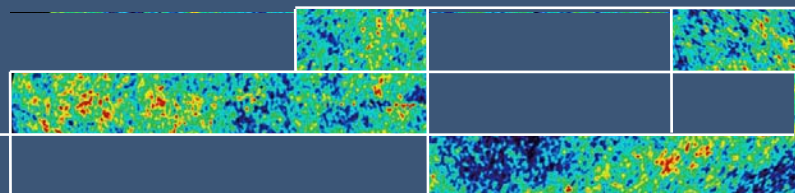
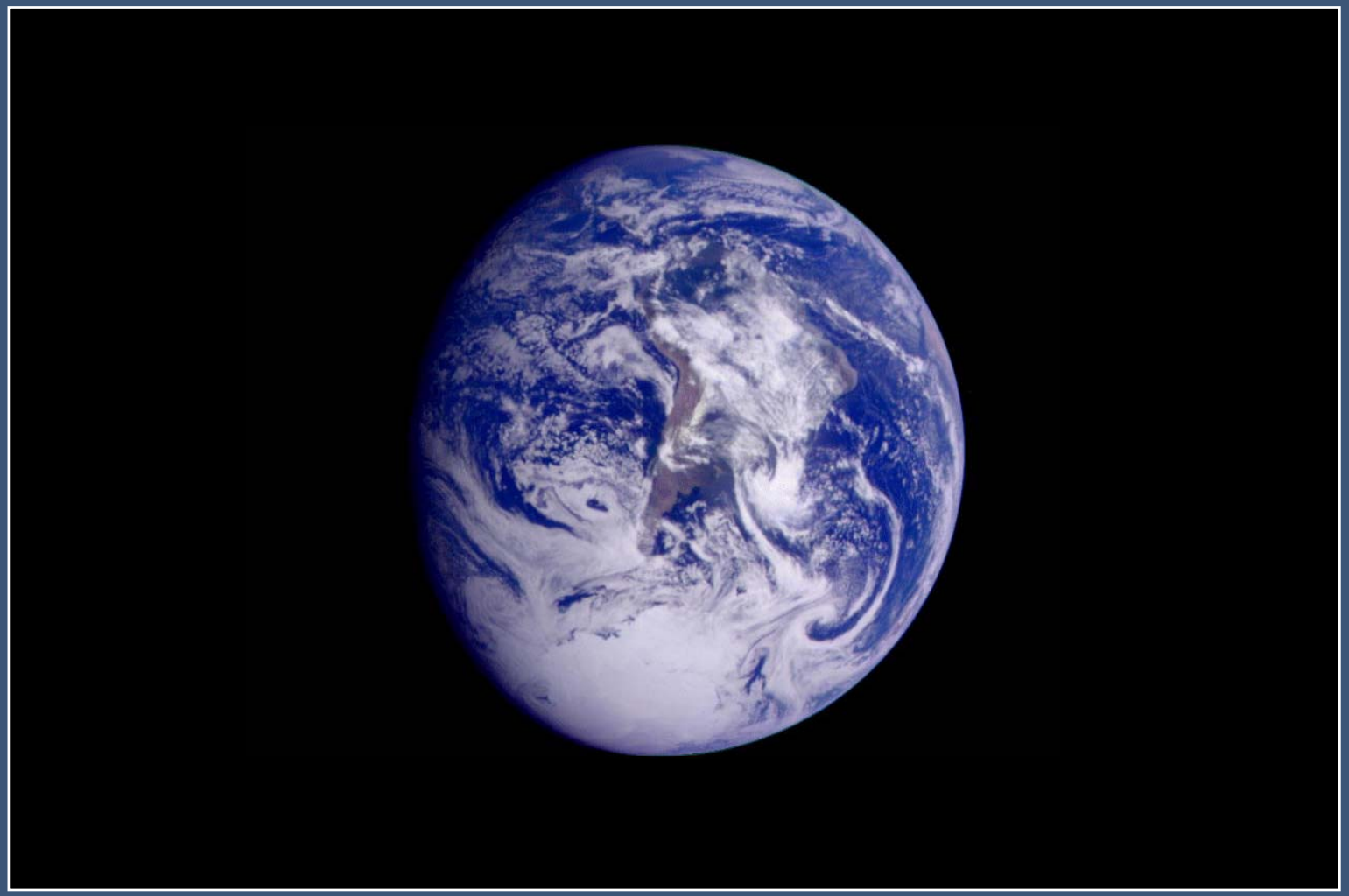
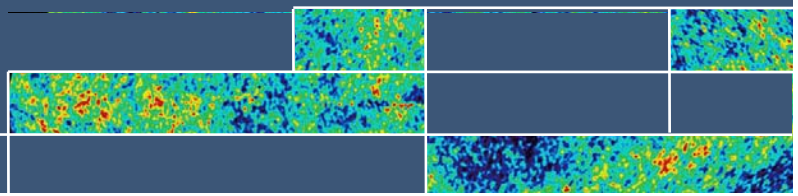
Cosmology

Christian Stegmann
University of Erlangen-Nuremberg



The Earth …

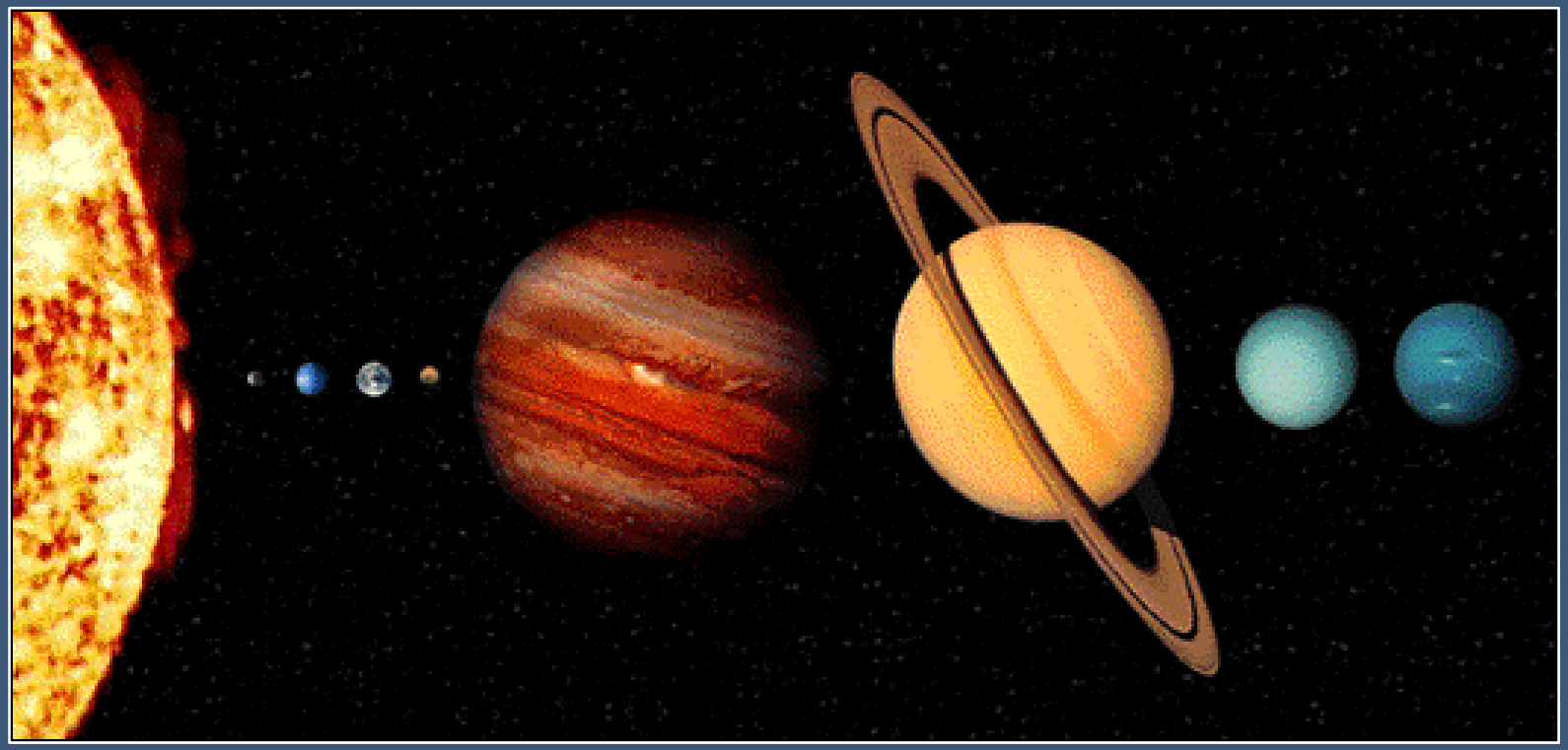


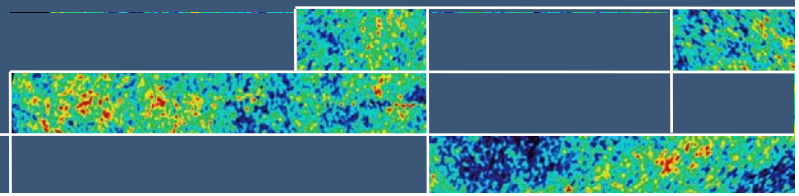


… one of eight planets

today

Time

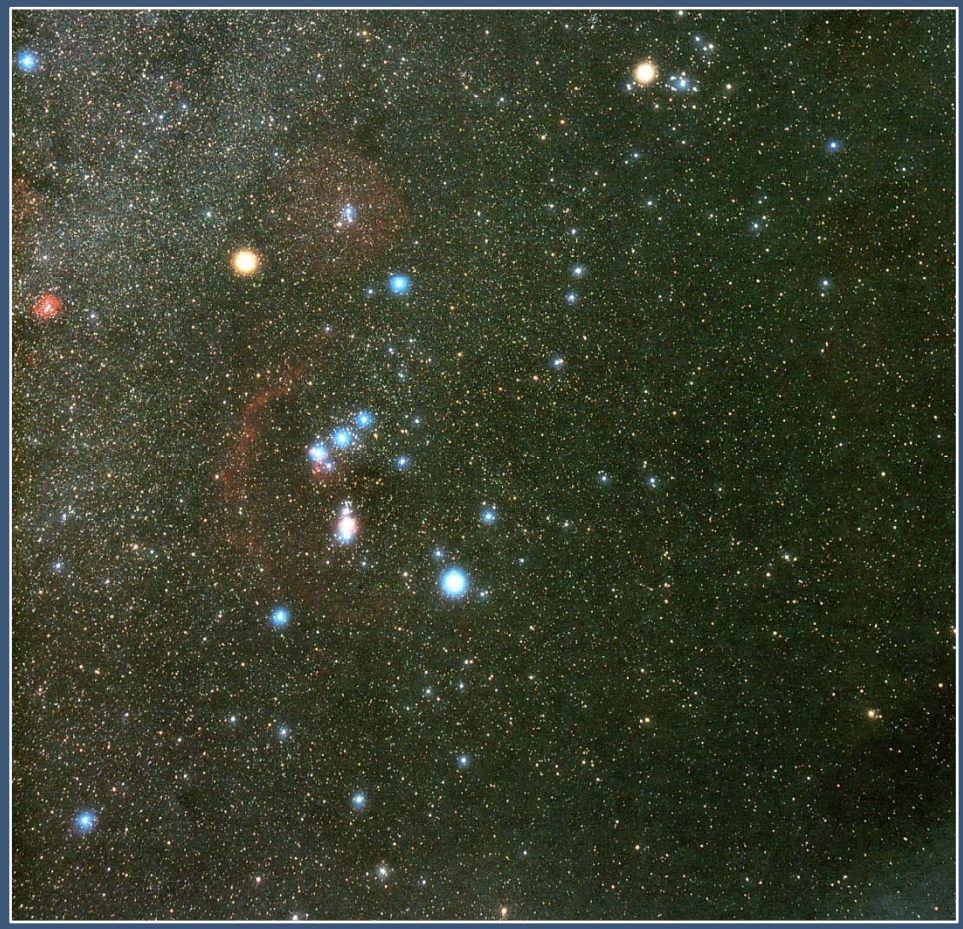


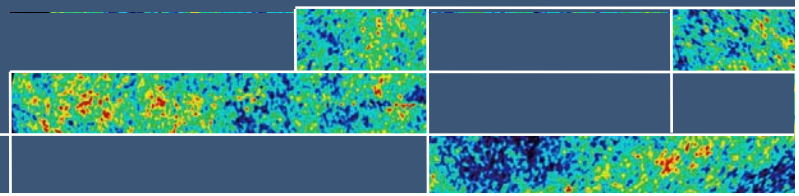


Stars

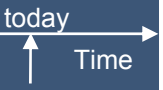
today

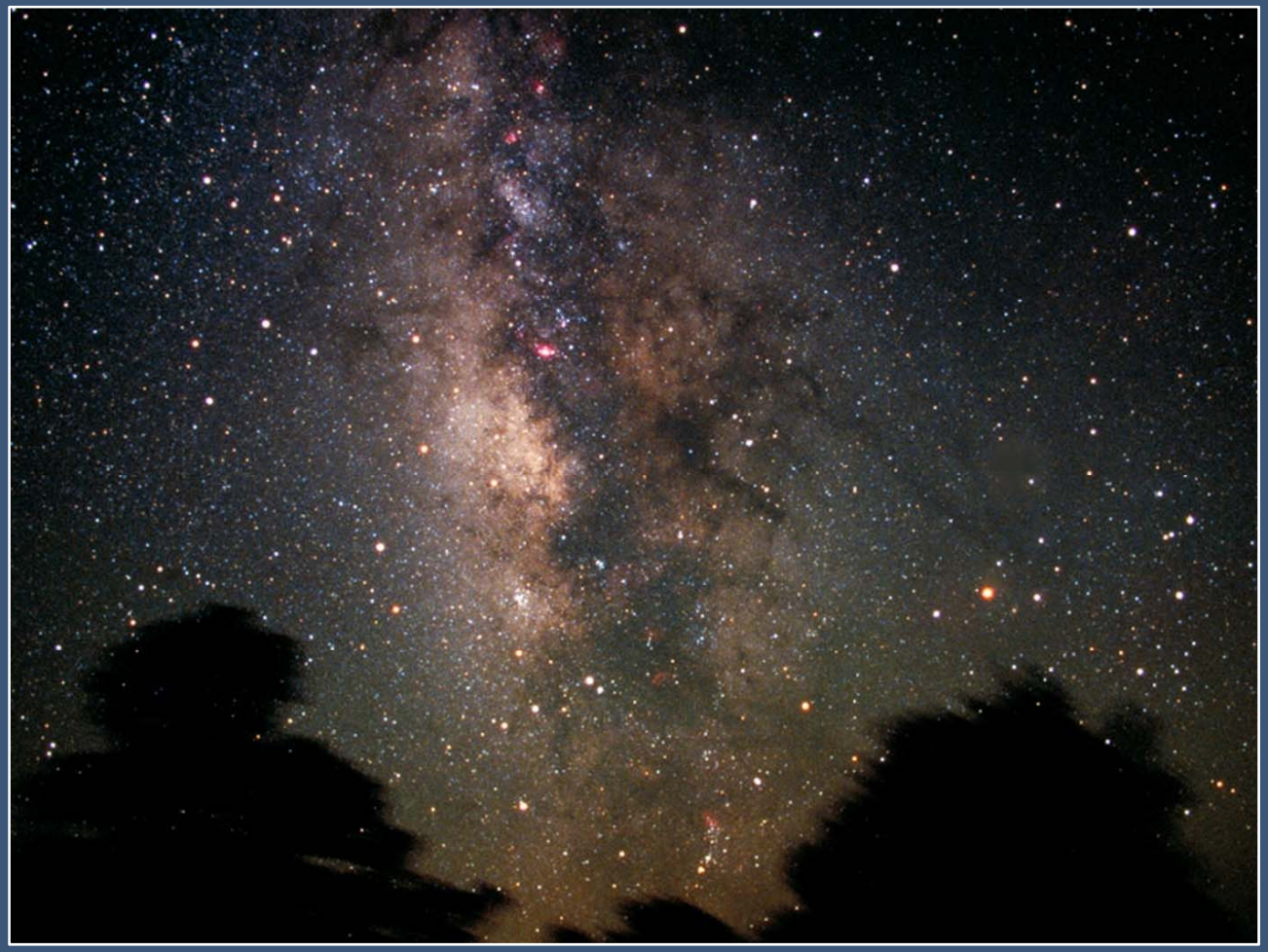
Time

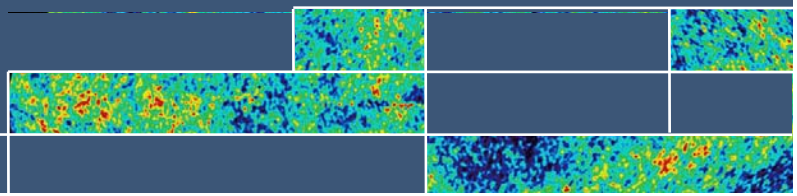




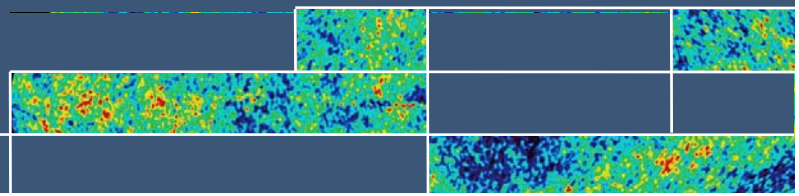
The Milky Way ...



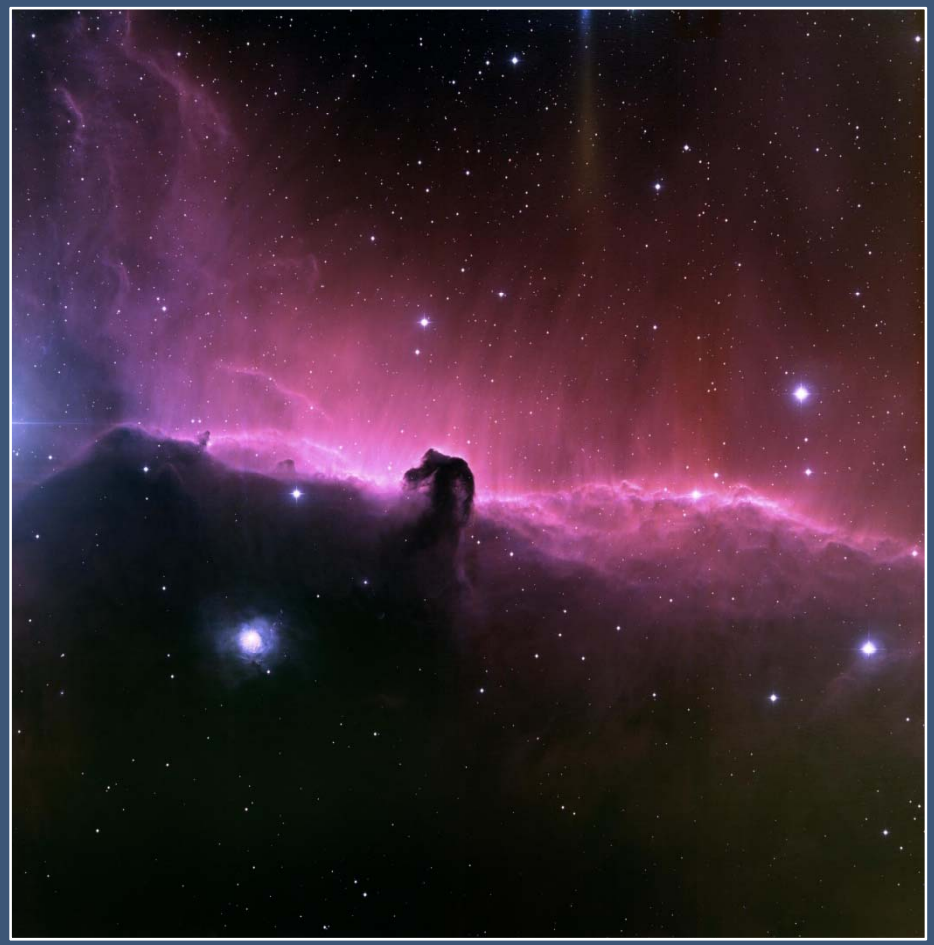


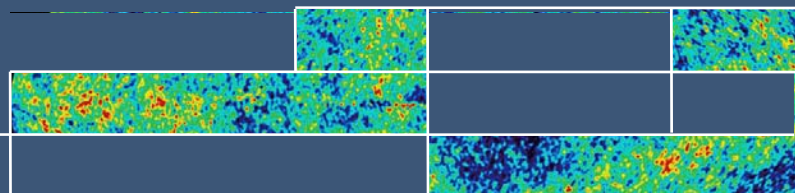


... full of stars

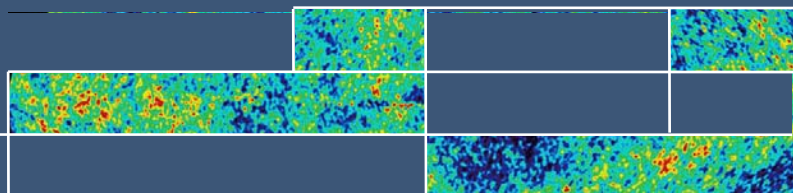


and nebulae

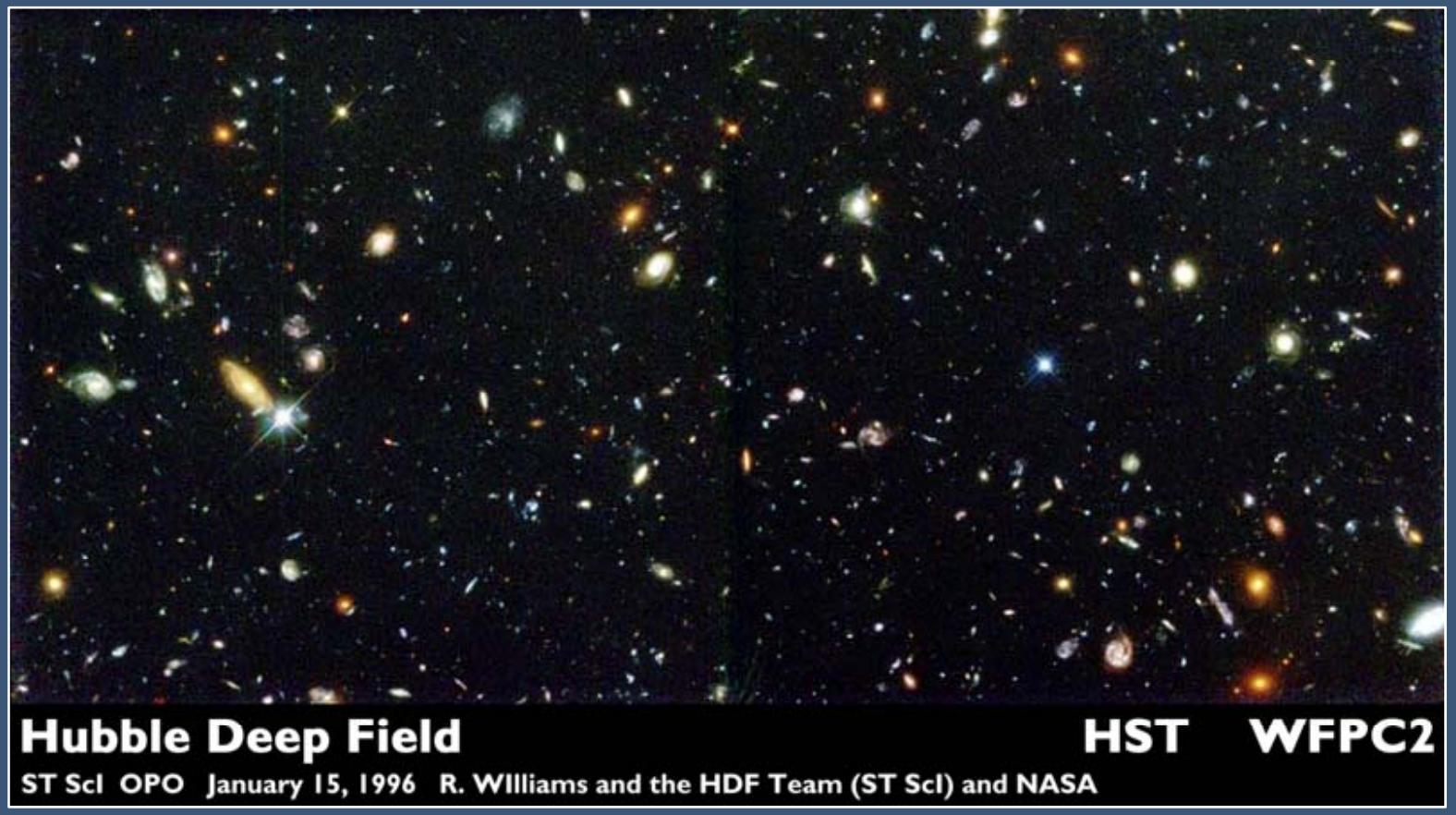


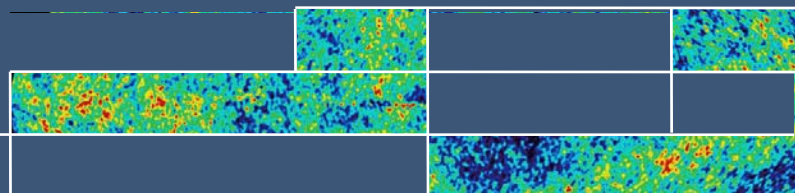


Our Milky Way



The Universe is full of galaxies

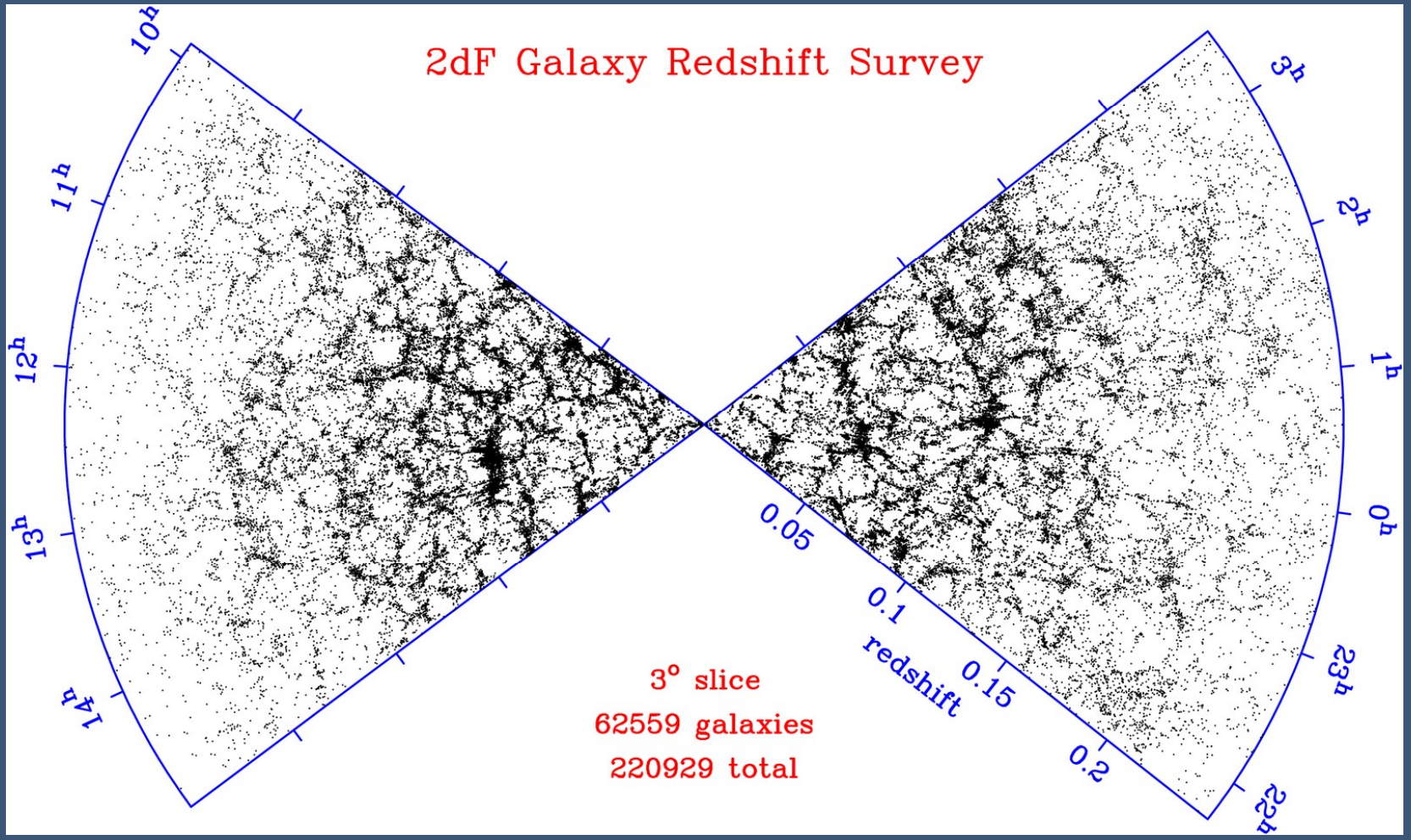


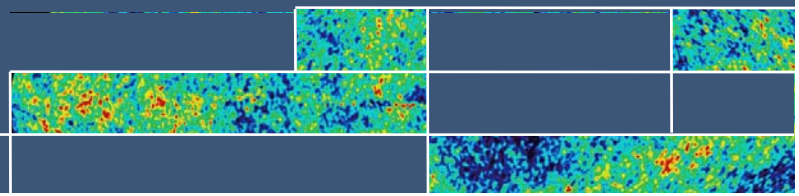


Galaxy cluster

today

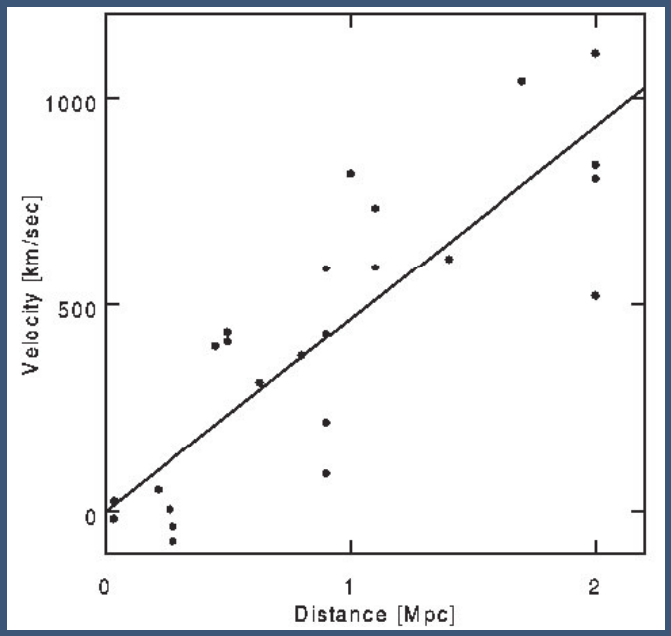
Time

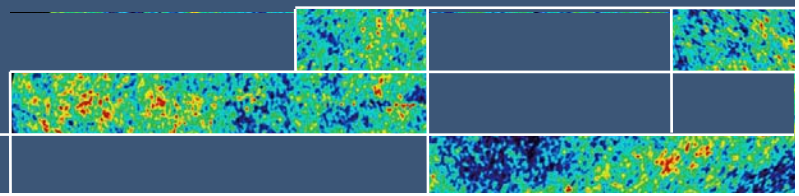




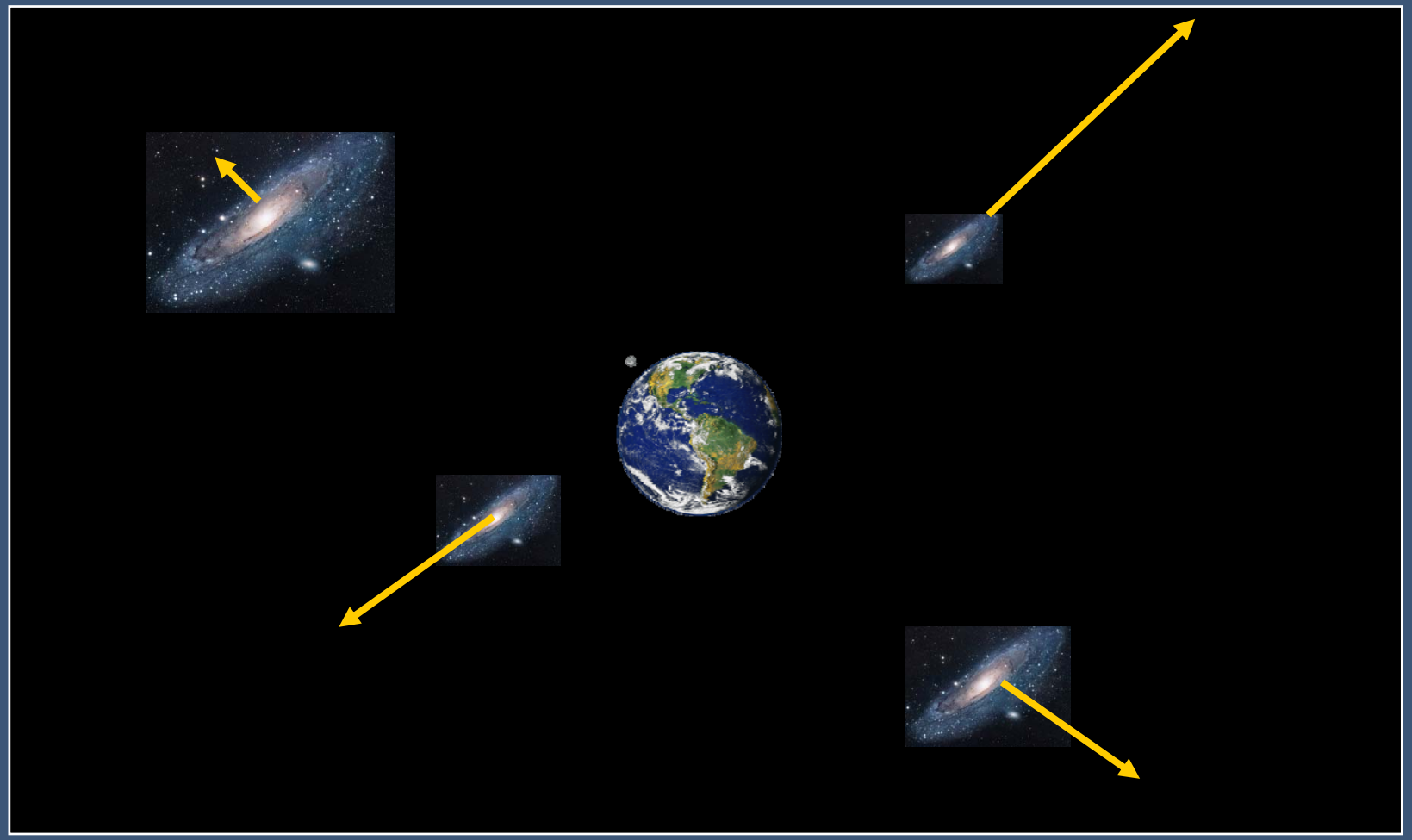
Edwin Hubbles Discovery

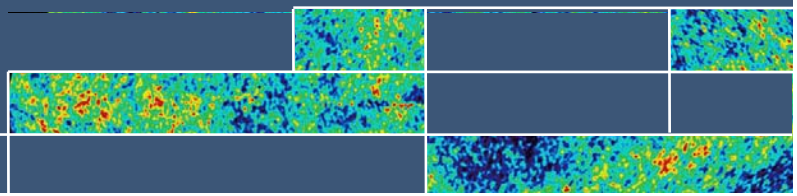
- Galaxies travel away from us
- the further away, the faster





Galaxies are moving

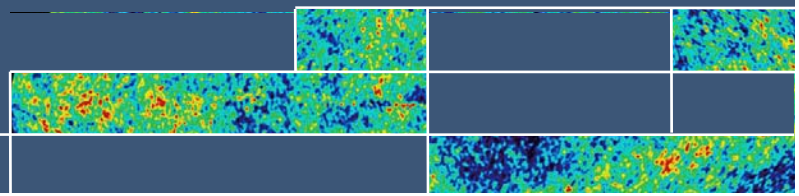




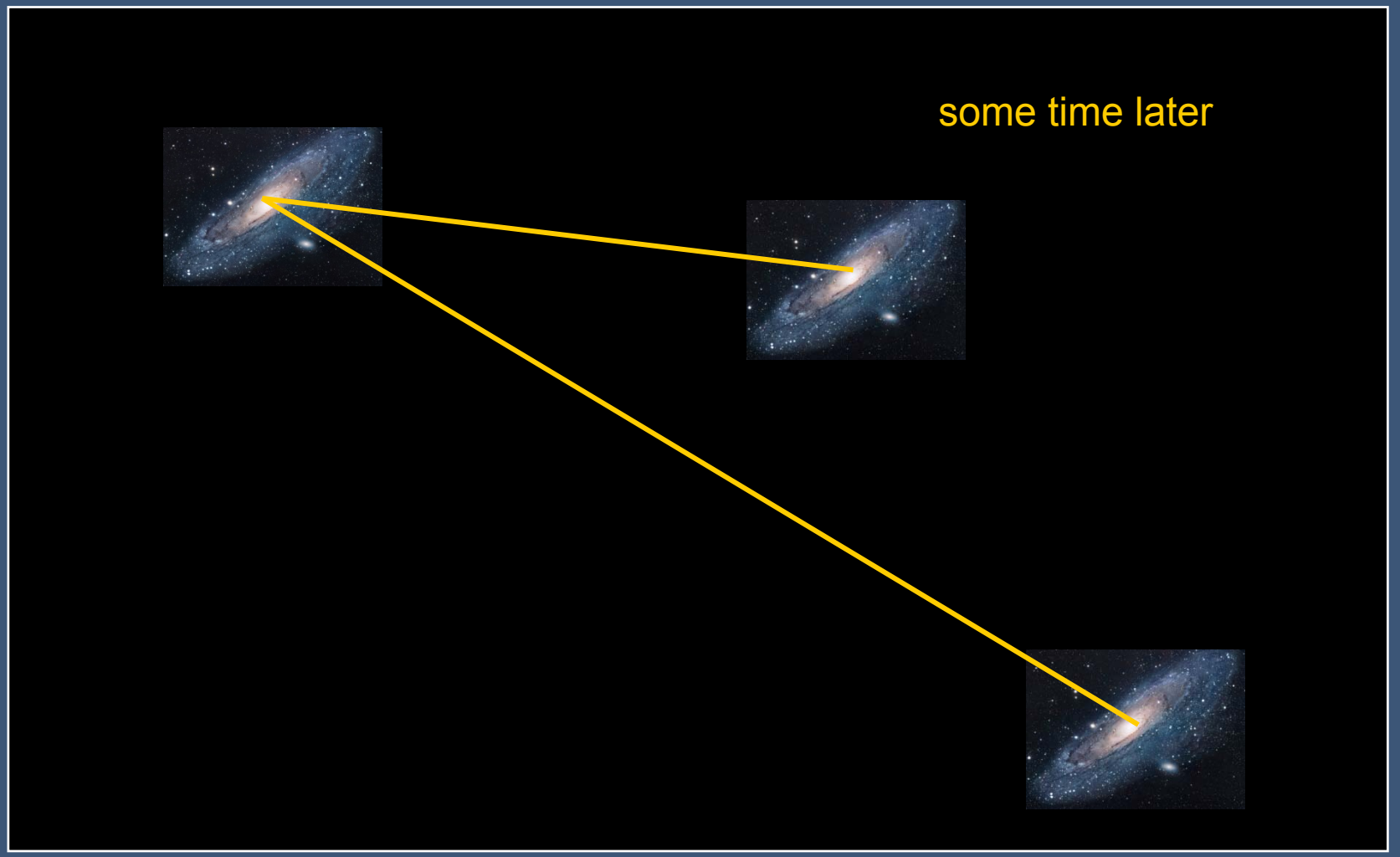
Do we understand that?

- We are the centre of the Universe!
- The Universe is expanding
  - Space between galaxies is getting larger

Scientifically more attractive!

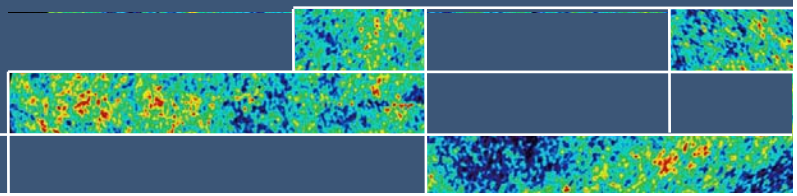


today
Time

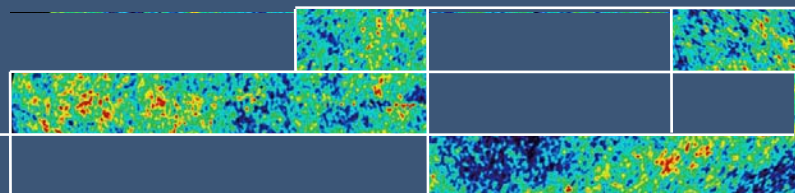

today
Time
some time later

How do we measure this?

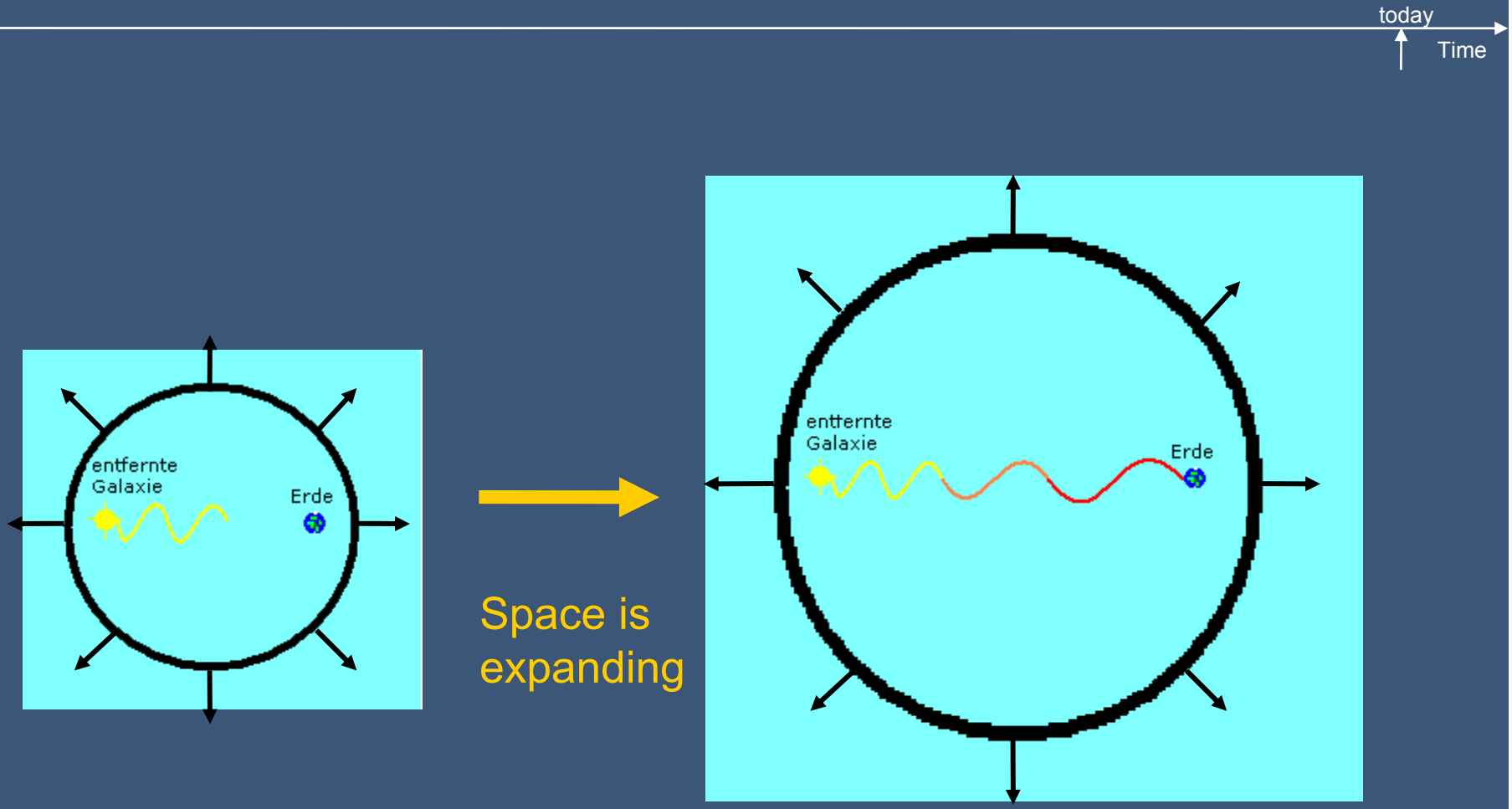
- Measurement of the velocity
  - velocity-meter?
- Distance
  - Ruler?



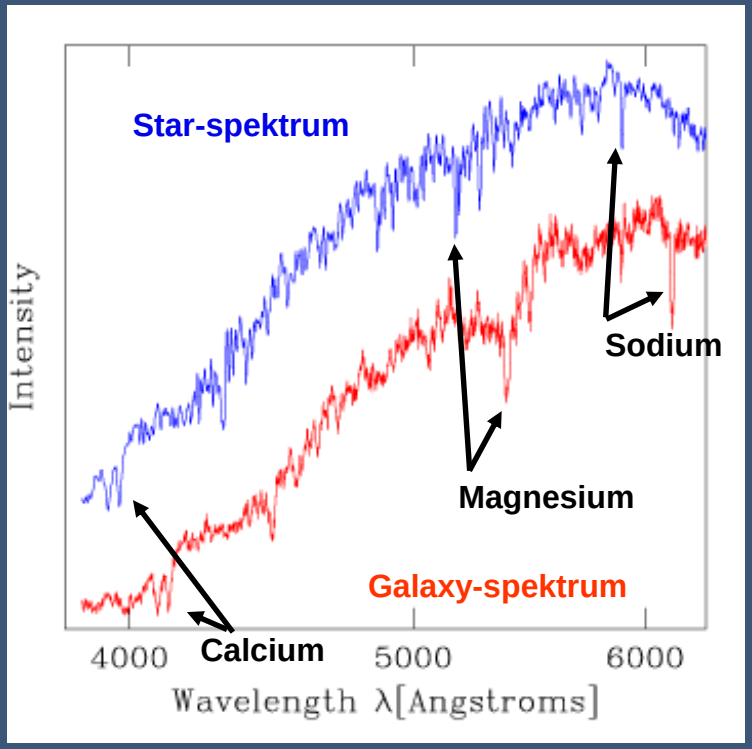
Measurement of the velocity via the red-shift

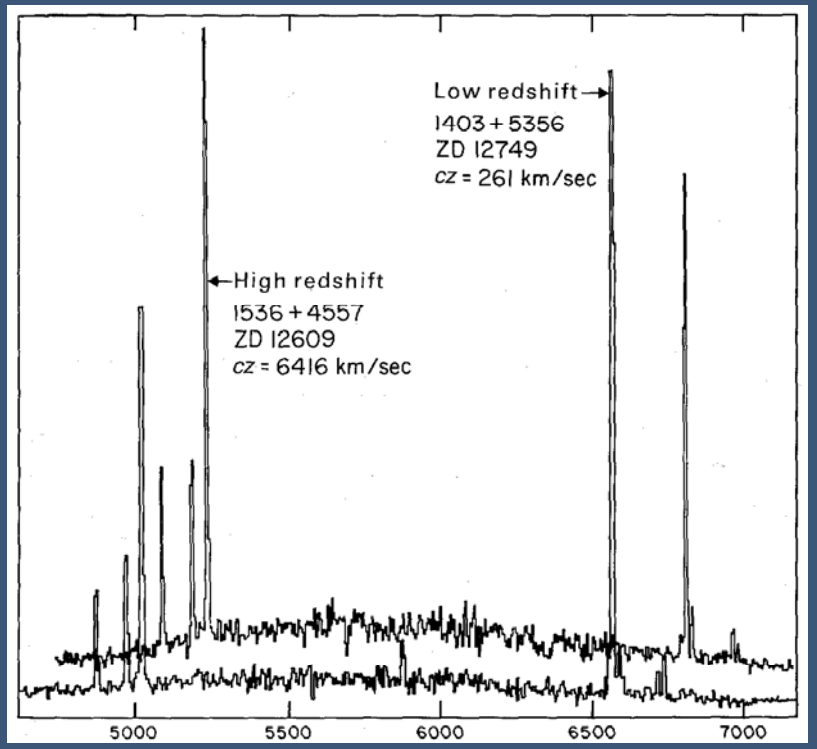


Cosmological red shift



Galaxy-spektroscopy

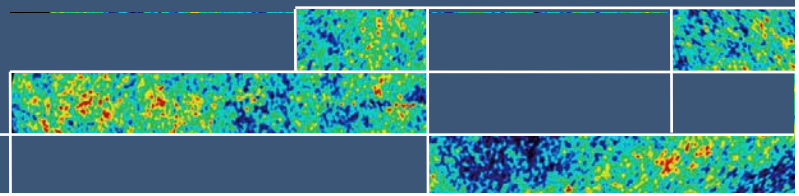




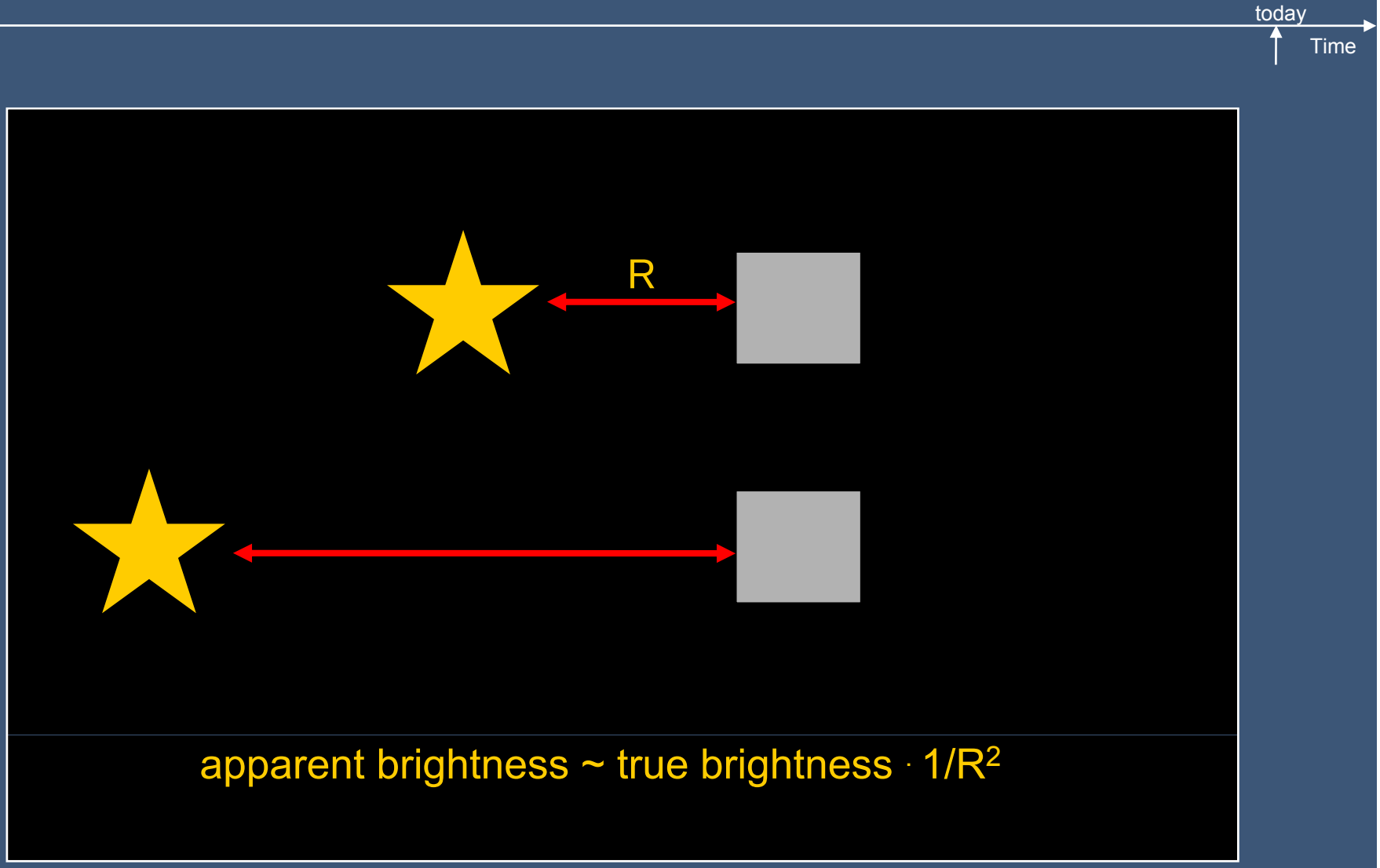
today

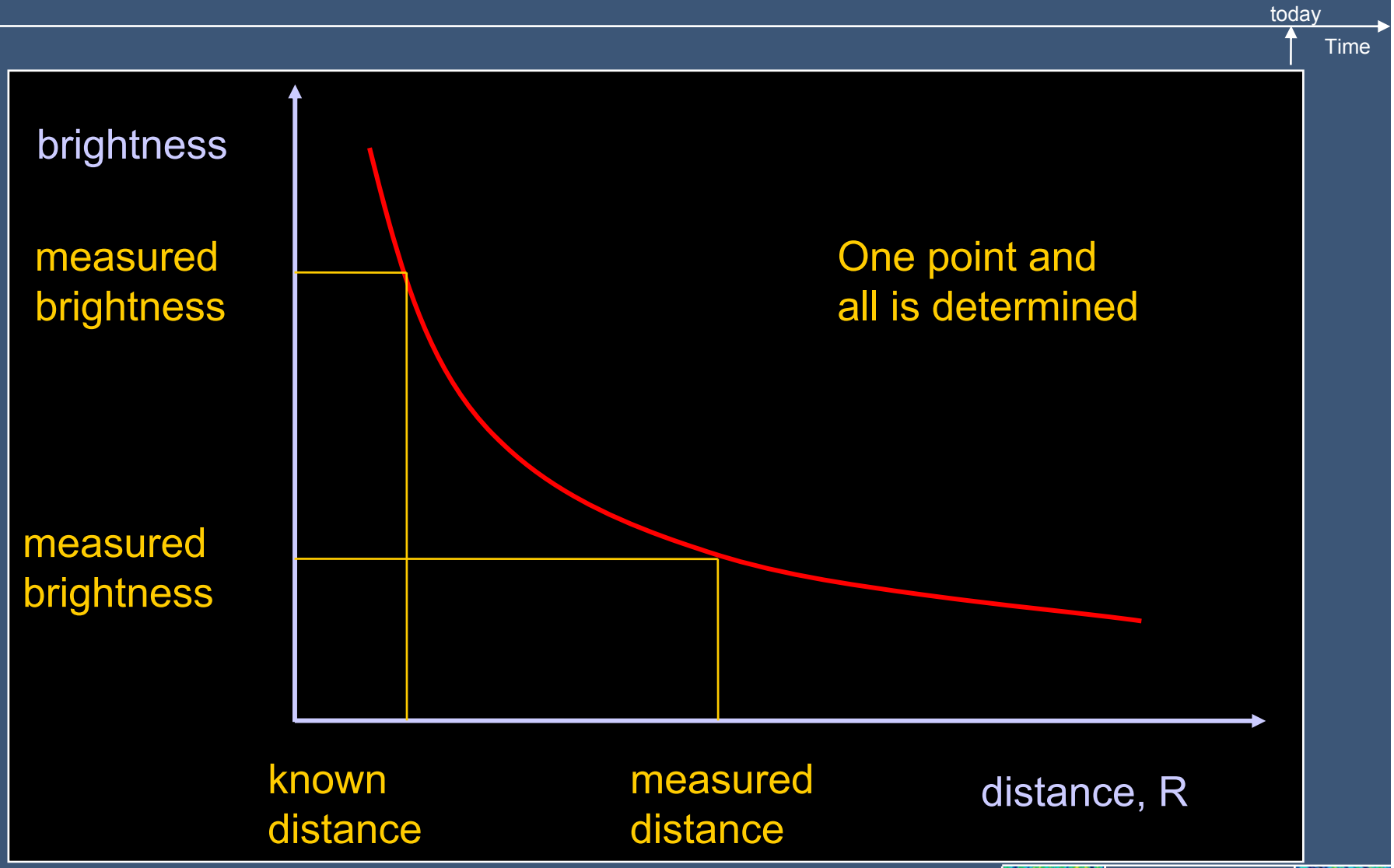
Time

v_{Galaxy} ~ 12000 km/s

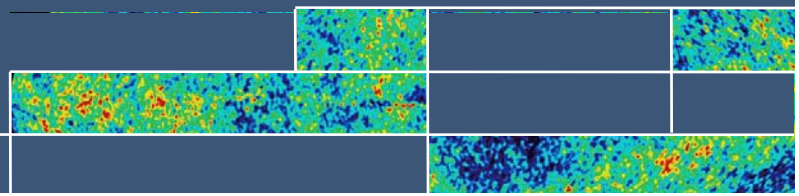


Distance measurement



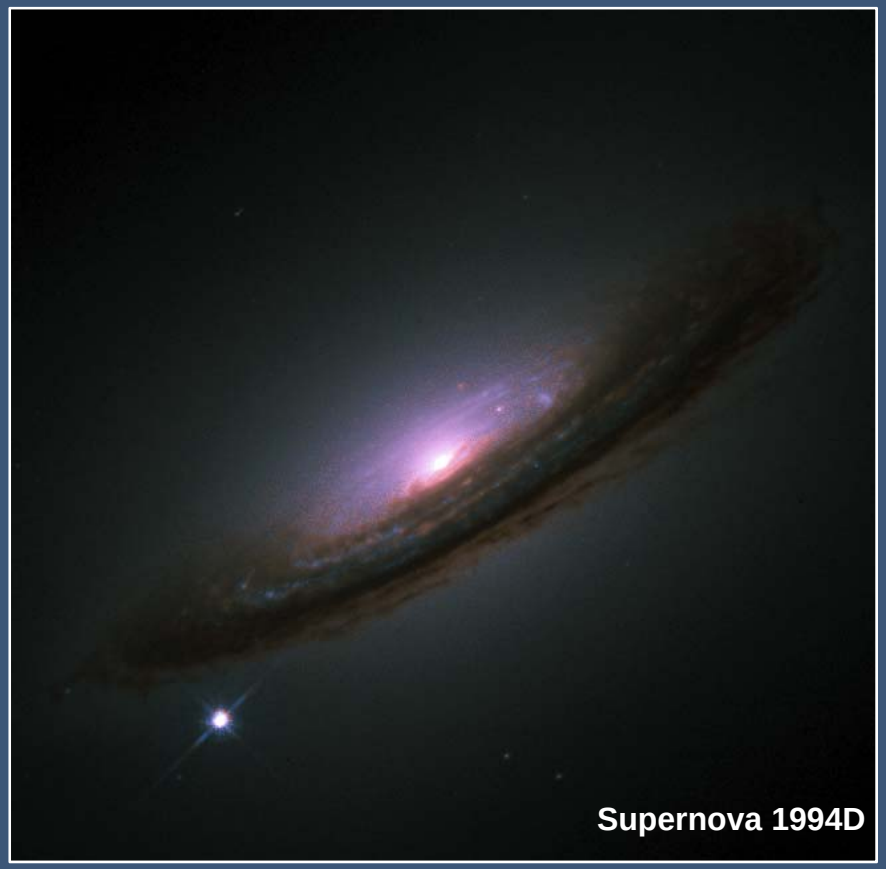

today
Time
brightness
measured
brightness
One point and
all is determined
measured
brightness
known
distance
measured
distance
distance, R

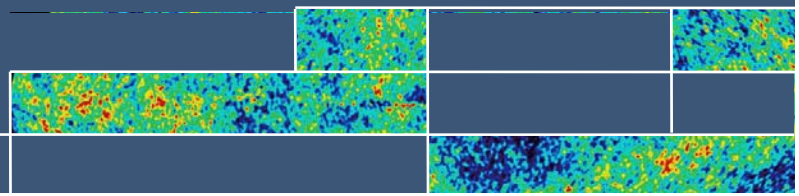
We need lamps!



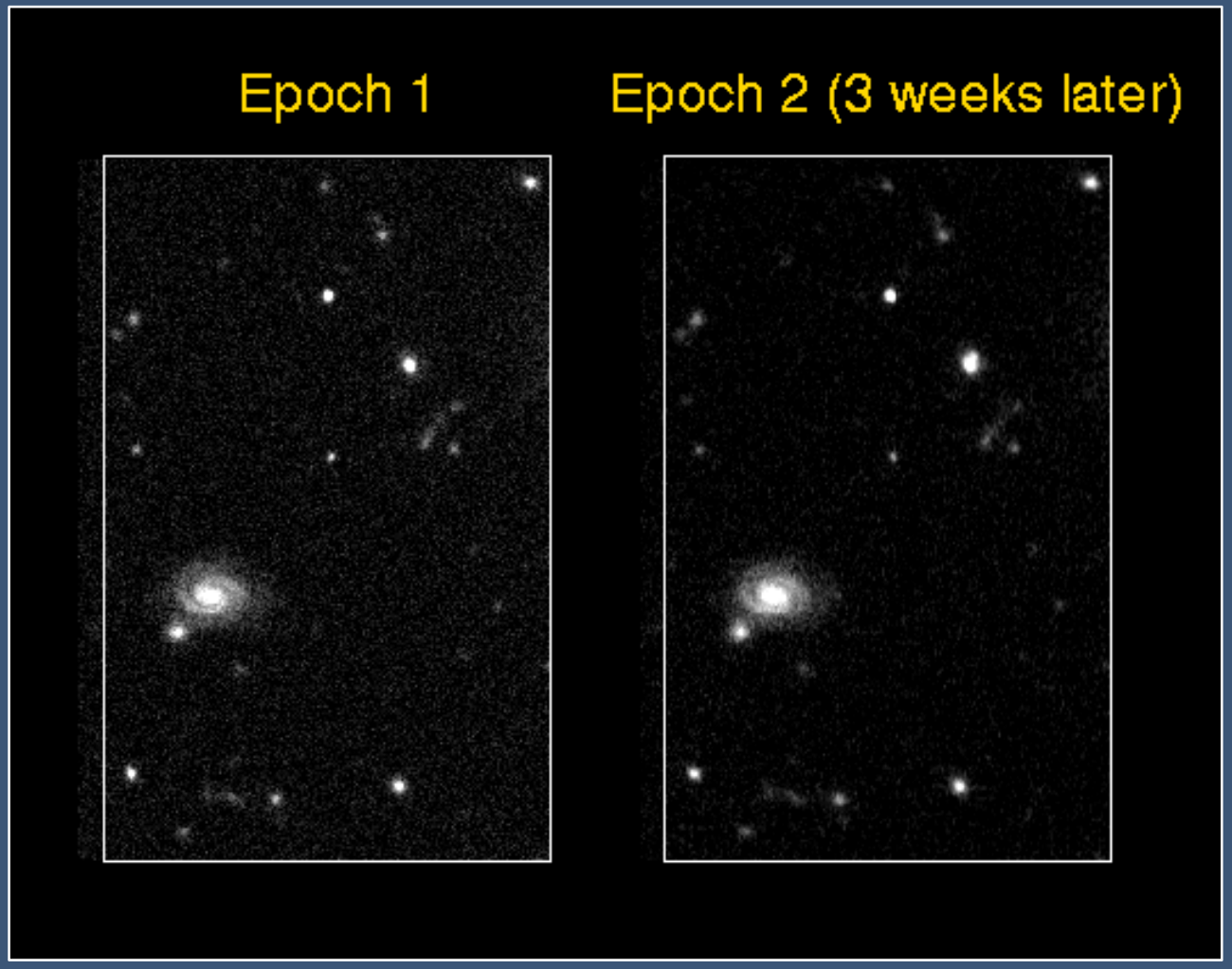
Star explosions

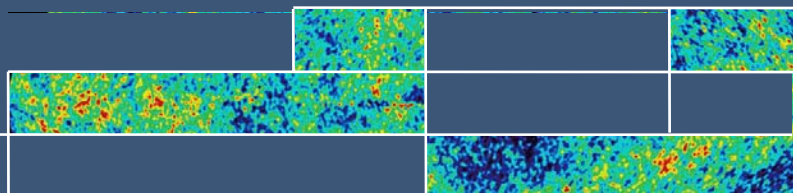
- Supernova Typ Ia
- Exploding white dwarfs
  - nuclear bomb of the size of the Earth!
- Bright as a whole galaxy
- Light up and disappear after a few weeks



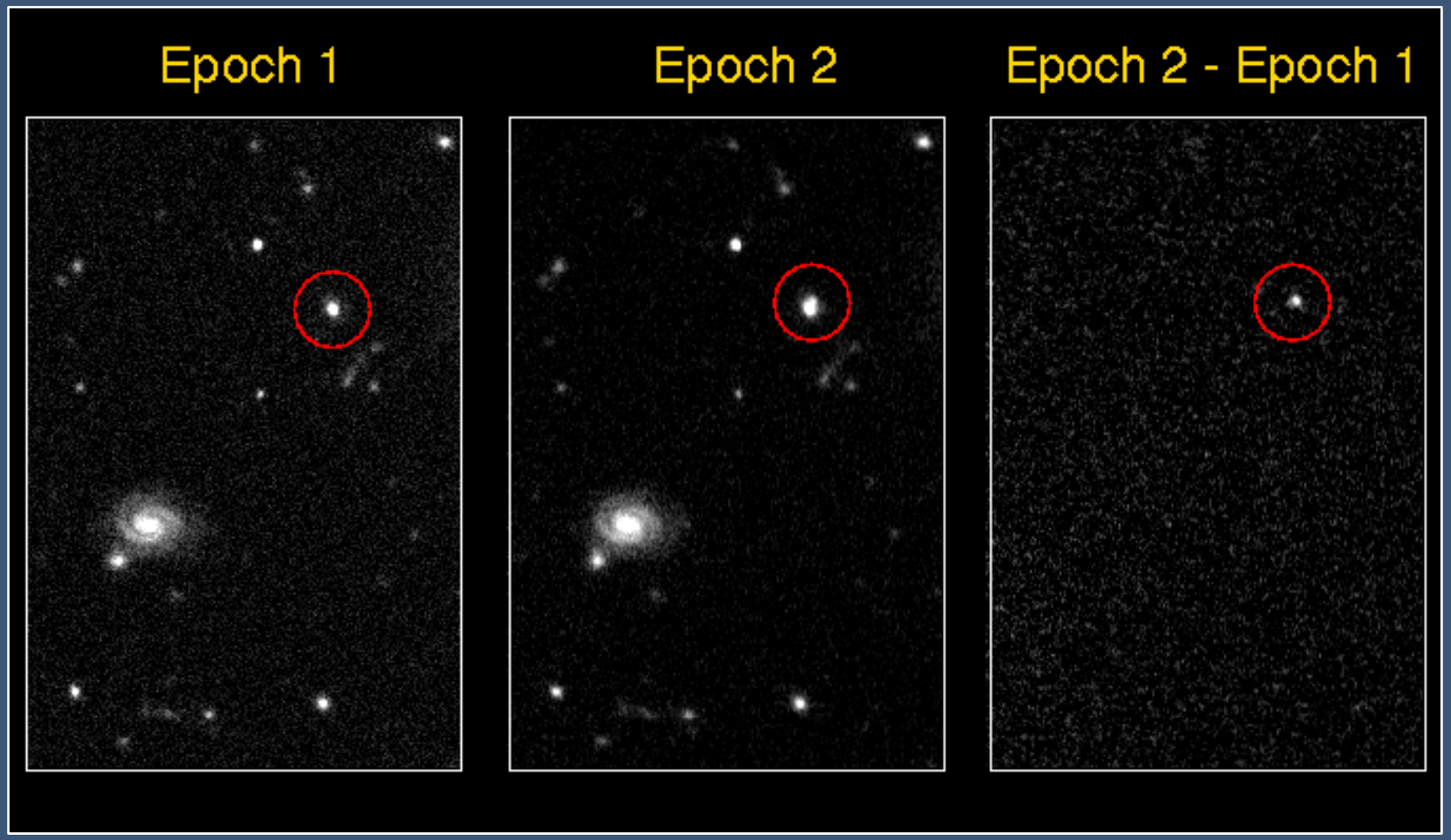


Where is the supernova?

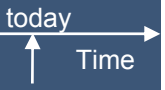


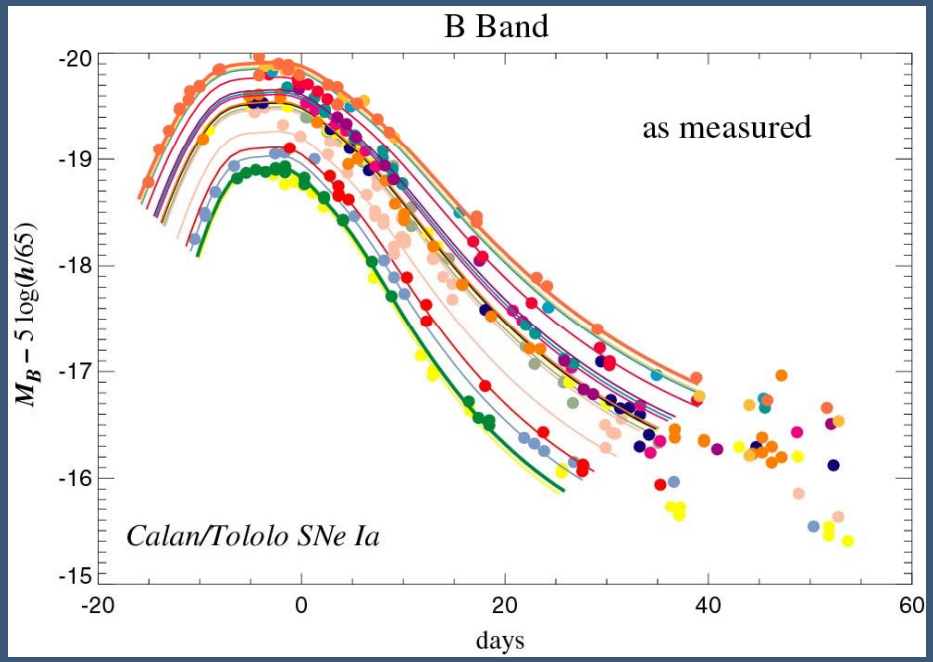


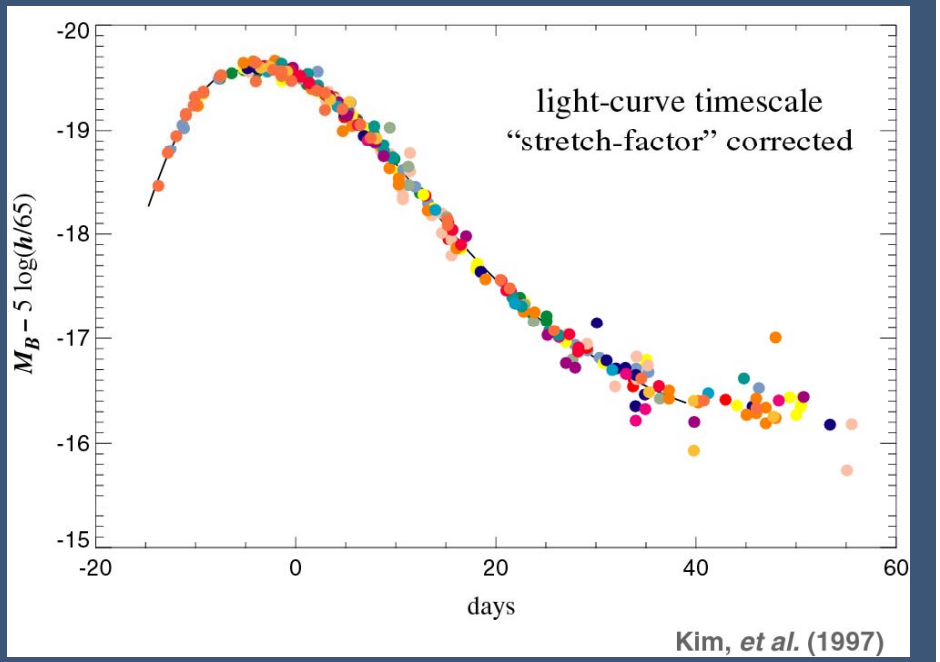
Here!

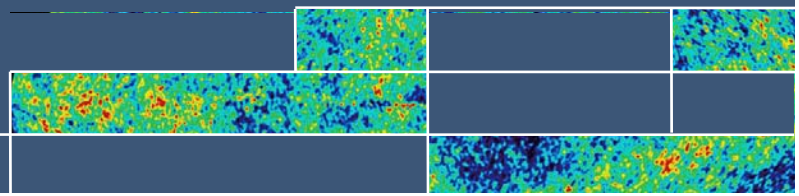


„Standard candles“





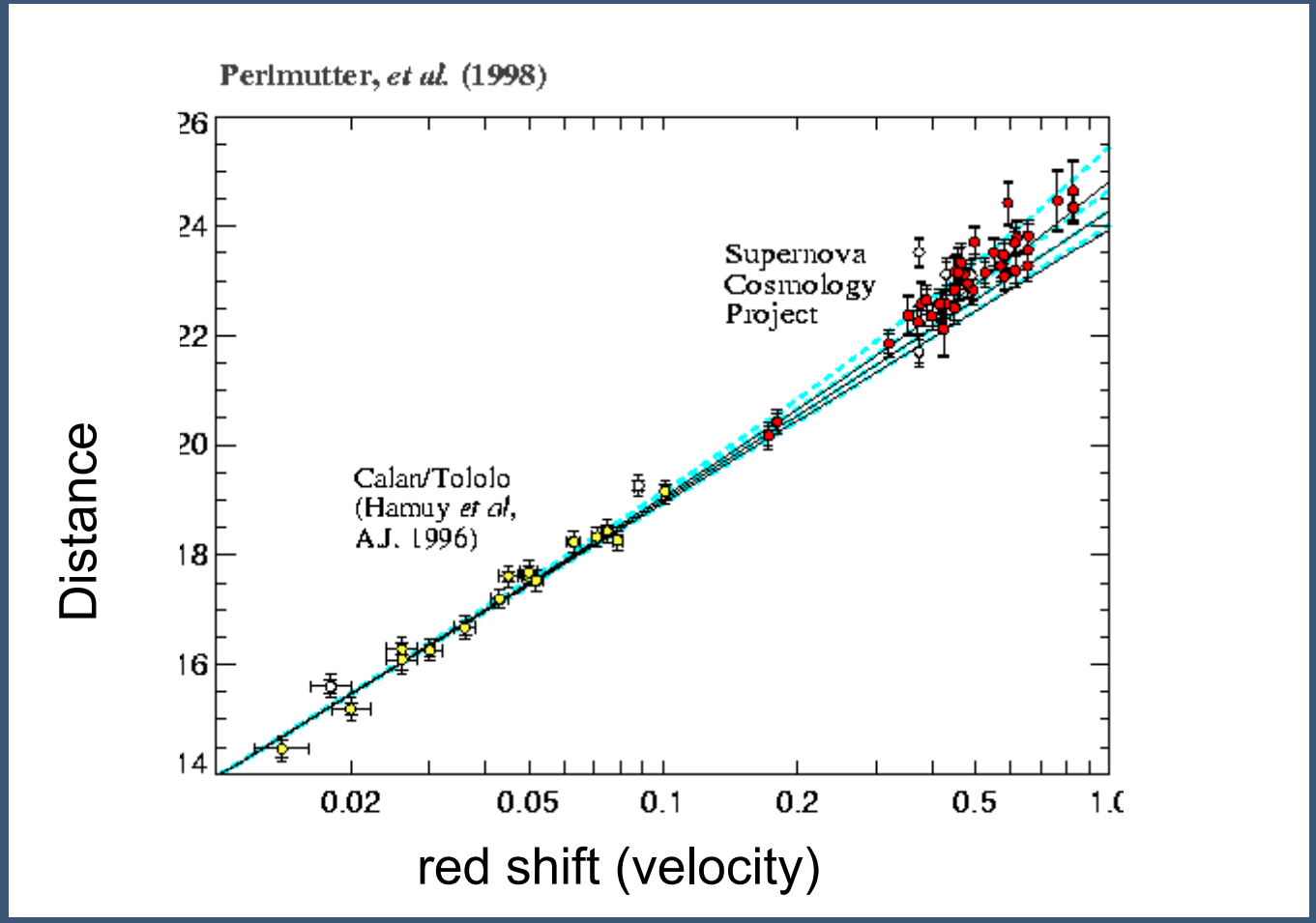




The Hubble-Diagram

Heute

Time



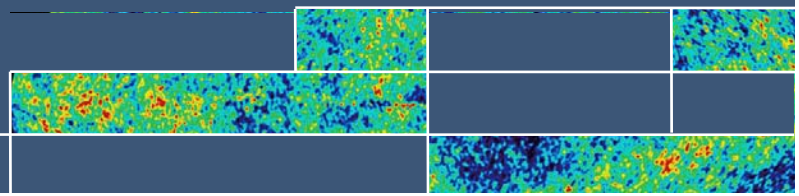
today

Time

- The Universe is expanding (acclerating)!
- The Universe was smaller at earlier times

- The Universe was created in a hot phase

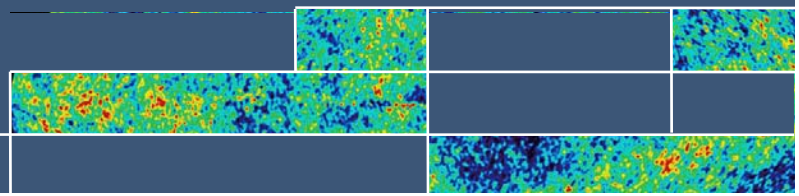
The Big Bang



today

Time

World models



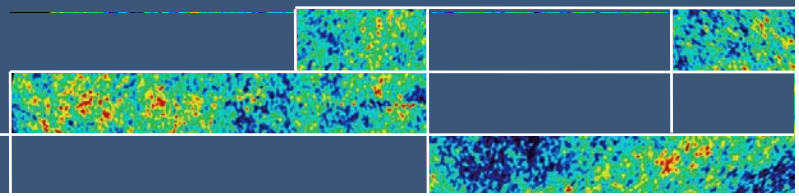
General relativity

today
Time

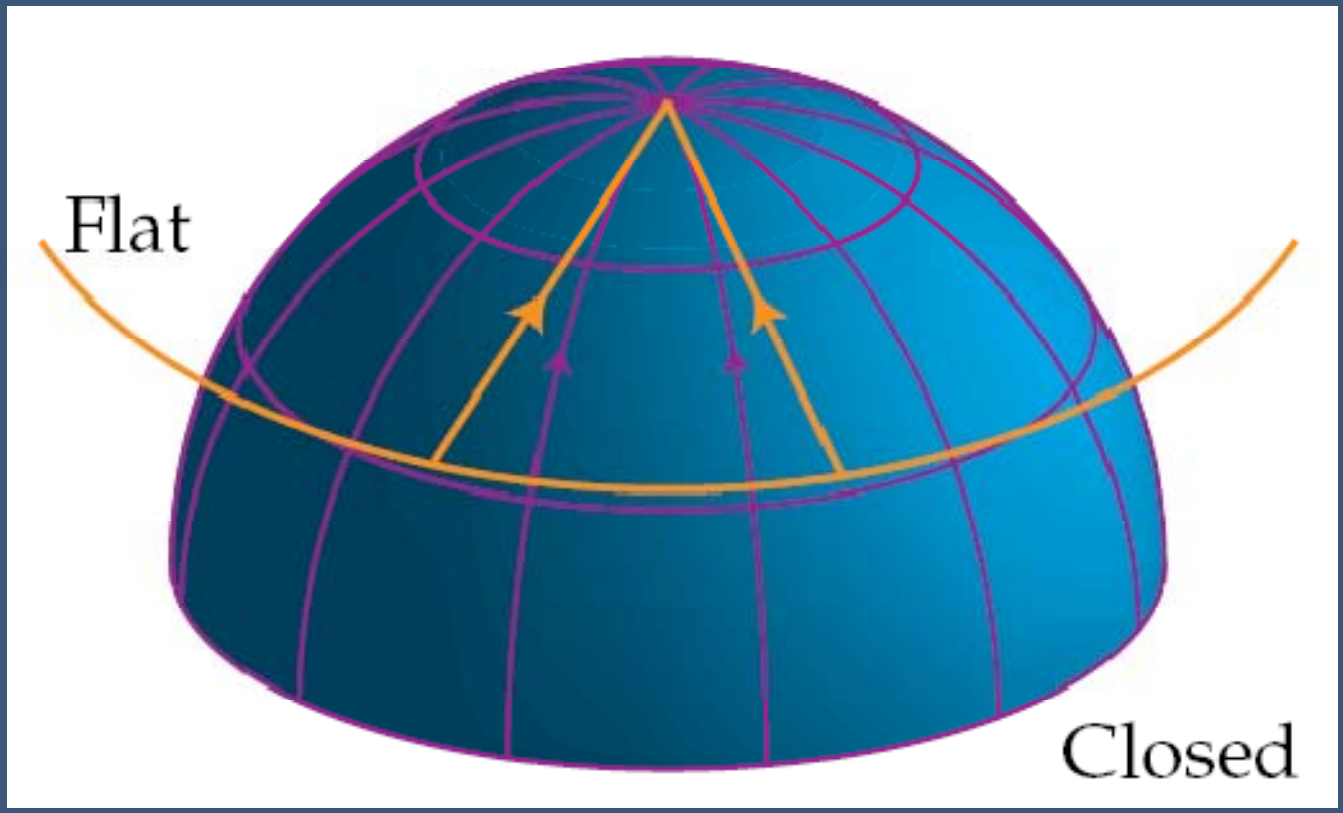
- Einstein 1916
- Describes all gravitationally bound systems
  - planets
  - black holes
  - the Universe

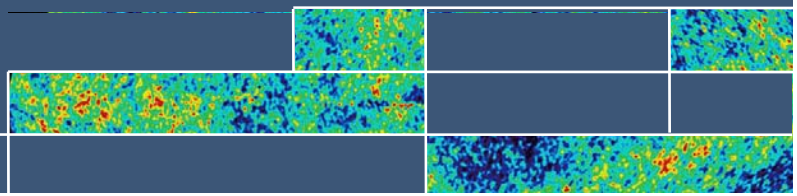
$$\mathbf{G}_{\mu\nu} - \Lambda\,\mathbf{g}_{\mu\nu} = \frac{8\pi G}{c^4}\,\mathbf{T}_{\mu\nu}$$

- Mass produces curvature of the space
- Curvature tells masses how to move
  → gravitation



Space curvature



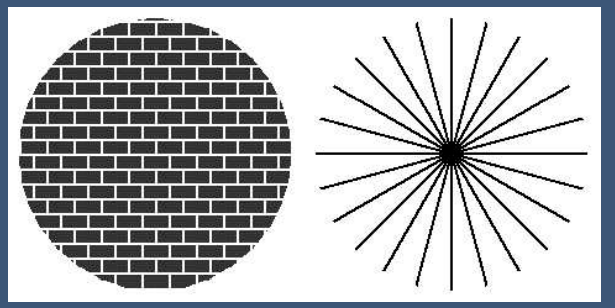


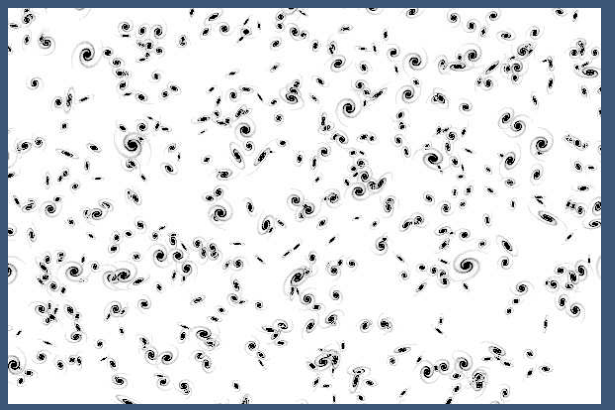
Solution

- Cosmological principle
  - We see what every other sees
  - Isotrop and homogeneous Universe
- Friedmann Universe (1922)
- World models depend only on
  - Expansion
  - Gravitational attraction

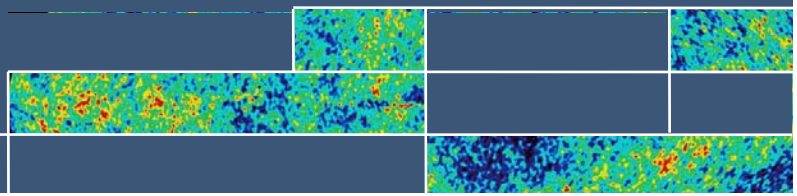
Homogeneous but not isotrop

Isotrop but not homogeneous

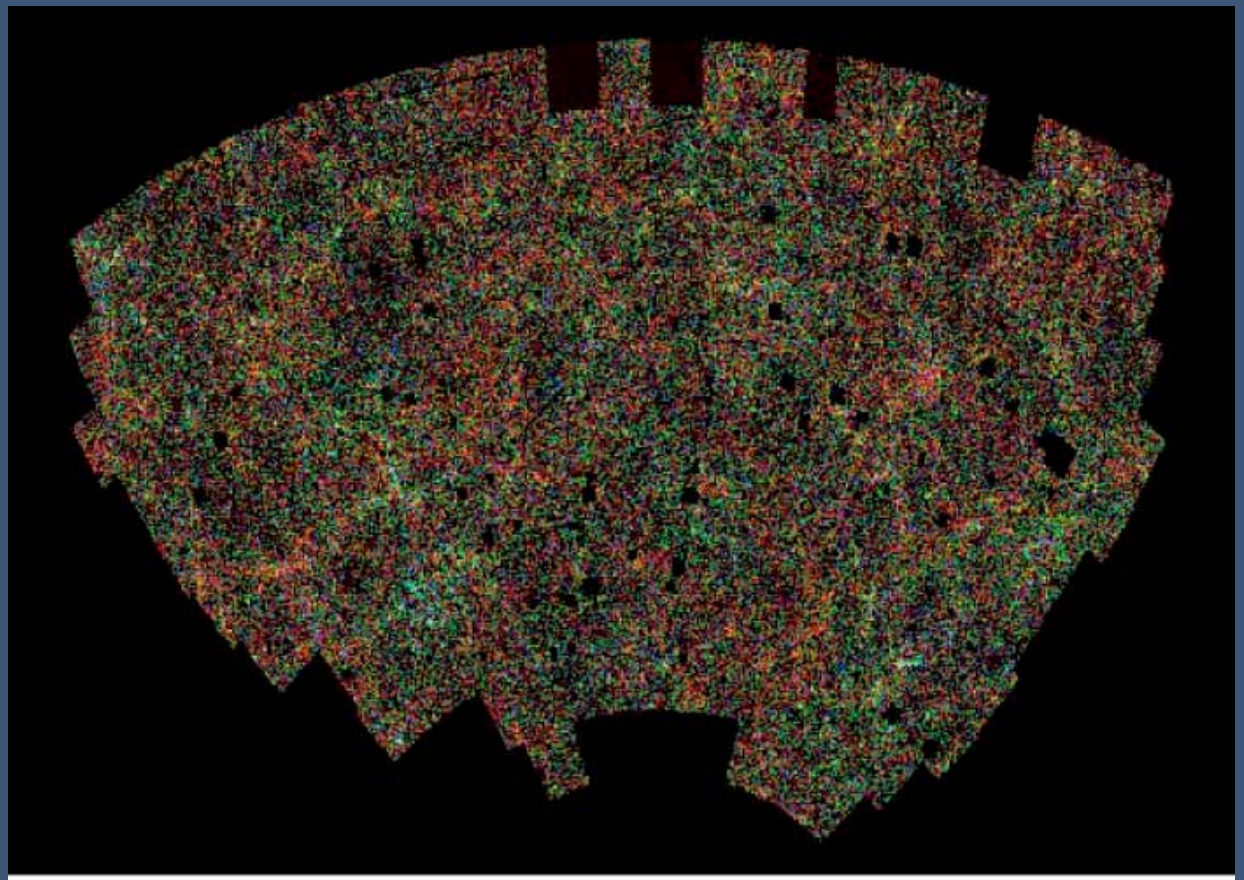




Isotrop **AND** homogeneous

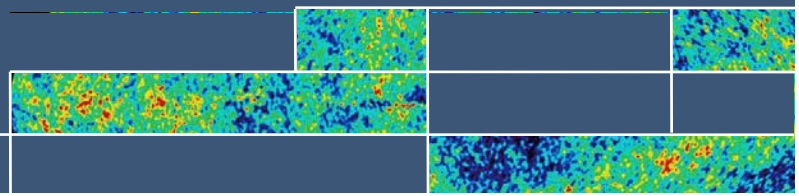


Distribution of galaxies



APM Survey picture of a large part of the sky, about 30 degrees across, showing almost a million galaxies out to a distance of about 2 billion light years.

MAP990047



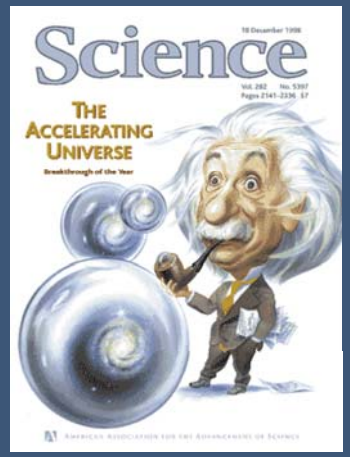
The accelerated Universe

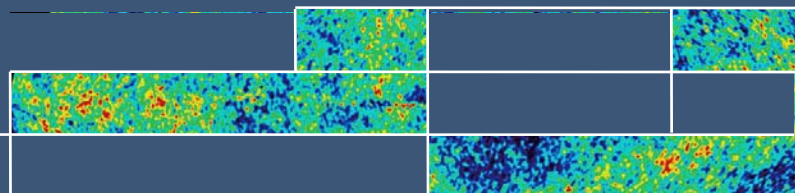
Time

- Einsteins cosmological constant

$$\mathbf{G}_{\mu\nu} - \Lambda\, \mathbf{g}_{\mu\nu} = \frac{8\pi G}{c^4}\, \mathbf{T}_{\mu\nu}$$

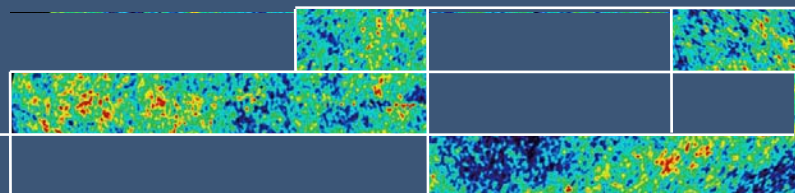
- cosmological constant acts like an anti-gravitation





Time

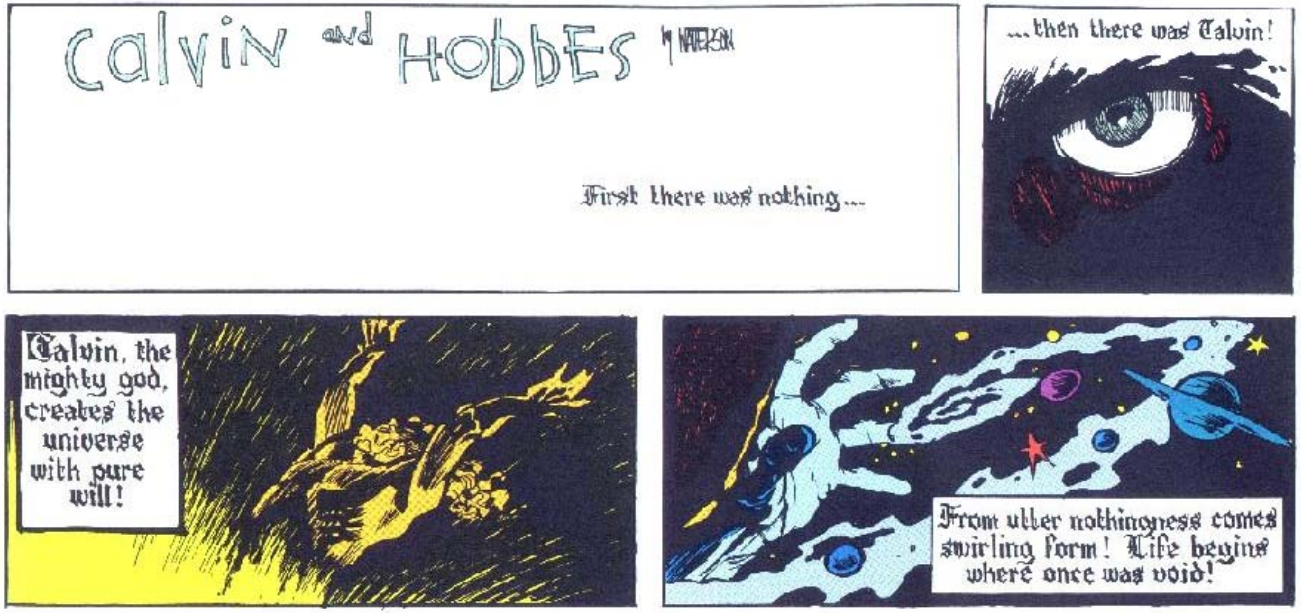
A travel through the time



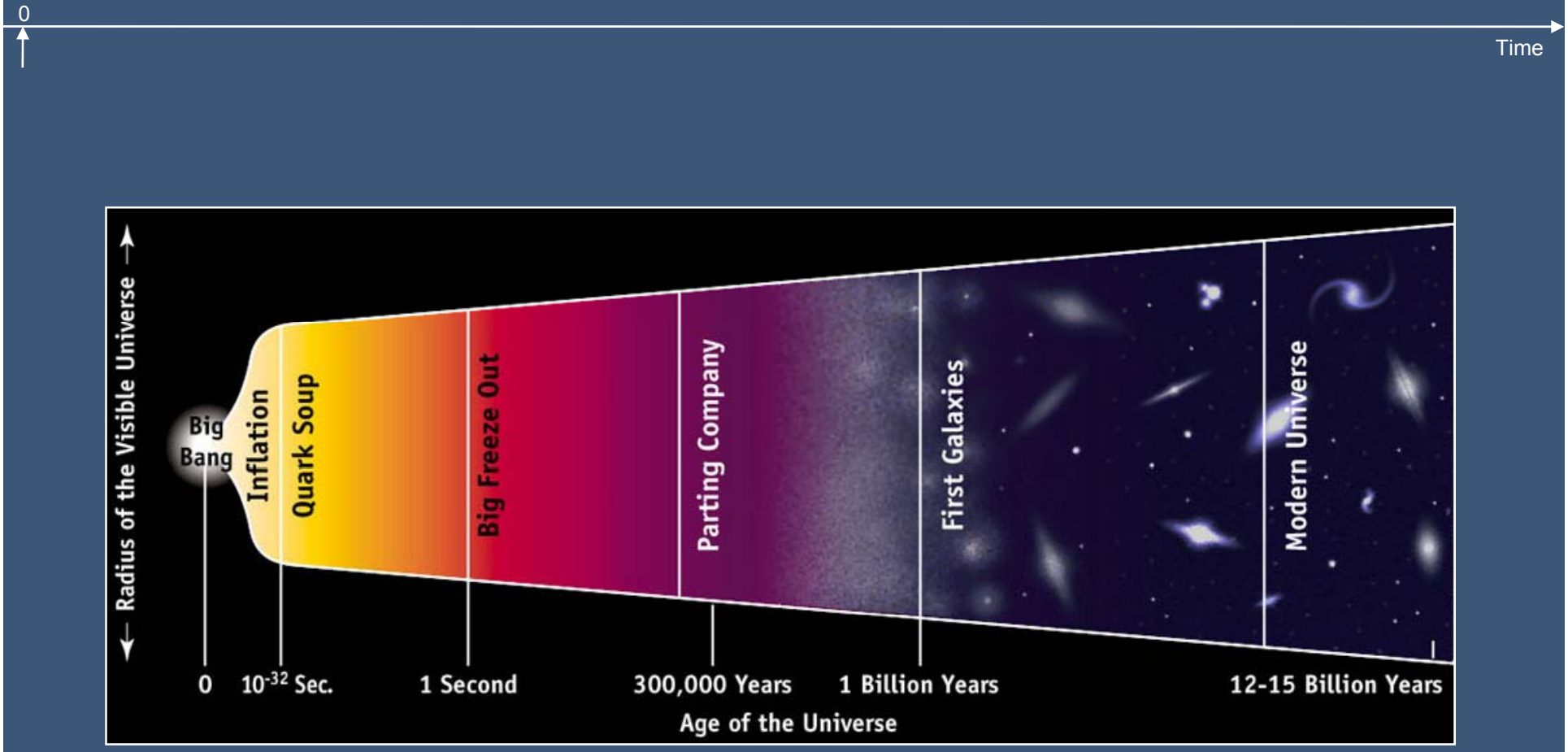
First there was …

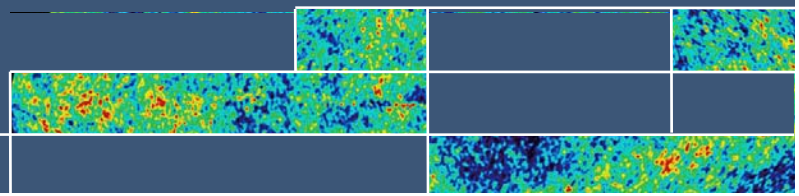
0

Time



From Big Bang until today



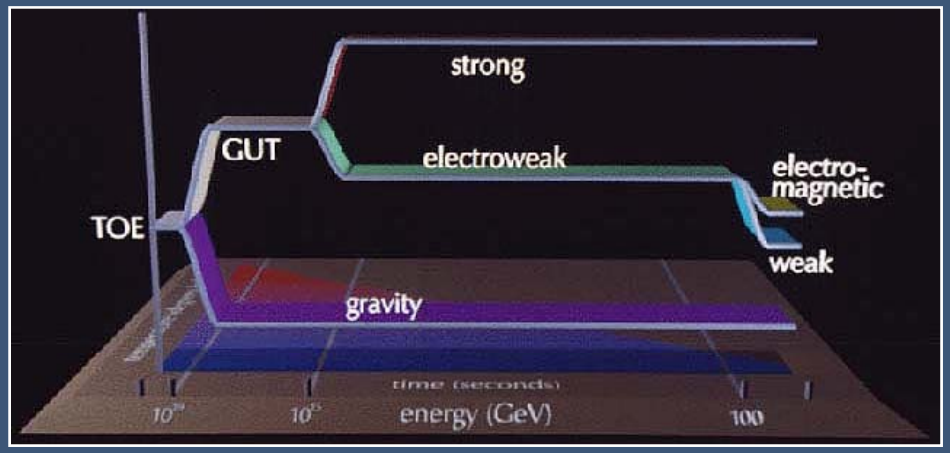


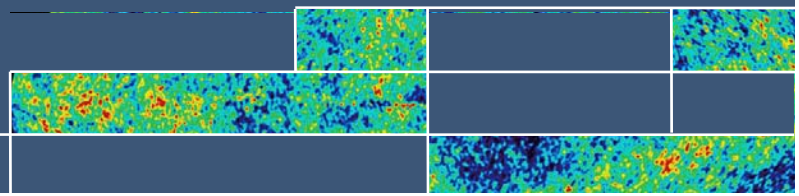
A time travel

10^{-42} s

Time

- Age = 10^{-42} s
  - The beginning of physics
- Age = 10^{-36} s, T = 10^{27} K
  - Strong and electroweak force decouple



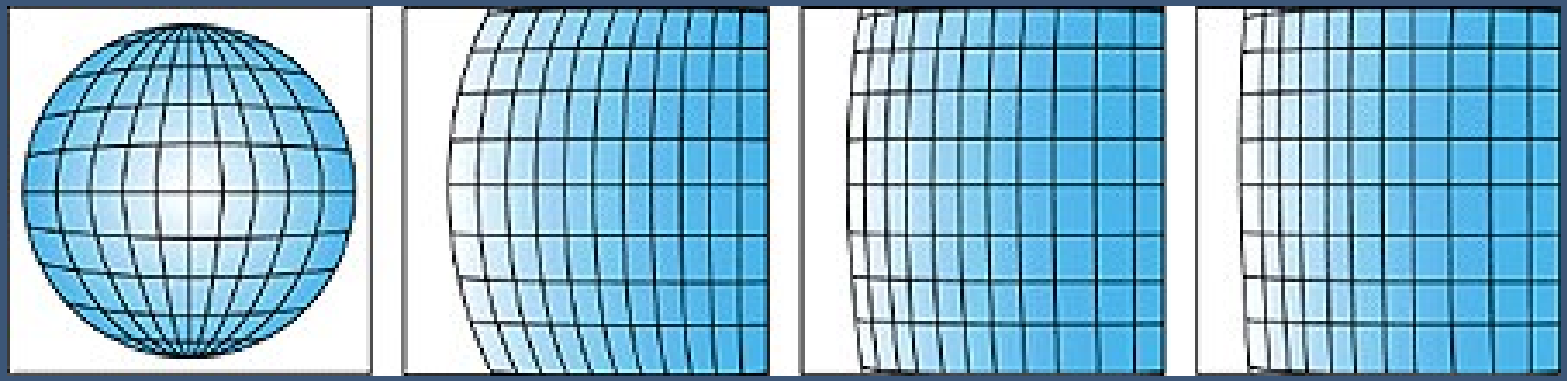


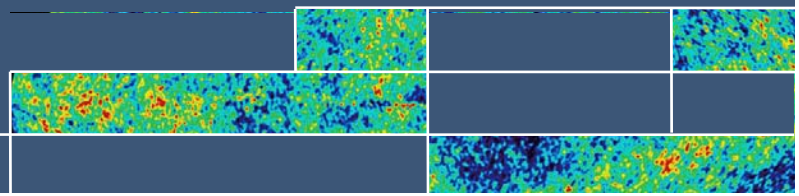
The inflation

10^{-36}s

Time

- Age = 10^{-36} s, T = 10^{21} K
  - Sudden expansion of the Universe by a factor 10^{20} – 10^{30}
  - The Universe gets flat!





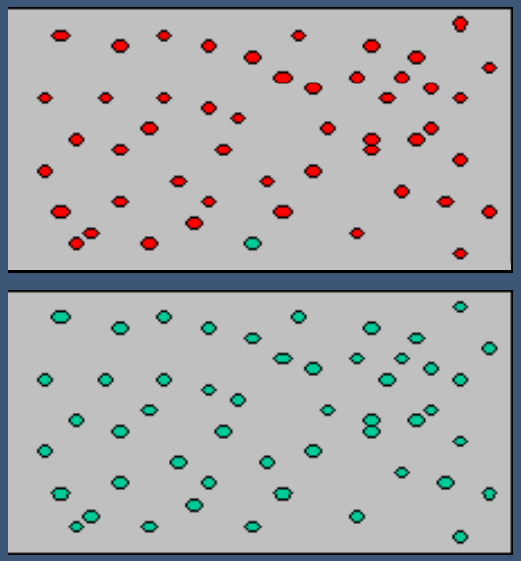
The battle

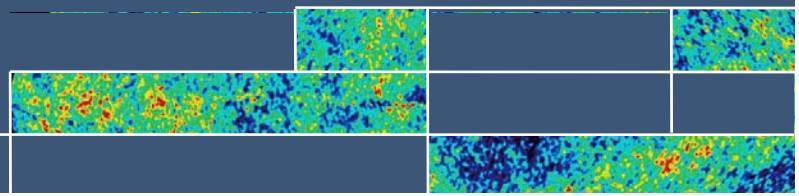
- Age = 10^{-6} s, T = 10^{12} Kelvin
  - Matter and antimatter annihilate
  - Matter-antimatter-ratio

    100000001 : 10000000

  - Matter-photon-ratio

    1 : 100000000



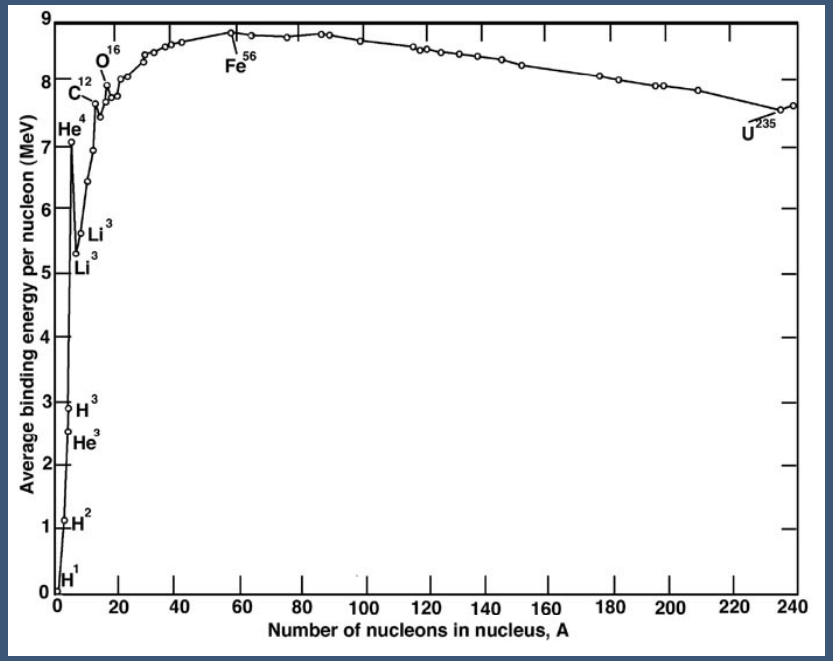


Nukleosynthesis

1 min

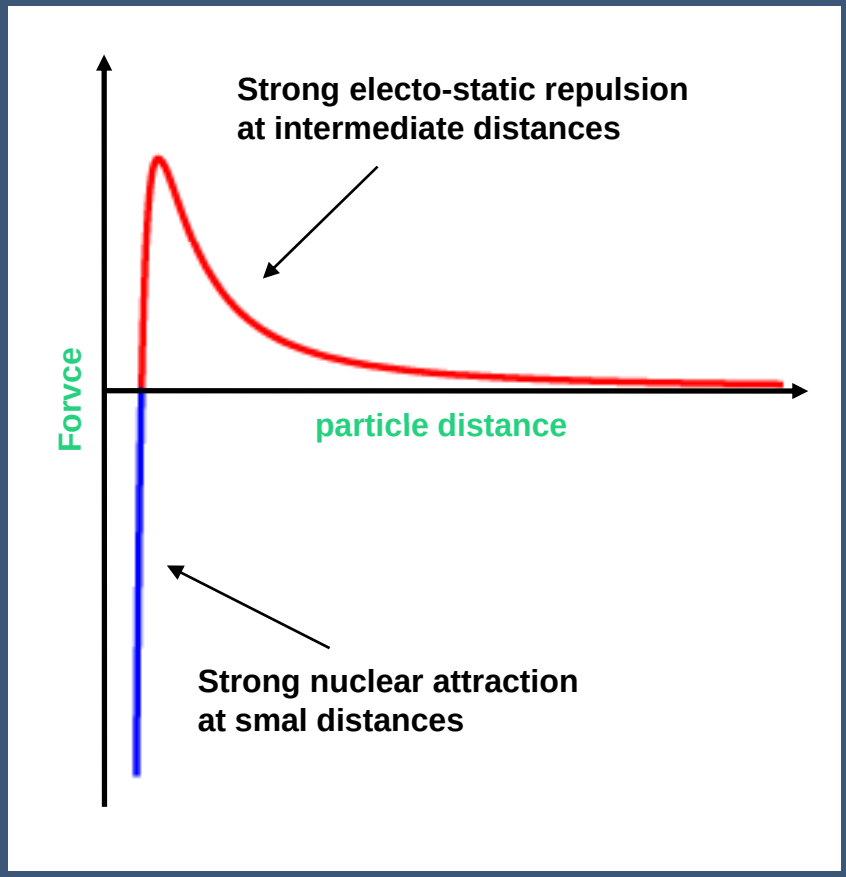
Time

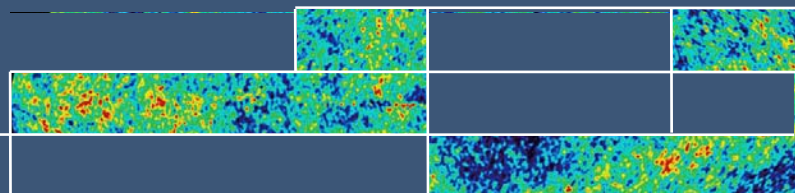
- Age = 1 min, T = 10^9 K
  - Generation of light elements
  - Hydrogen, Deuterium, Helium, Lithium



Nuclear fusion

- Fusion in collisions
- Fusion requries high temperatures and large densities



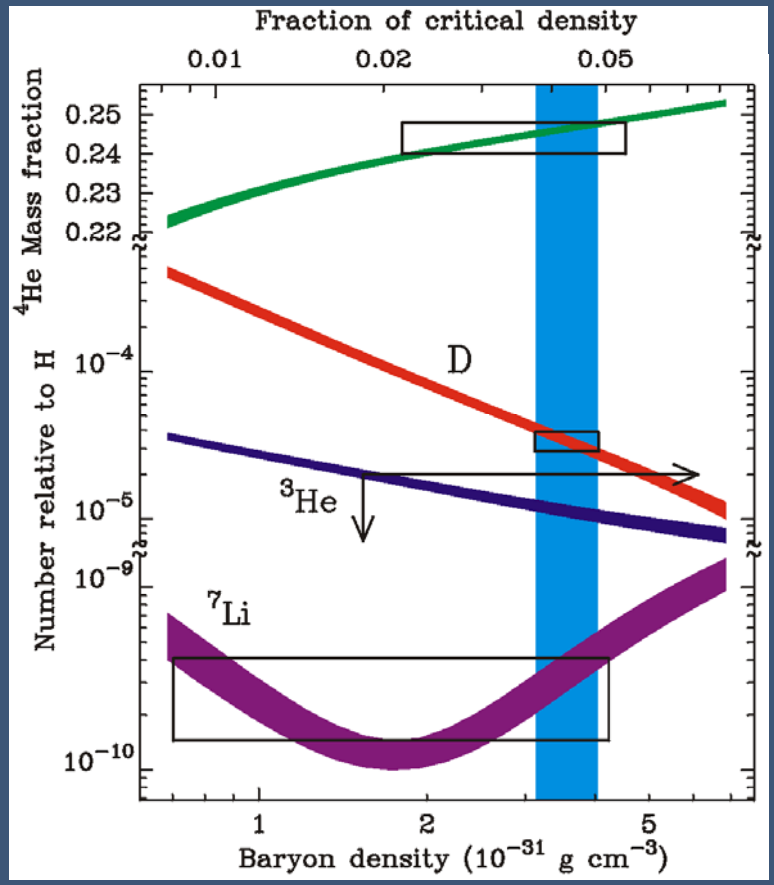


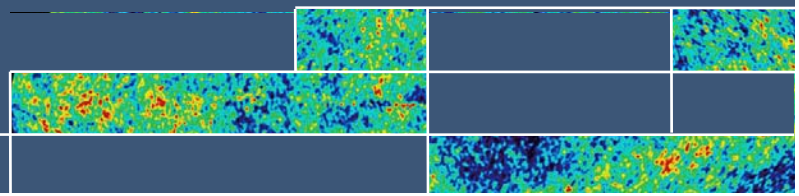
Primordiale Nukleosynthesis

1 min

Time

- Explains the abundances of light elements
  - 74% Hydrogen
  - 25% Helium
  - 1% other
- Baryonic density
  - $3{,}5 \cdot 10^{-31}$ g/cm^3 or
  - 0,2 Hydrogen atoms/m^3



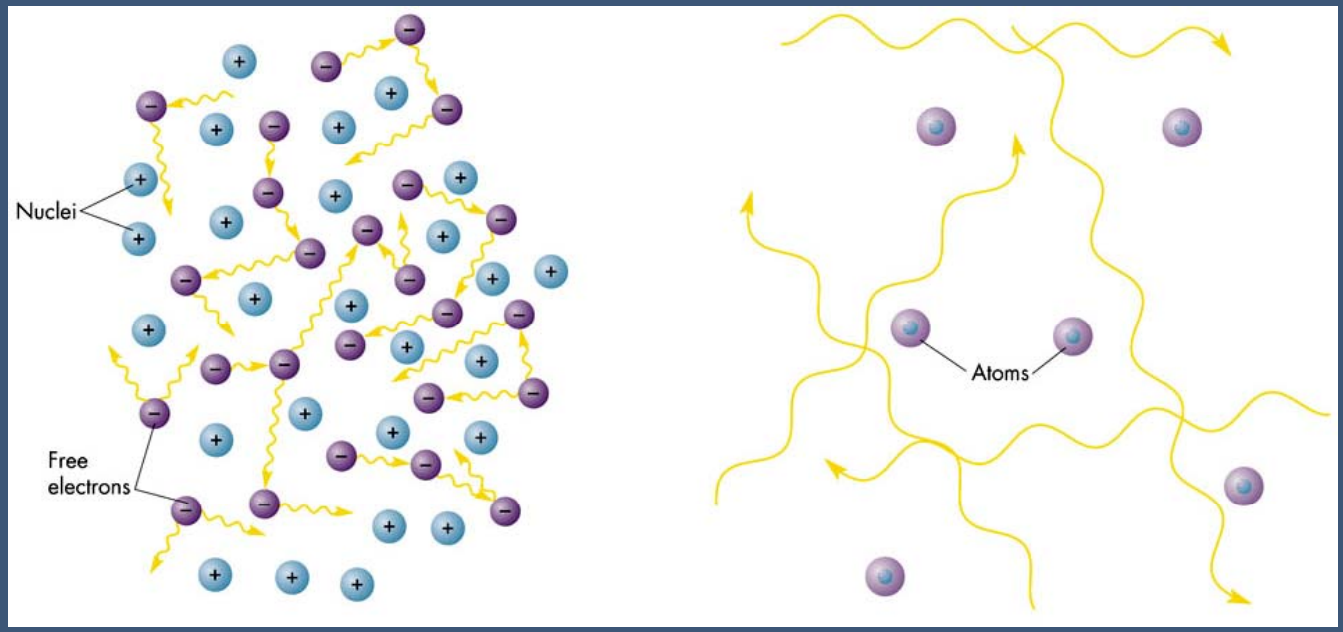


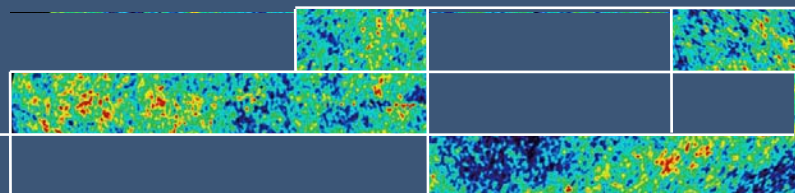
Generation of atoms

370000 years

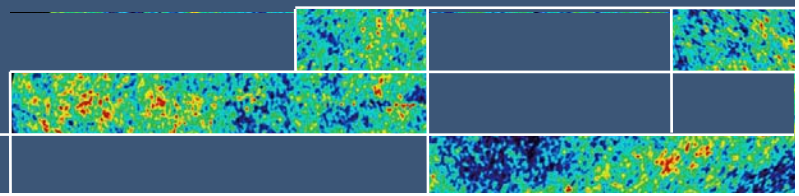
Time

- Age = 370000 Jahre, T = 3000 Kelvin
  - First atoms generated
  - The Universe becomes transparent

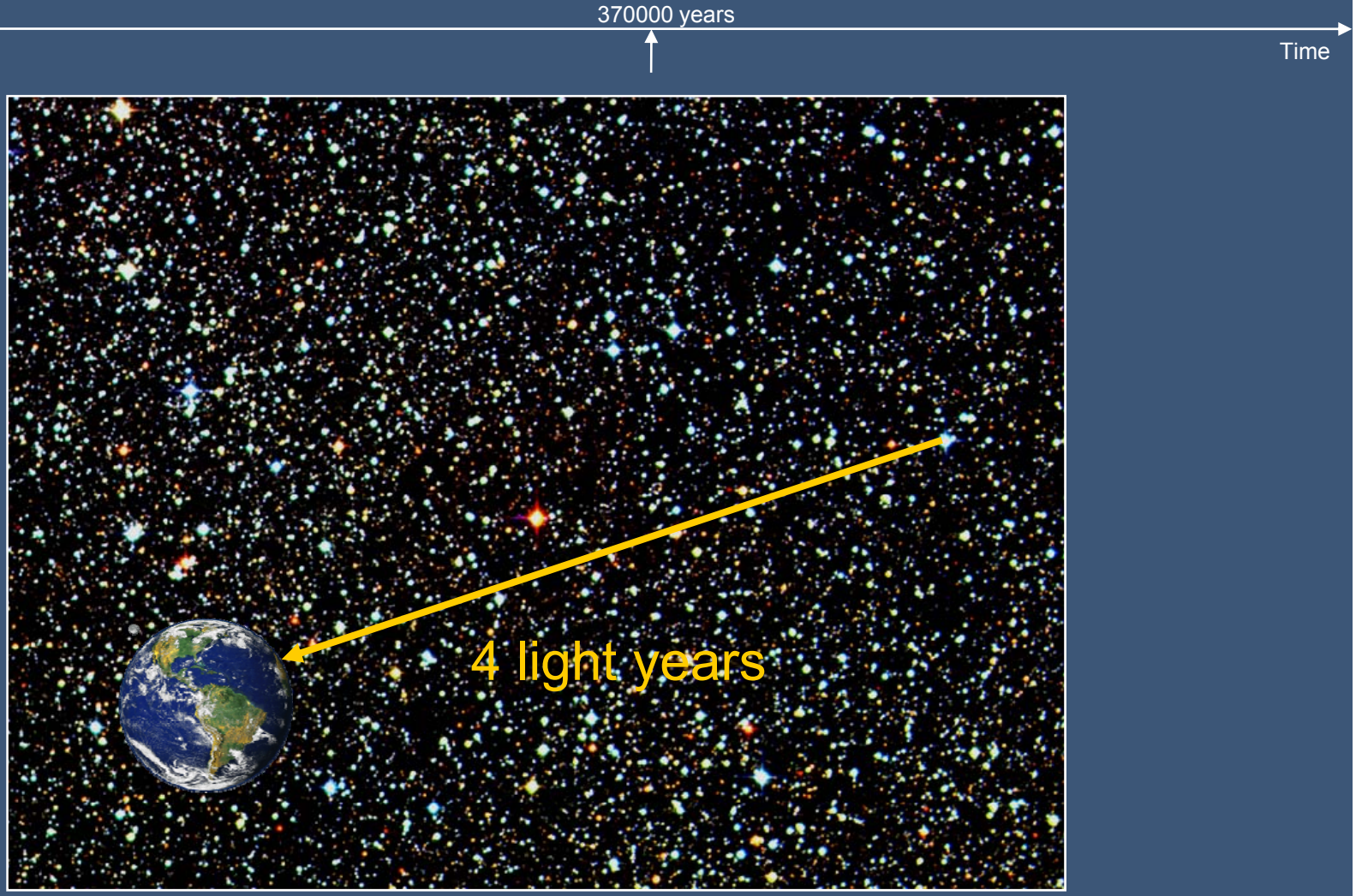


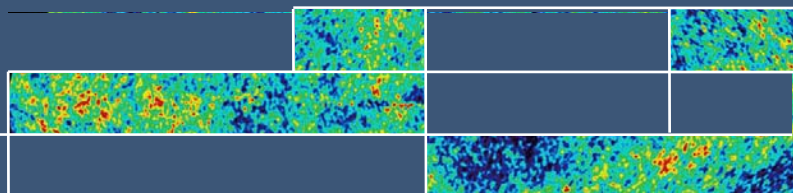


Can we see the Big Bang?



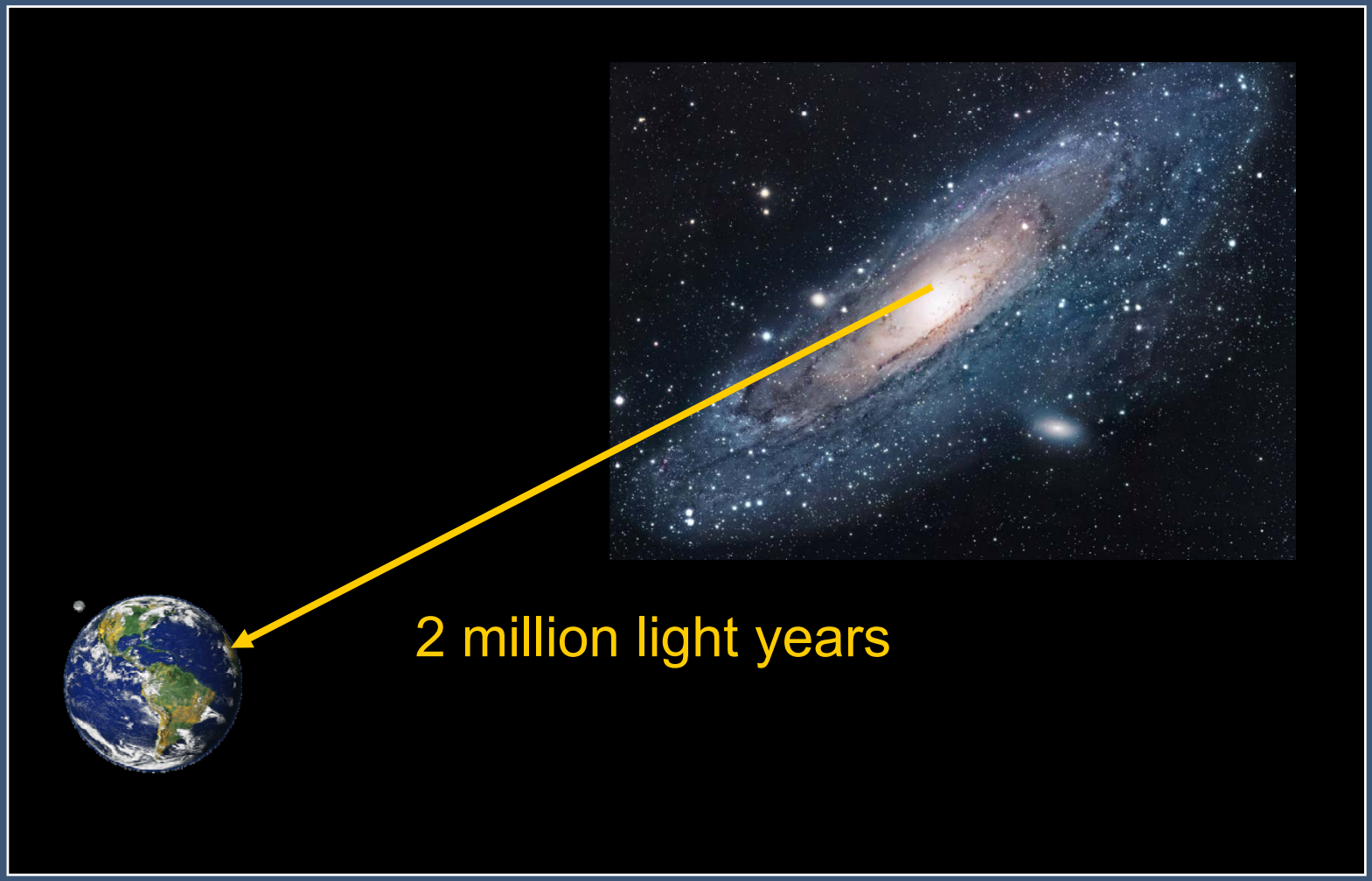
Back into the past

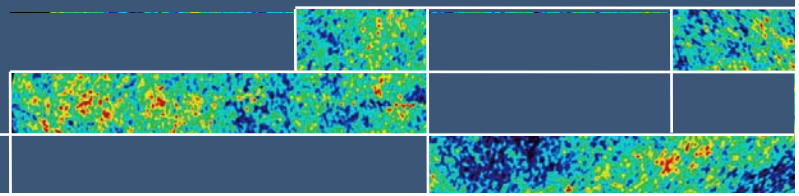




370000 years

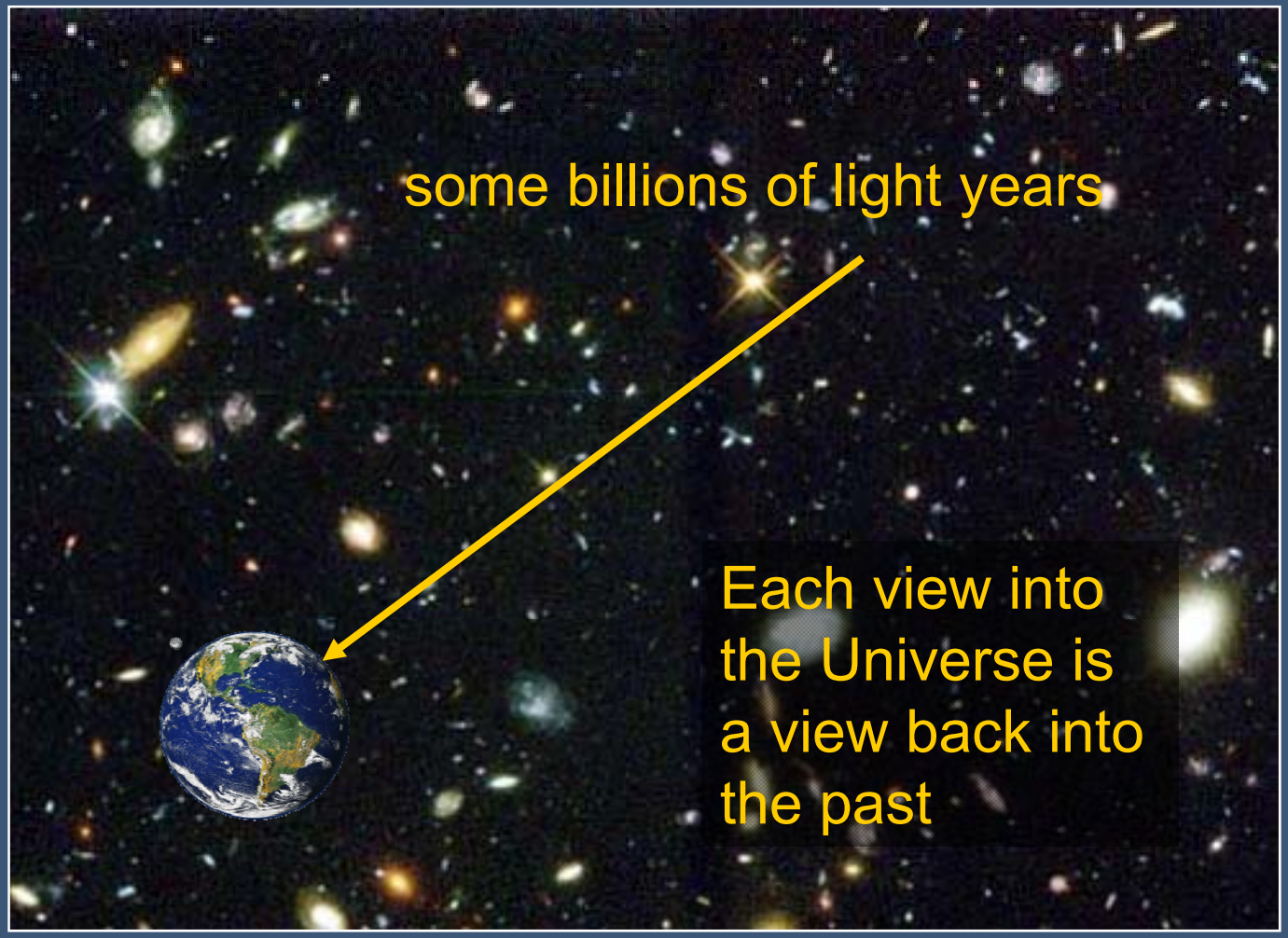
Time



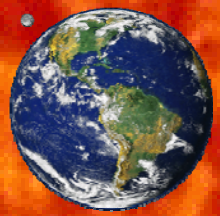


Back into the past

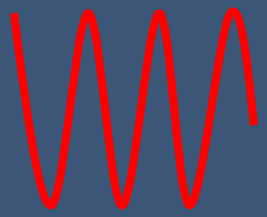
Time



The Big Bang fills the sky

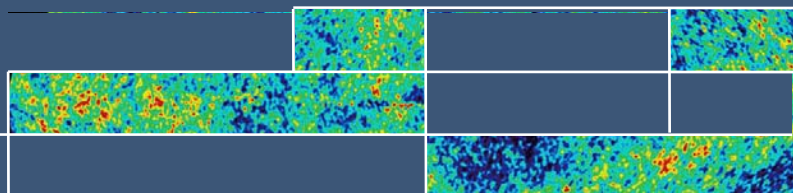


The Big Bang past - now



Past:
Light 3000 K

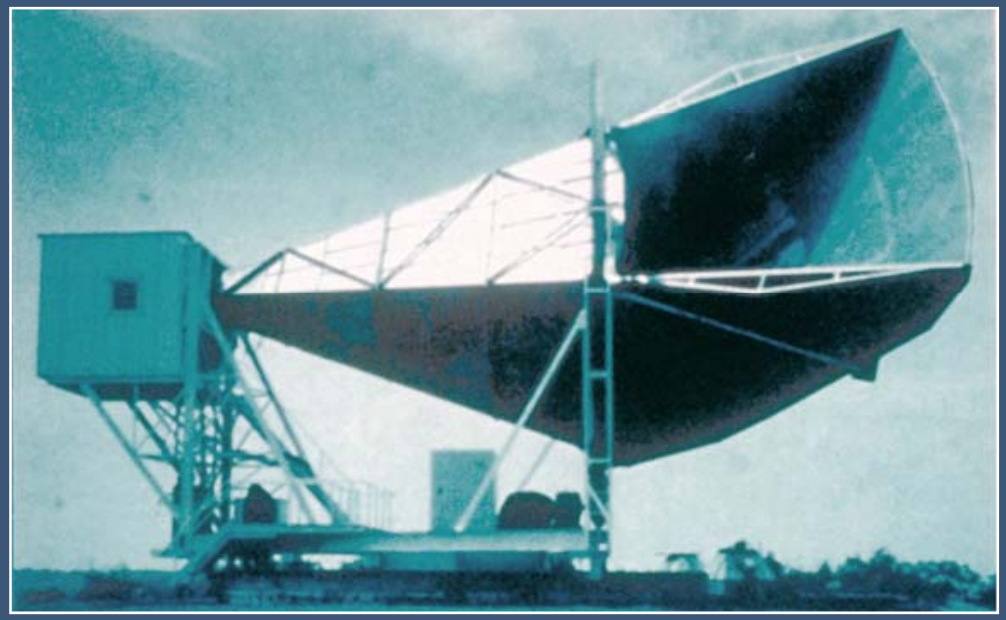
today:
Mikrowaves 3 K

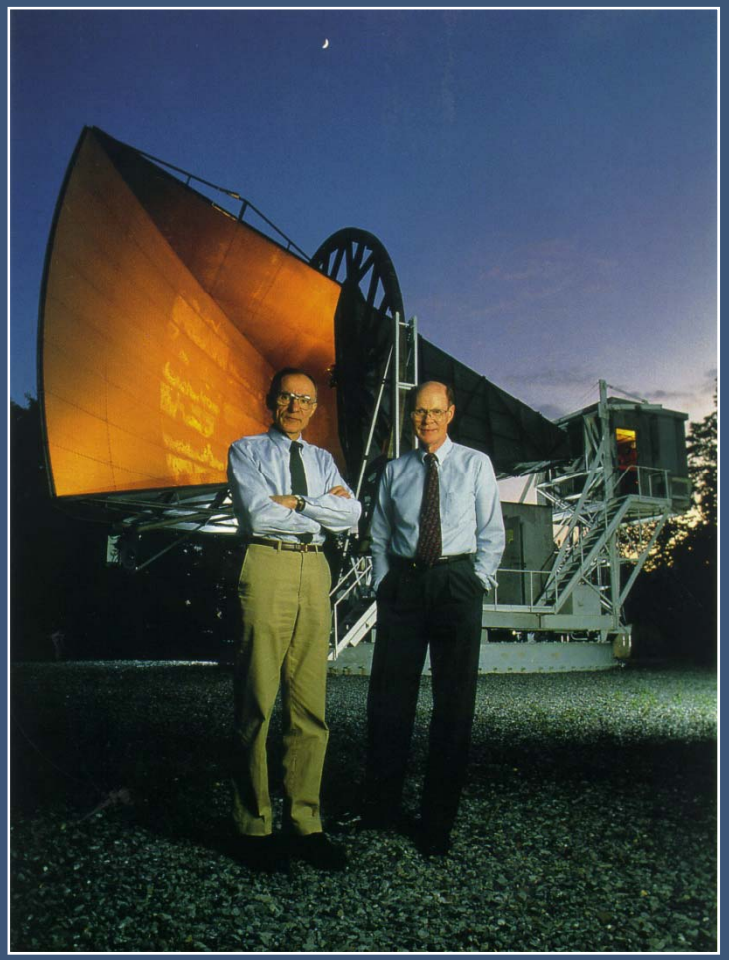


1965 – The discovery

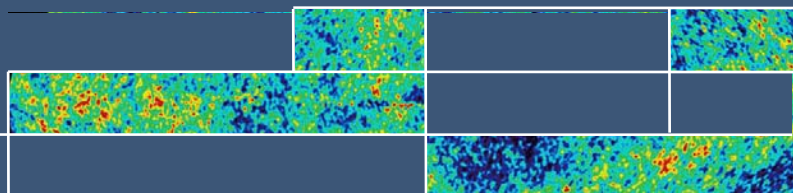
370000 years

Time



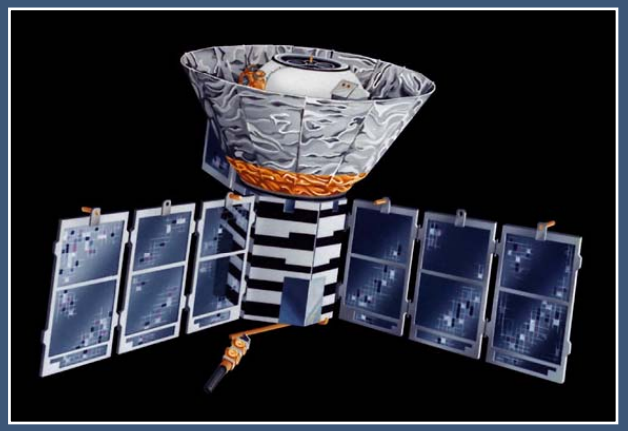


Microwave radiation
from the cosmos

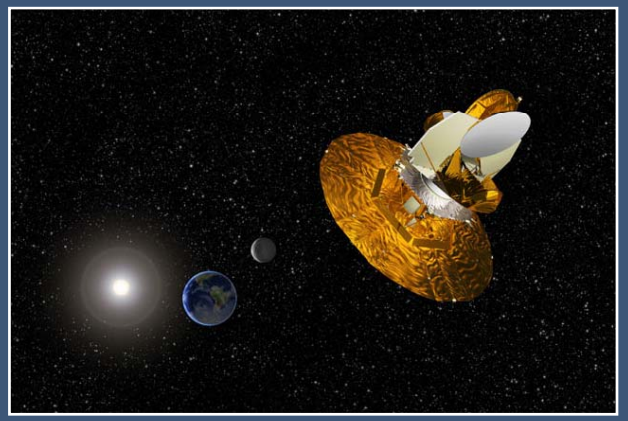


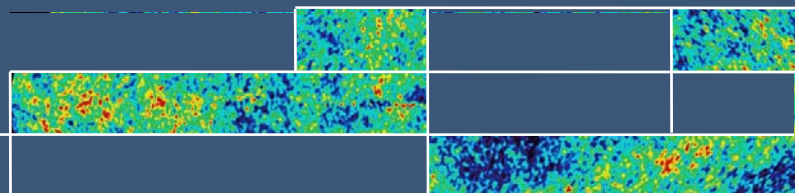
COBE and WMAP

- COBE
  - COsmic Background Explorer
  - 1989 – 1993
  - Nobel price 2006 (G. Smoot, J. Mather)

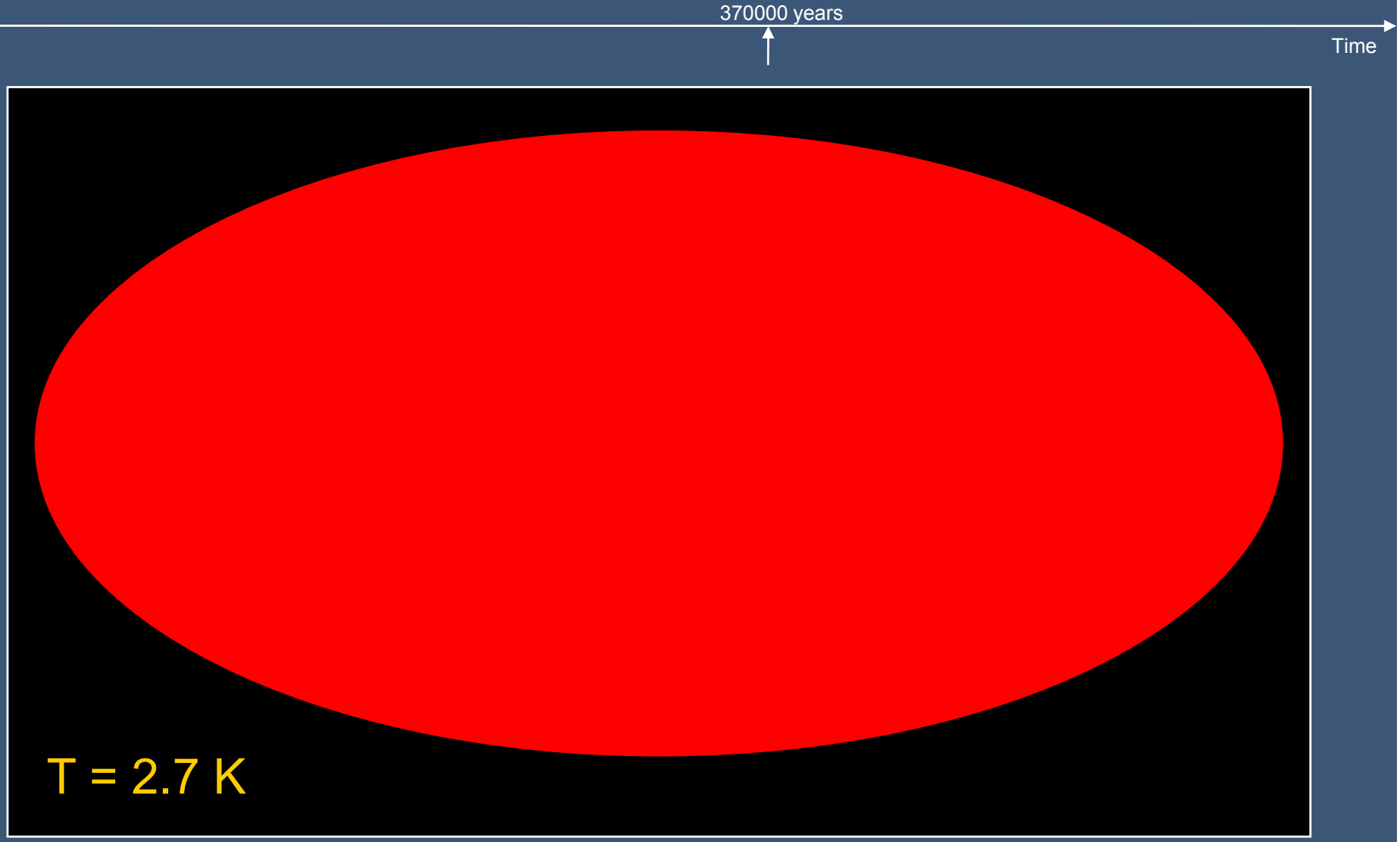


- WMAP
  - Wilkinson Microwave Anisotropy Probe
  - Start 2001





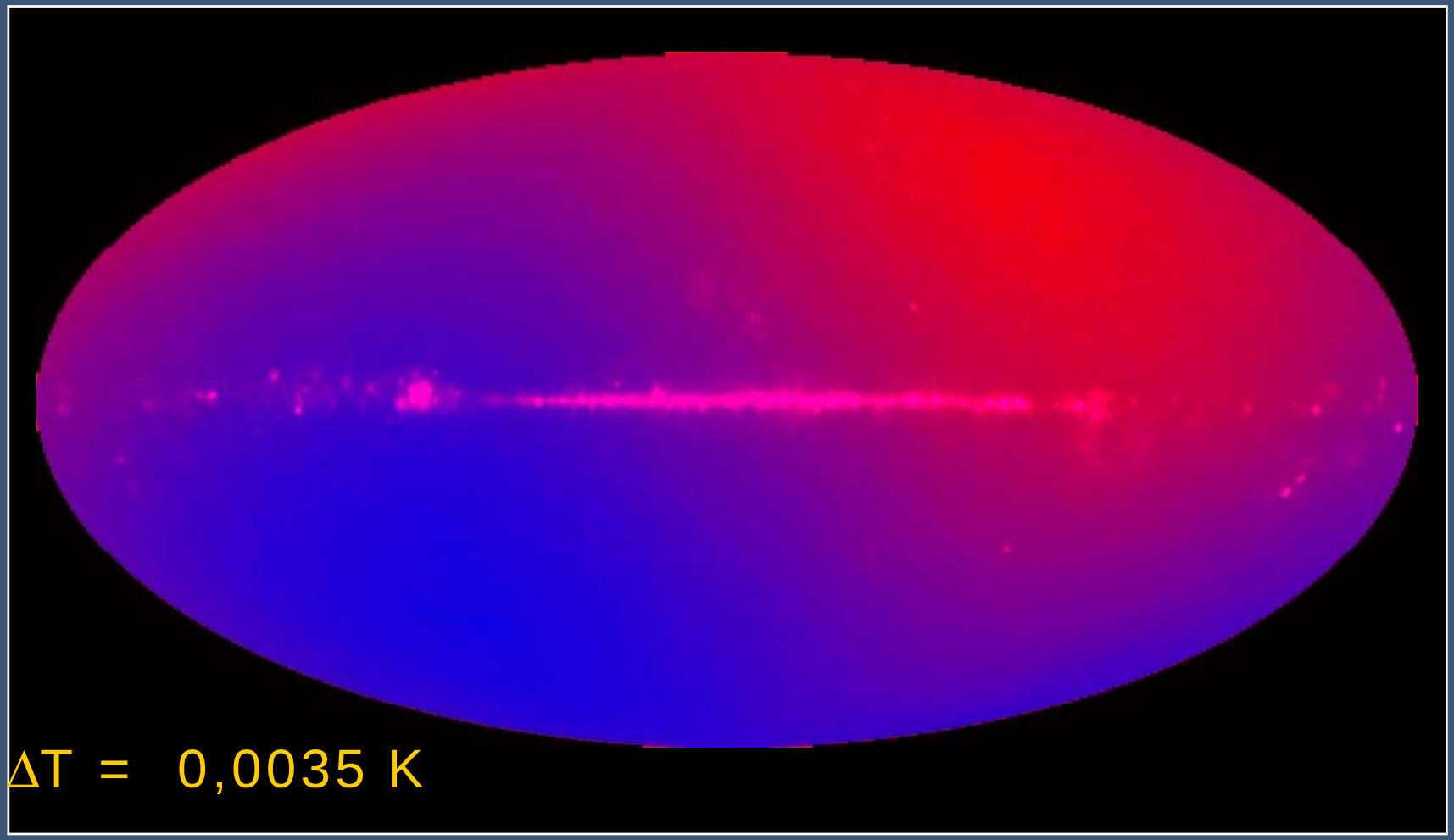
The microwave background

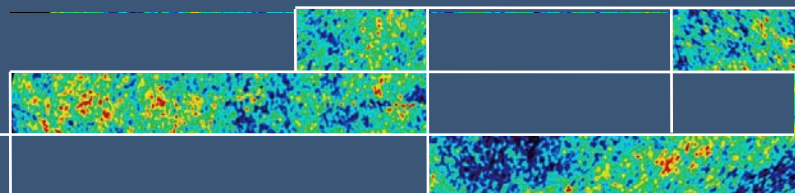


The Earth is moving

370000 years

Time

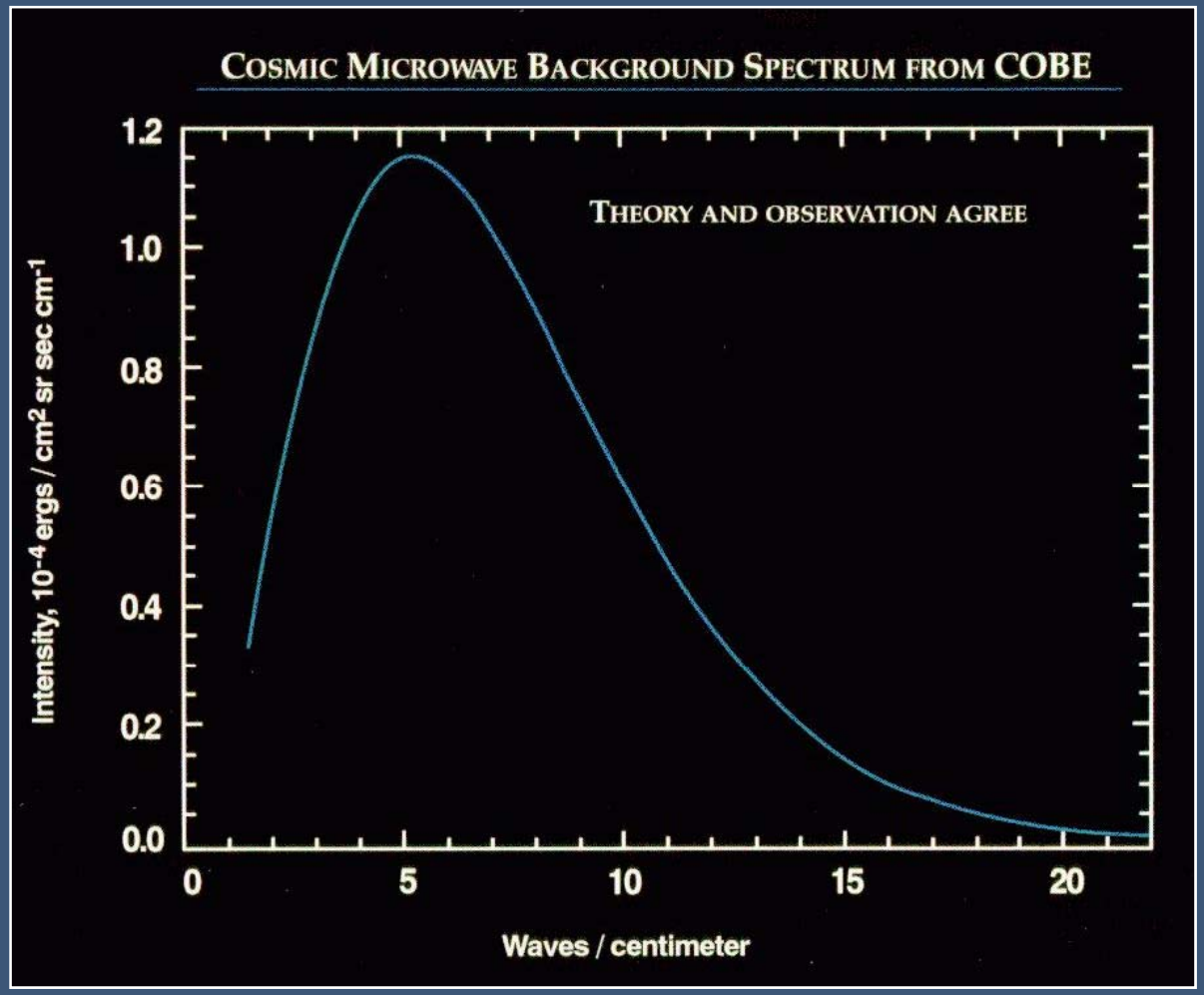


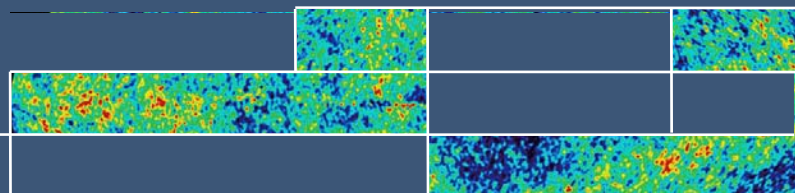


The spectrum

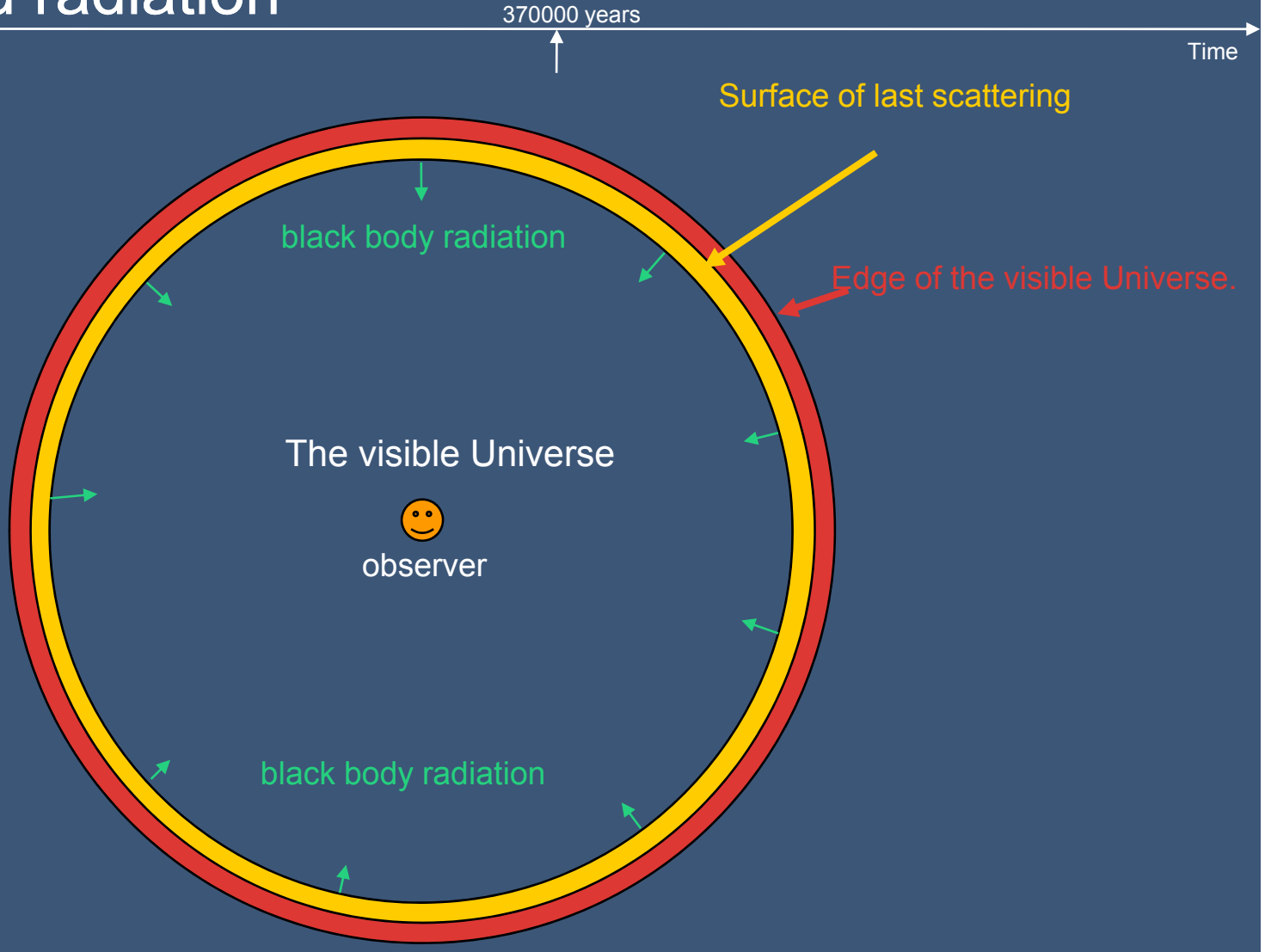
370000 years

Time





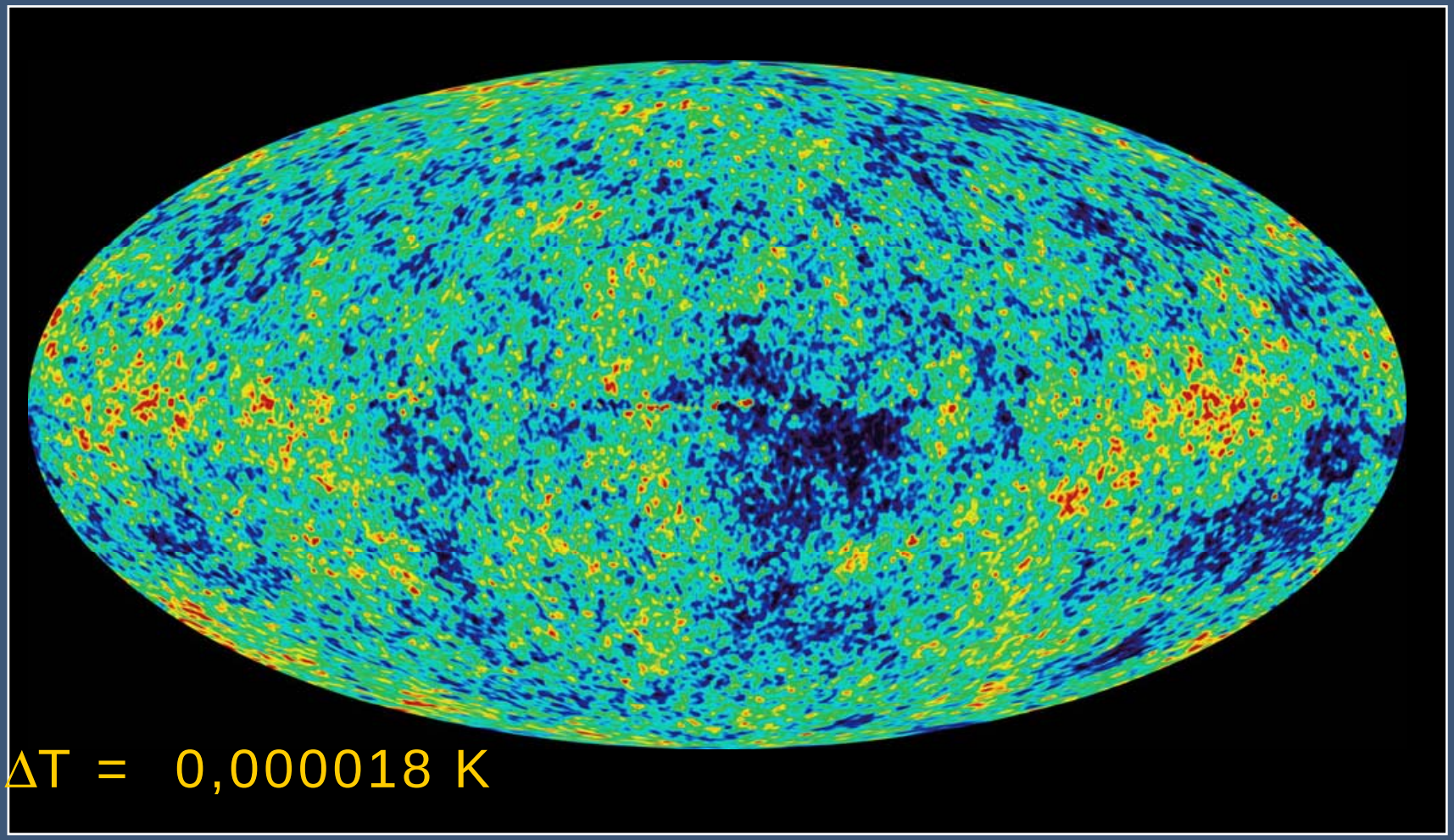
The history of the cosmic background radiation



The echo of the big bang

370000 years

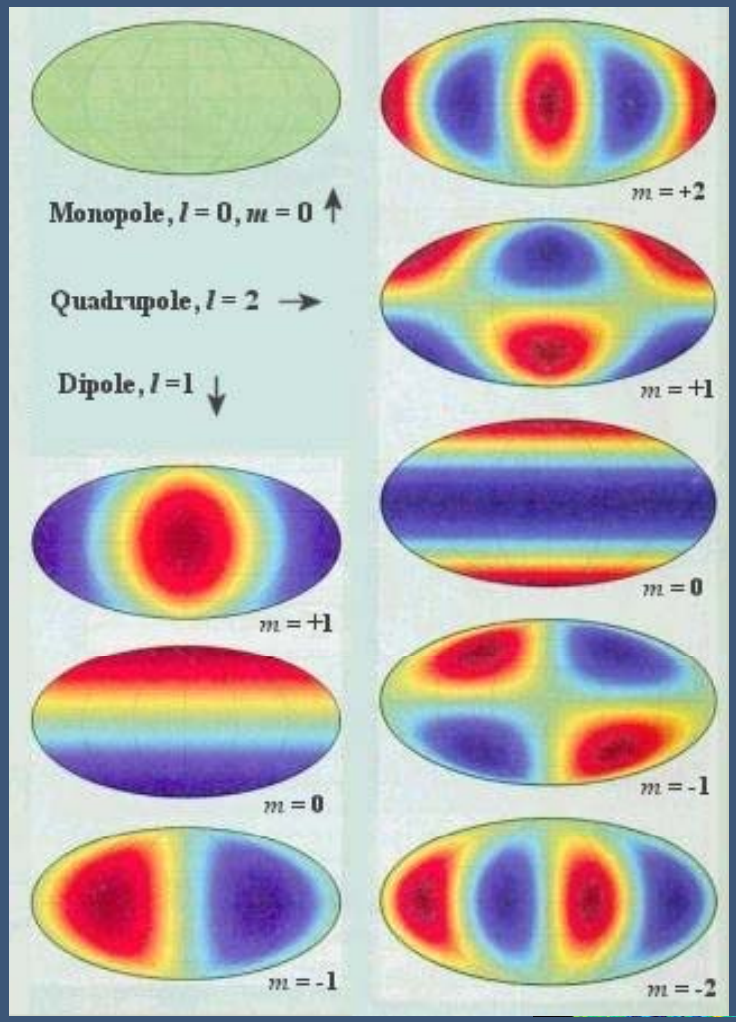
Time

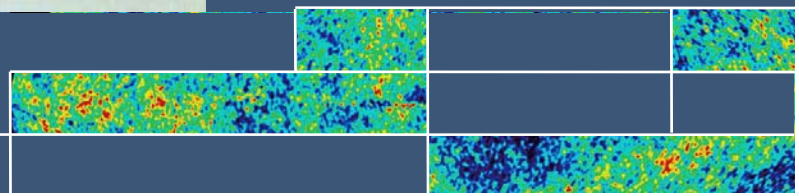


Multipol expansion

370000 years

Time

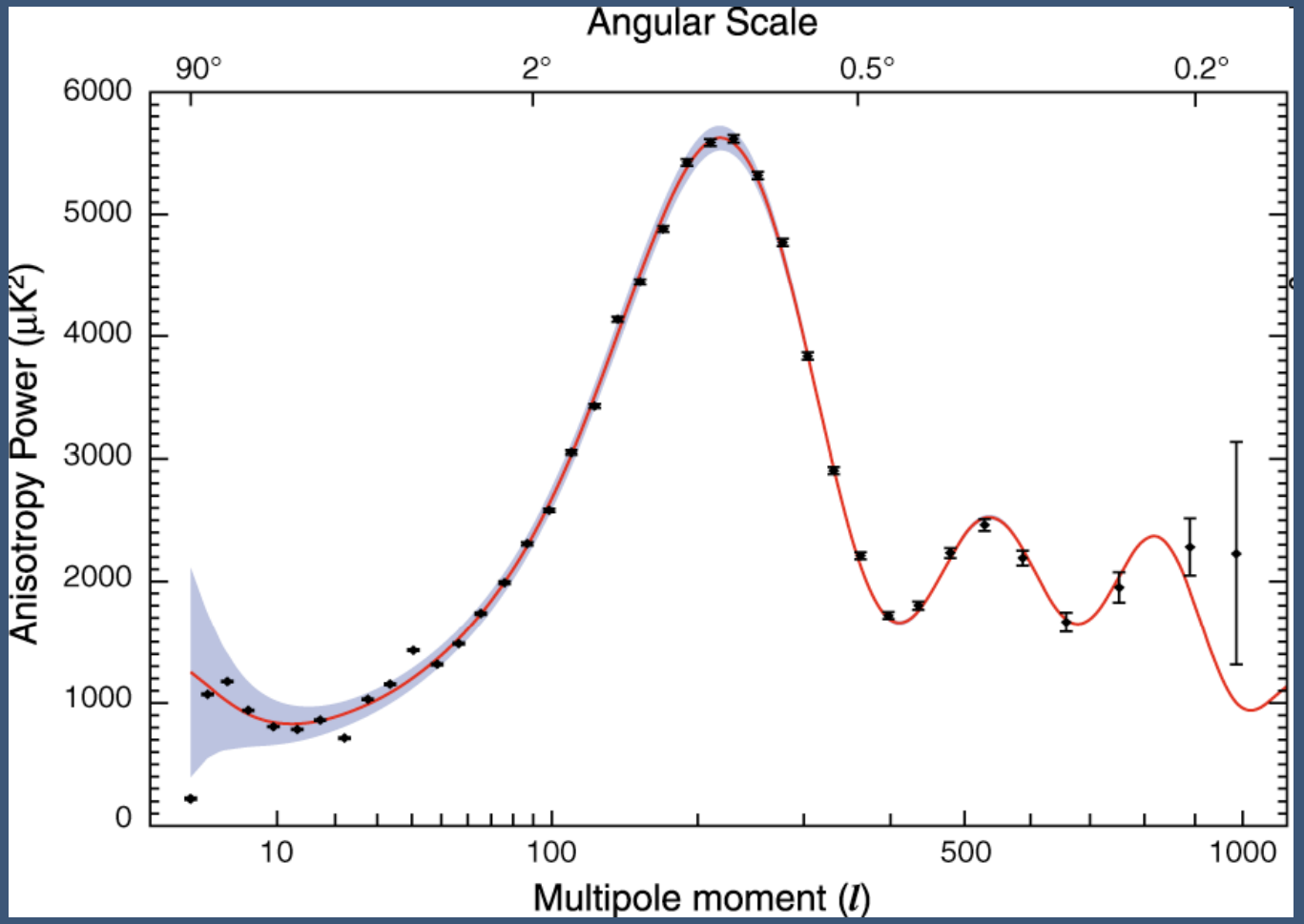


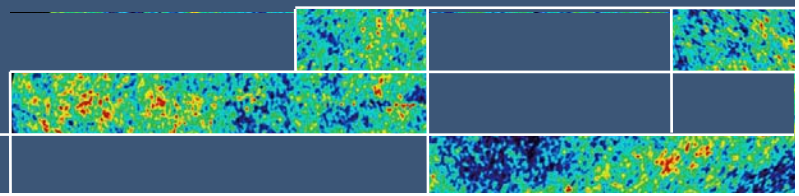


The power spectrum

370000 years

Time

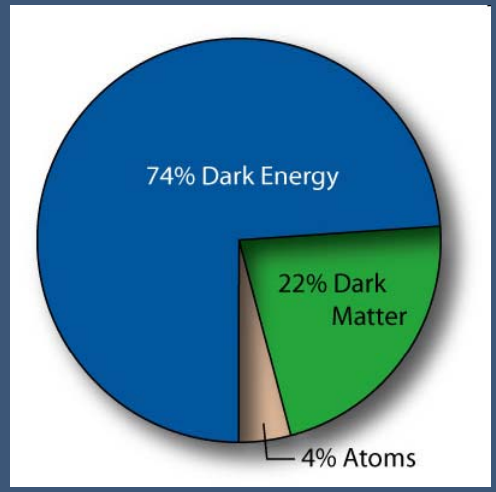


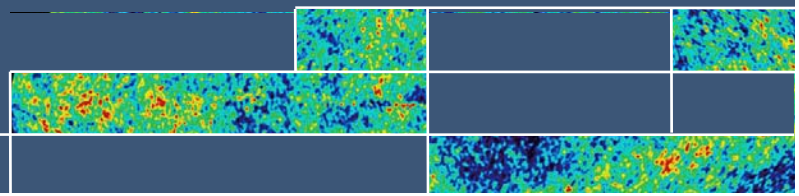


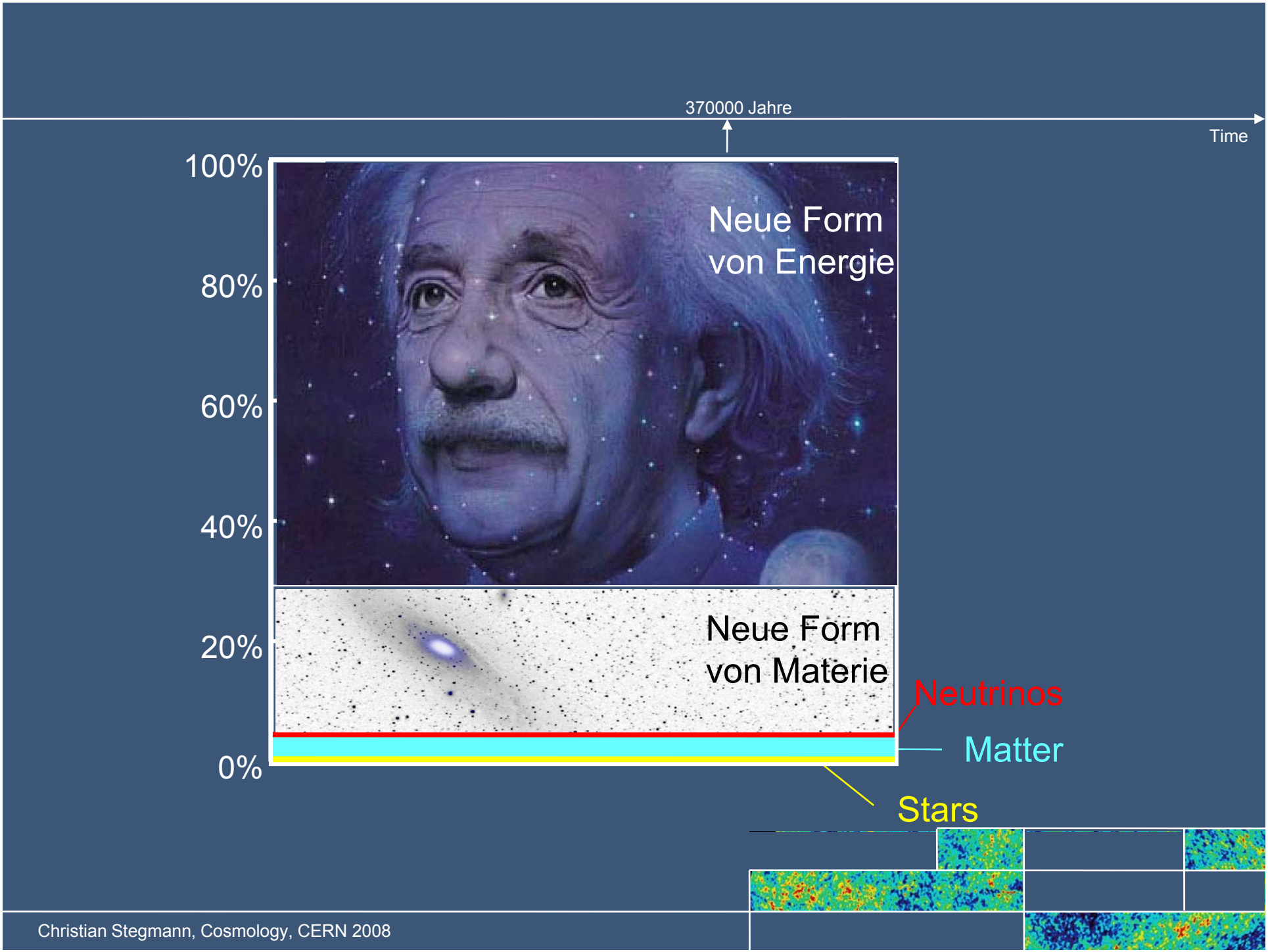
Cosmological Parameter

Time

- Total energiy density 1.003 ± 0.015
- Matter density 0.24 ± 0.04
- Baryon density 0.042 ± 0.004
- Vakuum energy density 0.76 ± 0.05
- Neutrino density < 0.014
- Age of the Universe 13.7 ± 0.2 Gyr



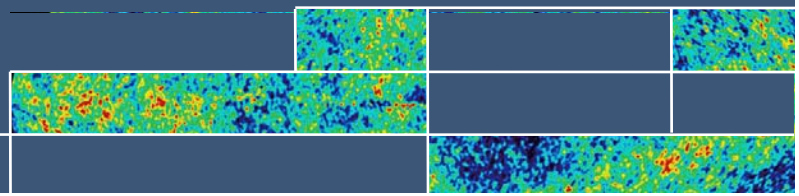



370000 Jahre
Time
100%
80%
60%
40%
20%
0%
Neue Form
von Energie
Neue Form
von Materie
Neutrinos
Matter
Stars

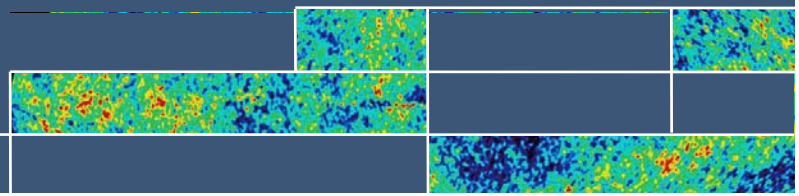
Summary

- Our Universe was created in a Big Bang
  - Galaxy move away from us
  - Abundances of light elements
  - Cosmic microwave background

- 97% of the energy density of the Universe is unknown!



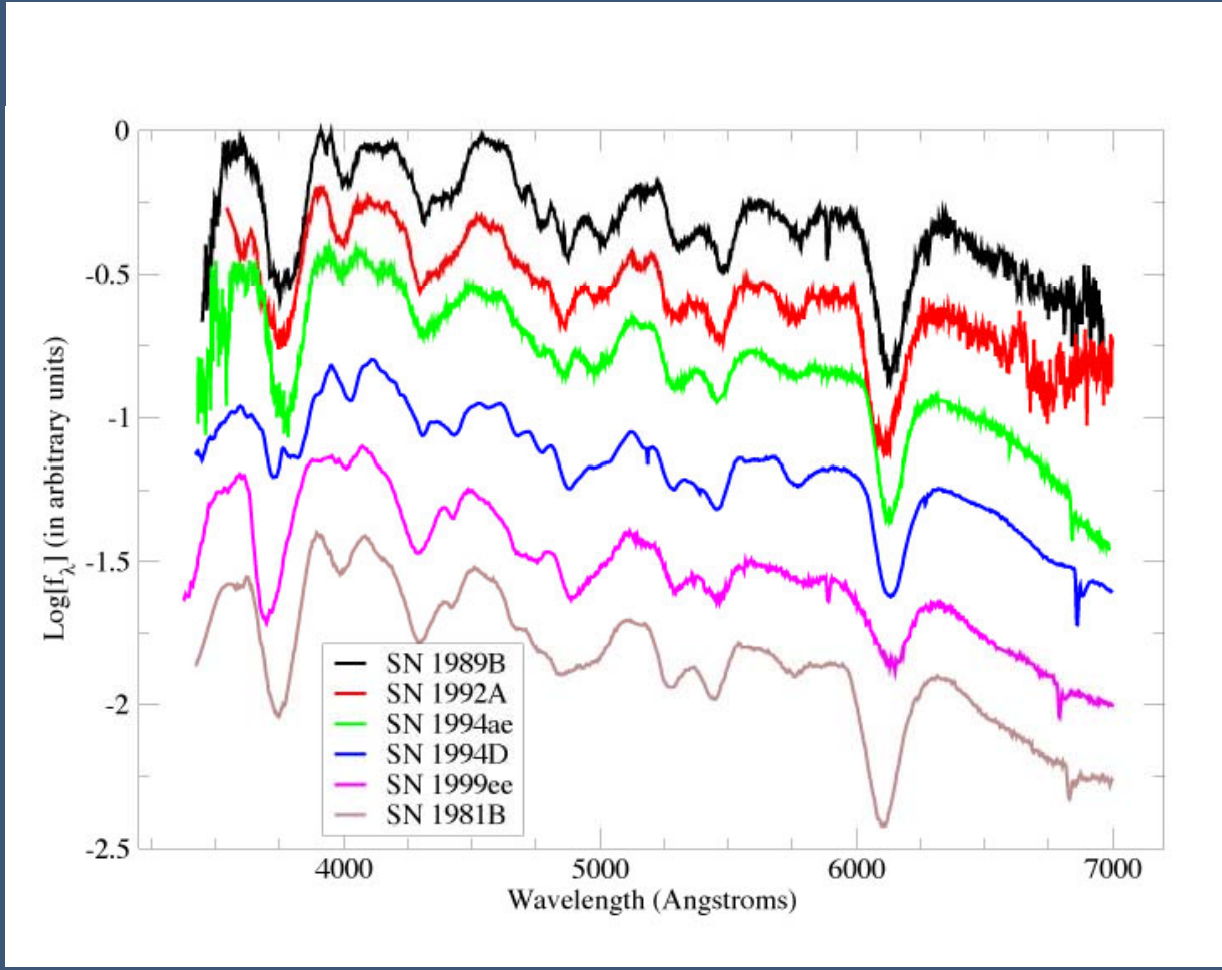
Time



Doppler effect

Spektra for identification

today
Time

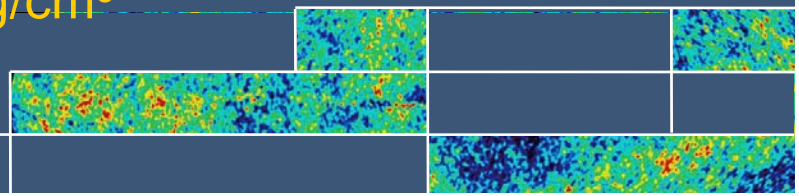


Parameter of an expanding Universe

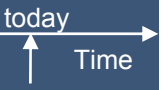
- Expansion ↔ Gravitational acceleration
- Expansion
  - Hubble constant H_0 is a measure for the strength of the expansion:

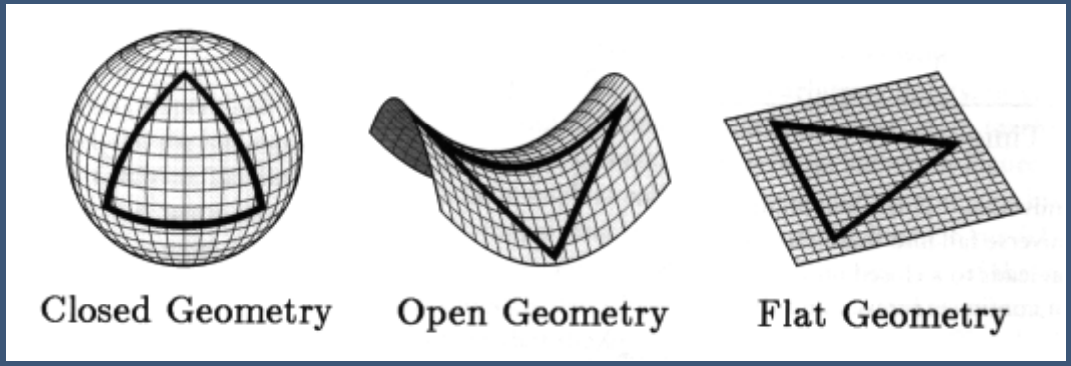
    $H_0 = 20$ km/s/MLj
- Gravitational acceleration
  - Normal matter slows down the expansion (mean density ρ)
  - critical density, requried to stop expansion:

$$\rho_{krit} = 3\,H_0^2/8\pi G = 10^{-29}\ g/cm^3$$

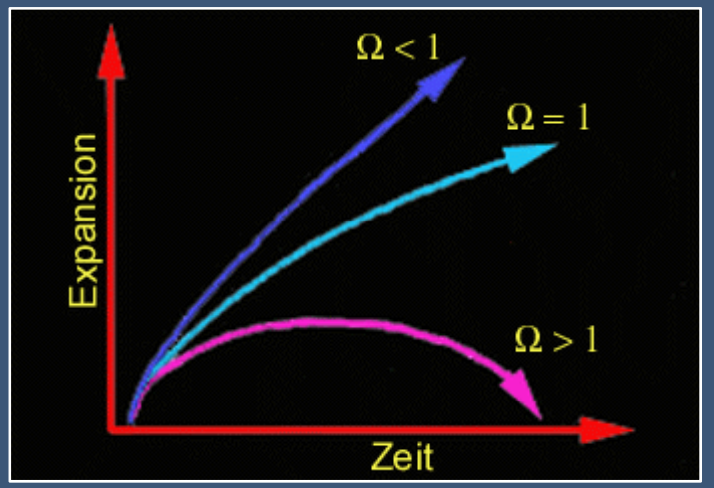


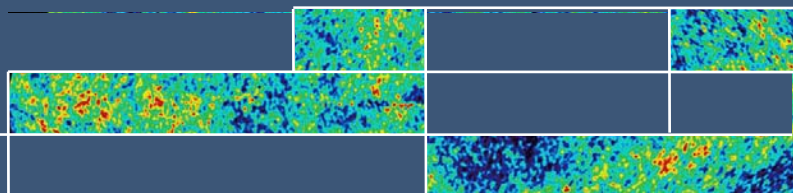
Geometry of the Universe





- Balance between contraction and expansion expresse by $\Omega_0 = \rho/\rho_{krit}$
  - $\Omega_0 > 1$, $\rho > \rho_{krit}$
    Gravitation wins, Universe collapse
  - $\Omega_0 = 1$, $\rho = \rho_{krit}$
    Expansion eventually stopps
  - $\Omega_0 < 1$, $\rho < \rho_{krit}$
    Expansion wins, Universum is expanding forever
- $\Lambda > 0$, fate of the Universe not connected to the geometry

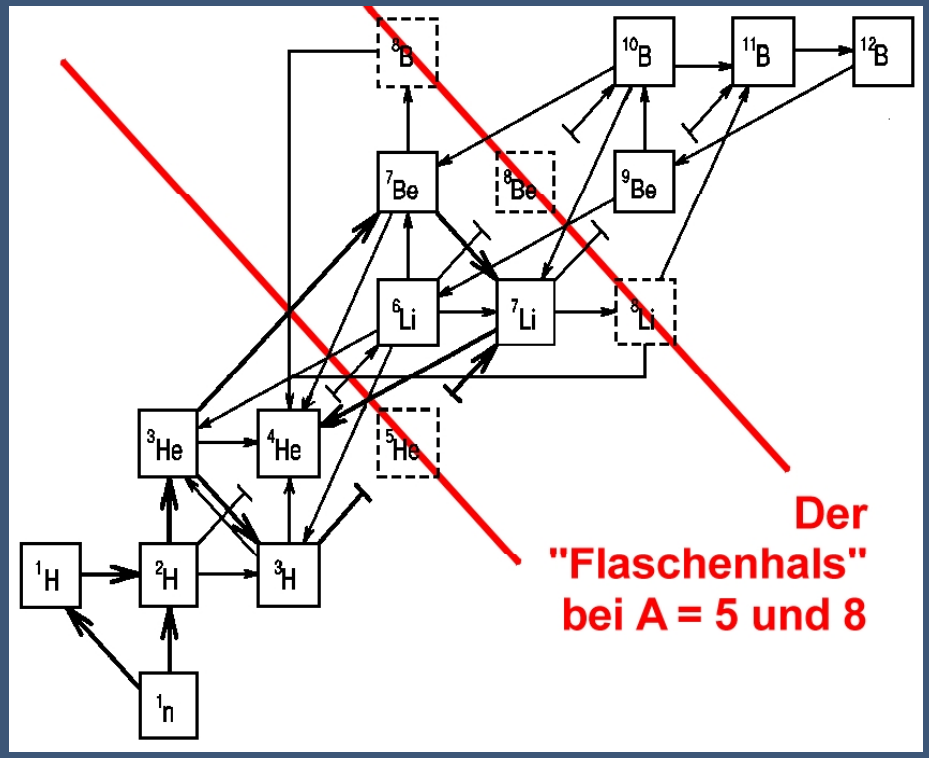




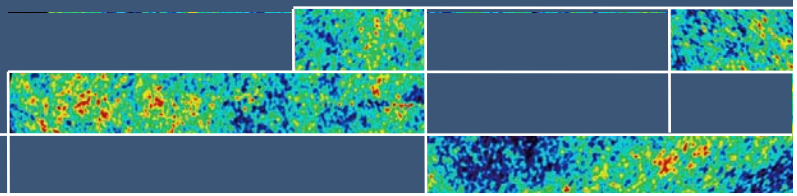
Primordial Nukleosynthesis

1 min

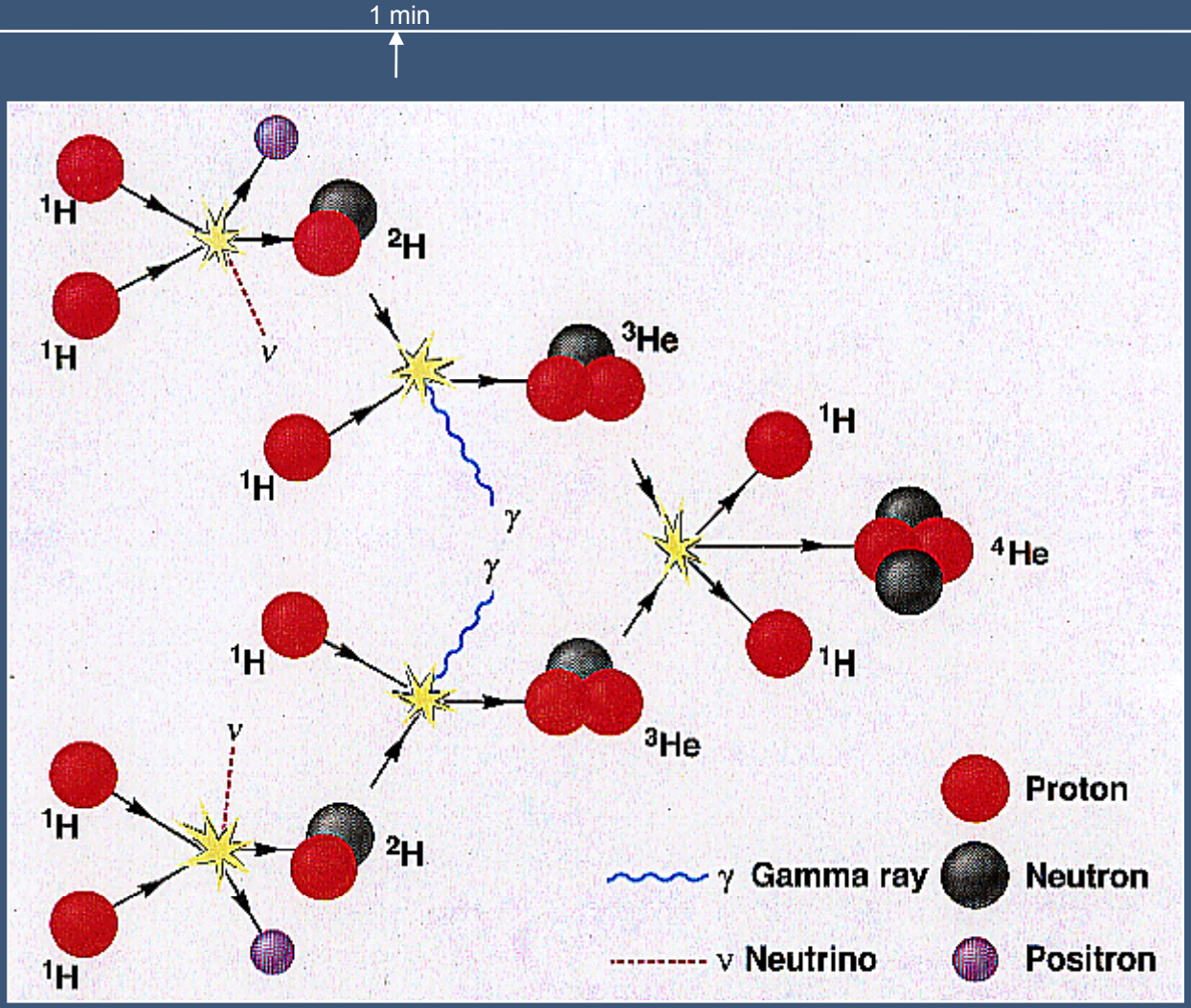
Time



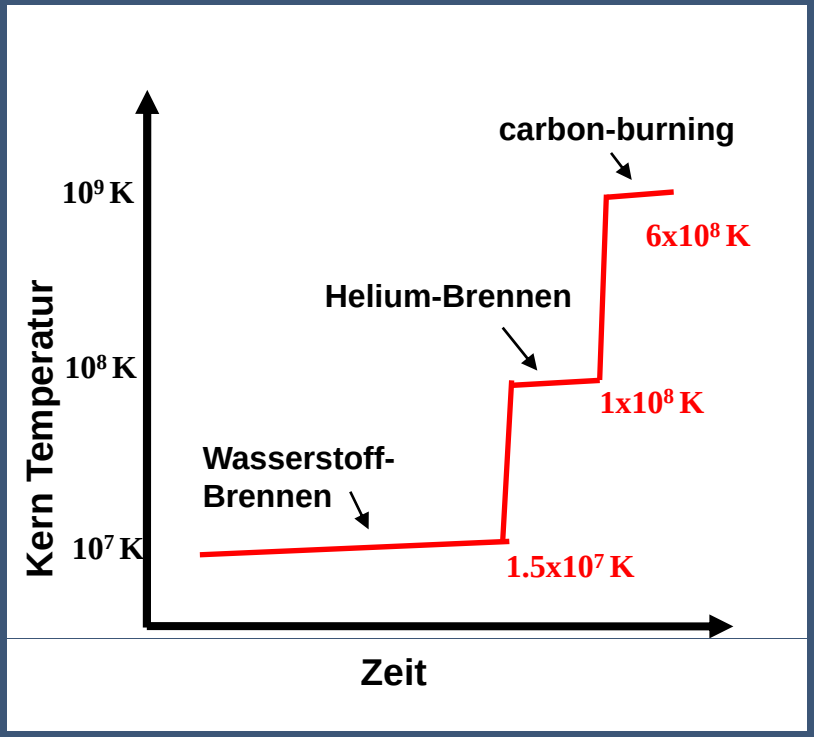
Why not in stars?

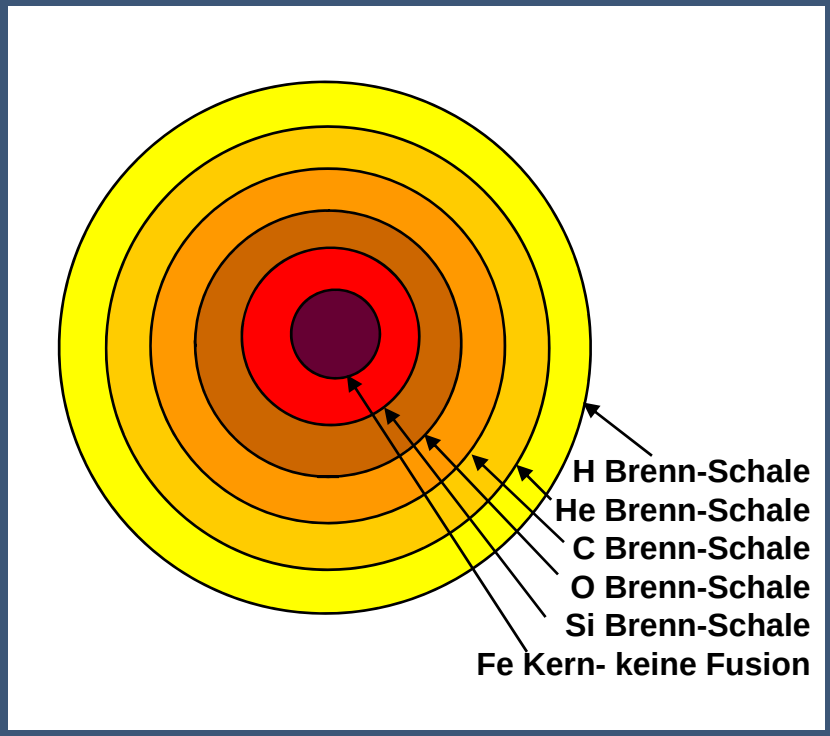


Fusion in stars

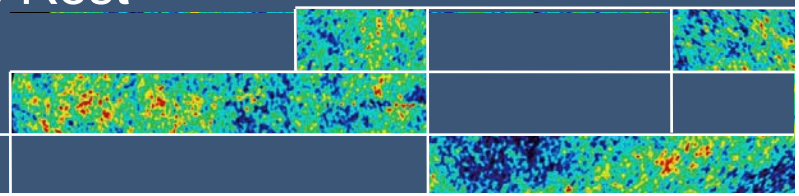


Fusion in stars



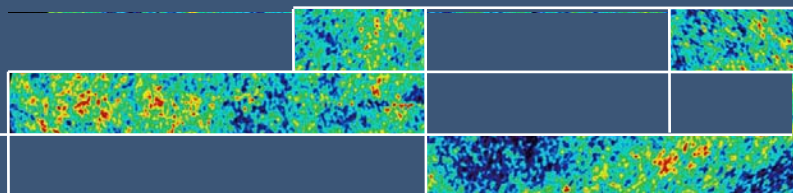


- Erwarte ungefähr genauso viel Helium wie andere Elemente mit großer Masse
  - Verhältnis: 75% H, 13% He, 12% Rest

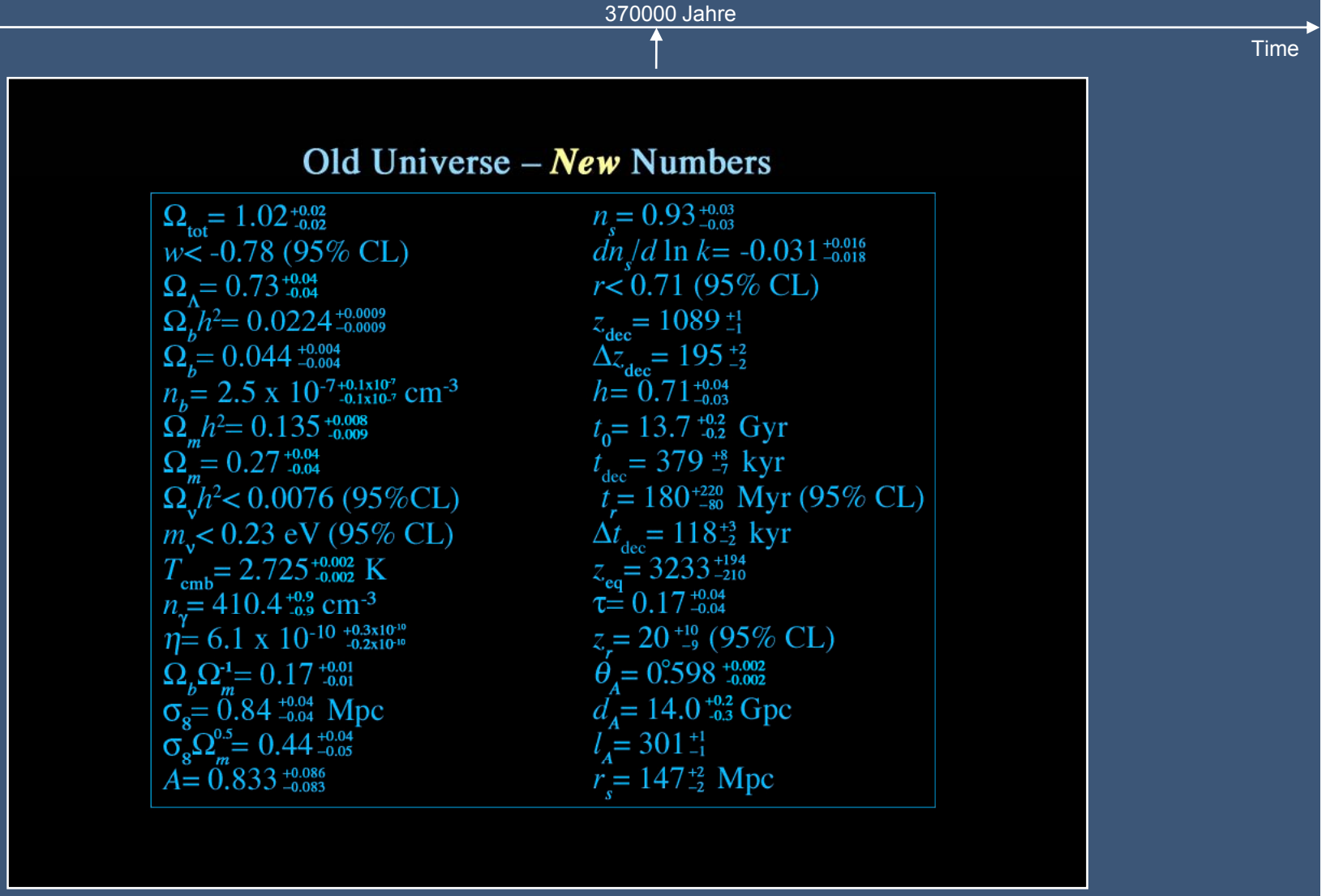


Vergleich Stellarer und Primordialer Nukleosynthese

	Stellare Nukleosynthese	Primordiale Nukleosynthese
Zeitskala	Milliarden von Jahren	Minuten
Temperatur-entwicklung	Ansteigend	Fallend
Dichte	100 g/cm^3	10^{-5} g/cm^3 (wie die Luft in diesem Raum)
Photon-Baryon-Verhältnis	1:1	10^9 : 1

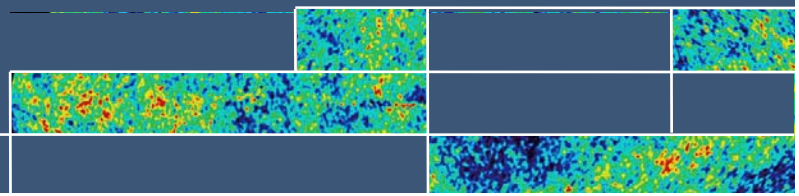


Kosmologische Parameter



Dunkle Materie

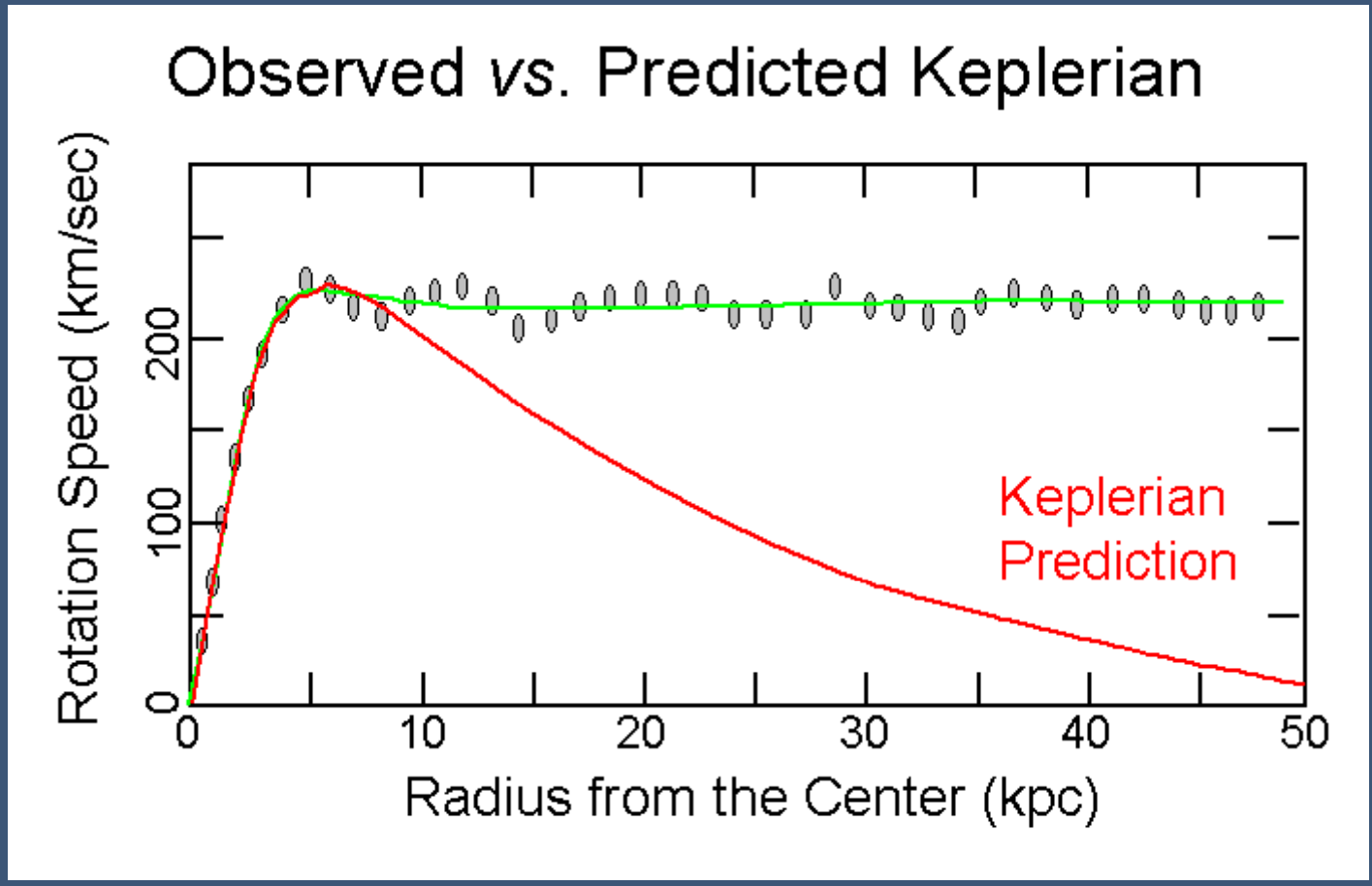
- Rotationskurven von Galaxien
- Elliptische Galaxien
- Gravitationslinsen
- Mikrowellen-Hintergrund



Rotationskurven

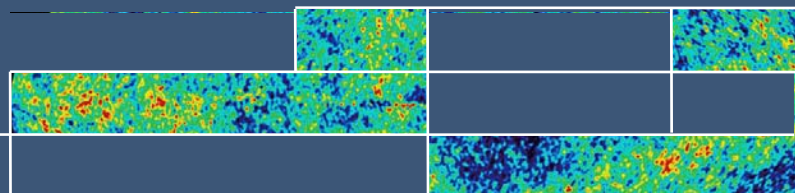
Heute

Time



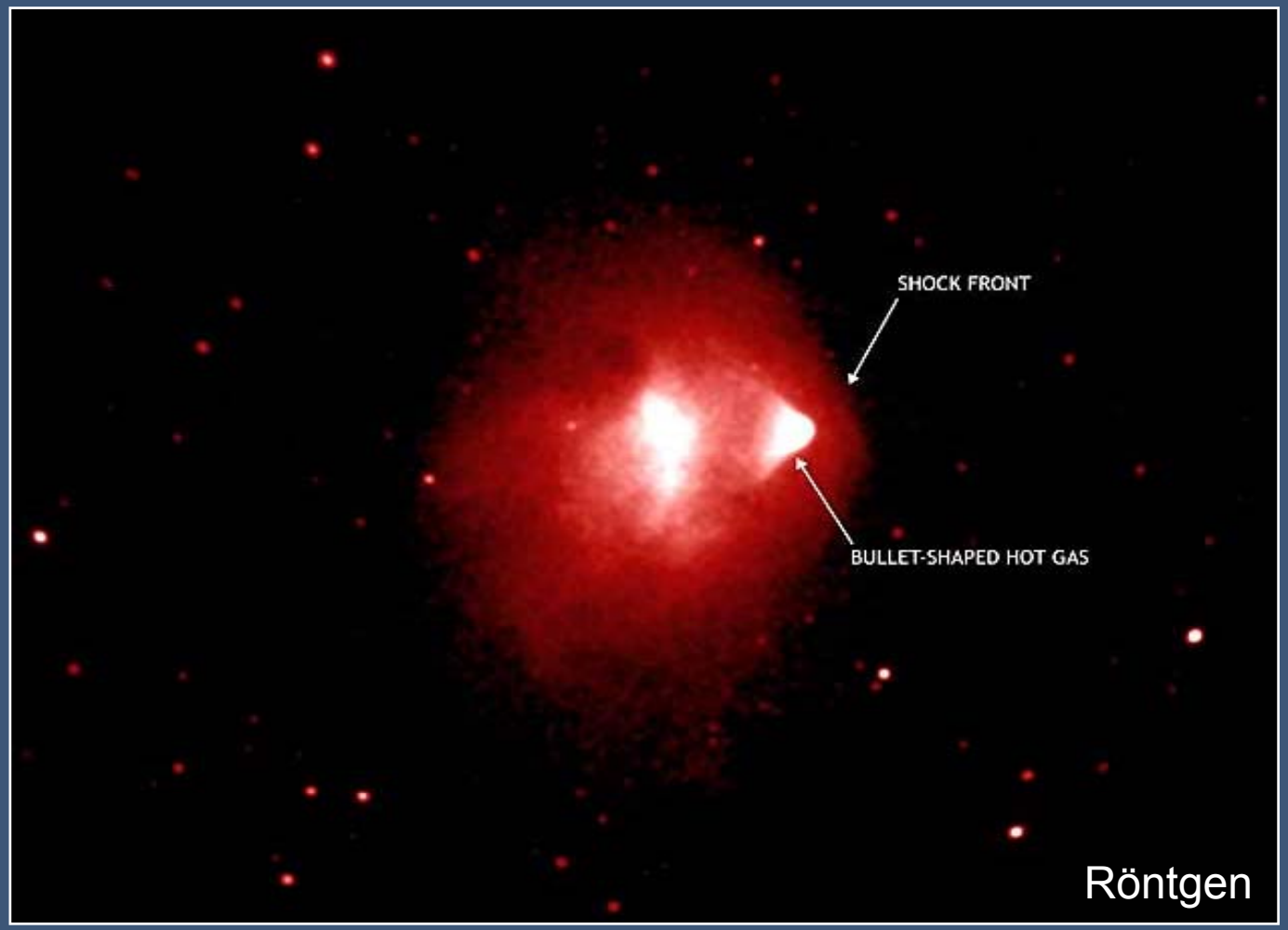
Galaxien-Cluster 1E 0657-56

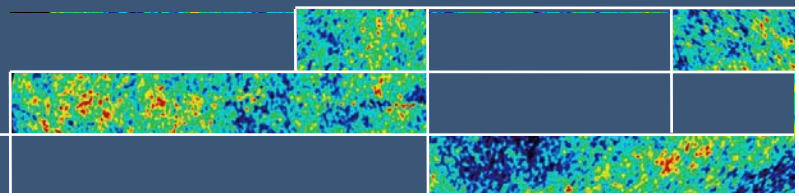
Time



Galaxien-Cluster 1E 0657-56

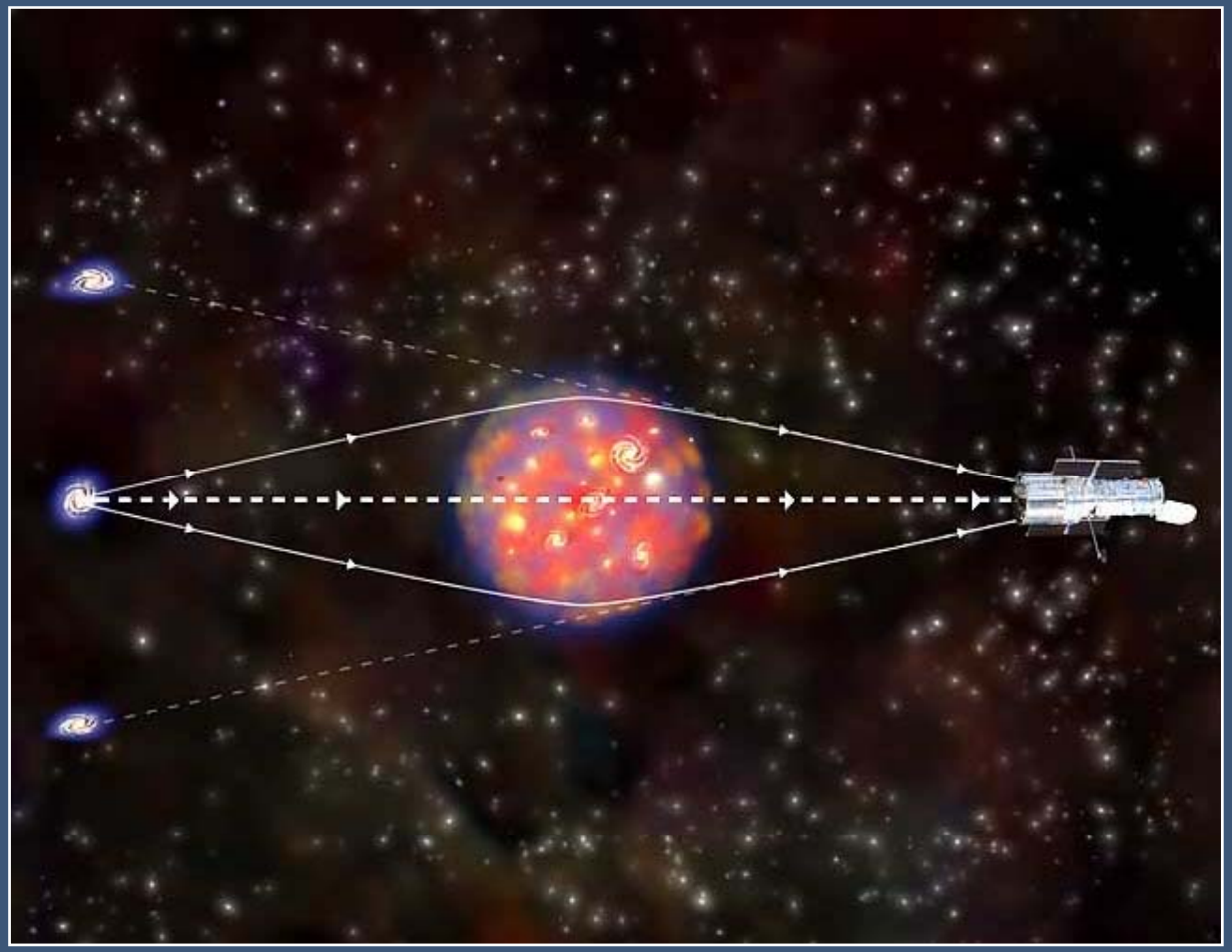
Time

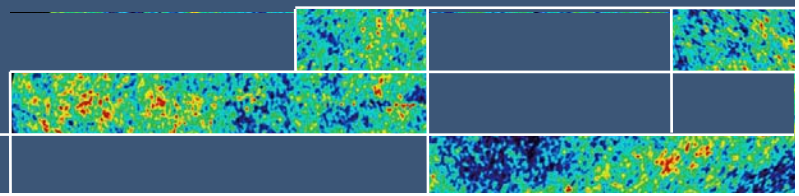




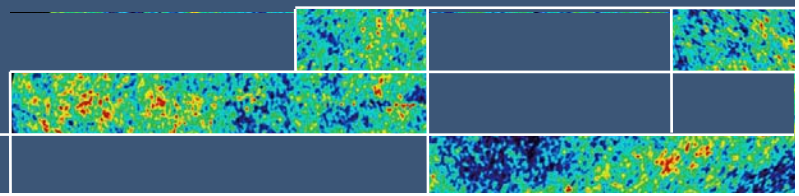
Gravitationslinsen

Time



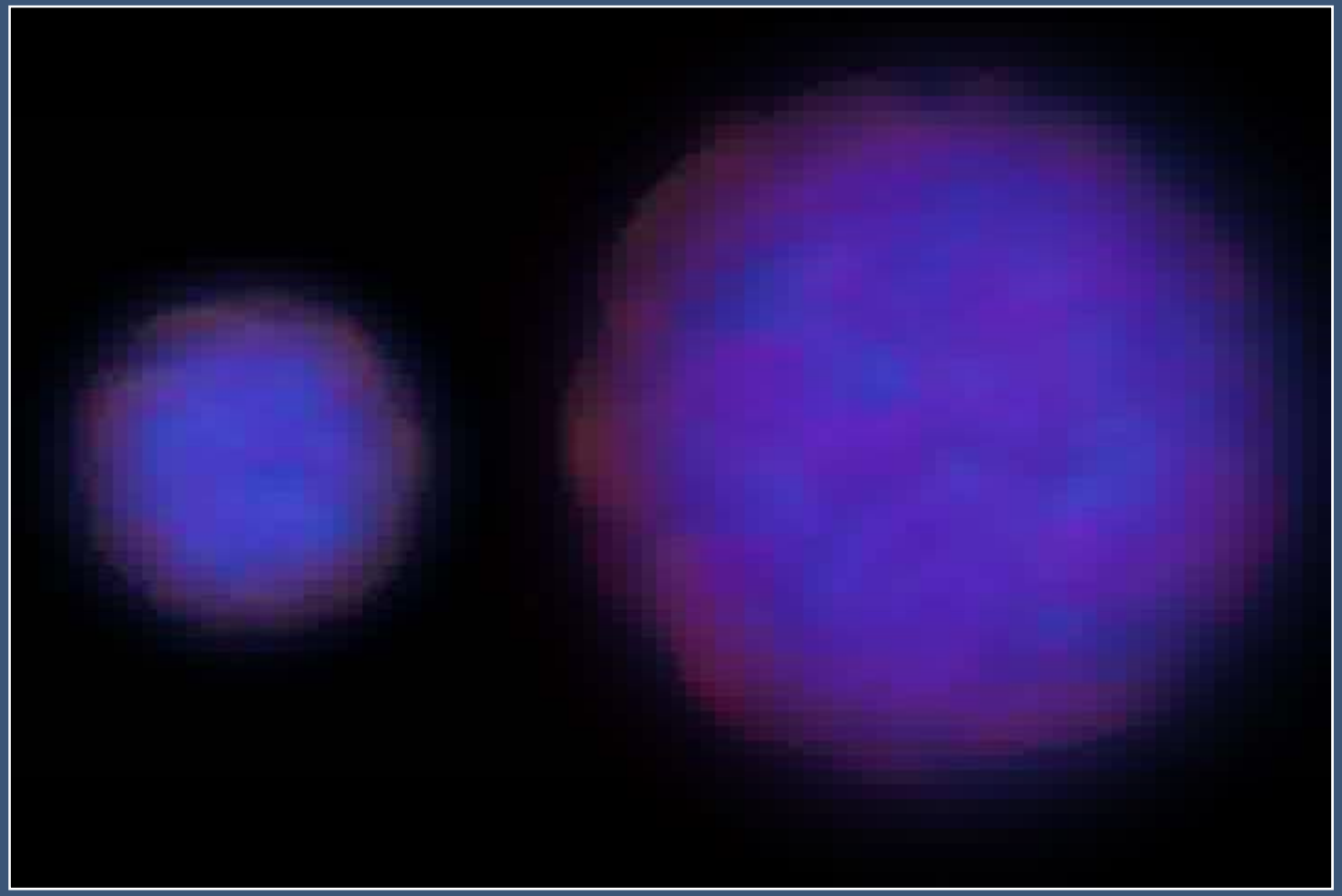


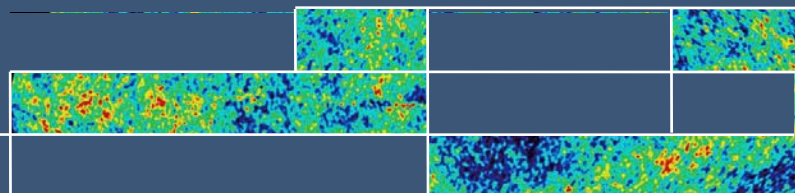
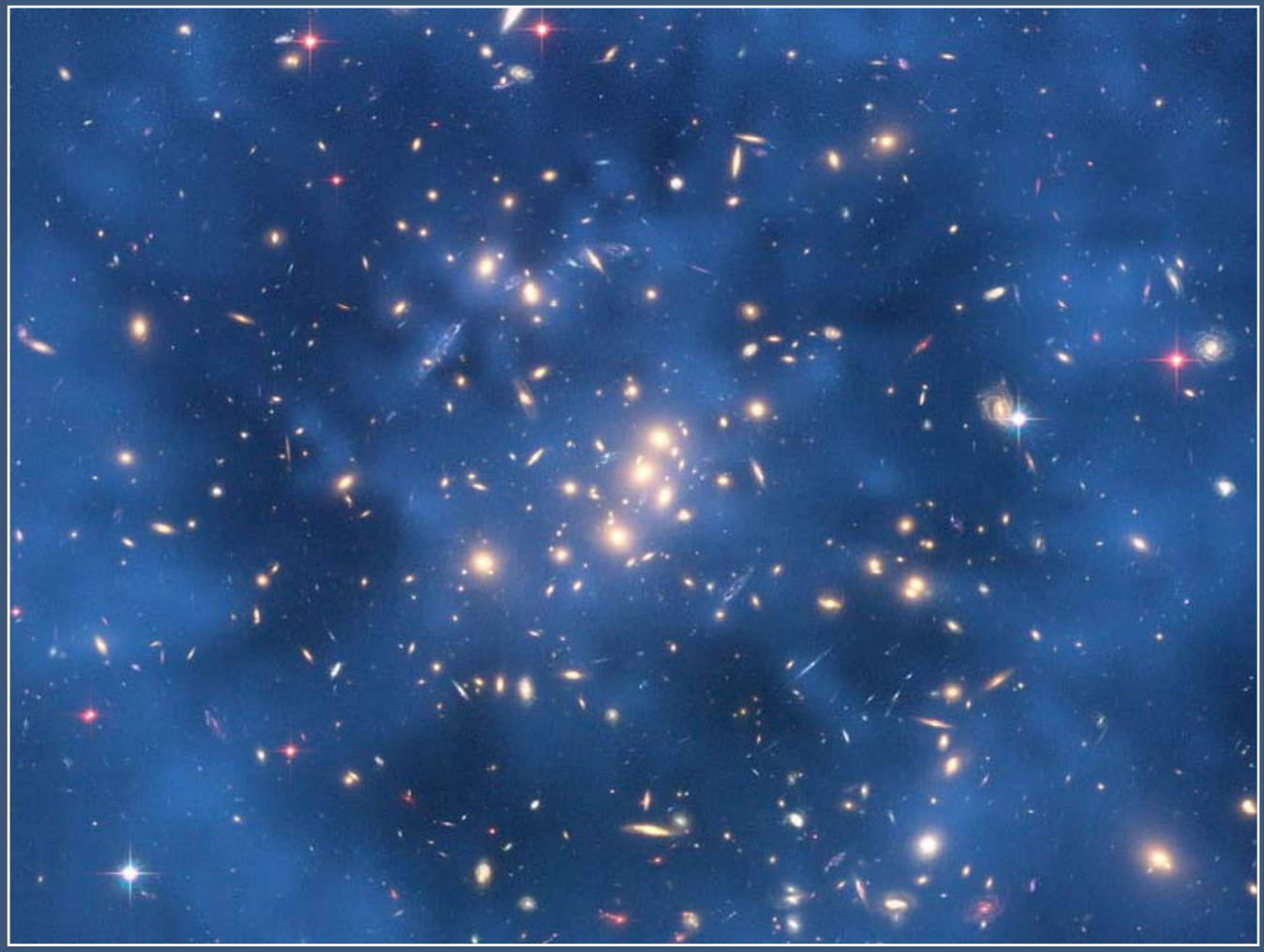
Time



Was ist passiert?

Time





Galaxien Cluster CL0024 17