Kosmologi i lys av Nobelprisen i fysikk til Jim Peebles 2019

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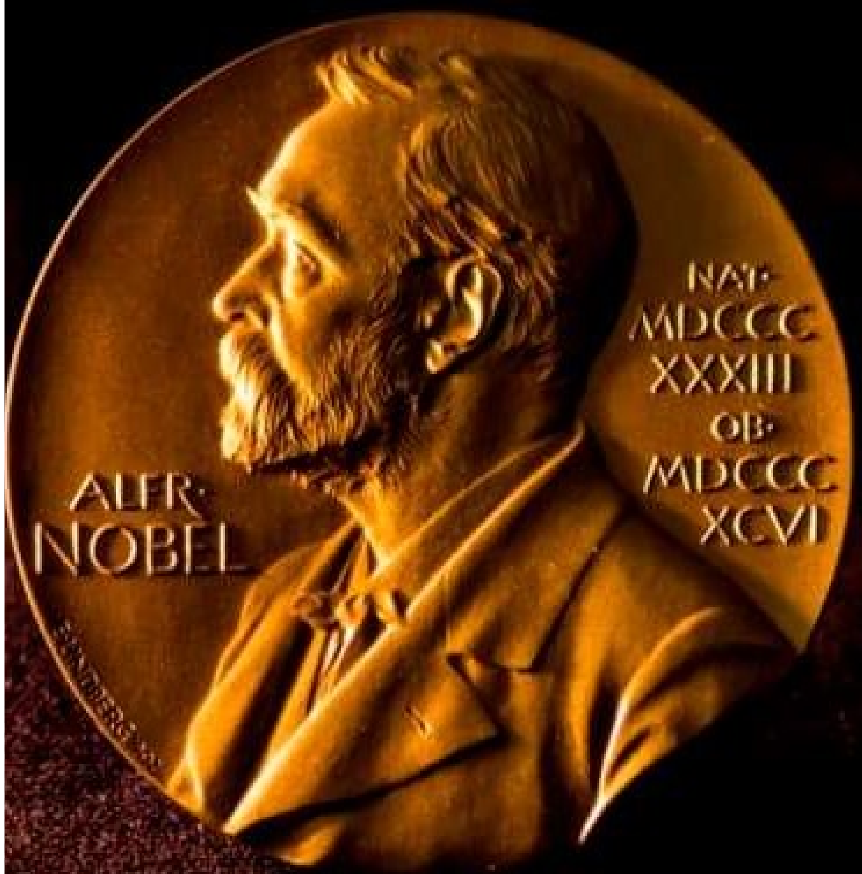
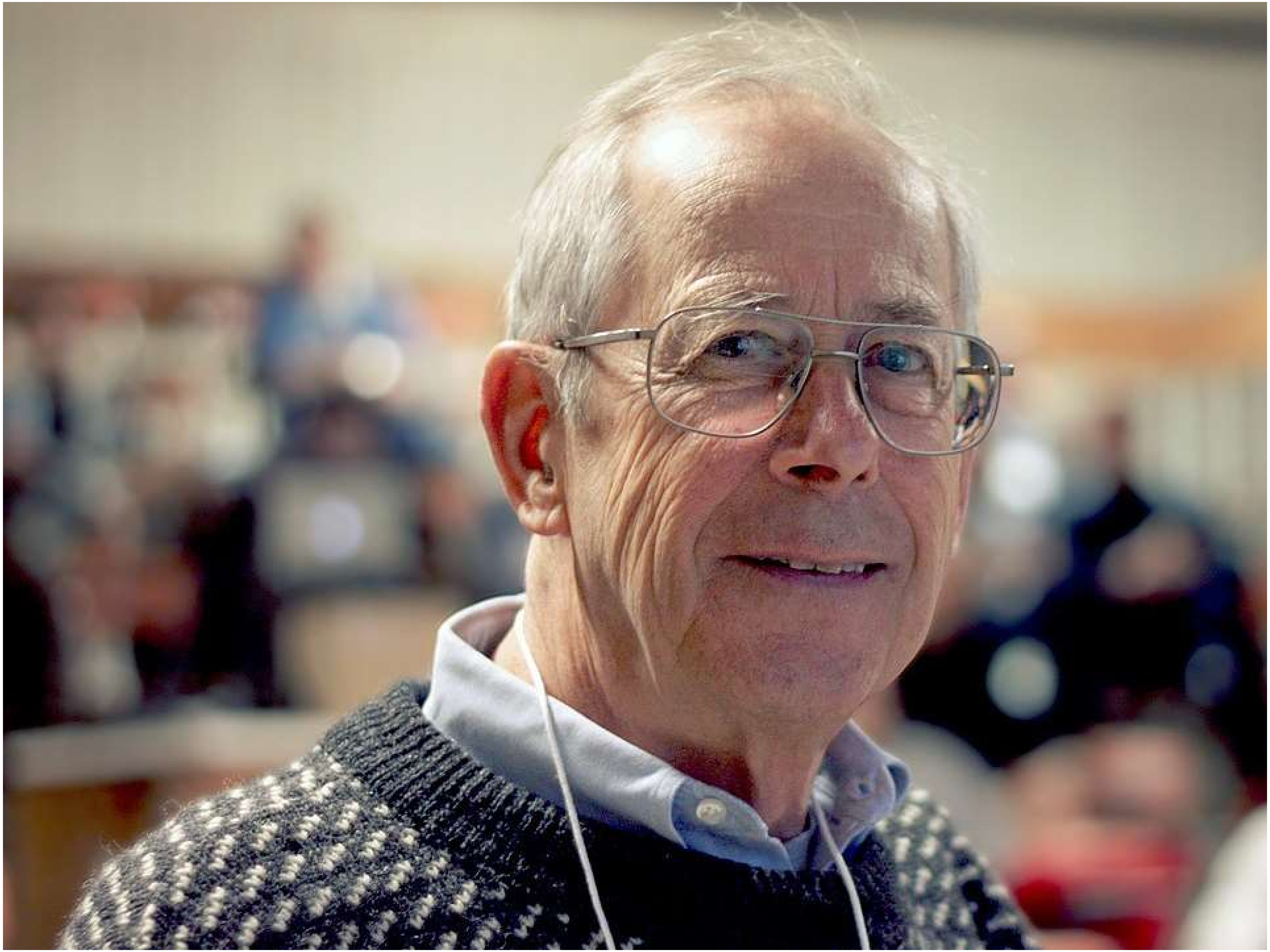
Trondheim Astronomiske Forening
29. oktober 2020



The Nobel Prize in Physics 2019 was awarded "for contributions to our understanding of the evolution of the universe and Earth's place in the cosmos"
with one half to James Peebles "for theoretical discoveries in physical cosmology",
the other half jointly to Michel Mayor and Didier Queloz "for the discovery of an exoplanet orbiting a solar-type star."



James Peebles
The Nobel Prize in Physics 2019

Born: 25 April 1935, Winnipeg, Canada

Affiliation at the time of the award: Princeton University, Princeton, NJ, USA

Prize motivation: "for theoretical discoveries in physical cosmology."

Prize share: 1/2

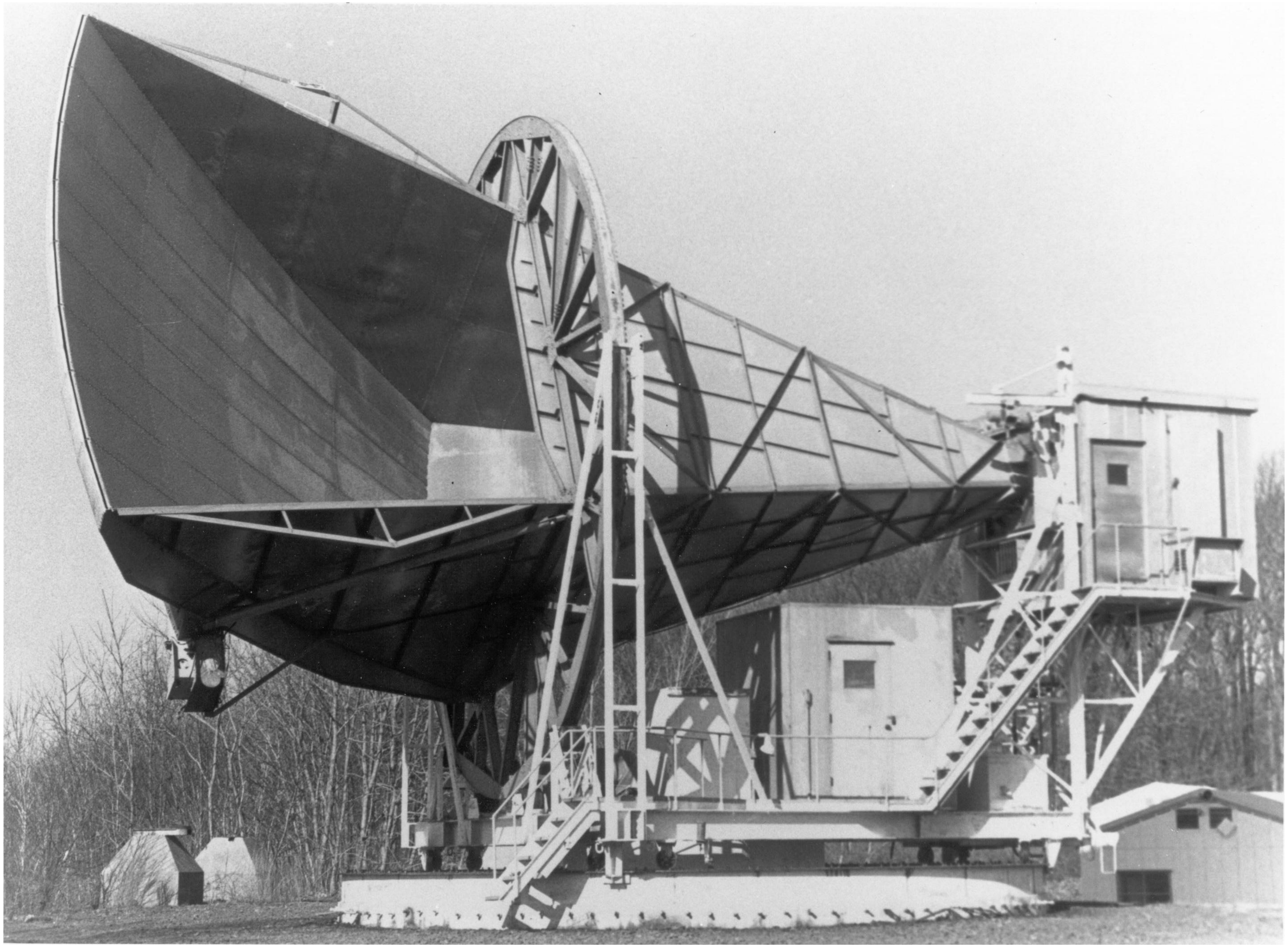
Jim Peebles at Princeton in 1998

The spring of 1965 was dramatic for cosmology.

In a paper dated 13 May and published
in The Astrophysical Journal Letters,
Arnold Penzias and Robert Wilson
described their discovery of what was to be identified as the
cosmic microwave background radiation.

For this they were awarded the Nobel Prize in Physics 1978.

The 20 foot Horn-Reflector



They had found the after glow of the enormous heat left over from the "BIG BANG".

The discovery was unexpected for the discoverers.
Only through contact with a team consisting of
Robert Dicke, Jim Peebles, Peter Roll and David Wilkinson
at Princeton University,
did Penzias and Wilson become aware of the cosmological
explanation for the cold radiation they had detected.

The significance of their discovery
was described in a paper in the same issue, dated 7 May:

[17] R.H. Dicke, P.J.E. Peebles, P.G. Roll and D.T. Wilkinson, *Cosmic black-body radiation*, Astrophys. J. **142**, 414 (1965)

I en artikkel skrevet i 1990 for å feire at det var 25 år siden oppdagelsen av
den kosmiske mikrobølge bakgrunnsstrålingen,
skrev den britiske fysikeren Dennis Sciama:

We may usefully distinguish three ways in which the cosmic microwave background changed our thinking:

a) From its use as a probe of conditions in the universe, particularly of its small-scale and large-scale isotropy.

b) dynamically, by its direct influence on cosmological phenomena.

c) fundamentally, by its significance for our understanding of the origin of the universe.

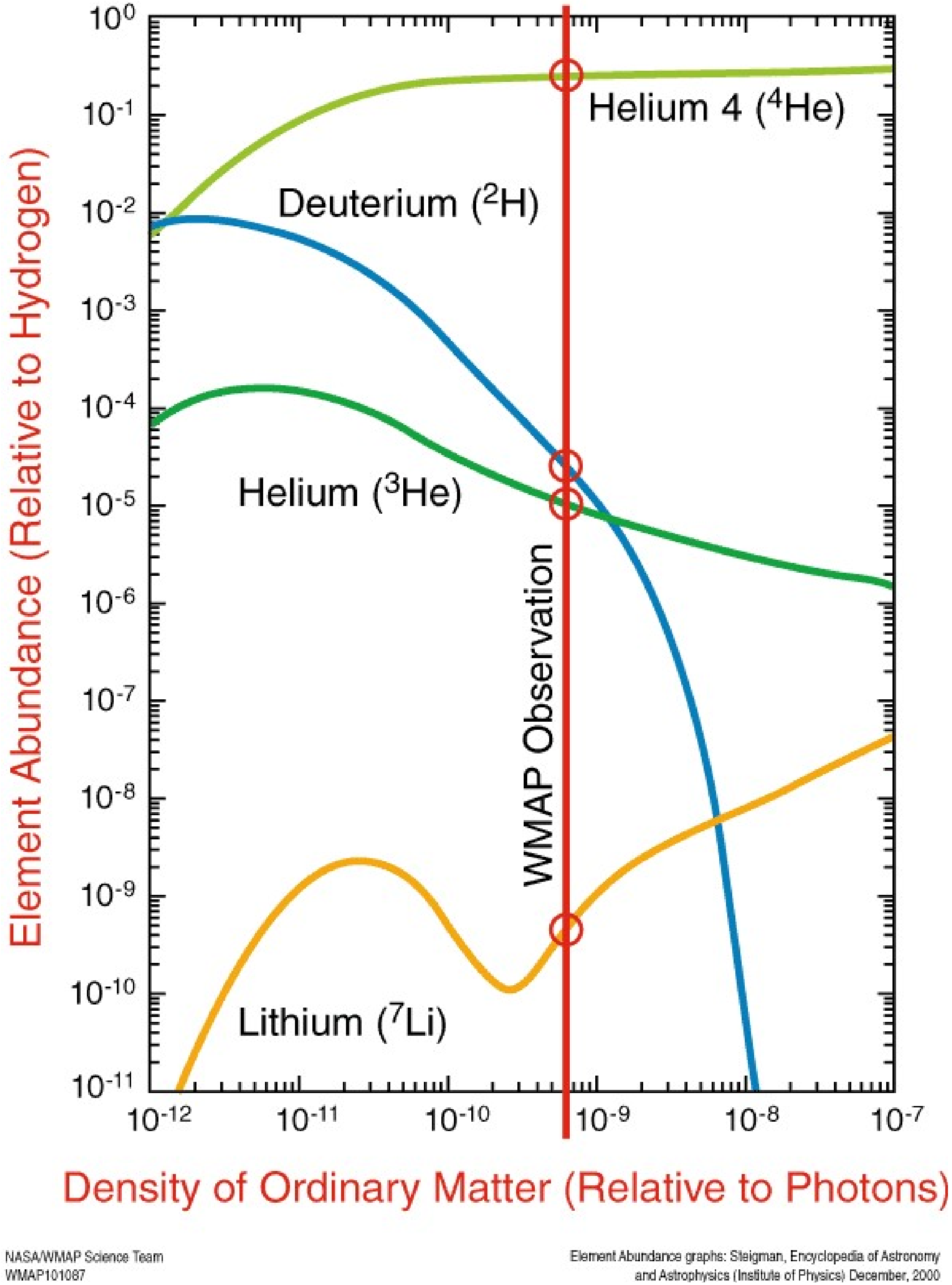
Big Bang nucleosynthesis

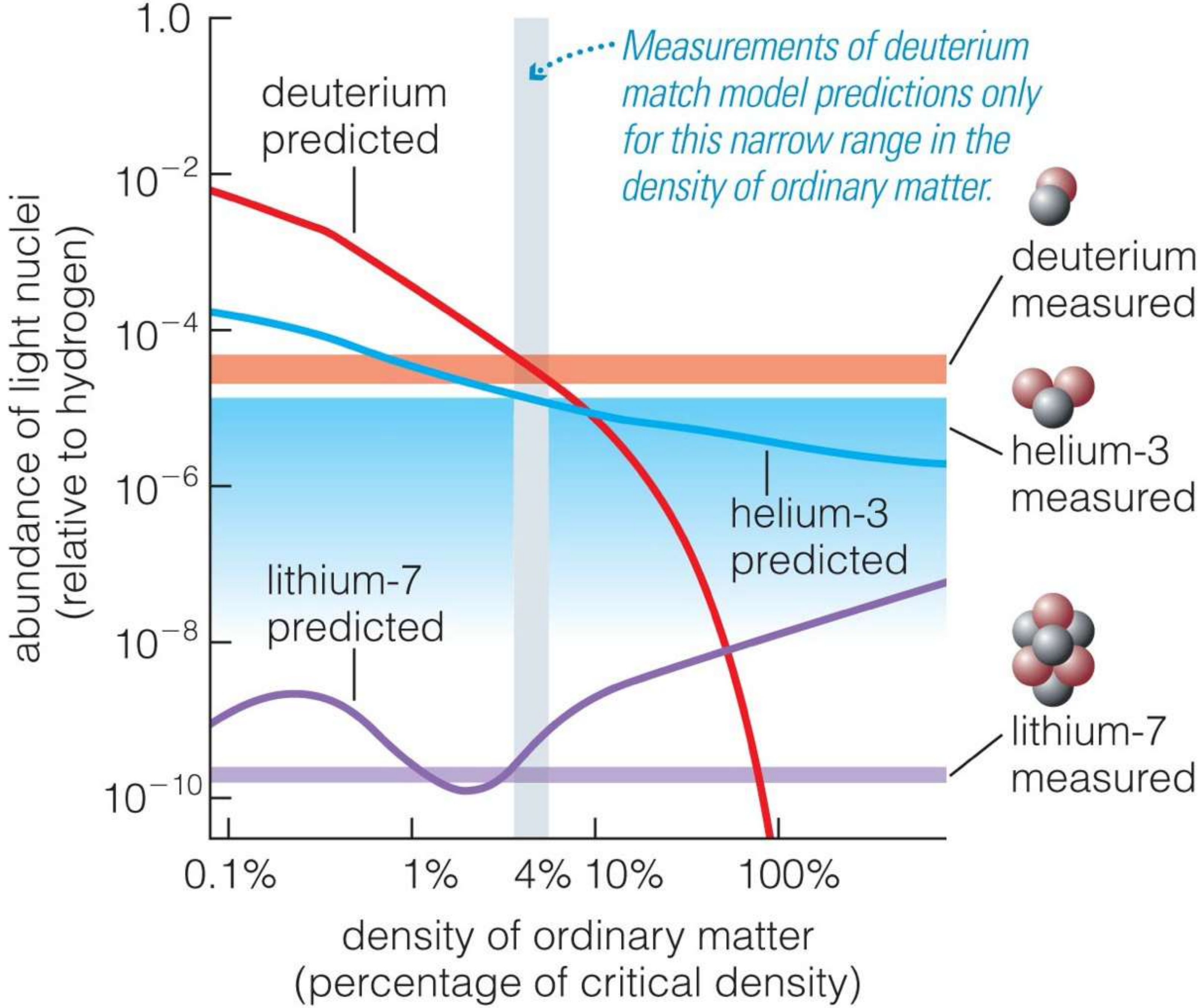
One second after the Big Bang, the temperature of the universe was roughly 10 billion (milliarder) degrees. The universe was then filled with a sea of neutrons, protons, electrons, anti-electrons (positrons), photons and neutrinos. As the universe cooled, the neutrons either decayed into protons and electrons or combined with protons to make deuterium (an isotope of hydrogen). During the first three minutes of the universe, most of the deuterium combined to make helium. Trace amounts of lithium were also produced at this time. This process of light element formation in the early universe is called “Big Bang nucleosynthesis” (BBN).

The graphs show the average cosmic mass densities of helium, deuterium and lithium relative to hydrogen predicted by the BBN-theory as function of the present ratio of the number density of ordinary matter atoms and photons. The ratios of the number densities of the light elements and hydrogen have been nearly constant since about 15 minutes after the Big Bang.

The upper curve means that about 24% of the ordinary matter in the universe should be helium produced in the Big Bang. This is in good agreement with observations.

The WMAP satellite measured the density of ordinary matter and found that it should make up 4.6% (±0.2%) of the contents of the universe. This is indicated by the vertical red line. It leads to predicted abundances of other light element isotopes as shown by the circles in the graph. These predictions are in good agreement with observed abundances.





1.0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
abundance of light nuclei
(relative to hydrogen)
deuterium
predicted
Measurements of deuterium
match model predictions only
for this narrow range in the
density of ordinary matter.
deuterium
measured
helium-3
measured
helium-3
predicted
lithium-7
predicted
lithium-7
measured
0.1%
1%
4%
10%
100%
density of ordinary matter
(percentage of critical density)

A key contribution is a paper by Peebles alone from the same year, 1965 [22]. He had already submitted it to The Astrophysical Journal on 8 March 1965, revised 1 June and published 15 November. The first sentence of the abstract states: “A critical factor in the formation of galaxies may be the presence of a black-body radiation content of the universe.”

This work, together with other contributions by the late Russian cosmologist Yakov Zeldovich [23], can be viewed as the starting point of physical cosmology, where the laws of physics are applied to the Universe at large. This is the moment when cosmology embarks on its way to become a science of precision and a tool to discover new physics.

A breakthrough in the understanding of the acoustic waves, and the peaks they cause in the power spectrum of the CMB, came through the works of Rashid Sunyaev and Yakov Zeldovich [27], as well as of Peebles and Jer Yu [28].

Sunyaev and Zeldovich [27] explained the physics behind the acoustic peaks and their periodic nature.

Peebles and Yu [28] had a different focus, using numerical methods to calculate and predict what actually could be measured. In their paper, they worked out power spectra of density fluctuations for different cosmological parameters.

[28] P.J.E. Peebles and J.T. Yu, *Primeval adiabatic perturbation in an expanding Universe*, Astrophys. J. **162**, 815 (1970)

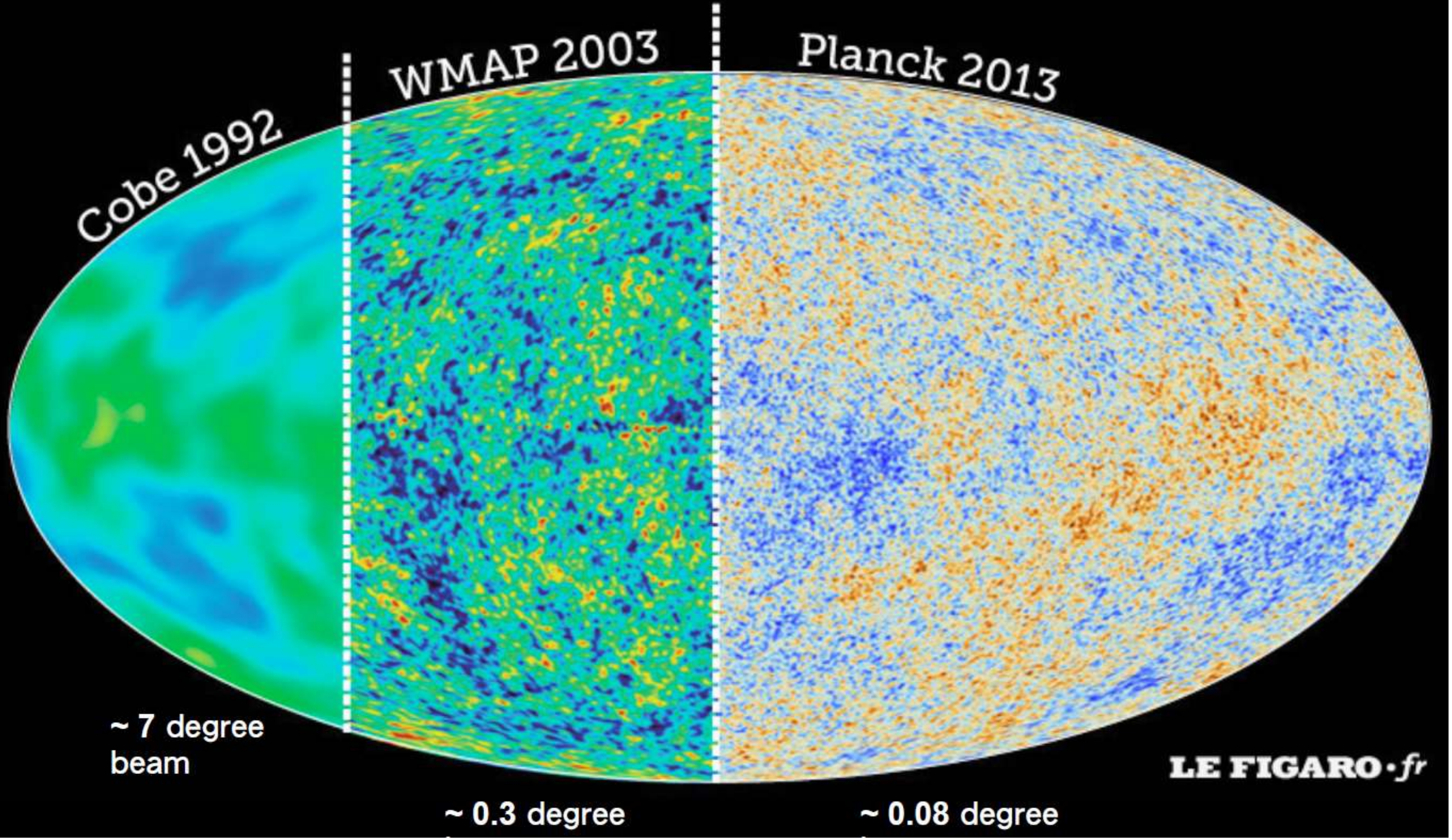
George Gamov (1904-1968)

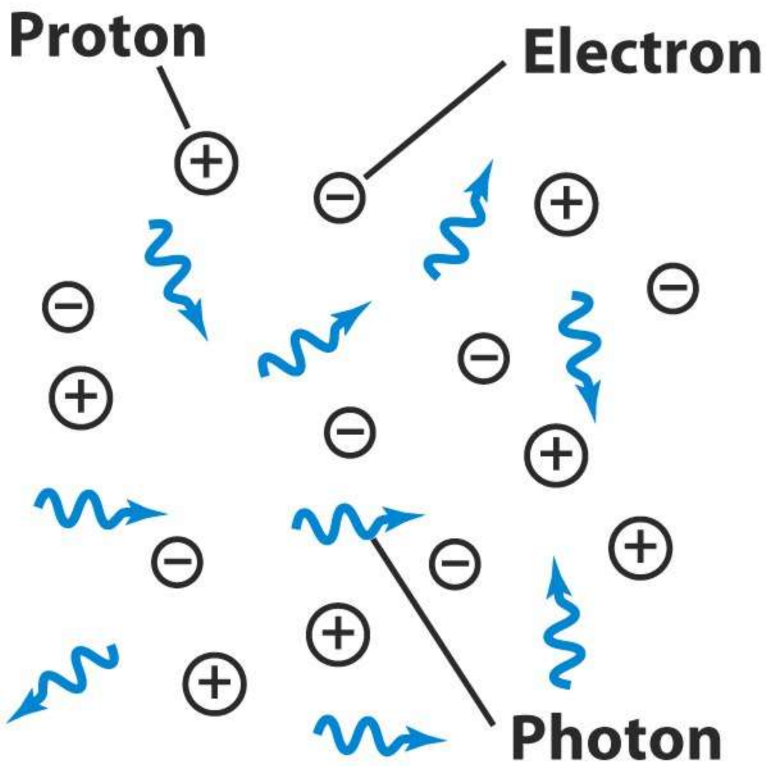
building on Georges Lemaître

- The Universe has evolved from a Big Bang with great density and high temperature.
- Alpher, Bethe & Gamow constructed in 1948 a theory for cosmic nucleosynthesis
  - success: The theory predicted that the cosmic matter should consist of about 25 % hydrogen and 24 % helium.
  - but: The theory could not explain the existence of elements heavier than lithium.

- Surprisingly this prediction of Gamow and coworkers was forgotten.
- The result was rediscovered by Dicke and Peebles early in the sixties. They then started building a receiver to observe this micro wave radiation.
- But before they had finished their detector the radiation was found by Penzias and Wilson.

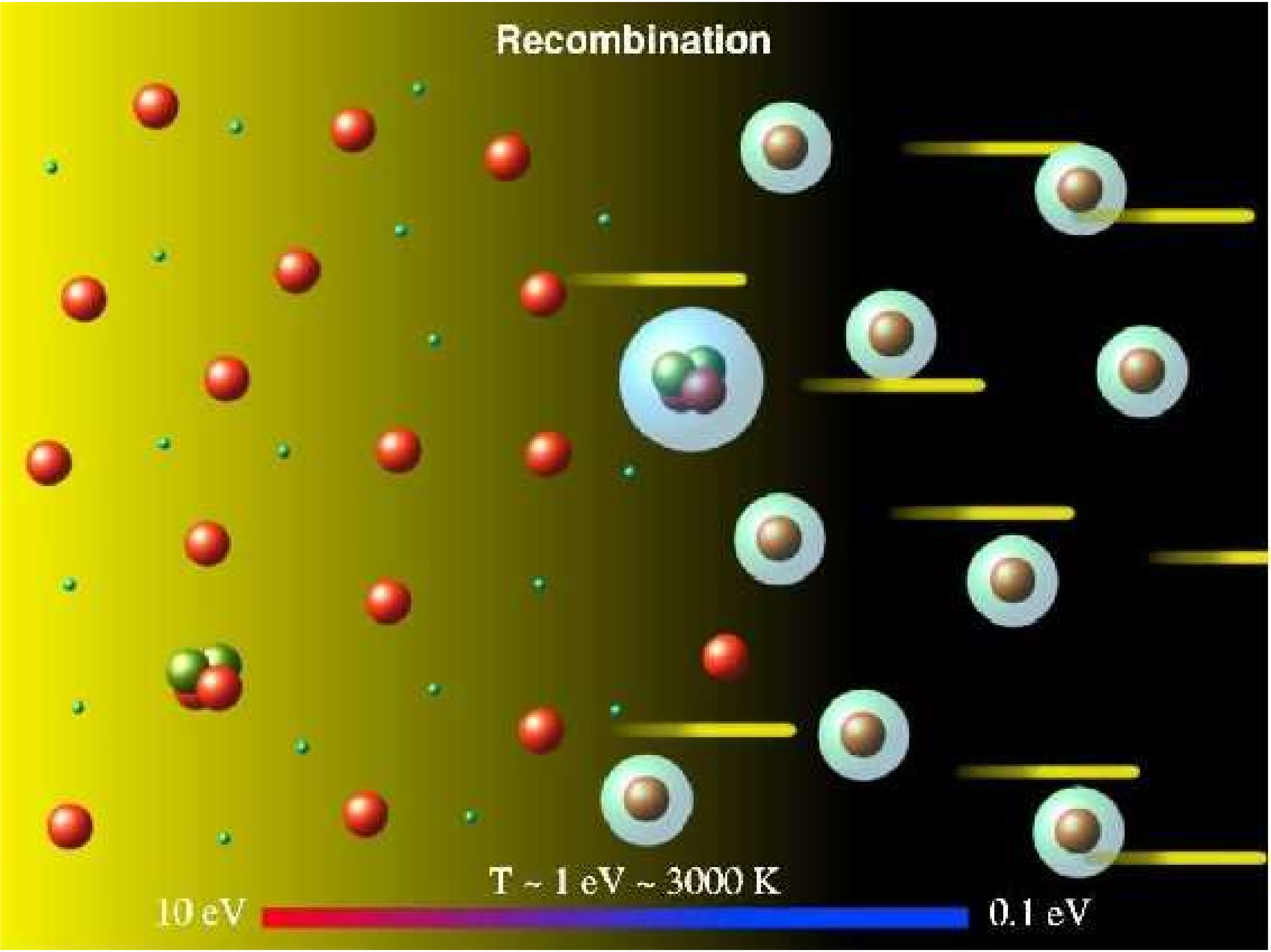
Dramatic improvements in angular resolution and sensitivity over the past decades!



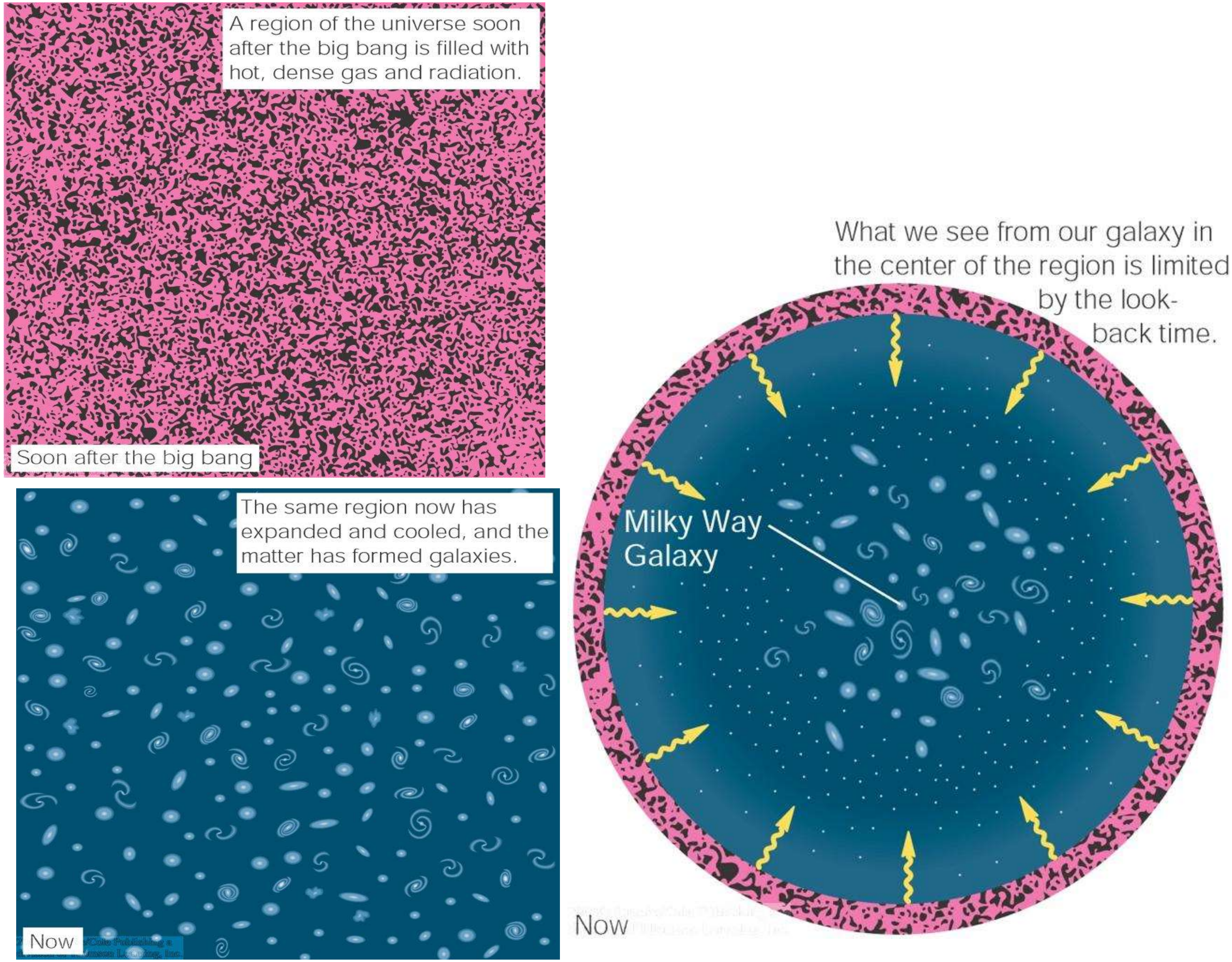


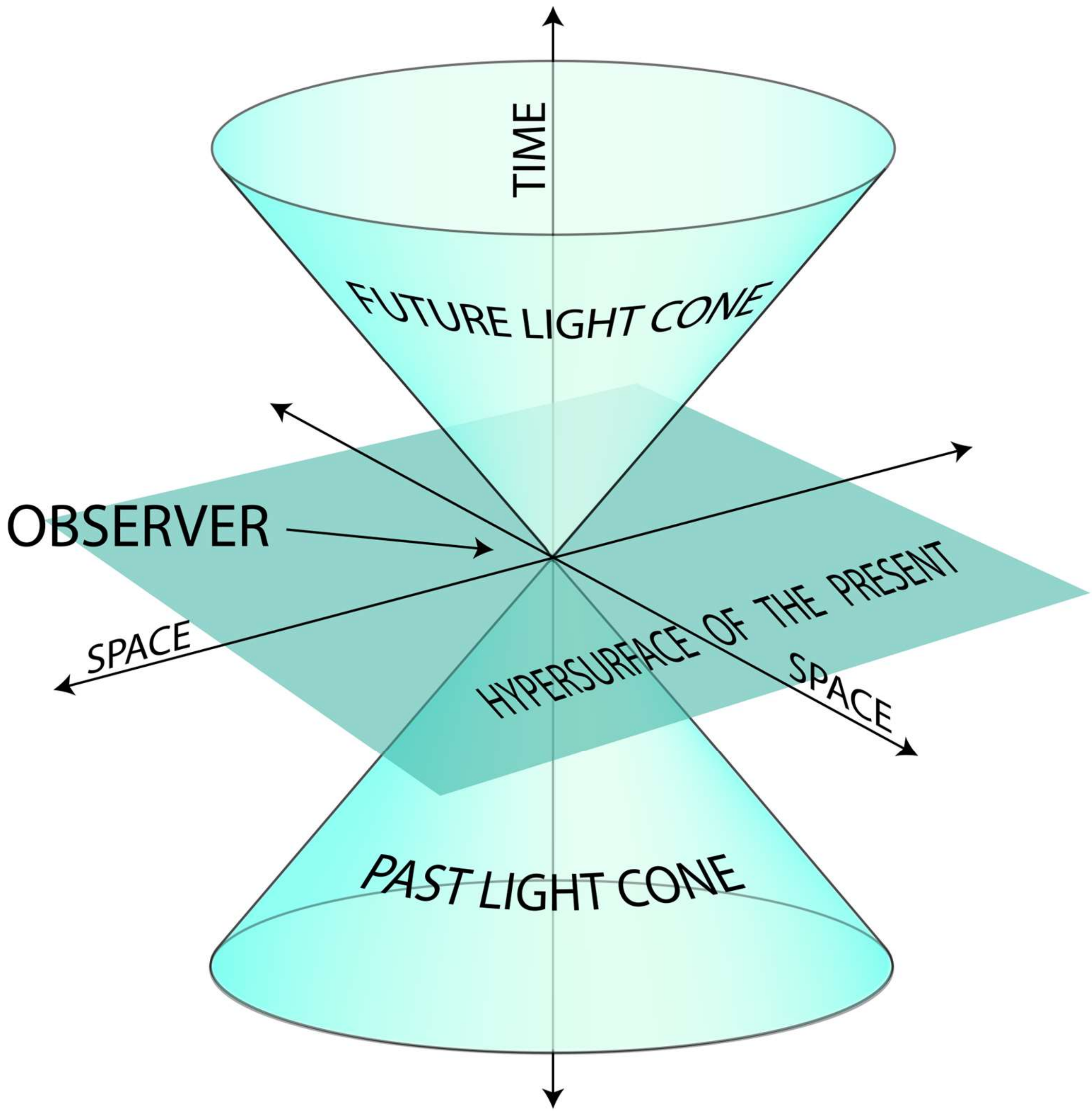
Before recombination:

- Temperatures were so high that electrons and protons could not combine to form hydrogen atoms.
- The universe was opaque: Photons underwent frequent collisions with electrons.
- Matter and radiation were at the same temperature.

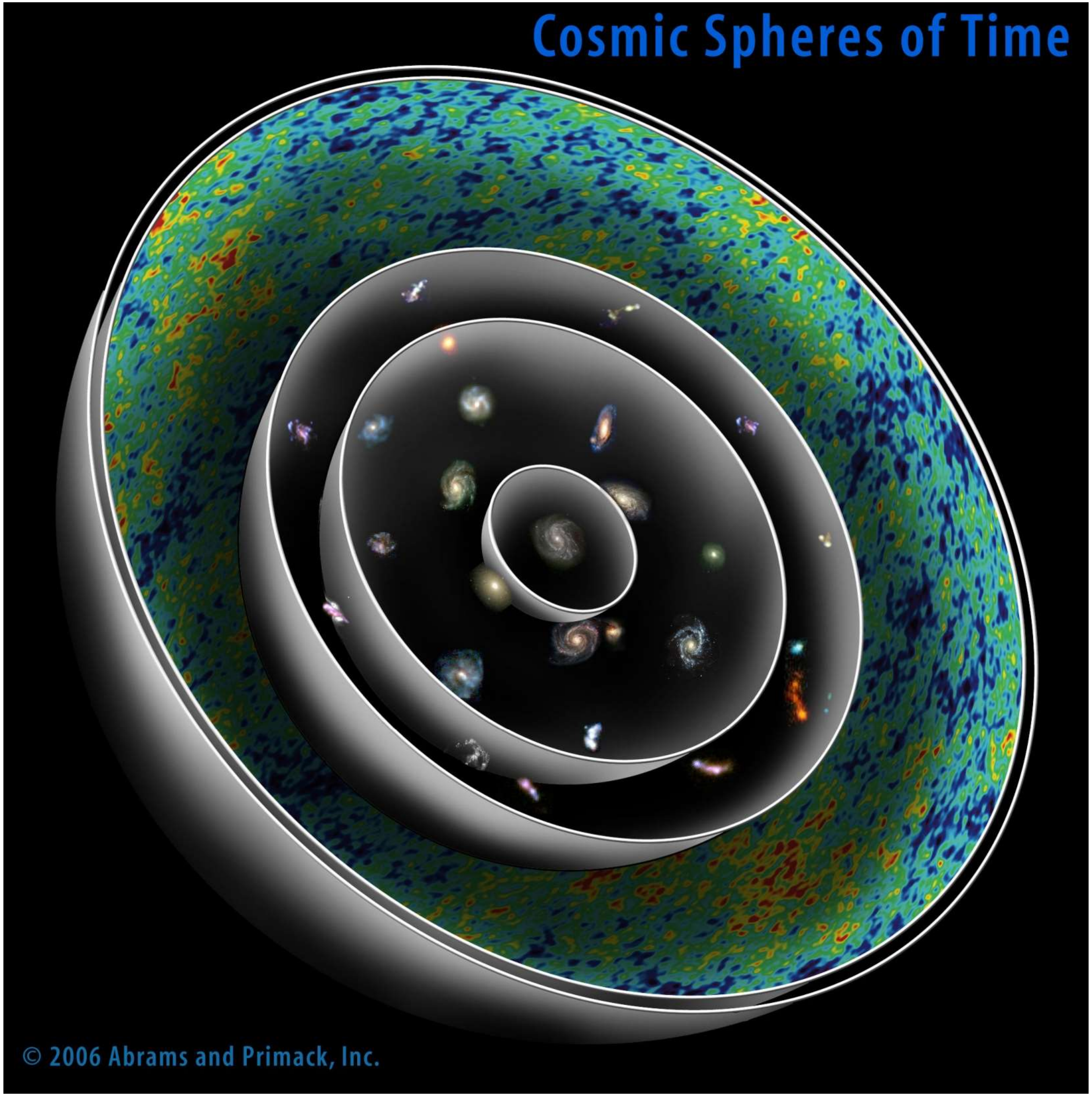

Recombination
T ~ 1 eV ~ 3000 K
10 eV
0.1 eV

Når vi observerer temperaturvariasjonene i den kosmiske bakgrunns-strålingen, ser vi hvordan universet var 400 000 år etter Big Bang.





We observe along the backwards light cone.
We see how an object was when it emitted the light we receive.
Looking outwards in the universe, we observe backwards in time.


Cosmic Spheres of Time
© 2006 Abrams and Primack, Inc.

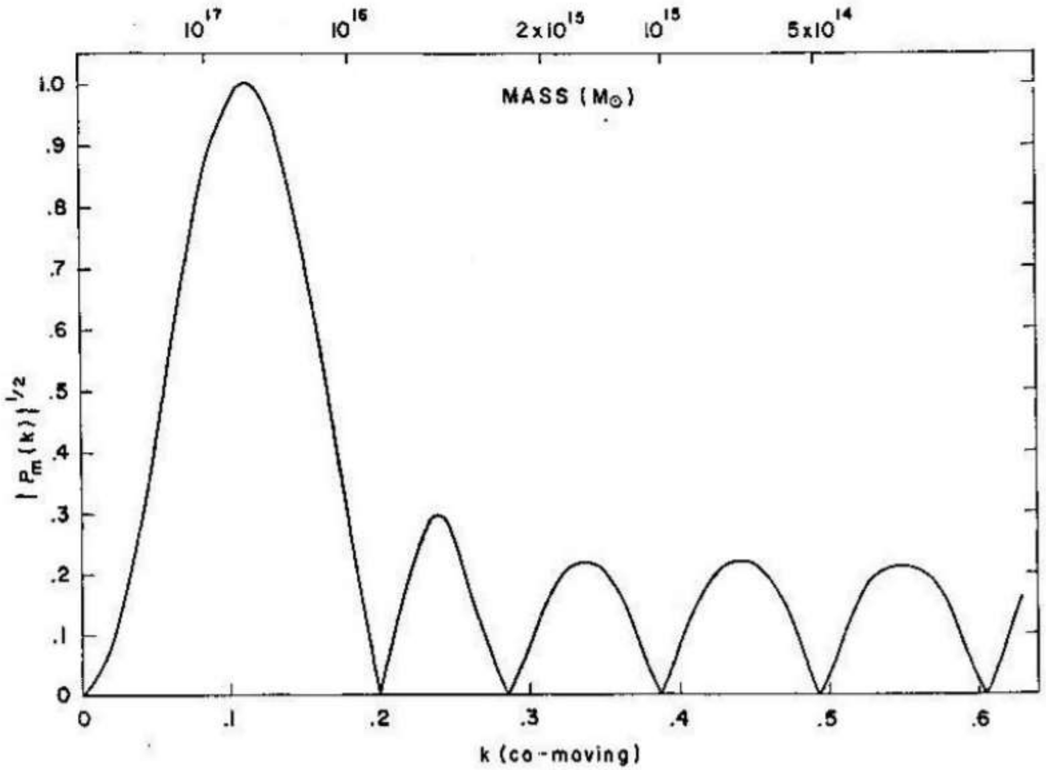


Figure 3. *Power spectrum for a flat universe according to Peebles and Yu [27], showing the acoustic peaks. The normalization is fixed to peak value unity.*

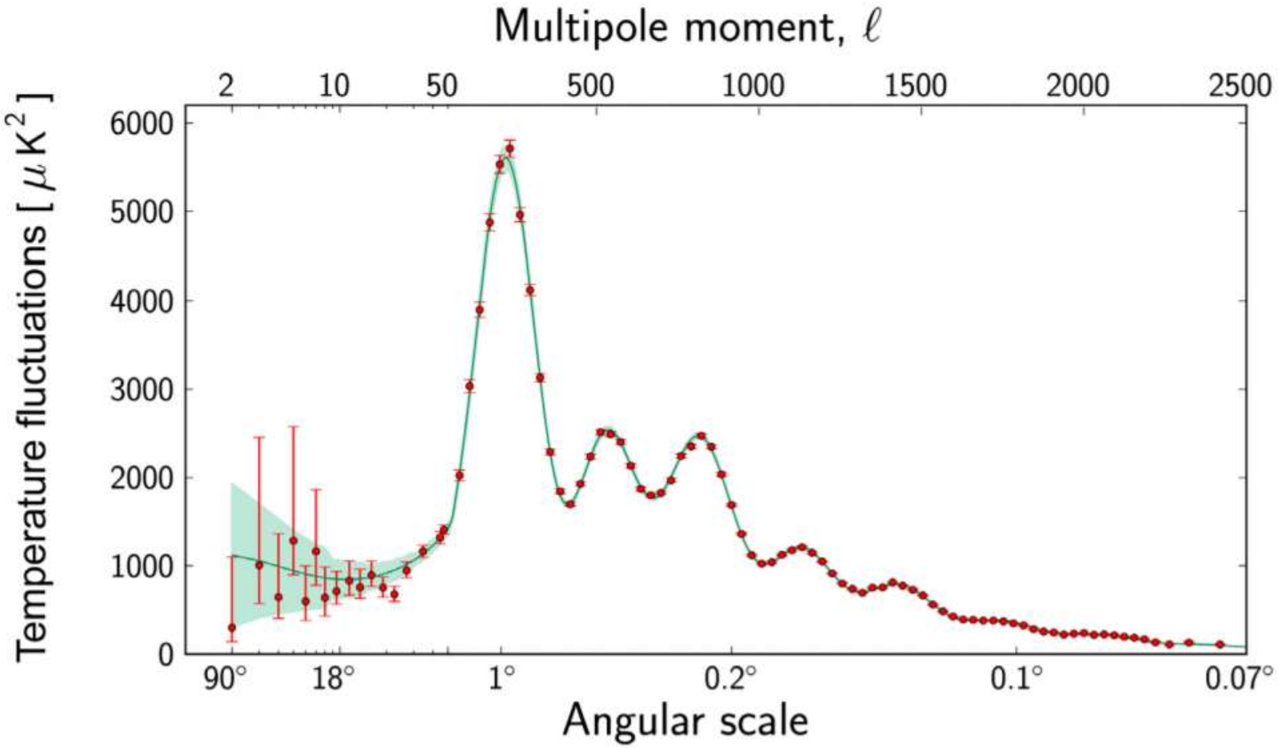
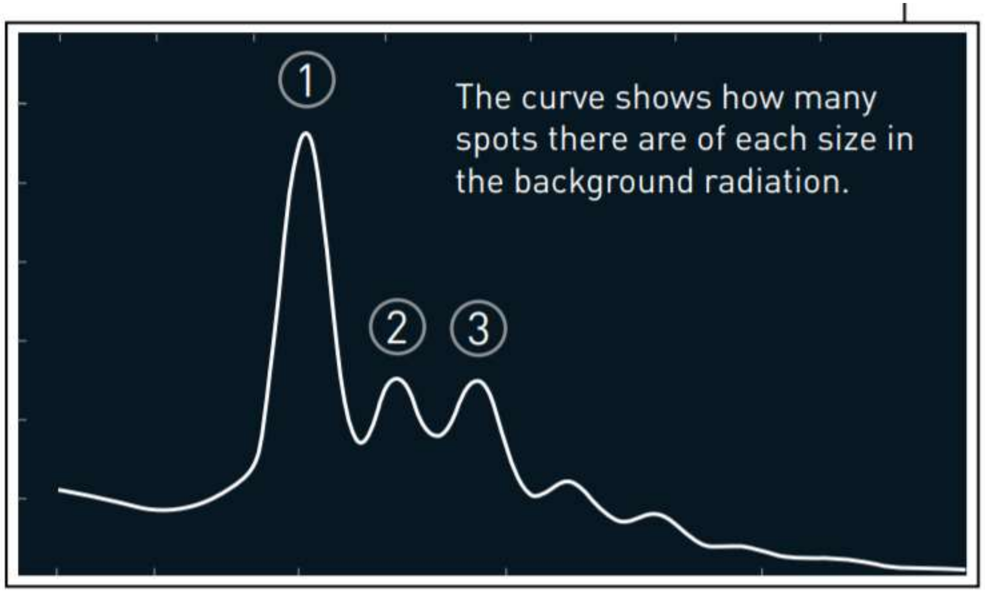


***Figure 4**. Anisotropies in the temperature of the CMB as measured by the Planck satellite. The acoustic peaks are clearly visible.*



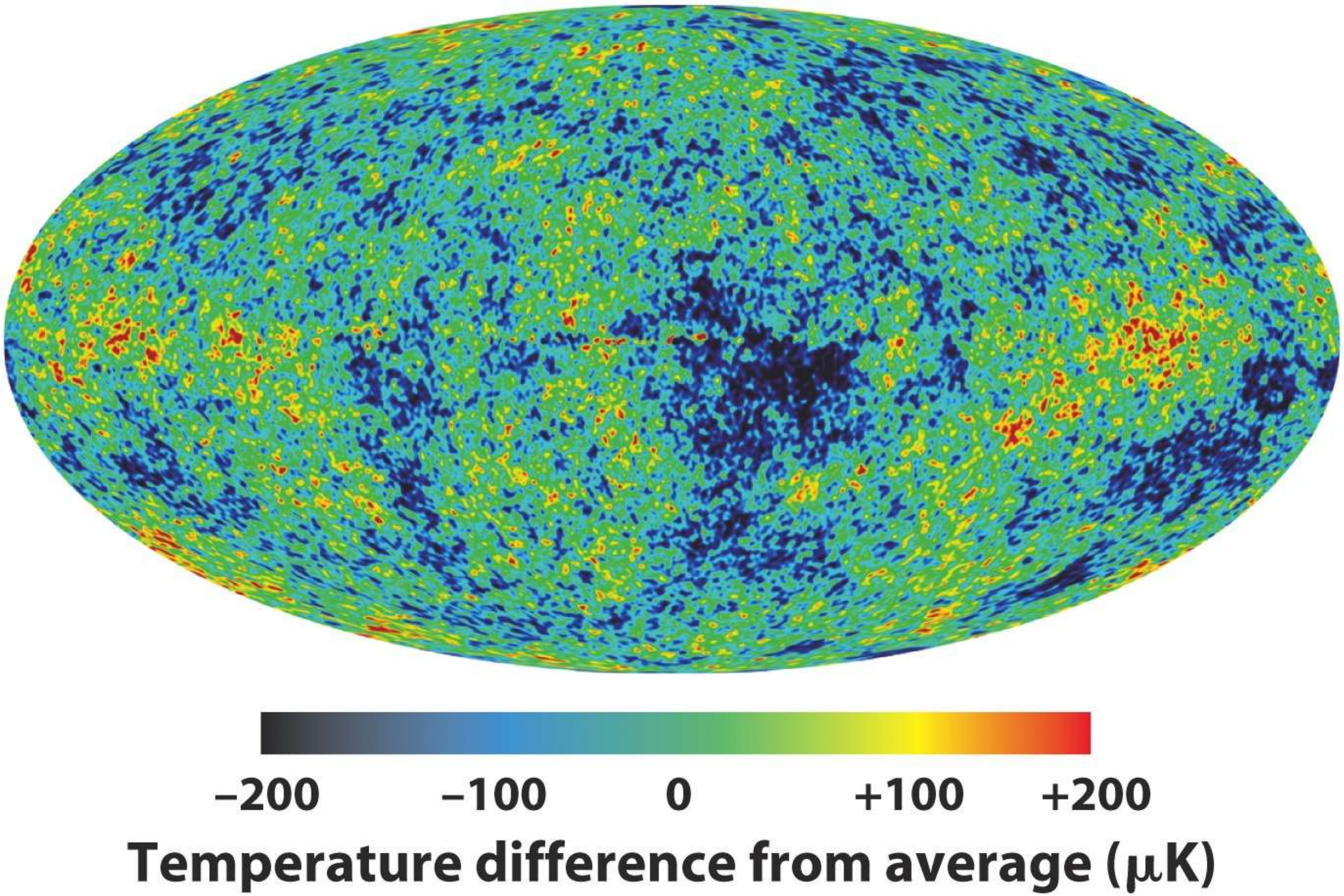
1. The first peak shows that the universe is geometrically flat, i.e. two parallel lines will never meet.

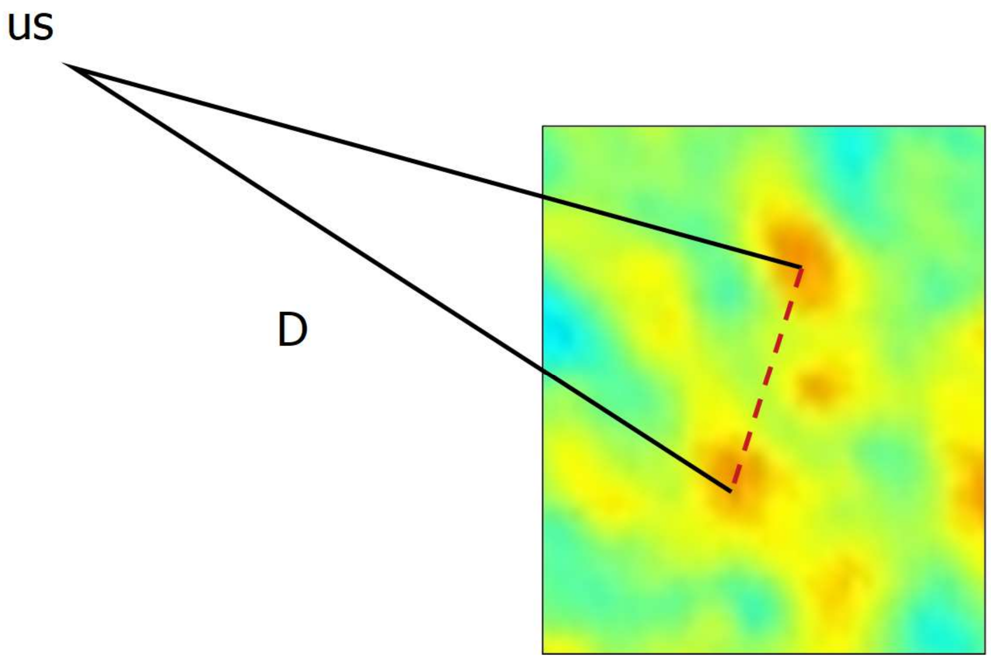
2. The second peak shows that ordinary matter is just 5% of the matter and energy in the universe.

3. The third peak shows that 26% of the universe consists of dark matter.

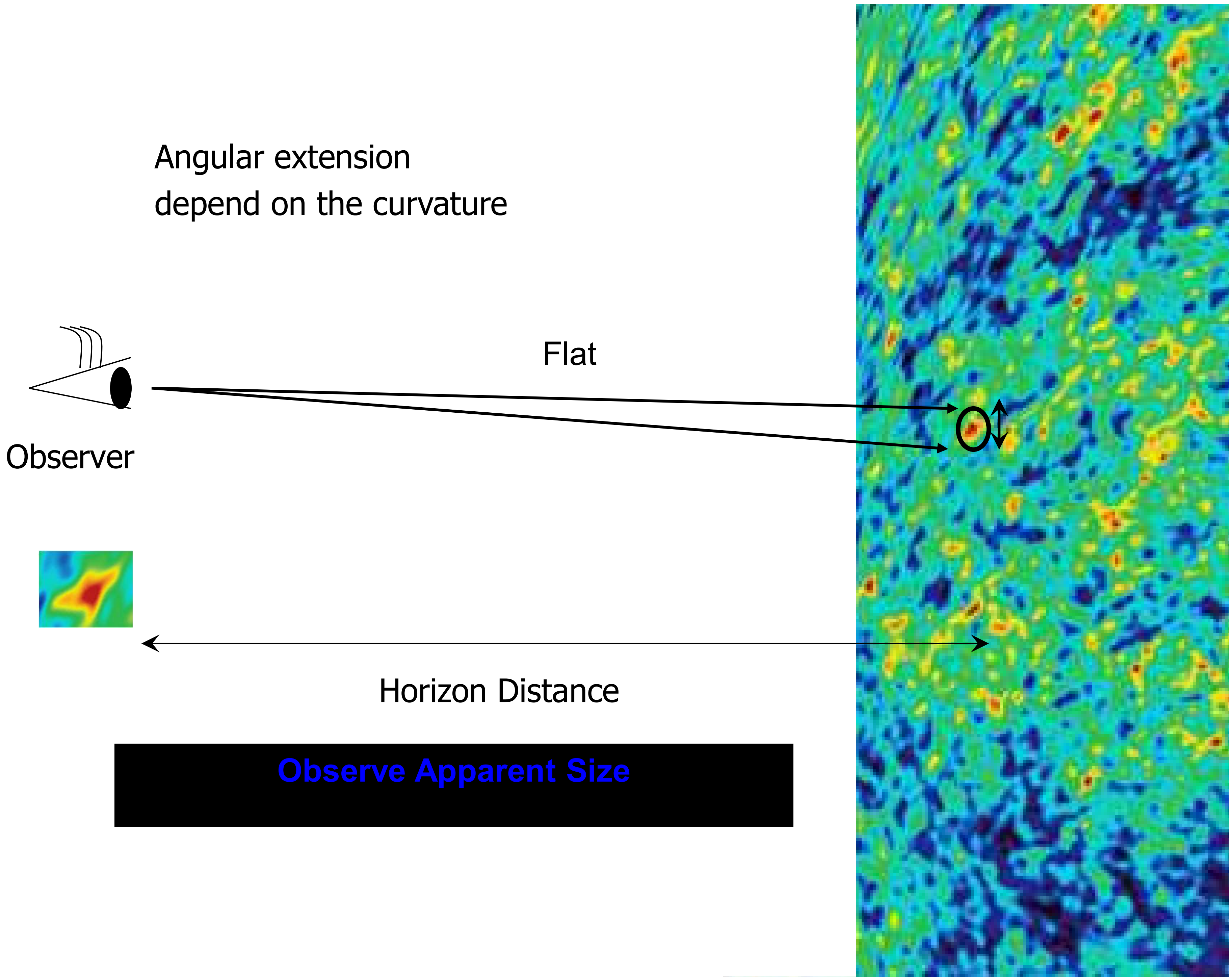
From these three peaks, it is possible to conclude that if 31% (5%+26%) of the universe is composed of matter, then 69% must be dark energy in order to fulfil the requirement for a flat universe.

Observations of temperature variations in the cosmic microwave background indicate that the universe is flat or nearly so, with a combined average mass density equal to the critical density



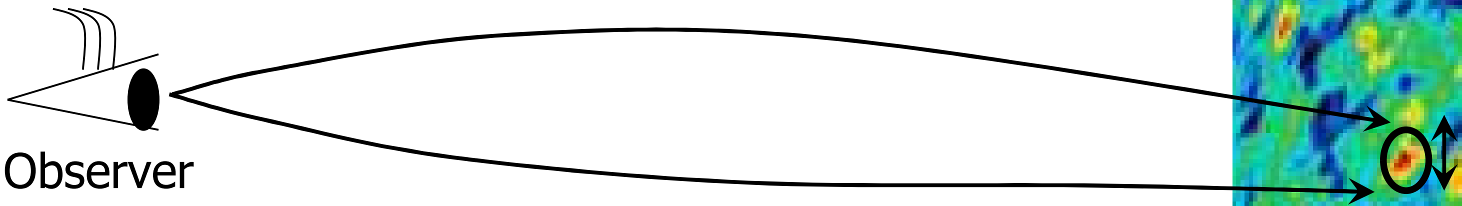


The distance, s, between two temperature minima
is equal to the velocity of the acoustic waves in the cosmic plasma
times 380 000 years.
This velocity can be calculated. Hence s is known.
At a distance of 13,7 billion (milliarder) light years
s spans an angle of about one degree in a flat Universe.

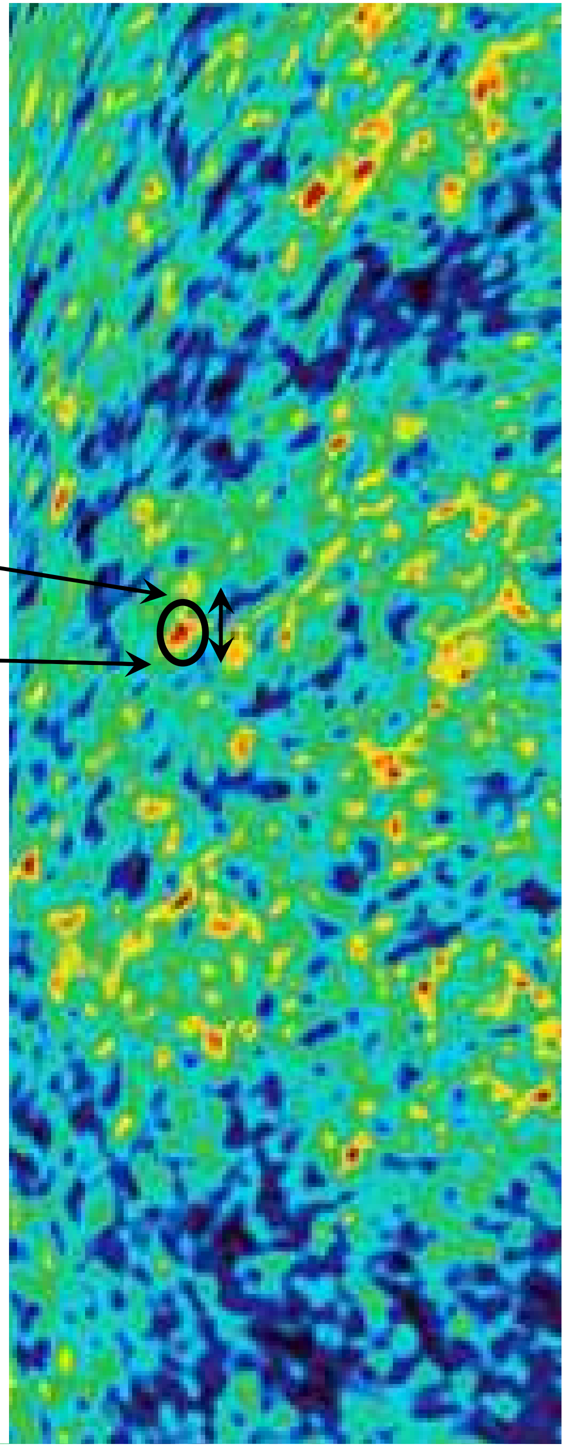

Angular extension
depend on the curvature
Flat
Observer
Horizon Distance
Observe Apparent Size

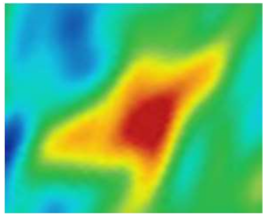
Space Curvature=Lens

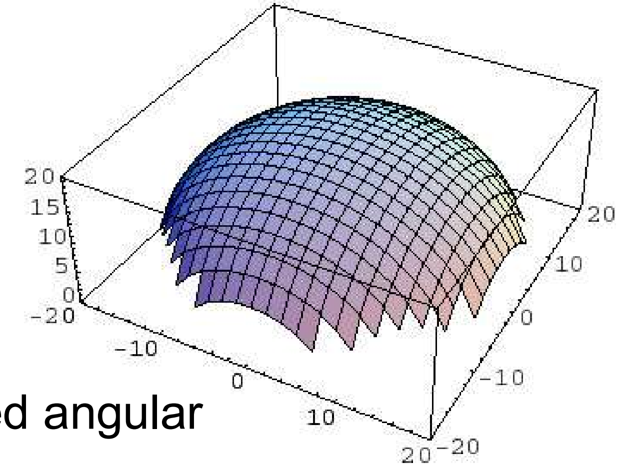
Positive Curvature



Observer



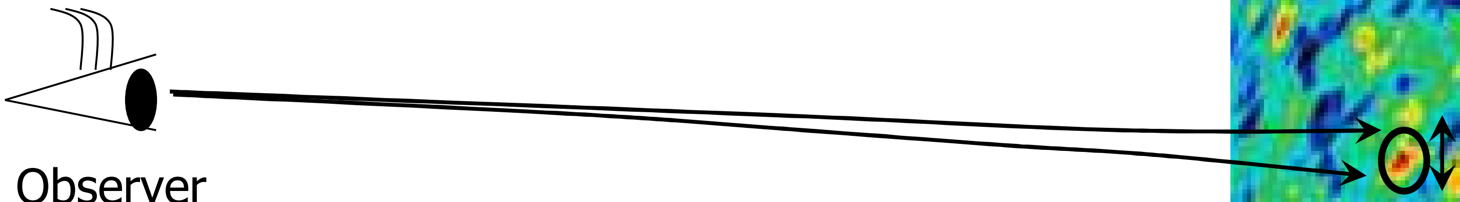




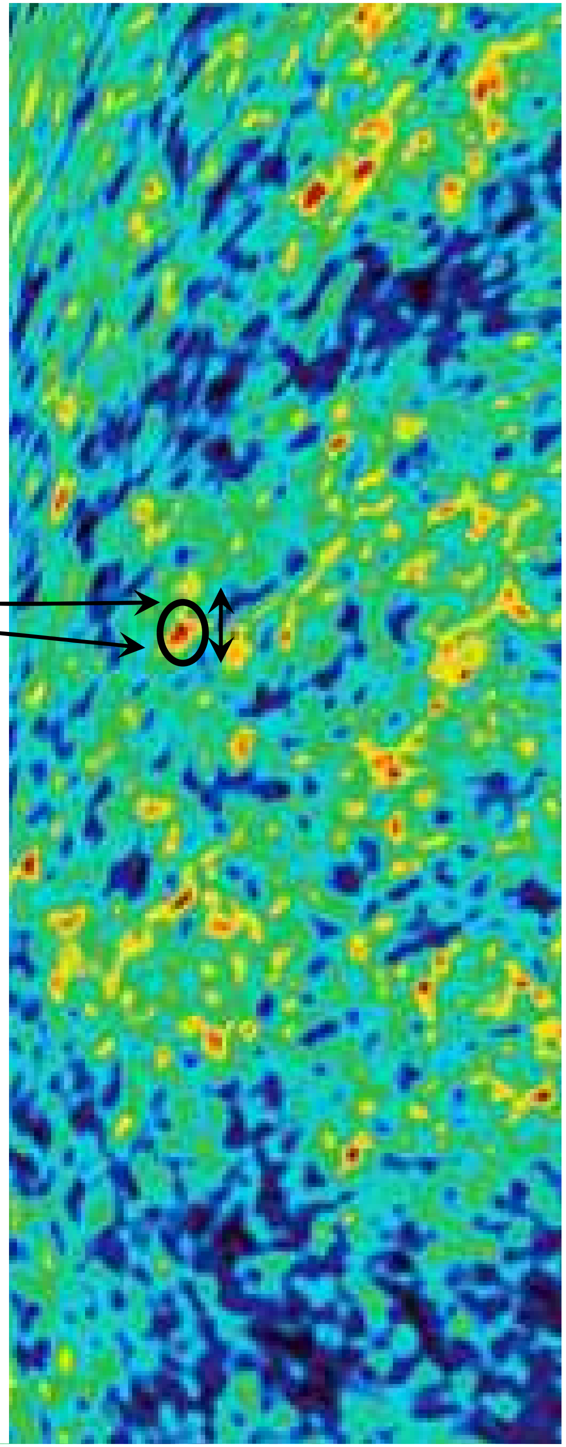
Larger observed angular extension

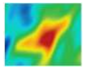
Space Curvature=Lens

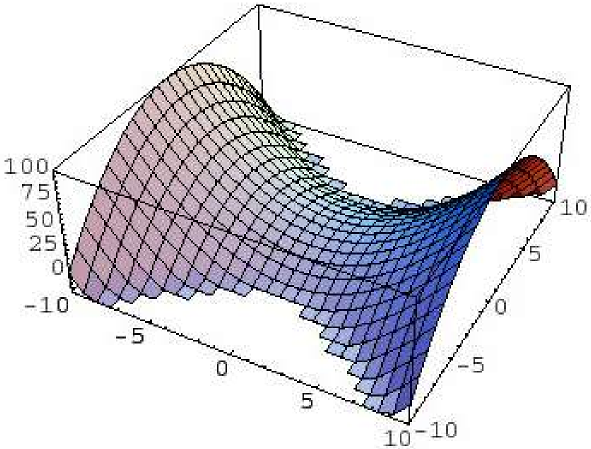
Negative Curvature



Observer



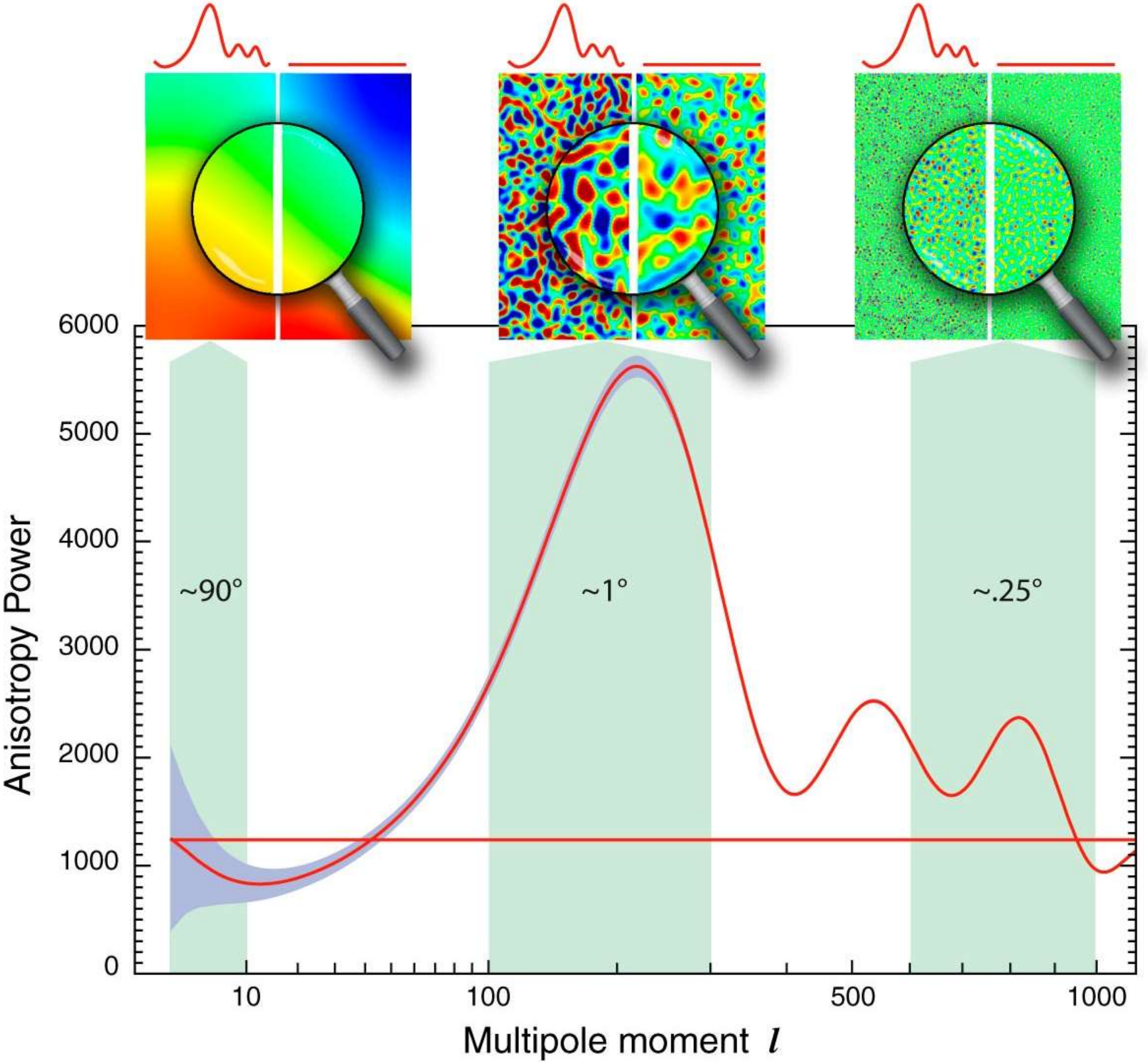


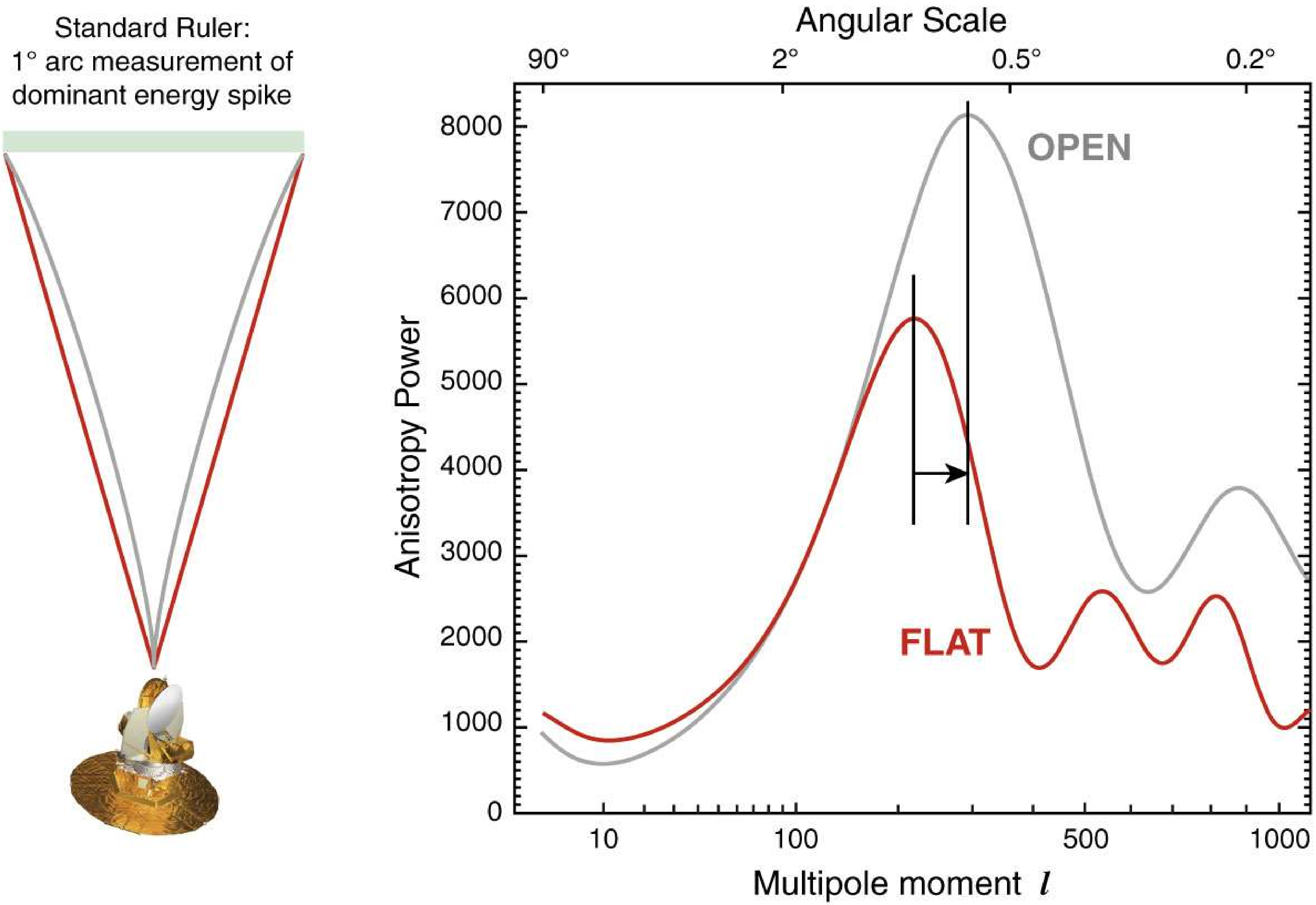


Smaller observed
angular extension

The curve represents mean temperature variation with angular separation.

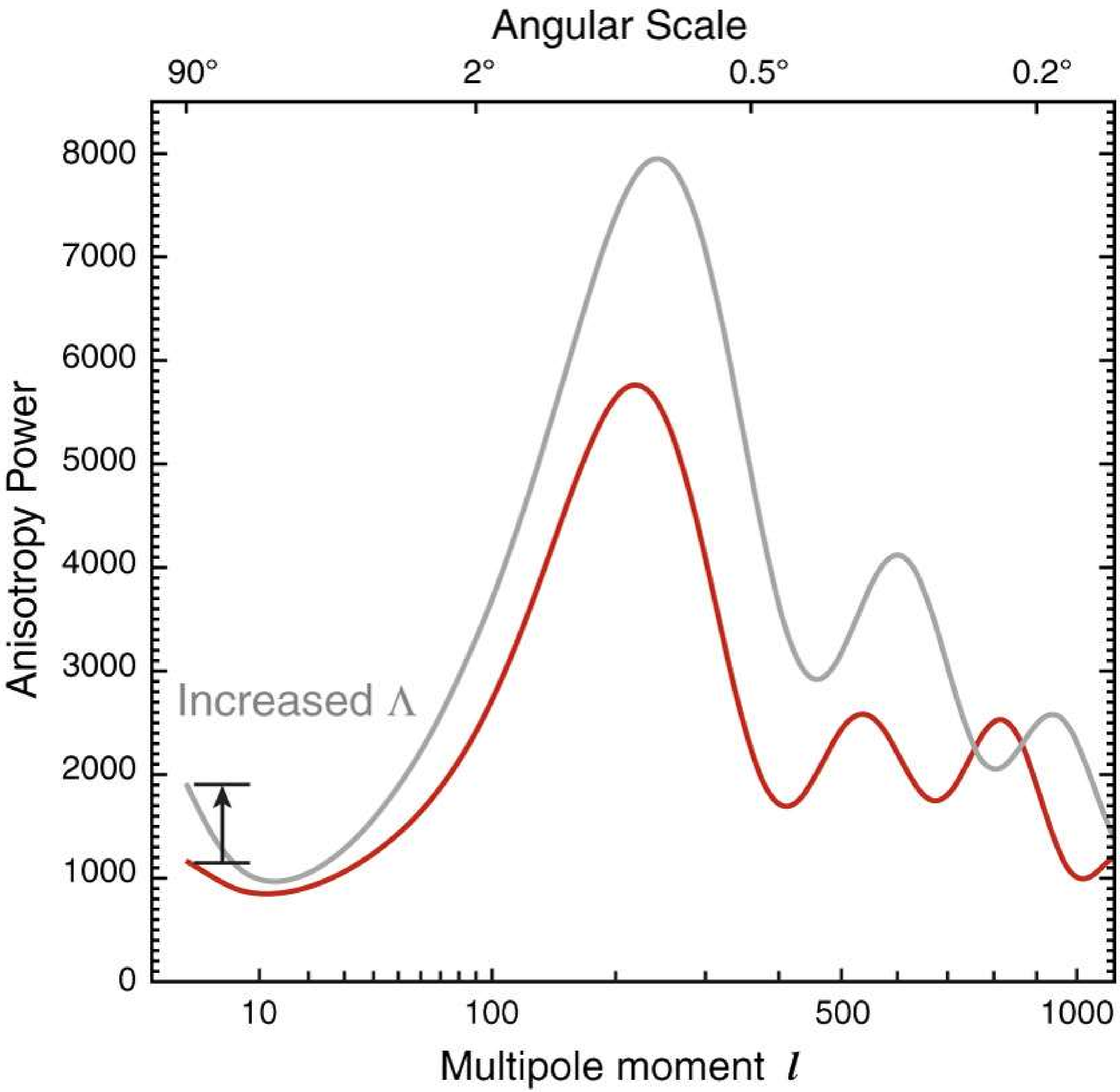
The multipole moment is large when the angular separation is small.



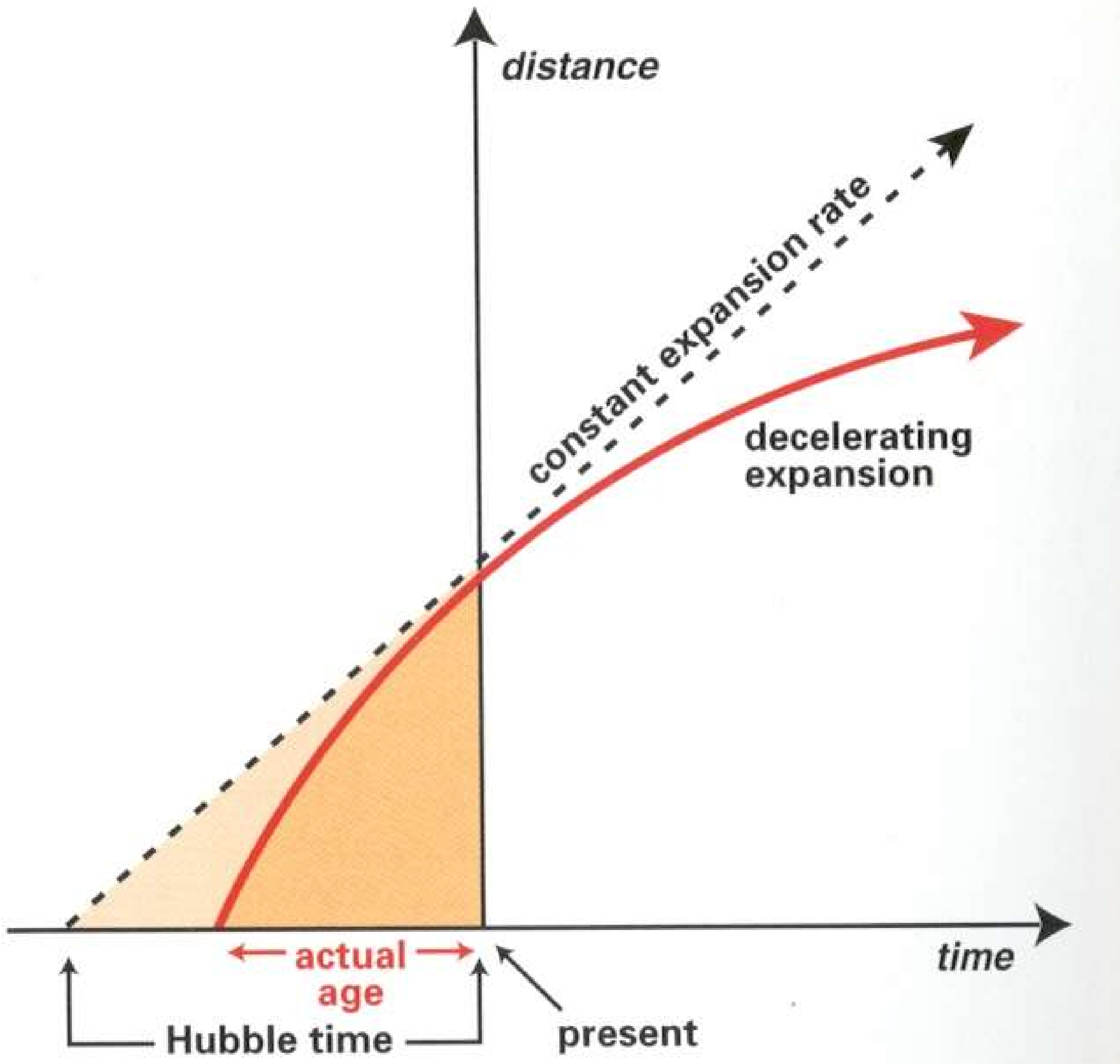

Standard Ruler:
1° arc measurement of
dominant energy spike
Angular Scale
90°
2°
0.5°
0.2°
OPEN
FLAT
Anisotropy Power
0
1000
2000
3000
4000
5000
6000
7000
8000
10
100
500
1000
Multipole moment l

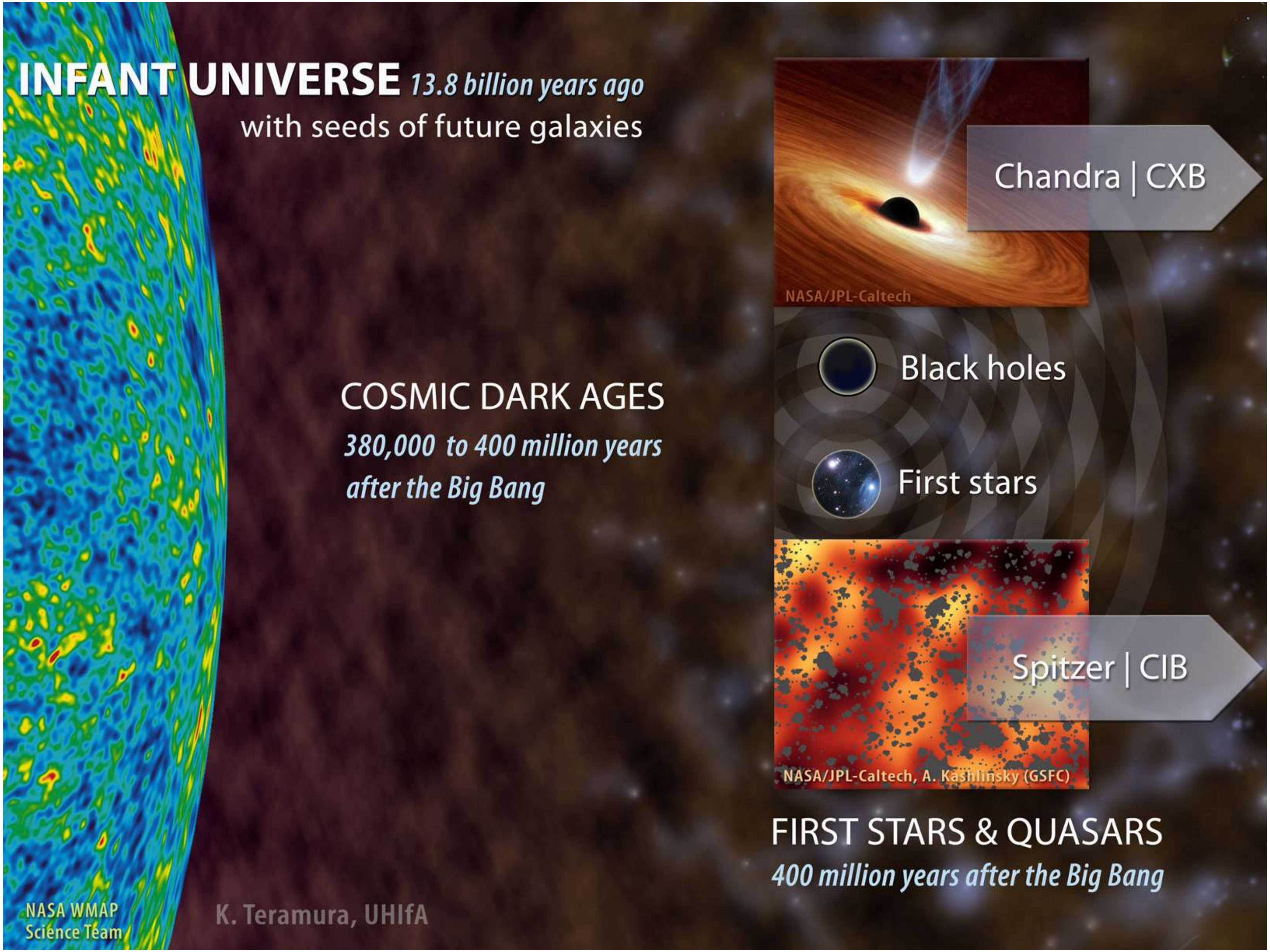
There will be larger temperature variations the larger the density of the vacuum energi is.

For Lorentz Invariant Vacuum Energy, LIVE, the density of the vacuum energy can be represented by a cosmological constant, Λ.



Observasjoner viser at universets alder er omtrent lik dets Hubble-alder.
Ekspansjonen var hurtigere før i et univers dominert av kald materie (rød kurve)
Alderen i er univers dominert av kald materie er for liten (se figuren).




INFANT UNIVERSE 13.8 billion years ago
with seeds of future galaxies
COSMIC DARK AGES
380,000 to 400 million years
after the Big Bang
NASA/JPL-Caltech
Chandra | CXB
Black holes
First stars
Spitzer | CIB
NASA/JPL-Caltech, A. Kashlinsky (GSFC)
FIRST STARS & QUASARS
400 million years after the Big Bang
NASA WMAP
Science Team
K. Teramura, UHIfA

In the early 1980s Peebles proposed the idea that the universe was filled with unseen “cold dark matter” — particles that did not interact with ordinary matter but whose gravitational pull formed galaxies and clusters of galaxies. The fluctuations in the density of dark matter 400 000 years after Big Bang was larger than those of the ordinary matter.

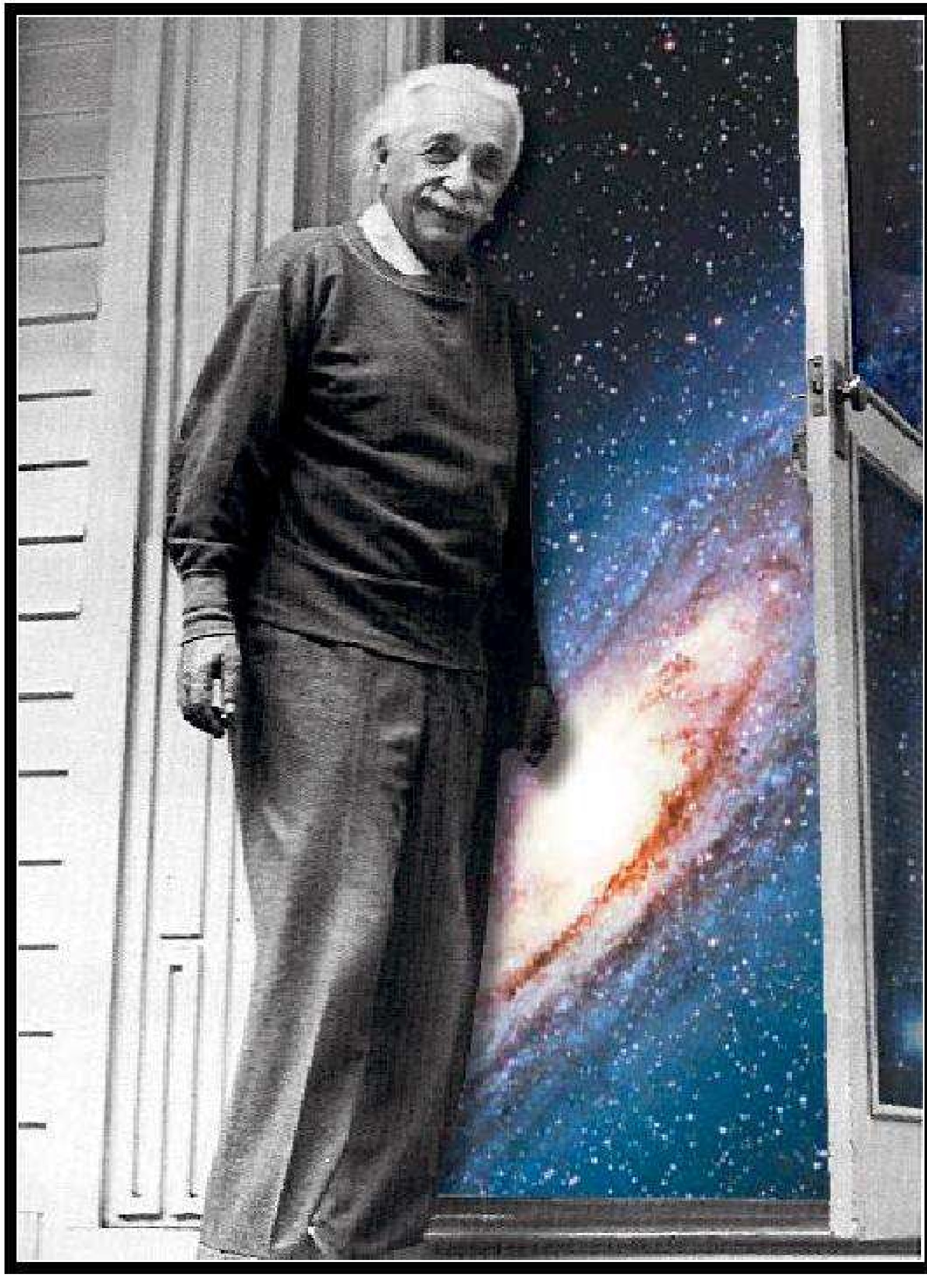
A couple of years later, he added to his model a so-called cosmological constant that Albert Einstein had originally proposed but later discarded as his “biggest blunder.”

In Peeble’s model the cosmological constant is interpreted in the way proposed by Georges Lemaitre, as representing the constant density of LIVE, which procuses repulsive gravity causing increased cosmic expansion velocity.

Einstein had introduced the cosmological constant to balance gravity and keep the universe static.
But astronomers established that the universe is expanding.

Peebles utilized the cosmological constant to show that the universe contained considerably less mass than was thought at the time.

In 1998 two teams of astronomers discovered that Peebles was right, and that the universe is not only expanding, but has increased the expansion velocity during the last 6 billion years.



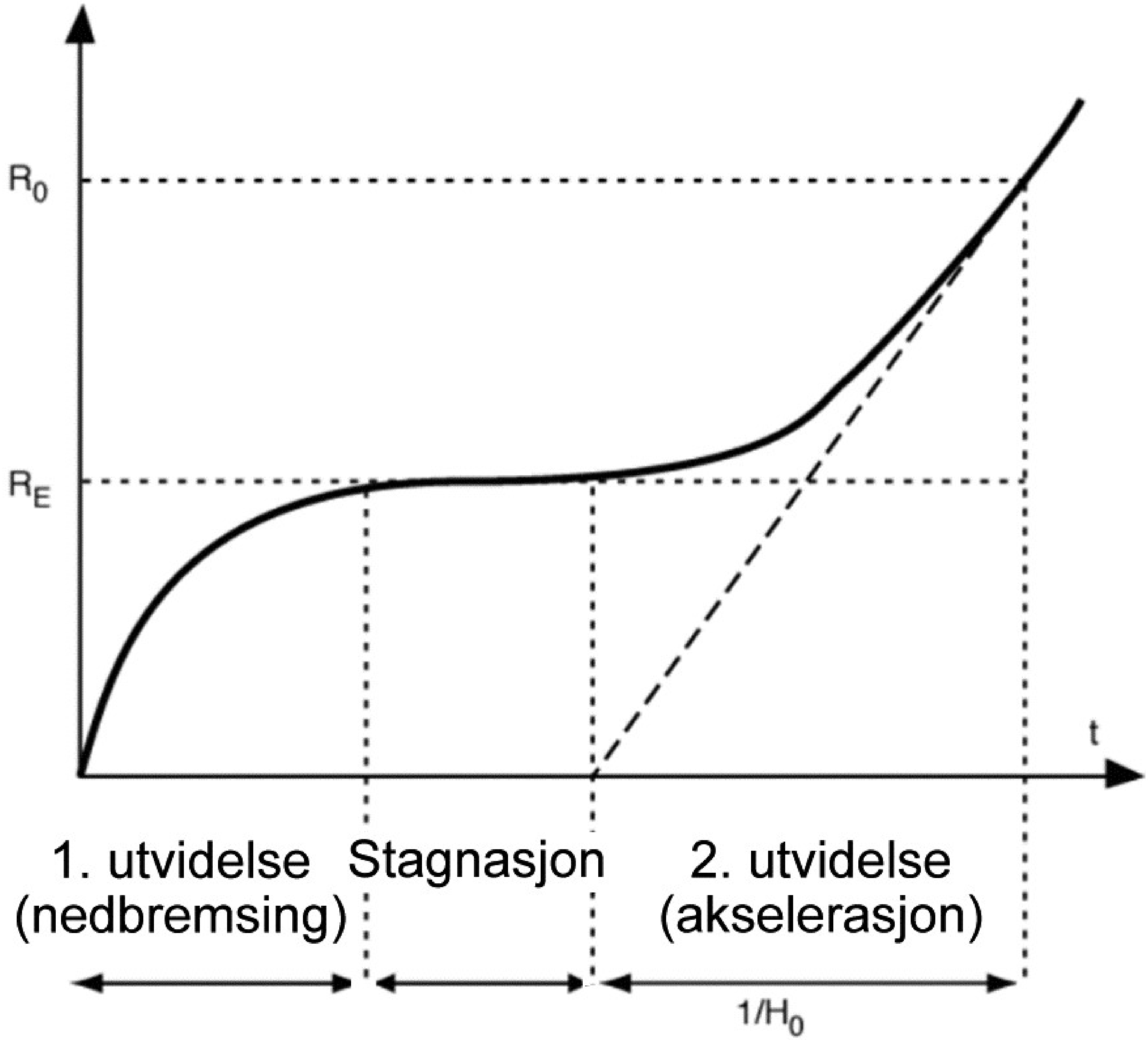
Einstein's Biggest Blunder?

1917 Einstein proposes cosmological constant

1929 Hubble discovers Expansion of the universe

1934 Einstein calls it "my biggest blunder"

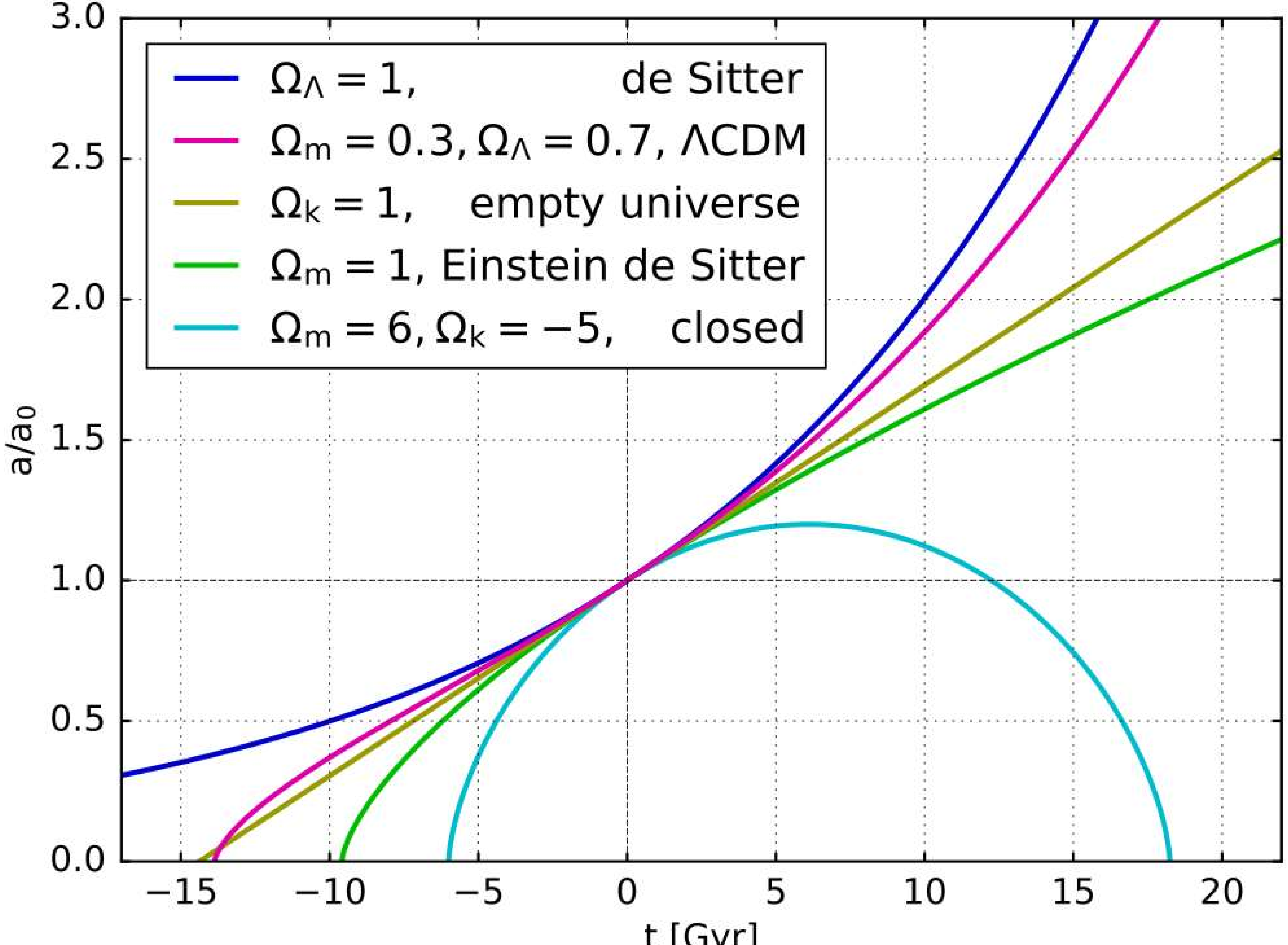
1998 Astronomers find evidence for it



R0
RE
t
1. utvidelse
(nedbremsing)
Stagnasjon
2. utvidelse
(akselerasjon)
1/H0

The previous figure was published by Lemaitre about 1935.
At this time the measurements of the Hubble parameter gave too large value. One divided by the Hubble constant is called the Hubble age of the universe. The Hubble age was estimated to be between 2 and 3 billion years, less than the age of the Earth.
In a mass dominated universe with decelerated expansion,
The expansion velocity was faster at earlier times, so the age of the universe in these model was even less than the Hubble age.
There was an age problem with this universe model.

Lemaitre solved this age problem by introducing vacuum energy causing repulsive gravity and accelerated expansion
as shown in the previous graph,
where the age of the universe is much larger than the Hubble age.
He predicted that we are now in an era with accelerated expansion.
With the present value of the Hubble constant the Hubble age is nearly equal to the age of the universe, as shown in the next graph.
The empty universe has an age exactly equal to the Hubble age.



$\Omega_\Lambda = 1$, de Sitter
$\Omega_m = 0.3, \Omega_\Lambda = 0.7$, ΛCDM
$\Omega_k = 1$, empty universe
$\Omega_m = 1$, Einstein de Sitter
$\Omega_m = 6, \Omega_k = -5$, closed
a/a_0
t [Gyr]

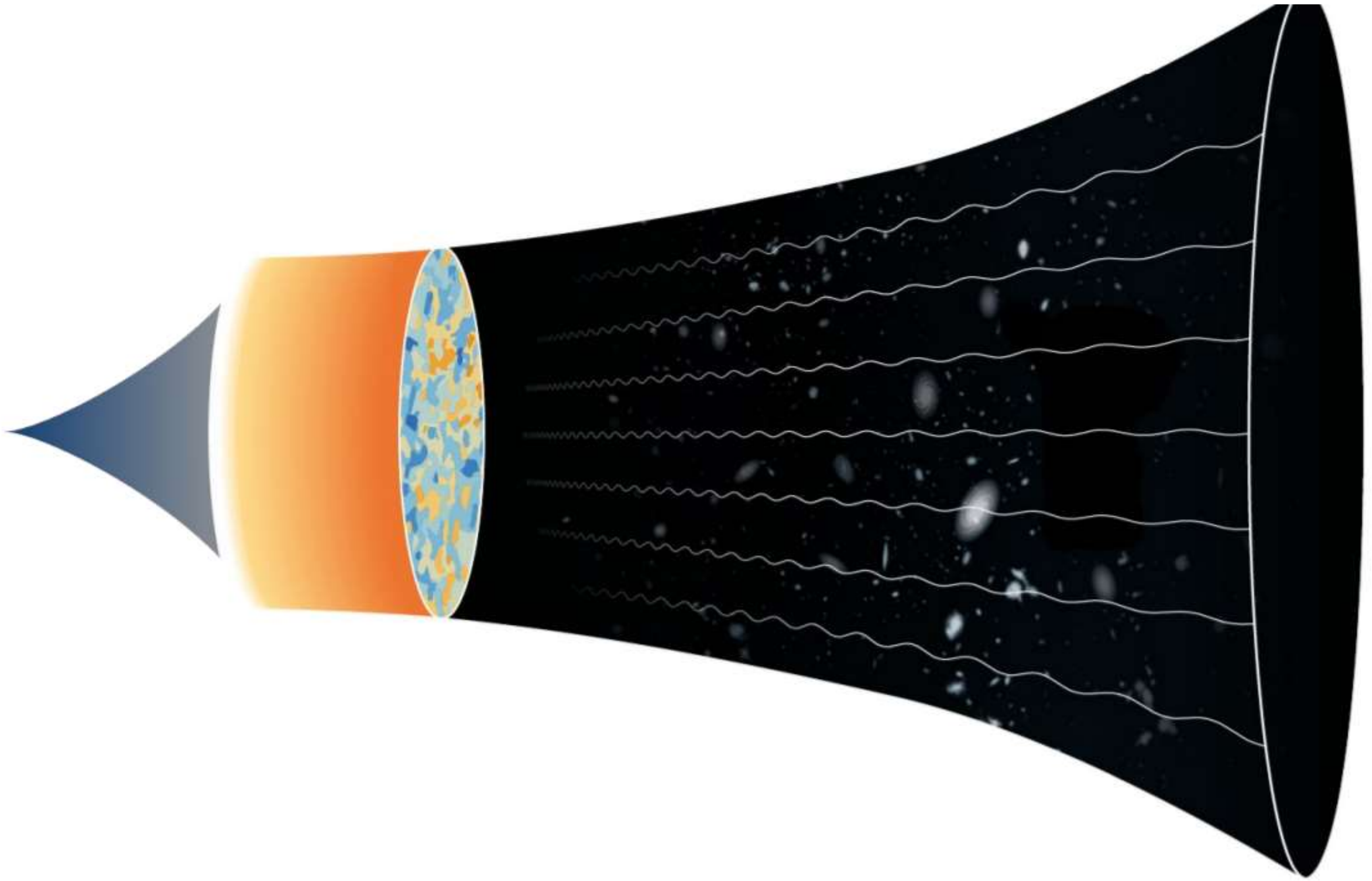
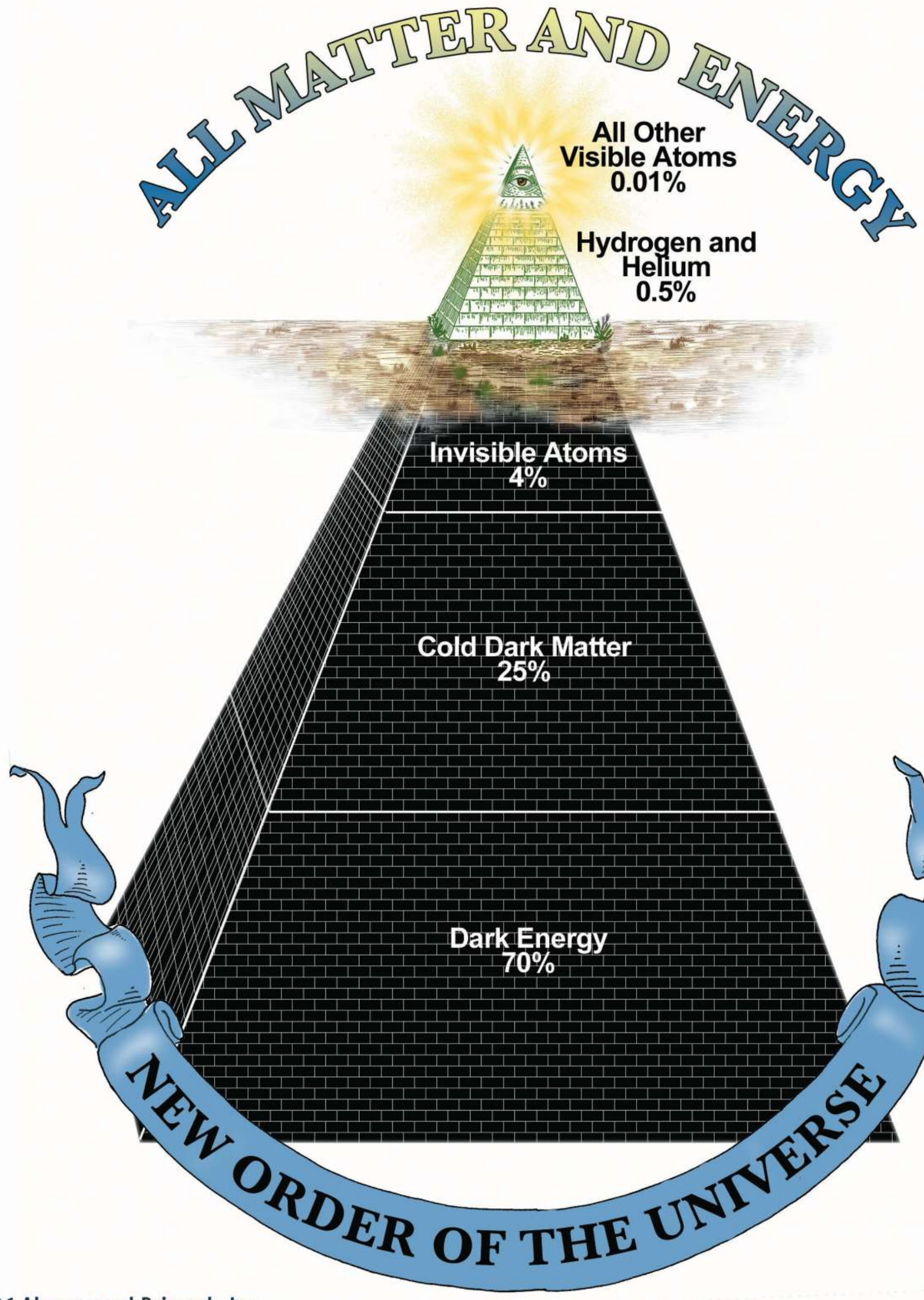


Figure 1. *A timeline of our Universe extending from an unknown origin on the left to a darkening future on the right.*


ALL MATTER AND ENERGY
All Other
Visible Atoms
0.01%
Hydrogen and
Helium
0.5%
Invisible Atoms
4%
Cold Dark Matter
25%
Dark Energy
70%
NEW ORDER OF THE UNIVERSE