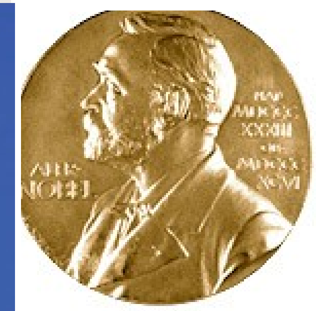
Нобелівська премія з фізики 2019

KUNGL. VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES



James Peebles | Michel Mayor | Didier Queloz

Джеймс Піблз
(Princeton University, USA)

Мішель Майор
(University of Geneva, Switzerland)

Дідье Кельо
(University of Geneva, Switzerland; University of Cambridge, UK)

“for contributions to our understanding of the evolution of the universe and Earth's place in the cosmos”

"за внесок у розуміння еволюції Всесвіту та місця Землі в космосі“

one half to James Peebles "for theoretical discoveries in physical cosmology",

the other half jointly to Michel Mayor and Didier Queloz "for the discovery of an exoplanet orbiting a solar-type star."

James Peebles

Born: 25 April 1935, Winnipeg, Canada

Affiliation at the time of the award: Princeton University, Princeton, NJ, USA

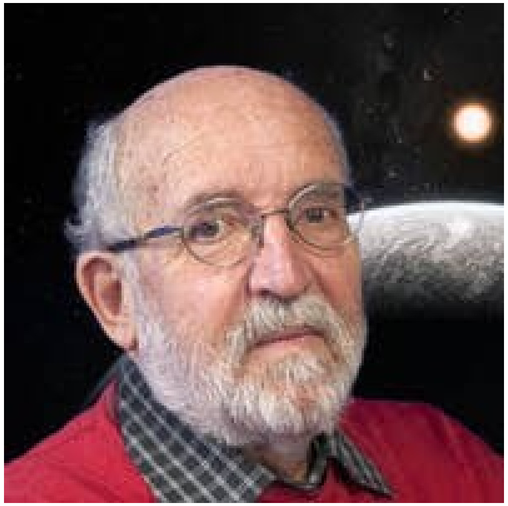
Prize motivation: "for theoretical discoveries in physical cosmology."

Professor Emeritus

Phone: 609-258-4386

Email Address: pjep@Princeton.EDU
Location: 216 Jadwin Hall

https://phy.princeton.edu/people/p-james-peebles



Michel Mayor

Born: 12 January 1942, Lausanne, Switzerland

Affiliation at the time of the award: University of Geneva, Geneva, Switzerland

Prize motivation: "for the discovery of an exoplanet orbiting a solar-type star."

MSc in physics at the University of Lausanne in 1966
PhD in astronomy in 1971 at the Geneva Observatory, which belongs to the University of Geneva.
Director of the Observatory of Geneva from 1998 to 2004 – until retiring in 2007.

https://www.iau.org/administration/membership/individual/2072/

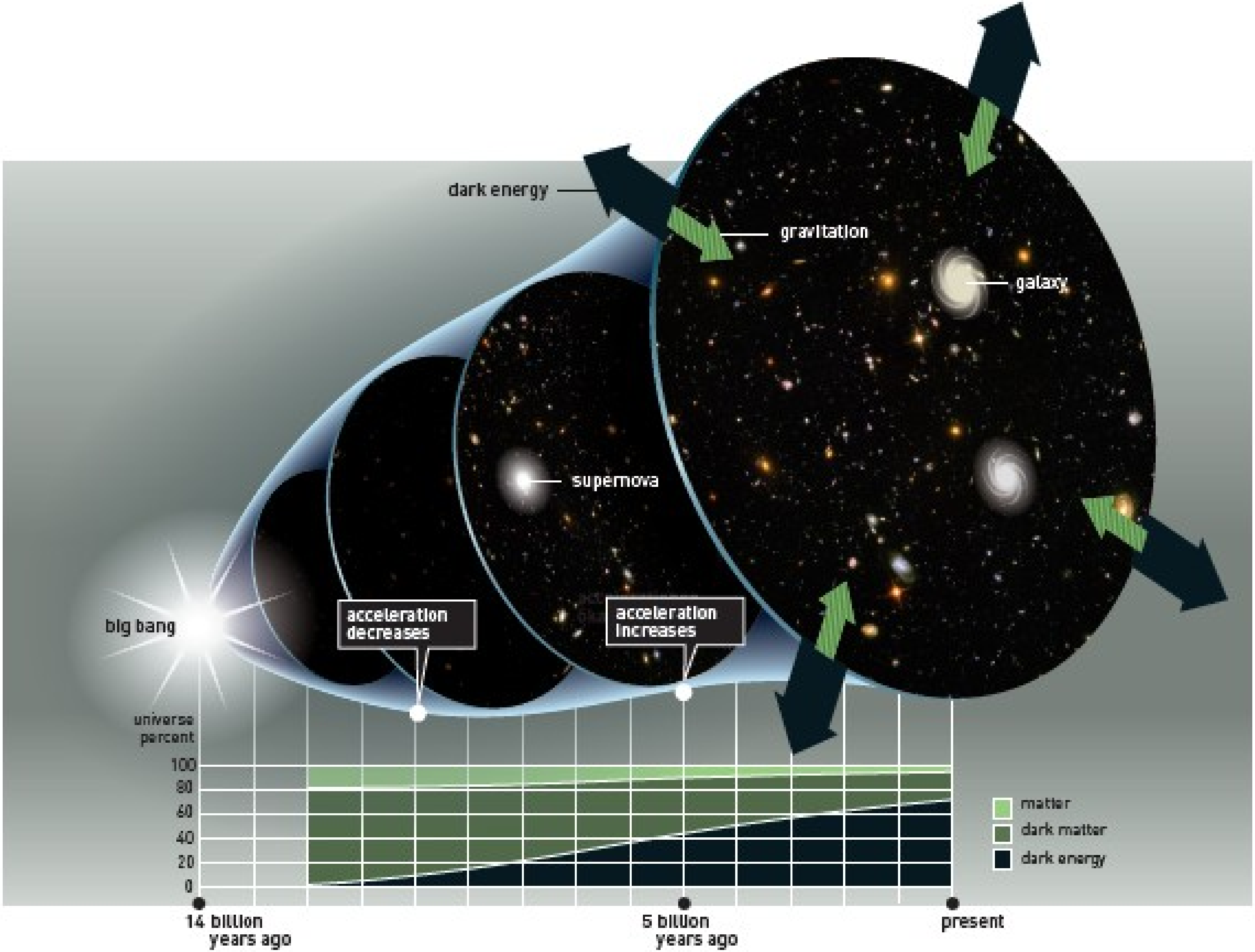
Didier Queloz

Born: 23 February 1966, Geneva, Switzerland

Affiliation at the time of the award: University of Geneva, Geneva, Switzerland, University of Cambridge, Cambridge, United Kingdom

Prize motivation: "for the discovery of an exoplanet orbiting a solar-type star."

https://www.astro.phy.cam.ac.uk/directory/prof-didier-queloz



dark energy
gravitation
galaxy
supernova
big bang
acceleration decreases
acceleration increases
universe percent
100
80
60
40
20
0
matter
dark matter
dark energy
14 billion years ago
5 billion years ago
present

ation.

Відкриття в космології

•1915 – Альберт Ейнштейн опублікував загальну теорію відносності (ЗТВ) і пояснив обертання перигелію Меркурія

•1916 – Альберт Ейнштейн показав, що польове рівняння загальної теорії відносності допускає хвильові розв’язки

• 1916 – Карл Шварцшильд запропонував розв'язок рівнянь ЗТВ, який може характеризувати чорну діру

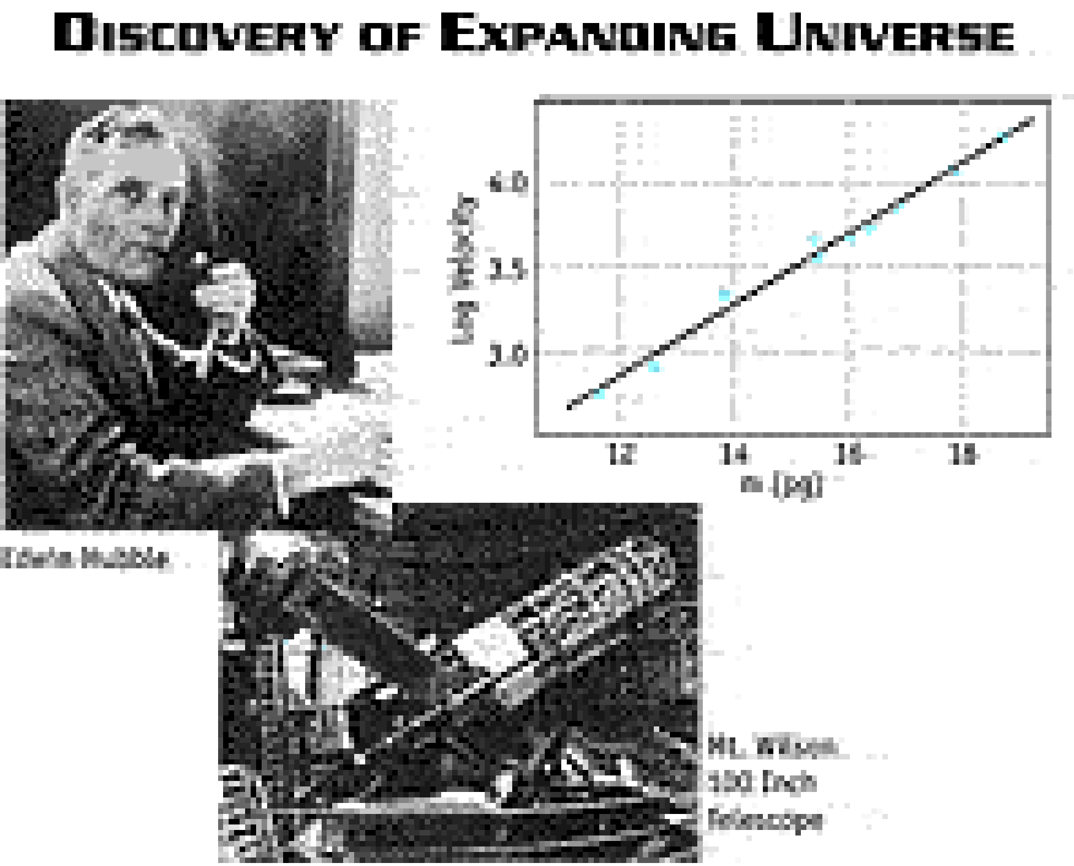
•1919 – Артур Едінгтон спостерігав гравітаційне відхилення світла Сонцем

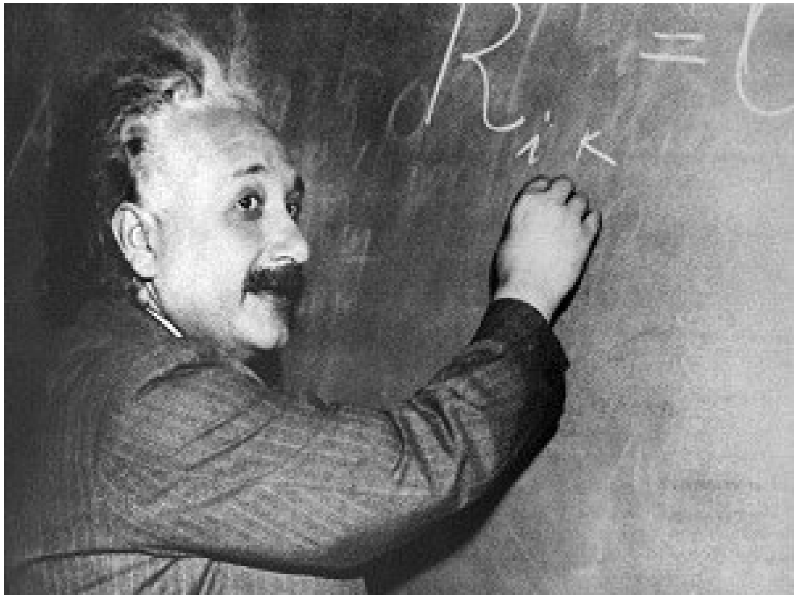
•1922 – Олександр Фрідман теоретично показав можливість нестаціонарного розв’язку рівнянь Загальної теорії відносності

•1927 – Жорж Леметр незалежно отримав нестаціонарні розв’язки рівнянь ЗТВ

•1929 – Едвін Габбл виявив лінійну залежність червоного зсуву галактик від відстані до них

http://www.astrosvit.in.ua/istoriia-astronomii/khronolohiia-astronomii

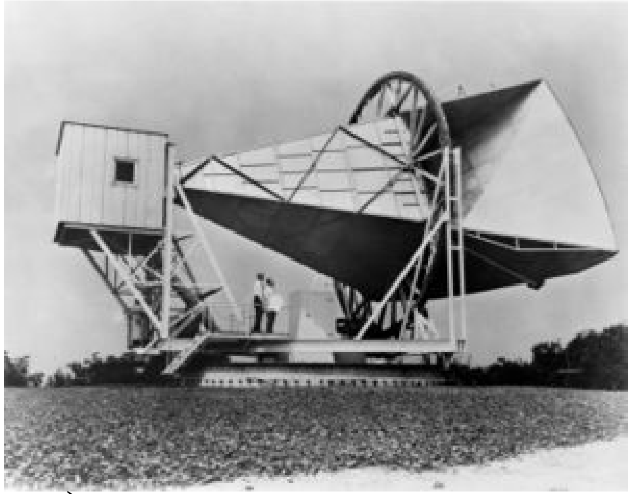




The current Planck Mission results show the Hubble Constant to be 67.80±0.77 (km/sec)/Mpc.

Відкриття в космології

- 1934 – Толмен показав, що при охолодженні випромінювання абсолютно чорного тіла зберігає форму спектрального розподілу
- 1941 – Ендрю МакКеллар показав, що лише наявність випромінювання міліметрового діапазону пояснює переходи в міжзоряних молекулах
- 1948 – Георгій Гамов, Ральф Альфер та Роберт Герман передбачили, що повинно існувати реліктове випромінювання
- 1952 – Отто Струве запропонував метод допплерівської спектроскопії для вивчення обертання зір.



- 1964 – Девід Вілкінсон та Пітер Ролл створили радіометр для дослідження реліктового випромінювання
- 1965 – Арно Пензіас и Роберт Вільсон – випадково виявили ізотропне реліктове випромінювання (Нобелівська премія 1978 р.)

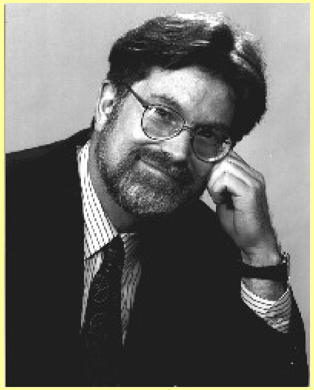
http://www.astrosvit.in.ua/istoriia-astronomii/khronolohiia-astronomii

Нобелівська премія з фізики 2006

KUNGL. VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

The Nobel Prize in Physics 2006

Джон Матер (John C. Mather)
NASA Goddard Space Flight Center,
Greenbelt, MD, USA,
та



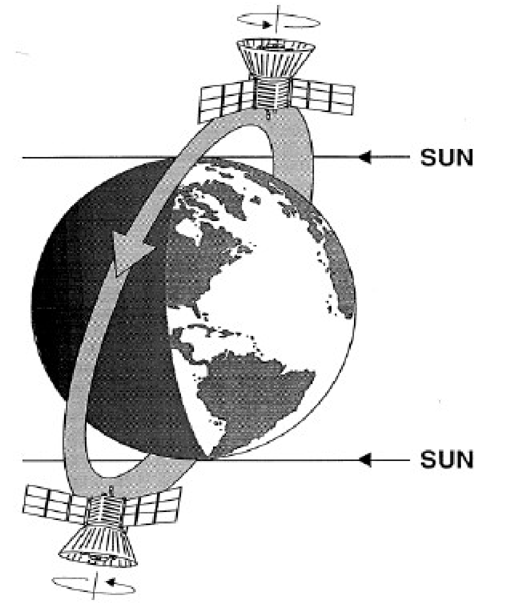
Джордж Смут (George F. Smoot)
University of California, Berkeley, CA, USA

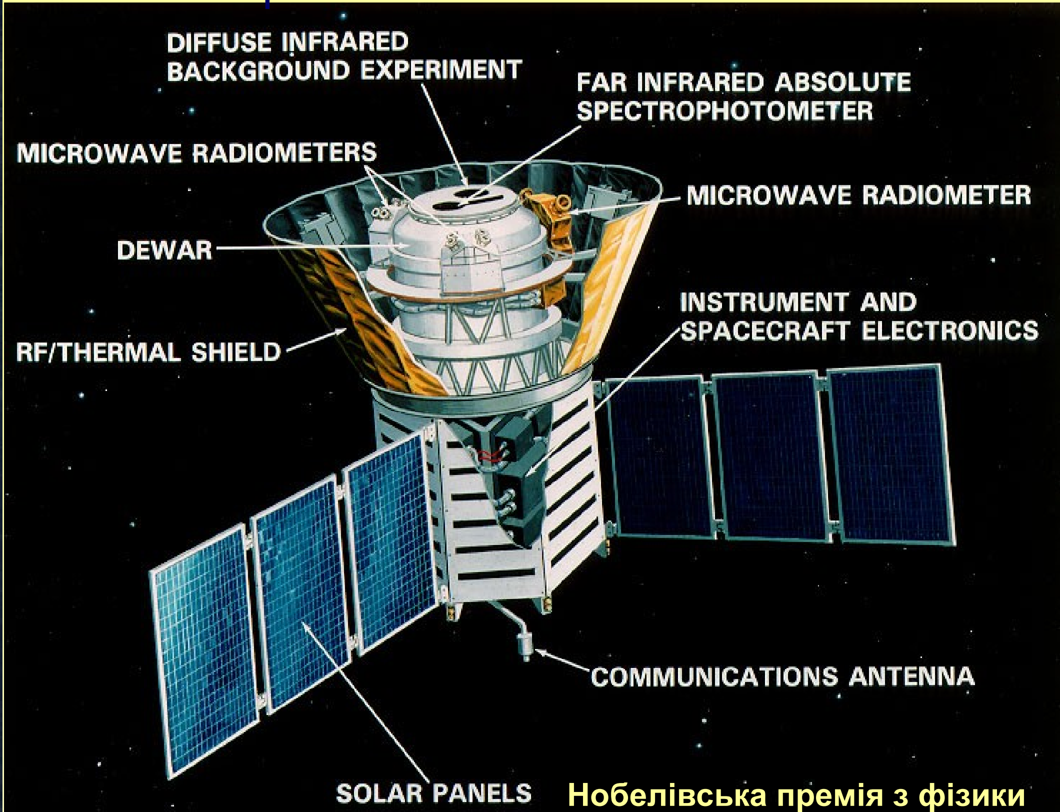
"За відкриття анізотропії та властивостей абсолютно чорного тіла у мікрохвильового фонового випромінювання"

COBE (Cosmic Background Explorer)

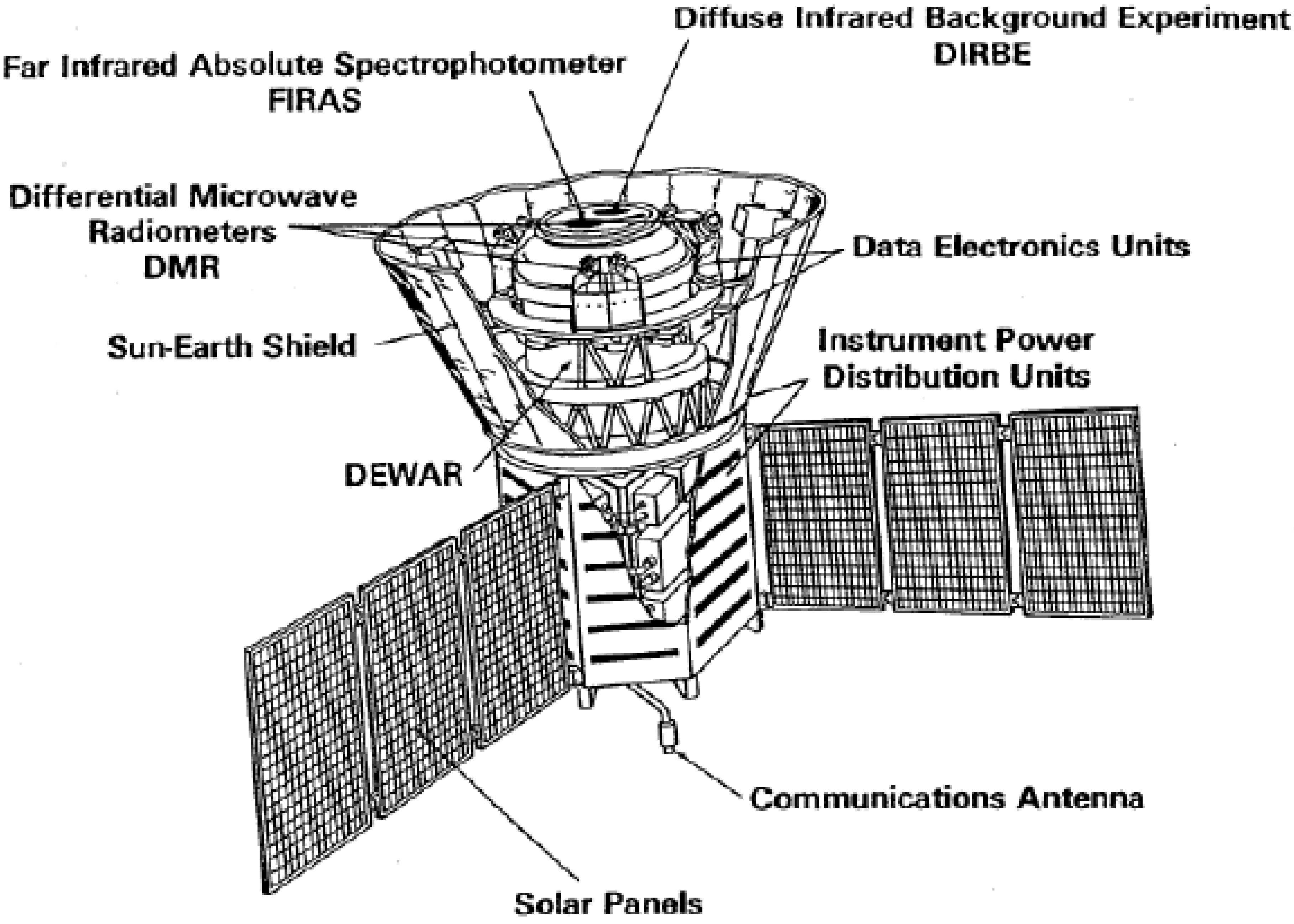
NASA 1989 - 1993

Поч. проекту – 1974р.
Заг. вартість
US$ 160 million
Запуск – 18.11.1989р.
Оголошення
результатів
23.04.1992р.

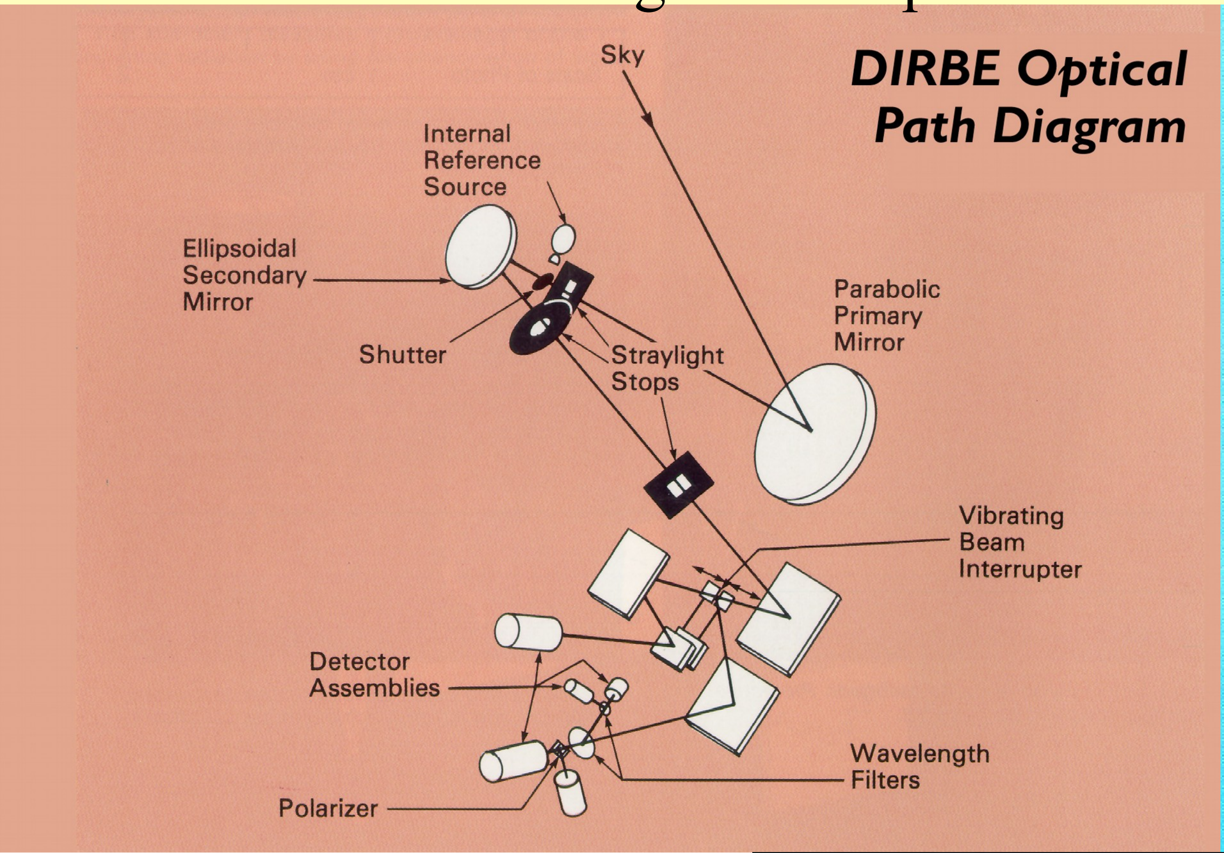


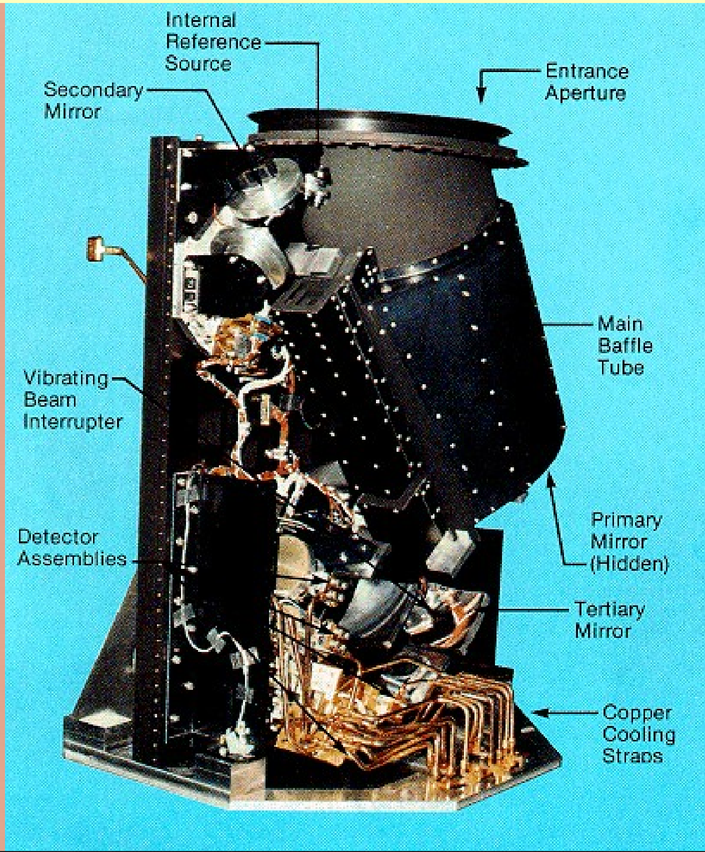


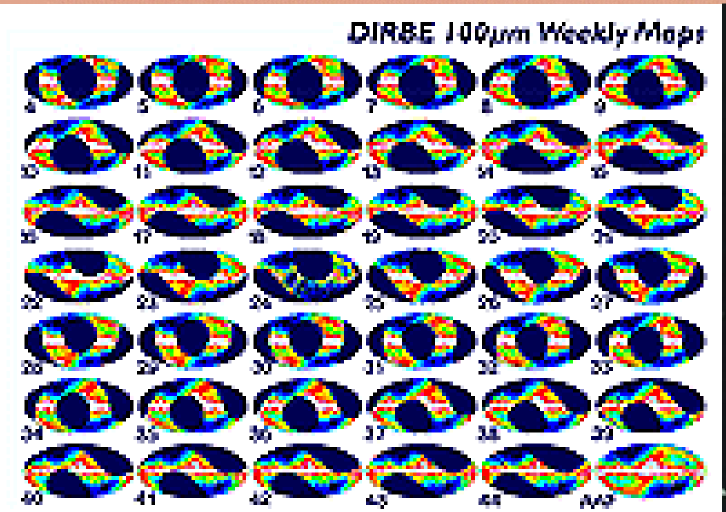
Нобелівська премія з фізики

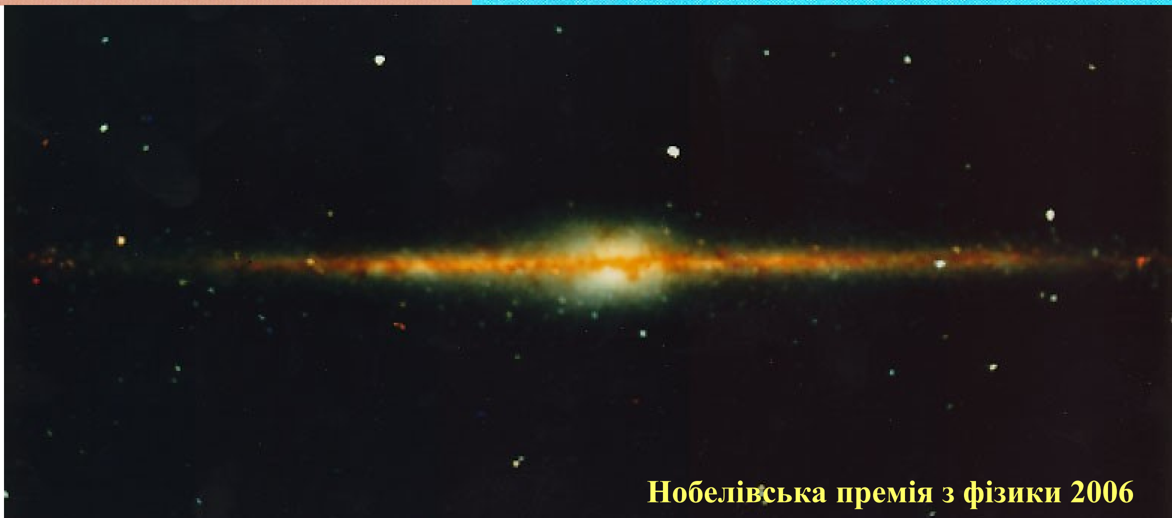

Diffuse Infrared Background Experiment
DIRBE
Far Infrared Absolute Spectrophotometer
FIRAS
Differential Microwave
Radiometers
DMR
Data Electronics Units
Sun-Earth Shield
Instrument Power
Distribution Units
DEWAR
Communications Antenna
Solar Panels

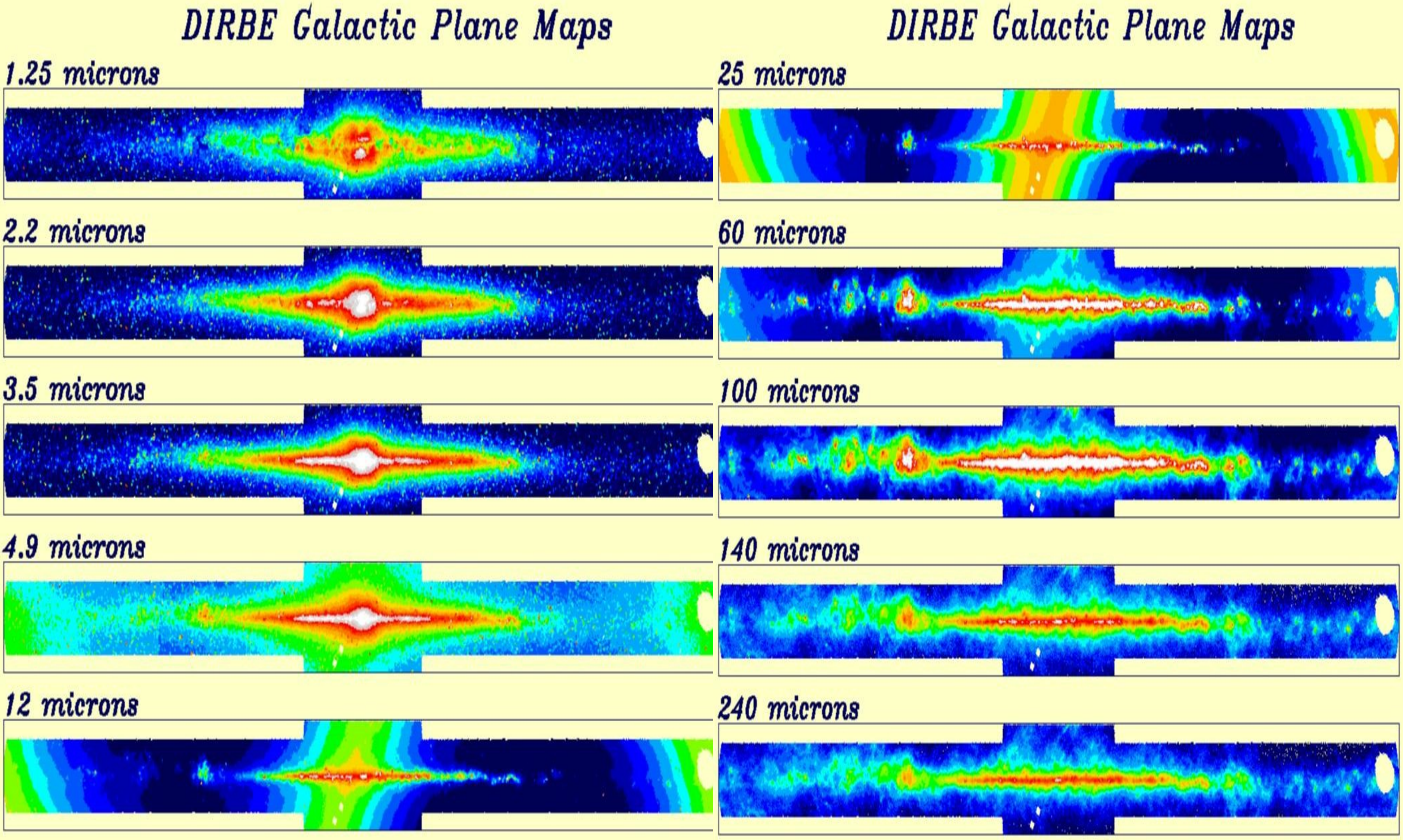
Diffuse InfraRed Background Experiment

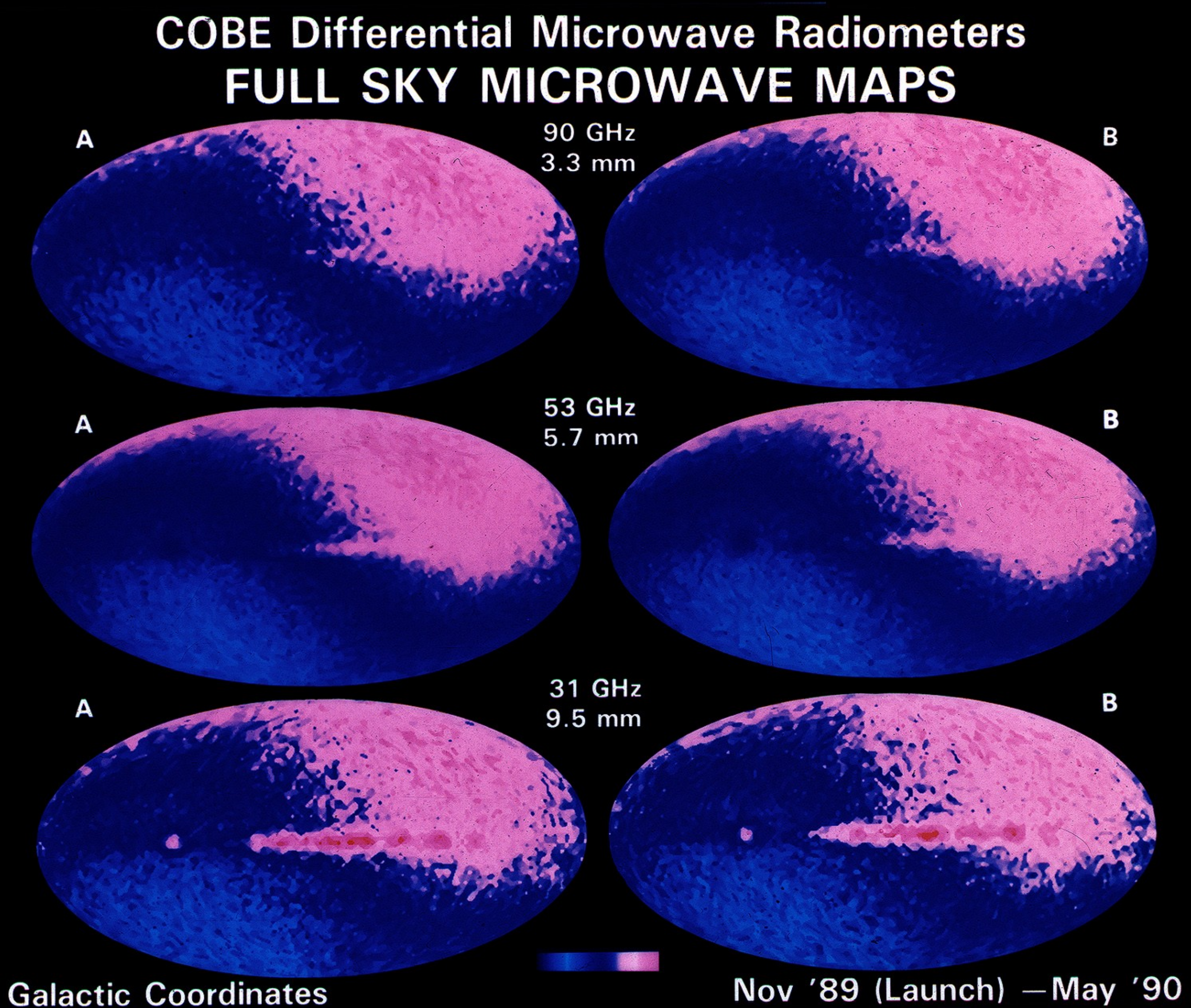






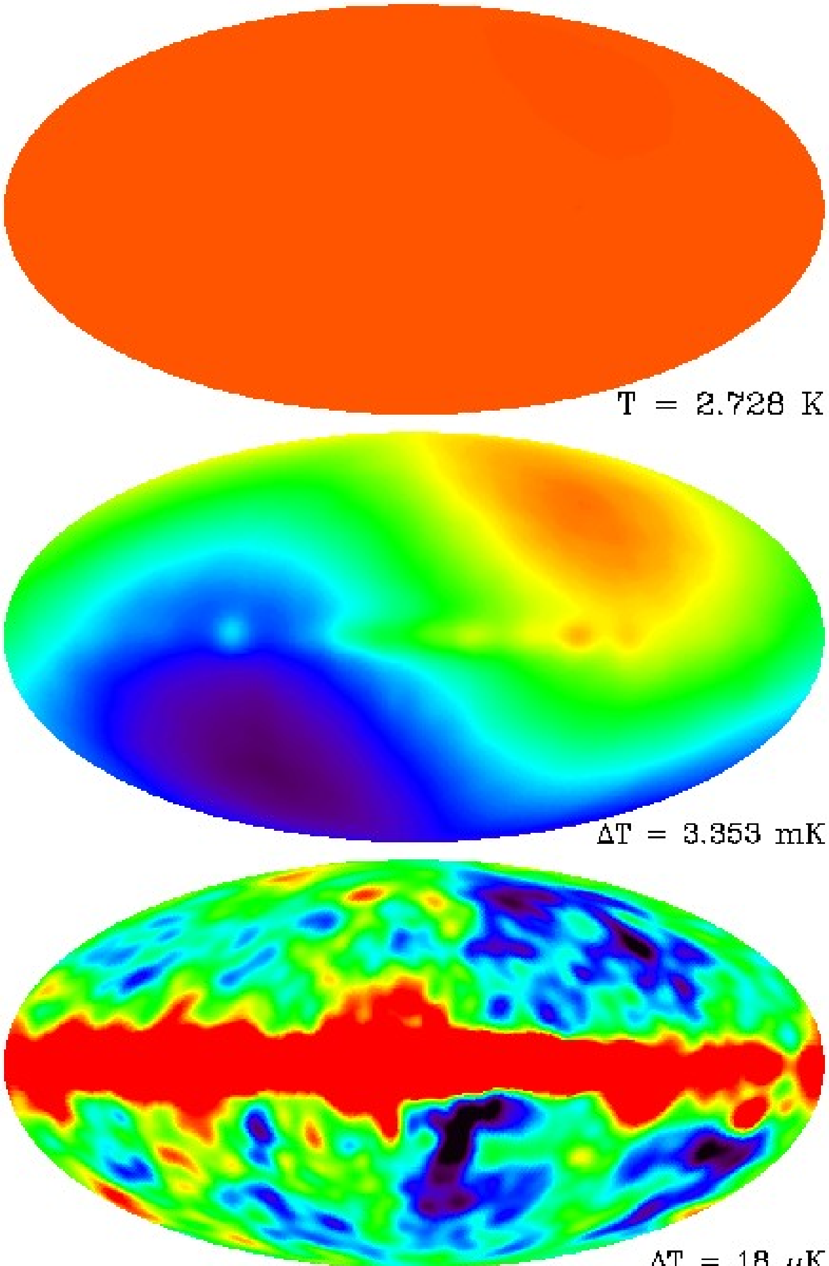


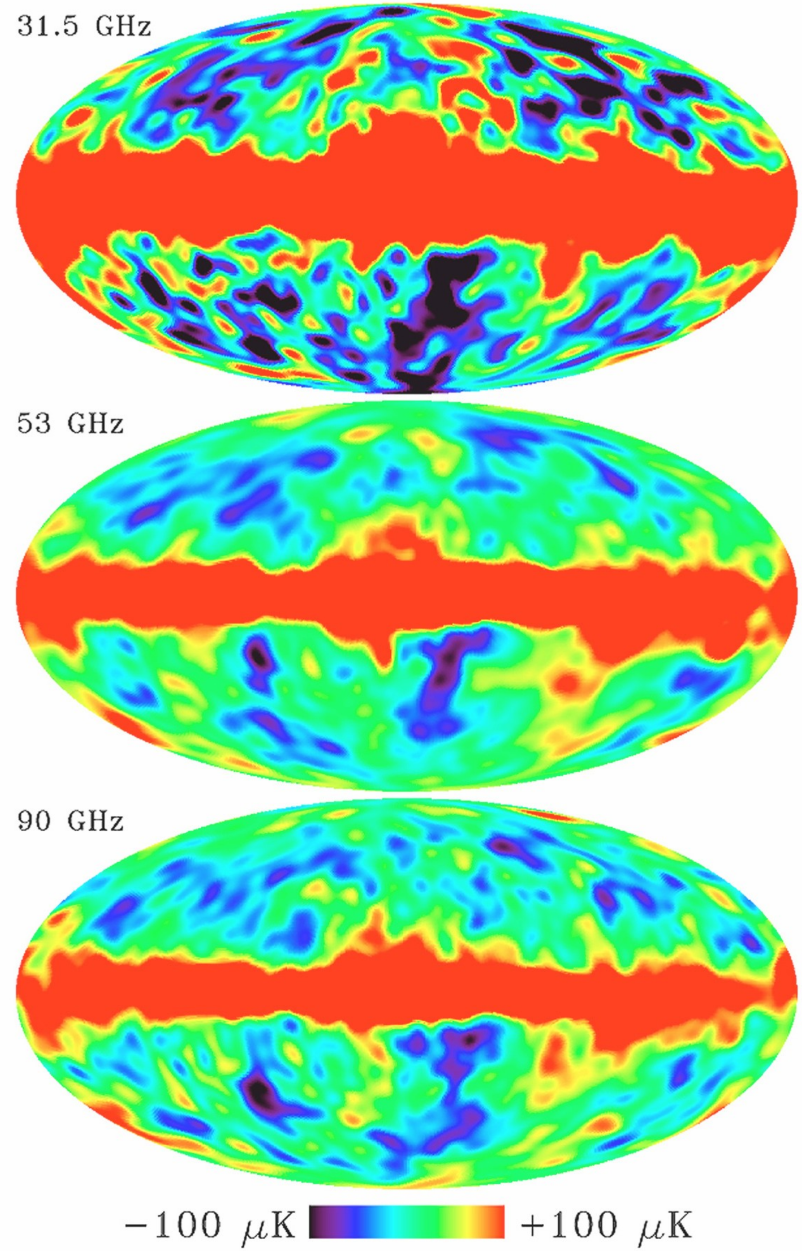

DIRBE Galactic Plane Maps
1.25 microns
2.2 microns
3.5 microns
4.9 microns
12 microns
DIRBE Galactic Plane Maps
25 microns
60 microns
100 microns
140 microns
240 microns



Нобелівська премія з фізики 2006

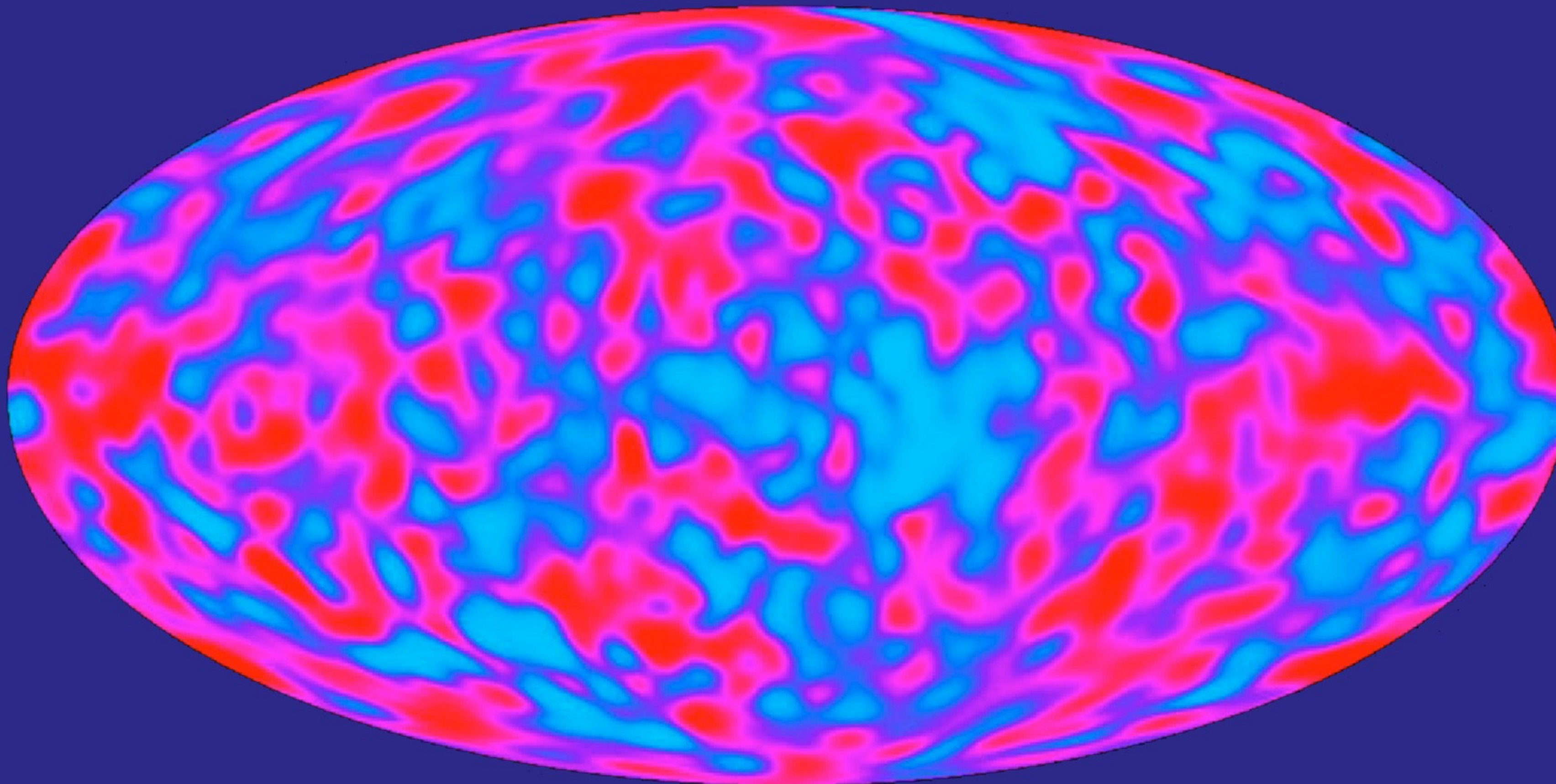
DMR Maps After Dipole Subtraction





Нобелівська премія з фізики

DMR's Two Year CMB Anisotropy Result

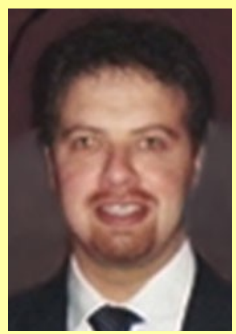


Нобелівська премія з фізики

Нобелівська премія з фізики 2011
The Nobel Prize in Physics 2011

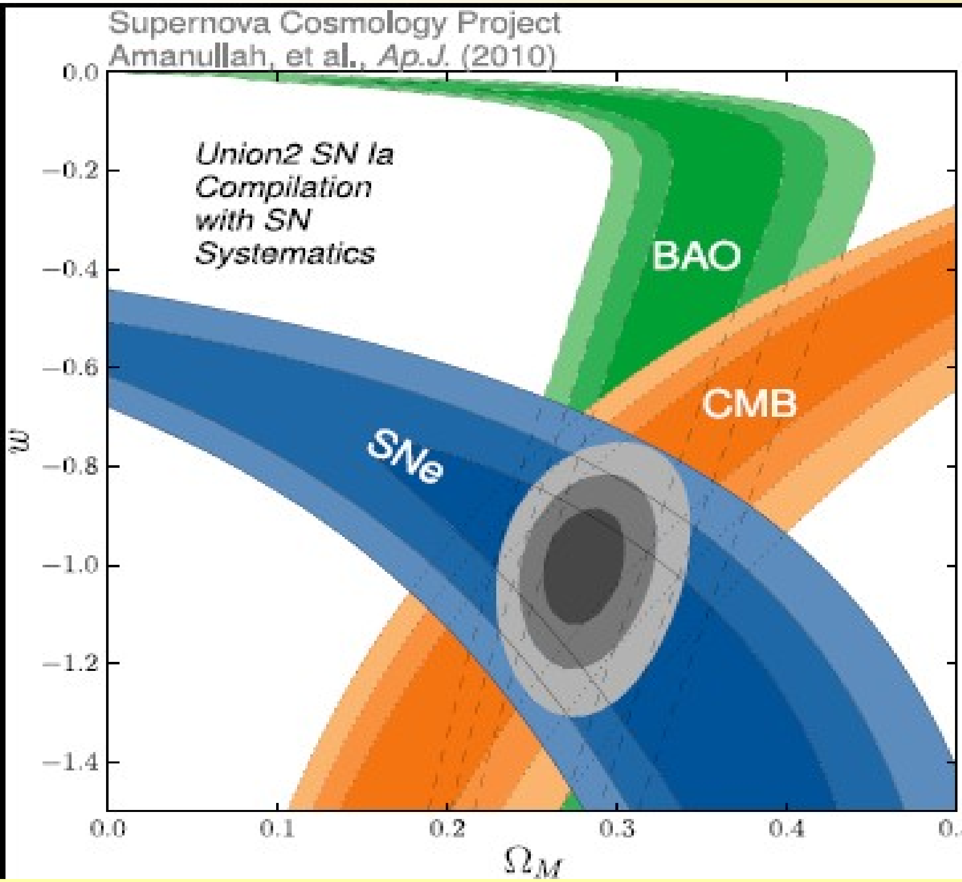
Сол Перлмуттер (Saul Perlmutter)
Lawrence Berkeley National Laboratory, Berkeley, USA

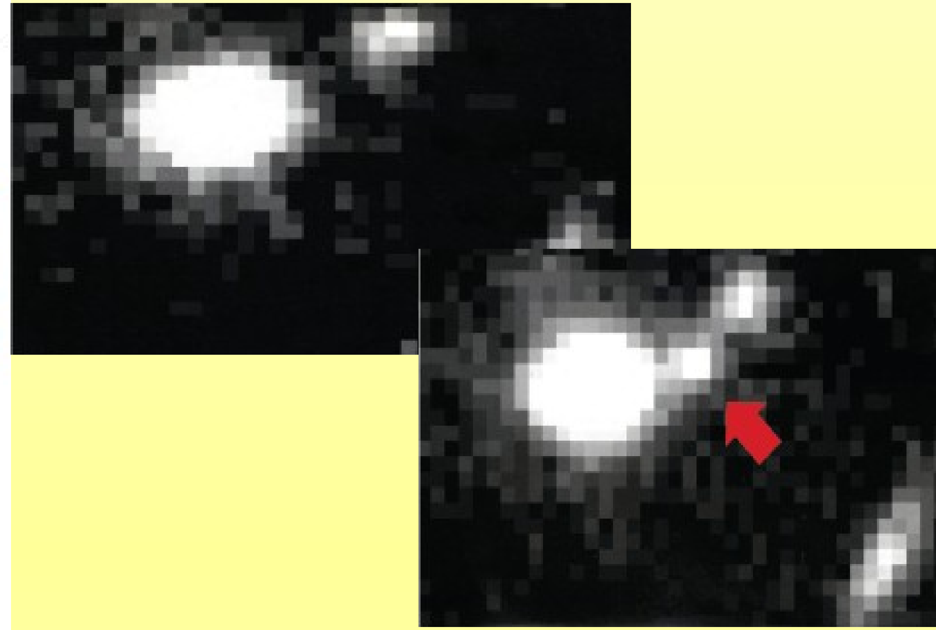
Браян Шмідт (Brian P. Schmidt)
Australian National University, Weston Creek, Australia

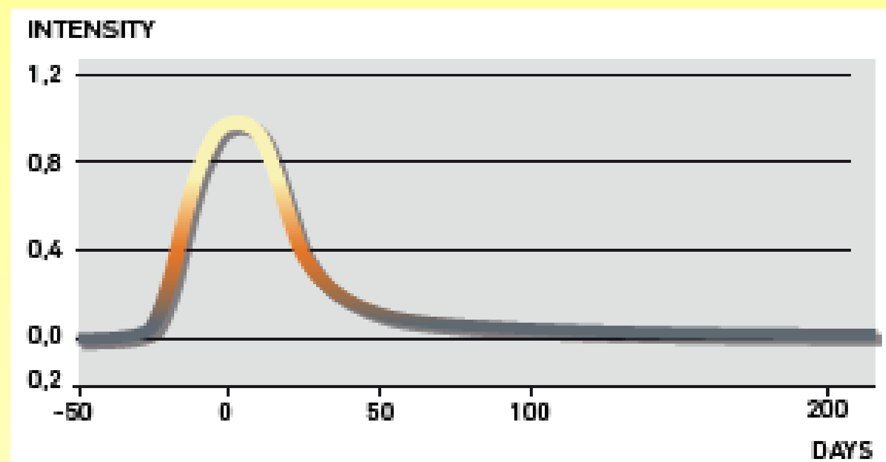


Адам Ріс (Adam G. Riess)
Johns Hopkins University, Baltimore, USA

"За відкриття прискореного розширення Всесвіту при спостереженнях за далекими суперновими"

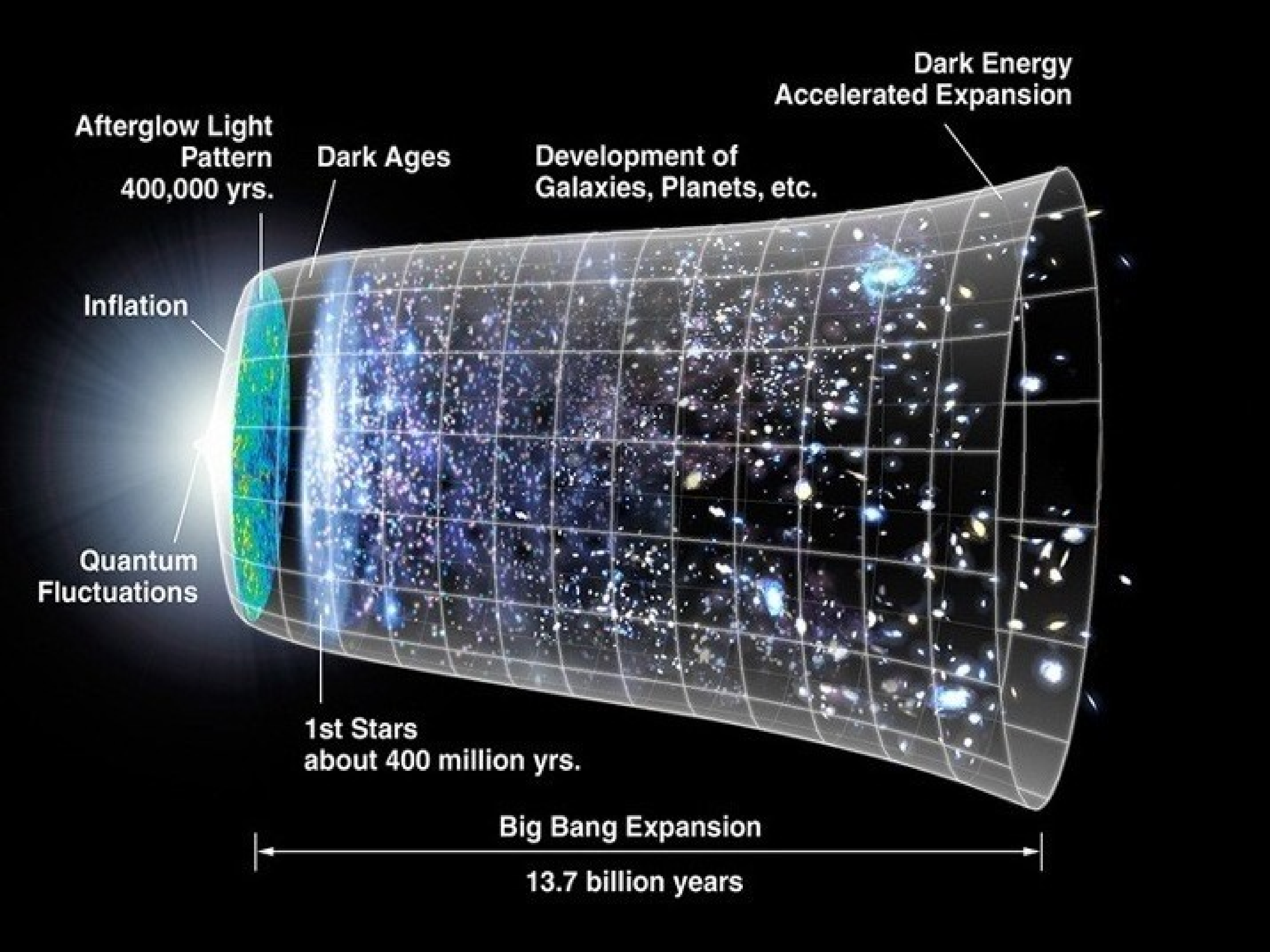




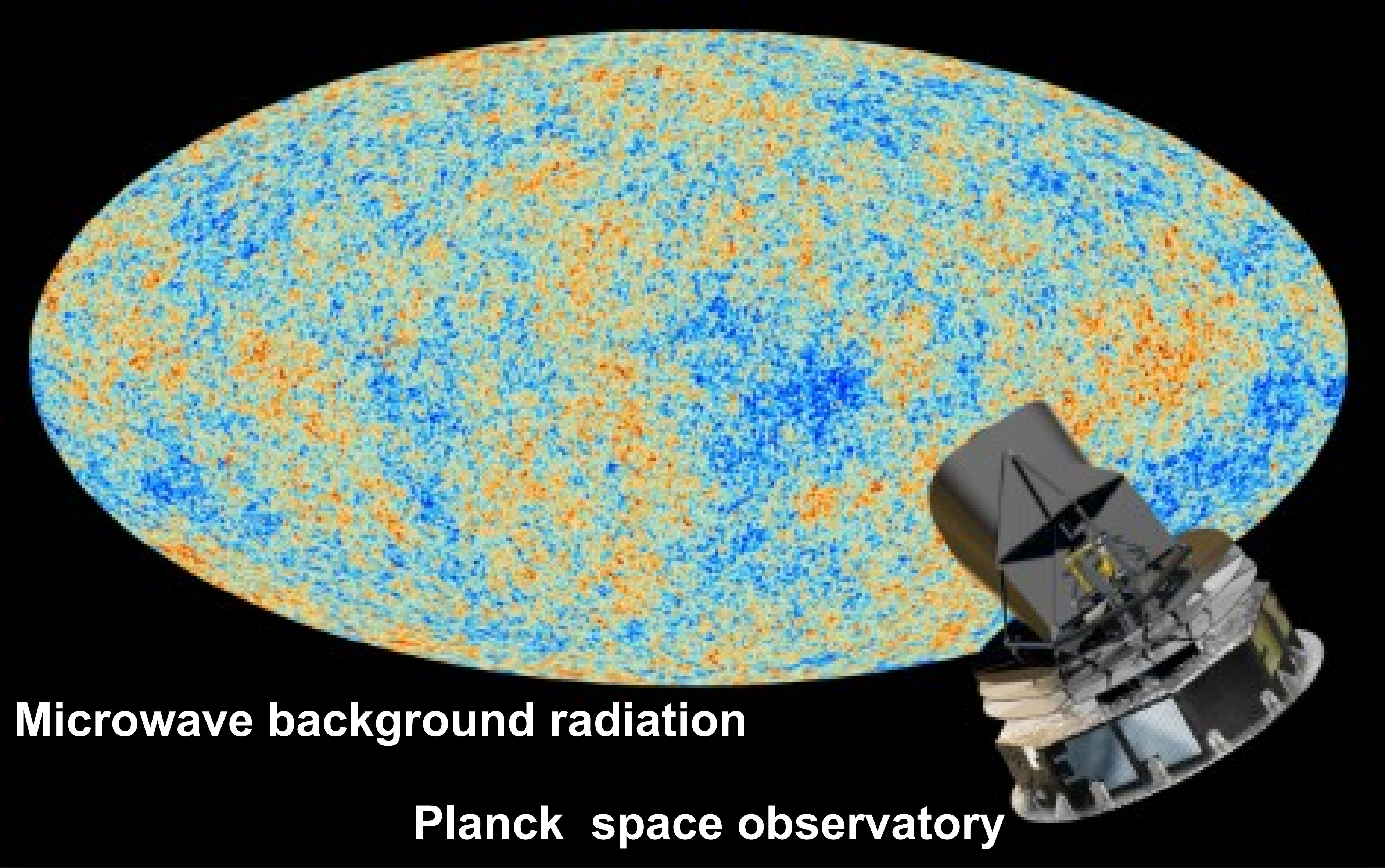


$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3}$$

Нобелівська премія з фізики 2011

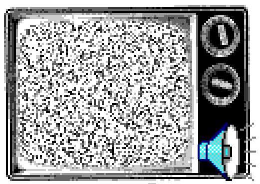


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years



The Sound of the Big Bang

John G. Cramer
Professor of Physics
University of Washington



Penzias, A. A. & Wilson, R. W. A Measurement of Excess Antenna Temperature at 4080 Mc/s. Astrophysical Journal, vol. 142, p.419-421,1965

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

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

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

http://articles.adsabs.harvard.edu//full/1965ApJ...142..419P/0000419.000.html

Нобелівська премія з фізики 2019

Nobel Prize in Physics — Part 1: James Peebles

1916: Einstein's general theory of relativity

field equations:

$$\underbrace{R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu}}_{\text{space time curvature}} = \overbrace{8\pi T_{\mu\nu}}^{\text{matter and energy}} - \Lambda g_{\mu\nu}$$

Λ — cosmological constant

→ ~~universe is expanding!~~

→ ~~universe stands still!~~

→ universe **is** expanding!

https://www.youtube.com/watch?v=KJhWhO0rxMU

Publications of the Astronomical Society of the Pacific, 111:274–284, 1999 March

Cosmology: The Nature of the Universe Debate

Is Cosmology Solved? An Astrophysical Cosmologist's Viewpoint

P. J. E. Peebles
Joseph Henry Laboratories, Princeton University, and Princeton Institute for Advanced Study; pjep@pupgg.princeton.edu

TABLE 1

Is Our Cosmology Predictive?

Hypotheses	Phenomena
1. Tests of the Expanding Universe	
Homogeneity	Isotropy
Expansion	Galaxy counts
Conventional local physics	Hubble's law $v = H_0 r$
	Galaxy evolution
	CBR thermal spectrum
2. Tests of Spa	
General relativity	
Ω_{baryon}	
Nonbaryonic matter	
Void matter	
Cosmological constant	
3. Tests of the Fried	
Primeval departures from homogeneity: composition, statistical character	
4. The Infla	
Inflation	

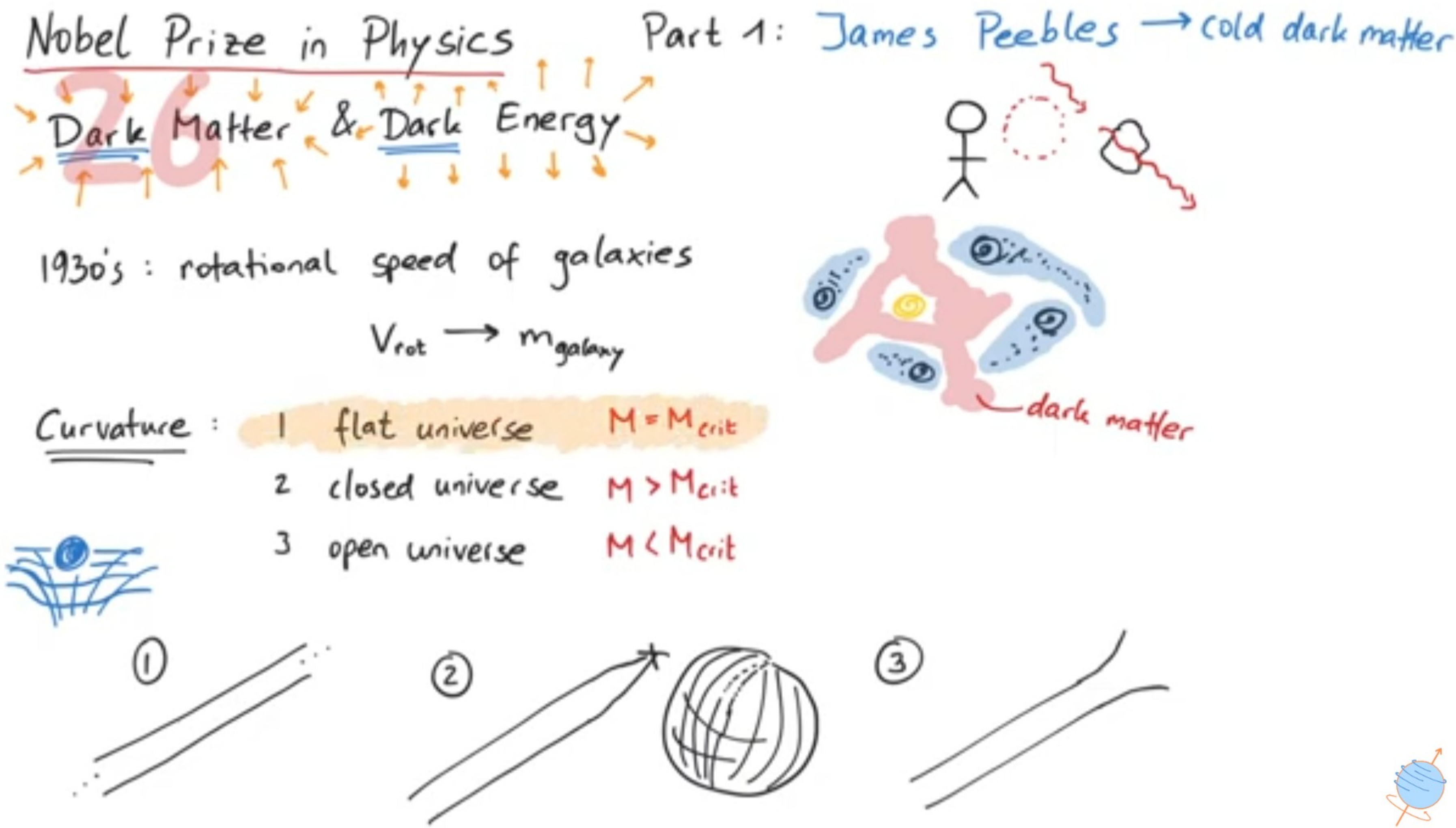
TABLE 2

The Cosmological Tests

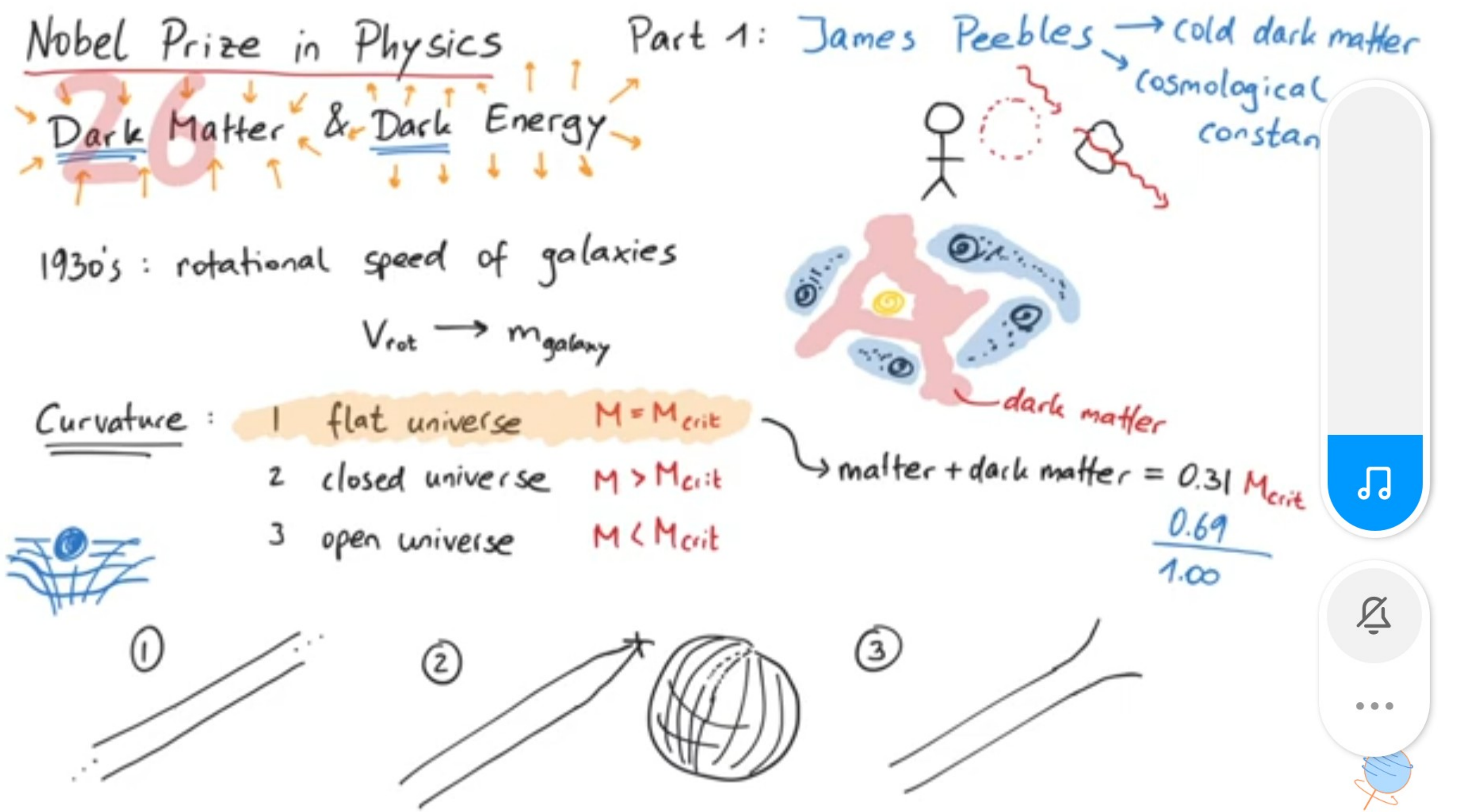
		$\Omega_m = 0.25 \pm 0.1$	
Test	Einstein–de Sitter	Flat	Open
1a. Dynamical mass measures	−	+	+
1b. World time $t(z)$: ages of stars and elements......	−??	+?	+?
1c. Redshift-magnitude relation	−	+	− ??
1d. Lensing of quasars by galaxies	+?	− ??	+?
1e. Counts: $dN = f(m, z) dm\, dz$	?	?	?
2a. Large-scale structure	−?	+?	+?
2b. CBR anisotropy	−?	+?	+ ??
2c. Cluster evolution	−?	+?	+?
2d. Baryon mass fraction in clusters	−	+	+
2e. Galaxy formation	?	?	?
3a. Aesthetics	+	−?	−?
3b. Inflation	+	+	??

1999 PASP, 111:274–284

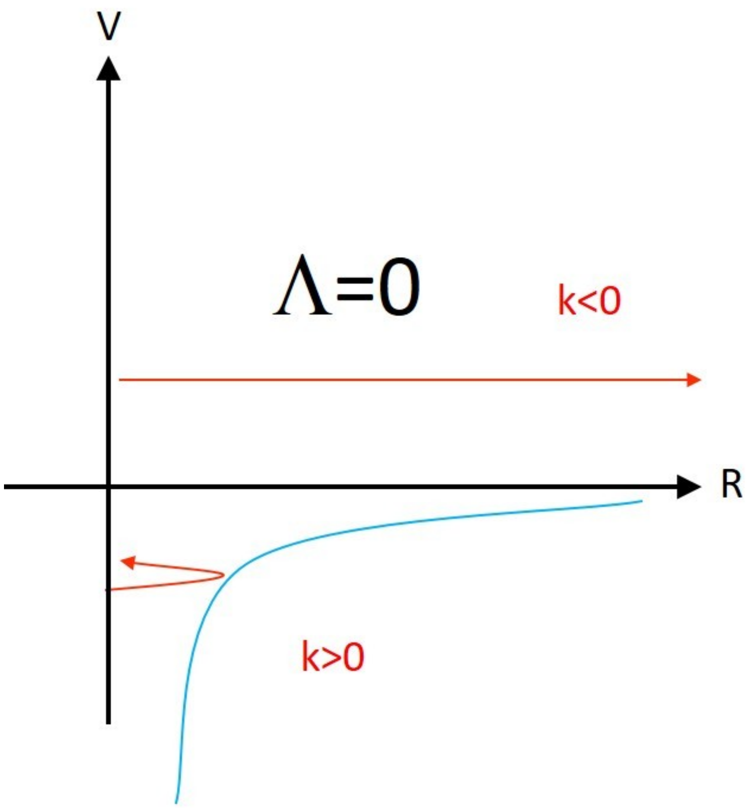
Нобелівська премія з фізики 2019

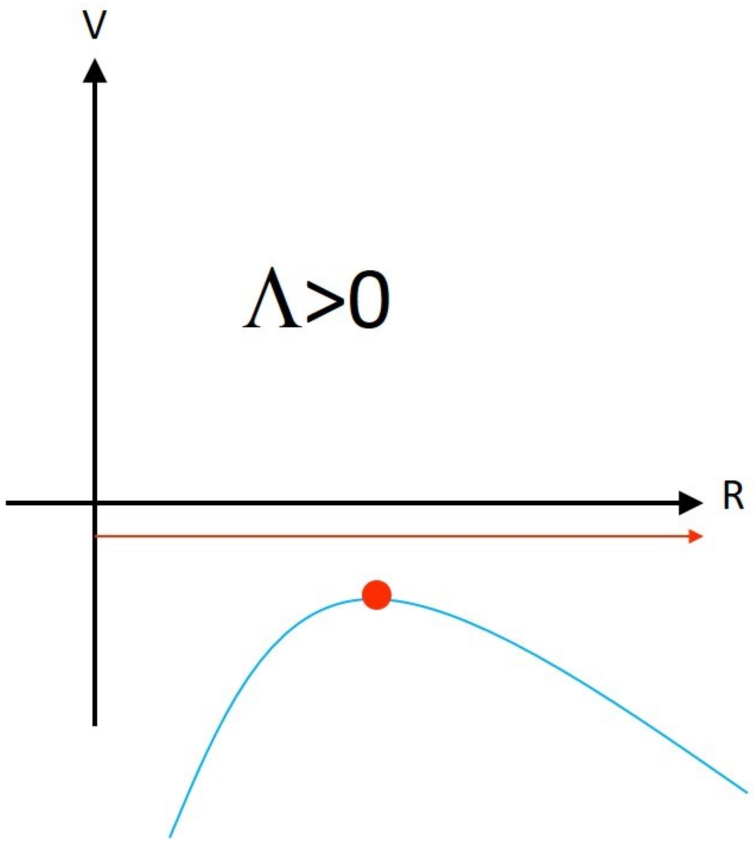


https://www.youtube.com/watch?v=KJhWhO0rxMU



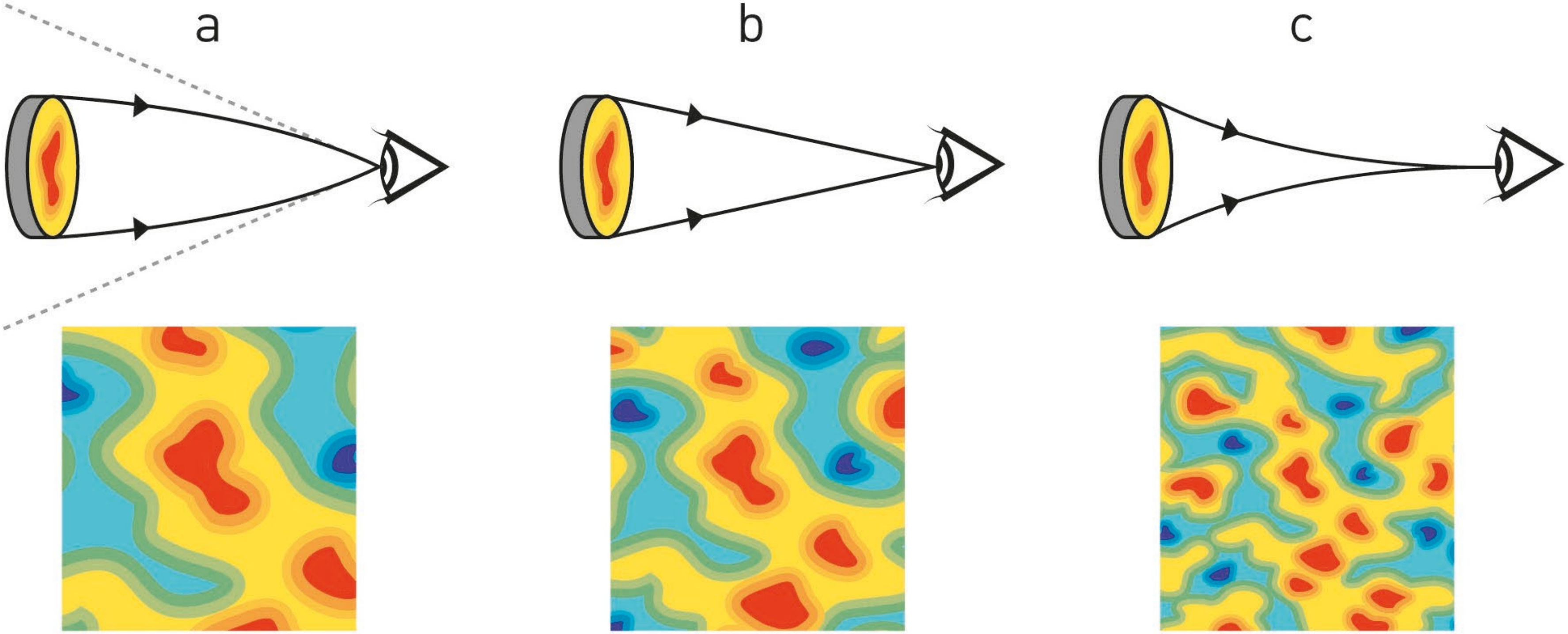
https://www.youtube.com/watch?v=KJhWhO0rxMU





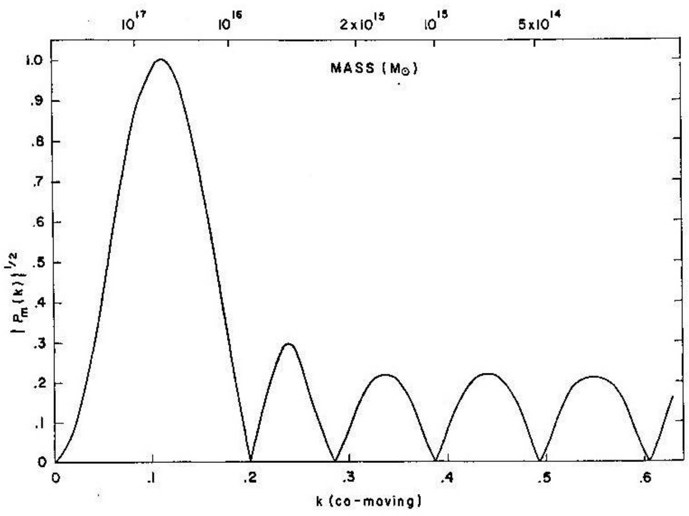
Scientific Background on the Nobel Prize in Physics 2019

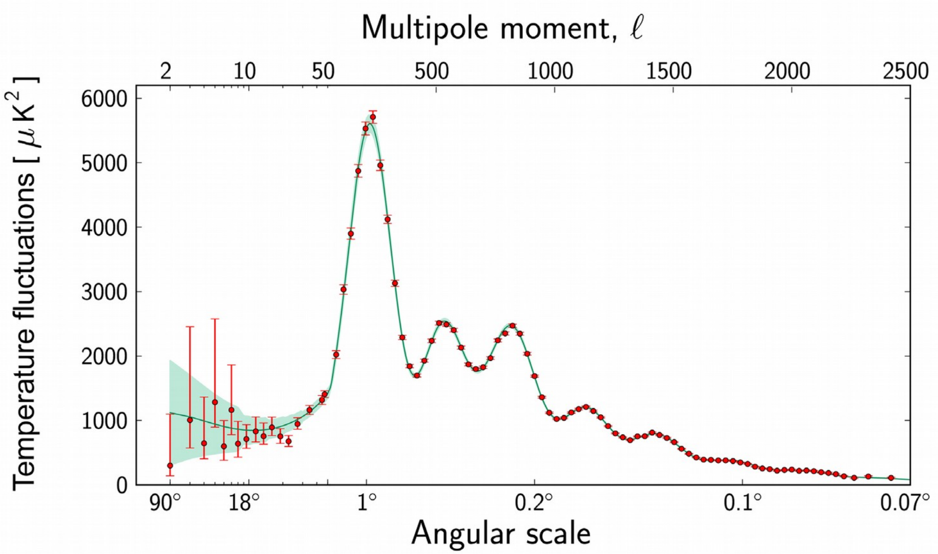
https://www.nobelprize.org/uploads/2019/10/advanced-physicsprize2019-3.pdf



The angular size of spots in the CMB are determined by the geometry

https://www.nobelprize.org/uploads/2019/10/advanced-physicsprize2019-3.pdf





Power spectrum for a flat universe according to Peebles and Yu [27], showing the acoustic peaks.

Anisotropies in the temperature of the CMB as measured by the Planck satellite. The acoustic peaks are clearly visible.

Scientific Background on the Nobel Prize in Physics 2019

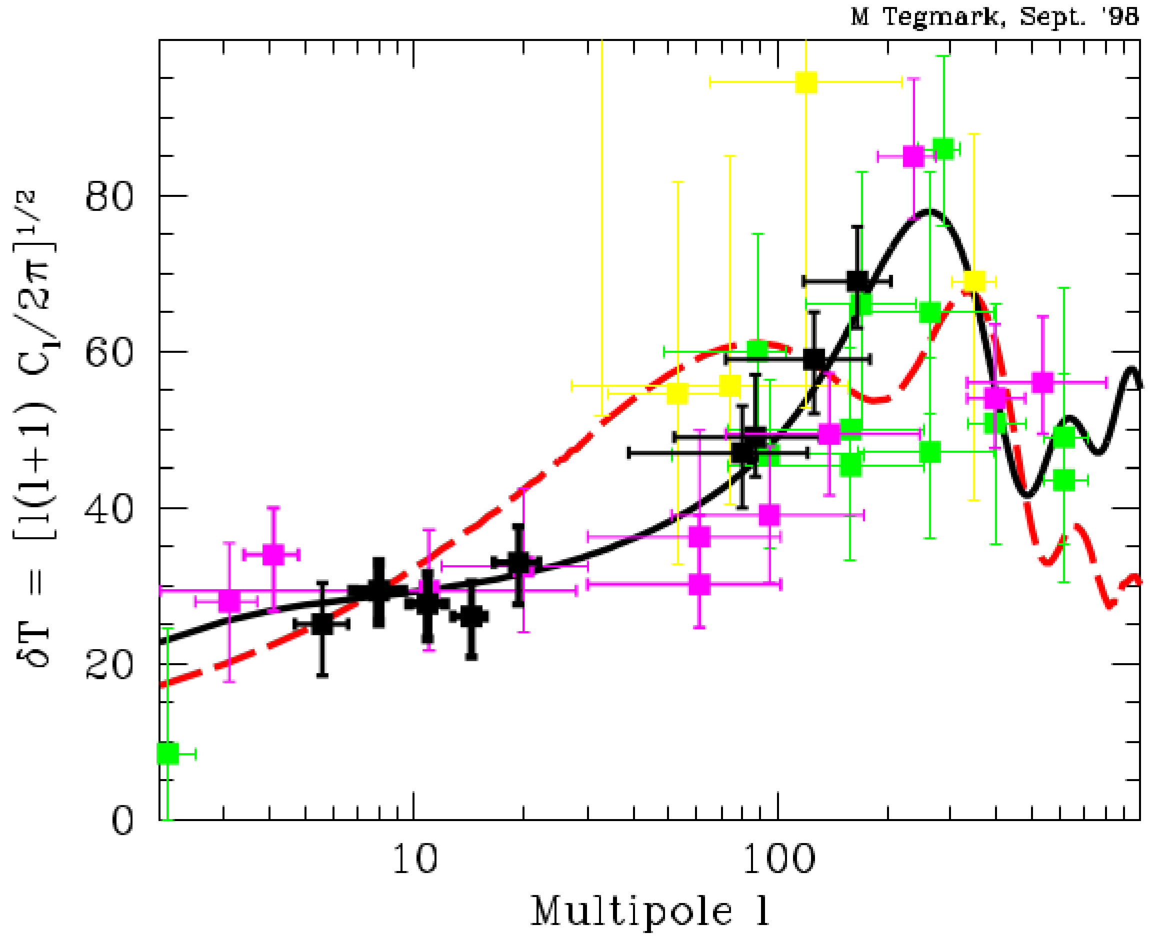
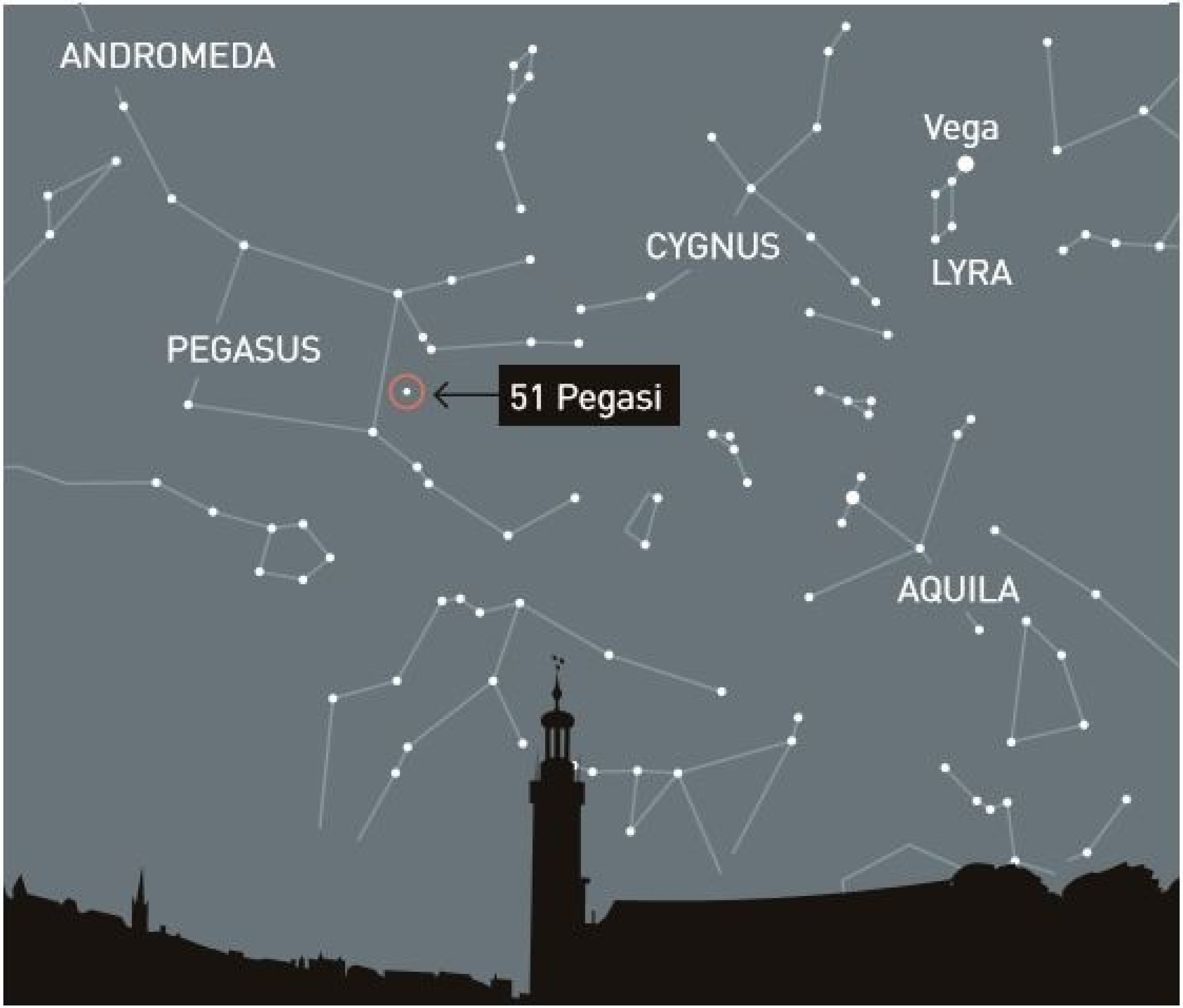
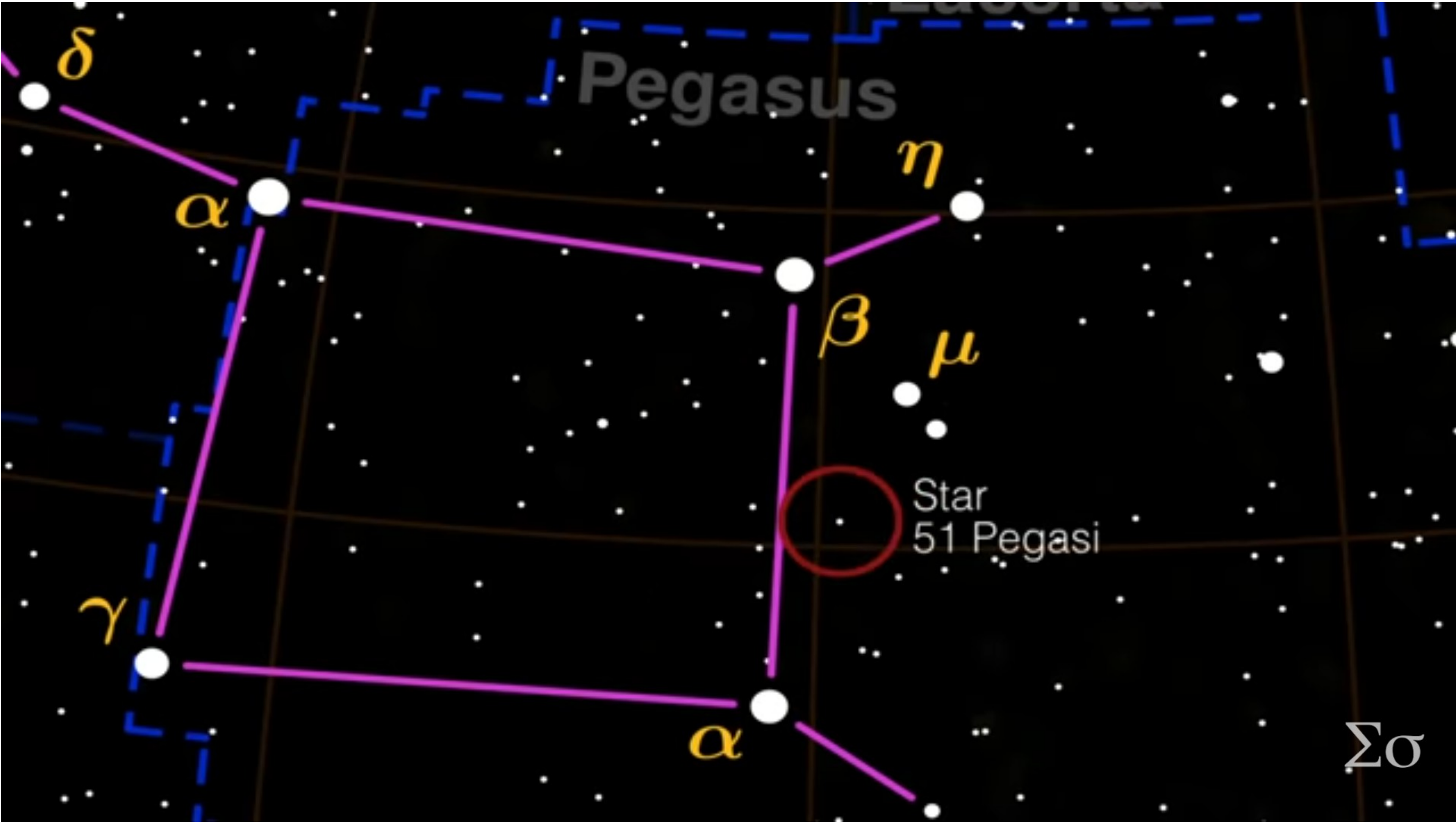


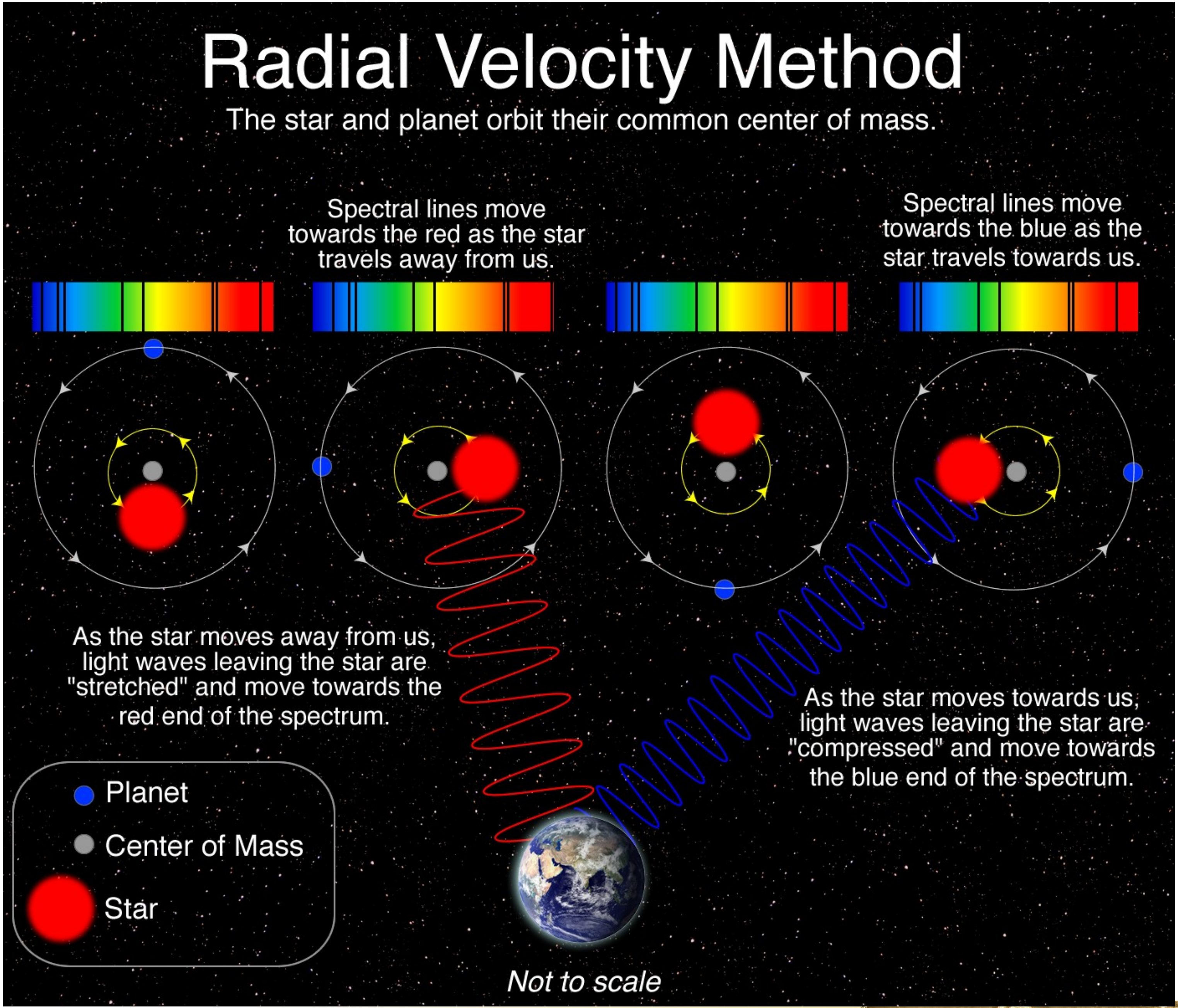
FIG. 3.—Spectrum of angular fluctuations of the CBR. The data are from the compilation by Tegmark (1998). The ΛCDM model prediction plotted as the solid line assumes the parameters in eq. (17) (Tegmark 1998). The ICDM model prediction plotted as the dashed line assumes the parameters in eq. (18).

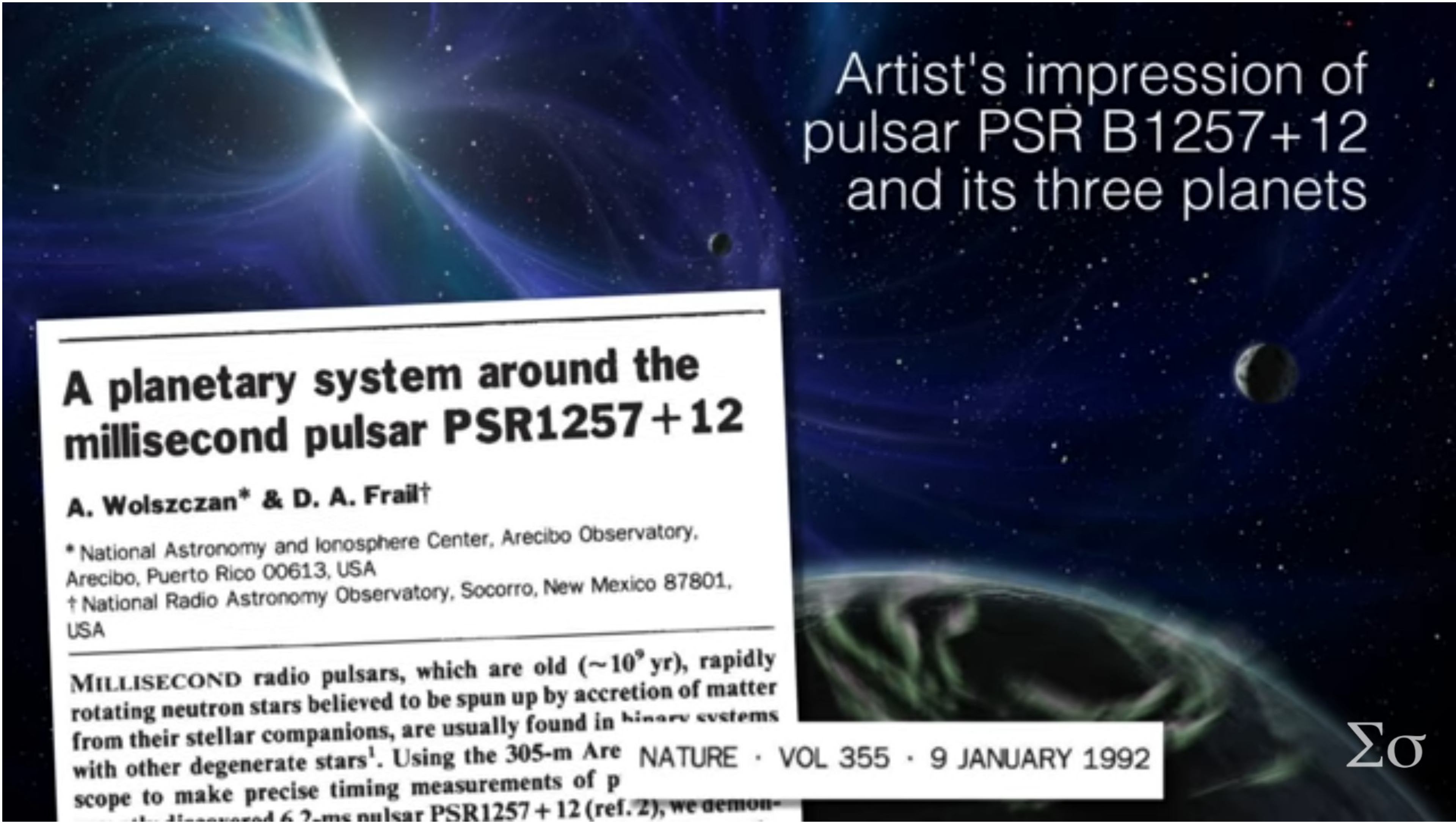


https://www.nobelprize.org/uploads/2019/10/advanced-physicsprize2019-3.pdf

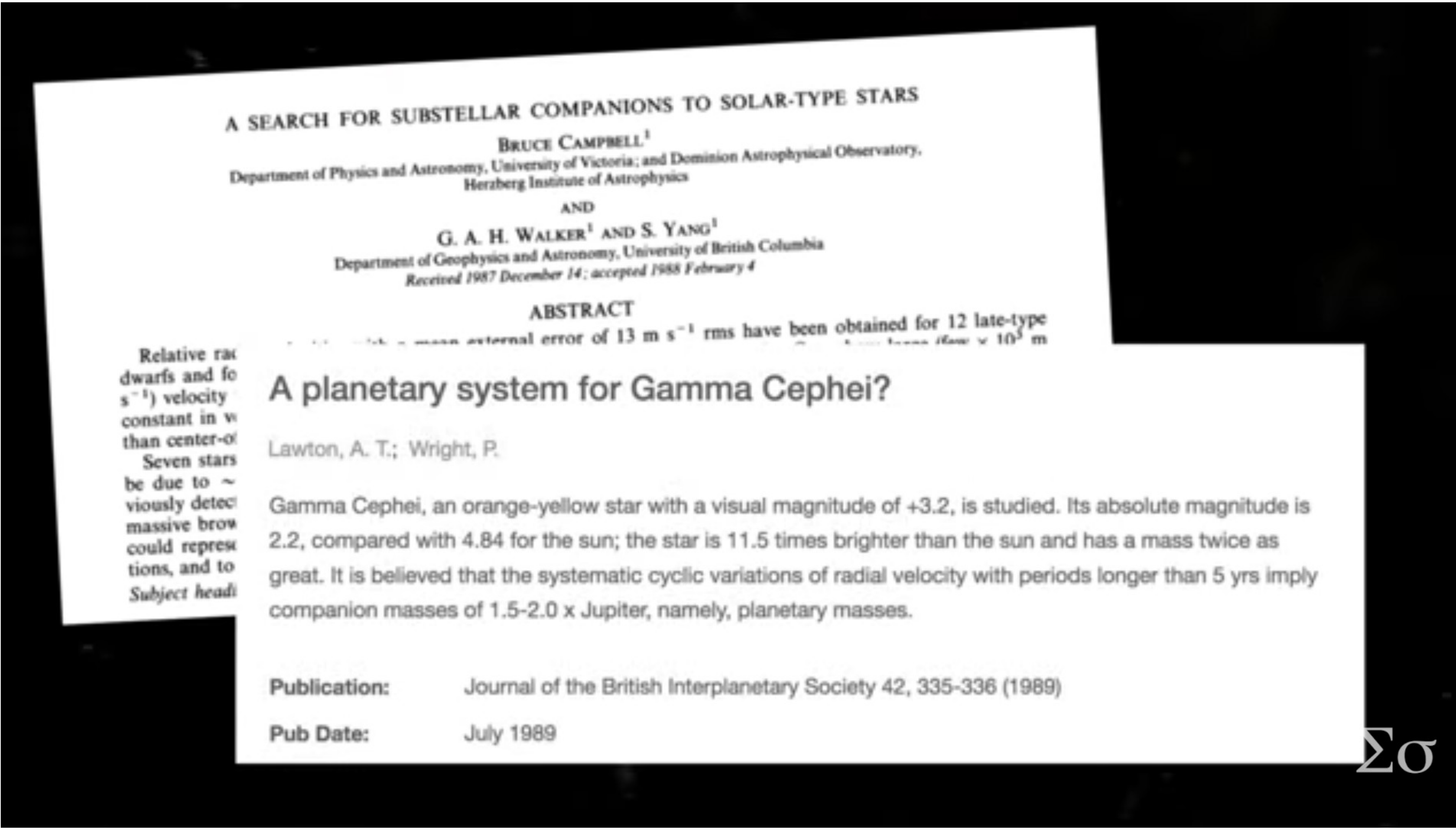


www.youtube.com/watch?v=Gq-atYZFKPQ


Radial Velocity Method
The star and planet orbit their common center of mass.
Spectral lines move towards the red as the star travels away from us.
Spectral lines move towards the blue as the star travels towards us.
As the star moves away from us, light waves leaving the star are "stretched" and move towards the red end of the spectrum.
As the star moves towards us, light waves leaving the star are "compressed" and move towards the blue end of the spectrum.
Planet
Center of Mass
Star
Not to scale



www.youtube.com/watch?v=Gq-atYZFKPQ



www.youtube.com/watch?v=Gq-atYZFKPQ

A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz

Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.

FOR more than ten years, several groups have been examining the radial velocities of dozens of stars, in an attempt to identify orbital motions induced by the presence of heavy planetary companions[1-5]. The precision of spectrographs optimized for Doppler studies and currently in use is limited to about 15 m s^{-1}. As the reflex motion of the Sun due to Jupiter is 13 m s^{-1}, all current searches are limited to the detection of objects with at least the mass of Jupiter (M_J). So far, all precise Doppler surveys have failed to detect any jovian planets or brown dwarfs.

Since April 1994 we have monitored the radial velocity of 142 G and K dwarf stars with a precision of 13 m s^{-1}. The stars in our survey are selected for their apparent constant radial velocity (at lower precision) from a larger sample of stars monitored for 15 years[6,7]. After 18 months of measurements, a small number of stars show significant velocity variations. Although most candidates require additional measurements, we report here the discovery of a companion with a minimum mass of 0.5 M_J, orbiting at 0.05 AU around the solar-type star 51 Peg. Constraints originating from the observed rotational velocity of 51 Peg and from its low chromospheric emission give an upper limit of 2 M_J for the mass of the companion. Alternative explanations to the observed radial velocity variation (pulsation or spot rotation) are unlikely.

The very small distance between the companion and 51 Peg is certainly not predicted by current models of giant planet formation[8]. As the temperature of the companion is above 1,300 K, this object seems to be dangerously close to the Jeans thermal evaporation limit. Moreover, non-thermal evaporation effects are known to be dominant[9] over thermal ones. This jovian-mass companion may therefore be the result of the stripping of a very-low-mass brown dwarf.

The short-period orbital motion of 51 Peg also displays a long-period perturbation, which may be the signature of a second low-mass companion orbiting at larger distance.

Discovery of Jupiter-mass companion(s)

Our measurements are made with the new fibre-fed echelle spectrograph ELODIE of the Haute-Provence Observatory, France[10]. This instrument permits measurements of radial velocity with an accuracy of about 13 m s^{-1} of stars up to 9 mag in an exposure time of <30 min. The radial velocity is computed

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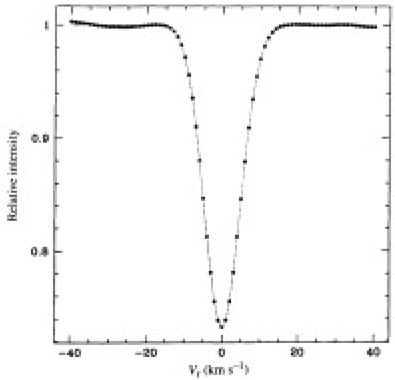

FIG. 1 Typical cross-correlation function used to measure the radial velocity. This function represents a mean of the spectral lines of the star. The location of the gaussian function fitted (solid line) is a precise measurement of the Doppler shift.

with a cross-correlation technique that concentrates the Doppler information of about 5,000 stellar absorption lines. The position of the cross-correlation function (Fig. 1) is used to compute the radial velocity. The width of the cross-correlation function is related to the star's rotational velocity. The very high radial-velocity accuracy achieved is a result of the scrambling effect of the fibres, as well as monitoring by a calibration lamp of instrumental variations during exposure.

The first observations of 51 Peg started in September 1994. In January 1995 a first 4.23-days orbit was computed and confirmed by intensive observations during eight consecutive nights in July 1995 and eight in September 1995. Nevertheless, a 24 m s^{-1} scatter of the orbital solution was measured. As this is incompatible with the accuracy of ELODIE measurements, we adjusted an orbit to four sets of measurements carried out at four different epochs with only the γ-velocity as a free parameter (see Fig. 2).

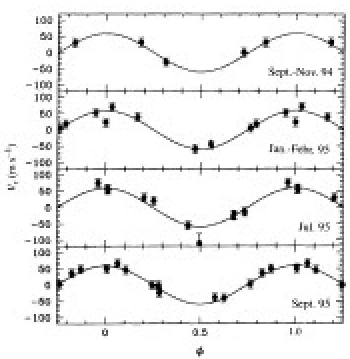

FIG. 2 Orbital motion of 51 Peg at four different epochs corrected from the γ-velocity. The solid line represents the orbital motion fitted on each time span with only the γ-velocity as a free parameter and with the other fixed parameters taken from Table 1.

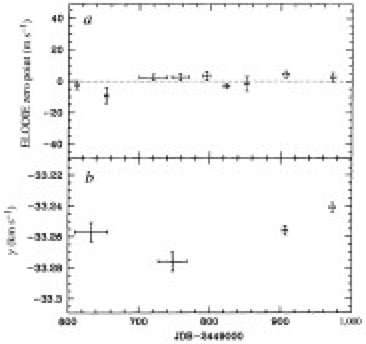

FIG. 3 *a*, ELODIE zero point computed from 87 stars of the sample having more than two measurements and showing no velocity variation. No instrumental zero point drift is detected. *b*, Variation of the γ-velocity of 51 Peg computed from the orbital fits displayed in Fig. 2. Considering the long-term stability of ELODIE this perturbation is probably due to a low-mass companion.

The γ-velocity in Fig. 3 shows a significant variation that cannot be the result of instrumental drift in the spectrograph. This slow perturbation of the short-period orbit is probably the signature of a second low-mass companion.

The long-period orbit cannot have a large amplitude. The 26 radial velocity measurements made during >12 years with the CORAVEL spectrometer do not reveal any significant variation at a 200 m s^{-1} level. Intensive monitoring of 51 Peg is in progress to confirm this long-period orbit.

In Fig. 4 a short-period circular orbit is fitted to the data after correction of the variation in γ-velocity. Leaving the eccentricity as a free parameter would have given $e = 0.09 \pm 0.06$ with almost the same standard deviation for the r.m.s. residual (13 m s^{-1}). Therefore we consider that a circular orbit cannot be ruled out. At present the eccentricity range is between 0 and about 0.15. Table 1 lists the orbital parameters of the circular-orbit solution.

An orbital period of 4.23 days is rather short, but short-period binaries are not exceptional among solar-type stars. (Five spectroscopic binaries have been found with a period <4 days in a volume-limited sample of 164 G-type dwarfs in the solar vicinity[6].) Although this orbital period is not surprising in binary stars, it is puzzling when we consider the mass obtained for the companion:

$$M_2 \sin i = 0.47 \pm 0.02\ M_J$$

where i is the (unknown) inclination angle of the orbit.

51 Peg (HR8729, HD217014 or Gliese 882) is a 5.5 mag star, quite similar to the Sun (see Table 2), located 13.7 pc (45 light yr) away. Photometric and spectroscopic analyses indicate a star slightly older than the Sun, with a similar temperature and slight overabundance of heavy elements. The estimated age[11] derived from its luminosity and effective temperature is typical of an old galactic-disk star. The slight overabundance of heavy elements in such an old disk star is noteworthy. But this is certainly not a remarkable peculiarity in view of the observed scatter of stellar metallicities at a given age.

Upper limit for the companion mass

A priori, we could imagine that we are confronted with a normal spectroscopic binary with an orbital plane almost perpendicular to the line of sight. Assuming a random distribution of binary orbital planes, the probability is less than 1% that the companion mass is larger than 4 M_J, and 1/40,000 that it is above the hydrogen-burning limit of 0.08 $M_\odot$. Although these probability estimates already imply a low-mass companion for 51 Peg, an even stronger case can be made from considerations of rotational velocity. If we assume that the rotational axis of 51 Peg is aligned with the orbital plane, we can derive $\sin i$ by combining the observed projected rotational velocity ($v \sin i$) with the equatorial velocity $V_{equ} = 2\pi R/P$ ($v \sin i = V_{equ} \cdot \sin i$).

Three independent precise $v \sin i$ determinations of 51 Peg have been made: by line-profile analysis[12], $v \sin i = 1.7 \pm 0.8$ km s^{-1}; by using the cross-correlation function obtained with the CORAVEL spectrometer[13], $v \sin i = 2.1 \pm 0.6$ km s^{-1}; and by using the cross-correlation function obtained with ELODIE, $v \sin i = 2.8 \pm 0.5$ km s^{-1}. The unweighted mean $v \sin i$ is 2.2 ± 0.3 km s^{-1}. The standard error is probably not significant as the determination of very small $v \sin i$ is critically dependent on the supposed macroturbulence in the atmosphere. We accordingly prefer to admit a larger uncertainty: $v \sin i = 2.2 \pm 1$ km s^{-1}.

51 Peg has been actively monitored for variability in its chromospheric activity[14]. Such activity, measured by the re-emission in the core of the Ca II lines, is directly related to stellar rotation via its dynamo-generated magnetic field. A very low level of chromospheric activity is measured for this object. Incidentally, this provides an independent estimate of an age of 10 Gyr (ref. 14), consistent with the other estimates. No rotational modulation has been detected so far from chromospheric emission, but a 30-day period is deduced from the mean chromospheric activity level *S*-index. A V_{equ} value of 2.2 ± 0.8 km s^{-1} is then computed if a 25% uncertainty in the period determination is assumed.

Using the mean $v \sin i$ and the rotational velocity computed from chromospheric activity, we finally deduce a lower limit of 0.4 for $\sin i$. This corresponds to an upper limit for the mass of the planet of 1.2 M_J. Even if we consider a misalignment as large as 10°, the mass of the companion must still be less than 2 M_J, well below the mass of brown dwarfs.

The 30-day rotation period of 51 Peg is clearly not synchronized with the 4.23-day orbital period of its low-mass companion, despite its very short period. (Spectroscopic binaries with similar periods are all synchronized.) The lack of synchronism on a timescale of 10^{10} yr is a consequence of the q^{-2} ($q = M_2/M_1$) dependence of the synchronization timescale[15]. In principle this can be used to derive an upper limit to the mass of the companion. It does at least rule out the possibility of the presence of a low-mass stellar companion.

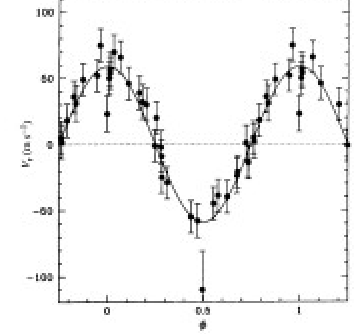

FIG. 4 Orbital motion of 51 Peg corrected from the long-term variation of the γ-velocity. The solid line represents the orbital motion computed from the parameters of Table 1.

TABLE 1 Orbital parameters of 51 Peg

P	4.2293 ± 0.0011 d
T	$2{,}449{,}797.773 \pm 0.036$
e	0 (fixed)
K_1	0.059 ± 0.003 km s^{-1}
$a_1 \sin i$	$(34 \pm 2)\ 10^5$ m
$f_1(m)$	$(0.91 \pm 0.15)\ 10^{-10}\ M_\odot$
N	35 measurements
(O − C)	13 m s^{-1}

P, period; *T*, epoch of the maximum velocity; *e*, eccentricity; K_1, half-amplitude of the velocity variation; $a_1 \sin i$, where a_1 is the orbital radius; $f_1(m)$, mass function; *N*, number of observations; (O − C), r.m.s. residual.

TABLE 2 Physical parameters of 51 Peg compared with those of the Sun

		51 Peg		
	Sun	Geneva photometry*	Spectroscopy†	Strömgren photometry and spectroscopy[11]
T_{eff} (K)	5,780	5,773	5,724	5,775
log g	4.45	4.32	4.30	4.18
Fe/H	0		0.19	0.06‡
M/H	0	0.20		
M_v	4.79	4.60		
$R/R_\odot$	1	1.29		

M/H is the logarithmic ratio of the heavy element abundance compared to the Sun (in dex).

* M. Grenon (personal communication).

† J. Valenti (personal communication).

‡ But other elements such as Na I, Mg I, Al I are overabundant, in excess of 0.20.

Alternative interpretations?

With such a small amplitude of velocity variation and such a short period, pulsation or spot rotation might explain the observations equally well[16,17]. We review these alternative interpretations below and show that they can probably be excluded.

Spot rotation can be dismissed on the basis of the lack of chromospheric activity and the large period derived from the *S* chromospheric index, which is clearly incompatible with the observed radial-velocity short period. A solar-type star rotating with a period of 4.2 days would have a much stronger chromospheric activity than the currently observed value[14]. Moreover, a period of rotation of 4.2 days for a solar-type star is typical of a very young object (younger than the Pleiades) and certainly not of an old disk star.

Pulsation could easily yield low-amplitude velocity variations similar to the one observed, but would be accompanied by luminosity and colour variations as well as phase-related absorption line asymmetries. The homogeneous photometric survey made by the Hipparcos satellite provides a comprehensive view of the intrinsic variability of stars of different temperatures and luminosities. The spectral type of 51 Peg corresponds to a region of the Hertzsprung–Russell diagram where the stars are the most stable[18].

Among solar-type stars no mechanisms have been identified for the excitation of pulsation modes with periods as long as 4 days. Only modes with very low amplitude ($\ll 1$ m s^{-1}) and periods from minutes to 1 h are detected for the Sun.

Radial velocity variations of a few days and <100 m s^{-1} amplitude have been reported for a few giant stars[19]. Stars with a similar spectral type and luminosity class are known to be photometric variables[18]. Their observed periods are in

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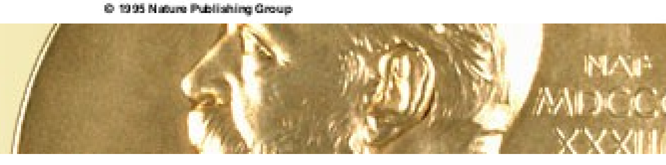
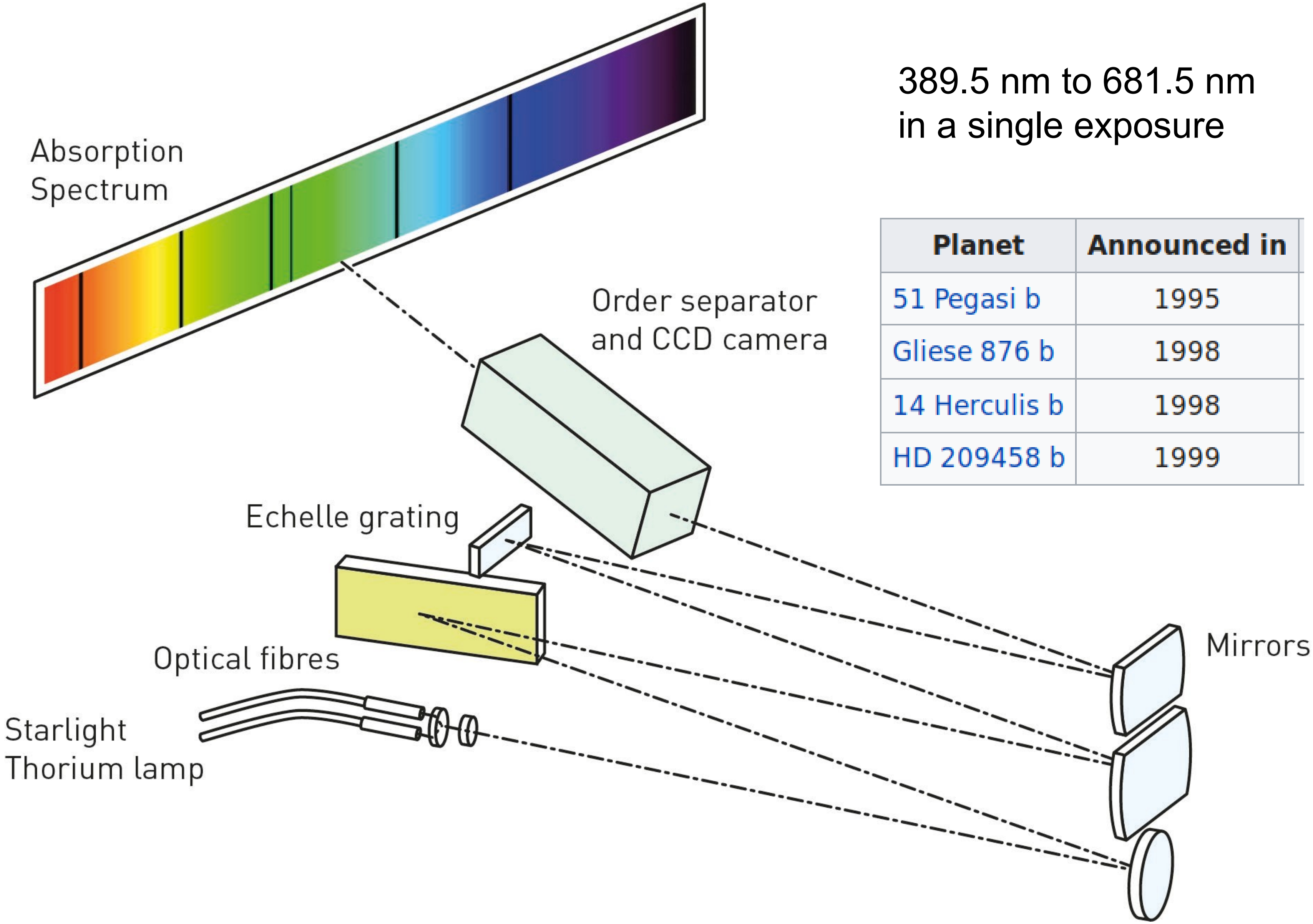


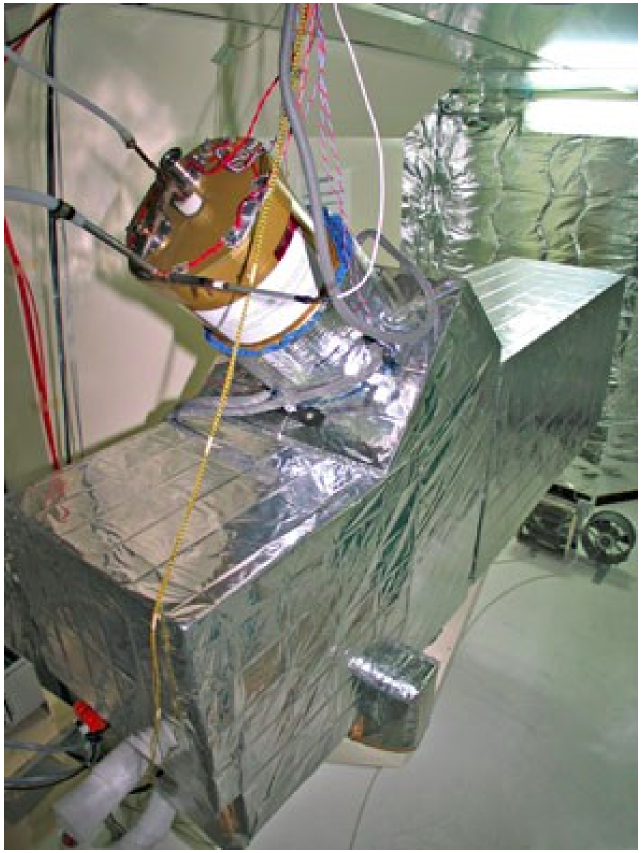
Спектрограф ELODIE

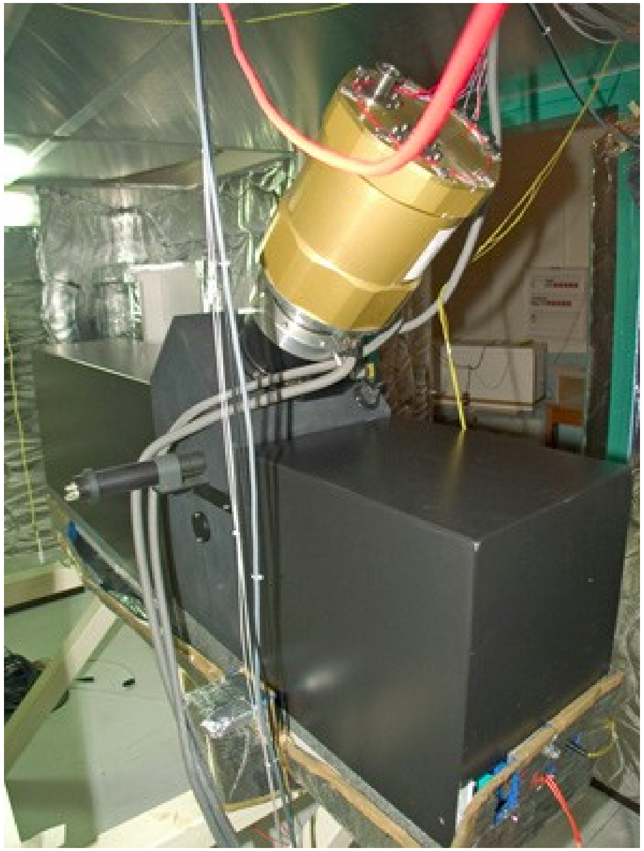


389.5 nm to 681.5 nm
in a single exposure

Planet	Announced in
51 Pegasi b	1995
Gliese 876 b	1998
14 Herculis b	1998
HD 209458 b	1999

Спектрограф ELODIE





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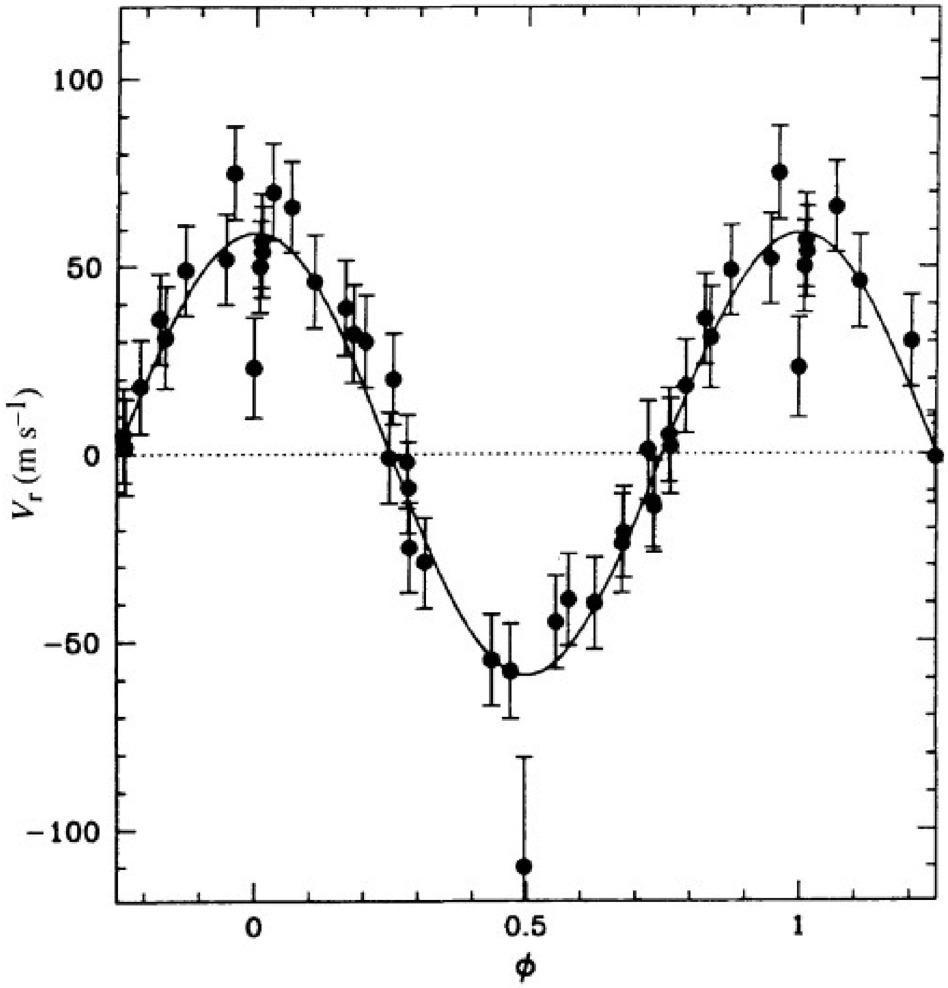
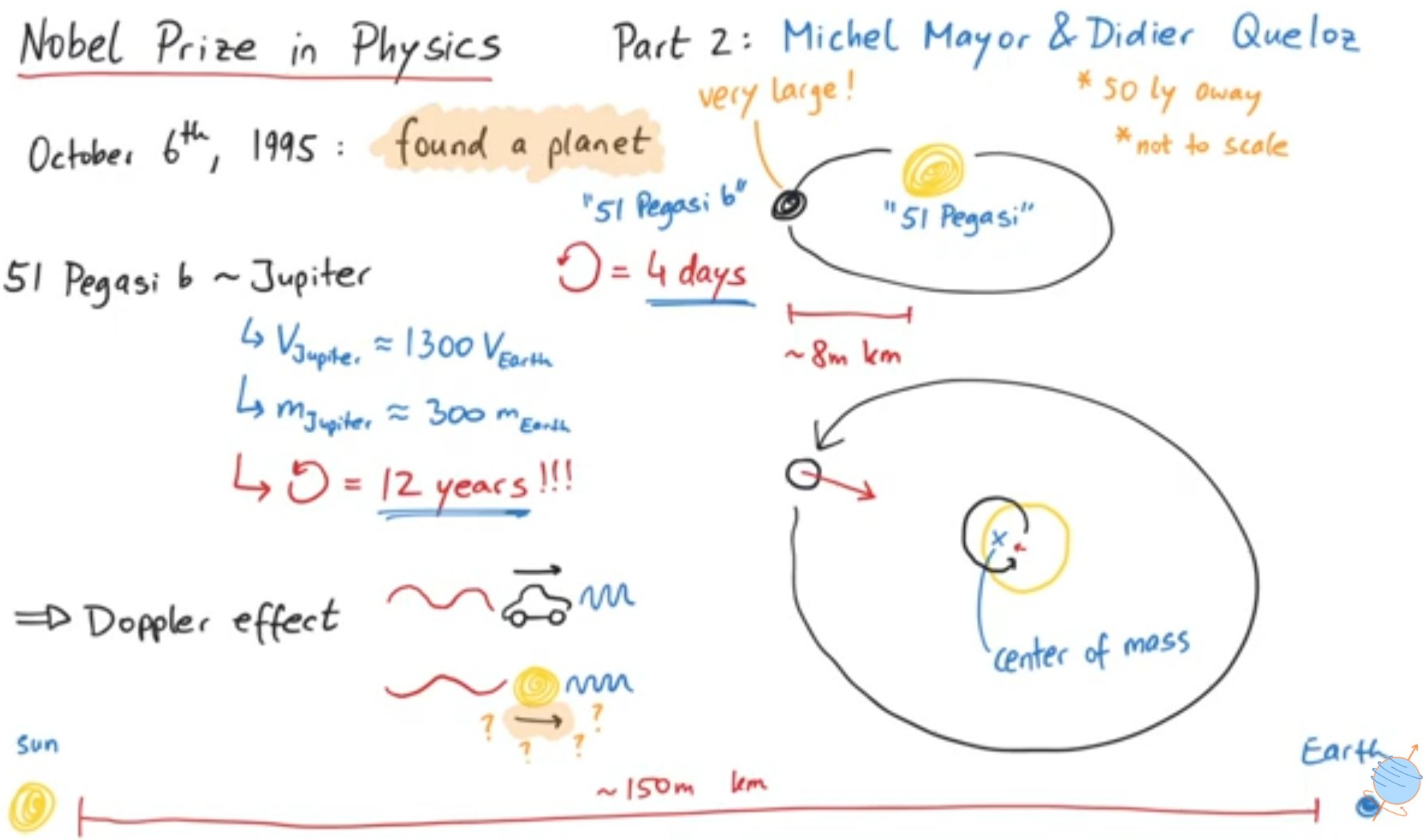


FIG. 4 Orbital motion of 51 Peg corrected from the long-term variation of the γ-velocity. The solid line represents the orbital motion computed from the parameters of Table 1.



https://www.youtube.com/watch?v=KJhWhO0rxMU

An illustration of 51 Pegasi, the first planet to be discovered orbiting a sunlike star.

NASA/JPL-Caltech

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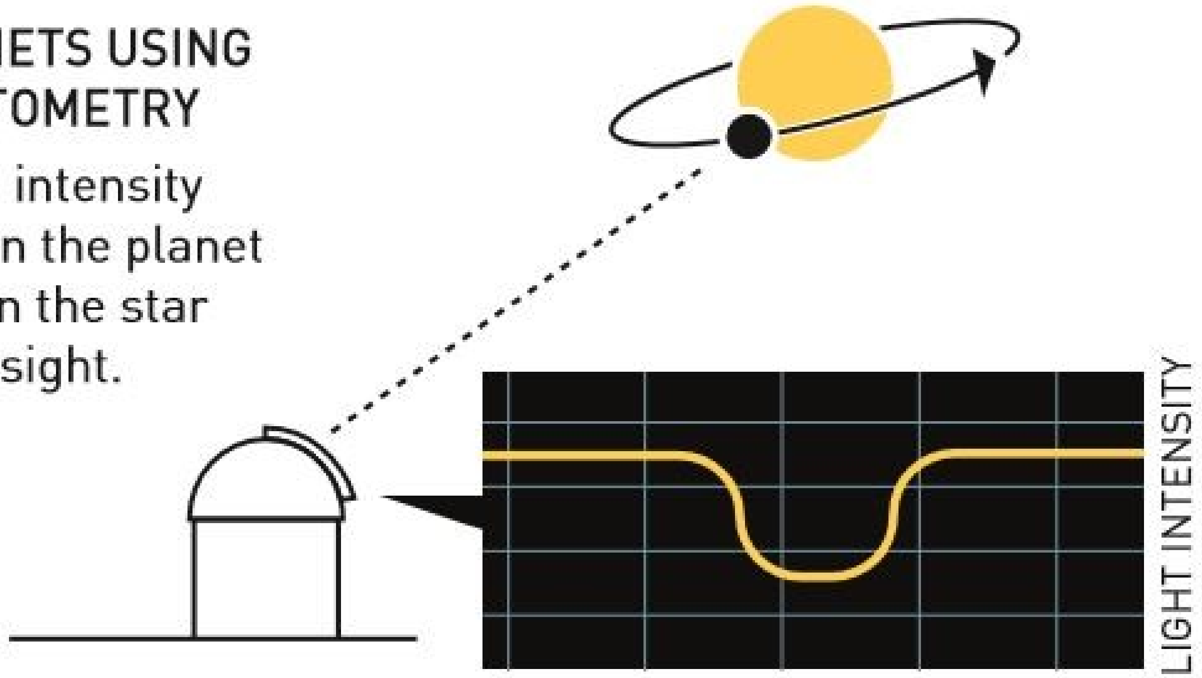
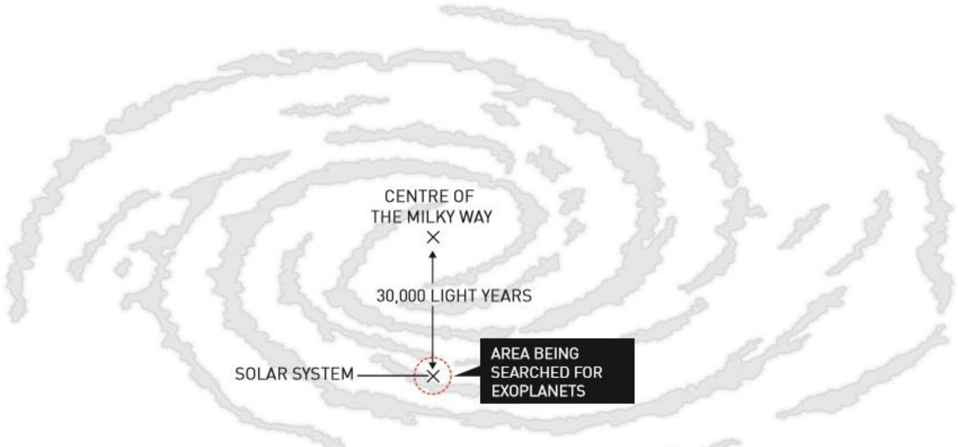
FINDING PLANETS USING TRANSIT PHOTOMETRY

The star's light intensity decreases when the planet passes between the star and our line of sight. This effect is observed by telescopes on Earth.





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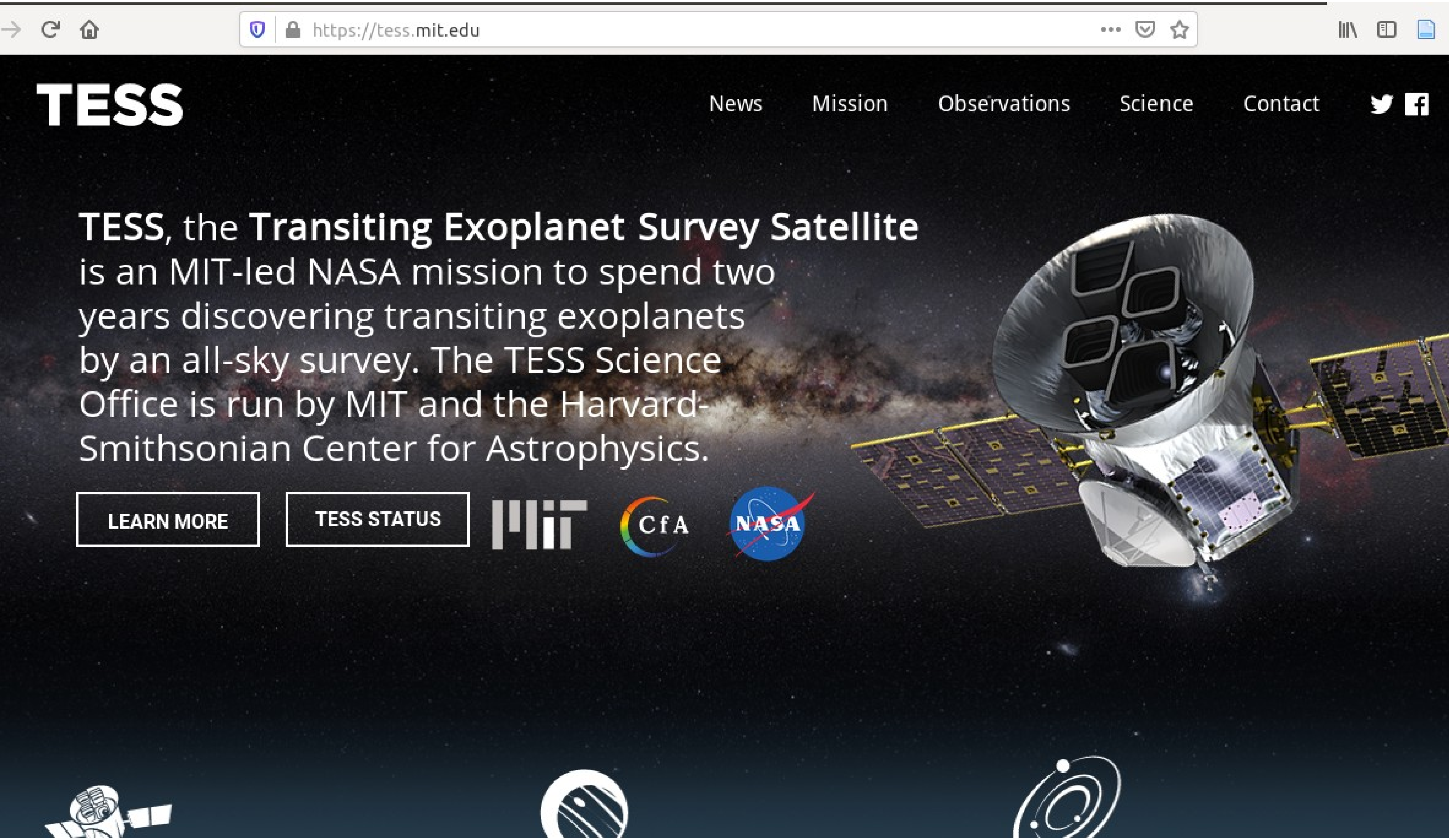

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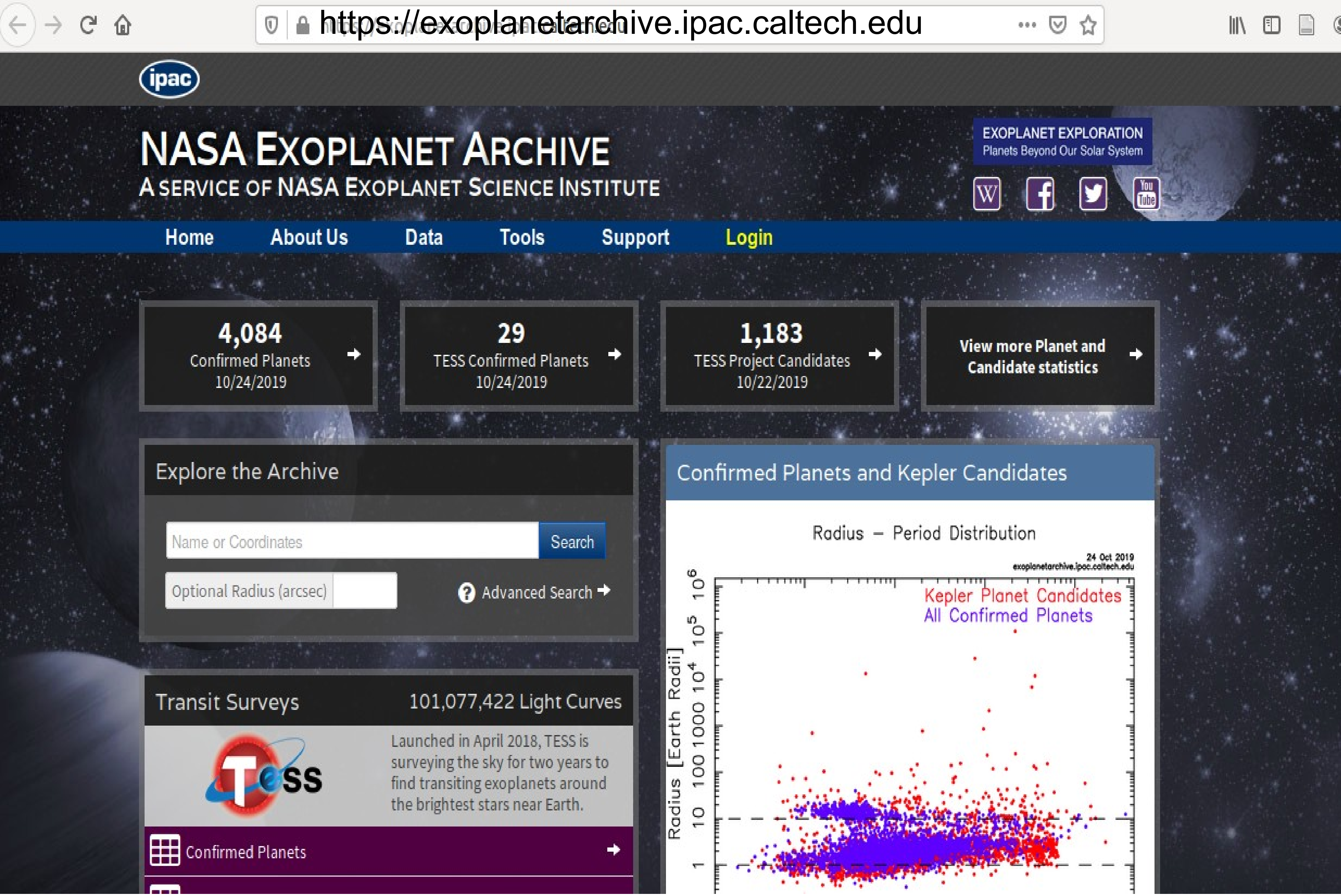

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Confirmed Planets

Host Name	Planet Letter	Planet Name	Discovery Method	Number of Planets in System	Orbital Period [days]	Orbit Semi-Major Axis [AU]	Eccentricity	Inclination [deg]	Planet Mass or M*sin(i) [Jupiter mass]	Distance [pc]
Proxima Cen	b	Proxima Cen b	Radial Velocity	1	$11.186^{+0.001}_{-0.002}$	$0.0485^{+0.0041}_{-0.0051}$	<0.35		$0.00400^{+0.00060}_{-0.00053}$	1.3012355557
GJ 411	b	GJ 411 b	Radial Velocity	1	12.9532±0.0079	0.0785±0.0027	0.22±0.13		0.00941±0.00145	2.5468±0.0043
eps Eri	b	eps Eri b	Radial Velocity	1	2502±10	3.39±0.36	0.702±0.039	30.1±3.8	1.55±0.24	3.2116±0.0011
Ross 128	b	Ross 128 b	Radial Velocity	1	9.8658±0.0070	0.0496±0.0017	0.116±0.097		0.00440±0.00066	3.3806±0.0064
GJ 15 A	b	GJ 15 A b	Radial Velocity	2	$11.4407^{+0.0017}_{-0.0016}$	$0.072^{+0.003}_{-0.004}$	$0.0940^{+0.0910}_{-0.0650}$		$0.00953^{+0.00145}_{-0.00138}$	3.5626461540
GJ 15 A	c	GJ 15 A c	Radial Velocity	2	7600^{+2200}_{-1700}	$5.4^{+1.0}_{-0.9}$	$0.27^{+0.28}_{-0.19}$		$0.11^{+0.08}_{-0.06}$	3.5626461540
YZ Cet	b	YZ Cet b	Radial Velocity	3	1.96876±0.00021	0.01557±0.00052	0.0±0.1		0.0024±0.0004	3.6
YZ Cet	c	YZ Cet c	Radial Velocity	3	3.06008±0.00022	0.02090±0.00070	0.040±0.110		0.00308±0.00044	3.6
YZ Cet	d	YZ Cet d	Radial Velocity	3	4.65627±0.00042	0.02764±0.00093	0.129±0.096		0.00359±0.00053	3.6
tau Cet	e	tau Cet e	Radial Velocity	4	$162.87^{+1.08}_{-0.46}$	0.538±0.060	$0.18^{+0.18}_{-0.14}$		$0.0124^{+0.0026}_{-0.0020}$	3.6033930383
tau Cet	f	tau Cet f	Radial Velocity	4	$636.13^{+11.70}_{-47.69}$	$1.334^{+0.017}_{-0.044}$	$0.16^{+0.07}_{-0.16}$		$0.0124^{+0.0033}_{-0.0043}$	3.6033930383
tau Cet	g	tau Cet g	Radial Velocity	4	$20.00^{+0.02}_{-0.01}$	$0.133^{+0.001}_{-0.002}$	$0.060^{+0.130}_{-0.060}$		$0.00551^{+0.00079}_{-0.00126}$	3.6033930383
tau Cet	h	tau Cet h	Radial Velocity	4	$49.41^{+0.08}_{-0.10}$	0.243±0.003	$0.23^{+0.16}_{-0.15}$		$0.00576^{+0.00214}_{-0.00082}$	3.6033930383
eps Ind A	b	eps Ind A b	Radial Velocity	1	16510^{+2100}_{-1740}	$11.55^{+0.98}_{-0.86}$	$0.26^{+0.07}_{-0.03}$	$64.25^{+13.80}_{-6.09}$	$3.25^{+0.39}_{-0.65}$	3.6389465505

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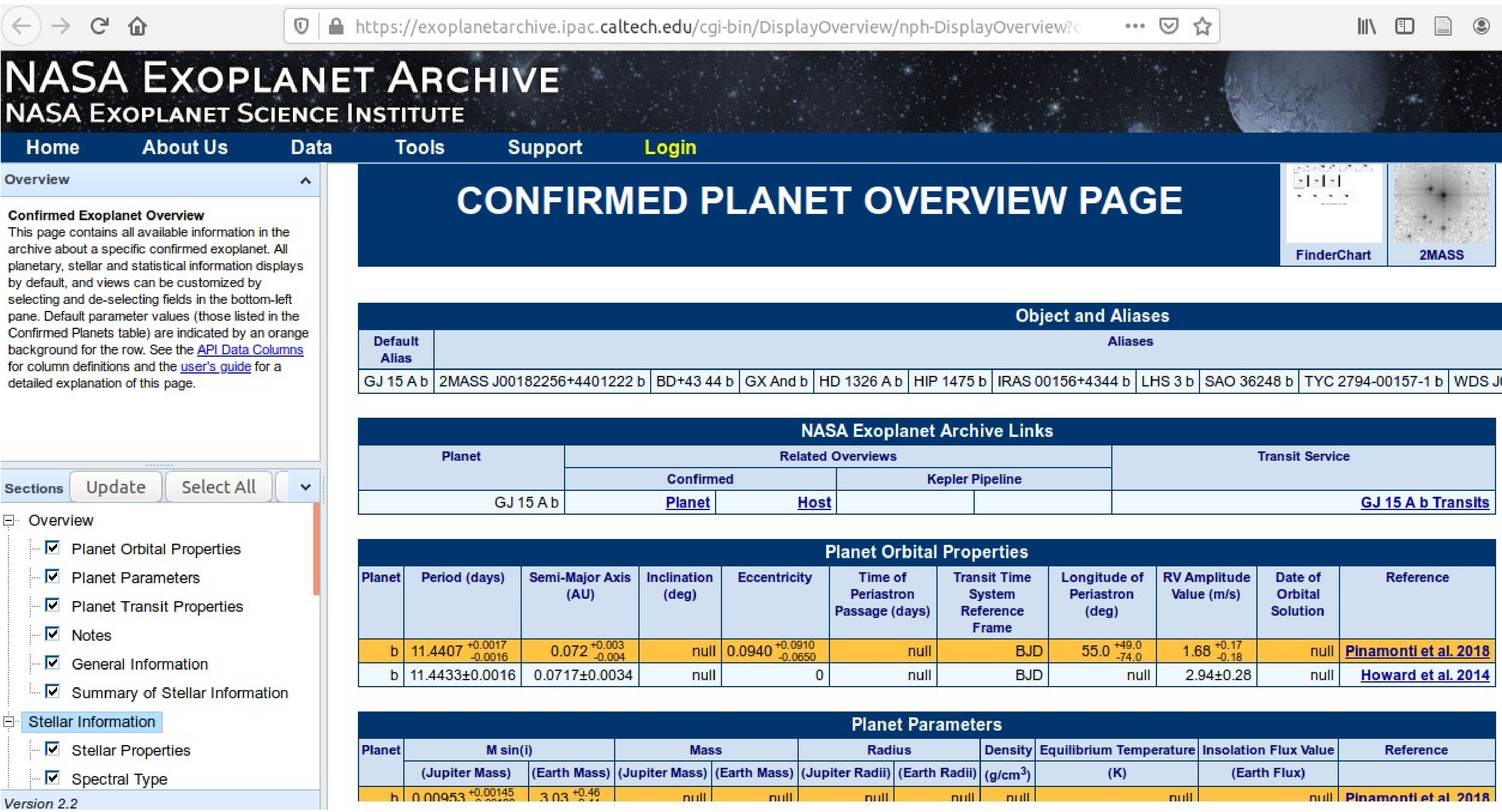

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Overview

Confirmed Exoplanet Overview
This page contains all available information in the archive about a specific confirmed exoplanet. All planetary, stellar and statistical information displays by default, and views can be customized by selecting and de-selecting fields in the bottom-left pane. Default parameter values (those listed in the Confirmed Planets table) are indicated by an orange background for the row. See the API Data Columns for column definitions and the user's guide for a detailed explanation of this page.

Sections | Update | Select All

- Overview
  - Planet Orbital Properties
  - Planet Parameters
  - Planet Transit Properties
  - Notes
  - General Information
  - Summary of Stellar Information
- Stellar Information
  - Stellar Properties
  - Spectral Type

Version 2.2

CONFIRMED PLANET OVERVIEW PAGE

FinderChart | 2MASS

Object and Aliases

Default Alias	Aliases									
GJ 15 A b	2MASS J00182256+4401222 b	BD+43 44 b	GX And b	HD 1326 A b	HIP 1475 b	IRAS 00156+4344 b	LHS 3 b	SAO 36248 b	TYC 2794-00157-1 b	WDS J

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Planet	Related Overviews: Confirmed		Kepler Pipeline		Transit Service
GJ 15 A b	Planet	Host			GJ 15 A b Transits

Planet Orbital Properties

Planet	Period (days)	Semi-Major Axis (AU)	Inclination (deg)	Eccentricity	Time of Periastron Passage (days)	Transit Time System Reference Frame	Longitude of Periastron (deg)	RV Amplitude Value (m/s)	Date of Orbital Solution	Reference
b	$11.4407^{+0.0017}_{-0.0016}$	$0.072^{+0.003}_{-0.004}$	null	$0.0940^{+0.0910}_{-0.0650}$	null	BJD	$55.0^{+49.0}_{-74.0}$	$1.68^{+0.17}_{-0.18}$	null	Pinamonti et al. 2018
b	11.4433±0.0016	0.0717±0.0034	null	0	null	BJD	null	2.94±0.28	null	Howard et al. 2014

Planet Parameters

Planet	M sin(i) (Jupiter Mass)	M sin(i) (Earth Mass)	Mass (Jupiter Mass)	Mass (Earth Mass)	Radius (Jupiter Radii)	Radius (Earth Radii)	Density (g/cm^3)	Equilibrium Temperature (K)	Insolation Flux Value (Earth Flux)	Reference
b	$0.00953^{+0.00145}$	$3.03^{+0.46}$	null	null	null	null	null	null	null	Pinamonti et al. 2018

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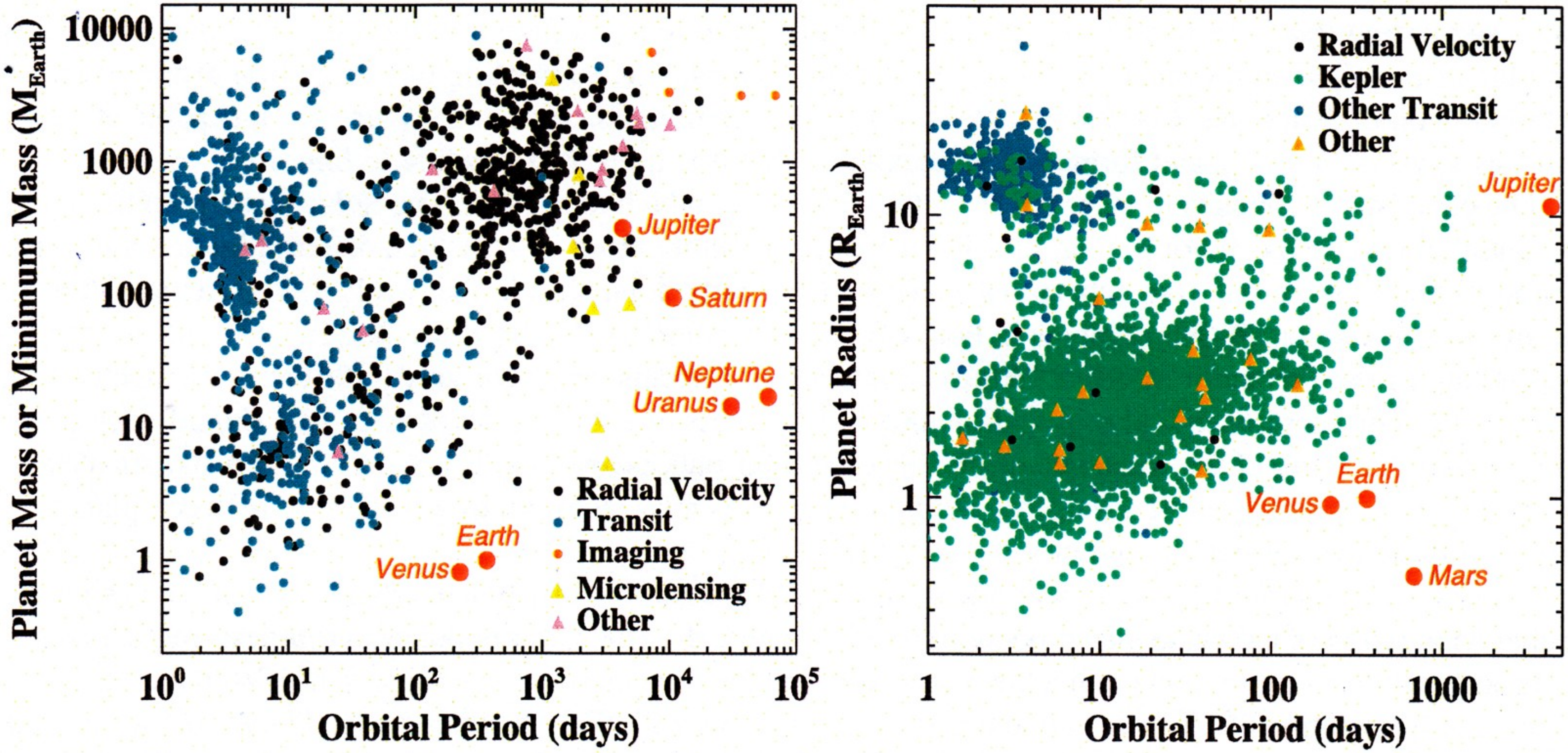
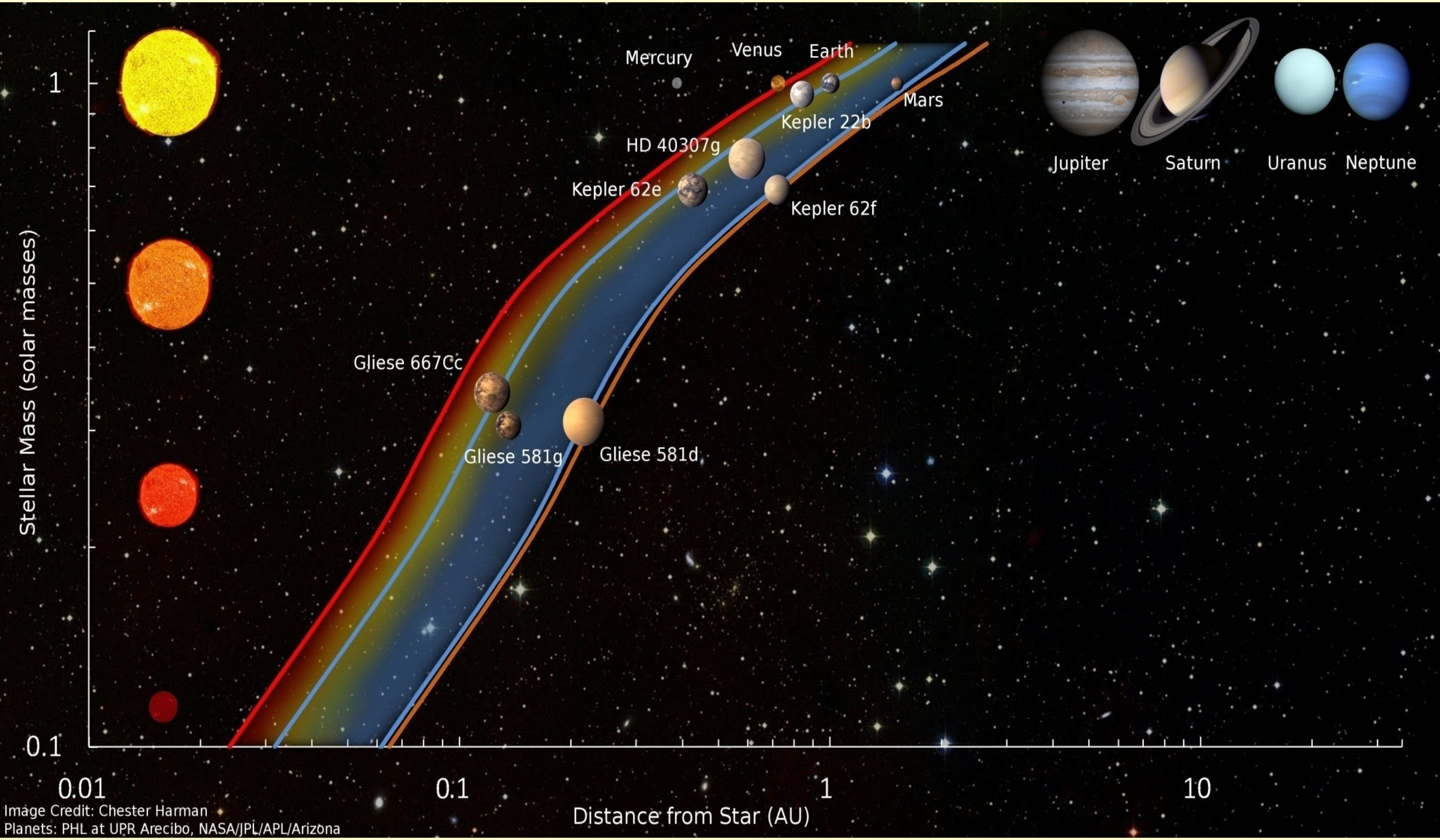
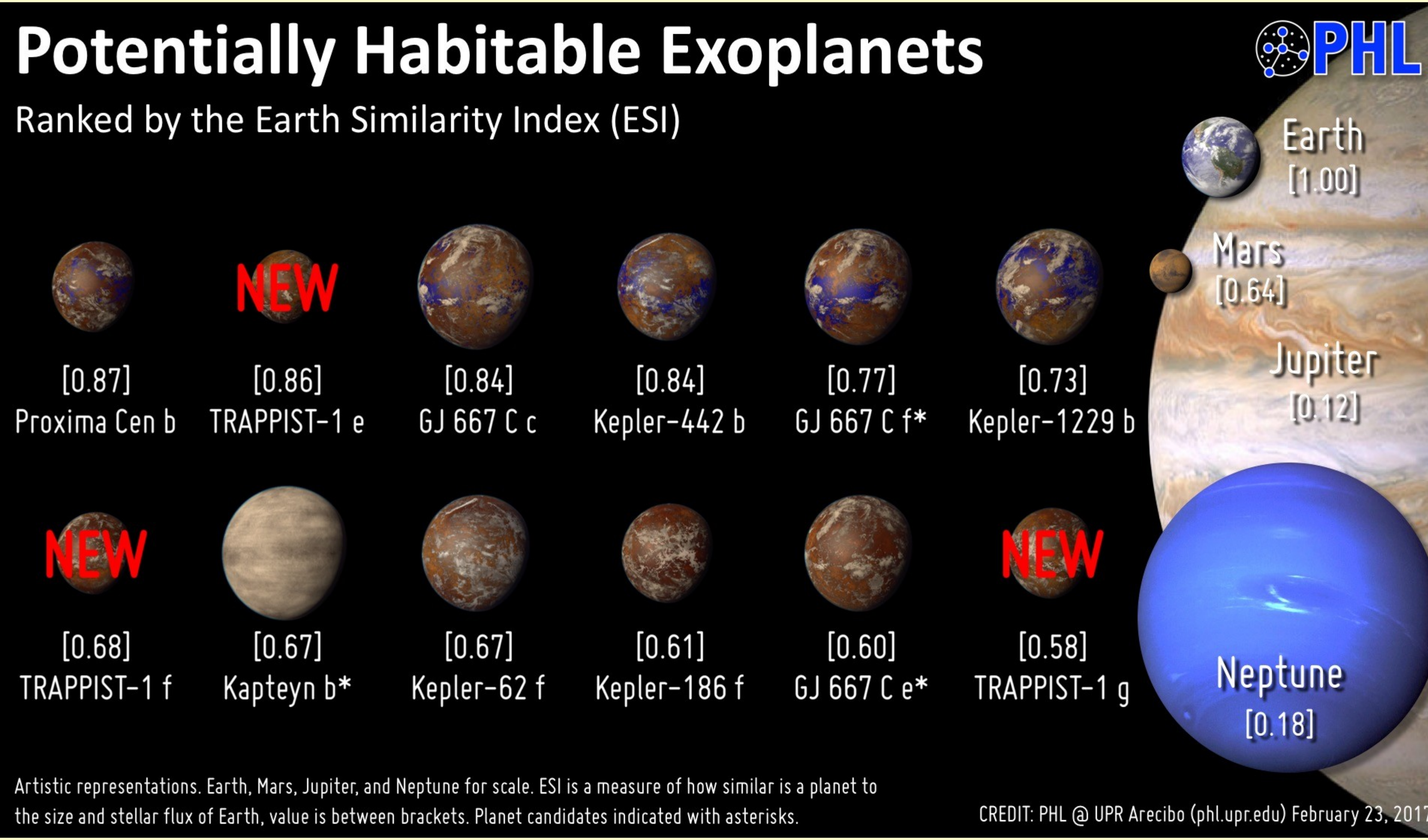
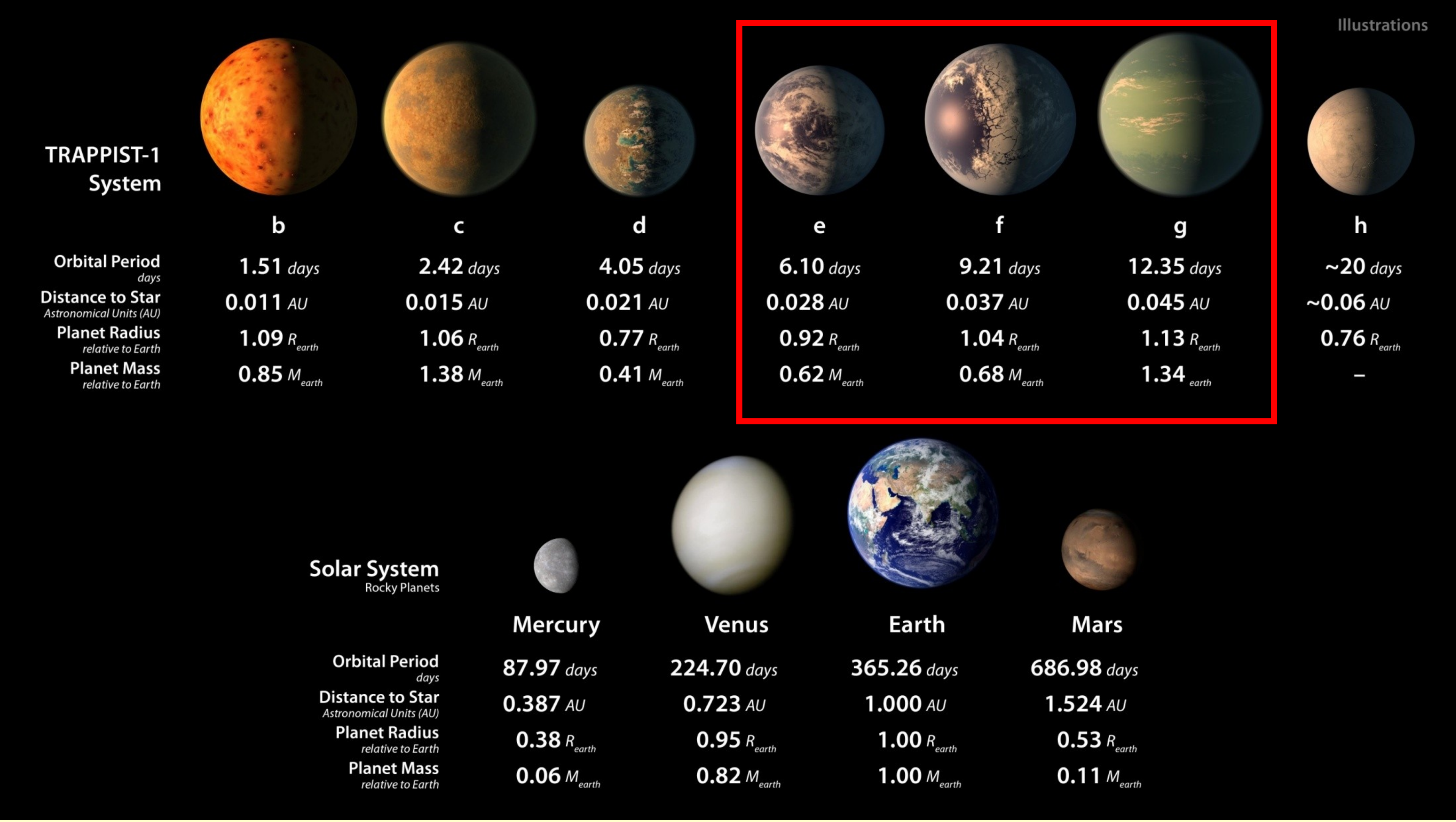


The distribution of known exoplanets as a function of their orbital periods and mass (left panel) and radius (right panel). In addition to the radial velocity and transit methods, which have been used to discover the vast majority of exoplanets, imaging and microlensing also have been used. Most of the exoplanets discovered via the radial velocity method do not transit, and hence only their masses are known, and not their radii. The opposite holds for transiting planets. In some cases, an exoplanet can be studied by both methods, in which case both the radius and mass can be determined. Exoplanets in the upper left corners are denoted “hot Jupiters”, to the right of those are the “warm Jupiters”, and below are the “super Earths”. (Reproduced from figure 3.1 in Exoplanet Science Strategy, National Academies Press, 2018.)

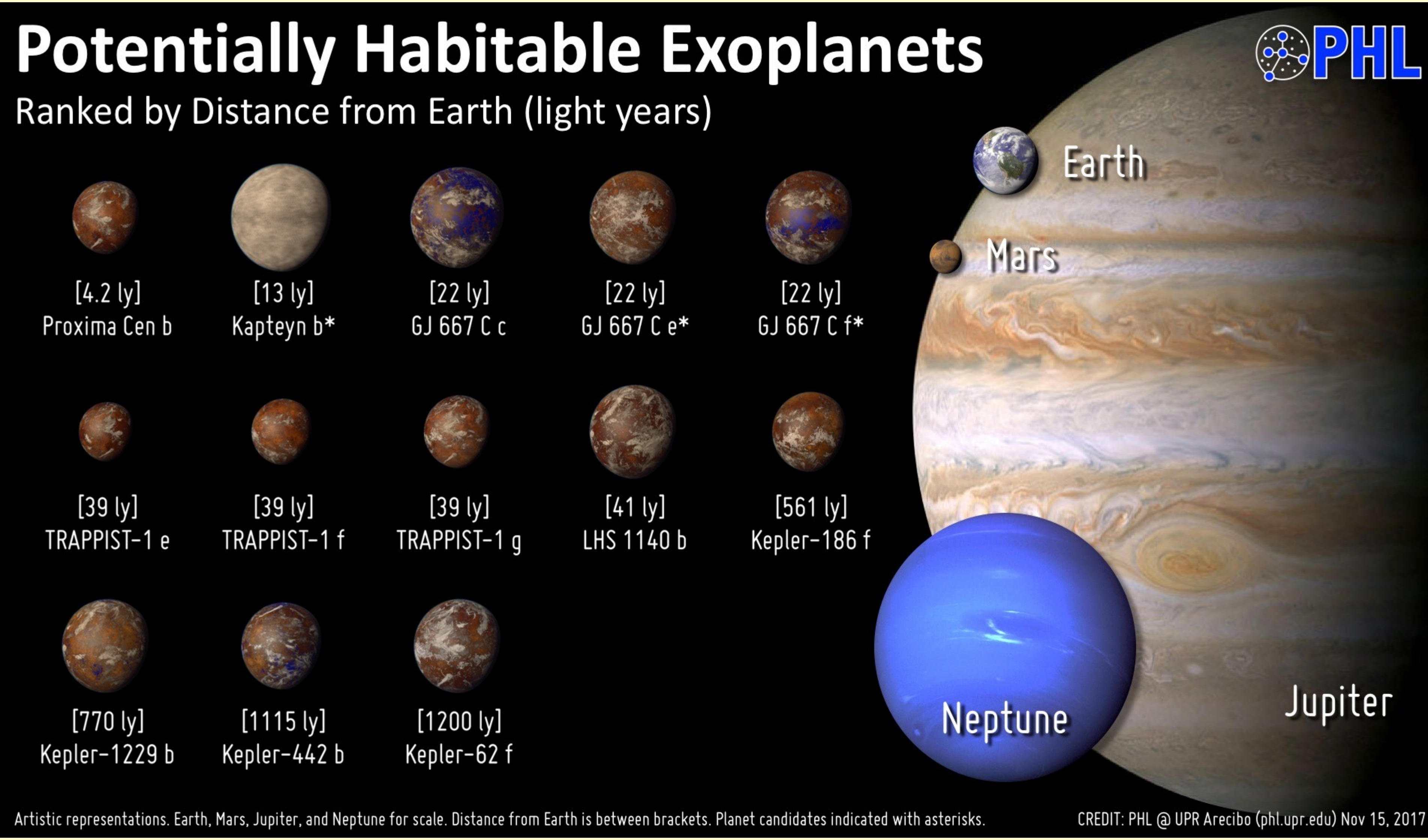

Mercury
Venus
Earth
Mars
Kepler 22b
HD 40307g
Kepler 62e
Kepler 62f
Gliese 667Cc
Gliese 581g
Gliese 581d
Jupiter
Saturn
Uranus
Neptune
Stellar Mass (solar masses)
1
0.1
0.01
0.1
1
10
Distance from Star (AU)
Image Credit: Chester Harman
Planets: PHL at UPR Arecibo, NASA/JPL/APL/Arizona



Potentially Habitable Exoplanets
Ranked by the Earth Similarity Index (ESI)
PHL
Earth
[1.00]
Mars
[0.64]
Jupiter
[0.12]
Neptune
[0.18]
NEW
NEW
NEW
[0.87]
Proxima Cen b
[0.86]
TRAPPIST-1 e
[0.84]
GJ 667 C c
[0.84]
Kepler-442 b
[0.77]
GJ 667 C f*
[0.73]
Kepler-1229 b
[0.68]
TRAPPIST-1 f
[0.67]
Kapteyn b*
[0.67]
Kepler-62 f
[0.61]
Kepler-186 f
[0.60]
GJ 667 C e*
[0.58]
TRAPPIST-1 g
Artistic representations. Earth, Mars, Jupiter, and Neptune for scale. ESI is a measure of how similar is a planet to the size and stellar flux of Earth, value is between brackets. Planet candidates indicated with asterisks.
CREDIT: PHL @ UPR Arecibo (phl.upr.edu) February 23, 2017



TRAPPIST-1 — ультрахолодний червоний карлик. Маса зорі становить приблизно 8% маси Сонця, а радіус — 11% радіуса Сонця. Температура на поверхні сягає 2550 K. Вік зорі щонайменше 500 мільйонів років, тоді як вік Сонця — приблизно 4,6 мільярди років, а температура на його поверхні сягає 5700 K.


Potentially Habitable Exoplanets
Ranked by Distance from Earth (light years)
PHL
[4.2 ly]
Proxima Cen b
[13 ly]
Kapteyn b*
[22 ly]
GJ 667 C c
[22 ly]
GJ 667 C e*
[22 ly]
GJ 667 C f*
[39 ly]
TRAPPIST-1 e
[39 ly]
TRAPPIST-1 f
[39 ly]
TRAPPIST-1 g
[41 ly]
LHS 1140 b
[561 ly]
Kepler-186 f
[770 ly]
Kepler-1229 b
[1115 ly]
Kepler-442 b
[1200 ly]
Kepler-62 f
Earth
Mars
Neptune
Jupiter
Artistic representations. Earth, Mars, Jupiter, and Neptune for scale. Distance from Earth is between brackets. Planet candidates indicated with asterisks.
CREDIT: PHL @ UPR Arecibo (phl.upr.edu) Nov 15, 2017

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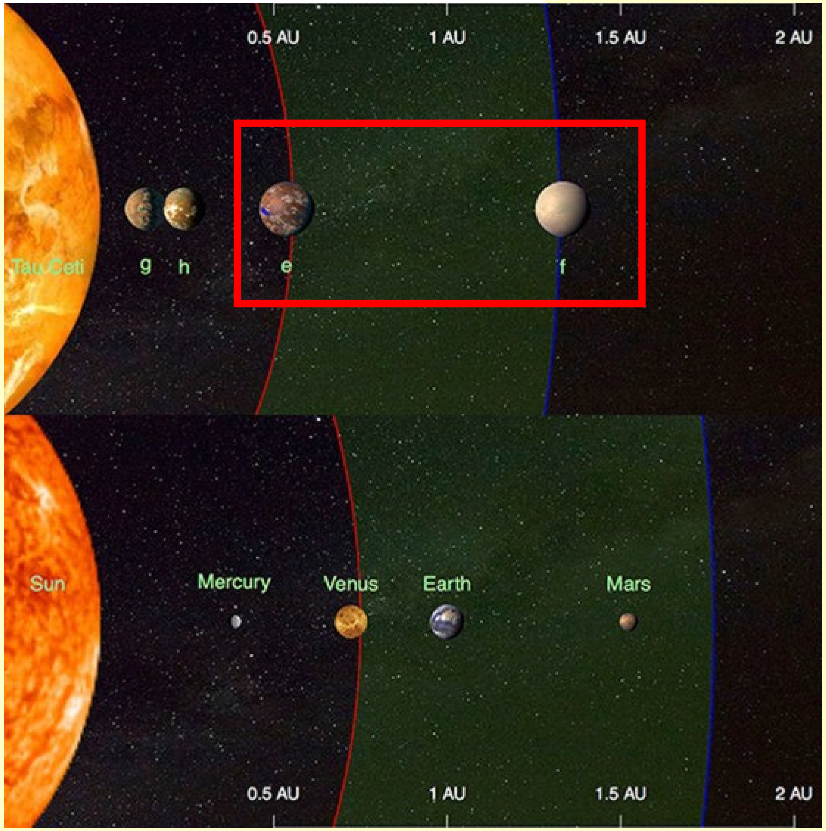
Color difference makes a difference: four planet candidates around tau Ceti

Fabo Feng, Mikko Tuomi, Hugh R.A. Jones, John Barnes, Guillem Anglada-Escude, Steven S. Vogt, R. Paul Butler

(Submitted on 7 Aug 2017)

The removal of noise typically correlated in time and wavelength is one of the main challenges for using the radial velocity method to detect Earth analogues. We analyze radial velocity data of tau Ceti and find robust evidence for wavelength dependent noise. We find this noise can be modeled by a combination of moving average models and "differential radial velocities". We apply this noise model to various radial velocity data sets for tau Ceti, and find four periodic signals at 20.0, 49.3, 160 and 642 d which we interpret as planets. We identify two new signals with orbital periods of 20.0 and 49.3 d while the other two previously suspected signals around 160 and 600 d are quantified to a higher precision. The 20.0 d candidate is independently detected in KECK data. All planets detected in this work have minimum masses less than $4M_\oplus$ with the two long period ones located around the inner and outer edges of the habitable zone, respectively. We find that the instrumental noise gives rise to a precision limit of the HARPS around 0.2 m/s. We also find correlation between the HARPS data and the central moments of the spectral line profile at around 0.5 m/s level, although these central moments may contain both noise and signals. The signals detected in this work have semi-amplitudes as low as 0.3 m/s, demonstrating the ability of the radial velocity technique to detect relatively weak signals.

Маси знайдених планет біля зірки Тау Кита (12 св.р.), схожої на Сонце, становлять близько 1,7 маси Землі.



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