The Hubble Tension

How are we trying to solve one of the biggest crises in Astronomy?

Dr. Adam Batten

Swinburne University of Technology

Public Astronomy Lecture

30-03-2023

SWINBURNE UNIVERSITY OF TECHNOLOGY

Acknowledgement of Country

We respectfully acknowledge the Wurundjeri People of the Kulin Nation, who are the Traditional Owners of the land on which Swinburne's Australian campuses are located in Melbourne's east and outer-east, and pay our respect to their Elders past, present and emerging.

We are honoured to recognise our connection to Wurundjeri Country, history, culture, and spirituality through these locations, and strive to ensure that we operate in a manner that respects and honours the Elders and Ancestors of these lands.

We also respectfully acknowledge Swinburne's Aboriginal and Torres Strait Islander staff, students, alumni, partners and visitors.

We also acknowledge and respect the Traditional Owners of lands across Australia, their Elders, Ancestors, cultures, and heritage, and recognise the continuing sovereignties of all Aboriginal and Torres Strait Islander Nations.

The Hubble Tension

How are we trying to solve one of the biggest crises in Astronomy?

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CAASTRO
ALL-SKY ASTROPHYSICS

$$H_0$$

$$H_0$$

The Hubble Constant

$$H_0$$

The Hubble Constant

73.3 km/s/Mpc **67.7** km/s/Mpc

H_0

The Hubble Constant

73.3 km/s/Mpc

Cosmic Distance Ladder

67.7 km/s/Mpc

$$H_0$$

The Hubble Constant

73.3 km/s/Mpc

Cosmic Distance Ladder

67.7 km/s/Mpc

Cosmic Microwave Background

73.3

Cosmic Distance Ladder

Reiss et al. (2022)

67.7

Cosmic Microwave Background

Planck Collaboration (2020)

73.3
Cosmic
Distance
Ladder

73.3
Cosmic Distance Ladder
CAASTRO
ALL-SKY ASTROPHYSICS

73.3
Cosmic Distance Ladder

Faster

Velocity

Slower

Closer

Distance

Farther

Image Credit: NASA/ESA

73.3
Cosmic Distance Ladder

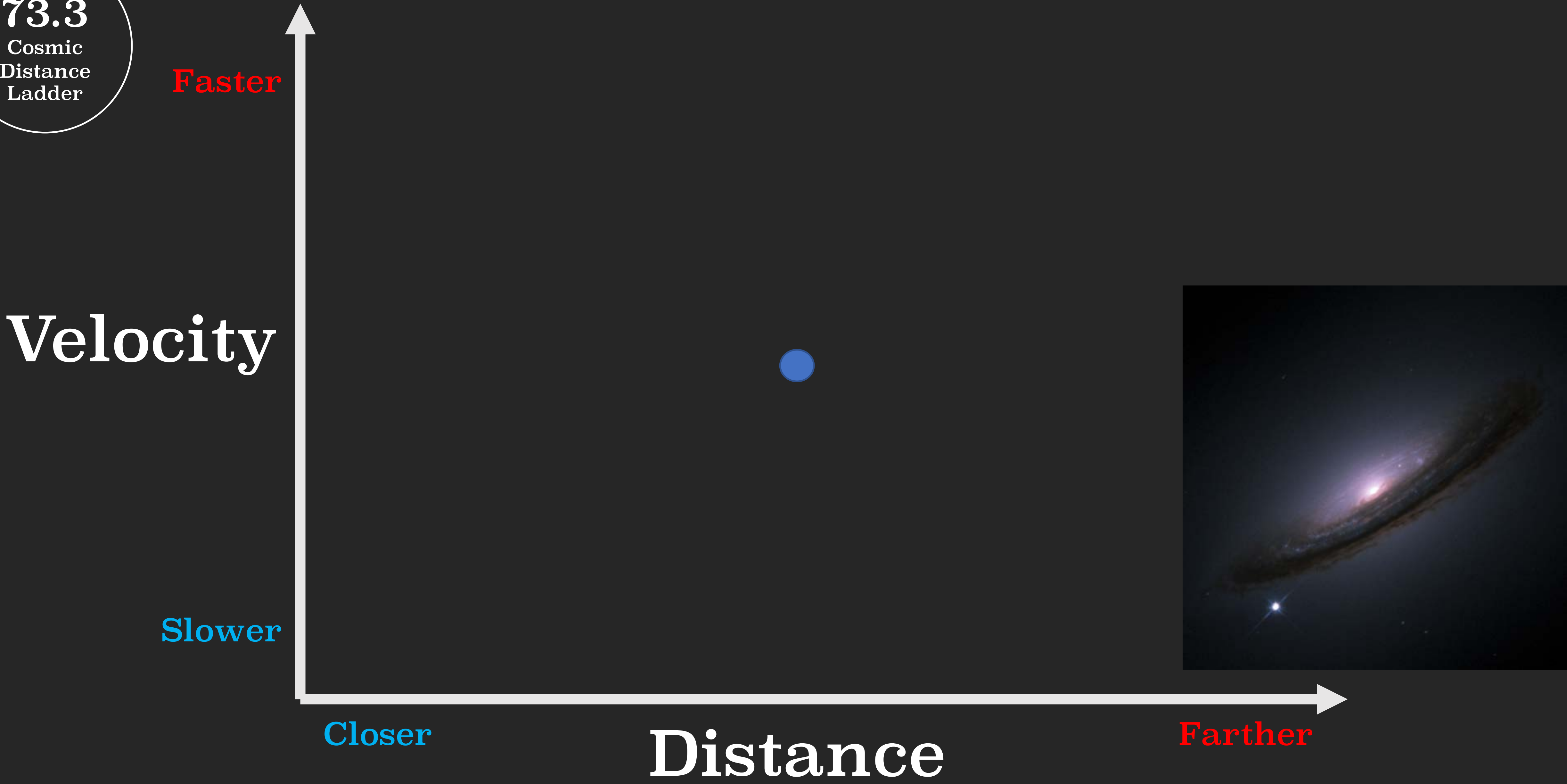


Image Credit: NASA/ESA

73.3
Cosmic Distance Ladder

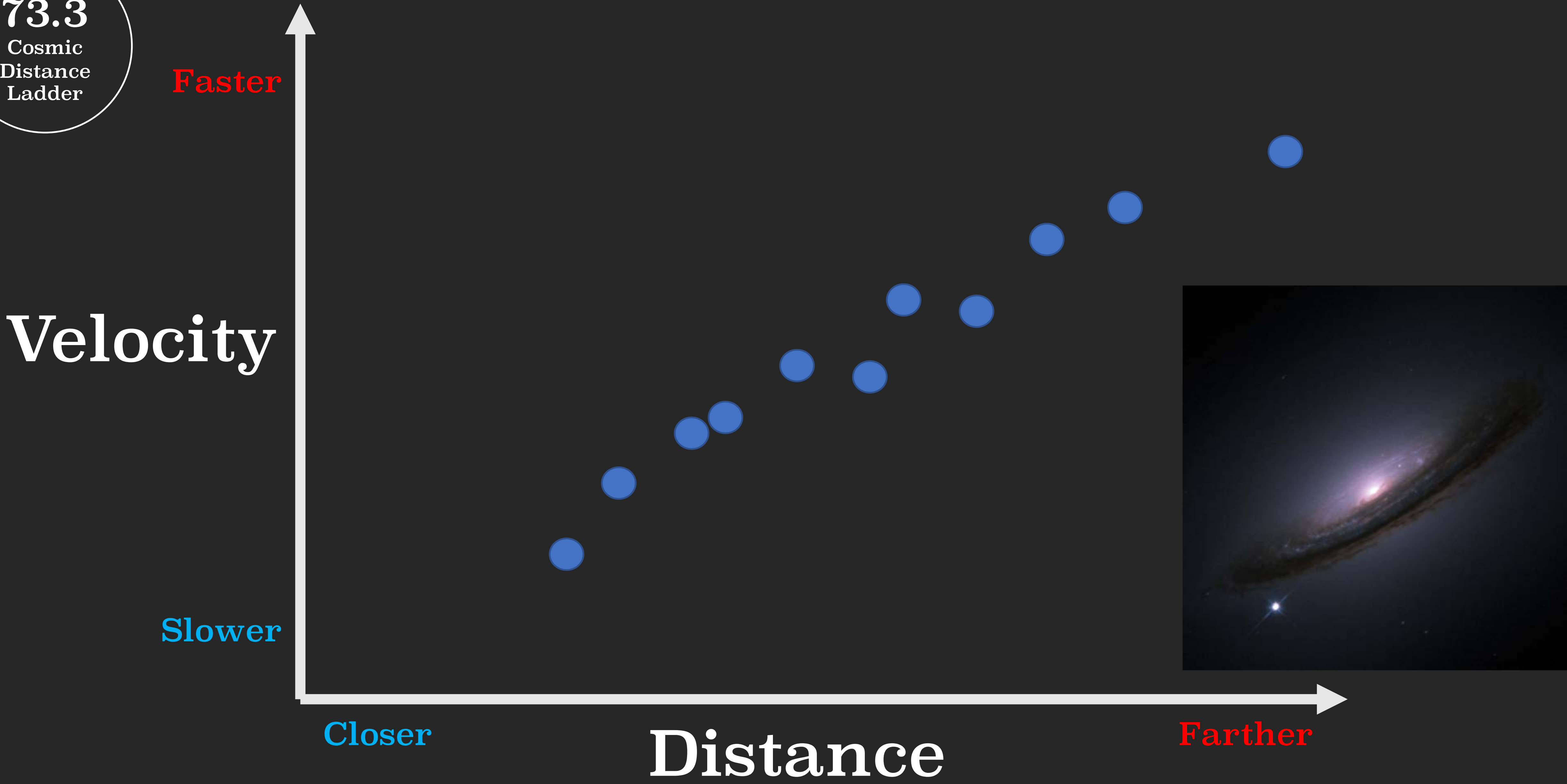


Image Credit: NASA/ESA

73.3
Cosmic Distance Ladder

Slope = Speed of Expansion (H0)

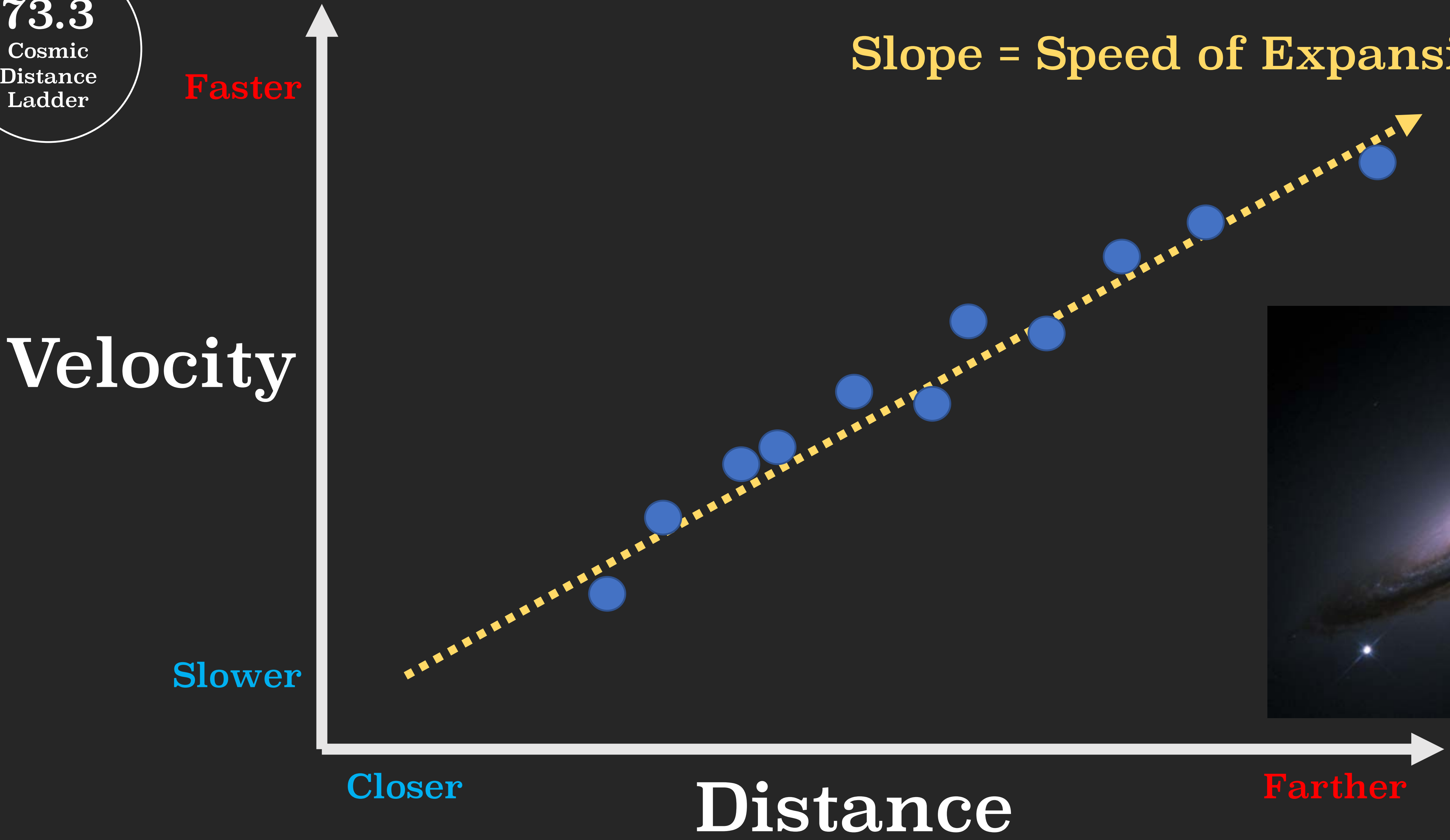
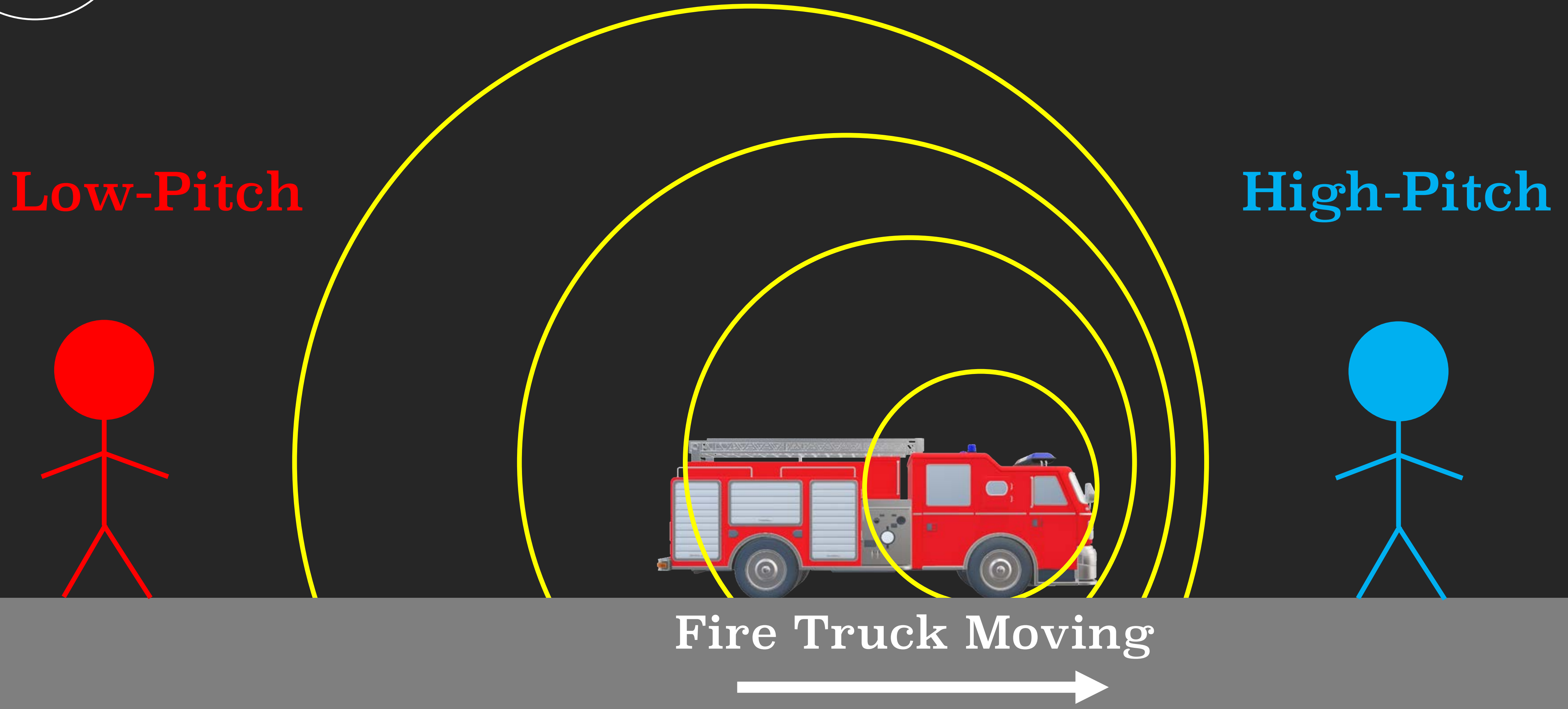


Image Credit: NASA/ESA

73.3
Cosmic
Distance
Ladder

How do you measure a galaxy's velocity?

How do you measure a galaxy's velocity?



73.3
Cosmic
Distance
Ladder

The Sun's Spectrum

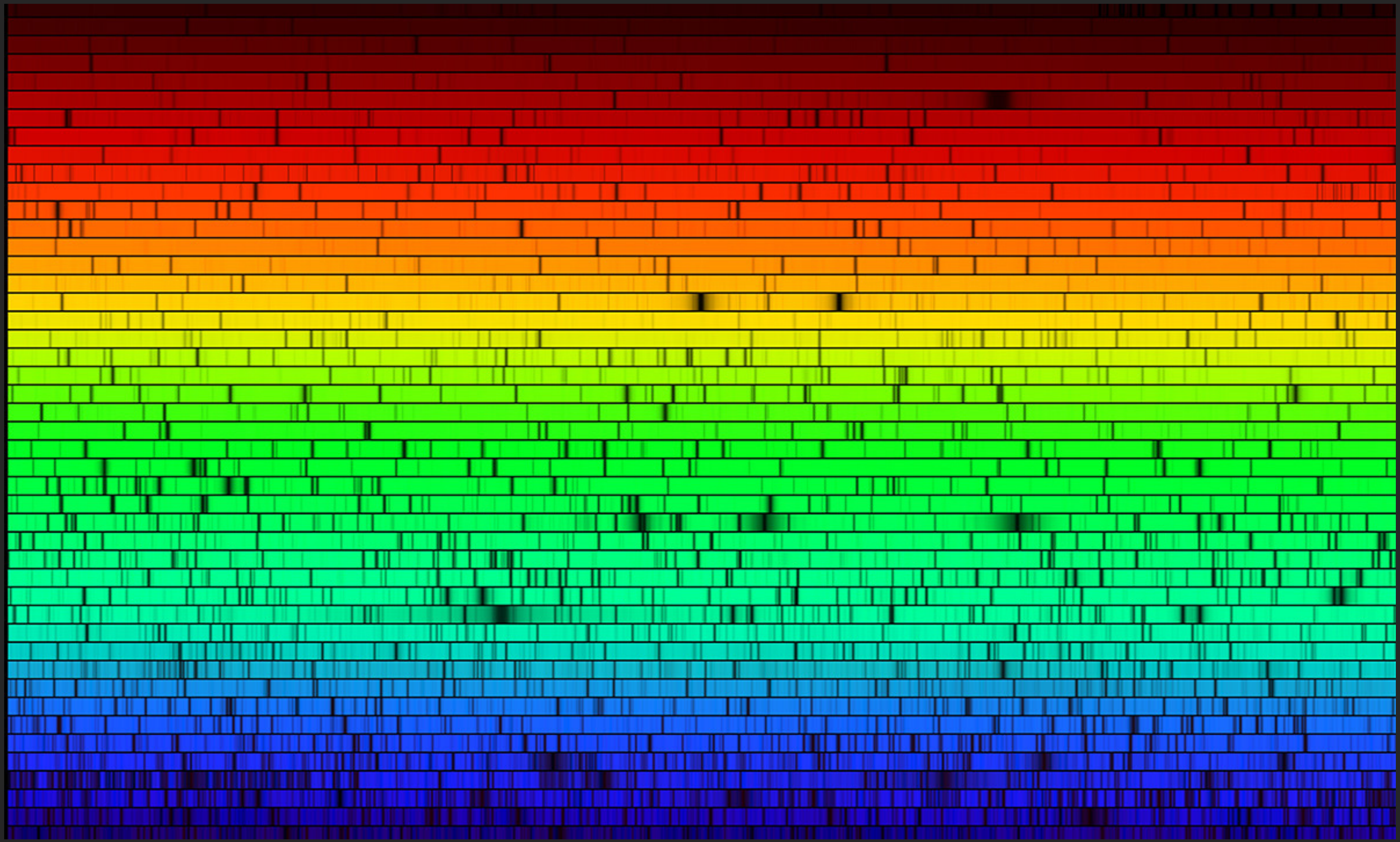
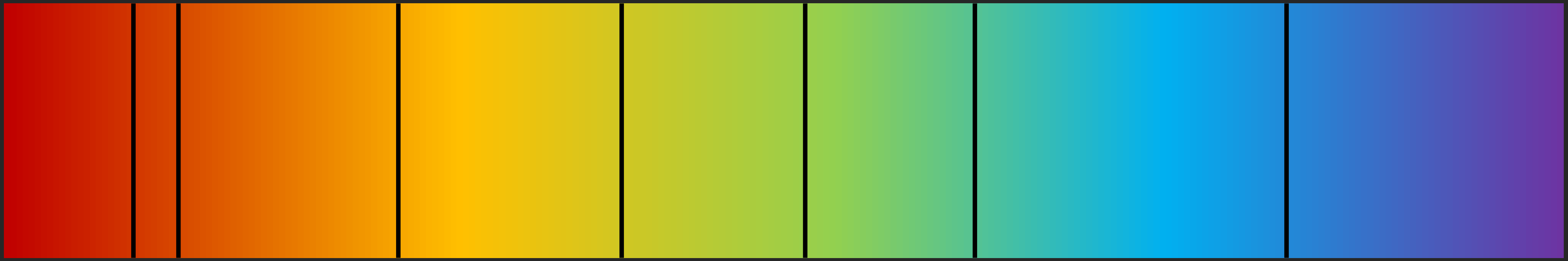


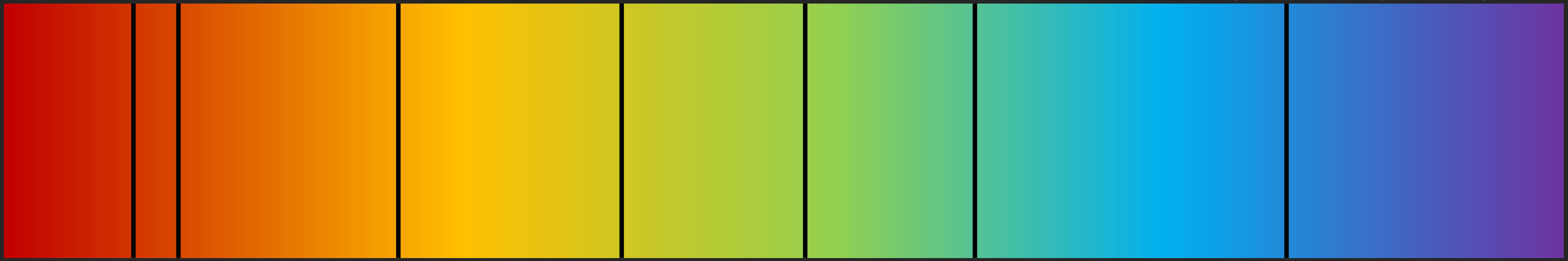
Image Credit: N.A.Sharp, NOAO/NSO/Kitt Peak FTS/AURA/NSF

73.3
Cosmic
Distance
Ladder

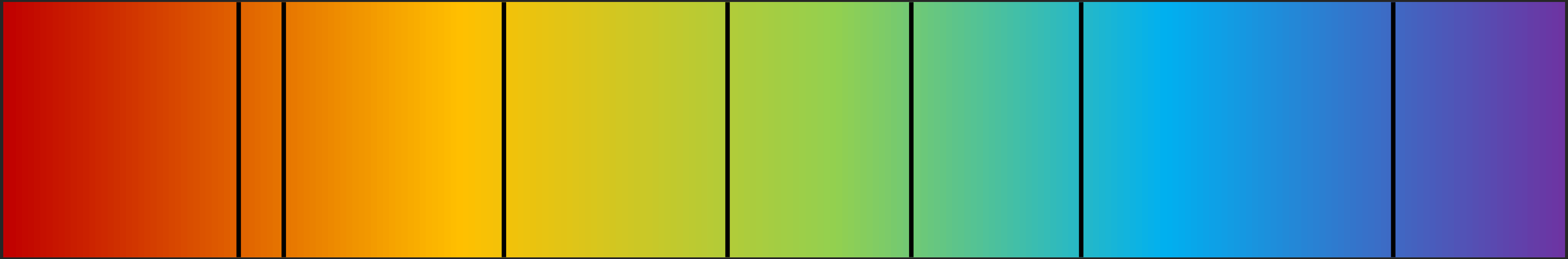
Object at Rest – Not Moving



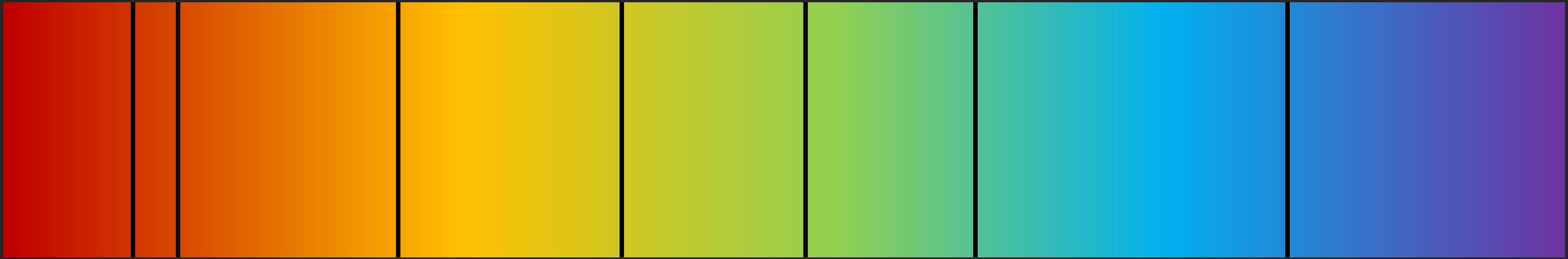
At Rest - Not Moving



Object moving towards us – “Blueshifted”

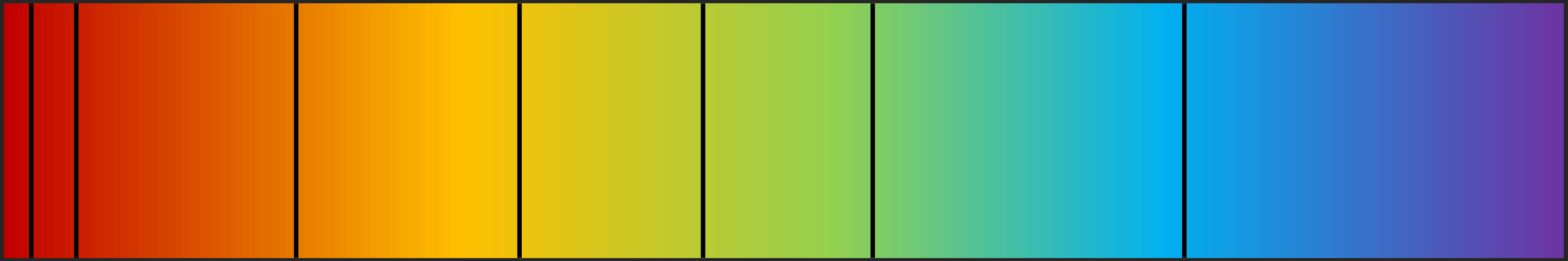


At Rest - Not Moving

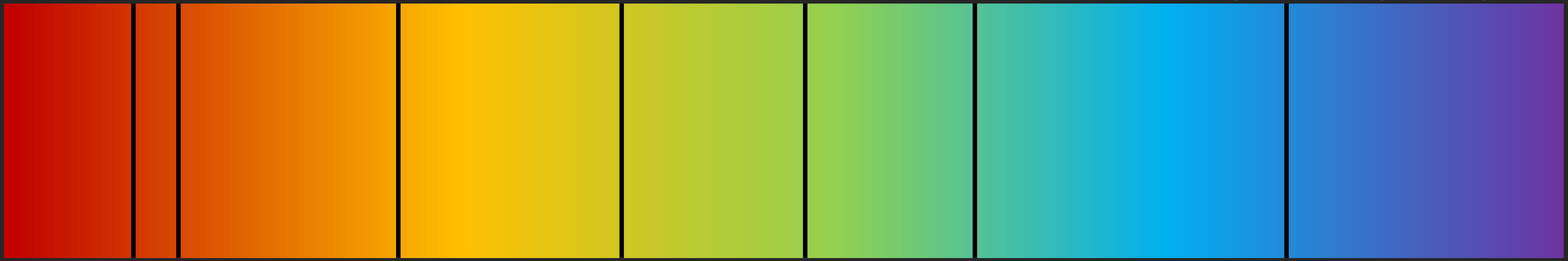


73.3
Cosmic
Distance
Ladder

Object moving away from us – “Redshifted”

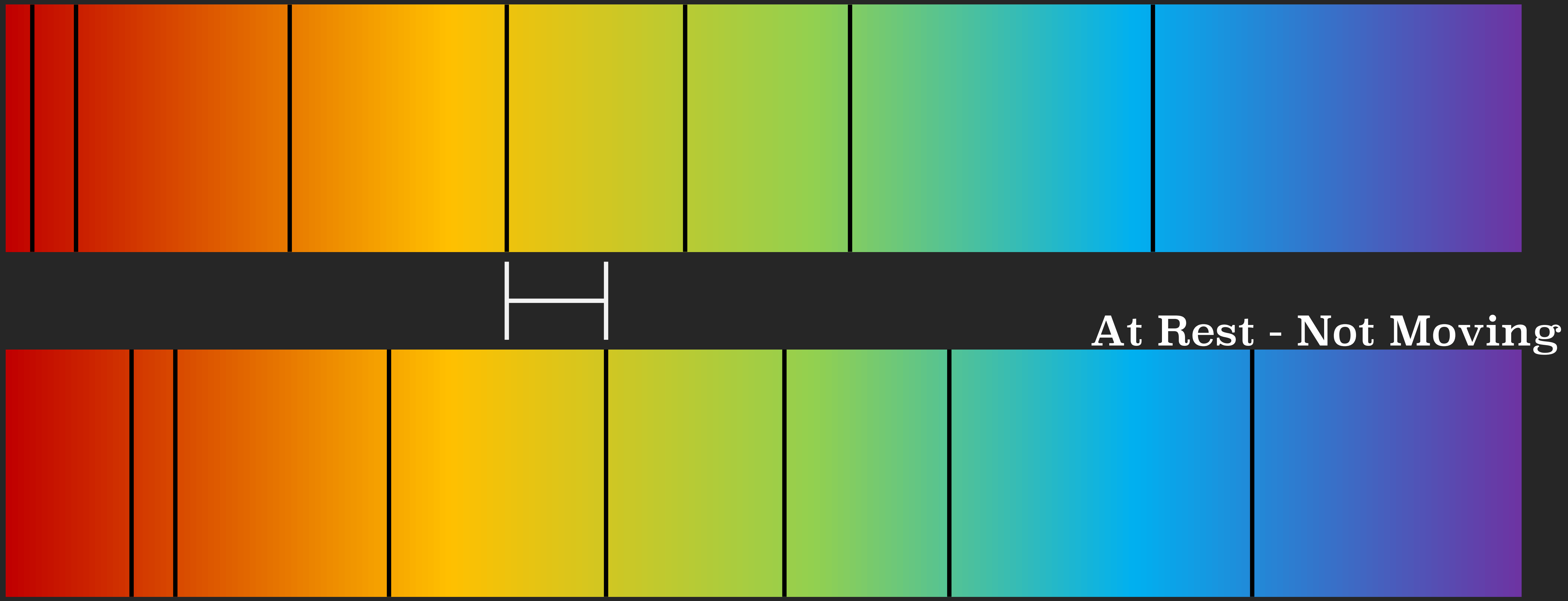


At Rest - Not Moving



73.3
Cosmic Distance Ladder

Object moving away from us – "Redshifted"



73.3

Cosmic Distance Ladder

73.3 Cosmic Distance Ladder

How far away is this galaxy?

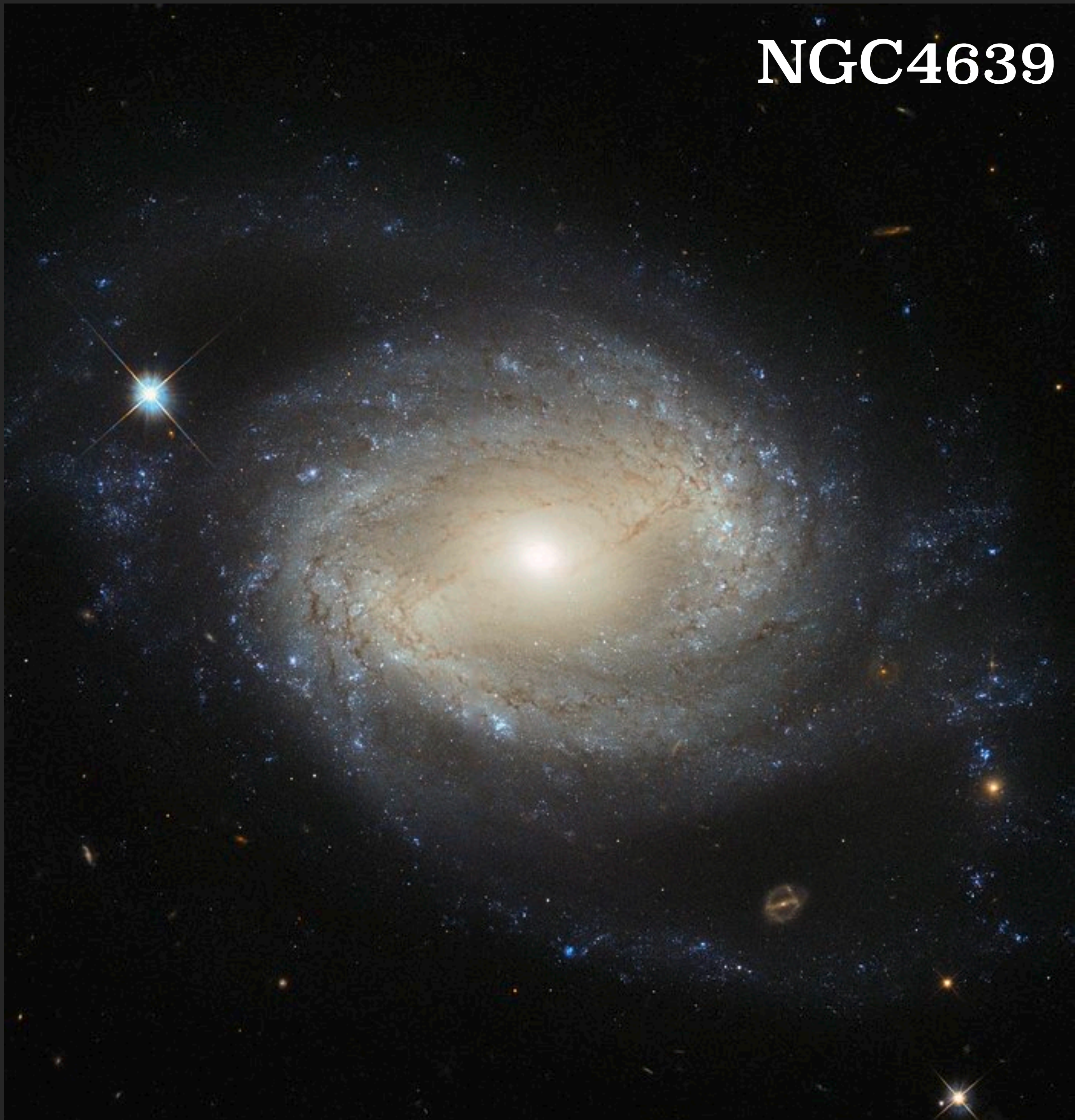


Image Credit: ESA/Hubble & NASA


73.3
Cosmic
Distance
Ladder
R.A.A.F.
UNITED KINGDOM
EUROPE
ATLANTIC
MIDDLE EAST
EAST INDIES
S.E. ASIA
NEW GUINEA
S.W. PACIFIC


73.3
Cosmic
Distance
Ladder
How far away is St. Paul's Cathedral?

73.3
Cosmic Distance Ladder

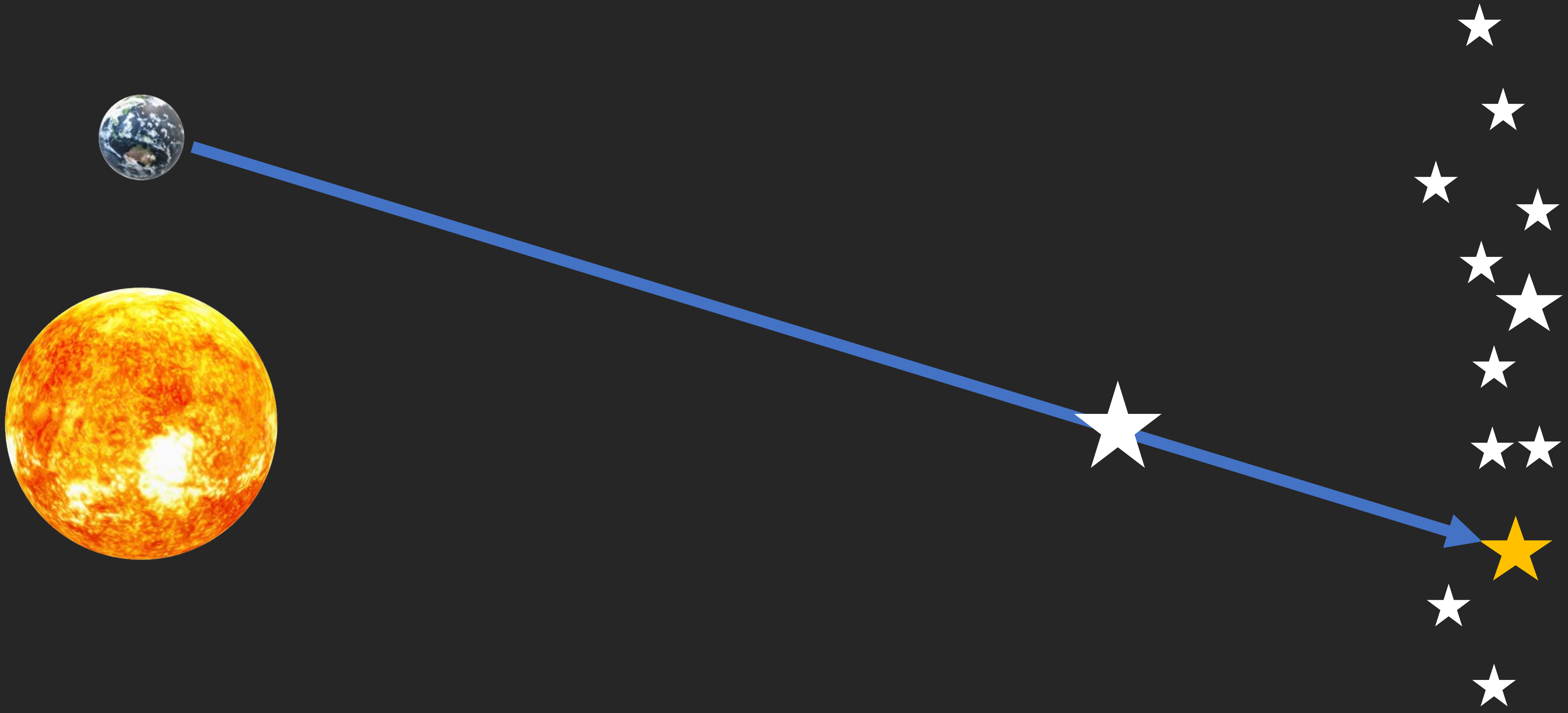
Distance Measurement Tool #1: Parallax

73.3
Cosmic Distance Ladder

Distance Measurement Tool #1: Parallax

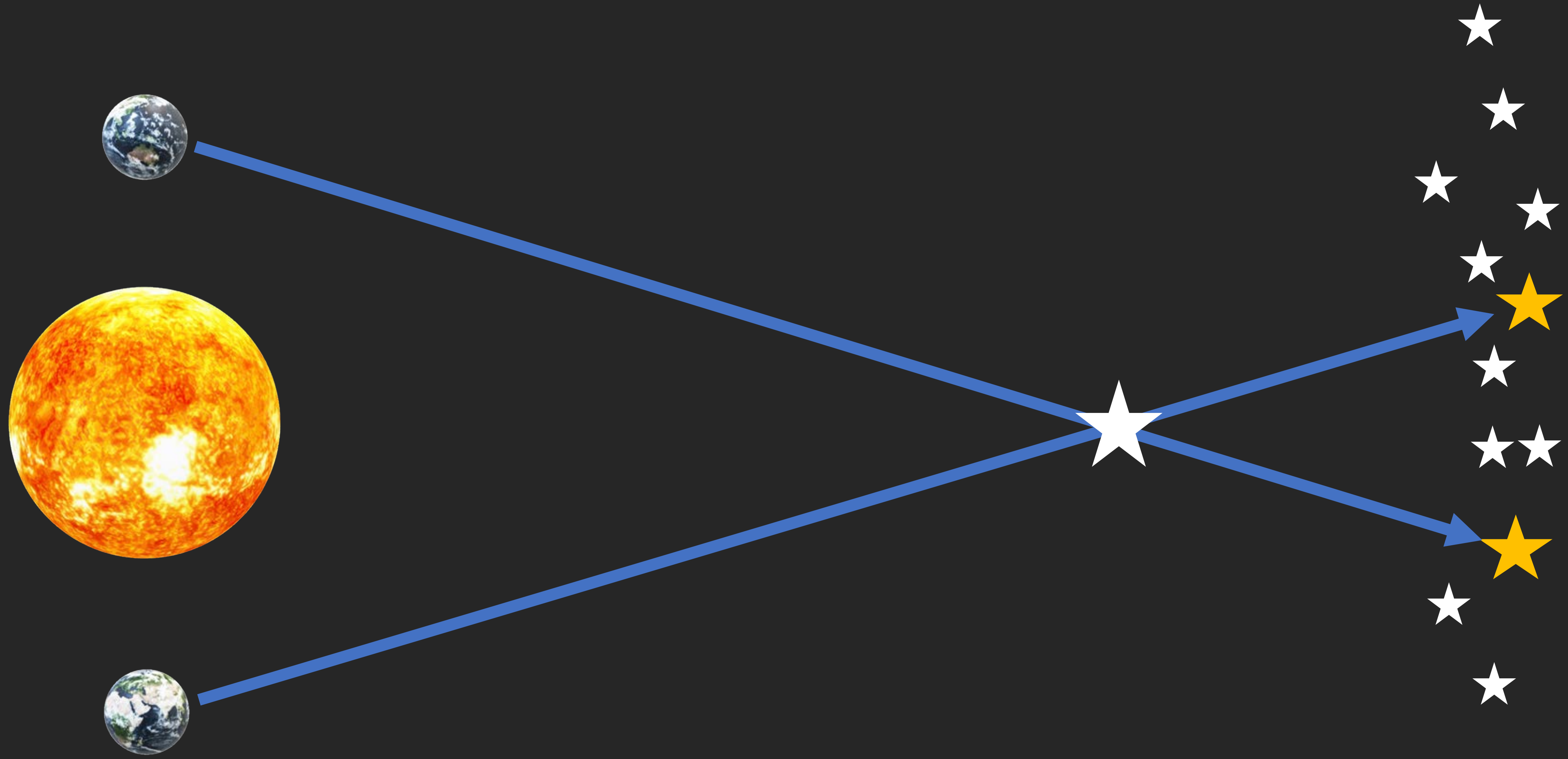
73.3
Cosmic Distance Ladder

Distance Measurement Tool #1: Parallax



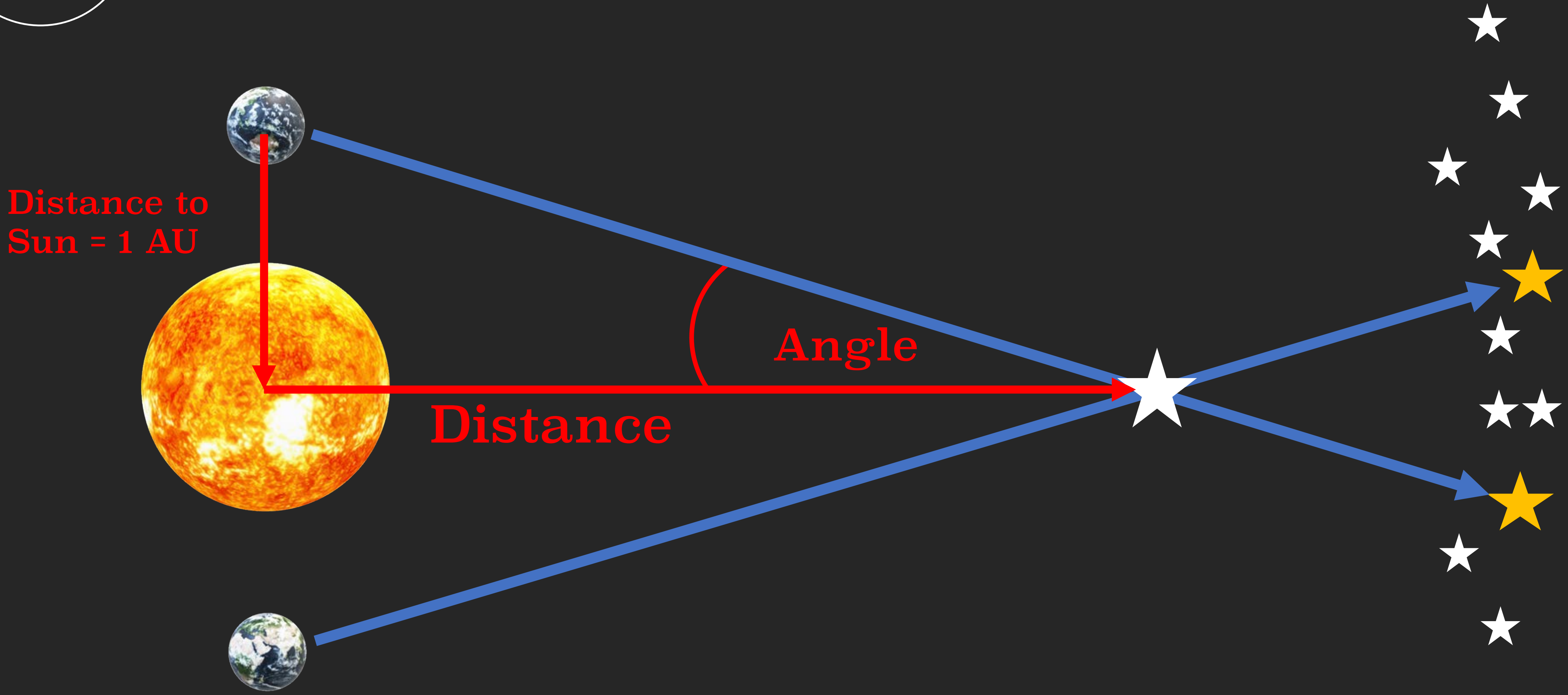
73.3
Cosmic Distance Ladder

Distance Measurement Tool #1: Parallax



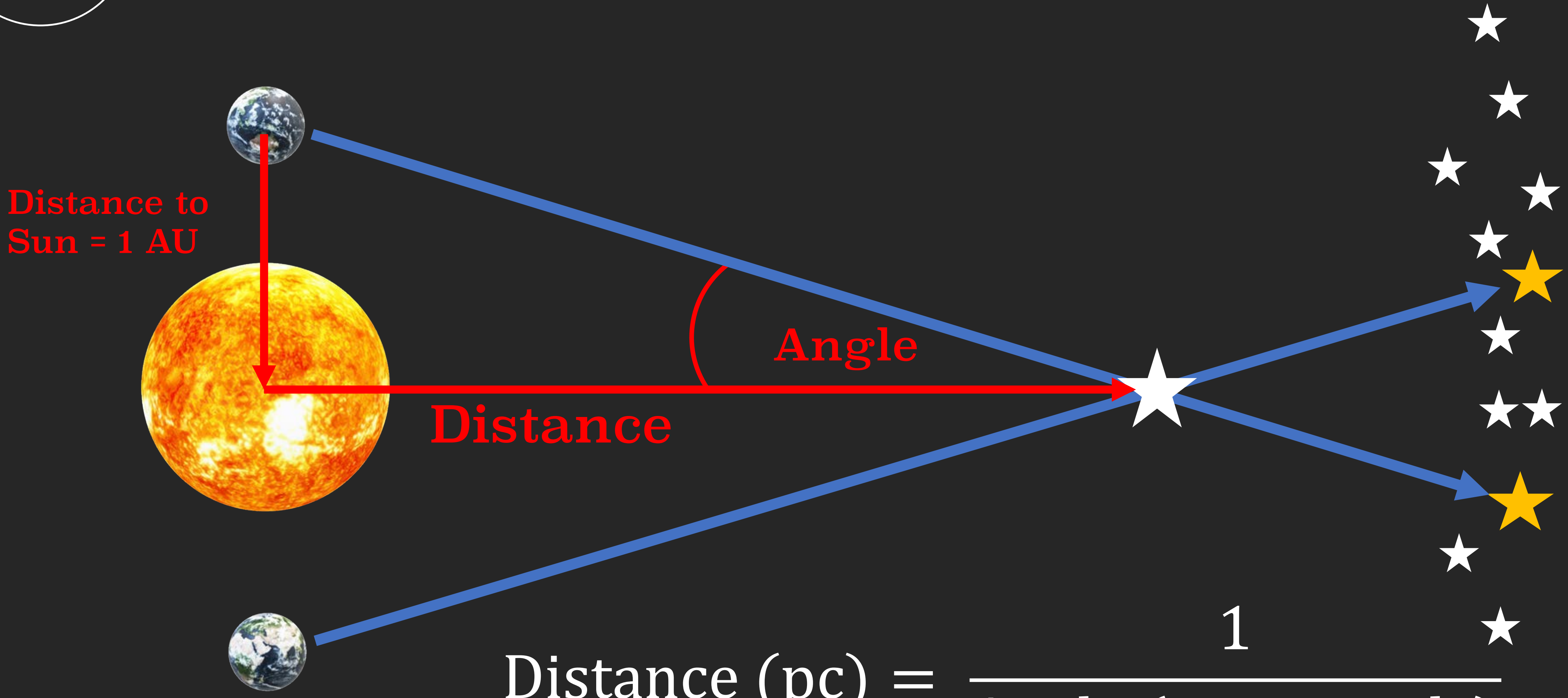
73.3
Cosmic
Distance
Ladder

Distance Measurement Tool #1: Parallax



73.3
Cosmic Distance Ladder

Distance Measurement Tool #1: Parallax



$$\text{Distance (pc)} = \frac{1}{\text{Angle (arcseconds)}}$$

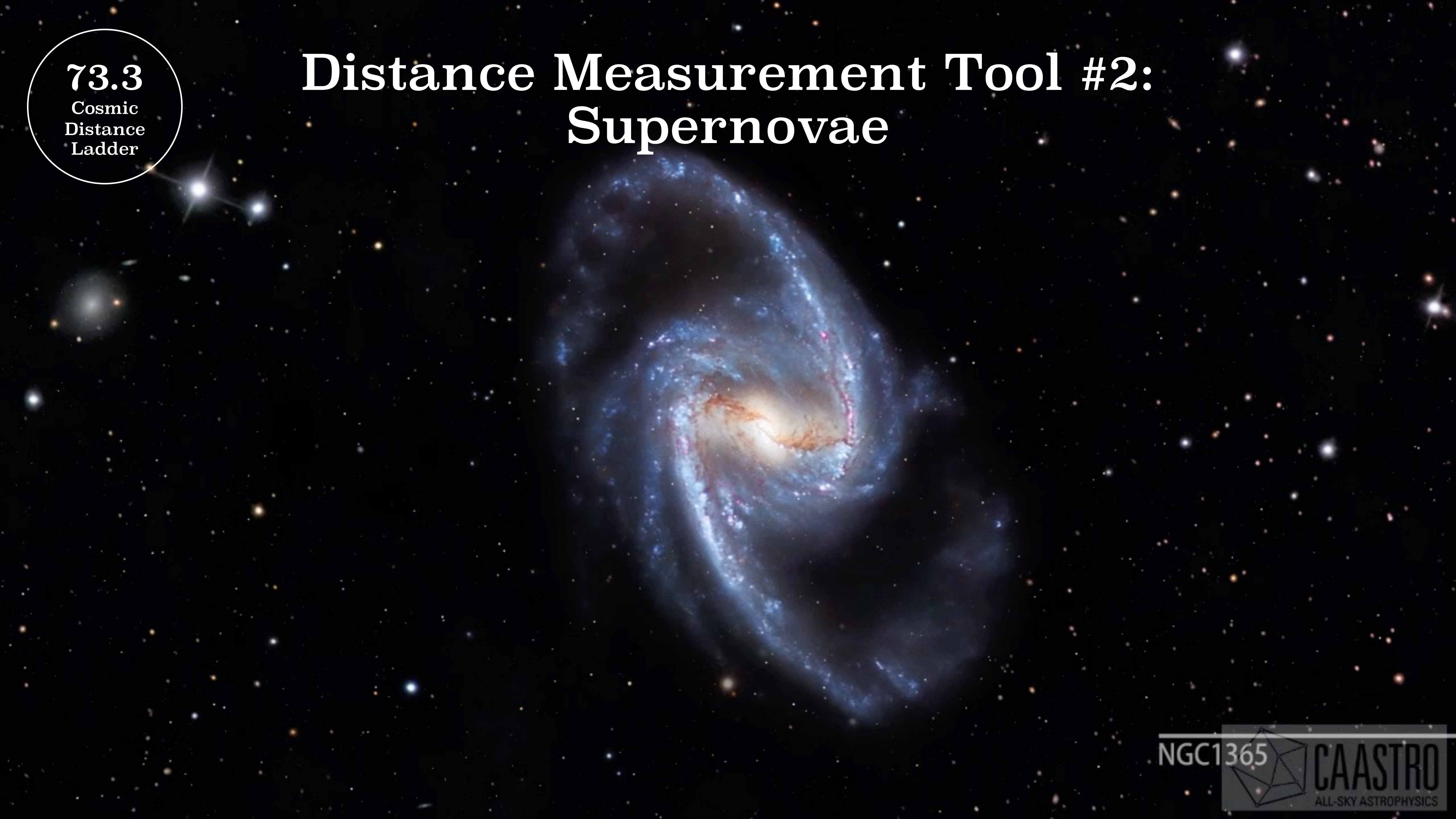
73.3
Cosmic Distance Ladder

Distance Measurement Tool #2:

CAASTRO ALL-SKY ASTROPHYSICS

73.3
Cosmic
Distance
Ladder

Distance Measurement Tool #2: Supernovae



73.3
Cosmic
Distance
Ladder

Distance Measurement Tool #2: Type Ia Supernovae

73.3
Cosmic Distance Ladder

Distance Measurement Tool #2: Type Ia Supernovae

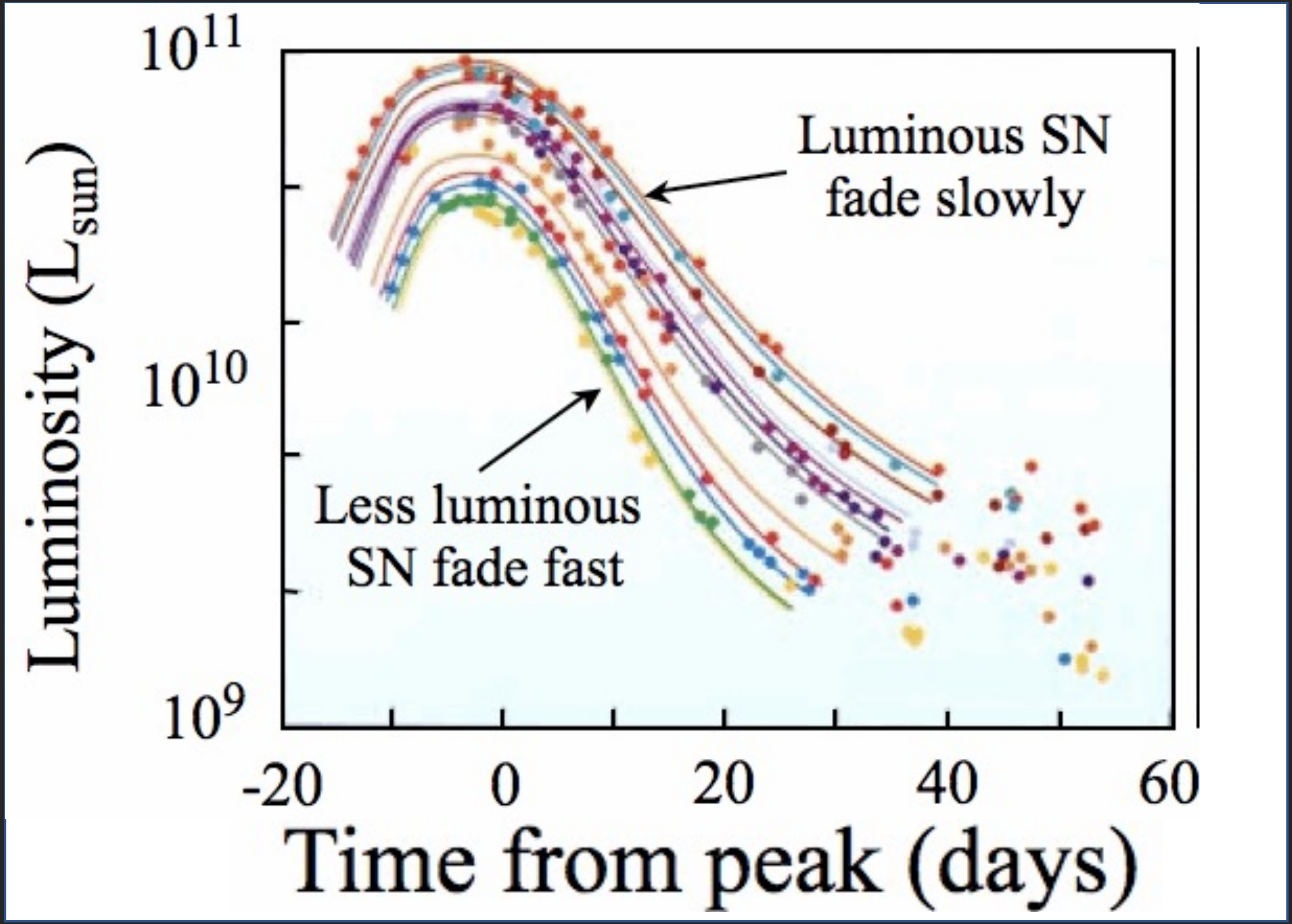
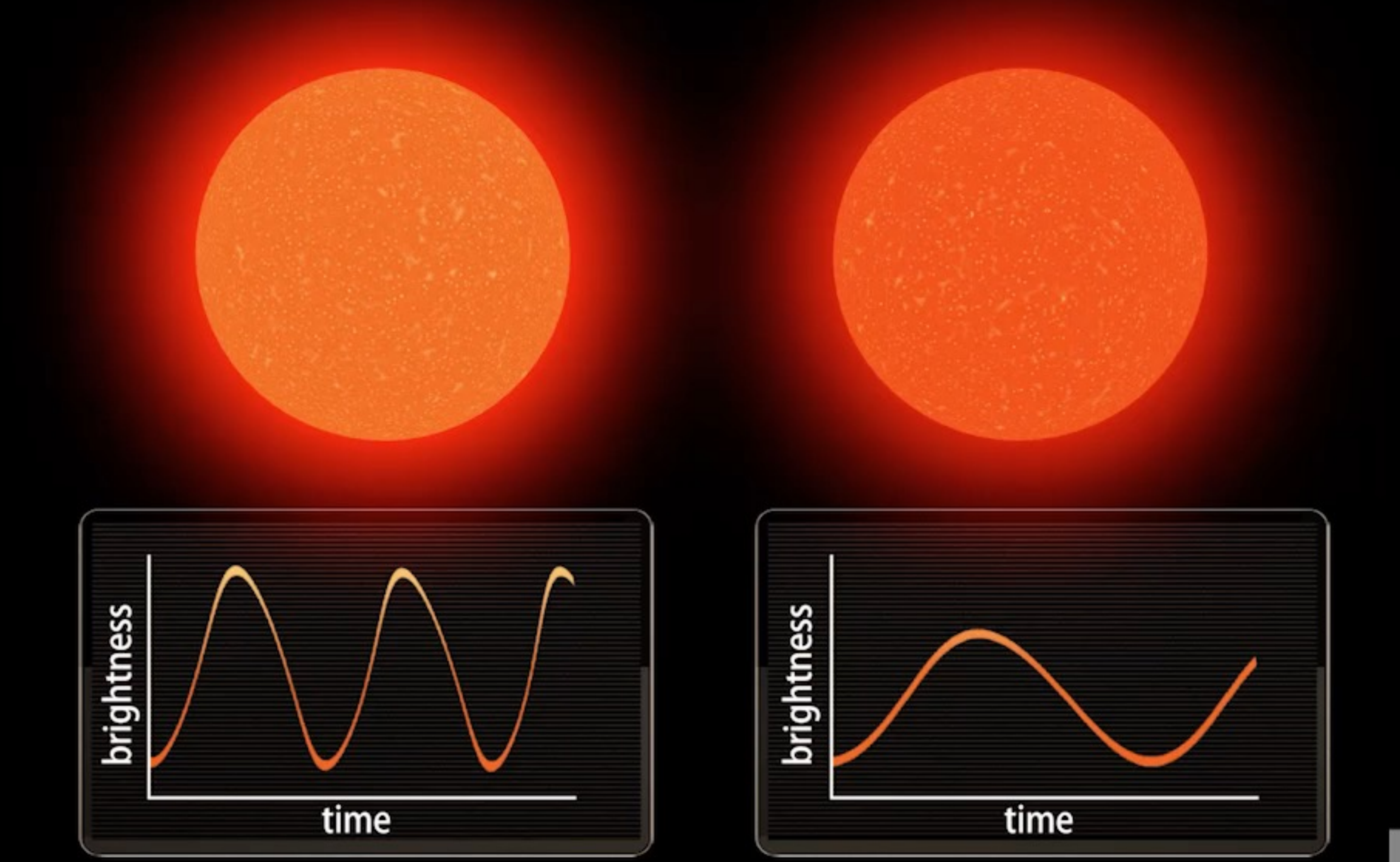


Image Credit: Durham Department of Physics

73.3
Cosmic Distance Ladder

Distance Measurement Tool #3: Cepheid Variable Stars



Cosmic Distance Ladder

Parallax

+ Accurate!

- Can only be used on stars inside our galaxy.

73.3
Cosmic Distance Ladder

Cosmic Distance Ladder

Parallax

+ Accurate!

- Can only be used on stars inside our galaxy.

Supernovae

+ Can be used for large distances!

- Needs to have calibrations from known distances.

73.3
Cosmic
Distance
Ladder

Cosmic Distance Ladder

Parallax

+ Accurate!

- Can only be used on stars inside our galaxy.

Supernovae

+ Can be used for large distances!

- Needs to have calibrations from known distances.

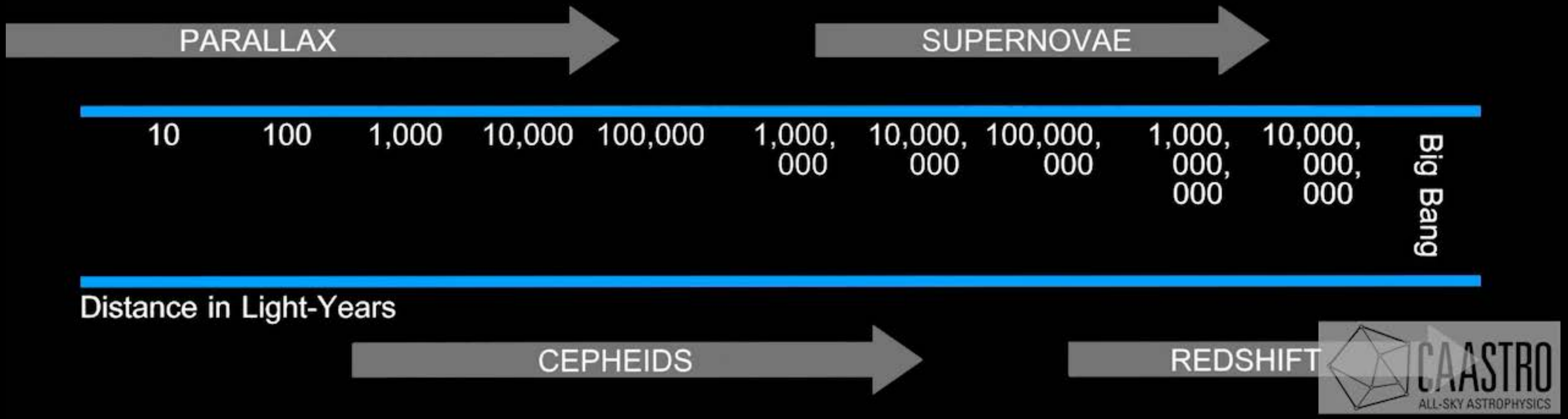
Cepheids

+ Can be found in our galaxy and nearby galaxies!

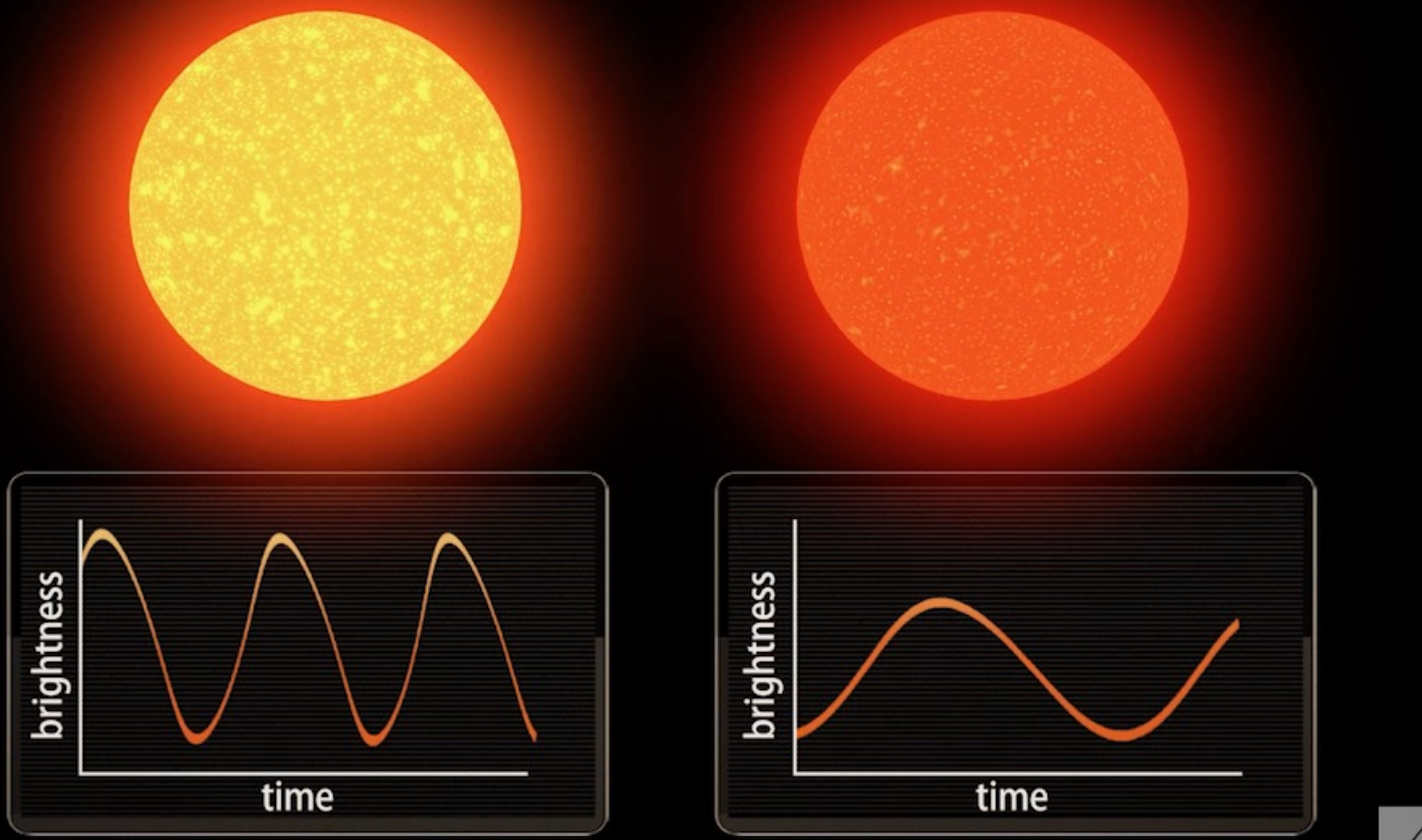
- Needs to have calibrations from known distances.

Cosmic Distance Ladder

73.3
Cosmic
Distance
Ladder



73.3
Cosmic Distance Ladder



CAASTRO
ALL-SKY ASTROPHYSICS

73.3
Cosmic Distance Ladder

Corrected Supernovae Luminosities

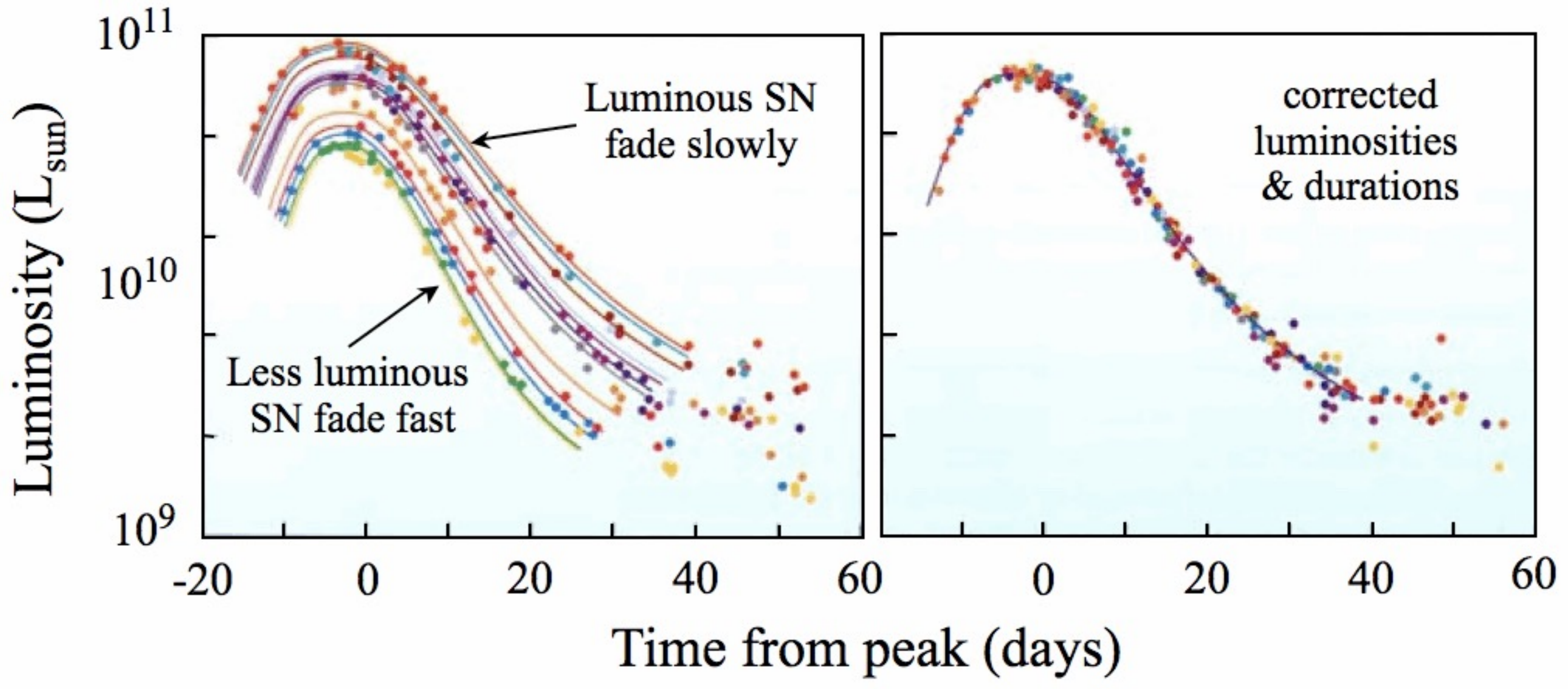
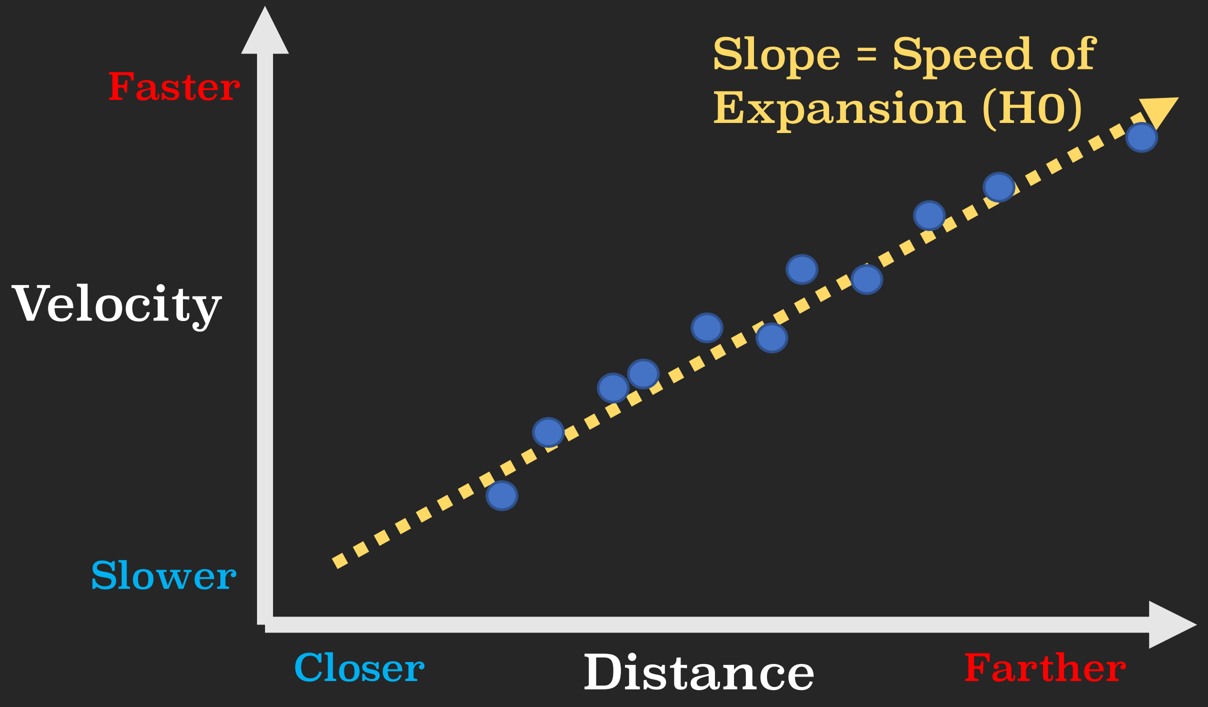


Image Credit: Durham Department of Physics

73.3
Cosmic Distance Ladder

Cosmic Distance Ladder



Distance to the Sun

↓

Parallax

↓

Cepheid Variable Stars

↓

Supernovae

↓

H_0

73.3

Cosmic Distance Ladder

Reiss et al. (2022)

67.7

Cosmic Microwave Background

Planck Collaboration (2020)

Cosmic Microwave Background (CMB)

67.7
Cosmic
Microwave
Background

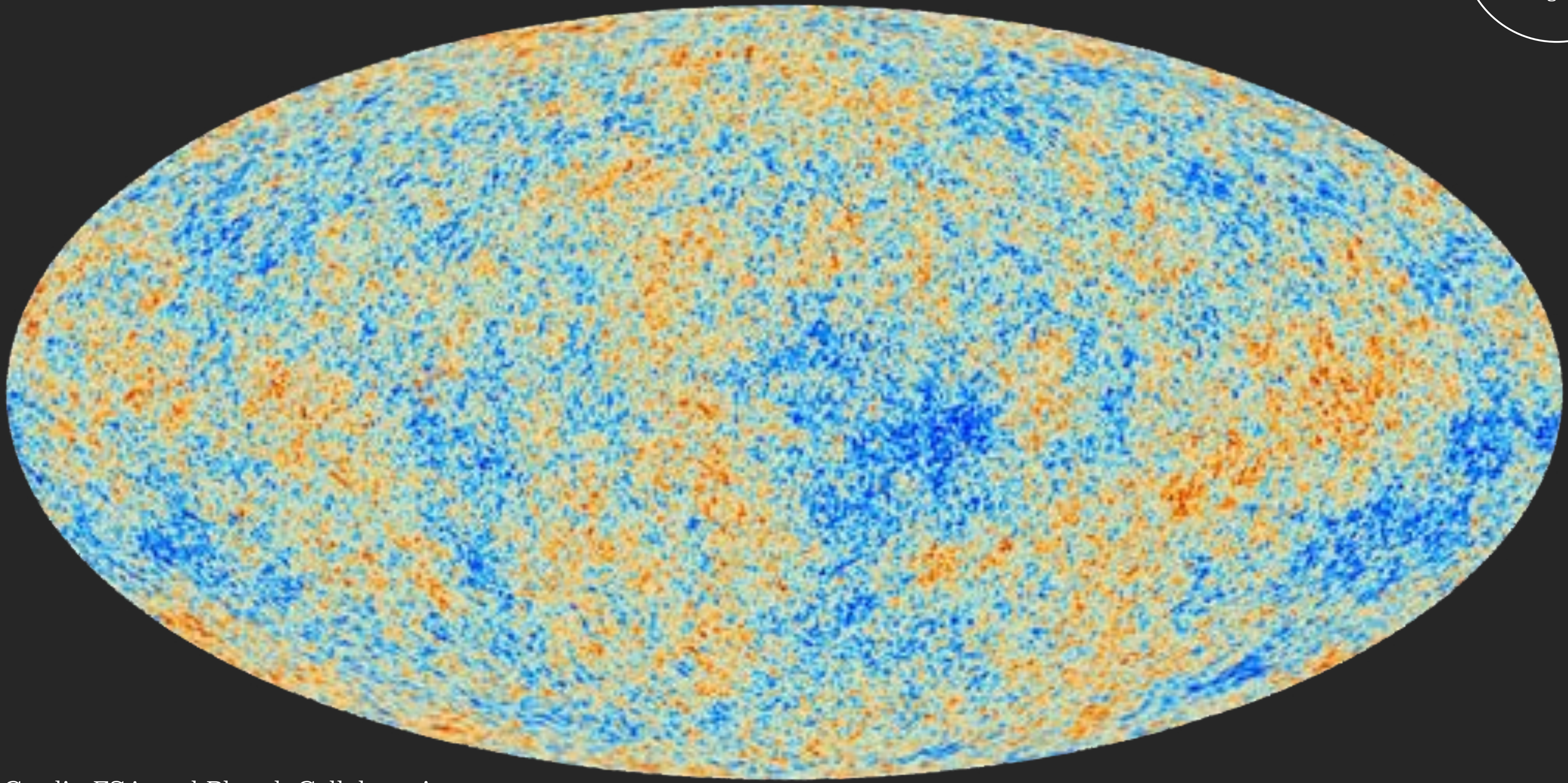
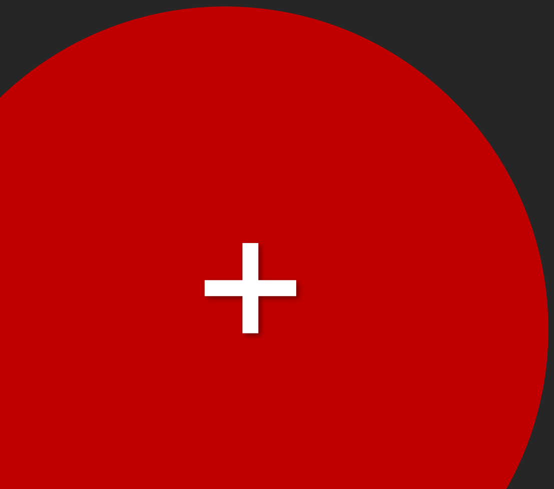
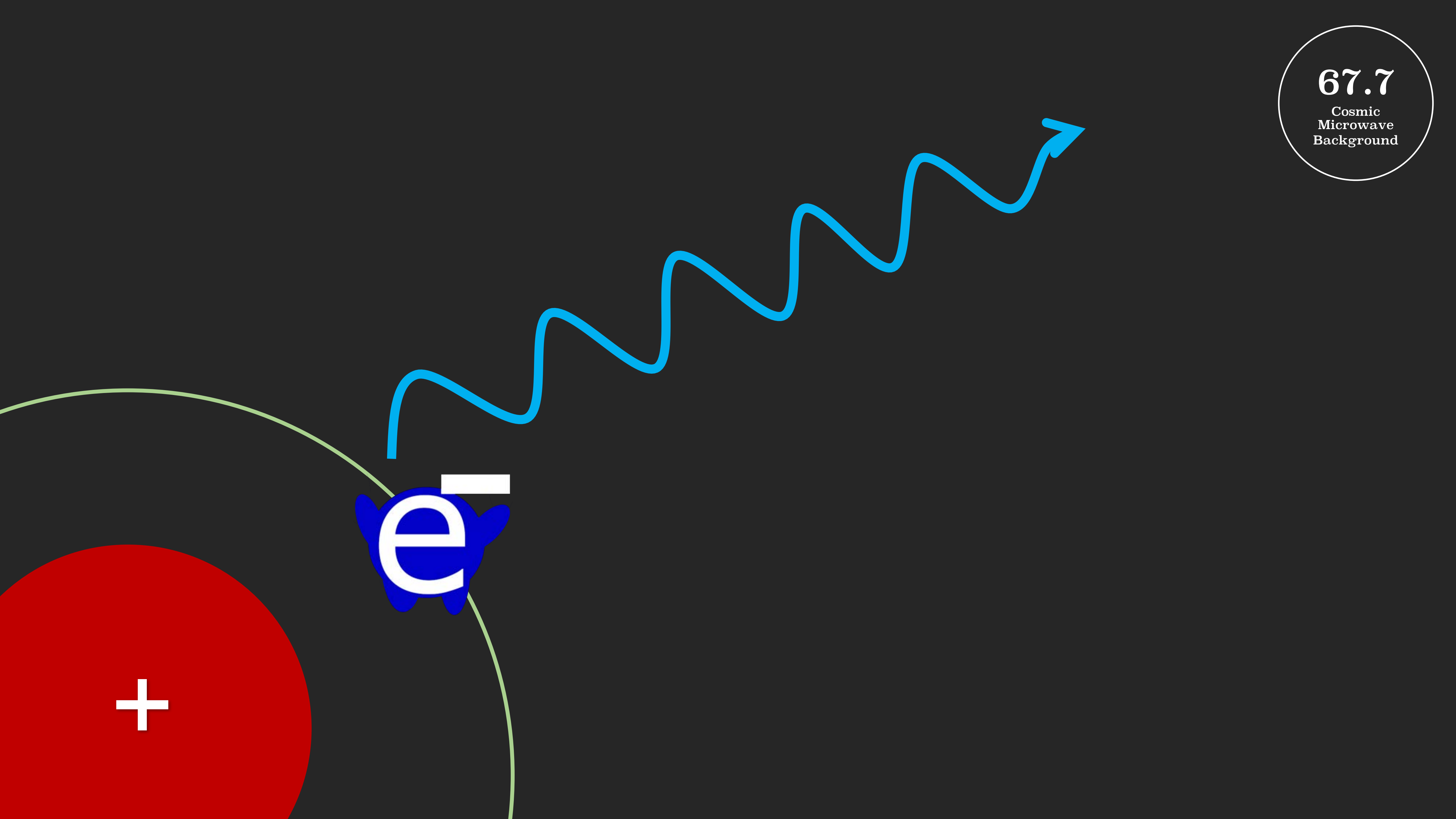


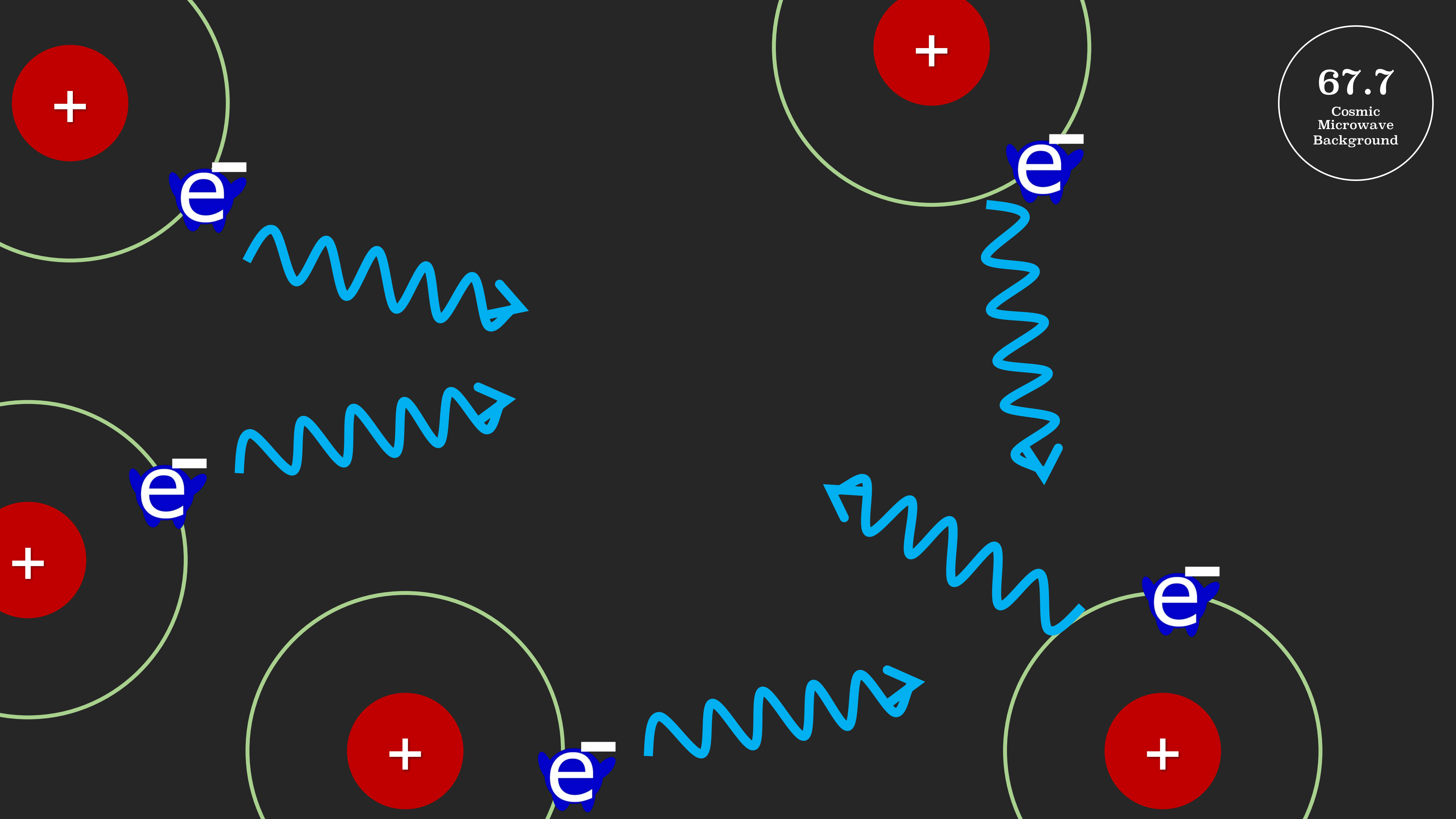
Image Credit: ESA and Planck Collaboration

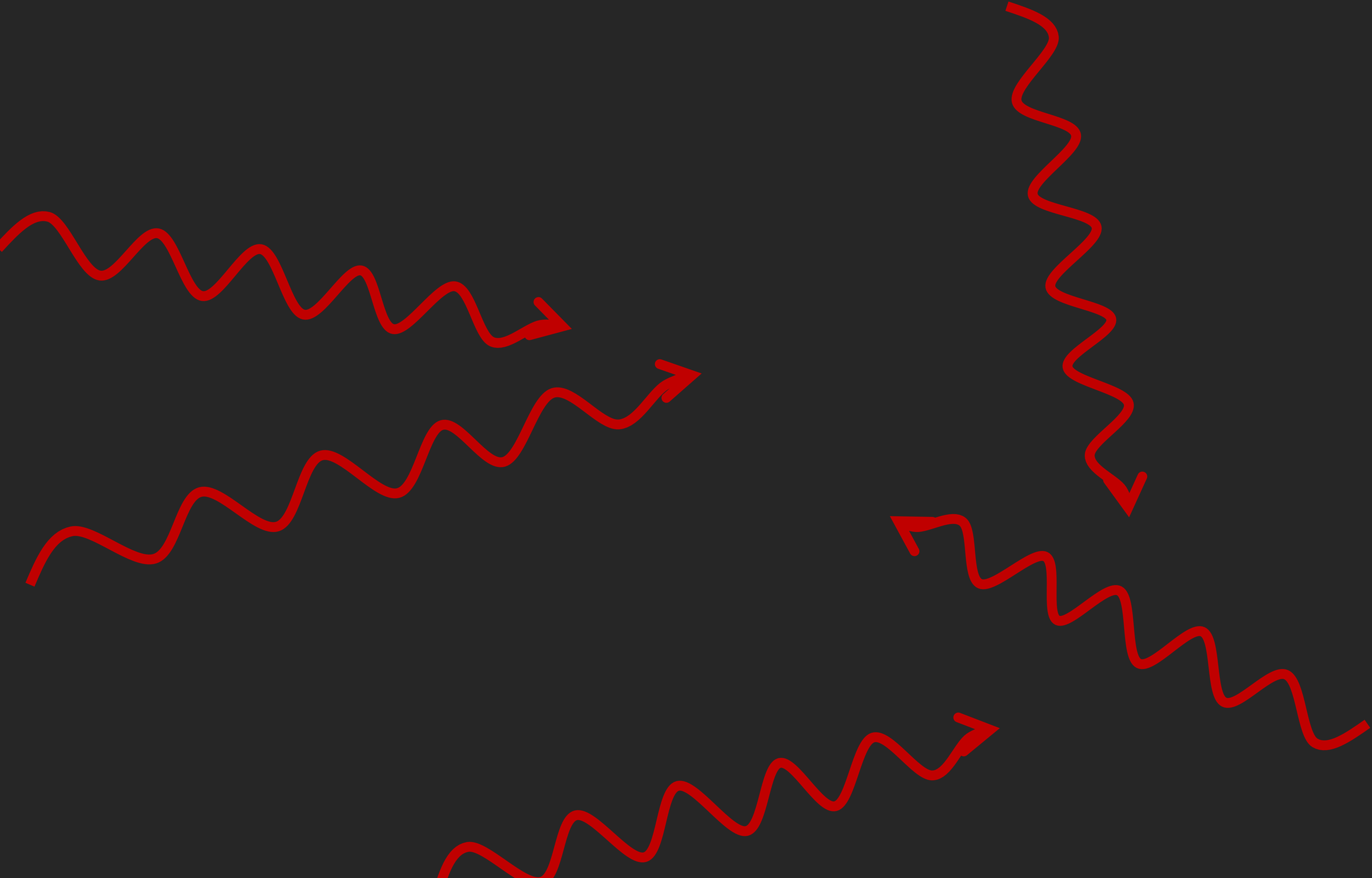
67.7

Cosmic Microwave Background




67.7
Cosmic
Microwave
Background
e⁻
+


67.7
Cosmic
Microwave
Background
+
e−



67.7
Cosmic
Microwave
Background

Cosmic Microwave Background (CMB)

67.7
Cosmic
Microwave
Background

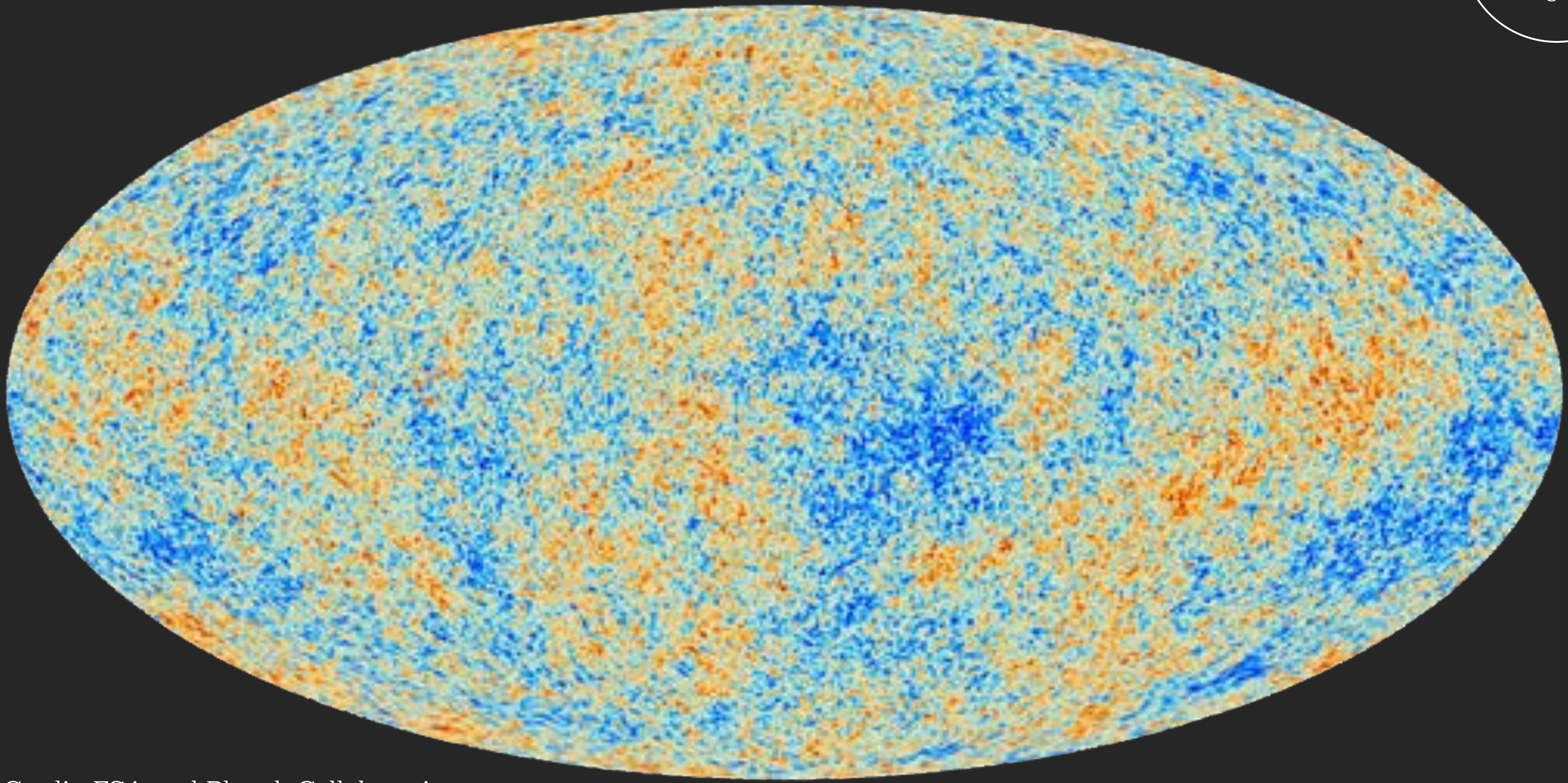


Image Credit: ESA and Planck Collaboration

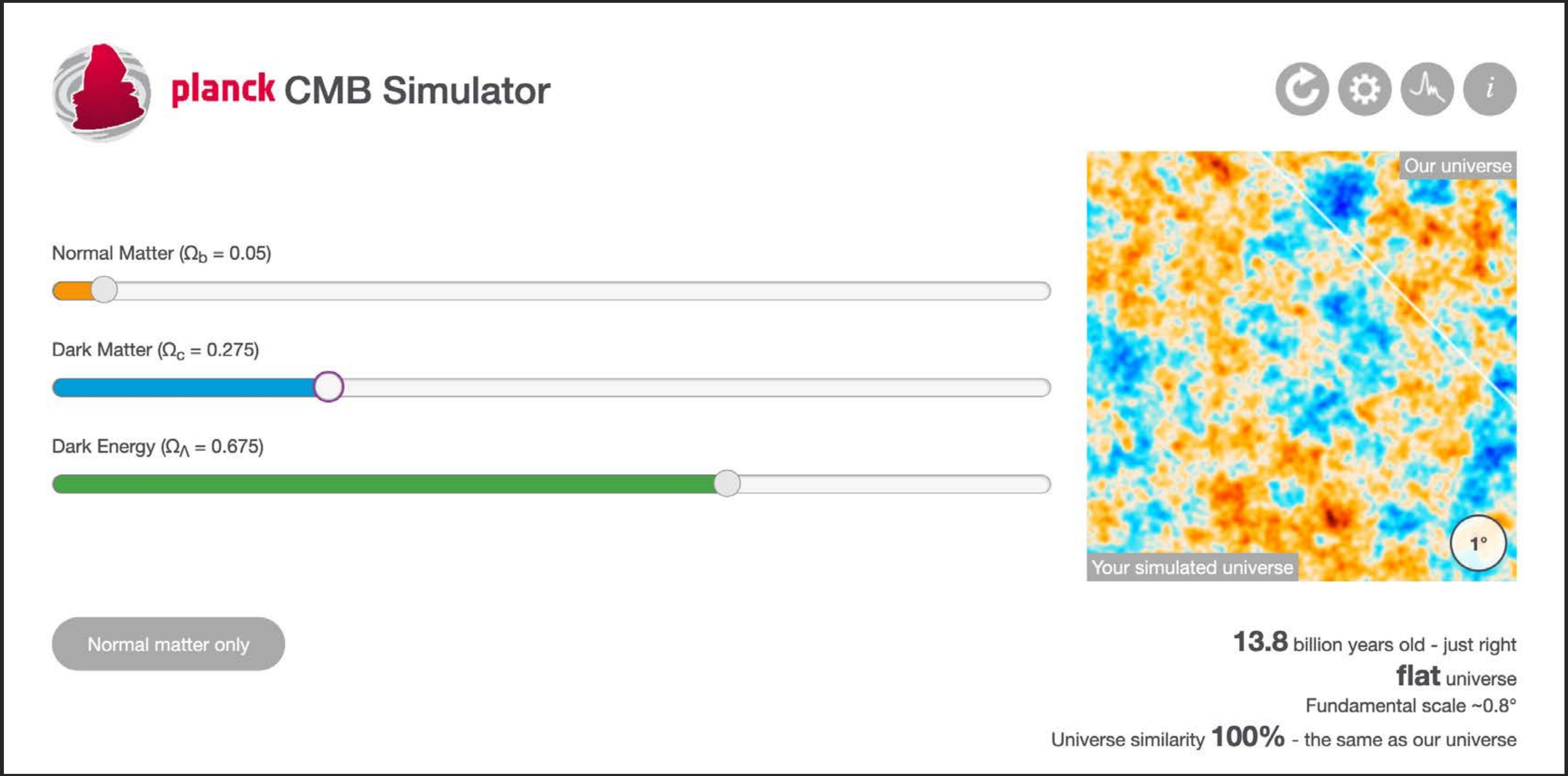
67.7

Cosmic Microwave Background

How does the cosmic microwave background tell you H_0?

https://plancksatellite.org.uk/cmb-sim/

67.7
Cosmic Microwave Background



How does the cosmic microwave background tell you H_0?

67.7
Cosmic
Microwave
Background

Warning: Equation Incoming!

How does the cosmic microwave background tell you H_0?

67.7
Cosmic Microwave Background

$$H_0 = \sqrt{\frac{8\pi G\rho}{3(\Omega_{\Lambda,0} + \Omega_{M,0}a^{-3} + \Omega_{\gamma,0}a^{-4})}}$$

Warning: Equation Incoming!

How does the cosmic microwave background tell you H_0?

67.7
Cosmic
Microwave
Background

$$H_0 = \sqrt{\frac{8\pi G\rho}{3(\Omega_{\Lambda,0} + \Omega_{M,0}a^{-3} + \Omega_{\gamma,0}a^{-4})}}$$

How does the cosmic microwave background tell you H_0?

67.7
Cosmic
Microwave
Background

$$H_0 = \sqrt{\frac{8\pi G\rho}{3(\Omega_{\Lambda,0} + \Omega_{M,0}a^{-3} + \Omega_{\gamma,0}a^{-4})}}$$

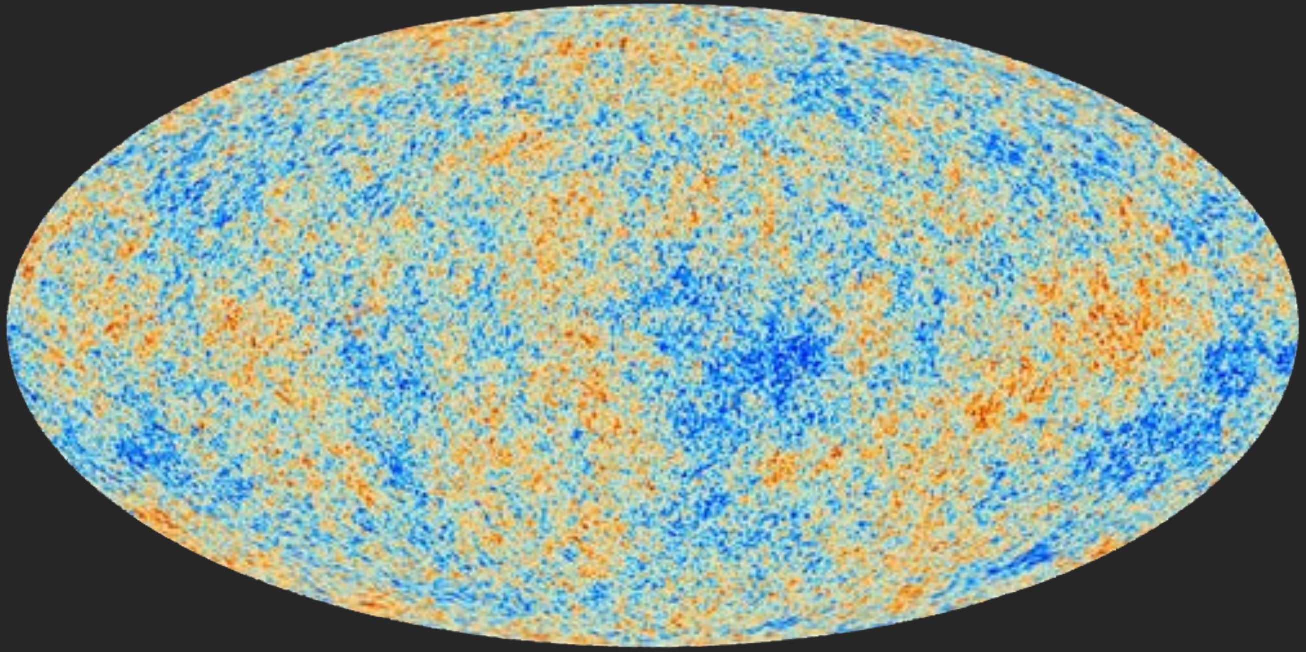
Dark Energy

Matter
(Dark and Regular)

Radiation or
Photons

Cosmic Microwave Background

67.7
Cosmic
Microwave
Background



CMB

↓

Determine properties of the Universe

↓

H0

73.3

Cosmic Distance Ladder

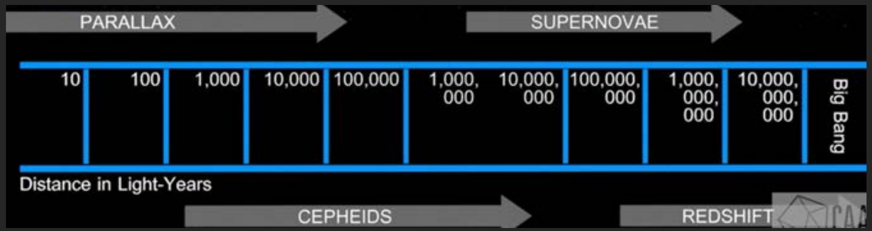
67.7

Cosmic Microwave Background

Reiss et al. (2022)

Planck Collaboration (2020)

73.3
Cosmic Distance Ladder



Distance to the Sun

↓

Parallax

↓

Cepheid Variable Stars

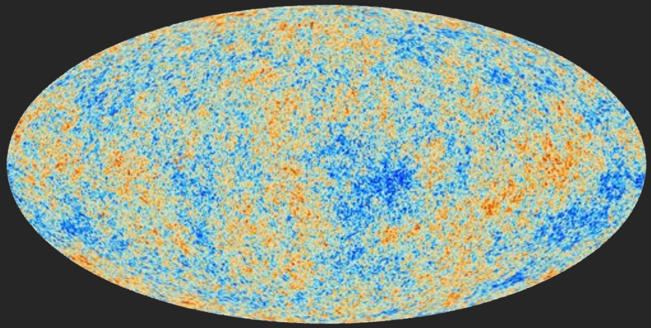
↓

Supernovae

↓

H_0

- Direct measurement of H_0.
- Based on our ability to calibrate each rung of the distance ladder.
- Many rungs in the distance ladder, and small errors can lead to large errors in H_0.



67.7
Cosmic Microwave Background

CMB

↓

Determine properties of the Universe

↓

H_0

- Indirect Measurement of H_0.
- Based on observations and our current model of the Universe.
- This is a model, and models can be wrong or overly simplistic.

Why is this a “crisis”?

73.3
Cosmic Distance Ladder

If the cosmic distance ladder measurement is incorrect:

1. We don't know how to measure distances in the local Universe.

If the CMB measurement is incorrect:

67.7
Cosmic Microwave Background

73.3
Cosmic Distance Ladder

If the cosmic distance ladder measurement is incorrect:

1. We don't know how to measure distances in the local Universe.

2. We also don't know where we are going wrong with out measurements to fix it.

If the CMB measurement is incorrect:

67.7
Cosmic Microwave Background

73.3
Cosmic Distance Ladder

If the cosmic distance ladder measurement is incorrect:

1. We don't know how to measure distances in the local Universe.

2. We also don't know where we are going wrong with out measurements to fix it.

If the CMB measurement is incorrect:

67.7
Cosmic Microwave Background

1. Our understanding of cosmology is wrong.

73.3
Cosmic Distance Ladder

If the cosmic distance ladder measurement is incorrect:

1. We don't know how to measure distances in the local Universe.

2. We also don't know where we are going wrong with out measurements to fix it.

If the CMB measurement is incorrect:

67.7
Cosmic Microwave Background

1. Our understanding of cosmology is wrong.

2. We don't understand what the cosmic microwave background is telling us.

How do we solve this crisis?

How do we solve this crisis?

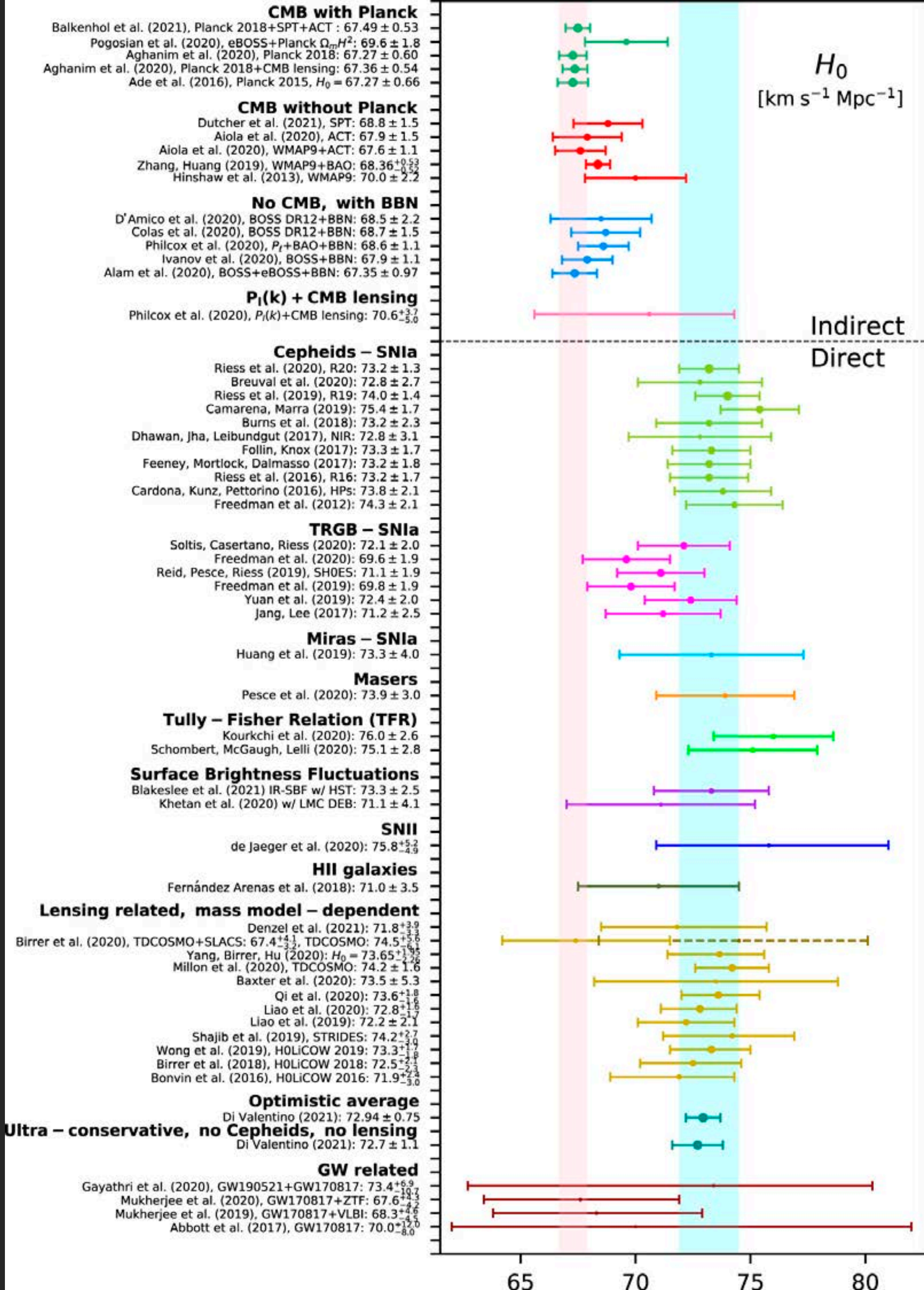


Image Credit: Valentino et al. (2021)

How do we solve this crisis?

I am using this one

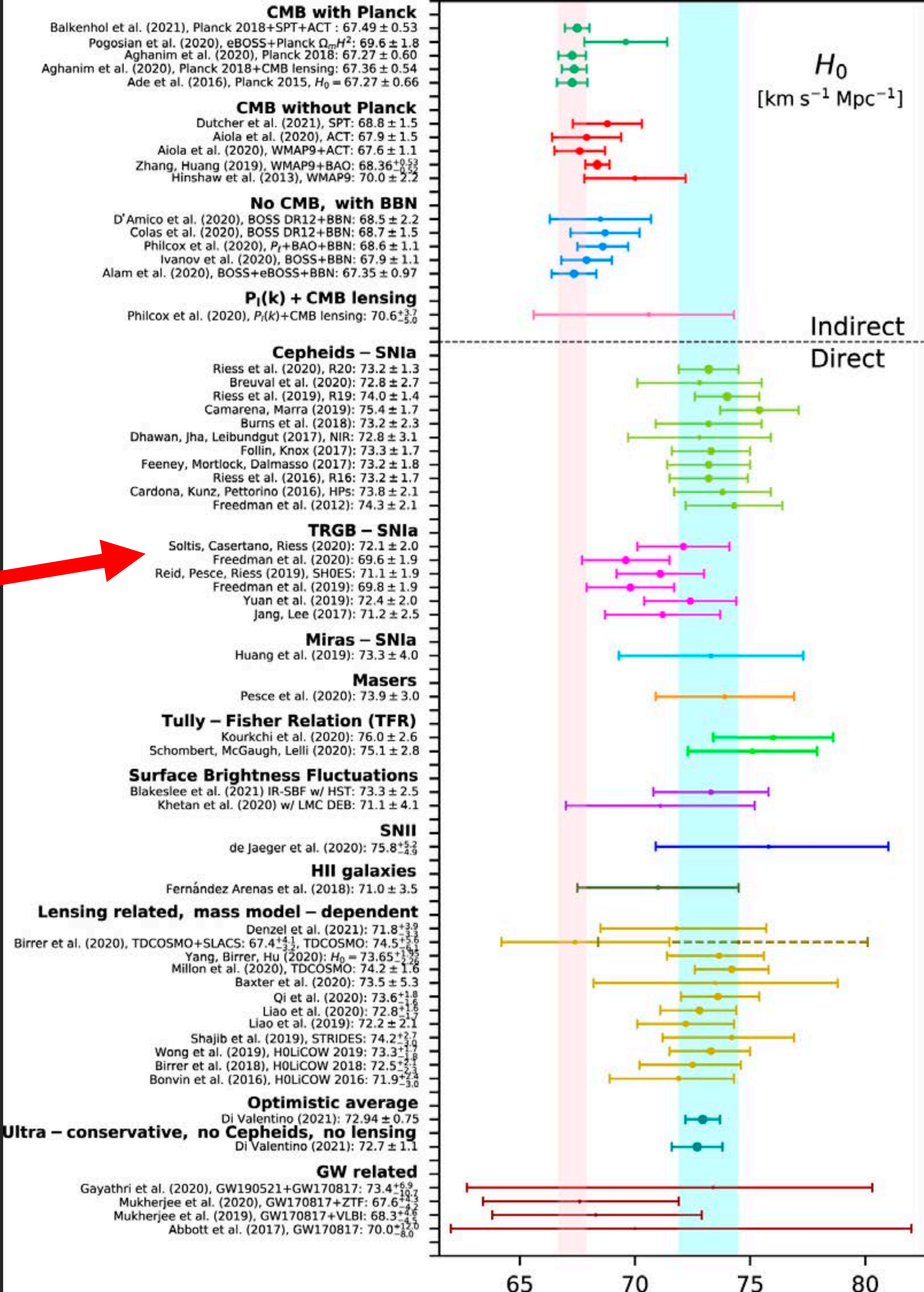


Image Credit: Valentino et al. (2021)

How do we solve this crisis?

I am using this one

"Tip of the Red Giant Branch Stars"

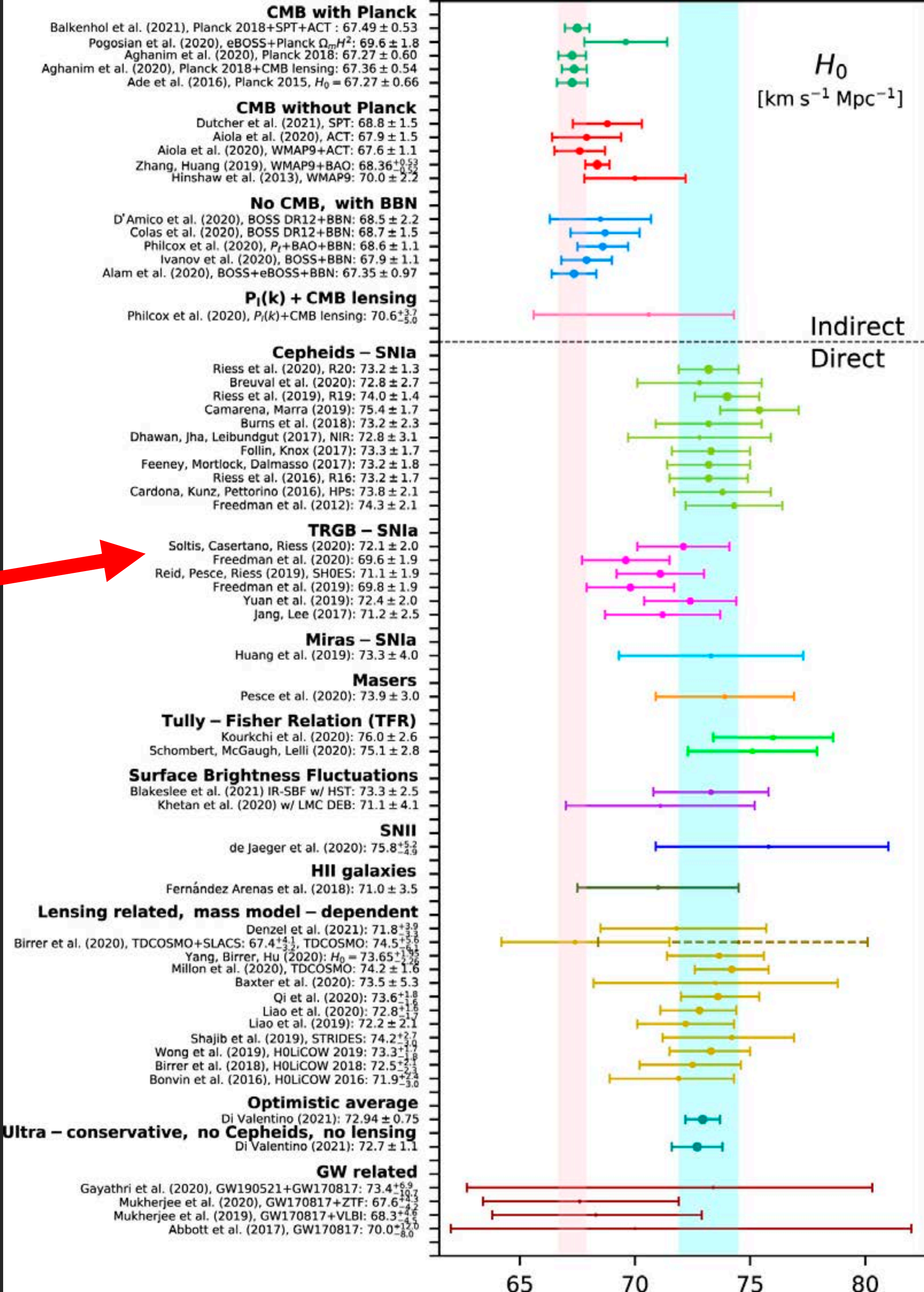


Image Credit: Valentino et al. (2021)

How far away is this galaxy?

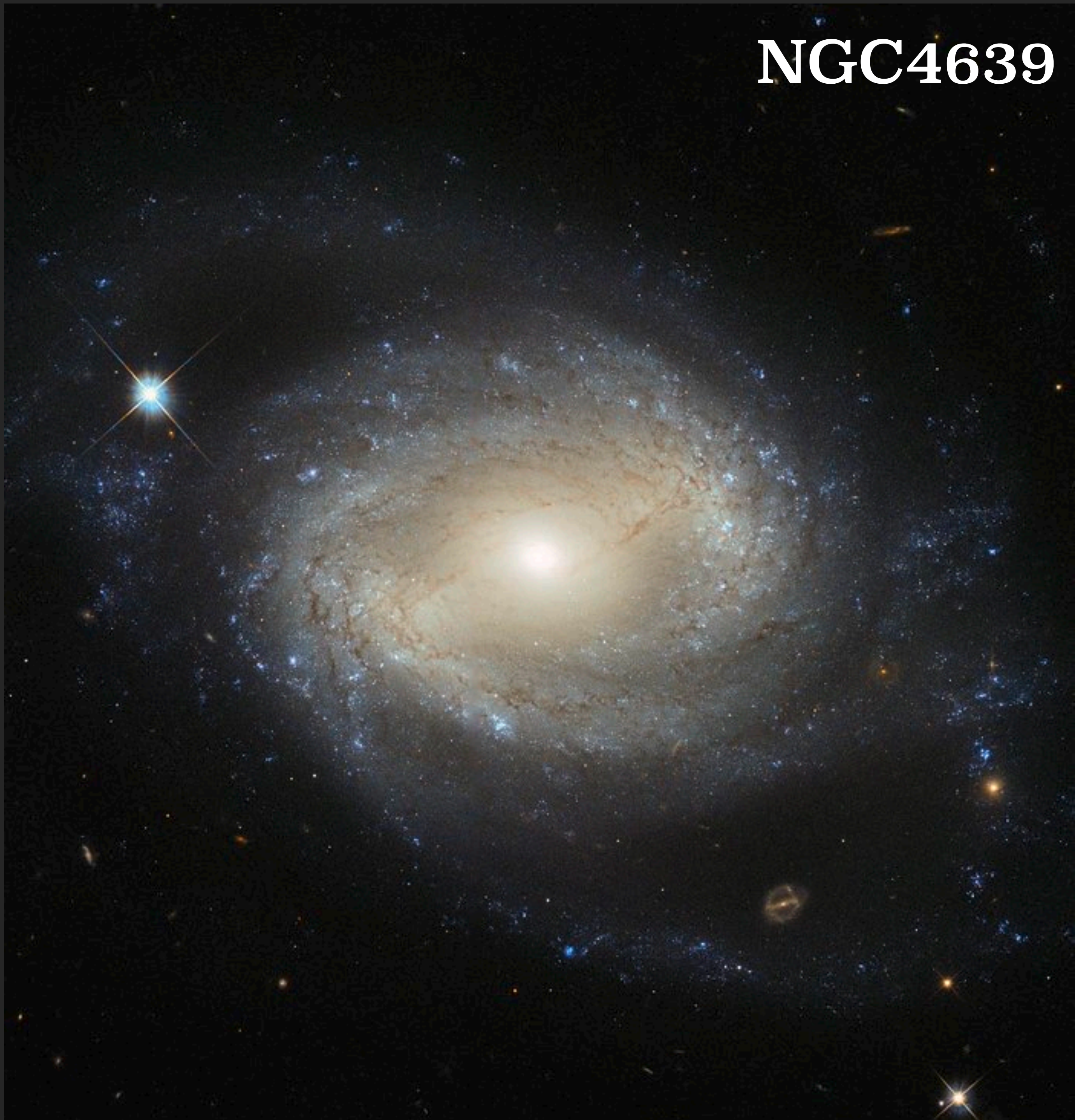


Image Credit: ESA/Hubble & NASA

73.3
Cosmic Distance Ladder

Bluer Stars

How far away is this galaxy?

Redder Stars

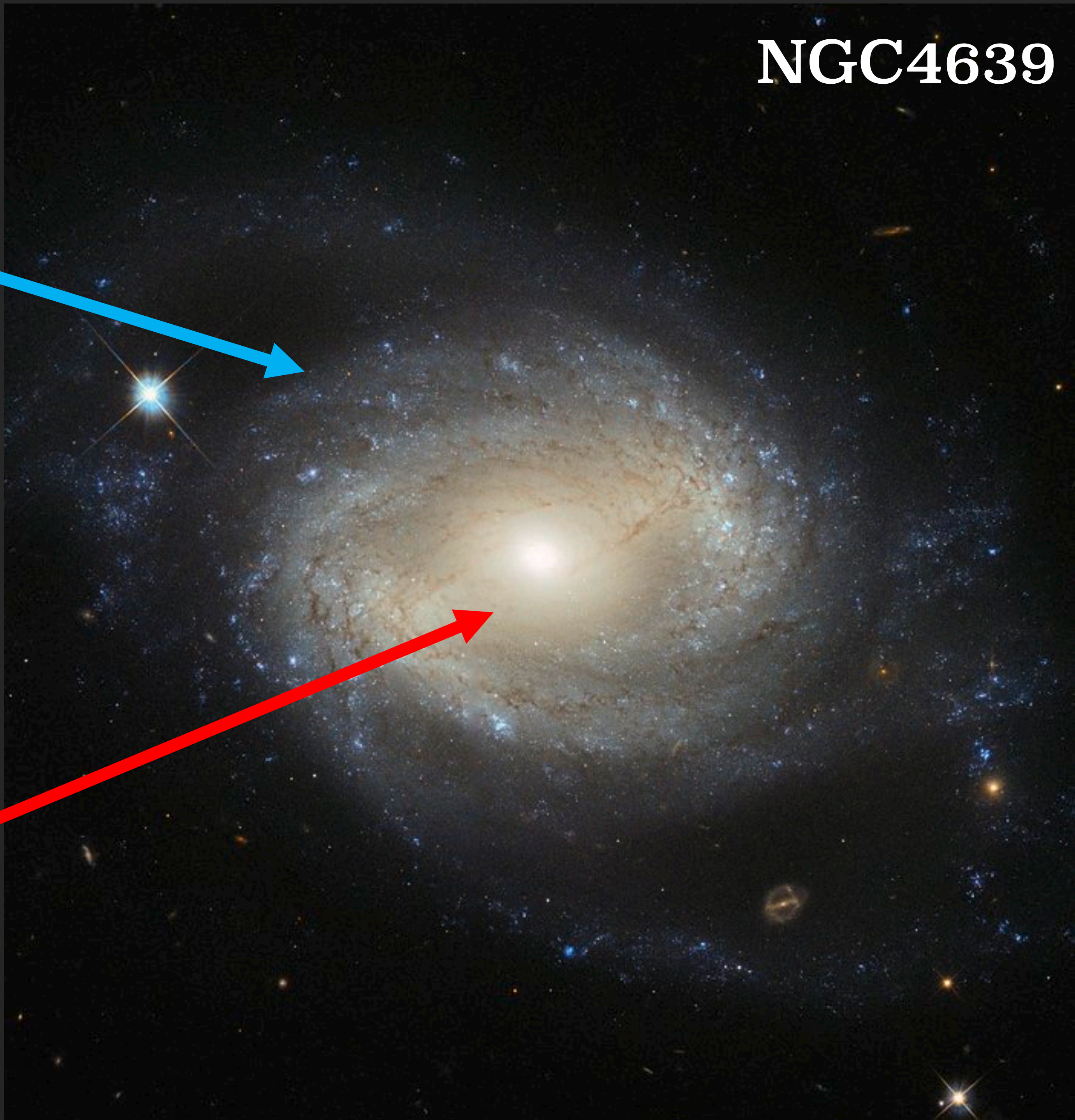
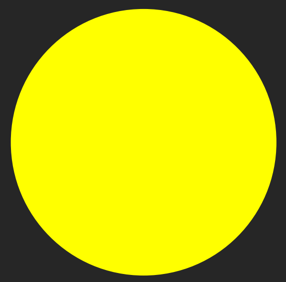
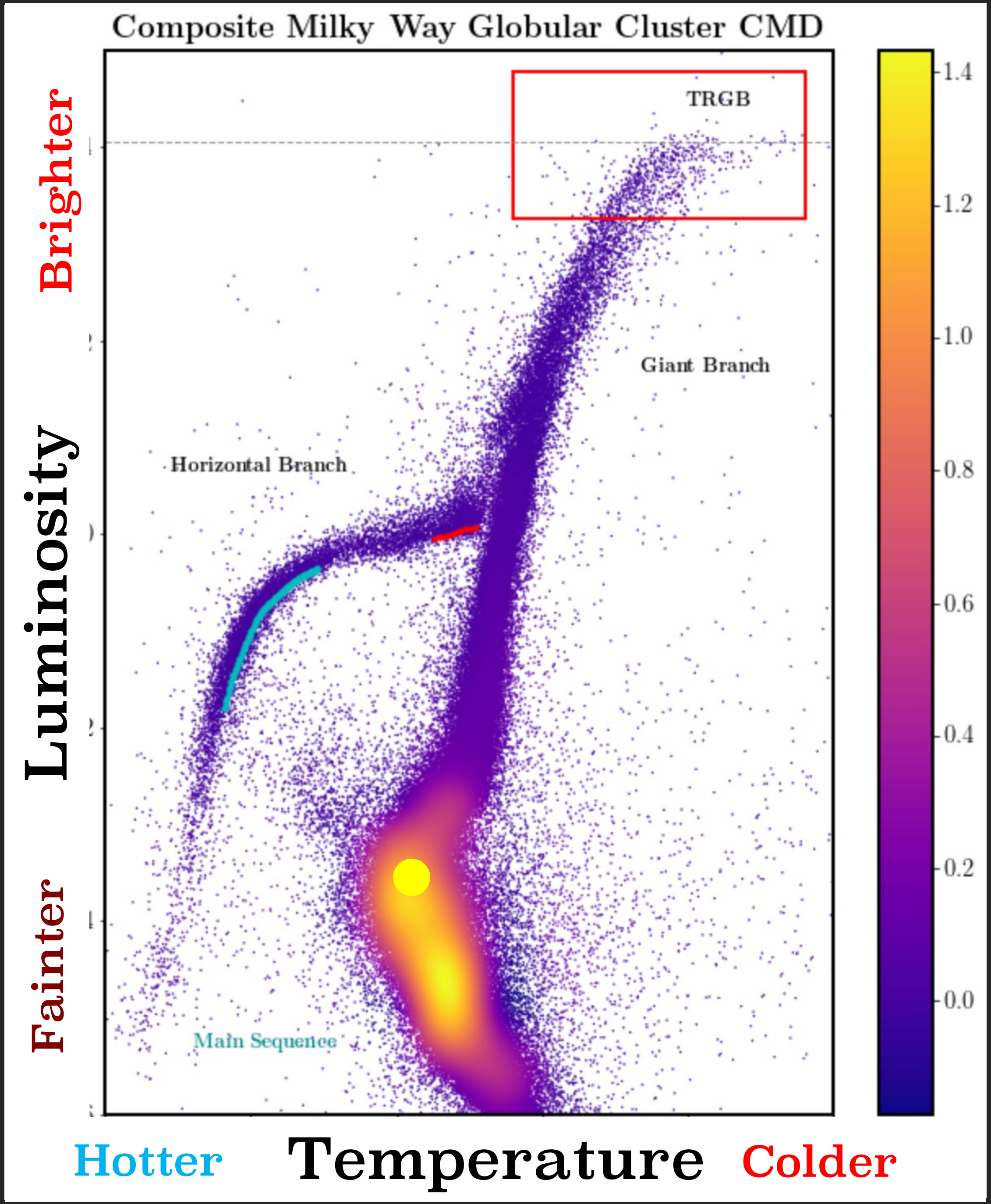


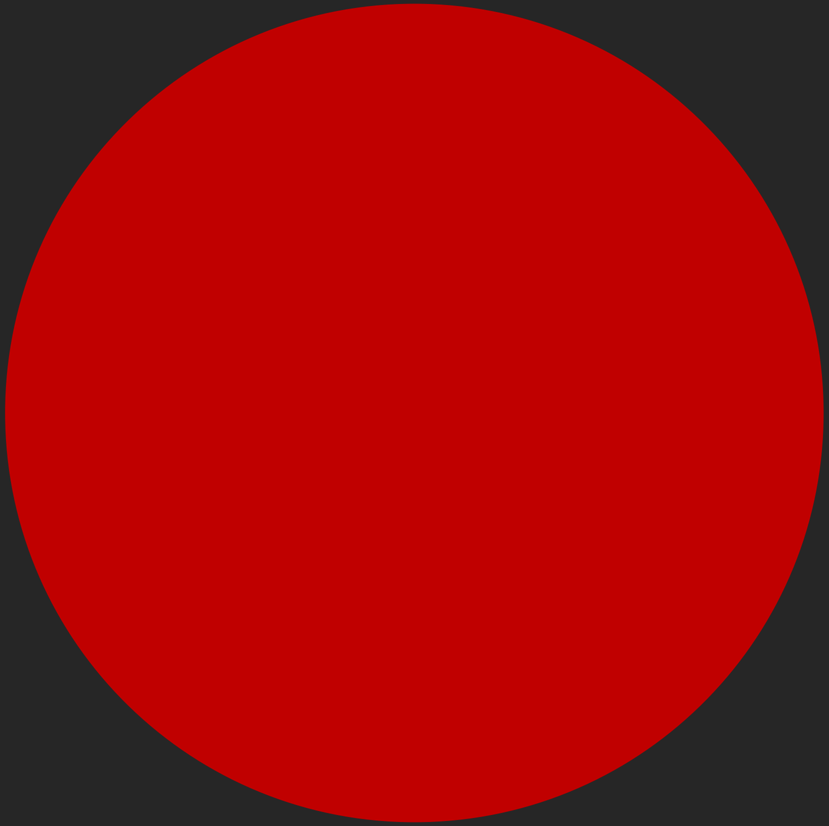
Image Credit: ESA/Hubble & NASA





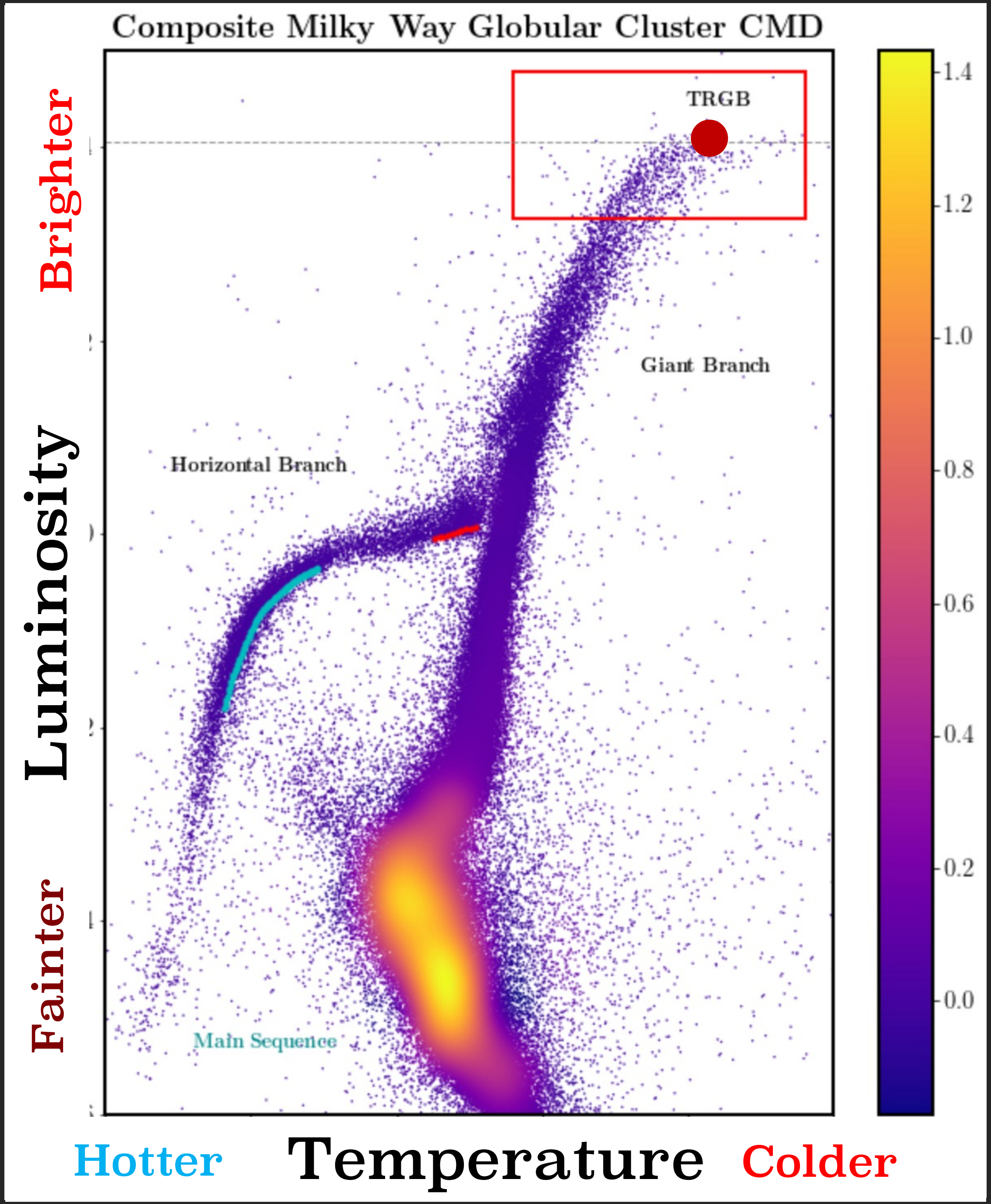
Main Sequence Star

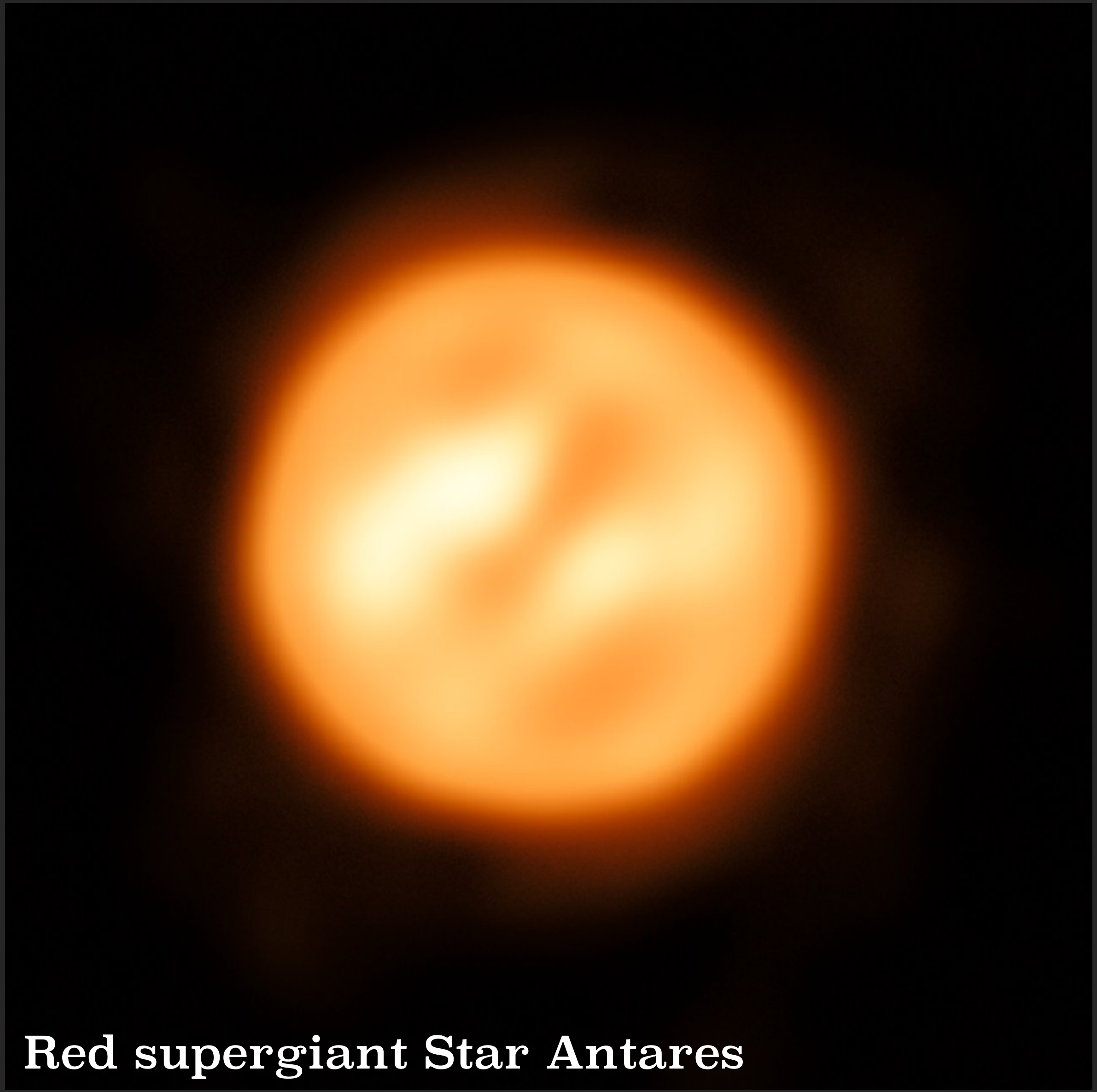
Image Credit: Freedman (2021)



Tip of the Red Giant Branch Star

Image Credit: Freedman (2021)





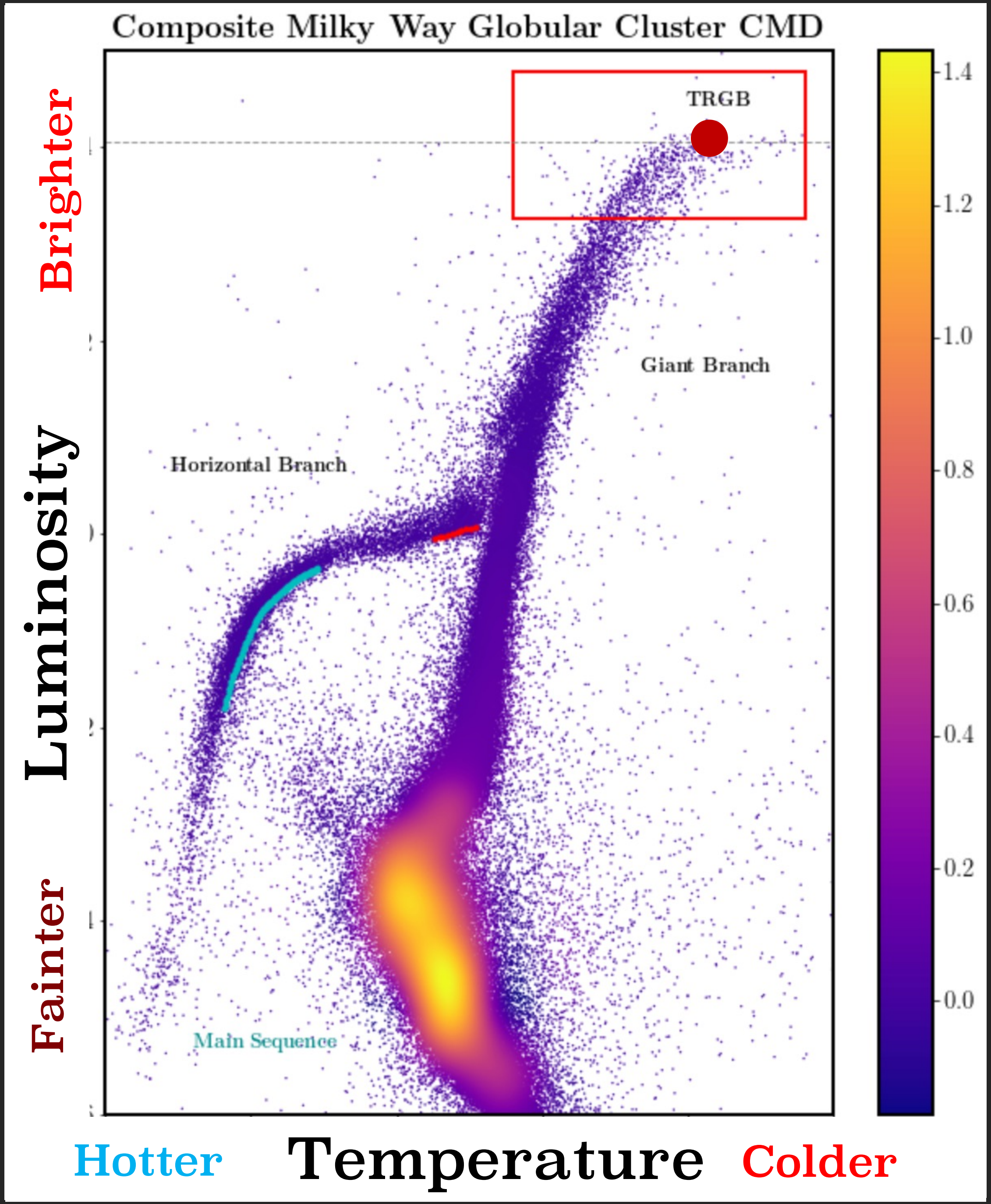


Image Credit: Freedman (2021) & NASA/ESO

We can find tip of the Red Giant Branch stars in the outskirts of nearby galaxies.

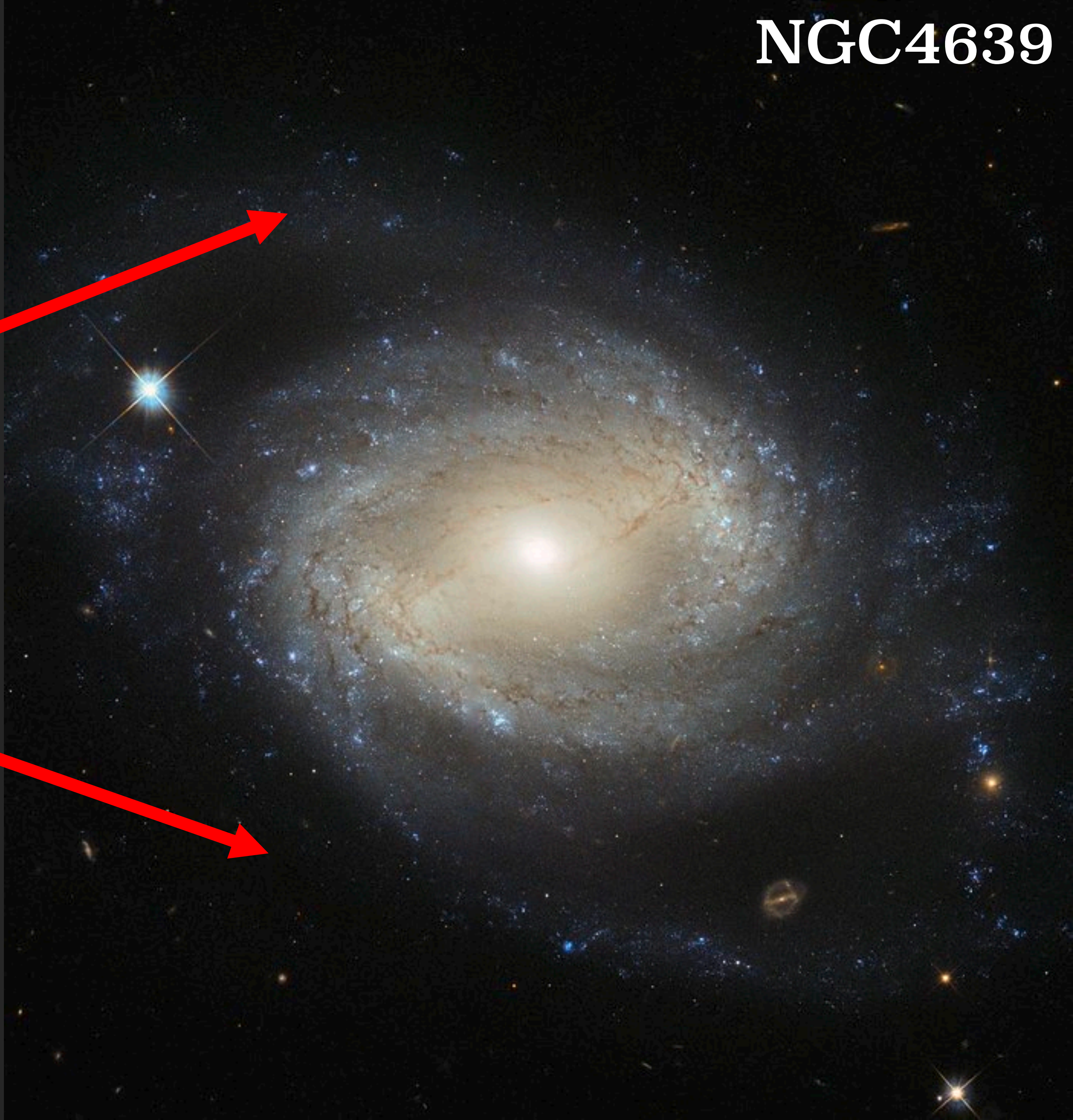
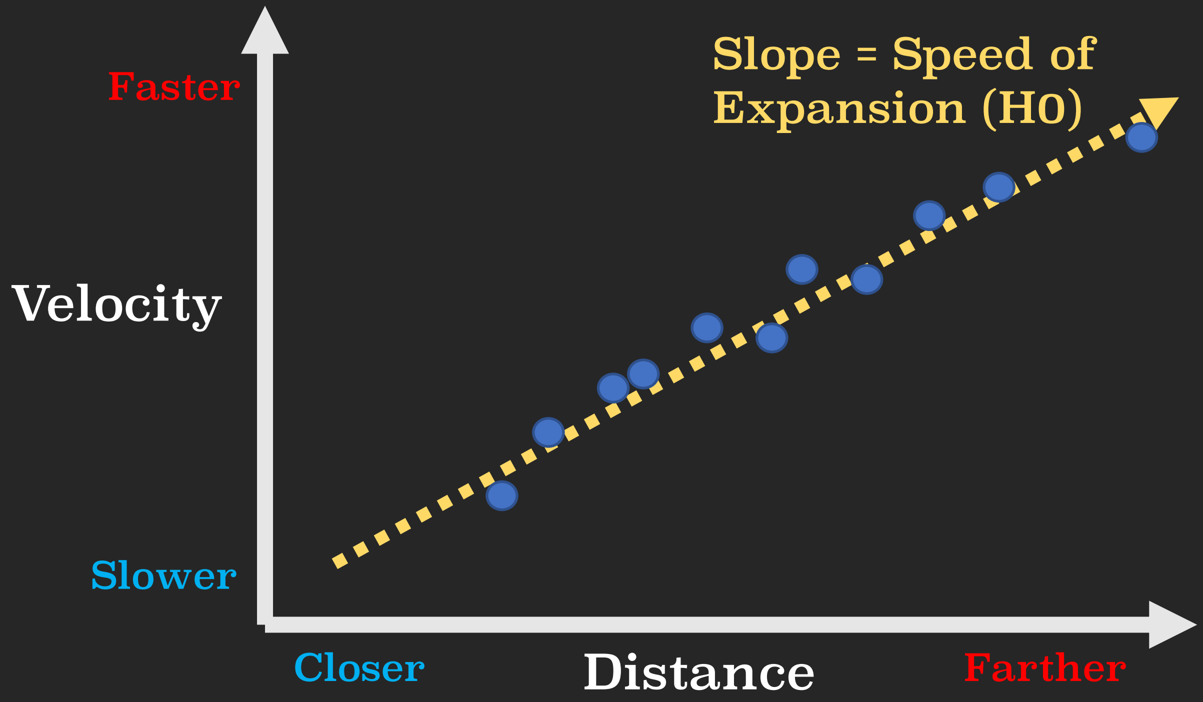


Image Credit: ESA/Hubble & NASA

73.3
Cosmic
Distance
Ladder

Cosmic Distance Ladder



Distance to the Sun

↓

Parallax

↓

Cepheid Variable
Stars

↓

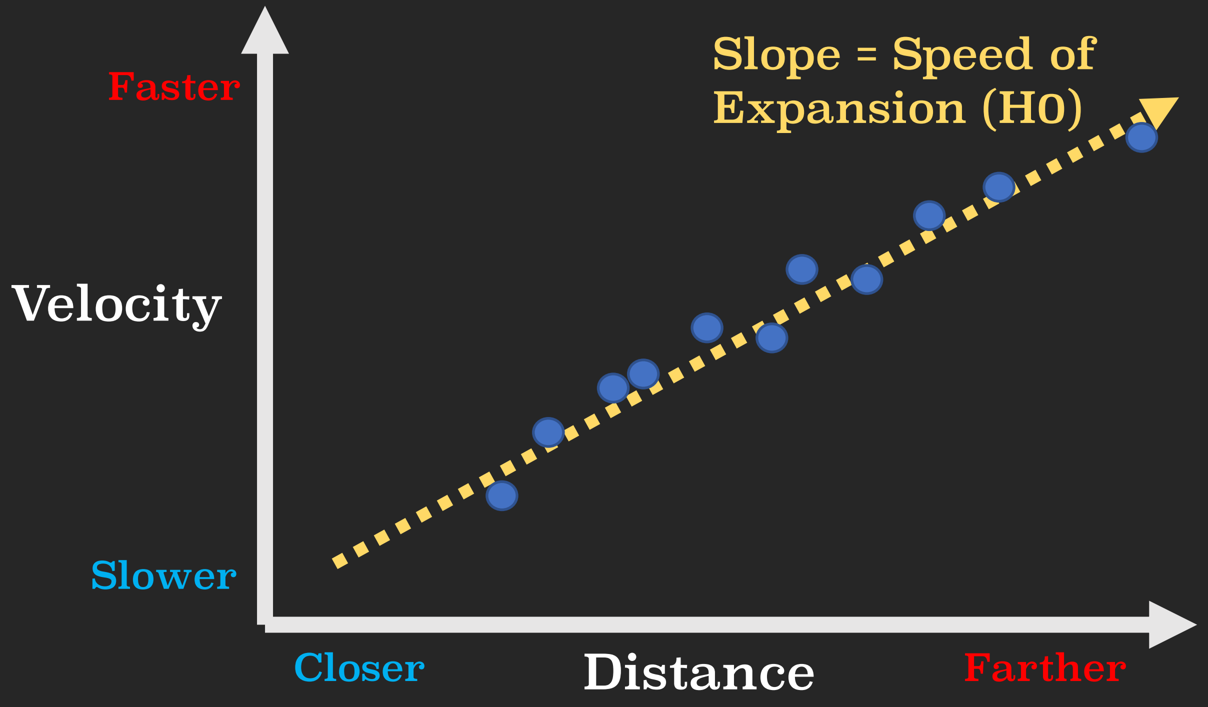
Supernovae

↓

H_0

73.3 Cosmic Distance Ladder

Cosmic Distance Ladder



Distance to the Sun

↓

Parallax

↓

~~Cepheid Variable Stars~~

↓

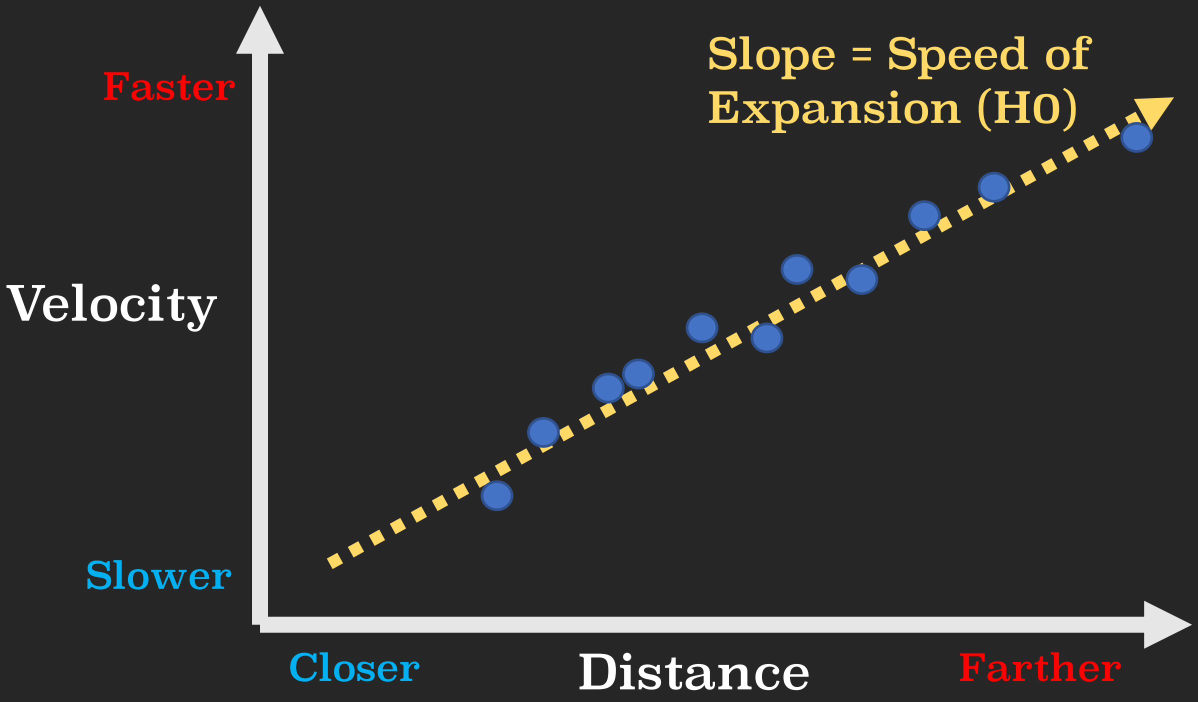
Supernovae

↓

H_0

73.3
Cosmic
Distance
Ladder

Cosmic Distance Ladder



Distance to the Sun

↓

Parallax

↓

Tip of the Red
Giant Branch Stars

↓

Supernovae

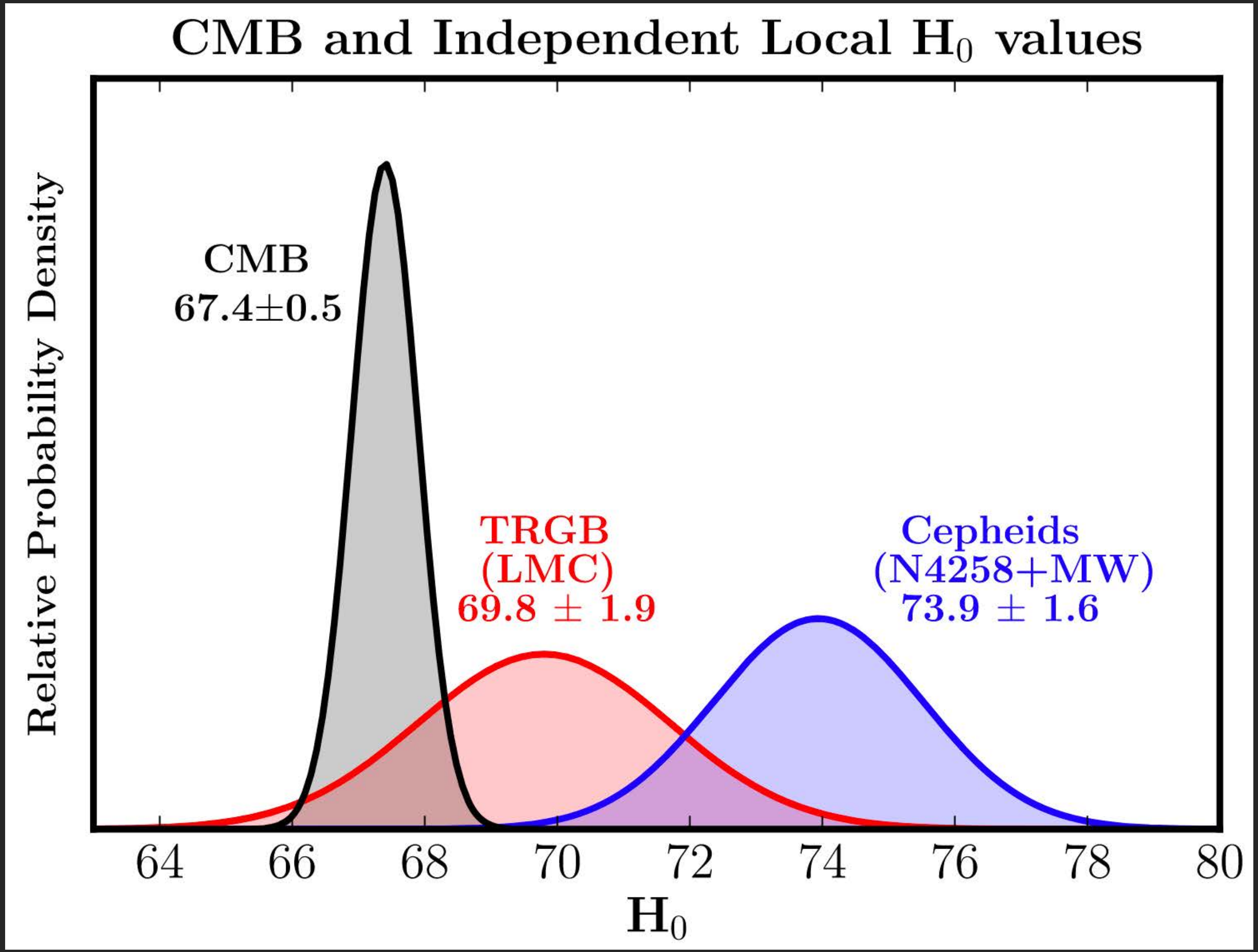
↓

H_0

69.8

Tip of the Red Giant Branch

Cosmic Distance Ladder (TRGB)



Distance to the Sun

Parallax

Tip of the Red Giant Branch Stars

Supernovae

H_0

Image Credit: Freedman et al. (2019)

Summary

Twitter: @adamjbatten

Slides: https://adambatten.com/talks/

- The Universe is expanding!

- The two main methods for measuring the rate of expansion of the Universe (H_0) are in tension.

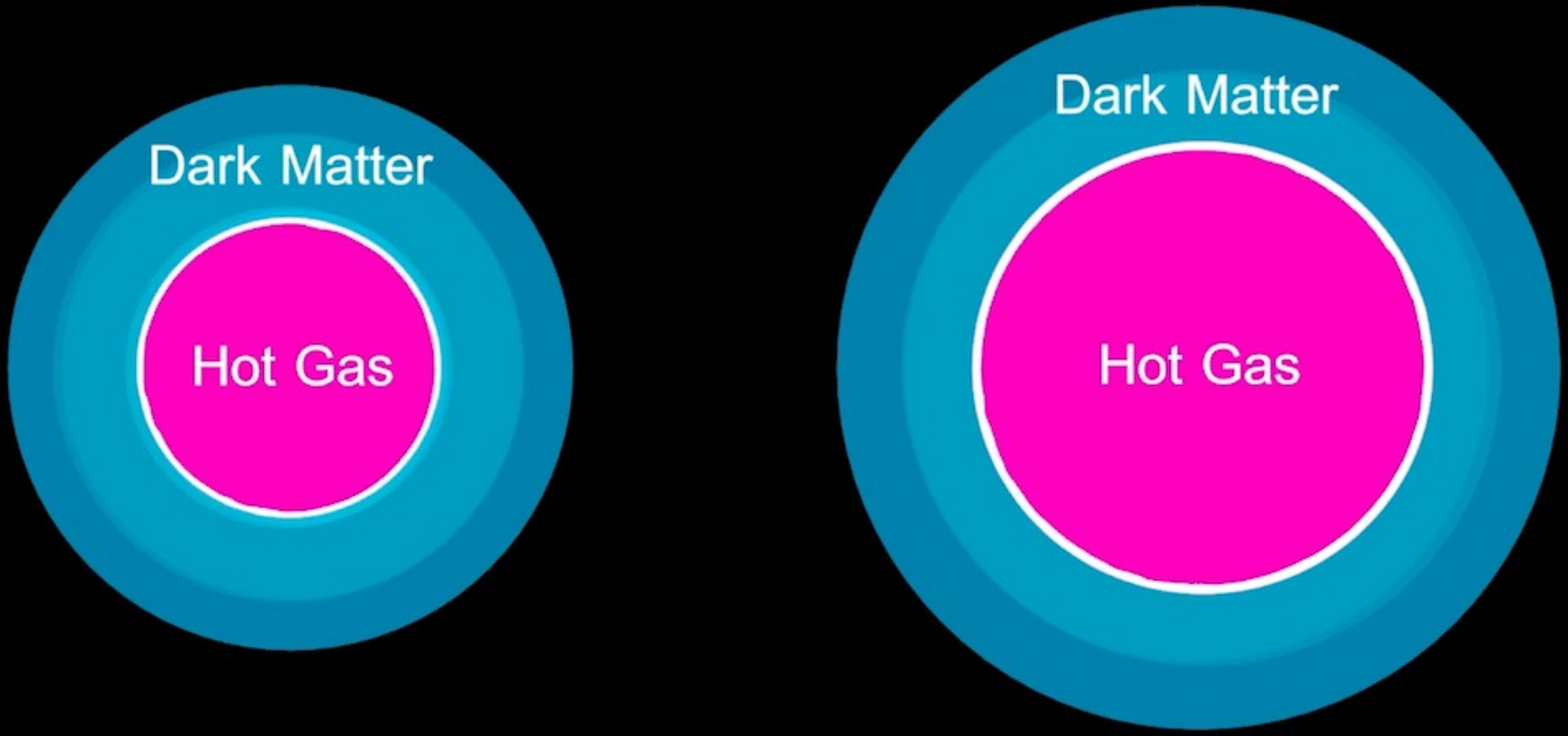
- The cosmic distance ladder: **73.3 km/s/Mpc**.
  - Distance to the Sun -> Parallax
  - Parallax -> Cepheid Variables
  - Cepheid Variables -> Supernovae
  - Supernovae -> H_0

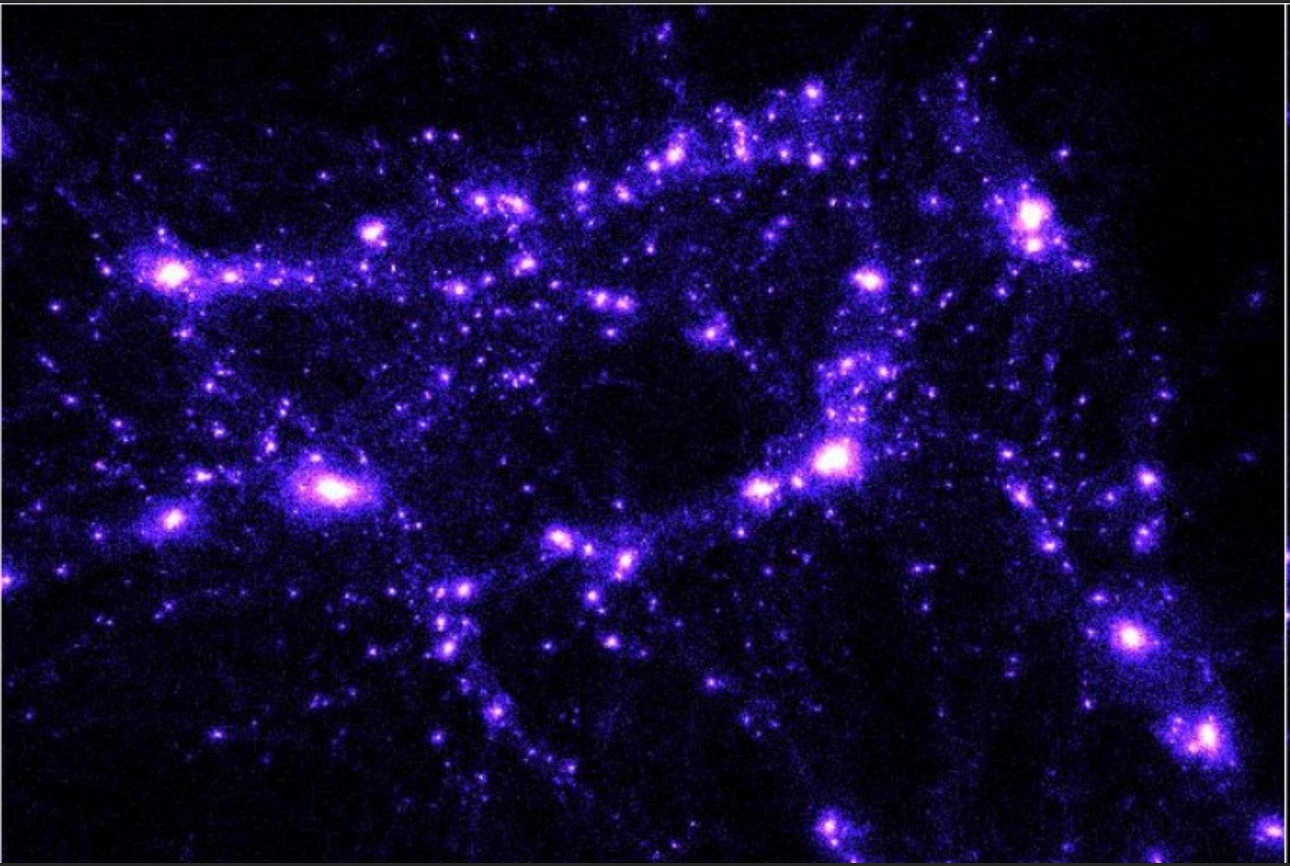
- Cosmic microwave background: **67.7 km/s/Mpc**.
  - Determines the amount of matter, dark matter, dark energy and radiation in the Universe.
  - Uses these quantities to calculate H_0.

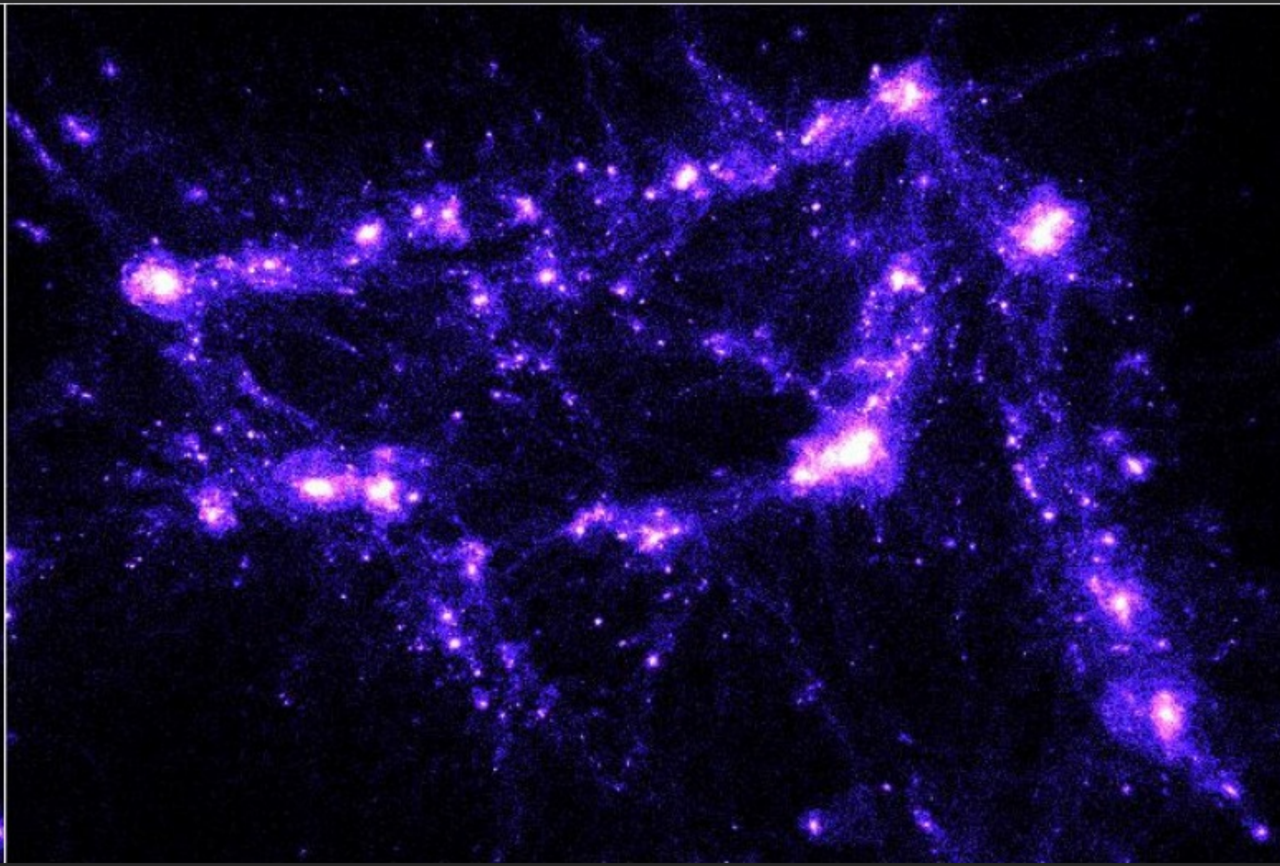
- I am using stars at the tip of the red giant branch to recalibrate supernovae for the cosmic distance ladder.

BONUS SLIDES!


The Bullet Cluster
CAASTRO
ALL-SKY ASTROPHYSICS


Dark Matter
Hot Gas
Dark Matter
Hot Gas





Dark Matter + Dark Energy

Modified Newtonian Dynamics