
the
Big Bang

Gravity:

Ruler of the Universe

Four Fundamental Forces of Nature

- **Strong Nuclear Force**

  Responsible for holding particles together inside the nucleus.
  The nuclear strong force carrier particle is called the gluon.
  The nuclear strong interaction has a range of 10^{-15} m (diameter of a proton).

- **Electromagnetic Force**

  Responsible for electric and magnetic interactions, and determines structure of atoms and molecules.
  The electromagnetic force carrier particle is the photon (quantum of light)
  The electromagnetic interaction range is infinite.

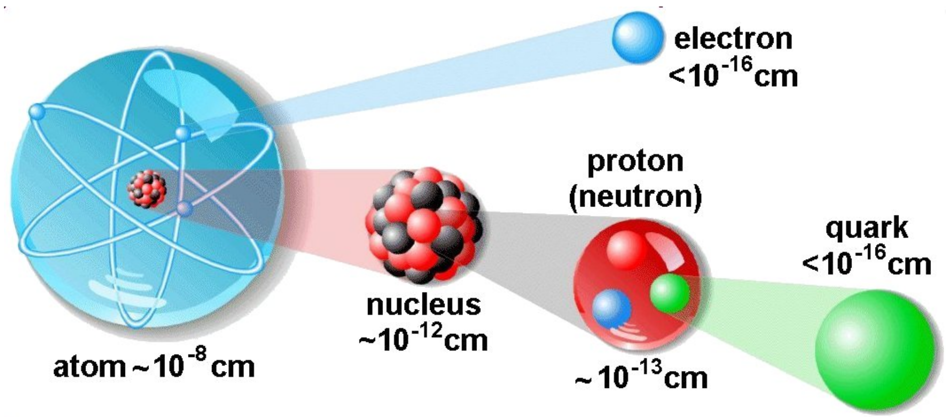
- **Weak Force**

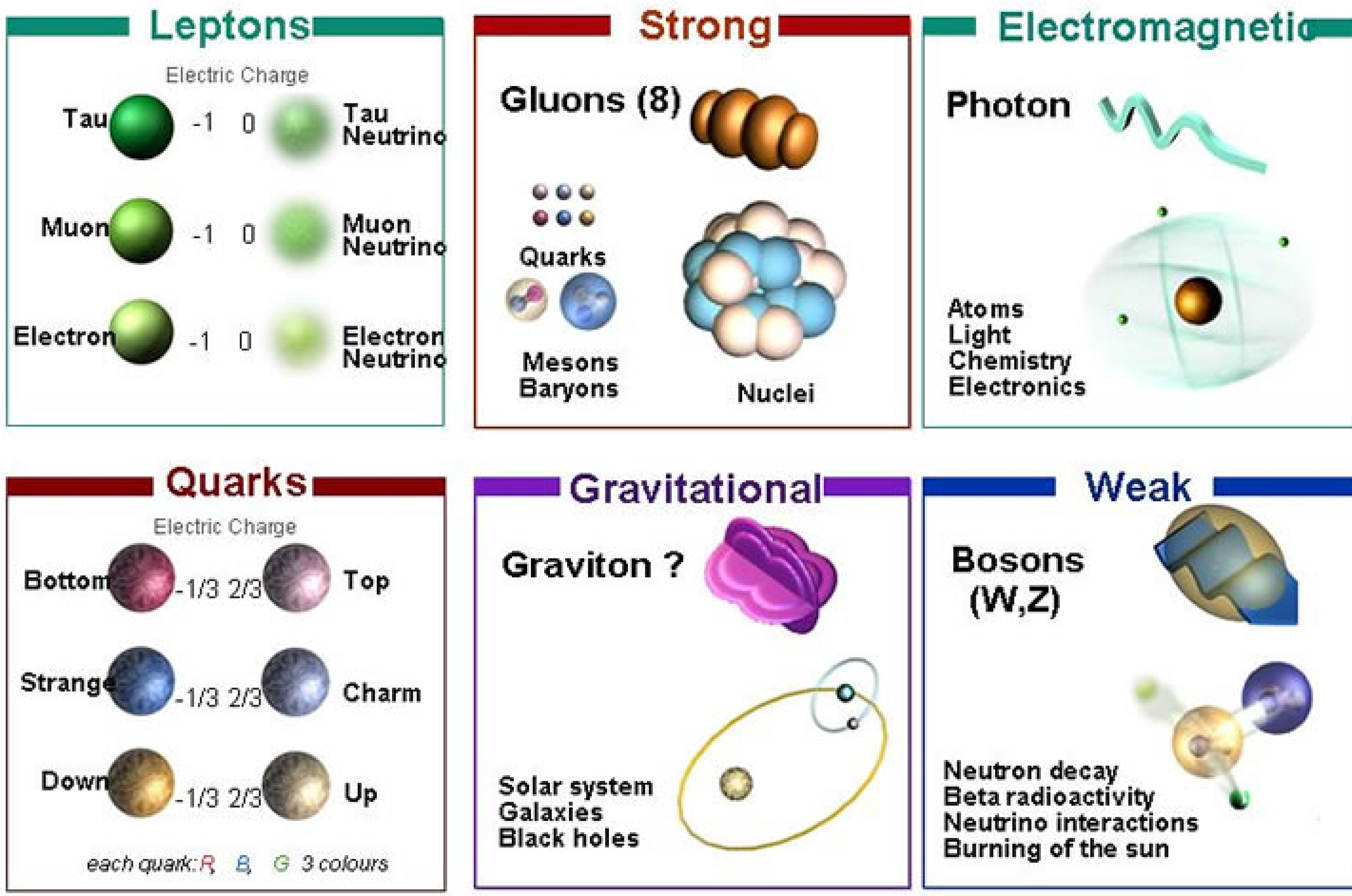
  Responsible for (beta) radioactivity.
  The weak force carrier particles are called weak gauge bosons (Z, W^+, W^-).
  The nuclear weak interaction has a range of 10^{-17} m (1% of proton diameter).

- **Gravity**

  Responsible for the attraction between masses. Although the gravitational force carrier
  The hypothetical (carrier) particle is the graviton.
  The gravitational interaction range is infinite.
  By far the weakest force of nature.

Four Fundamental Forces of Nature





Interaction	Current Theory	Mediators	Relative Strength[1]	Long-Distance Behavior	Range(m)
Strong	Quantum chromodynamics (QCD)	gluons	10^{38}	1 (see discussion below)	10^{-15}
Electromagnetic	Quantum electrodynamics (QED)	photons	10^{36}	$\frac{1}{r^2}$	infinite
Weak	Electroweak Theory	W and Z bosons	10^{25}	$\frac{e^{-m_{W,Z}r}}{r}$	10^{-18}
Gravitation	General Relativity (GR)	gravitons	1	$\frac{1}{r^2}$	infinite

The weakest force is Gravity !

$$g = G\frac{m}{r^2}$$

However, note that

- .

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The weakest force is Gravity !

However:

- **its range is infinite, not shielded**
- **it is cumulative as all mass adds,**

  while electromagetic charges can be + or - , cancelling each others effect.

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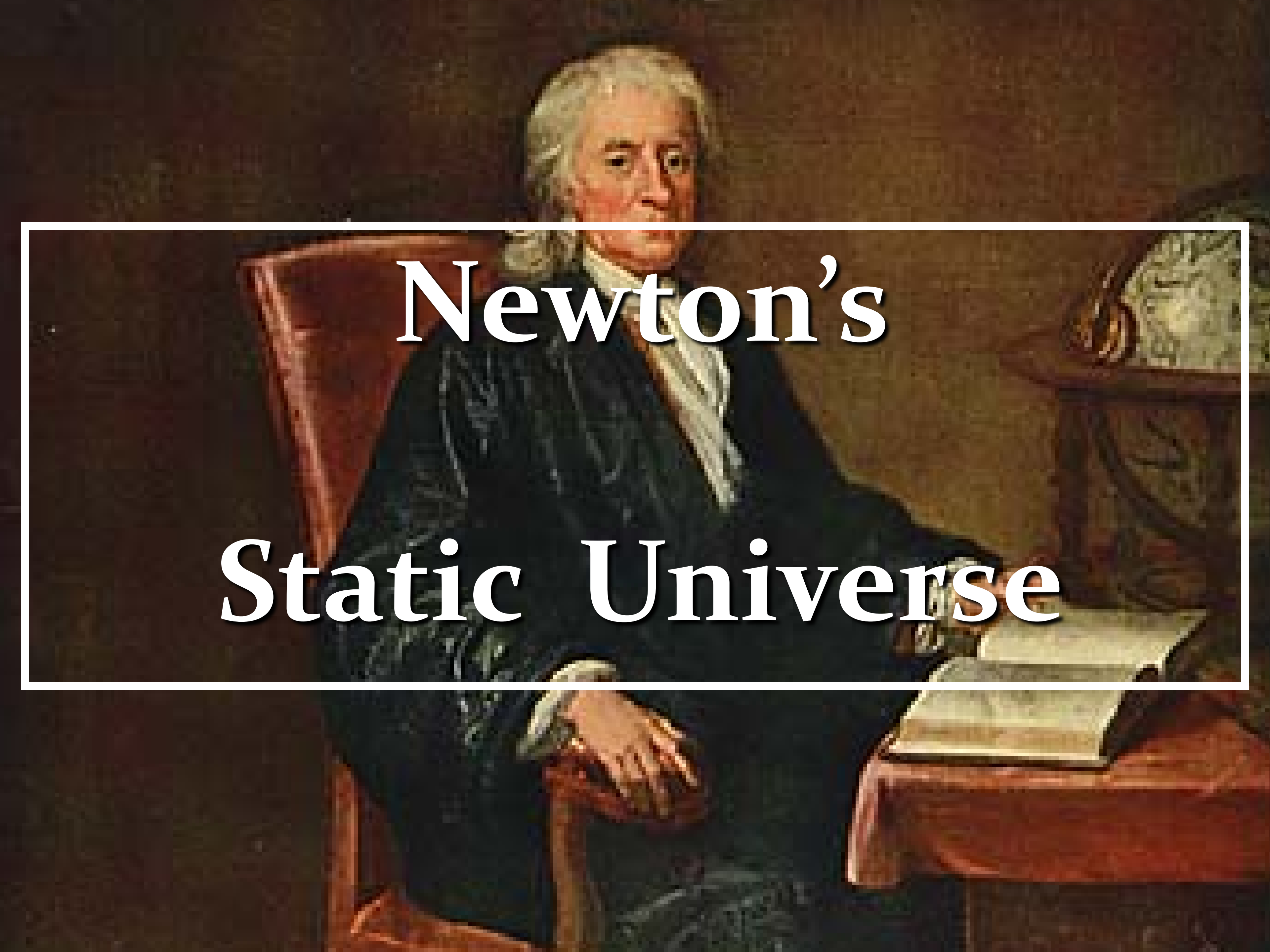
The weakest force, by far, rules the Universe …

Gravity has dominated its evolution, and determines its fate …


Newton's
Static Universe

The Unchanging Universe

- In two thousand years of astronomy, no one ever guessed that the universe might be expanding.

- To ancient Greek astronomers and philosophers, the universe was seen as the embodiment of perfection, the heavens were truly heavenly:
  – unchanging, permanent, and geometrically perfect.

- In the early 1600s, Isaac Newton developed his law of gravity, showing that motion in the heavens obeyed the same laws as motion on Earth.

Newton's Universe

- However, Newton ran into trouble when he tried to apply his theory of gravity to the entire universe.

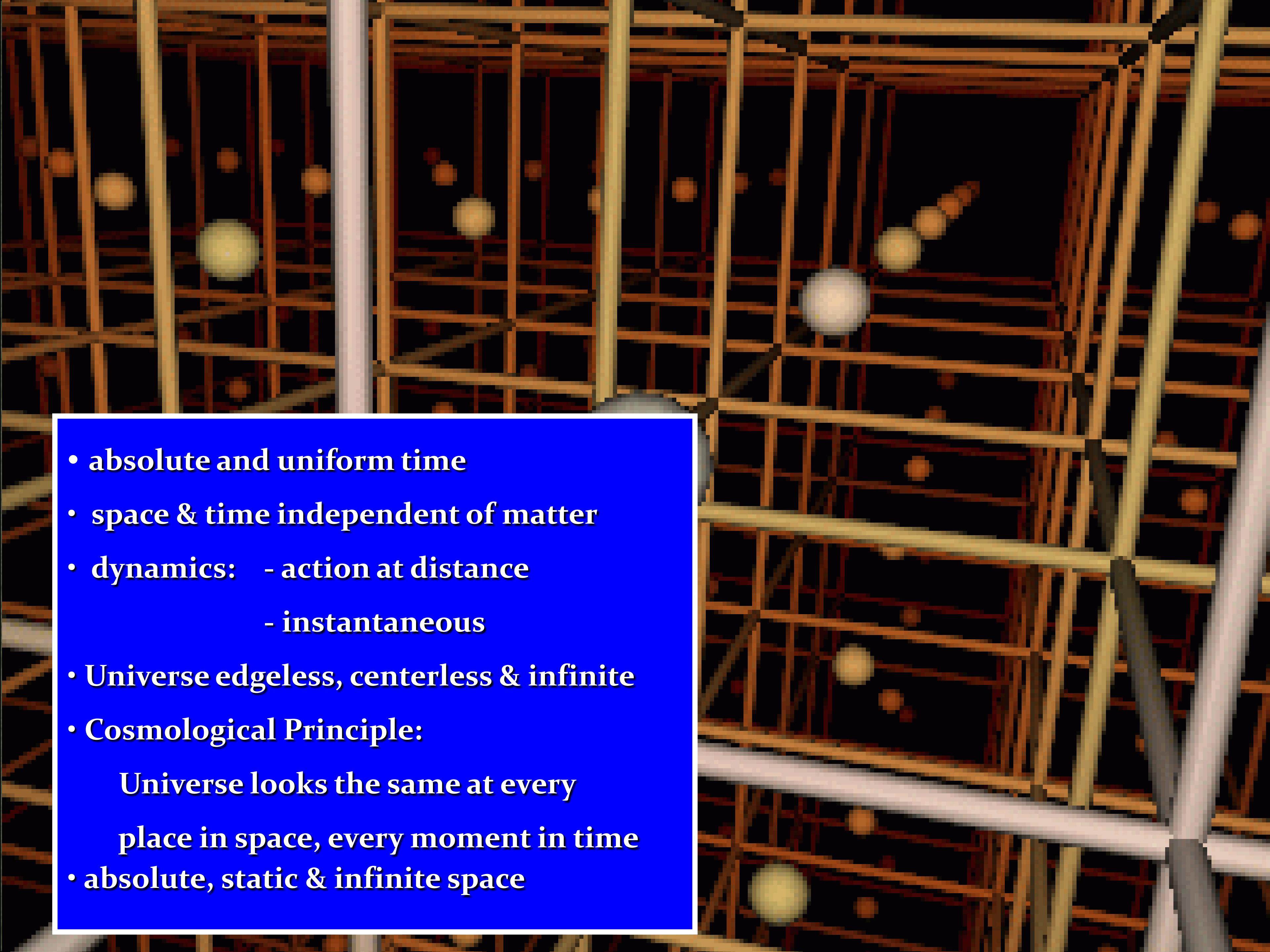
- Since gravity is always attractive, his law predicted that all the matter in the universe should eventually clump into one big ball.

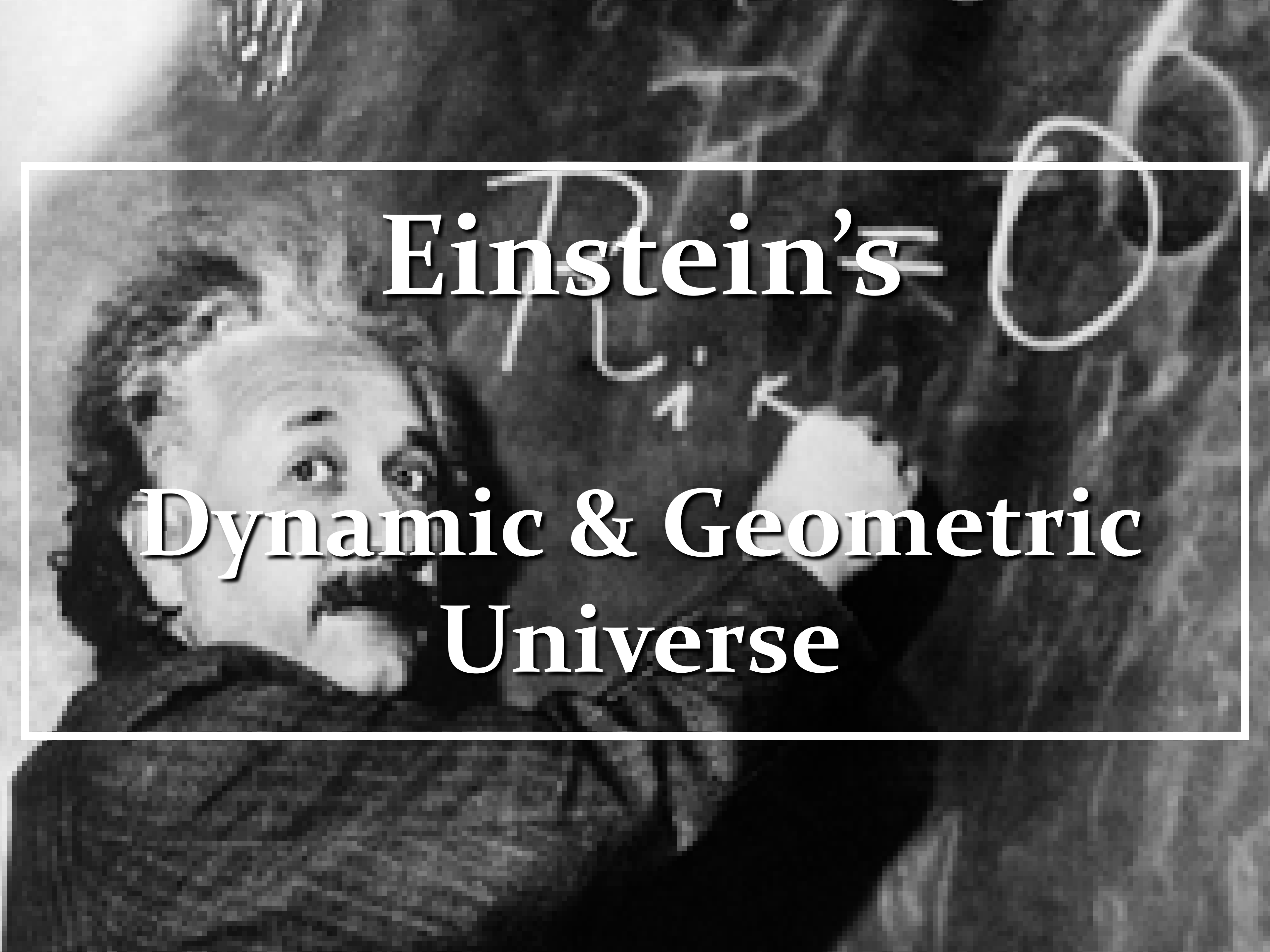
- Newton knew this was not the case, and assumed that the universe had to be static

- So he conjectured that:

the Creator placed the stars such that they were

``at immense distances from one another.”


• absolute and uniform time
• space & time independent of matter
• dynamics: - action at distance
- instantaneous
• Universe edgeless, centerless & infinite
• Cosmological Principle:
Universe looks the same at every
place in space, every moment in time
• absolute, static & infinite space



Einstein's

Dynamic & Geometric Universe

Albert Einstein

Albert Einstein

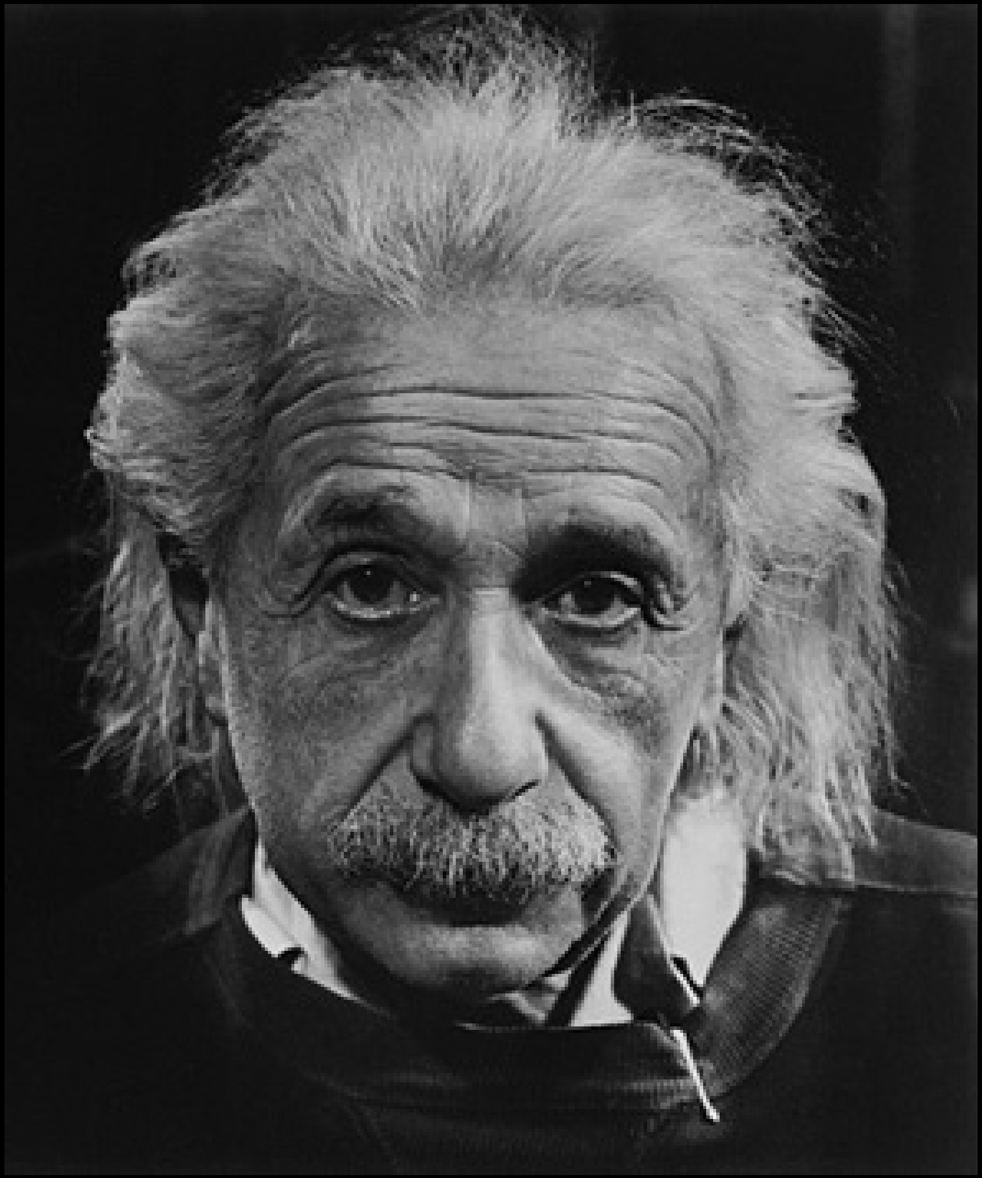
(1879-1955; Ulm-Princeton)

father of
General Relativity (1915),

opening the way towards
Physical Cosmology

The supreme task of the physicist is to arrive at those universal elementary laws from which the cosmos can be built up by pure deduction.

(Albert Einstein, 1954)



Relativity: Space & Time

- ***Special Relativity,***
  published by Einstein in 1905

- states that there is no such thing as
  absolute Space or ***Time***

- ***Space*** and ***Time*** are
  not wholly independent,
  but aspects of a single entity,
  Spacetime

Einstein's principle of relativity

- **Principle of relativity**:
  - All the laws of physics are identical in all inertial reference frames.
- **Constancy of speed of light**:
  - Speed of light is same in all inertial frames (e.g. independent of velocity of observer, velocity of source emitting light)

Einstein's Universe

In 1915,
Albert Einstein completed his General Theory of Relativity.

- General Relativity is a "metric theory":
  gravity is a manifestation of the geometry, curvature, of space-time.

- Revolutionized our thinking about the nature of space & time:
  - no longer Newton's static and rigid background,
  - a dynamic medium, intimately coupled to the universe's content of matter and energy.

- All phrased into perhaps
  the most beautiful and impressive scientific equation
  known to humankind, a triumph of human genius,

Einstein Field Equations

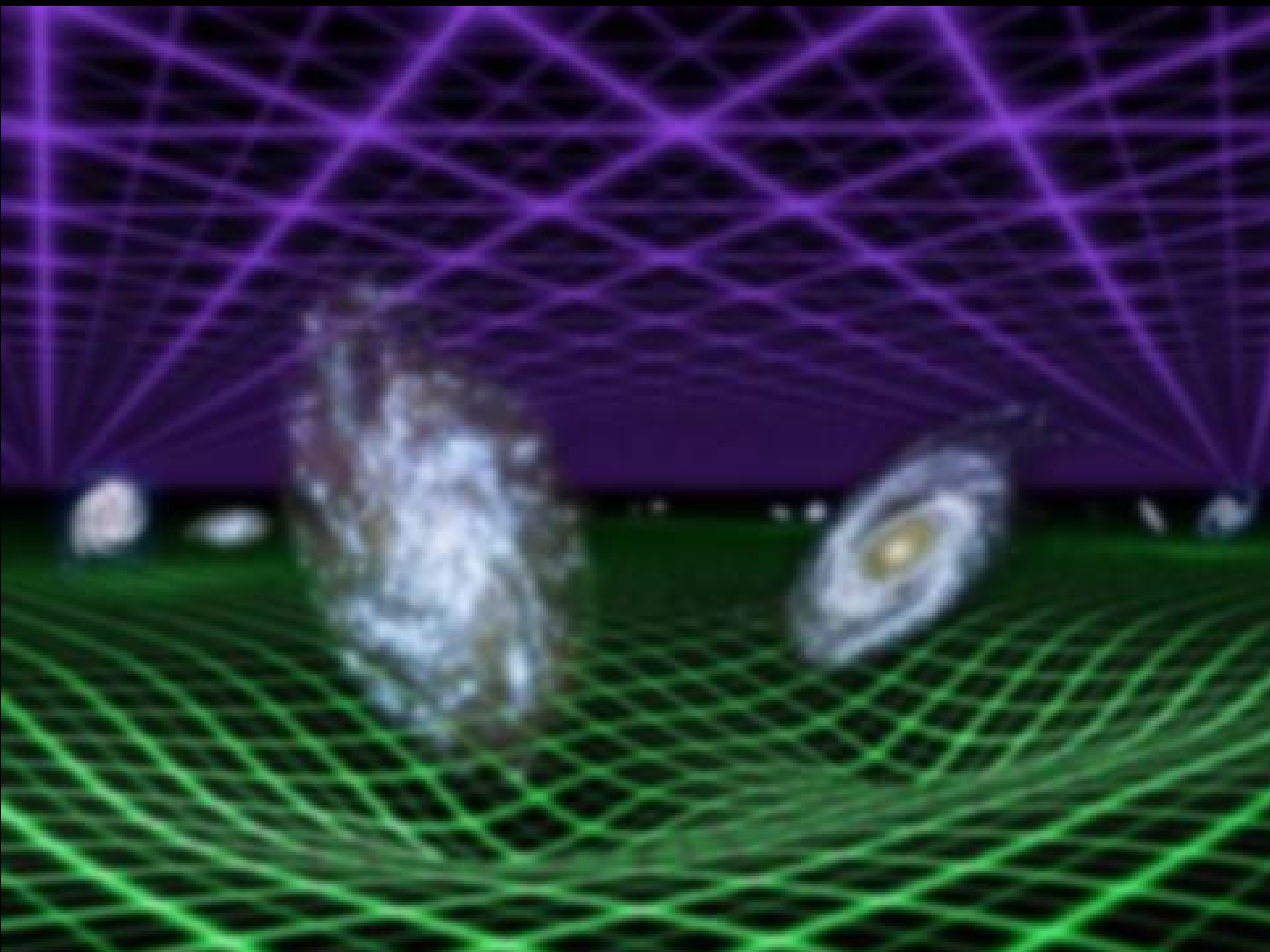
... Spacetime becomes a dynamic continuum,
integral part of the structure of the cosmos ...
curved spacetime becomes force of gravity

$$R^{\alpha\beta} - \frac{1}{2} R\, g^{\alpha\beta} = -\frac{8\pi G}{c^4} T^{\alpha\beta}$$

... its geometry rules the world,
the world rules its geometry...

Einstein's Universe

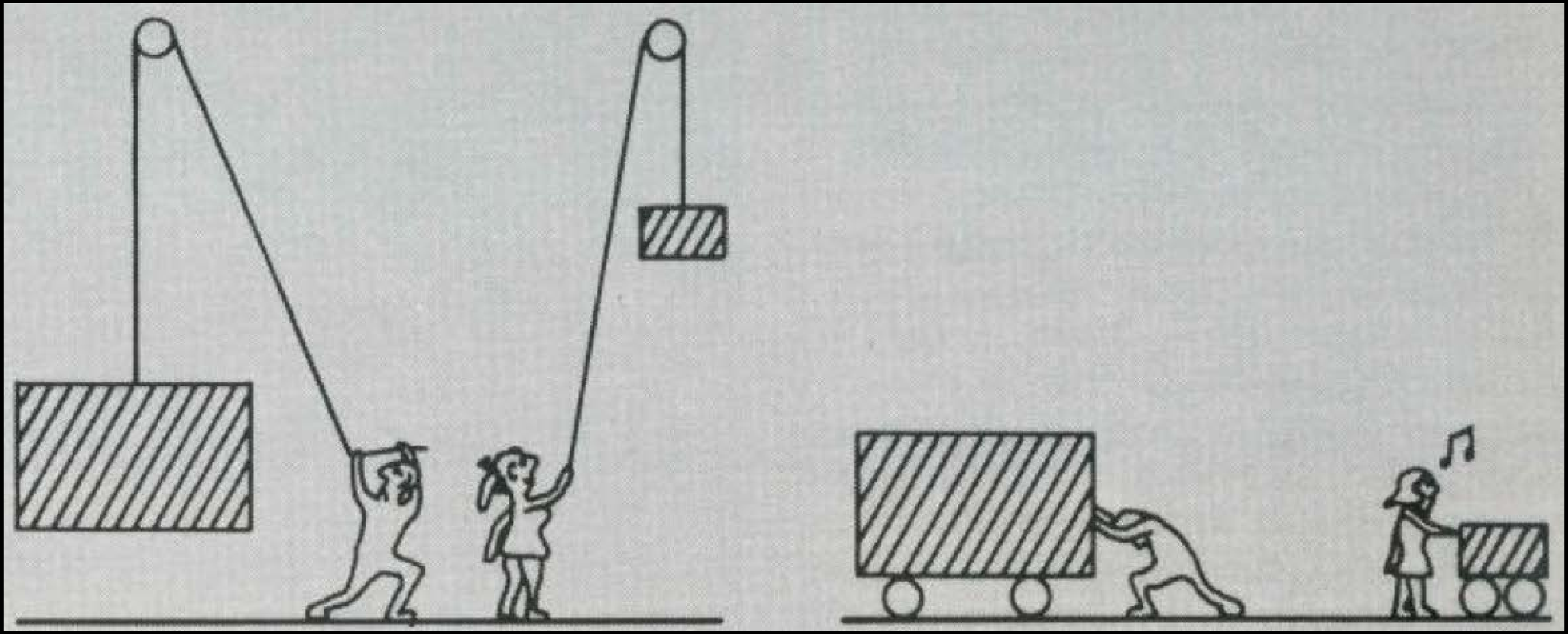
- spacetime is dynamic
- local curvature & time determined by mass
- bodies follow shortest path through curved spacetime (geodesics)
- dynamics: - action through curvature space
  - travels with velocity of light



Einstein's
Metric theory of Gravity:

how Gravity = Curved Space

Inertial vs Gravitational Mass



- a larger mass experiences a stronger gravitational force than a light mass
- a larger mass is more difficult to get moving than a ligt mass
- As a result, a heavy mass falls equally fast as the light mass:

gravitational mass

inertial mass

Gravitational Mass = Inertial Mass

Equivalence Principle

Einstein's "happiest thought" came from the realization of

the equivalence principle

Einstein reasoned that:

There is no experiment that can distinguish between

uniform acceleration and

a uniform gravitational field.

Equivalence Principle

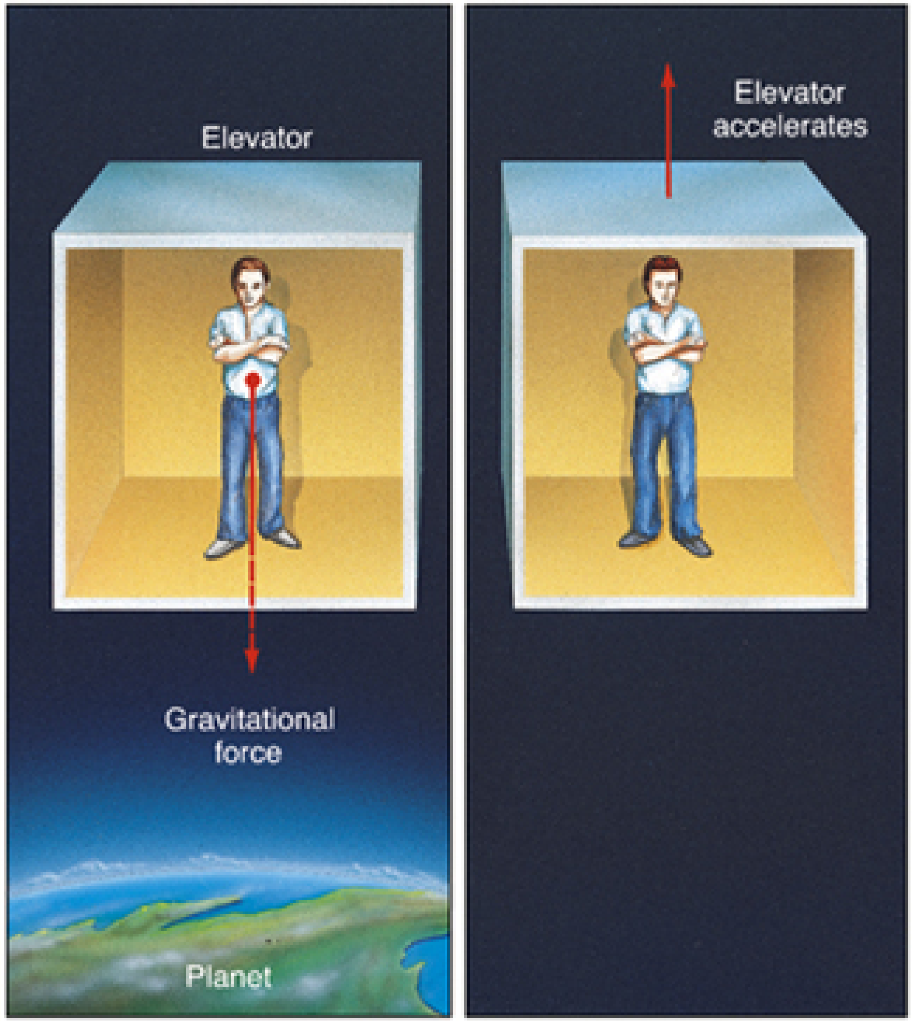
being in

an accelerating frame

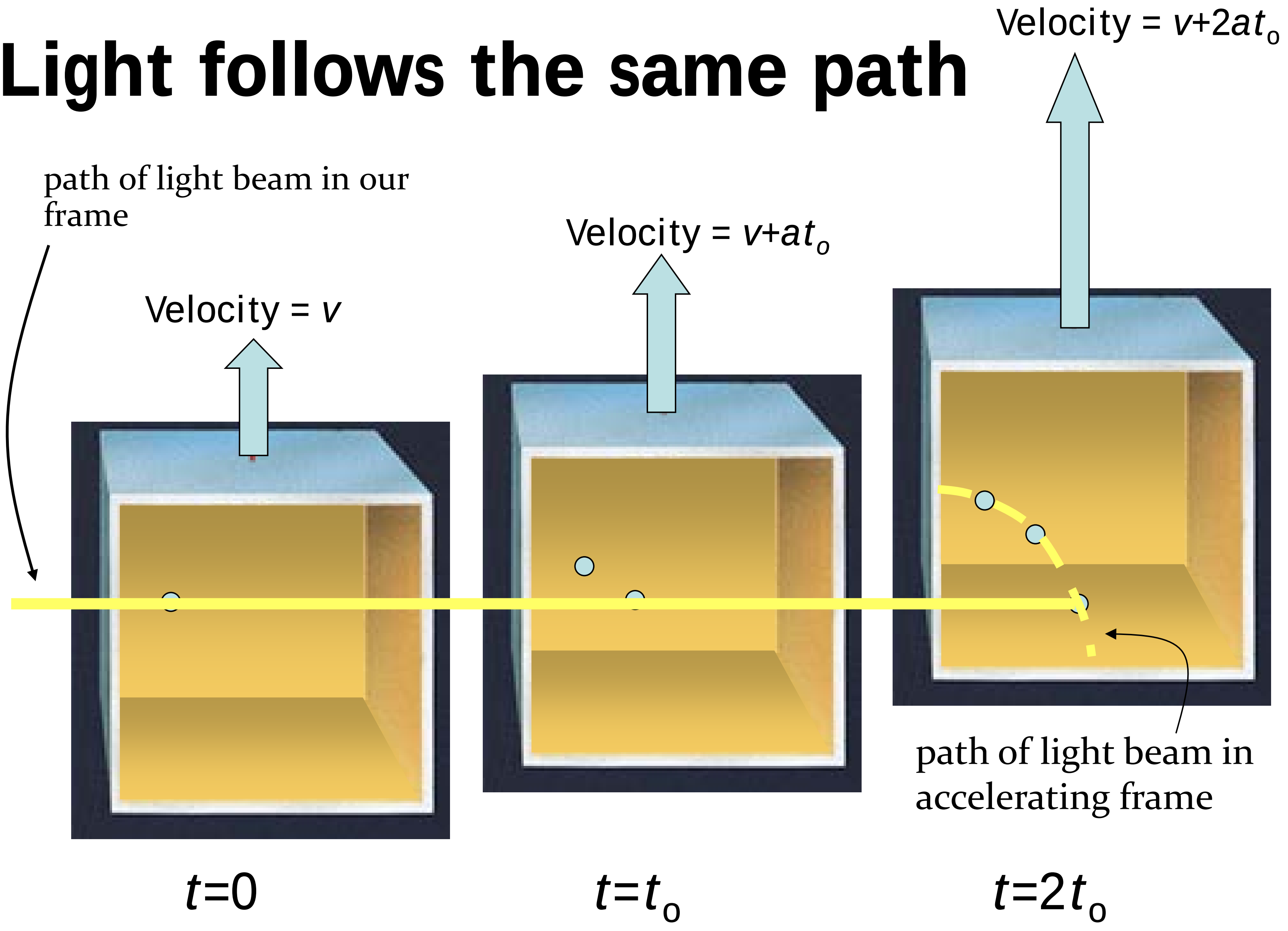
indistinguishable

from being in

a gravitational field



Light follows the same path



Gravity & Curved Spacetime

- Equivalence of acceleration of a frame &
  location in gravitational field

⇒ in gravity field, light follows a curved path

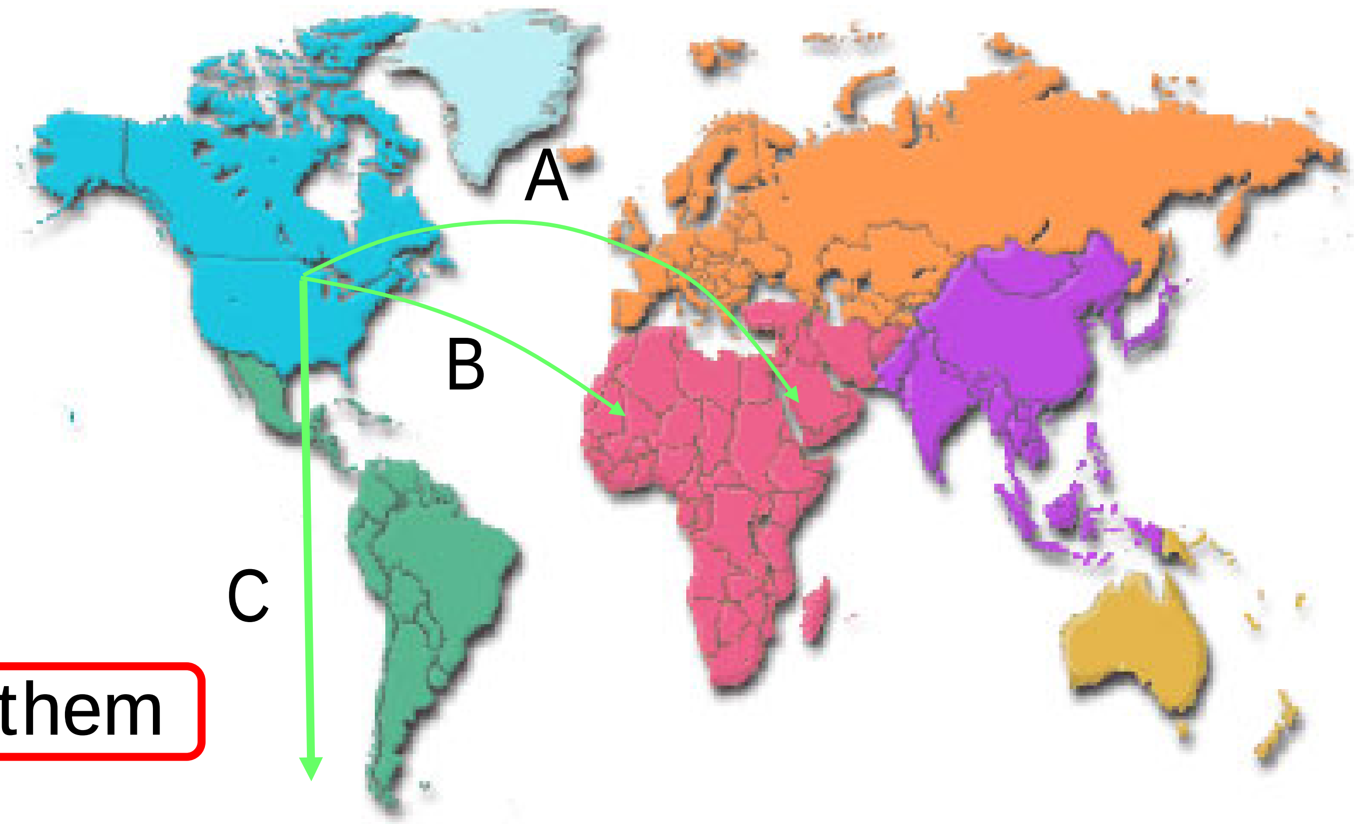
- Curved paths:

  straight lines in curved spacetime: ***Geodesics***
  (cf. flightpaths airplanes over surface Earth)

- Fundamental tenet of ***General Relativity***:

  !!!!!!!! **Gravity is the effect of curved spacetime** !!!!!!!!

which of these is a straight line?



A. A

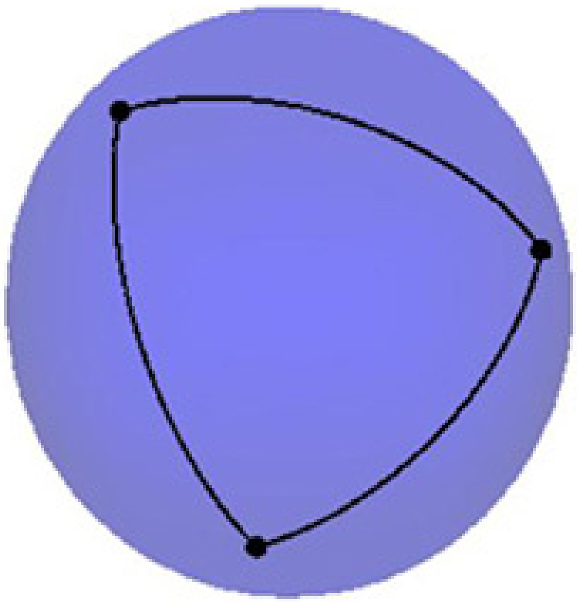
B. B

C. C

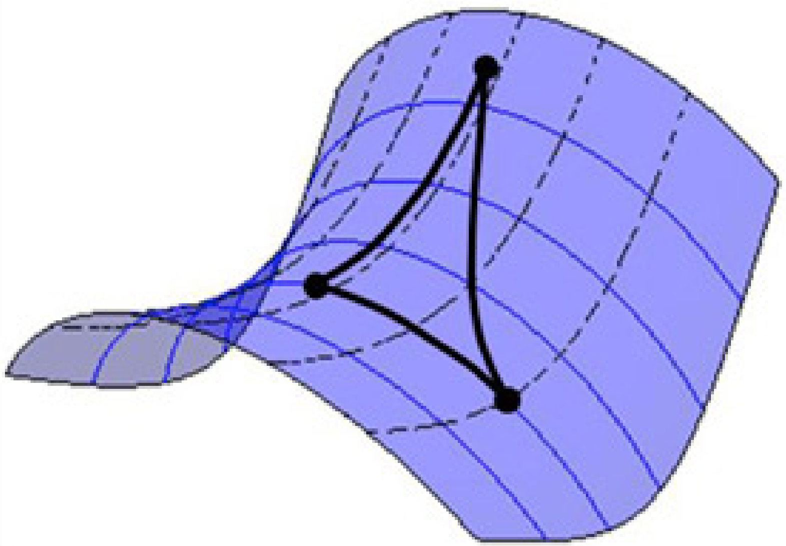
D. All of them

Curved Space:

Positive vs. Negative



positively curved space
sphere



negatively curved space
saddle

Triangle angles >180 degrees

Circle circumference < $2\pi r$

Triangle angles <180 degrees

Circle circumference > $2\pi r$

the

Cosmological Principle

General Relativity

A crucial aspect of any particular configuration is the geometry of spacetime: because Einstein's General Relativity is a metric theory, knowledge of the geometry is essential.

Einstein Field Equations are notoriously complex, essentially 10 equations. Solving them for general situations is almost impossible.

However, there are some special circumstances that do allow a full solution. The simplest one is also the one that describes our Universe. It is encapsulated in the

Cosmological Principle

On the basis of this principle, we can constrain the geometry of the Universe and hence find its dynamical evolution.

Cosmological Principle: the Universe Simple & Smooth

"God is an infinite sphere whose centre is everywhere and its circumference nowhere"
Empedocles, 5th cent BC

Cosmological Principle:

Describes the symmetries in global appearance of the Universe:

- **Homogeneous** → The Universe is the same everywhere:
  - physical quantities (density, T,p,...)
- **Isotropic** → The Universe looks the same in every direction
- **Universality** → Physical Laws same everywhere
- **Uniformly Expanding** → The Universe "grows" with same rate in
  - every direction
  - at every location

"all places in the Universe are alike"
Einstein, 1931

Geometry of the Universe

Fundamental Tenet

of (Non-Euclidian = Riemannian) Geometry

There exist no more than THREE uniform spaces:

1)	Euclidian (flat) Geometry	Euclides
2)	Hyperbolic Geometry	Gauß, Lobachevski, Bolyai
3)	Spherical Geometry	Riemann

uniform=
homogeneous & isotropic
(cosmological principle)

Geometry of the Universe

Positive Curvature

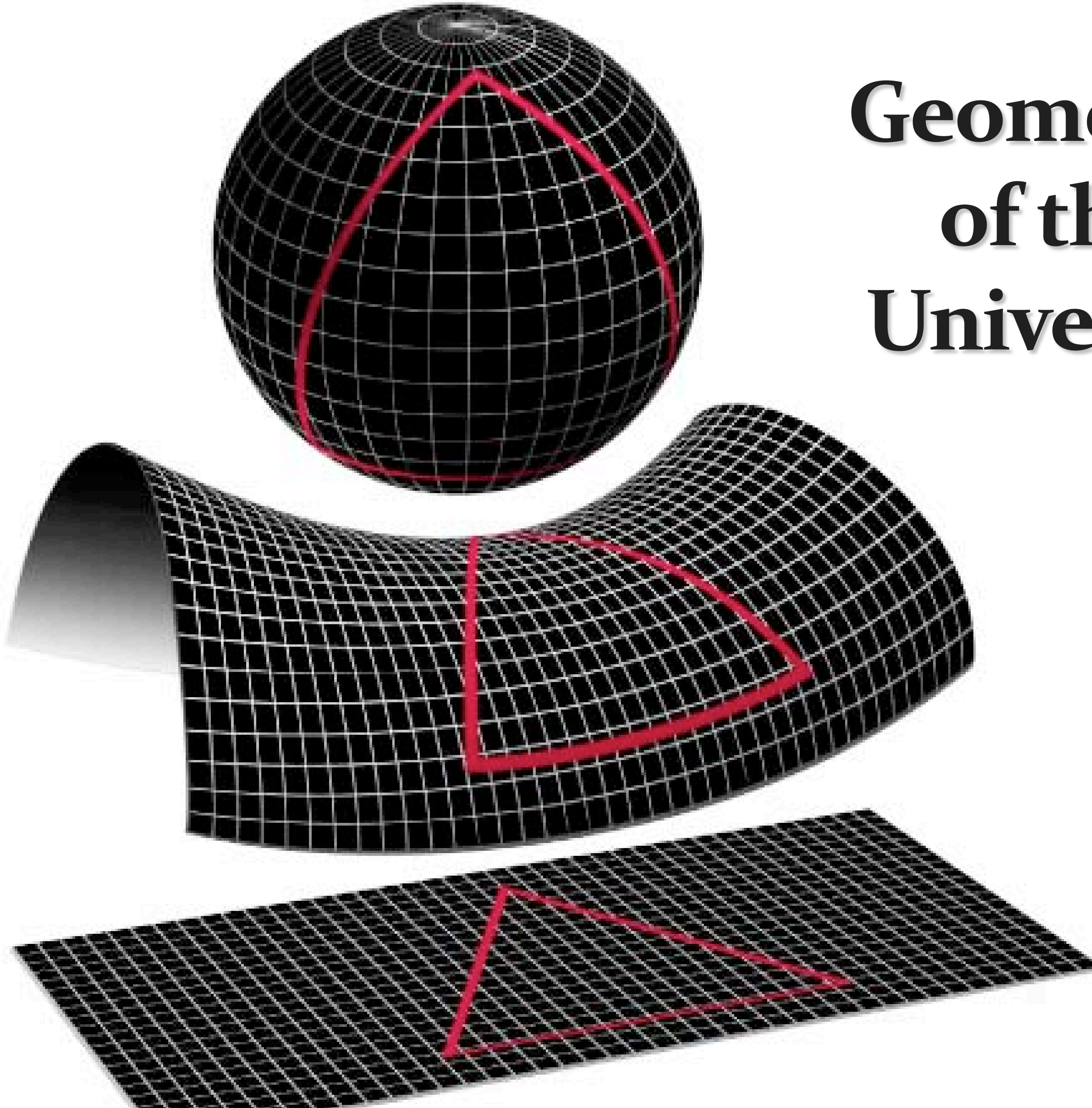
$k = +1$

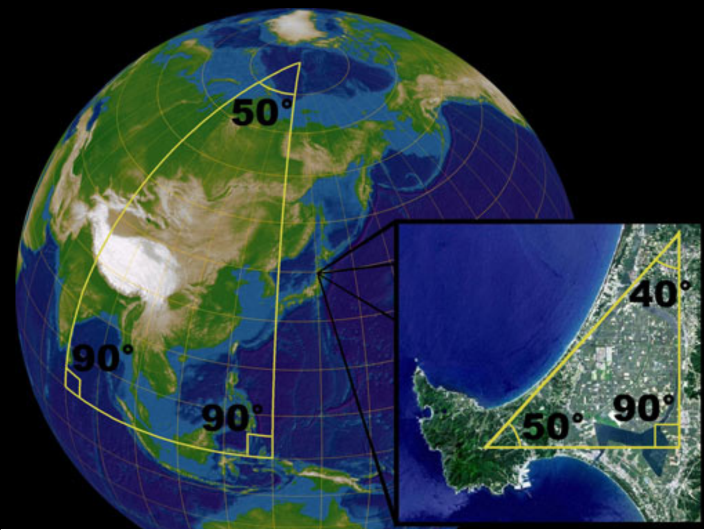
Negative Curvature

$k = -1$

Flat

$k = 0$





Uniform Spaces:

Geometric Characteristics

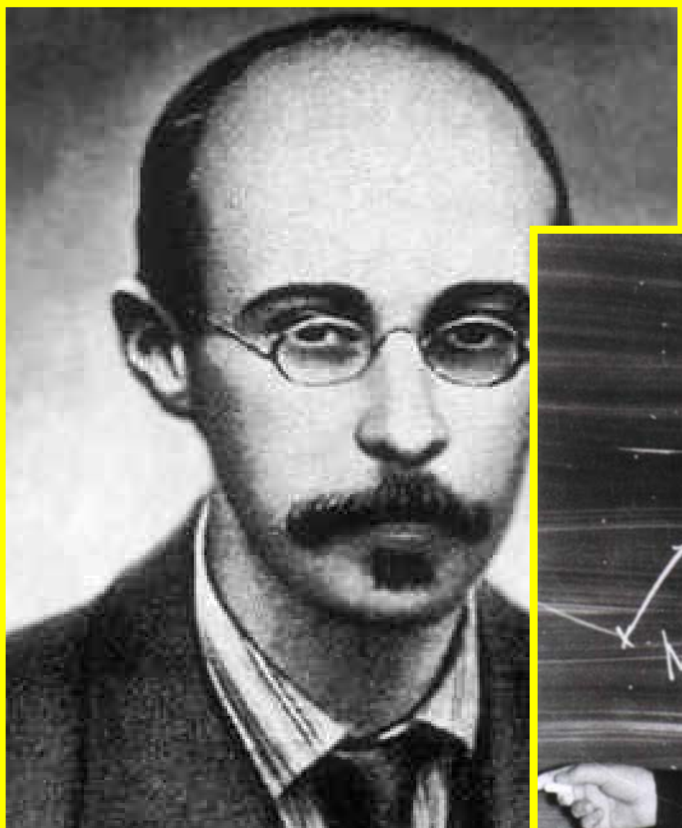
	Parallel Lines	Triangular Angles	Circumference Circle	Curvature	Extent	Boundary
		$\alpha + \beta + \gamma$	$x \equiv \frac{S}{2r}$	k		
Flat Space	parallels: 1 never intersects	π	π	0	open: infinite	unbounded
Spherical Space	parallels: ∞ along great circles, all intersect	$> \pi$	$< \pi$	$1/R^2$ > 0	closed: finite	unbounded
Hyperbolic Space	parallels: ∞ diverge & never intersect	$< \pi$	$> \pi$	$-1/R^2$ < 0	open: infinite	unbounded

Friedmann, Lemaitre

&

Cosmic Expansion History

Friedmann & Lemaitre



Alexander Friedmann (1888 -1925)
George Lemaitre (1894-1966)

They discovered (independently) theoretically the expansion of the Universe as a solution to the Theory of General Relativity.

... and derived the equations that describe the expansion and evolution of the universe,

the foundation for all of modern Cosmology:

Friedmann-Lemaitre Equation

Evolving Universe

- Einstein, de Sitter, Friedmann and Lemaitre all realized that in General Relativity, there cannot be a stable and static Universe:

- The Universe either expands, or it contracts ...

- Expansion Universe encapsulated in a

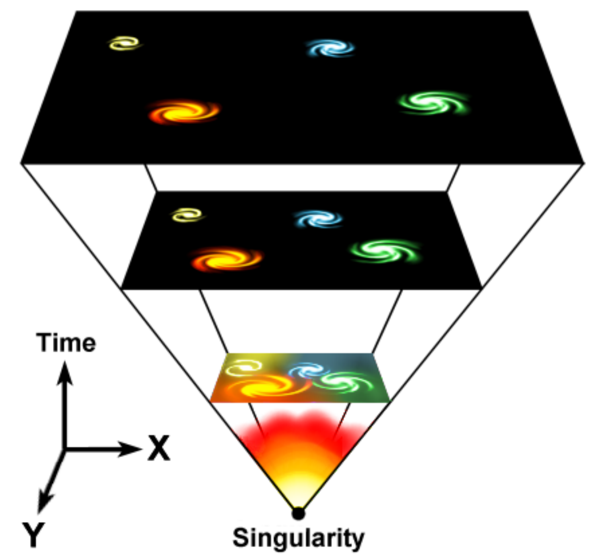
GLOBAL expansion factor a(t)

- All distances/dimensions of objects uniformly increase by a(t):

at time t, the distance between two objects i and j has increased to

$$\vec{r}_i - \vec{r}_j = a(t)\left(\vec{r}_{i,0} - \vec{r}_{j,0}\right)$$

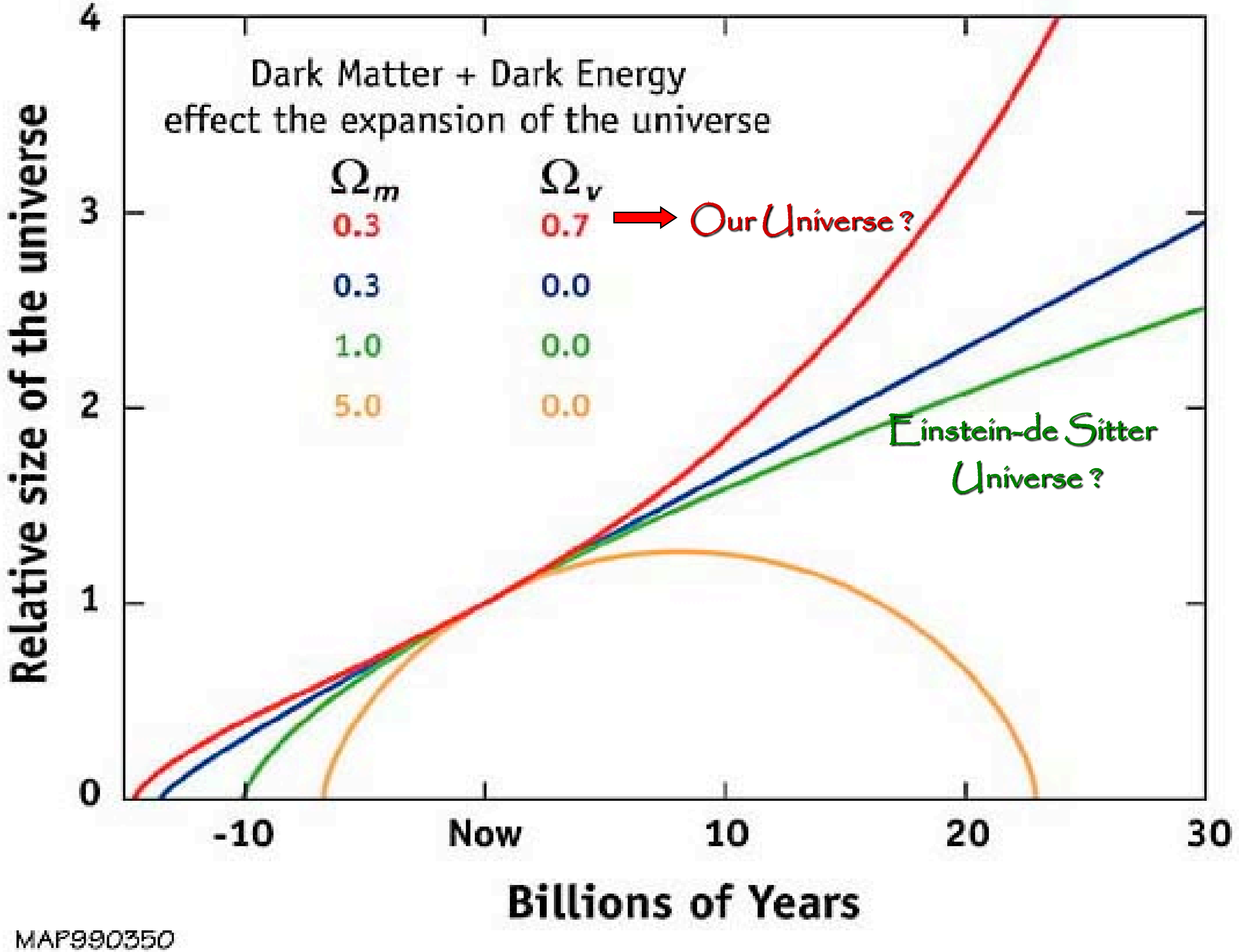
- Note: by definition we chose $a(t_0)=1$, i.e. the present-day expansion factor



Evolution & Fate
Friedmann-Robertson-Walker-Lemaitre Universe

Completely determined by 3 factors:

- energy and matter content
  (density and pressure)
- geometry of the Universe
  (curvature)
- Cosmological Constant



Dark Matter + Dark Energy
effect the expansion of the universe
Ω_m
Ω_v
0.3
0.7
Our Universe ?
0.3
0.0
1.0
0.0
5.0
0.0
Einstein-de Sitter
Universe ?
Relative size of the universe
0
1
2
3
4
-10
Now
10
20
30
Billions of Years
MAP990350

Friedmann-Robertson-Walker-Lemaitre Universe

$$\ddot{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)a + \frac{\Lambda}{3}a$$

$$\dot{a}^2 = \frac{8\pi G}{3}\rho a^2 - \frac{kc^2}{R_0^{\,2}} + \frac{\Lambda}{3}a^2$$

Friedmann-Robertson-Walker-Lemaitre Universe

Because of General Relativity, the evolution of the Universe is determined by four factors:

- density $\rho(t)$
- pressure $p(t)$
- curvature $kc^2 / R_0^{\,2}$ $k = 0, +1, -1$
  - R_0: present curvature radius
- cosmological constant Λ

- Density & Pressure:
  - in relativity, energy & momentum need to be seen as one physical quantity (four-vector)
  - pressure = momentum flux
- Curvature:
  - gravity is a manifestation of geometry spacetime
- Cosmological Constant:
  - free parameter in General Relativity
  - Einstein's "biggest blunder"
  - mysteriously, since 1998 we know it dominates the Universe

FRW Dynamics

In a FRW Universe,
densities are in the order of the critical density,
the density at which the Universe has a flat curvature

$$\rho_{crit} = \frac{3H_0^{\,2}}{8\pi G} = 1.8791 h^2 \times 10^{-29}\, g\, cm^{-3}$$

$$\rho_0 = 1.8791 \times 10^{-29}\, \Omega h^2 \;\; g\, cm^{-3}$$
$$= 2.78 \times 10^{11}\, \Omega h^2 \qquad M_{\odot} Mpc^{-3}$$

FRW Dynamics

In a matter-dominated Universe,
the evolution and fate of the Universe entirely determined
by the (energy) density in units of critical density:

$$\Omega \equiv \frac{\rho}{\rho_{crit}}$$

Arguably, ▯ is the most important parameter of cosmology !!!

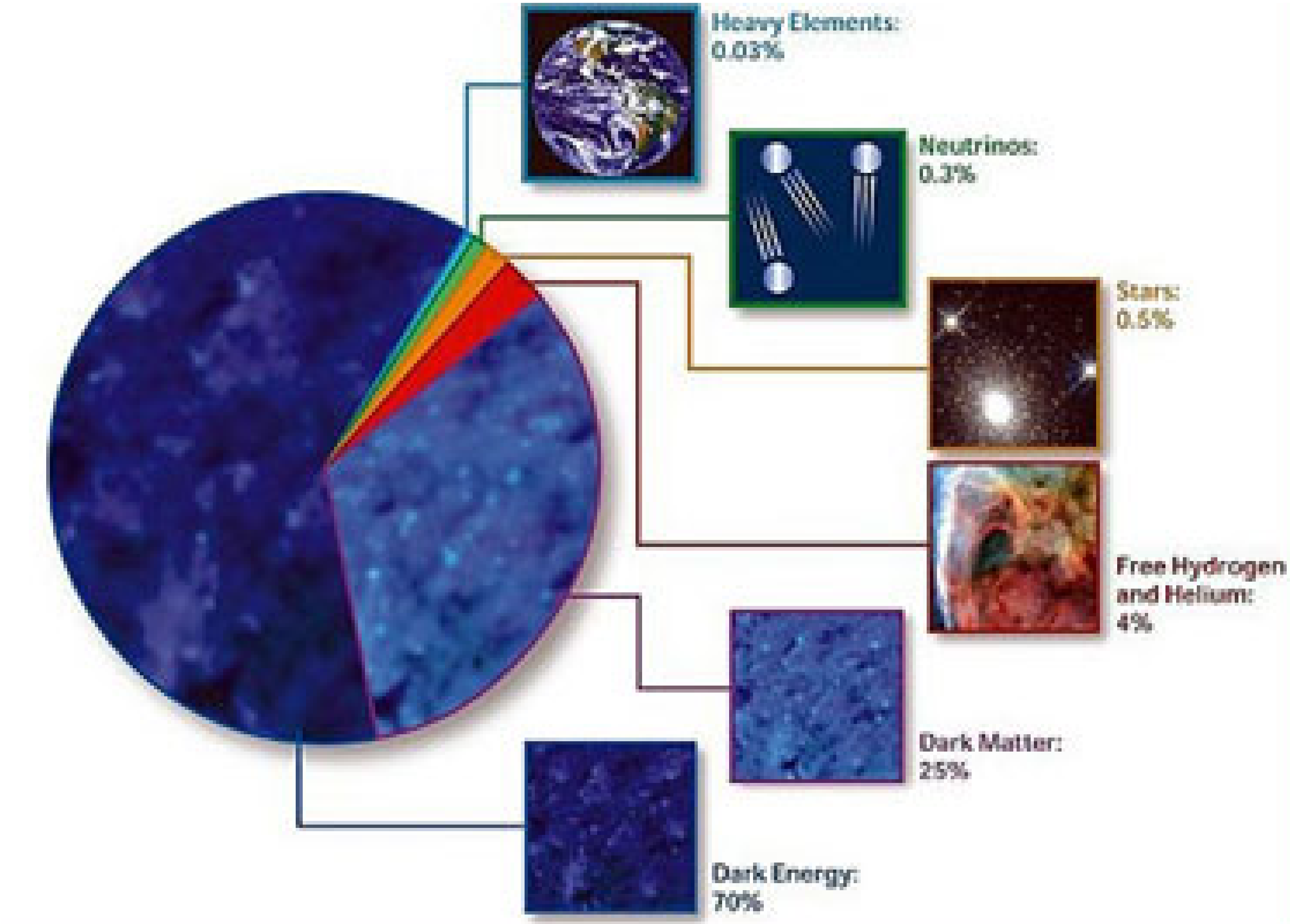
Present-day
Cosmic Density:

$$\rho_0 = 1.8791 \times 10^{-29}\,\Omega h^2 \;\; g\,cm^{-3}$$
$$= 2.78 \times 10^{11}\,\Omega h^2 \quad M_{\odot} Mpc^{-3}$$

what the Universe exists of:

Cosmic Constituents

Cosmic Components



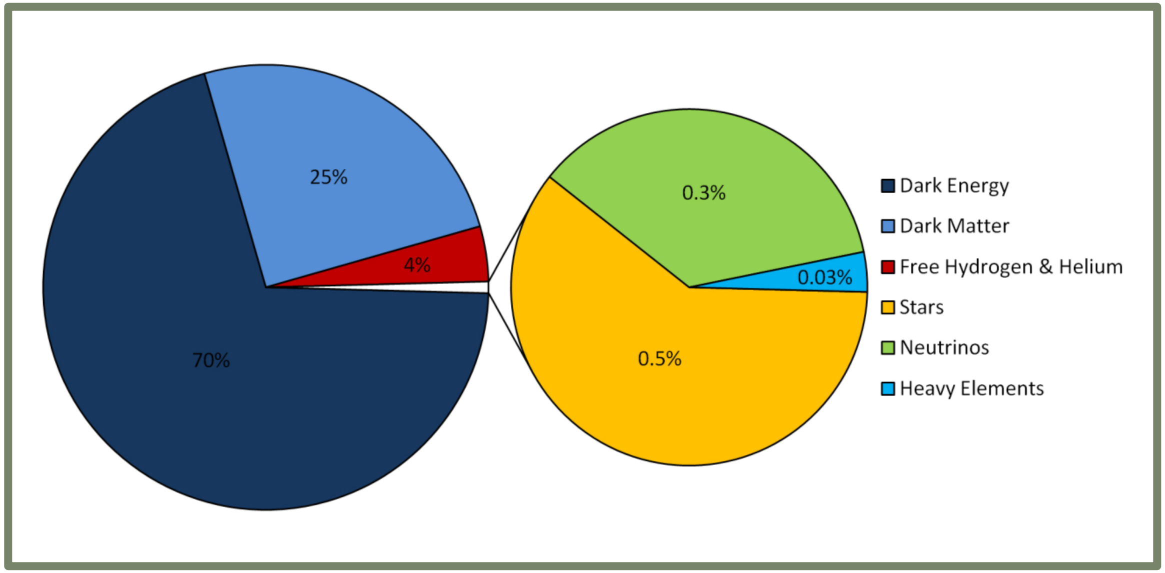
Cosmic Energy Inventarisation

1	dark sector				0.954 ± 0.003
1.1	dark energy			0.72 ± 0.03	
1.2	dark matter			0.23 ± 0.03	
1.3	primeval gravitational waves			$\lesssim 10^{-10}$	
2	primeval thermal remnants				0.0010 ± 0.0005
2.1	electromagnetic radiation			$10^{-4.3\pm0.0}$	
2.2	neutrinos			$10^{-2.9\pm0.1}$	
2.3	prestellar nuclear binding energy			$-10^{-4.1\pm0.0}$	
3	baryon rest mass				0.045 ± 0.003
3.1	warm intergalactic plasma			0.040 ± 0.003	
3.1a	virialized regions of galaxies		0.024 ± 0.005		
3.1b	intergalactic		0.016 ± 0.005		
3.2	intracluster plasma			0.0018 ± 0.0007	
3.3	main sequence stars	spheroids and bulges		0.0015 ± 0.0004	
3.4		disks and irregulars		0.00055 ± 0.00014	
3.5	white dwarfs			0.00036 ± 0.00008	
3.6	neutron stars			0.00005 ± 0.00002	
3.7	black holes			0.00007 ± 0.00002	
3.8	substellar objects			0.00014 ± 0.00007	
3.9	HI + HeI			0.00062 ± 0.00010	
3.10	molecular gas			0.00016 ± 0.00006	
3.11	planets			10^{-6}	
3.12	condensed matter			$10^{-5.6\pm0.3}$	
3.13	sequestered in massive black holes			$10^{-5.4}(1+\epsilon_n)$	
4	primeval gravitational binding energy				$-10^{-6.1\pm0.1}$
4.1	virialized halos of galaxies			$-10^{-7.2}$	
4.2	clusters			$-10^{-6.9}$	
4.3	large-scale structure			$-10^{-6.2}$	

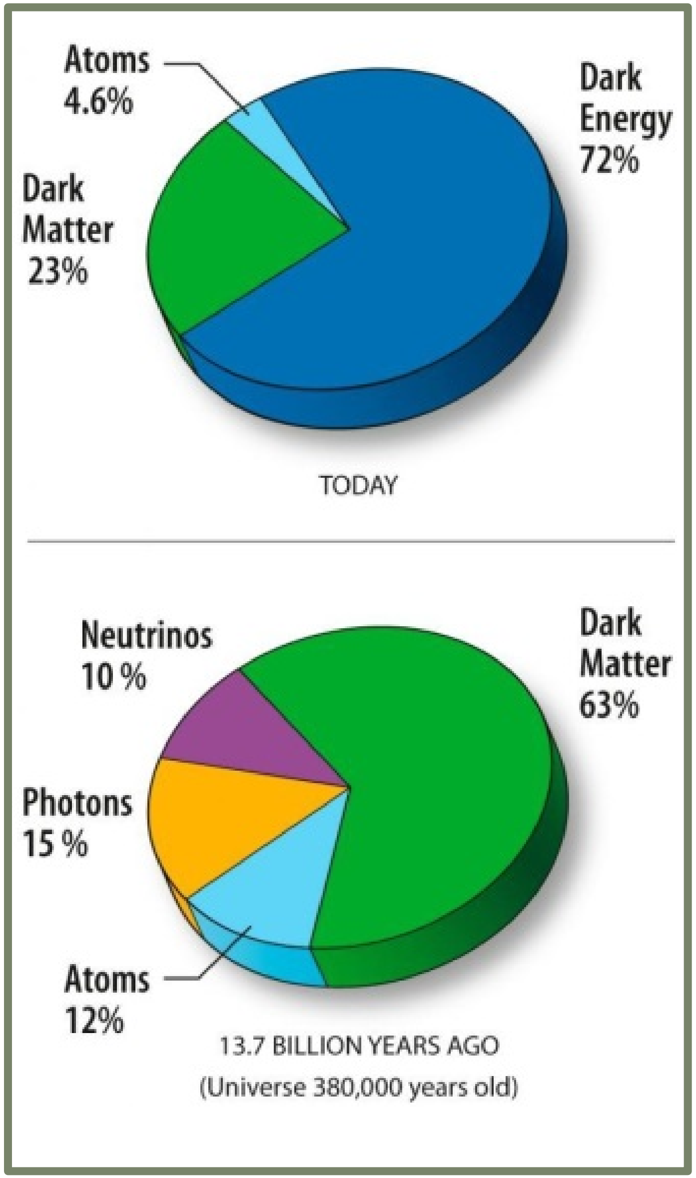
sterren slechts ~0.1% energie Heelal

Fukugita & Peebles 2004

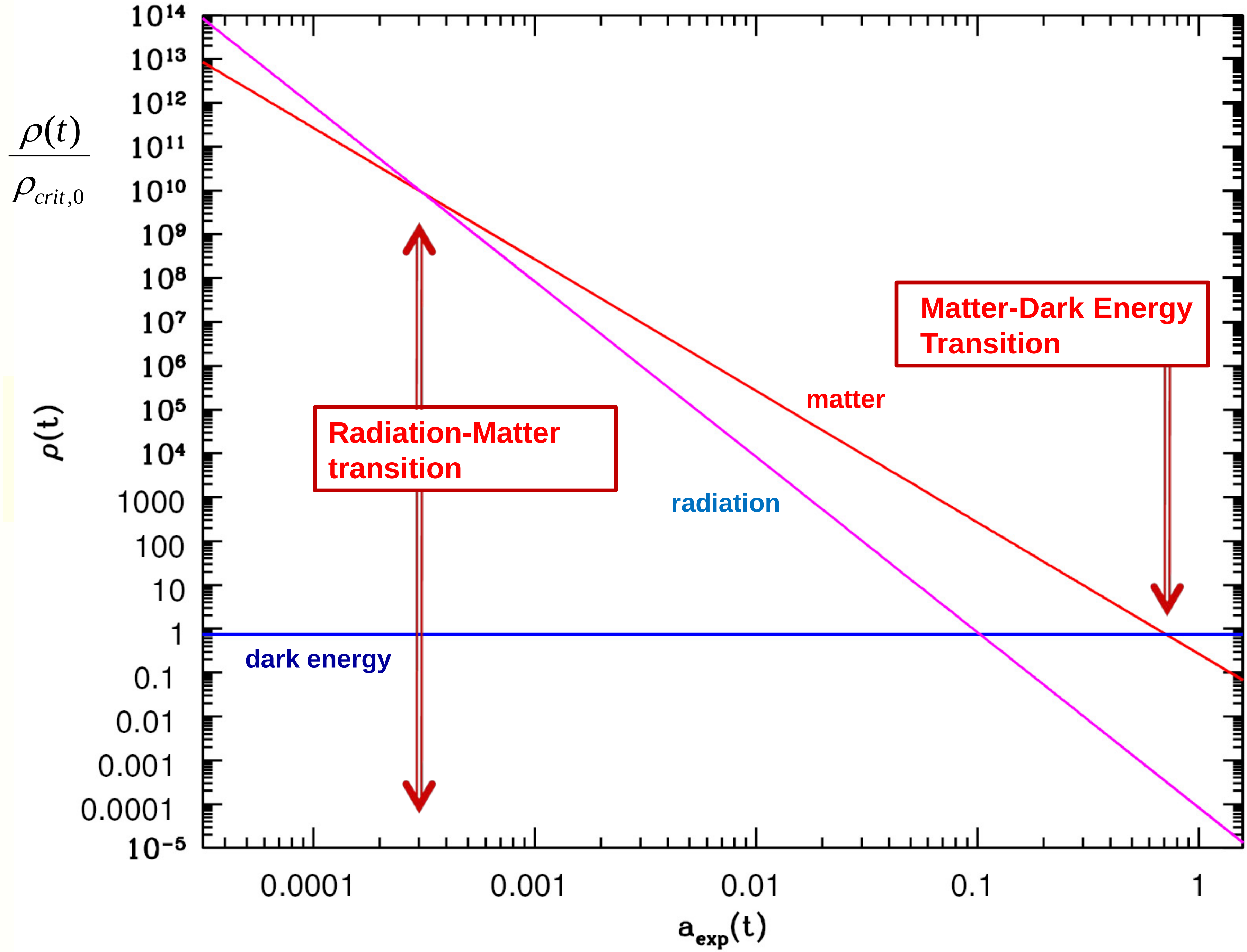
Cosmic Constitution



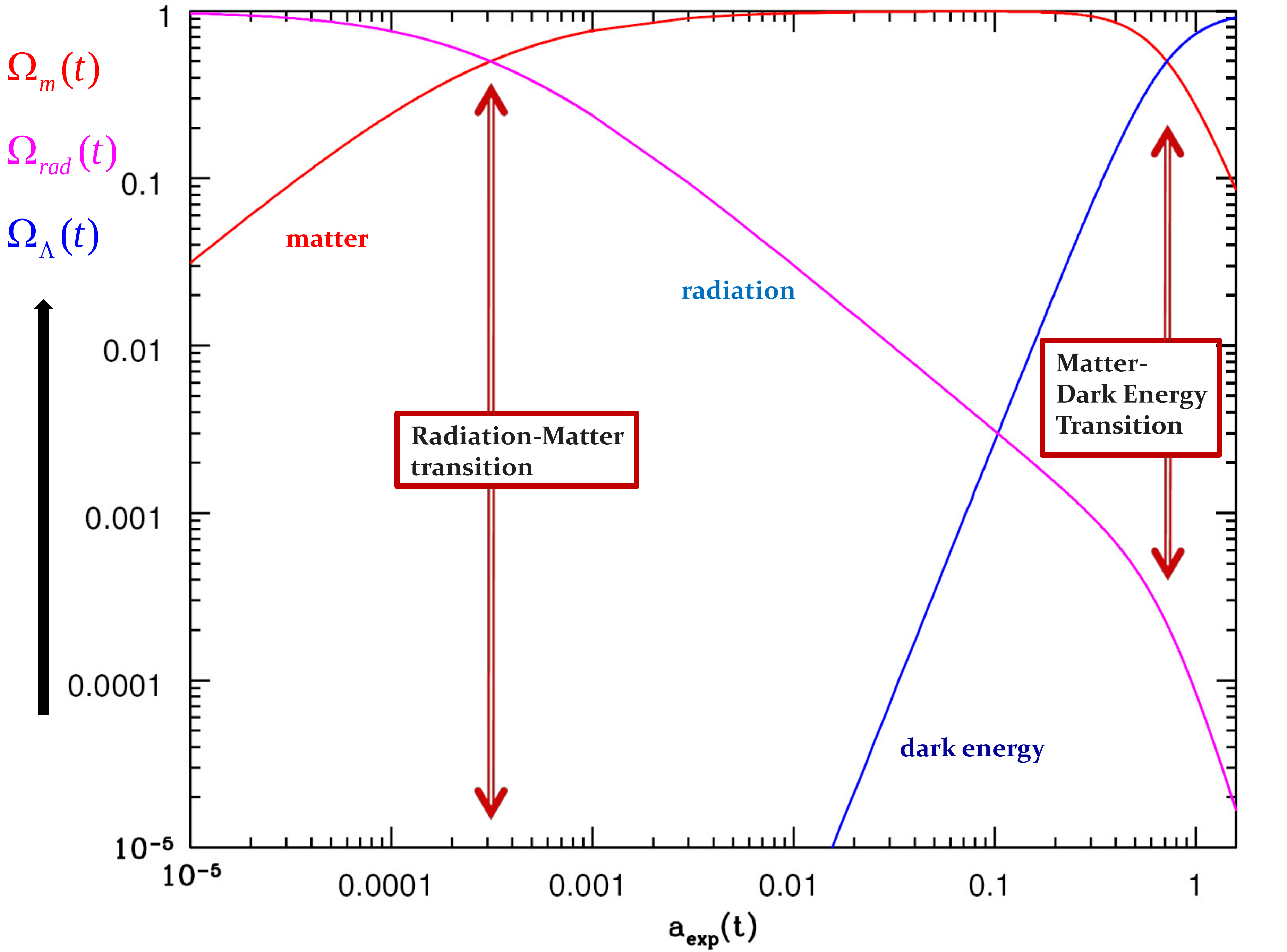
Cosmic Pie Diagram



Changes in Time:



$\frac{\rho(t)}{\rho_{crit,0}}$
ρ(t)
10¹⁴
10¹³
10¹²
10¹¹
10¹⁰
10⁹
10⁸
10⁷
10⁶
10⁵
10⁴
1000
100
10
1
0.1
0.01
0.001
0.0001
10⁻⁵
0.0001
0.001
0.01
0.1
1
$a_{exp}(t)$
Radiation-Matter
transition
Matter-Dark Energy
Transition
matter
radiation
dark energy



$\Omega_m(t)$
$\Omega_{rad}(t)$
$\Omega_\Lambda(t)$
matter
radiation
dark energy
Radiation-Matter transition
Matter-Dark Energy Transition
1
0.1
0.01
0.001
0.0001
10^{-5}
10^{-5}
0.0001
0.001
0.01
0.1
1
$a_{exp}(t)$

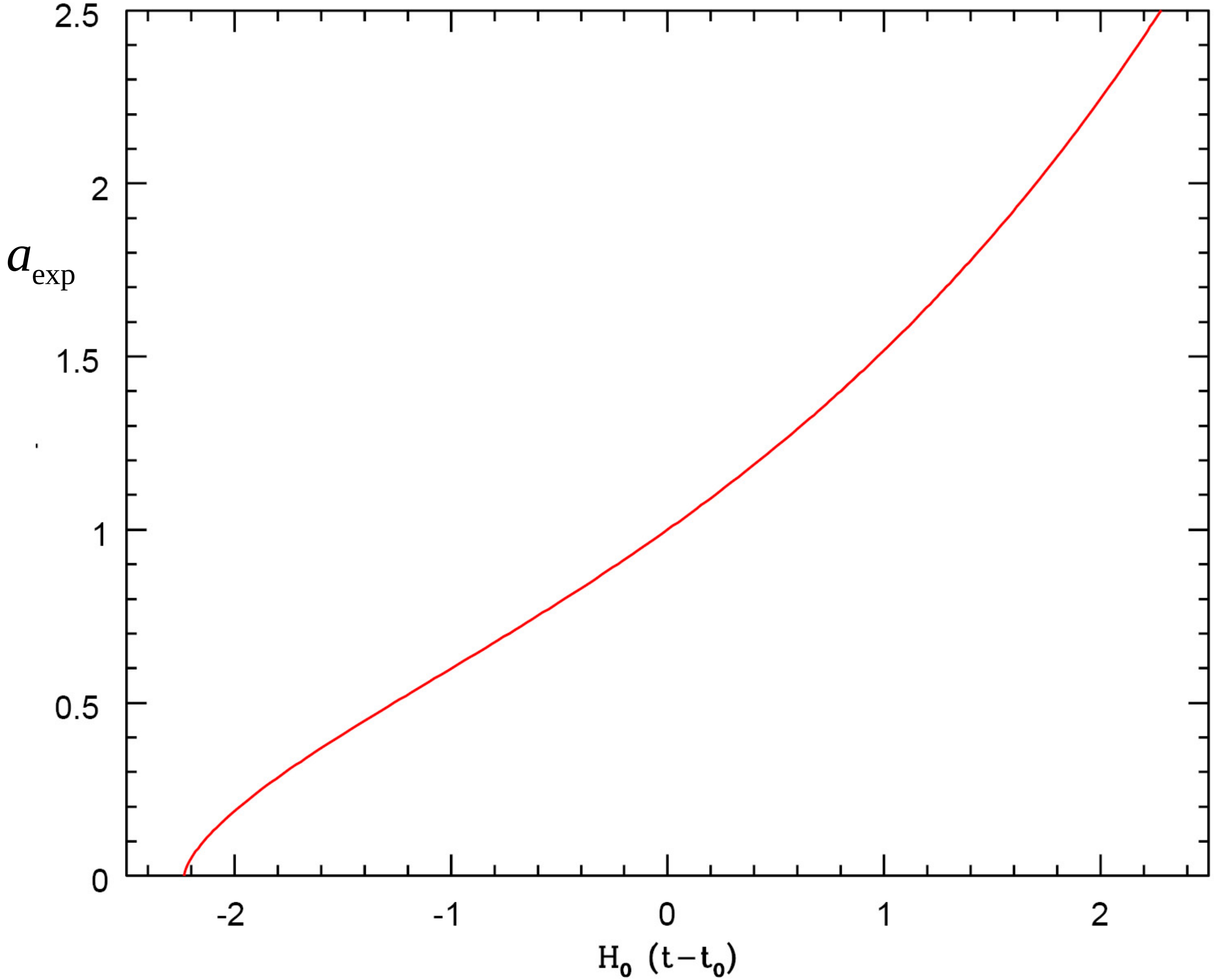
Our Universe:

the Concordance Cosmos

Concordance Universe Parameters

Hubble Parameter		$H_0 = 71.9 \pm 2.6\ km\ s^{-1}\ Mpc^{-1}$	
Age of the Universe		$t_0 = 13.8 \pm 0.1\ Gyr$	
Temperature CMB		$T_0 = 2.725 \pm 0.001 K$	
Matter	**Baryonic Matter** **Dark Matter**	$\Omega_m = 0.27$	$\Omega_b = 0.0456 \pm 0.0015$ $\Omega_{dm} = 0.228 \pm 0.013$
Radiation	**Photons (CMB)** **Neutrinos (Cosmic)**	$\Omega_{rad} = 8.4 \times 10^{-5}$	$\Omega_\gamma = 5 \times 10^{-5}$ $\Omega_\nu = 3.4 \times 10^{-5}$
Dark Energy		$\Omega_\Lambda = 0.726 \pm 0.015$	
Total		$\Omega_{tot} = 1.0050 \pm 0.0061$	

Concordance Expansion

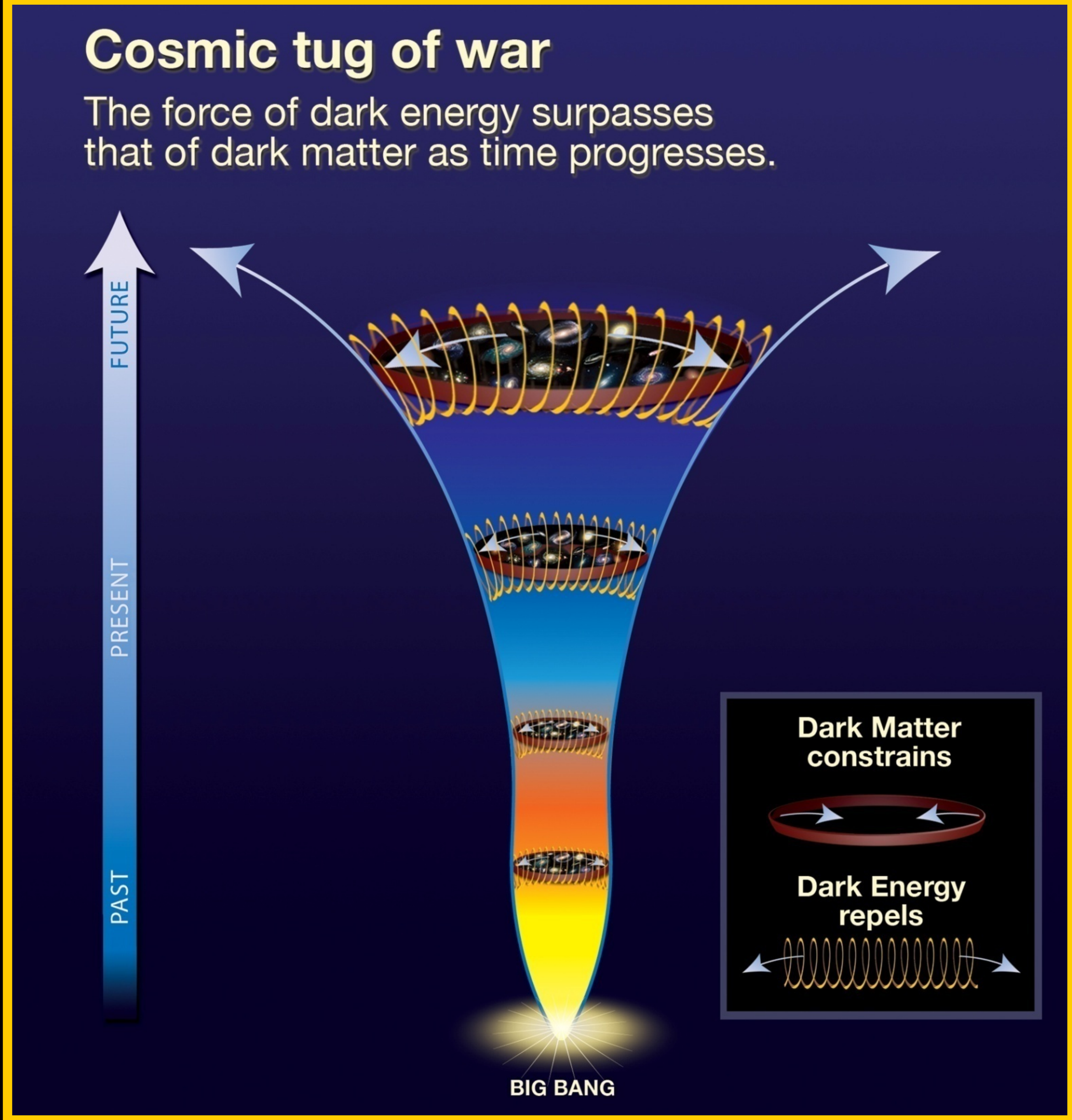


Heden & Toekomst:

VERSNELLING

Vroeger:

VERTRAGING



Age of the Universe

Hubble Time

- The repercussions of Hubble's discovery are truly tremendous:

  the inescapable conclusion is that the universe has a finite age !

- Just by simple extrapolation back in time we find that at some instant the objects will have touched upon each other, i.e. $r(t_H)=0$. If we assume for simplicity that the expansion rate did remain constant (which it did not !), we find a direct measure for the age of the universe, the

Hubble Time:

$$t_H = \frac{1}{H}$$

$$H_0 = 100h \;\; km\, s^{-1} Mpc^{-1}$$

$$\Downarrow$$

$$t_0 = 9.78 h^{-1} \; Gyr$$

The Hubble parameter is usually stated in units of km/s/Mpc.

It's customary to express it in units of 100 km/s/Mpc, expressing the real value in terms of the dimensionless value $h=H_0/[100 \text{ km/s/Mpc}]$.

The best current estimate is $H_0=72$ km/s/Mpc. This sets $t_0 \sim 10$ Gyr.

Hubble Parameter

- For a long time, the correct value of the Hubble constant H_o was a major unsettled issue:

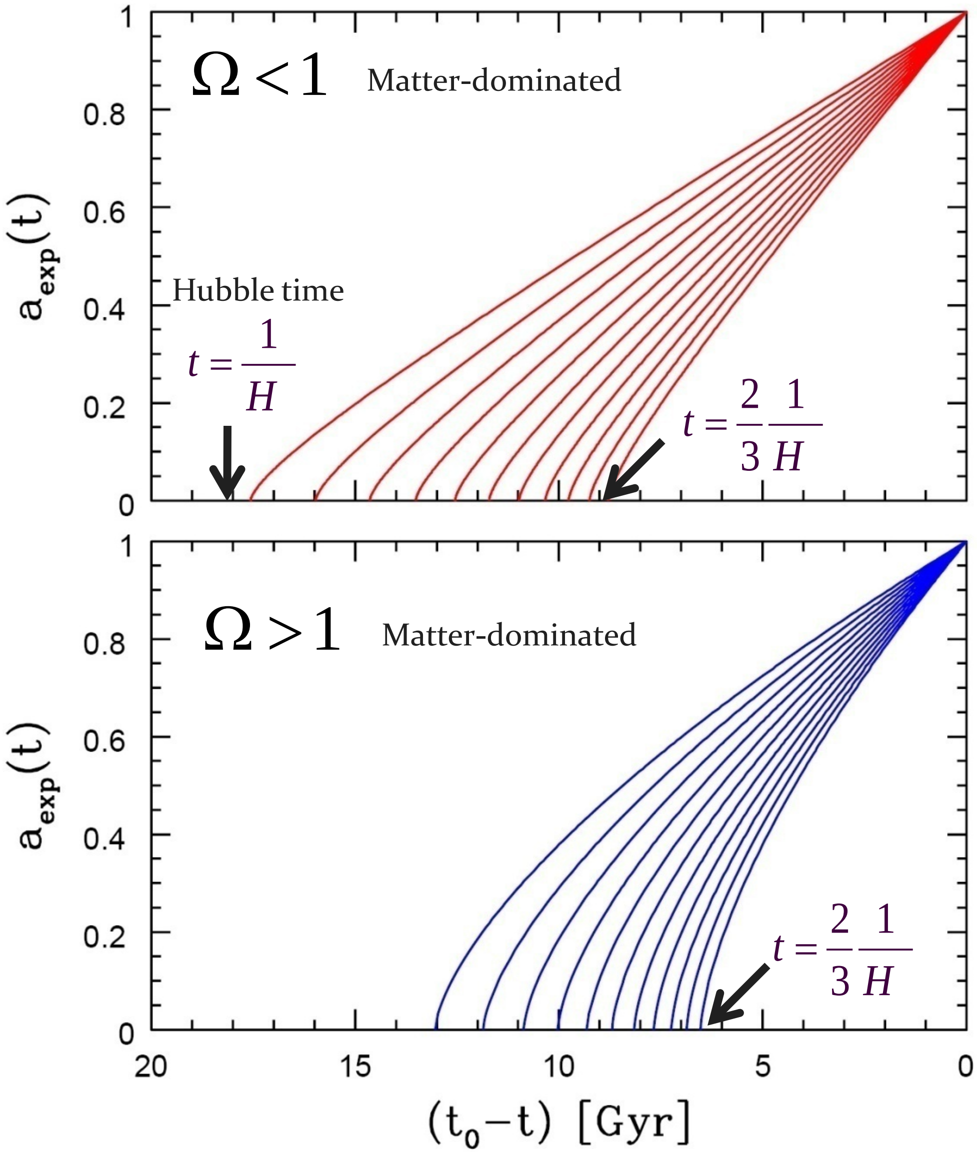
$H_o = 50$ km s^{-1} Mpc^{-1} ⟷ $H_o = 100$ km s^{-1} Mpc^{-1}

- This meant distances and timescales in the Universe had to deal with uncertainties of a factor 2 !!!

- Following major programs, such as Hubble Key Project, the Supernova key projects and the WMAP CMB measurements,

$$H_0 = 71.9^{+2.6}_{-2.7}\, km\, s^{-1} Mpc^{-1}$$

Age of the Universe



Age of a FRW universe at
Expansion factor a(t)

$$H\,t = \int_0^a \frac{da}{\sqrt{\frac{\Omega_{rad}}{a^2} + \frac{\Omega_m}{a} + \Omega_\Lambda a^2 + (1 - \Omega)}}$$

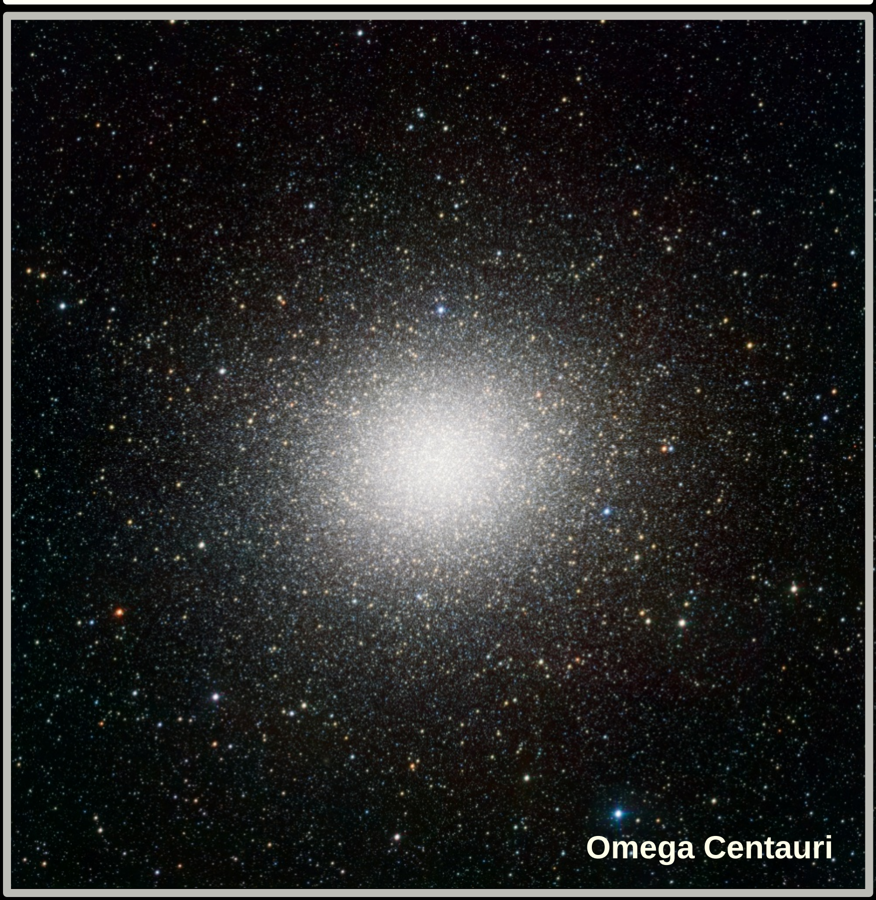
Cosmic Age

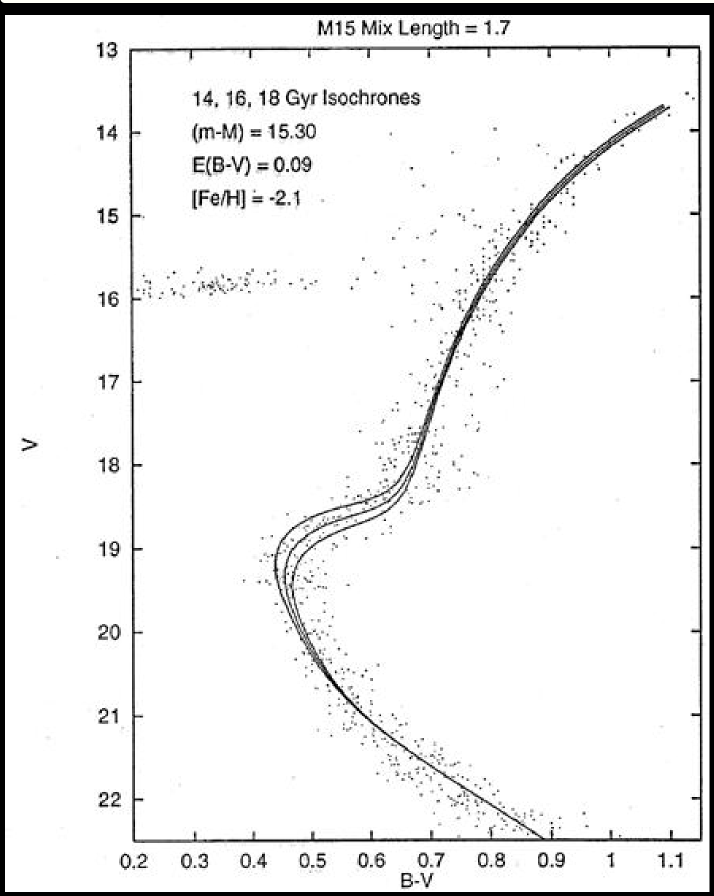
estimated age of the oldest stars in Universe far in excess of estimated age of matter-dominated FRW Universe:

Globular cluster stars: 13-15 Gyr
Universe: 10-12 Gyr

Globular Clusters

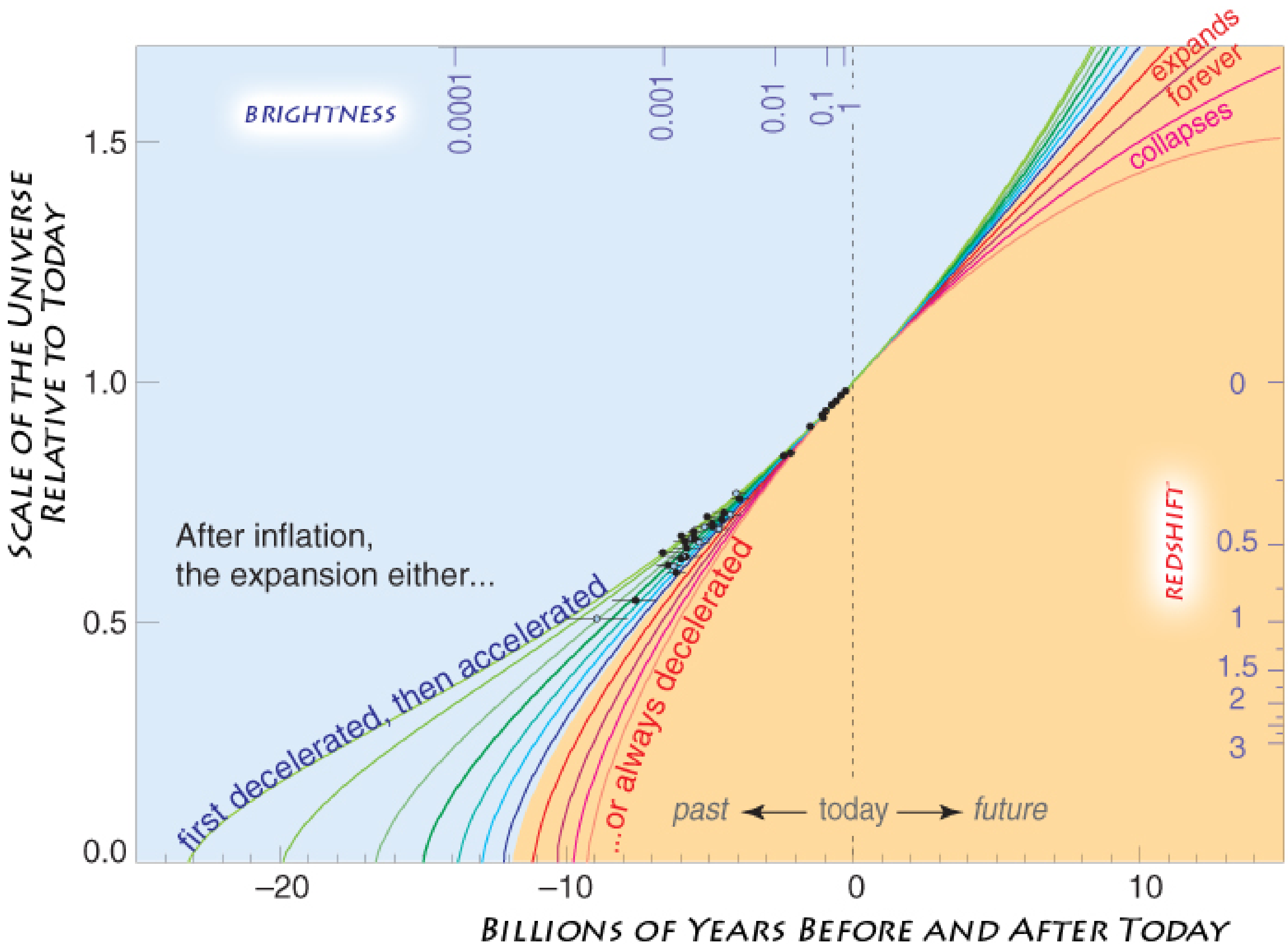
- Roughly spherical assemblies of 100,000-200,000 stars
- Radius ~ 20-50 pc: extremely high star density
- Globulars are very old, amongst oldest objects in local Universe
- Stars formed around same time: old, red, population
- Colour-magnitude diagram characteristic: accurate age determination on the basis of stellar evolution theories.





Typical 1980-1990s isochrone fit

Concordance Expansion



Adiabatic Expansion

Adiabatic Expansion

- The Universe of Einstein, Friedmann & Lemaitre expands *adiabacally*

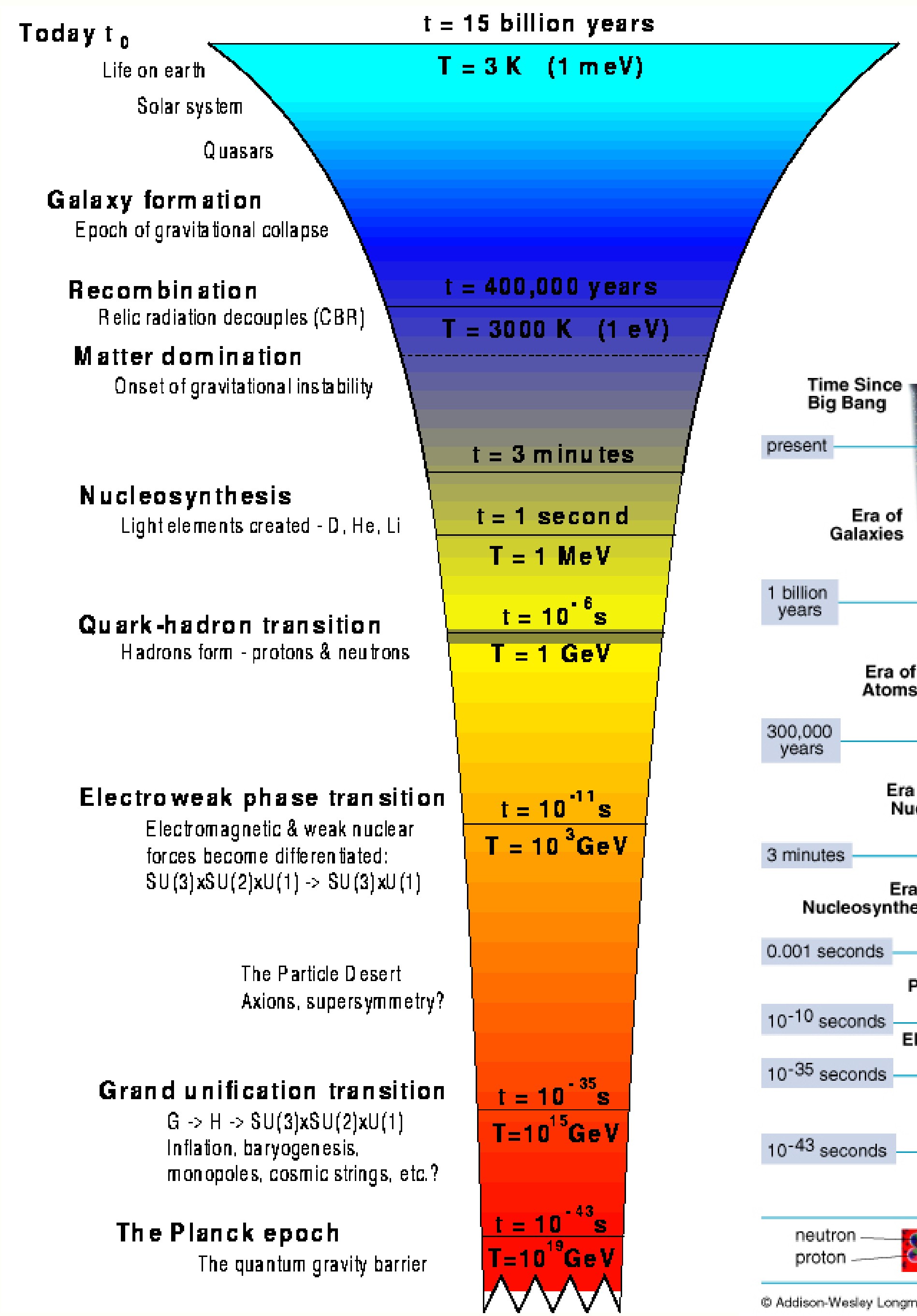
- Energy of the expansion of the Universe corresponds to the decrease in the energy of its constituents

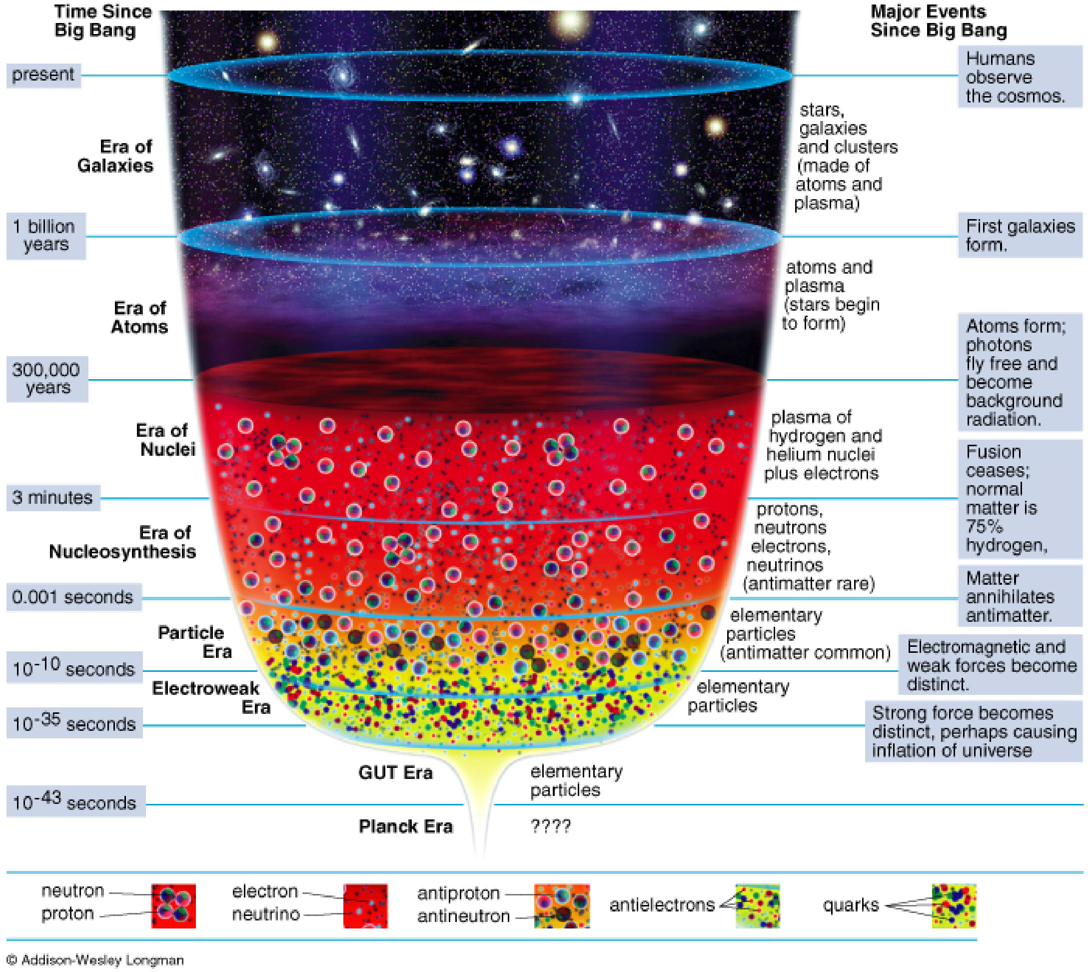
- *The Universe COOLS as a result of its expansion !*

$$T(t) \propto 1/a(t)$$

Adiabatic Expansion

reconstruction Thermal History of the Universe





Cosmic Epochs

Epoch	Events	Time
Planck Epoch		$t < 10^{-43}$ sec
Phase Transition Era	GUT transition electroweak transition quark-hadron transition	10^{-43} sec $< t < 10^{5}$ sec
Hadron Era		$t \sim 10^{-5}$ sec
Lepton Era	muon annihilation neutrino decoupling electron-positron annihilation primordial nucleosynthesis	10^{-5} sec $< t <$ 1 min
Radiation Era	radiation-matter equivalence recombination & decoupling	1 min $< t <$ 379,000 yrs
Post-Recombination Era	Structure & Galaxy formation Dark Ages Reionization Matter-Dark Energy transition	$t >$ 379,000 yrs

Big Bang:

the Evidence

Big Bang Evidence

- <u>Olber's paradox:</u>
  the night sky is dark
  ➡ finite age Universe (13.7 Gyr)

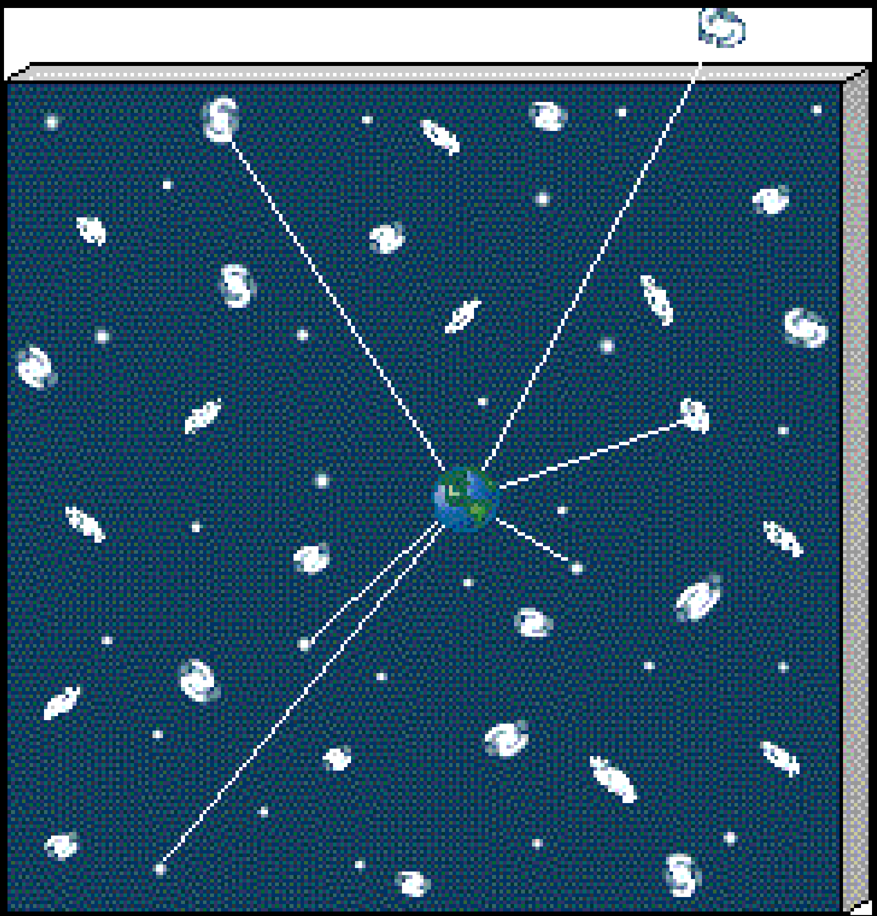
- <u>Hubble Expansion</u>
  uniform expansion, with
  expansion velocity ~ distance: $v = H\,r$

- <u>Explanation Helium Abundance 24%:</u>
  light chemical elements formed (H, He, Li, ...)
  after ~3 minutes ...

- <u>The Cosmic Microwave Background Radiation:</u>
  the 2.725K radiation blanket, remnant left over
  hot ionized plasma ➡ neutral universe
  (379,000 years after Big Bang)

- <u>Distant, deep Universe indeed looks different ...</u>

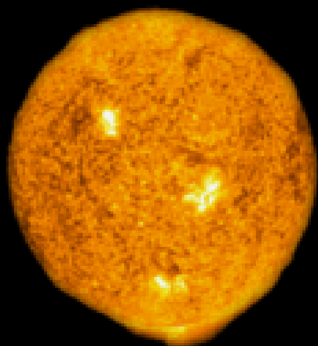
1. Olber's Paradox



In an infinitely large, old and unchanging Universe each line of sight would hit a star:

Sky would be as bright as surface of star:

1. Olber's Paradox



In an infinitely large, old and unchanging Universe each line of sight would hit a star:

⟹

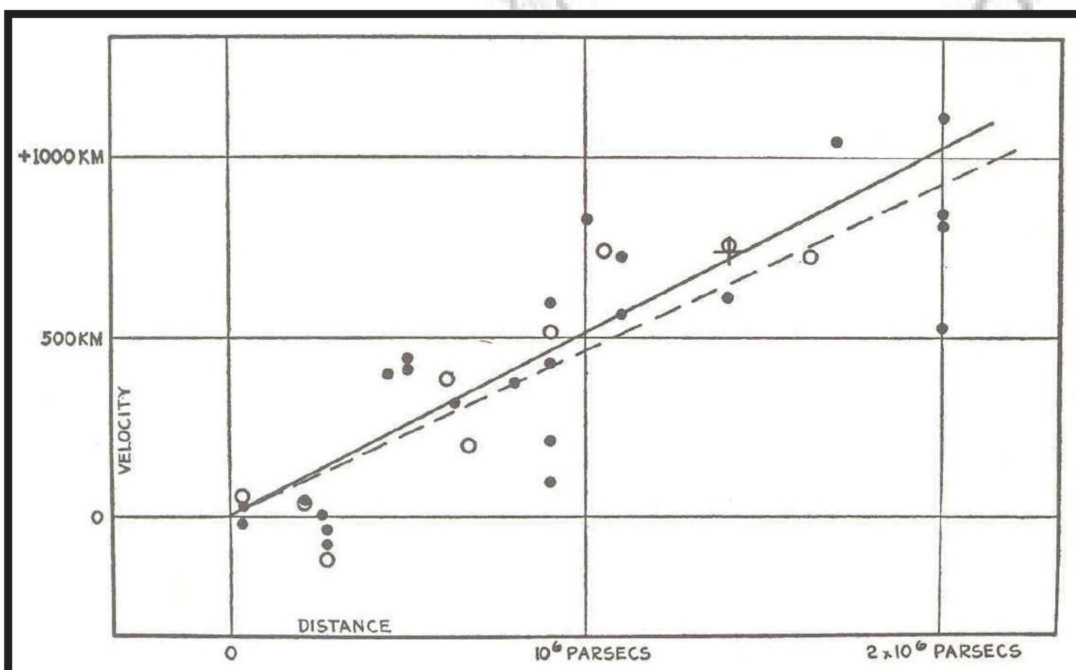
Sky would be as bright as surface of star:

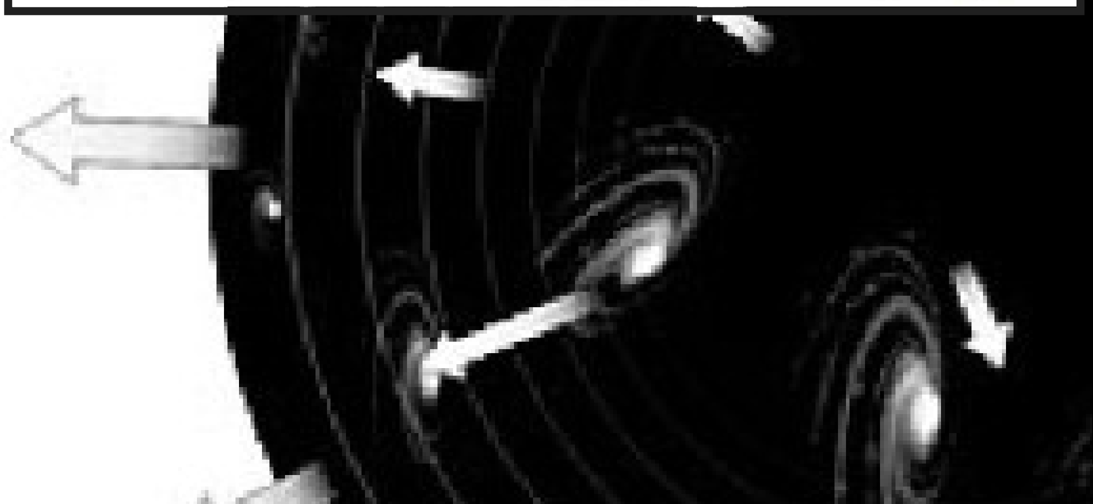
Night sky as bright as Solar Surface, yet the night sky is dark

⟹

finite age of Universe (13.8 Gyr)

2. Hubble Expansion

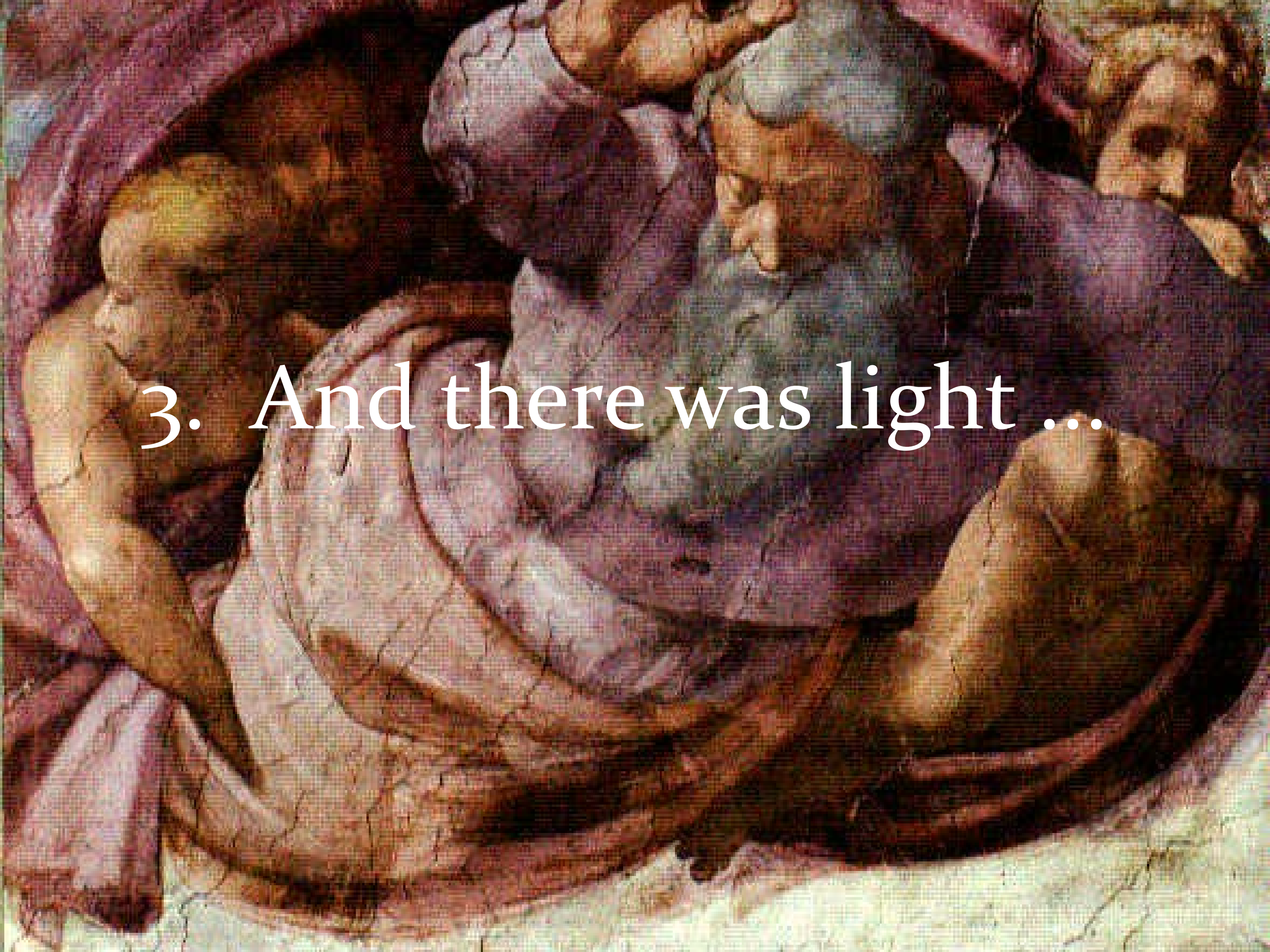




$$v_{rad} = cz = H_0 r$$

H_0 : **Hubble constant**

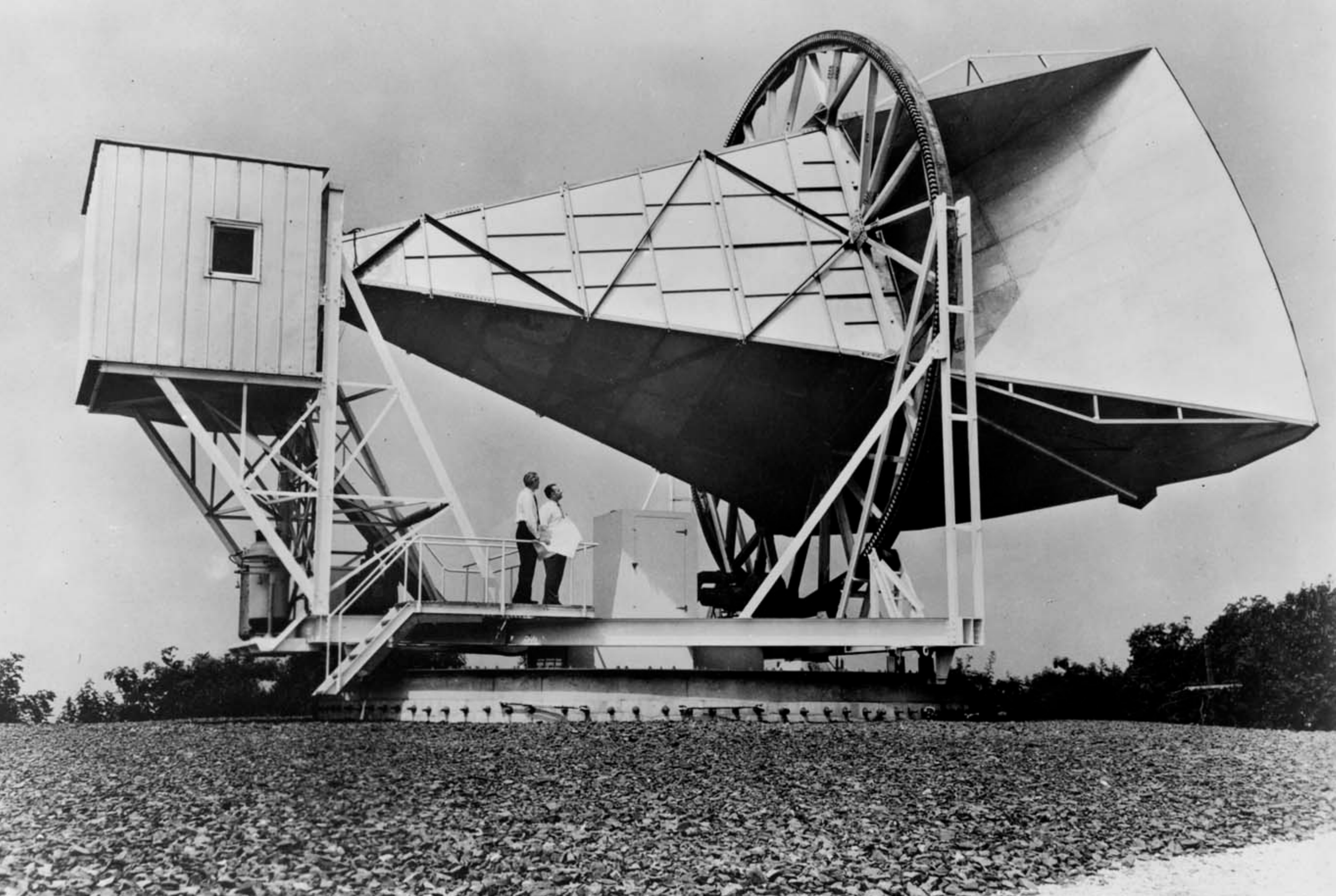
specifies expanssion rate of the Universe


3. And there was light …

... and there was light ...

379.000 years
after the Big Bang

3. Cosmic Microwave Background Radiation



Cosmic Light (CMB): the facts

- Discovered serendipitously in 1965 **Penzias & Wilson, Nobelprize 1978 !!!!!**

- Cosmic Licht that fills up the Universe uniformly

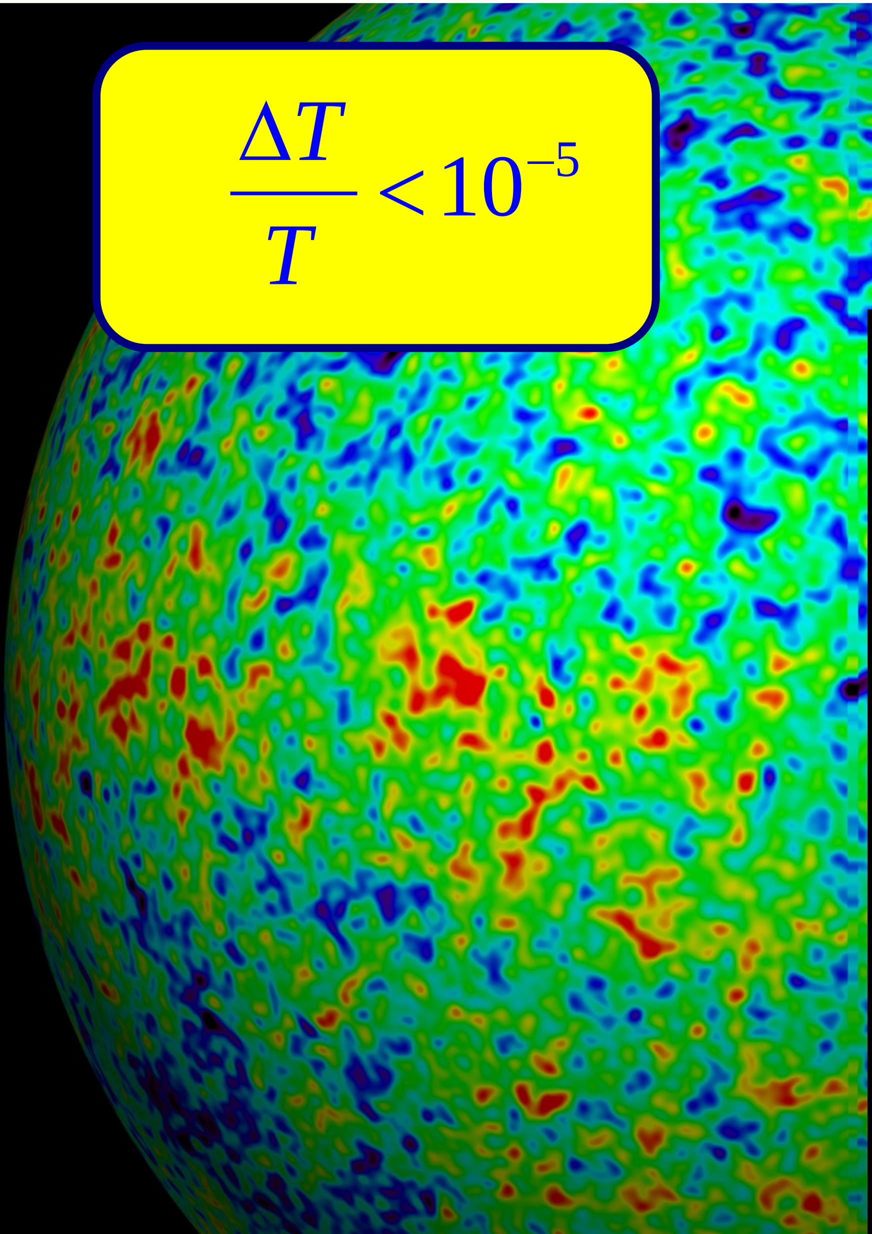
- Temperature: $T_{\gamma}=2.725$ K
- (CMB) photons most abundant particle in the Universe: $n_{\gamma} \sim 415\ cm^{-3}$

- Per atom in the Universe: $n_{\gamma}/n_{B} \sim 1.9 \times 10^{9}$

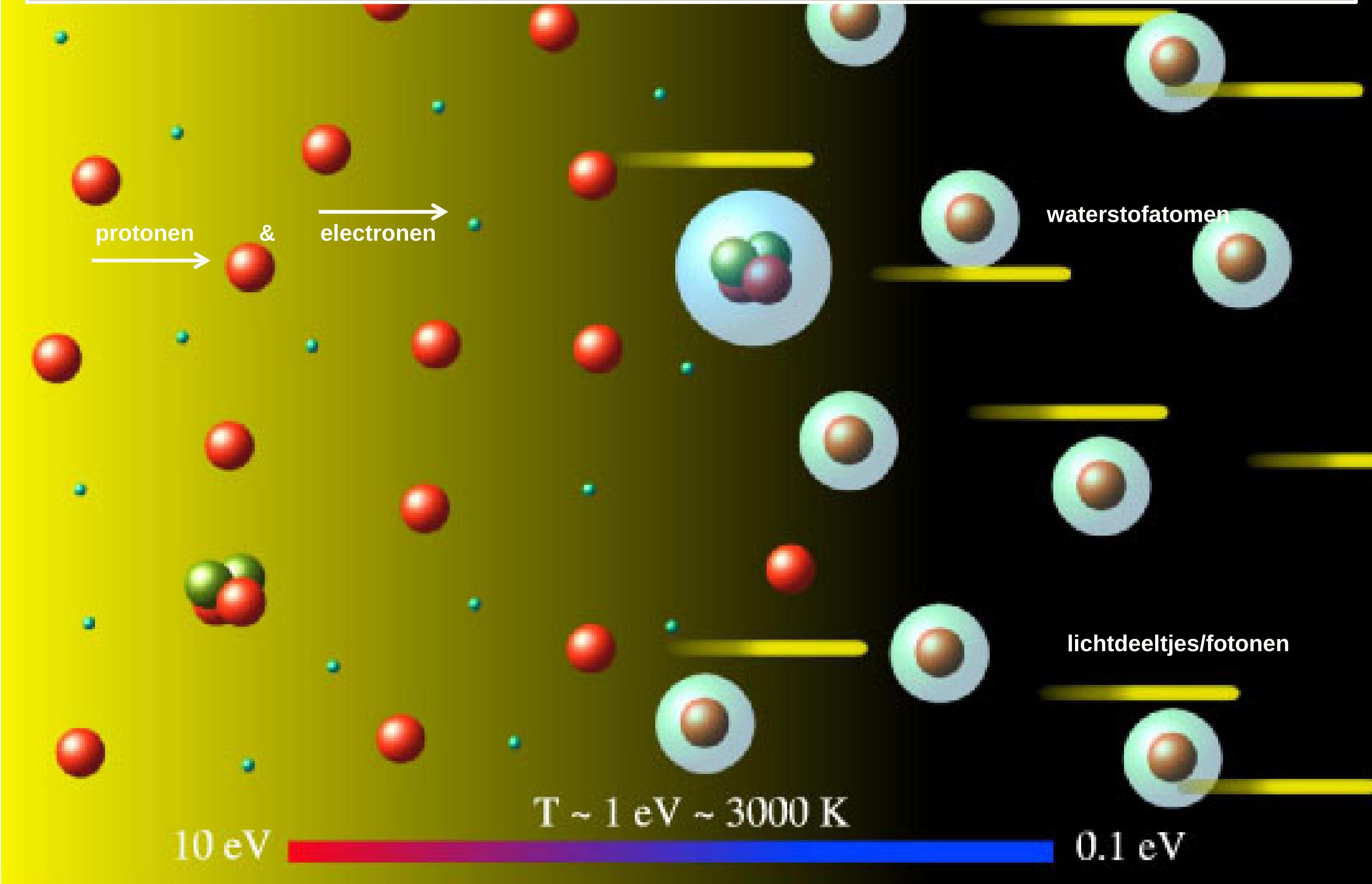
- **Ultimate evidence of the Big Bang !!!!!!!!!!!!!!!!!!!!**

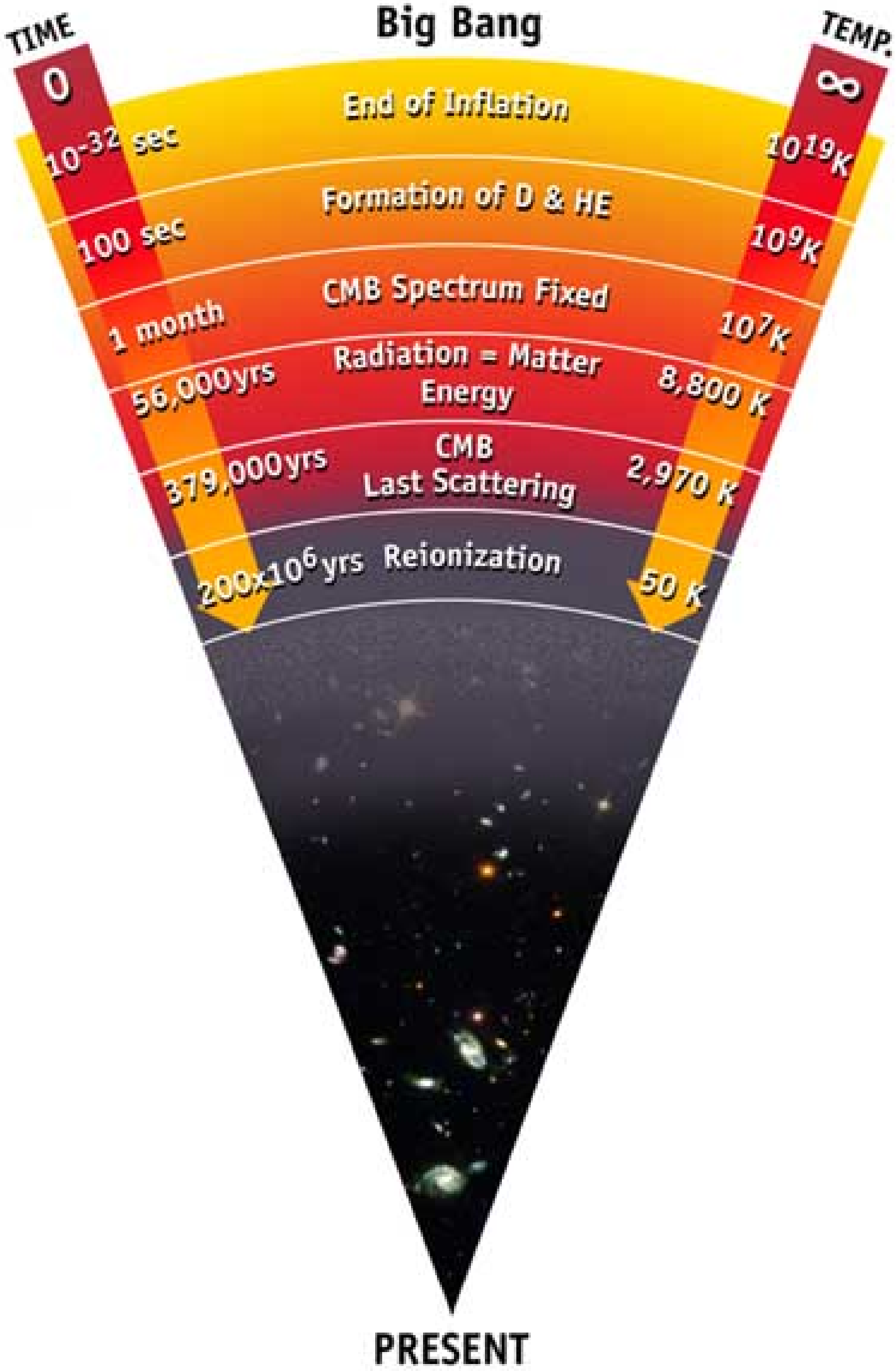
Extremely Smooth Radiation Field

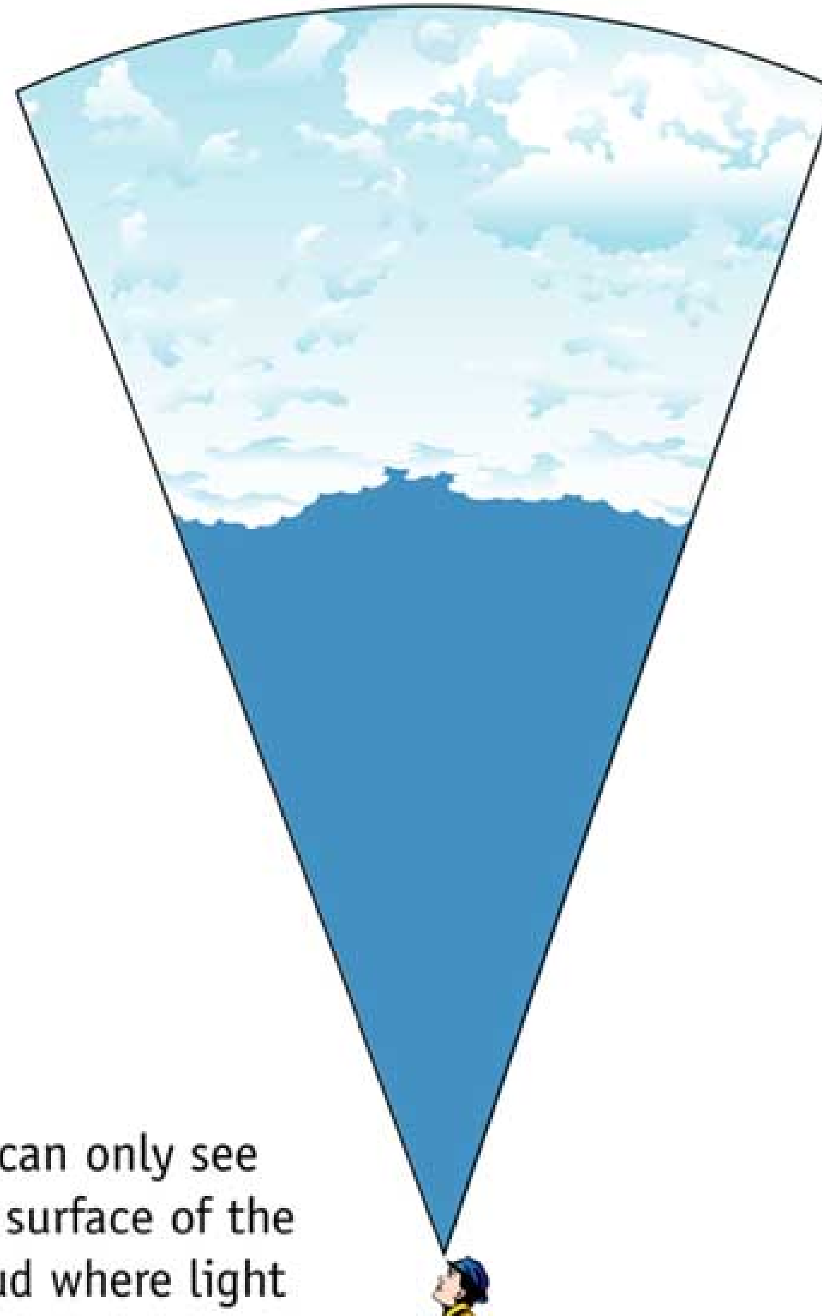
$$\frac{\Delta T}{T} < 10^{-5}$$



Recombination & Decoupling







We can only see the surface of the cloud where light

the Cosmic TV Show

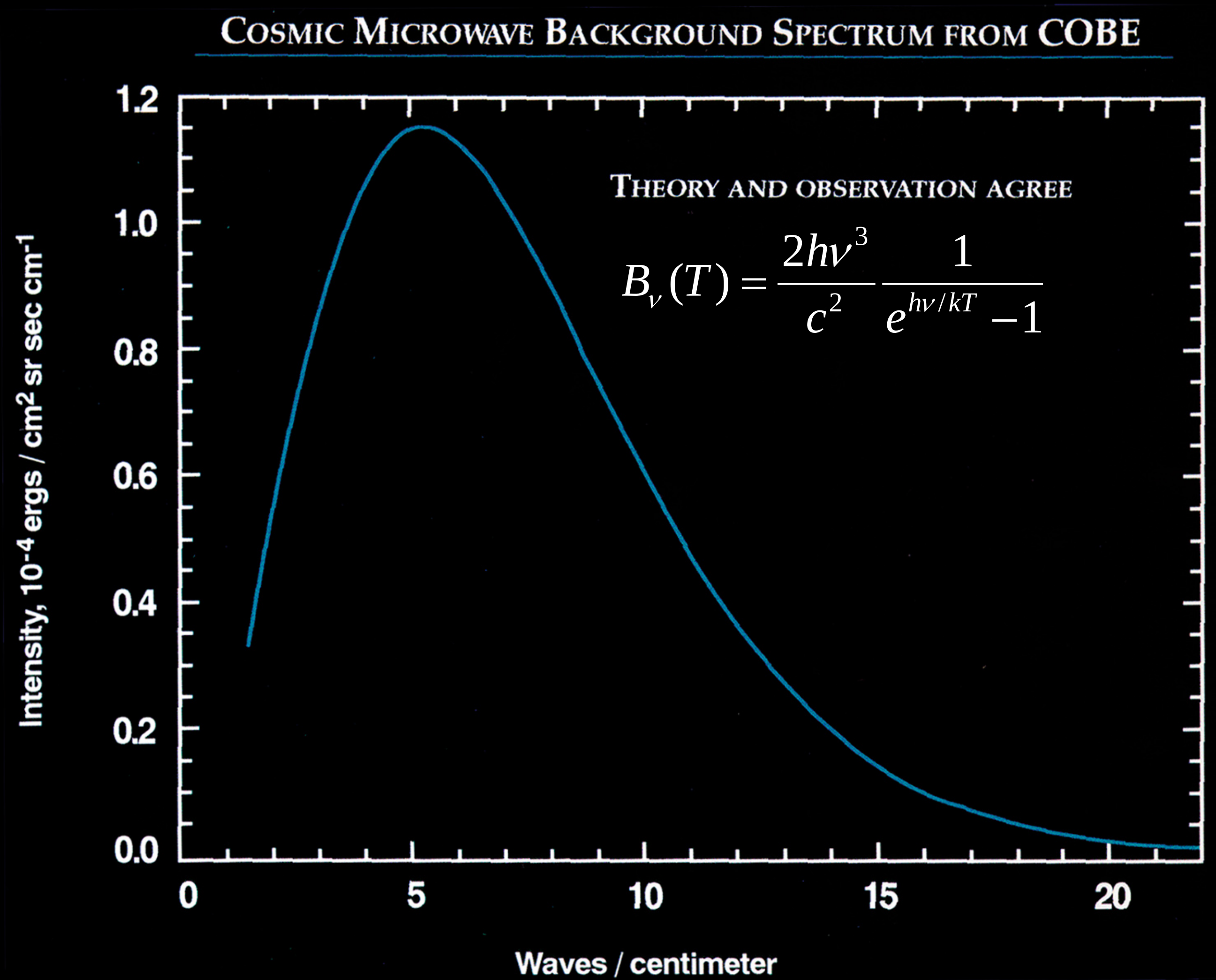
<u>Note:</u>

far from being an exotic faraway phenomenon, realize that the CMB nowadays is counting for approximately 1% of the noise on your (camping) tv set ...

!!!! Live broadcast from the Big Bang !!!!

Courtesy: W. Hu

Energy Spectrum Cosmic Light



- COBE-DIRBE:

  temperatureT = 2.725 K

- John Mather

  Nobelprize physics

  2006

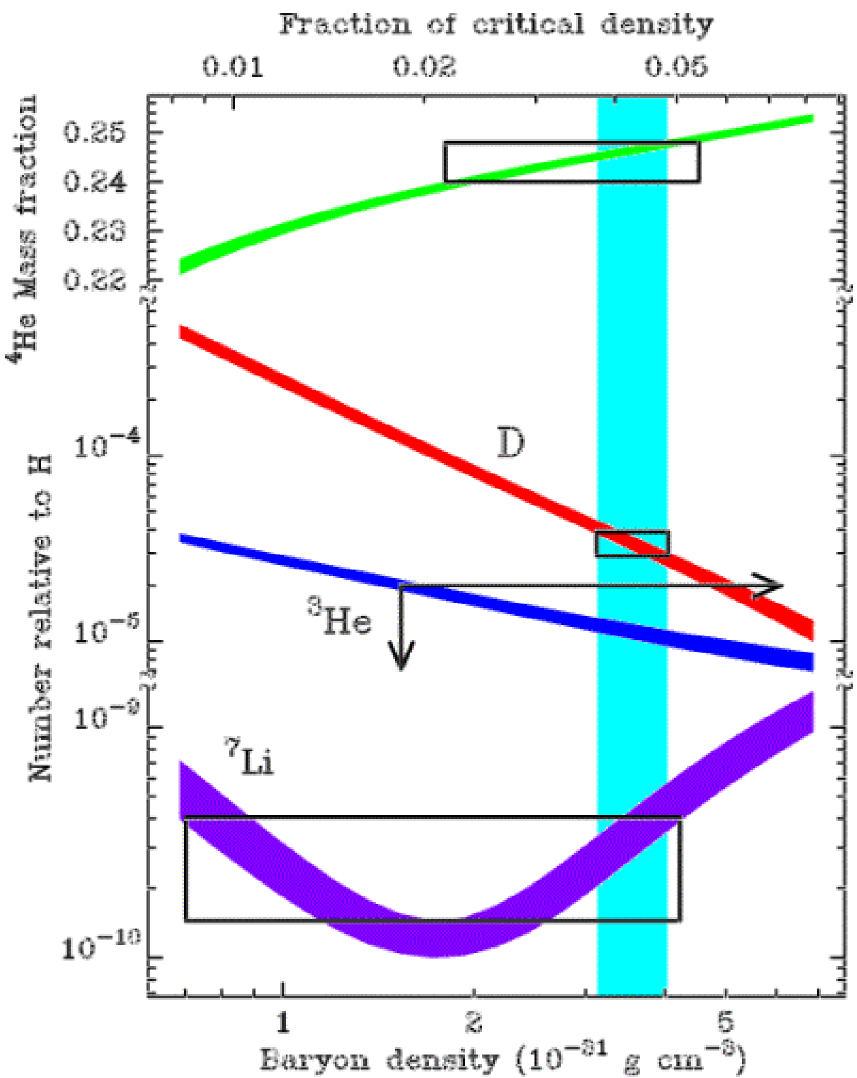
- Most perfect

  Black Body

  Spectrum ever seen !!!!

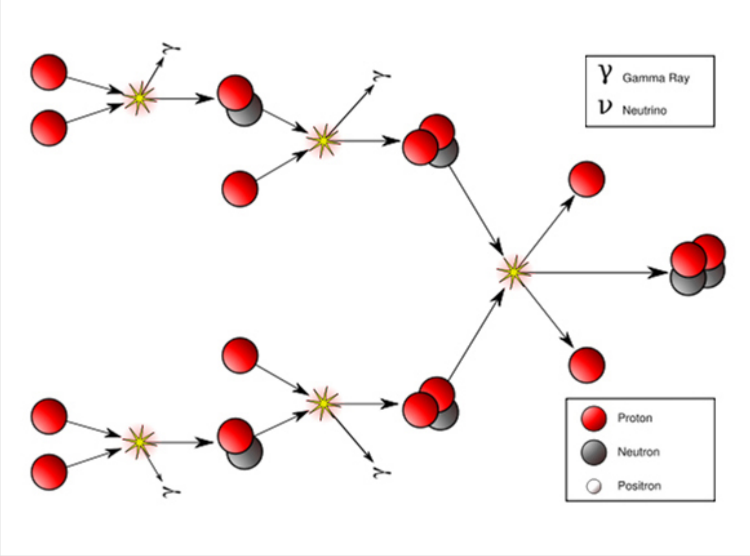
4. Proton-Neutron & Helium

p/n ~1/7: 1 min na BB



Mass Fraction Light Elements

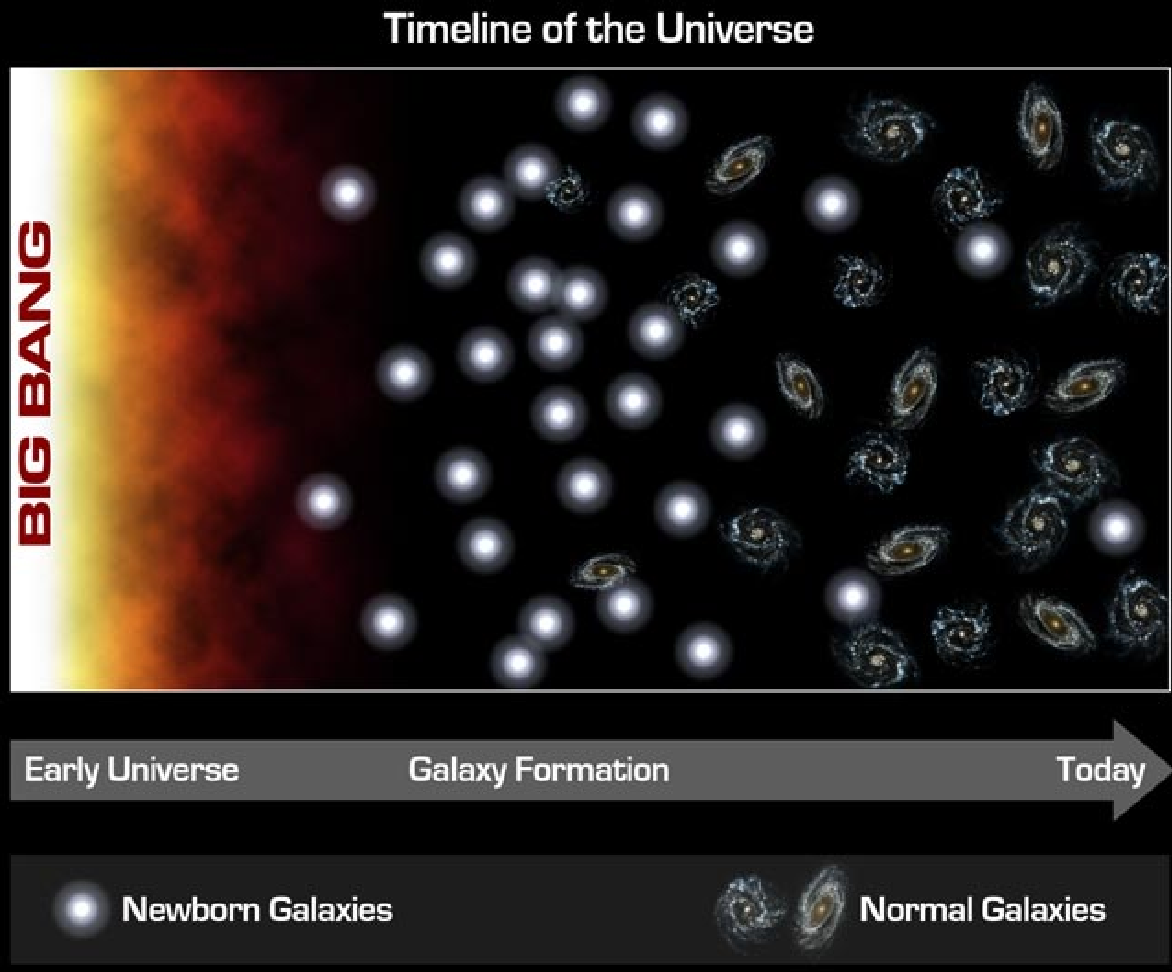
24%	^{4}He	nuclei
traces	D, ^{3}He, ^{7}Li	nuclei
75%	H	nuclei (protons)



Between 1-200 seconds after Big Bang, temperature dropped to 10^9 K:

Fusion protons & neutrons into light atomic nuclei

5. the Changing Universe

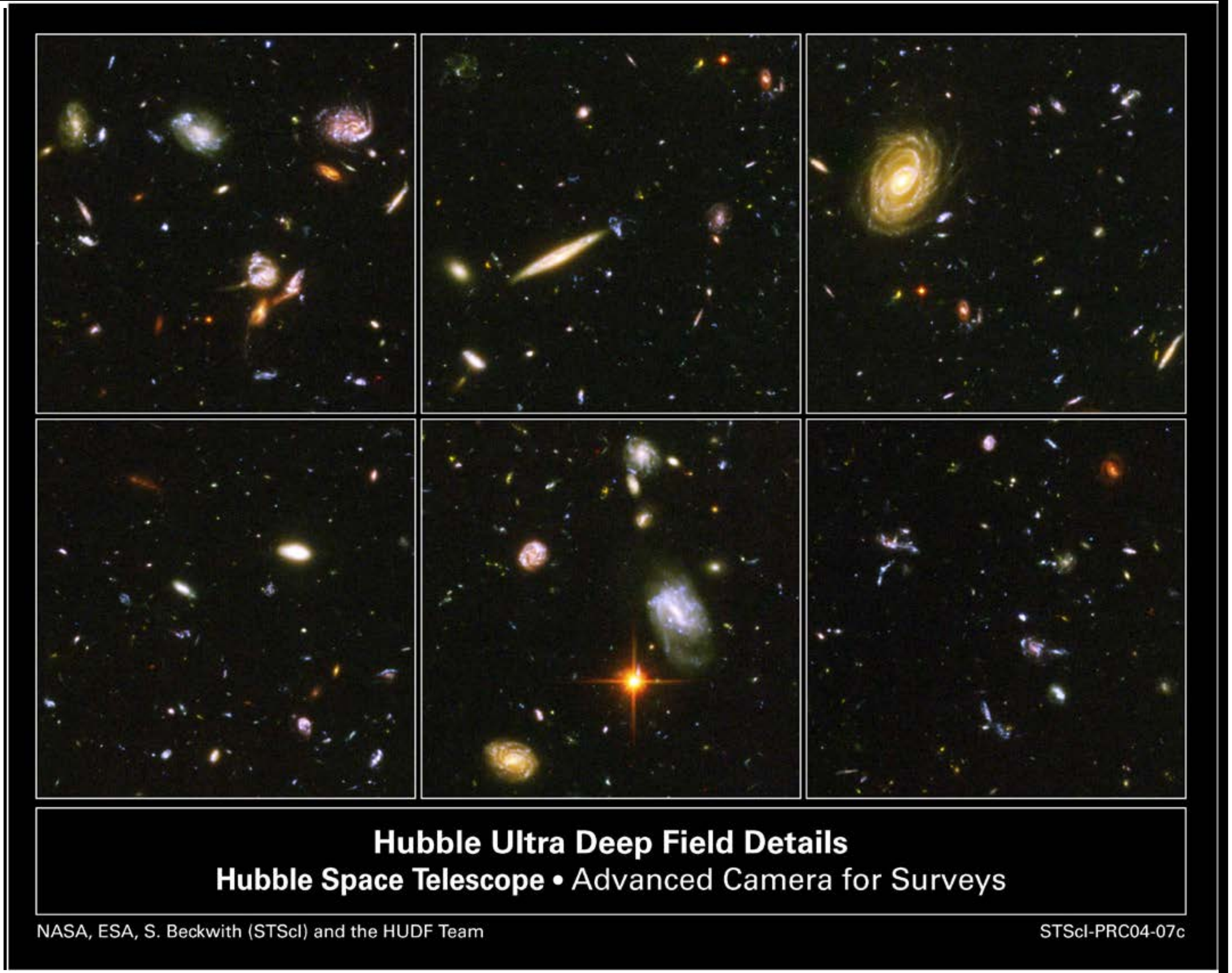


At great depths the Universe looks completely different

- and thus long ago : Depth= Time

Galaxies in Hubble Ultra Deep Field

5. the Changing Universe



At great depths the Universe looks completely different

- and thus long ago : Depth= Time

→

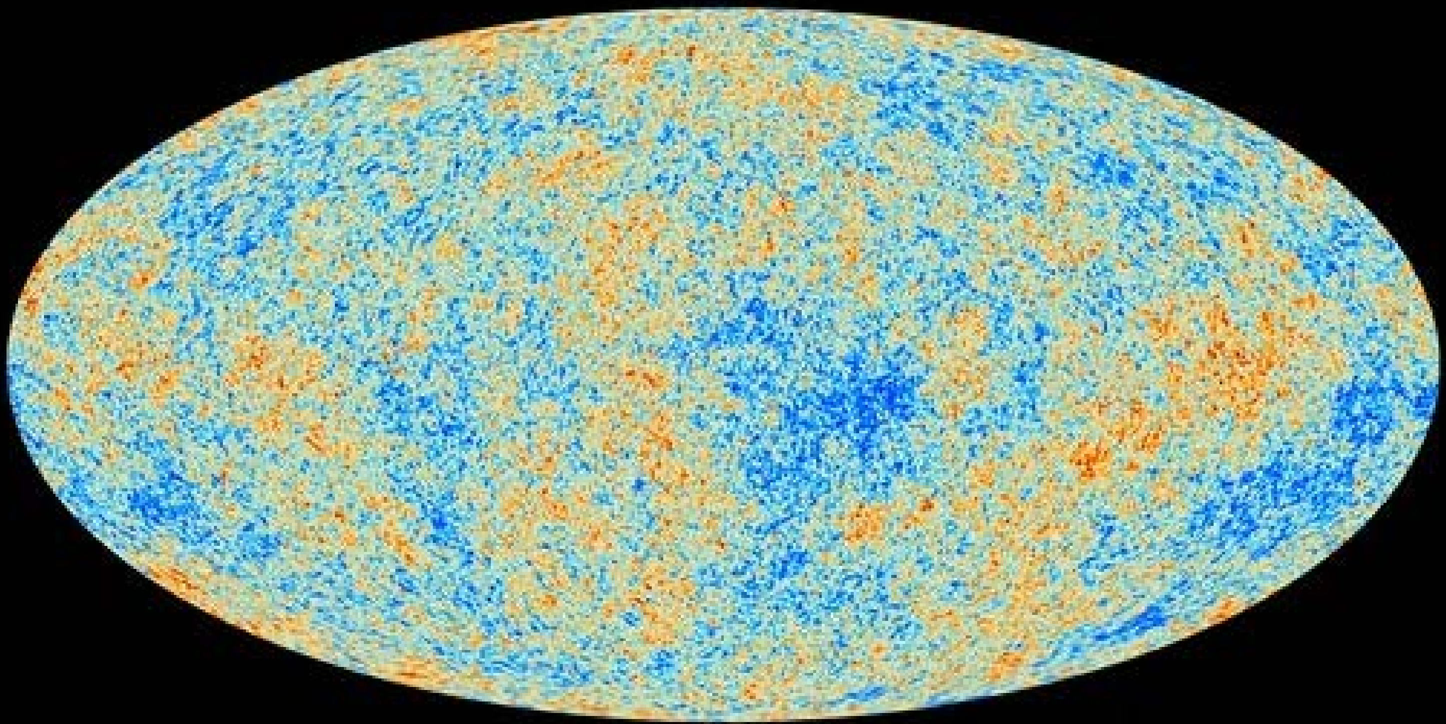
Galaxies in Hubble Ultra Deep Field

Cosmic Curvature

How Much ?

Cosmic Curvature

Cosmic Microwave Background



Map of the Universe at Recombination Epoch (Planck, 2013):

- **379,000 years after Big Bang**
- **Subhorizon perturbations: primordial sound waves**
- **$\Delta T/T < 10$-5**

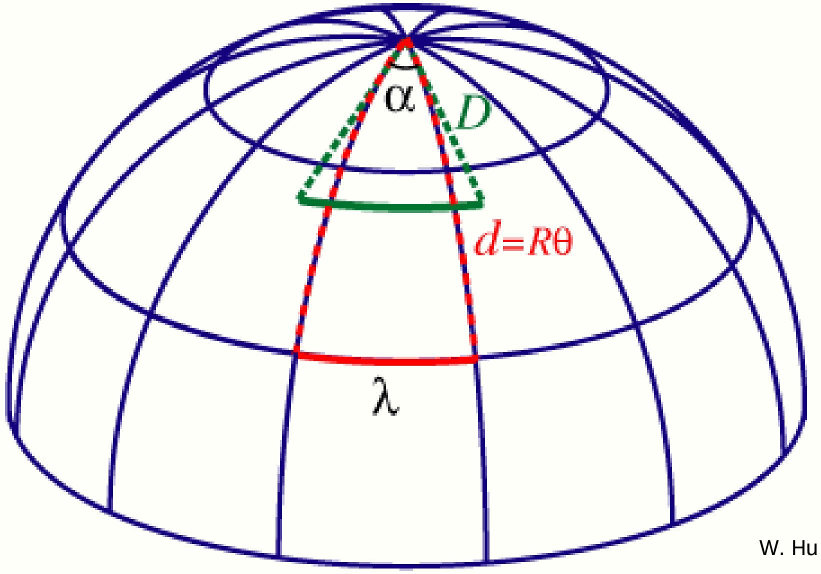
Measuring Curvature

Measuring the Geometry of the Universe:

- **Object with known physical size, at large cosmological distance**
- **Measure angular extent on sky**
- **Comparison yields light path, and from this the curvature of space**

⬇

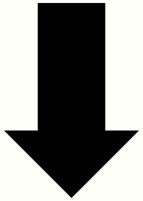
Geometry of Space



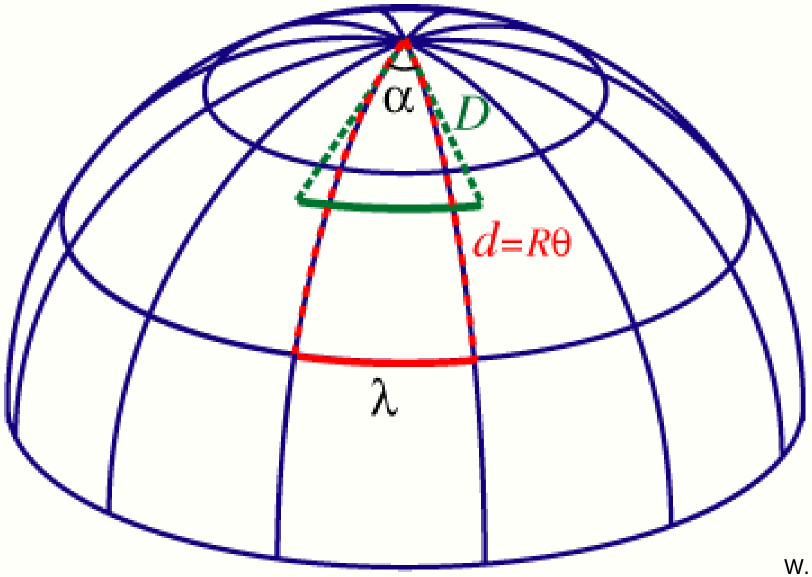
Measuring Curvature

- **Object with known physical size, at large cosmological distance:**

- **Sound Waves in the Early Universe !!!!**

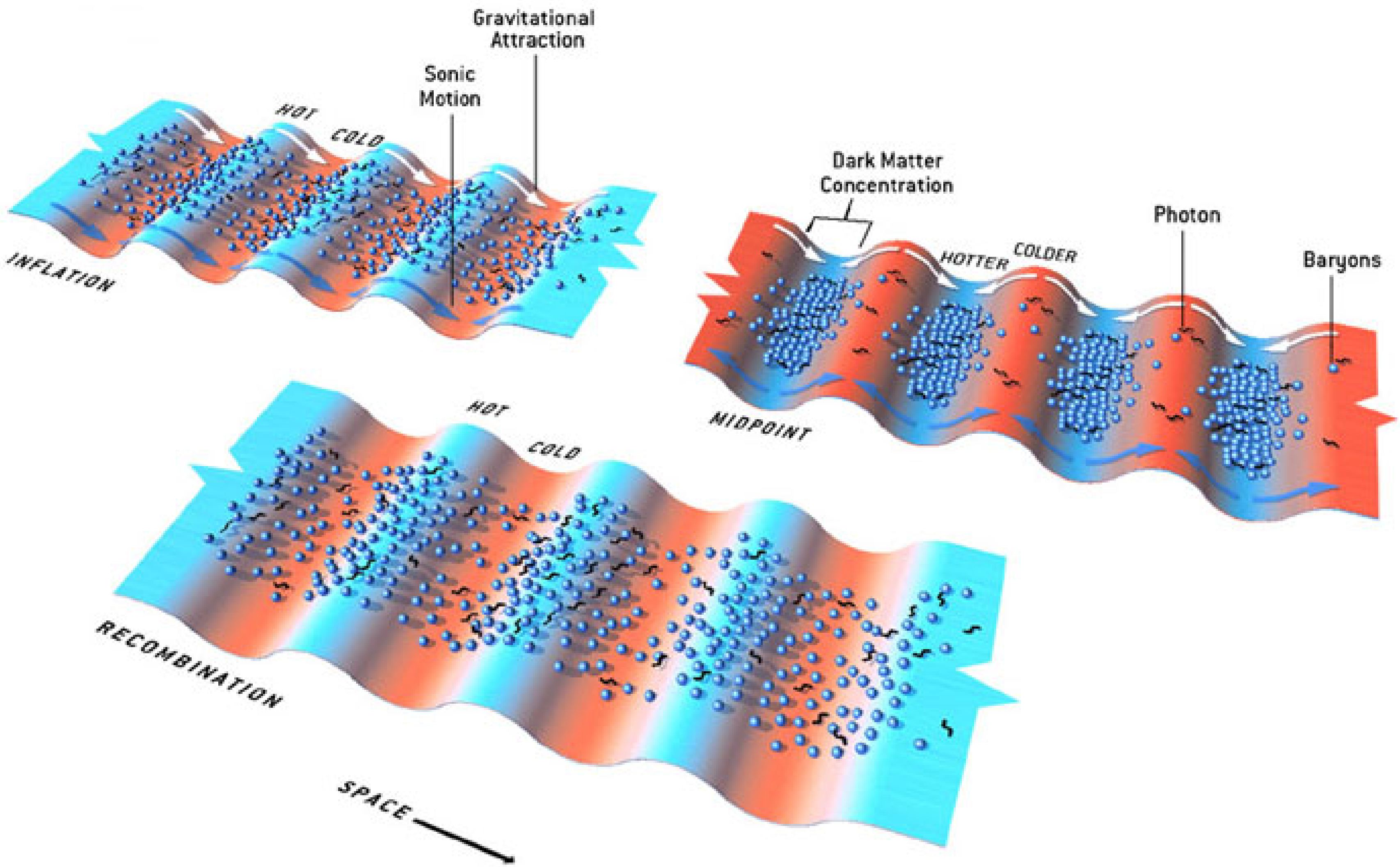


Temperature Fluctuations CMB



W. Hu

Fluctuations-Origin



Music of the Spheres

- small ripples in
  primordial matter & photon distribution
- gravity:
  - compression primordial photon gas
  - photon pressure resists

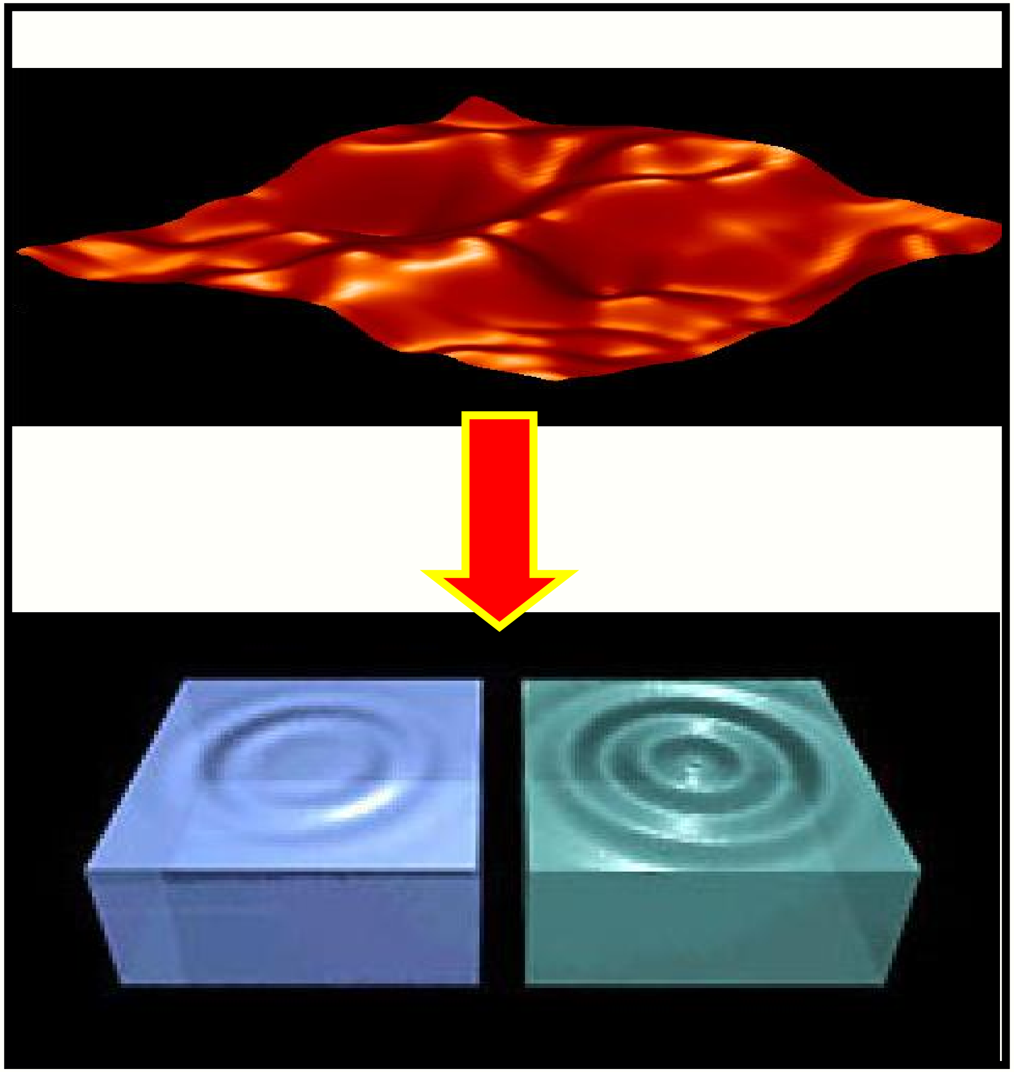
- compressions and rarefactions
  in photon gas: sound waves

- sound waves not heard, but seen:
  - compressions: (photon) T higher
  - rarefactions: lower

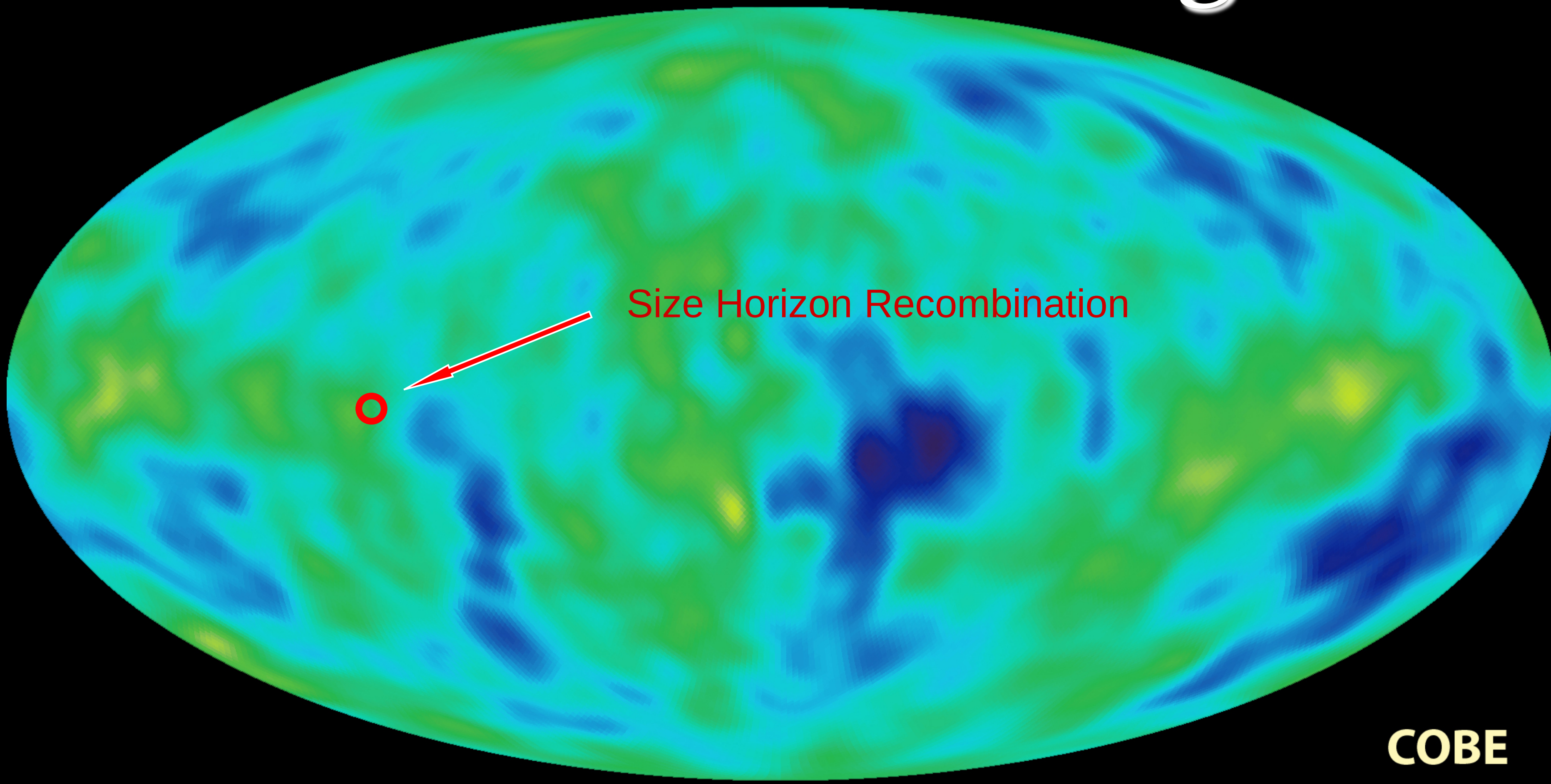
- fundamental mode sound spectrum
  - size of “instrument”:
  - (sound) horizon size last scattering

- Observed, angular size: $\theta \sim 1^{o}$
  - exact scale maximum compression, the “cosmic fundamental mode of music”

W. Hu



Cosmic Microwave Background

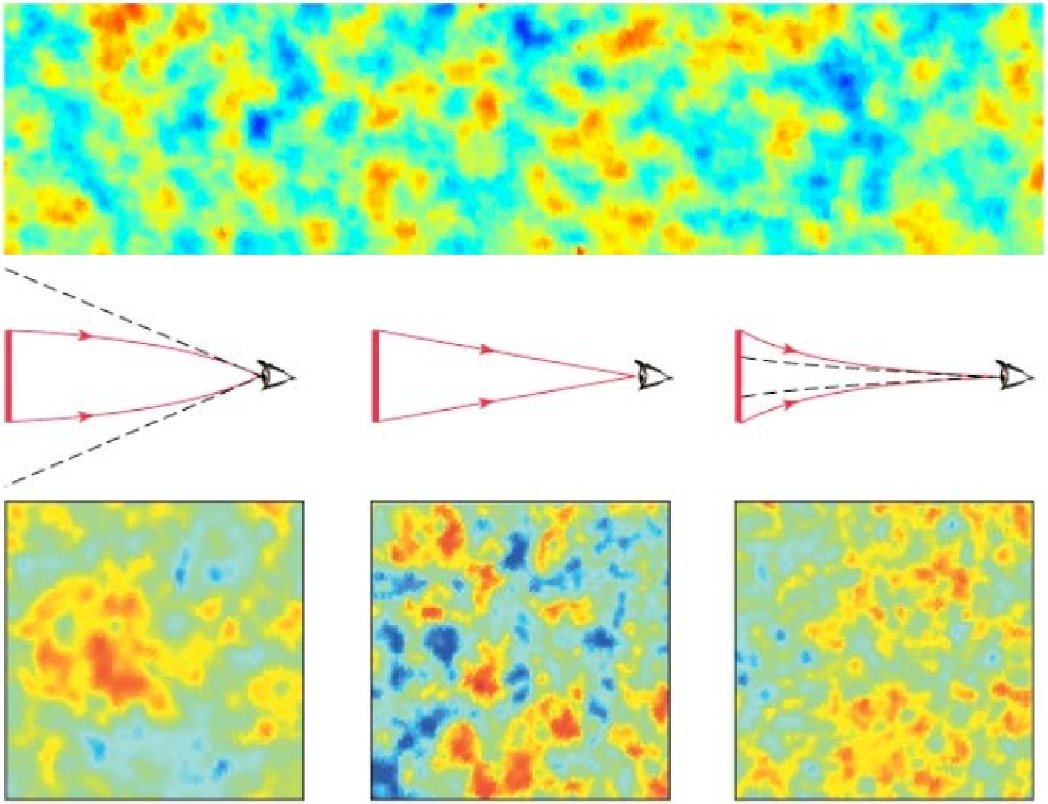


COBE measured fluctuations: $> 7^{\circ}$

Size Horizon at Recombination spans angle $\sim 1^{\circ}$

Flat universe from CMB

- **First peak: flat universe**



Closed:
hot spots
appear larger

Flat:
appear as big
as they are

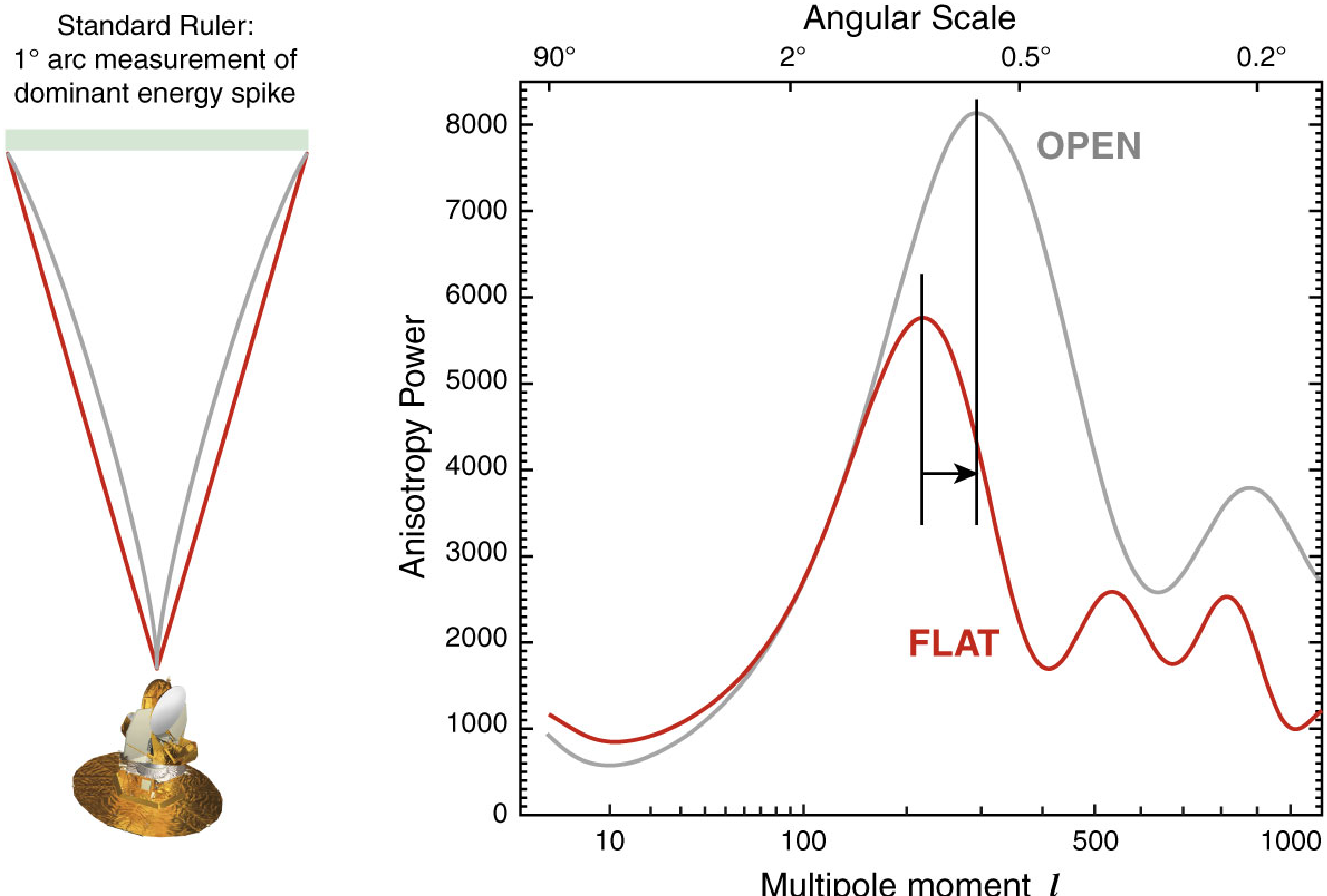
Open:
spots appear
smaller

We know the redshift and the time it took for the light to reach us:

from this we know the
- length of the legs of the triangle
- the angle at which we are measuring the sound horizon.

$$v \approx \frac{c}{\sqrt{3}}$$

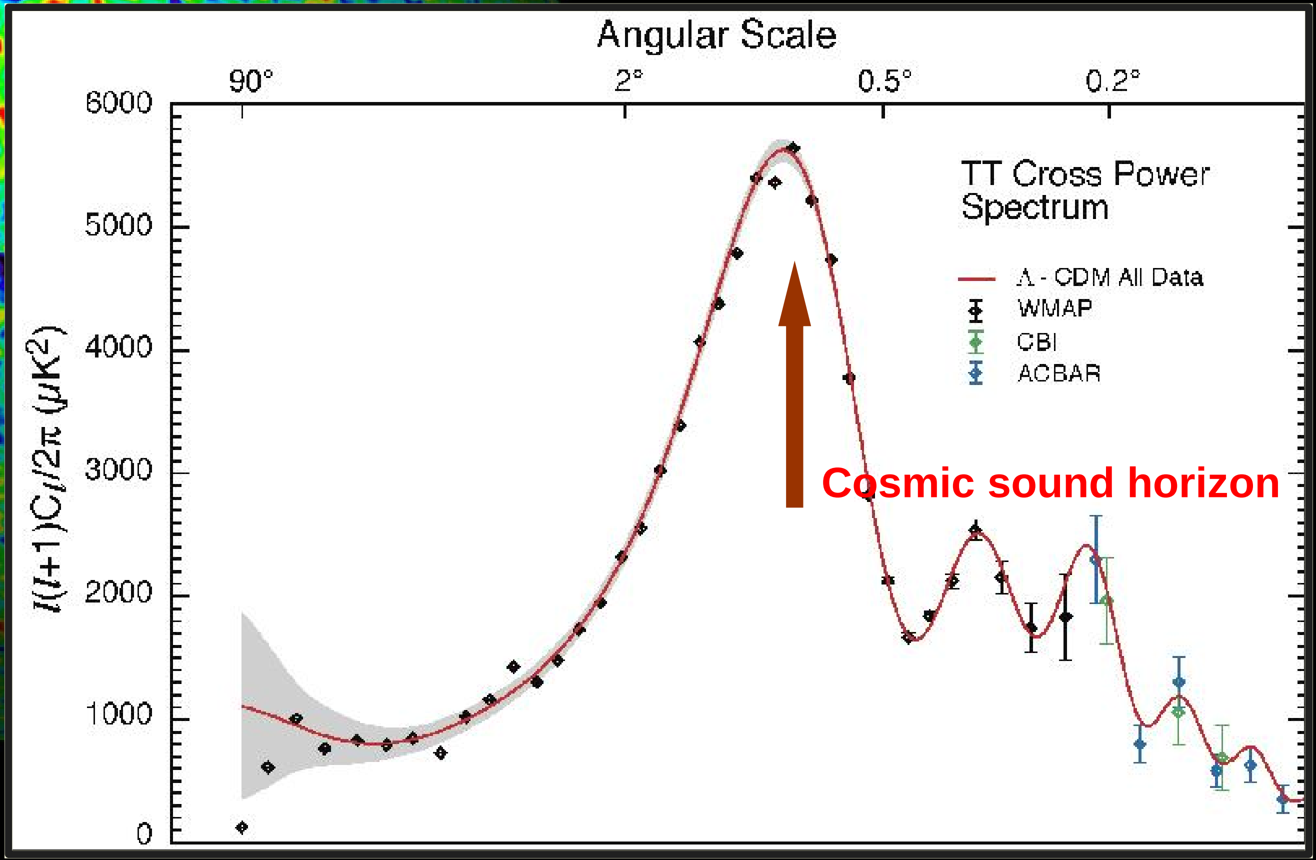
$$\ell \approx 200/\sqrt{1-\Omega_k}$$



Standard Ruler:
1° arc measurement of
dominant energy spike
Angular Scale
90°
2°
0.5°
0.2°
OPEN
FLAT
Anisotropy Power
8000
7000
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l

The Cosmic Tonal Ladder

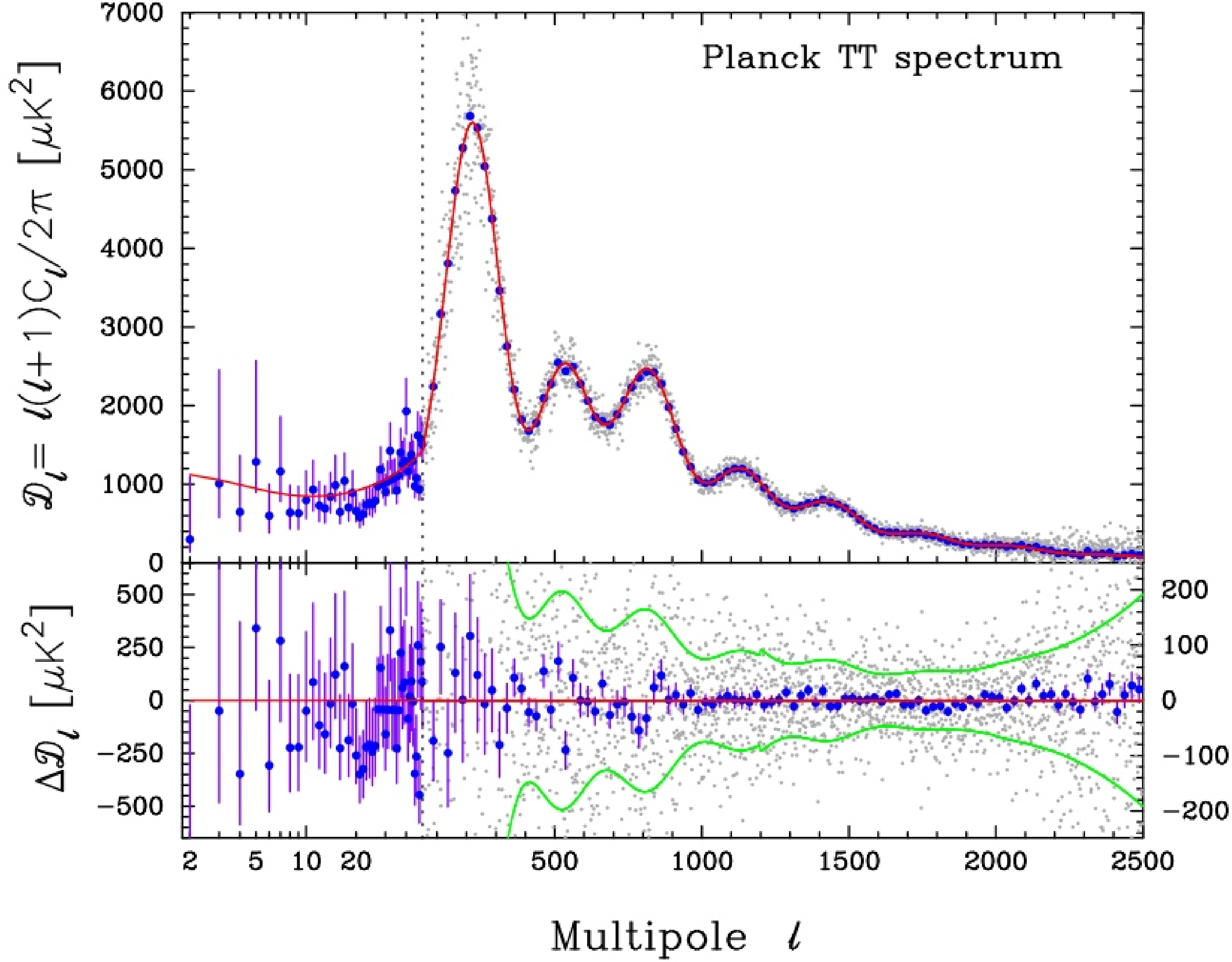
The WMAP CMB temperature power spectrum



The Cosmic Microwave Background Temperature Anisotropies:

Universe is almost perfectly FLAT !!!!

CMB - Fluctuations



Cosmic Horizons

Cosmic Horizons

Fundamental Concept for our understanding of the physics of the Universe:

- Physical processes are limited to the region of space with which we are or have ever been in physical contact.

- What is the region of space with which we are in contact ?
  Region with whom we have been able to exchange photons
  (photons: fastest moving particles)

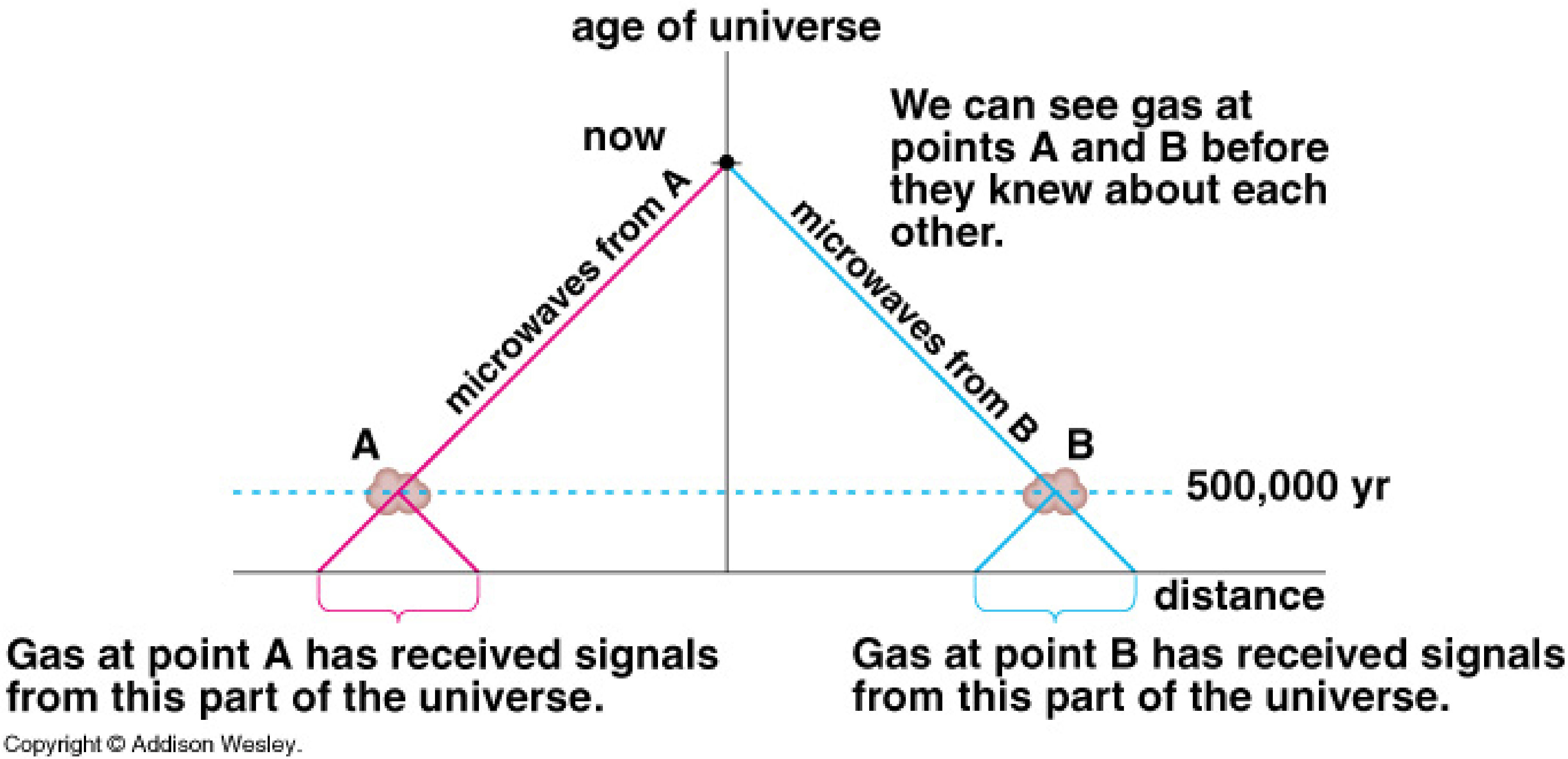
- From which distance have we received light.

- Complication: - light is moving in an expanding and curved space
  - fighting its way against an expanding background

- This is called the

Horizon of the Universe

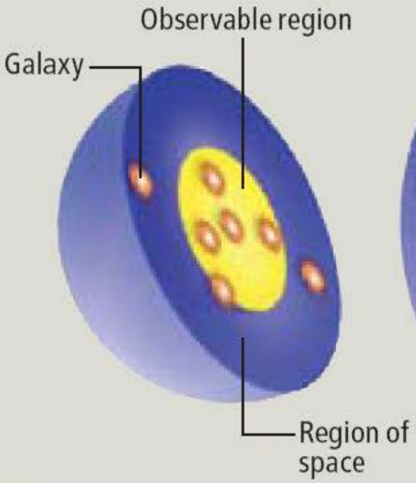
Cosmic Horizons



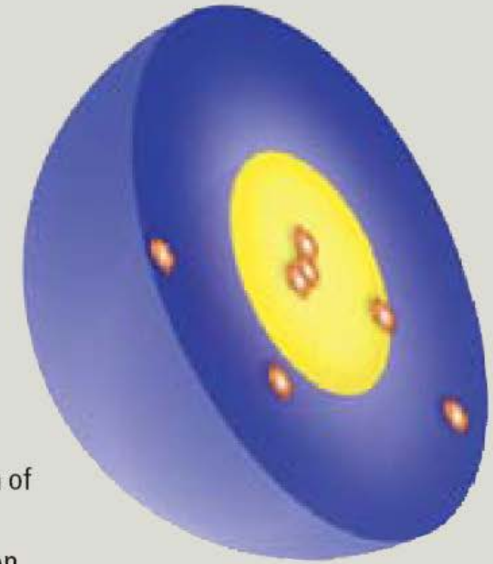
Horizon of the Universe:
distance that light travelled since the Big Bang

EXPANDING UNIVERSE, SHRINKING VIEW

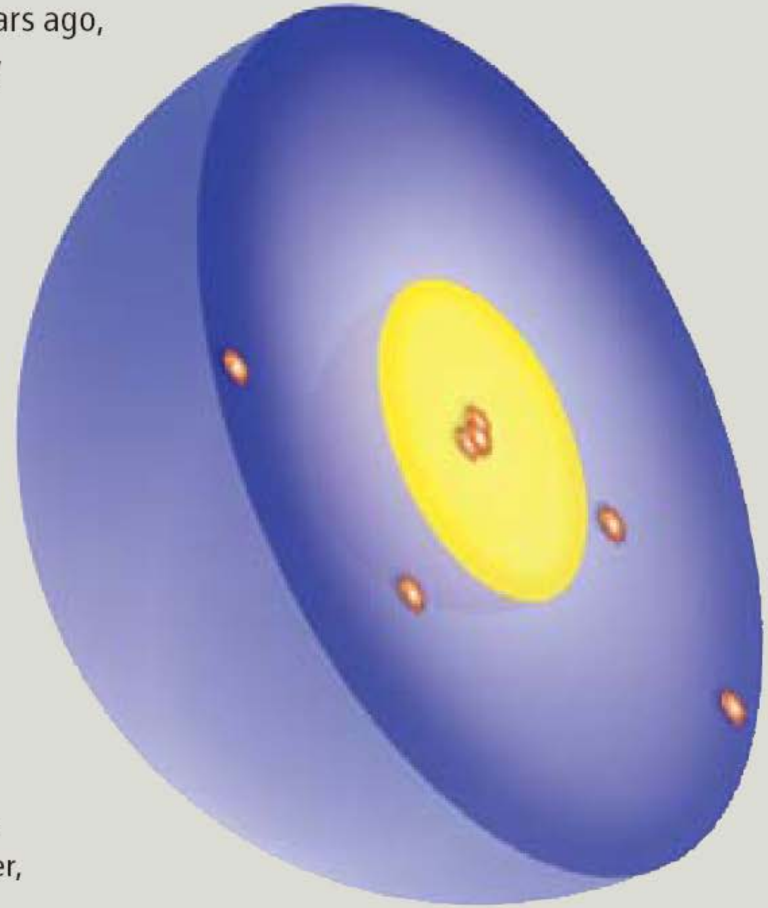
The universe may be infinite, but consider what happens to the patch of space around us (*purple sphere*), of which we see only a part (*yellow inner sphere*). As space expands, galaxies (*orange spots*) spread out. As light has time to propagate, we observers on Earth (or our predecessors or descendants) can see a steadily increasing volume of space. About six billion years ago, the expansion began to accelerate, carrying distant galaxies away from us faster than light.



1 At the onset of acceleration, we see the largest number of galaxies that we ever will.



2 The visible region grows, but the overall universe grows even faster, so we actually see a smaller fraction of what is out there.



3 Distant galaxies (those not bound to us by gravity) move out of our range of view. Meanwhile, gravity pulls nearby galaxies together.

NOTE:
Because space is expanding uniformly, alien beings in other galaxies see this same pattern.

Cosmic Future

Cosmic Fate

100 Gigayears:
the end of Cosmology