Cosmology

Ting Li

Saturday Morning Physics

04/30/2019

Courtesy Brian Nord

Cosmology

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What is Cosmology?

What is Cosmology?

A. A branch of trigonometry that focuses on the "**Cosine**"

B. The study of **cosmetics**

C. The study of the **cosmos**

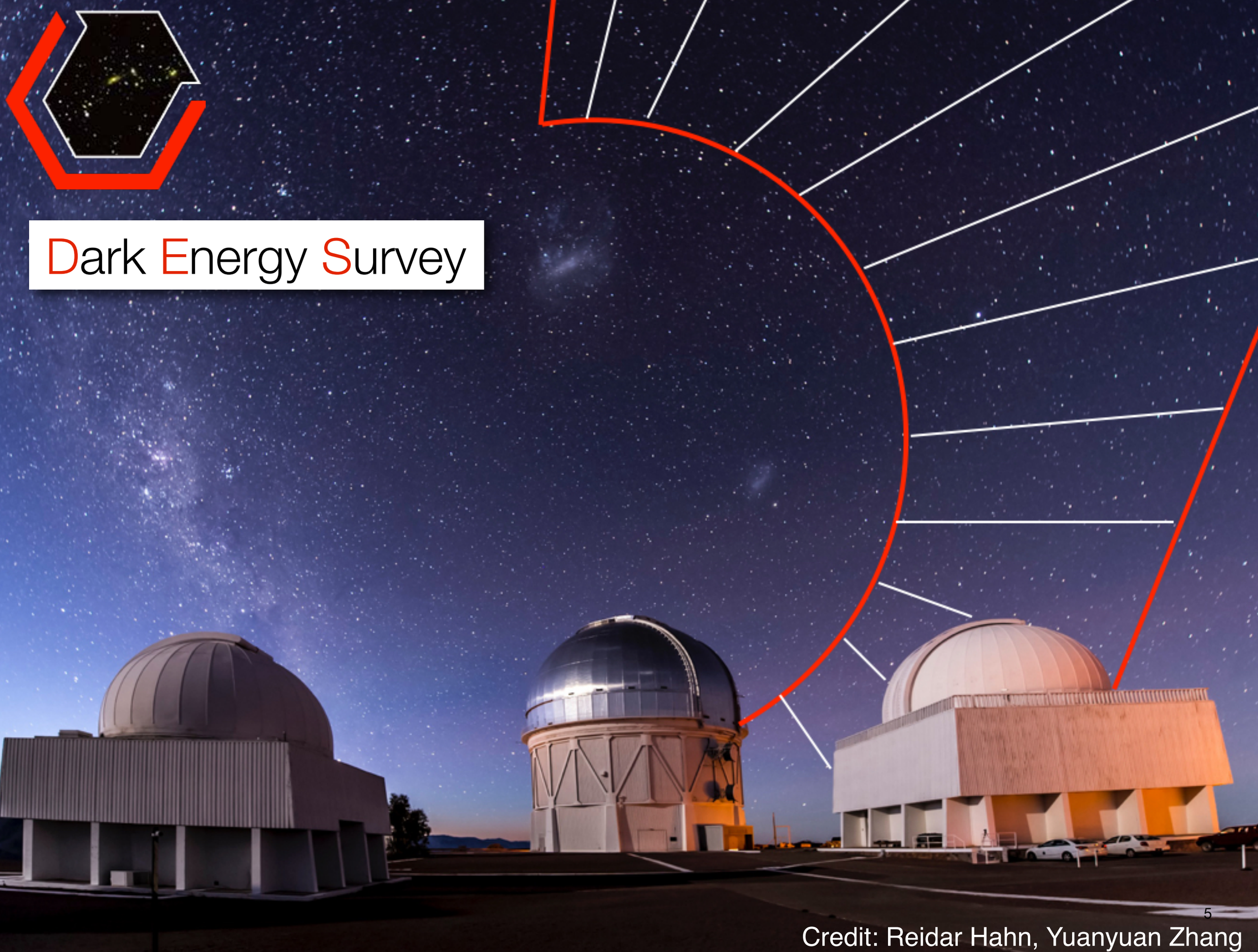
D. The study of Soviet-era **Cosmonauts**

What is Cosmology?

The origin, evolution, and ultimate fate of the Universe

About me

- Ting Li
- PhD in Physics from Texas A&M University
- Joined Fermilab as a Postdoctoral Fellow in 2016
- Optical 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

UK Consortium:
UCL, Cambridge, Edinburgh, Nottingham, Portsmouth, Sussex

ETH Zurich

LMU Ludwig-Maximilians Universität

Spain Consortium:
CIEMAT, IEEC, IFAE

Brazil Consortium

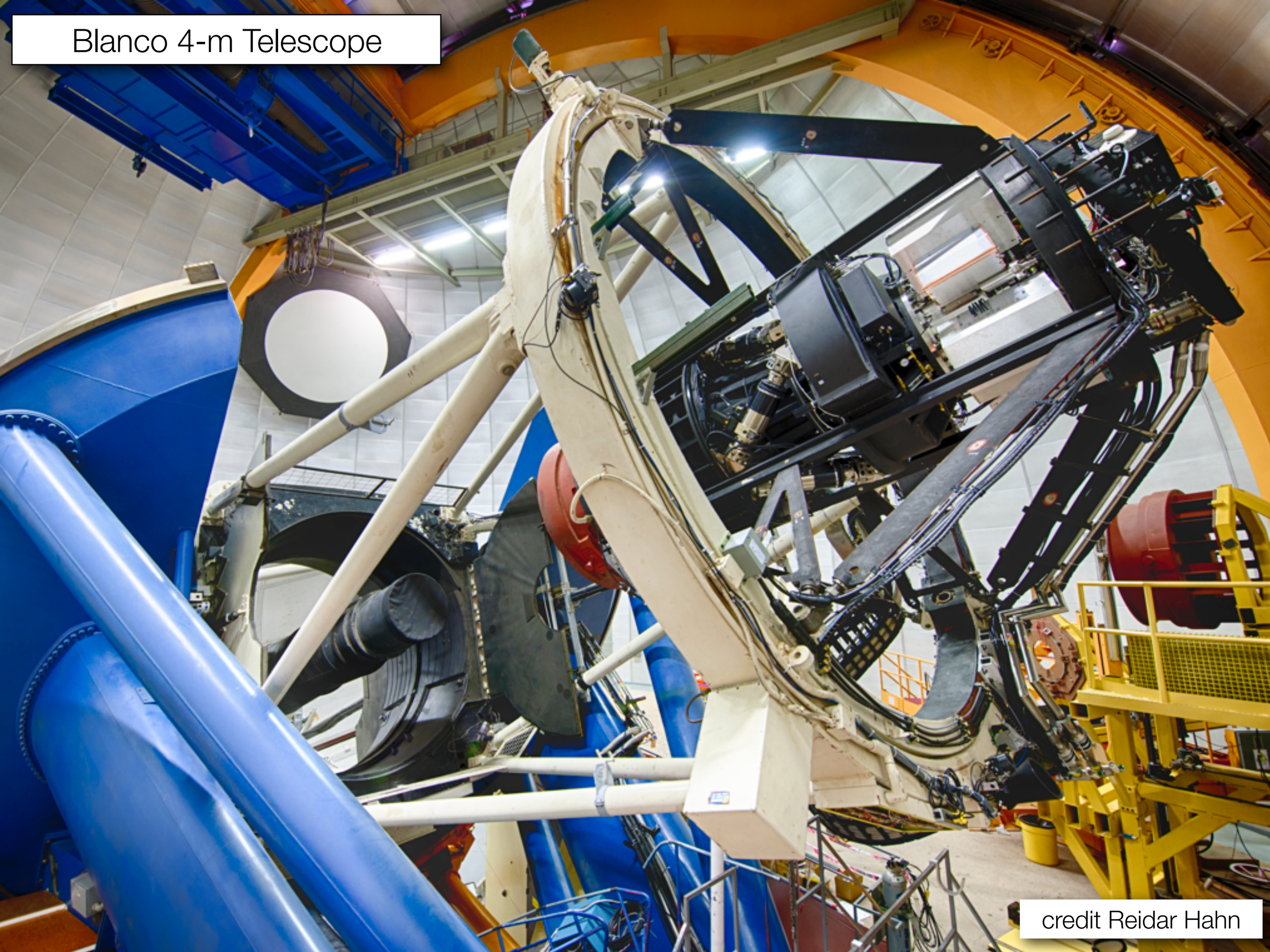
OzDES Consortium

CTIO

Cerro-Tololo Inter-American Observatory

Credit: Reidar Hahn, Yuanyuan Zhang

Blanco 4-m Telescope



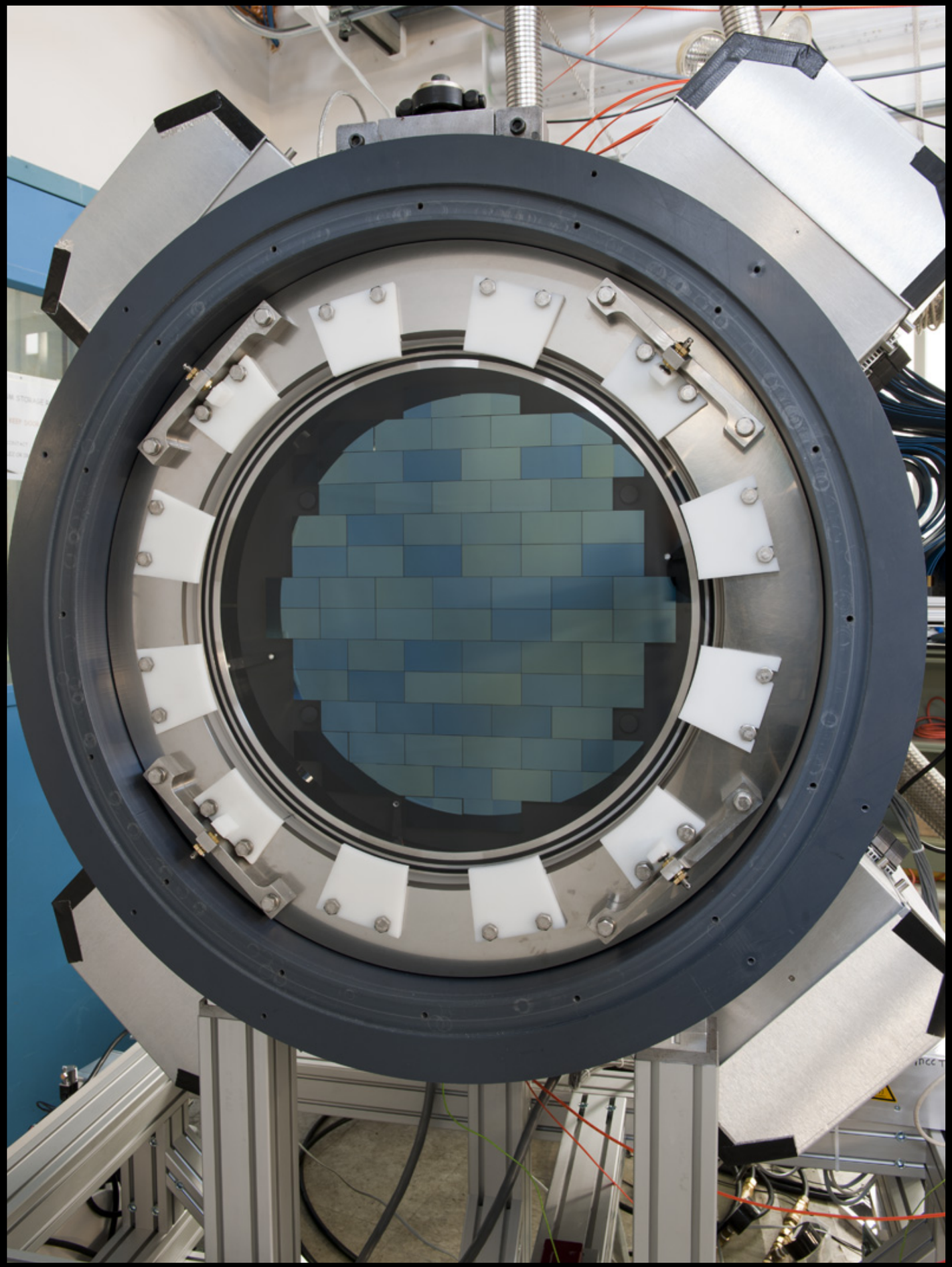
credit Reidar Hahn

570-Million pixel
Dark Energy Camera

Built here at Fermilab

Installed on the Blanco telescope in 2012

What are the other light detectors?



DARK ENERGY SURVEY

First Images

Fornax Cluster of Galaxies

First Light on Sept. 12, 2012

DARK ENERGY SURVEY

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Fornax Cluster of Galaxies

First Light on Sept. 12, 2012

DARK ENERGY SURVEY

First Images

Galaxy NGC 1365 in Fornax Cluster

image from a single detector

DES Observing I

Credit Elisabeth Krause

DES Observing I

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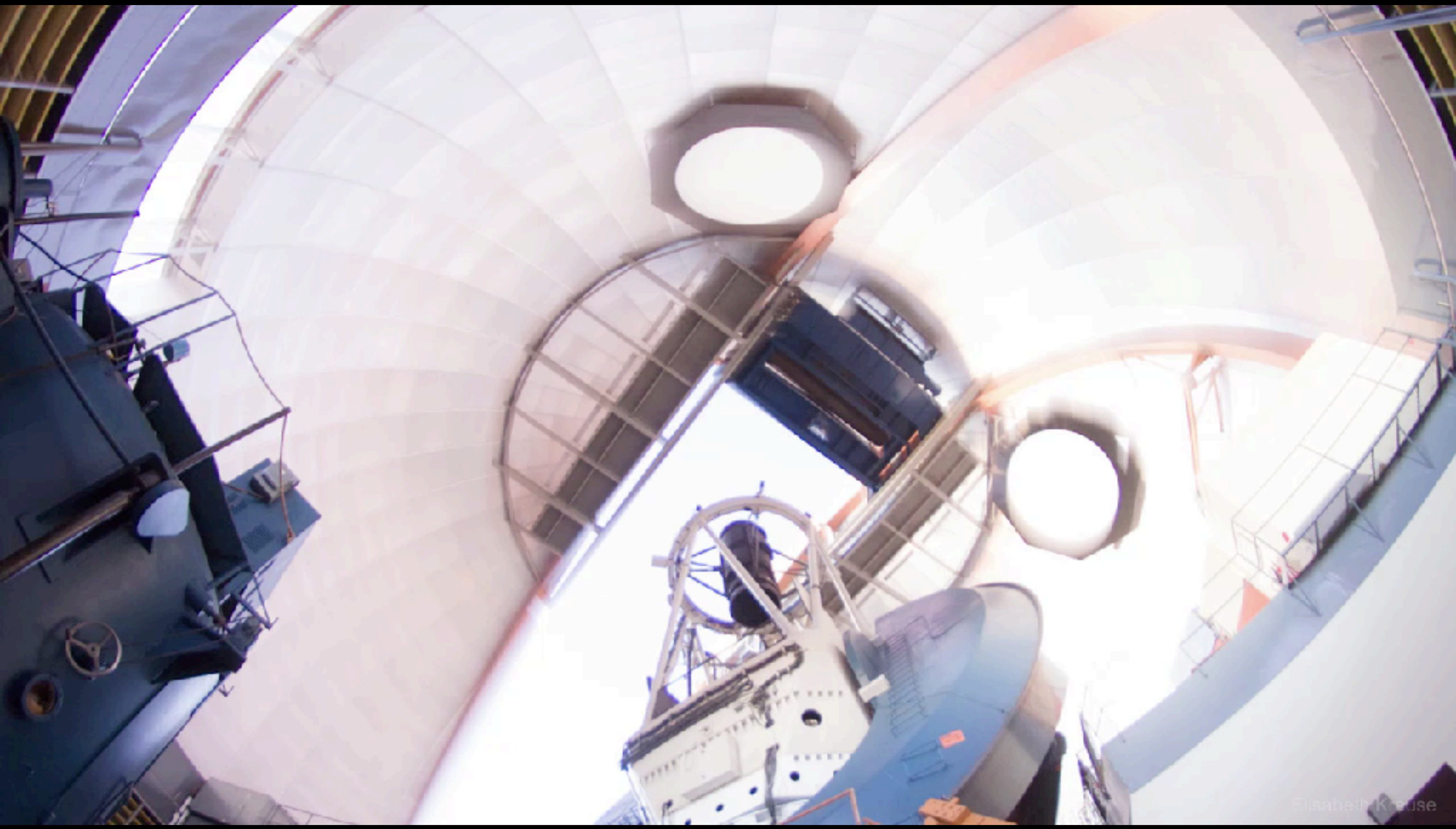
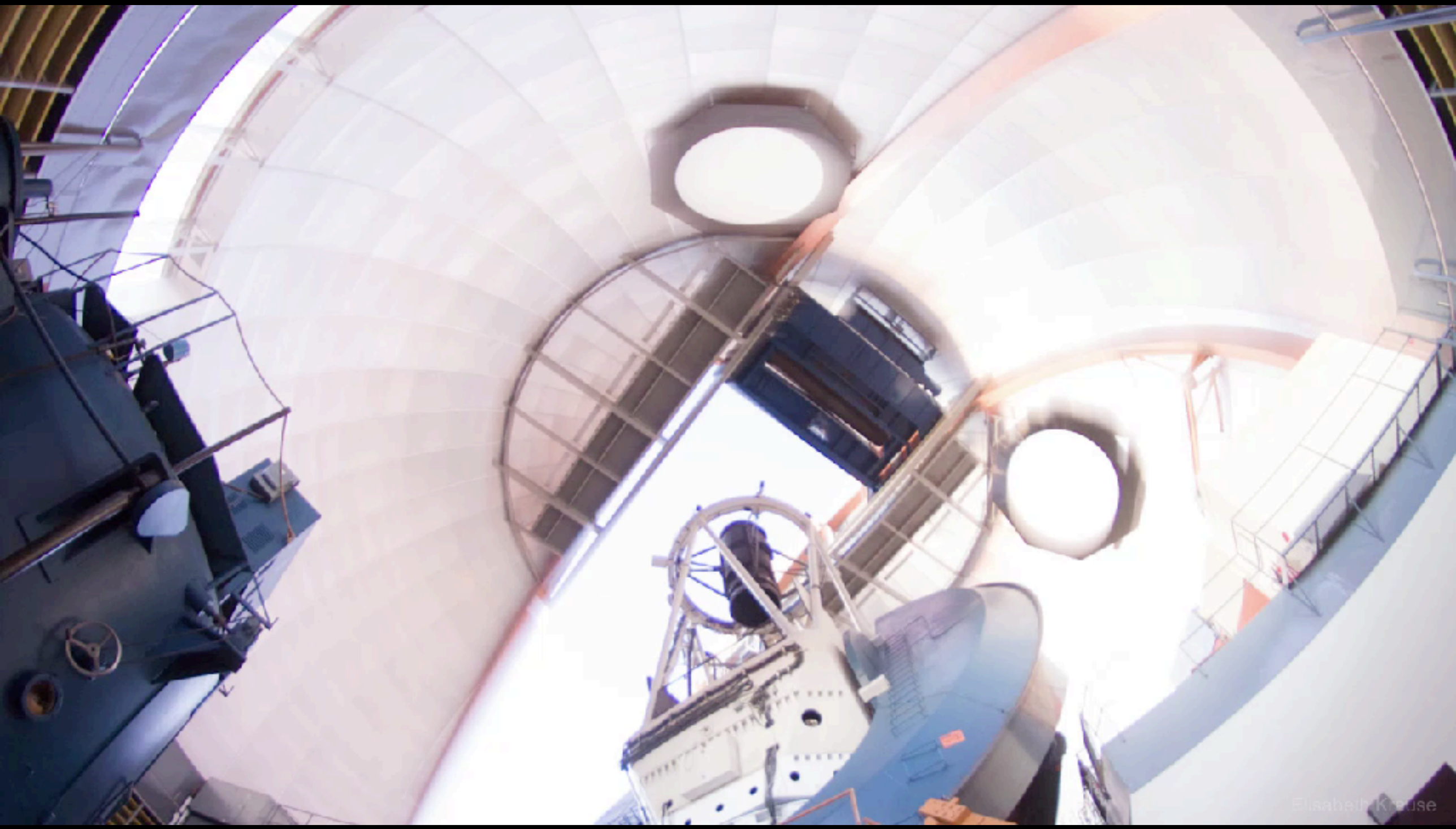
DES Observing II



Credit Elisabeth Krause

DES Observing II



Credit Elisabeth Krause

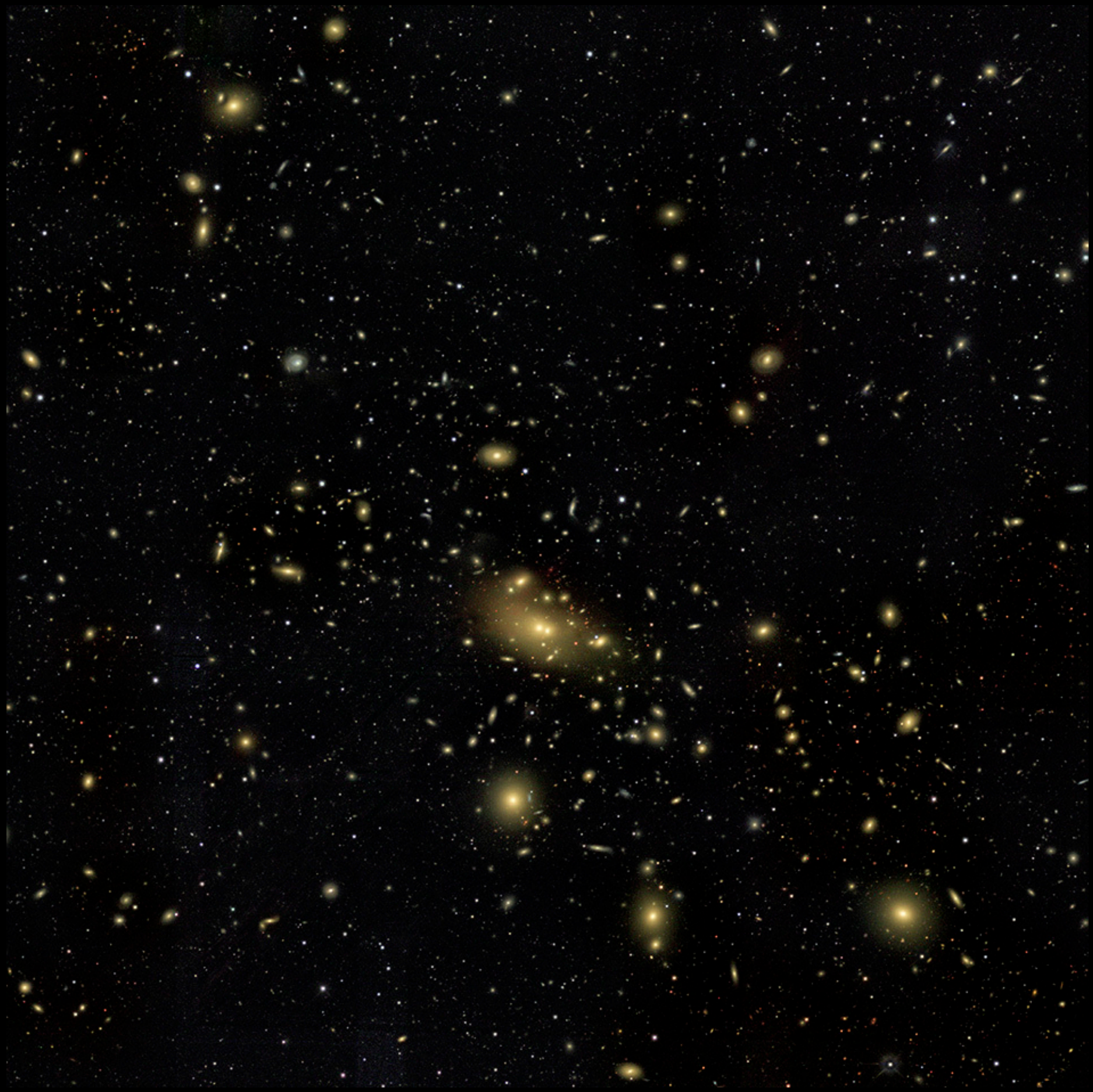
DES Observing III

Credit Brian Nord

DES Observing III

Credit Brian Nord

NGC 1512 at 38 million light-years



Cluster of Galaxies

Comet Lovejoy

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

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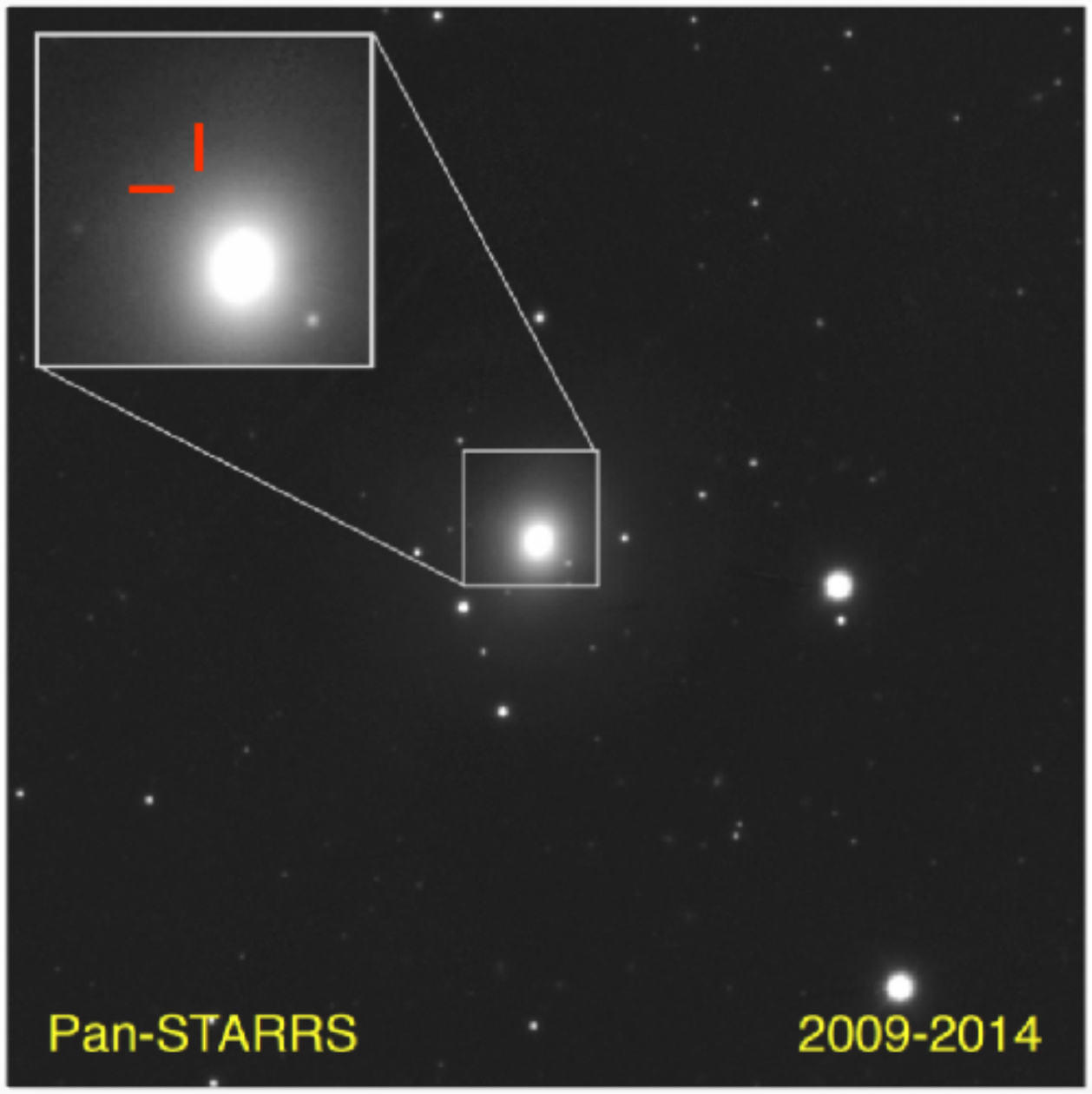

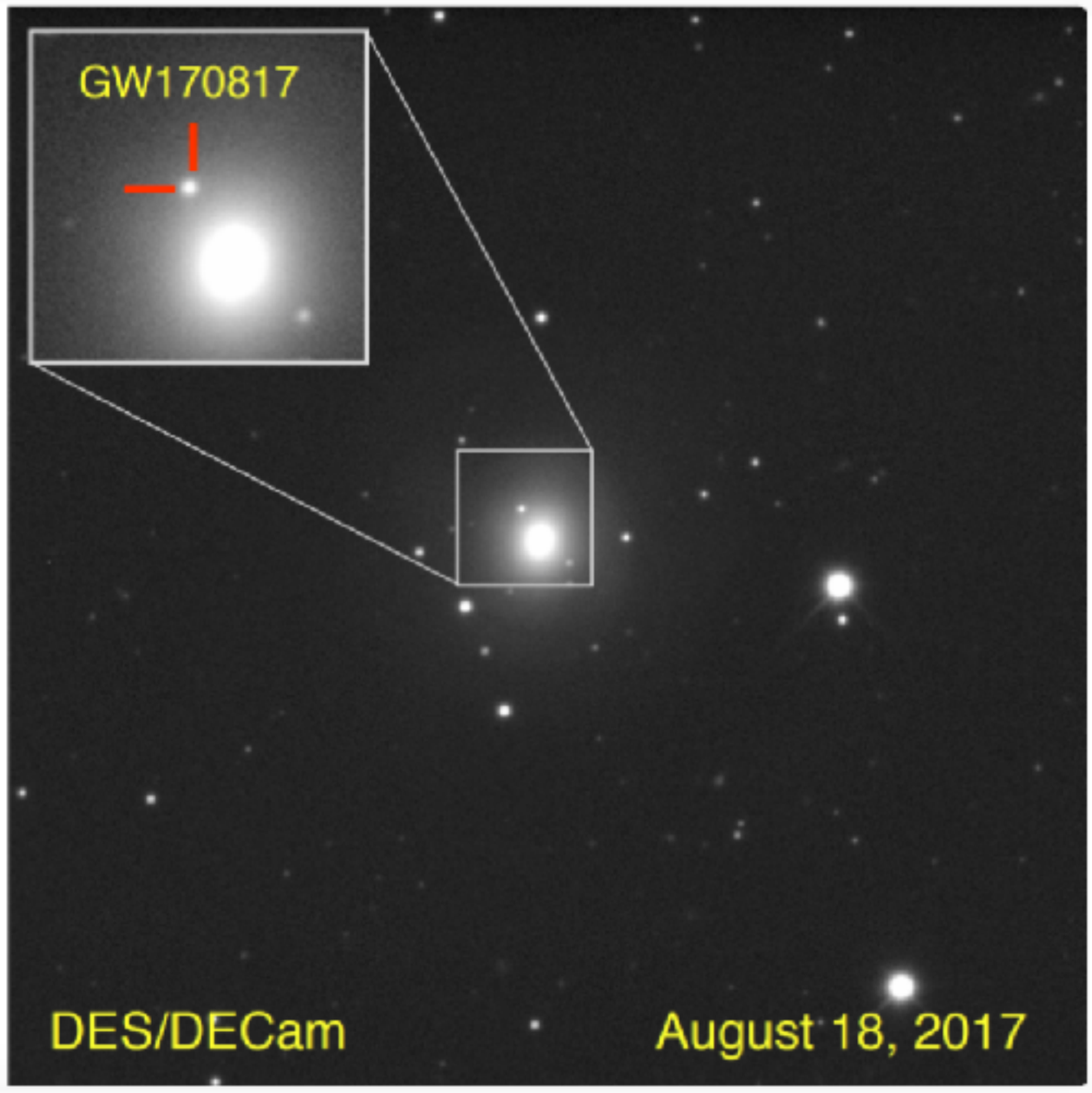

Credit: P. K. Blanchard / E. Berger / Pan-STARRS / DECam

Gravitational Wave: GW170817
Binary Neutron Star Merger
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Binary Neutron Star Merger
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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

We are all Stardust

The Universe is mostly “Dark”

The Universe started with a Big Bang

The Origin

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The Origin

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The Evolution

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The Universe started with a Big Bang

The Origin

We are all Stardust

The Evolution

The Universe is mostly “Dark”

The Fate

But How?

But How?

Through Astronomical Observations!

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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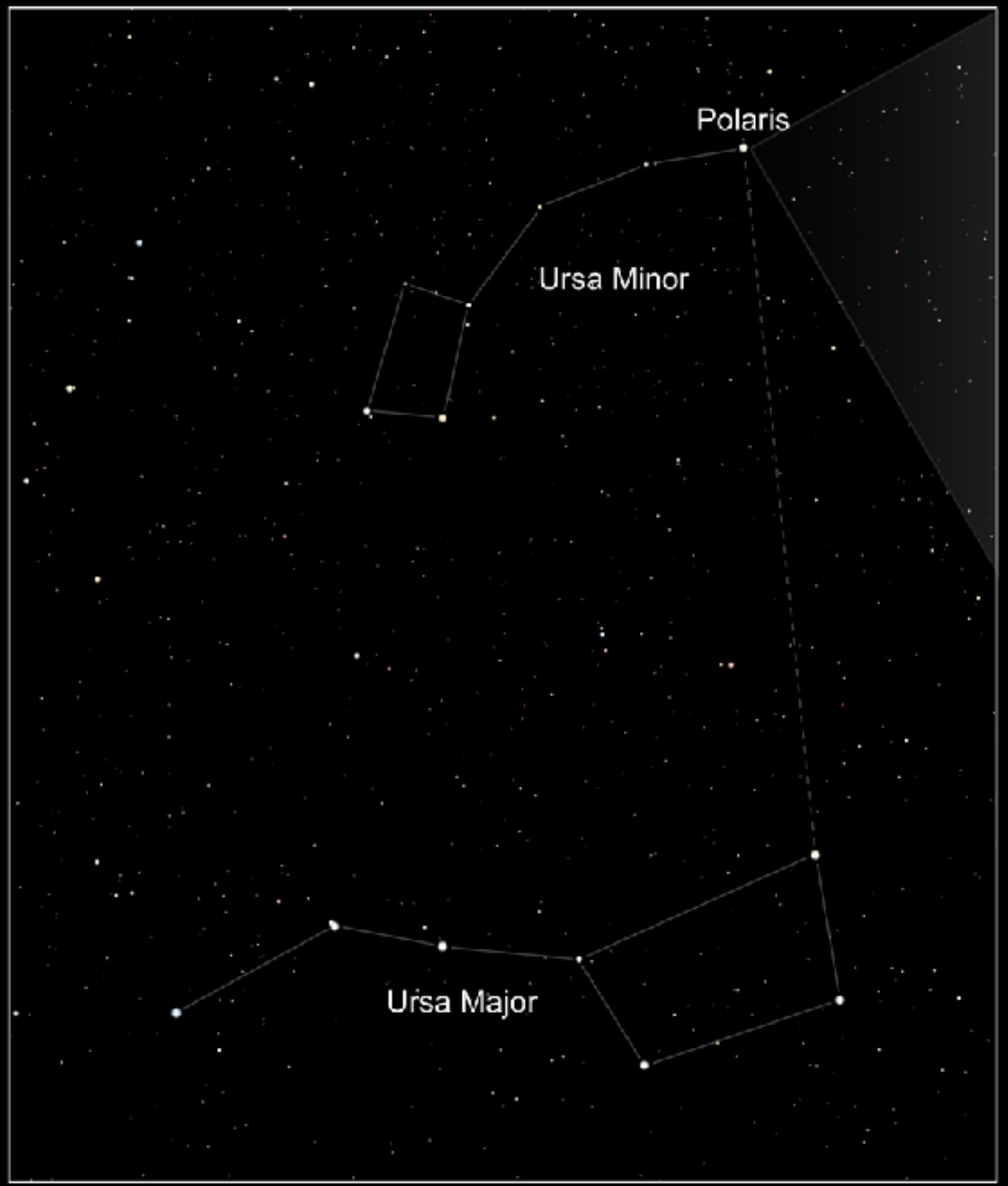
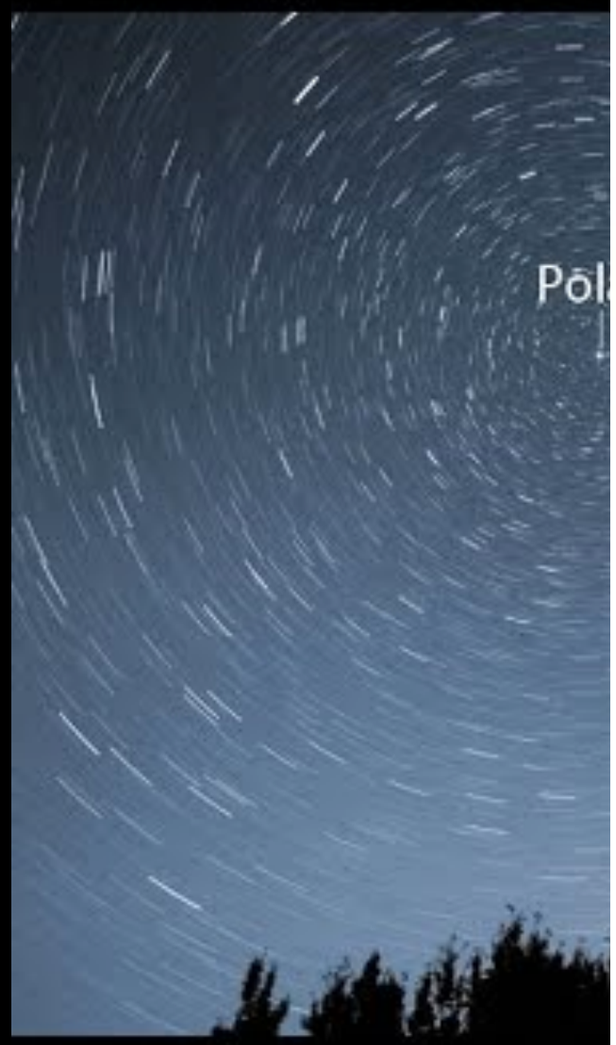
Polaris



Polaris

Polari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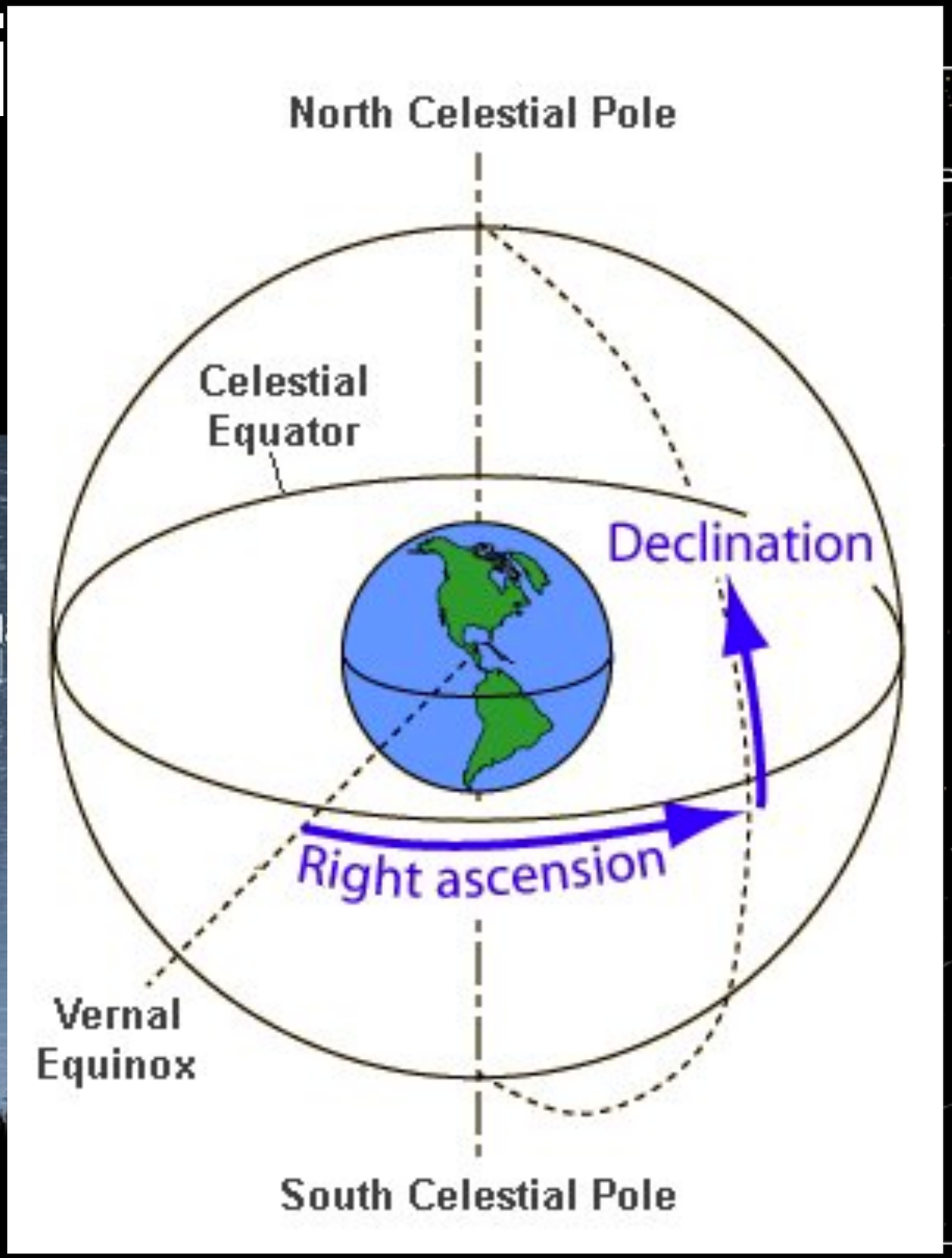
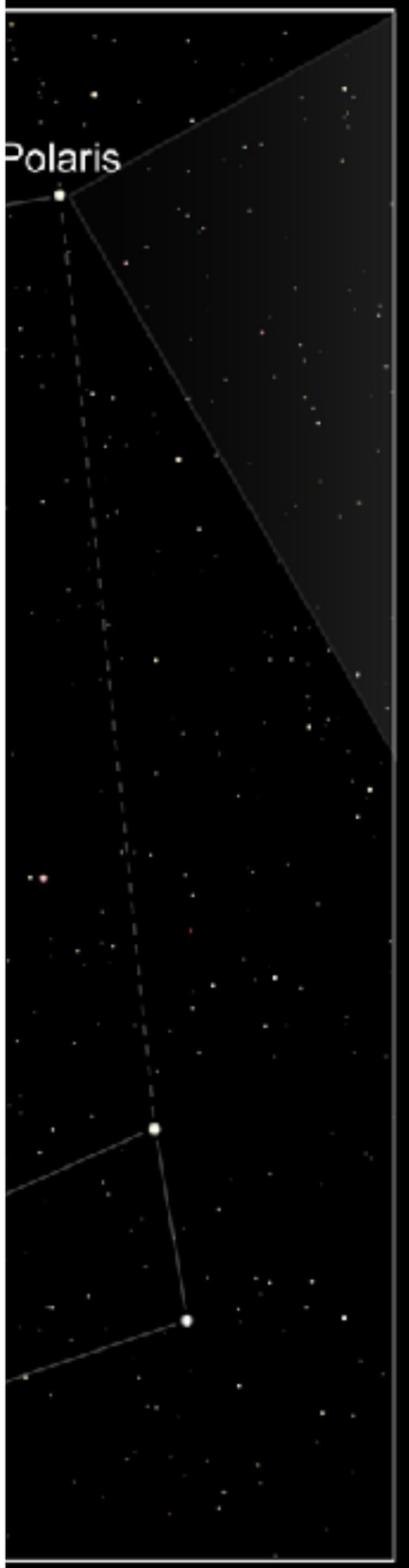

North Celestial Pole
Celestial Equator
Declination
Right ascension
Vernal Equinox
South Celestial Pole


Polaris

Polaris

Right Ascension — RA
(celestial longitude)

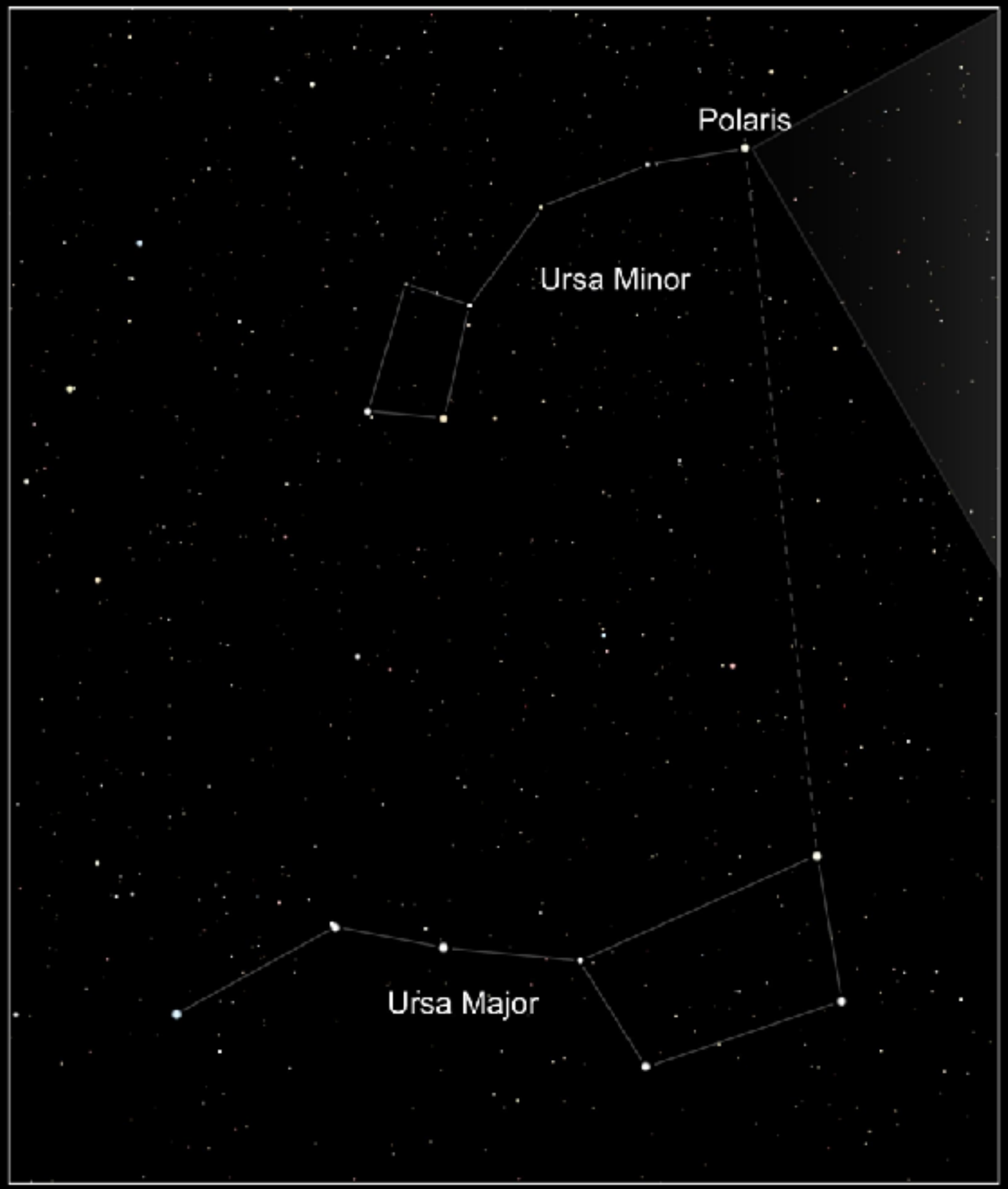
02h 30m 41.6s

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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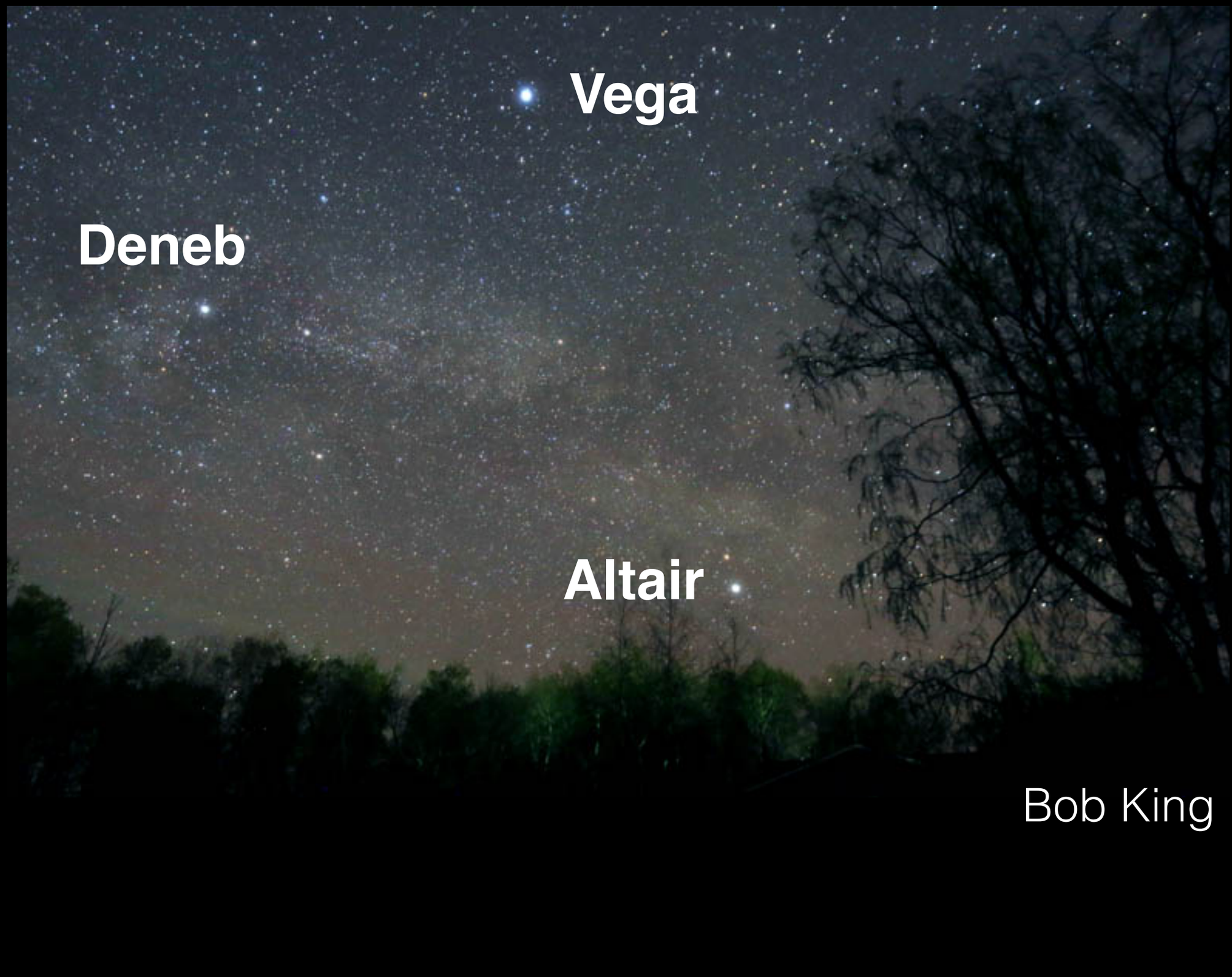
Summer Triangle

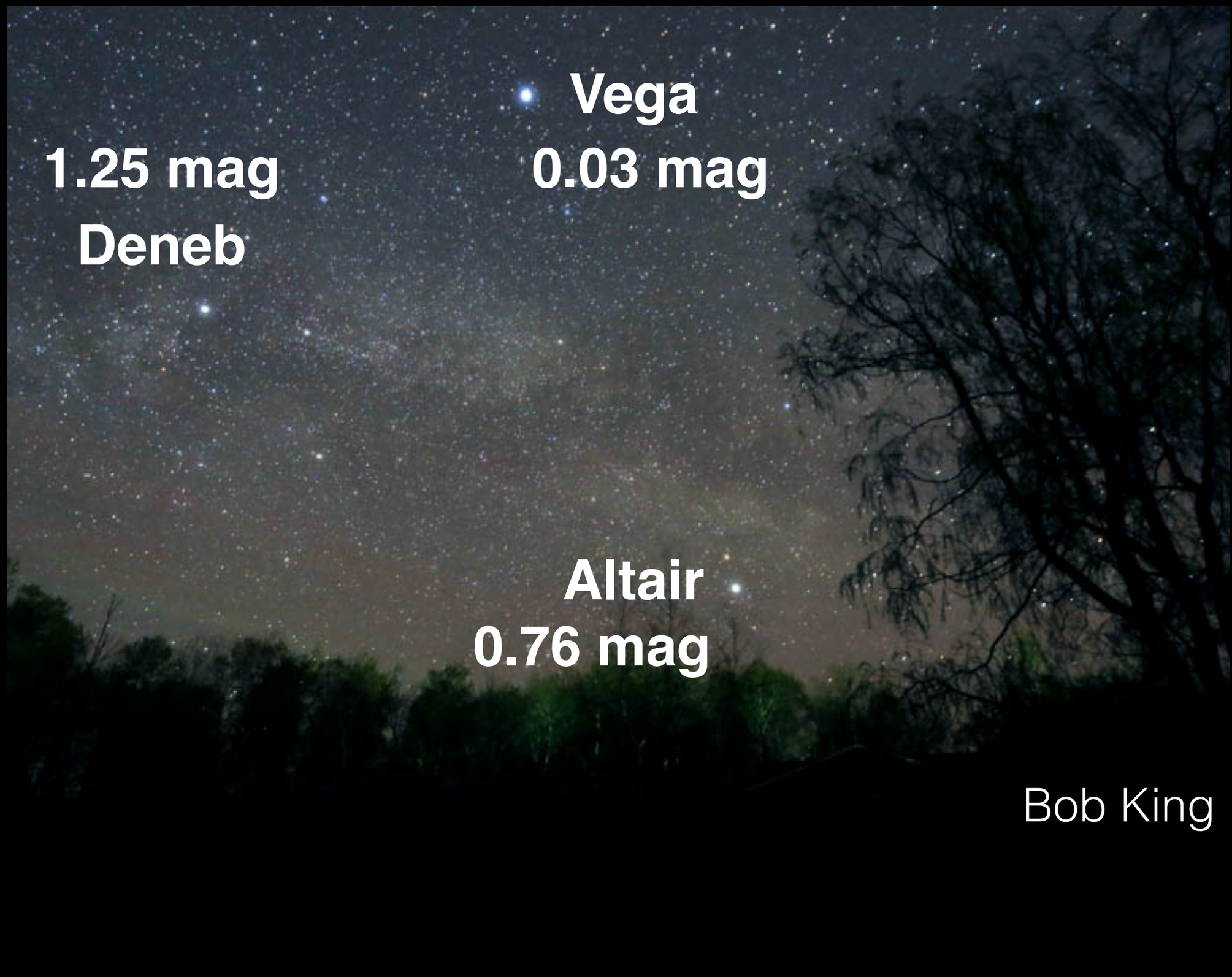
Bob King

Summer Triangle



Bob King

Summer Triangle



Bob King

Summer Triangle

Bob King

Brighter stars has smaller magnitude

Magnitude System

- Introduced by Greek Astronomer Hipparchus around 100 BC
  - “brightest” star: 1st class/magnitude
  - stars barely visible to the naked eye: 6th class/ magnitude
- 1th mag star is 100x brighter than 6th mag:
- in log scale:1 magnitude = 2.512x fainter
- current state-of-art: 25th mag — 10^{10} fainter than 0th mag

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Doppler Effect

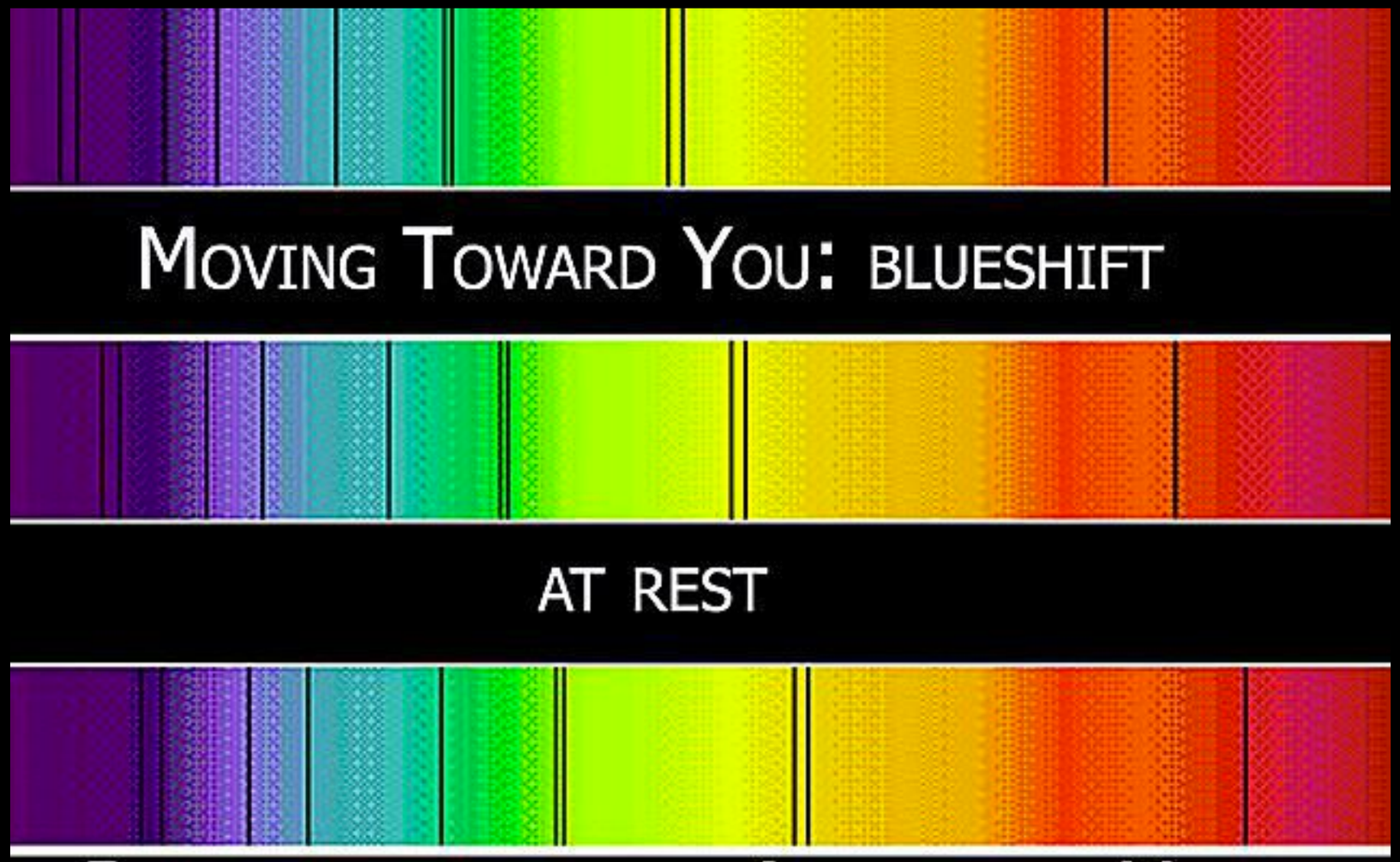
Doppler Effect

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

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$$\frac{v}{c} = \frac{\Delta\lambda}{\lambda} = \frac{500.5 - 500}{500}$$

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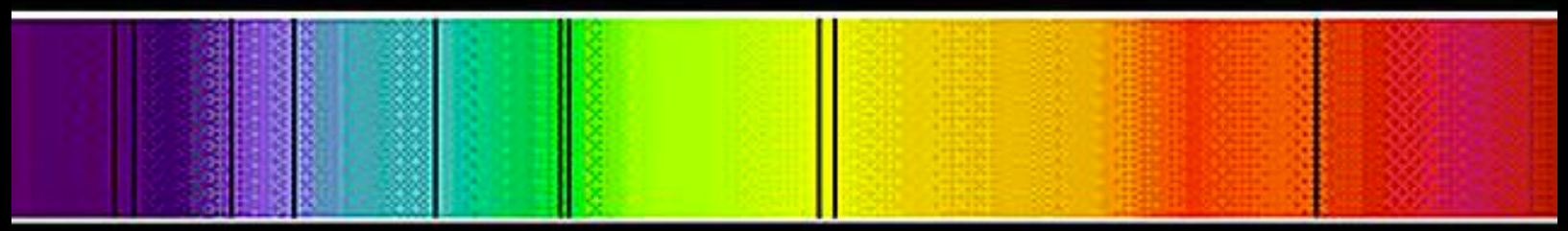
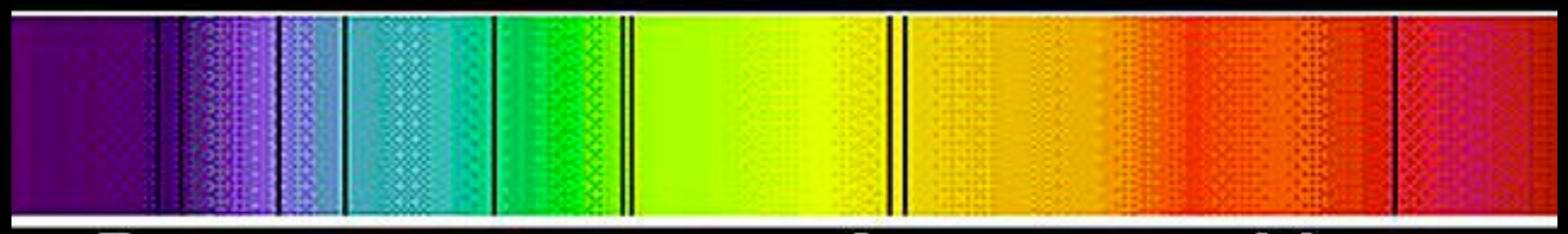
$$\frac{v}{c} = \frac{\Delta\lambda}{\lambda} = \frac{500.5 - 500}{500} \rightarrow v = 0.001c = 300 \text{ km/s}$$



AT REST



REDSHIFTED: MOVING AWAY FROM YOU

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Units for Distances/Length

light-year (ly)

Units for Distances/Length

miles

light-year (ly)

km

minutes

meter

Ångström

km/s

parsec

Mpc

Astronomical Unit (AU)

kilograms

Units for Distances/Length

miles

km

1000 meter

meter

light-year (ly)

9×10^{15} meter

minutes

km/s

Ångström

10^{-10} meter

Mpc

parsec

kilograms

Astronomical Unit (AU)

1.5×10^{11} meter

Units for Distances/Length

miles

light-year (ly)

9×10^{15} meter

km

1000 meter

minutes

meter

Ångström

10^{-10} meter

km/s

Mpc

parsec

kilograms

Astronomical Unit (AU)

1.5×10^{11} meter

Question:
How to measure
distance?

Trigonometric Parallaxes

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

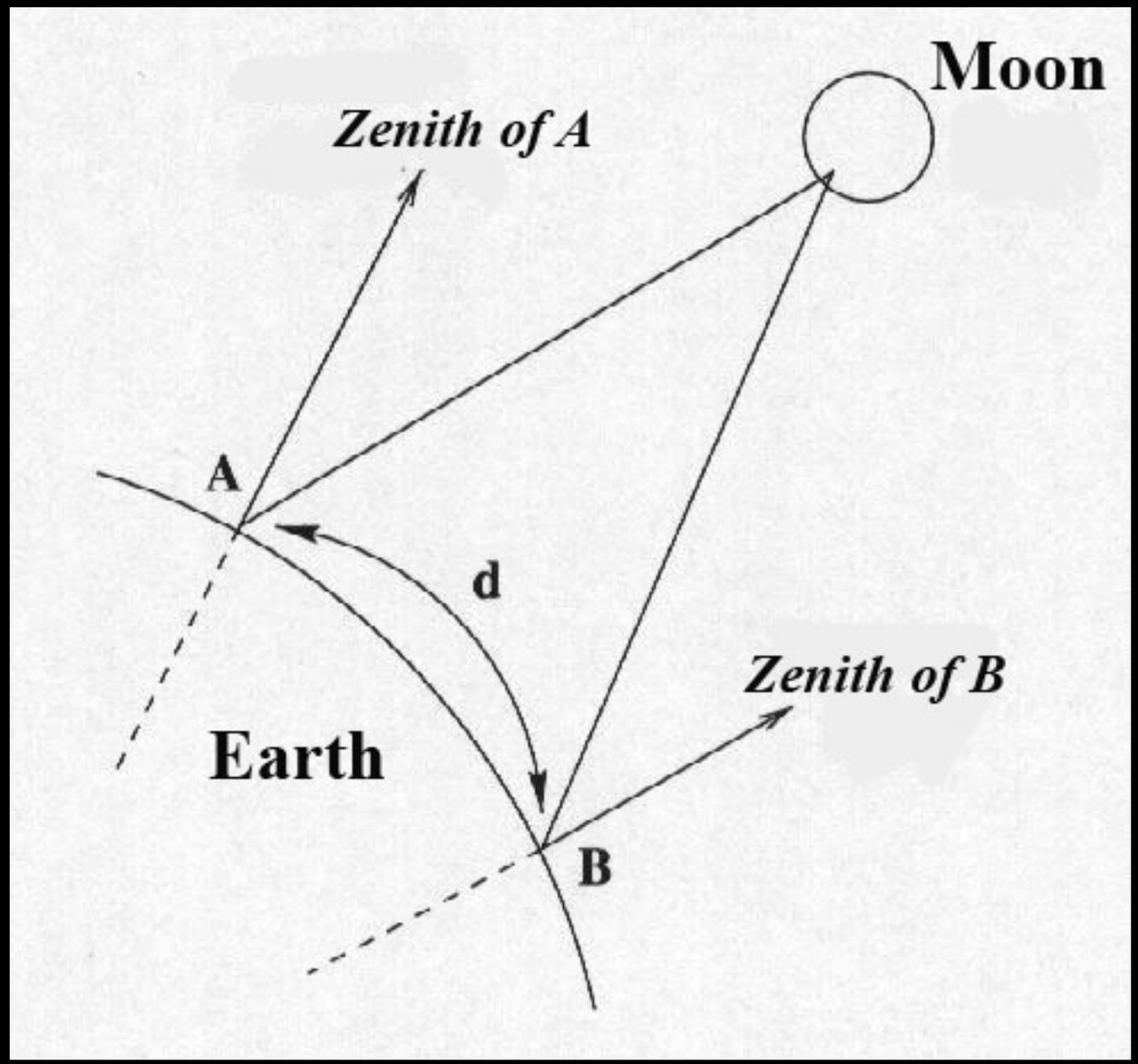
Experiment with your finger

Trigonometric Parallaxes — 2

Distance to the Moon

Trigonometric Parallaxes — 2

Distance to the Moon

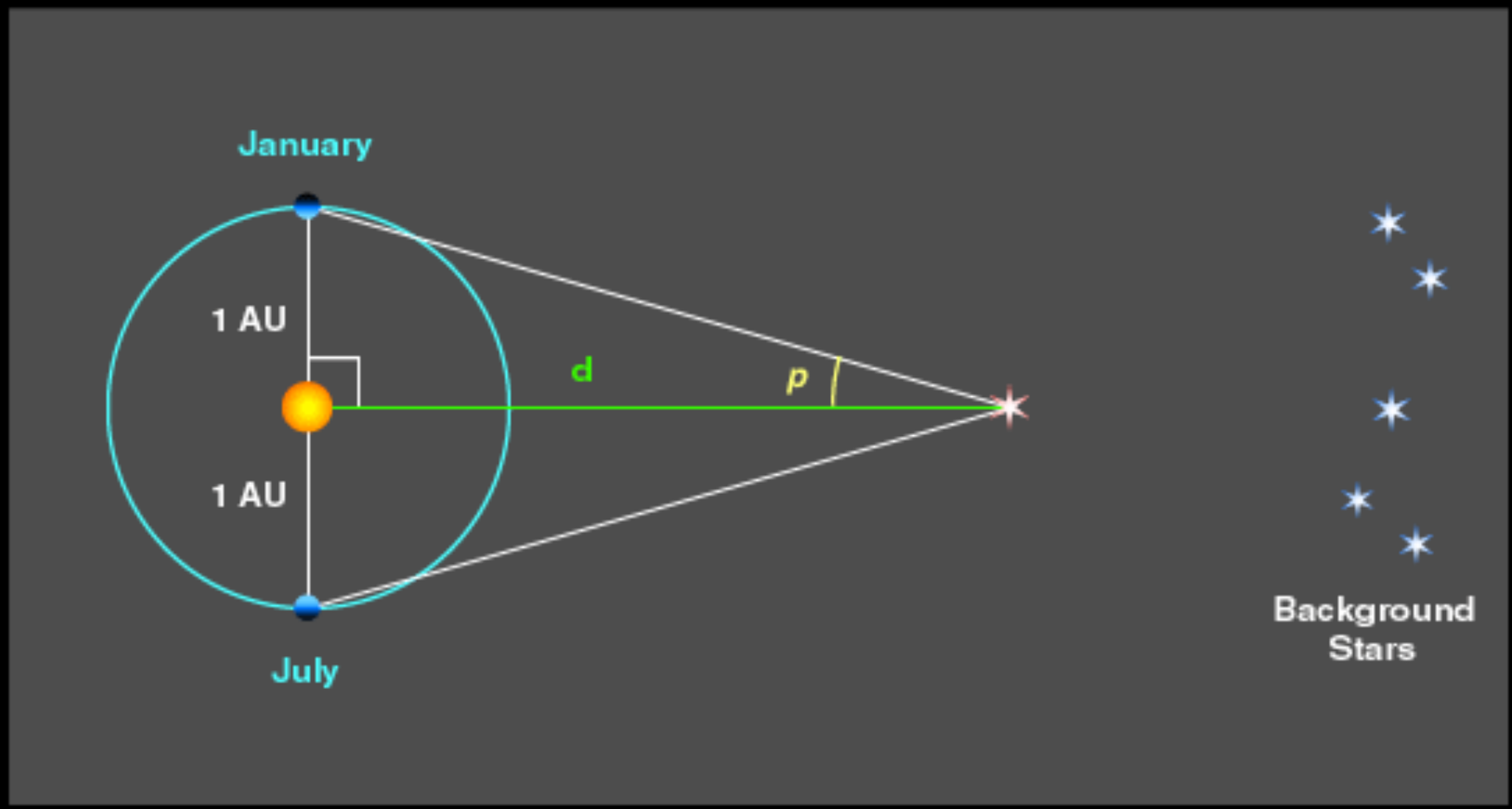


Trigonometric Parallaxes — 2

What is the longest baseline we can have?

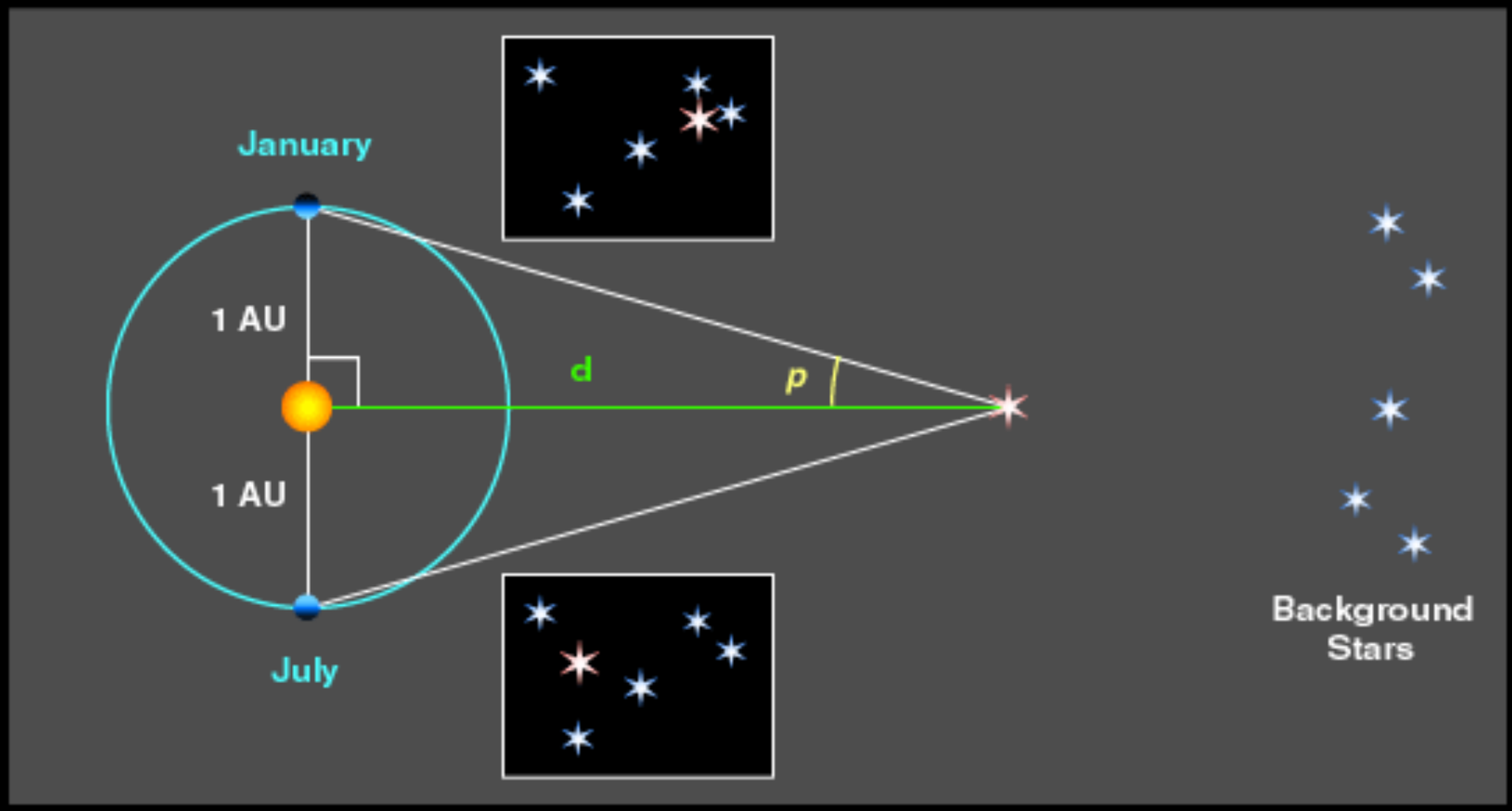
Trigonometric Parallaxes — 3

Distance to a Star



Trigonometric Parallaxes — 3

Distance to a Star



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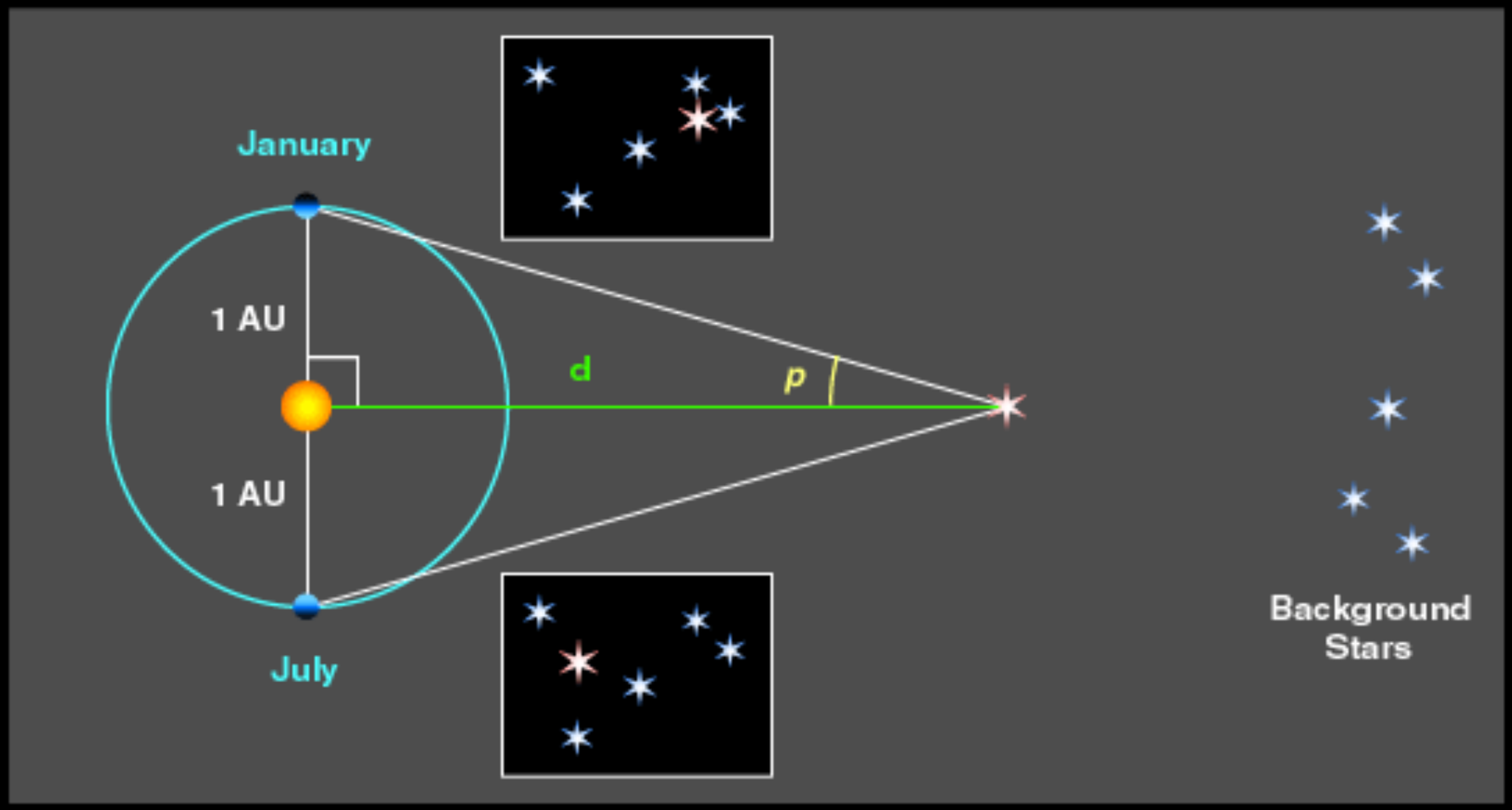


Measure the Position of the Stars

Trigonometric Parallaxes — 3

Definition

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

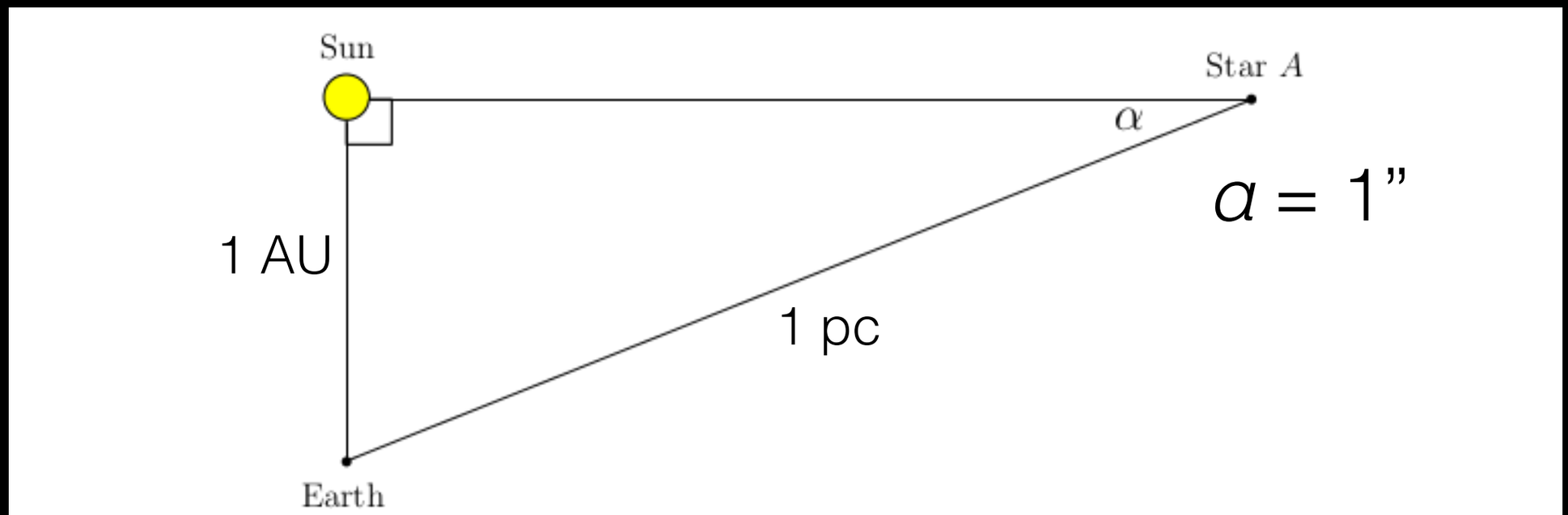
$$d = 1/p$$

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 measure

d ~ 10,000 pc ~ 10 kpc

p = 0.0001”

Trigonometric Parallaxes — 3

The Farthest Star Parallax can measure

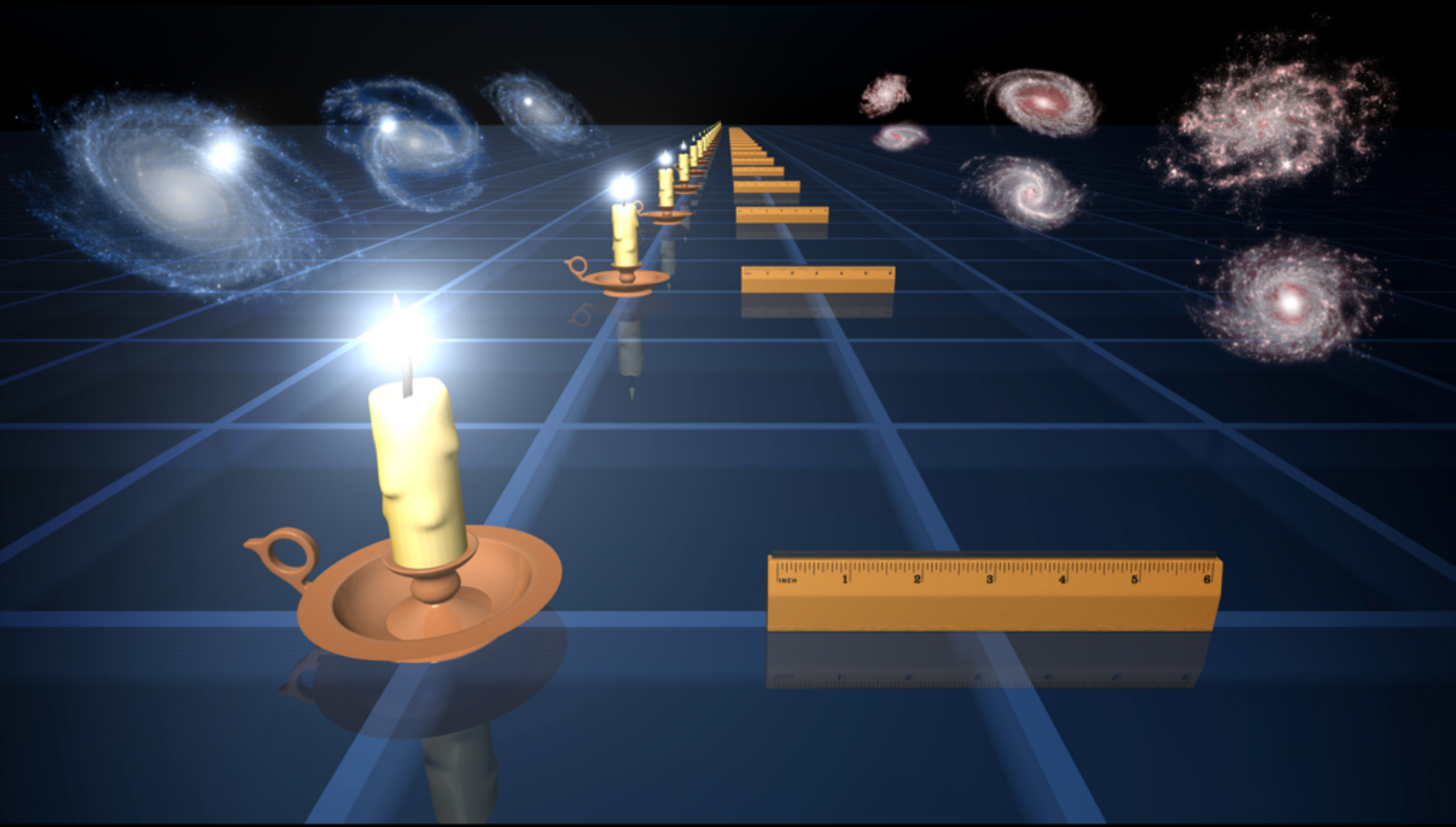
d ~ 10,000 pc ~ 10 kpc

p = 0.0001”

What about more distance stars?

Standard Candles

Standard Rulers



Standard Candles

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

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.

Standard Candles

Measure the Brightness of the Stars

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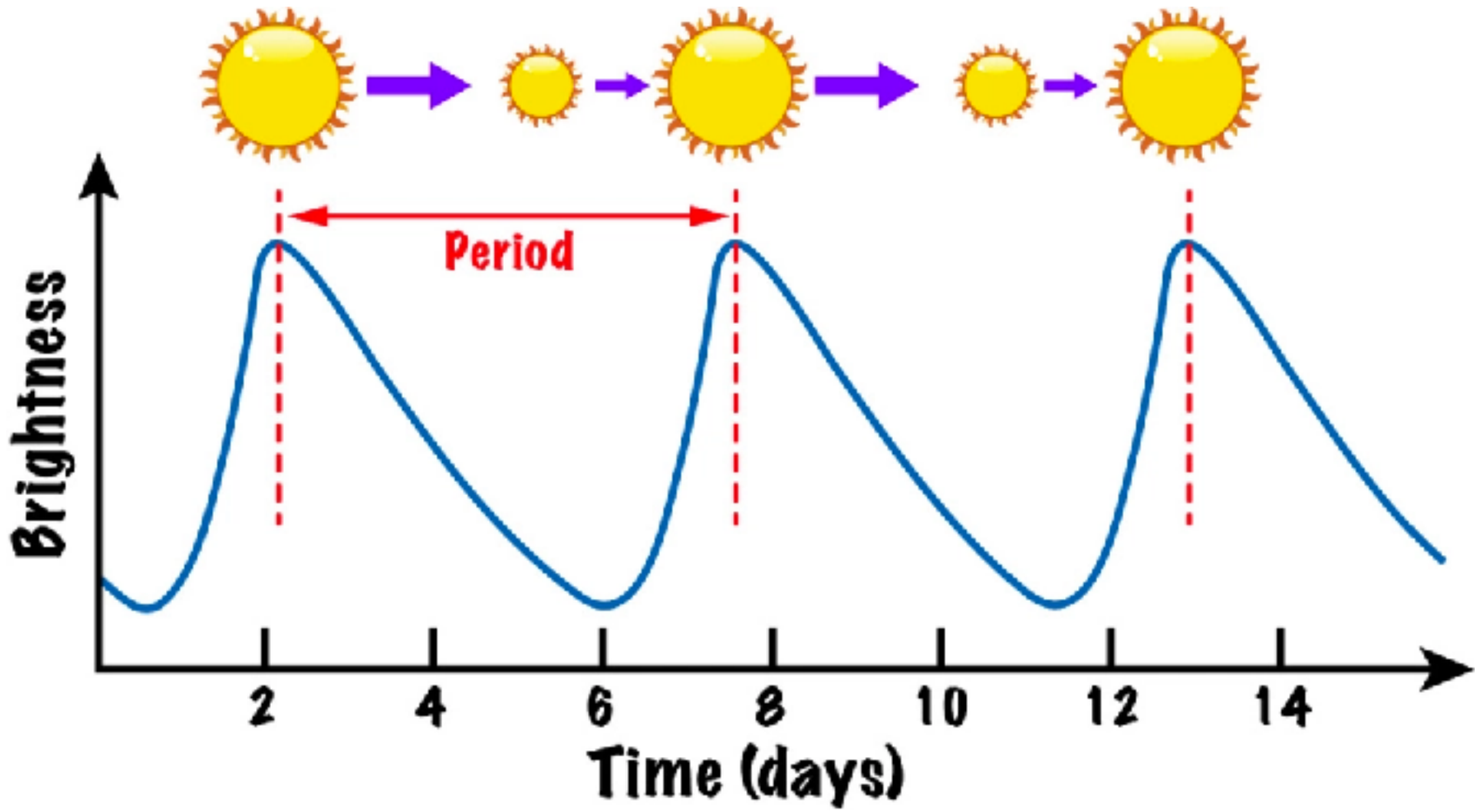
Standard Candles: Cepheid variable stars



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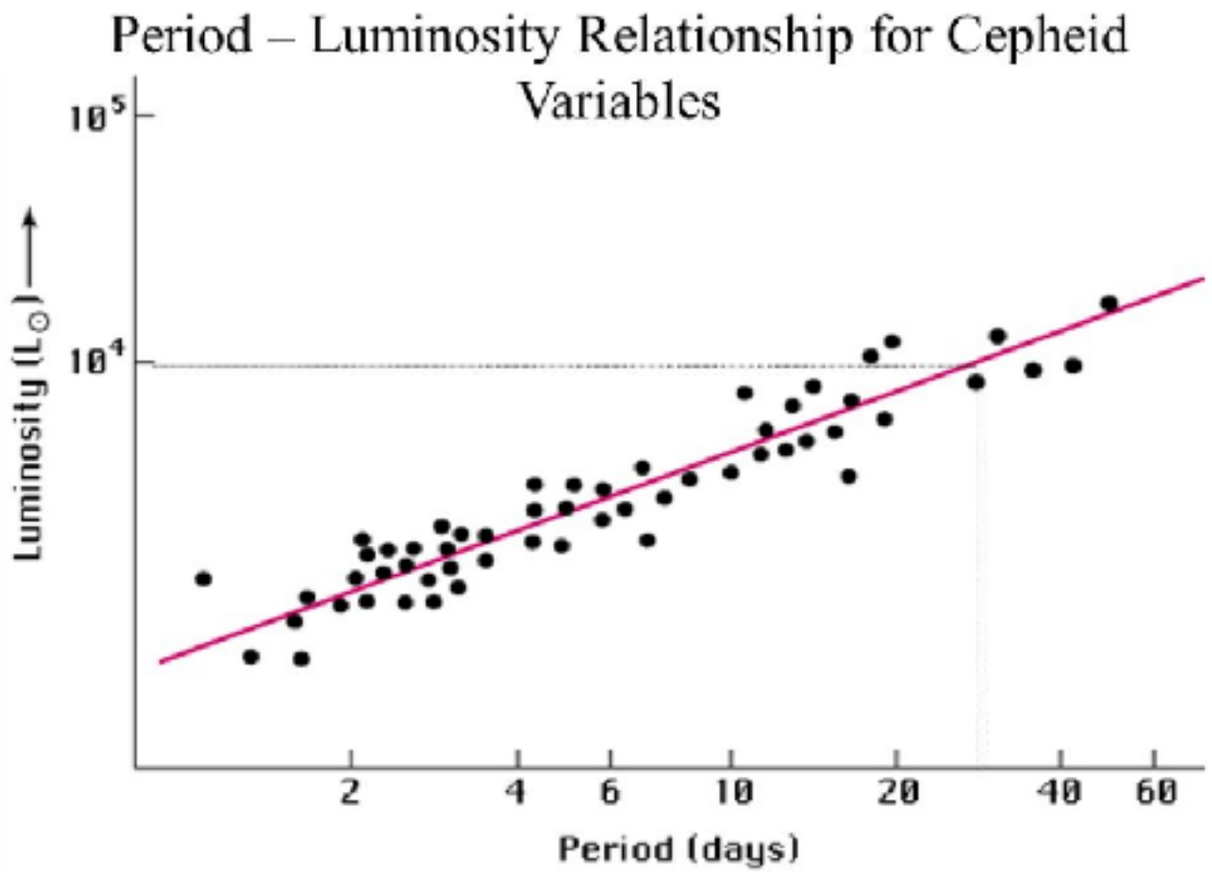
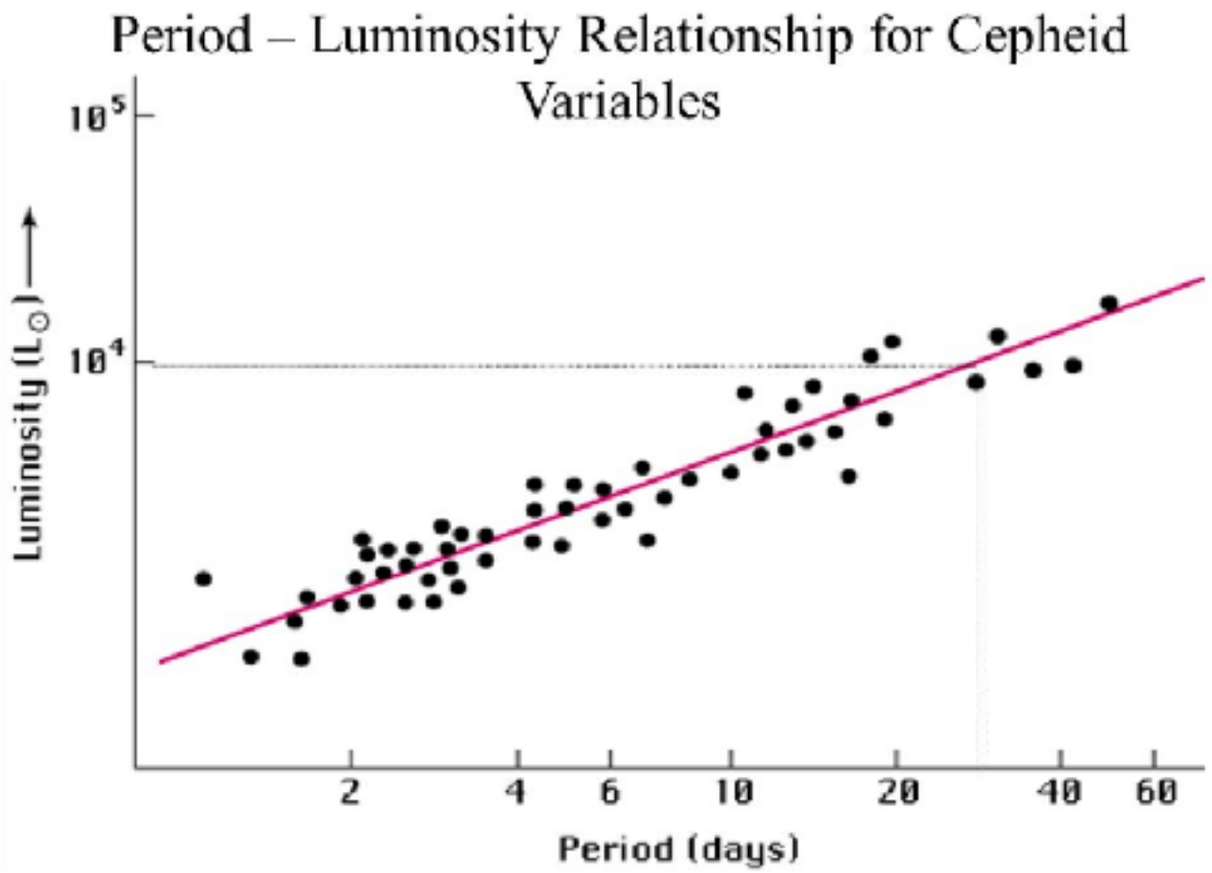


Henrietta Leavitt (1912)

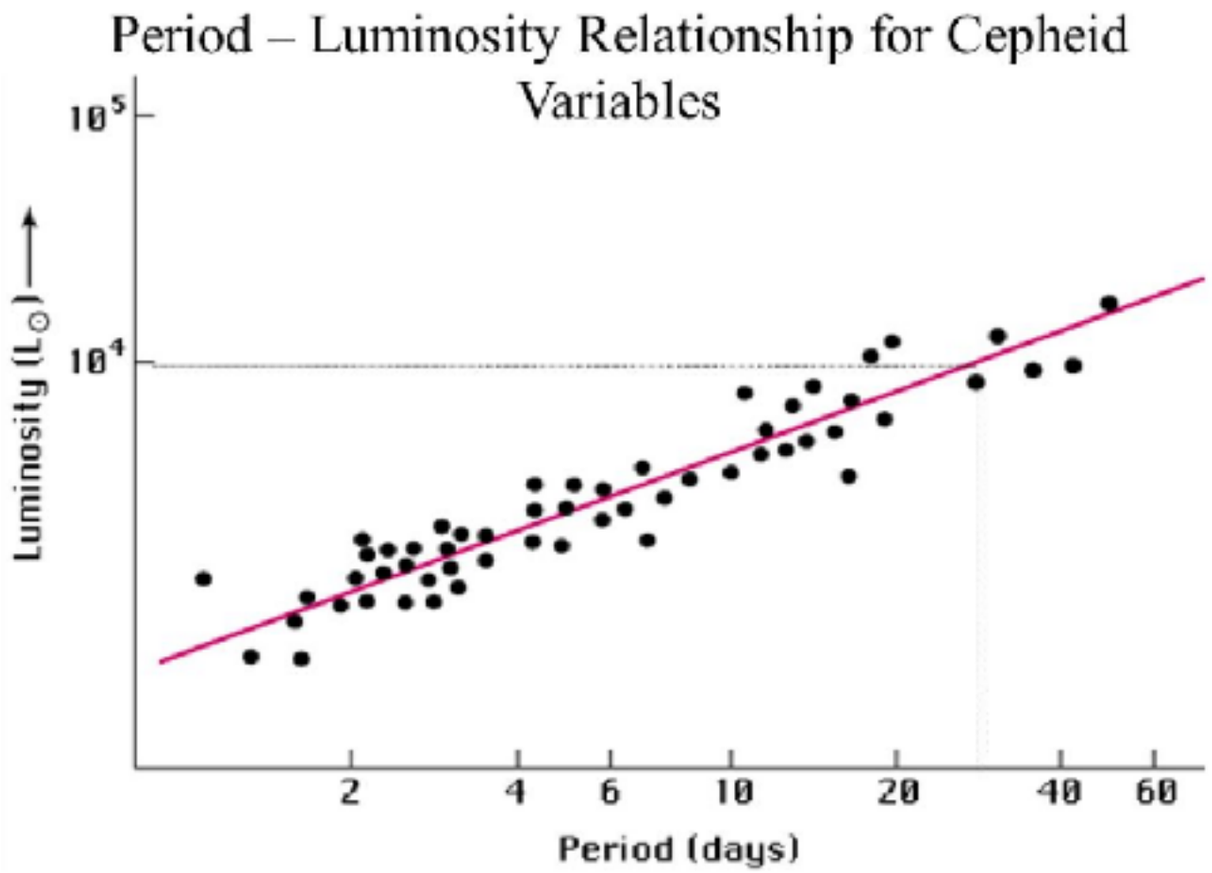
Standard Candles: Cepheid variable stars



Henrietta Leavitt (1912)

Period

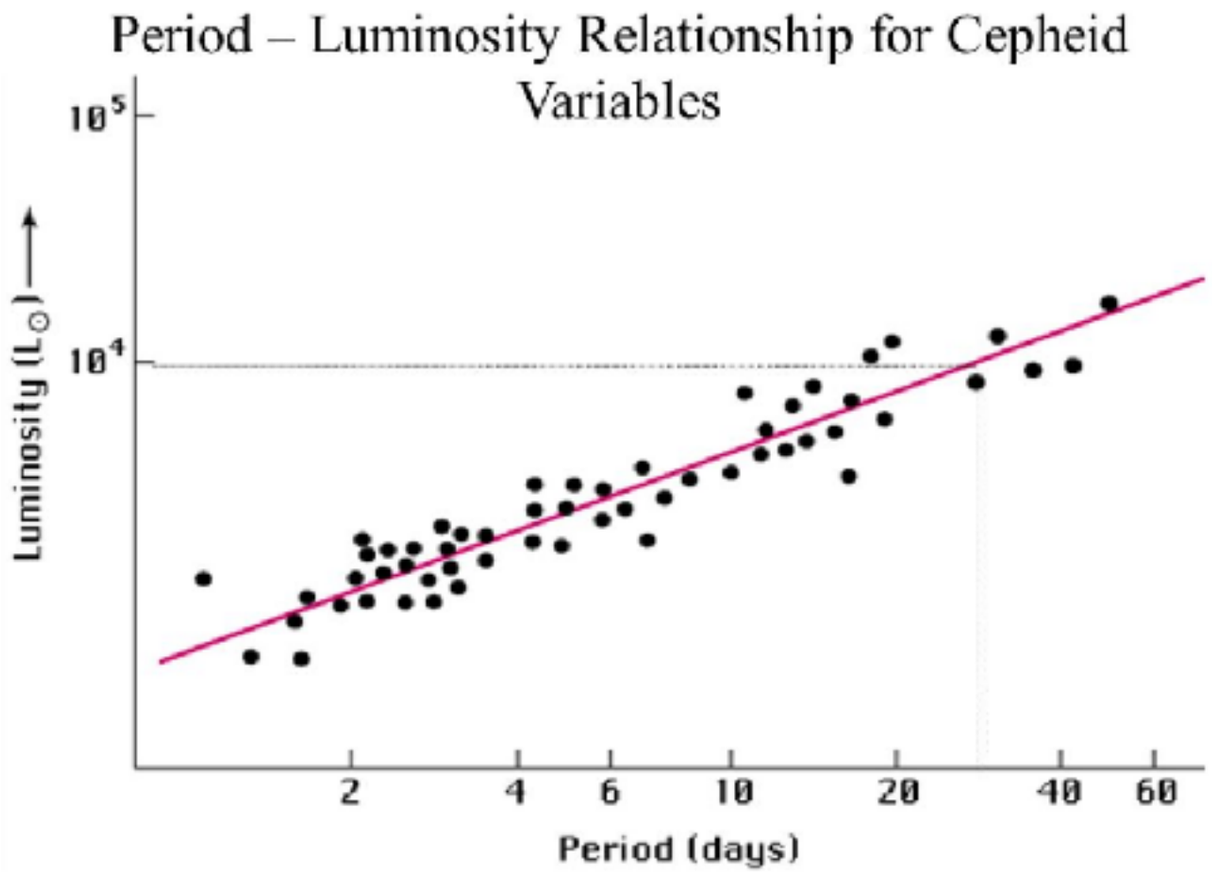
Standard Candles: Cepheid variable stars



Henrietta Leavitt (1912)

Period ⟶

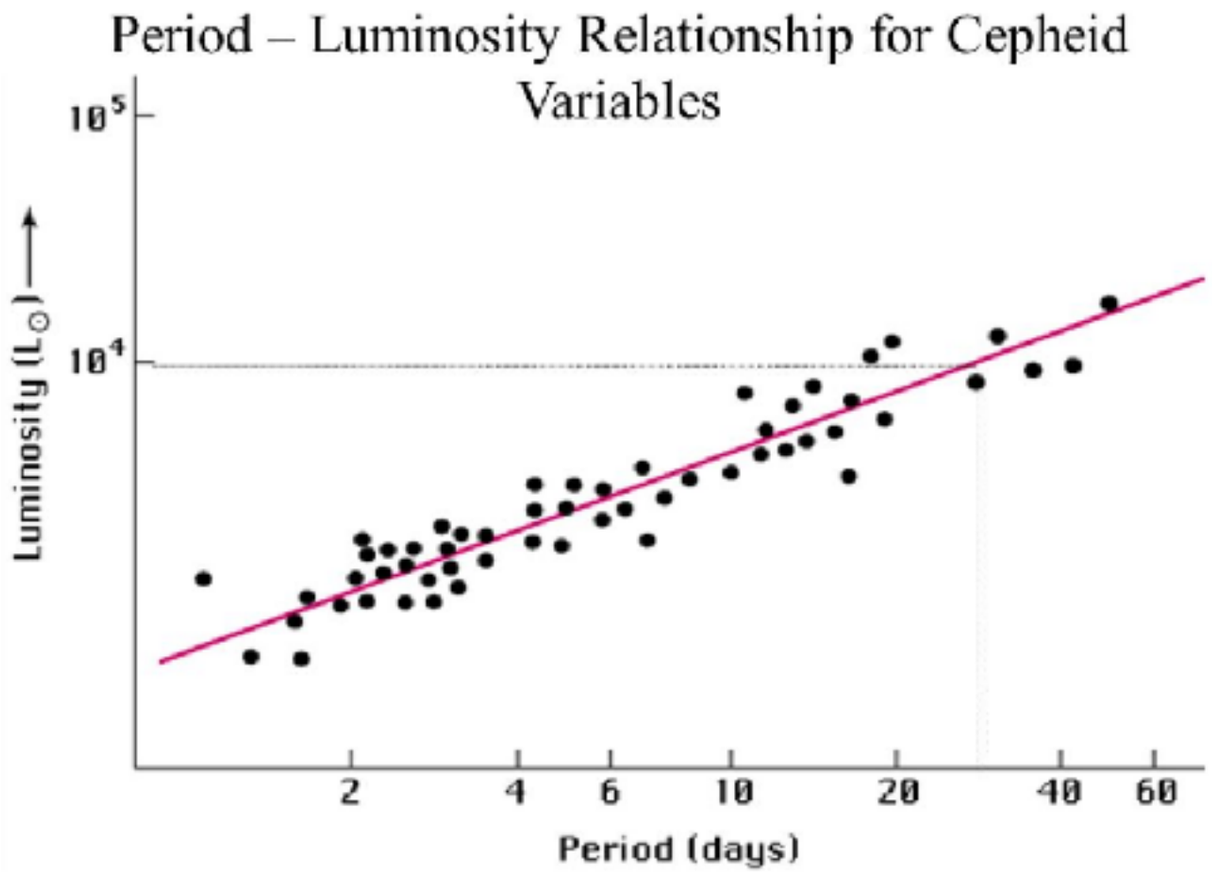
Standard Candles: Cepheid variable stars



Henrietta Leavitt (1912)

Period → Luminosity

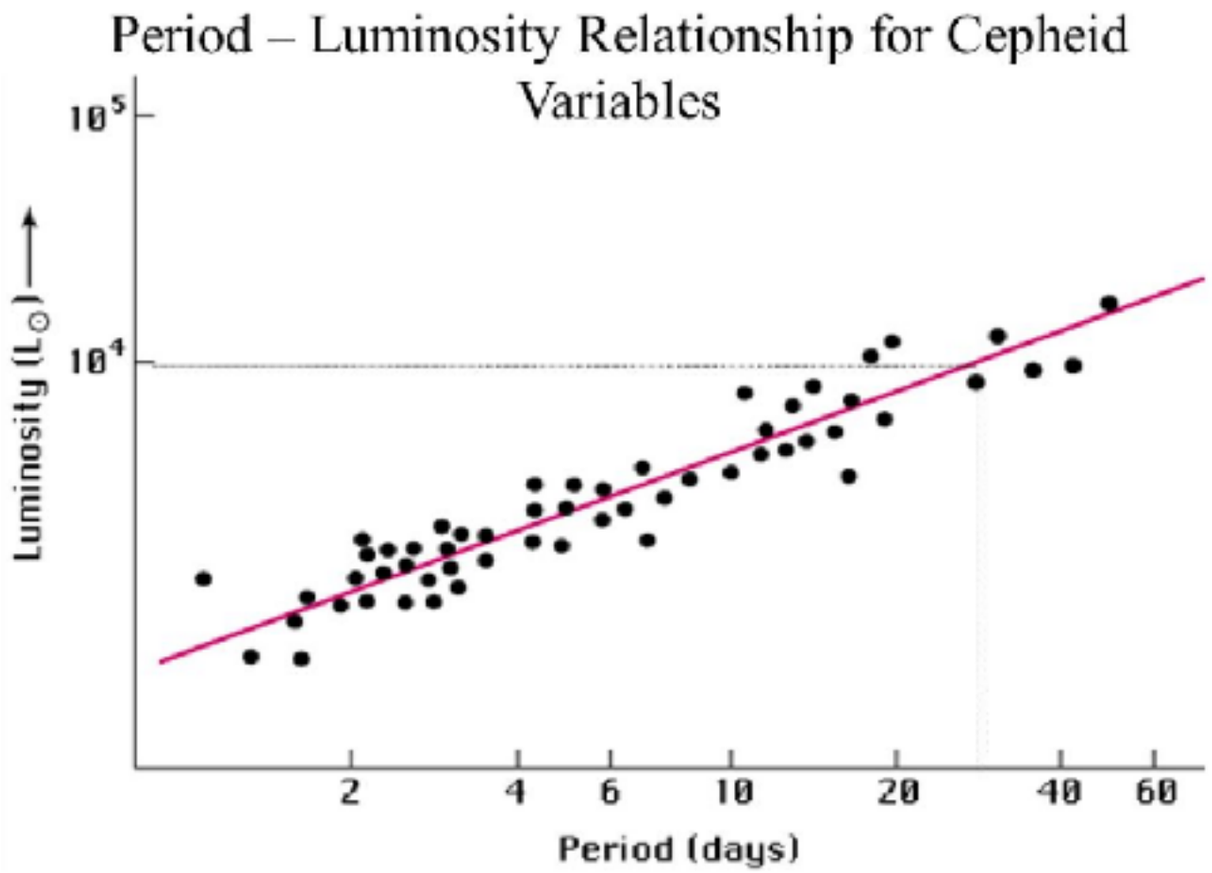
Standard Candles: Cepheid variable stars



Henrietta Leavitt (1912)

Period → **Luminosity** →

Standard Candles: Cepheid variable stars

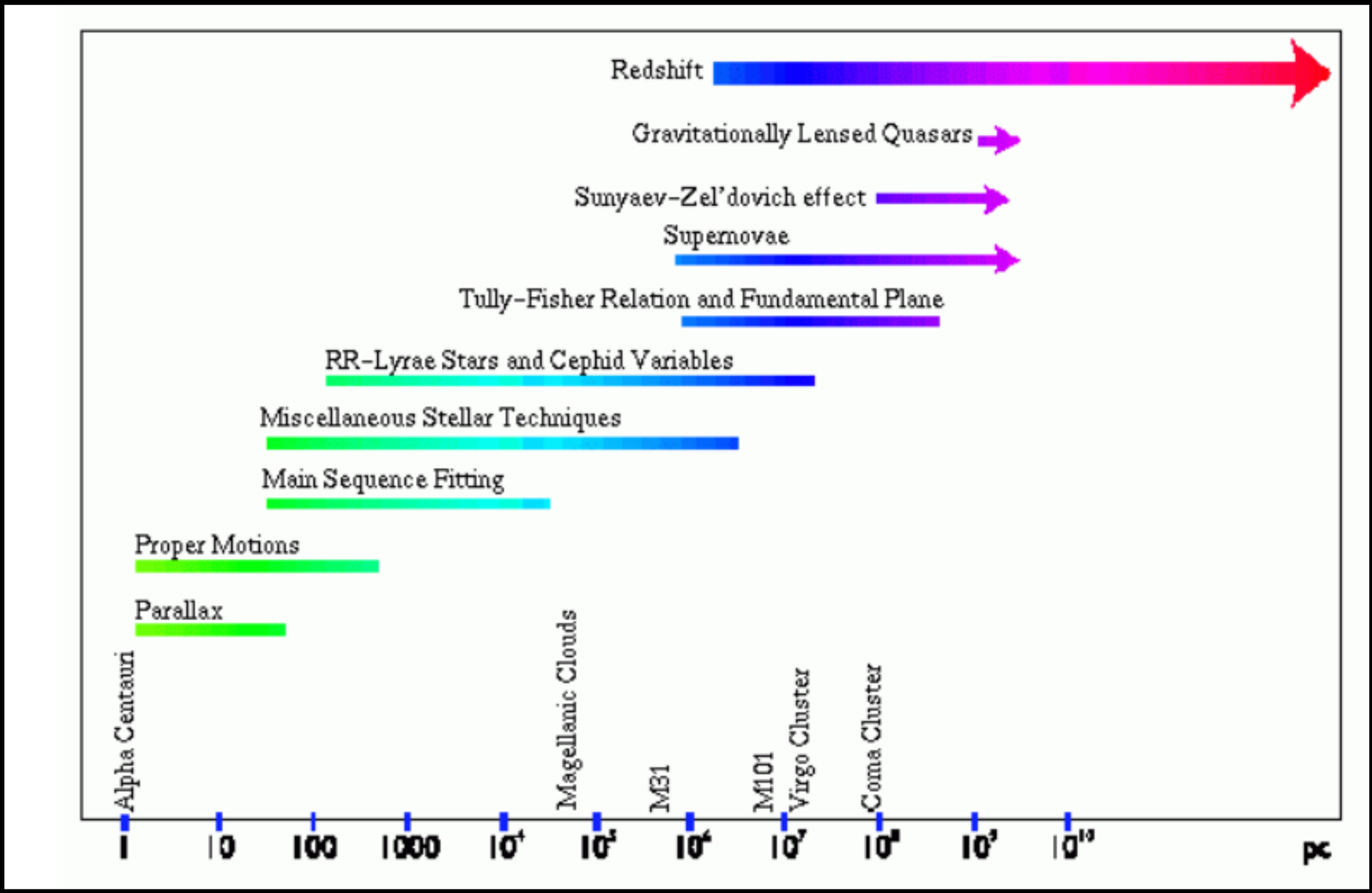


Henrietta Leavitt (1912)

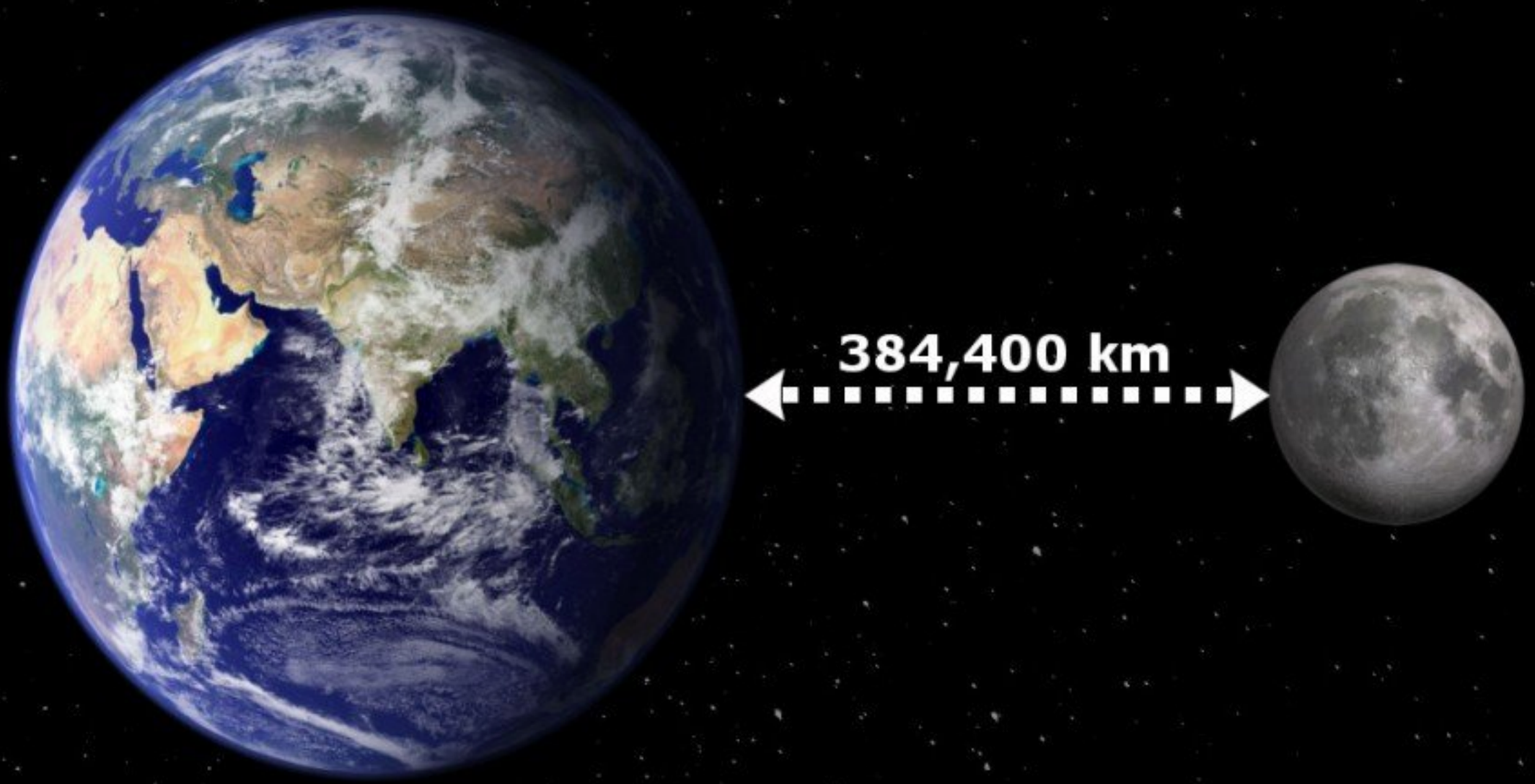
Period → **Luminosity** → **Distance**

Supernova: an exploding star.
A Standard Candle.

Distance Ladder



Distance to the Moon



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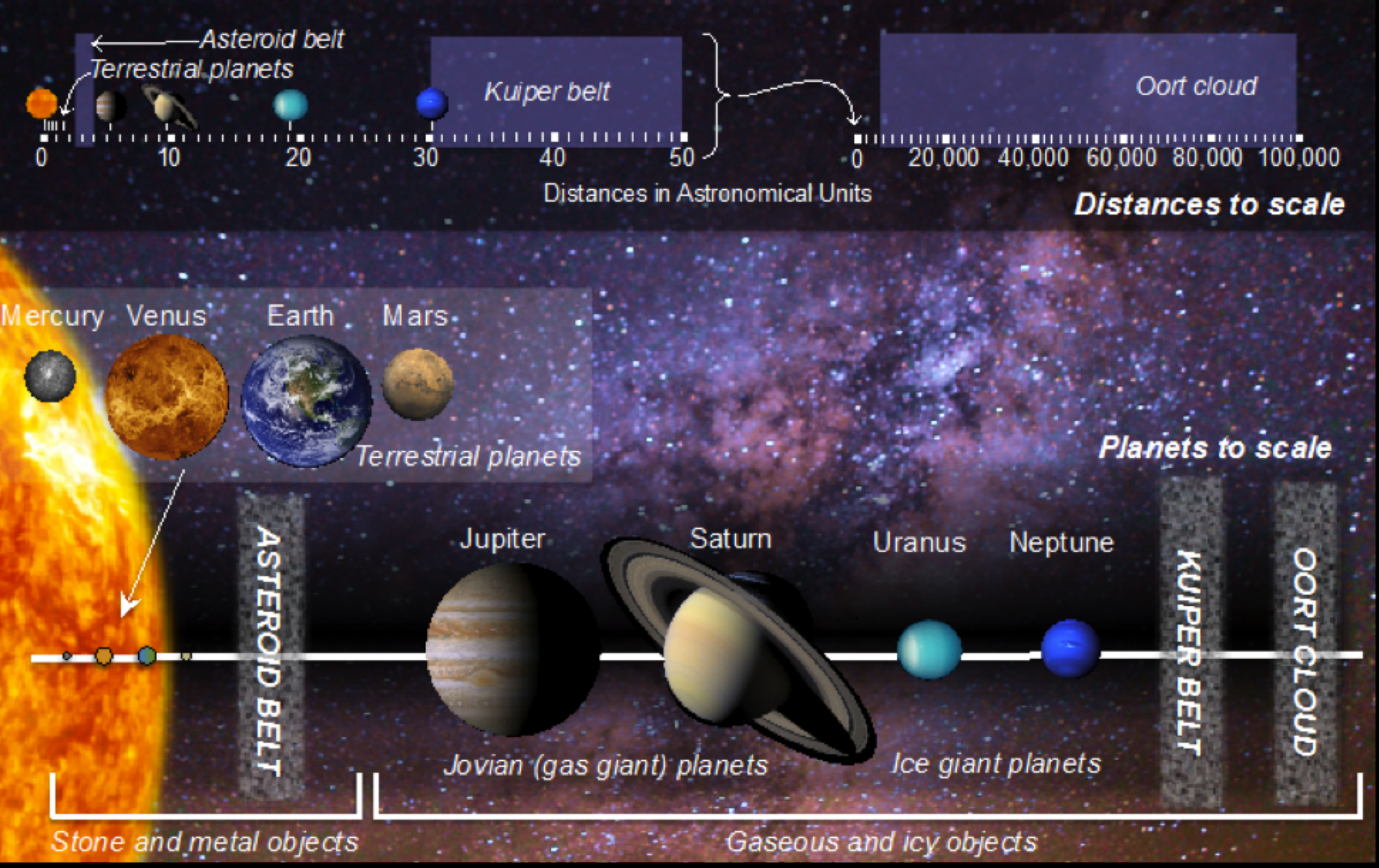
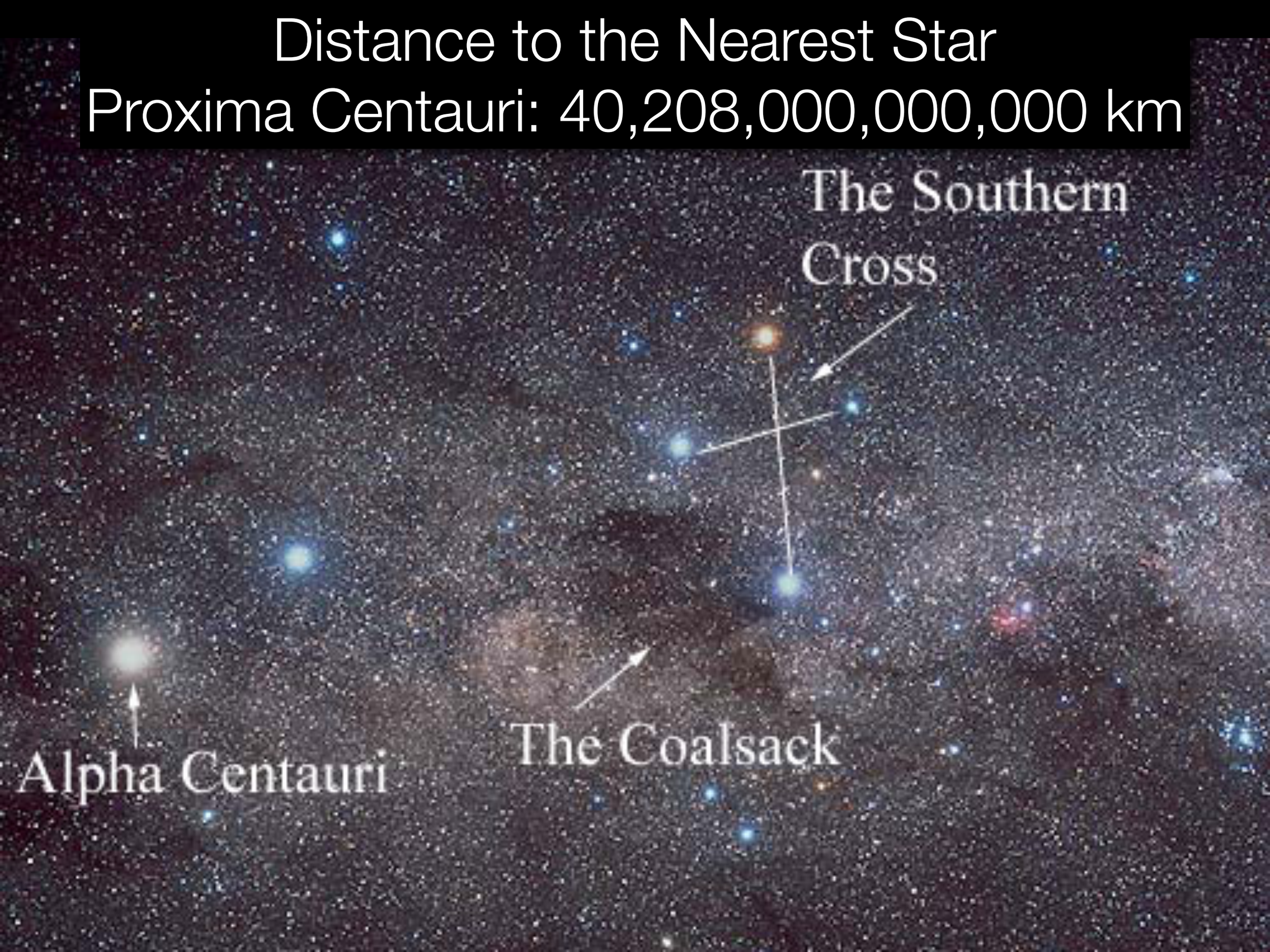


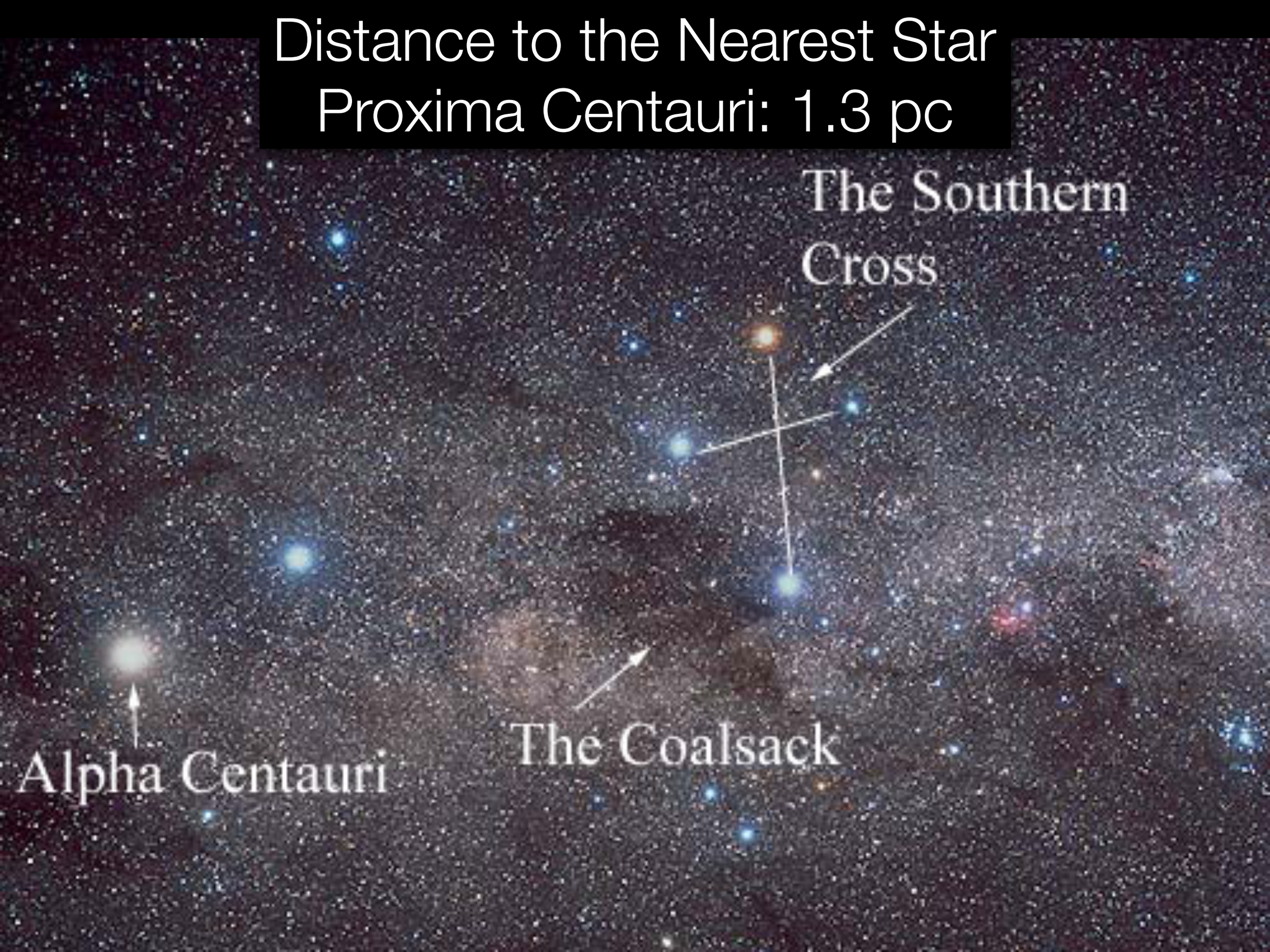
Distance to the Edge of Solar System: 150,000,000 km

Distance to the Nearest Star

Proxima Centauri: 40,208,000,000,000 km

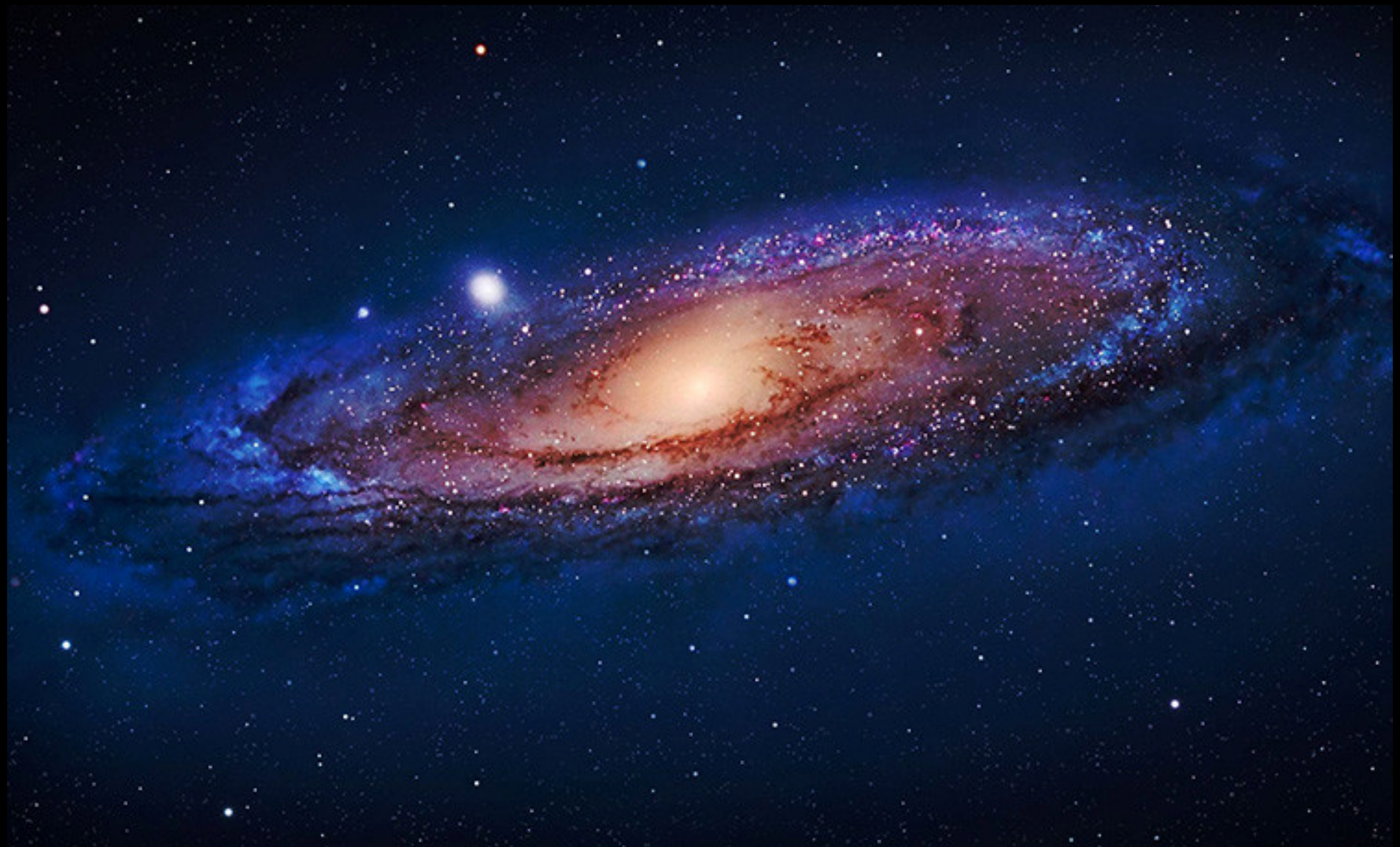


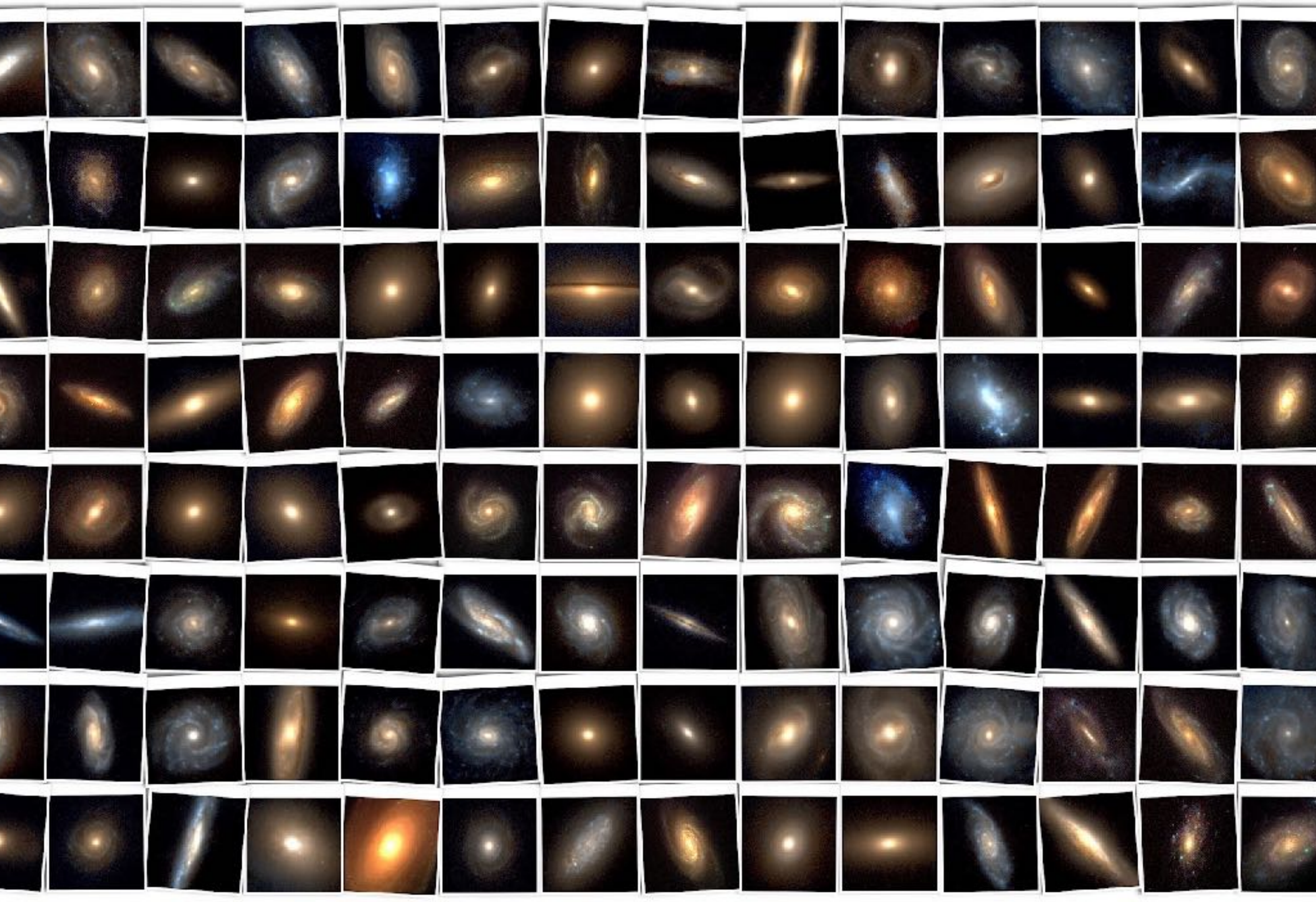
Distance to the Nearest Star
Proxima Centauri: 1.3 pc

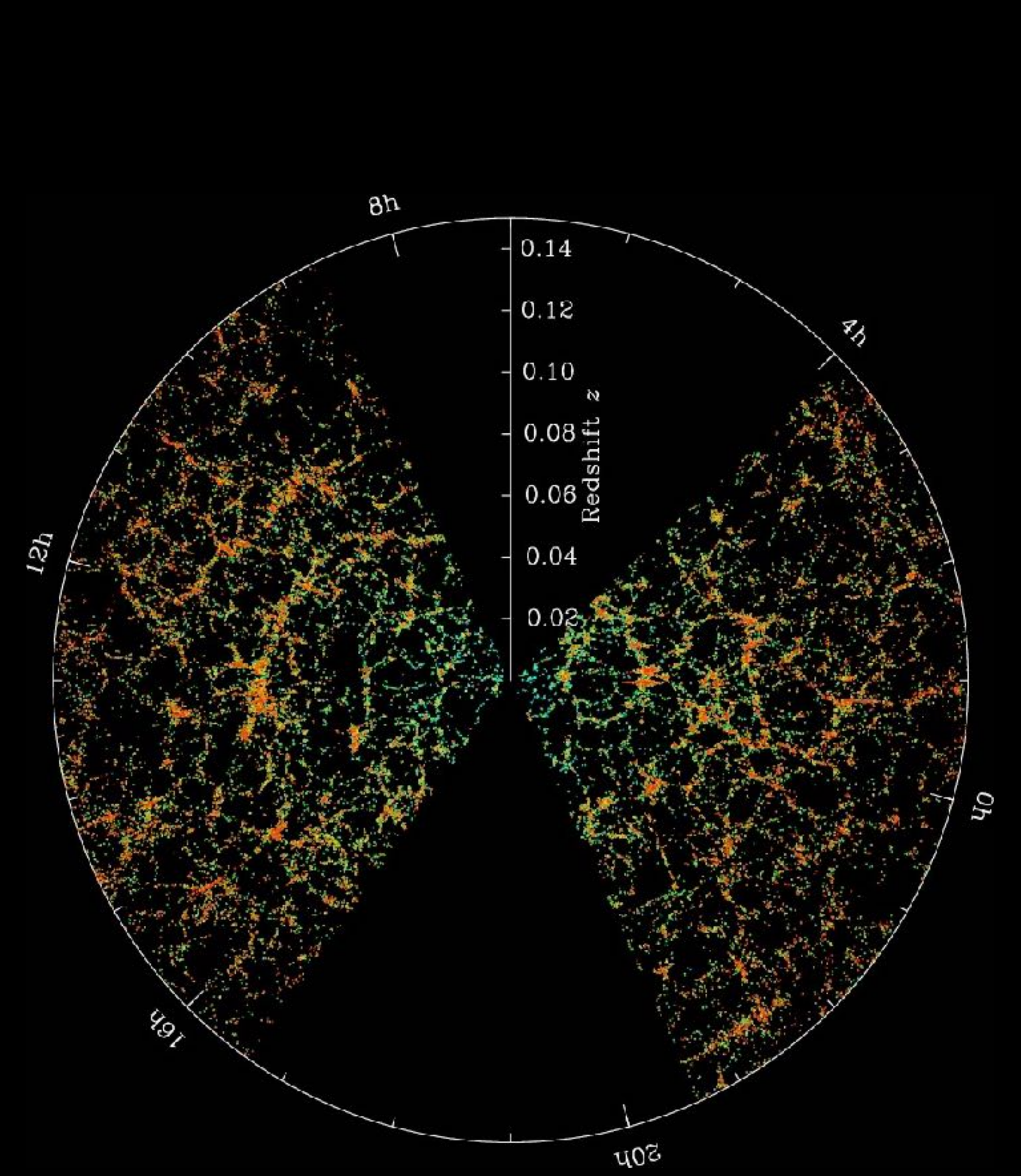


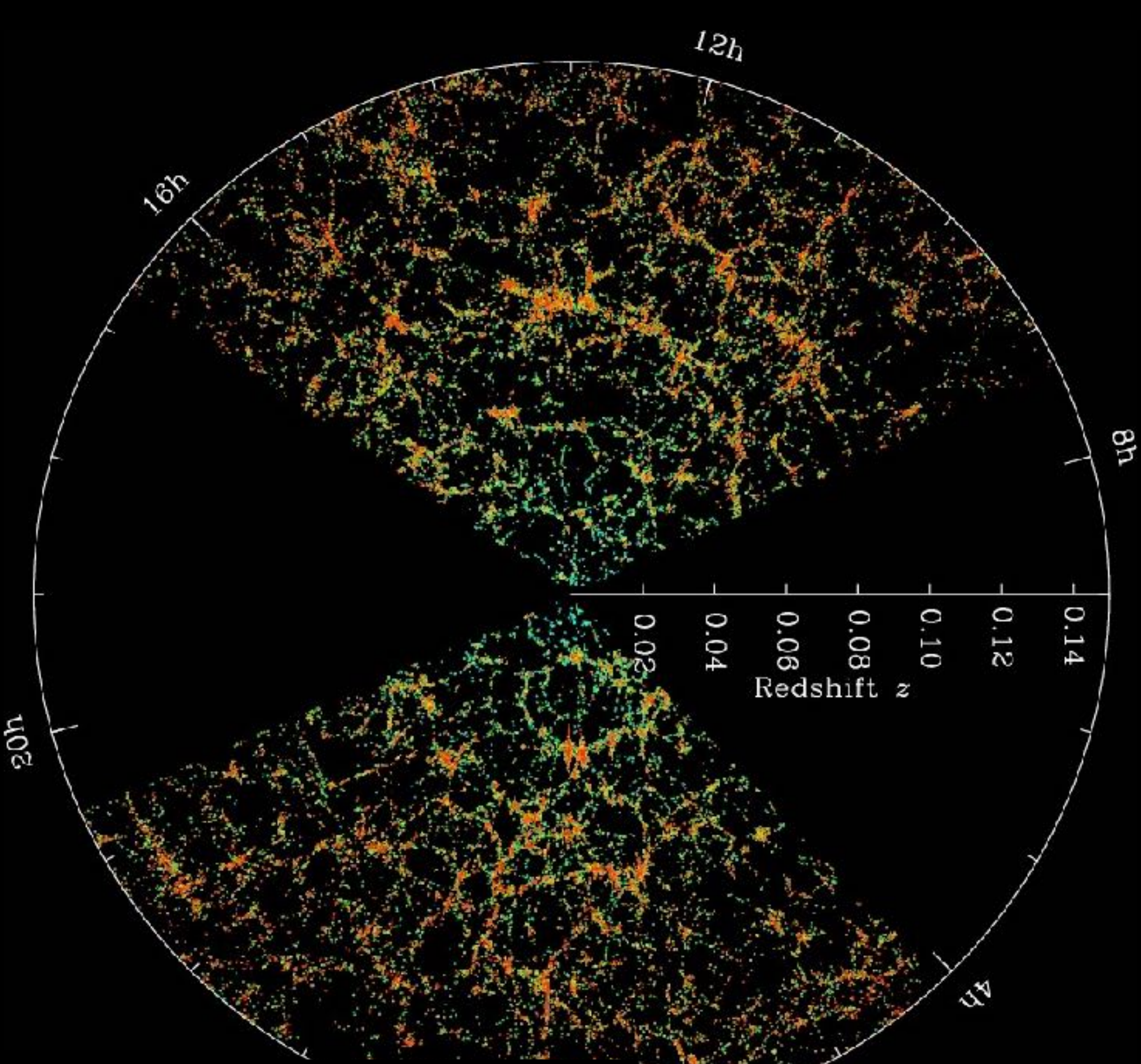
stars in the Milky Way ~ 1pc -100 kpc

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






8h
4h
0h
20h
16h
12h
0.14
0.12
0.10
0.08
0.06
0.04
0.02
Redshift z



600 Mega-parsecs (Mpc)

Size of Observable Universe

- 14 000 Mpc (14 Gpc)

Size of an Atom

- 1 Ångström

Ratio ~ 10^{36}

To summarize …

Distance Measurements

- **Trigonometric Parallaxes**
- **Standard Candles**
- **……**

To summarize …

Distance Measurements

- **Trigonometric Parallaxes** — position / astrometry
- **Standard Candles**
- **……**

To summarize …

Distance Measurements

- **Trigonometric Parallaxes**
  position / astrometry
- **Standard Candles**
  brightness / photometry
- ……

Now you know how to take astronomical observations!

- 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?

The Universe started with a Big Bang

The Origin

We are all Stardust

The Evolution

The Universe is mostly “Dark”

The Fate

Edwin Hubble

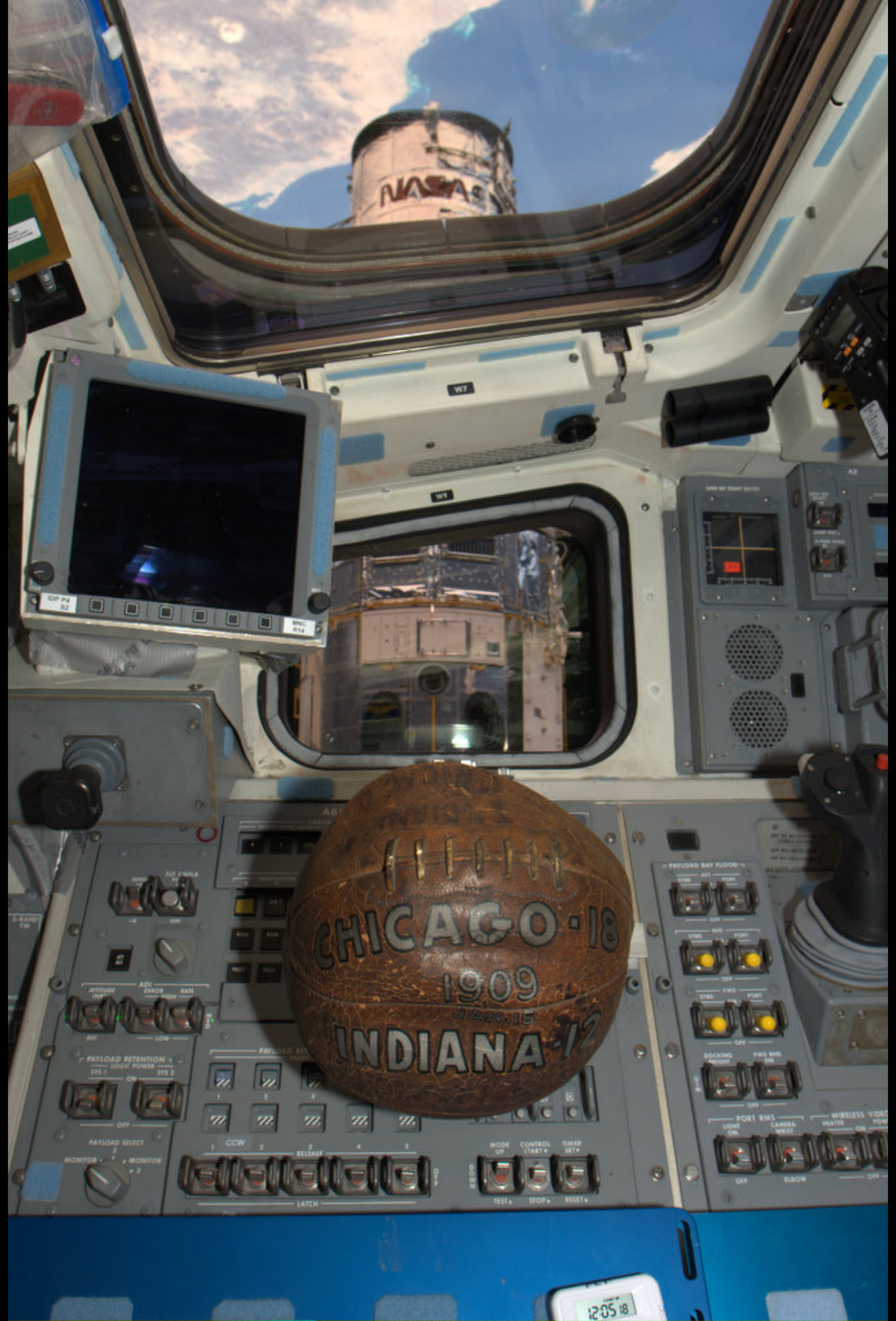
University of Chicago 1909 National Champions

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

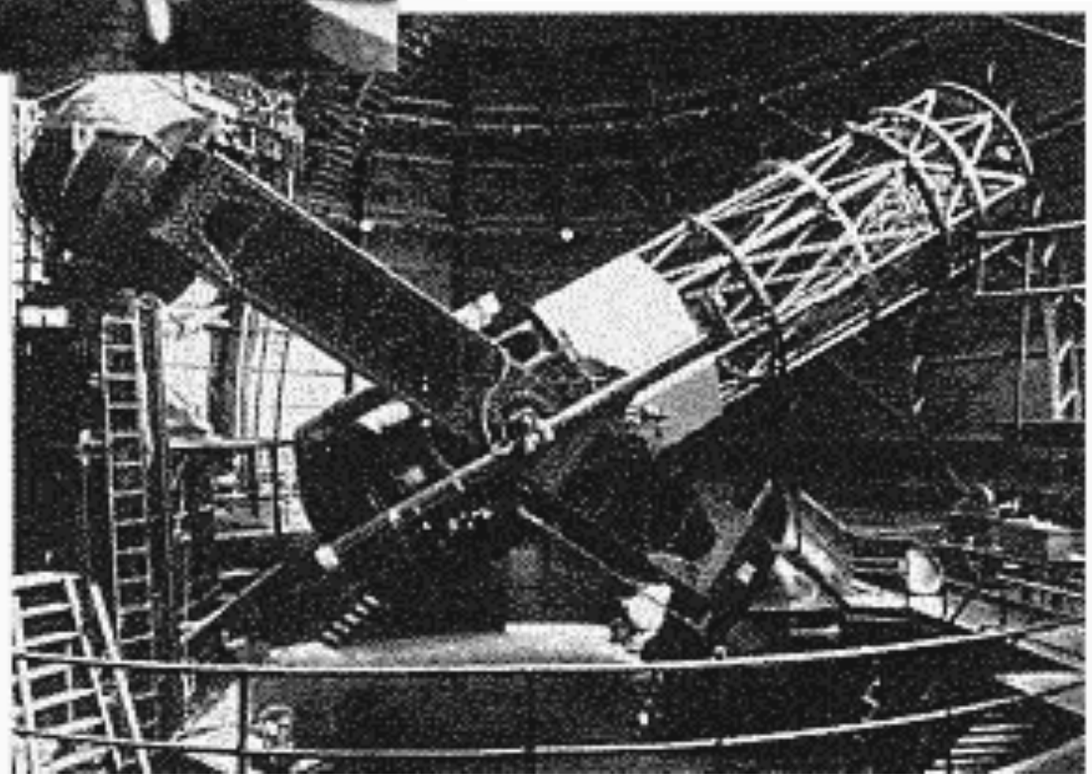


Discovery of Expanding Universe

Edwin Hubble

Nearby Galaxies → Motions

Nearby Galaxies → Distances



Mt. Wilson
100 Inch
Telescope

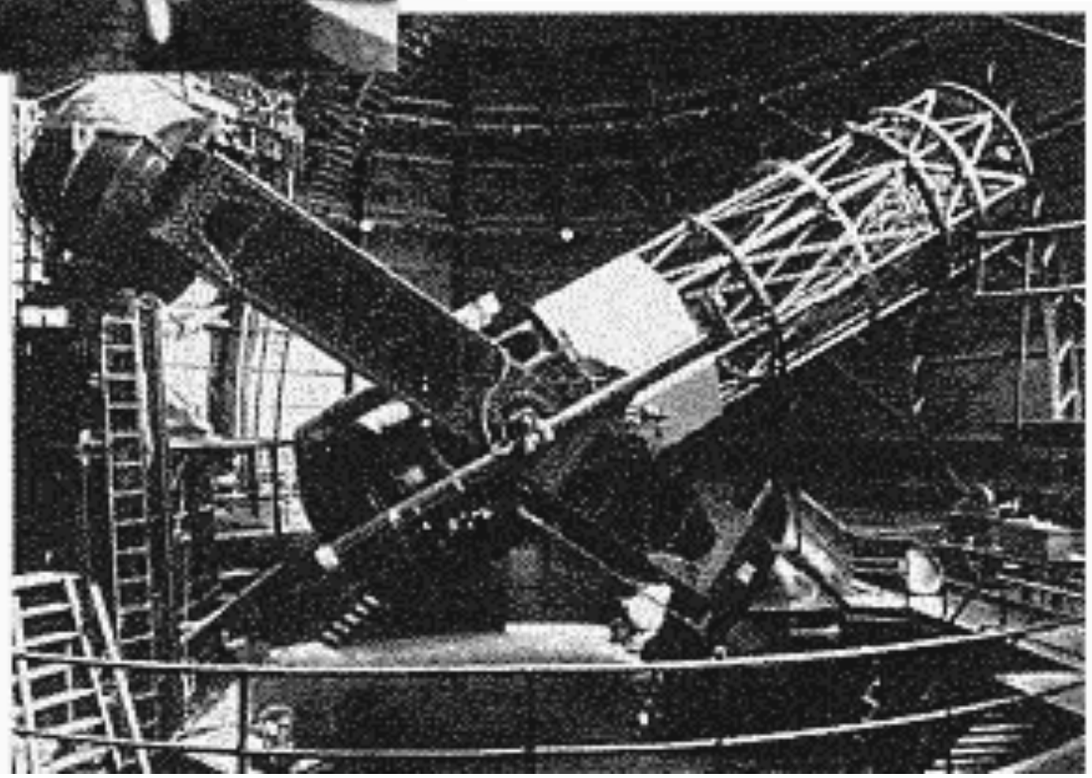
Discovery of Expanding Universe

Edwin Hubble

Nearby Galaxies → Motions

Nearby Galaxies → Distances

Standard Candles: Cepheid variable stars



Mt. Wilson
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Discovery of Expanding Universe

Edwin Hubble

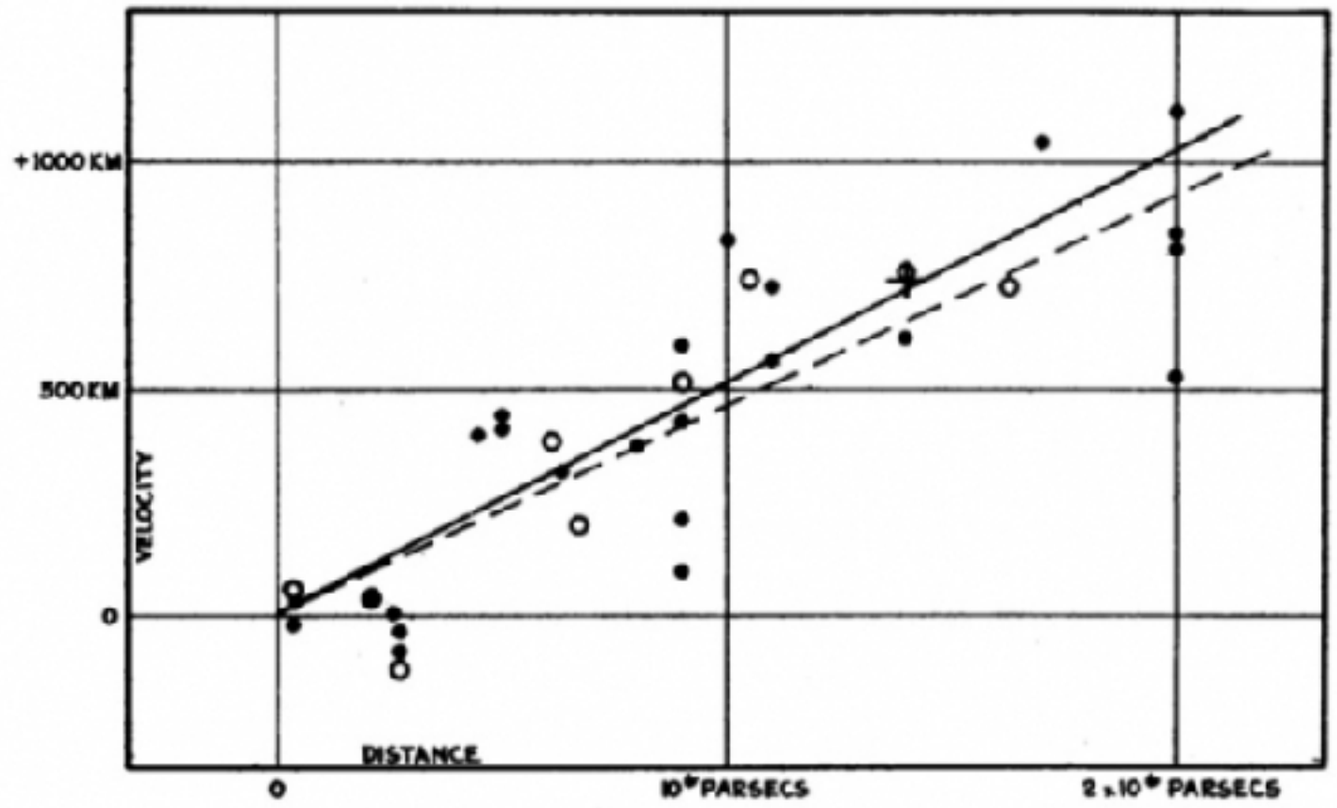
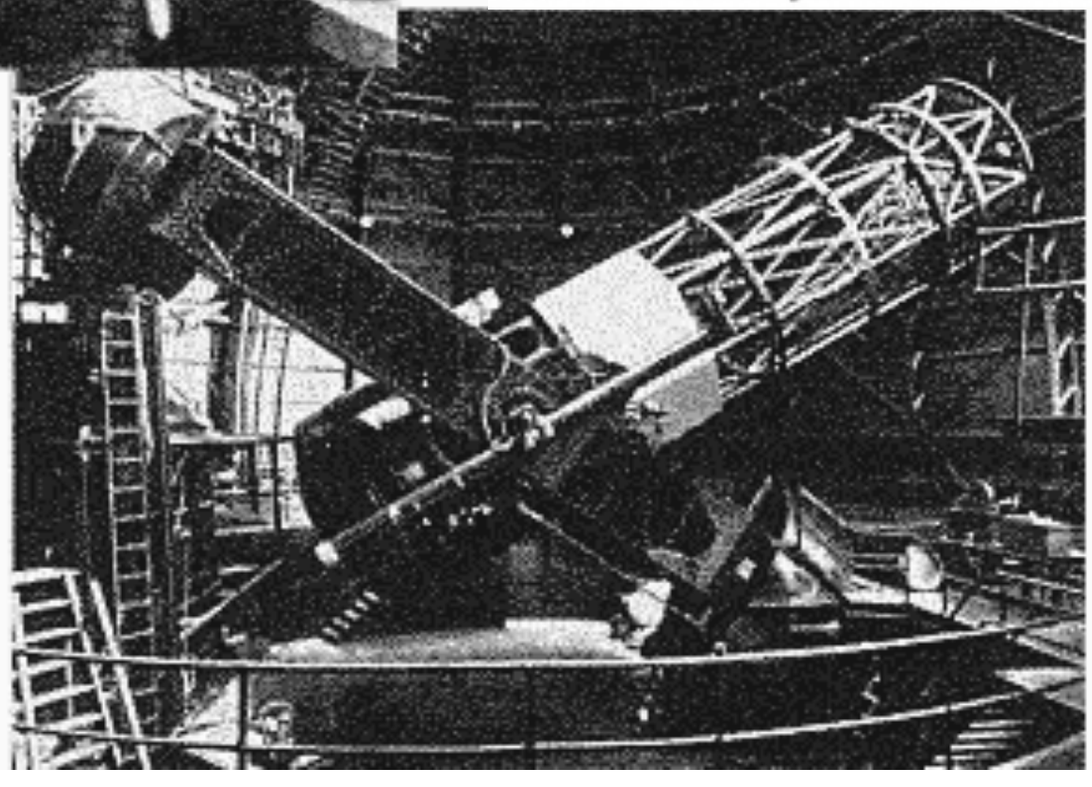


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

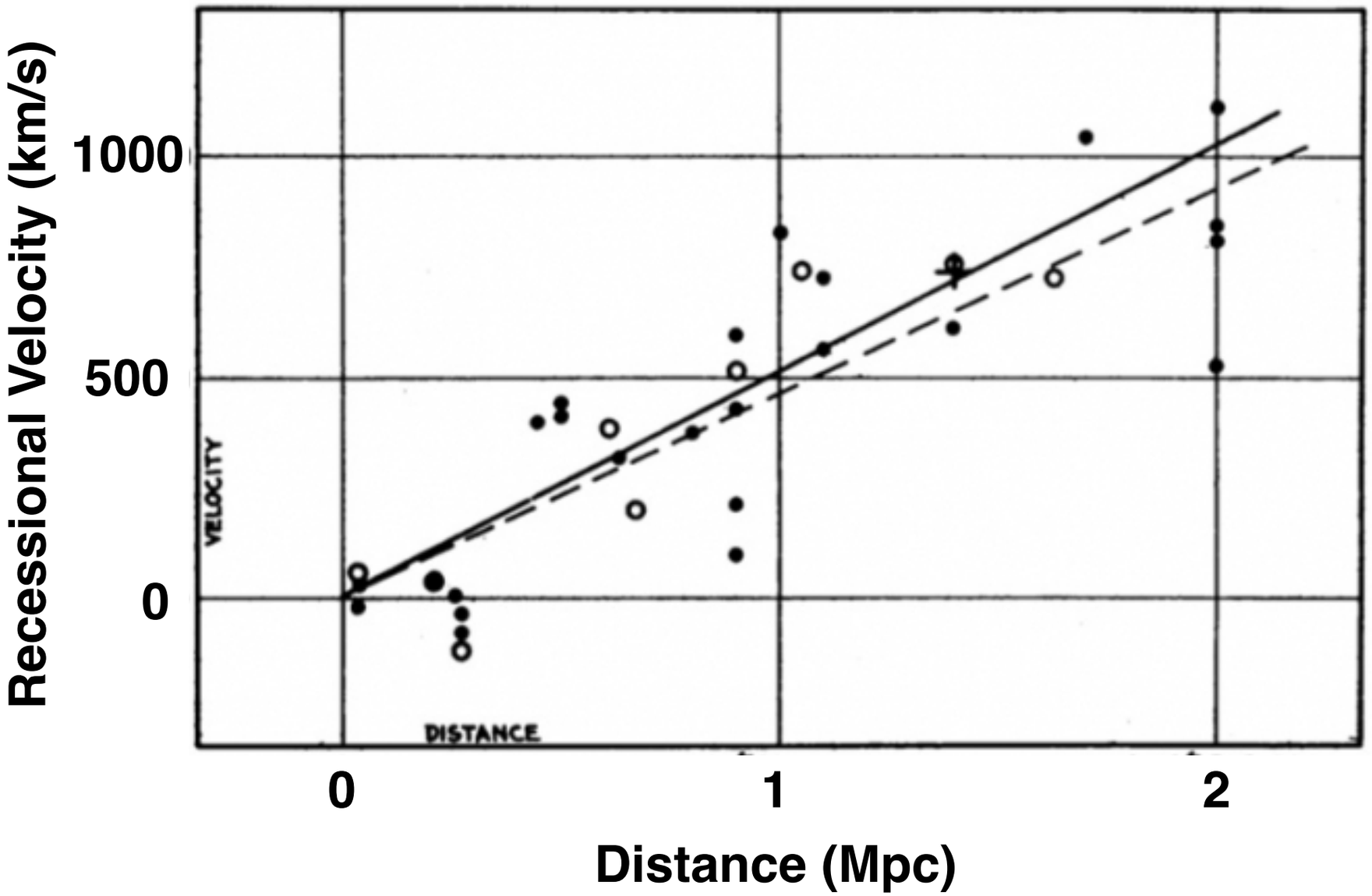
Hubble (1929)

Measure the Cepheid Variable stars in nearby galaxies



Mt. Wilson
100 Inch
Telescope

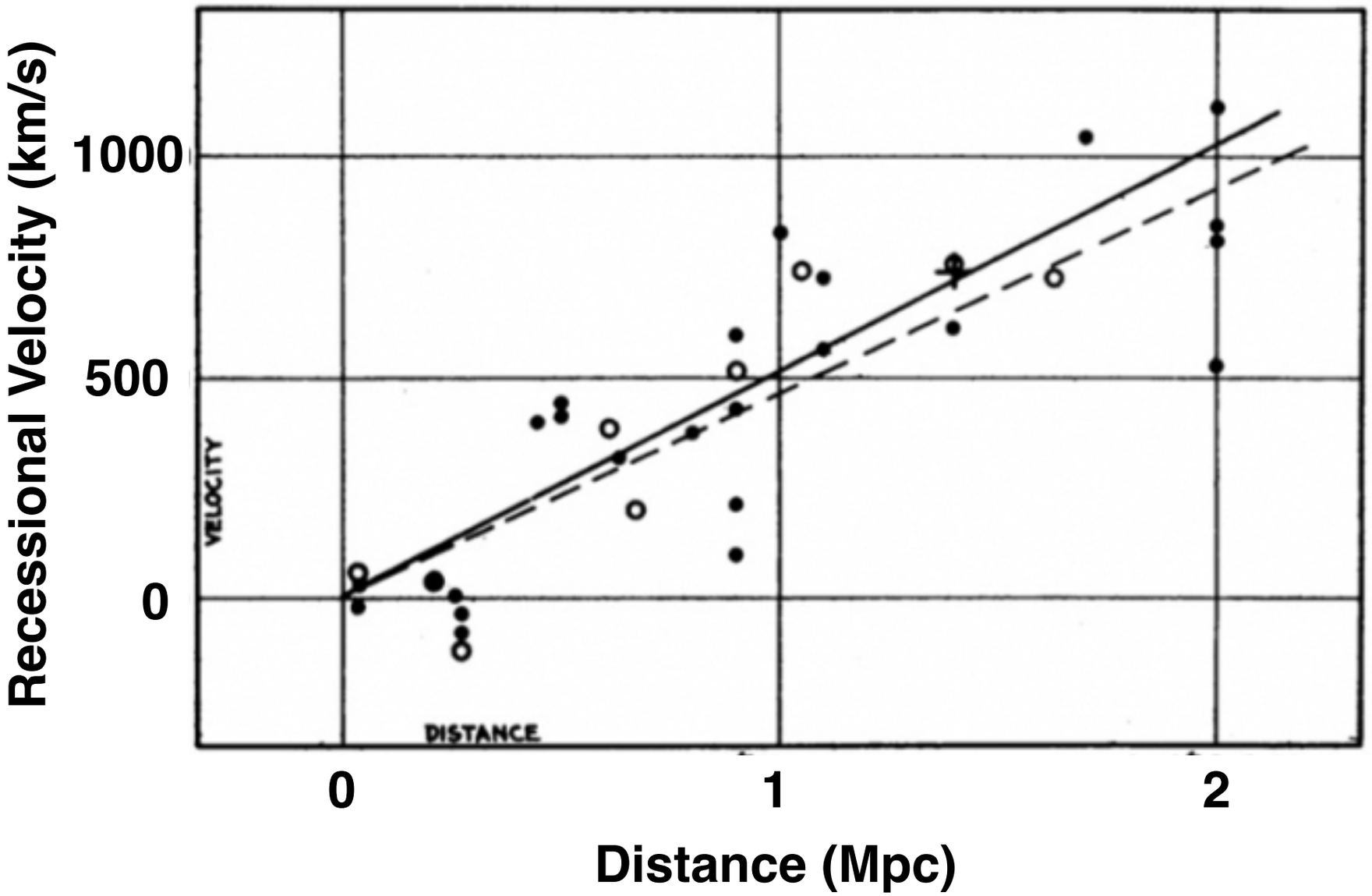
Hubble's Law


Recessional Velocity (km/s)
1000
500
0
VELOCITY
DISTANCE
0
1
2
Distance (Mpc)

Hubble's Law


Recessional Velocity (km/s)
1000
500
0
VELOCITY
DISTANCE
0
1
2
Distance (Mpc)
Bad Science Example:
No Error Bars

Hubble's Law


Recessional Velocity (km/s)
1000
500
0
VELOCITY
DISTANCE
0
1
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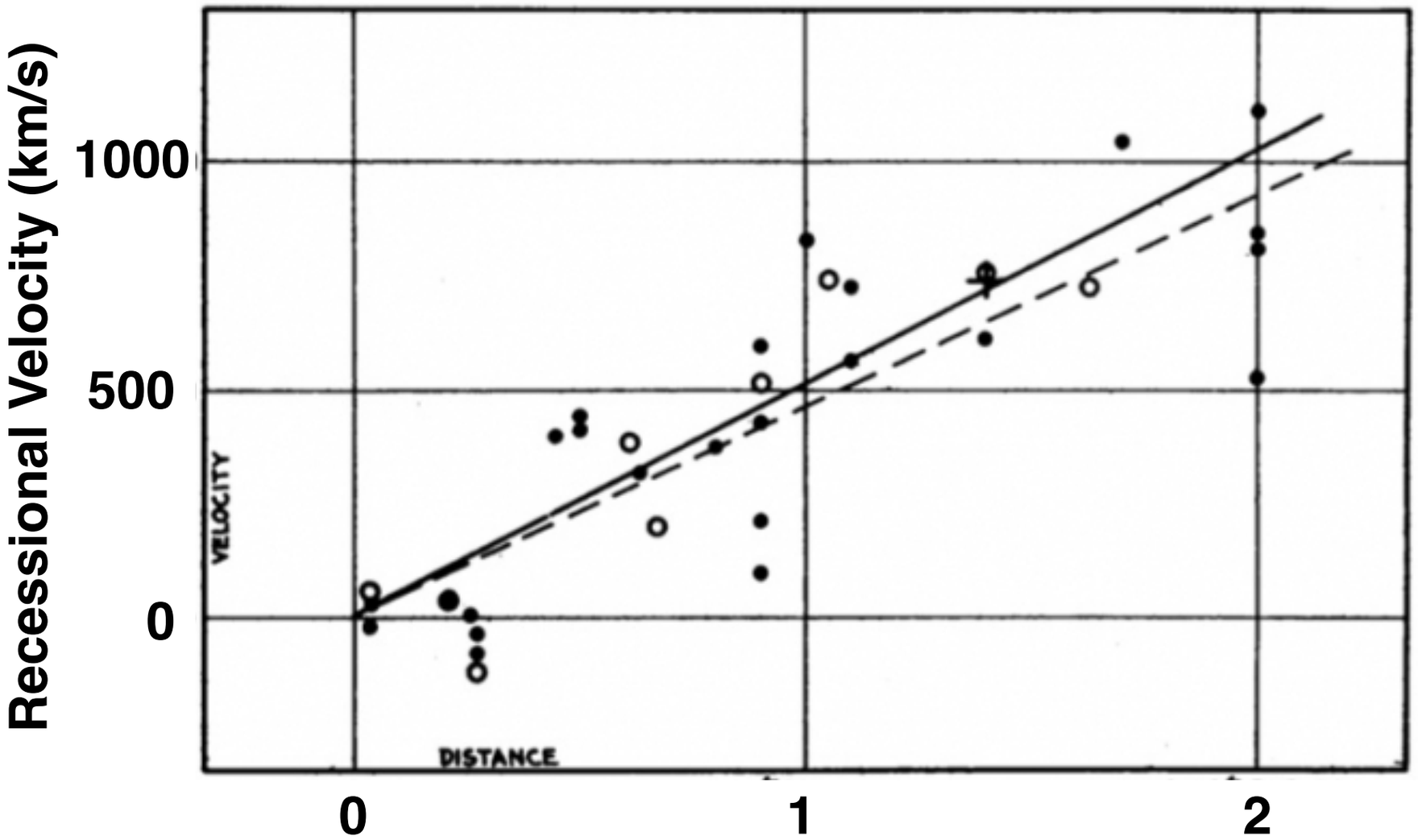
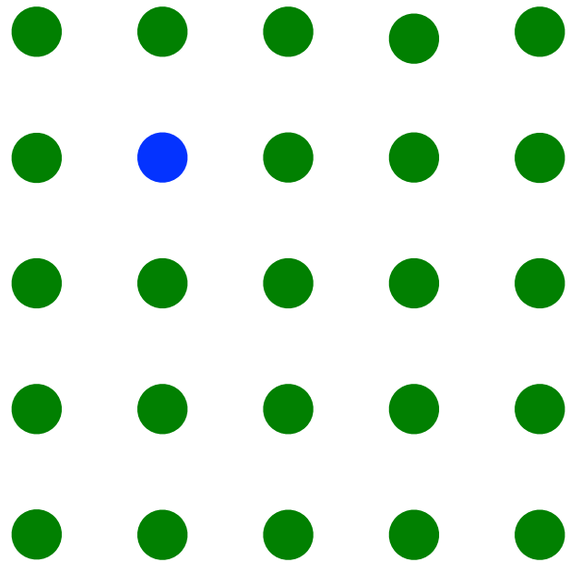
Hubble's Law

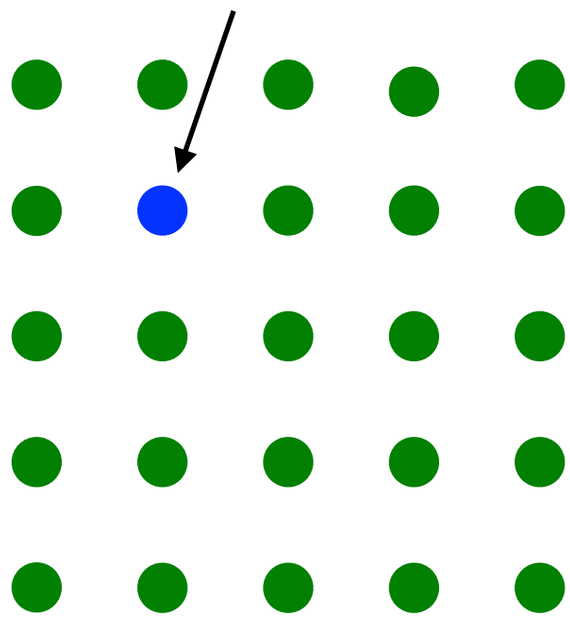


The further the galaxies, the faster they are moving away from us.

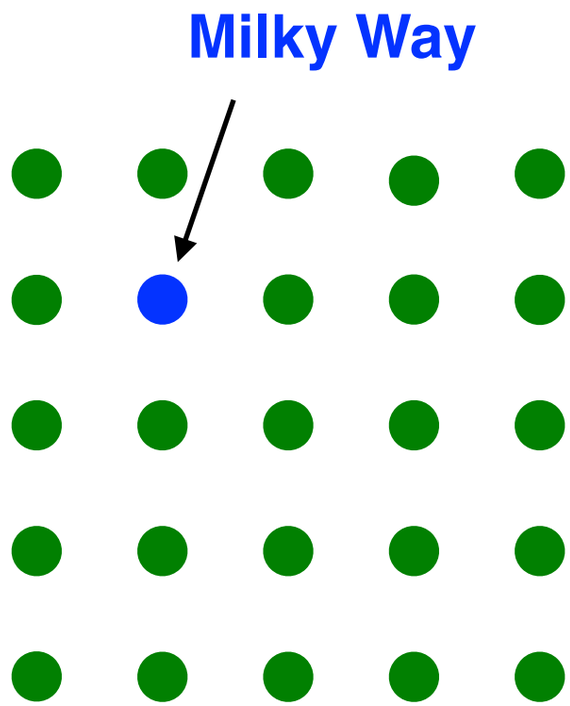
The Universe is Expanding



The Universe is Expanding

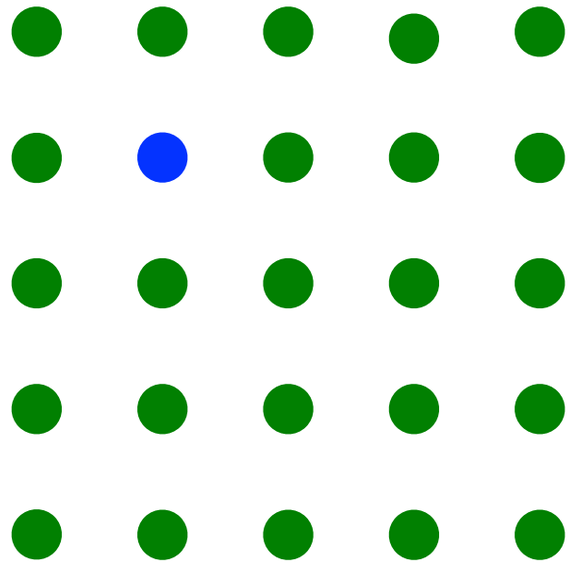


The Universe is Expanding



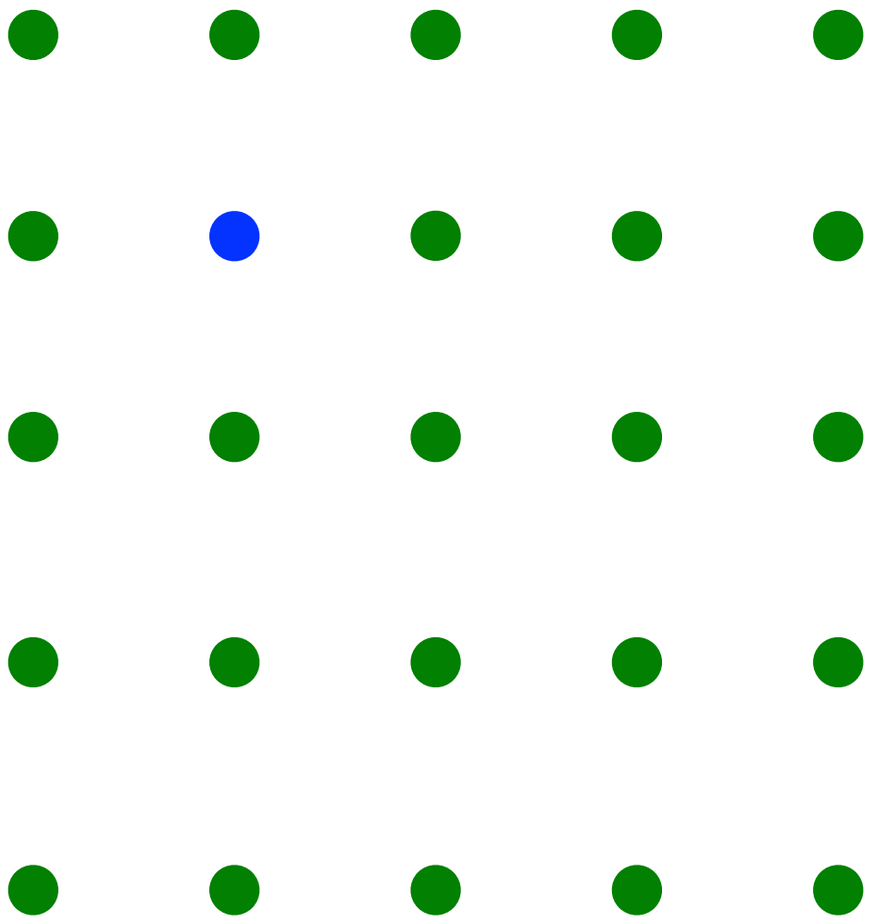
The Universe is Expanding

$t = t_1$

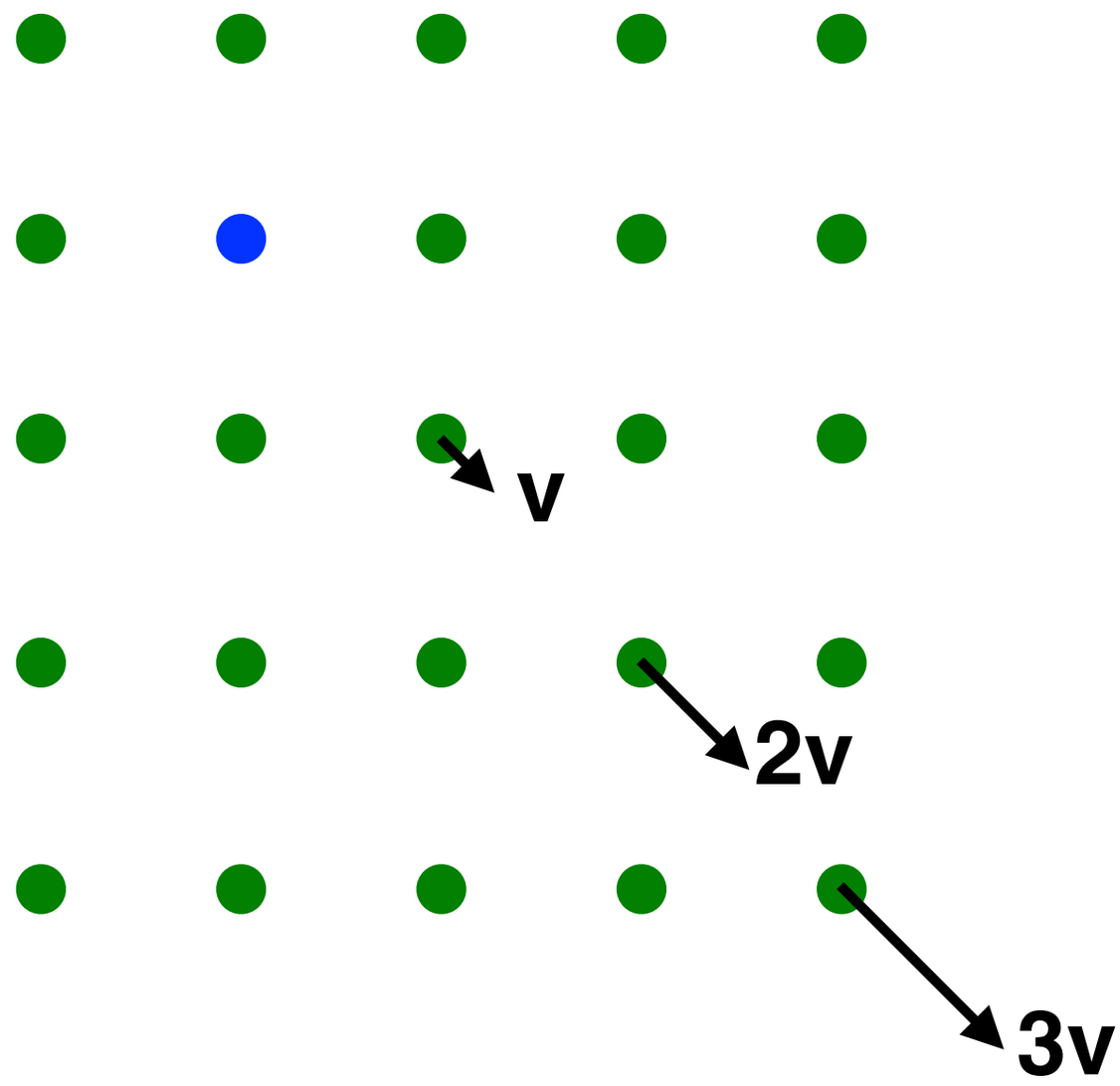


The Universe is Expanding

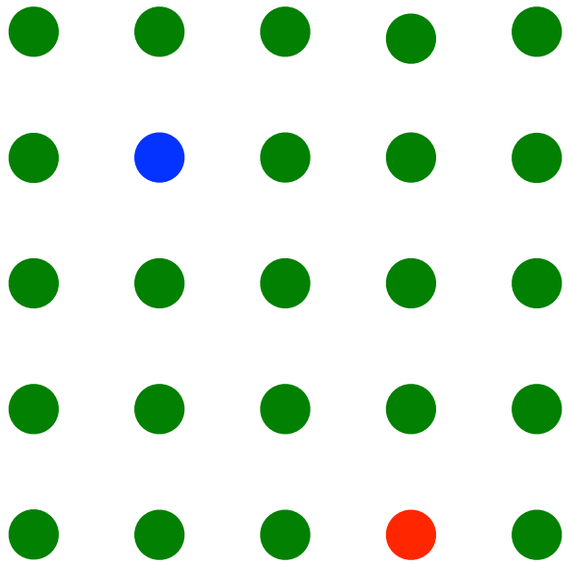
$t = t_2$



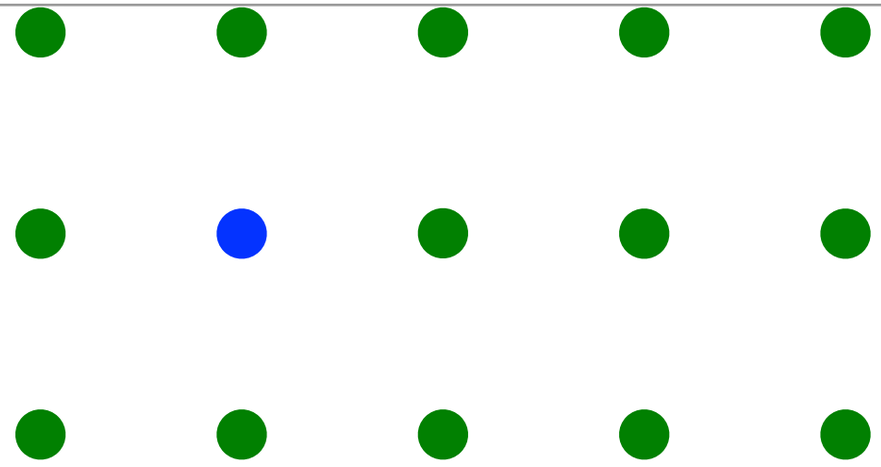
The Universe is Expanding



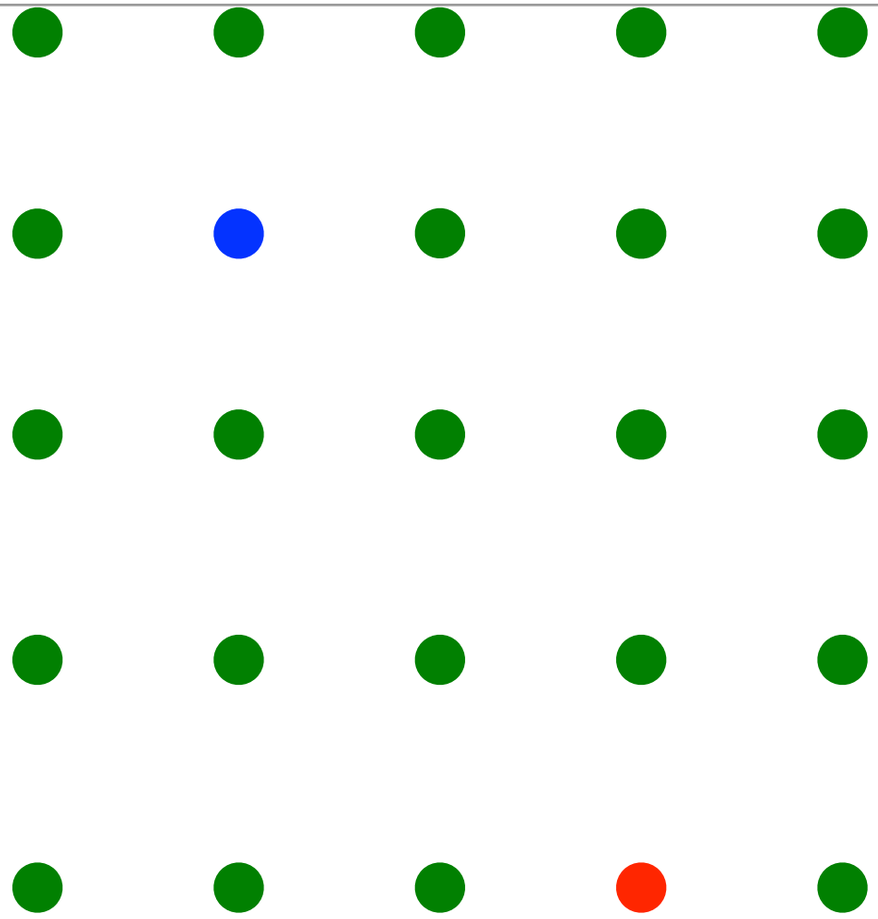
Are We the Center of the Universe?



Are We the Center of the Universe?

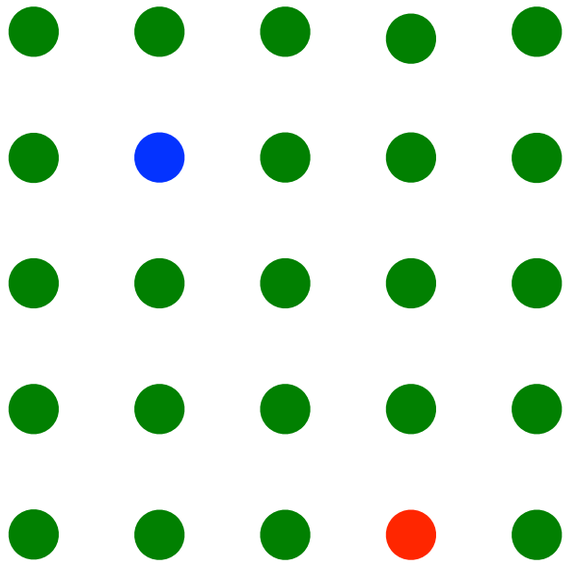


Are We the Center of the Universe?

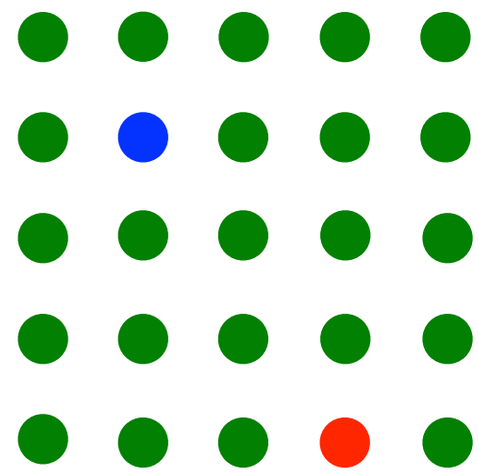


NO!

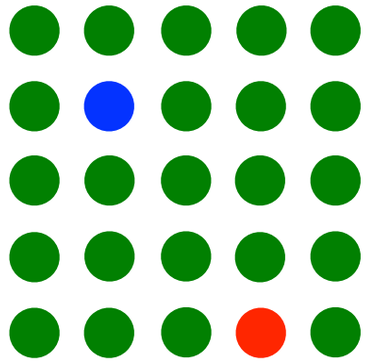
How about backwards in time?



How about backwards in time?

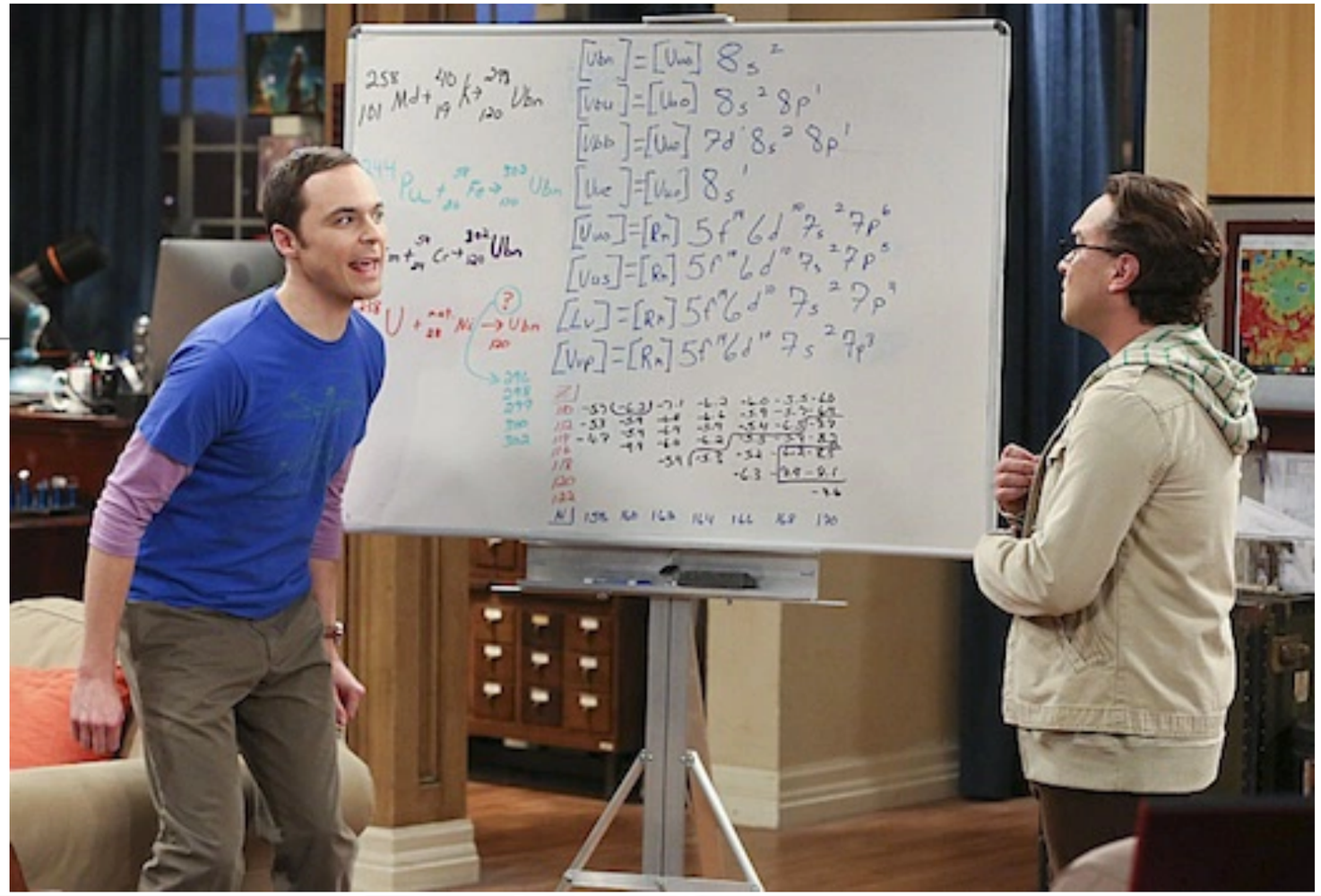


How about backwards in time?



How about backwards in time?

the BIG BANG THEORY



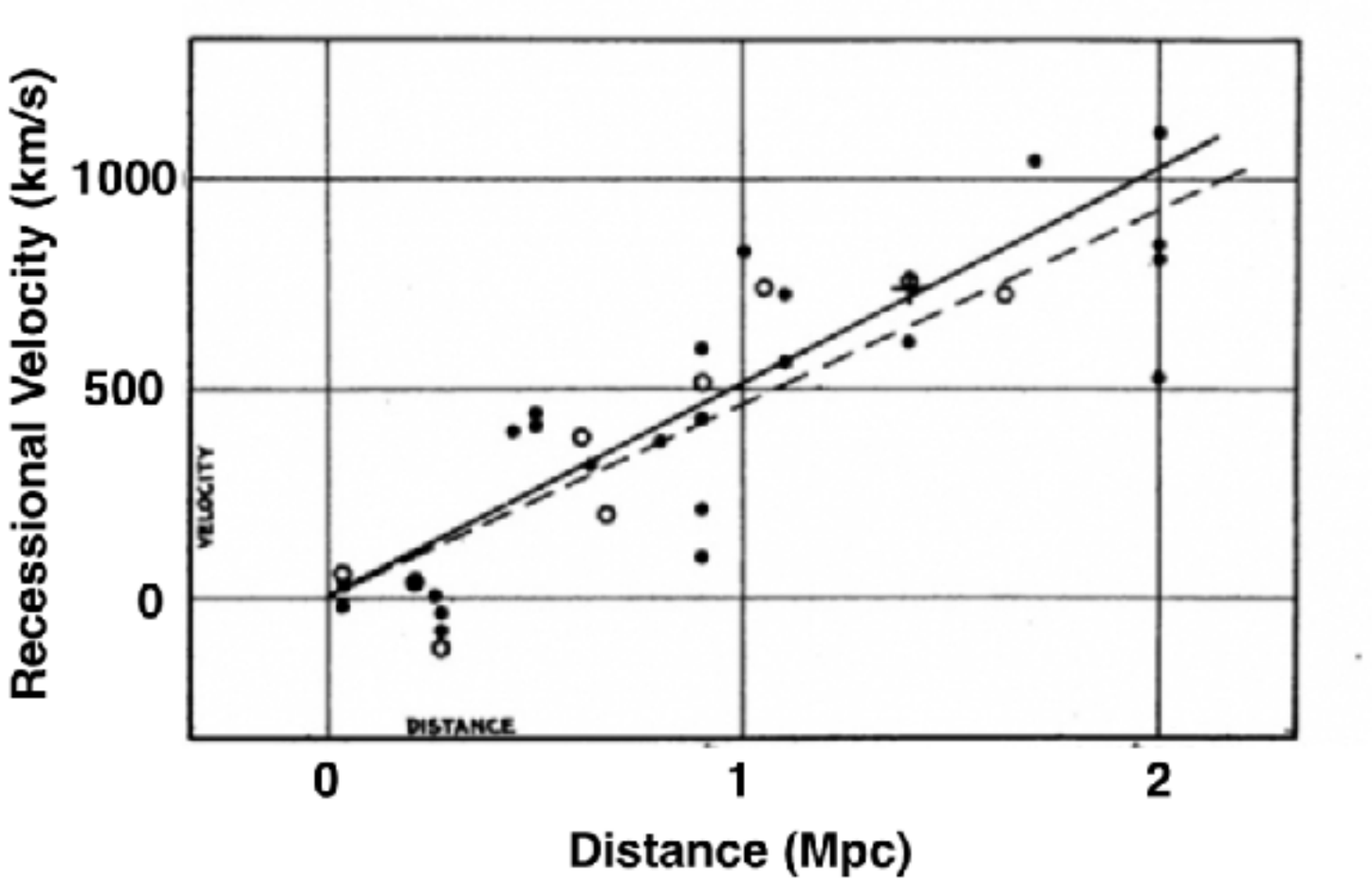
Steady State Model vs "Big Bang" Model

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

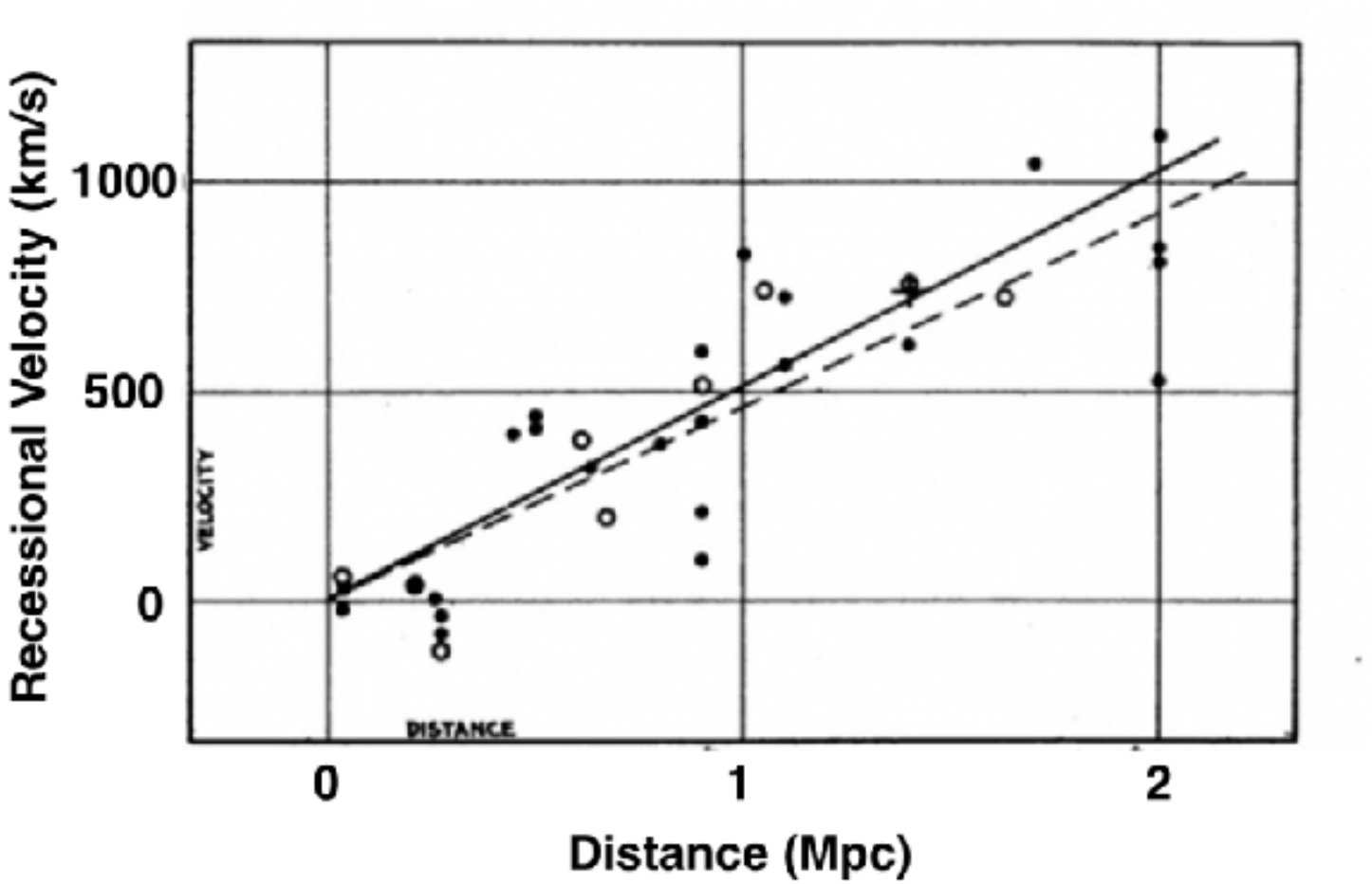
Fred Hoyle
(1915-2001)

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

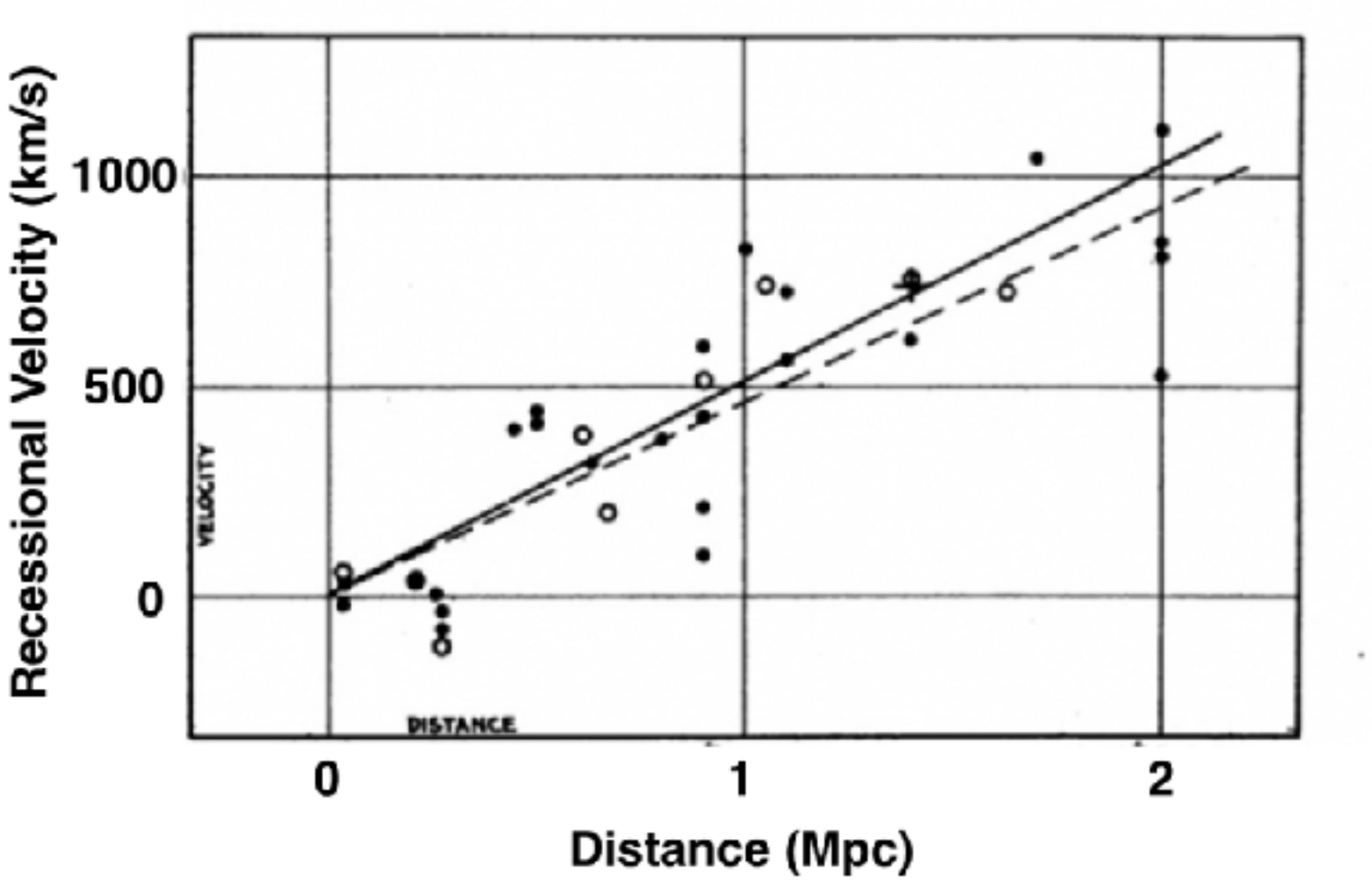
George Gamow
(1904-1968)


Recessional Velocity (km/s)
1000
500
0
VELOCITY
DISTANCE
0
1
2
Distance (Mpc)

Hubble Constant
H_0 = velocity / distance

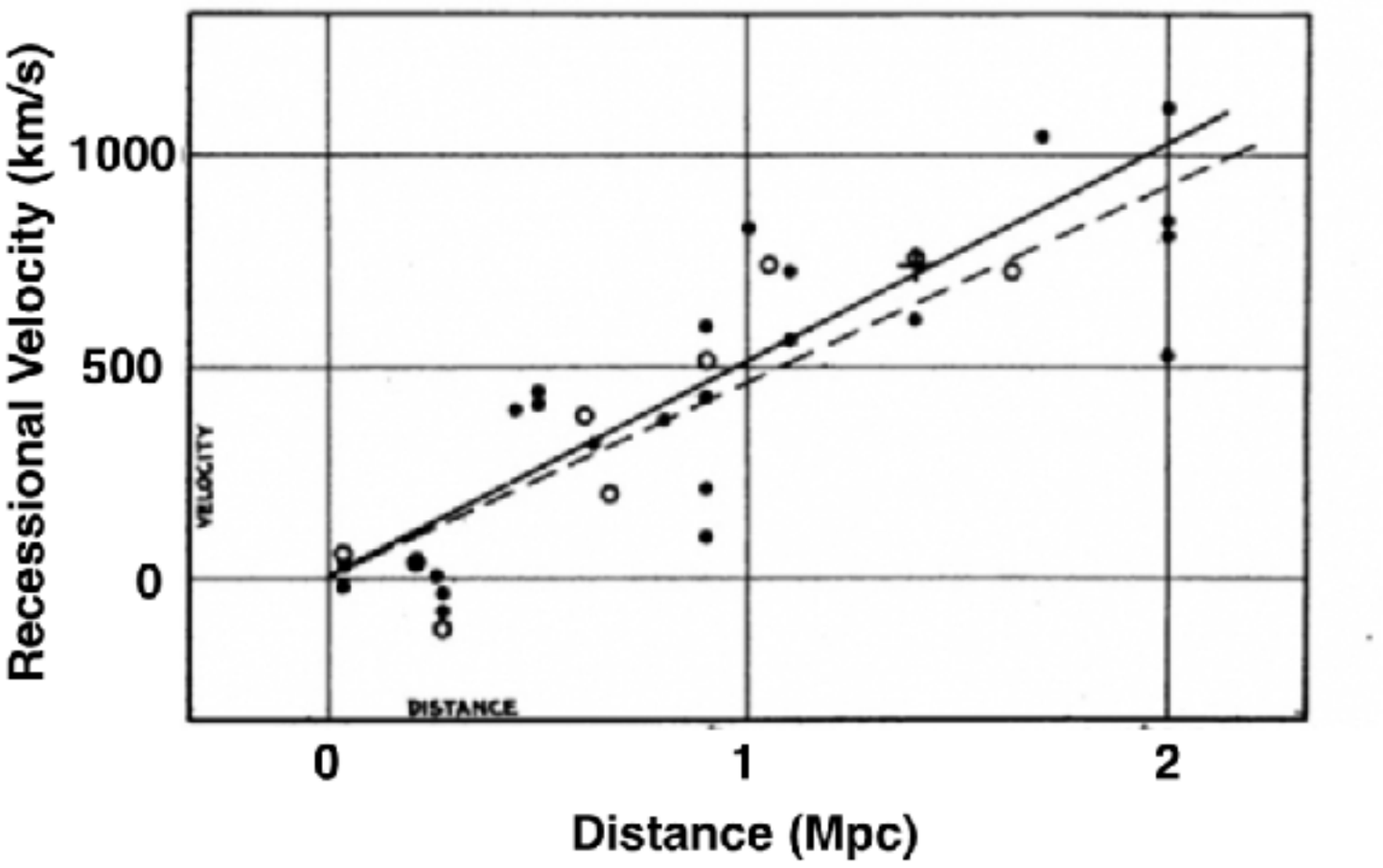


Hubble Constant
H_0 = velocity / distance



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

Hubble Constant
H_0 = velocity / distance

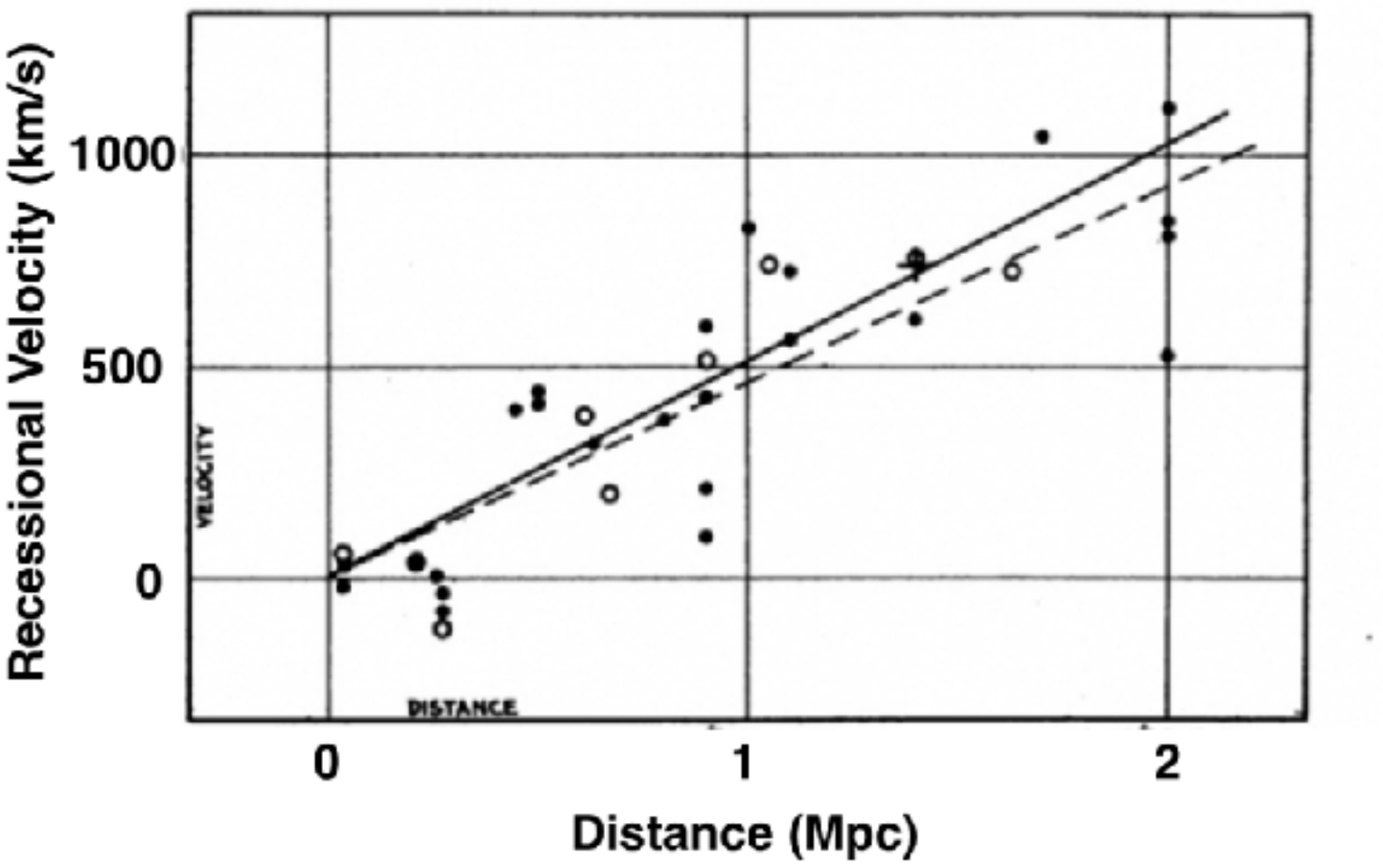


Hubble's estimation

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

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

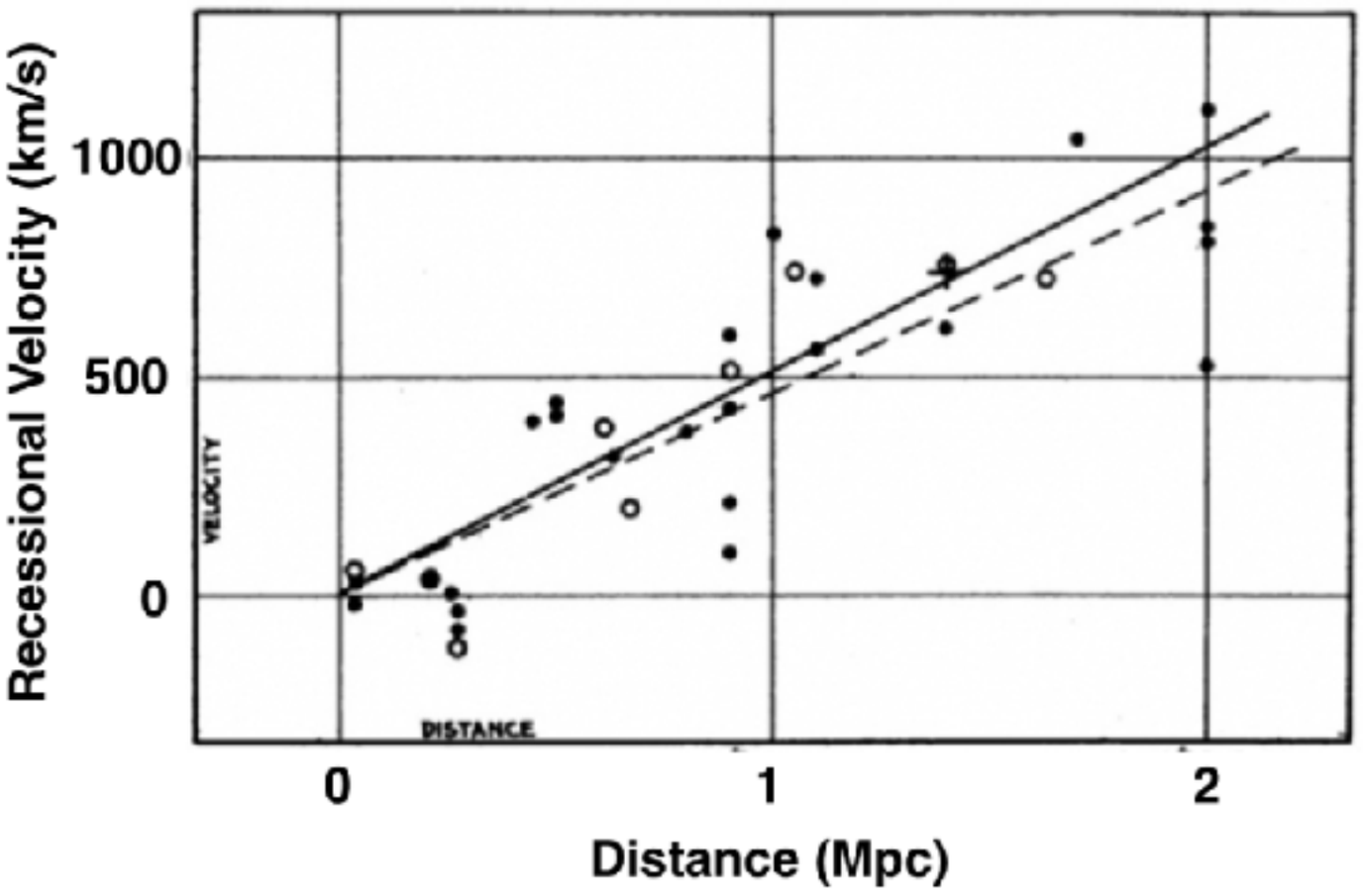
Hubble Constant
H_0 = velocity / distance



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

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

Hubble Constant
H_0 = velocity / distance

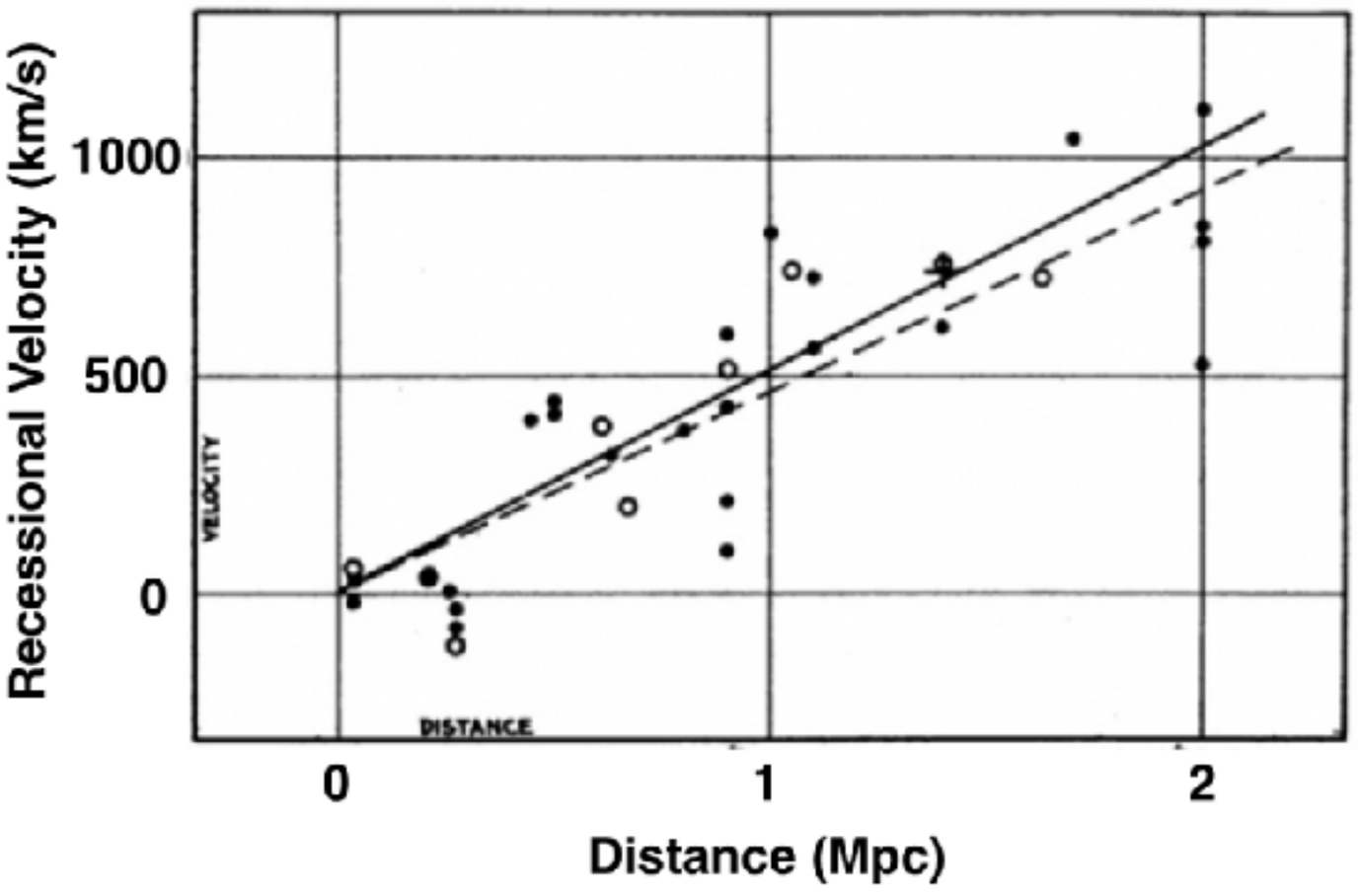


Hubble's estimation
$H_0 = 500$ km s^{-1} Mpc^{-1}

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

Age of the Universe
~ 2 billion years

Hubble Constant
H_0 = velocity / distance



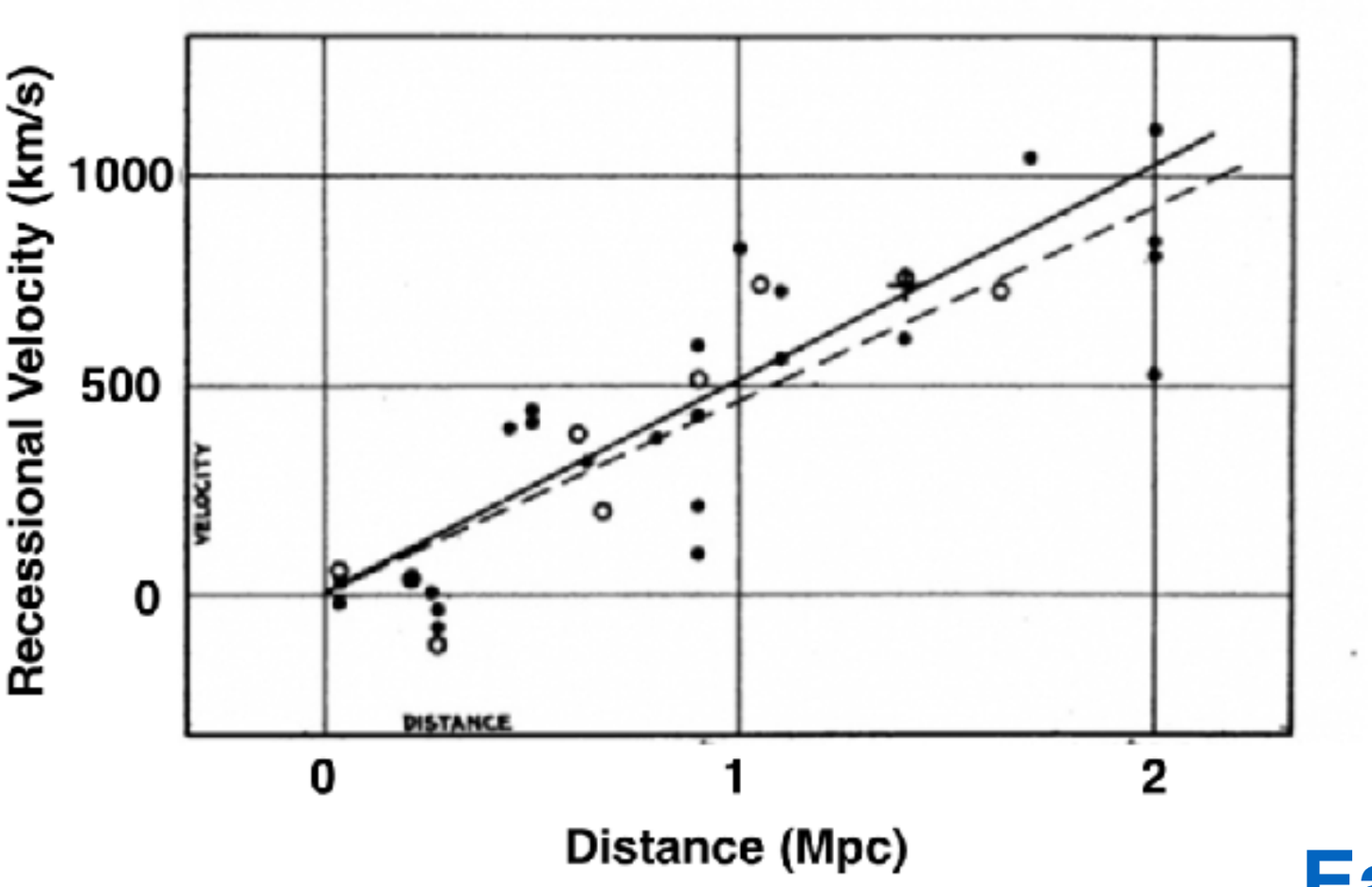
Hubble's estimation
$H_0 = 500$ km s^{-1} Mpc^{-1}

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

Age of the Universe
~ 2 billion years

Earth ~ 4.6 billion years

Hubble Constant
H_0 = velocity / distance



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

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

Age of the Universe
~ 2 billion years

Earth ~ 4.6 billion years

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

→

Age of Universe
~ 14 billion years

Steady State Model vs "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

Steady State Model vs "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?

Steady State Model vs "Big Bang" Model

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Scientific Method

Steady State Model vs "Big Bang" Model

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Scientific Method

⟶ Making testable predictions!

Some Critical Thinking

Some Critical Thinking

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

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As the Universe expands, the temperature drops.

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

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What signal will we see for this 3 K Universe?

Some Critical Thinking

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Universe glow in microwave.

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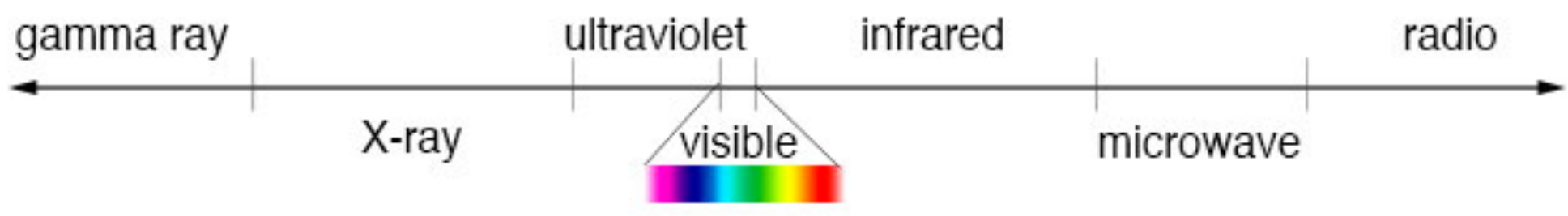
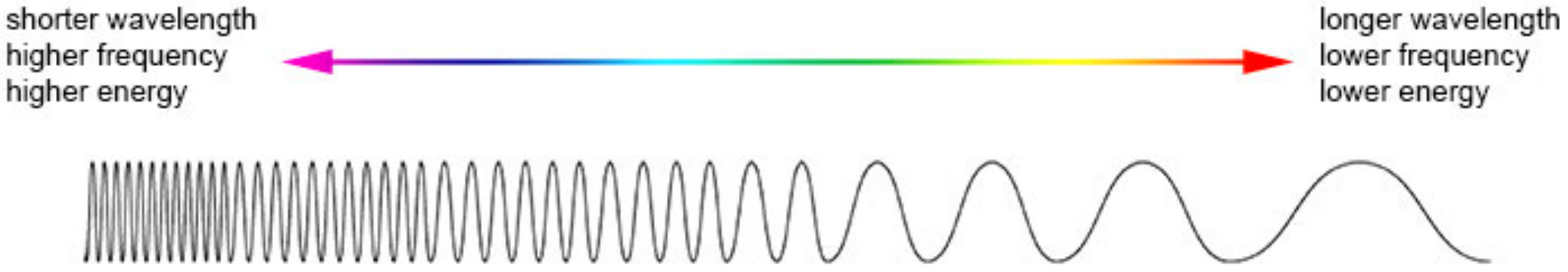
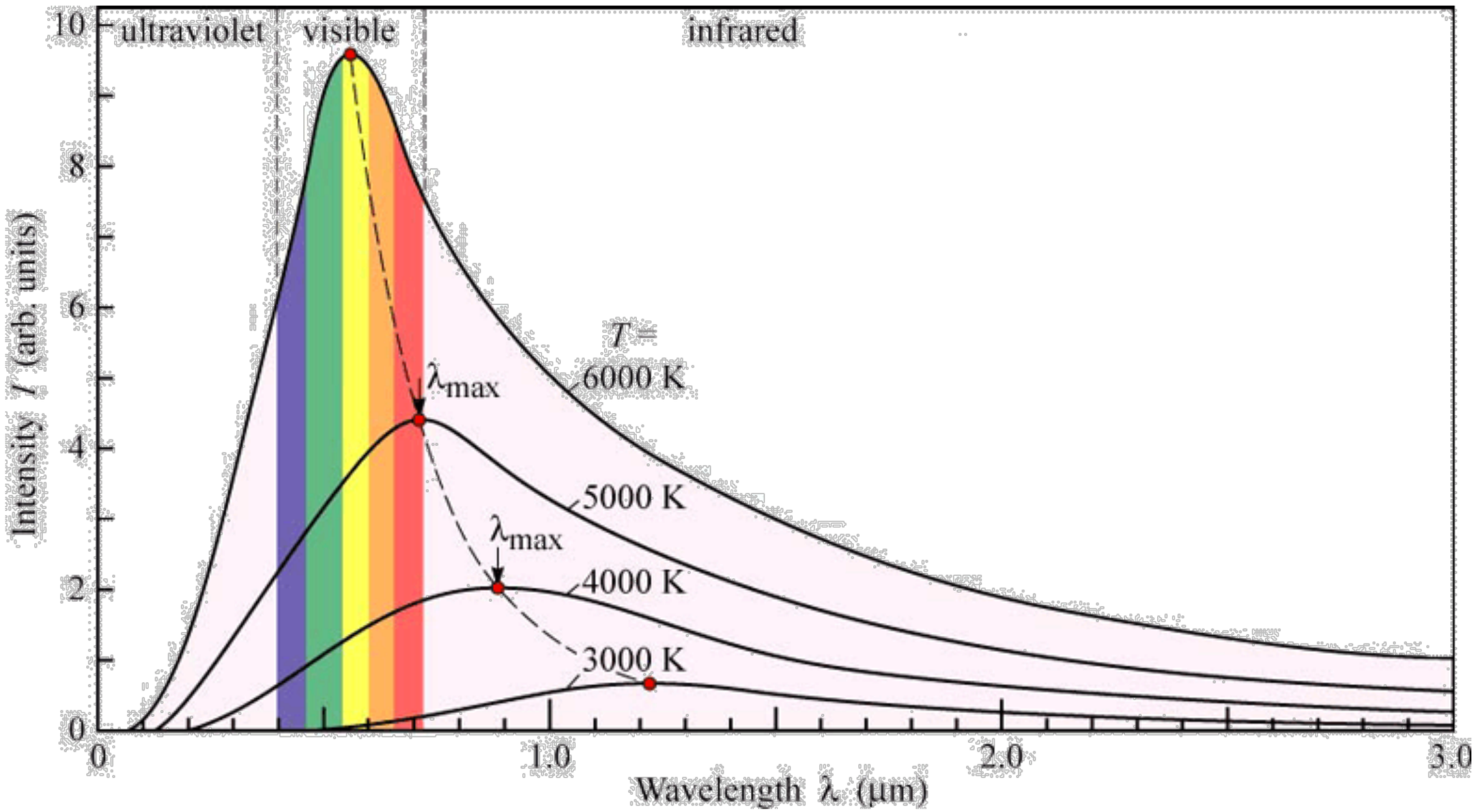
Cosmic Microwave Background Radiation

Electromagnetic Spectrum



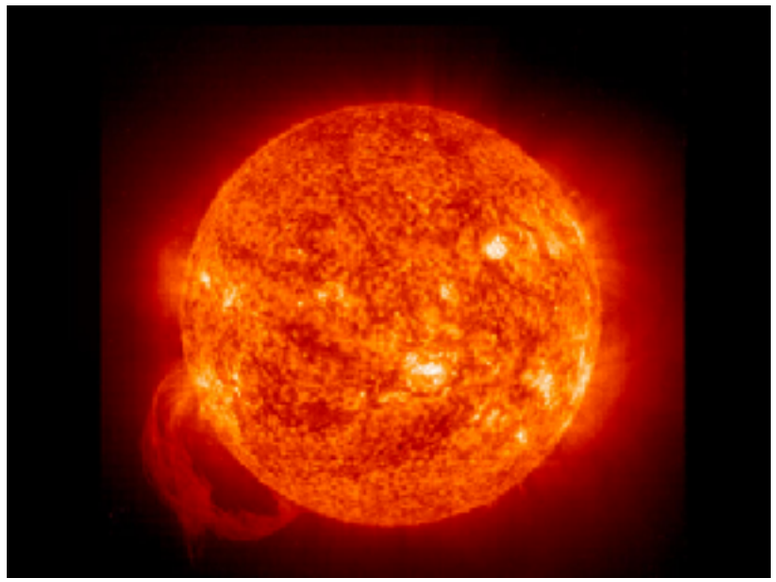


Thermal/Blackbody Radiation

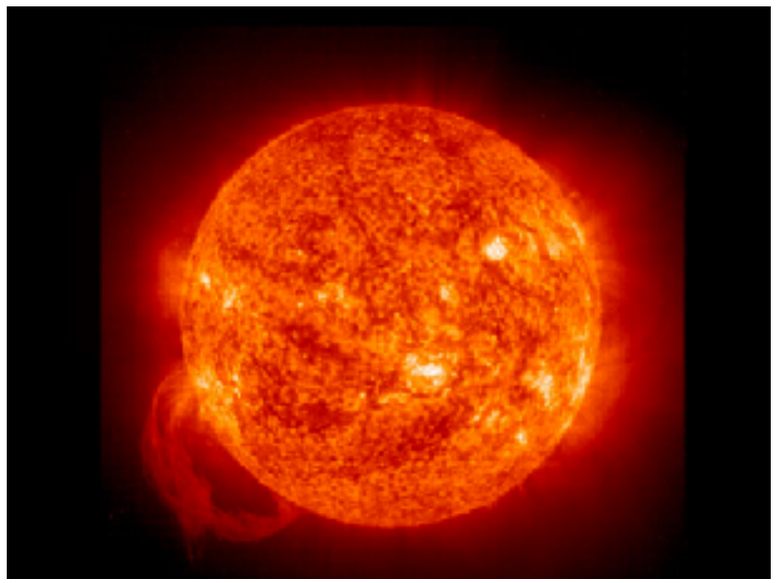


Thermal/Blackbody Radiation

Thermal/Blackbody Radiation

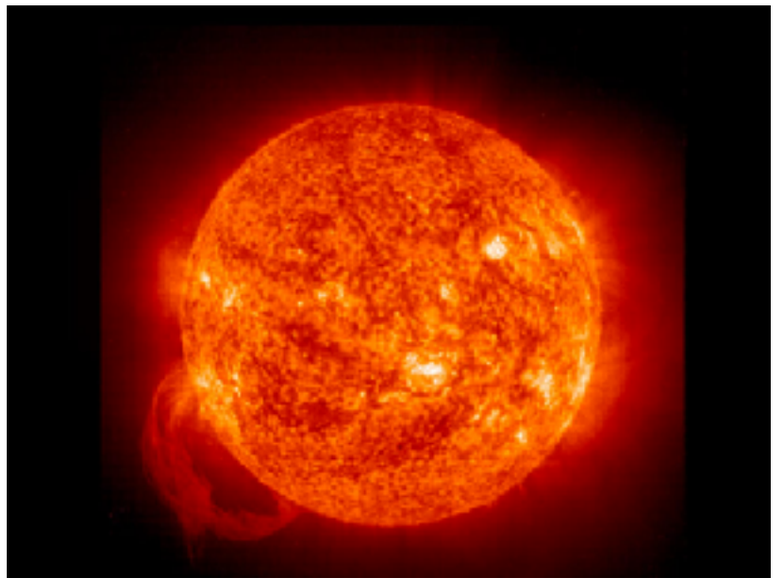


Thermal/Blackbody Radiation



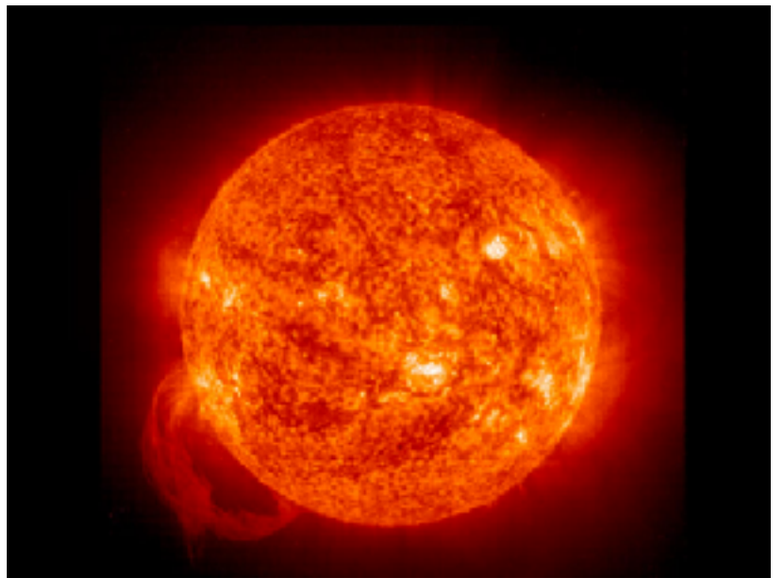
Sun (~6000 K) glow in visible.

Thermal/Blackbody Radiation



Sun (~6000 K) glow in visible.

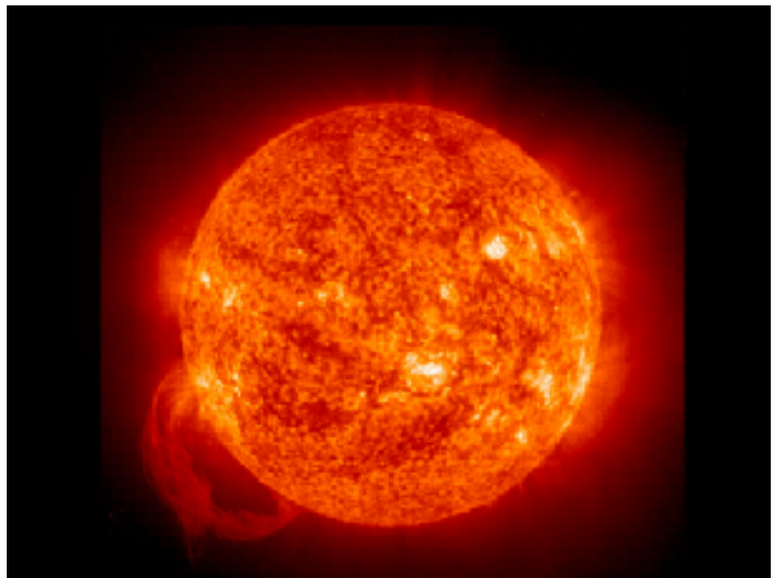
Thermal/Blackbody Radiation



Sun (~6000 K) glow in visible.

We (~300 K) glow in infrared.

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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What signal will we see for this 3 K Universe?

Universe glow in microwave.

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.

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What signal will we see for this 3 K Universe?

Universe glow in microwave.

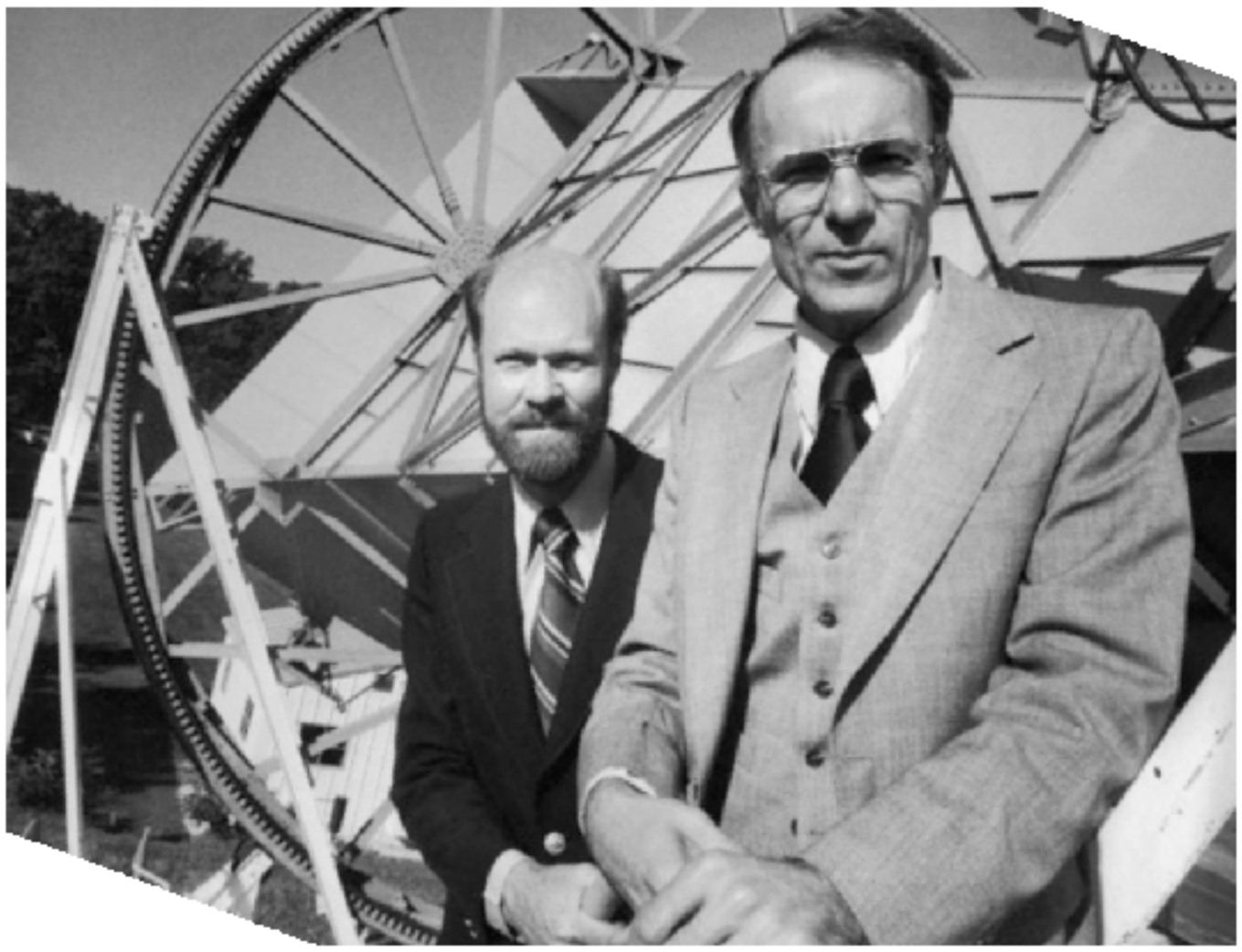
Cosmic Microwave Background Radiation (CMB Radiation)

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.

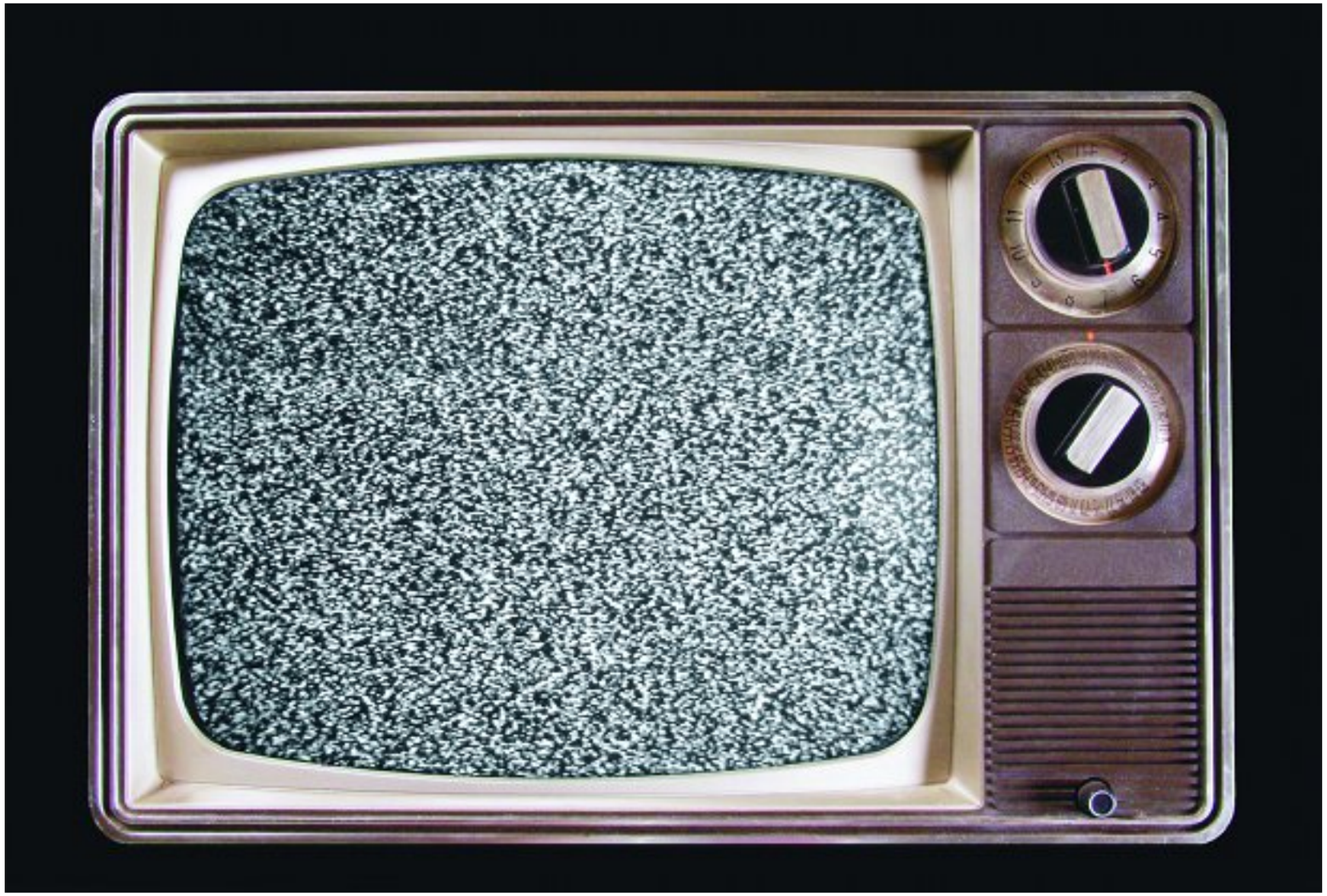
They detected a continuous noise from all directions of the sky.

The noise in microwave is similar to what a 3K blackbody will radiate.



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

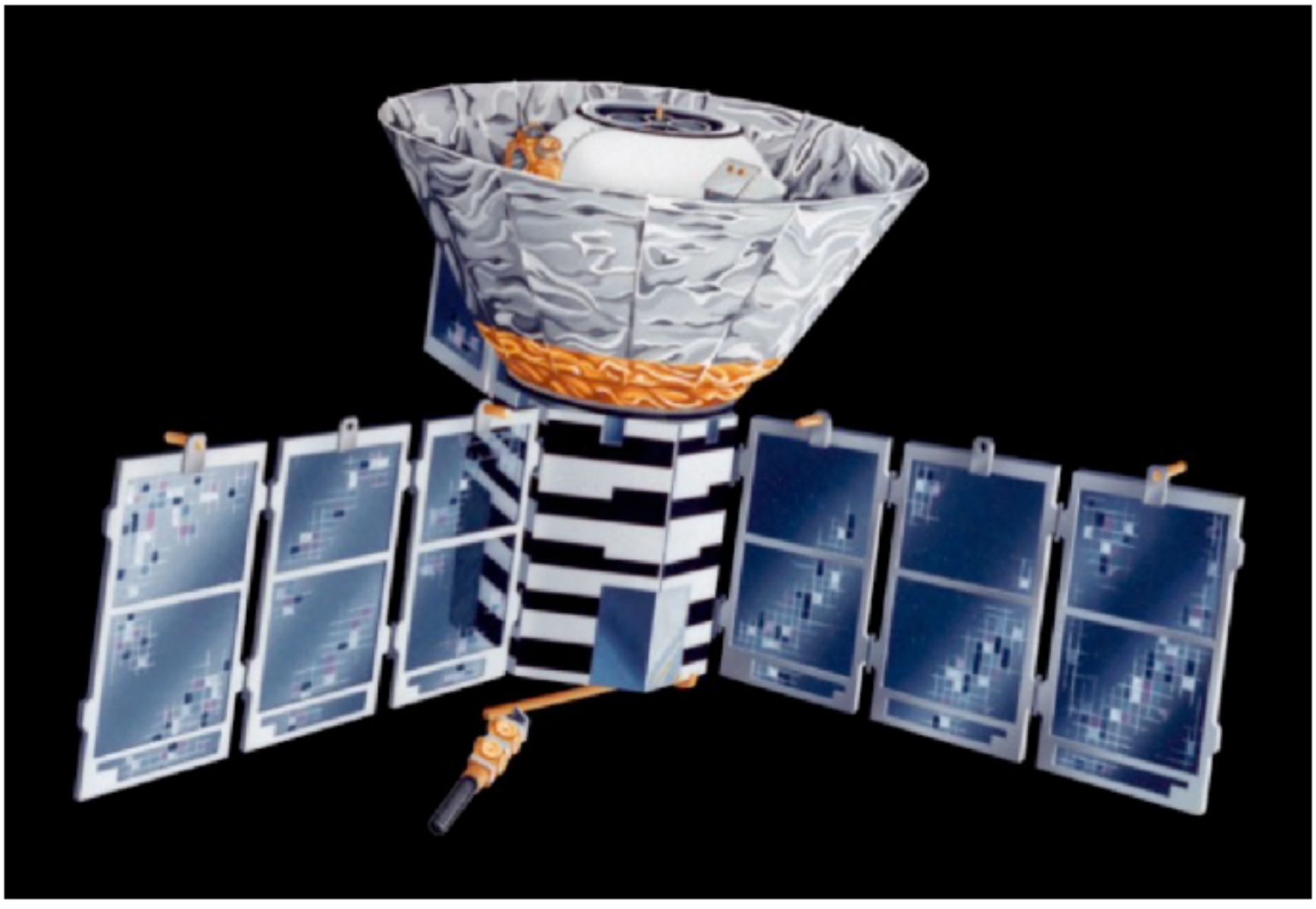
Story of the Discovery



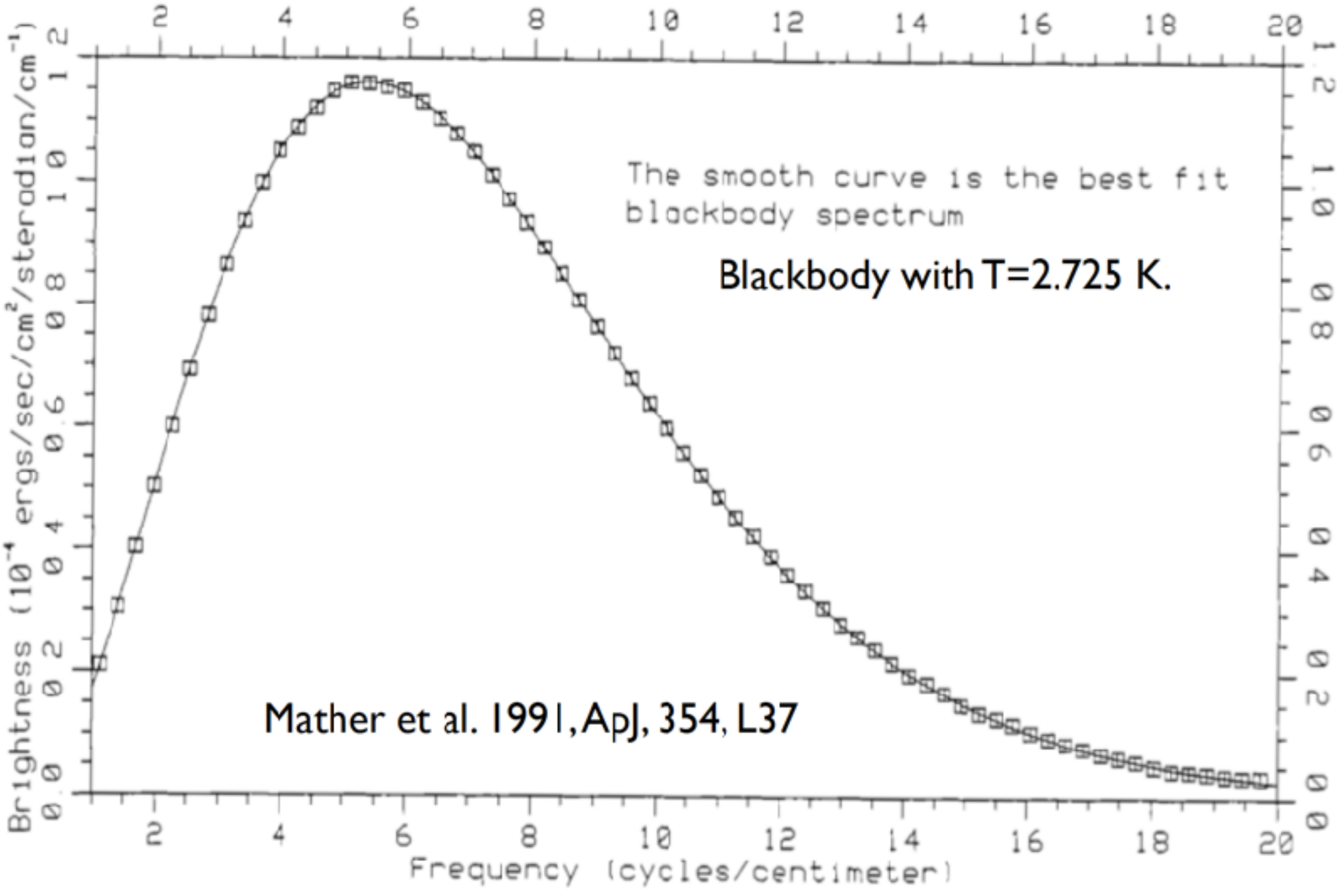
A very small fraction of the TV noise is from the CMB radiation

COsmic Background Explorer (COBE)

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



Cosmic Microwave Background Radiation



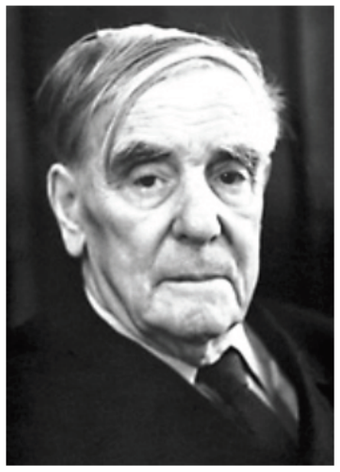
This result was a death sentence for the Steady State Model.

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"



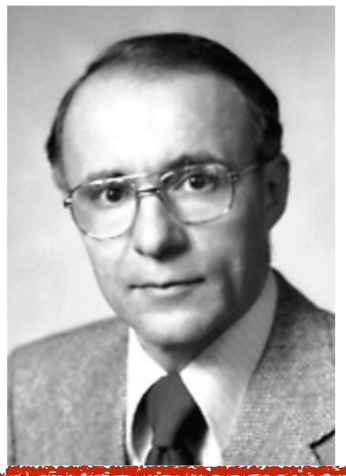
Pyotr Leonidovich Kapitsa

1/2 of the prize

USSR

Academy of Sciences
Moscow, USSR

b. 1894
d. 1984



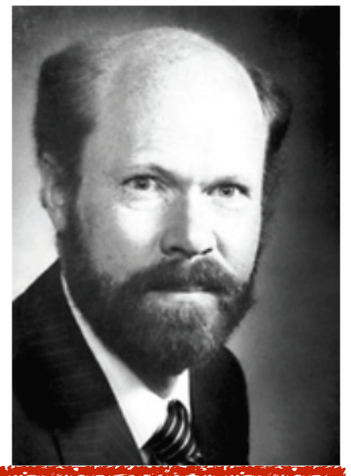
Arno Allan Penzias

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.
Photos: Copyright © The Nobel Foundation

The Nobel Prize in Physics 2006

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

Photo: NASA

John C. Mather

1/2 of the prize

USA

NASA Goddard Space Flight Center
Greenbelt, MD, USA

b. 1946

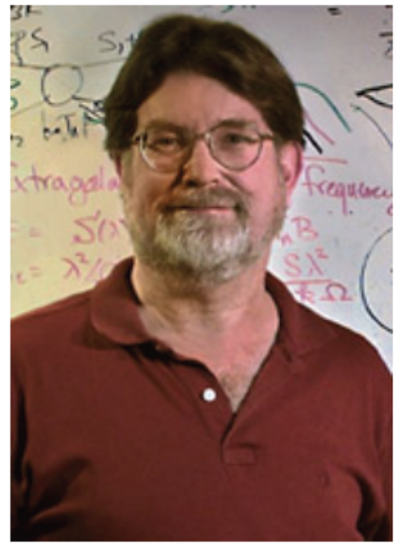


Photo: R. Kaltschmidt/LBNL

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.
Photos: Copyright © The Nobel Foundation

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

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H Hydrogen 1.00794	Atomic # Symbol Name Atomic Mass															2 He Helium 4.002602
2	3 Li Lithium 6.941	4 Be Beryllium 9.012182										5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.0067	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
3	11 Na Sodium 22.98976928	12 Mg Magnesium 24.3050										13 Al Aluminium 26.9815386	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948
4	19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955912	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938045	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798
5	37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium (97.9072)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293
6	55 Cs Caesium 132.9054519	56 Ba Barium 137.327	57–71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium (208.9824)	85 At Astatine (209.9871)	86 Rn Radon (222.0176)
7	87 Fr Francium (223)	88 Ra Radium (226)	89–103	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (277)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (271)	111 Rg Roentgenium (272)	112 Uub Ununbium (285)	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (292)	117 Uus Ununseptium	118 Uuo Ununoctium (294)

C Solid
Hg Liquid
H Gas
Rf Unknown

Metals: Alkali metals; Alkaline earth metals; Lanthanoids; Actinoids; Transition metals; Poor metals
Nonmetals: Other nonmetals; Noble gases

57 La Lanthanum 138.90547	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.9668
89 Ac Actinium (227)	90 Th Thorium 232.03806	91 Pa Protactinium 231.03588	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

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Ptable.com

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1	H																	He
2	Li	Be											B	C	N	O	F	Ne
3	Na	Mg											Al	Si	P	S	Cl	Ar
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	Cs																	
7	Fr																	

Atomic #
Symbol
Name
Atomic Mass

C Solid
Hg Liquid
H Gas
Rf Unknown

Metals
- Alkali metals
- Alkaline earth metals
- Lanthanoids
- Actinoids
- Transition metals
- Poor metals

Nonmetals
- Other nonmetals
- Noble gases

Hydrogen, helium, and very little lithium were made at the beginning of the Universe (Big Bang Nucleosynthesis).

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

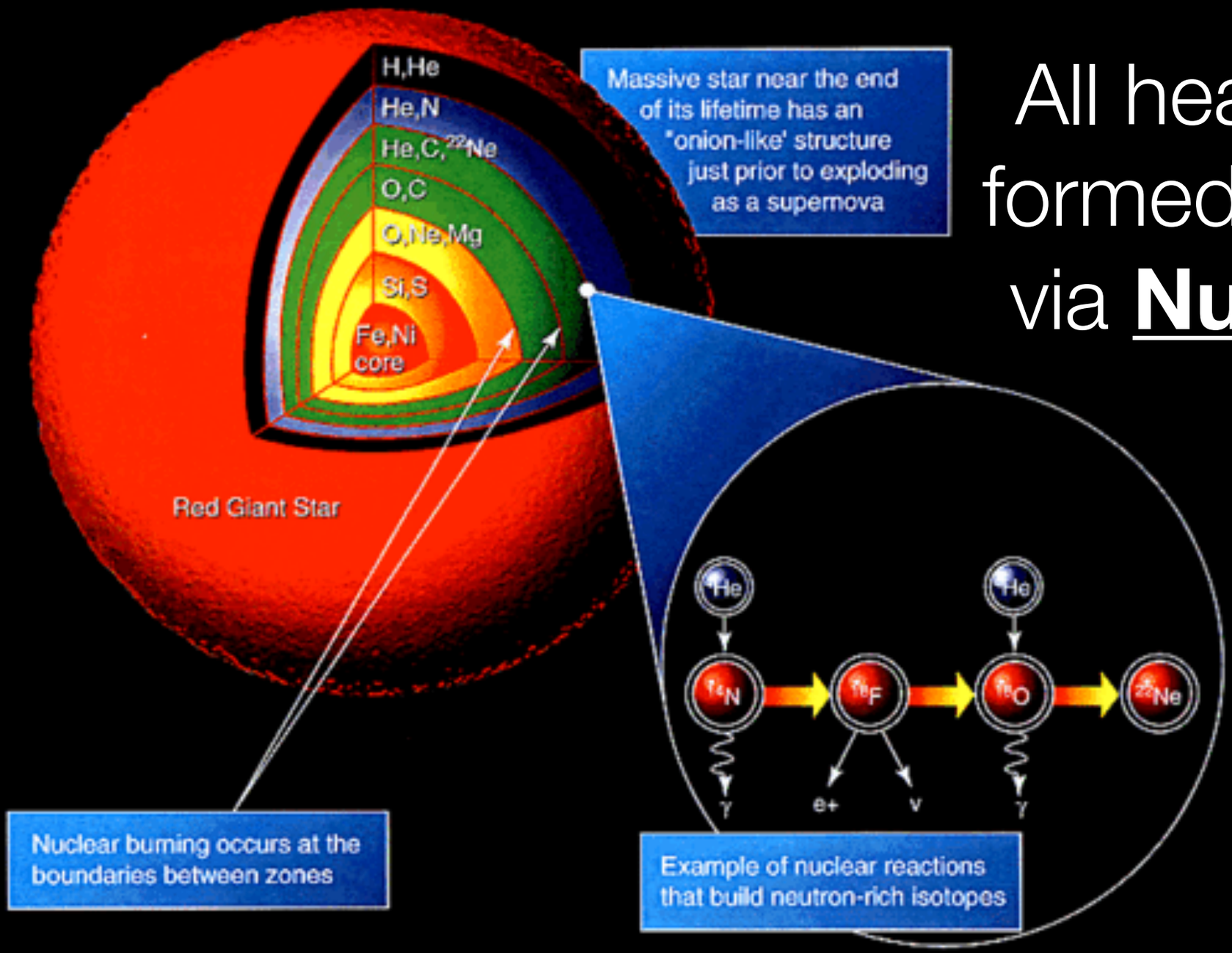
Ptable.com

Where are the heavier elements from?

How can our Sun produce heat?

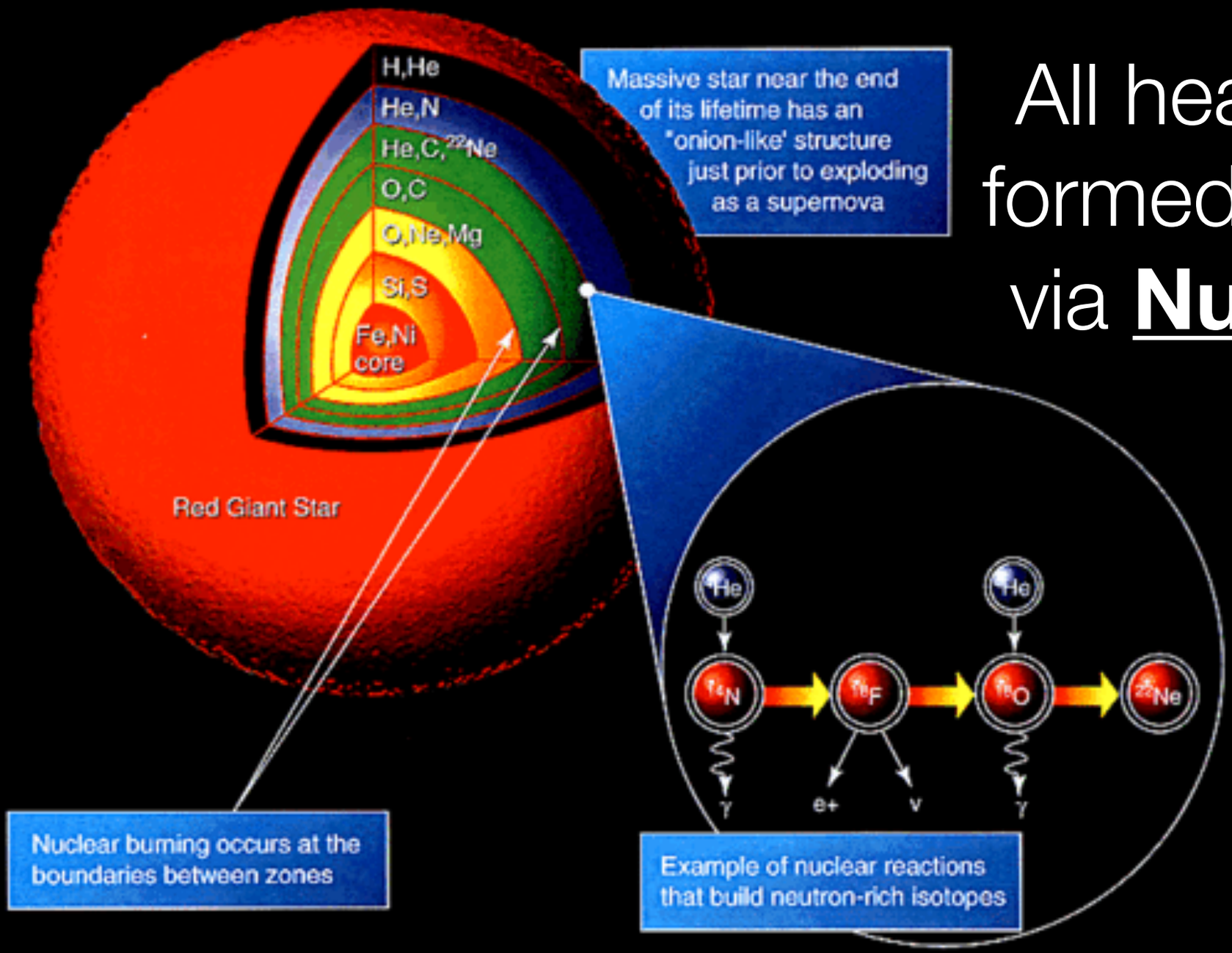
How can our Sun produce heat?

Nuclear Fusion



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

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



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

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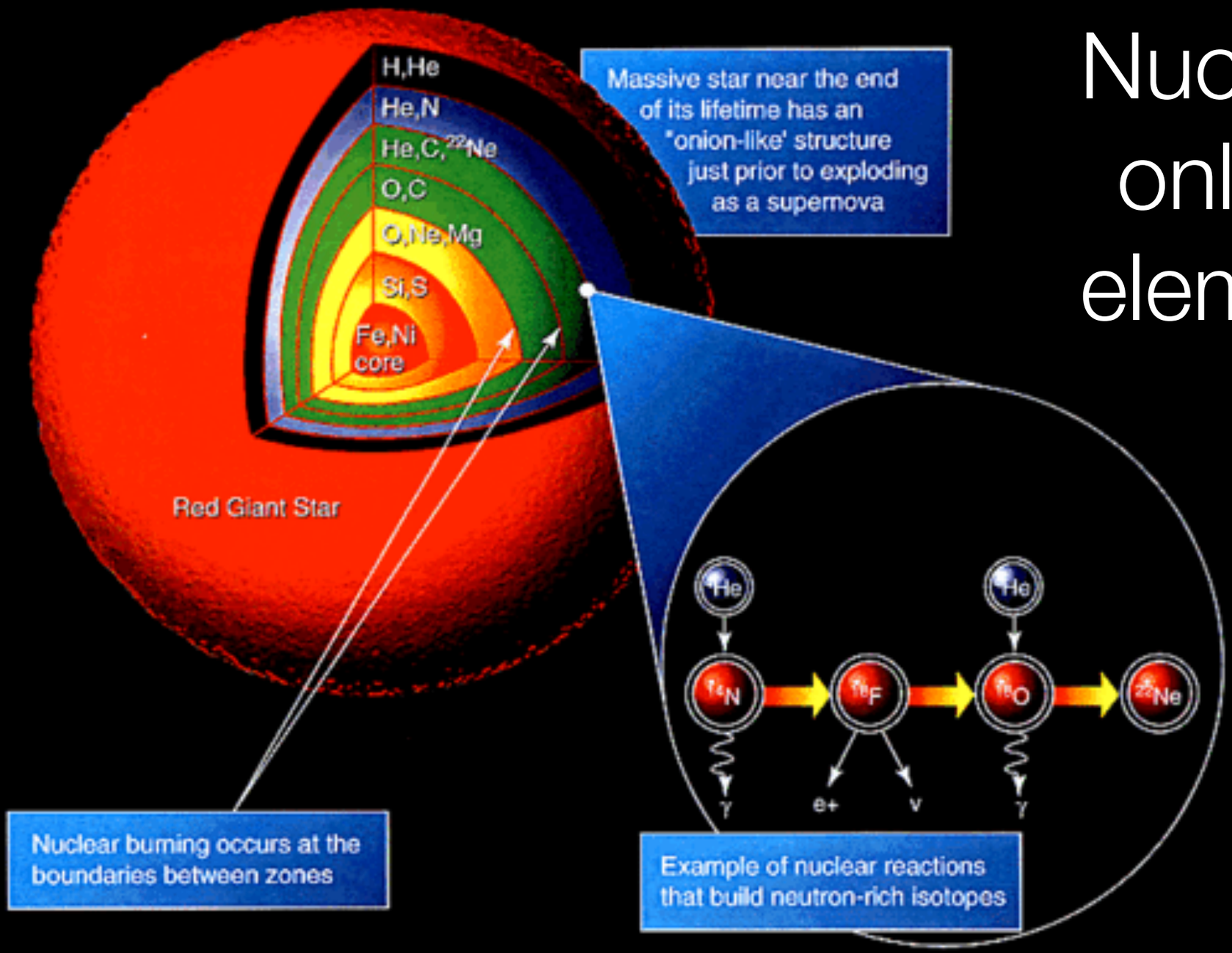
Stellar Nucleosynthesis

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


Fermilab


Fermilab

Gold are produced via Binary Neutron Star Merger

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For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

Ptable.com

The Origin of the Solar System Elements

1 H		big bang fusion															2 He
3 Li	4 Be	merging neutron stars										5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg	dying low mass stars										13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			89 Ac	90 Th	91 Pa	92 U											

cosmic ray fission

exploding massive stars

exploding white dwarfs

Graphic created by Jennifer Johnson

Astronomical Image Credits:
ESA/NASA/AASNova

Questions?

The Universe started with a Big Bang

The Origin

We are all Stardust

The Evolution

The Universe is mostly “Dark”

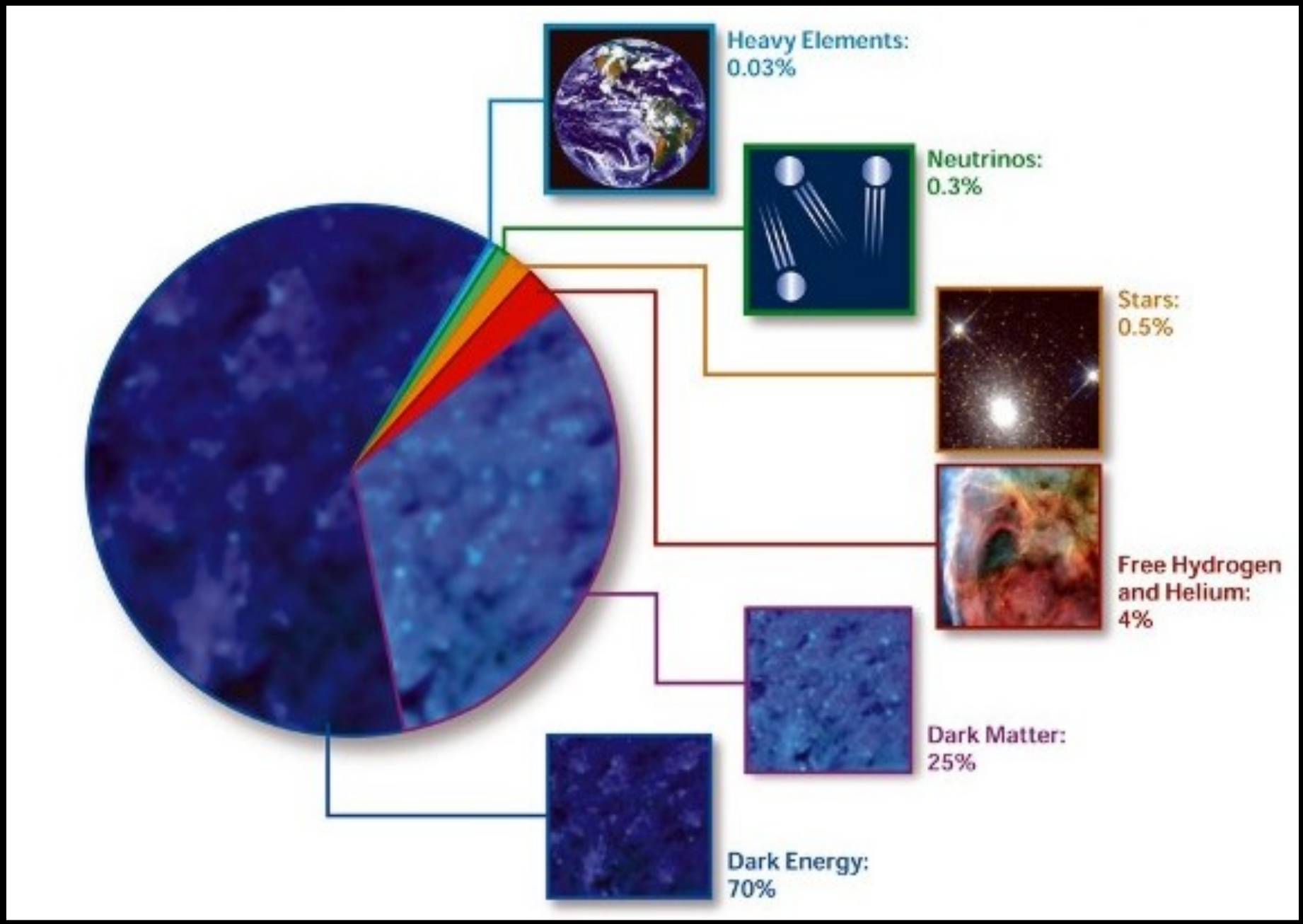
The Fate

95 % of the Universe is Dark

Ordinary Matter:
Stars, Planets, Gas — atoms
5%

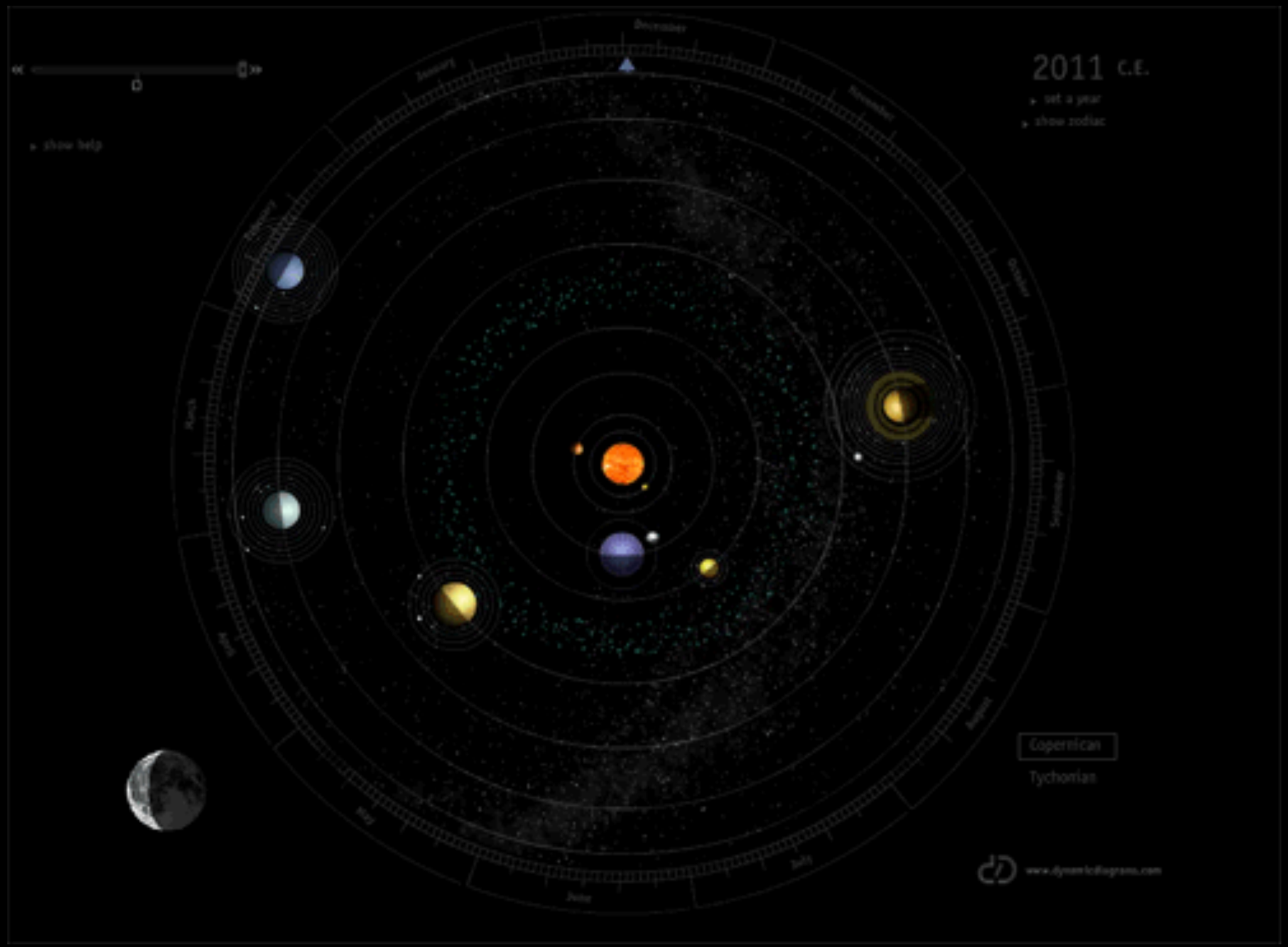
Dark Matter:
25%

Dark Energy:
70%



Dark Matter

Orbital Motion of Planets in Our Solar System



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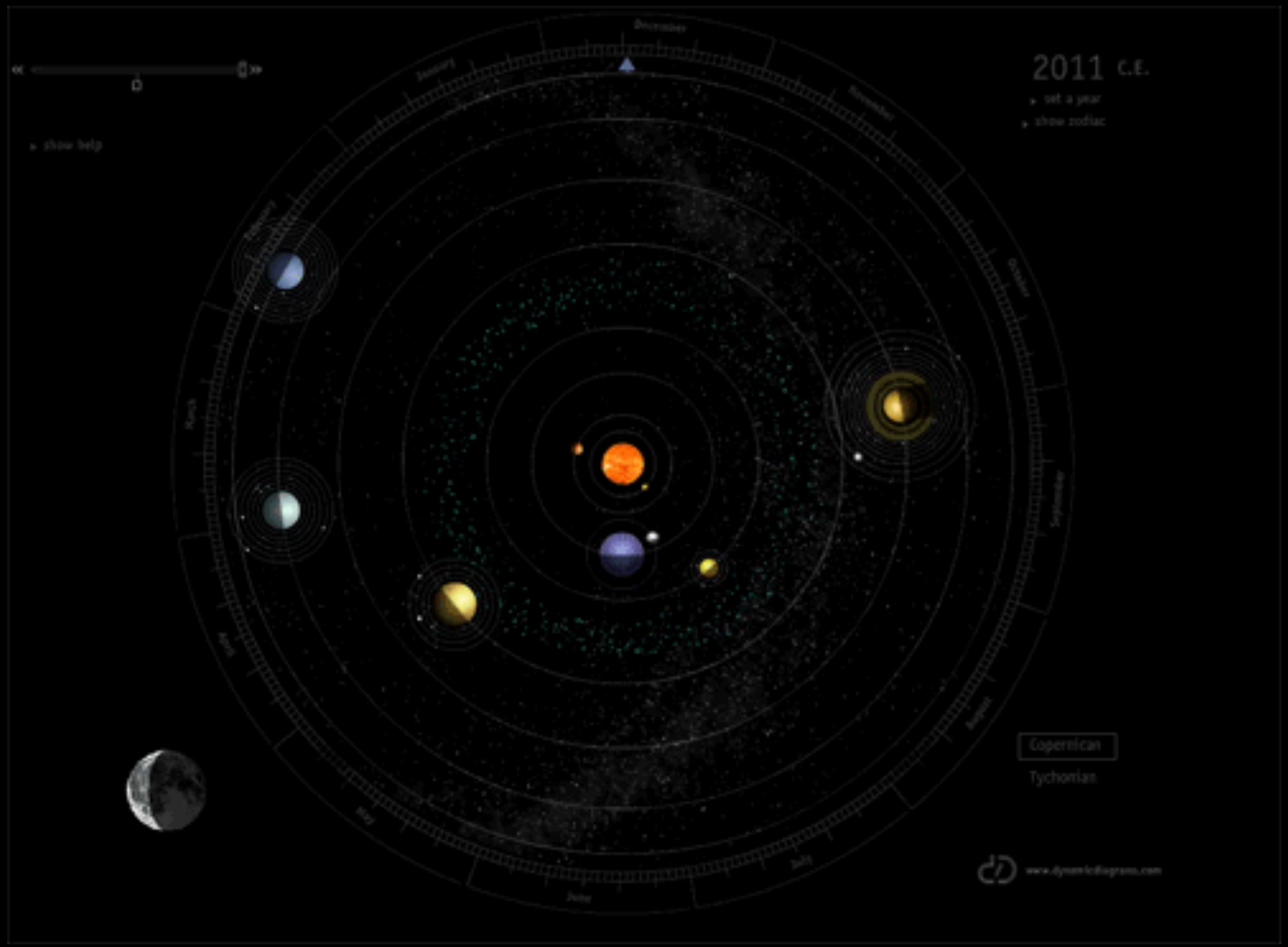
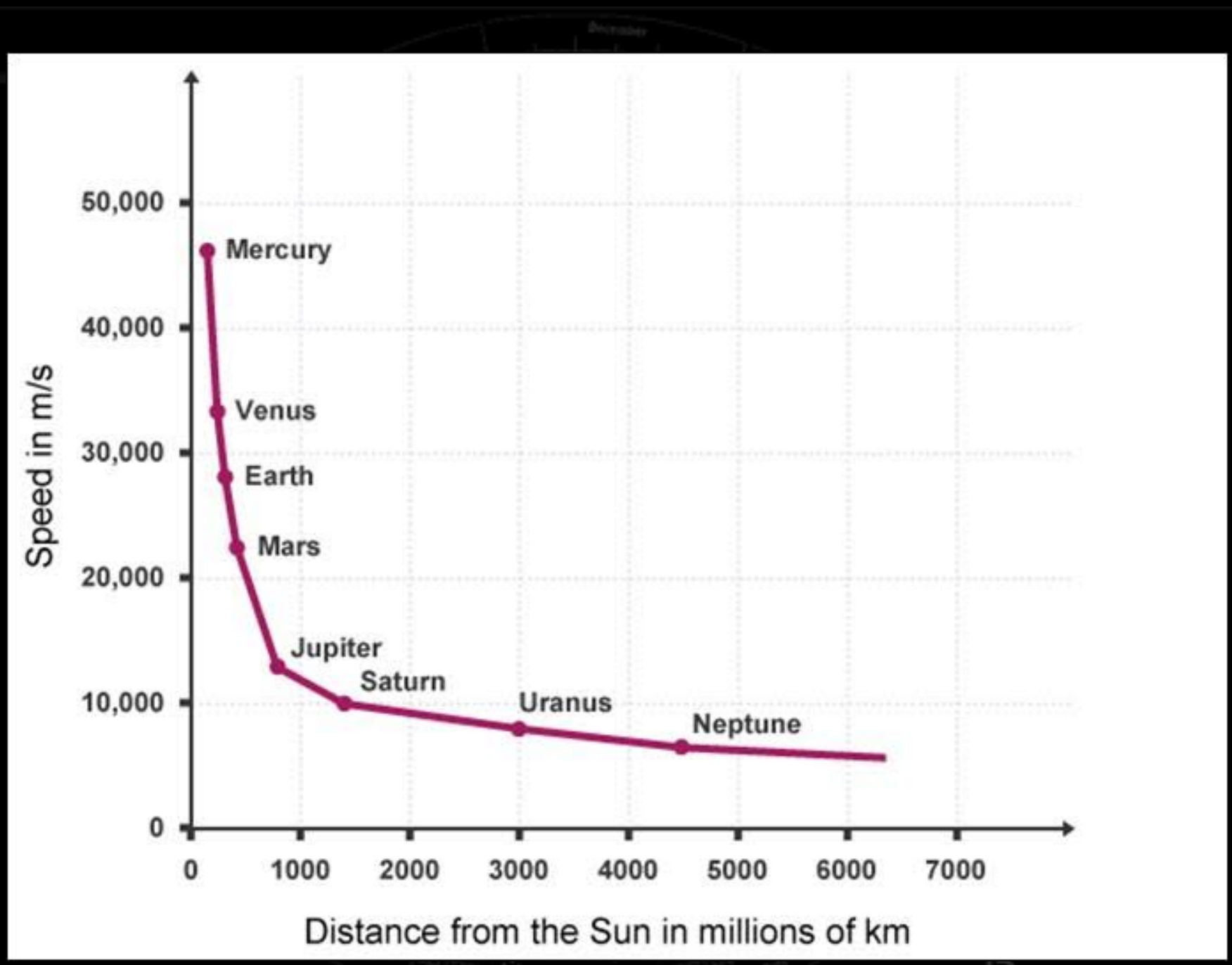


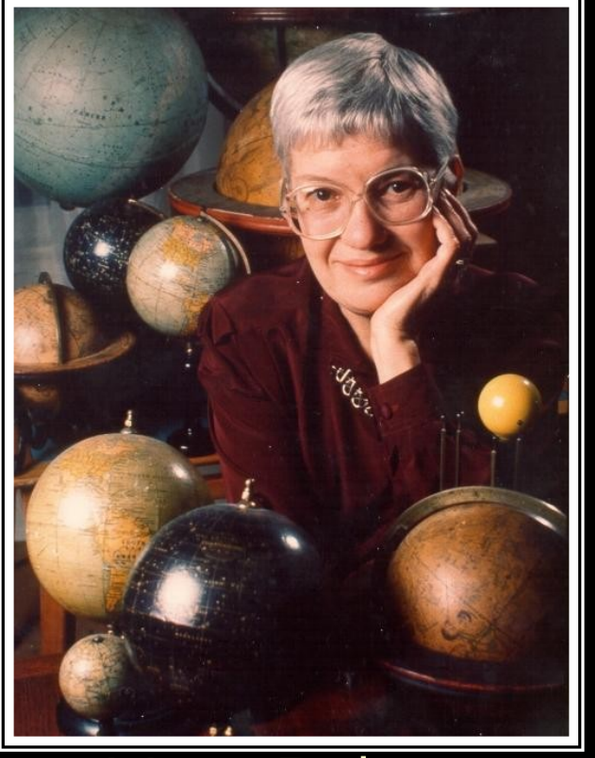
Orbital Motion of Planets in Our Solar System



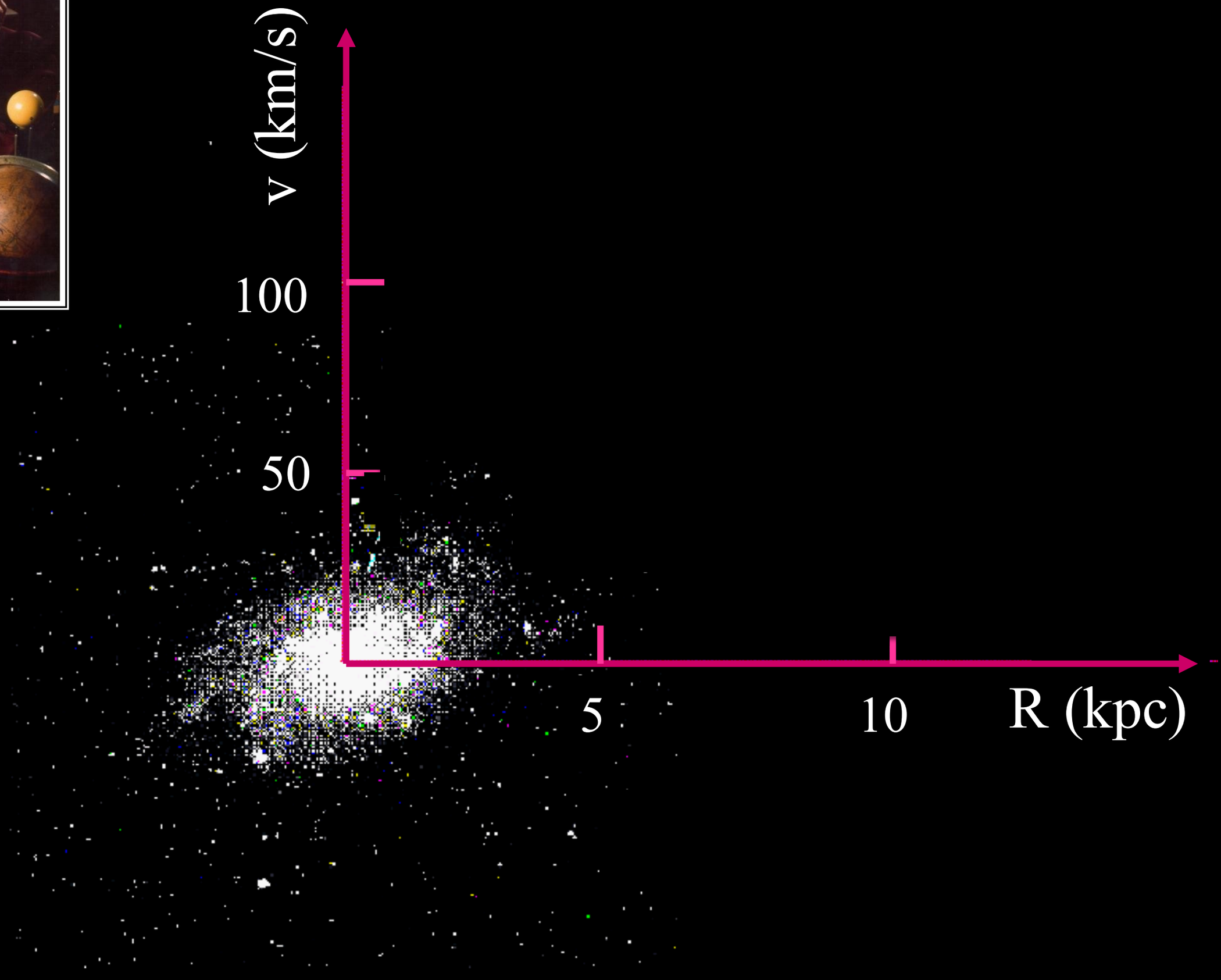
How about the Orbital Motion in a Galaxy?

Galaxy M33
Triangulum Galaxy

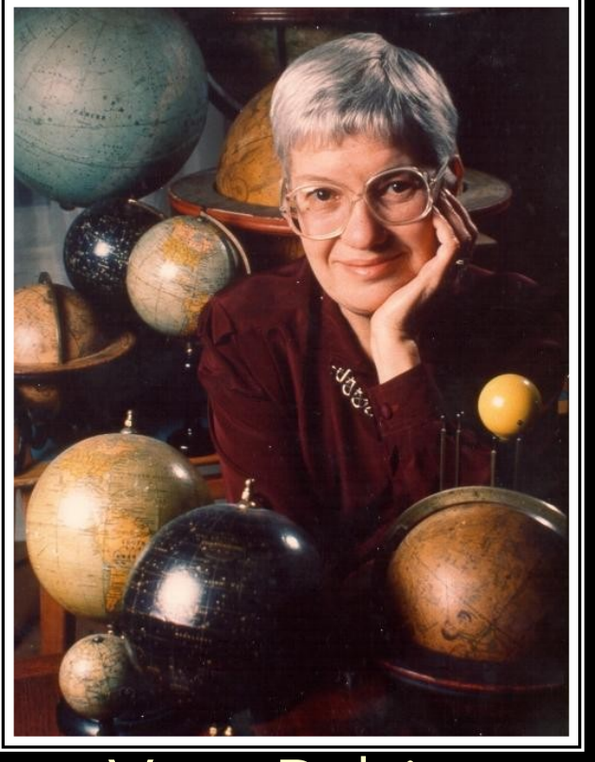
Orbital Motion in Galaxy M33



Vera Rubin
(1970's)



Orbital Motion in Galaxy M33



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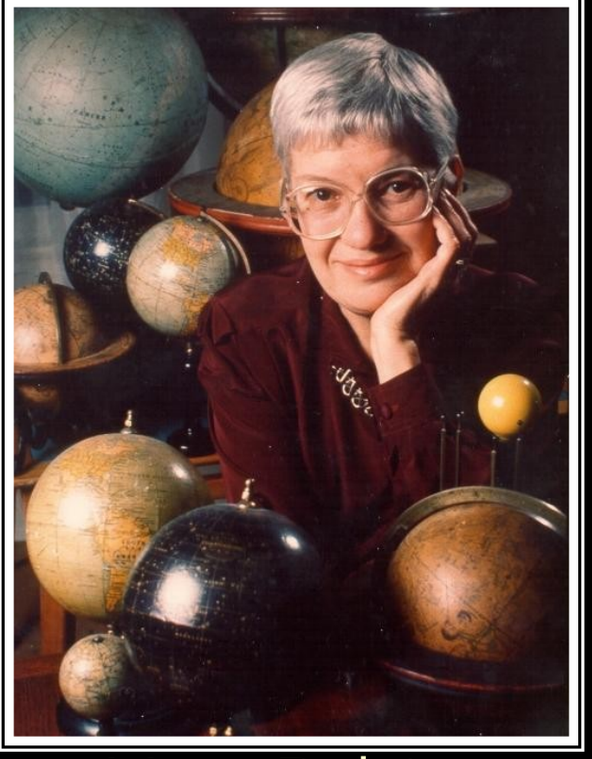

Vera Rubin
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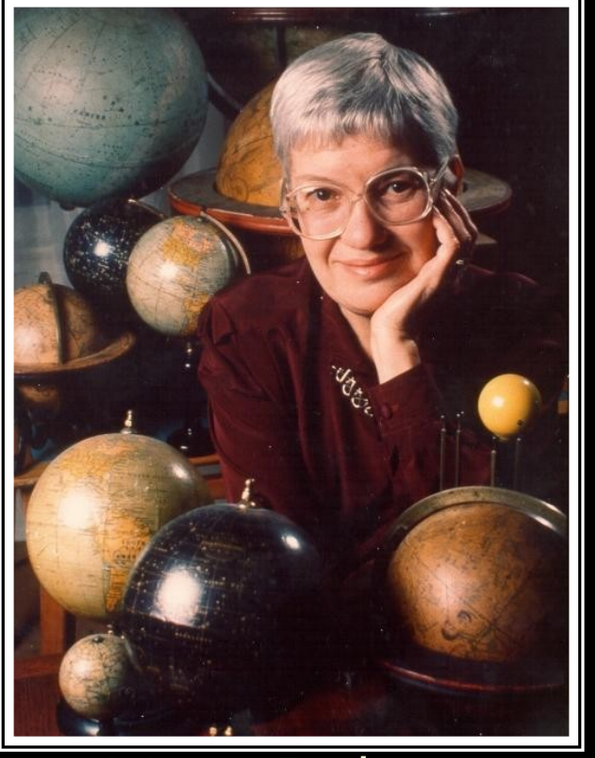
Orbital Motion in Galaxy M33



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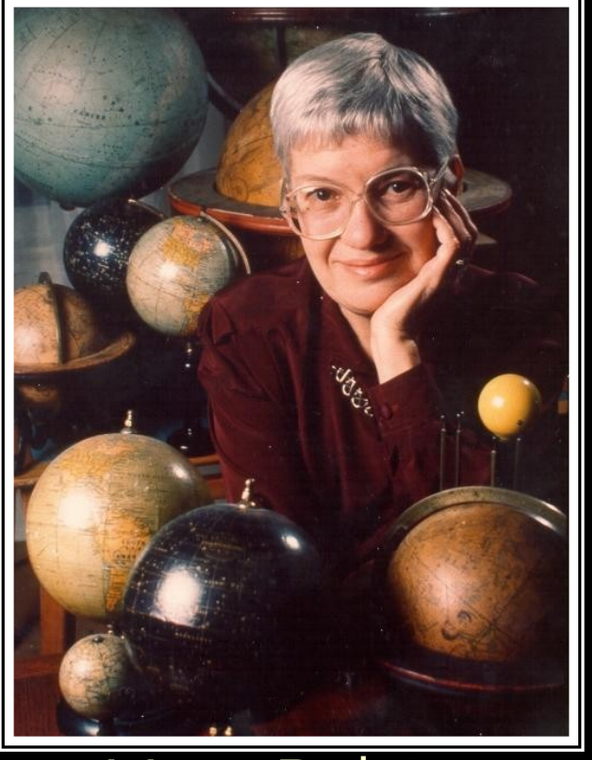

Vera Rubin
(1970's)

Orbital Motion in Galaxy M33

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 Ultimate Fate of the Universe

- The Universe is expanding.

The Ultimate Fate of the Universe

- The Universe is expanding. Big Bang

The Ultimate Fate of the Universe

- The Universe is expanding. Big Bang

- Gravity pull everything together.

The Ultimate Fate of the Universe

- The Universe is expanding. Big Bang

- Gravity pull everything together. ordinary matter and dark matter

The Ultimate Fate of the Universe

- The Universe is expanding. Big Bang

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- The expansion should be slowing down.

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?

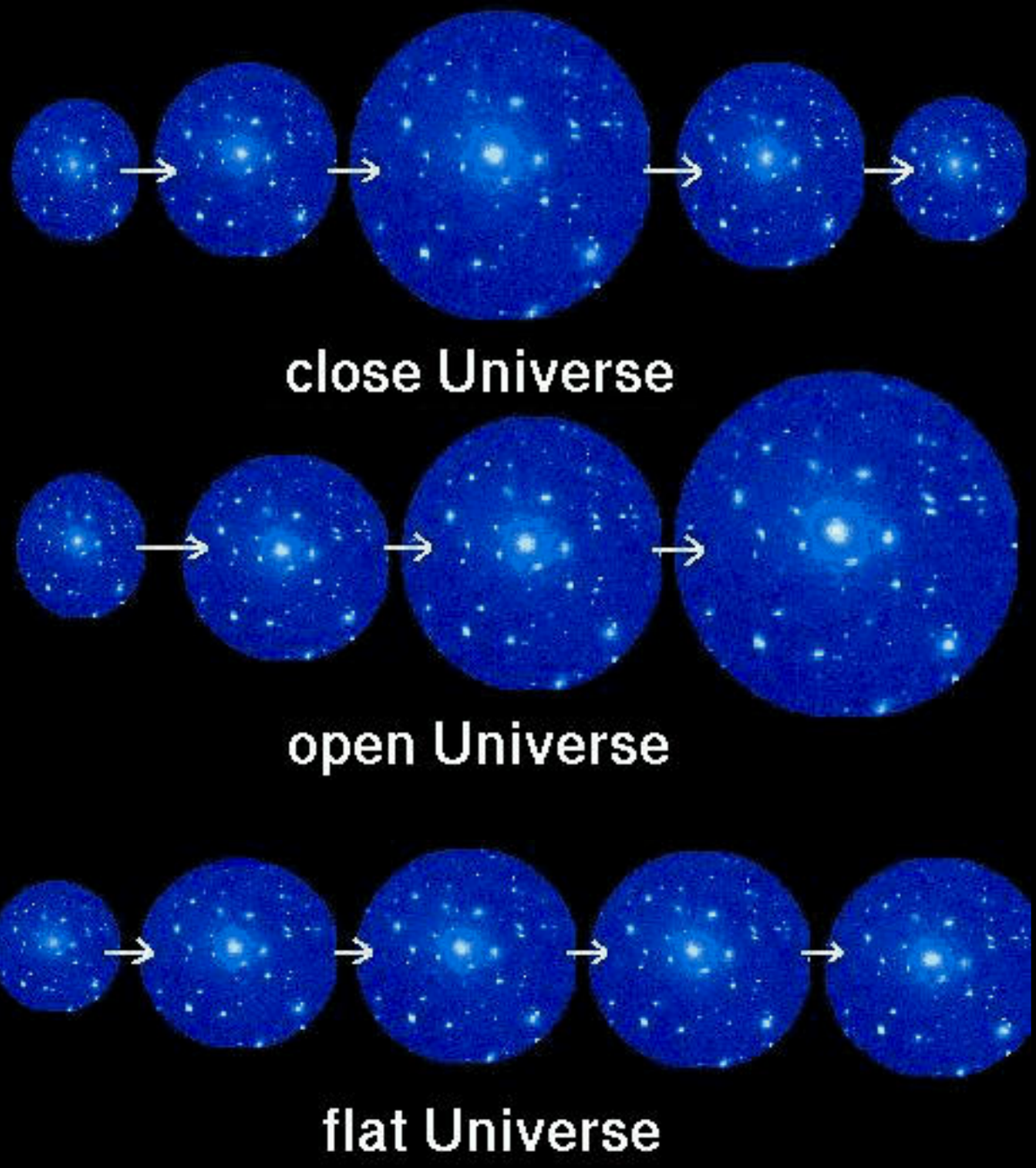
Group Discussion

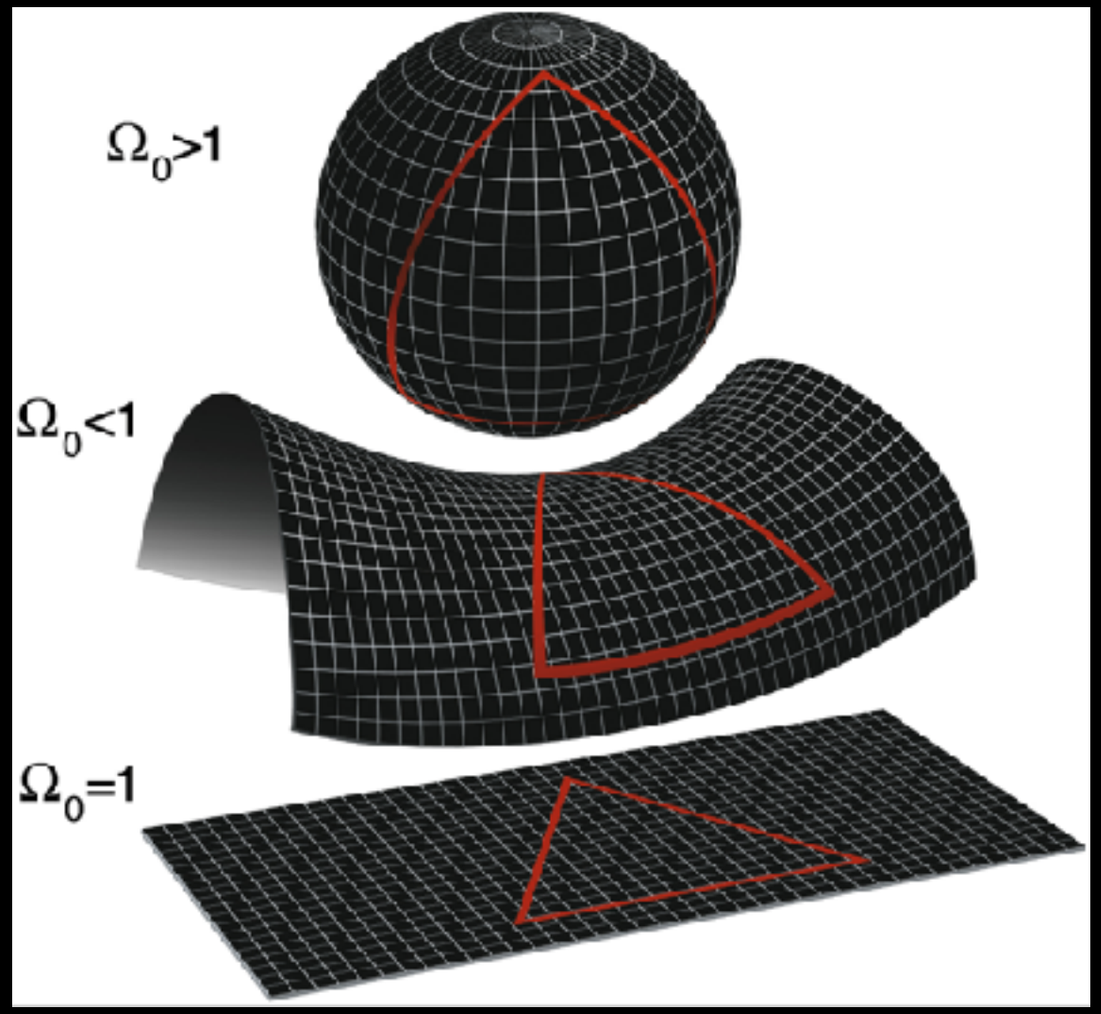
Throw a ball to the sky and what will happen?

- 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

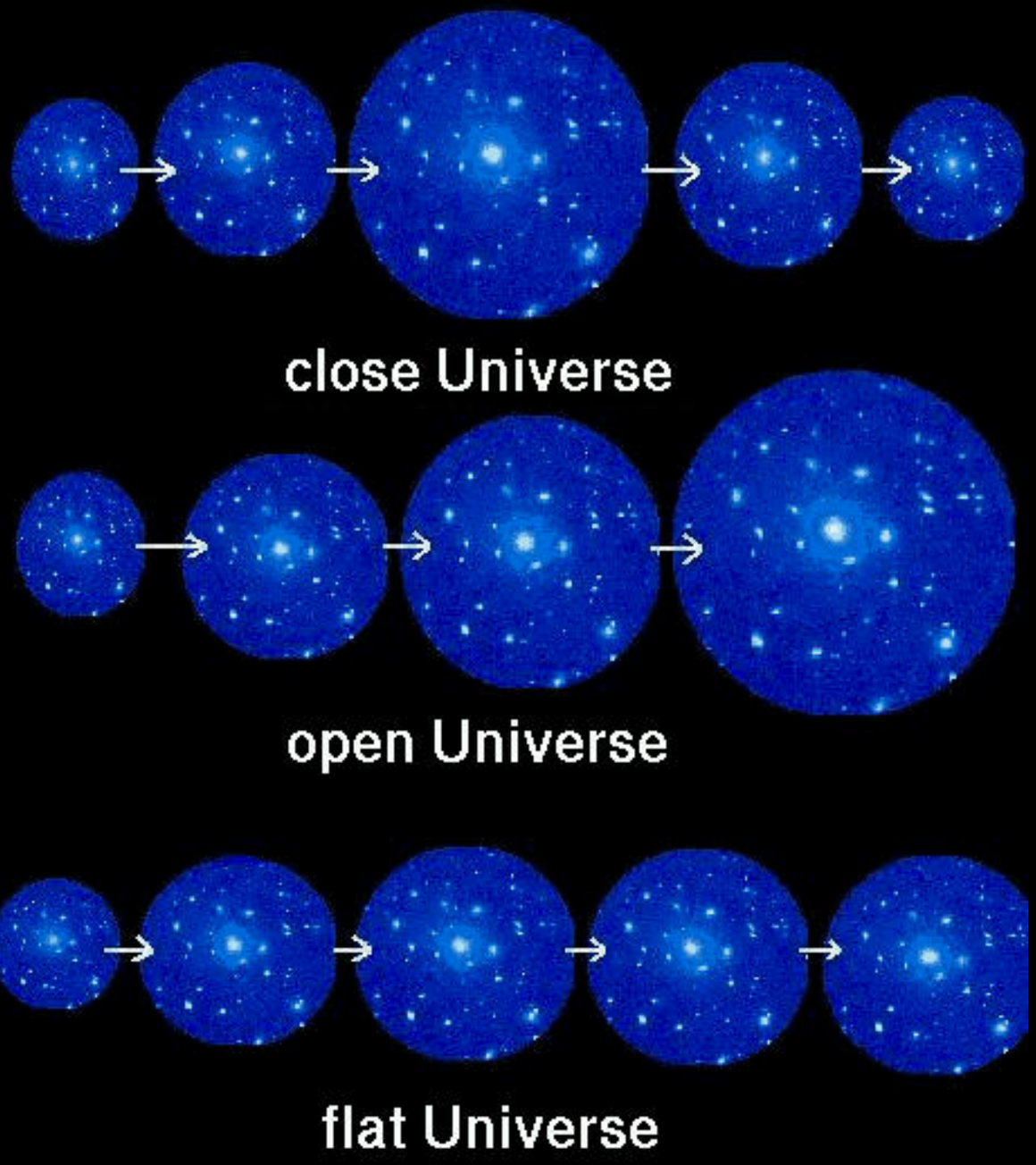


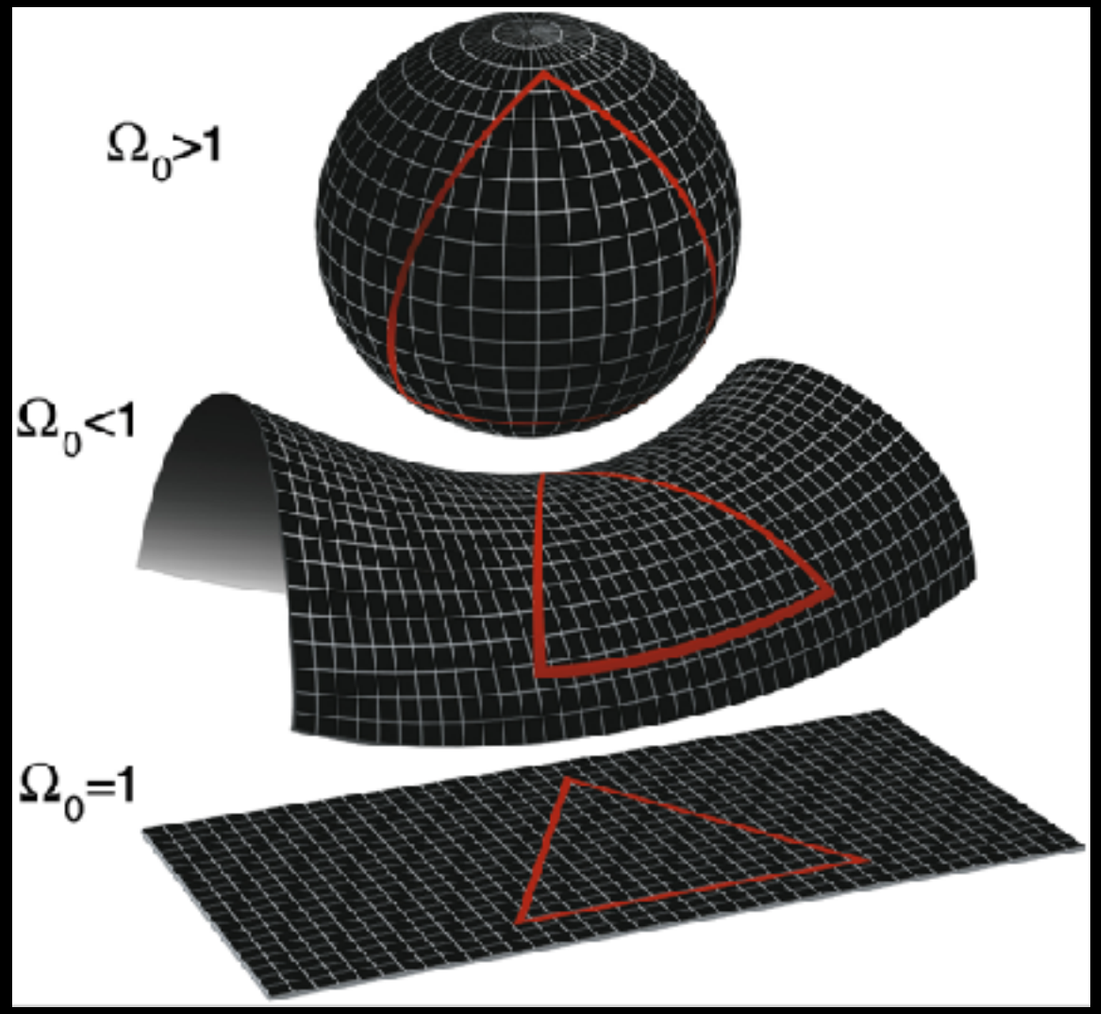


Initial Expansion Speed

Density of the Universe

measuring the deceleration rate q_0





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

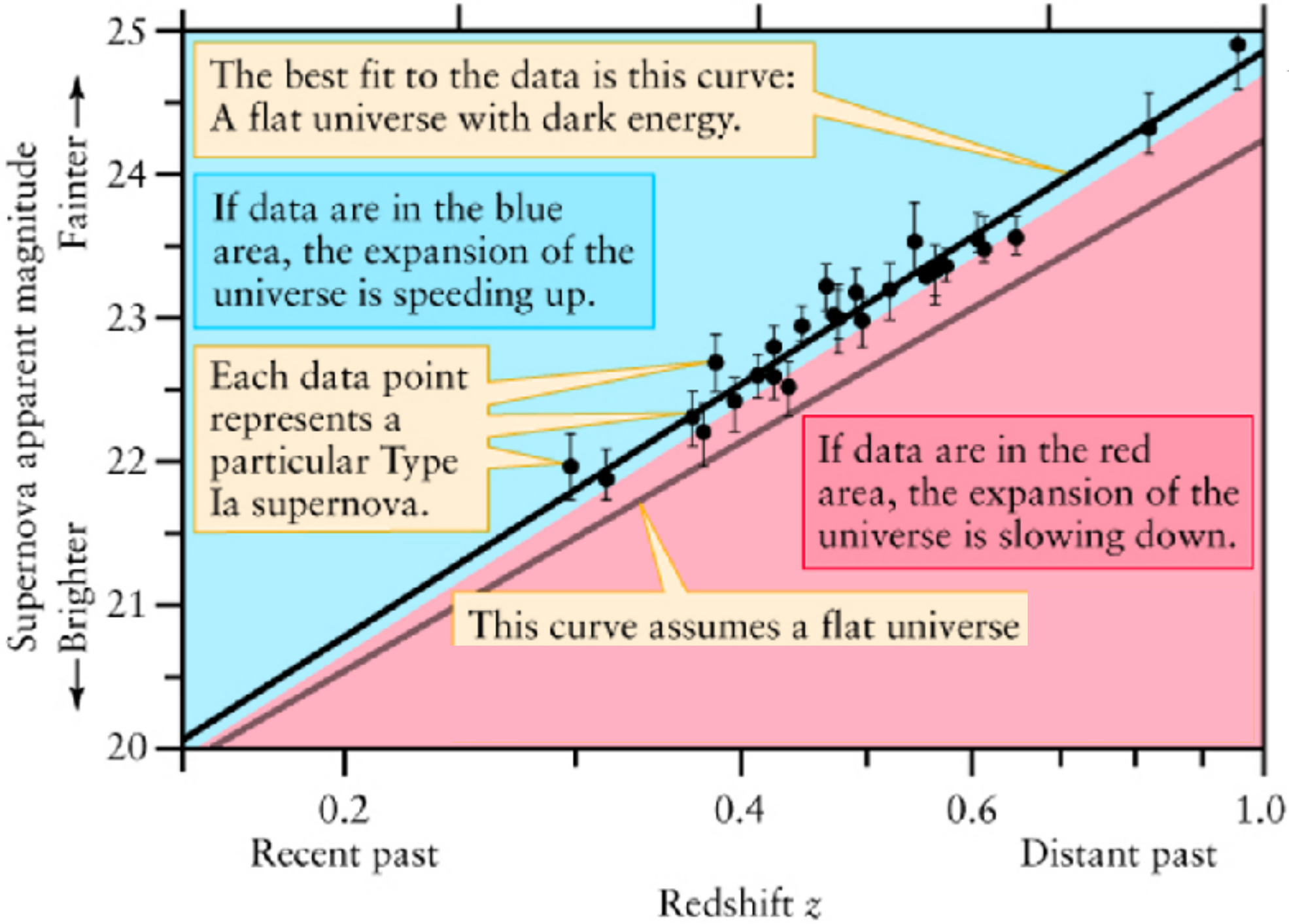
B. The ball will slow down but leave the Earth / open Universe

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

D. None of the above.

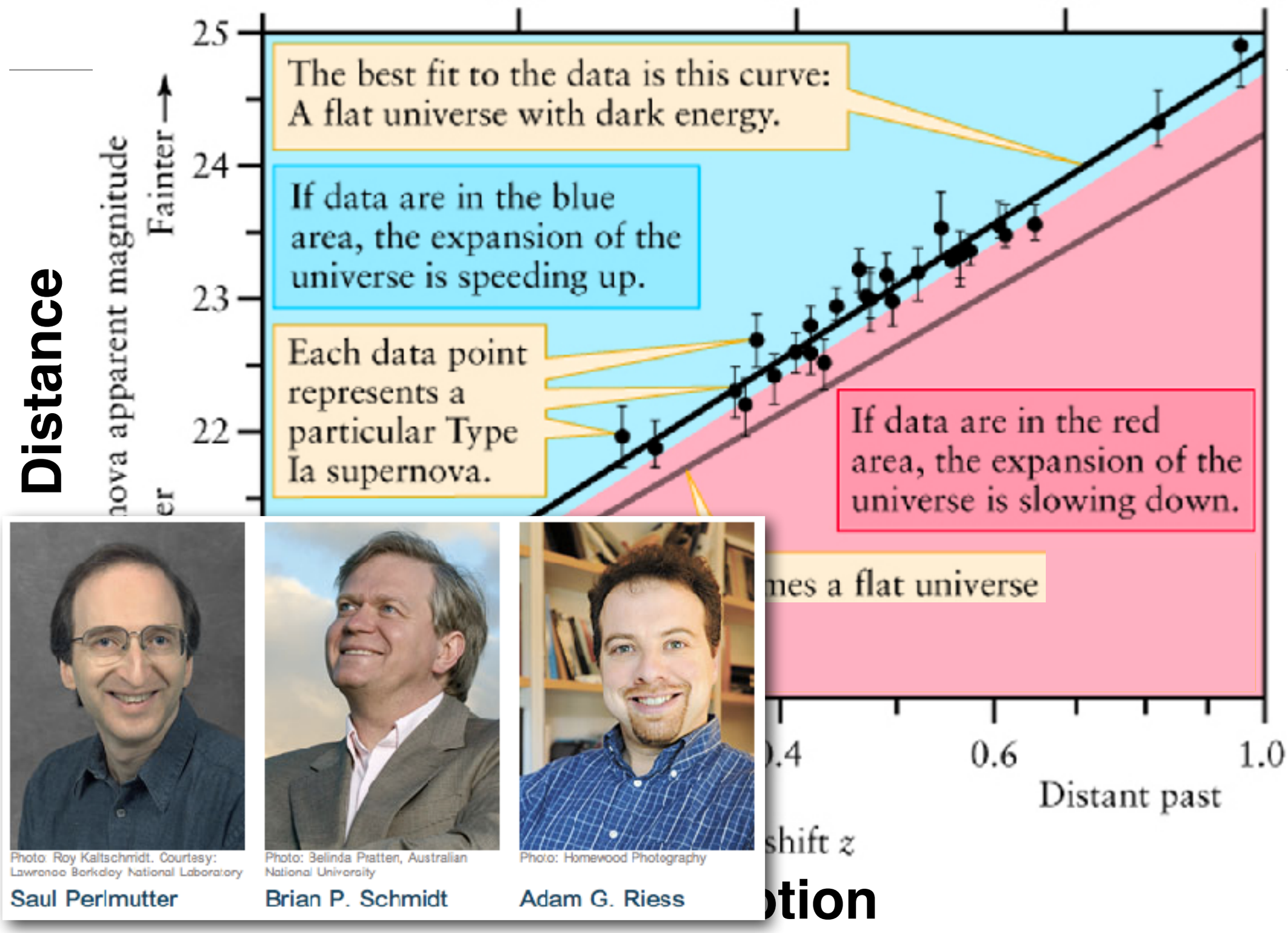
Supernova: an exploding star.
A Standard Candle.

Distance

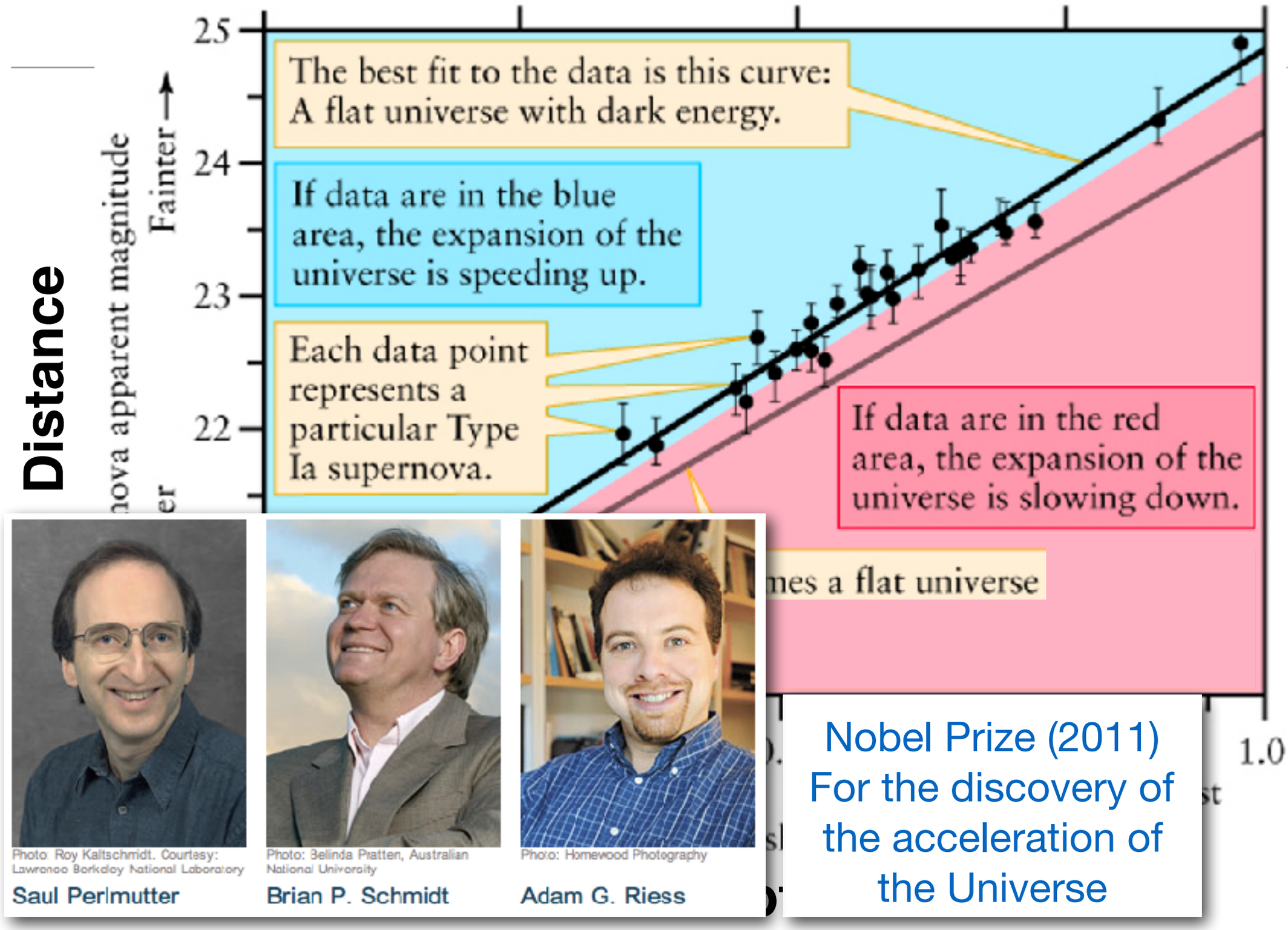


Motion

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



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



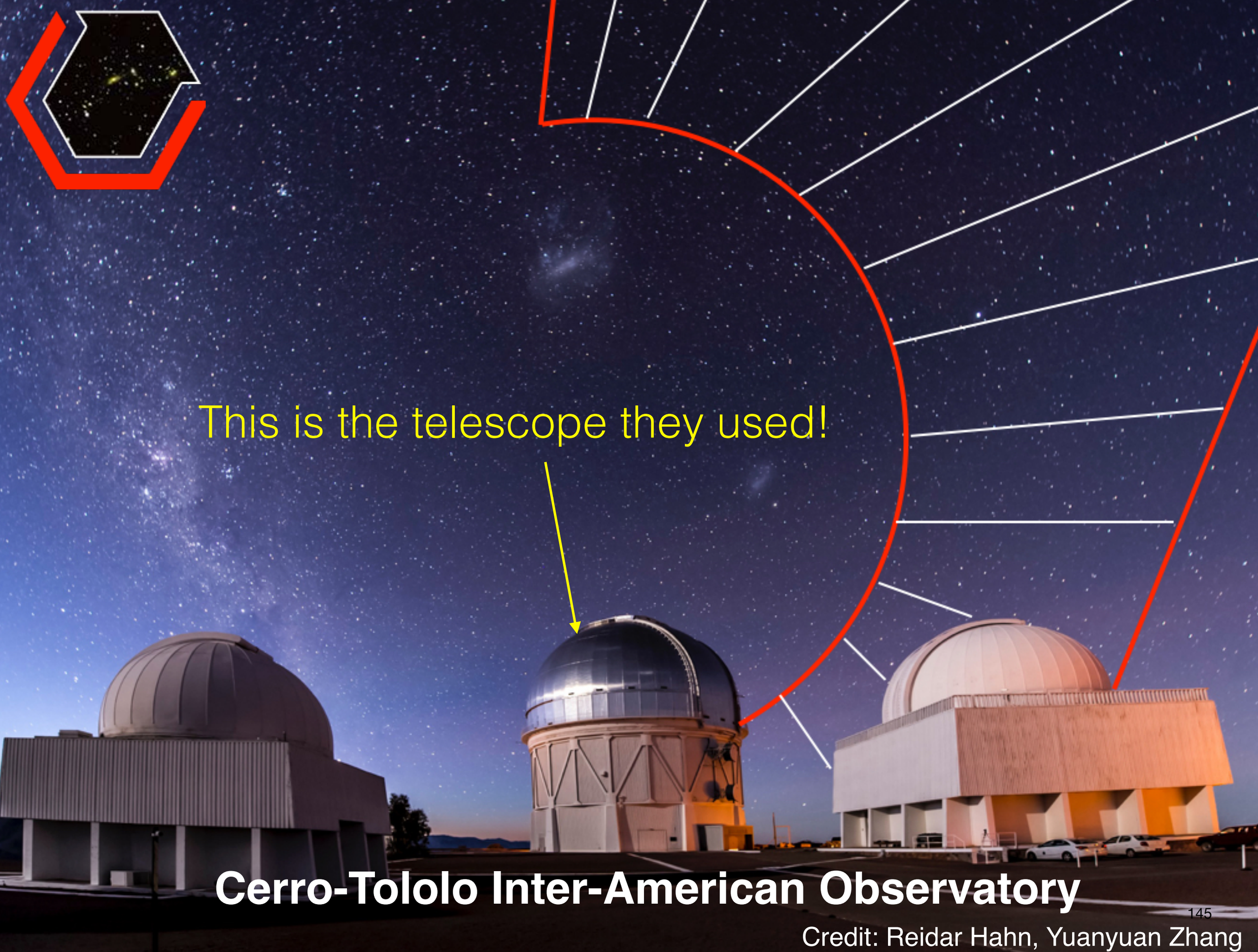
from https://sites.ualberta.ca/~pogosyan/teaching/ASTRO_122/lect30a/lecture30a.html

1929

The Universe is Expanding

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

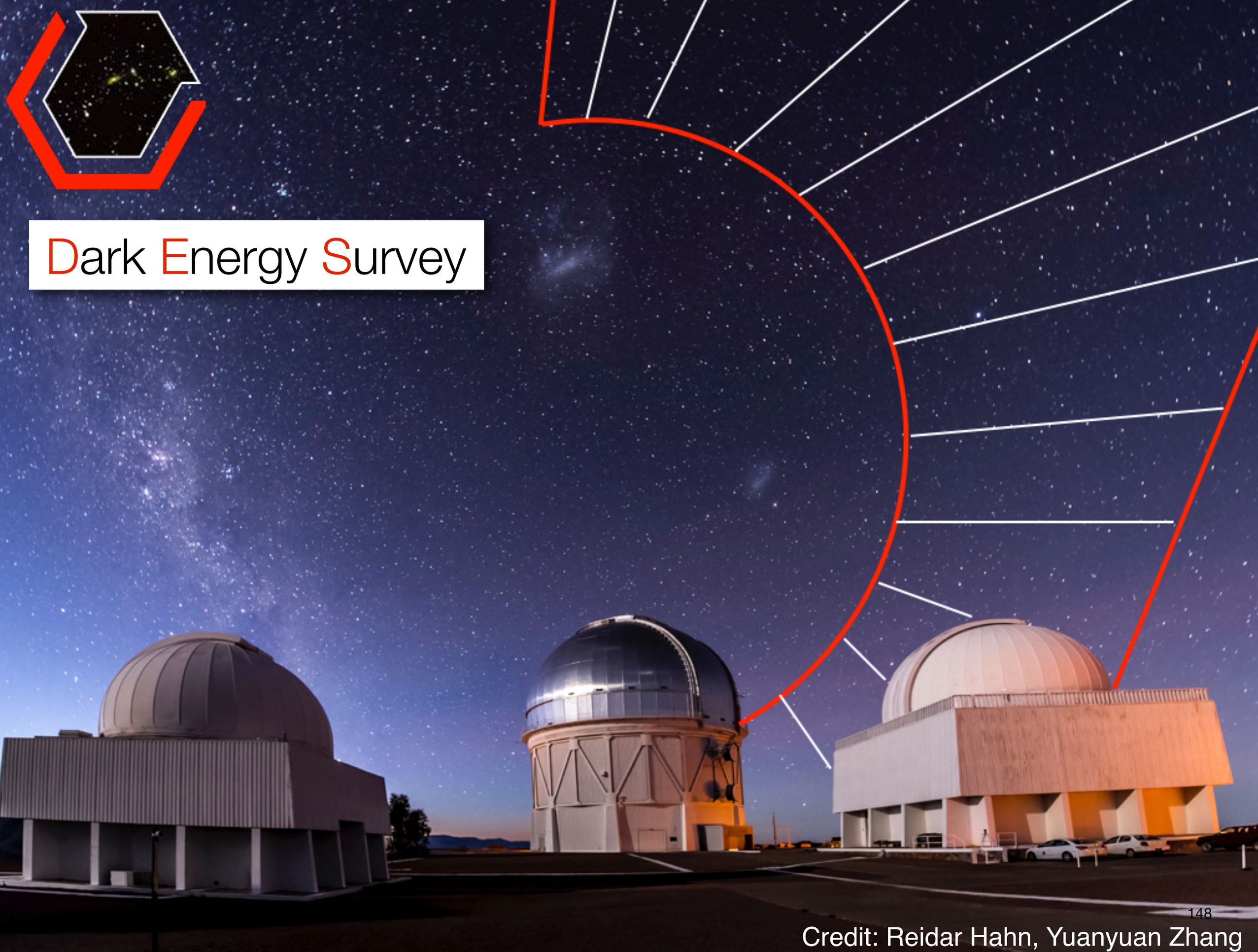
What causes Cosmic Speed-up?

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.



Credit: Reidar Hahn, Yuanyuan Zhang

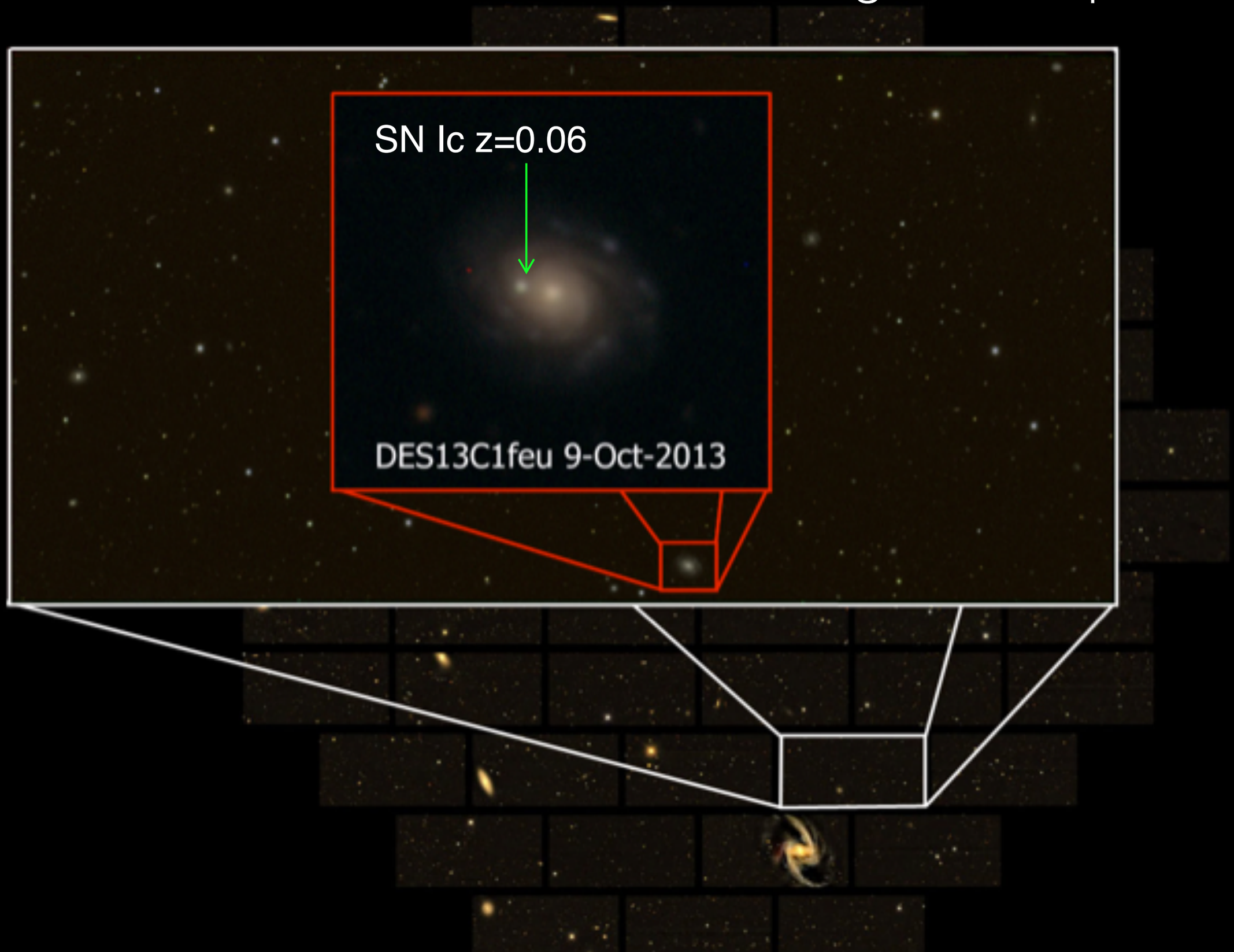
THE DARK ENERGY SURVEY

THE DARK ENERGY SURVEY

THE DARK ENERGY SURVEY

THE DARK ENERGY SURVEY

Finding more supernovae



Questions?

The Universe started with a Big Bang

The Origin

We are all Stardust

The Evolution

The Universe is mostly “Dark”

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)

Courtesy Brian Nord

Courtesy Brian Nord

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

Courtesy Brian Nord

Feel free to email me at
tingli@fnal.gov

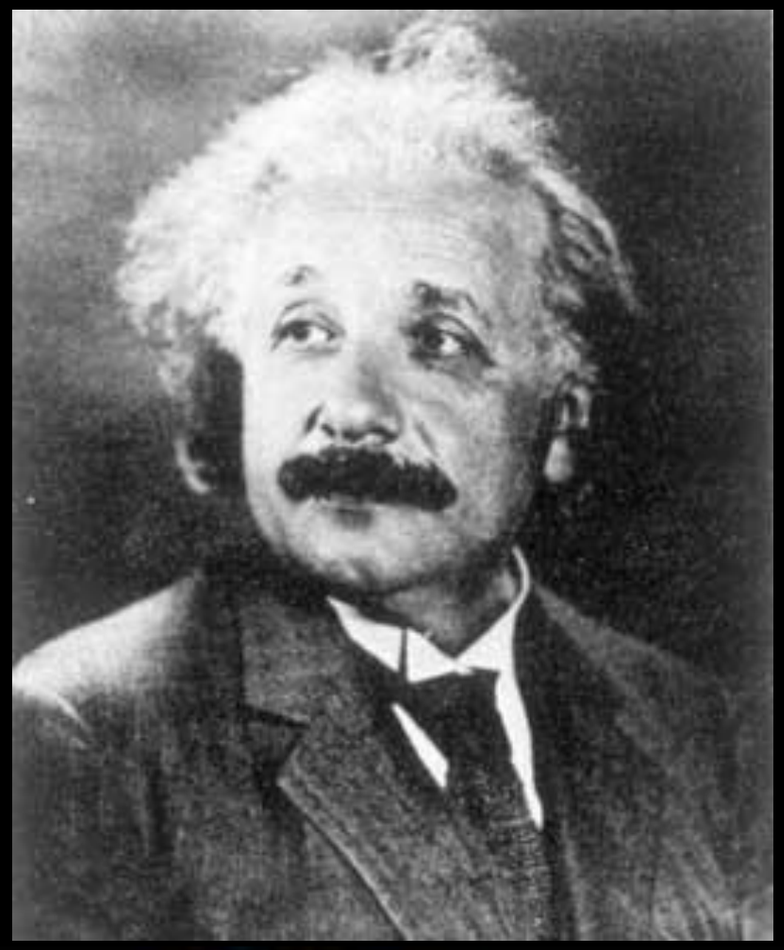
THE END

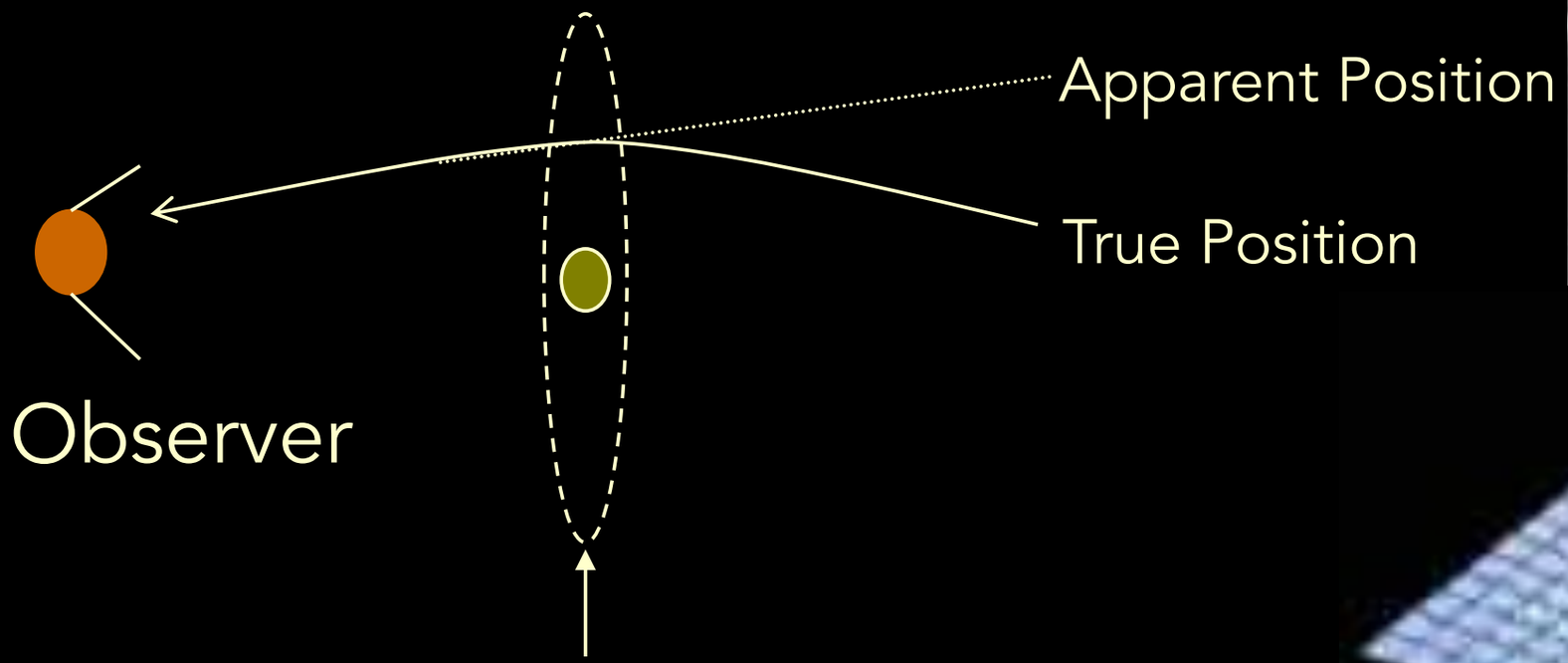
THANK YOU

Einstein's Theory of Gravity: General Relativity

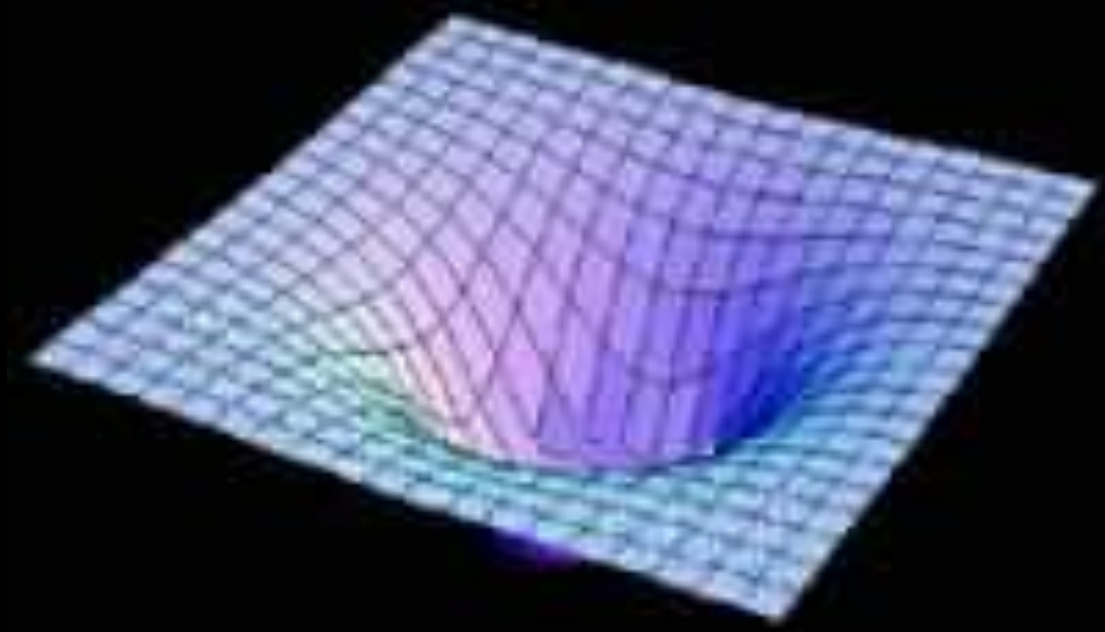
Matter and Energy curve Space-Time

Everything, including light, moves in this curved Space-time

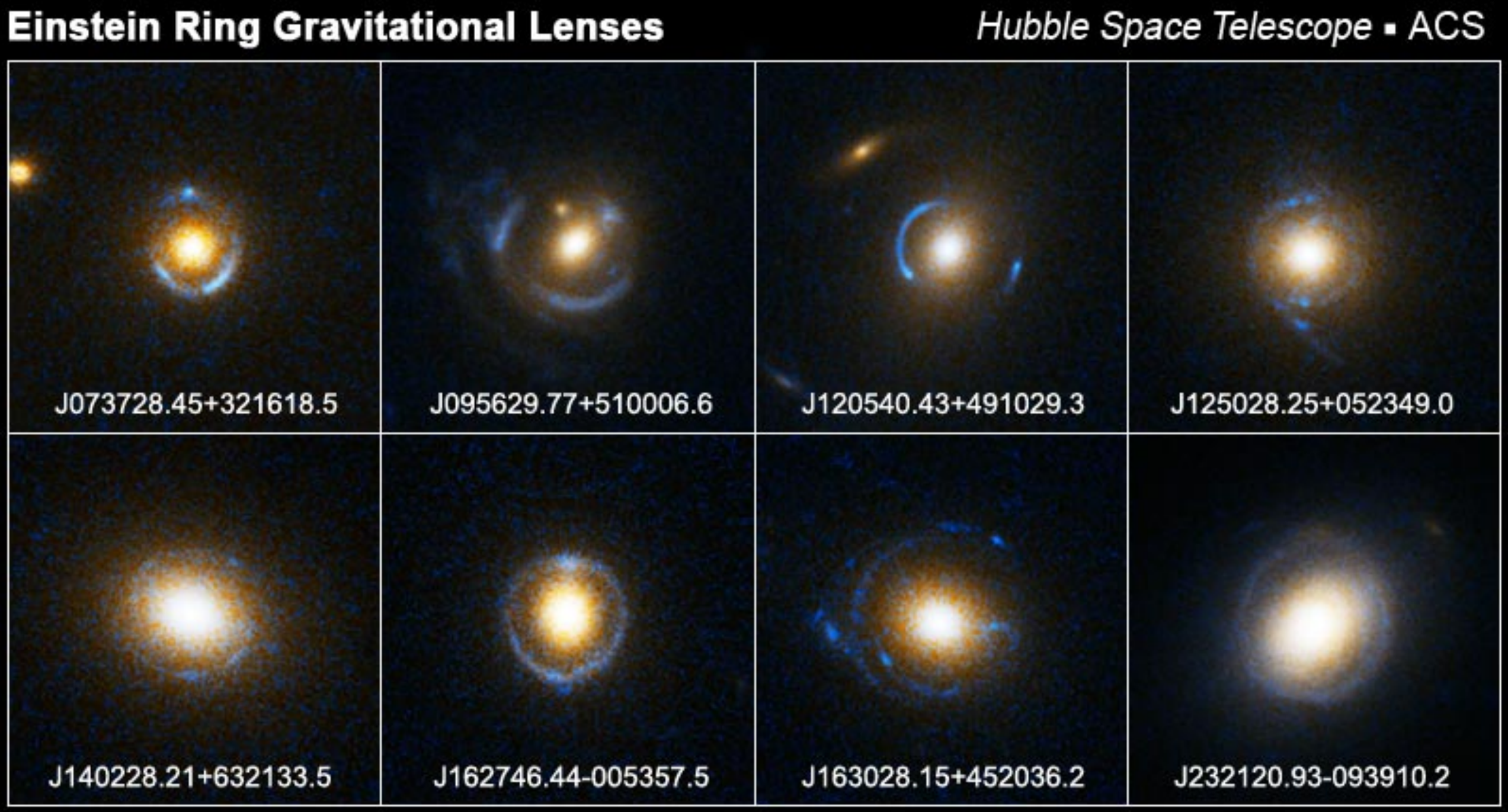




Gravitational "lens"
(e.g., Galaxy or Galaxy Cluster)

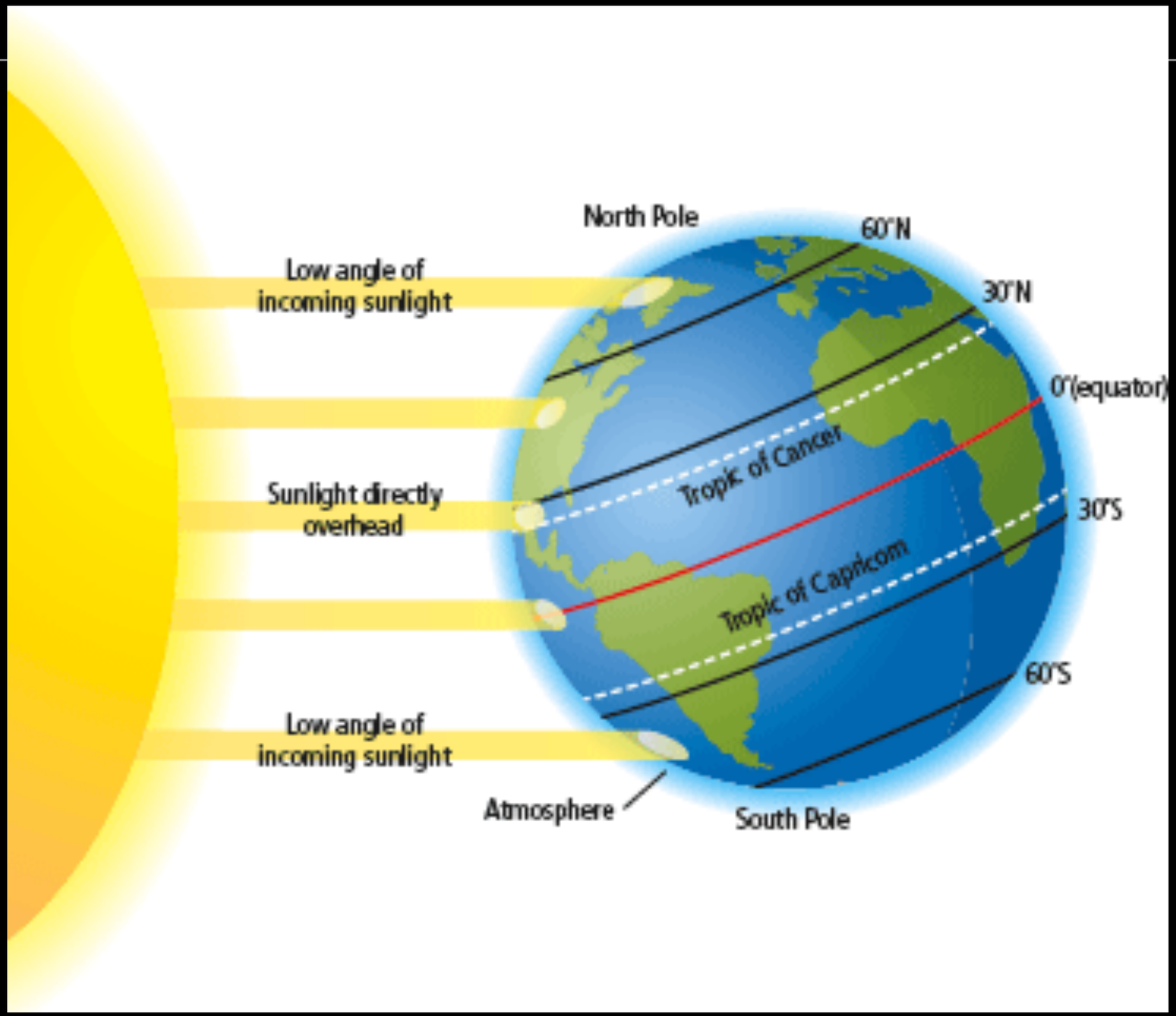


Einstein Ring from Gravitational Lensing

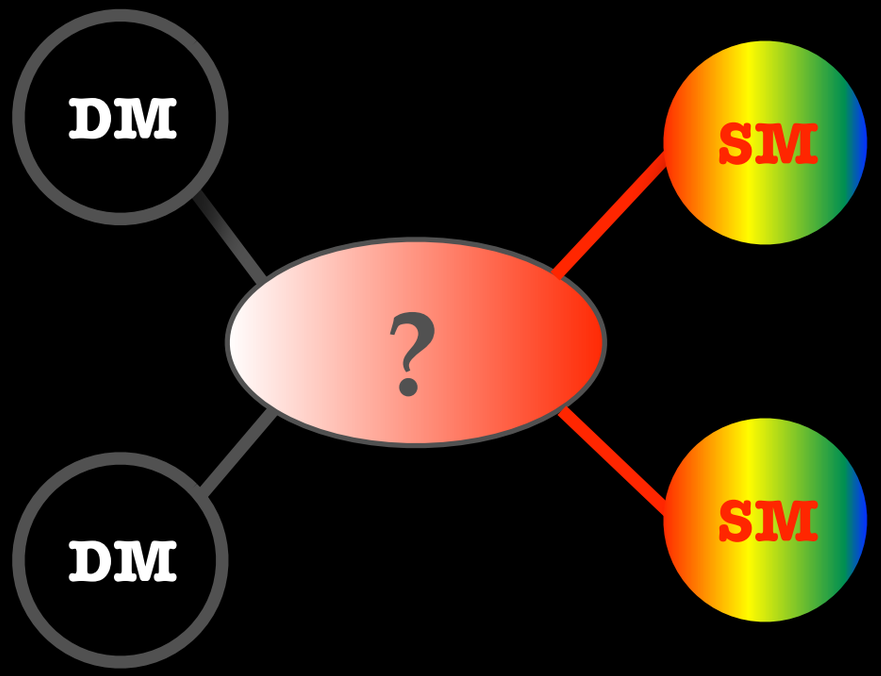


“Seeing” Dark Matter in a Galaxy Cluster

Abell 2218 HST

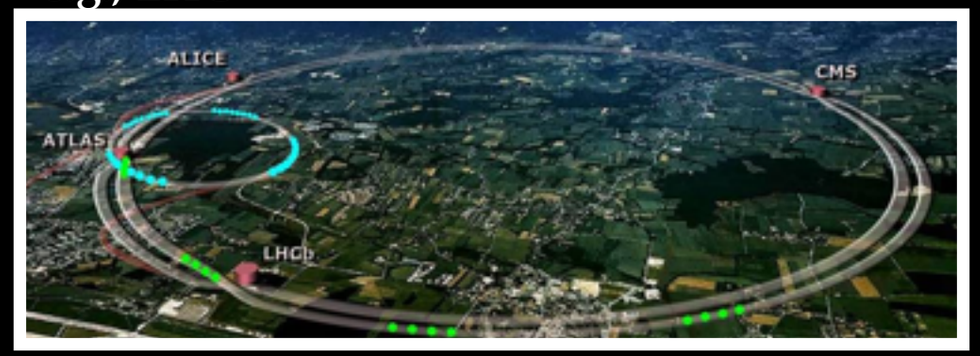

North Pole
60°N
30°N
0°(equator)
30°S
60°S
South Pole
Low angle of incoming sunlight
Sunlight directly overhead
Low angle of incoming sunlight
Tropic of Cancer
Tropic of Capricorn
Atmosphere

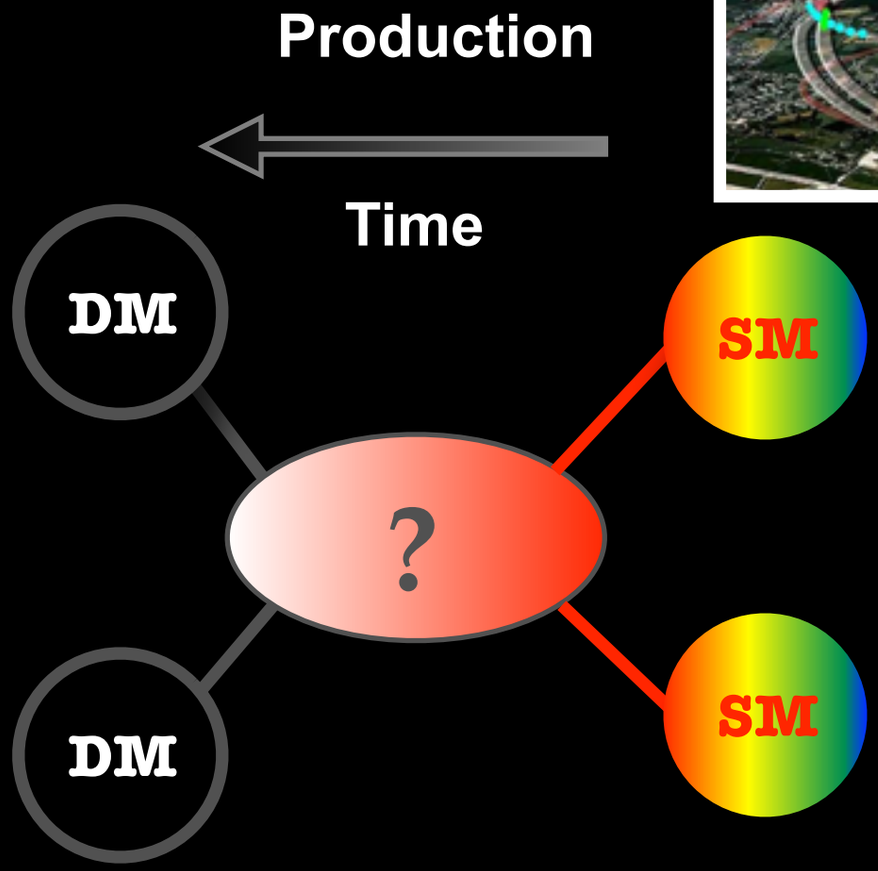
The Hunt for Dark Matter



The Hunt for Dark Matter

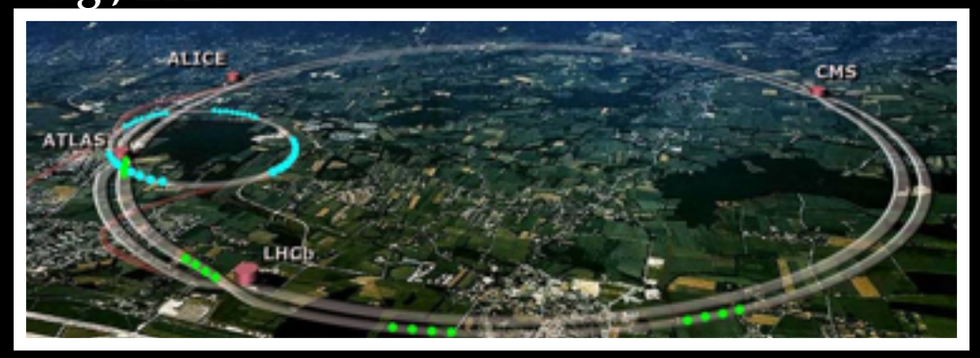
e.g., LHC





The Hunt for Dark Matter

e.g., LHC

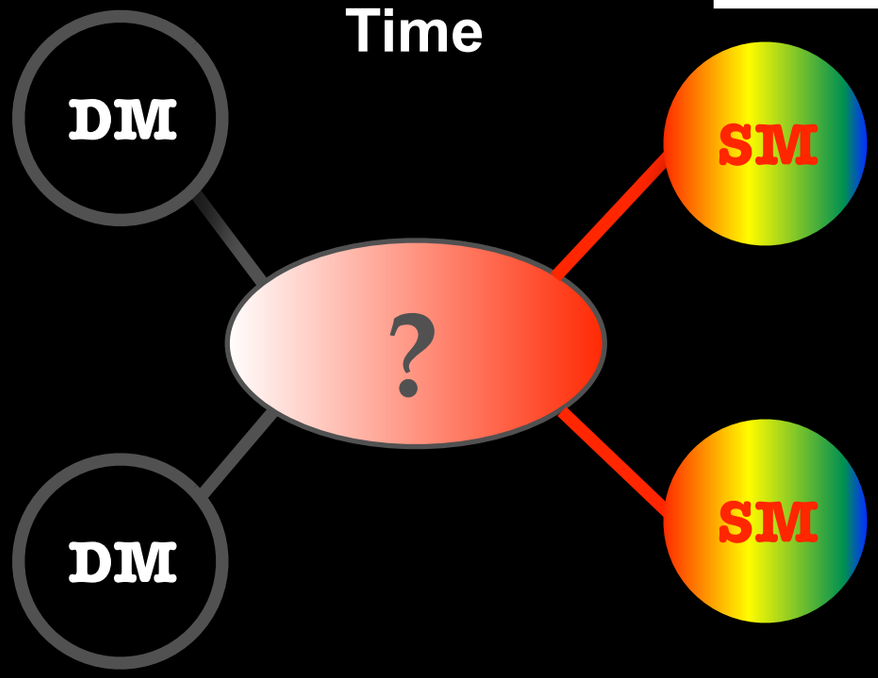


Production

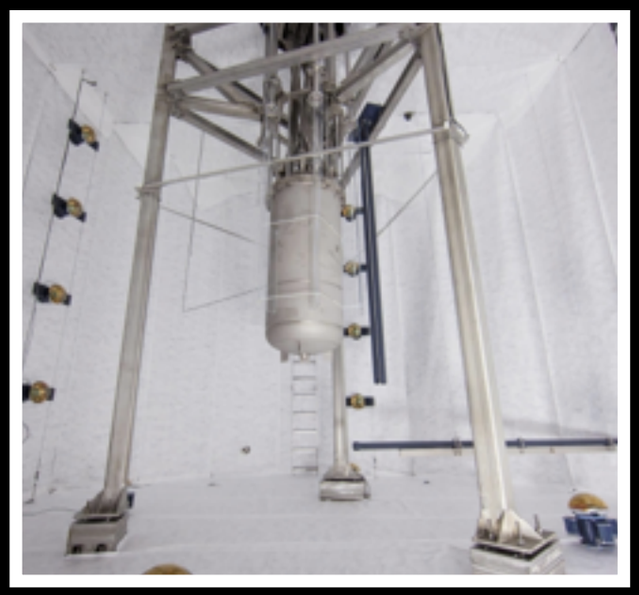
Time

Direct Detection

Time

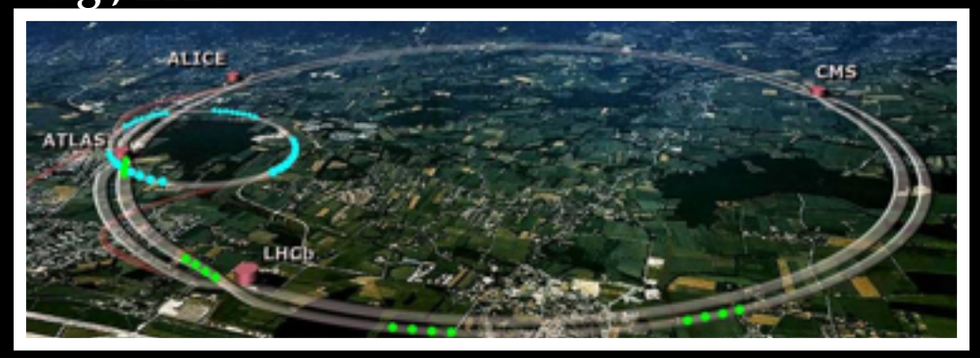


e.g., LUX



The Hunt for Dark Matter

e.g., LHC



Production

Time

DM

SM

Direct Detection

Time

?

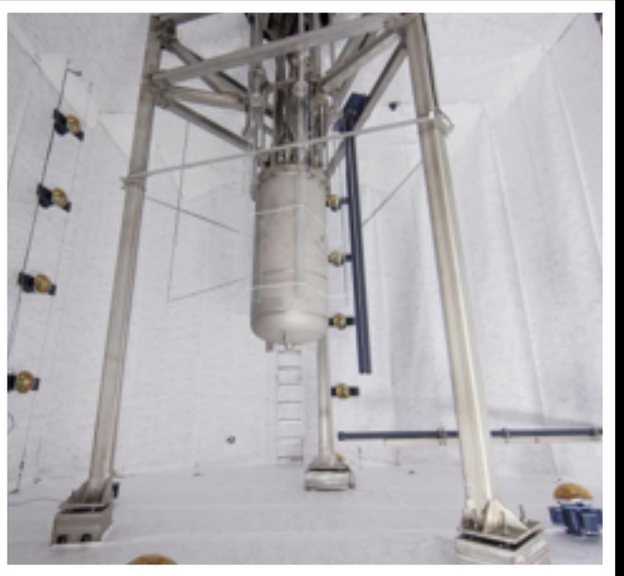
DM

SM

Time

Indirect Detection

e.g., LUX



e.g., Fermi-LAT