Kozmologija

"veda o kozmosu"

- sestava vesolja
- struktura
- izvor
- razvoj
- končna usoda

- religiozna/filozofska vprašanja -> znanstvena
- fizika zelo majhnega + zelo velikega

Kopernikanski princip – nimamo posebnega položaja v vesolju

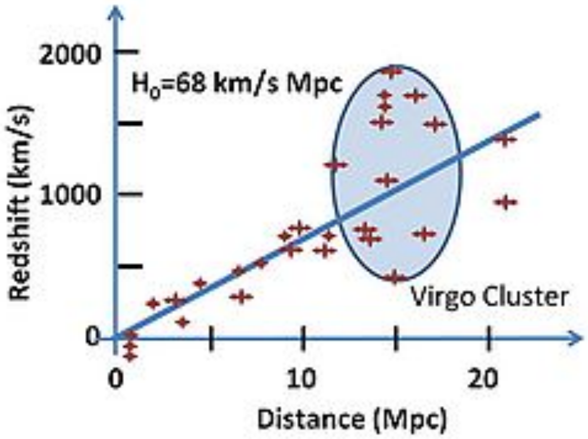
Kaj vemo o vesolju?

- snov
- sevanje
- uniformno vesolje
- vesolje se širi

Olbersov paradoks

- najenostavnejše kozmološko opazovanje: nočno nebo je temno
- neskončno, nespremenljivo vesolje -> svetlo nebo
- 2D analogija:

oddaljevanje galaksij, vesolje se širi



$\propto d$

Edwin Powell Hubble (1889 -1953)

Hubblov zakon (1929):

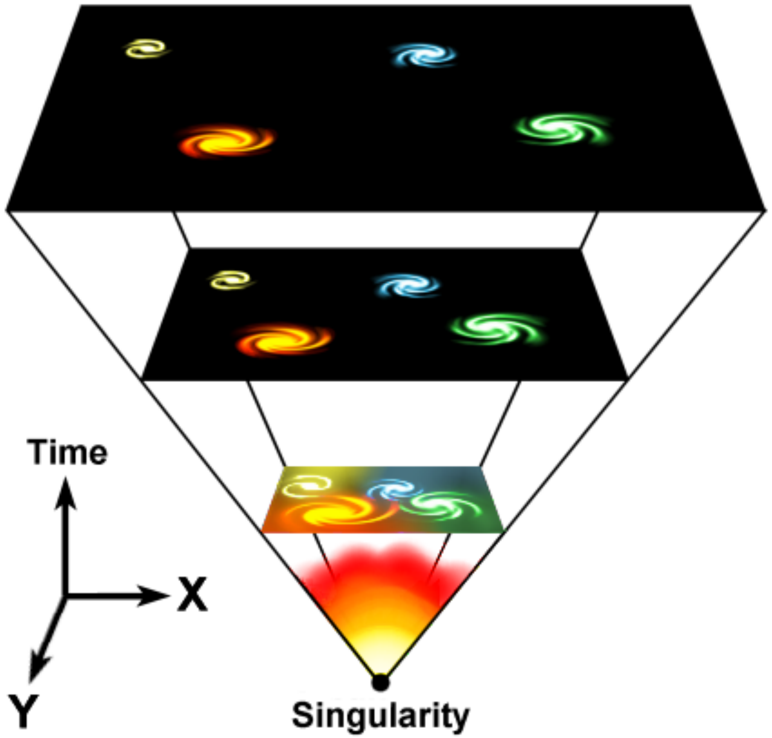
$v = H\ d$

(danes: za $z<0.2$: $z=(H/c)d$)

Prva opazovalna podpora teorije Velikega poka

Veliki pok

- 1927



Georges Lemaître (1894 – 1966)

fizika in matematični modeli

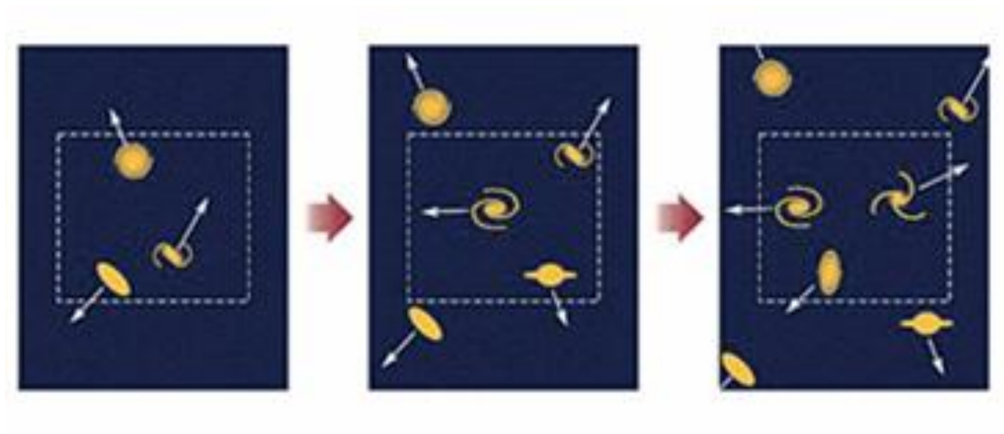
- Einsteinova splošna relativnost
- Kozmološki princip:
- Homogeno in izotropno vesolje
- Friedmannove enačbe

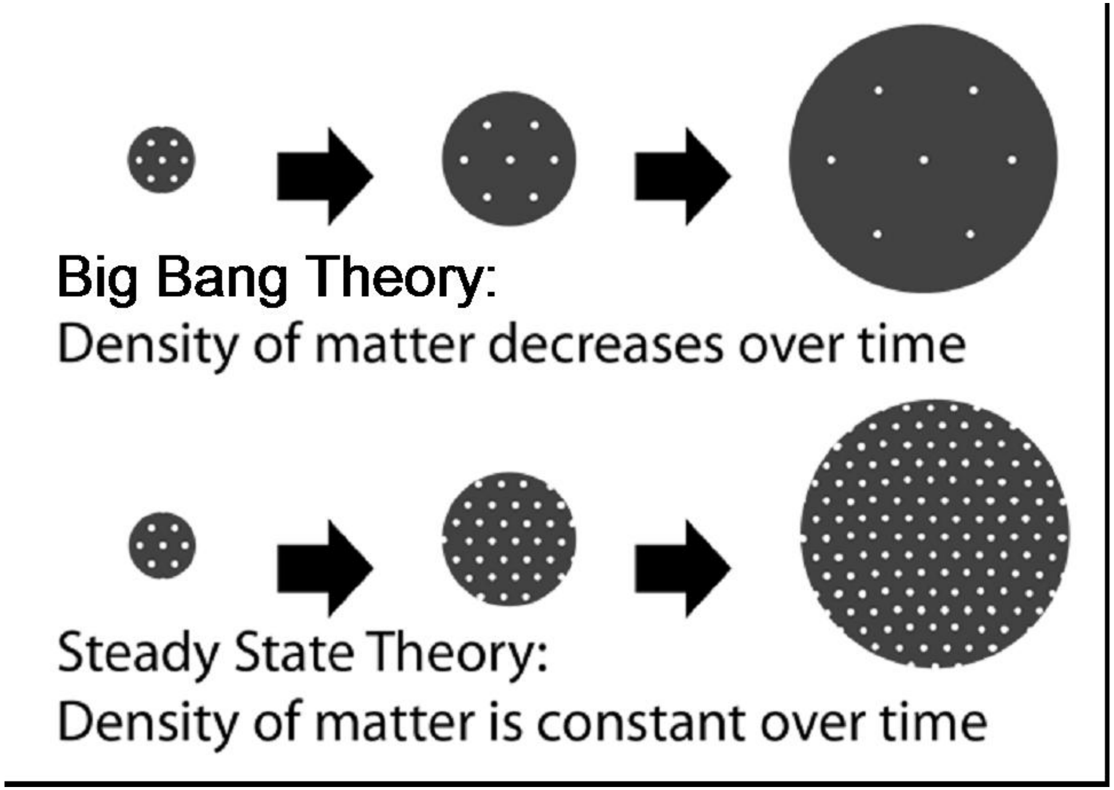
- opis vesolja od Velikega poka naprej

- Fred Hoyle – 1949

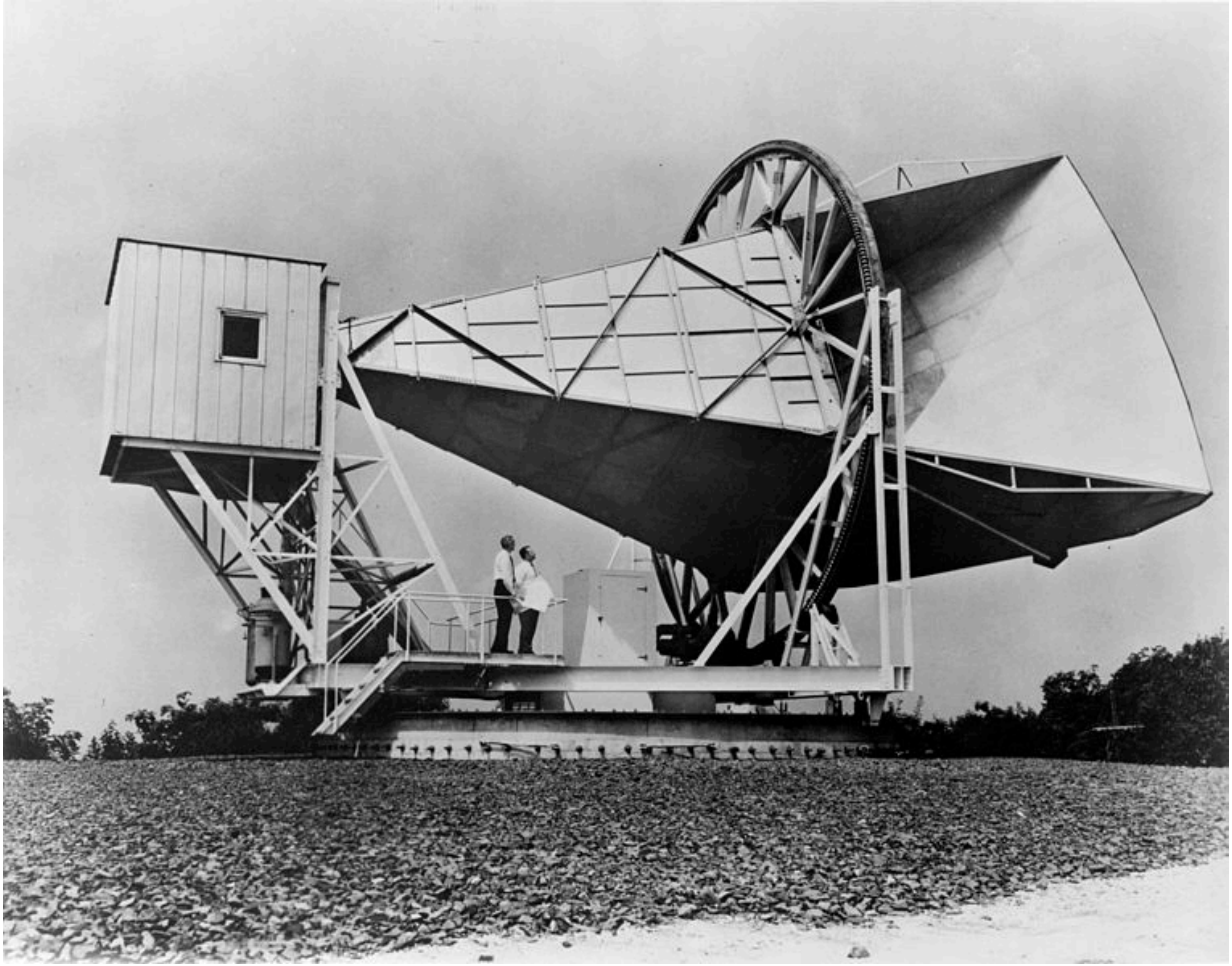
Alexander Friedman
(1888 – 1925)

Sir Fred Hoyle
(1915 - 2001)

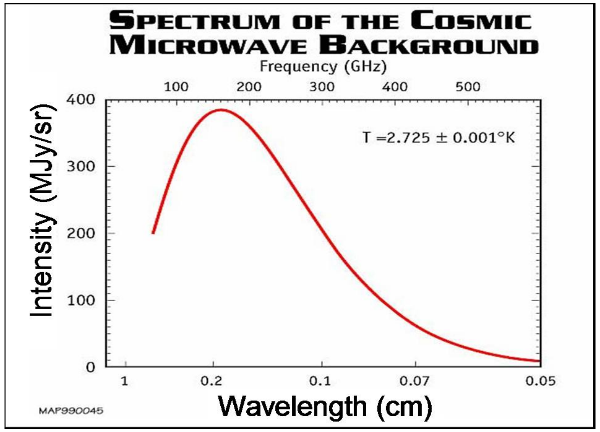


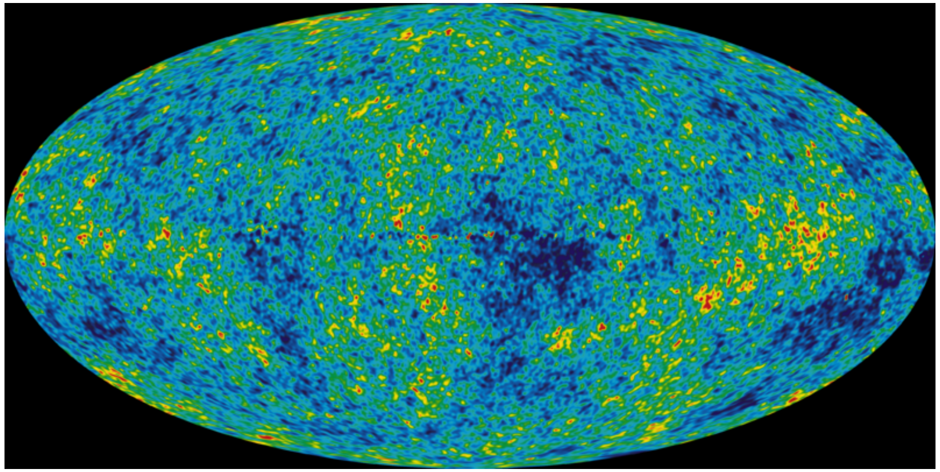


vesolje je
izotropno in homogeno
v prostoru in času

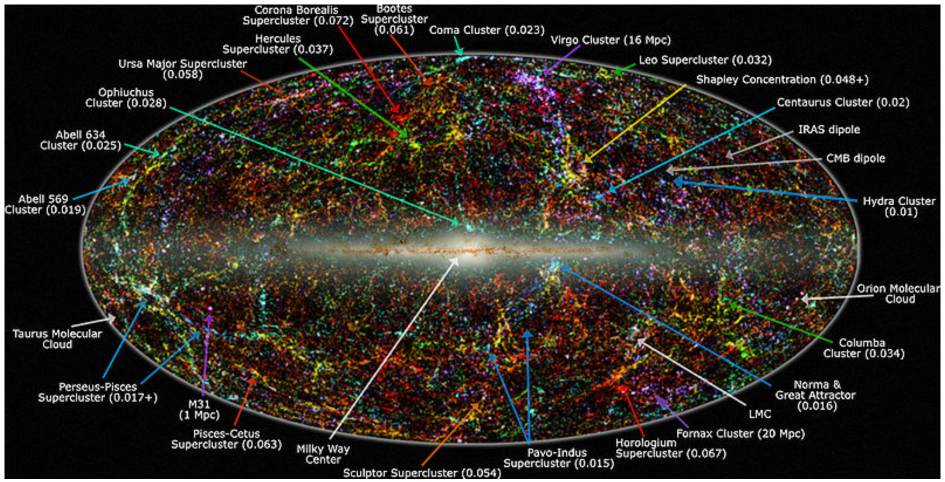


- 1964 – Arno Penzias and Robert Wilson - odkritje prasevanja – CMB – mikrovalovno sevanje ozadja s T=2.725 K

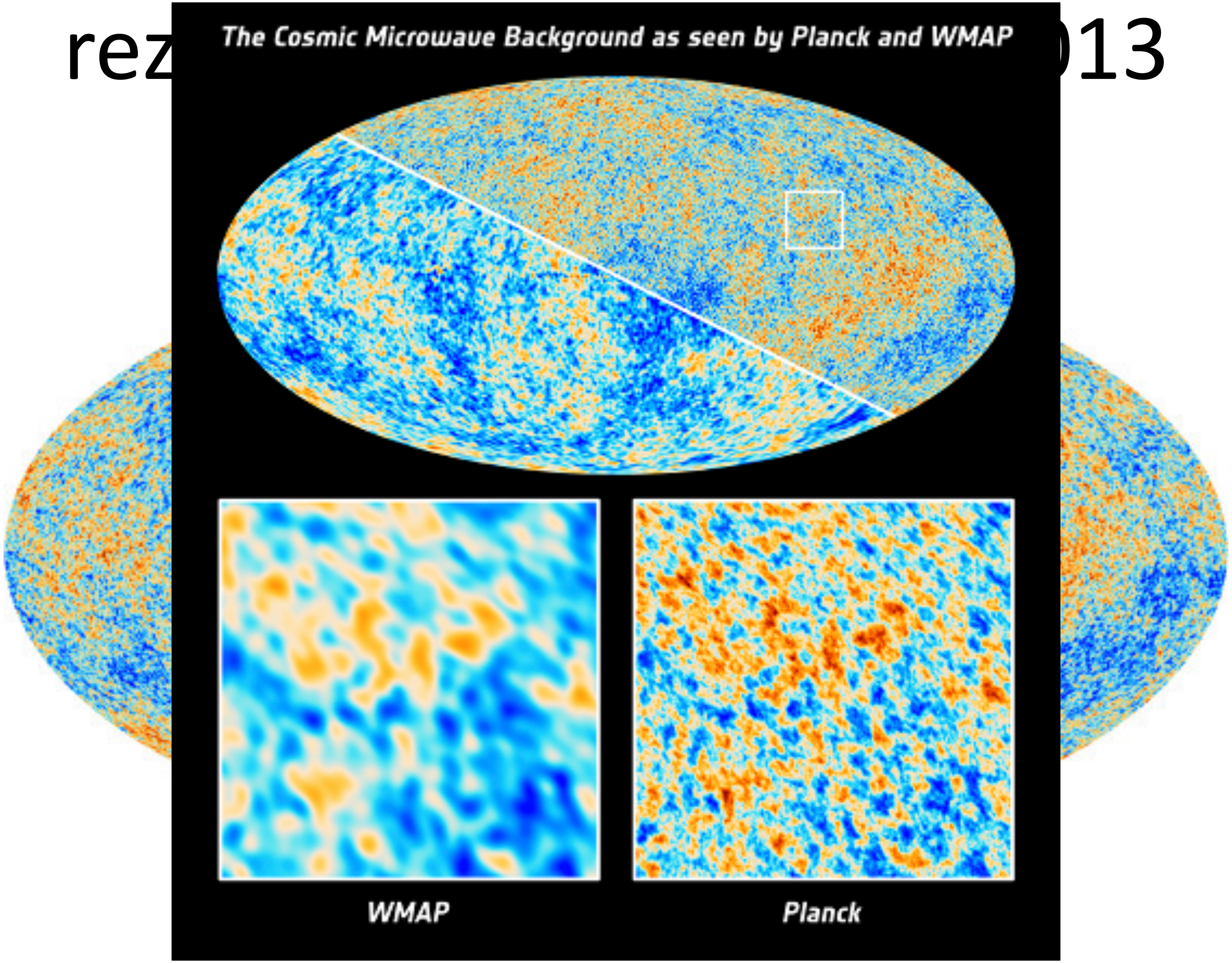




- Porazdelitev in razvoj galaksij



rez 013



The Cosmic Microwave Background as seen by Planck and WMAP
WMAP
Planck

- http://sci.esa.int/science-e-media/video/64/571_Planck_CMB_with_foreground_emission_layers.mov

Prapok

- širjenje, prasevanje – nekoč manjše, vroče
- t=0
- v pospeševalnikih: $T<10^{15}$K, $t>10^{-9}$ s
- Planckova razdalja in čas:

$d_{Planck}= (Gh/2\pi c^3)^{1/2}=1.6\times10^{-35}$ m

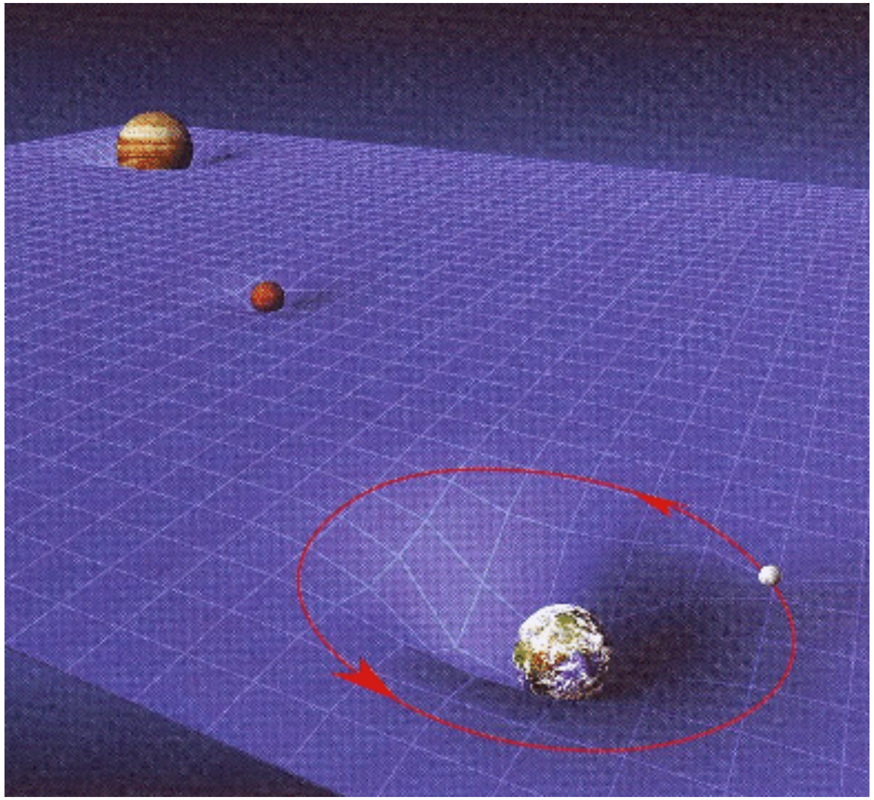
$t_{Planck}=(Gh/2\pi c^5)^{1/2}=5.4\times10^{-44}$ s

- kvantna fizika (standardna teorija delcev)
- splošna teorija relativnosti
- nimamo še kvantne gravitacije

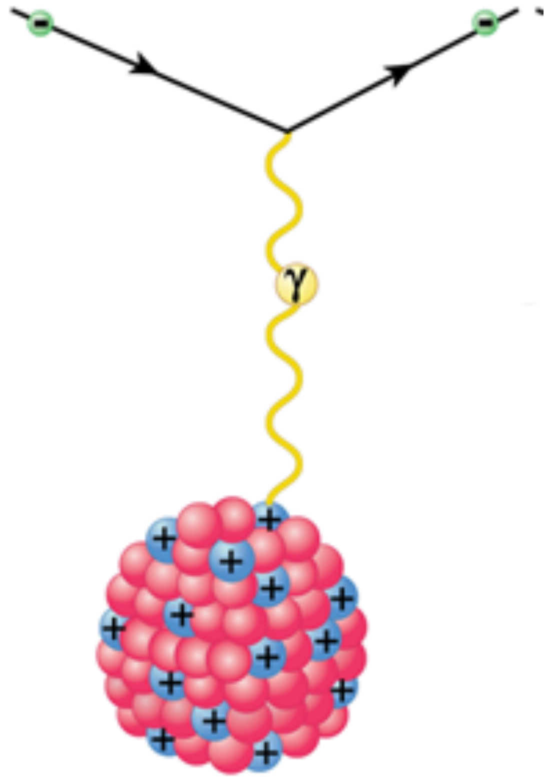
4 sile

- gravitacijska: dolgega dosega; med Zemljo in Soncem, galaksijami itd.
- splošna teorija relativnosti:

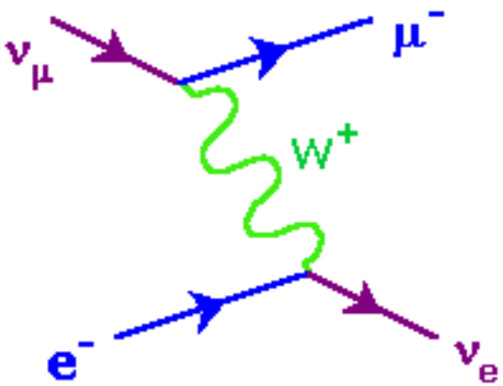
ukrivljanje prostor-časa

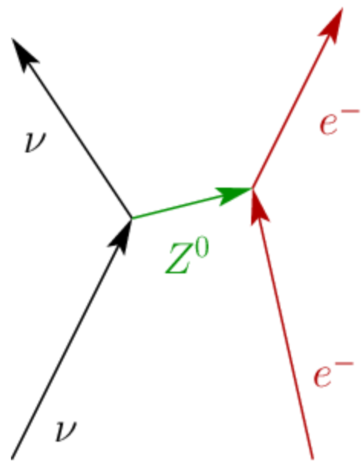


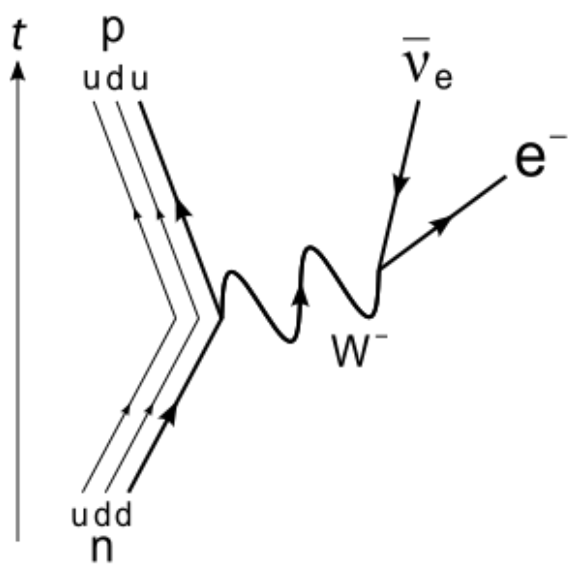
- elektromagnetna: dolgega dosega, med nabitimi delci, drži e^- vezane v atomih
- standardni model: izmenjava fotonov



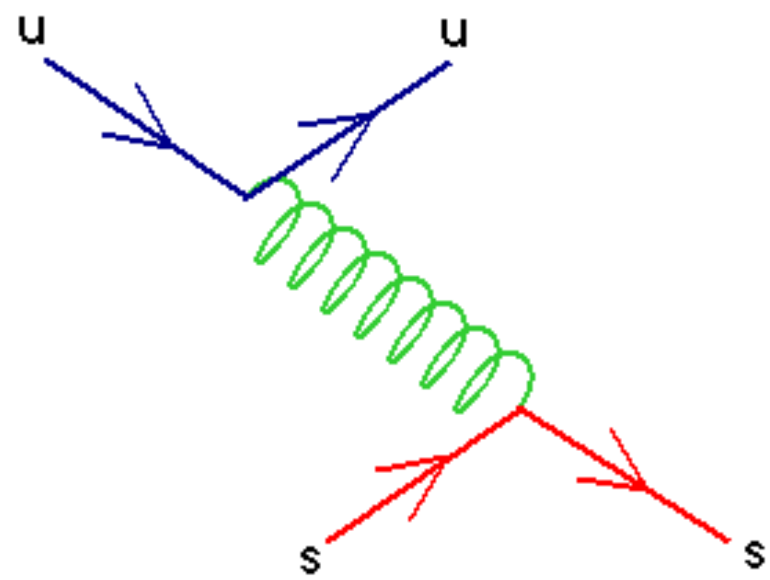
- šibka: kratkega dosega, odgovorna za β razpad ($n \rightarrow p + e^- + \text{anti-}\nu_e$)
- standardni model: izmenjava šibkih bozonov Z^0, W^+, W^-



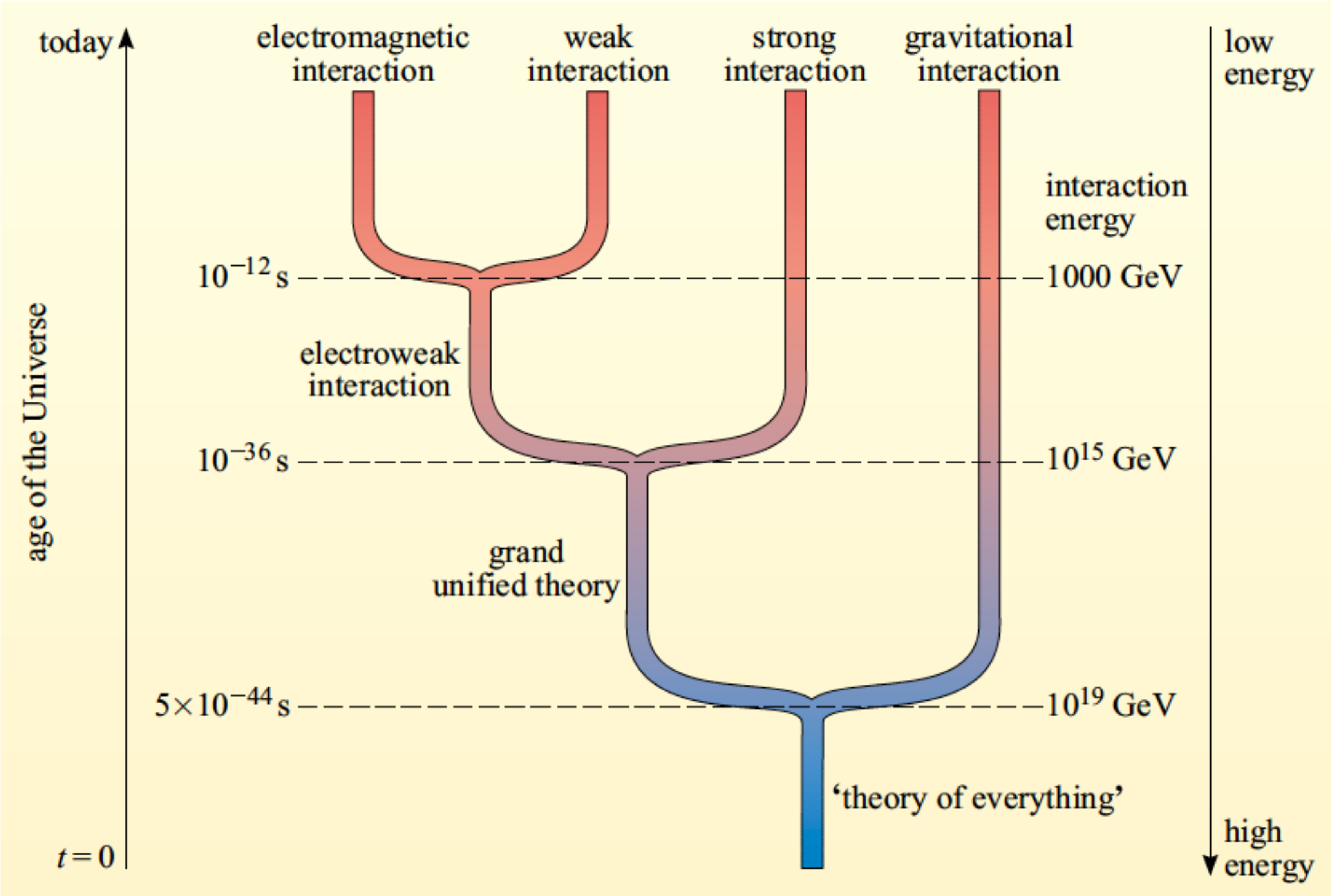




- močna: kratkega dosega, med kvarki, drži p in n v atomskem jedru
- standardni model: izmenjava gluonov



teorija vsega in poenotenje



tvorba parov delec-antidelec

$E=kT$

$E \geq 2mc^2$

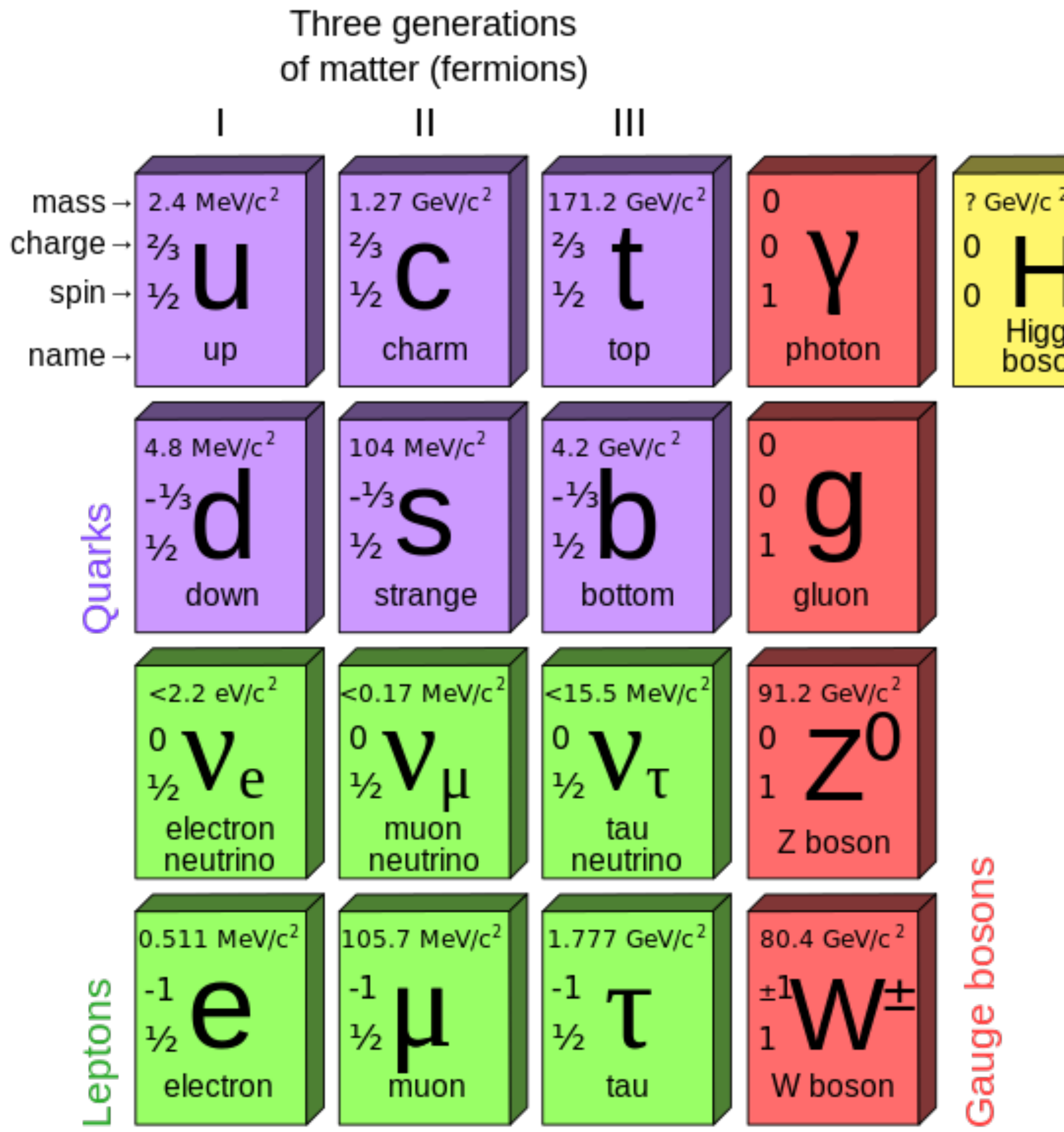
Primer:

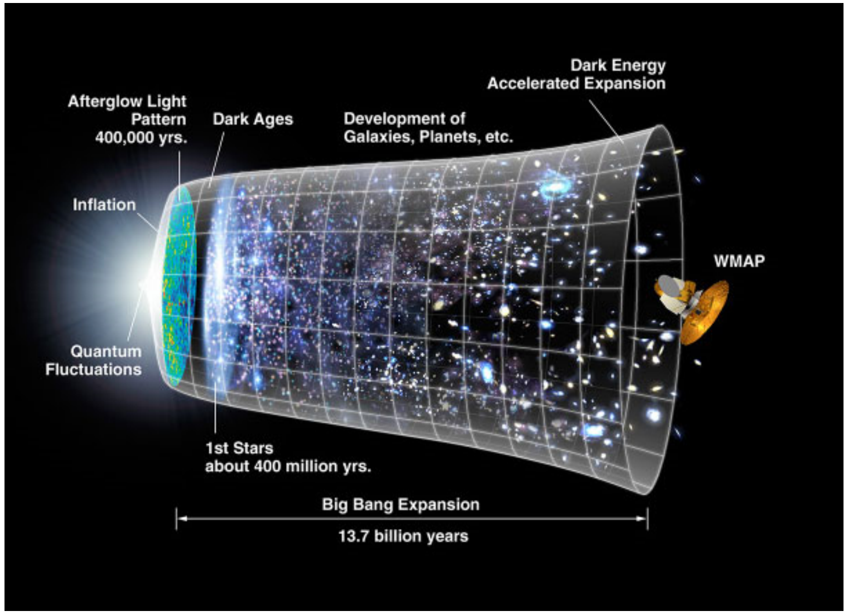
$t \approx 10^{-12}$ s, $T \approx 10^{16}$ K:

$E \approx 10^3$ GeV

> mase kvarkov in leptonov:

juha leptonov, kvarkov in njihovih antidelcev





1.nastanek do inflacije –

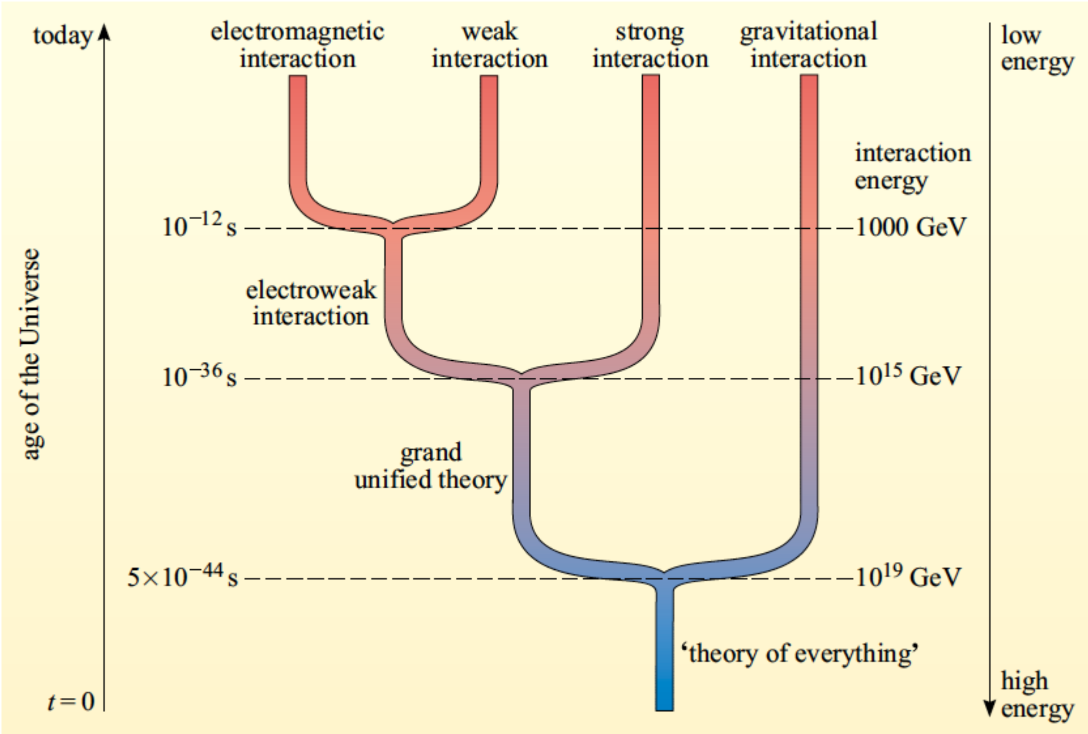
Planckova era:

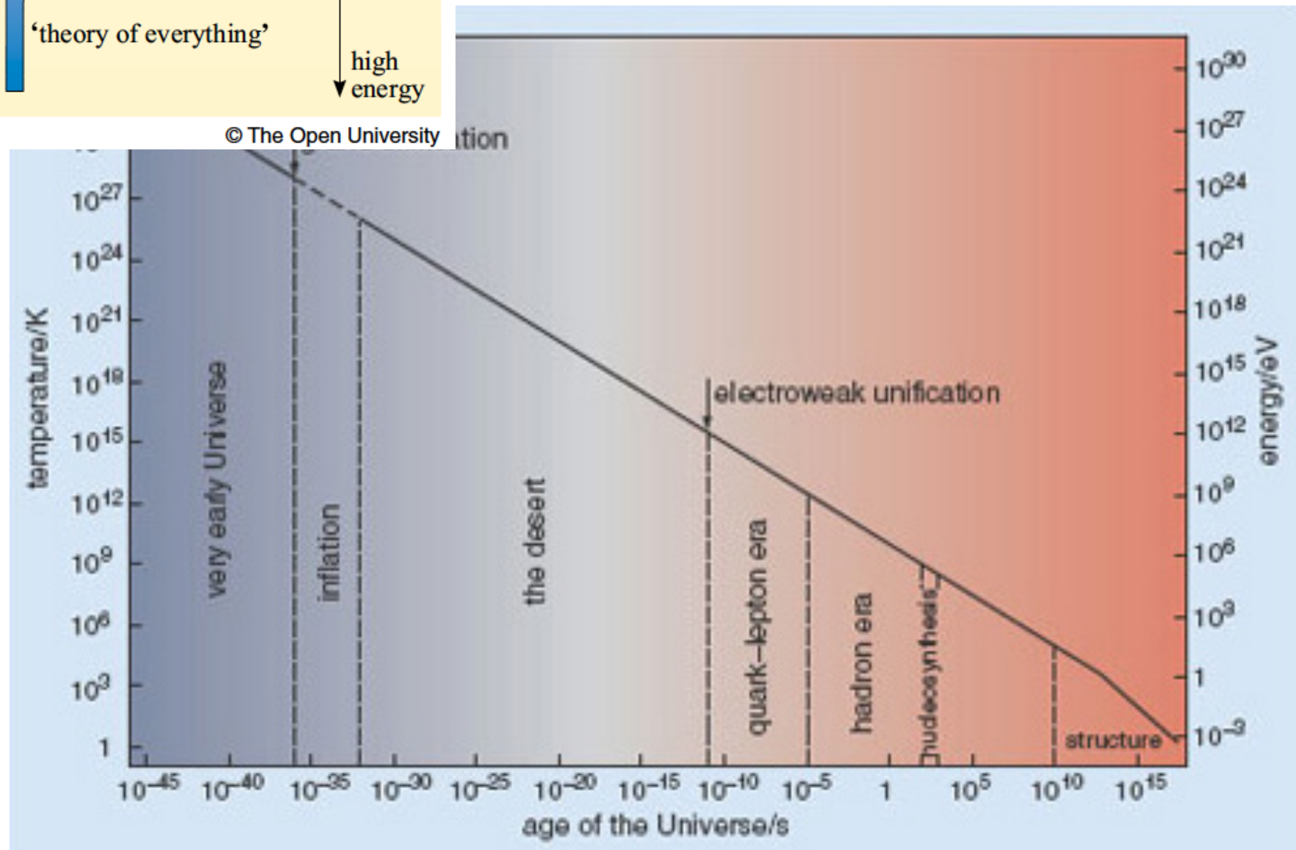
0-5x10^{-44} s, T~ 10^{32} K - odcepitev gravitacije

GUT era:

10^{-36} s, T~ 10^{28} K – odcepitev močne interakcije → sprostitev ogromne energije (energija 'false' vakuma)→

Inflacija: 10^{-36} s - 10^{-34} s se eskponentno širi, poveča za faktor 10^{35} ali celo 10^{50}.


today
electromagnetic interaction
weak interaction
strong interaction
gravitational interaction
low energy
interaction energy
10^{-12} s
1000 GeV
electroweak interaction
10^{-36} s
10^{15} GeV
grand unified theory
5×10^{-44} s
10^{19} GeV
'theory of everything'
age of the Universe
$t=0$
high energy


tion
electroweak unification
very early Universe
inflation
the desert
quark–lepton era
hadron era
nucleosynthesis
structure
temperature/K
energy/eV
age of the Universe/s
10^{27}
10^{24}
10^{21}
10^{18}
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}
1
10^{30}
10^{-3}
10^{-45} 10^{-40} 10^{-35} 10^{-30} 10^{-25} 10^{-20} 10^{-15} 10^{-10} 10^{-5} 1 10^{5} 10^{10} 10^{15}

2. **elektrošibka doba:**

10^{-34} do 10^{-12} s

juha osnovnih delcev: fotoni, gluoni, kvarki, leptoni

Razklopitev šibke in EM interakcije ob $t \approx 10^{-12}$ s, $T \approx 10^{16}$ K

3. Doba delcev:

10^{-12} do 1 s

kvarki in antikvarki se anihilirajo

kršitev simetrije → presežek kvarkov (10^{-9}) → snov

Hadronska doba: med 10^{-6} do 10^{-5} s, T~ 10^{15} K:

kvarki → hadroni

nestabilni razpadejo, ostanejo p in n (n nestabilni, $t_{1/2}$=615 s)

Leptonska doba:

Večina leptoni in antileptoni → anihilacija → presežek leptonov

4. **od 1 do 100 s**

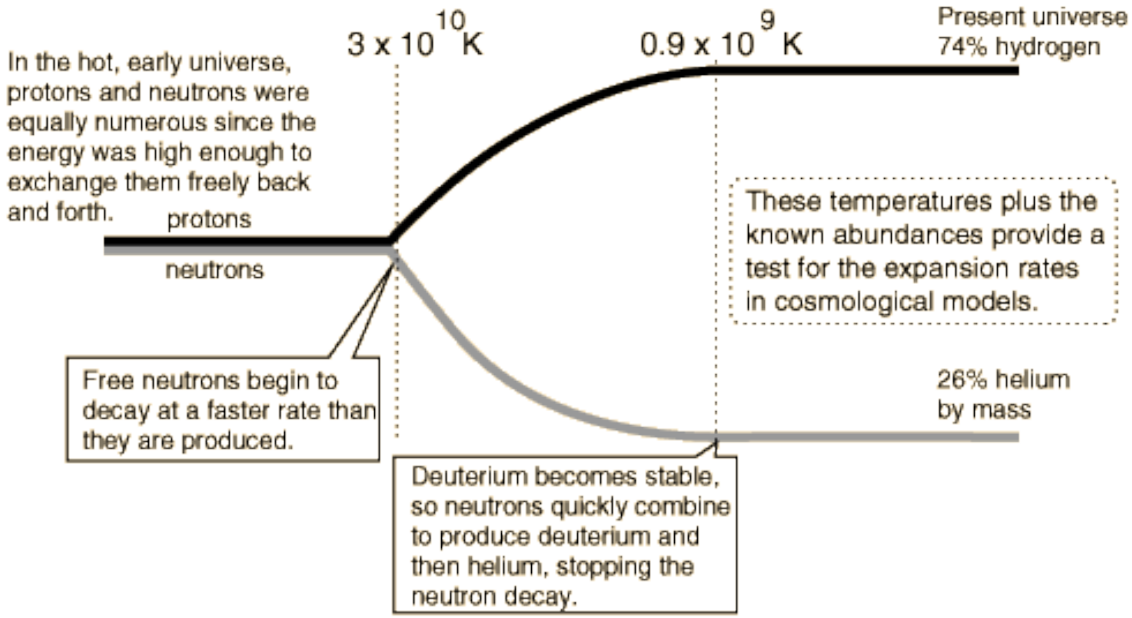
$n \leftrightarrow p + e^- + \text{anti-}\nu_e$

$n + e^+ \leftrightarrow p + \text{anti-}\nu_e$ $\qquad n_n/n_p = e^{-(m\_n-m\_p)/kT}$

$n + \nu_e \leftrightarrow p + e^-$

pri T~ 10 GK, E~ 1 MeV

se ustavlja: $n_n/n_p = 0.223$



nevtroni:

β razpad $t_{1/2}$=615 s

5. 3 min - 20 min

ko T pade na ~ 1 GK nastaja devterij:

$p + n \leftrightarrow {}^2_1H + \gamma$

Ostane:

$n_p : n_n = 7:1 \rightarrow n_{He} : n_H = 1:12$ oz. $m_{He} : m = 0.25$

$n + p \rightarrow {}^2_1H + \gamma$.

${}^2_1H + n \rightarrow {}^3H + \gamma$ in ${}^2_1H + p \rightarrow {}^3He + \gamma$.

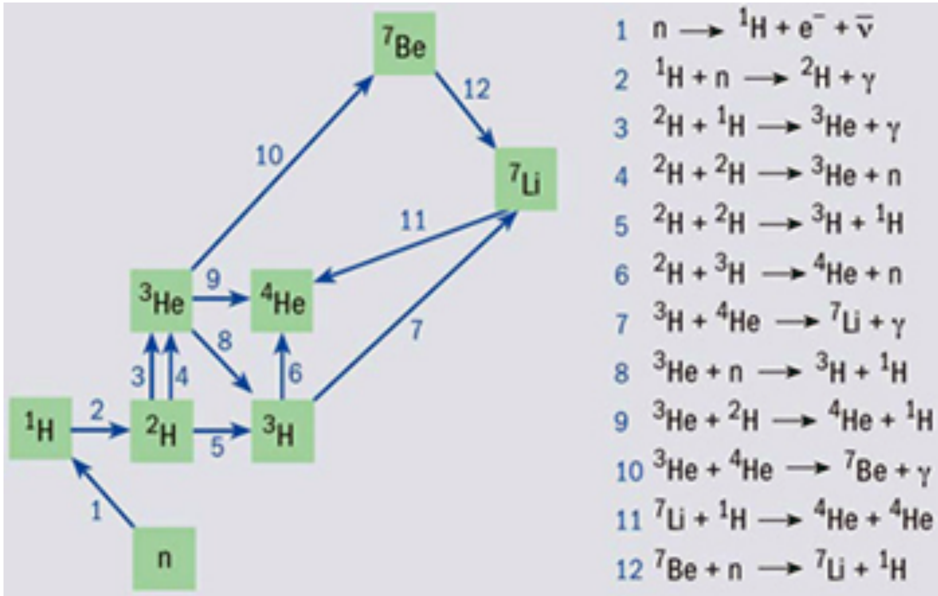
Končno, ^4He nastane:

${}^2_1H + {}^2_1H \rightarrow {}^4He + \gamma$, ${}^3He + n \rightarrow {}^4He + \gamma$ in ${}^3H + p \rightarrow {}^4He + \gamma$.

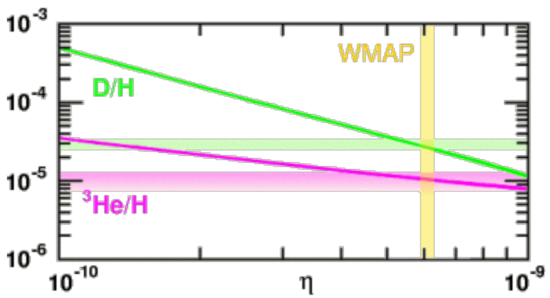
Nastajajo atomska jedra:

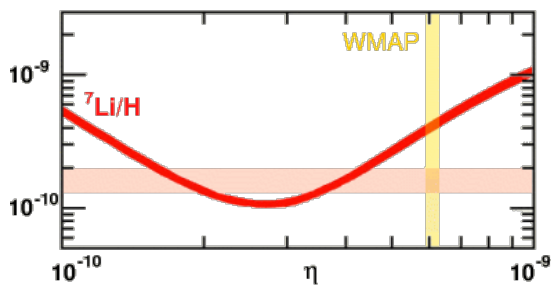
večina n gre v He,

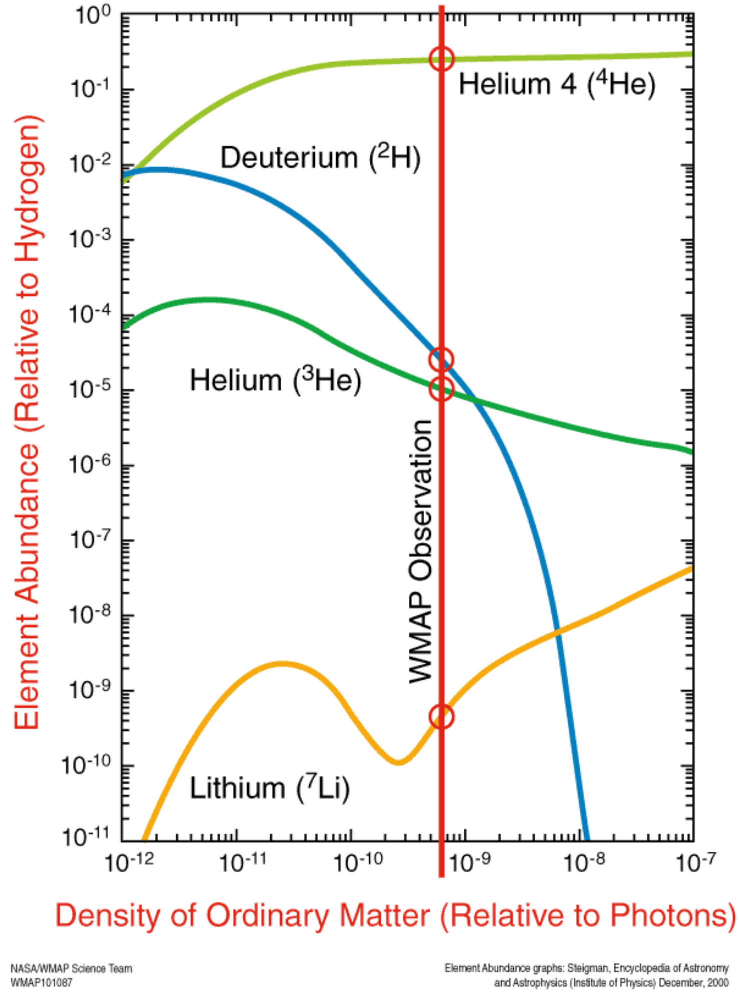
malo v litij, berilij, devterij



- ni elementov > Be
- ker ni stabilnih jeder z A=5 ali 8 (rabili bi trojni alfa proces)
- vesolje se širi
- Li: $^{4}_{2}\mathrm{He}+^{3}_{1}\mathrm{H}\text{->}^{7}_{3}\mathrm{Li}+\gamma$
- primerjava z opazovanji: WMAP







Prapok in prvinska nukleosinteza

- Alpher-Bethe-Gamow (1948)
- napove količino ^{4}He, ^{3}He, ^{2}H in ^{7}Li glede na ^{1}H
- odvisnost od $\eta = n_B/n_\gamma \leftarrow$ prasevanja

$\Rightarrow$ masni %

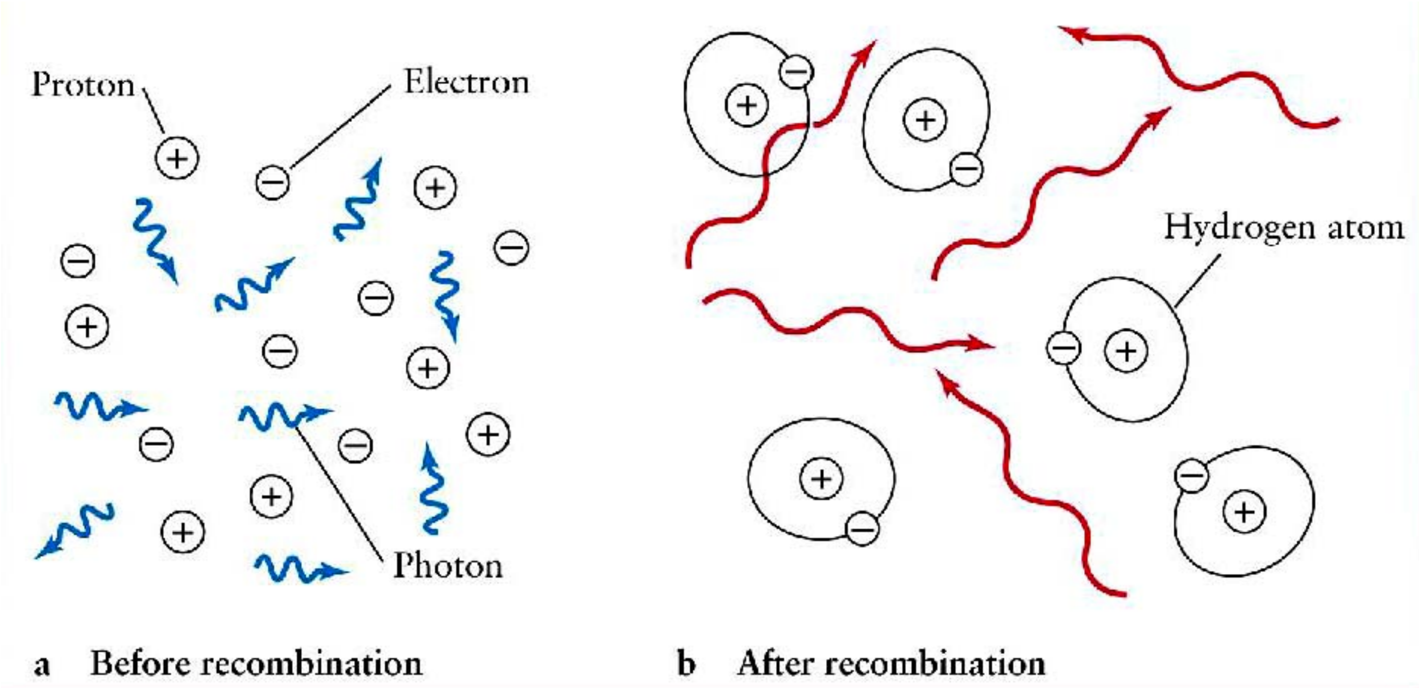
- 75% H
- 25% ^{4}He, (~)
- ~ 10^{-4} ^{2}H, (OK)
- ~ 10^{-4} ^{3}He
- ~ 10^{-10} ^{7}Li, ^{7}Be (2x)

- **10.000 let:**

  konec “radiation era”, začne “matter era”

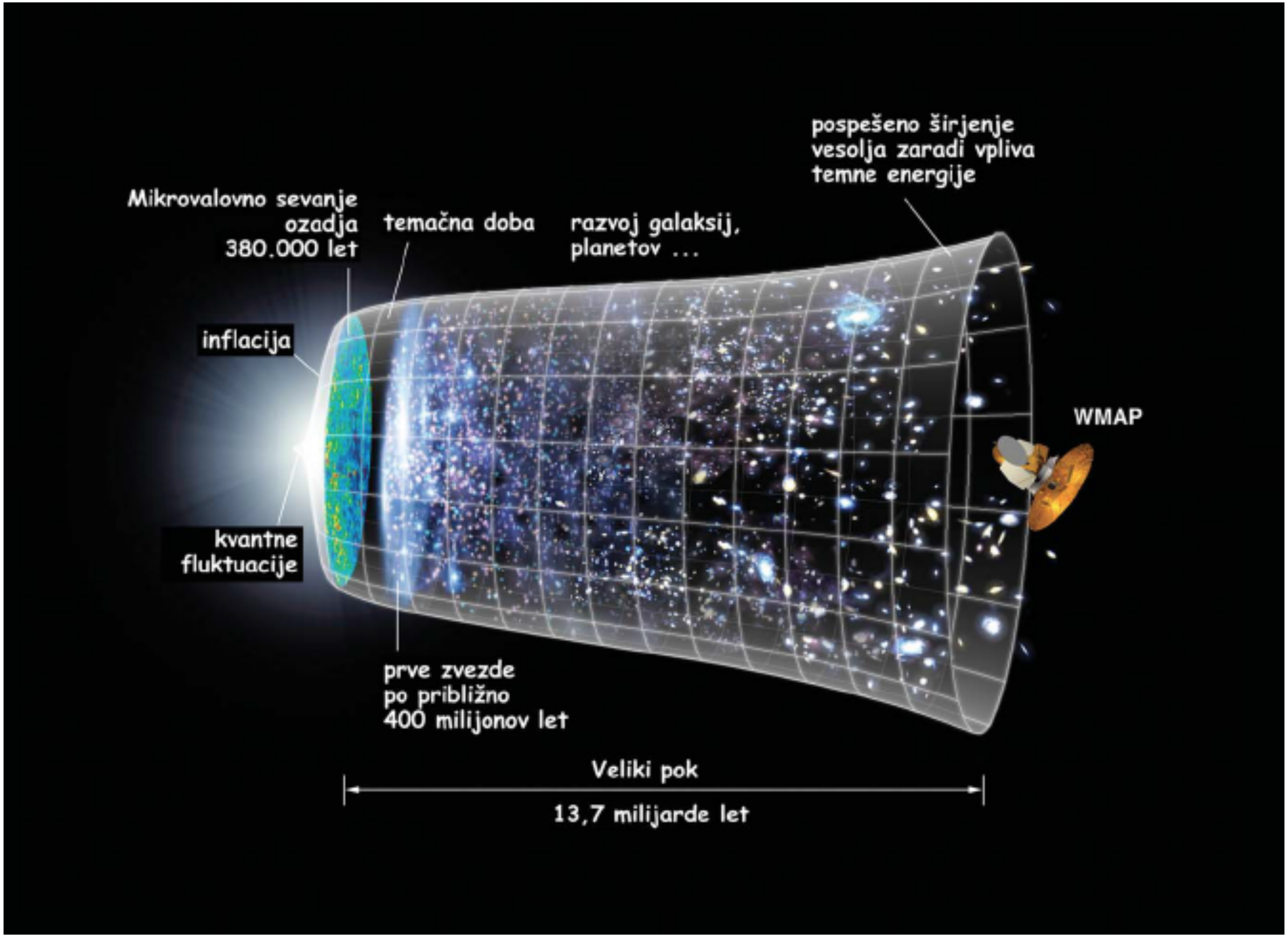
- **300.000-400.000 let:**

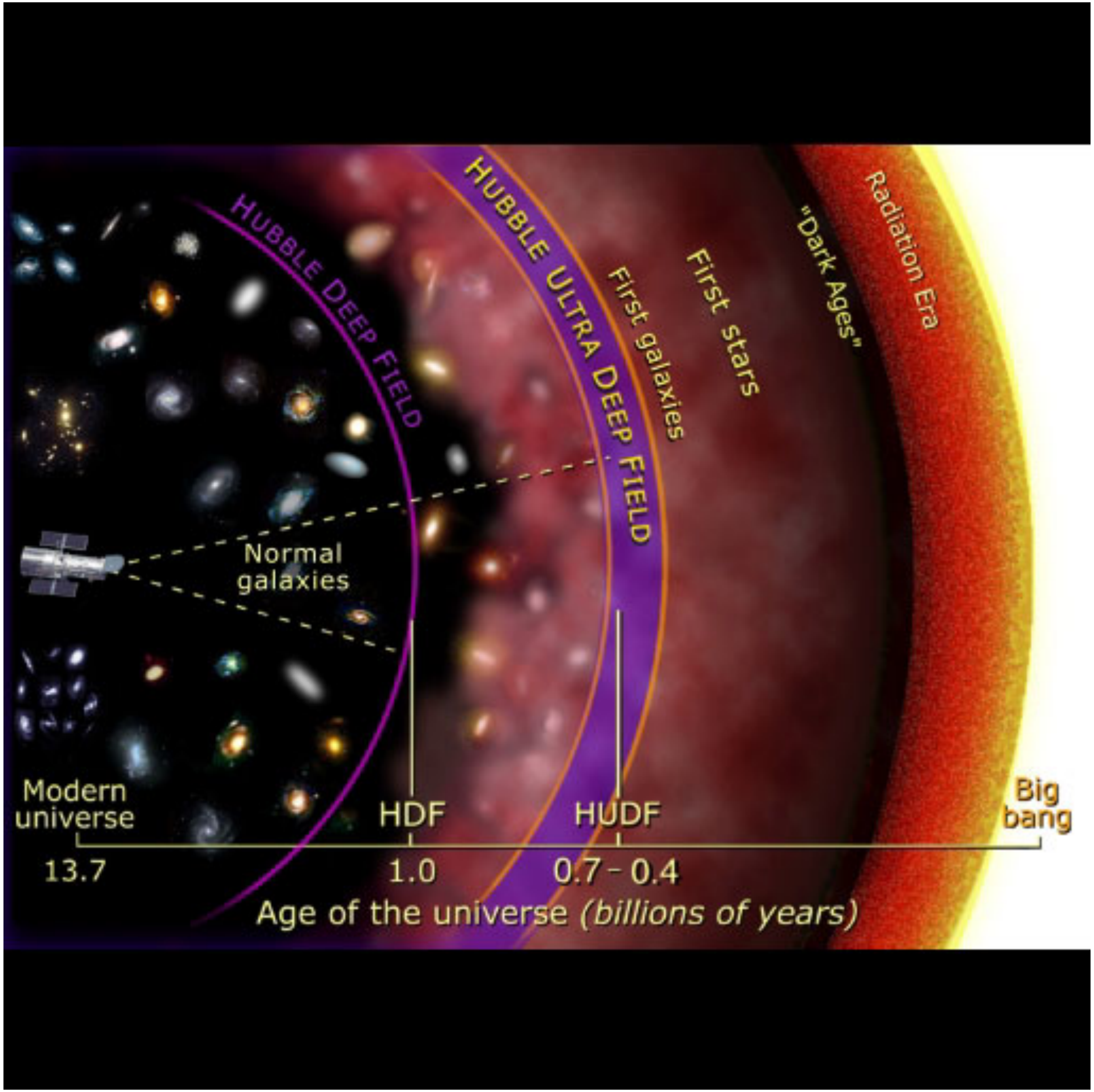
  T~3000 K – nastajajo atomi, razklopitev snovi in sevanja – vesolje postane prozorno → cosmic microwave background ali prasevanje



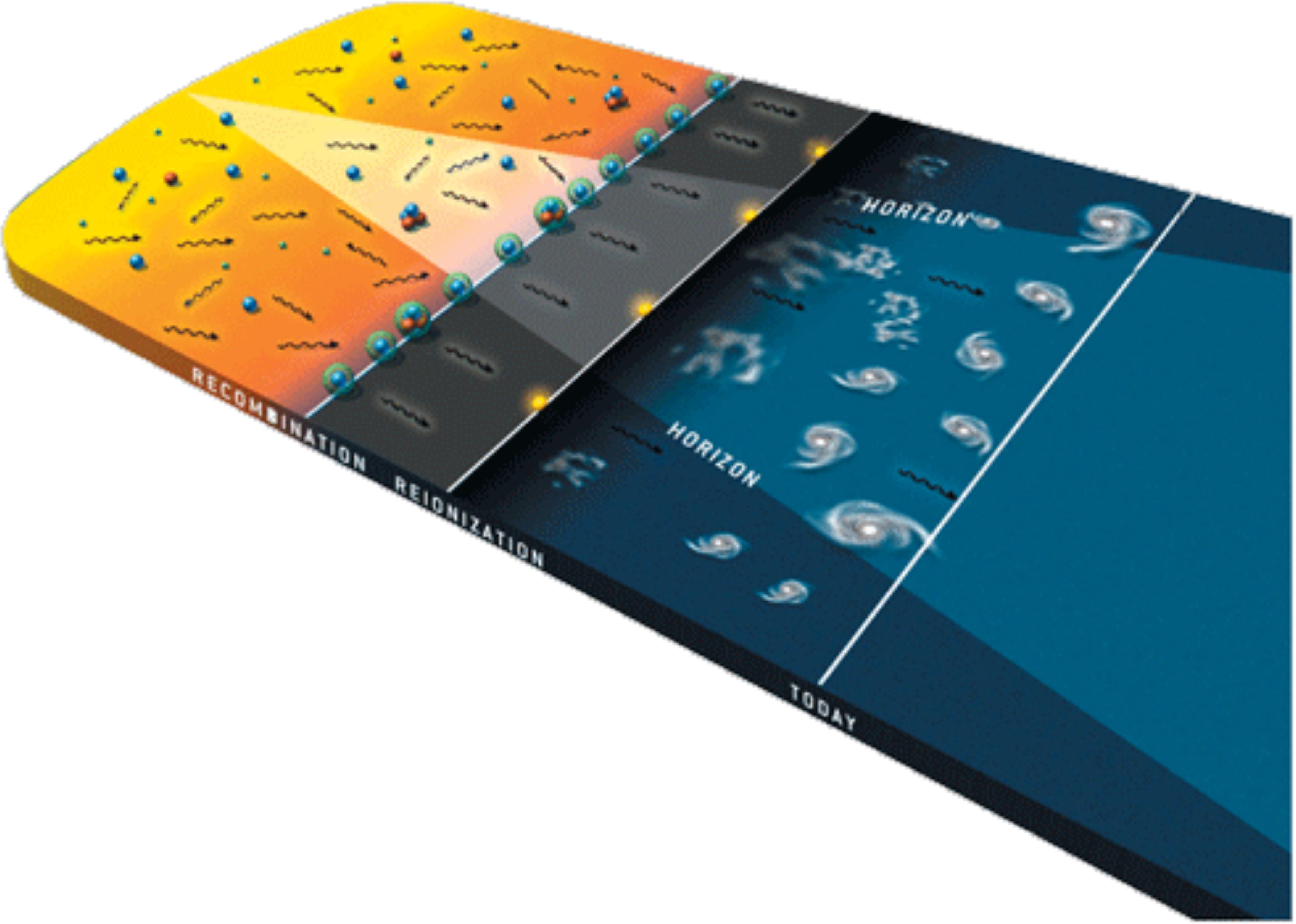
- **>400 Mlet**:

  nastajanje zvezd, galaksij, planetov...





HUBBLE DEEP FIELD
HUBBLE ULTRA DEEP FIELD
First galaxies
First stars
"Dark Ages"
Radiation Era
Normal galaxies
Modern universe
HDF
HUDF
Big bang
13.7
1.0
0.7 – 0.4
Age of the universe (billions of years)


RECOMBINATION
REIONIZATION
TODAY
HORIZON
HORIZON

dokazi za Veliki pok /prapok

- Olbersov paradoks
- oddaljevanje galaksij
- prasevanje
- prvinska nukleosinteza
- starost vesolja
- razvoj teles z oddaljenostjo (z)

supernove Ia – standardna svetila

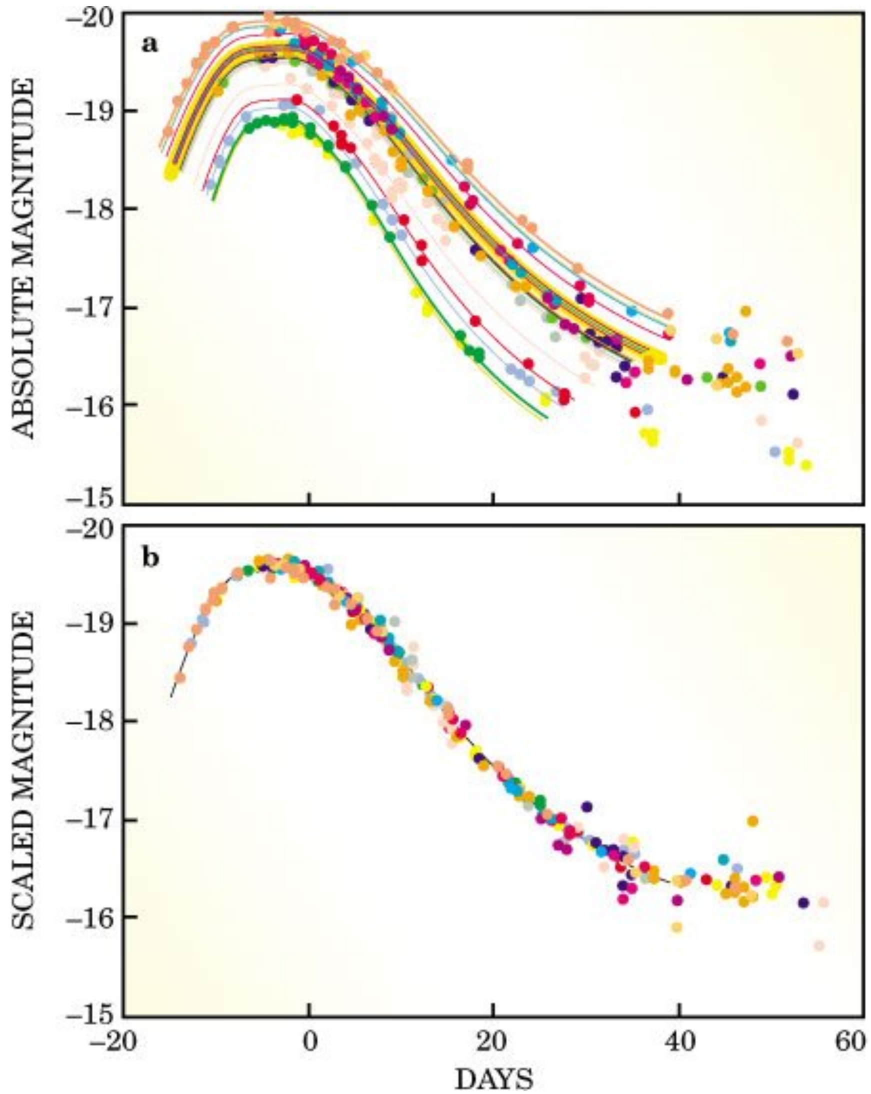


Photo: U. Montan

Saul Perlmutter

Photo: U. Montan

Brian P. Schmidt

Photo: U. Montan

Adam G. Riess

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"*.

supernove Ia in pospešeno širjenje vesolja

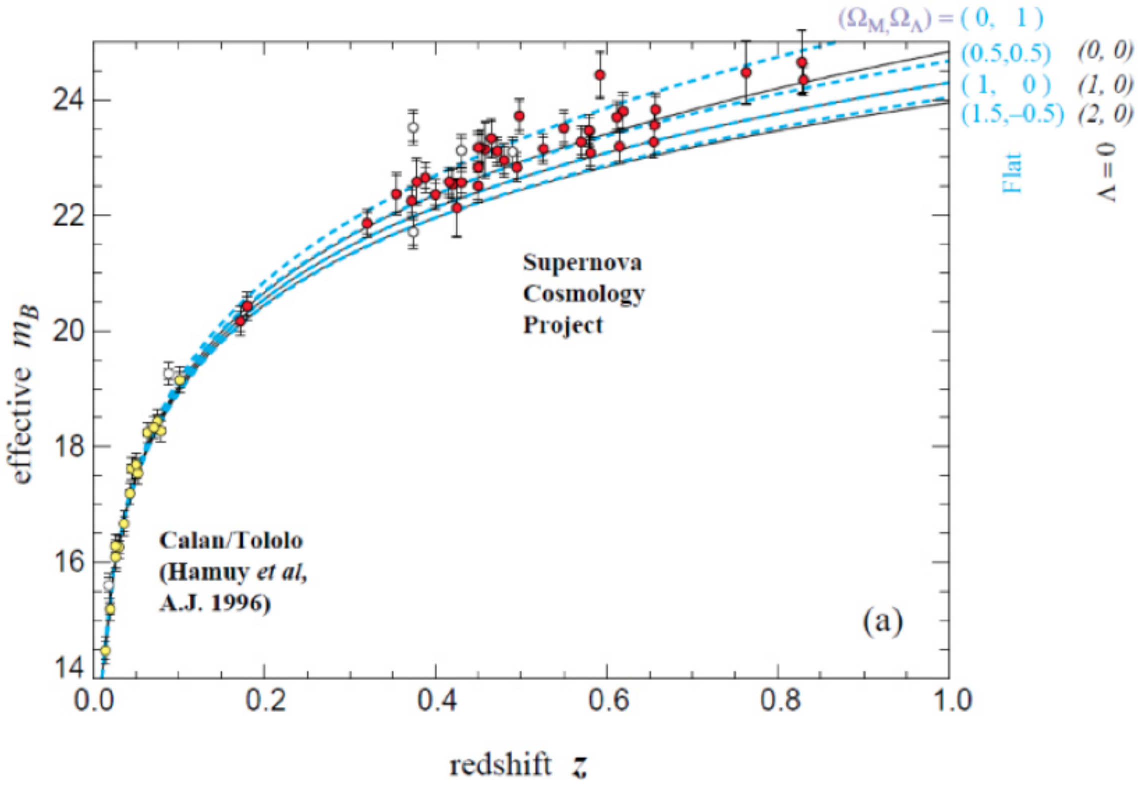


Figure 1: The Hubble diagram for 42 high redshift type Ia supernovae from SCP and 18 low redshift supernovae from the Calan/Tololo Supernova Survey. The solid curves represent a range of cosmological models with $\Lambda = 0$ and $\Omega_M = 0$, 1 and 2. The dashed curves show a range of "flat" models where $\Omega_M + \Omega_\Lambda = 1$. Note the linear redshift scale.

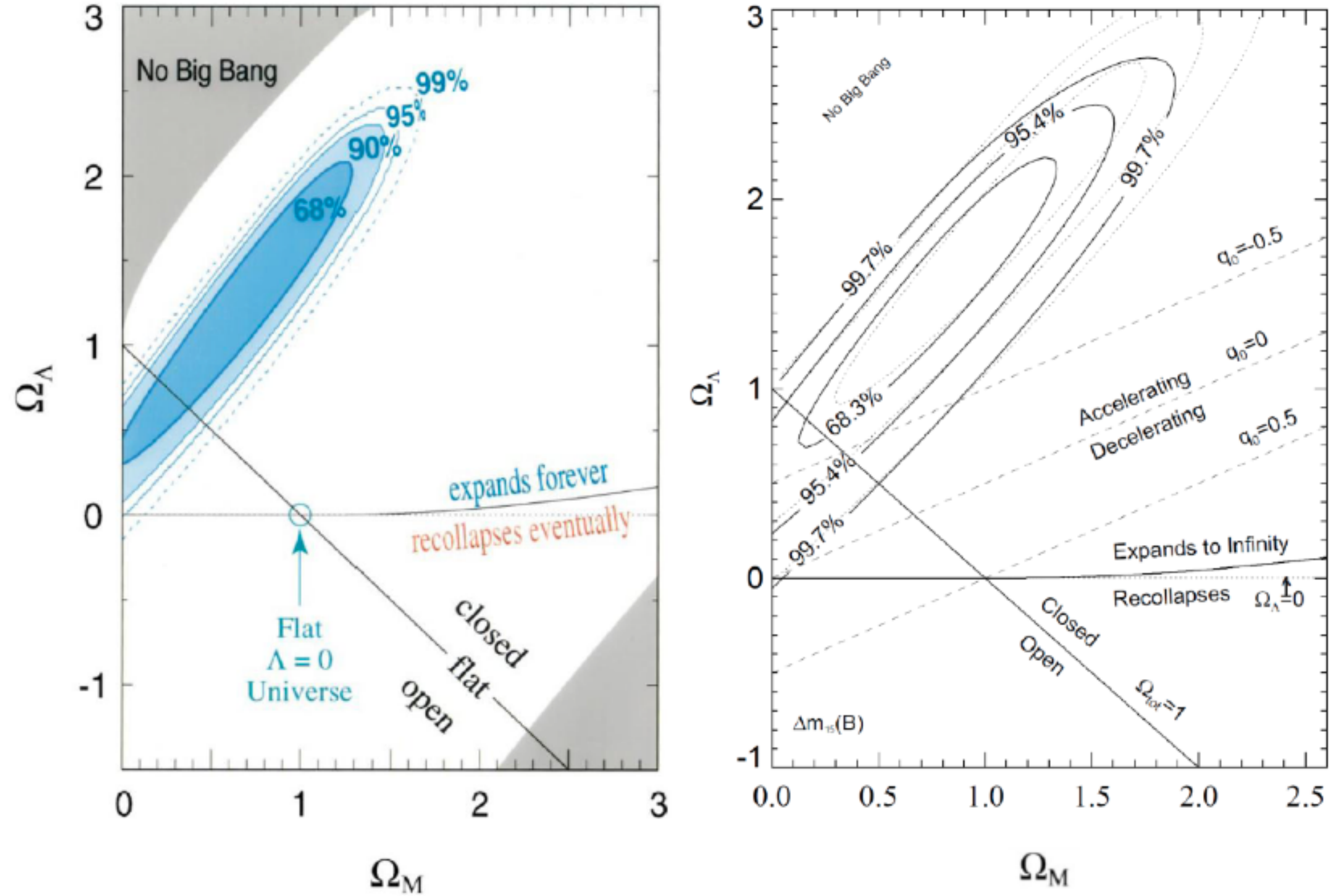
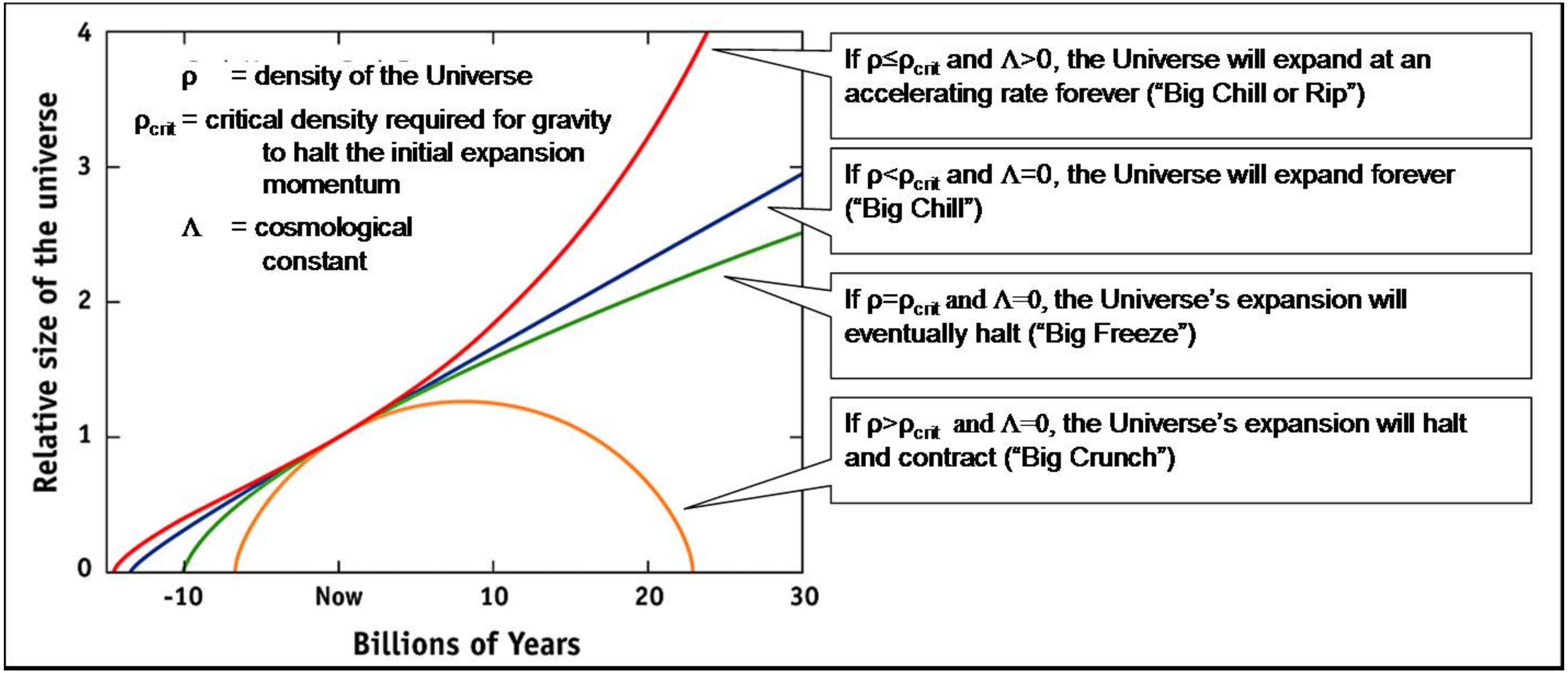
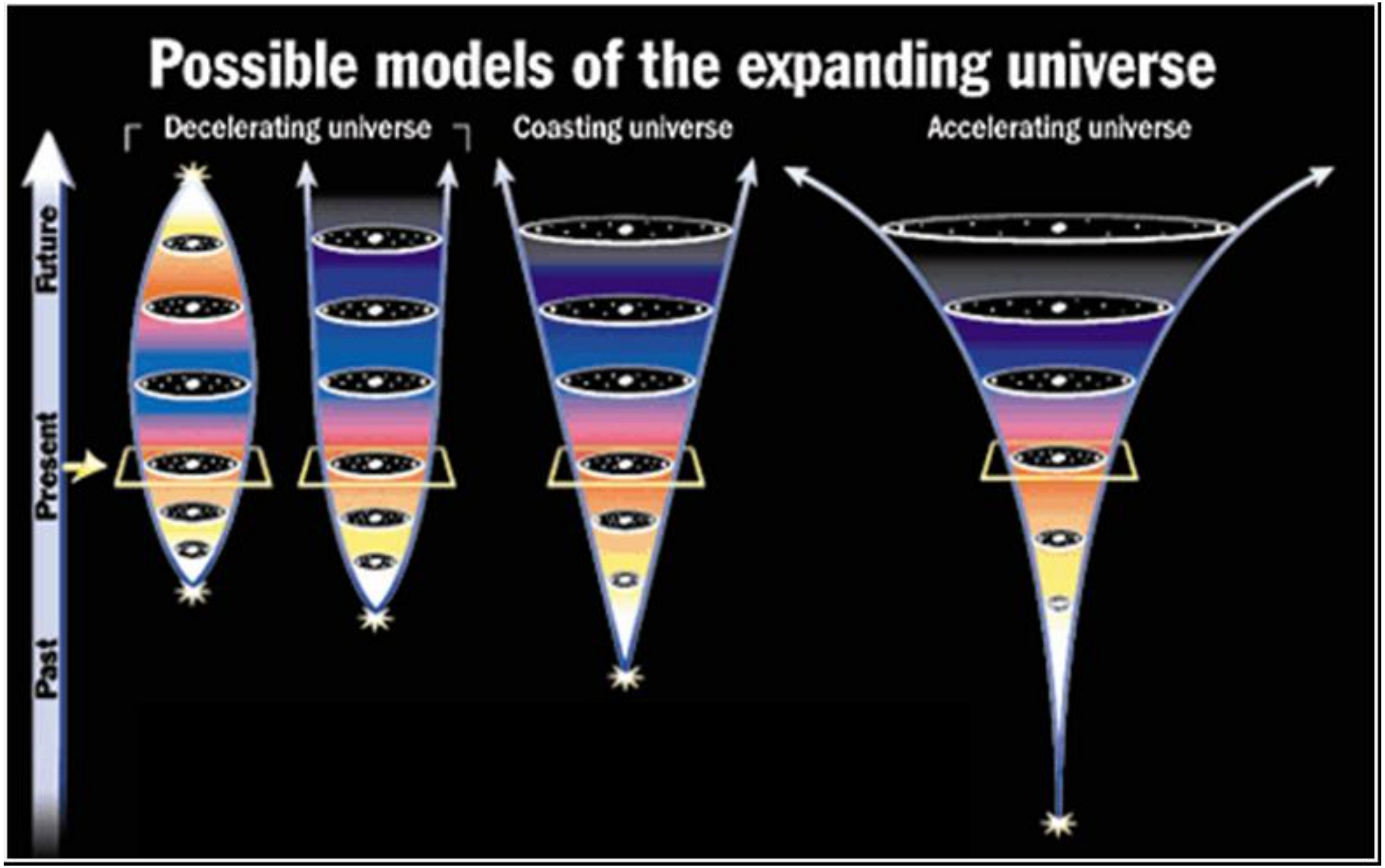


Figure 2. The left-hand panel shows the results of fitting the SCP supernova data to cosmological models, with arbitrary Ω_M and Ω_Λ [28]. The right-hand panel shows the corresponding results from HZT [27].



ρ = density of the Universe
ρcrit = critical density required for gravity to halt the initial expansion momentum
Λ = cosmological constant
If ρ≤ρcrit and Λ>0, the Universe will expand at an accelerating rate forever ("Big Chill or Rip")
If ρ<ρcrit and Λ=0, the Universe will expand forever ("Big Chill")
If ρ=ρcrit and Λ=0, the Universe's expansion will eventually halt ("Big Freeze")
If ρ>ρcrit and Λ=0, the Universe's expansion will halt and contract ("Big Crunch")
Relative size of the universe
4
3
2
1
0
-10
Now
10
20
30
Billions of Years


Possible models of the expanding universe
Decelerating universe
Coasting universe
Accelerating universe
Future
Present
Past

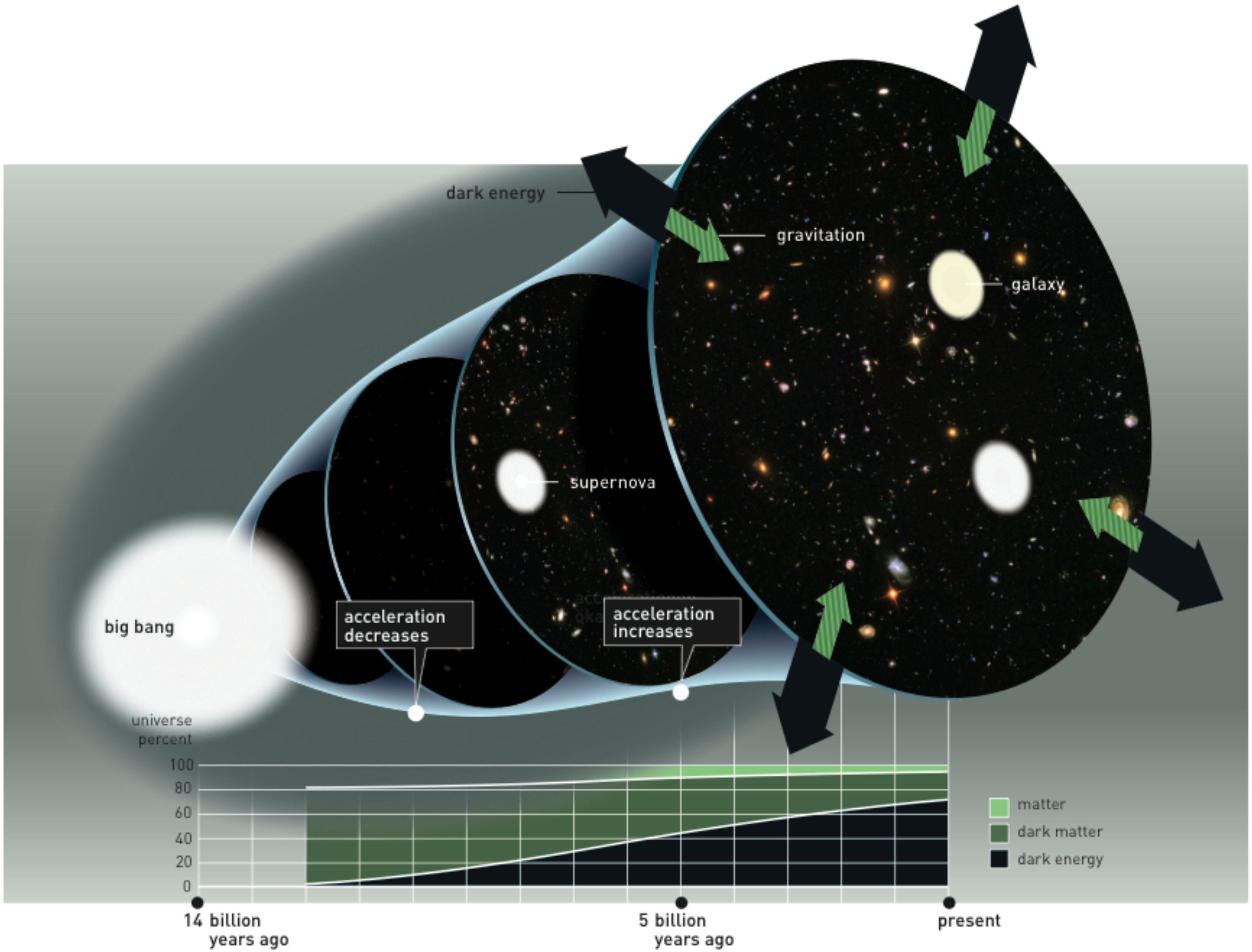


Figure 1. The world is growing. The expansion of the Universe began with the Big Bang 14 billion years ago, but slowed down during the first several billion years. Eventually it started to accelerate. The acceleration is believed to be driven by dark energy, which in the beginning constituted only a small part of the Universe. But as matter got diluted by the expansion, the dark energy became more dominant.

verse becomes a very inhospitable place. The the wilderness of eternity.

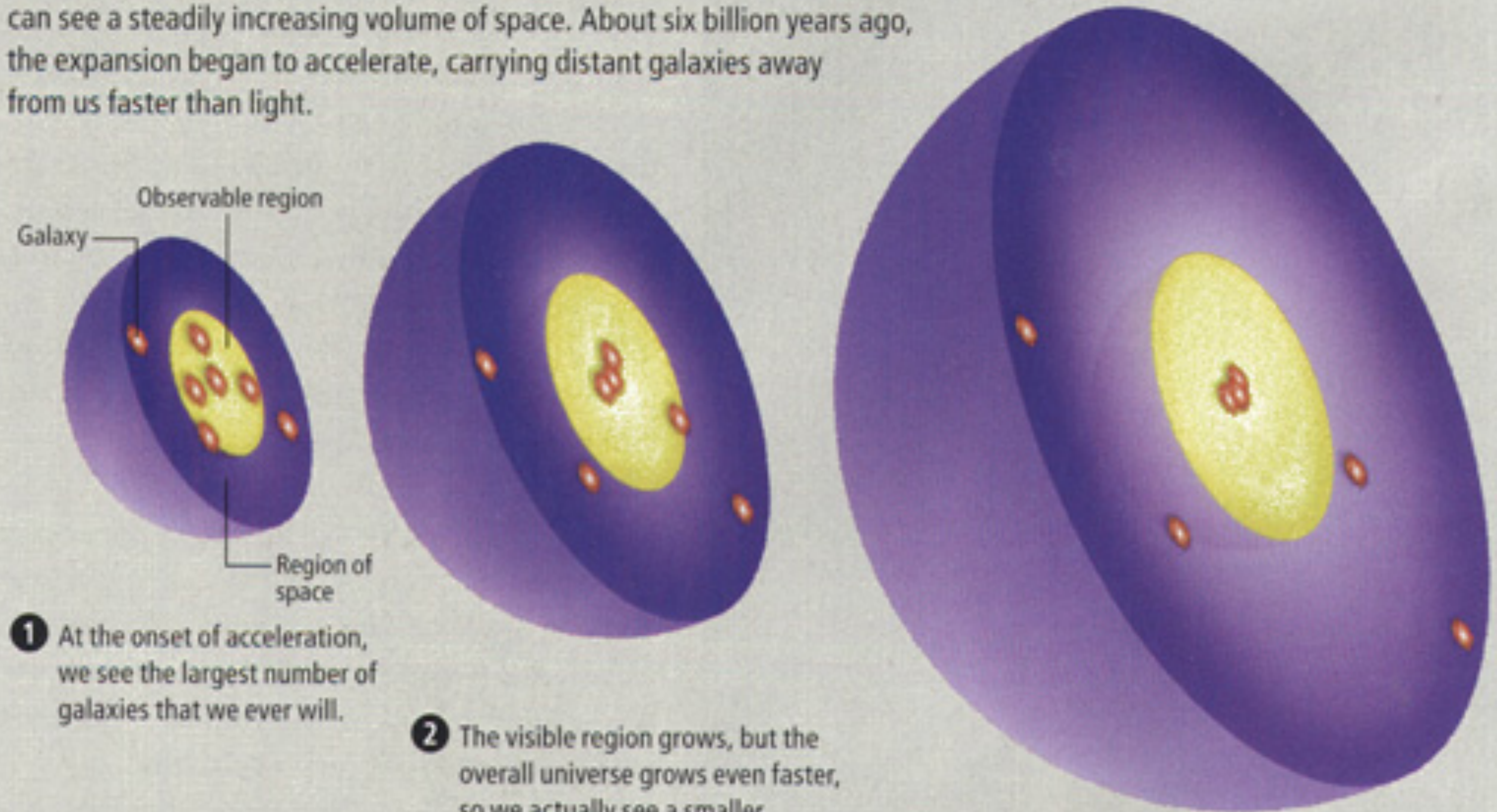
STEV

[THE AUTHORS]

Lawrence M. Krauss (*right*) and Robert J. Scherrer (*left*) began working together two years ago, when Krauss spent a sabbatical year at Vanderbilt University and came to know every honky-tonk in Nashville. Krauss is a cosmologist at Case Western Reserve University and director of its Center for Education and Research in Cosmology and Astrophysics. He is the author of seven books and an activist for the public understanding of science. Scherrer is a cosmologist, chair of the Department of Physics and Astronomy at Vanderbilt and a published science-fiction author. They both enjoy doing cosmology while there is still time left.

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.



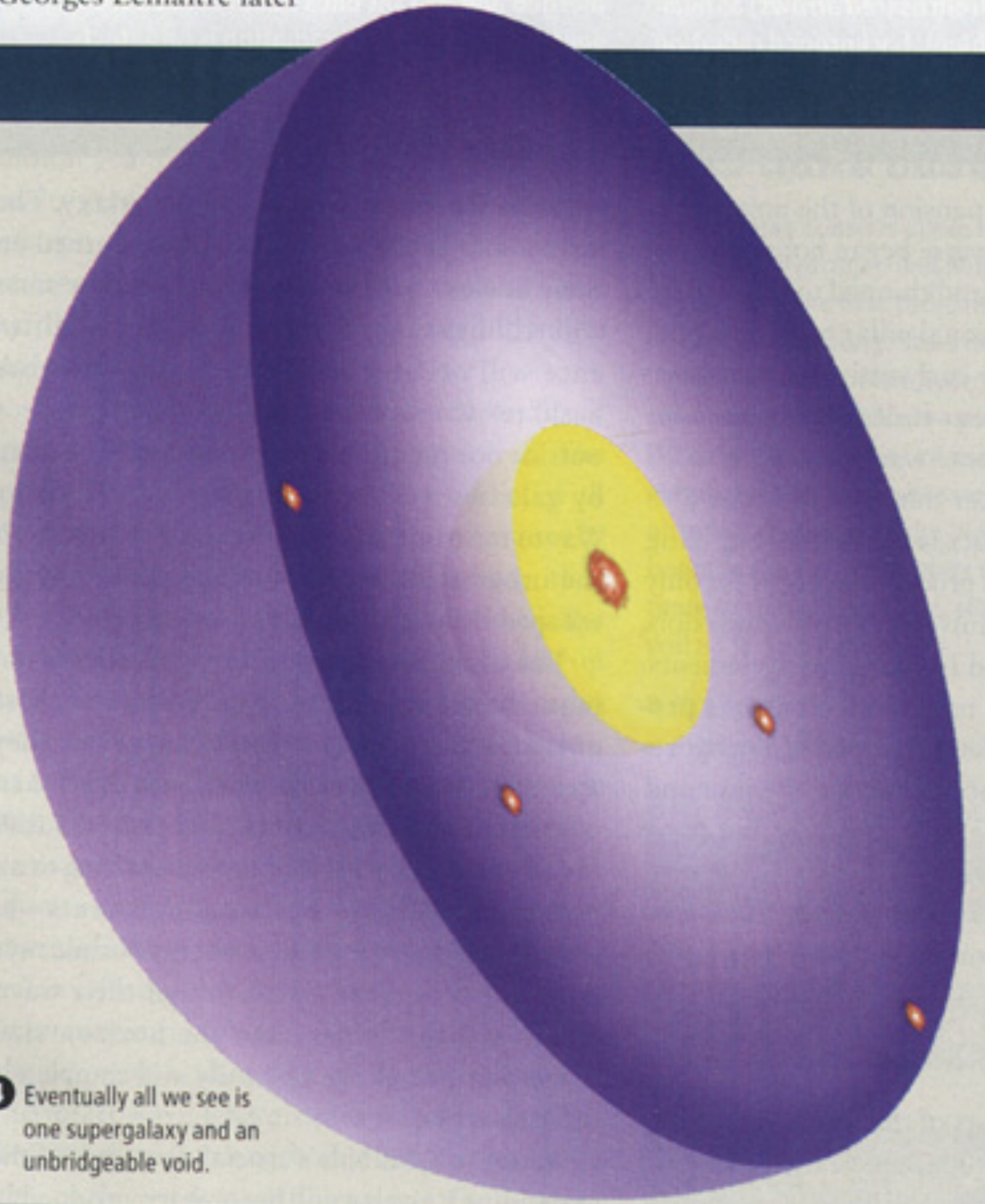
❶ At the onset of acceleration, we see the largest number of galaxies that we ever will.

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

❸ 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.

Georges Lemaître later

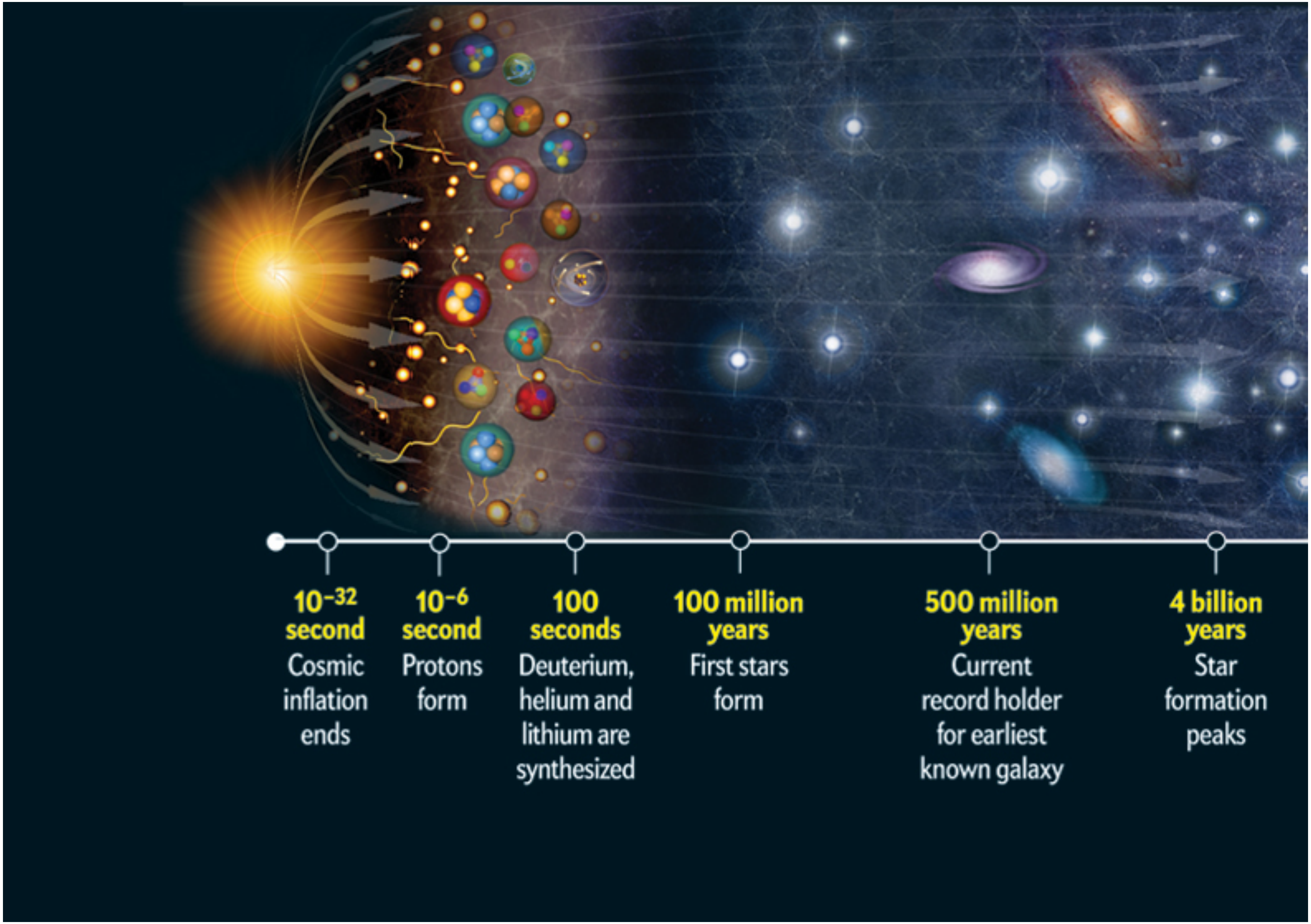


❹ Eventually all we see is one supergalaxy and an unbridgeable void.

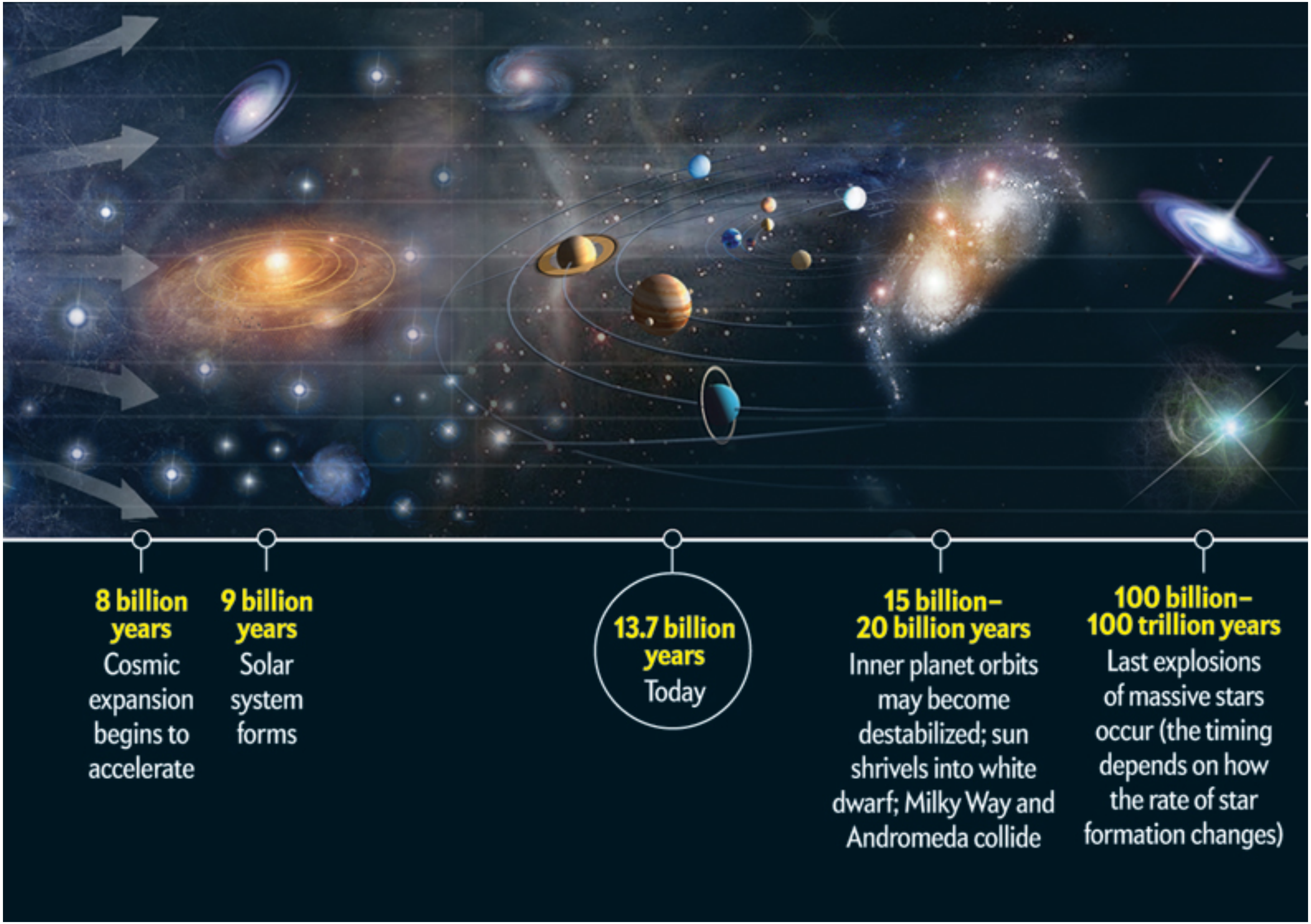
these galaxies were moving away fr
seemed to be sitting at the center of
expansion.

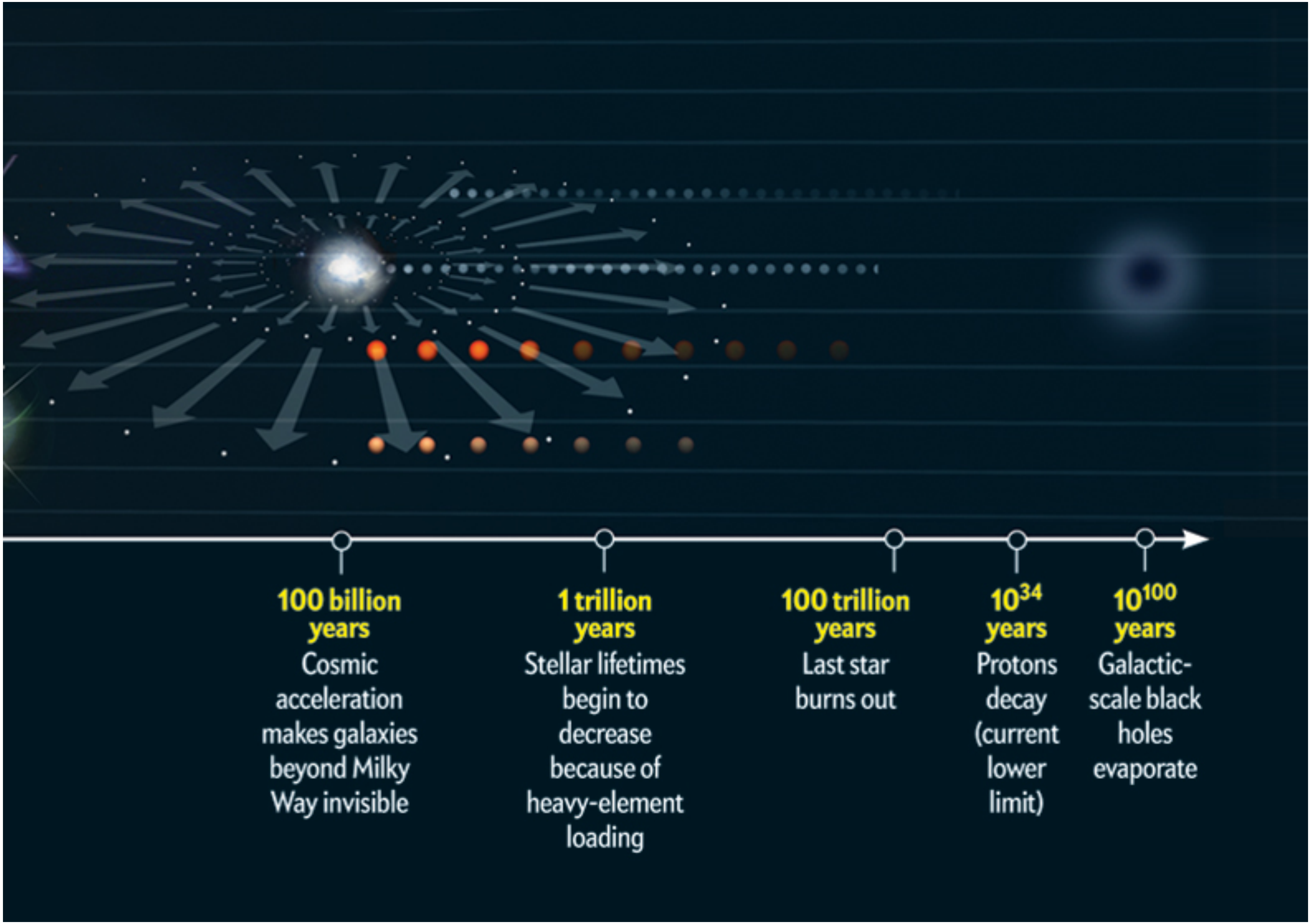
The person who is generally cred
covering the expansion of the univ
Slipher but American astronomer E
ble. (When was the last time you rea
Slipher Space Telescope?) Hubble d
not just the velocities of nearby galax
their distances. His measurements
conclusions that justify his fame. Fi
showed that galaxies were so far awa
really were independent collections o
like our own galaxy. Second, he di
simple relation between the distance
and their velocities. The velocity w
proportional to its distance from u
twice as far away as another was mo
as fast. This relation between dis
velocity is exactly what happens wh
verse is expanding. Hubble's mea
have since been refined, most recen
observations of distant supernovae,
to the discovery of dark energy.

The third pillar is the faint glow of
microwave background, discovered
tously in 1965 by Bell Labs physicist
zias and Robert Wilson as they trac
sources of radio interference. This rad
quickly recognized to be a relic left ov



10^{-32} second
Cosmic inflation ends
10^{-6} second
Protons form
100 seconds
Deuterium, helium and lithium are synthesized
100 million years
First stars form
500 million years
Current record holder for earliest known galaxy
4 billion years
Star formation peaks

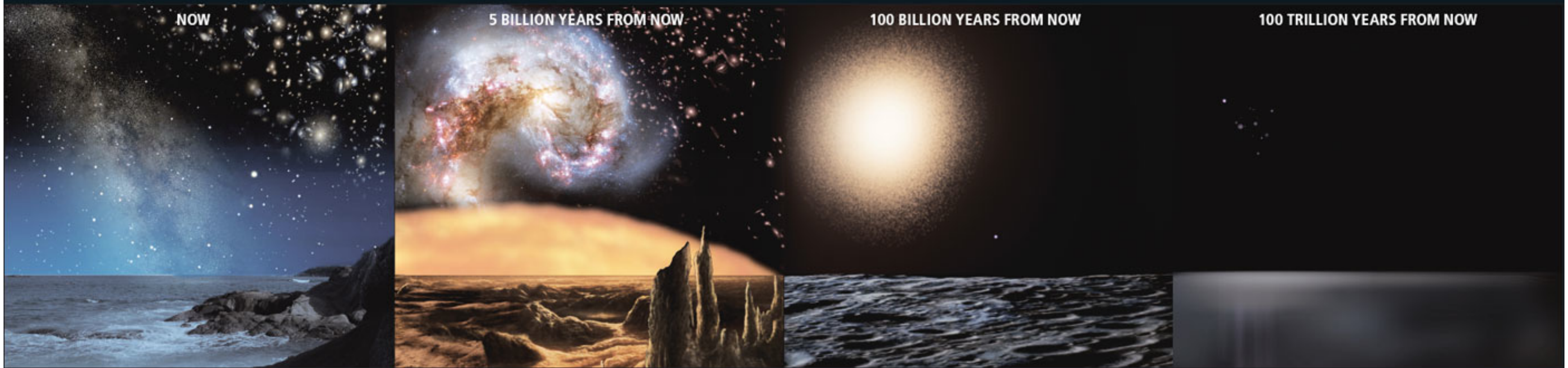

8 billion years
Cosmic expansion begins to accelerate
9 billion years
Solar system forms
13.7 billion years
Today
15 billion–20 billion years
Inner planet orbits may become destabilized; sun shrivels into white dwarf; Milky Way and Andromeda collide
100 billion–100 trillion years
Last explosions of massive stars occur (the timing depends on how the rate of star formation changes)



100 billion years
Cosmic acceleration makes galaxies beyond Milky Way invisible
1 trillion years
Stellar lifetimes begin to decrease because of heavy-element loading
100 trillion years
Last star burns out
10^{34} years
Protons decay (current lower limit)
10^{100} years
Galactic-scale black holes evaporate

FADE TO BLACK

The night sky on Earth (assuming it survives) will change dramatically as our Milky Way galaxy merges with its neighbors and distant galaxies recede beyond view.



DIFFUSE BAND stretching across the sky is the disk of the Milky Way. A few nearby galaxies, such as Andromeda and the Magellanic Clouds, are visible to the naked eye. Telescopes reveal billions more.

ANDROMEDA has been moving toward us and now nearly fills the sky. The sun swells to red giant size and subsequently burns out, consigning Earth to a bleak existence.

SUCCESSOR to the Milky Way is a ball-like supergalaxy, and Earth may float forlornly through its distant outskirts. Other galaxies have disappeared from view.

LIGHTS OUT: The last stars burn out. Apart from dimly glowing black holes and any artificial lighting that civilizations have rigged up, the universe goes black. The galaxy later collapses into a black hole.

Merjenje parametrov

- starost vesolja
- H_0 in q_0
- gostota snovi

- prasevanje!

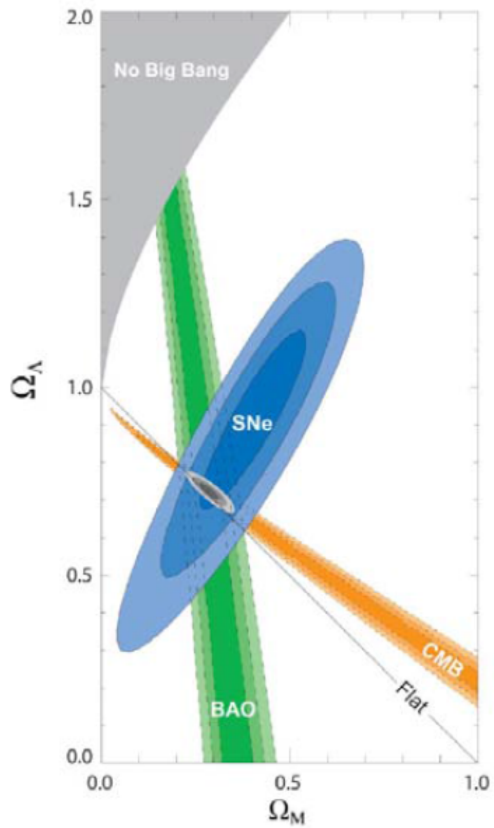
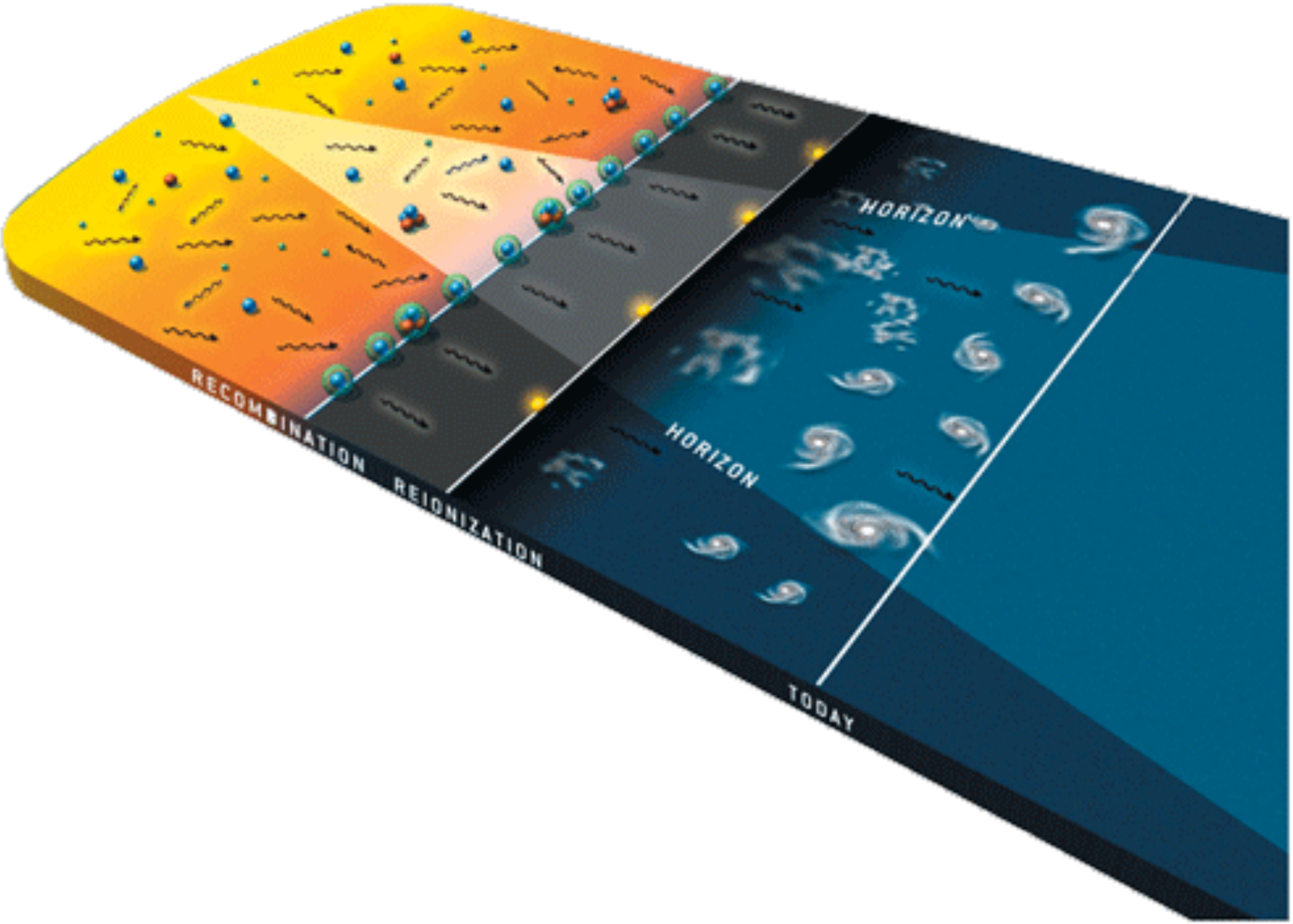
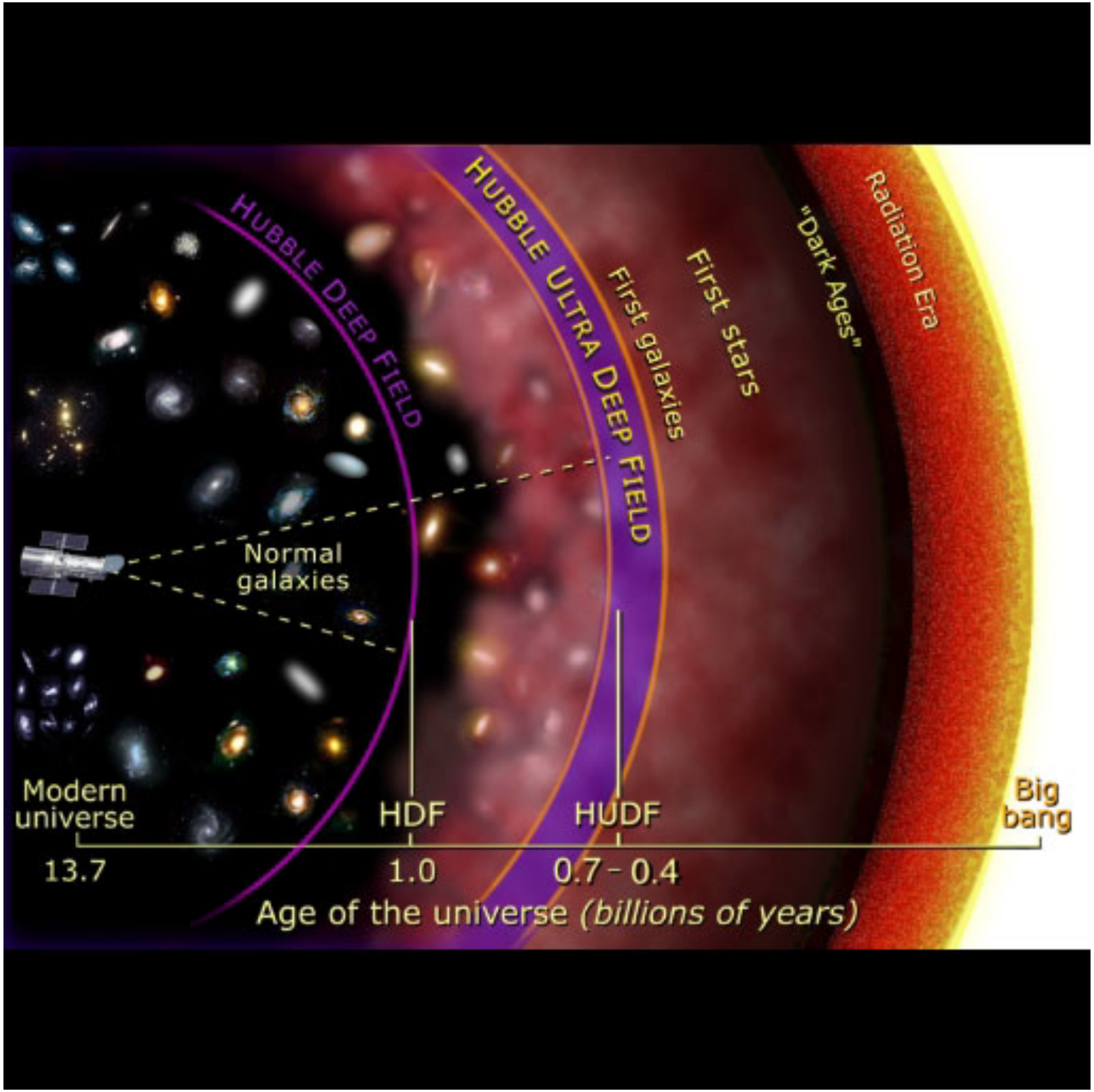


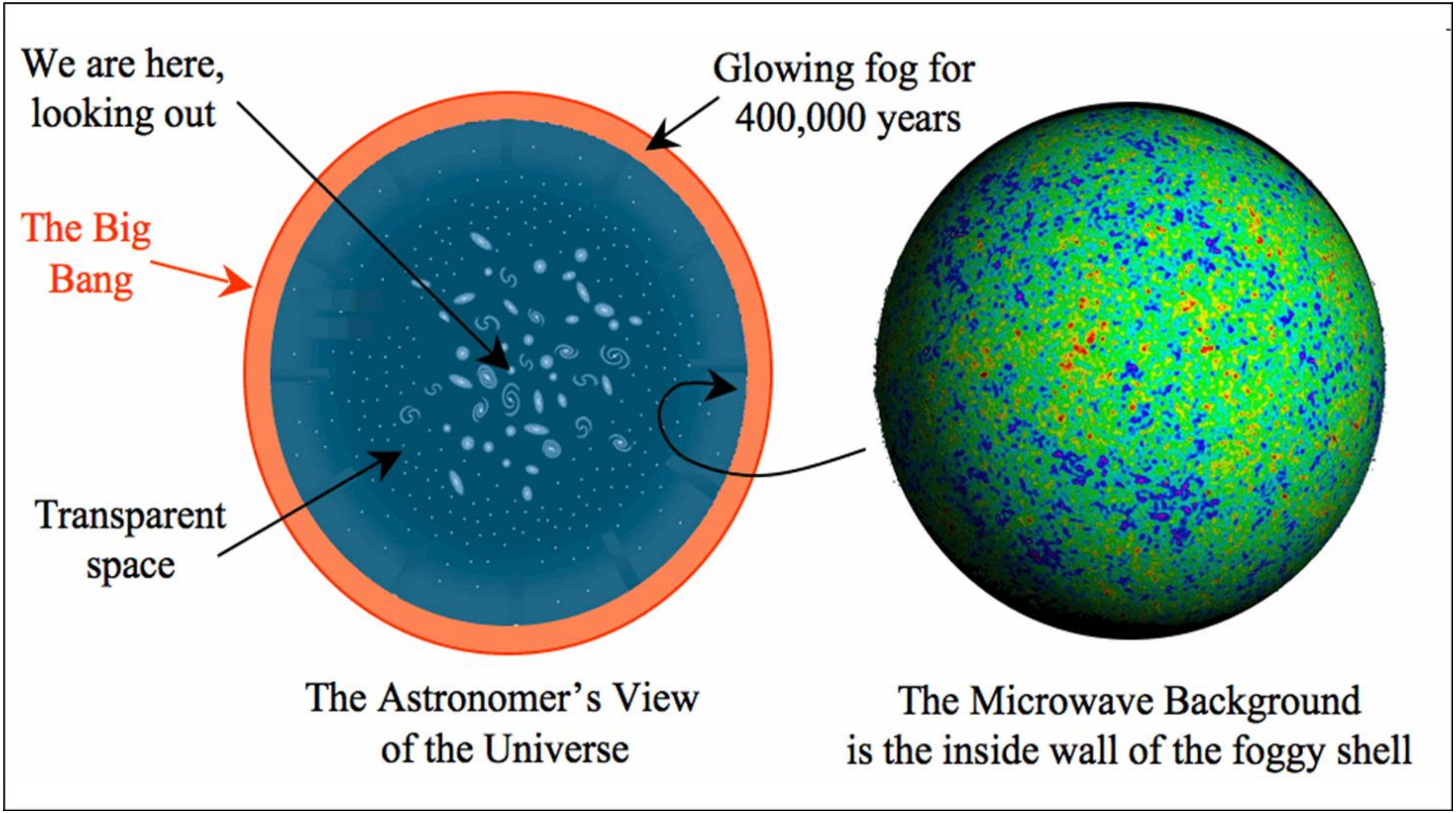
Figure 3. A summary figure from Review of Particle Properties, http://rpp.lbl.gov, showing the combination of supernova observations (SNe), the microwave background (CMB) and the spatial correlation between galaxies ("Baryon Acoustic Oscillations", *BAO).*


RECOMBINATION
REIONIZATION
HORIZON
HORIZON
TODAY



HUBBLE DEEP FIELD
HUBBLE ULTRA DEEP FIELD
First galaxies
First stars
"Dark Ages"
Radiation Era
Normal galaxies
Modern universe
HDF
HUDF
Big bang
13.7
1.0
0.7 – 0.4
Age of the universe (billions of years)

prasevanje

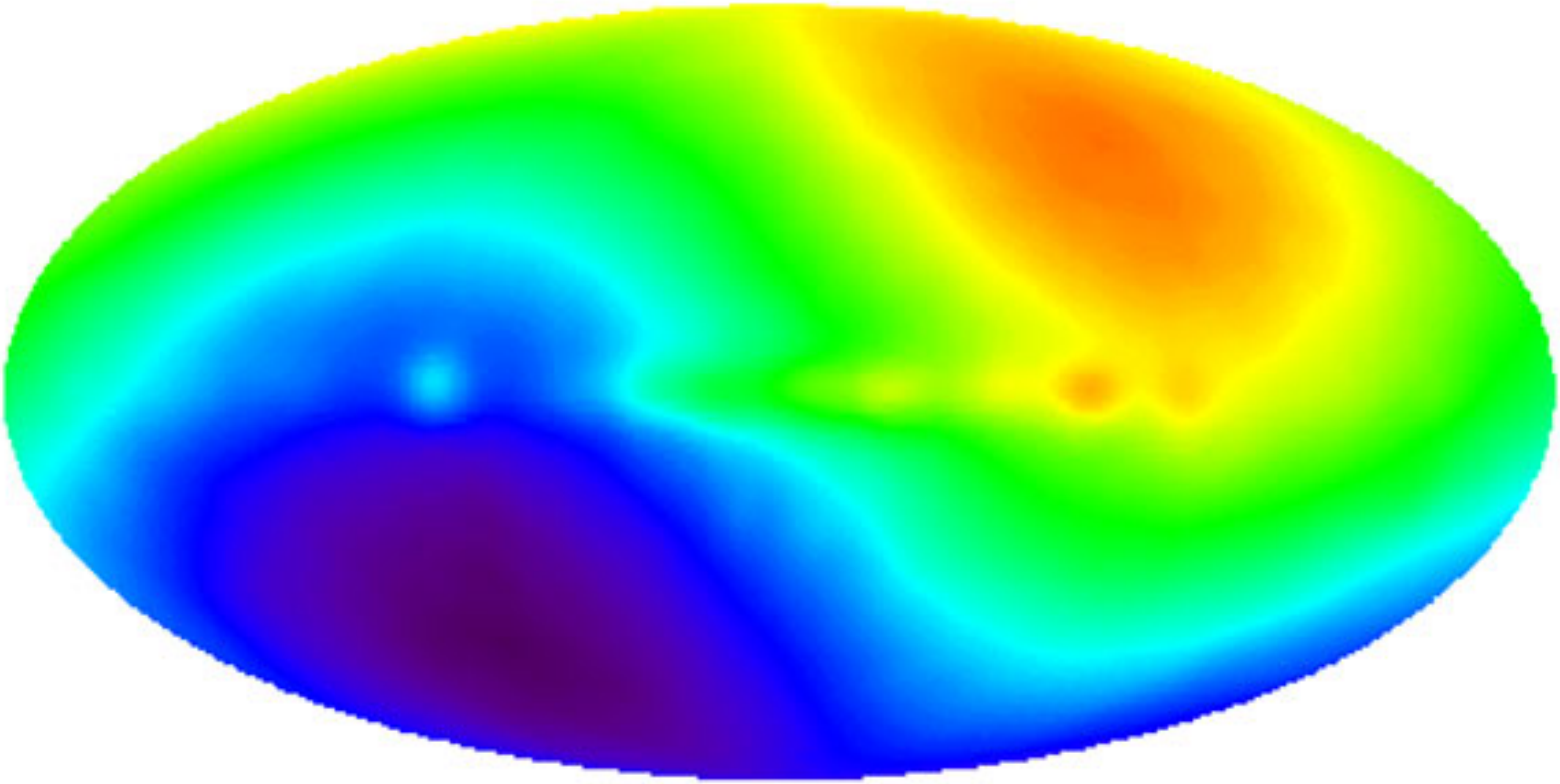


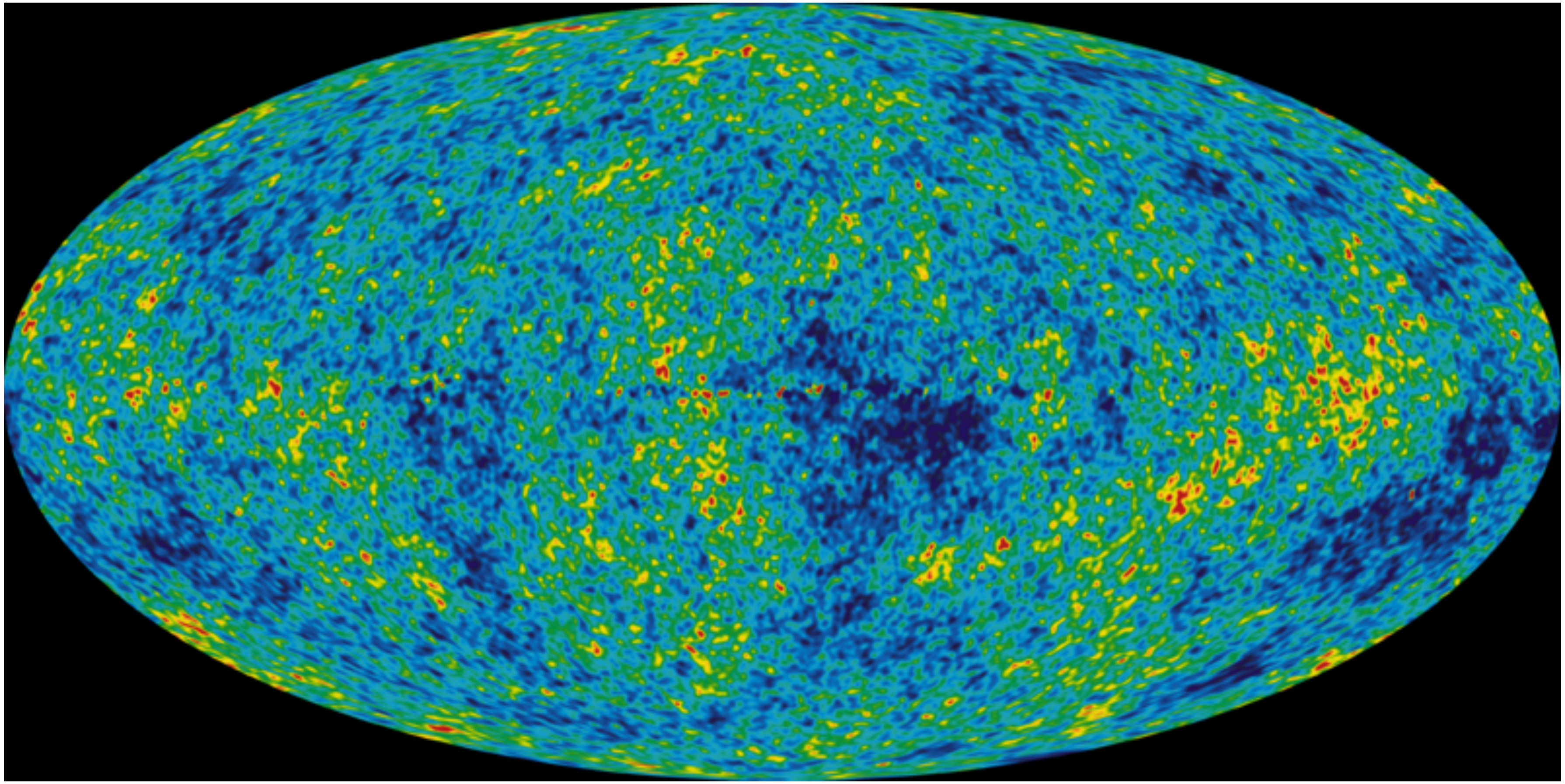
We are here, looking out
Glowing fog for 400,000 years
The Big Bang
Transparent space
The Astronomer's View of the Universe
The Microwave Background is the inside wall of the foggy shell

dipol

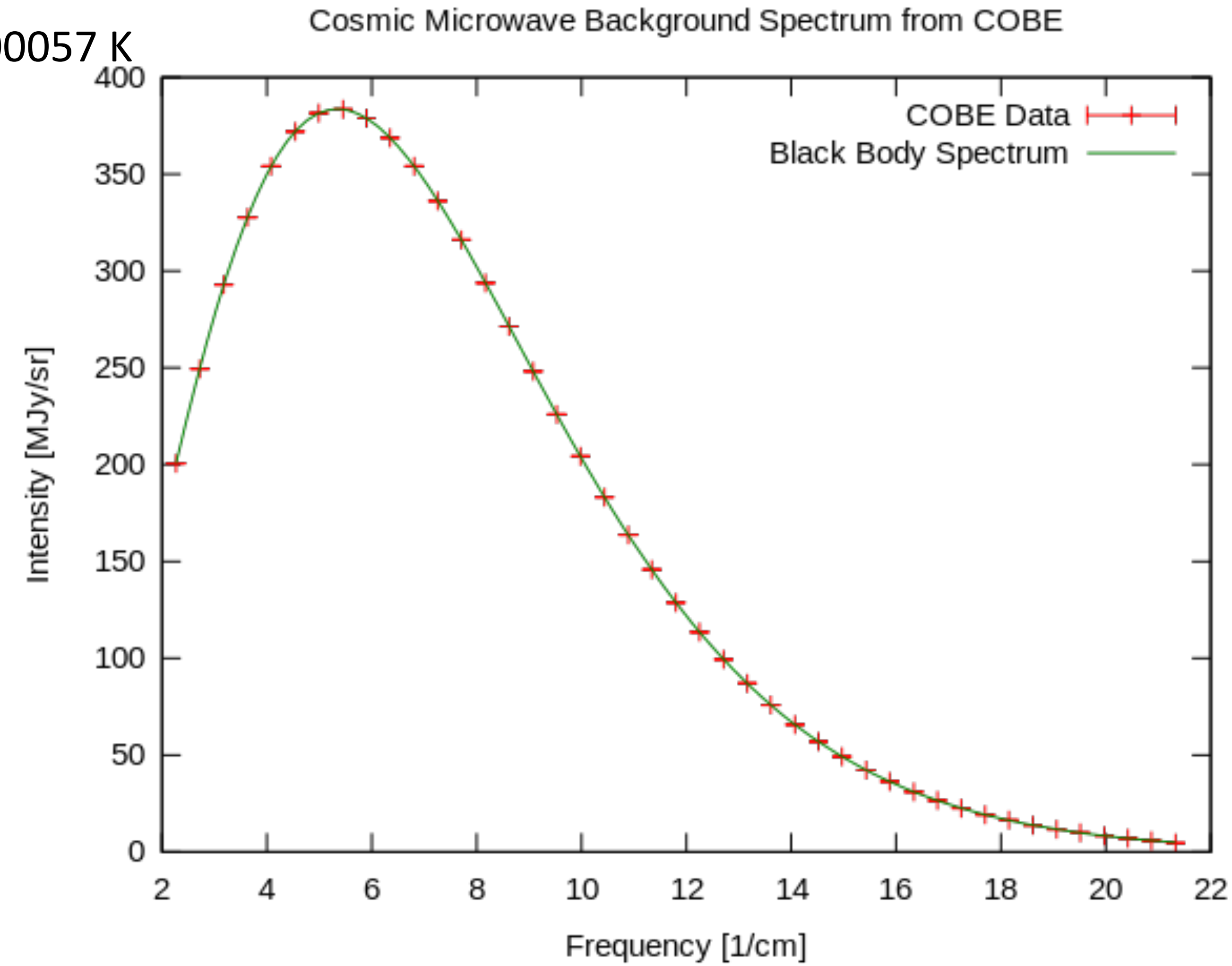
$dT/T \approx 10^{-3}$, $dT = 3.36$ mK

naše gibanje s 365 km/s

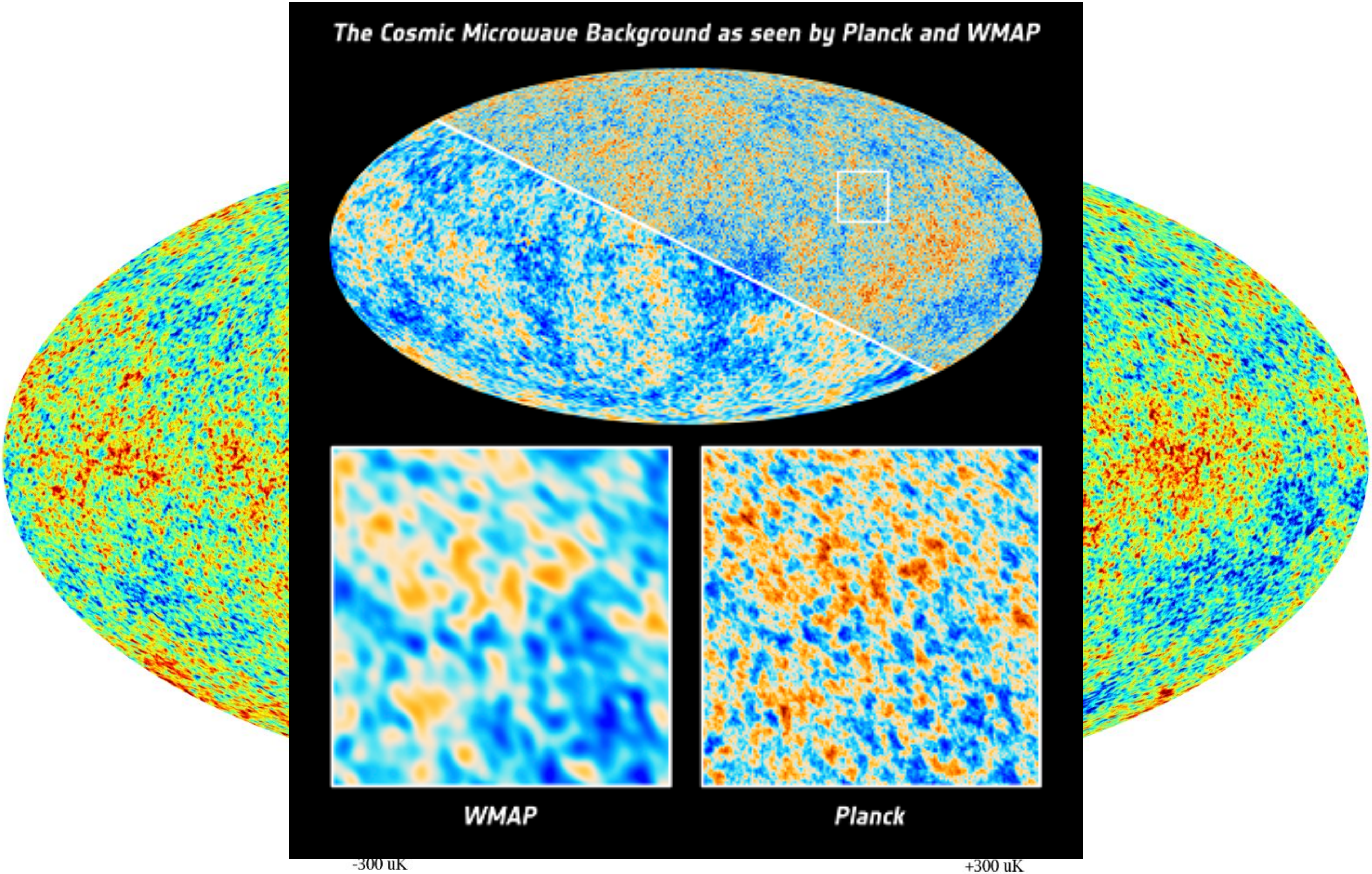




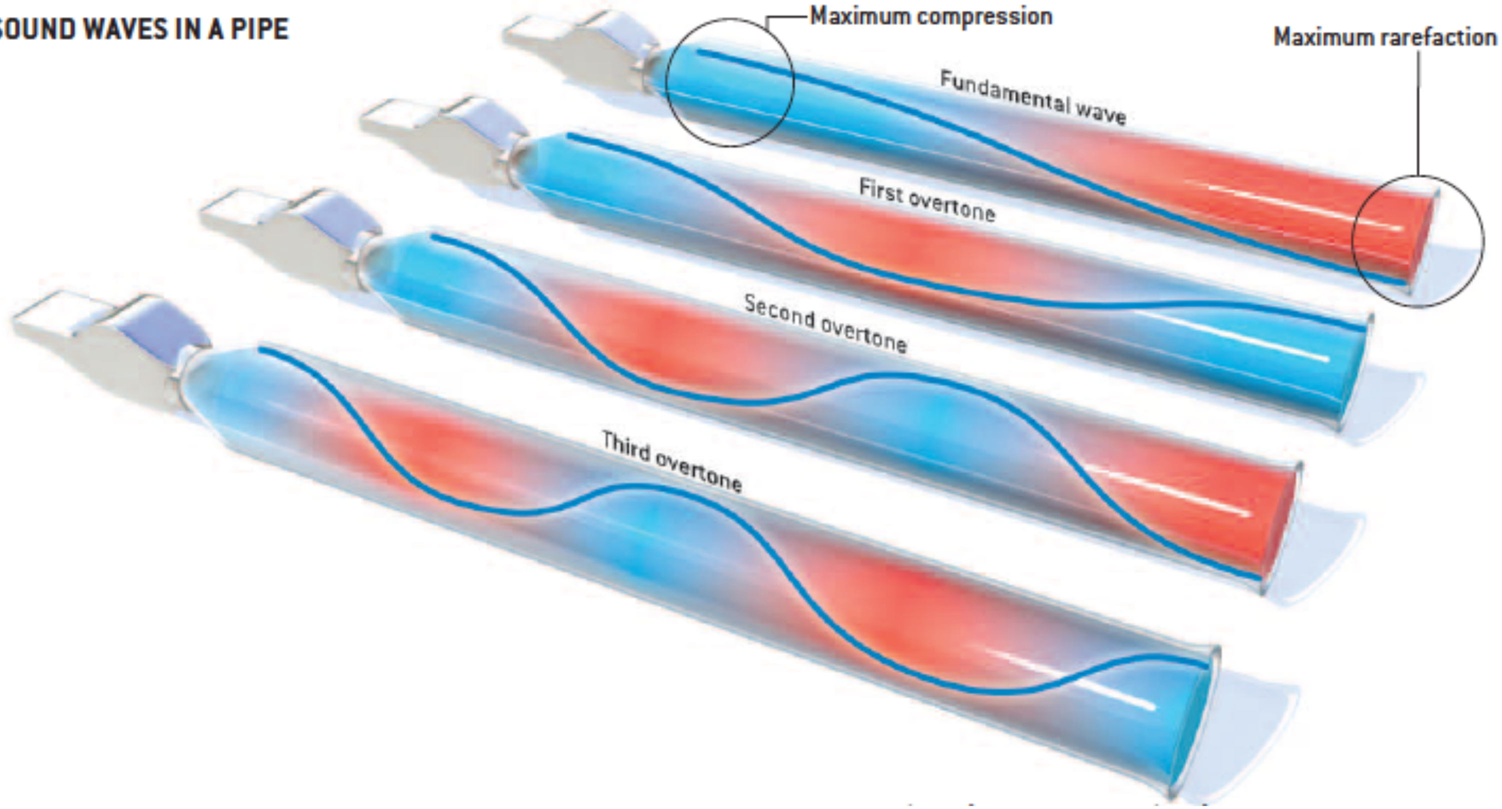
T=2.72548+-0.00057 K



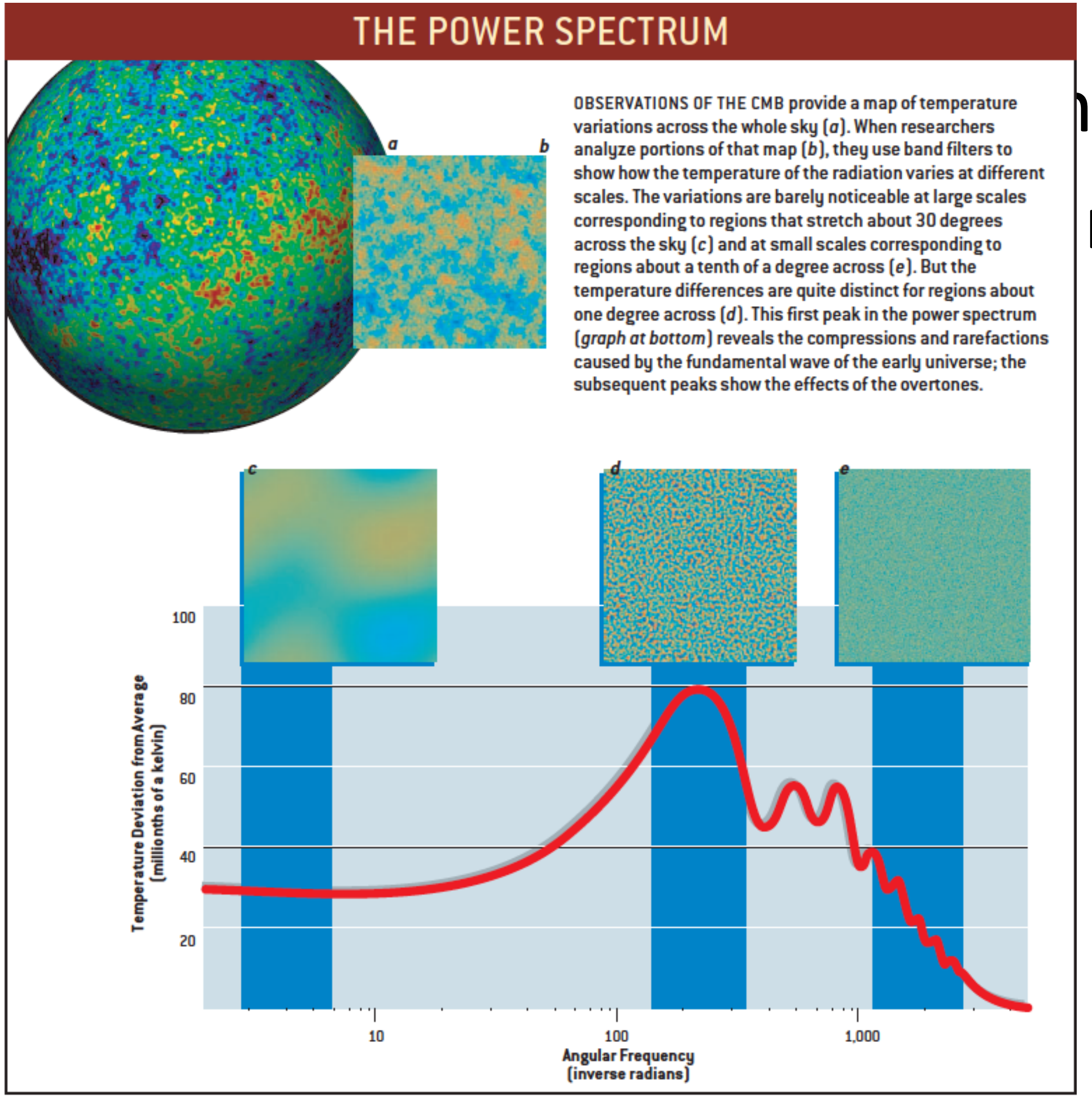
- http://sci.esa.int/science-e-media/video/64/571_Planck_CMB_with_foreground_emission_layers.mov


The Cosmic Microwave Background as seen by Planck and WMAP
WMAP
Planck
-300 uK
+300 uK

SOUND WAVES IN A PIPE



fluktuacije v prasevanju

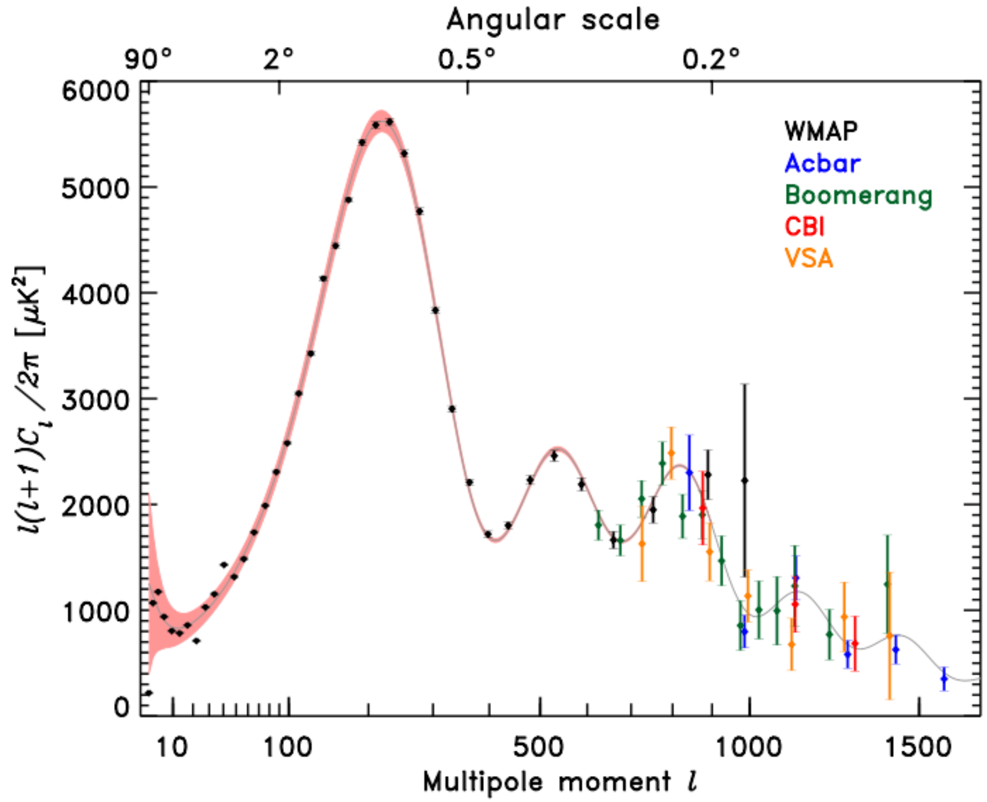


Y_{lm}

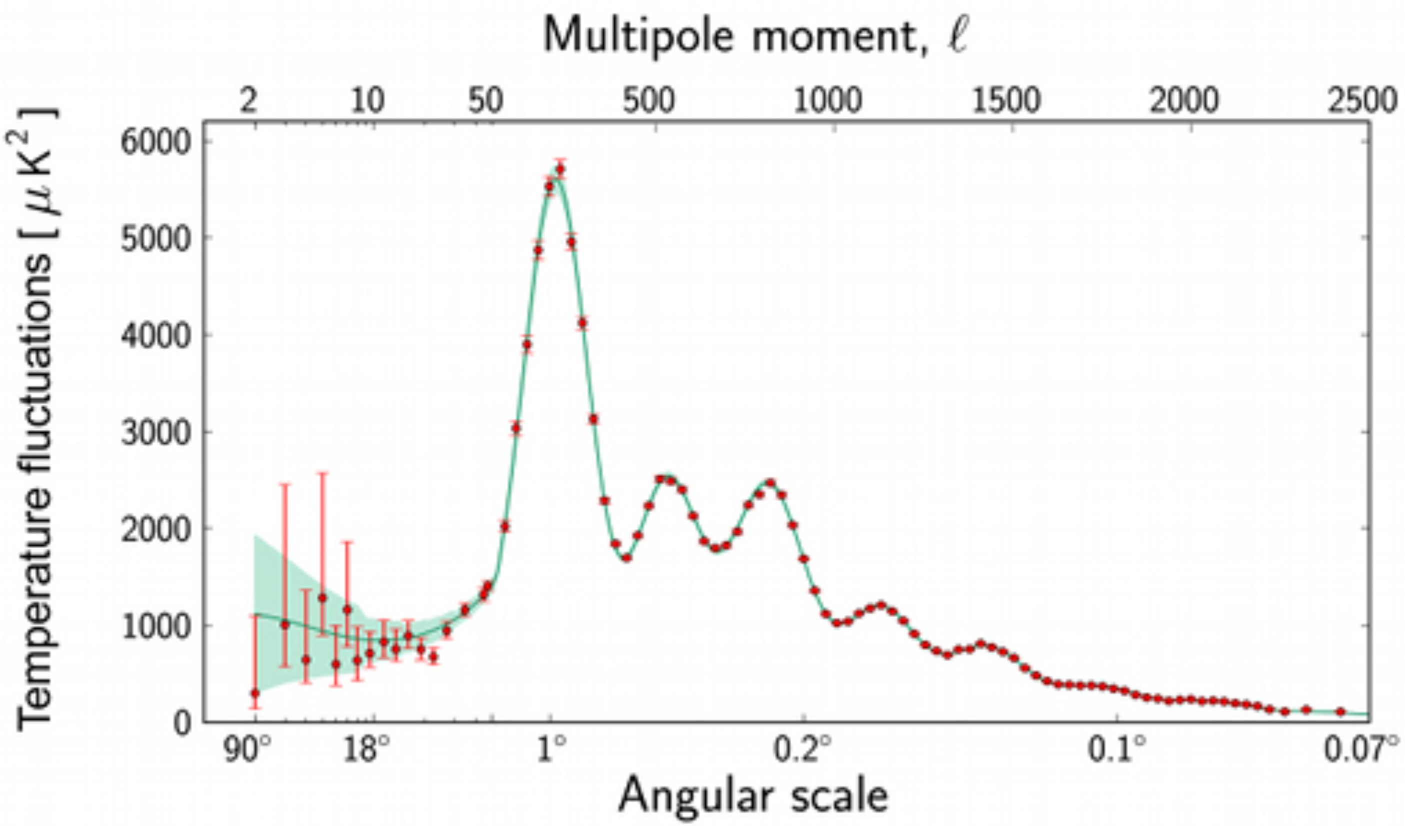
na skalah $\theta=180°/l$

spekter moči

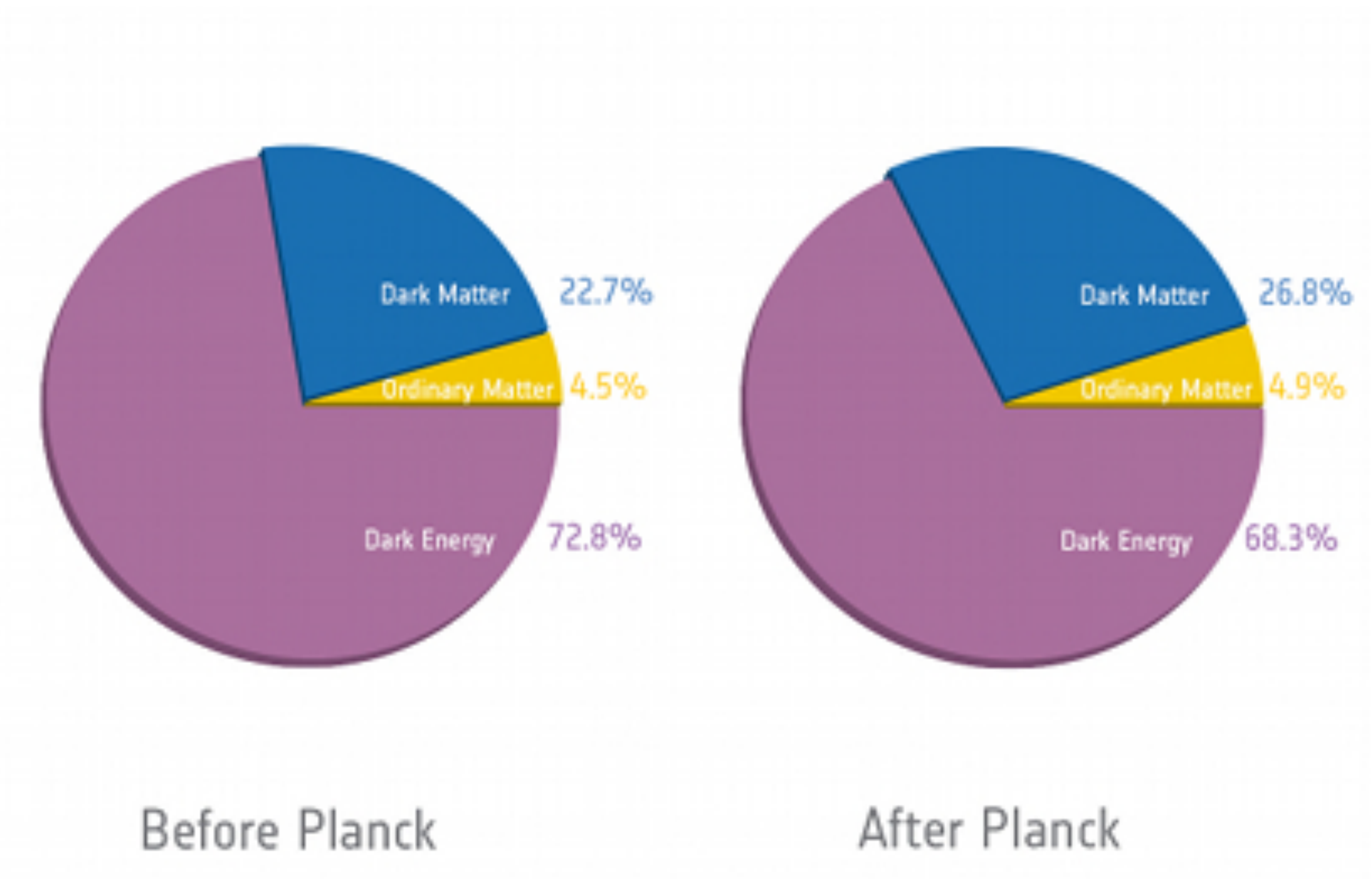
- iz meritev lahko določijo C_l in primerjajo z napovedmi različnih kozmoloških modelov– tako lahko določijo kozmološke parametre: Ω_λ, Ω_m, Ω_{tot}



Planck 2013



Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μK^2]
6000
5000
4000
3000
2000
1000
0
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale



Ω_{λ}=0.685, Ω_{m}=0.315, Ω_{tot}=1

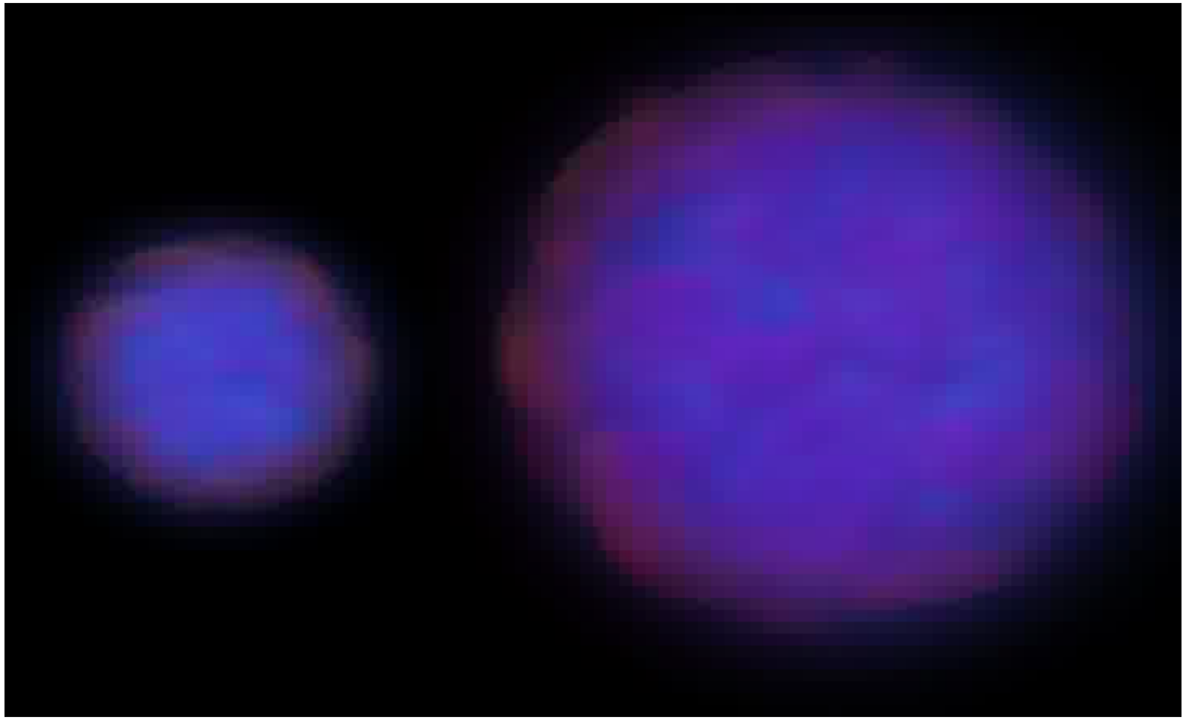
- nehomogenost in rast struktur

dokazi za Veliki pok /prapok

- Olbersov paradoks
- oddaljevanje galaksij
- prasevanje
- prvinska nukleosinteza
- starost vesolja
- razvoj teles z oddaljenostjo (z)

Odprta vprašanja

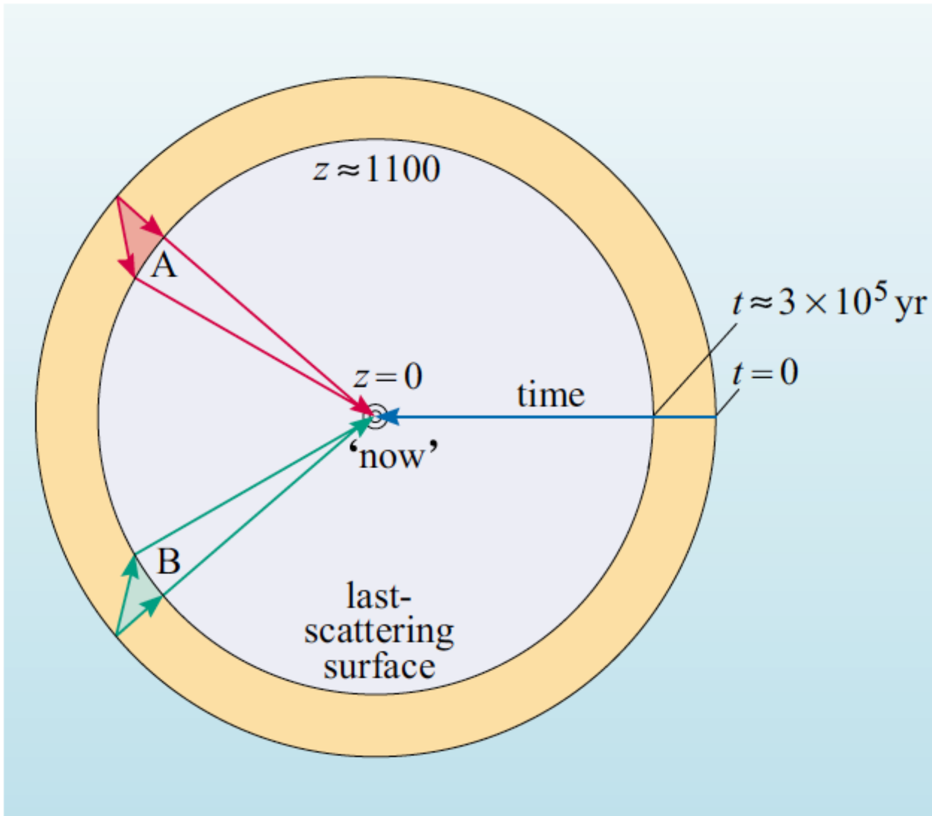
- # Kaj je temna snov?
- 15% snovi barionske (vidne in nevidne), večina snovi nebarionske (WIMP)
- MOdified Newtonian Dynamics – MOND
- rabimo hladno temno snov (supesimetrični delec?)



- Kaj je temna energija?
- kozmološka konstanta Λ
- energija vakuma
- kvintesenca

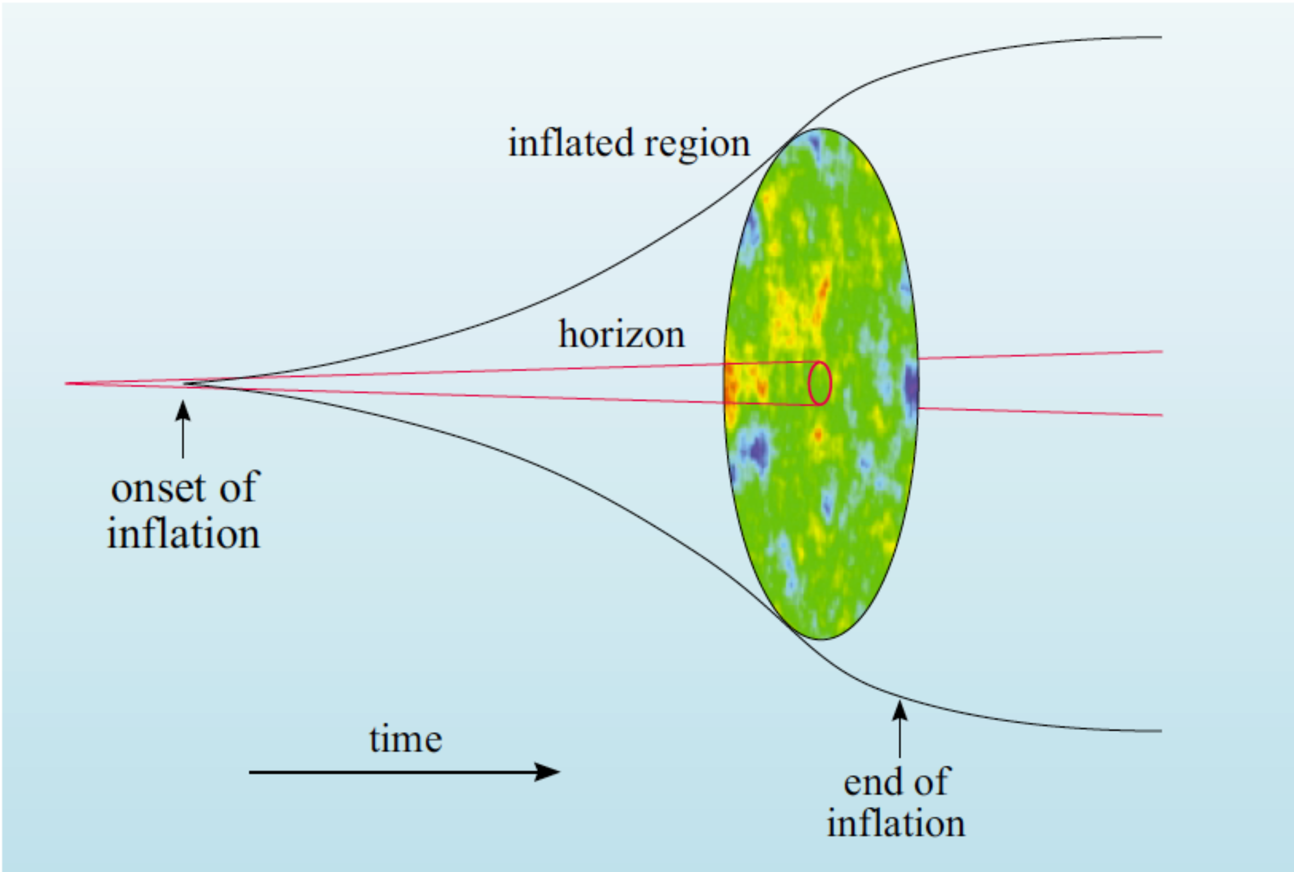
zakaj je vesolje enakomerno in ravno?

- problem horizonta:
- območji A in B nista bili v "kavzalnem" stiku – zakaj imata enako T?



inflacija

- dodatek k modelu prapoka



- problem ravnosti (flatness problem):
- zakaj je tako točno: $k=0$ oz. $\Omega+\Omega_{\Lambda}=1$?
- slučaj?
- inflacija?

- izvor stuktur:
- od kje fluktuacije?
- rast?

- zakaj več snovi kot antisnovi?
- po ali ob inflaciji?

- kaj se je zgodilo ob času t=0?

- zakaj je vesolje tako kot je?
- šibko in močno antropično načelo

- npr. Martin Rees: 6 števil