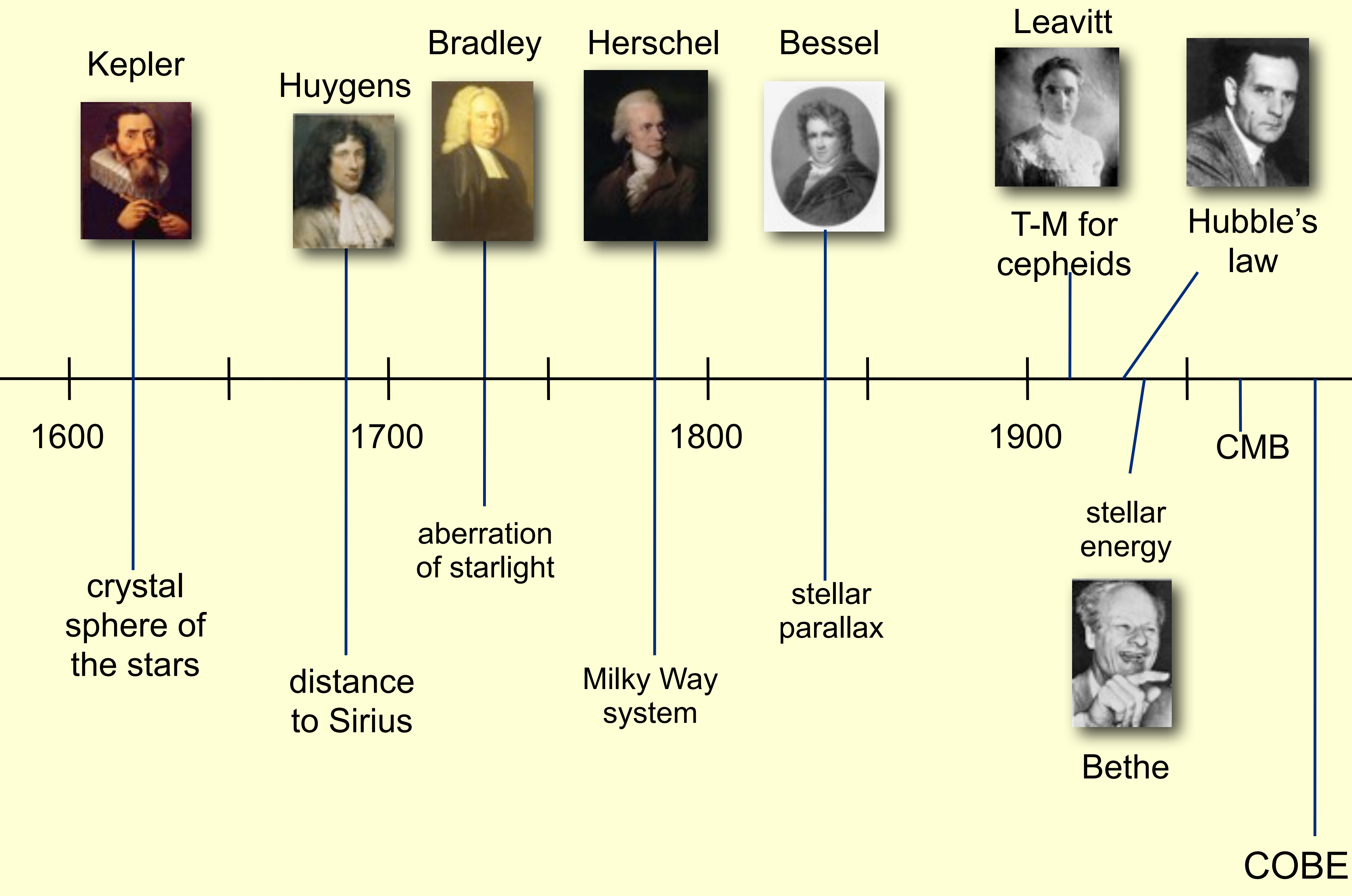
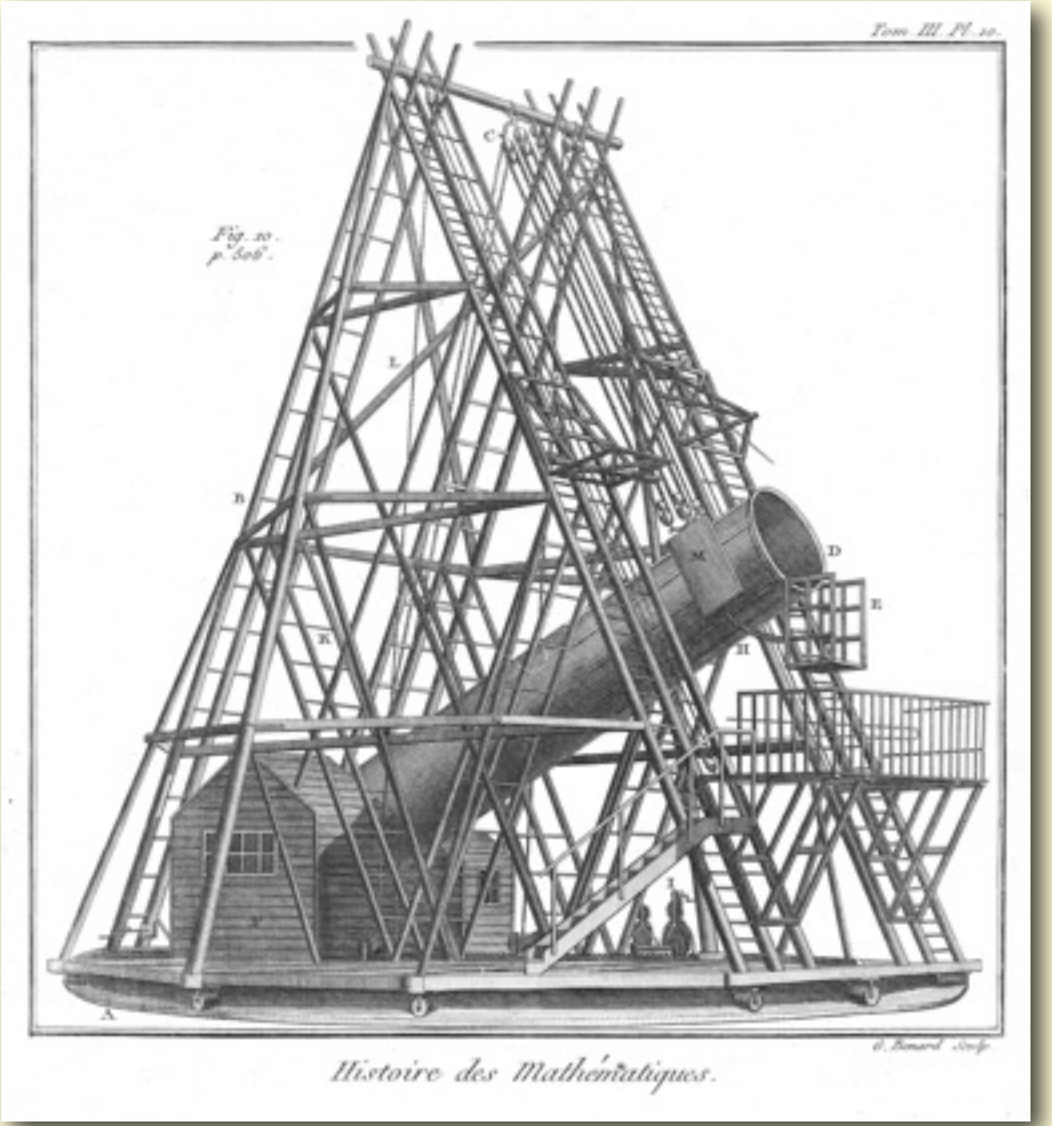
Physics of the XXth century
Part 4

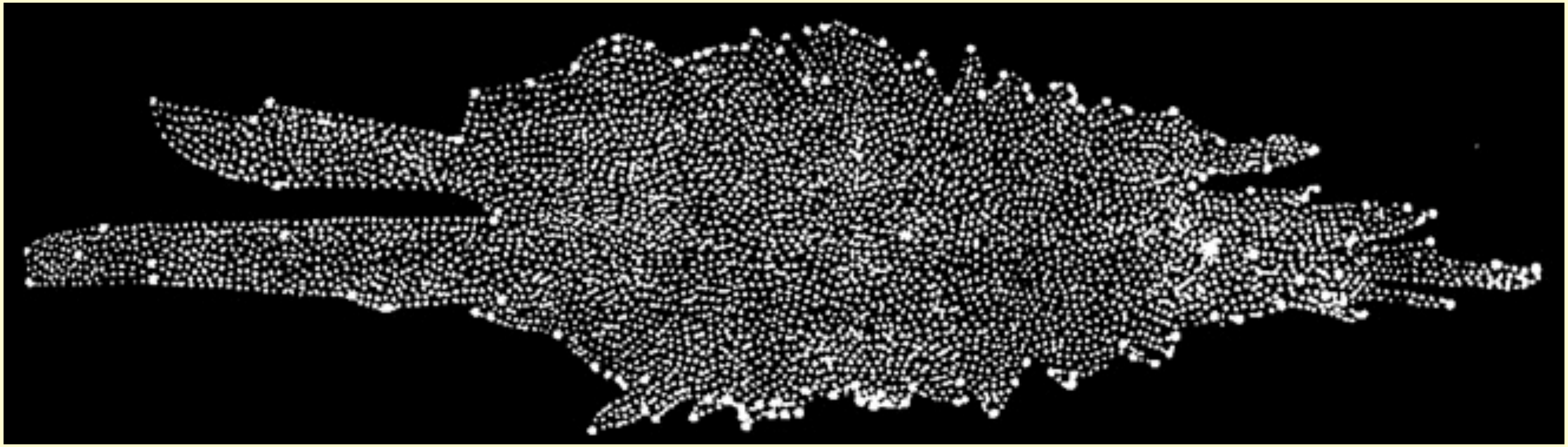
Development of astronomy and astrophysics

Four centuries of development of astronomy



William Herschel





W. Herschel, *On the Constitution of the Heavens*, Phil. Trans. **75**, 213 (1785)

The length of our flattened system of stars is about 800 times larger than the distance from the Sun to bright stars, Sirius or Antares, and its thickness is about 5 times smaller than that distance

# Herschel's assumptions	What we know now
1. All stars have the same absolute magnitude	wrong
2. There is no absorption of light in space	wrong

Hence: just apply $1/r^2$ law

Friedrich Wilhelm Bessel

parallax of 61 Cyg = 0.3136 ± 0.0202 arcseconds
distance equal to about 657,700 astronomical units (1838)

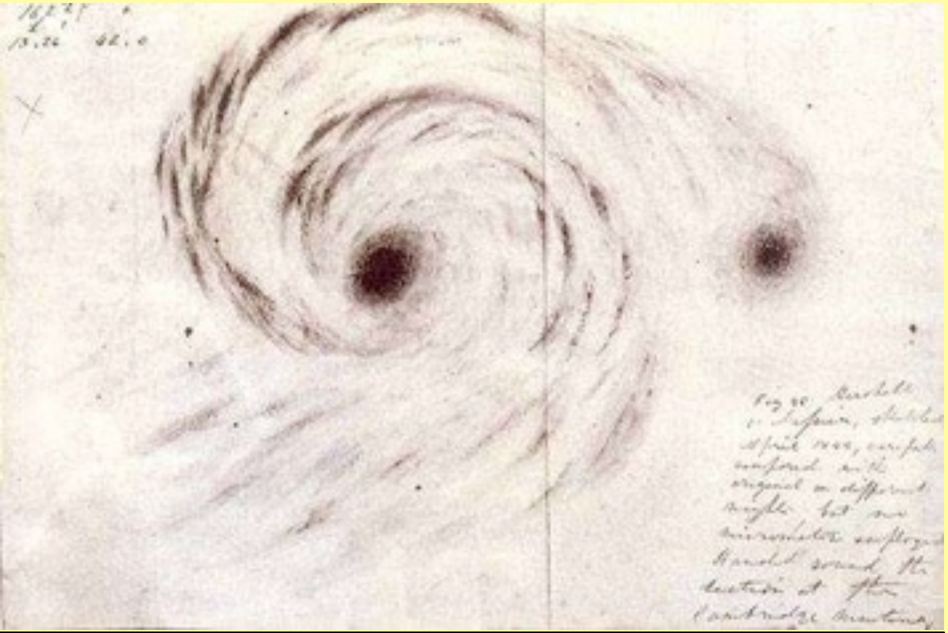
(1698 Christiaan Huygens: Sirius at 27,664 astronomical units)

open clusters

globular clusters

nebulae

spiral nebulae



Drawing of M 51 spiral nebula
by Lord Ross
and a modern photograph

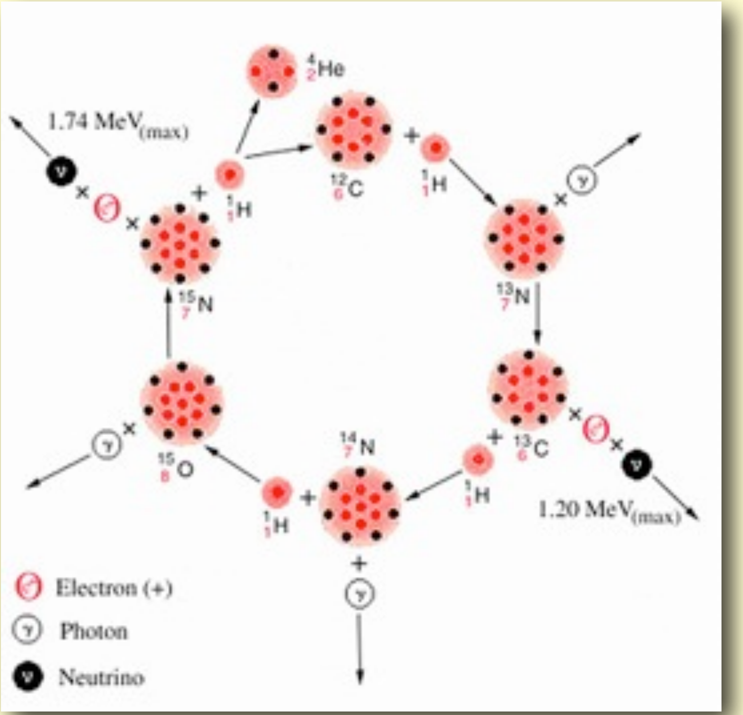
Agnes Clerke

”The question whether nebulae are external galaxies hardly any longer needs discussion. It has been answered by the progress of discovery. No competent thinker, with the whole of the available evidence before him, can now, it is safe to say, maintain any single nebula to be a star system of coordinate rank with the Milky Way. A practical certainty has been attained that the entire contents, stellar and nebular, of the sphere belong to one mighty aggregation...”

A. Clerke, *The System of the Stars*, p. 368 (London, 1890).

”The explanation now generally accepted was first given by the great German physicist Hermann von Helmholtz in a popular lecture in 1854. The sun possesses an immense store of energy in the form of the mutual gravitation of its parts; if from any cause it shrinks, a certain amount of gravitational energy is necessarily lost and takes some other form. In the shrinkage of the sun we have therefore a possible source of energy. The precise amount of energy liberated by a definite amount of shrinkage depends upon the internal distribution of density in the sun, which is uncertain, but making any reasonable assumption as to this we find that the amount of shrinking required to supply the sun’s expenditure of heat would only diminish the diameter by a few hundred feet annually, and would therefore be imperceptible with our present telescopic power for centuries, while no earlier records of the sun’s size are accurate enough to shew it...”

Arthur Berry, *A Short History of Astronomy* (1898)



Hans Bethe - Energy production in stars,

Phys. Rev. **55**, 434 (1939)

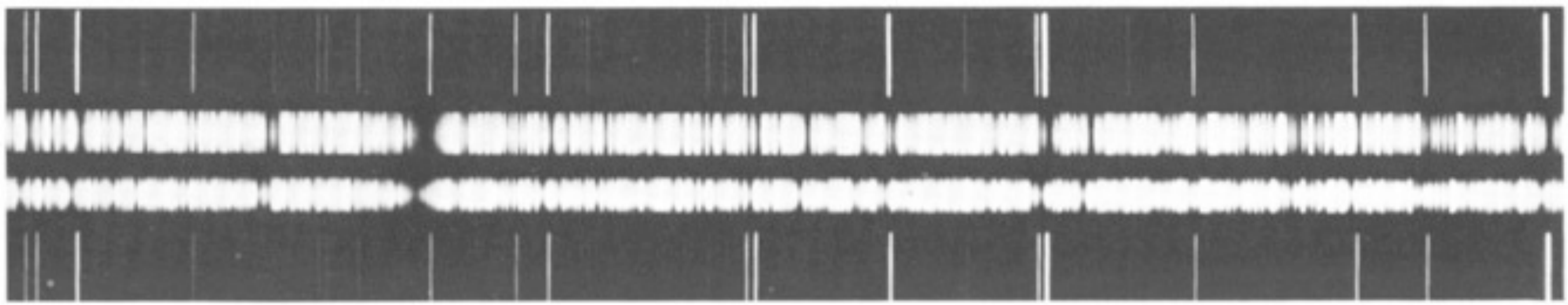
Doppler effect in astronomy

William Huggins (1824-1910)
Pioneering studies of radial velocities

Sirius is receding from us
with velocity of 46 km/s (1868)

Doppler effect in astronomy

(a)
(b)

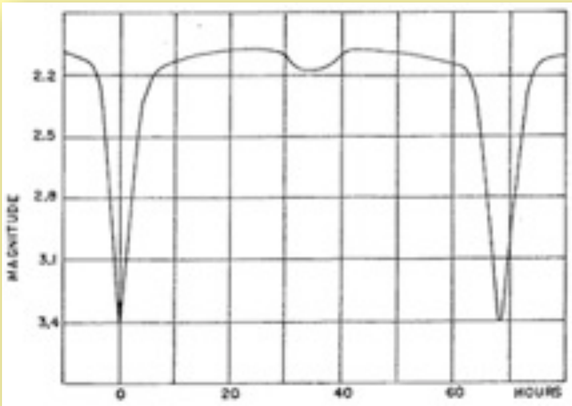


Spectra (420 – 430 nm) of the star Arcturus taken about six months apart

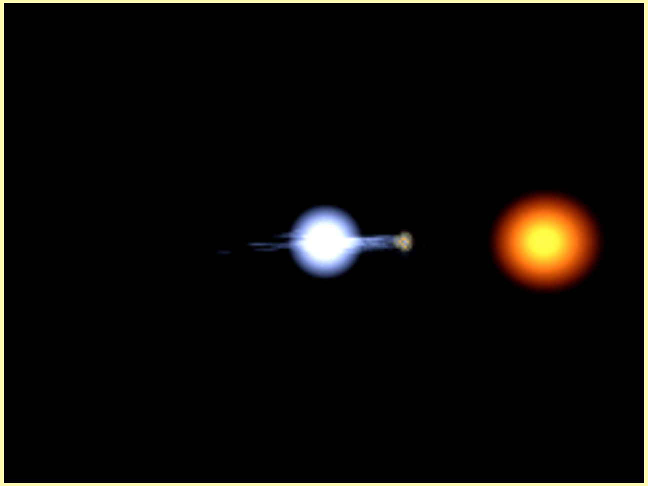
(a) July 1, 1939 measured velocity + 18 km/s
(b) January 19, 1940 „ „ - 32 km/s

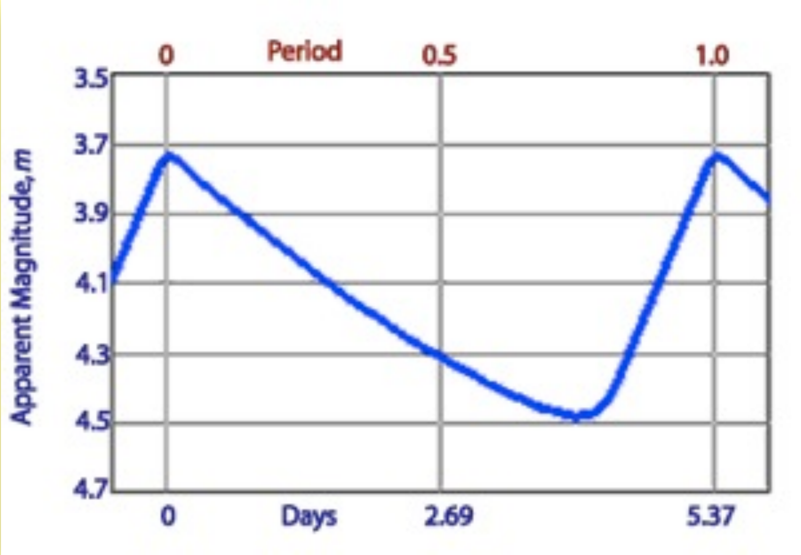
The difference of 50 km/s is due to the orbital velocity of the earth

Variable stars

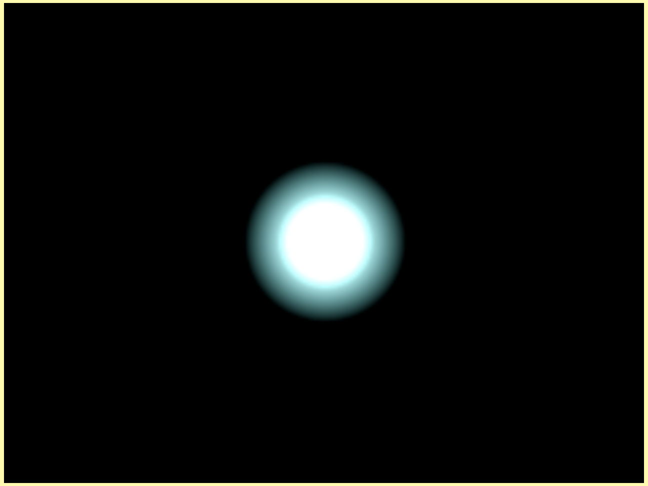


Algol type stars

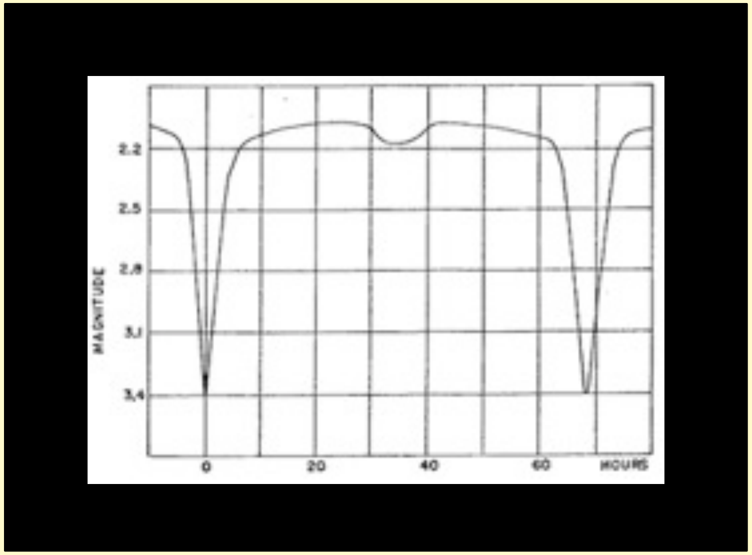


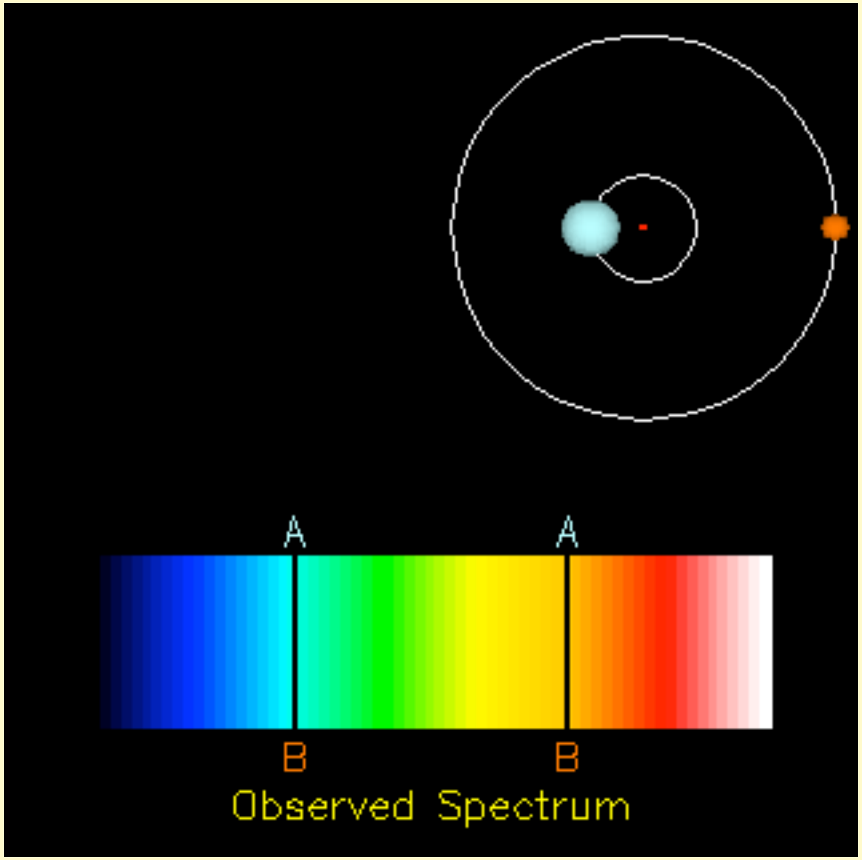


δ Cephei type stars (cepheids)

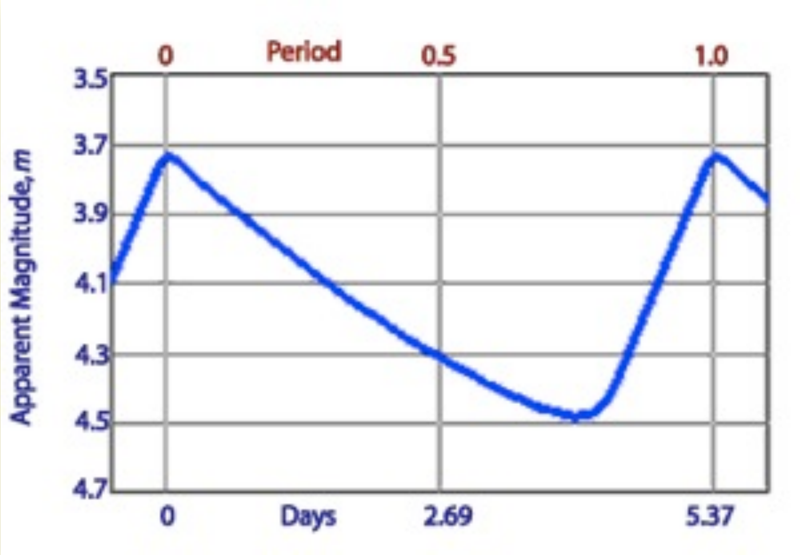


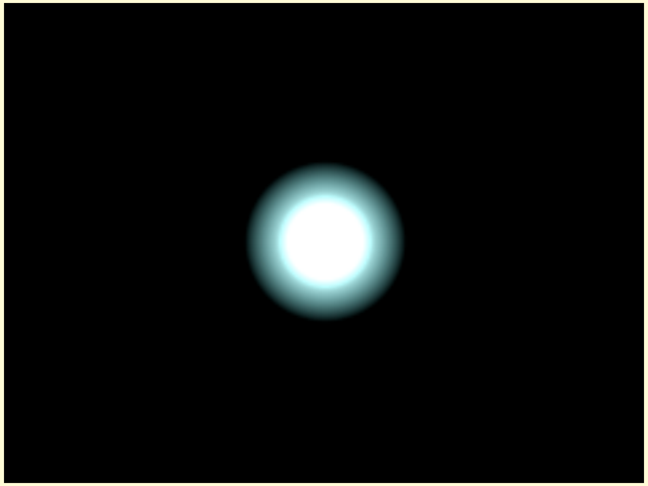
Periodic variations of radial velocity of Mizar (Pickering) and Algol (Vogel) discovered in 1889, proved that these are eclipsing variable stars





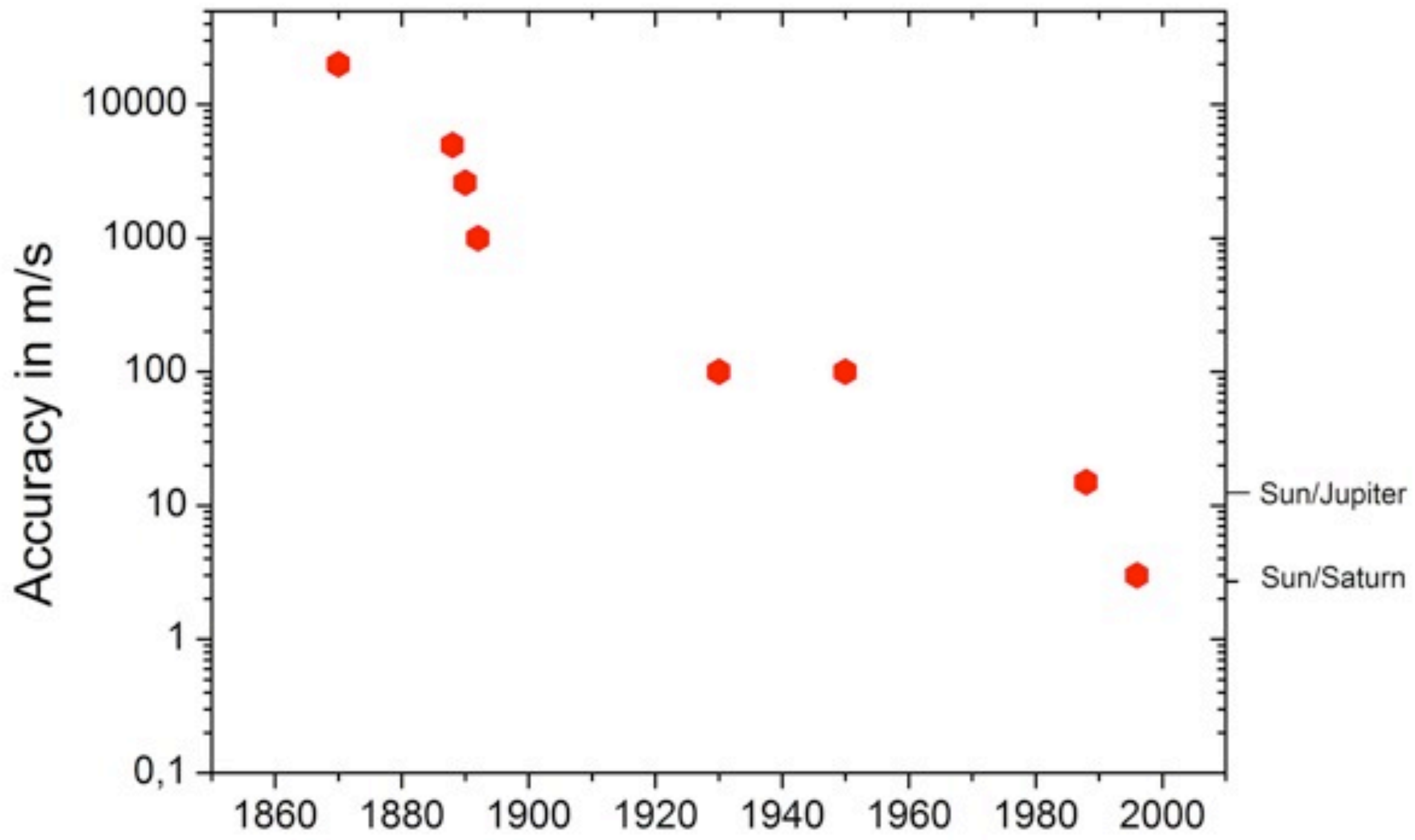
Periodic variations of radial velocity of Delta Cephei, first measured in 1894 by Belopolski, proved that its variation of brightness results from radial pulsation



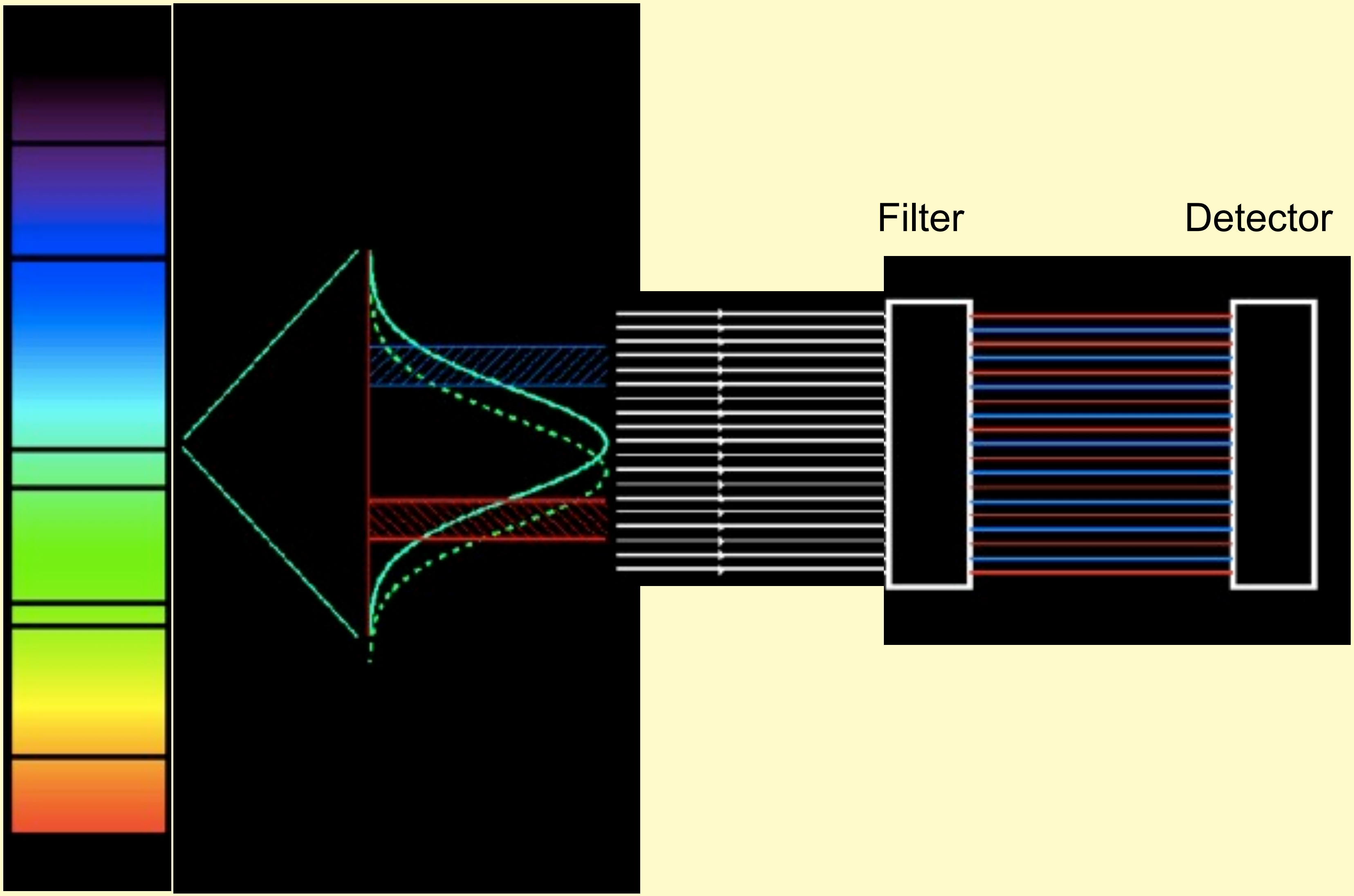


pulsating stars – cepheids (e.g. δ Cephei)

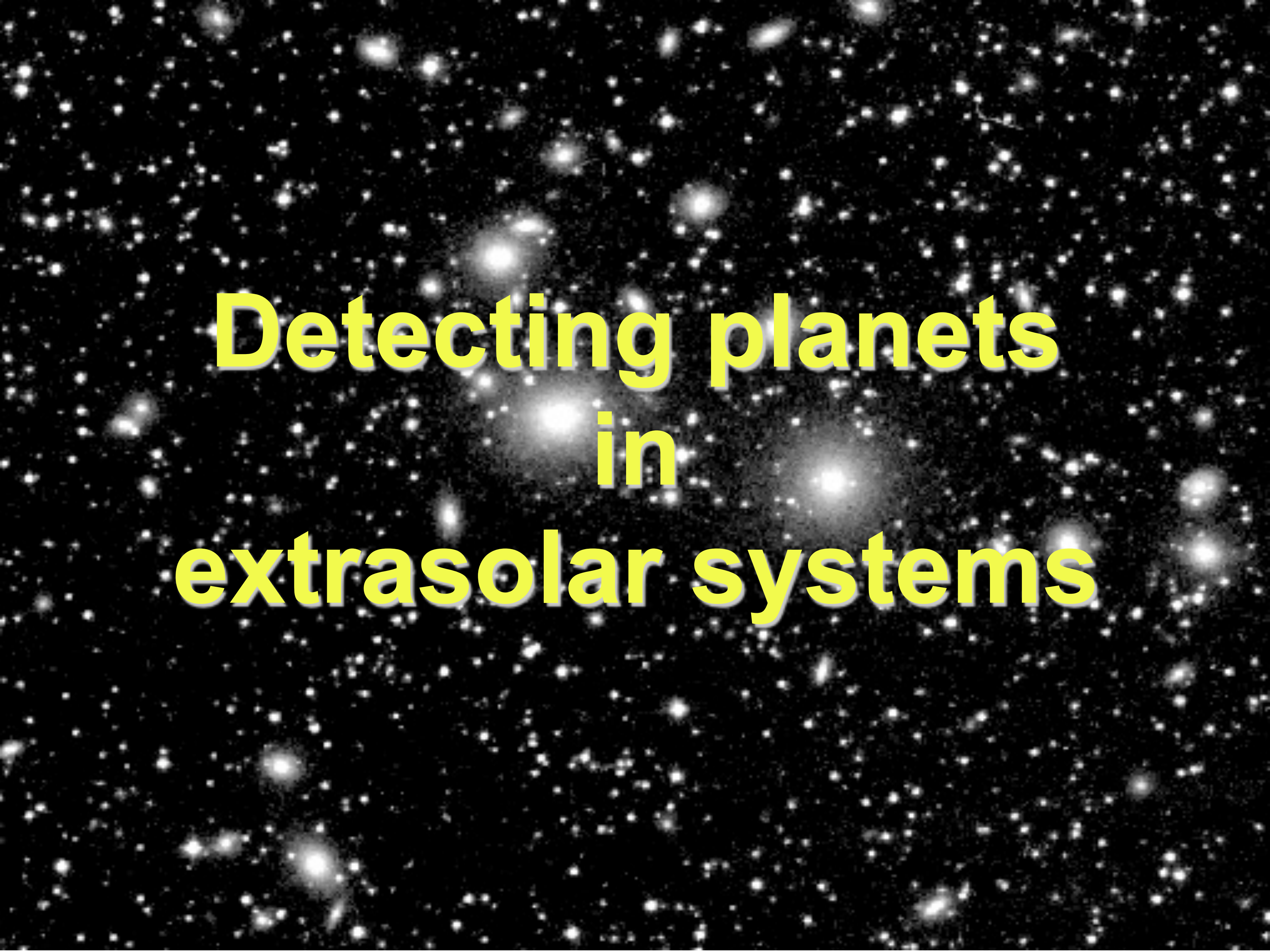
Progress in radial velocity measurements

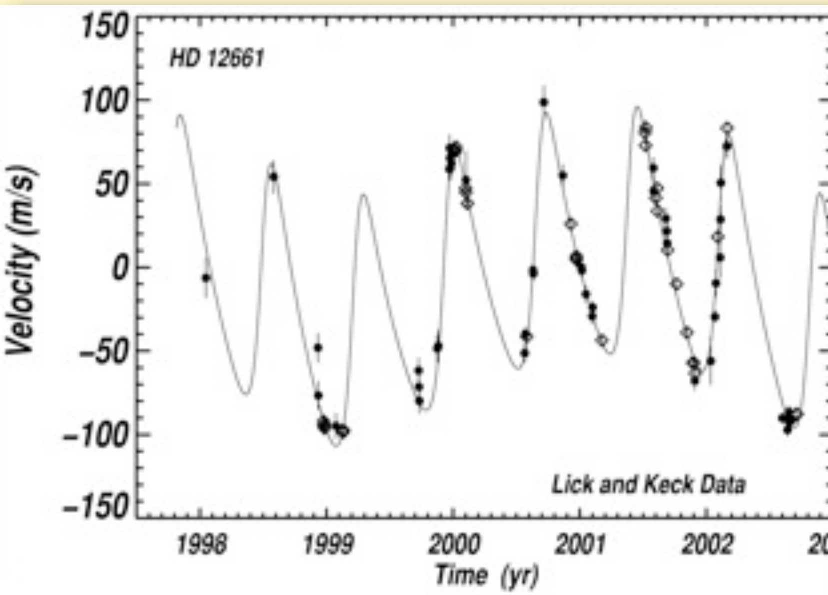


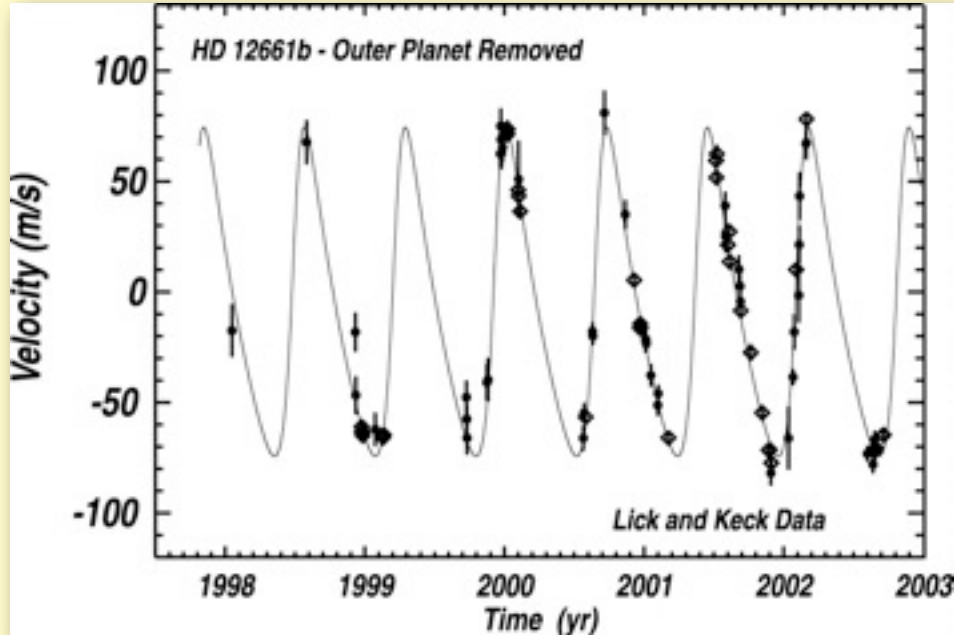
Detection of very small line shifts

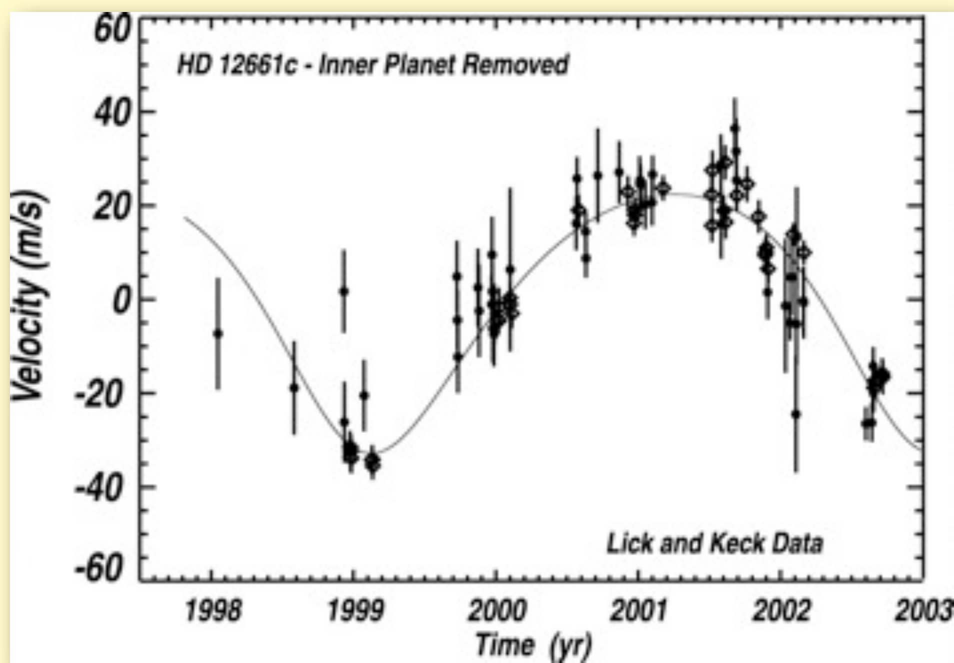


Detecting planets in extrasolar systems

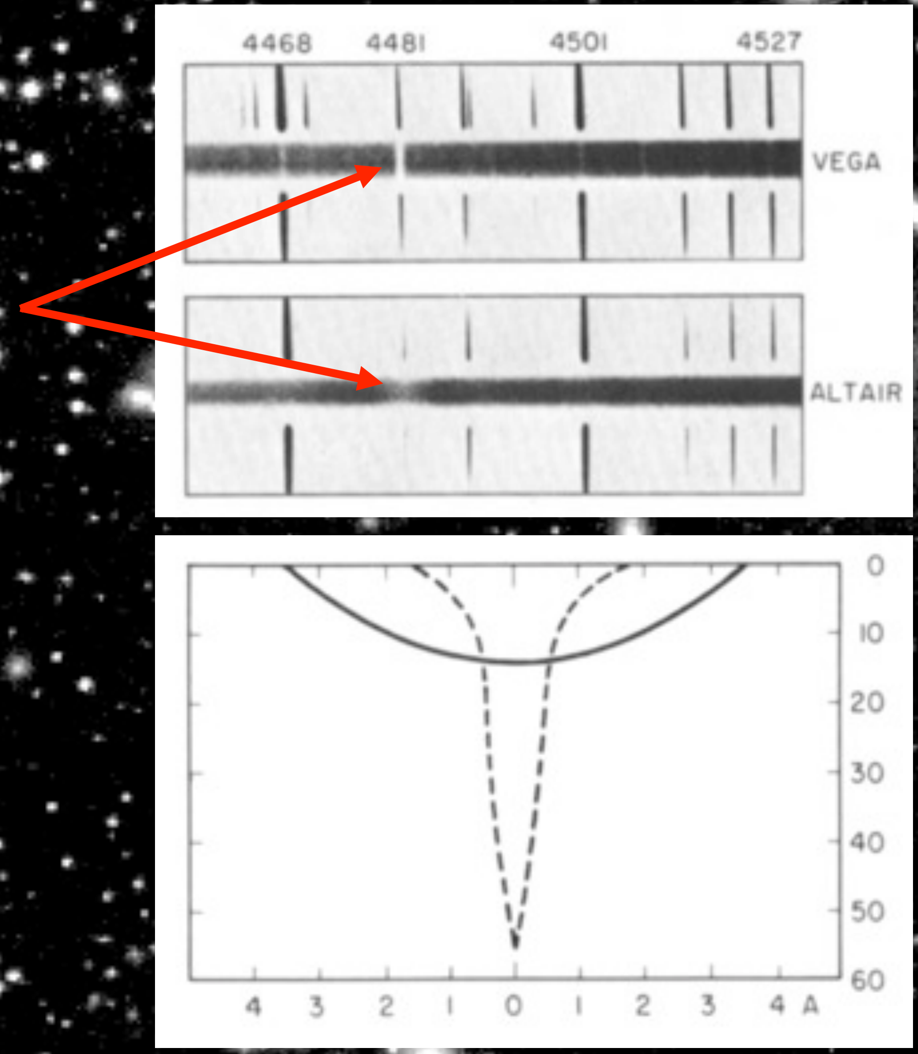








D. A. Fischer et al.
Astroph. Journ. **586**, 1394 (2003)

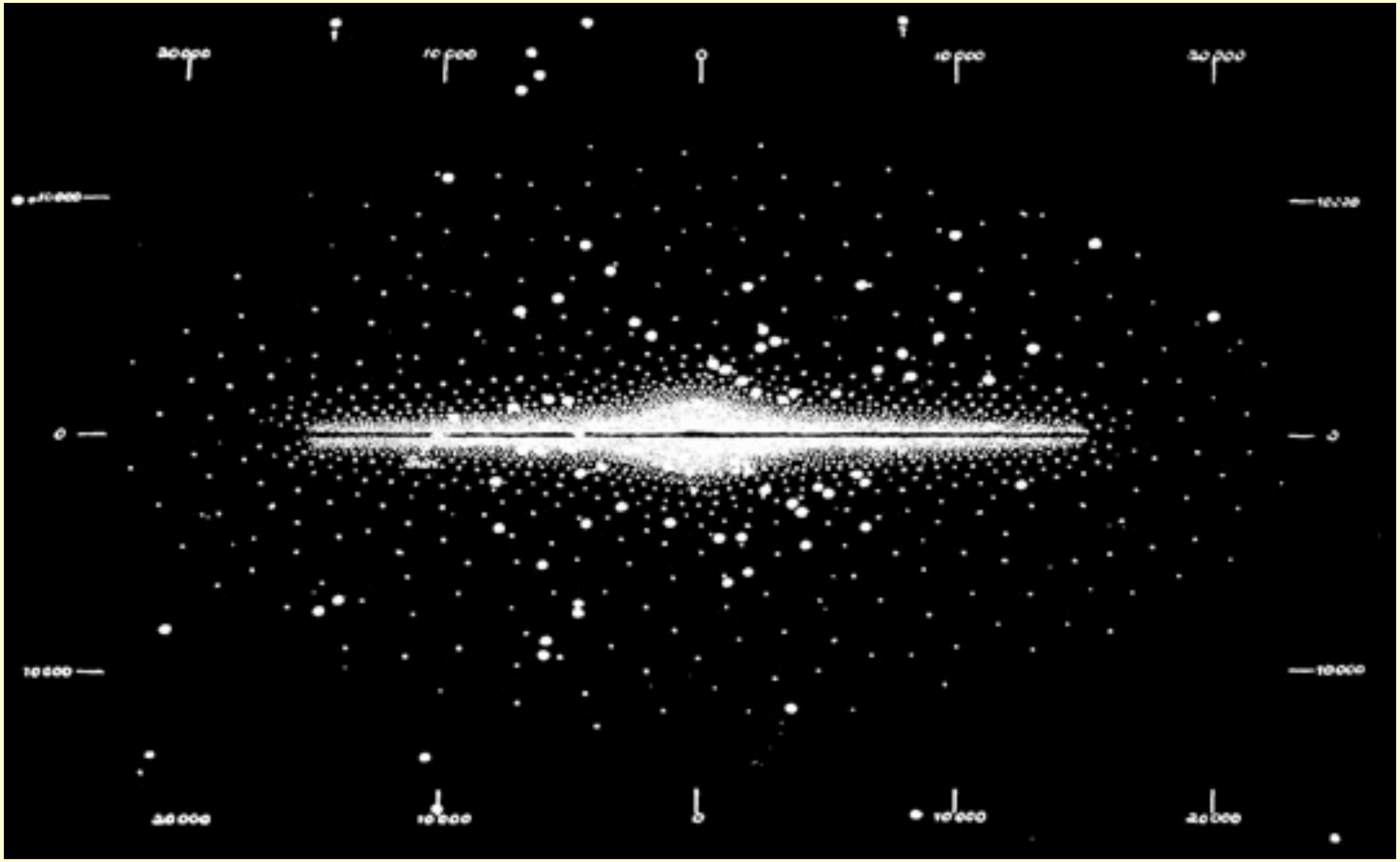


Doppler broadening of spectral lines due to stellar rotation

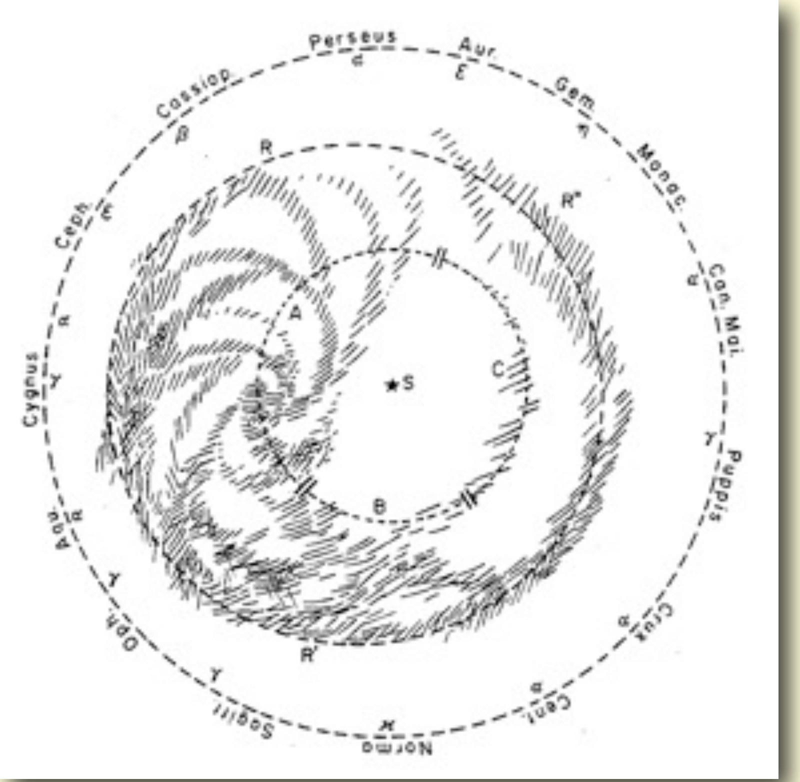
Dimensions of the Milky Way system in l.y.

William Herschel (1785)	(16,000 x 3,000)
Hugo von Seeliger (1884-1909)	23,000 x 6,000
Karl Schwarzschild (1910)	30,000 x 6,000
Jacobus Kapteyn (1912)	55,000 x 11,000
Harlow Shapley (1917)	300,000 x 30,000
present	**98,000 x 13,000**

A model of the Milky Way galaxy (1930)



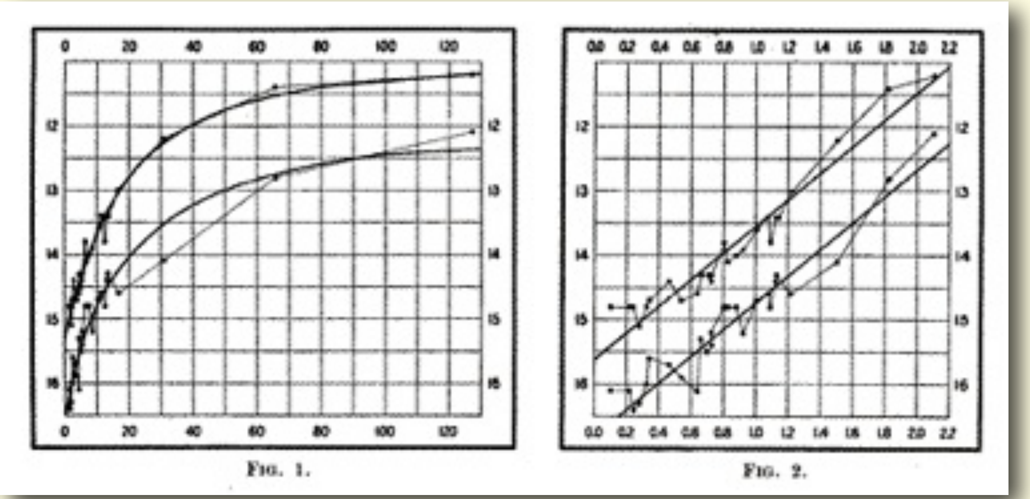
The first model of our Galaxy showing spiral arms (by Cornelius Easton, 1900)



Large and Small Magellanic Clouds

Period-brightness relation for cepheids in SMC

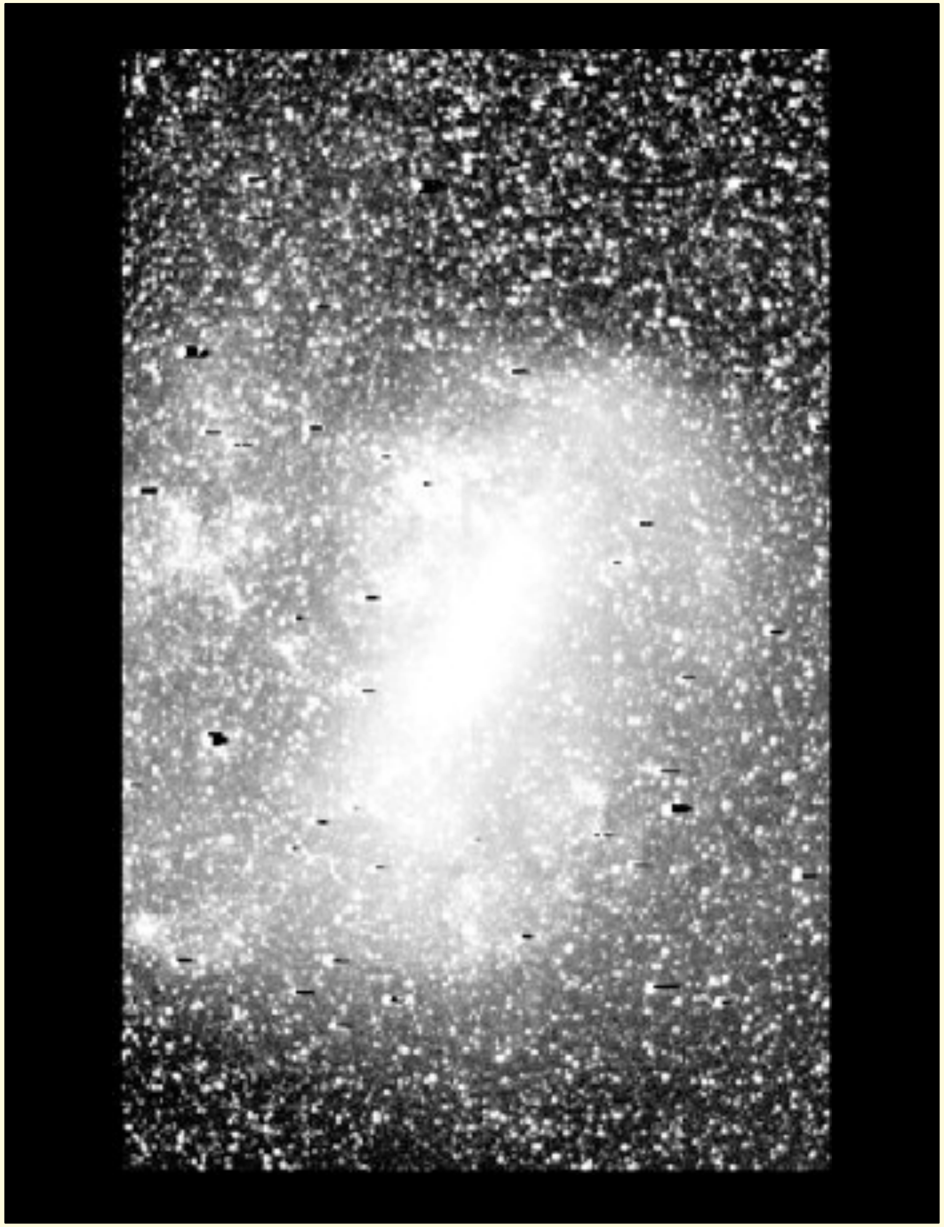
Henrietta Swan Leavitt
(1868-1921)



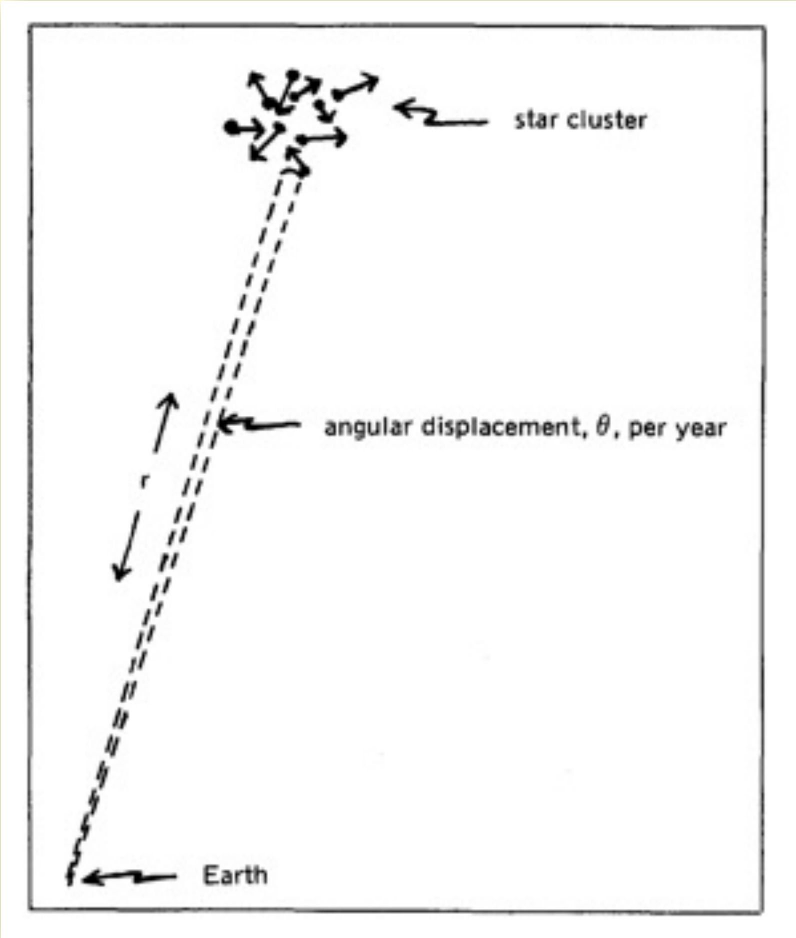
”A remarkable relation between the brightness of these variables and the length of their periods will be noticed.”

Harvard Observatory Circular
No. 173, 3 March 1912

How to find the distance to the Small Magellanic Cloud?



Hertzsprung (1913) 37,000 l.y.
Shapley (1918) 95,000



Ejnar Hertzsprung (1913)
statistical method of determining
distances of stars in a cluster

Doppler shift gives radial velocity *v* of each star. Angular displacement per year gives transverse velocity in θ /year. Assuming that the average radial velocity of all stars is also average transverse velocity we get transverse *v* in km/s. Then we may calculate the distance *r* from $r = v\ (3 \times 10^7 \text{ s/year})/\theta$

The Andromeda galaxy (M 31)

Author	Distance in l.y.
Bohlin (1907)	19
Very (1911)	1,600
Curtis (1919)	500,000
Lundmark (1919)	650,000
Hubble (1924)	850,000
Present	2,000,000

M 31 approaches us at 300 km/s
Vesto Melvin Slipher (1912)

M 13 globular cluster of stars

estimates of the distance of M 13 in l.y.

Shapley (1915)	100,000
Charlier (1916)	170
Shapley (1917)	**36,000**
Schooten (1918)	4,300
Lundmark (1920)	21,700
Curtis (1920)	**3,600 (8,000)**
present	**26,700**

In 1924 Edwin Hubble identified first cepheids in M 31 and could measure its distance

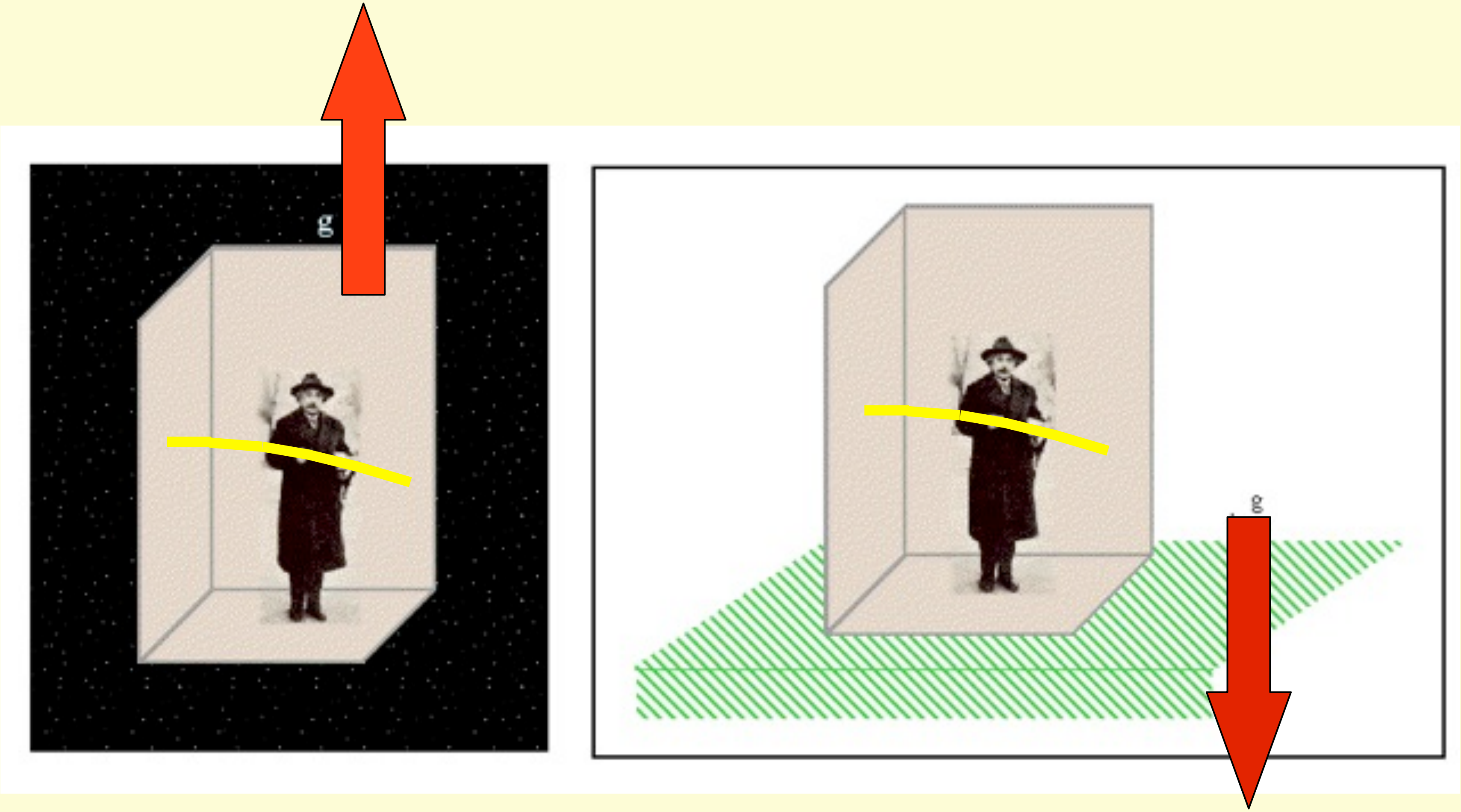
Shapley: ”this letter [from Hubble] destroyed my model of the Universe”

General relativity theory

”The breakthrough came suddenly one day.
I was sitting on a chair in my patent office in Bern.
Suddenly a thought struck me: If a man falls freely, he would not feel his weight. I was taken aback. This simple thought experiment made a deep impression on me. This led me to the theory of gravitation...
I decided to extend the theory of relativity to the reference frames with acceleration.”

A. Einstein, *How I created the theory of relativity* (1922)

The equivalence principle (1907)



An observer in a closed windowless chamber will not be able to distinguish between the two situations

'The luckiest thought in my life' - Albert Einstein

Minkowski's Space-time

Hermann Minkowski

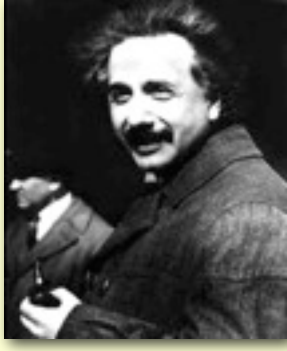
”The views of space and time which I wish to lay before you have sprung from the soil of experimental physics, and therein lies their strength. These views are radical. Henceforth Space by itself, and Time by itself, are doomed to fade away into shadows, and only a kind of a union of the two will preserve an independent reality...”

Raum und Zeit, lecture at Göttingen, September 21, 1908, 81st Meeting of the Deutscher Naturforscher und Ärzte

Special relativity theory (1905)

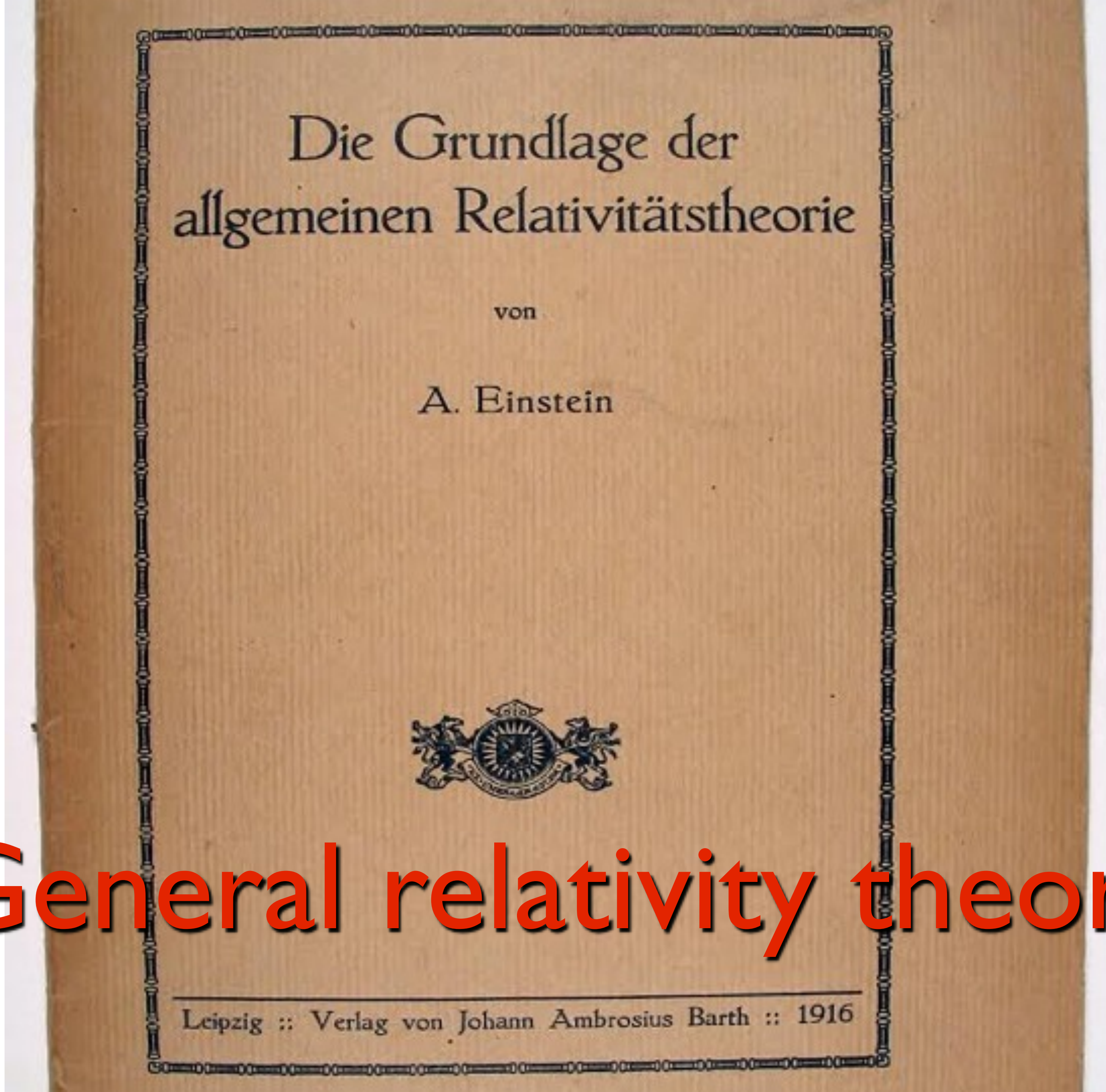
The laws of physics are the same for all observers in uniform rectilinear motion

General relativity theory
November 25, 1915



The laws of physics are the same for all observers in free-fall
There exist only local inertial frames

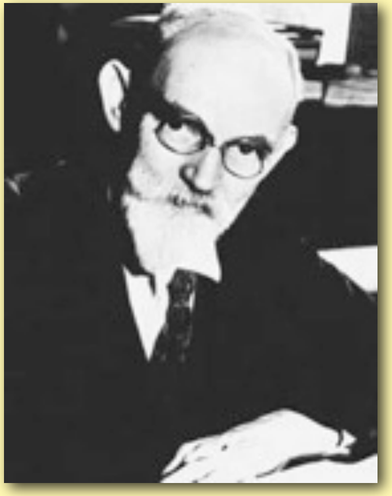
Reminder: the universe is full of free-falling bodies: the moon falls toward the earth, the planets fall toward the sun, etc.

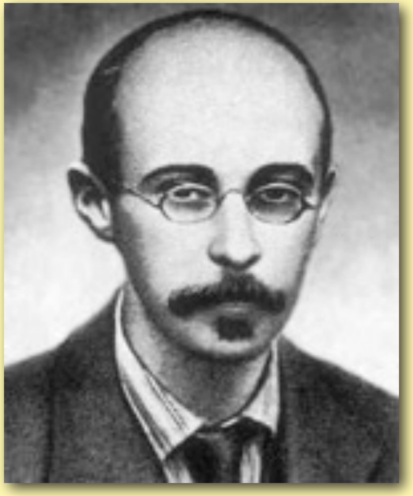


General relativity theory

1915 Einstein – General relativity theory
1916 Karl Schwarzschild – first solution of Einstein's equations (Schwarzschild radius)
1917 Einstein – 'cosmological constant' introduced to secure a static universe
1917 Willem de Sitter – alternative solution of Einstein's equations
1919 Observational detection of gravitational bending of light by the sun
1922 Aleksandr Friedman – solution of Einstein's equations without the 'cosmological constant'
1928 Georges Lemaître – 'Big Bang' hypothesis
1929 Edwin Hubble – observational evidence of the expansion of the universe


Schwarzschild


de Sitter


Friedman


Lemaître & Einstein

February 8, 1917; Einstein: ”*Cosmological considerations on the general theory of relativity*” – introduction of the ‘cosmological constant’

”At any rate, this view is logically consistent, and from the standpoint of the general theory of relativity lies nearest at hand; whether, from the standpoint of present astronomical knowledge, it is tenable, will not here be discussed. In order to arrive at this consistent view, we admittedly had to introduce an extension of the field equations of gravitation which is not justified by our actual knowledge of gravitation. It is to be emphasized, however, that a positive curvature of space is given by our results, even if the supplementary term is not introduced. That term is necessary only for the purpose of making possible a quasi-static distribution of matter, as required by the fact of the small velocities of the stars.”

The mathematics in the GRT is quite advanced

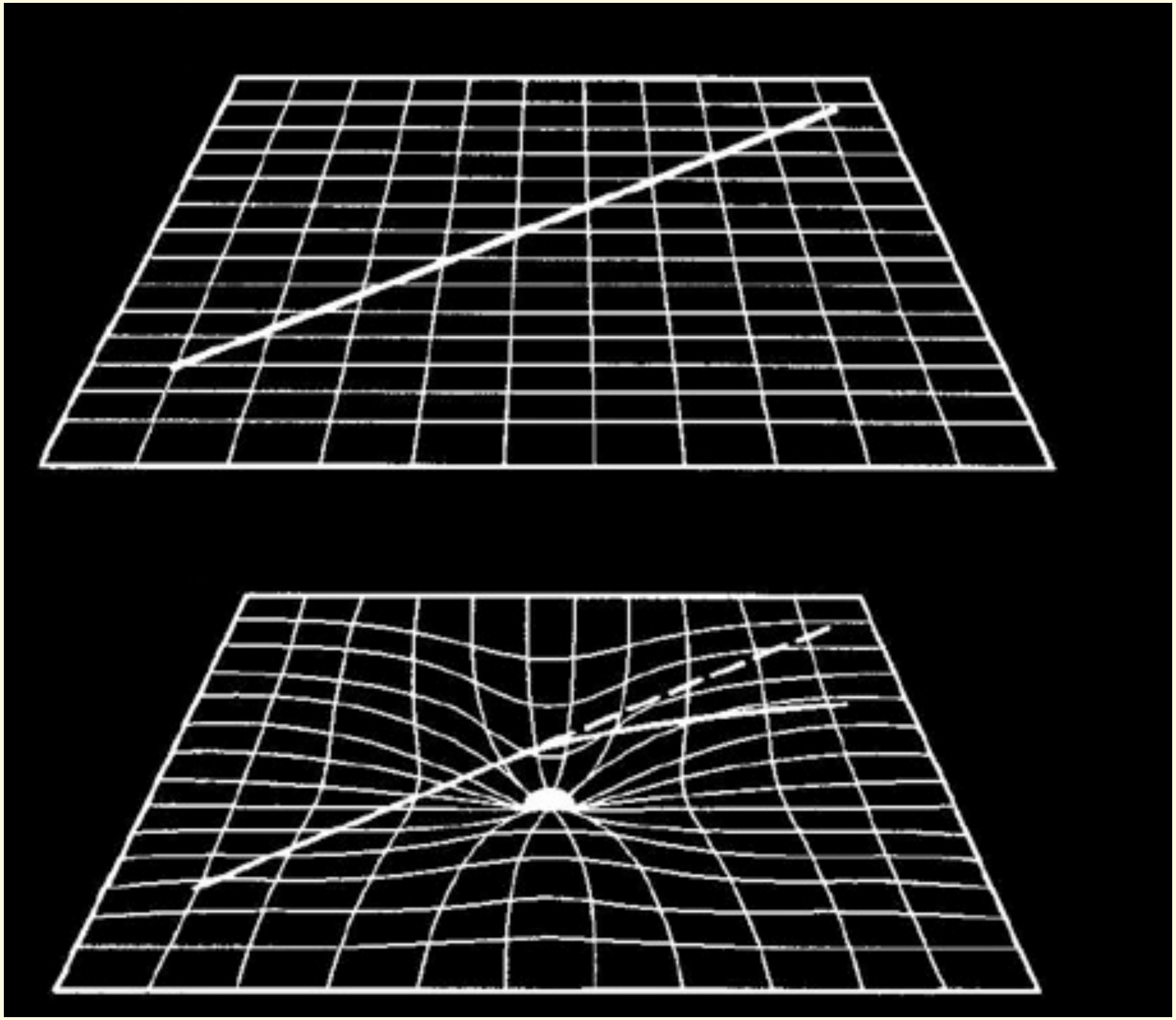
$$G_{\mu\nu} = \kappa \, T_{\mu\nu}$$

Einstein's tensor

Energy-momentum tensor

$$\kappa = 8\pi G/c^4 \cong 2 \cdot 10^{-48} \text{ (cgs units)}$$

A two-dimensional explanation of curved space



Gravitation is the effect of curved spacetime

Predictions of the General Relativity Theory:

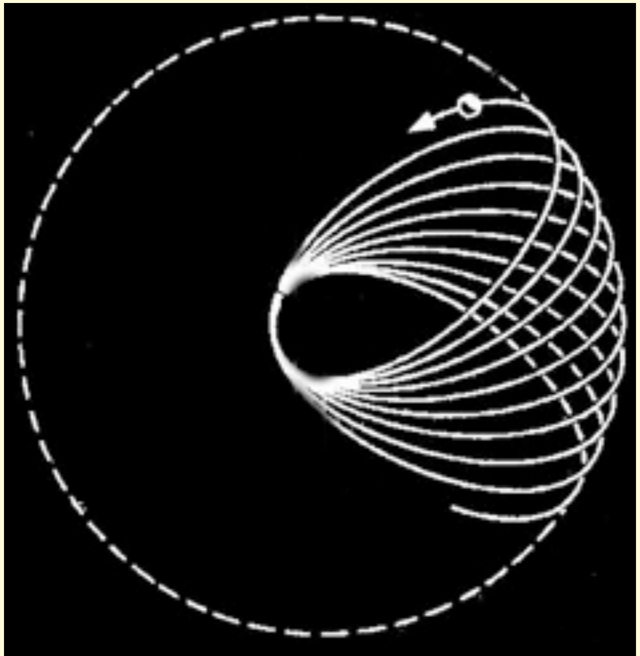
Advancement of Mercury’s perihelium

Deflection of light in a gravitational field

Red-shift of spectral lines in a gravitational field

Advancement of Mercury's perihelium in arcseconds per century

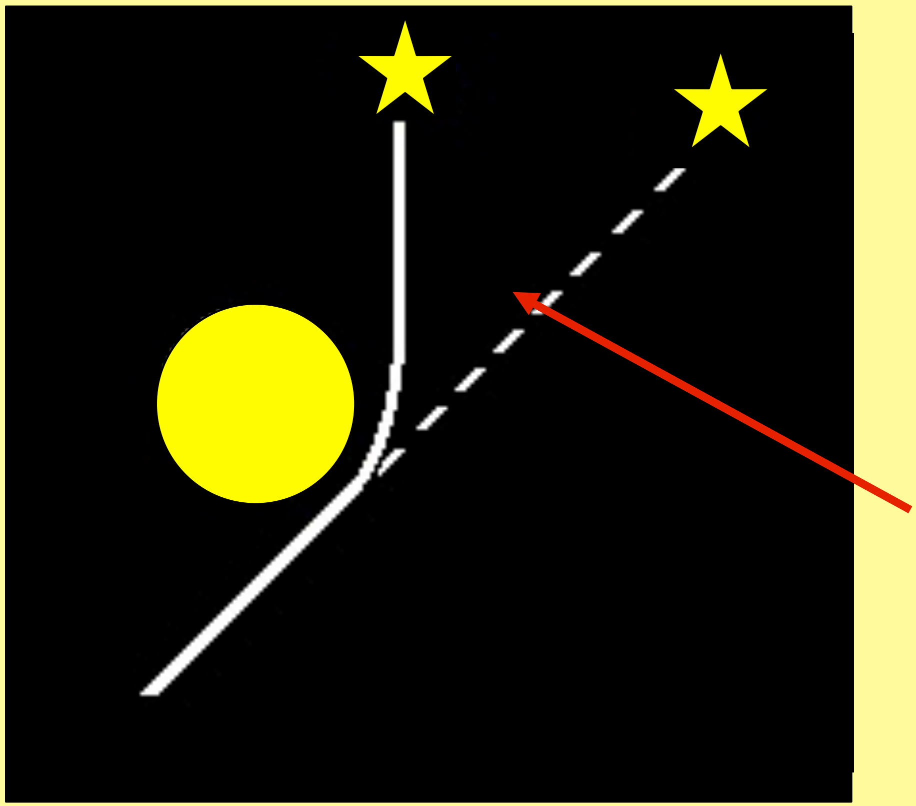
5599.74 ± 0.41	total
5025.64 ± 0.50	astronomical precession
531.54 ± 0.68	known perturbations from planets
	(277.856 Venus; 153.584 Jupiter; 90.038 Earth)
5557.18 ± 0.85	total Newtonian prediction
42.56 ± 0.94	**difference**
43.03 ± 0.03	**prediction of general relativity**



Other proposals (within classical physics)

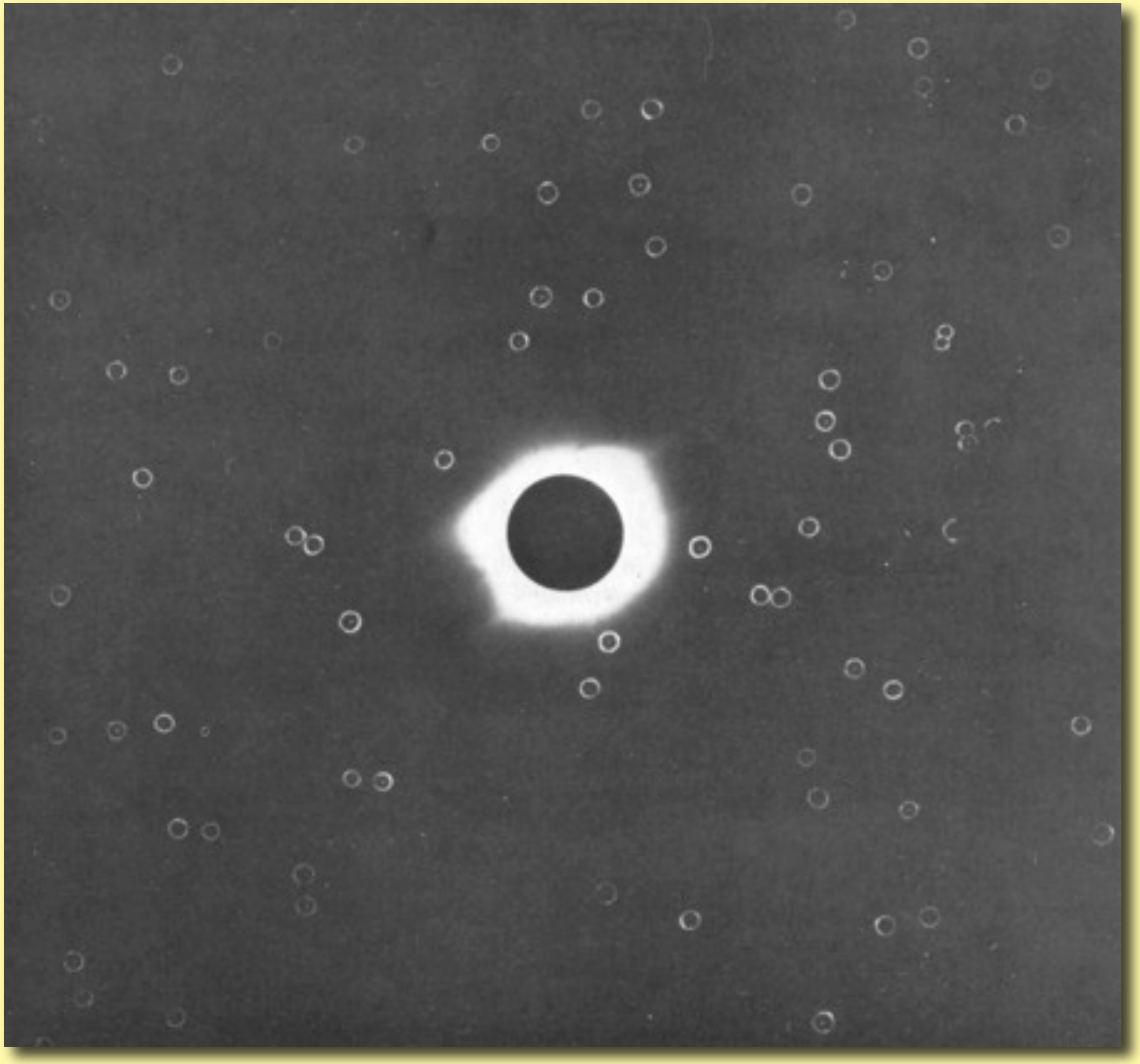
1. Intramercurial planet – Vulcan	**Not found**
2. Oblateness of the Sun	**Not observed**
3. Interplanetary matter in the vicinity of the Sun	**Not possible (too many other effects)**

Light deflection in the gravitational field



1.75 arc seconds for light which passes by the sun at its edge

First confirmation in 1919 from observations of stars during the total solar eclipse



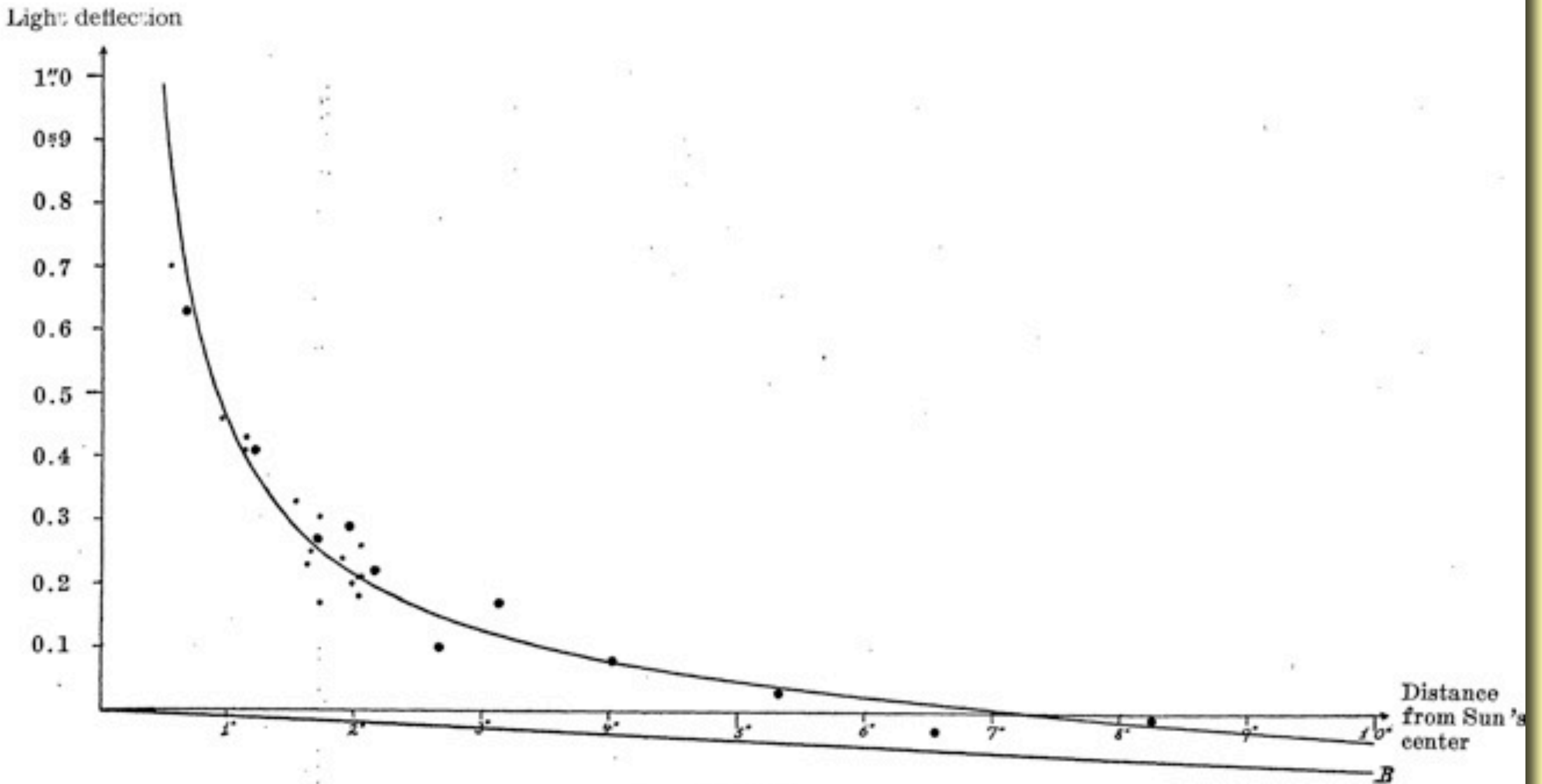
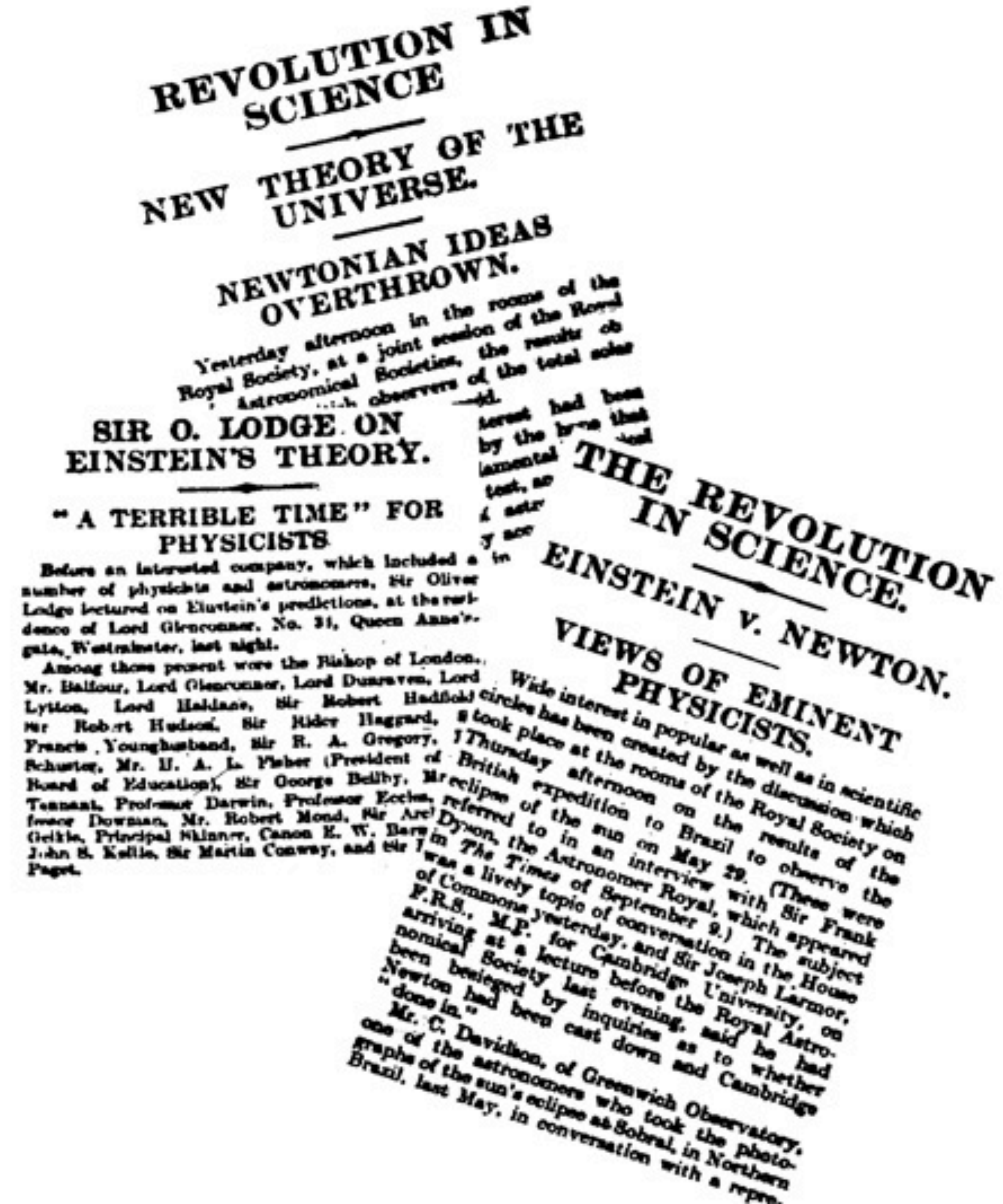


FIGURE 1.
Radial components of observed light deflections compared with Einstein's theory.



Press sensationalism November, 1919

Observed Light Deflection at the Sun's Limb

Date	Station	Fo-cus	No. of Plates	No. of Stars	Observed Deflection	Observers
1919						
May 29 . .	Sobral	19 ft.	7	7	1.98 ±0.12 pe	Dyson Davidson Eddington
	Sobral	11	16*	6–12	(0.86)± .1 pe	
	Principe	11	2	5	1.61 ± .3 pe	
1922						
Sept. 21 . .	Wallal	10	2	18	1.74 ± .3 pe	Chant Young
	Wallal	15	4	62–85	1.72 ± .11 pe	Campbell Trumpler
		5	6	134–143	1.82 ± .15 pe	
	Cordillo-Downs	5	2	14	1.77 ± .3 pe	Dodwell Davidson
1929						
May 9 . .	Takengon	28 ft.	4	17–18	2.24 ± .10 me	Freundlich von Klüber von Brunn
					1.75 ± .13 pe	Trumpler's reduction of Potsdam Measures
					1.98 ± .14 me	Jackson's solution of residuals for scale

* Poor focus caused by distortion of the mirrors.

Charles E. St. John, *Observational basis of general relativity*, Publ. Astron. Soc. Pacific 44, 277 (1932)

There were physicists, including some quite famous, such as Oliver Lodge, who complained about very sophisticated and difficult mathematics of relativity theory.

However, mathematics quickly became
a smokescreen behind which many scientists concealed their inability to explain the theory to the public or even their own lack of understanding the new concepts.
It caused the public to believe that relativity theory could be understood only by a few chosen people.

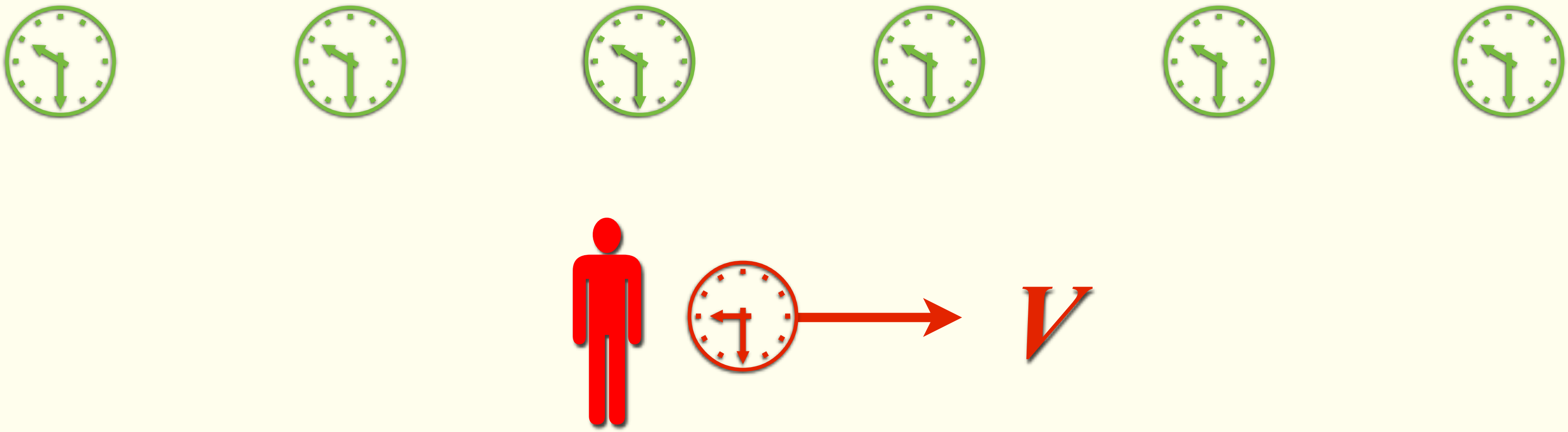
In 1924 Dayton Miller announced that he succeeded to detect the ether drift in an experiment of M-M type.

It temporarily added to confusion concerning relativity; but shortly a series of more precise and conceptually new experiments (e.g. Kennedy & Thorndike – 1932; Ives & Stilwell – 1938) disproved Miller's result as result of experimental errors and sloppy analysis, and gave even more solid basis for Einstein's theories.

See Robertson, *Rev. Mod. Physics* **21**, 378 (1949)

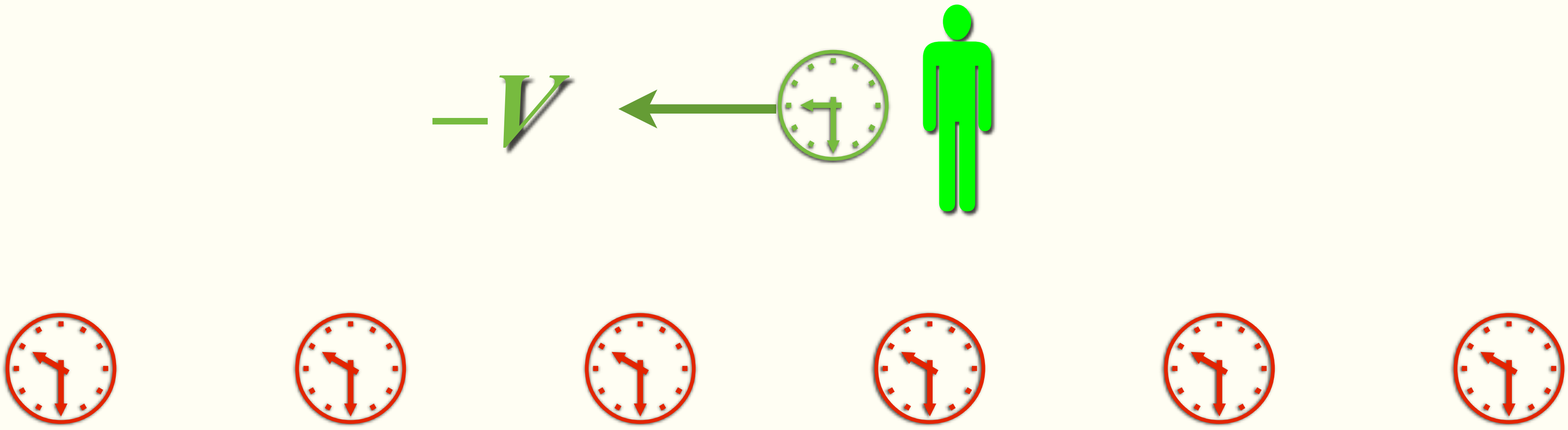
After about 1940 Einstein’s relativity theories became well established and generally accepted by physicists

Some consequences of special and general relativity



When Mister **RED**
compares his **clock** with **clocks** synchronized
in the **GREEN system**, which he passes
with velocity ***V***, he finds that
his clock is running late

The same is observed by Mister **GREEN**
who compares his **clock**
with **clocks** synchronized
in the **RED system**, which he passes
with velocity $-V$



In both cases a single clock in one system is being compared <u>with a</u> <u>series of clocks</u> synchronized in the other system

The effect of time dilation is reciprocal as are other effects of kinematic origin

Kinematic dilation of time
is of the order of $(v/c)^2$
and is hard to be noticed
in everyday life

For the „Apollo" ships $v/c \approx 0{,}0001$

This gives a difference in clocks of about 10^{-8}

In 2010 kinematic dilation of time has been experimentally observed at the level of 10^{-16} („Science" 24 IX 2010)

Time in relativity theory

Dilation of time in special relativity - kinematic effect

Dilation of time in general relativity - time runs slower in stronger gravitational field

Experimental checks

Gravitational dilation of time $T_h - T_E = T_E\,(gR/c^2)$ for a clock at height h compared with a clock at Earth's surface

Checked experimentally many times;
very important for the GPS

Leads to redshift of light emitted from the surface of a massive body; checked first by observations of the shift of spectral lines of massive white dwarfs (Sirius B, Eridani 40)

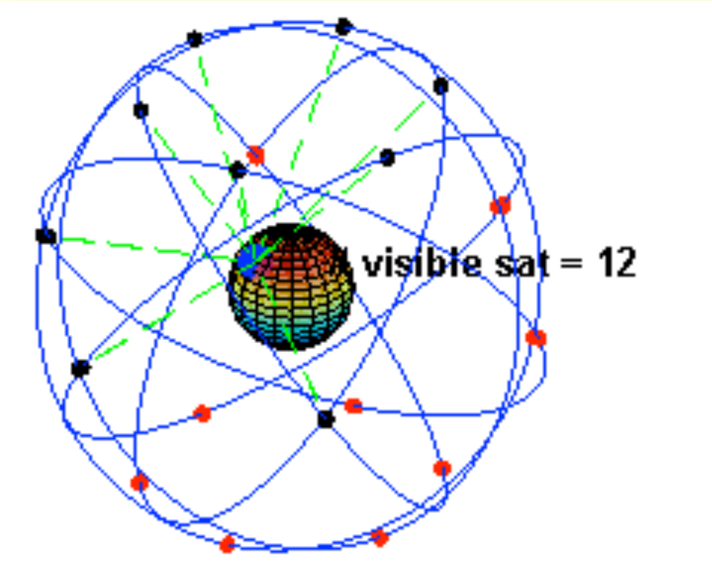
The first experiment with atomic clocks

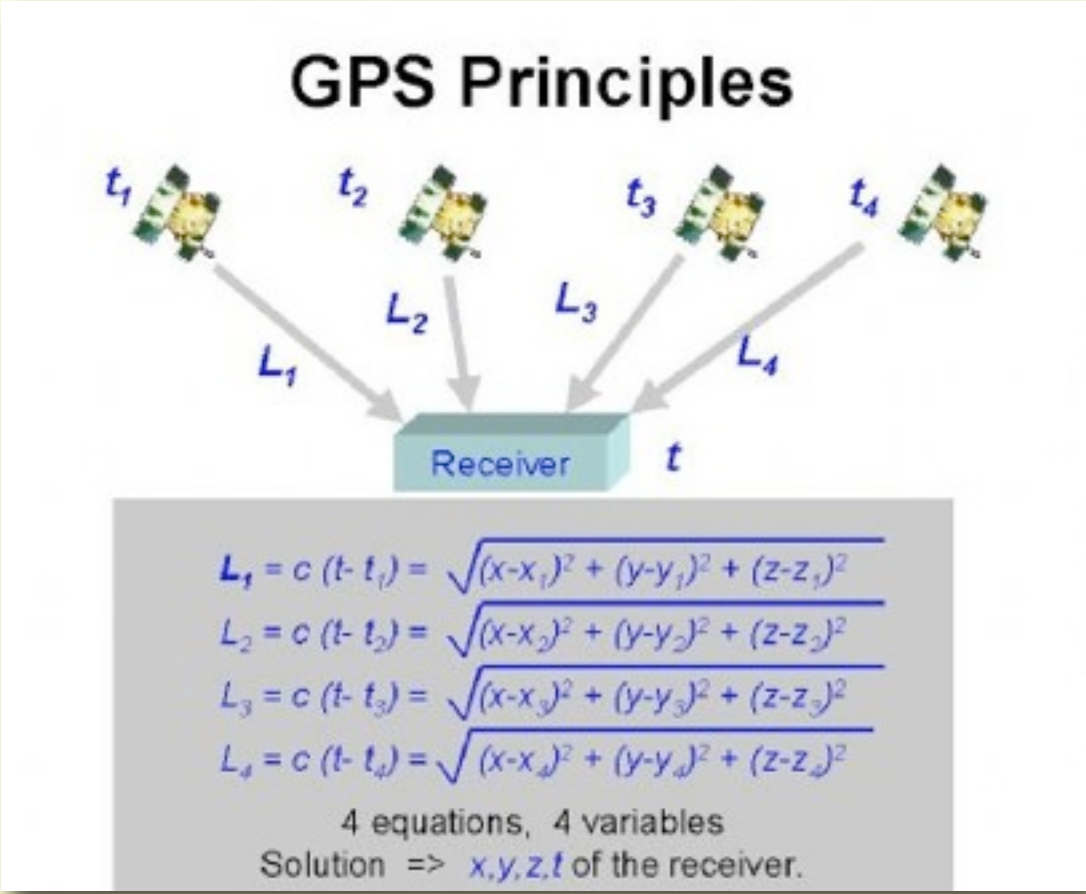
(J. C. Hafele and R. E. Keating, Science **77**, 166, 1972)

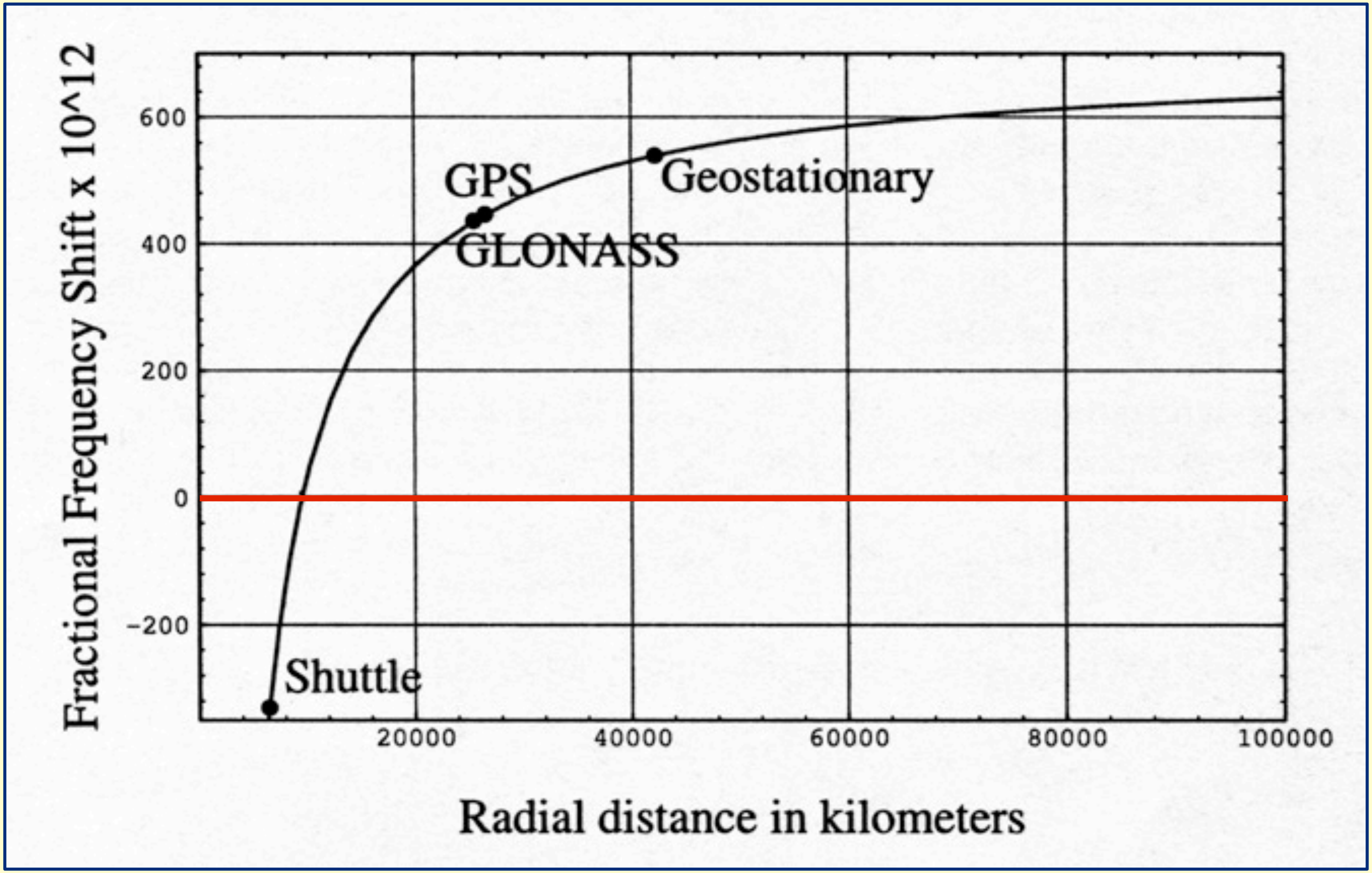
	Eastward flight	Westward flight
		
Prediction (nanoseconds)		
gravitational	+144 ± 14	+179 ± 18
kinematic	–184 ± 18	+96 ± 10
total	**– 40 ± 23**	**275 ± 21**
Experiment	**–59 ± 10**	**273 ± 7**
clock 1	–57	277
clock 2	–74	284
clock 3	–55	266
clock 4	–51	266

Experiments with atomic clocks
(Joseph C. Hafele i Richard E. Keating, 1972)

GPS – Global Positioning System





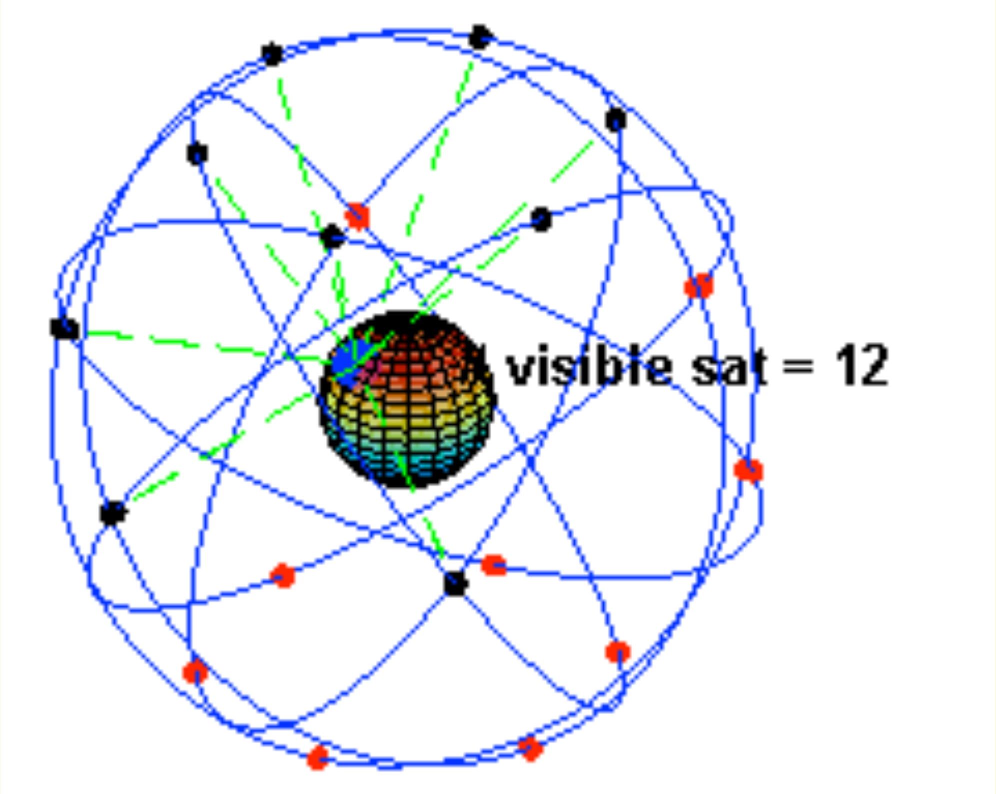


Fractional Frequency Shift x 10^12
600
400
200
0
-200
GPS
GLONASS
Geostationary
Shuttle
20000
40000
60000
80000
100000
Radial distance in kilometers

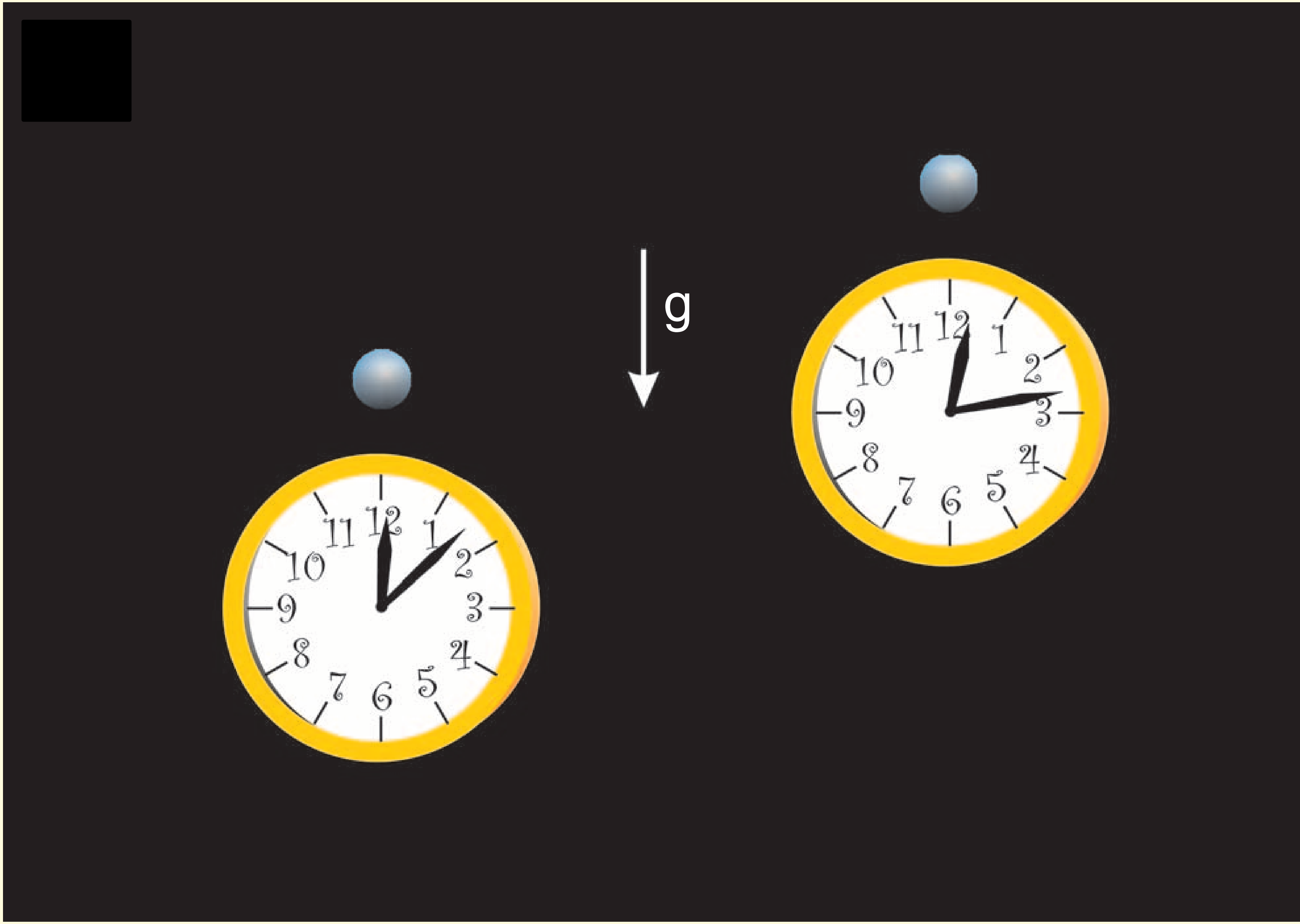
GPS satellites are orbiting Earth at 20200 km above its surface with velocity of about 3.9 km/s

grawitational dilation of time = + 46 microseconds/day
kinematic dilation of time = - 7 microseconds/day
total effect = + 39 microseconds/day

Local second at GPS satellites must be longer by about 0.44 ns

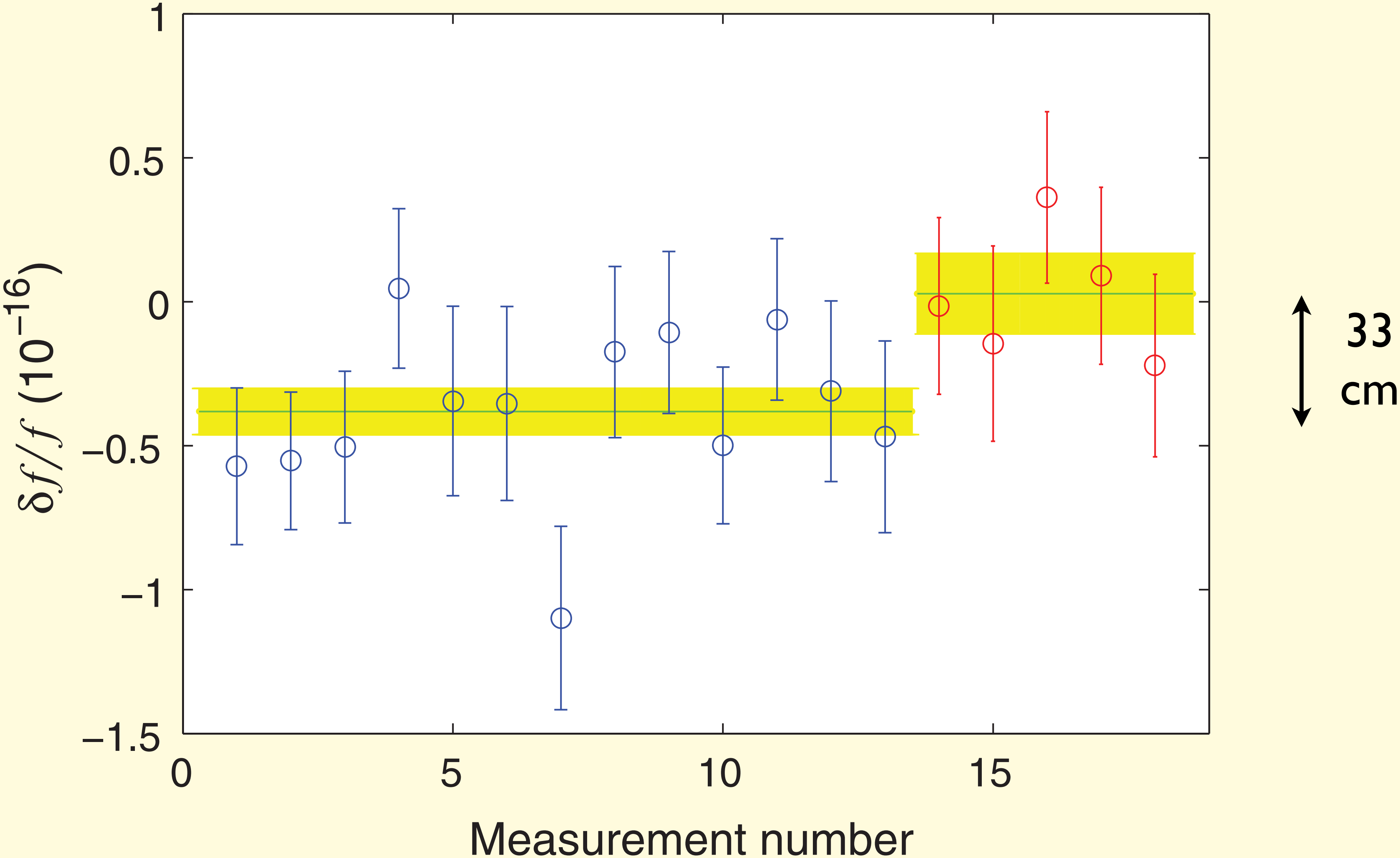


A clock at an altitude of 1 km above ground will run faster
by 3 seconds in a million years
compared with an identical clock at the ground level

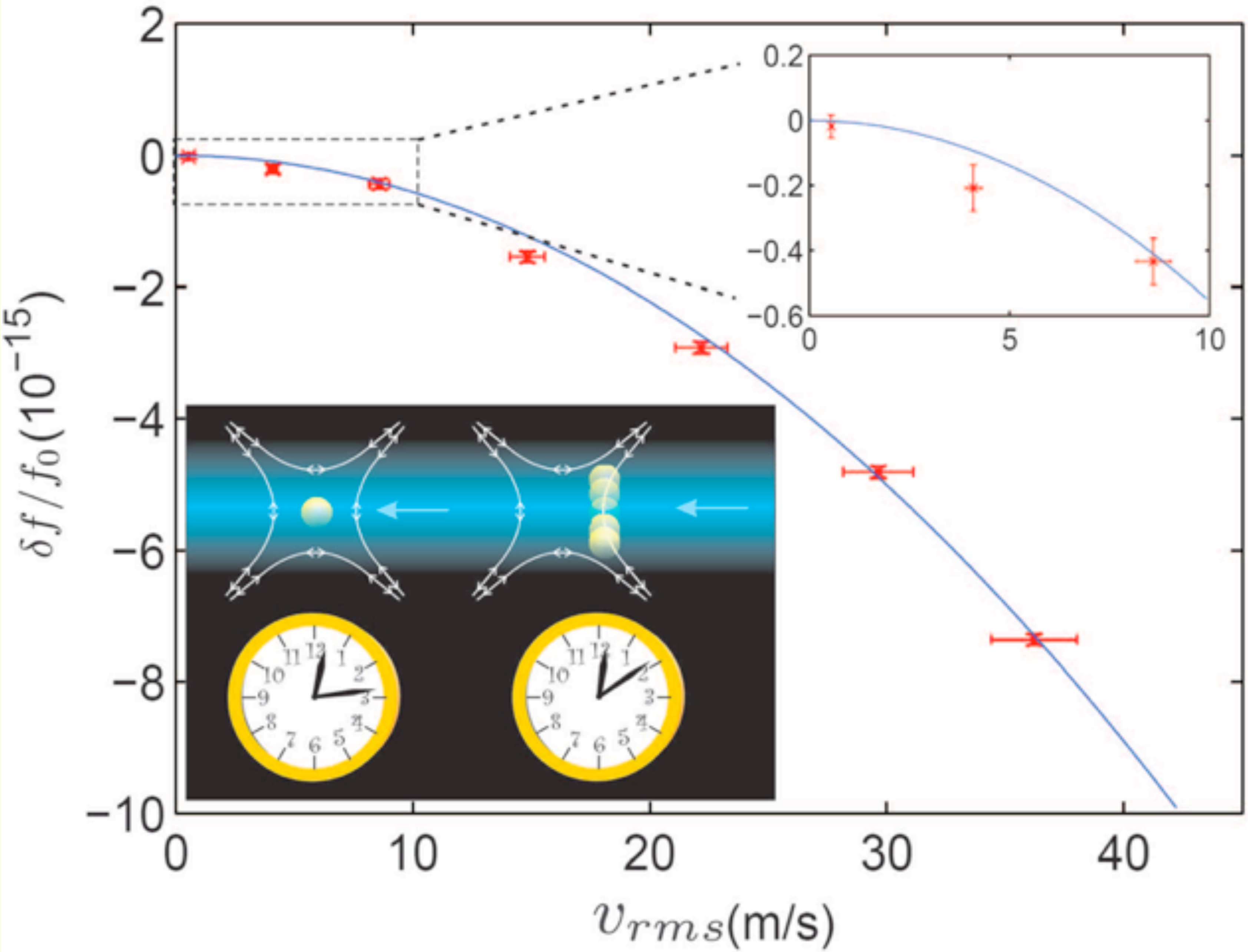


National Bureau of Standards, Boulder

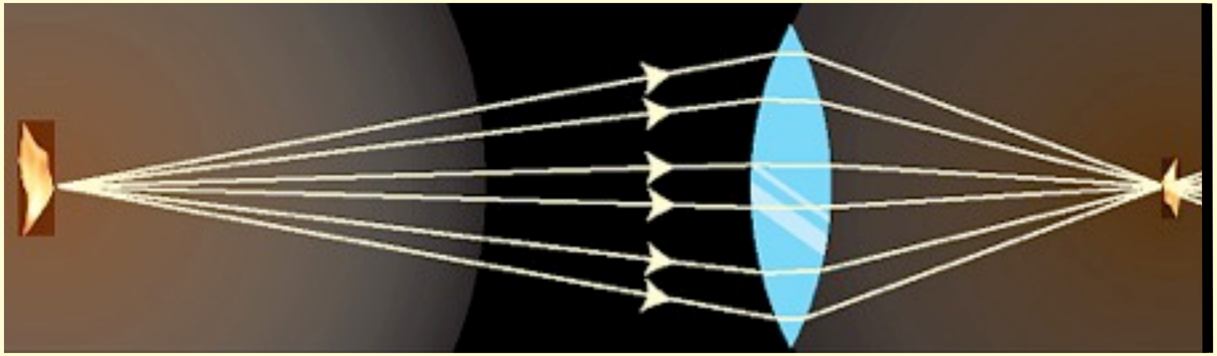
„Science" 24 September 2010



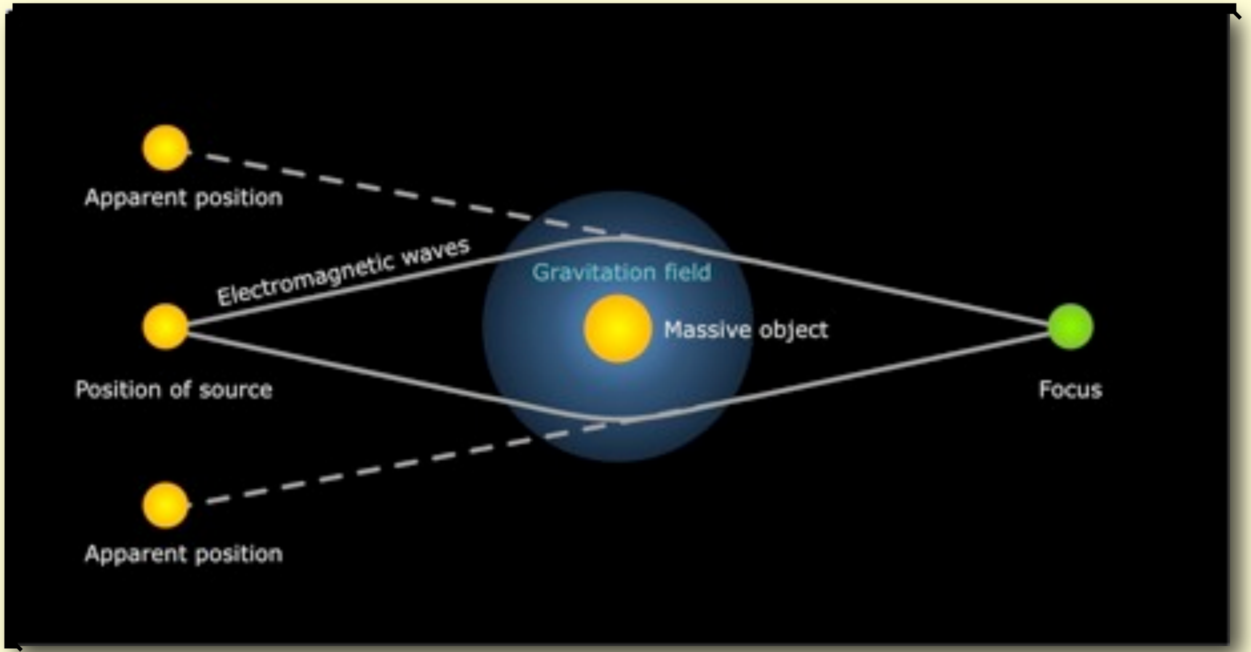
National Bureau of Standards, Boulder „Science" 24 September 2010



2
0
−2
−4
−6
−8
−10
0
10
20
30
40
$\delta f / f_0 (10^{-15})$
v_{rms}(m/s)
0.2
0
−0.2
−0.4
−0.6
0
5
10

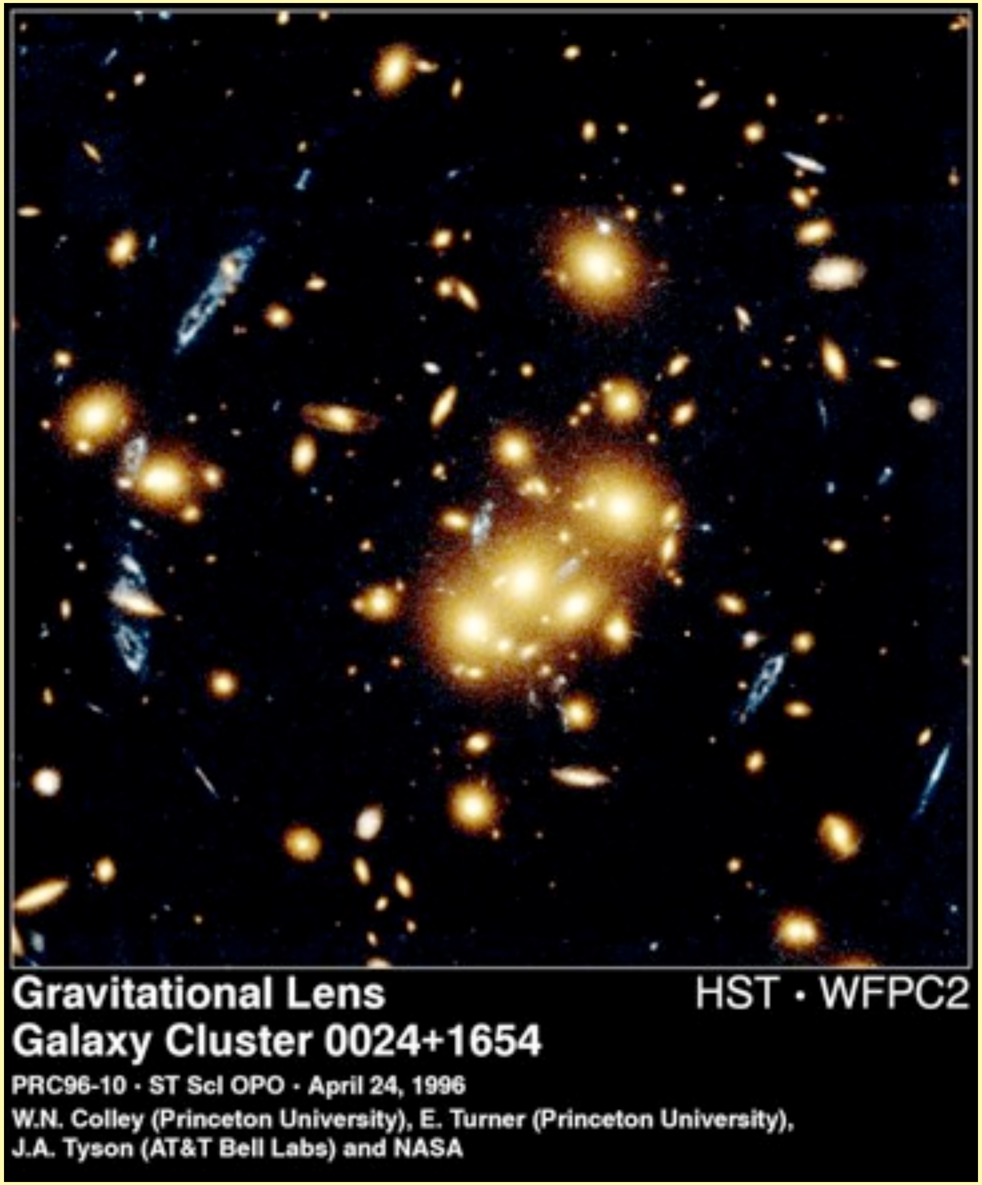


optical lens



gravitational lens

A photograph from the Hubble Telescope


Gravitational Lens
Galaxy Cluster 0024+1654
HST · WFPC2
PRC96-10 · ST ScI OPO · April 24, 1996
W.N. Colley (Princeton University), E. Turner (Princeton University),
J.A. Tyson (AT&T Bell Labs) and NASA

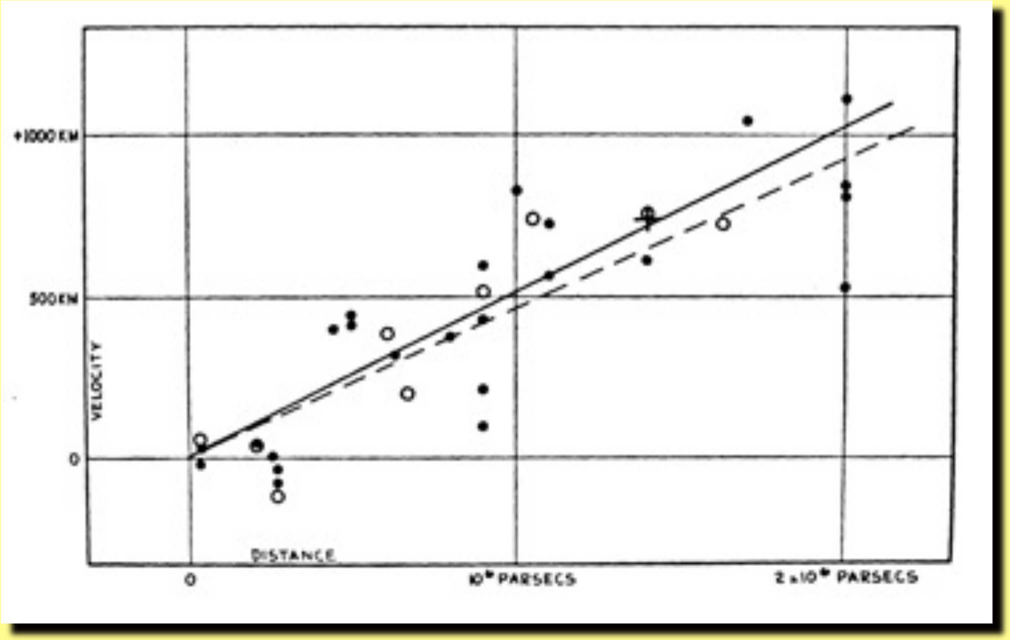
The expanding universe

Vesto Melvin Slipher
(1875-1969)

Edwin Hubble
(1889-1953)

Milton Humason
(1891-1972)

The expanding universe

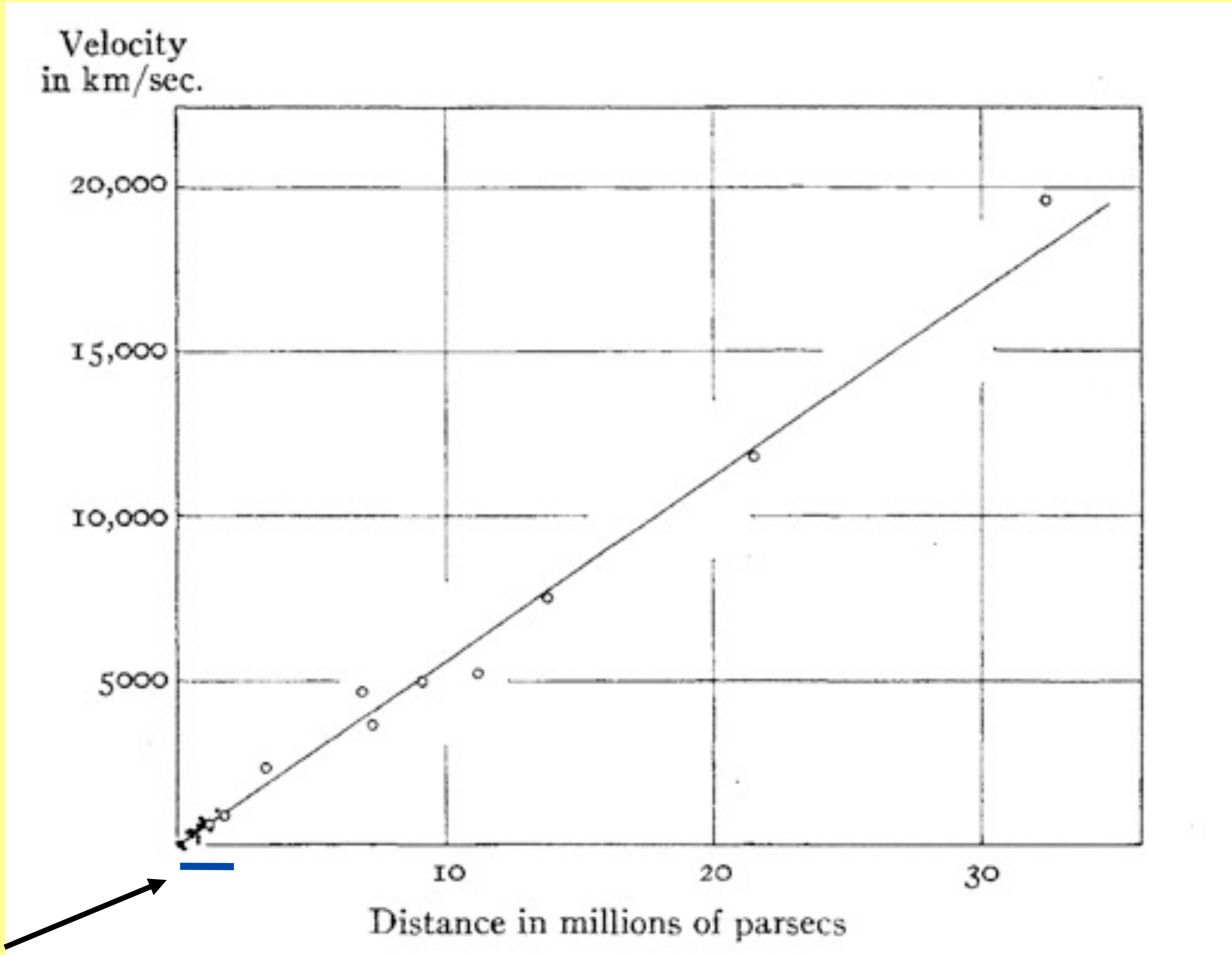


Edwin Hubble - ”A relation between distance and radial velocity among extra-galactic nebulae”,

Proc. Nat. Acad. Sci. 15, 168 (1929).

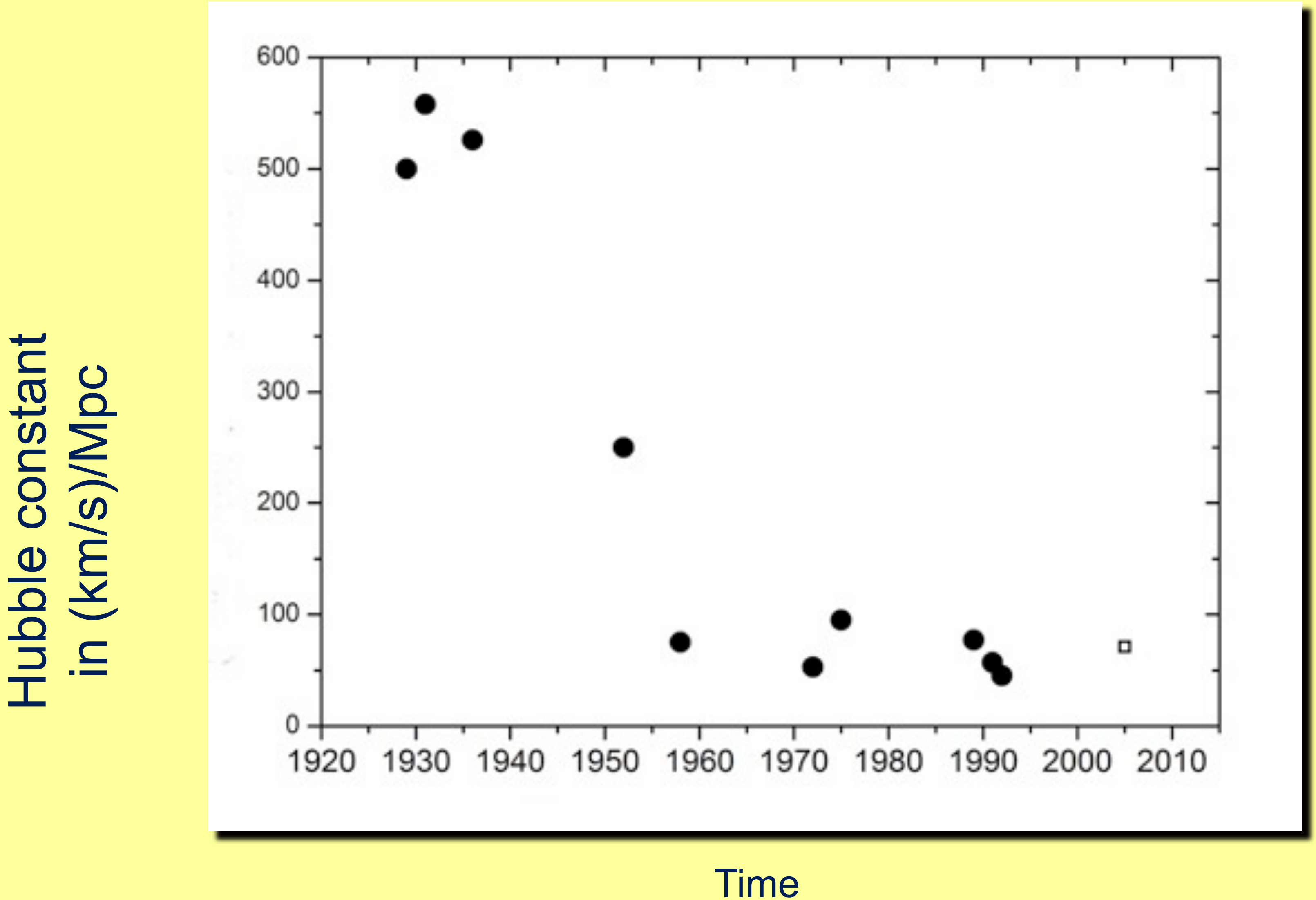
”The outstanding feature, however, is the possibility that the velocity-distance relation may represent the de Sitter effect, and hence that numerical data may be introduced into discussions of the general curvature of space.”

The expanding universe



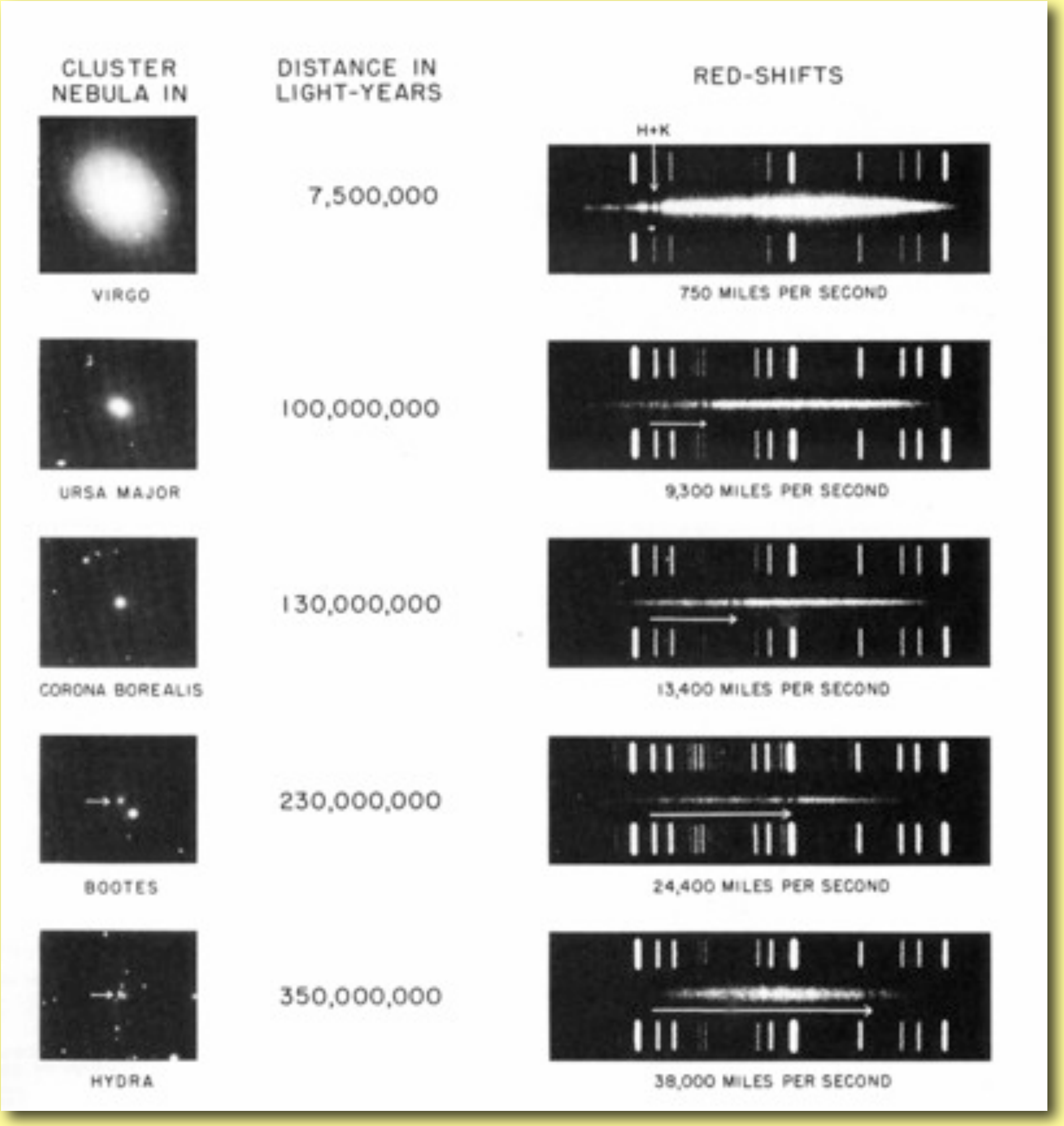
Hubble 1929

Hubble & Humason (1931)

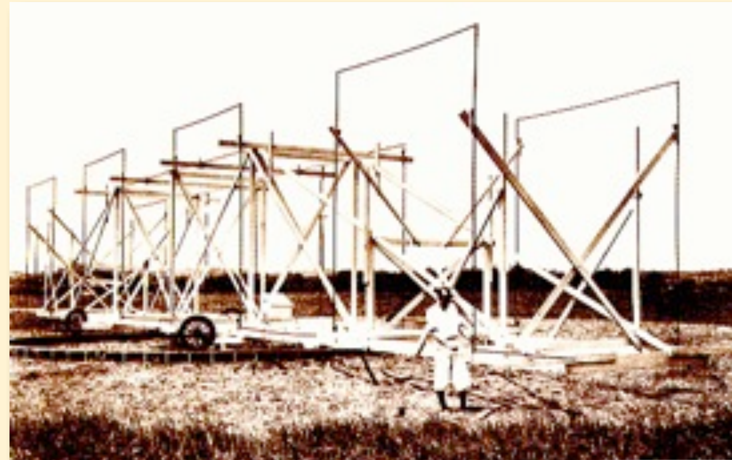


Elimination of various systematic errors caused considerable changes of the Hubble constant. The presently accepted value is H = 71 (km/s)/Mpc (± 5%).
$H = 2.30 \cdot 10^{-18}\ s^{-1} = 7.258 \cdot 10^{-11}\ year^{-1} \rightarrow$ Hubble age of 13.78 billion years

The expanding universe

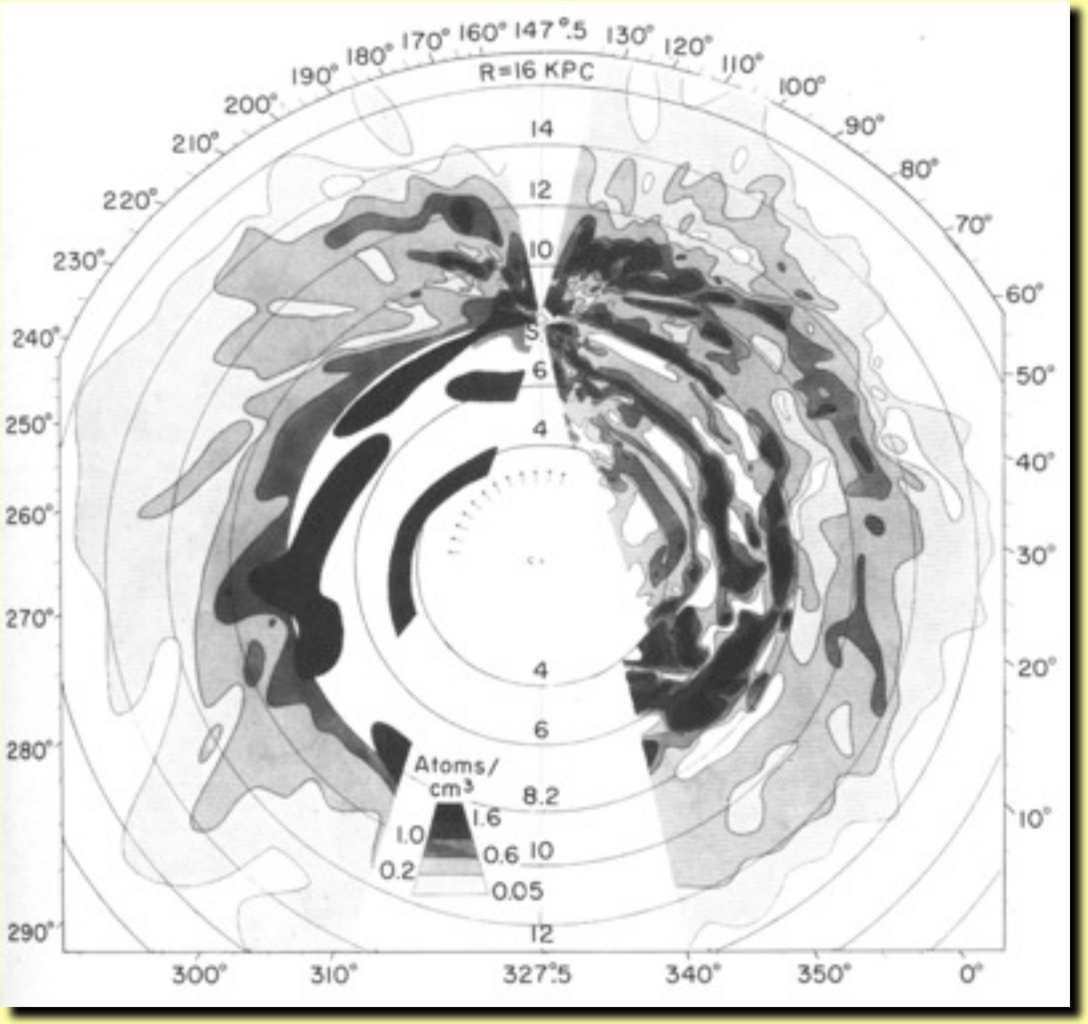


Radioastronomy



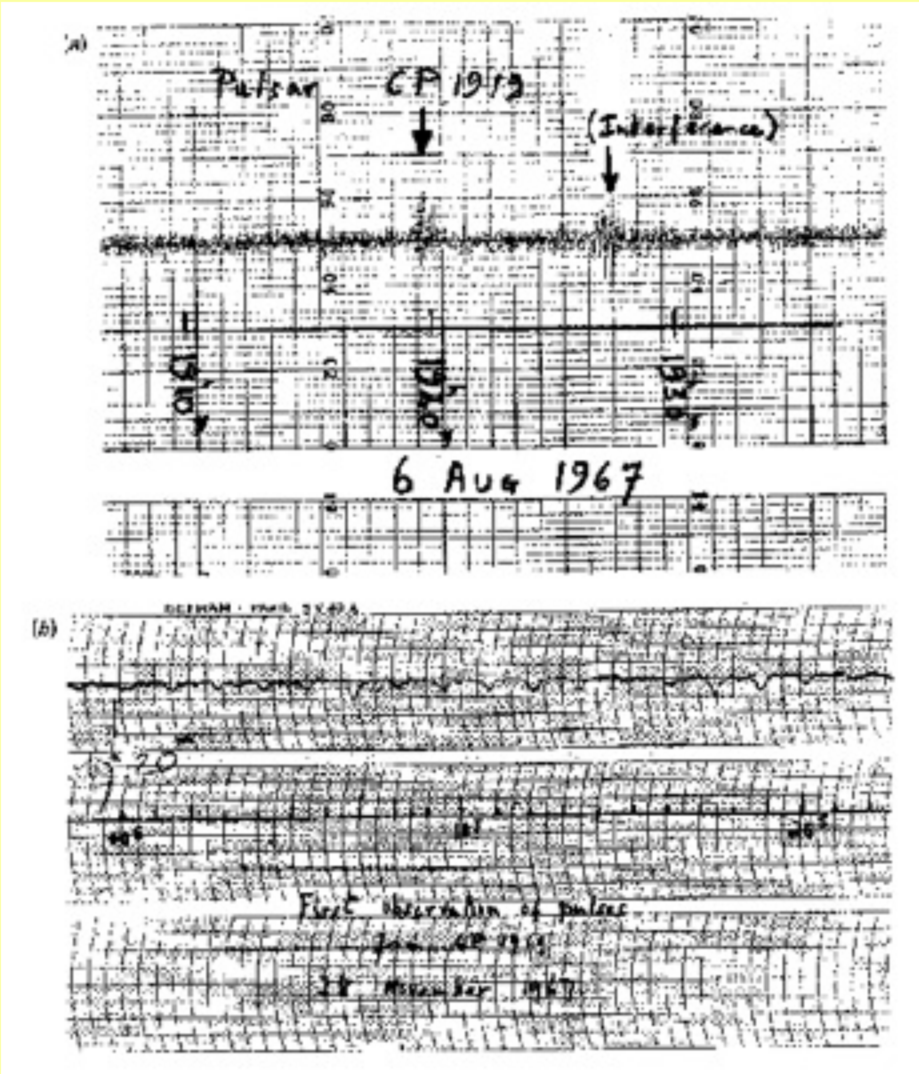
Karl Jansky and his radioantenna in 1932

Modern radiotelescopes



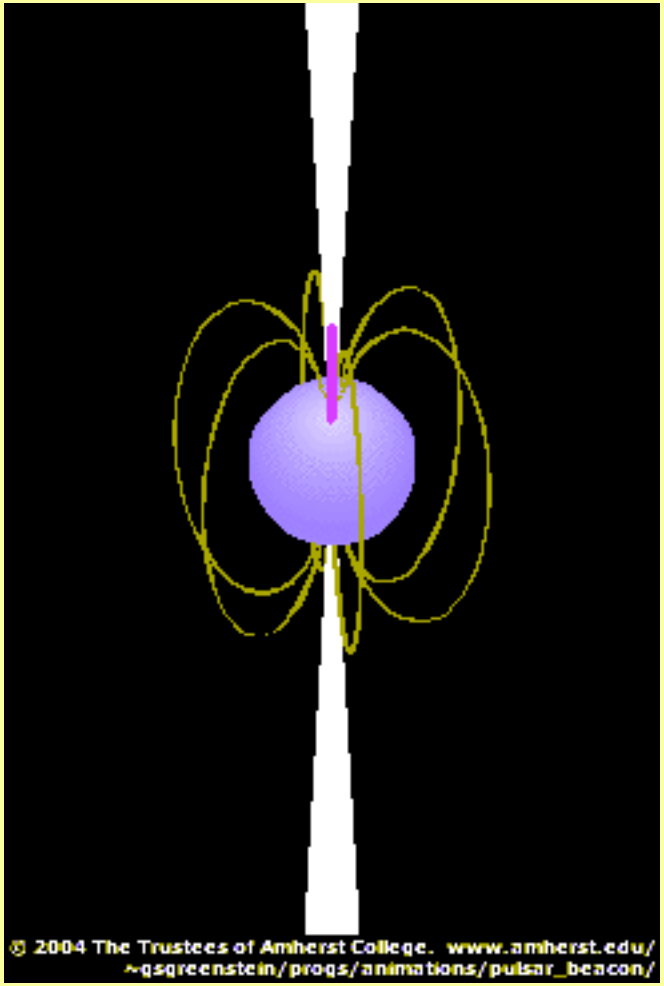
Spiral structure of the Galaxy from observations of the 21 cm line of neutral hydrogen (1958)

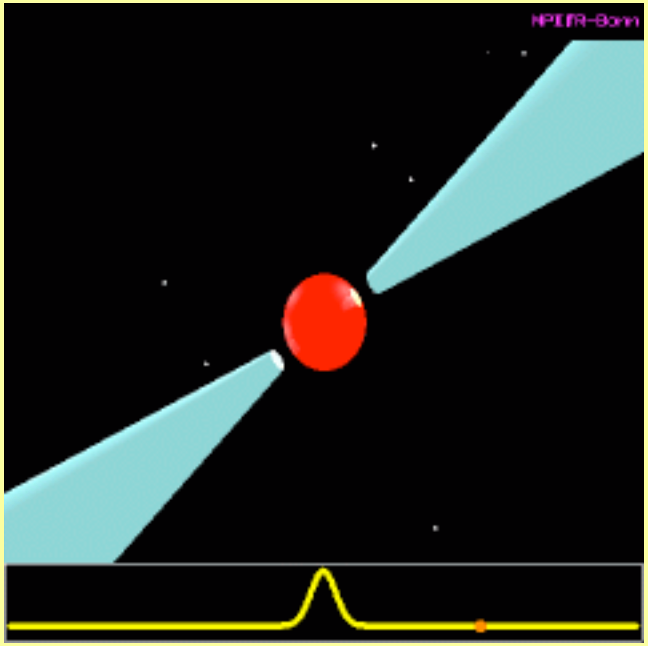
Pulsars



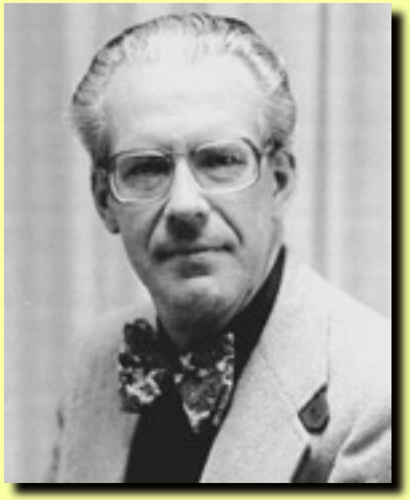
Jocelyn Bell-Burnell

Pulsars

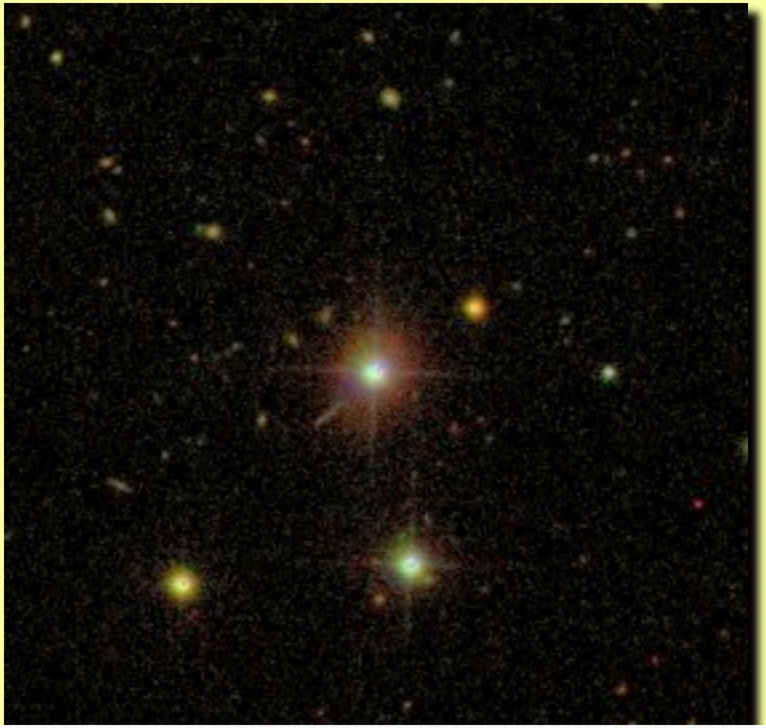

© 2004 The Trustees of Amherst College. www.amherst.edu/
~gsgreenstein/progs/animations/pulsar_beacon/

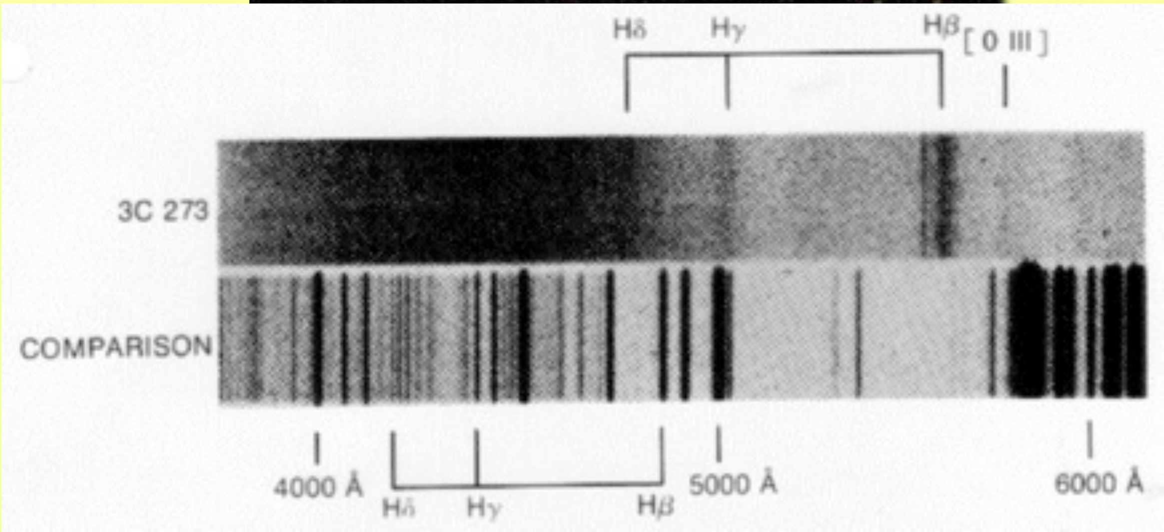

MPIfR-Bonn

Mysterious quasars



Marteen Schmidt

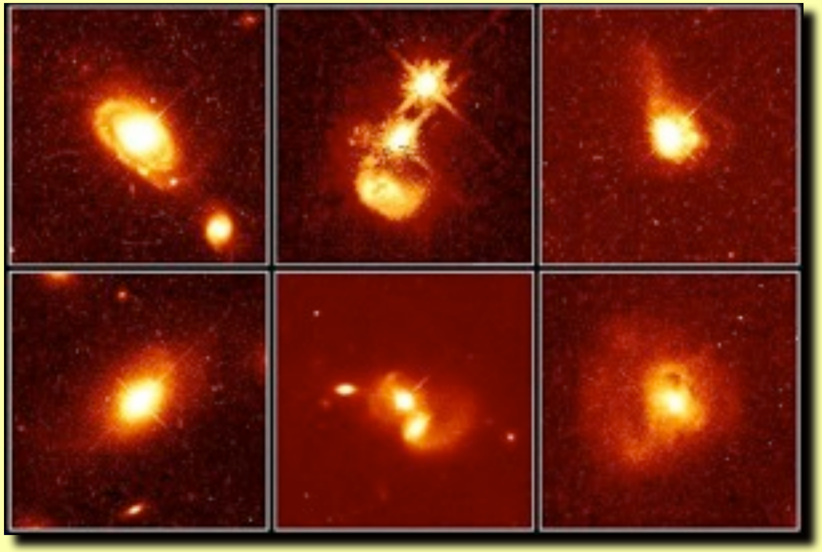




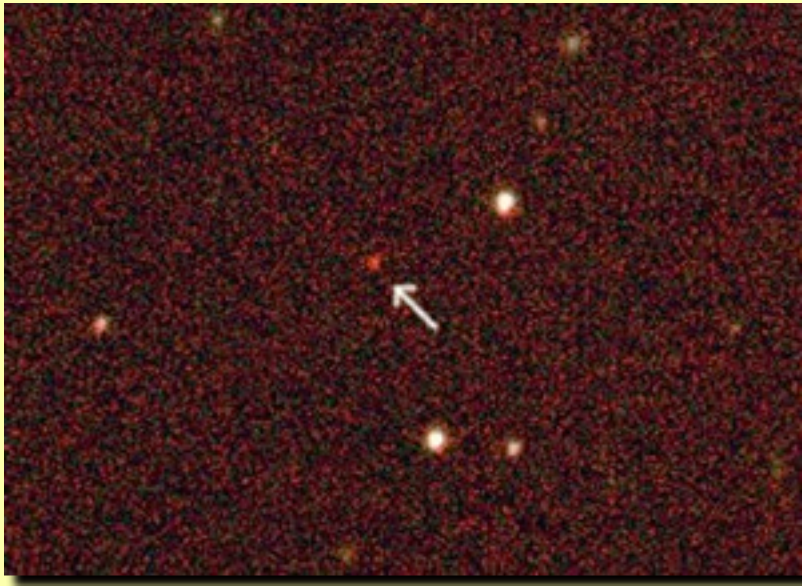
”3C 273: a starlike object with a large redshift”

Nature **197**, 1040 (1963)

Mysterious quasars



The farthest quasars



$z = \Delta\lambda/\lambda$ = 5.82 (IV 2000)

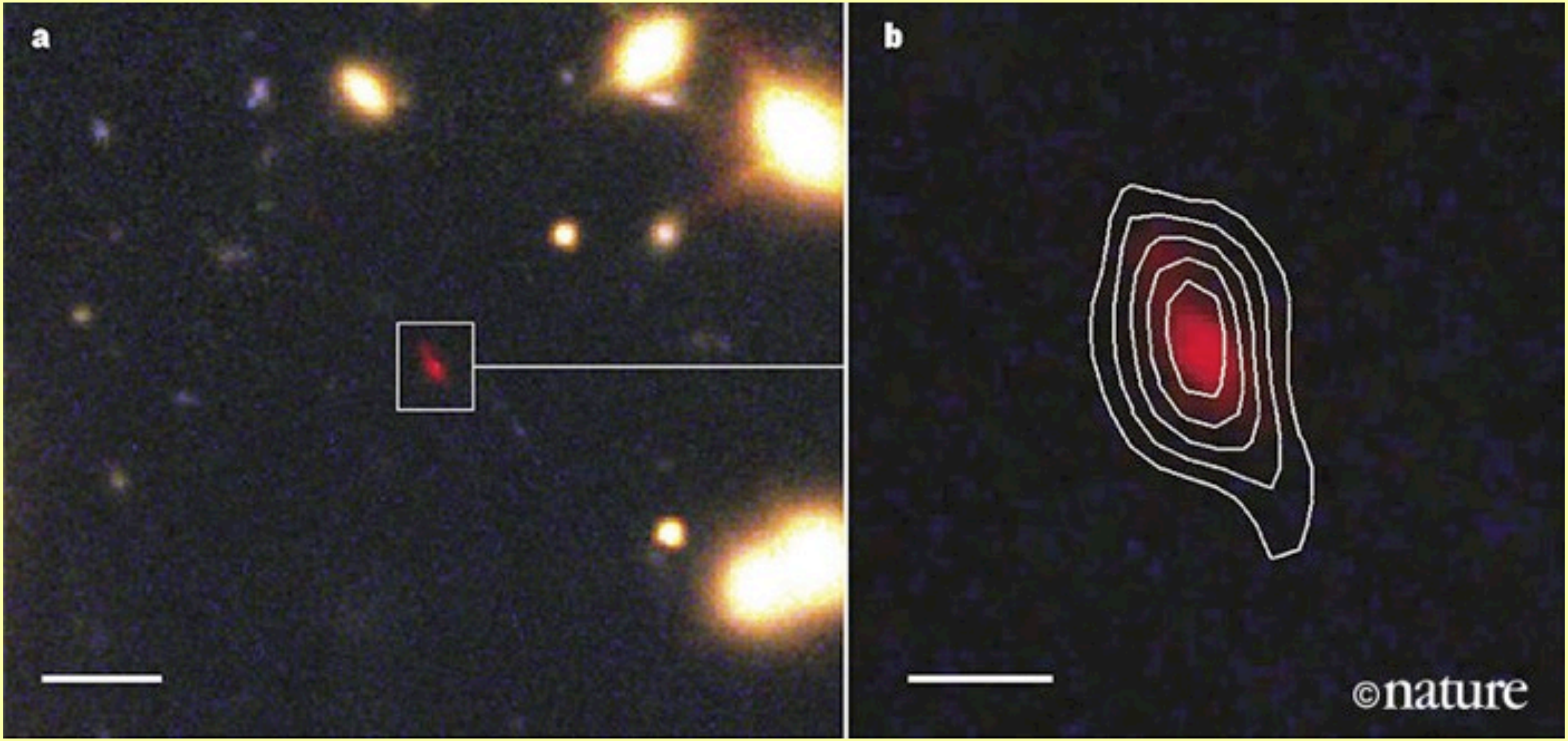
6.4 (X 2002)

10 (III 2004) ?

7.1 (VII 2013)

7.8 (IV 2015)

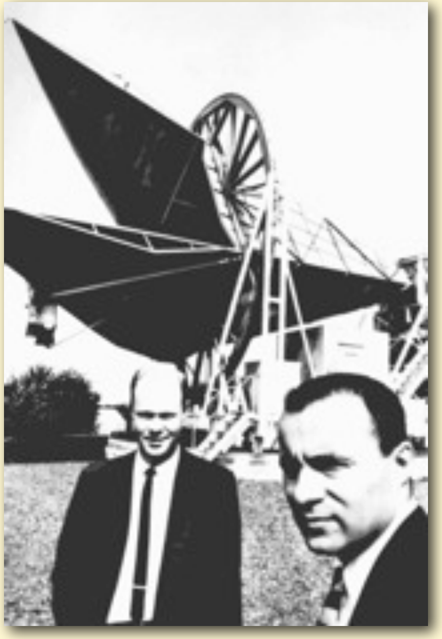
The most distant galaxy



z = 9.1; galaxy formed just about 250 million years after the Big Bang

Nature, May 17, 2018

The cosmic microvave radiation

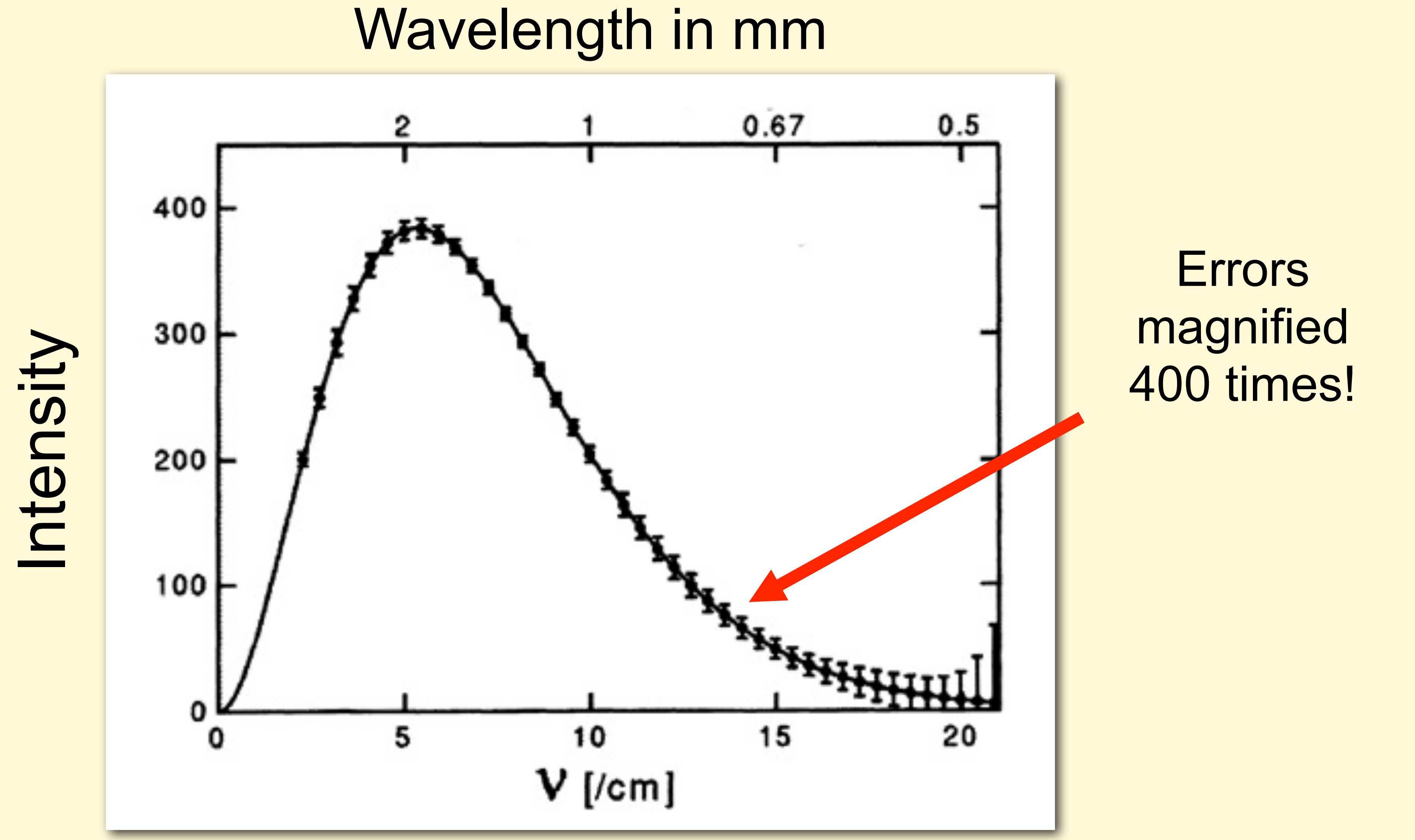


1955	3 ± 2 K	Le Roux
1957	4 ± 3 K	Shmaonov
1962	≈ 3 K	Rose
1961	2.3 ± 0.2 K	Ohm

Arno Penzias, Robert W. Wilson,
”A measurement of excess antenna temperature at 4080 Mc/s”,
ApJ **142**, 419-420 (1965)

R. H. Dicke, P. J. E. Peebles, P. G. Roll, D. T. Wilkinson,
”Cosmic black-body radiation”,
ApJ **142**, 414-419 (1965)

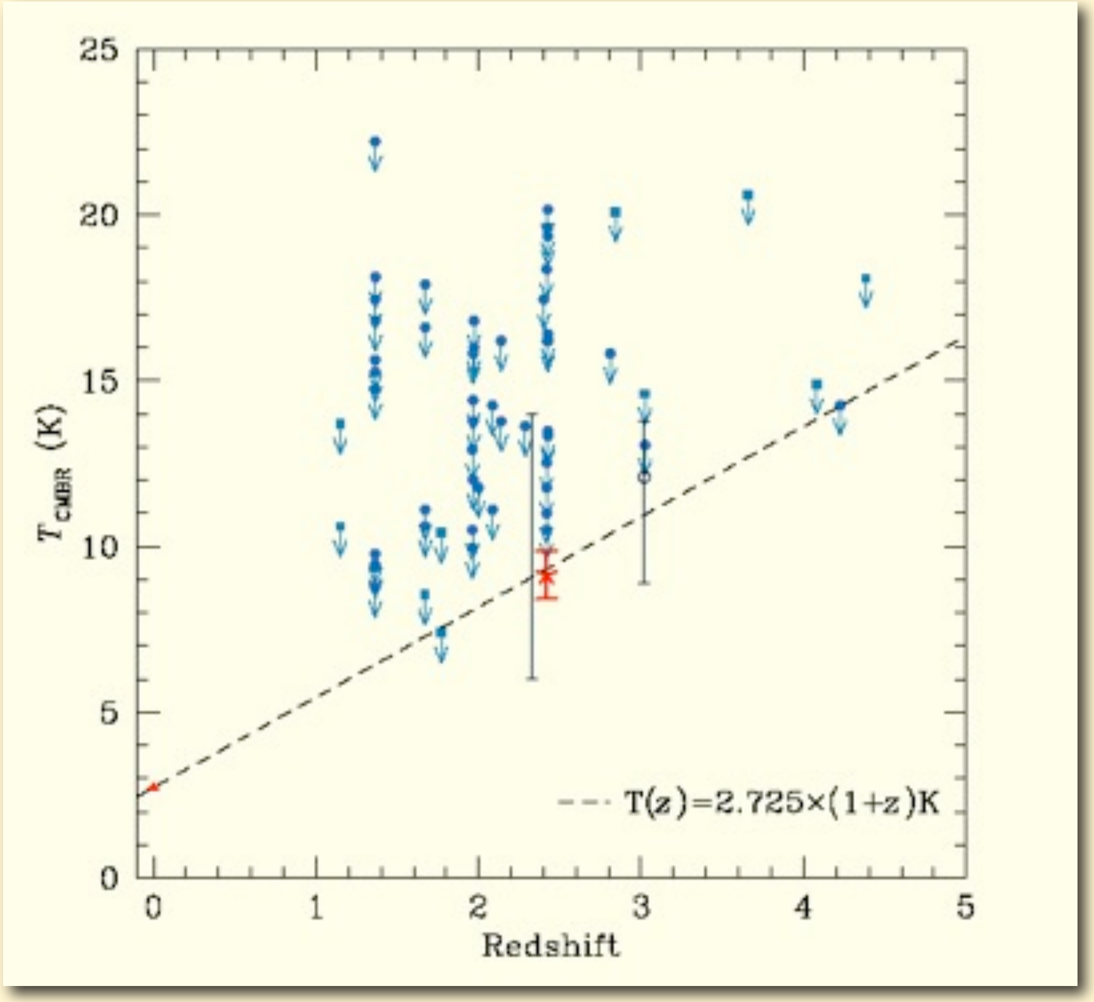
(NYT 21 V 1965)



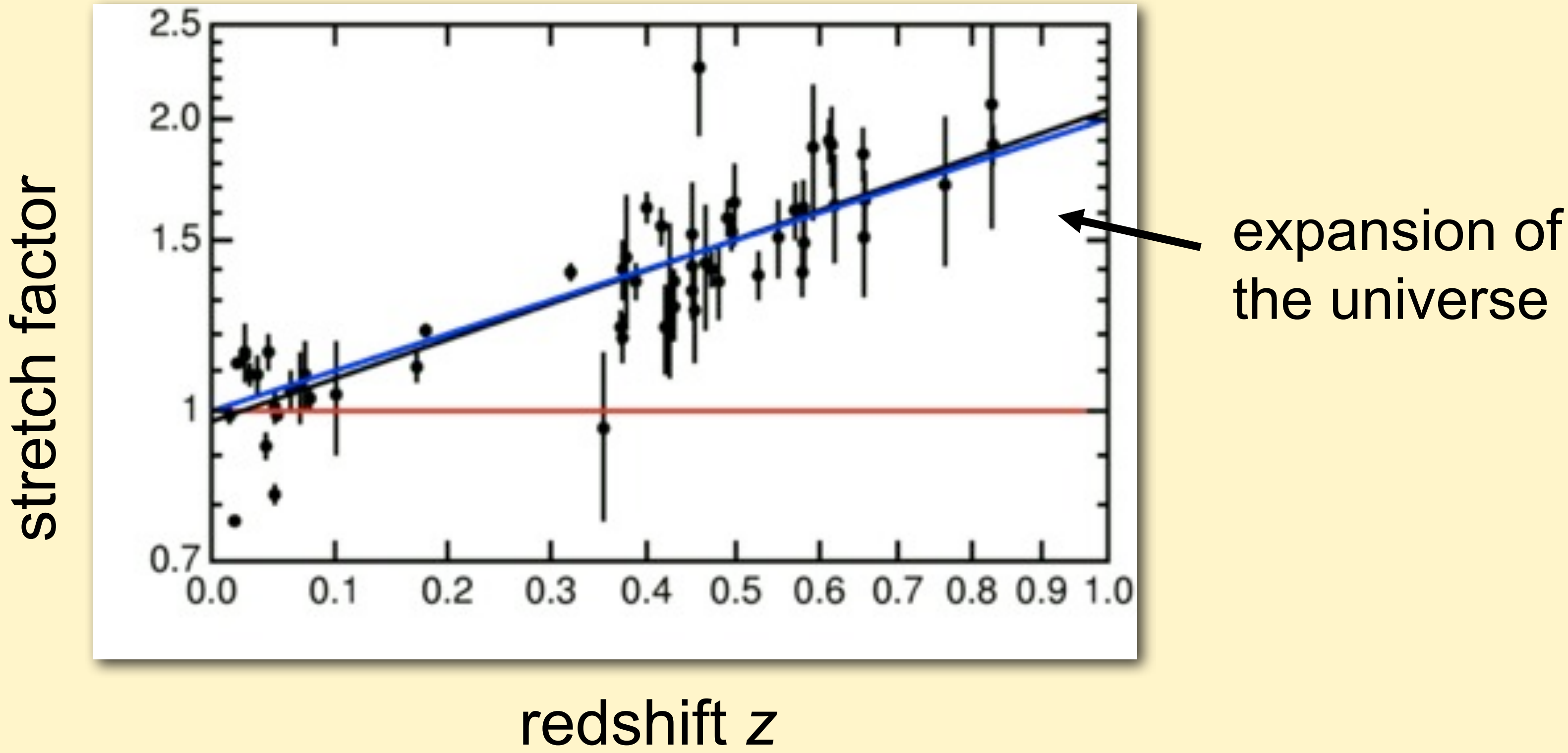
T = (2.726 ± 0.010) K

(411 ± 2) photons in cm^3

Observational evidence for expansion and cooling of the universe



R. Srianand, P. Noterdaeme, P. Petitjean, C. Ledoux, *Astronomy & Astrophysics* **482** (2008)



”Finally, it is interesting to note that while the redshift of the light measures the expansion of the universe with a ”microscopic clock” of period, typically T $\approx$ 2•10^{-15} s, our ”macroscopic clocks”, the Type Ia SNe measure the expansion over a 4 week period, or T $\approx$ 2.4•10^{6} seconds. The $1+z$ expansion effect is thus consistent for two time periods that differ by 21 orders of magnitude.”

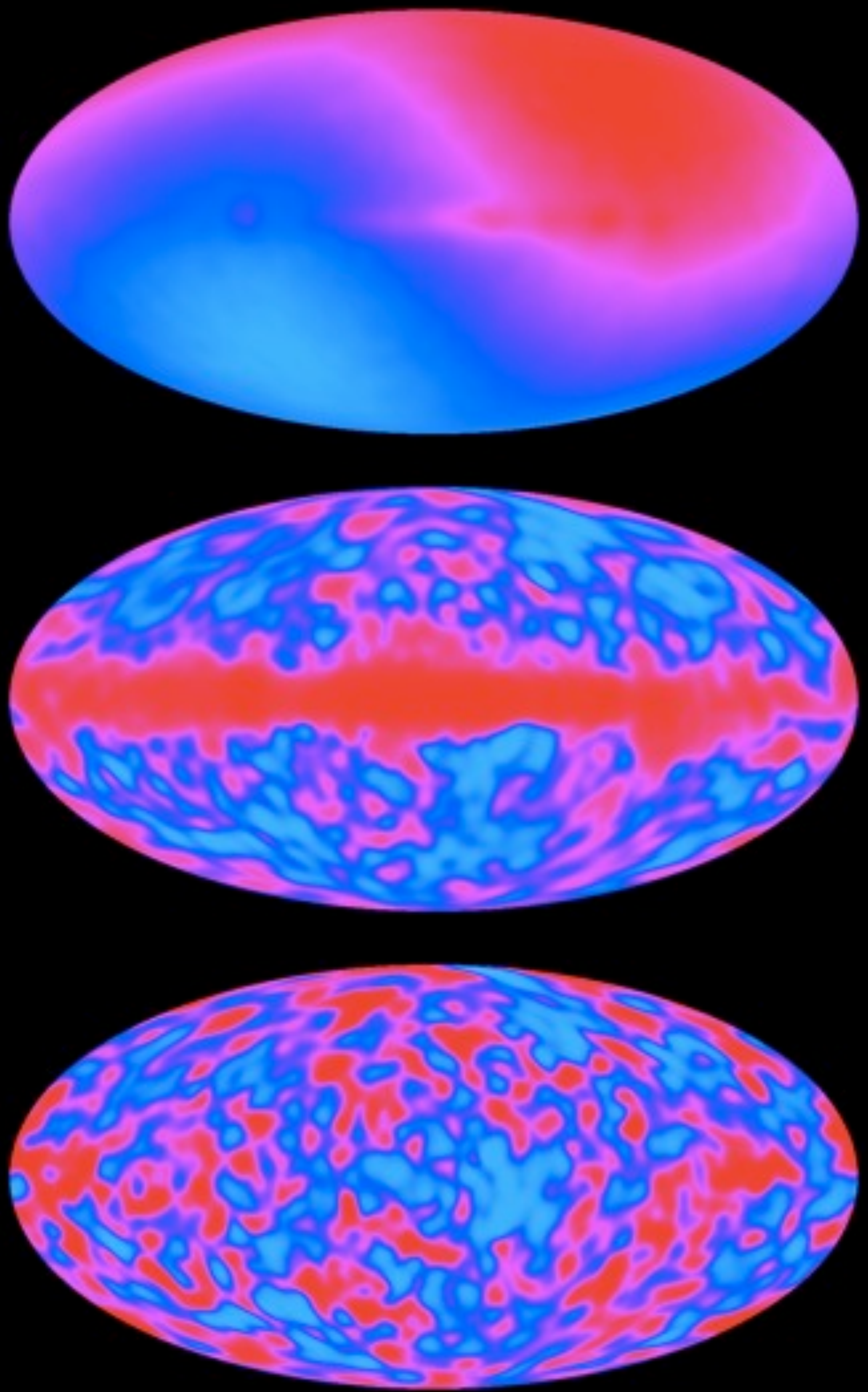
G. Goldhaber i in. (The Supernova Cosmology Project), *Ap. J.* **558**, 338 (2001)

During the last decades cosmology became an exact science based on precise results of observations

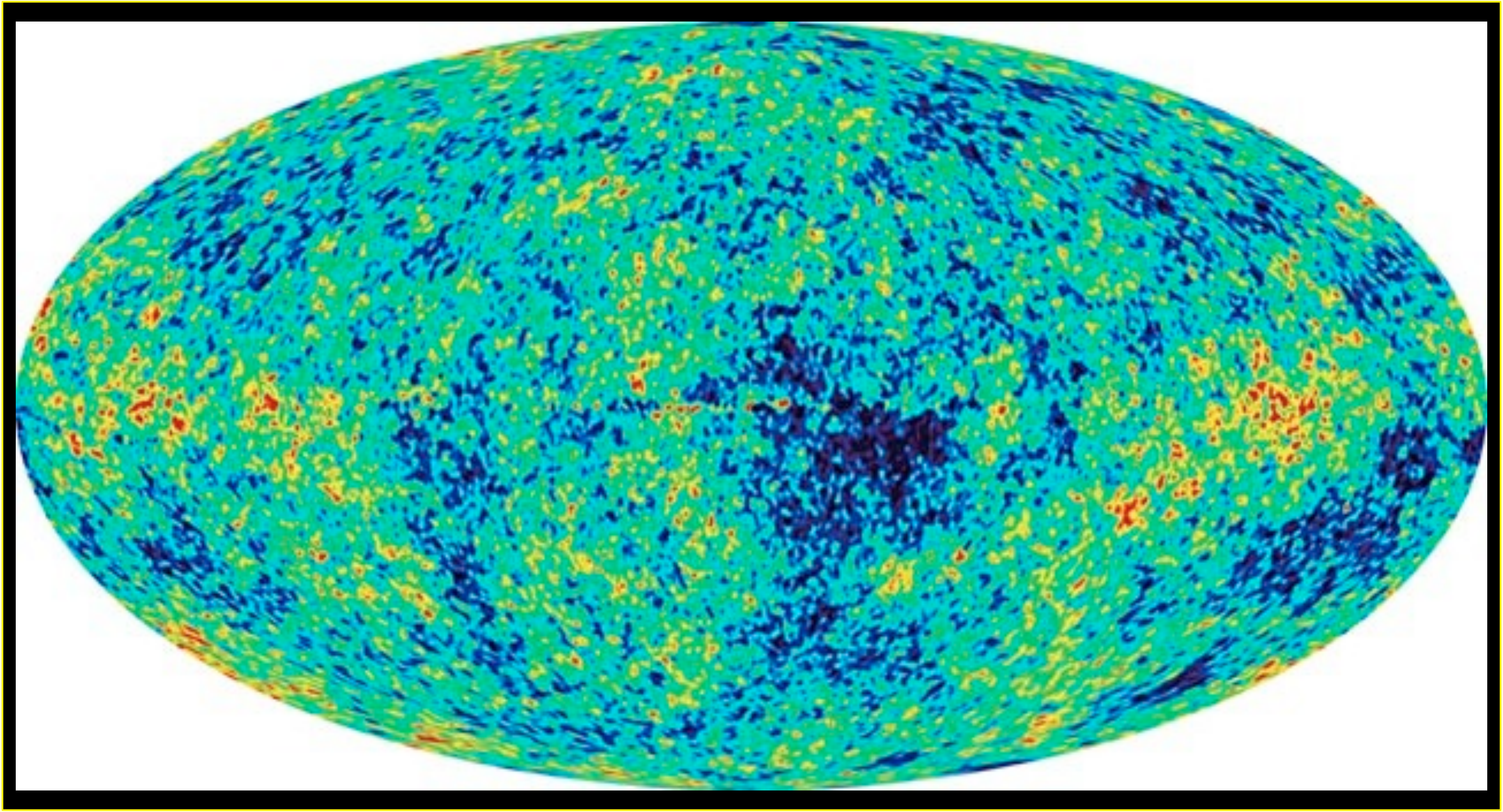
1981 inflation model of the universe (Alan Guth)
(1982 Andrei Linde, Andreas Albrecht, Paul Steinhardt)
1992 COBE satellite (Cosmic Background Explorer)
1999 baloon experiment BOOMERANG (Balloon Observations of Millimetric Extragalactic Radiation and Geomagnetics)
2000 results of MAXIMA (Millimeter Anisotropy Experiment Imaging Array) from 1998-1999
2001 baloon experiment ARCHEOPS
2003 WMAP (Wilkinson Microwave Anisotropy Probe)
2013 PLANCK probe
2014 BICEP2 results on polarization of CMB (withdrawn!)

Cosmic microwave background radiation

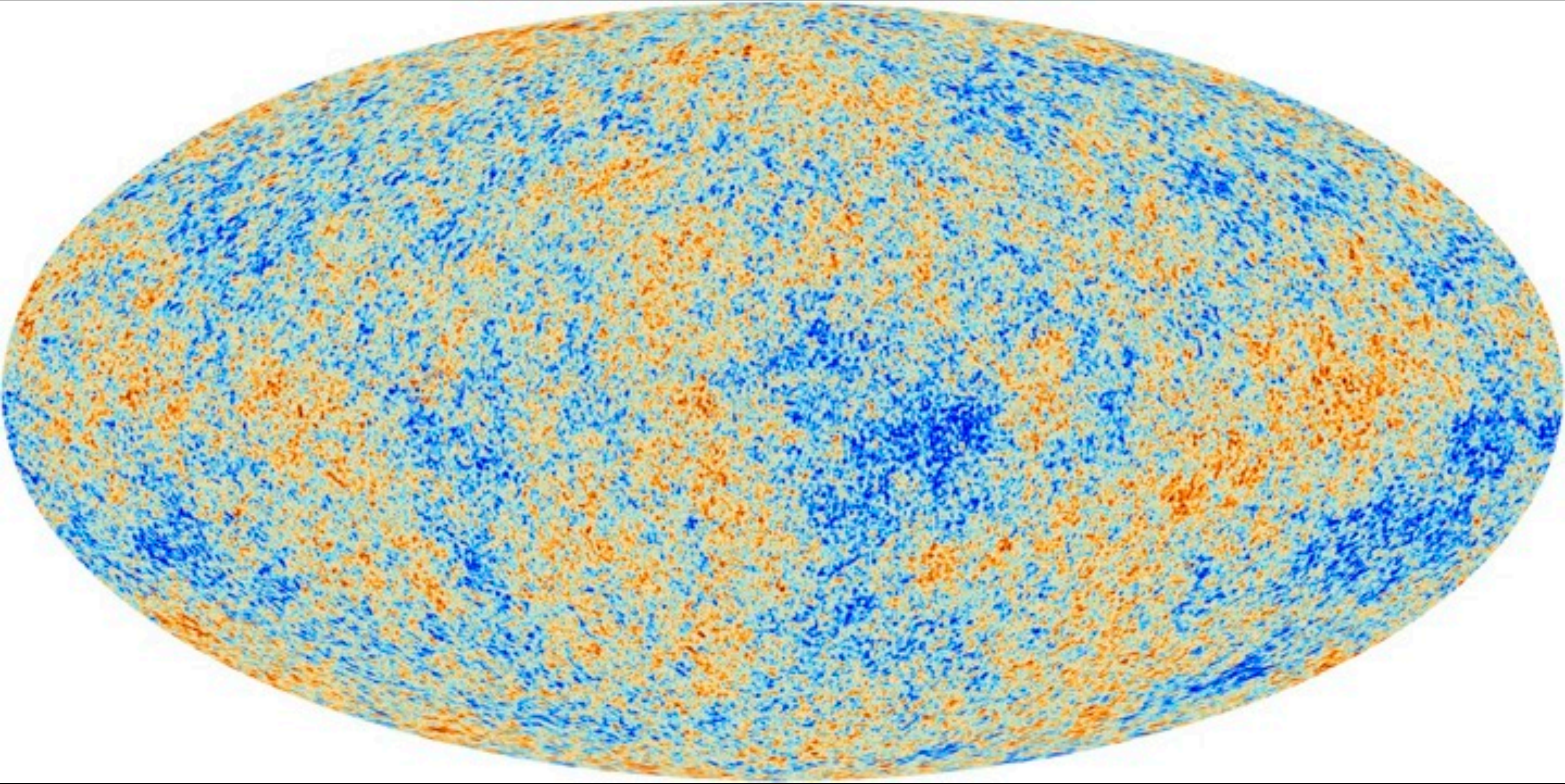
COBE results



Results from WMAP (Wilkinson Microwave Anisotropy Probe) (2003)



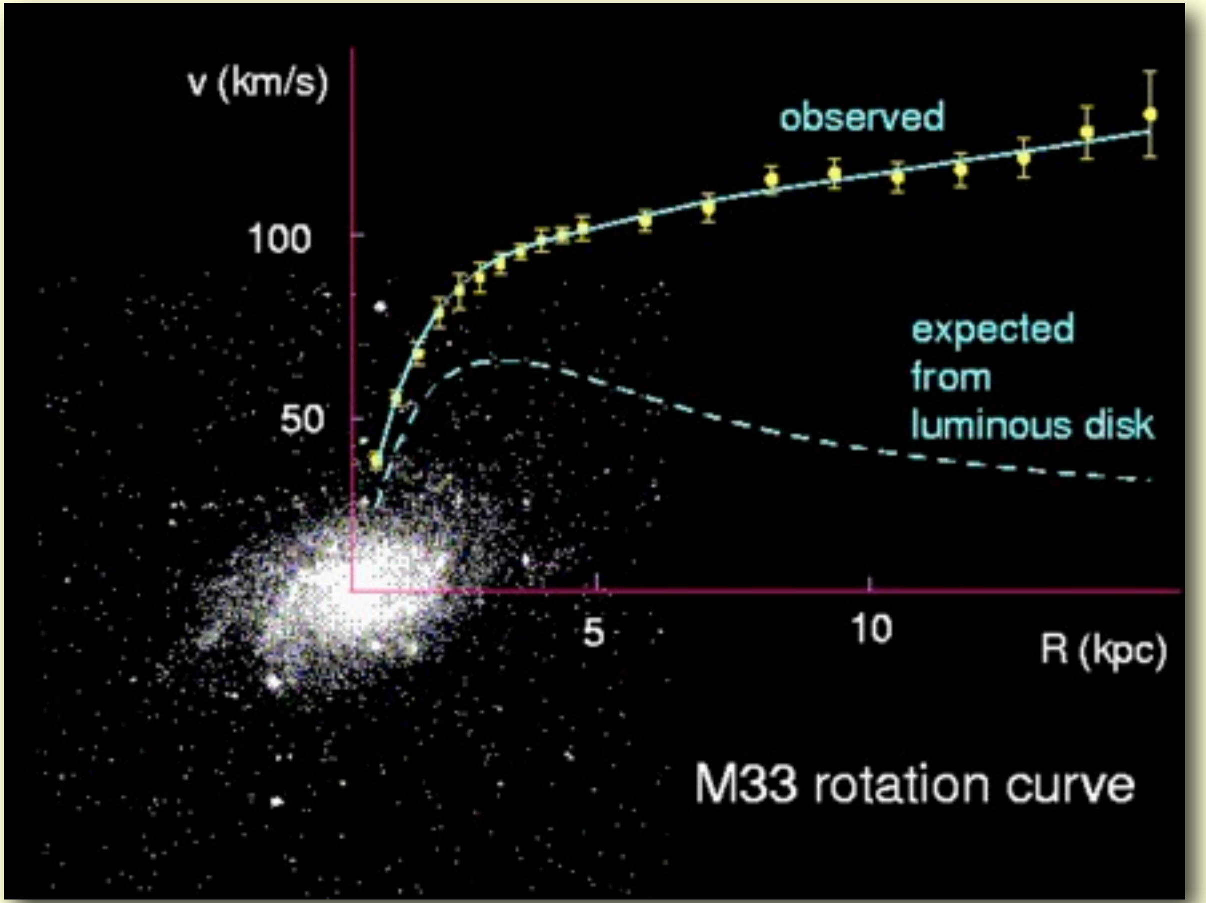
Results from ESA PLANCK Space Telescope (2013)



A surprise from studies of the rotation of galaxies

Zwicky (1933);

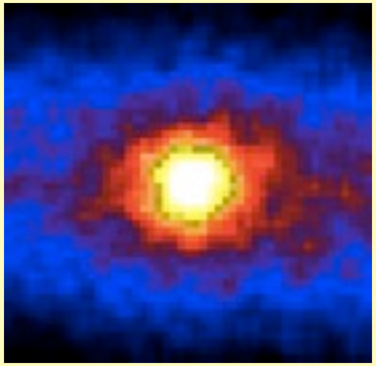
Rubin, Ford and Thonnard (1978)



Conventional explanation: dark matter in the form of **W**eakly **I**nteracting **M**assive **P**articles (WIMPs) – not yet detected in spite of numerous experiments

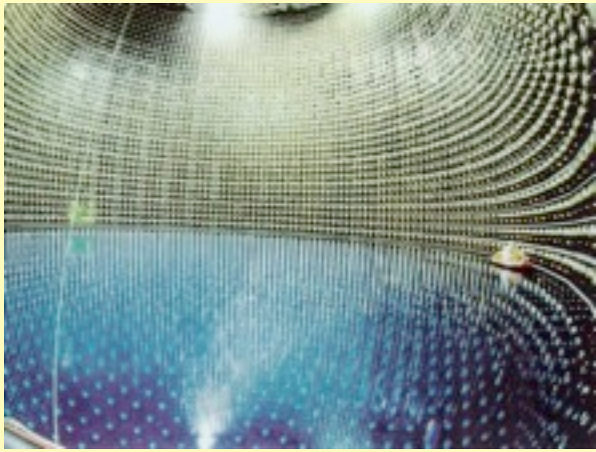
Other scenarios: e.g. **MOND** (**Mo**dified **N**ewtonian **D**ynamics)

Stay tuned !



Neutrinos from the sun

1967 first solar neutrinos detected
– **Homestake** detector (Davis et al.)

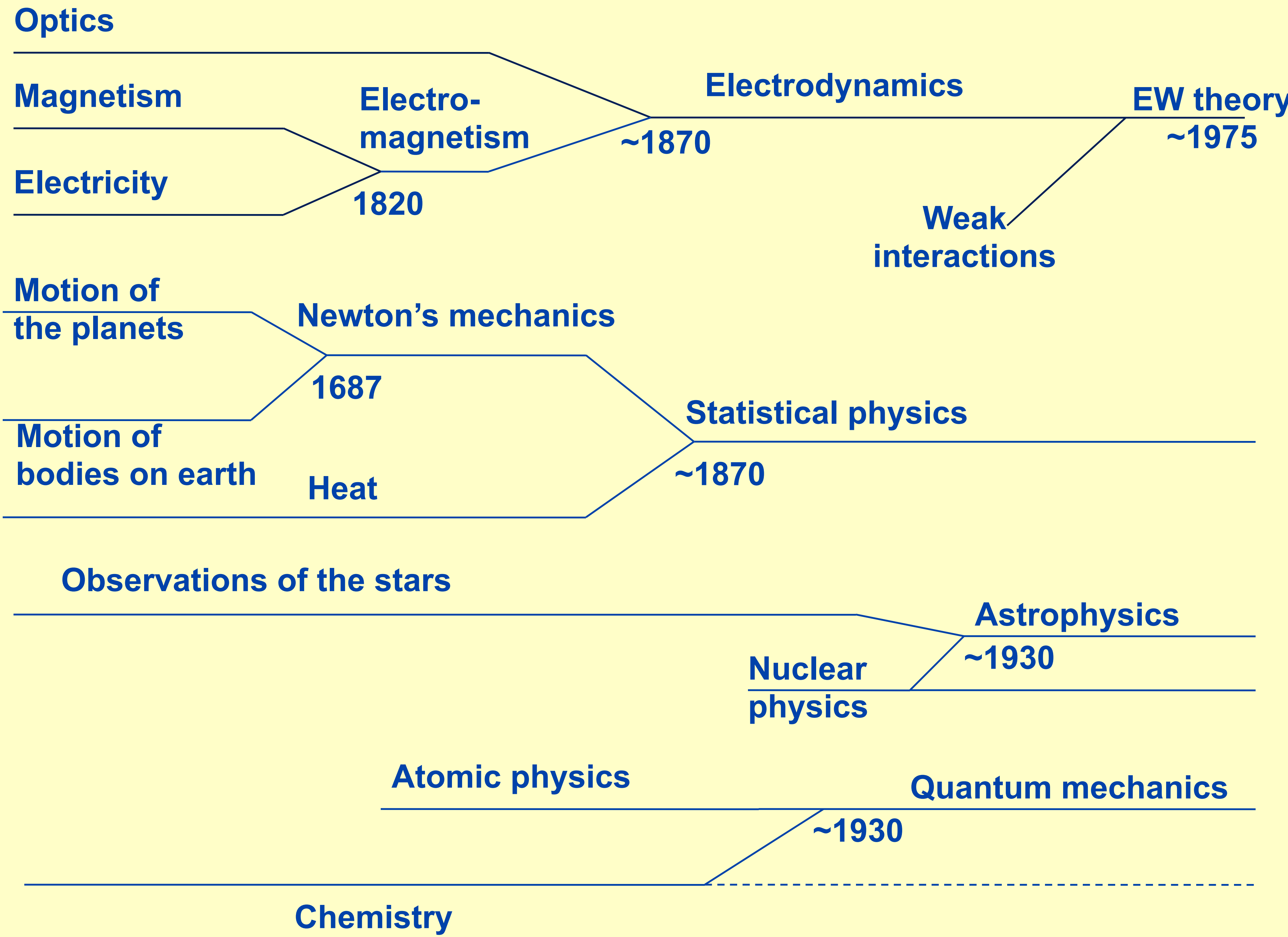


1998 neutrinos have non-zero mass
– results from the international
Superkamiokande Collaboration

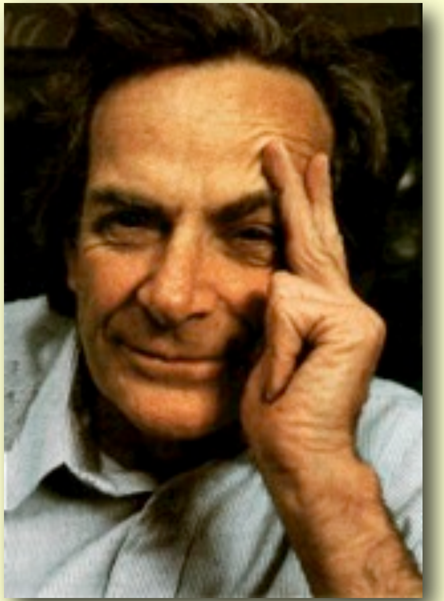
2002 confirmation of solar neutrino oscillations (SNO)

Solar Neutrino Observatory

Concluding remarks


Optics
Magnetism
Electricity
Electro-
magnetism
1820
Electrodynamics
~1870
EW theory
~1975
Weak
interactions
Motion of
the planets
Newton's mechanics
1687
Motion of
bodies on earth
Heat
Statistical physics
~1870
Observations of the stars
Astrophysics
~1930
Nuclear
physics
Atomic physics
Quantum mechanics
~1930
Chemistry

Where are we ?



”If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe, it is the atomic *hypothesis* (or the atomic *fact*, or whatever you wish to call it) that *all things are made of atoms*...
In that one sentence,....there is an enormous amount of information about the world, if just a little imagination and thinking are applied.”

The Feynman Lectures on Physics, vol.1, § 1.2 (1963)

[Today Feynman perhaps would have written:
”all things are made of quarks and leptons”]

Unexpected discoveries

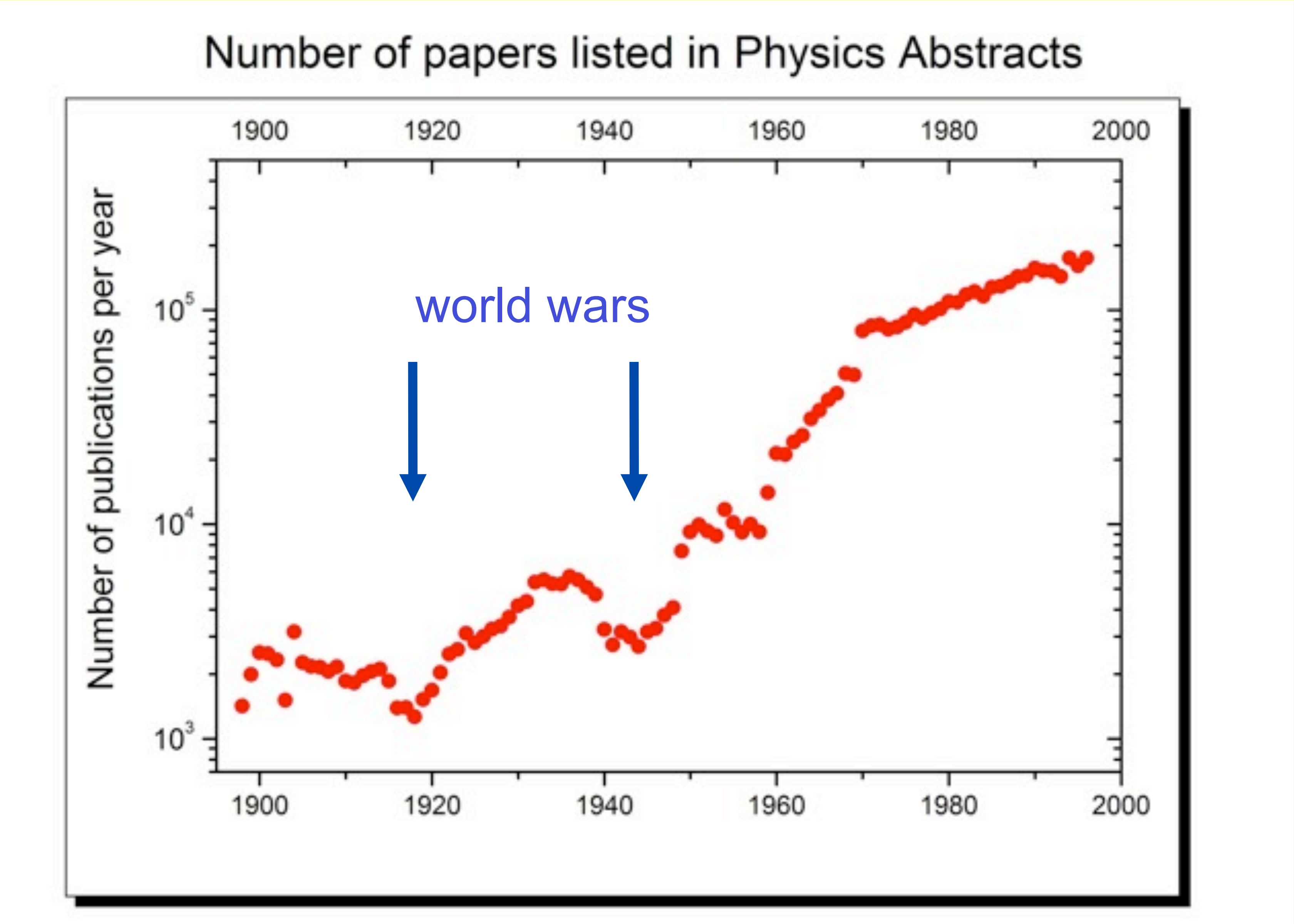
Kapitsa (1959) defined unexpected discovery as such that could neither be predicted within theories existing earlier, nor fully explained by them. According to Kapitsa there were only eight such unexpected discoveries in the last 200 years:

- Electric current (Galvani, 1780)
- The magnetic effect of a current (Oersted, 1820)
- The photoelectric effect (Hertz, 1887)
- The negative result of the Michelson-Morley experiment (1887)
- The electron (J. J. Thomson, 1897)
- Radioactivity (Becquerel, 1896)
- Cosmic radiation (Hess, 1912)
- Fission of uranium (Hahn and Strassmann, 1938)

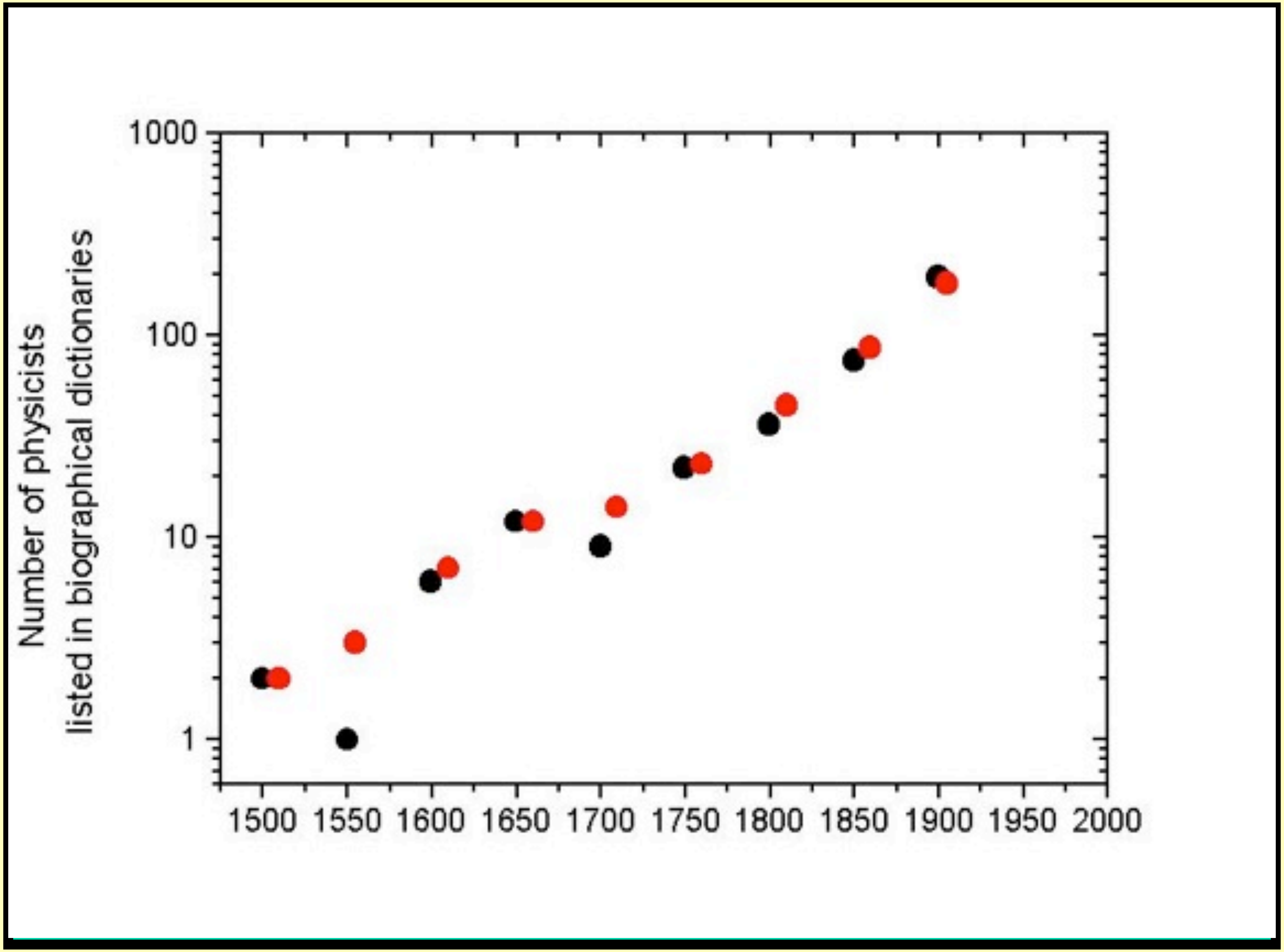
Kapitsa's choice could perhaps be disputed (e.g. What about X-rays? and Why the electron?) but one may surely enlarge the list by a few more items:

- Strange particles (Rochester and Butler,1947)
- Quasars (Schmidt, 1963)
- High temperature superconductivity (Bednorz and Müller, 1986)

We may be sure that there will be more unexpected discoveries in the future



Number of papers listed in Physics Abstracts
Number of publications per year
1900
1920
1940
1960
1980
2000
10^5
10^4
10^3
world wars



Lexikon der Naturwissenschaftler (Berlin 2000)
Физики - Биографический справочник (Moscow 1983)

- The total number of physicists in 1900 was about 1100, of which about 200, or 20% were ”important”, so that after hundred years they are still listed in biographic dictionaries.
- The total number of physicists around 2000 probably exceeded one million. It is clear that biographic dictionaries in 2100 will list much less than 20% of them.
- With the percentage of ”important” physicists clearly decreasing in time, physics changes its character and becomes more like an ”industry” with increasing number of ”scientific workers”.

The Breakthrough Prize for Fundamental Physics

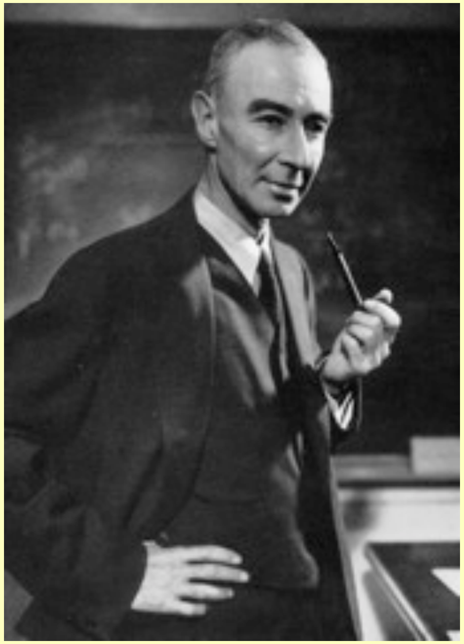
• 2016 Prize awarded to five experiments investigating neutrino oscillations [Super K Collaboration, Daya Bay Collaboration, SNO Collaboration, T2K Collaboration, KamLAND Collaboration] $\longrightarrow$ several hundred members!

• 2016 Special Prize awarded to the discoverers of gravitational waves on February 11, 2016 [LIGO-VIRGO Collaboration, 1012 people]

It is difficult to predict evolution of physics in the next decades.

It is, however, certain that

- physics will not be finished soon
- physics research will become even more collective and will include even more authors
- there will be unexpected discoveries
- there will also be wrong turns and twists (as in the past)



"Physics will change even more. If it is radical and unfamiliar and a lesson that we are not likely to forget, we think that the future will be only more radical and not less, only more strange and not more familiar, and that it will have its own new insights for the inquiring human spirit."

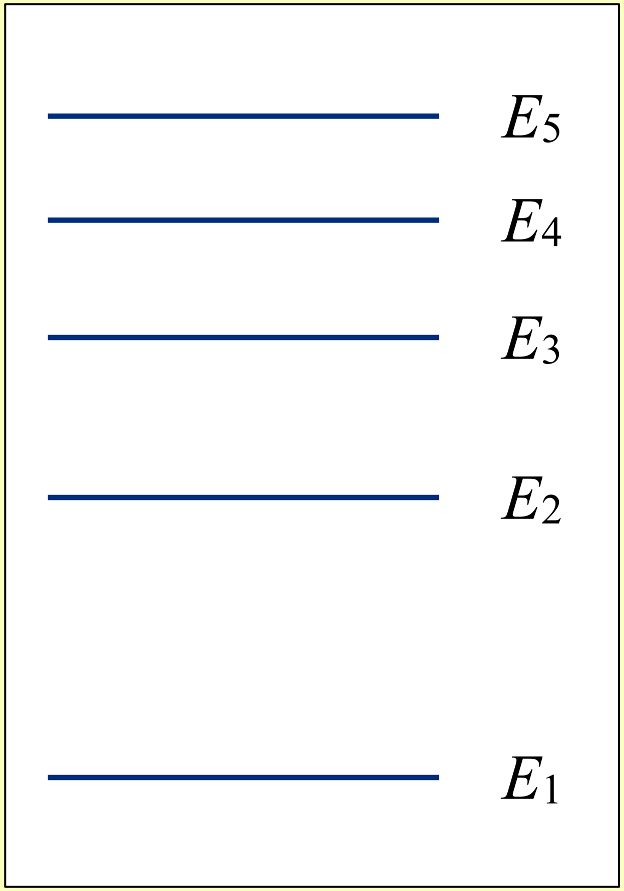
J. Robert Oppenheimer

This is the end of the course

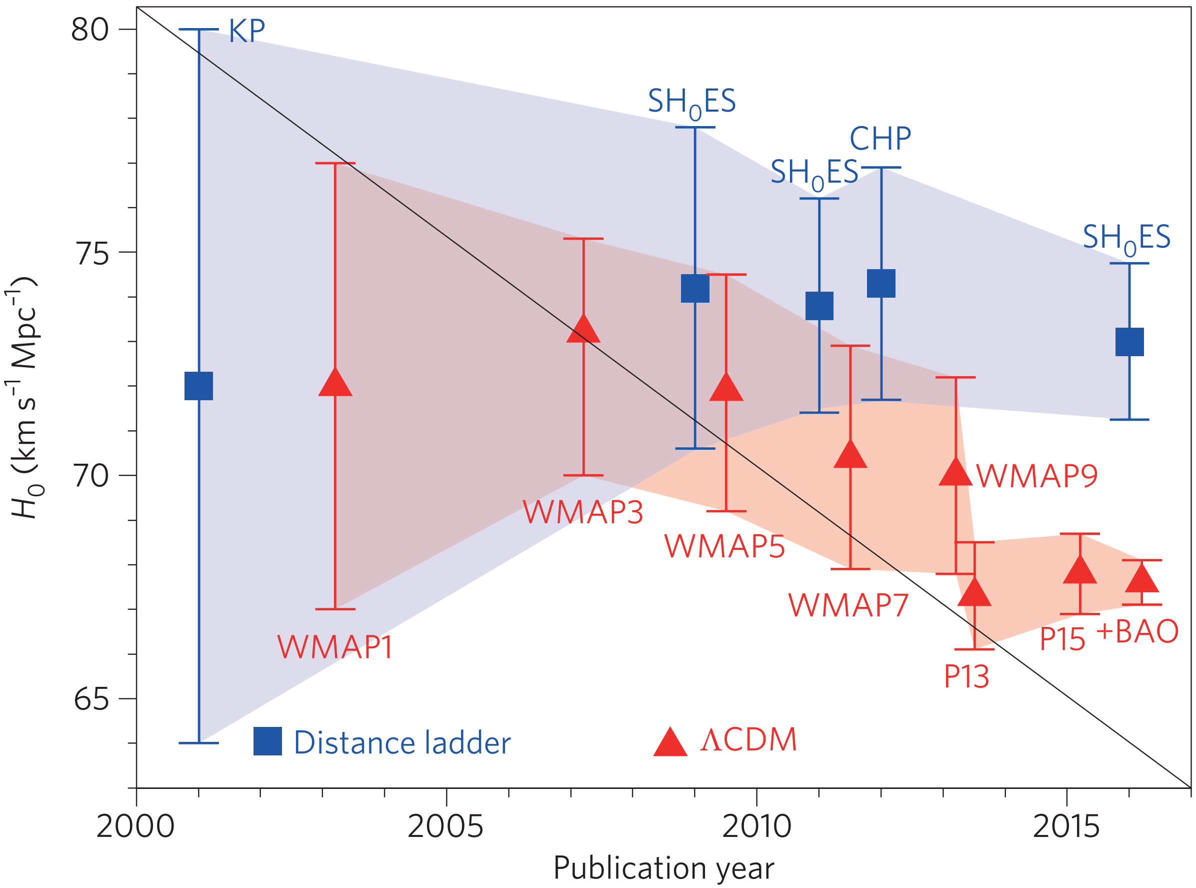
Additional explanatory slides

Boltzmann energy distribution law

$$n_i \sim exp\ (E_i/kT)$$



intensities of spectral lines ⇒ occupation of energy levels ⇒ T



Wendy L. Freedman, *Cosmology at a crossroads*, Nature Astronomy 1, 0121 (May 2, 2017)

Difficulties for the dark matter cosmology

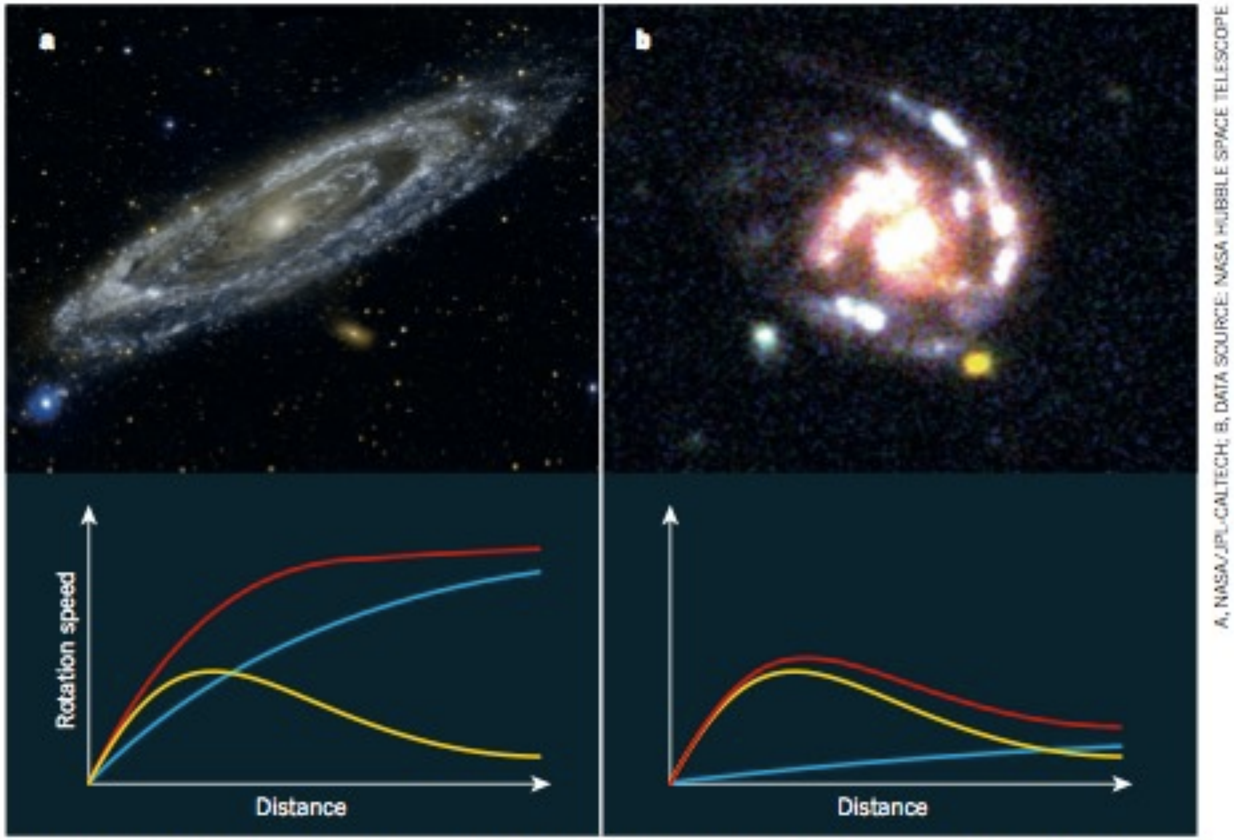


Figure 1 | Galaxy rotation curves. **a**, Nearby spiral galaxies such as Andromeda (shown here) are observed[1] to have flat 'rotation curves' — away from the galactic centre, the rotation speeds of stars are approximately constant as a function of distance from the centre (red). This is in contrast to the rotation curves expected from the distribution of visible matter (yellow). To explain this discrepancy, astronomers proposed that the mass of galaxies is dominated by invisible 'dark matter' (blue). **b**, Genzel *et al.*[2] report observations of six massive star-forming galaxies in the distant Universe (an example of such a galaxy, UDFJ033237-274751, is shown here). The authors find that these galaxies have rotation curves that, after rising to a peak, decrease with distance, suggesting that they contain relatively little dark matter.

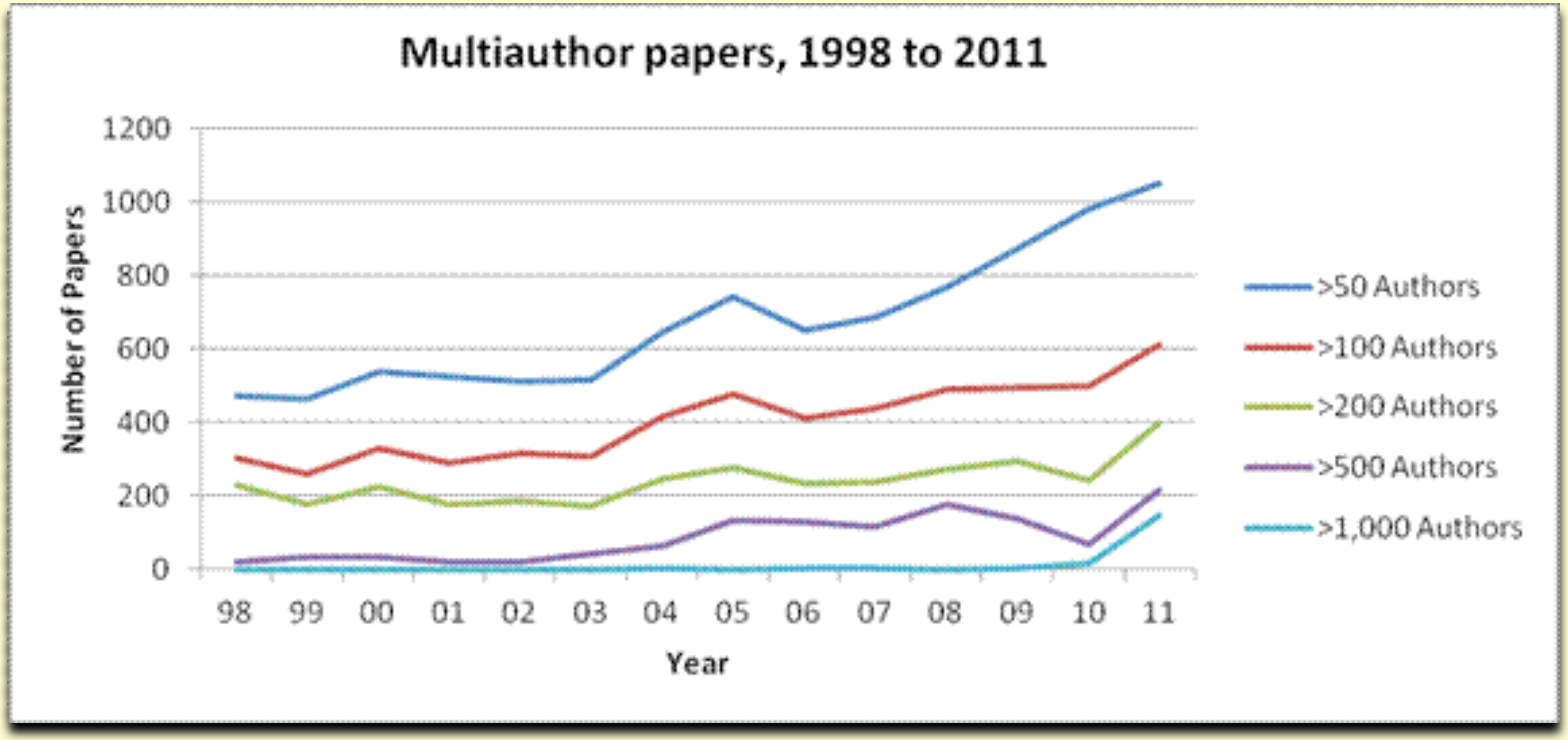
Genzel et al., Nature, March 16, 2017

Science, February 2, 2018

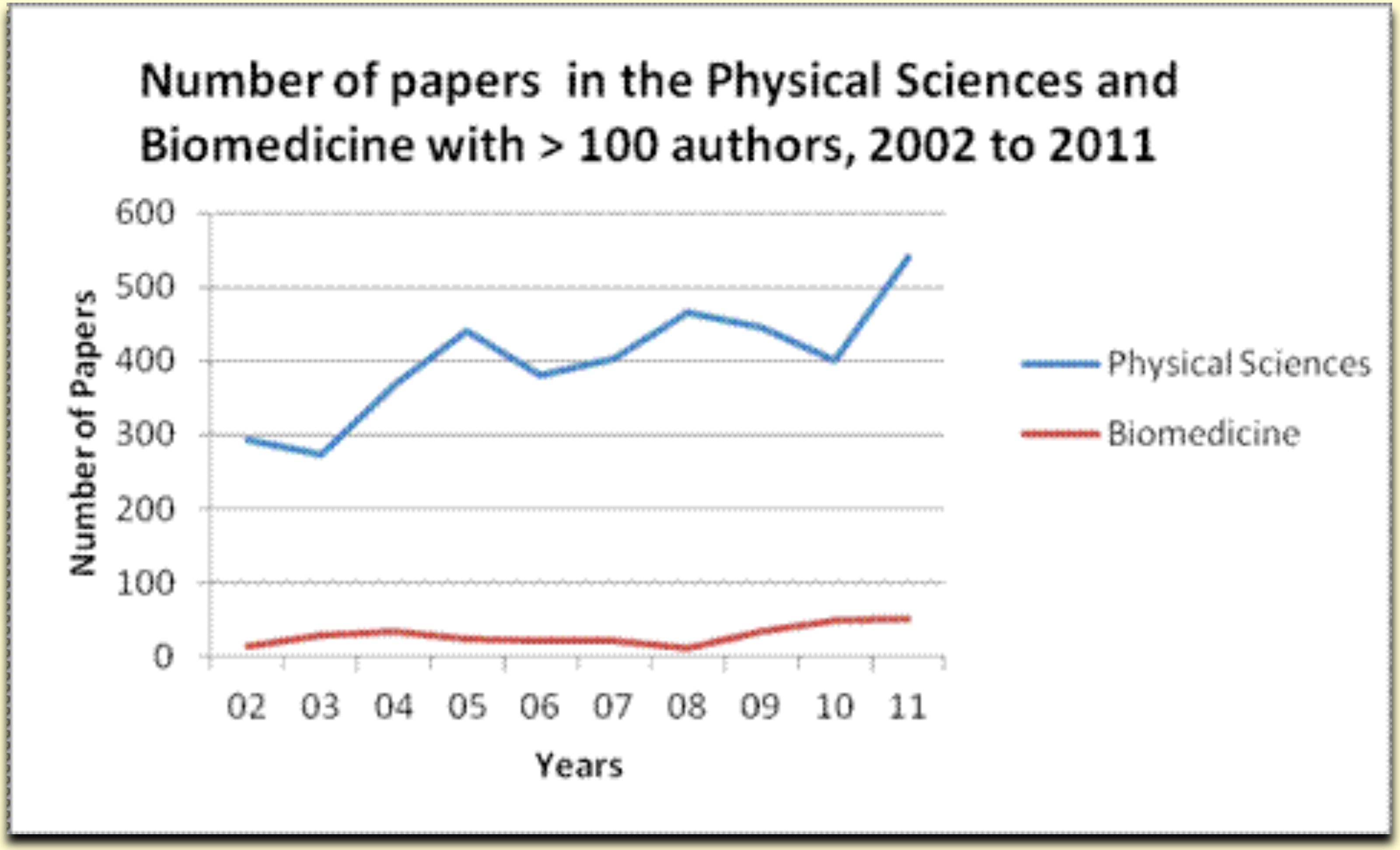
A whirling plane of satellite galaxies around Centaurus A challenges cold dark matter cosmology

Oliver Müller,[1*] Marcel S. Pawlowski,[2] Helmut Jerjen,[3] Federico Lelli[4]

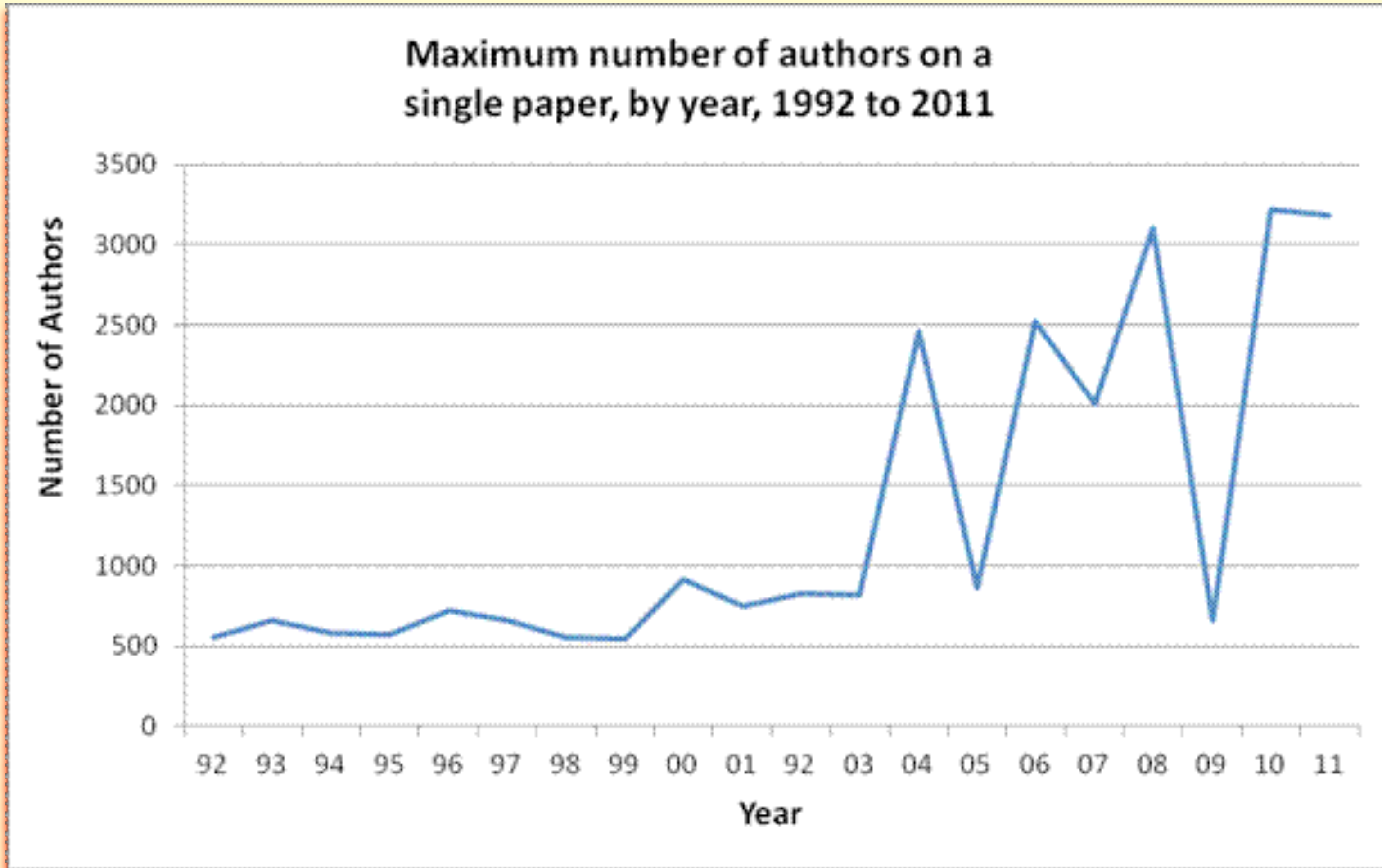
The Milky Way and Andromeda galaxies are each surrounded by a thin plane of satellite dwarf galaxies that may be corotating. Cosmological simulations predict that most satellite galaxy systems are close to isotropic with random motions, so those two well-studied systems are often interpreted as rare statistical outliers. We test this assumption using the kinematics of satellite galaxies around the Centaurus A galaxy. Our statistical analysis reveals evidence for corotation in a narrow plane: Of the 16 Centaurus A satellites with kinematic data, 14 follow a coherent velocity pattern aligned with the long axis of their spatial distribution. In standard cosmological simulations, <0.5% of Centaurus A–like systems show such behavior. Corotating satellite systems may be common in the universe, challenging small-scale structure formation in the prevailing cosmological paradigm.



Ch. King, Multiauthor Papers: Onward and Upward, „Science Watch”, July 2012



Ch. King, Multiauthor Papers: Onward and Upward, „Science Watch", July 2012



Ch. King, Multiauthor Papers: Onward and Upward, „Science Watch", July 2012

Multiauthor papers

	Papers with ≥ 1000 co-authors
2009-2013	573
2014-2018	1315

„Nature”, December 2019

MEGA Study Group (H. Nakamura, et al.), „Design and baseline characteristics of a study of primary prevention of coronary events with pravastatin among Japanese with mildly elevated cholesterol levels," Circulation J., 68(9), 860-7, 2004 - 2459 authors

LIGO-Virgo and IceCube Collaborations (M.G. Artsen et al.), „Multimessenger search for sources of gravitational waves and high-energy neutrinos: Initial results for LIGO-Virgo and IceCube", Phys. Rev. D90, 102002 (2014) - 1188 authors

Present record

Selected for a Viewpoint in *Physics*
PRL **114,** 191803 (2015) PHYSICAL REVIEW LETTERS week ending 15 MAY 2015

Combined Measurement of the Higgs Boson Mass in *pp* Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments

G. Aad *et al.*[*]

(ATLAS Collaboration)[†]
(CMS Collaboration)[‡]
(Received 25 March 2015; published 14 May 2015)

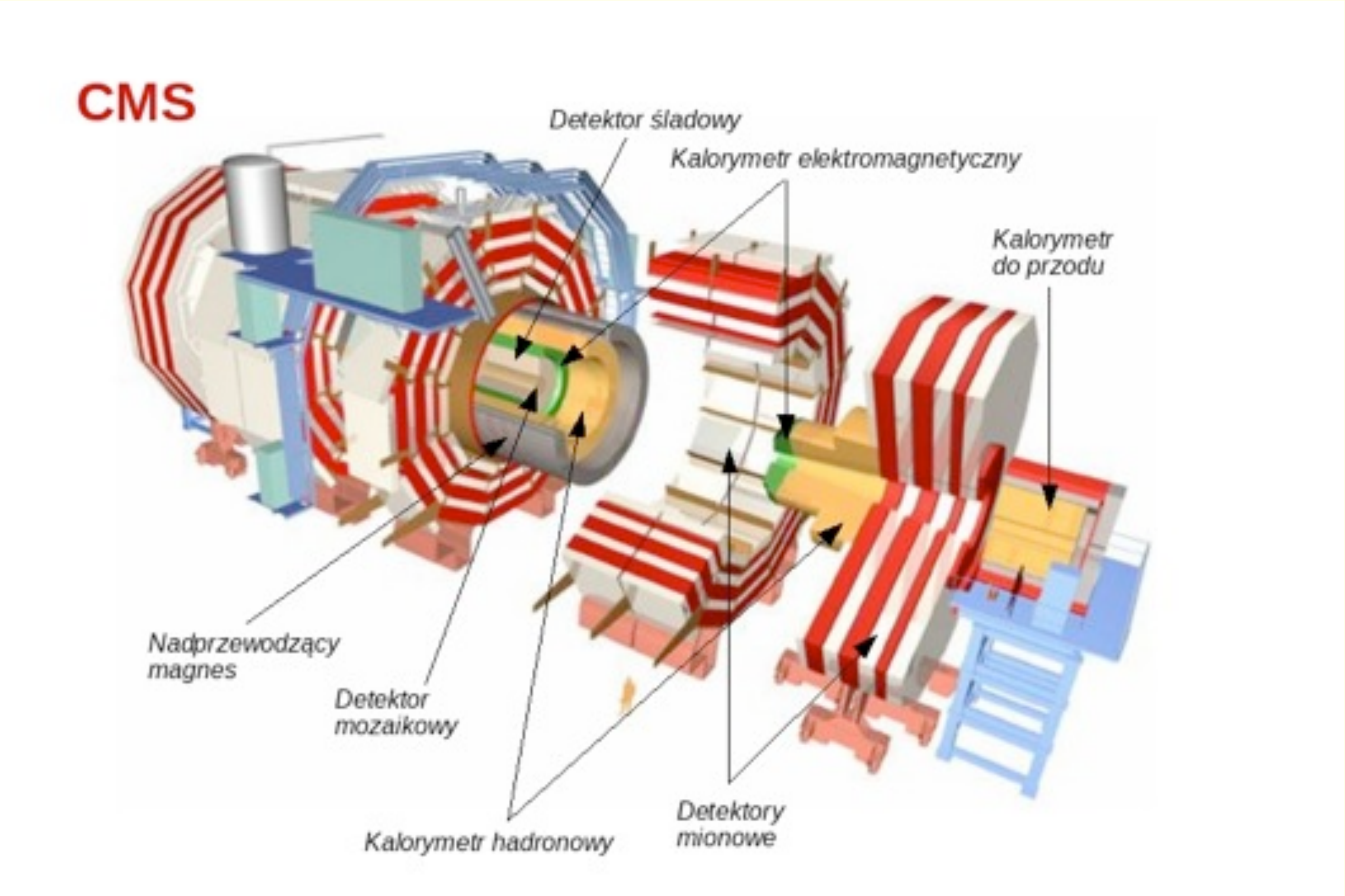
A measurement of the Higgs boson mass is presented based on the combined data samples of the ATLAS and CMS experiments at the CERN LHC in the $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$ decay channels. The results are obtained from a simultaneous fit to the reconstructed invariant mass peaks in the two channels and for the two experiments. The measured masses from the individual channels and the two experiments are found to be consistent among themselves. The combined measured mass of the Higgs boson is $m_H = 125.09 \pm 0.21\,(\text{stat}) \pm 0.11\,(\text{syst})$ GeV.

5154 authors from 416 institutions
(including 45 physicists from 5 Polish institutions)

That joint paper of ATLAS and CMS

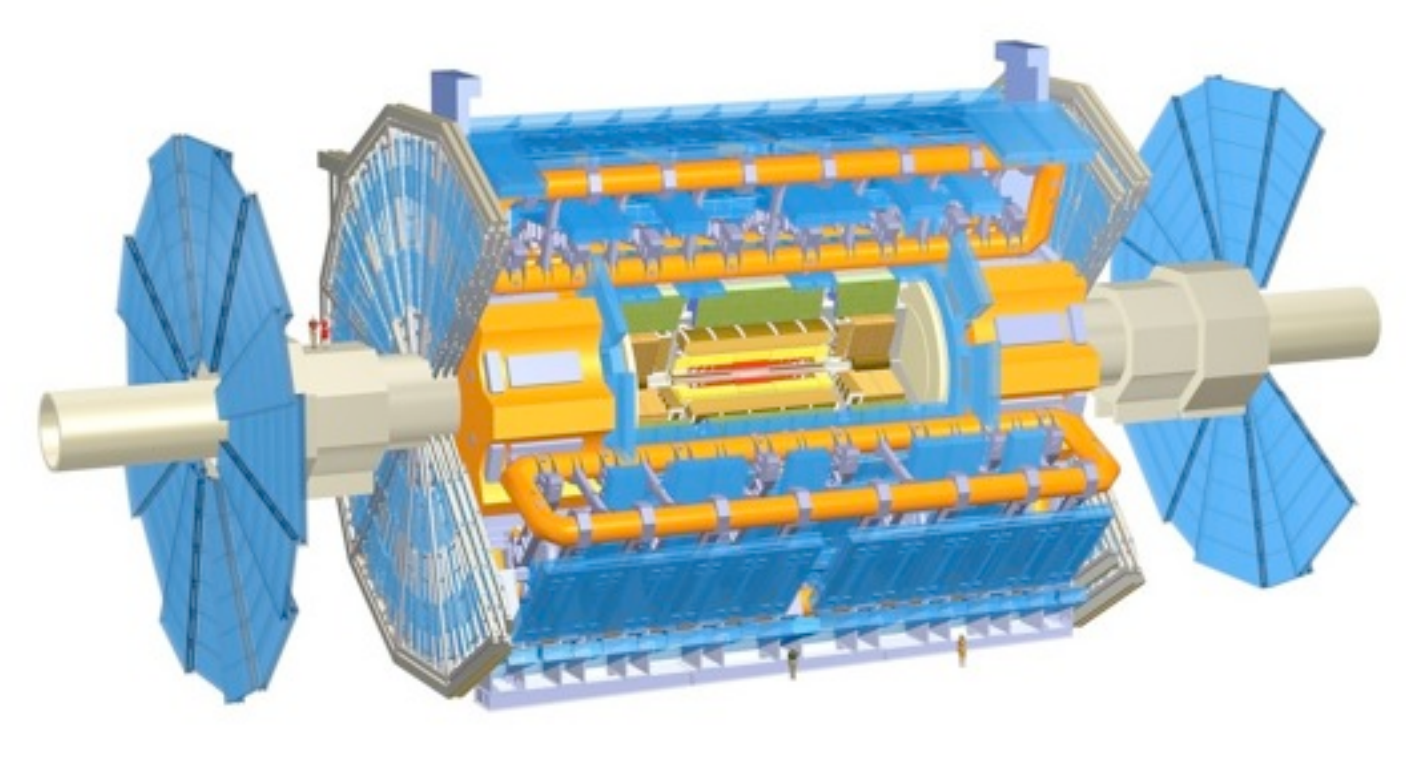
occupies 33 pages in „Physical Review Letters”; presentation of the results takes 9 pages, whereas the list of authors and their institutions fills the remaining 24 pages

CMS (**C**ompact **M**uon **S**olenoid)



Most complicated apparatus ever constructed
length 22 m, diameter 15 m, mass 14000 t.,
ca. 100 million elements,
its building, assembling and testing took over 15 years

ATLAS - (**A T**oroidal **L**HC **A**pparatu**S**)



Most complicated apparatus ever constructed
length 46 m, diameter 25 m, mass 7000 t.,
ca. 100 million elements,
its building, assembling and testing took over 15 years