What is Cosmology?

A. A branch of trigonometry that focuses on the “**Cosine**”

B. The study of **cosmetics**

C. The study of the **cosmos**

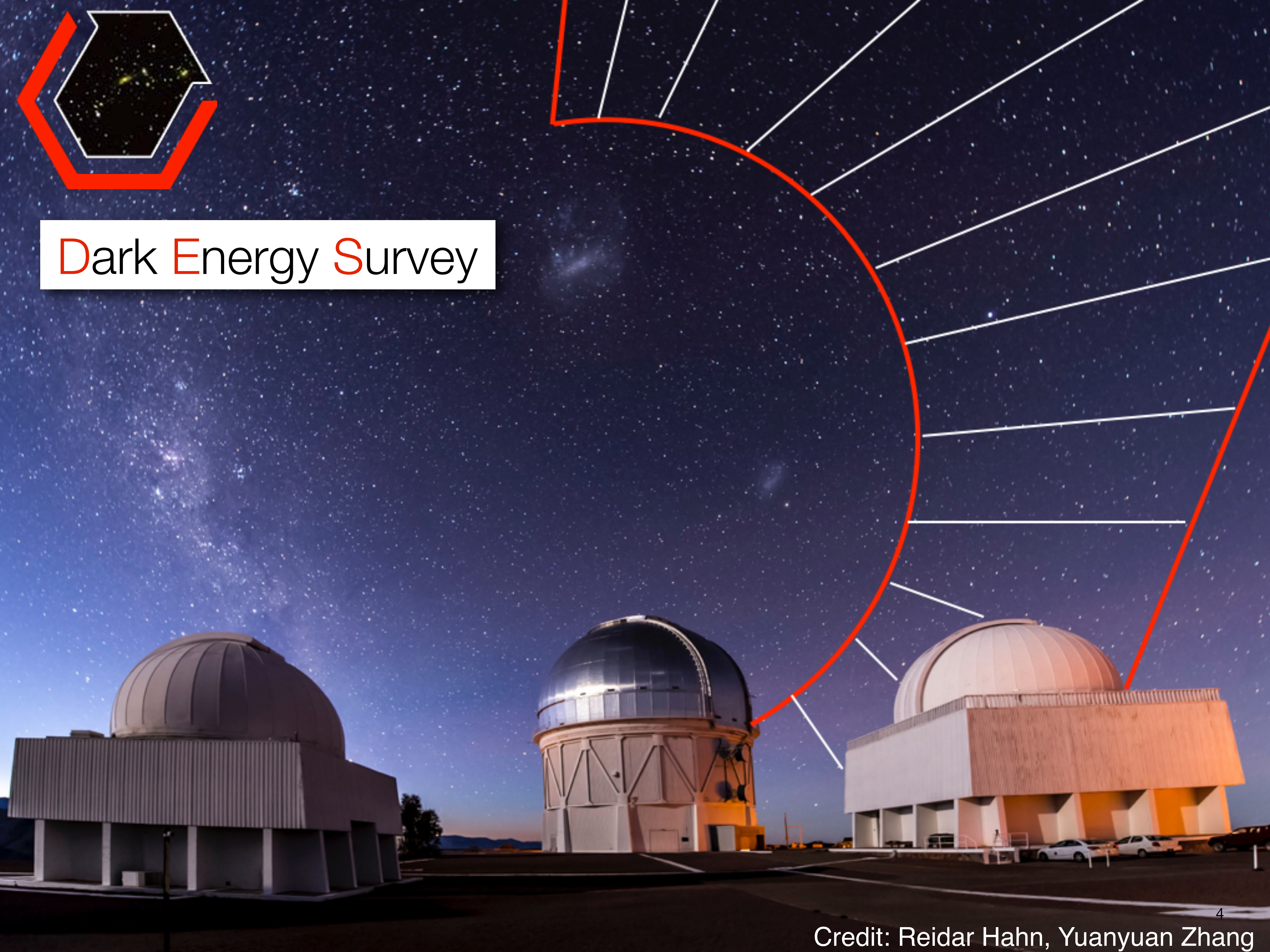
D. The study of Soviet-era **Cosmonauts**

What is Cosmology?

The origin, evolution, and ultimate fate of the Universe

About myself

- Ting Li
- PhD in Physics in 2016 from Texas A&M University
- Joined Fermilab as a Postdoctoral Fellow
- Observational Cosmologist/Astrophysicist
- Working on Dark Energy Survey Experiment

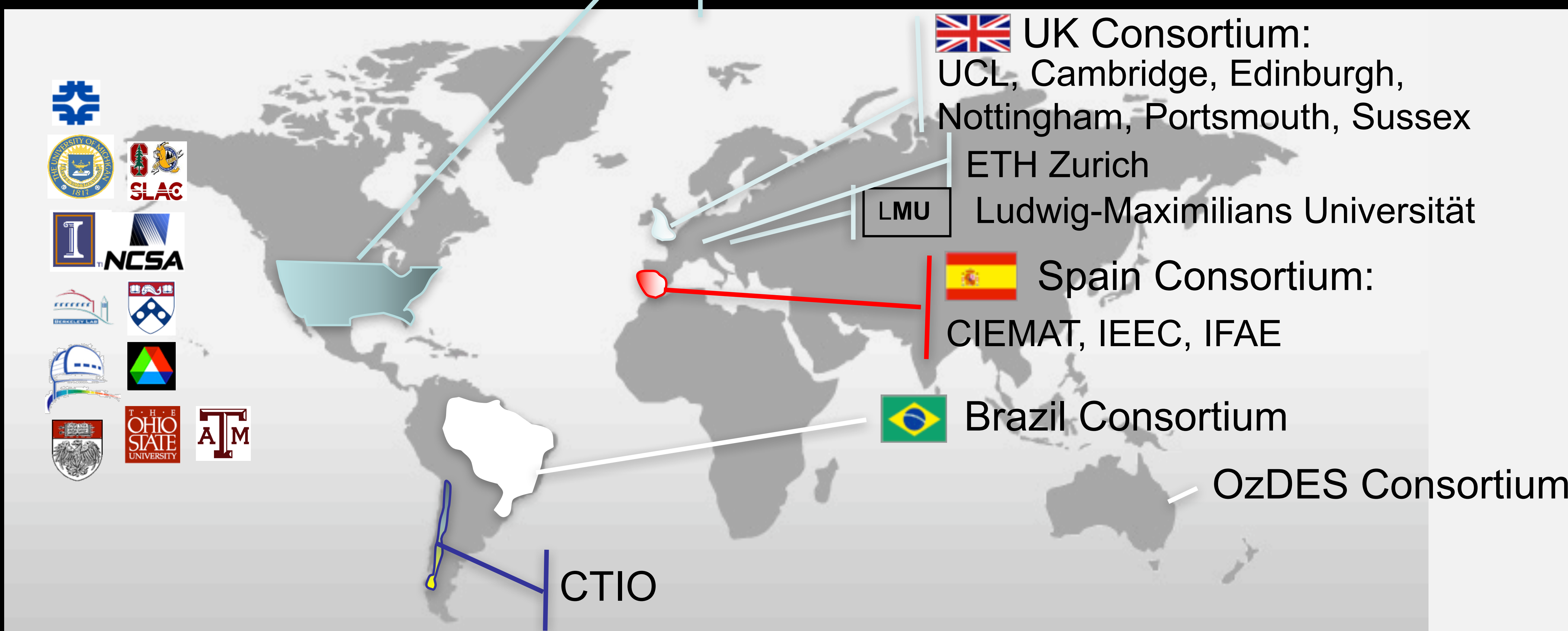


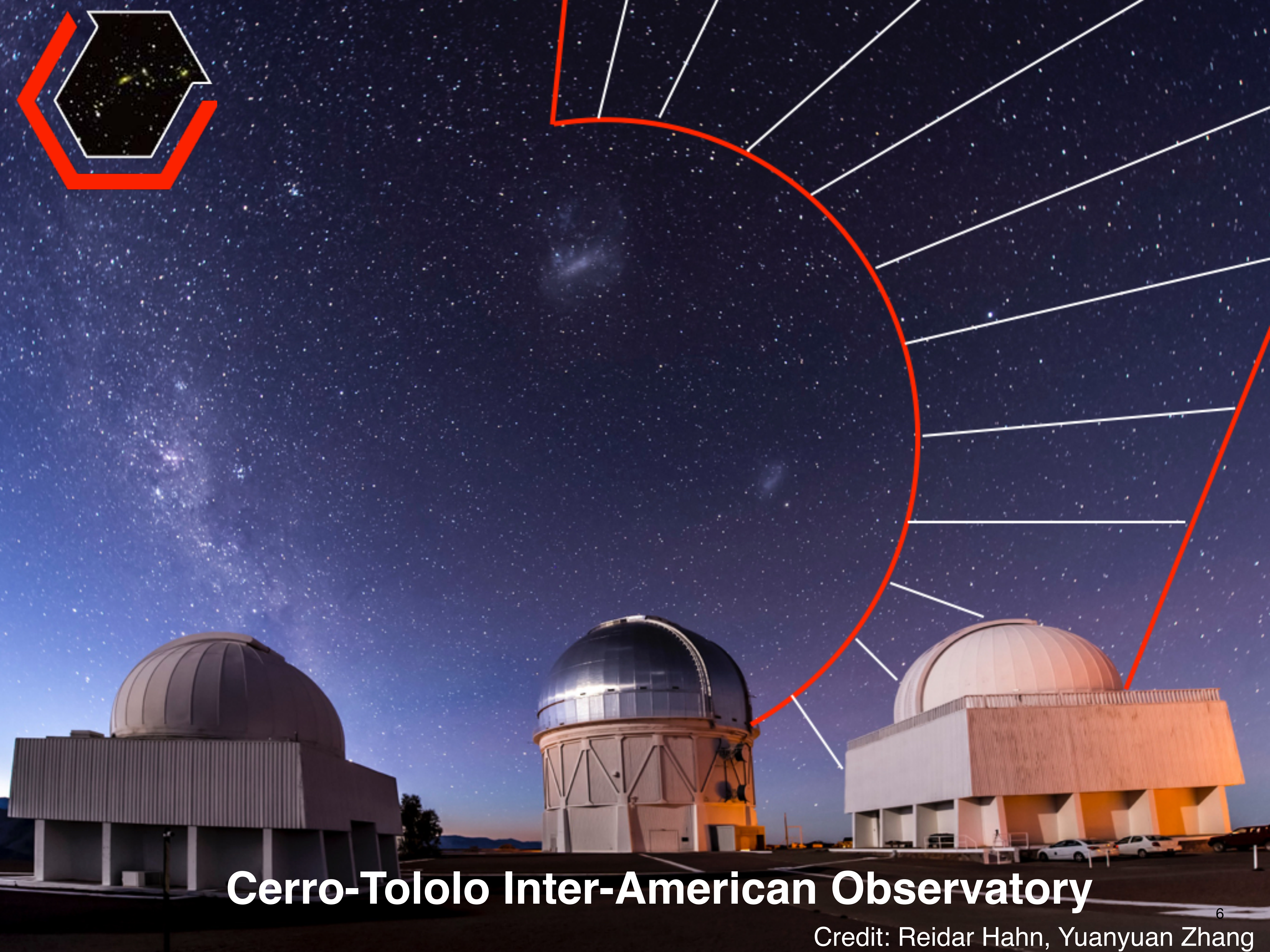
Credit: Reidar Hahn, Yuanyuan Zhang

Dark Energy Survey Collaboration

~400 scientists from around the world

Fermilab, UIUC/NCSA, University of Chicago, LBNL, NOAO, University of Michigan, University of Pennsylvania, Argonne National Lab, Ohio State University, Santa-Cruz/SLAC/Stanford, Texas A&M

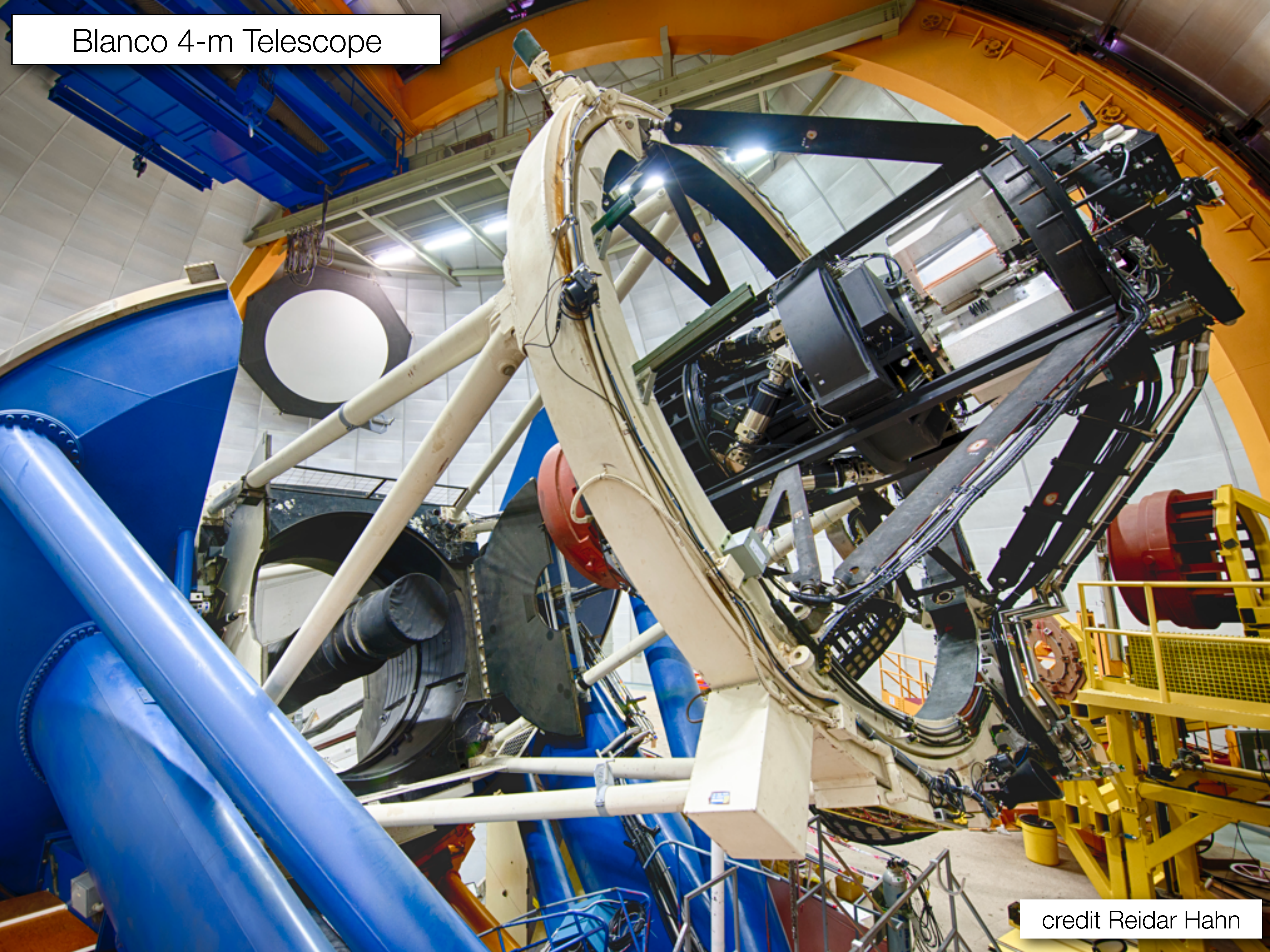




Cerro-Tololo Inter-American Observatory

Credit: Reidar Hahn, Yuanyuan Zhang

Blanco 4-m Telescope

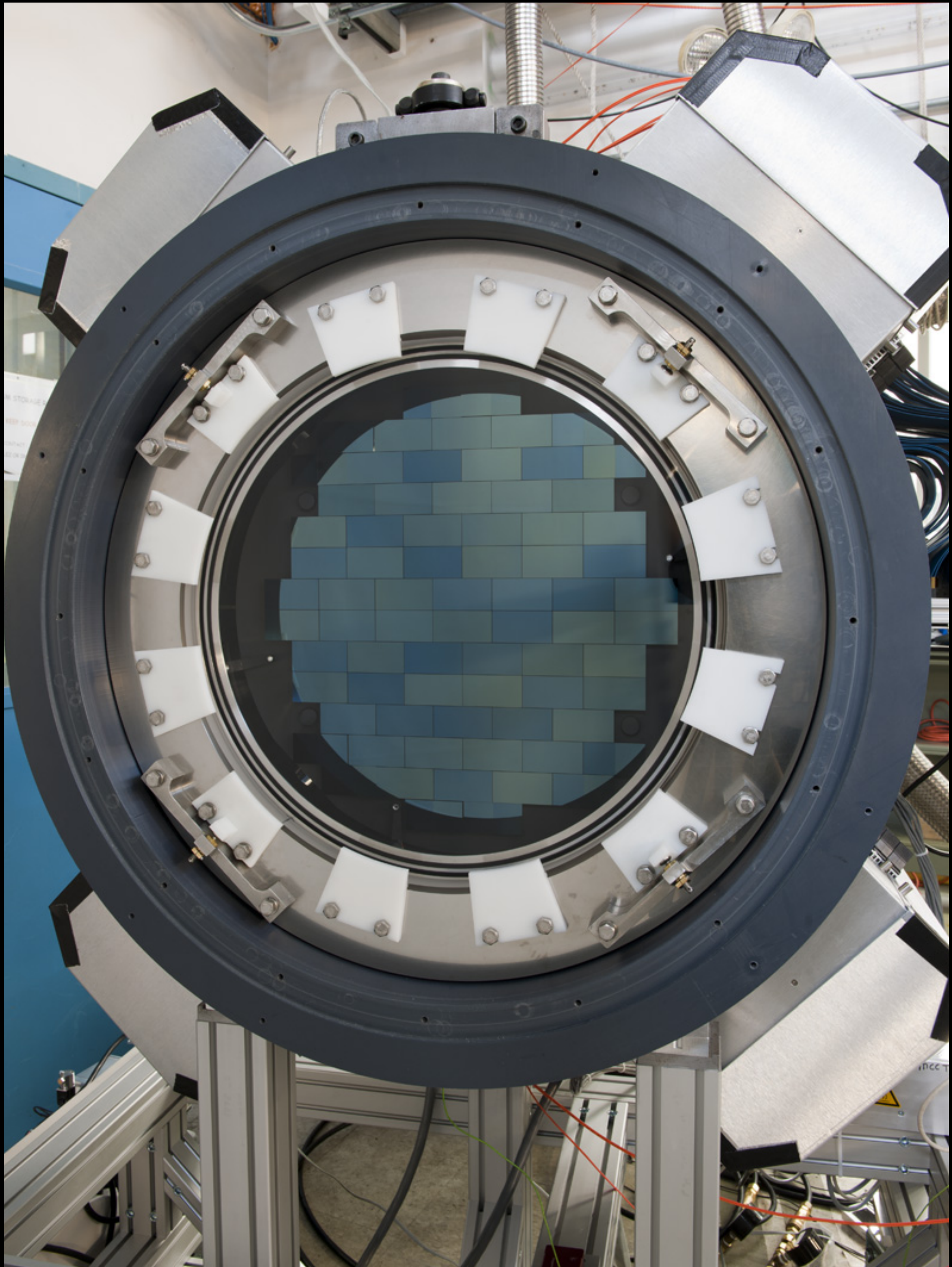


credit Reidar Hahn

570-Million pixel
Dark Energy Camera

Built here at Fermilab

Installed on the Blanco telescope in 2012



First Images

Fornax Cluster of Galaxies

First Light on Sept. 12, 2012

First Images

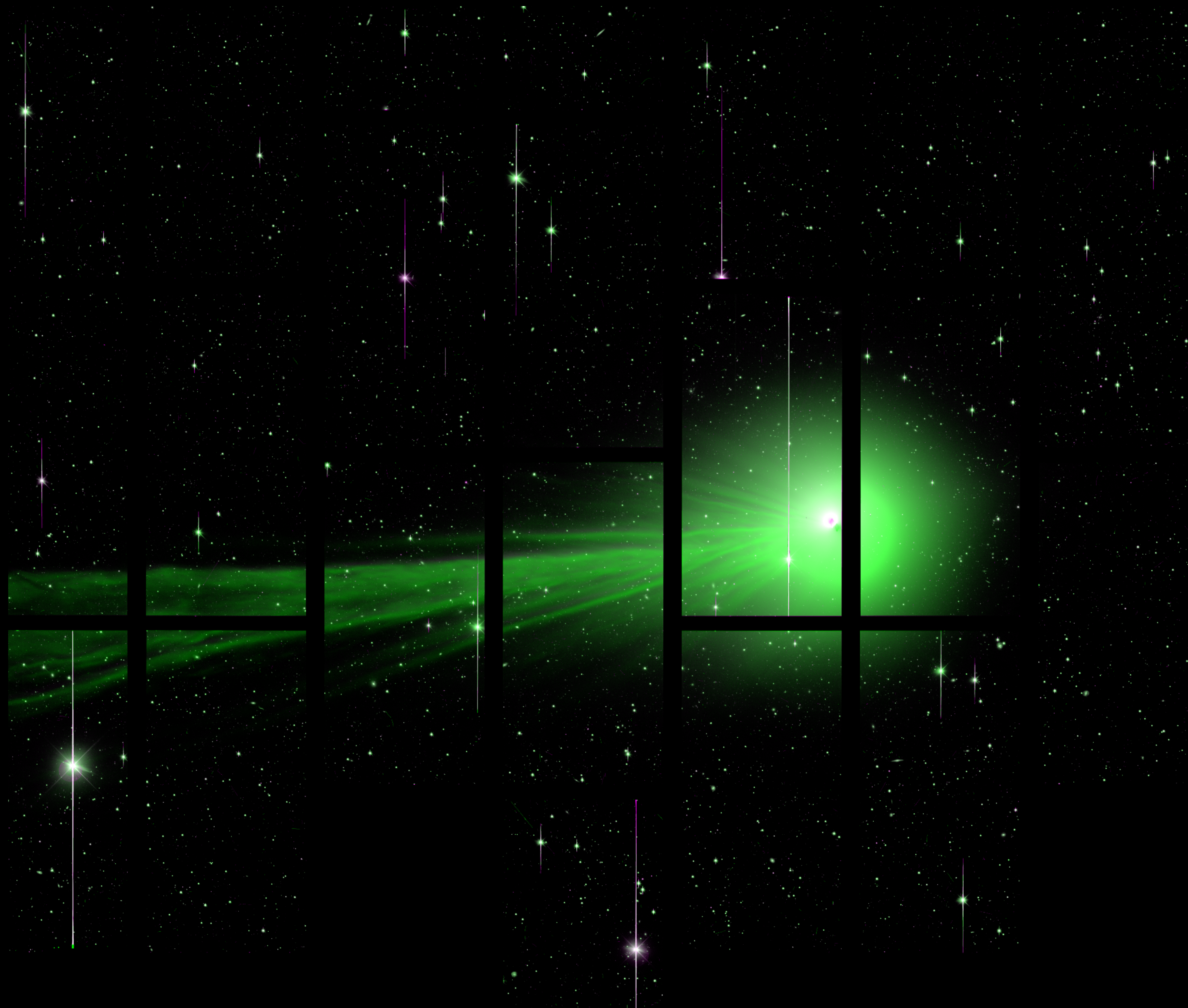
Galaxy NGC 1365 in Fornax Cluster

image from a single detector

NGC 1512 at 38 million light-years

Cluster of
Galaxies


Orion nebula



Comet Lovejoy

Gravitational Wave: GW170817
Binary Neutron Star Merger
Optical Counterpart —Kilonova

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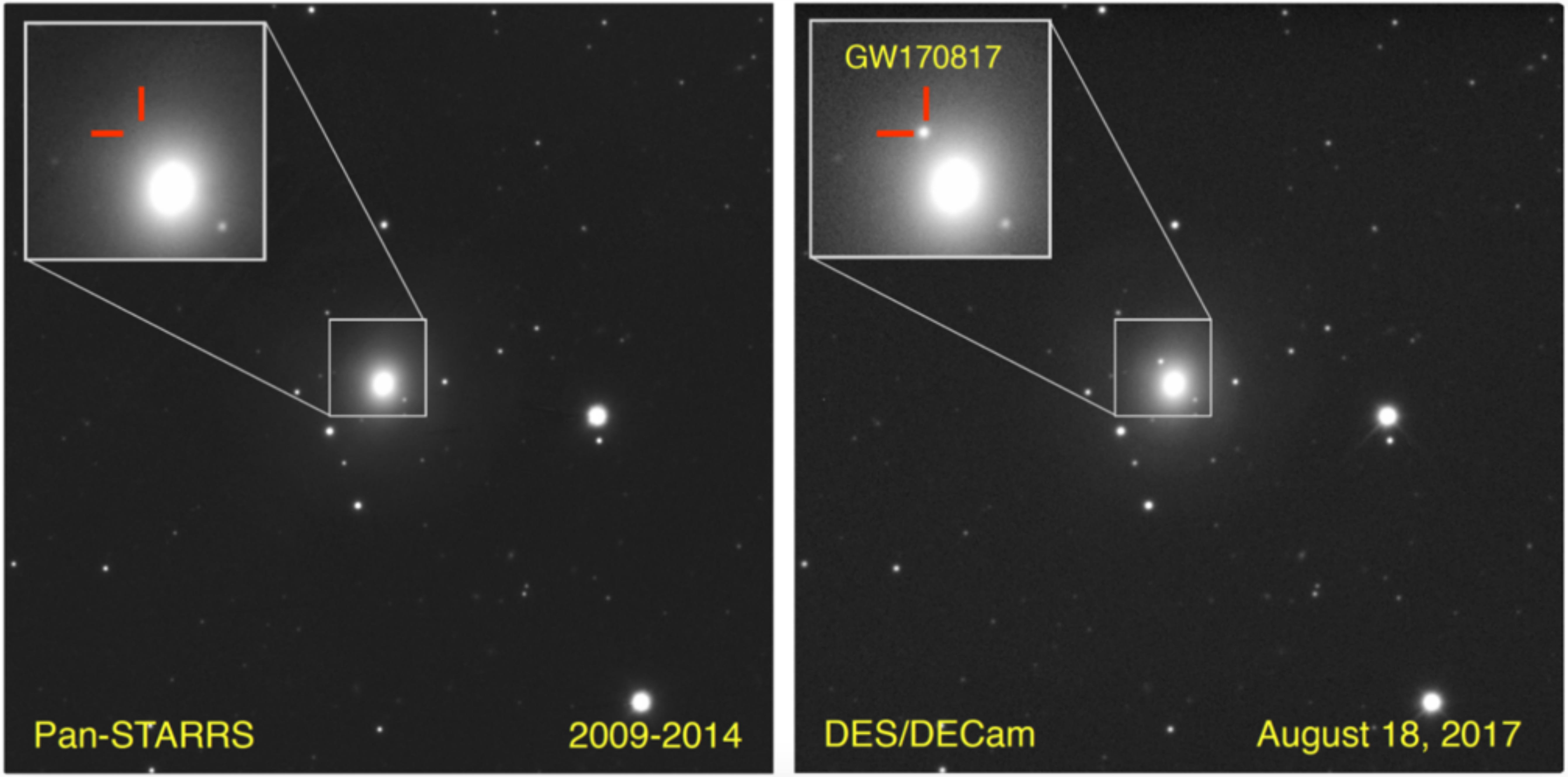
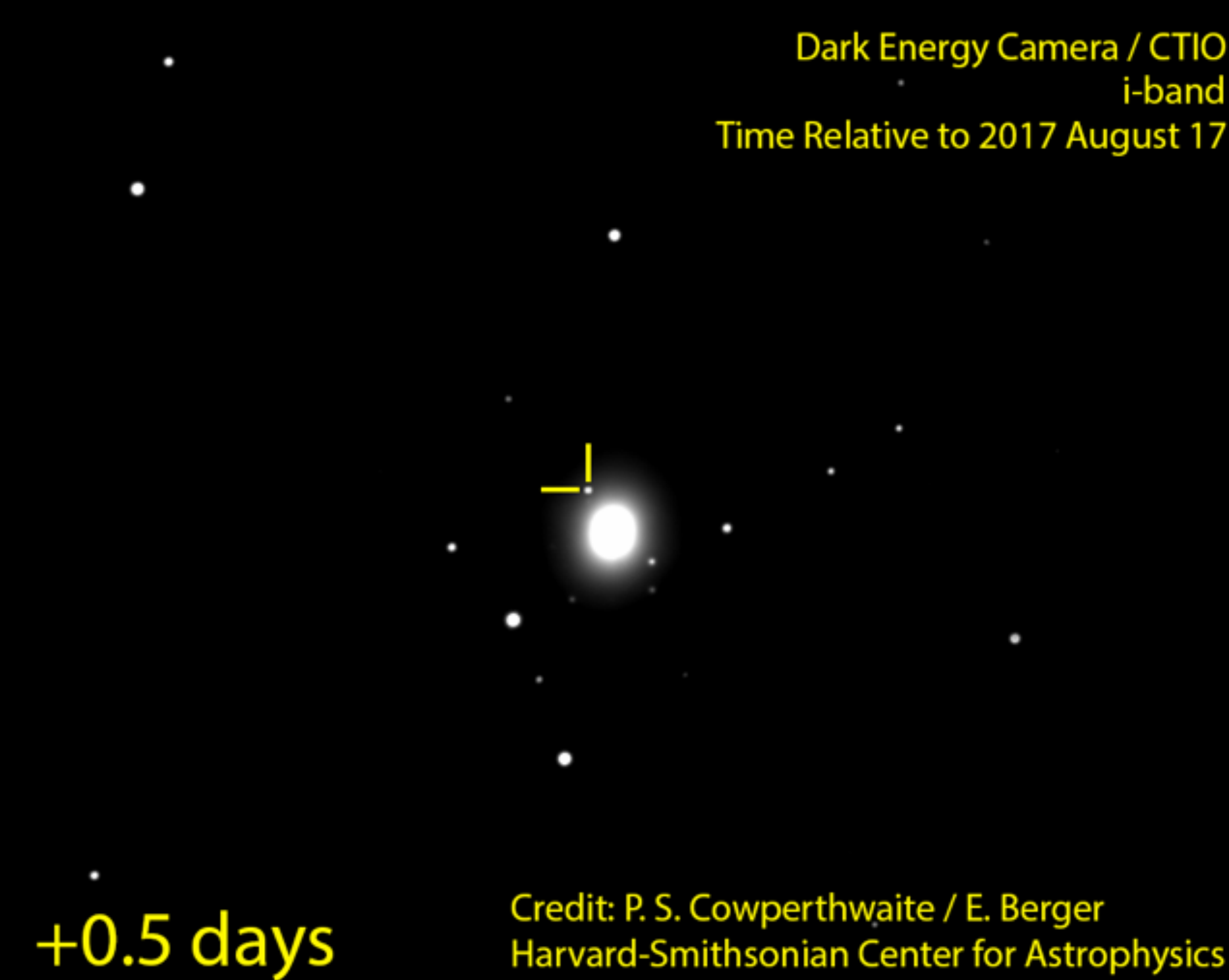
Binary Neutron Star Merger
Optical Counterpart —Kilonova



Credit: P. K. Blanchard / E. Berger / Pan-STARRS / DECam

Gravitational Wave: GW170817
Binary Neutron Star Merger
Optical Counterpart —Kilonova



Questions?

Now Let's Learn Something About the Universe!

What is Cosmology?

The origin, evolution, and ultimate fate of the Universe

The Universe started with a Big Bang

The Origin

We are all Stardust

The Evolution

The Universe is mostly “Dark”

The Fate

Some preparations are required!

Observations

Measurements

Scientists use numbers and units

What is the most difficult measurement in observational cosmology?

- A. Positions of the stars/galaxies on the sky
- B. Brightnesses of the stars/galaxies
- C. Motions of the stars/galaxies
- D. Distances to the stars/galaxies

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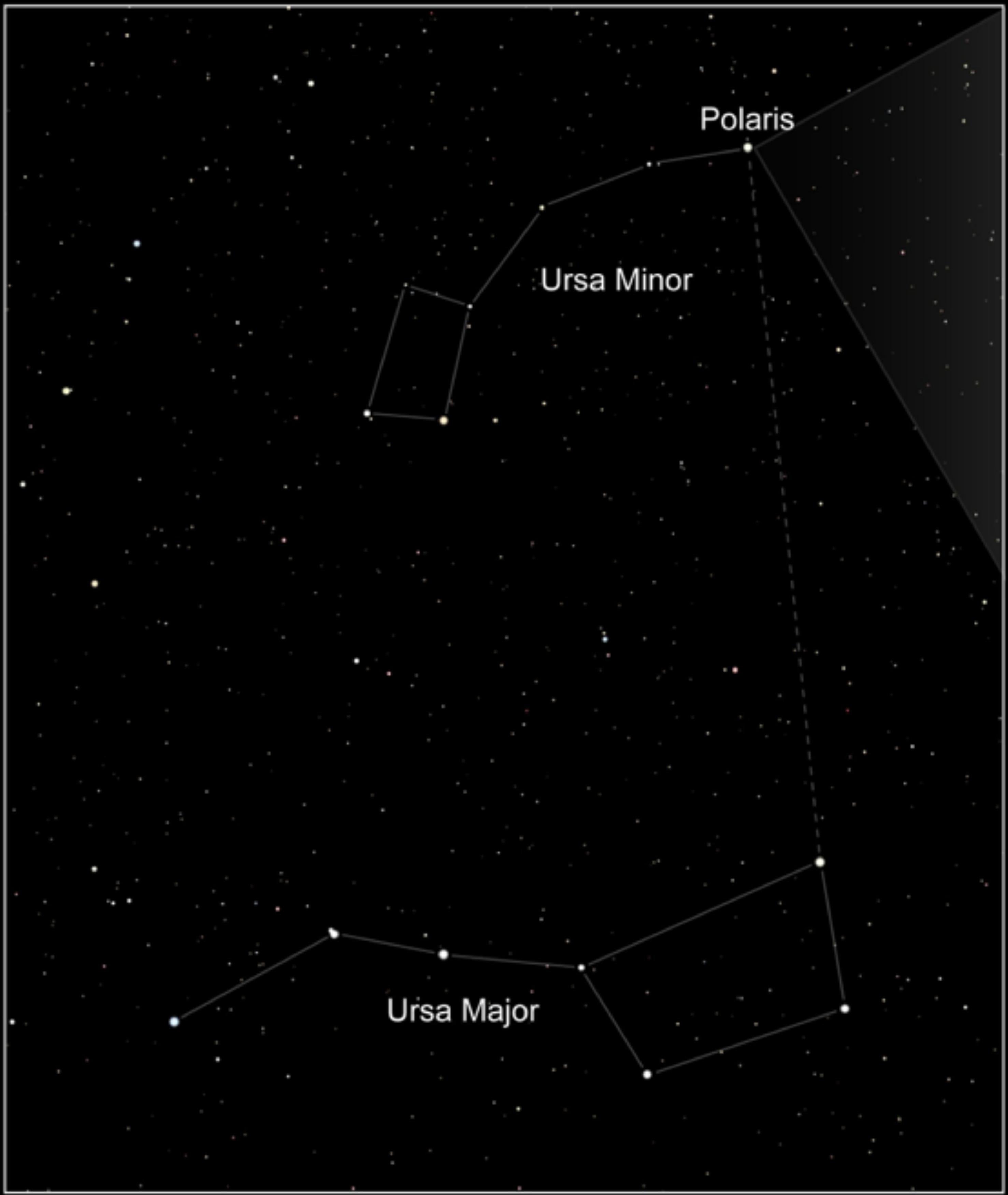
Polaris



Polaris

Polaris

Right Ascension — RA
(celestial longitude)

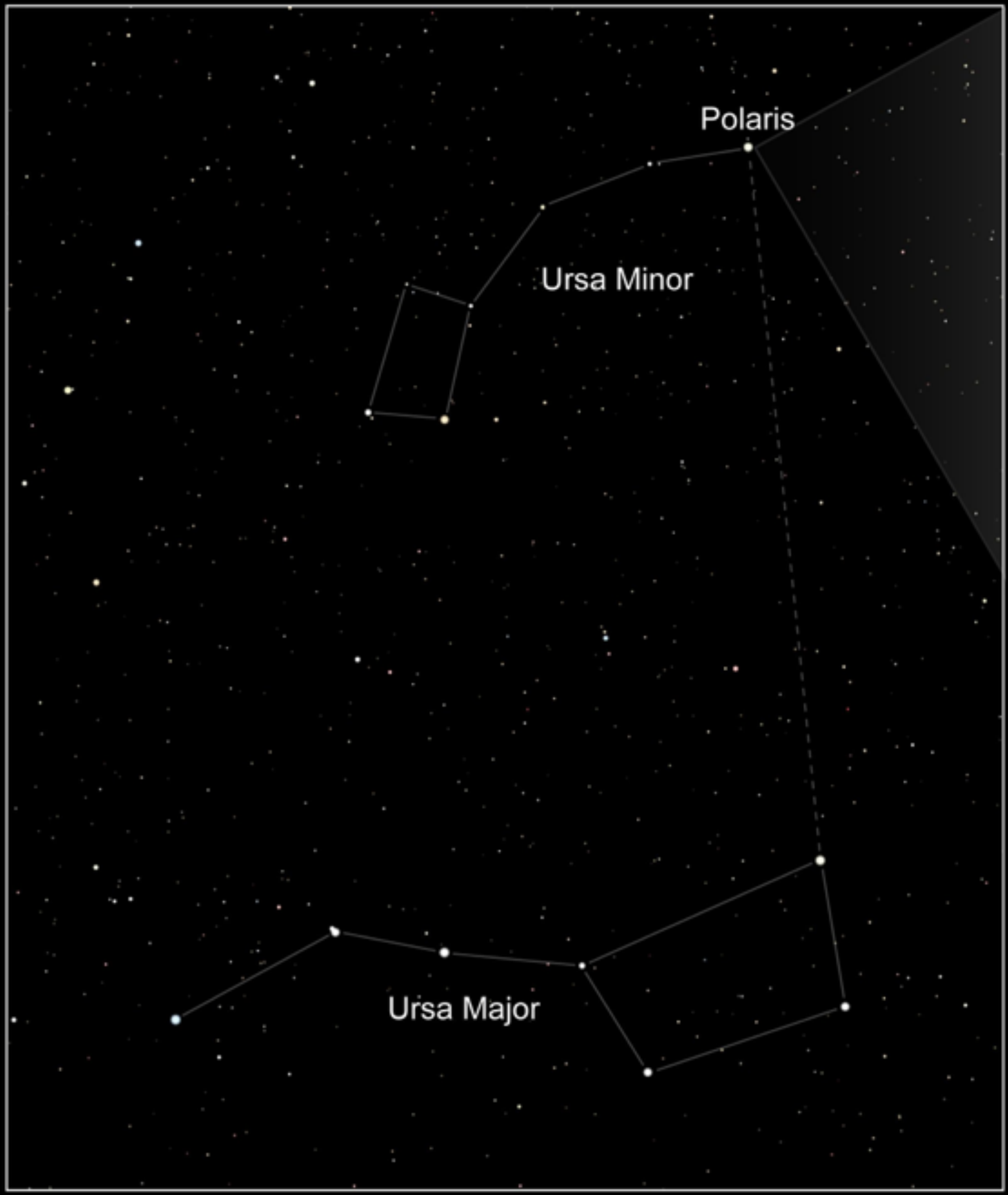
02h 30m 41.6s

Declination — Dec
(celestial latitude)

+89° 15′ 38.1″

24 hours = 360 deg / 1 circle
1 hour = 15 deg
60 minute = 1 hour
60 second = 1 minute

60 arcminute (′) = 1 deg
60 arcsecond (″) = 1 arcminute
15 arcsecond = 1 second



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Summer Triangle

Bob King

Brighter stars has smaller magnitude

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  — spectroscopy

- **D. Distances to the stars/galaxies**

Question:
How to measure distance?

Units for Distances/Length

miles

light-year (ly)

km

minutes

meter

mph

Ångström

km/s

parsec

Mpc

foot

Astronomical Unit (AU)

kilograms

Units for Distances/Length

miles

light-year (ly)

9×10^{15} meter

km

1000 meter

minutes

meter

mph

Ångström

km/s

10^{-10} meter

parsec

Mpc

foot

Astronomical Unit (AU)

kilograms

1.5×10^{11} meter

Question:
How to measure distance?

Trigonometric Parallaxes

- First word: Trigonometry + metric (measure) = Trigonometric: Measuring the angles.

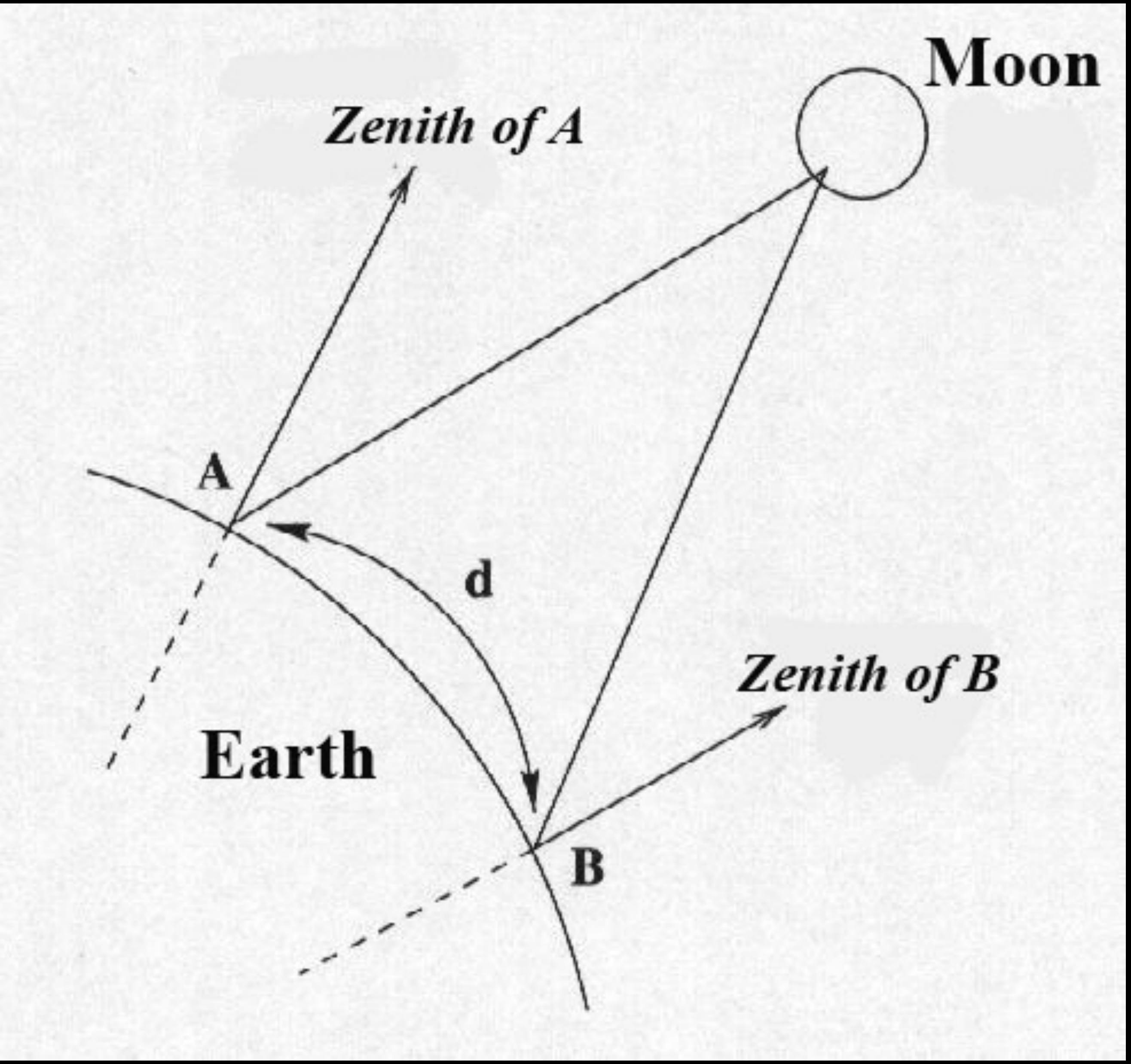
- Second word: Base is Parallel. Parallax means measuring the amount that an object shifts from two different vantage points.

Trigonometric Parallaxes — 1

Experiment with your finger

Trigonometric Parallaxes — 2

Distance to the Moon

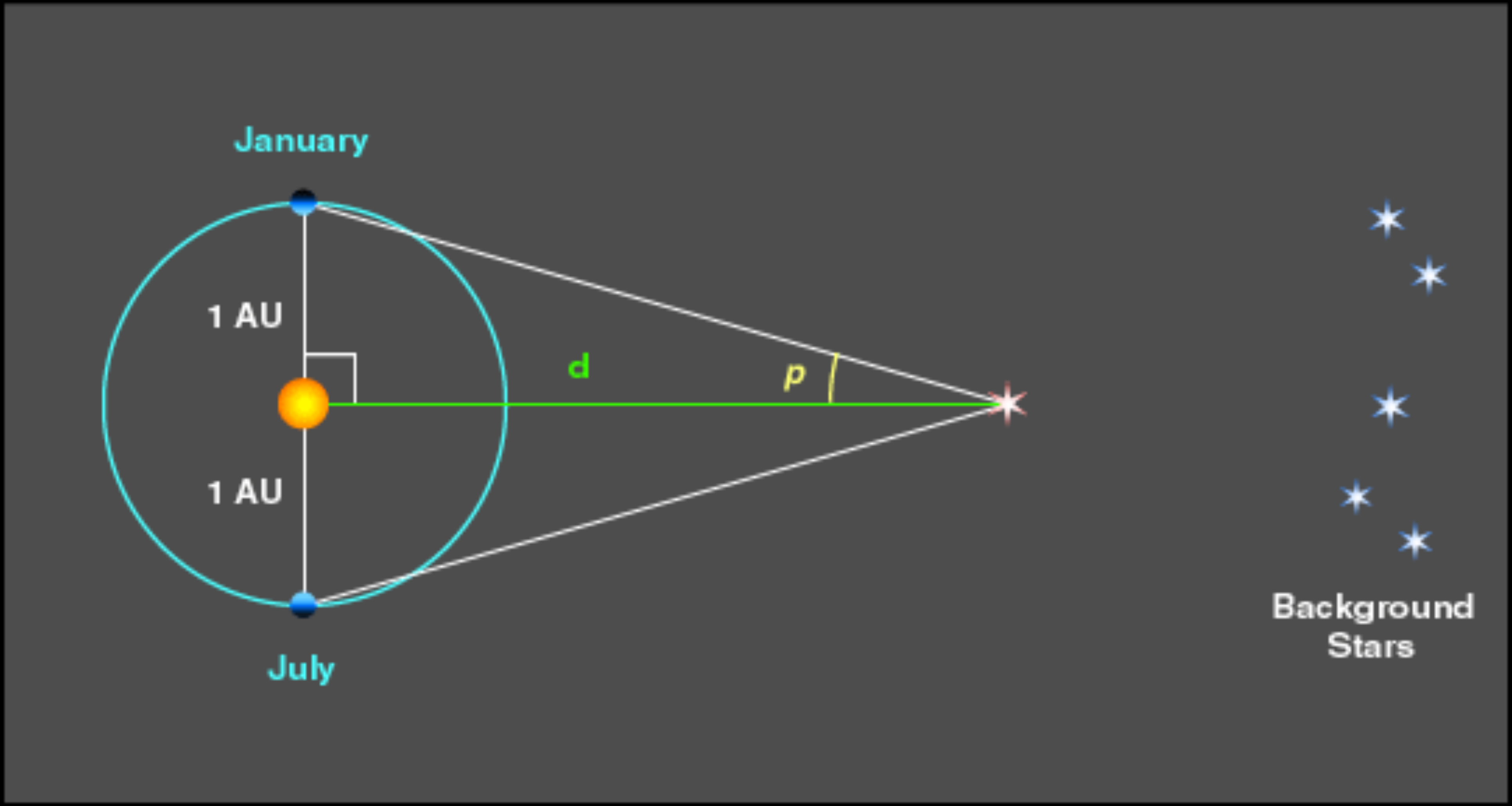


Trigonometric Parallaxes — 2

What is the longest baseline we can have?

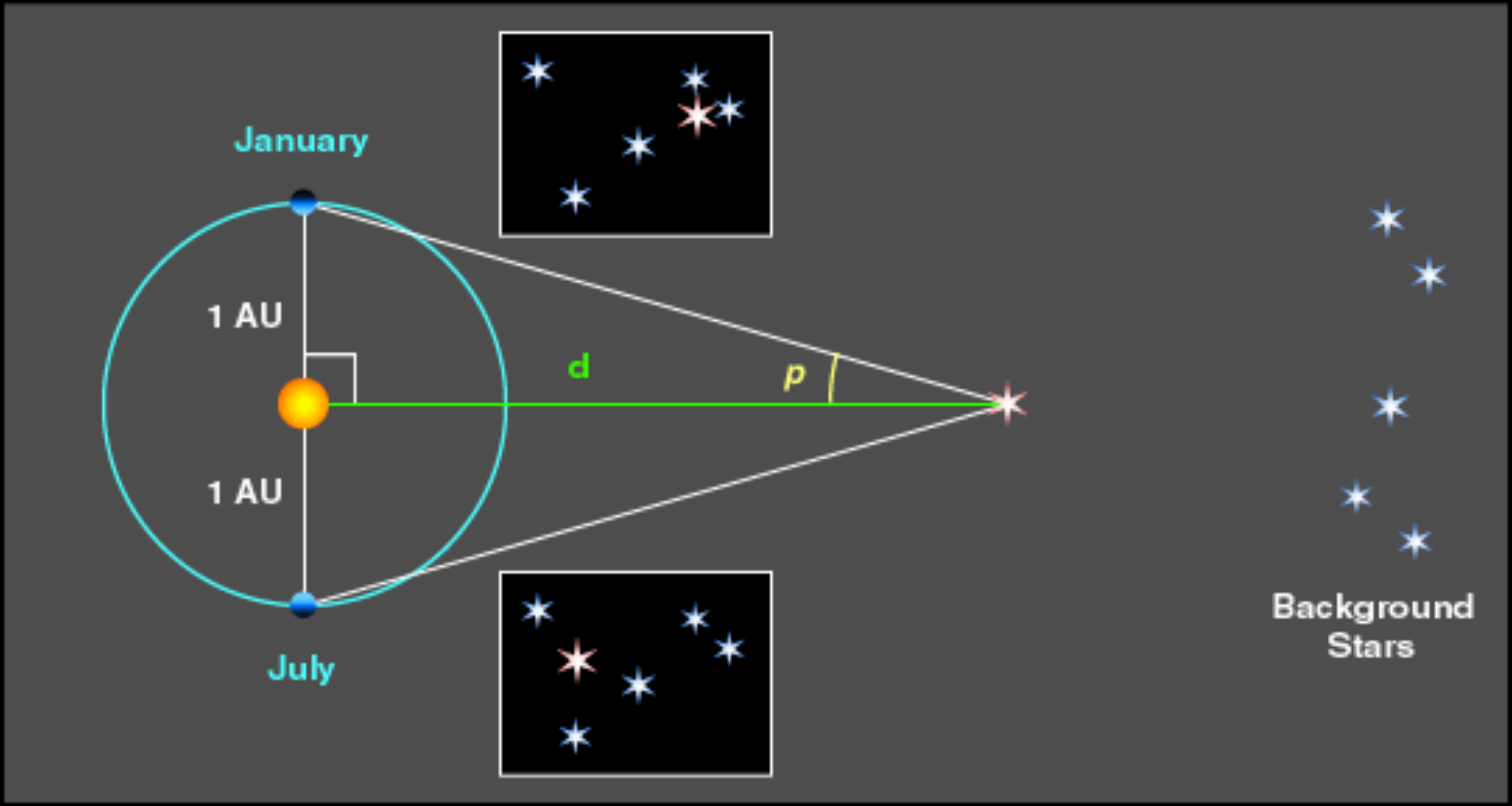
Trigonometric Parallaxes — 3

Distance to a Star



Trigonometric Parallaxes — 3

Distance to a Star



Measure the Position of the Stars

Trigonometric Parallaxes — 3

Definition

Baseline = 1 AU
Measure a shift of *p* in arcsecond
Distance to the star in parsec (pc) is

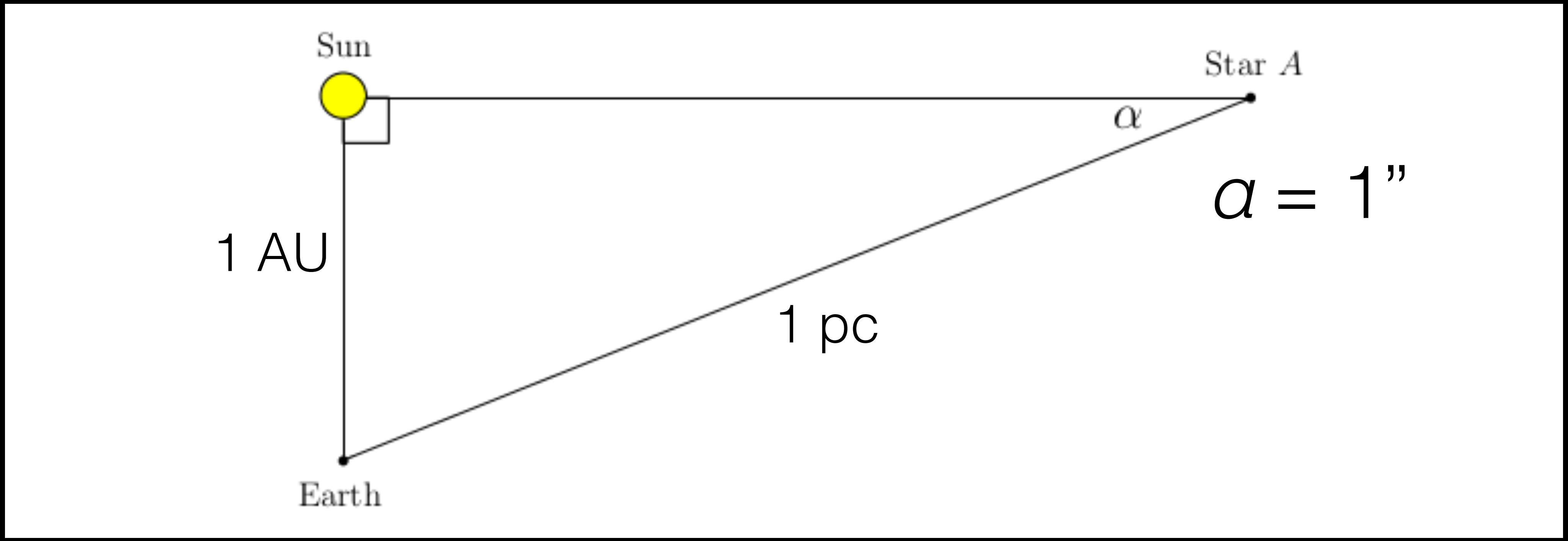
$$d = 1/p$$

shift = 1" , d = 1 pc
shift = 0.5", d = 2 pc

...

Trigonometric Parallaxes — 3

Distance to a Star



1 pc = 3.26 ly = 3 x 10^{16} m

Trigonometric Parallaxes — 3

The Farthest Star Parallax can go

$d \sim 10{,}000$ pc ~ 10 kpc

$p = 0.0001''$

Trigonometric Parallaxes — 3

The Farthest Star Parallax can go

$d \sim 10{,}000$ pc ~ 10 kpc

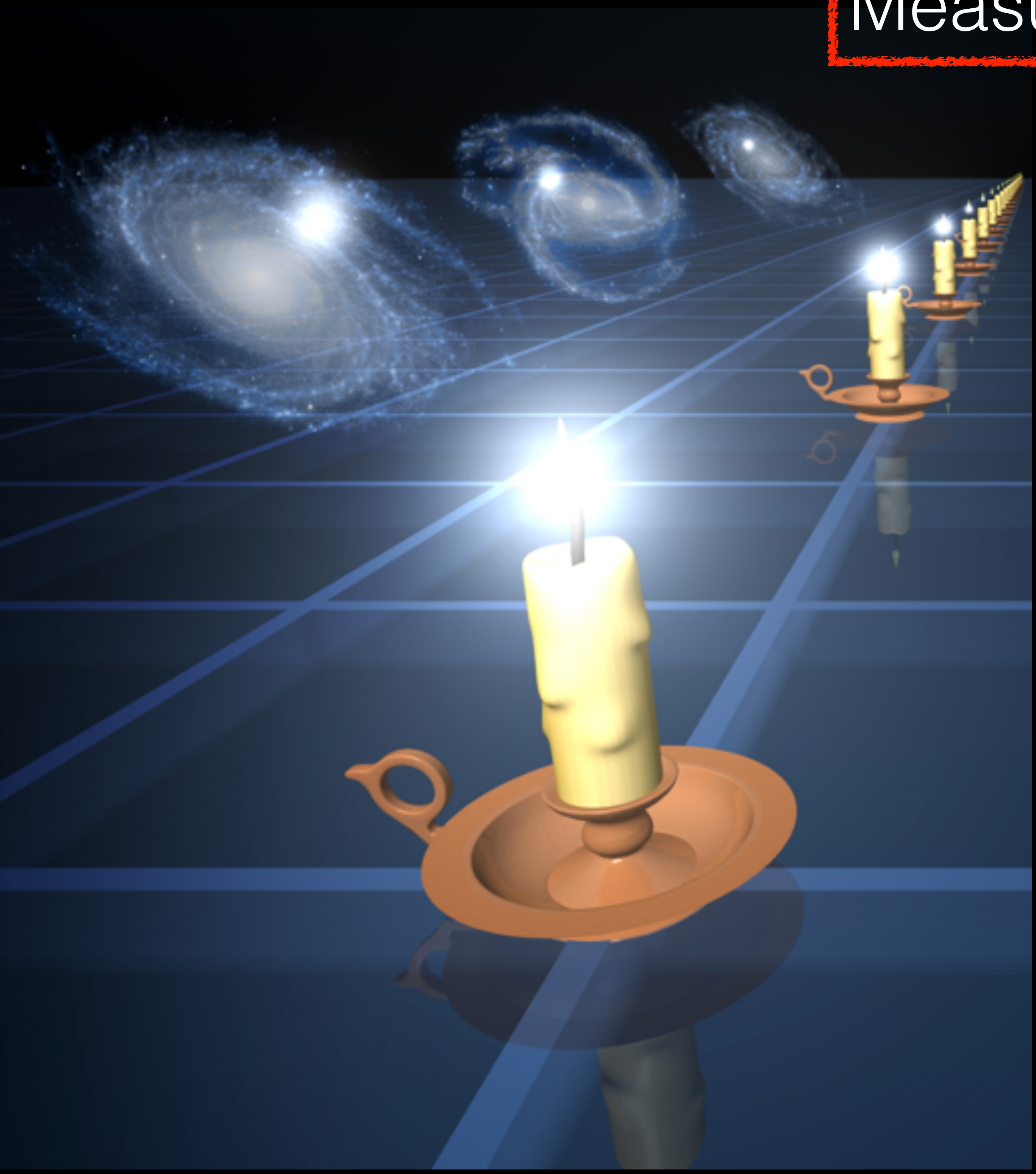
$p = 0.0001''$

What about more distance stars?

Standard Candles   Standard Rulers

Standard Candles

Measure the Brightness of the Stars

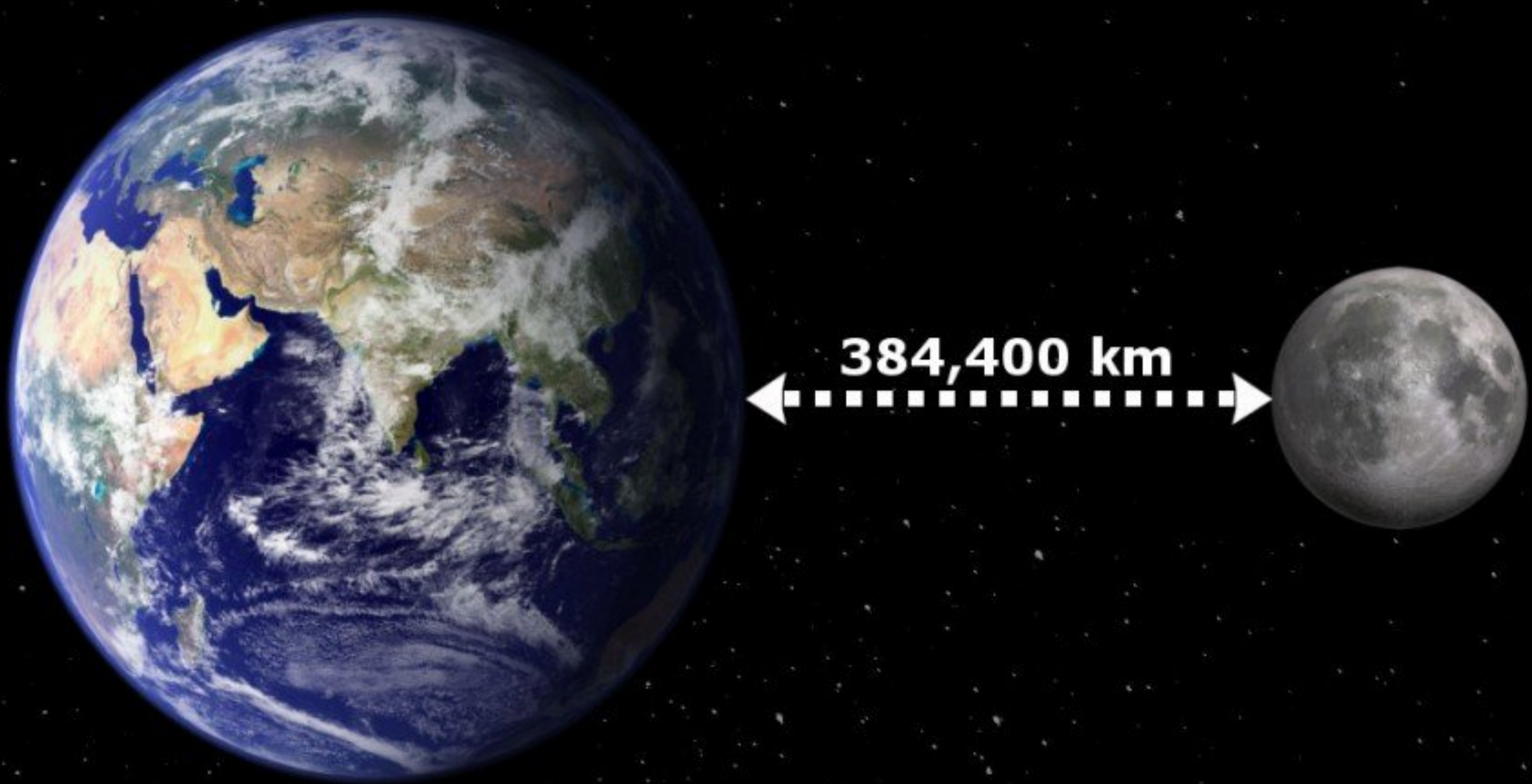


$$\text{Brightness} = \frac{\text{Luminosity}}{4\pi\ d^2}$$

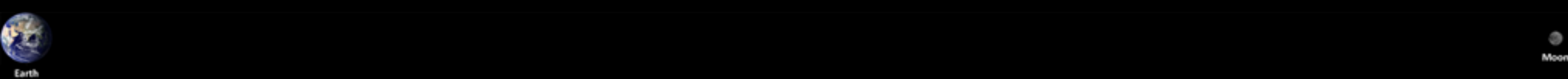
If the candle is twice further, then it is four times dimmer.

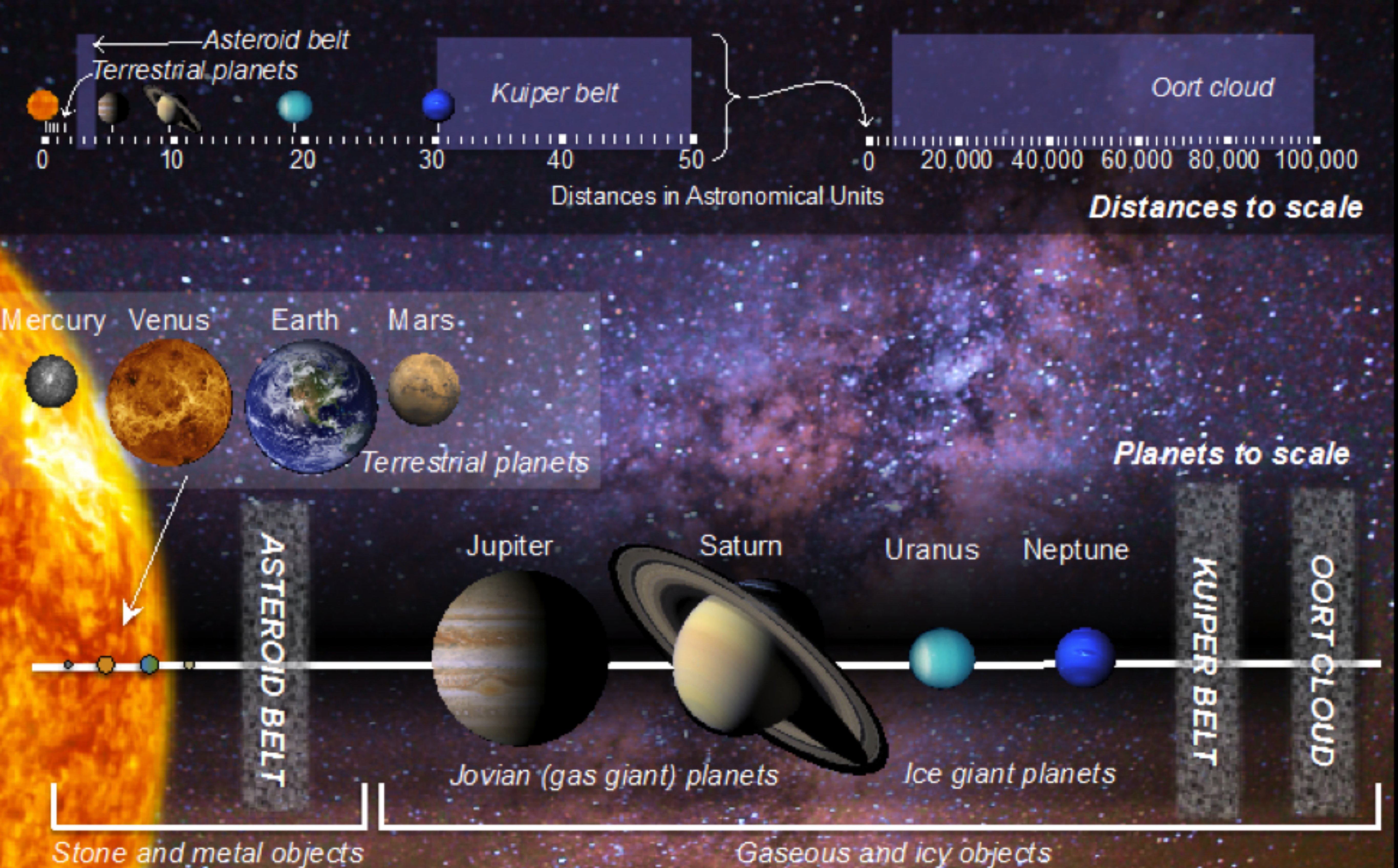
If we know the luminosity of a star or a galaxy, then we can measure the distance to it.

Distance to the Moon



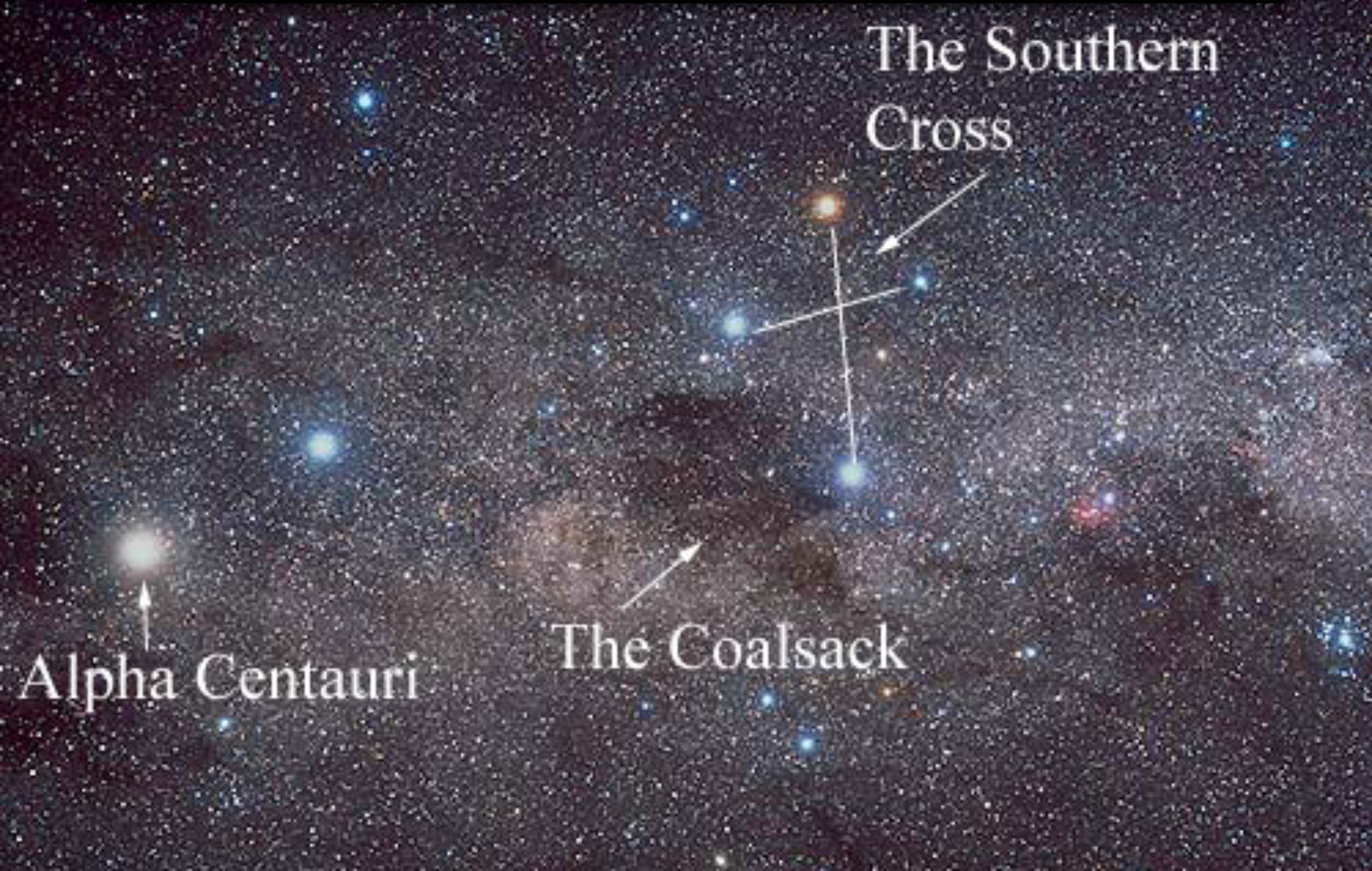
Distance to the Moon



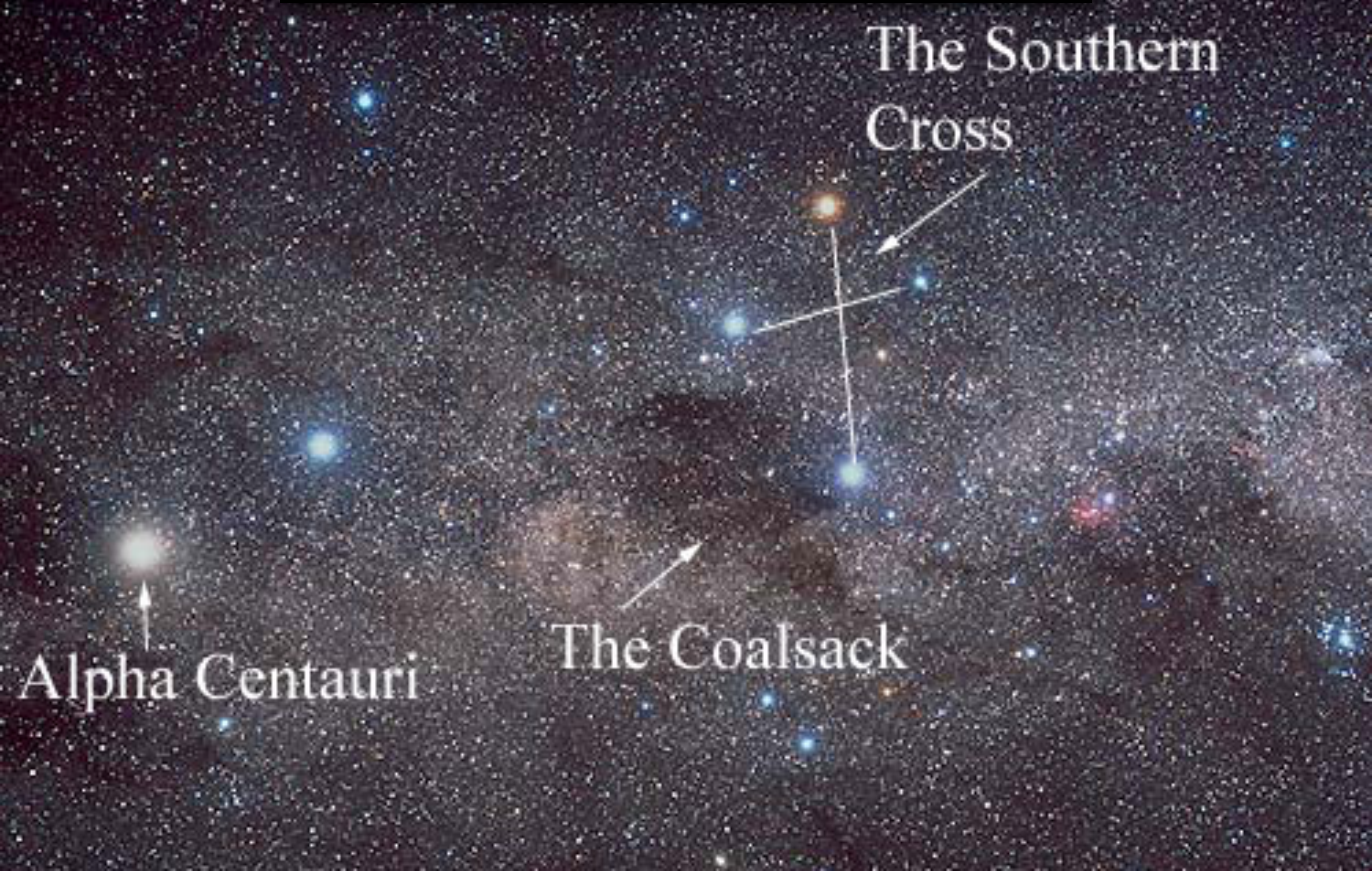


Distance to the Edge of Solar System:
150,000,000 km

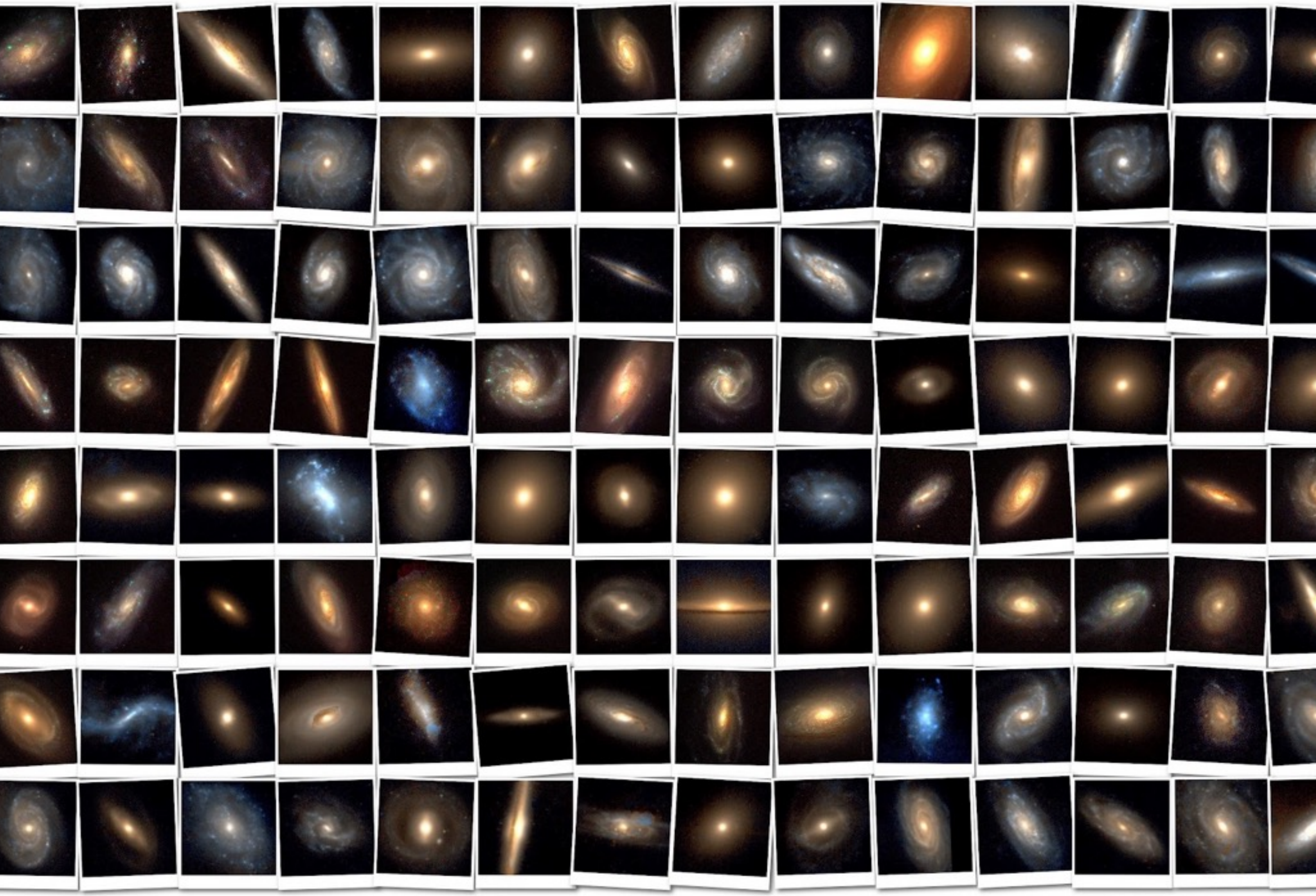
Distance to the Nearest Star
Proxima Centauri: 40,208,000,000,000 km



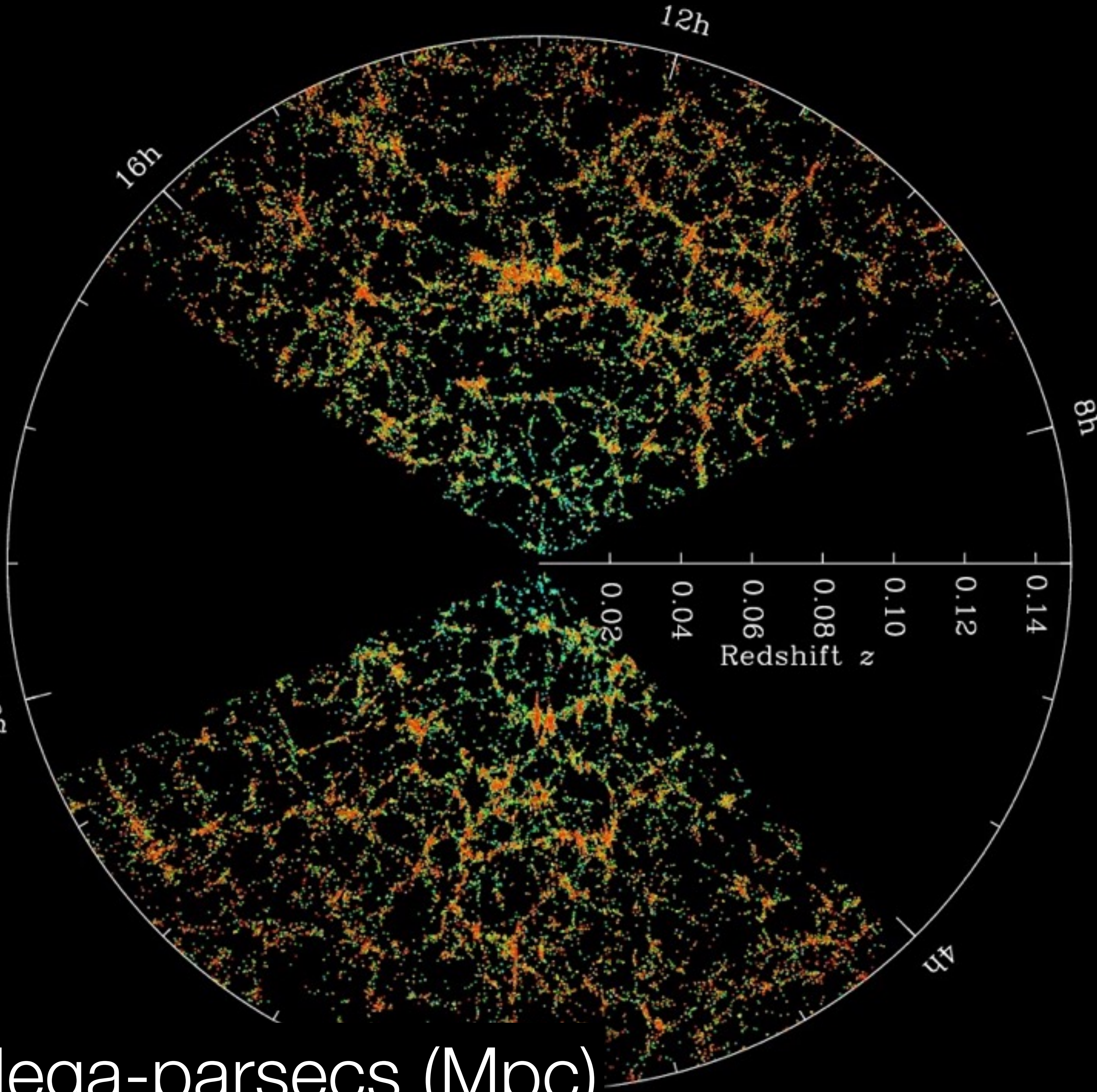
Distance to the Nearest Star
Proxima Centauri: 1.3 pc



Distance to Our Neighbor
Andromeda Galaxy (M31): 0.8 Mpc



Created by Zsolt Frei and James E. Gunn



600 Mega-parsecs (Mpc)

Size of Observable Universe

- 14 000 Mpc (14 Gpc or 46 billion light-years)

Size of an Atom

- 1 Ångström

Ratio ~ 10^{36}

To summarize …

Distance Measurements → **Trigonometric Parallaxes**

position / astrometry

Distance Measurements → **Standard Candles**

brightness / photometry

Distance Measurements → **……**

What is the most difficult measurement in observational cosmology?

- A. Positions of the stars/galaxies on the sky

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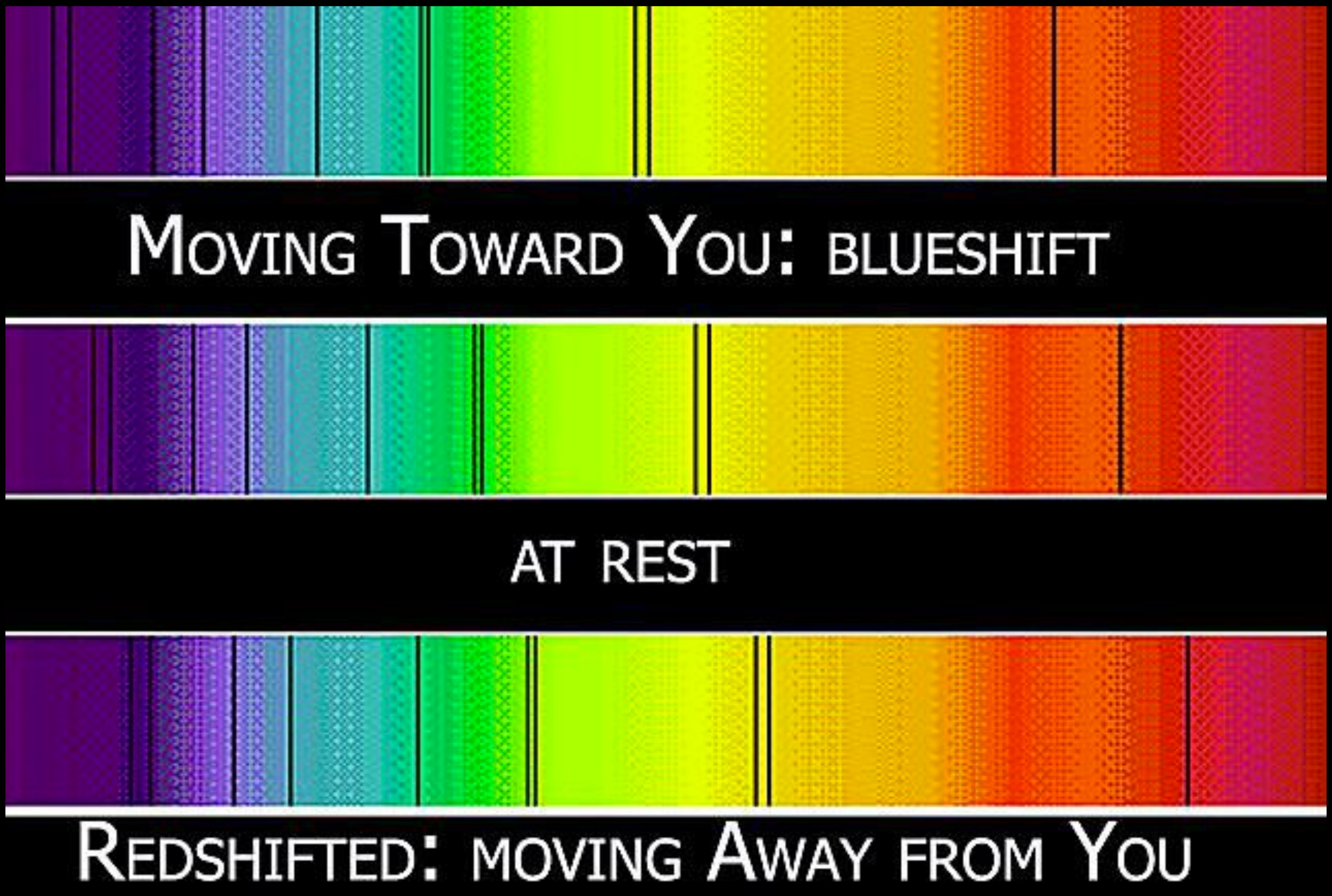
- **D. Distances to the stars/galaxies**

Stellar Spectrum

300 nm 700 nm

Doppler Effect



Motion of a Star

For example, if a line at 500 nm, is shifted to 500.5 nm, then the star is moving away from us at a speed of

$$\frac{v}{c} = \frac{\Delta\lambda}{\lambda} = \frac{500.5 - 500}{500} \rightarrow v = 0.001c = 300 \text{ km/s}$$

What is the most interesting/ important/difficult measurements in observational cosmology?

- A. Positions of the stars/galaxies on the sky

  — astrometry

- B. Brightnesses of the stars/galaxies

  — photometry

- C. Motions of the stars/galaxies

  — spectroscopy

- D. Distances to the stars/galaxies

Questions?

Now Let’s Learn Something About the Universe!

The Universe started with a Big Bang

The Origin

We are all Stardust

The Evolution

The Universe is mostly “Dark”

The Fate

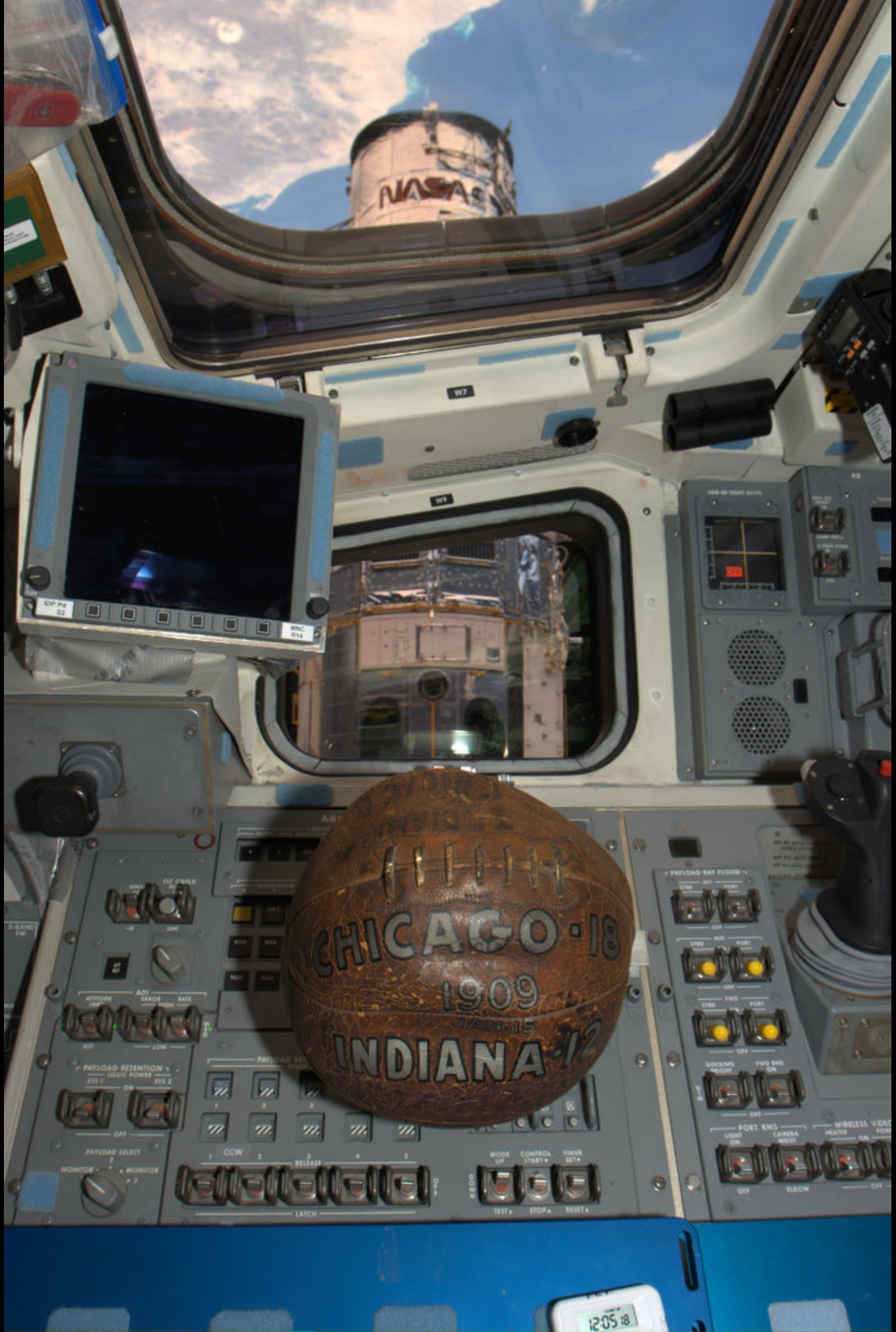
University of Chicago 1909 National Champions

March Madness 1909

Chicago 18
Indiana 12

Hubble's U.Chicago National Championship Basketball on board of the Space Shuttle

Hubble Space Telescope in background



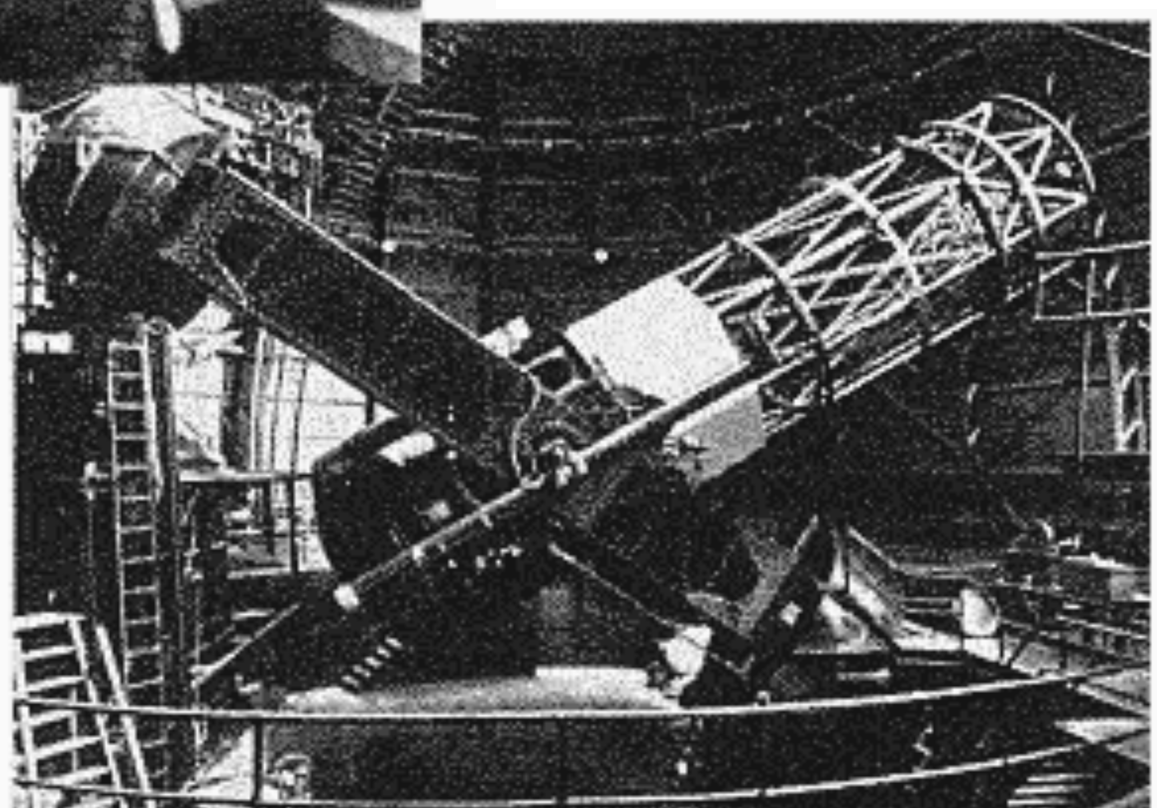
DISCOVERY OF EXPANDING UNIVERSE

Edwin Hubble

Nearby Galaxies → Motions

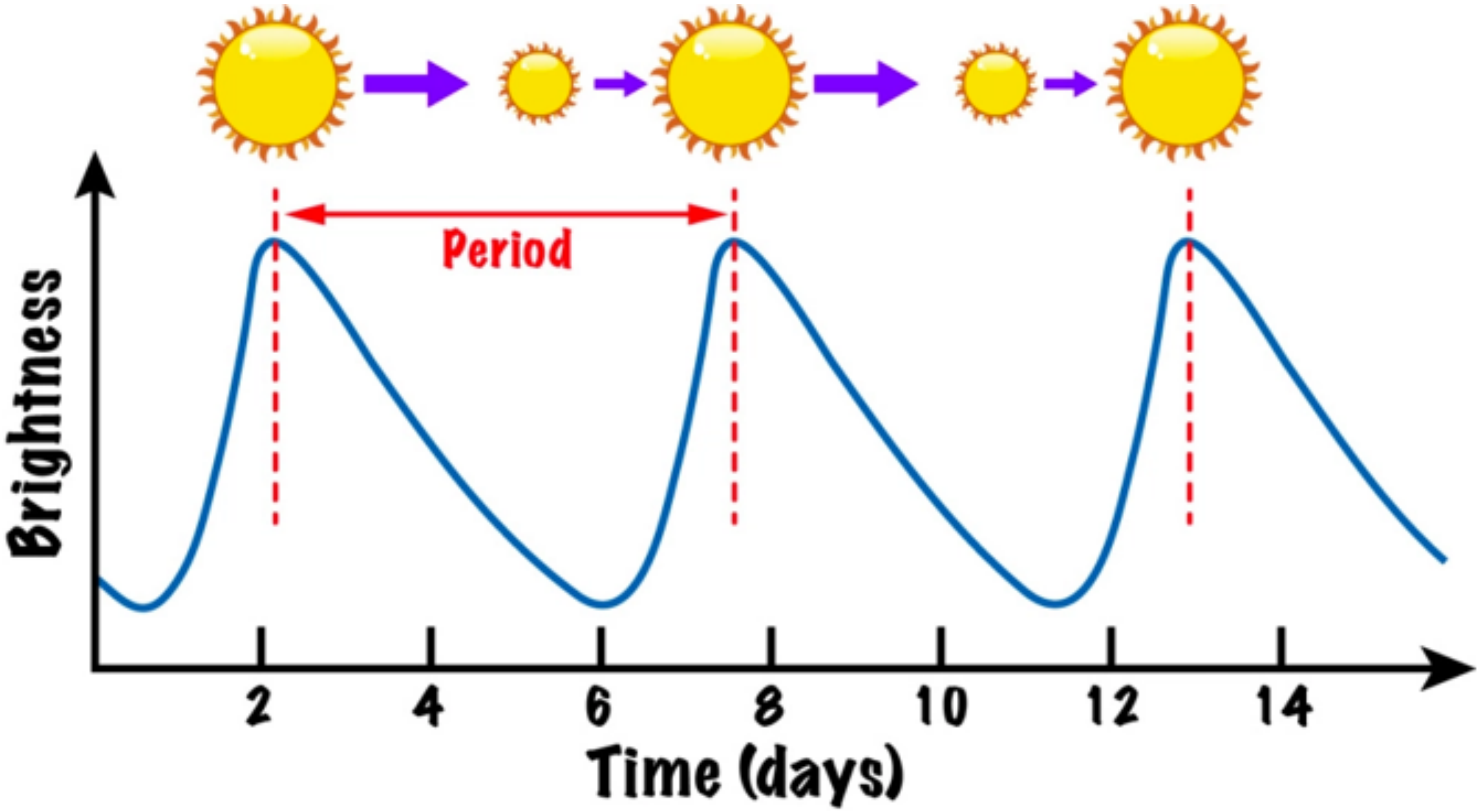
Nearby Galaxies → Distances

Standard Candles: Cepheid variable stars



Mt. Wilson
100 Inch
Telescope

Standard Candles: Cepheid variable stars



Period → Luminosity → Distance

DISCOVERY OF EXPANDING UNIVERSE

Edwin Hubble

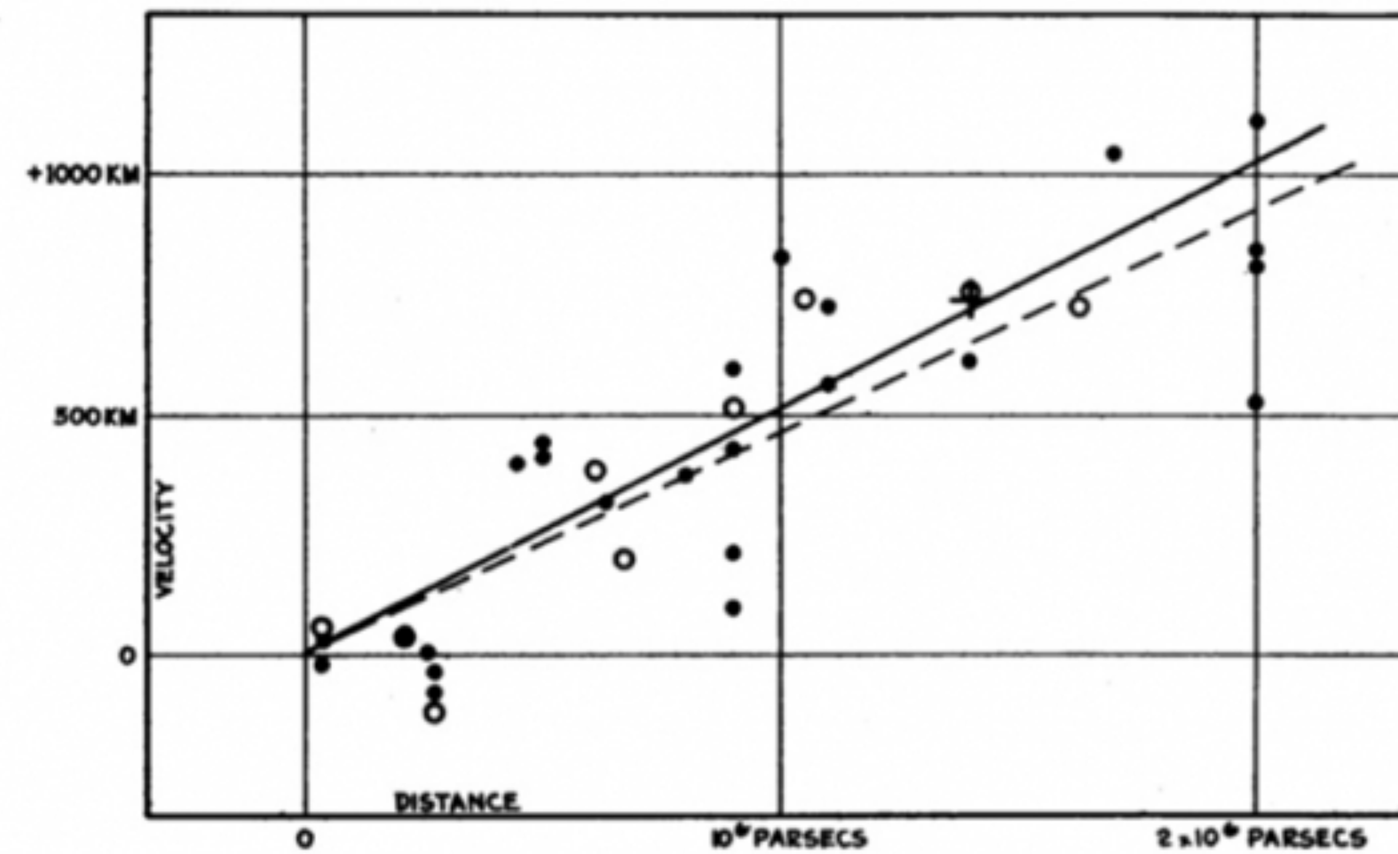
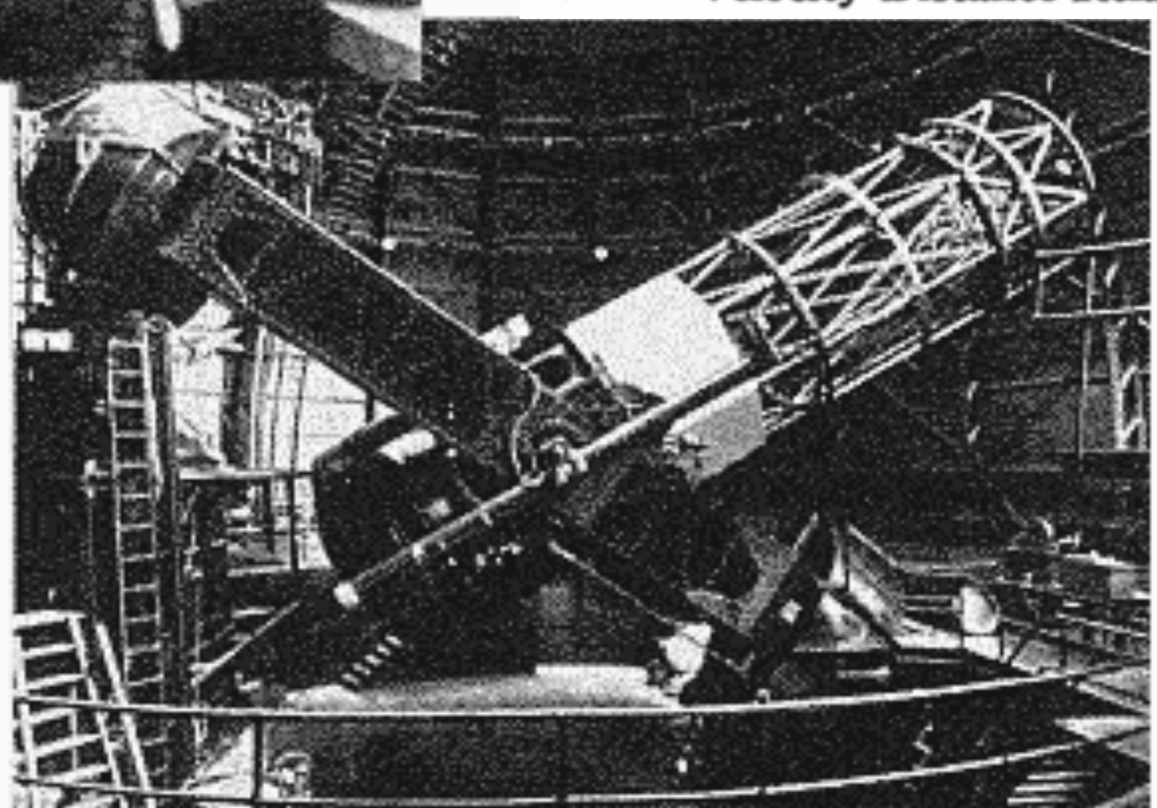


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

Hubble (1929)

Measure the Cepheid Variable stars in nearby galaxies



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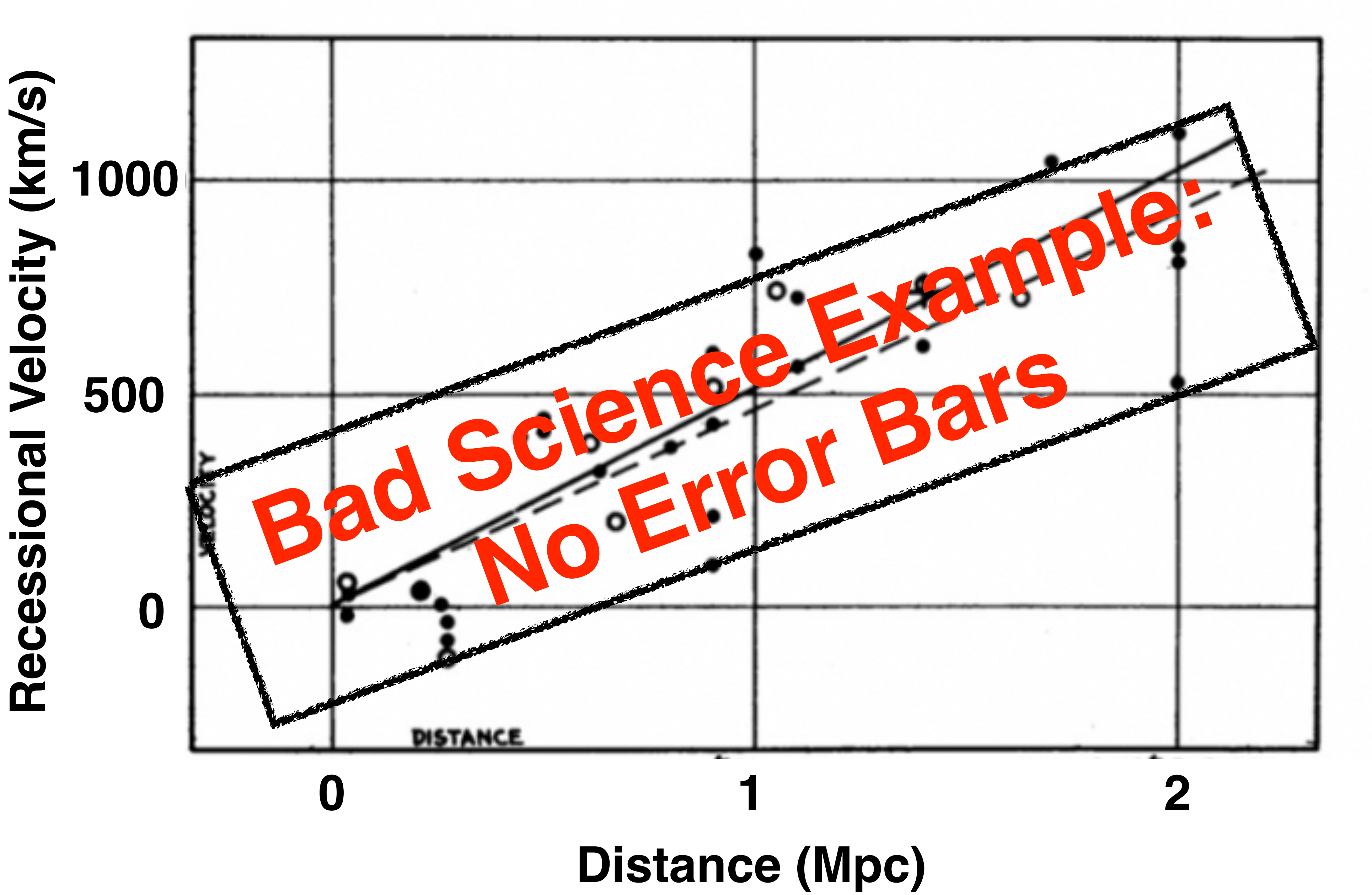
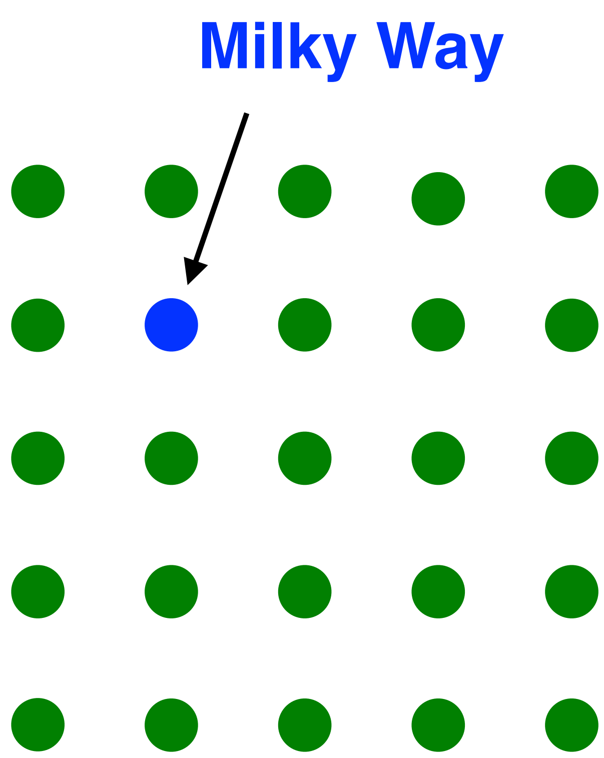
100 Inch
Telescope

Hubble's Law



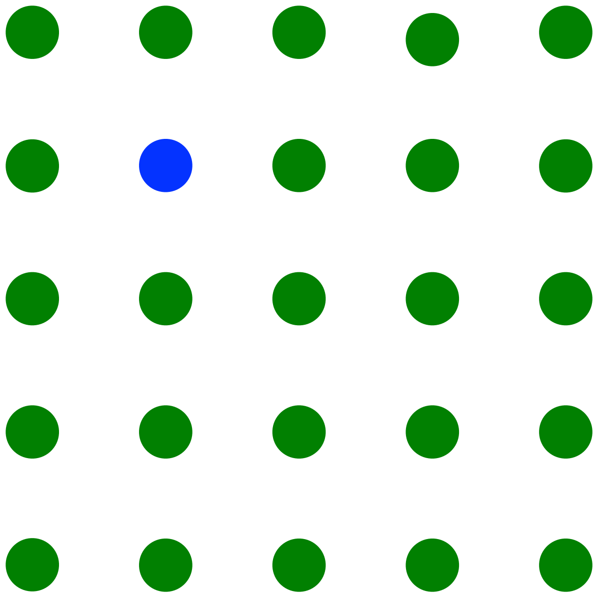
The further the galaxies, the faster they are moving away from us.

The Universe is Expanding



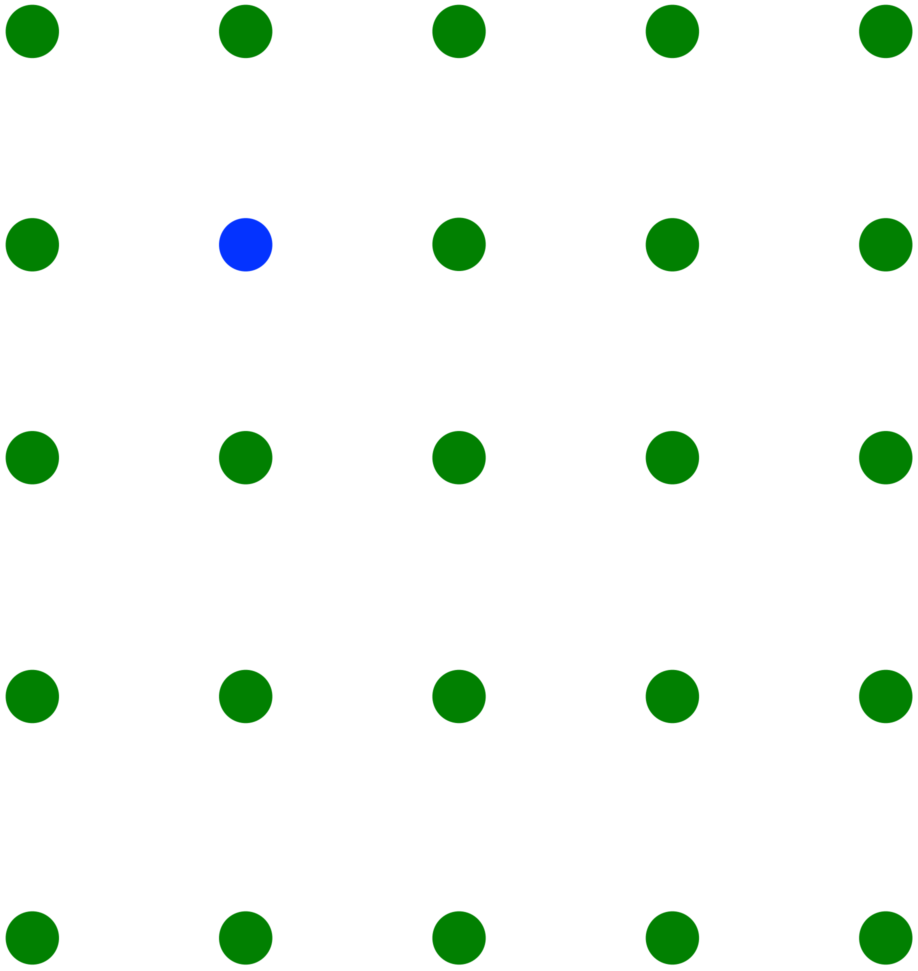
The Universe is Expanding

$t = t_1$

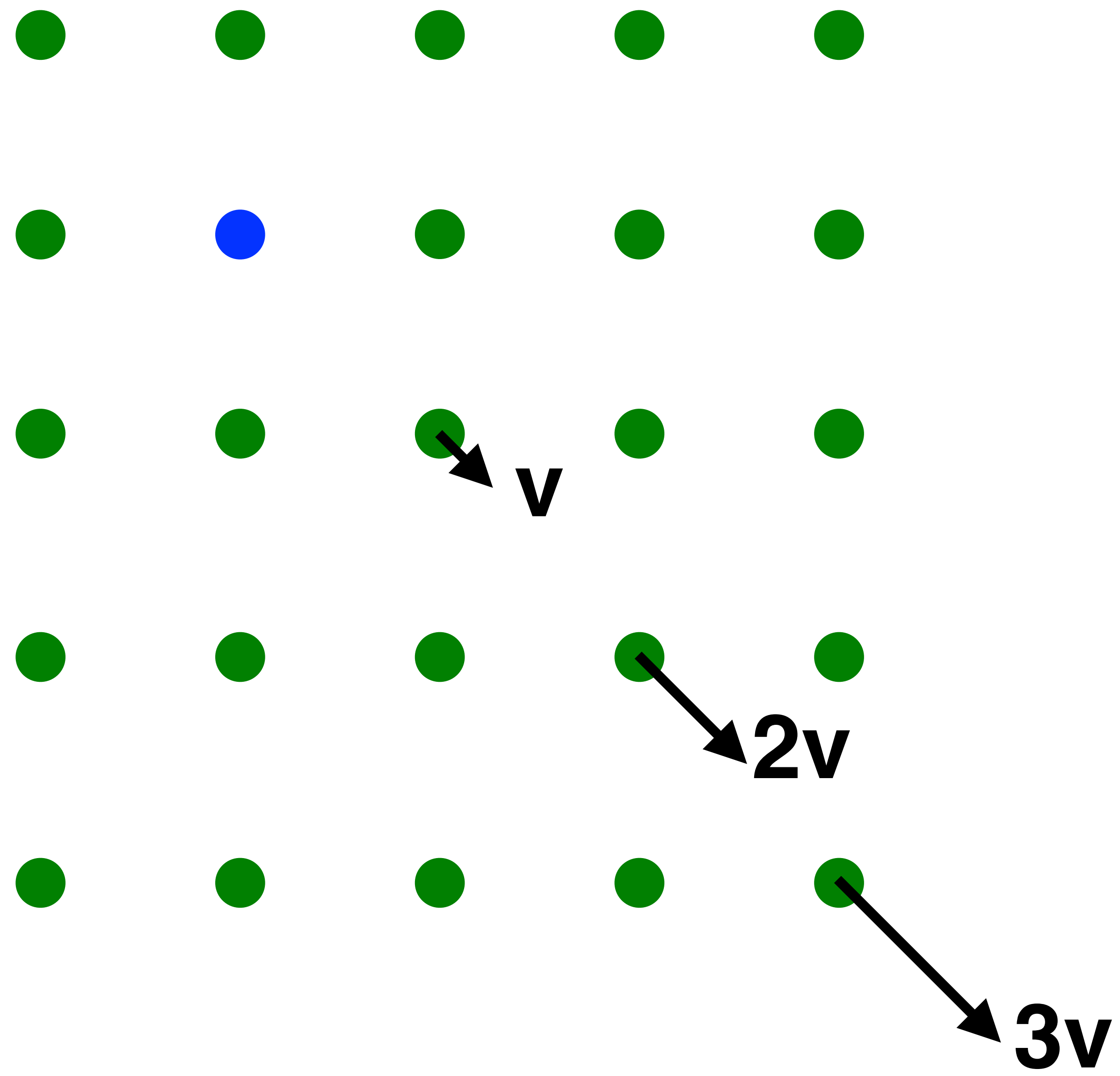


The Universe is Expanding

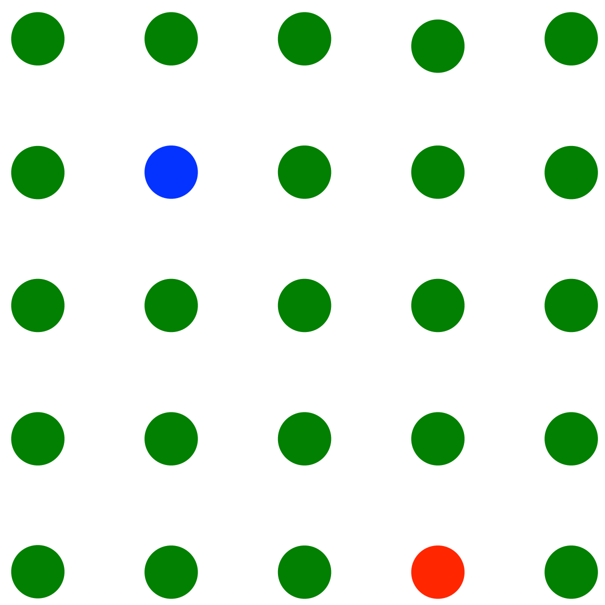
$t = t_2$



The Universe is Expanding



Are We the Center of the Universe?



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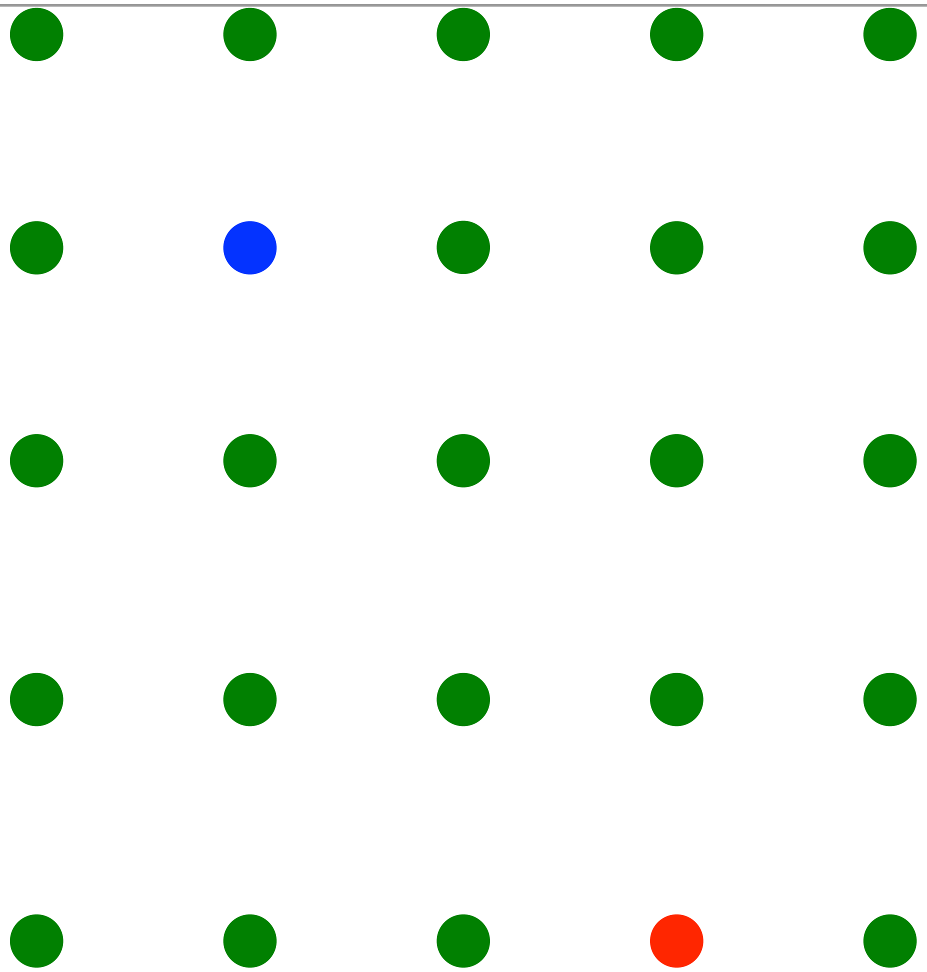
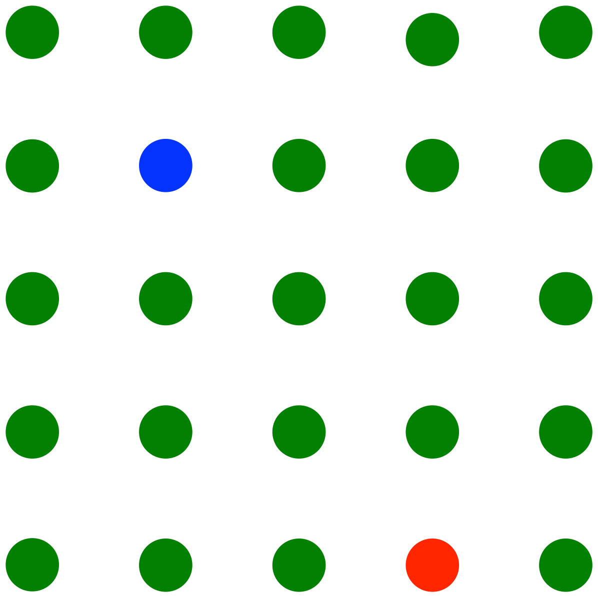


NO!

How about backwards in time?



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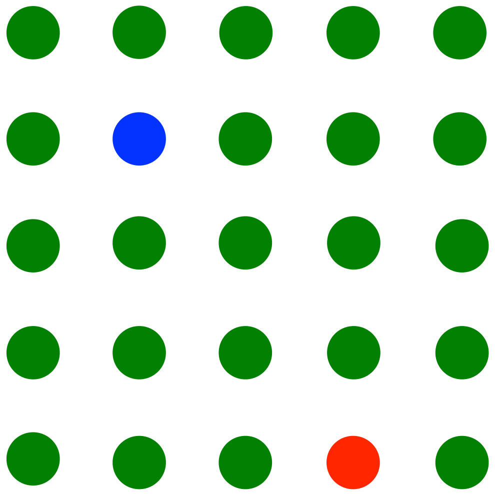

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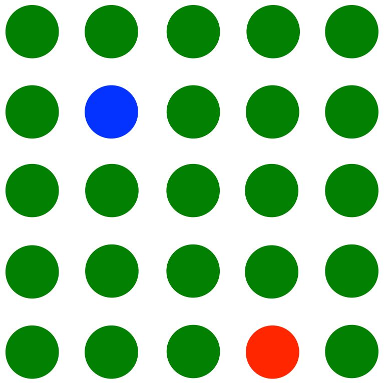
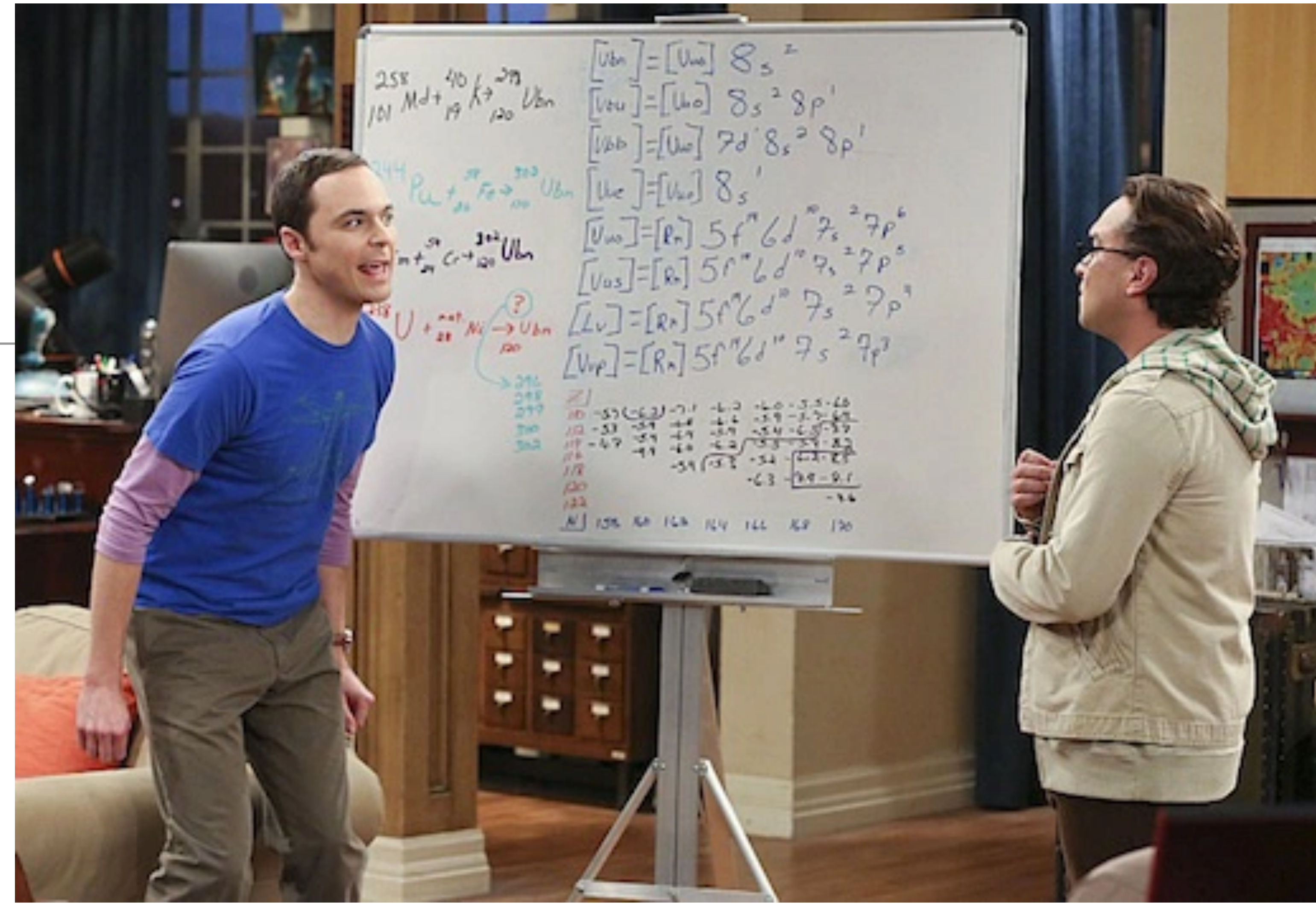


the BIG BANG THEORY



Steady State Model vs "Big Bang" Model

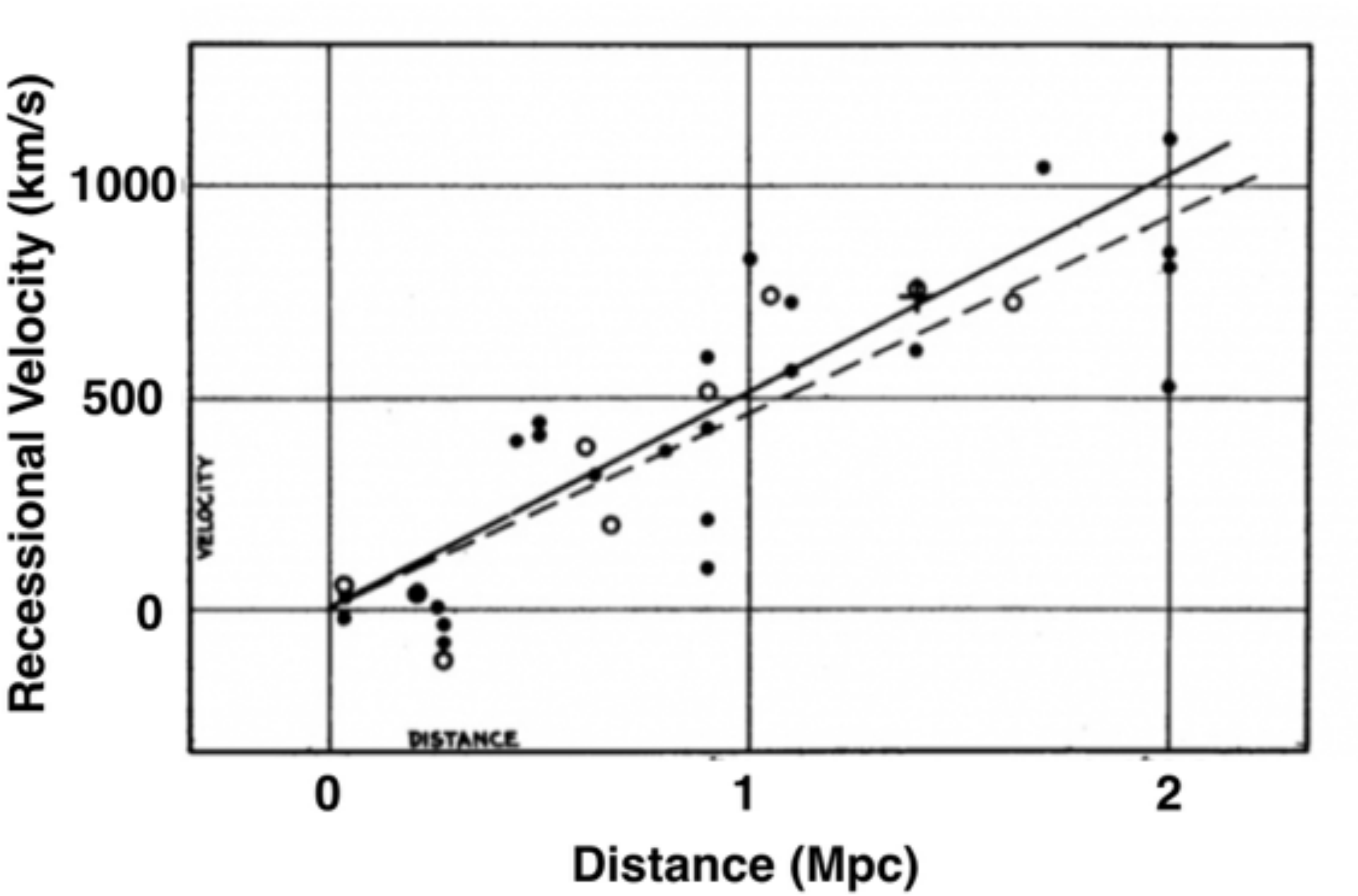
Universe is infinitely old, time has no beginning and no end.

Fred Hoyle
(1915-2001)

Universe is finite, and was hotter and denser in the past.

George Gamow
(1904-1968)

Hubble Constant
H_0 = velocity / distance

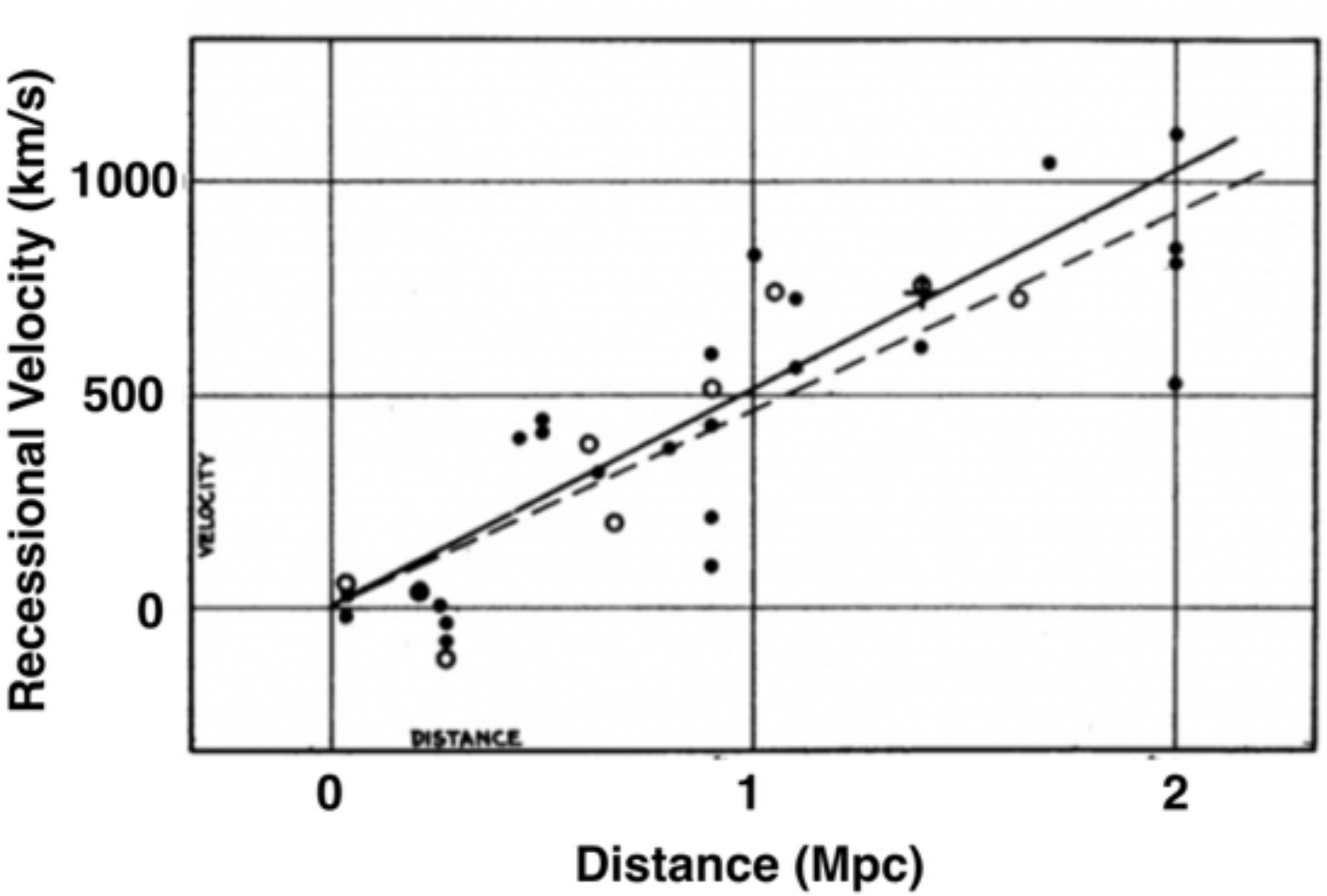


Hubble's estimation

$H_0 = 500 \text{ km s}^{-1} \text{ Mpc}^{-1}$

$$\frac{1}{H_0} \sim \frac{\text{Distance}}{\text{Velocity}}$$

Hubble Constant
H_0 = velocity / distance



Hubble's estimation
$H_0 = 500 \text{ km s}^{-1} \text{ Mpc}^{-1}$

$$\frac{1}{H_0} \sim \textbf{TIME}$$

Age of the Universe
~ 2 billion years

Earth ~ 4.6 billion years

Current best estimation
$H_0 \sim 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$

→

Age of Universe
~ 14 billion years

Steady State Model vs "Big Bang" Model

Steady State Model	"Big Bang" Model
Universe is infinitely old, time has no beginning and no end	Universe is finite, and was hotter and denser in the past

Two hypotheses. Which one is correct?

Scientific Method

→ Making testable predictions!

Some Critical Thinking

If "Big Bang" theory is correct, the Universe is very hot and dense at the beginning.

As the Universe expands, the temperature drops.

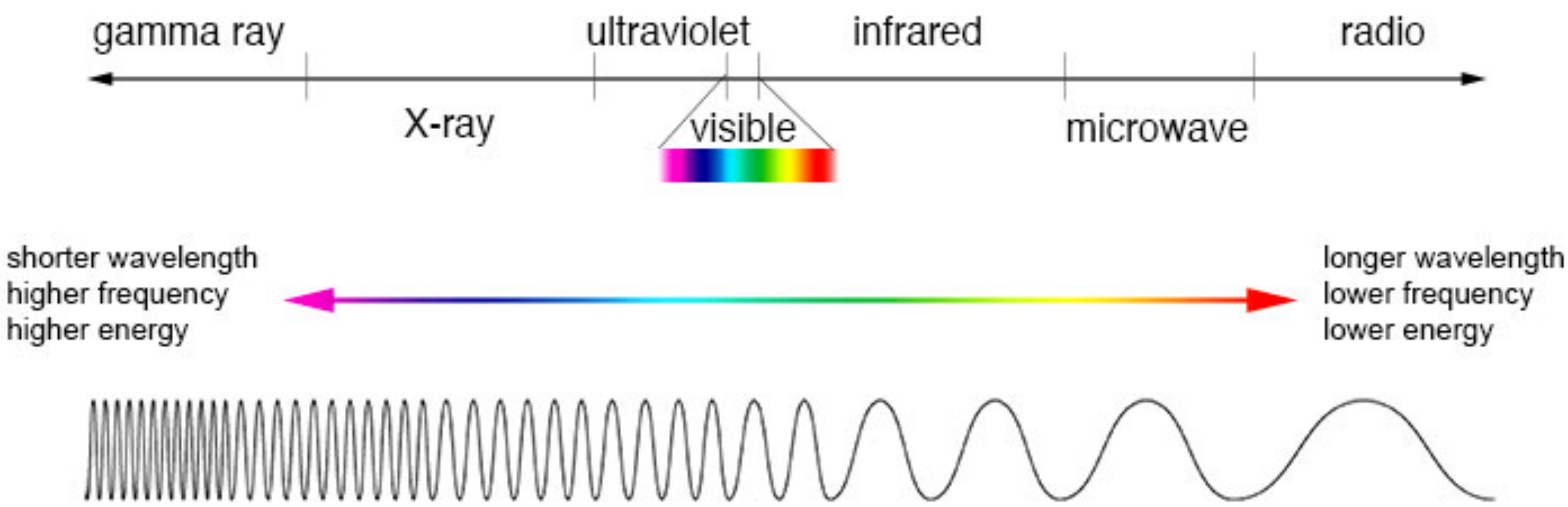
Physicists calculated that current Universe should have a temperature of 3 K. (-454.27 °F)

What signal will we see for this 3 K Universe?

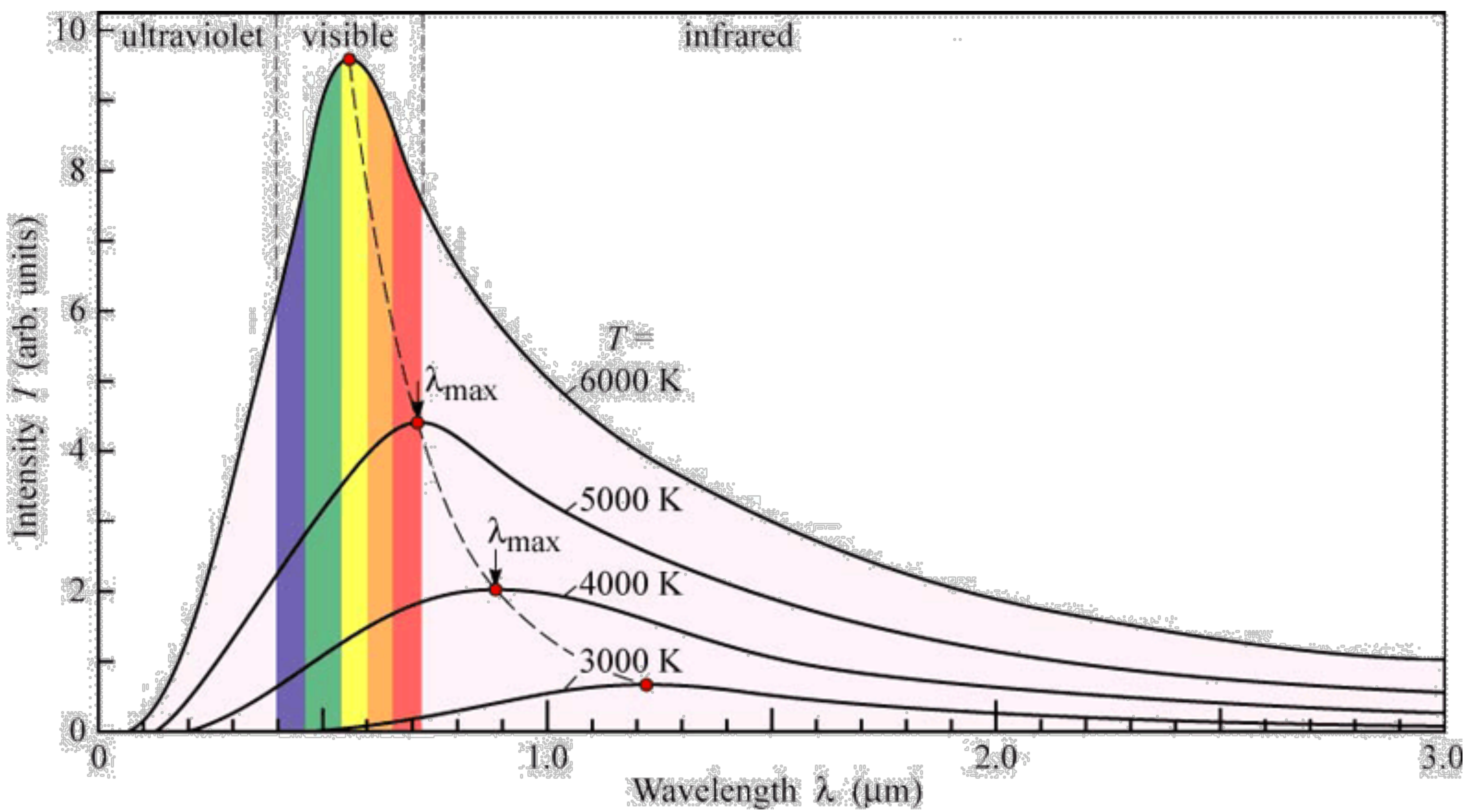
Universe glow in microwave.

Cosmic Microwave Background Radiation

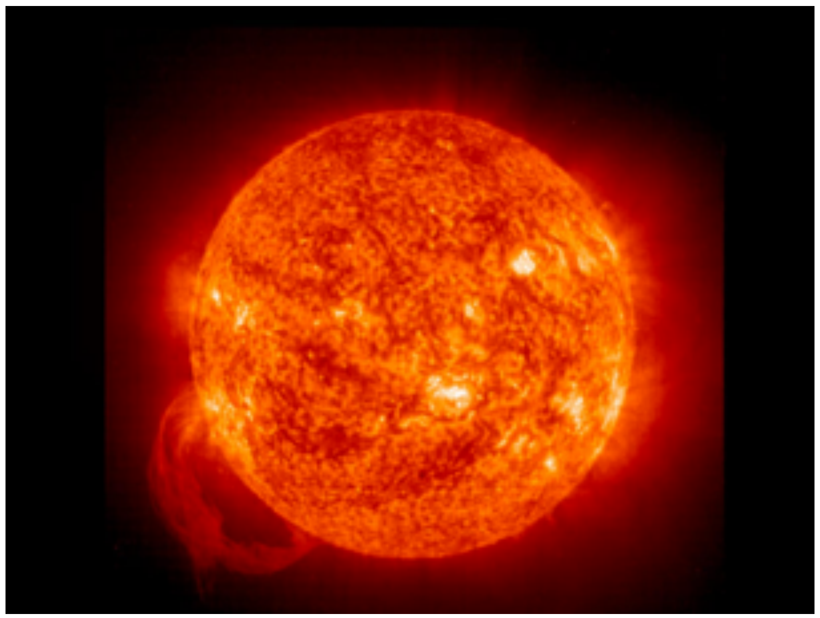
Electromagnetic Spectrum



Thermal/Blackbody Radiation



Thermal/Blackbody Radiation



Sun (~6000 K) glow in visible.

We (~300 K) glow in infrared.

The Universe (~3 K) glow in microwave.

Some Critical Thinking

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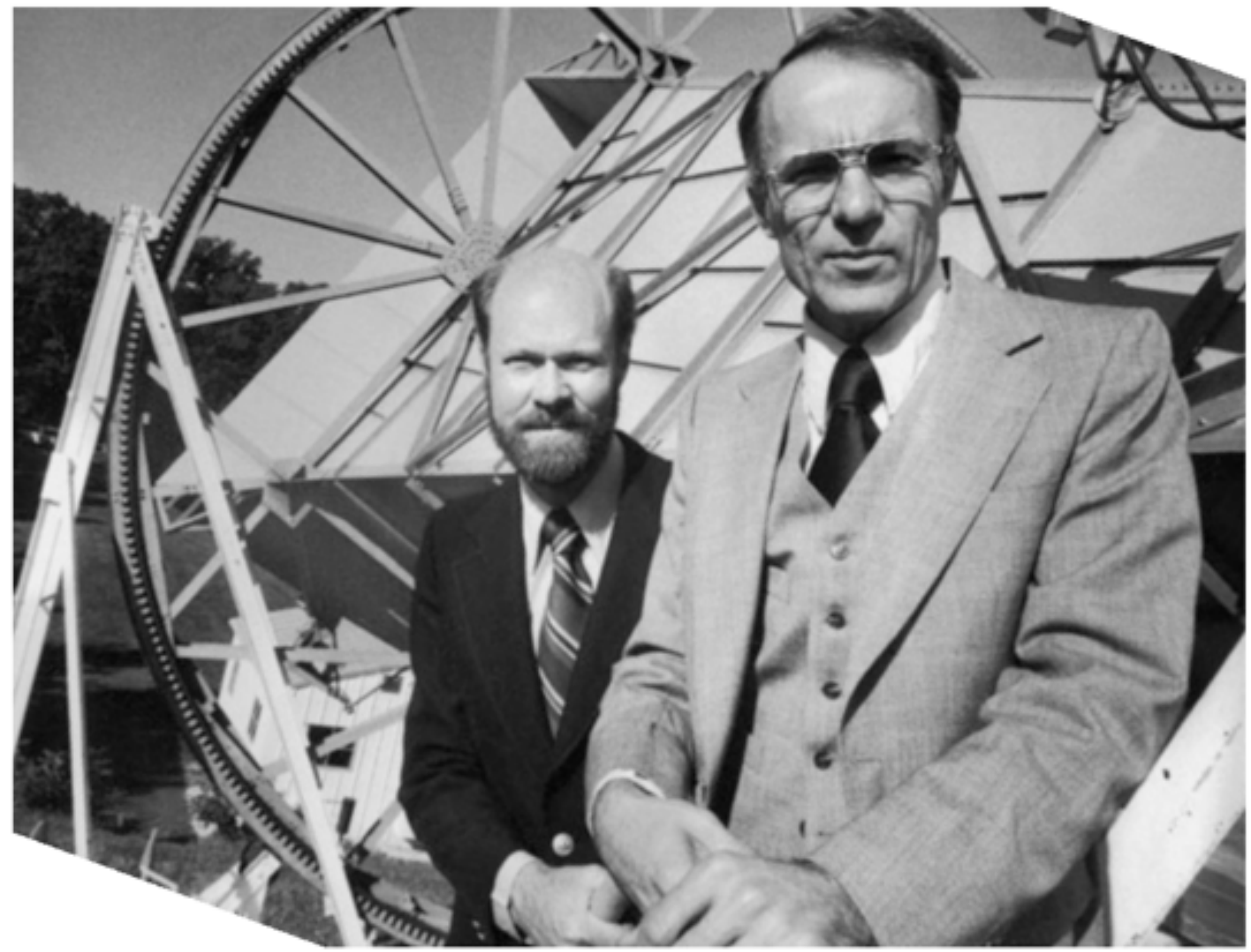
Cosmic Microwave Background Radiation

Story of the Discovery

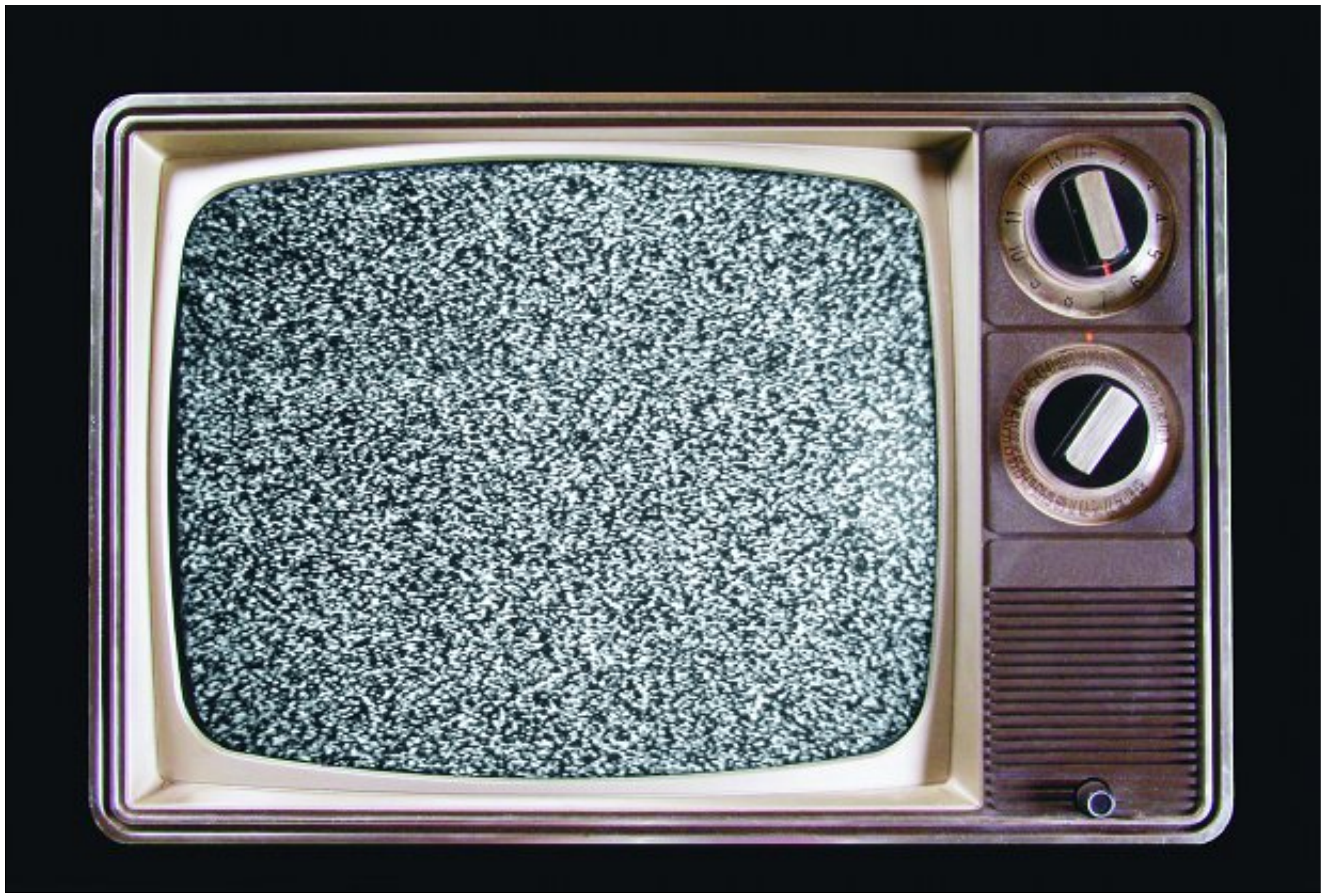
Working for Bell Lab, in 1964 Wilson and Penzias were building a huge horn antennae to communicate with AT&T's Telstar satellite.

They detected a continuous noise from all directions of the sky.



Robert Wilson (left) and Arno Penzias (right) with their 6m Microwave antennae (horn).

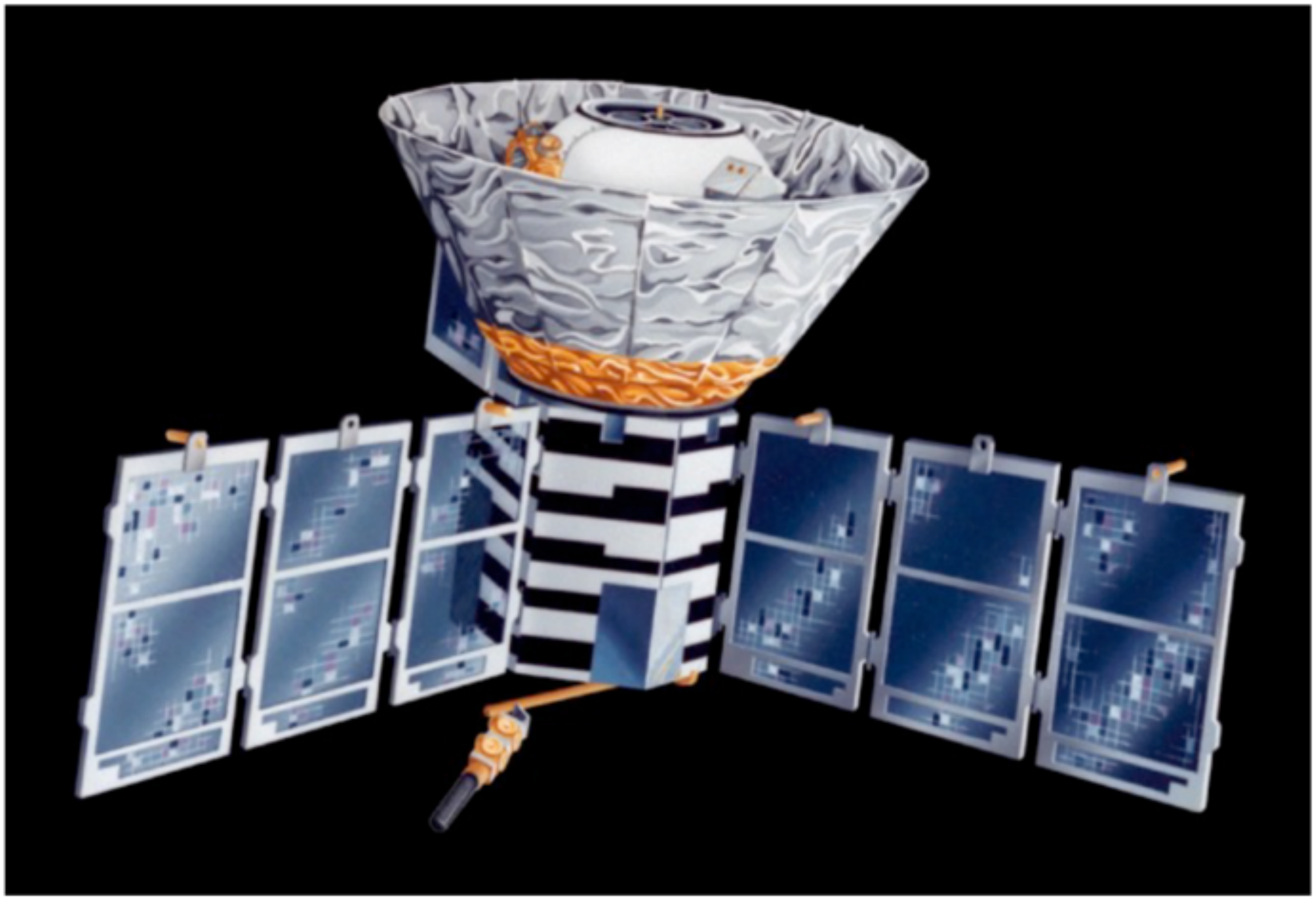
Story of the Discovery



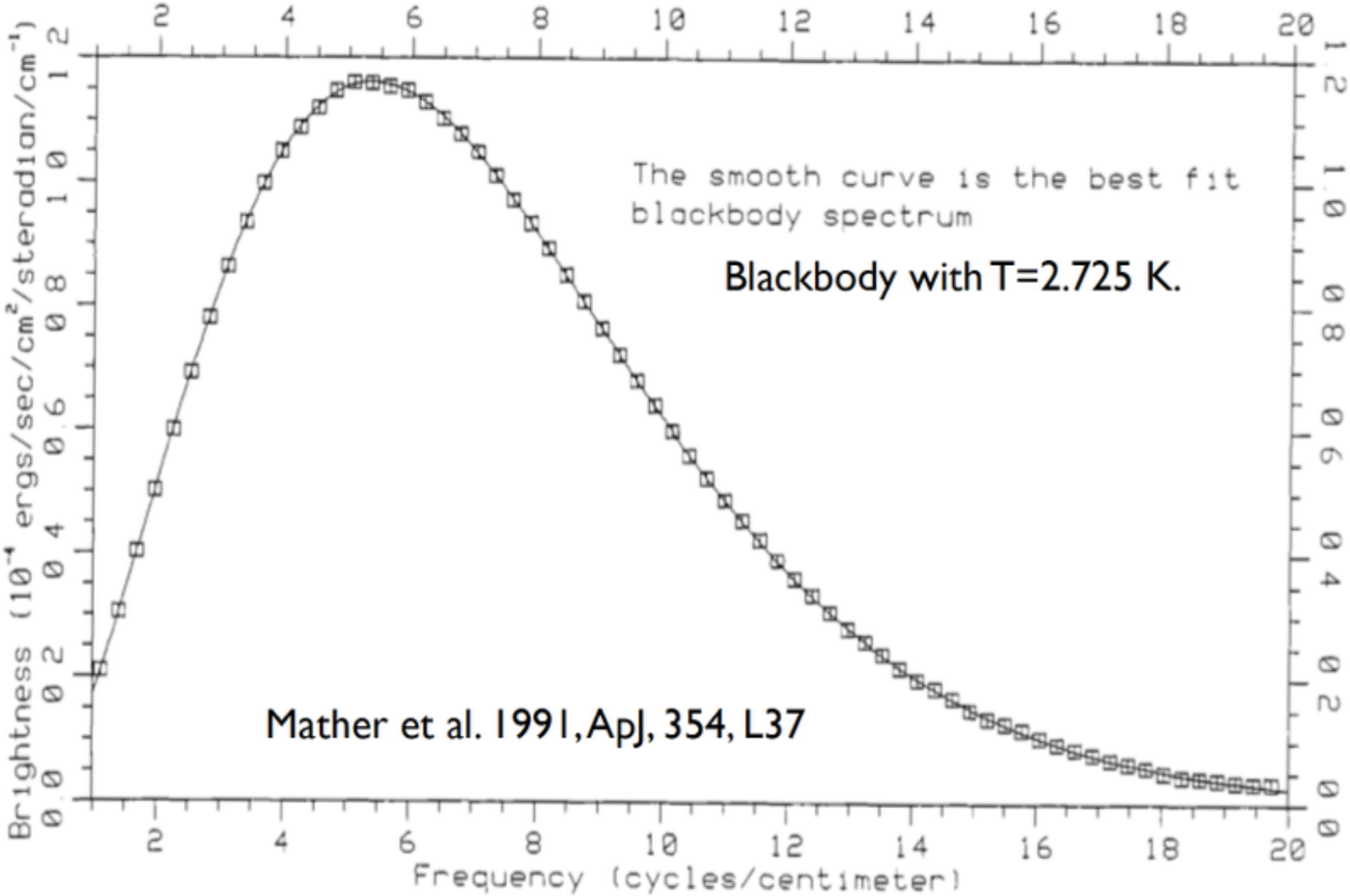
A very small fraction of the TV noise is from the CMB radiation

COsmic Background Explorer (COBE)

In 1991 the COBE satellite measured the full spectrum of the CMB.



Cosmic Microwave Background Radiation



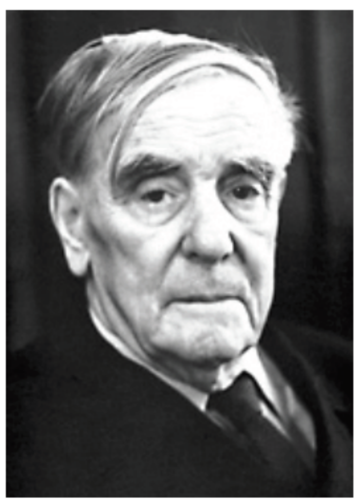
This result was a death sentence for the Steady State Model.

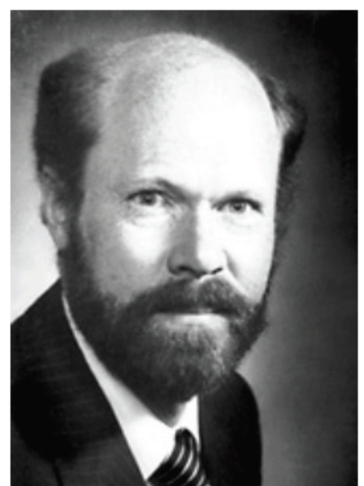
Cosmic Microwave Background Radiation

The Nobel Prize in Physics 1978

"for his basic inventions and discoveries in the area of low-temperature physics"

"for their discovery of cosmic microwave background radiation"





Pyotr Leonidovich Kapitsa

1/2 of the prize

USSR

Academy of Sciences
Moscow, USSR

b. 1894
d. 1984

Arno Allan Penzias

1/4 of the prize

USA

Bell Laboratories
Holmdel, NJ, USA

b. 1933
(in Munich, Germany)

Robert Woodrow Wilson

1/4 of the prize

USA

Bell Laboratories
Holmdel, NJ, USA

b. 1936

Titles, data and places given above refer to the time of the award.

The Nobel Prize in Physics 2006

"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"

Photo: NASA

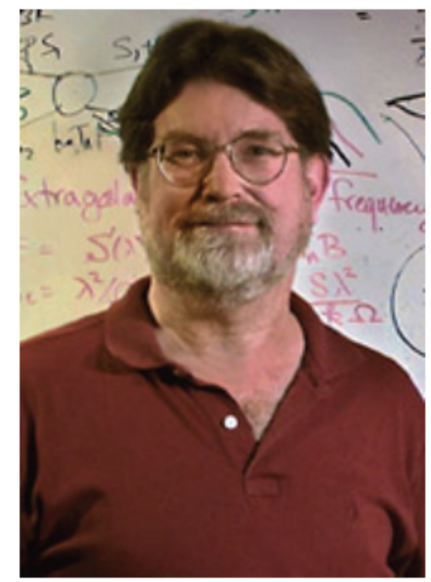


Photo: R. Kaltschmidt/LBNL

John C. Mather

1/2 of the prize

USA

NASA Goddard Space Flight Center
Greenbelt, MD, USA

b. 1946

George F. Smoot

1/2 of the prize

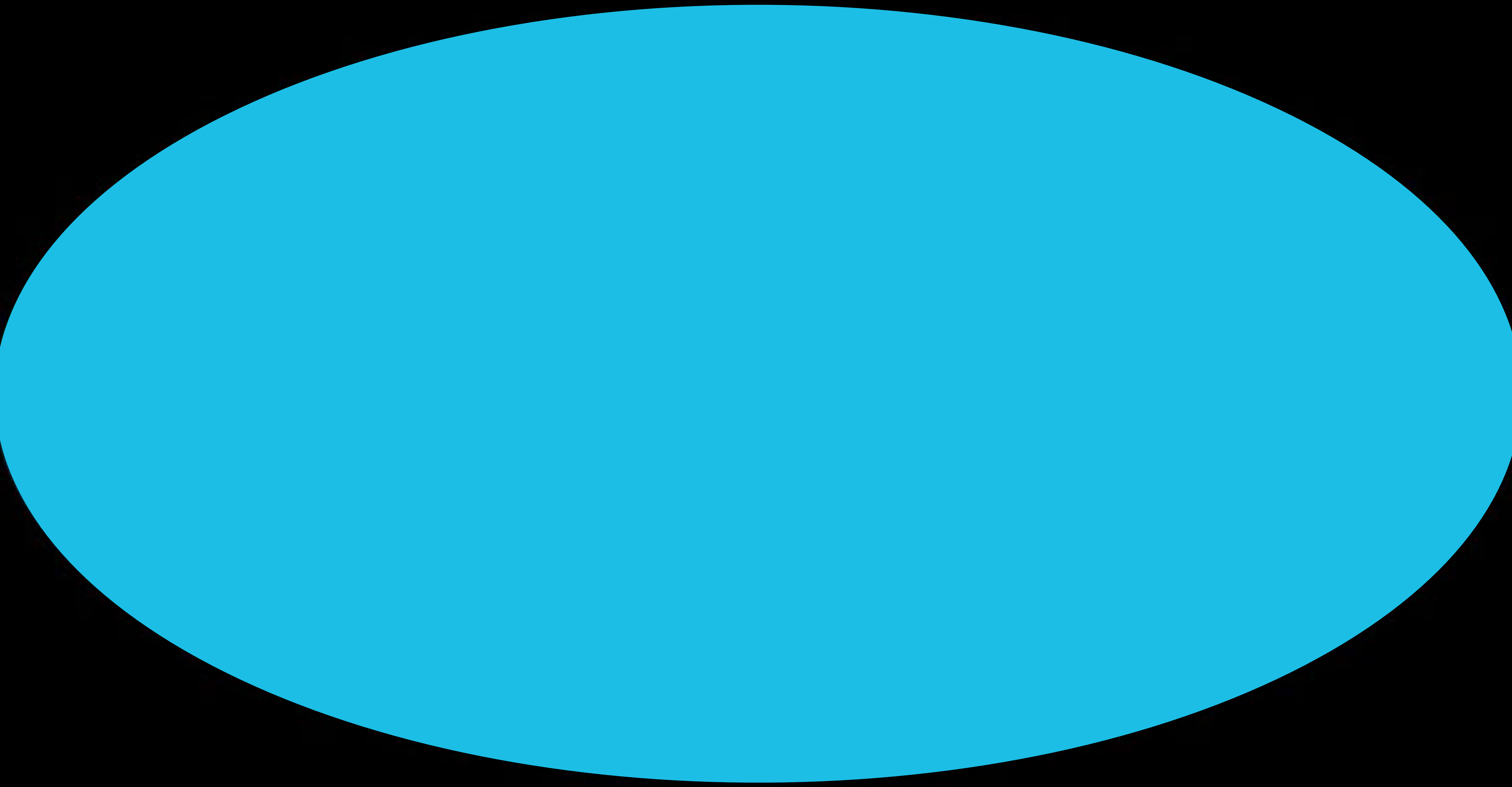
USA

University of California
Berkeley, CA, USA

b. 1945

Titles, data and places given above refer to the time of the award.

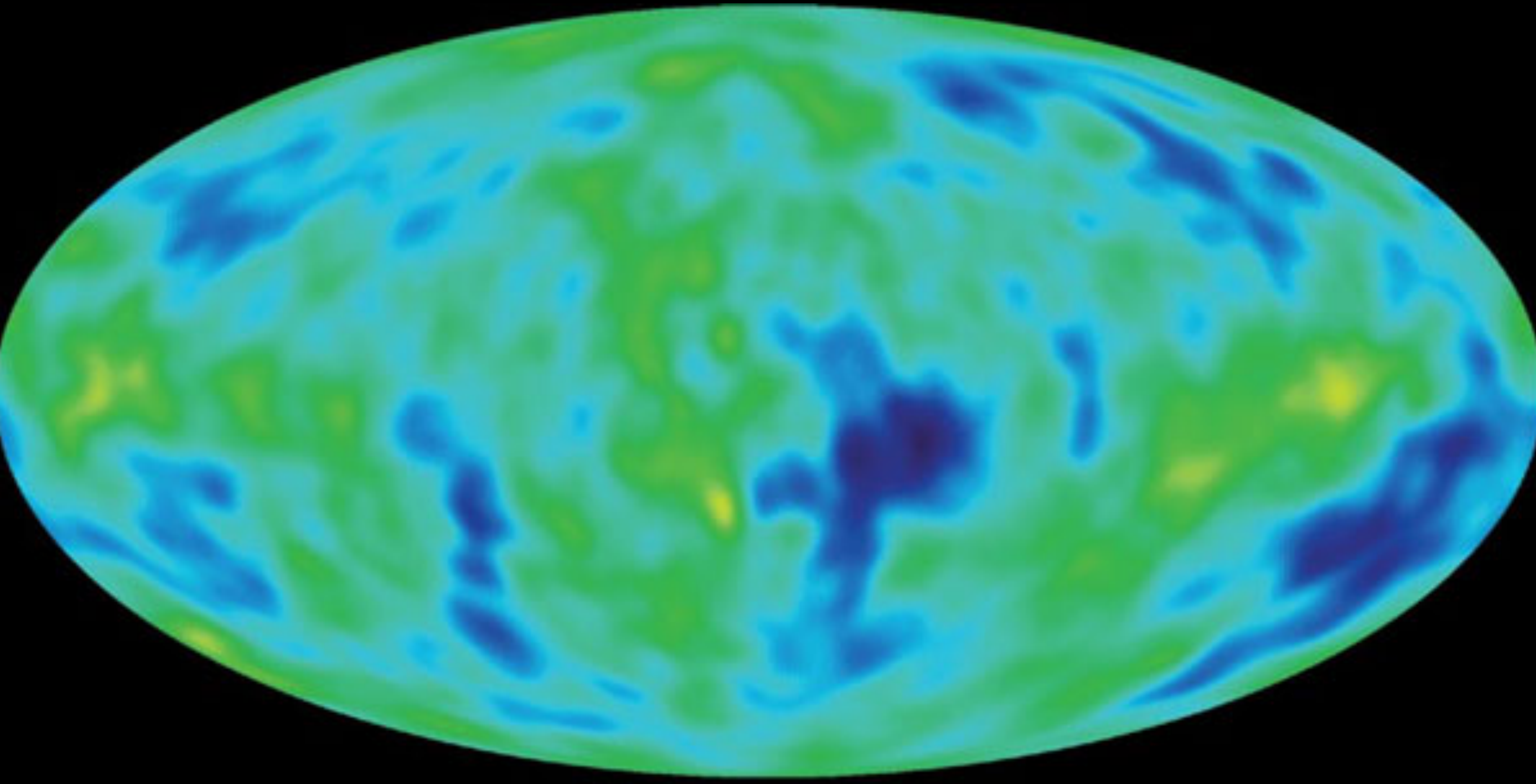
Cosmic Microwave Background Radiation



COBE Satellite

Temperature ~ 2.7 K

Cosmic Microwave Background Radiation

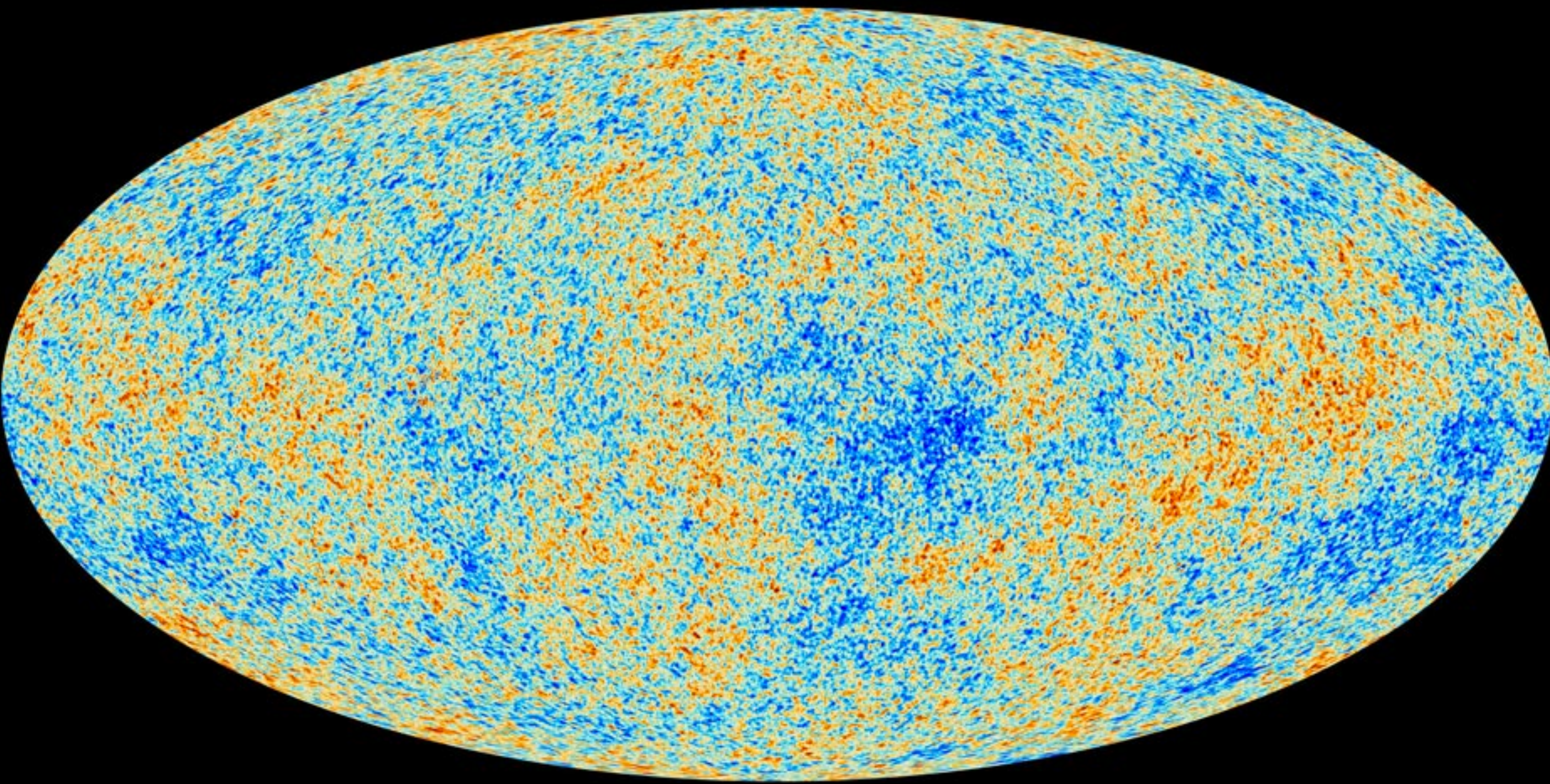


COBE Satellite

Temperature ~ 2.7 K

Temperature difference < 0.01 K

Cosmic Microwave Background Radiation



Planck Satellite

Temperature ~ 2.7 K

Temperature difference < 0.01 K

Questions?

The Universe started with a Big Bang

The Origin

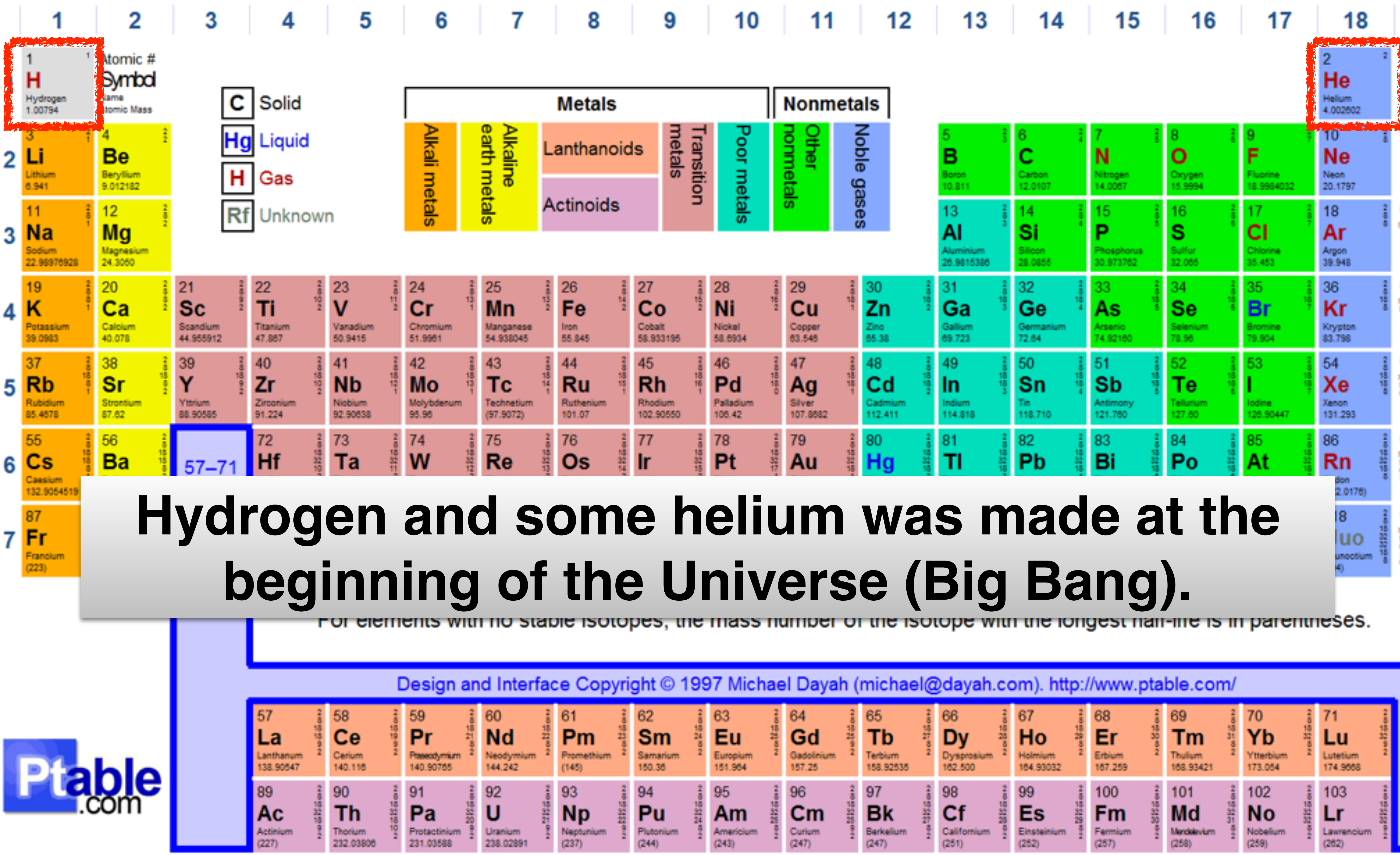
We are all Stardust

The Evolution

The Universe is mostly "Dark"

The Fate

Periodic Table of Elements

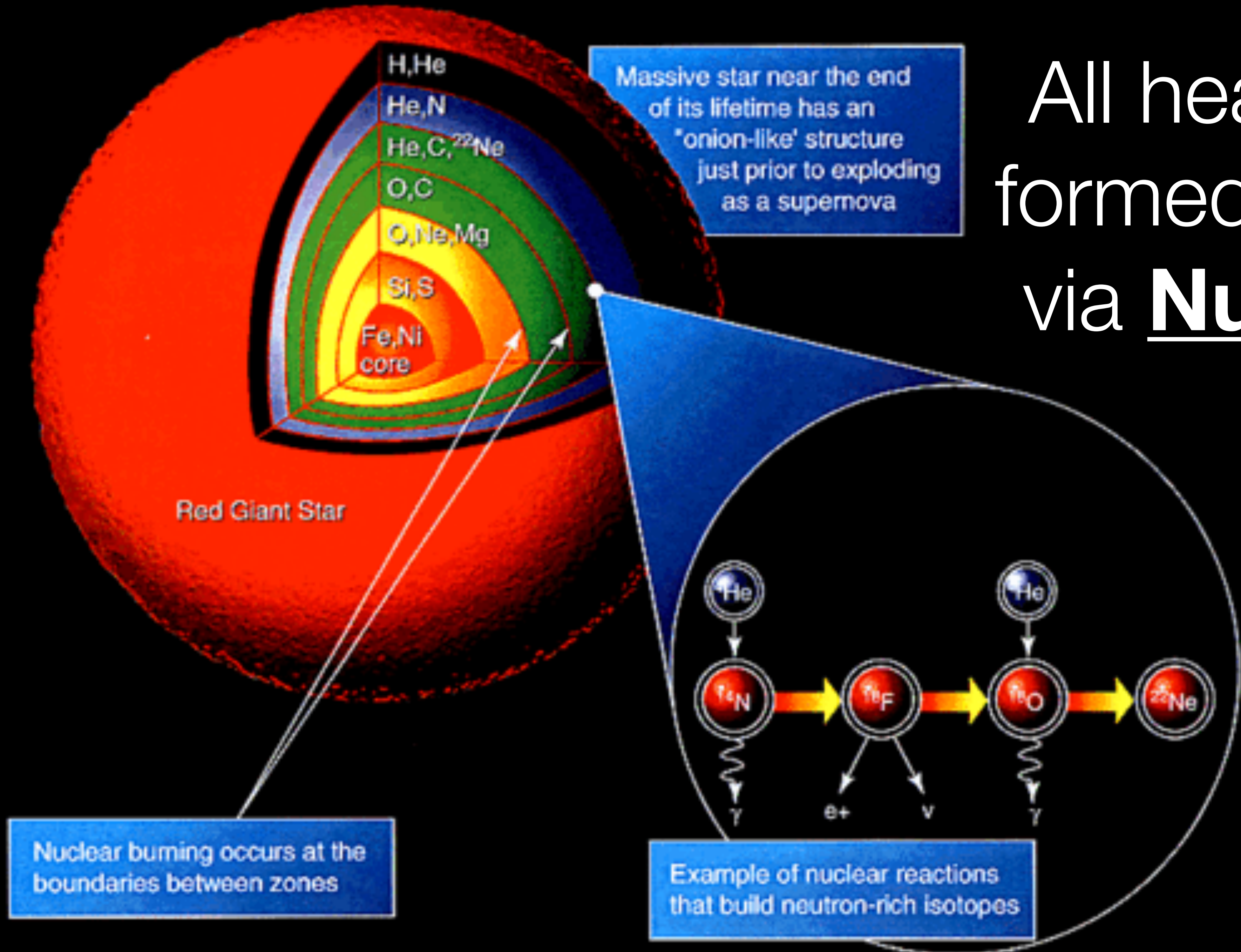


Hydrogen and some helium was made at the beginning of the Universe (Big Bang).

Where are the heavier elements from?

How can our Sun produce heat?

Nuclear Fusion

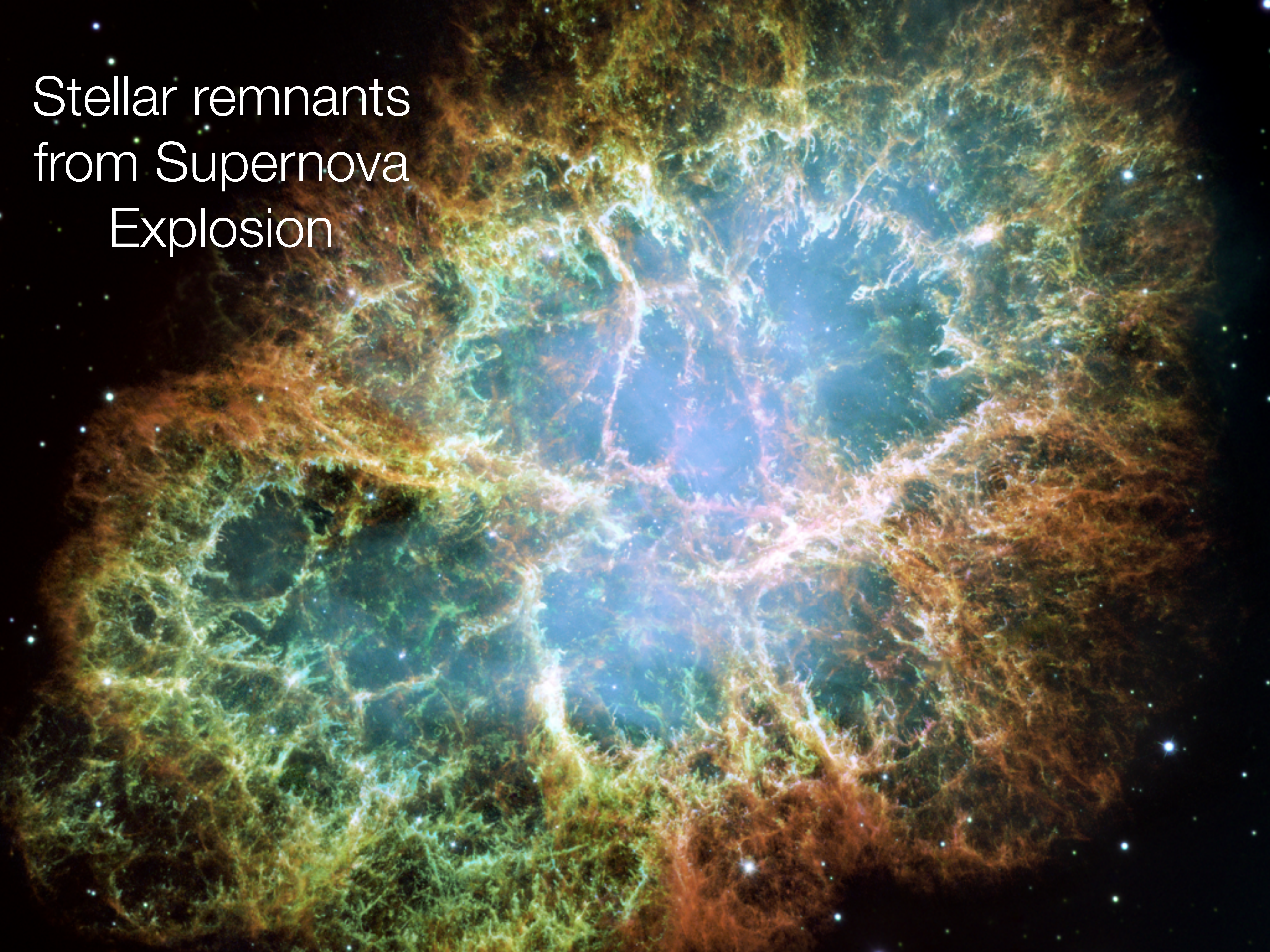


All heavier elements formed inside of stars via **Nuclear Fusion**

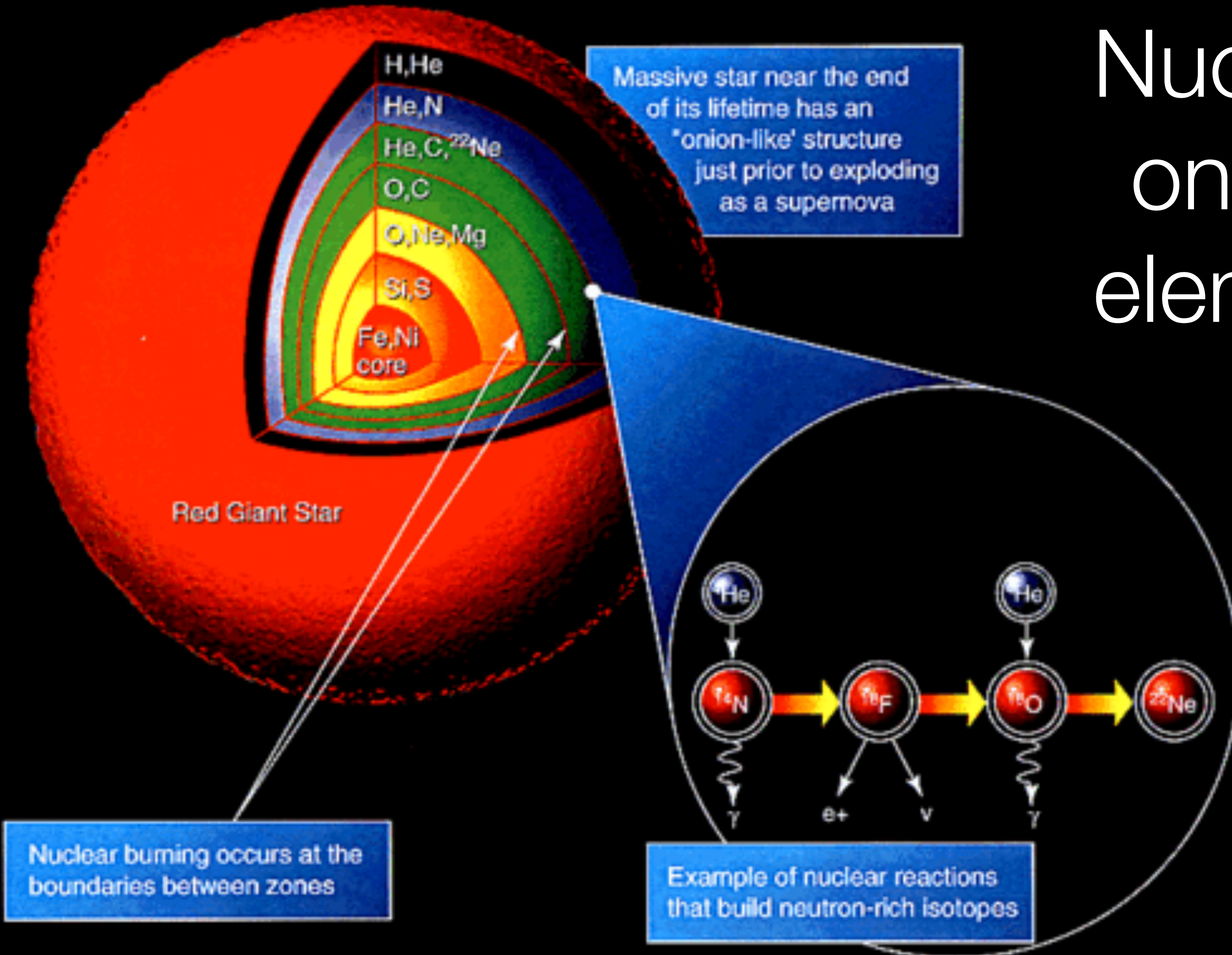
Hydrogen→Helium→Carbon→Oxygen→Neon→Magnesium→Silicon→Iron

Stellar Nucleosynthesis


Supernova: an exploding star.
The death of a massive star.


Stellar remnants
from Supernova
Explosion

Nuclear Fusion only produce elements up to **iron**.



Hydrogen→Helium→Carbon→Oxygen→Neon→Magnesium→Silicon→Iron

Think about an element heavier than iron.

Gold

Gold are produced via Binary Neutron Star Merger

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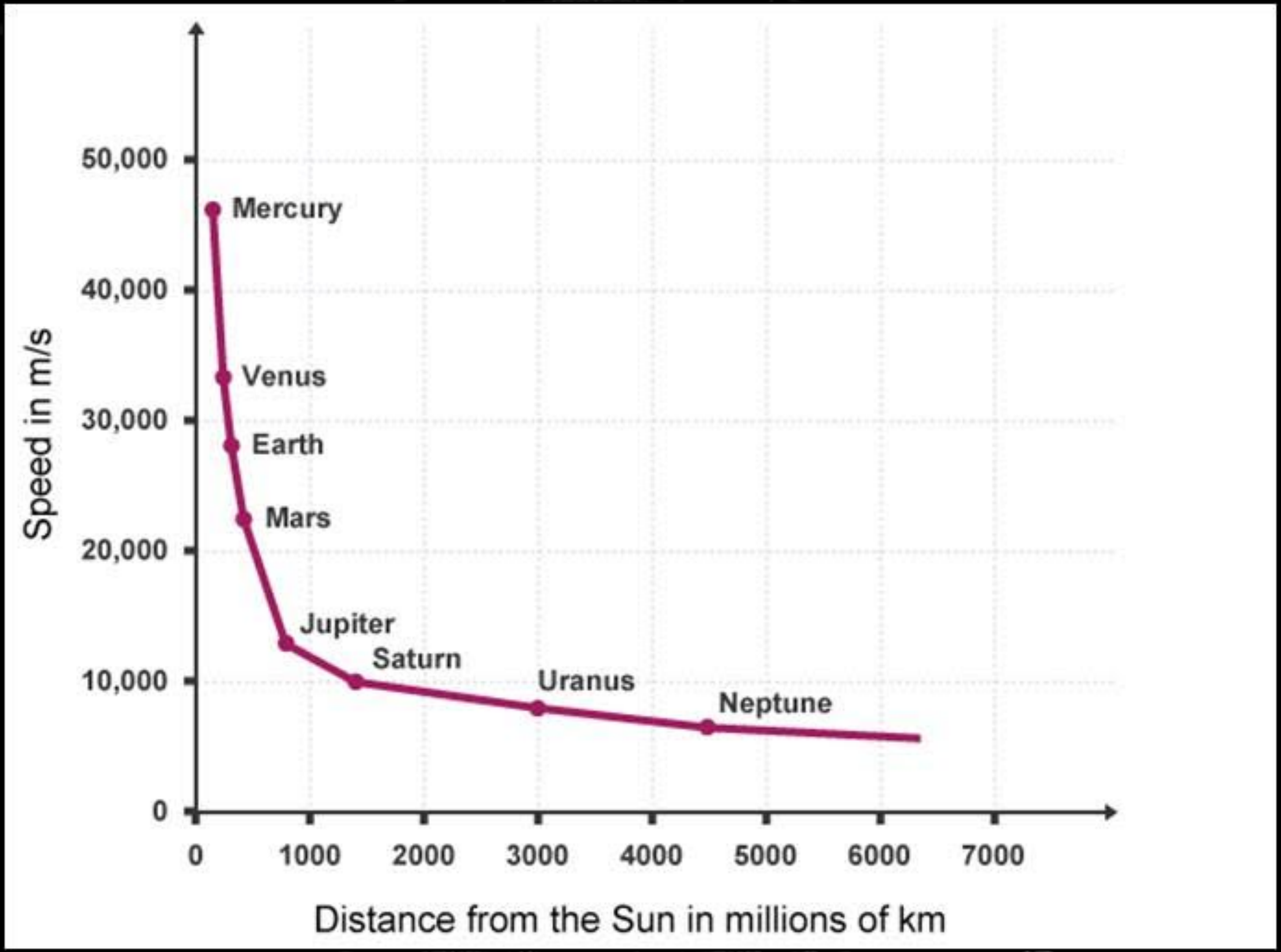
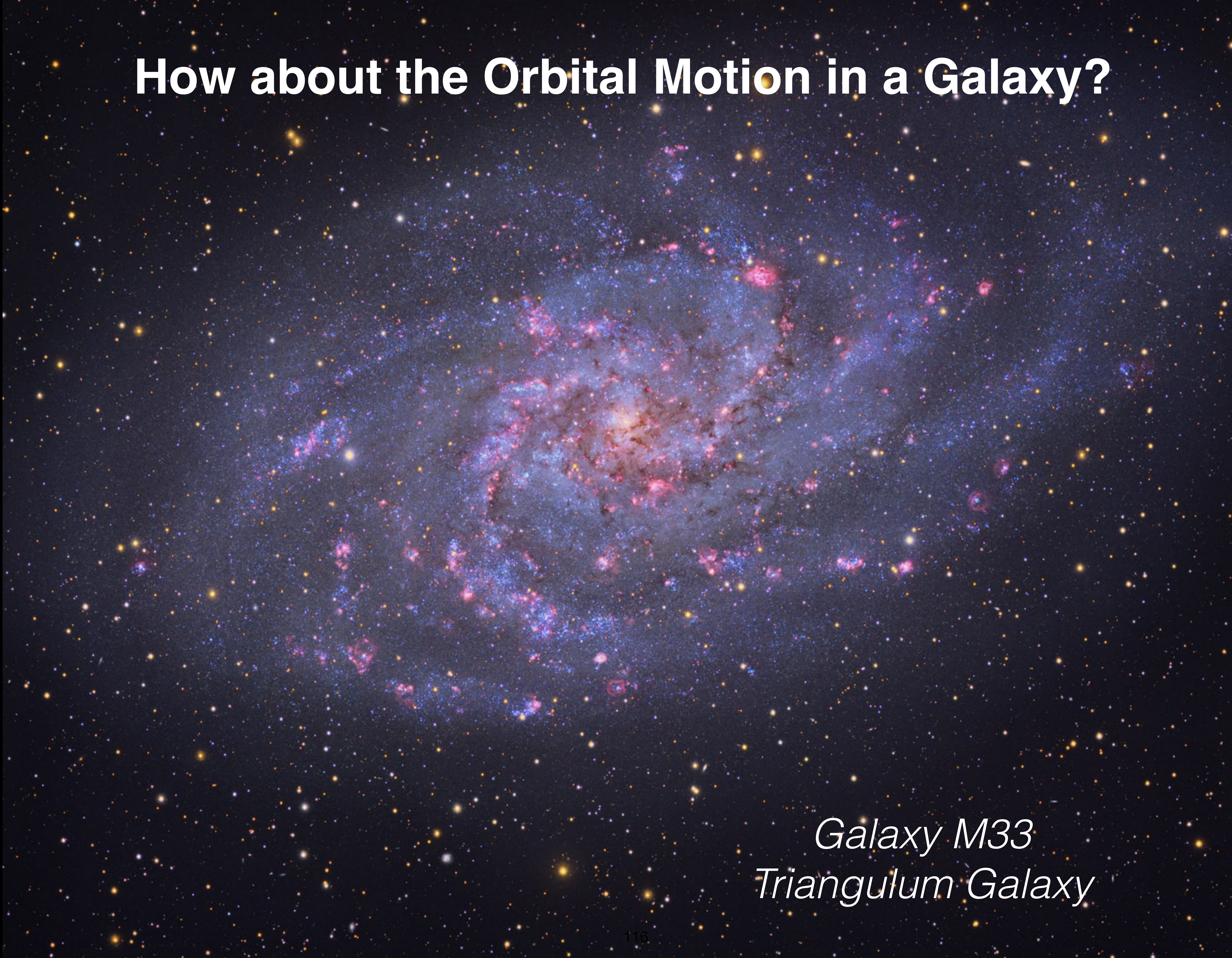
Orbital Motion of Planets in Our Solar System

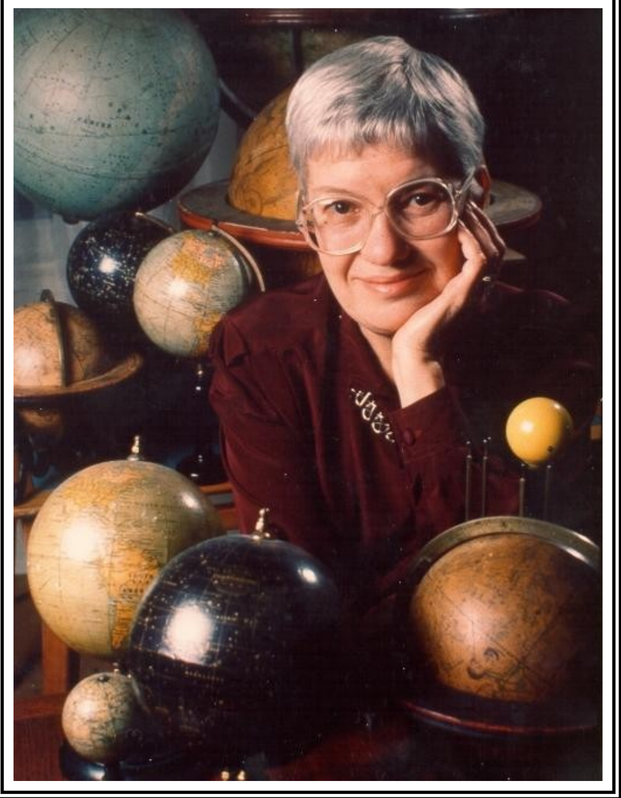


How about the Orbital Motion in a Galaxy?

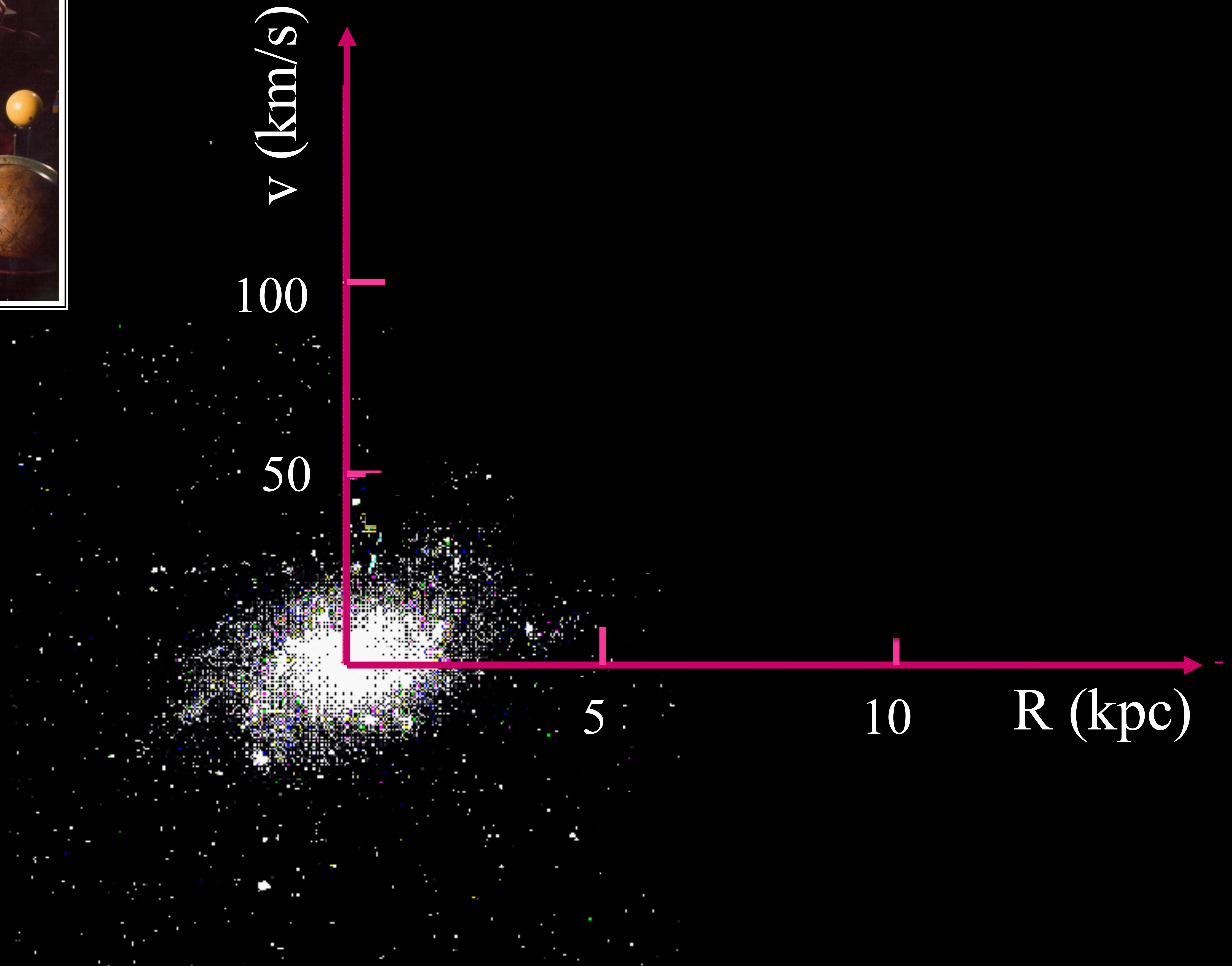


Galaxy M33
Triangulum Galaxy

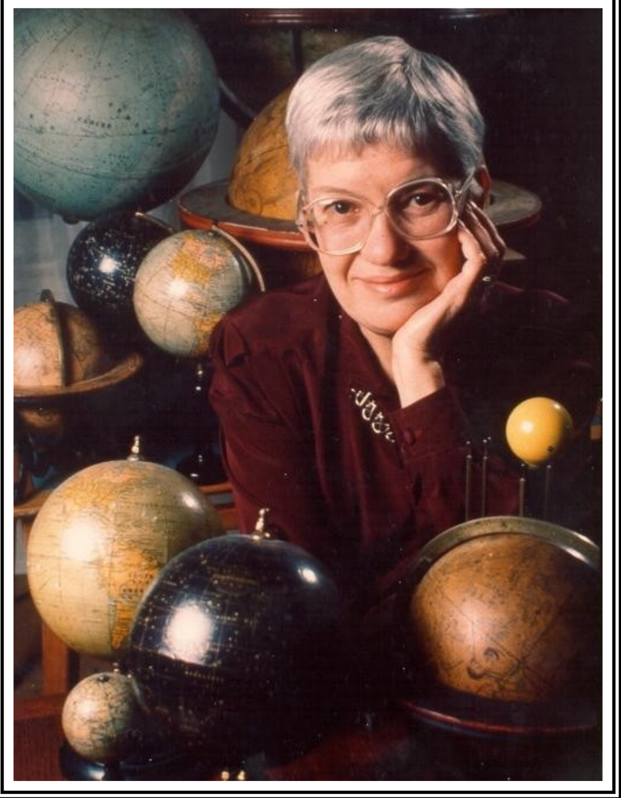
Orbital Motion in Galaxy M33



Vera Rubin
(1970's)



Orbital Motion in Galaxy M33



Vera Rubin
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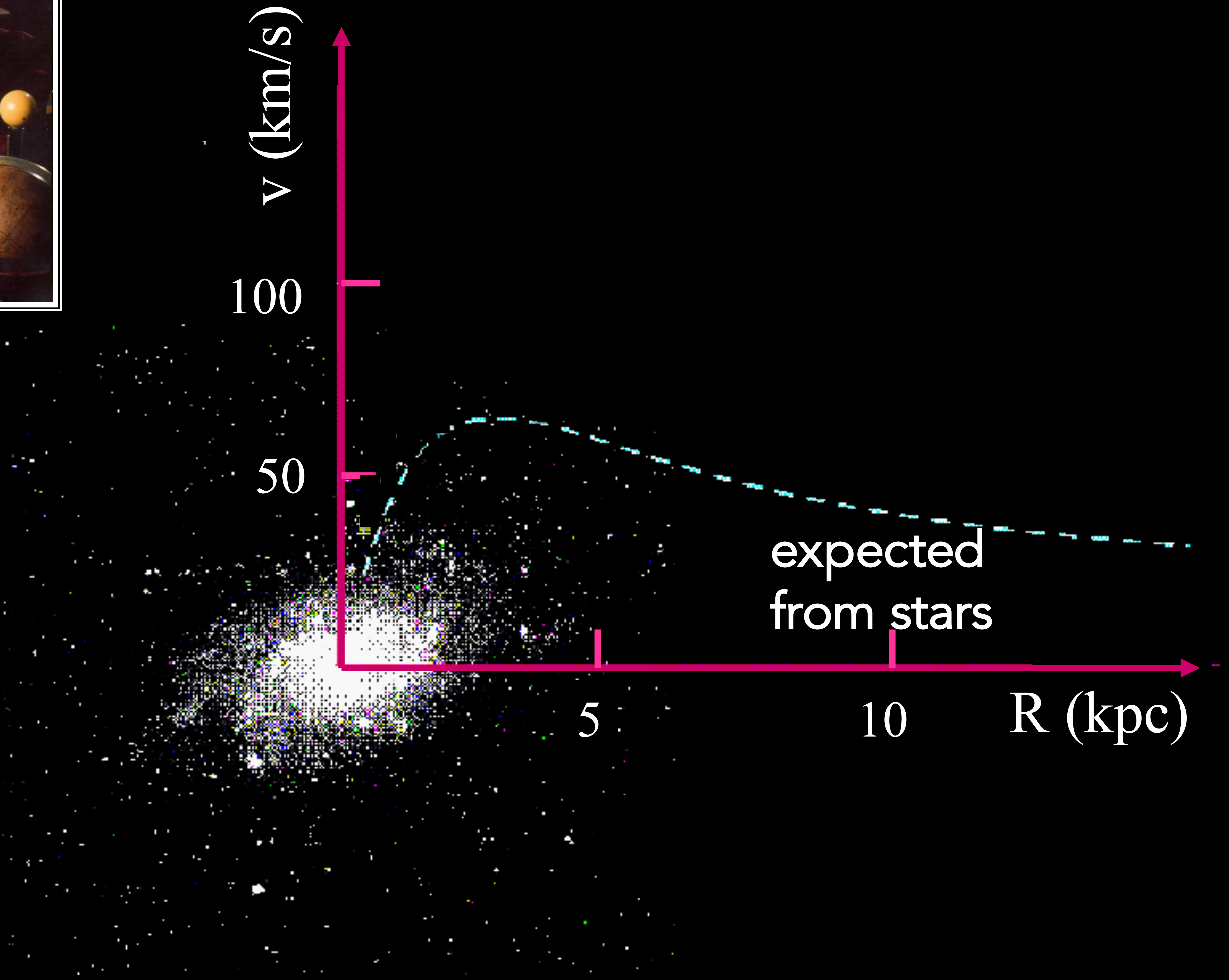
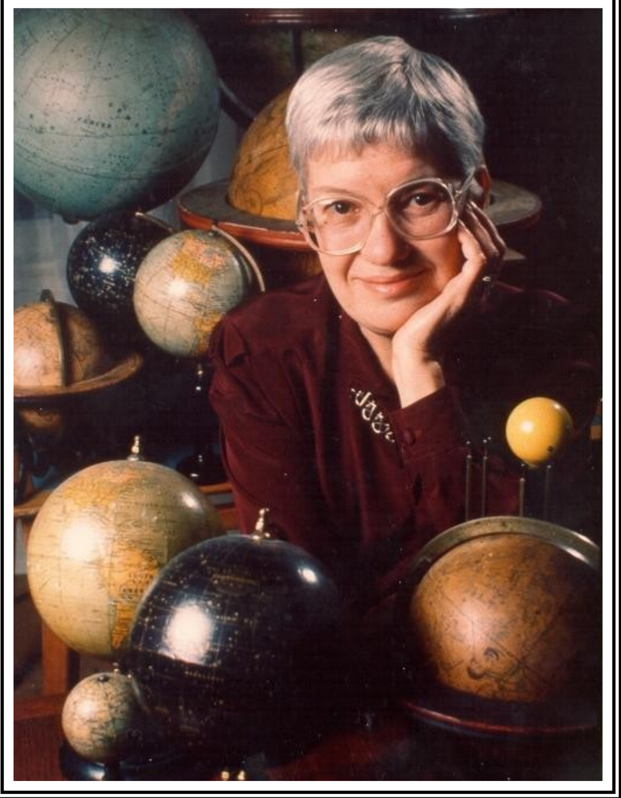


Orbital Motion in Galaxy M33



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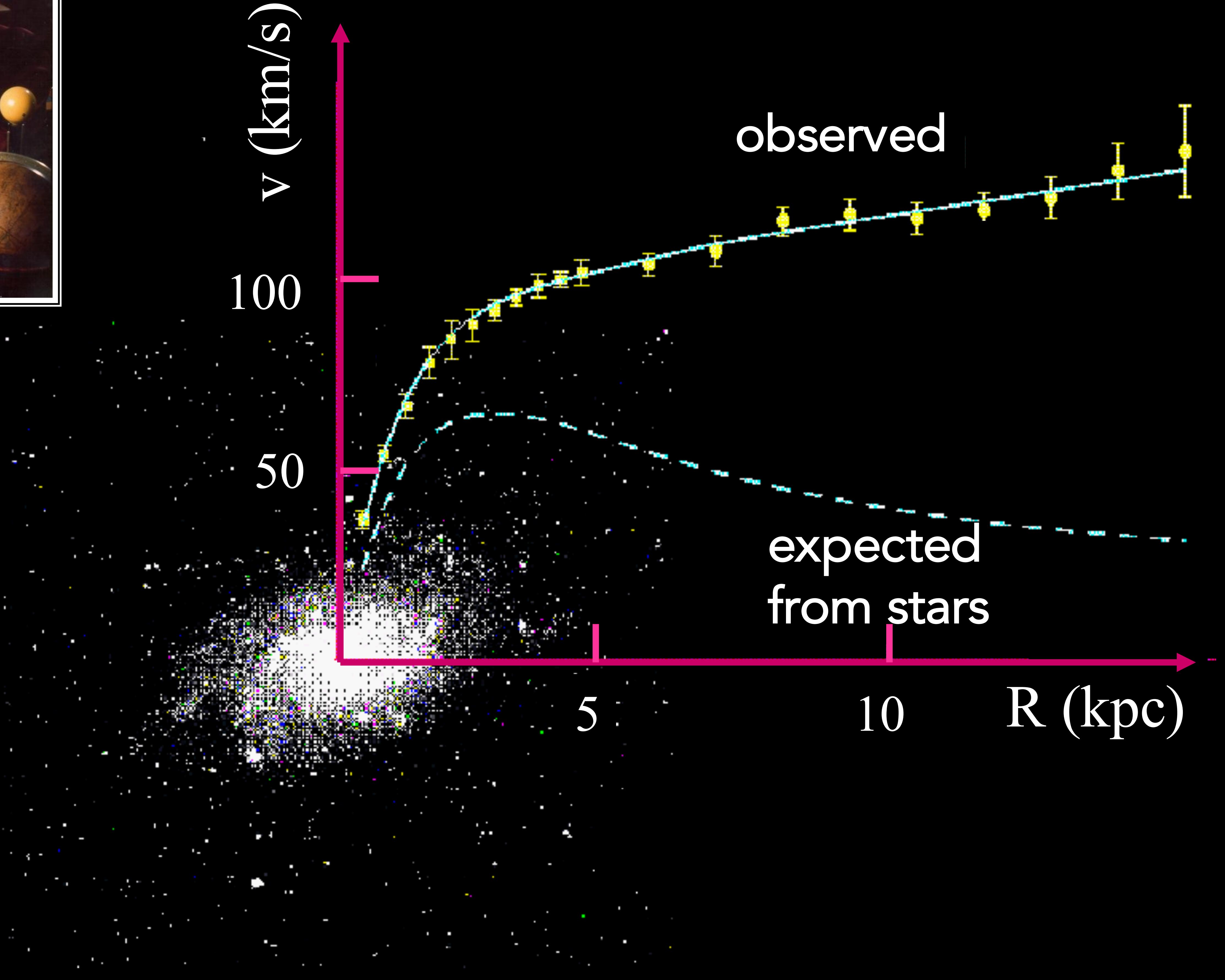
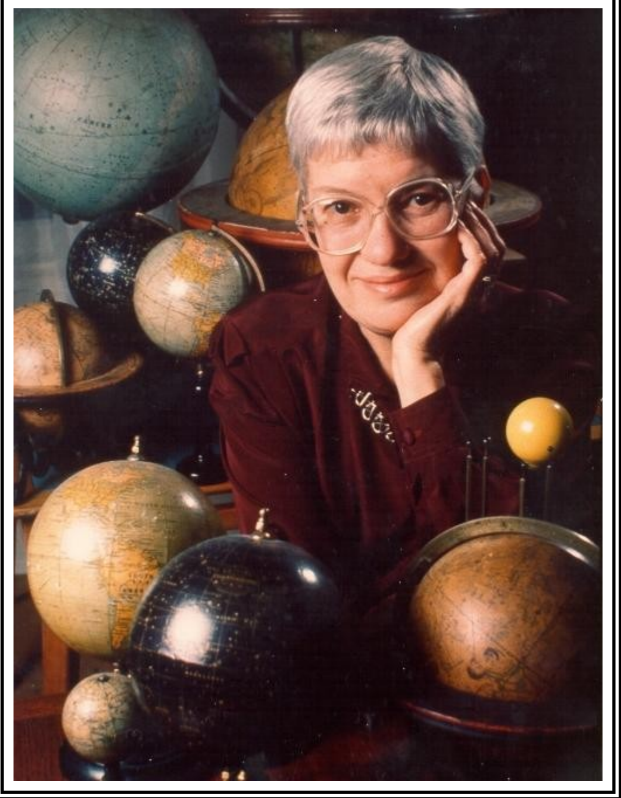


Orbital Motion in Galaxy M33



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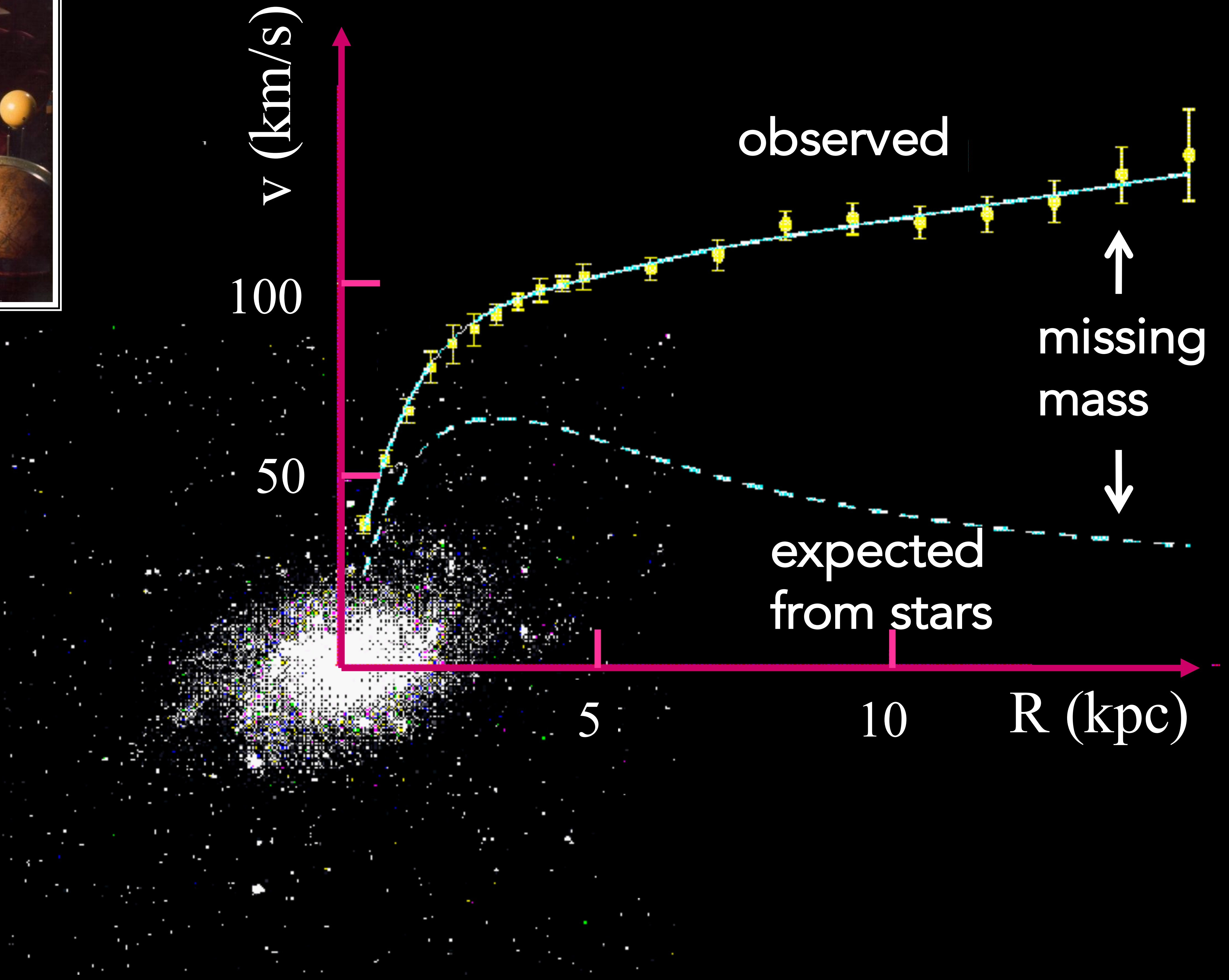
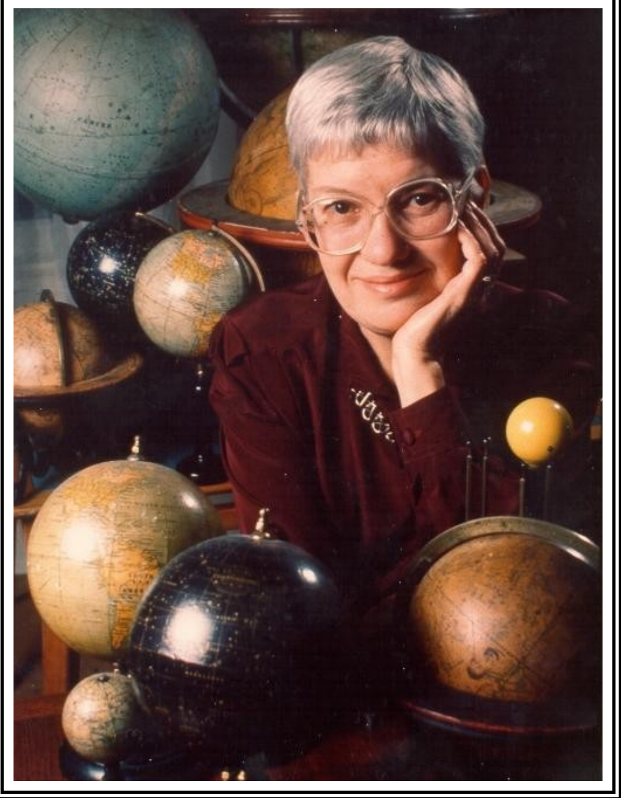
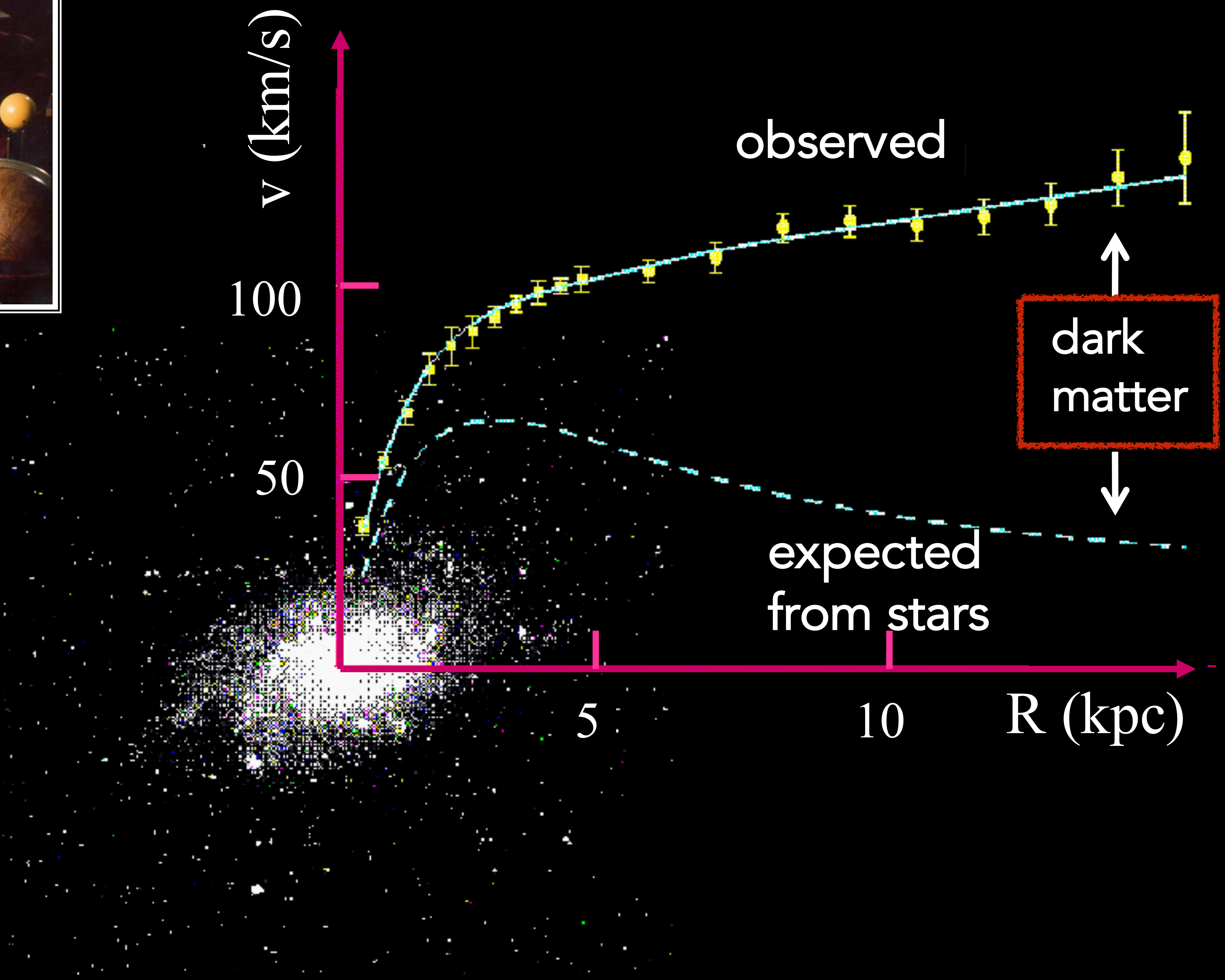


Orbital Motion in Galaxy M33



Vera Rubin
(1970's)



What is Dark Matter?

- Dark matter does not produce any light or electromagnetic wave
- We know dark matter is there because it exerts gravitational pull on the stars we can see in galaxies.
- Dark matter must be made of something other than atoms (or quarks): perhaps a new kind of elementary particle that we've never seen before.

Questions?

The Ultimate Fate of the Universe

- The Universe is expanding. Big Bang

- Gravity pull everything together.

ordinary matter and dark matter

- The expansion should be slowing down.

measuring the deceleration rate q_0

Throw a ball to the sky and what will happen?

Group Discussion

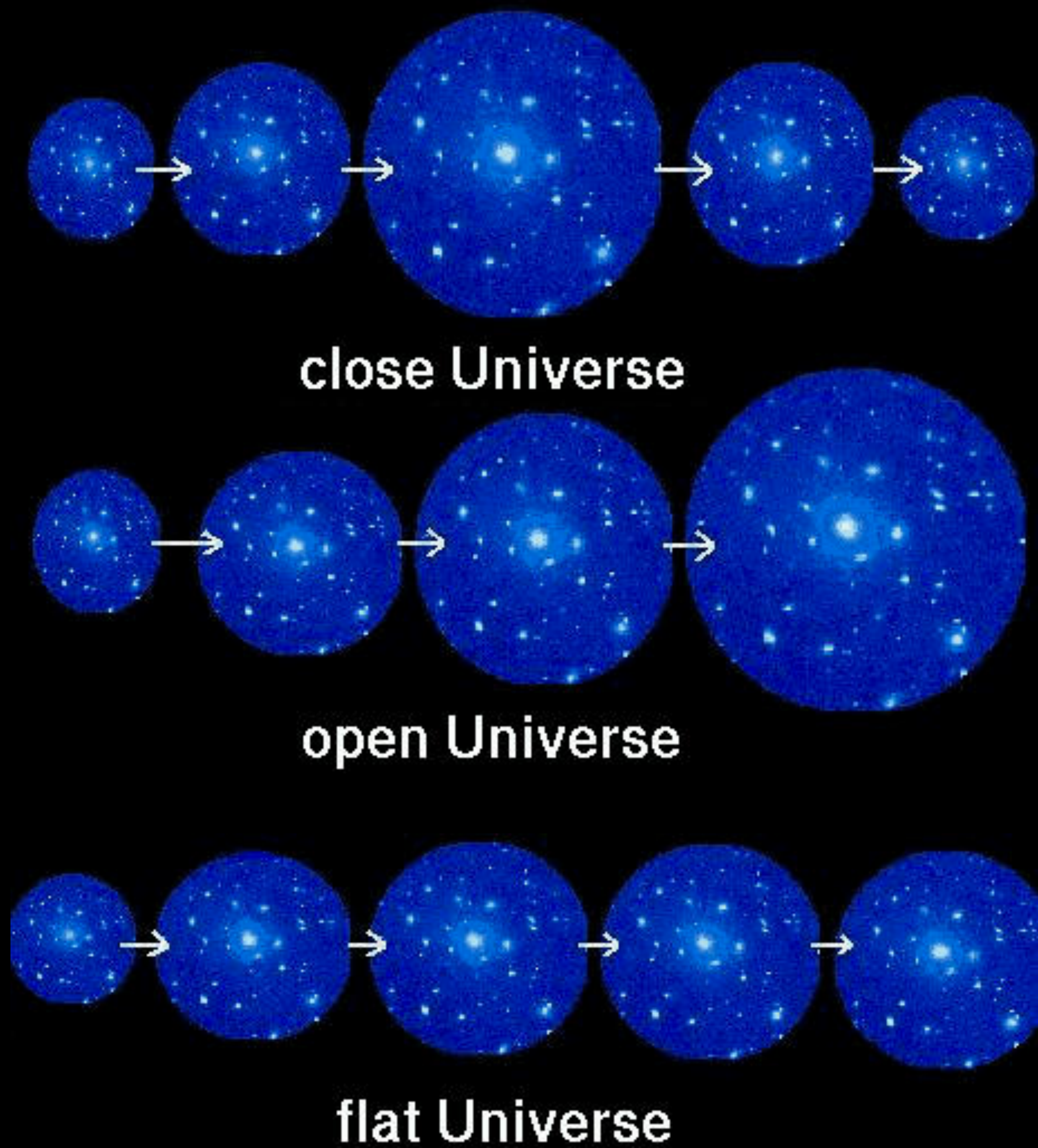
Throw a ball to the sky and what will happen?

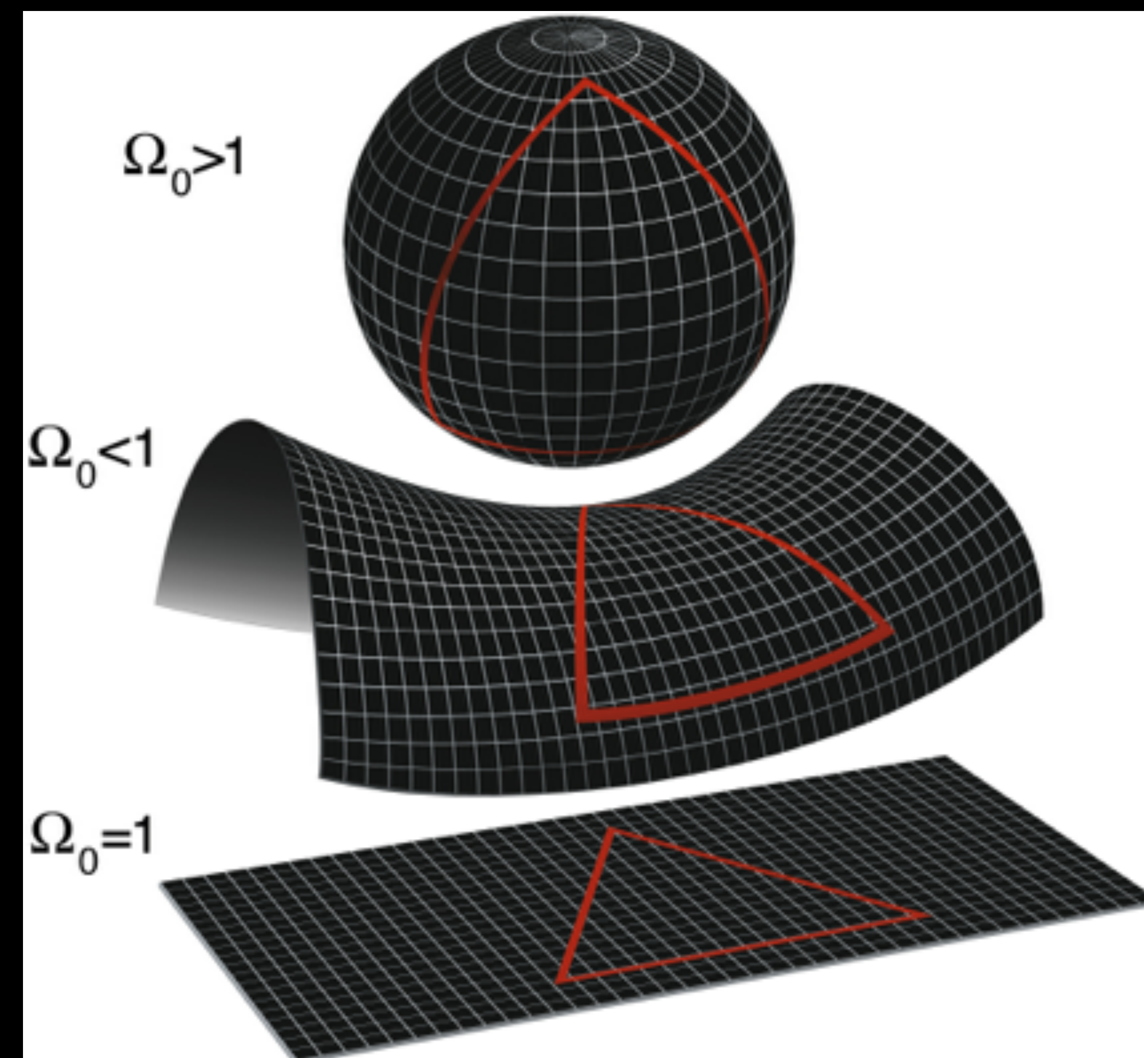
- The ball will slow down and fall back.
- The ball will slow down but leave the Earth.
- The ball will slow down and orbit the Earth.

Initial Speed　　　Mass of the Earth

The Ultimate Fate of the Universe

measuring the deceleration rate





Initial Expansion Speed

Density of the Universe

Which one if the fate of the Universe?

A. The ball will slow down and fall back / close Universe

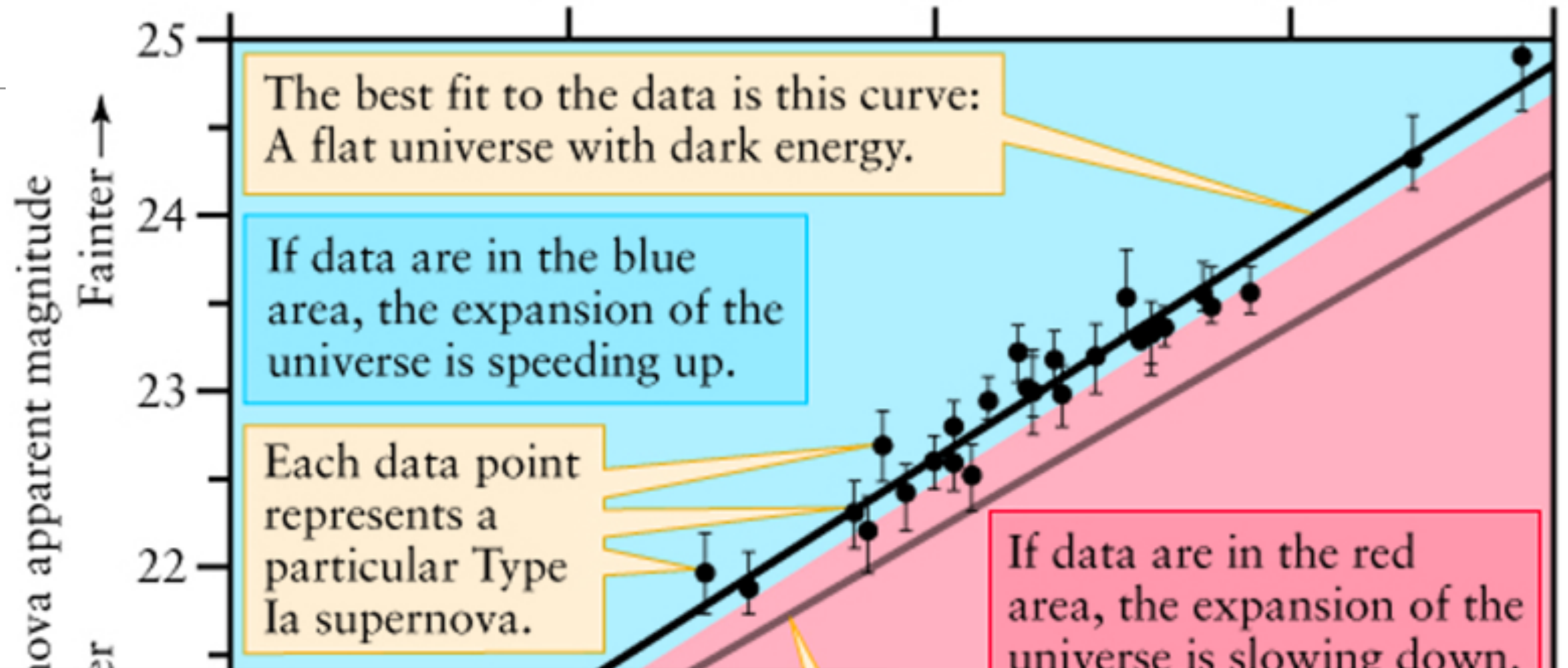
B. The ball will slow down but leave the Earth / open Universe

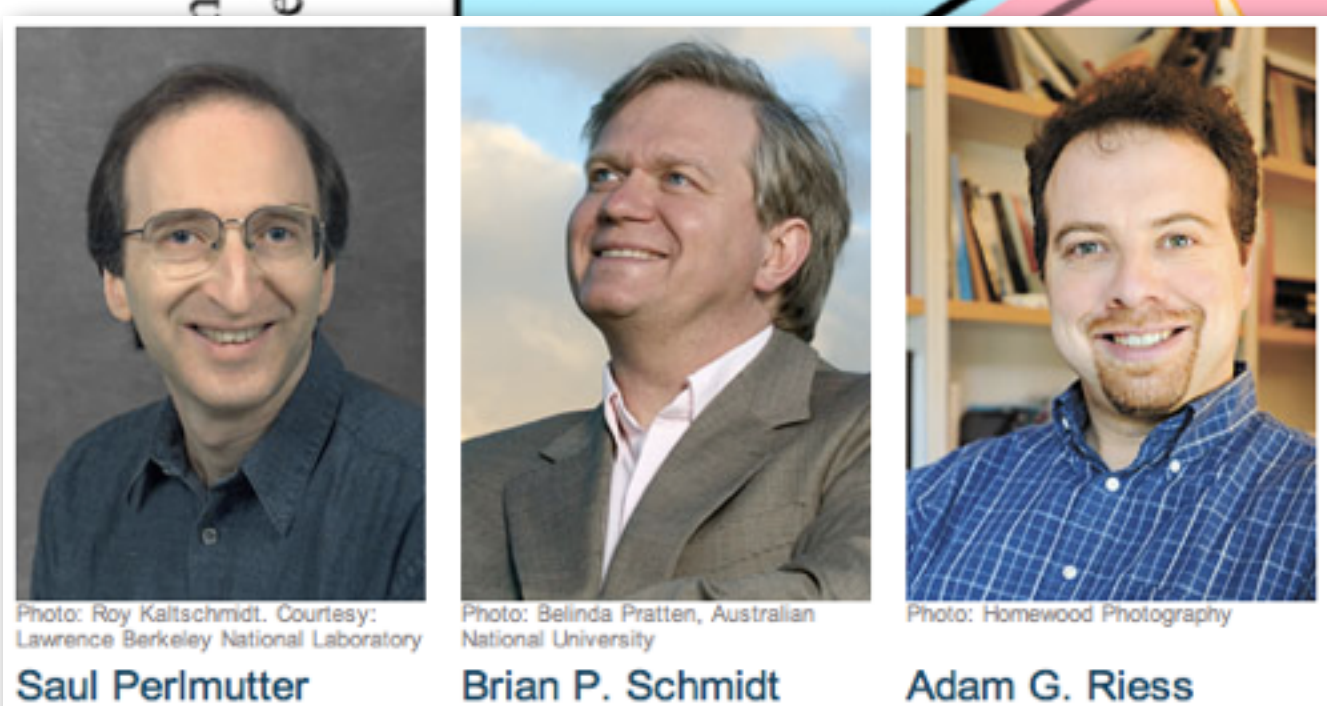
C. The ball will slow down and orbit the Earth / flat Universe

D. None of the above.


Supernova: an exploding star.
A Standard Candle.

Distance



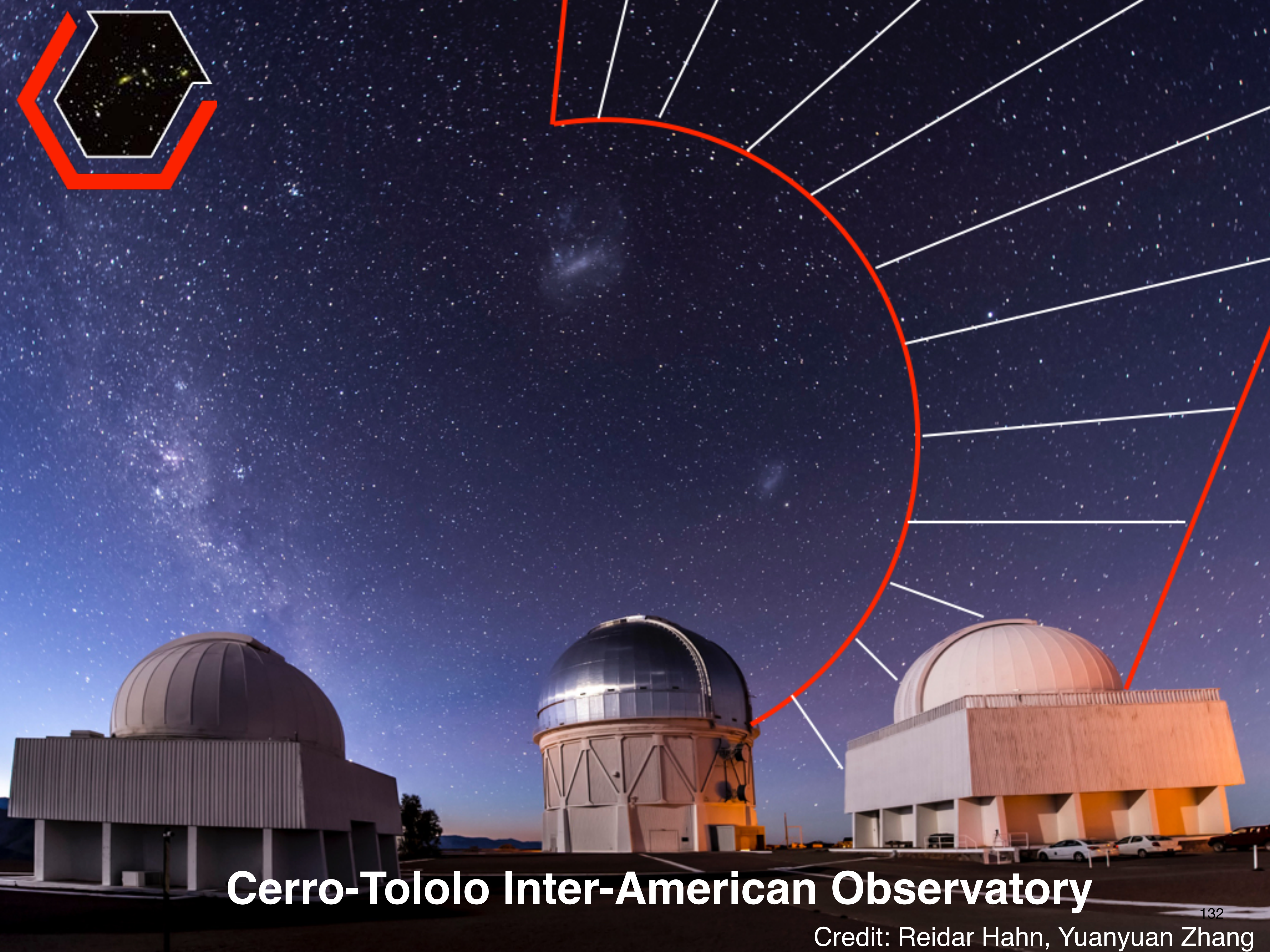


Nobel Prize (2011)
For the discovery of the acceleration of the Universe

from https://sites.ualberta.ca/~pogosyan/teaching/ASTRO_122/lect30a/lecture30a.html

1998

The Universe is Accelerating!


Cerro-Tololo Inter-American Observatory
Credit: Reidar Hahn, Yuanyuan Zhang

Throw a ball straight up and what will happen?

A. The ball will slow down and fall back.

B. The ball will slow down but leave the Earth.

C. The ball will slow down and orbit the Earth.

D. The ball speed up and rocket out of the Earth

What causes Cosmic Speed-up?

Two possibilities:

1. The Universe is filled with stuff that gives rise to `anti-gravity’. We now call this

   Dark Energy

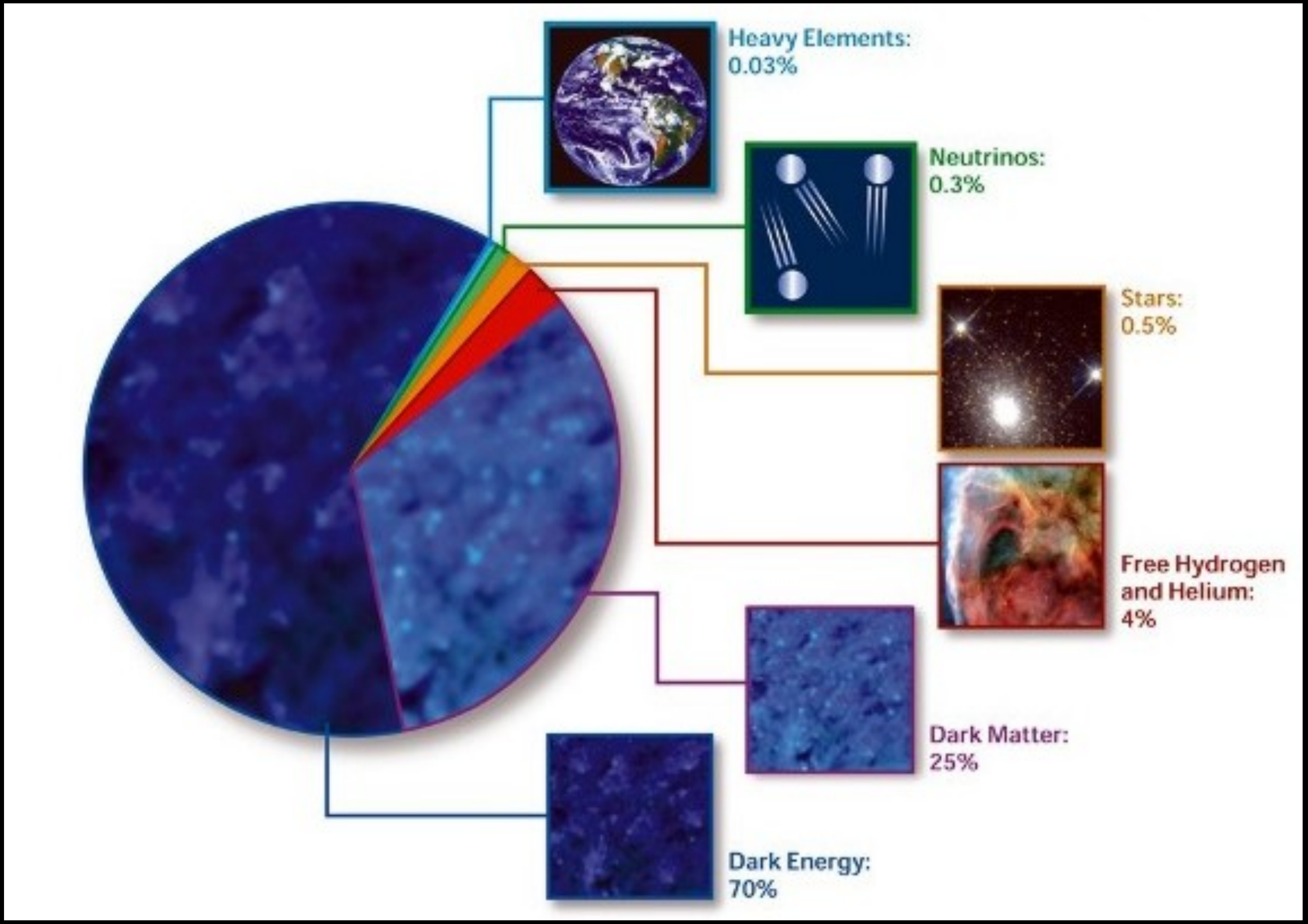
2. Our understanding of gravity (which comes from Einstein) is wrong.

95% of the Universe is Dark

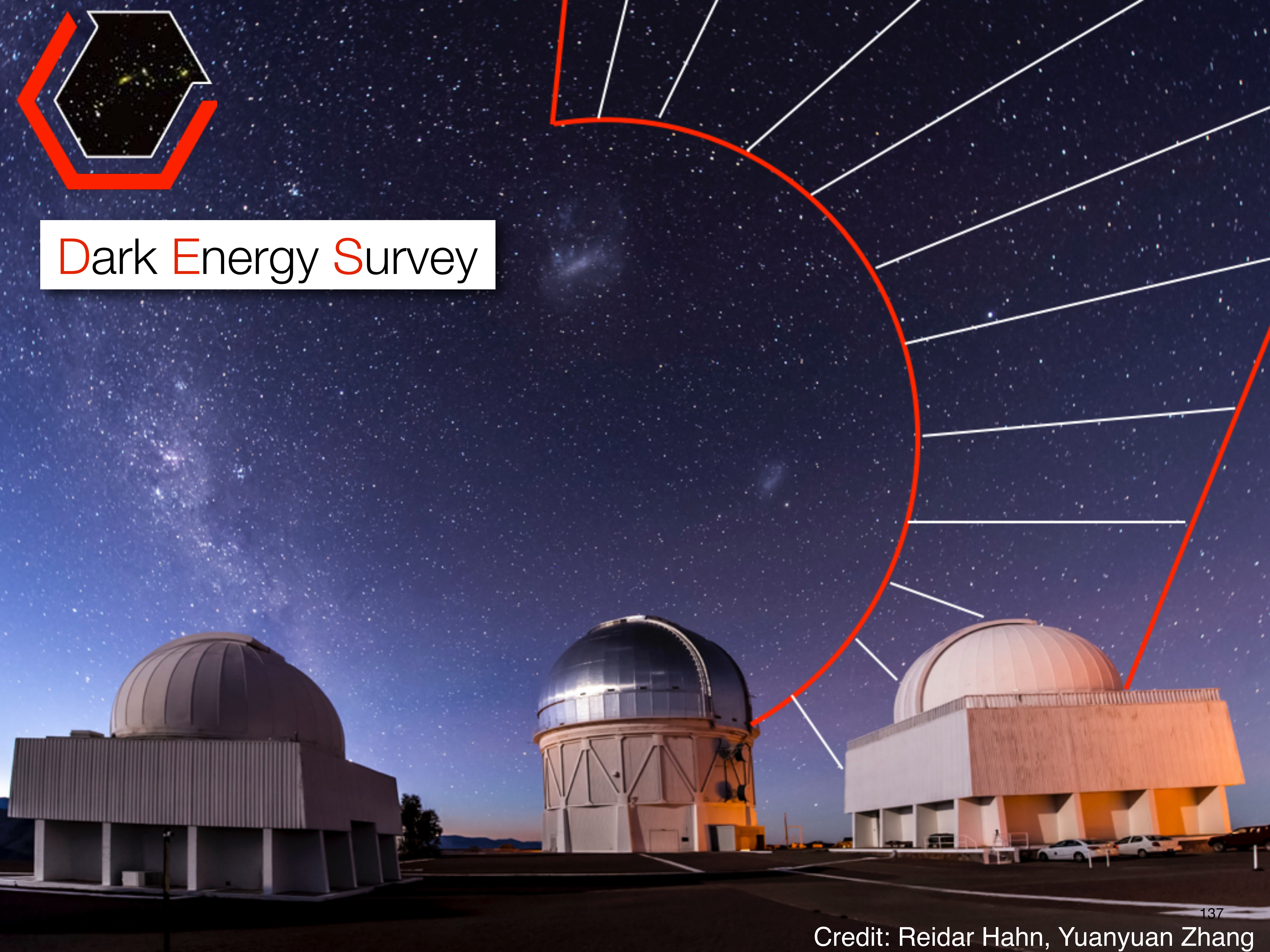
Ordinary Matter: atoms

Dark Matter: holds galaxies together, helps them form

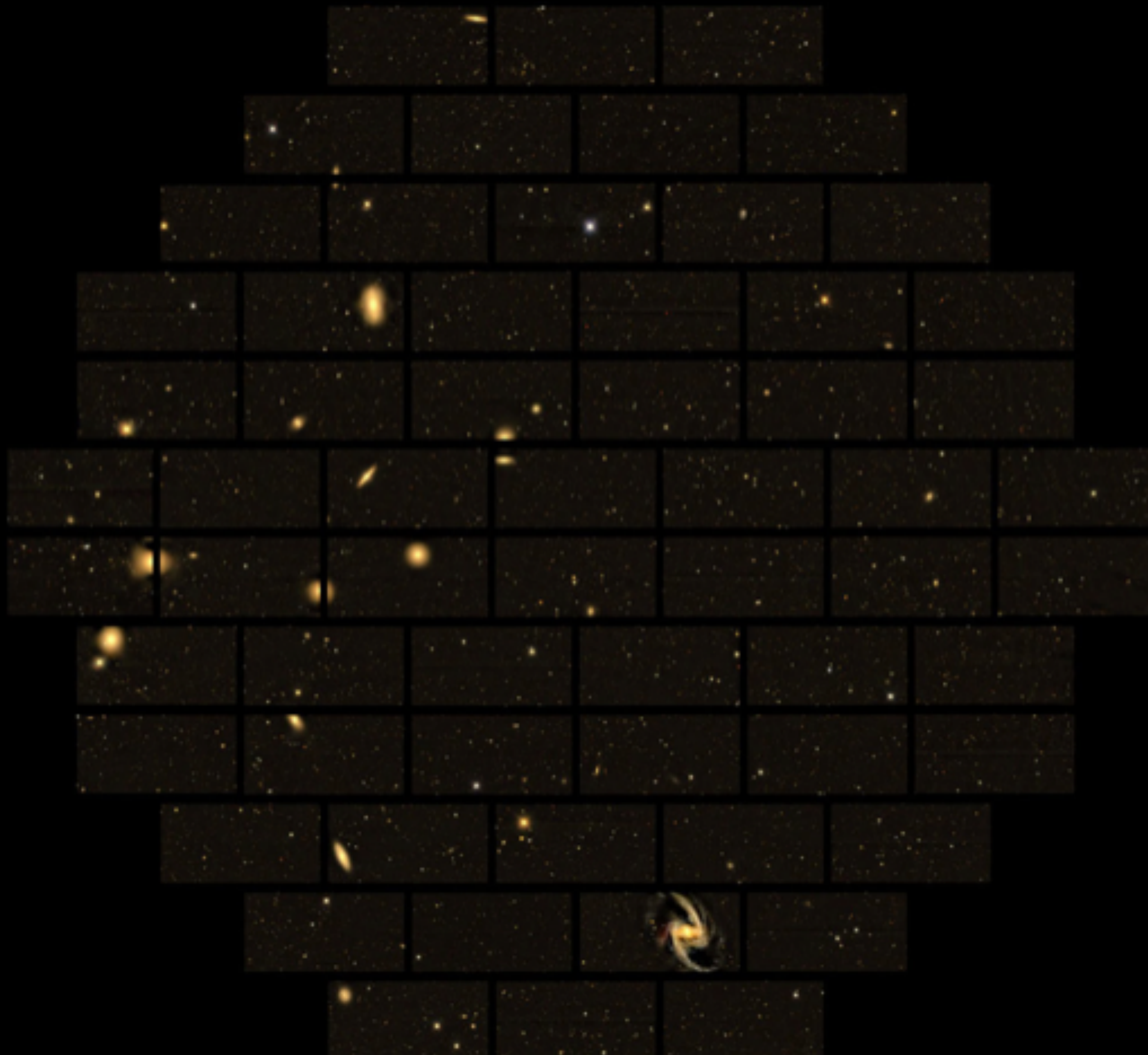
Dark Energy: `gravitationally repulsive' stuff that speeds up cosmic expansion



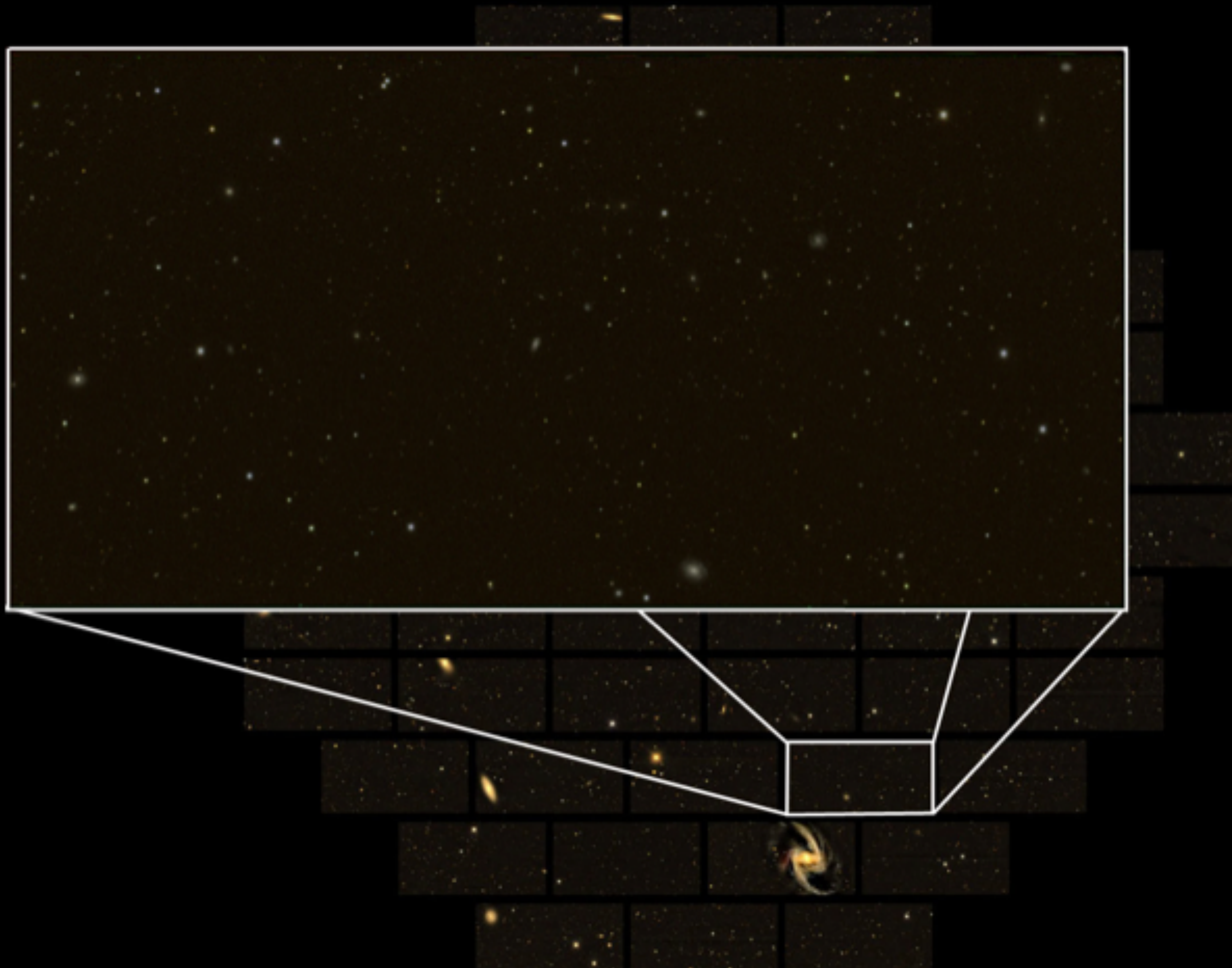
What is Dark Energy?


Dark Energy Survey
Credit: Reidar Hahn, Yuanyuan Zhang

THE DARK ENERGY SURVEY



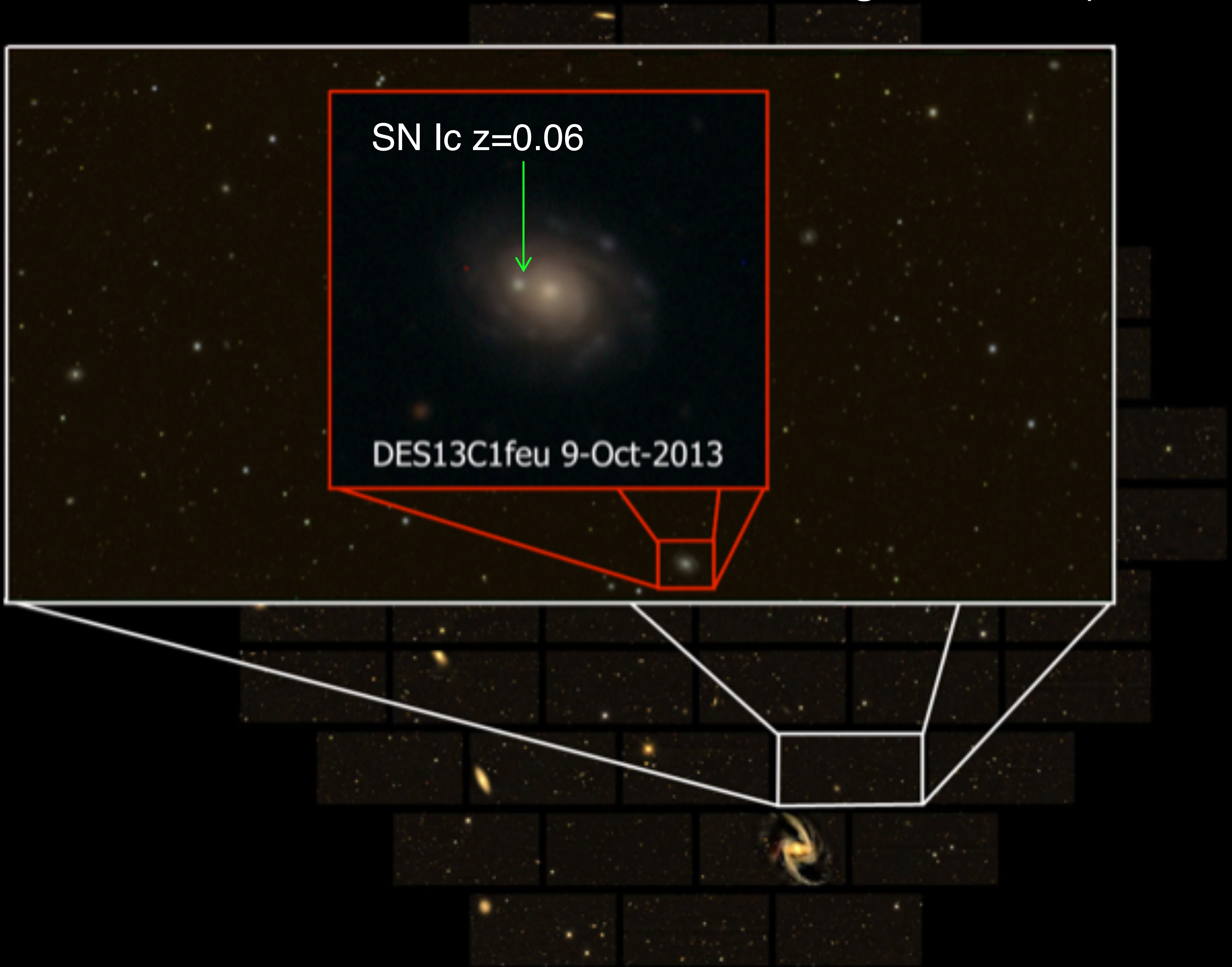
THE DARK ENERGY SURVEY



THE DARK ENERGY SURVEY

THE DARK ENERGY SURVEY

Finding more supernovae



Questions?

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The Fate

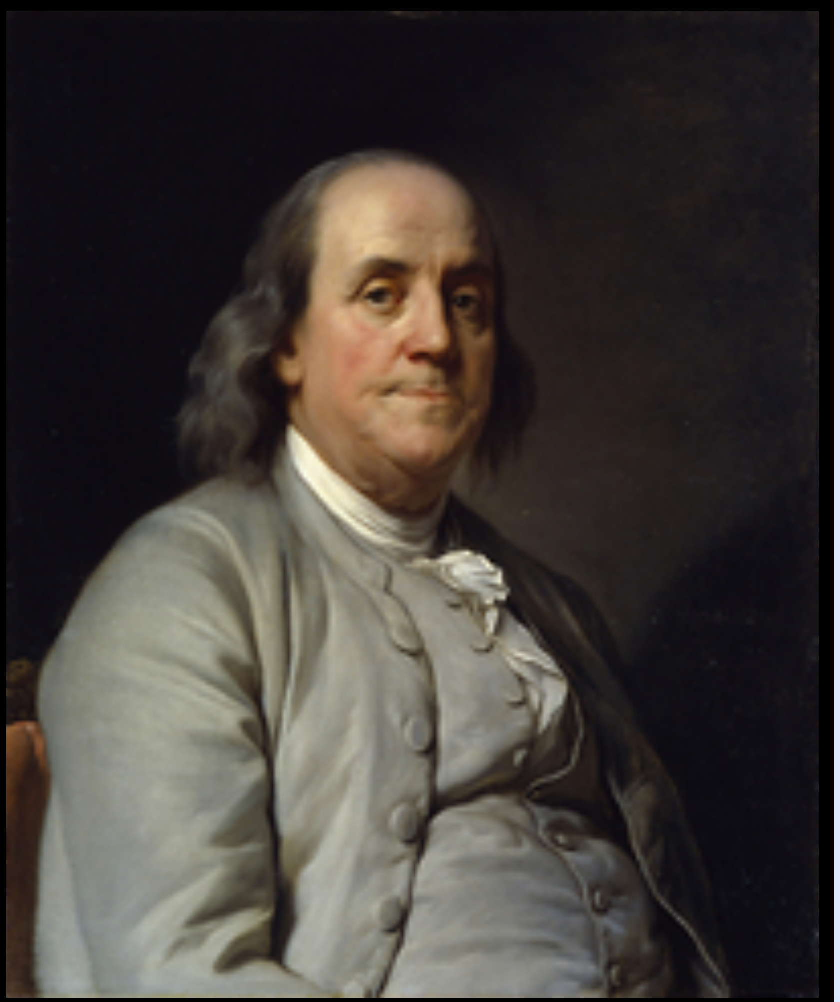
Great Scientists may not make best figures — Hubble

The important scientific discoveries are sometimes not from the scientists — engineers

When you are set to measure something A (deceleration rate), then you found something B (acceleration)

Cosmology

The origin, evolution, and ultimate fate of the Universe



Benjamin Franklin (1706-1790)

> "Chagrined a little that we have been hitherto able to produce nothing in this way of use to mankind; and the hot weather coming on, when the electrical experiments are not so agreeable, it is proposed to put an end to them for this season, somewhat humorously, in a party of pleasure on the banks of the Skuylkill. Spirits, at the same time, are to be fired by a spark sent from side to side through the river, without any other conductor than the water; an experiment which we some time since performed to the amazement of many. A turkey is to be killed for our dinner by electrical shock, and roasted by the electrical jack, before a fire kindled by the electrified bottle; when the healths of all the famous electricians in England, Holland, France, and Germany are to be drank in electrified bumpers [toasting glasses], under the discharge of guns from the electrical battery."

Across the Earth, right now, millions of people are looking up into the night sky. No one owns the stars or the planets or the Milky Way. No one owns the Moon. We all see the same sky, and the sky belongs to all mankind; it is our inheritance from the Creation of the Universe.

I believe this is a part of basic human rights -- the right to wonder. It is also the most revolutionary of human rights, because it is the right to question and discover. It is the right to lift our souls and hopes into the sky, and to receive in return a sense of connection among human beings that transcends all boundaries and that, one day, may bring us peace.

-- Nicholas B. Suntzeff

THE END

THANK YOU