INDIAN SPACE SCIENCE OLYMPIAD

Our Universe!

The world we see and the model we construct.

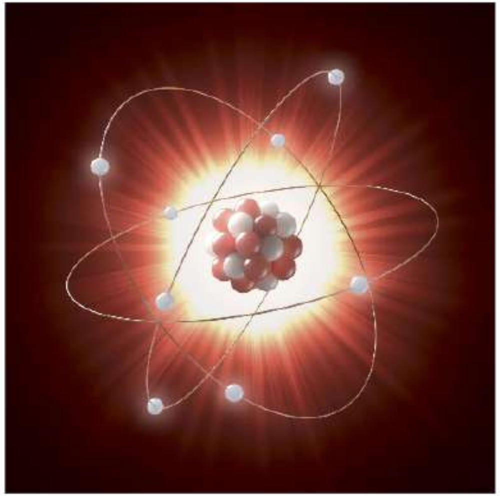
What is "Universe"?

Universe is the collection of everything that exist including where in space and when in time.

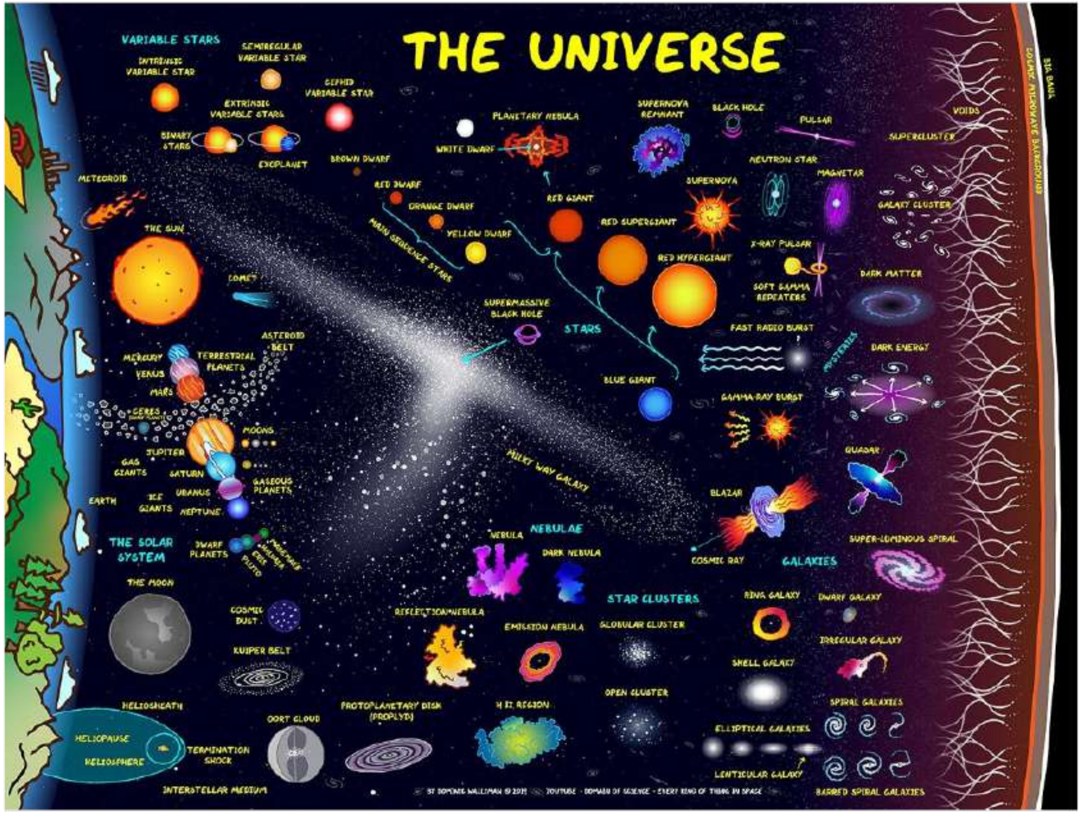
1. Things in this Universe

2. What is space

3. What is time



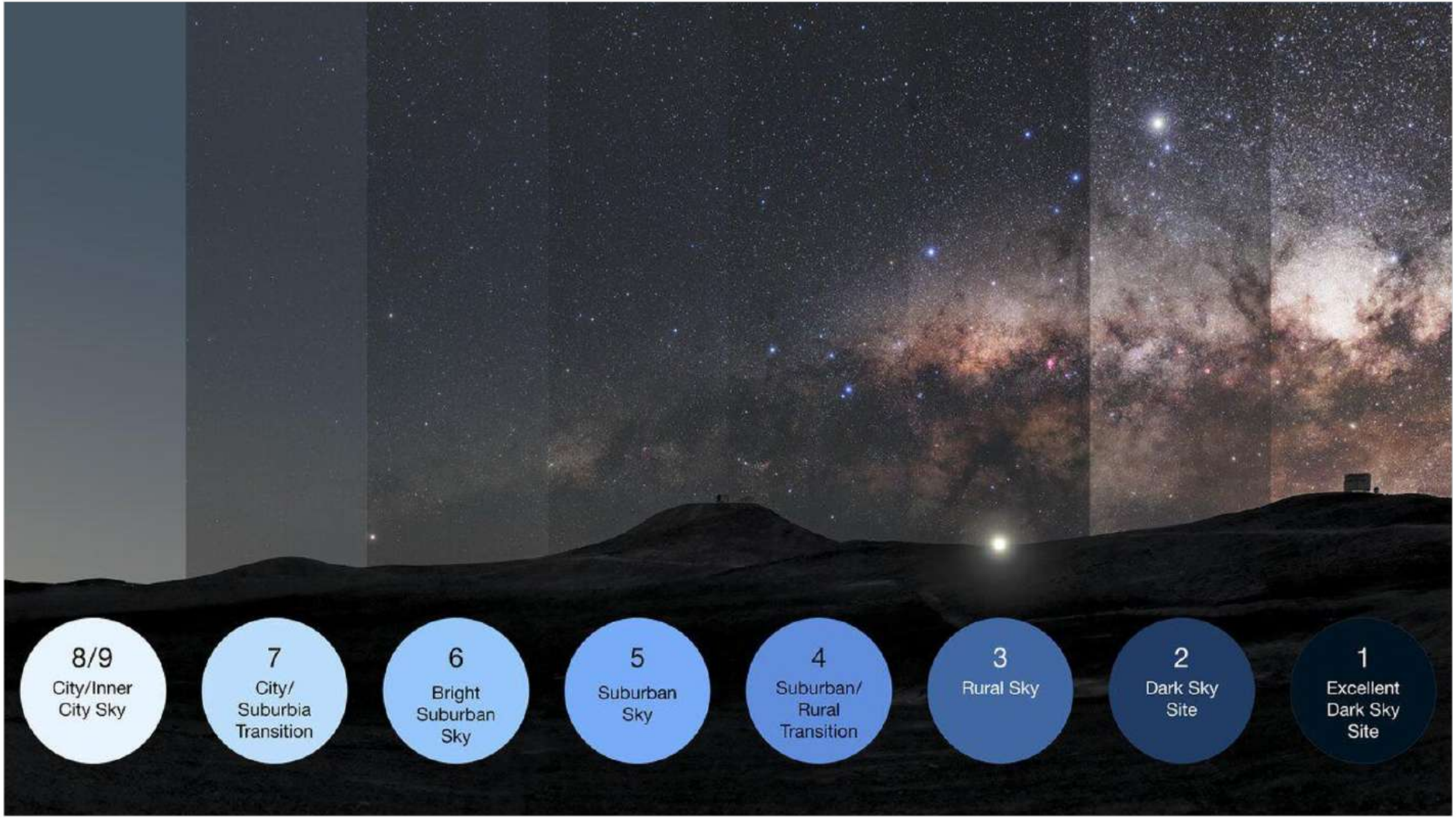
1. Things in the Universe



Things we **see** tells a story about our universe.

"The Model of the Universe"

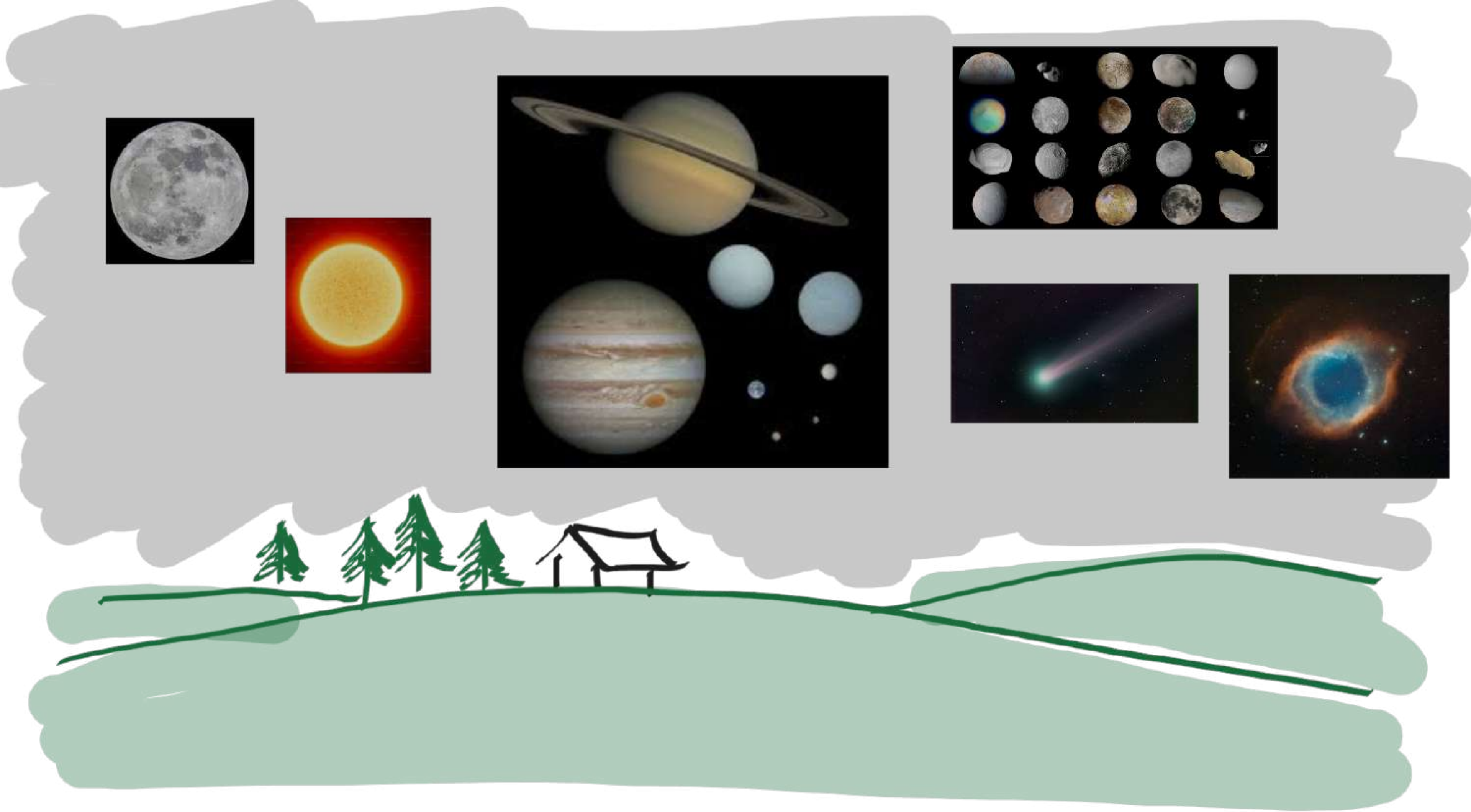
So what do we SEE?


8/9
City/Inner City Sky
7
City/ Suburbia Transition
6
Bright Suburban Sky
5
Suburban Sky
4
Suburban/ Rural Transition
3
Rural Sky
2
Dark Sky Site
1
Excellent Dark Sky Site

SEE

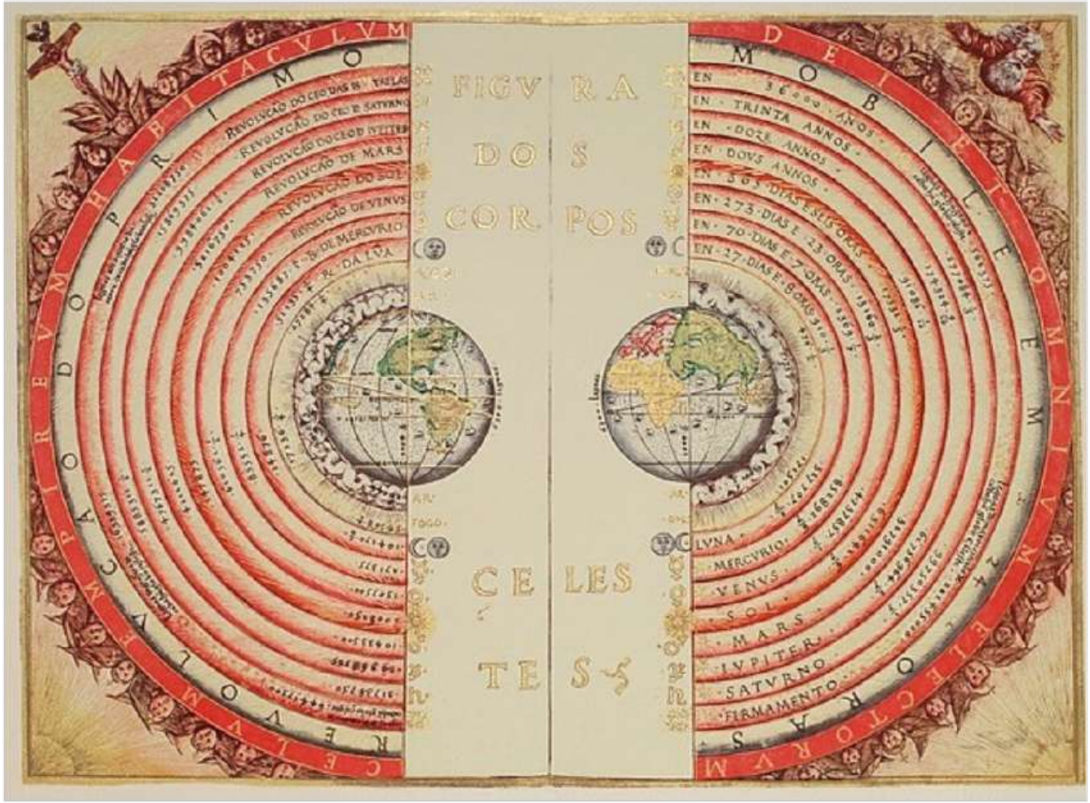
What we see in the night sky

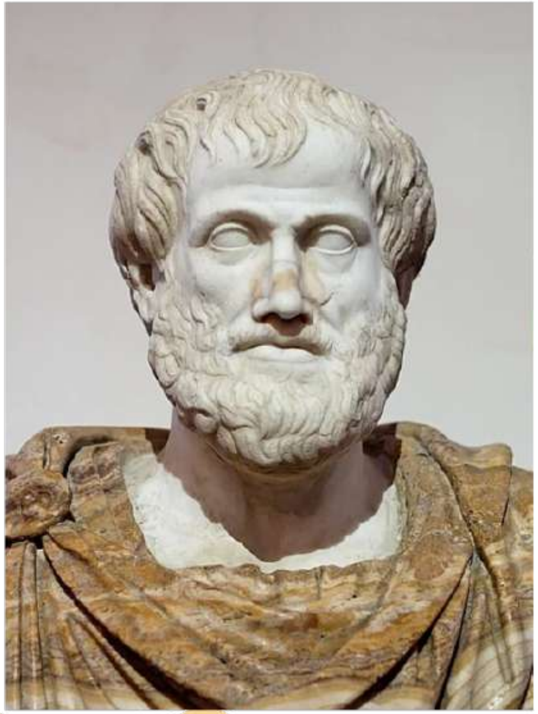
1. Stars
2. Planets
3. Moon
4. Clouds ...



Based on everything we **SEE**,
we construct a **MODEL**.

Geocentric model of our "Universe"





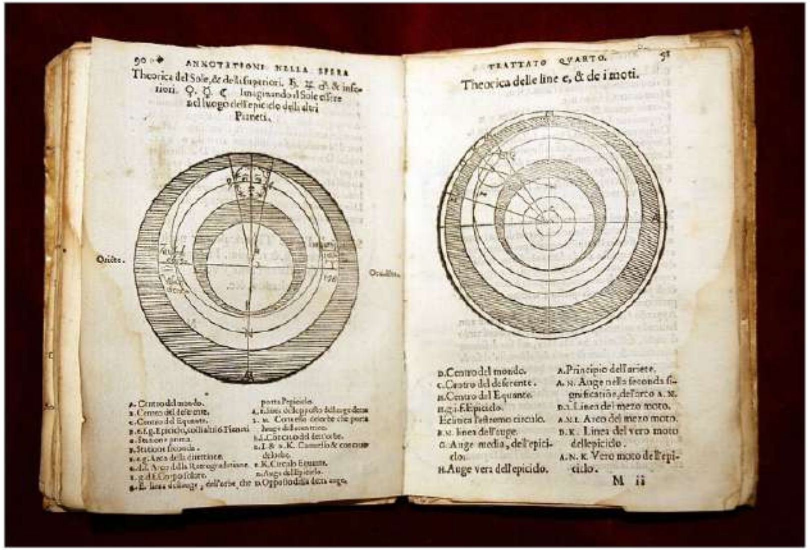
Aristotle (384 BC)

Ptolemy (100 AD)

1. Spherical Earth

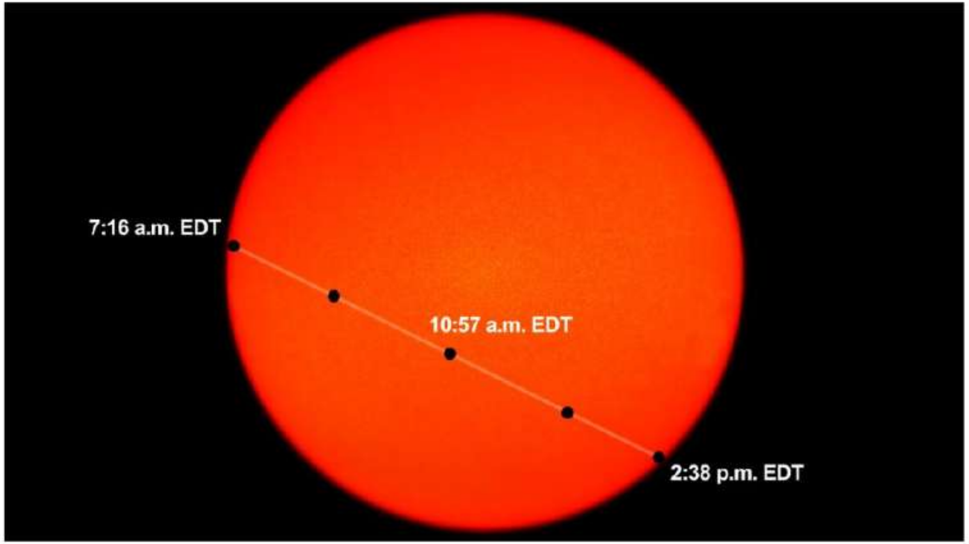
2. Circular Orbits

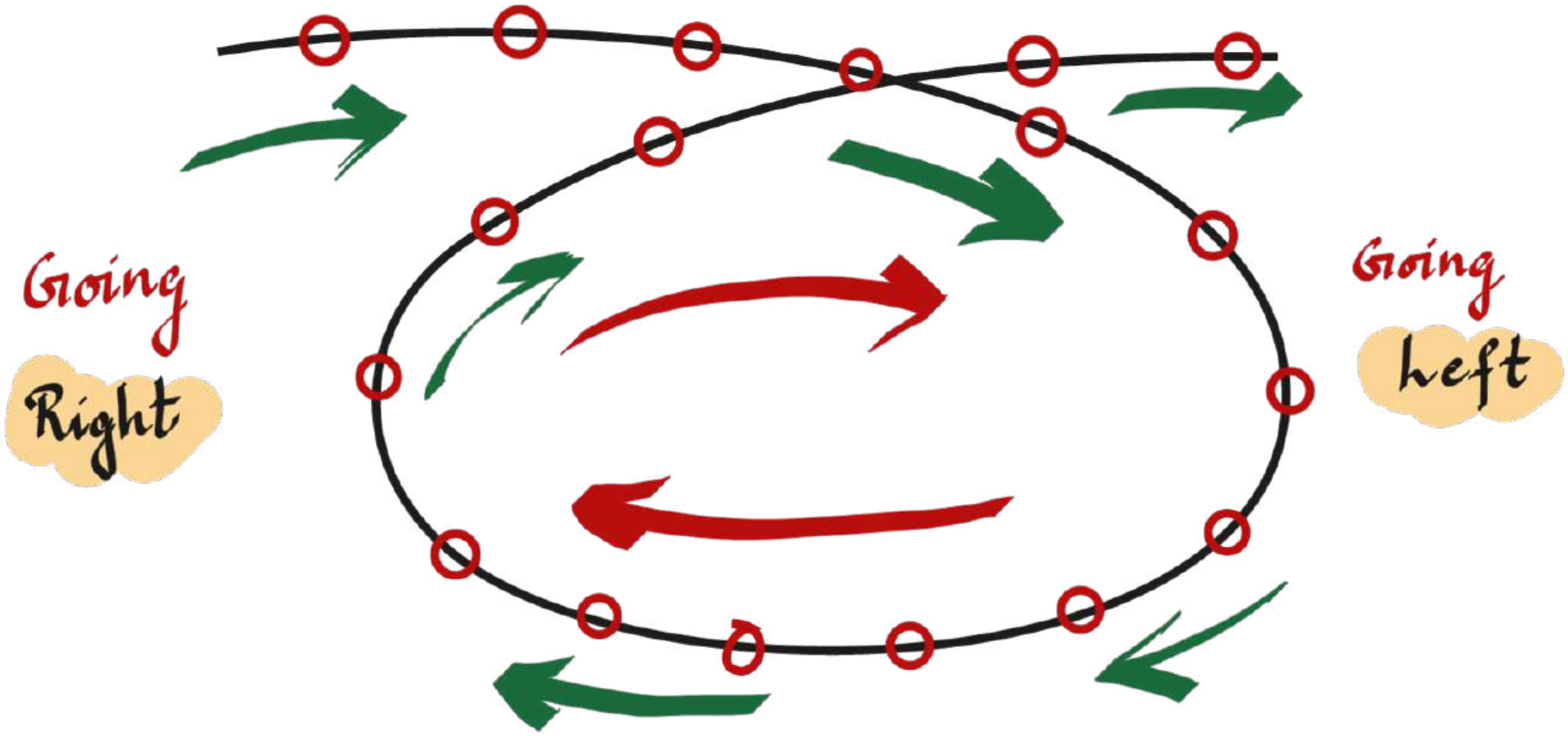
3. Stars are fixed



"well this is what we SEE"

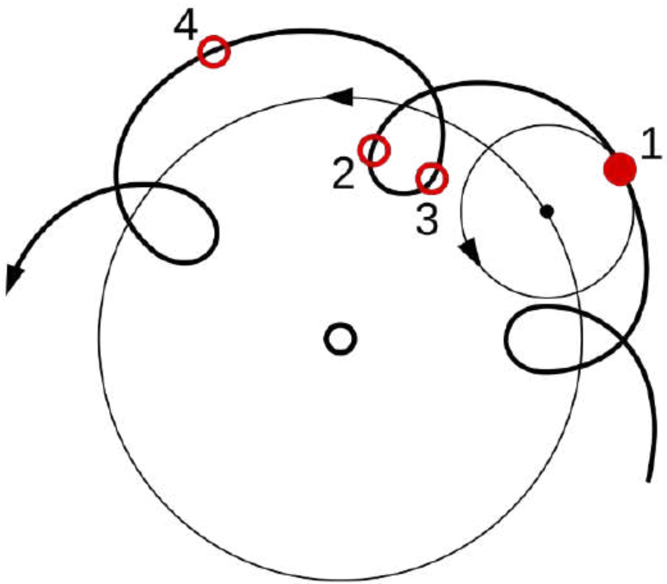
Retrograde motion

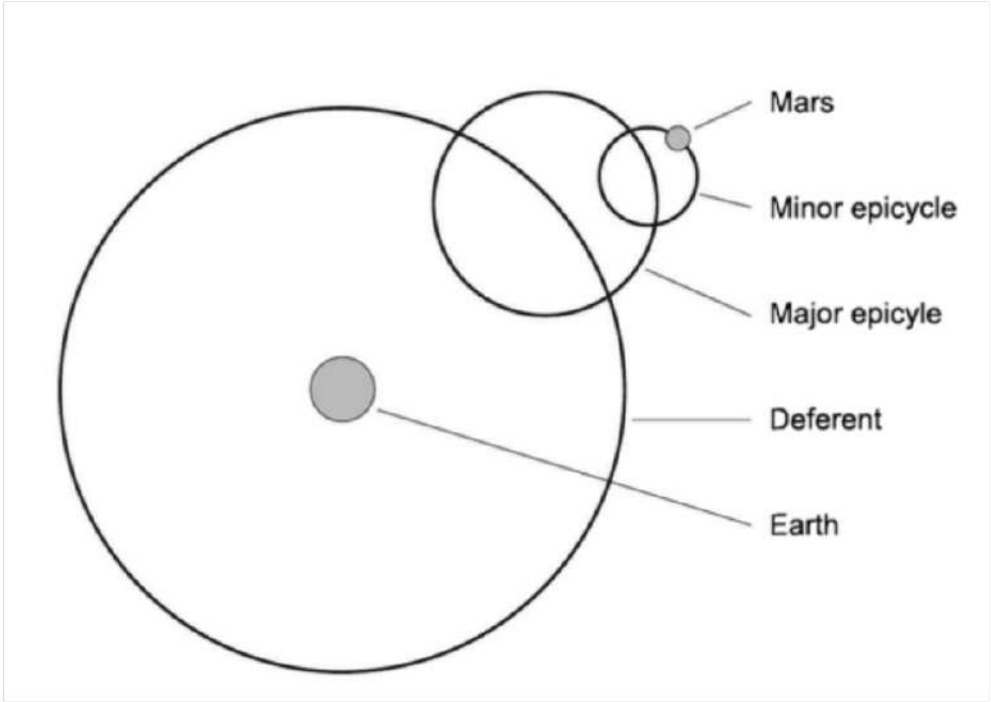


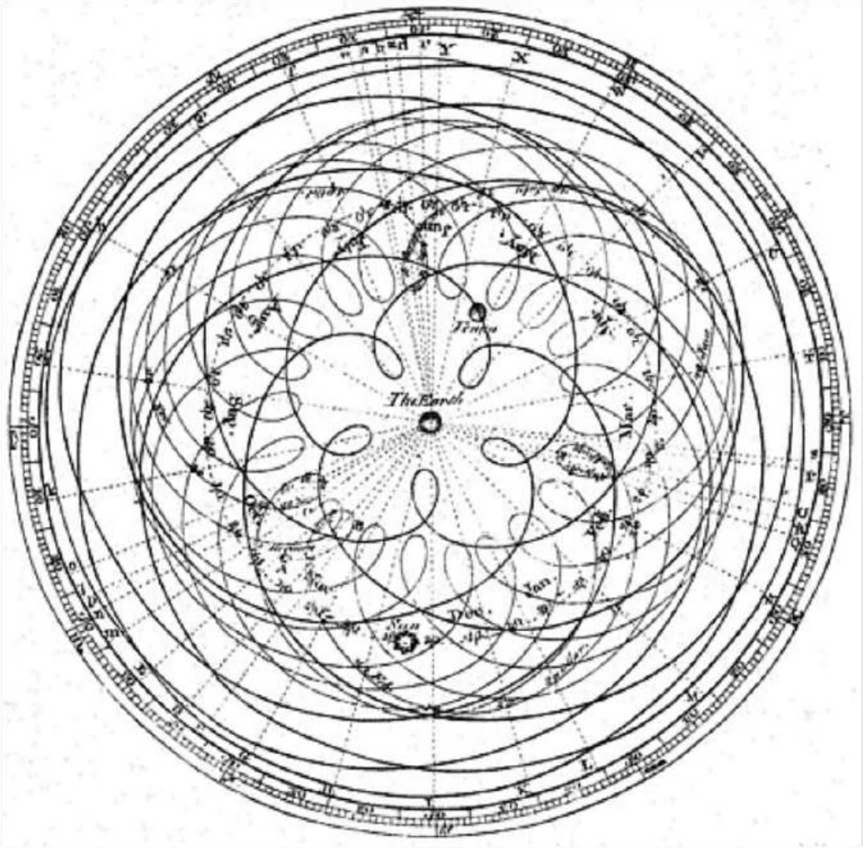


Circular orbits are not simple

Epicycle(s)







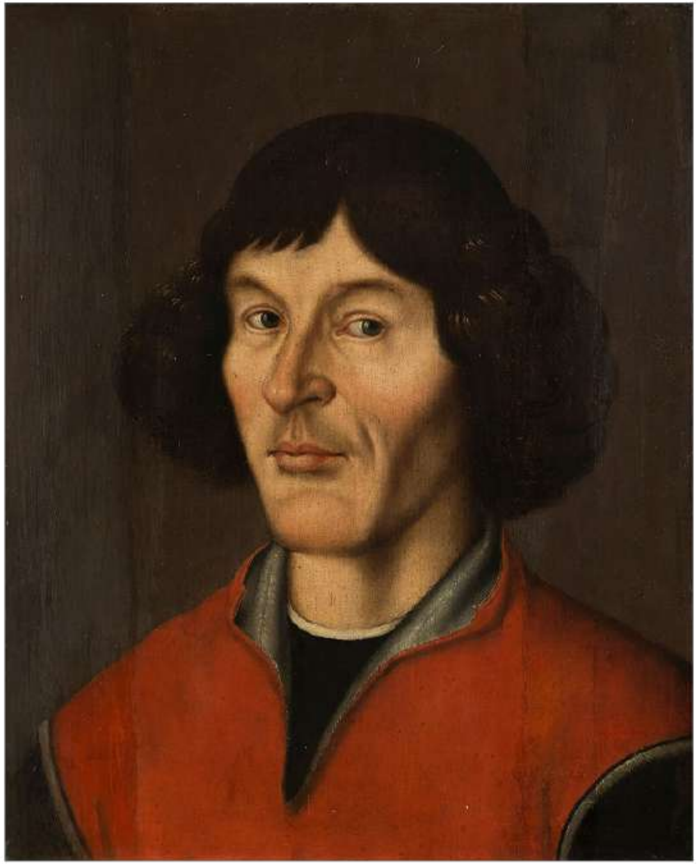
The orbits became more complex and tedious

"Bad Science?"

Geocentric model of our "**Universe**"

→

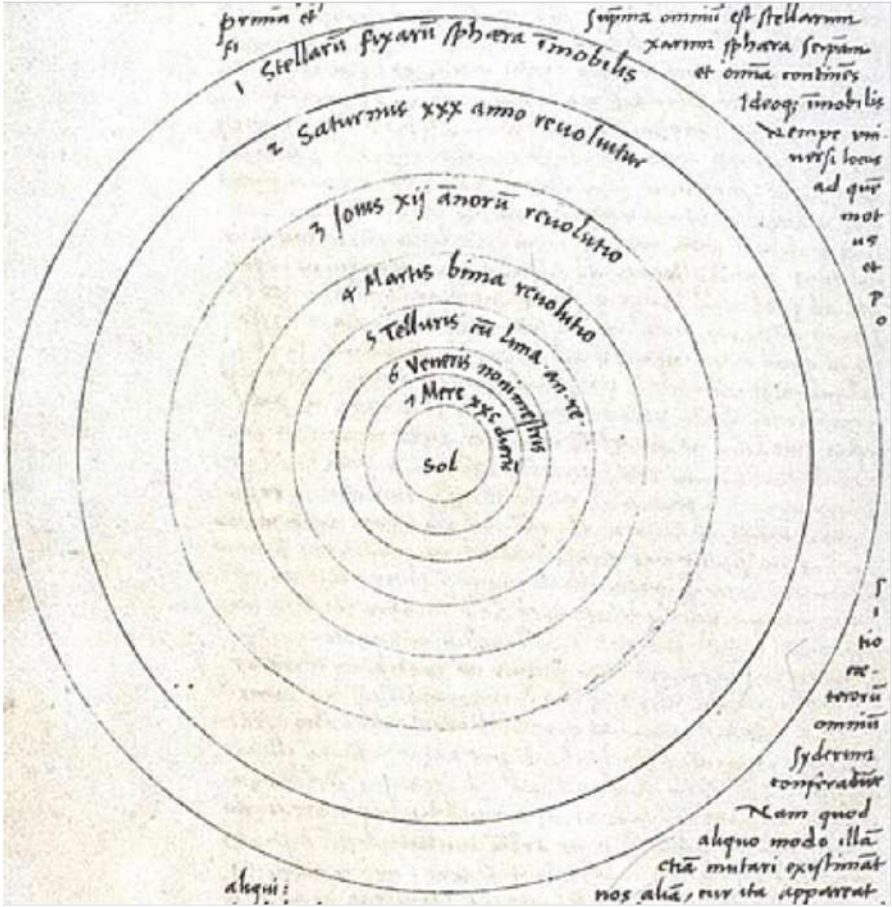
Heliocentric model of our "**Universe**"



Nicolaus Copernicus

(1473 - 1543)

Heliocentric model was a big step. It took more than a thousand years to get established.



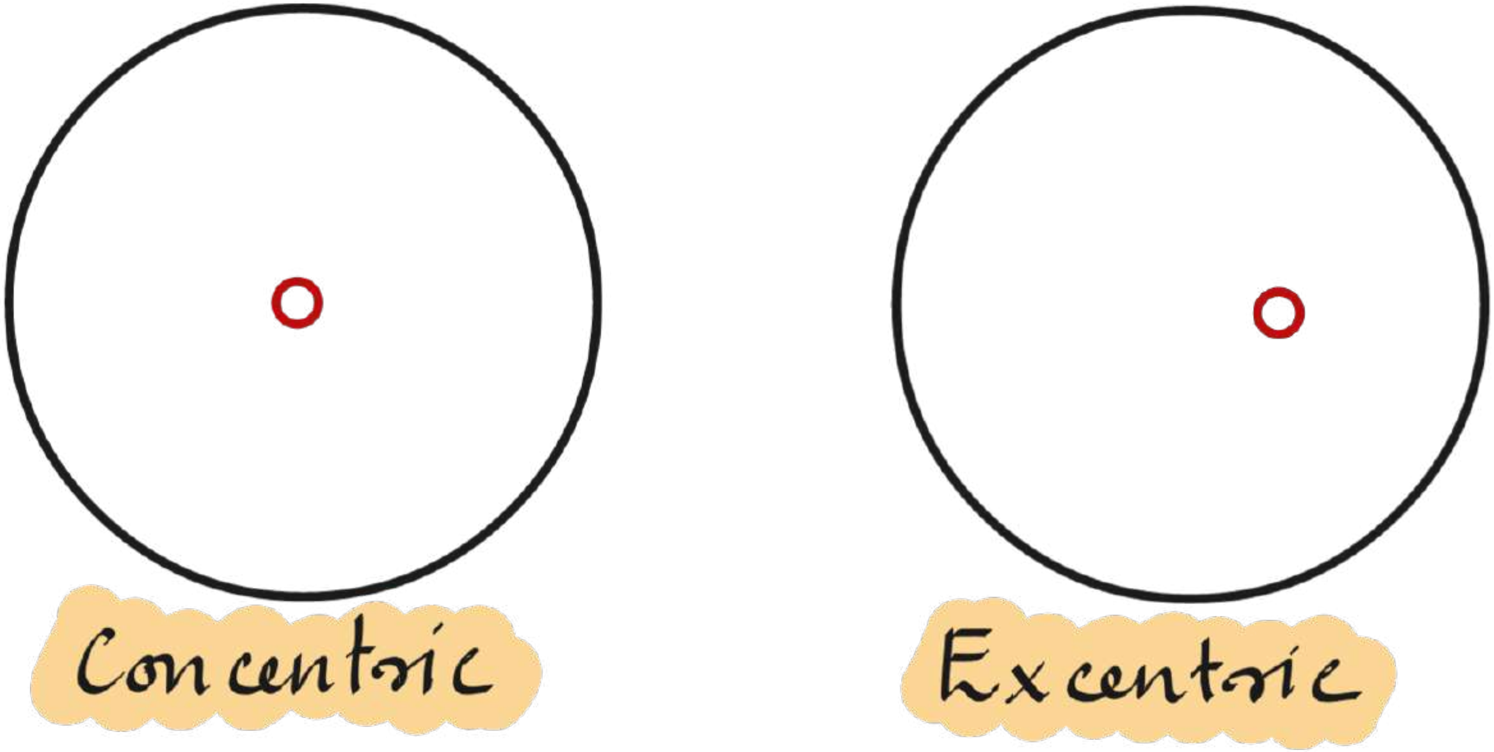
1. Sun at center (almost)
2. Planets in Circular orbits
3. Stars at edge

One simple "BIG" paradigm shift

"Good Science !!!"

No more complicated epicycles

More observations → More details



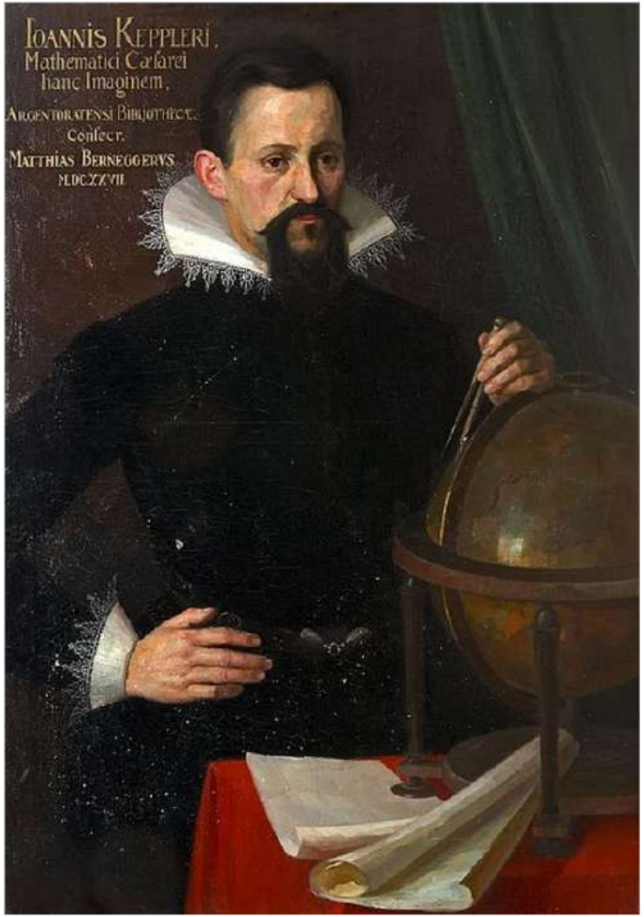
Even more details

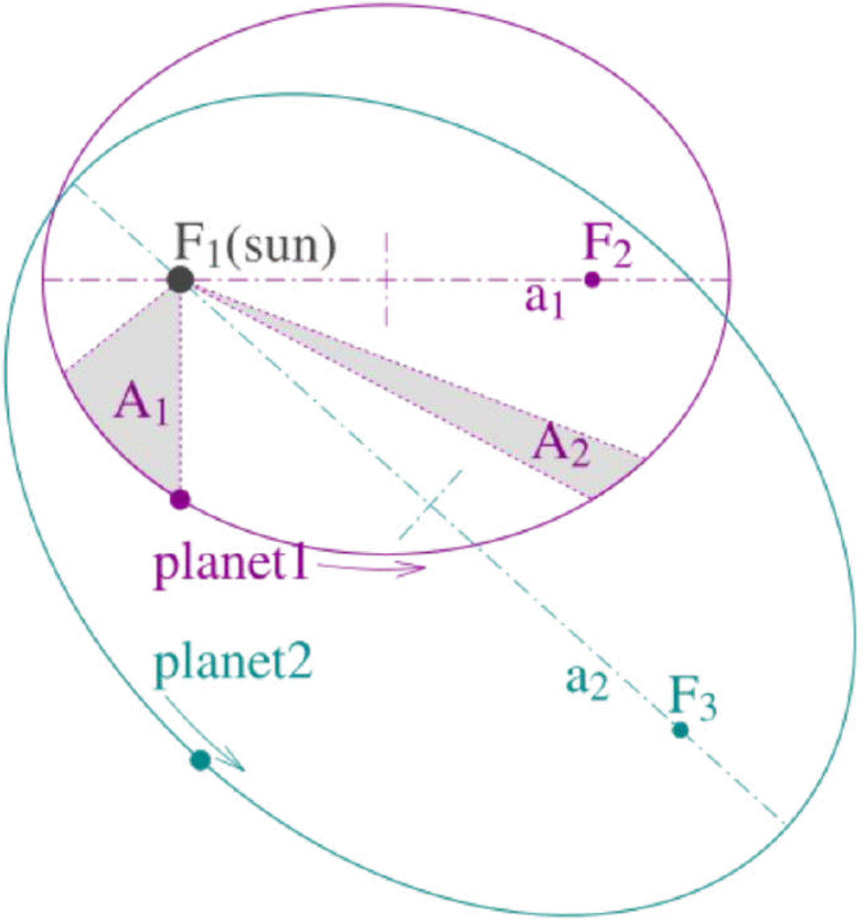
Tycho Brahe (1546 - 1601)

Johannes Kepler

(1571 - 1630)

Kepler's Law of Planetary Motion



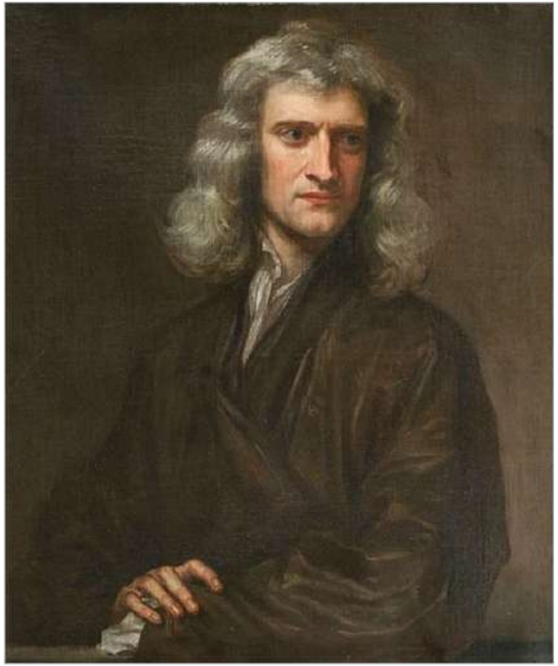


Ellipse

Equal area in equal time

$T^2 \propto a^3$

From observations to model to laws of Nature



Modern Physics!

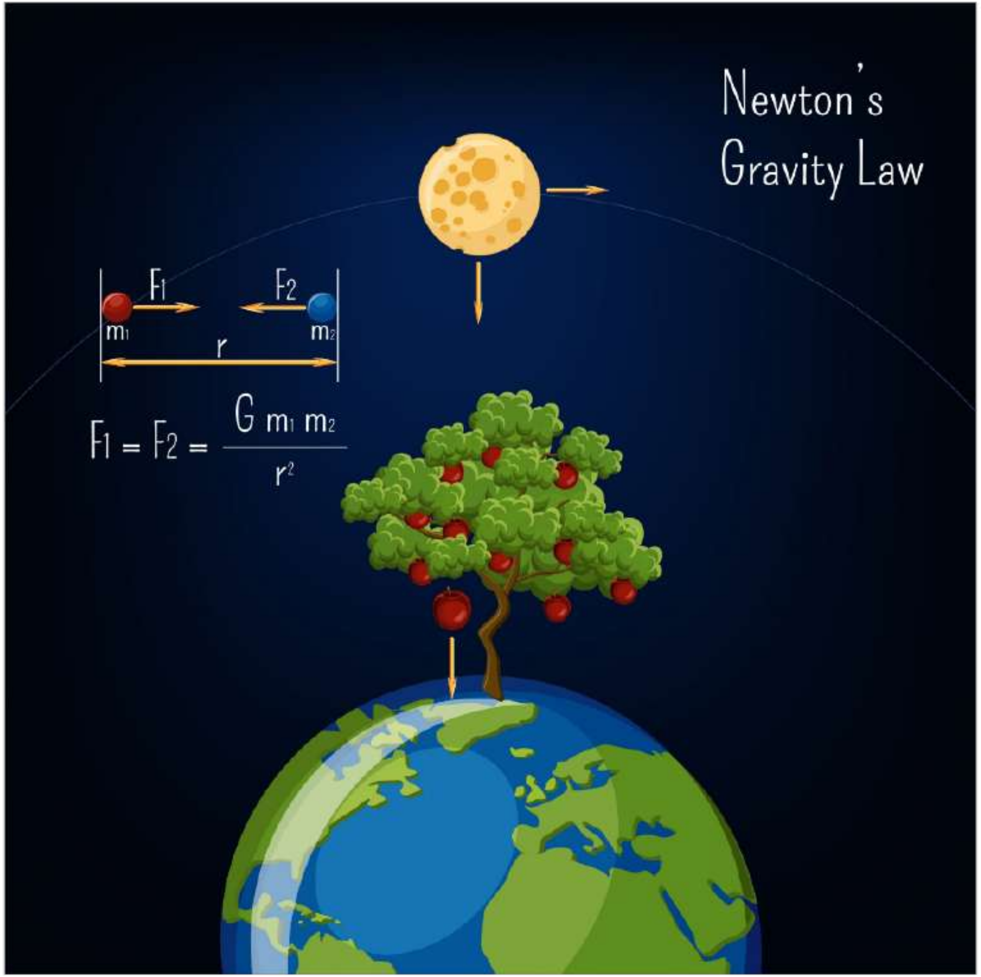
Laws of Motion &

Universal law of Gravity

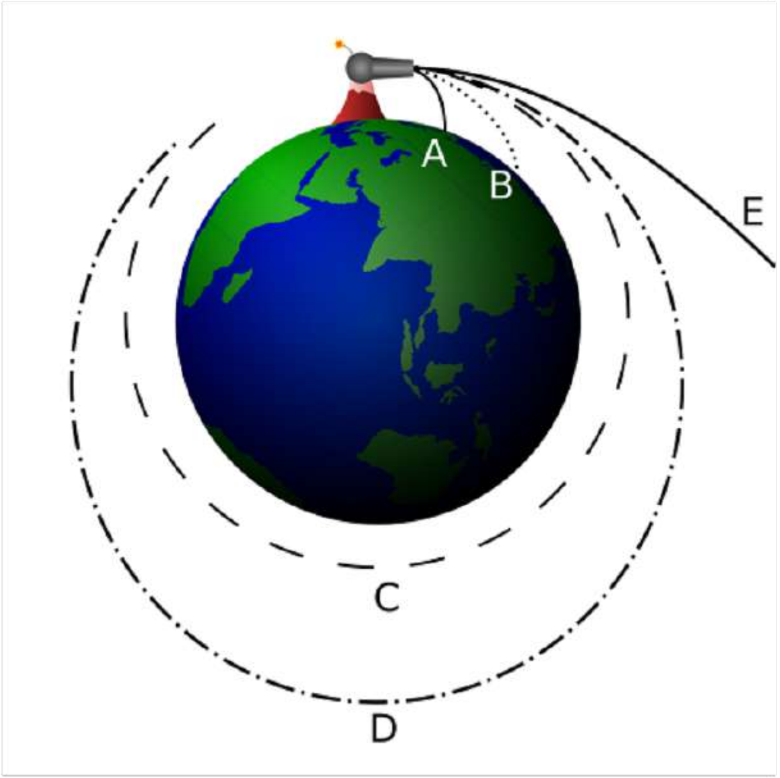
↓

Same law of things on Earth

and beyond

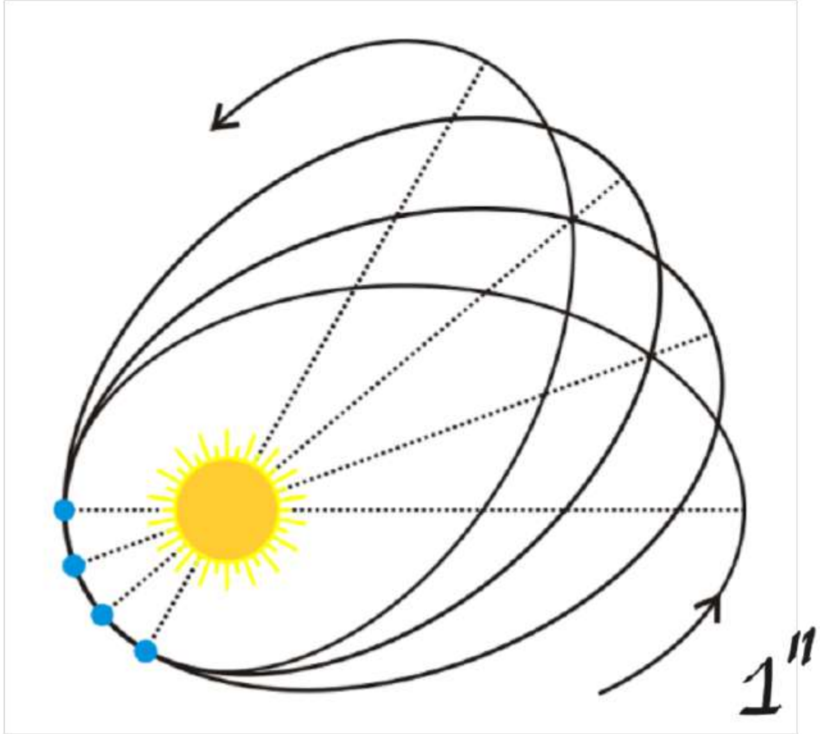


Newton's
Gravity Law
F1
F2
m1
m2
r
F1 = F2 = G m1 m2 / r²



A
B
C
D
E

More observations → More details



Precession of the perihelion of Mercury

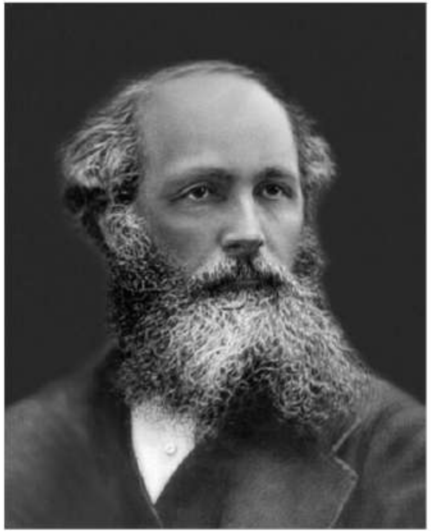
$\sim 43''$ of arc / 100 yr

$1''$ of arc $\simeq 0.00028^\circ$

More Physics

A Theory of light

"Maxwell's Classical Electrodynamics"



Classical theory of light

↝

Special Theory of Relativity.

Special Relativity

1. The laws of Physics are invariant in all inertial frames of reference
2. Speed of light in vacuum is same for all observers.

But Newton's Law are **not in agreement** with special Relativity.

Oops!!!

Newton → Gravity has infinite speed.

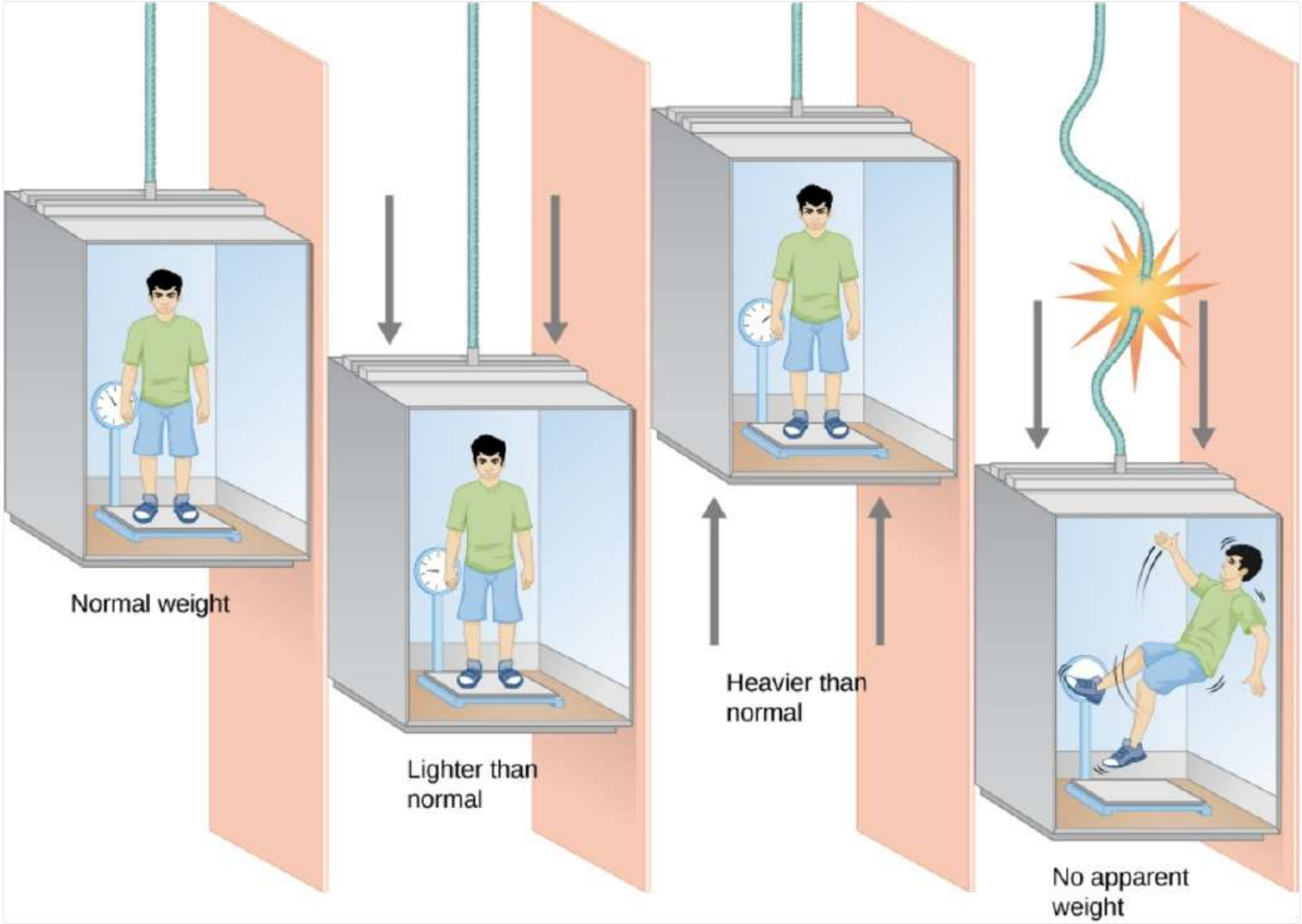
universal speed limit

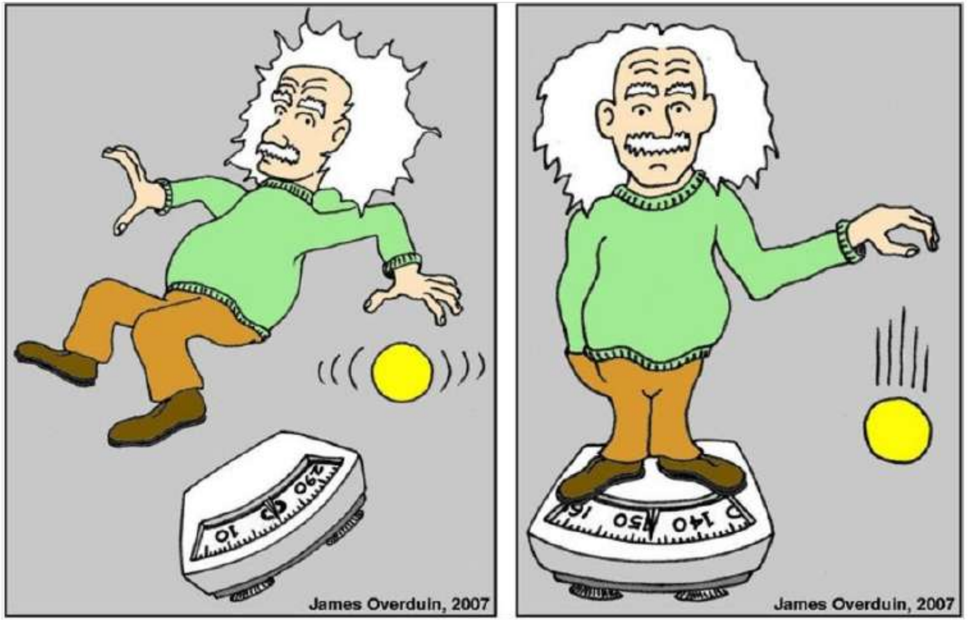
Einstein ⇝ Gravity has finite speed

Build a theory of gravity that agrees with special theory of gravity.

"Happiest thought of my life"

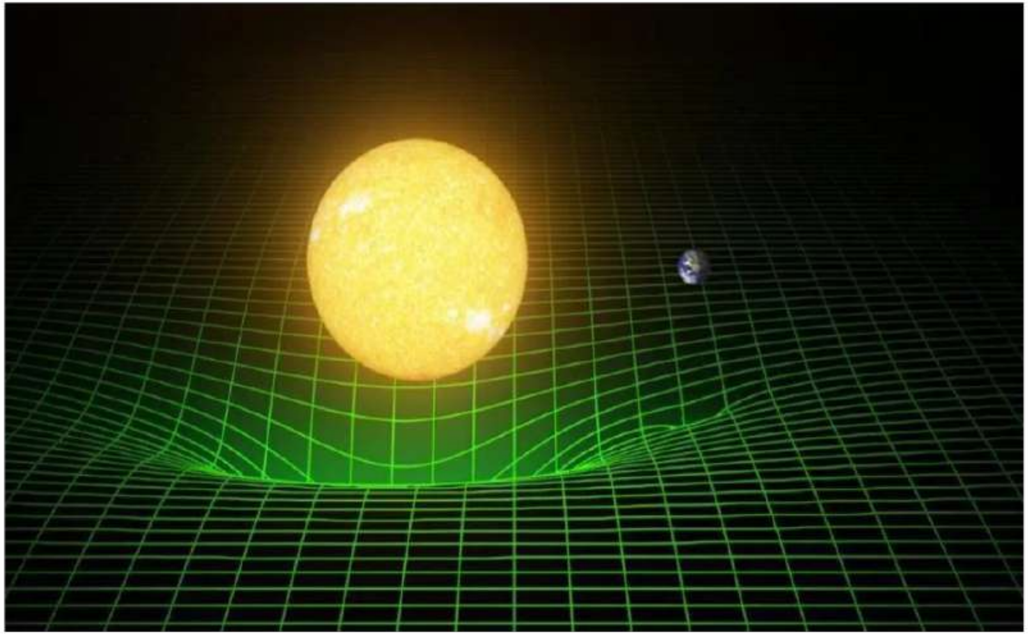
Albert Einstein


Normal weight
Lighter than normal
Heavier than normal
No apparent weight



Gravity = Acceleration

Strong Equivalence Principle



Gravity is not a force, but curvature of Space time

Special Relativity

+

Strong equivalence principle

⇝

General Theory of Relativity

Einstein Field Equations

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

G → Newton's constant

c → speed limit

R = Ricci Scalar

$R_{\mu\nu}$ = Ricci Tensor

$g_{\mu\nu}$ = Metric Tensor

Geometry

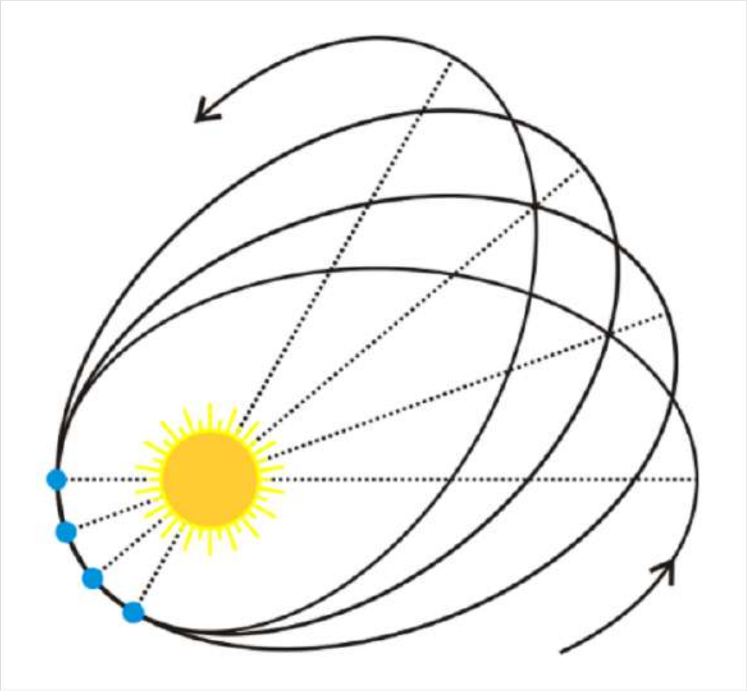
$T_{\mu\nu}$ = Energy Momentum Tensor

Matter

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

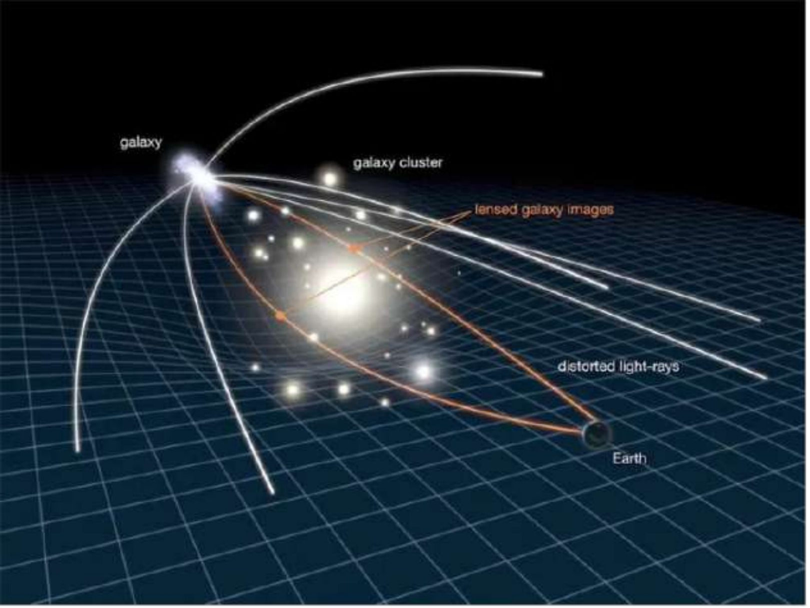
Geometry   Matter

Geometry tells matter (energy) how to move, matter tells spacetime how to curve



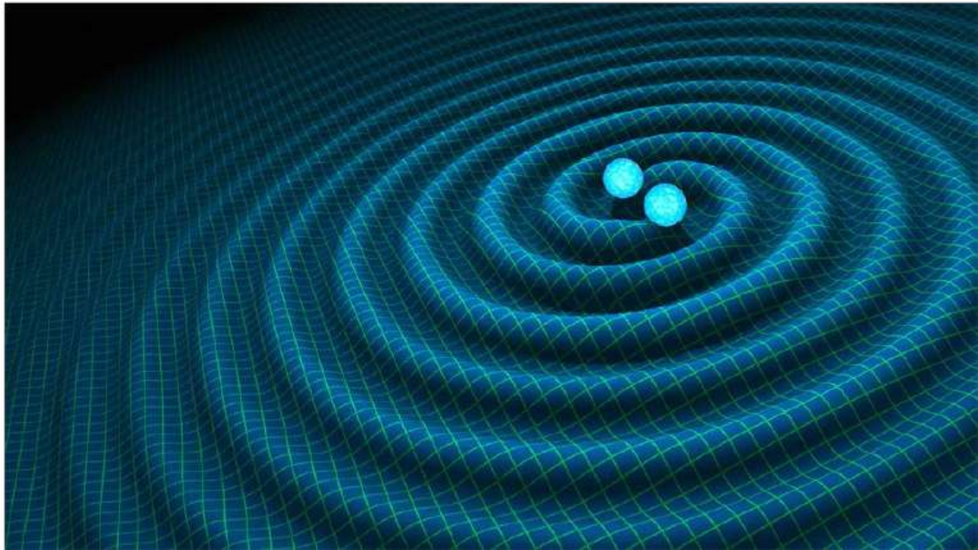
General Relativity can explain the orbit of Mercury !!!

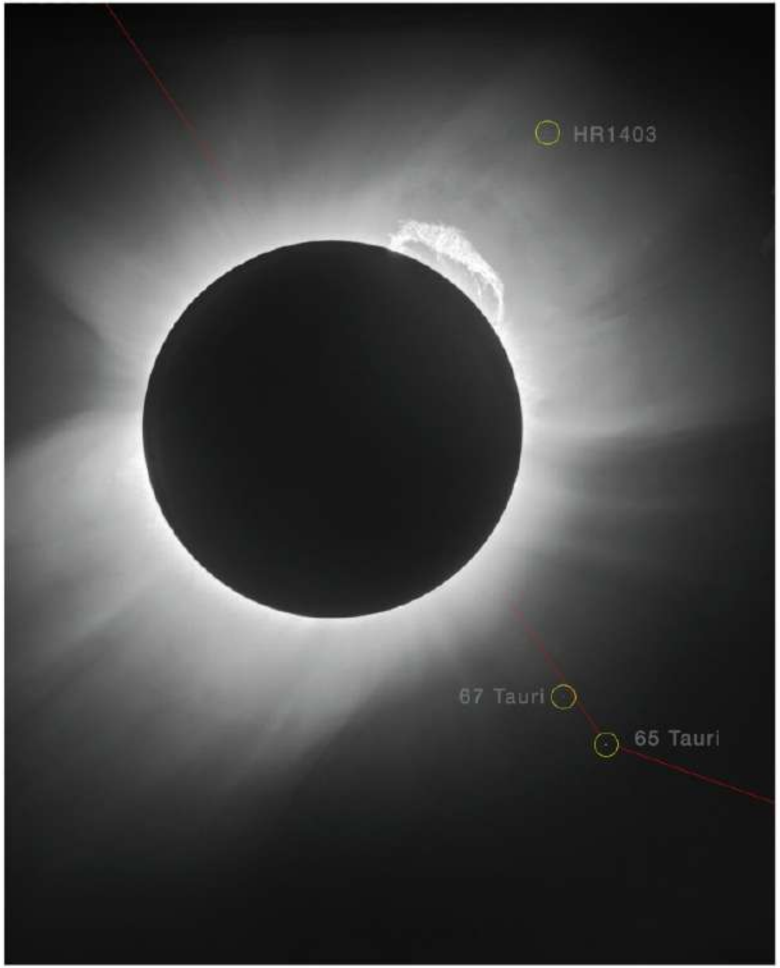
"Good Science"

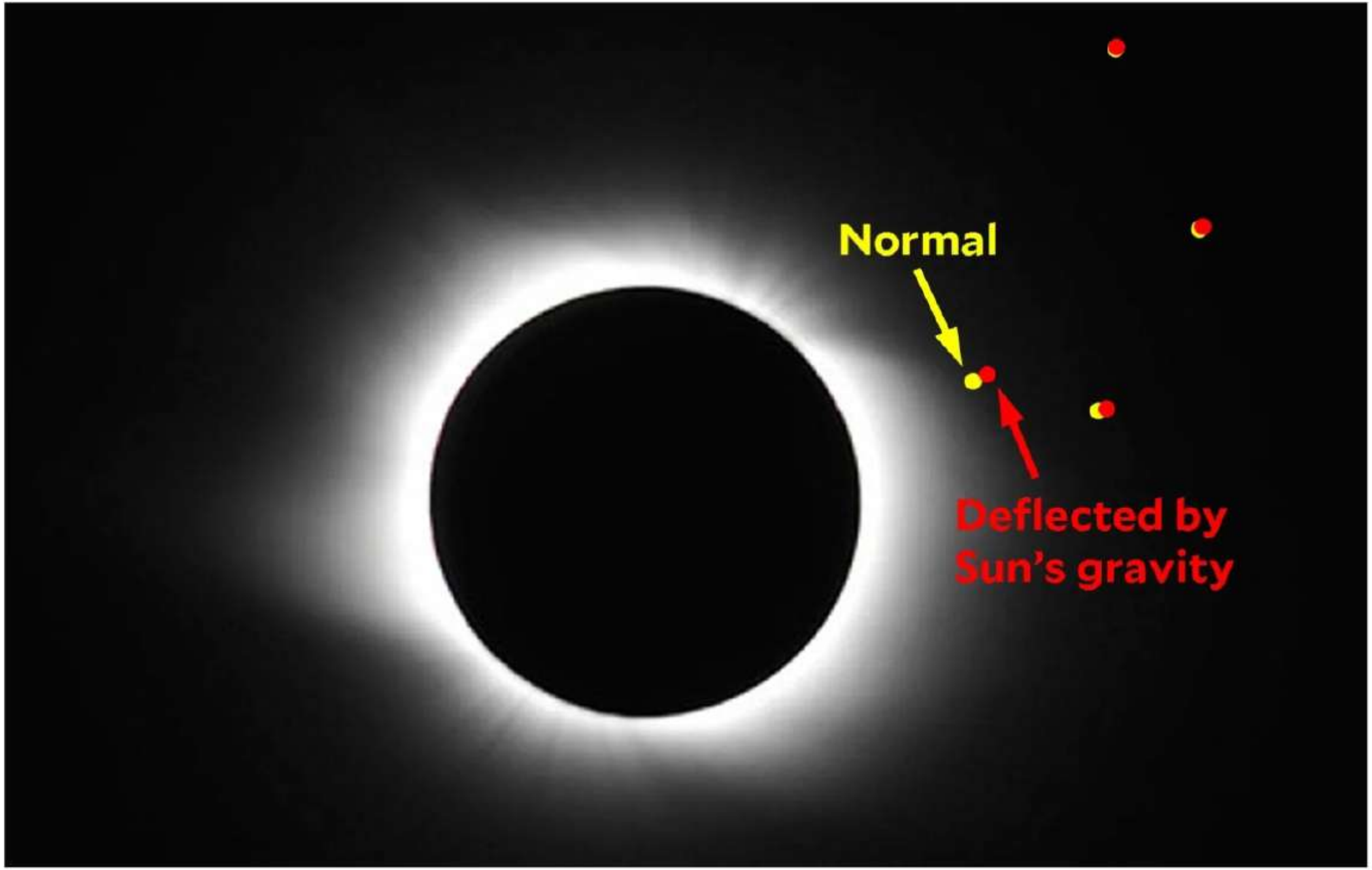


Bending of light

Gravitational waves





HR1403
67 Tauri
65 Tauri


Normal
Deflected by
Sun's gravity

The solutions to Einstein's Equation

$g_{\mu\nu}$

Find the metric tensor

Friedmann
Lemaitre
Robertson
Walker

FLRW
metric

FLRW metric

1. Homogeneity
2. Isotropy

$$-c^2 d\tau^2 = \underbrace{-c^2 dt^2}_{\text{time}} + \underbrace{a(t) d\Sigma^2}_{\text{space}}$$

$a(t)$ = scale factor

→ can depend on time

$$d\Sigma^2 = \frac{dr^2}{1 - kr^2} + r^2 d\Omega^2$$

k → curvature of space

$$k = \begin{cases} -1 \\ 0 \\ +1 \end{cases}$$

$k = 0$ Flat Universe

$$R = \frac{6}{c^2}\left(\frac{\ddot{a}}{a} + \frac{\dot{a}^2}{a^2} + \frac{k}{a^2}\right)$$

On the Curvature of Space†

By A. Friedman in Petersburg *

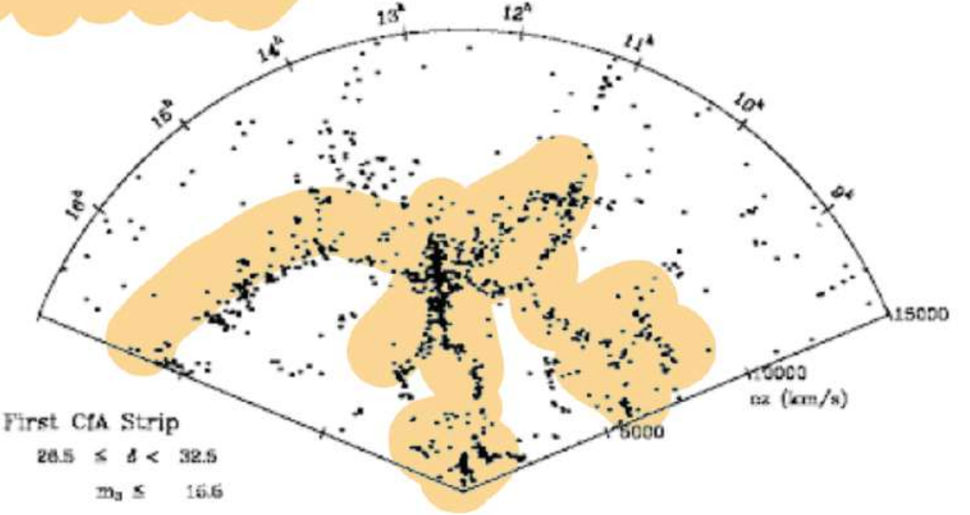
With one figure. Received on 29. June 1922

§1. 1. In their well-known works on general cosmological questions, Einstein[1] and de Sitter[2] arrive at two possible types of the universe; Einstein obtains the so-called cylindrical world, in which space[3] has constant, time-independent curvature, where the curvature radius is connected to the total mass of matter present in space; de Sitter obtains a spherical world in which not only space, but in a certain sense also the world can be addressed as a world of constant curvature.[4] In doing so both Einstein and de Sitter make certain presuppositions about the matter tensor, which correspond to the incoherence of matter and its relative rest, i.e. the velocity of matter will be supposed to be sufficiently small in comparison to the fundamental velocity[5] — the velocity of light.

Origin of Modern Cosmology

"LESS NOTICED"

The large scale structure of our Universe



A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE

BY EDWIN HUBBLE

MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON

Communicated January 17, 1929

Determinations of the motion of the sun with respect to the extra-galactic nebulae have involved a K term of several hundred kilometers which appears to be variable. Explanations of this paradox have been sought in a correlation between apparent radial velocities and distances, but so far the results have not been convincing. The present paper is a re-examination of the question, based on only those nebular distances which are believed to be fairly reliable.

Distances of extra-galactic nebulae depend ultimately upon the application of absolute-luminosity criteria to involved stars whose types can be recognized. These include, among others, Cepheid variables, novae, and blue stars involved in emission nebulosity. Numerical values depend upon the zero point of the period-luminosity relation among Cepheids,

Velocity-Distance Relation among Extra-Galactic Nebulae.

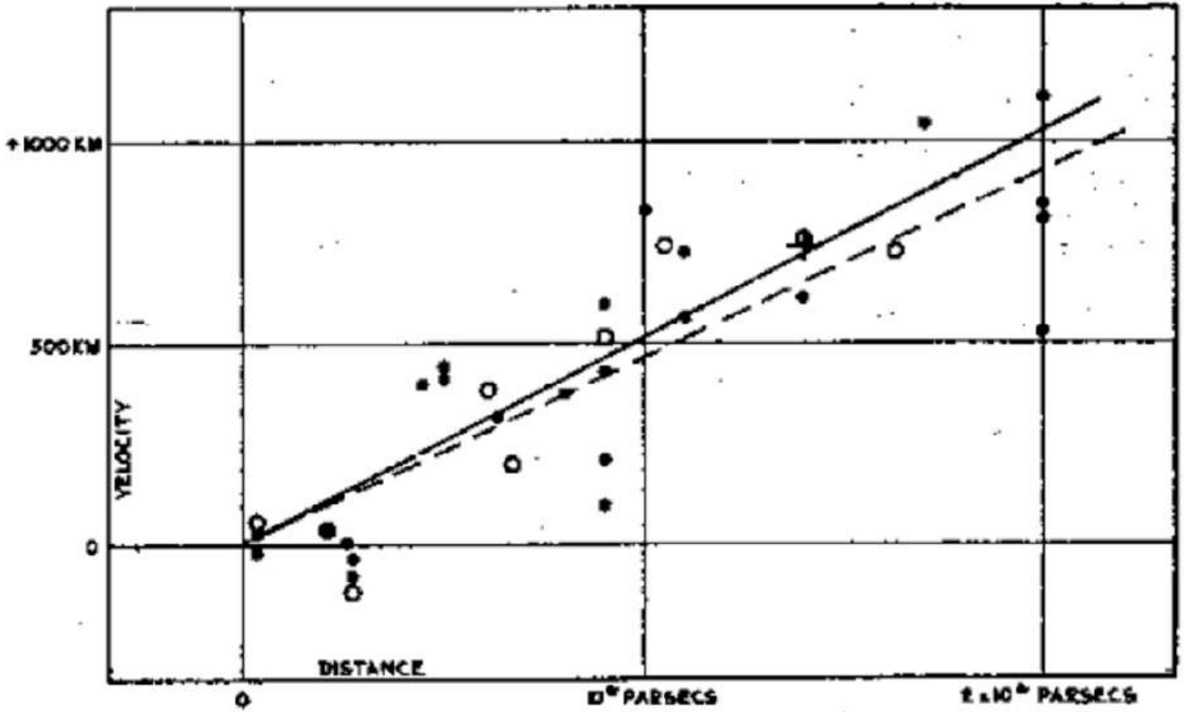


FIGURE 1

Velocity

$\propto$

Distance

Vesto Melvin Slipher

First to show that distant galaxies are **Red shifted**.

Connected redshift to velocity.

Carl Wilhelm Wirtz

Showing the existence of redshift - distance correlation for spiral galaxies.

The Hubble's Law

$$v = H_0 D$$

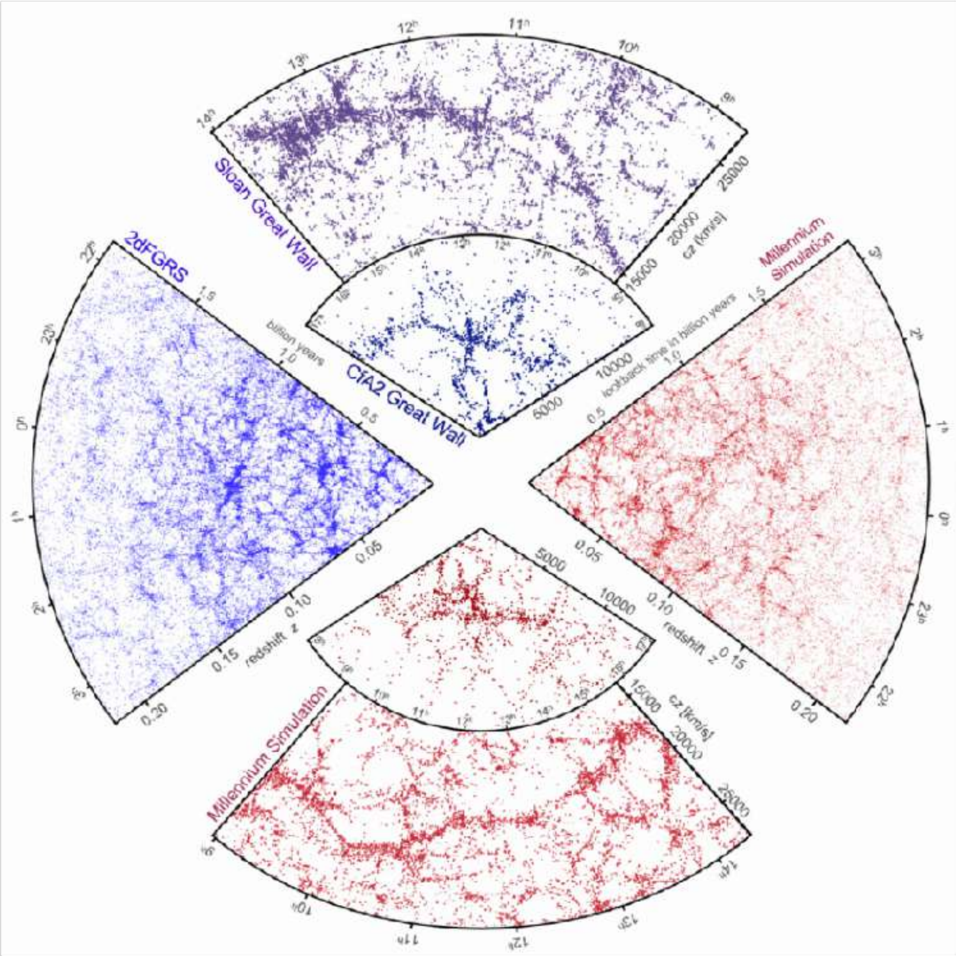
- v → velocity
- H_0 → Hubble's Constant
- D → Distance (Proper distance)

observed velocity will have "peculiar velocity"

$$v_r = H_0 D + v_{pec}$$

$$H_0 = 70 \text{ km/s/Mpc}$$

$$1 \text{ Mpc} = 3.09 \times 10^{19} \text{ km}$$

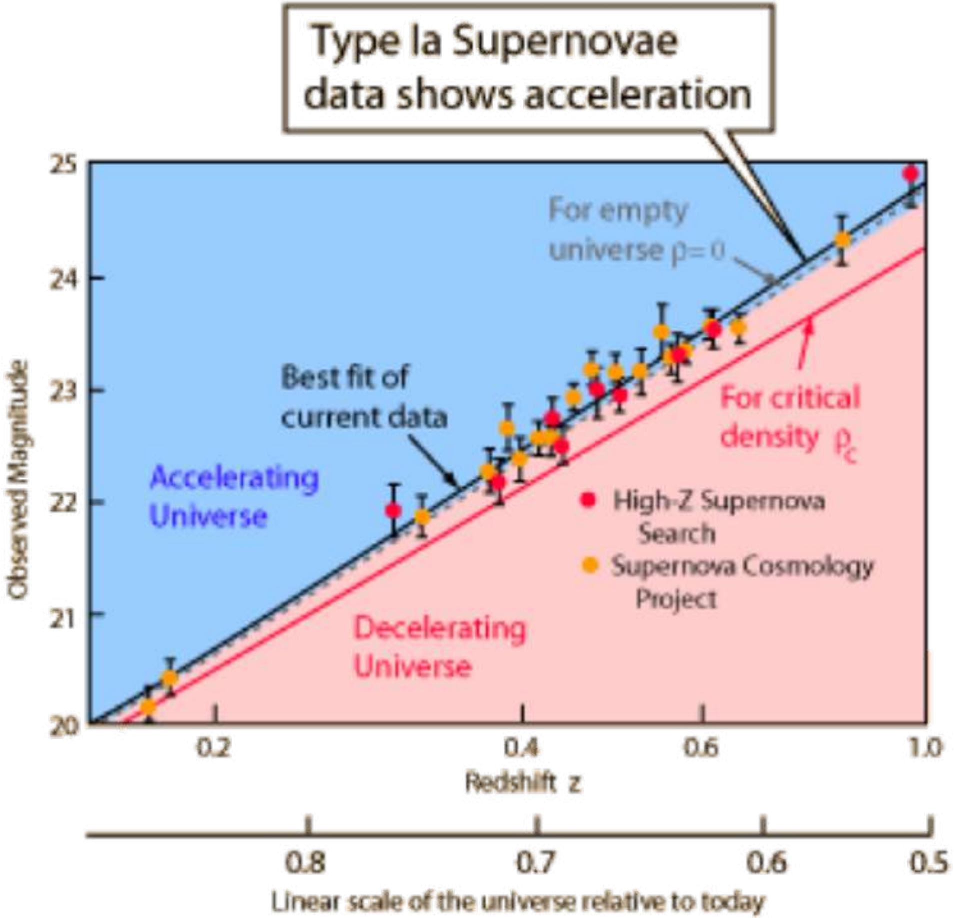


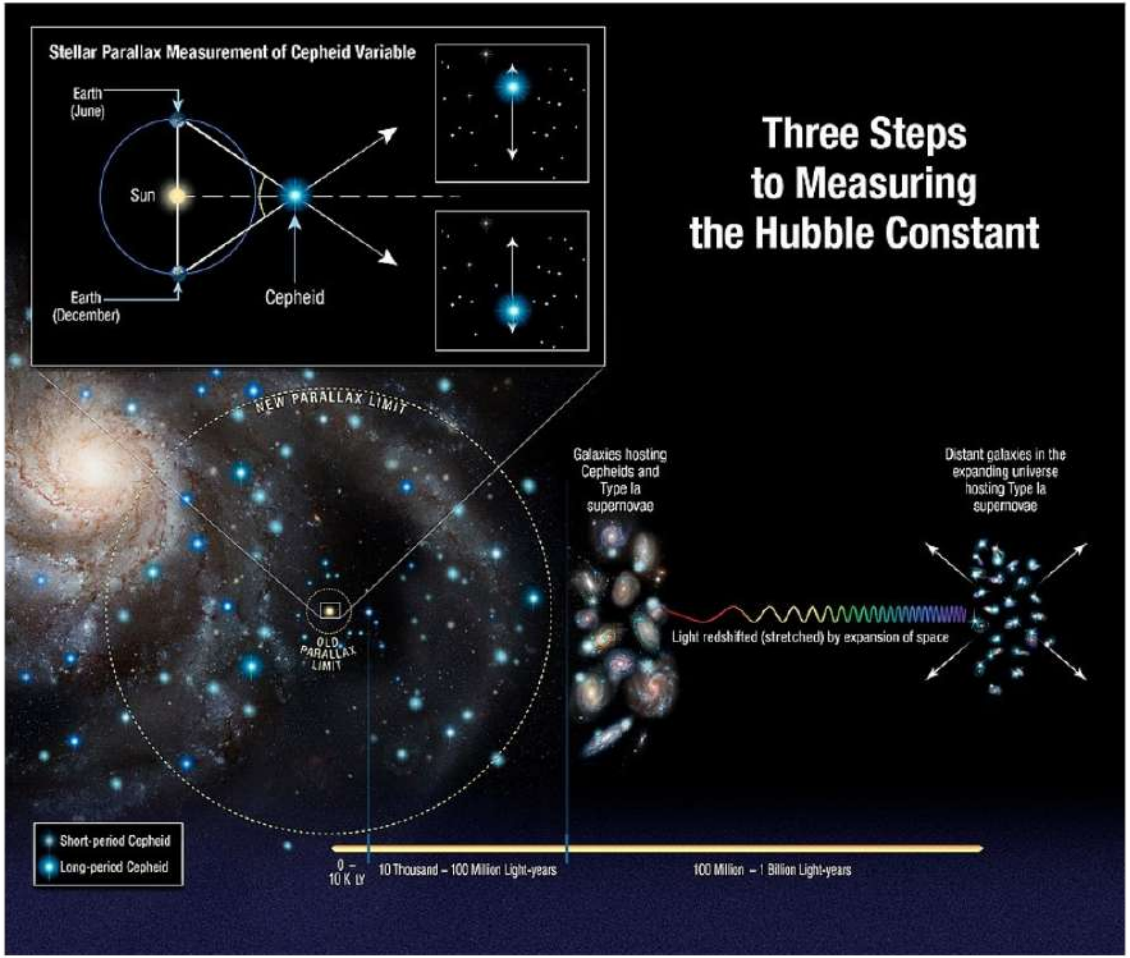
Observations

vs

Simulation

Discovery of Cosmic Acceleration





Parallax

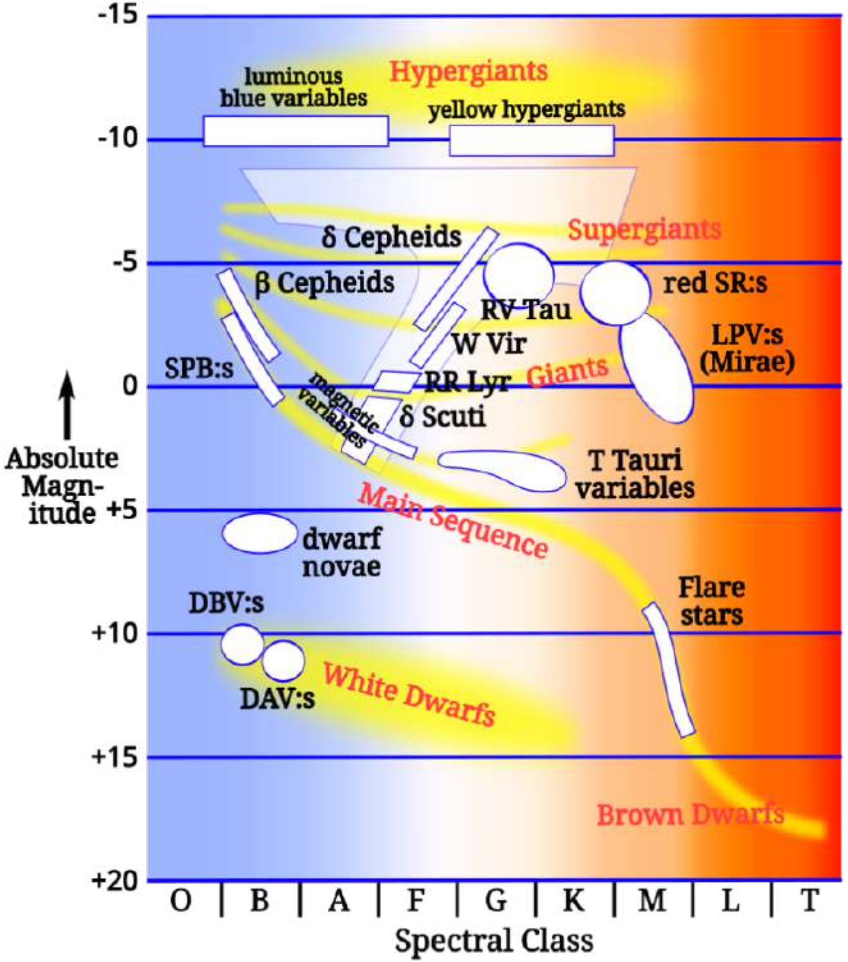
→

Cepheid period - luminosity

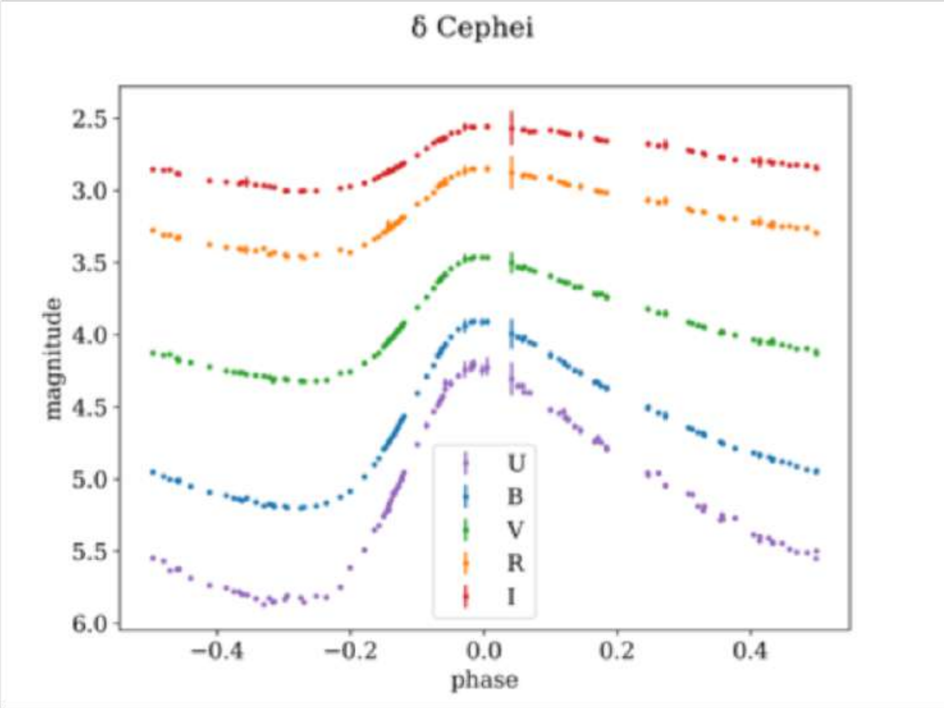
→

Type Ia Supernova

Distance Ladder



-15
-10
-5
0
+5
+10
+15
+20
Absolute Magn- itude
luminous blue variables
Hypergiants
yellow hypergiants
δ Cepheids
Supergiants
β Cepheids
red SR:s
RV Tau
W Vir
LPV:s (Mirae)
SPB:s
RR Lyr
Giants
magnetic variables
δ Scuti
T Tauri variables
Main Sequence
dwarf novae
DBV:s
Flare stars
DAV:s
White Dwarfs
Brown Dwarfs
O
B
A
F
G
K
M
L
T
Spectral Class



δ Cephei
magnitude
phase
U
B
V
R
I

Period - Luminosity Relation

Henrietta Swan Leavitt

The key to local observational cosmology

From the Friedmann Equation

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

CC ($\Lambda c^2/3$)

cosmic fluids (ρ)

The standard Cosmological Model.

Lambda

ΛCDM

Cold dark matter

In the ΛCDM model

$$H^2 = H_0^2 \left[\Omega_m (1+z)^3 + \Omega_{de} (1+z)^{3(1+w)} \right]$$

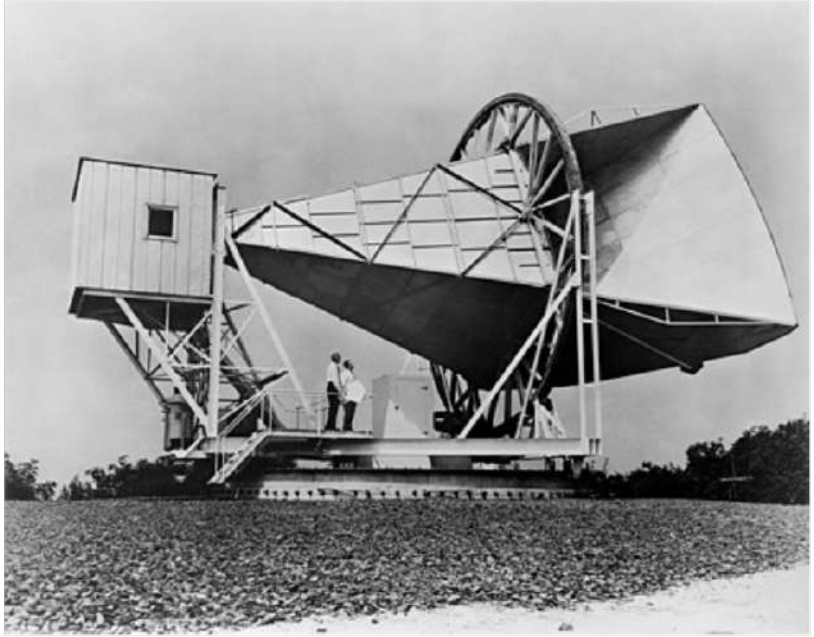
H_0 → Present value of Hubble Parameter

Ω_m → matter density

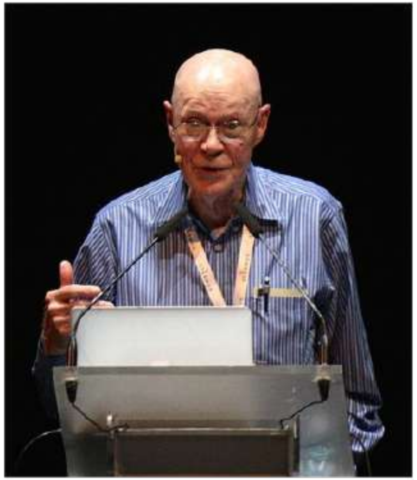
Ω_{de} → Dark energy density

w → Dark energy equation of state

The first light

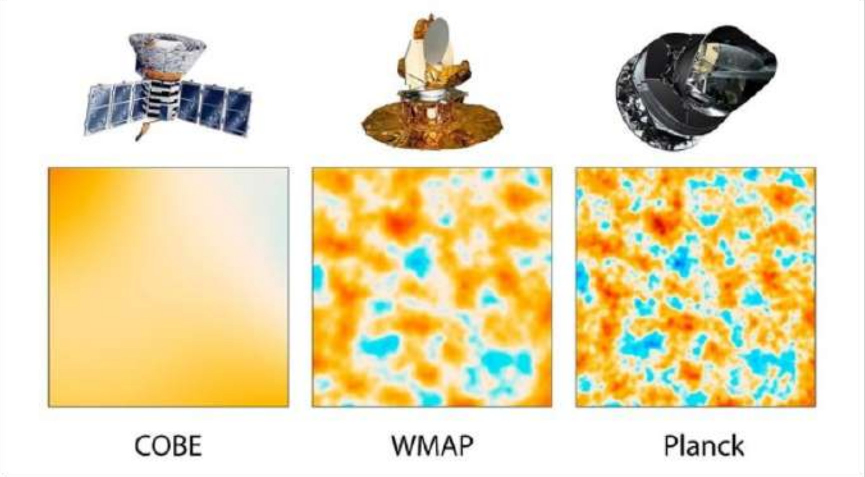


Penzias



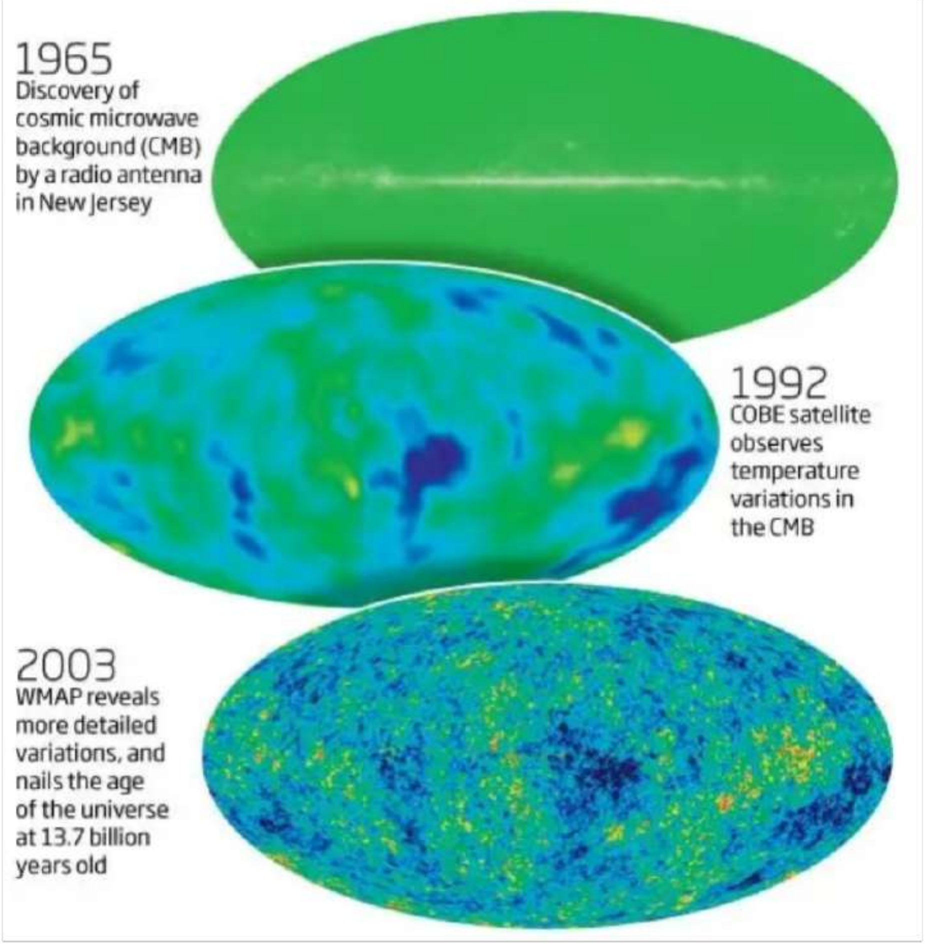
Wilson

The Cosmic Microwave Background Radiation

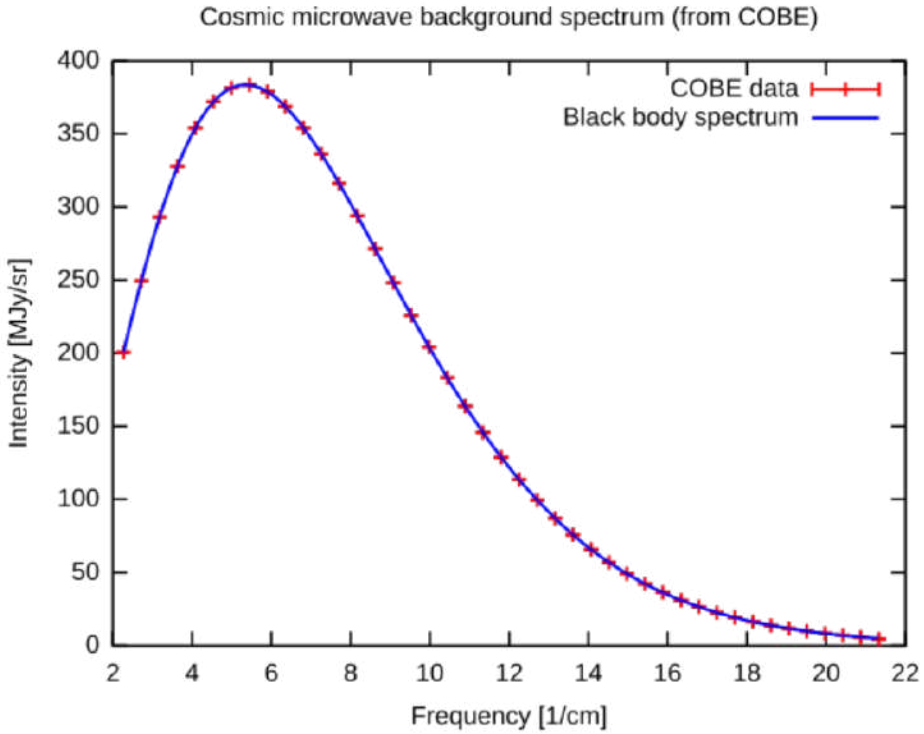


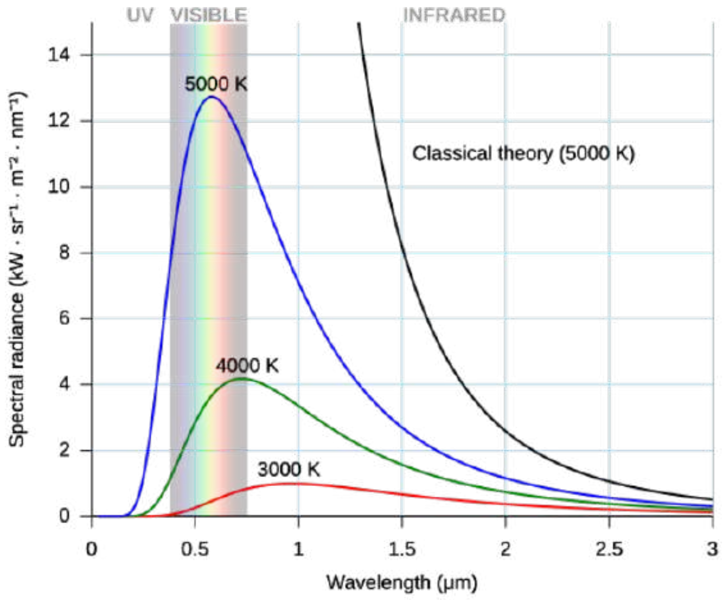
Redshift ~ 1100

$T \sim 2.725\,K$



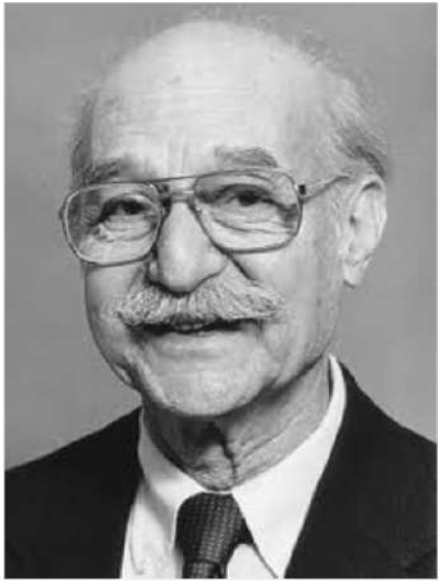
The Cosmic Black body





The CMB was first predicted by

Ralph Alpher & Robert Herman



Letters to the Editor

PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

The Origin of Chemical Elements

R. A. ALPHER*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland
AND
H. BETHE
Cornell University, Ithaca, New York
AND
G. GAMOW
The George Washington University, Washington, D. C.
February 18, 1948

AS pointed out by one of us,[1] various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must imagine the early stage of matter as a highly compressed neutron gas (overheated neutral nuclear fluid) which started decaying into protons and electrons when the gas pressure fell down as the result of universal expansion. The radiative capture of the still remaining neutrons by the newly formed protons must have led first to the formation of deuterium nuclei, and the subsequent neutron captures resulted in the building up of heavier and heavier nuclei. It must be remembered that, due to the comparatively short time allowed for this process,[1] the building up of heavier nuclei must have proceeded just above the upper fringe of the stable elements (short-lived Fermi elements), and the present frequency distribution of various atomic species was attained only somewhat later as the result of adjustment of their electric charges by β-decay.

Thus the observed slope of the abundance curve must not be related to the temperature of the original neutron gas, but rather to the time period permitted by the expansion process. Also, the individual abundances of various nuclear species must depend not so much on their intrinsic stabilities (mass defects) as on the values of their neutron capture cross sections. The equations governing such a building-up process apparently can be written in the form:

$$\frac{dn_i}{dt} = f(t)(\sigma_{i-1}n_{i-1} - \sigma_i n_i) \quad i = 1, 2, \cdots 238, \qquad (1)$$

where n_i and σ_i are the relative numbers and capture cross sections for the nuclei of atomic weight i, and where $f(t)$ is a factor characterizing the decrease of the density with time.

We may remark at first that the building-up process was apparently completed when the temperature of the neutron gas was still rather high, since otherwise the observed abundances would have been strongly affected by the resonances in the region of the slow neutrons. According to Hughes,[2] the neutron capture cross sections of various elements (for neutron energies of about 1 Mev) increase exponentially with atomic number halfway up the periodic system, remaining approximately constant for heavier elements.

Using these cross sections, one finds by integrating Eqs. (1) as shown in Fig. 1 that the relative abundances of various nuclear species decrease rapidly for the lighter elements and remain approximately constant for the elements heavier than silver. In order to fit the calculated curve with the observed abundances[3] it is necessary to assume the integral of $\rho_n dt$ during the building-up period is equal to 5×10^4 g sec./cm^3.

On the other hand, according to the relativistic theory of the expanding universe[4] the density dependence on time is given by $\rho \cong 10^6/t^2$. Since the integral of this expression diverges at $t = 0$, it is necessary to assume that the building-up process began at a certain time t_0, satisfying the relation:

$$\int_{t_0}^{\infty} (10^6/t^2)dt \cong 5 \times 10^4, \qquad (2)$$

which gives us $t_0 \cong 20$ sec. and $\rho_0 \cong 2.5 \times 10^3$ g sec./cm^3. This result may have two meanings: (a) for the higher densities existing prior to that time the temperature of the neutron gas was so high that no aggregation was taking place, (b) the density of the universe never exceeded the value 2.5×10^3 g sec./cm^3 which can possibly be understood if we

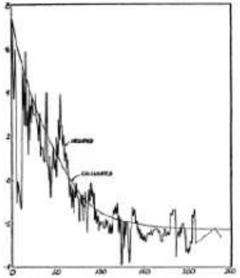
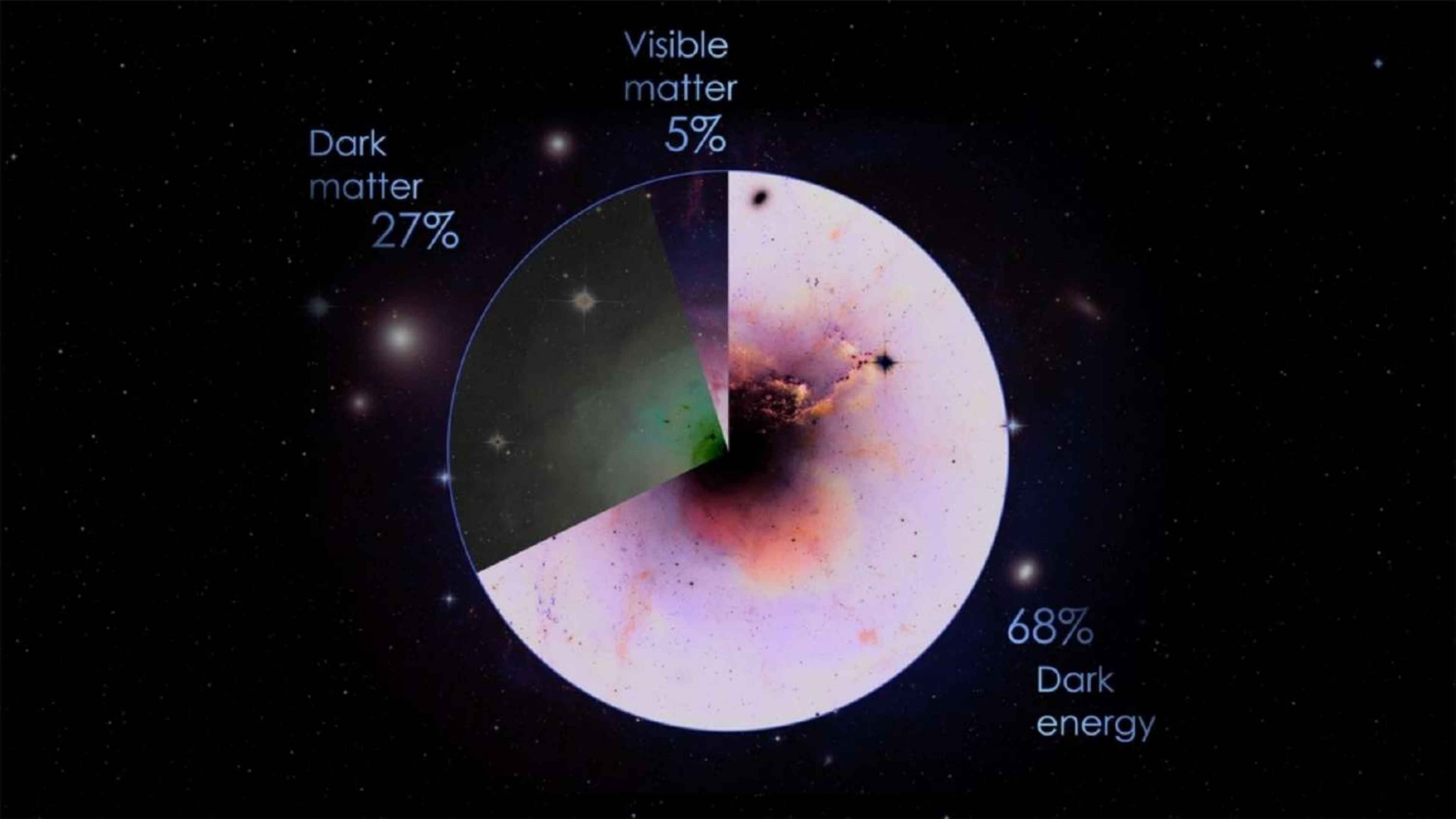


FIG. 1.
Log of relative abundance
Atomic weight

The α-β-γ

The Origin of Chemical Elements

Big Bang Nucleosynthesis


Visible matter
5%
Dark matter
27%
68%
Dark energy

The cosmic fluid

Matter = Baryonic matter + Dark matter

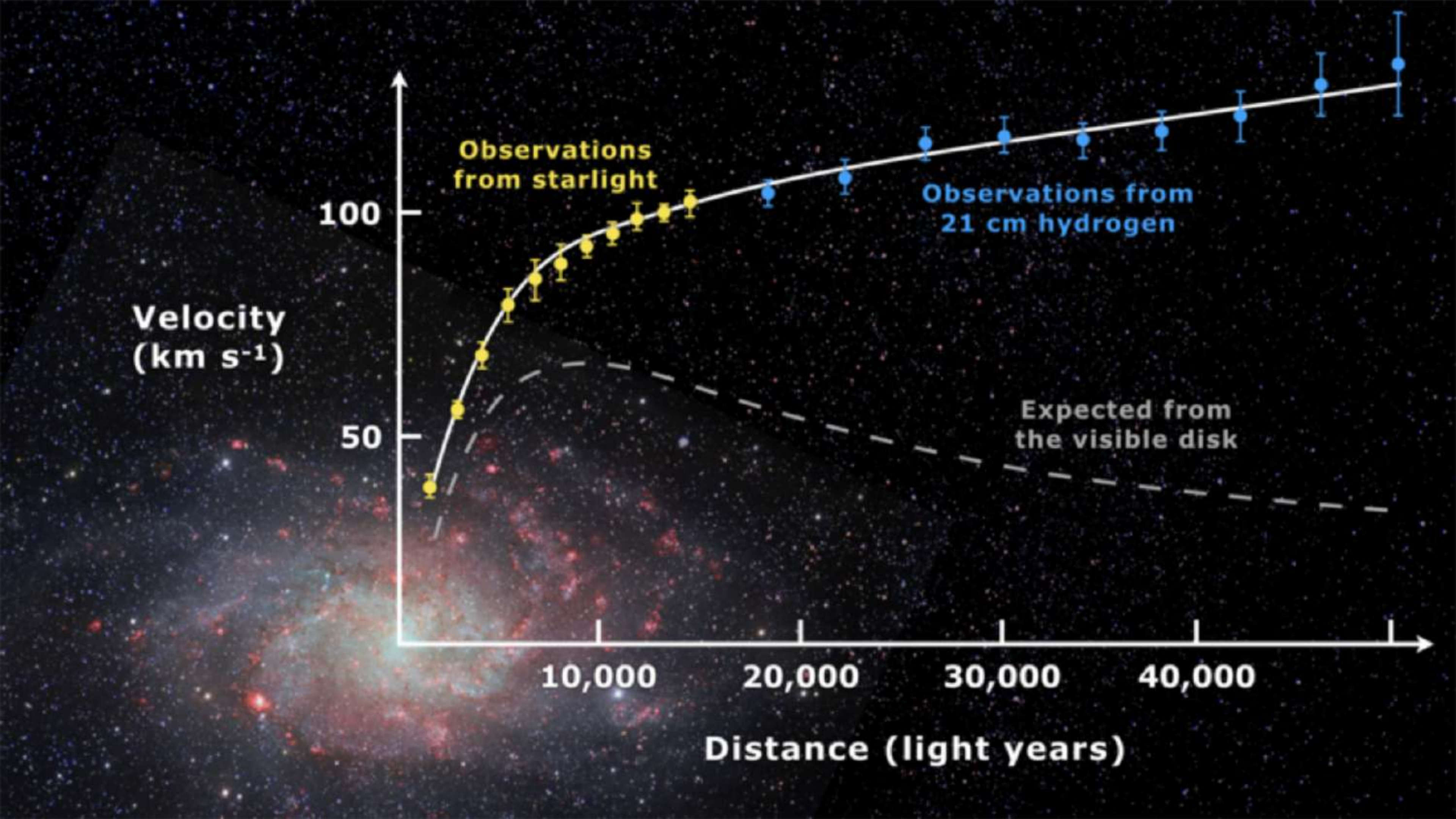
\+ **Radiation** + **Dark energy**

Equation of state

$$P = w \rho$$

↳ Equation of state

$$w = \begin{cases} 0 \rightarrow \text{matter} \\ 1/3 \rightarrow \text{radiation} \\ -1 \rightarrow \text{cosmological constant} \end{cases}$$


Observations from starlight
Observations from 21 cm hydrogen
Expected from the visible disk
Velocity (km s-1)
100
50
10,000
20,000
30,000
40,000
Distance (light years)

More Observations → More details

Several tensions are there in modern cosmology.

1. The Hubble tension
   - CMB ~ 67 km/s/Mpc
   - local ~ 73 km/s/Mpc
2. Very early galaxies
3. What is dark energy & dark matter?

The quest continues


DARK
ENERGY
SPECTROSCOPIC
INSTRUMENT