Space, Time and Matter

Robert Brandenberger
McGill University

Fall 2021

Outline

Goals of the Class

- Starting point: Newton's classical view of space, time and matter
- The three revolutions of 20th century physics
- Special Relativity: unification of space and time
- General Relativity: space-time not absolute
- Quantum Mechanics: overturns classical view of matter.
- $\rightarrow$ technology revolution.
- New challenges for physics of the 21st century
- In search of a new revolution: flavour of current forefront research

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Texts

- E. R. Harrison, *Cosmology*, second edition (Cambridge Univ. Press, Cambridge, 2000).
- P.C.W. Davies, *Space and Time in the Modern Universe*, (Cambridge Univ. Press, Cambridge, 1977).
- R. Stannard, *The New World of Mr. Tompkins* (Cambridge Univ. Press, Cambridge, 1999).
- Brian Greene, *The Elegant Universe* (W.H. Norton, New York, 1999).
- R. Feynman, *Six Easy Pieces* (Basic Books, 2005).

Format

- Lectures - focusing on the important concepts
- Independent reading
- Homework sets (roughly bi-weekly)
- Final essay
- Office hours: TBA (via zoom, see Outline on myCourses)

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Grading Scheme

- Homework sets: 40%
- Midterm exam (in class): 15%
- Final essay: 15%
- Final exam (3 hrs): 30%

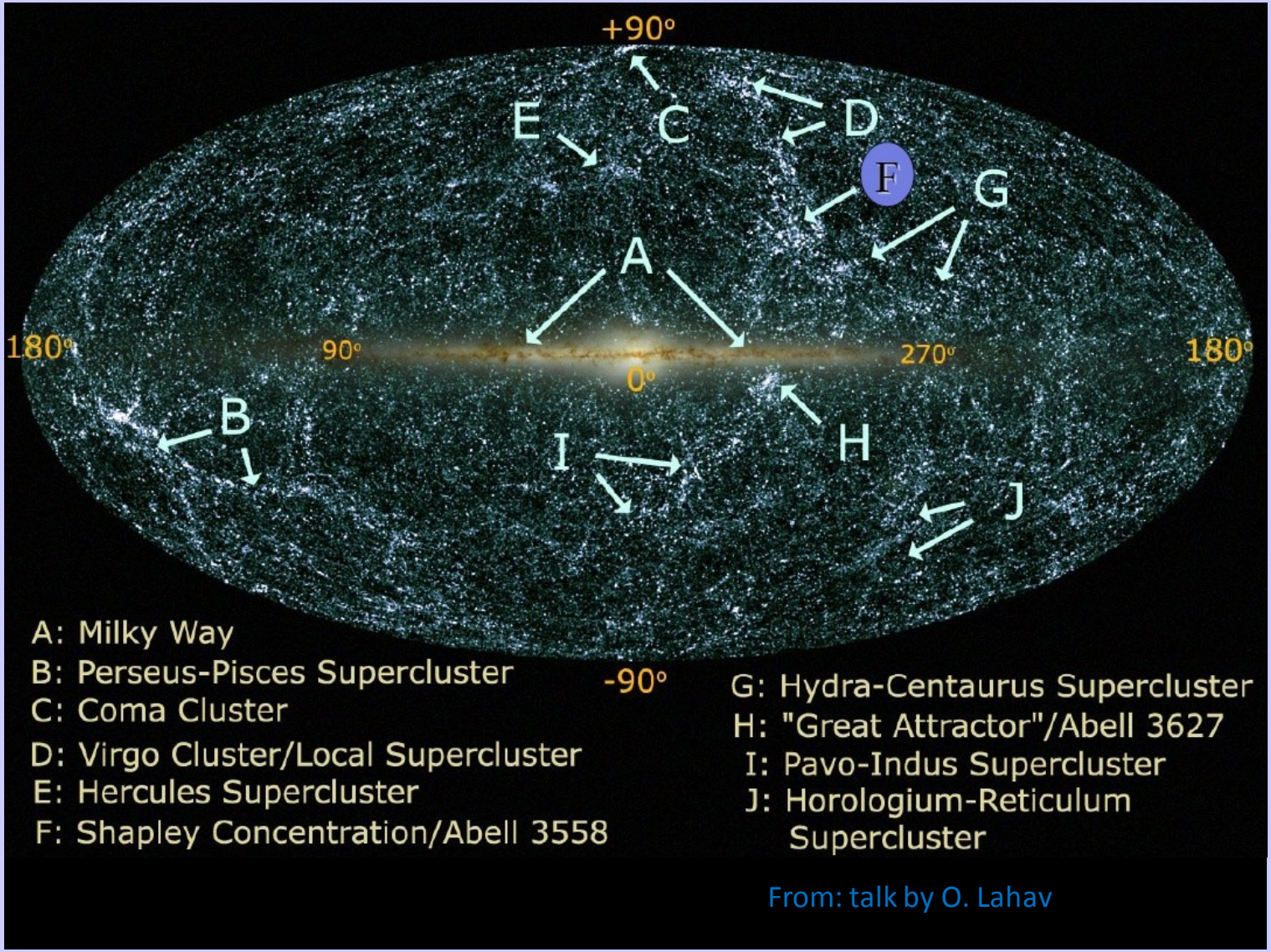
My Research: Theoretical Cosmology

1. Understand origin and early evolution of the universe.
   - What is the “Big Bang"?
   - Was there a “Big Bang"?
   - What was before the “Big Bang"?

Optical Telescopes: Gemini Telescope

Galaxies: Building Blocks of the Cosmology

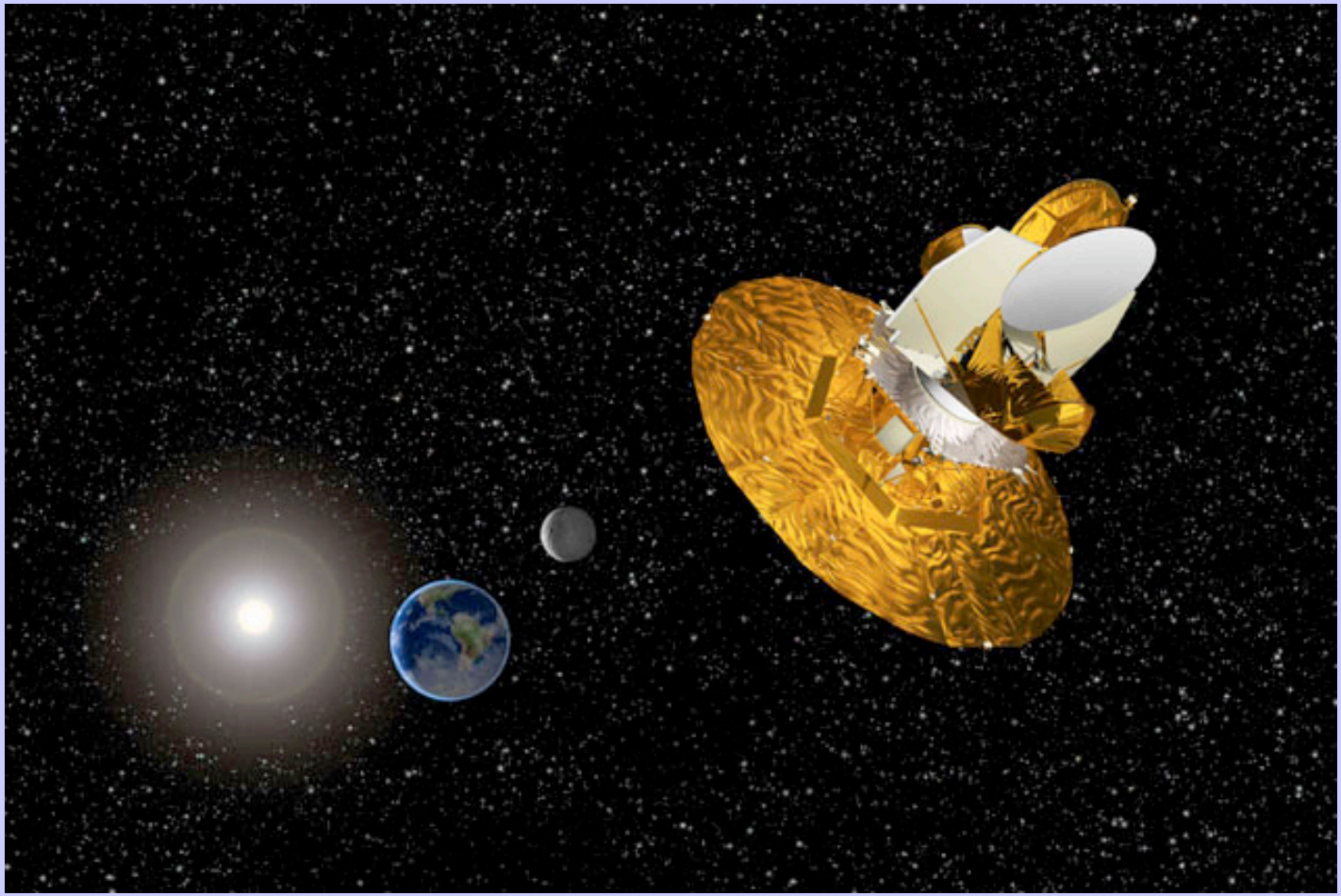
Large-Scale Structure



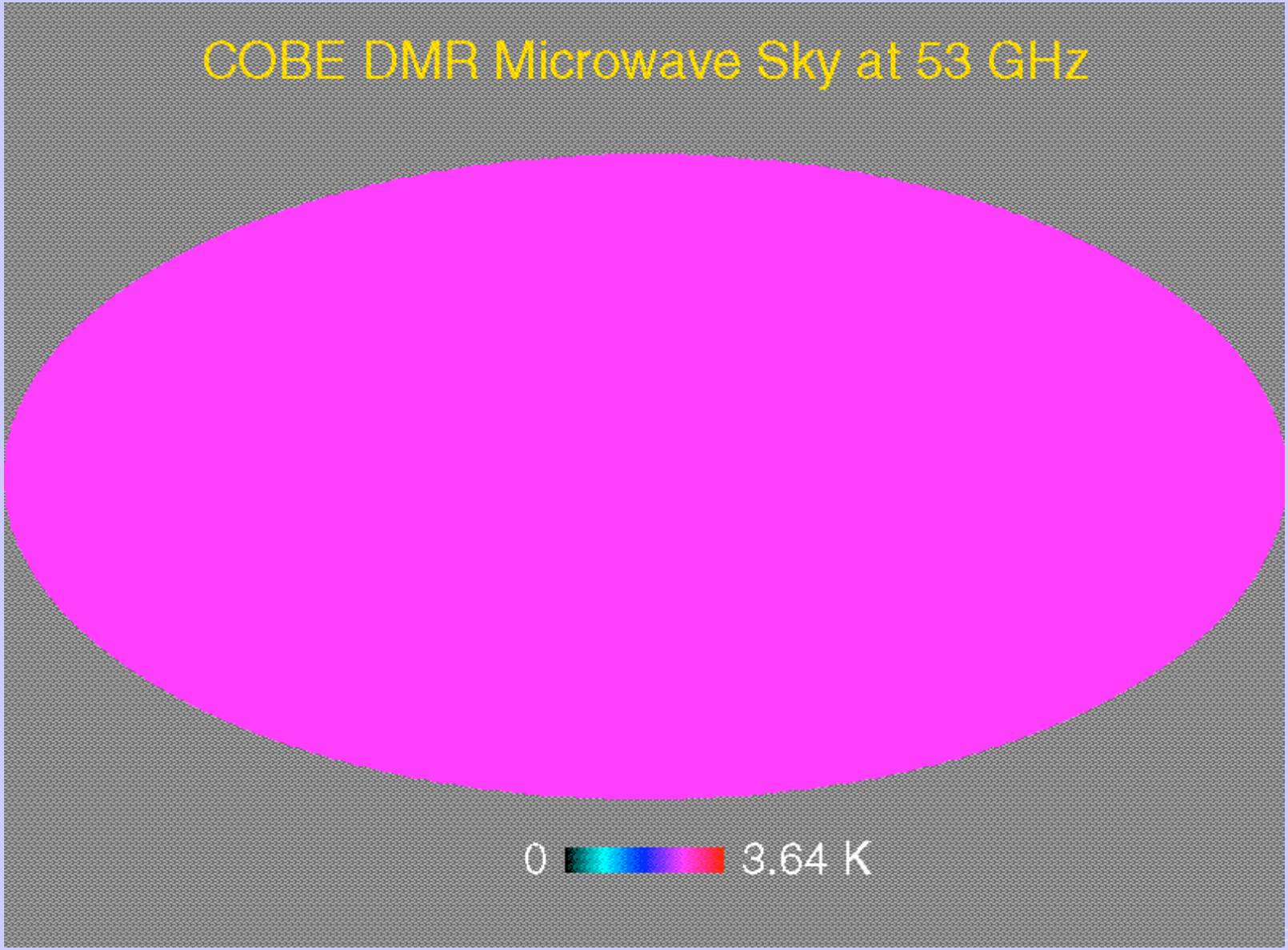
From: talk by O. Lahav

South Pole Microwave Telescope

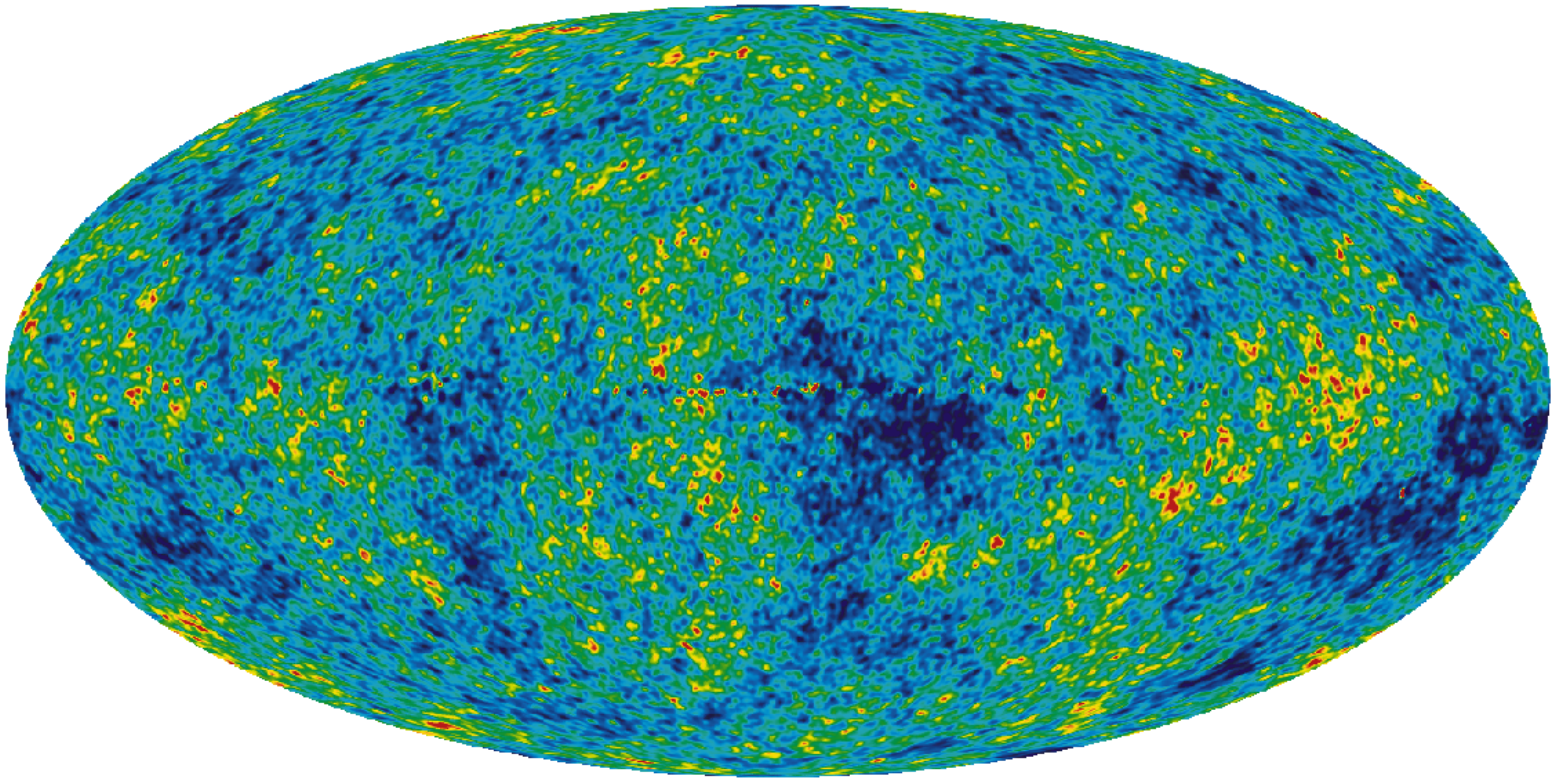
WMAP Microwave Telescope



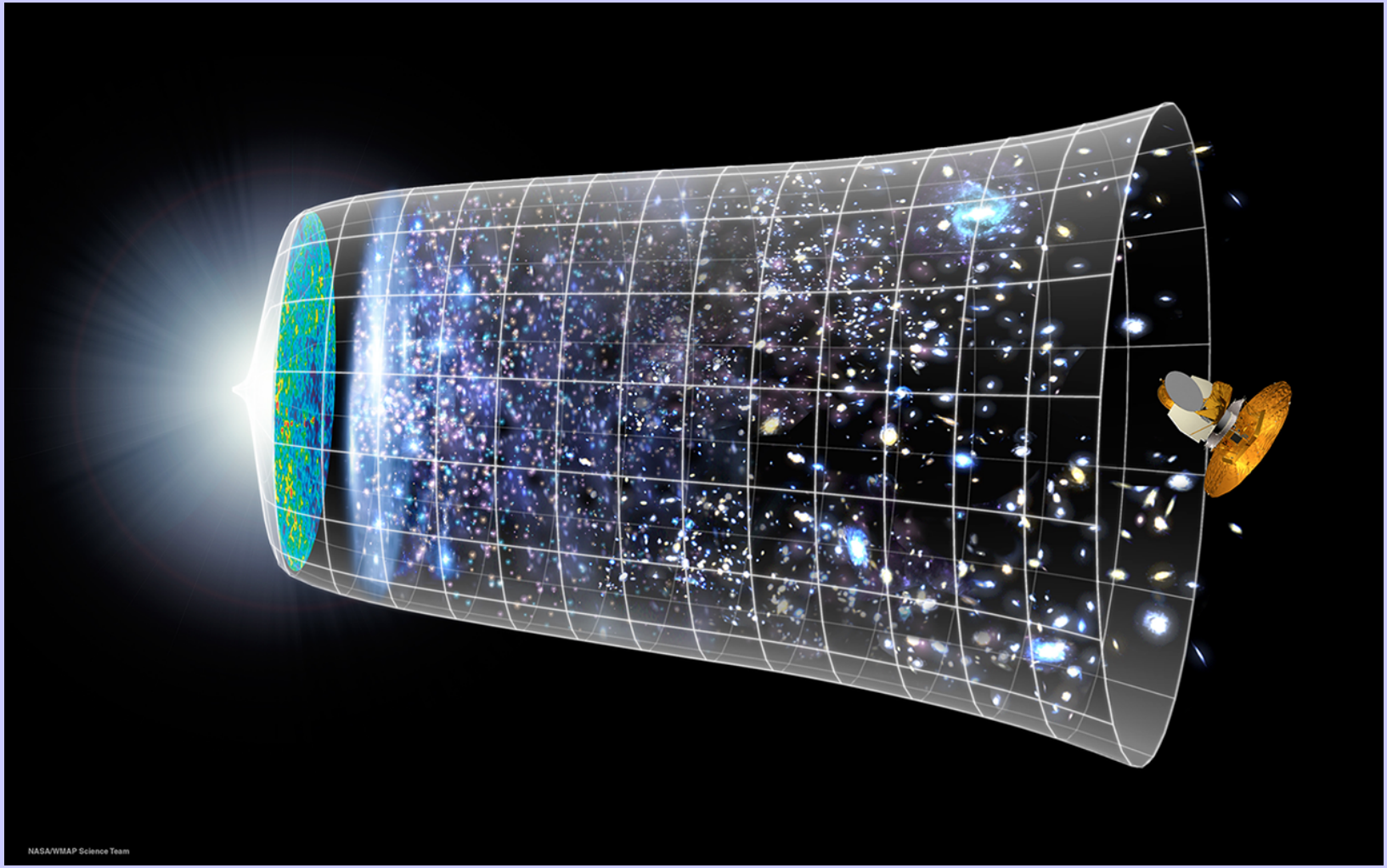
Isotropic CMB Background



WMAP Map of the Cosmic Micrwave Background



History of the Universe



Goals of Early Universe Cosmology

1. Understand origin and early evolution of the universe.
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   - Was there a “Big Bang"?
   - What was before the “Big Bang"?

2. Explain observed large-scale structure.
   - Patterns in the distribution of galaxies on large scales.
   - Anisotropies in CMB maps.

3. Make predictions for future observations.

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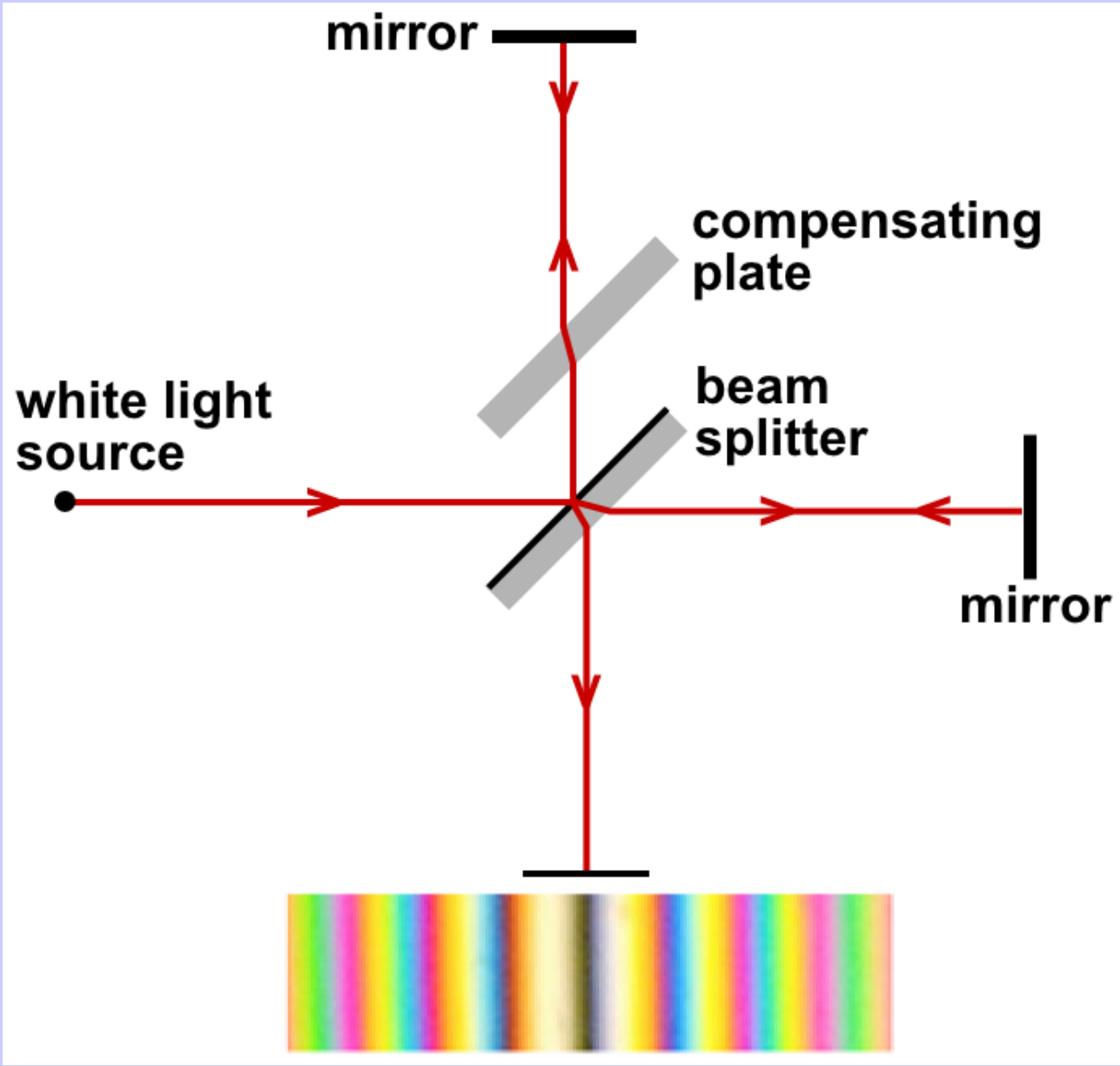
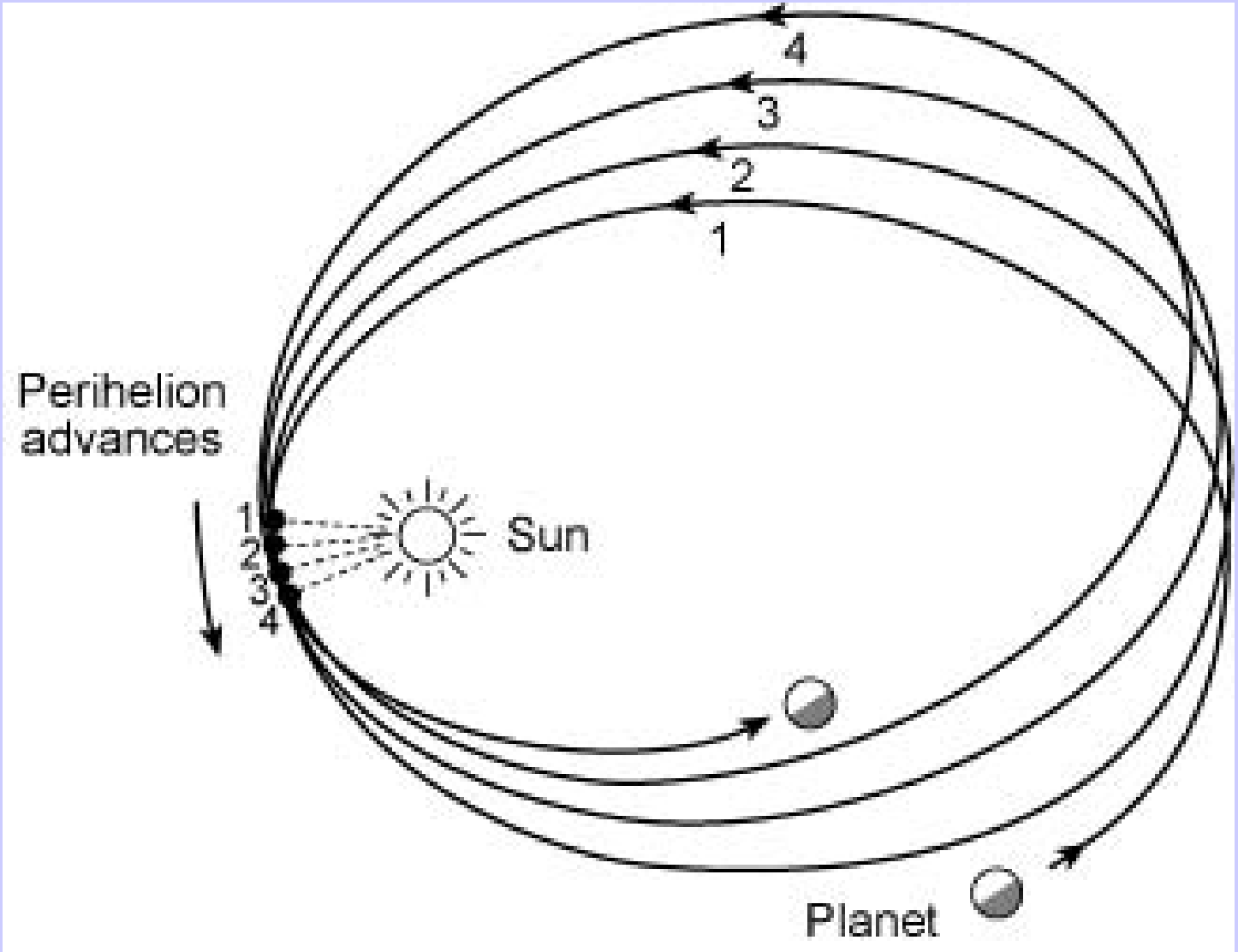
Michelson-Morley Experiment



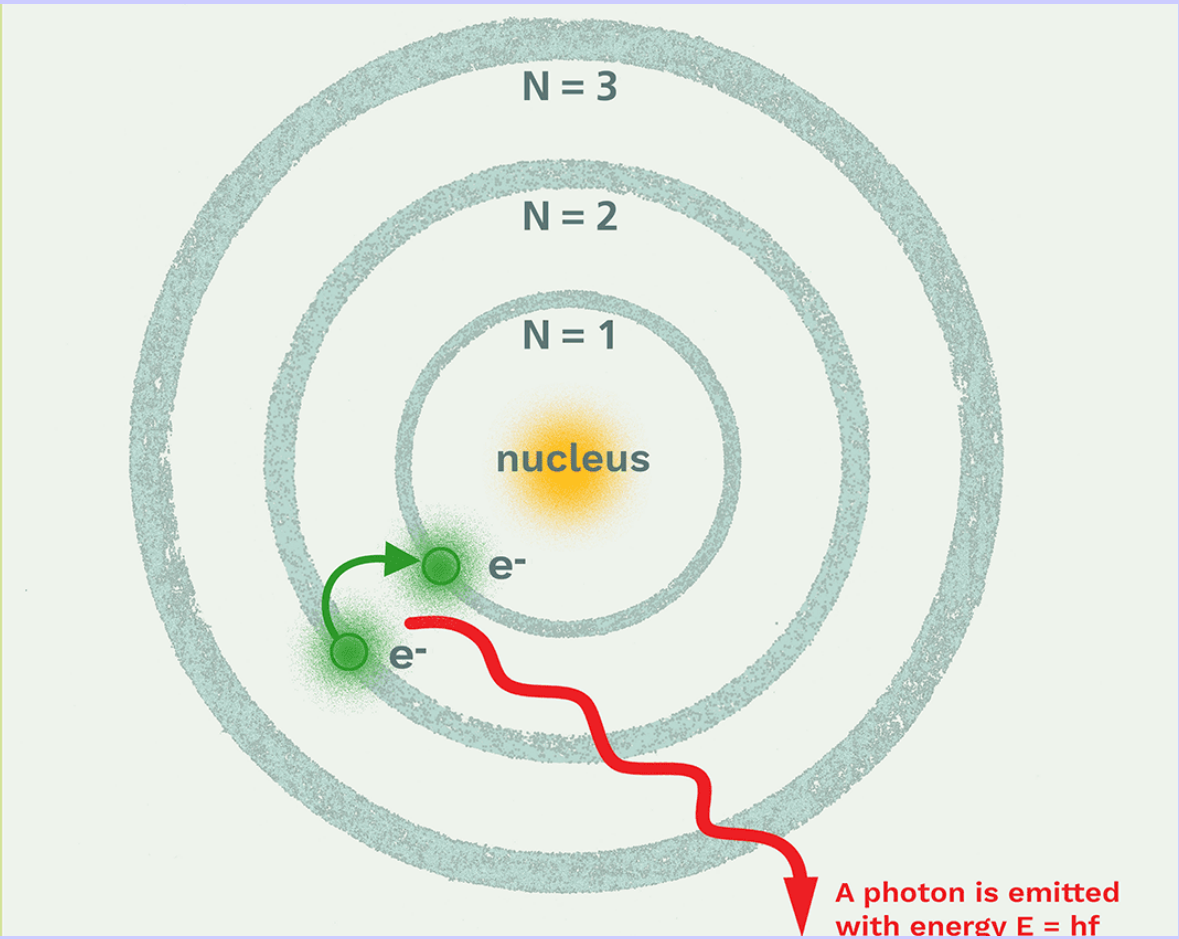
Perihelion Advance of Mercury



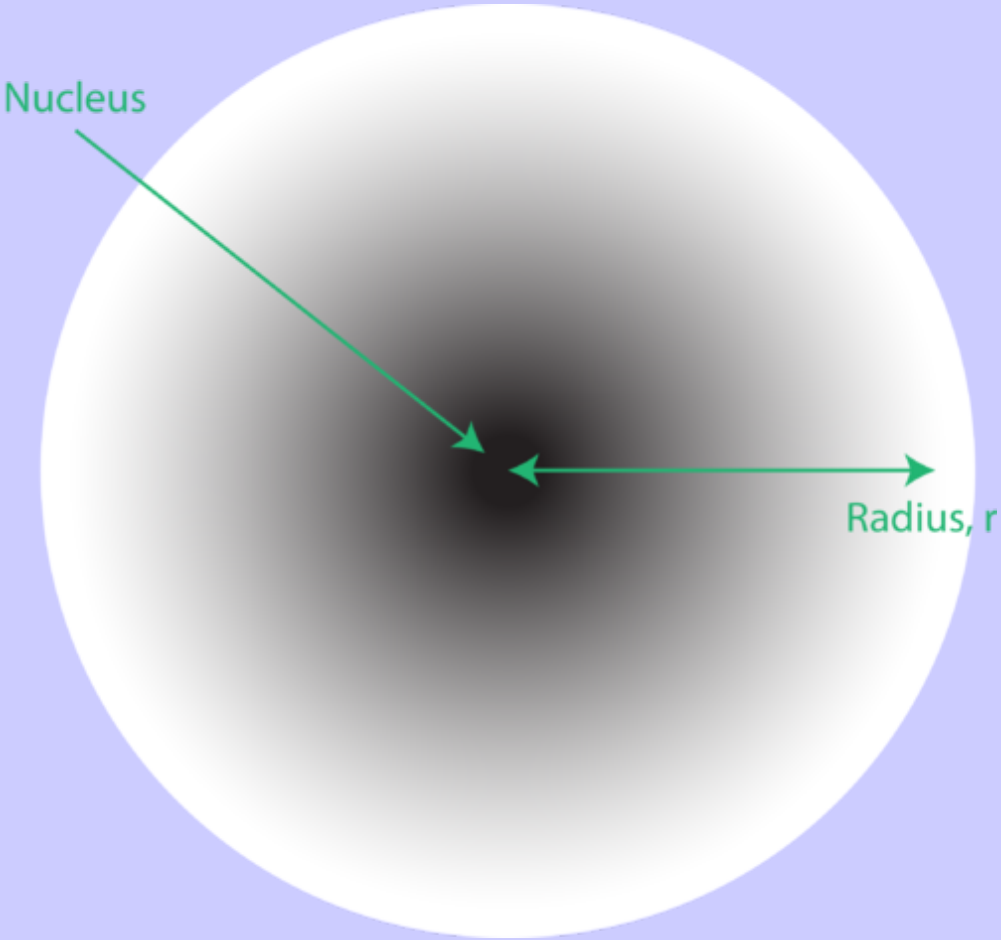
Bohr Model

Bohr Model of the Atom

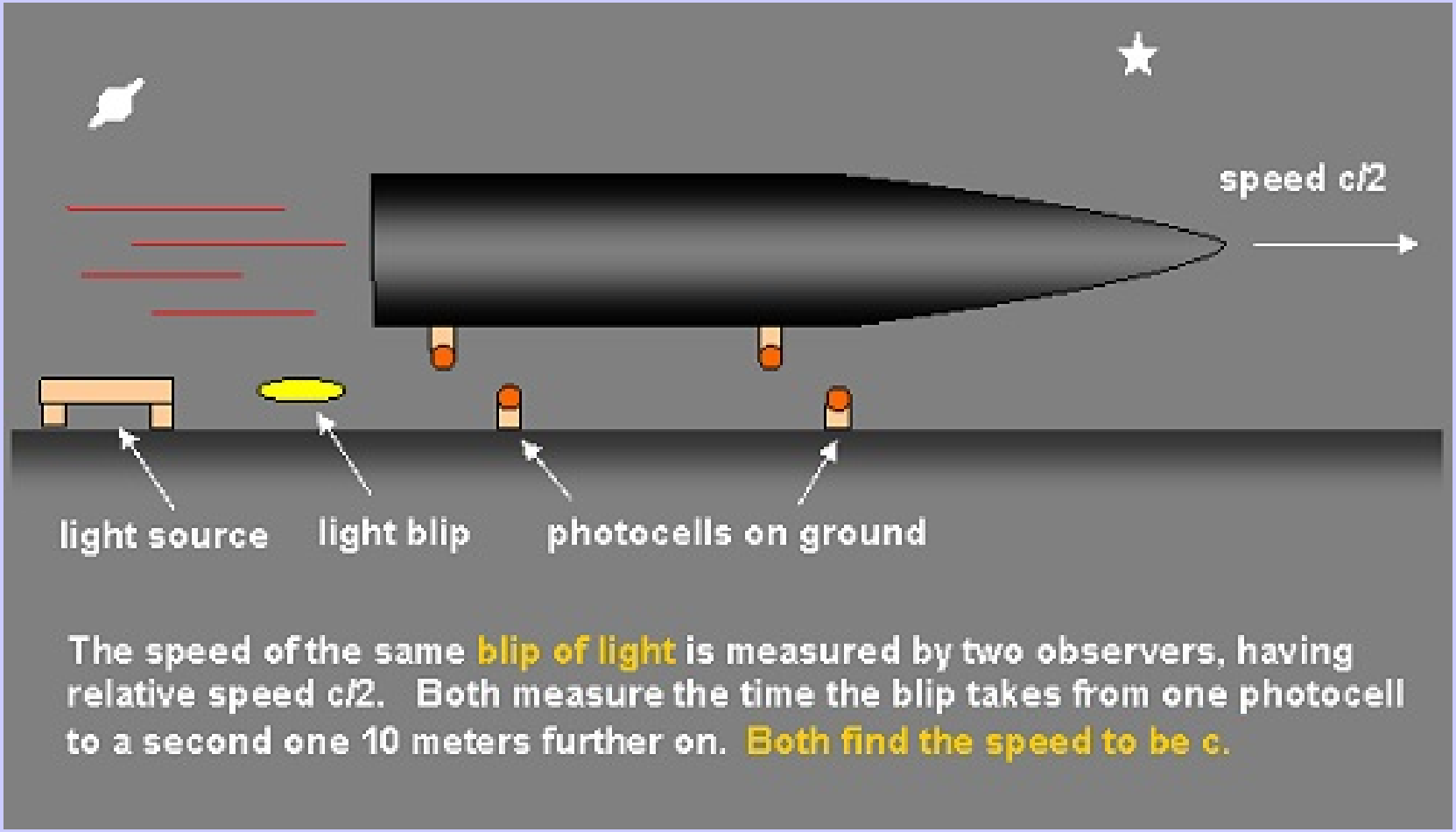
The Bohr model is a planetary model in which negatively-charged electrons orbit a positively-charged nucleus.



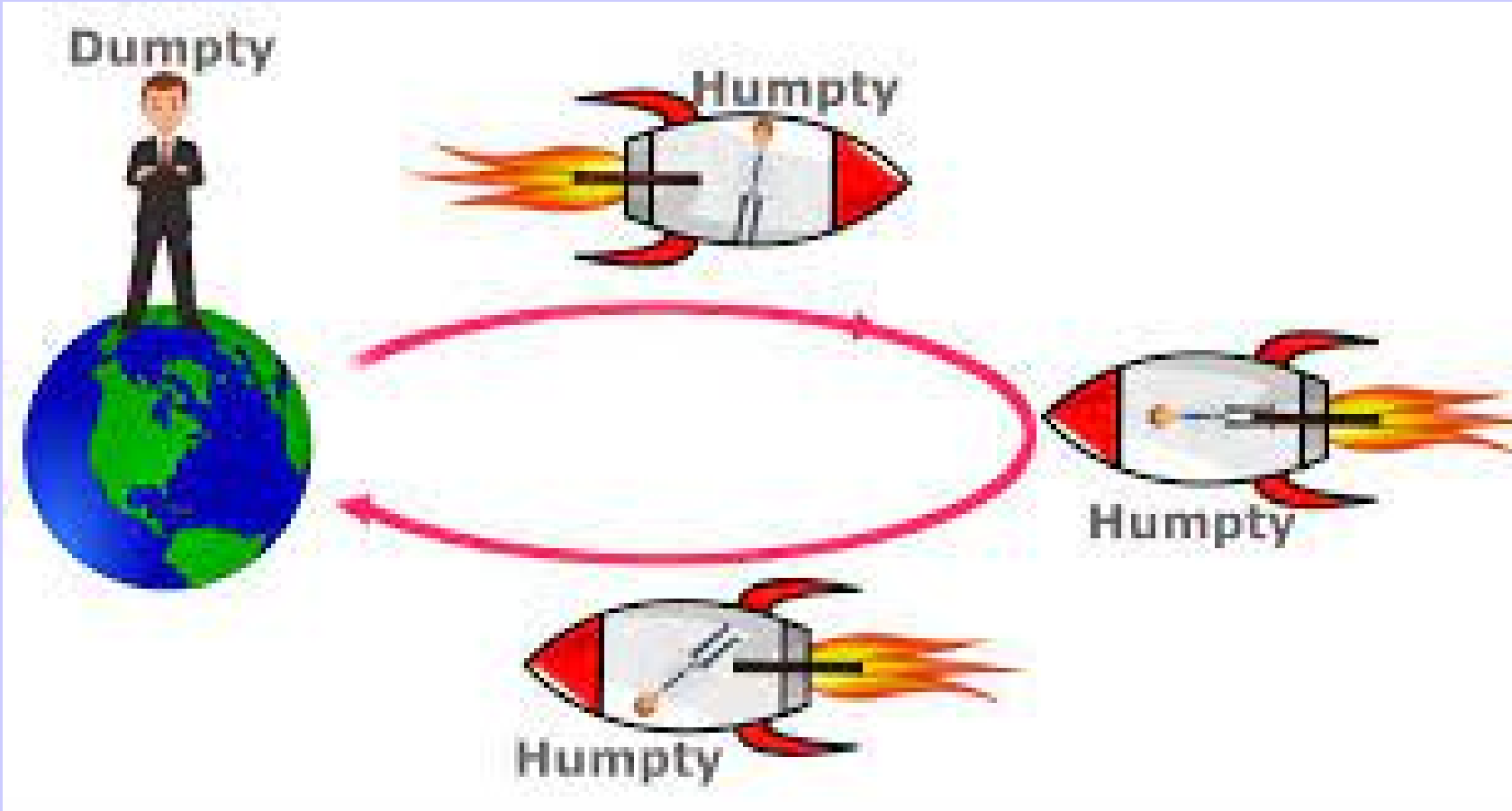
Quantum Mechanical Model of the Atom

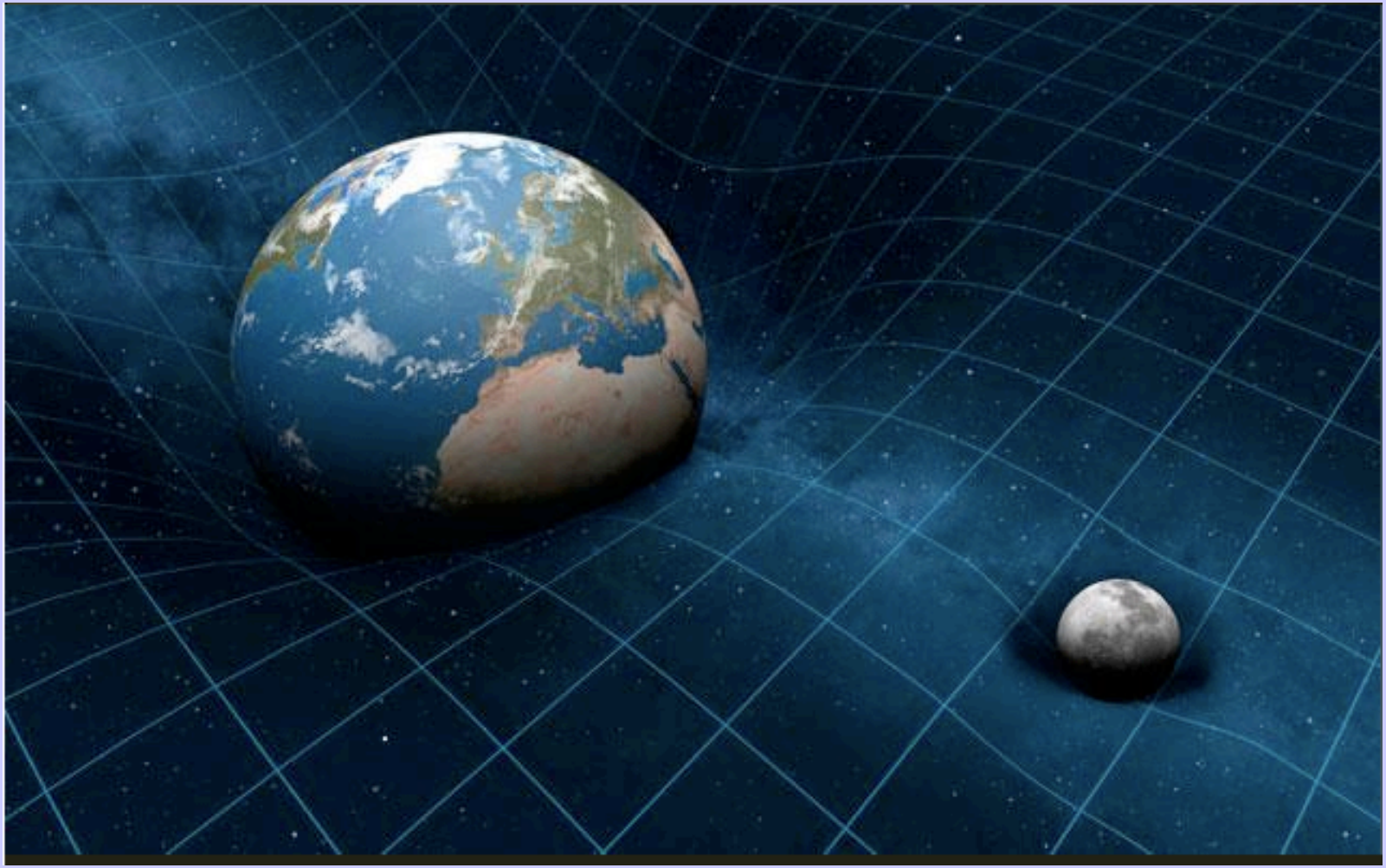


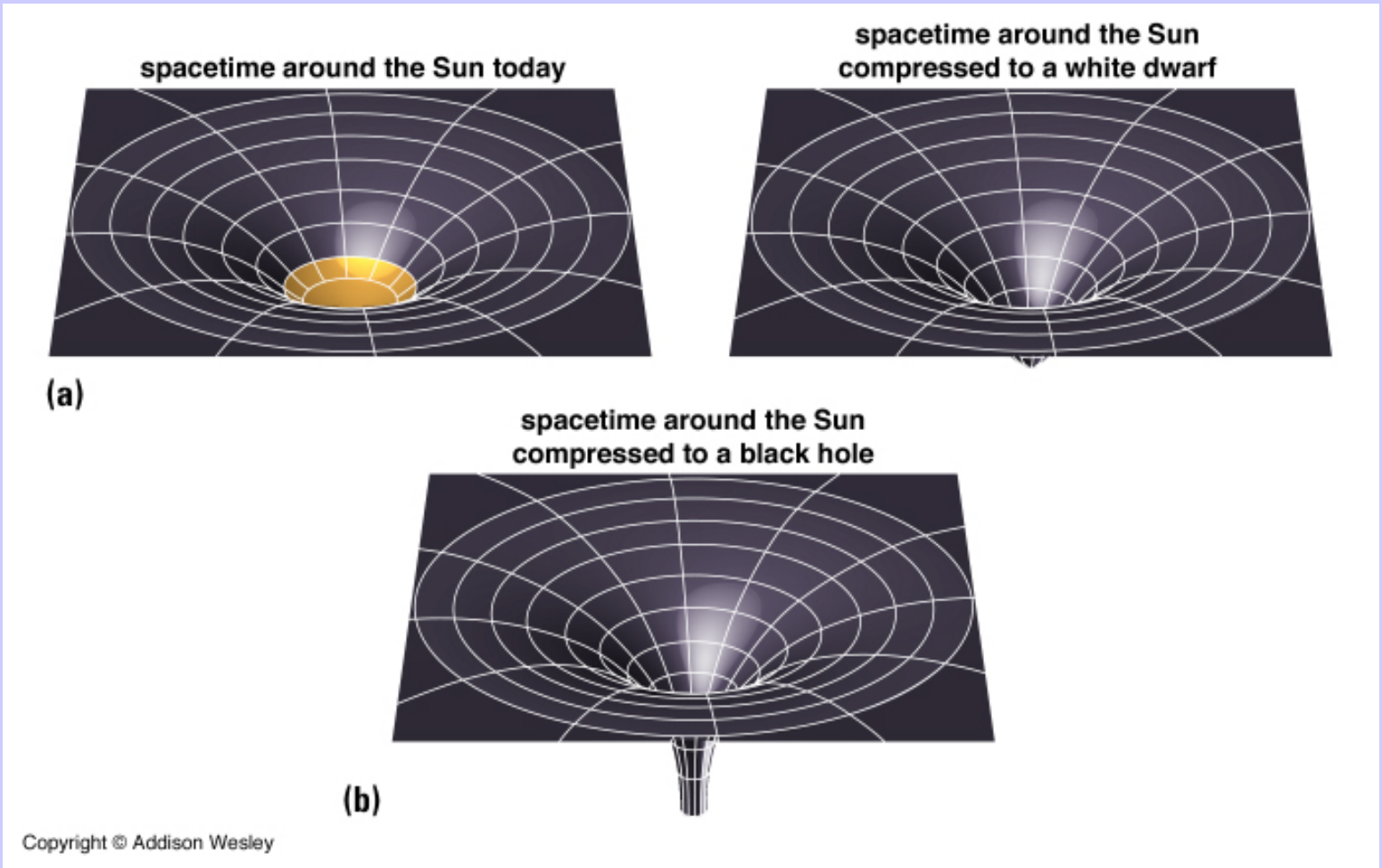
Constancy of Speed of Light



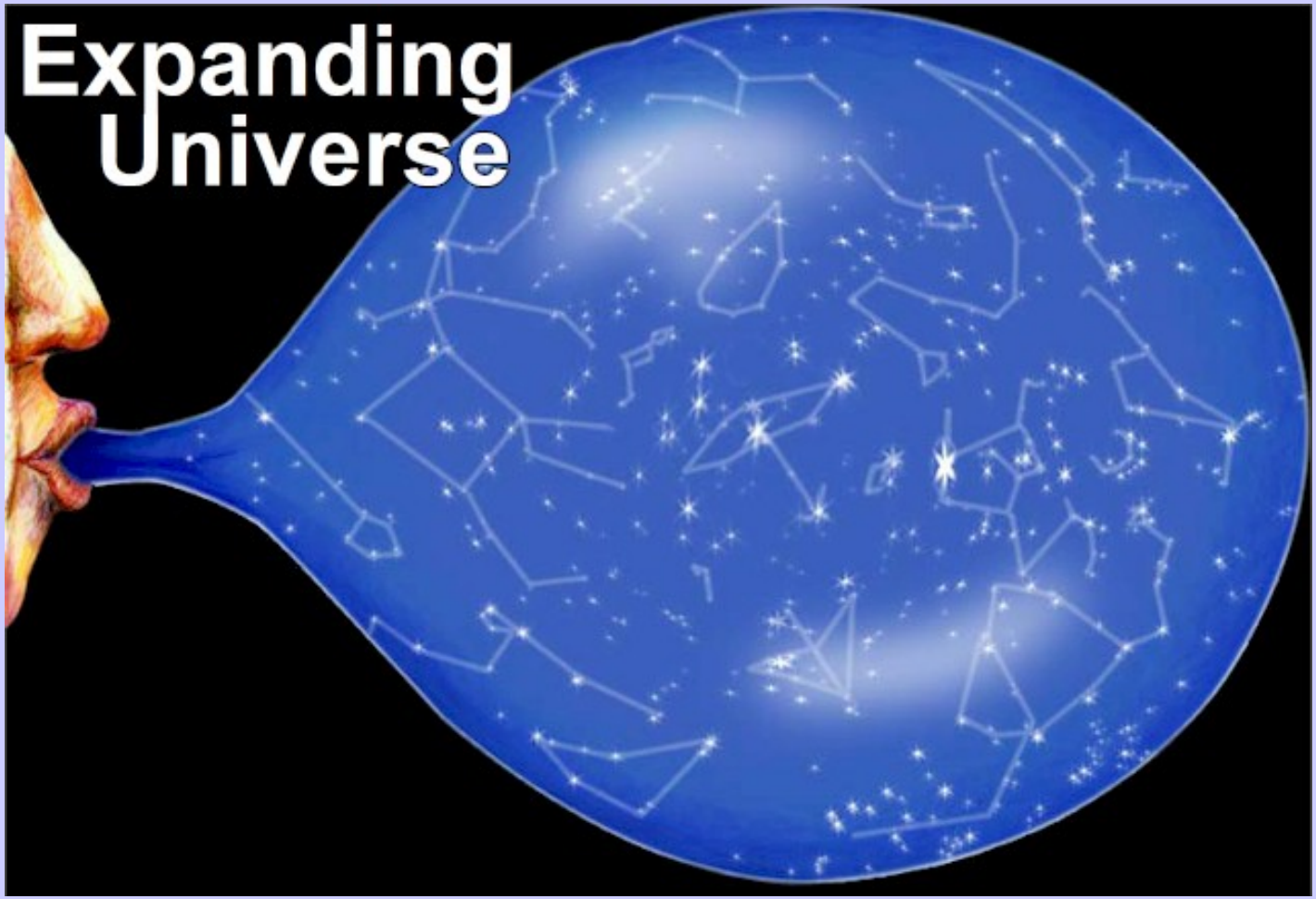
Twin Paradox







Expanding Universe



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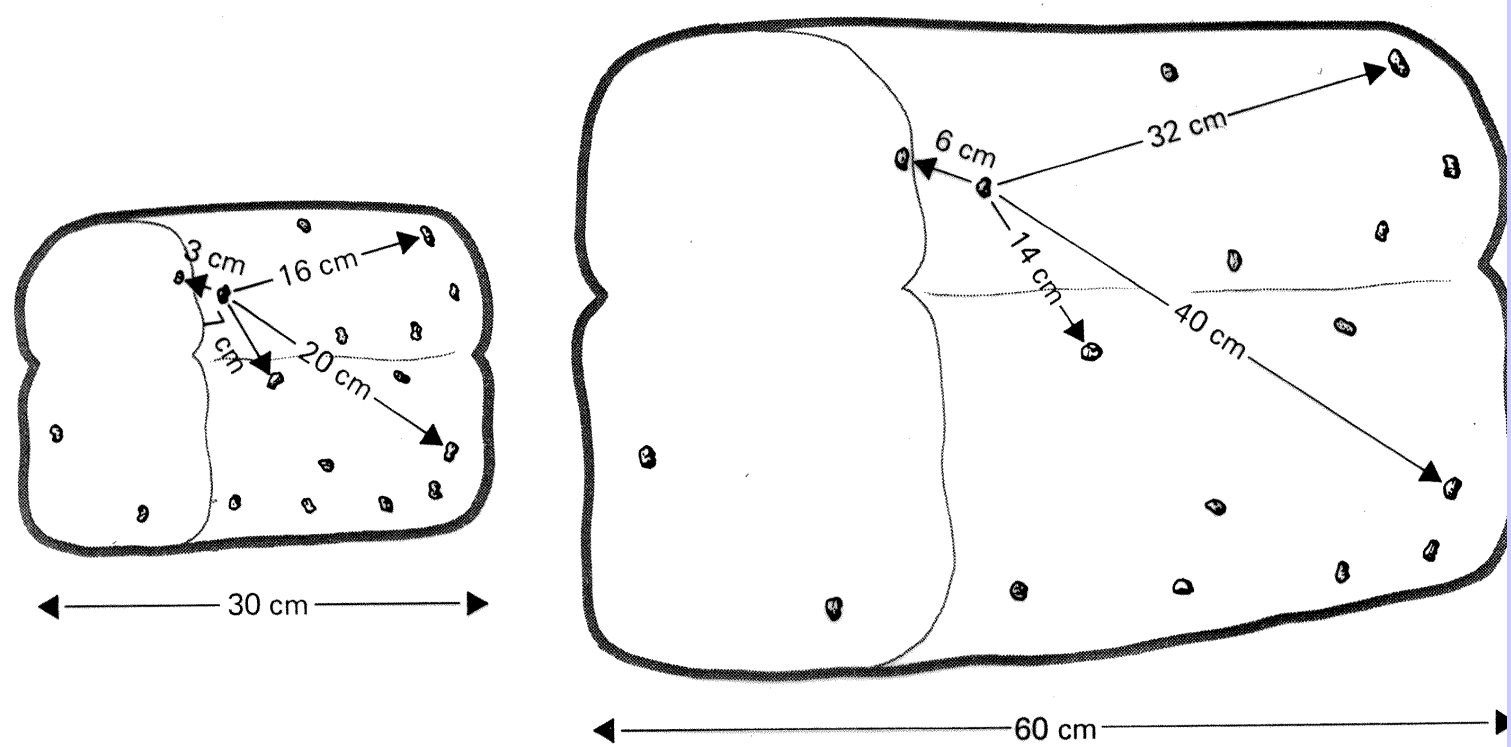
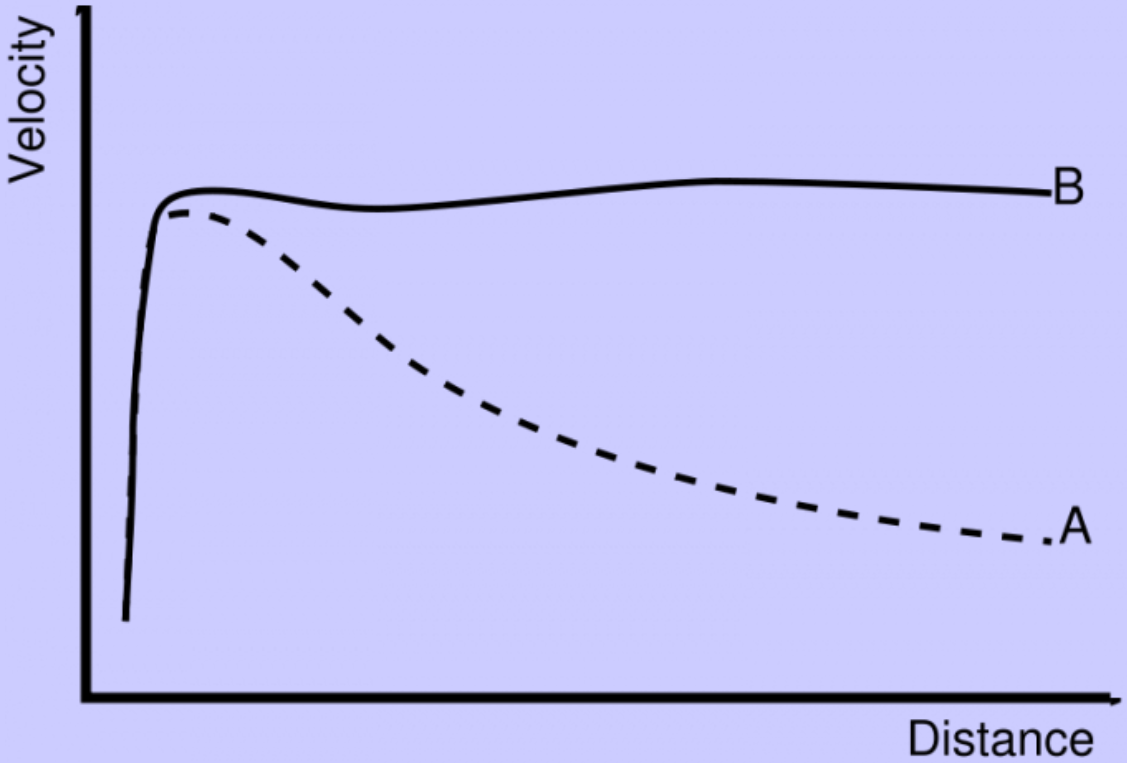
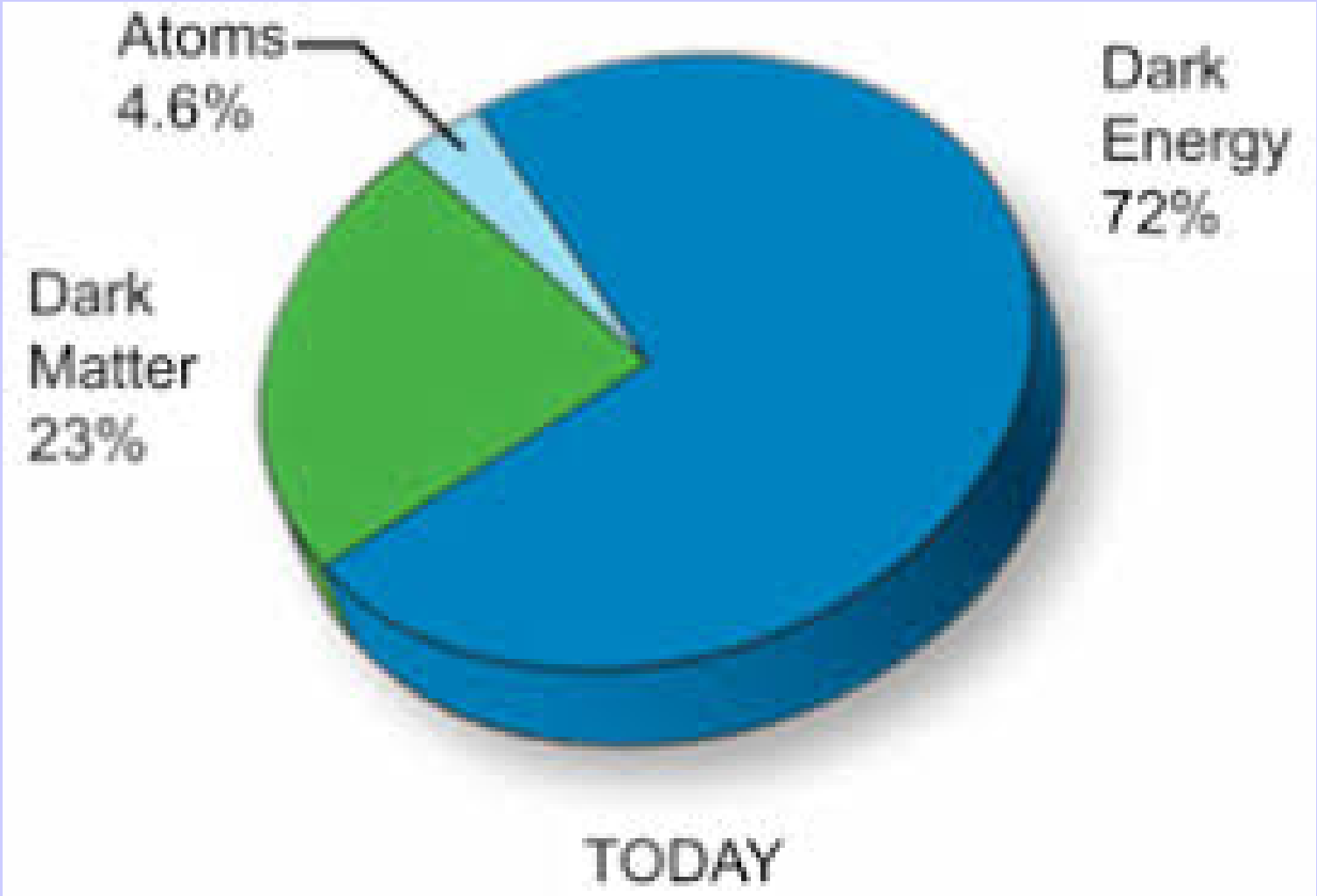


Figure 37.4 Expanding raisin bread.

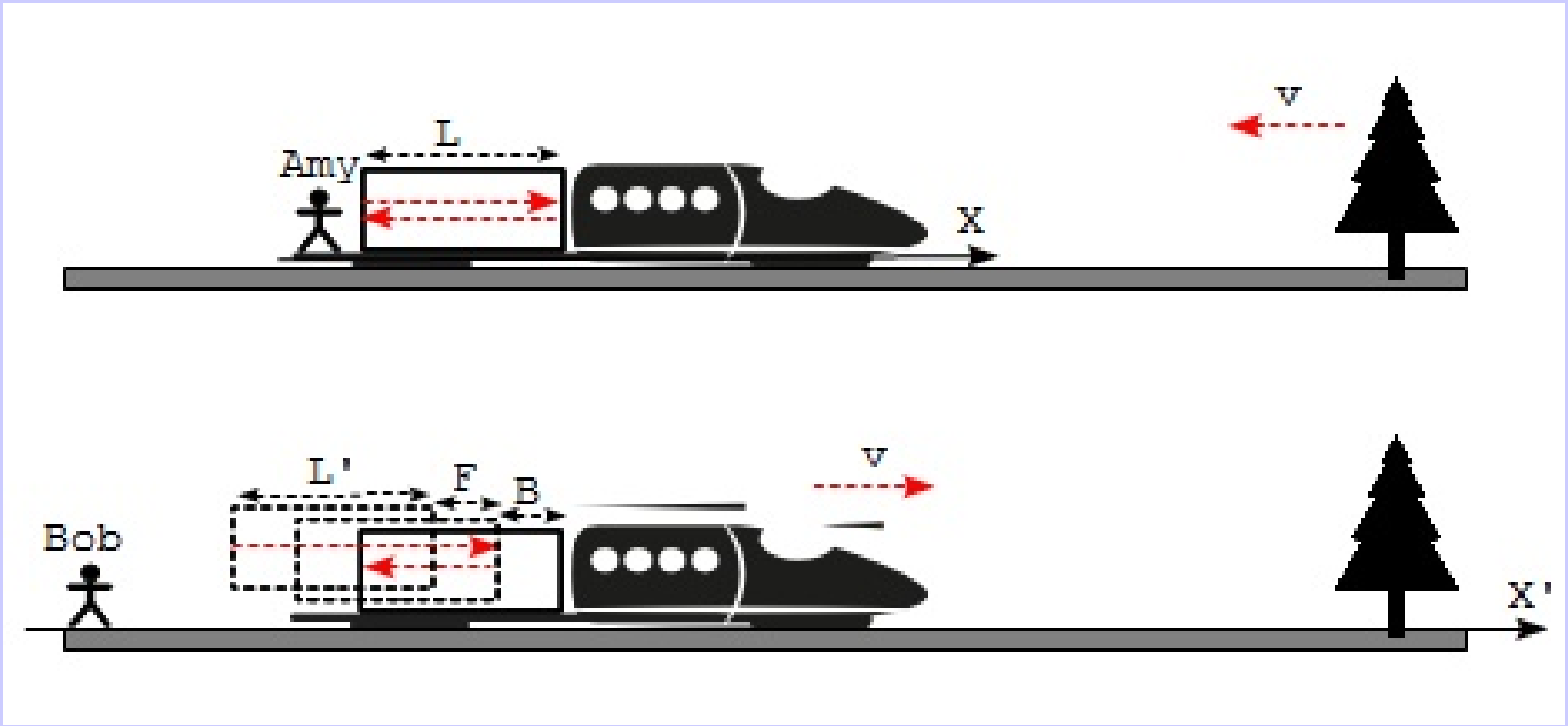
Galaxy Rotation Curves: Evidence for Dark Matter



Energy Budget of the Universe

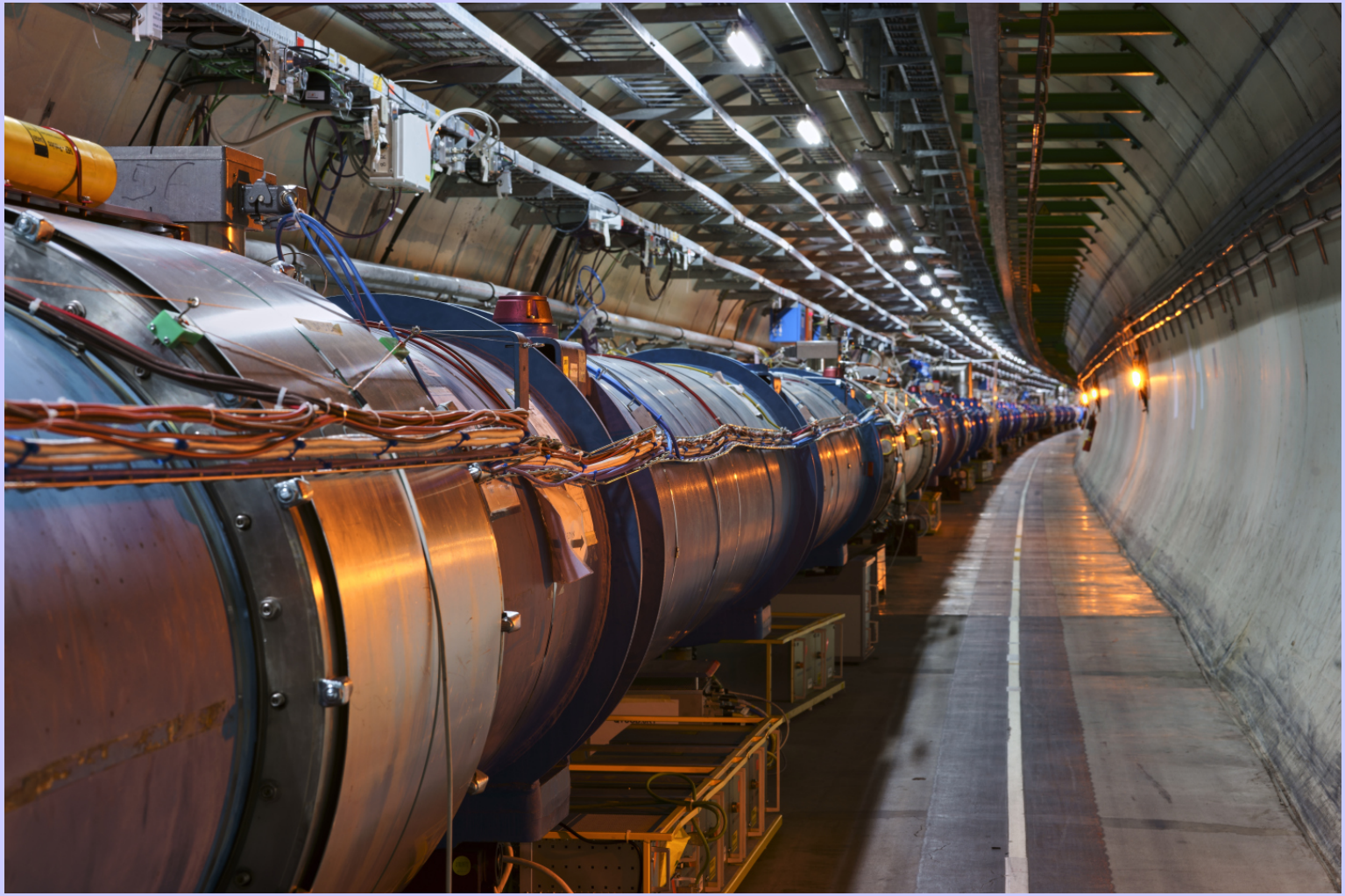


Length Contraction

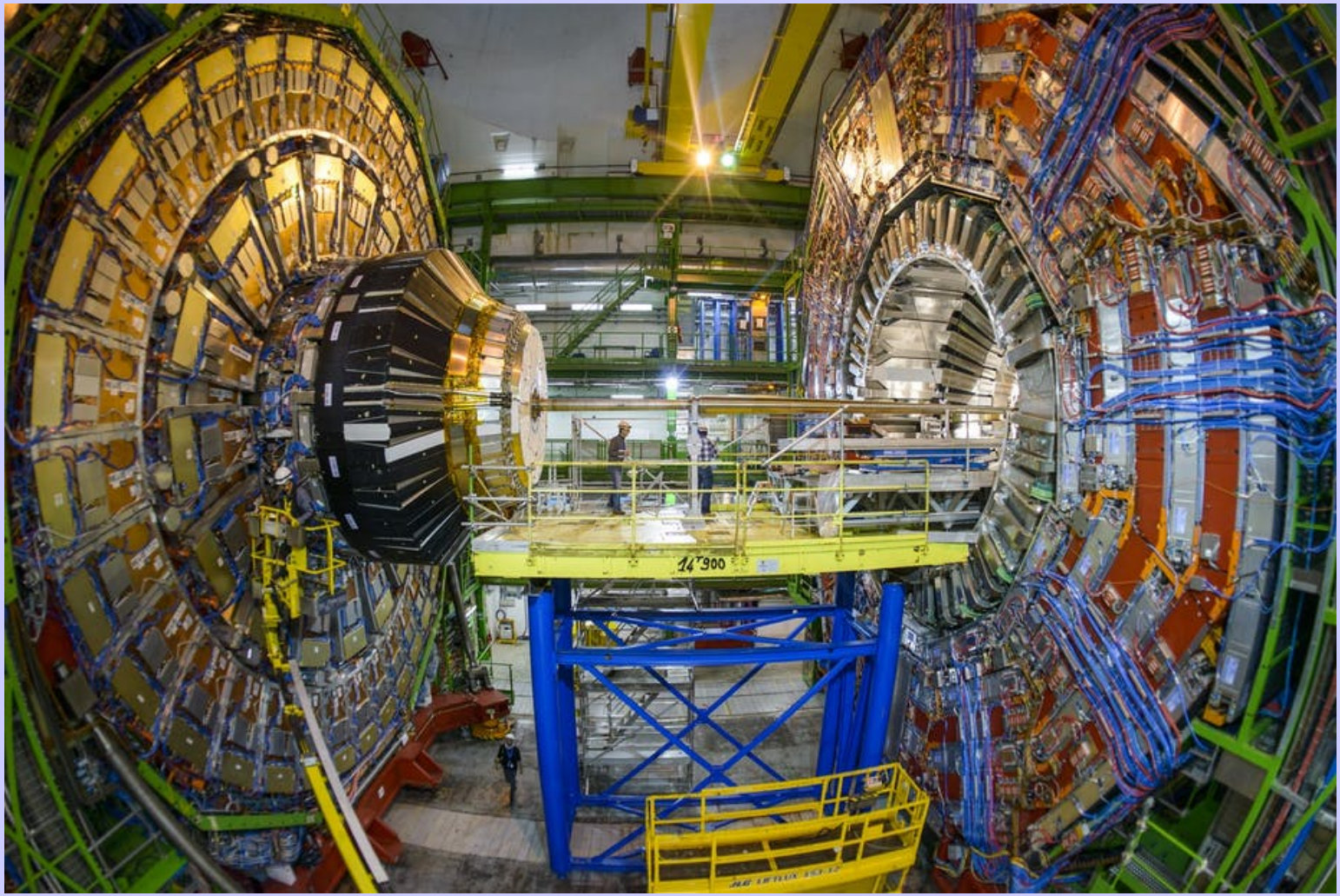


CERN Site

CERN LHC Tunnel

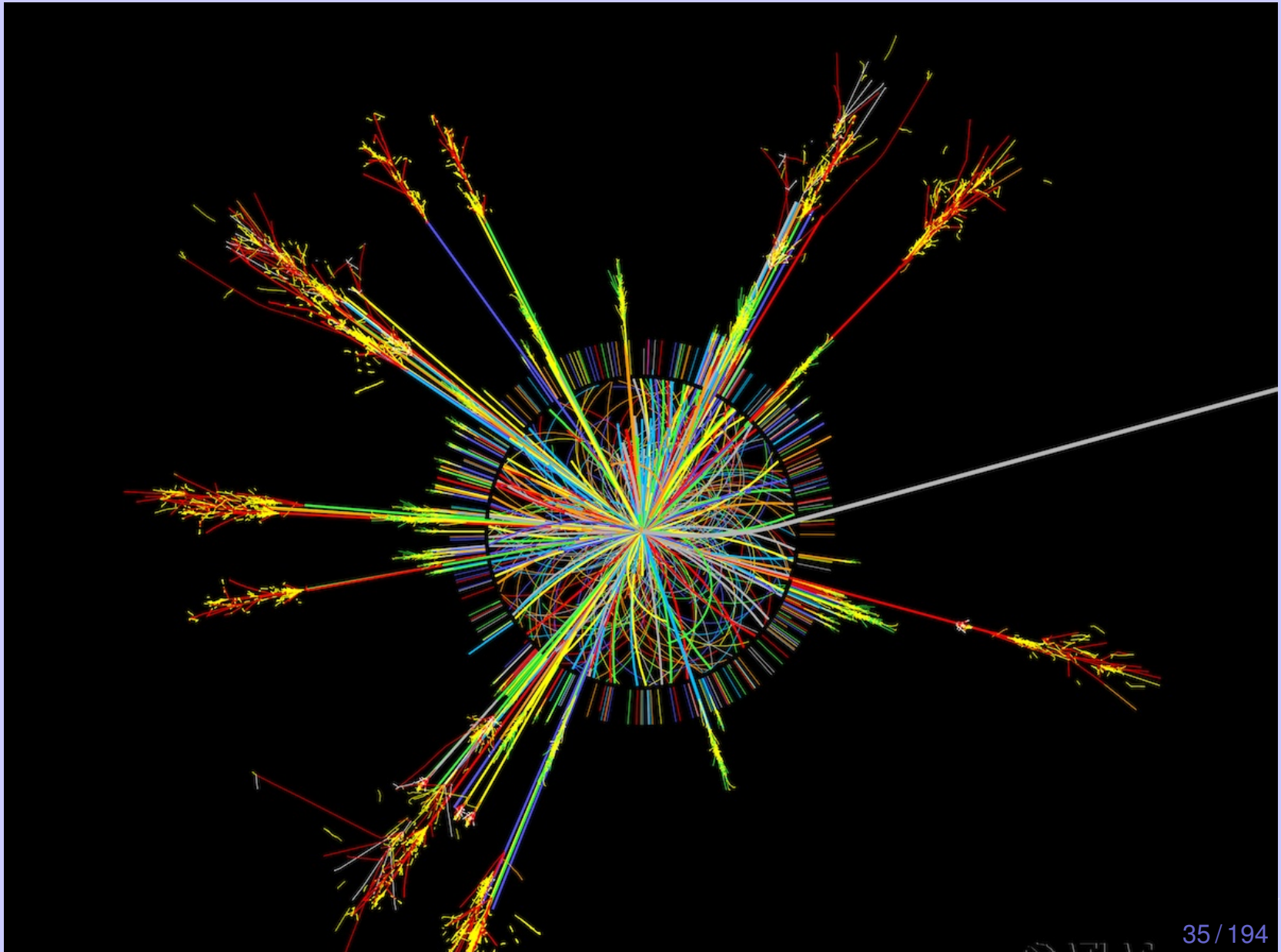


CERN LHC Detector



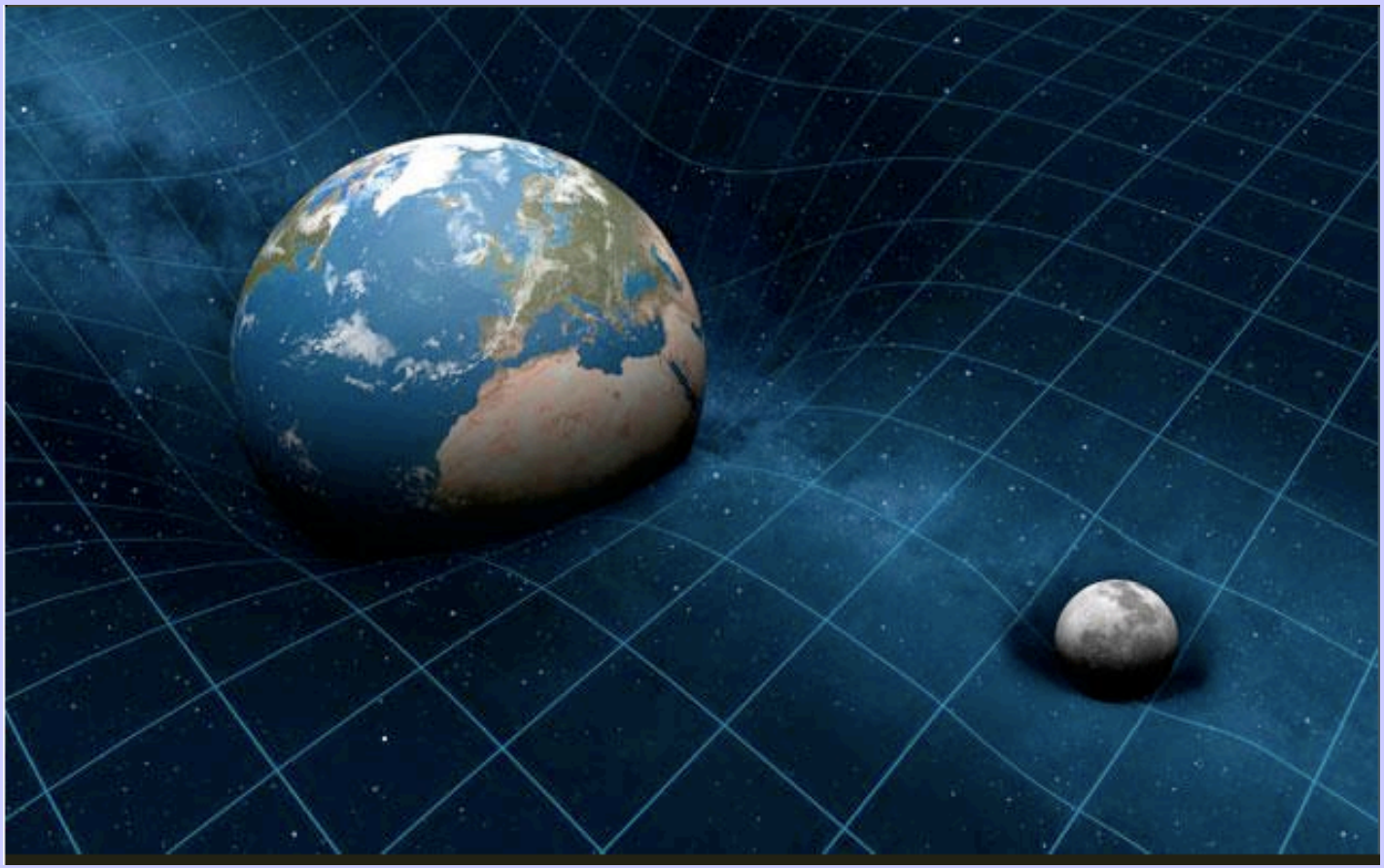
CERN Director: Fabiola Gianotti

Particle Collision Event

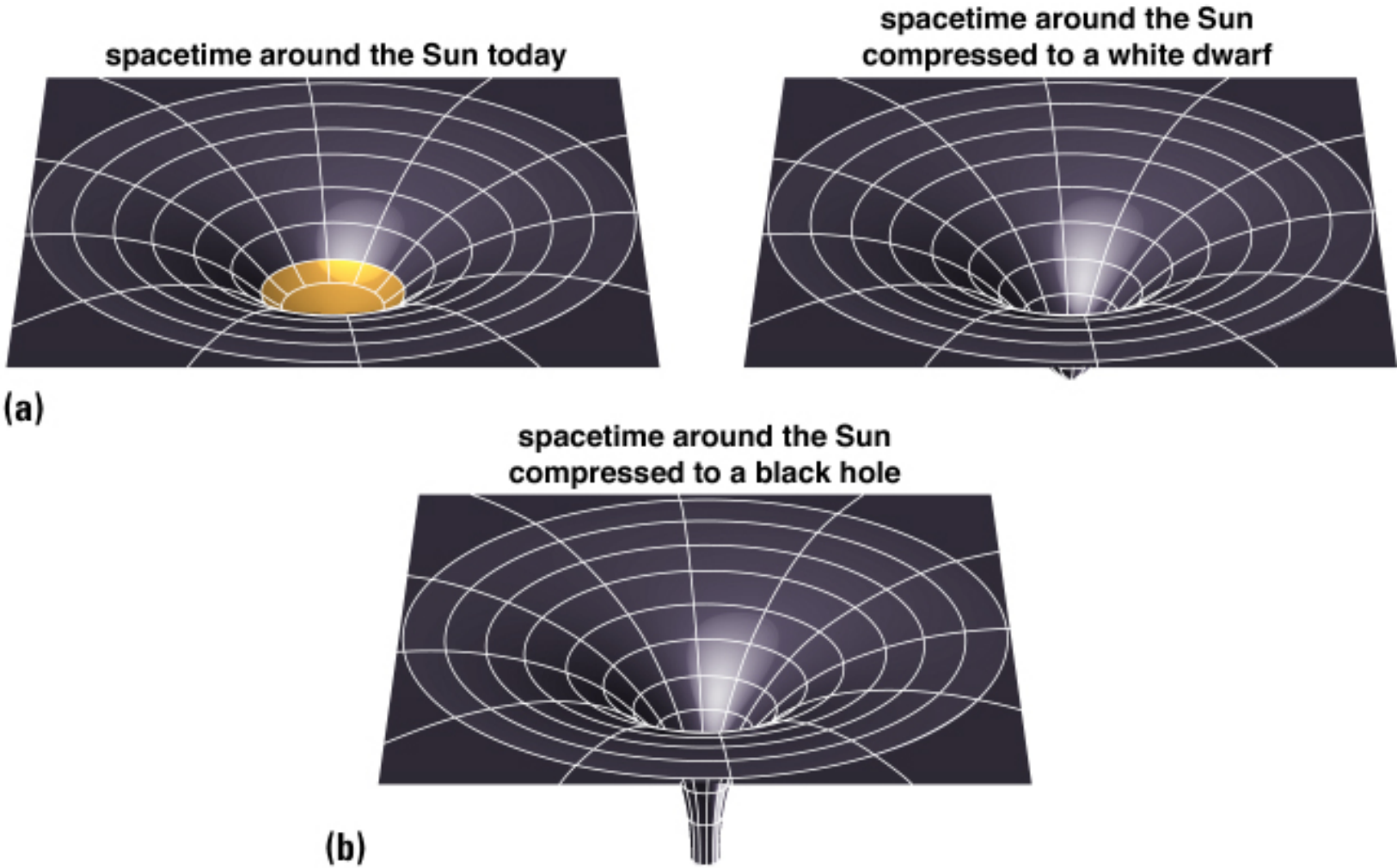


Atom Bomb

Mass curves Space-Time



Sun as a Black Hole



Curved Space-Time

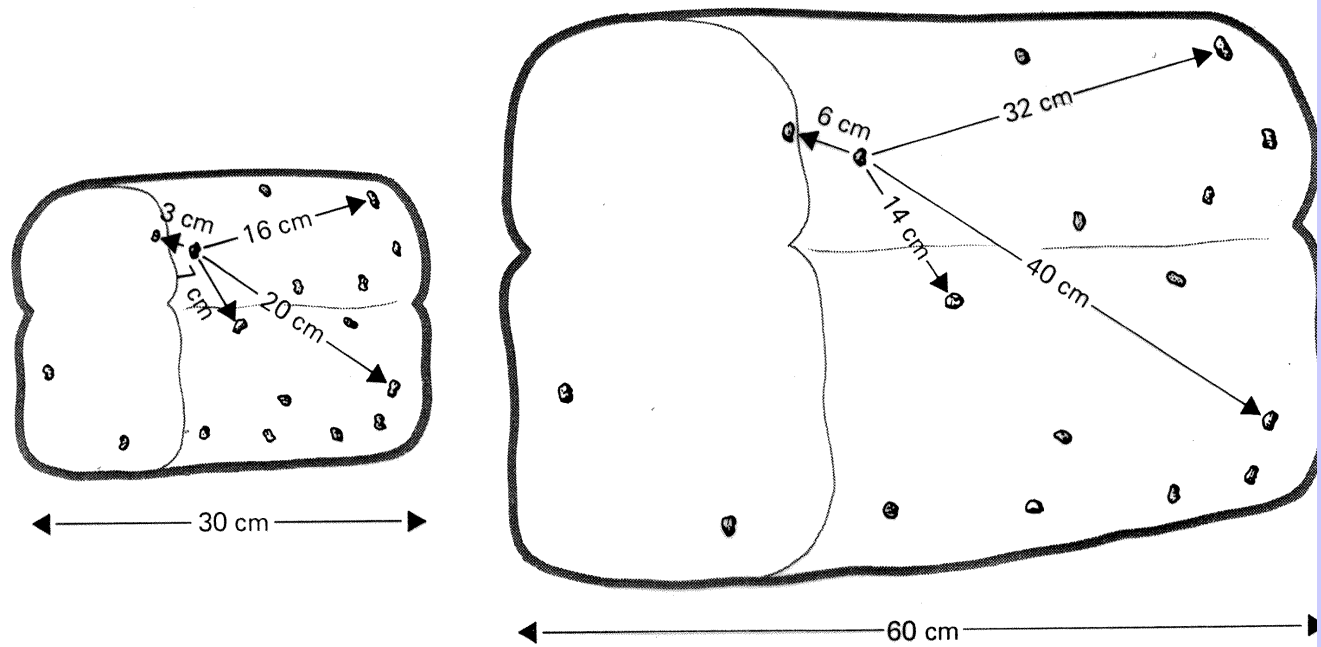
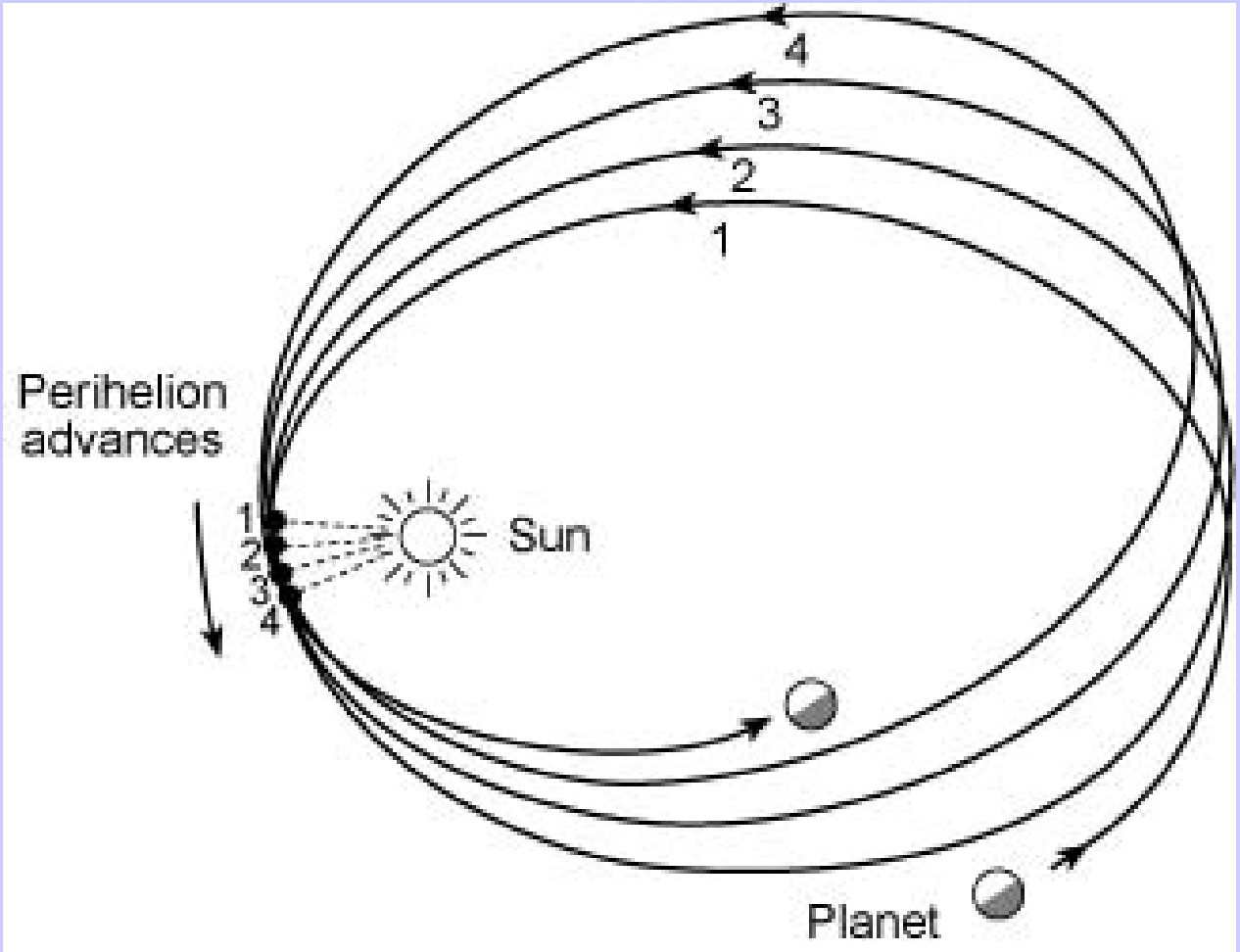


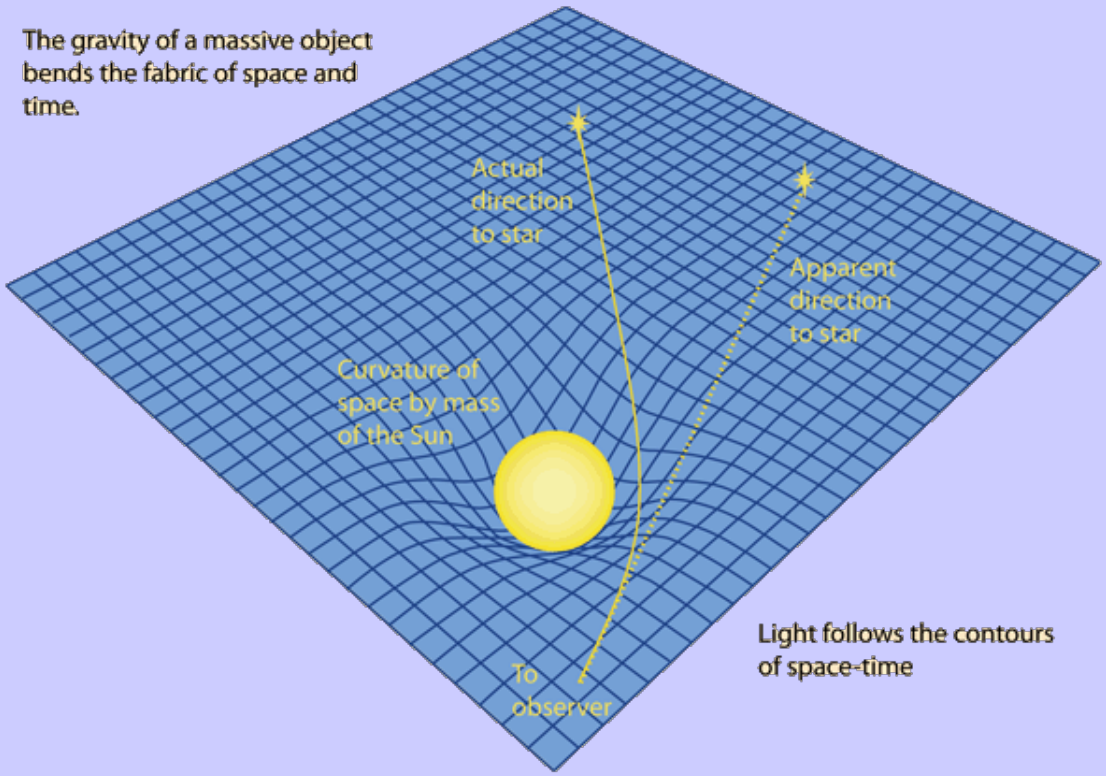
Figure 37.4 Expanding raisin bread.

Geodesics on the Earth

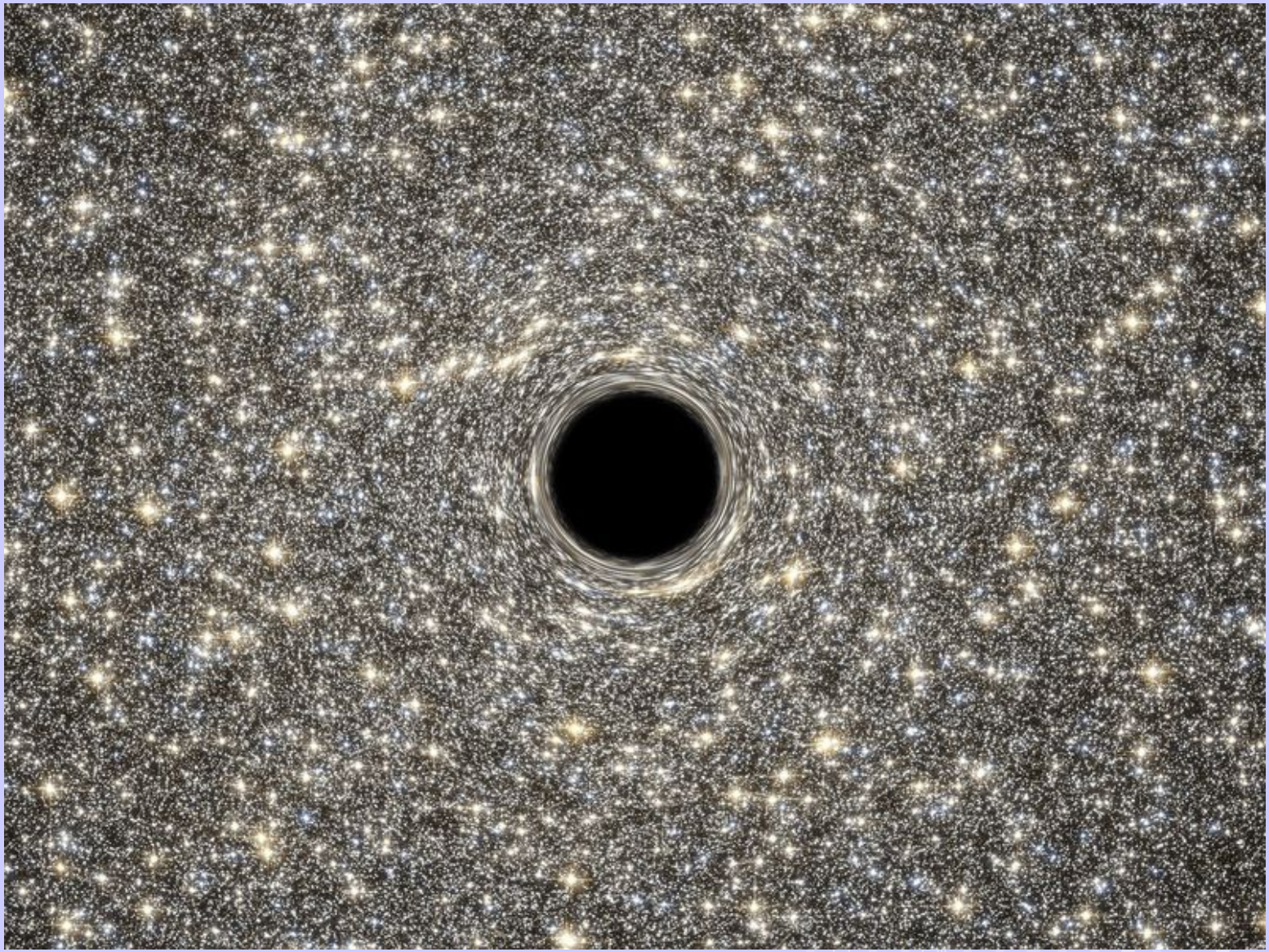
Postdiction: Perhelion Precession of Mercury



Prediction: Bending of Light



Prediction: Black Holes



Prediction: Expansion of the Universe

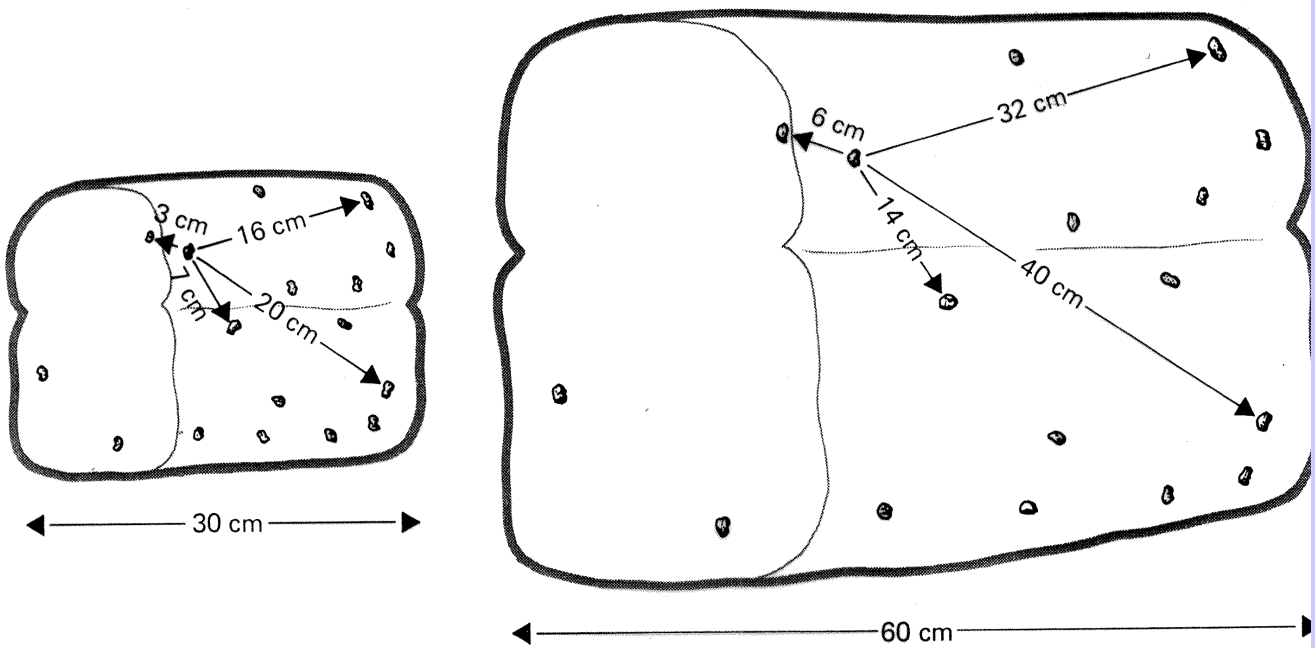
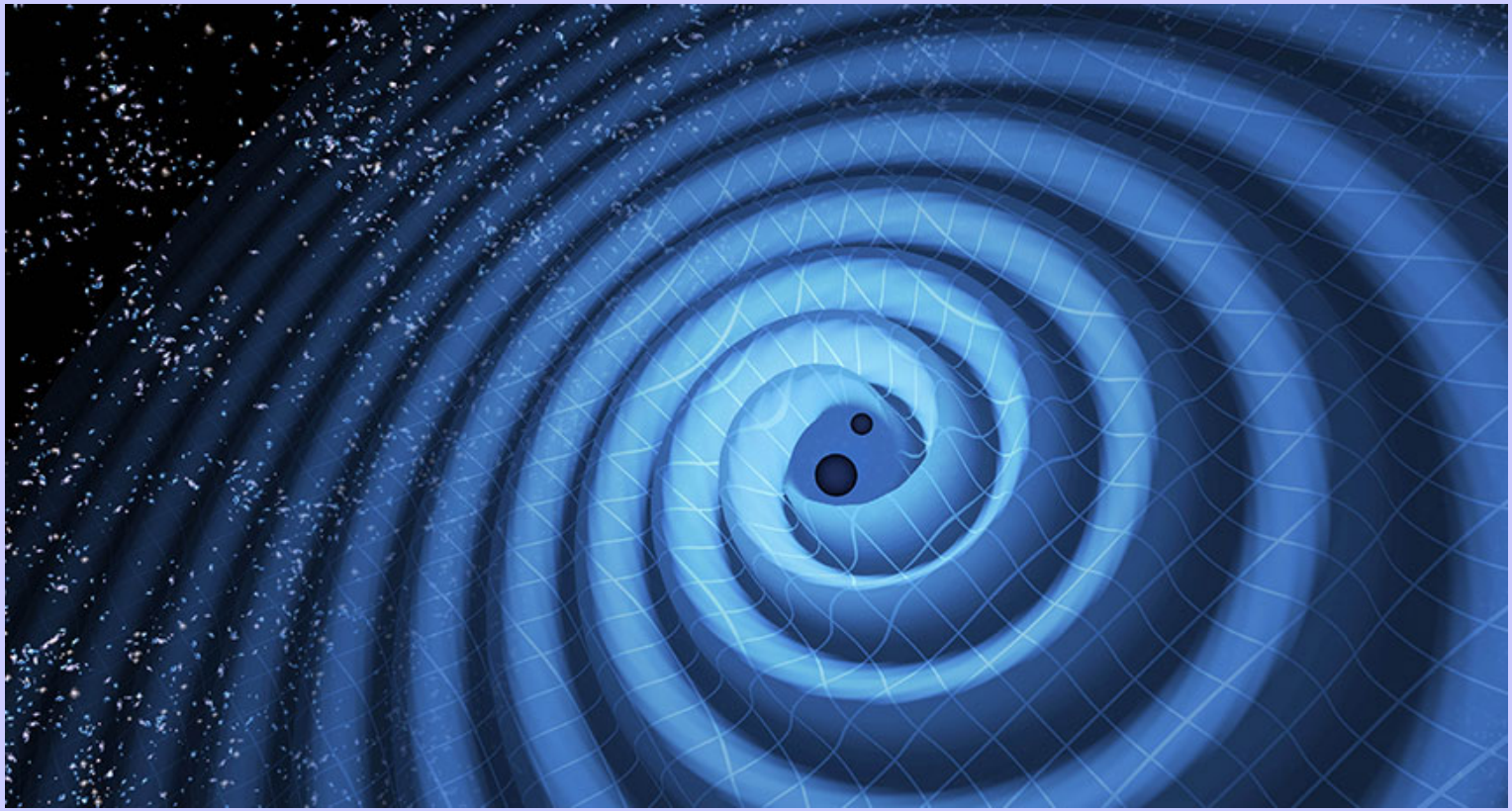
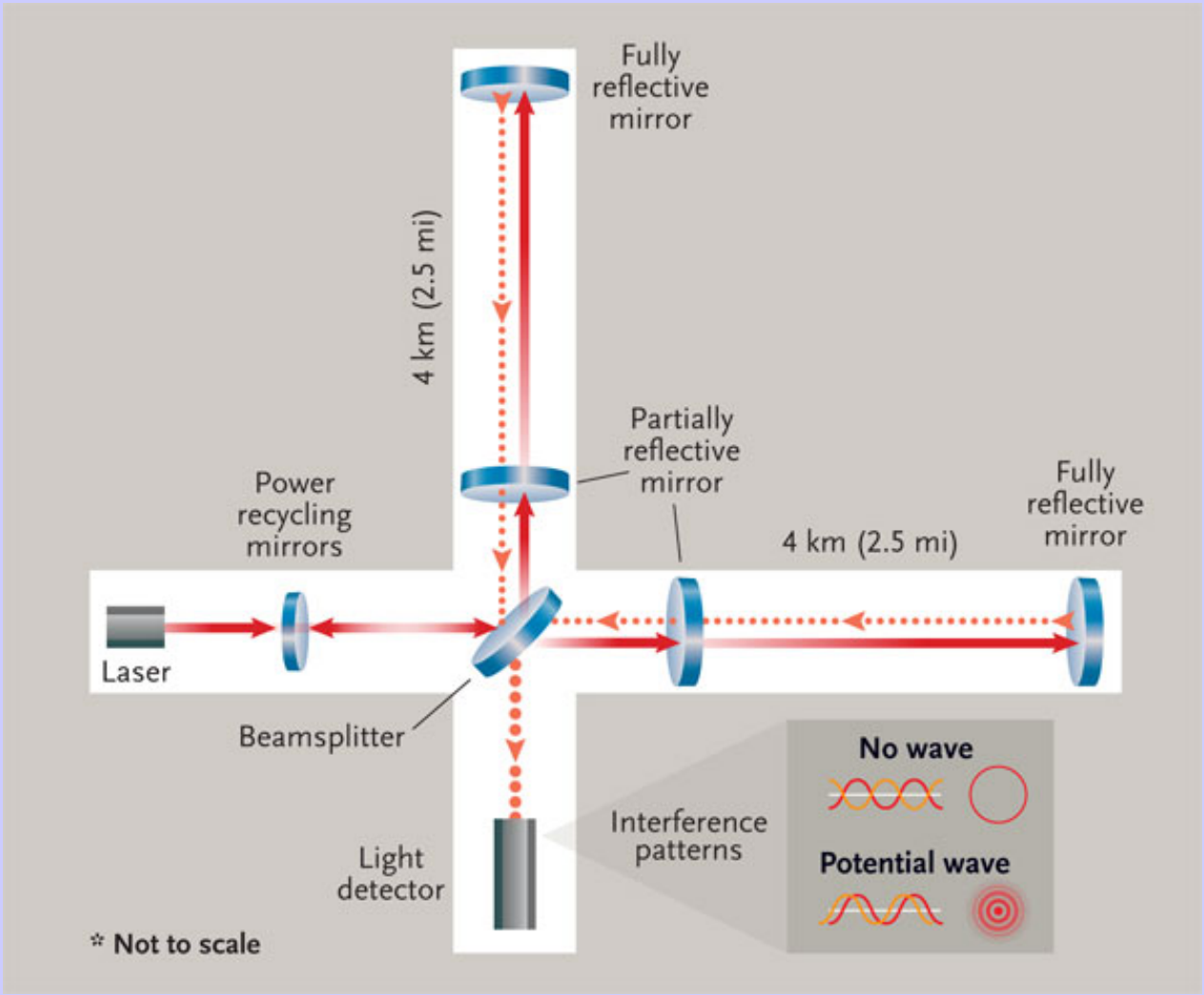


Figure 37.4 Expanding raisin bread.

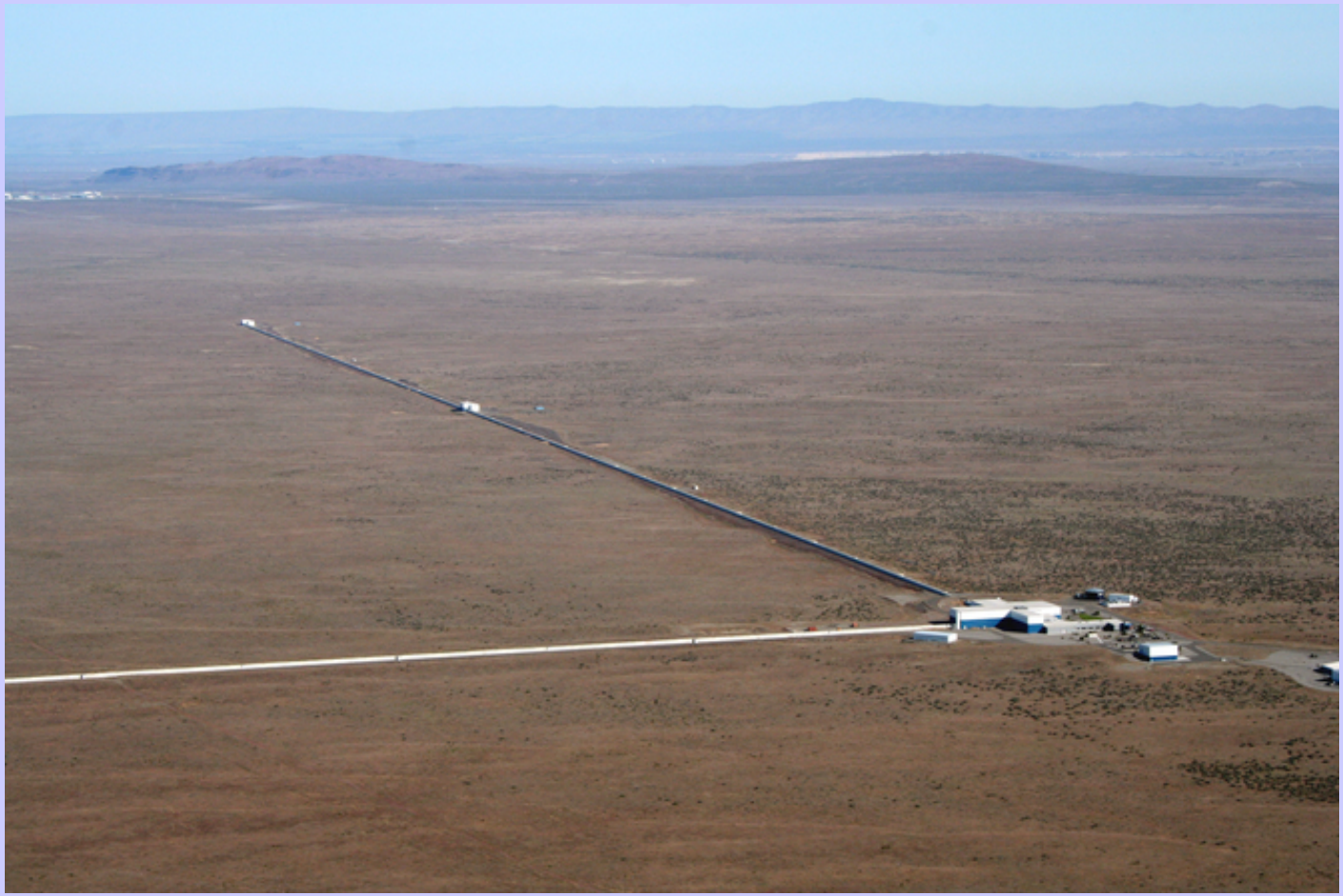
Prediction: Gravitational Waves Exist



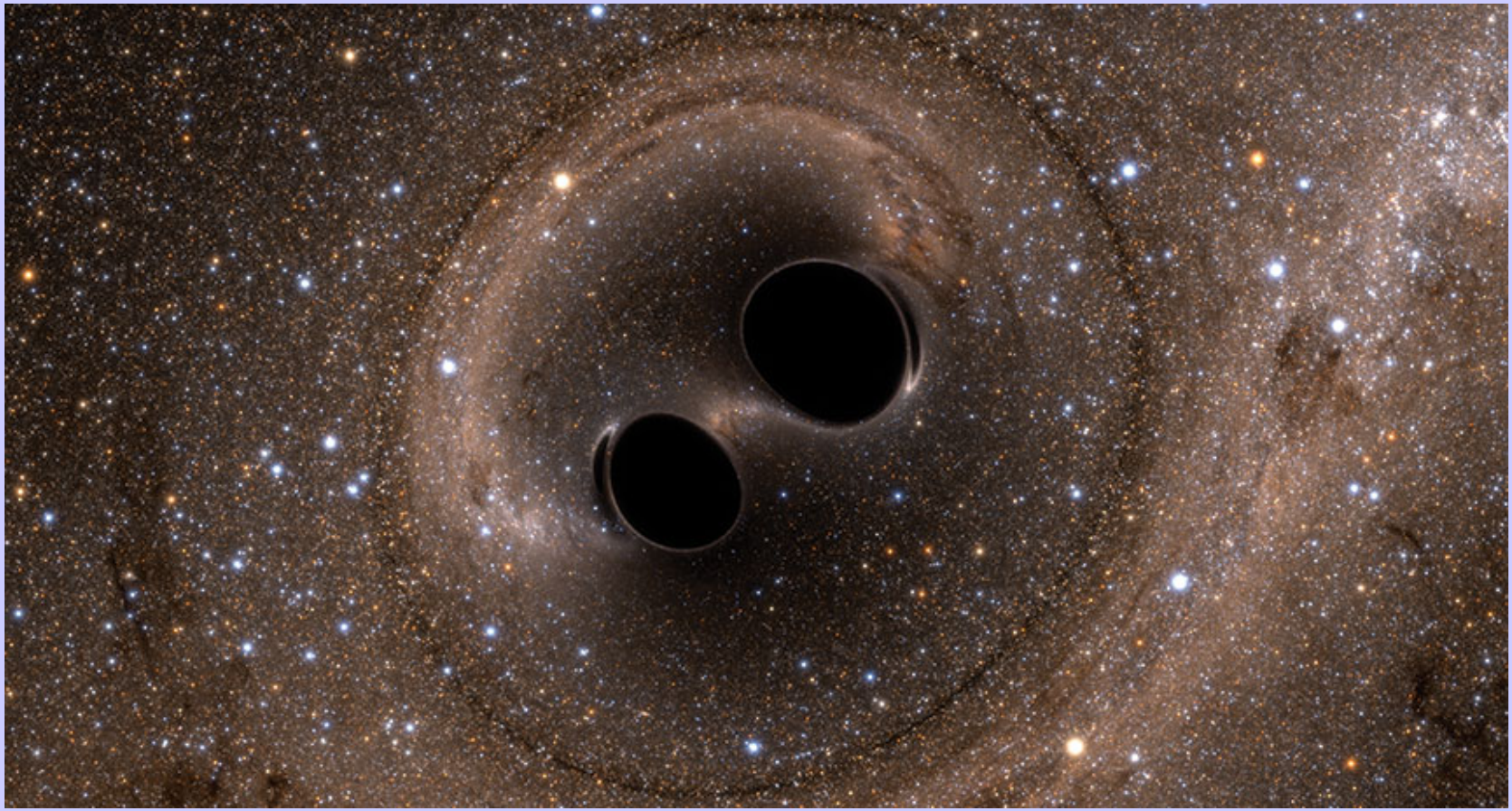
LIGO Schematic



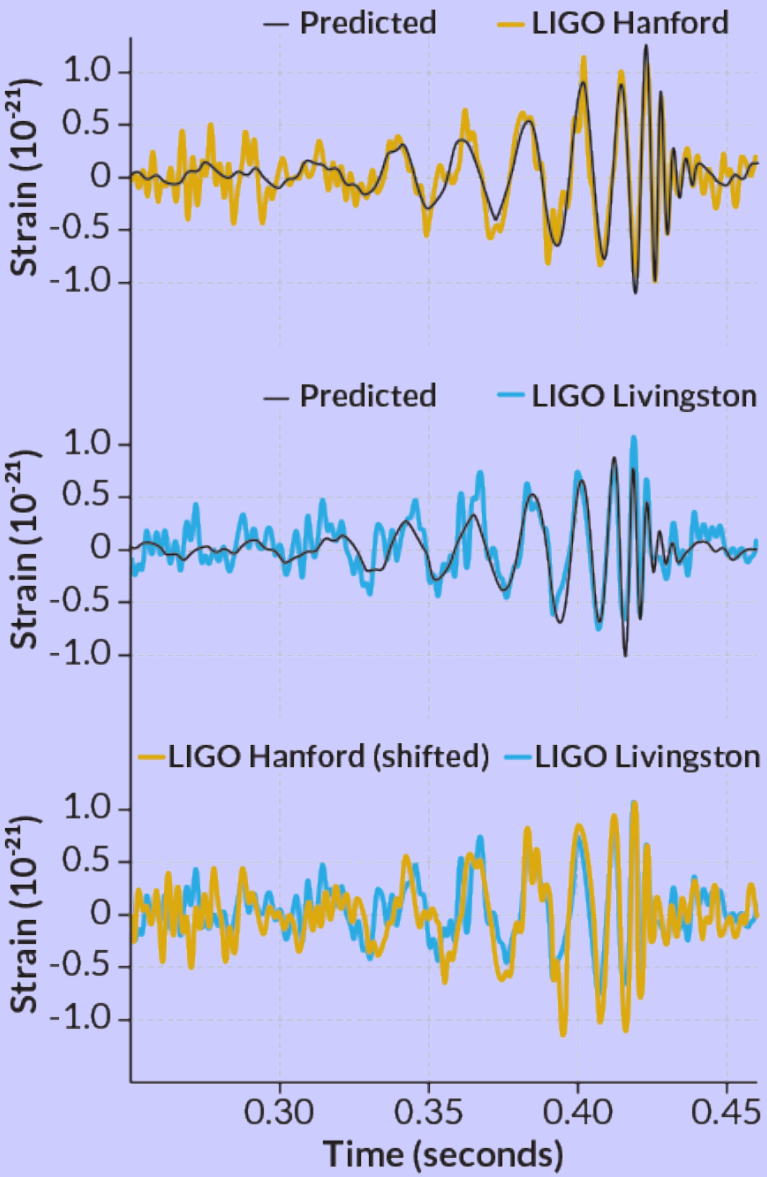
LIGO Hanford Site



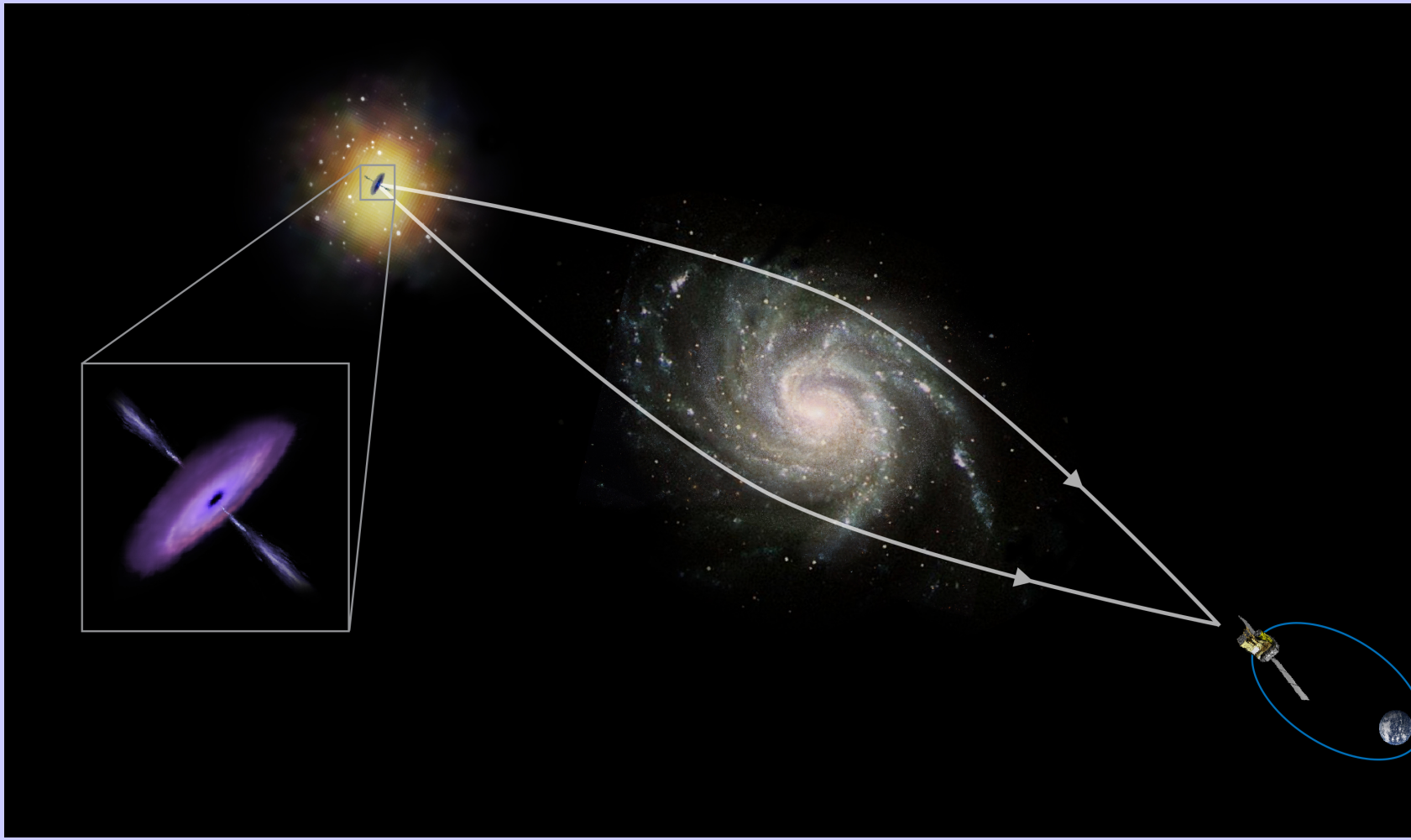
Binary Black Hole



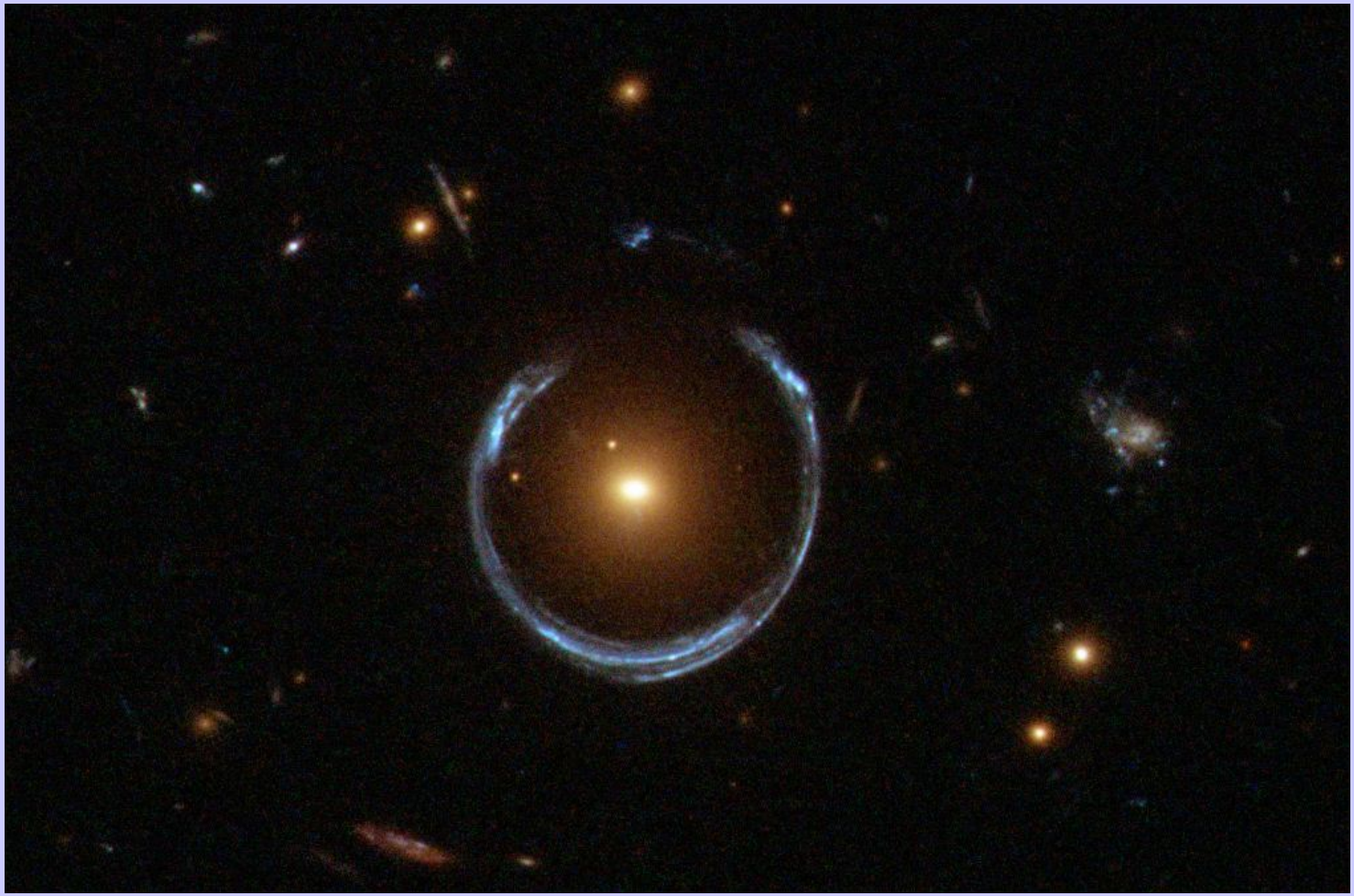
LIGO Event


Predicted
LIGO Hanford
Strain (10^{-21})
1.0
0.5
0
-0.5
-1.0
Predicted
LIGO Livingston
Strain (10^{-21})
LIGO Hanford (shifted)
LIGO Livingston
0.30
0.35
0.40
0.45
Time (seconds)

Principle of Gravitational Lensing

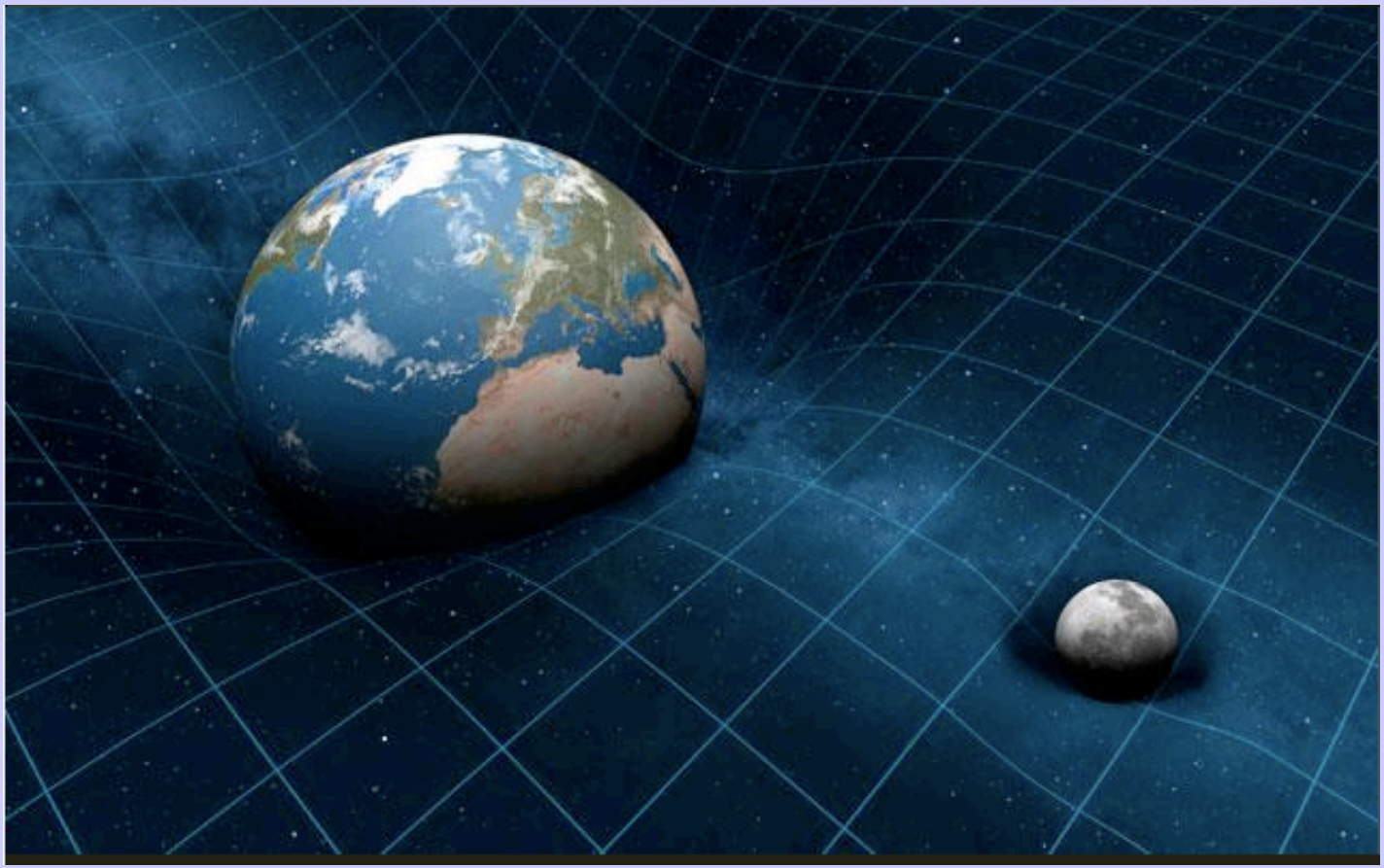


Gravitational Lensing Ring (Einstein Ring)

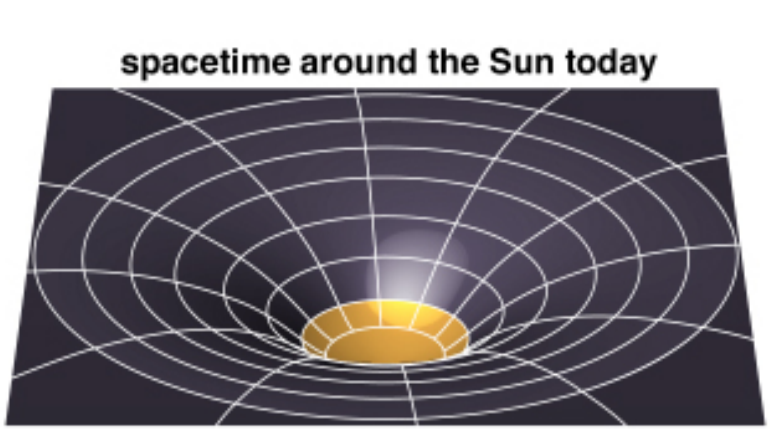


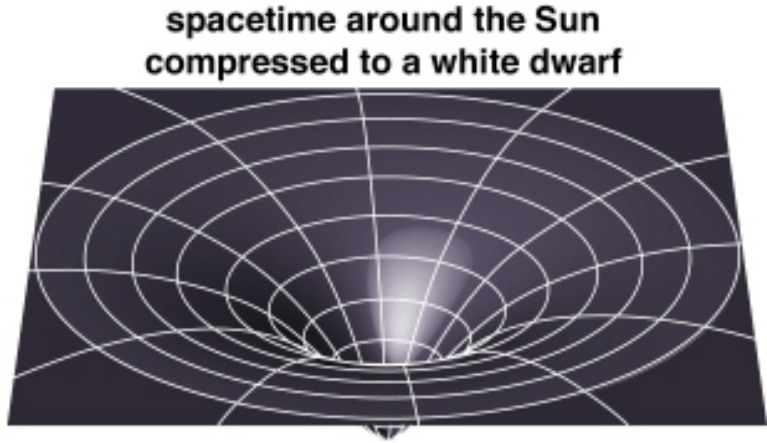
Gravitational Lensing (HST Picture)

Mass curves Space-Time

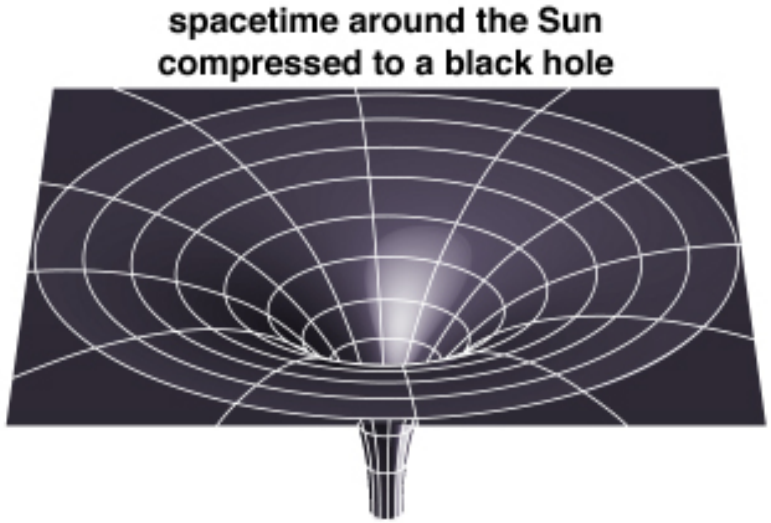


Sun as a Black Hole



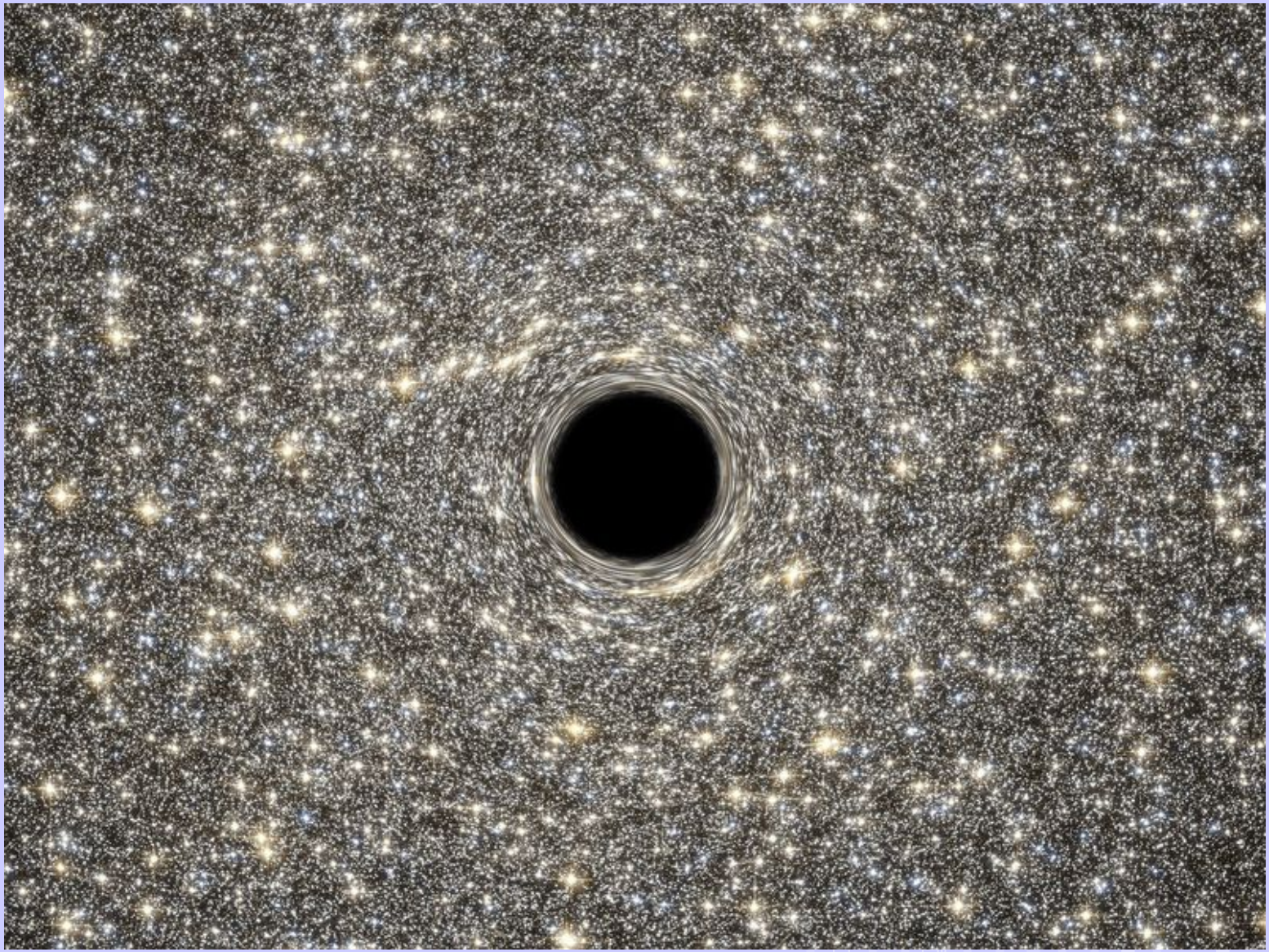


(a)

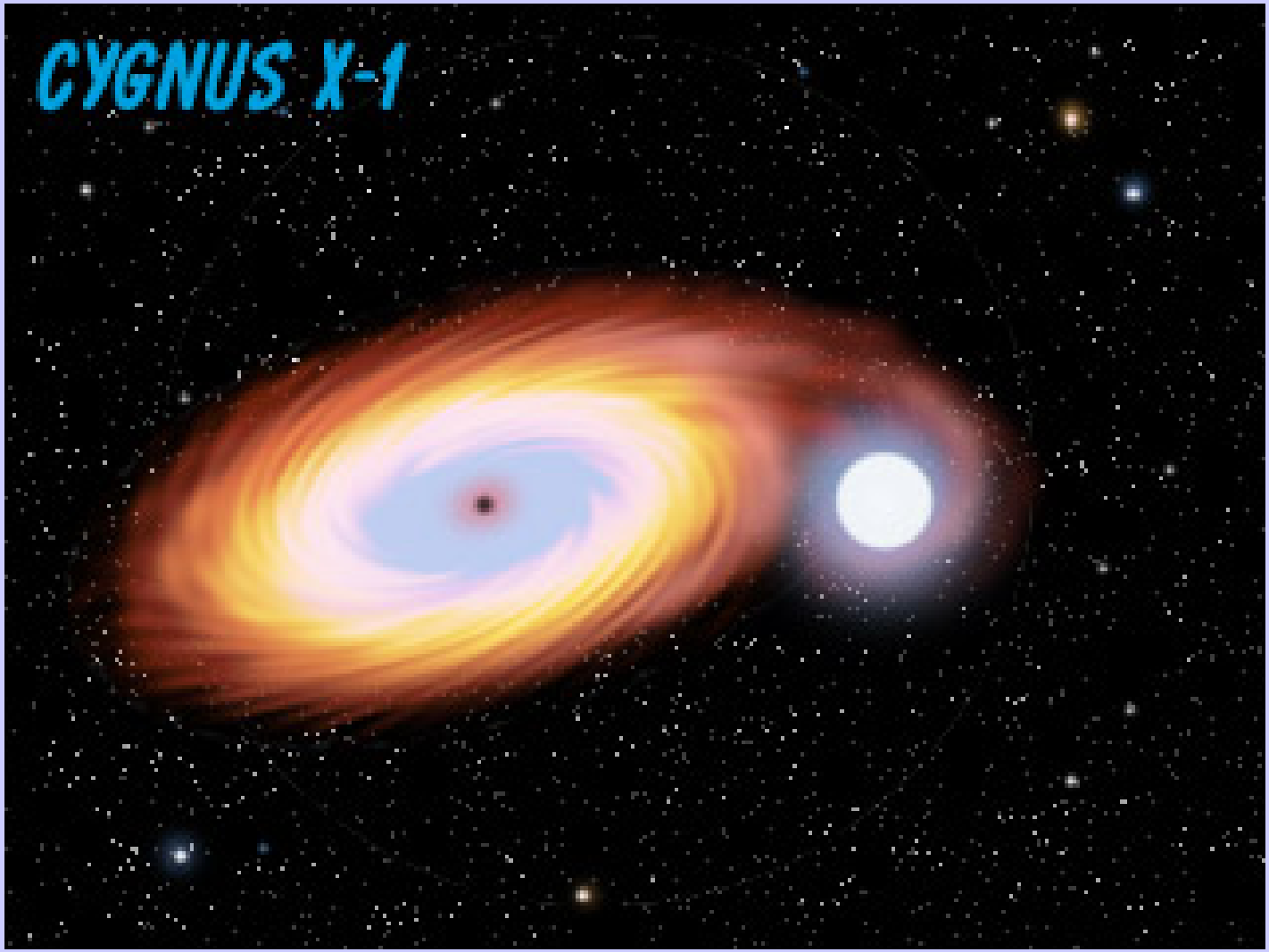


(b)

Prediction: Black Holes



Cygnus X1



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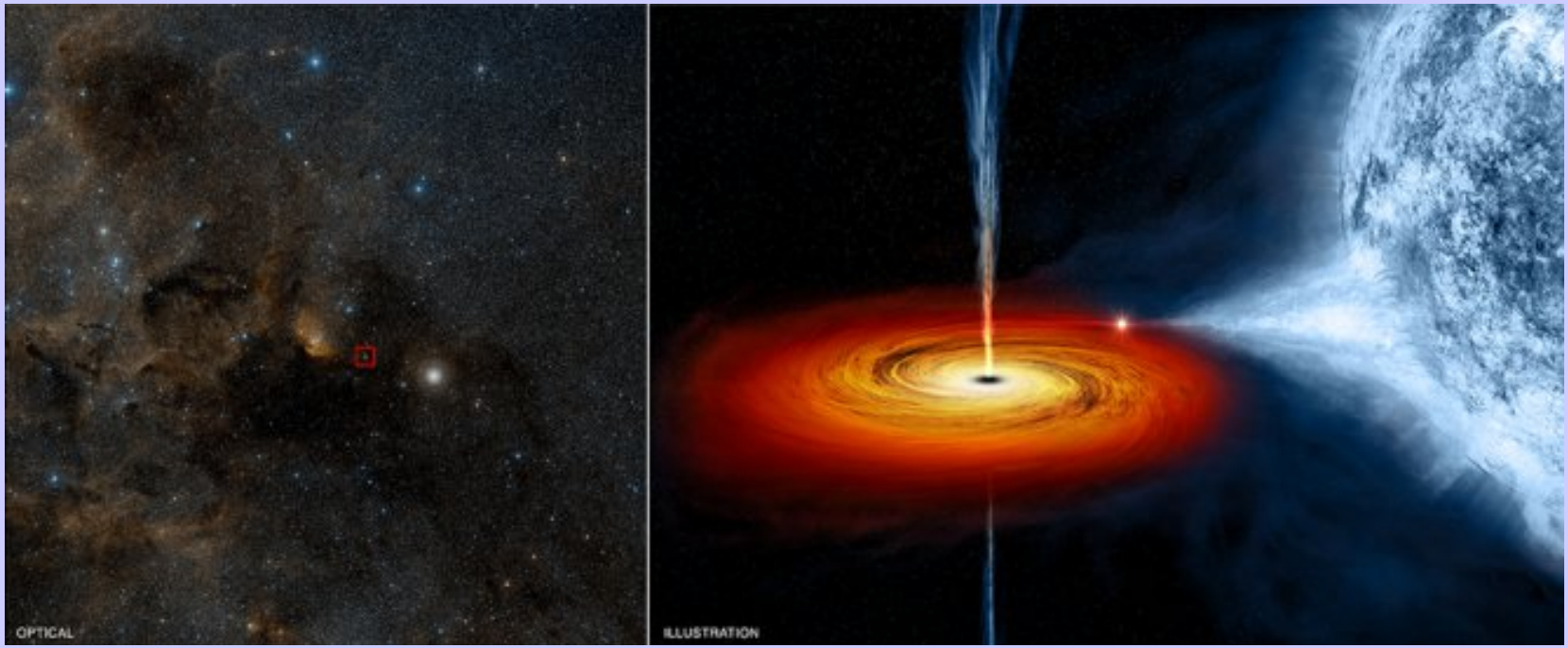
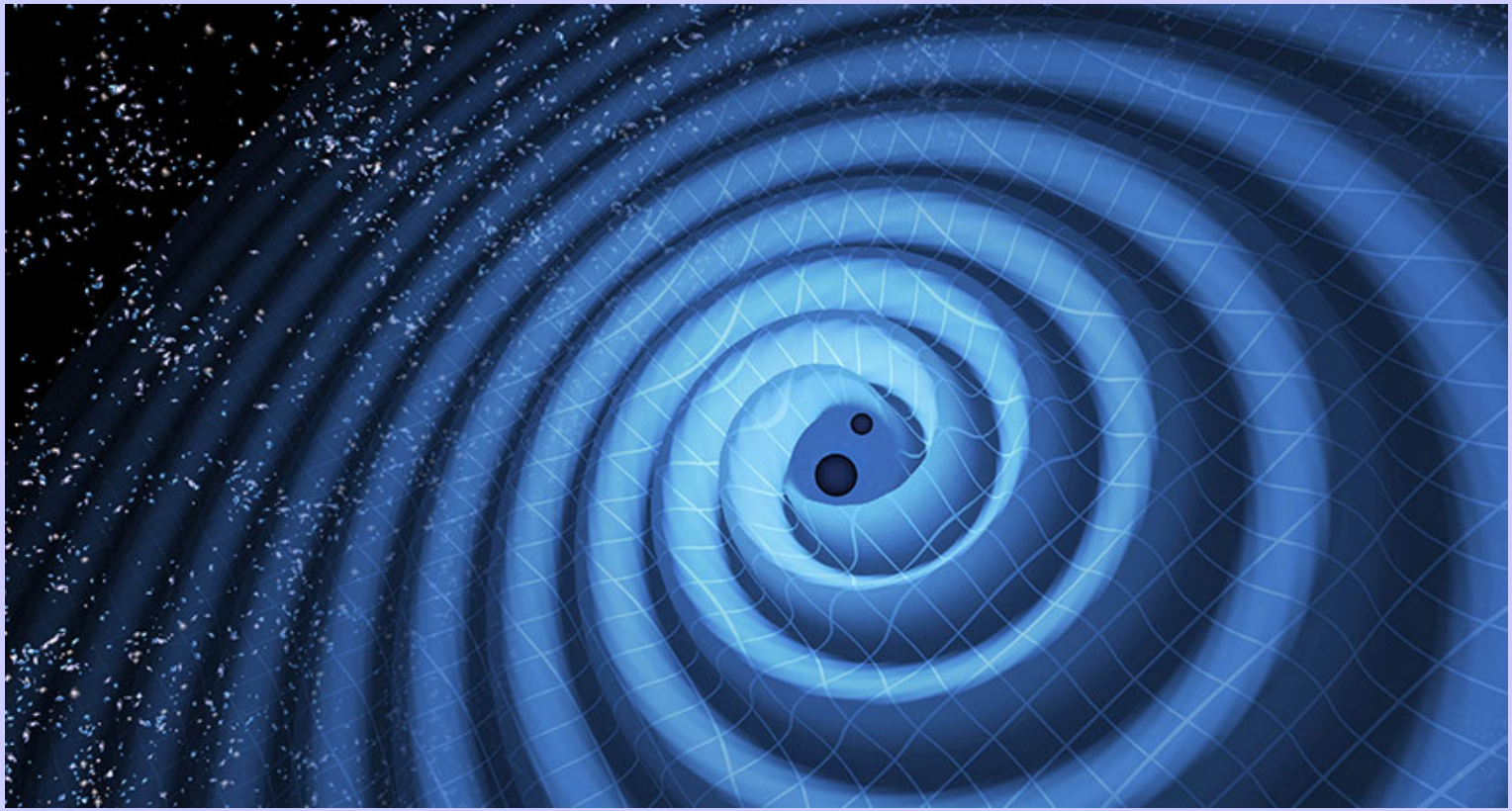


Prediction: Gravitational Waves Exist



Gravitational Waves

Gravitational Waves:

- **Fluctuations of vacuum space-time.**
- Obey the wave equation.
- Travel with c.
- Two polarization states.
- **Are created by localized accelerating matter with a non-vanishing quadrupole moment.**

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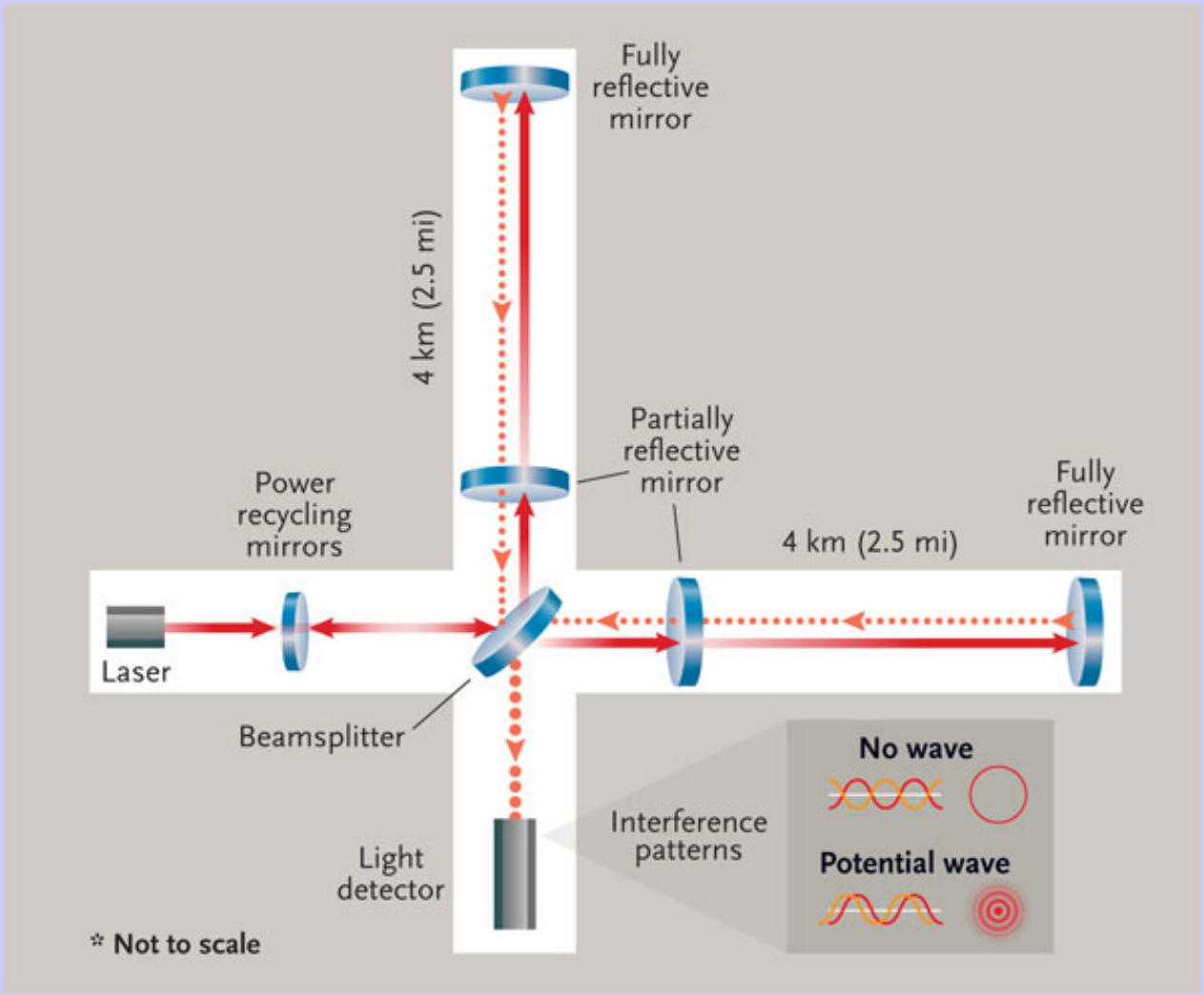
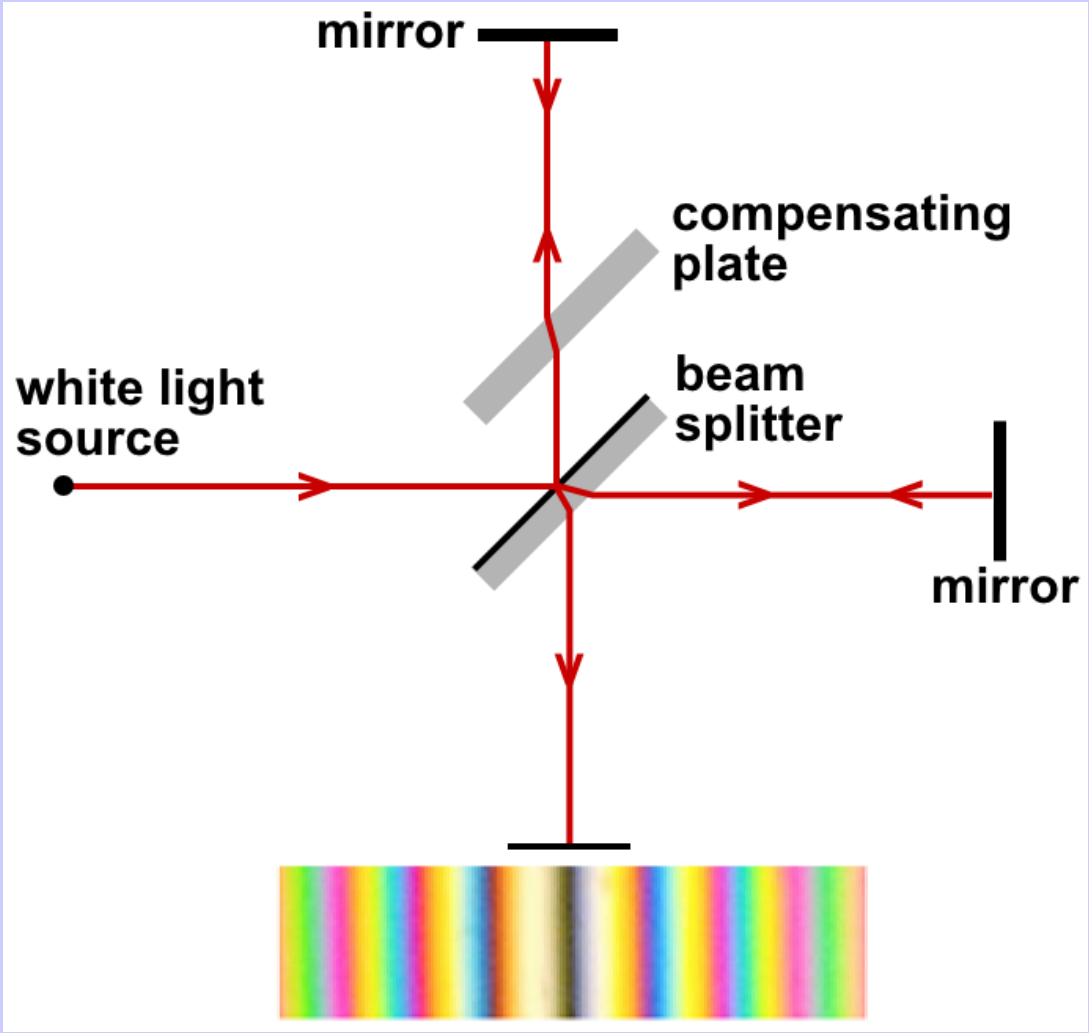
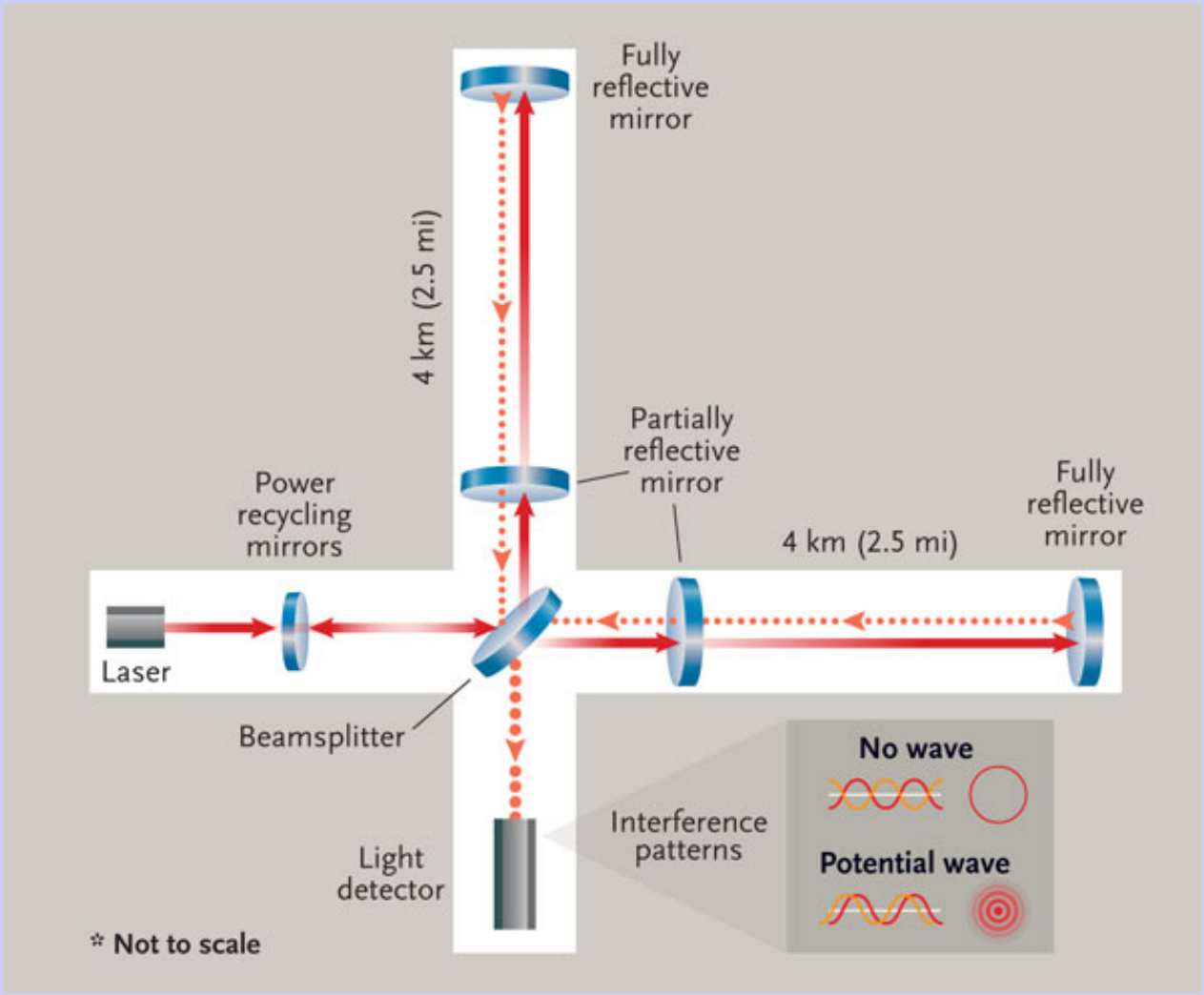
LIGO Schematic



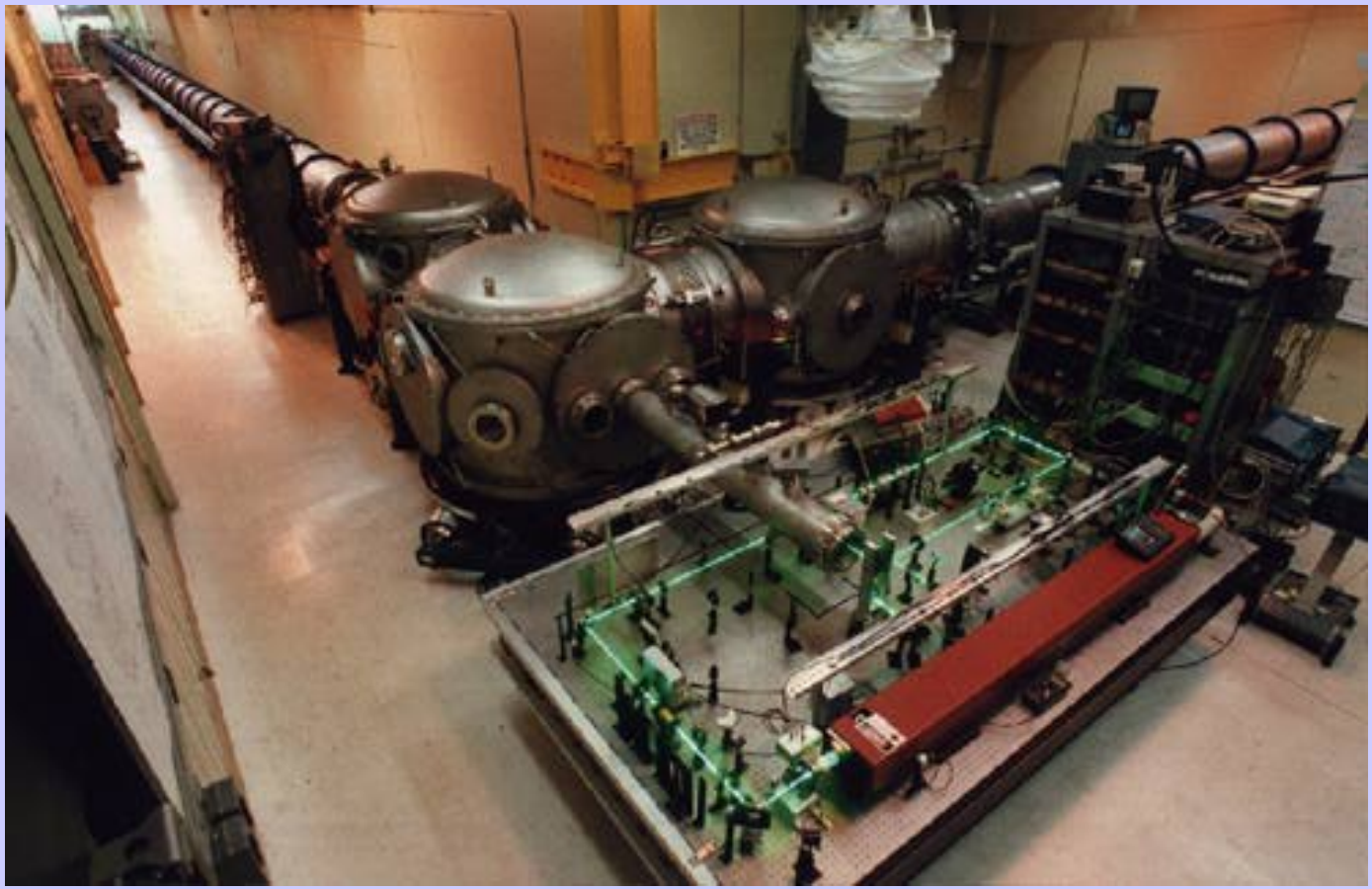
Michelson-Morley Interferometer



LIGO Schematic

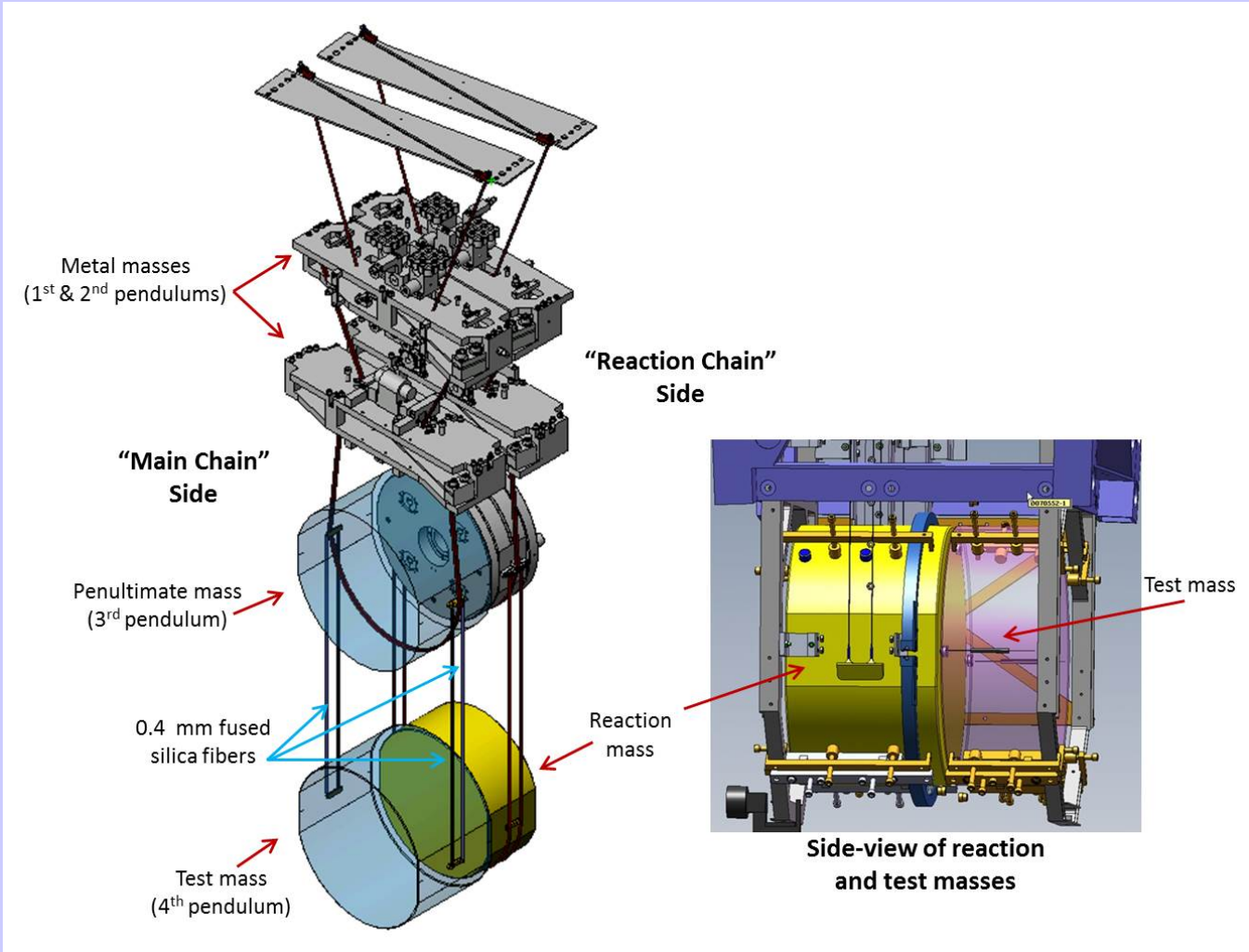


LIGO Laser (Prototype)

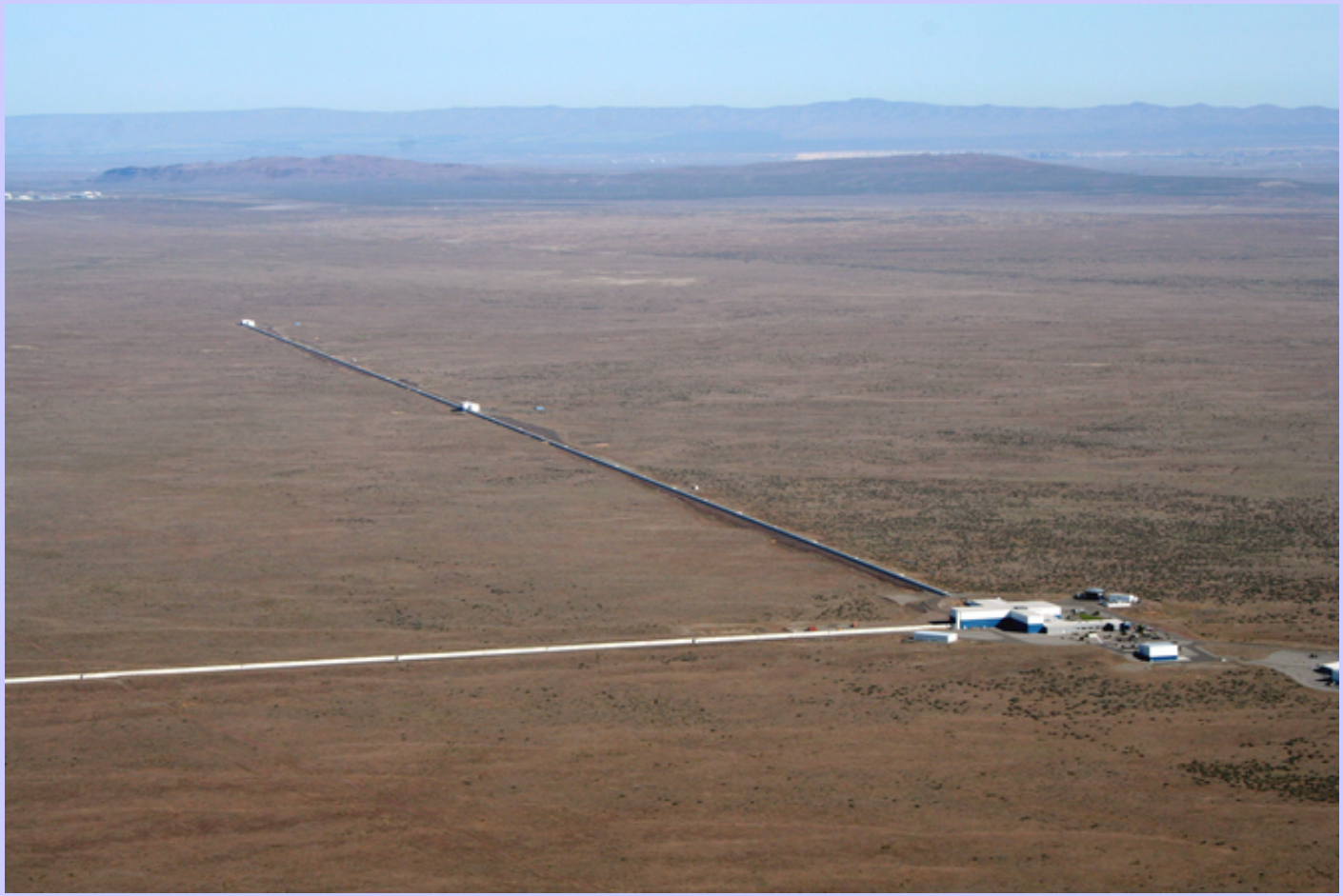


LIGO Mirrors

LIGO Seismic Isolation



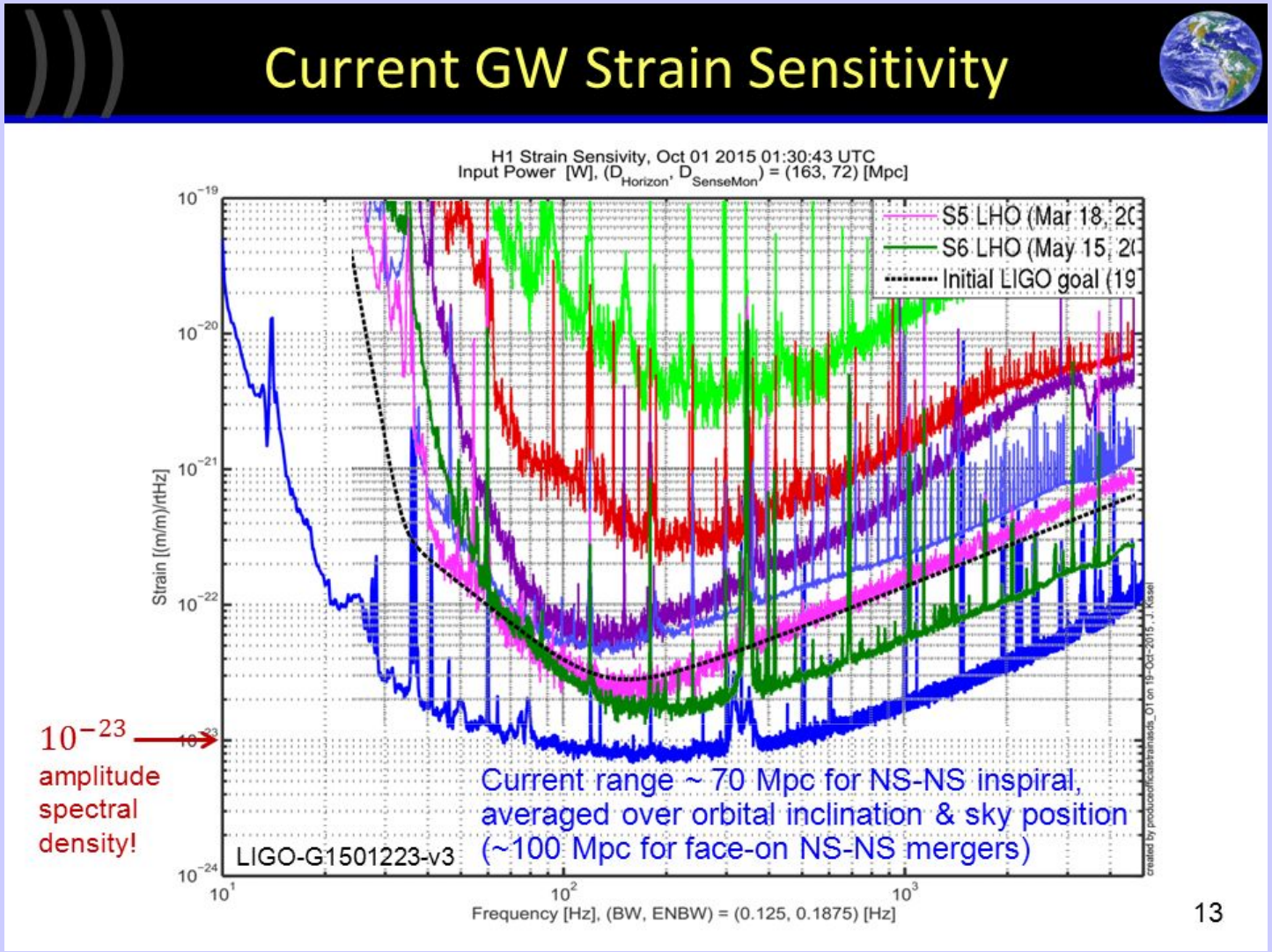
LIGO Hanford Site



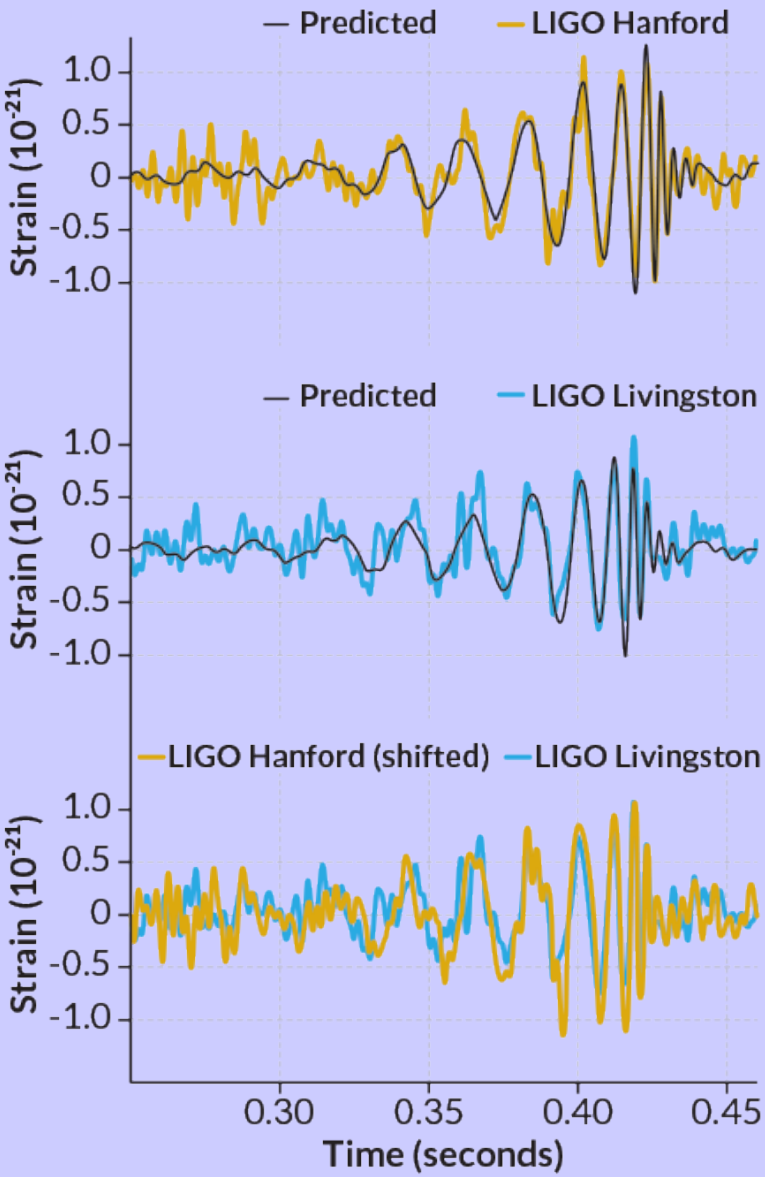
LIGO Livingstone Site

VIRGO Laboratory

LIGO Sensitivity

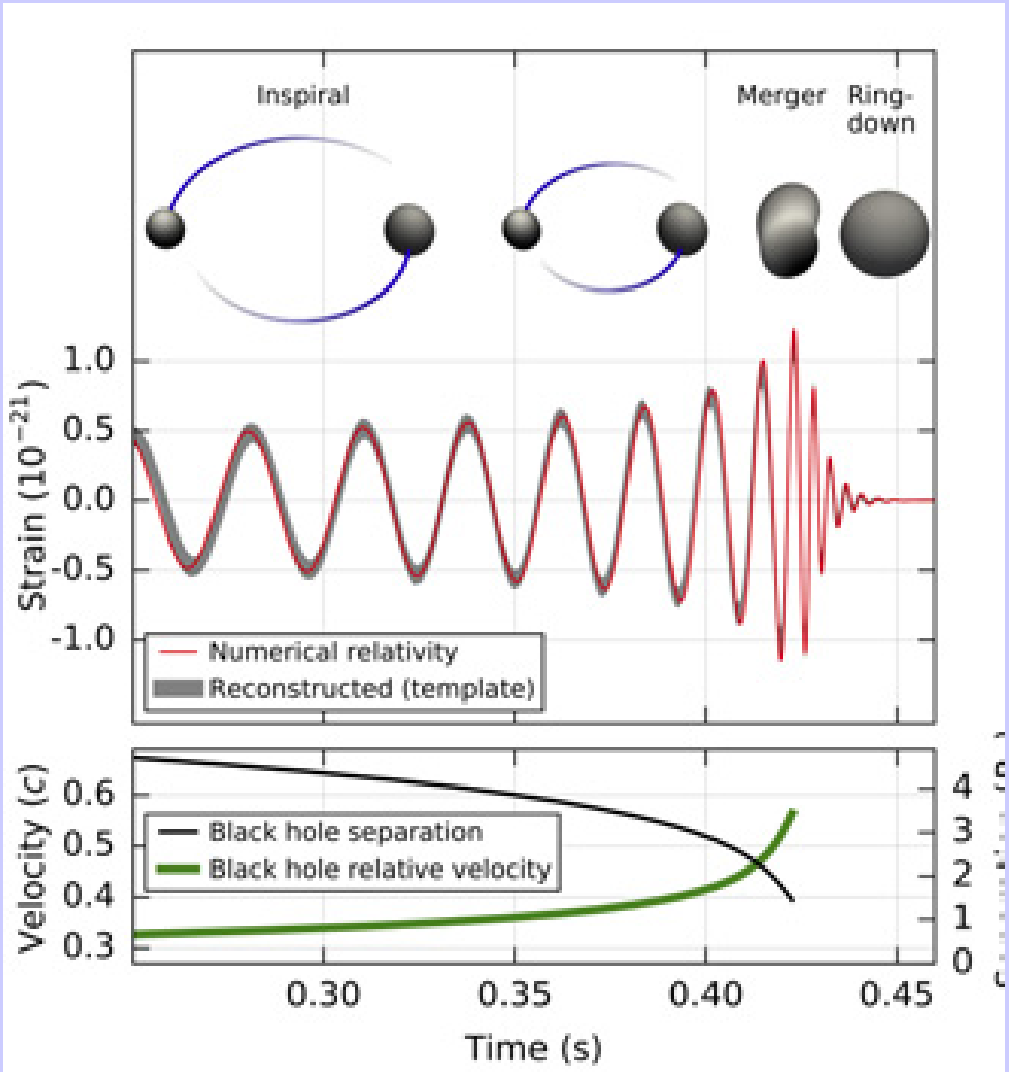


LIGO Event (Sept. 2015): Nobel Prize 2017

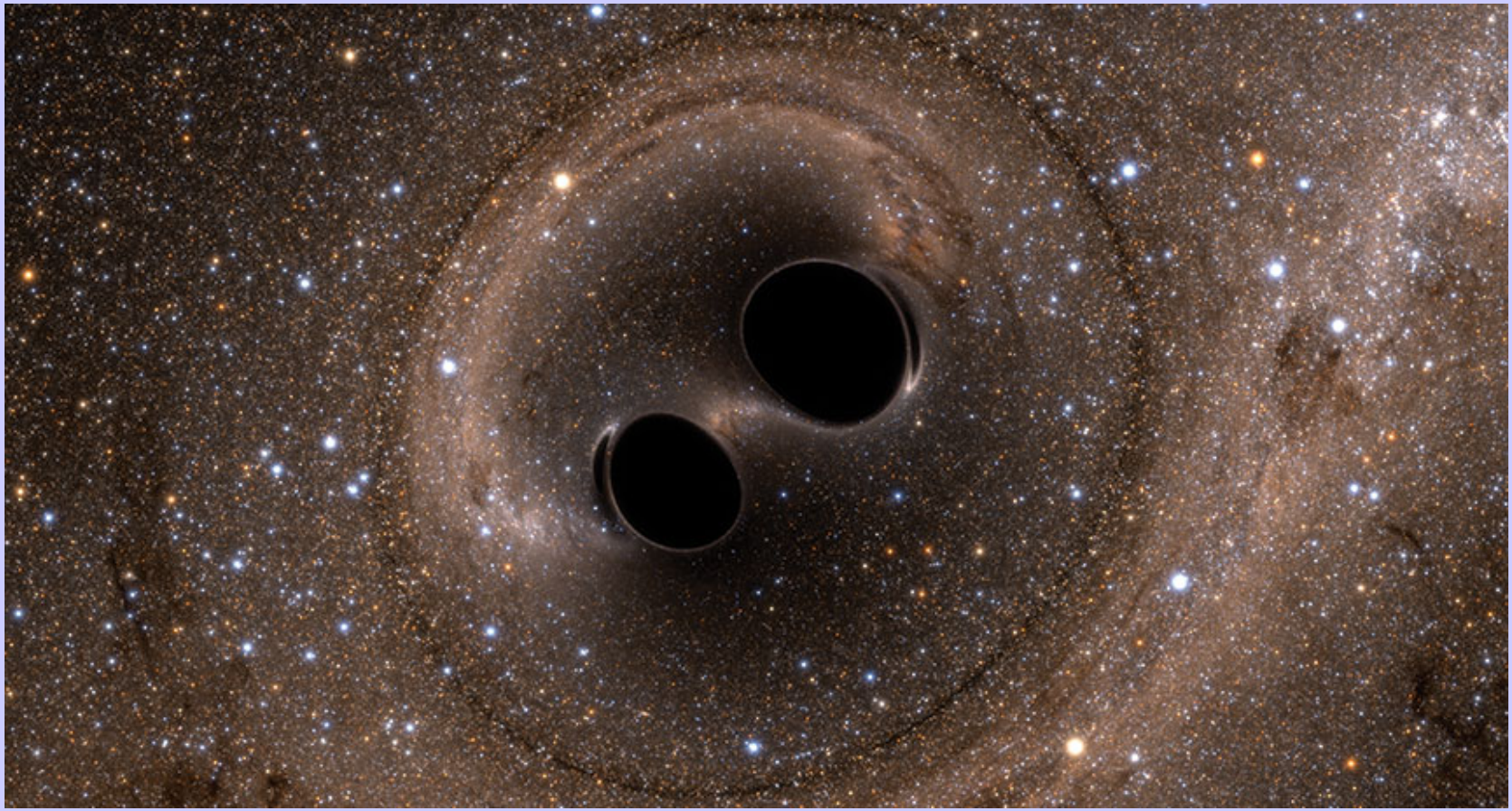


Prof. Rainer Weiss, MIT

Prediction (Numerical GR)



Binary Black Hole



What have we learned?

- FIrst direct detection of gravitational waves.
- Best evidence for the existence of a black hole horizon.
- Best test of General Relativity close to a black hole horizon.
- First detection of a black hole binary system.
- Rate of black hole binaries.

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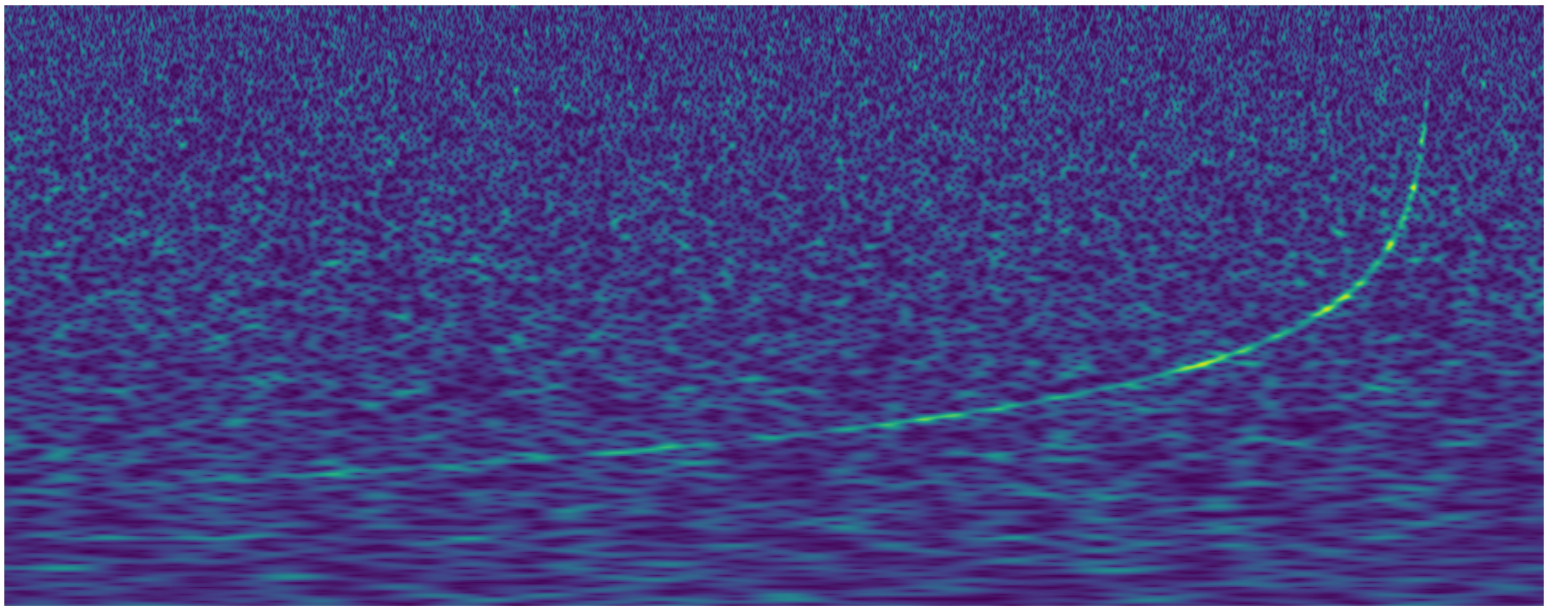
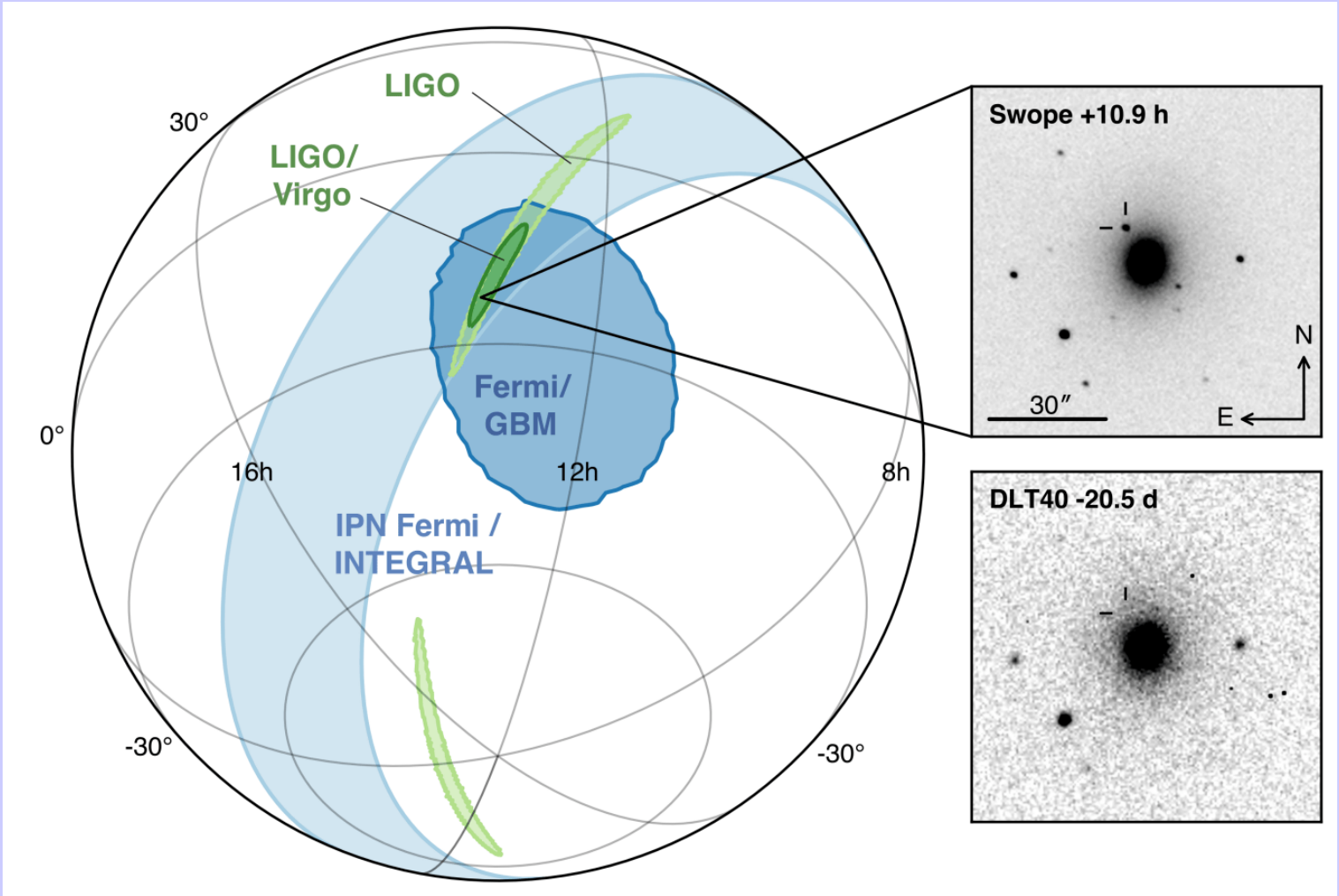
Neutron Star Merger Discovery: August 17 2017



Birth of Multimessenger Astronomy: August 17 2017



What have we learned?

- First detection of an optical counterpart to a direct gravitational wave signal.
- Birth of the field of Multi-Messenger Astronomy.
- First multi-wavelength observation of a kilonova.
- Verification that kilonovae can produce heavy elements (like supernovae).
- Stringent test of the Einstein equivalence principle.
- Many alternative gravity models ruled out.
- New standard candle $\rightarrow$ new way to directly measure the Hubble expansion rate.

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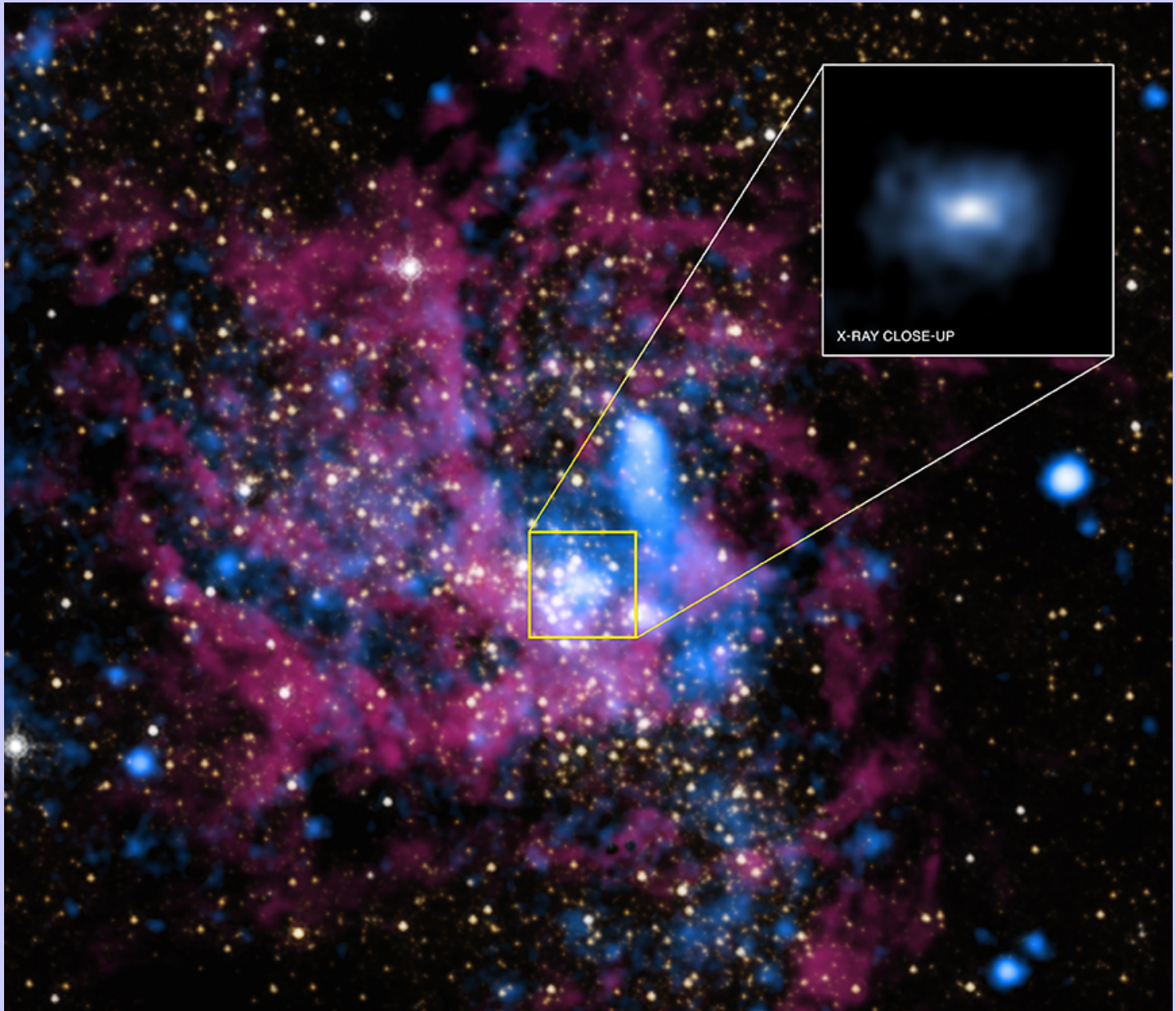
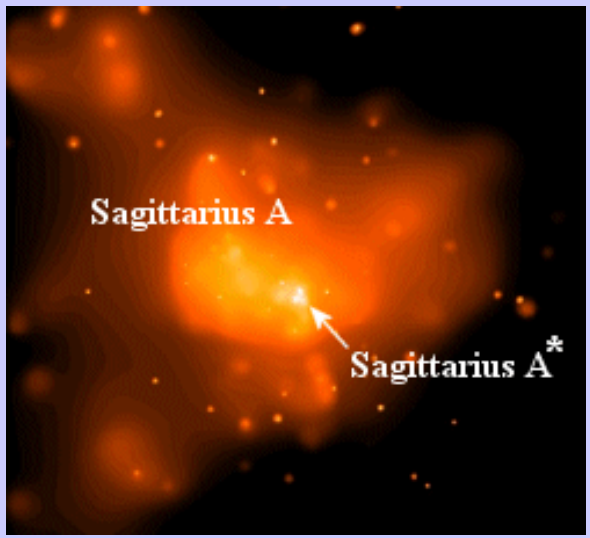
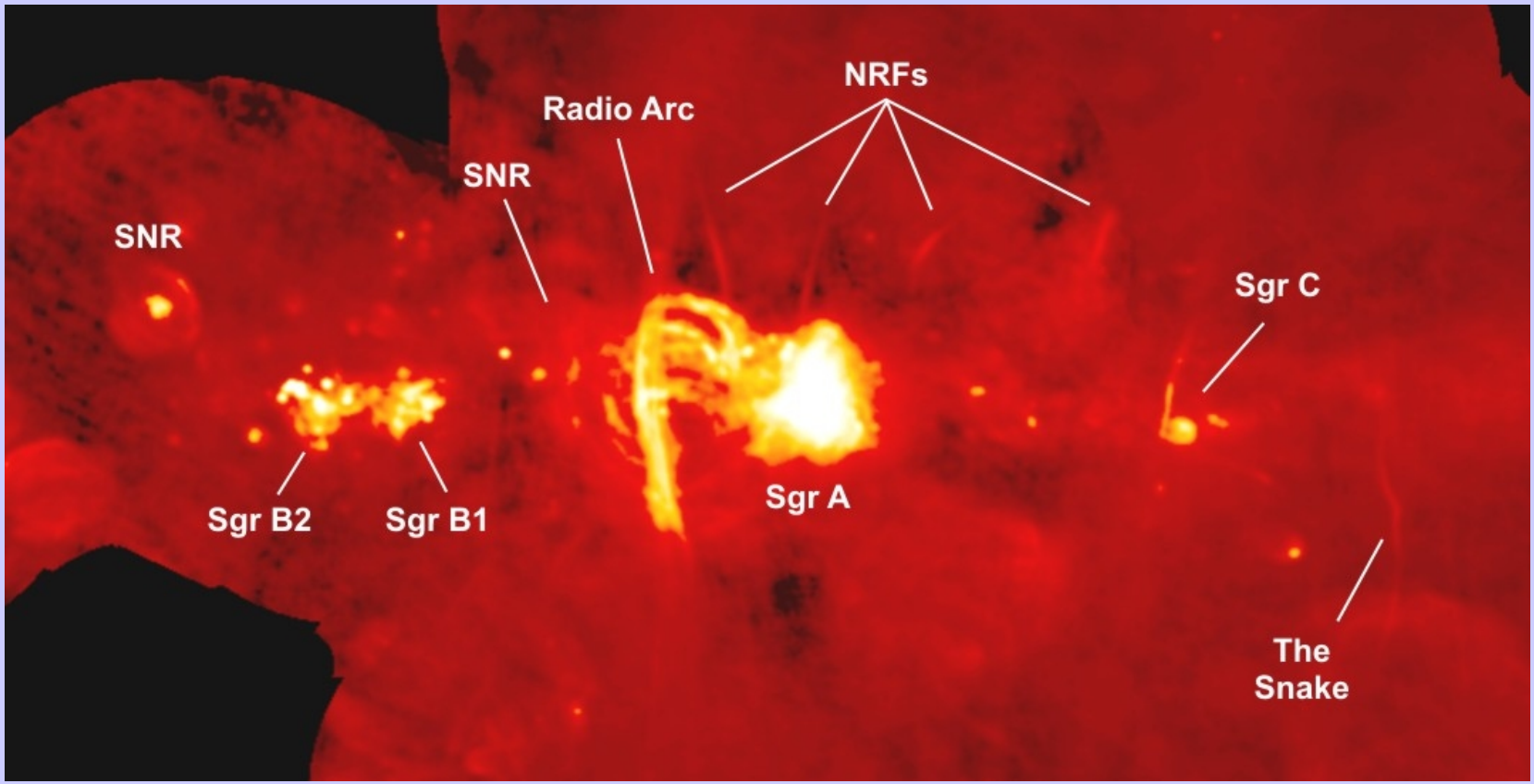
Super-Massive Black Hole in the Center of the Milky Way



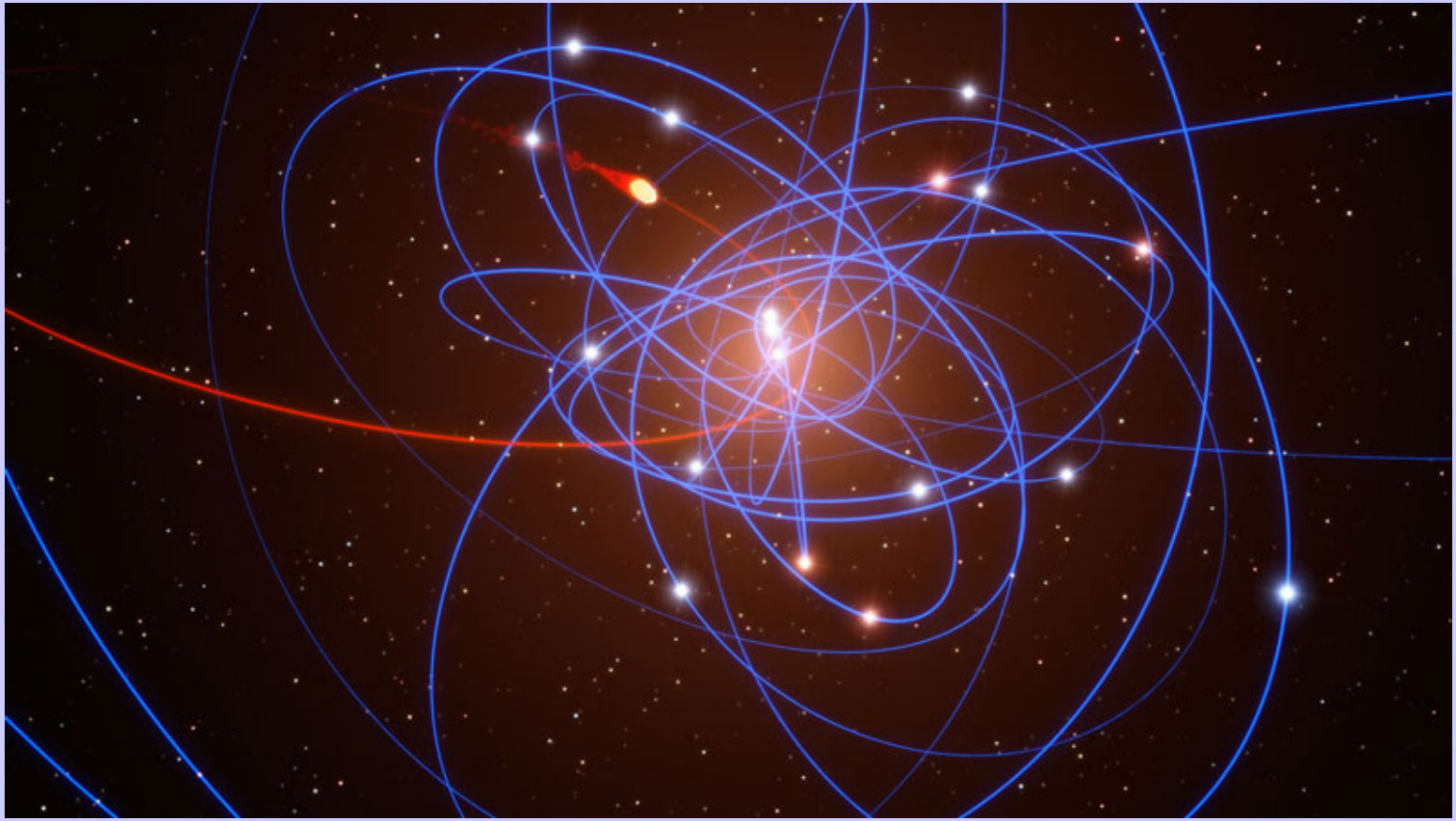
Sagittarius A* in X-Ray



Sagittarius A* in Radio



Orbits of Stars about our Super-Massive Black Hole



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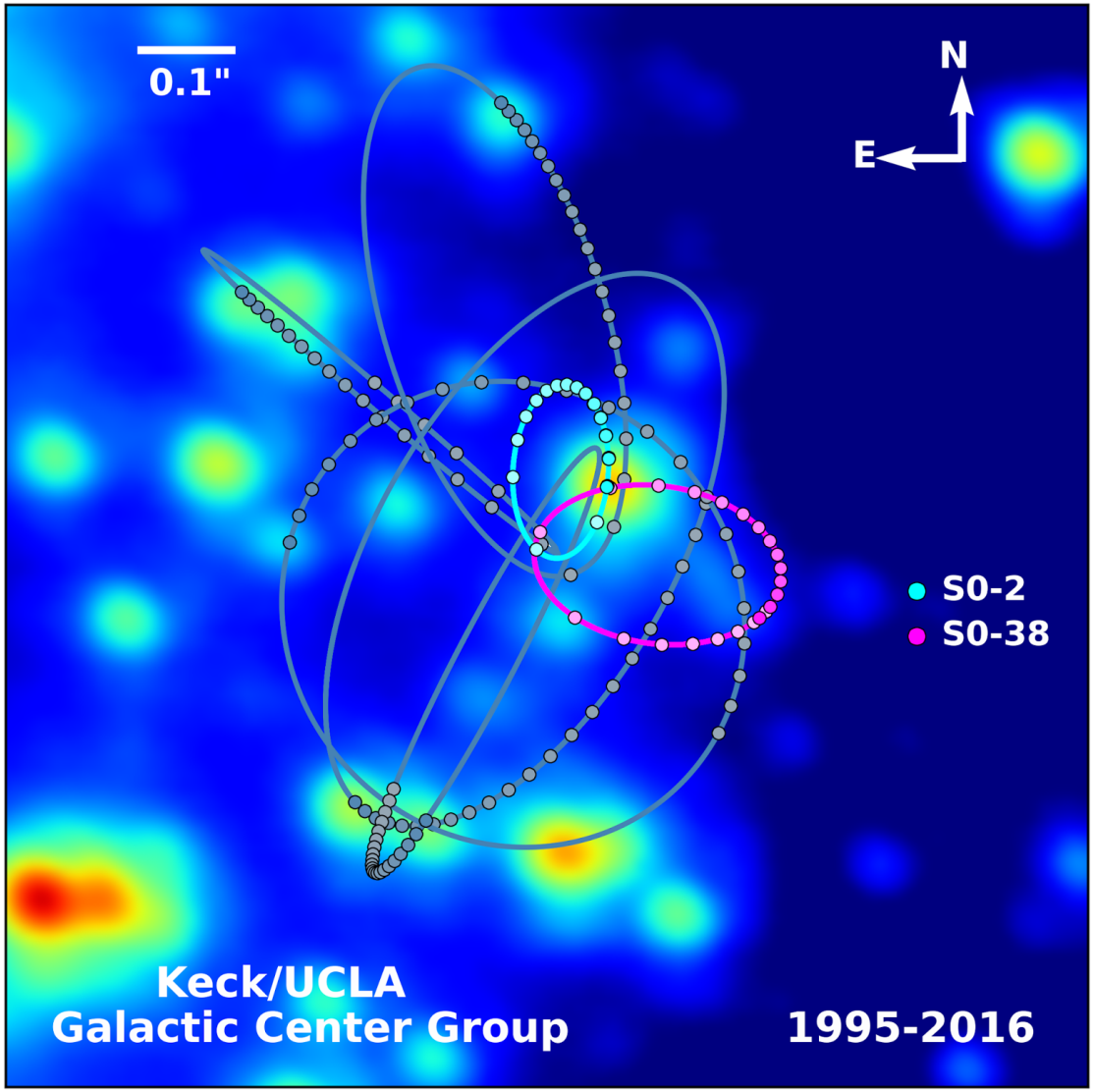
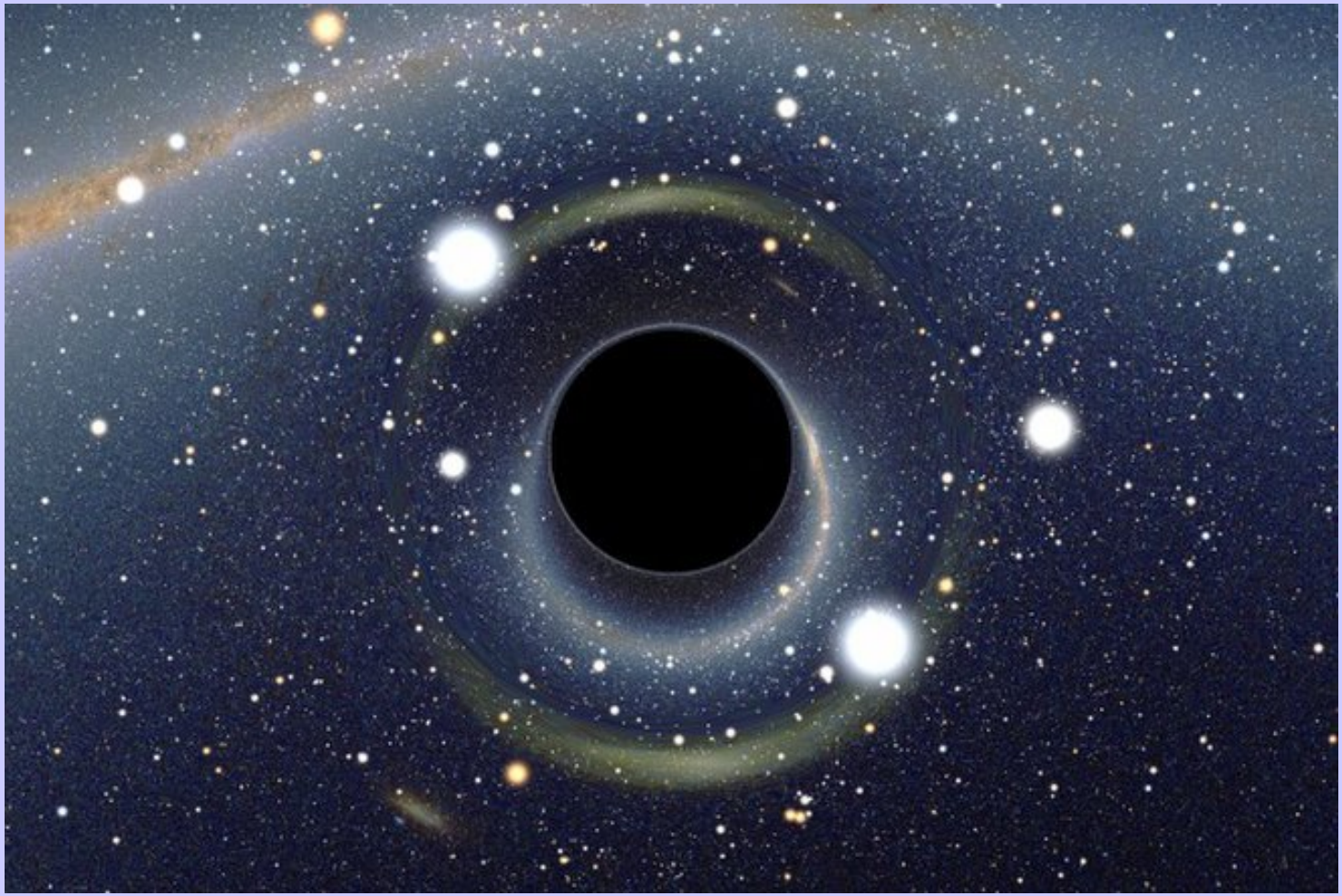
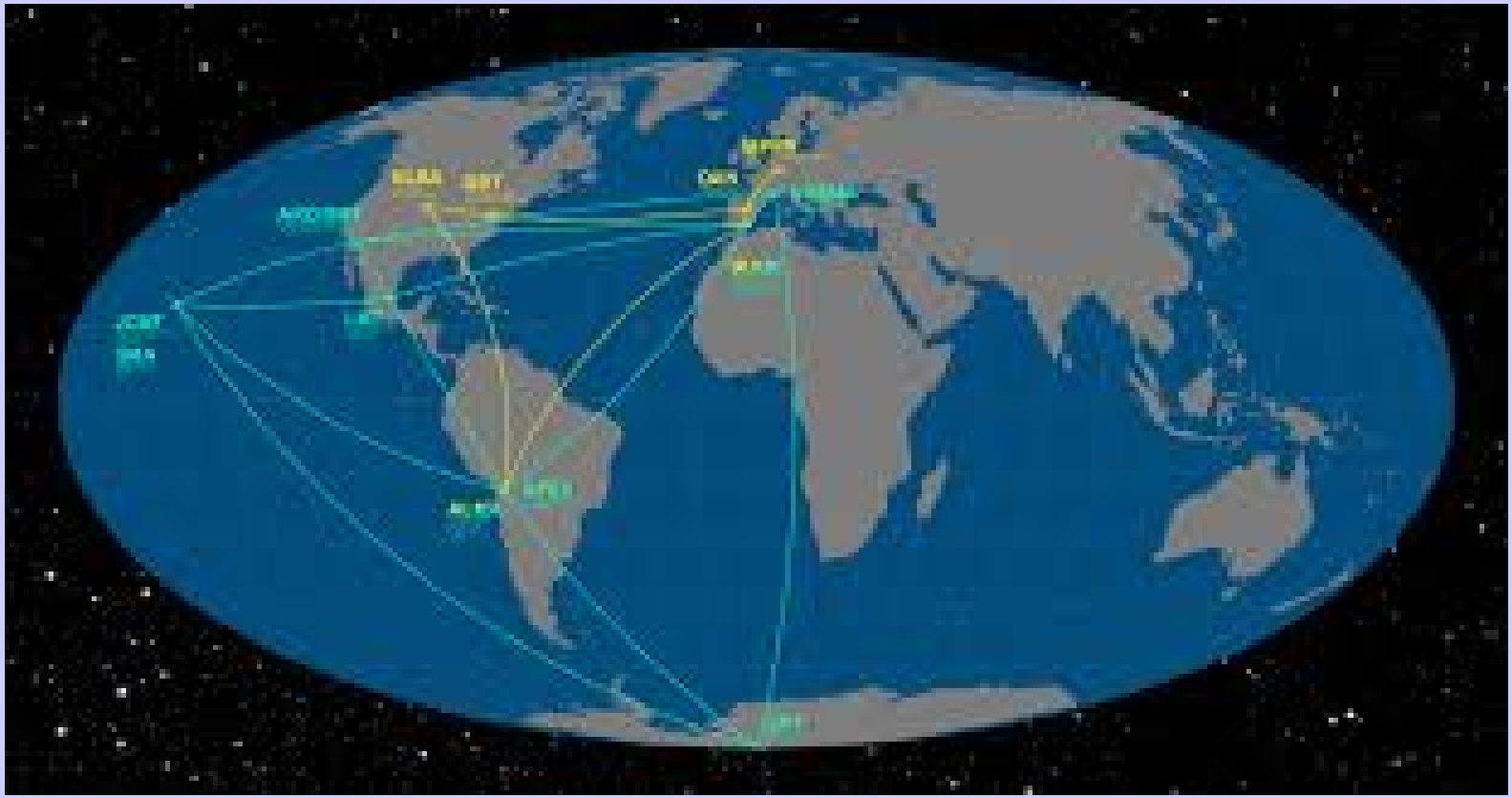


Leader of the UCLA Group: Prof. A. Ghez (Nobel Prize 2020)

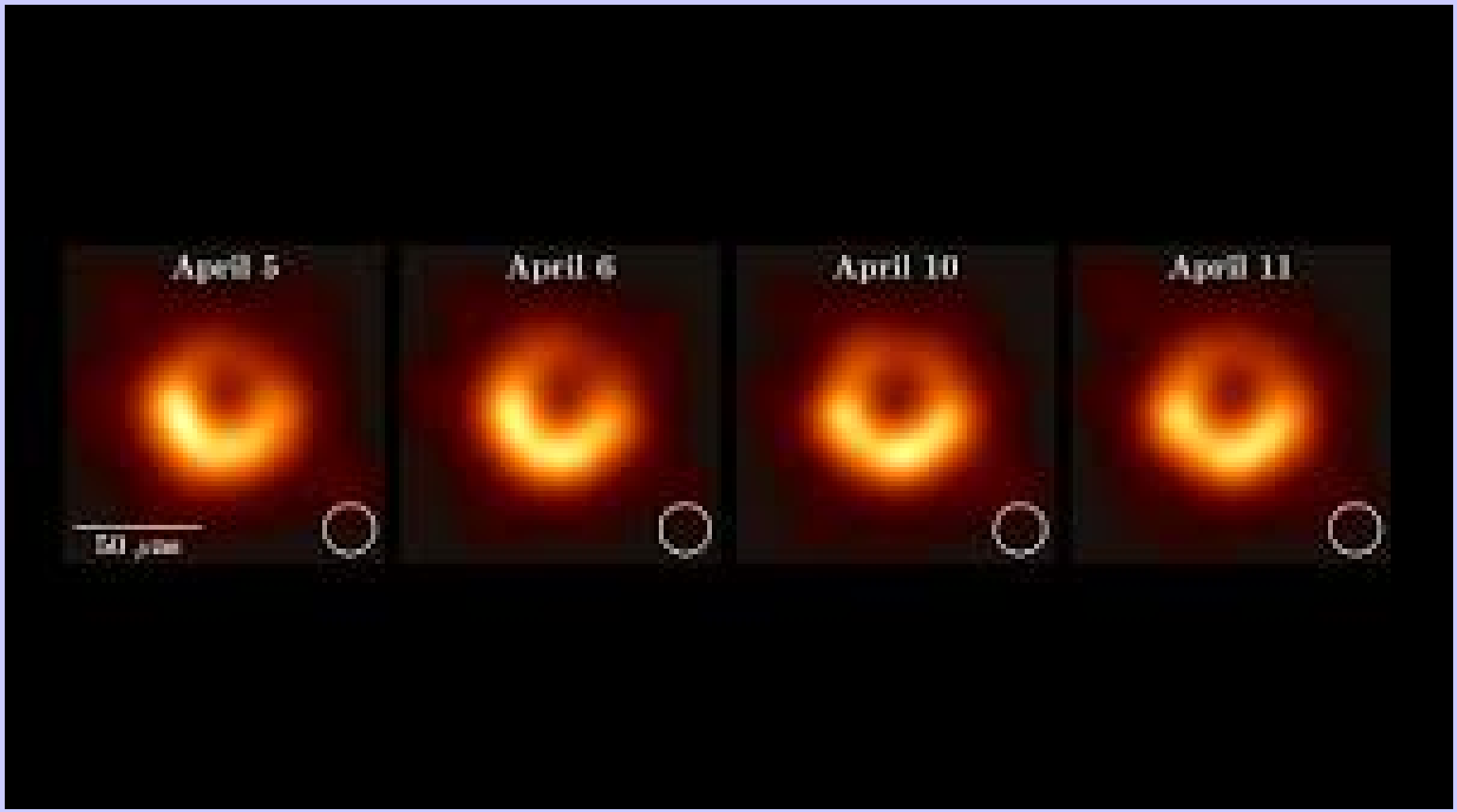
Illustration of our Super-Massive Black Hole



Event Horizon Telescope Program



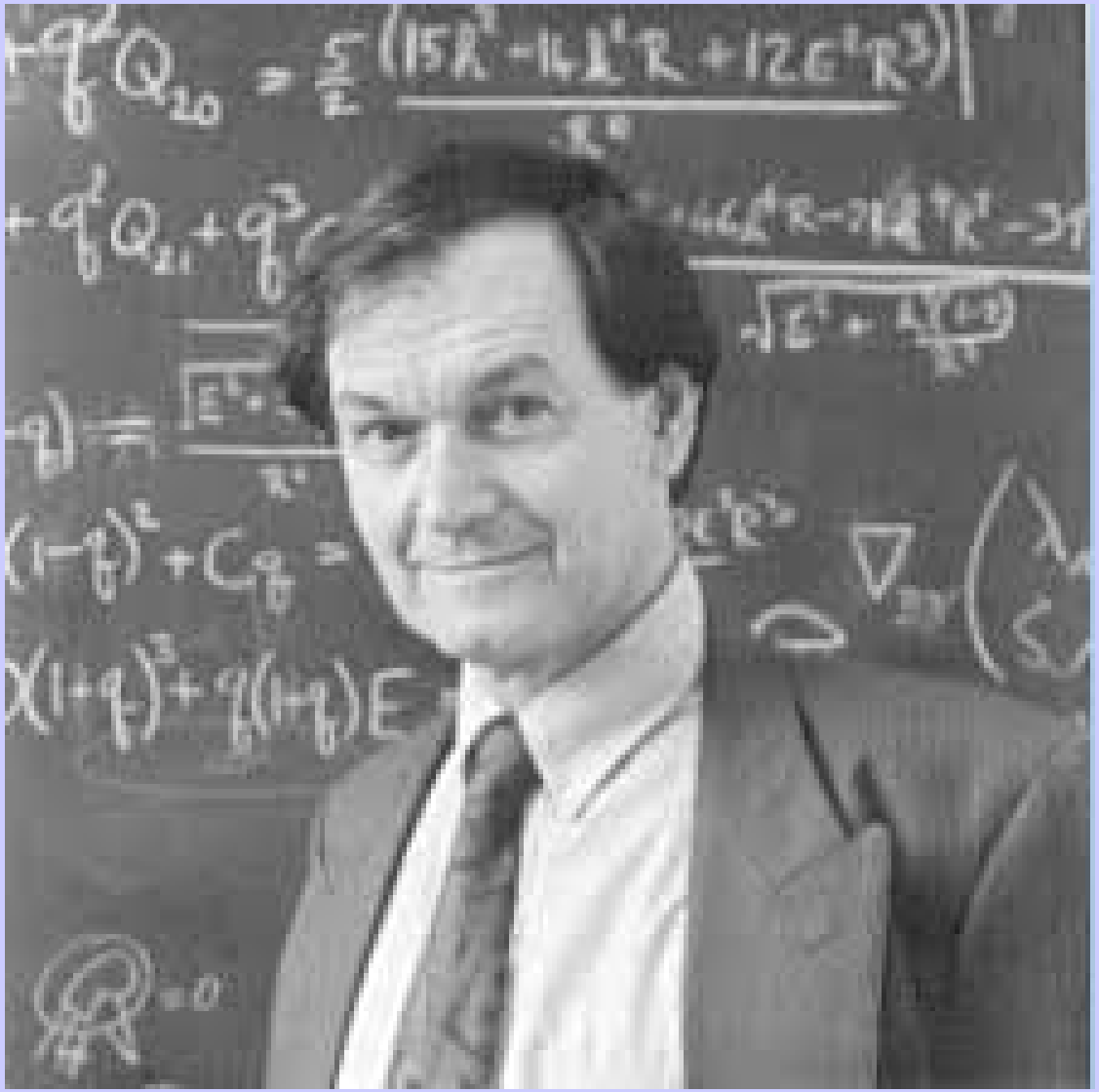
Event Horizon Telescope Image (2019)



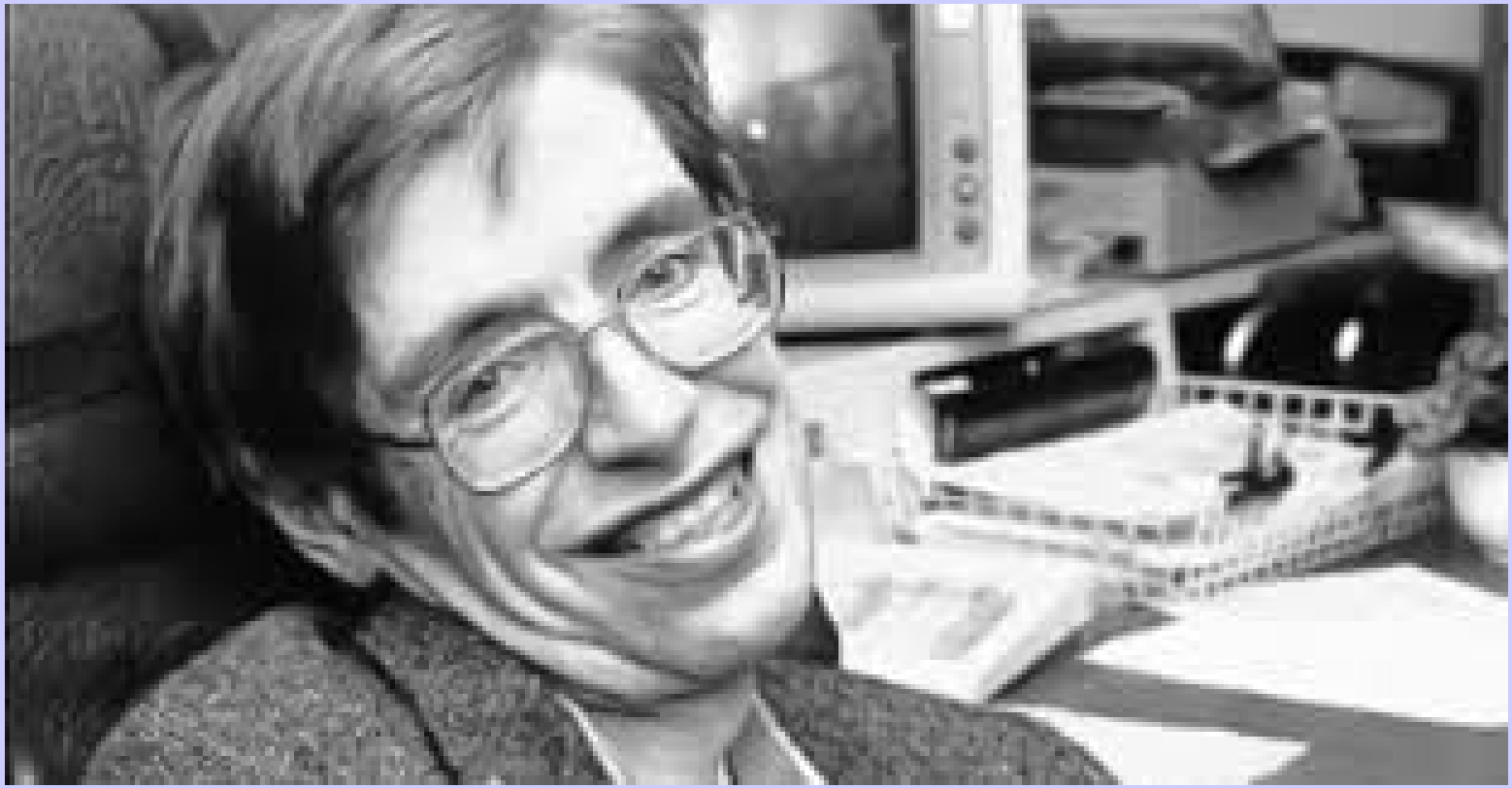
Note: Breakthrough Prize, 2019

Event Horizon Telescope Image (2019)

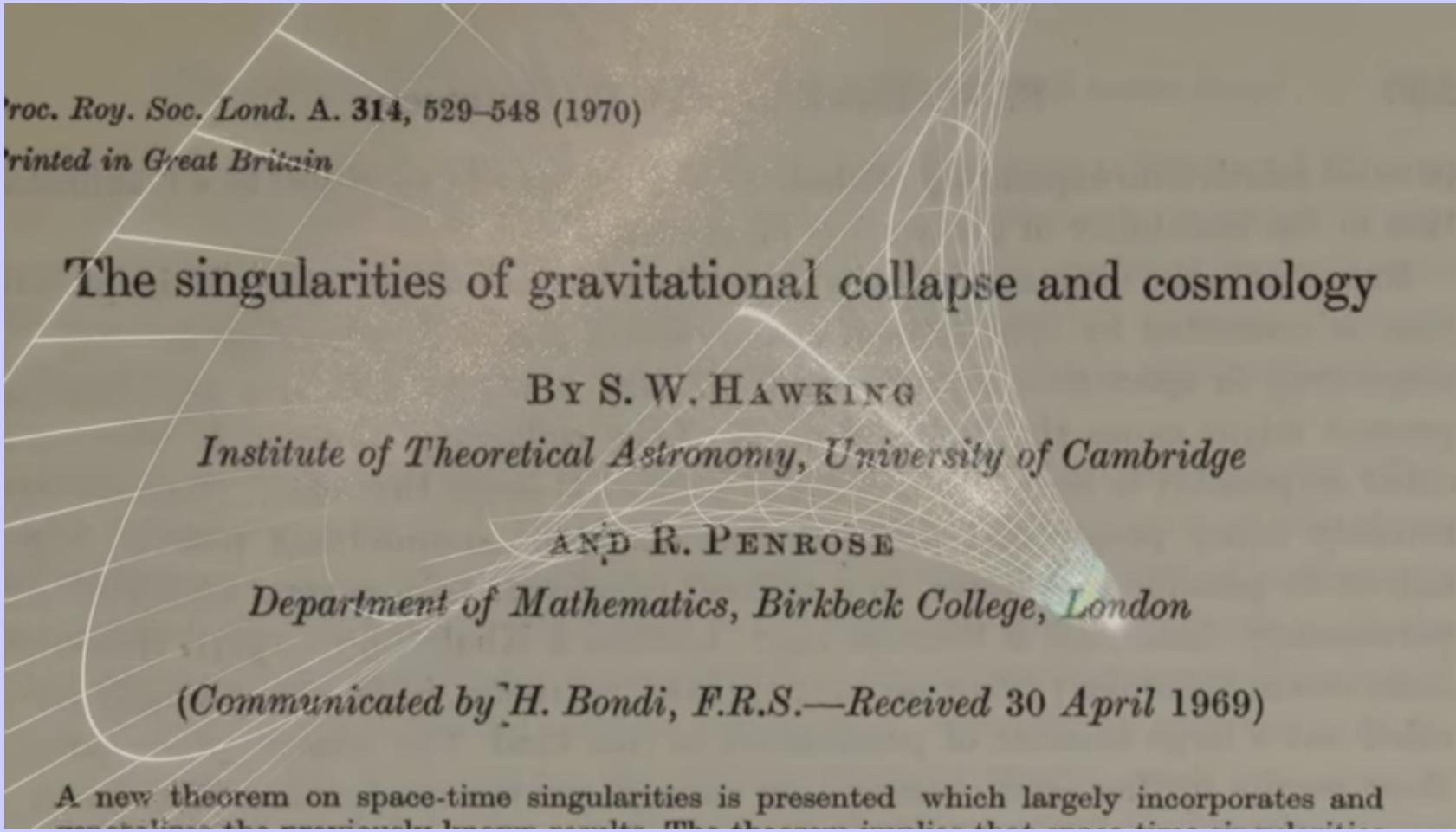
Roger Penrose, Nobel Prize 2020



Stephen Hawking



Hawking-Penrose Singularity Theorems



roc. Roy. Soc. Lond. A. 314, 529–548 (1970)
rinted in Great Britain

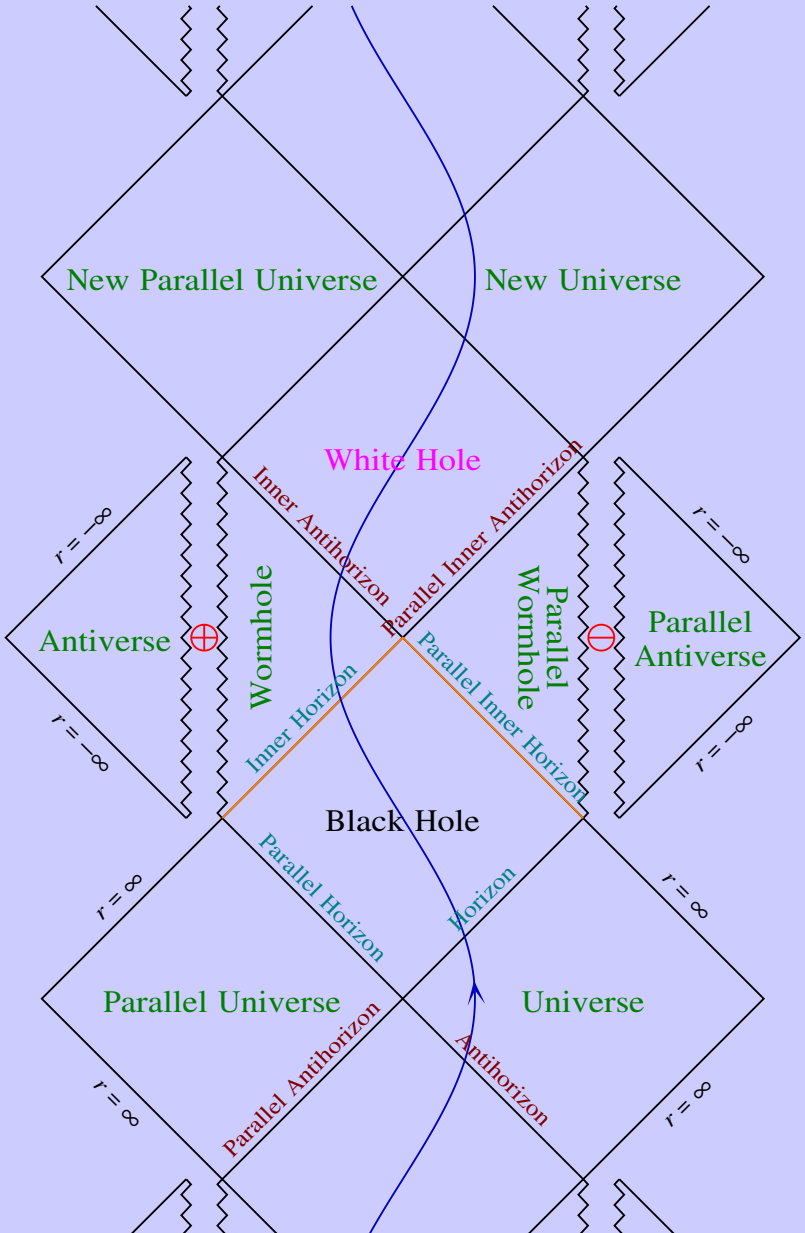
The singularities of gravitational collapse and cosmology

By S. W. Hawking
Institute of Theoretical Astronomy, University of Cambridge
and R. Penrose
Department of Mathematics, Birkbeck College, London

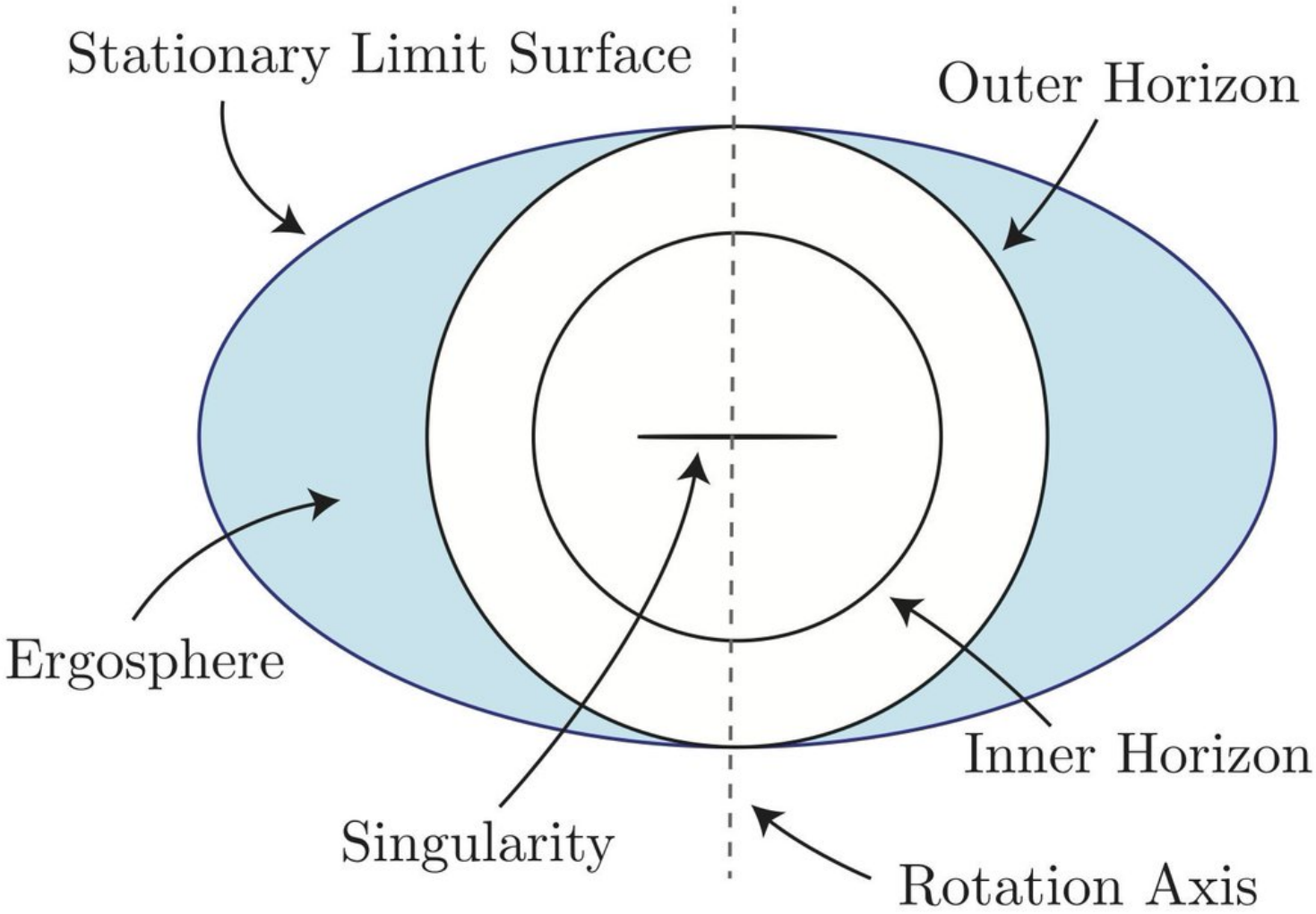
(*Communicated by H. Bondi, F.R.S.—Received* 30 *April* 1969)

A new theorem on space-time singularities is presented which largely incorporates and

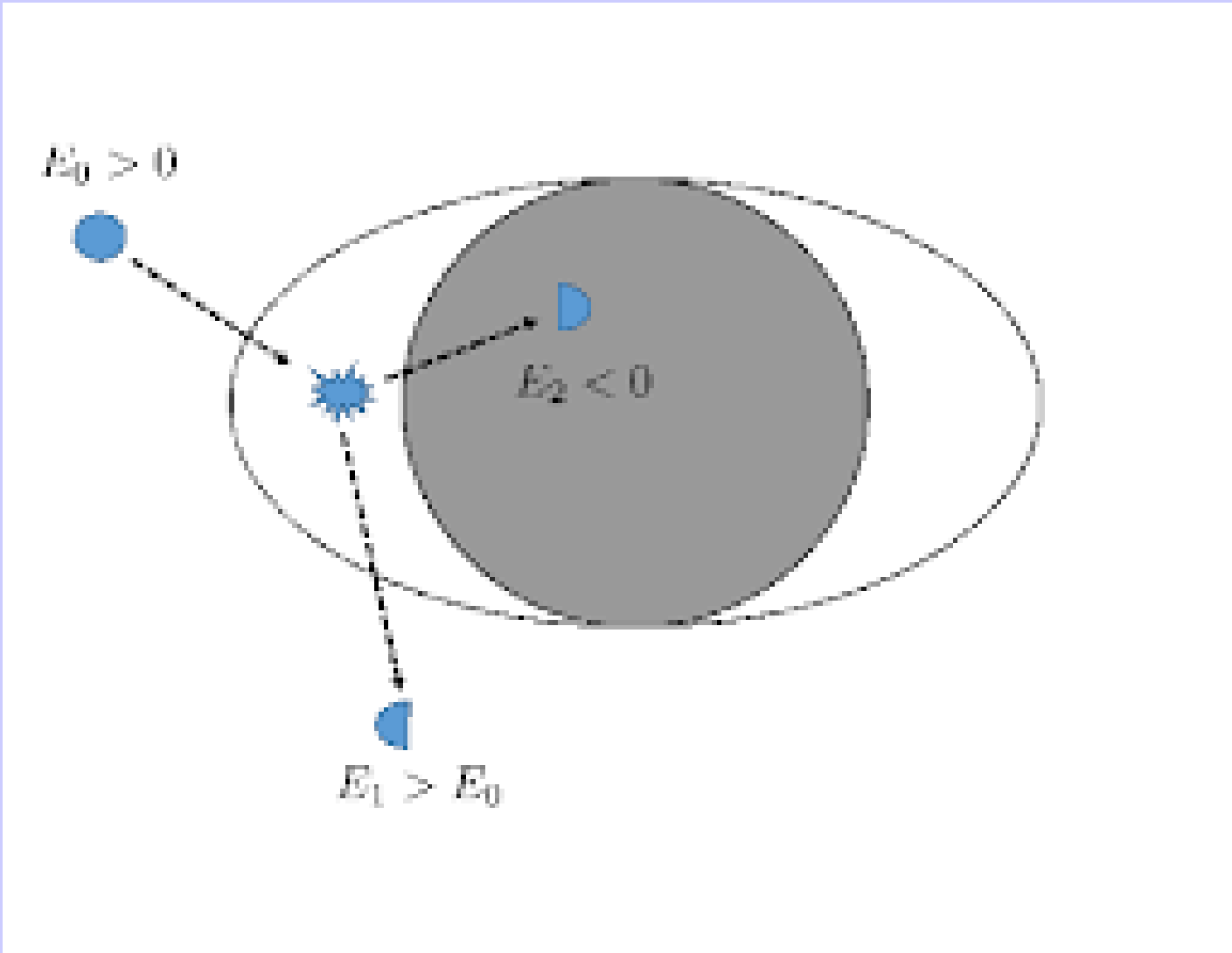
Penrose Diagram of a Charged Black Hole



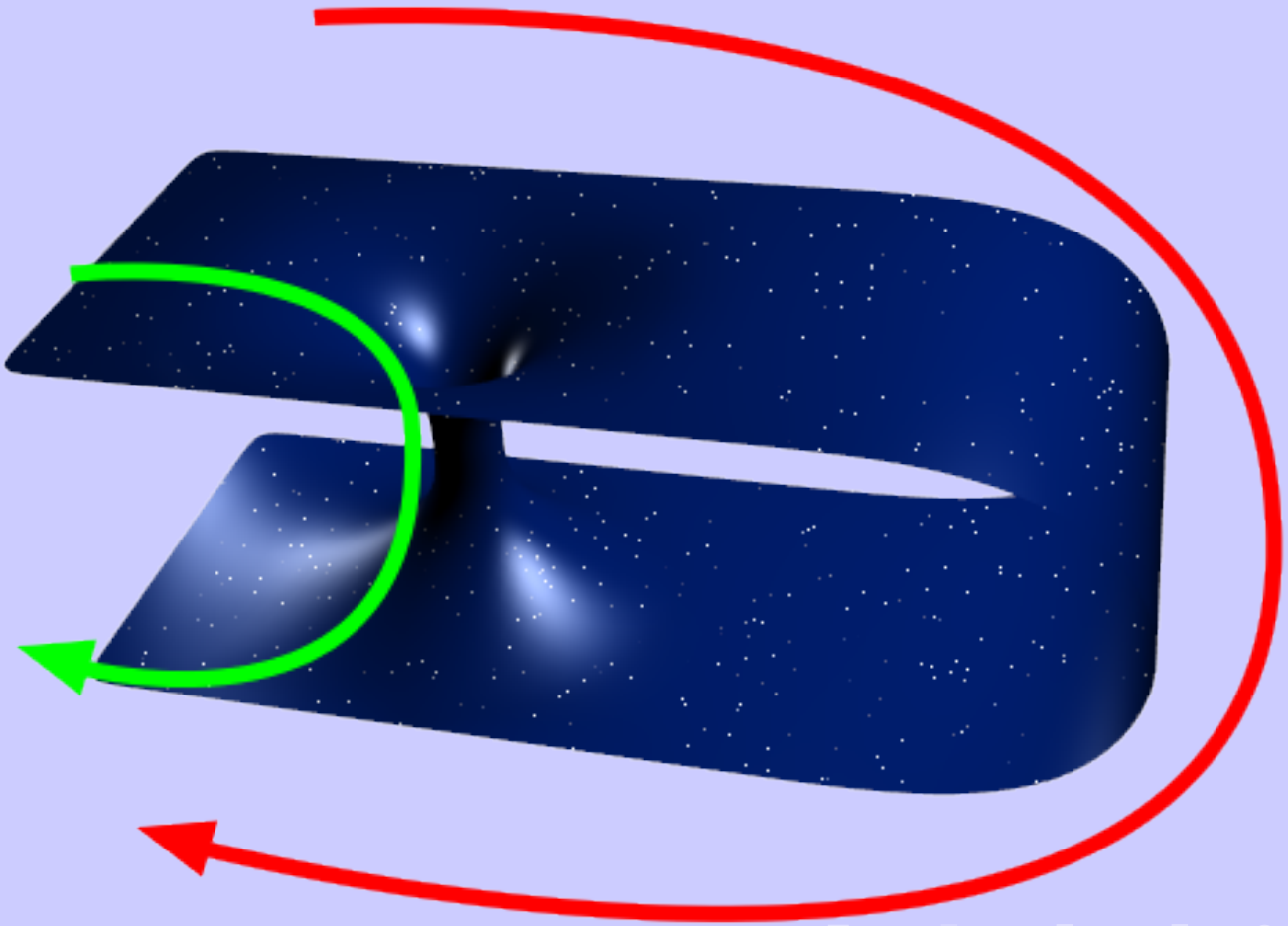
Kerr (rotating) Black Hole



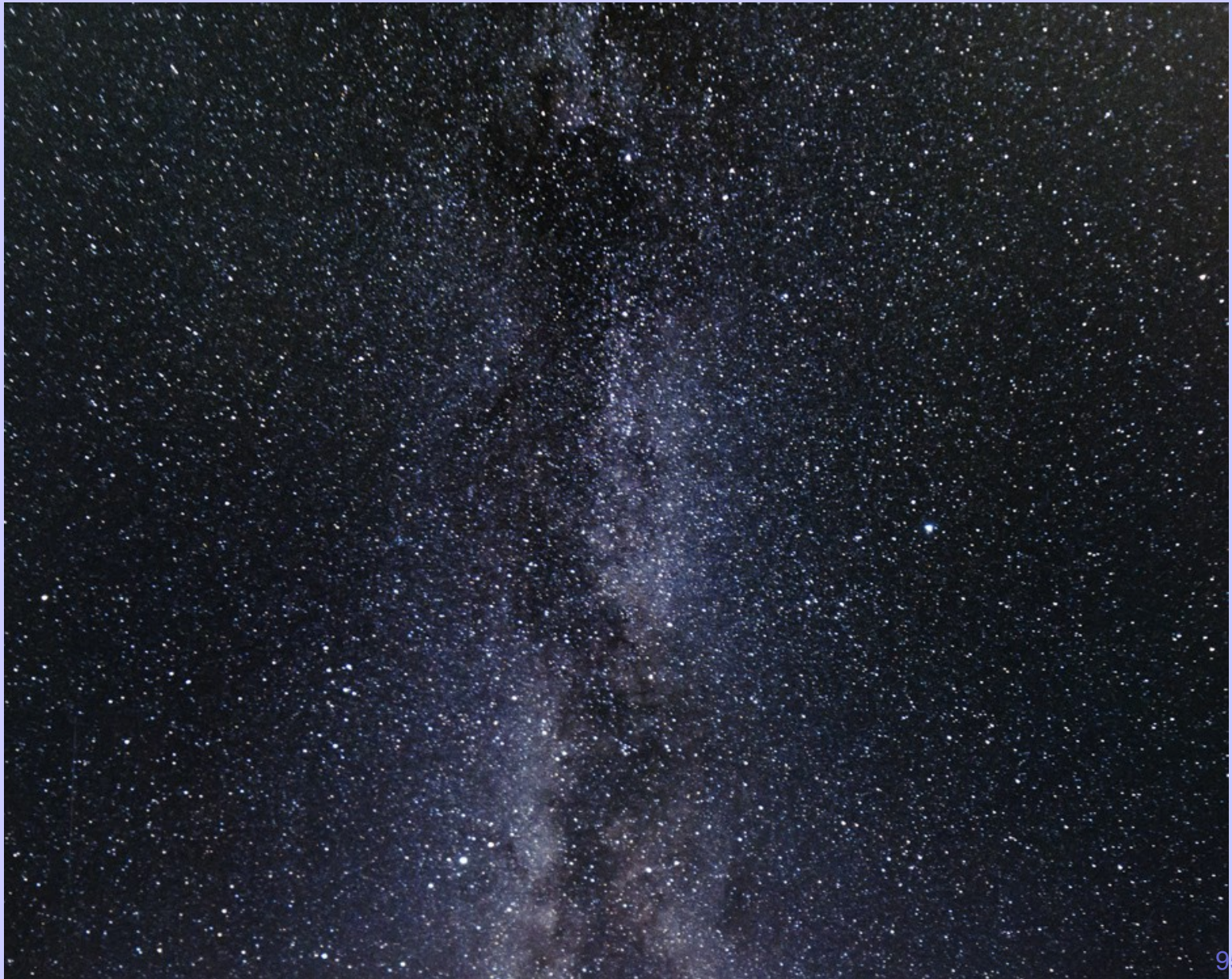
Penrose Process



Wormhole Visualization

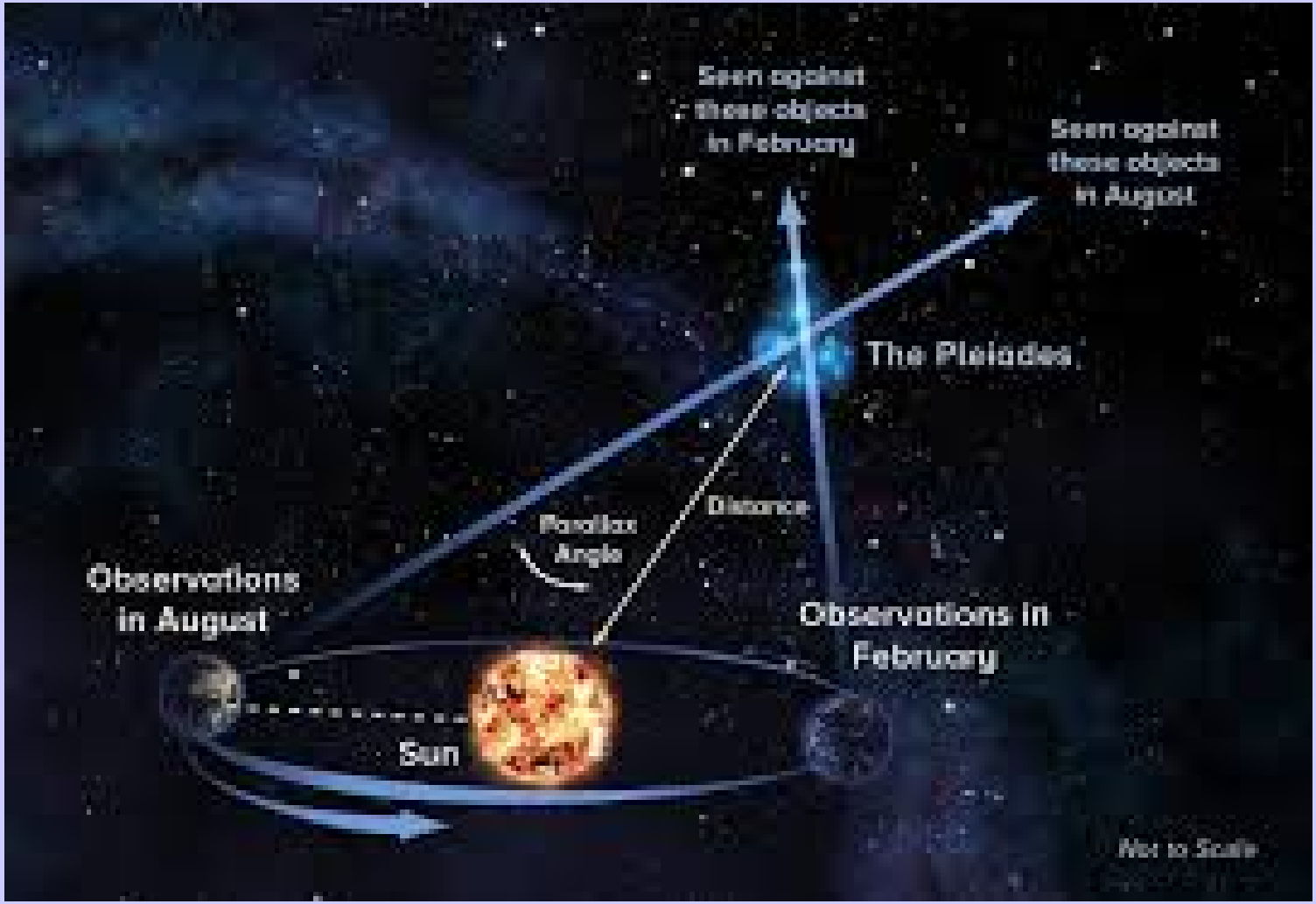


The Night Sky

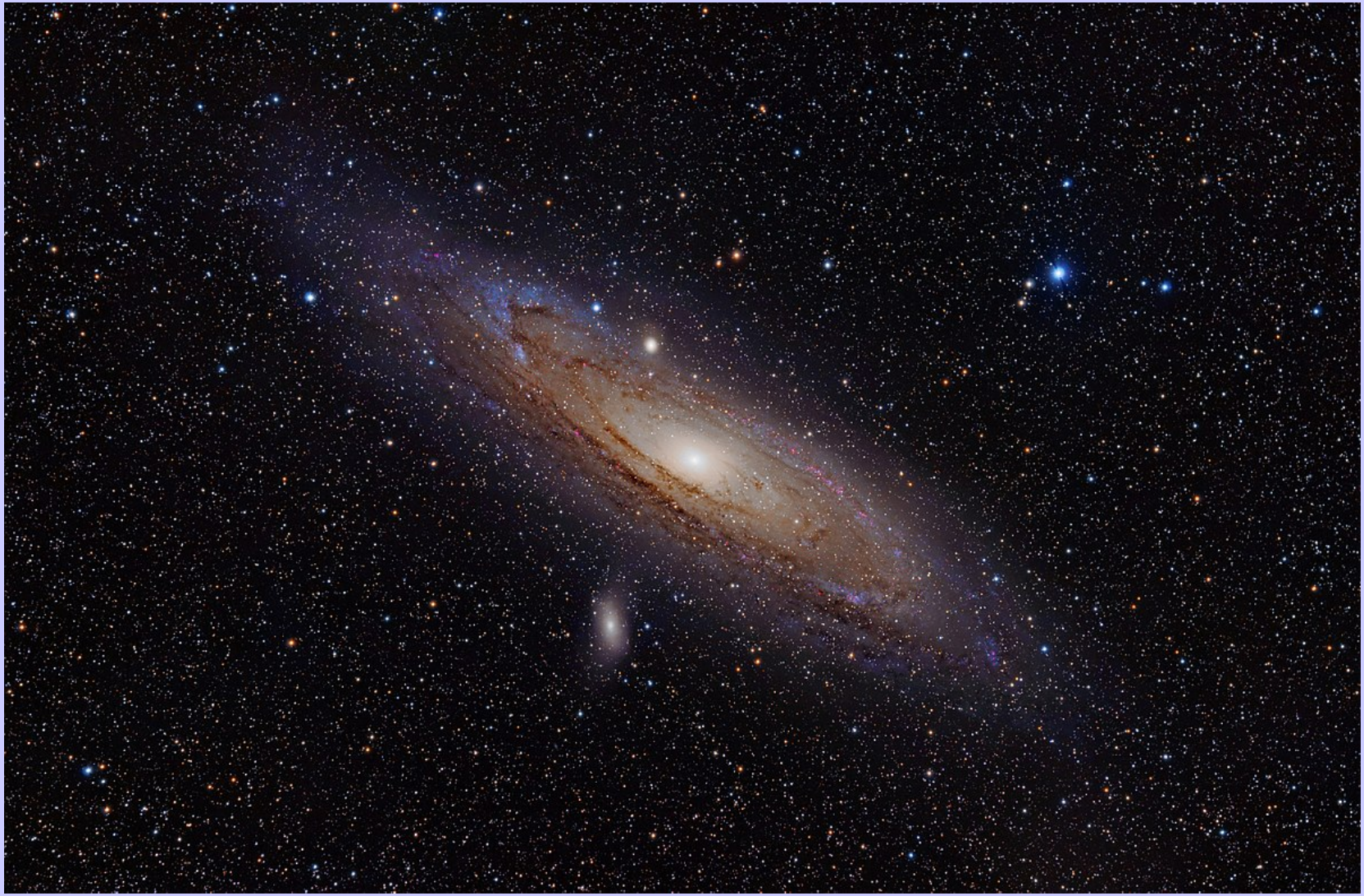


Stars

Parallax Method

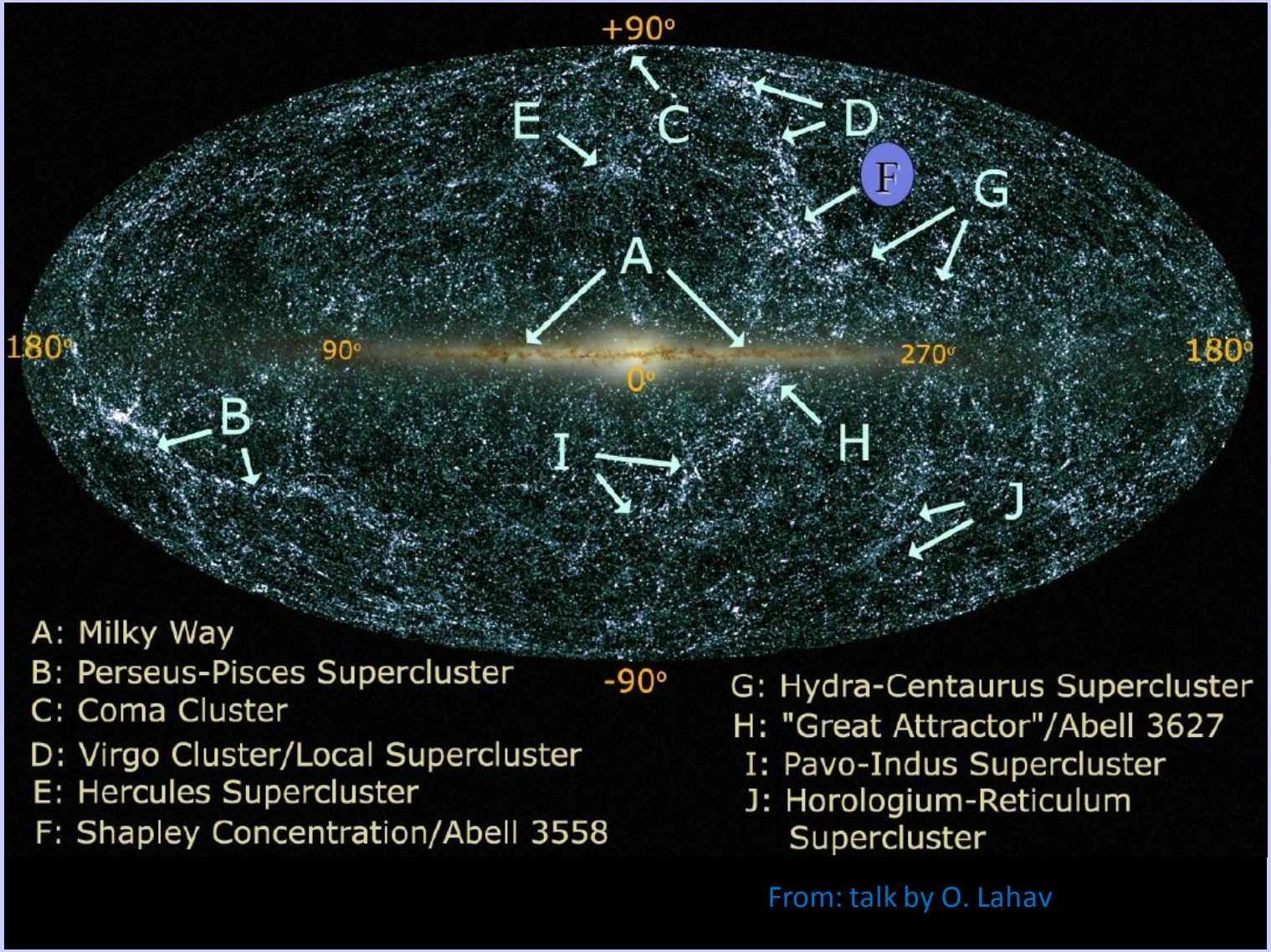


Andromeda Galaxy



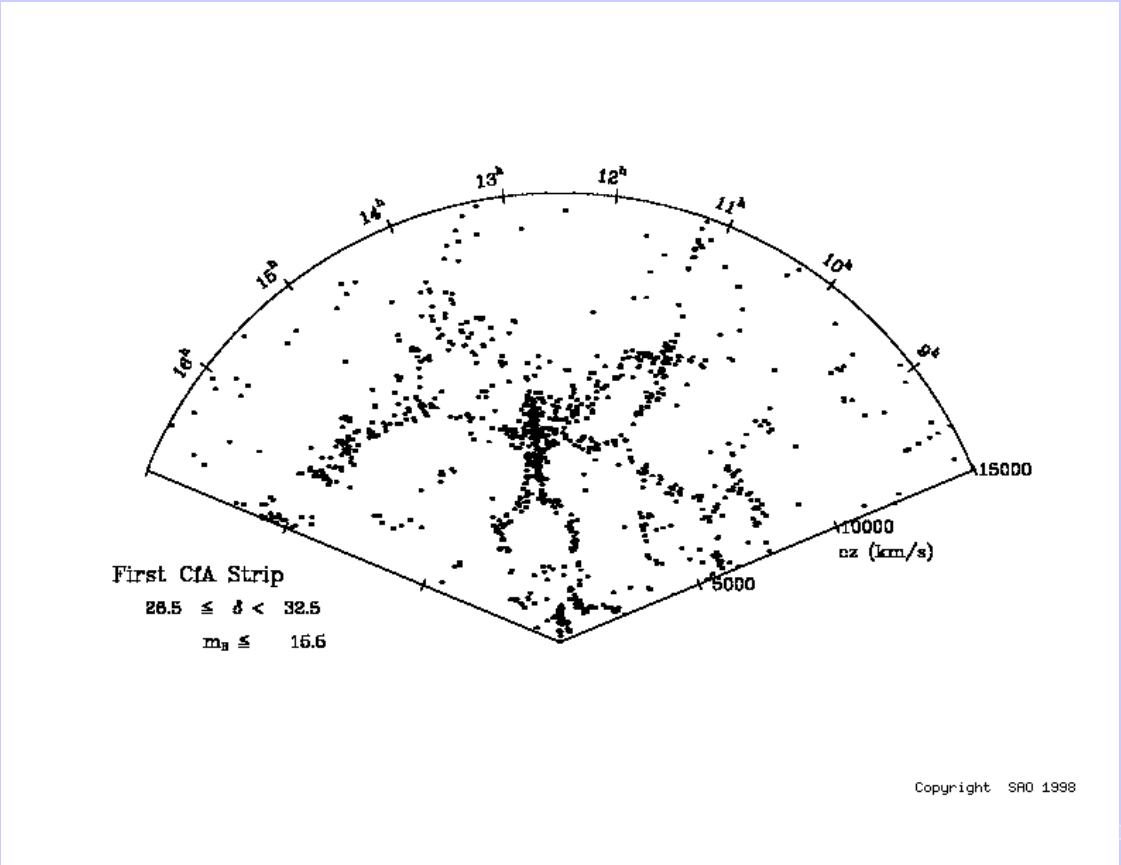
Galaxies

Large-Scale Structure

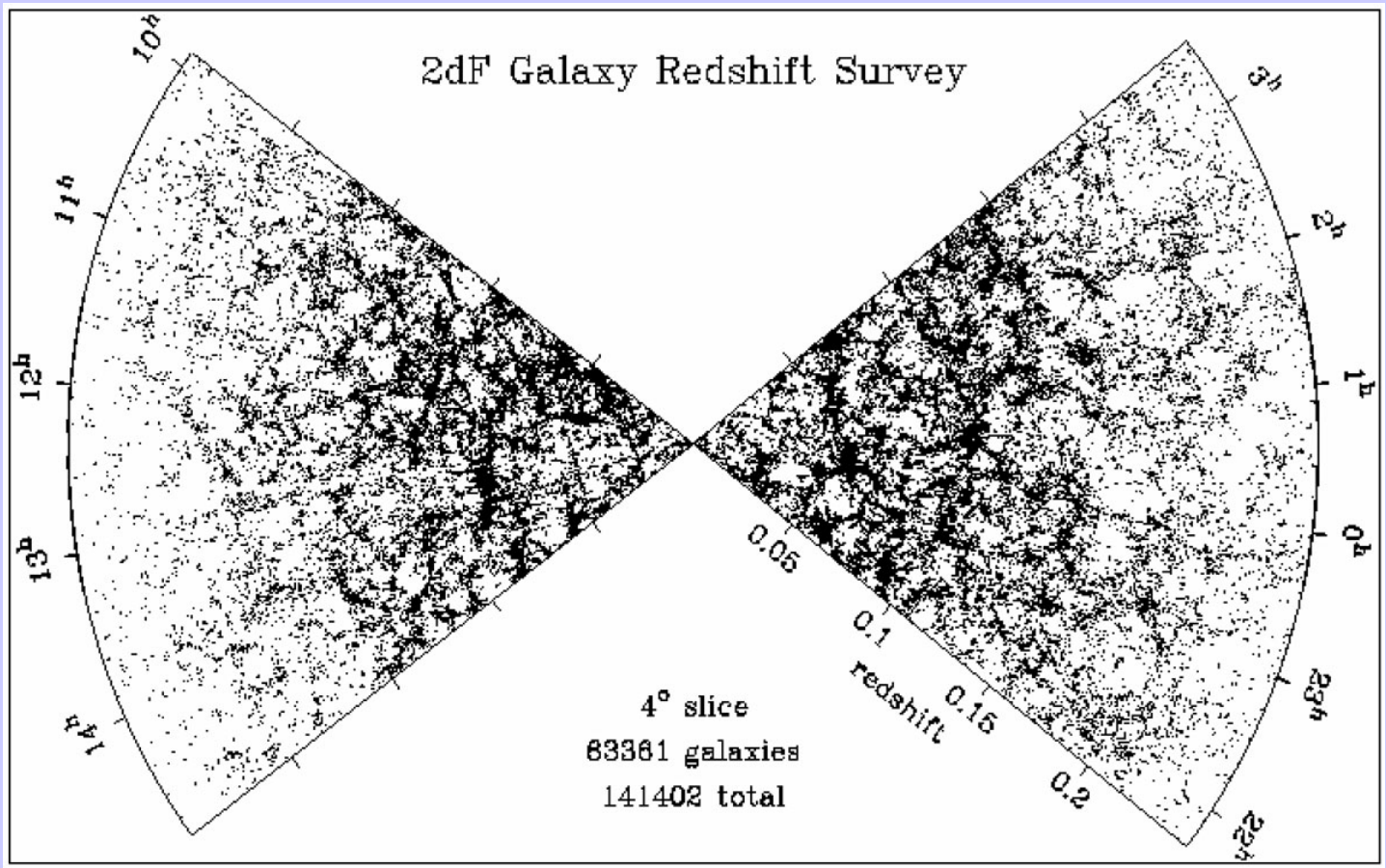


From: talk by O. Lahav

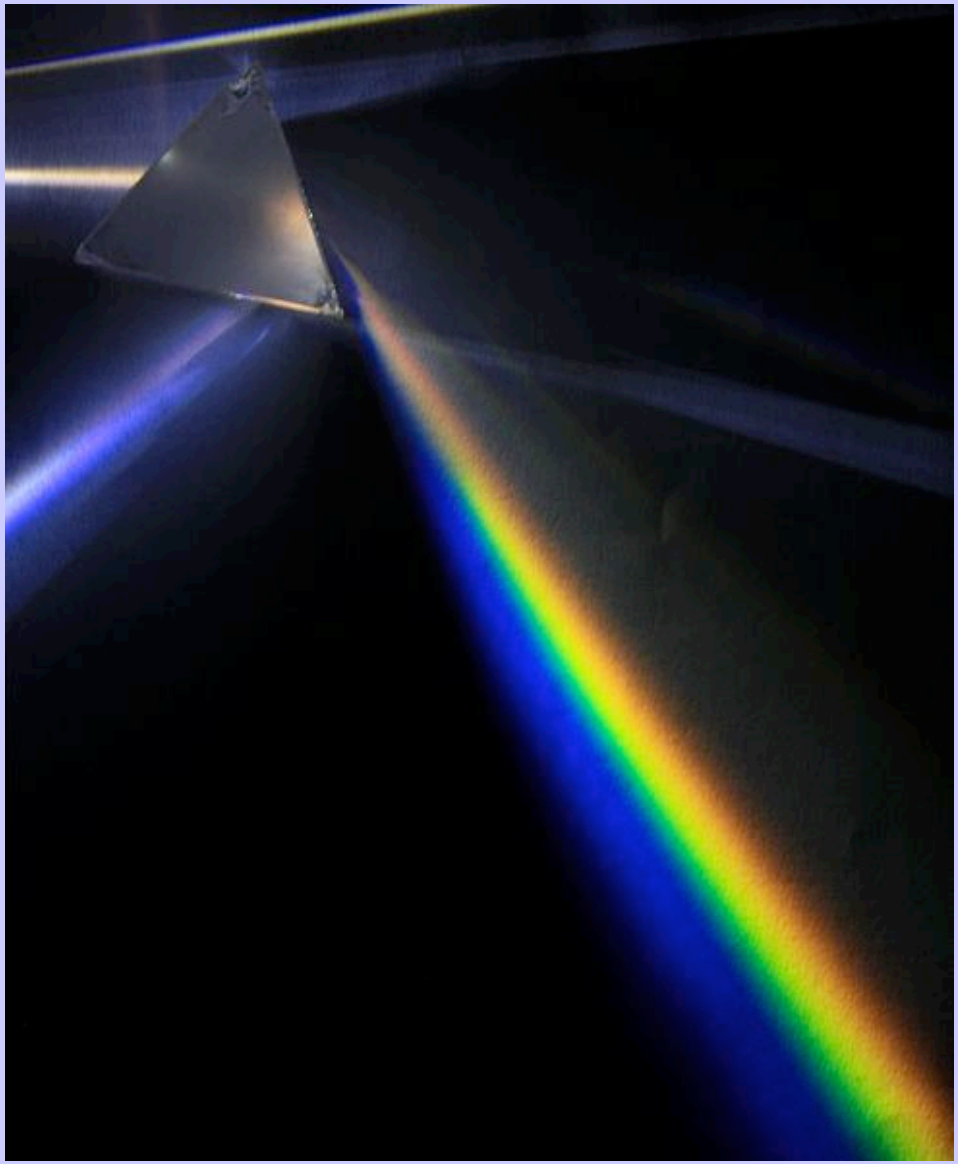
Large-Scale Structure



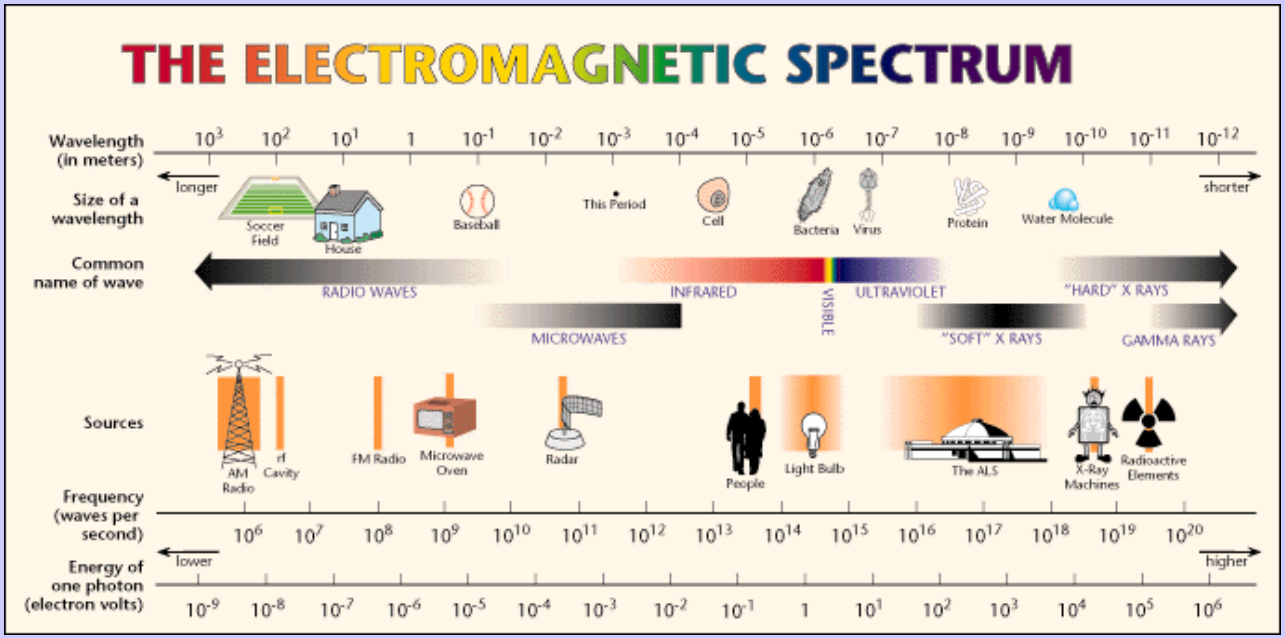
Redshift Survey Results in 2003



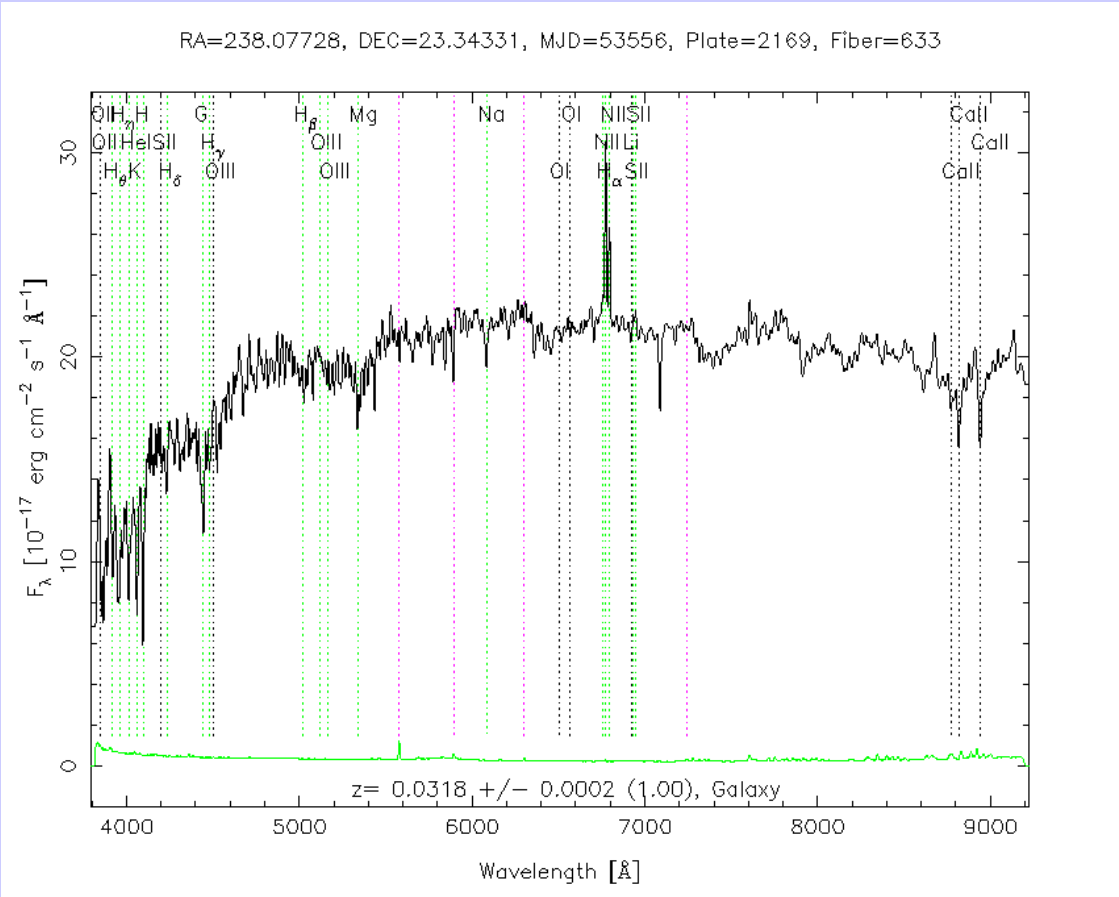
Spectrometer



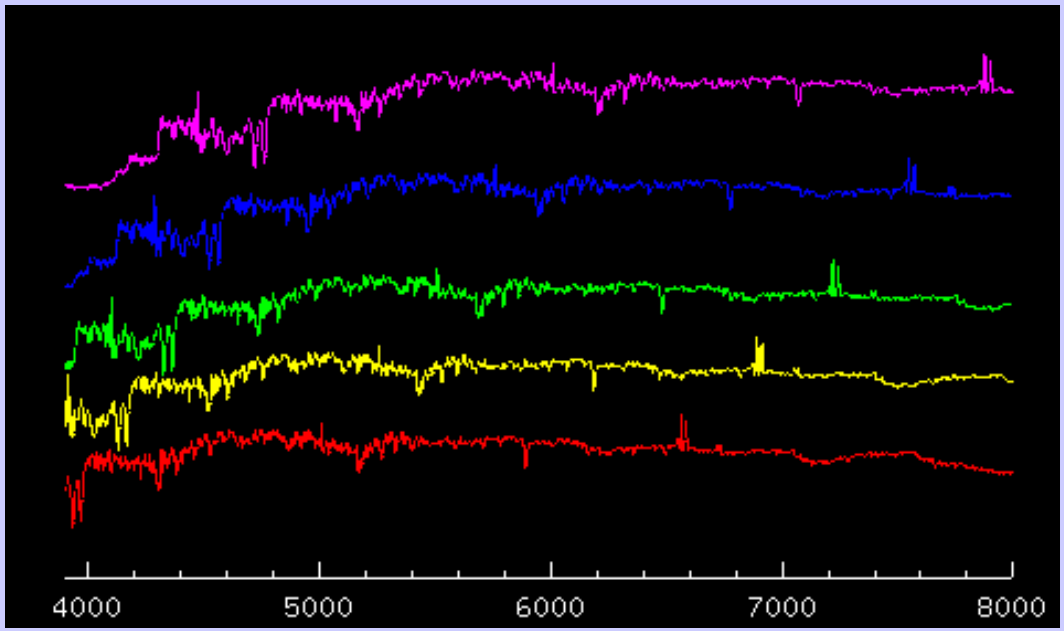
Electromagnetic Spectrum



Galaxy Spectrum



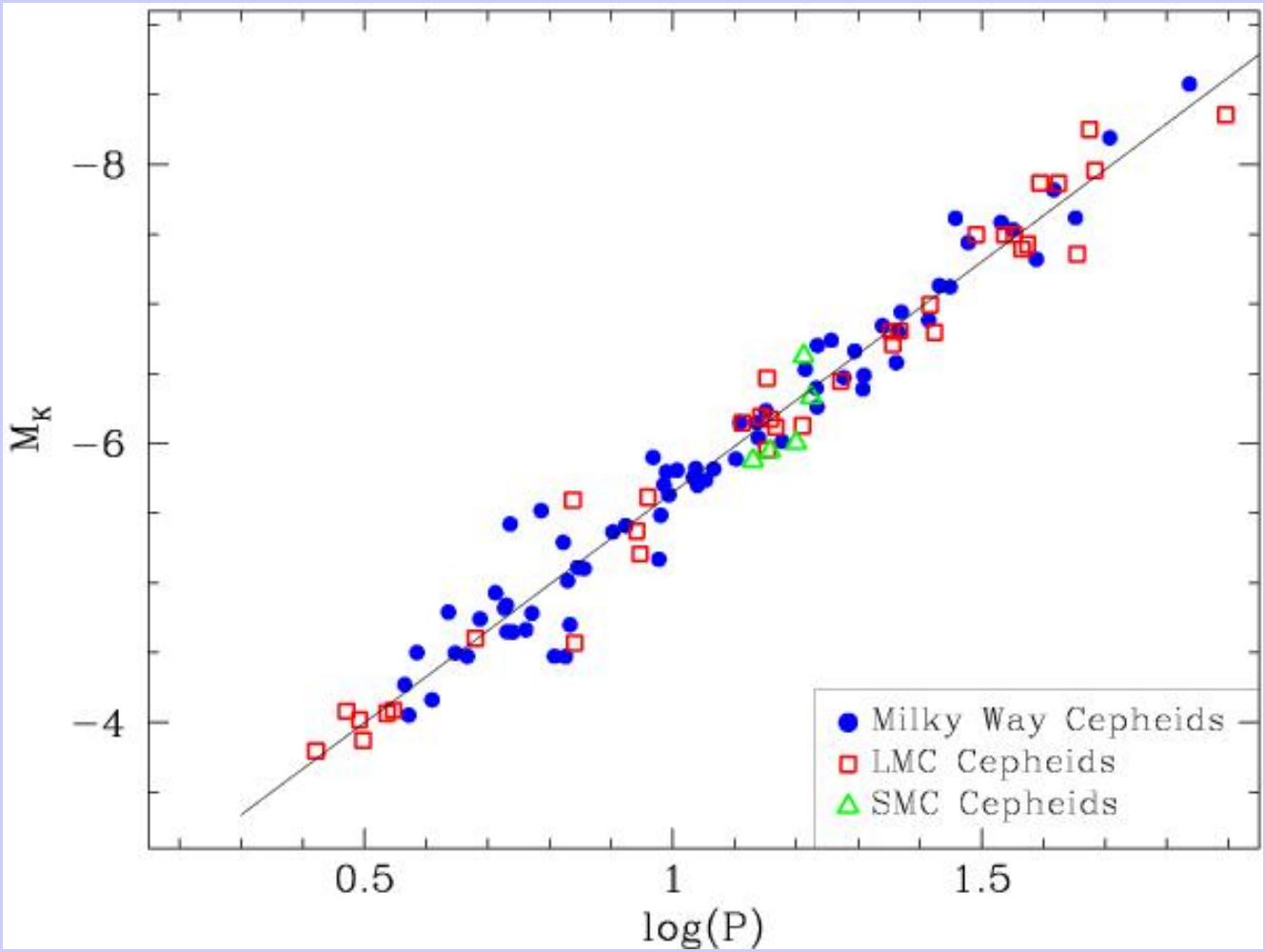
Galaxy Redshift



Vesto Slipher: 1875 - 1969

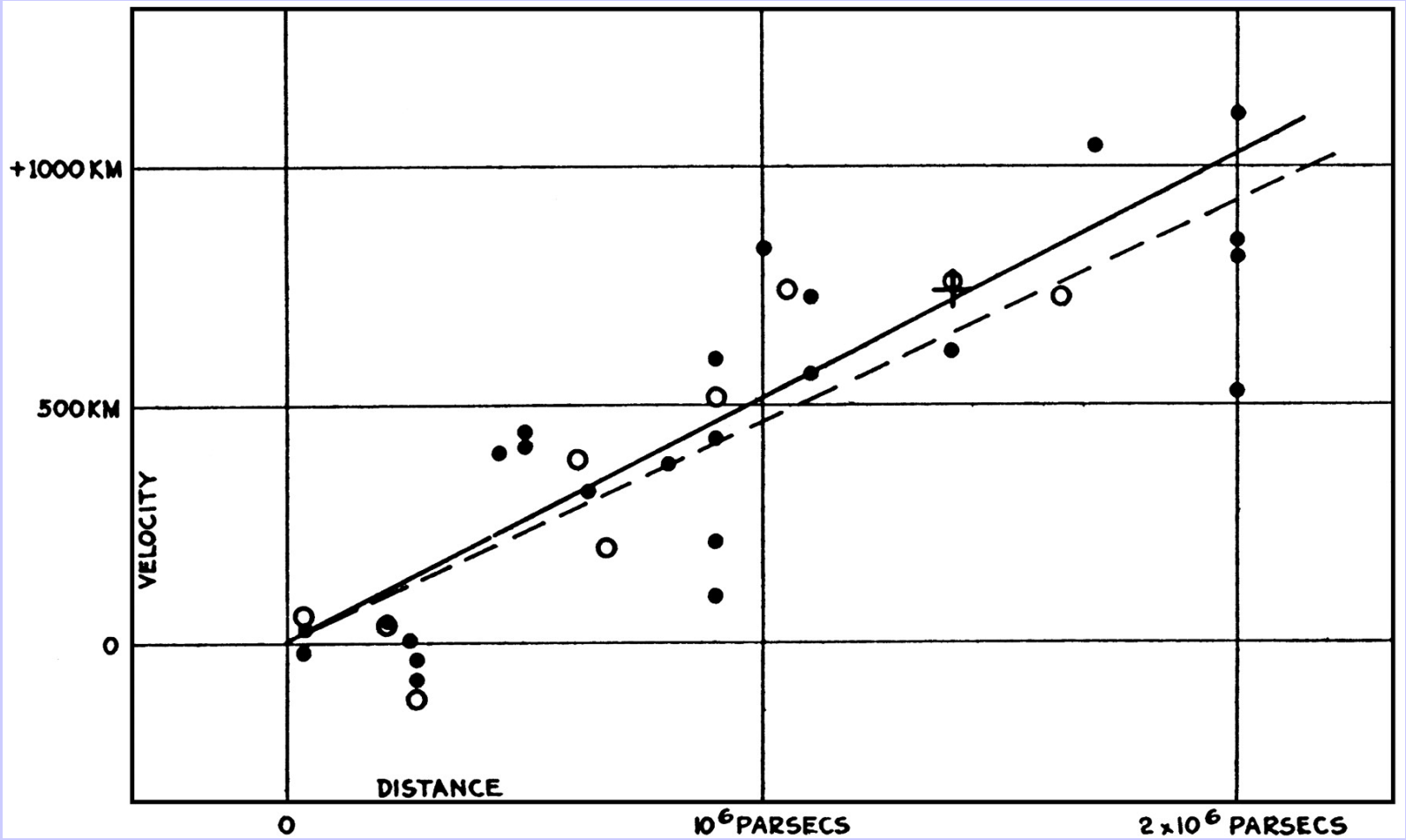
Henrietta Leavitt: 1868 - 1921

Cepheid Period Luminosity Relation

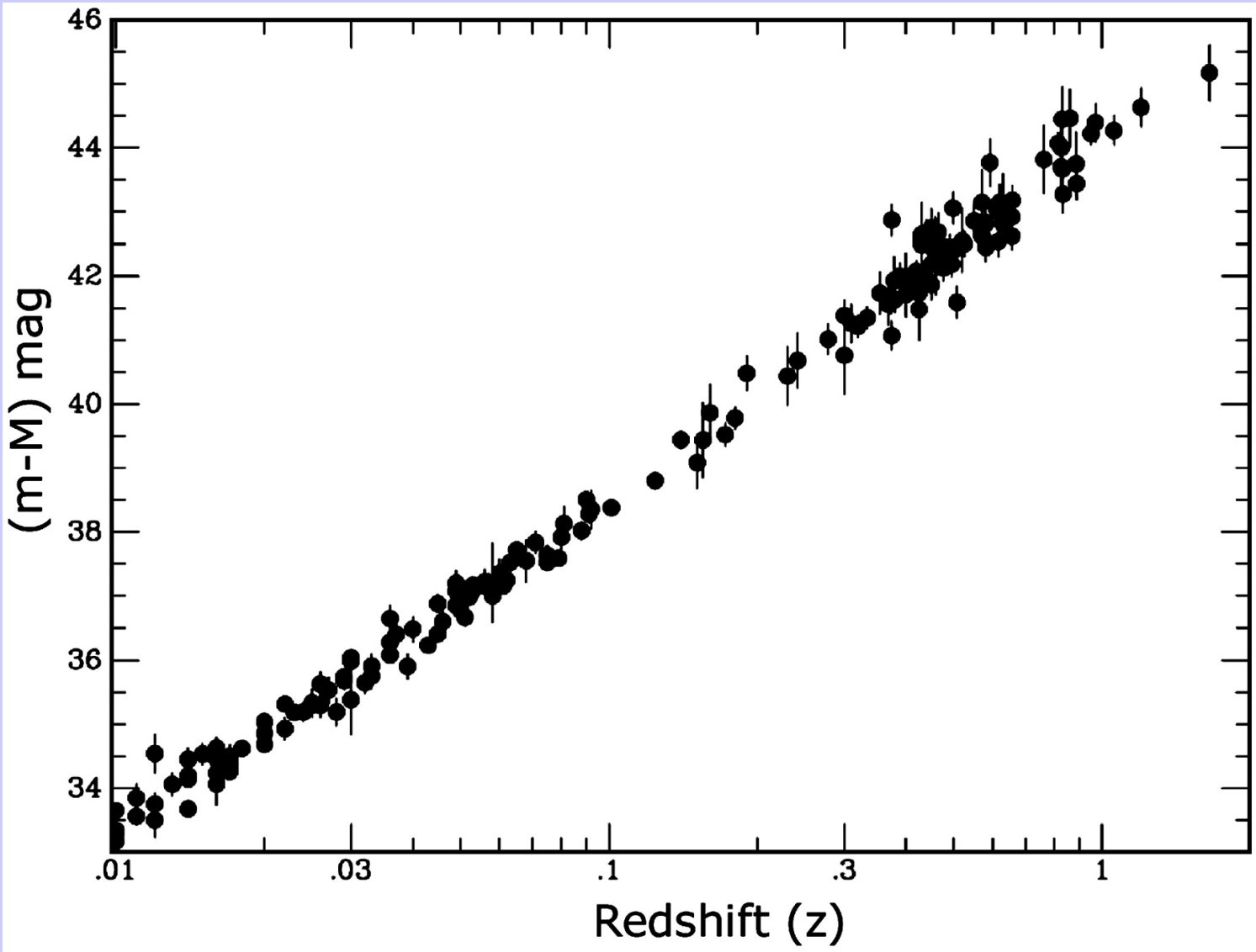


Edwin Hubble: 1889 - 1953

Hubble's Results



Modern Hubble Diagram



Curved Space-Time

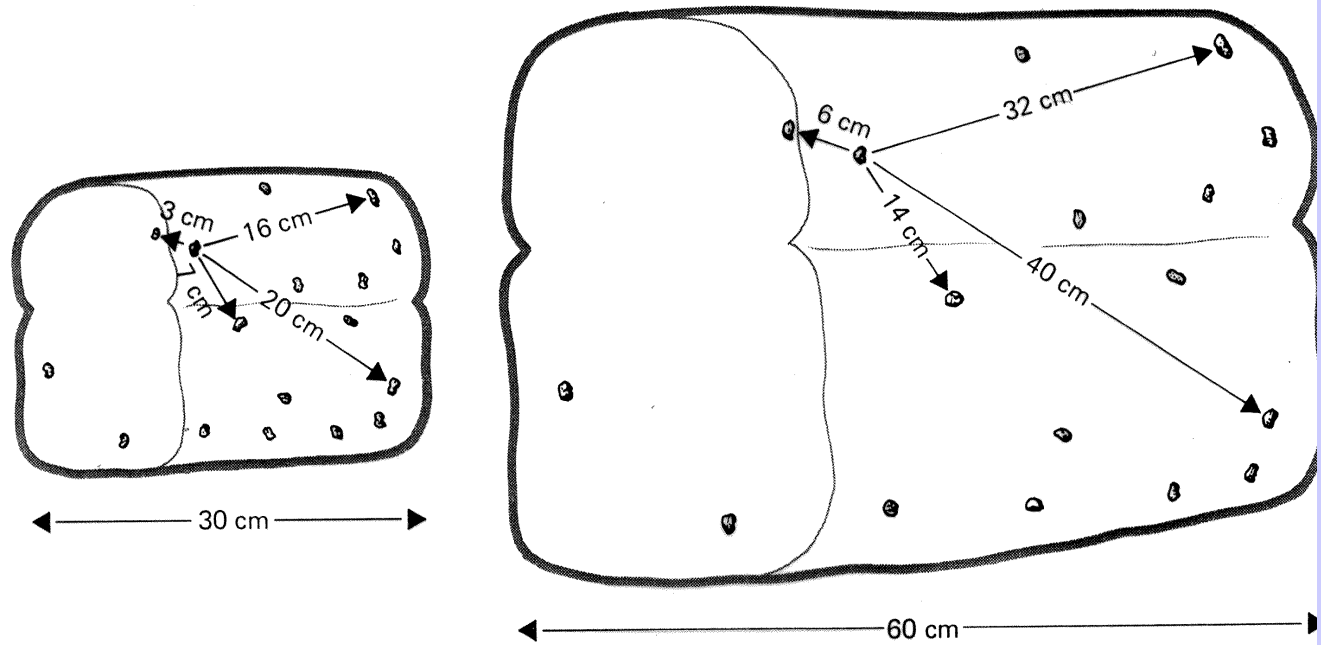


Figure 37.4 Expanding raisin bread.

Georges Lemaitre: 1894 - 1966

Standard Big Bang Cosmology (SBB)

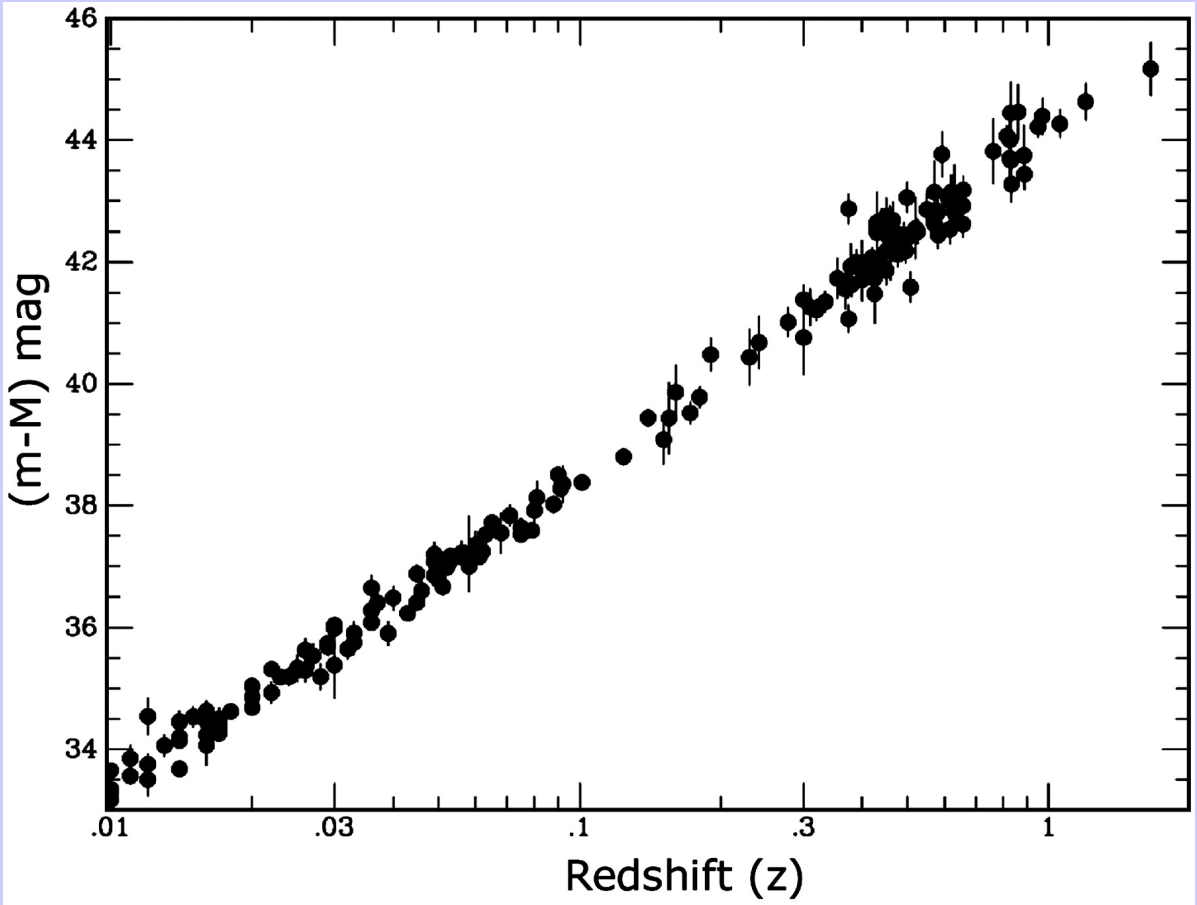
Assumptions

- 1. Space-Time described by **classical General Relativity**
- 2. Matter described by **classical matter**: superposition of ideal gases
- Cold matter: $p = 0$
- Radiation: $p = \frac{1}{3}\rho$
- 3. Space is **homogeneous** and **isotropic** (Cosmological Principle)

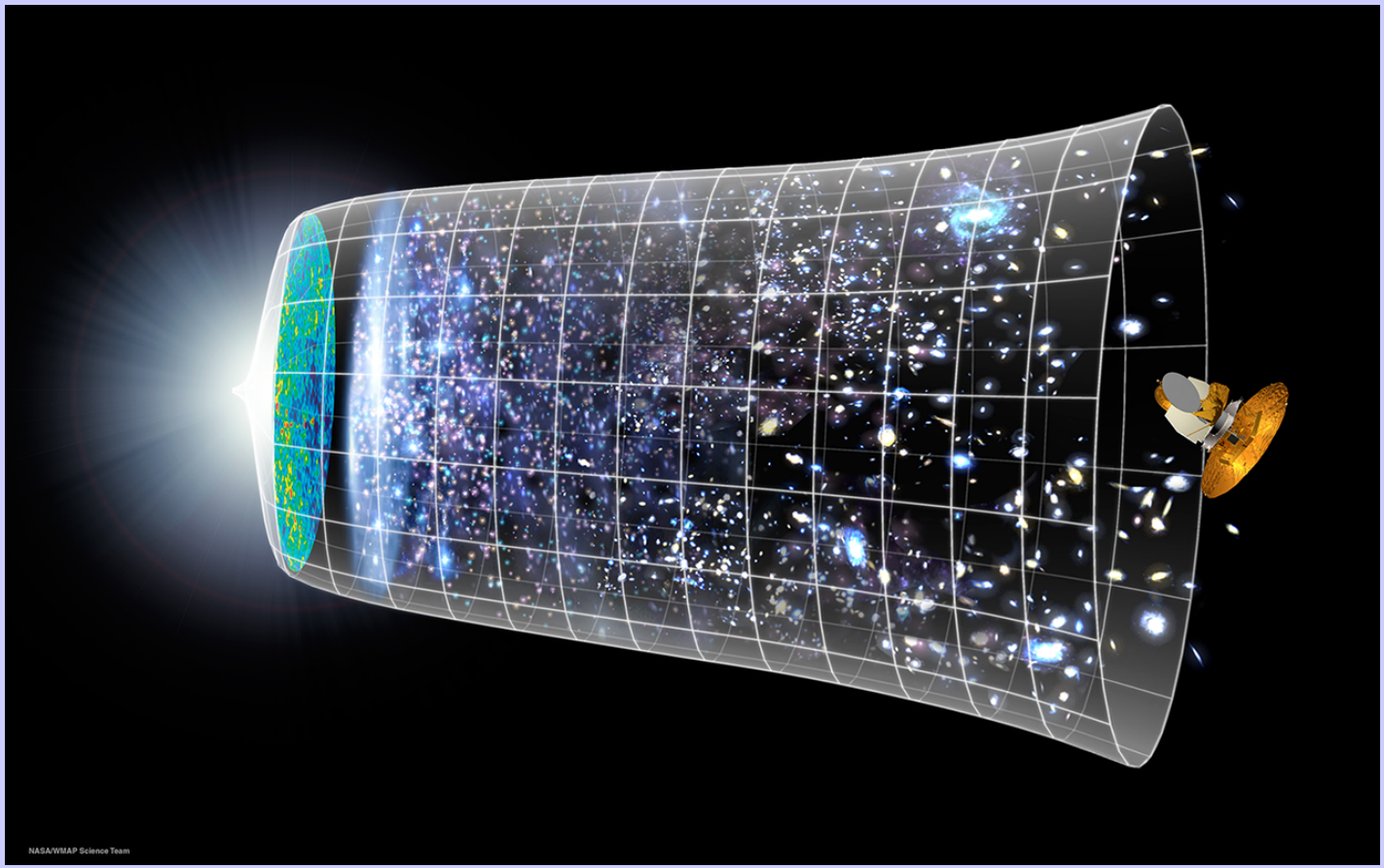
Successes

- Hubble law - Space is expanding
- Existence and Black Body nature of the Cosmic Microwave Background
- Nucleosynthesis - Abundances of light elements

Hubble Law

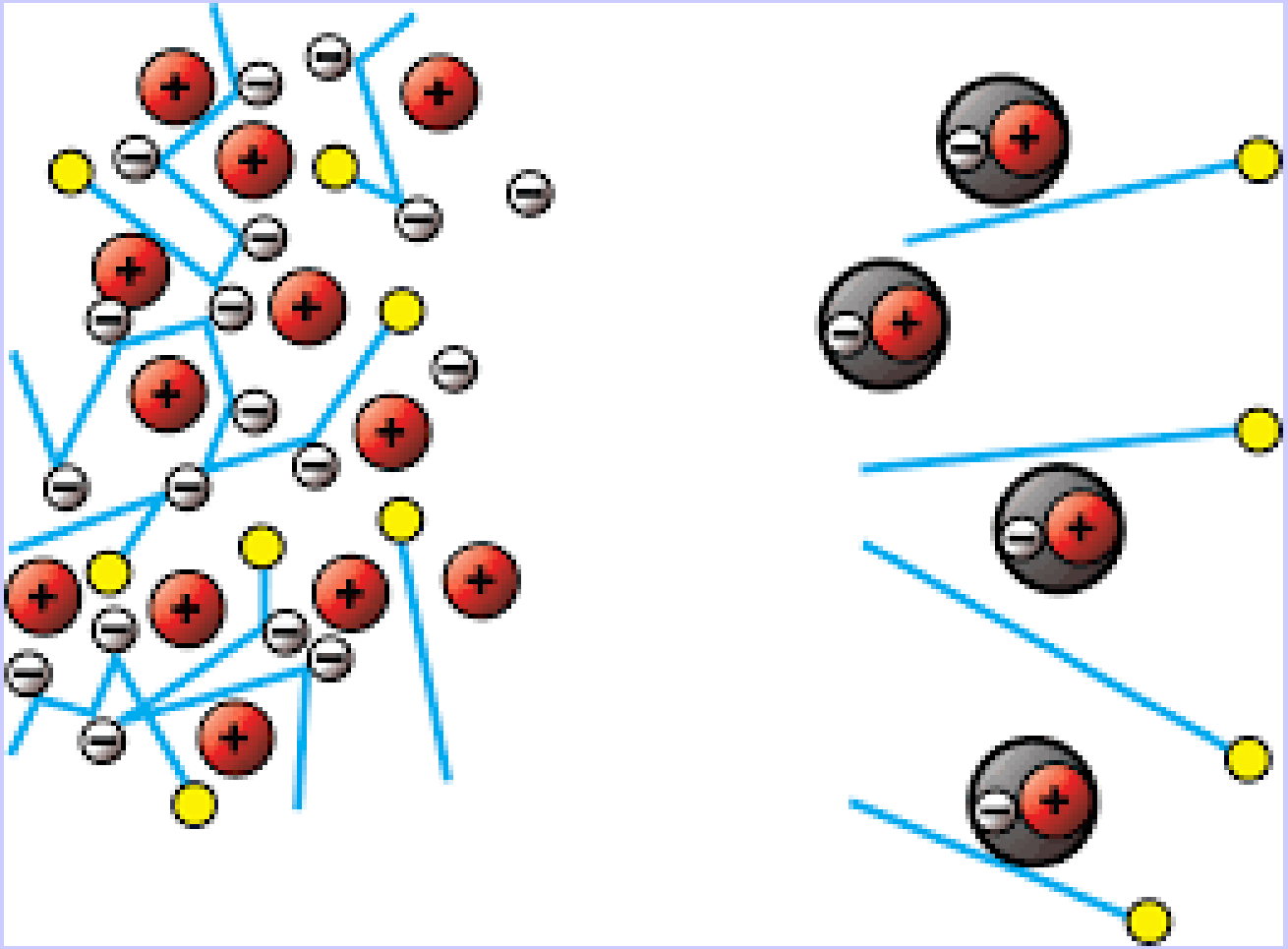


Time Line: Big Bang Cosmology

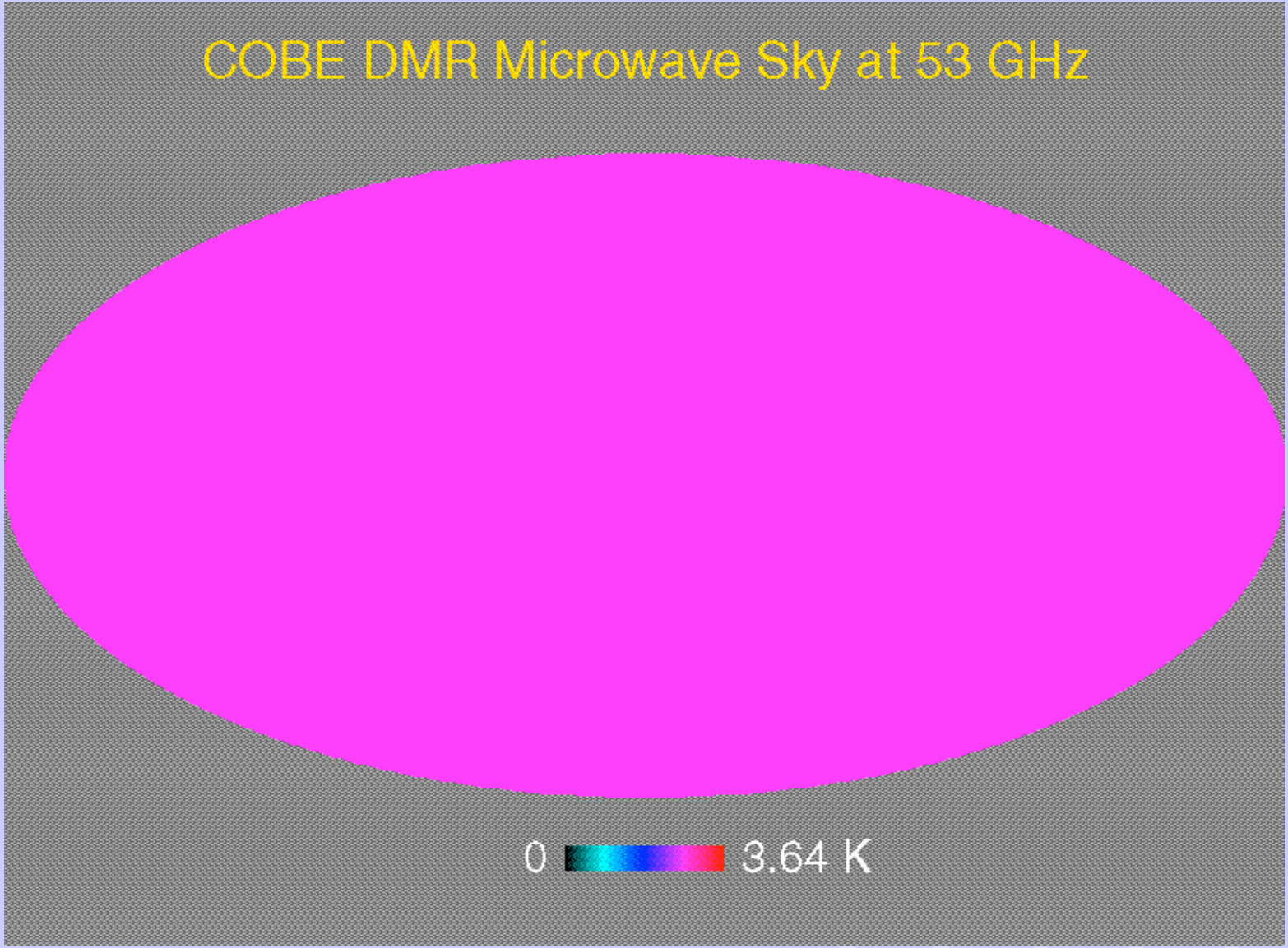


Credit: NASA/WMAP Science Team

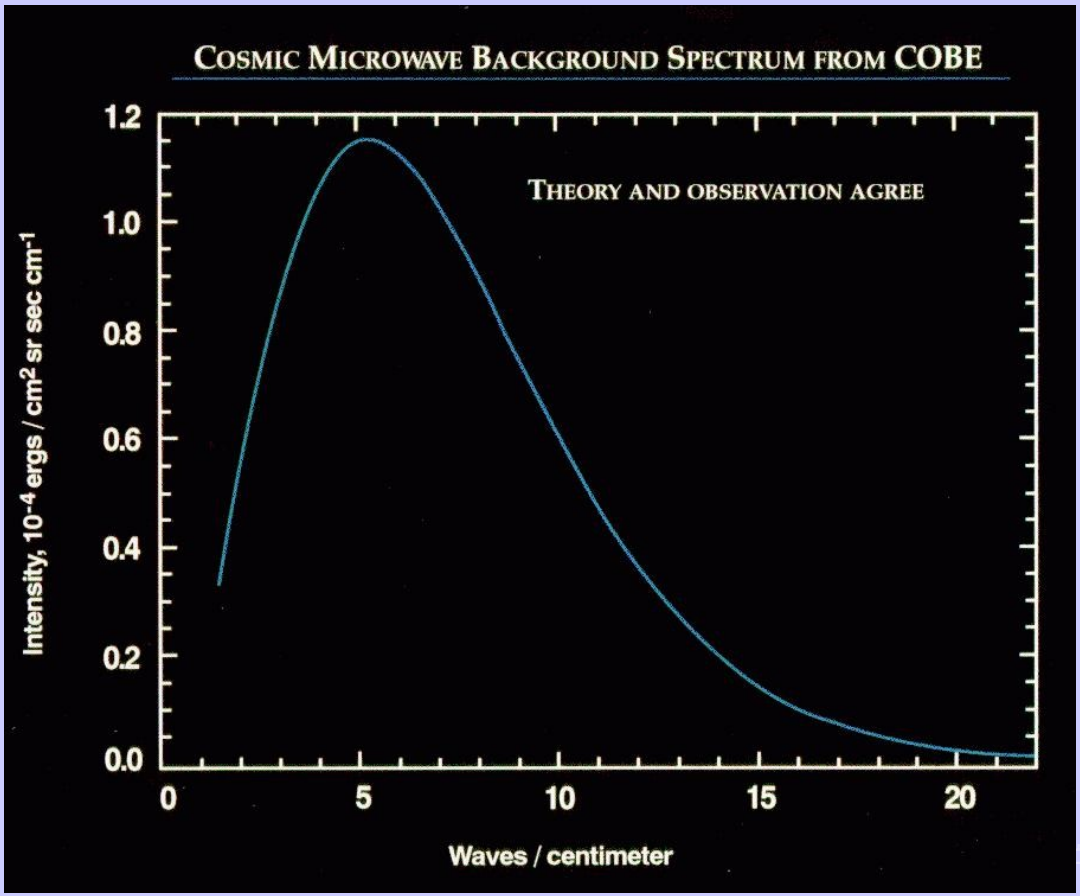
Recombination



Map of the Cosmic Microwave Background (CMB)

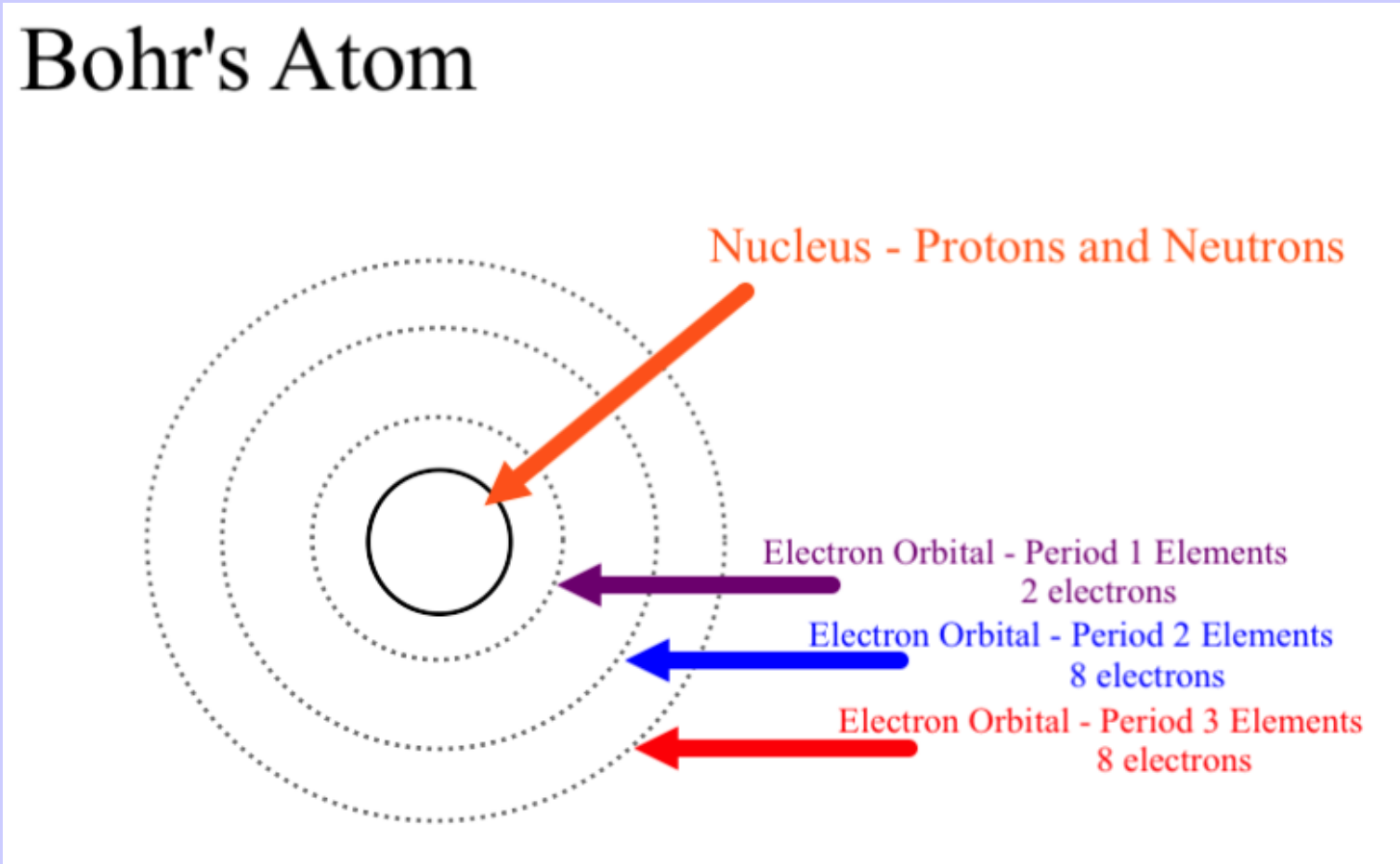


Spectrum of the CMB

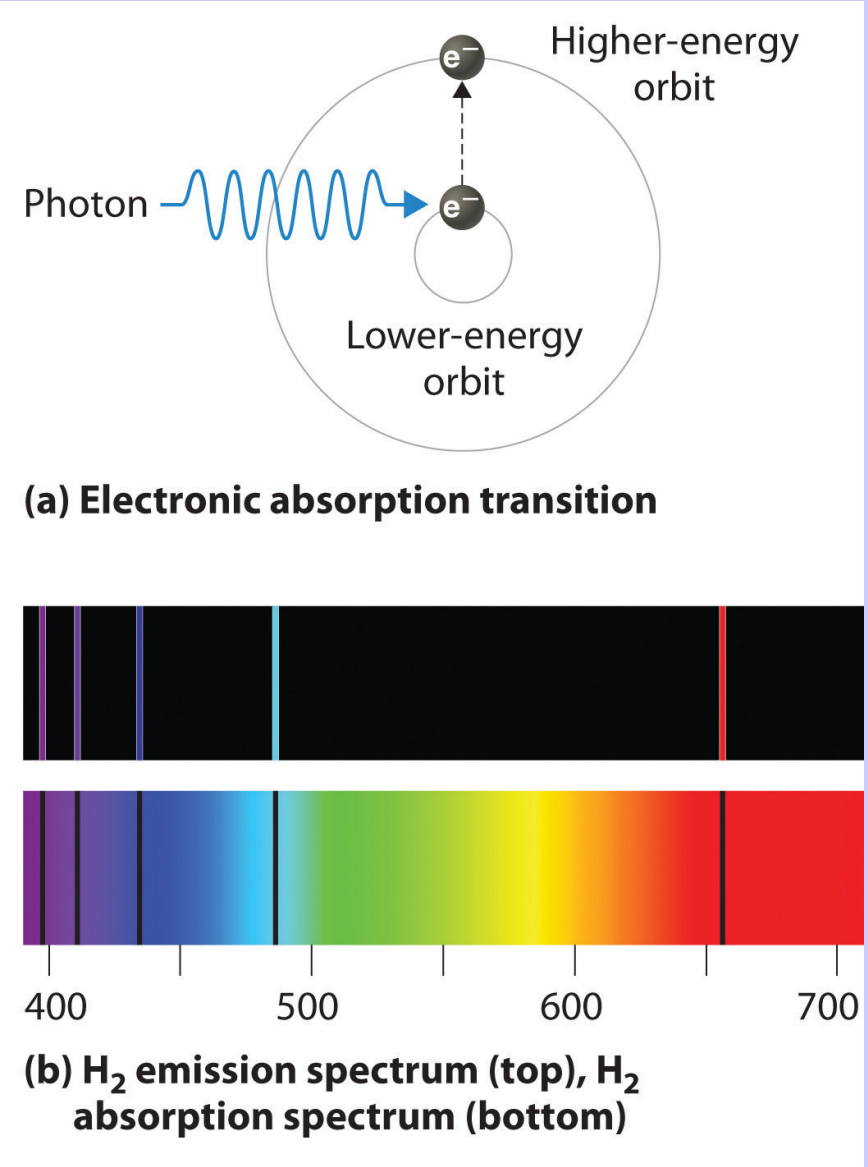


Niels Bohr (1885 - 1962)

Bohr Model of the Atom



Spectrum of Hydrogen

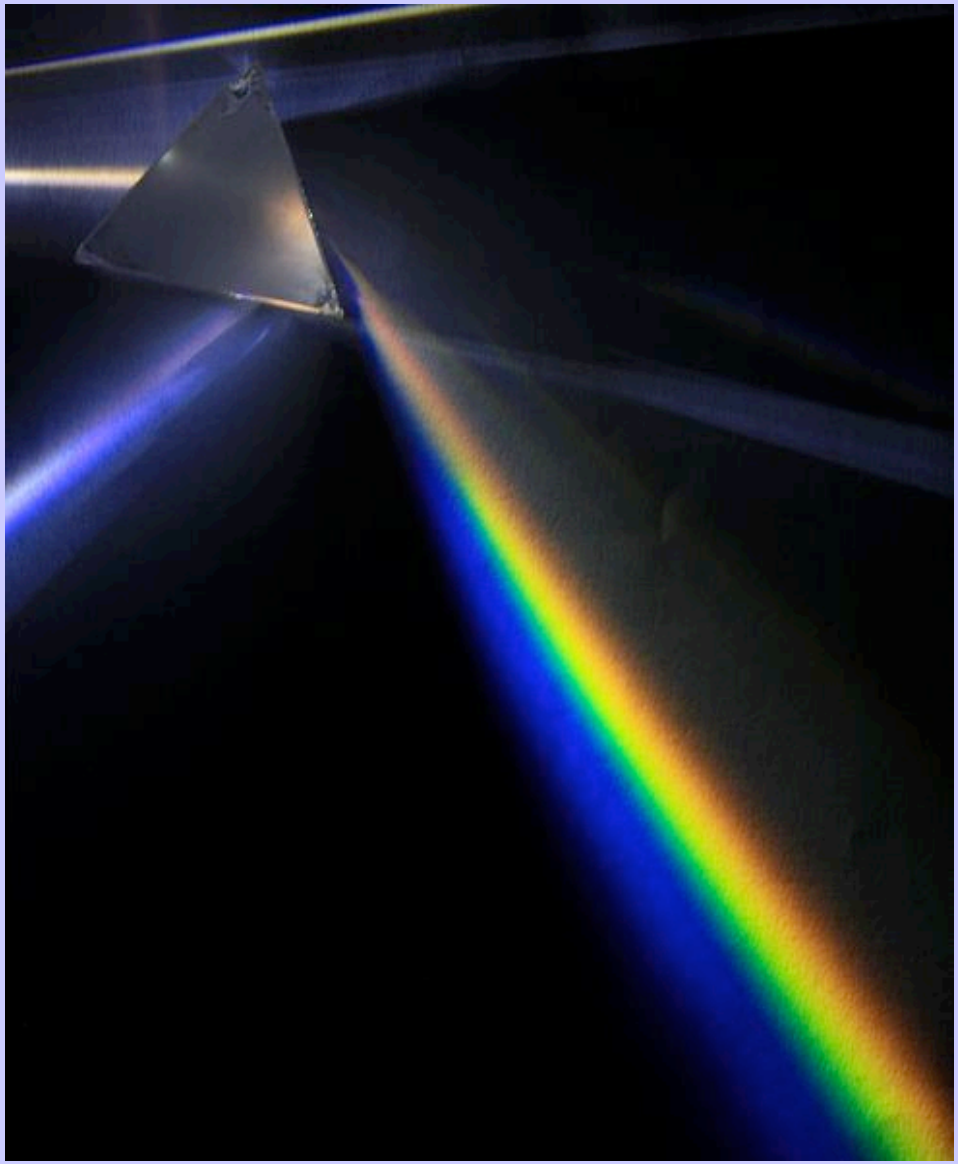


(a) Electronic absorption transition

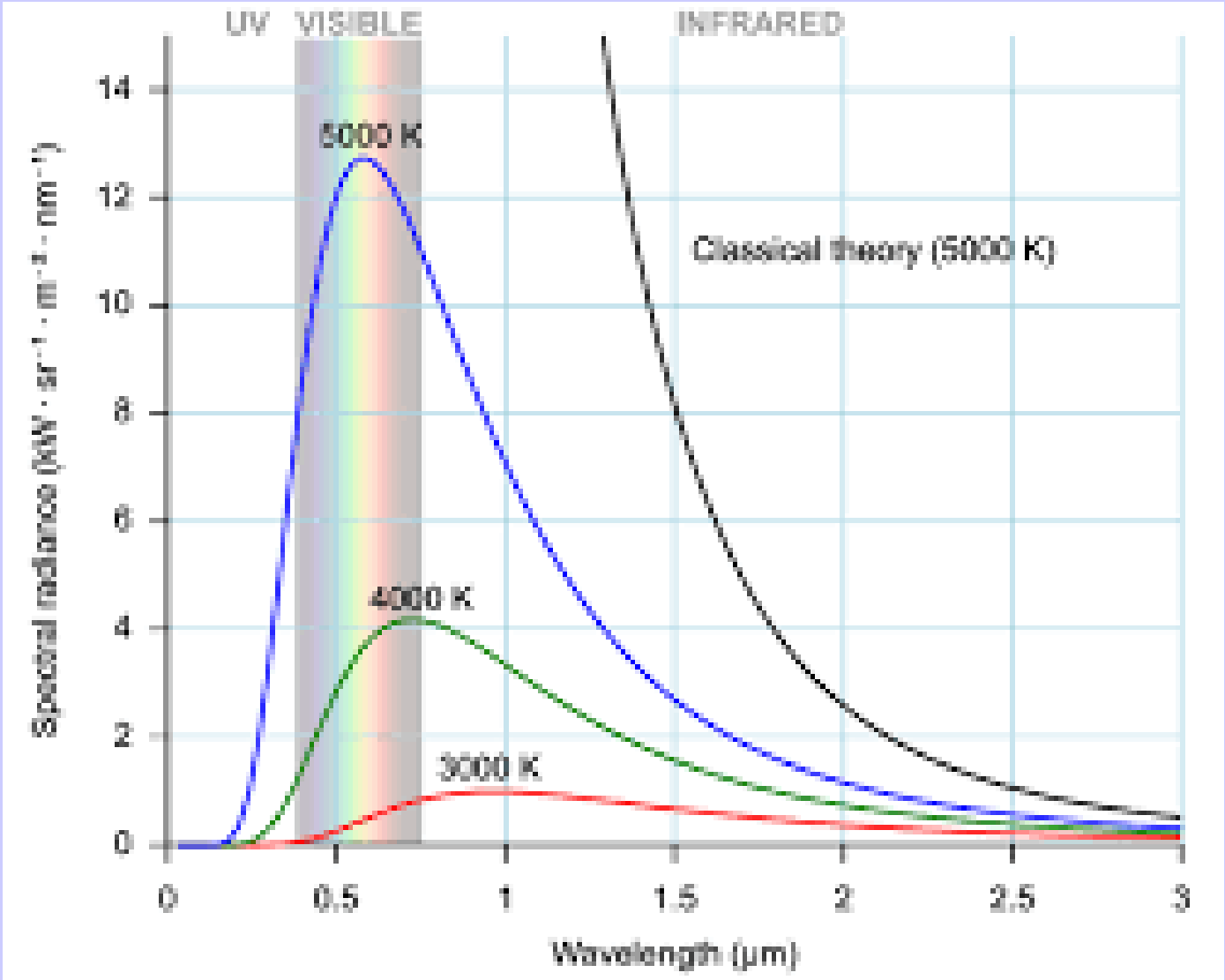
(b) H_2 emission spectrum (top), H_2 absorption spectrum (bottom)

Max Planck (1858 - 1947)

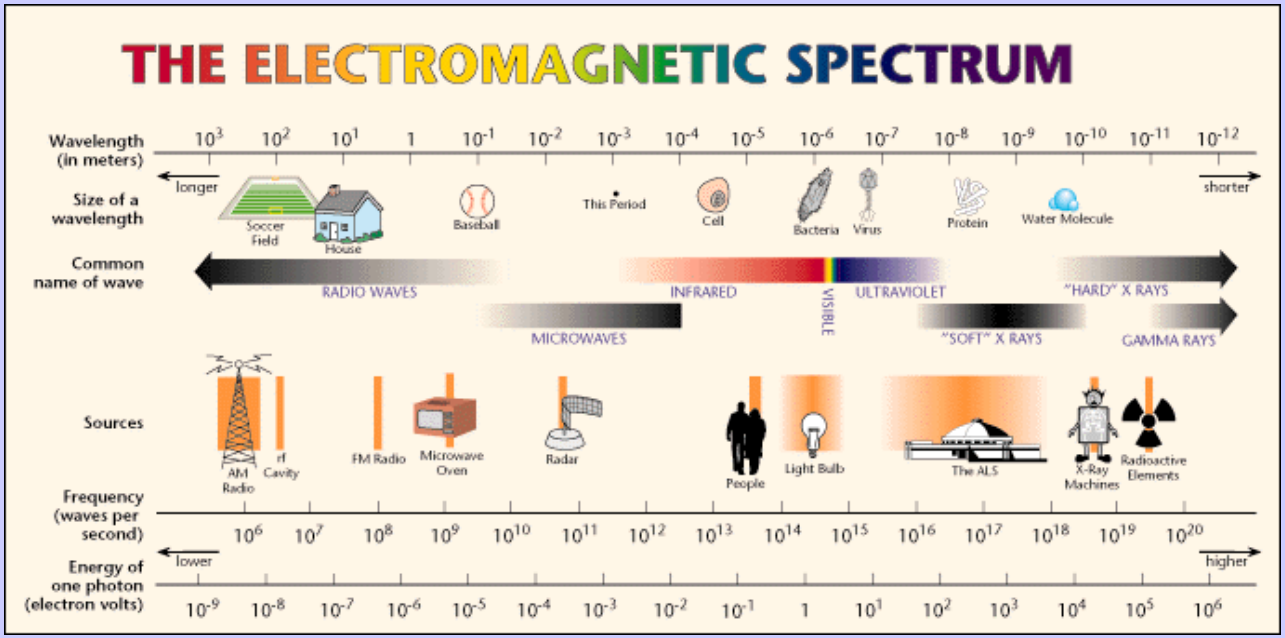
Spectrometer



Black Body Spectrum



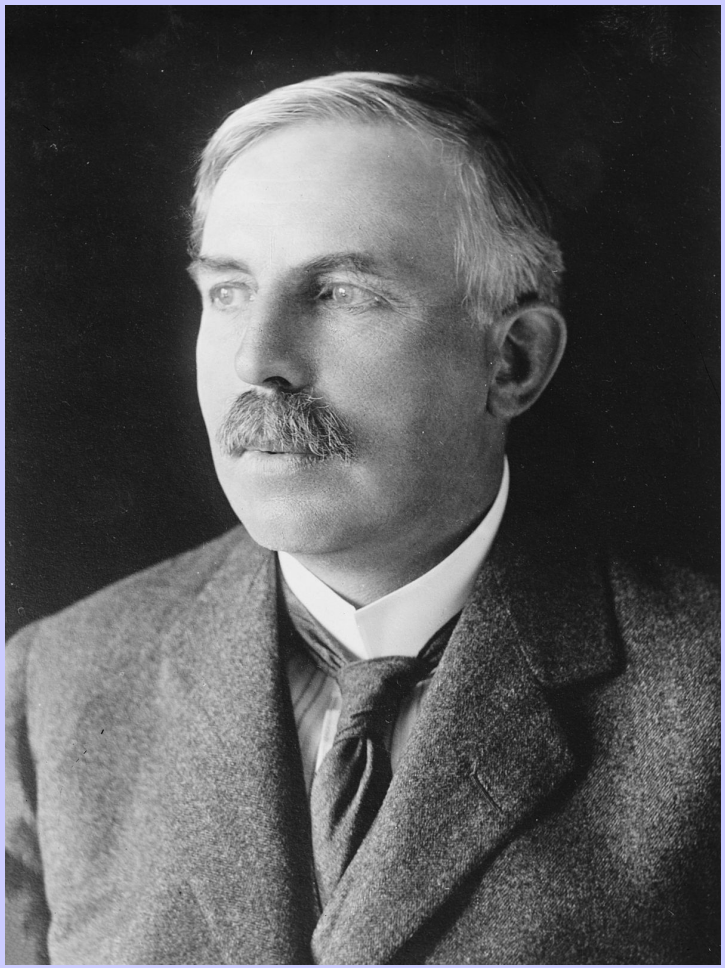
Electromagnetic Spectrum



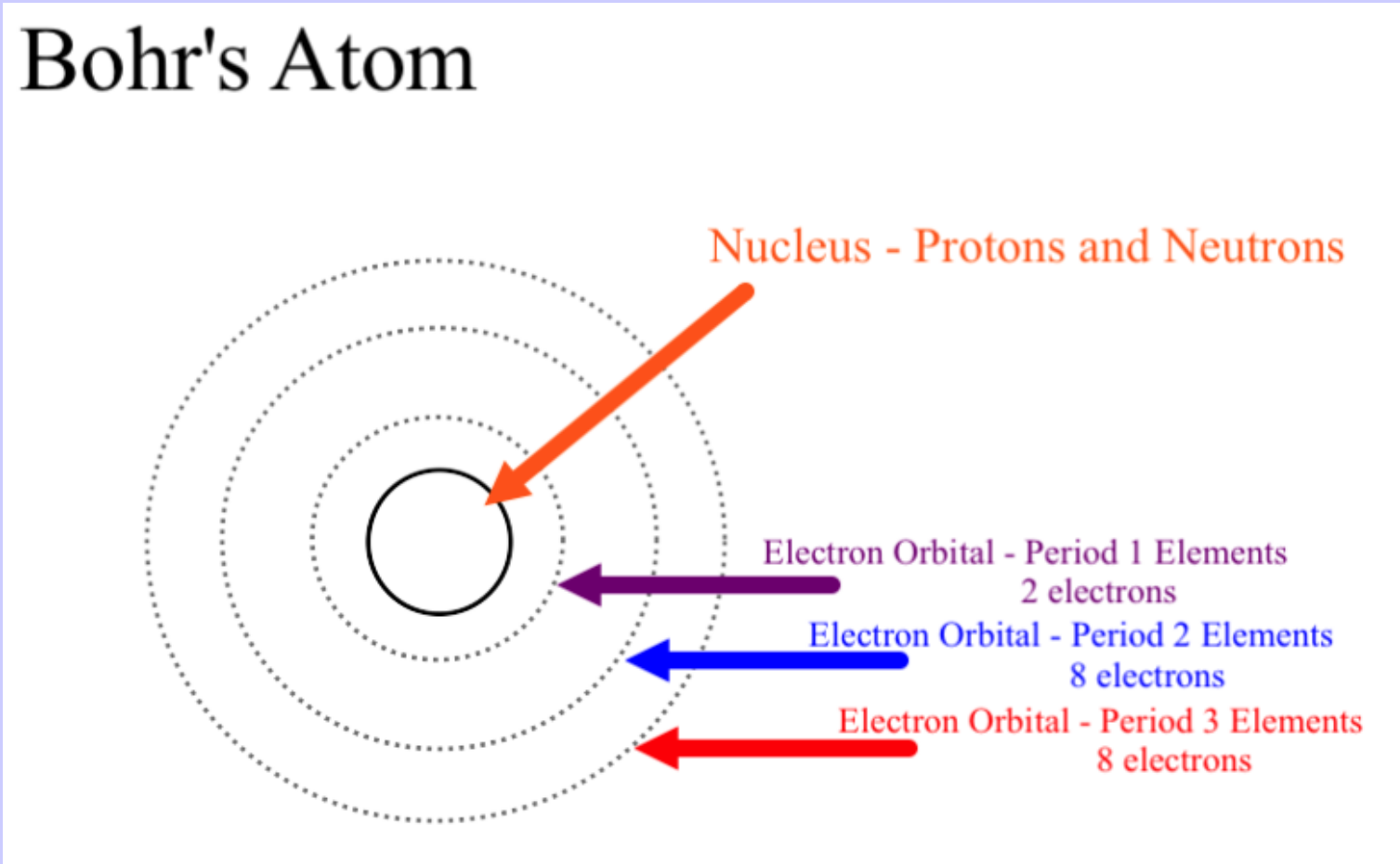
Werner Heisenberg (1901 - 1976)

Erwin Schroedinger (1887 - 1961)

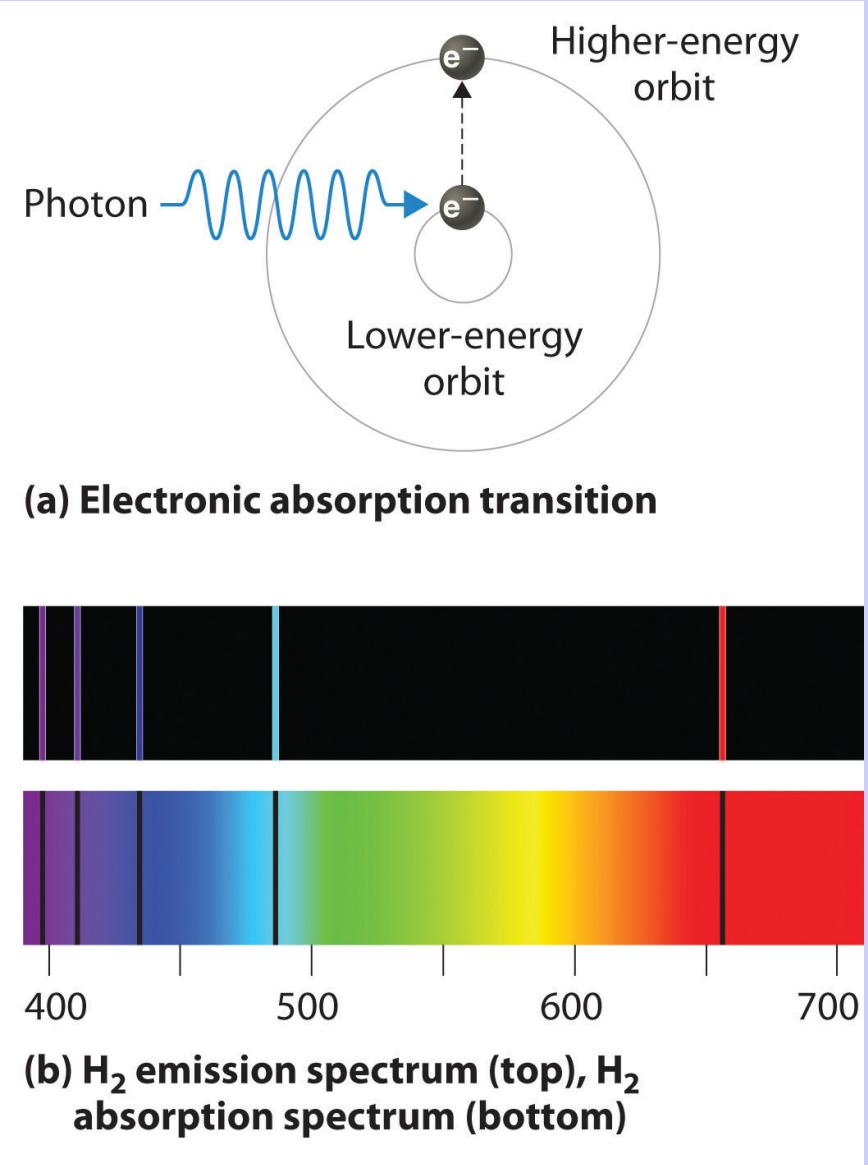
Ernest Rutherford (1871 - 1937)



Bohr Model of the Atom



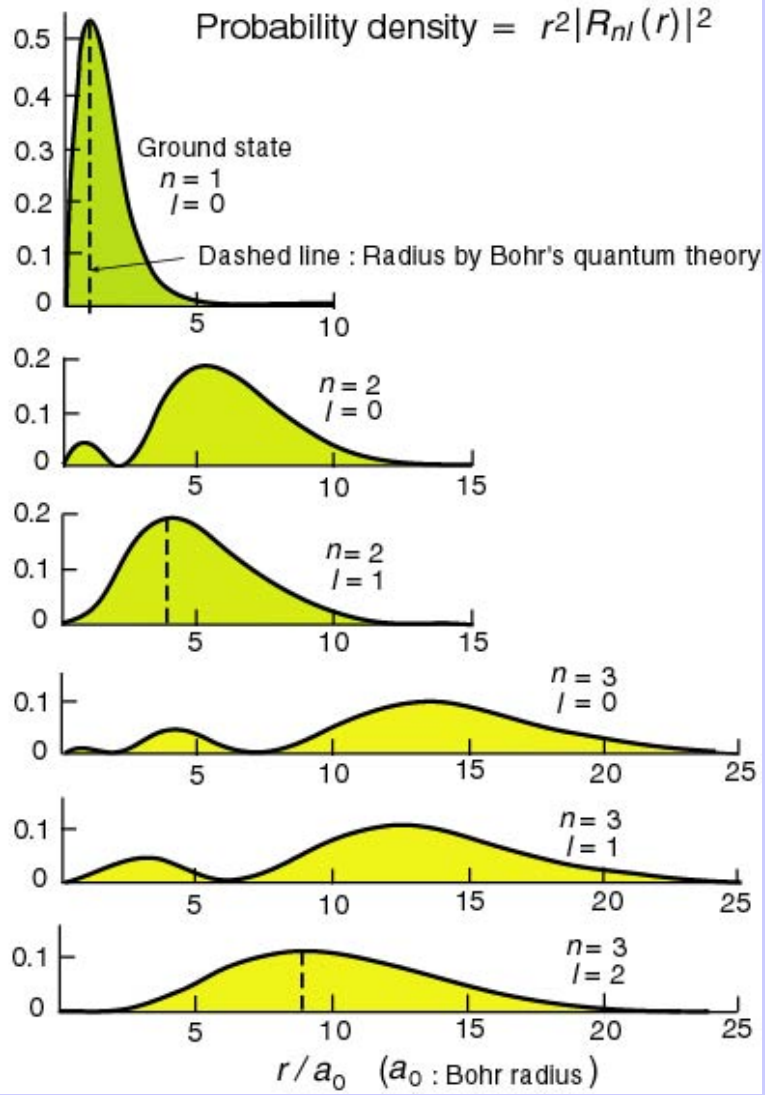
Spectrum of Hydrogen



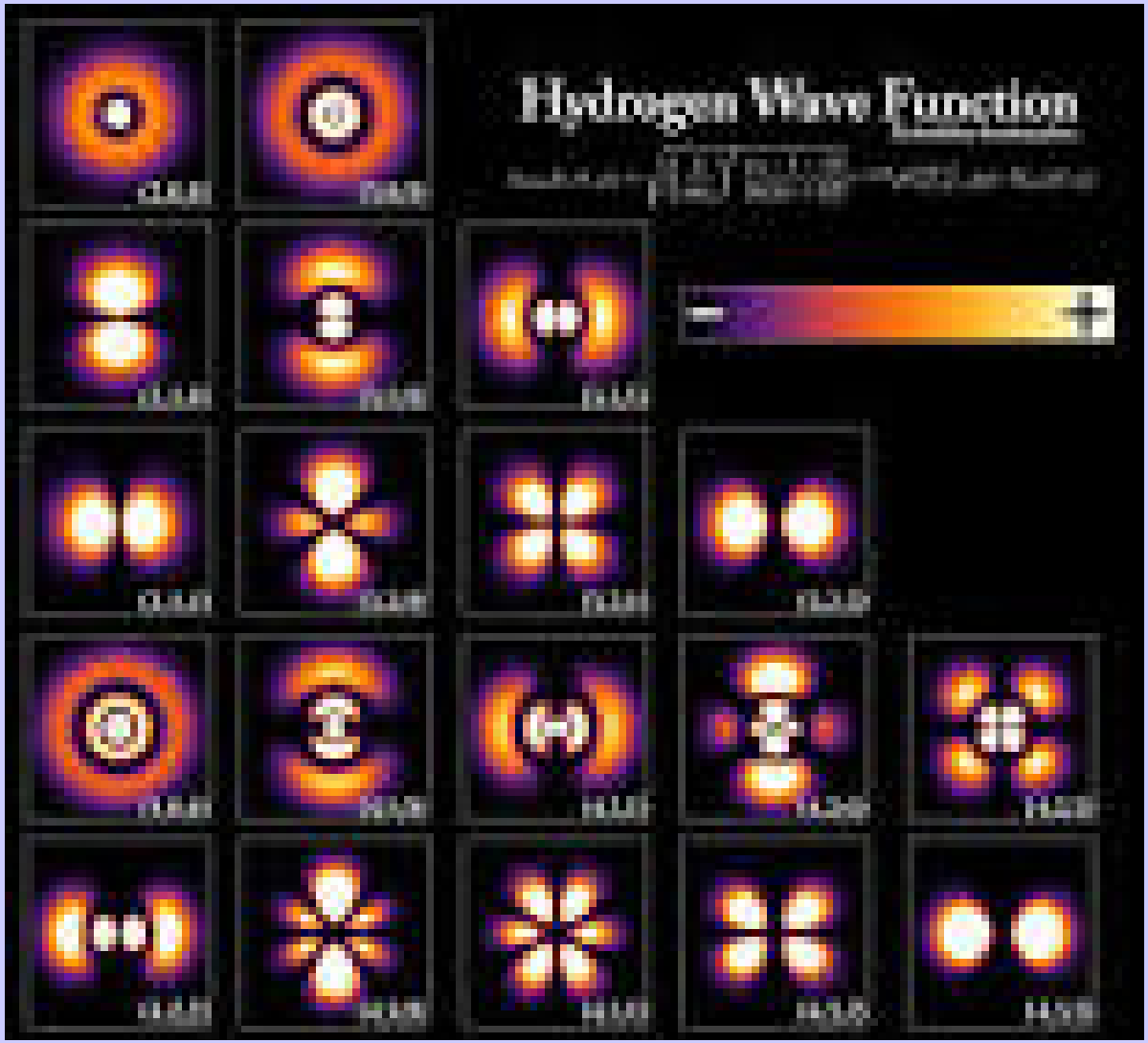
Max Born (1882 - 1970)

Hydrogen Wave Functions

Fig. (C)

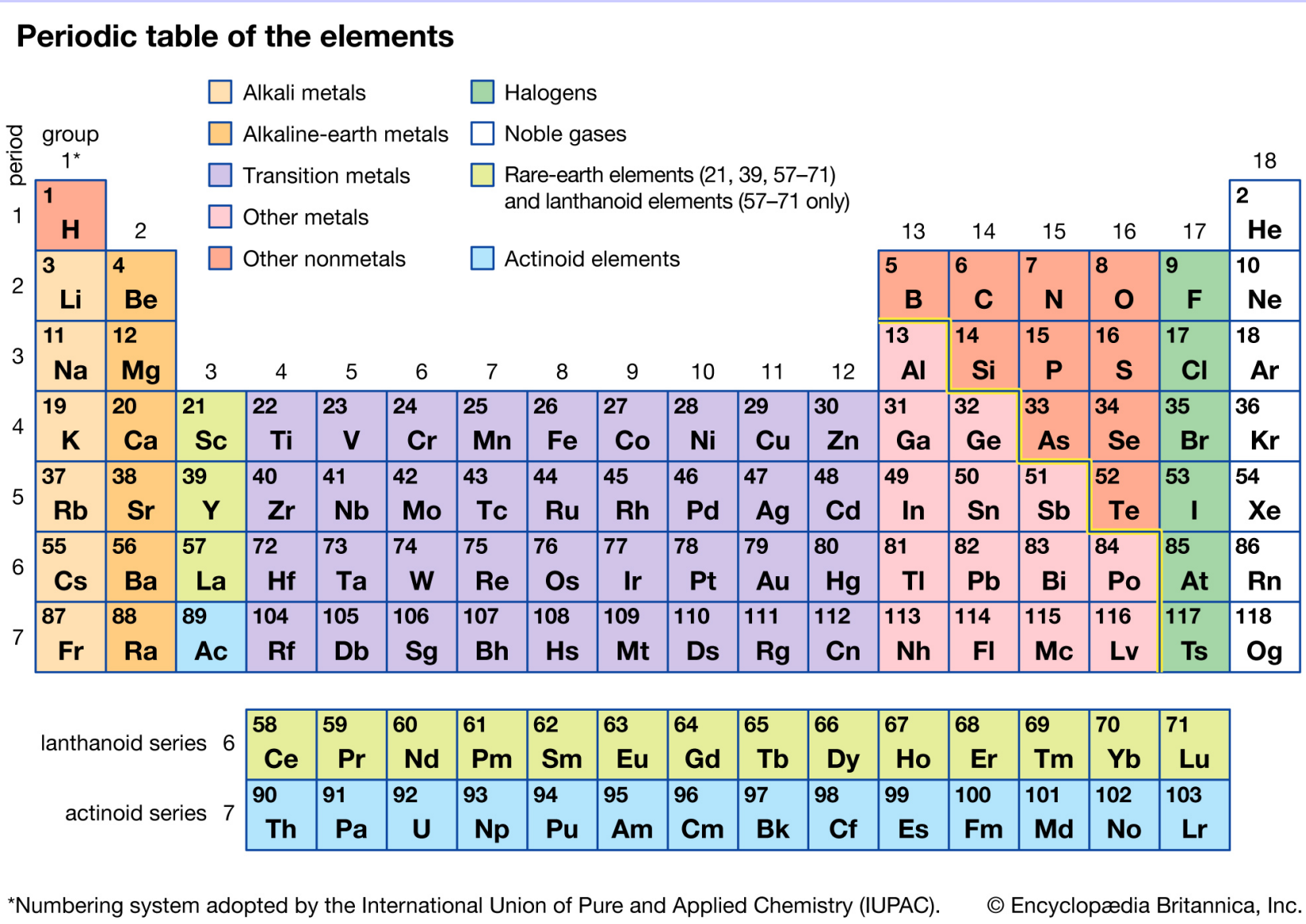


Hydrogen Wave Functions



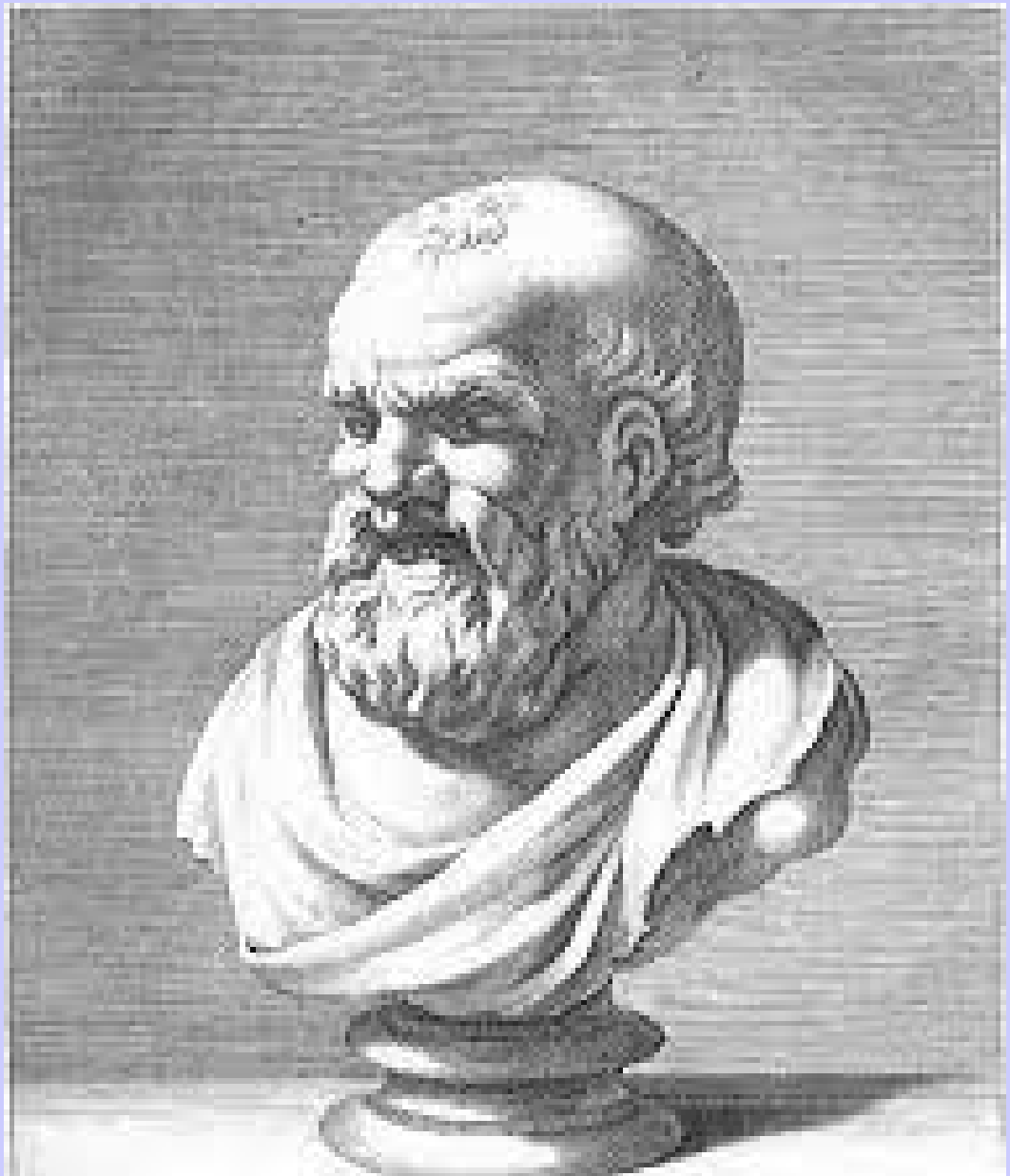
Wolfgang Pauli (1900 - 1958)

Periodic Table



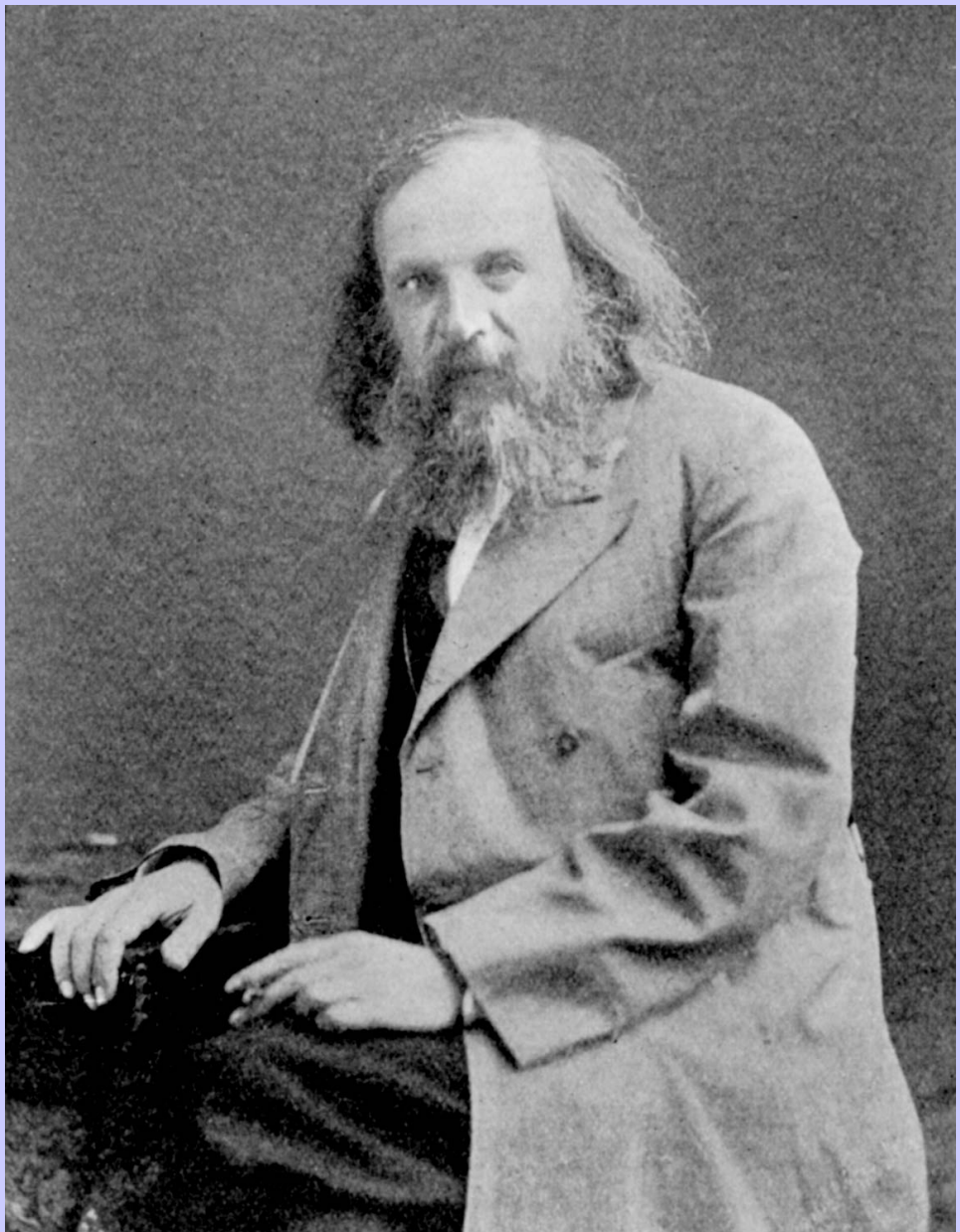
Marie Curie (1867 - 1934)

Democritos (4th century BC)

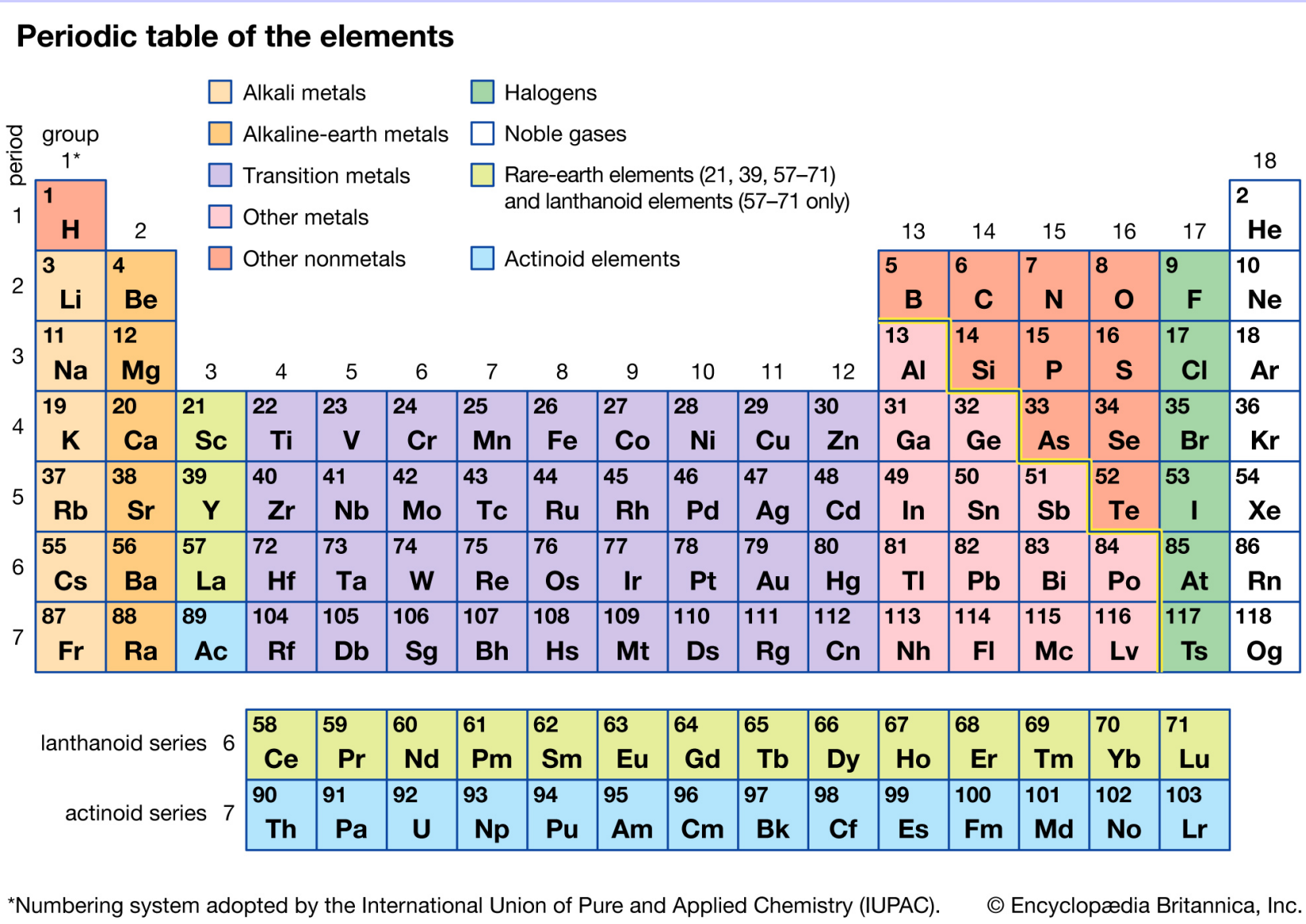


Henry Cavendish (1731 - 1810)

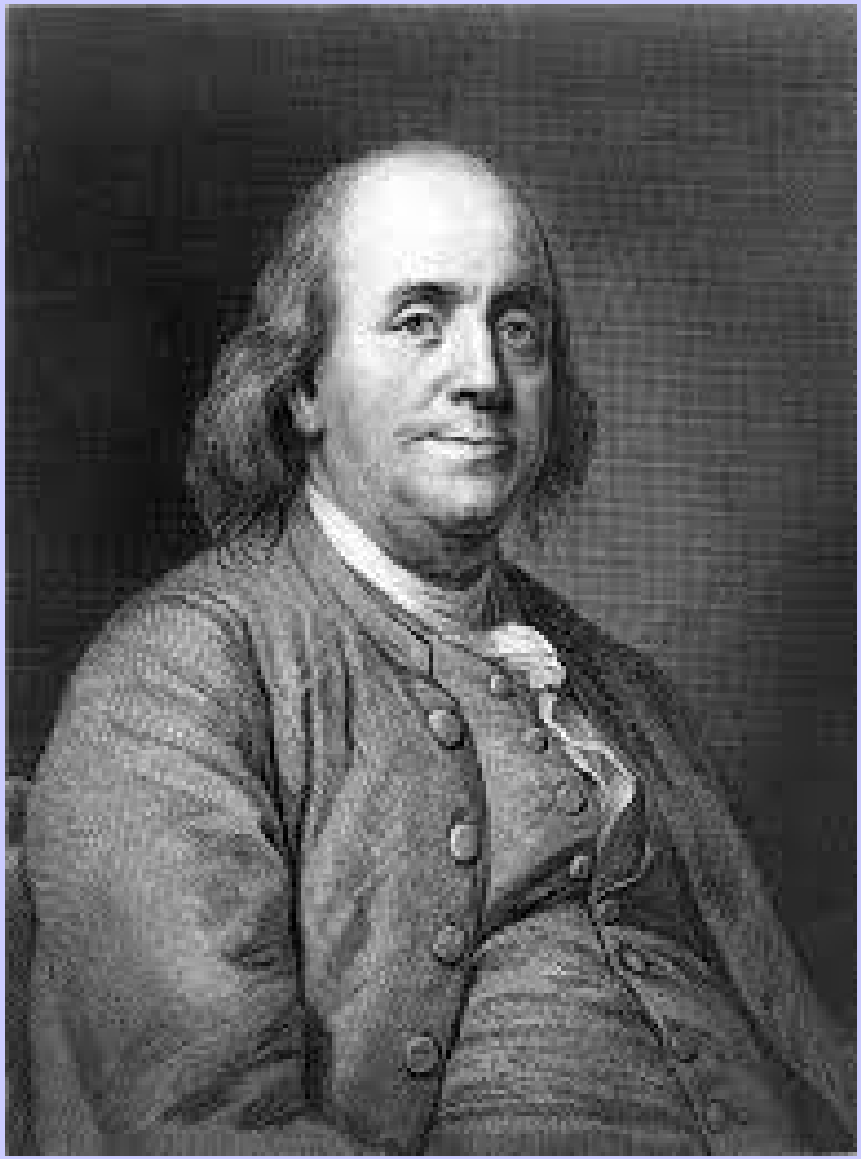
Dmitri Mendeleev (1834 - 907)



Periodic Table

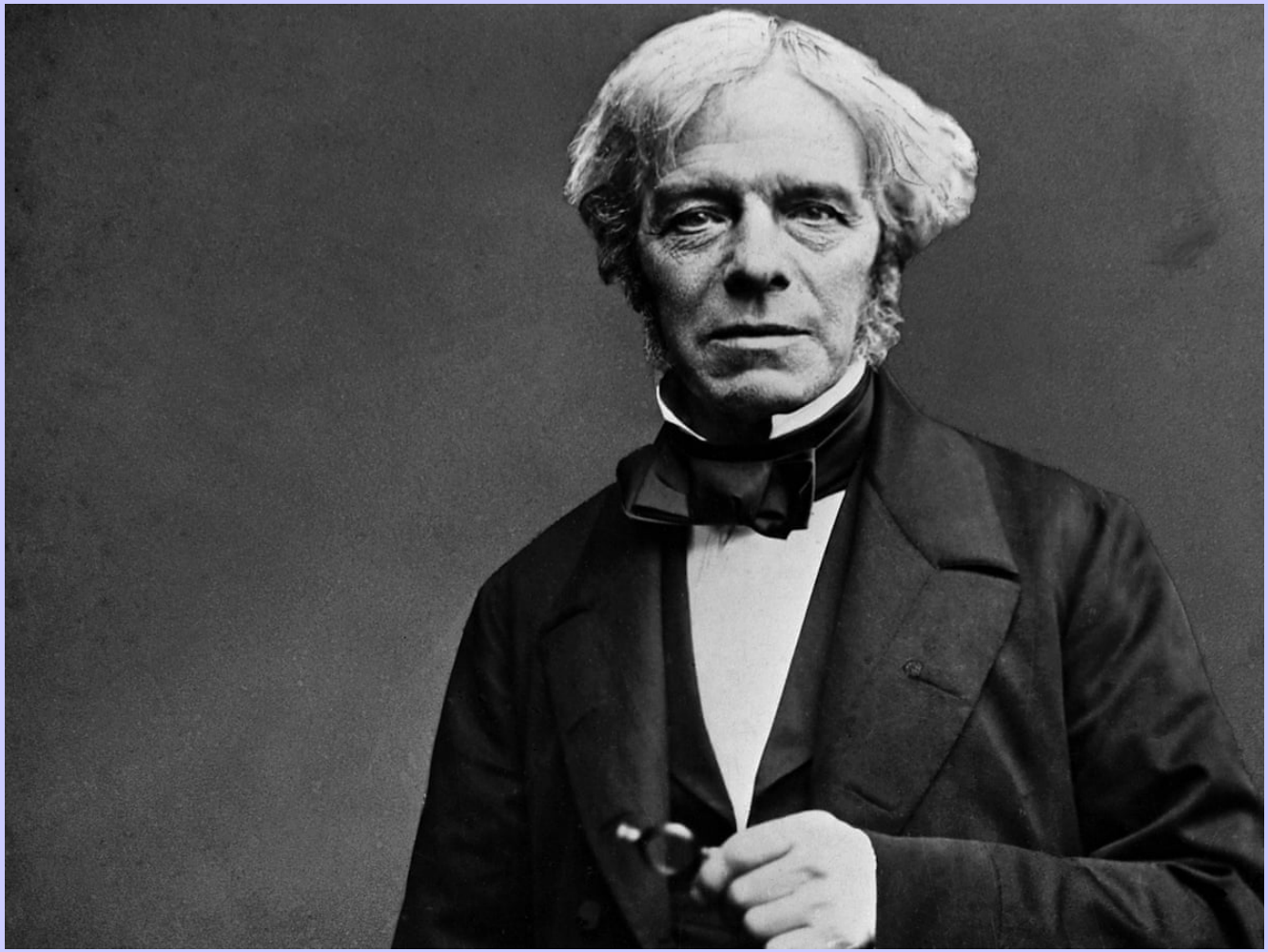


Benjamin Franklin (1706 - 1790)

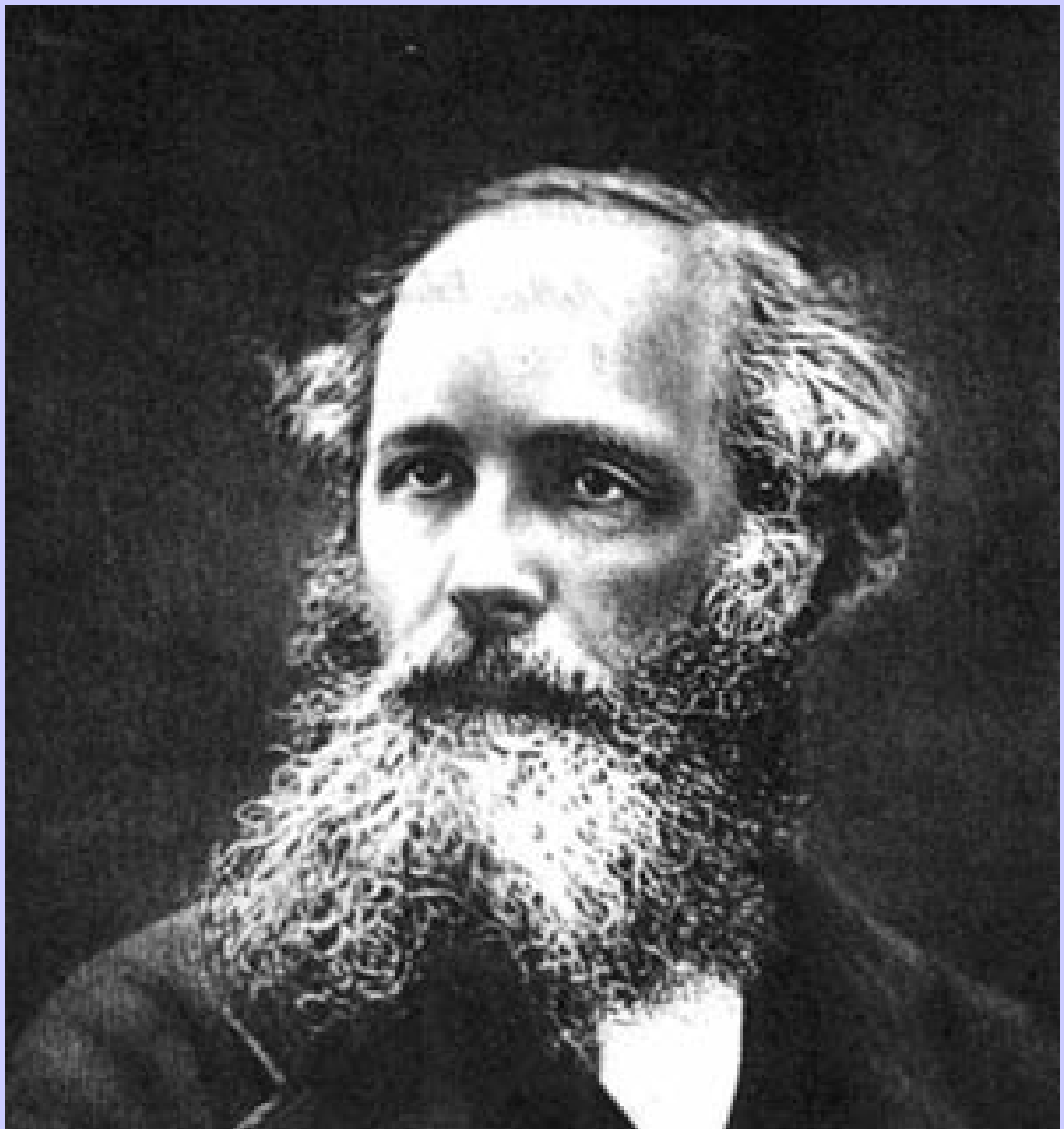


Charles-Augustin de Coulomb (1736 - 1806)

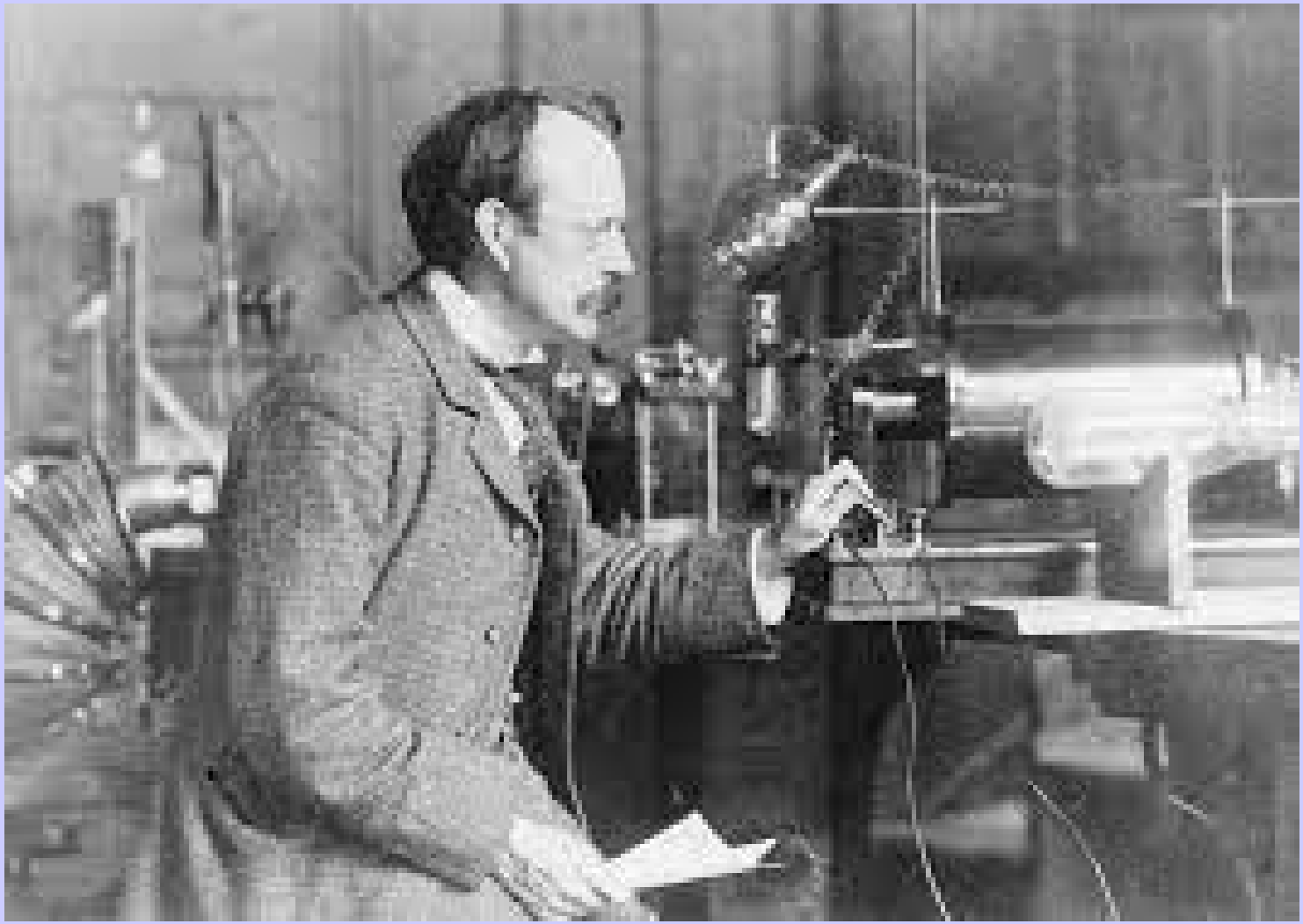
Michael Faraday (1791 - 1867)



James Clerk Maxwell (1831 - 1879)

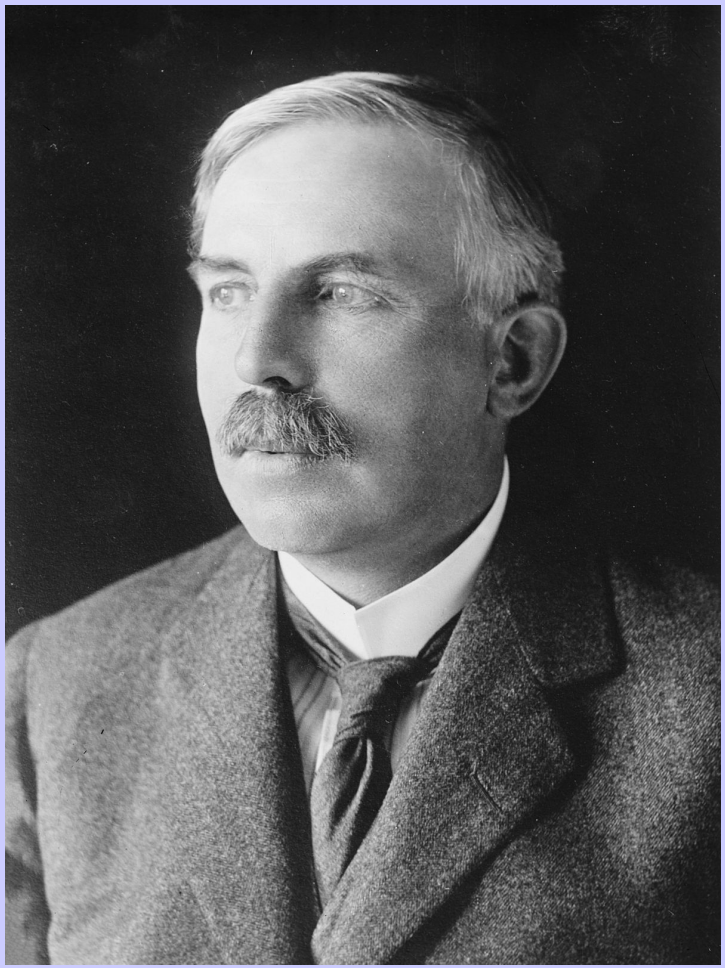


J. J. Thomson (1856 - 1940)

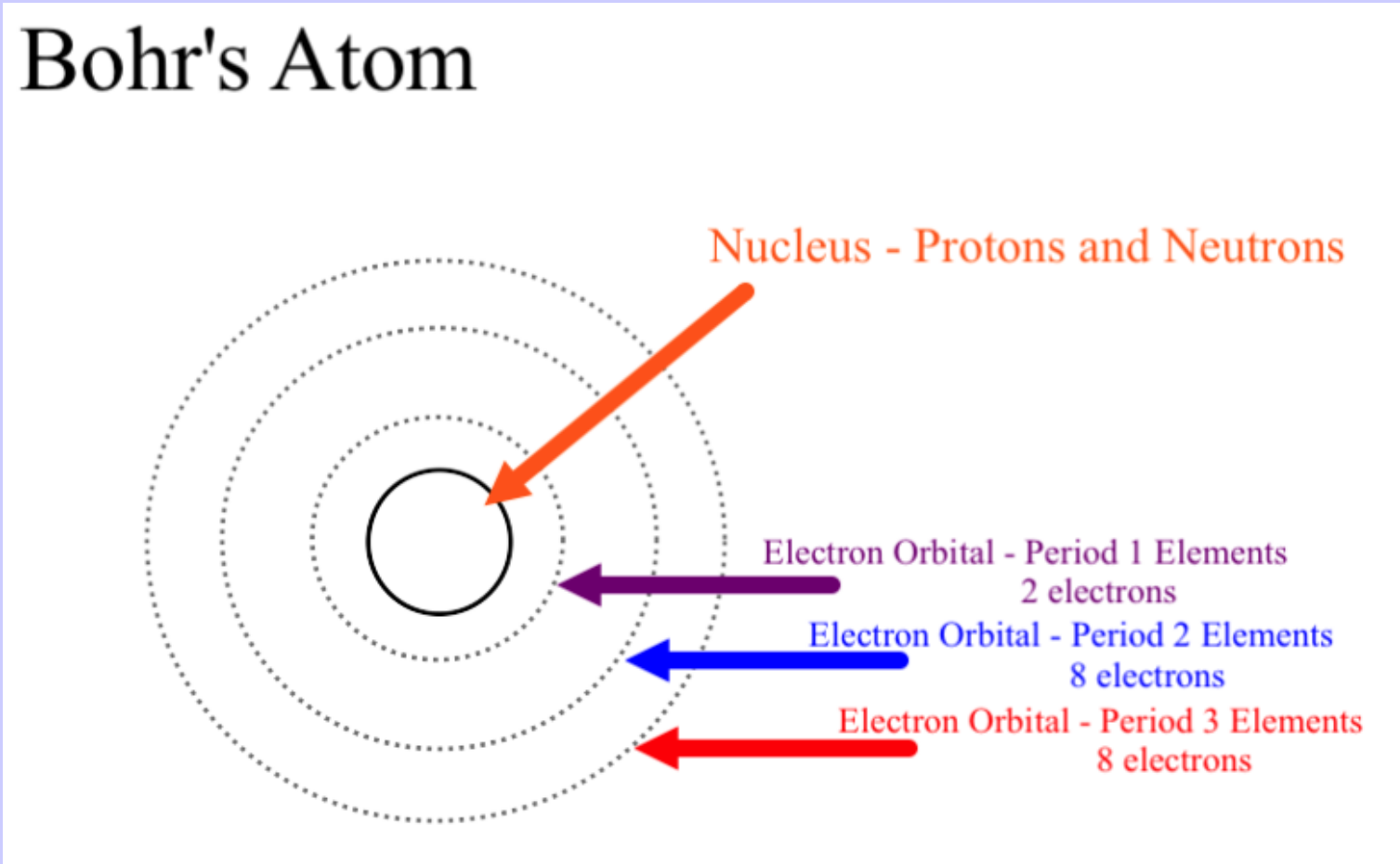


Marie Curie (1867 - 1934)

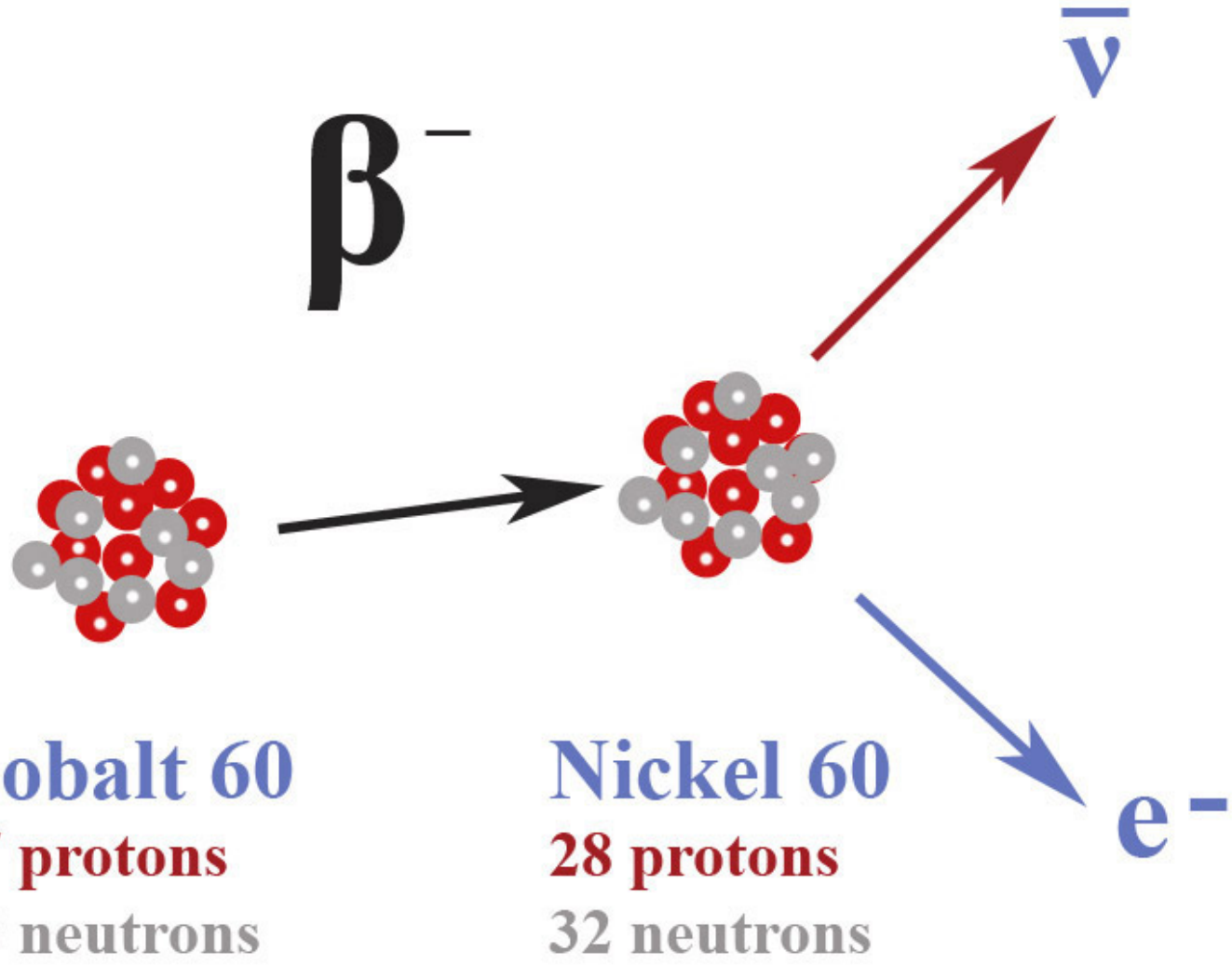
Ernest Rutherford (1871 - 1937)



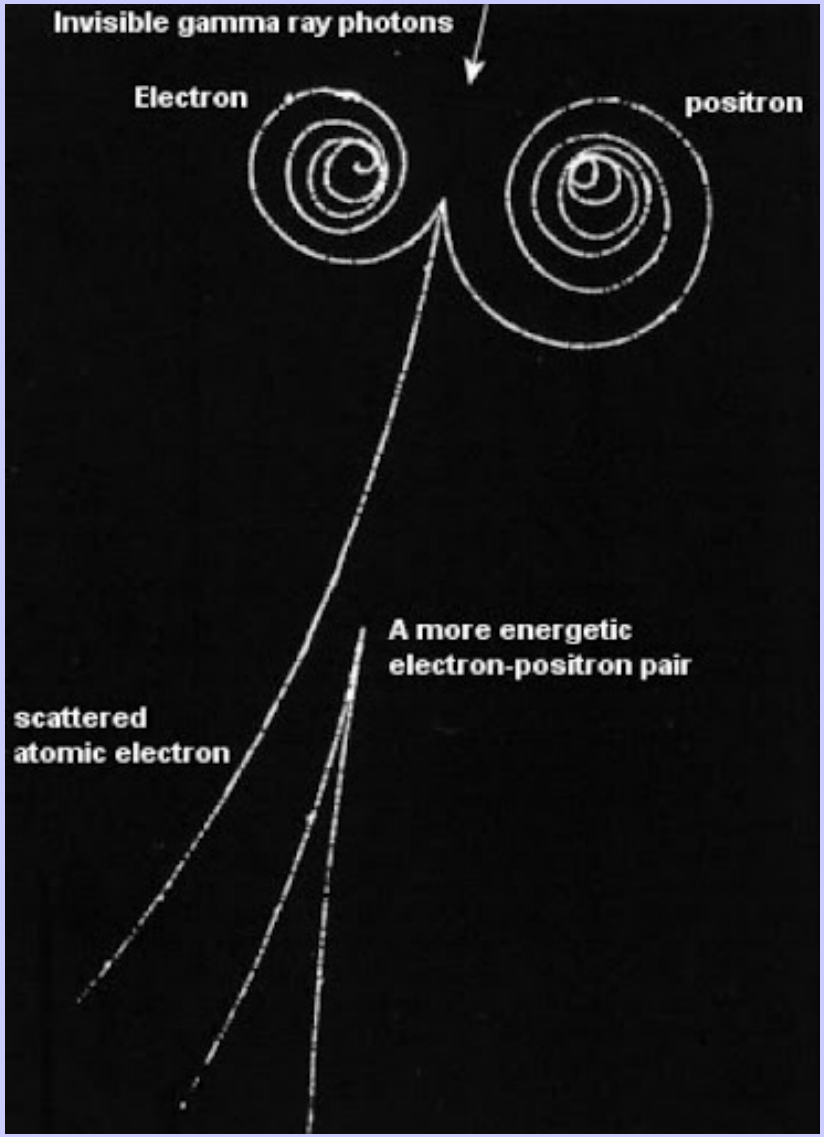
Bohr Model of the Atom



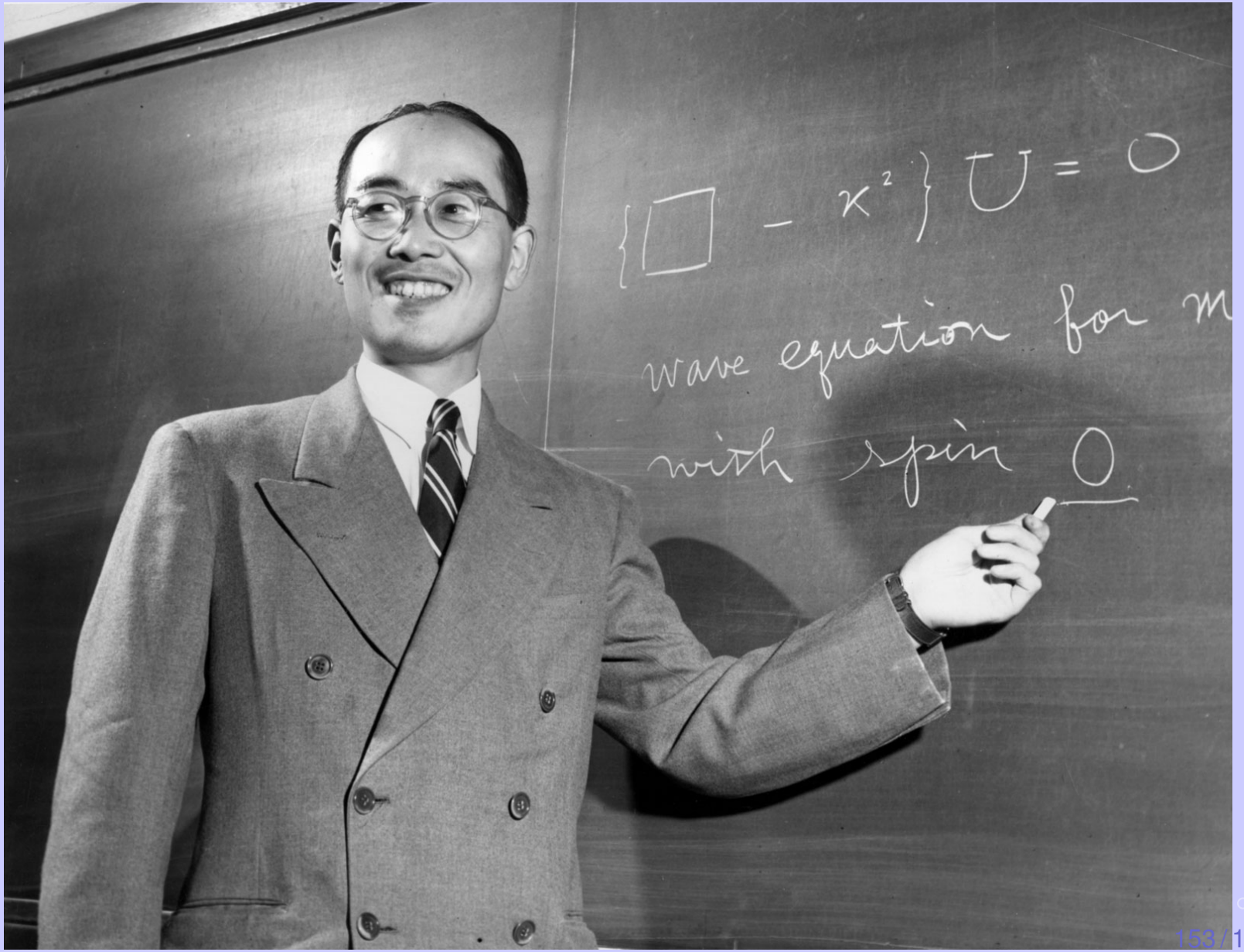
Beta Decay


β⁻
ν̄
e⁻
Cobalt 60
27 protons
33 neutrons
Nickel 60
28 protons
32 neutrons
© Astronoo.com

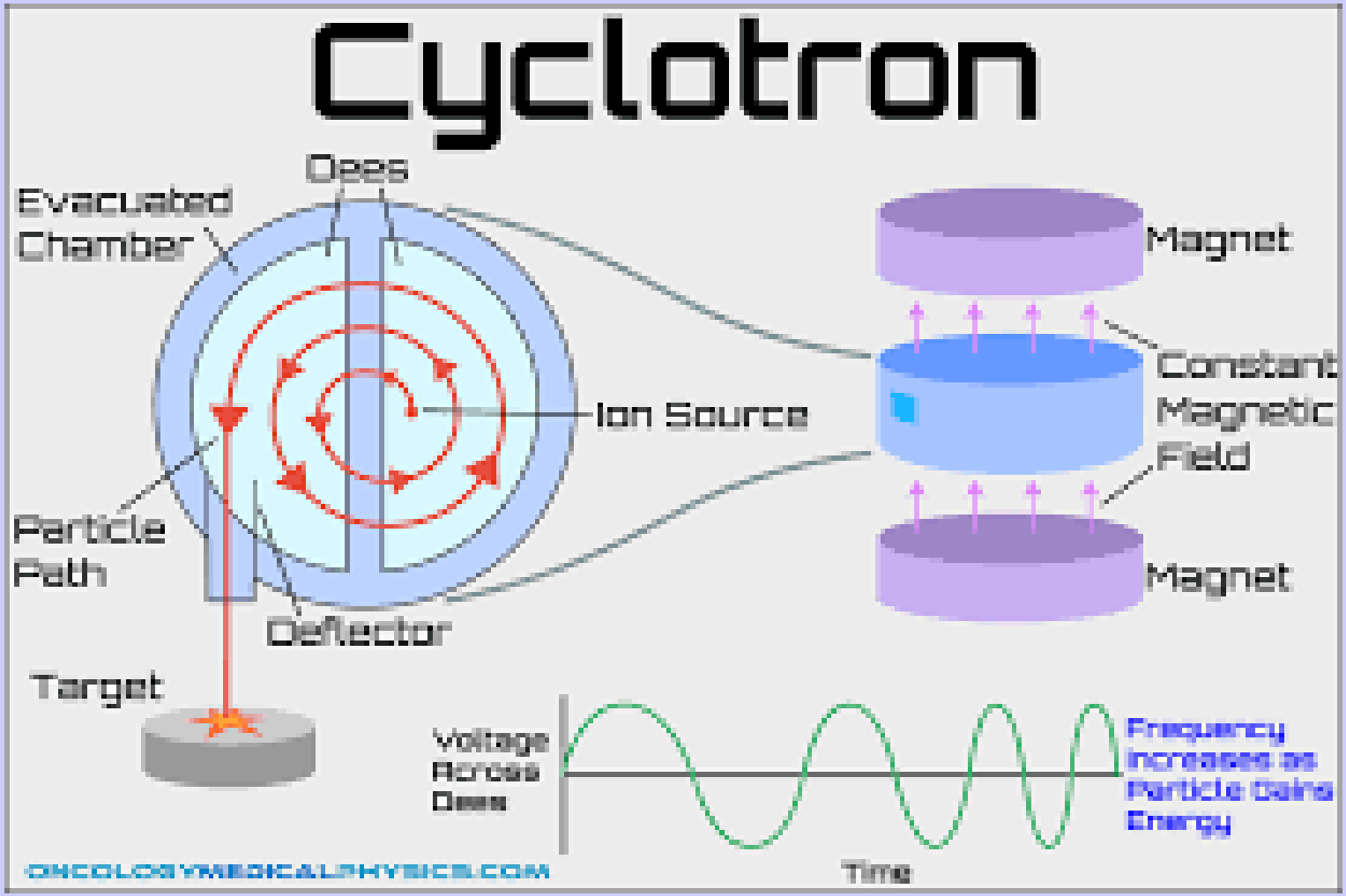
Positron Tracks in a Cloud Chamber



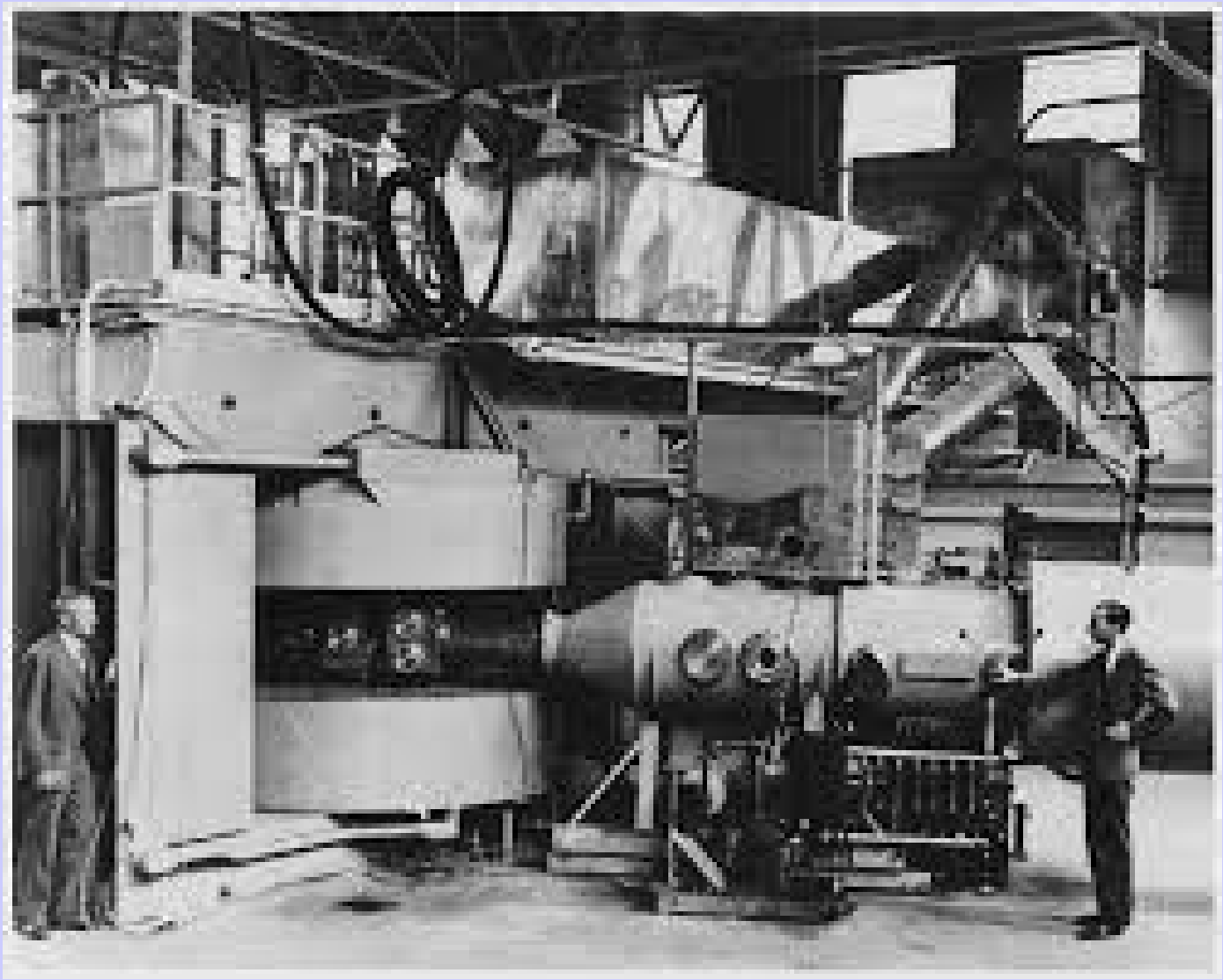
Hideki Yukawa



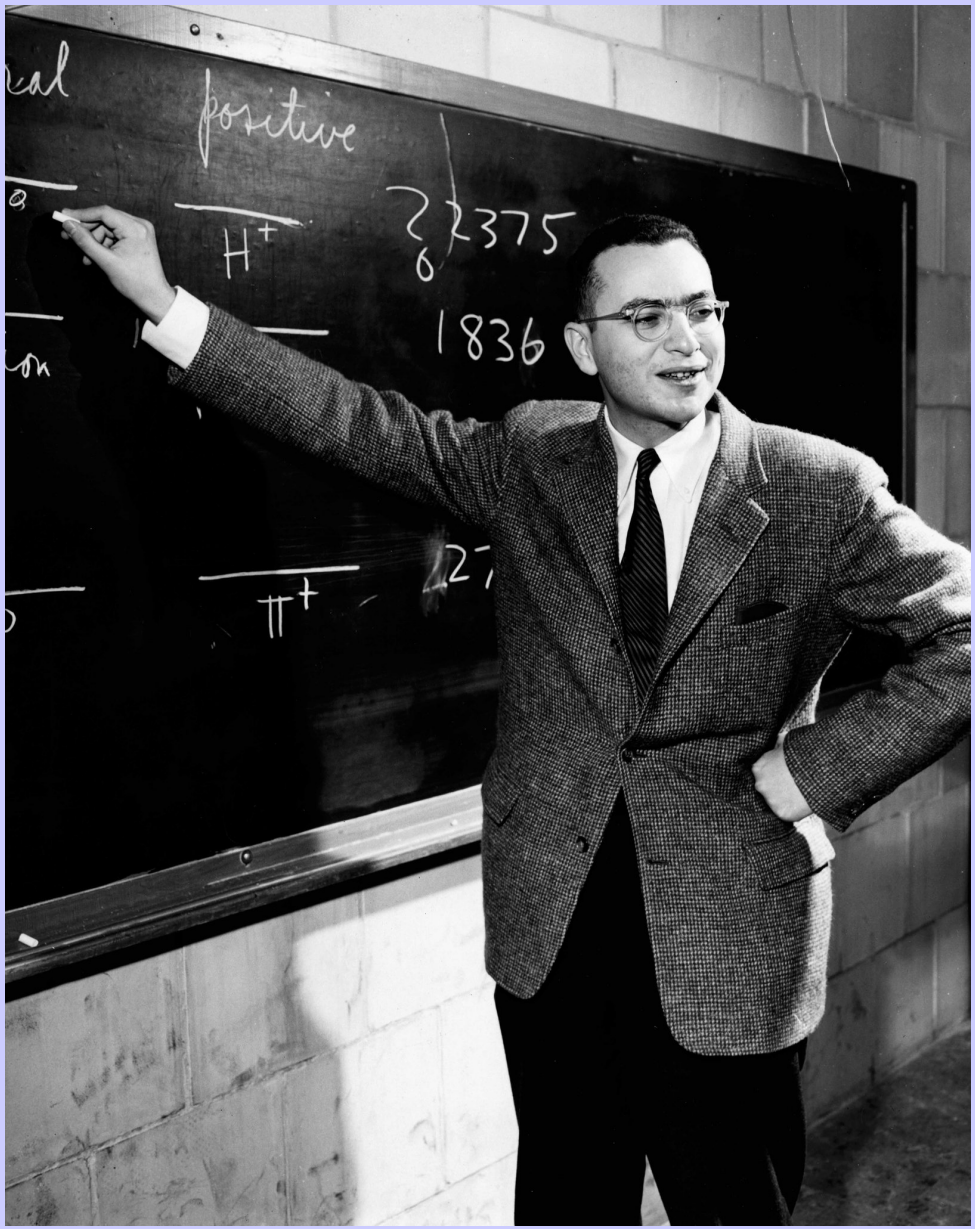
Cyclotron Sketch



Cyclotron Image

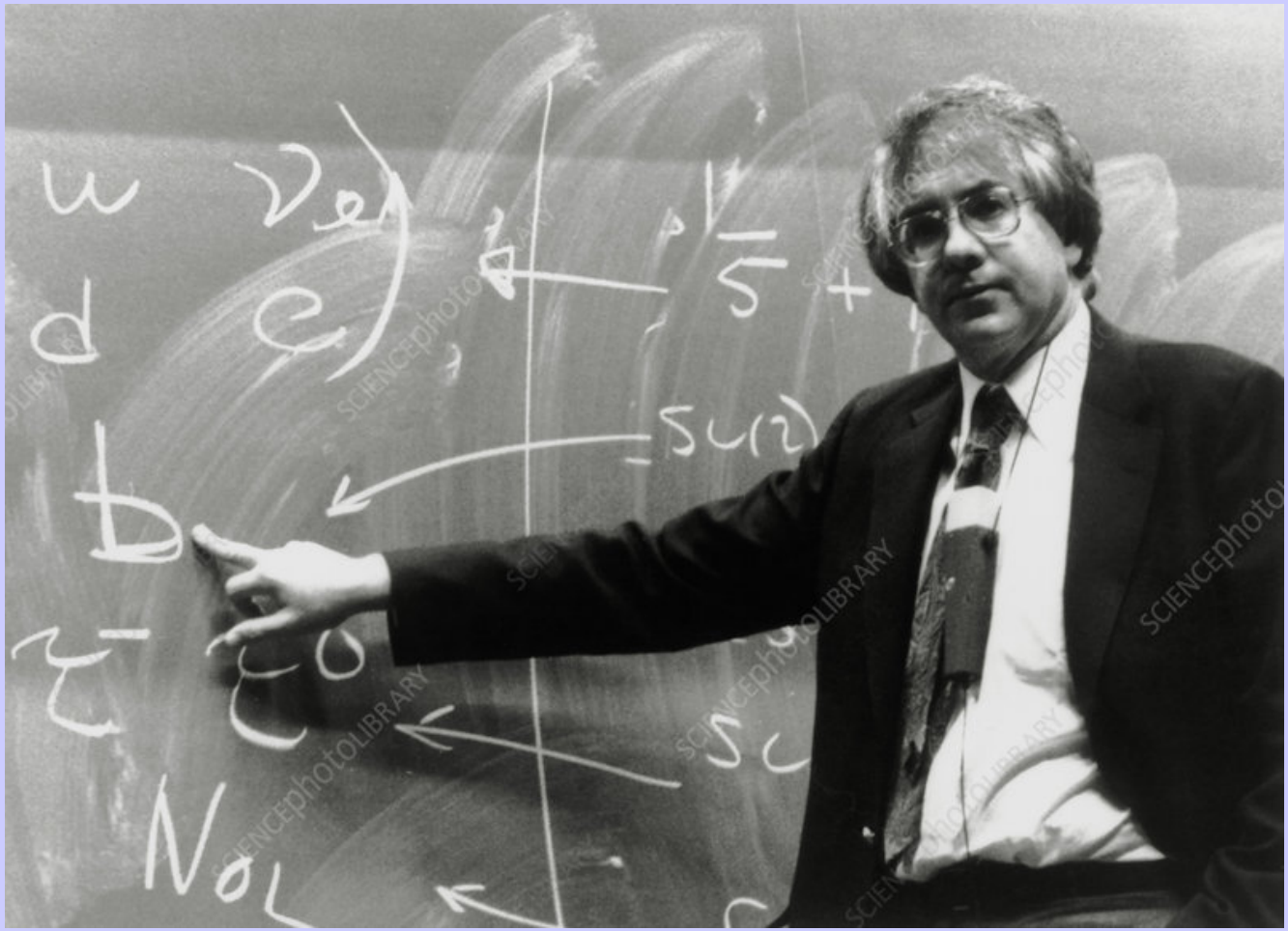


Murray Gell-Mann



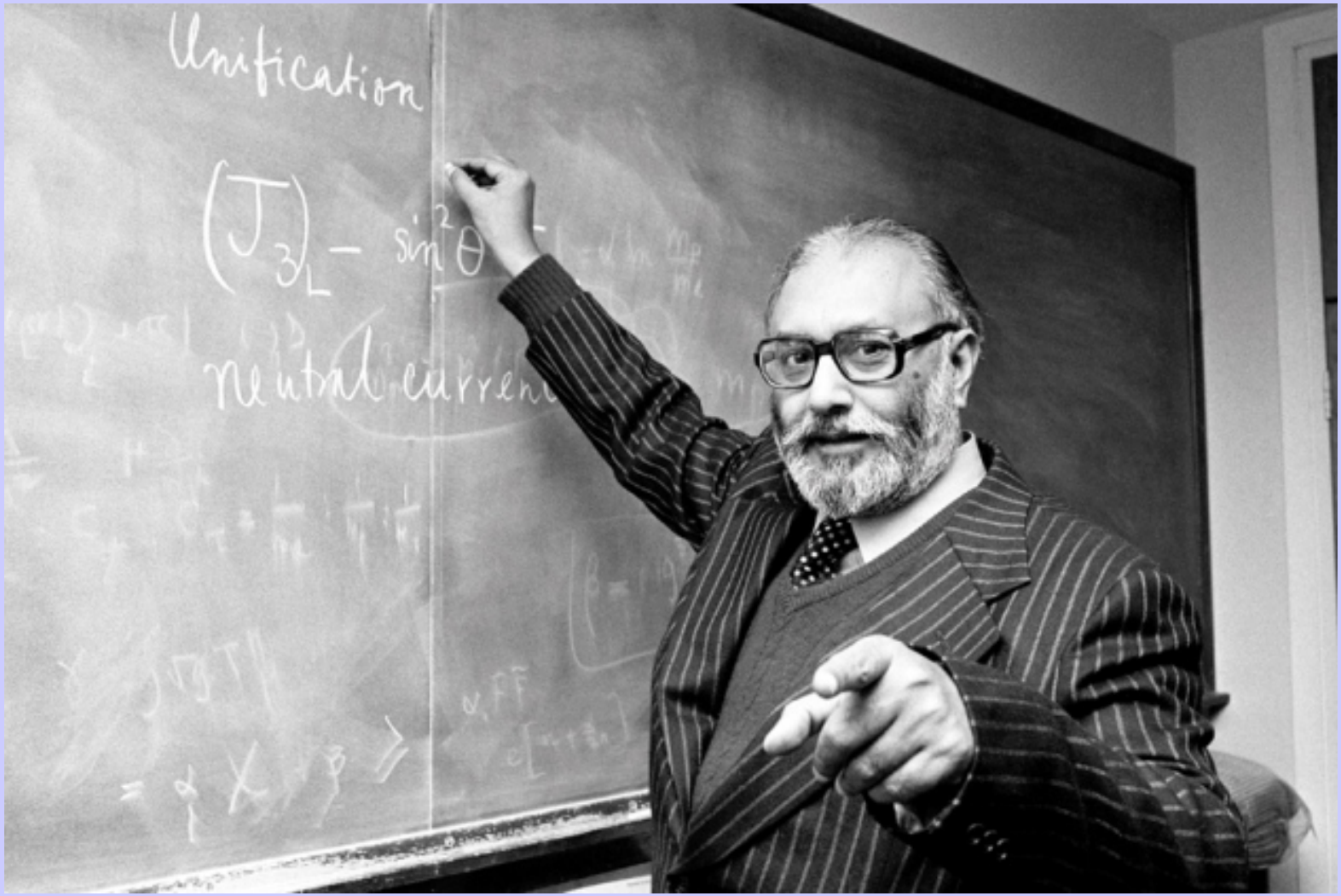
Georg Zweig

Sheldon Glashow

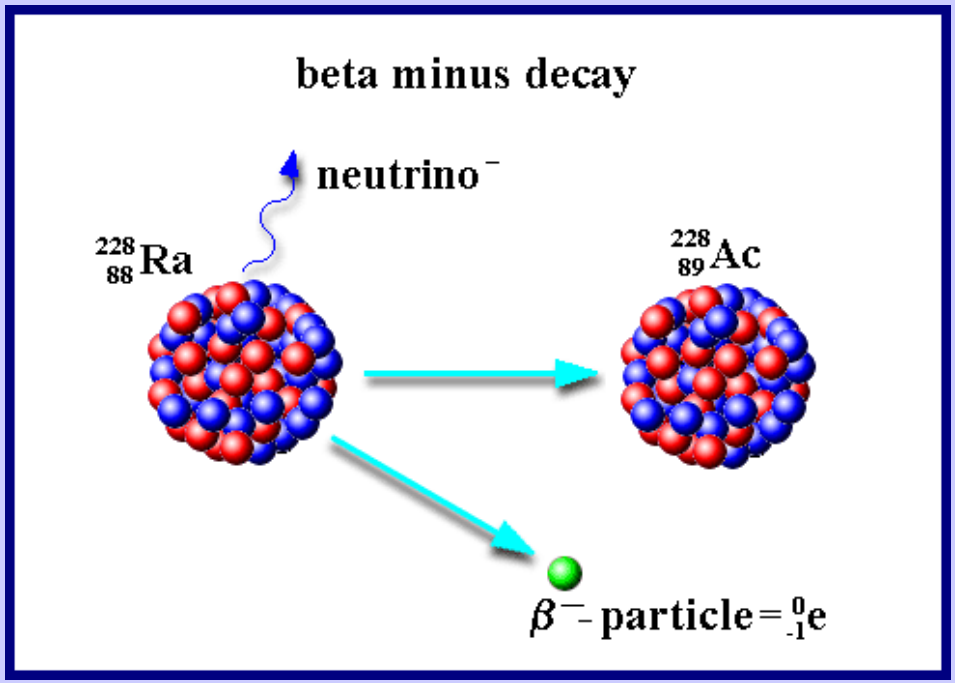


Steven Weinberg

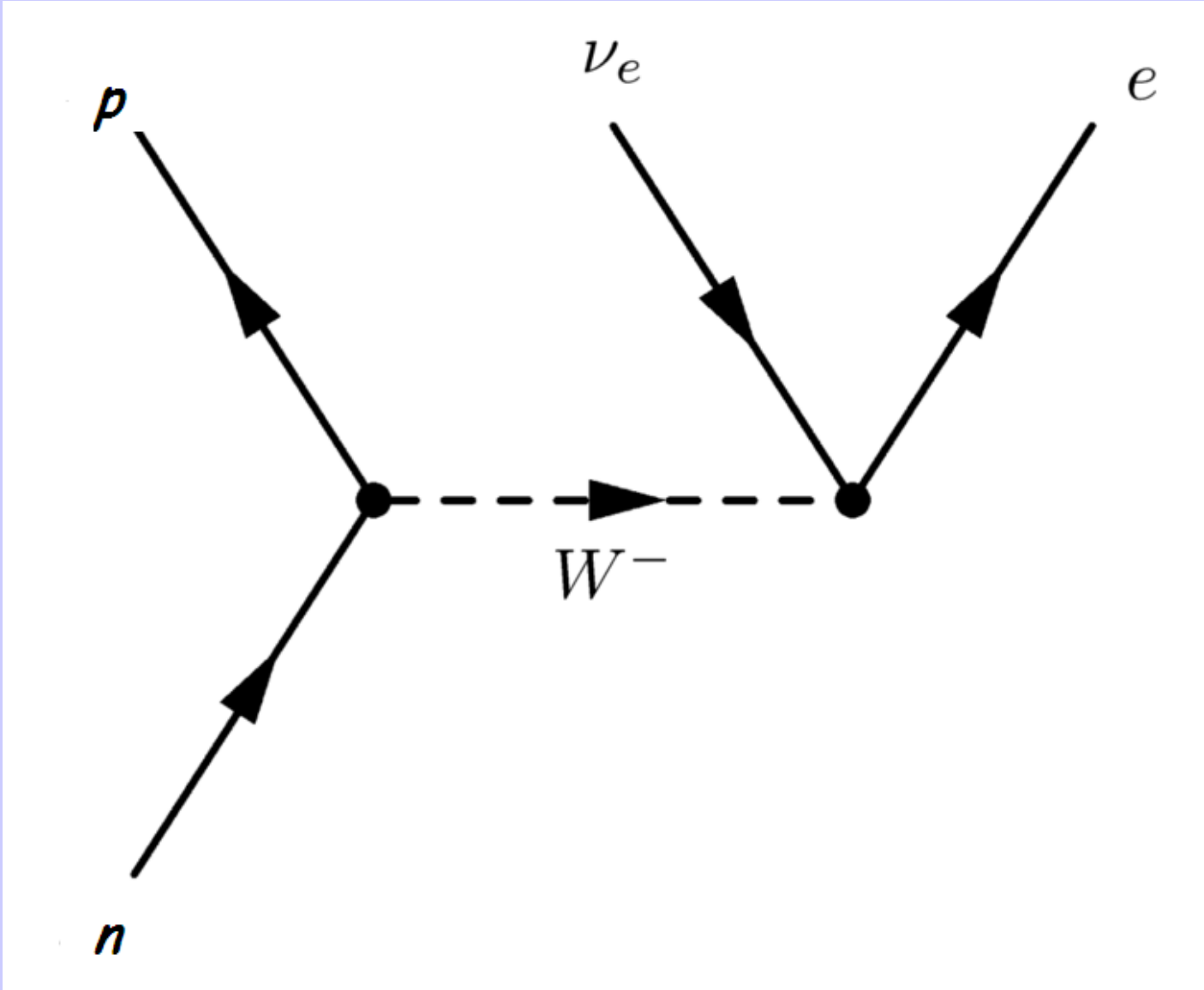
Abdus Salam



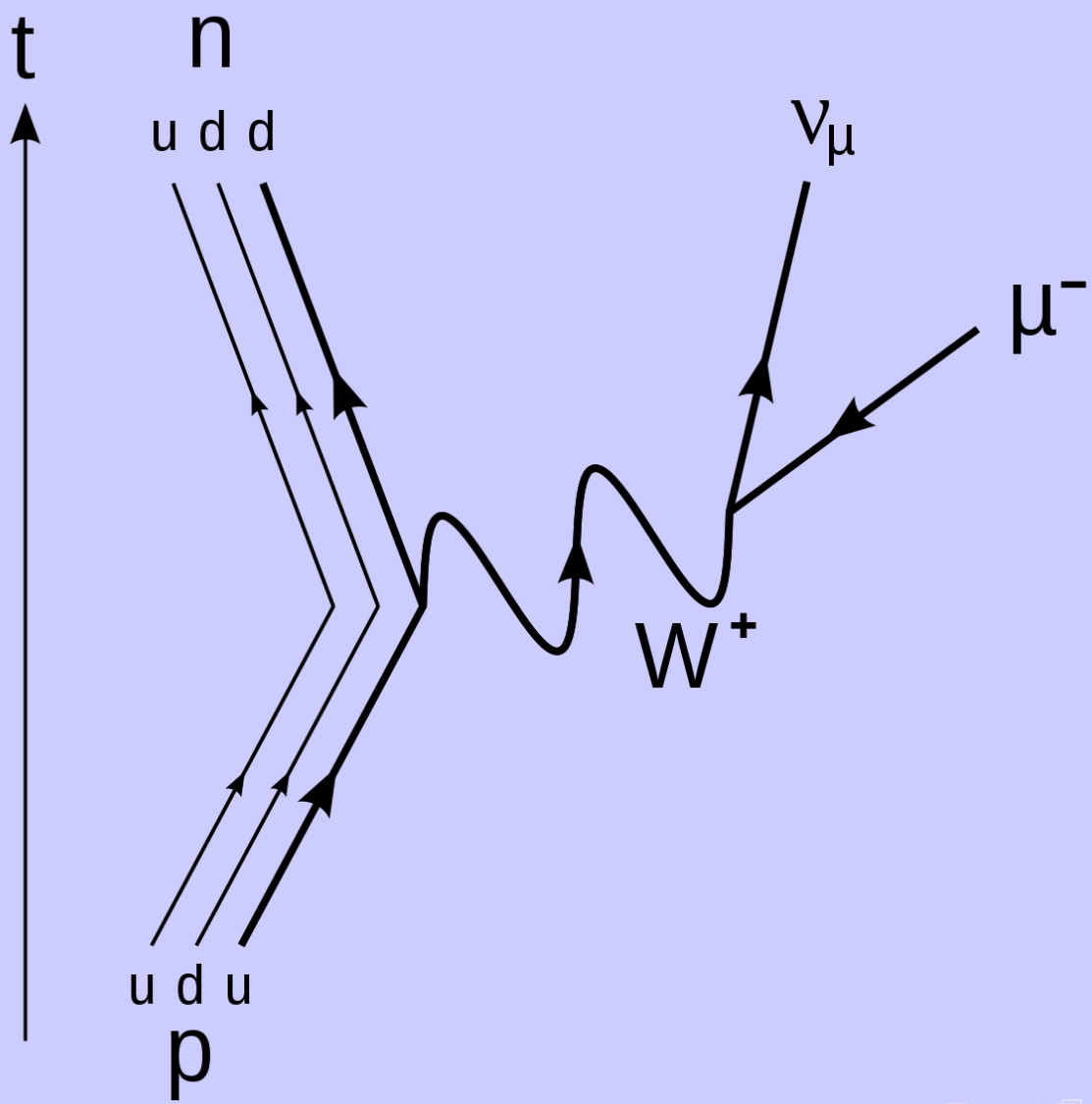
Beta Decay


beta minus decay
neutrino⁻
$^{228}_{88}$Ra
$^{228}_{89}$Ac
β^- - particle = $^{0}_{-1}$e

Beta Decay



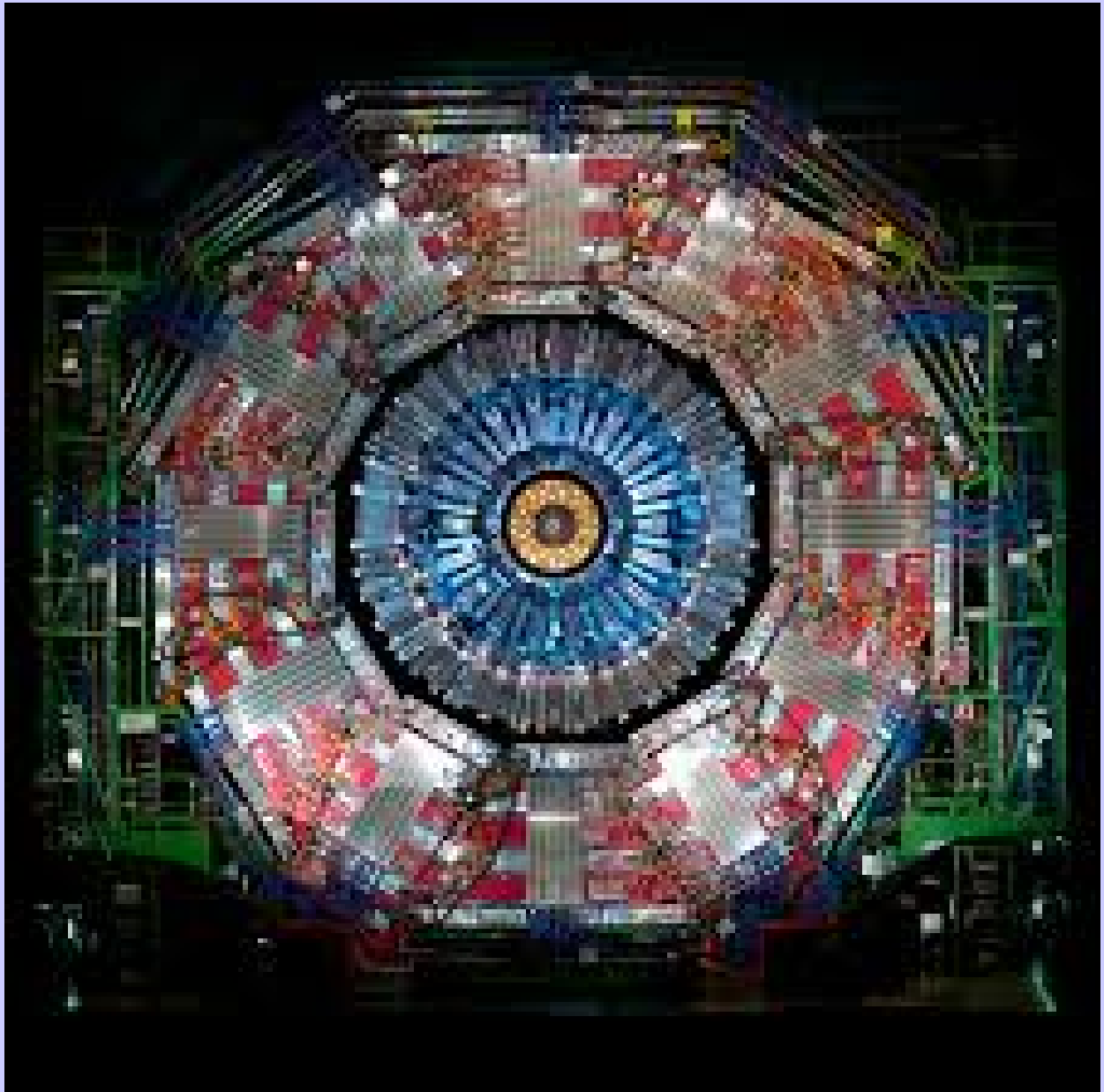
Beta Decay



CERN Laboratory

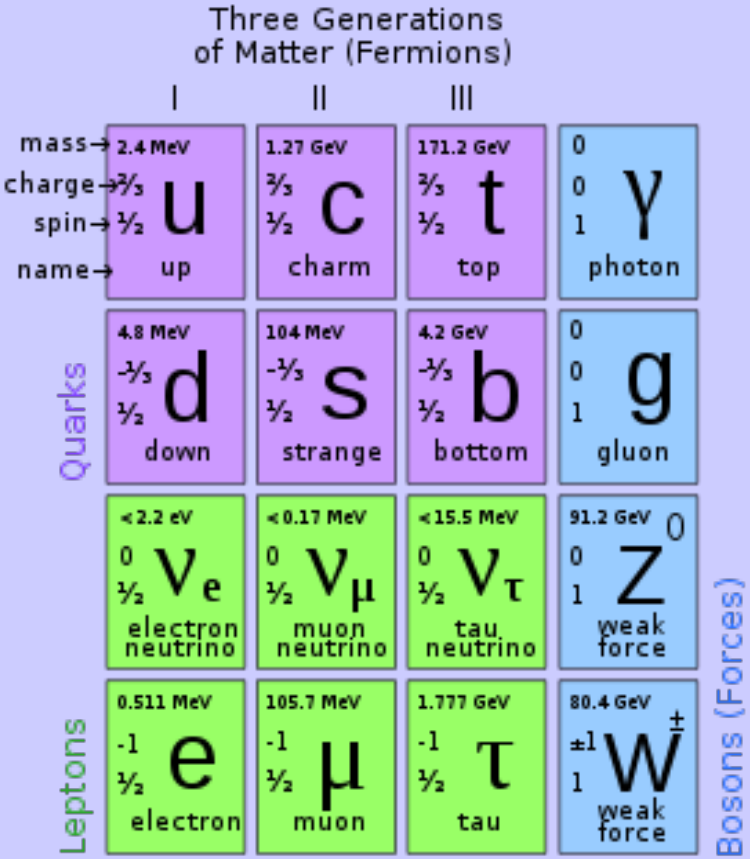
CERN: Beam Pipe

CERN: Detector

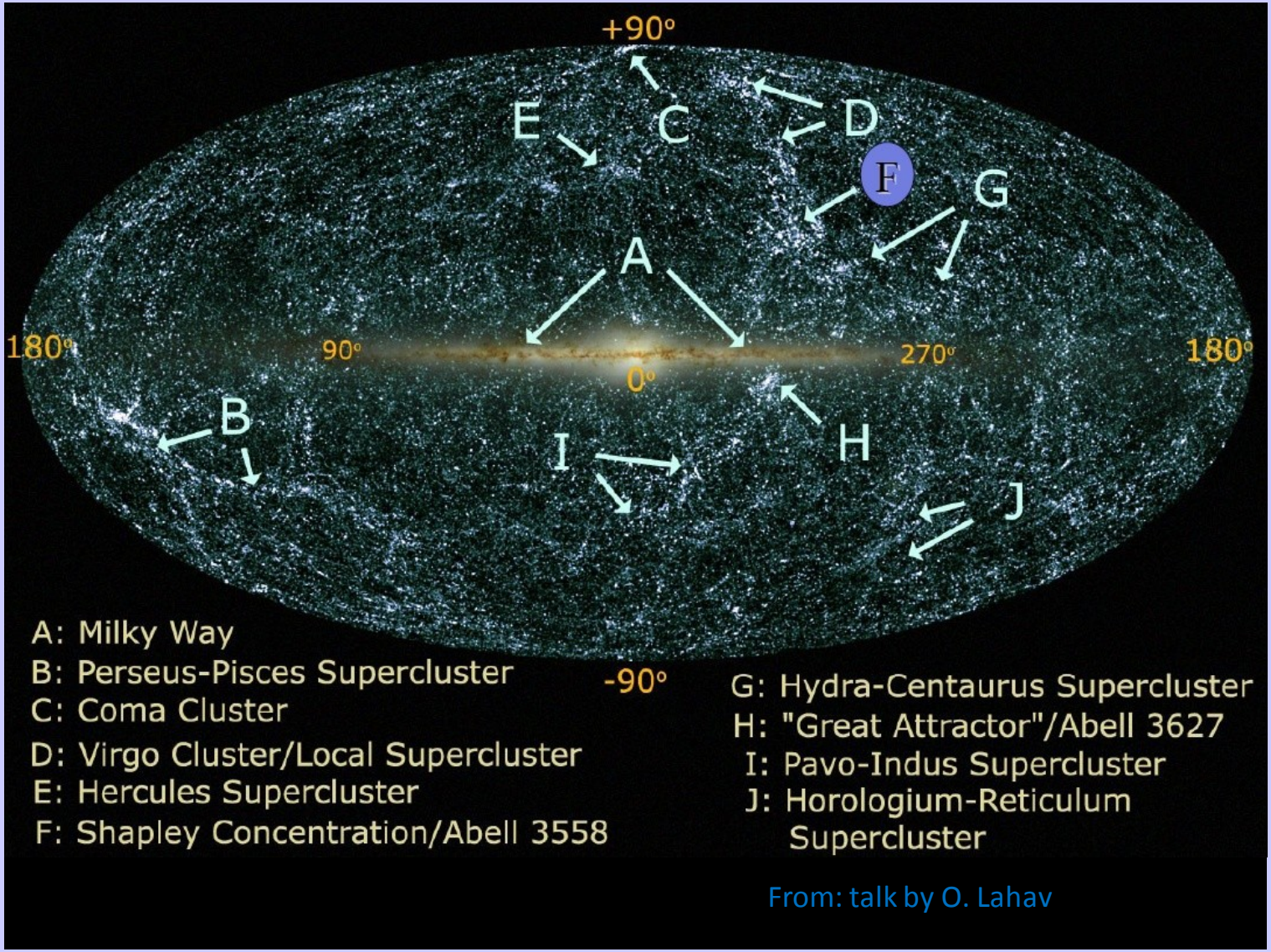


CERN: Director General Fabiola Gianotti

Standard Model of Particle Physics

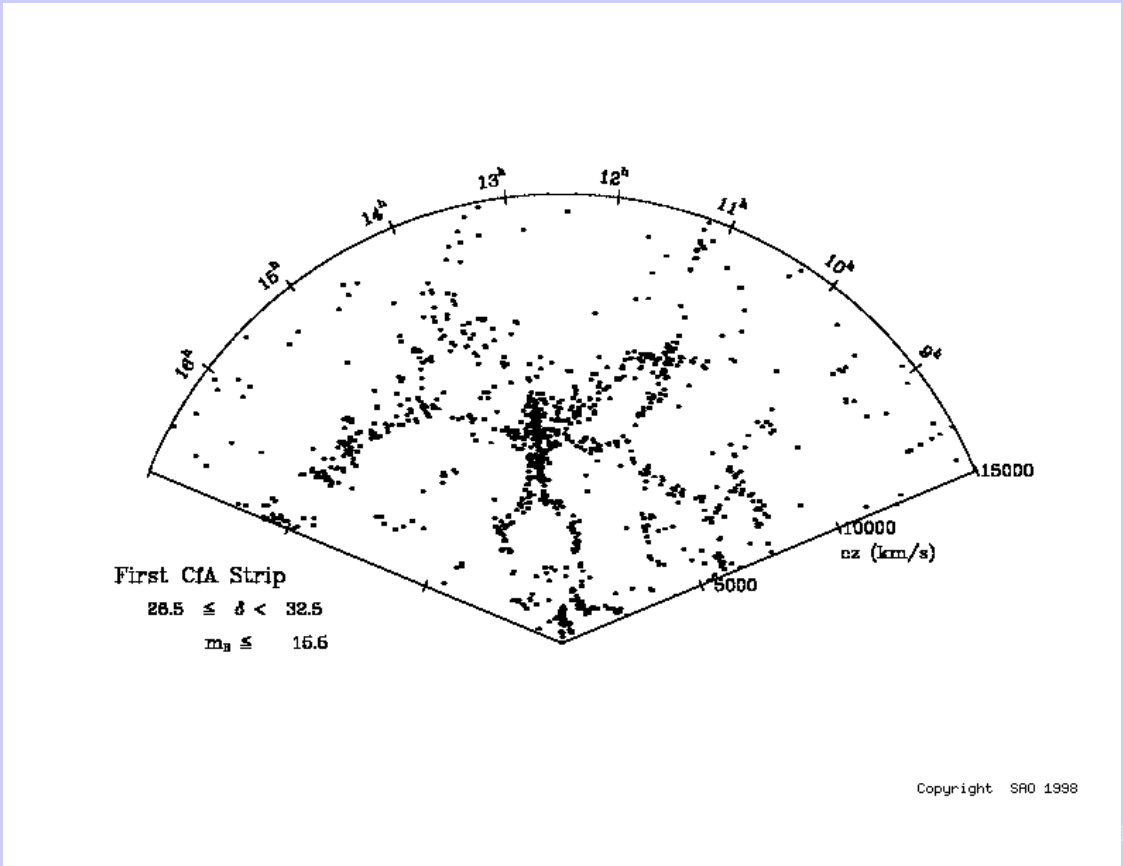


Large-Scale Structure

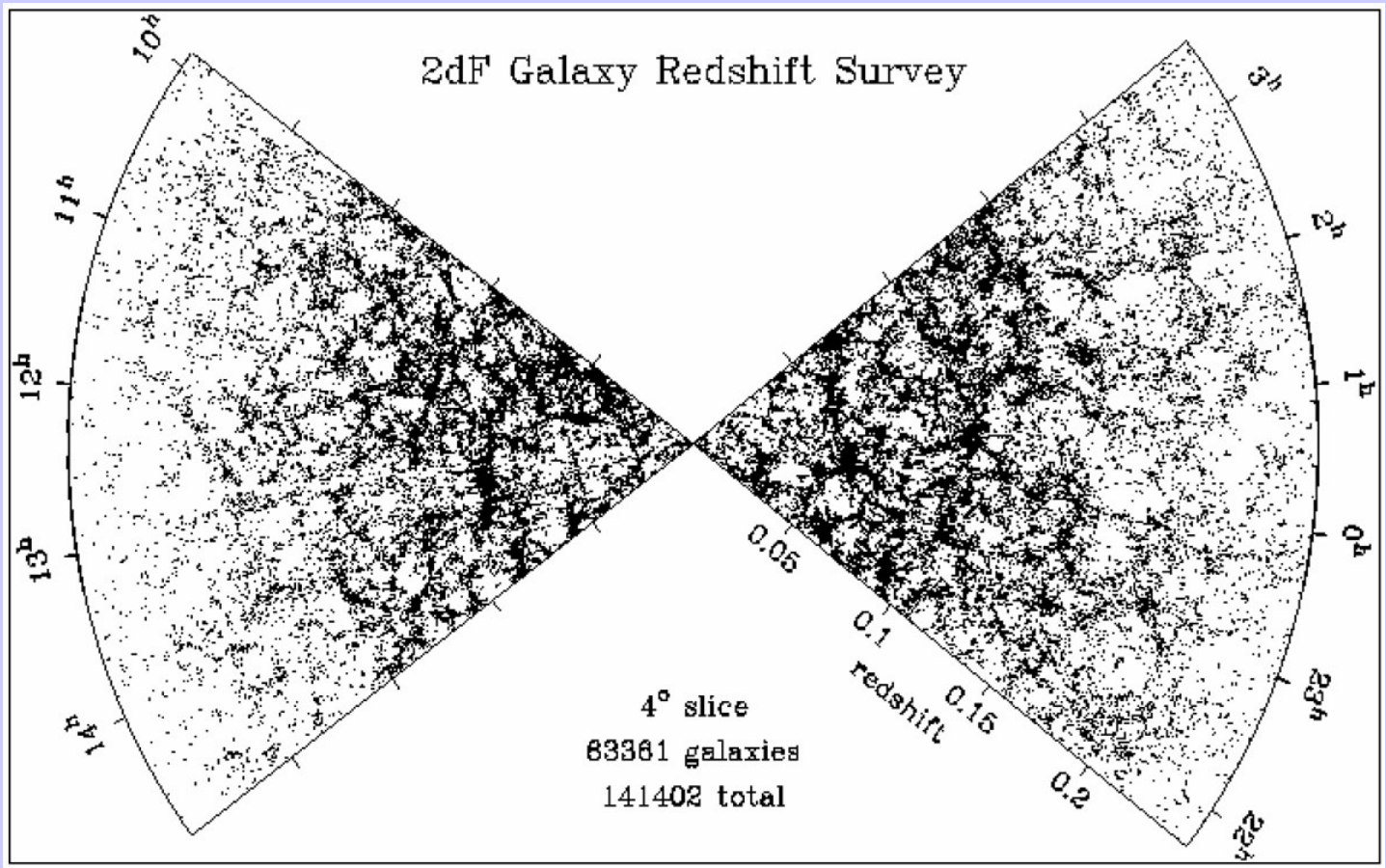


From: talk by O. Lahav

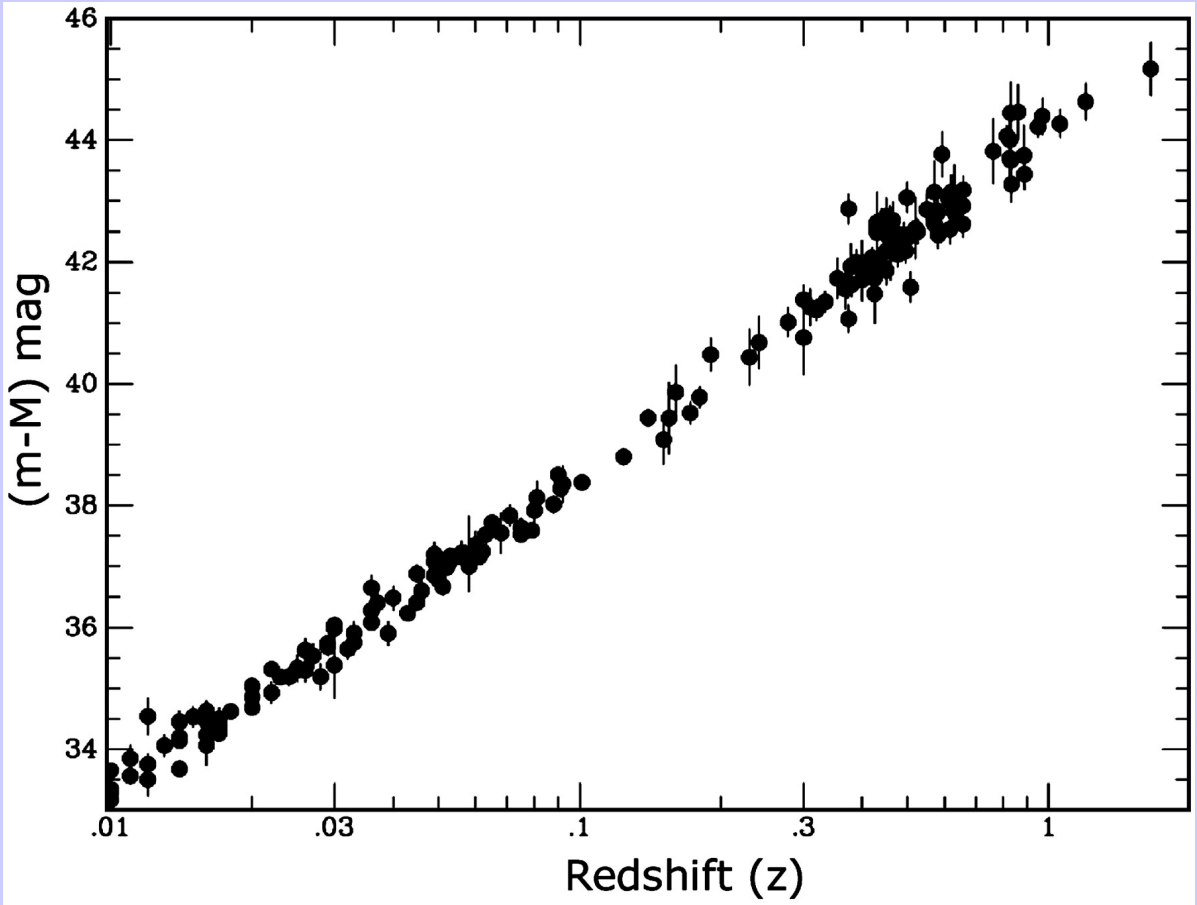
Large-Scale Structure



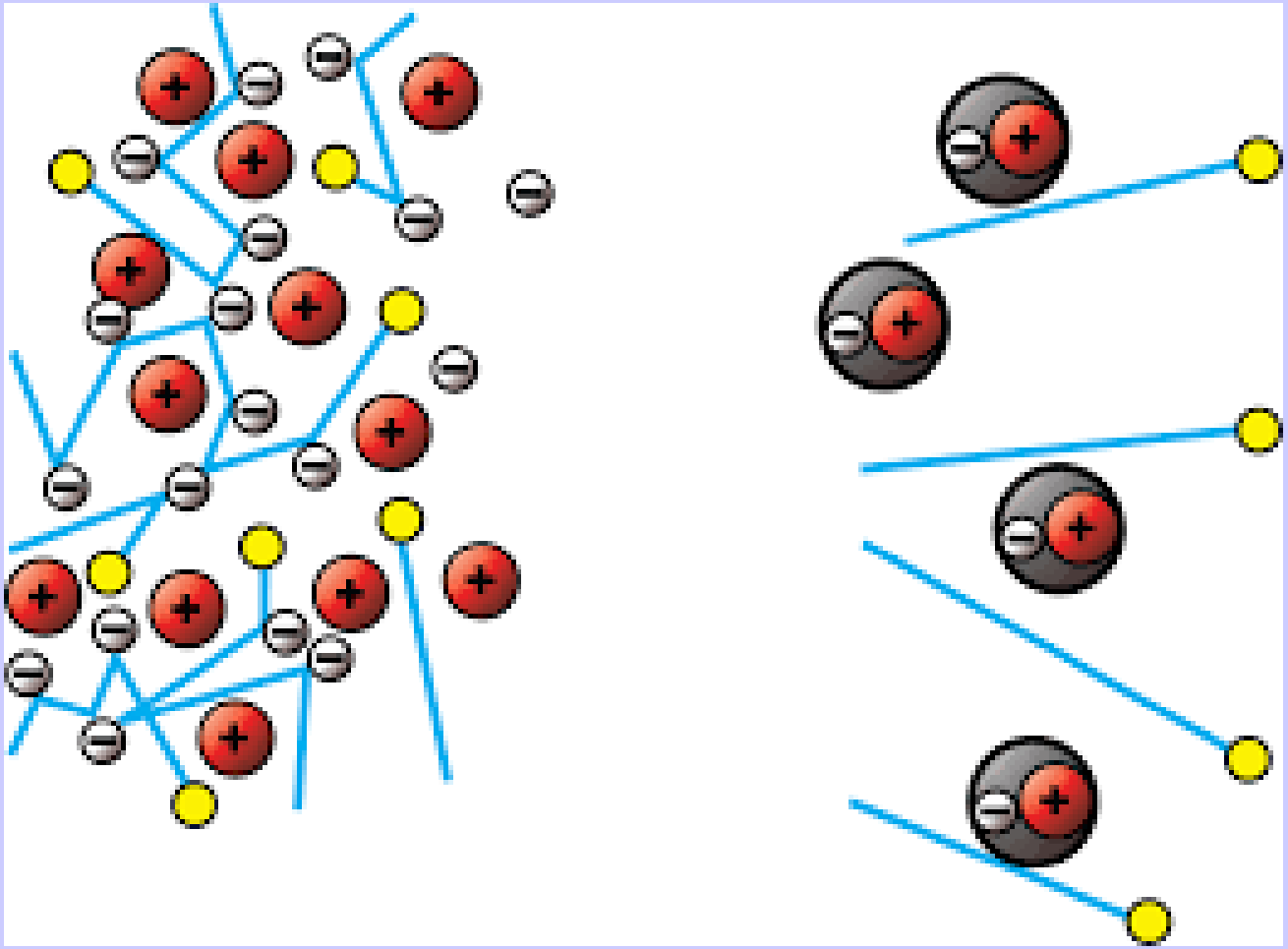
Redshift Survey Results in 2003



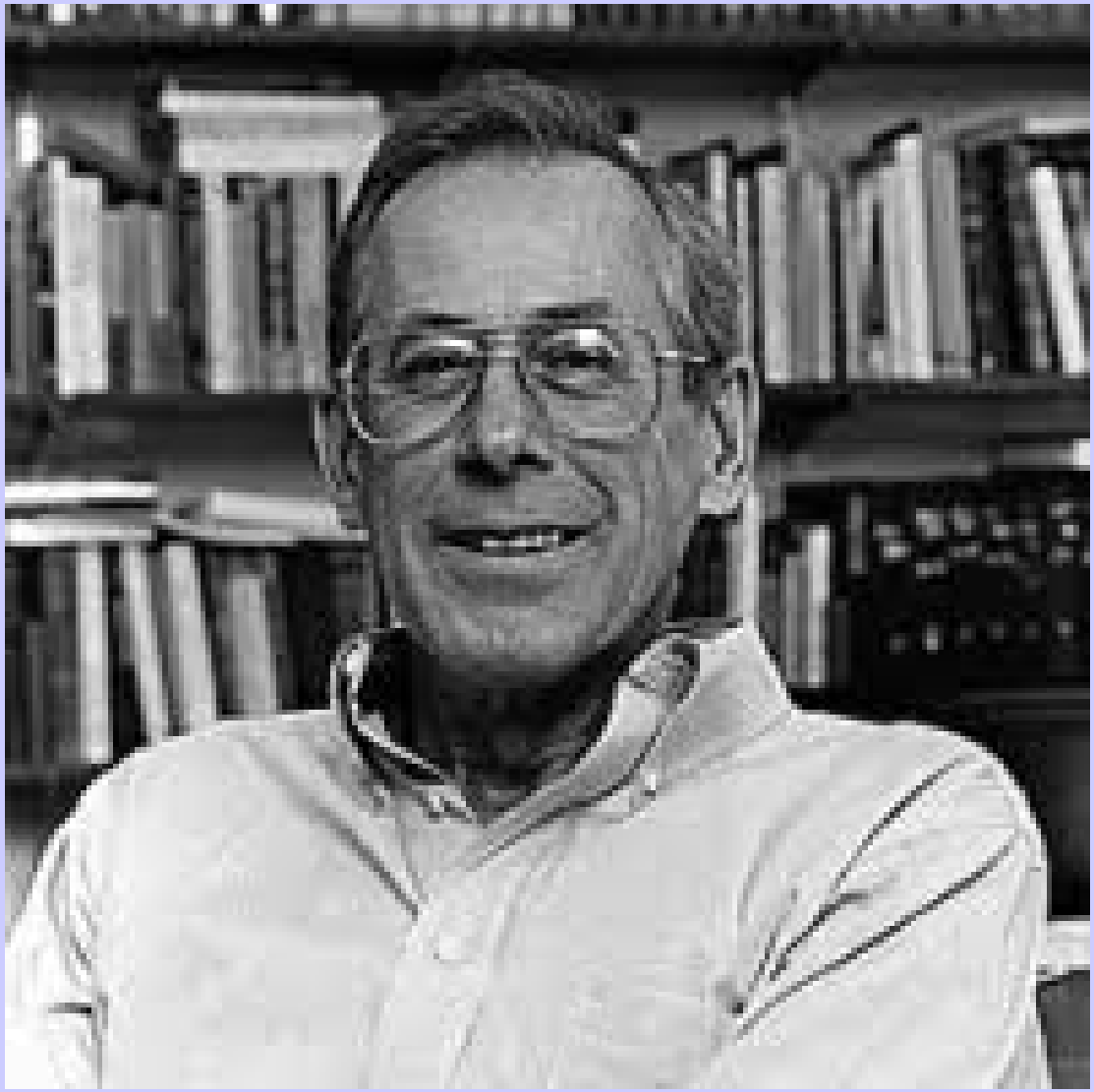
Hubble Law



Recombination



Jim Peebles: Nobel Prize 2019



Prediction of the Cosmic Microwave Background

of the first four interlopers, provided the initial clue to the existence of radio-quiet, blue, quasi-stellar galaxies (QSG) whose optical properties are similar to those of QSS's (Sandage 1965).

Spectrograms were subsequently obtained for BSO 1, BSO 8, and BSO 16 by Schmidt and by Sandage in an attempt to verify the existence of QSG. The spectrum of BSO 16 shows that this object is a hot star having the Balmer lines in absorption near their rest wavelengths. This was expected on the basis of the non-peculiar $U - B$, $B - V$ colors. The spectrum of BSO 8 (called "BSO 105" by Sandage 1965 on an older numbering system) is continuous with no prominent absorption or emission lines. BSO 1 has a large redshift of $\Delta\lambda/\lambda_0 = 1.2410$, as described elsewhere (Sandage 1965).

Table 1 lists the precise optical positions of the first four interlopers, and estimated positions, accurate to perhaps $\pm 20''$, for the thirty-one survey objects. Where available, the colors and magnitudes determined photoelectrically at the 200-inch are also shown.

These blue objects are undoubtedly of the same class as the faint objects in the catalogues of Iriarte and Chavira (1957), Chavira (1958), and Haro and Luyten (1962). With the identification of most of these objects as intrinsically bright stellar-appearing galaxies, these catalogues provide a large finding list that can be surveyed by radio techniques to determine if the QSG's are weak radio emitters. It is expected that such study will shed light on the evolutionary process of radio decay after the intense QSS radio phase.

ALLAN SANDAGE
PHILIPPE VÉRON

May 21, 1965
MOUNT WILSON AND PALOMAR OBSERVATORIES
CARNEGIE INSTITUTION OF WASHINGTON
CALIFORNIA INSTITUTE OF TECHNOLOGY

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Sandage, A. 1965, *Ap. J.*, **141** (in press).

COSMIC BLACK-BODY RADIATION*

One of the basic problems of cosmology is the singularity characteristic of the familiar cosmological solutions of Einstein's field equations. Also puzzling is the presence of matter in excess over antimatter in the universe, for baryons and leptons are thought to be conserved. Thus, in the framework of conventional theory we cannot understand the origin of matter or of the universe. We can distinguish three main attempts to deal with these problems.

1. The assumption of continuous creation (Bondi and Gold 1948; Hoyle 1948), which avoids the singularity by postulating a universe expanding for all time and a continuous but slow creation of new matter in the universe.

2. The assumption (Wheeler 1964) that the creation of new matter is intimately related to the existence of the singularity, and that the resolution of both paradoxes may be found in a proper quantum mechanical treatment of Einstein's field equations.

3. The assumption that the singularity results from a mathematical over-idealization,

* This research was supported in part by the National Science Foundation and the Office of Naval Research of the U.S. Navy.

Prediction of the Cosmic Microwave Background

high pressure, such as the zero-mass scalar, capable of speeding the universe through the period of helium formation. To have a closed space, an energy density of 2×10^{-29} gm/cm^3 is needed. Without a zero-mass scalar, or some other "hard" interaction, the energy could not be in the form of ordinary matter and may be presumed to be gravitational radiation (Wheeler 1958).

One other possibility for closing the universe, with matter providing the energy content of the universe, is the assumption that the universe contains a net electron-type neutrino abundance (in excess of antineutrinos) greatly larger than the nucleon abundance. In this case, if the neutrino abundance were so great that these neutrinos are degenerate, the degeneracy would have forced a negligible equilibrium neutron abundance in the early, highly contracted universe, thus removing the possibility of nuclear reactions leading to helium formation. However, the required ratio of lepton to baryon number must be $> 10^9$.

We deeply appreciate the helpfulness of Drs. Penzias and Wilson of the Bell Telephone Laboratories, Crawford Hill, Holmdel, New Jersey, in discussing with us the result of their measurements and in showing us their receiving system. We are also grateful for several helpful suggestions of Professor J. A. Wheeler.

R. H. Dicke
P. J. E. Peebles
P. G. Roll
D. T. Wilkinson

May 7, 1965
Palmer Physical Laboratory
Princeton, New Jersey

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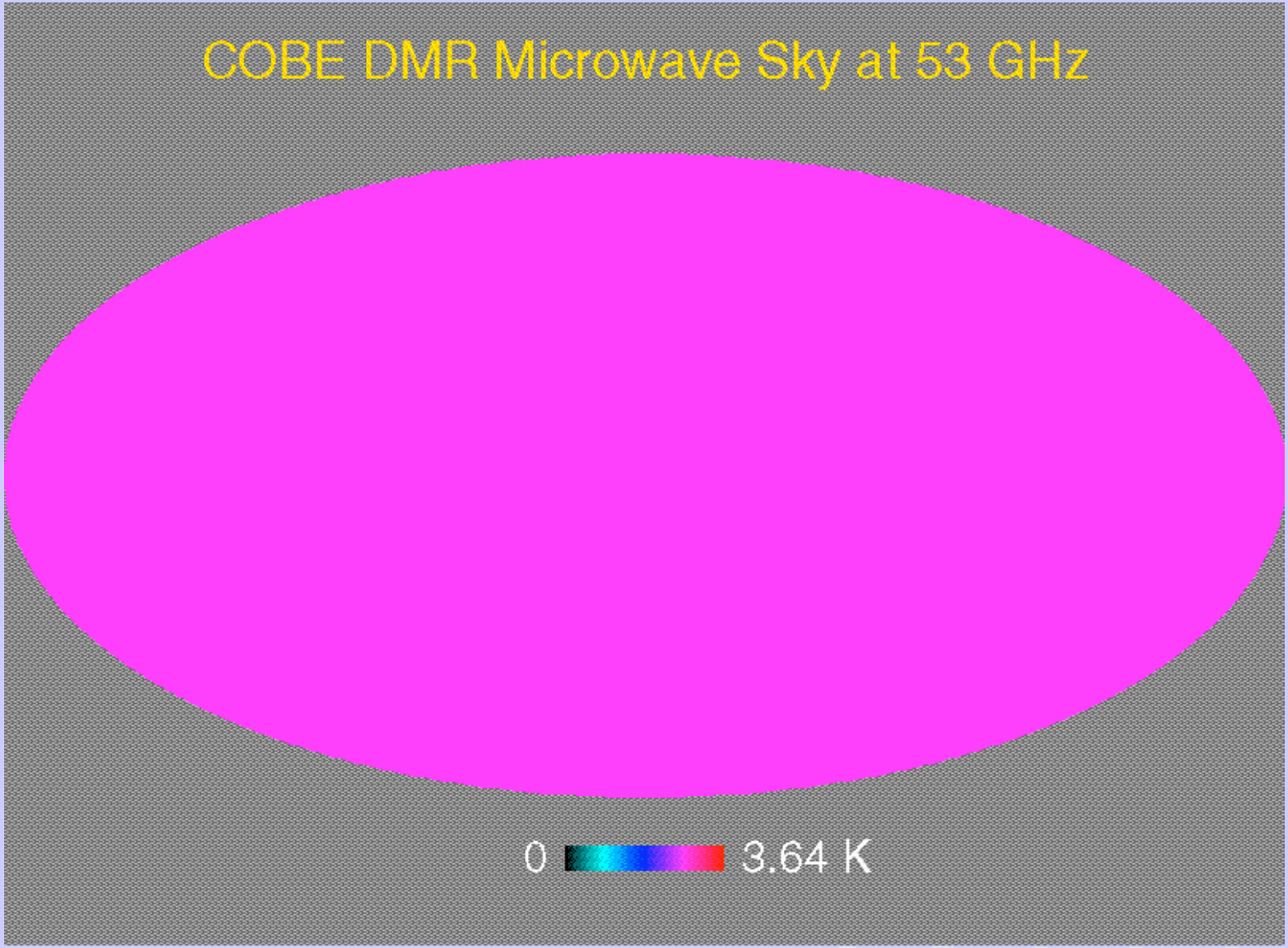
A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

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

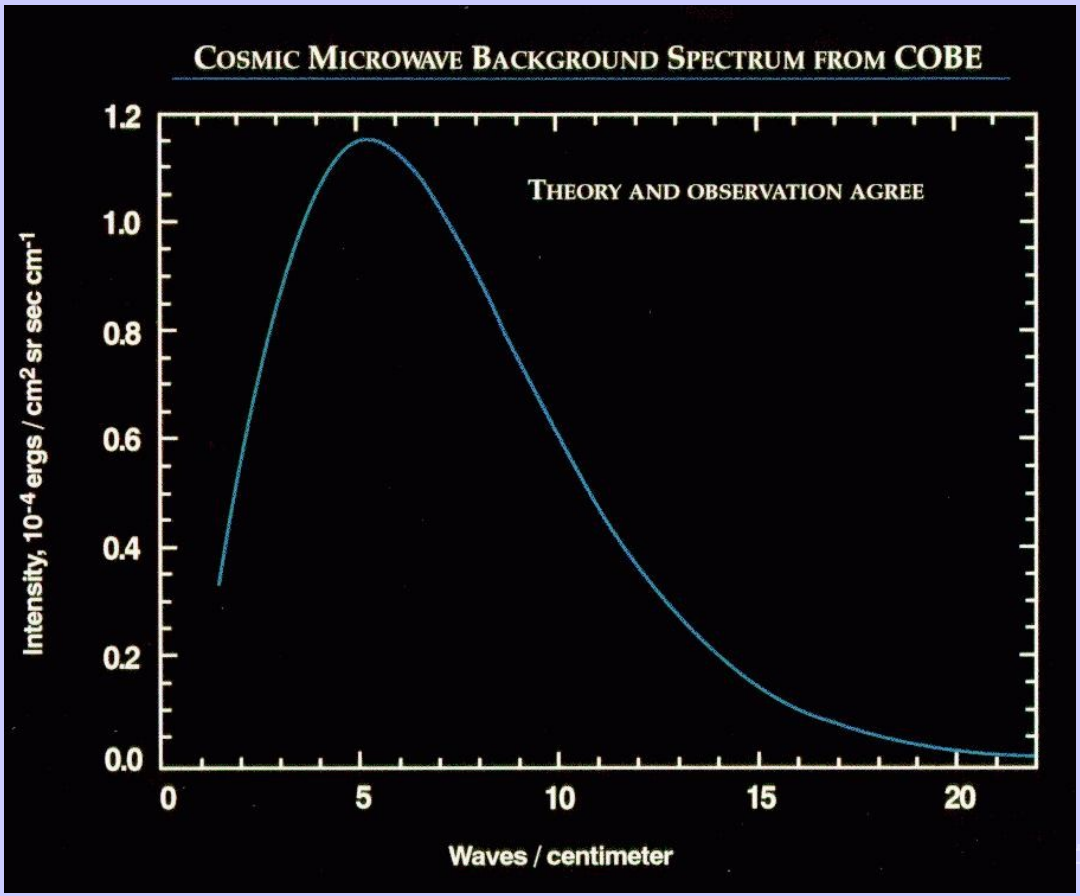
Penzias & Wilson page

Discovery of the Cosmic Microwave Background

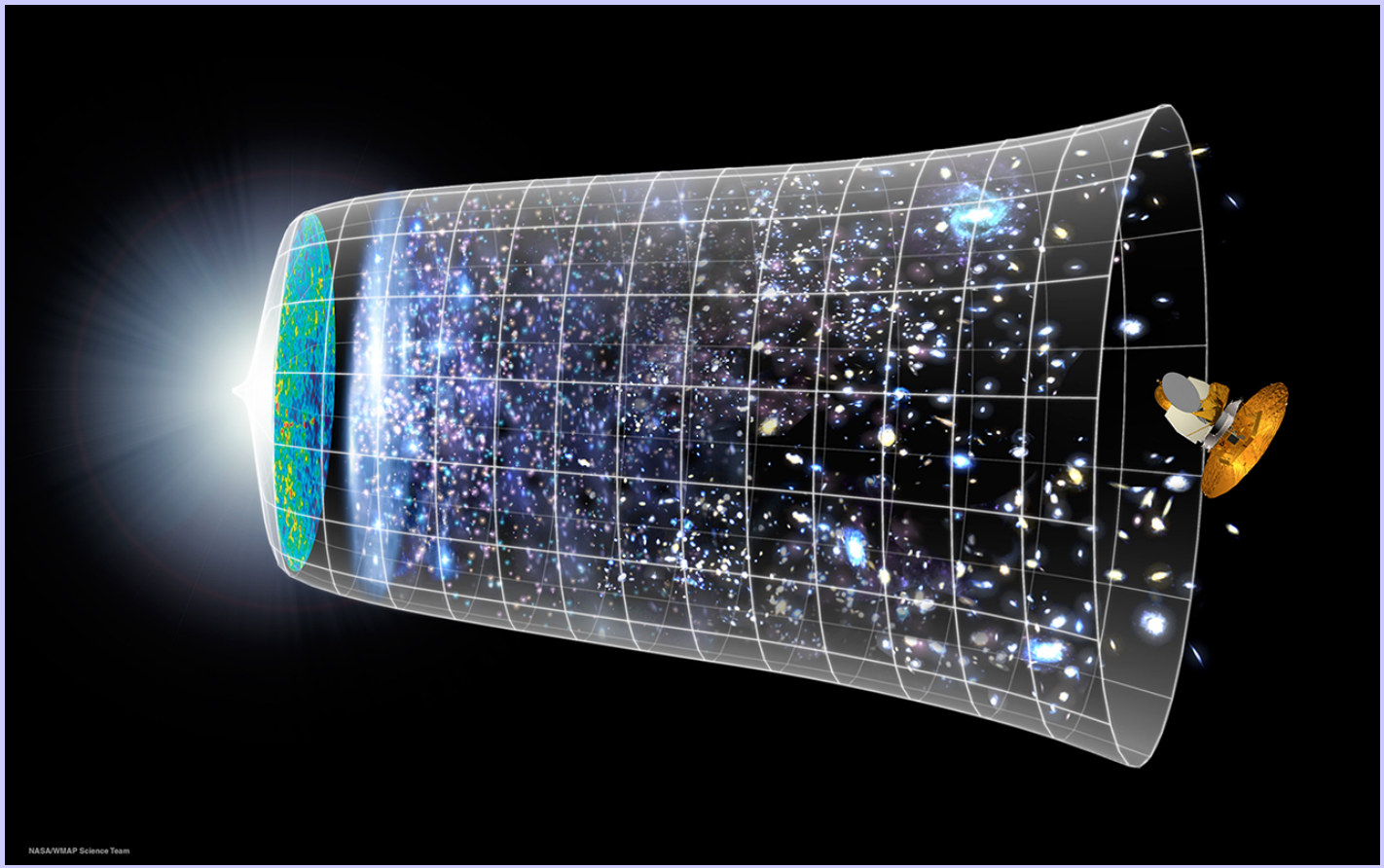
Map of the Cosmic Microwave Background (CMB)



Spectrum of the CMB

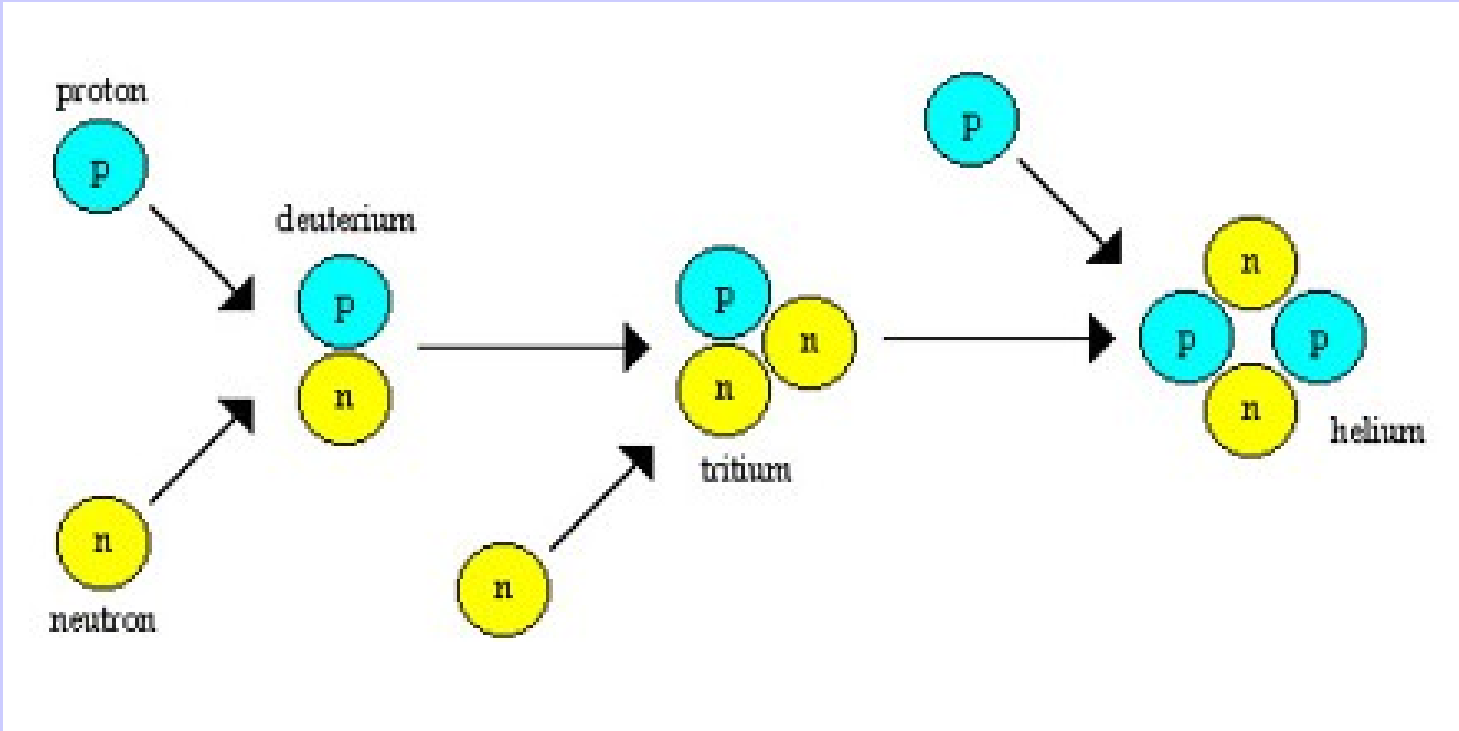


Time Line: Big Bang Cosmology

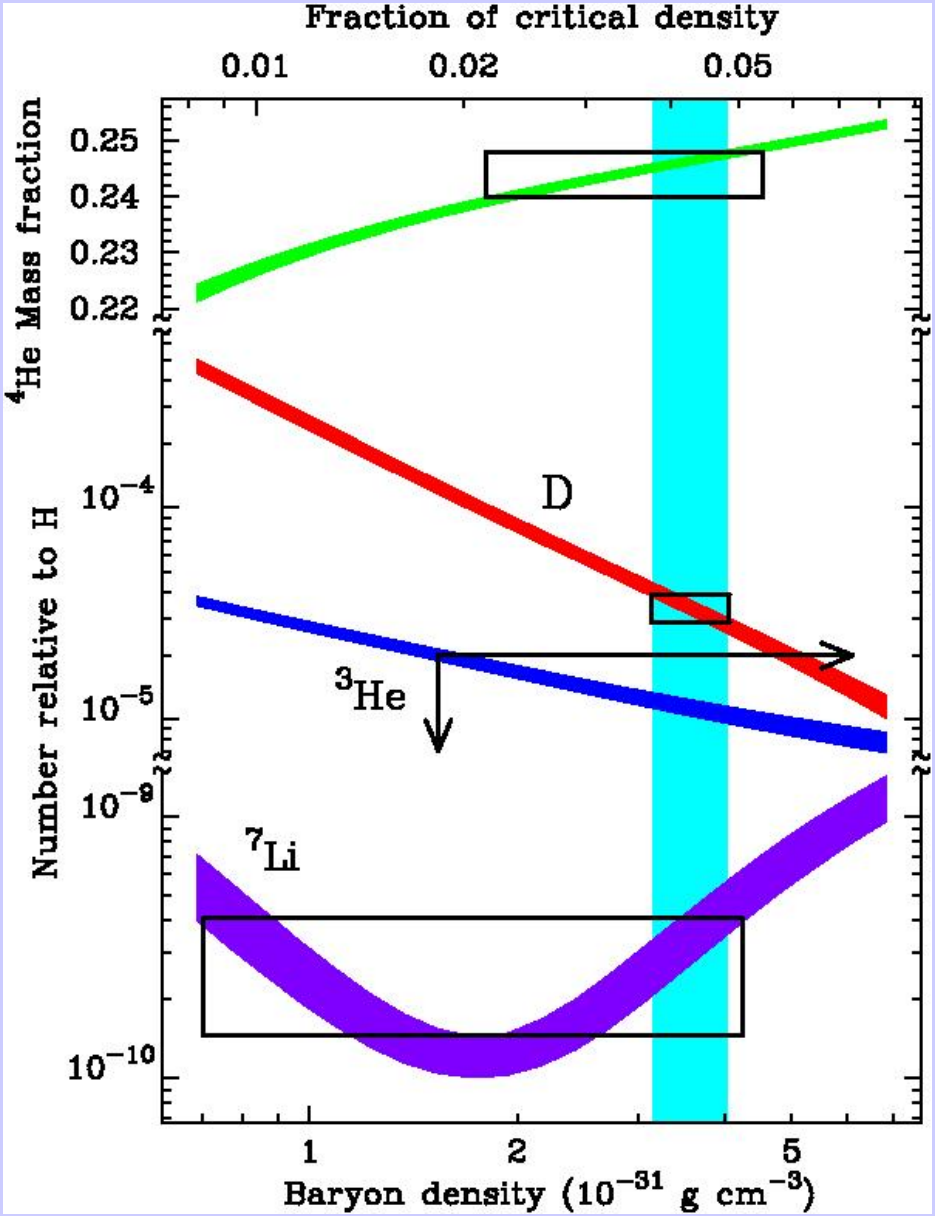


Credit: NASA/WMAP Science Team

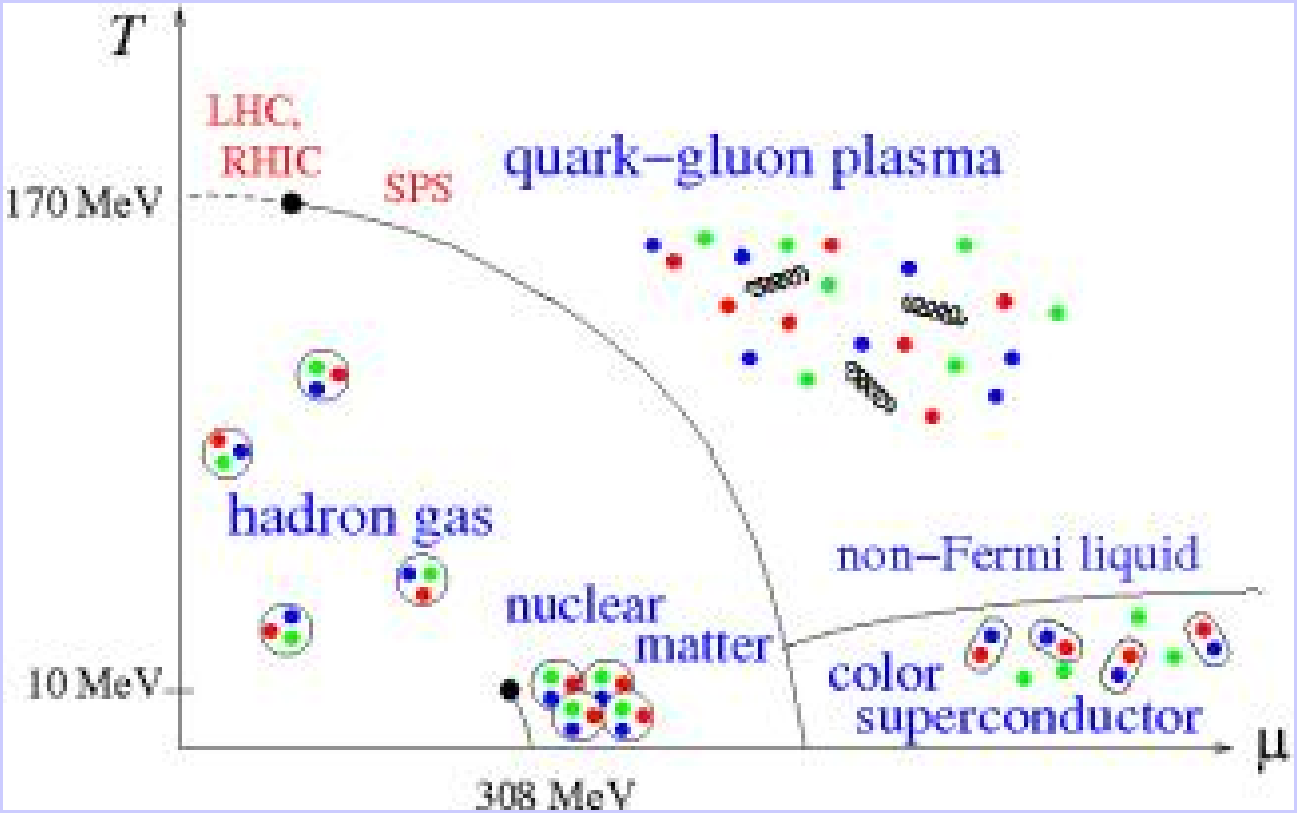
Nucleosynthesis



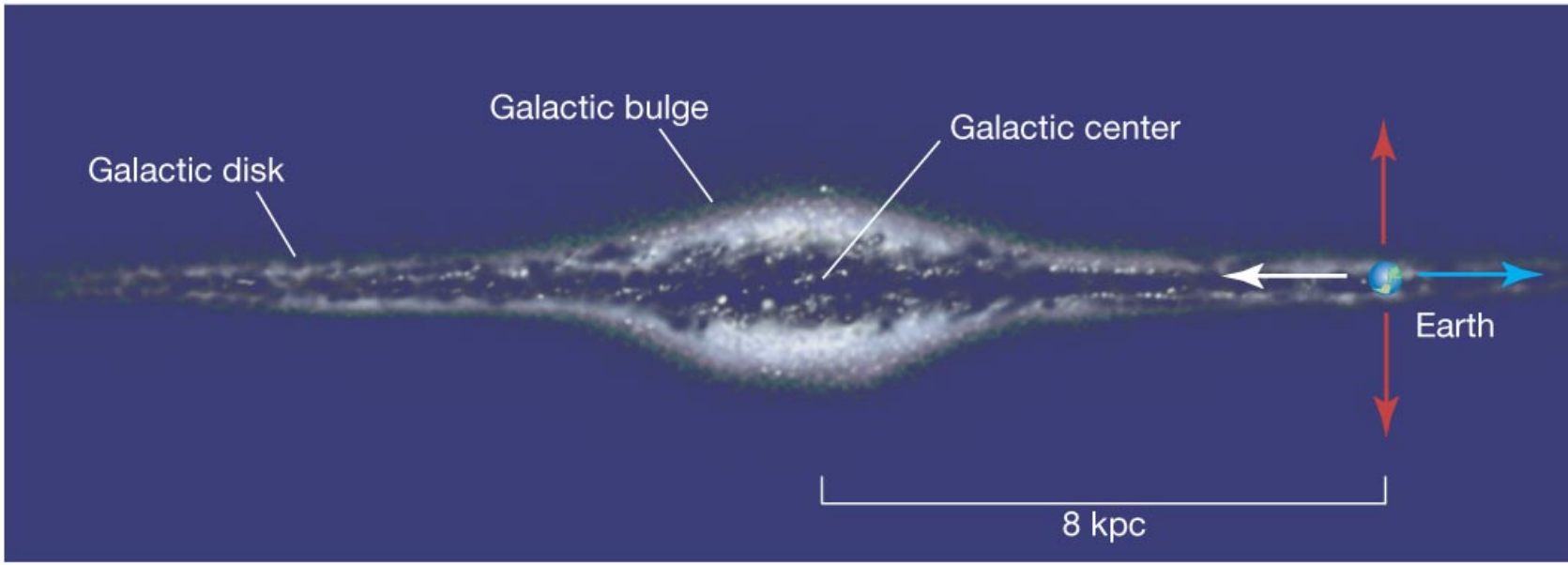
Nucleosynthesis: Predictions vs. Observations



Quark-Gluon Phase Transition

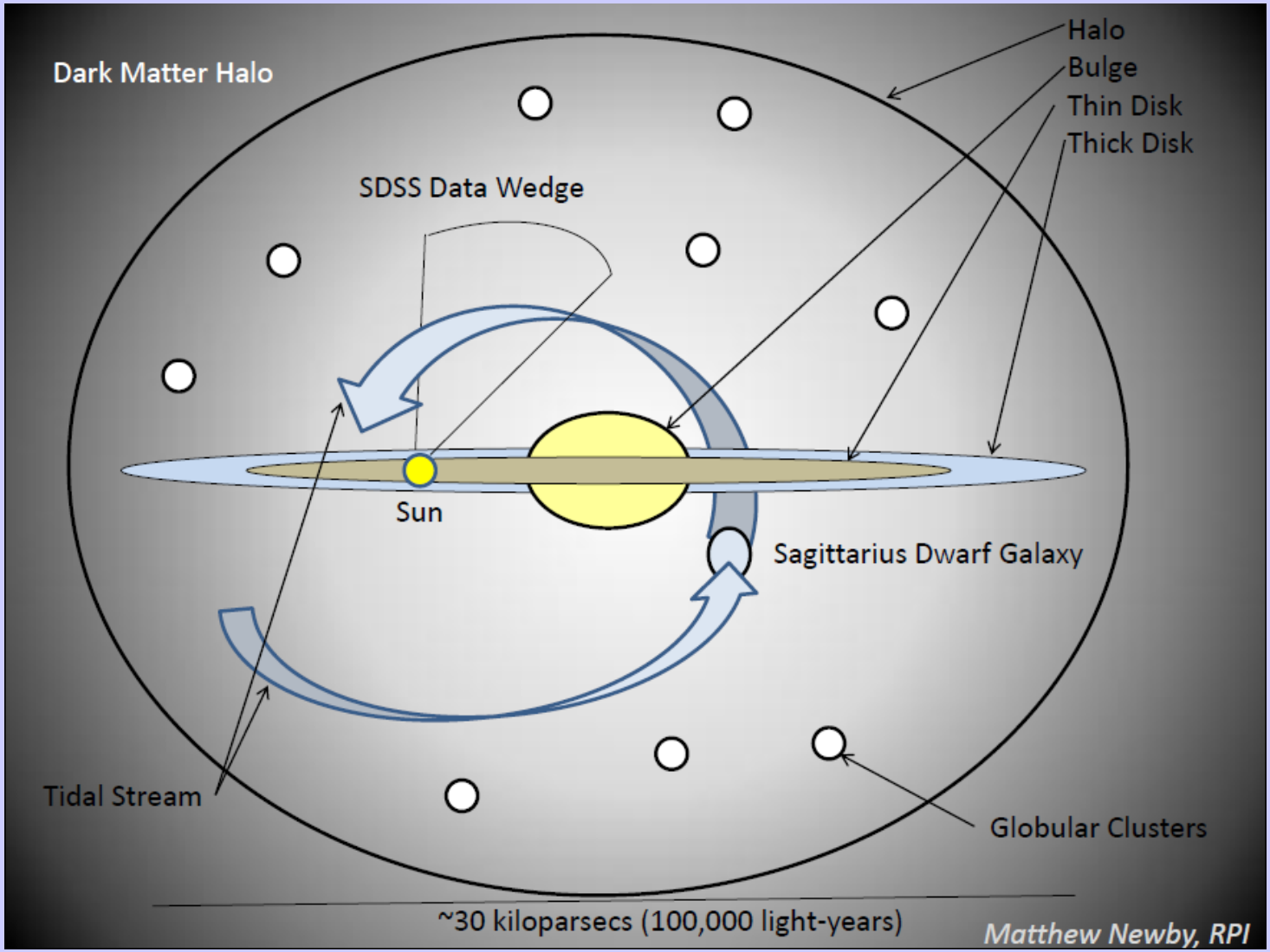


Side View of the Milky Way Galaxy



(a) Artist's view of Milky Way from afar

Structure of the Milky Way Galaxy



Galaxy Rotation Velocity

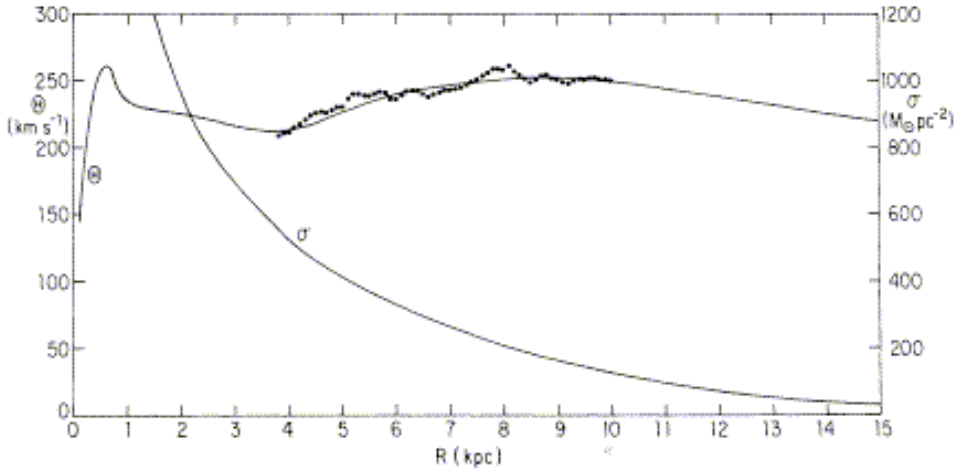
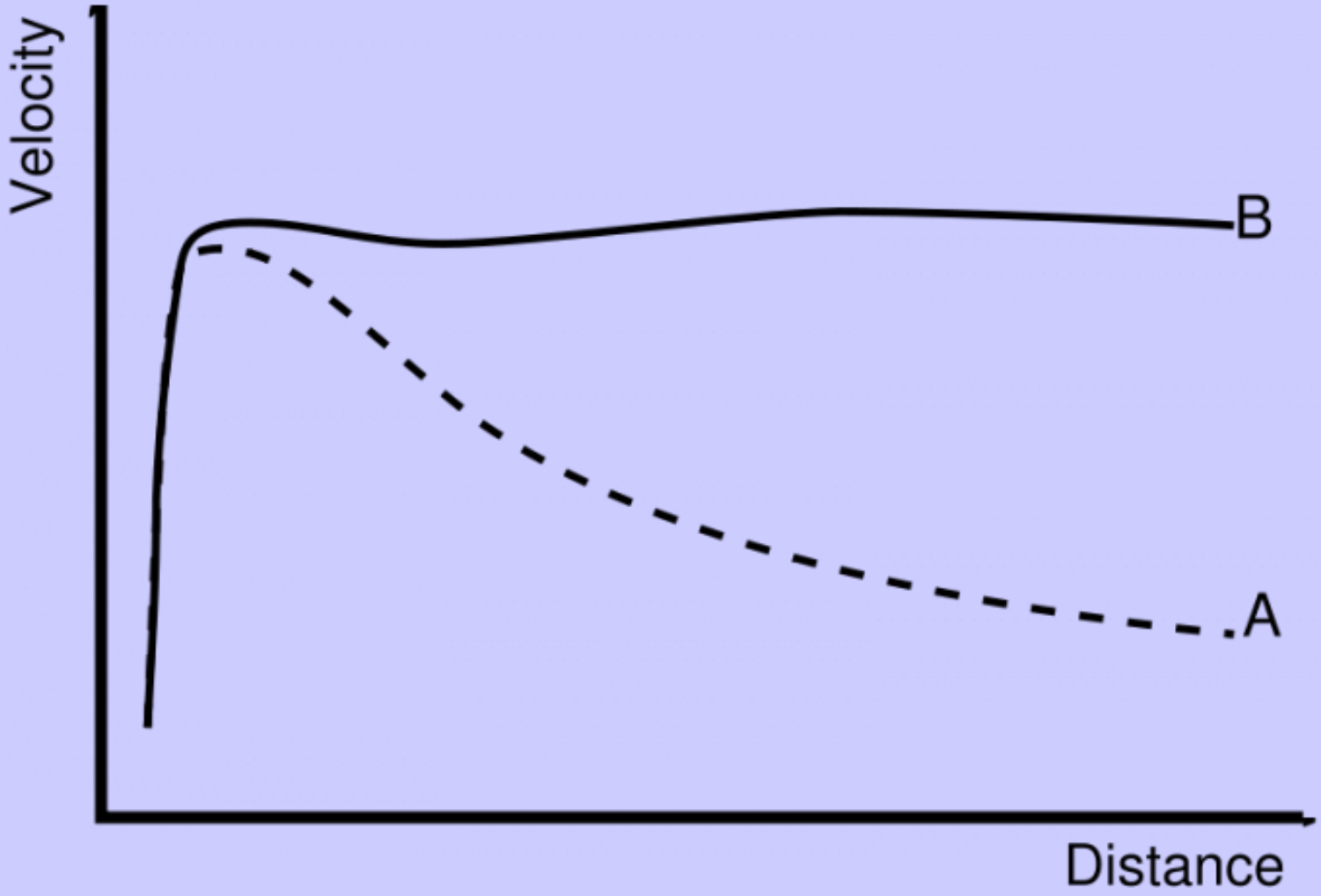


Figure 2 Variation with distance from the galactic center of the linear velocity of differential rotation, $\Theta(R)$, according to Simonson & Mader (1973) at $R < 5$ kpc and according to Schmidt (1965) at $R > 5$ kpc, and of the corresponding total galactic mass surface density, $\sigma(R)$, according to Innanen (1973). The dots show the rotational velocities found from H I observations of the subcentral-point region by Shane & Bieger-Smith (1966).

Galaxy Rotation Velocity



Galaxy Rotation Velocity

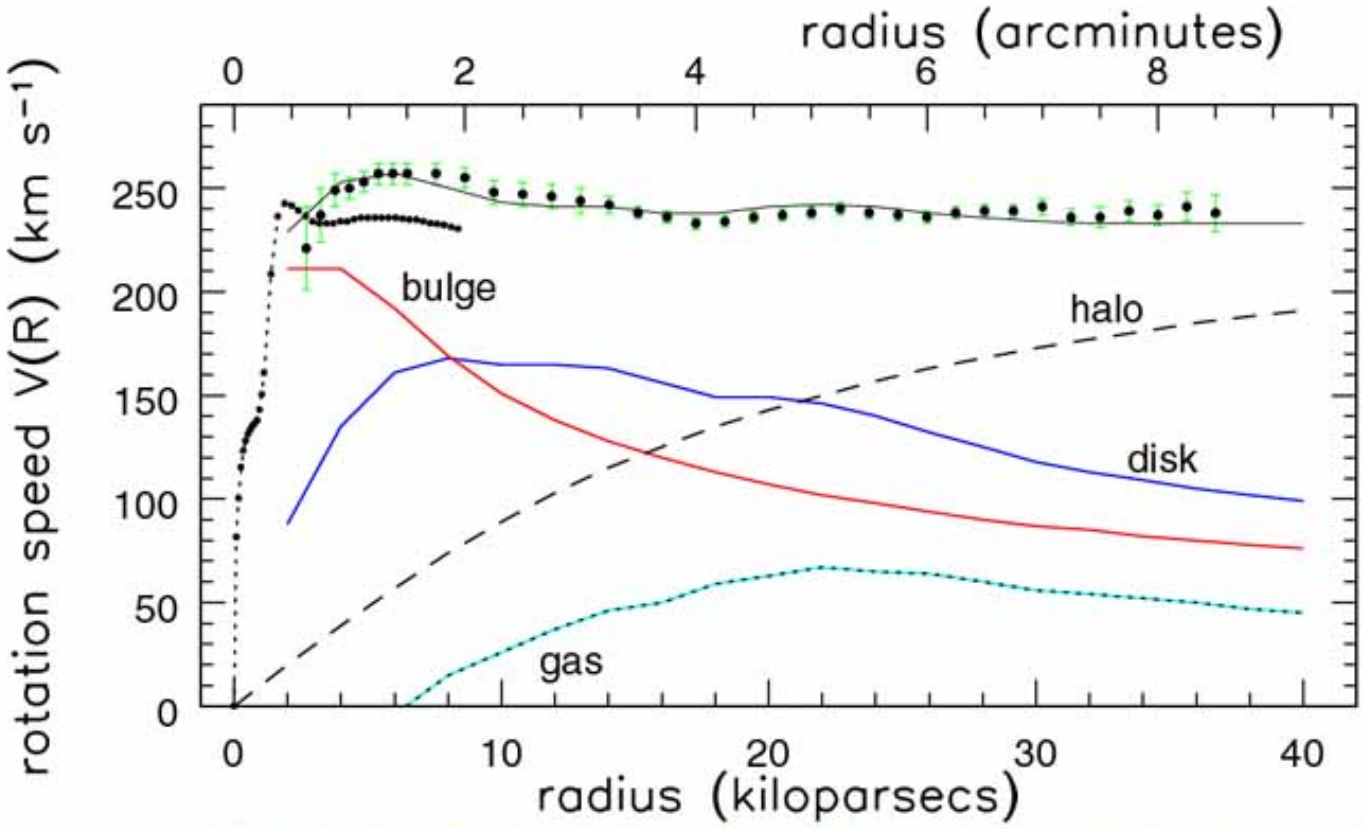
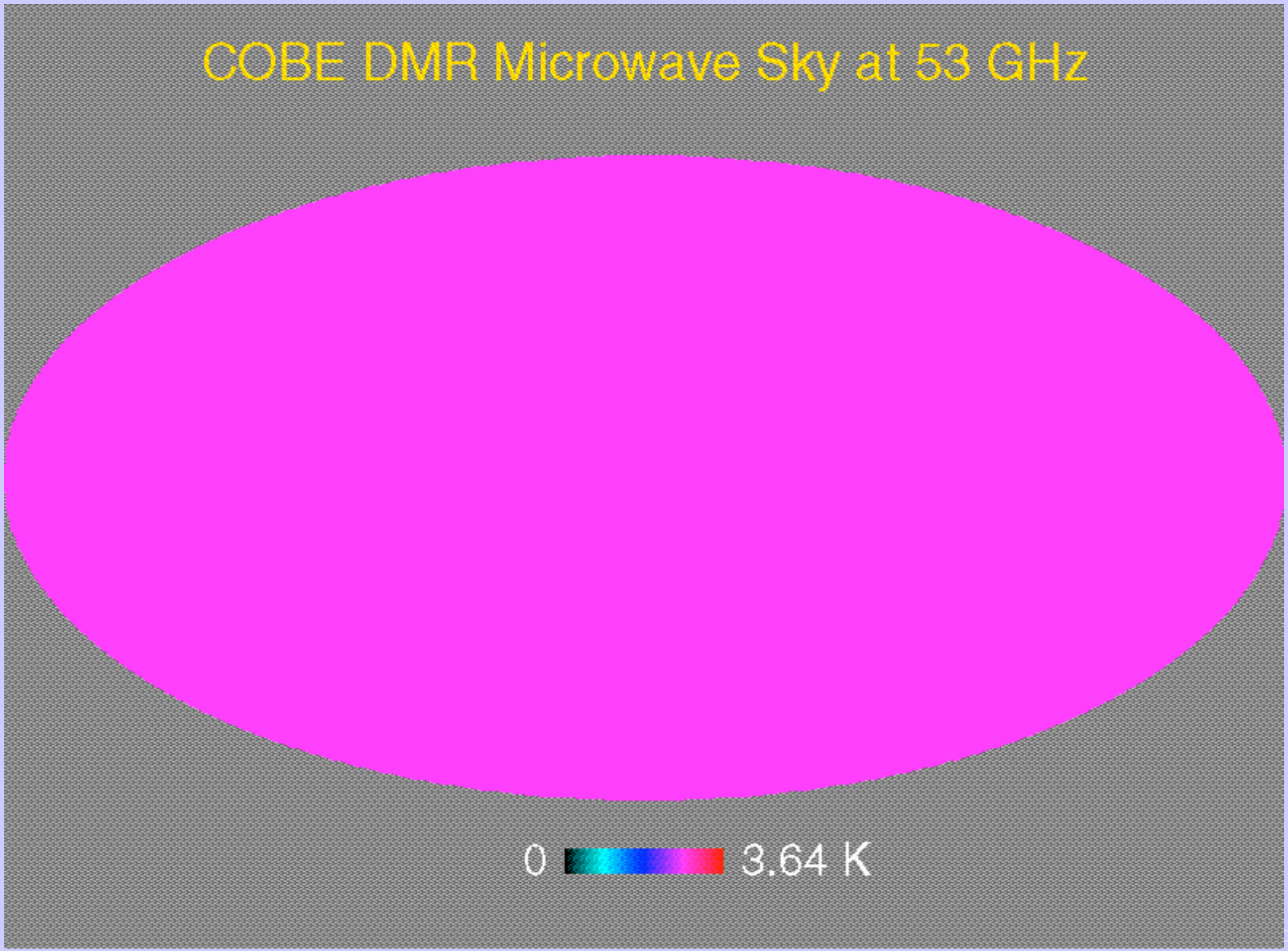
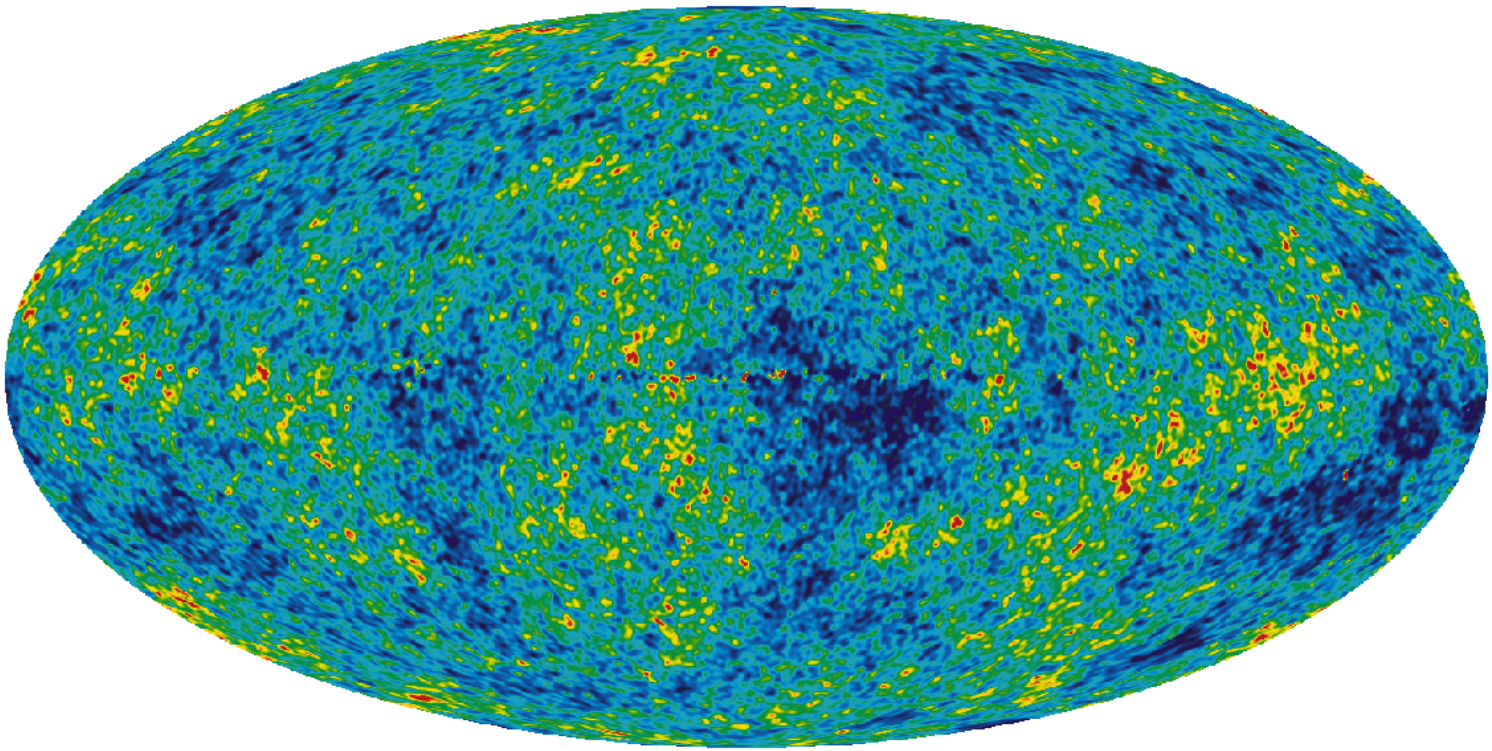


Fig 5.20 (Begeman, Sofue) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

CMB Background

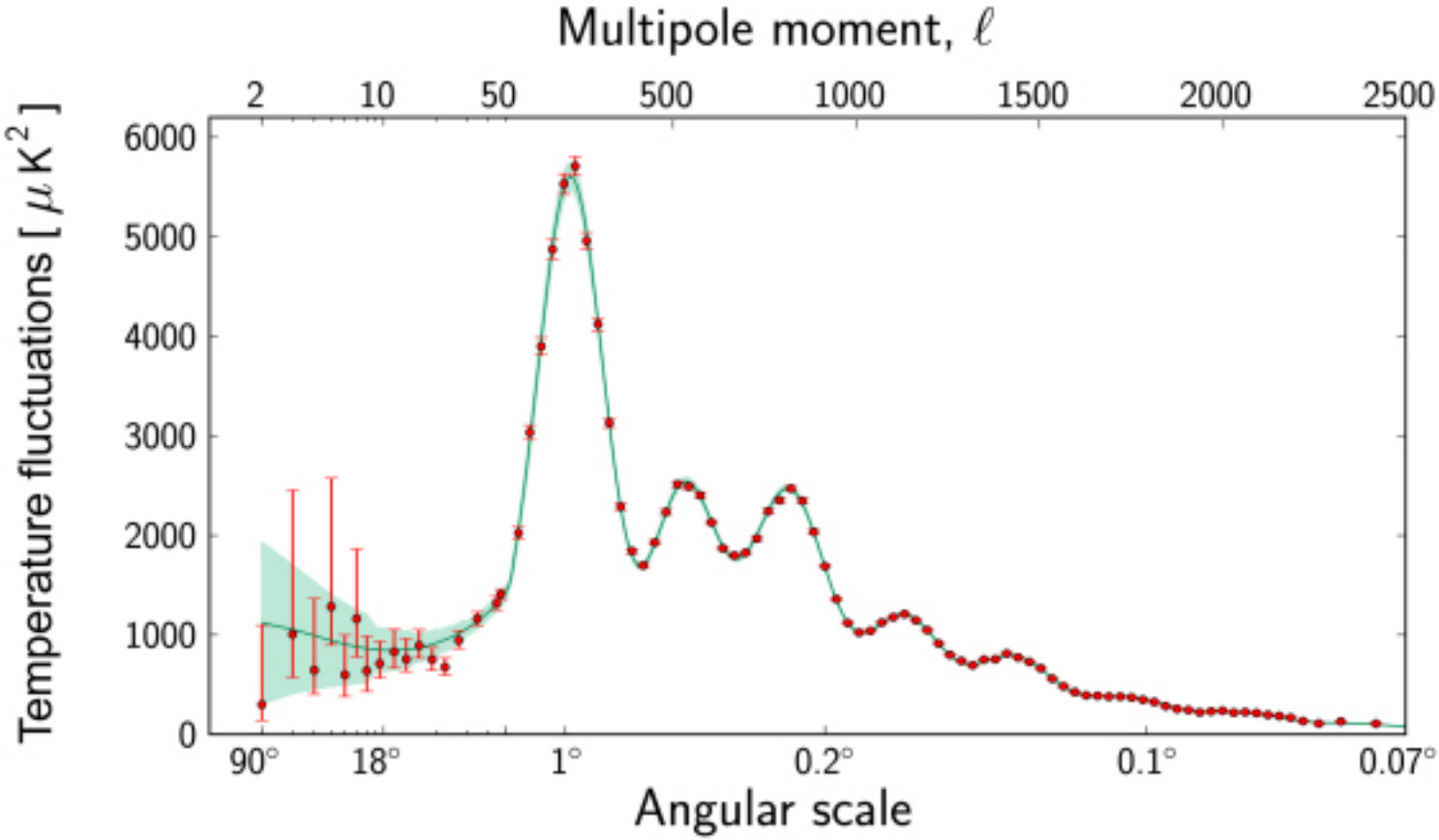


Anisotropies in the Cosmic Microwave Background (CMB)

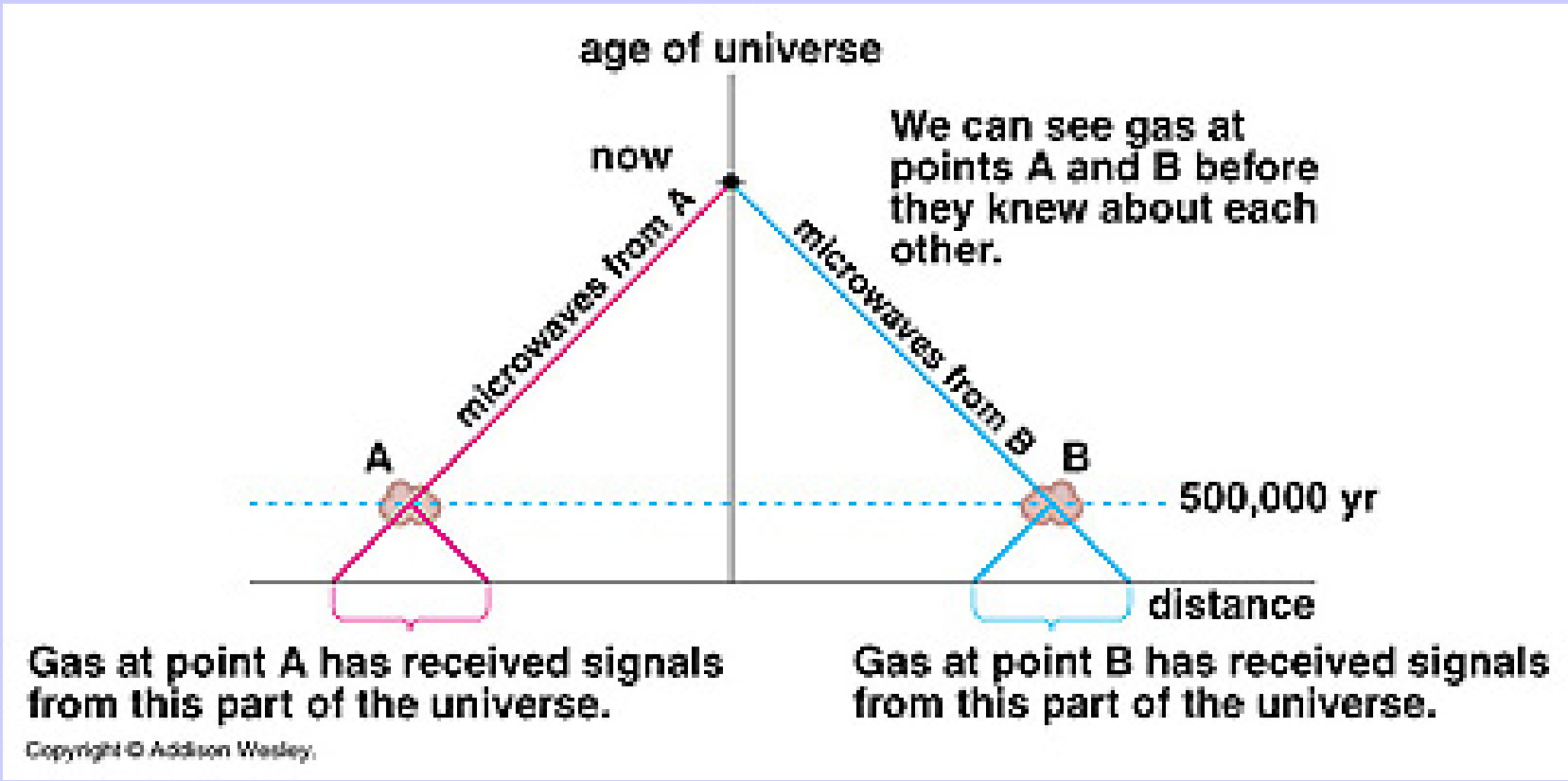


Credit: NASA/WMAP Science Team

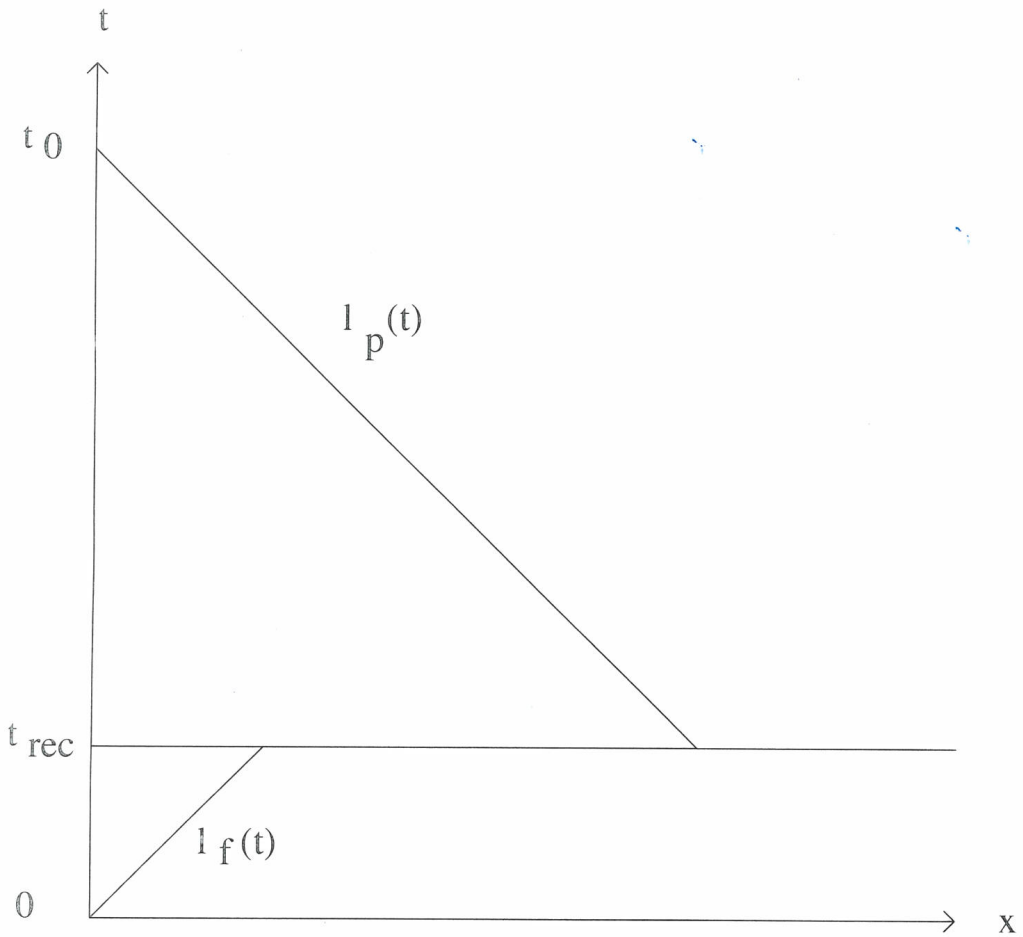
Microwave Anisotropies



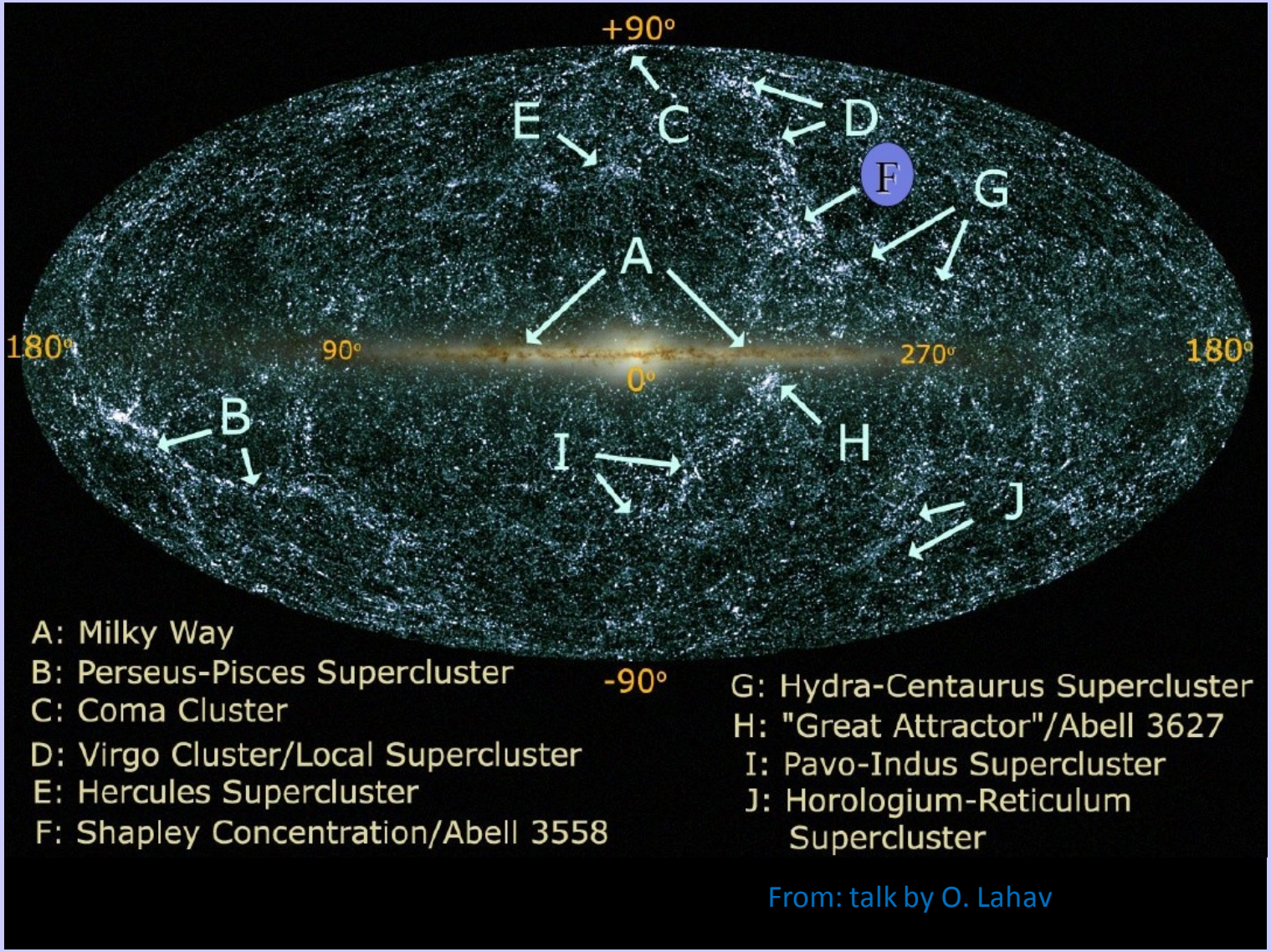
Horizon Problem



Horizon Problem

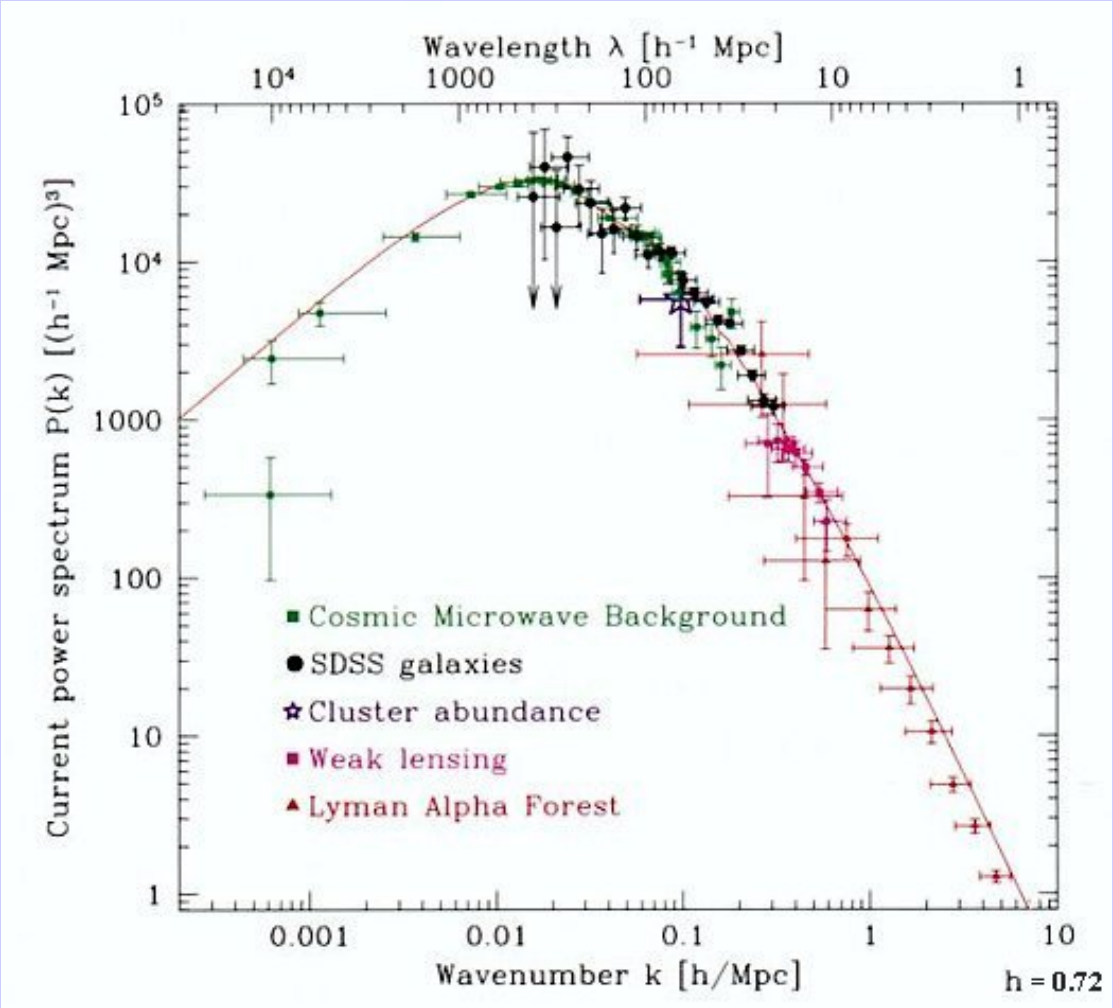


Large-Scale Structure

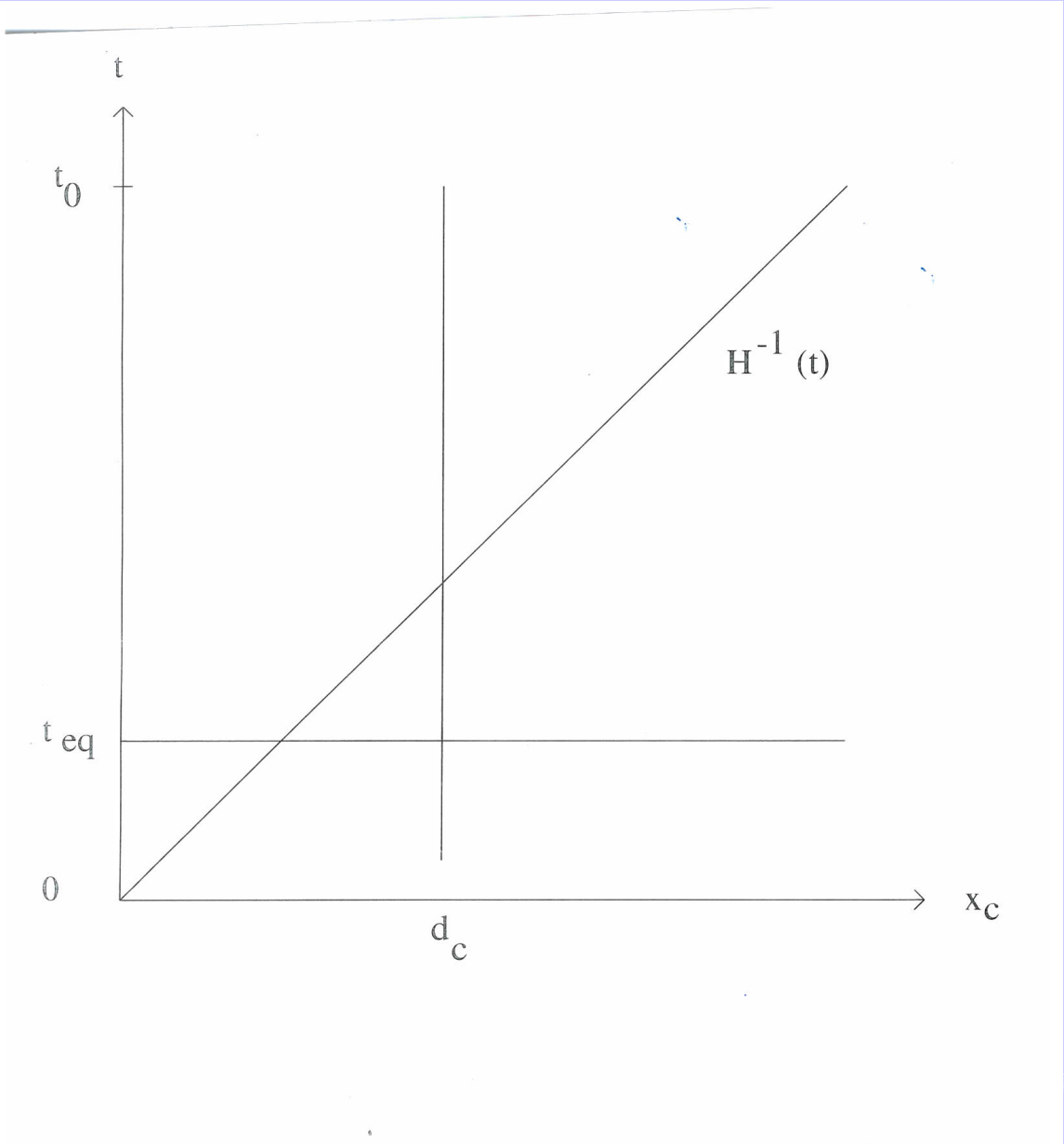


From: talk by O. Lahav

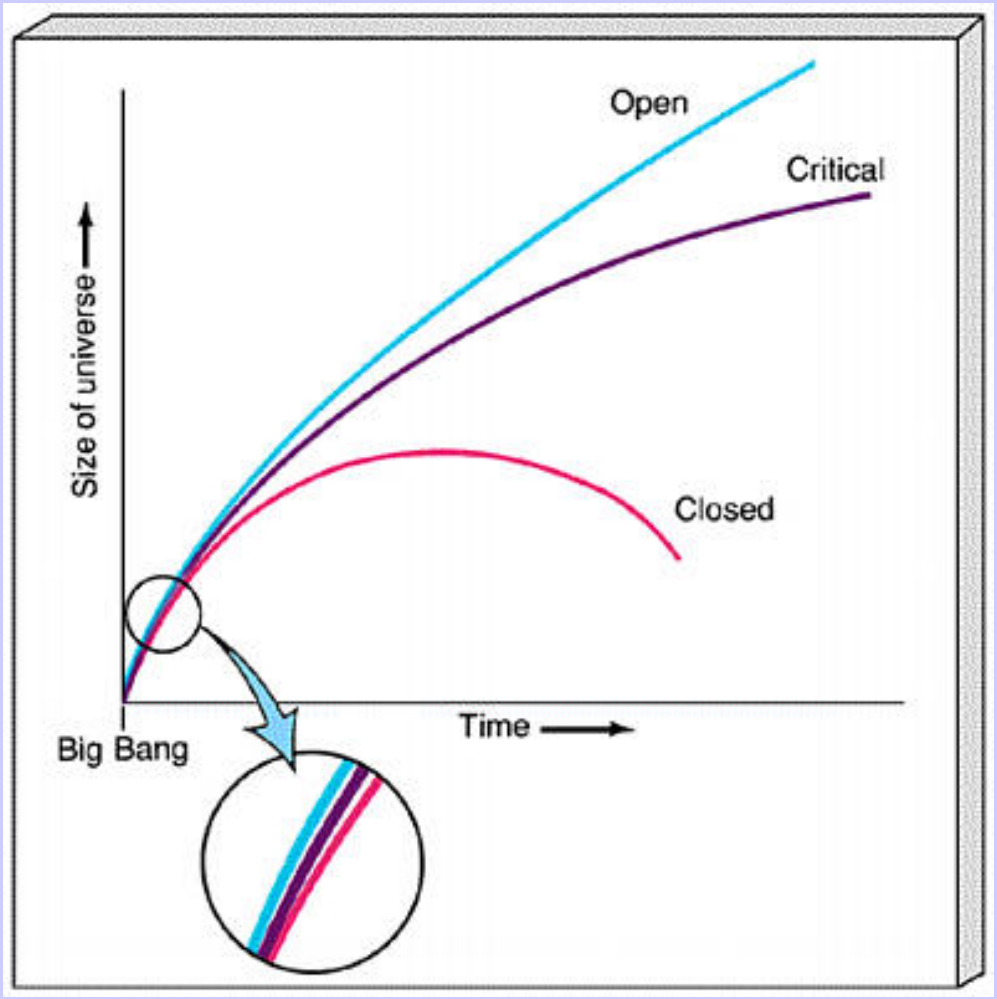
Cosmological Density Fluctuations



Structure Formation Problem



Flatness Problem



Flatness Problem