Weighing the Universe

Prof Roberto Trotta

Visiting Professor of Cosmology

@R_Trotta

www.robertotrotta.com

Imperial College London

GRESHAM COLLEGE
Founded 1597

Weight ≠ Mass

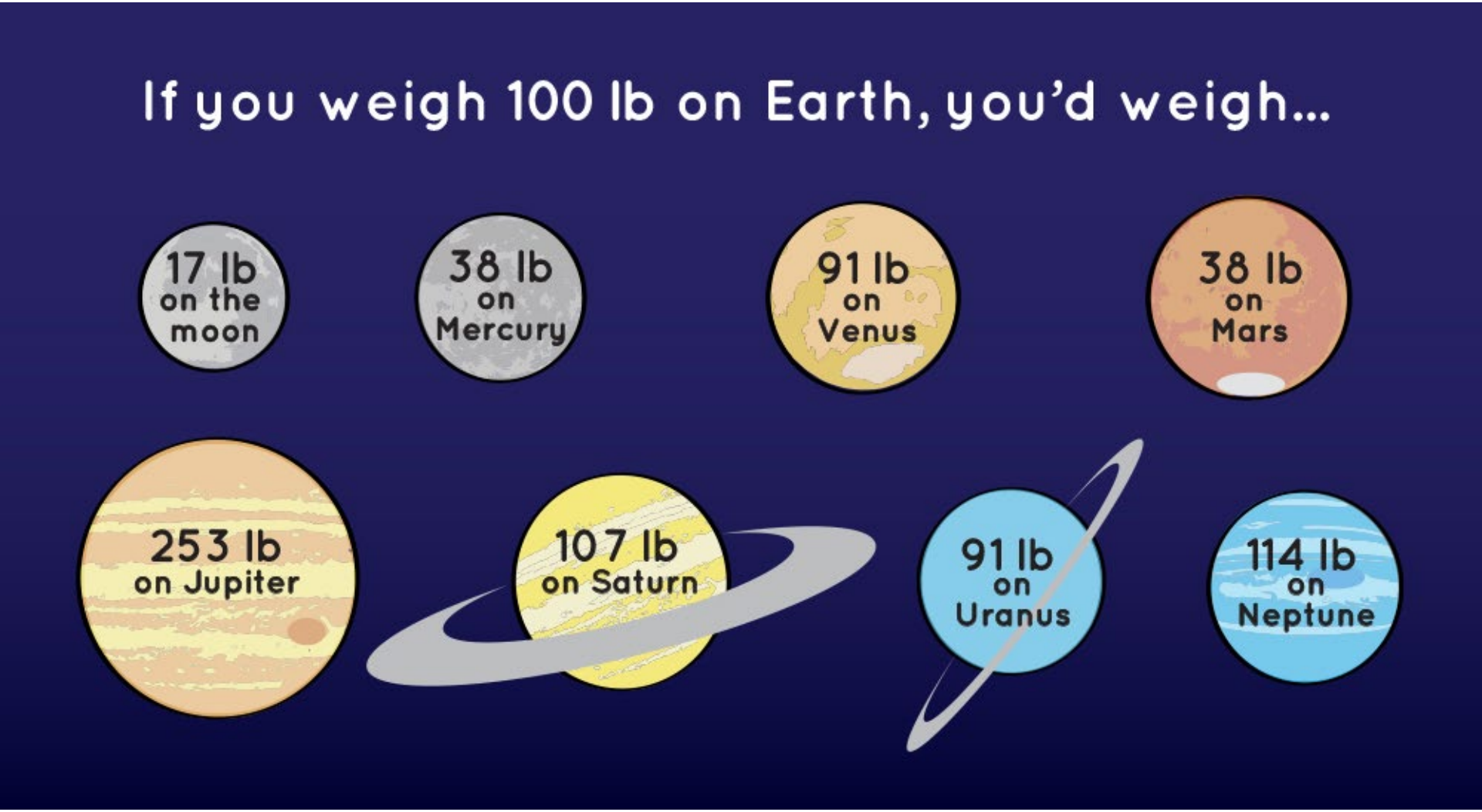


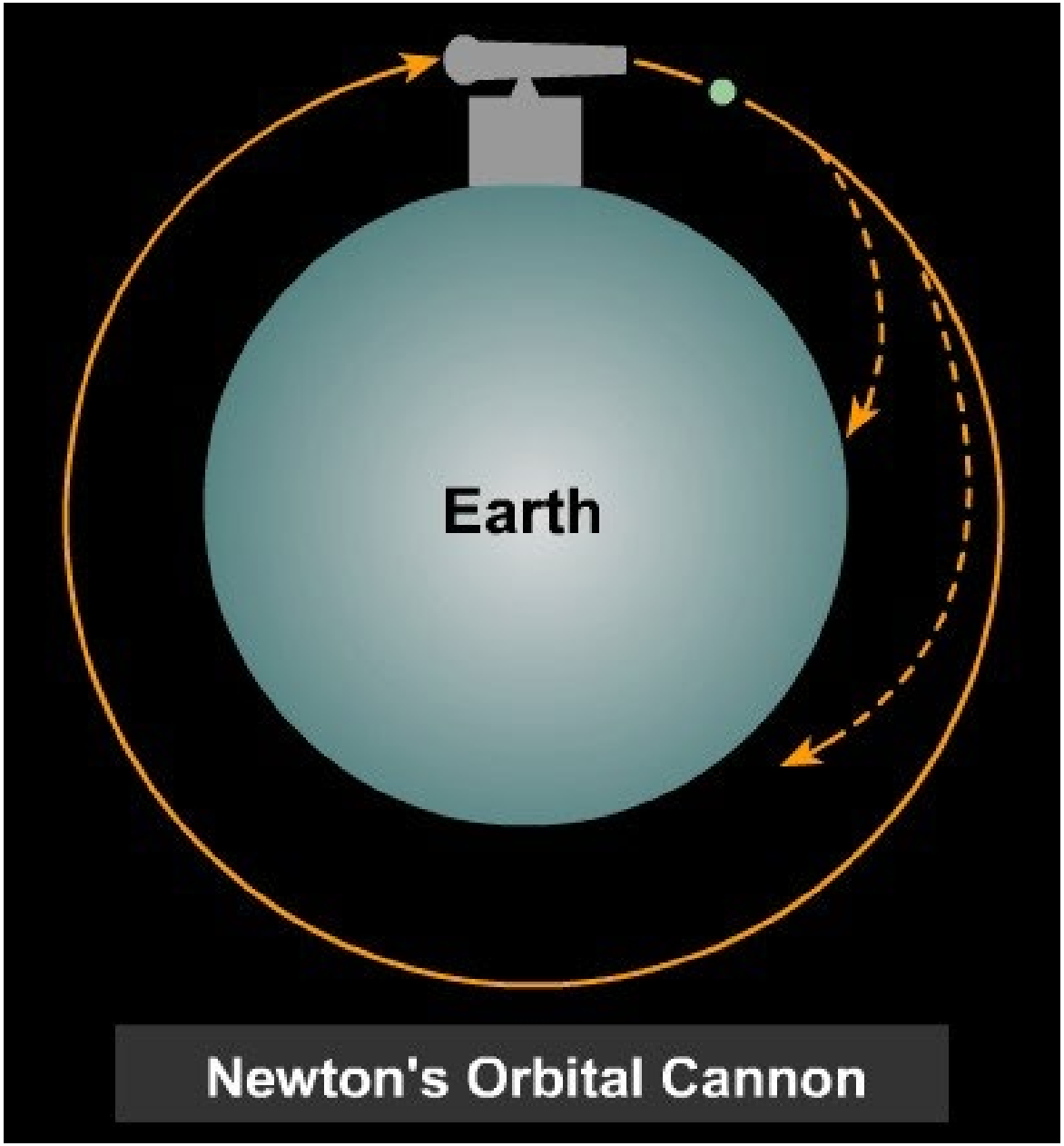
Image credit: NASA

Newton and the apple tree

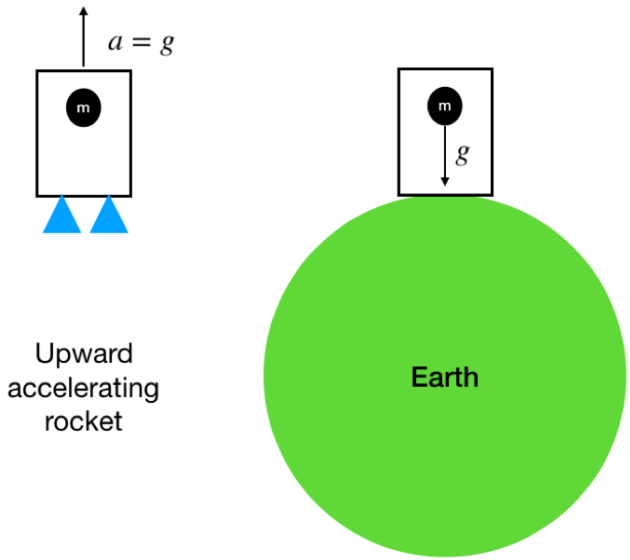
Imperial College London

"The story was certainly true, but let's say it got better with the telling."

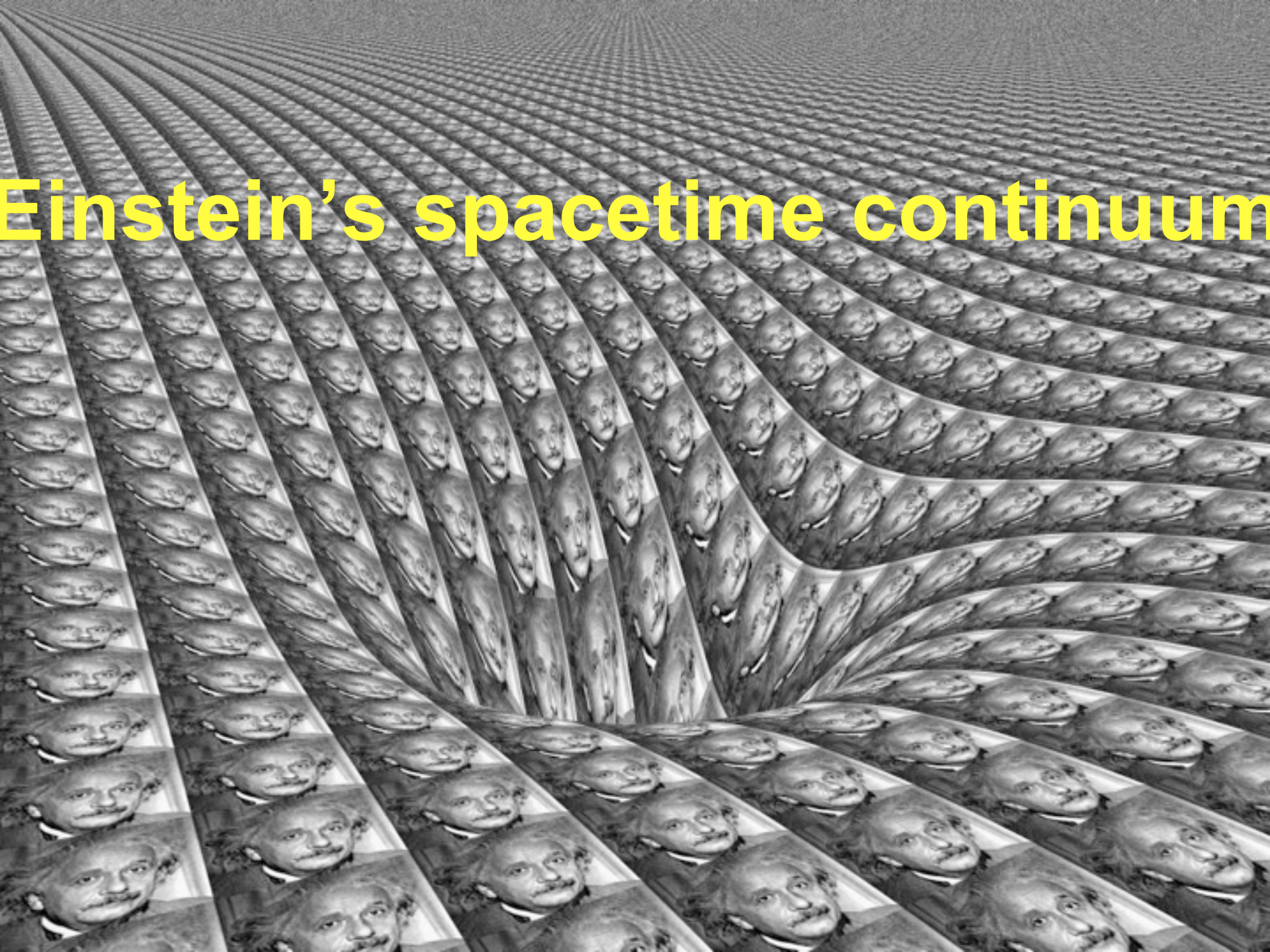
Keith Moore, Head of Archives, Royal Society

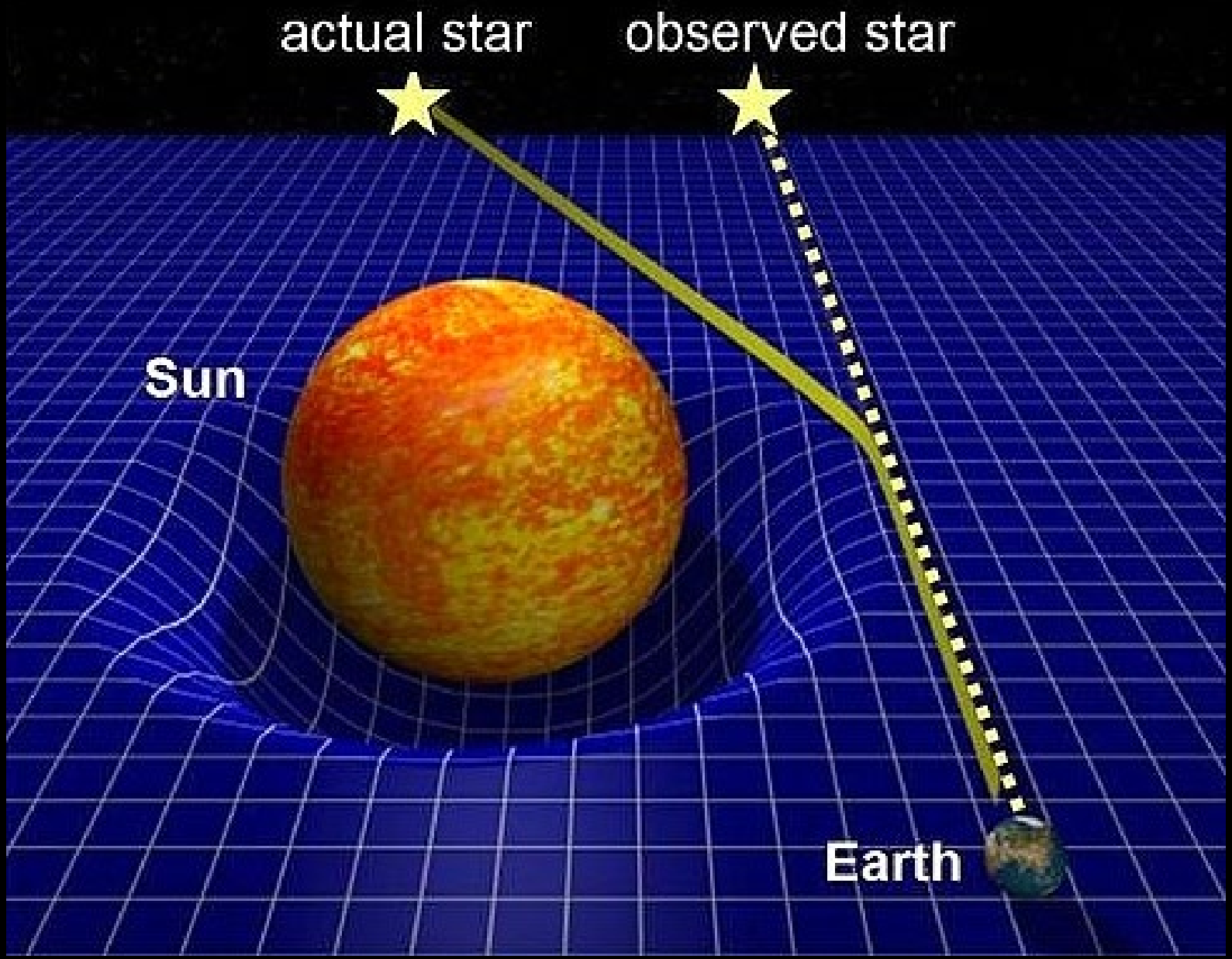

Earth
Newton's Orbital Cannon

Massive particle



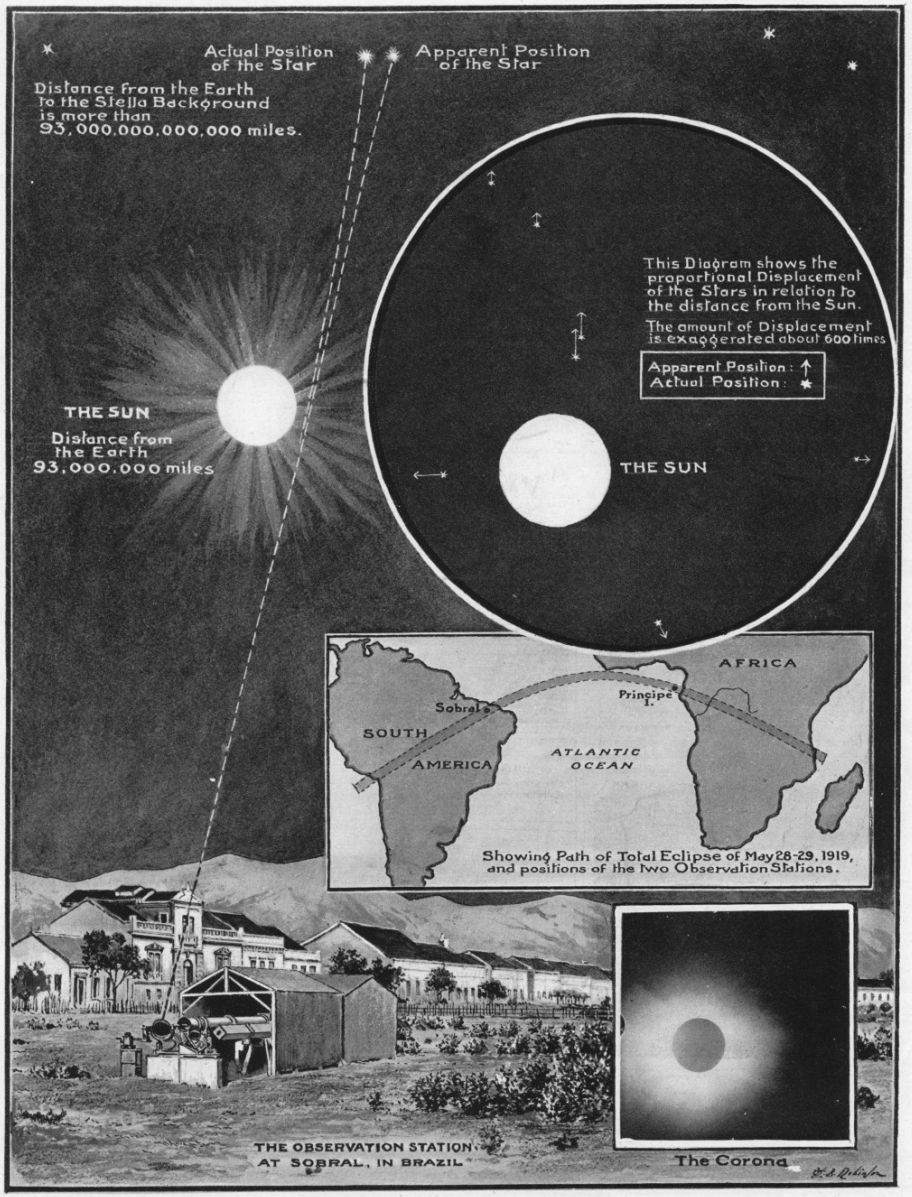
Upward accelerating rocket


Einstein's spacetime continuum


actual star
observed star
Sun
Earth

"STARLIGHT BENT BY THE SUN'S ATTRACTION": THE EINSTEIN THEORY.

DRAWN BY W. B. ROBINSON, FROM MATERIAL SUPPLIED BY DR. CROMMELIN.



THE CURVATURE OF LIGHT: EVIDENCE FROM BRITISH OBSERVERS' PHOTOGRAPHS AT THE ECLIPSE OF THE SUN.

The results obtained by the British expeditions to observe the total eclipse of the sun last May verified Professor Einstein's theory that light is subject to gravitation. Writing in our issue of November 15, Dr. A. C. Crommelin, one of the British observers, said: "The eclipse was specially favourable for the purpose, there being no fewer than twelve fairly bright stars near the limb of the sun. The process of observation consisted in taking same region taken when the sun was not in the neighbourhood. Then if the starlight is bent by the sun's attraction, the stars on the eclipse plates would seem to be pushed outward compared with those on the other plates. . . . The second Sobral camera and the one used at Principe agree in supporting (Einstein's theory). . . . It is of profound philosophical interest. Straight lines in Einstein's space cannot exist; they are

LIGHTS ALL ASKEW IN THE HEAVENS
Special Cable to THE NEW YORK TIMES.
New York Times 1857; Nov 10, 1919; ProQuest Historical Newspapers The New York Times (1851 - 2004)
pg. 17

LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

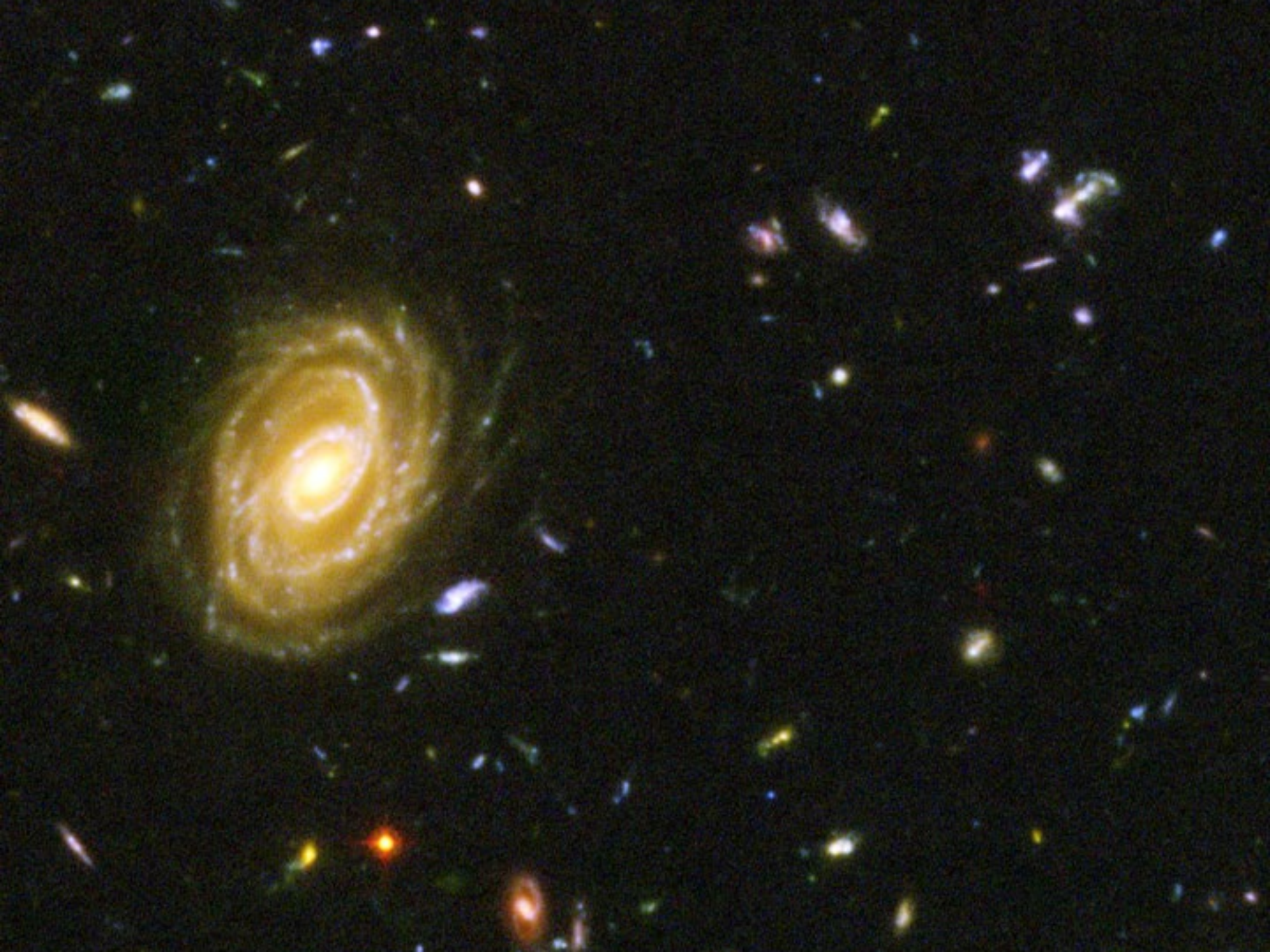
A BOOK FOR 12 WISE MEN

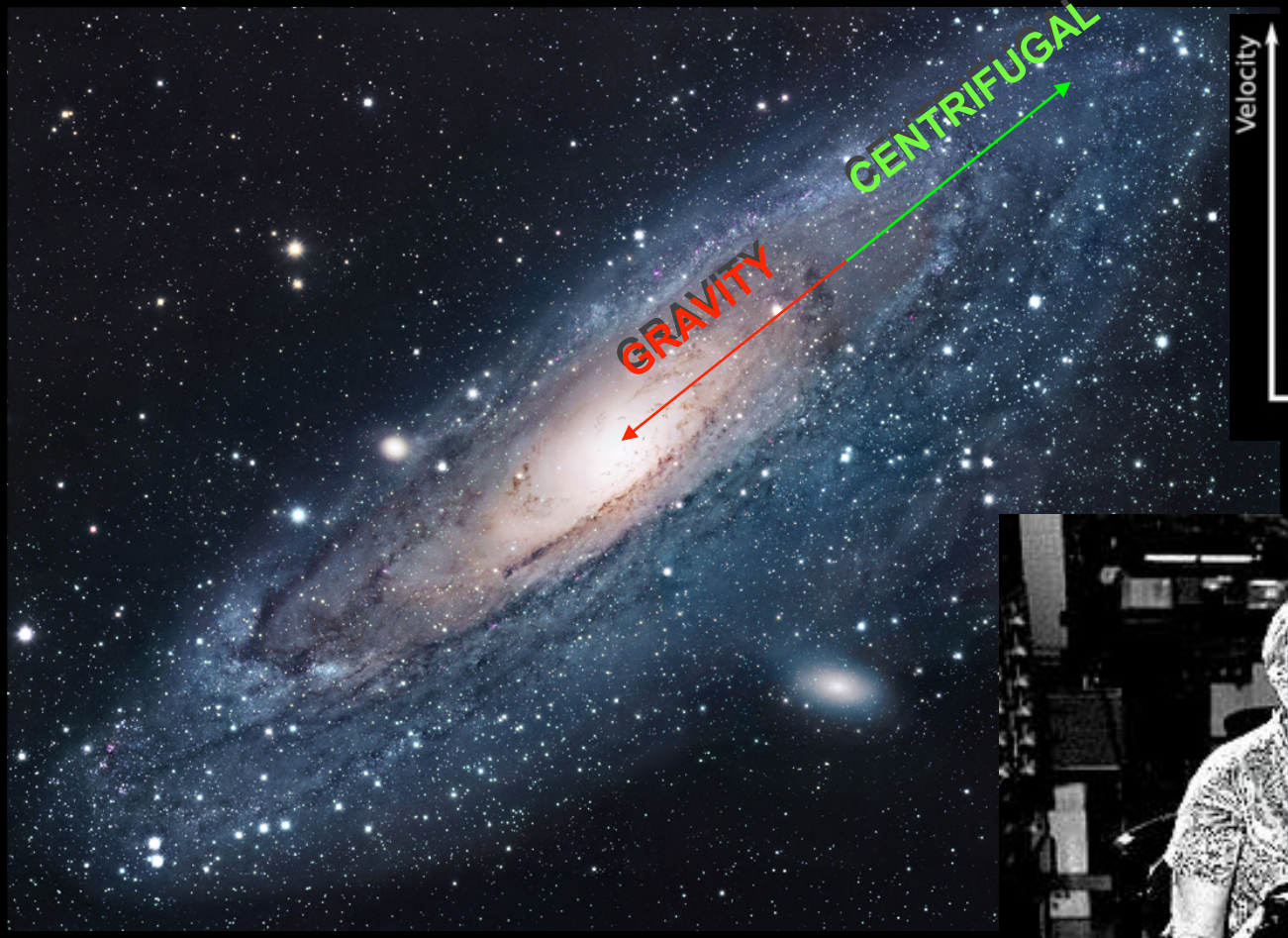
No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

New York Times headline of November 10, 1919.

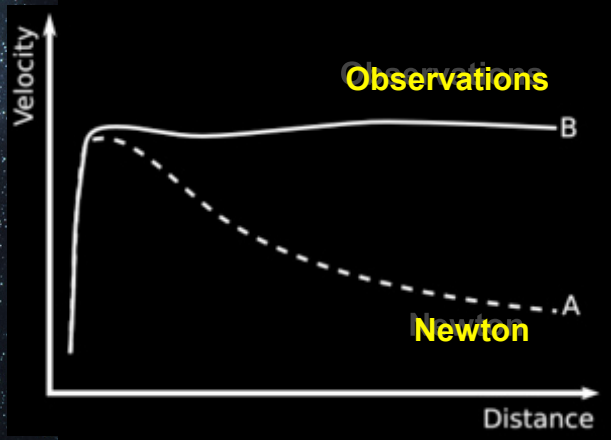
CLOSE


Moon
to scale
XDF



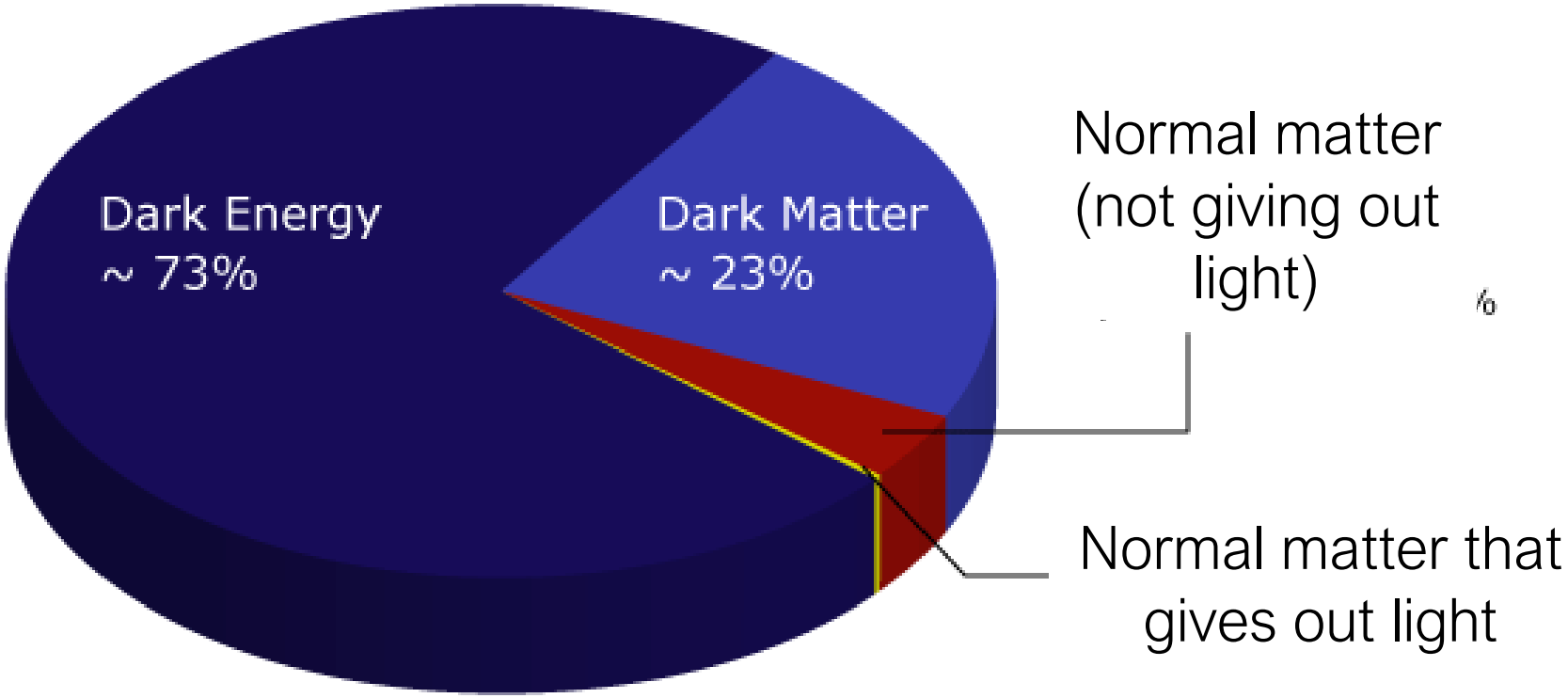


The Andromeda Galaxy (M31)



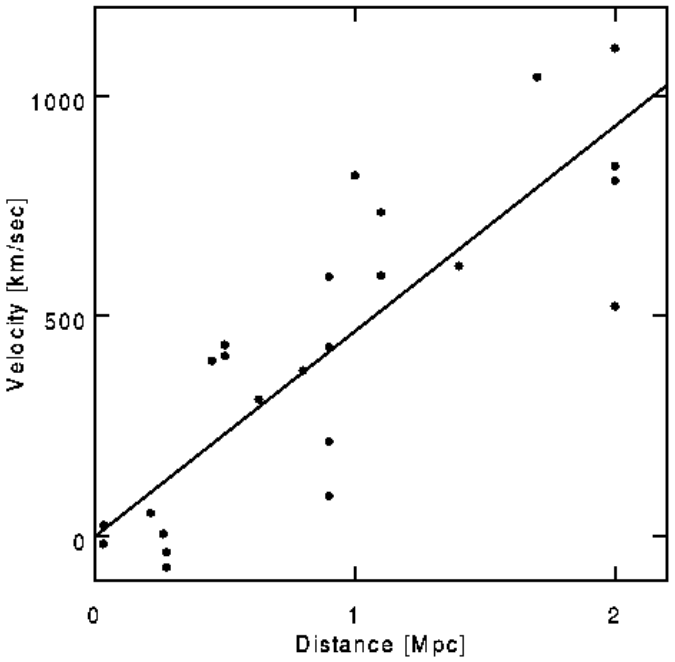

BREAKING NEWS!
96%
UNIVERSE
MISSING

What the Universe is made of:



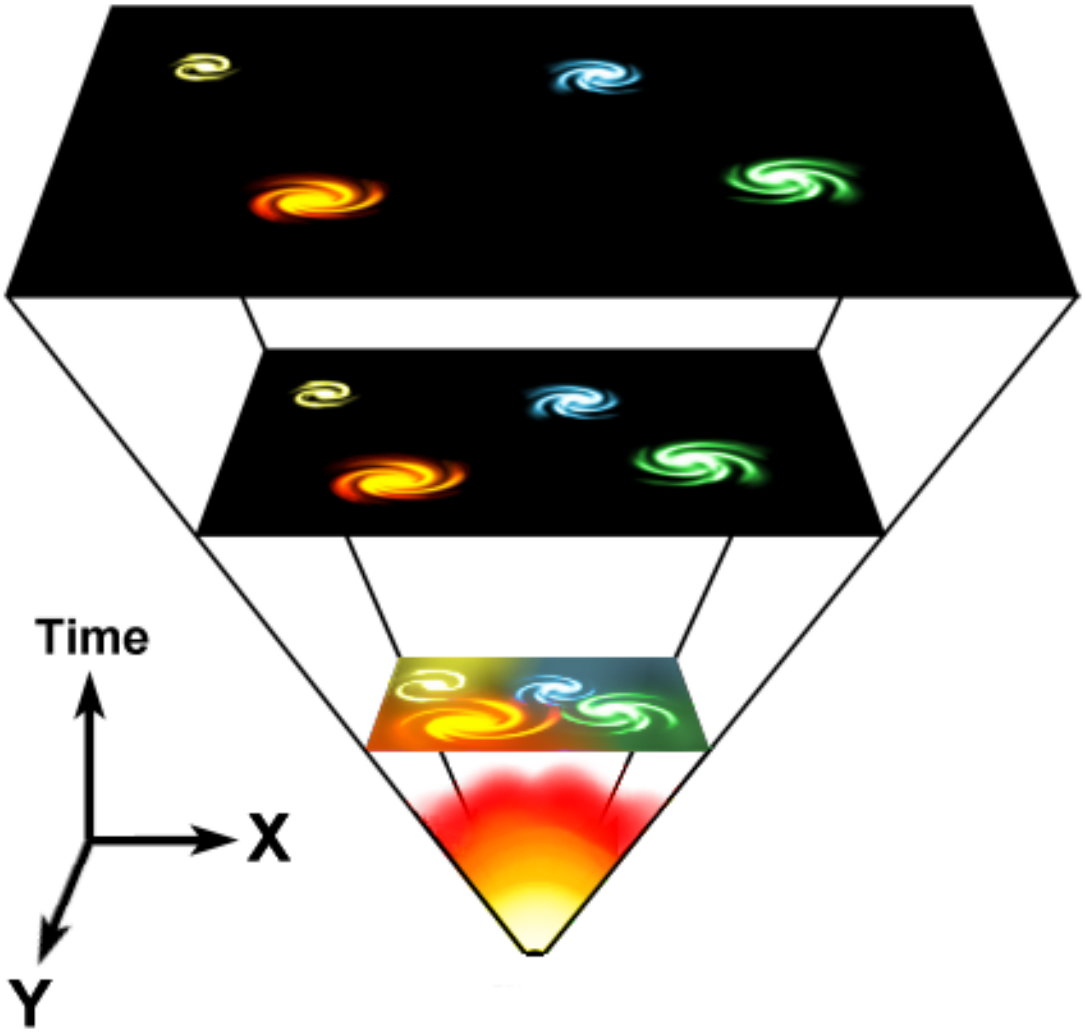
95% of the Universe is dark!

1929
Hubble-Lemaître Law



The Expanding Universe… in Your Kitchen!

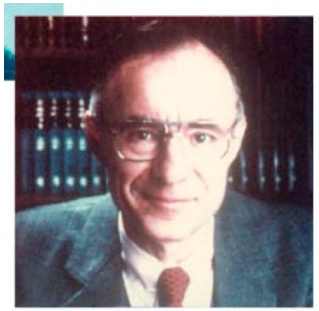
Time


Time
X
Y

The New York Times
Published: May 21, 1965

The left-over "heat" from the Big Bang:

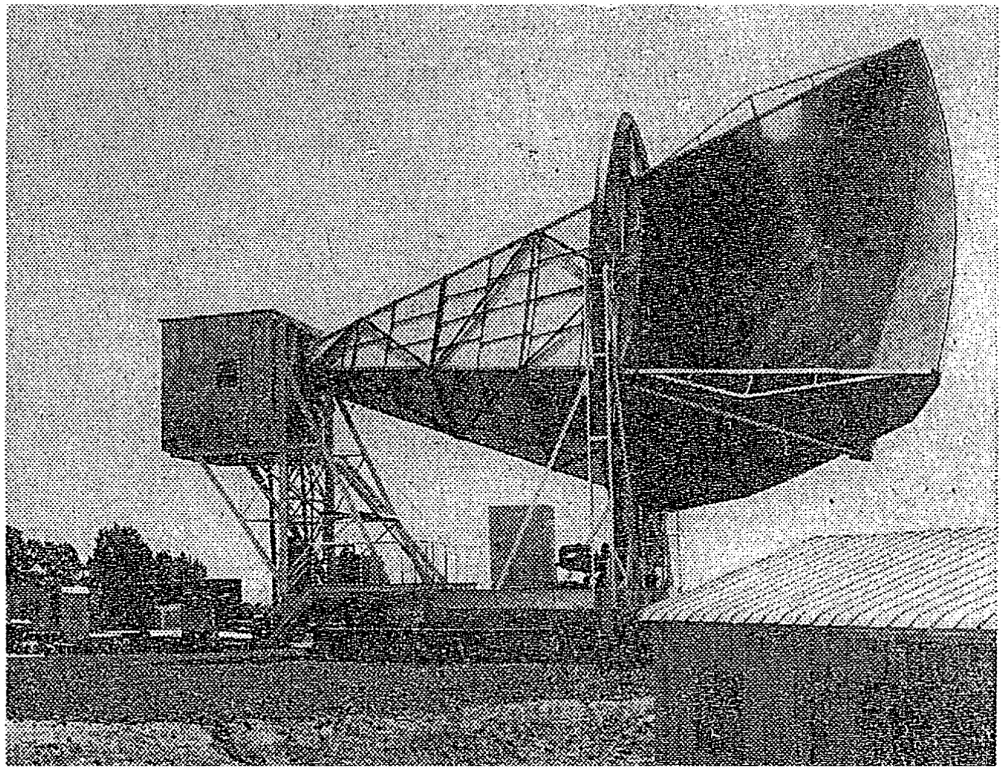
−270.425 ºC



Arno Penzias

Robert Wilson

Signals Imply a 'Big Bang' Universe



Horn antenna, used in space exploration, at the Bell Laboratories in Holmdel, N. J.

By WALTER SULLIVAN

Scientists at the Bell Telephone Laboratories have observed what a group at Princeton University believes may be remnants of an explosion that gave birth to the universe.

These remnants are thought to have originated in the burst of light from that cataclysmic event.

Such a primordial explosion is embodied in the "big bang" theory of the universe. It seeks to explain the observation that virtually all distant galaxies are flying away from the earth. Their motion implies that they all originated at a single point 10 or 15 billion years ago.

The Bell observations, made by Drs. Arno A. Penzias and Robert W. Wilson from a hilltop in Holmdel, N. J., were of radio waves that appear to be flying in all directions through the universe. Since radio waves and light waves are identical, except for their wavelength, these are thought to be remnants of light waves from the primordial flash.

The waves were stretched into radio waves by the vast expansion of the universe that has occurred since the explosion and release of the waves from the expanding gas cloud born of the fireball.

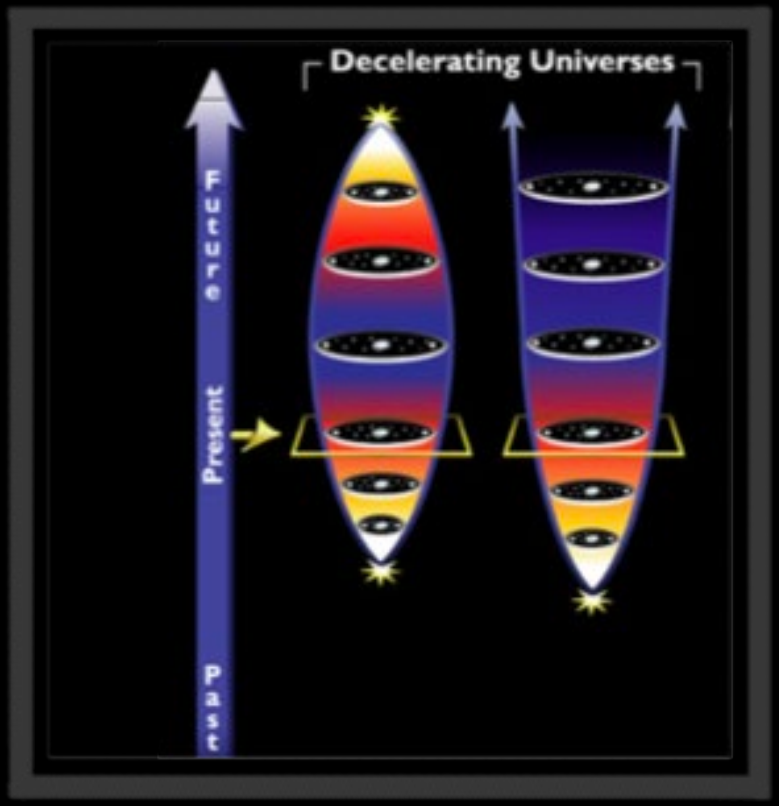
In what may prove to be one of the most remarkable coincidences in scientific history, the existence of such waves was predicted at

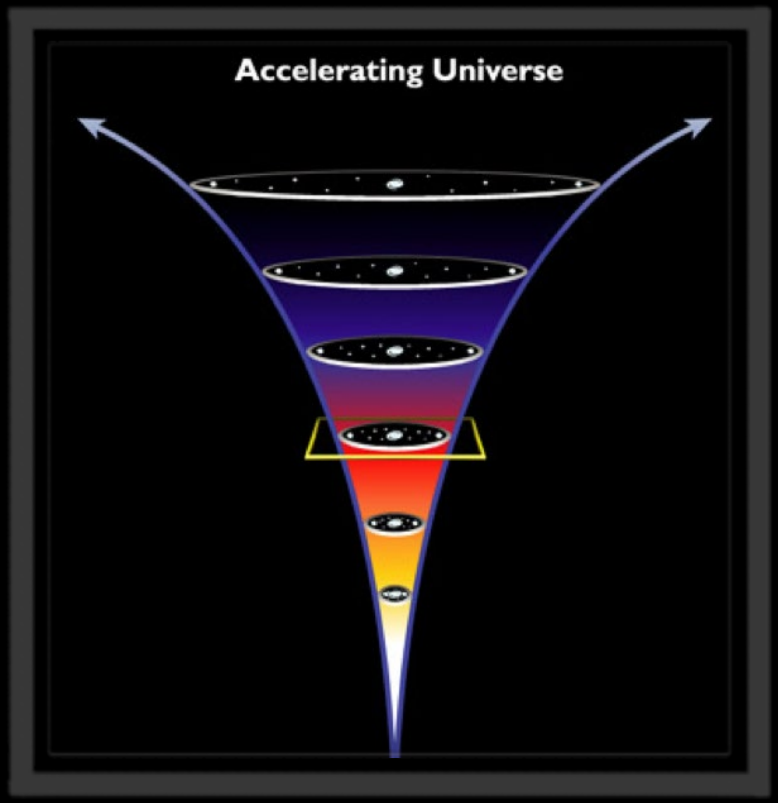
Continued on Page 18, Column 1

The fate of the Universe

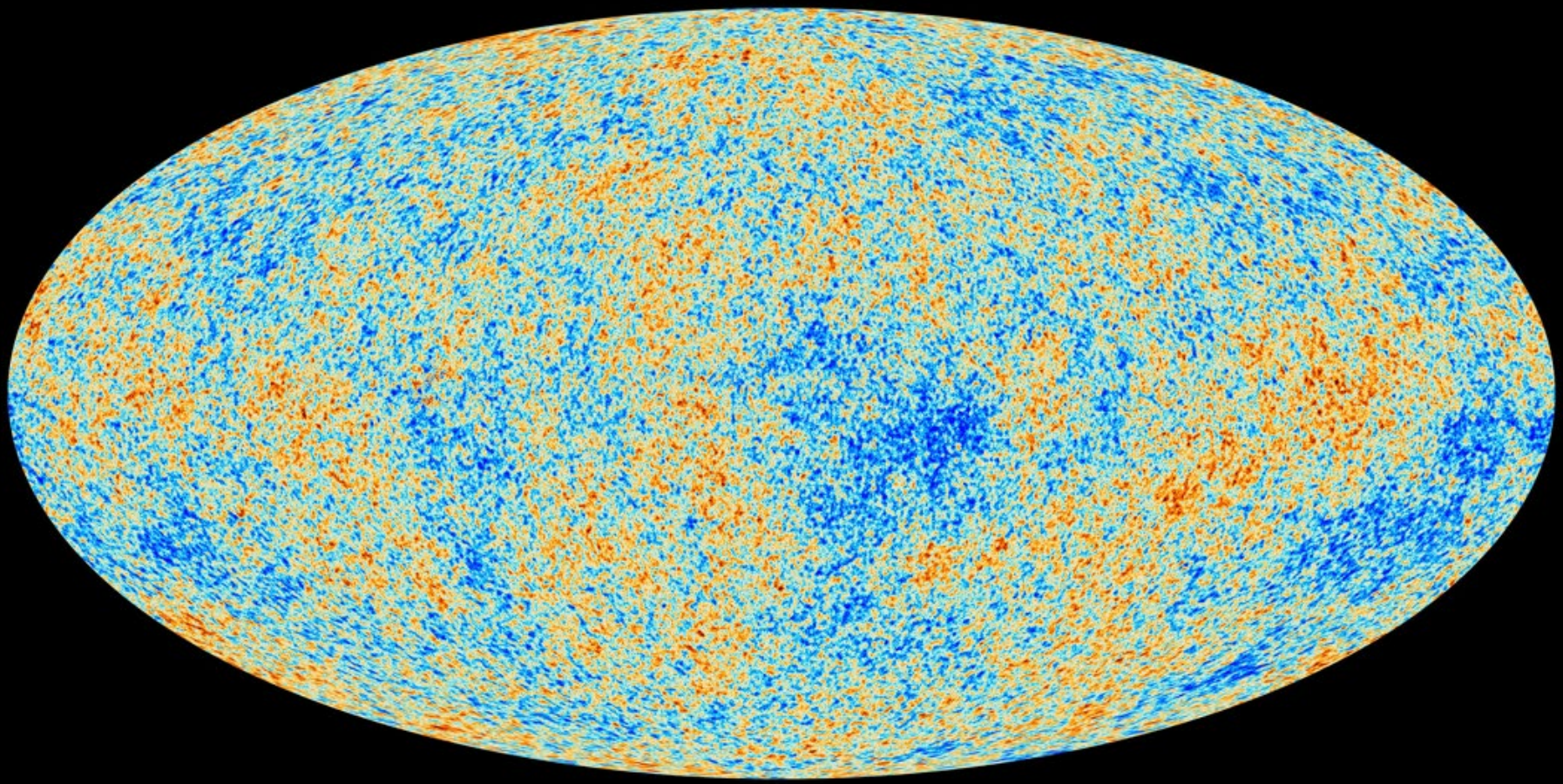
Matter (visible+dark)
GRAVITY

Dark Energy
ANTI-GRAVITY





The end of the visible Universe

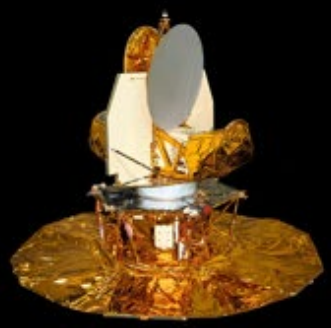


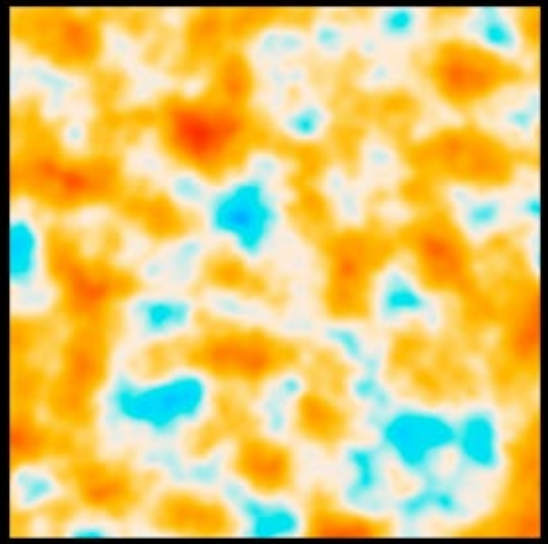
380,000 years after the Big Bang

1994

COBE

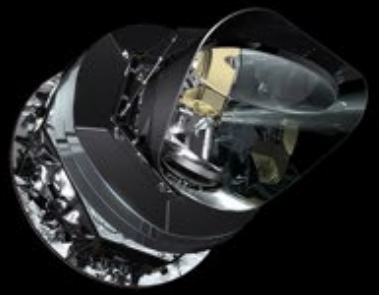
2001-2010

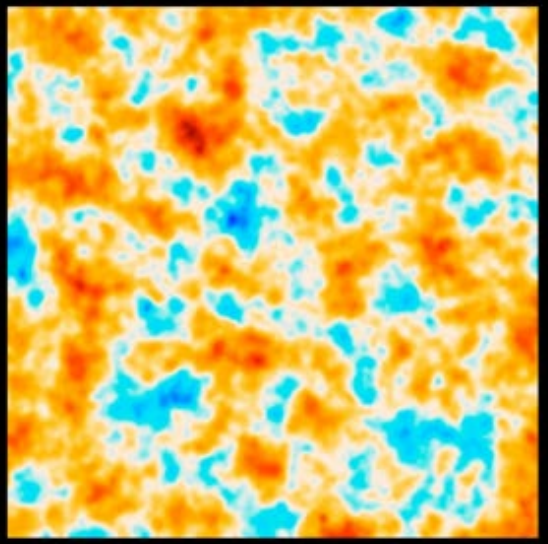




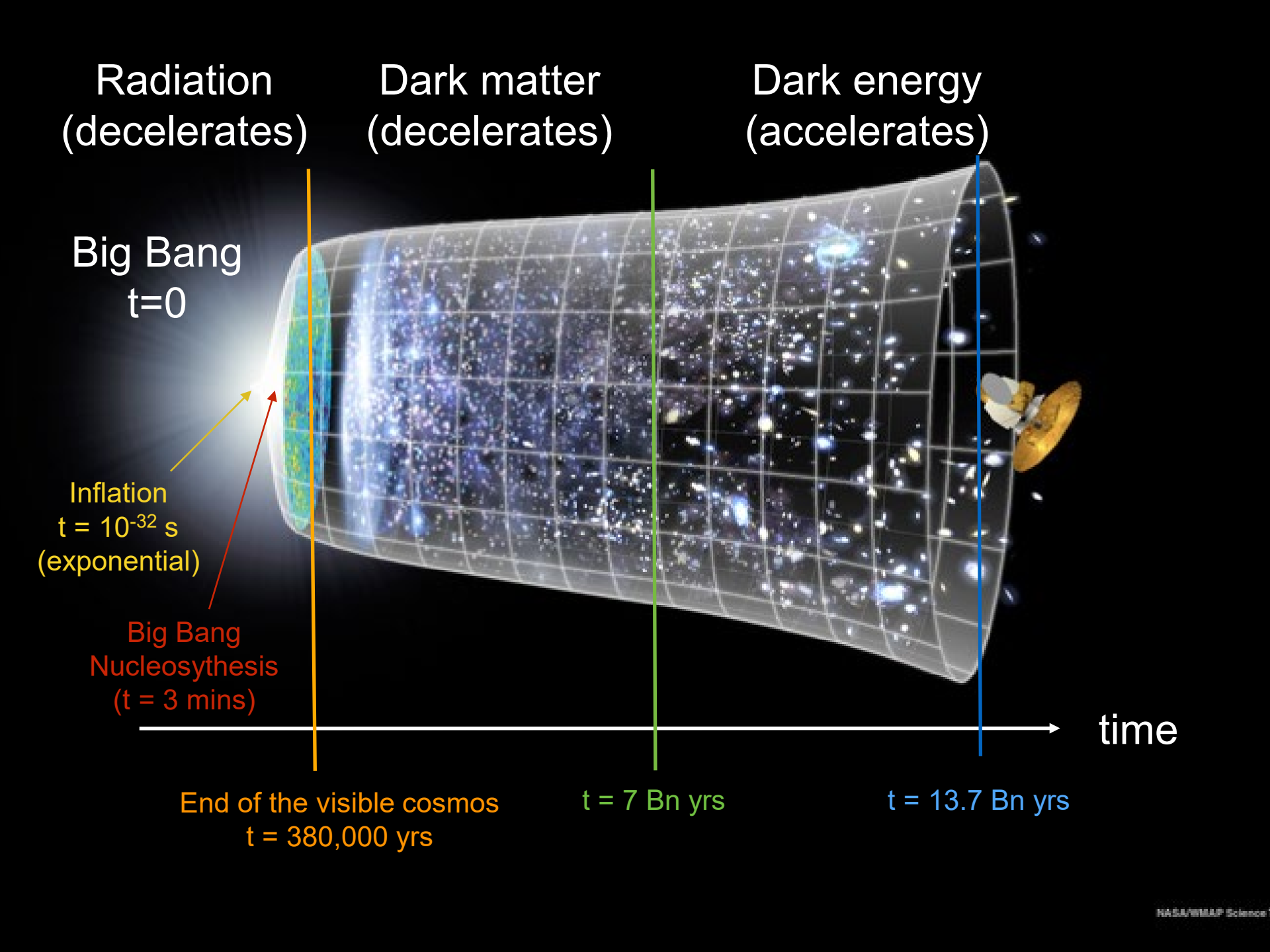
WMAP

2013-2018





Planck


Radiation
(decelerates)
Dark matter
(decelerates)
Dark energy
(accelerates)
Big Bang
t=0
Inflation
t = 10-32 s
(exponential)
Big Bang
Nucleosythesis
(t = 3 mins)
time
End of the visible cosmos
t = 380,000 yrs
t = 7 Bn yrs
t = 13.7 Bn yrs

How old is the Universe?

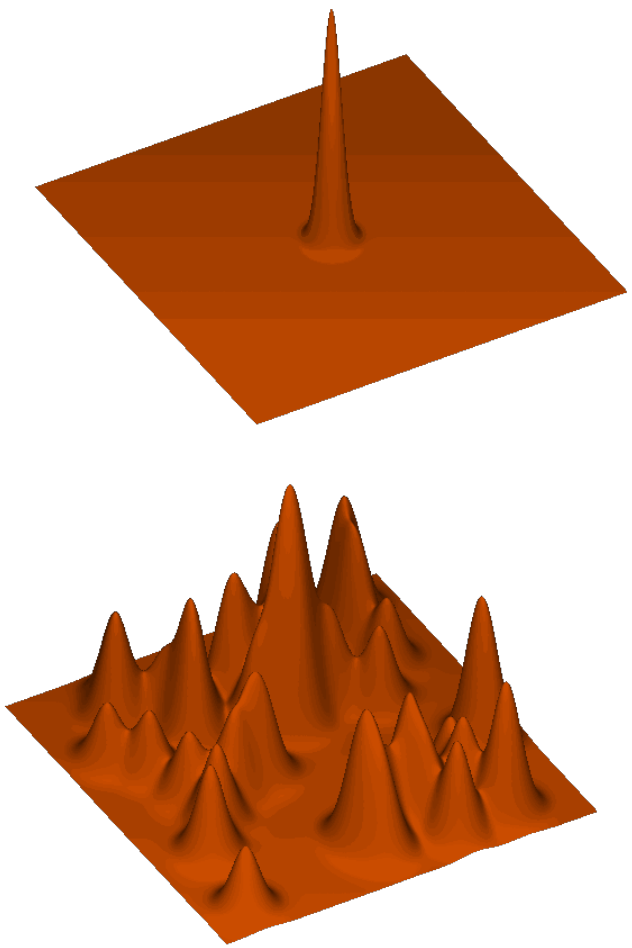
@R_Trotta

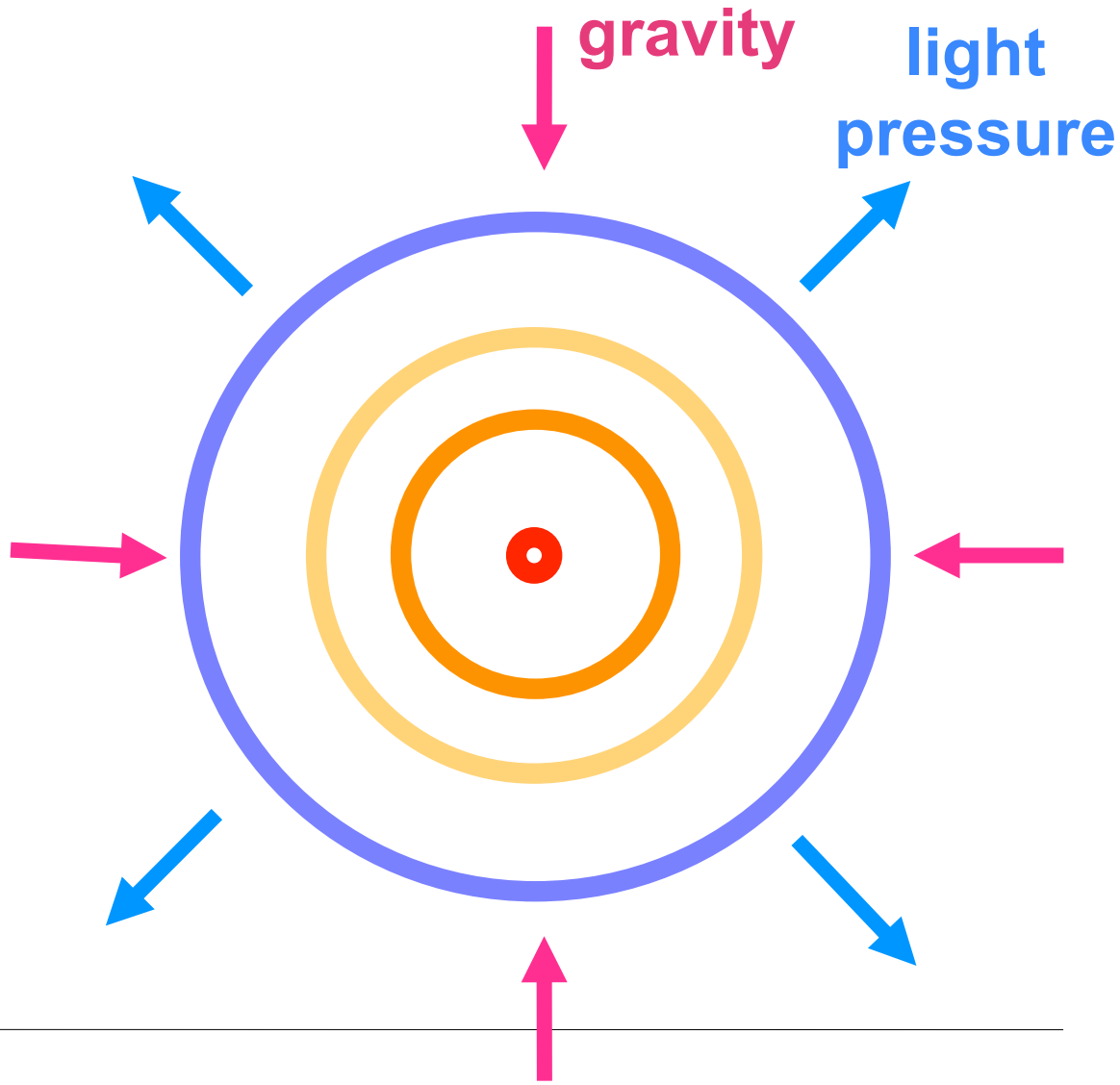
Age =13.798 billion years*

*(give or take 29 million years)

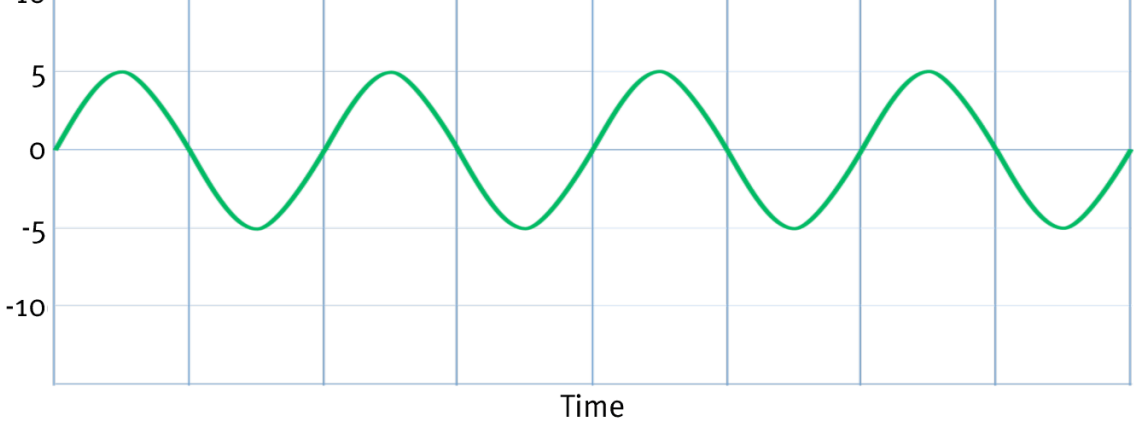
Seeing cosmic sound

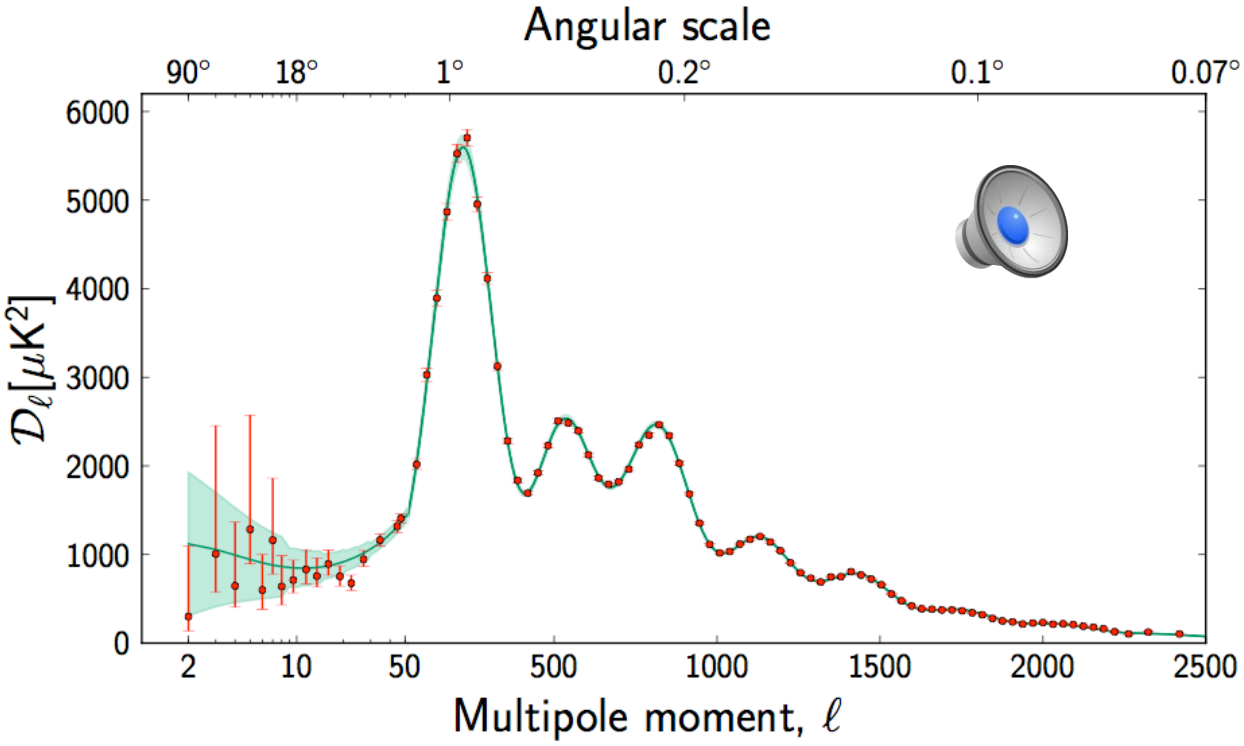
@R_Trotta



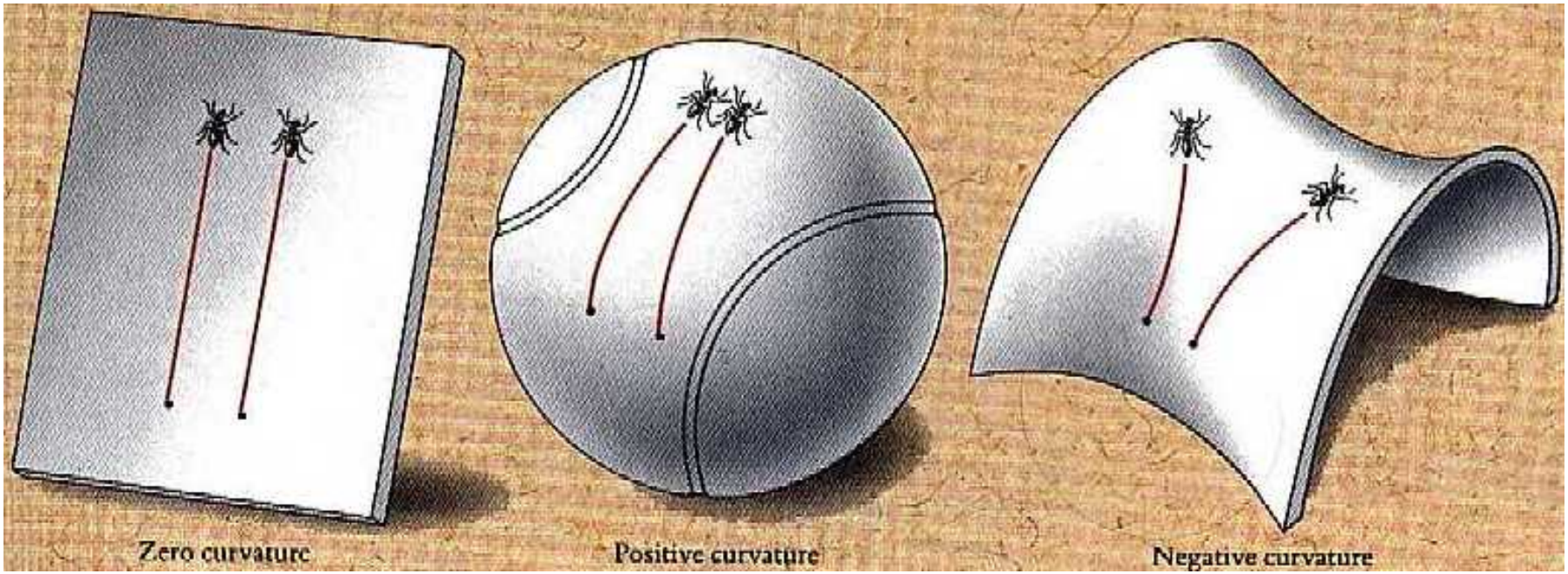


Credit: Daniel Eisenstein


5
0
-5
-10
Time


Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ

An ant's perspective:



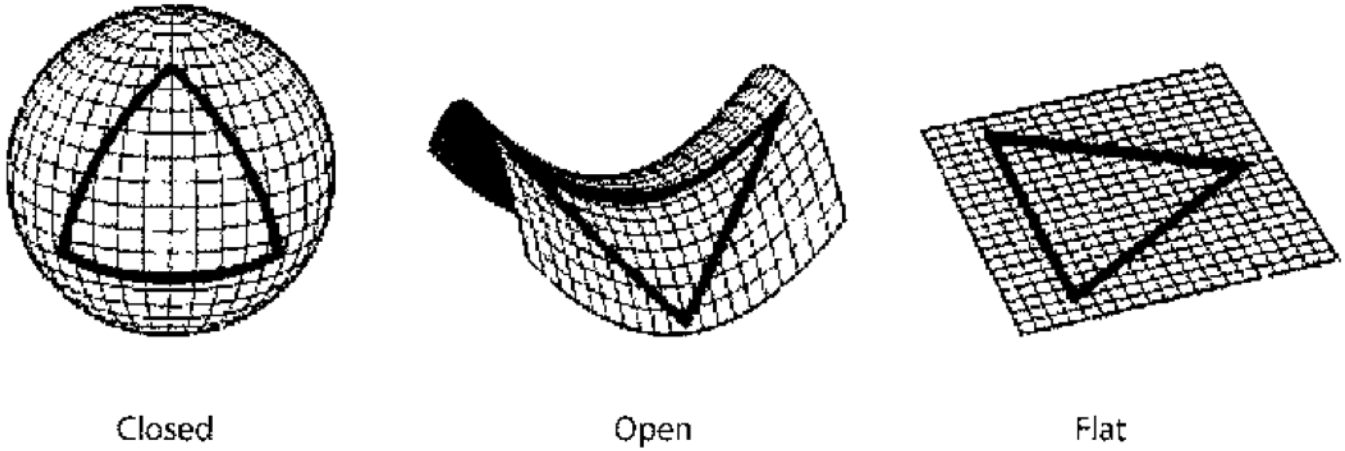
Flat
(Euclidean)

Closed
(spherical)

Open
(hyperbolic
)

The Geometry of the Universe

@R_Trotta

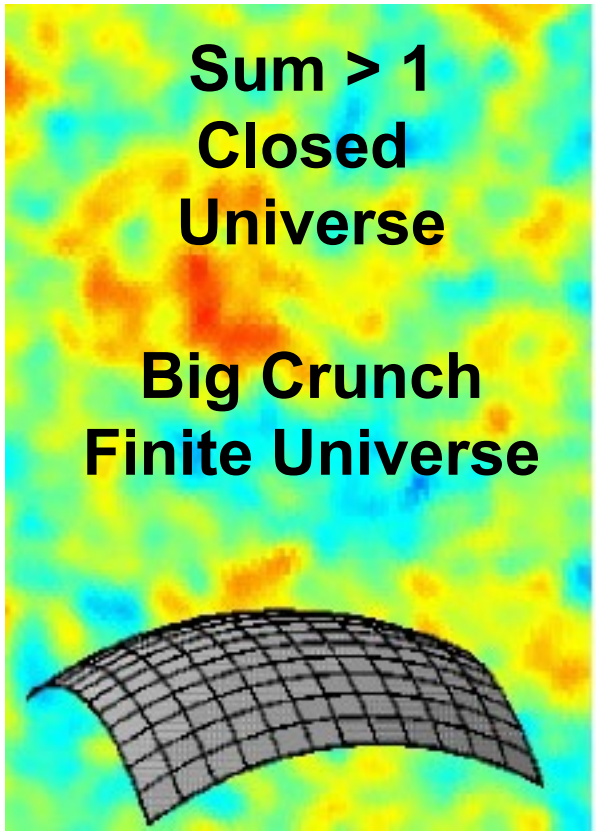


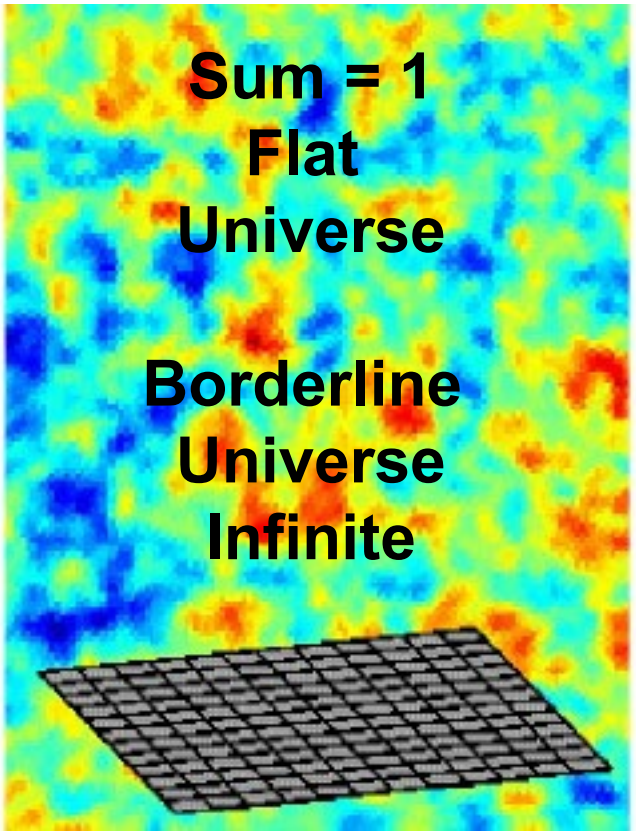
The three different possible geometries of the Universe.

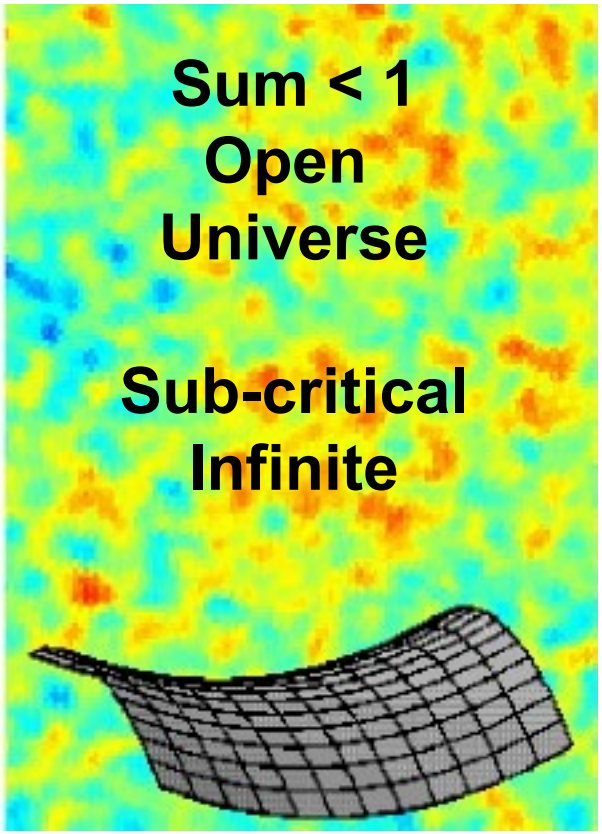
Ref: Schneider (2006)

Einstein:

Geometry = Energy + Matter



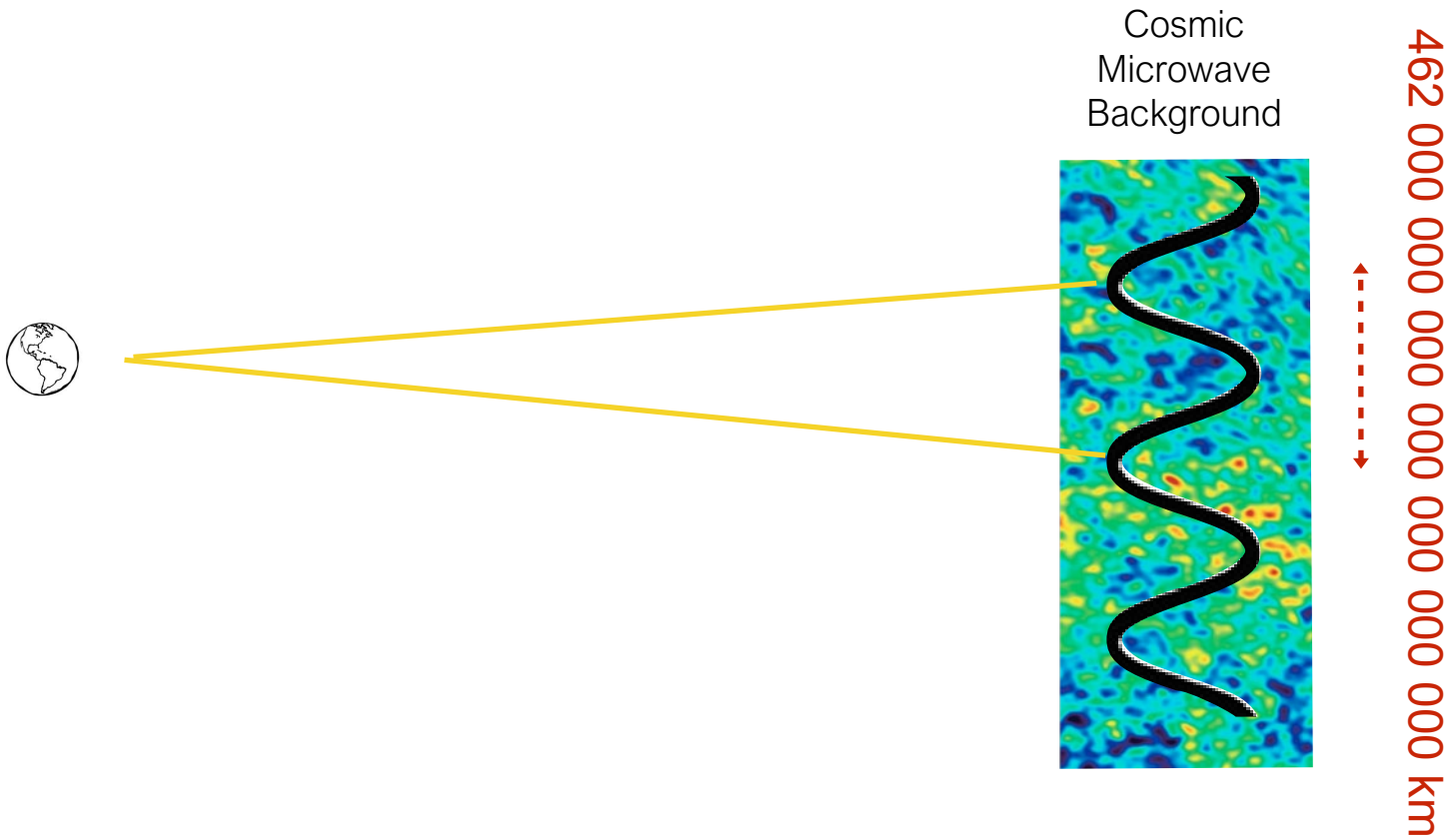




Credit: Babak Tafreshi / ESO

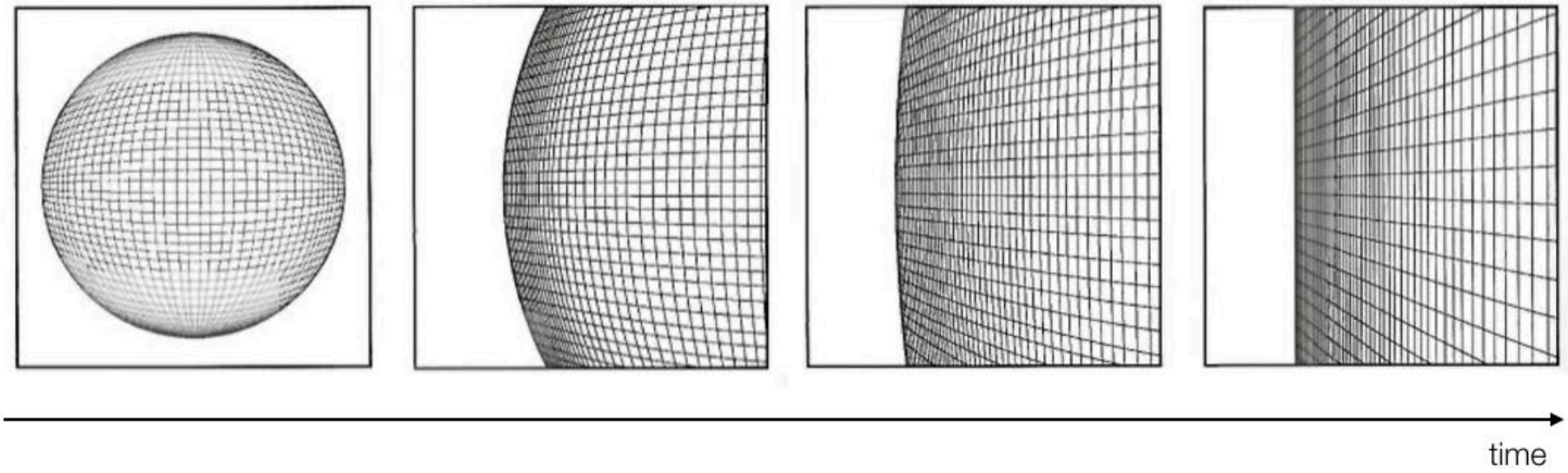
Weighing the Universe

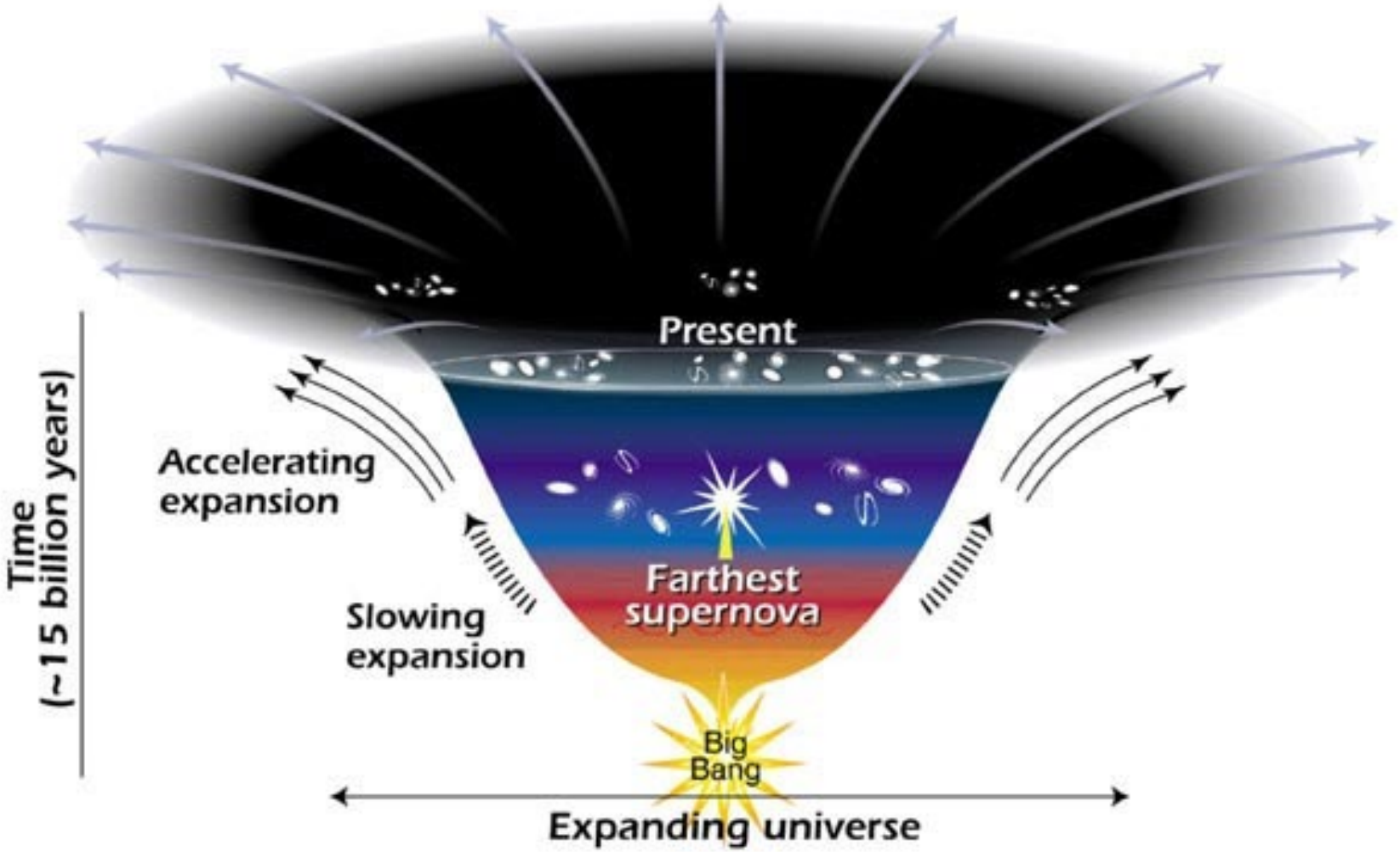
@R_Trotta

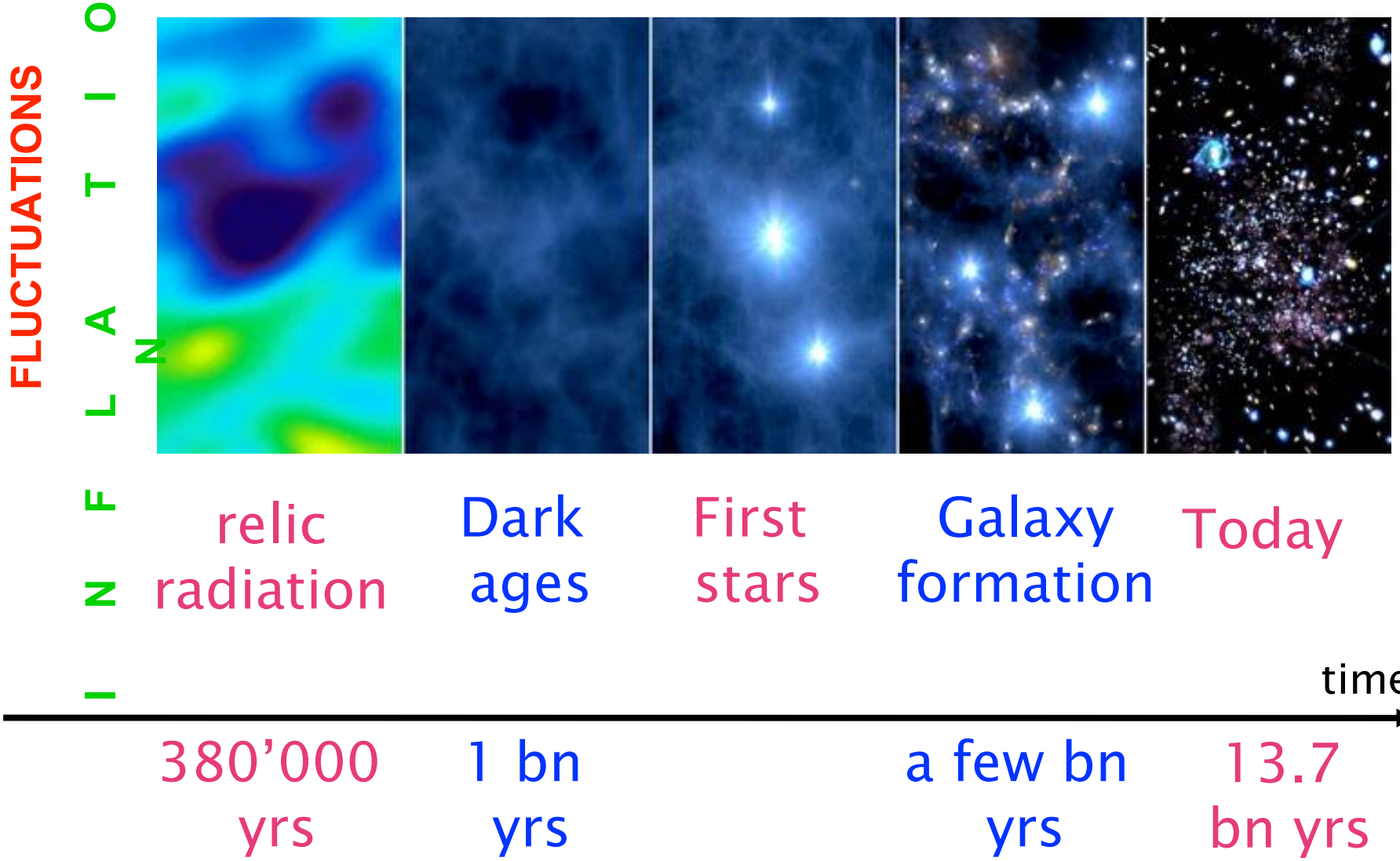


$$\Omega_\kappa = 0.0005 \pm 0.0060$$

In a flat universe, this quantity would be exactly 0 equal to 0.

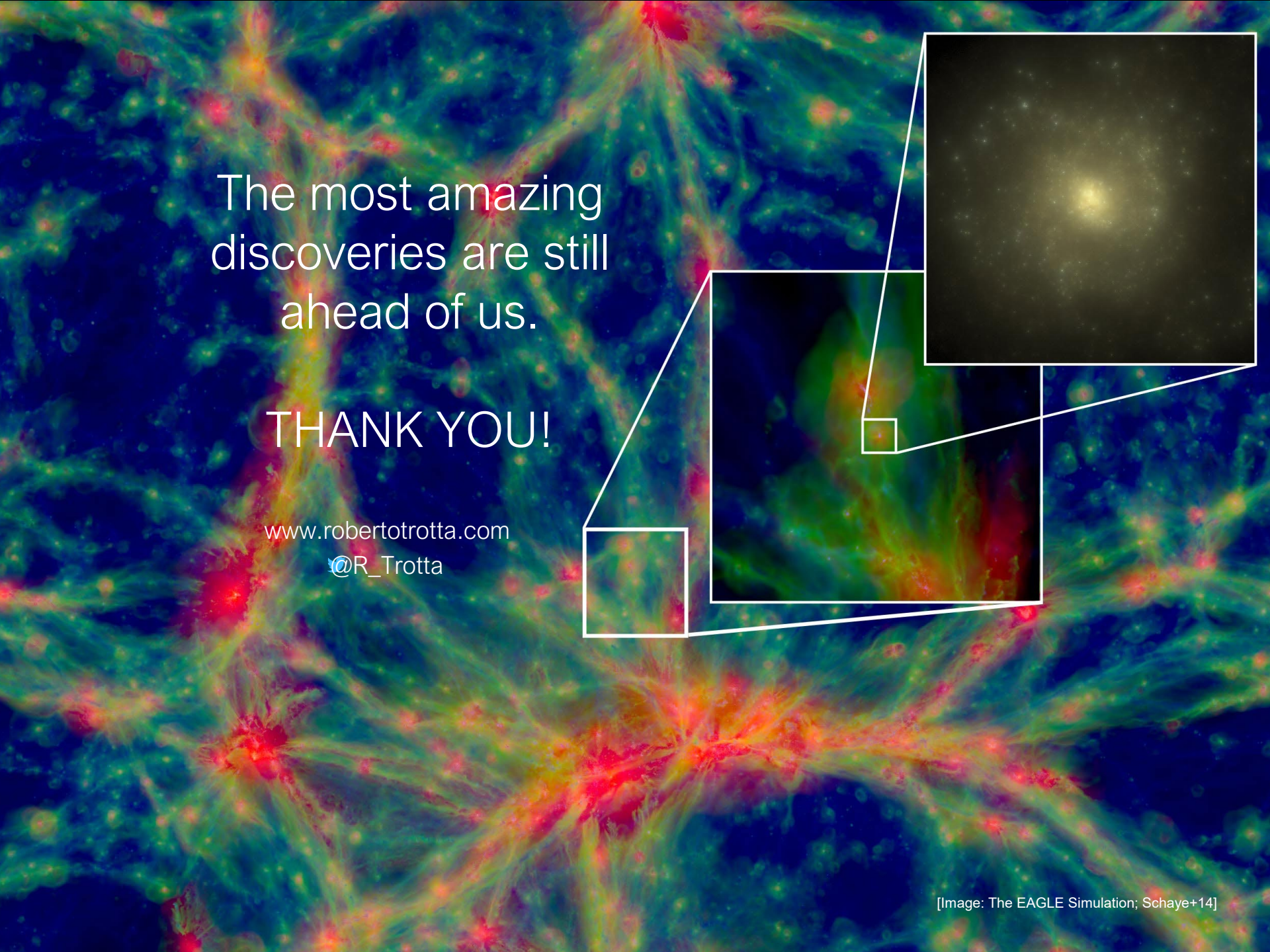

time

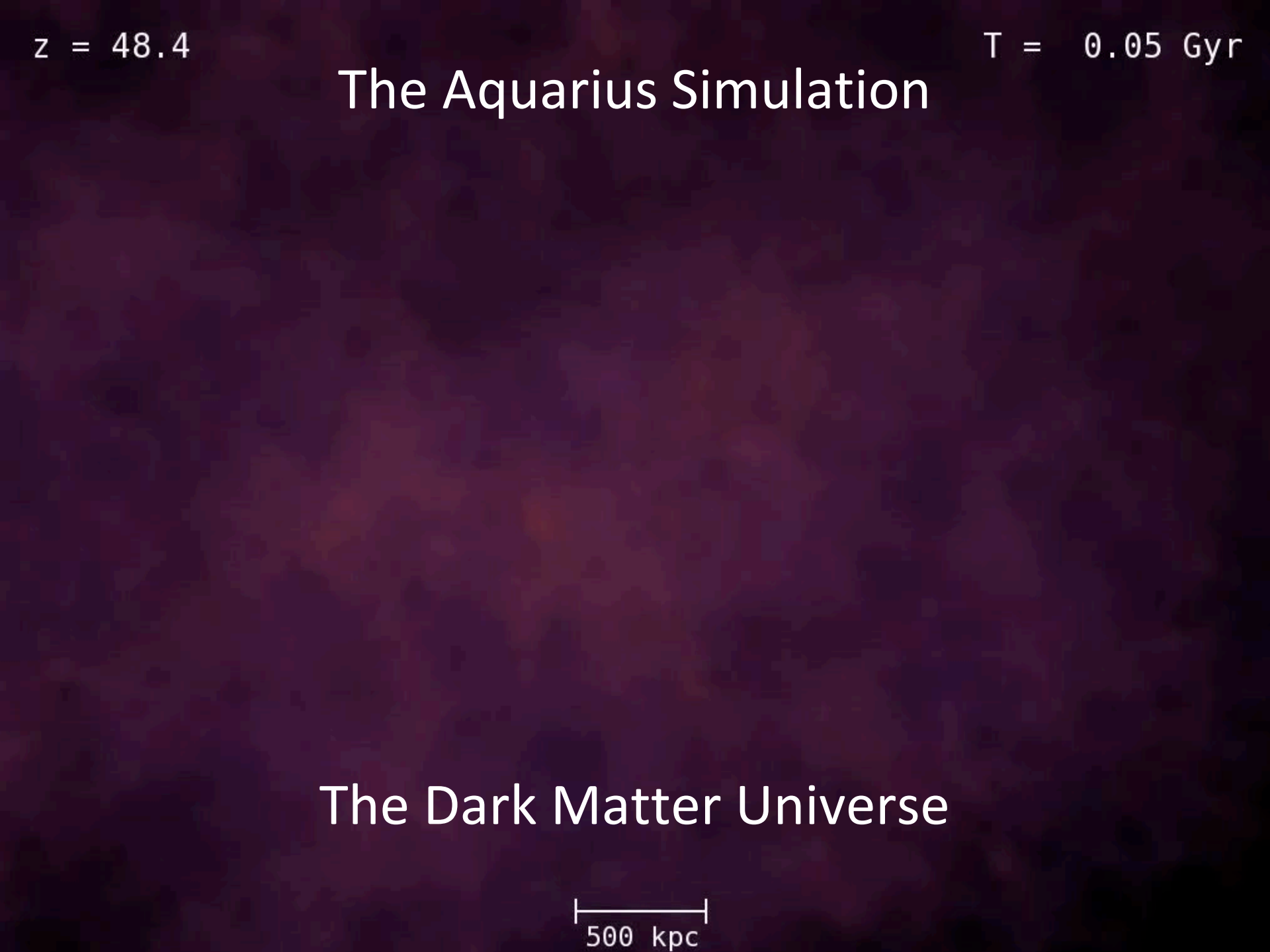

Present
Accelerating expansion
Slowing expansion
Farthest supernova
Big Bang
Time (~15 billion years)
Expanding universe


QUANTUM FLUCTUATIONS
INFLATION
relic radiation
Dark ages
First stars
Galaxy formation
Today
time
380'000 yrs
1 bn yrs
a few bn yrs
13.7 bn yrs

Average mass density of the Universe:

$0.000\ 000\ 000\ 000\ 000\ 000\ 000\ 000\ 003\ 837\ g/cm^3$


The most amazing discoveries are still ahead of us.
THANK YOU!
www.robertotrotta.com
@R_Trotta
[Image: The EAGLE Simulation; Schaye+14]


z = 48.4
T = 0.05 Gyr
The Aquarius Simulation
The Dark Matter Universe
500 kpc