Formation of structure in the universe

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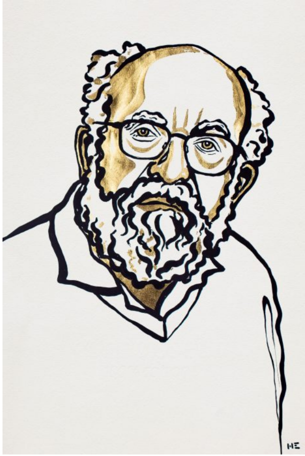
James Peebles of Princeton University, New Jersey, USA, was awarded half of the Nobel Prize in Physics for the year 2019 '*for theoretical discoveries in physical cosmology*'.

Indian Physics Association
Indira Gandhi Centre for Atomic Research, Kalpakkam
February 13, 2020

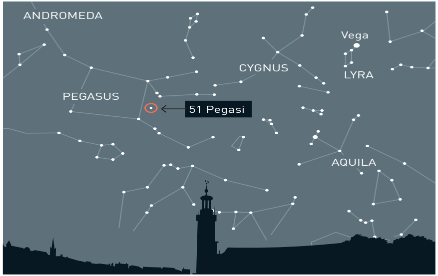
Nobel prize in Physics 2019[1]



The other half of the Nobel Prize in Physics 2019 was awarded jointly to Michel Mayor (on the left) and Didier Queloz (on the right) '*for the discovery of an exoplanet orbiting a solar-type star*'.

[1] Images from https://www.nobelprize.org/prizes/physics/2019/press-release/.

Discovery of the first exoplanet: 51 Pegasi b



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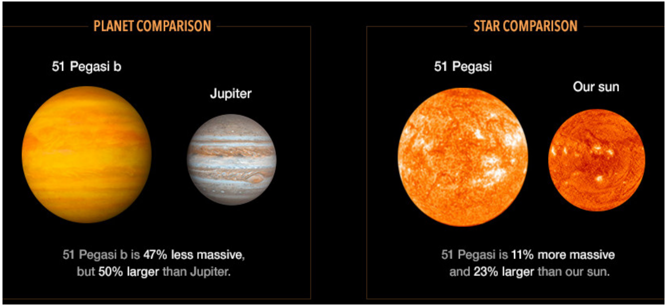


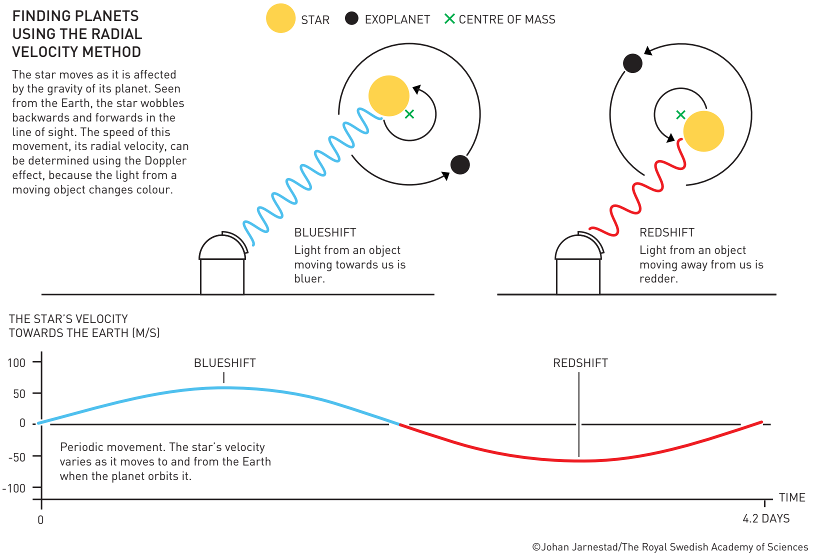
At an observatory in southern France, using custom-made instruments, in 1995, Mayor and Queloz had discovered planet 51 Pegasi b (at the location in the star chart on the left[2]), a gaseous ball comparable with the solar system's biggest gas giant, Jupiter (as illustrated in the image on the right[3]).

The discovery of Mayor and Queloz started a revolution and since then more than 4000 exoplanets have been discovered in our galaxy.

[2] Image from https://www.nobelprize.org/prizes/physics/2019/press-release/.

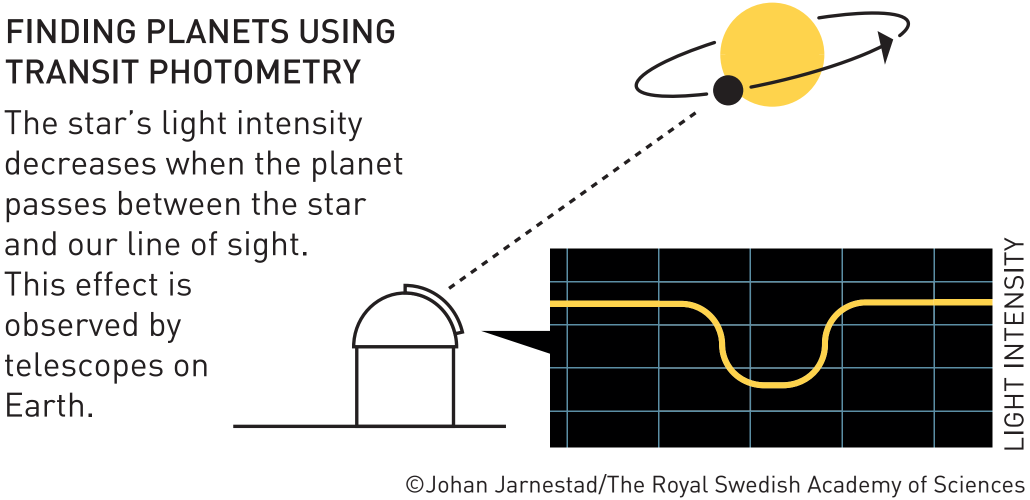
[3] Image from https://exoplanets.nasa.gov/resources/289/infographic-profile-of-planet-51-pegasi-b/.

Discovering exoplanets: Method I[4]



[4] Image from https://www.nobelprize.org/prizes/physics/2019/press-release/.

Discovering exoplanets: Method II[5]



[5] Image from https://www.nobelprize.org/prizes/physics/2019/press-release/

Plan of the talk

1. The universe at large

Plan of the talk

1. The universe at large
2. The expanding universe

Plan of the talk

1. The universe at large
2. The expanding universe
3. The cosmic microwave background

Plan of the talk

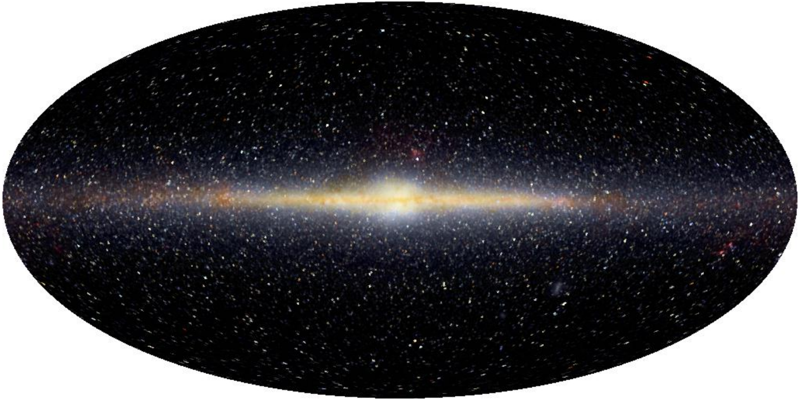
Plan of the talk

1. The universe at large
2. The expanding universe
3. The cosmic microwave background
4. The need for dark matter
5. Formation of large scale structure

Plan of the talk

Plan of the talk

An infrared image of our galaxy



Our galaxy – the Milky Way – as observed by the COsmic Background Explorer (COBE) satellite at the infrared wavelengths[6]. The diameter of the disc of our galaxy is, approximately, $45 \times 10^3\,\mathrm{ly}$ or $15\,\mathrm{kpc}$ (*i.e.* a kilo parsec, with $1\,\mathrm{pc} \simeq 3.26\,\mathrm{ly}$). It contains about 10^{11} stars such as the Sun, and its mass is about $2 \times 10^{12}\,\mathrm{M}_{\odot}$.

[6] Image from http://aether.lbl.gov/www/projects/cobe/cobe_pics.html.

Our galactic neighbors and the local group[7]

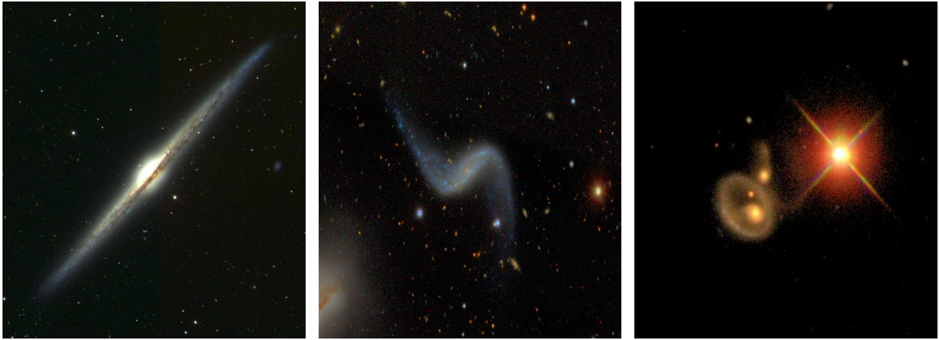
Left: The Andromeda galaxy and its two companion galaxies. The Andromeda galaxy is very similar to our galaxy and is located at a distance of about $700\ \mathrm{kpc}$.

Right: The Triangulum galaxy M33. These galaxies, along with our galaxy, are major members of a local group of about 30 galaxies that are bound gravitationally. The size of the local group is estimated to be about $1.3\ \mathrm{Mpc}$.

Back to rotation curves of spiral galaxies

[7] Images from http://www.seds.org/messier/m/m031.html and http://www.seds.org/messier/m/m033.html.

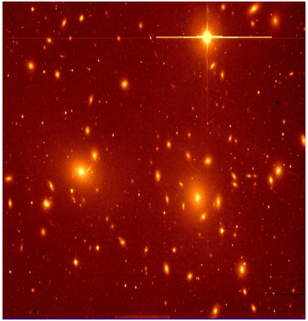
Varieties of galaxies[8]



Left: The disk galaxy NGC 4565 seen edge on in this image from the Sloan Digital Sky Survey (SDSS). The galaxy has a clear bulge, but little light can be seen from its halo.
Center: An image of the spiral galaxy NGC 3187 from SDSS.
Right: CGCG 180-023 is a superb example of a ring galaxy. Ring galaxies are believed to form when a compact smaller galaxy plunges through the center of a larger more diffuse rotating disk galaxy.

[8] Images from http://www.sdss.org/iotw/archive.html and http://cosmo.nyu.edu/hogg/rc3.

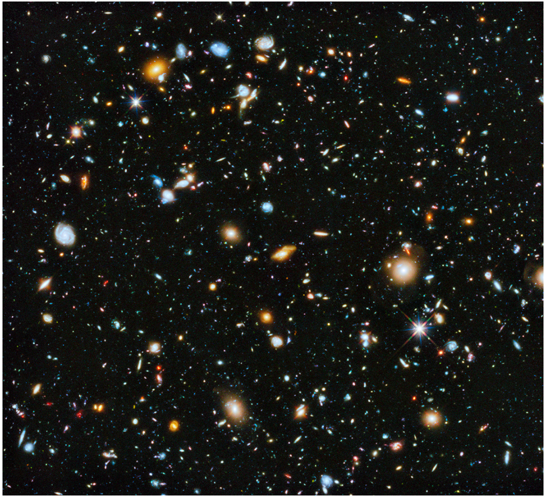
The Virgo, the Coma and the Hercules cluster of galaxies[9]

Left: The Virgo cluster, whose center is considered to be located at a distance of about $20\ \mathrm{Mpc}$. Consisting of over 100 galaxies, it strongly influences the nearby galaxies and galaxy groups gravitationally due to its enormous mass.
Center: The Coma cluster of galaxies, which contains more than 1000 bright galaxies. It is about $20\ \mathrm{Mpc}$ across, and is located at a distance of about $100\ \mathrm{Mpc}$.
Right: An SDSS image of the Hercules galaxy cluster that is located at a distance of about $100\ \mathrm{Mpc}$ from us.

[9] Images from http://apod.nasa.gov/apod/ap000220.html, http://www.astr.ua.edu/gifimages/coma.html and http://www.sdss.org/iotw/archive.html.

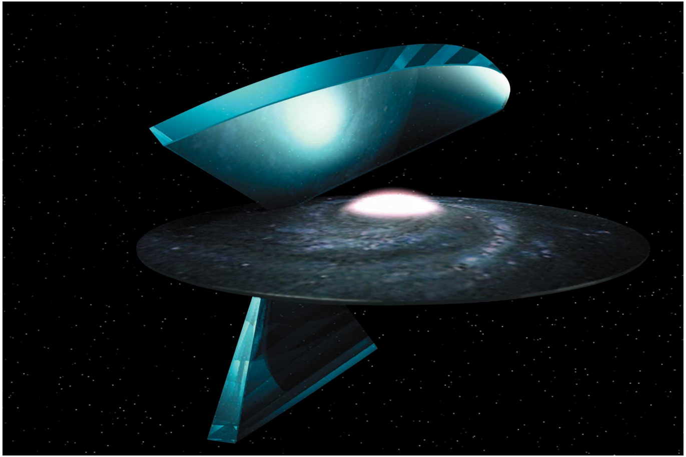
Deepest views in space



An ultra deep field image from the Hubble Space Telescope (HST). The image contains a bewildering variety of galaxy shapes and colors[10].

[10] Image from http://hubblesite.org/newscenter/archive/releases/2014/27.

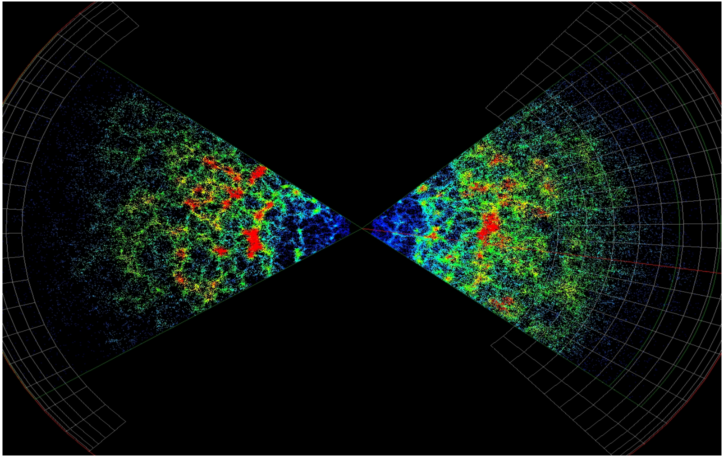
Surveying the universe



A schematic drawing showing the directions of the regions observed by the 2 degree field (2dF) redshift survey with respect to our galaxy[11]. The survey regions actually extend more than 10^5 times further than shown here.

[11] Image from http://magnum.anu.edu.au/˜TDFgg/Public/Pics/2dF3D.jpg.

Distribution of galaxies in the universe



The distribution of more than two million galaxies as observed by the 2dF redshift survey[12]. (Note that each dot in the picture represents a galaxy.) The density and the 'radius' of the universe are estimated to be about $10^{-28}\ \mathrm{kg/m^3}$ and $3000\ \mathrm{Mpc}$, respectively.

[12] Image from http://magnum.anu.edu.au/~TDFgg/Public/Pics/2dFGRS_top_view.gif.

The Sloan digital sky survey

- The Sloan Digital Sky Survey (SDSS) is one of the most ambitious and influential surveys in the history of astronomy[13].
- Over eight years of operations, it has obtained deep, multi-color images covering more than a quarter of the sky and created three-dimensional maps containing more than $930,000$ galaxies and more than $120,000$ quasars.

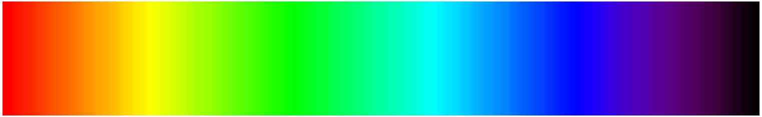
Play SDSS movie

[13] See, http://www.sdss.org/.

Plan of the talk

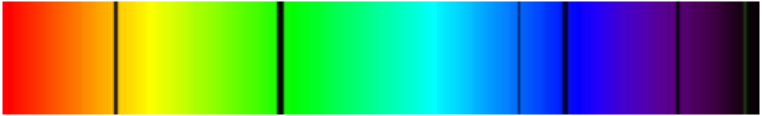
Continuous, emission and absorption spectra[14]

A typical continuous spectrum from an opaque hot body:



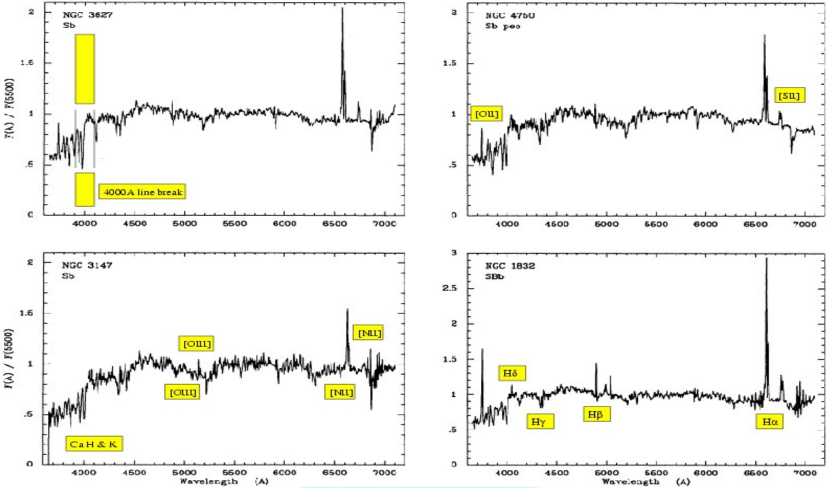
Emission spectrum, as from a given element:

Absorption spectrum, as due to an intervening cool gas:



[14] Images from http://hea-www.harvard.edu/~efortin/thesis/html/Spectroscopy.shtml.

Typical spectra of galaxies[15]

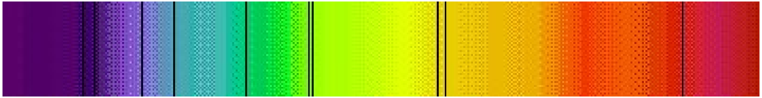


Spectra of some spiral galaxies. The spectra usually contain characteristic emission and absorption lines.

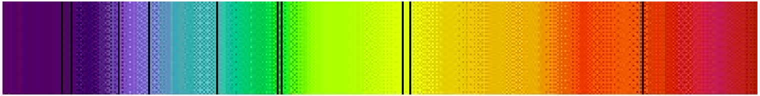
[15] Image from http://astronomy.nmsu.edu/nicole/teaching/ASTR505/lectures/lecture26/slide01.html.

The 'Doppler effect' and redshift[16]

If the source is receding, the spectrum will be red-shifted



when compared to the spectrum in the source's frame



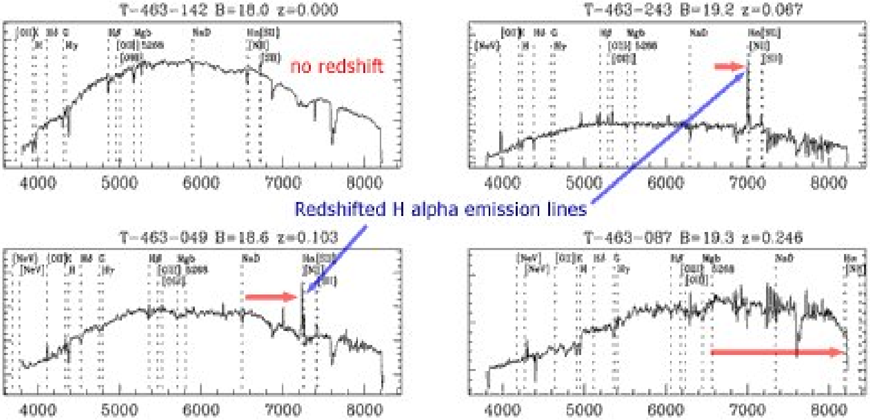
The redshift z of the receding source is defined as:

$$1 + z = \frac{\lambda_{\rm O}}{\lambda_{\rm E}} = \frac{\omega_{\rm E}}{\omega_{\rm O}},$$

where $\lambda_{\rm O}$ and $\omega_{\rm O}$ denote the observed wavelength and frequency of the source, while $\lambda_{\rm E}$ and $\omega_{\rm E}$ denote its emitted wavelength and frequency, respectively.

[16] Images from http://www.astronomynotes.com/light/s10.htm.

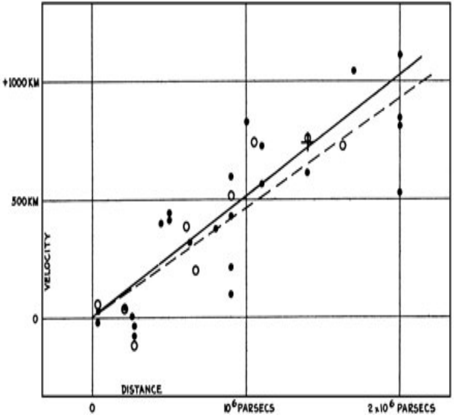
Runaway galaxies[17]

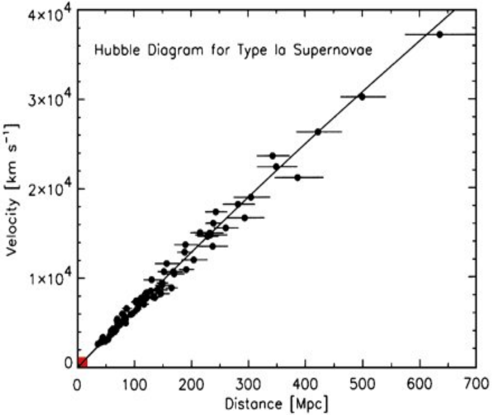


Spectra of four different galaxies from the 2dF redshift survey. On top left is the spectrum of a star from our galaxy, while on the bottom right we have the spectrum of a galaxy that has a redshift of $z = 0.246$. The other two galaxies show prominent Hα emission lines, which have been redshifted from the rest frame value of 6563 Å.

[17] Image from http://outreach.atnf.csiro.au/education/senior/astrophysics/spectra_astro_types.html.

Relation between the velocity and the distance of galaxies[18]



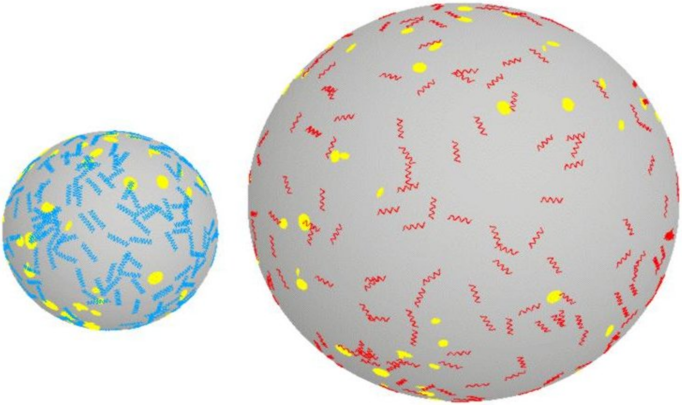


Left: The original Hubble data. The slope of the two fitted lines are about $500\ \mathrm{km/sec/Mpc}$ and $530\ \mathrm{km/sec/Mpc}$.

Right: A more recent Hubble diagram. The slope of the straight line is about $72\ \mathrm{km/sec/Mpc}$. The small red region in the lower left marks the span of Hubble's original diagram.

[18] R. Kirshner, Proc. Natl. Acad. Sci. USA **101**, 8 (2004).

Visualizing the expanding universe

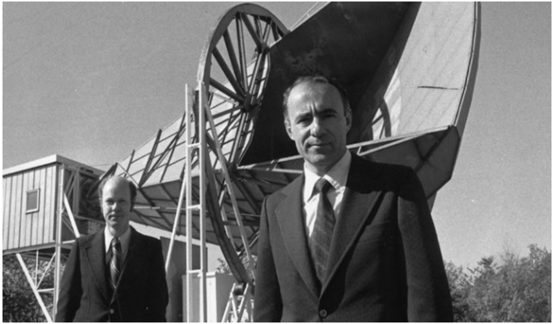


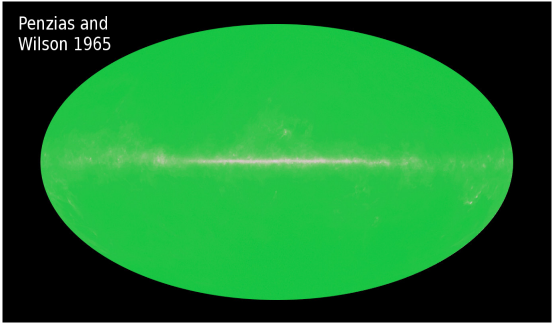
A two-dimensional analogy for the expanding universe[19]. The yellow blobs on the expanding balloon denote the galaxies. Note that the galaxies themselves do not grow, but the distance between the galaxies grows and the wavelengths of the photons shift from blue to red as the universe expands.

[19] Image from http://www.astro.ucla.edu/˜wright/balloon0.html.

Plan of the talk

Discovery of the Cosmic Microwave Background (CMB)[20]





The horn antenna used by Penzias and Wilson (on the left) and the CMB as observed by them (on the right).

▸ Anisotropies in the CMB

[20] In this context, see, for instance, S. G. Brush, Sci. Am. **267**, 62 (1992).

A glimpse of the original papers

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.

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May 7, 1965
PALMER PHYSICAL LABORATORY
PRINCETON, NEW JERSEY

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Liftshitz, E. M., and Khalatnikov, I. M. 1963, *Adv. in Phys.*, **12**, 185.
Oort, J. H. 1958, *La Structure et l'évolution de l'universe* (11th Solvay Conf. [Brussels: Éditions Stoops]), p. 163.
Peebles, P. J. E. 1965, *Phys. Rev.* (in press).
Penzias, A. A., and Wilson, R. W. 1965, private communication.
Wheeler, J. A., 1958, *La Structure et l'évolution de l'universe* (11th Solvay Conf. [Brussels: Éditions Stoops]), p. 112.
——— 1964, in *Relativity, Groups and Topology*, ed. C. DeWitt and B. DeWitt (New York: Gordon & Breach).
Zel'dovich, Ya. B. 1962, *Soviet Phys.—J.E.T.P.*, **14**, 1143.

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

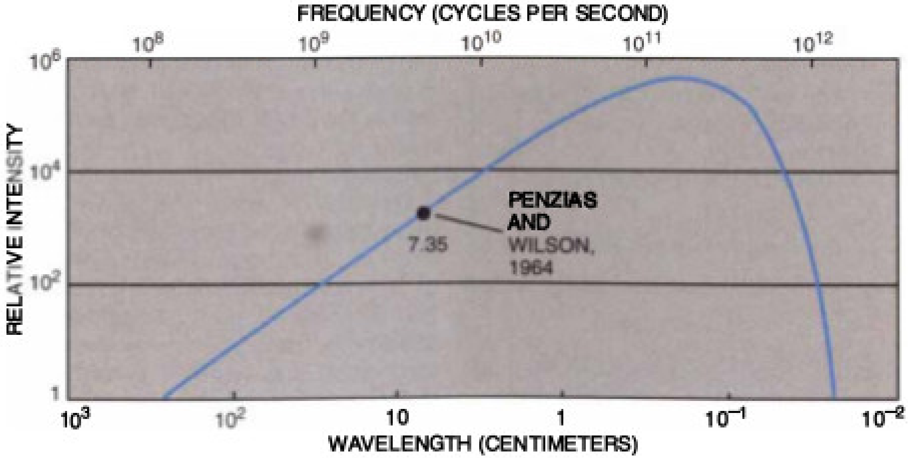
Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our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

Back to WMAP data

The original papers by Peebles and collaborators[21] and by Penzias and Wilson[22].

[21] R. H. Dicke, P. J. E. Peebles, P. G. Roll and D. T. Wilkinson, Astrophys. J. **142**, 414 (1965).
[22] A. A. Penzias and R. W. Wilson, Astrophys. J. **142**, 419 (1965).

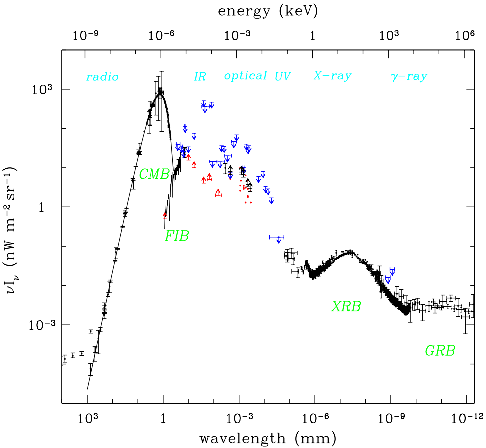
The thermal nature of the CMB



The region of the thermal spectrum observed by Penzias and Wilson[23]

[23] Image from, S. G. Brush, Sci. Am. **267**, 62 (1992).

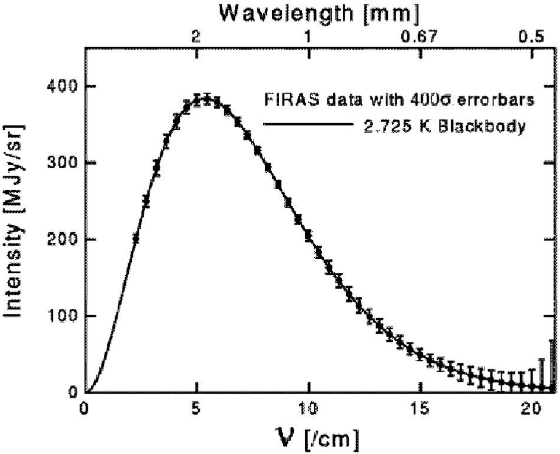
Complete spectrum of the cosmological background radiation



The energy density spectrum of cosmological background radiation has been plotted as a function of wavelength[24]. Note that the CMB contributes the most to the overall background radiation.

[24] Figure from, D. Scott, arXiv:astro-ph/9912038.

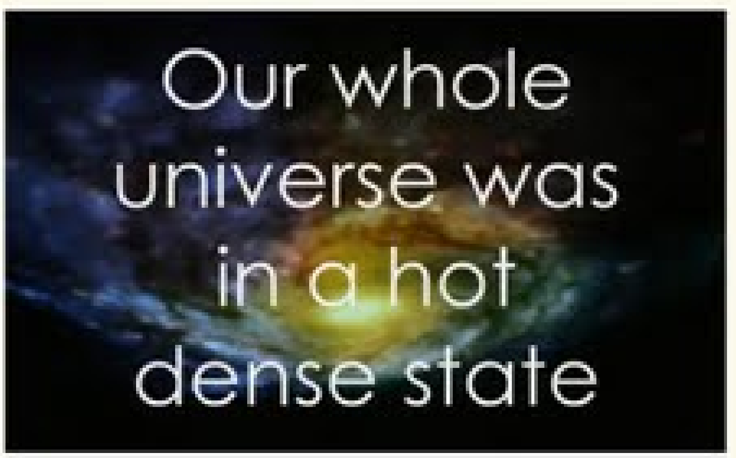
Spectrum of the CMB



The spectrum of the CMB as measured by the COBE satellite[25]. It is a perfect Planck spectrum (corresponding to a temperature of $2.725^\circ\ \mathrm{K}$) which is unlikely to be bettered in the laboratory. The error bars have been amplified 400 times so that they are visible!

[25]Image from http://www.astro.ucla.edu/˜wright/cosmo_01.htm.

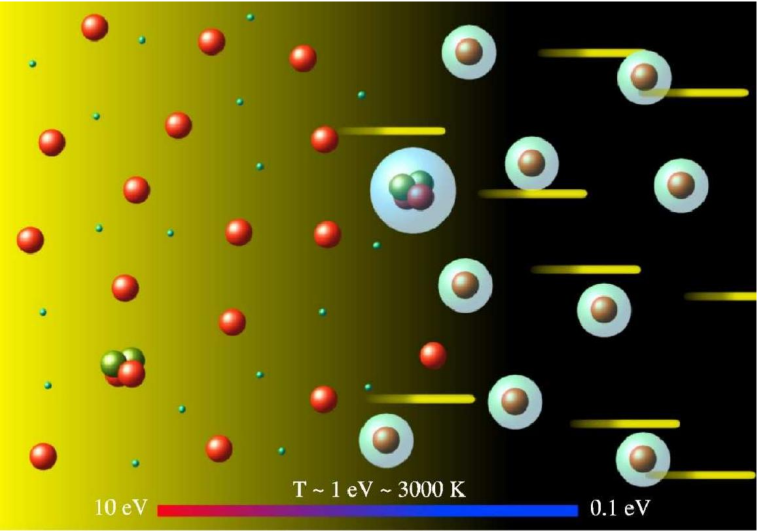
The big bang model seems popular!



The current view of the universe, encapsulated in the hot big bang model, seems popular. The above image is a screen grab from the theme song of the recent American sitcom 'The Big Bang Theory'[26]!

[26] See http://www.cbs.com/shows/big_bang_theory/.

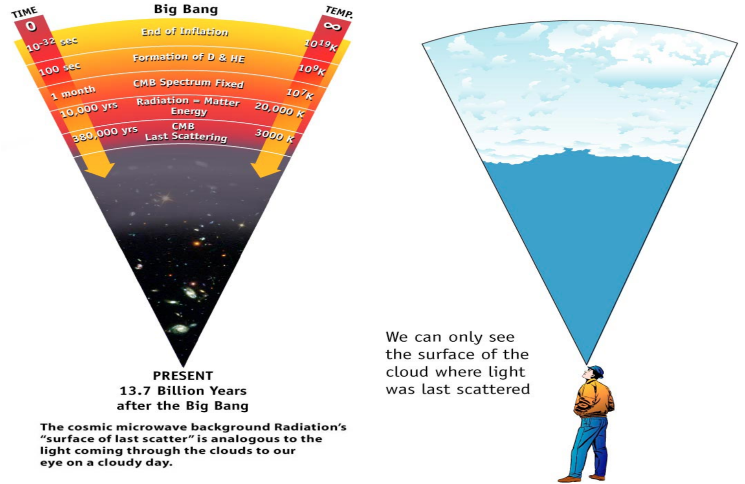
Decoupling of matter and radiation



The CMB arises because matter and radiation cease to interact at an early time[27].

[27] Image from W. H. Kinney, arXiv:astro-ph/0301448v2.

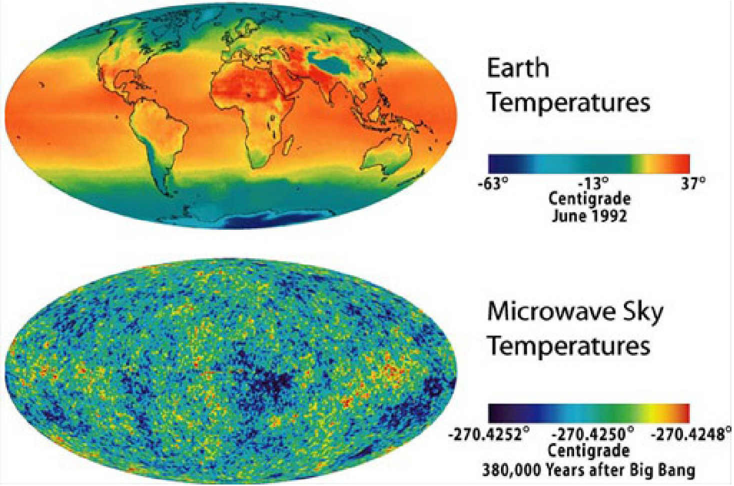
The last scattering surface and the freestreaming CMB photons



The CMB photons streams to us freely from the last scattering surface when radiation decoupled from matter[28].

[28] Image from http://map.gsfc.nasa.gov/media/990053/990053.jpg.

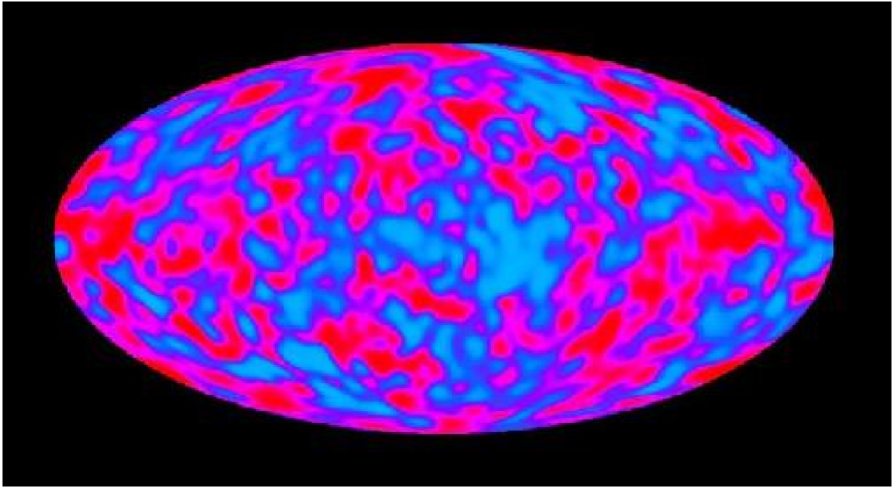
Projecting the last scattering surface



The temperature of the CMB on the last scattering surface can be projected on to a plane as the surface of the Earth is often projected[29].

[29] Image from http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/planckcmb.html.

Anisotropies in the CMB



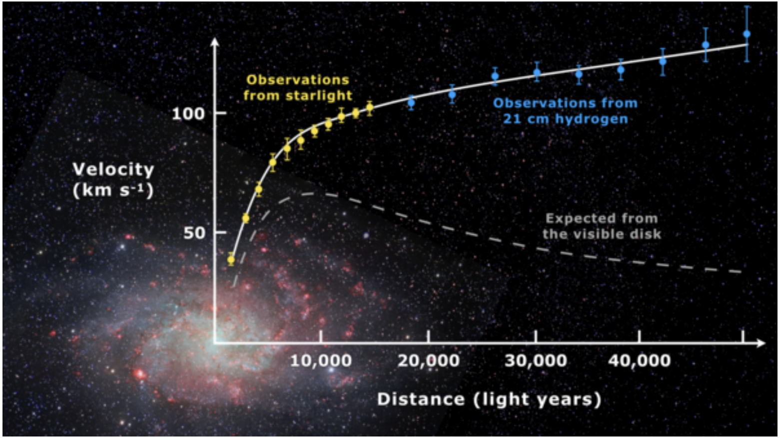
The fluctuations in the temperature of the CMB as seen by COBE[30]. The CMB turns out to be isotropic to one part in 10^5.

The smooth CMB

[30] Image from http://aether.lbl.gov/www/projects/cobe/COBE_Home/DMR_Images.html.

Plan of the talk

Rotation curves of spiral galaxies



The M33 galaxy

The observed rotation curve of the spiral galaxy M33 (yellow and blue points with error bars), and the predicted curve from the distribution of visible matter (gray line). The observed curve can be accounted for by embedding the galaxy in a dark matter halo[31].

[31] Image from https://en.wikipedia.org/wiki/Galaxy_rotation_curve.

The idea of the dark matter halo

THE ASTROPHYSICAL JOURNAL, 186:467–480, 1973 December 1
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A NUMERICAL STUDY OF THE STABILITY OF FLATTENED GALAXIES: OR, CAN COLD GALAXIES SURVIVE?*

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Princeton University Observatory
AND
P. J. E. PEEBLES
Joseph Henry Laboratories, Princeton University
Received 1973 May 29

ABSTRACT

To study the stability of flattened galaxies, we have followed the evolution of simulated galaxies containing 150 to 500 mass points. Models which begin with characteristics similar to the disk of our Galaxy (except for increased velocity dispersion and thickness to assure local stability) were found to be rapidly and grossly unstable to barlike modes. These modes cause an increase in random kinetic energy, with approximate stability being reached when the ratio of kinetic energy of rotation to total gravitational energy, designated t, is reduced to the value of 0.14 ± 0.02. Parameter studies indicate that the result probably is not due to inadequacies of the numerical N-body simulation method. A survey of the literature shows that a critical value for limiting stability $t \simeq 0.14$ has been found by a variety of methods.

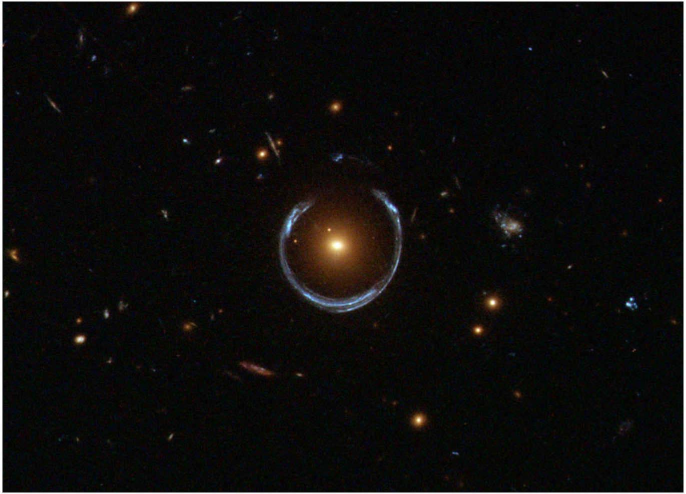
Models with added spherical (halo) component are more stable. It appears that halo-to-disk mass ratios of 1 to $2\frac{1}{2}$, and an initial value of $t \simeq 0.14 \pm 0.03$, are required for stability. If our Galaxy (and other spirals) do not have a substantial unobserved mass in a hot disk component, then apparently the halo (spherical) mass *interior* to the disk must be comparable to the disk mass. Thus normalized, the halo masses of our Galaxy and of other spiral galaxies *exterior* to the observed disks may be extremely large.

Subject headings: galactic structure — stellar dynamics

The paper by Peebles and Ostriker which numerically illustrated the stability of flattened galaxies by introducing a halo of dark matter[32].

[32] J. P. Ostriker and P. J. E. Peebles, Astrophys. J. **186**, 467 (1973).

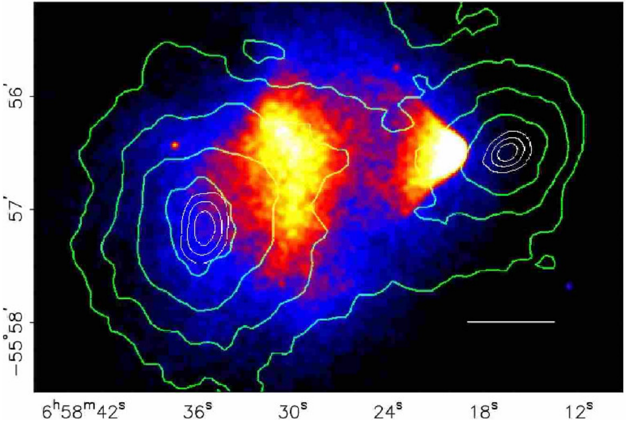
Gravitational lensing reveals the distribution of matter



A near perfect Einstein ring! The ring is formed due to the gravitational field of the foreground luminous red galaxy which distorts the light from a more distant blue galaxy[33].

[33] Image from https://apod.nasa.gov/apod/ap111221.html.

The bullet cluster



Merger of two clusters of galaxies revealing the existence of dark matter[34]. While the contours indicate the spatial distribution of mass (determined from gravitational lensing of background galaxies), the colored patches trace the hot plasma in a galaxy. Note that most of the matter resides in a location different from the plasma.

[34] Image from D. Clowe *et al.*, Astrophys. J. **648**, L109 (2006).

Dark matter and the CMB

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LARGE-SCALE BACKGROUND TEMPERATURE AND MASS FLUCTUATIONS DUE TO SCALE-INVARIANT PRIMEVAL PERTURBATIONS

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ABSTRACT

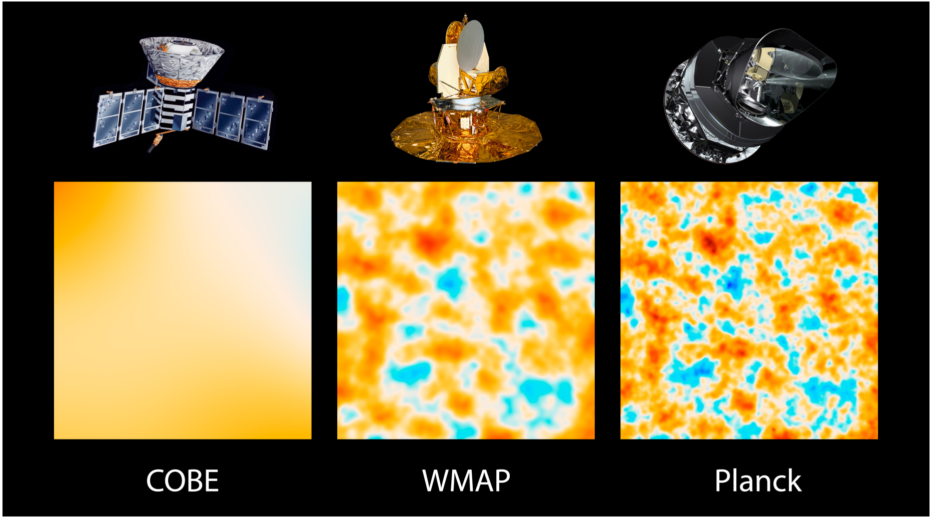
The large-scale anisotropy of the microwave background and the large-scale fluctuations in the mass distribution are discussed under the assumptions that the universe is dominated by very massive, weakly interacting particles and that the primeval density fluctuations were adiabatic with the scale-invariant spectrum $P \propto$ wavenumber. This model yields a characteristic mass comparable to that of a large galaxy independent of the particle mass, m_x, if $m_x \gtrsim 1$ keV. The expected background temperature fluctuations are well below present observational limits.

Subject headings: cosmic background radiation — cosmology — galaxies: formation

The paper by Peebles highlighting the role of cold dark matter in inducing anisotropies in the CMB and the formation of large scale structure[35].

[35] P. J. E. Peebles, Astrophys. J. **263**, L1 (1982).

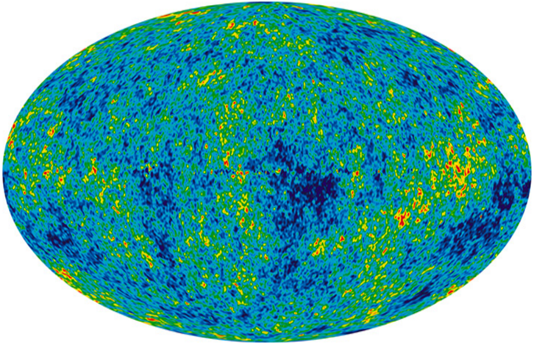
Satellite missions that brought the CMB into sharper focus

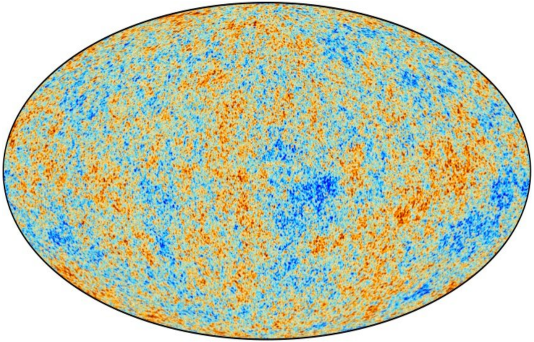


COBE, WMAP and Planck observed the CMB with ever increasing resolution[36].

[36]Image from https://www.nasa.gov/sites/default/files/images/735694main_pia16874-full_full.jpg.

CMB anisotropies as seen by WMAP and Planck





Left: All-sky map of the anisotropies in the CMB created from nine years of Wilkinson Microwave Anisotropy Probe (WMAP) data[37]. ▸ Wilkinson

Right: CMB intensity map derived from the joint analysis of Planck, WMAP, and 408 MHz observations[38]. The above images show temperature variations (as color differences) of the order of $200^\circ\ \mu\mathrm{K}$.

[37] Image from http://wmap.gsfc.nasa.gov/media/121238/index.html.

[38] P. A. R. Ade *et al.*, arXiv:1502.01582 [astro-ph.CO].

Plan of the talk

The origin and the evolution of the perturbations

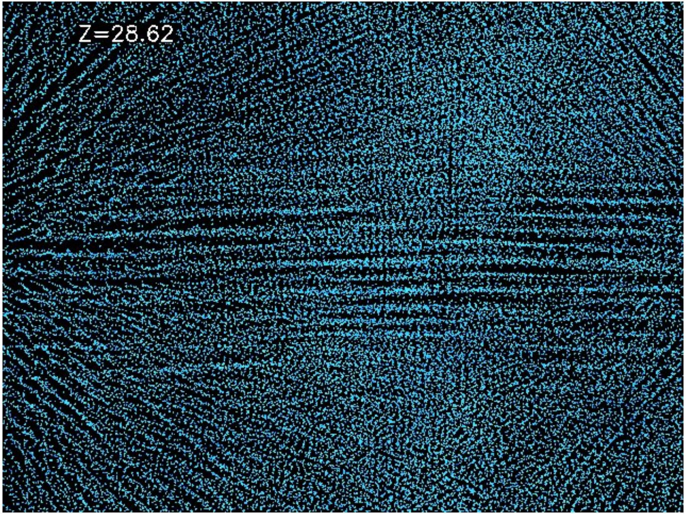
- The anisotropies in the CMB arise due to quantum fluctuations in the early universe.

  Play movie

- The fluctuations in the CMB in turn grow in magnitude due to gravitational instability and develop into the structures that we see around us today.

  Play movie

Formation of structures due to gravitational instability



Simulation illustrating the formation of structures due to gravitational instability[39].

[39] Images from http://cfcp.uchicago.edu/lss/group.html.

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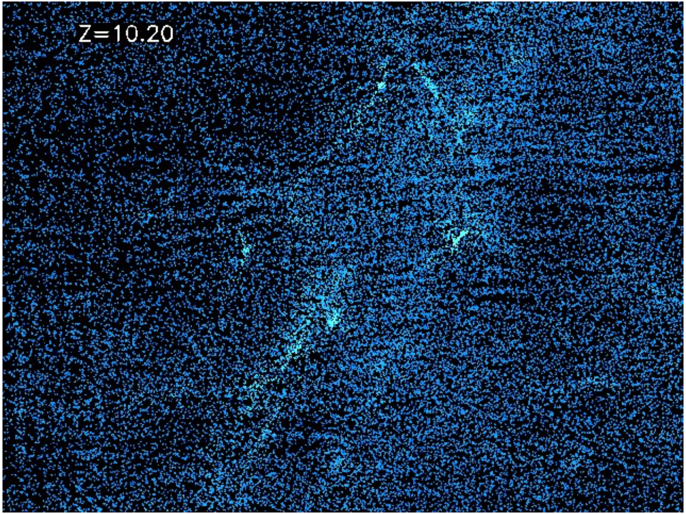

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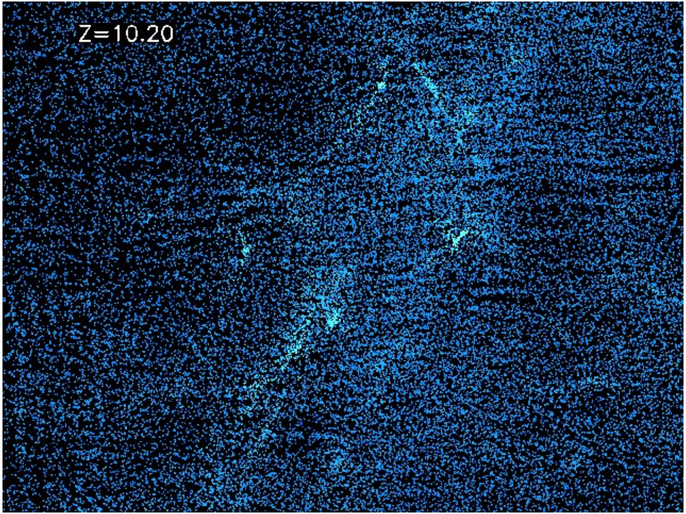

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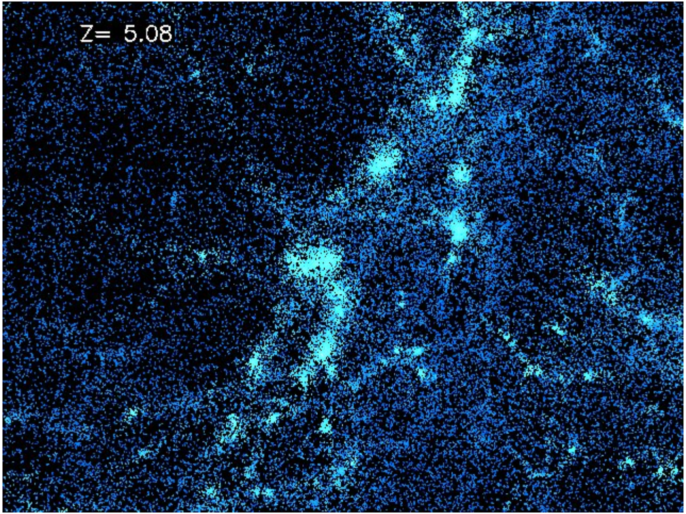

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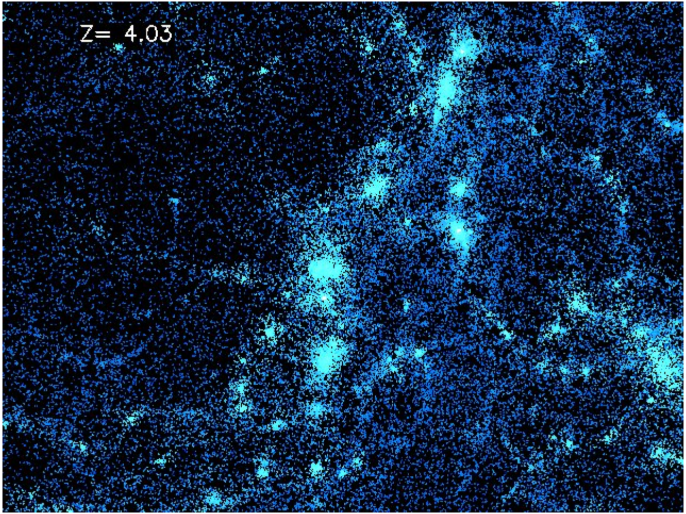

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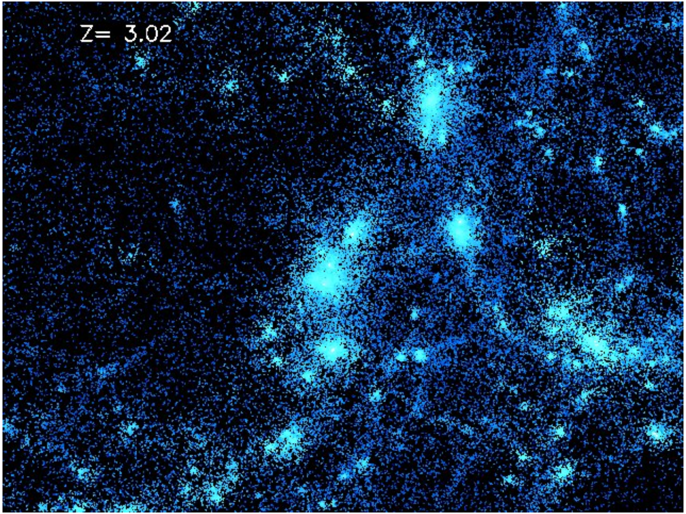

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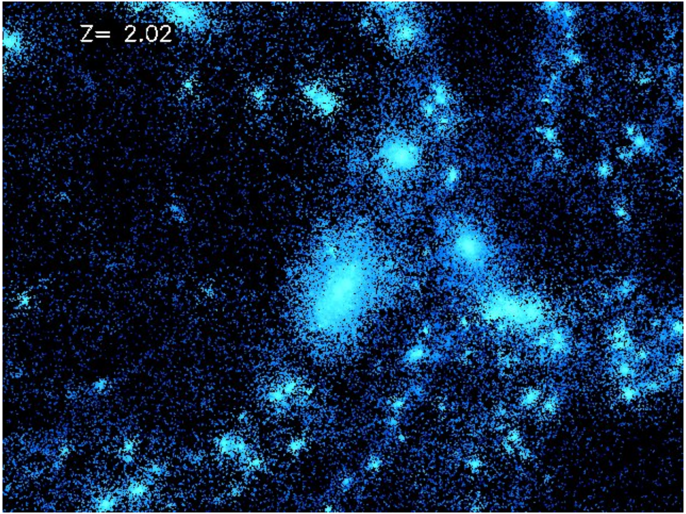

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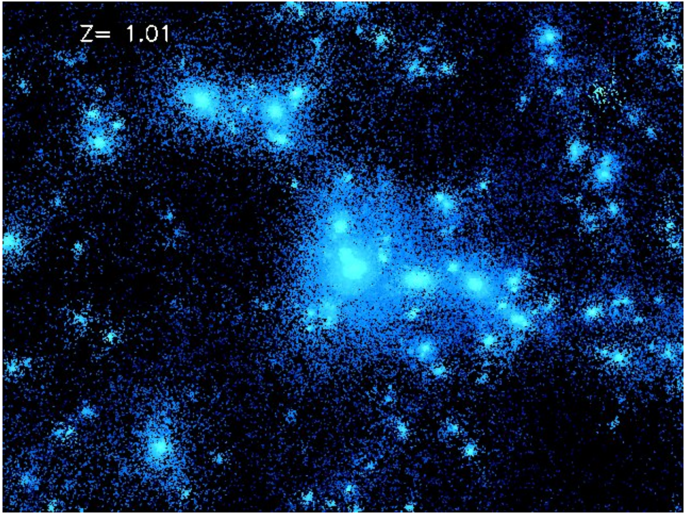

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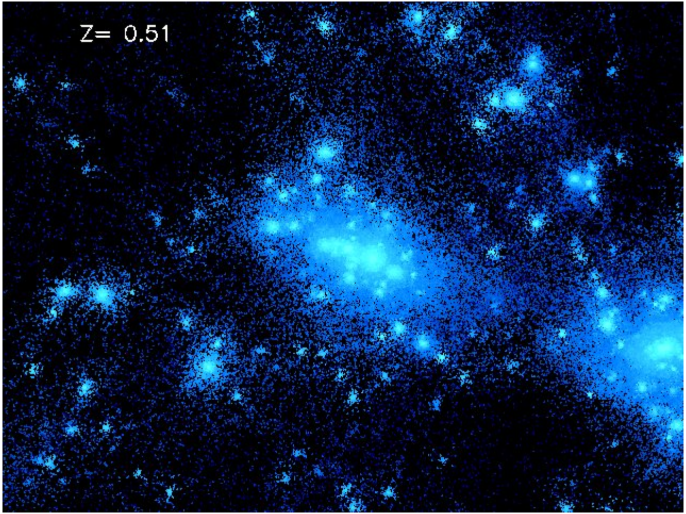

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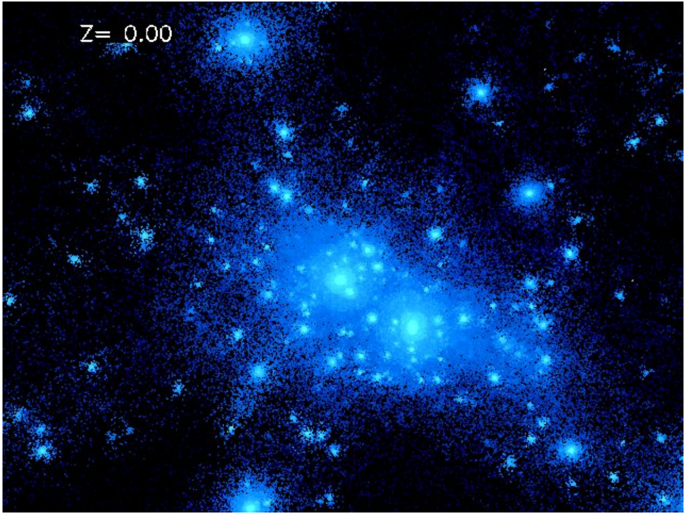

Play again

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The millennium simulation

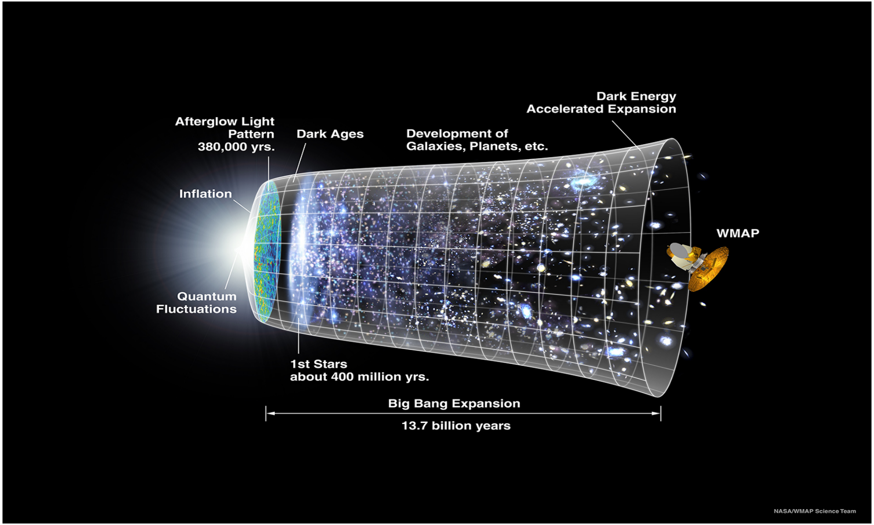
- The Millennium Run used more than 10 billion particles to trace the evolution of the matter distribution in a cubic region of the universe over 2 billion light years on a side[39].
- It kept busy the principal supercomputer at the Max Planck Society's Supercomputing Centre in Garching, Germany for more than a month.

Play movie

[39] See http://www.mpa-garching.mpg.de/galform/virgo/millennium/.

Plan of the talk

The timeline of the universe



A pictorial timeline of the universe[40].

[40] Image from http://wmap.gsfc.nasa.gov/media/060915/060915_CMB_Timeline150.jpg.

Elements of the standard cosmological model

- The universe is homogeneous and isotropic at length scales of the order of $100\ \mathrm{Mpc}$ and above.
- Baryons, *i.e.* matter as we know it, contribute less than 5% to the total density of the universe today. Most of the matter today is, in fact, dark.
- Quantum fluctuations in the early universe leave their imprints as anisotropies in the CMB.
- Gravitational instability then takes over, and converts the tiny perturbations in the CMB into the large scale structures that we see around us today as galaxies and clusters of galaxies.

Thank you for your attention