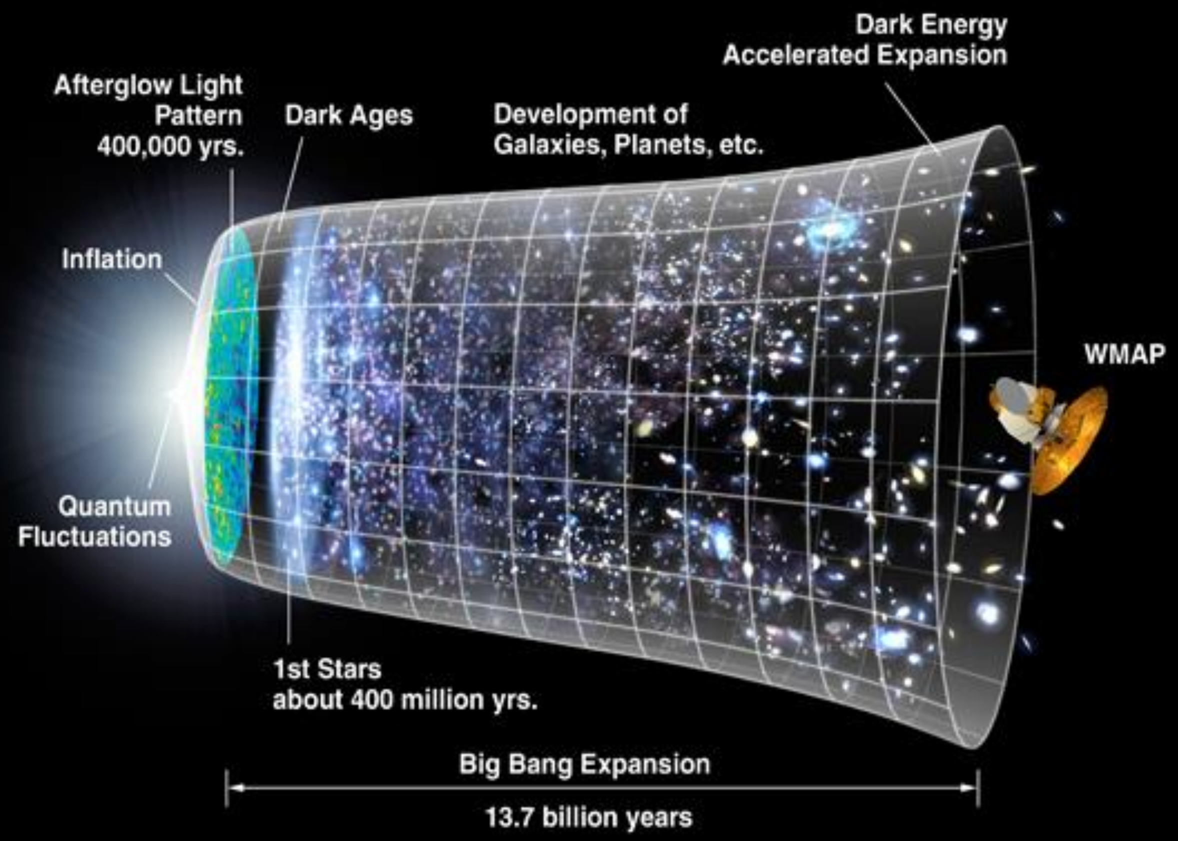
Cosmic Microwave Background – The sound of the Universe

Introduction to Cosmology



Matthias Weißwange

Outline:

- Chronology of the Universe
  - Standard Cosmology
  - Particle Cosmology
  - Quantum Cosmology

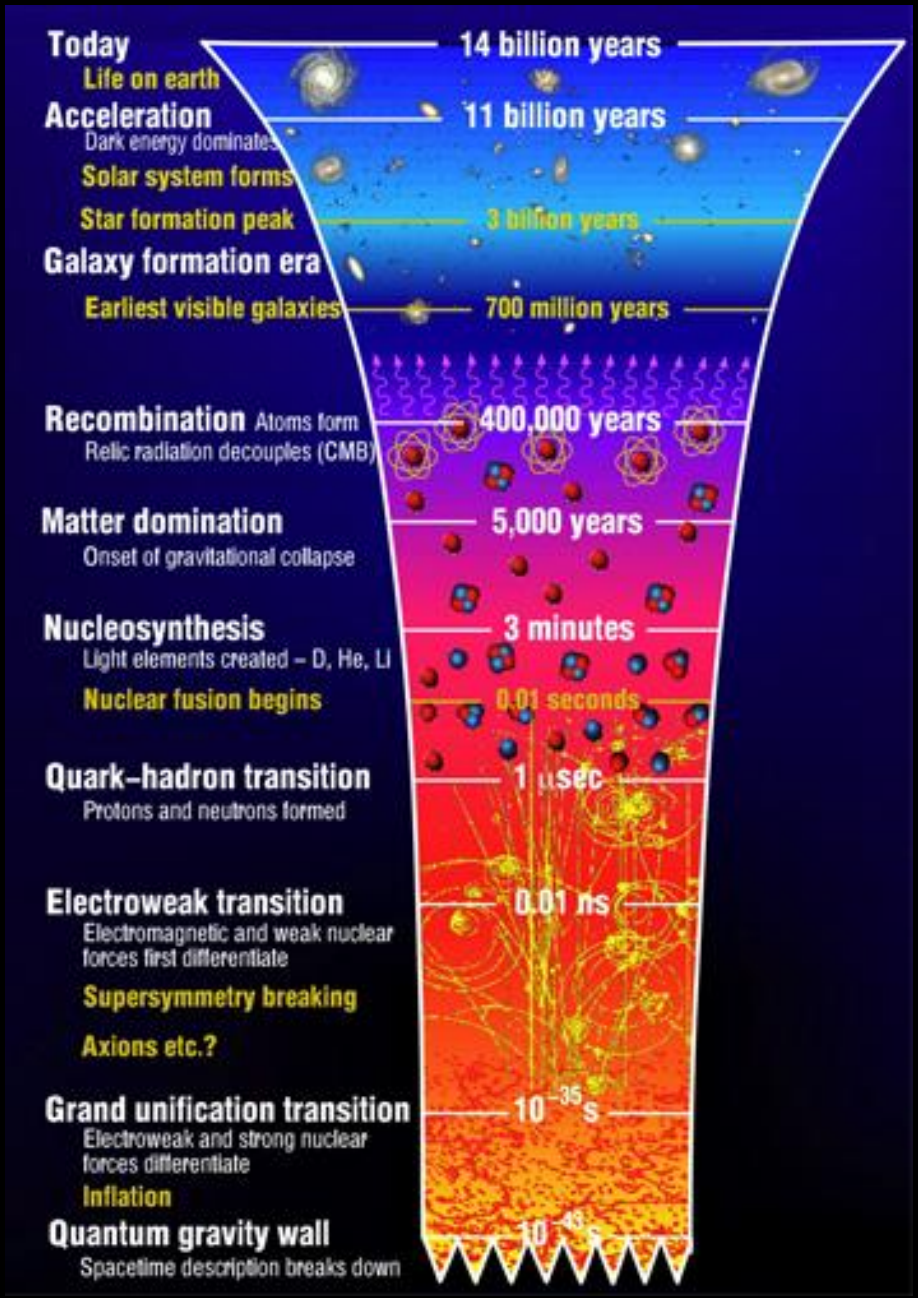
- The four Pillars of the Standard Cosmology
  - Expansion of the Universe
    - Theory of Inflation
    - Geometry and Density of the Universe
  - Cosmic Microwave Background (CMB)

Cosmological Chronology:

- Standard Cosmology
  - Spanning the time about 1/100 of a second after the Big Bang through to the present day

- Particle Cosmology
  - Builds a picture of the Universe prior to the standard Cosmology
  - 10^-12 seconds after the Big Bang

- Quantum Cosmology
  - Considers questions about the origin of the Universe itself
  - From the beginning of the Universe to 10^-43 seconds after its beginning (Planck-era)
  - The temperature of the Universe at the Planck-time was 1.4*10^32 K (Planck-temperature)



http://www.ctc.cam.ac.uk/outreach/origins/big_bang_three.php

The four Pillars of the Standard Cosmology:

- Expansion of the Universe
- Origin of the Cosmic Microwave Background (CMB)
- Nucleosynthesis of the light elements
- Formation of galaxies and large-scale structure

Expansion of the Universe:

- The Universe began about 13.8 billion years ago in an explosion (Big Bang)
- The Universe expanded exponentially at the beginning (Theory of Inflation)
- The Universe is still expanding (accelerated expansion)
- Galaxies are escaping from us in all directions in consequence of this initial explosion

$$v = H*d$$

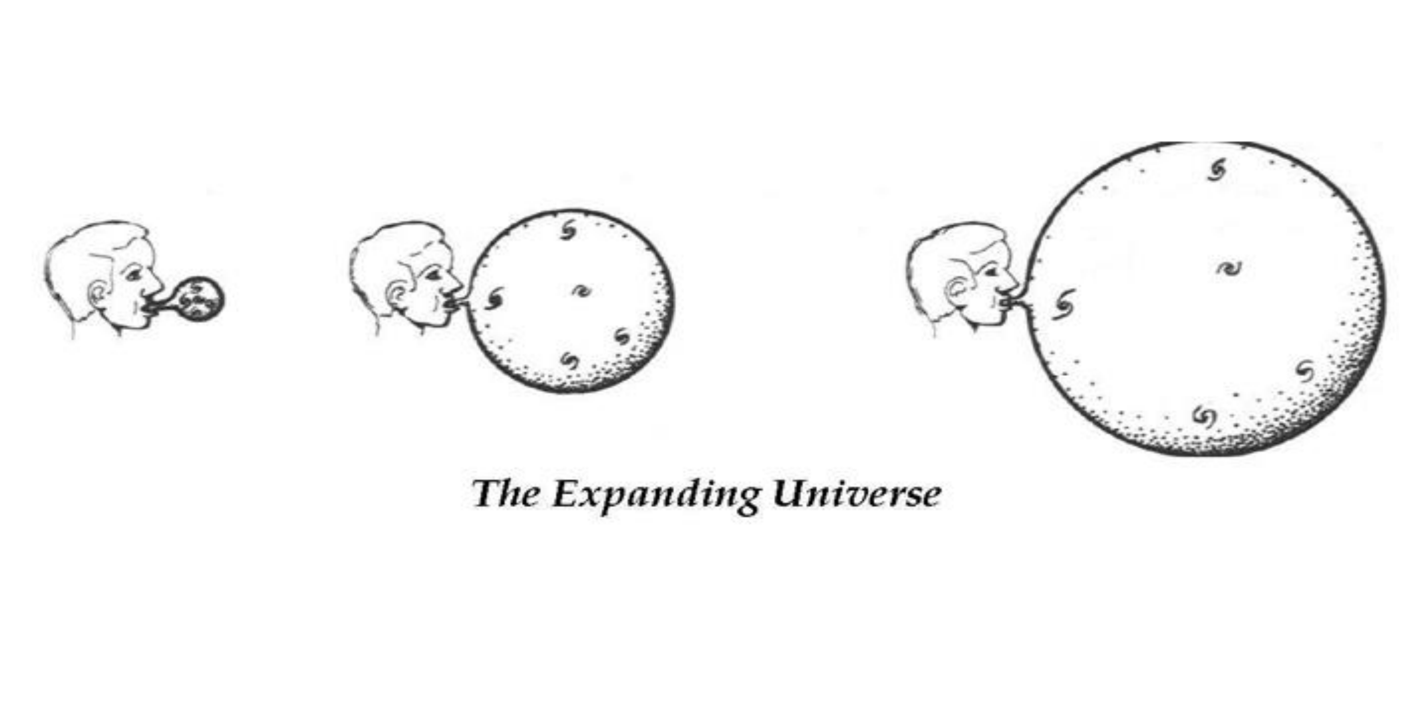
H: Hubble's constant

v: Escape Velocity

d: Distance

The analogy of an expanding balloon:

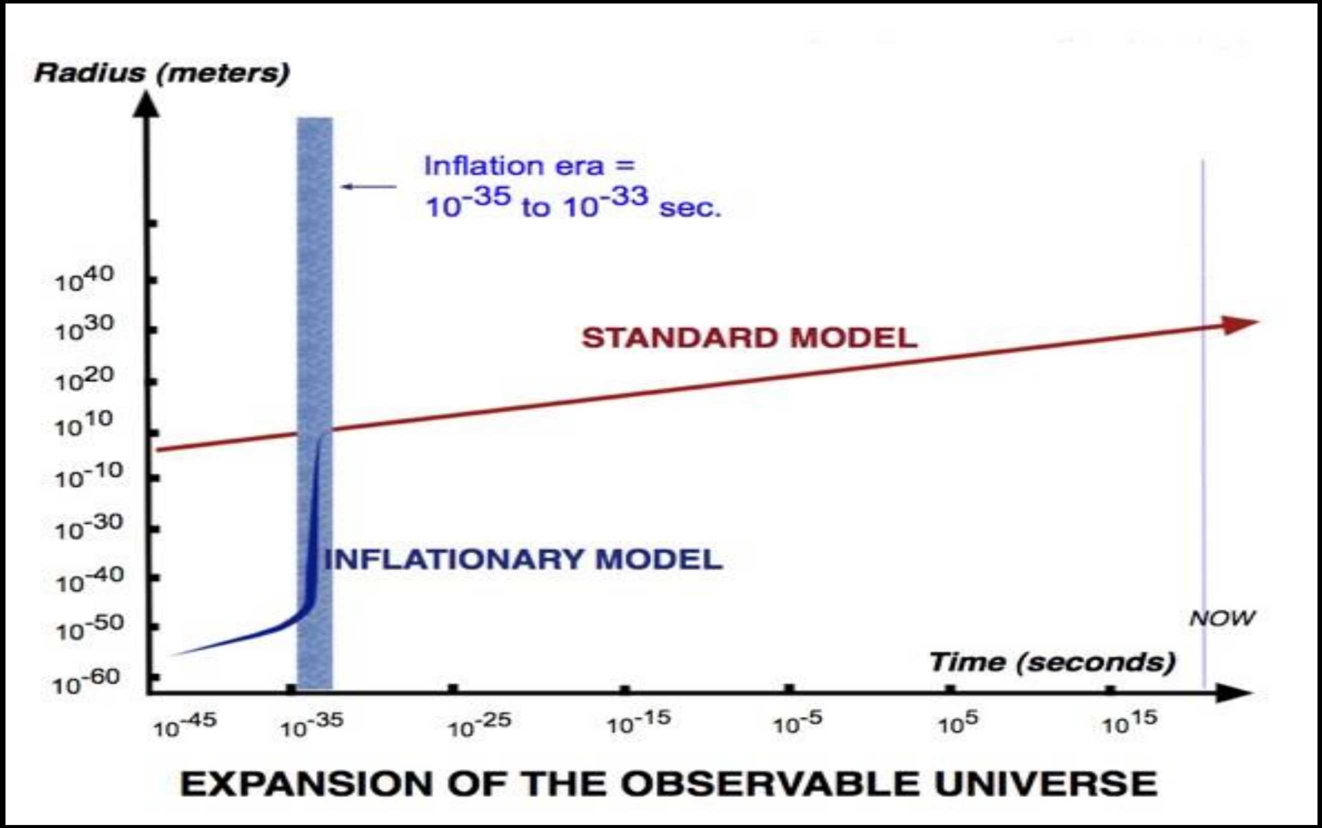
- As the balloon is inflated, the distance between all neighboring points grows
- The Universe grows but there is no preferred Centre
  - The Copernican or cosmological principle
    - The Universe appears the same in every direction from every point in space
    - The best evidence for this uniformity comes from the CMB



http://www.ctc.cam.ac.uk/outreach/origins/inflation_zero.php

The inflationary Universe:

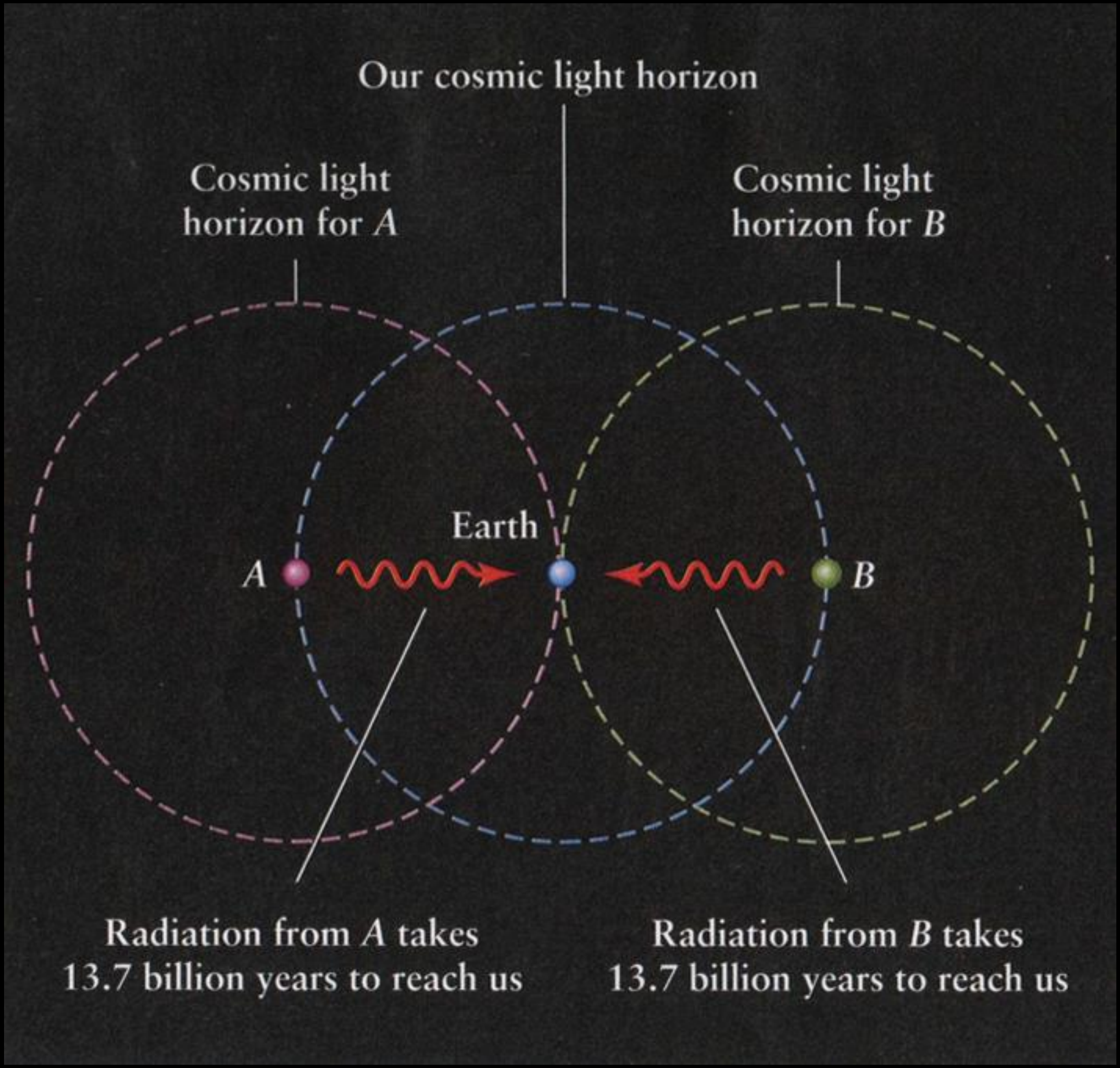
- The early Universe expanded exponentially fast for a fraction of a second
  - The Universe expanded faster than the speed of light
  - It expanded by a factor of 10^26 in only a small fraction of a second
- This Theory solved several important problems in cosmology
  - The horizon problem
    - Why is the CMB black-body-radiation?
    - Why is the Universe in thermal balance?
  - The flatness problem



http://www.physicsoftheuniverse.com/topics_bigbang_inflation.html

The Horizon Problem:

- Are these 2 Photons causally disconnected?
- We observe that photons from opposite directions must have communicated somehow
  - Because of the uniformity of the CMB
- This problem can be solved by the idea that the Universe expanded faster than the speed of light
- Causal connection before this period of inflation



http://www.ctc.cam.ac.uk/outreach/origins/inflation_zero.php

Why is the expansion of the Universe accelerated:

– It is expected that due to gravity's influence, bringing matter together, would slow down the acceleration of the expansion of the Universe

– Whatever is responsible for this acceleration is not normal matter

  – This Unknown physical phenomenon is known as Dark Energy

– There has to be a lot of Dark Energy to completely explain the acceleration

– 4.9% Luminous Matter: $\Omega_B = 0.049$

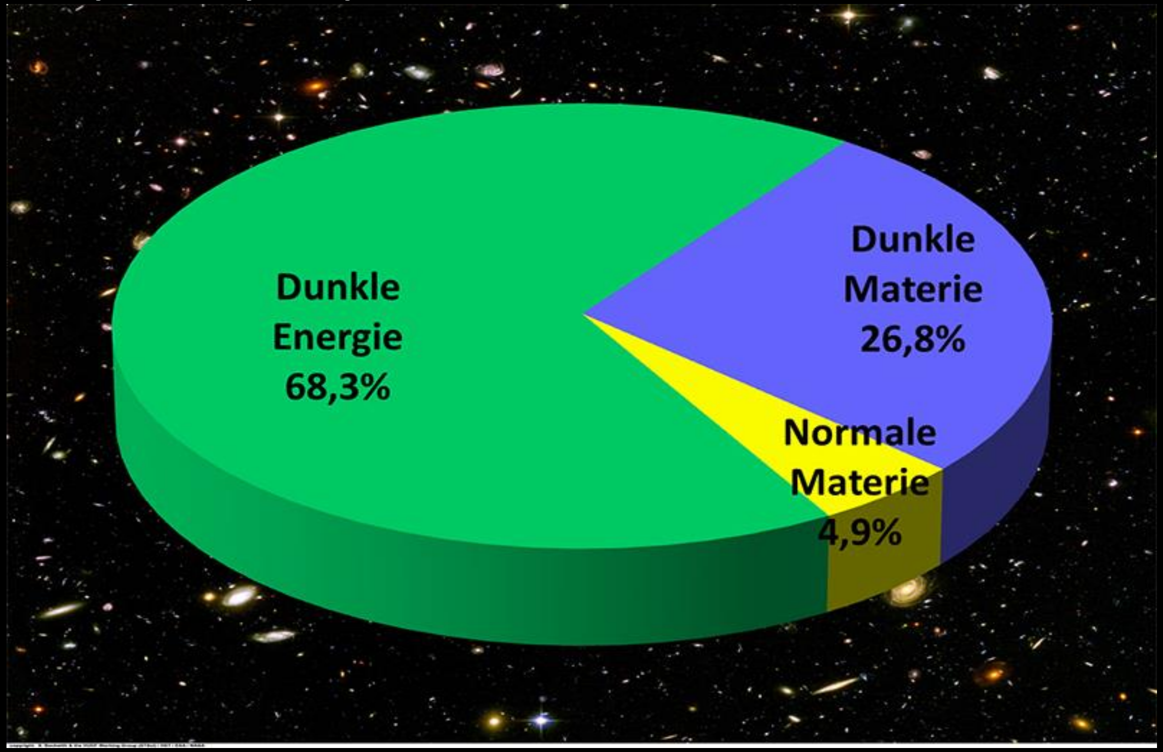
– 26.8% Dark Matter: $\Omega_{DM} = 0.268$

– 68.3% Dark Energy: $\Omega_V = 0.683$

– The Universe is flat on large scales:

  – $\Omega = \Omega_B + \Omega_{DM} + \Omega_V = 1.00$

    – Ω: Energy content



https://www.mpg.de/7696088/MPIK_JB_2014?c=8236817

Dark Energy:

- Dark Energy non-rarefiable
- It works against gravity (repelling force)
- Does Dark Energy has a negative pressure?
  - The second Friedmann-equation

$$\frac{\ddot{a}}{a} = -\frac{4*\pi*G}{3} * (\frac{3*P}{c^2} + \rho)$$

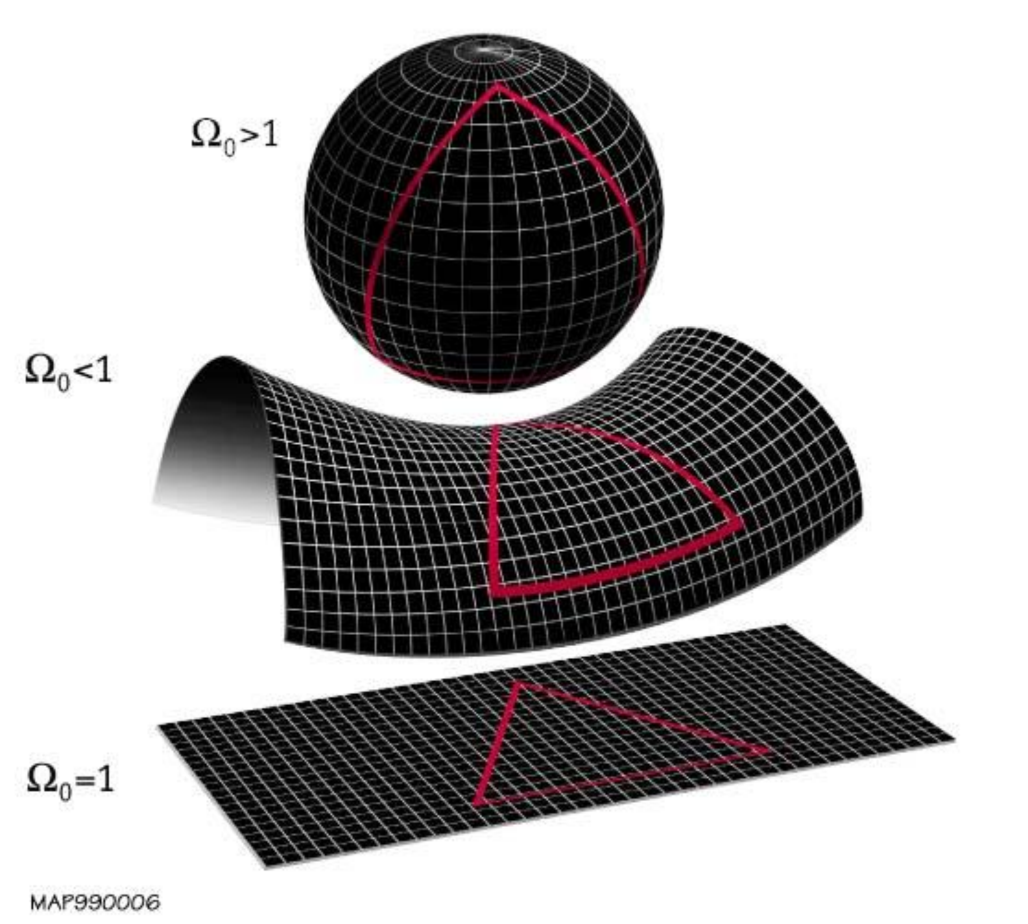
  - Einstein’s modification

$$\frac{\ddot{a}}{a} = -\frac{4*\pi*G}{3} * (\frac{3*P}{c^2} + \rho) + \frac{\Lambda}{3}$$

- a: scale factor; H = $\dot{a}/_{a}$; in [m]
- G: gravitational constant
- P: Pressure
- c: Speed of light
- ρ: Density
- Λ: Cosmological Constant

Geometry and Density of the Universe:

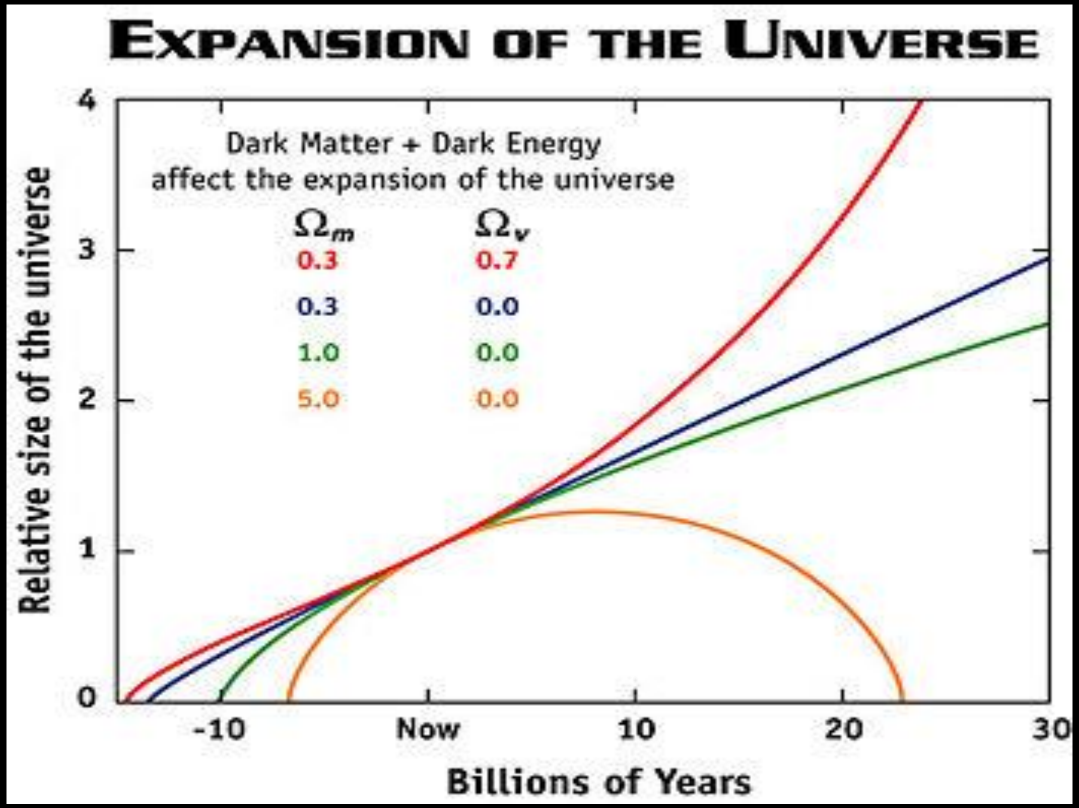
- Gravity is understood in terms of geometry rather than as just another ordinary force
- Matter tells spacetime how to curve and the resulting spacetime curvature tells bodies how to move
- Spherical geometry
  - A Universe of supercritical density ($\Omega > 1$)
  - Positive curvature (closed Universe)
  - The expansion will stop and turn into a contraction at some point
- Hyperbolic geometry
  - A Universe of subcritical density ($\Omega < 1$)
  - Negative curvature (open Universe)
  - The Universe will expand forever
- Euclidean geometry
  - A Universe of critical density (Ω=1)
  - Zero curvature (Flat)
  - The expansion will stop after an infinite amount of time



http://lexikon.astronomie.info/kosmos/hintergrundstrahlung/vermessung.html

Our Universe:

- The geometry of our Universe is flat (critical density)
- The WMAP spacecraft measured the basic parameters of the Big Bang Theory
  - WMAP confirmed that the Universe is flat with only 0.4% margin of error
- There is strong evidence that our Universe is following the red curve
- A large fraction of the matter, the Dark Energy causes the expansion of the Universe to speed up (accelerate)



http://map.gsfc.nasa.gov/universe/uni_fate.html

Cosmic Microwave Background (CMB):

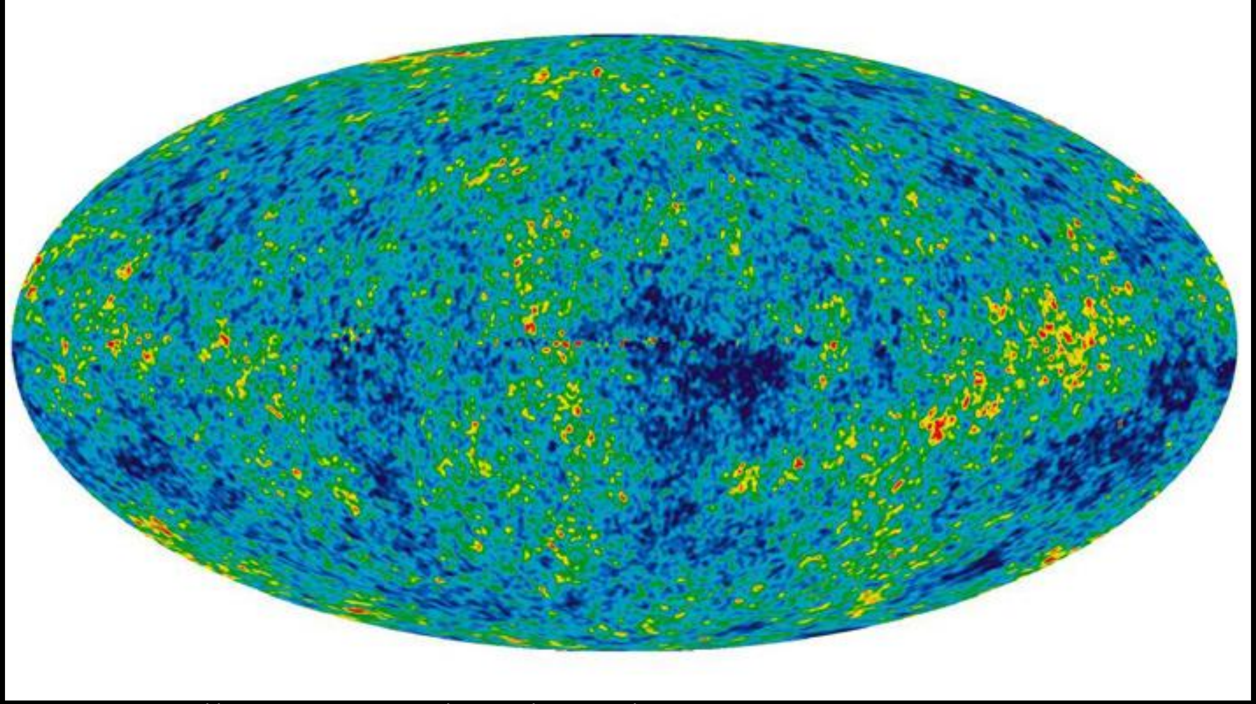
- The CMB has its origin between t=10^-43sec and t=10^-33 sec
  - Almost the same amount of matter and anti-matter particles came into existence (but there was a small anti-symmetry)
  - They annihilated each other to radiation

- Up to 380’000 years after the Big Bang
  - Protons, electrons, Helium-cores and photons constituted a hot, dense plasma (free movable electrons)
  - Photons were scattered by collisions with charged particles and “trapped” by that matter
  - The Universe was non-transparent
  - Temperature was above 3000 K

- After 380’000 years after the Big Bang
  - The Universe expanded and cooled down (3000 K and less)
  - Electrons and protons came together to form neutral atoms
  - The Universe became transparent
  - Photons spread unimpeded

Cosmic Microwave Background (CMB):

- The radiation we observe is over 13 billion years old
  - It illustrates the Universe as it was 380’000 years old
- Scanned CMB signals look almost identical in every direction
  - Homogeneity and isotropy of the CMB at large scales supports the theory of inflation
- Shifting pattern of temperature fluctuations in magnitude of micro kelvin resulted by any disturbance in the early Universe
  - Compressions heated the plasma
  - Rarefactions cooled the plasma
  - Temperature variations allow us to estimate the age, composition and geometry of the Universe



http://map.gsfc.nasa.gov/media/080997/080997_5yrFullSky_WMAP_2048W.png

Resources:

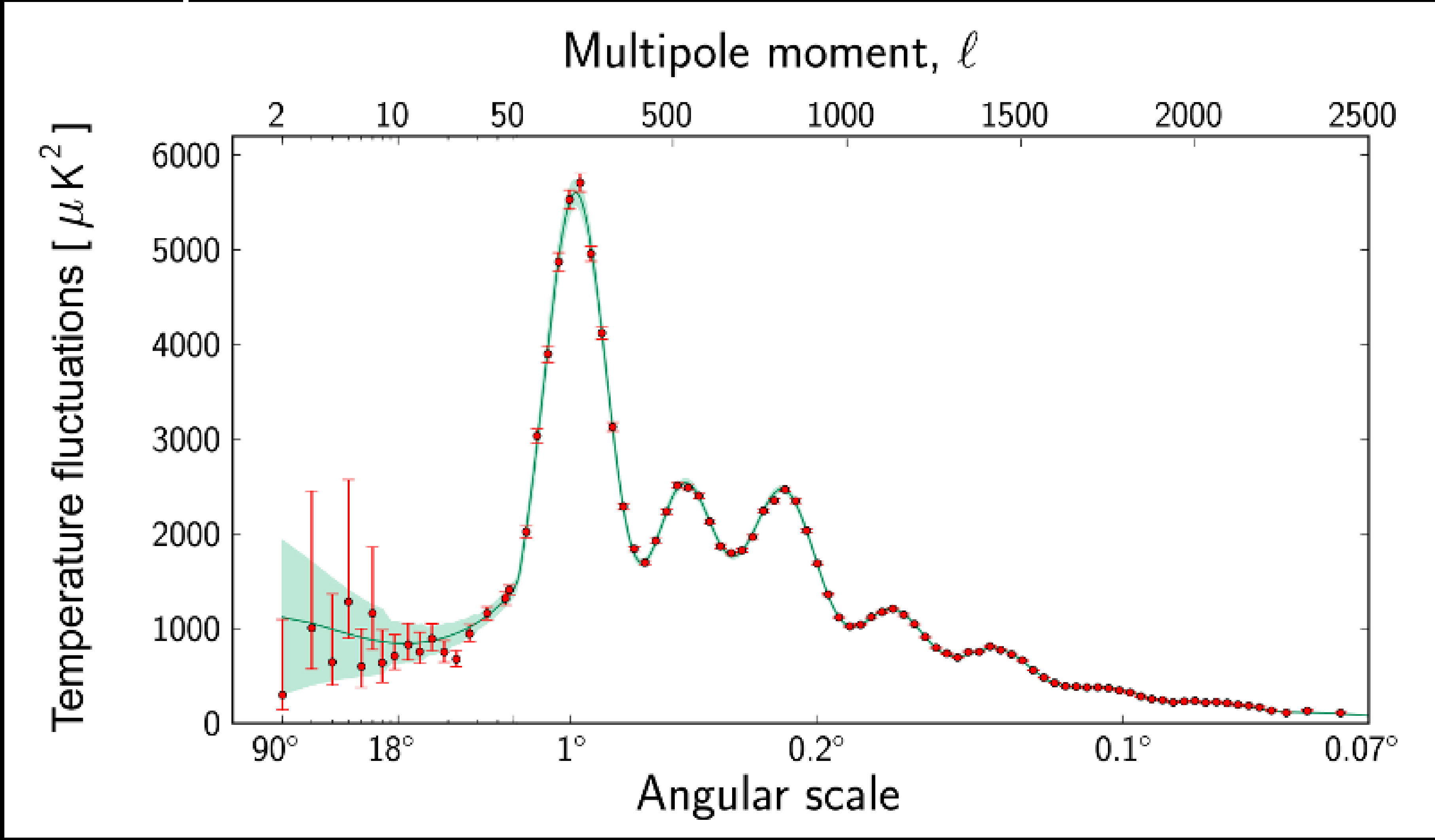
- http://map.gsfc.nasa.gov/universe/
- http://www.ctc.cam.ac.uk/outreach/origins/big_bang_one.php
- http://background.uchicago.edu/~whu/SciAm/sym1.html
- https://en.wikipedia.org/wiki/Lambda-CDM_model
- http://www.weltderphysik.de/gebiet/astro/kosmische-strahlung/planck-und-die-mikrowe/
- https://physics.aps.org/articles/v7/64
- http://background.uchicago.edu/~whu/physics/physics.html
- https://en.wikipedia.org/wiki/Inflation_%28cosmology%29
- http://csep10.phys.utk.edu/astr162/lect/cosmology/inflation.html
- http://www.space.com/25075-cosmic-inflation-universe-expansion-big-bang-infographic.html

Back-up Slides

Shortcomings of the Standard Cosmology:

- The flatness problem
  - Solved by the theory of inflation
- The horizon problem
  - Solved by the theory of inflation
- The density fluctuation problem
- The dark matter problem
- The exotic relics problem
- The thermal state problem
- The cosmological constant problem
- The singularity problem

Power spectrum of the CMB:



http://sci.esa.int/planck/51555-planck-power-spectrum-of-temperature-fluctuations-in-the-cosmic-microwave-background/