Past, Present and Future of the Expanding Universe

Peter Hertel University of Osnabrück, Germany

Talk presented at TEDA College on the occasion of its Tenth Anniversary

October 17, 2010

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Motto



Make things as simple as possible, but not simpler!

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Introduction



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Matter, Star	Normal matter
Univers	Stars
Cosmolog	Distances
Underway	Spectra
Normal matter	

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Matter, Stars	Normal matter
Universe	Stars
Cosmology	Distances
Underway	Spectra
Normal matter	

- $\bullet\,$ Consists of protons (p), neutrons (n), and electrons (e).
- There are also the massless neutrino ($\nu)$ and photon ($\gamma)$

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- They form nuclei, atoms, molecules...

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- They form nuclei, atoms, molecules...
- and gases, liquids, solids...

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- planets, stars, galaxies and clusters of galaxies

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Nuclear fusion	

• Nuclear fusion, e. g. $(pn)+(pn) \rightarrow (ppnn)$

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- Many more nuclear fusion reactions

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	Matter, Stars Universe Cosmology Underway	Normal matter Stars Distances Spectra	
Stars			

• Because of universal gravitation, mass tends to accumulate

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	Matter, Stars Universe Cosmology Underway	Normal matter Stars Distances Spectra	
Stars			

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- The mass of a white dwarf cannot exceed 1.44 M_{\odot} (Nobel prize Chandrasekhar 1930).

Normal matter Stars Distances Spectra

Distances

earth – sun	8 Lmin
next fixed star	4 Ly
to center of galaxy	25 kLy
M31 (Andromeda galaxy)	2.2 MLy
la-Supernova 1994D	50 MLy
AM 0644-741 (ring galaxy)	300 MLy
Hubble Deep Field Survey	several GLy
Abell 1835	pprox 13 GLy

Normal matter Stars Distances Spectra

M83



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M83, diameter 60 thousand light years

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Normal matter Stars Distances Spectra

Andromeda nebula



2.2 million light years

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 Matter, Stars
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la Supernova

• Burnt out medium-sized stars end up as white dwarfs. In only a few weeks more energy is produced than before in ten billion years, the lifetime of an ordinary star.

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Normal matter Stars **Distances** Spectra

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Normal matter Stars **Distances** Spectra

la Supernova

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- The mass of a white star may increase at the cost of a neighboring star.
- When surpassing 1.44 M_{\odot} there will be a la supernova with allways the same time profile and absolute brightness (standard candle).
- If absolute and apparent brightness are known, the distance of the la supernova can be worked out.

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Normal matter Stars Distances Spectra

IaSN 1994D



60 million light years away

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Normal matter Stars **Distances** Spectra

Ring galaxy



300 million light years away

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Normal matter Stars **Distances** Spectra

Hubble Deep Field Survey



10 days light collection, more than one billion light years deep.

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Normal matter Stars **Distances** Spectra

Abell 1835



Abell 1835 IR1916 - the Farthest Galaxy - Seen in the Near-Infrared (VLT ANTU + ISAAC)



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ESO PR Photo 05a/04 (1 March 2004)

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approximately 13 billion light years

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redshift
$$z = \frac{\lambda' - \lambda}{\lambda}$$

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	Matter, Stars Universe Cosmology Underway	Hubble's law Abundance of light elements Background radiation Summary	
Hubble's law			

• Observation: red shift increases with decreasing brightness of la Supernovae (distance)

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Hubble's law Abundance of light elements Background radiation Summary

Hubble's law

- Observation: red shift increases with decreasing brightness of la Supernovae (distance)
- Premature explanation: Doppler effect, explosion

Matter, Stars	Hubble's law
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$$z = \sqrt{\frac{c+v}{c-v}} - 1 \approx \frac{v}{c} \propto d$$

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• Today's explanation: space is expanding. The older the light, the more its photons have been stretched meanwhile.

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$$z = \sqrt{\frac{c+v}{c-v}} - 1 \approx \frac{v}{c} \propto d$$

- Today's explanation: space is expanding. The older the light, the more its photons have been stretched meanwhile.
- Unavoidable conclusion: Big Bang

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Hubble's law Abundance of light elements Background radiation Summary

Synthesis in an early stage of the universe



Synthesis in the early universe

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Hubble's law Abundance of light elements Background radiation Summary

Microwave background radiation



Wilkinson Microwave Asymmetry Probe (WMAP), NASA, 2003

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Hubble's law Abundance of light elements Background radiation Summary

WMAP sattelite



Orbits the sun in sync with earth, four times moon distance

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Hubble's law Abundance of light elements Background radiation Summary

Four important facts

• Big Bang¹.

¹In the beginning God created heaven and earth. First sentence of the Jewish bible

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Hubble's law Abundance of light elements Background radiation Summary

Four important facts

- Big Bang¹.
- The universe, on a big scale, is isotropic and expands more and more.

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Matter, Stars Hubble's law Universe Abundance of Cosmology Background Underway Summary

Hubble's law Abundance of light elements Background radiation Summary

Four important facts

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- Also the cosmic background radiation (afterglow) is isotropic.

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Hubble's law Abundance of light elements Background radiation Summary

Four important facts

- Big Bang¹.
- The universe, on a big scale, is isotropic and expands more and more.
- Also the cosmic background radiation (afterglow) is isotropic.
- Abundance of elements indicates extreme temperature of the early universe.

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Principles General relativity Standard model

Basic principles of a cosmological theory

• The Universe is a physical system.

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Principles General relativity Standard model

Basic principles of a cosmological theory

- The Universe is a physical system.
- Einstein's theory of gravitation (General Relativity)

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Principles General relativity Standard model

Basic principles of a cosmological theory

- The Universe is a physical system.
- Einstein's theory of gravitation (General Relativity)
- Cosmological principle: all locations and all directions are equivalent.

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Principles General relativity Standard model

Space, time and matter

• Space-time metric $ds^2 = g_{ik}(x)dx^i dx^k$

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Principles General relativity Standard model

Space, time and matter

- Space-time metric $ds^2 = g_{ik}(x)dx^i dx^k$
- Metric determines curvature tensor R_{ik}(x) and curvature scalar R(x)

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Principles General relativity Standard model

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- $T_{ik}(x)$ is energy-momentum tensor

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$$R_{ik} - \frac{1}{2}g_{ik}R = \frac{8\pi G}{c^4}T_{ik} + \Lambda g_{ik}$$

Principles General relativity Standard model

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• Mass and radiation propagates along geodesic lines...

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- Mass and radiation propagates along geodesic lines...
- which are defined by the metric (see above)

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Principles General relativity Standard model

Can you still follow me?



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Principles General relativity Standard model

Einstein is right!

• Light deflection by the sun (1919)

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Principles General relativity Standard model

Einstein is right!

- Light deflection by the sun (1919)
- Advance of perihelion of innermost planet Mercury

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Principles General relativity Standard model

Einstein is right!

- Light deflection by the sun (1919)
- Advance of perihelion of innermost planet Mercury
- GPS

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Principles General relativity Standard model

Einstein is right!

- Light deflection by the sun (1919)
- Advance of perihelion of innermost planet Mercury
- GPS
- Neutron double stars

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Principles General relativity Standard model

Einstein is right!

- Light deflection by the sun (1919)
- Advance of perihelion of innermost planet Mercury
- GPS
- Neutron double stars
- Gravitational lens

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Gravitational lens



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Black hole in the center of our Galaxy





Orbit in 15 years, closest distance 17 light hours, more than four million sun masses

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Principles General relativity Standard model

Cosmological standard model

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$$ds^2 = c^2 dt^2 - \alpha(t)^2 \{ \frac{dr^2}{1 - kr^2} + r^2 d\Omega^2 \}$$

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(a)

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- mass density ρ and pressure p (equation of state) must be known

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Today's status (**A**DCM)

• $\rho/\rho_{kr} = 1.02 \pm 0.02$. Cosmos is flat (k=0).

Principles General relativity Standard model

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- Radiation decoupled from matter after 380 thousand years.

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Principles General relativity Standard model

History

Big Bang	13.7 GY
solar system	4.6 GY
first protozoae	3.5 GY
vertebrates	500 MY
flowering plants	100 MY
mammals	50 MY
Homo habilis	2 MY
Homo sapiens	200 kY
early civilizations	5 kY

	Matter, Stars Universe Cosmology Underway	SDSS Planck Theory
SDSS		

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	Matter, Stars Universe Cosmology Underway	SDSS Planck Theory	
SDSS			

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Planck	

• Successor of WMAP, 1800 kg

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	Matter, Stars Universe Cosmology Underway	SDSS Planck Theory	
Planck			

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	Matter, Stars Universe Cosmology Underway	SDSS Planck Theory	
Planck			

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- Ariane rocket, start 2008

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	Matter, Stars Universe Cosmology Underway	SDSS Planck Theory	
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- Ariane rocket, start 2008
- much better angular resolution

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Planck	

- Successor of WMAP, 1800 kg
- European Space Agency ESA
- Ariane rocket, start 2008
- much better angular resolution
- however: enormous amount of data

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Universe	SD: Die
Cosmology	
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WMAP detail



Temperature fluctuations - detail of the WMAP map

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Underway	The

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Planck detail



Temperature fluctuations - as Planck will see it

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Dark energy?			

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$$\left| R_{ik} - \frac{1}{2} g_{ik} R = \frac{8\pi G}{c^4} T_{ik} + \Lambda g_{ik} \right|$$

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- causes 73% of the expansion of the universe!
- Virtual particle/antiparticle pairs? Vacuum zero point energy?
- ... or even more exotic quantum effects?

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Planck Theory



The most incomprehensible thing about the world is that it is at all comprehensible.

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