



UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

Light, horizons, and the geometry of space-time

Light!

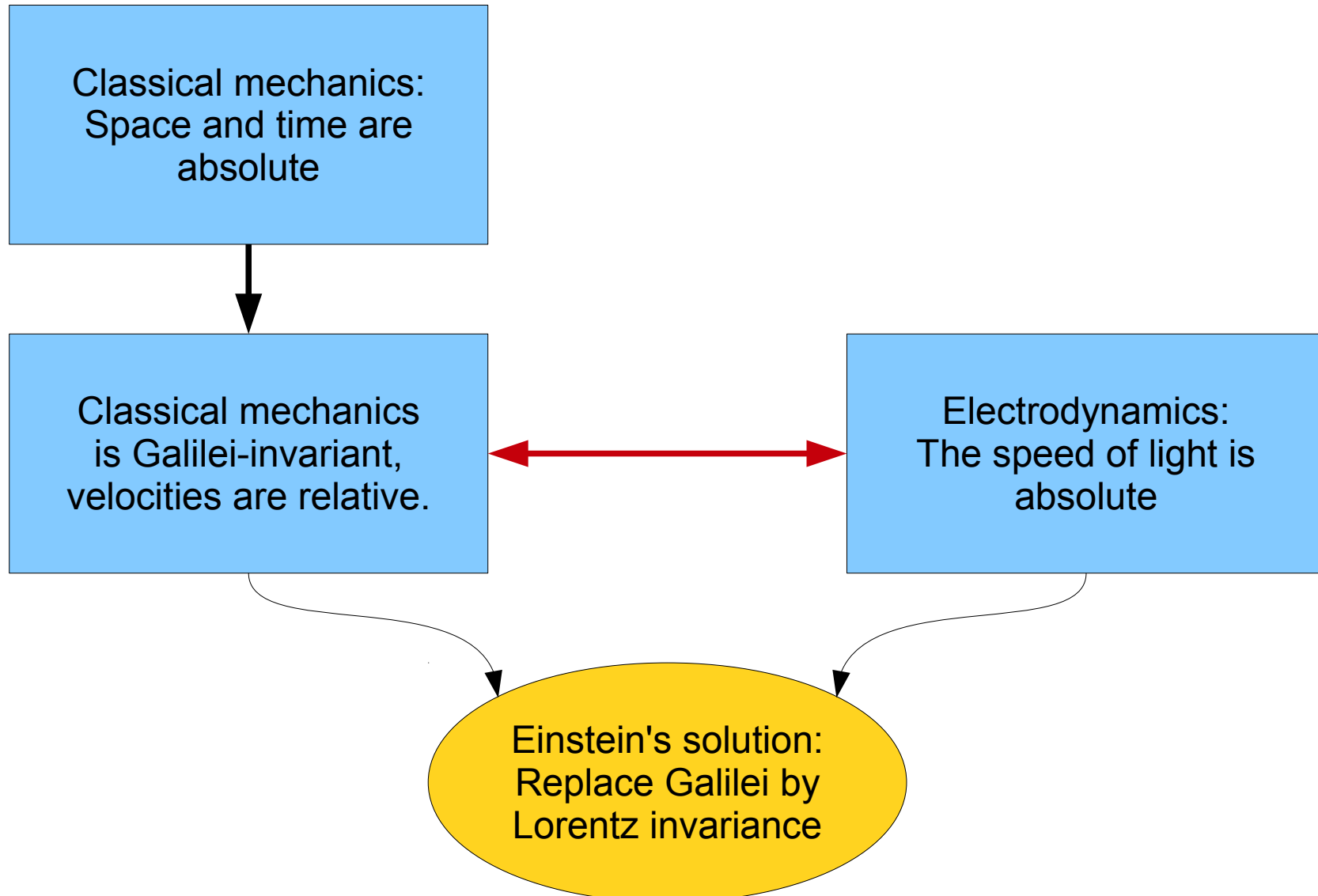
European Summer School 2015

Strasbourg, July 2015

Matthias Bartelmann

Universität Heidelberg, Zentrum für Astronomie

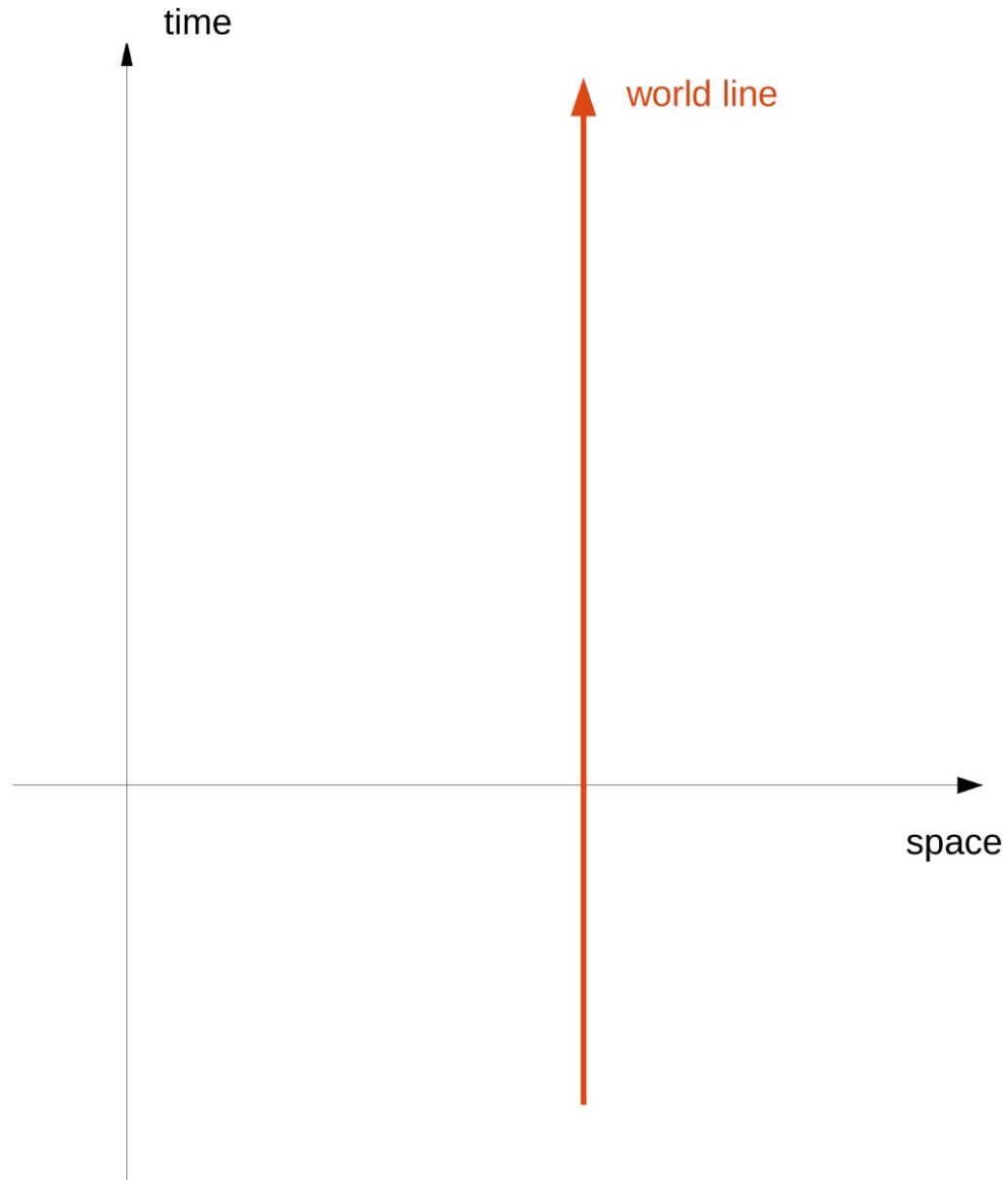
Relativity



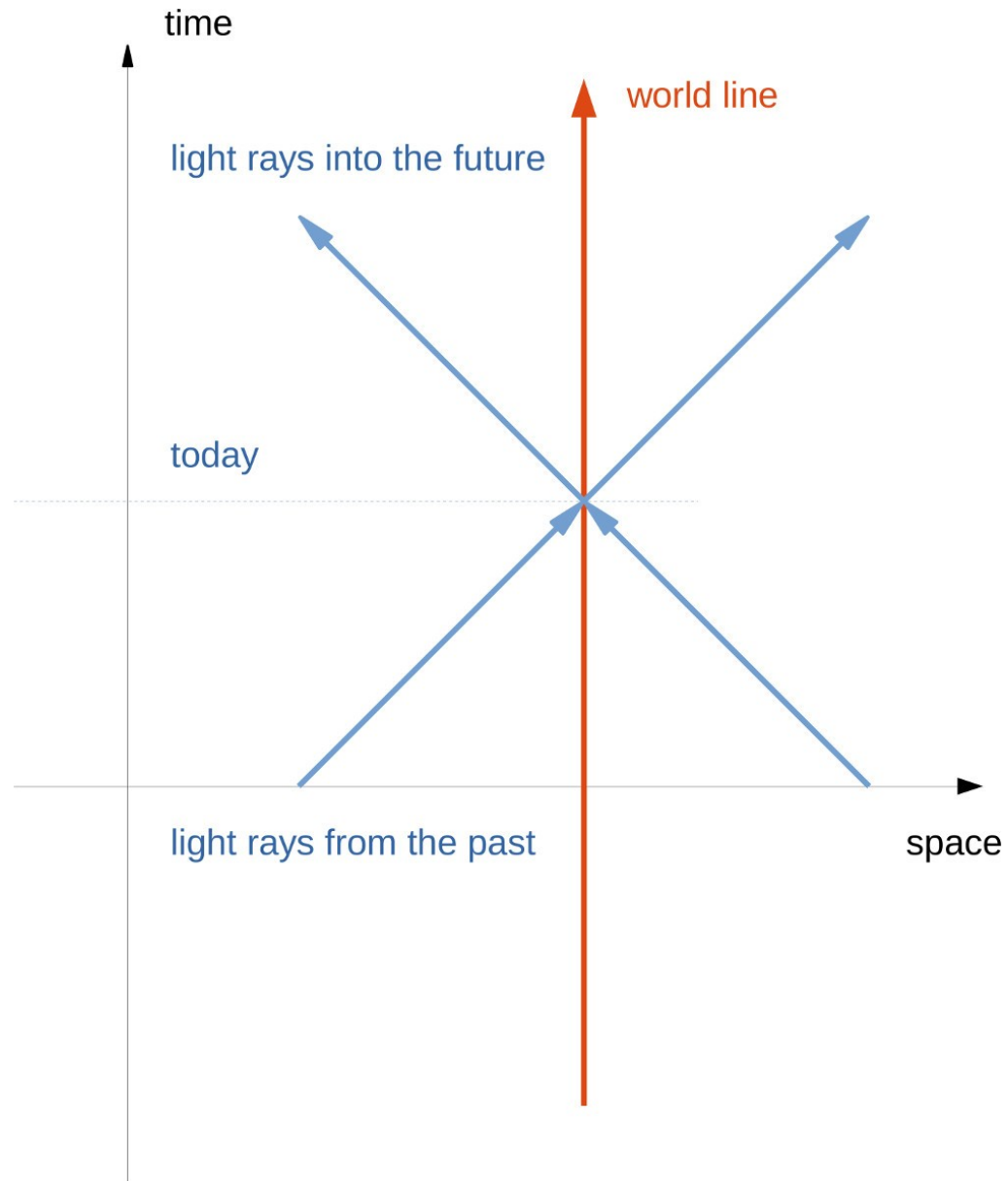
Special relativity



UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386



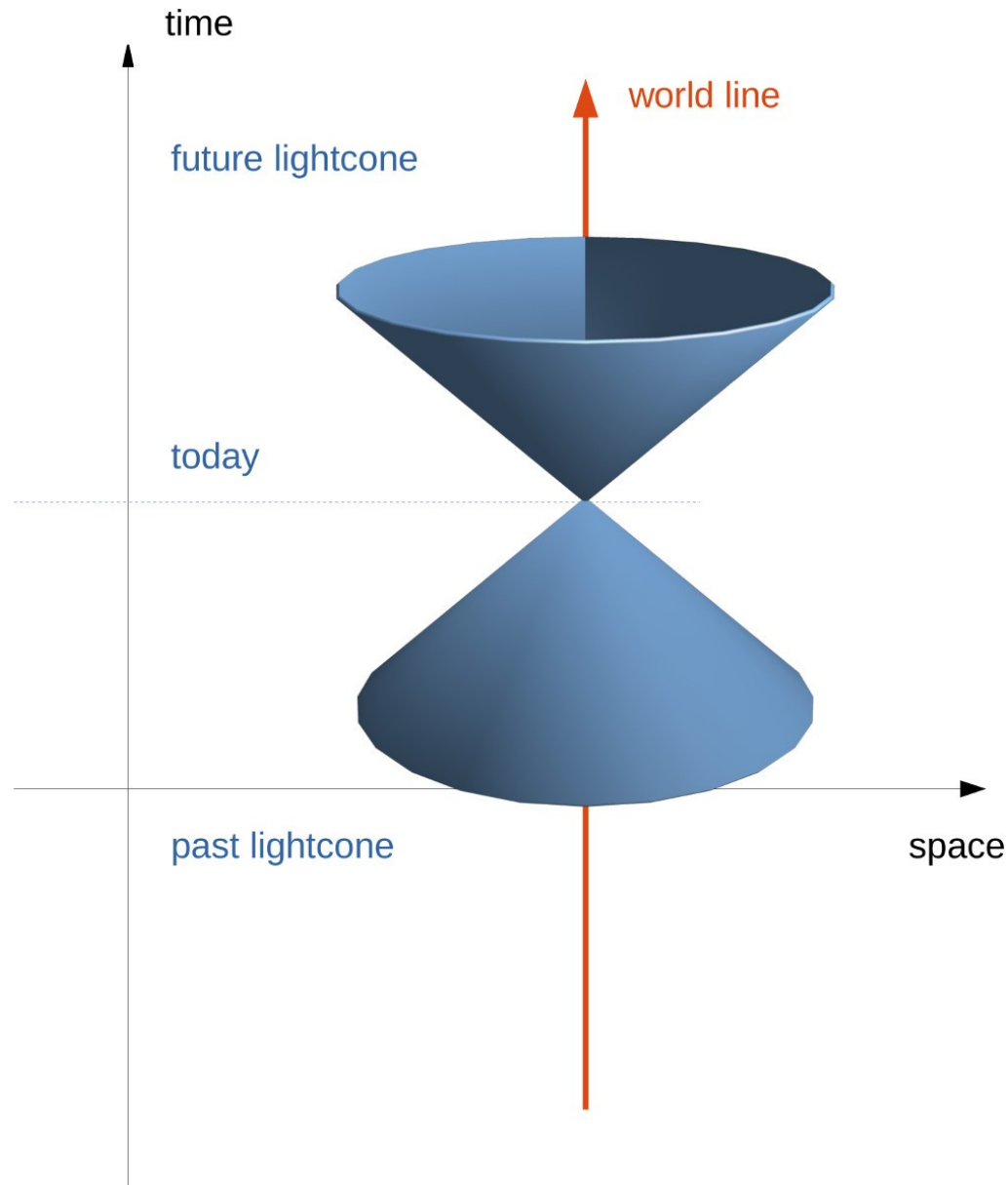
Special relativity, light propagation



Special relativity, past and future light cones



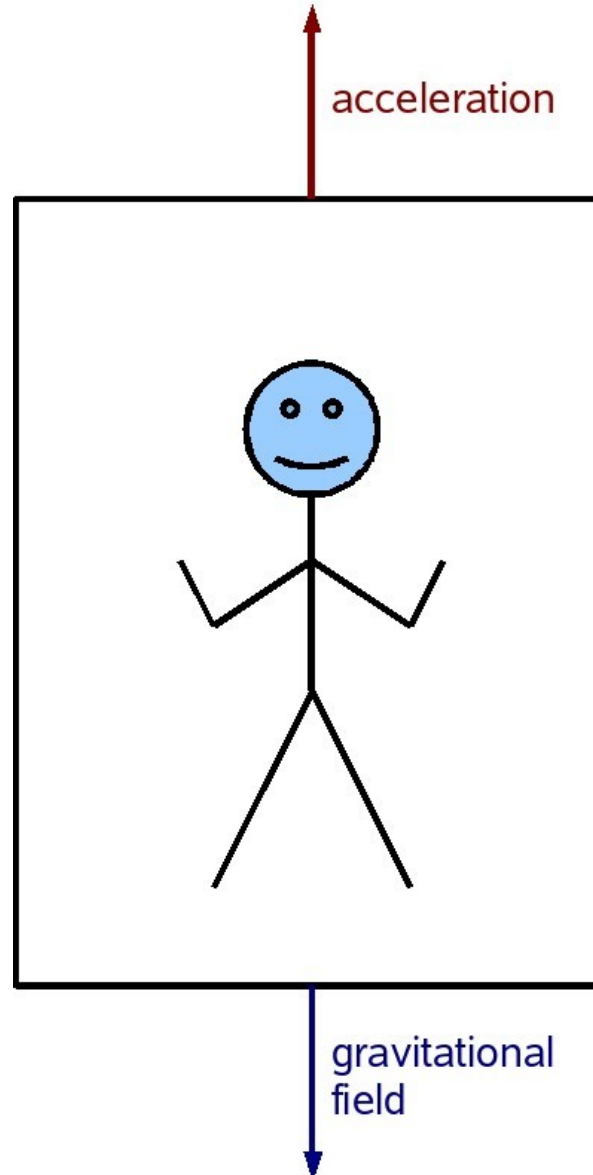
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386



Light-cone structure
is defined by the
Minkowski metric η .

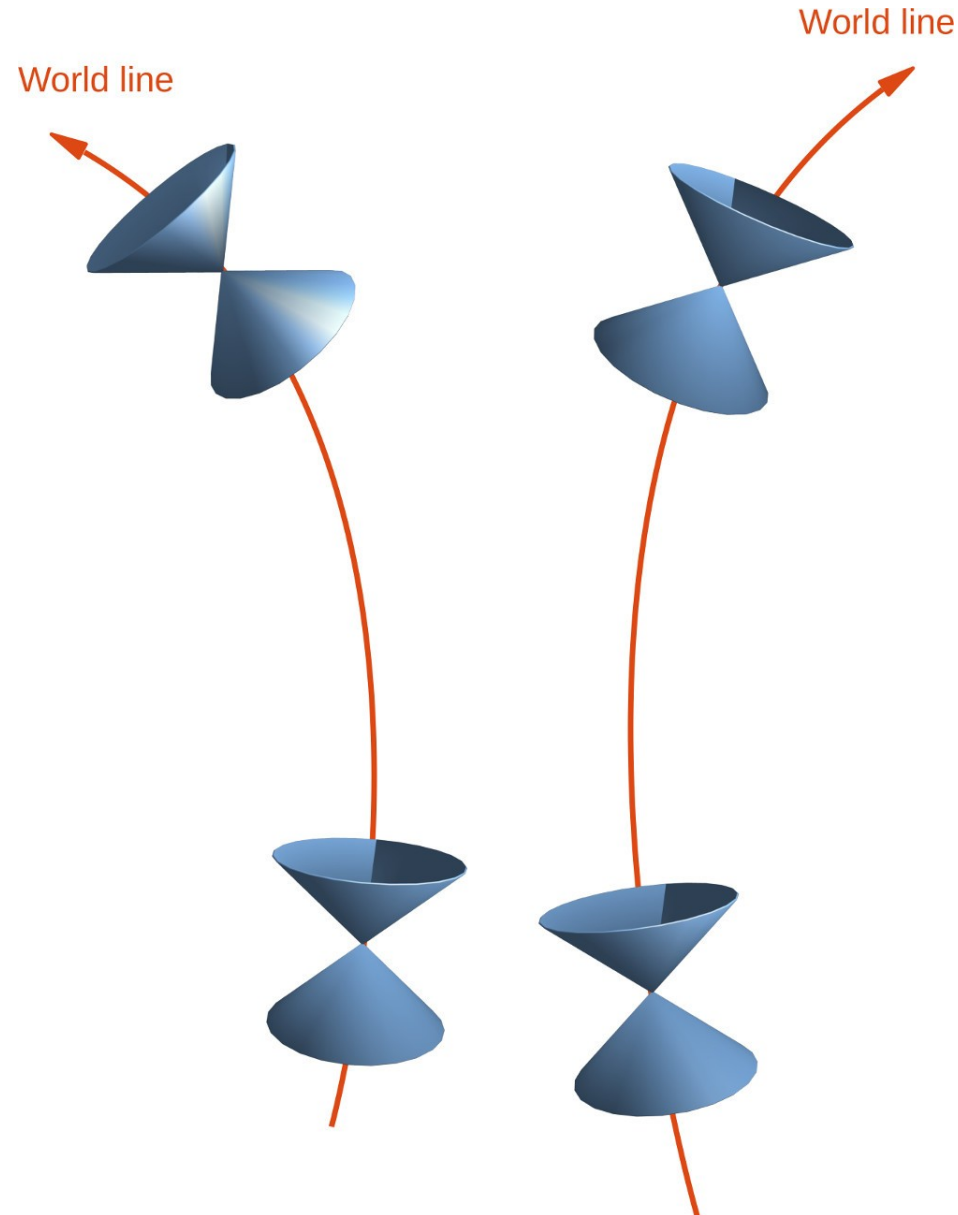
$$ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu$$

General relativity, equivalence principle



Special relativity
must continue to
hold in freely falling
reference frames.

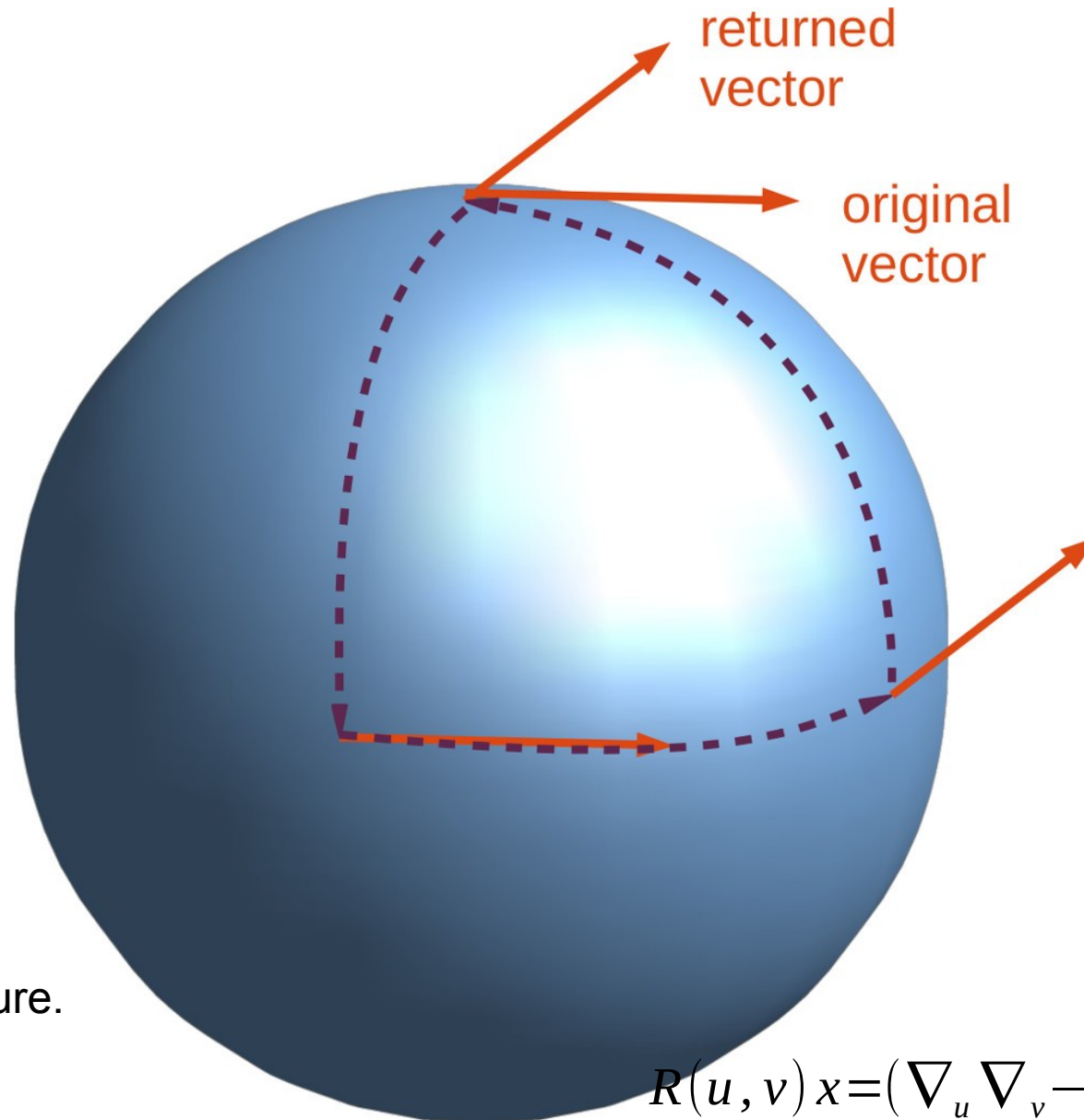
General relativity, light-cone structure



Metric η must turn into
a dynamical field g .

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

General relativity, curvature



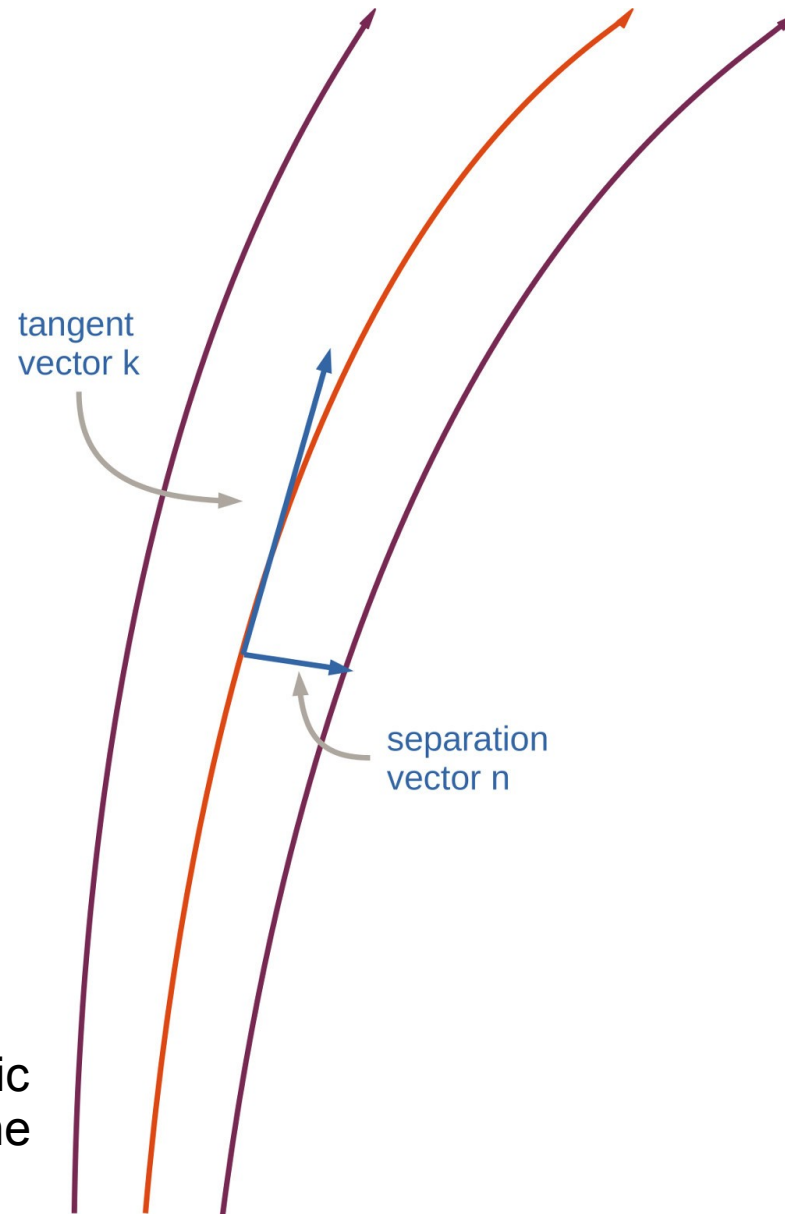
Riemann tensor
quantifies curvature.

$$R(u, v)X = (\nabla_u \nabla_v - \nabla_v \nabla_u - \nabla_{[u, v]})X$$

General relativity, curvature



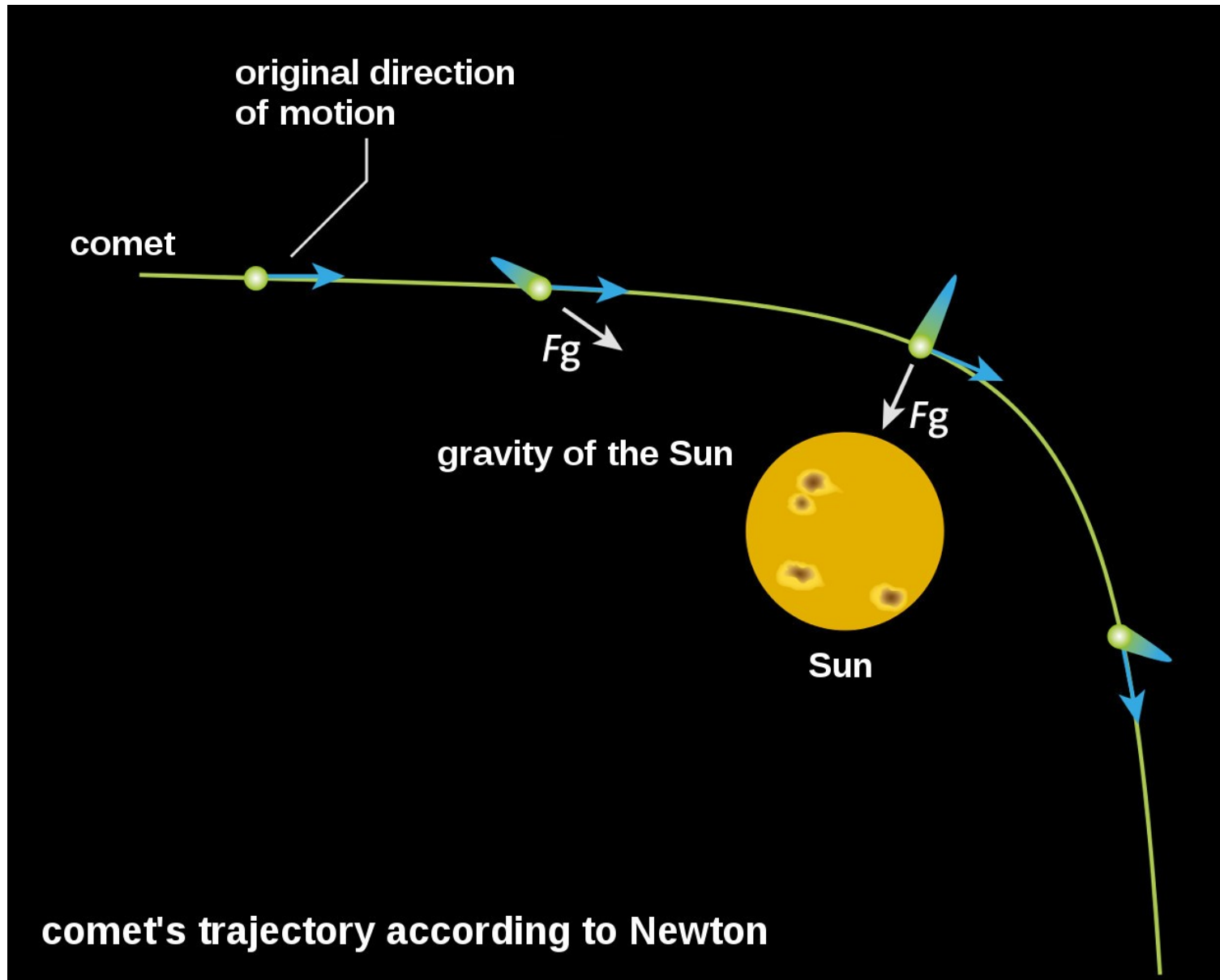
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386



The evolution of a geodesic bundle is determined by the Riemann tensor.

$$\nabla_k^2 n = R(k, n)k$$

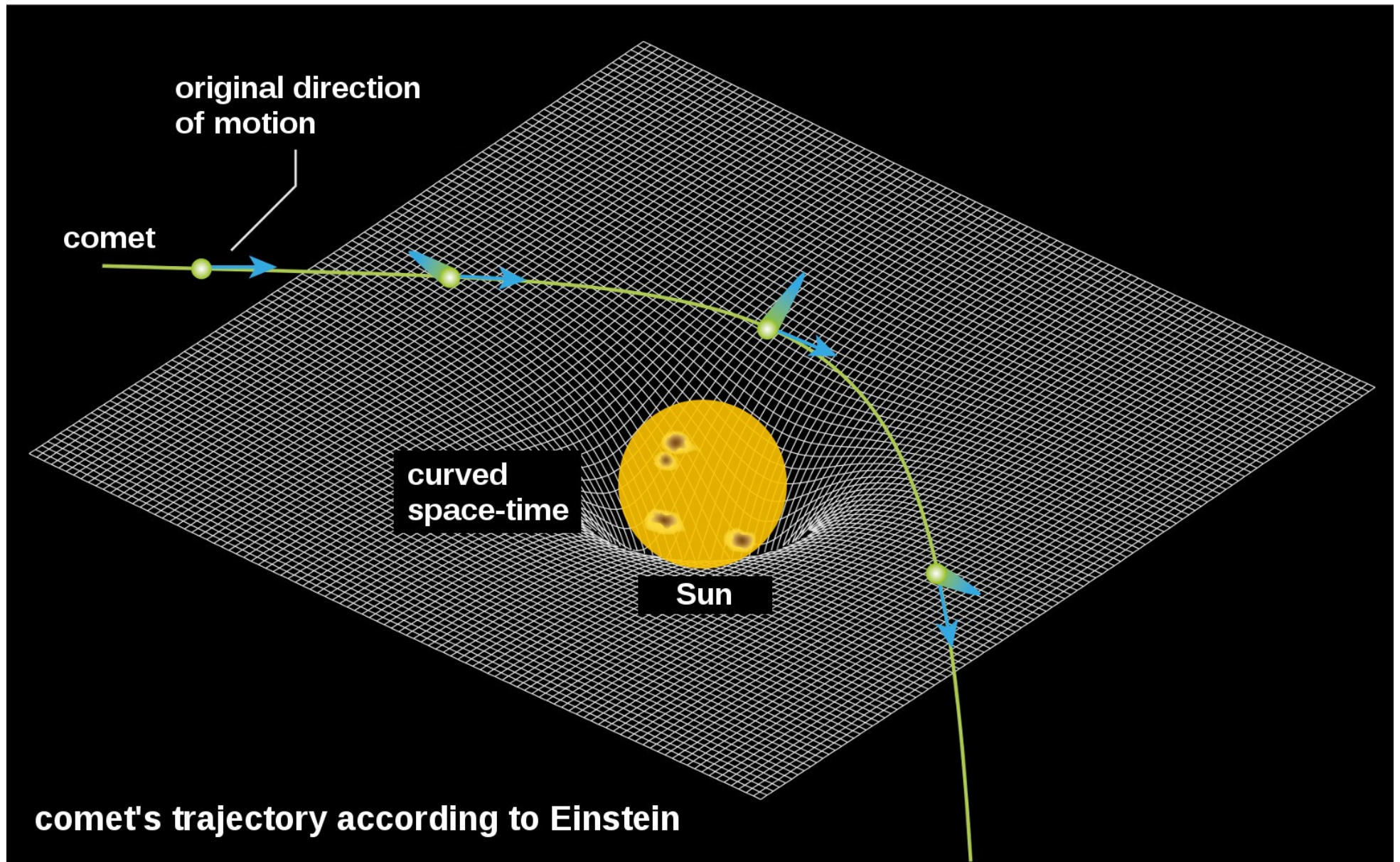
Gravity according to Newton



Gravity according to Einstein

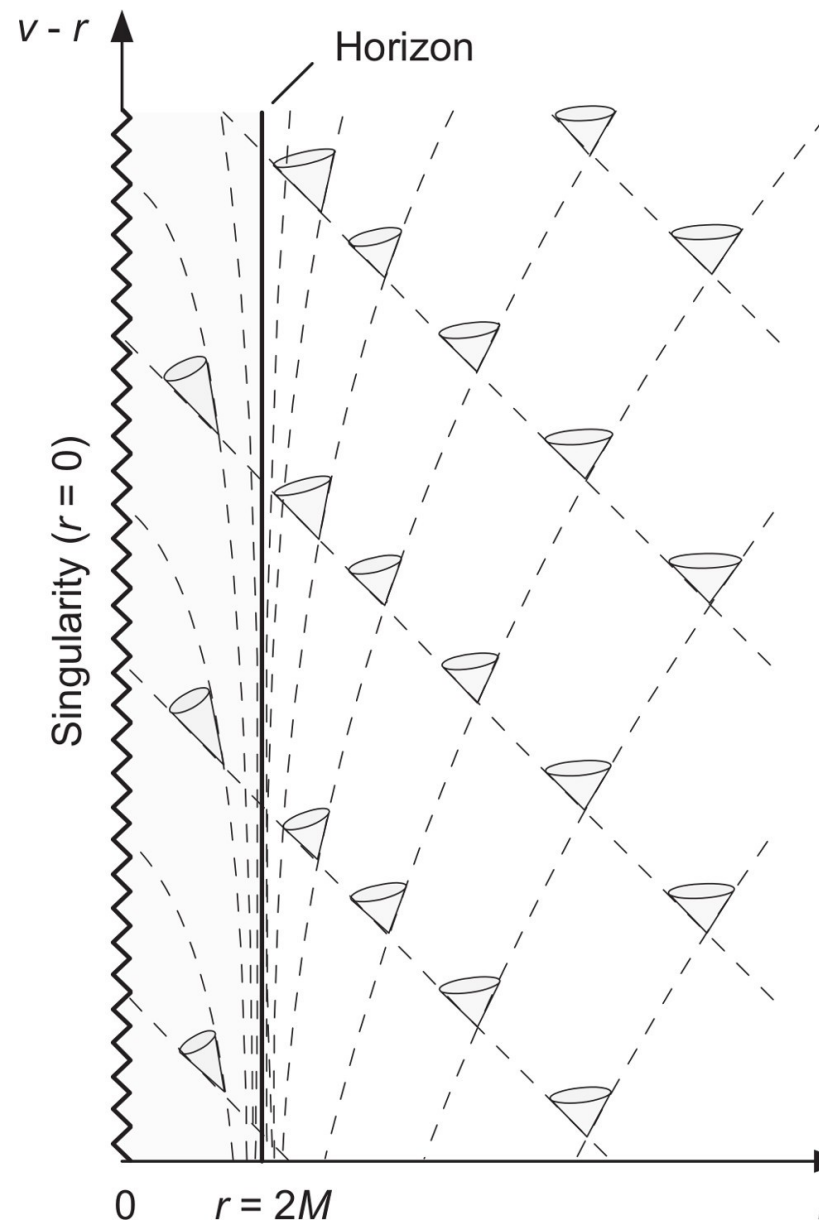
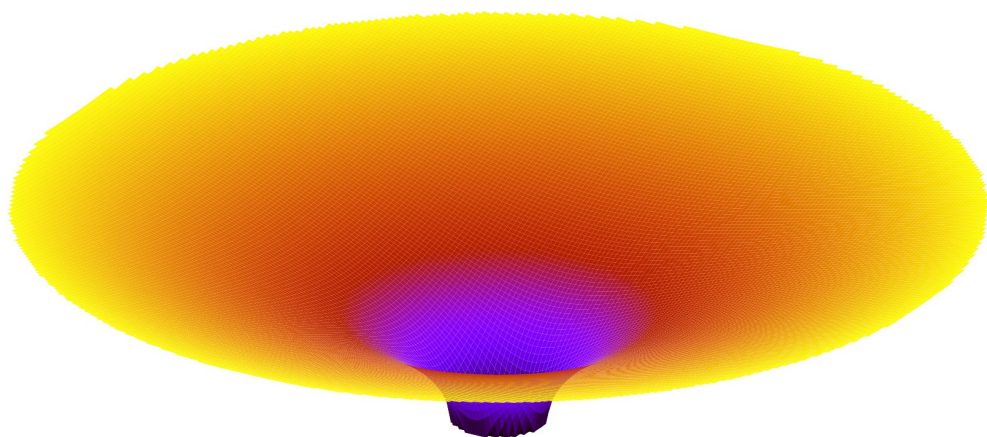


UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

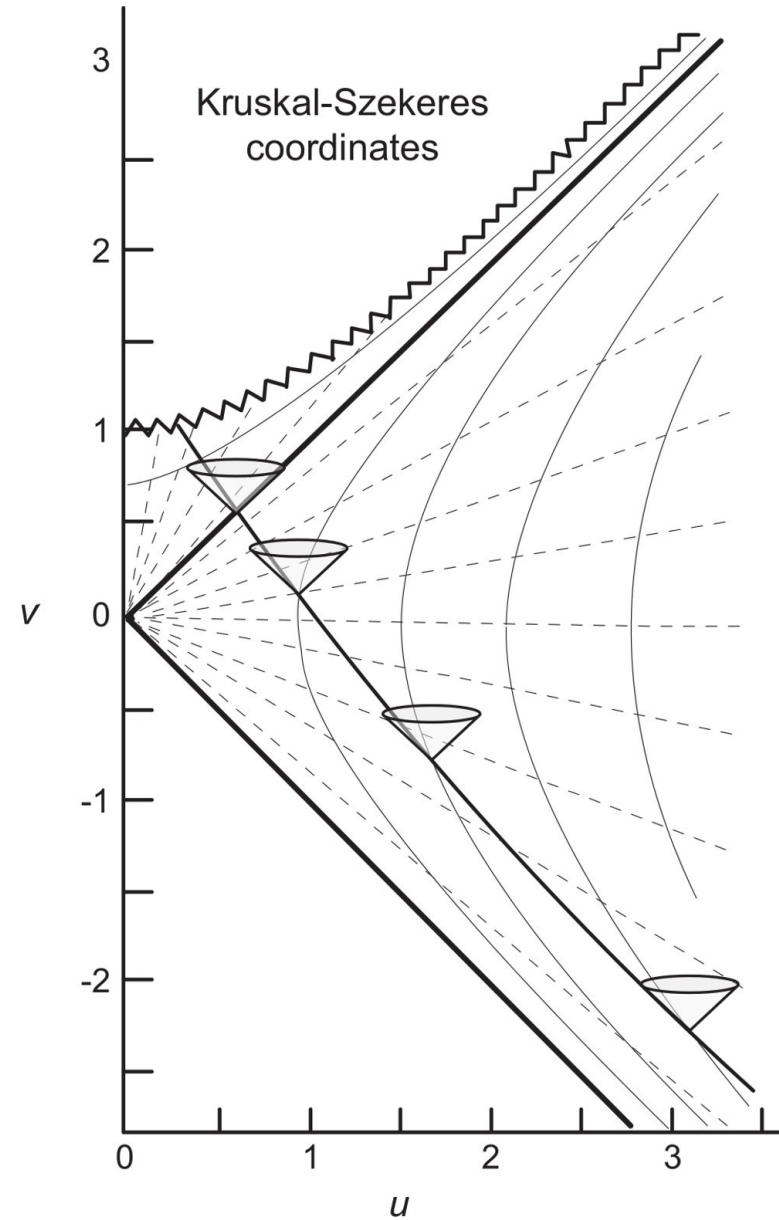
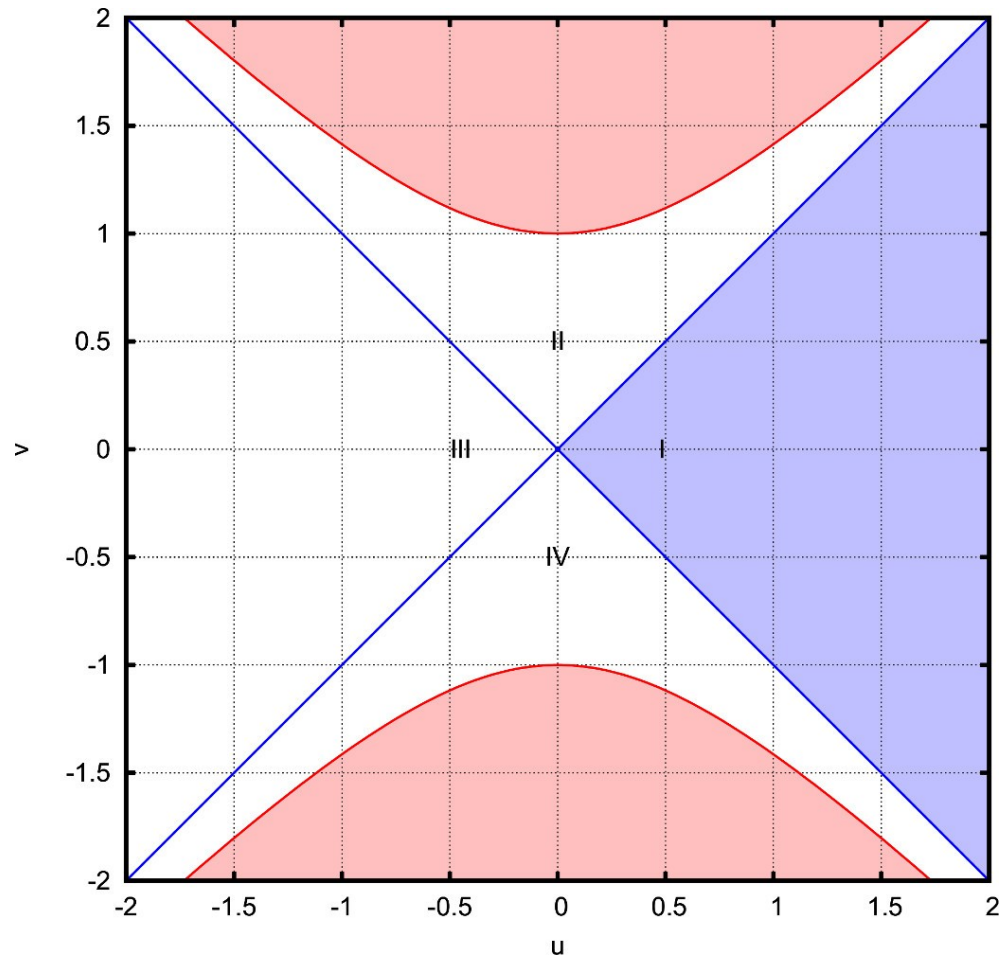


comet's trajectory according to Einstein

Horizons near black holes



Black holes in Kruskal coordinates



Horizons in cosmology



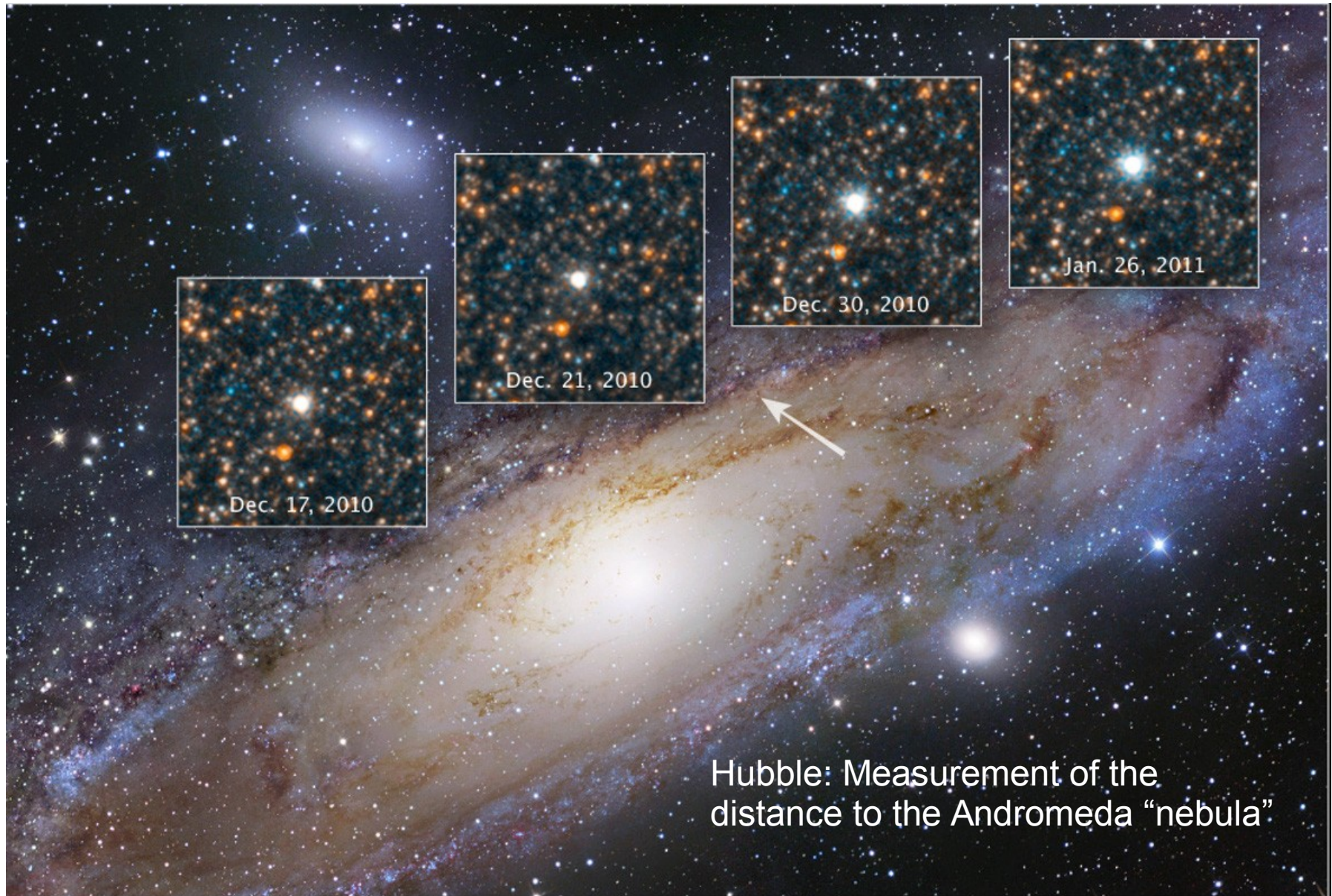
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386



Distance measurement



UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386



Hubble: Measurement of the distance to the Andromeda "nebula"

Recession of the galaxies



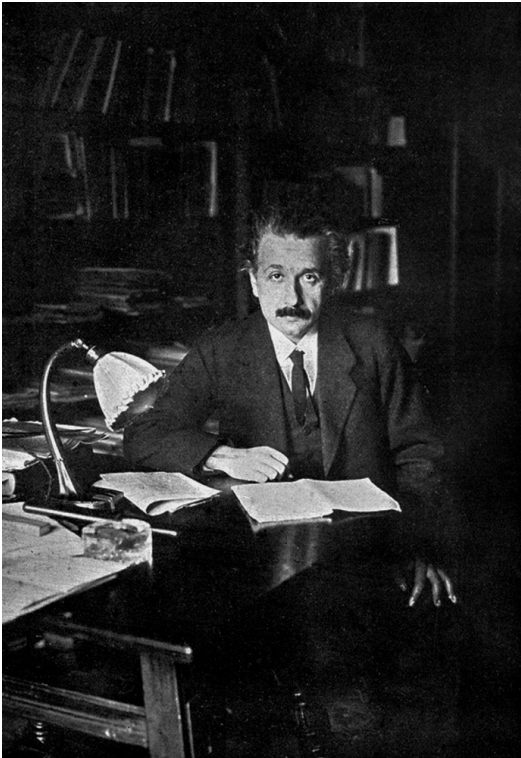
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386



Expanding world models



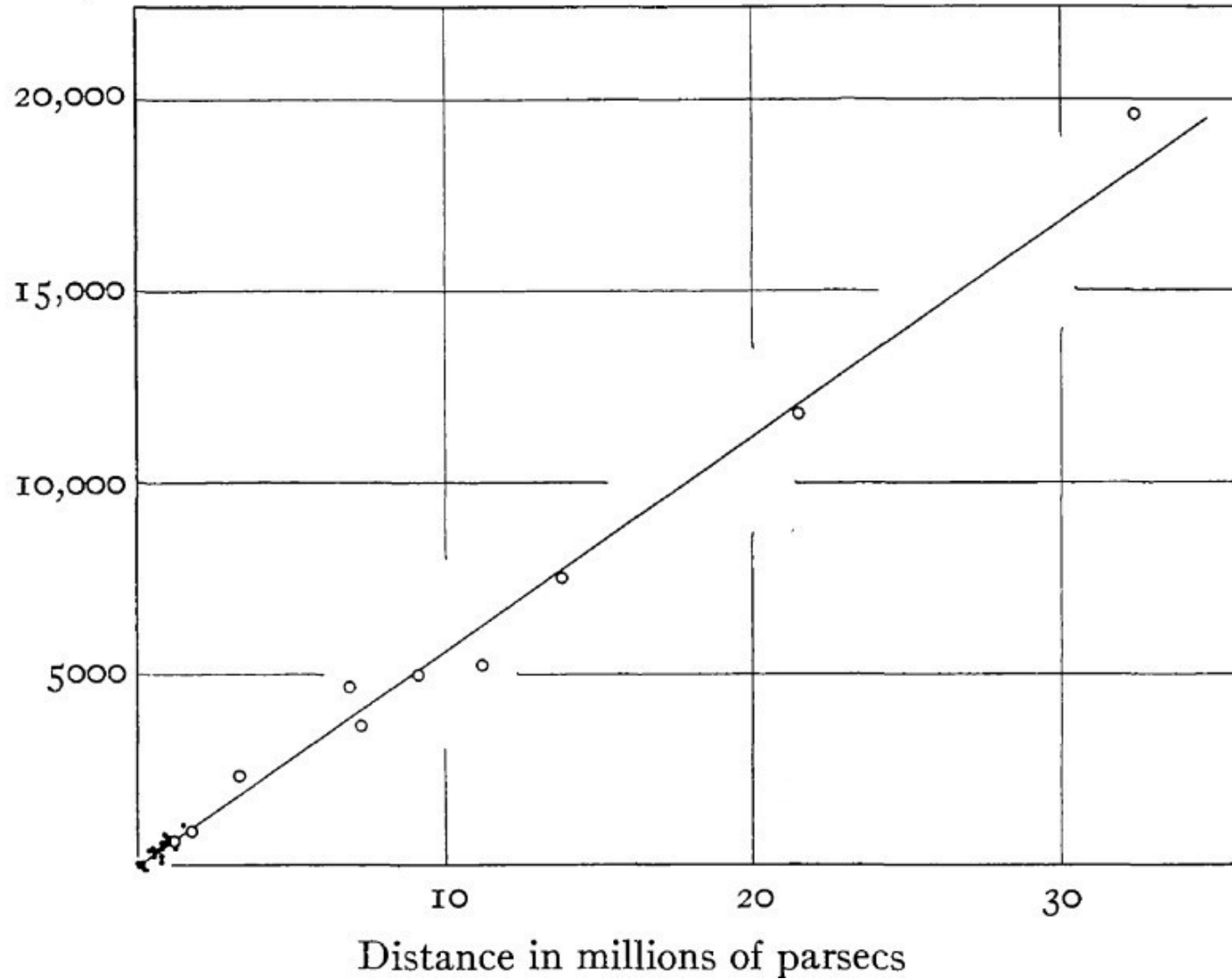
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386



Hubble diagram



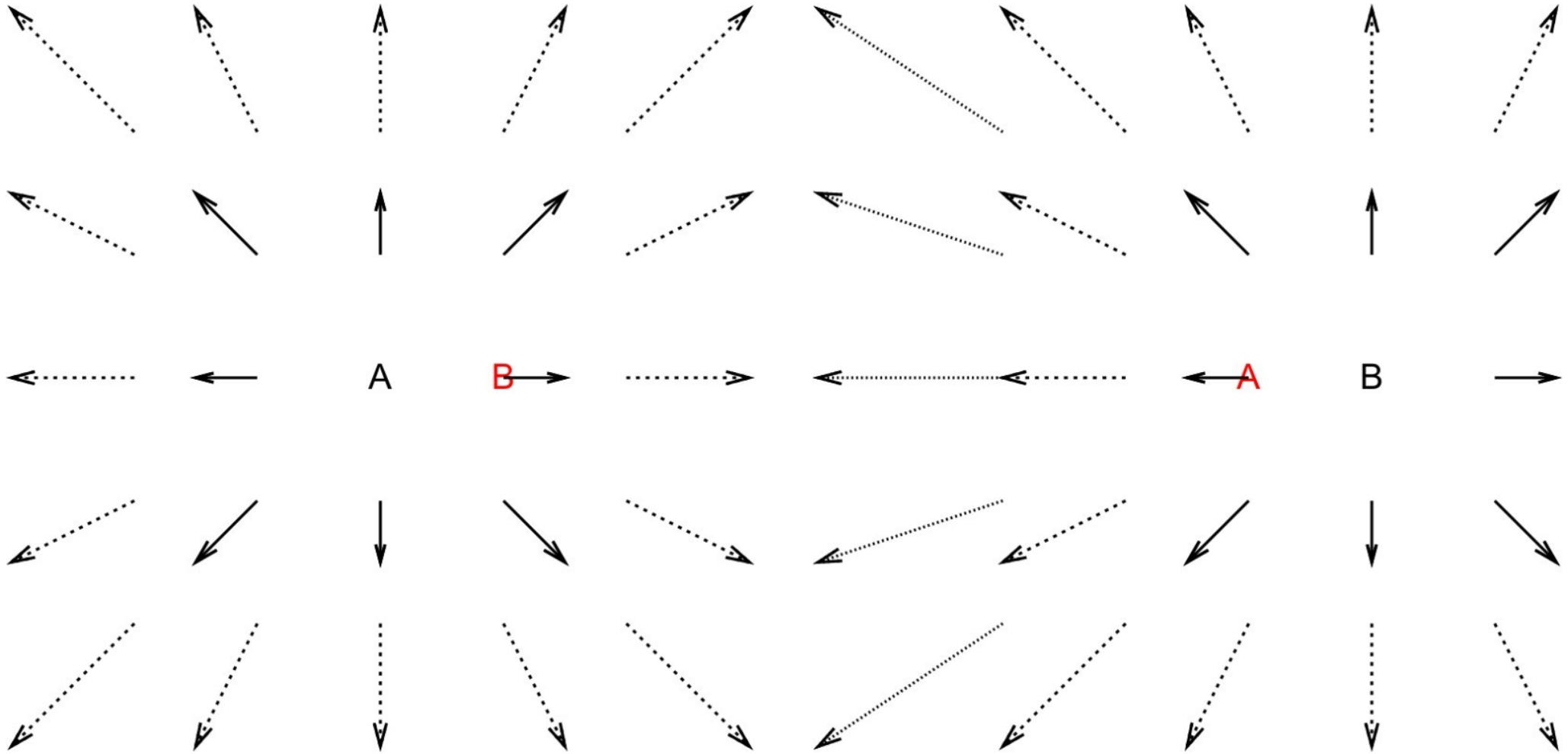
Velocity
in km/sec.



Expansion of the Universe



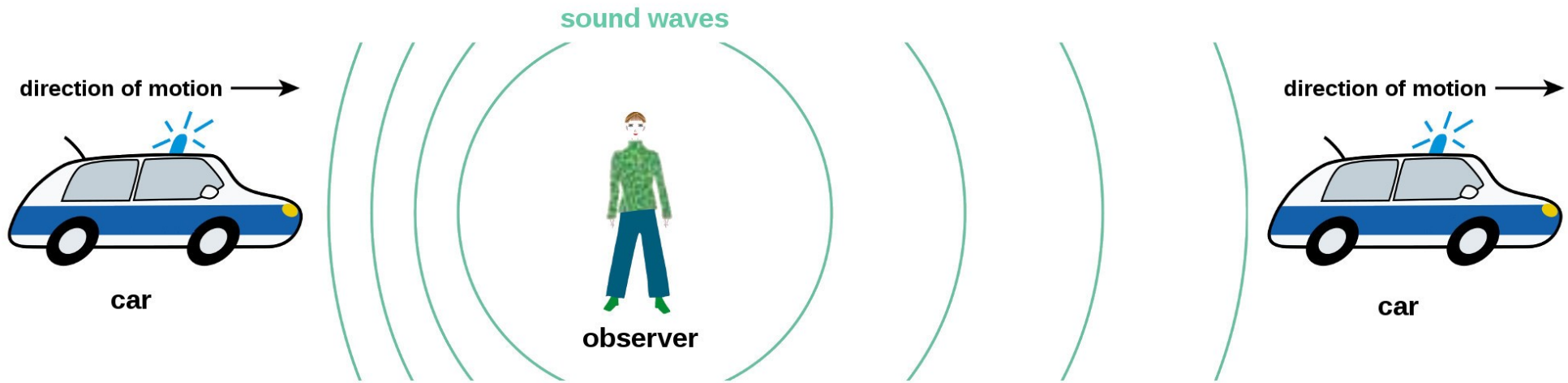
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386



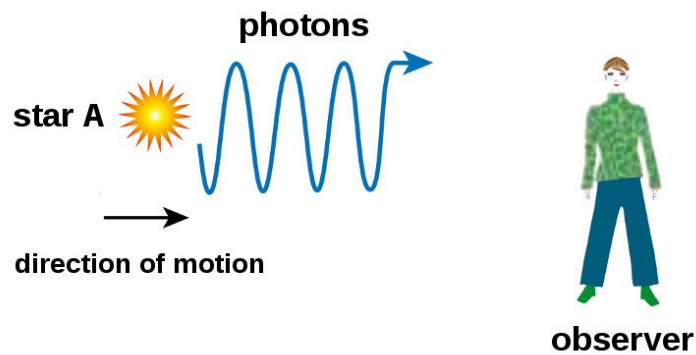
Doppler effect and redshift



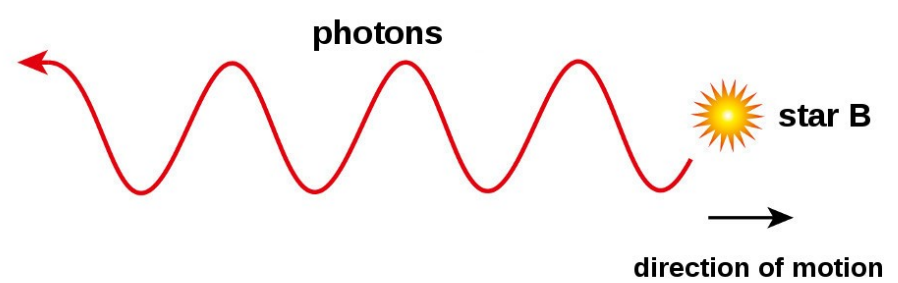
Doppler red- or blueshift



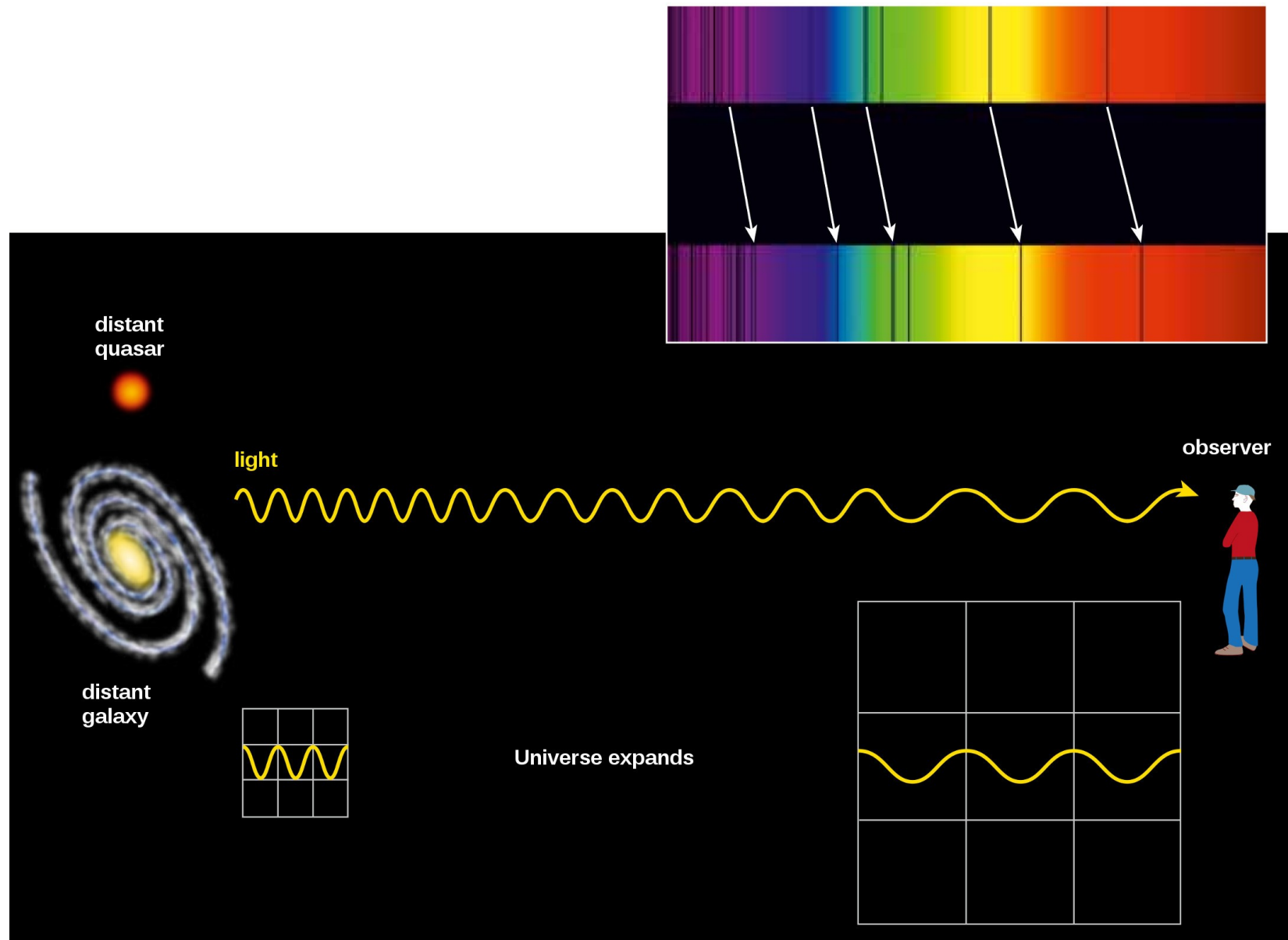
blueshift



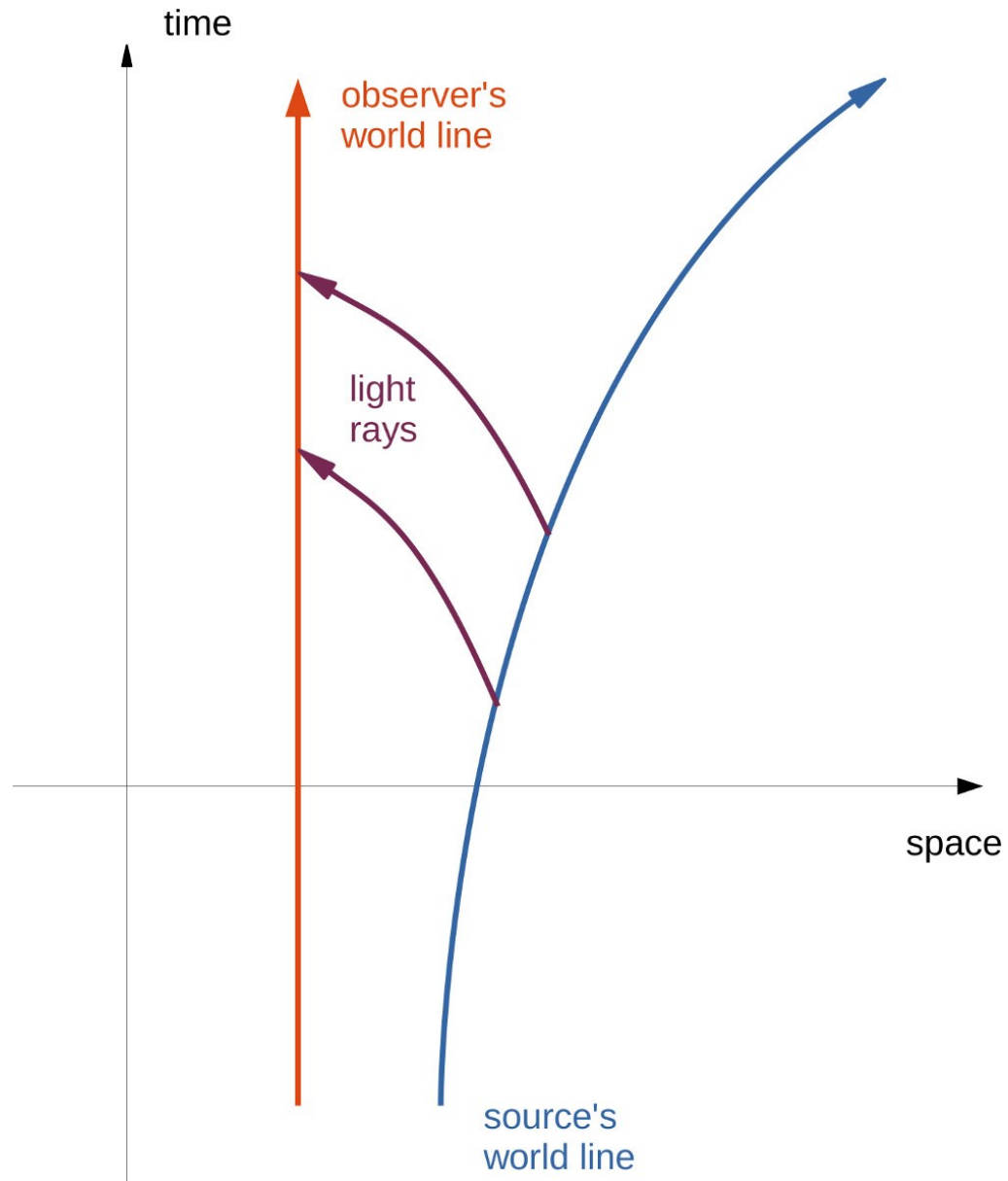
redshift



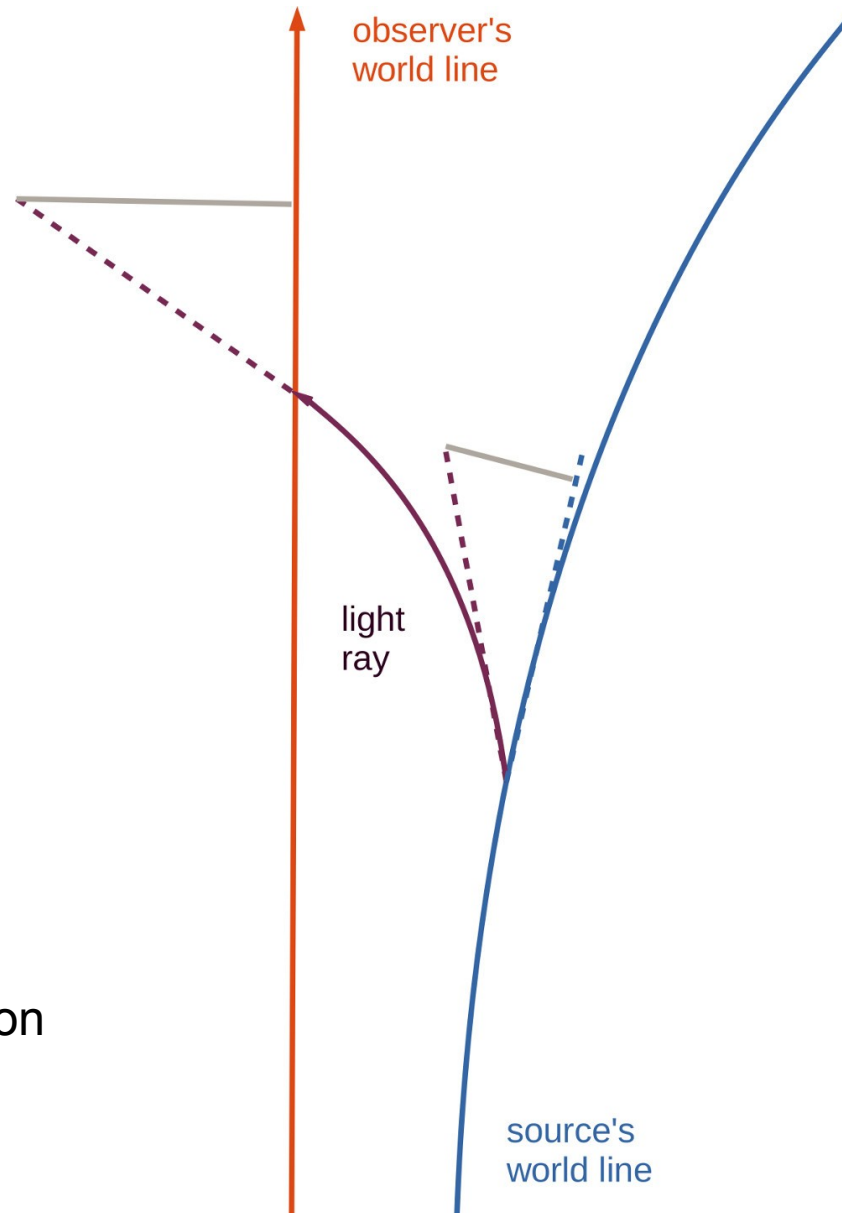
Cosmological redshift



Relativistic redshift



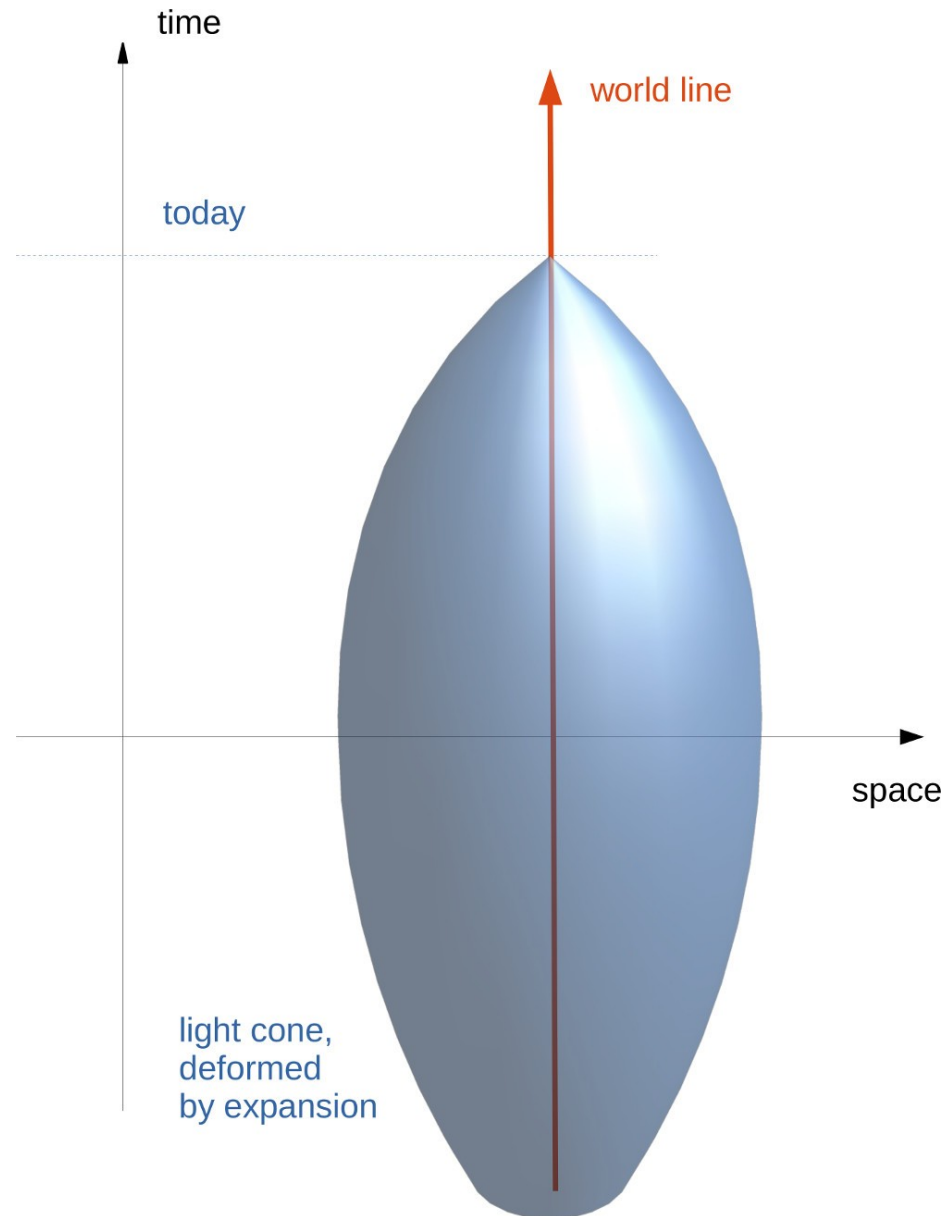
Relativistic redshift



Frequency is the projection of the tangent to the light ray on the tangent of the world line.

$$\omega = -\langle k, u \rangle = -k_{\mu} u^{\mu}$$

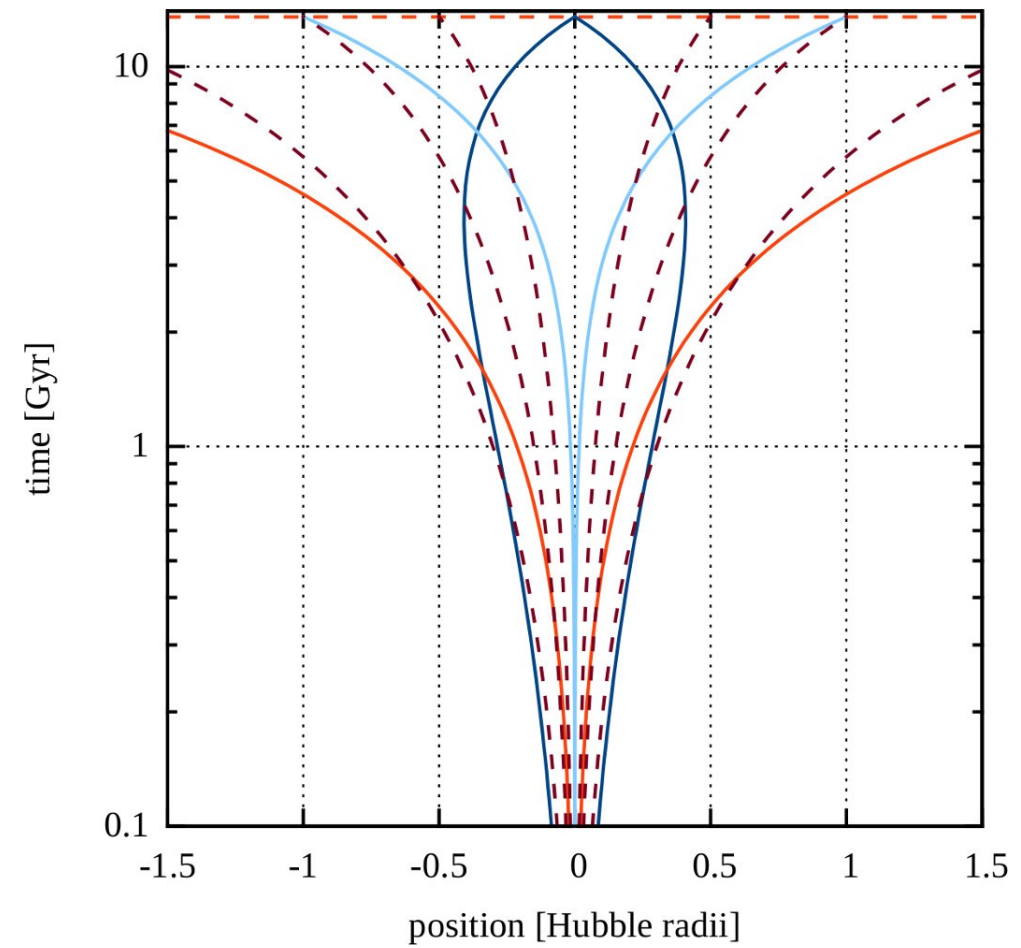
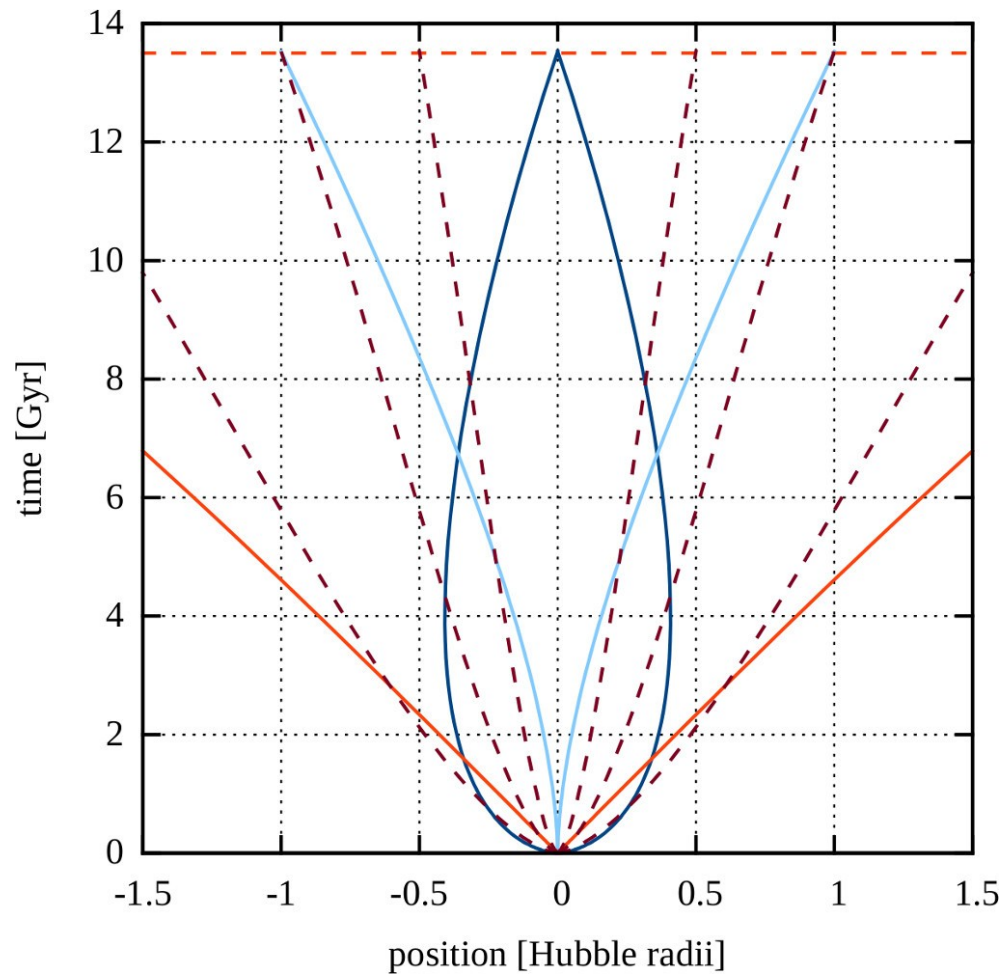
Past light cone in cosmology



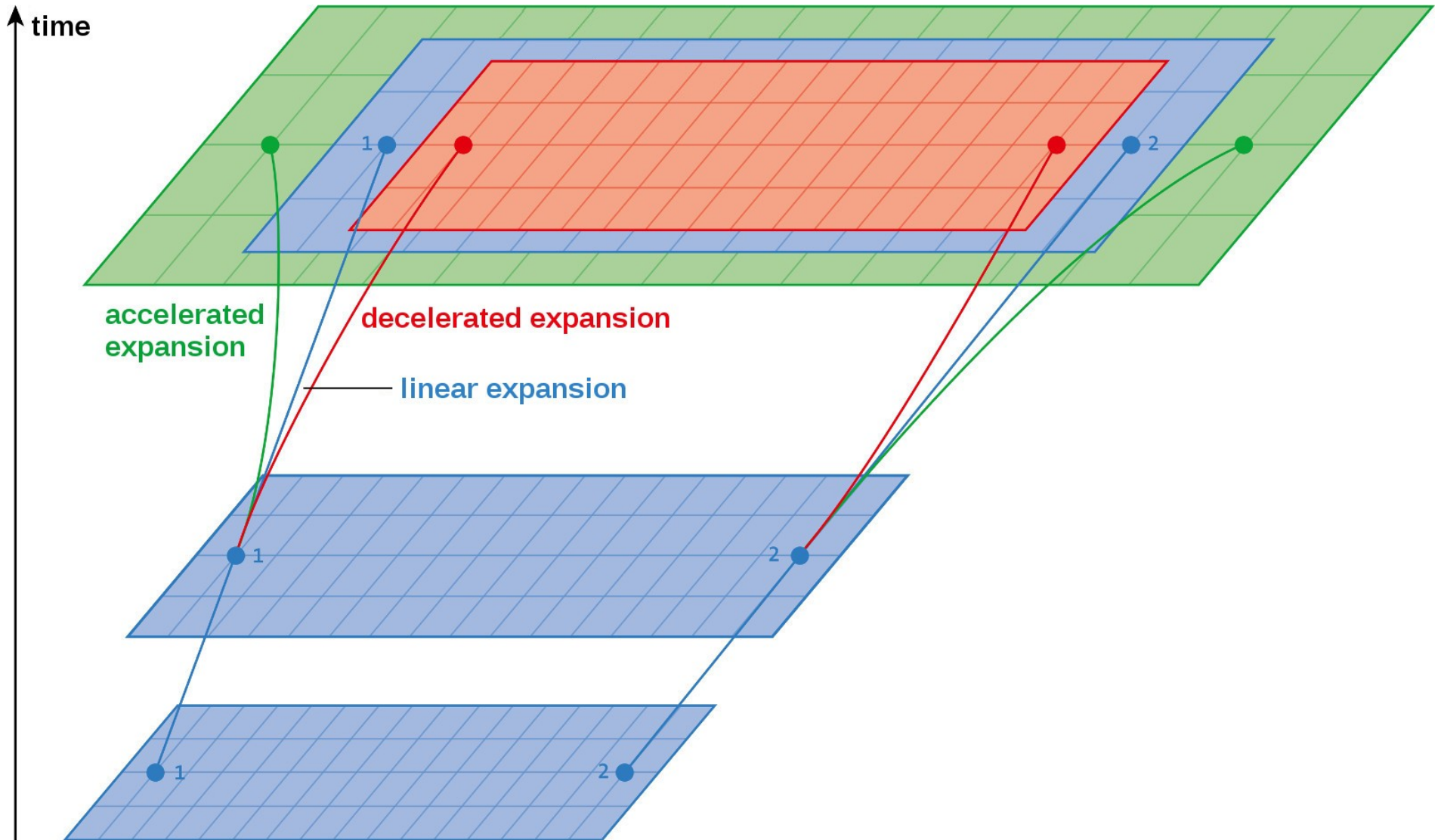
Past light cone in cosmology



UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

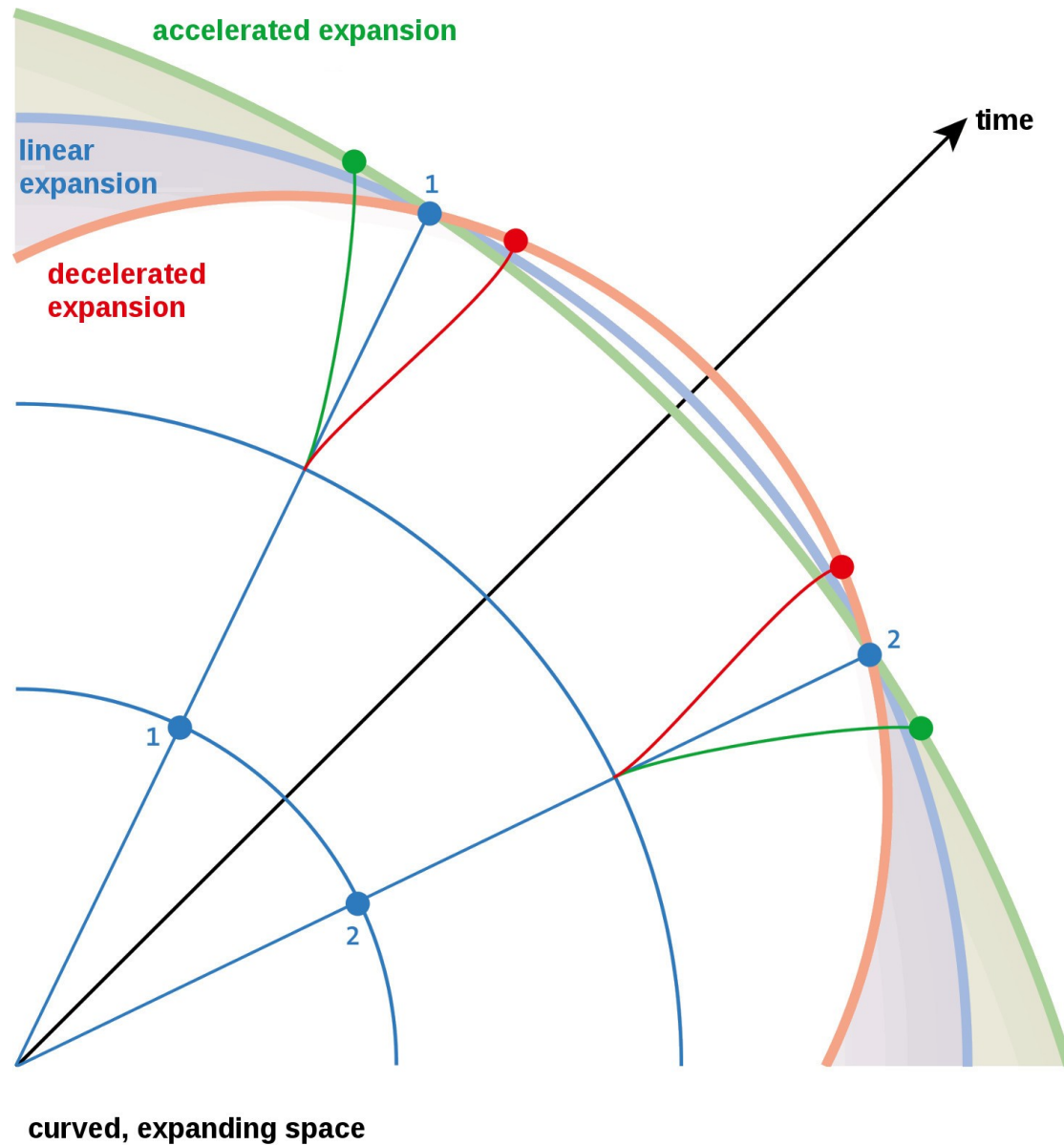


Space-time curvature



flat, expanding space

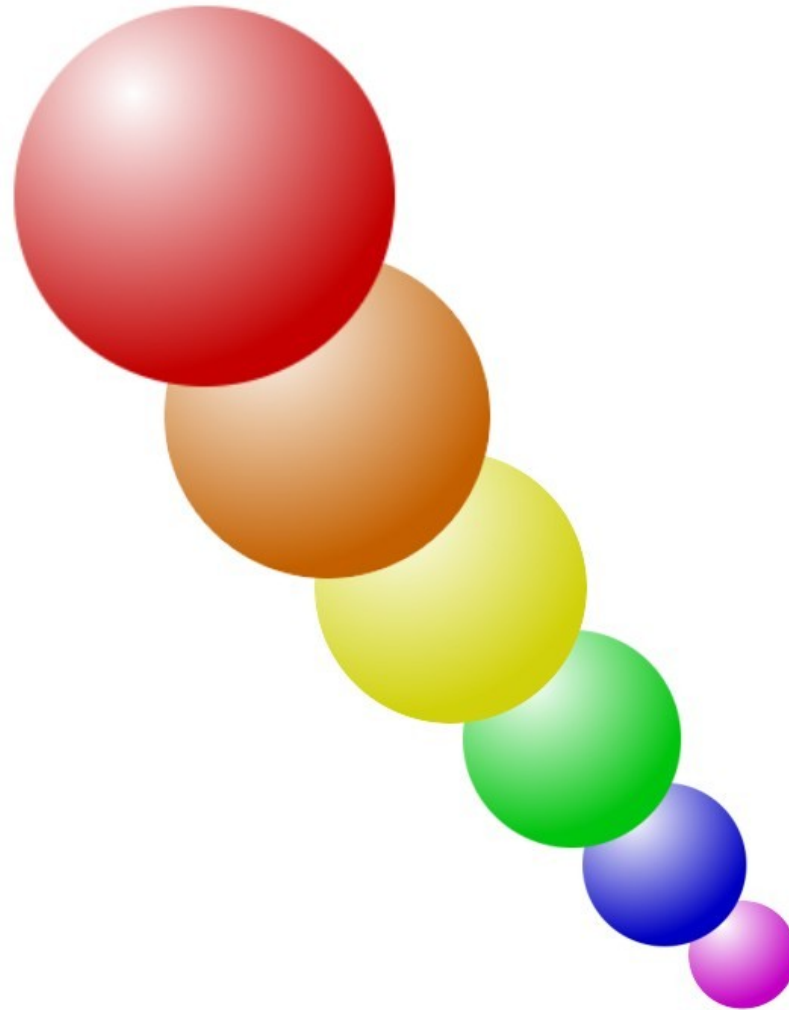
Space-time curvature



Expansion and temperature



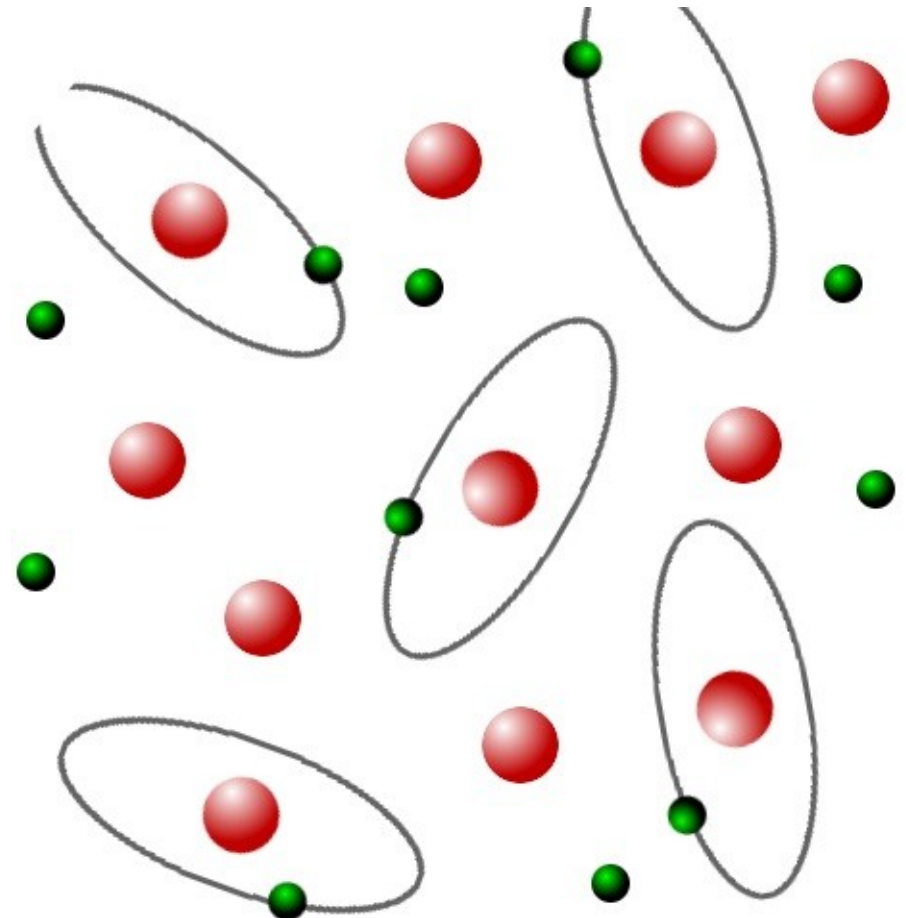
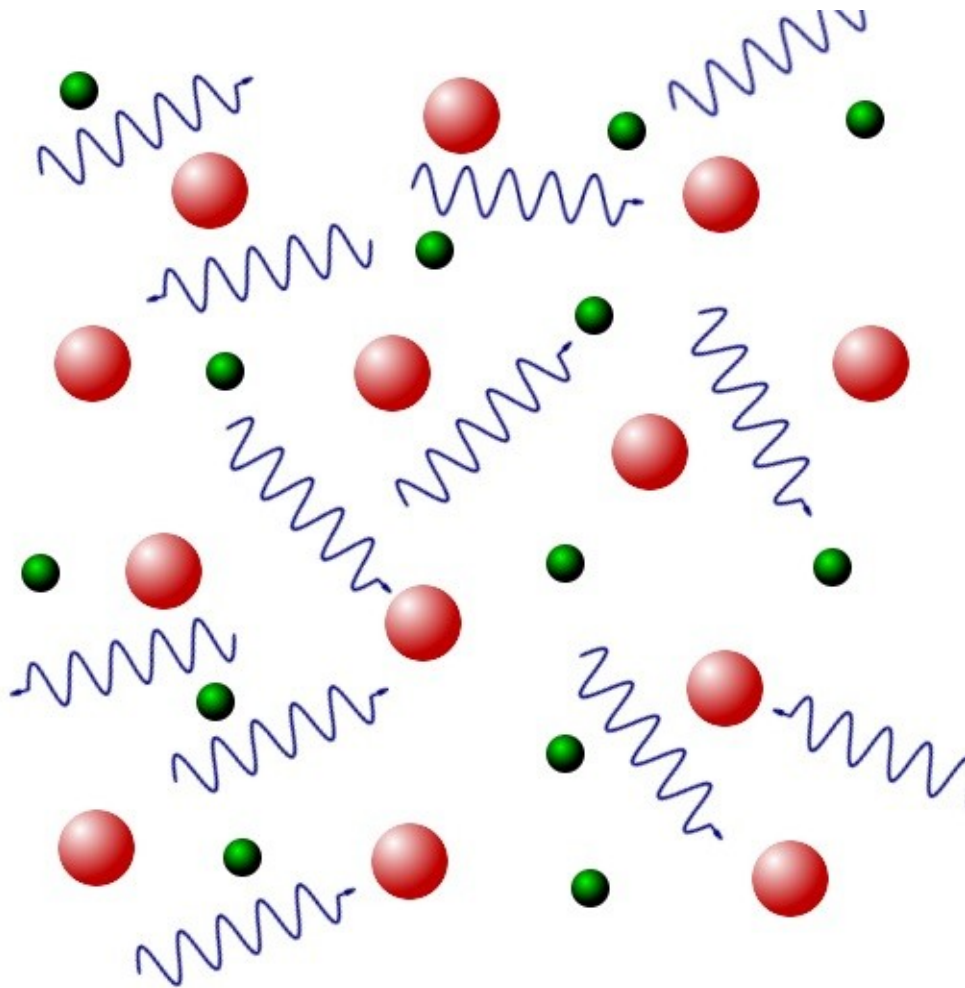
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386



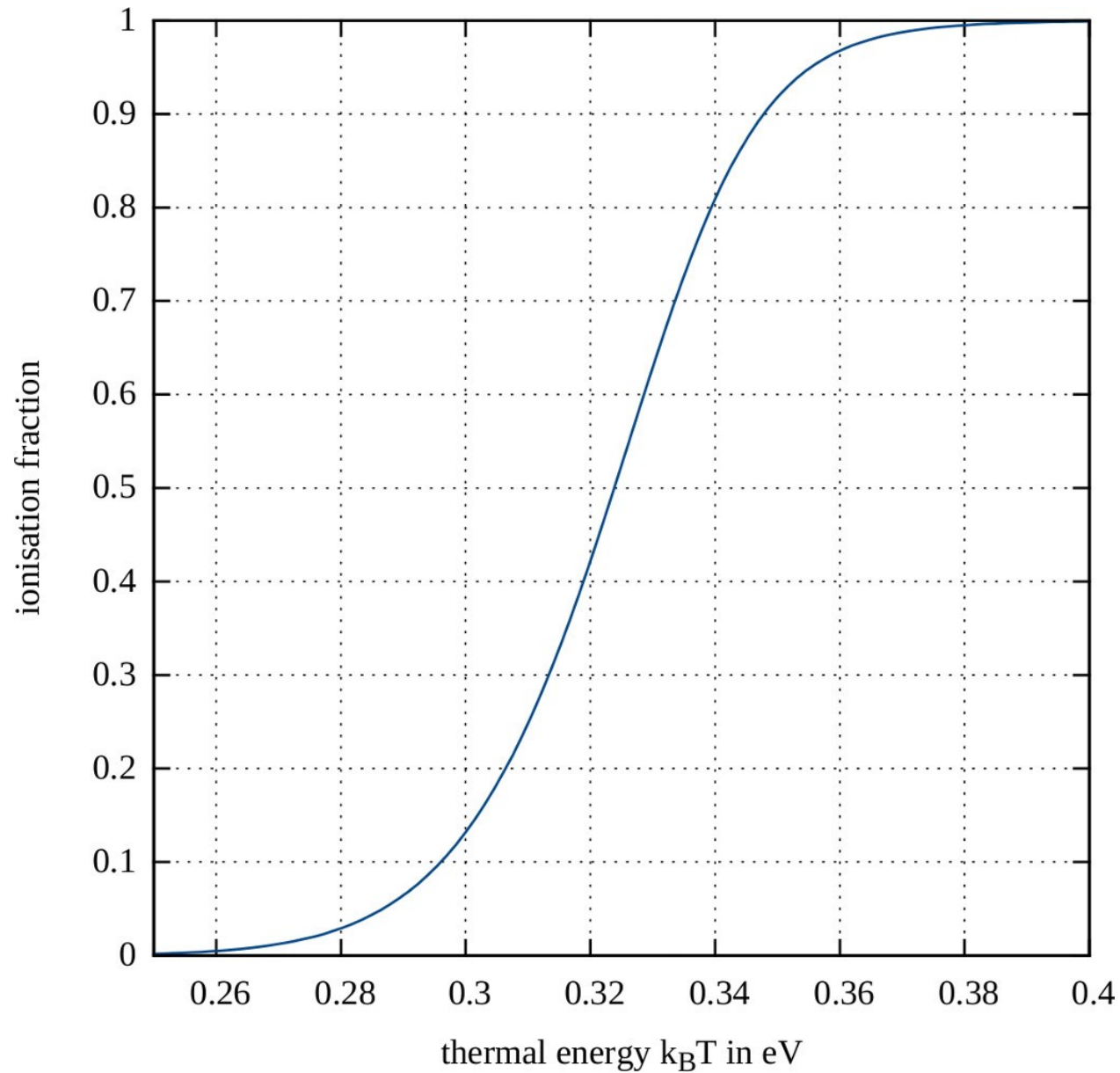
Early plasma and early light



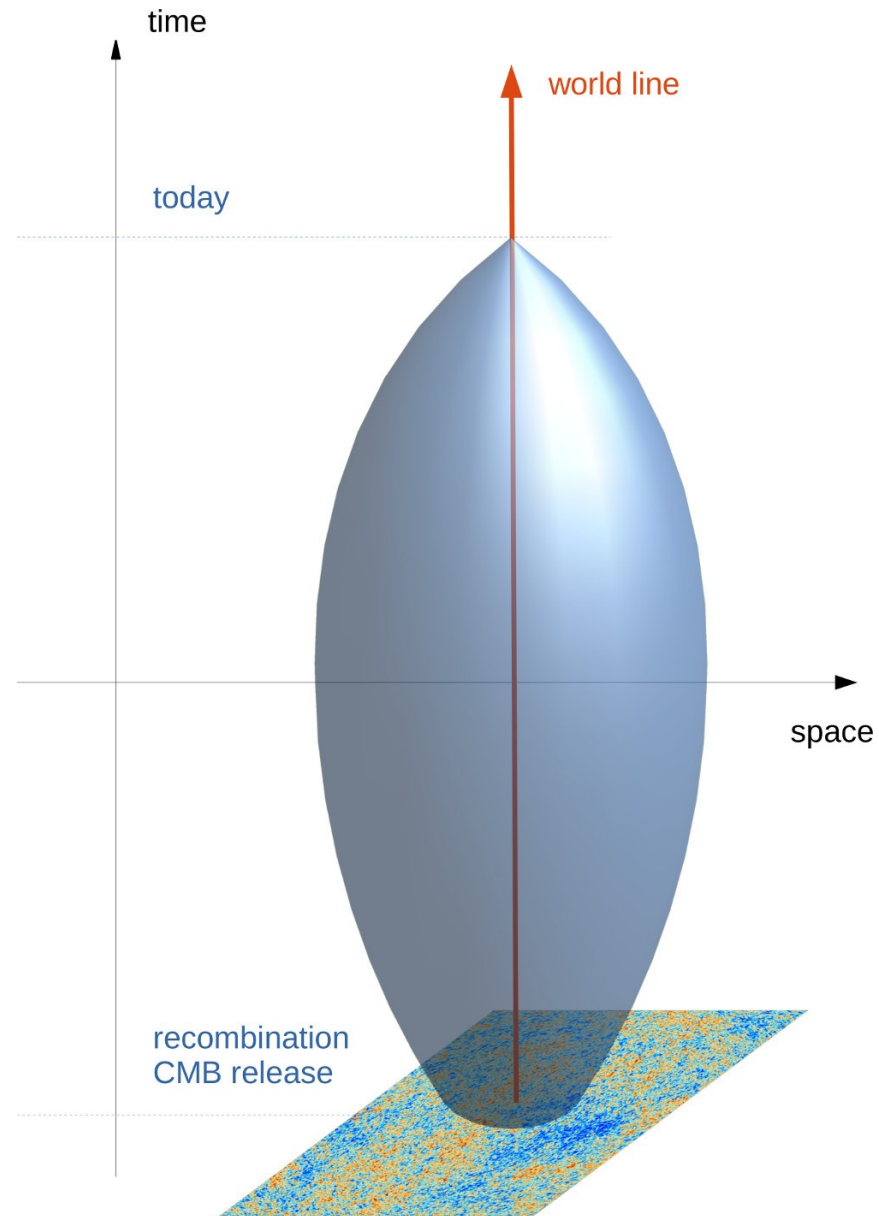
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386



“Re”-combination



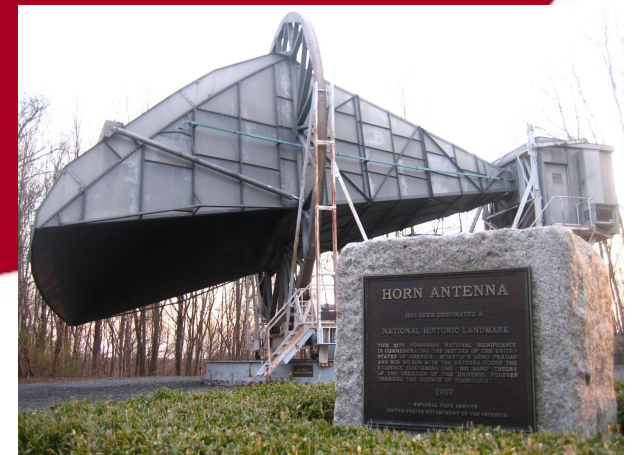
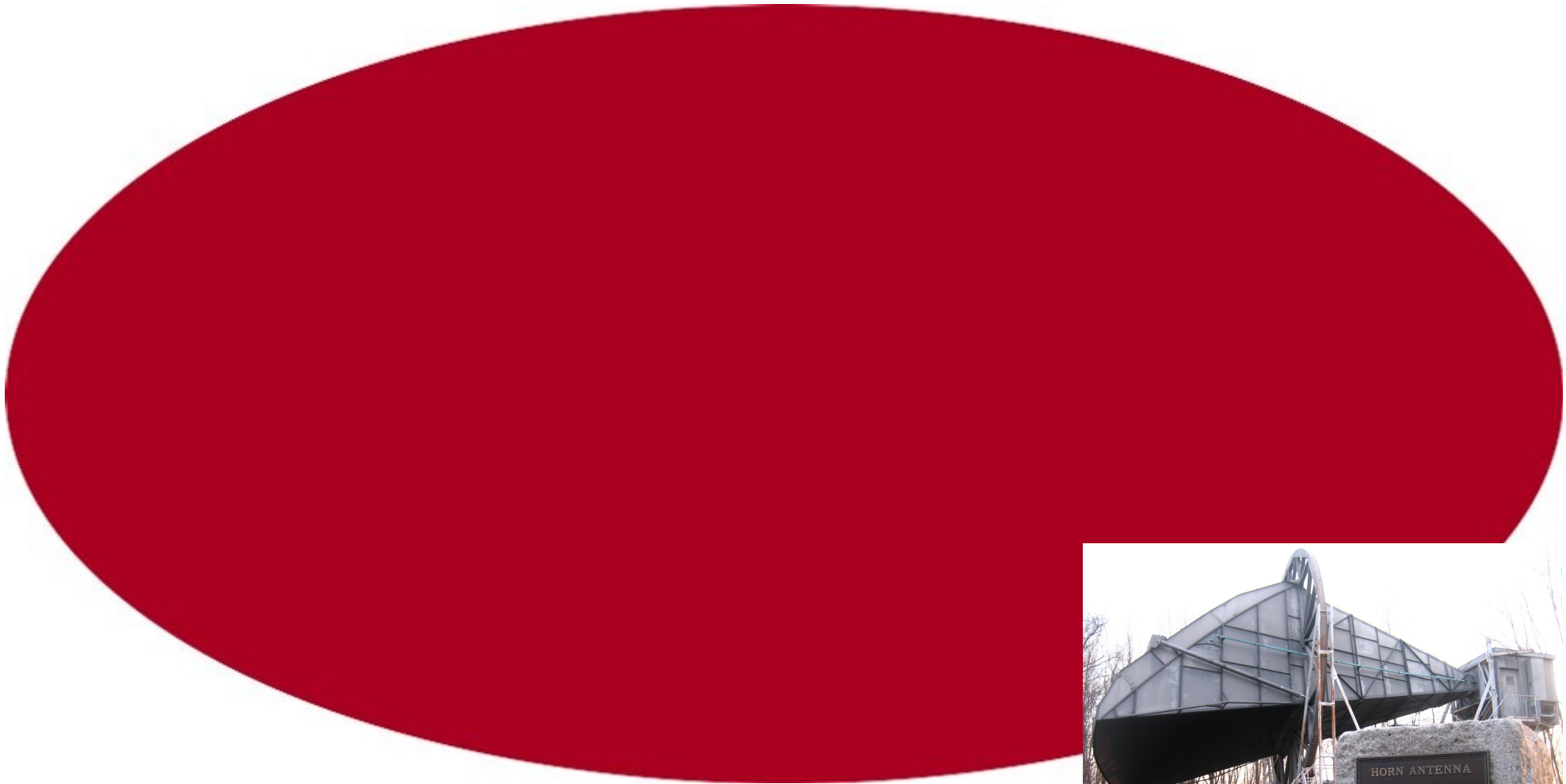
Recombination in the past light cone



Cosmic microwave background (CMB)



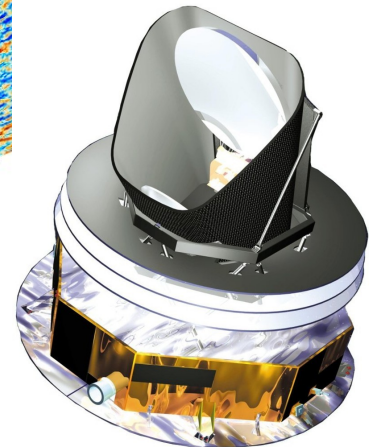
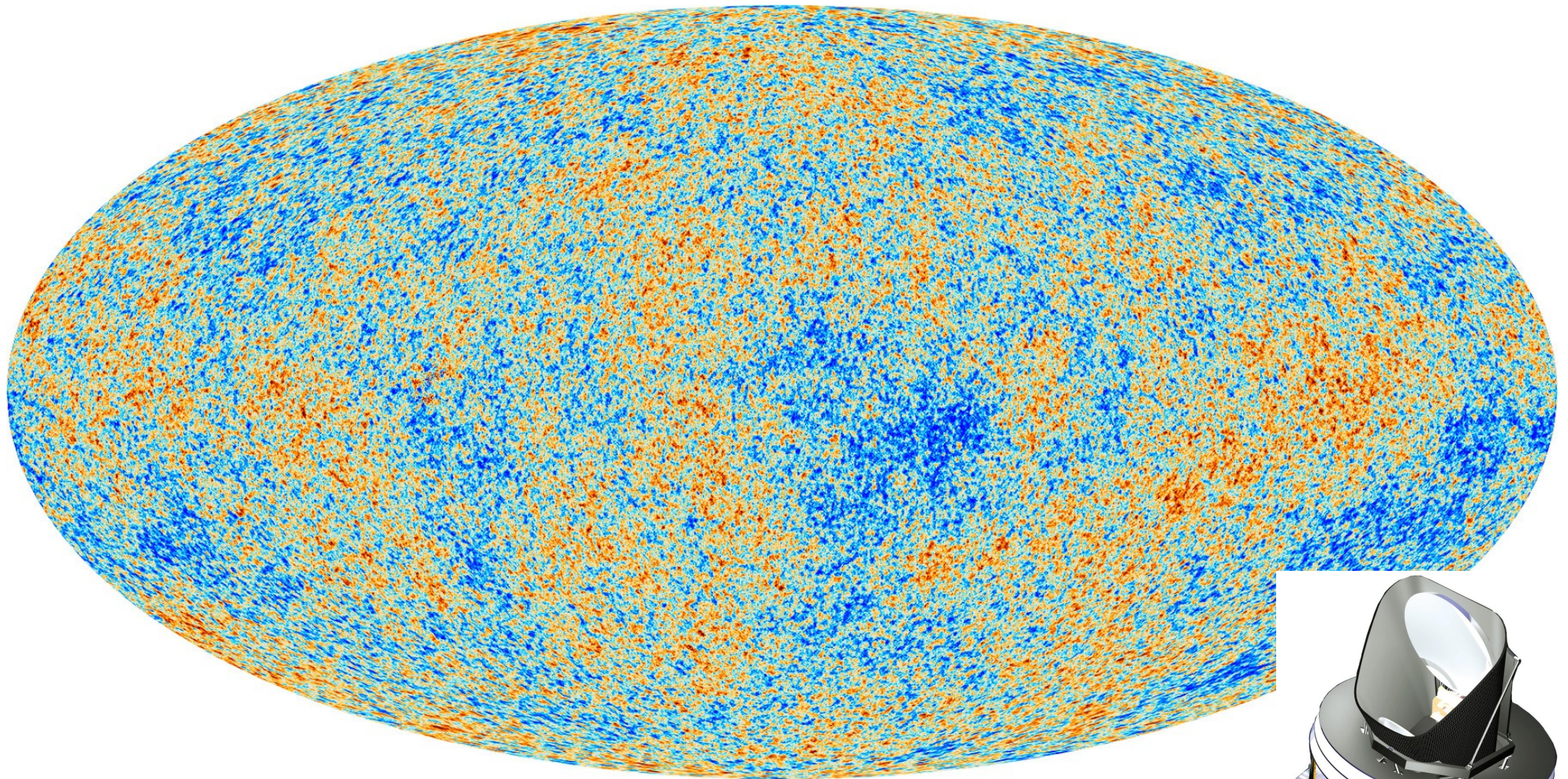
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386



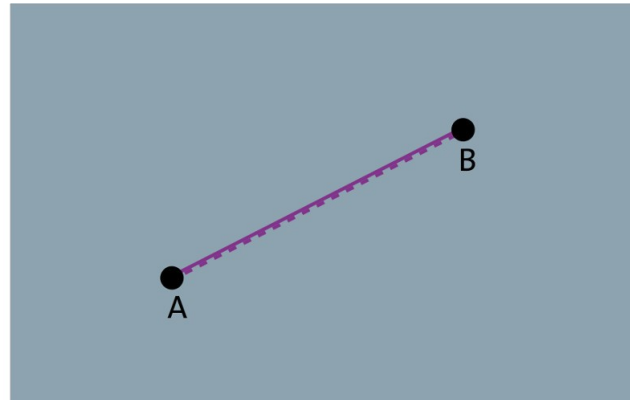
Structures in the CMB



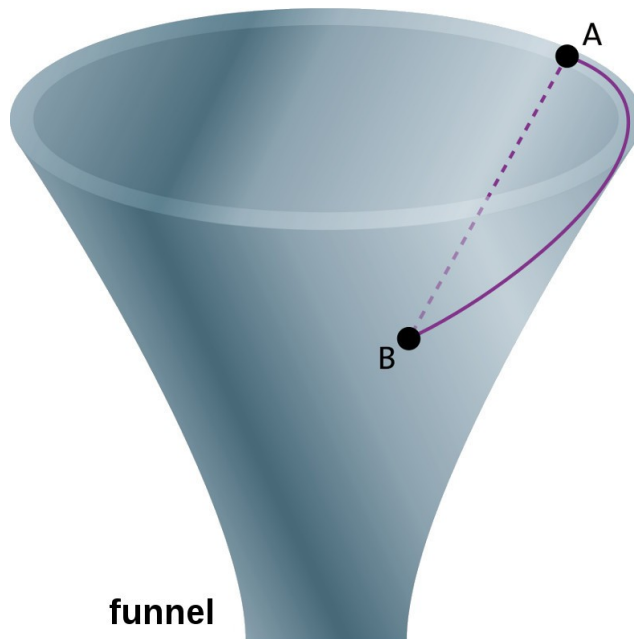
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386



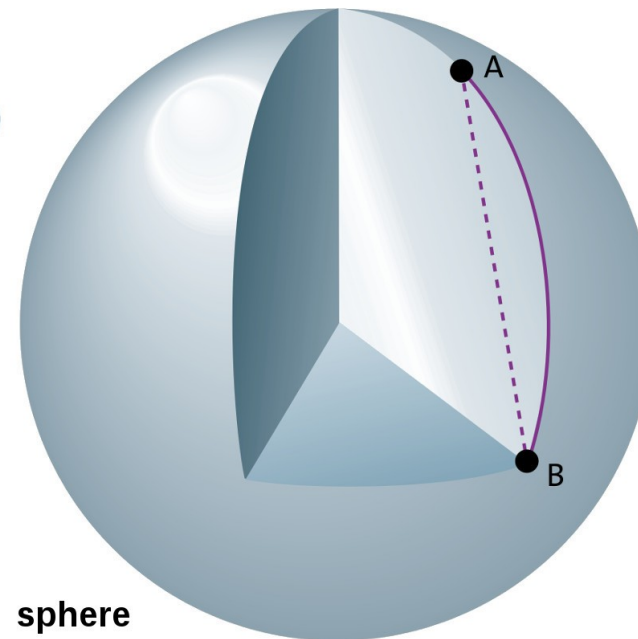
Distances in curved space-time



flat space

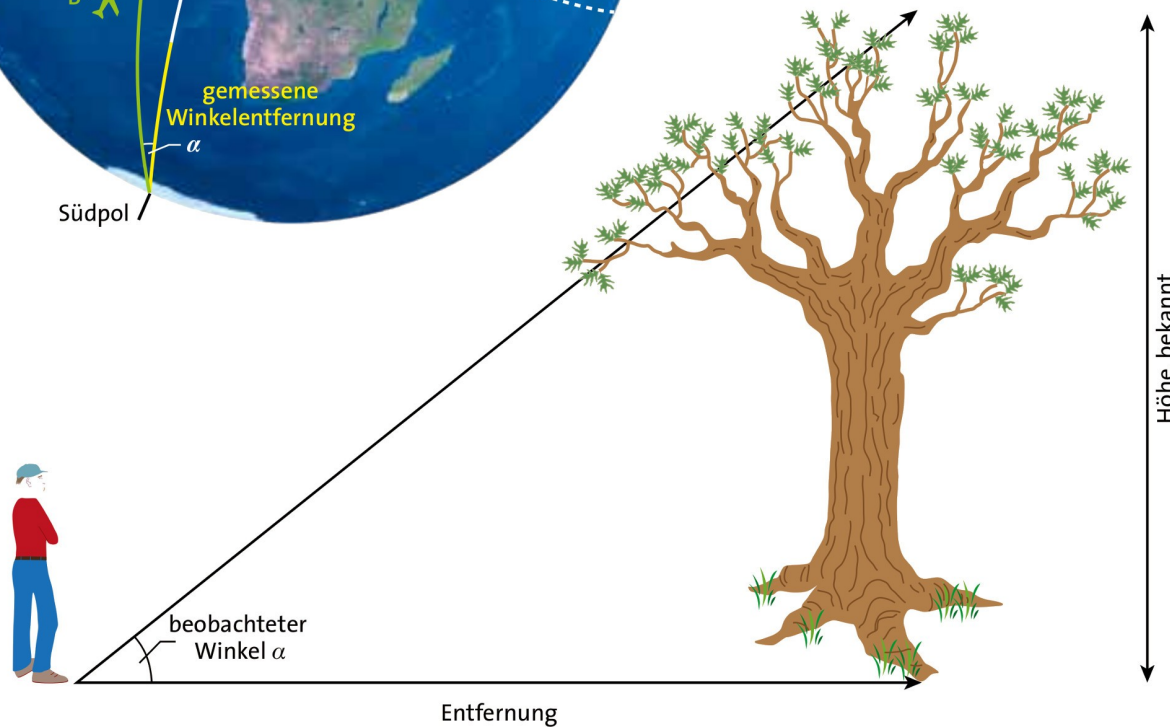
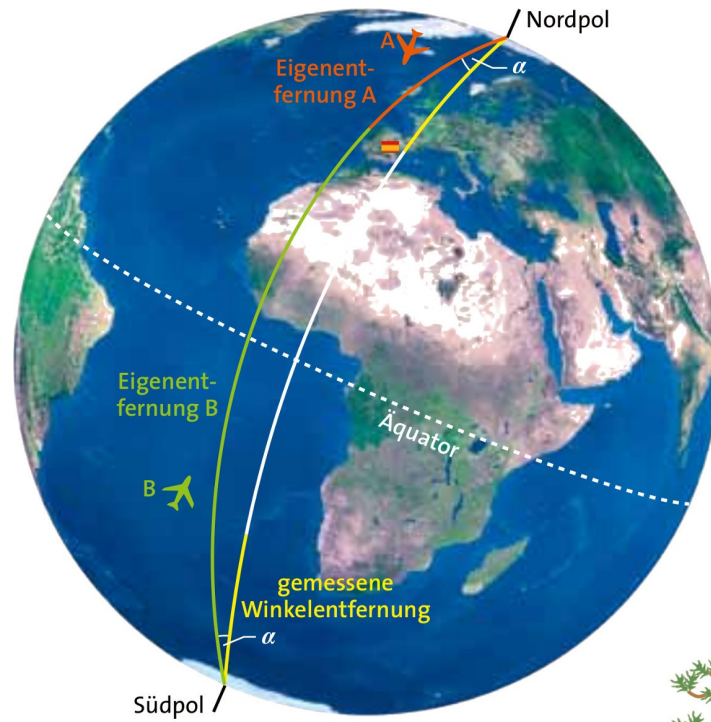


funnel

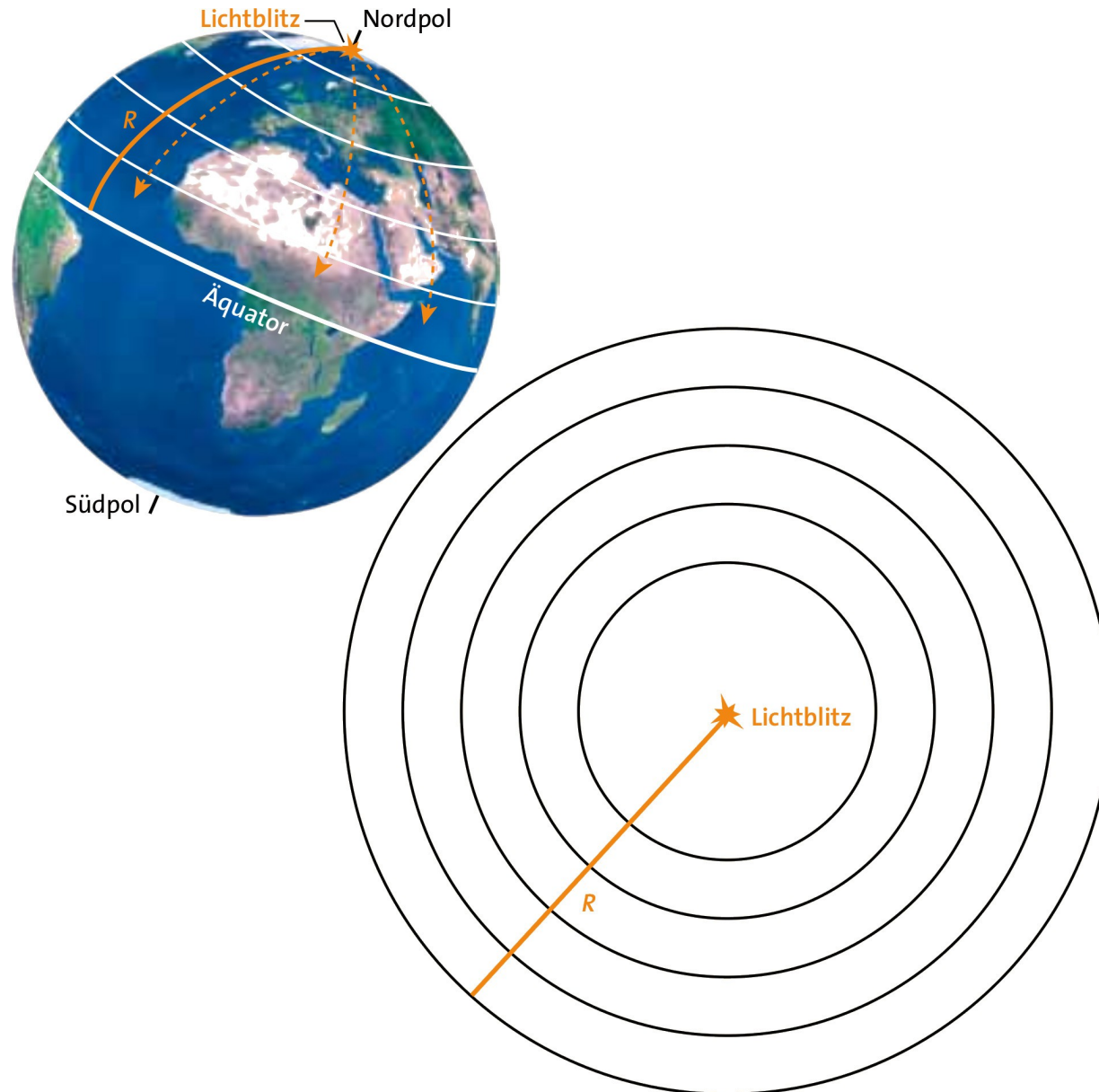


sphere

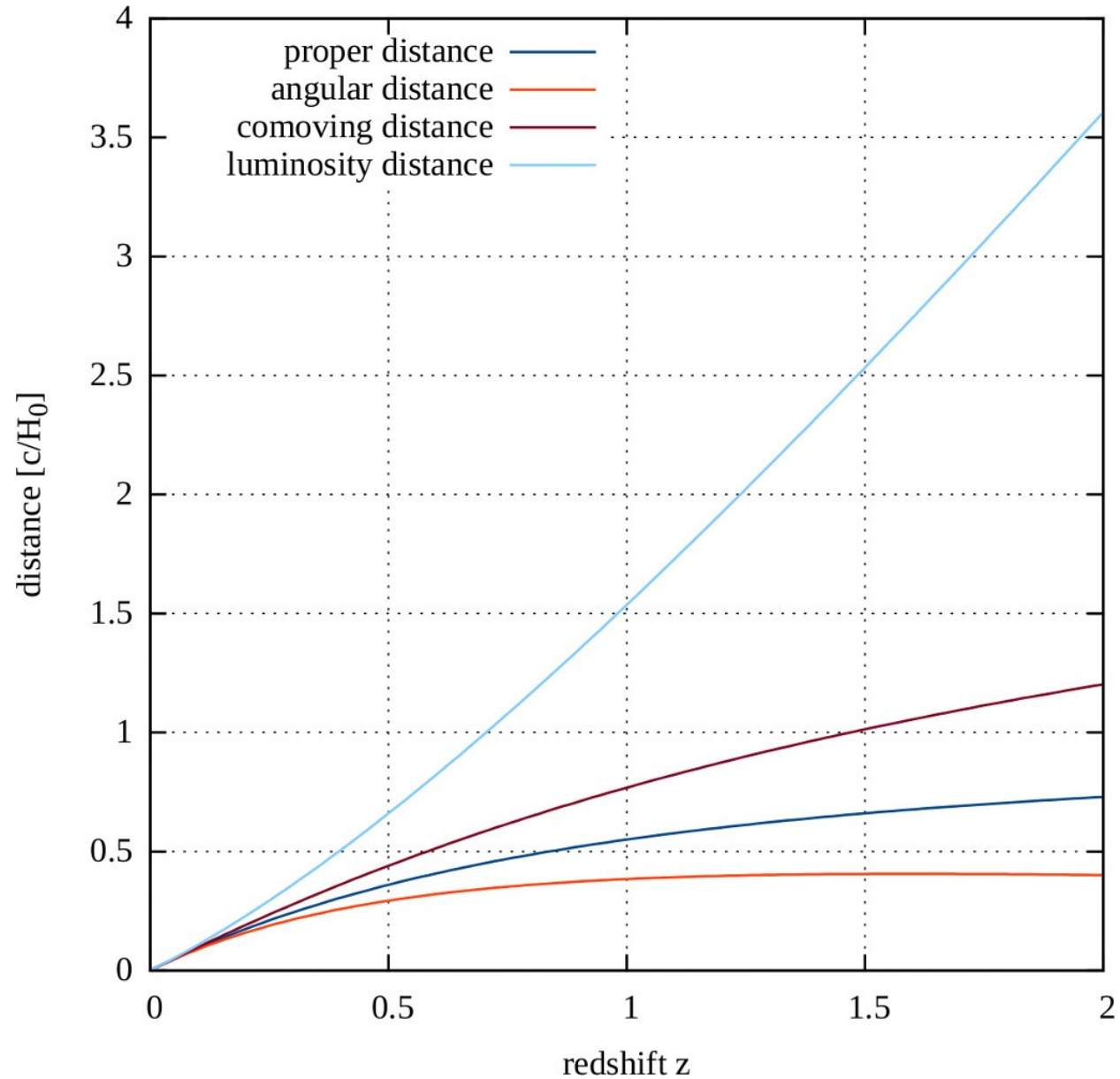
Angular-diameter distance



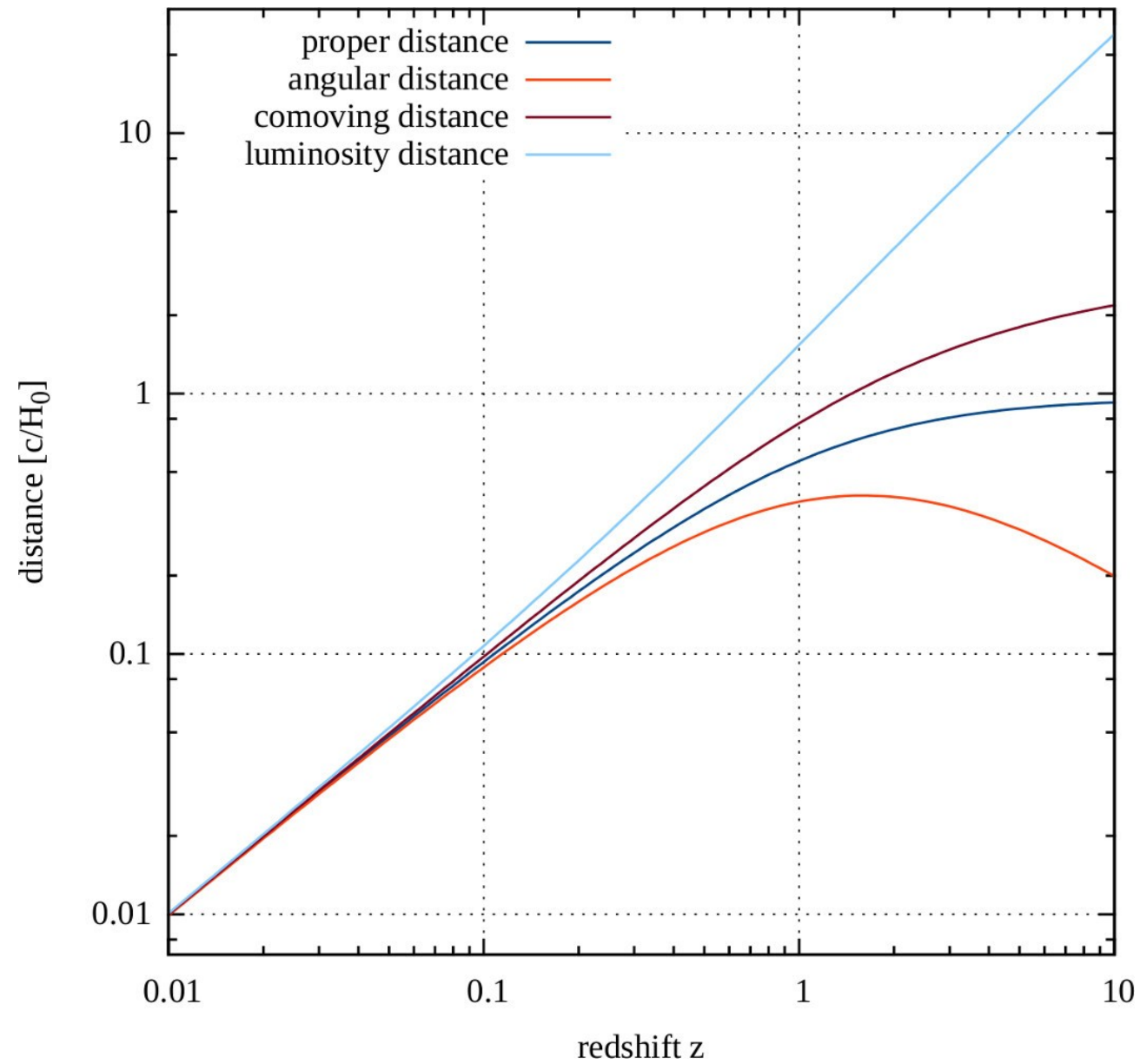
Luminosity distance



Different measures of distance



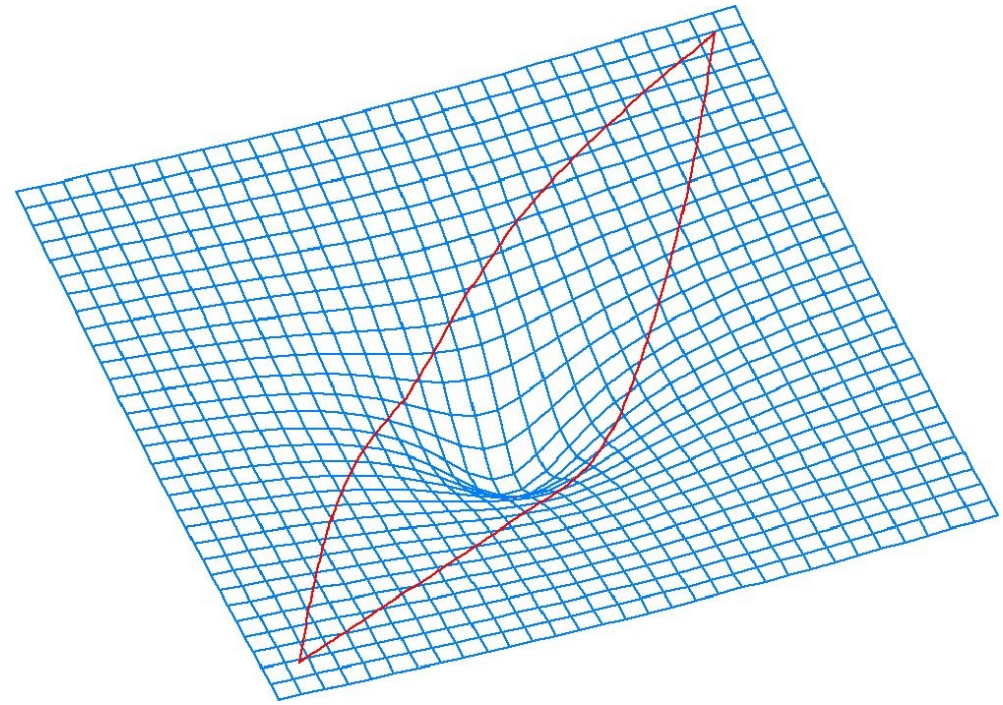
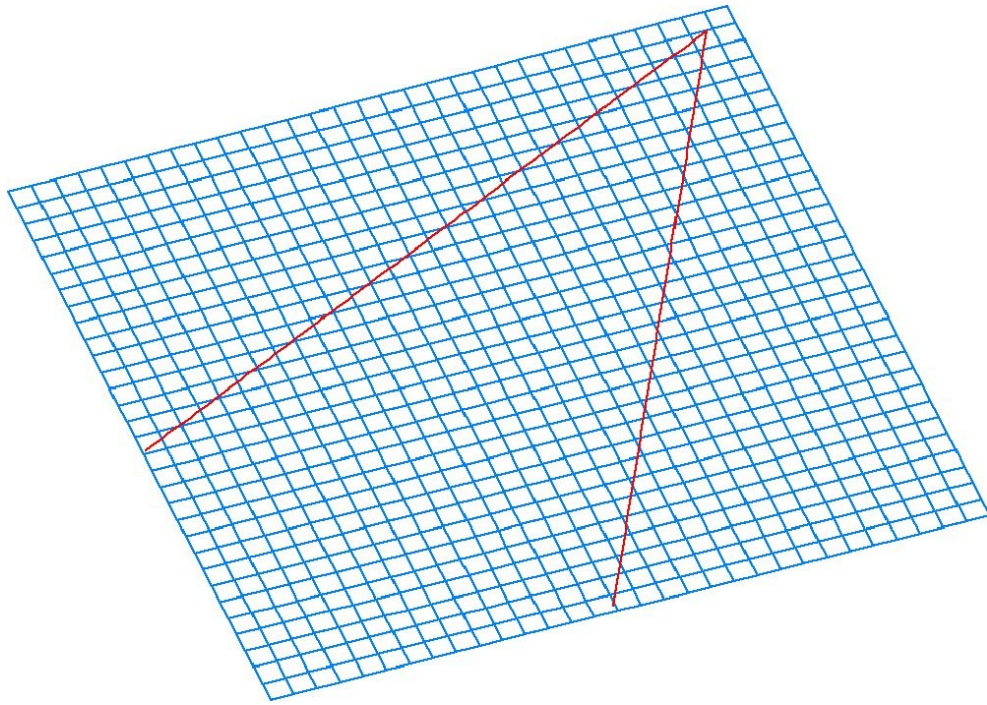
Non-monotonic distance



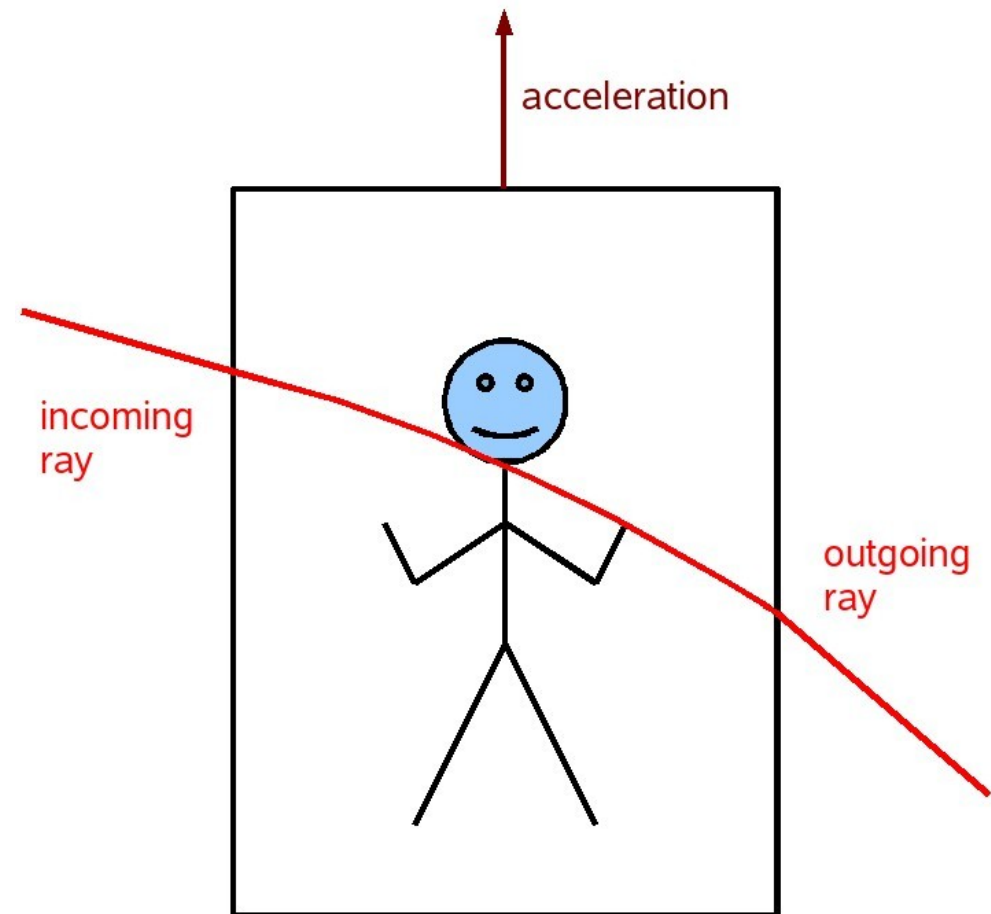
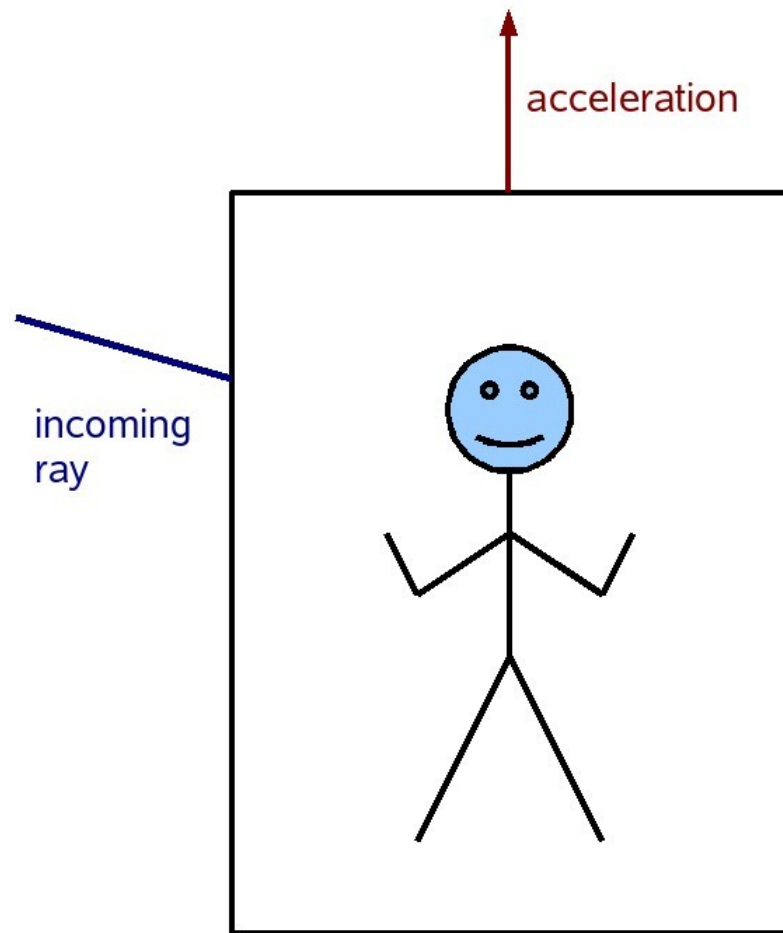
Propagation of light in curved space-time



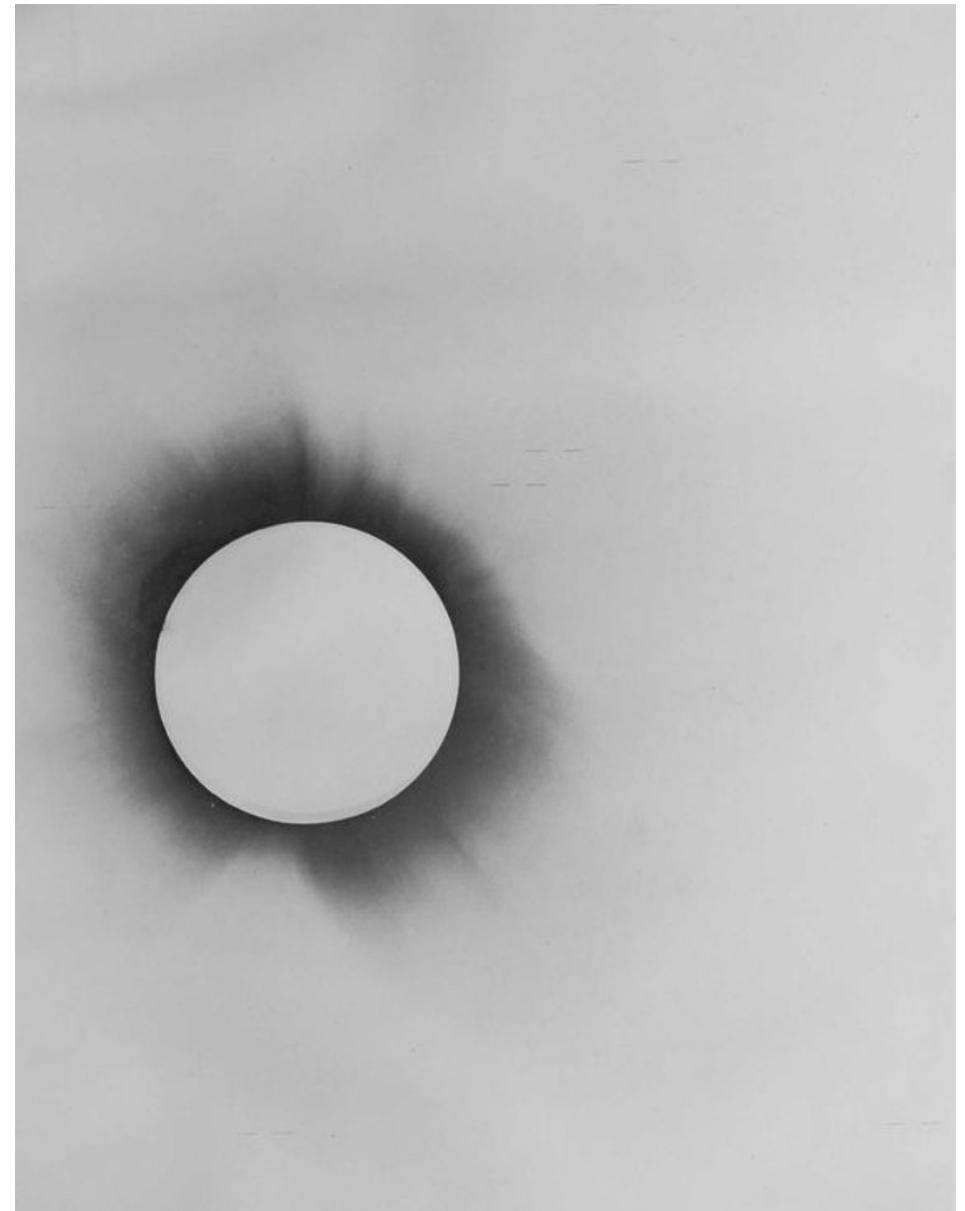
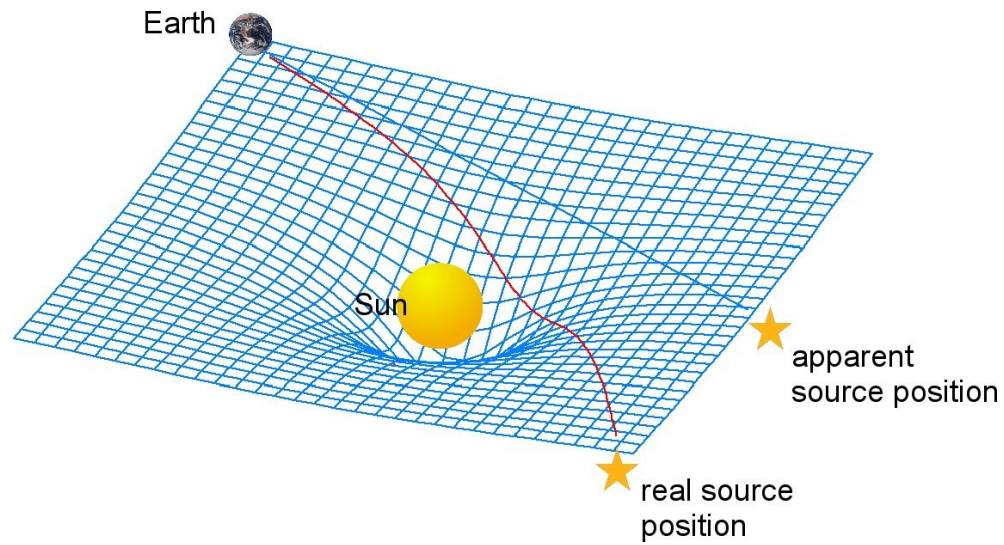
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386



Light deflection and equivalence principle



Light deflection by the Sun



Gravitational lensing in everyday life



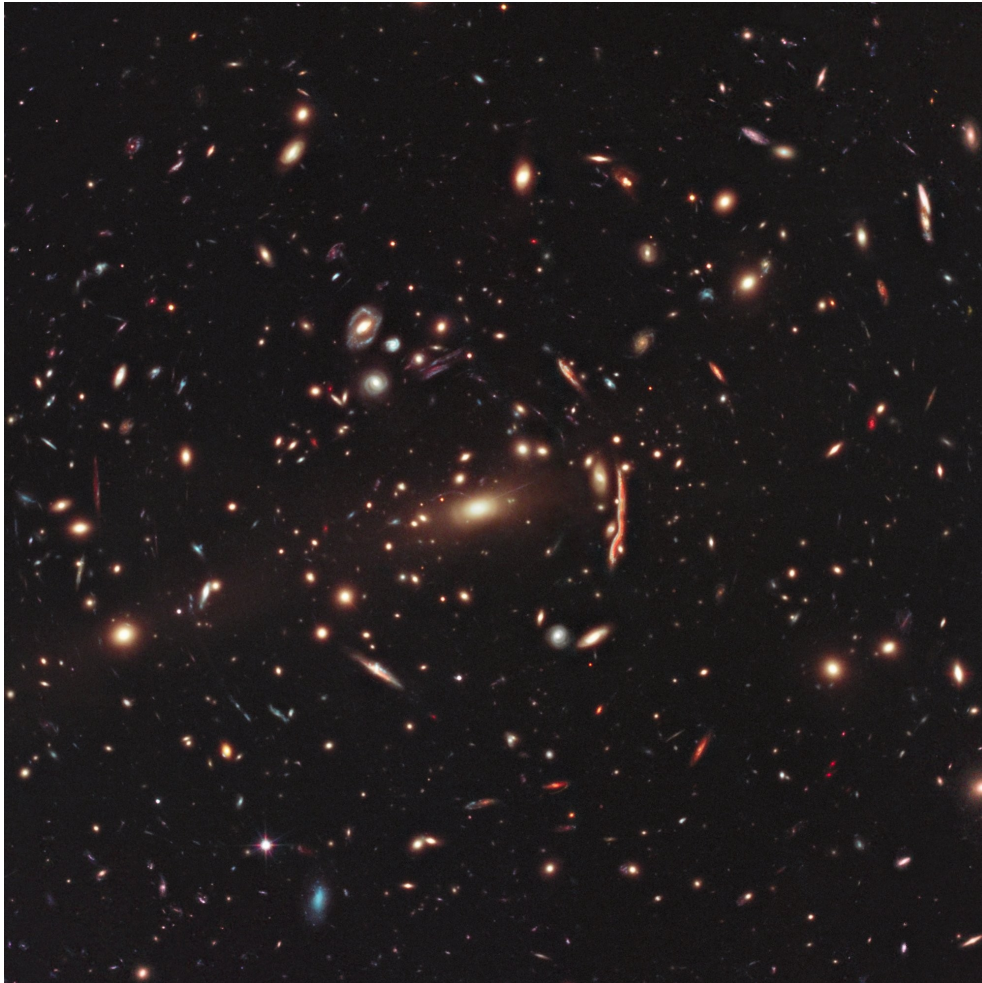
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386



Strong gravitational lensing in a galaxy cluster



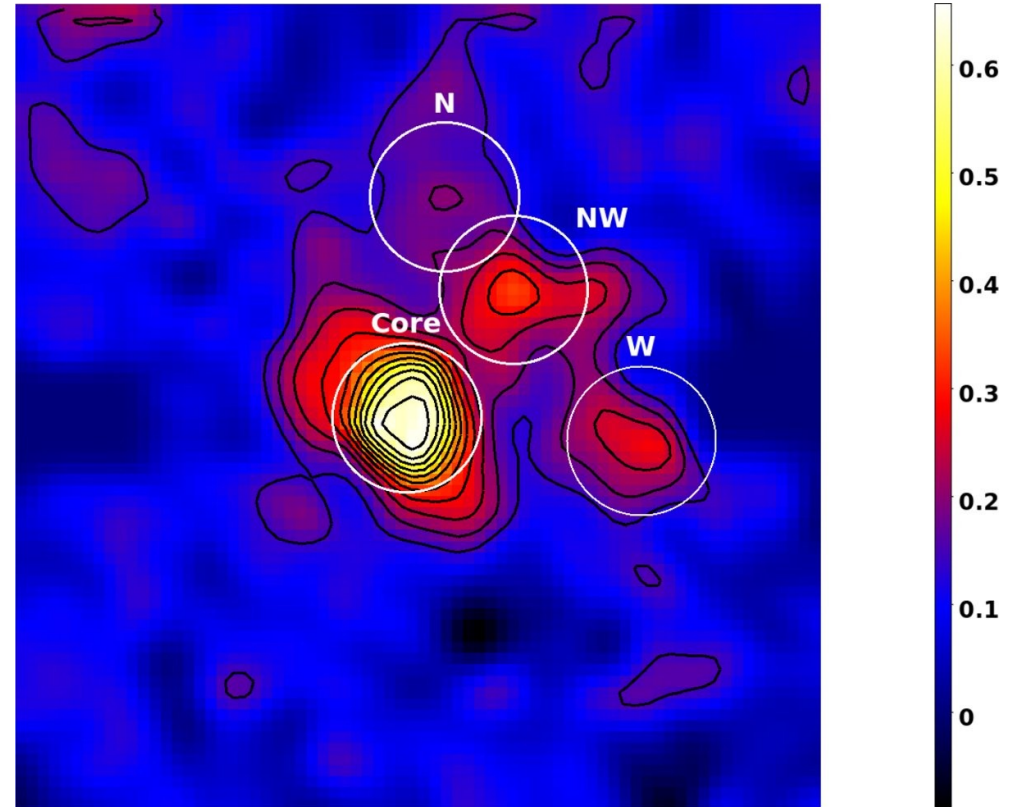
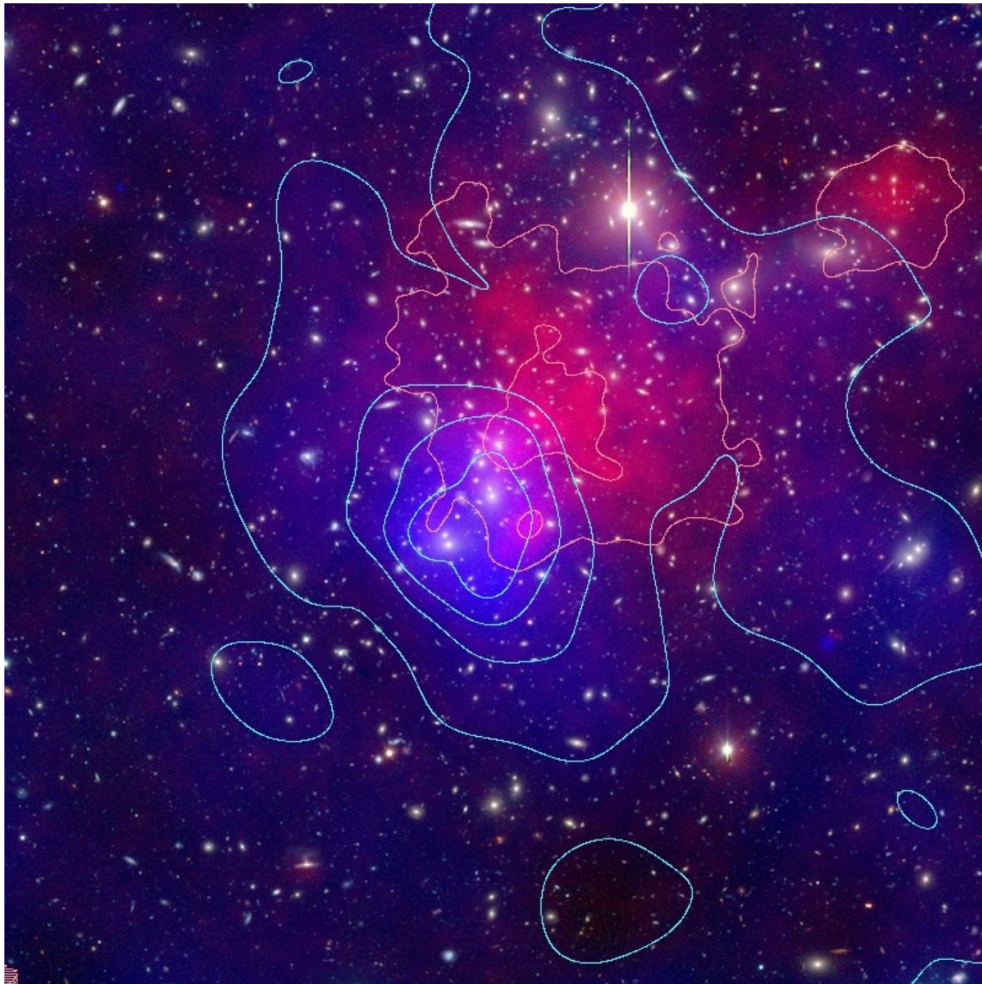
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386



Mapping dark matter



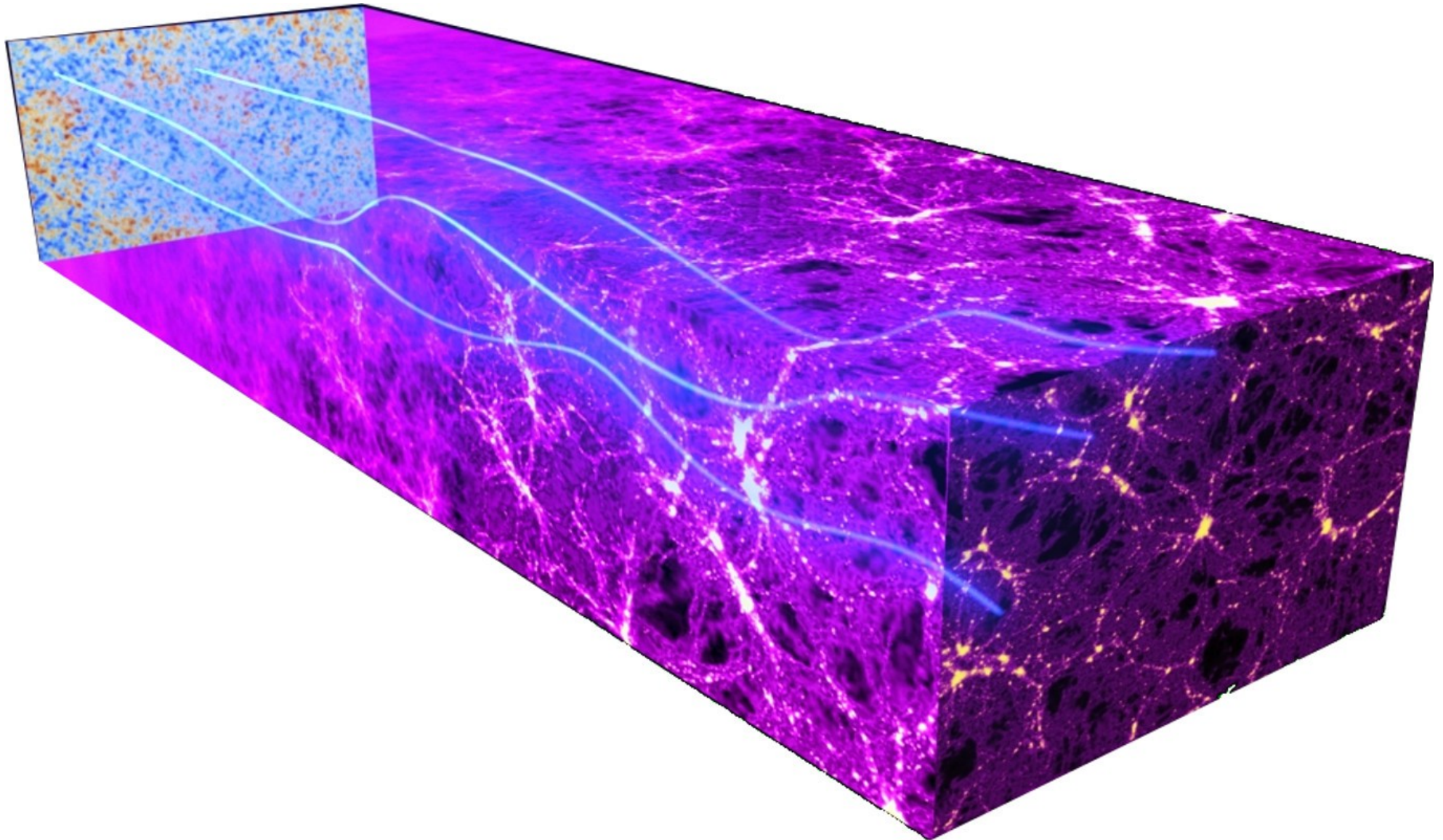
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386



Light propagation through the Universe



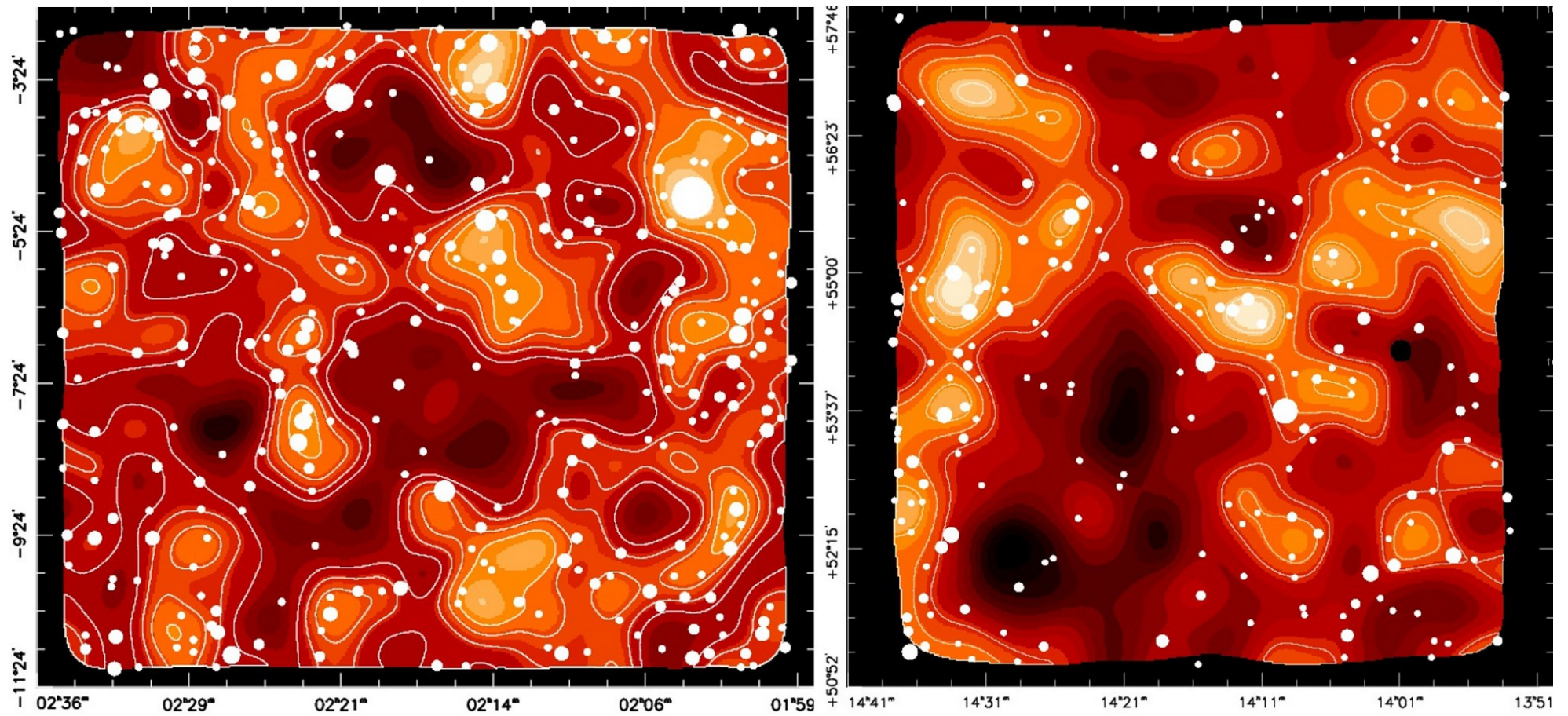
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386



Mapping large-scale structures



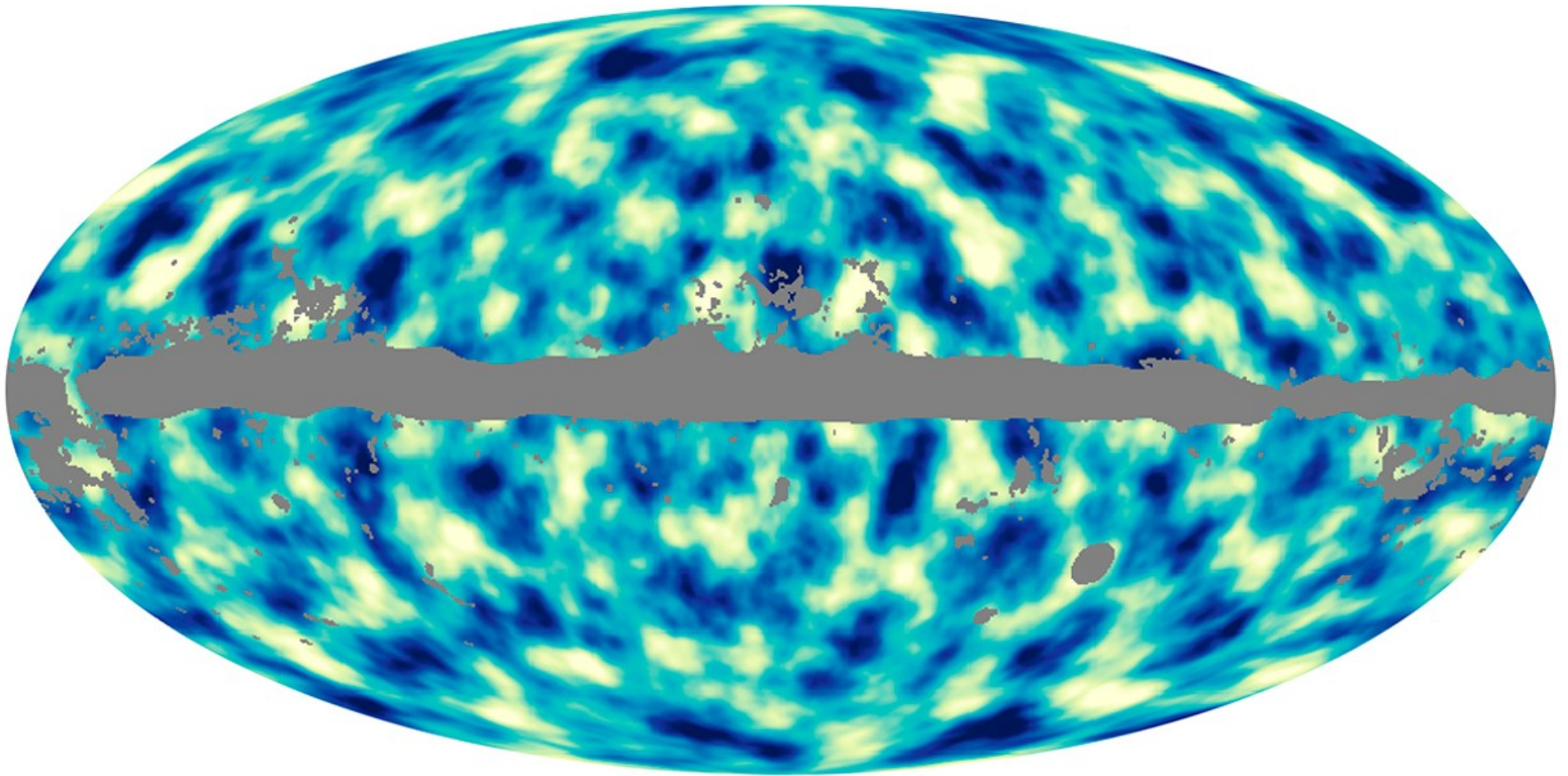
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386



Gravitational lensing of the CMB



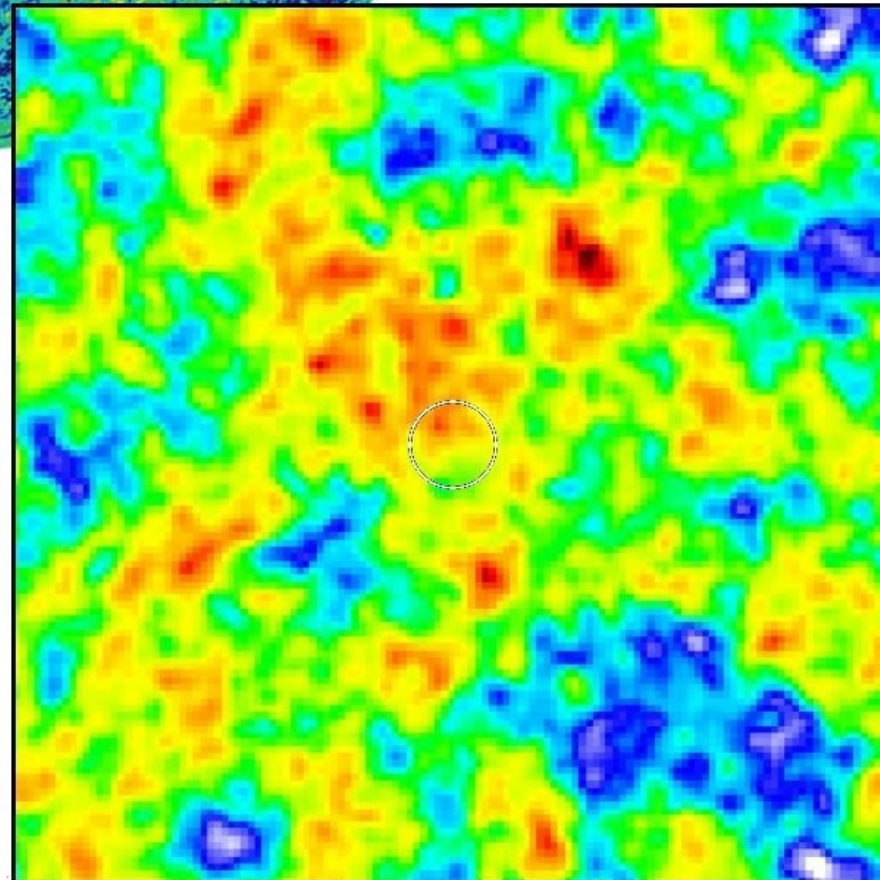
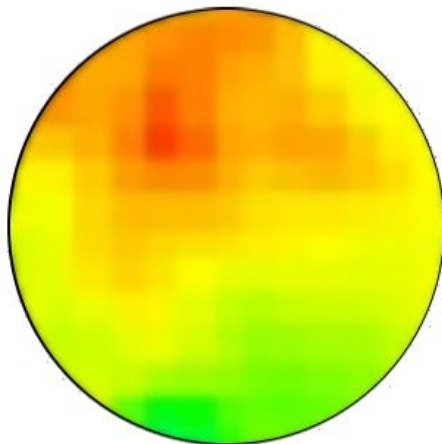
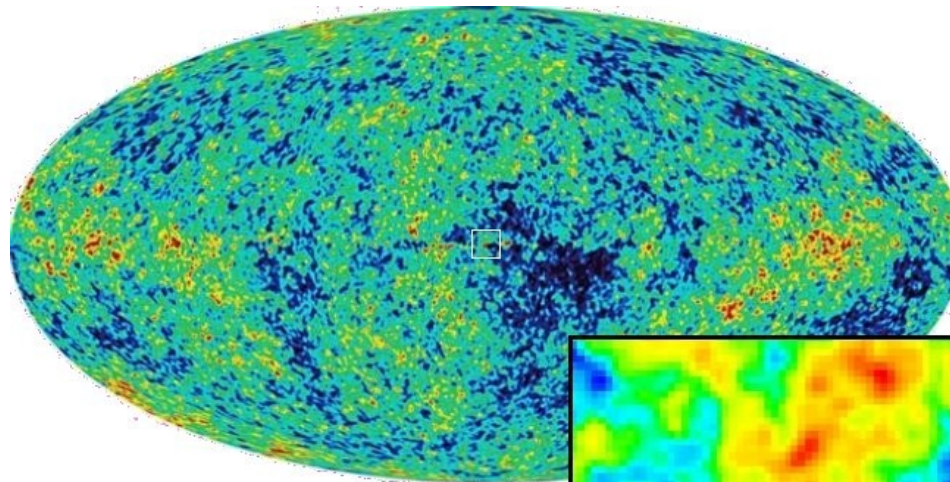
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386



Inflation



UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386



Inflation in the space-time diagram

