Key problems in fundamental physics

Title:

Key problems in fundamental physics

Lectures:

(1) Physical time and the beginning Universe   11.11.

- Clocks and the vacuum
- Time coordinates in general relativity and cosmology
  (proper time, conformal time, cosmic time)
- Field transformations and frame invariance:
  Is the age of the Universe 13.8 billion years?
- Physical time for the beginning Universe
- What is the meaning of expanding space and slowing time?

(2) What is quantum gravity?   25.11.

- Fields and symmetries
- General coordinate invariance as a gauge symmetry
- Quantum field theory for metric or vierbein
- The role of metric fluctuations
- Asymptotic safety
- Lattice approaches and string theory
- Can one observe quantum gravity effects?

Key problems in fundamental physics

(3) Origin of wave functions and operators for quantum mechanics 9.12.

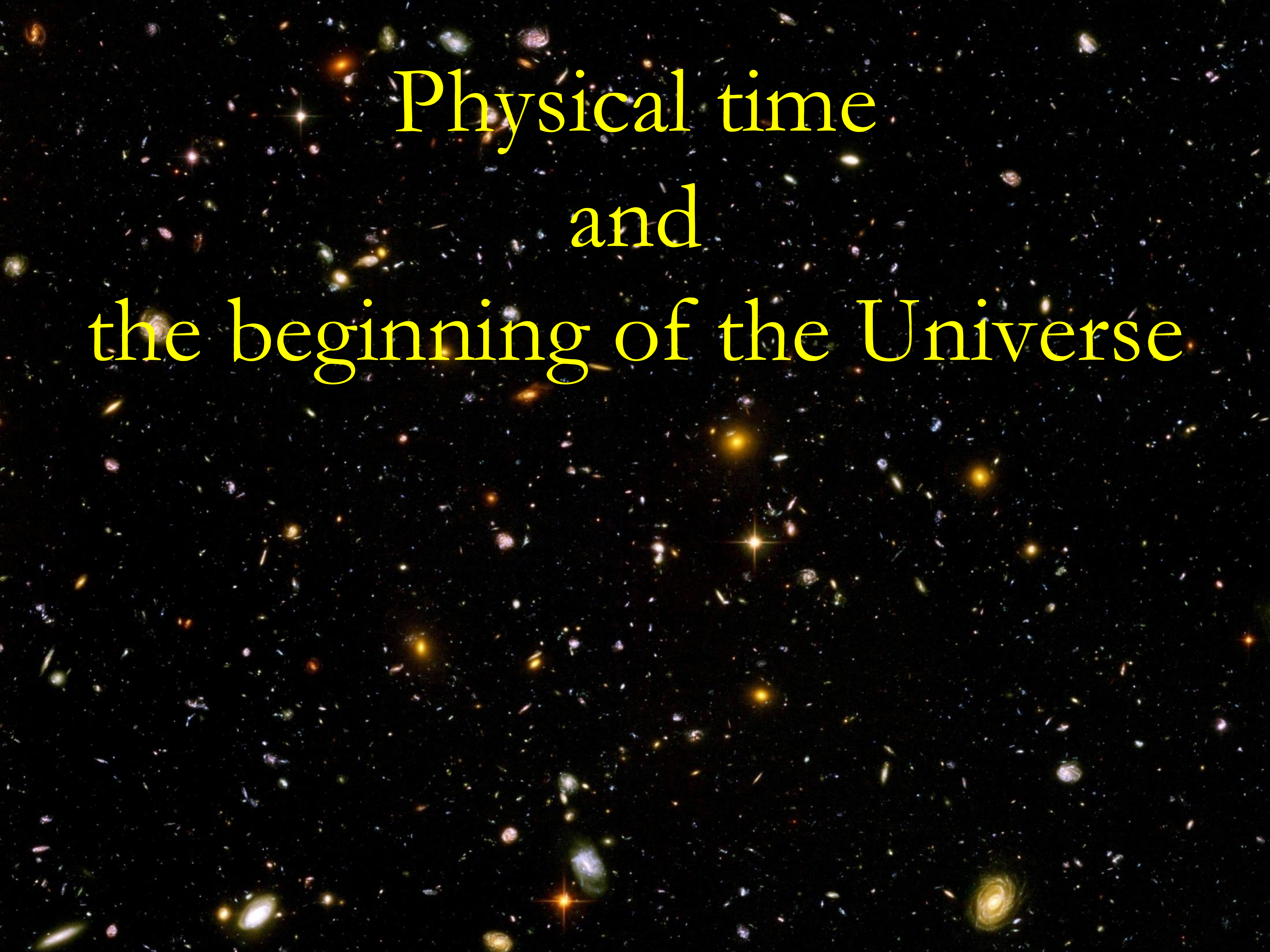
- Evolution in classical probabilistic systems
- Wave functions and time local probabilities in classical statistics
- Transfer matrix and step evolution operator
- The non-commuting structures in classical statistics
- Unitary evolution and quantum mechanics
- Probabilistic cellular automata as simple quantum systems

(4) Quantum field theory from classical probabilities 20.1.

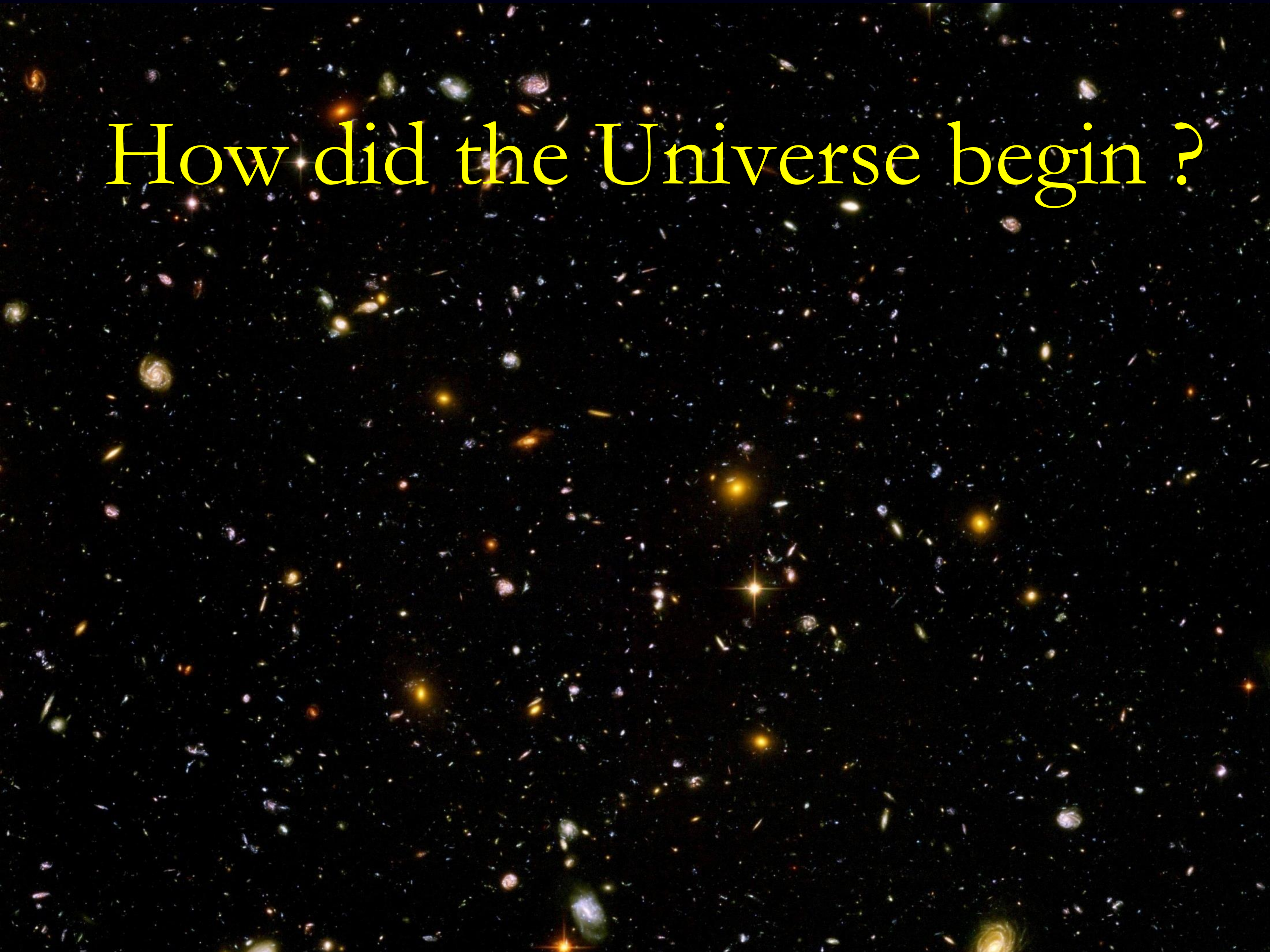
- Functional integral approach to quantum field theory
- Generalized Ising models as "functional integrals“
- Minkowski and euclidean time
- Fermions as Ising spins
- Simple probabilistic cellular automaton for fermionic quantum field theory in one time and one space dimension
- Vacuum, operators and correlation functions

(5) Cosmological constant and dynamical dark energy

Physical time
and
the beginning of the Universe



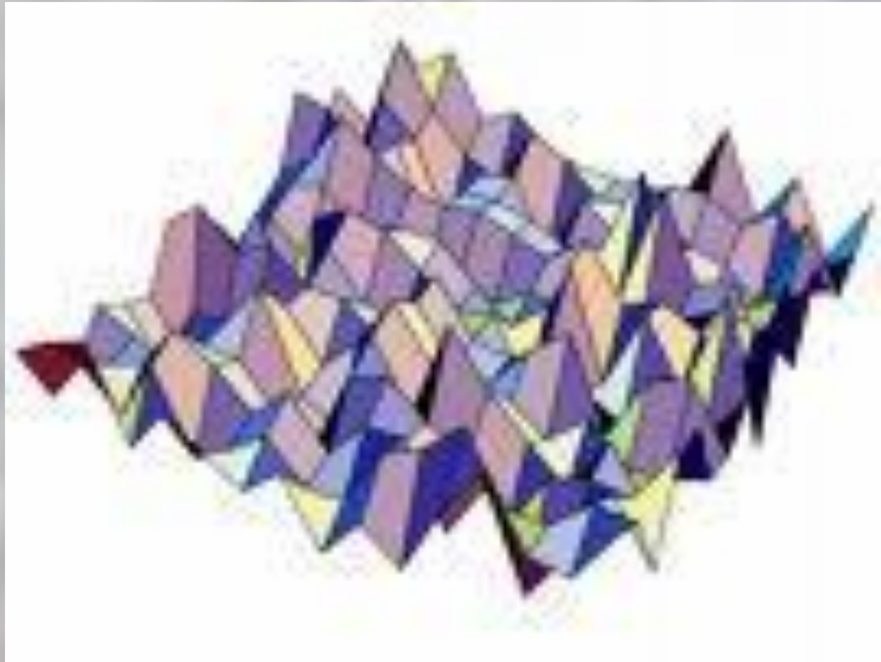
How did the Universe begin ?



Inflationary Universe

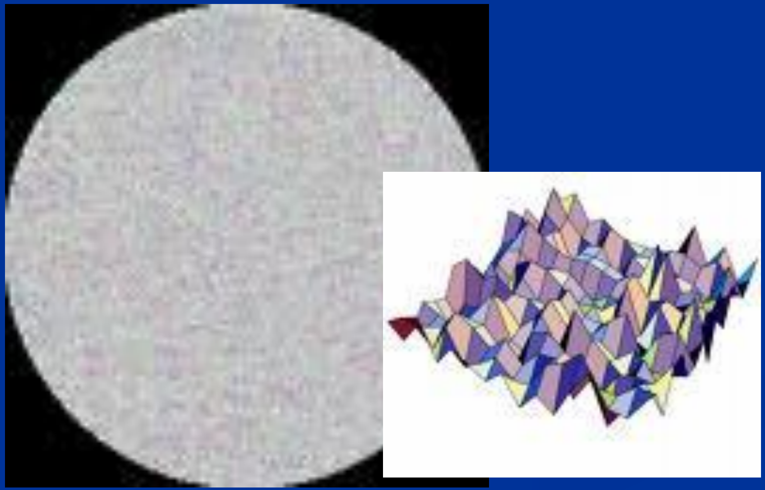
Only fields and their fluctuations

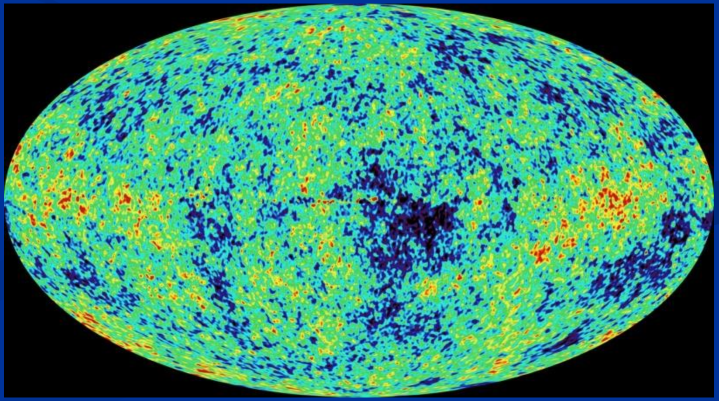
Exponential expansion of space



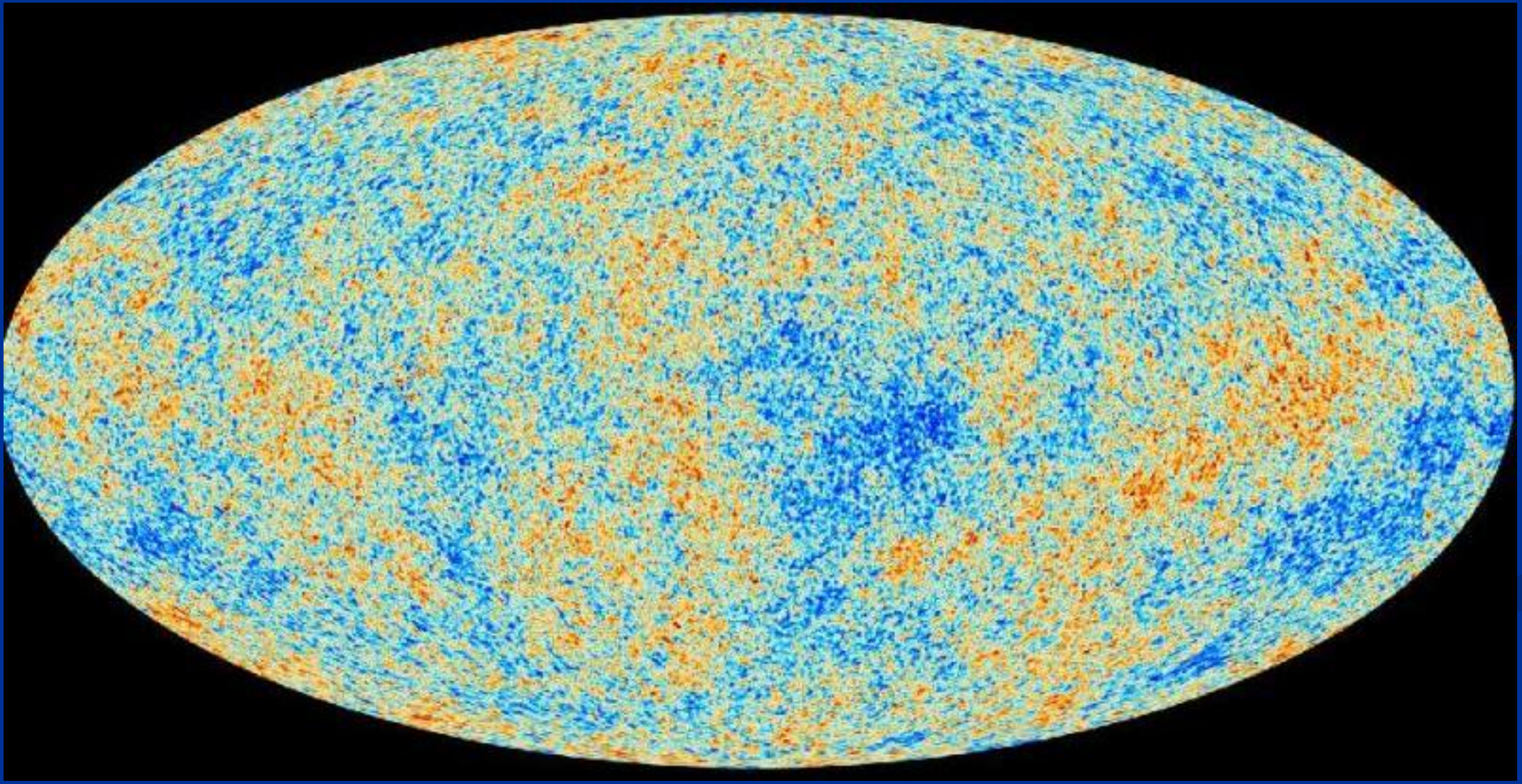
Inflationary Universe

- Singularity
- Exponential expansion lasts ca 10^{-30} - 10^{-40} seconds after singularity
- Has happened 13.8 billion years before our time
- Observations possible : CMB

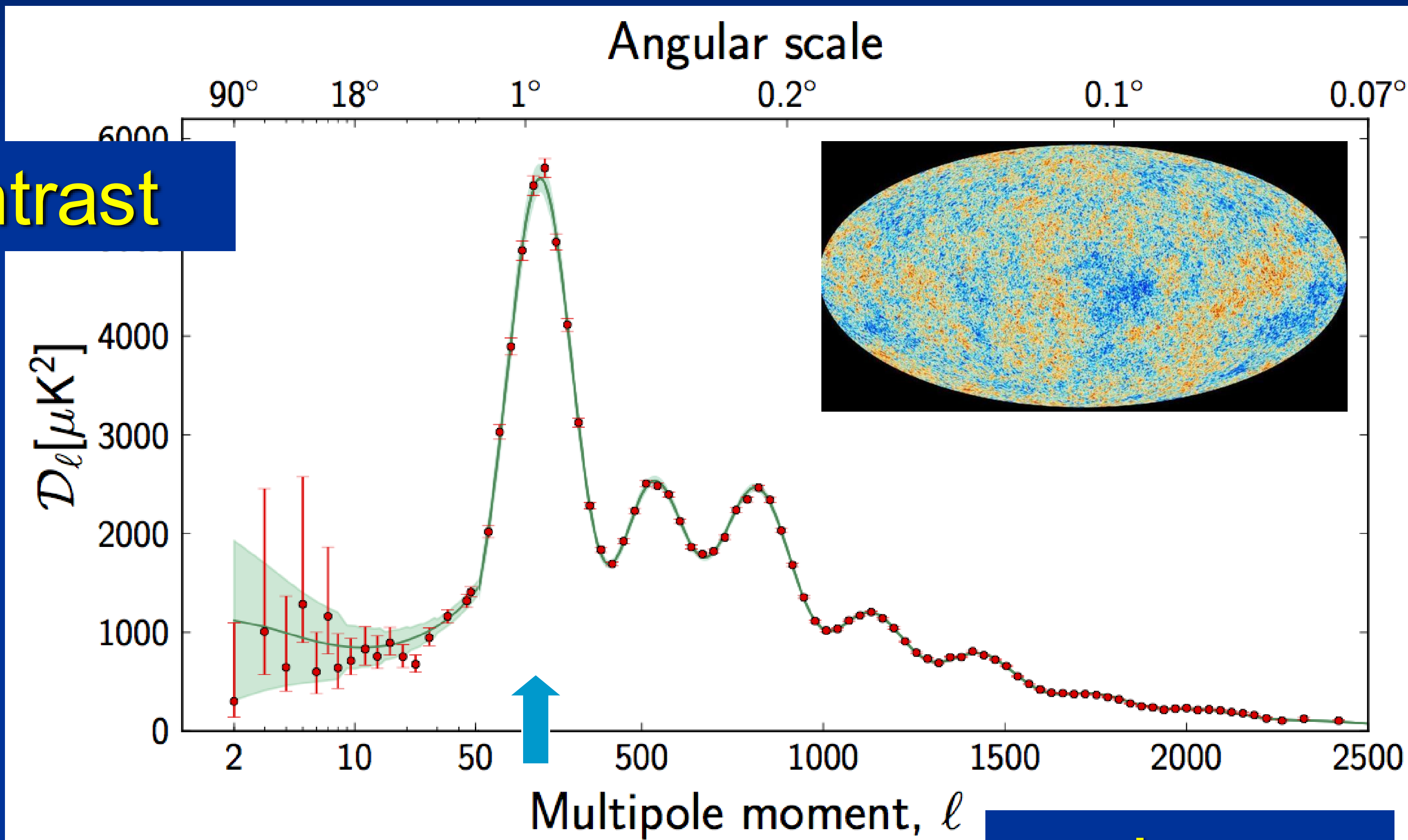




CMB anisotropies



Temperature
in dependence on size of fluctuations (angle)



contrast

angle

ca 10 dg ca 1 dg

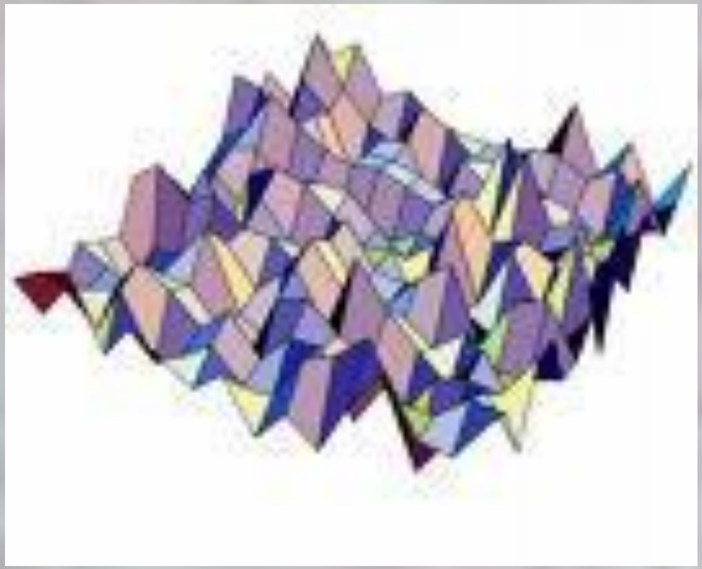
Eternal light-vacuum or singularity ?

Everywhere almost nothing
only fields and their fluctuations

Very few particles:
all move with light velocity,
similar to photons

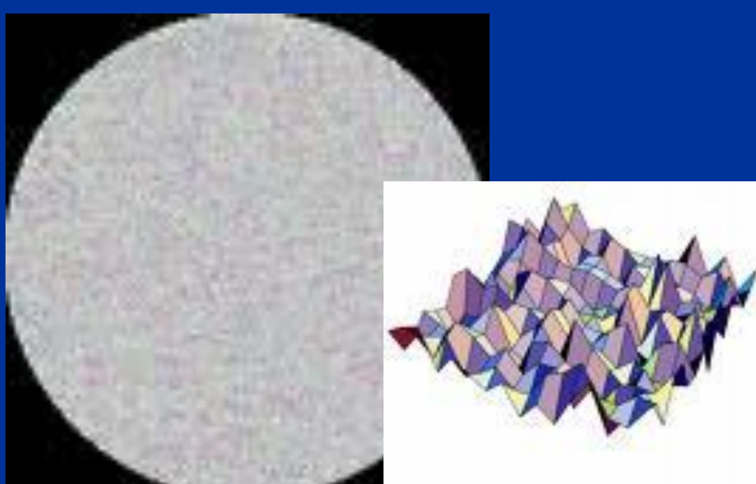
Only very slow expansion

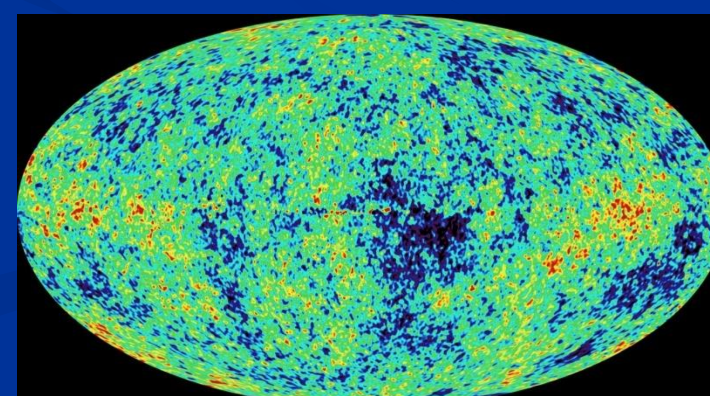
Eternal light vacuum valid
to infinite past



Eternal light-vacuum is unstable

- Slow increase of particle masses
- Only slow change of space-time geometry
- Creation of particles and entropy
- Consequence for observation : primordial fluctuations become visible in cosmic background radiation
- We see fluctuations in a stage 5000 billion years ago, or similar number depending on model





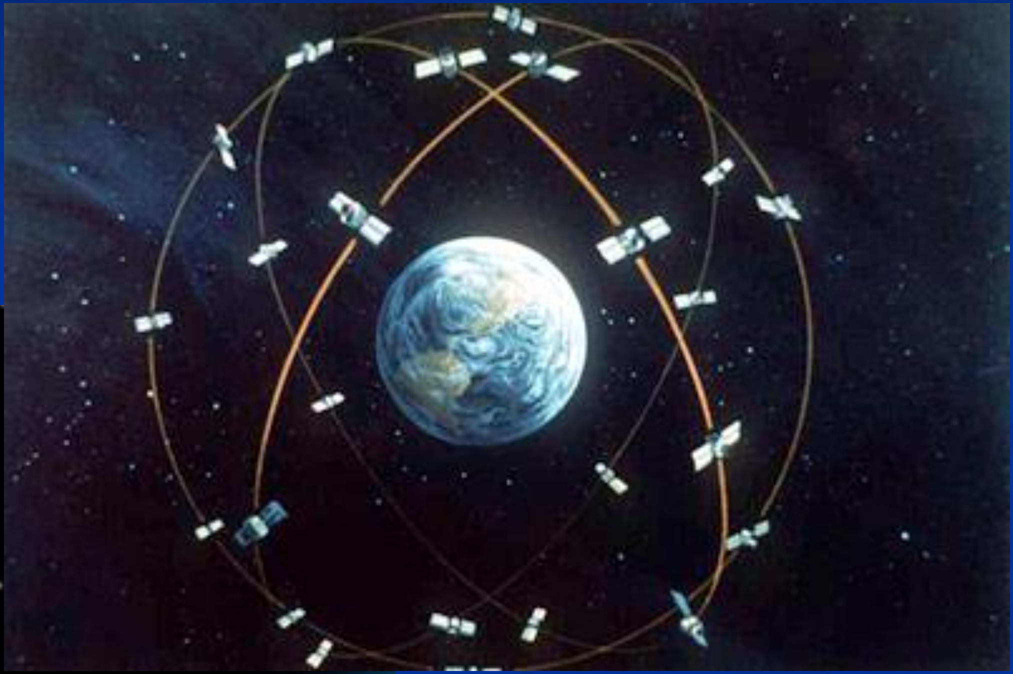
What is physical time ?

Bild : pm-magazin

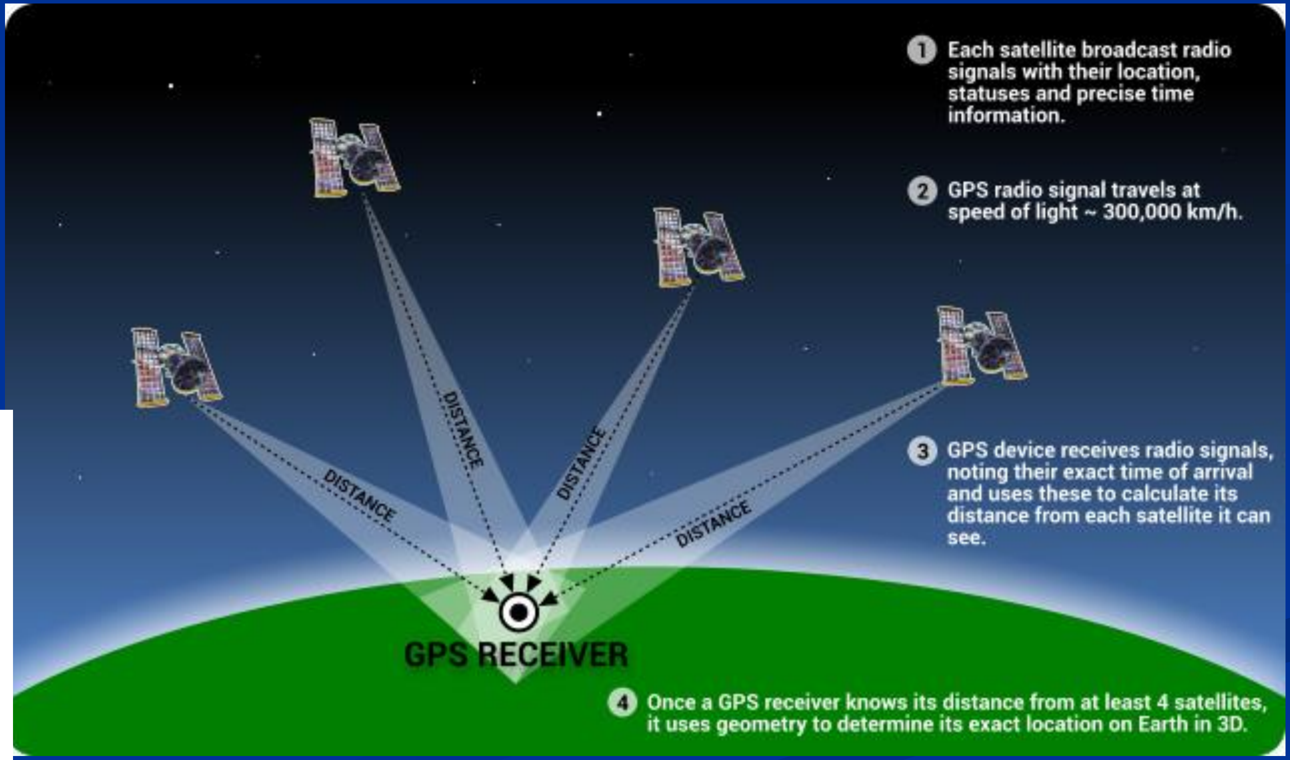
What is space-time ?

- describes relations between observables
- not something independent of matter and fields, into which matter and fields are placed

„Construction of space with light“



GPS uses electromagnetic waves, with time differences used to construct distances

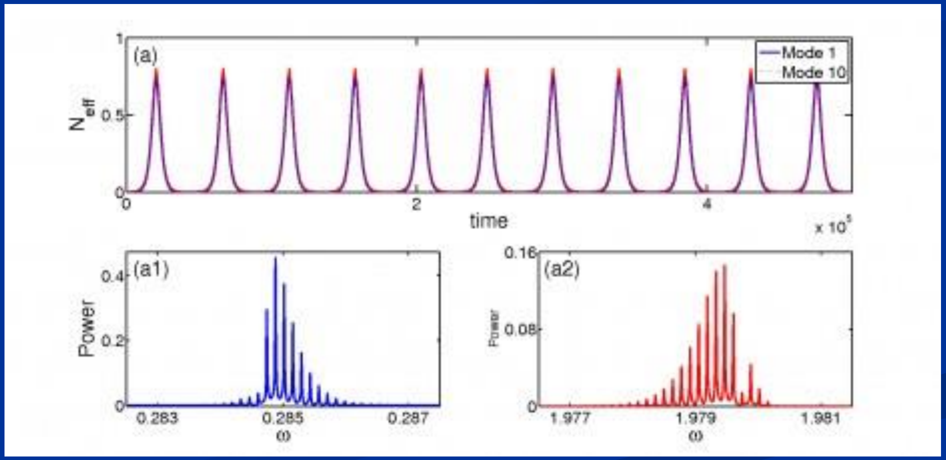


Spacetime

light + clock

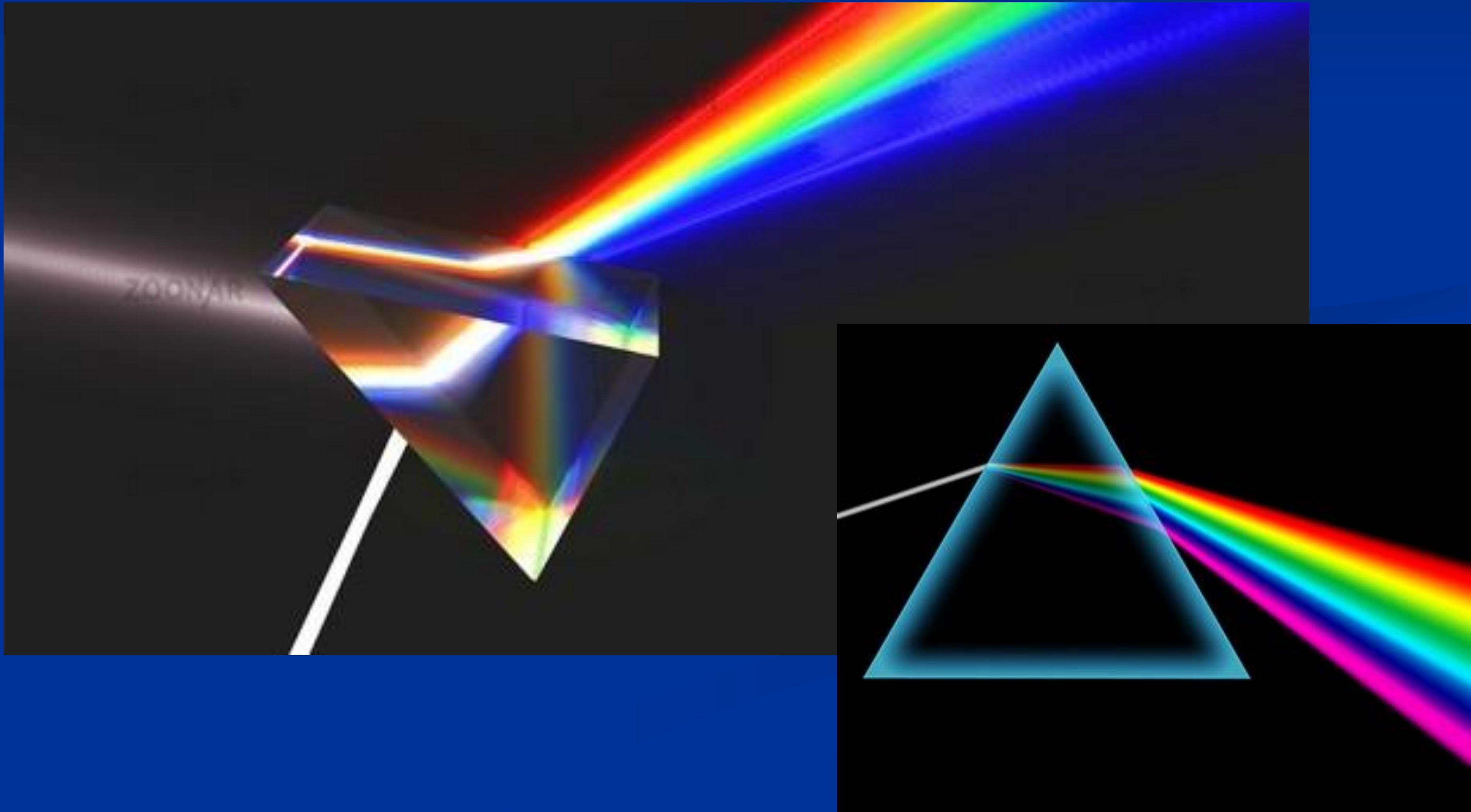
Physical time

count oscillations ….

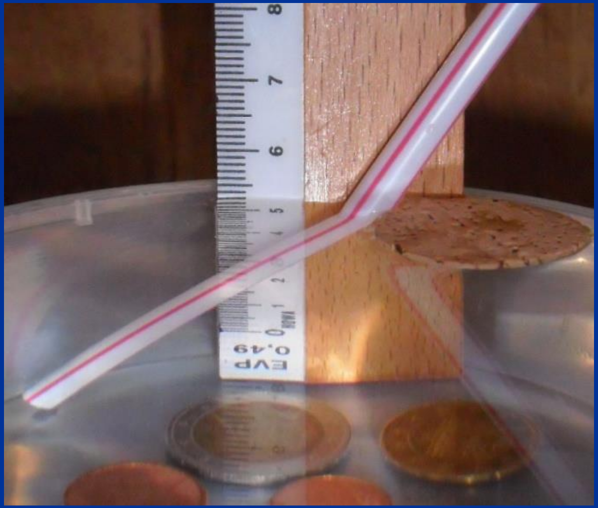


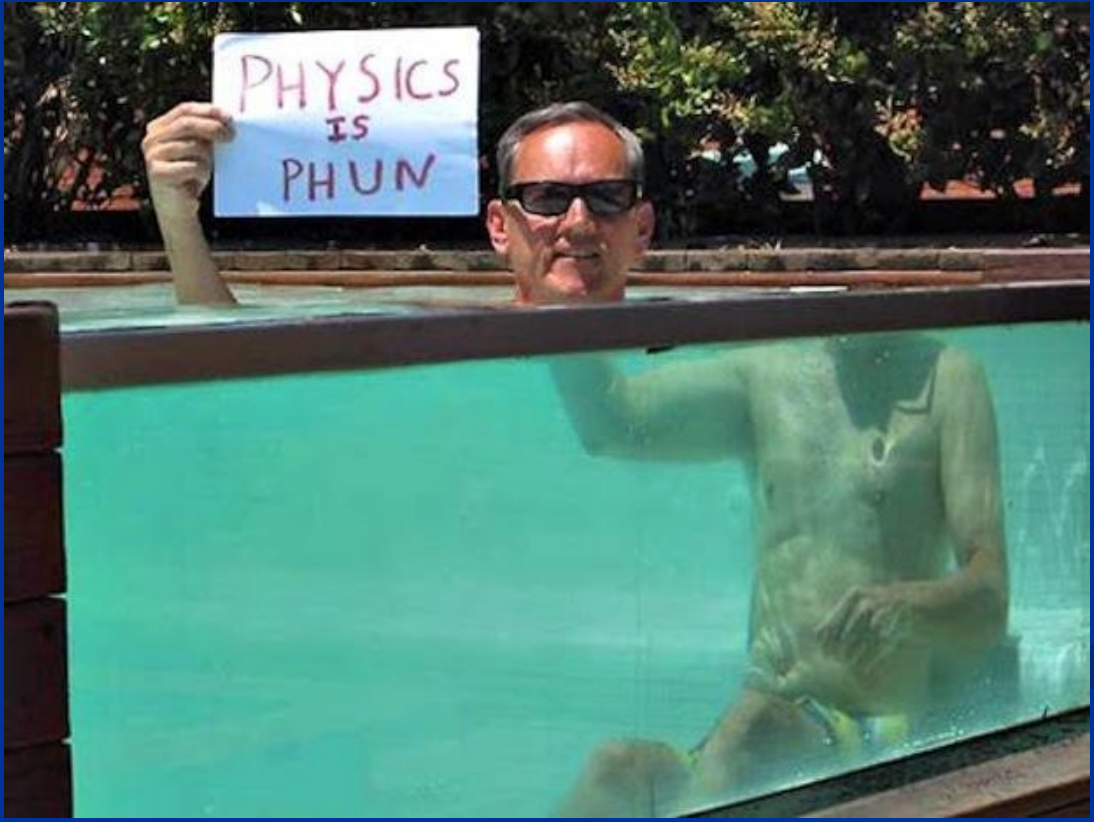
Spacetime depends on „vacuum“

Maxwell equations in medium

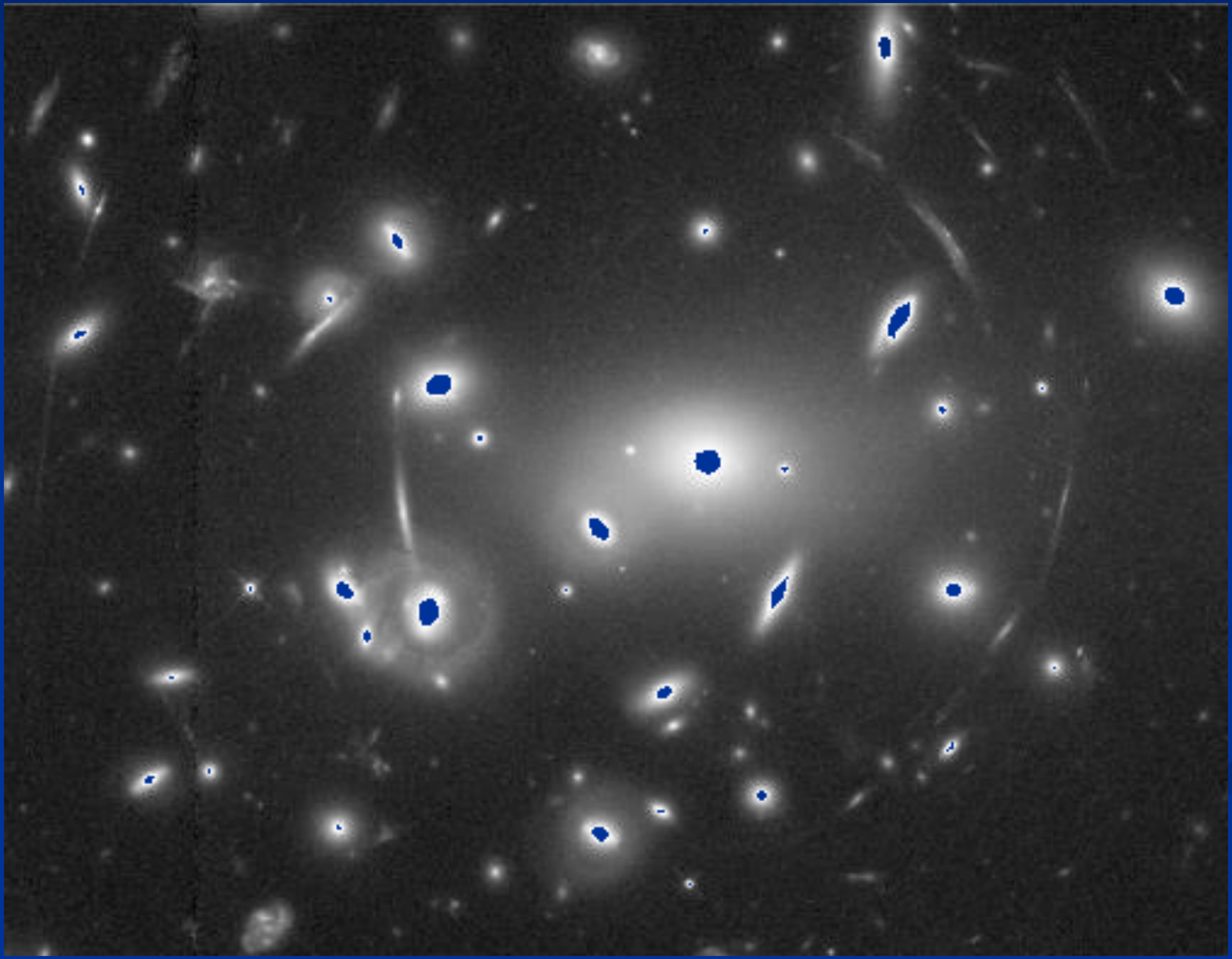


Propagation of light is influenced by medium

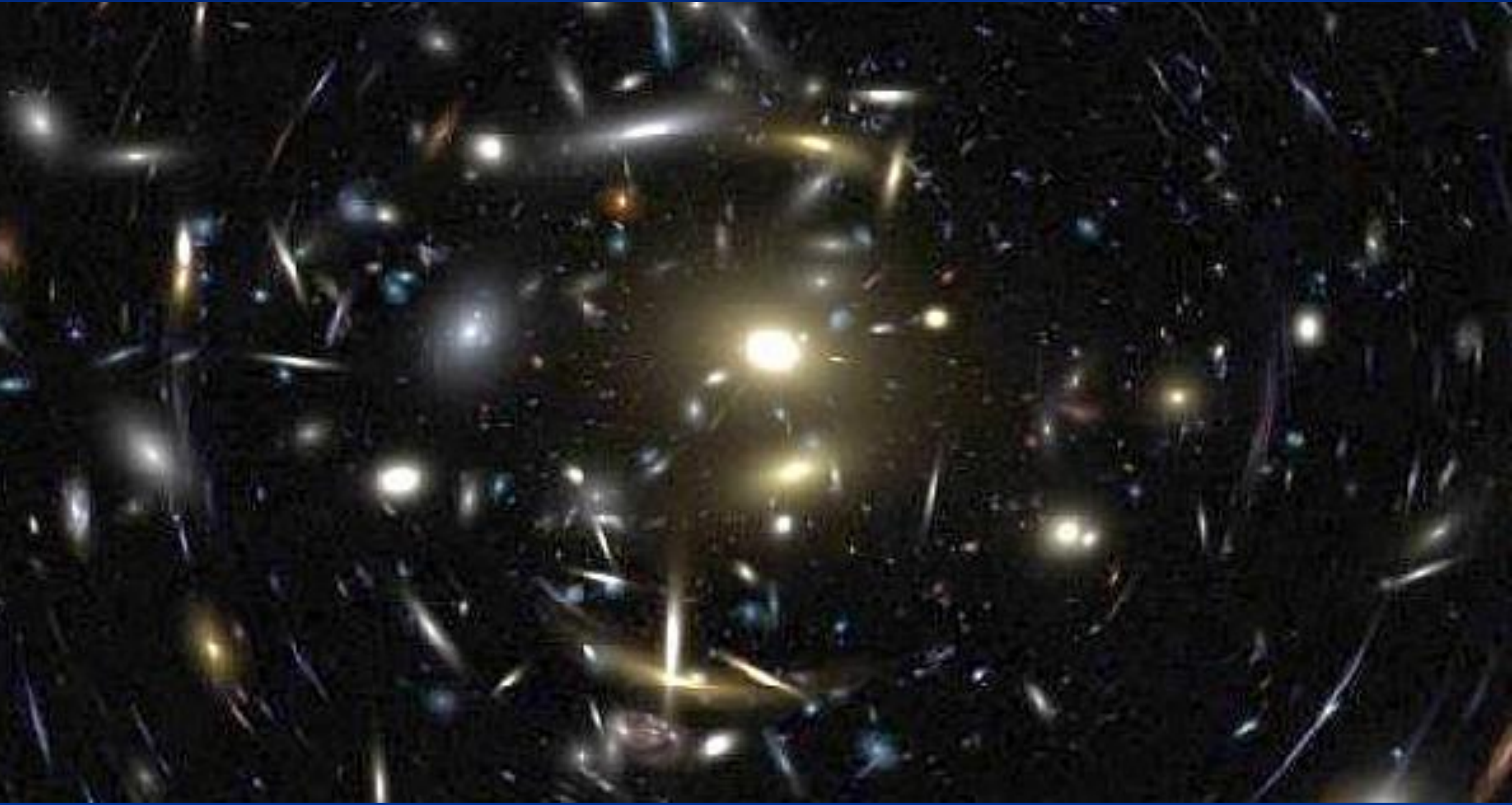




and also by empty space



Gravitational lenses



Vacuum is not nothing

Physical laws depend on vacuum

Metric

Metric field

- Vacuum is characterized by fields and their fluctuations
- Magnetic field : at each location and time three real numbers
- Metric field : at each location and time ten real numbers

Metric : ten numbers

$$g_{\mu\nu}(t, x, y, z)$$

$$g_{\mu\nu} = g_{\nu\mu}$$

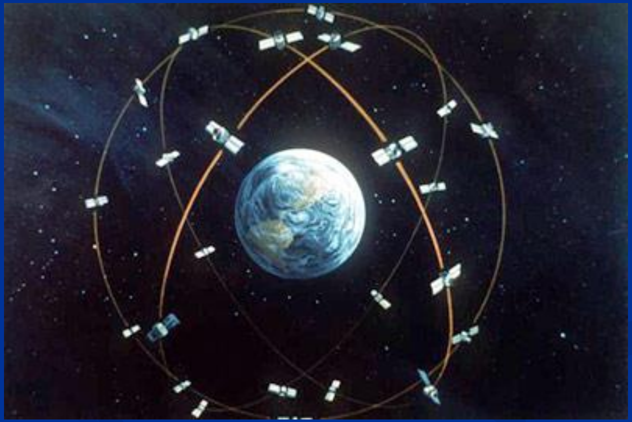
$$g_{\mu\nu} : (g_{00}, g_{01}, g_{02}, g_{03}, g_{11}, g_{12}, g_{13}, g_{22}, g_{23}, g_{33})$$

matrix :

$$g_{\mu\nu} : \begin{pmatrix} g_{00} & , & g_{01} & , & g_{02} & , & g_{03} \\ g_{10} & , & g_{11} & , & g_{12} & , & g_{13} \\ g_{20} & , & g_{21} & , & g_{22} & , & g_{23} \\ g_{30} & , & g_{31} & , & g_{32} & , & g_{33} \end{pmatrix}$$

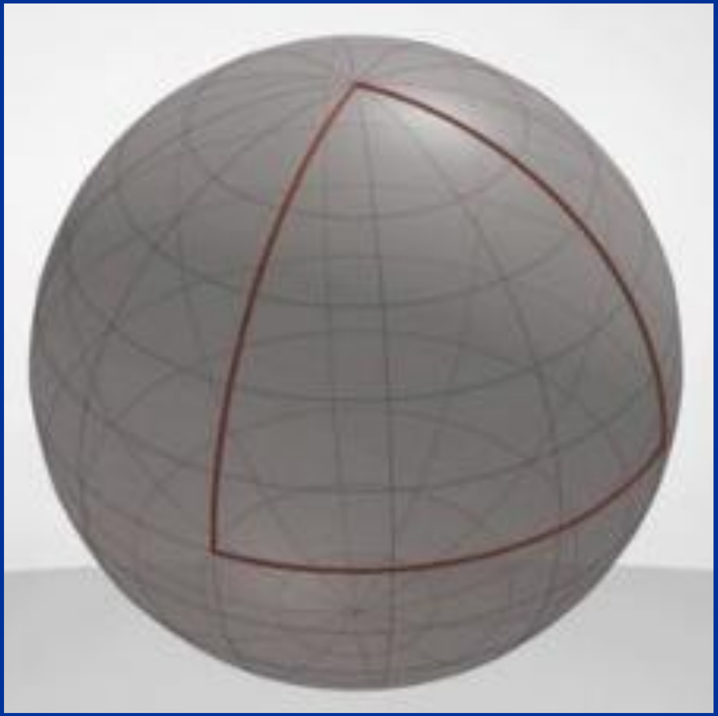
One of the components is Newton's gravitational potential

Metric influences propagation of light



Distances in space depend on metric

Metric defines a geometry



$$ds^2 = \sum_{\mu=0}^{3} \sum_{\nu=0}^{3} g_{\mu\nu} dx^\mu dx^\nu$$

The gravitational field defines a metric for spacetime

Geometry of curved space

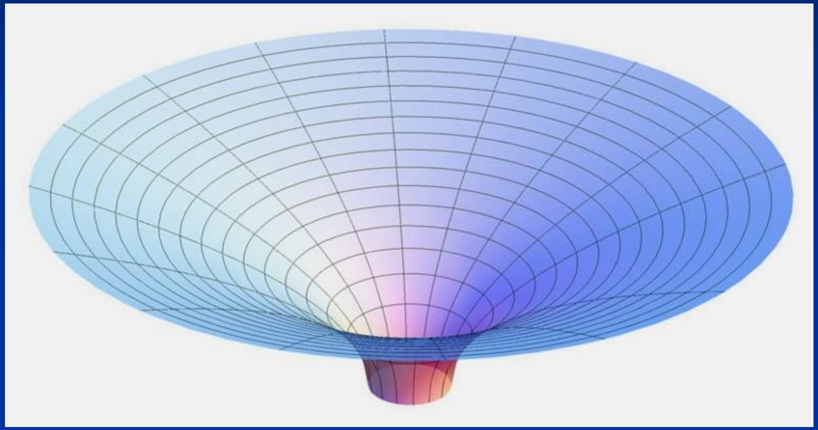
Gauss

Riemann

General coordinate invariance

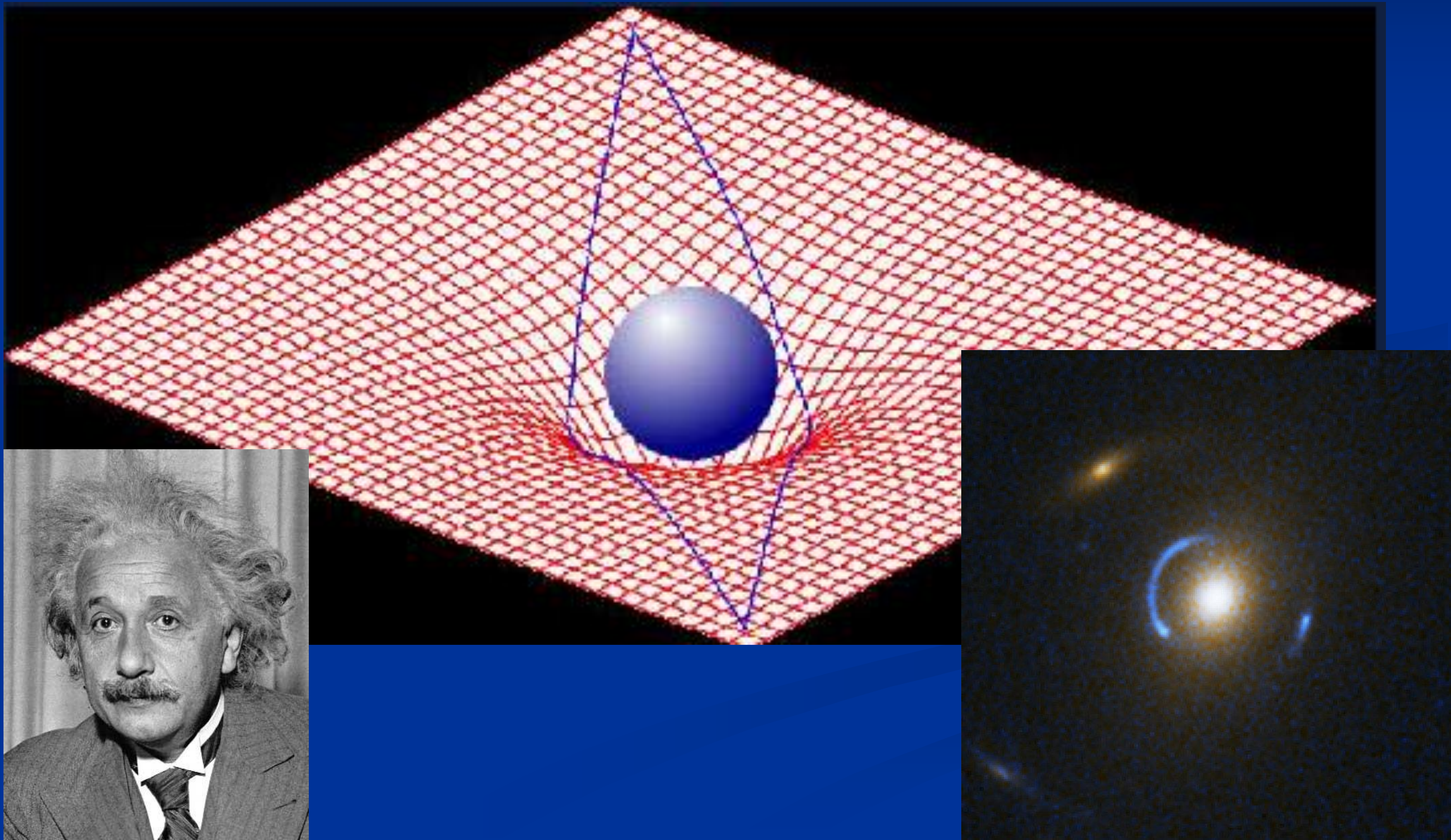
- Metric and electromagnetic fields depend on coordinates
- Symmetry principle : invariance under general coordinate transformations
(diffeomorphism symmetry)
- Fixes the coupling of the two fields
- Fixes how light propagates in a given metric
- Inversely: propagation of light can be used to construct metric ? Is metric unique ?

Metric is influenced by matter



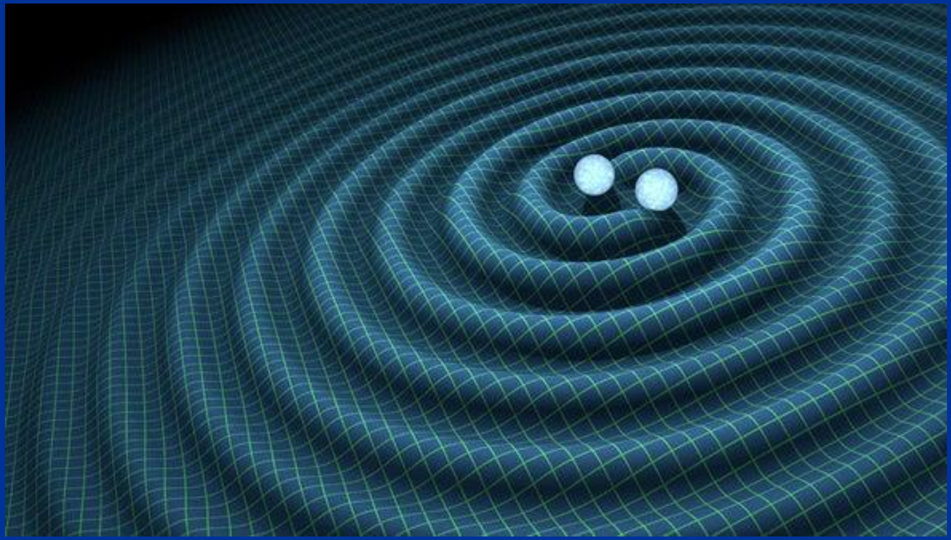
- Diffeomophism symmetry also fixes coupling of metric to matter (atoms etc.)
- Metric is influenced by matter – matter distorts space geometry

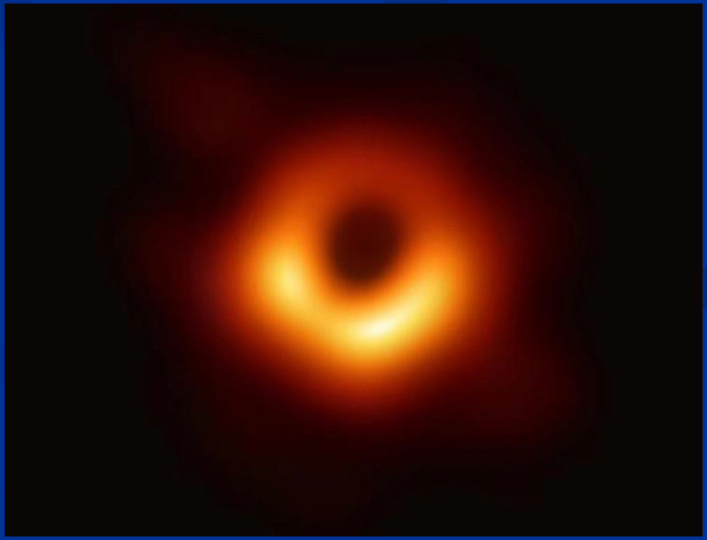
Light propagation influenced by matter



Metric $g_{\mu\nu}$

- Metric field **$g_{\mu\nu}$ (t , x)** is central ingredient for gravity
- similar to electric or magnetic fields
- generalizes gravitational field in Newtonian gravity





Time in the Universe

metric of the Universe

homogenous and isotropic

$$g_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & a^2(t) & 0 & 0 \\ 0 & 0 & a^2(t) & 0 \\ 0 & 0 & 0 & a^2(t) \end{pmatrix}$$

$$\mathrm{d}s^2 = g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = -\mathrm{d}t^2 + a^2(t)\mathrm{d}x^i \mathrm{d}x^j \delta_{ij}$$

Space distances are proportional a(t)

Expansion of space if a(t) increases

Expansion of space

- Field changes its value
- That’s all
- not: “space is created” etc.

Beginning as a point?

g_{ij}=0 : all distances are zero

$$ds^2 = \sum_{\mu=0}^{3}\sum_{\nu=0}^{3} g_{\mu\nu} dx^\mu dx^\nu$$

a=0 : singularity ?

$$g_{\mu\nu} : \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & a^2(t) & 0 & 0 \\ 0 & 0 & a^2(t) & 0 \\ 0 & 0 & 0 & a^2(t) \end{pmatrix}$$

Conformal time

$$g_{\mu\nu} = a^2(\eta)\eta_{\mu\nu}$$

$$\eta_{\mu\nu} = \mathrm{diag}(-1, 1, 1, 1)$$

$$g_{\mu\nu} : \begin{pmatrix} -a^2(t) & 0 & 0 & 0 \\ 0 & a^2(t) & 0 & 0 \\ 0 & 0 & a^2(t) & 0 \\ 0 & 0 & 0 & a^2(t) \end{pmatrix}$$

$$a^2 d\eta^2 = dt^2$$

$$dt = a\, d\eta$$

inflationary cosmology

$$a(t) = a_0 e^{Ht}$$

$$\eta = -\frac{1}{Ha_0} e^{-Ht}$$

$$t \to -\infty$$

$$\eta \to -\infty$$

$$a(\eta) = -\frac{1}{H\eta}$$

Cosmic time and proper time

t : cosmic time

$$\mathrm{d}s^2 = g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu$$
$$= -\mathrm{d}t^2 + a^2(t)\mathrm{d}x^i \mathrm{d}x^j \delta_{ij}$$

Proper time counts oscillations for a clock moving with an observer

Proper time does not depend on choice of coordinates

Cosmic time is proper time for comoving observer

Eternal Universe ?

For typical models of inflation:

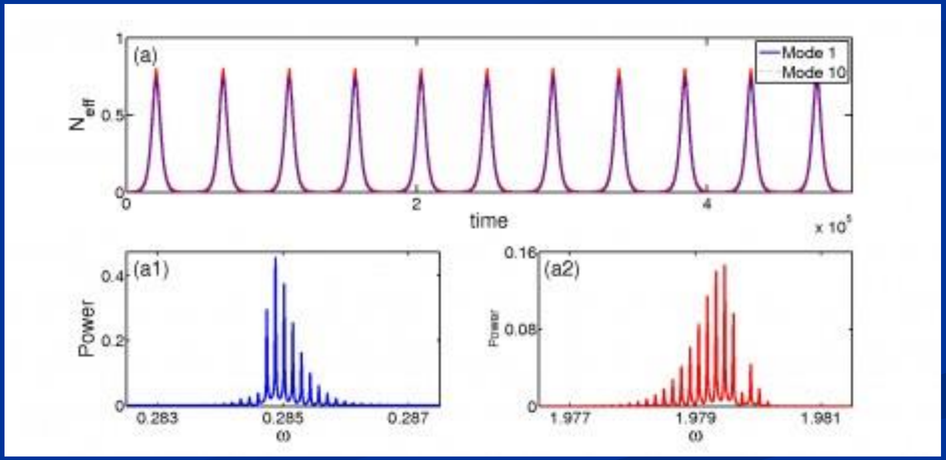
Both conformal time and cosmic time can be extended to - infinity.

Scale factor a(t) goes to zero in the infinite past.

$$a(\eta) = -\frac{1}{H\eta} \qquad a(t) = a_0 e^{Ht}$$

Physical time

count oscillations ….



Photon clock

Radiation dominated Universe : no observers with clocks

Oscillating electromagnetic waves are present
and can be used as clocks

wave function in momentum space

$$(\partial_\eta^2 + 2\mathcal{H}\partial_\eta + k^2)\varphi(\vec{k}) = 0$$

solution

$$\varphi(\eta, \vec{x}) = B(\eta) \exp\left\{i(\vec{k}\vec{x} - k\eta)\right\}$$

counting

$$n_{\vec{k}} = \frac{k\eta}{2\pi}$$

Physical time = conformal time

Physical time

field equation for scalar field mode

$$(\partial_\eta^2 + 2Ha\partial_\eta + k^2 + a^2 m^2)\varphi_k = 0$$

$$\varphi_k = \frac{\tilde{\varphi}_k}{a} \qquad \left\{\partial_\eta^2 + k^2 + a^2\left(m^2 - \frac{R}{6}\right)\right\}\tilde{\varphi}_k = 0$$

determine physical time by counting number of oscillations

$$\tilde{t}_p = n_k \qquad n_k = \frac{k\eta}{\pi}$$

(m=0)

Geodesic incompleteness

- Proper time for observer with non-vanishing (pecular)velocity:

  remains finite in inflationary models for

  $t \to -\infty$

  $\eta \to -\infty$

- Geodesics for such observers are "incomplete"

- Singularity reached at finite time ?
- Which time should one take ?

Frame transformations

Cosmology with metric and scalar field

different possible choices for the metric field

$$g'_{\mu\nu} = \frac{\chi^2}{M^2} g_{\mu\nu}$$

Field relativity : different pictures of cosmology

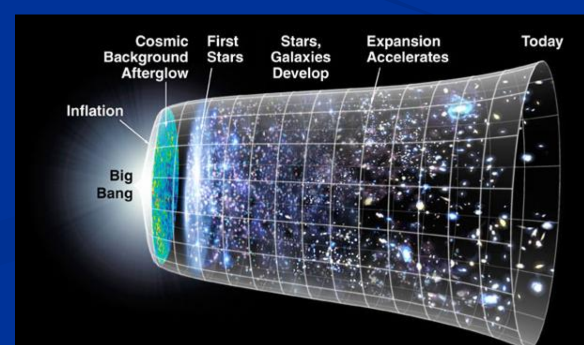
- same physical content can be described by different pictures
- related by field – redefinitions ,
- observables cannot depend on choice of fields
- different fields: different variables in differential equations
- metric is one of the fields

Field relativity

Weyl scaling :

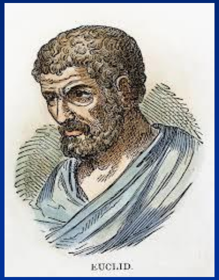
$$g'_{\mu\nu} = \frac{\chi^2}{M^2} g_{\mu\nu}$$

changes geometry,
not a coordinate transformation

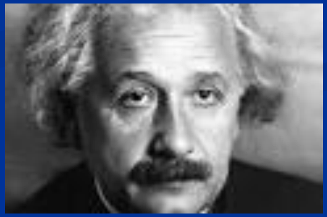


Relativity of geometry

- Euclid … Newton : space and time are absolute and observable



- Special relativity : space and time depend on observer
- General relativity : space-time is influenced by matter (including radiation)



  geometry is independent of coordinates

  geometry is observable
- Field relativity : geometry is relative

Metric frames

different choices of metric :

different metric frames

Primordial flat frame can be constructed:

Flat spacetime for beginning Universe

geodesically complete

Physical time

- counting : discrete
- invariant under field transformations
- same in all frames
- physical time towards the past: infinite number of oscillations

Time completeness

- Geodesic completeness depends on metric frame
- Generaliztion : time completeness

Geodesic (in)completeness in general metric frames

V. A. Rubakov[a], C. Wetterich[b]

[a] *Institute for Nuclear Research of the Russian Academy of Sciences, 60th October Anniversary Prospect, 7a, 117312 Moscow, Russia*

[b] *Institute for Theoretical Physics, Heidelberg University, Philosophenweg 16, 69120 Heidelberg, Germany*

Abstract

The geometric concept of geodesic completeness depends on the choice of the metric field or "metric frame". We develop a frame-invariant concept of "generalised geodesic completeness" or "time completeness". It is based on the notion of physical time defined by counting oscillations for some physically allowed process. Oscillating solutions of wave functions for particles with varying mass permit the derivation of generalised geodesics and the associated notion of completeness. Time completeness involves aspects of particle physics and is no longer a purely geometric concept.

Beginning of the Universe

Beginning of Universe

Zu Anfang war die Welt öd und leer und währte ewig.

In the beginning the Universe was empty and lasted since ever.

The great emptiness story

In the beginning was light-like emptiness.

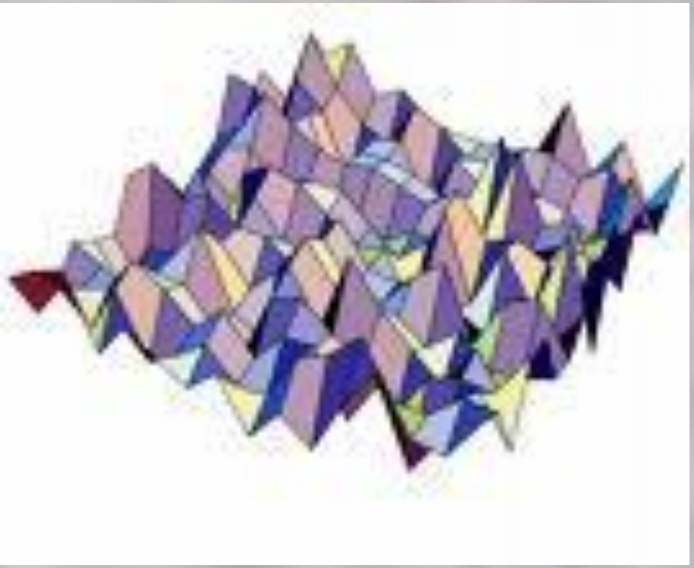
Physical properties during inflationary epoch

- All particles get effectively massless as singularity is approached
- Relevant quantity : mass /momentum
- Momentum diverges
- Ratio goes to zero

Eternal light-vacuum

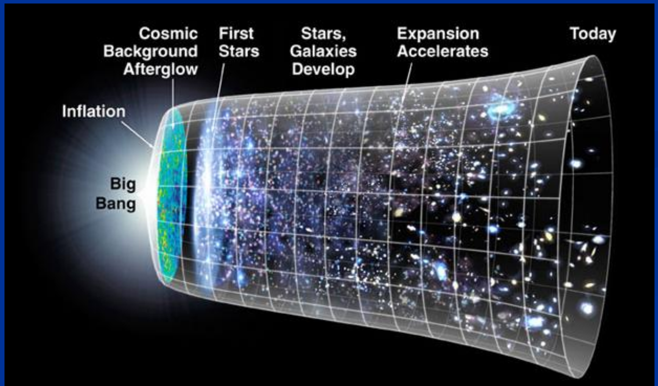
Everywhere almost nothing
only fields and their fluctuations

All particles move
with light velocity,
similar to photons



The big bang story

- dramatic hot big bang
- started 13.8 billion years ago
- at the beginning extremely short period of cosmic inflation with almost exponential expansion of the Universe, duration around 10^{-40} seconds
- start with singularity : our whole observable Universe evolves from one point



Field relativity

- Both stories are equivalent
- related by field transformation of the metric

$$g'_{\mu\nu} = \frac{\chi^2}{M^2} g_{\mu\nu}$$

- different metrics related by Weyl transformation, which depends on scalar field (inflaton)

Field - singularity

- Big Bang is field - singularity
- similar (but not identical with)
  coordinate - singularity

$$g'_{\mu\nu} = \frac{\chi^2}{M^2} g_{\mu\nu}$$

Big bang is not wrong,

but alternative pictures exist !

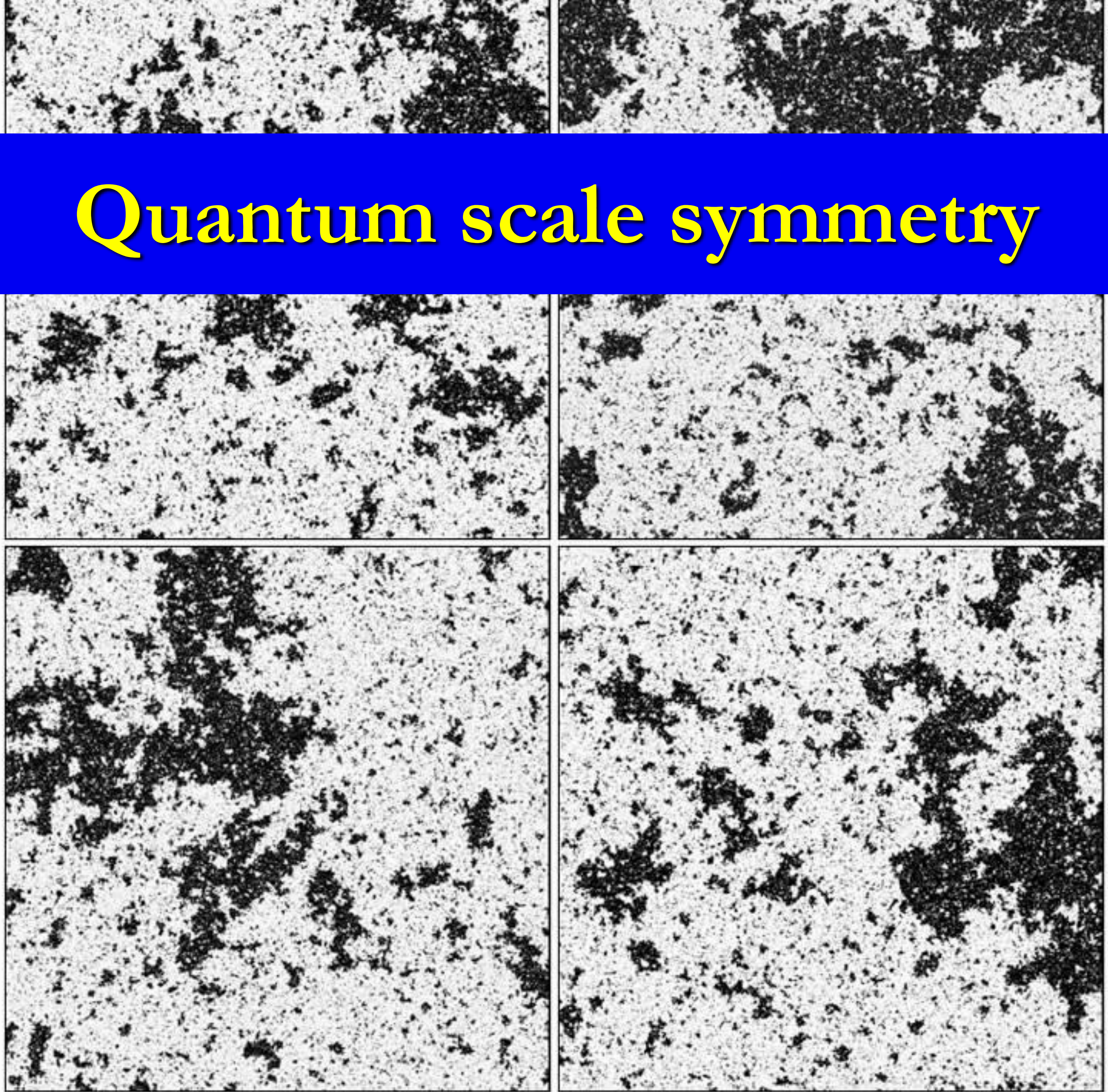
Conclusion

- There are equivalent pictures of the Universe with different geometry
- Singularity free choice of fields is preferable for the description of the beginning

No scales in the infinite past

- No time scale : time is infinite and no change of properties as time goes to minus infinity
- No length scale : Universe is infinite
- No mass scale : all particles are massless

Quantum scale symmetry



Scale transformation

- Scale all lengths and time with constant factor
- Scale all masses with inverse factor

Quantum scale symmetry

No parameter with dimension of length or mass is present in the quantum effective action.

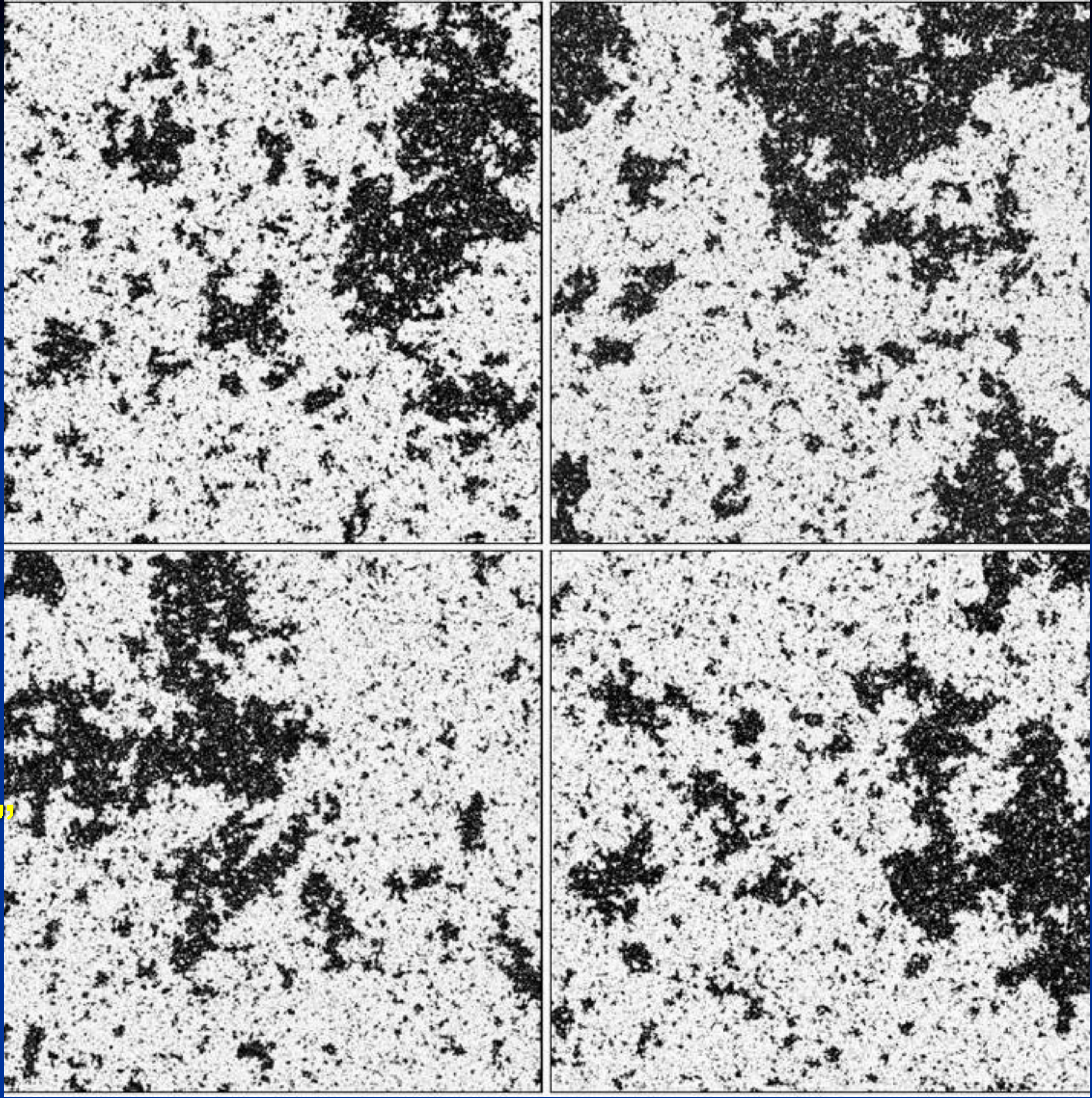
Then invariance under dilatations or global scale transformations is realized.

Continuous global symmetry

Unbroken scale symmetry :

Physics looks the same on all scales

All “particles” are massless



Quantum scale symmetry

- quantum fluctuations can violate scale symmetry
- running dimensionless couplings
- fixed point : no running of couplings
- at fixed points , scale symmetry is exact !
- quantum fluctuations can generate scale symmetry !

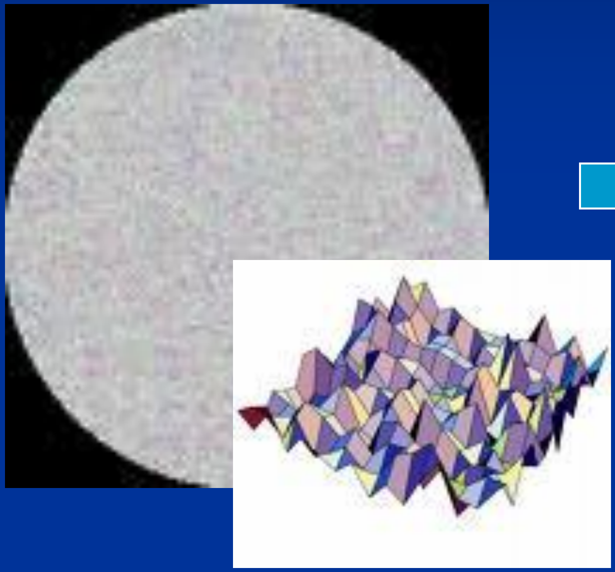
Have we observed
scale symmetry in cosmology ?

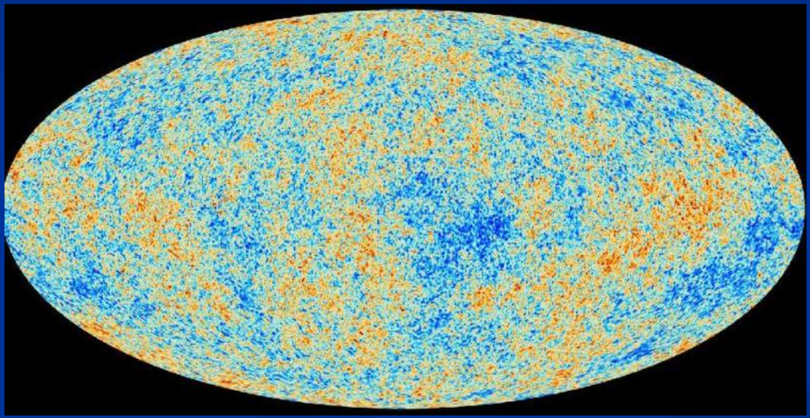
Approximate scale symmetry near fixed points

- UV : approximate scale invariance of primordial fluctuation spectrum from inflation

- IR : cosmon is pseudo Goldstone boson of
  spontaneously broken scale symmetry,
  tiny mass,
  responsible for dynamical Dark Energy

Almost scale invariant primordial fluctuation spectrum seeds all structure in the universe

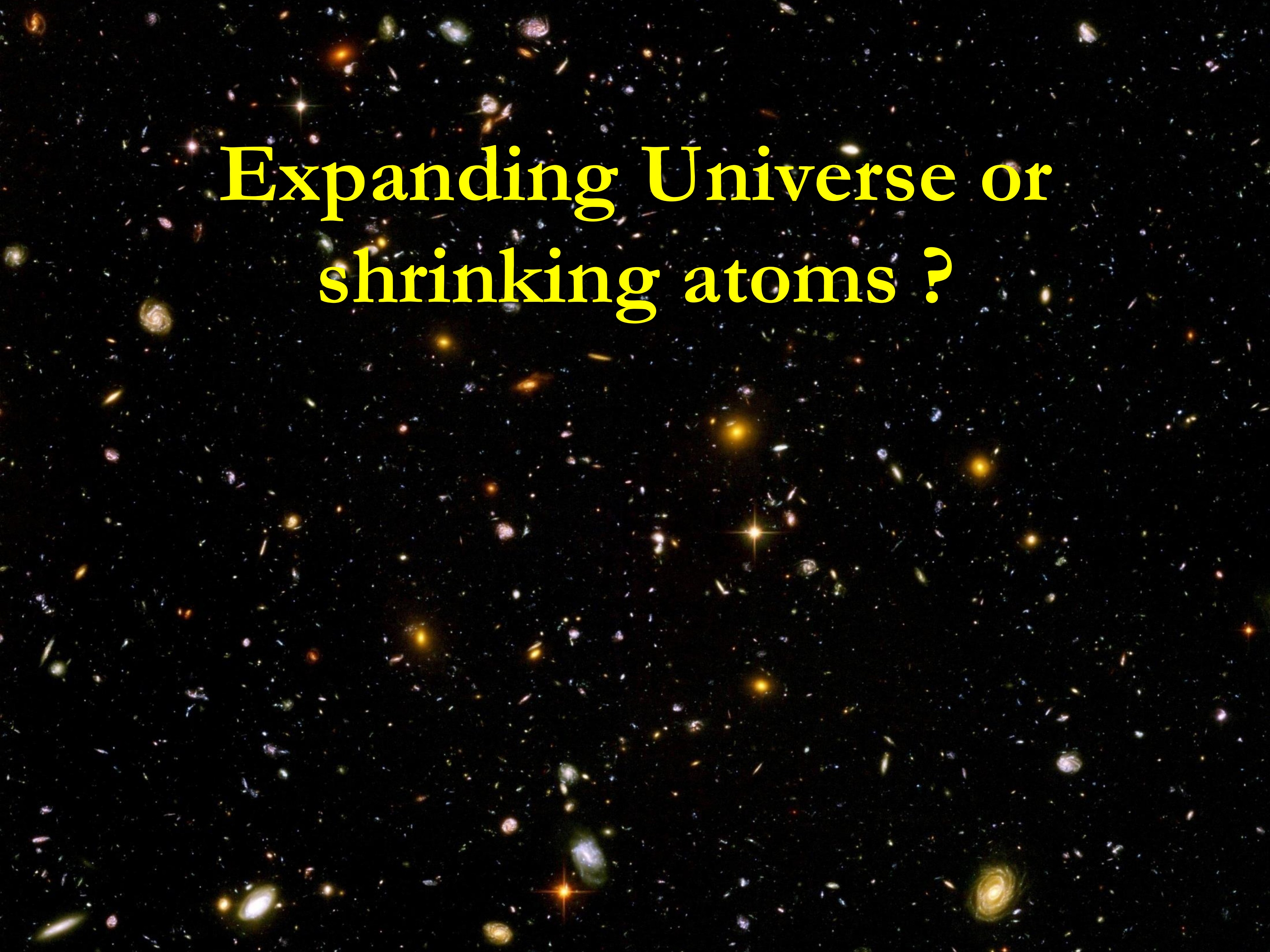




Conclusion

The beginning of the Universe is the reign of quantum scale symmetry

Expanding Universe or shrinking atoms ?



Expansion of the Universe

- What does expansion of space mean ?
- A field changes its value

that's all

- Propagation of particles and photons depend on the value of the metric field

- Frame transformation changes metric and expansion history

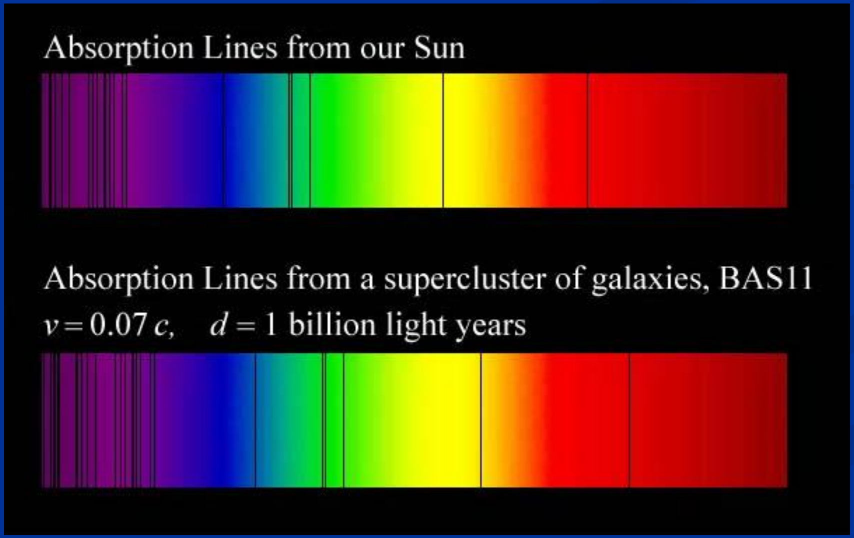
Particle masses can change with time ?

- Particle masses are proportional to scalar field χ . Similar to Higgs field.
- Scalar field varies with time.
- Ratios of particle masses are independent of χ and therefore remain constant.
- Compatibility with observational bounds on time dependence of particle mass ratios.
- Dimensionless couplings are independent of χ .

Do we know that the Universe expands ?

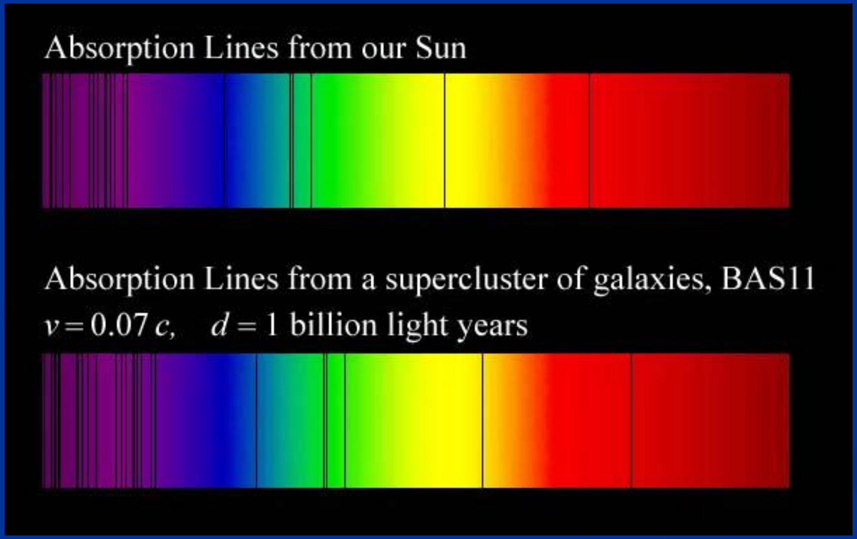
instead of redshift due to expansion :

smaller frequencies have been emitted in the past, because electron mass was smaller !



Why do we see redshift of photons emitted in the distant past ?

photons are more red because they have been emitted with longer wavelength



frequency ~ mass

wavelength ~ atomsize

What is increasing ?

Ratio of distance between galaxies
over size of atoms !

atom size constant : expanding geometry

alternative : shrinking size of atoms

ratio is frame invariant

Inhomogeneities

- certain inhomogeneous cosmological solutions diverge towards the past
- relative inhomogeneities in metric increase towards the past in inflationary cosmology
- relative inhomogeneities are frame invariant
- which metric ? vierbein or metric ?

$$g_{\mu\nu} = e_\mu^a e_\nu^b \eta_{ab}$$

$$a(\eta) = -\frac{1}{H\eta}$$

$$e_\mu^a \longrightarrow 0$$

$$g_{\mu\nu} = \langle e_\mu^a e_\nu^b \rangle \eta_{ab}$$

$$g_{\mu\nu} \neq 0$$

$$\eta_{ab} = \mathrm{diag}(-1, 1, 1, 1)$$

Conclusions

- Quantum scale symmetry crucial for understanding the beginning of the Universe
- Simple ”scaling frame” for the choice of the metric field gives simple description without any singularities
- Big bang singularity is a field singularity
- Universe can be eternal in the past

end