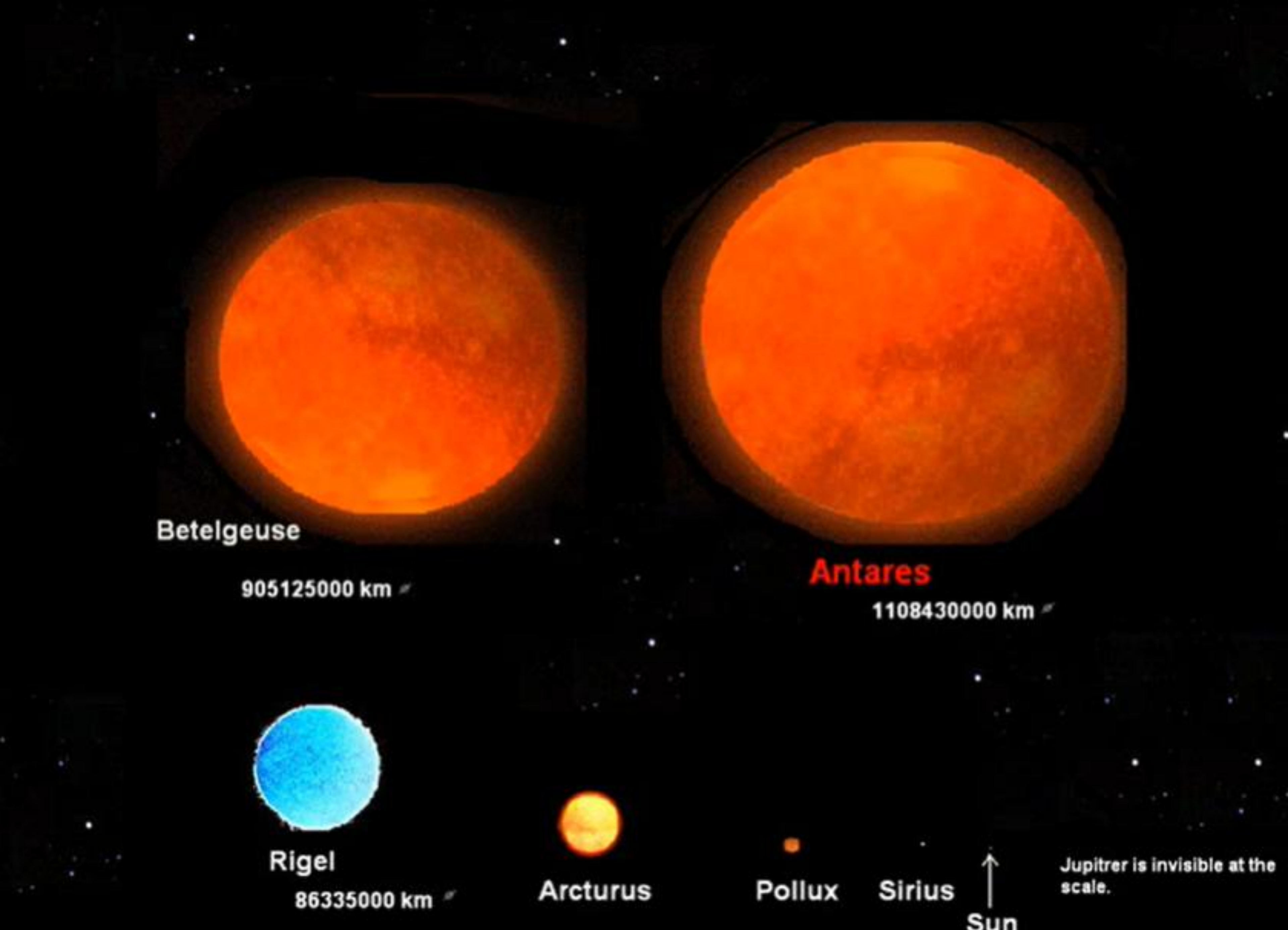

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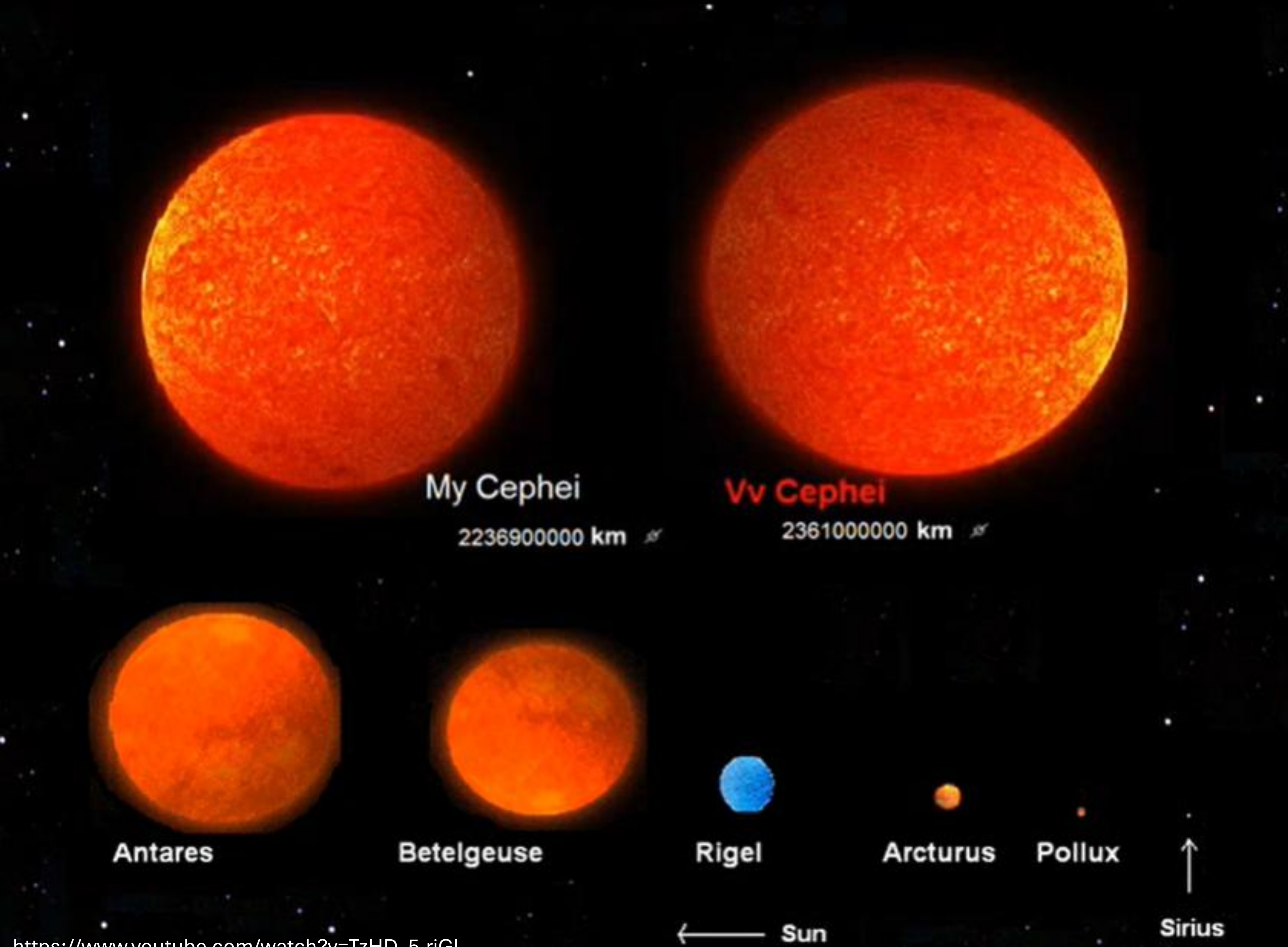

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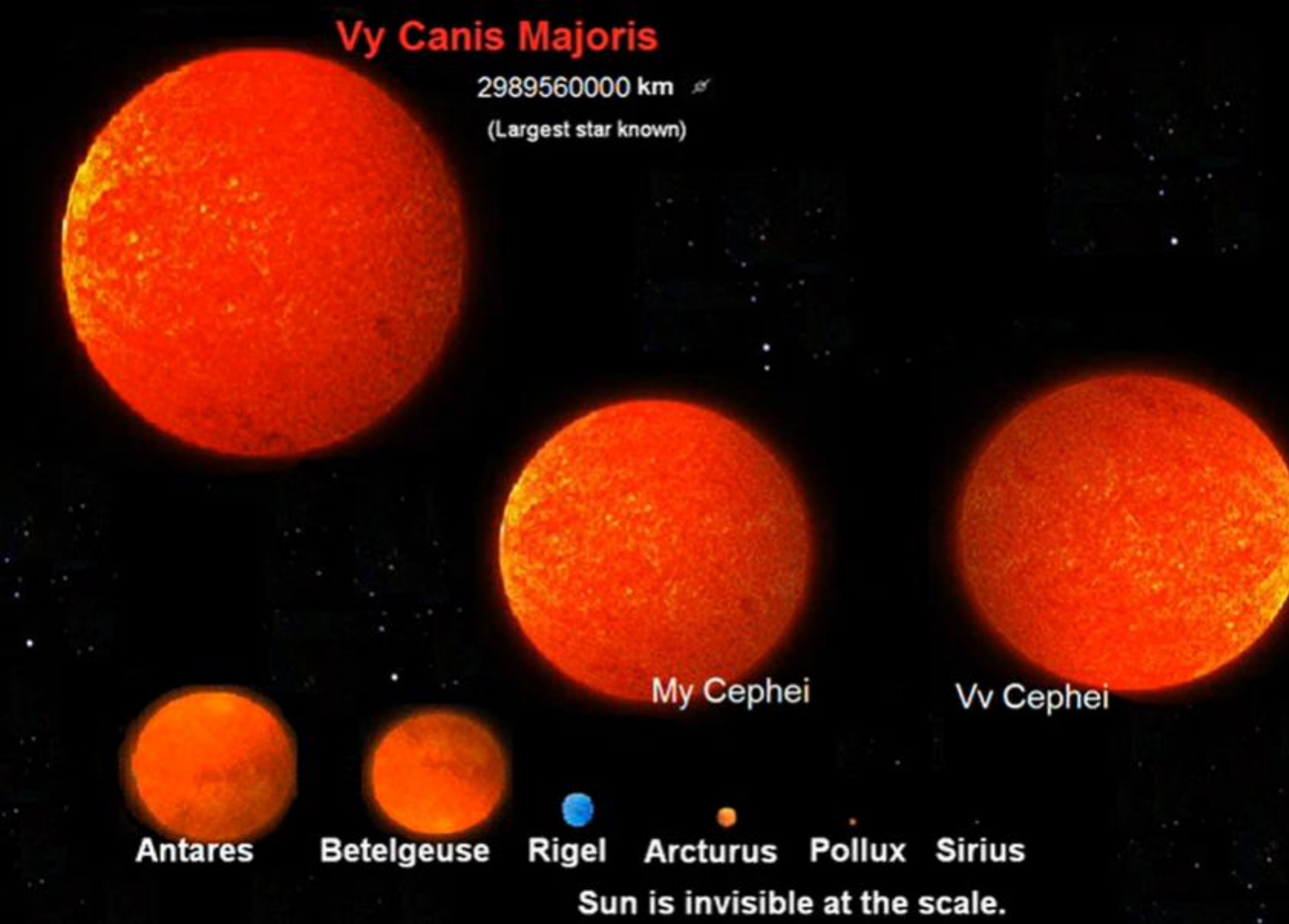

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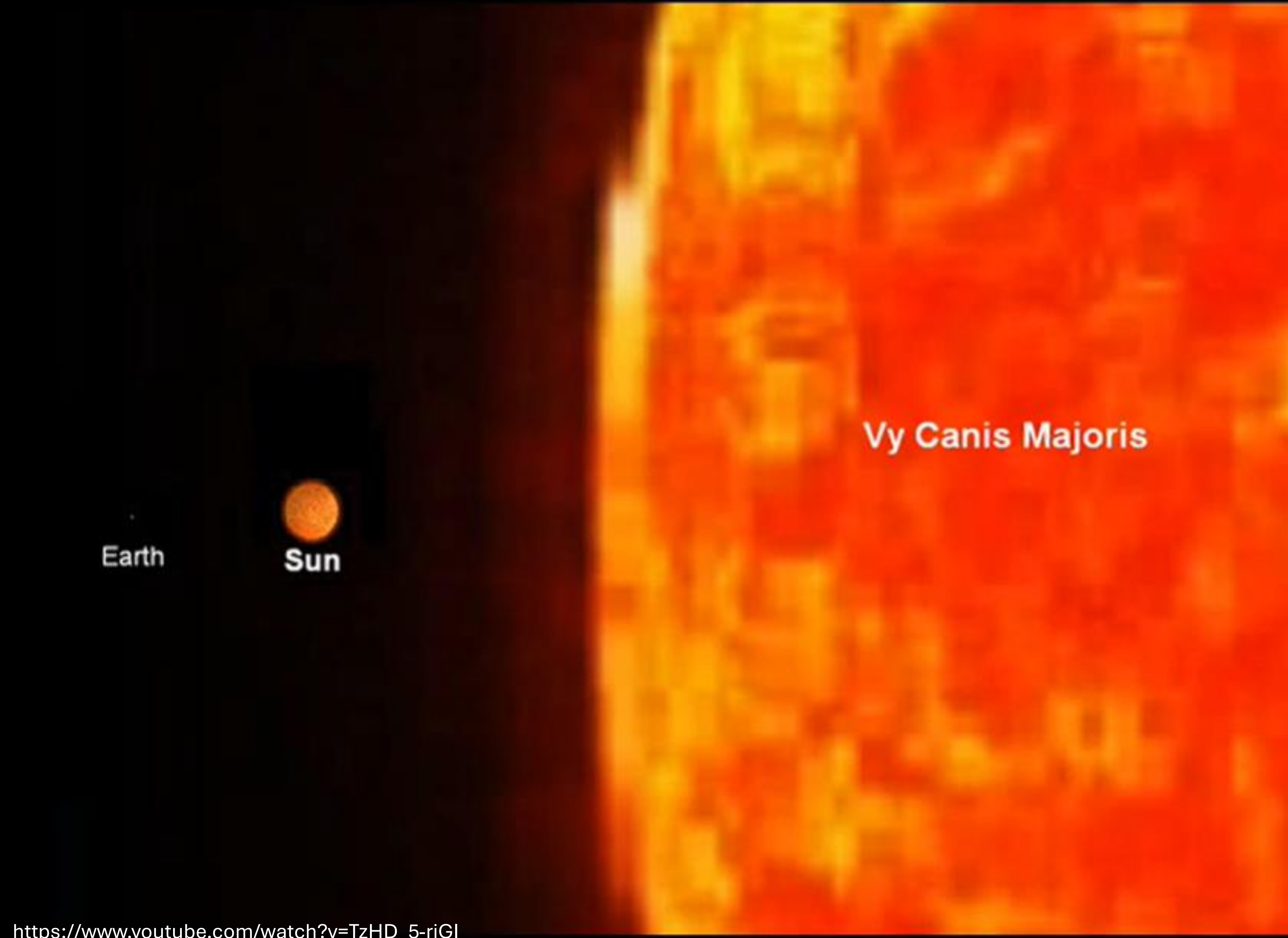

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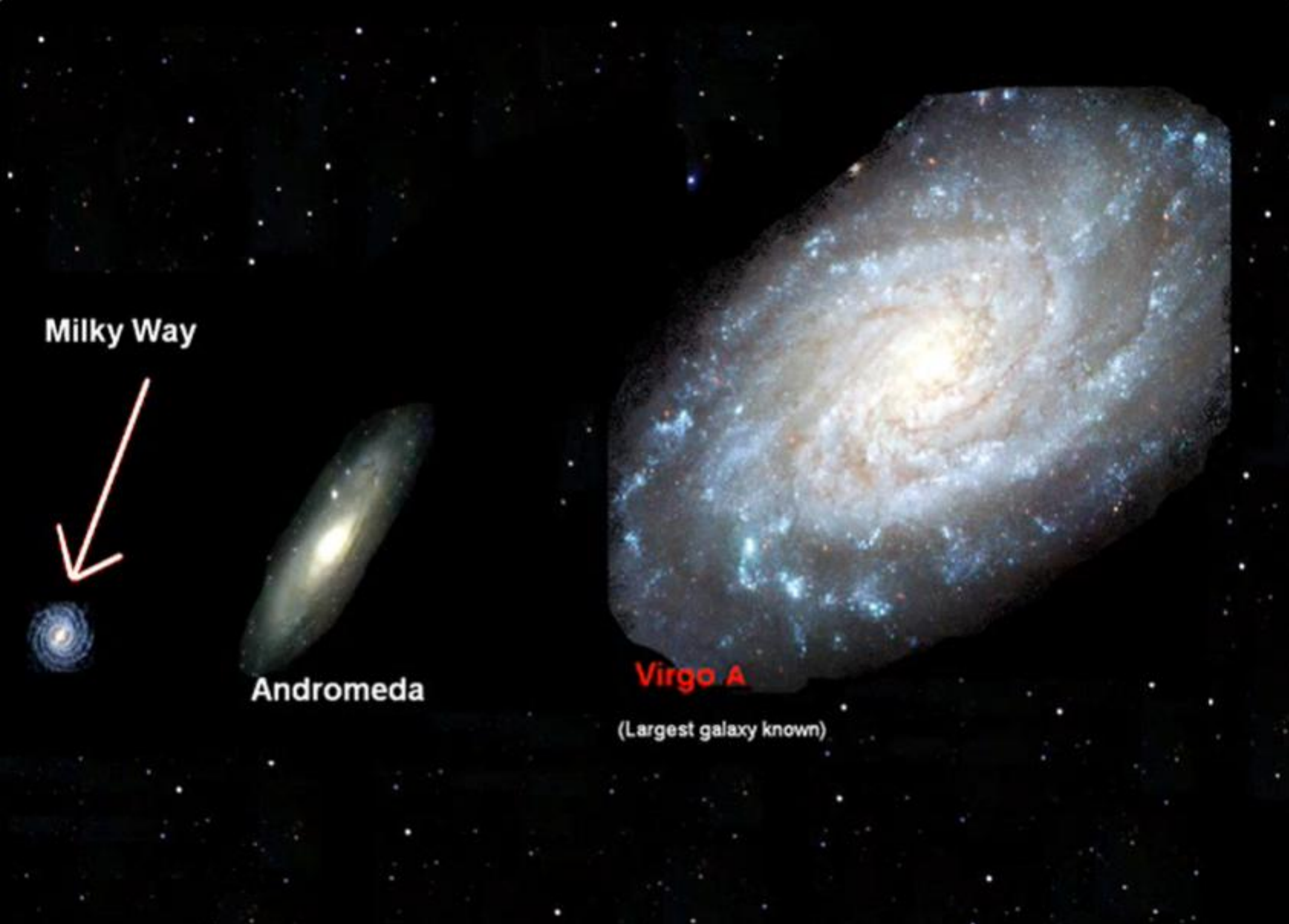

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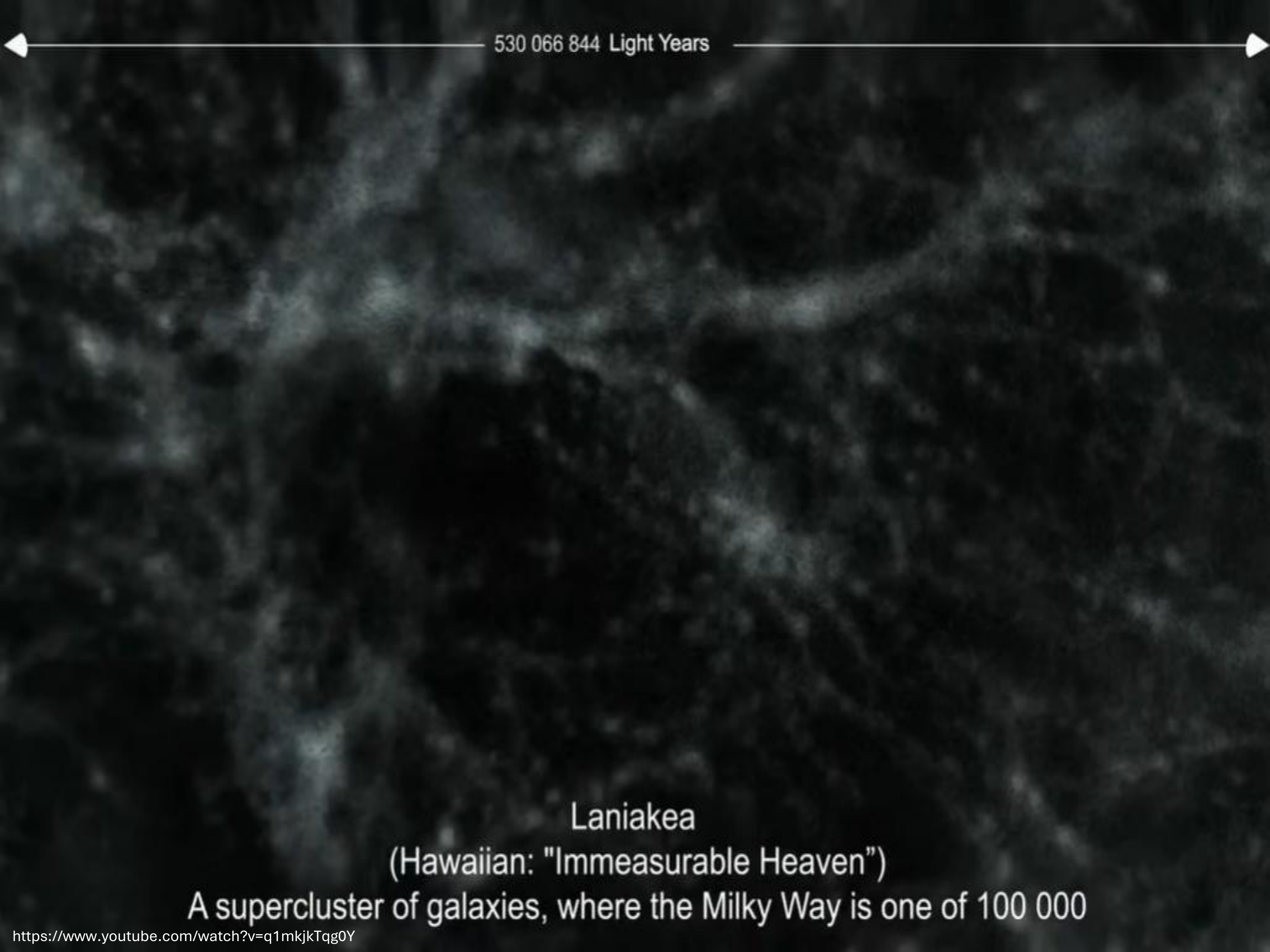
https://www.youtube.com/watch?v=q1mkjkTqg0Y



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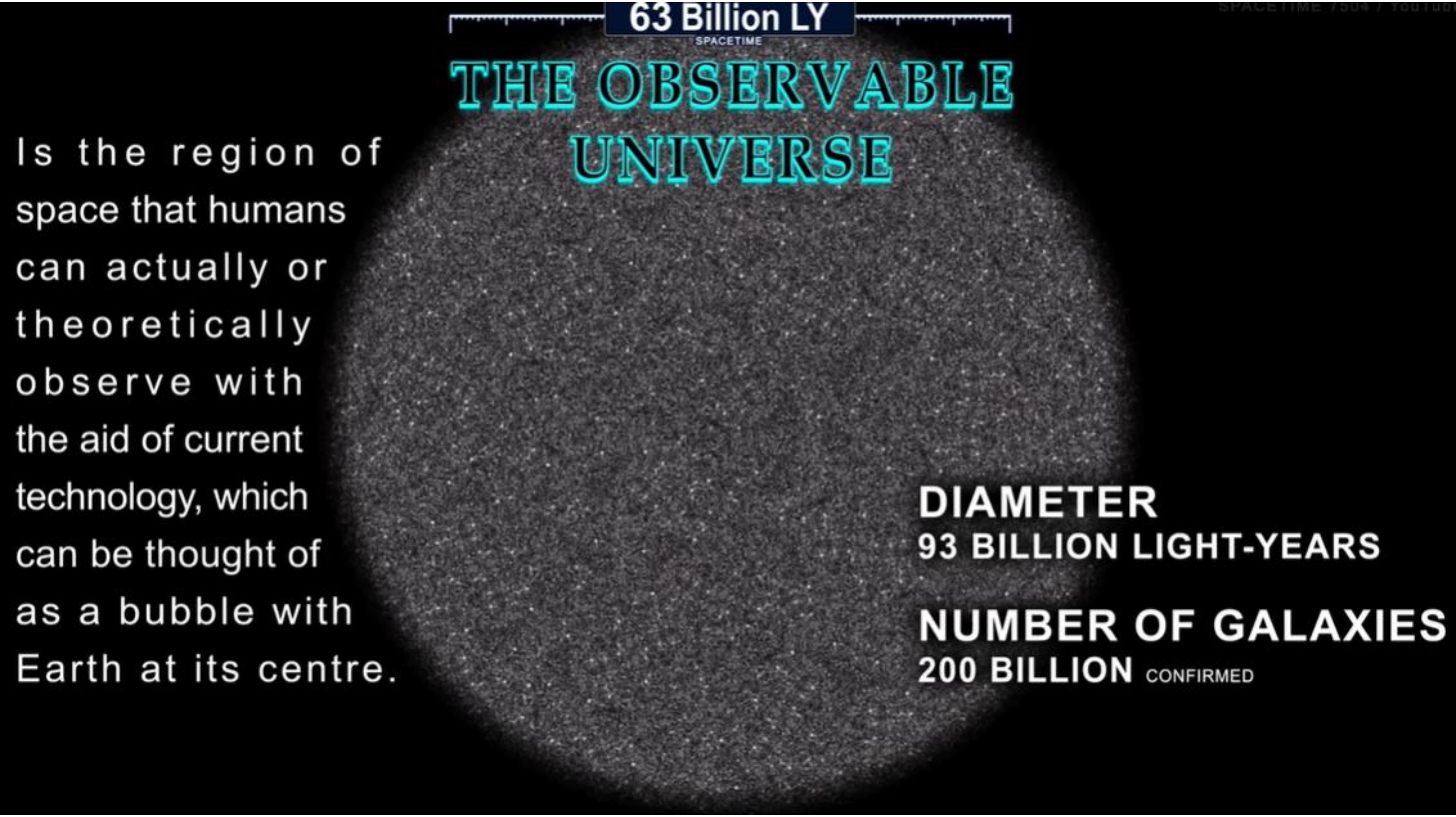
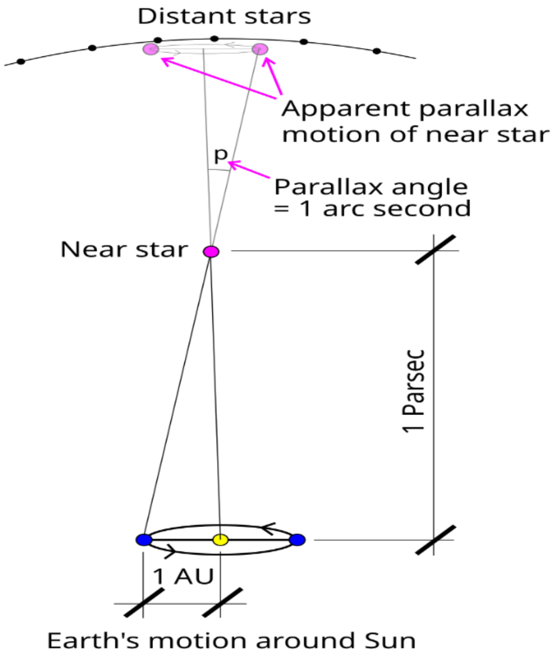


https://www.youtube.com/watch?v=U9WOMerccoM

Units

- Generally, in physics, we use SI units: metre (m, length), second (s, time), kilogram (kg, mass), etc.
- Due to large scales, in cosmology (also in astronomy), we use
  - light year (ly, length): $1\ \mathrm{ly} = 9.461 \times 10^{15}\ \mathrm{m} = 9.461\ \mathrm{Pm}$
  - parsec (pc, length): $1\ \mathrm{pc} = 3.26\ \mathrm{ly}$



https://upload.wikimedia.org/wikipedia/commons/7/7d/Stellarparallax_parsec1.svg

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  - parsec (pc, length): $1\ \mathrm{pc} = 3.26\ \mathrm{ly}$
  - year (yr, time): $1\ yr = 3.156 \times 10^{7}\ s$
  - solar mass ($\mathrm{M}_\odot$, mass): $1\ \mathrm{M}_\odot = 1.989 \times 10^{30}\ \mathrm{kg}$

Astrophysics and Cosmology

Astrophysics

- Focuses on small to medium-sized structures, such as stars, galaxies, and black holes.
- Views galaxies as a group of many stars.

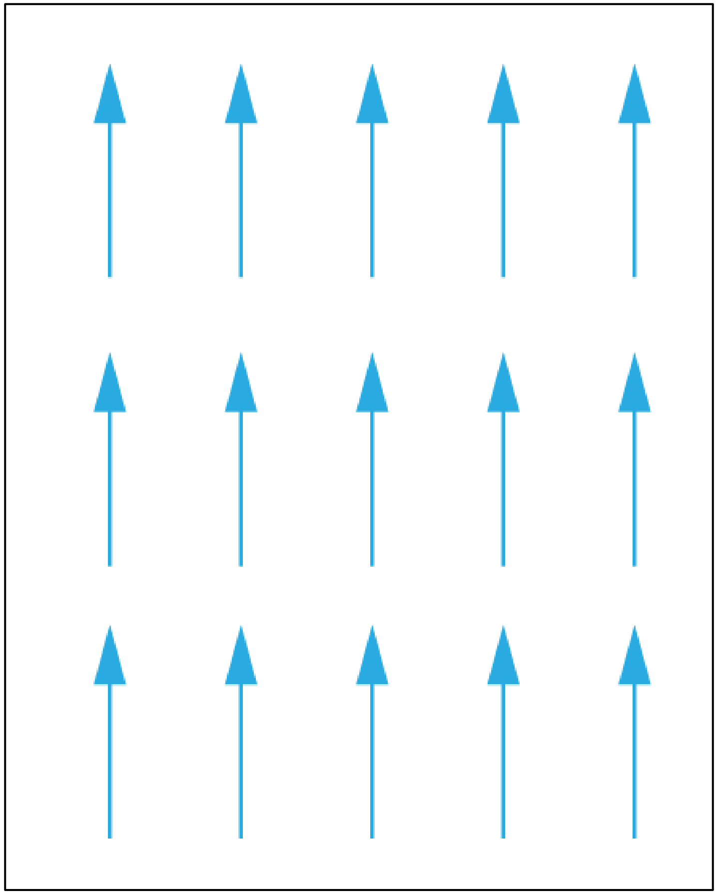
Cosmology

- Focuses on the large-scale properties of the universe, including its overall structure, history, and future.
- Views galaxies as point particles.

https://www.stockvault.net/data/2016/07/14/204361/preview16.jpg

Cosmological Principle: Homogeneity

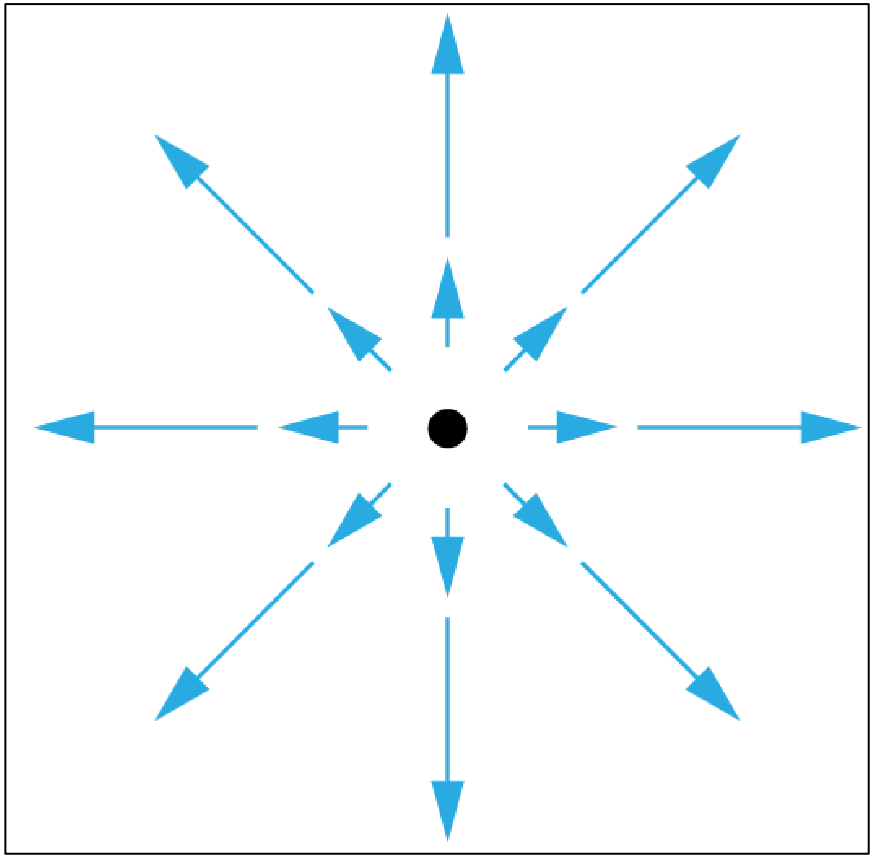
- The universe looks the same everywhere (in large enough scale).



https://cococubed.com/images/astro101/isotropic_homogeneous.pdf

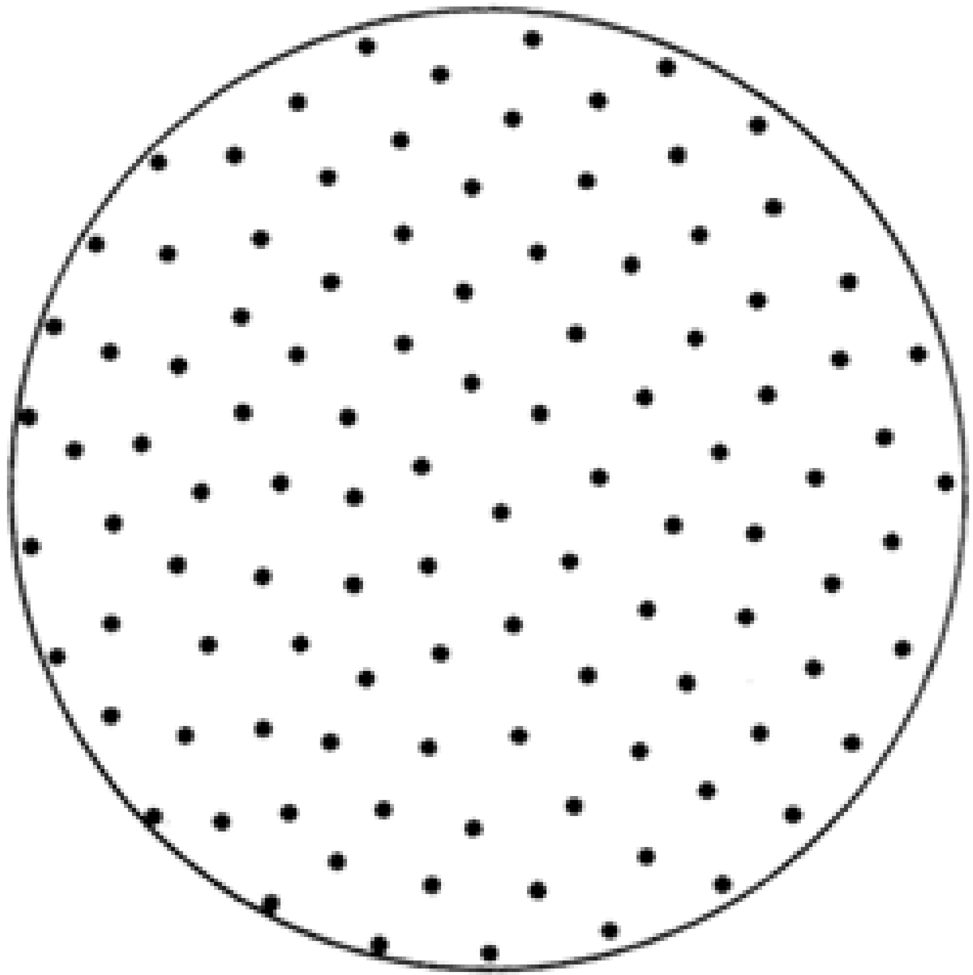
Cosmological Principle: Isotropy

- The universe looks the same in every direction (in large enough scale).



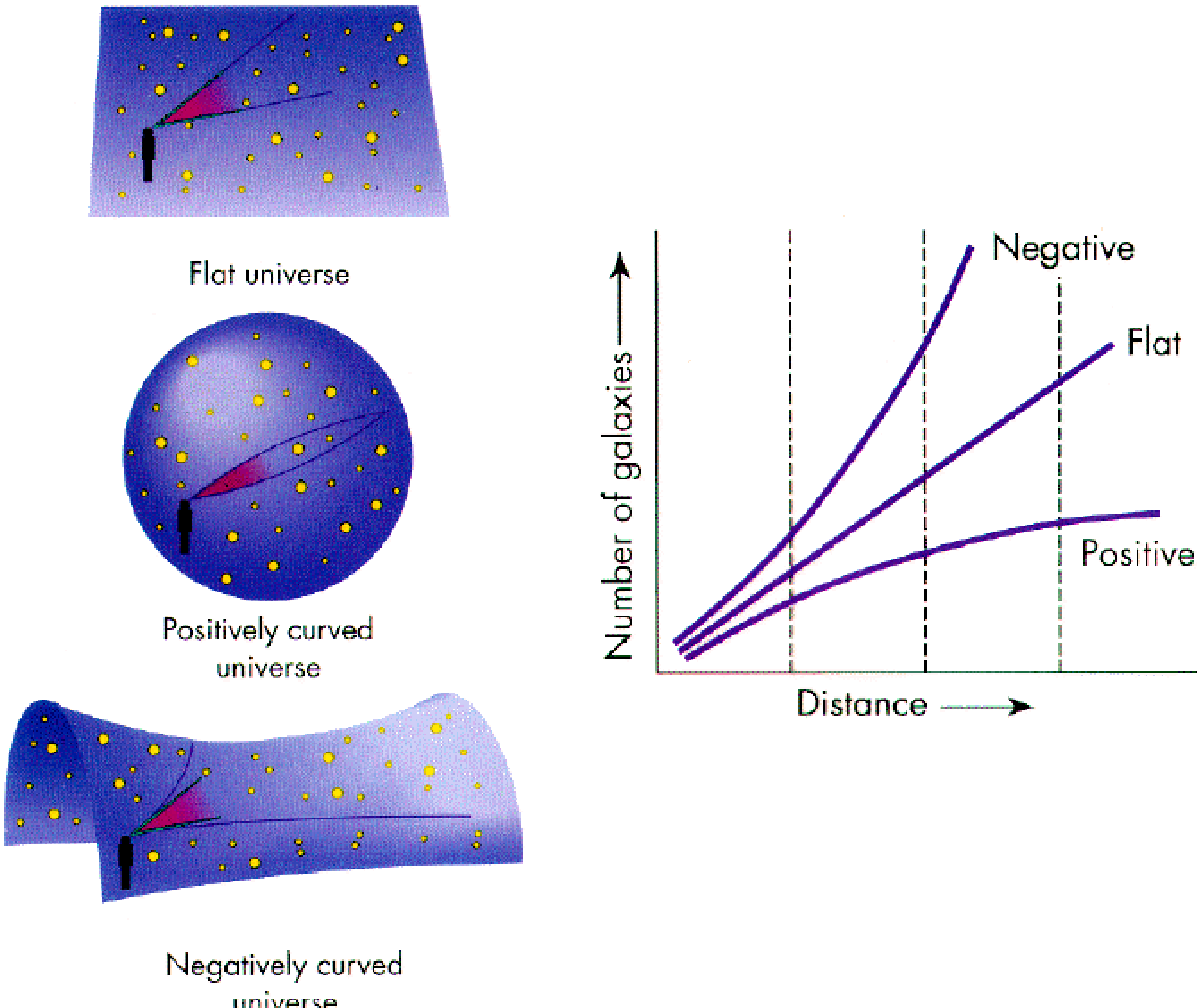
https://cococubed.com/images/astro101/isotropic_homogeneous.pdf

Example with Both Homogeneity and Isotropy



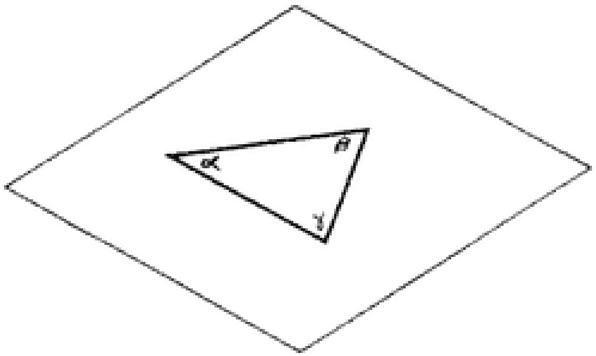
https://history.aip.org/exhibits/cosmology/ideas/larger-image-pages/pic-bigbang-expanding-universe.htm

Possible Geometry



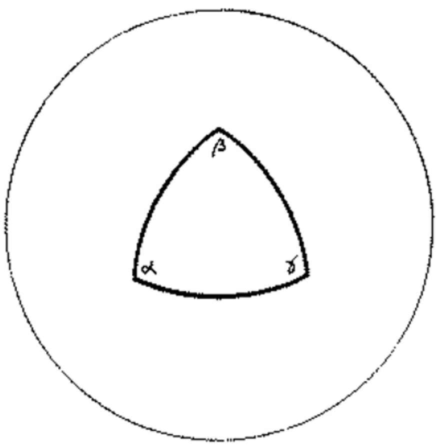
https://pages.uoregon.edu/jschombe/images/curvature.gif

Possible Geometry



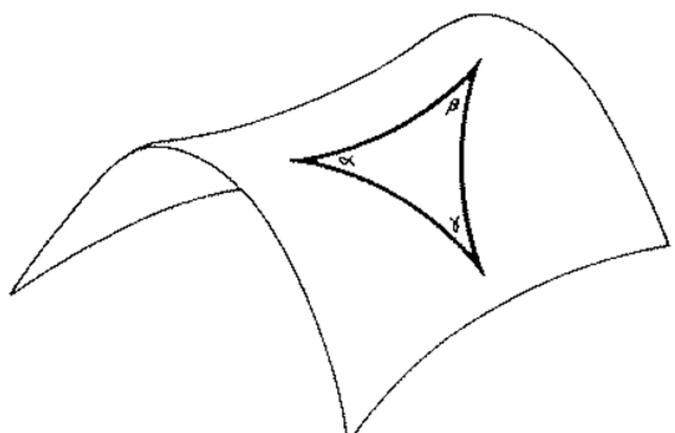
Flat

$$\alpha + \beta + \gamma = 180°$$



Positively Curved

$$\alpha + \beta + \gamma > 180°$$



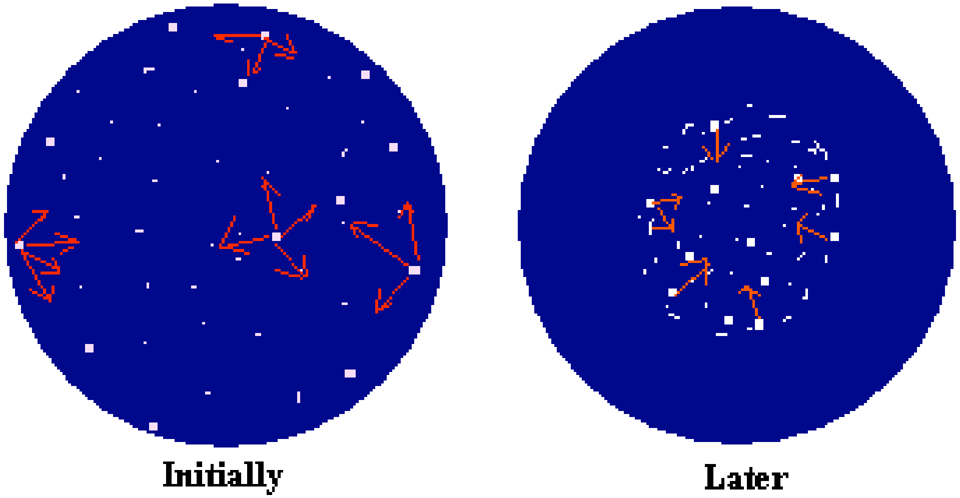
Negatively Curved

$$\alpha + \beta + \gamma < 180°$$

https://www.physicsforums.com/insights/journey-cosmos-flrw-metric-friedmann-equation/

Static Universe

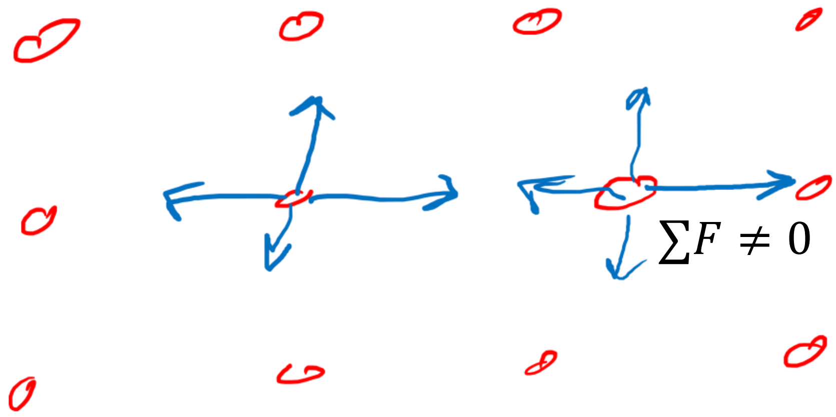
- From Newton's point of view, he believed the universe was static, and the static universe must be infinitely large; otherwise, it is going to collapse due to gravitation.



https://sites.uni.edu/morgans/astro/course/Notes/section3/finite.gif

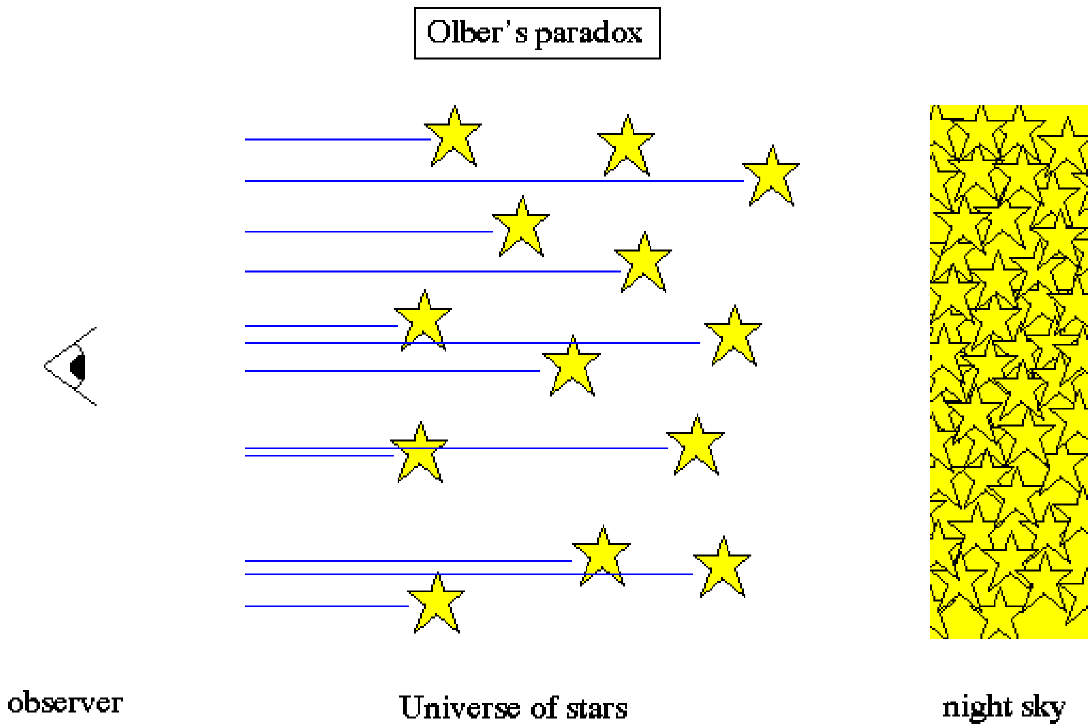
Problems with the Static Universe

- Highly Unstable: If there is a little bit of perturbation, that region exerted by the perturbation will collapse under its own gravity.



Problems with the Static Universe

- Olbers' paradox: Why is the sky dark at night?



https://pages.uoregon.edu/jschombe/images/olbers_paradox.gif

Problems with the Static Universe

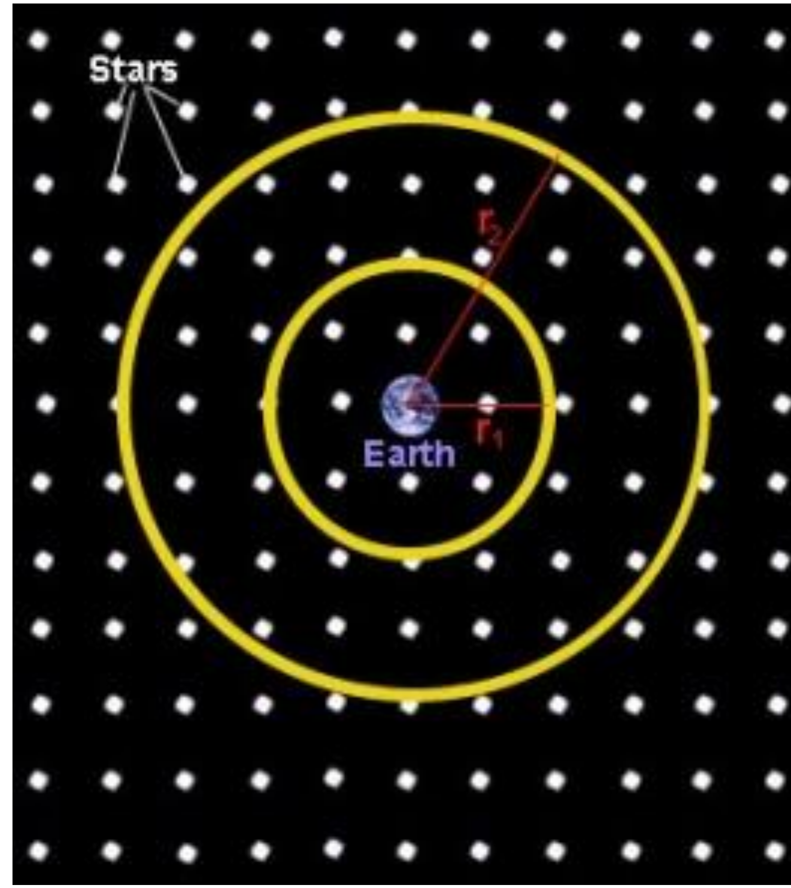
- Olbers' paradox:

Let's calculate the flux

$$F = \sum \frac{L}{4\pi r^2} = \int_0^\infty \frac{4\pi r^2 n dr}{4\pi r^2}$$

$$= n \int_0^\infty dr \quad \longrightarrow \quad \infty \text{ !!!}$$

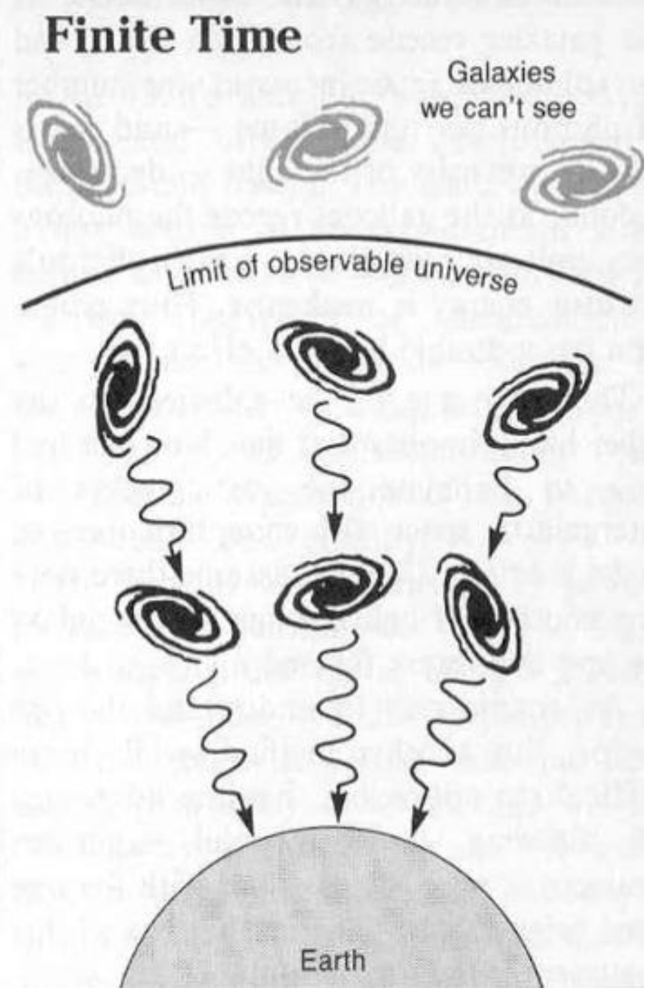
where n is the luminosity of the stars per unit volume.



https://universeadventure.org/big_bang/popups/conseq-dtrh-olbersmath.htm

Solution to Olbers' Paradox

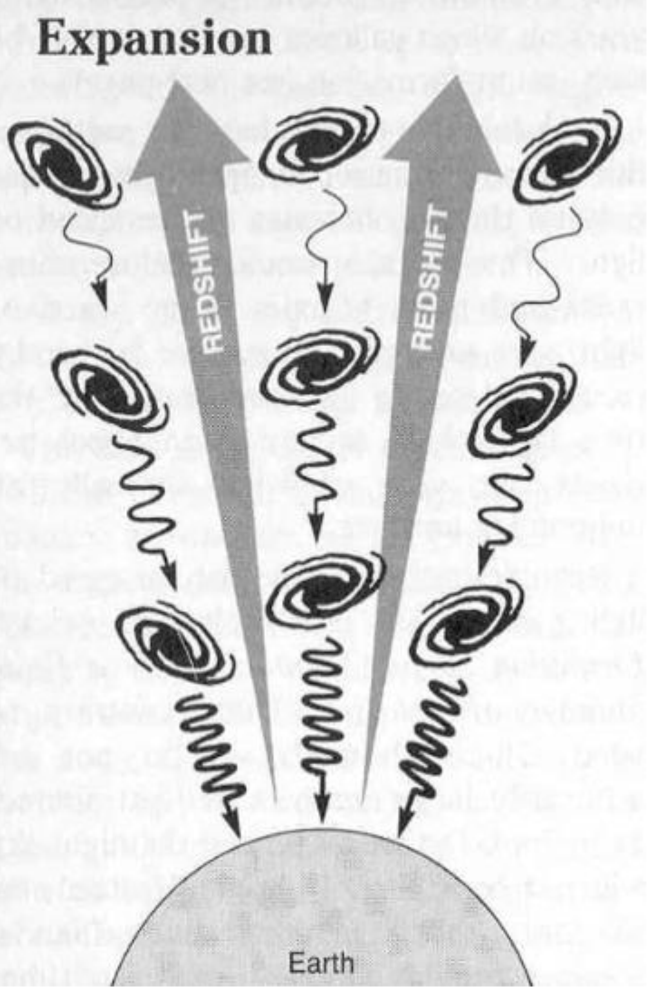
- The universe has finite age—the light from the very distant galaxies has not reached us yet.



https://www.3towers.com/Essays/OlbersParadox/Olbers01.html

Solution to Olbers' Paradox

- The universe is expanding—the light from the very distant galaxies is redshifted to the invisible spectrum.



https://www.3towers.com/Essays/OlbersParadox/Olbers01.html

Standard Candles

- How is the distance be measured?
  - We use the source with known luminosity, and calculate the distance by the irradiance

$$F = \frac{L}{4\pi r^2}$$

In logarithmic scale,

the apparent magnitude

$$m = \log_{10}\left(\frac{F}{F_0}\right)$$, where $F_0 = 24.8\ \mathrm{nW/m^2}$

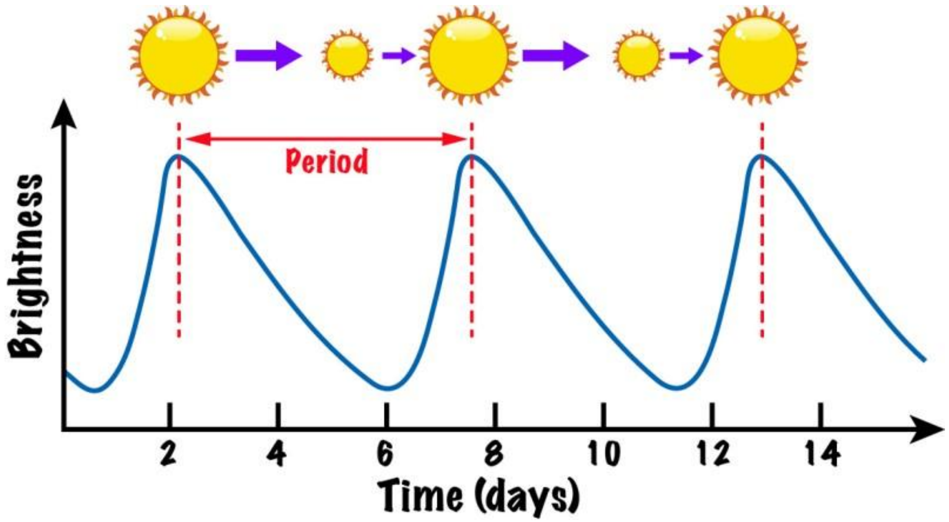
and the absolute magnitude

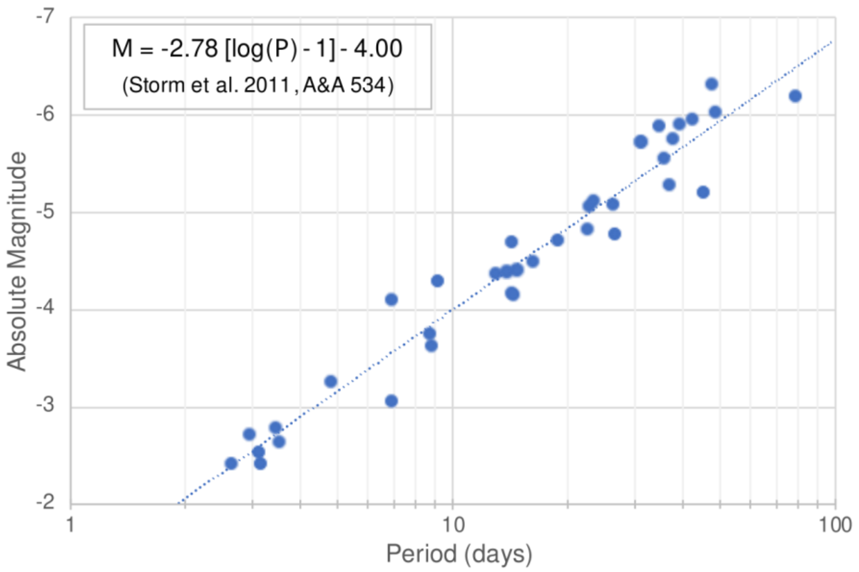
$$M = \log_{10}\left(\frac{F_{(r=10\mathrm{pc})}}{F_0}\right)$$

Standard Candles

- Examples of standard sources with known luminosity or standard candles

  - Cepheid Variables

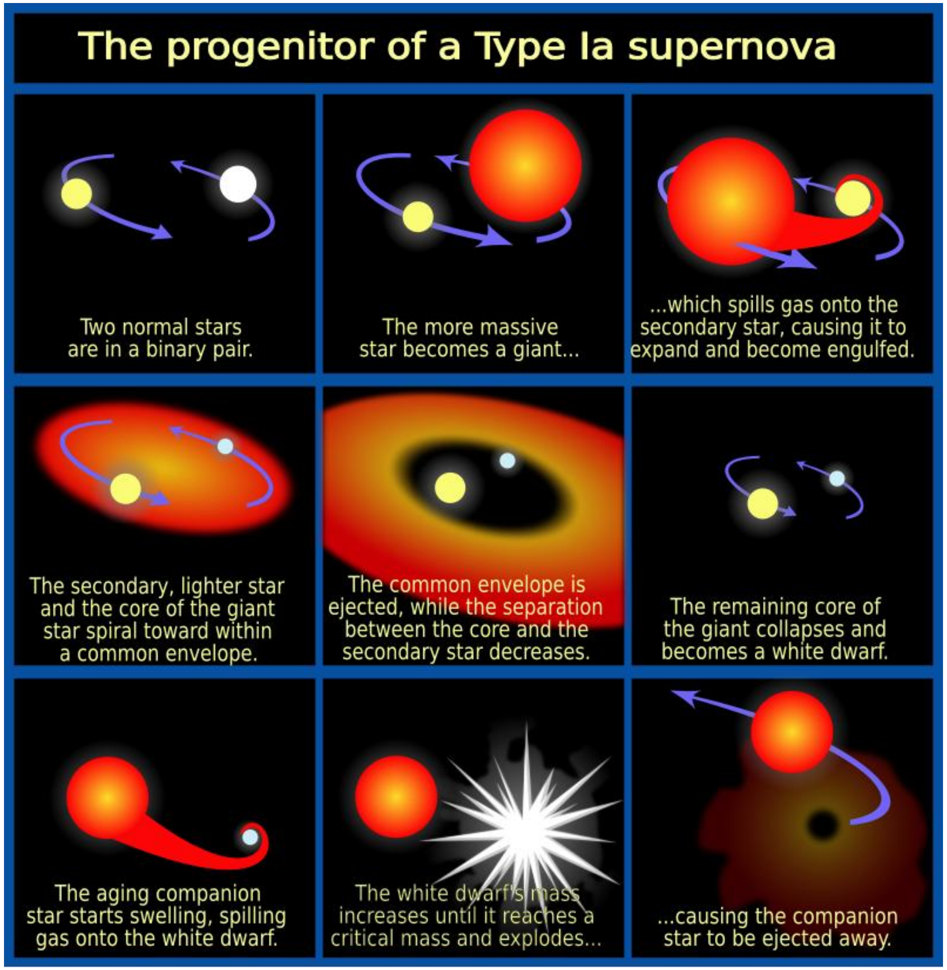


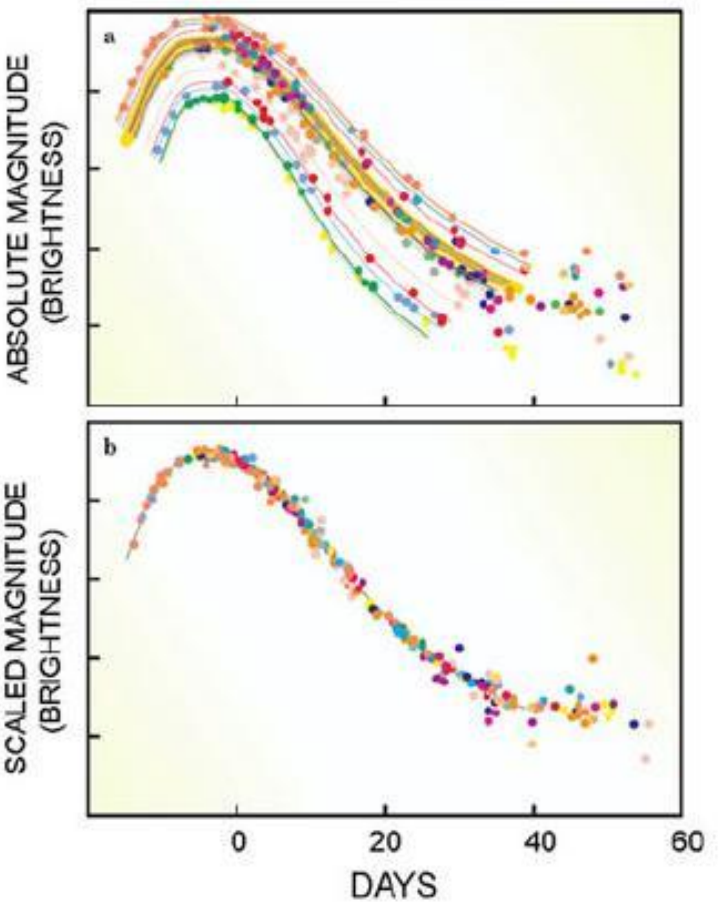


https://writescience.wordpress.com/wp-content/uploads/2015/03/deltacephei_lightcurve.jpg?w=1024

Standard Candles

- Examples of standard sources with known luminosity or standard candles
  - Type Ia Supernovae





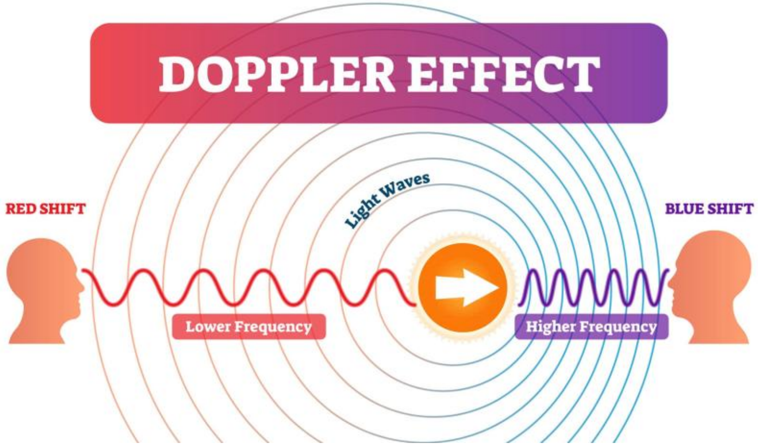
https://en.wikipedia.org/wiki/Type_Ia_supernova#/media/File:Progenitor_IA_supernova.svg

https://briankoberlein.com/post/supernova/stretch_correction_hu_55dadc1f3657e848.jpg

Relation between Redshift and Velocity

The redshift parameter is defined by

$$z = \frac{\lambda_{\mathrm{observed}} - \lambda_{\mathrm{emitted}}}{\lambda_{\mathrm{emitted}}}$$



In special relativity, the relation is

$$z = \sqrt{\frac{c+v}{c-v}} - 1$$

https://online-learning-college.com/wp-content/uploads/2022/05/The-Doppler-effect.jpg

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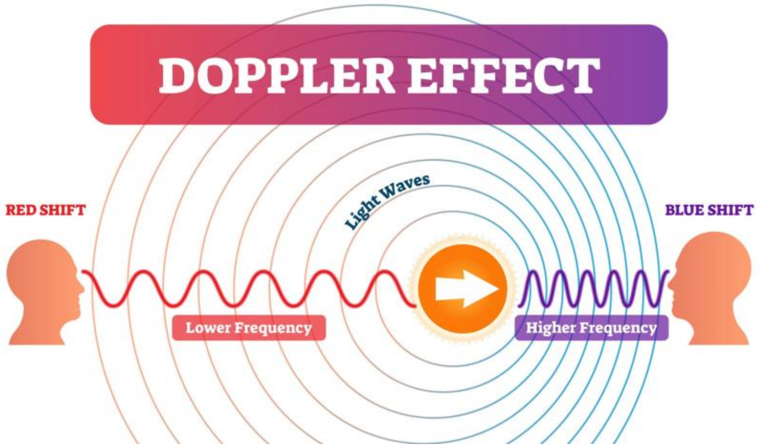

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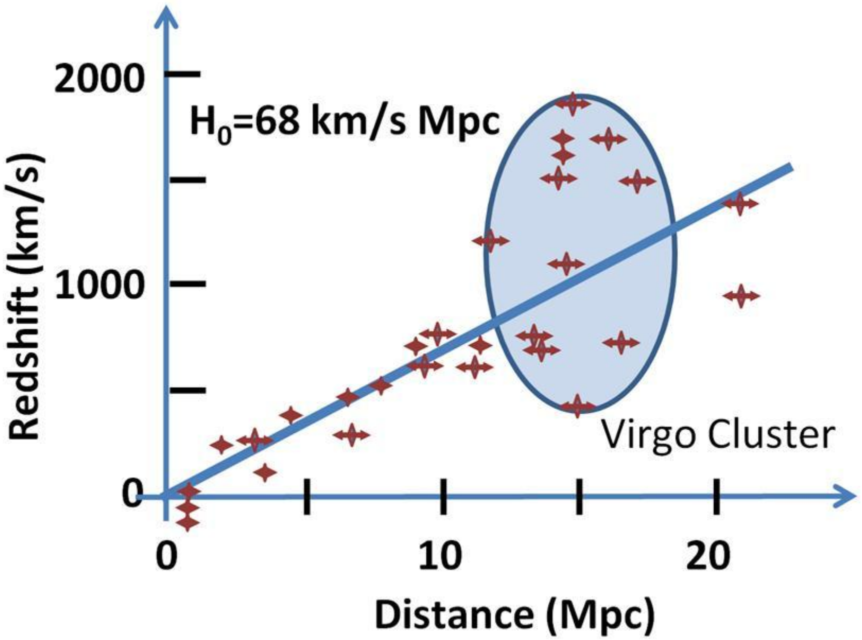
For nearby galaxies, the velocity $v \ll c$, so the classical limit yields

$$z \simeq \frac{v}{c}$$

https://online-learning-college.com/wp-content/uploads/2022/05/The-Doppler-effect.jpg

The Hubble's Law

The light from distant galaxies was found by Edwin Hubble in 1929 to be shifted toward the red end of the spectrum, a process known as redshift. According to the Doppler effect, this occurs because the light waves are stretched to longer wavelengths as the galaxy moves away from the observer.



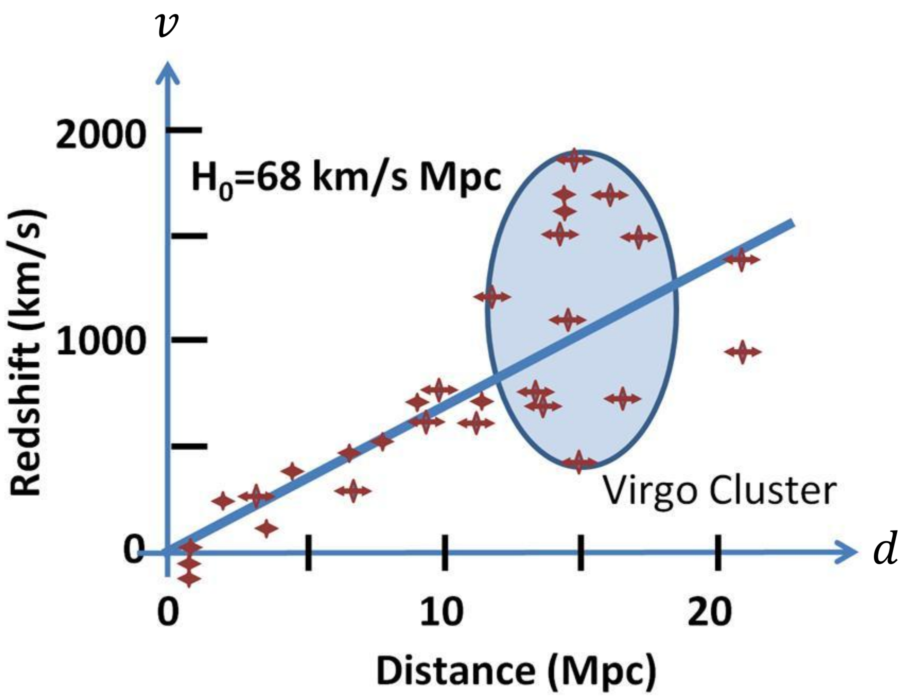
https://upload.wikimedia.org/wikipedia/commons/2/2c/Hubble_constant.JPG

The Hubble's Law

The Hubble's law is written as equation:

$$v = H_0 d$$

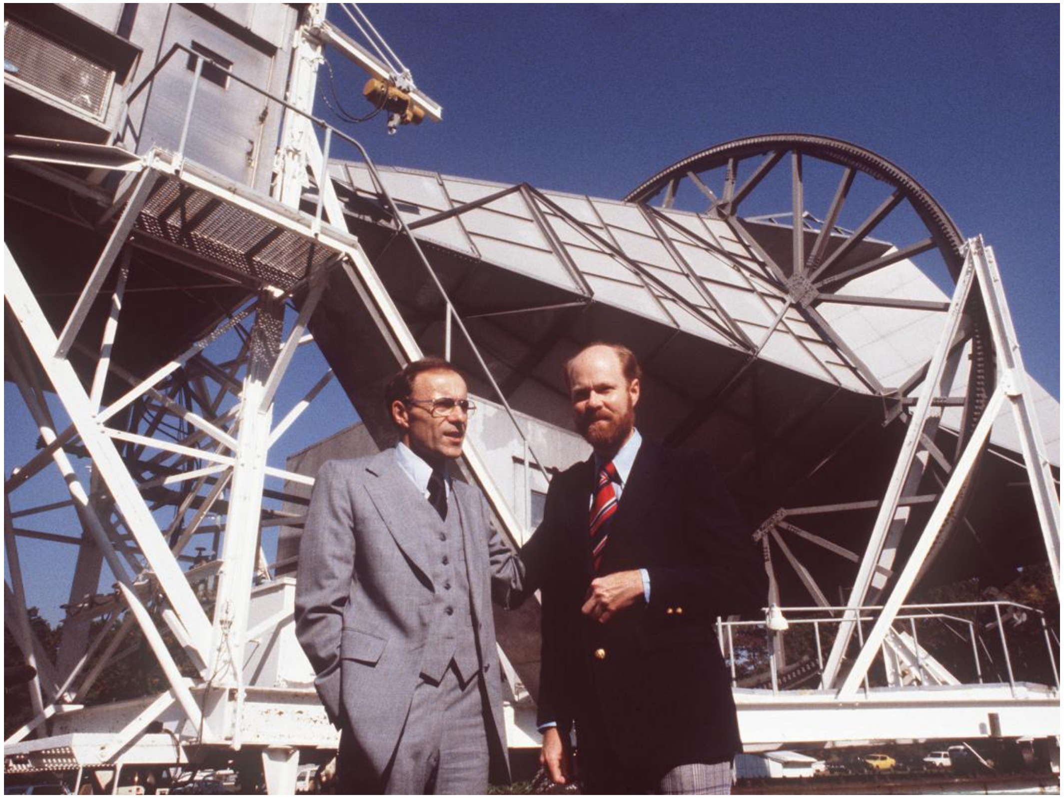
where v is a galaxy's recessional velocity, d is the distance of the galaxy, and H_0 is the Hubble constant at present time.



https://upload.wikimedia.org/wikipedia/commons/2/2c/Hubble_constant.JPG

Cosmic Microwave Background (CMB)

In 1964, at Bell Labs in New Jersey, Arno Penzias and Robert Wilson detected a persistent, uniform microwave "hiss" with a large antenna. After ruling out all possible sources of interference—including pigeon droppings—they realized the noise came uniformly from every direction in the sky.



Arno Penzias (left) and Robert Wilson (right)

https://www.lindahall.org/about/news/scientist-of-the-day/robert-woodrow-wilson/

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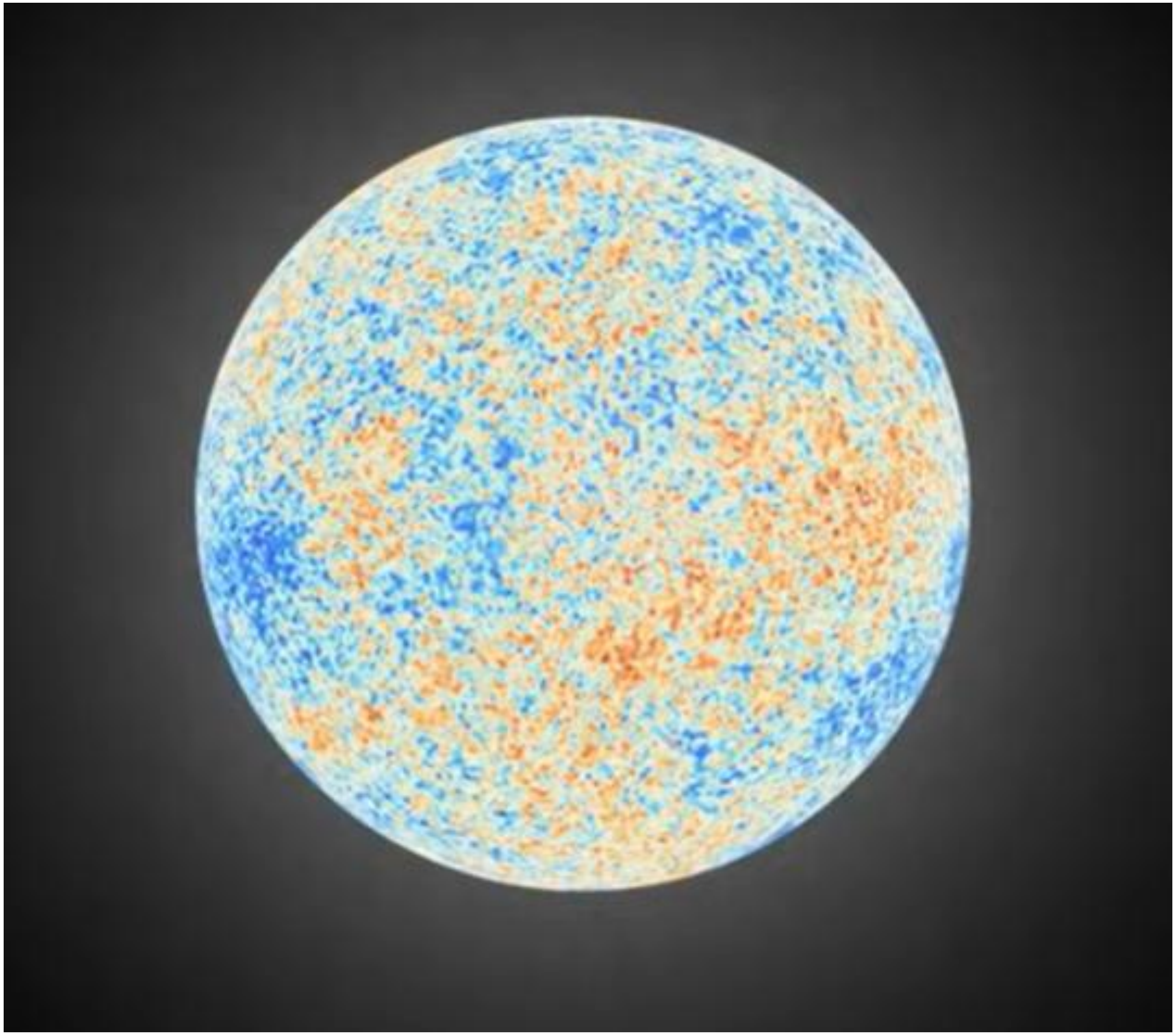

https://www.youtube.com/watch?v=q1mkjkTqg0Y

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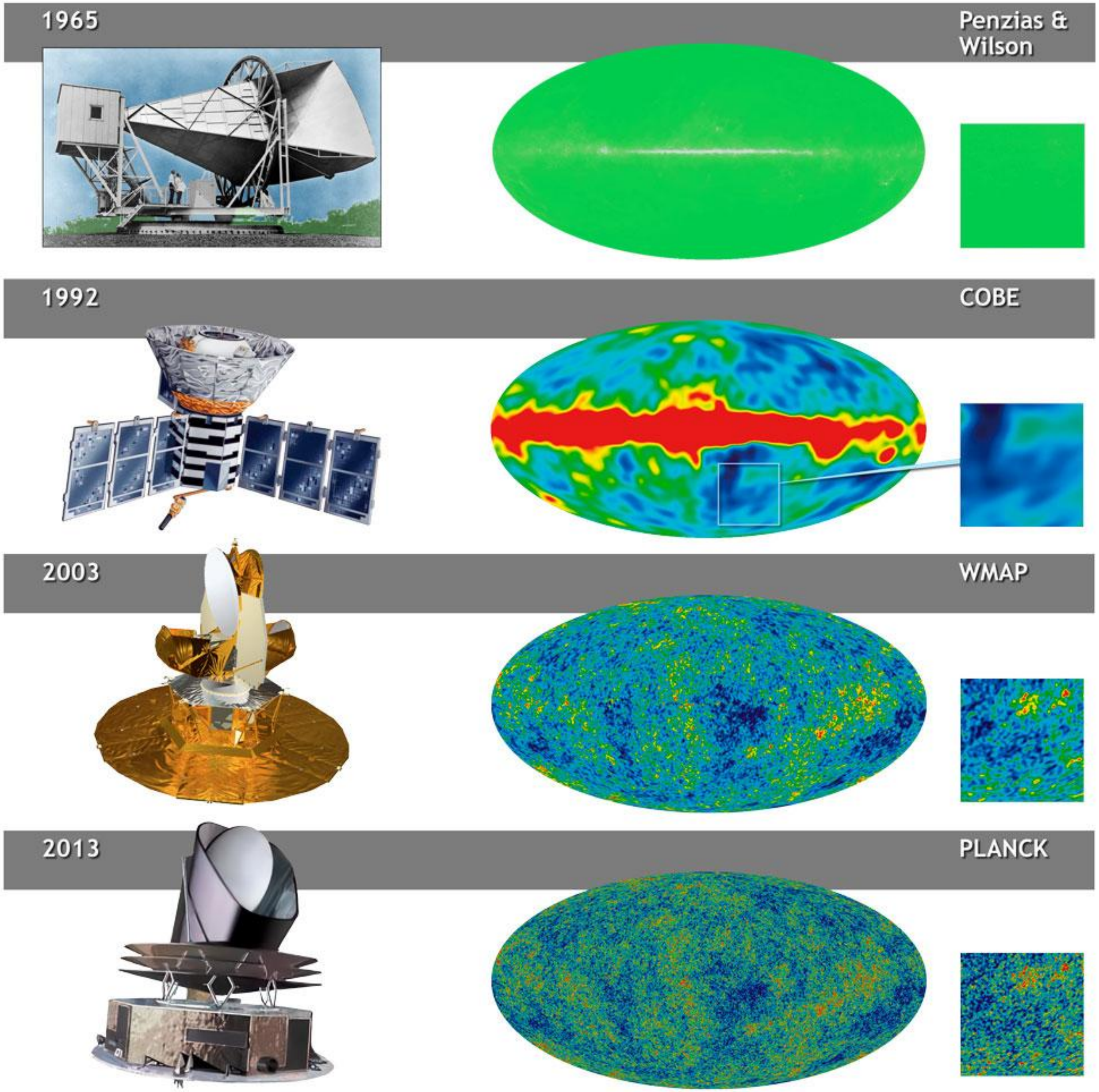
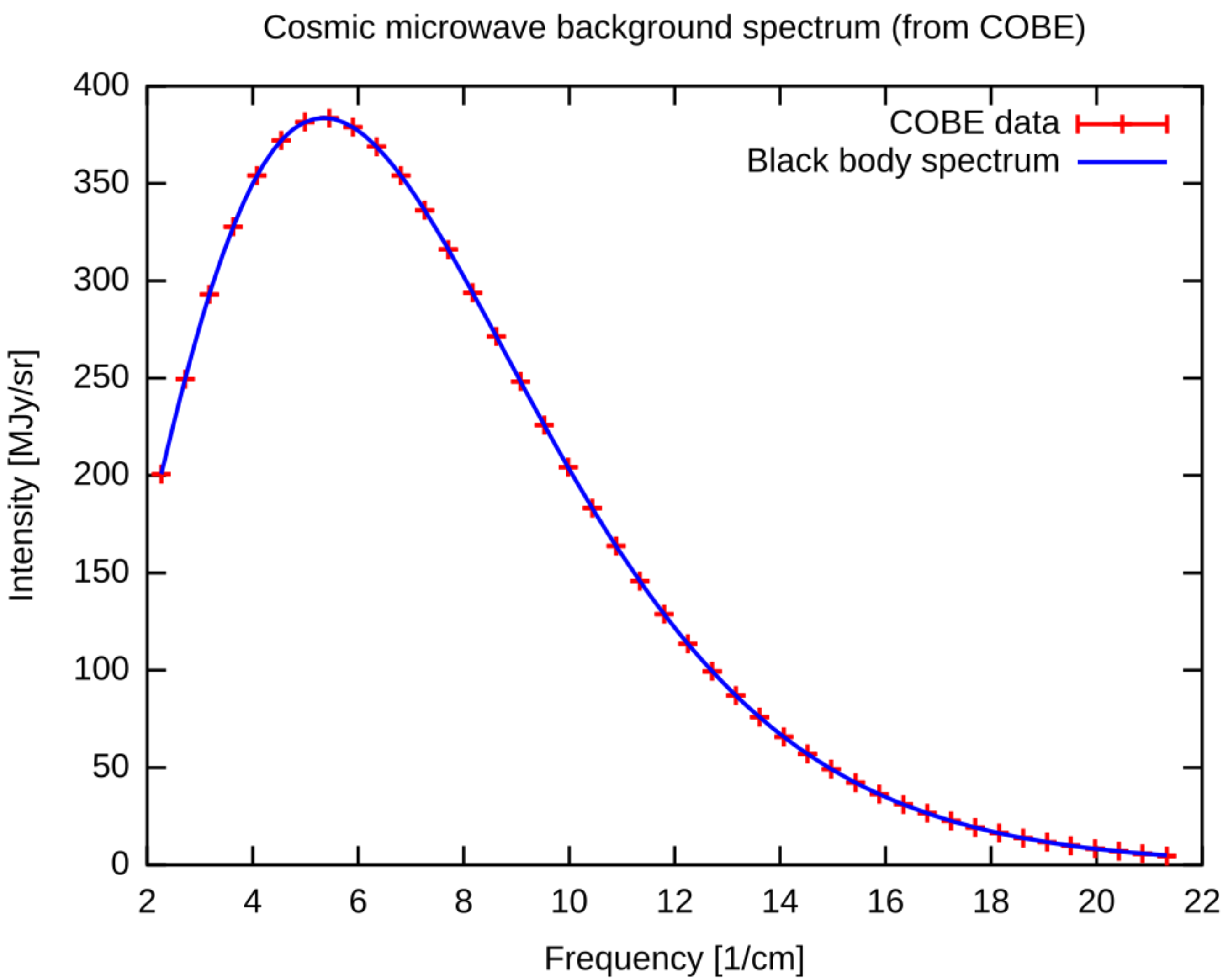
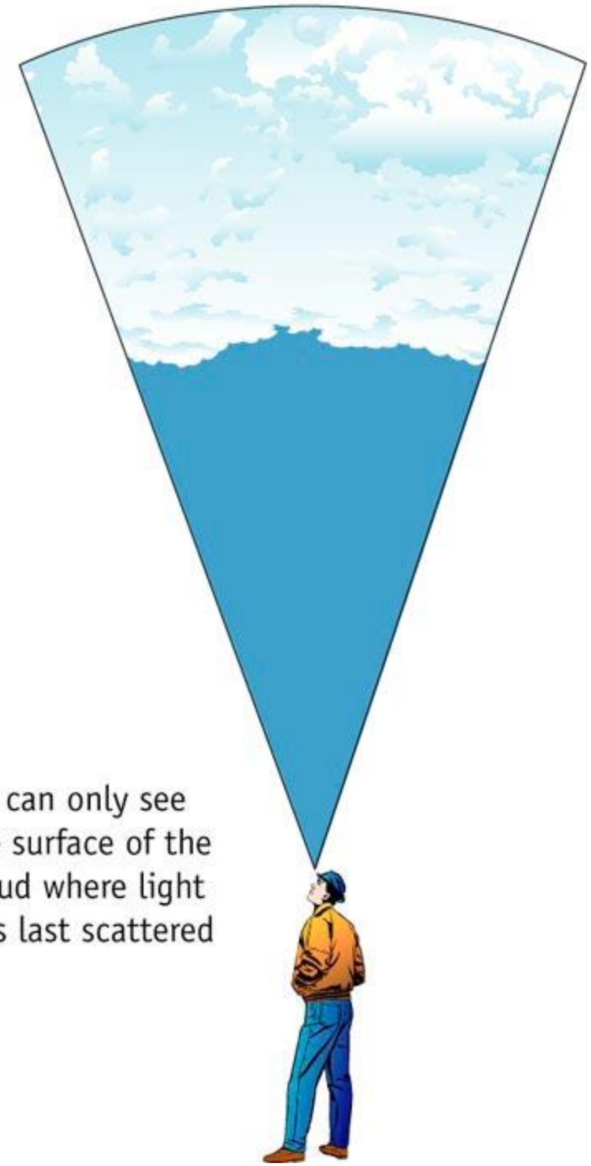


https://lambda.gsfc.nasa.gov/education/lambda_graphics/cmb_discovery.html



It is blackbody radiation at a temperature of $2.72548 \pm 0.00057\ \mathrm{K}$ (Fixsen, D. J., 2009).

Cosmic Microwave Background (CMB)



The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

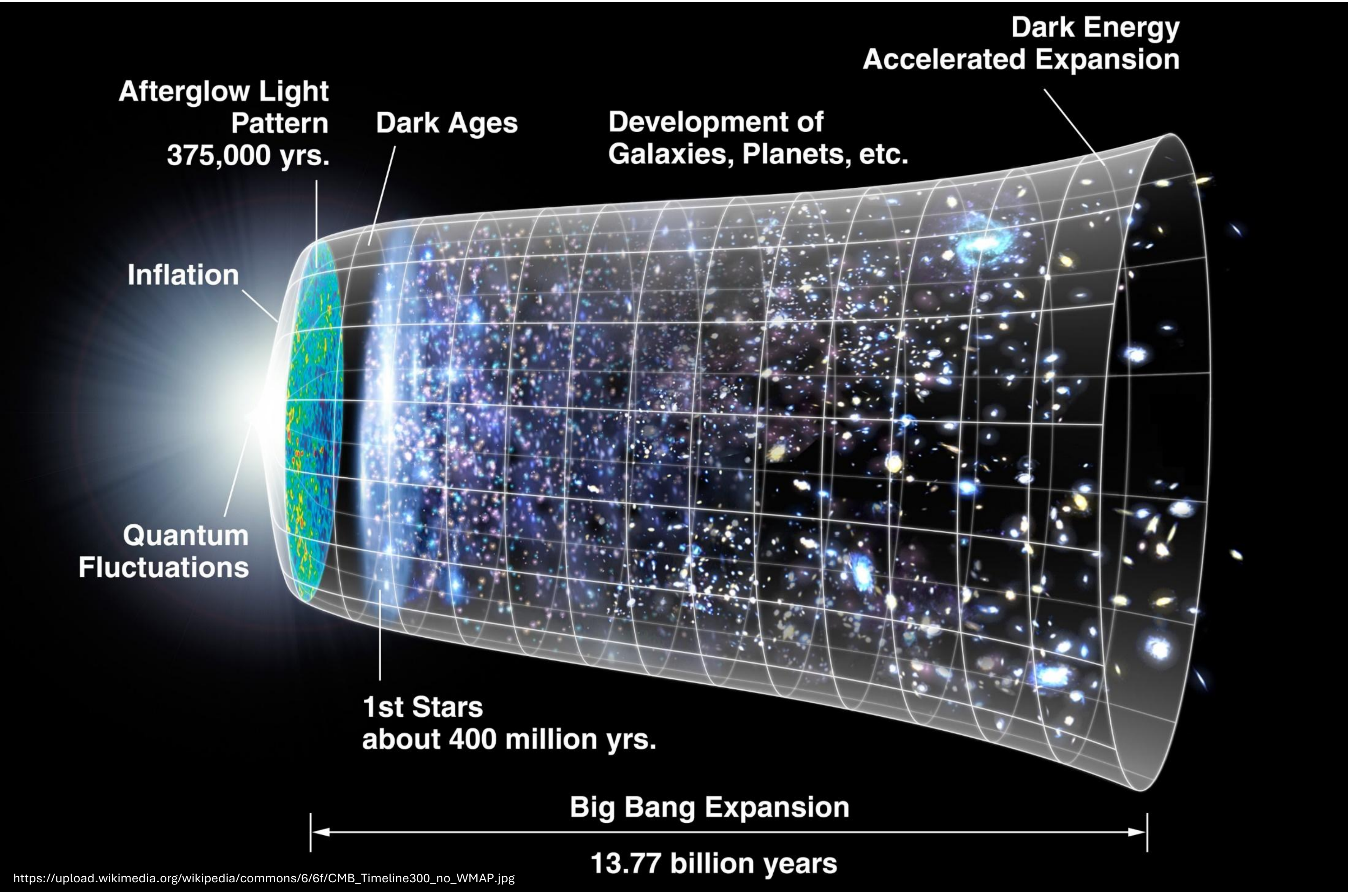
https://map.gsfc.nasa.gov/media/990053/index.html

Cosmic Microwave Background (CMB)

CMB observations confirm the Big Bang theory predictions:

- **Near-perfect blackbody spectrum**: The CMB has the most perfect blackbody spectrum ever measured, which is the signature of thermal energy in equilibrium. This matches the Big Bang's prediction of a hot, dense early universe in equilibrium.
- **Remarkable uniformity**: The CMB's temperature is almost perfectly uniform across the entire sky, supporting the idea that the early universe was nearly homogeneous.
- **Tiny temperature fluctuations**: Subtle temperature variations, or anisotropies, in the CMB reveal areas of slightly different densities in the early universe. These fluctuations acted as the "seeds" for all large-scale cosmic structures, like galaxies.

The Big Bang

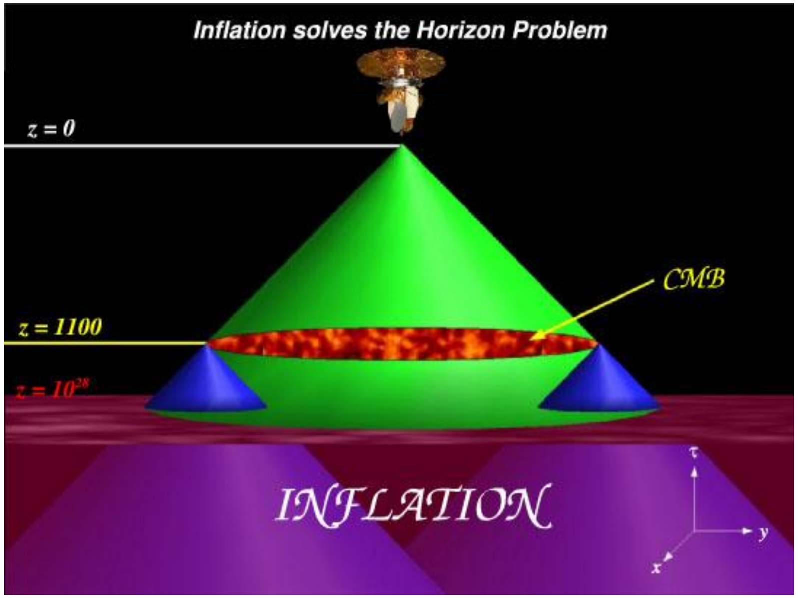


https://upload.wikimedia.org/wikipedia/commons/6/6f/CMB_Timeline300_no_WMAP.jpg

Inflation

Inflation resolves key puzzles of the standard Big Bang model.

- It explains the universe's uniformity (Horizon Problem) by ensuring distant regions were once in causal contact.
- It accounts for the universe's observed flatness (Flatness Problem) by stretching out any curvature.
- It solves the missing monopole problem by diluting these theoretical particles to undetectable levels.



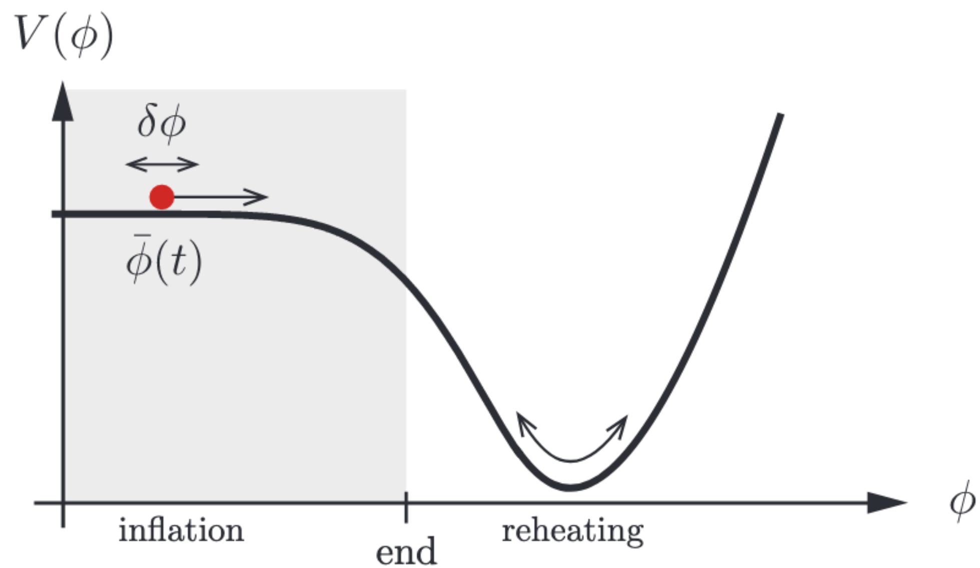
$$\boxed{eg = \frac{n\hbar c}{2}}$$

Electric charge quantisation needs existence of a magnetic monopole.

https://ned.ipac.caltech.edu/level5/Sept02/Kinney/Figures/figure12.jpg

Reheating

- Inflation ended with the decay of the inflaton field, which powered the expansion.
- Its energy was rapidly transferred to produce all the particles of the Standard Model.
- This process instantly reheated the cold, empty universe and filled it with a dense particle soup.
- The universe then transitioned into the hot, radiation-dominated state described by the standard Big Bang model.

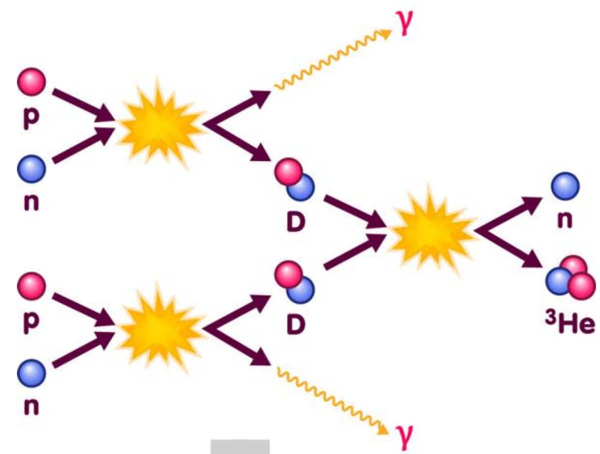


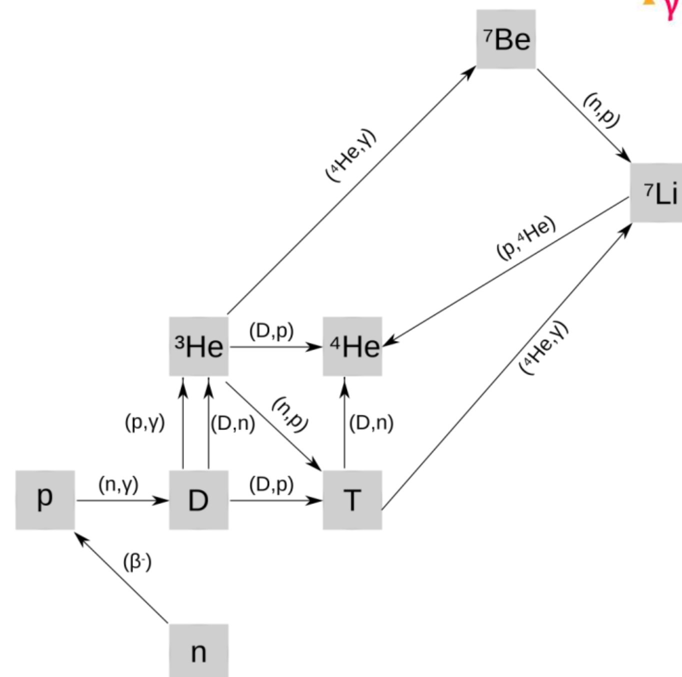
Baumann

https://cmb.wintherscoming.no/theory_initial.php

Big Bang Nucleosynthesis (BBN)

- Occurred from about 3 to 20 minutes after the Big Bang, following the reheating epoch.
- The universe cooled to $\sim 10^9\ \mathrm{K}$ allowing for nuclear fusion.
- Established the primordial abundances of elements:
  - $\sim 75\%$ Hydrogen
  - $\sim 24\%$ Helium
  - $\sim 1\%$ Metals



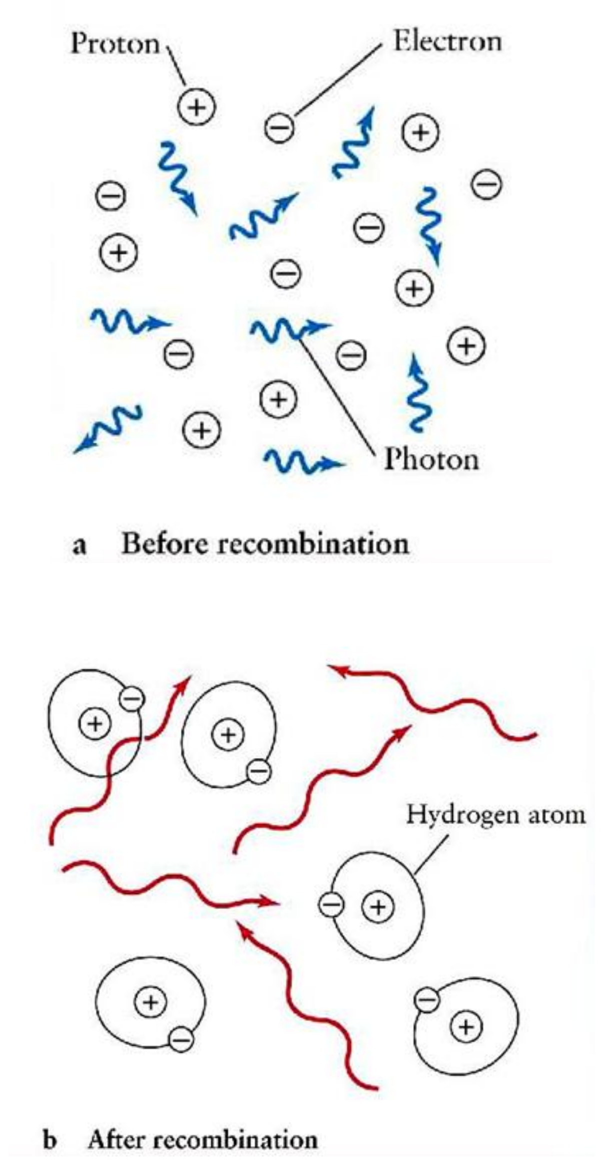


https://www.einstein-online.info/wp-content/uploads/Kosmologie_Kernfusion_zu_Helium-3_%C2%A9_Daniela_Leitner_Markus_Poessel_Einstein-Online.jpg

Recombination

The universe's transition to transparency

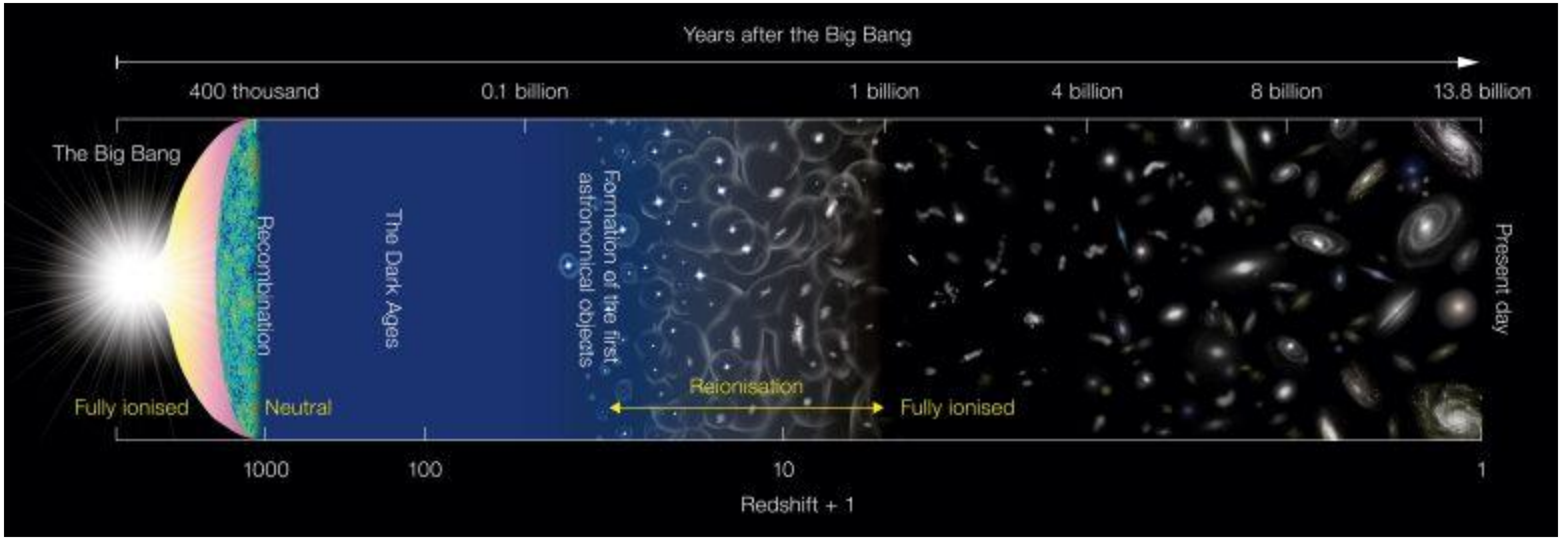
- It occurred $\sim 380{,}000$ years after the Big Bang, as the universe cooled to $\sim 3000\ \mathrm{K}$.
- Protons and electrons combined to form neutral hydrogen and helium atoms.
- Before recombination, the universe was an opaque plasma, where free electrons scattered light.
- After recombination, the universe is transparent universe, where photons could travel freely for the first time.
- The released photons are what we observe today as the Cosmic Microwave Background (CMB).

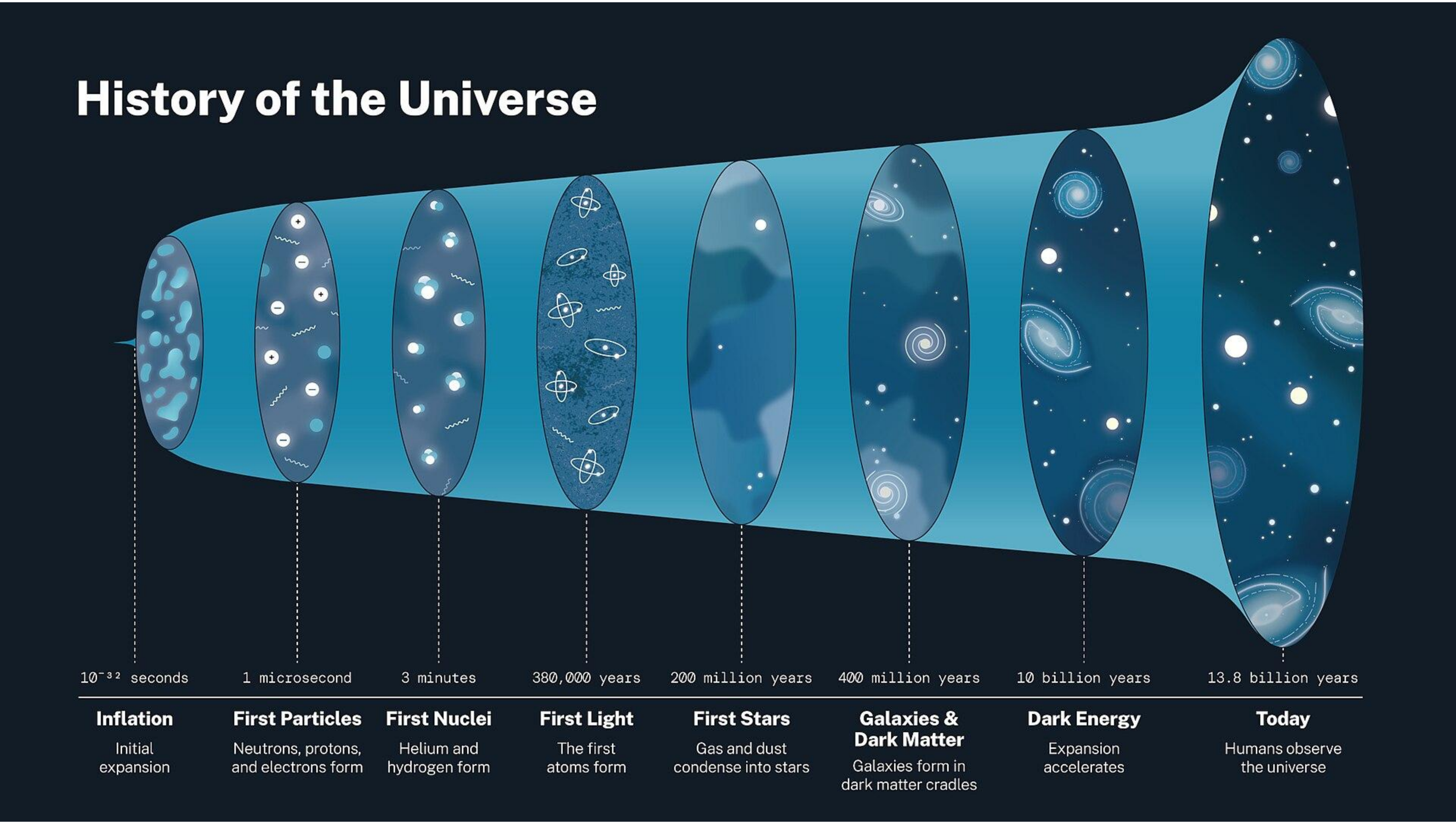


James N. Imamura of University of Oregon

Dark Ages

- Approximately 380,000 to 400 million years after the Big Bang.
- The universe was filled with a dense, opaque fog of neutral hydrogen and helium gas. This gas absorbed or scattered light, making the cosmos dark.
- While outwardly dark, gravity worked silently behind the scenes. Dark matter halos gathered the gas, creating the seeds for the first stars and galaxies.
- The era ended with the "Cosmic Dawn," when the first massive stars ignited. Their powerful ultraviolet light began to reionise the surrounding neutral gas.

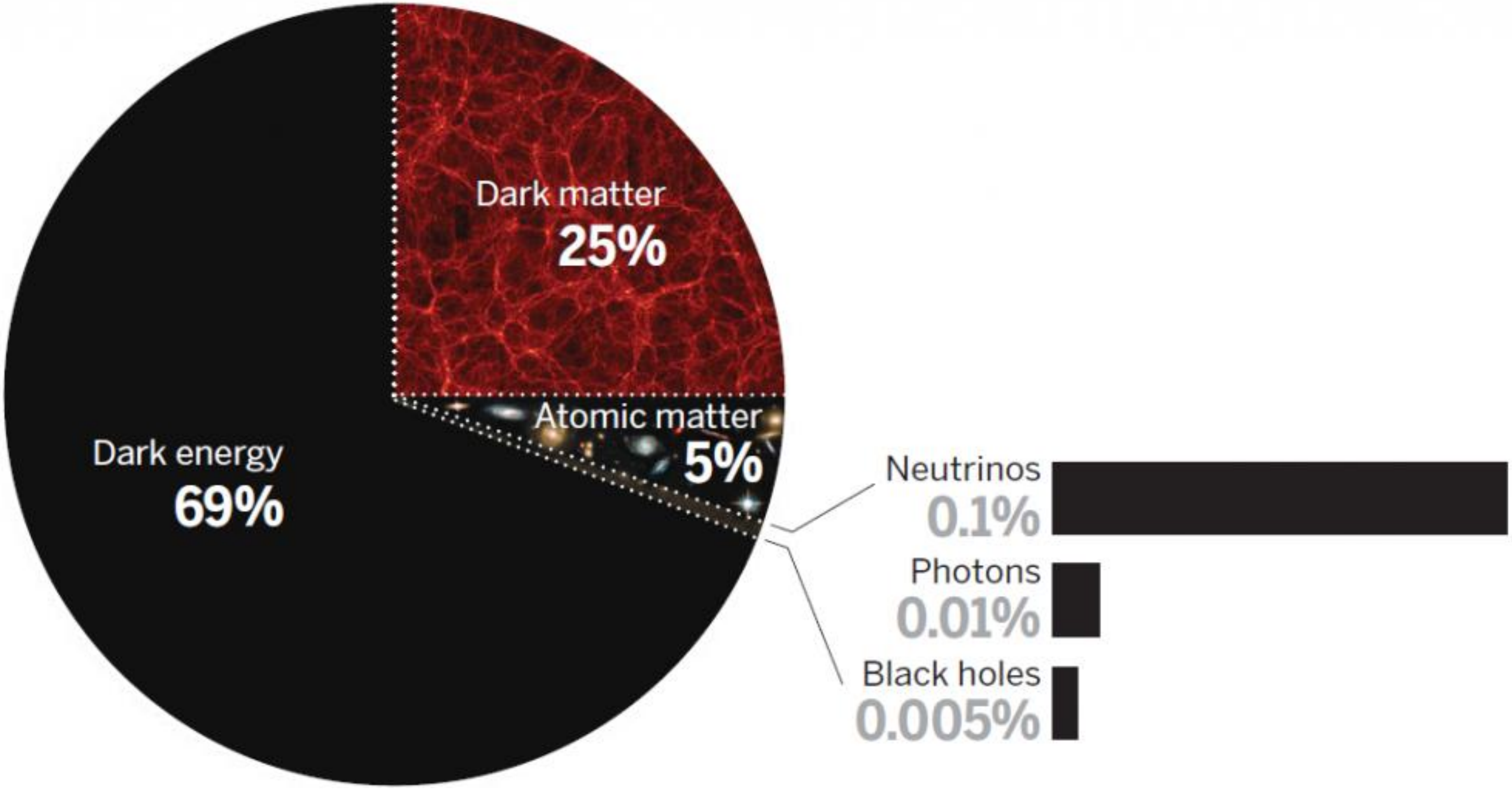




https://upload.wikimedia.org/wikipedia/commons/thumb/3/38/History-of-the-Universe.jpg/1920px-History-of-the-Universe.jpg

The multiple components that compose our universe

Current composition (as the fractions evolve with time)



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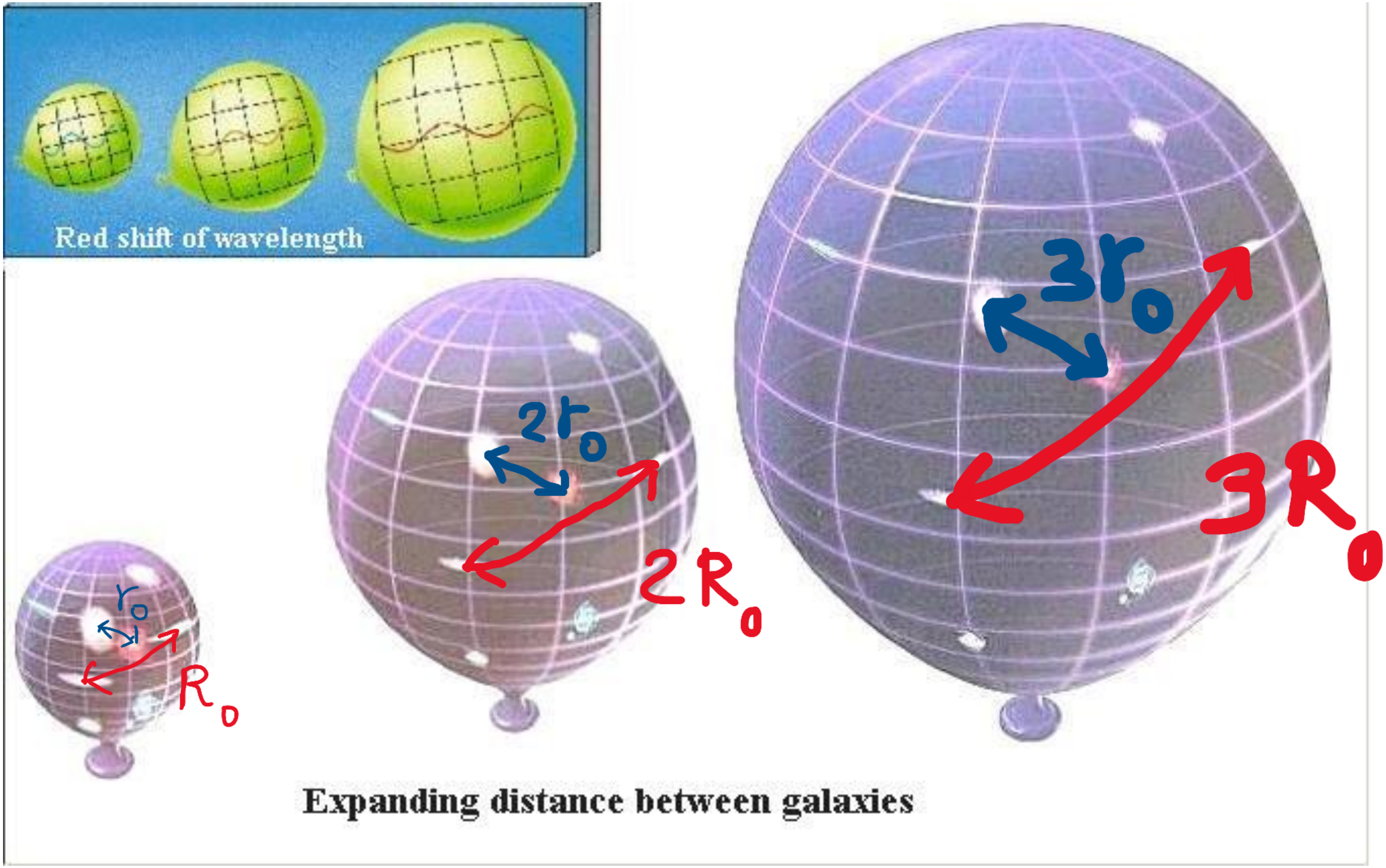
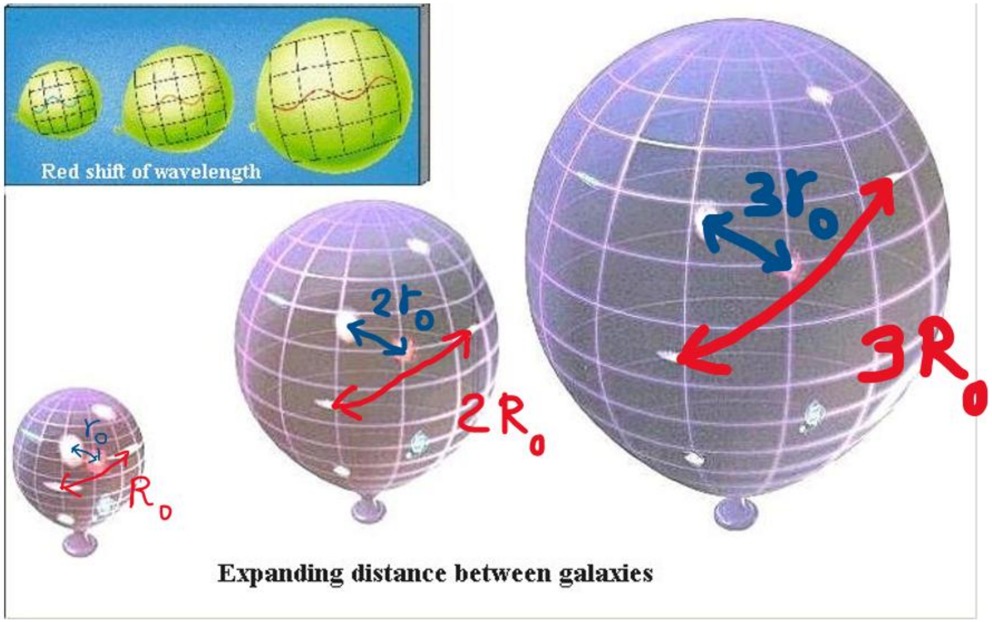
Cosmic Expansion



https://universe-review.ca/I02-06-expansion.jpg

Cosmic Expansion



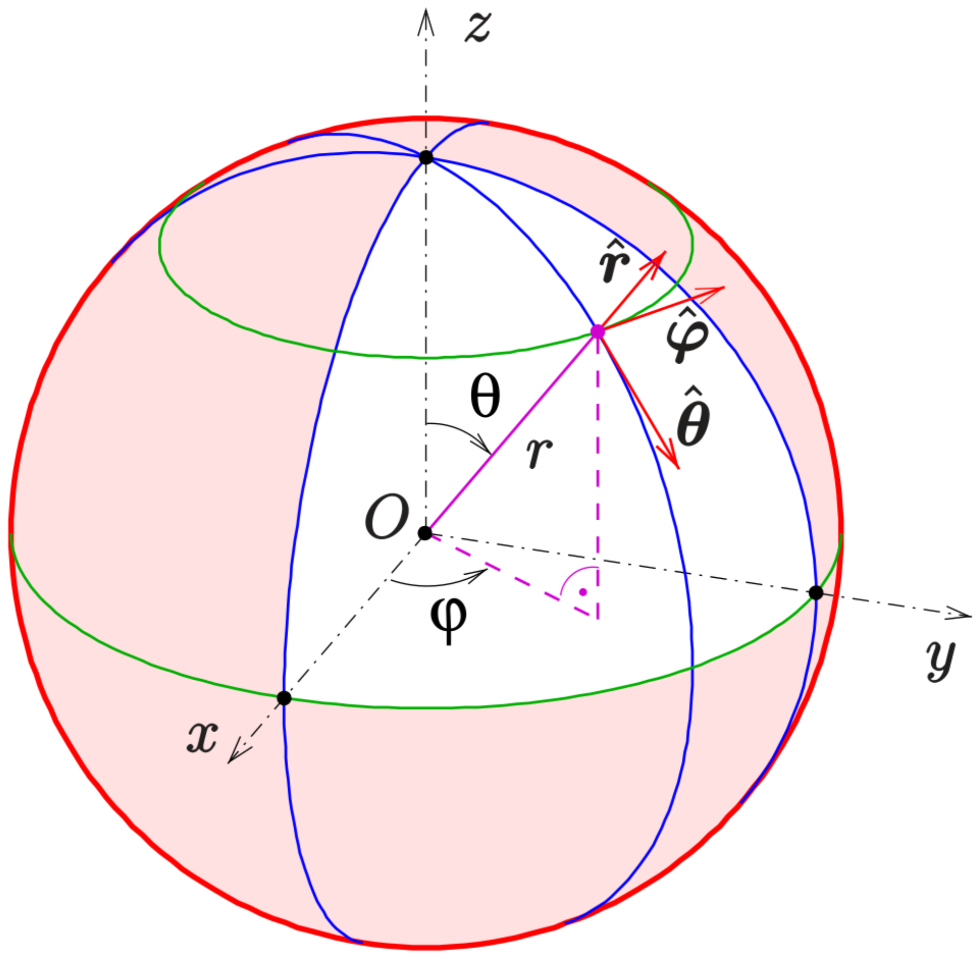
- At a certain time, the distance between two specific galaxies is

$$r = ar_0$$

where a is the scale factor.

https://universe-review.ca/I02-06-expansion.jpg

Friedmann–Lemaître–Robertson–Walker Metric



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Friedmann–Lemaître–Robertson–Walker Metric

- The most general coordinate system satisfying the cosmological principle:

$$(t, r, \theta, \varphi)$$

with line element (Friedmann–Lemaître–Robertson–Walker, FLRW metric)

$$ds^2 = -c^2 dt^2 + a^2(t)\left[\frac{dr^2}{1 - kr^2} + r^2(d\theta^2 + \sin^2\theta\, d\varphi^2)\right]$$

where

k is a constant representing the spatial curvature: $\{-1,0,1\}$ for {negative, flat, positive} curvatures respectively,

and $a(t)$ is the scale factor.

Thank you!