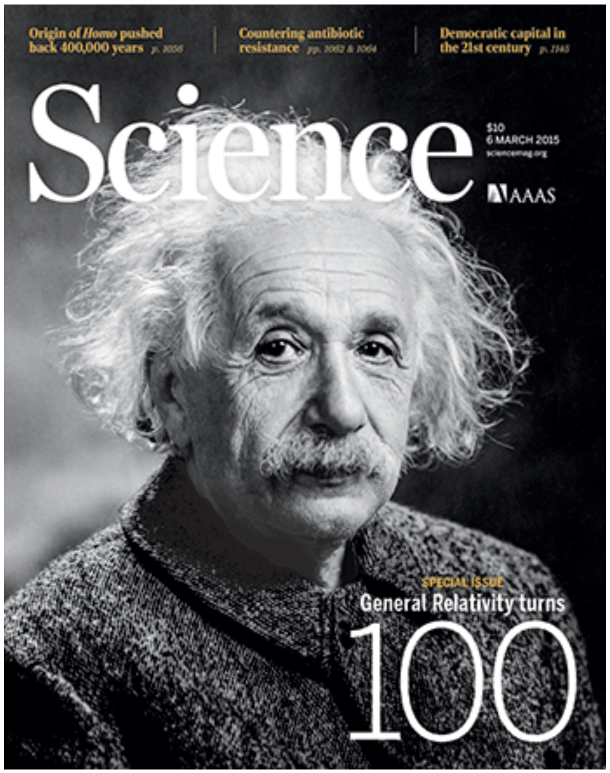
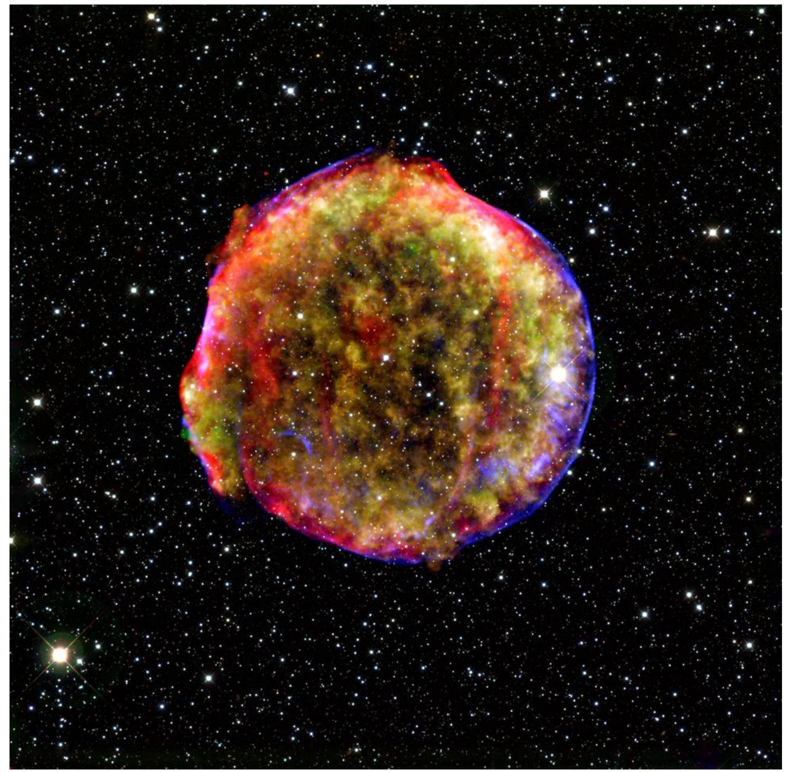
Einstein, Cosmology and the Universe

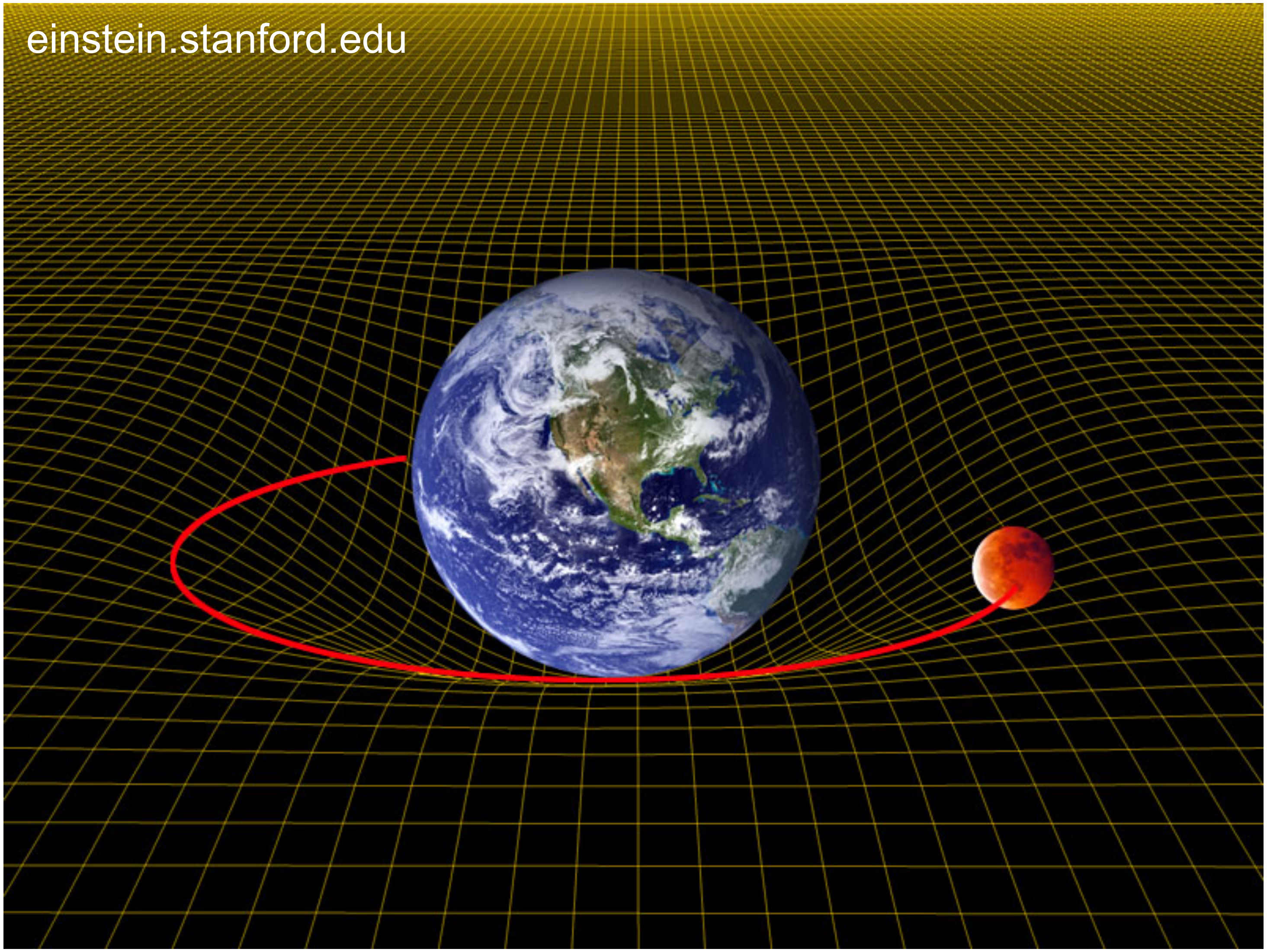
From Static to Expanding to Accelerating





Levon Pogosian

Simon Fraser University



"Spacetime tells matter how to move; matter tells spacetime how to curve."

John A. Wheeler (1911-2008)

Einstein's Perfect Universe

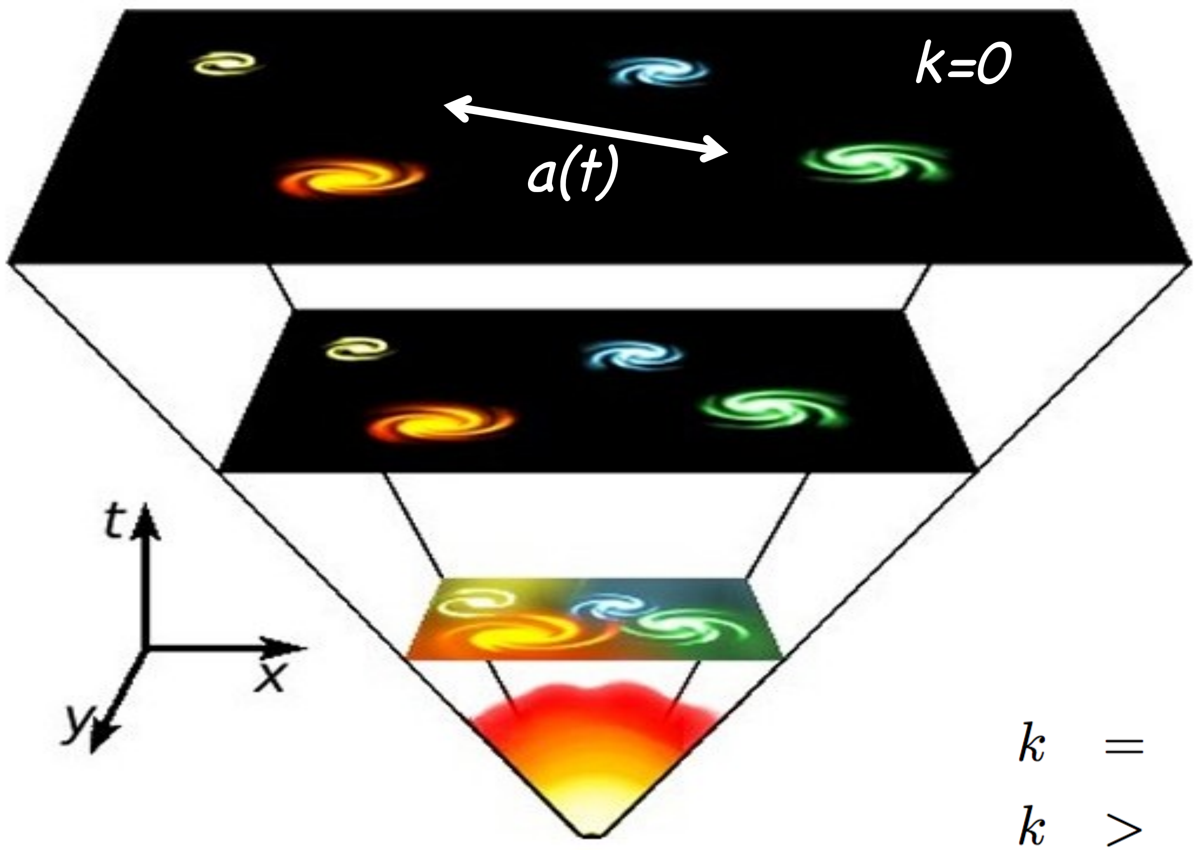
Same Everywhere

no evidence for this in 1916
turned out to be correct!

Ever the Same

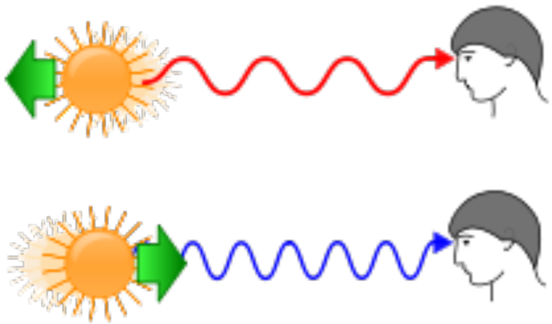
turned out to be wrong

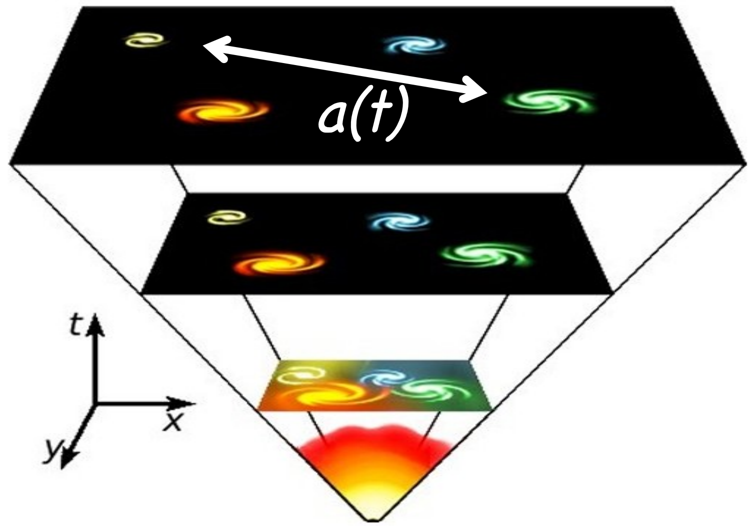
Expanding Universe



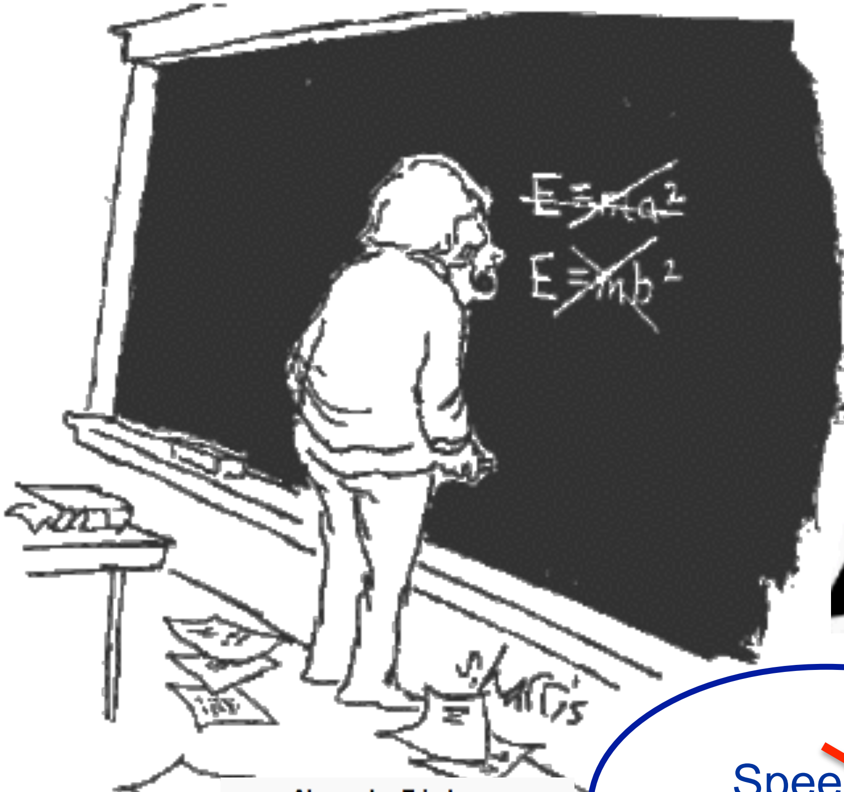
$$
\begin{aligned}
k &= 0, \text{ flat} \\
k &> 0, \text{ closed} \\
k &< 0, \text{ open}
\end{aligned}
$$

Redshift z

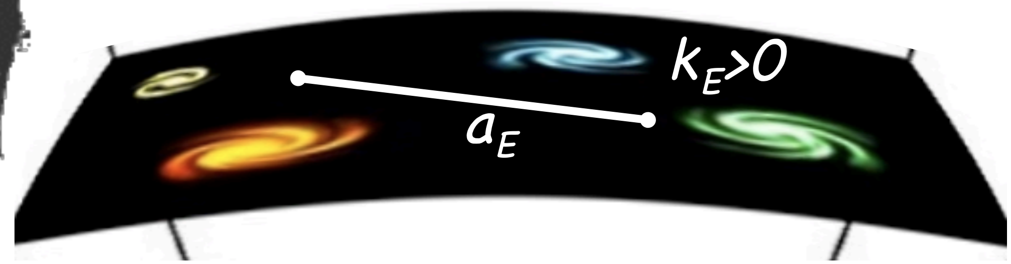




$$1 + z = \frac{\lambda_{\rm obsv}}{\lambda_{\rm emit}} = \frac{a_{\rm now}}{a_{\rm then}} = \frac{1}{a}$$



Einstein's Static Universe



Alexander Friedmann

Speed of expansion

$$= \frac{8\pi G\rho_M}{3} - \frac{k_E}{a_E^2} + \frac{\Lambda_E}{3} = 0$$

Acceleration of expansion

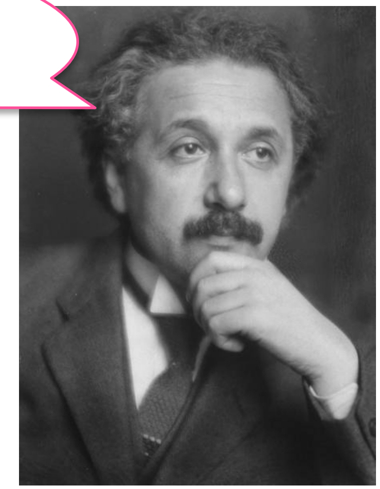
$$= -\frac{4\pi G}{3}\rho_M + \frac{\Lambda_E}{3} = 0$$

$$\Lambda_E = 4\pi G\rho_M; \quad k_E = 4\pi G\rho_M a_E^2$$

A. Friedmann, "Über die Krümmung des Raumes", Zeitschrift für Physik (1922)

Theory of the Universe in 1920's

- **Alexander Friedmann**, *"Über die Mög*
Welt mit konstanter negativer Krümmun
Zeitschrift für Physik (1924) (Eng: On the possibi
with constant negative curvature of space)



- **Georges Lemaître**, *"Un univers homogène de masse constante et de rayon croissant rendant compte de la vitesse radiale des nébuleuses extra-galactiques"*, Annales de la Société Scientifique de Bruxelles (1927)

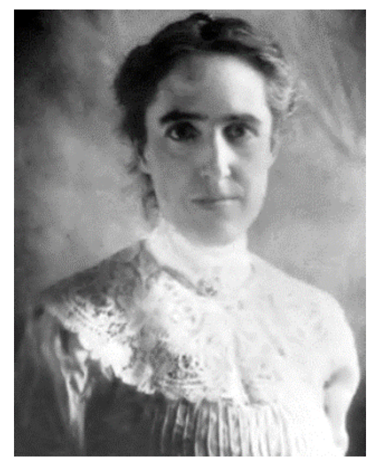
Observations

- **Henrietta Leavitt** (1912) discovered a relation between the luminosity and the period of Cepheids' pulsation

- **Cepheids used as "standard candles"**

- **Vesto Slipher**, *"The radial velocity of the Andromeda nebula"*, Lowell Observatory Bulletin, 58, vol II:56-57 (1913)

- **Carl Wirtz** (1924) and **Knut Lundmark** (1925): further nebulae (galaxies) recede faster



Henrietta Leavitt
(1868–1921)

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

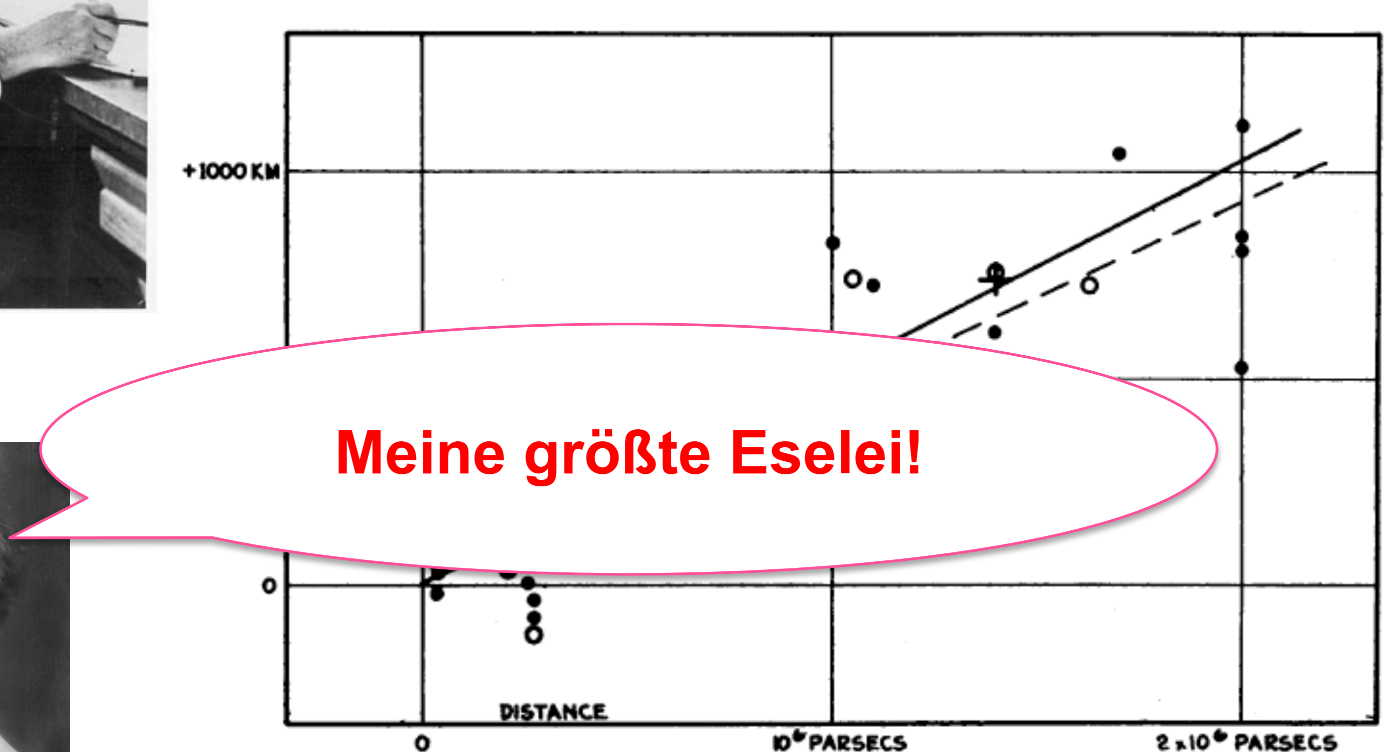
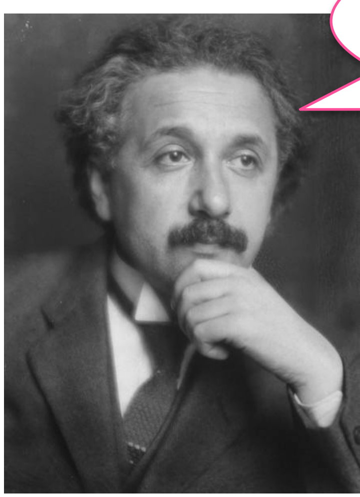


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

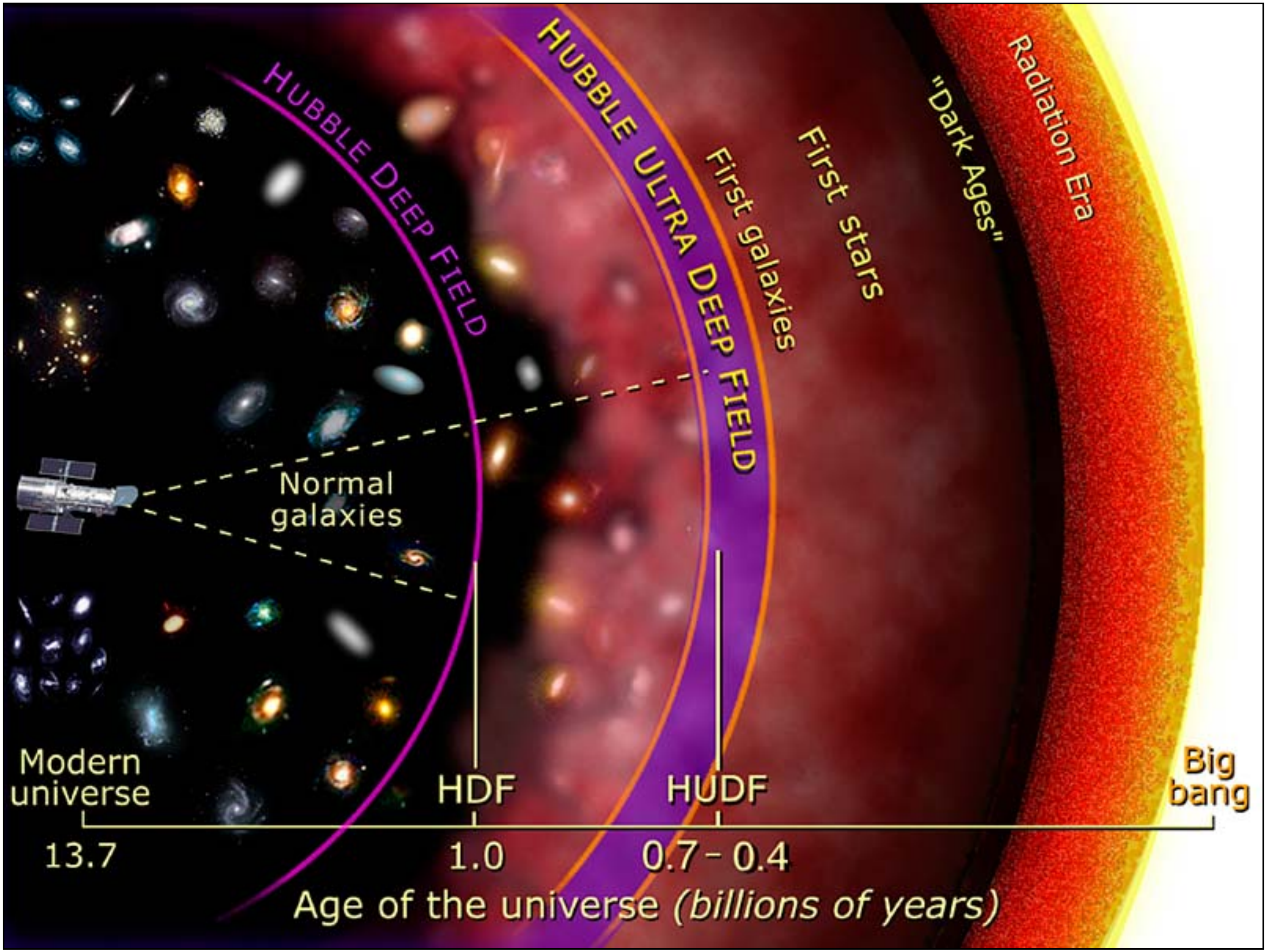


Implication of the expansion:

the universe was dense and hot in the past

We can see the evidence:

looking deep into space = looking back in time



Hubble Deep Field
Hubble Ultra Deep Field
First galaxies
First stars
"Dark Ages"
Radiation Era
Normal galaxies
Modern universe
HDF
HUDF
Big bang
13.7
1.0
0.7 – 0.4
Age of the universe (billions of years)

Live, from the **Big Bang!**

Discovery of the Cosmic Microwave Background

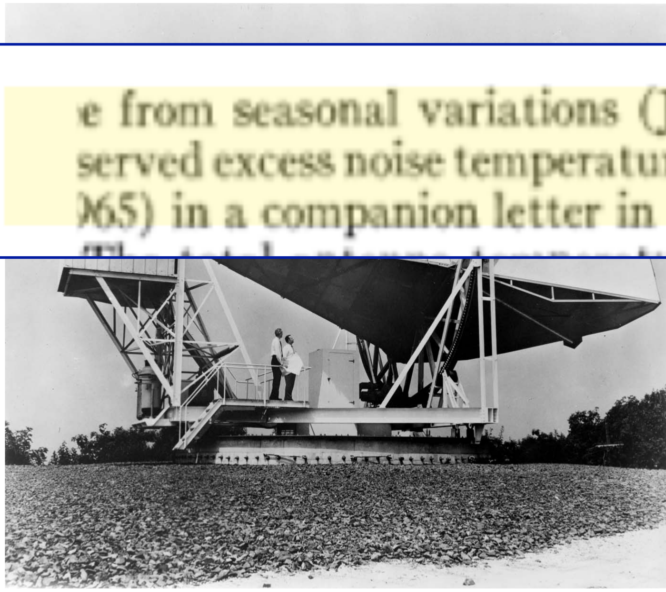
0 LETTERS TO THE EDITOR Vol. 142

e from seasonal variations (July, 1964–April, 1965). A possible explanation for the served excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson)65) in a companion letter in this issue.

The total antenna temperature measured at the zenith is 6.7° K of which 2.3 e to atmospheric absorption. The calculated contribution due to ohmic losses tenna and back-lobe response is 0.9° K.

The radiometer used in this investigation has been described elsewhere (Penzia

e from seasonal variations (July, 1964–April, 1965). A possible explanation for the served excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson)65) in a companion letter in this issue.



lues (Hogg 1959; DeGrasse, Hogg, Ohm, and Scovil 1959; Ohm 1961).

The contribution to the antenna temperature from ohmic losses is computed ° ± 0.4° K. In this calculation we have divided the antenna into three parts: (1 n-uniform tapers approximately 1 m in total length which transform betwee -inch round output waveguide and the 6-inch-square antenna throat opening; uble-choke rotary joint located between these two tapers; (3) the antenna itself s taken to clean and align joints between these parts so that they would nc icantly increase the loss in the structure. Appropriate tests were made for leakag s in the rotary joint with negative results.

The possibility of losses in the antenna horn due to imperfections in its seam minated by means of a taping test. Taping all the seams in the section near the t d most of the others with aluminum tape caused no observable change in antenna nperature.

The backlobe response to ground radiation is taken to be less than 0.1° K for two sons: (1) Measurements of the response of the antenna to a small transmitter located the ground in its vicinity indicate that the average back-lobe level is more than 30 db low isotropic response. The horn-reflector antenna was pointed to the zenith for these asurements, and complete rotations in azimuth were made with the transmitter in ch of ten locations using horizontal and vertical transmitted polarization fr sition. (2) Measurements on smaller horn-reflector antennas at these labo using pulsed measuring sets on flat antenna ranges, have consistently shown a b level of 30 db below isotropic response. Our larger antenna would be expected to even lower back-lobe level.

From a combination of the above, we compute the remaining unaccounted-for temperature to be 3.5° ± 1.0° K at 4080 Mc/s. In connection with this result i be noted that DeGrasse *et al.* (1959) and Ohm (1961) give total system tempera 5650 Mc/s and 2390 Mc/s, respectively. From these it is possible to infer upper the background temperatures at these frequencies. These limits are, in both case same general magnitude as our value.

We are grateful to R. H. Dicke and his associates for fruitful discussions of sults prior to publication. We also wish to acknowledge with thanks the useful co and advice of A. B. Crawford, D. C. Hogg, and E. A. Ohm in connection w problems associated with this measurement.

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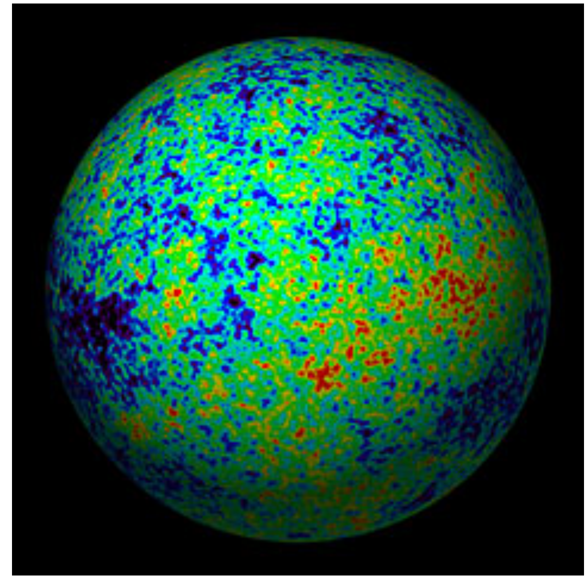
Crawford, A. B., Hogg, D. C., and Hunt, L. E. 1961, *Bell System Tech. J.*, **40**, 1095.
DeGrasse, R. W., Hogg, D. C., Ohm, E. A., and Scovil, H. E. D. 1959, "Ultra-low Noise Receiving System for Satellite or Space Communication," *Proceedings of the National Electronics Conference*, **15**, 370.
Dicke, R. H., Peebles, P. J. E., Roll, P. G., and Wilkinson, D. T. 1965, *Ap. J.*, **142**, 414.
Hogg, D. C. 1959, *J. Appl. Phys.*, **30**, 1417.
Ohm, E. A. 1961, *Bell System Tech. J.*, **40**, 1065.
Pauliny-Toth, I. I. K., and Shakeshaft, J. R. 1962, *M.N.*, **124**, 61.
Penzias, A. A. 1965, *Rev. Sci. Instr.*, **36**, 68.
Penzias, A. A., and Wilson, R. W. 1965, *Ap. J.* (in press).

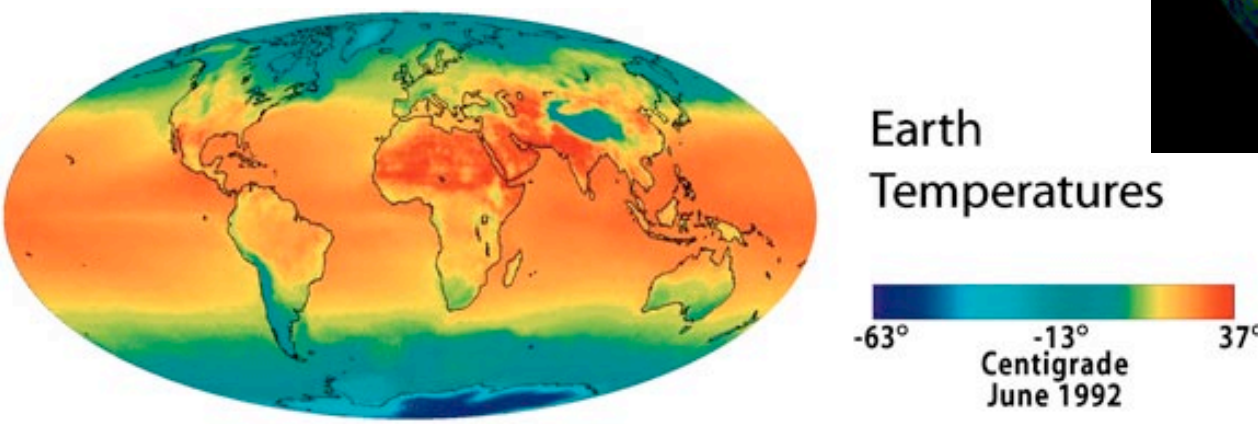
A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

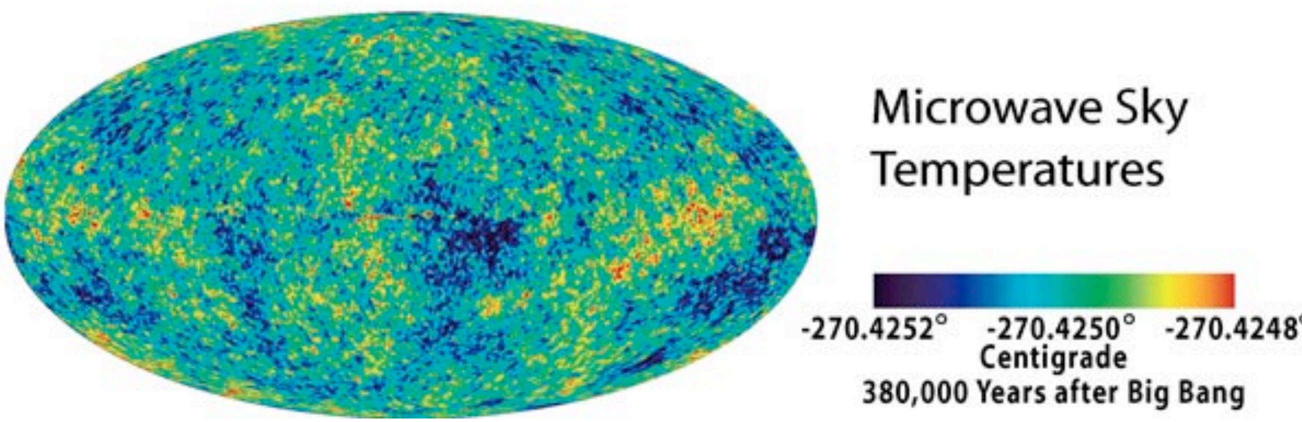
Measurements of the effective zenith noise temperature of the 20-foot horn-re antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Ho New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected excess temperature is, within the limits of our observations, isotropic, unpolarize

1965: A. Penzias and R. W. Wilson of Bell Labs
1978 Nobel Prize in Physics

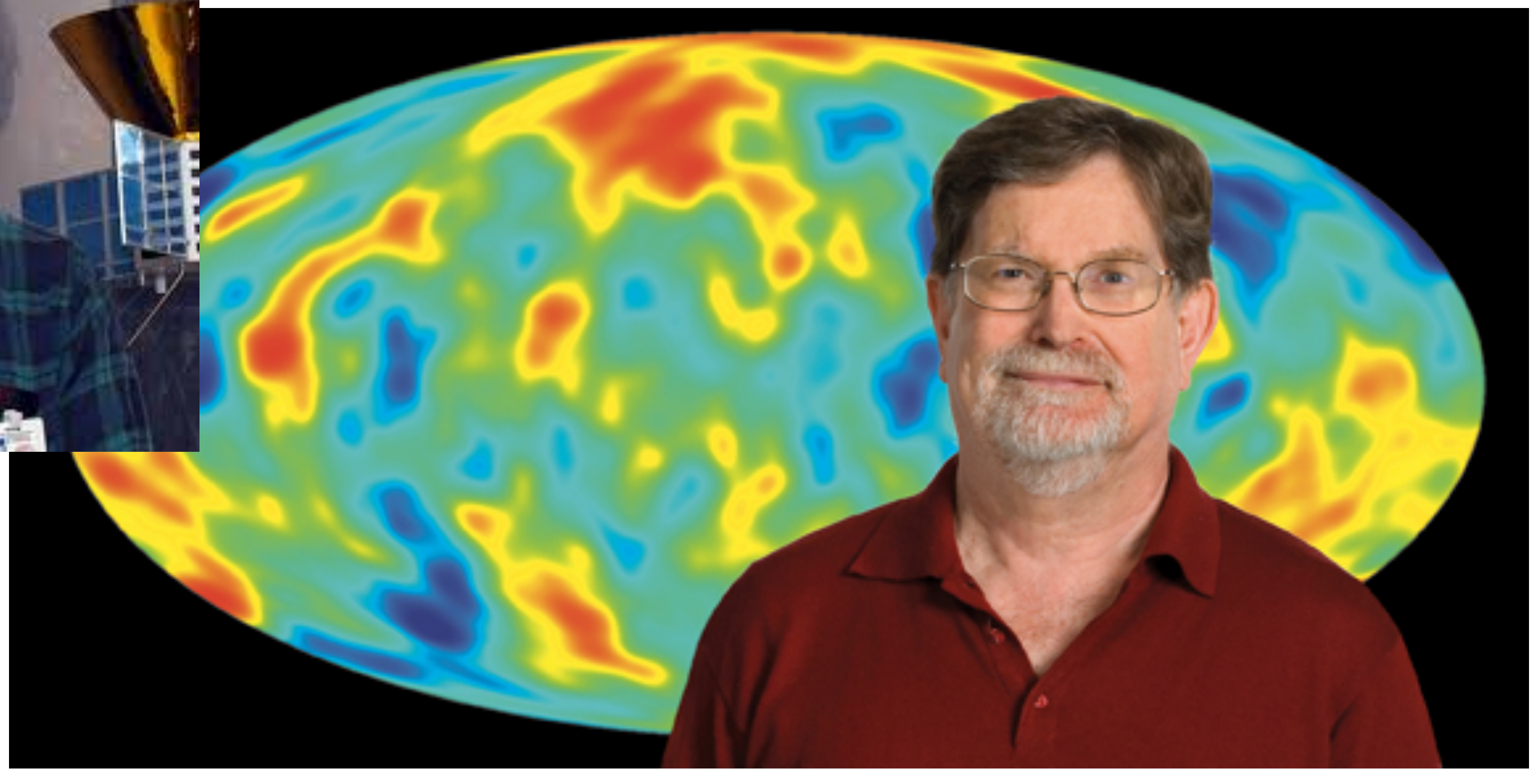
The map




Earth
Temperatures
-63°
-13°
37°
Centigrade
June 1992


Microwave Sky
Temperatures
-270.4252°
-270.4250°
-270.4248°
Centigrade
380,000 Years after Big Bang

1992 COBE



John Mather and George Smoot, 2006 Nobel Prize in Physics

The wild 90's

- Working model based on a flat, expanding, decelerating universe
- Only 10%-50% of total energy in the universe is due to matter, where is the rest?
- The Age Problem: some stars are older then the universe

THE COSMOLOGICAL CONSTANT IS BACK

Lawrence M. Krauss[1] and Michael S. Turner[2,3]

As we shall discuss, the observational case for a cosmological constant is so compelling today that it merits consideration in spite of its checkered history. On the theoretical side the value of the cosmological constant remains extremely puzzling, and it just could be that cosmology will provide a crucial clue. Fortunately, there are observations that should settle the issue sooner rather than later.

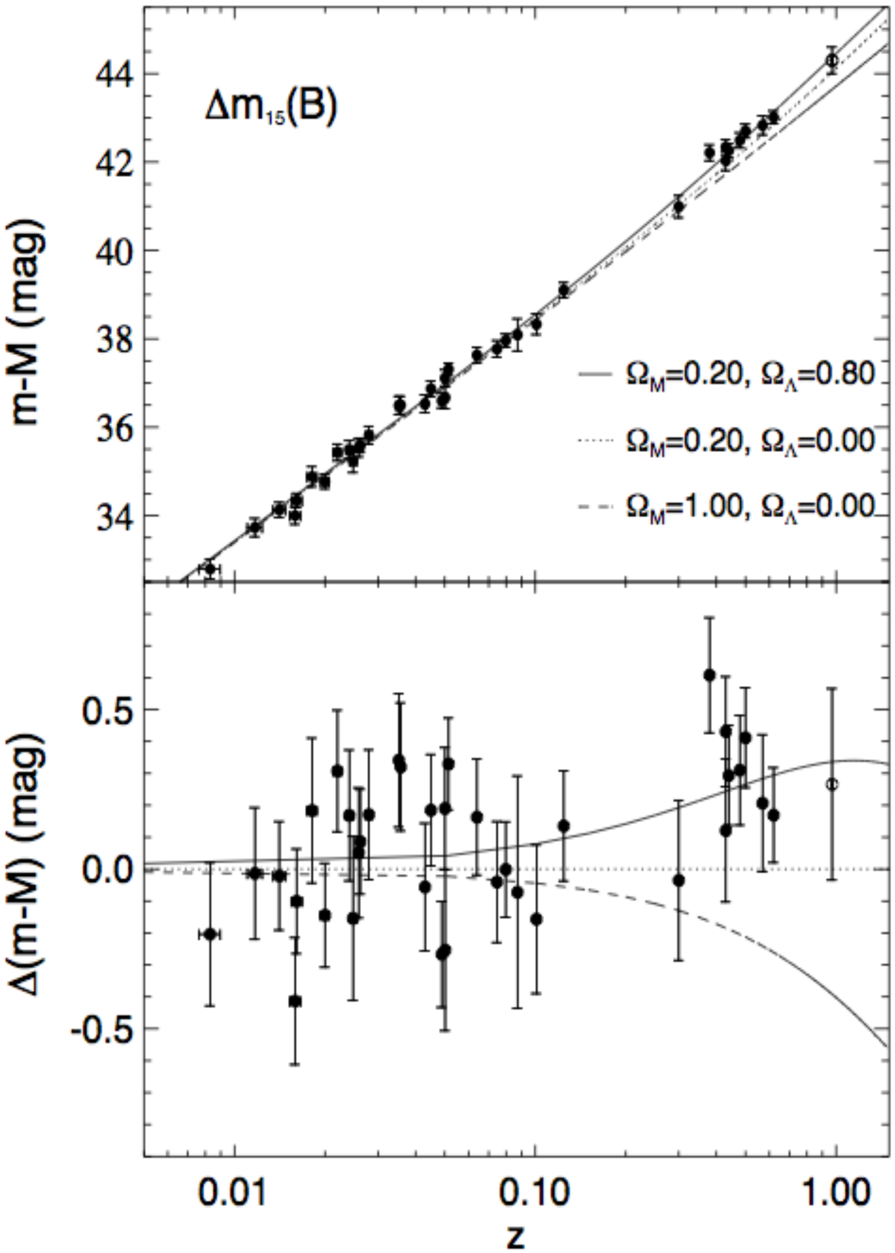
[3]*NASA/Fermilab Astrophysics Center*
Fermi National Accelerator Laboratory, Batavia, IL 60510-0500

(submitted to *Gravity Research Foundation Essay Competition*)

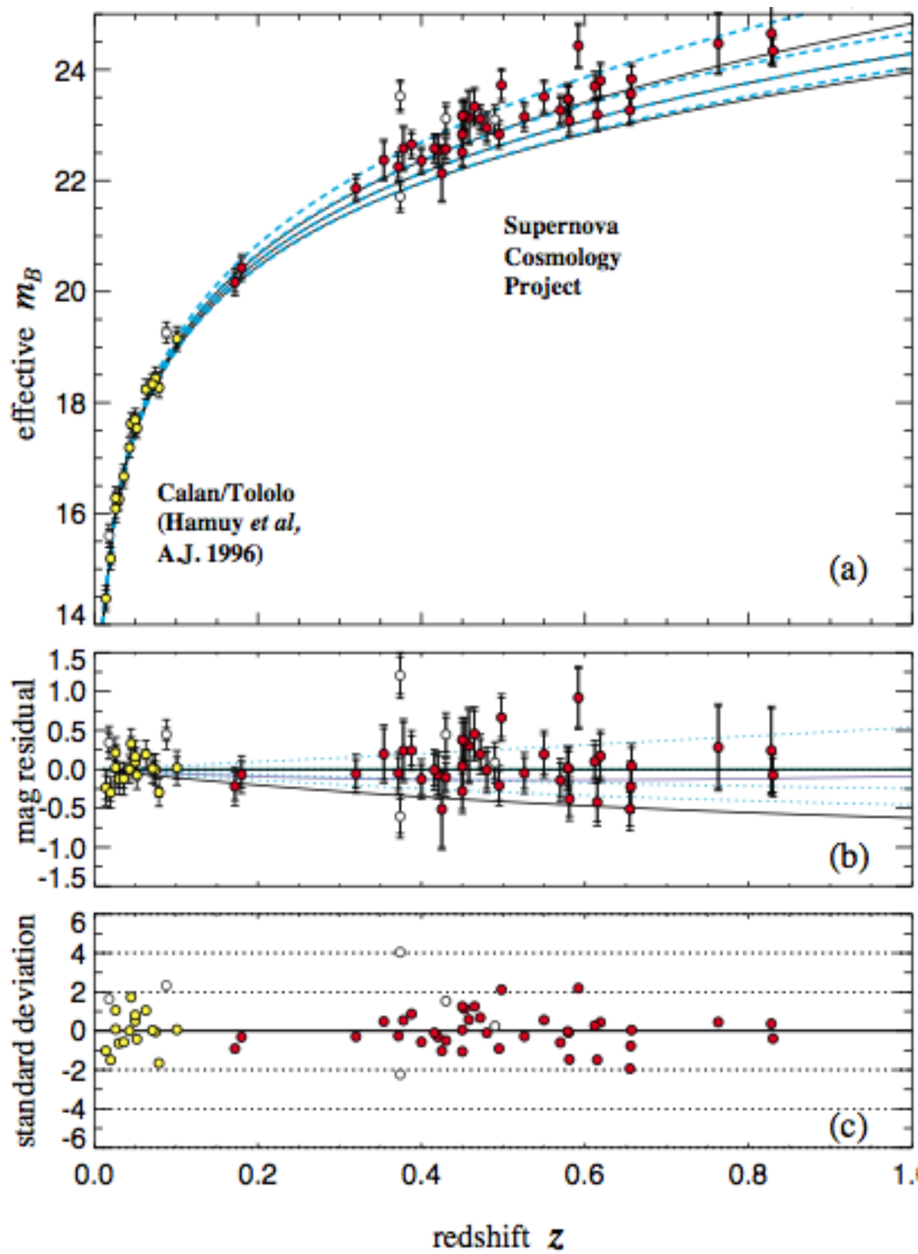
SUMMARY

A diverse set of observations now compellingly suggest that Universe possesses a nonzero cosmological constant. In the context of quantum-field theory a cosmological

1998: the evidence

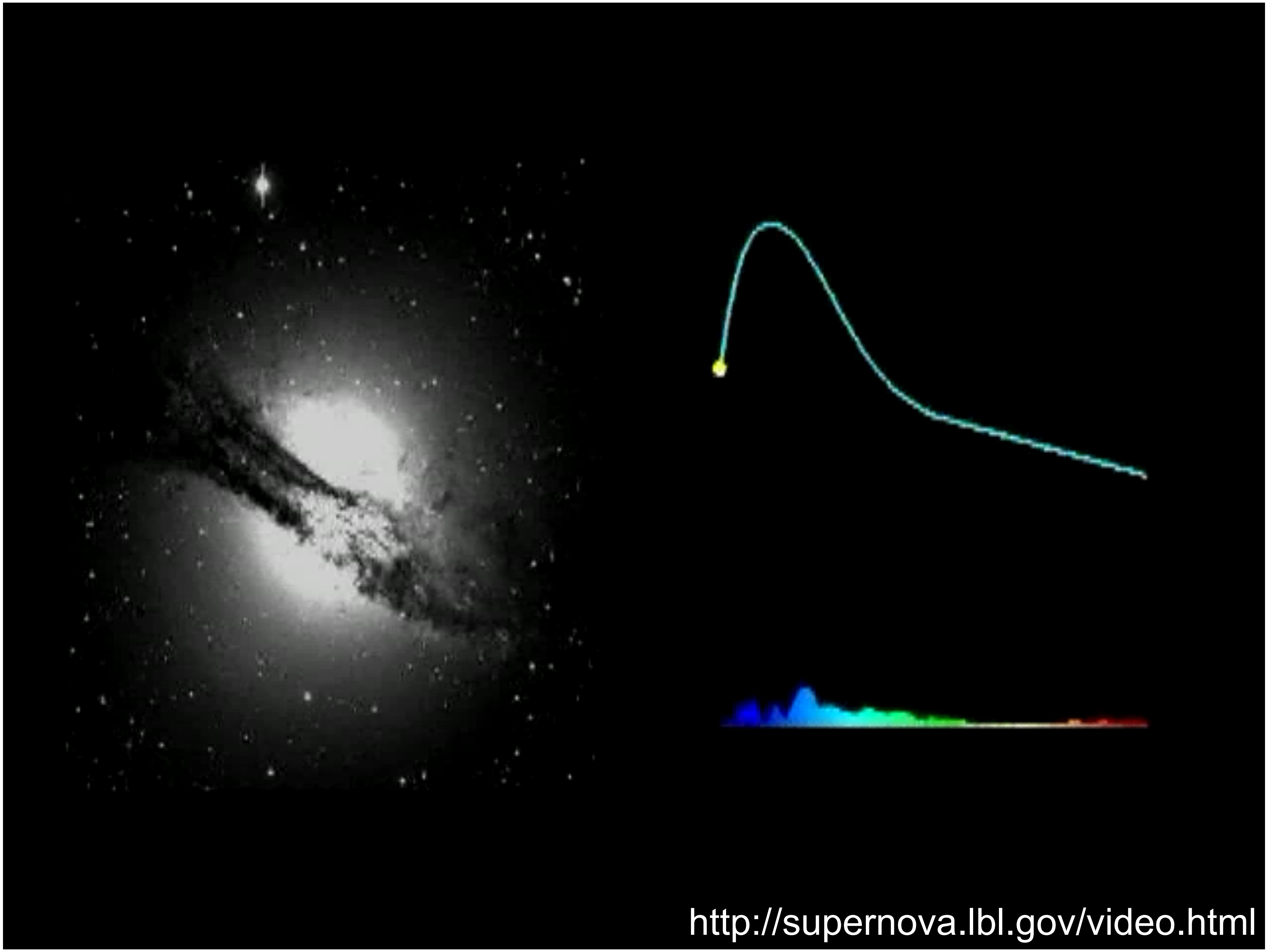


A. Riess et al, Astron.J.116:1009-1038 (1998)



S. Perlmutter, Astrophys.J.517:565-586 (1999)

Standard Candles: Supernovae Type IA



Supernovae on Demand

Saul Perlmutter's idea:

Look at thousands of galaxies for 2-3 nights every 2-3 weeks with a wide-field imager. Follow up with spectroscopy, scheduled in advance

Saul Perlmutter starts the Supernovae Cosmology Project in 1988

Brian Schmidt starts the High-Z SN Search Team in 1994

Adam Riess leads the analysis for HZT

By 1998, SCP reported 42 reliable SNIa, HZT added another 16

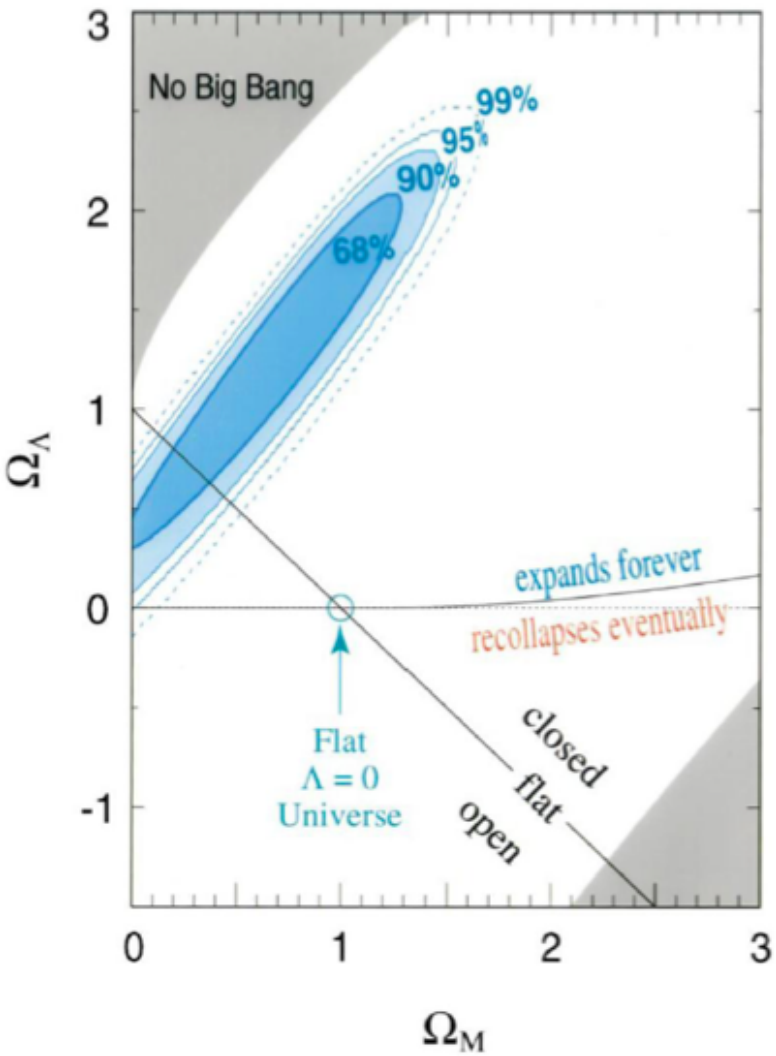
Key pieces of information

The redshift of the host galaxy

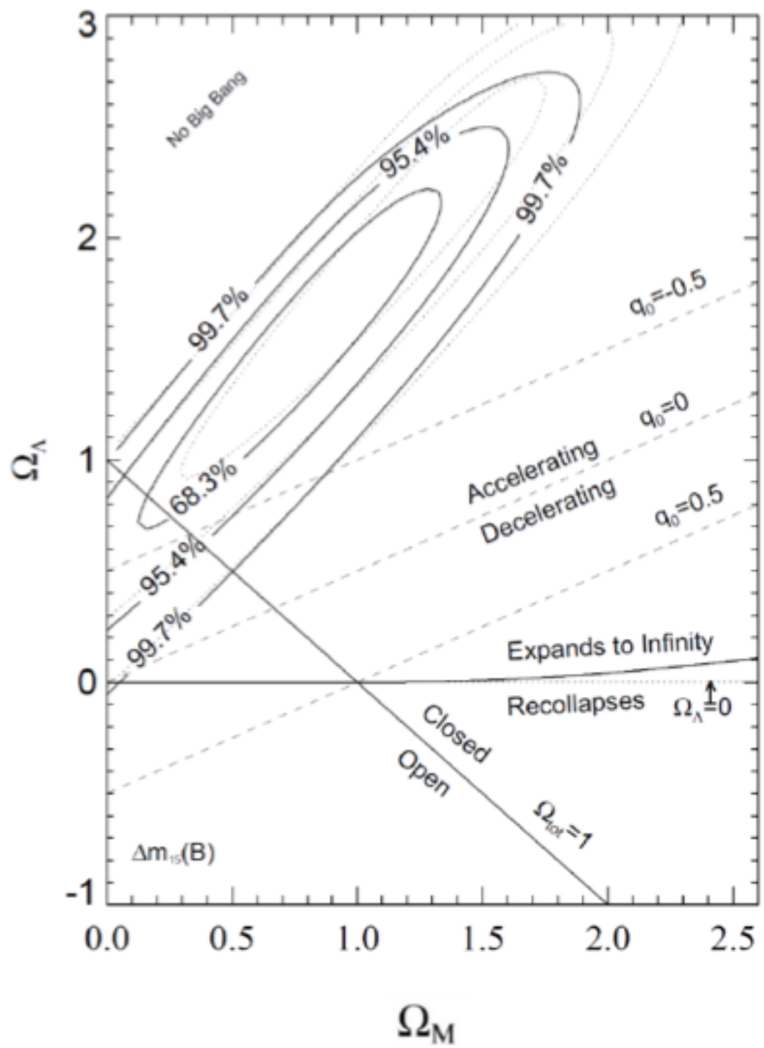
The distance to the supernovae

$$\text{Observed Luminosity} = \frac{\text{Intrinsic Luminosity}}{4\pi\ \text{Distance}^2} = \frac{L}{4\pi d_L^2}$$

Use Einstein's equations to find the expansion history and the content of the universe from the way distance changes with redshift



S. Perlmutter, Astrophys.J.517:565-586 (1999)



A. Riess et al, Astron.J.116:1009-1038 (1998)

2011 Nobel Prize in Physics

Photo: Ariel Zambelich, Copyright © Nobel Media AB

Saul Perlmutter

Photo: Belinda Pratten, Australian National University

Brian P. Schmidt

Photo: Homewood Photography

Adam G. Riess

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"*.

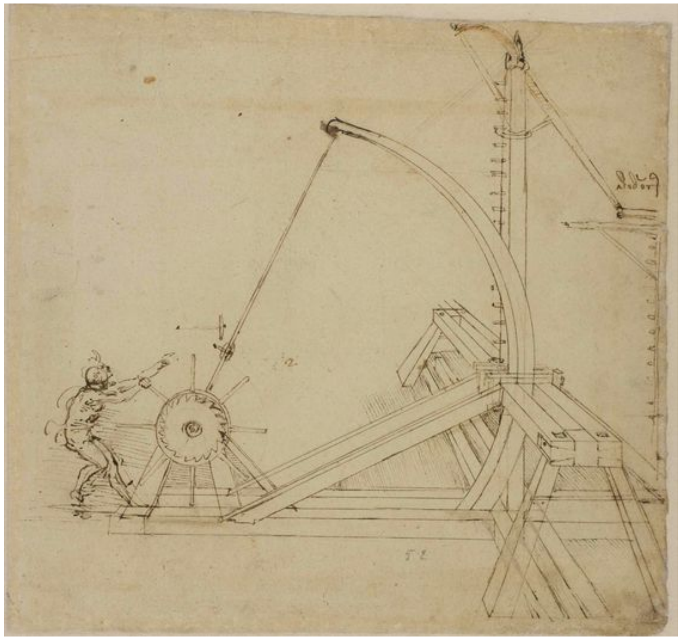
Why is it accelerating?

Lambda is a constant energy density of empty space

Vacuum energy is persistent, it is a feature of space itself
(the vacuum density does not decrease with expansion)

Constant vacuum density = constant curvature

Curvature causes acceleration



How much energy is in the vacuum?

Observations measure the sum of vacuum energy and Lambda

$$\rho_{\mathrm{obs}}^{(\mathrm{vac}+\Lambda)} \approx 2.4 \times 10^{-12}\ \mathrm{kCal/m^3}$$

Quantum theory predicts a huge vacuum energy

$$\rho_{\mathrm{theory}}^{(\mathrm{vac})} \sim 10^{120} \rho_{\mathrm{obs}}^{(\mathrm{vac}+\Lambda)}$$

Something is NOT right

The Two Cosmological Constant Problems

THE OLD PROBLEM:

What is the vacuum energy and how does it gravitate?

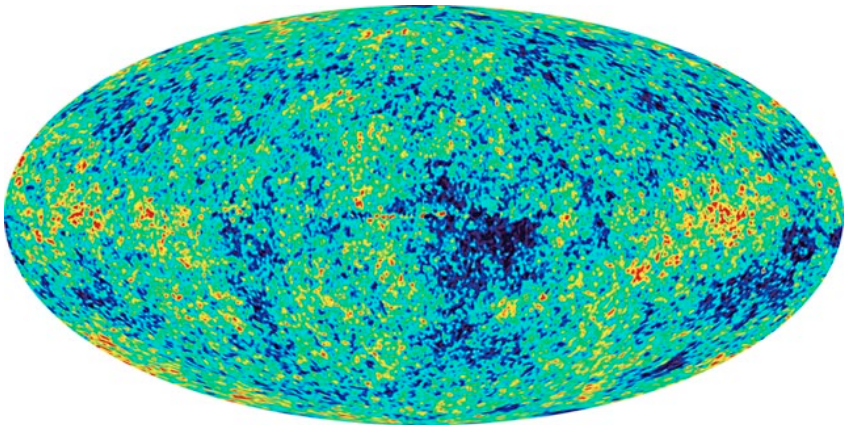
THE NEW PROBLEM (Dark Energy)

What sets the observed value of Lambda?

The only existing “solution” to both problems is “anthropic”
(Weinberg 1989, Vilenkin 1995):

IF Lambda could take on ANY value, its value should be consistent
with existence of galaxies like ours

Since 1998



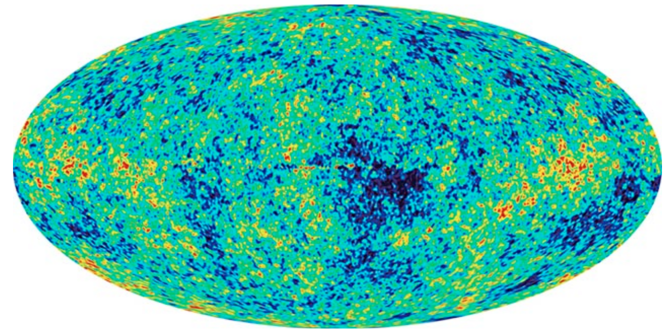
WMAP and Planck satellite provided spectacular CMB measurements

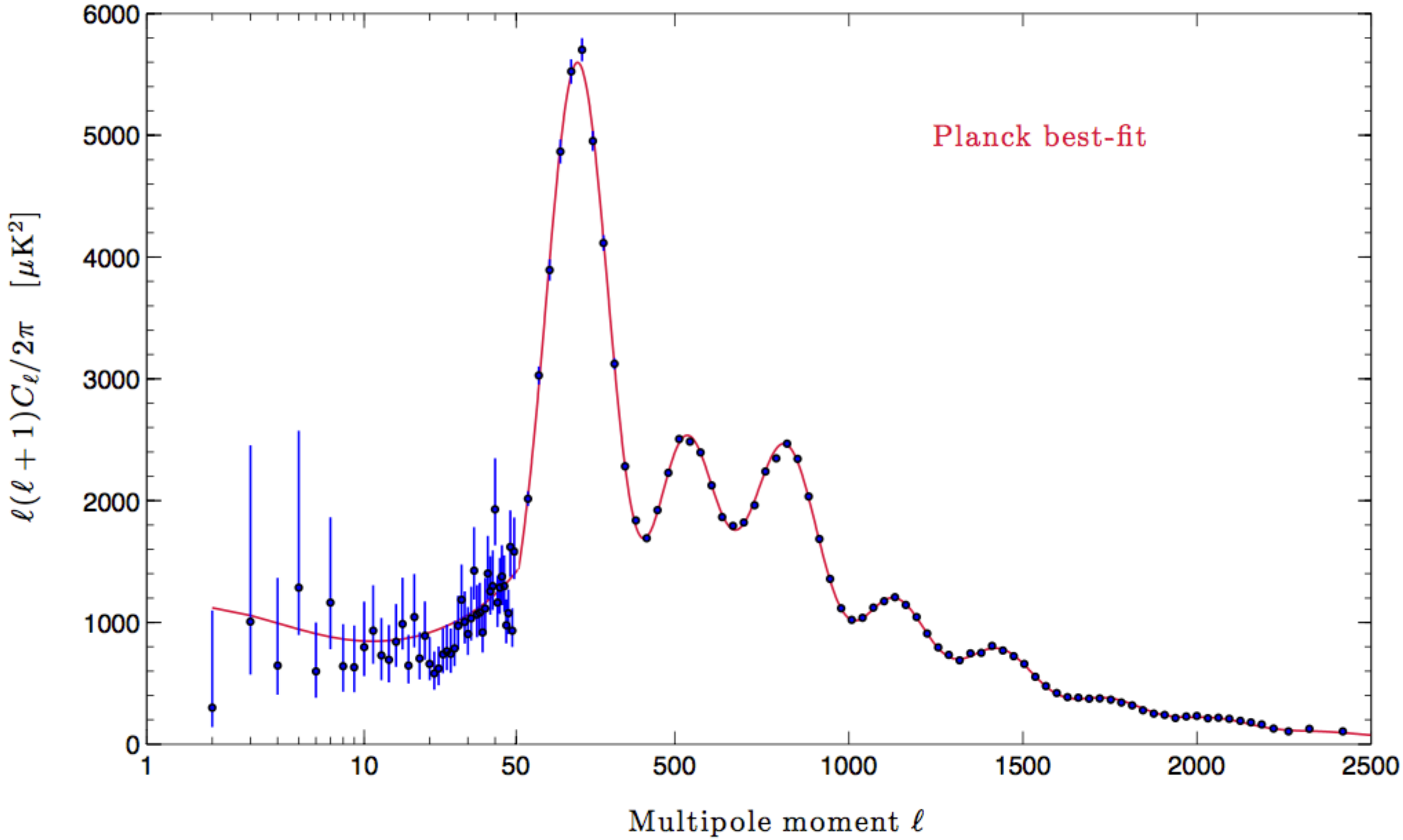
Sloan Digital Sky Survey provided millions of galaxy redshifts

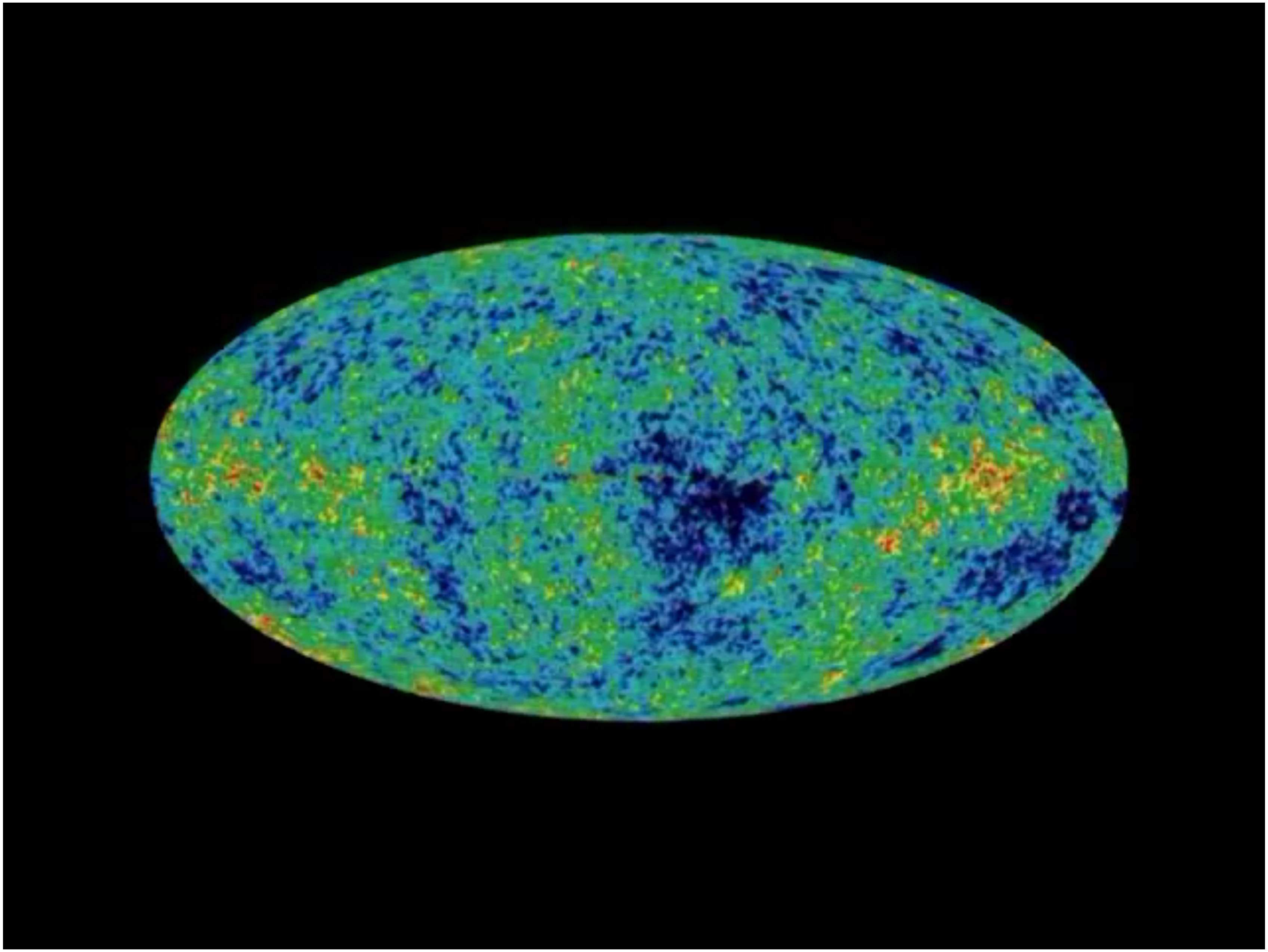
Around 1000 supernovae, compared to 42+17 in 1998

We have a working model of the visible universe

CMB Theory vs Data







Credit: NASA

Need dark matter

Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)

Inhaltsangabe. Diese Ar
male extragalaktischer Nebel,
selben gedient haben. Insbes
tischer Nebel eingehend disku
dieses wichtigen Phänomens
Schliesslich wird angedeutet,
der durchdringenden Strahlu

Gravitational mass of the galaxies within the Coma cluster are at least 400 times greater than expected from their luminosity.

Rotverschiebung extragalaktischer Nebel. 125

Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

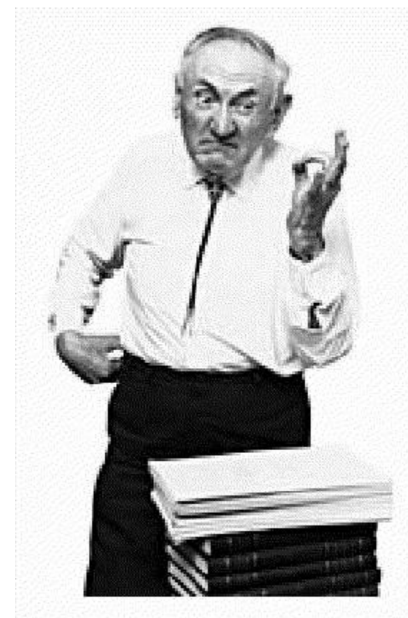
VOLUME 86 OCTOBER 1937 NUMBER 3

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

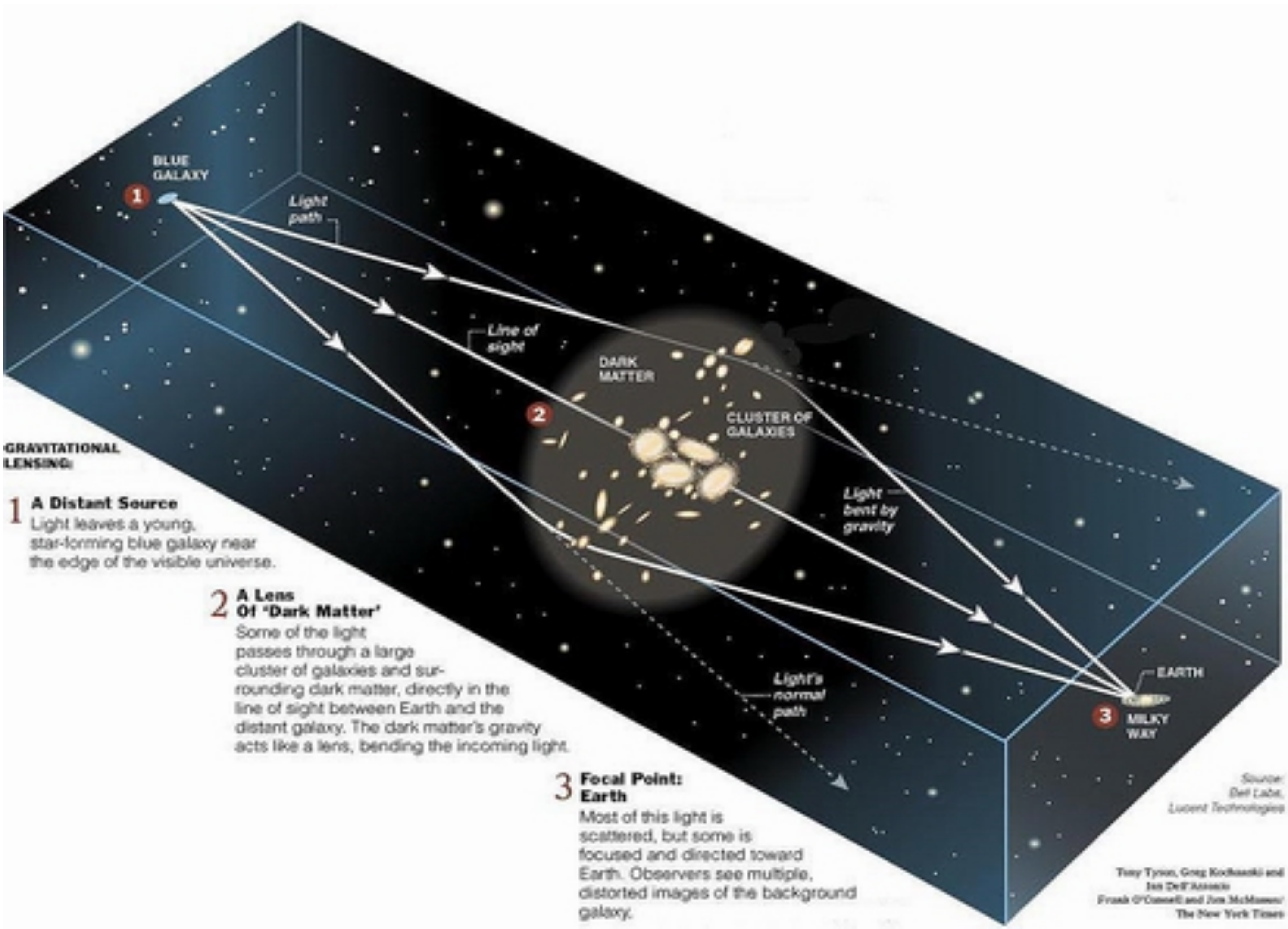
IV. NEBULAE AS GRAVITATIONAL LENSES

As I have shown previously,[6] the probability of the overlapping of images of nebulae is considerable. The gravitational fields of a number of "foreground" nebulae may therefore be expected to deflect the



Fritz Zwicky
(1898 –1974)

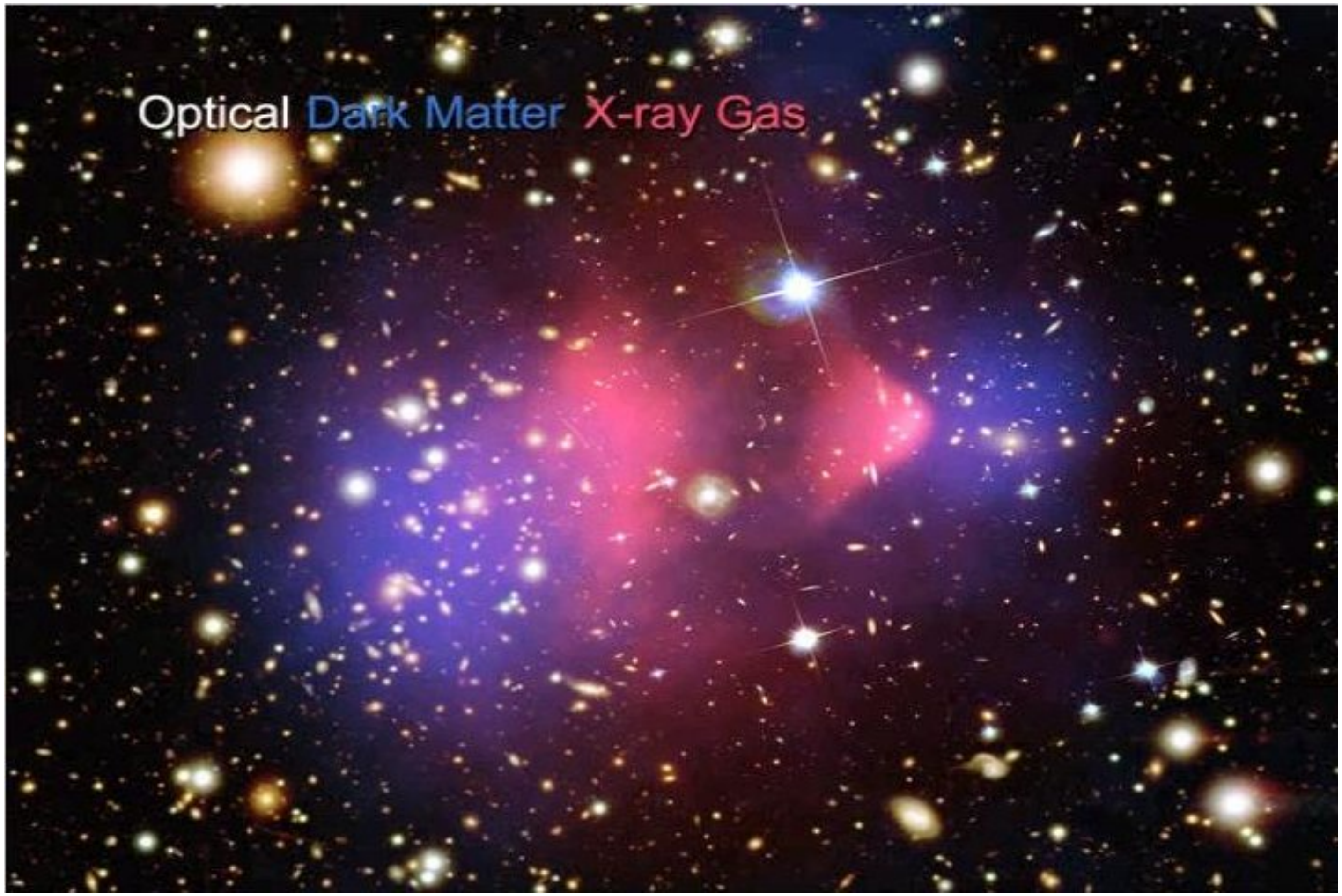
Gravity Bends Light



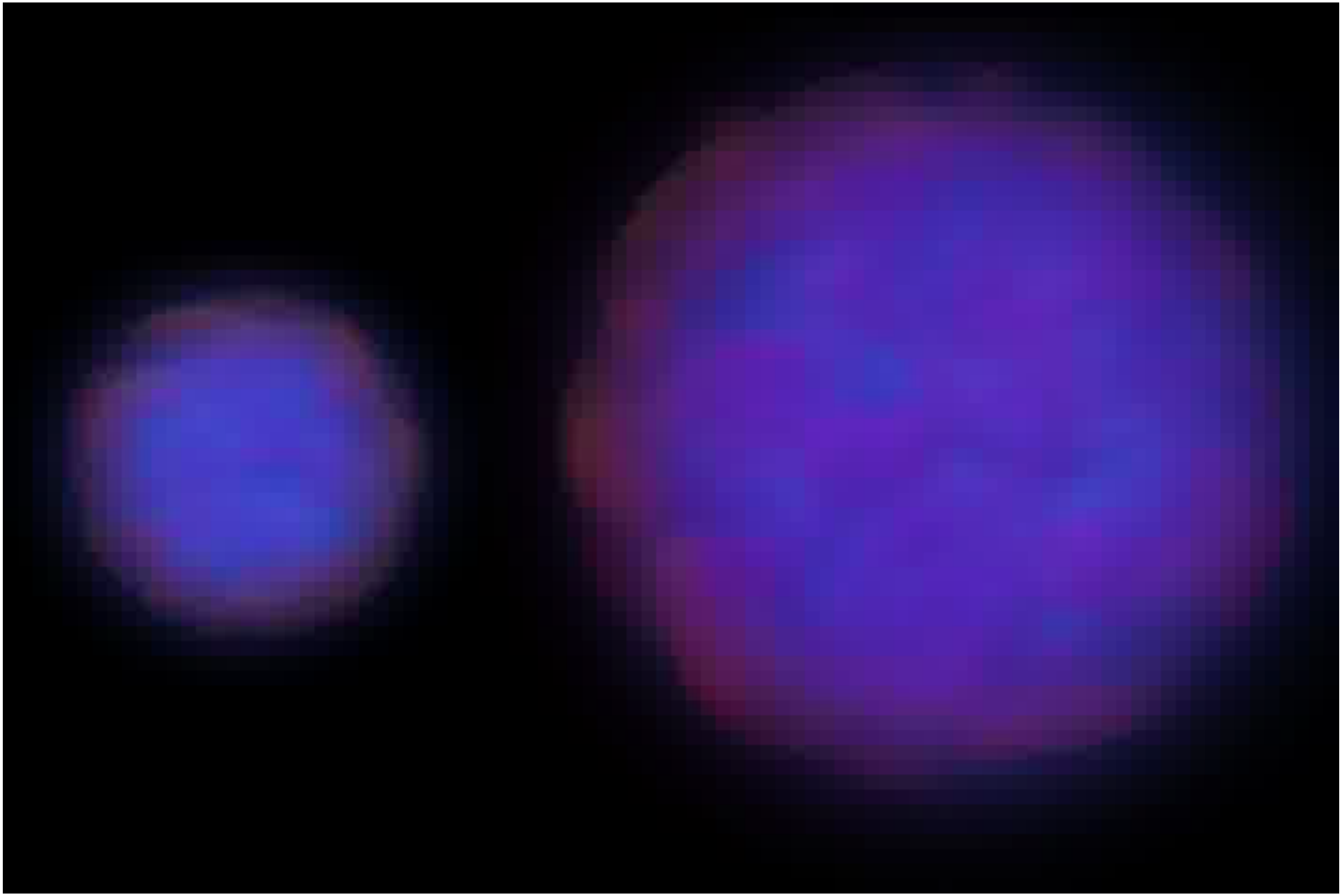
Gravitational Lensing

from Hubble telescope

The “Bullet” cluster



Chandra, VLT, Hubble, Magellan, 2006



Credit: NASA/CXC/M.Weiss

A working theory of an accelerating universe

two key ingredients:

Dark Matter (25%)
Dark Energy (70%)

just a couple of remaining unknowns:

Dark Matter
Dark Energy

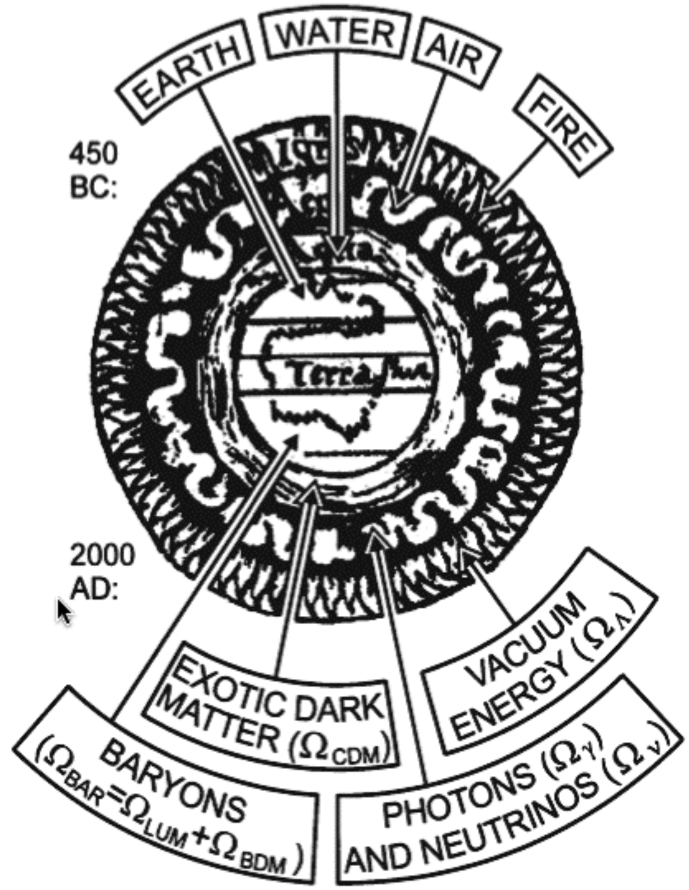


Fig. 1. The "four elements" of modern cosmology (adapted from a figure in a 1519 edition of Aristotle's *Libri de Caelo*)

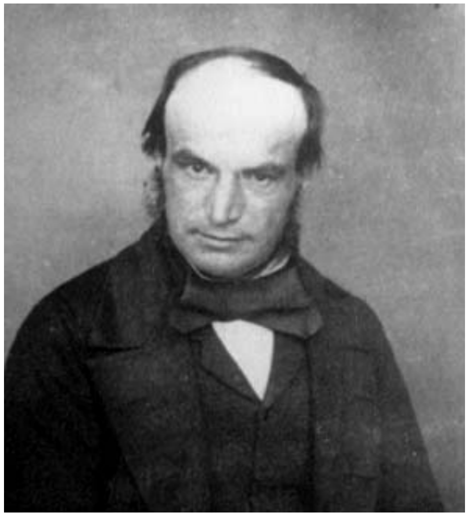
Is there a reason to doubt Einstein?

Dark Matter vs Modified Gravity

1:0

Discovery of Neptune in 1846

Urbain Jean Joseph Le Verrier
1811 – 1877



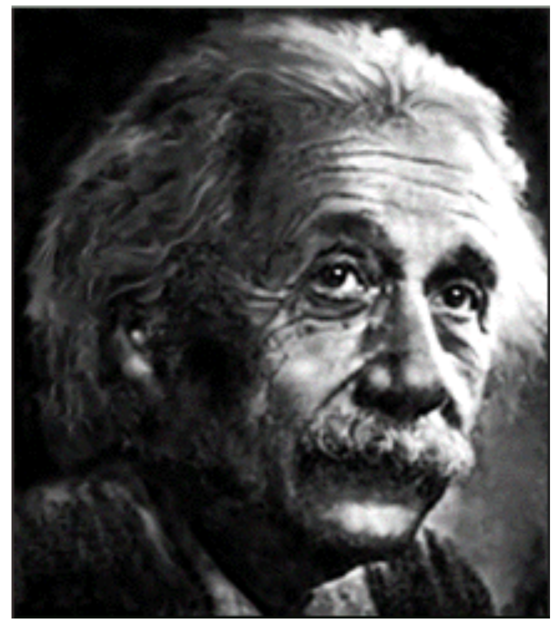
John Couch Adams
1819-1892

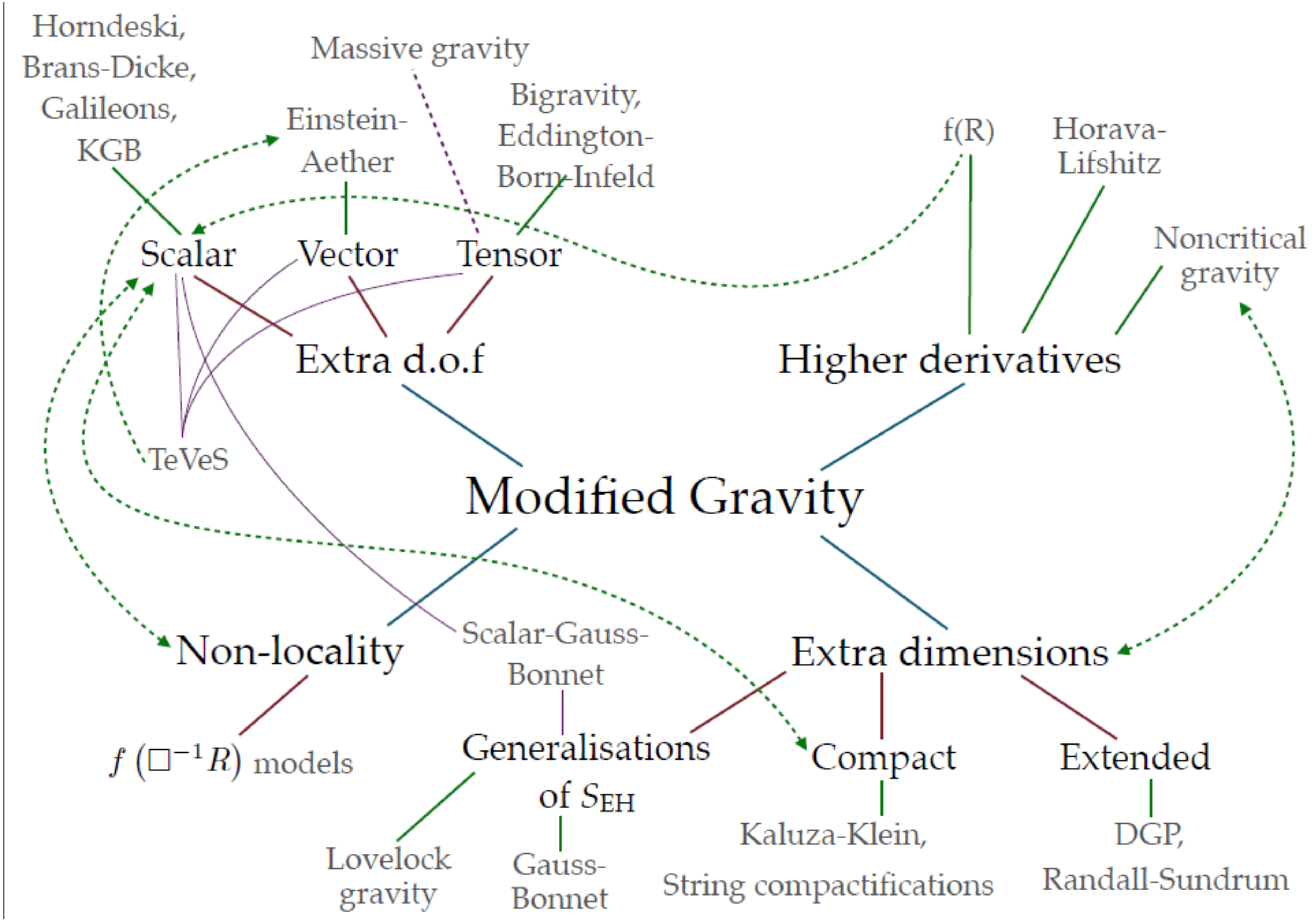
Dark Matter vs Modified Gravity

1:1

Precession of Mercury’s perihelion

Urbain Jean Joseph Le Verrier
1811 – 1877





Credit: Tessa Baker's PhD Thesis

The Smoking Gun of Modified Gravity

"Spacetime tells matter how to move; matter tells spacetime how to curve."

John A. Wheeler (1911-2008)

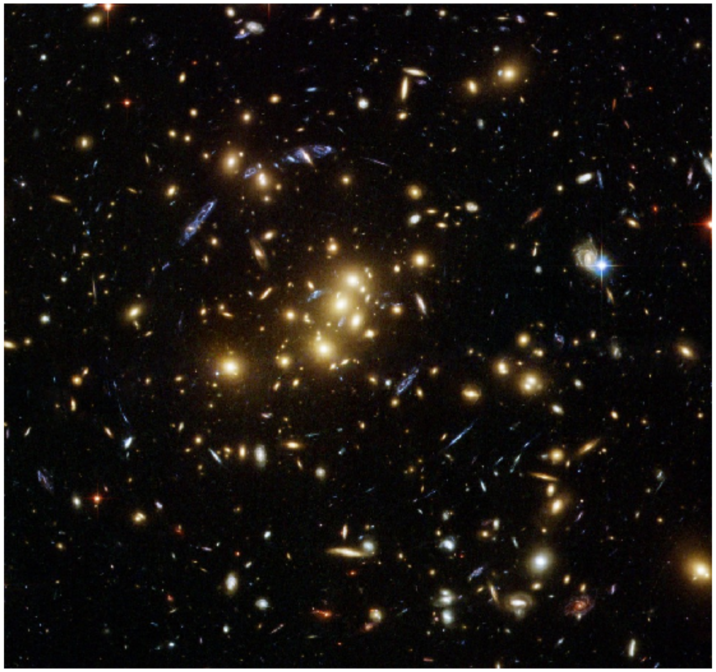
Einstein: photons (light) and free falling matter follow same paths

General Relativity posits that the curvature of space is the same as the gravitational potential

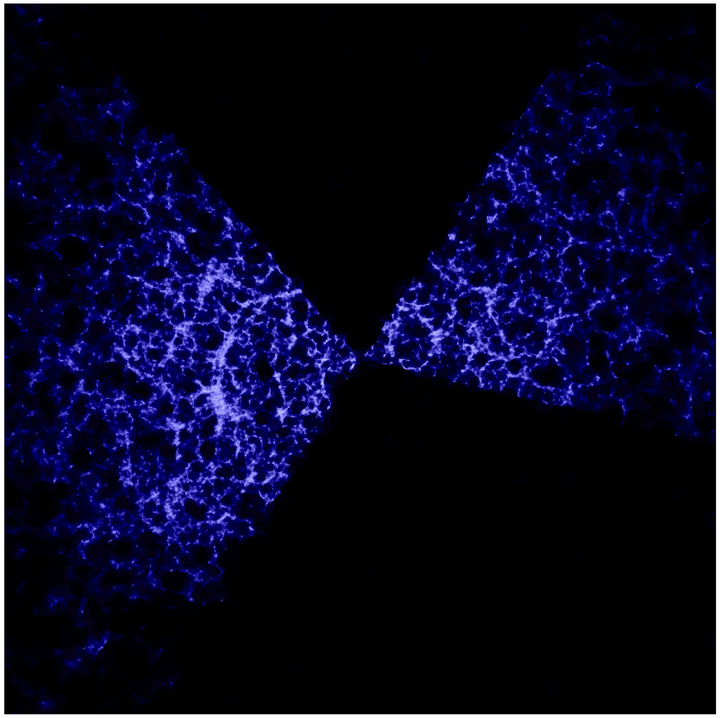
In modified gravity theories the two are typically different

Check if trajectories of light are consistent with the motion of matter

How?



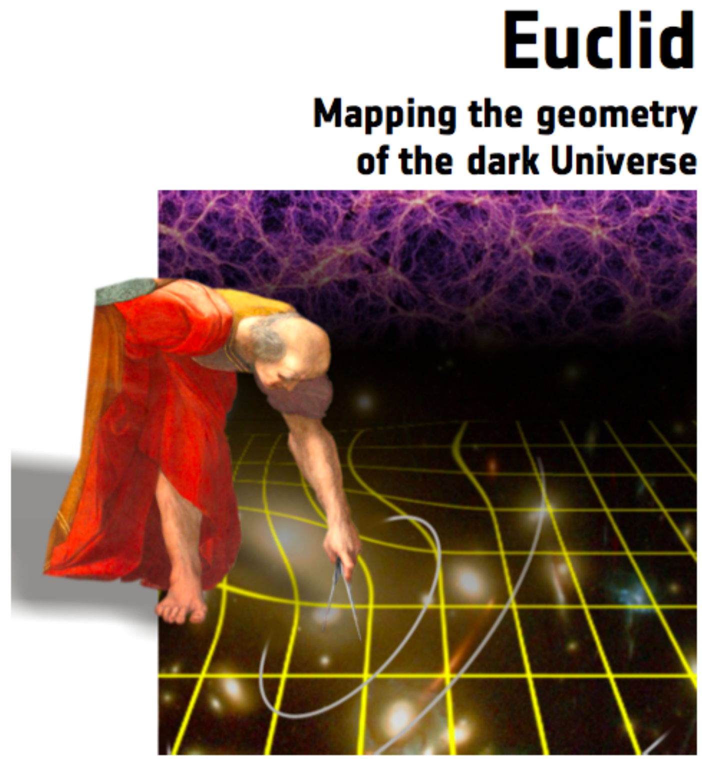
By studying lensed images of distant galaxies we test trajectories of light



By studying redshifts of galaxies we test the motion of matter

Dark Energy Survey (DES) ongoing

- Blanco 4-meter telescope
- 5 years
- galaxy shapes, photo-z’s, redshifts, SNe

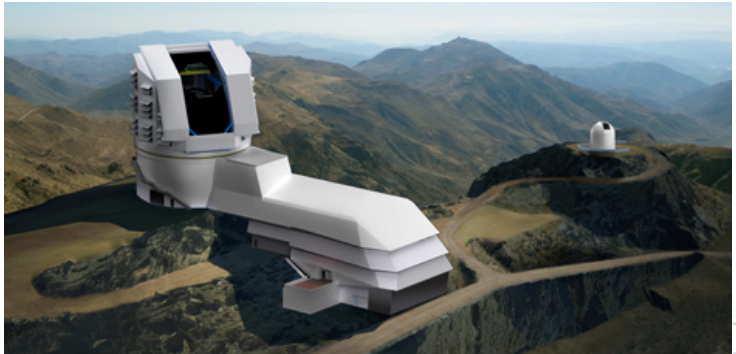


Euclid, ESA, 2019 launch

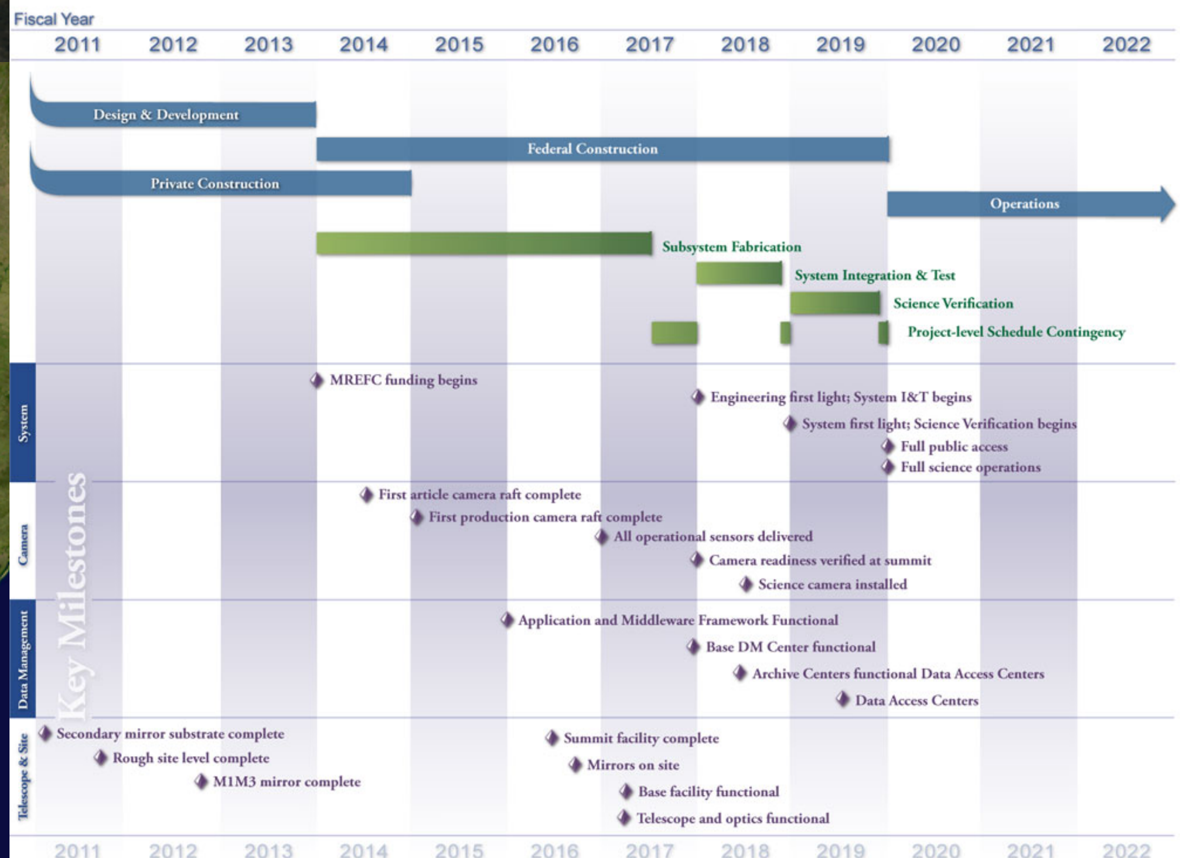
- L2 Orbit
- 5-6 year mission
- galaxy shapes, photo-z’s, redshifts

Large Synoptic Survey Telescope

the widest, fastest, deepest eye of the new digital age



- 8.4 meter mirror
- half of the sky to redshift z=3
- galaxy shapes, photo-z's, SNe



Summary

100 years of scientific breakthroughs and big surprises

Acceleration of cosmic expansion is beyond reasonable doubt

- Einstein's theory of General Relativity is yet to be seriously tested outside our solar system
- We do not know how Vacuum gravitates
- We do not know what Dark Matter is

A key test of Einstein:

- Differences between trajectories of light and matter
- New data is coming, big potential for new discoveries