Hawking's ideas on the origin of the universe

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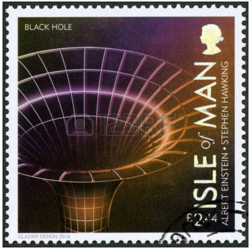

Tamilnadu Science Forum

Anna Centenary Library, Chennai

July 8, 2018

Plan of the talk

1. Hawking's academic history
2. A survey of the universe
3. The composition and evolution of the smooth universe
4. The generation and evolution of perturbations
5. Ideas on the origin of the universe
6. Status and outlook

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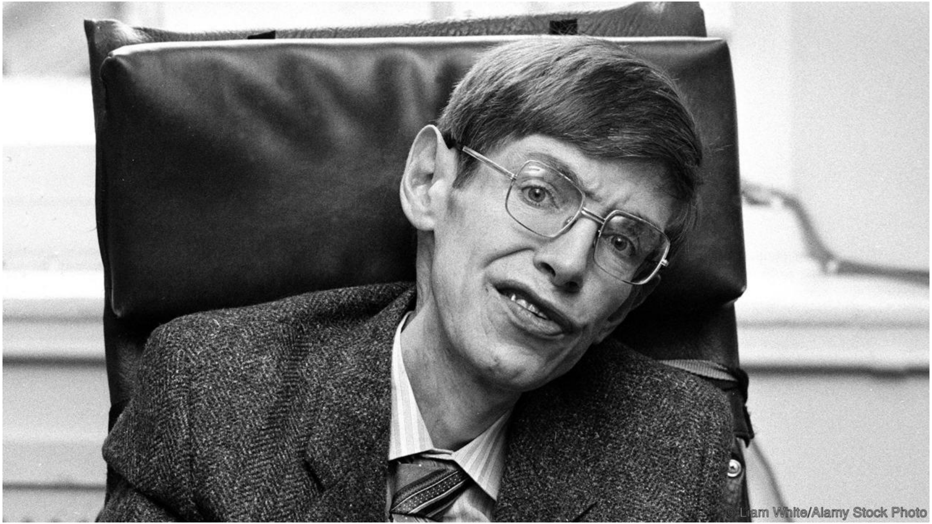
Stephen Hawking



Stephen Hawking: January 8, 1942 – March 14, 2018[1].

[1] Photo from http://www.bbc.com/earth/story/20160107-these-are-the-discoveries-that-made-stephen-hawking-famous.

Academic history[2]

- B.A., University College, Oxford, England, 1959–1962
- M.A., Ph.D., Department of Applied Mathematics and Theoretical Physics (DAMTP), University of Cambridge, Cambridge, England, 1962–66
  Thesis title: Properties of expanding universes
  Ph.D. supervisor: Dennis Sciama
- Research Fellow, Gonville and Caius College (Caius), Cambridge, England, 1966–69
- Professorial Fellow, Caius, 1969
- Research Assistant, Institute of Astronomy, University of Cambridge, Cambridge, England, 1969–73
- Research Assistant, DAMTP, 1973–75
- Reader, DAMTP, 1975–77
- Professor, DAMTP, 1977–79
- Lucasian Professor of Mathematics, DAMTP, 1979–2009
- Director of Research, DAMTP, 2009–18

[2] Source http://www.hawking.org.uk/ and https://www.ast.cam.ac.uk/content/stephen.hawking.1942–2018.

This talk is largely based on...

- S. W. Hawking, *The development of irregularities in a single bubble inflationary universe*, Phys. Letts. B **115**, 295 (1982).
- J. B. Hartle and S. W. Hawking, *Wave function of the universe*, Phys. Rev. D **28**, 2960 (1983).
- J. J. Halliwell and S. W. Hawking, *Origin of structure in the universe*, Phys. Rev. D **31**, 1777 (1985).

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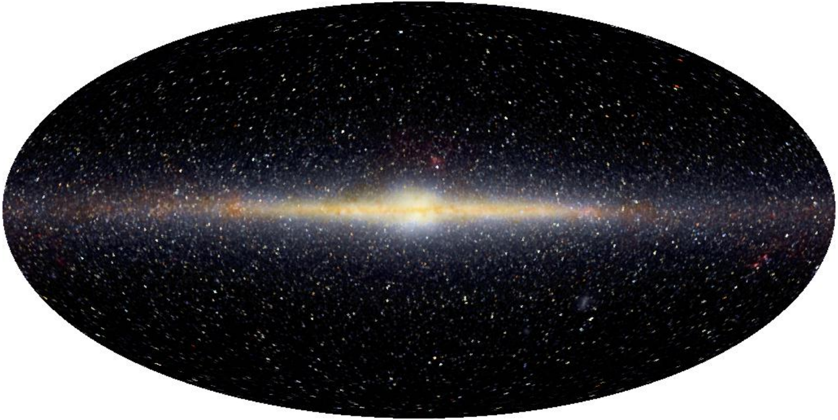
An infrared image of our galaxy



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

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

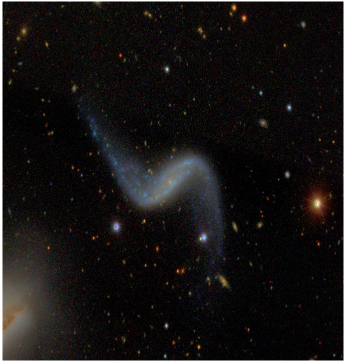
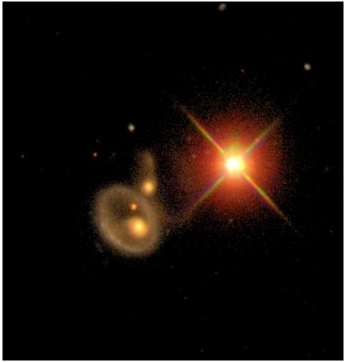
Our galactic neighbors and the local group[4]

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. 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 $1.3\ \mathrm{Mpc}$.

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

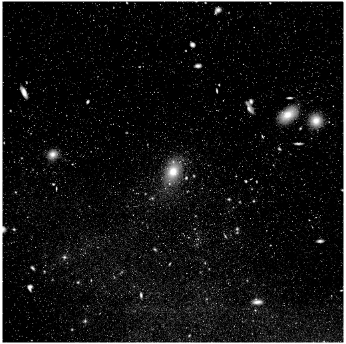
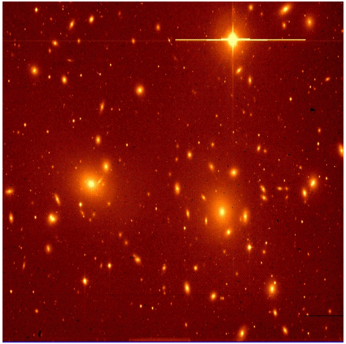
Varieties of galaxies[5]

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.

[5] 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[6]

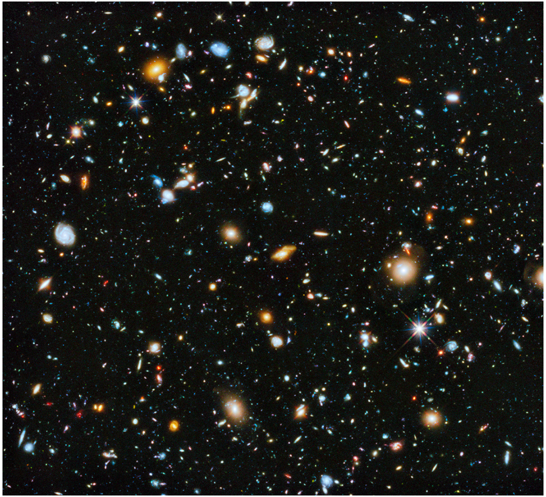

Left: The Virgo cluster, whose center is considered to be located at a distance of about $20\ \mathrm{Mpc}$. Consisting of over 100 galaxies, it strongly influences the nearby galaxies and galaxy groups gravitationally due to its enormous mass.

Center: The Coma cluster of galaxies. The cluster is nearly spherical in shape and 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.

[6] 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.

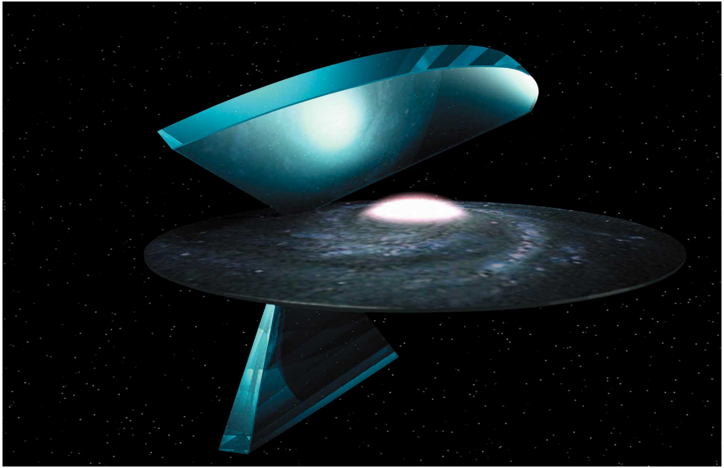
Deepest views in space



An ultra deep field image from the Hubble Space Telescope (HST). The image contains a bewildering variety of galaxy shapes and colors[7].

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

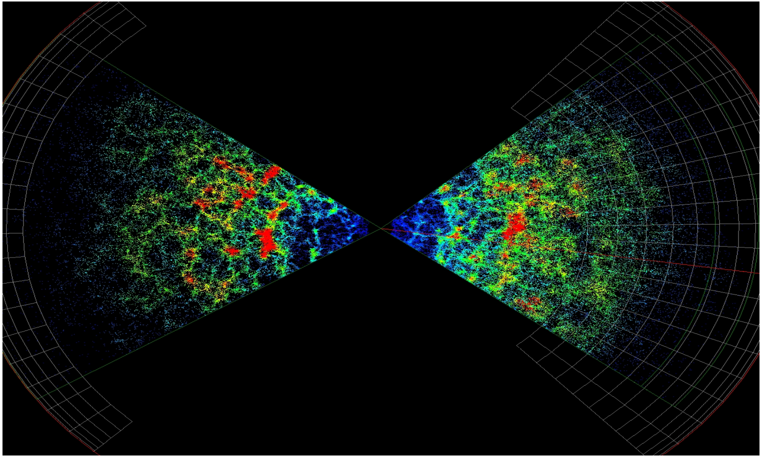
Surveying the universe



A schematic drawing showing the directions of the regions observed by the 2 degree field (2dF) redshift survey with respect to our galaxy[8]. The survey regions actually extend more than 10^5 times further than shown here.

[8] 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[9]. (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.

[9] 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.
- 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

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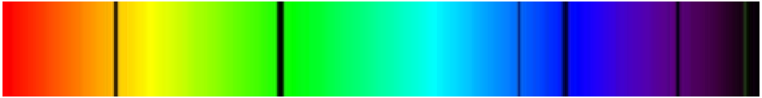
Continuous, emission and absorption spectra[10]

A typical continuous spectrum from an opaque hot body:

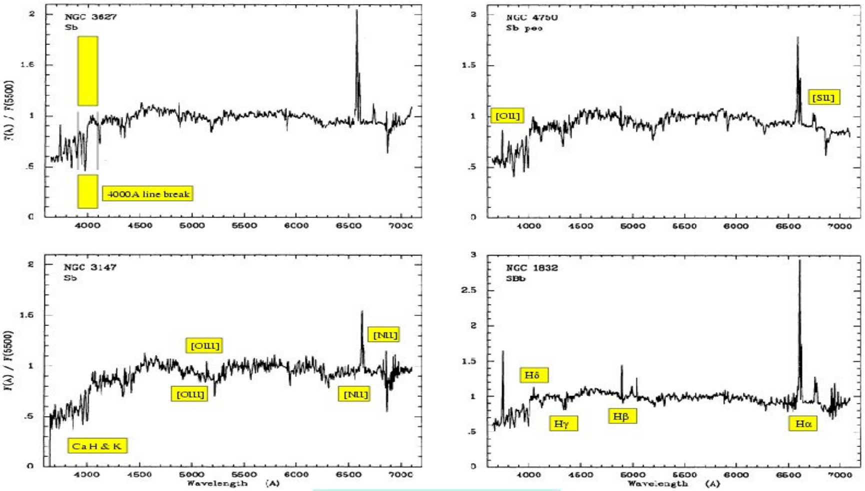
Emission spectrum, as from a given element:

Absorption spectrum, as due to an intervening cool gas:



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

Typical spectra of galaxies[11]

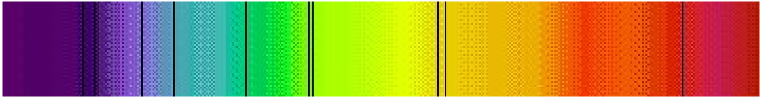


Spectra of some spiral galaxies. The spectra usually contain characteristic emission and absorption lines.

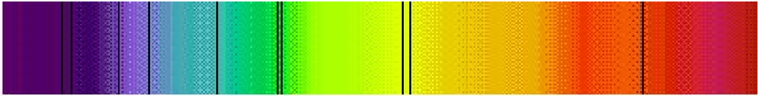
[11] Image from http://astronomy.nmsu.edu/nicole/teaching/ASTR505/lectures/lecture26/slide01.html.

The 'Doppler effect' and redshift[12]

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



when compared to the spectrum in the source's frame



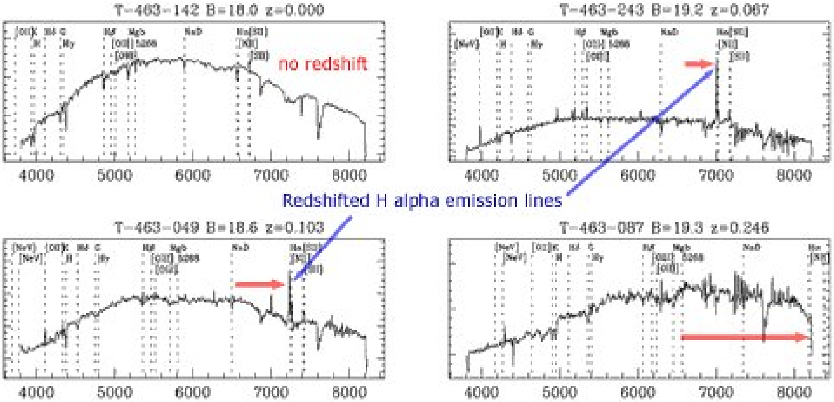
The redshift z of the receding source is defined as:

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

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.

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

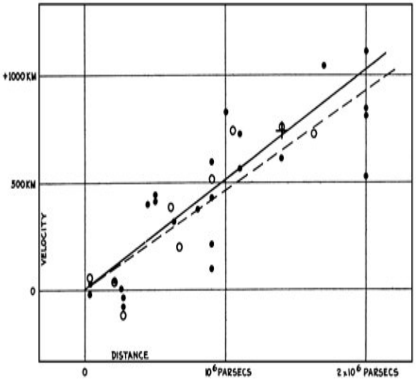
Runaway galaxies[13]

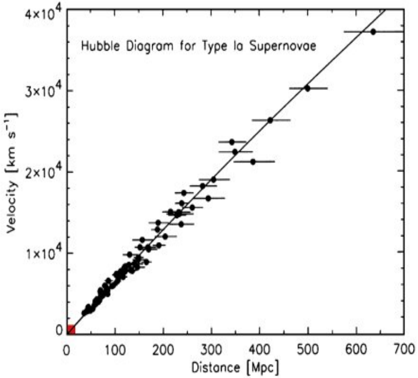


Spectra of four different galaxies from the 2dF redshift survey. On top left is the spectrum of a star from our galaxy, while on the bottom right we have the spectrum of a galaxy that has a redshift of $z = 0.246$. The other two galaxies show prominent Hα emission lines, which have been redshifted from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

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

Relation between the velocity and the distance of galaxies[14]





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 found to be about $72\ \mathrm{km/sec/Mpc}$. The small red region in the lower left marks the span of Hubble's original diagram.

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

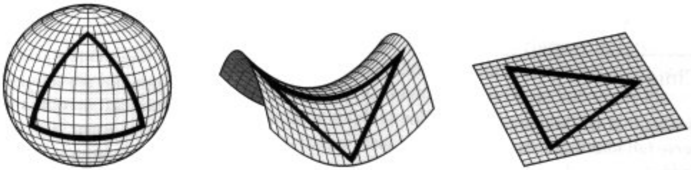
The Friedmann-Lemaître-Robertson-Walker metric

The homogeneous, isotropic and expanding universe can be described by the following Friedmann-Lemaître-Robertson-Walker (FLRW) line element:

$$\mathrm{d}s^2 = \mathrm{d}t^2 - a^2(t)\left[\frac{\mathrm{d}r^2}{(1-\kappa\, r^2)} + r^2\,\left(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2\right)\right],$$

where t is the cosmic time and $a(t)$ denotes the scale factor, while $\kappa = 0, \pm 1$.

The quantity κ denotes the spatial geometry of the universe. It can be flat ($\kappa = 0$), closed ($\kappa = 1$) or open ($\kappa = -1$) depending on the total energy density of matter present in the universe[15].



Positive Curvature   Negative Curvature   Flat Curvature

[15]Image from http://abyss.uoregon.edu/~js/lectures/cosmo_101.html.

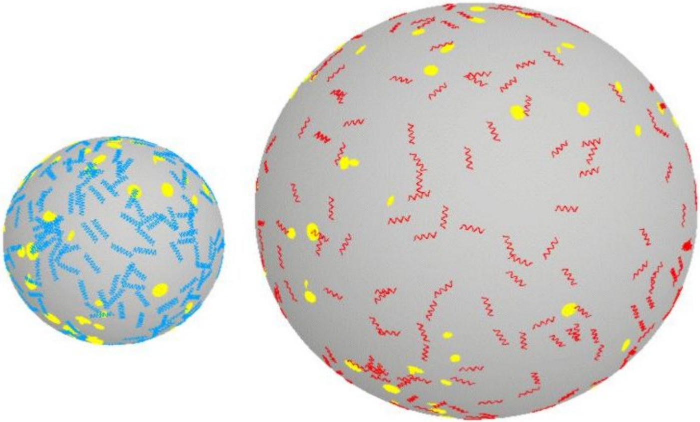
The Friedmann equations

If ρ and p denote the energy density and pressure of the smooth component of the matter field that is driving the expansion, then the Einstein's equations for the FLRW metric lead to the following equations for the scale factor $a(t)$:

$$\begin{aligned} H^2 + \frac{\kappa}{a^2} &= \frac{8\,\pi\,G}{3}\,\rho, \\ \frac{\ddot{a}}{a} &= -\frac{4\,\pi\,G}{3}\,(\rho + 3\,p)\,, \end{aligned}$$

where $H = \dot{a}/a$ is the Hubble parameter.

Visualizing the expanding universe



A two-dimensional analogy for the expanding universe[16]. 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.

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

The cosmological redshift

Recall that, we had defined the redshift z of a receding source as follows:

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

where $\omega_{\rm O}$ and $\omega_{\rm E}$ denote the observed and emitted frequencies, respectively.

In an expanding universe, it can be shown that the frequency of electromagnetic radiation decreases with the expansion as follows:

$$\omega(t) \propto \frac{1}{a(t)},$$

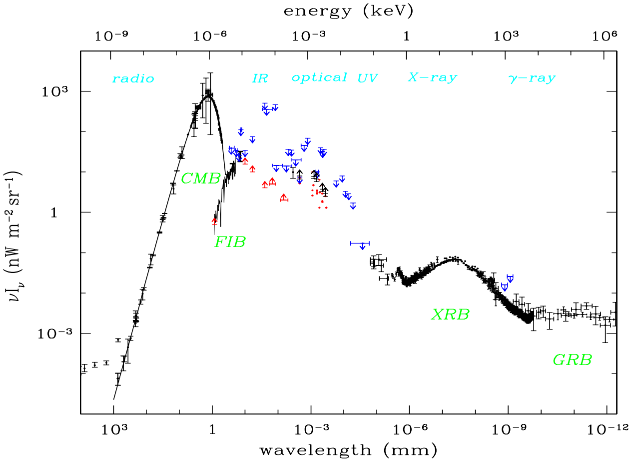
where $a(t)$ is the scale factor that characterizes the expansion.

Therefore, in terms of the scale factor, the cosmological redshift z is given by

$$\frac{a_0}{a(t)} = 1 + z,$$

where a_0 denotes the value of the scale factor *today* (*i.e.* at $t = t_0$).

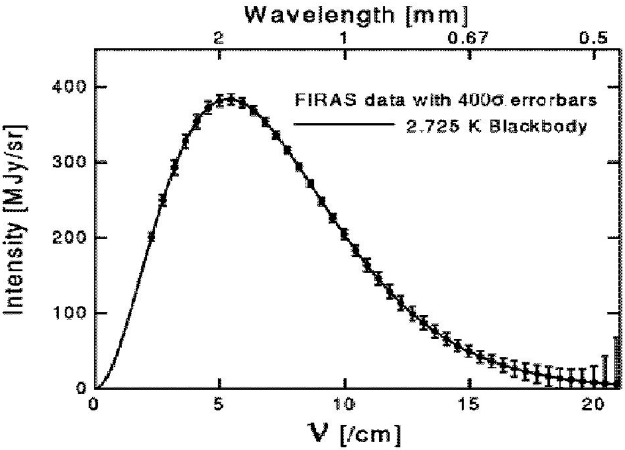
The Cosmic Microwave Background (CMB)



The energy density spectrum of cosmological background radiation has been plotted as a function of wavelength[17]. Note that the CMB contributes the most to the overall background radiation.

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

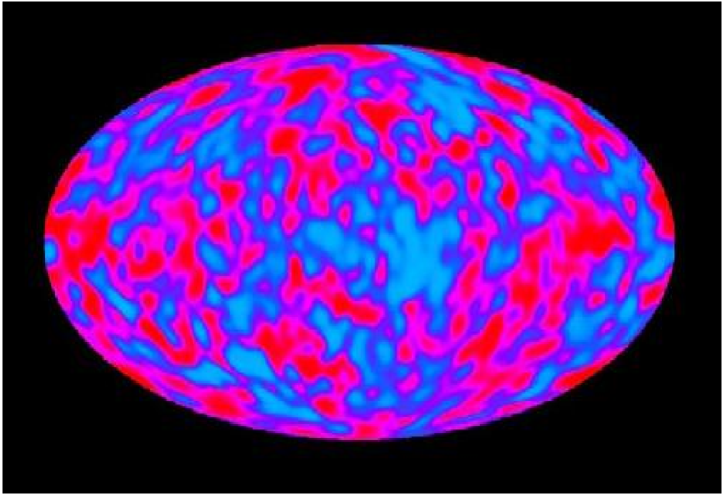
The spectrum of the CMB



The spectrum of the CMB as measured by the COBE satellite[18]. It is such a perfect Planck spectrum (corresponding to a temperature of 2.725° K) that it is unlikely to be bettered in the laboratory. The error bars in the graph above have been amplified 400 times so that they can be seen!

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

The extent of isotropy of the CMB



The fluctuations in the temperature of the CMB as seen by COBE[19]. The CMB turns out to be isotropic to one part in 10^5.

Back to observations by WMAP and Planck

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

Equilibrium between matter and radiation at early epochs

In an evolving universe, the temperature of the CMB goes as

$$T \propto \frac{1}{a(t)},$$

so that the energy density of radiation behaves as

$$\rho_{\rm R} \propto \frac{1}{a^4(t)}.$$

In contrast, the energy density of non-relativistic (*i.e.* pressureless) matter goes as

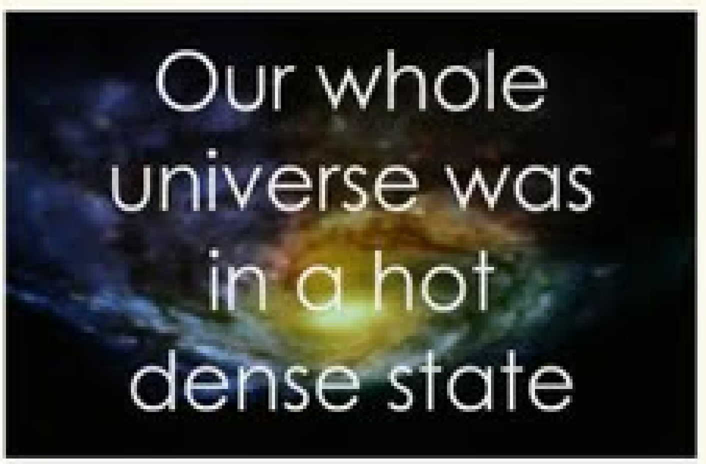
$$\rho_{\rm NR} \propto \frac{1}{a^3(t)}.$$

Observations indicate that, today,

$$\rho_{\rm R} \simeq \frac{\rho_{\rm NR}}{10^4}.$$

This points to the fact that matter and radiation would have interacted strongly and, hence would have been in thermal equilibrium, when the universe was about 10^4 times smaller.

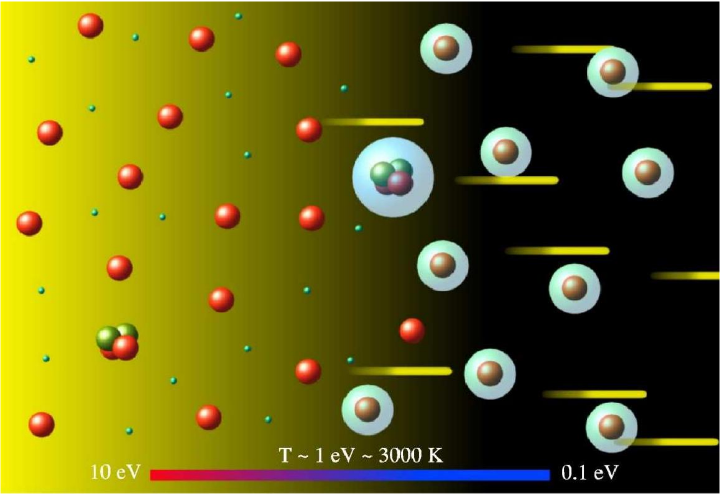
The big bang model seems popular!



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'[20]!

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

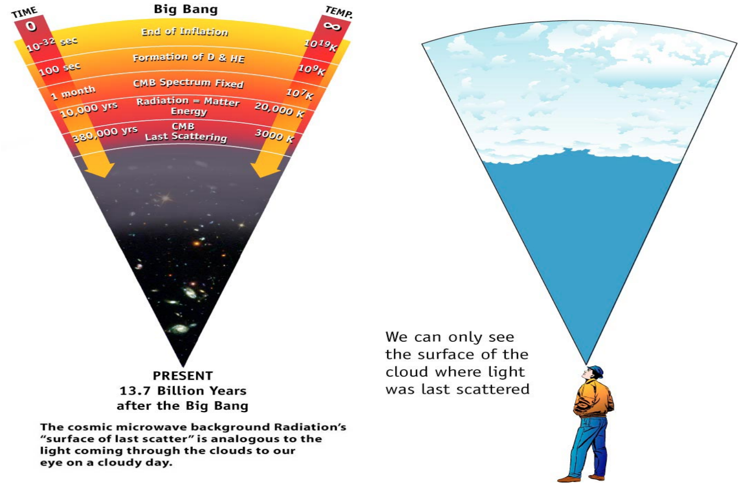
Decoupling of matter and radiation[21]



Matter and radiation cease to interact at a temperature of about $T \simeq 3000^\circ\ \mathrm{K}$, which corresponds to a redshift of about $z \simeq 1000$.

[21] 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[22].

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

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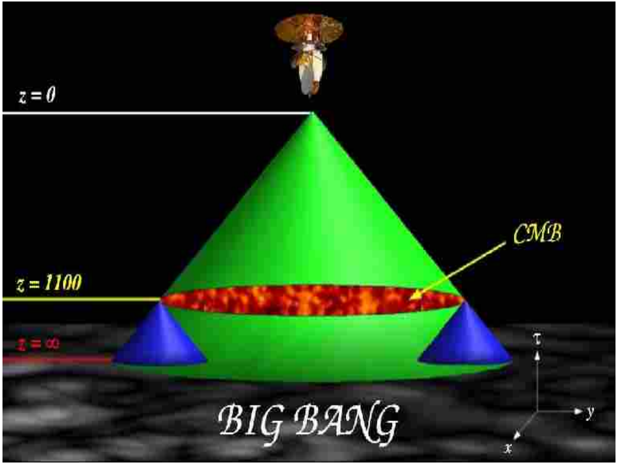
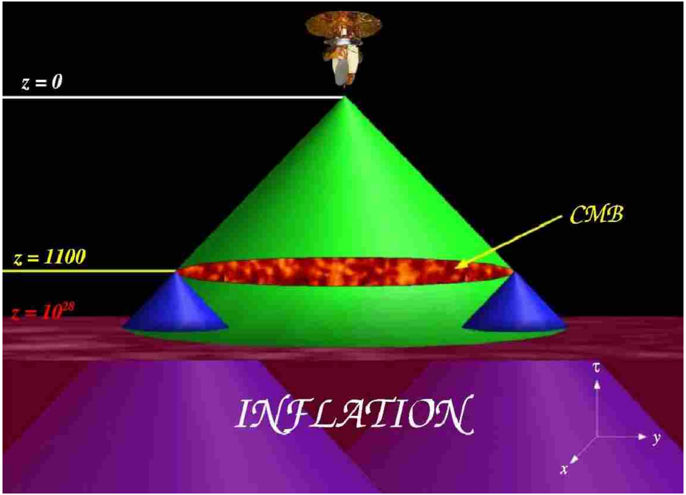
The horizon problem



The radiation from the CMB arriving at us from regions separated by more than the Hubble radius at the last scattering surface (which subtends an angle of about 1° today) could not have interacted before decoupling[23].

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

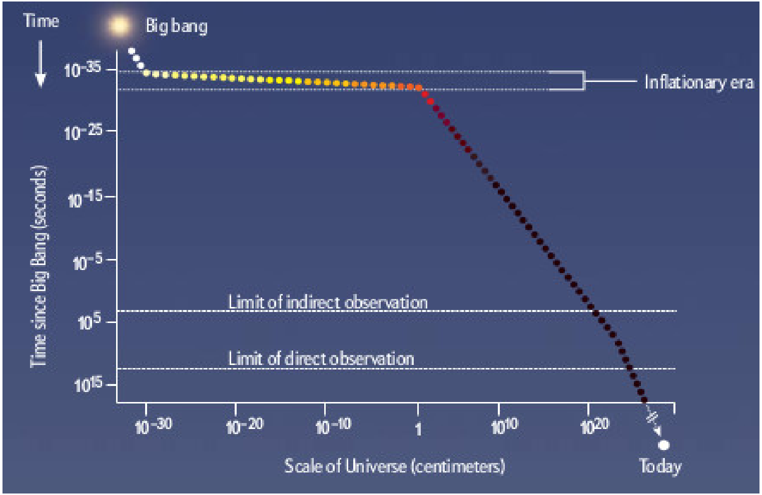
Inflation resolves the horizon problem



An illustration of how an early and sufficiently long epoch of inflation (*viz.* a phase when $\ddot{a} > 0$) resolves the horizon problem[24].

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

The time and duration of inflation



Inflation – a brief period of accelerated expansion – is expected to have taken place during the very stages of the universe[25].

[25] Image from P. J. Steinhardt, Sci. Am. **304**, 18 (2011).

The origin and the evolution of the perturbations

- Inflation is typically driven with the aid of scalar fields. It is the quantum fluctuations associated with these scalar fields which are responsible for the origin of the perturbations[26].
- These perturbations are amplified during the inflationary epoch, which leave their imprints as anisotropies in the CMB.

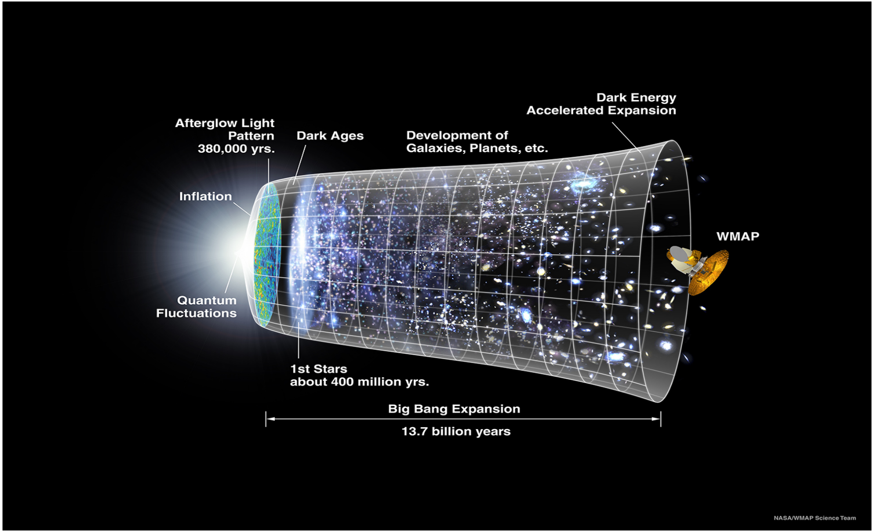
Play movie

- 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

[26] S. W. Hawking, Phys. Letts. B **115**, 295 (1982).

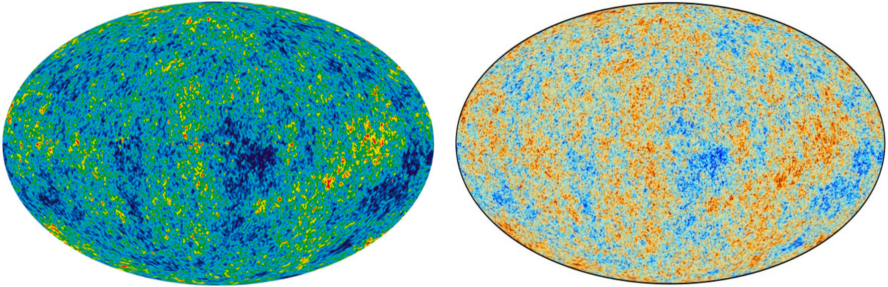
The timeline of the universe



A pictorial timeline of the universe[27].

[27] See http://wmap.gsfc.nasa.gov/media/060915/060915_CMB_Timeline150.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[28].

▸ Observations by COBE

Right: CMB intensity map derived from the joint analysis of Planck, WMAP, and $408\,\mathrm{MHz}$ observations[29]. The above images show temperature variations (as color differences) of the order of $200^\circ\ \mu\mathrm{K}$. The angular resolution of WMAP was about 1°, while that of Planck was about $5'$. These temperature fluctuations correspond to regions of slightly different densities, and they represent the seeds of all the structure around us today.

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

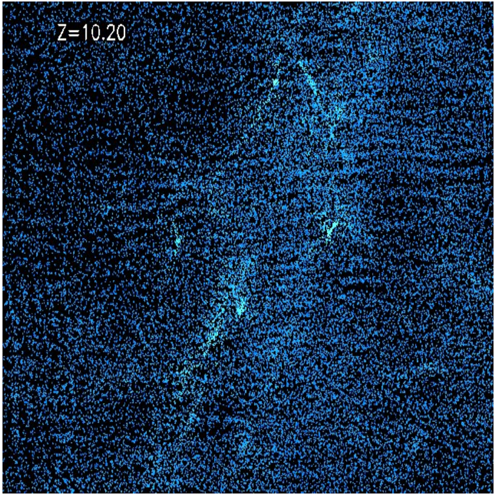
[29] P. A. R. Ade *et al.*, arXiv:1502.01582 [astro-ph.CO].

Formation of structures due to gravitational instability

A numerical simulation illustrating the formation of large scale structures due to gravitational instability[30].

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

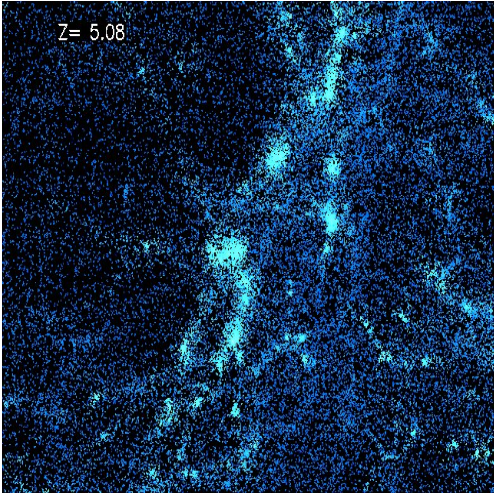
Formation of structures due to gravitational instability



A numerical simulation illustrating the formation of large scale structures due to gravitational instability[30].

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

Formation of structures due to gravitational instability



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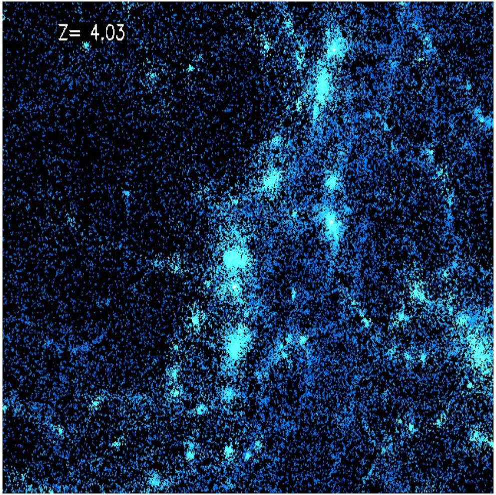

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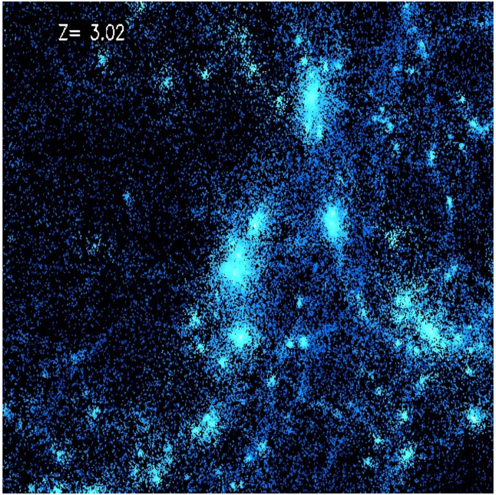
Formation of structures due to gravitational instability



A numerical simulation illustrating the formation of large scale structures due to gravitational instability[30].

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

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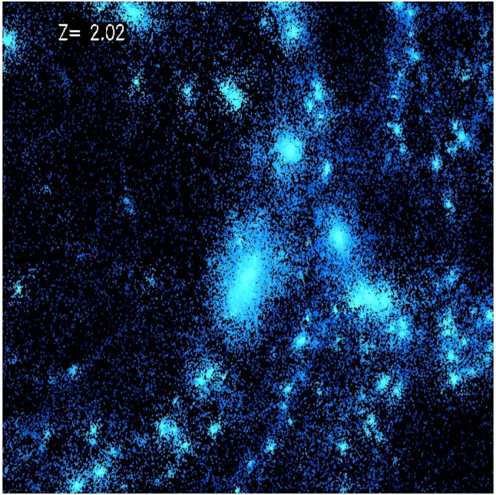

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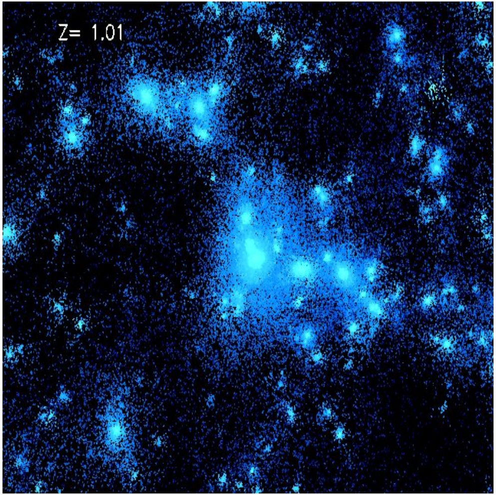

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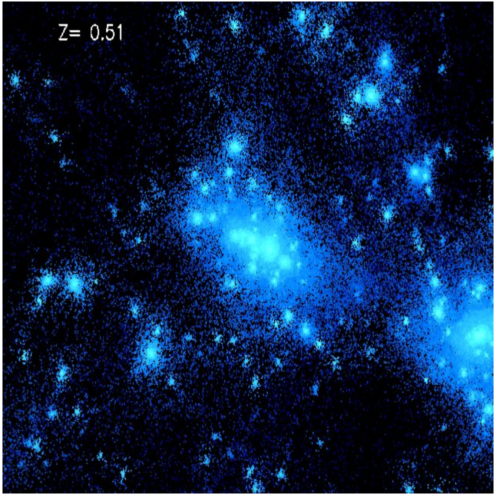

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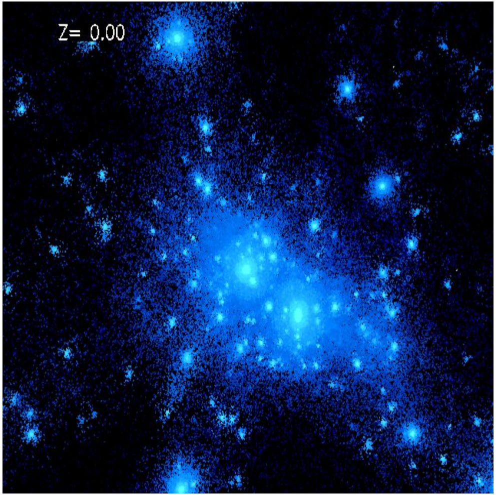

A numerical simulation illustrating the formation of large scale structures due to gravitational instability[30].

Play again

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

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[30].
- It kept busy the principal supercomputer at the Max Planck Society's Supercomputing Centre in Garching, Germany for more than a month.

Play movie

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

Plan of the talk

1. Hawking's academic history
2. A survey of the universe
3. The composition and evolution of the smooth universe
4. The generation and evolution of perturbations
5. Ideas on the origin of the universe
6. Status and outlook

Quantum mechanics of the universe

- There exists an idea, originally due to John Wheeler and Bryce DeWitt, to describe the universe quantum mechanically.
- In this picture, the universe is described by a wavefunction that is governed by a suitable Schrodinger equation, known as the Wheeler-DeWitt equation.
- The wavefunction of the universe is a function (actually, a *functional*) of the geometry of space and the matter fields present. Under certain simplifying assumptions, given the boundary conditions, it is possible to solve the Wheeler-DeWitt equation and understand the behavior of the universe.

Determining the wavefunction of the universe

- Hawking and co-workers had proposed a specific method (through a path integral with Euclidean time) to determine the ground state of the universe[31].
- In the presence of a cosmological constant, they had found that the ground state corresponds to the so-called de Sitter spacetime describing an inflationary universe.
- Interestingly, using the approach, they were also able to describe the generation of the inflationary perturbations and also evaluate the spectrum of perturbations[32].

[31] J. B. Hartle and S. W. Hawking, Phys. Rev. D **28**, 2960 (1983).

[32] J. J. Halliwell and S. W. Hawking, Phys. Rev. D **31**, 1777 (1985).

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Status and outlook

- It is now commonly believed that it is the inflationary epoch which is responsible for the generation of perturbations in the early universe. Also, the predictions of the inflationary scenario are found to be remarkably consistent with the observed pattern of the anisotropies in the CMB.
- It is expected that a working quantum theory of gravity will provide us clues to the origin of our universe. However, despite decades of effort through different approaches, a viable quantum theory of gravity still eludes us.

Popular books

- S. W. Weinberg, *The First Three Minutes*, Updated edition (Basic Books, New York, 1993).
- A. G. Guth, *The Inflationary Universe* (Basic Books, New York, 1998).
- J. Silk, *The Big Bang*, Third Edition (Times Books, New York, 2000).
- S. Singh, *Big Bang* (Harper Perennial, New York, 2005).

Thank you for your attention