The **Helmholtz – DIAS** International School **"Cosmology, Strings, New Physics"**.

The lectures will be supplemented by evening discussion sessions.

Particle physics, NEW PHYSICS @ LHC, Dark Matter search:

Dmitry Kazakov, Eduard Boos, Oleg Teryaev, Dmitri Gorbunov, Sergei Demidov

SUSY, SUGRA, SuperStrings:

Wilfried Buchmueller, Timm Wrase, Edvard Musaev,
Sergey Fedoruk, Vyacheslav Spiridonov,

Classical & Quantum Gravity:

Dmitry Gal'tsov, Dmitry Fursaev, Viacheslav Mukhanov, ATF

Classical & Quantum Cosmology. Inflation:

Alexey Starobinsky, V. Mukhanov, Valery Rubakov, D. Gorbunov, T. Wrase, ATF

Quantum gravity and Cosmological inflation deserve a preliminary short discussion

COSMOS (as seen by a 6-year-old-boy)

4-2000 BC. **First astronomical observations** in Egypt, Central America, England (Stonehenge)
IV cent BC. Greeks *Eudoxus, Aristotle*: an earth-centered universe.
260 BC. Greek *Aristarchus of Samos* (c. 315–230 BC) proposes a sun-centered universe.
c. 150 AD. Greek-Egyptian Ptolemy (2nd century AD) developed an earth-centered universe.

1543. *Copernicus* publishes his sun-centered theory of the universe (solar system).
1576. English mathematician *Thomas Digges* (c. 1546–1595) proposes that **Universe is infinite** because the **stars are at varying distances**
1576-1597. *Tycho de Brahe's* most complete observations of stars positions.
1584. Italian philosopher Giordano Bruno (1548–1600) states that the **Universe is infinite**.

1609-1610. *Galileo*'s observations with his `telescope'. Kepler's telescope with 2 lenses.
1632. Galileo champions Copernicus's sun-centered universe, but is forced Inquisition to recant.
1666-1671. Newton constructs the first telescope - reflector…
1687, 1713, 1726 Newton's `Principia'. 1729 edition with added *"The Laws of the Moon's Motion, according to Gravity"* by John Machin
1705. *Edmond Halley* discovers the **proper movements of stars.**
1779-1784. *F. W. Herschel* (astronomer and composer) discovers binary and multiply stars

1845. William Parsons (Lord Ross) discovers **spiral structure** of some nebulae ……….

(Differential geometry: Gauss, Lobachevski; Riemann, Hemholtz; Beltrami, Levi-Civita, Ricci…)

1912-1914. Vesto Slipher determines high velocities of 11 **spiral nebulae fast fleeing away**…

COSMOLOGICAL OBSERATIONS - THEORIES - PREDICTIONS - DISCOVERIES

end XIX – begin. XX: …Maxwell, Hertz, Lorentz, Poincare, Planck, Einstein, …. - new theor. physics…

1915-1916. *Einstein*'s **General Relativity** (GR) (the final equations; the detailed review 20.03.16)

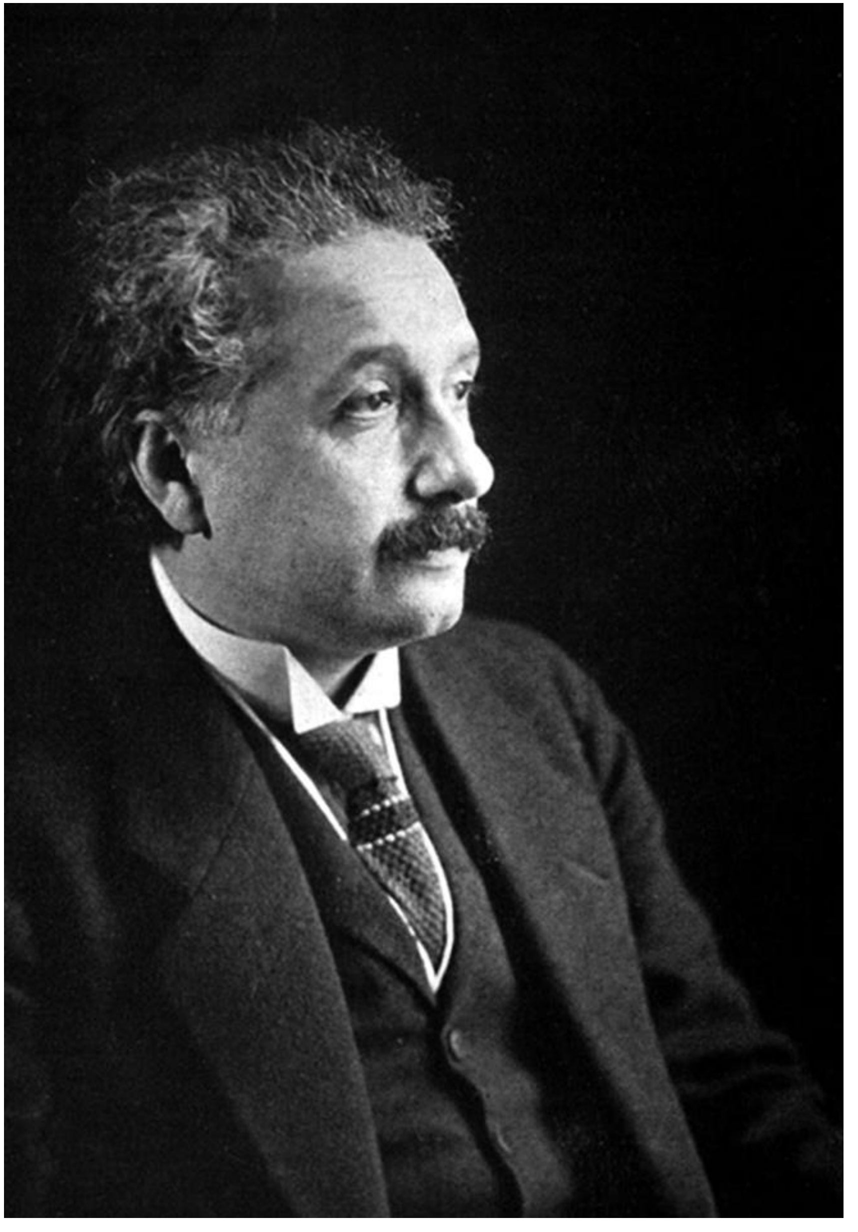
1917. *Einstein* proposes a closed static universe theory (the **first relativistic Cosmology**)
Further predictions: **Gravitational Waves; Black Holes** *(K.Schwarzschild);*
controversial **cosmological constant**

1922. *Alexander A. Friedmann* : the **expanding Universe** solutions of Einstein's equations
1923: *Einstein*: Extension of GR to **affine geometry** with additional vector field (DE and DM ??)
1927… *G. Lemaître* proposes a detailed theory of the **expanding Universe** (using Slipher's and, later, Hubble's data). Earlier, he independently derived the Friedmann solutions (unpublished)
Mathematical work: *H.Weyl, E.Cartan, O.Klein*

1929. *Edwin Hubble* demonstrates *(in fact)* the expansion of the Universe (also with Sl.'s dt.)

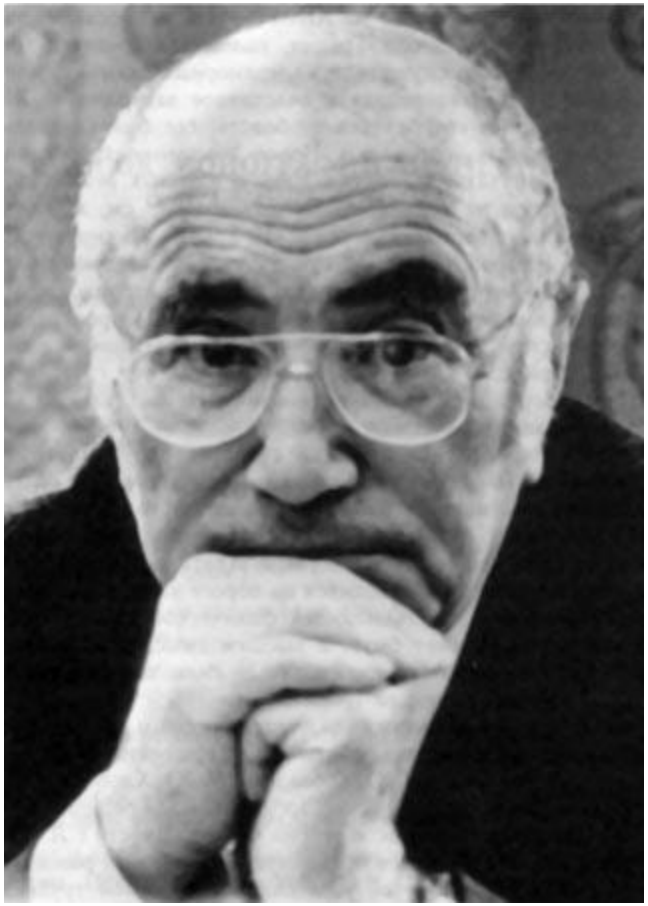
1935 *Einstein-Rosen* **bridge (ER)**, *ER + Boris Podolsky* **paradox (EPR)**
1937. *Einstein* and *Nathan Rosen* derived exact cylindrical **gravitational waves**

1946. *George A. Gamov* **– the Hot Big-Bang theory, prediction of Relic photons at 3 K (CMB).**
1965. *Al. Penzias and Rob. Wilson* – observation of bkg. radiation (*rem.* Dicke e.a.)



Albert Einstein, 14.03.1879 – 18.04.1955

Georgij Antonovich Gamov
4.03.1904 – 20.08.1968



Yakov Borisovich Zel’dovich
8.03.1914 – 2.12.1987

Now certainly discovered:

Background Radiation, homogeneity and isotropy of the Universe (with corrections);

Black Holes, Dark Energy, Dark Matter; the \`Age' and \`Radius' of our Universe.

Well established theoretical models:

Realistic FLRW cosmological models (homogeneous, isotropic, based on GR)

Inflationary Models (GR + scalaron) with possibility to confront them to observations (*small amplitude* GW).

Observed! Nonlinear Gravitational Waves from collision of 2 black holes!

The problem of **baryons** in our Universe (abundance clarified, antibarions problem still-?)

* Beginning of **Inflationary** models and **Quantum Creation of Universe** ideas

A. A. Starobinsky, "A New Type of Isotropic Cosmological Models Without Singularity", Phys.Lett. **B 91** (1980) 99.

V. F. Mukhanov and G. V. Chibisov, "Quantum fluctuations in nonsingular Universe", JETP Lett. **33** (1981) 532.

A. H. Guth, "The inflationary Universe: a possible solution to the horizon and flatness problem", Phys. Rev. **D 23** (1981) 347.

A. D. Linde, "Chaotic inflation", Phys. Lett. **B 129** (1983) 177.

A.D.Linde, A new inflationary Universe scenario: a possible solution of ….1982

Books and reviews on early universe and inflation

A. D. Linde, *Particle physics and inflationary cosmology*, Harwood, Chur, Switzerland (1990); arXiv:hep-th/0503203 (2005).

V. Mukhanov, *Physical foundations of cosmology,* Cambridge Univ. Press, NY, 2005.

D. Gorbunov and V. Rubakov, *Introduction to the theory of the early universe: cosmological perturbations and inflationary theory*, World Sci. Publ. Co., Singapore, 2010.

A. Linde, "Inflationary cosmology after Planck 2013", arXiv:1402.0525 (2014).

J. Martin, "The observational status of cosmic inflation after Planck", arXiv:1502.05733

A.Linde, A brief history of multiverse. 1512.01203

Generalizing Quantum Mechanics for Quantum Spacetime[1]

James B. Hartle gr-qc/0602013

Three features of quantum theory are striking from the present perspective: its success, its rejection by some of our deepest thinkers, and the absence of compelling alternatives.

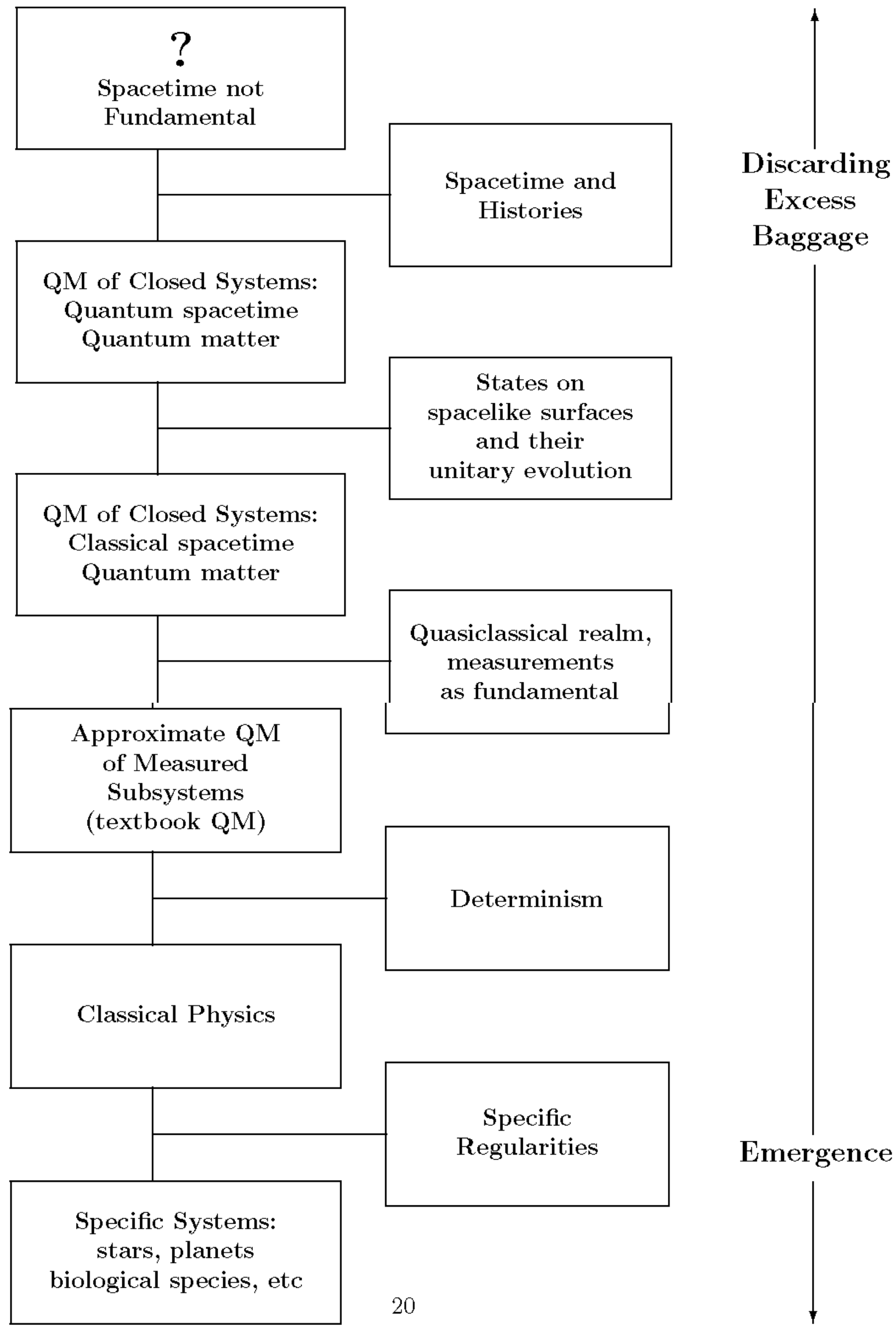
A Short History of Spacetime and Quantum Theory

Newtonian Physics	Fixed 3-d space and a single universal time t.	**Non-relativistic Quantum Theory:** The Schrödinger equation $$i\hbar(\partial\Psi/\partial t) = H\Psi$$ holds between measurements in the Newtonian time t.
Special Relativity	Fixed flat, 4-d spacetime with many diifferent timelike directions.	**Relativistic Quantum Field Theory:** Choose a Lorentz frame with time t. Then (between measurements) $$i\hbar(\partial\Psi/\partial t) = H\Psi\,.$$ The results are unitarily equivalent to those from any other choice of Lorentz frame

General Relativity	Fixed, but curved spacetime geometry	**Quantum Field Theory in Curved Spacetime:** Choose a foliating famliy of spacelike surfaces labeled by t. Then (between measurements) $$i\hbar(\partial\Psi/\partial t) = H\Psi\,.$$ But the results are *not* generally unitarily equivalent to other choices.
Quantum Gravity	Geometry is *not* fixed, but rather a quantum variable	**The Problem of Time:** What replaces the Schrödinger equation when there is no fixed notion of time(s)?
M-theory, Loop quantum gravity, Posets, etc.	Spacetime is not even a fundamental variable	?

The founders of quantum theory thought that the indeterminacy of quantum theory "reflected the unavoidable interference in measurement dictated by the magnitude of the quantum of the action" (Bohr). But what then is the origin of quantum indeterminacy in a closed quantum universe which is never measured? Why enforce the principle of superposition in a framework for prediction of the universe which has but a single quantum state? In short, the endpoint of this journey of generalization forces us to ask John Wheeler's famous question, "How come the quantum?" [60].

Could quantum theory itself be an emergent effective theory? Many have thought so (Section 2). Extending quantum mechanics until it breaks could be one route to finding out. 'Traveler, there are no paths, paths are made by walking.'


?
Spacetime not Fundamental
Spacetime and Histories
QM of Closed Systems: Quantum spacetime Quantum matter
States on spacelike surfaces and their unitary evolution
QM of Closed Systems: Classical spacetime Quantum matter
Quasiclassical realm, measurements as fundamental
Approximate QM of Measured Subsystems (textbook QM)
Determinism
Classical Physics
Specific Regularities
Specific Systems: stars, planets biological species, etc
Discarding Excess Baggage
Emergence

Beginning of quantum cosmology

J.Halliwell, Introductory lectures on quantum cosmology, 1990 (arXiv:0909.2566)
(a thorough review of approaches to quantum cosmology, including work of J.Wheeler, B.De Witt, S.Hawking, J.Hartle, A.Vilenkin, V.Rubakov, etc.).
[see also A.Vilenkin, `Many worlds in one'(2006). @Rus.tr.]
Note the pioneering works of Ya.B. Zeldovich and A.D.Sakharov, not mentioned in the review.

Ideas on relation between entanglement in quantum theory and gravity

Raphael Bousso and Leonard Susskind, The multiverse interpretation of quantum mechanics, 1105.3796 (discussion of decoherence of q-states in modern approach)

Mark van Raamsdonk, Comments on quantum gravity and entanglement, 0907.2939
Building up spacetime with quantum entanglement, 1005.3035 (short essay)

Dmitri Fursaev, Proof of holographic formula for entanglement entropy, hep-th/0606184

Juan Maldacena and L. Susskind, Cool horizons for entangled black hole, 1306.0533

L.Susskind, Copenhagen vs **Everett**, **teleportation**, and **ER=EPR**, 1604.02589, Maldacena and Susskind, *Cool horizons for entangled black holes,* 1306.0533.

General relativity contains solutions in which two distant black holes are connected through the interior via a wormhole, or Einstein-Rosen bridge. These solutions can be interpreted as maximally entangled states of two black holes that form a complex EPR pair. We suggest that similar bridges might be present for more general entangled states.

THANKS!

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Familiar textbook quantum mechanics assumes a fixed background spacetime to define states on spacelike surfaces and their unitary evolution between them. Quantum theory has changed as our conceptions of space and time have evolved. But quantum mechanics needs to be generalized further for quantum gravity where spacetime geometry is fluctuating and without definite value. This paper reviews a fully four-dimensional, sum-over-histories, generalized quantum mechanics of cosmological spacetime geometry. This generalization is constructed within the framework of generalized quantum theory. This is a minimal set of principles for quantum theory abstracted from the modern quantum mechanics of closed systems, most generally the universe. In this generalization, states of fields on spacelike surfaces and their unitary evolution are emergent properties appropriate when spacetime geometry behaves approximately classically. The principles of generalized quantum theory allow for the further generalization that would be necessary were spacetime not fundamental. Emergent spacetime phenomena are discussed in general and illustrated with the example of the classical spacetime geometries with large spacelike surfaces that emerge from the 'no-boundary' wave function of the universe. These must be Lorentzian with one, and only one, time direction. The essay concludes by raising the question of whether quantum mechanics itself is emergent.

The Classical Universes of the No-Boundary Quantum State

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(Dated: March 11, 2008)

Abstract

We analyze the origin of the quasiclassical realm from the no-boundary proposal for the universe's quantum state in a class of minisuperspace models. The models assume homogeneous, isotropic, closed spacetime geometries, a single scalar field moving in a quadratic potential, and a fundamental cosmological constant. The allowed classical histories and their probabilities are calculated to leading semiclassical order. We find that for the most realistic range of parameters analyzed a minimum amount of scalar field is required, if there is any at all, in order for the universe to behave classically at late times. If the classical late time histories are extended back, they may be singular or bounce at a finite radius. The ensemble of classical histories is time symmetric although individual histories are generally not. The no-boundary proposal selects inflationary histories, but the measure on the classical solutions it provides is heavily biased towards small amounts of inflation. However, the probability for a large number of efoldings is enhanced by the volume factor needed to obtain the probability for what we observe in our past light cone, given our present age. Our results emphasize that it is the quantum state of the universe that determines whether or not it exhibits a quasiclassical realm and what histories are possible or probable within that realm.