

Mapping the Cosmos

– General Relativity and Timeline of the Universe –

L. Sriramkumar

Centre for Strings, Gravitation and Cosmology,
Department of Physics, Indian Institute of Technology Madras, Chennai

Cosmic Connections: Bridging the Early and Late Universe

The Institute of Mathematical Sciences, Chennai

July 28–August 1, 2025

Plan of the talk

- 1 Universe at large
- 2 Expanding universe and general relativity
- 3 Cosmic microwave background and hot big bang model
- 4 Inflationary scenario
- 5 Generation and evolution of perturbations
- 6 Summary

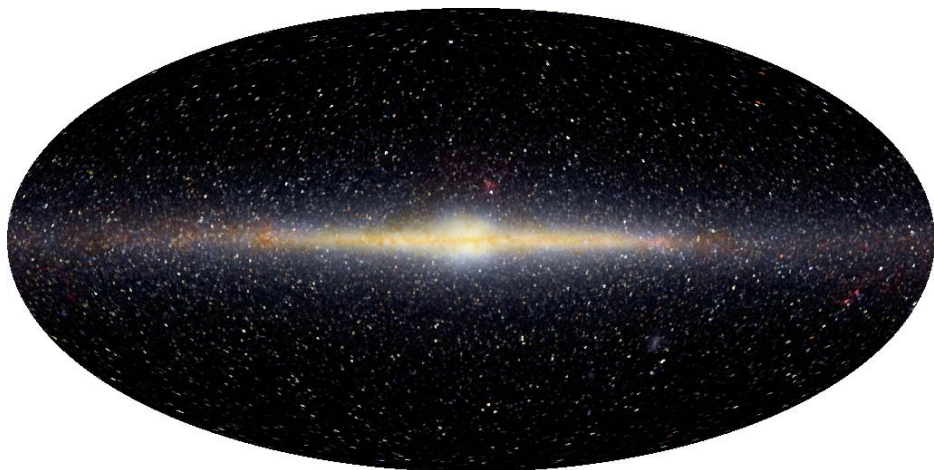


Plan of the talk

- 1 Universe at large
- 2 Expanding universe and general relativity
- 3 Cosmic microwave background and hot big bang model
- 4 Inflationary scenario
- 5 Generation and evolution of perturbations
- 6 Summary



An infrared image of our galaxy

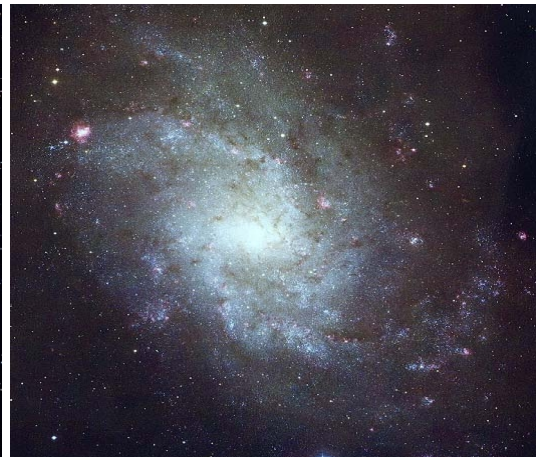


Our galaxy – the Milky Way – as observed by the COsmic Background Explorer (COBE) satellite in the infrared wavelengths¹. The diameter of the disc of our galaxy is approximately 45×10^3 ly or 15 kpc, i.e. a kilo parsec, with $1 \text{ pc} \simeq 3.26$ ly.

¹Image from http://aether.lbl.gov/www/projects/cobe/cobe_pics.html.



Local group of galaxies

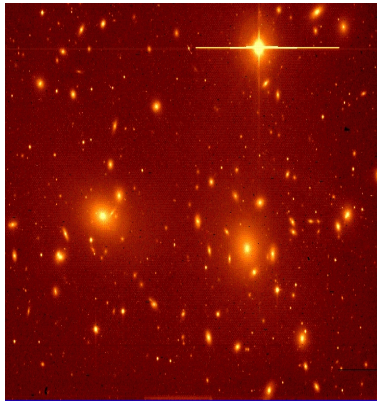


Andromeda (on the left) and Triangulum (on the right) galaxies, which are part of the local group of galaxies². The Andromeda galaxy is located at a distance of **700** kpc and the size of the local group is estimated to be about **1.3** Mpc.

²Images from <http://www.seds.org/messier/m/m031.html> and <http://www.seds.org/messier/m/m033.html>.



Clusters of galaxies

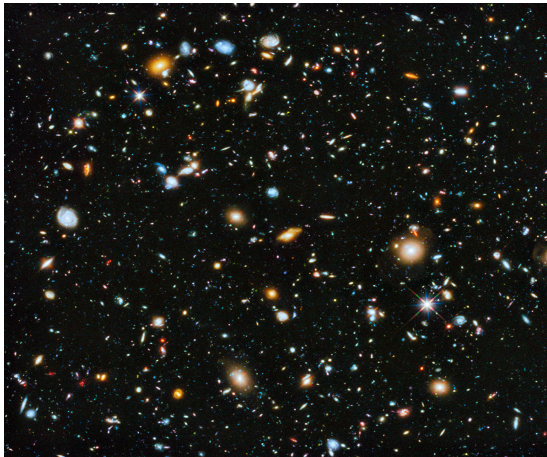


Virgo (on the left), Coma (in the middle) and Hercules (on the right) clusters of galaxies³. The clusters contain about 10^2 – 10^3 galaxies and can be up to about 10 Mpc in size.

³Images 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



Ultra deep field images from the Hubble Space Telescope (on the left)⁴ and the James Webb Space Telescope (on the right)⁵.

⁴Image from <http://hubblesite.org/newscenter/archive/releases/2014/27>.

⁵Image from <https://www.nasa.gov/image-article/nasas-webb-delivers-deepest-infrared-image-of-universe-yet/>.



Surveying the universe

Over eight years of operations, the Sloan Digital Sky Survey has obtained deep images covering more than a quarter of the sky and created three-dimensional maps containing more than 930,000 galaxies⁶.

► Survey by SDSS

⁶See <http://www.sdss.org/>.

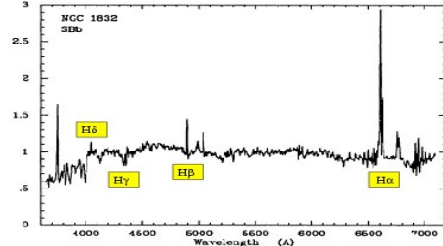
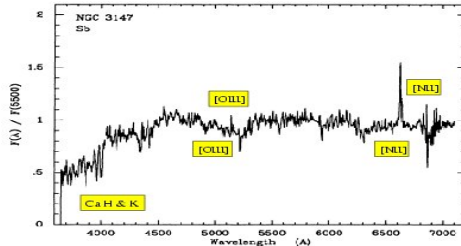
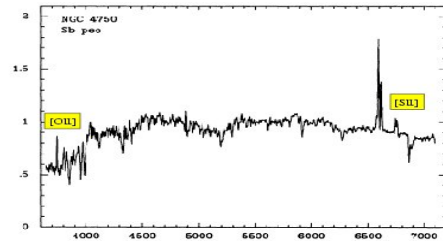
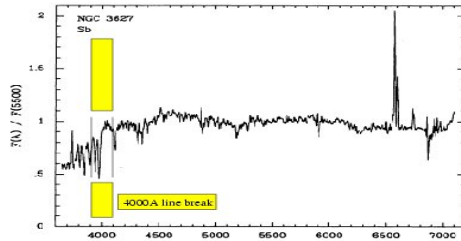


Plan of the talk

- 1 Universe at large
- 2 Expanding universe and general relativity
- 3 Cosmic microwave background and hot big bang model
- 4 Inflationary scenario
- 5 Generation and evolution of perturbations
- 6 Summary



Typical spectra of galaxies⁷

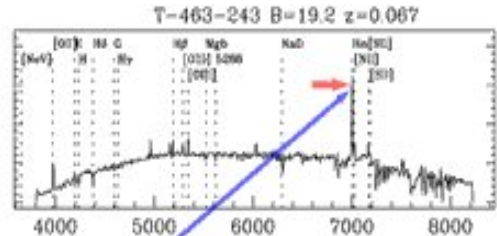
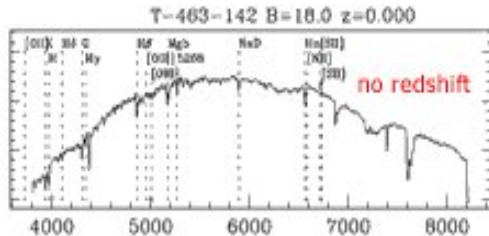


Spectra of some spiral galaxies with characteristic emission and absorption lines.

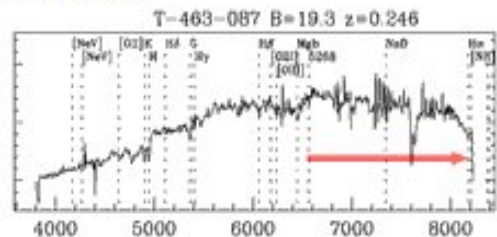
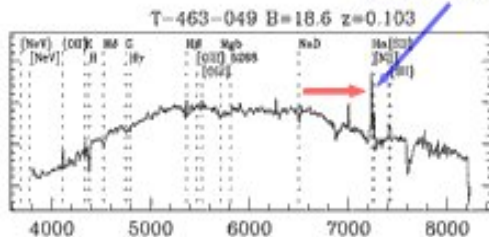
⁷ Image from <http://astronomy.nmsu.edu/nicole/teaching/ASTR505/lectures/lecture26/slide01.html>.



Runaway galaxies⁸



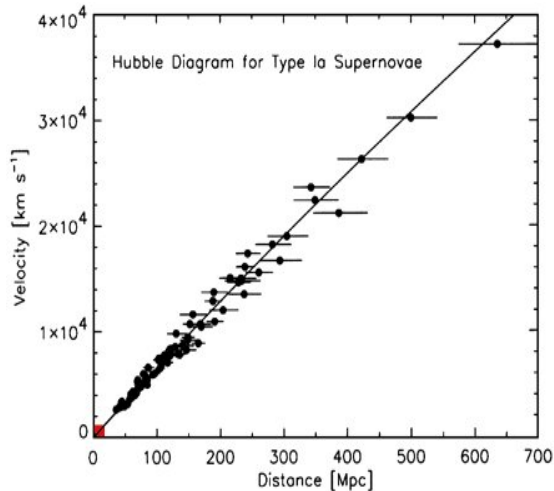
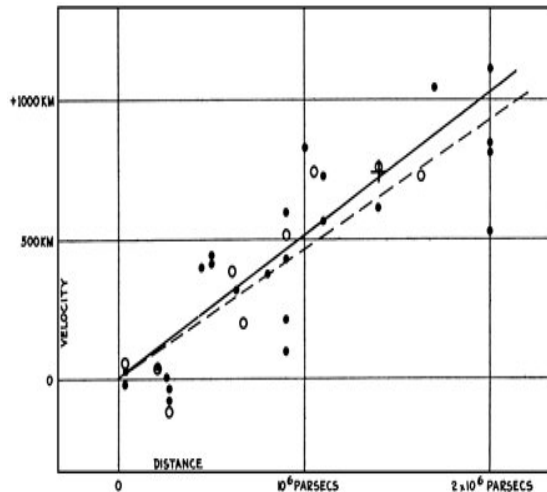
Redshifted H alpha emission lines



Spectra of four galaxies which exhibit redshift.

⁸Image from http://outreach.atnf.csiro.au/education/senior/astrophysics/spectra_astro_types.html.

Relation between velocity and distance of galaxies⁹

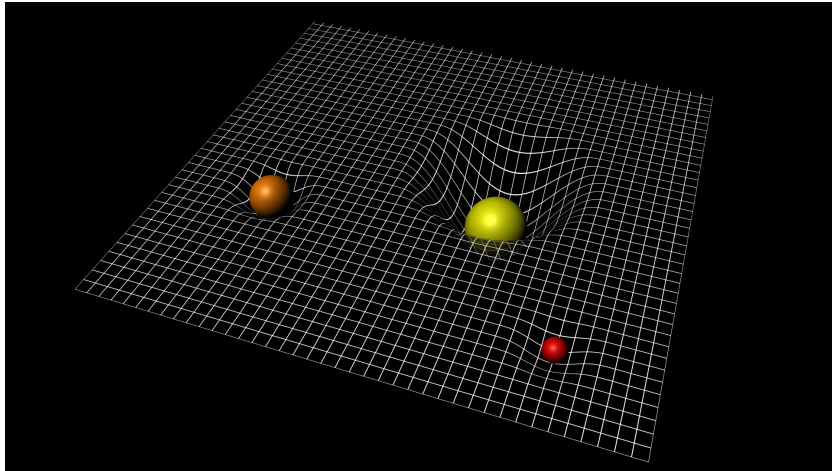


The original Hubble data (on the left) and a more recent Hubble diagram (on the right). The slopes of the fit are about **500** km/sec/Mpc and **72** km/sec/Mpc.

⁹R. Kirshner, Proc. Natl. Acad. Sci. USA **101**, 8 (2004).



General theory of relativity and Einstein's equations



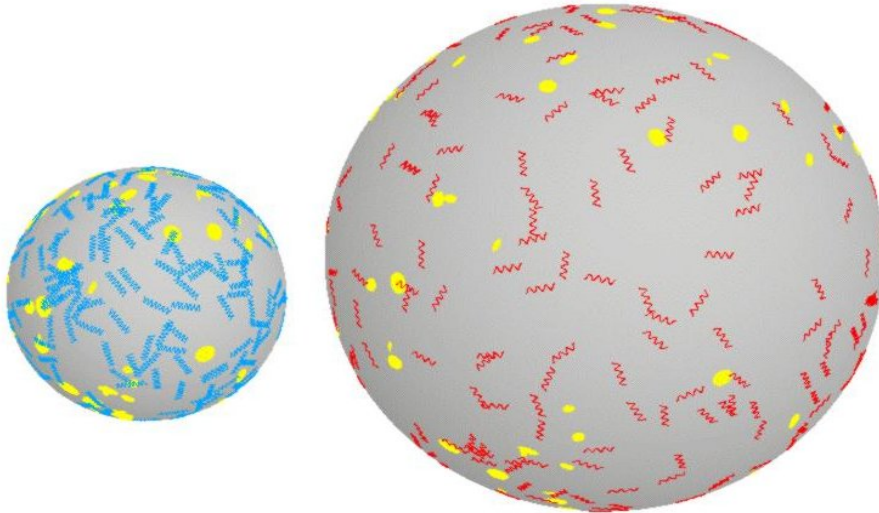
Spacetime tells matter how to move and matter tells spacetime how to curve¹⁰. The curvature of spacetime is related to the matter content through the Einstein's equations¹¹

¹⁰ J. A. Wheeler, *Geons, Black Holes, and Quantum Foam: A Life in Physics* (W. W. Norton, New York, 2010).

¹¹ Image from http://www.esa.int/spaceinimages/Images/2015/09/Spacetime_curvature.



Expanding universe and cosmological redshift



A two-dimensional analogy for the expanding universe¹².

¹²Image from <http://www.astro.ucla.edu/~wright/balloon0.html>.

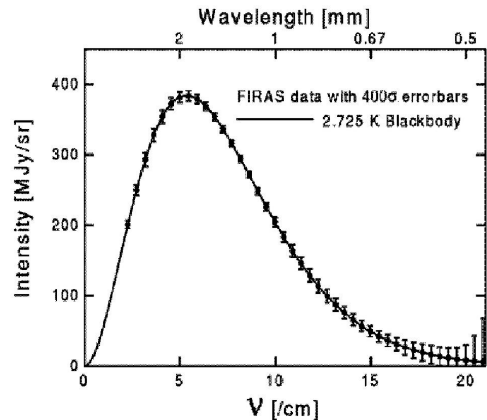
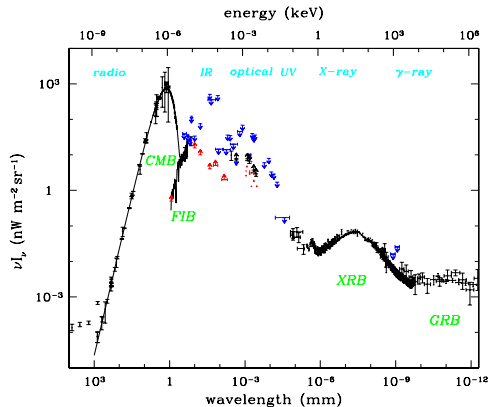


Plan of the talk

- 1 Universe at large
- 2 Expanding universe and general relativity
- 3 Cosmic microwave background and hot big bang model
- 4 Inflationary scenario
- 5 Generation and evolution of perturbations
- 6 Summary



Cosmic Microwave Background (CMB)



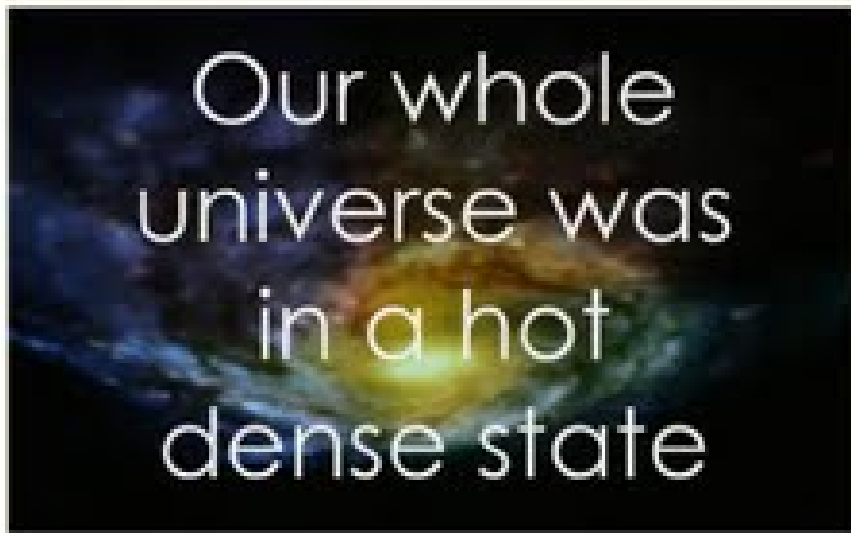
The spectrum of the cosmological background radiation¹³ and the spectrum of the CMB as measured by the COBE satellite¹⁴. The spectrum of the CMB corresponds to that of a perfect black body, with a temperature of **2.725° K**.

¹³Figure from D. Scott, arXiv:astro-ph/9912038.

¹⁴Image from http://www.astro.ucla.edu/~wright/cosmo_01.htm.



The big bang model seems popular!

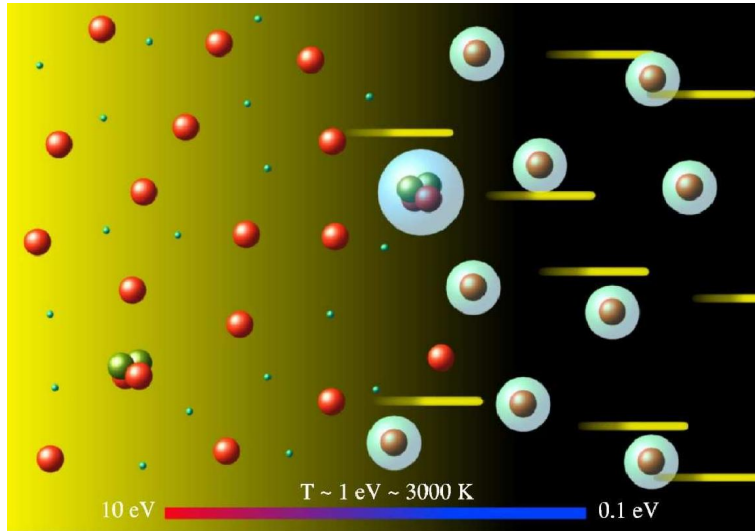


A screen grab from the theme song of the American sitcom 'The Big Bang Theory'¹⁵

¹⁵See http://www.cbs.com/shows/big_bang_theory/.



Decoupling of matter and radiation

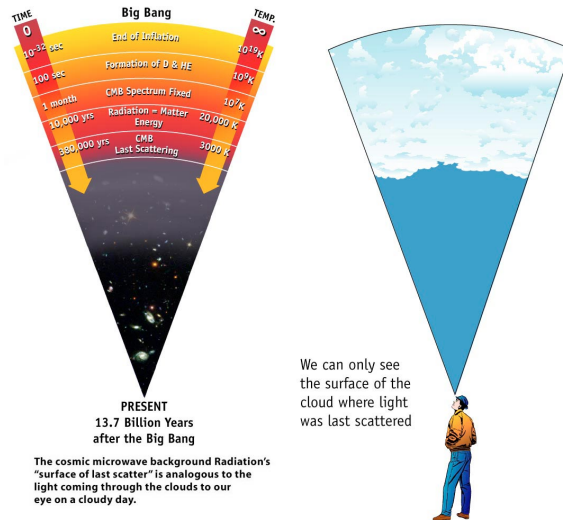


CMB arises because matter and radiation cease to interact at an early time¹⁶.

¹⁶Image from W. H. Kinney, [arXiv:astro-ph/0301448v2](https://arxiv.org/abs/astro-ph/0301448v2).



Last scattering surface (LSS) and free streaming CMB photons

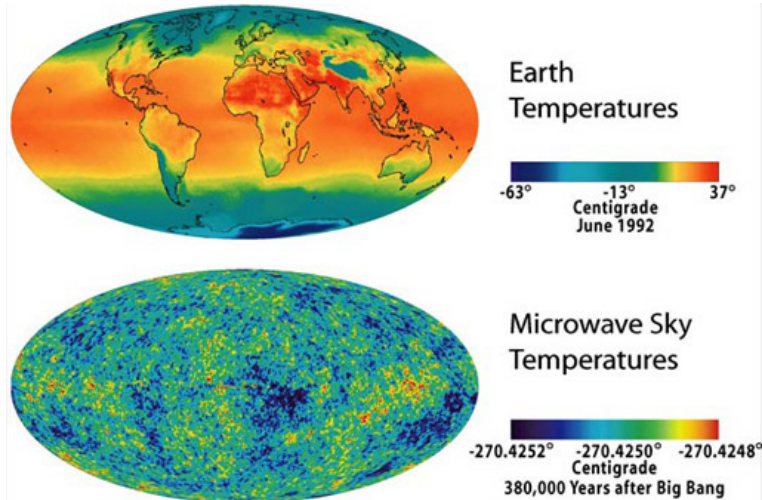


CMB photons stream to us freely from the LSS when radiation decoupled from matter¹⁷

¹⁷Image from <http://map.gsfc.nasa.gov/media/990053/990053.jpg>.



Projecting the LSS

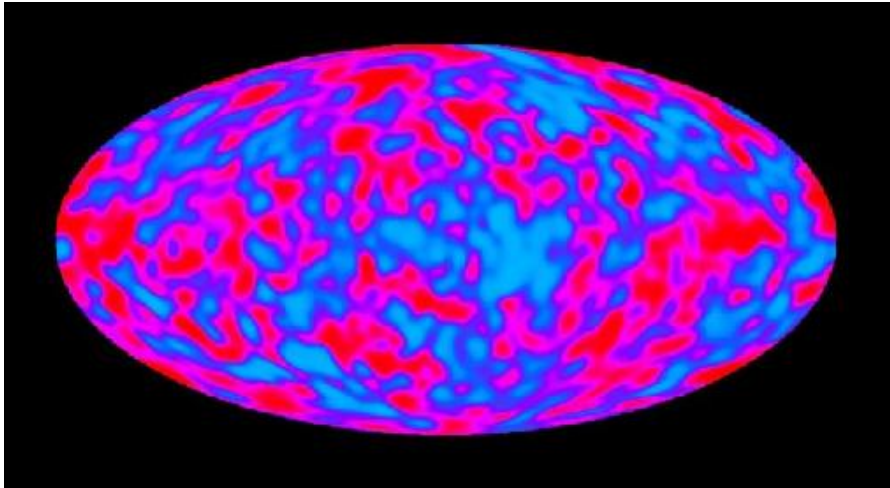


The temperature of the CMB on the LSS can be projected on to a plane as the surface of the Earth is often projected¹⁸.

¹⁸Image from <http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/planckcmb.html>.



Anisotropies in the CMB



Fluctuations in the temperature of the CMB as seen by COBE¹⁹. The CMB turns out to be isotropic to one part in 10^5 .

► Anisotropies observed by WMAP and Planck

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

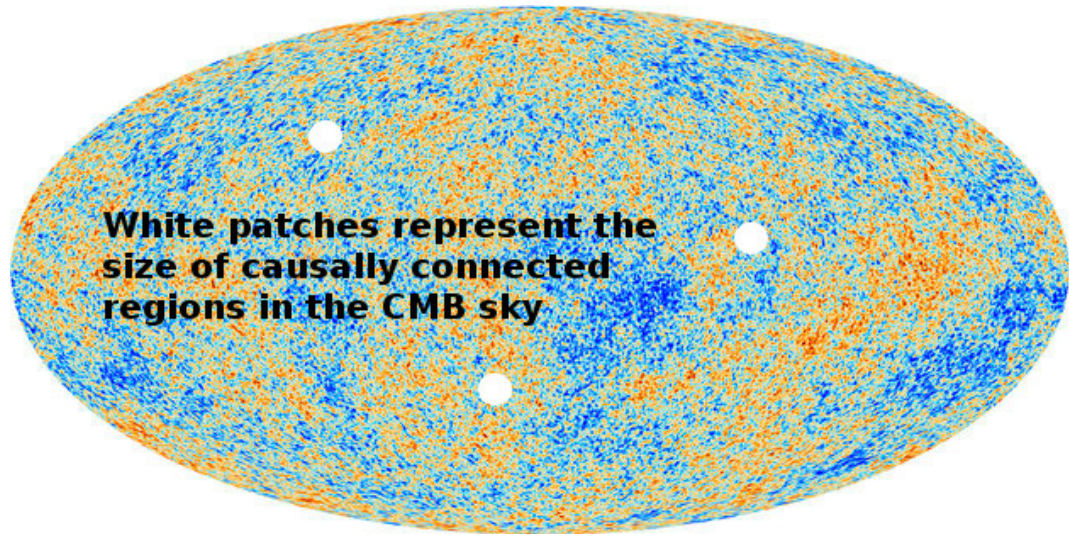


Plan of the talk

- 1 Universe at large
- 2 Expanding universe and general relativity
- 3 Cosmic microwave background and hot big bang model
- 4 Inflationary scenario**
- 5 Generation and evolution of perturbations
- 6 Summary



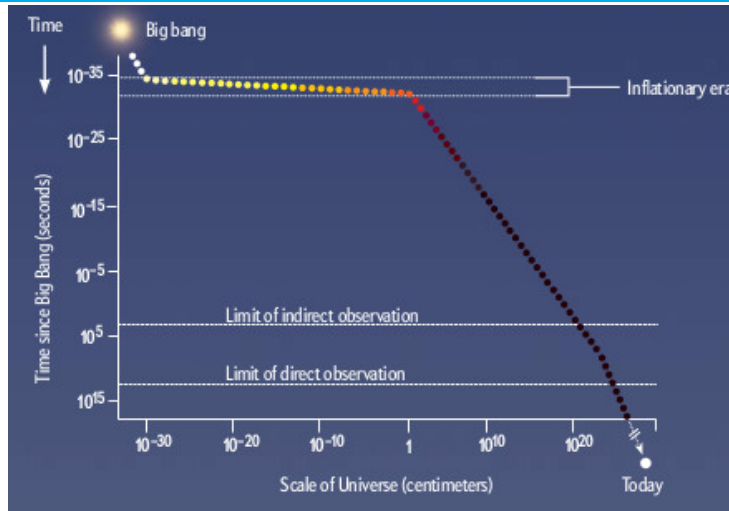
Horizon problem



Radiation from the CMB arriving from regions separated by angles greater than 1° could not have interacted before decoupling.



Time and duration of inflation

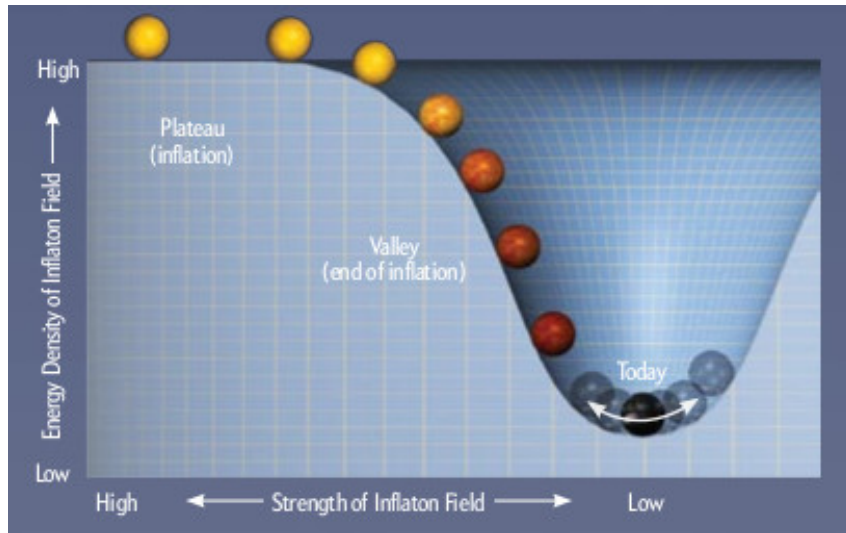


Inflation – a brief period of accelerated expansion – is expected to have taken place during the very stages of the universe²⁰.

²⁰Image from P. J. Steinhardt, *Sci. Am.* **304**, 18 (2011).



Driving inflation with scalar fields



Inflation can be achieved with scalar fields encountered in high energy physics²¹.

²¹ Image from P. J. Steinhardt, *Sci. Am.* **304**, 34 (2011).



Plan of the talk

- 1 Universe at large
- 2 Expanding universe and general relativity
- 3 Cosmic microwave background and hot big bang model
- 4 Inflationary scenario
- 5 Generation and evolution of perturbations**
- 6 Summary

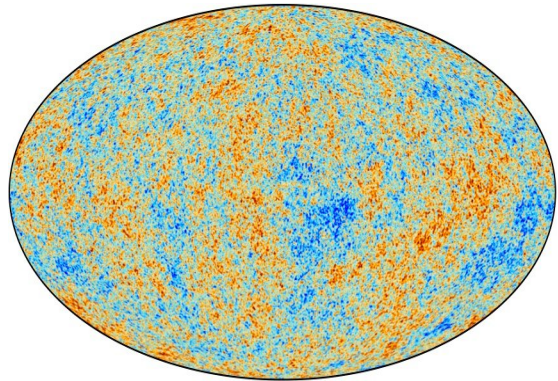
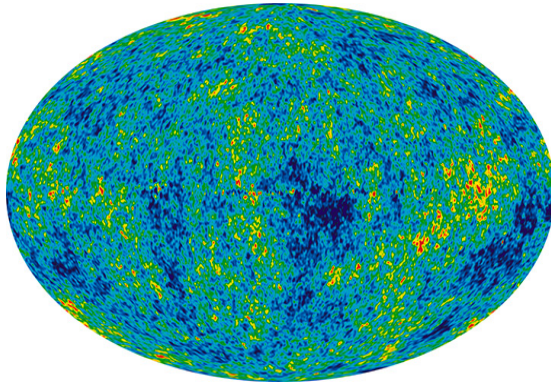


Origin and evolution of perturbations

- ◆ It is the quantum fluctuations associated with the scalar fields that drive inflation which are supposed to be responsible for the origin of the primordial perturbations.
- ◆ These perturbations are amplified during the inflationary epoch, which leave their imprints as anisotropies in the CMB. ► From inflation to CMB
- ◆ 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. ► From CMB to large-scale structure



CMB anisotropies as seen by WMAP and Planck



Anisotropies in the CMB as observed by the Wilkinson Microwave Anisotropy Probe²² and Planck²³. These images show temperature variations (as color differences) of the order of $200^\circ \mu\text{K}$.

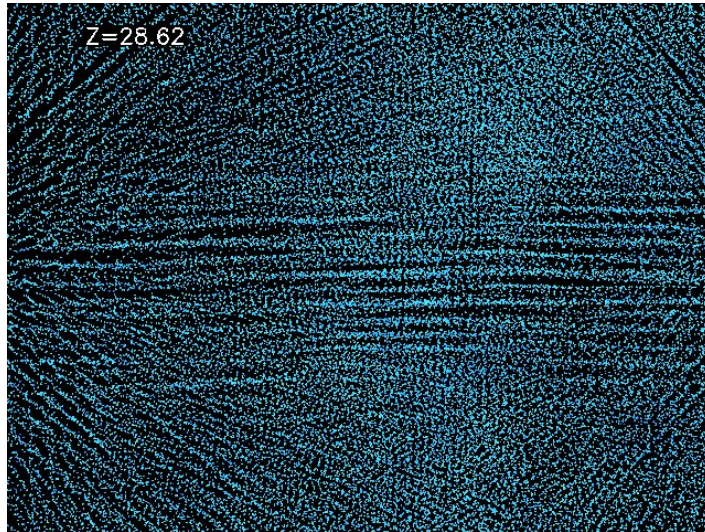
► Anisotropies observed by COBE

²²Image from <http://wmap.gsfc.nasa.gov/media/121238/index.html>.

²³P. A. R. Ade *et al.*, arXiv:1502.01582 [astro-ph.CO].



Formation of structures due to gravitational instability

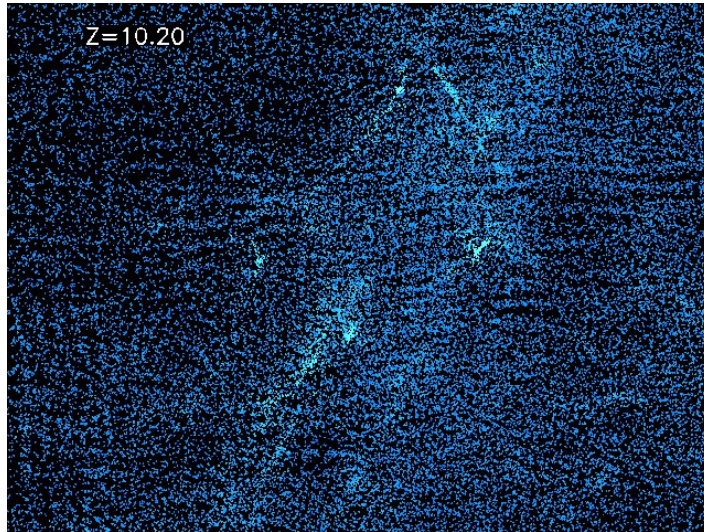


Simulation illustrating the formation of structures due to gravitational instability²⁴.

²⁴Images from <http://cfcp.uchicago.edu/lss/group.html>.



Formation of structures due to gravitational instability

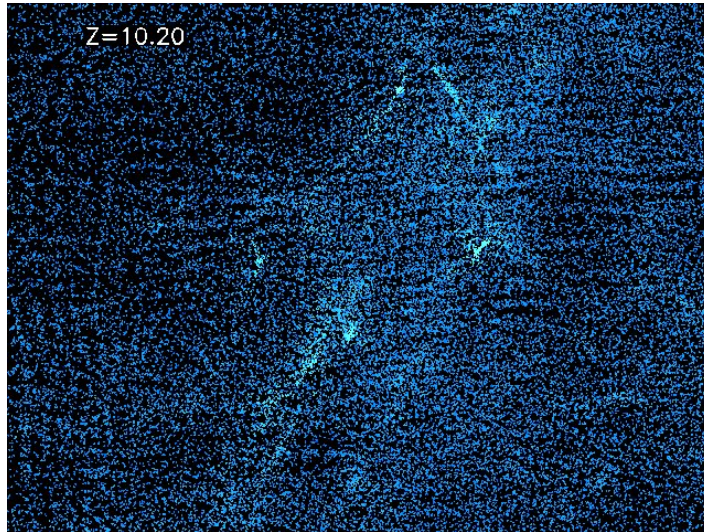


Simulation illustrating the formation of structures due to gravitational instability²⁴.

²⁴Images from <http://cfcp.uchicago.edu/lss/group.html>.



Formation of structures due to gravitational instability

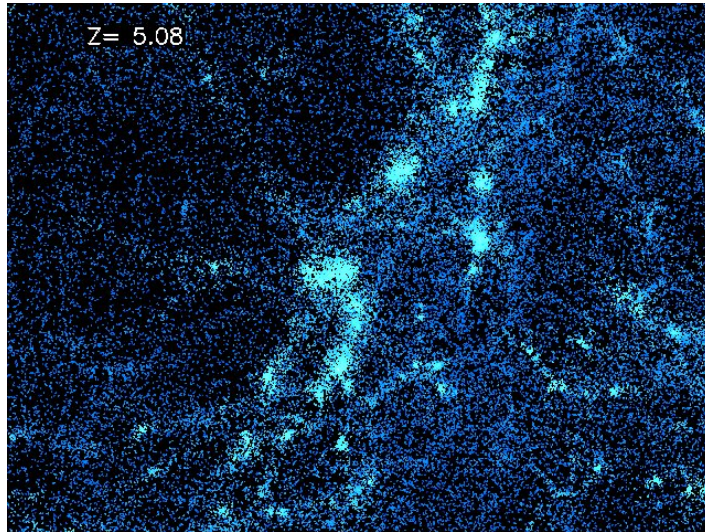


Simulation illustrating the formation of structures due to gravitational instability²⁴.

²⁴Images from <http://cfcp.uchicago.edu/lss/group.html>.



Formation of structures due to gravitational instability

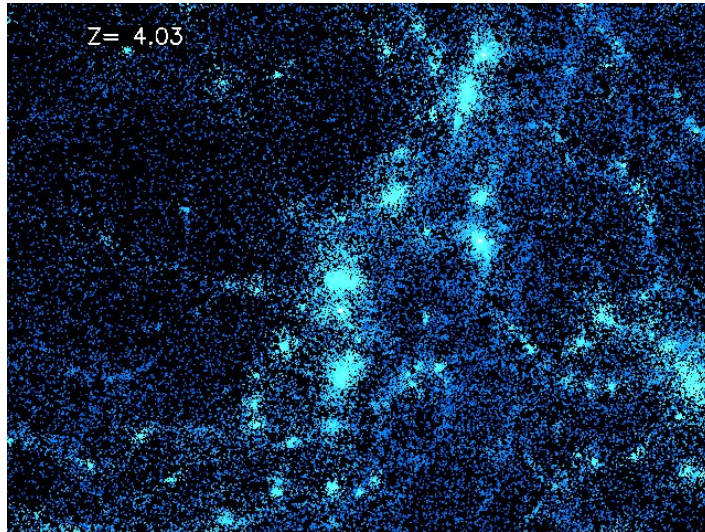


Simulation illustrating the formation of structures due to gravitational instability²⁴.

²⁴Images from <http://cfcp.uchicago.edu/lss/group.html>.



Formation of structures due to gravitational instability

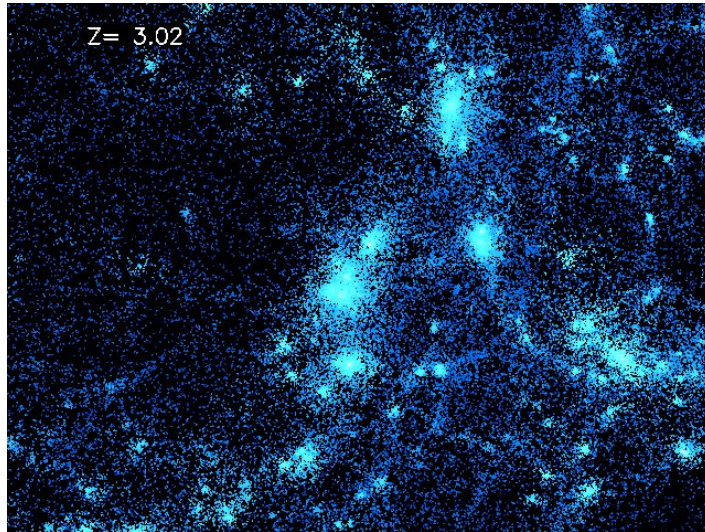


Simulation illustrating the formation of structures due to gravitational instability²⁴.

²⁴Images from <http://cfcp.uchicago.edu/lss/group.html>.



Formation of structures due to gravitational instability

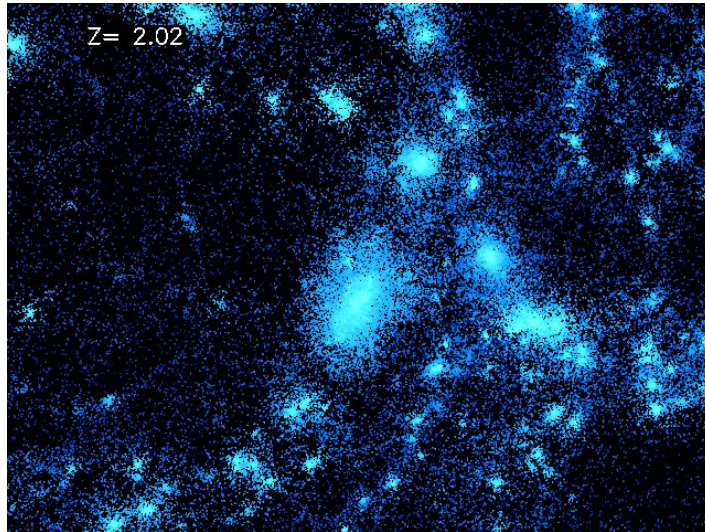


Simulation illustrating the formation of structures due to gravitational instability²⁴.

²⁴Images from <http://cfcp.uchicago.edu/lss/group.html>.



Formation of structures due to gravitational instability

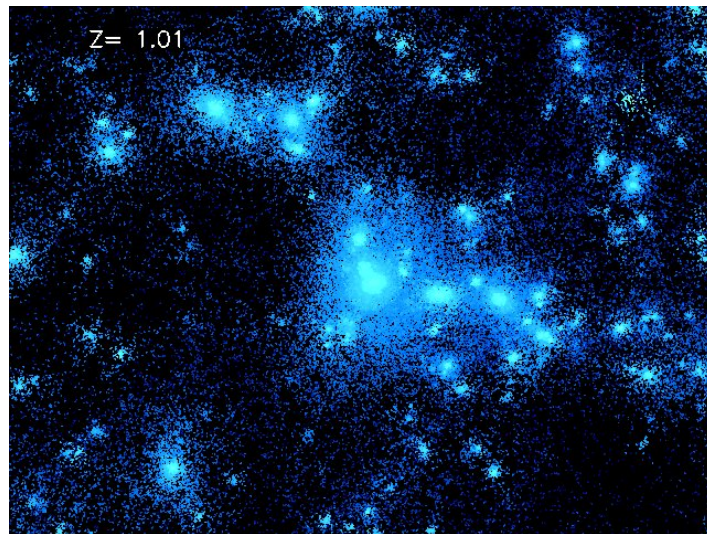


Simulation illustrating the formation of structures due to gravitational instability²⁴.

²⁴Images from <http://cfcp.uchicago.edu/lss/group.html>.



Formation of structures due to gravitational instability

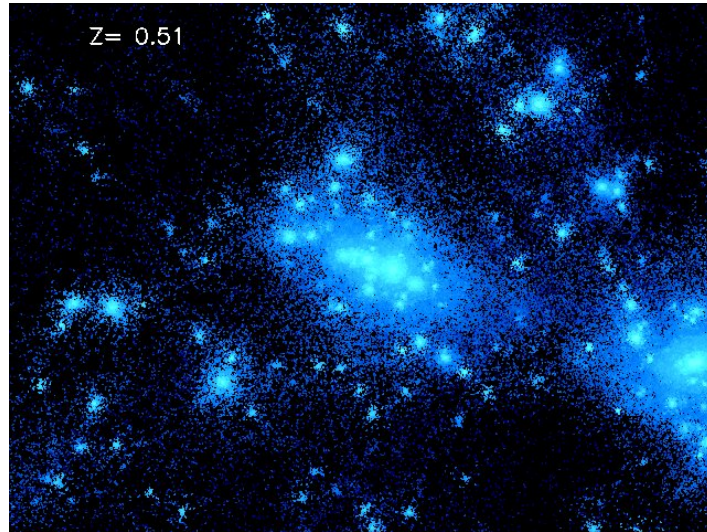


Simulation illustrating the formation of structures due to gravitational instability²⁴.

²⁴Images from <http://cfcp.uchicago.edu/lss/group.html>.



Formation of structures due to gravitational instability

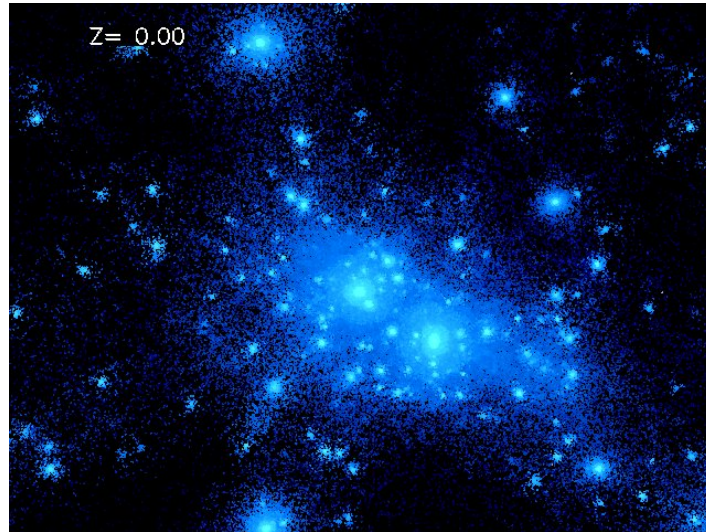


Simulation illustrating the formation of structures due to gravitational instability²⁴.

²⁴Images from <http://cfcp.uchicago.edu/lss/group.html>.



Formation of structures due to gravitational instability

[▶ Play again](#)

Simulation illustrating the formation of structures due to gravitational instability²⁴.

²⁴Images from <http://cfcp.uchicago.edu/lss/group.html>.

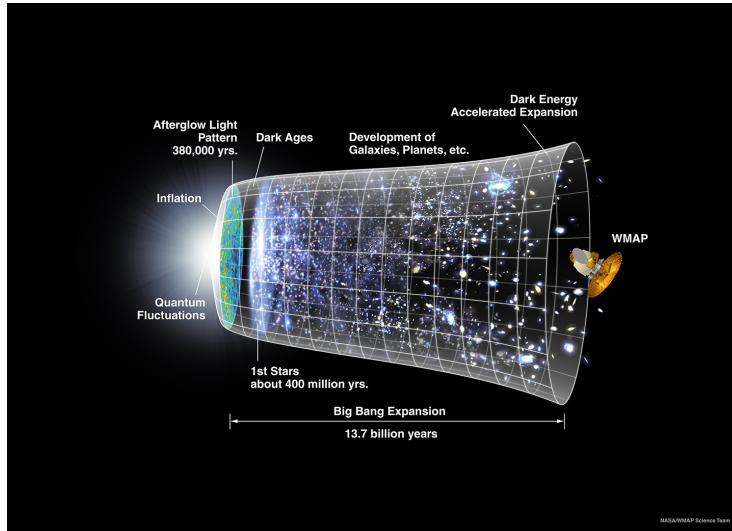


Plan of the talk

- 1 Universe at large
- 2 Expanding universe and general relativity
- 3 Cosmic microwave background and hot big bang model
- 4 Inflationary scenario
- 5 Generation and evolution of perturbations
- 6 Summary



Timeline of the universe



A pictorial timeline of the universe²⁴.

²⁴See http://wmap.gsfc.nasa.gov/media/060915/060915_CMB_Timeline150.jpg.

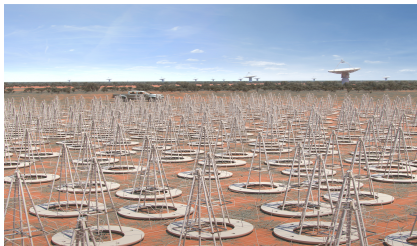


Summary

- ◆ According to the currently prevalent view, the inflationary epoch magnifies the tiny fluctuations in the quantum fields present at the beginning of epoch and converts them into classical perturbations.
- ◆ These inhomogeneities leave their imprints as anisotropies in the CMB.
- ◆ Gravitational instability then takes over, and converts the small anisotropies in the CMB into the large scale structures that we see around us today as galaxies and clusters of galaxies.
- ◆ Increasingly precise observations of the anisotropies in the CMB and the distribution of the large scale structure allow us to reconstruct the physics of the early universe.



Ongoing and future missions



The **BICEP** (top left), **Euclid** (top right), **Square Kilometer Array** (bottom left) and the **Dark Energy Survey** (bottom right) missions are expected to provide unprecedented amount and quality of cosmological data that can help us unravel the mysteries of the universe.



Thank you for your attention