Lectures on radio astronomy: 7

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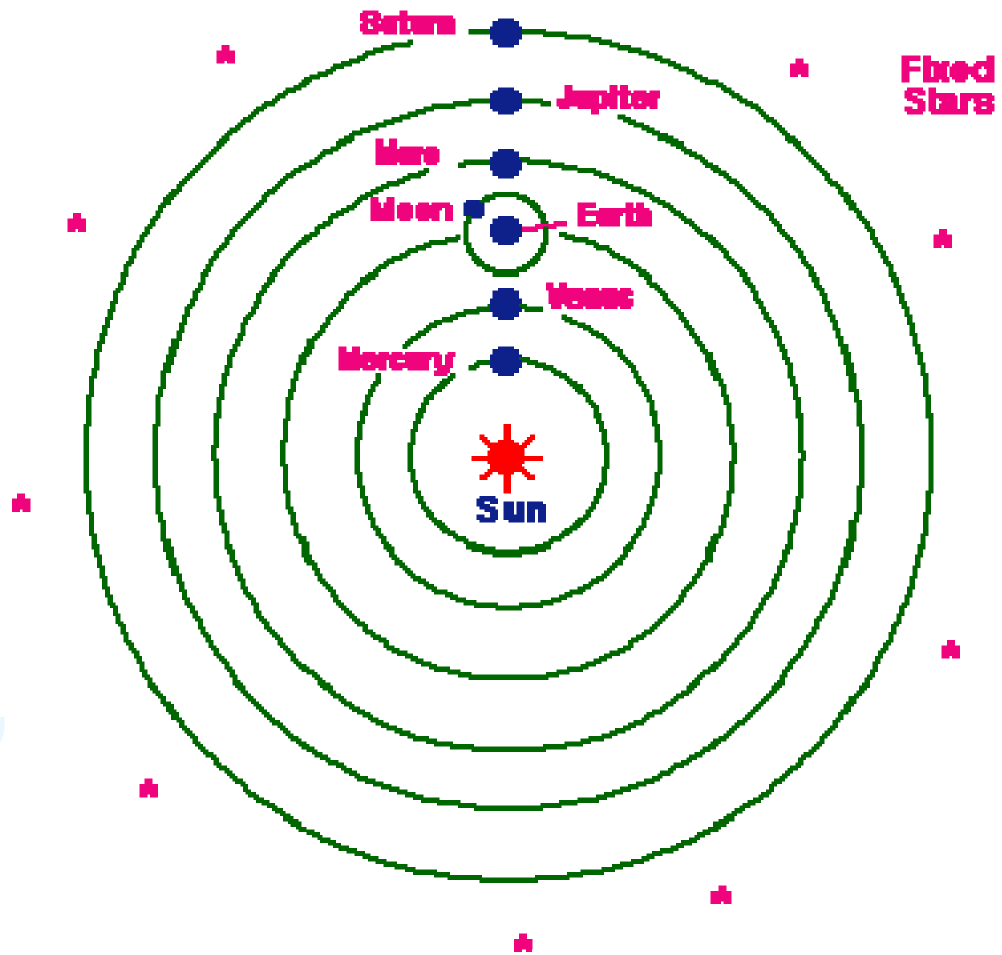
Introduction to cosmology: from Steady State controversy to CMB

The solar system according to Copernicus



Result of Copernicus, Kepler, Galileo,… : modern science

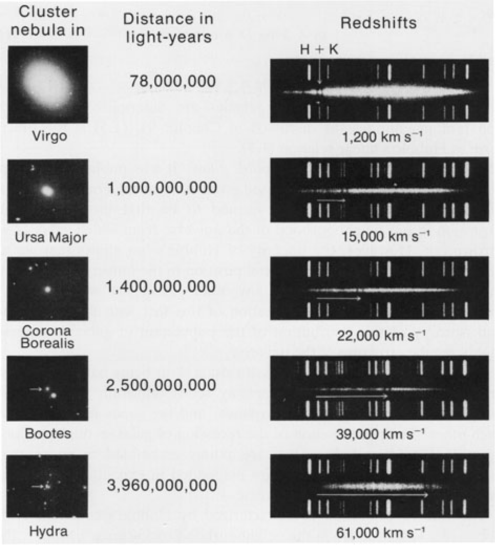
- Scientific method developed: ideas had to be tested by observation
- Mathematics became tool of science
- “Cosmology” was still the study of the solar system
- Only with detailed study of stars in 19th C. does “universe” extend to Milky Way
- Modern cosmology begins with sensitive observations of galaxies in 20th C.

After Copernicus, Earth (and man) not at center of things

- At the beginning of the 20^{th} C., the Sun was thought to be near the center of the Milky Way
- By the 1920s, became clear that the Sun was an average star, in the outer parts of the Milky Way, which was a fairly typical galaxy, of which there were many
- So, even the Sun, the most important star to us, was not special

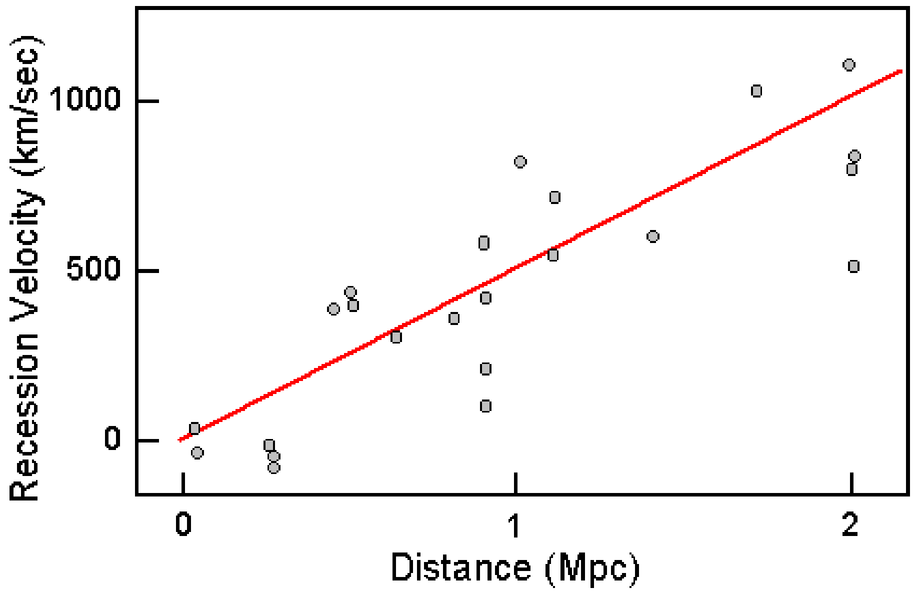
Particularly important were observations by E. Hubble

- Light from galaxies has spectral features (lines)
- Lines have fixed wavelengths
- Wavelengths shift as galaxy moves: blue if coming toward us, red if moving away
- This is well-known Doppler effect
- All galaxy shifts were toward red (shown by Slipher by 1917)
- Galaxies all move away from us!



Hubble found galaxies moving away in a systematic way

Hubble's Data (1929)



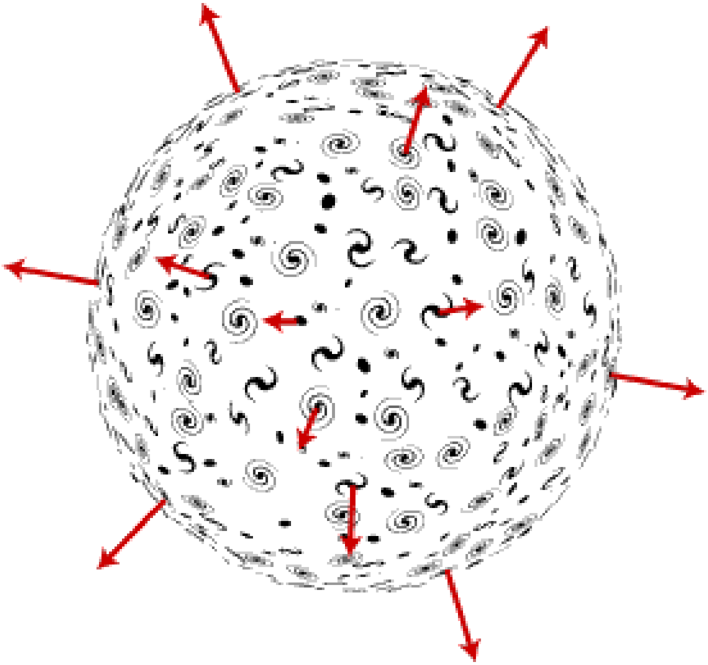
- Hubble (& Humason) used star brightness to determine distances
- And found on average, more distant galaxies moved away faster
- This is Hubble's law: the universe expands in a systematic way (Humason tends to be forgotten)

So, the universe was not static, but expanding

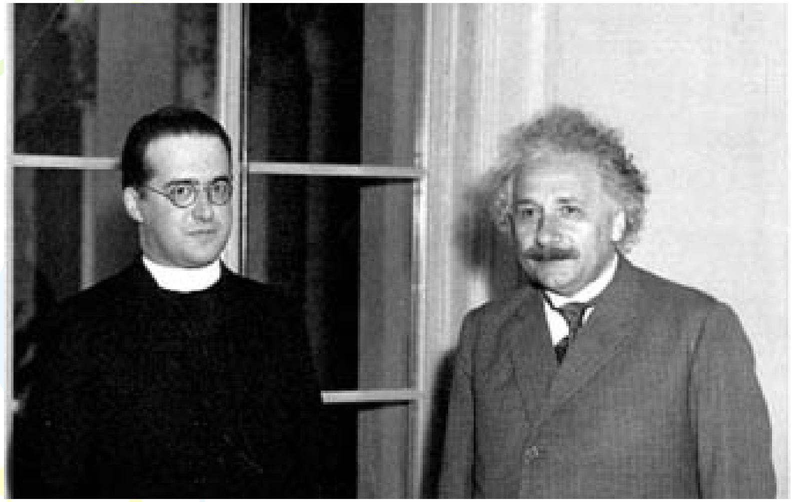
- Einstein’s general relativity (GR) describes space and time – it treats cosmology
- Einstein’s equations did not give a static universe (this was 1915, before Hubble), so he introduced a constant (of integration) to make it static: Λ (later said it was, “The biggest mistake of my life.”)
- Theoreticians – De Sitter, Friedman – developed models based on GR

E.A. Milne developed model using special relativity

- One simple thing Milne pointed out was that Hubble's law occurs quite naturally
- Take many objects, give them random velocities, and wait
- After awhile, the fastest will be most distant, slowest won't have moved far



Georges Lemaître (1931): proposes primordial atom



- Having already shown that the universe should expand,
- Lemaître suggested that at the beginning, all the matter in the universe was bound up in a single giant atom
- This primordial atom suddenly exploded (split, as in nuclear fission), and the expansion of the universe began

To understand & model a universe, need to make some assumptions

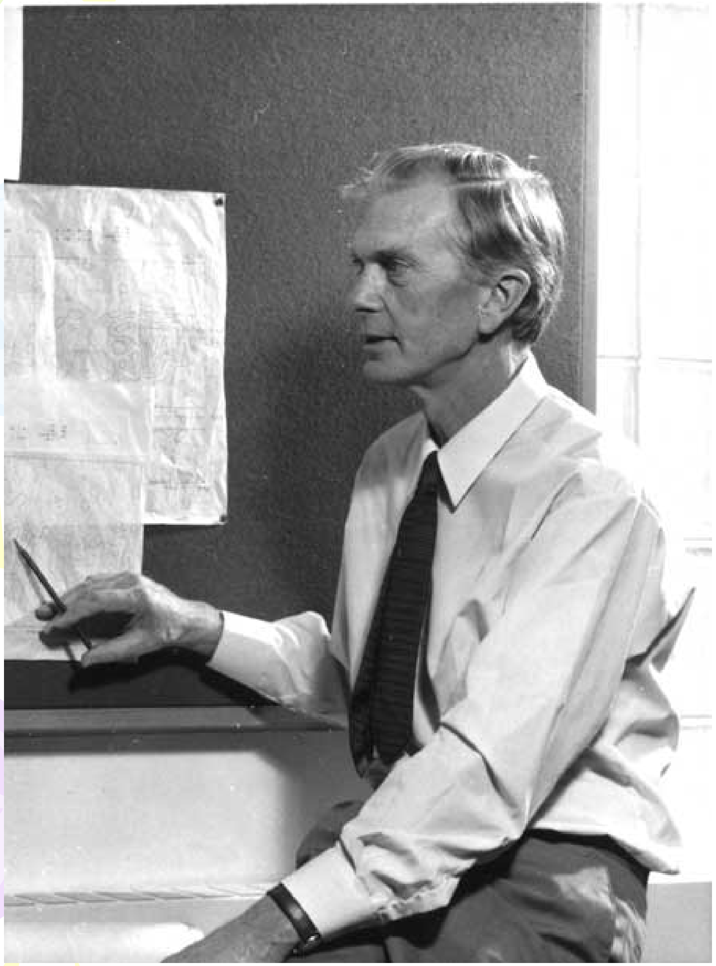
- Empirical science requires that we test our theories against Nature – we must observe
- In cosmology, things are remote: we cannot do experiments
- A fundamental assumption we make is that the laws of physics are the same everywhere in the universe
- A football would bounce the same way on a planet like ours anywhere in the universe

Then there are two rules: the **Cosmological Principle**

- **The universe is isotropic:** on average, it looks the same in all directions (there are no “edges”)
- **The universe is homogeneous:** although there are lumpy things like stars and galaxies, all observers will on average measure the same properties (density, etc.) at the same cosmic time

(Principle was due to Milne, 1933)

After 1945, various techniques used to study cosmology



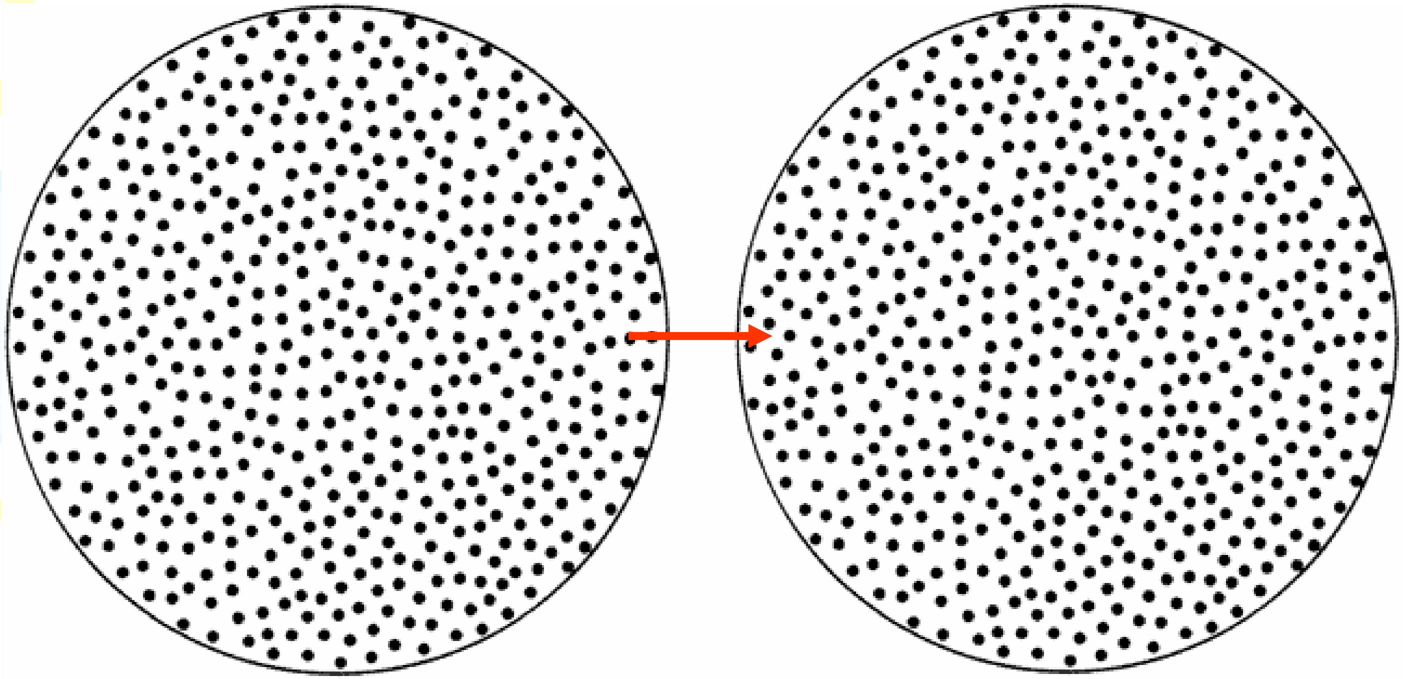
- One of the techniques was radio astronomy, developed by people like Martin Ryle (photo)
- Galaxies at much greater distances could be "seen" with radio telescopes
- And from statistics of radio sources, could probe structure of universe

Three clever theoreticians came up with a new idea

Gold, Bondi and Hoyle (1948) formulated the **Perfect Cosmological Principle:**

The universe is isotropic and homogeneous for all observers at *all times*

Expansion would mean density of universe decreases (left to right)



This new “Steady-State Universe” would have no beginning or end, the density remained constant

Philosophically, this seemed very attractive

- Not only is there nothing special about any *place* in the universe, there is nothing special about any *time*
- The universe looks the same at all times, on average nothing changes
- There is no beginning or end – time goes on (and has gone on) forever!
- But isn't there a problem? How can the universe expand, and not change?

Of course they realized that, and had an answer

(Theoreticians *always* have an answer)

- It was quite simple, really: to make sure the density remained the same, extra material had to be added, little by little: here a few hydrogen atoms, there a bit of helium, an electron or a proton
- Matter had to be spontaneously created, to fill in gaps caused by expansion
- Doesn't it violate, uh... something?

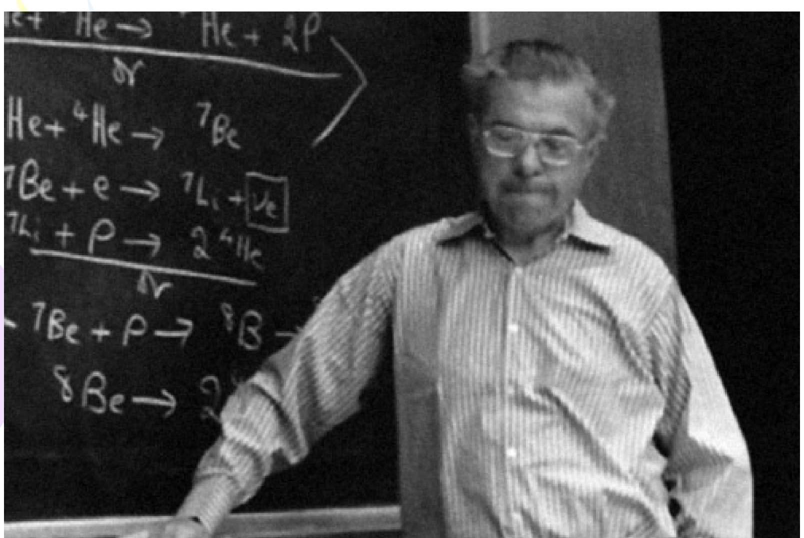
…like conservation of energy?

$$E = mc^2$$

Well, yes, it does seem to violate conservation laws

- But they came up with something called the C (for creation) field
- For at least 10 years, Steady State cosmology was discussed, supported, criticized, dismissed by astronomers
- Ryle and Hoyle were both at Cambridge – Ryle hated the idea (and didn't think much of Hoyle, I gather)
- He was sure his radio sources disproved it

Hoyle coined the term “Big Bang” to *ridicule* the theory!



- In a radio interview, he sarcastically referred to “this *big bang* idea”
- Ironically, it was universally adopted, and has been used ever since
- Here, Sir Fred lecturing in 1970s

Cartoon suggests what Hoyle might have thought...

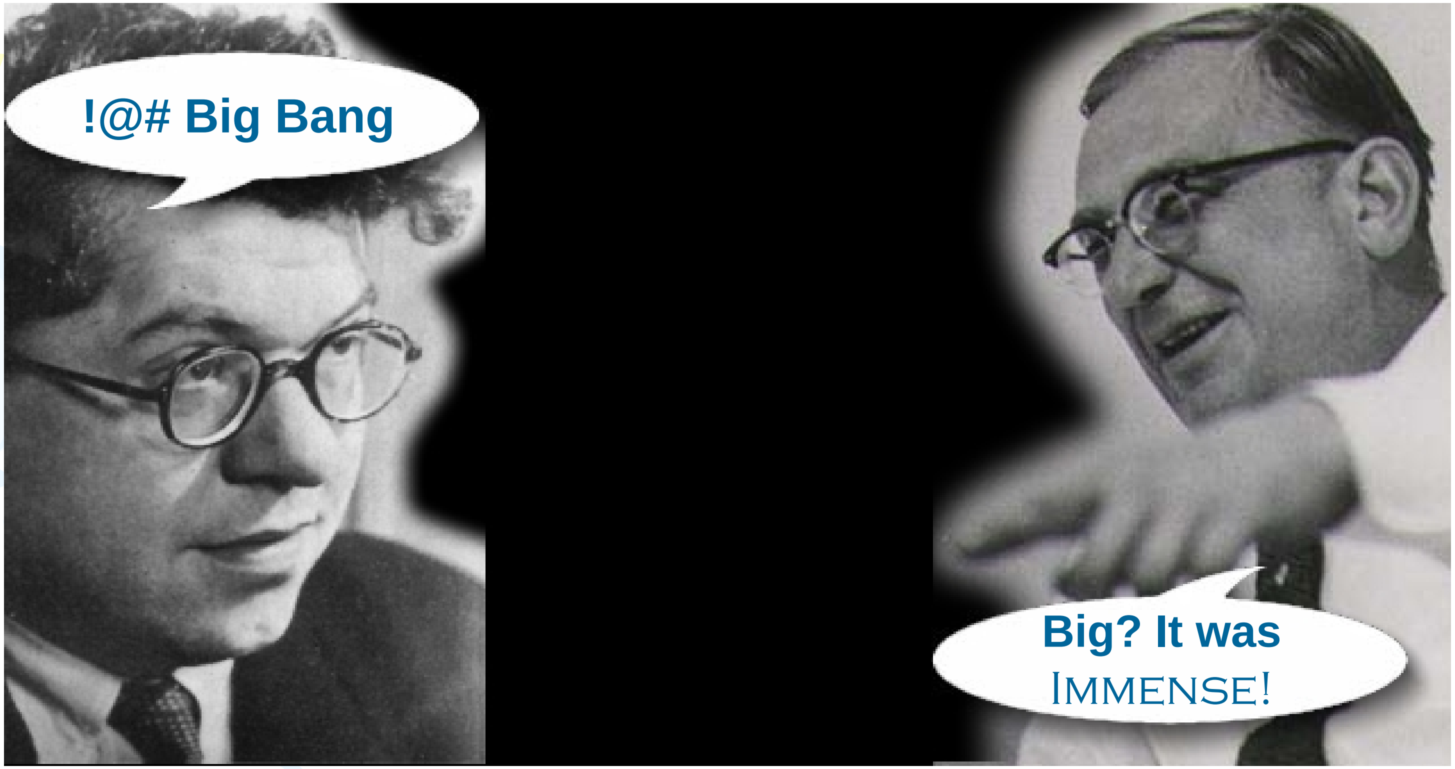
What Hoyle actually did say:

- “[The Big Bang] is an irrational process that cannot be described in scientific terms ... [nor] challenged by an appeal to observation.”
- This may have seemed true when Hoyle wrote it 50 years ago, but it is remarkable that so many observational techniques have been developed since then which can be used to test our ideas about the structure and evolution of the universe

Then in 1952, even the Pope got involved, endorsing the Big Bang

- Pope Pius XII: big-bang cosmology affirmed idea of a transcendental creator & agreed with Christian dogma
- Steady-state: no beginning, no end; for some, associated with atheism
- George Gamow: Steady state was in accord with the Communist Party line
- Hoyle associated steady state with personal freedom & anti-communism

Hoyle also argued with Big Bang supporters like Gamow



George Gamow studied synthesis of heavy elements during the initial hot explosion

Gamow had a rare sense of humor

He wrote the following verse, the words spoken by Fred Hoyle, who suddenly appears from empty space:

The universe, by Heaven's decree
Was never formed in time gone by,
But is, has been, shall ever be —
For so say Bondi, Gold and I.

In another one of his verses, Gamow imagines Hoyle & Ryle...

Ryle:

"Your years of toil,"

Said Ryle to Hoyle,

"Are wasted years, believe me.

The steady state

Is out of date.

Unless my eyes deceive me

Hoyle:

You see, my friend,

It has no end

And there was no beginning,

As Bondi, Gold,

And I will hold

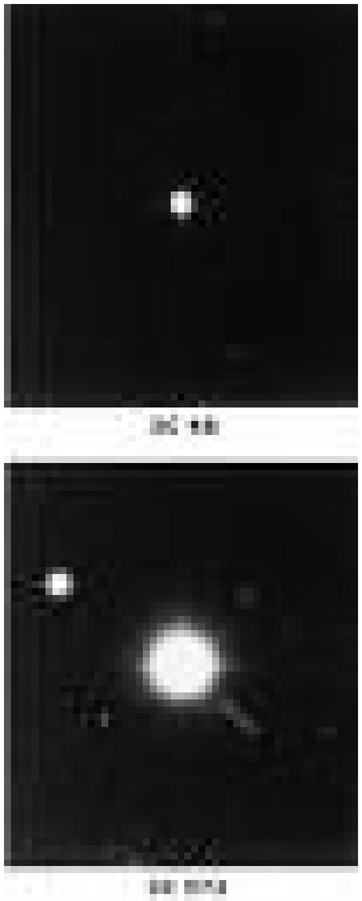
Until our hair is thinning!"

Overall, the conflict was probably good for science

- It gave observers goals to test the two theories: Does density change with time? Are galaxies now older than in the past?
- Because some of the predictions of the two were so different, there was some hope of seeing the differences
- And it made theoreticians on both sides sharpen their arguments and mathematical tools

By 1960, a related controversy arose: about the Doppler shifts

- Optical emission from some of the radio sources was strange
- The Doppler (now called red-) shifts: did they always relate to universal expansion?
- Especially with the discovery of star-like radio sources, the so-called quasars
- They had strange spectra, not possible to interpret at first



1963: Maarten Schmidt unravels spectrum of 3C 273

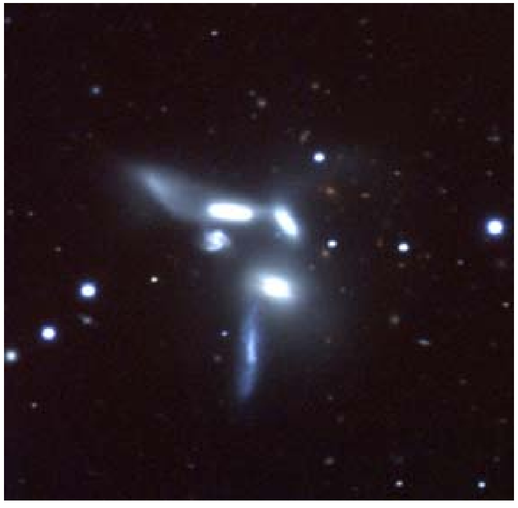
- 3C 273 was a bright quasar, with strong emission lines
- Schmidt, a Dutch-born astronomer at CalTech, was able to identify lines in its spectrum
- But the Doppler shift implied was huge for that time
- This led some astronomers to question whether the redshift was related to motion
- If not, implications for steady state?

Once 3C 273's spectrum was understood, others followed

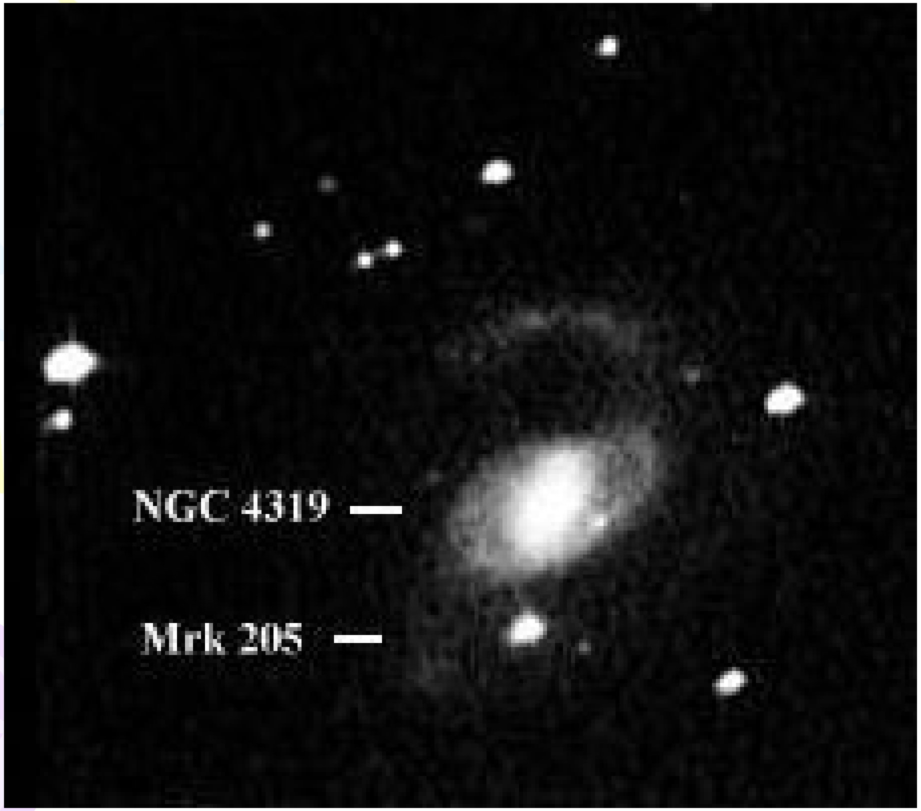
- Very quickly, objects 10 $\times$ further away than 3C 273 were being found
- These objects were very bright – could they really be so far?
- Maybe the redshift didn't relate to the actual motion, and then maybe most of the radio sources were not so distant
- Then one piece of evidence against Steady State would disappear

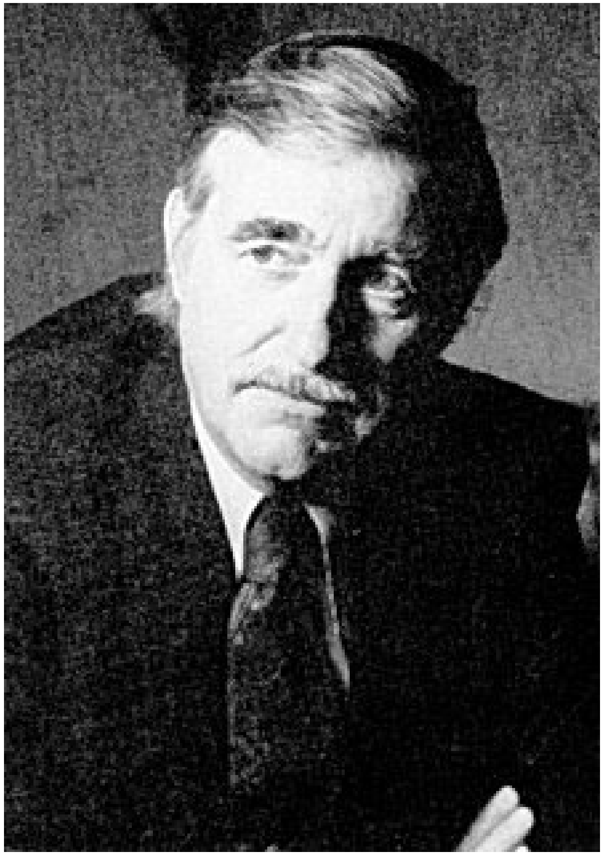
But if redshifts didn't give distance, what could one use?

- Small galaxy groups were thought to be associated
- In Stefan's quintet, one member has a different redshift from the rest
- Something similar in Seyfert's sextet
- H.C. Arp, in particular, used these and similar examples to argue that redshifts could not be cosmological

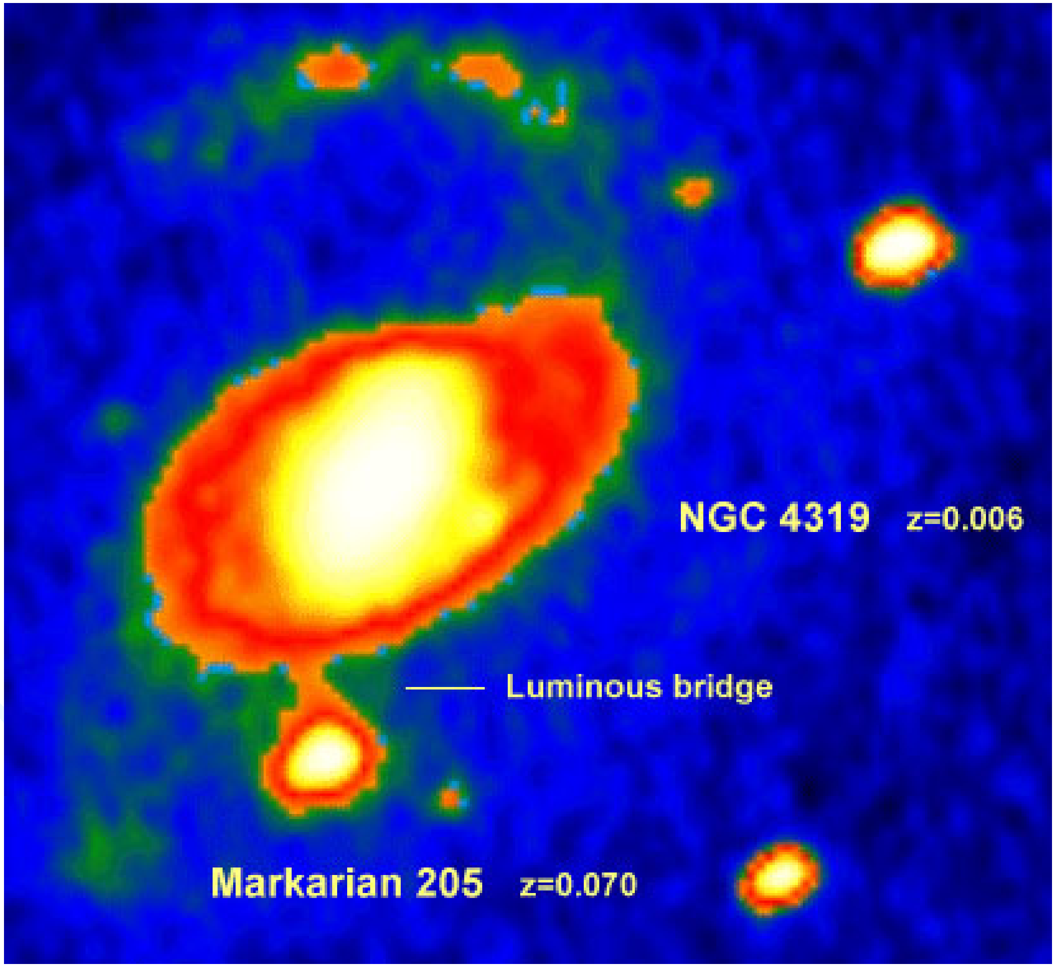


Arp investigated NGC 4319 and Markarian 205





Arp argued that there was a filament connecting them



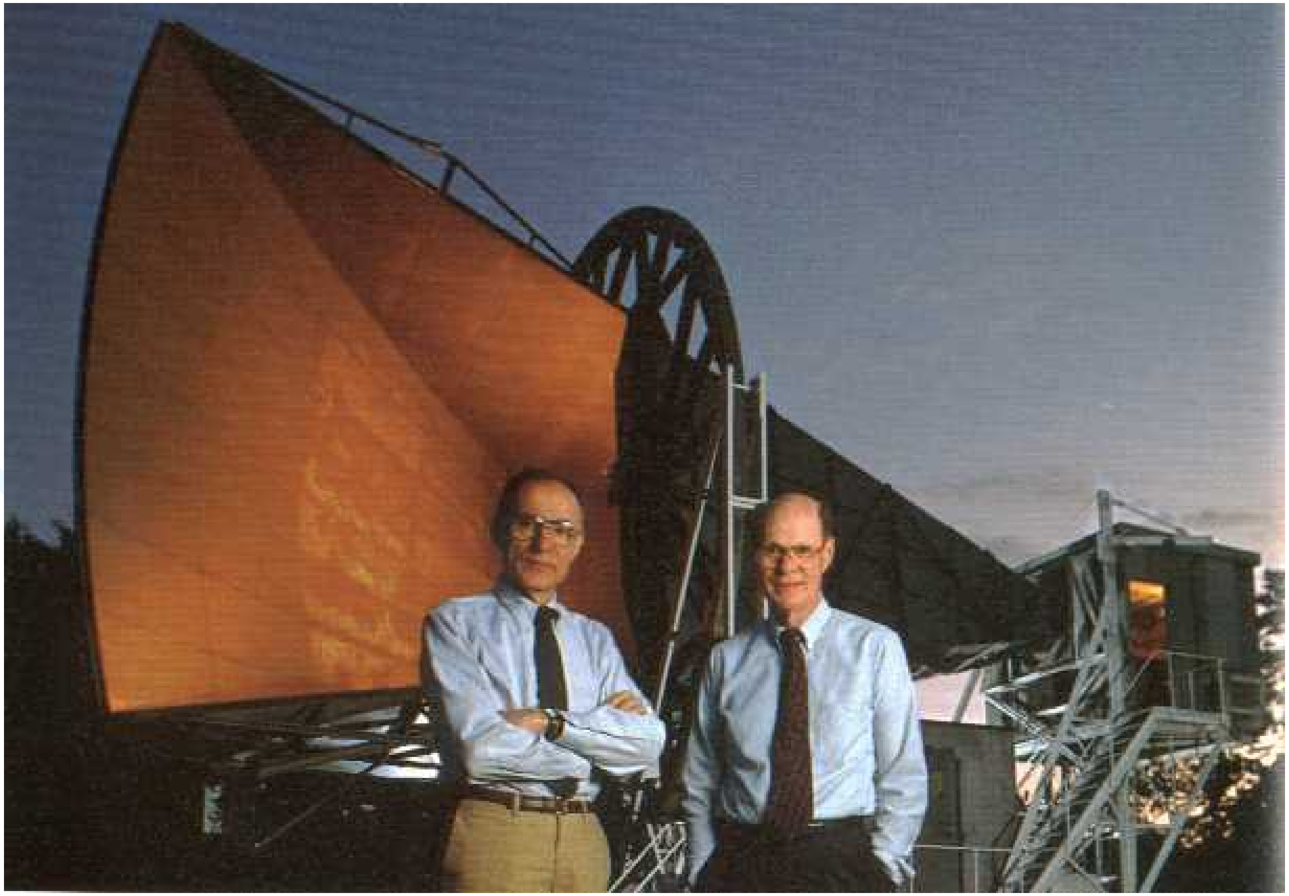
Today, most astronomers would discount Arp's work

- Evidence that redshifts are cosmological is pretty overwhelming
- Arp's "filaments" either instrumental or overlapping emission from adjacent objects
- Only a few people still support Arp's idea
- Seen by some, however, as an example of how majority tries to suppress minority ideas

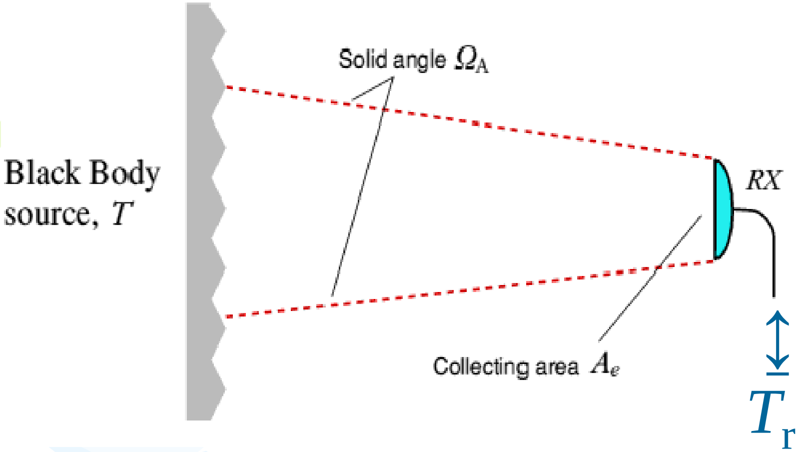
Discovery of cosmic back-ground ended Steady State

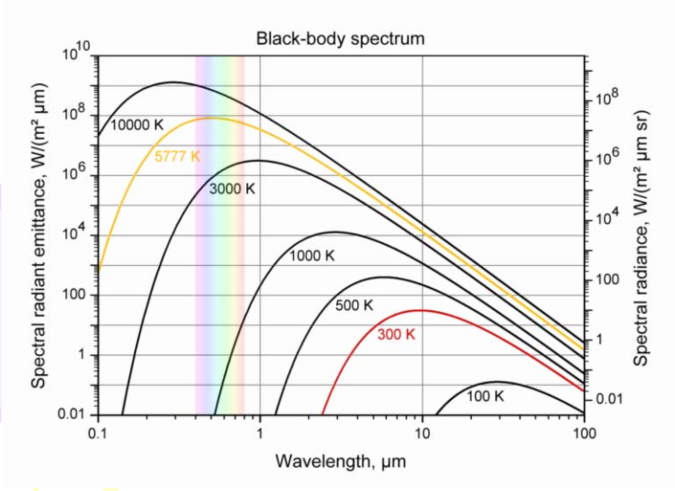
- The heat left over from the explosion is expected in Big Bang, not Steady State
- People like Hoyle tried to keep Steady State alive for quite a few years
- Philosophically it was a nice idea, but science is only interested in the facts
- Most would agree that having two competing ideas was good for science – it stimulated research

Penzias & Wilson were calibrating their antenna, and had a problem



What did their (or does any) antenna measure?





- The power from a source radiating over frequency range Δf can be expressed as, $P = kT\Delta f$
- This can be compared with noise source, like a resistor at some known temperature, T_r
- We say temperature of antenna, T_A, is related to source temperature

They had carefully measured their antenna, and found excess power

- Sources of outside radiation, expressed as temperature, were: atmosphere (T_{atm}), electrical resistance loss in antenna (T_{loss}), radiation from ground (T_{gnd}) & sky (T_{sky})
- They measured or calculated, T_{atm}=2.3±0.3 K, T_{loss}=0.9±0.4 K, T_{gnd}<0.1 K; T_{sky} ≈ 0 (expected)
- So, looking straight up, expected T_A was: $T_A = T_{atm} + T_{loss} + T_{gnd} + T_{sky}$ = 2.3+0.9+<0.1+0 = 3.2 K
- They found T_A = 6.7 K, so $T_?$ = 3.5 K remained

$T_?$ = 3.5 K, where could it come from?

- First they were fairly sure they knew the cause
- The horn is pretty large, and open to the universe
- It makes a nice home for...

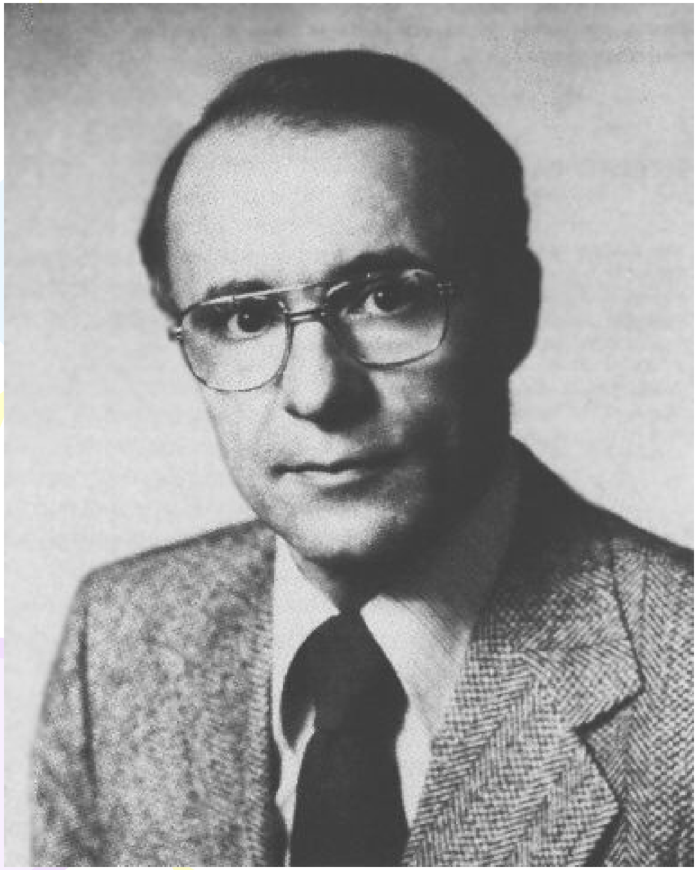
  ...uh, pigeons
- Pigeons are not the cleanest of house guests
- They tend to leave stuff – white stuff – behind

Solution: eviction & thorough cleanup

Pigeon trap

Result: $T_? = 3.5$ K

They tried everything they could think of; the mystery signal remained

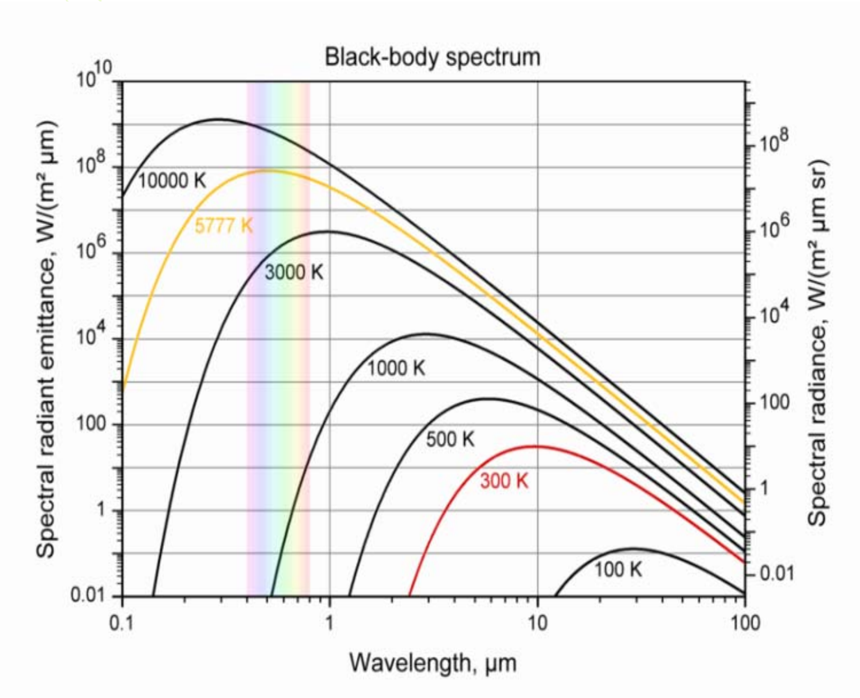


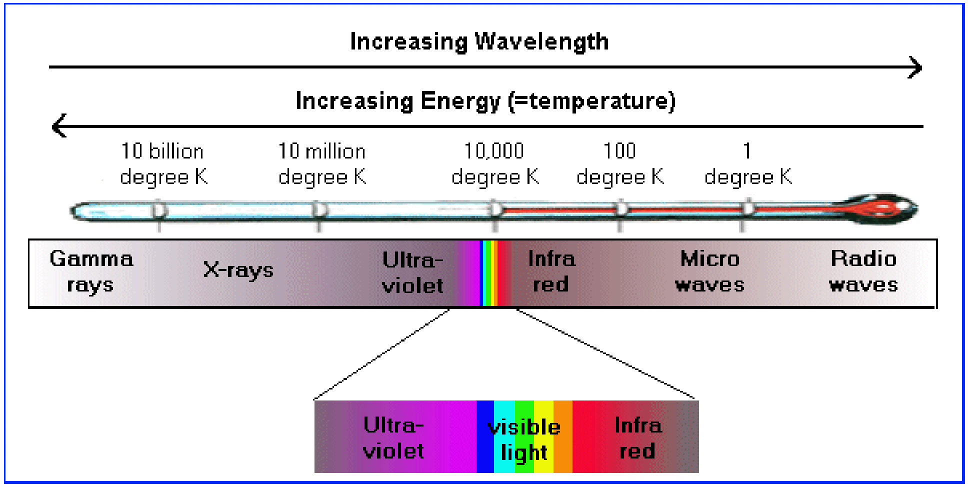
- Penzias had a telephone conversation with MIT radio astronomer Bernie Burke
- He mentioned the problem of the unexplained noise signal
- Burke had heard about an idea of Robert Dicke, which predicted background radiation
- Dicke was at Princeton, just down the road

Robert H. Dicke was a physicist who contributed much to radio technique

- His idea to stabilize the output of a radio telescope receiver by comparing it with a reference (“Dicke switch”) is used to this day – and was used by Penzias & Wilson
- He measured atmospheric radio emission before 1946 and had set a limit to the sky brightness (and probably could have measured it)

A black body radiates amount of power which depends on its temperature

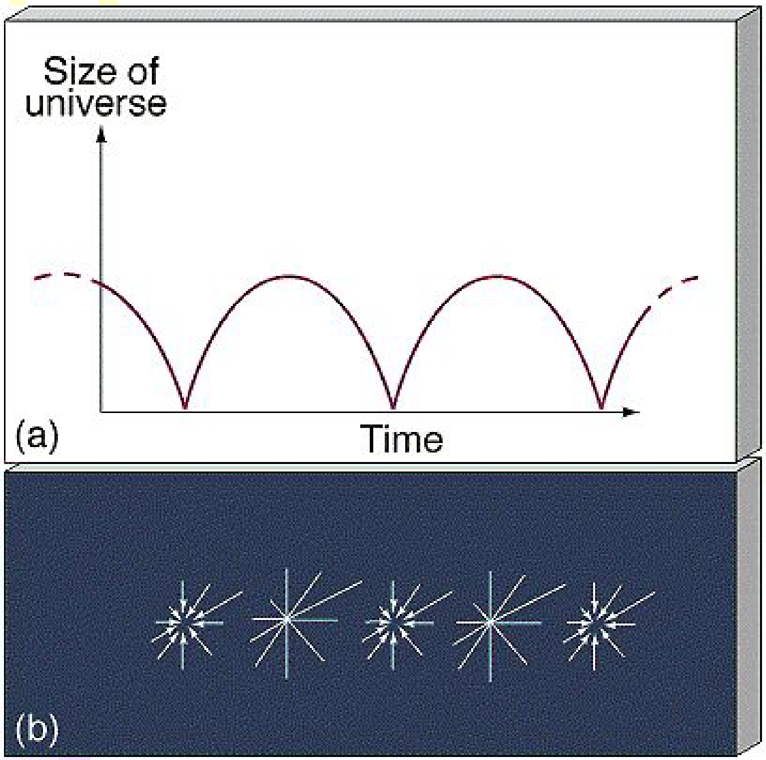




- Each one of the black body curves of increasing temperature lies above those of lower temperature
- Even at long wavelengths, a black body's temperature can be uniquely determined

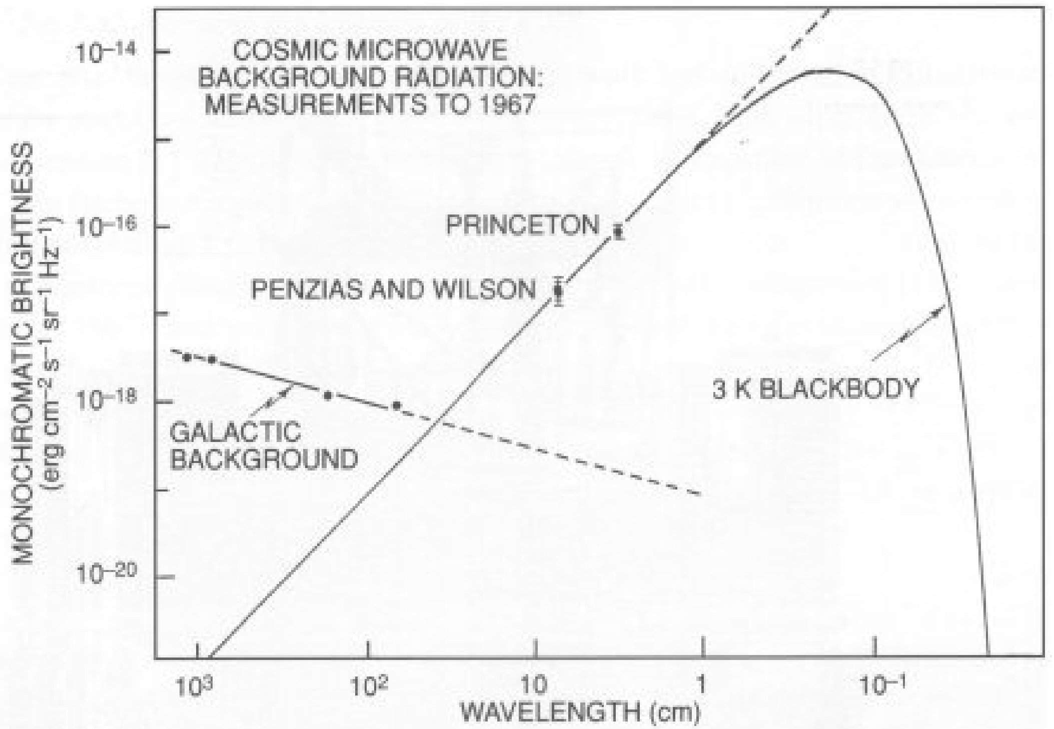
Dicke’s group: looking for what Penzias & Wilson found by accident

Dicke's motivation was a cosmological model he preferred



- Dicke liked an oscillating universe, with expansion followed by contraction, and repeated big bangs
- We happen to be in one of the expansion phases
- When he heard from Penzias & Wilson of their detection, he told his students, "Boys, we've been scooped."

Here's what they found



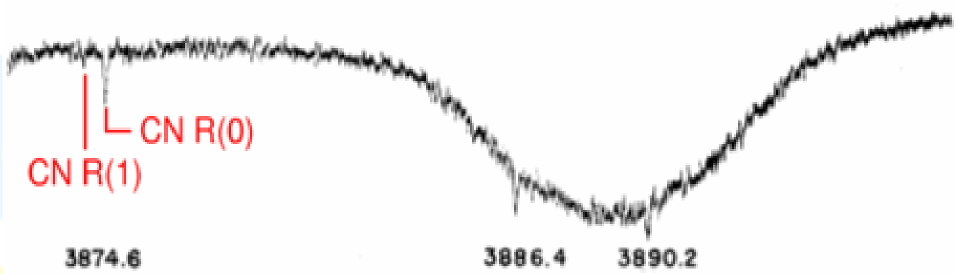
A second measurement of the CBR at 3.0 cm (Roll and Wilkinson, 1966) confirms the discovery of a thermal background and refines the value for T_0.

But there had already been a prediction of the effect

Alpher, Bethe & Gamow had predicted synthesis of Helium

- Ralph Alpher, Gamow's PhD student, calculated how much hydrogen would be converted to helium in the very early hot phase after the big bang
- The result, 10% He, agreed well with what astronomers found
- Gamow, with his sense of humor, added Bethe's name *in absentia*, and ever since the paper has been called, αβγ

Stranger yet, the CMB had already been measured, accidentally



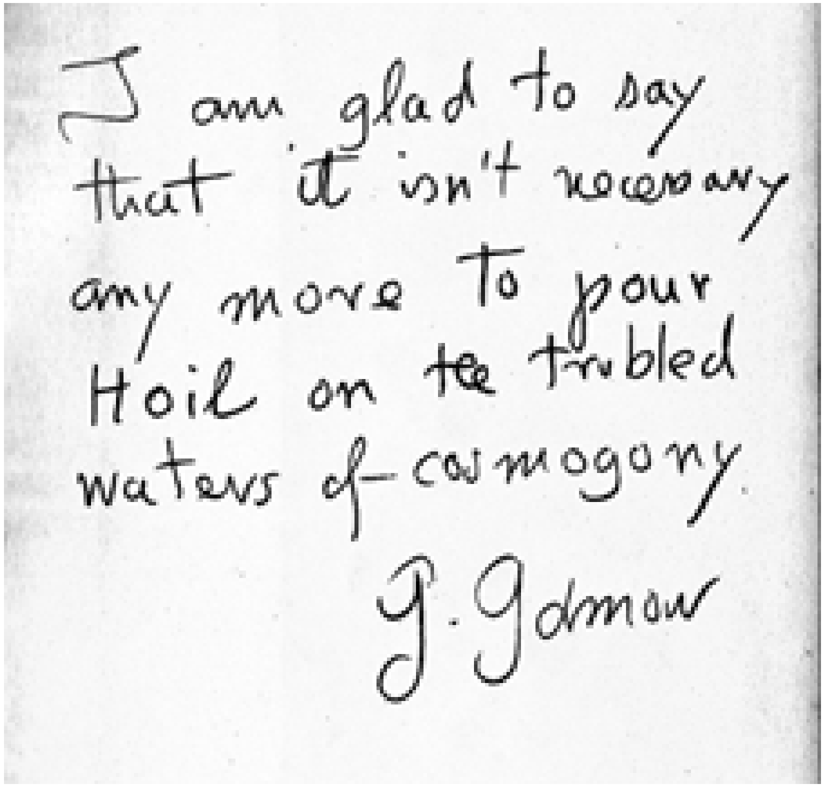
- In 1940, A. McKellar observed CN absorption lines in the spectra of bright stars, and found that the line strengths indicated an excitation temperature of 2.3 K. The effect was unexplained at the time
- The potential importance of this discovery was not realized for many years

There is much irony in this early history of CMB

- Gamow, proponent of the big bang, ignored the CN result
- Hoyle, in a review of a book by Gamow (where the background temperature was estimated to be 11 K) viewed the CN value of 2.3 K as disproving Gamow's big bang
- In 1950, the Nobel-Prize winning spectroscopist G. Herzberg said the CN result had "only a very restricted meaning"

When the CMB “proved” the big bang model, Gamow wrote a note...

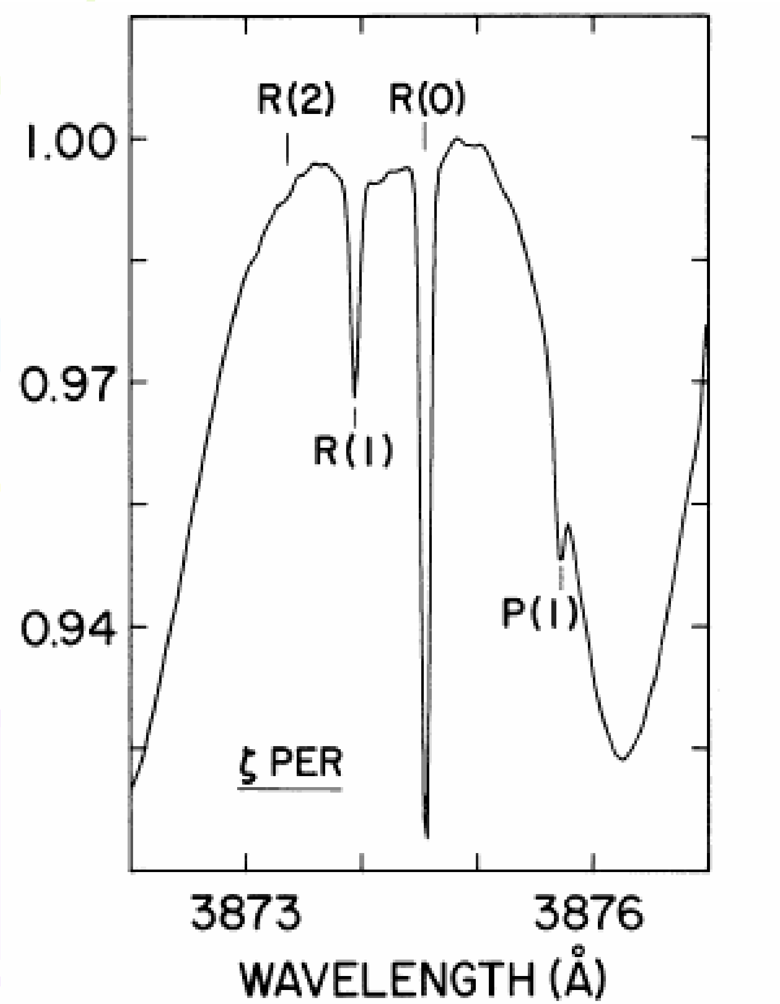
- “Hoil” (oil) = Hoyle, and cosmogony = cosmology
- Which is not to say cosmology had ceased to be controversial.
- Gamow tried to get his other student Robert Herman to change his name to Delpher, so there could be an αβγδ – but Herman never agreed!


I am glad to say
that it isn't necessary
any more to pour
Hoil on the troubled
waters of cosmogony
G. Gamow

There were several strange errors of omission in the CMB story

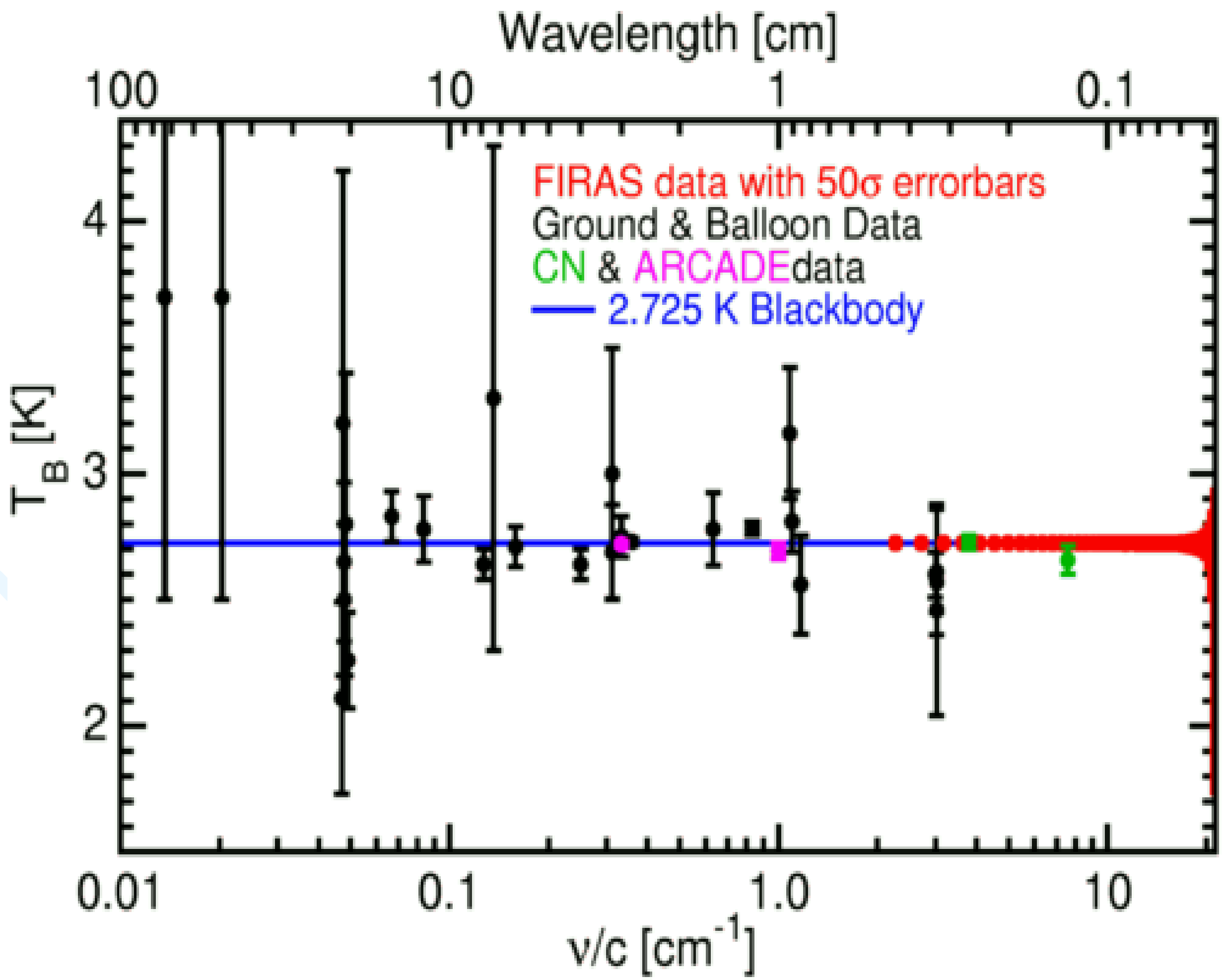
- Dicke forgot, it seems, his own wartime measurement of atmospheric emission, and limit of T_{sky}<20 K
- He also later acknowledged the oversight of not referring to the result from Gamow's group
- Penzias & Wilson say little about the possible cosmological implications of their detection, referring to Dicke et al. They didn't really believe in it, though it got them a Nobel Prize

Modern CN measurement

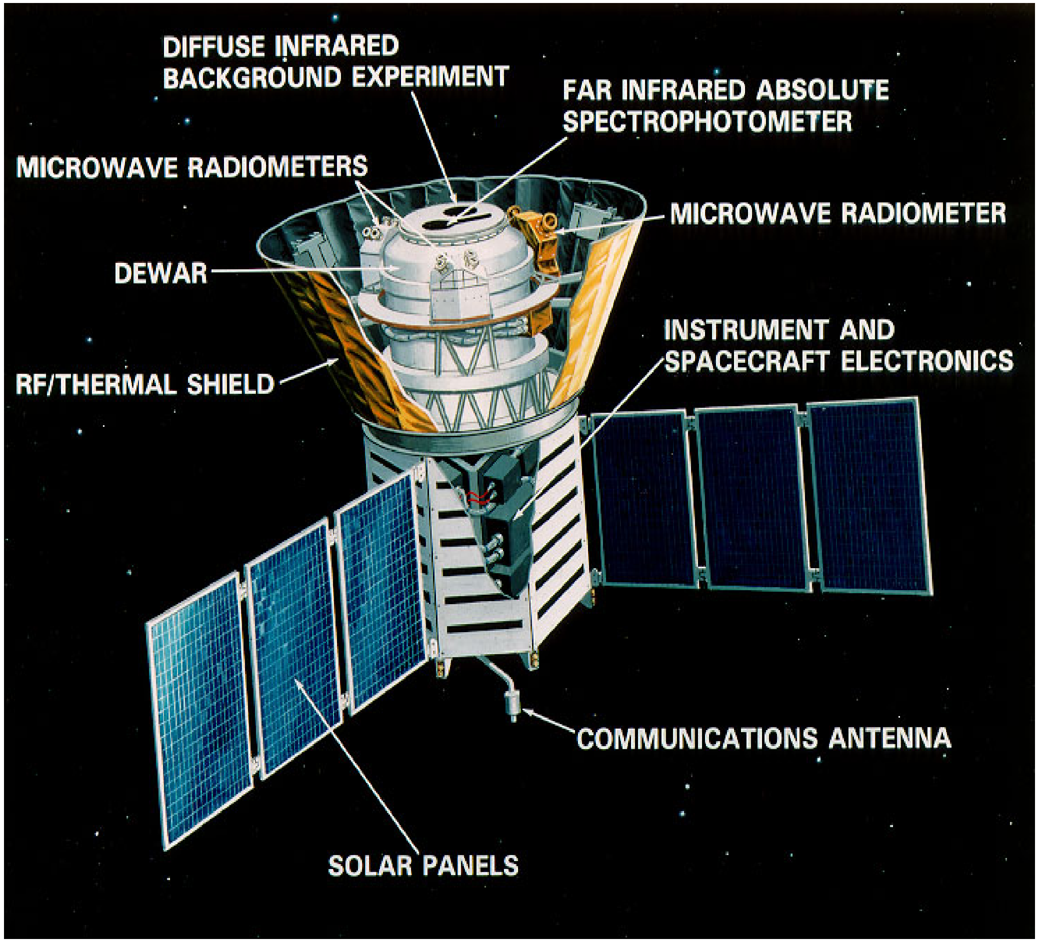


- After the radio discovery, improved observations were made to tie down the CMB temperature near the black body peak
- The CN measurement determines the background temperature at 2.64 mm wavelength, a wavelength difficult to measure from the ground

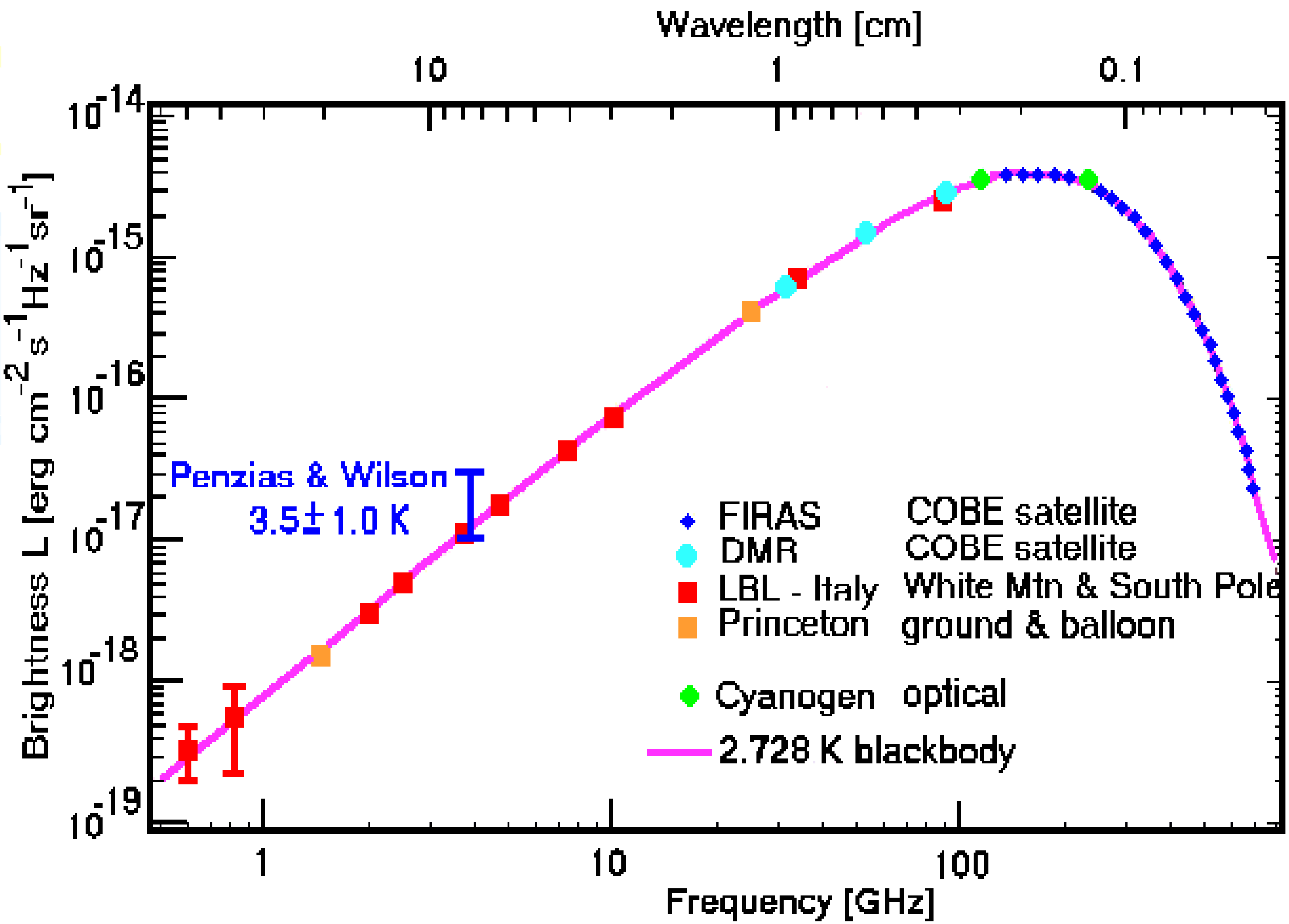
Overview of many of the CMB temperature measurements



One of the biggest advances: the COBE satellite

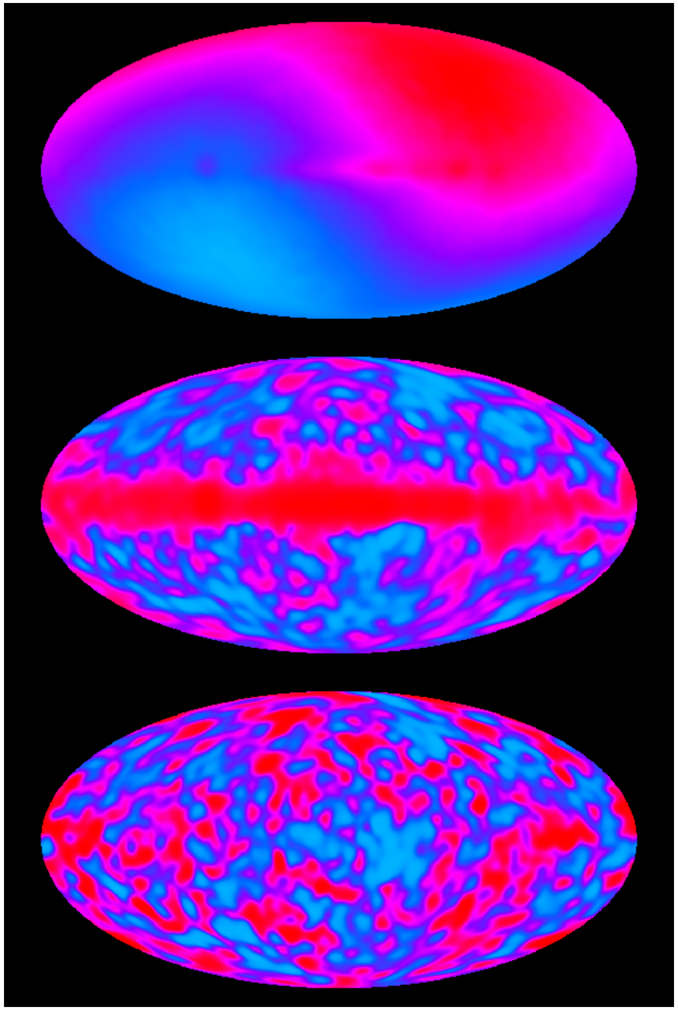


COBE measured the average temperature over the whole sky...

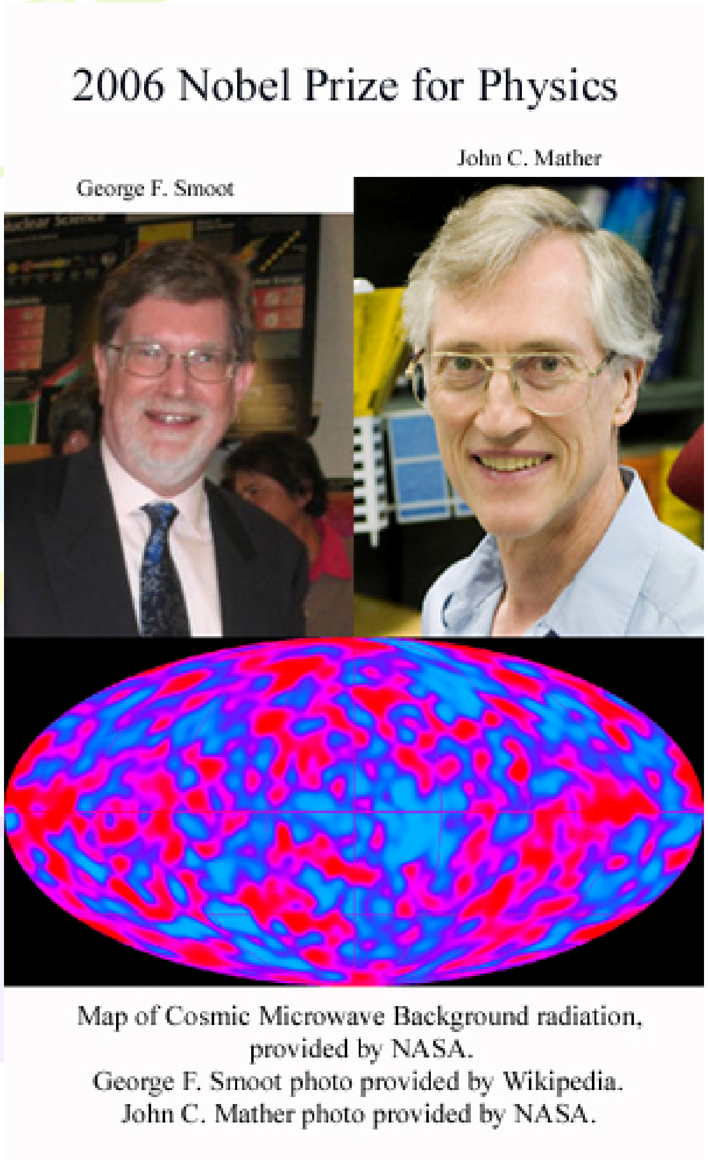


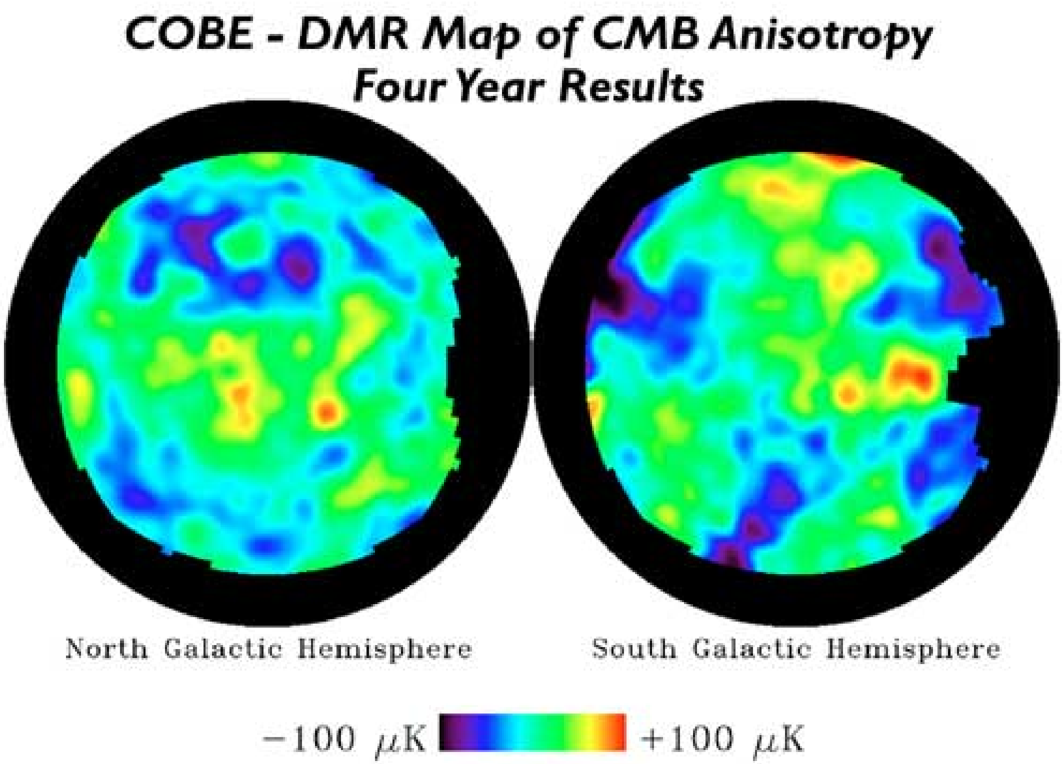
...and mapped the temperature in every direction

- Here we see the deviations from T=2.728 K
- The 1st (biggest) one, at about 0.001 K, is due to the motion of the solar system
- In the next one, the plane of the Milky Way is seen
- The 3rd shows small scale deviations caused by density variations in early universe – later clusters of galaxies

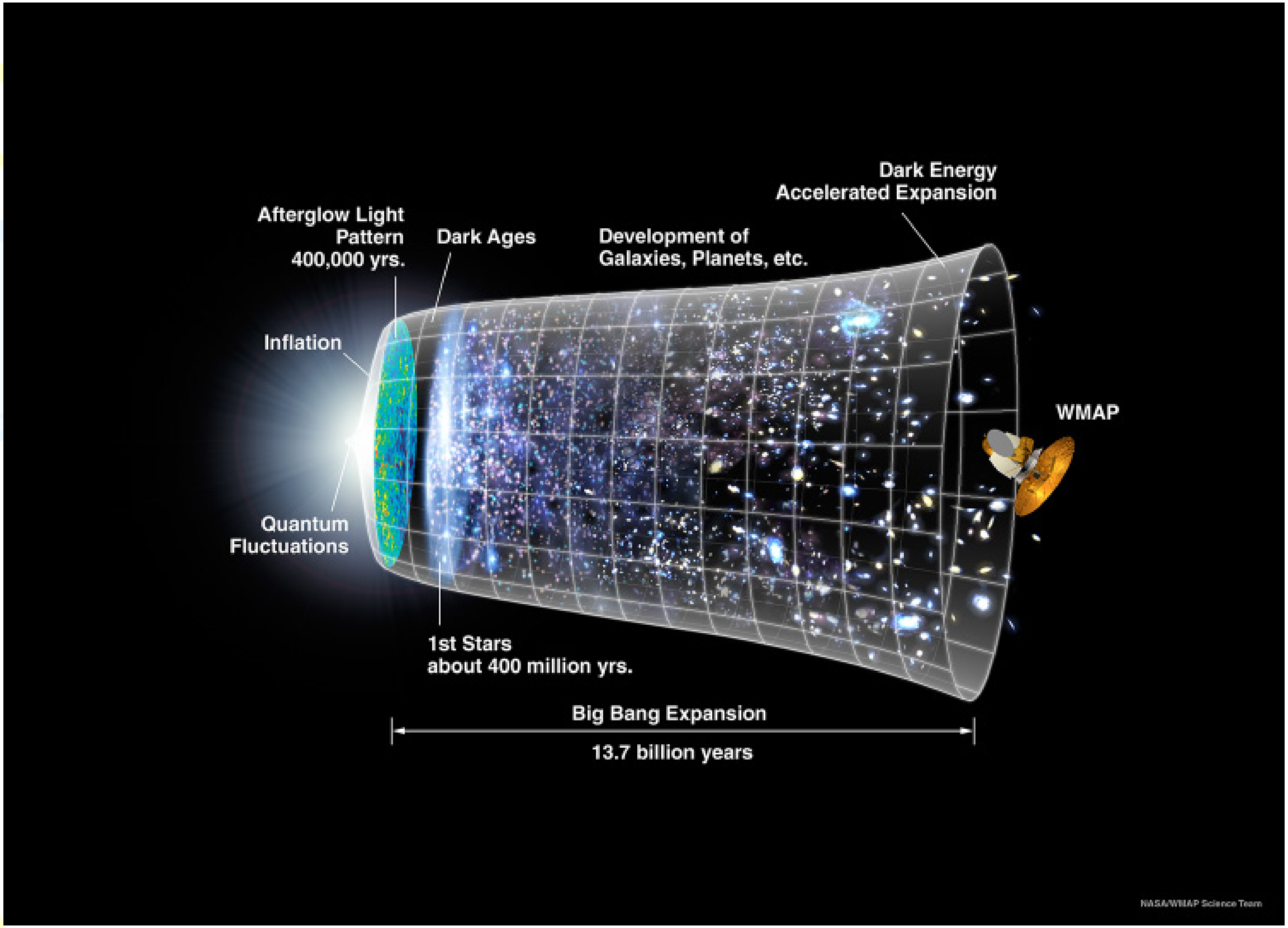


For the COBE work, Smoots & Mather shared the 2006 physics Nobel Prize

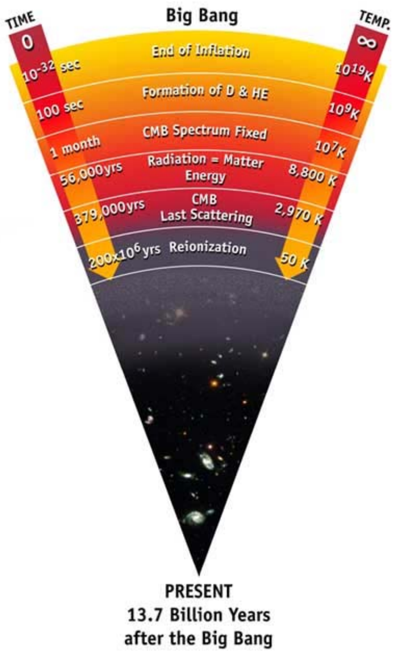


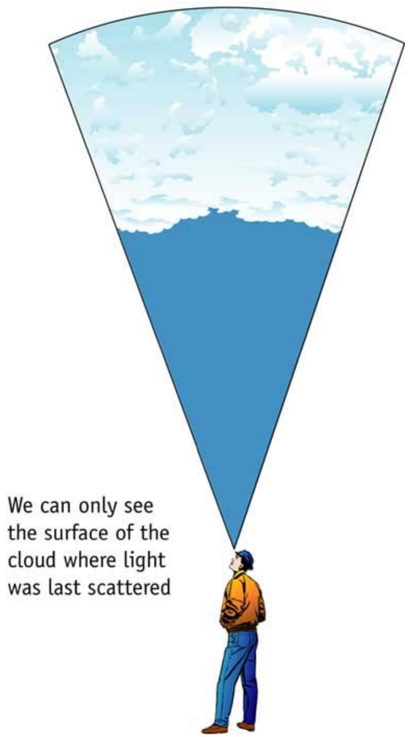


CMB preserves imprint of matter distribution in early universe



The CMB seen today comes from the "surface of last scattering"

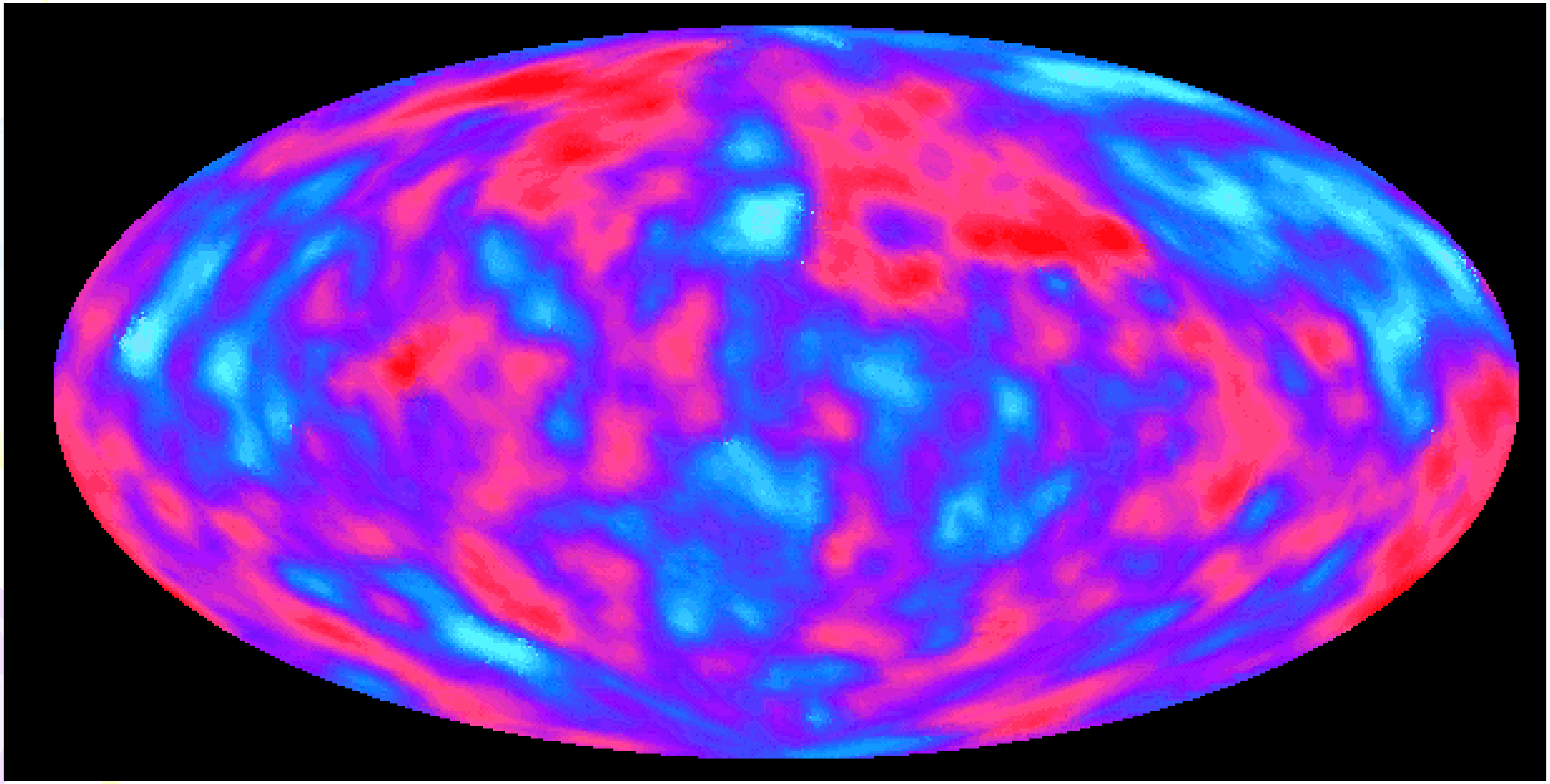




The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

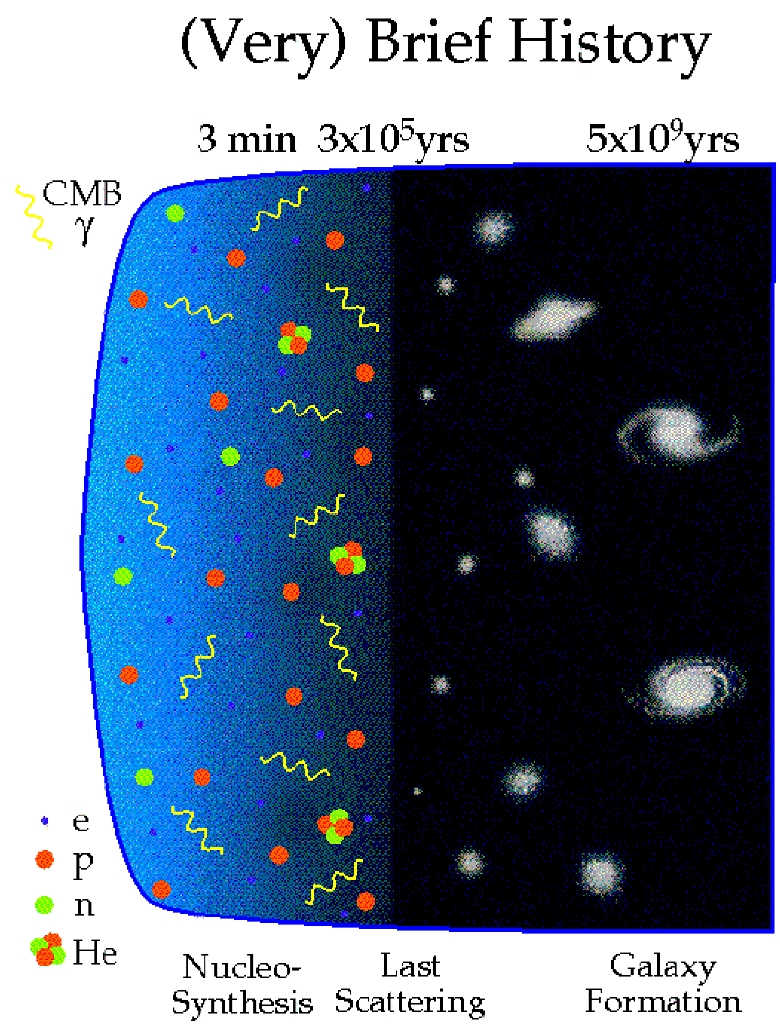
- Before last scattering, the photons and particles were in an opaque "soup" as if within a cloud
- The last scattering point is like the bottom side of the cloud: we can't look farther than that
- Any fluctuations in density appear as CMB bumps

These lumps ("wrinkles") are from when matter and light decoupled



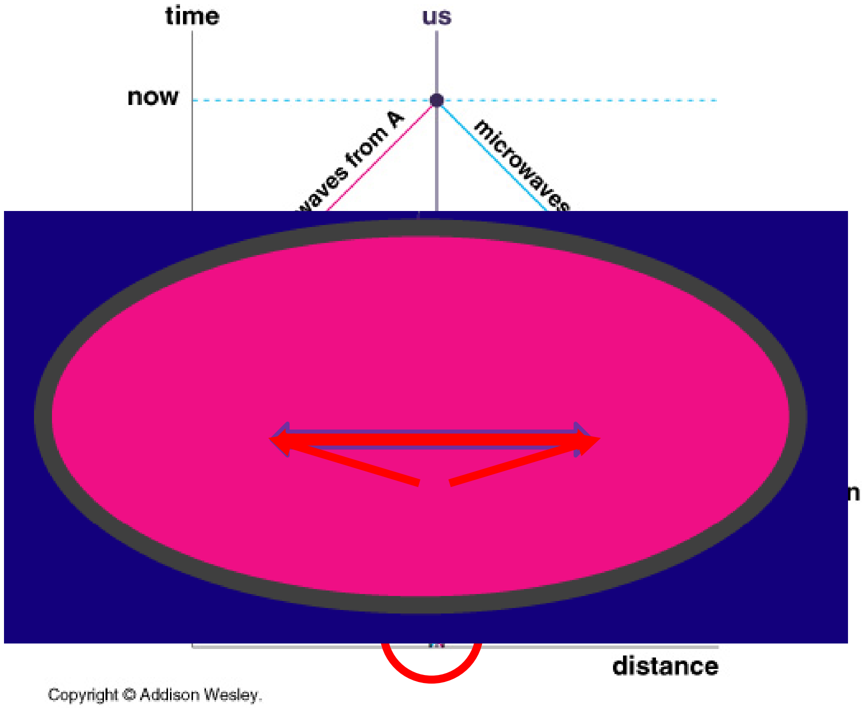
The lumps are believed to come from "quantum fluctuations" at early time

- Shown schematically here, it has been proposed that the very early universe underwent a short period of extremely rapid expansion – "inflation" – in which the fluctuations grew in size
- This inflation is also needed to solve some other inconsistencies in the simple Big Bang model

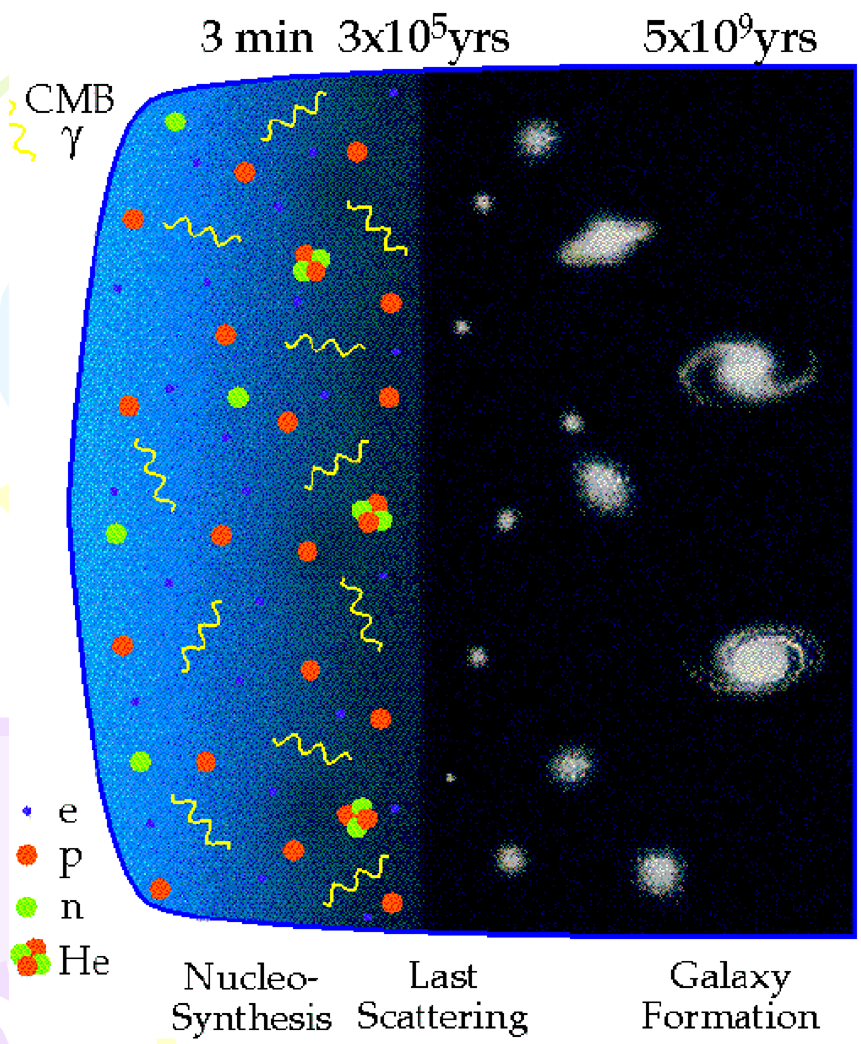


Why do we need inflation?

- Given the present age and size of the universe, A and B can never have been in contact
- This has always been true
- But the CMB 2.728 K is incredibly smooth
- How is this possible if A & B were never in contact?
- Need early, fast expansion

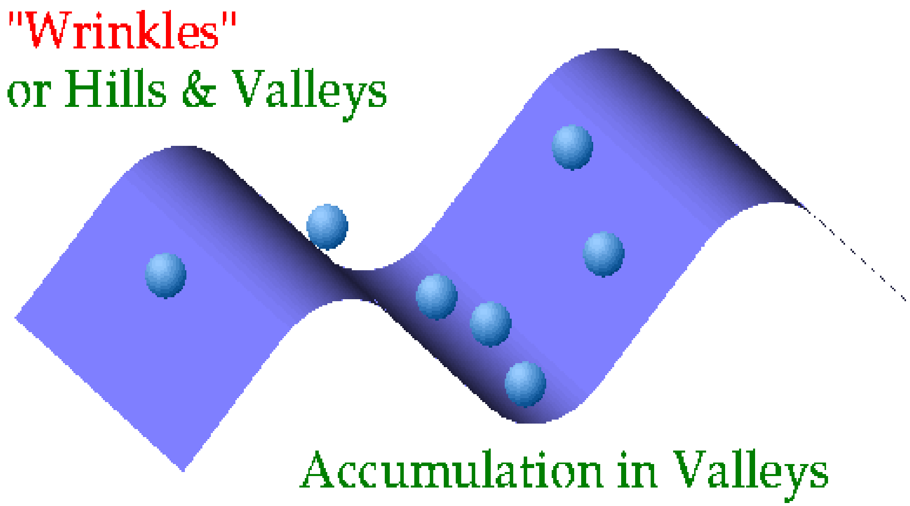


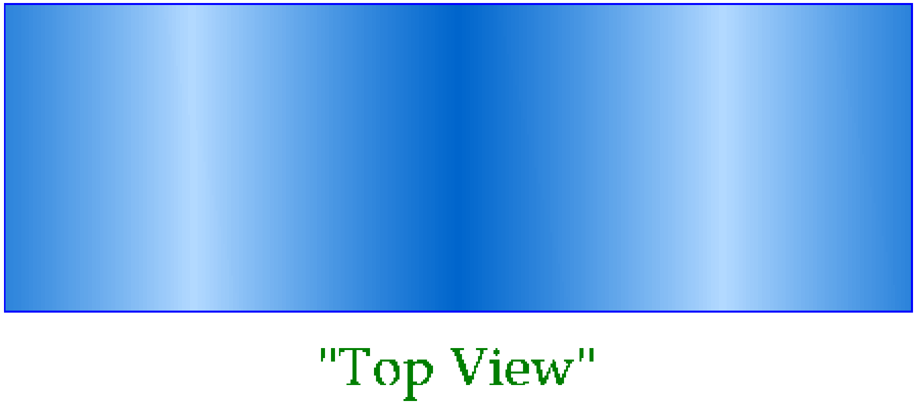
But there are other problems with the lumps we observe



- These fluctuations grew with inflation
- But as observed in the CMB, they are larger than the sizes of galaxies
- In that case, where did the galaxies come from?

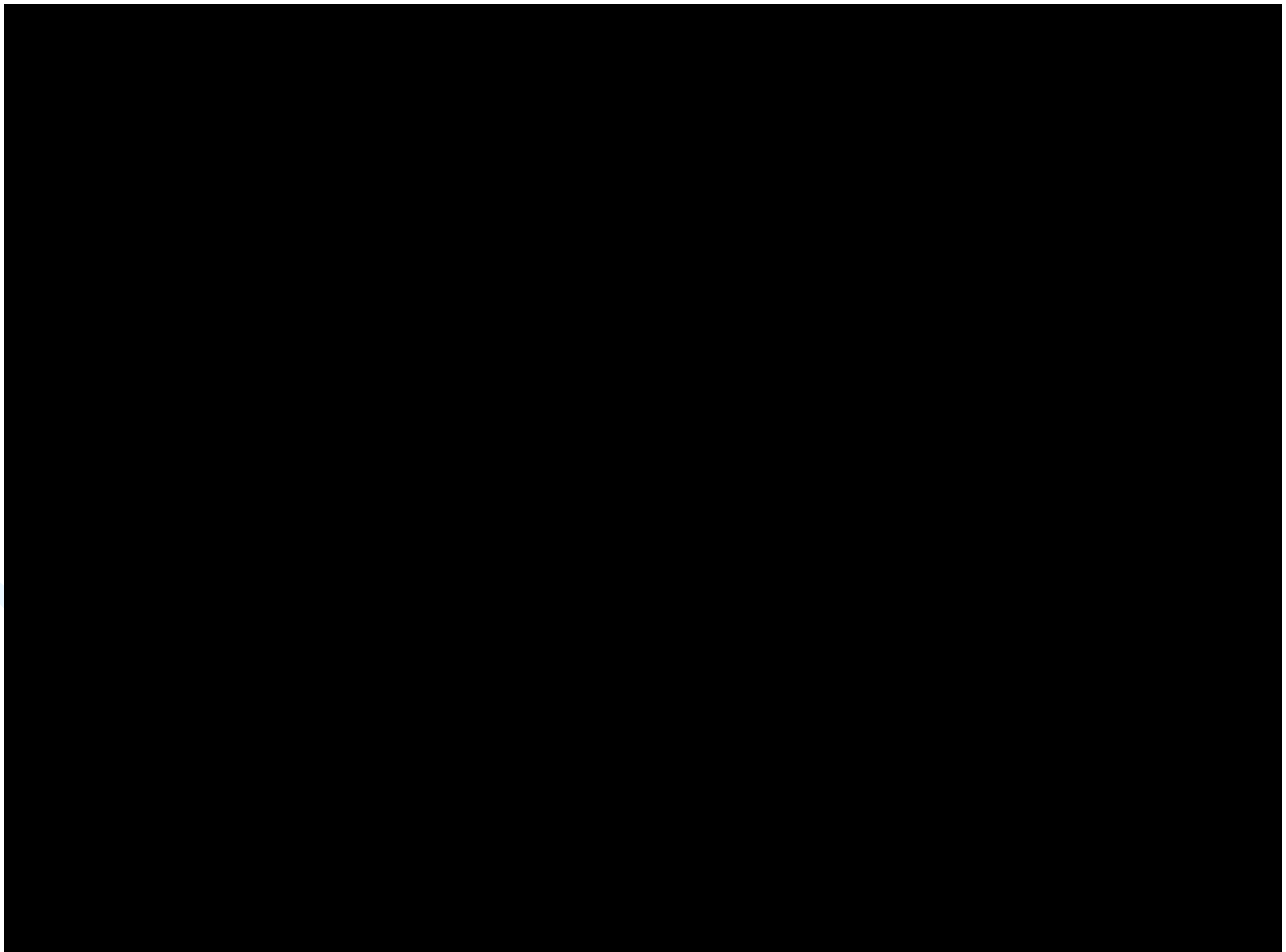
The large-scale fluctuations are viewed as the seeds of galaxy clusters



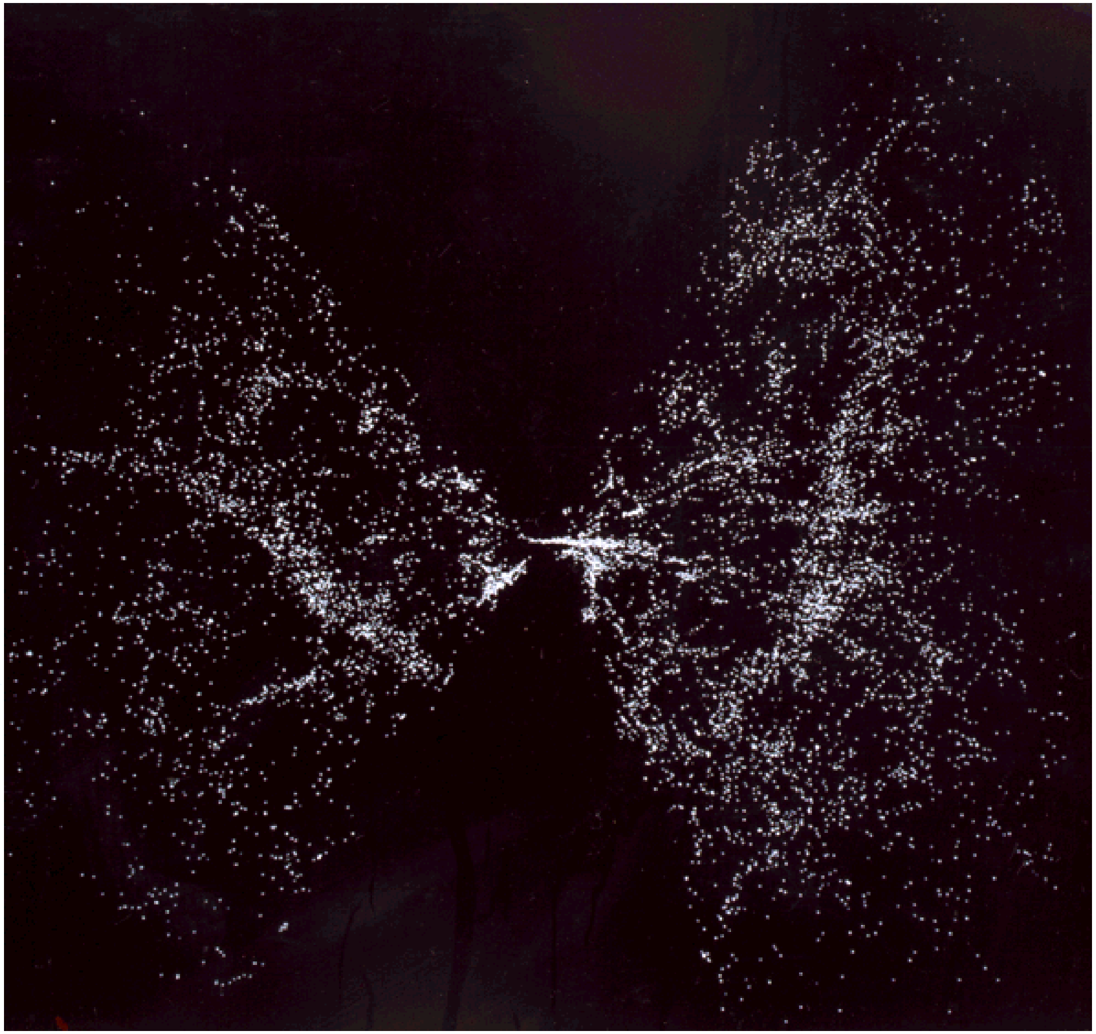


- Matter (shown here by balls) will tend to concentrate in the “valleys” of the quantum fluctuations
- We can illustrate the waves by shading as in the lower drawing
- Cosmologists model how these waves evolve into clusters

The result of modeling – density change from z ≈ 29 to present

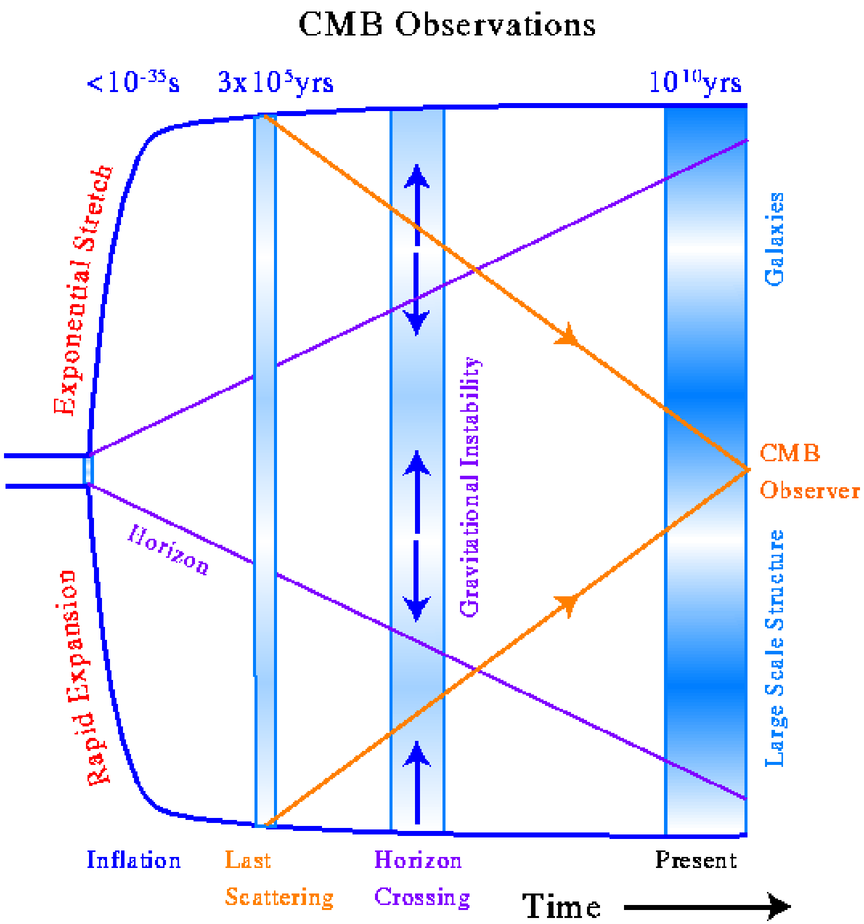


What the distribution of galaxies actually looks like locally

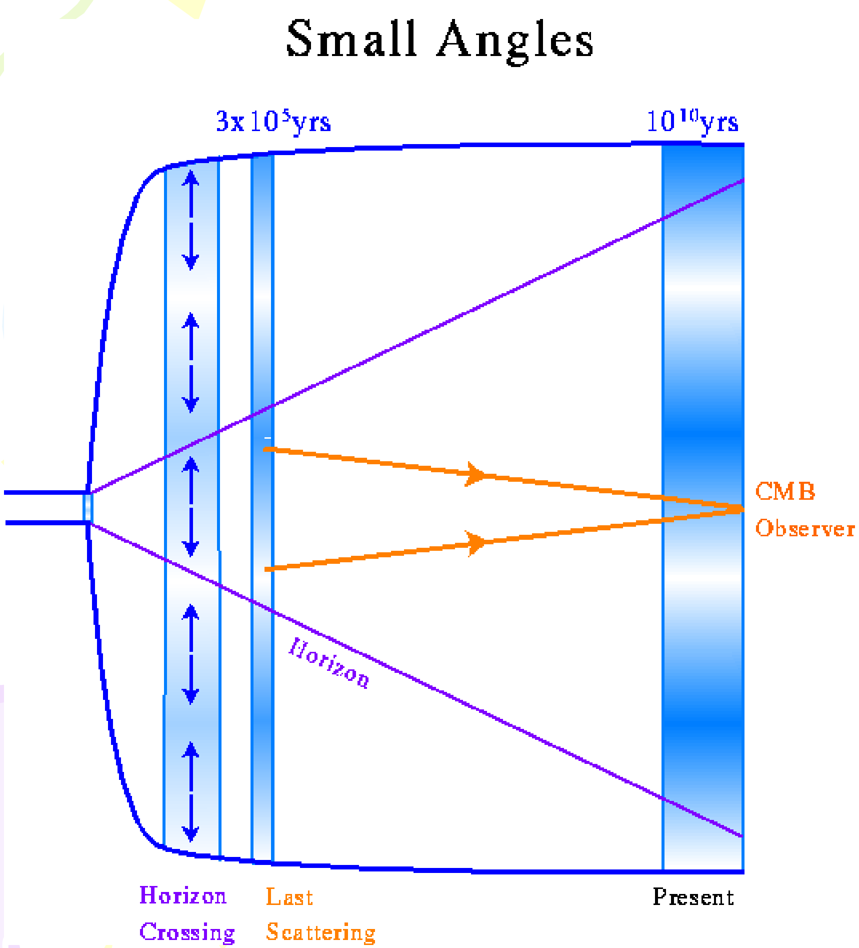


The large-scale CMB fluctuations reflect the density at decoupling

- This is what the COBE observations provide
- The finite speed of light, and the fact that there is more time for it to reach us at later epochs, means the distance to the horizon increases with cosmic time
- Within the horizon we observe smaller scales

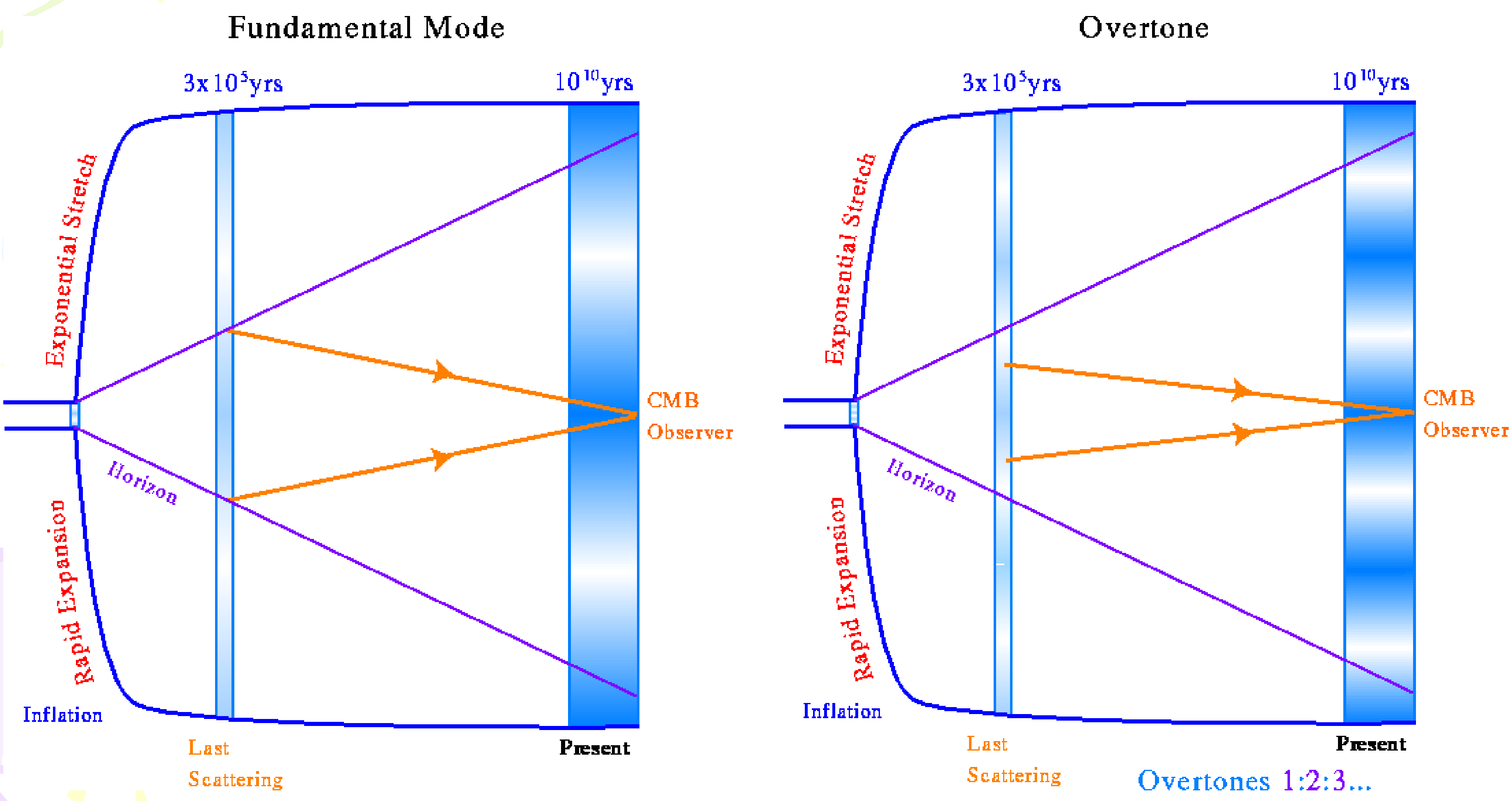


What can the smaller scale fluctuations tell us?

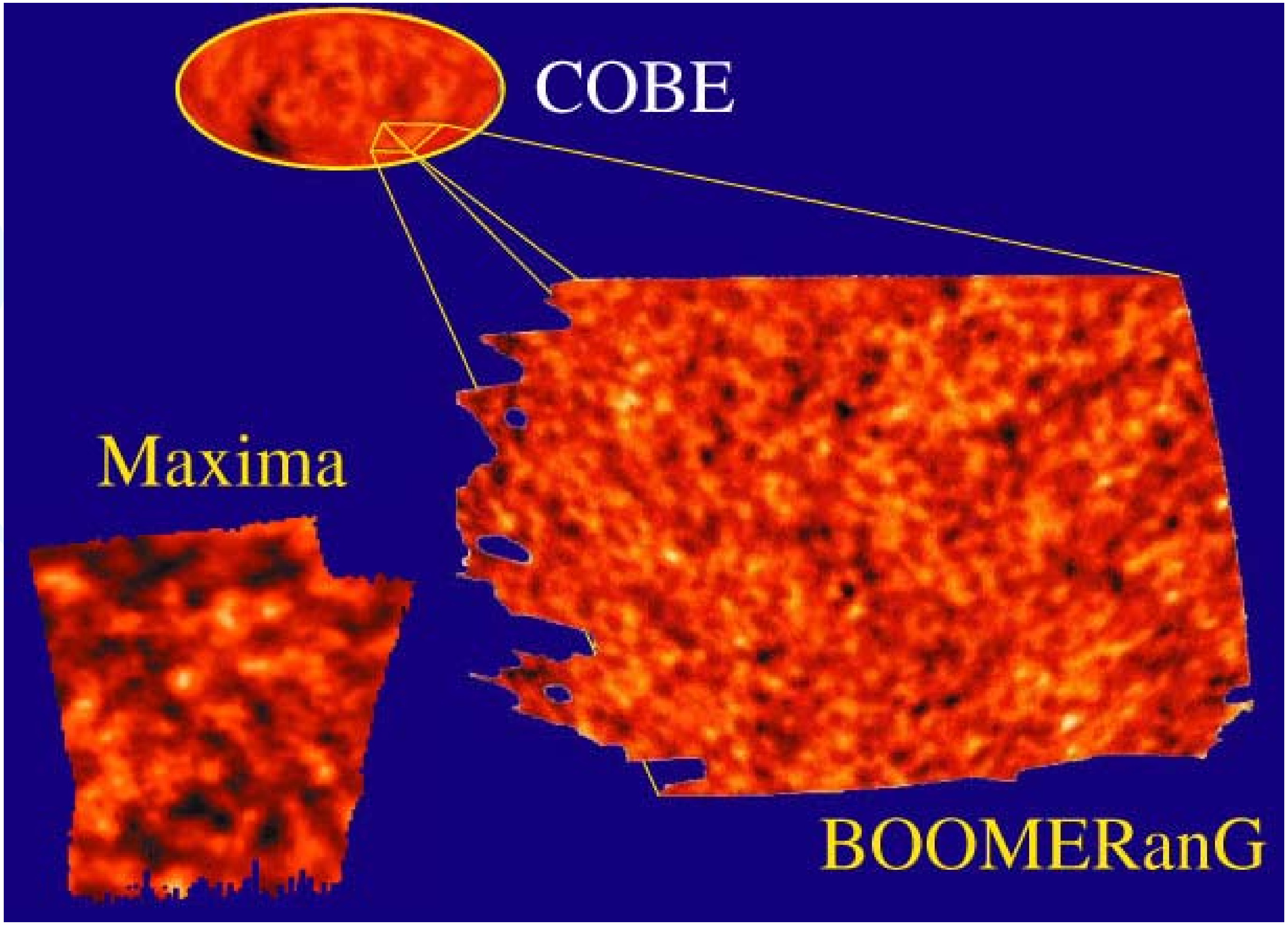


- On the smaller scales we are no longer looking at the primordial lumps, but rather at later structure formation at work
- The fluctuations represent pressure waves in the material – in fact, sound
- Where the density is higher, the CMB is hotter – we see acoustic photons

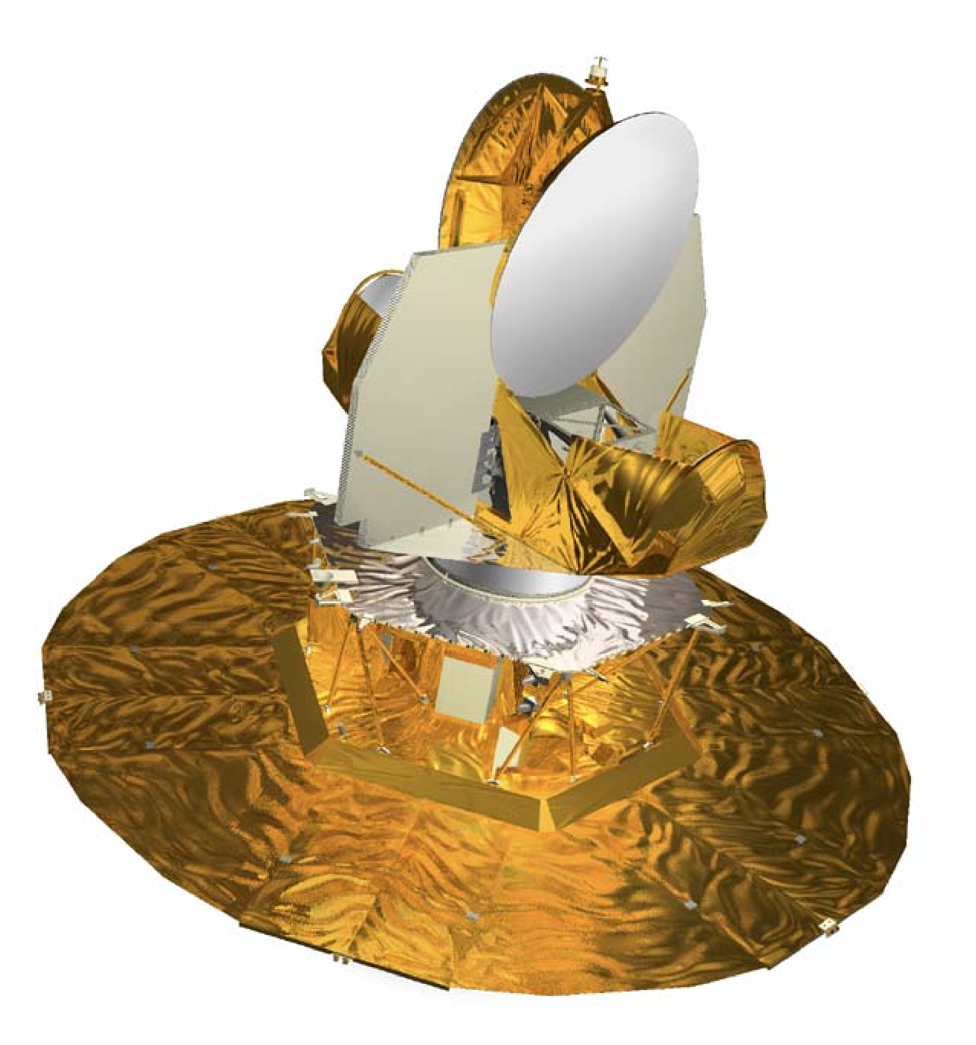
The whole spectrum of waves lets us probe the scale of structure formation



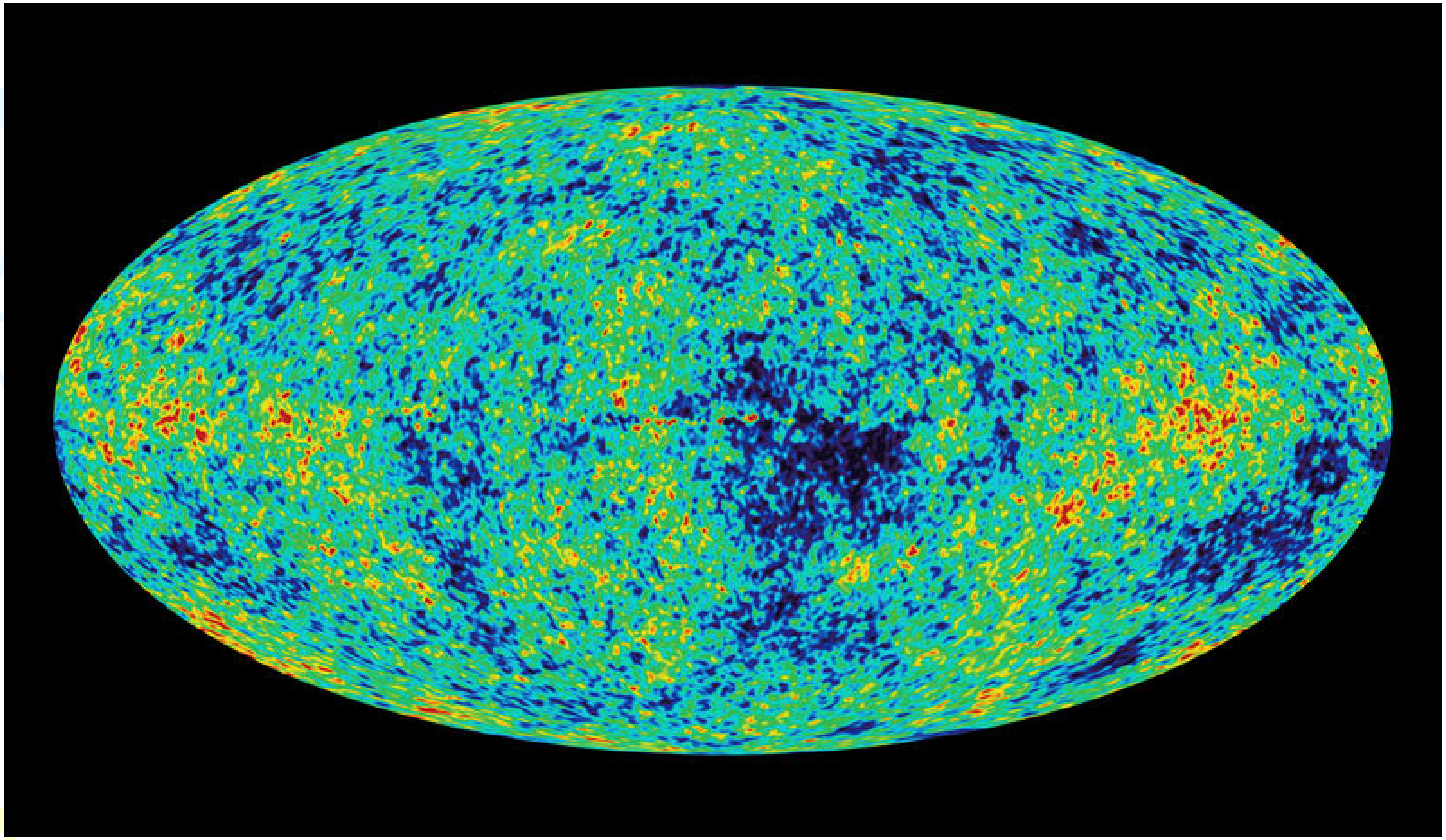
After COBE, various projects probed CMB on smaller scales



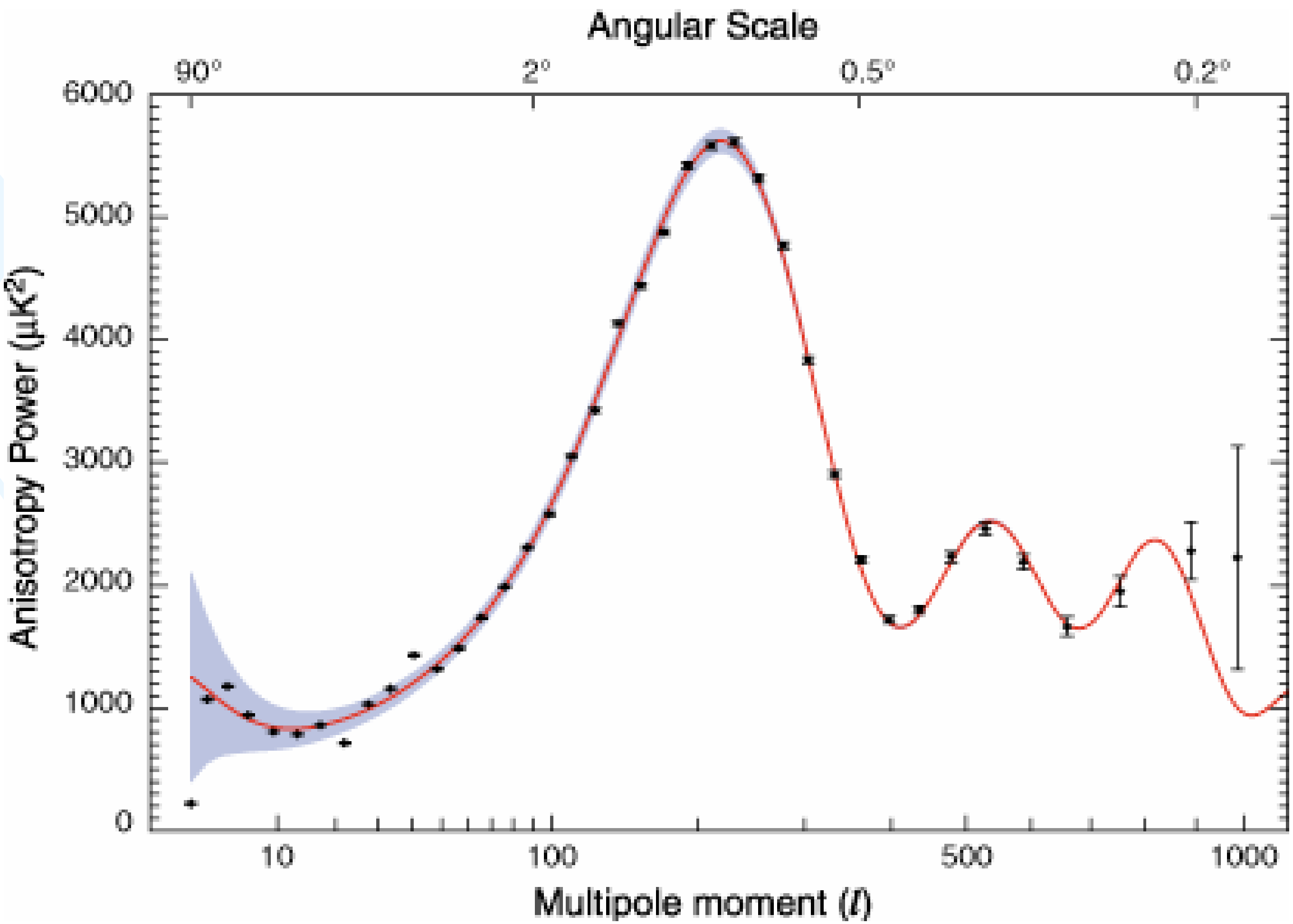
This culminated in the Wilkinson Microwave Anisotropy Probe (WMAP)



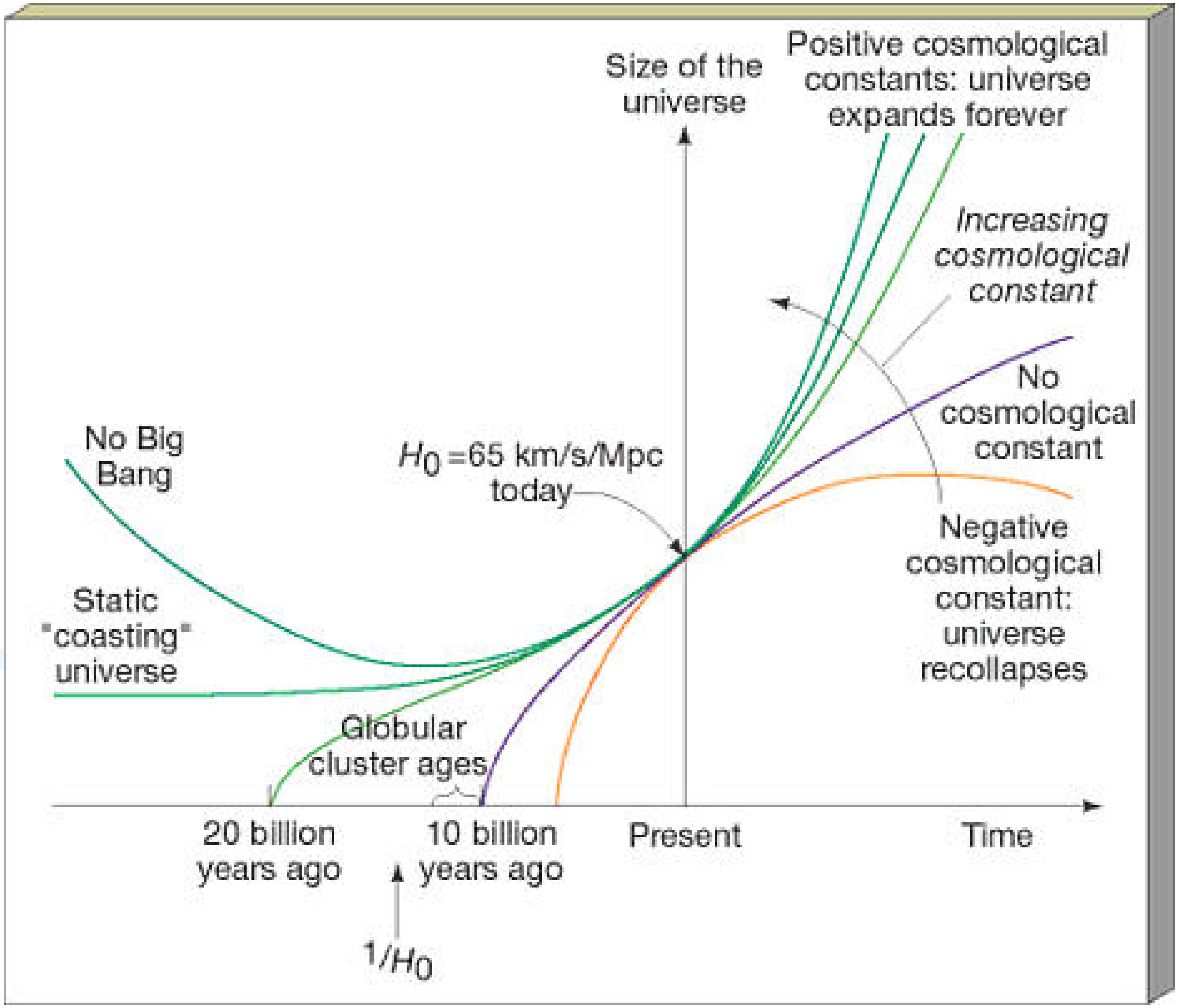
Objective of the WMAP project is to look at the CMB deviations more closely



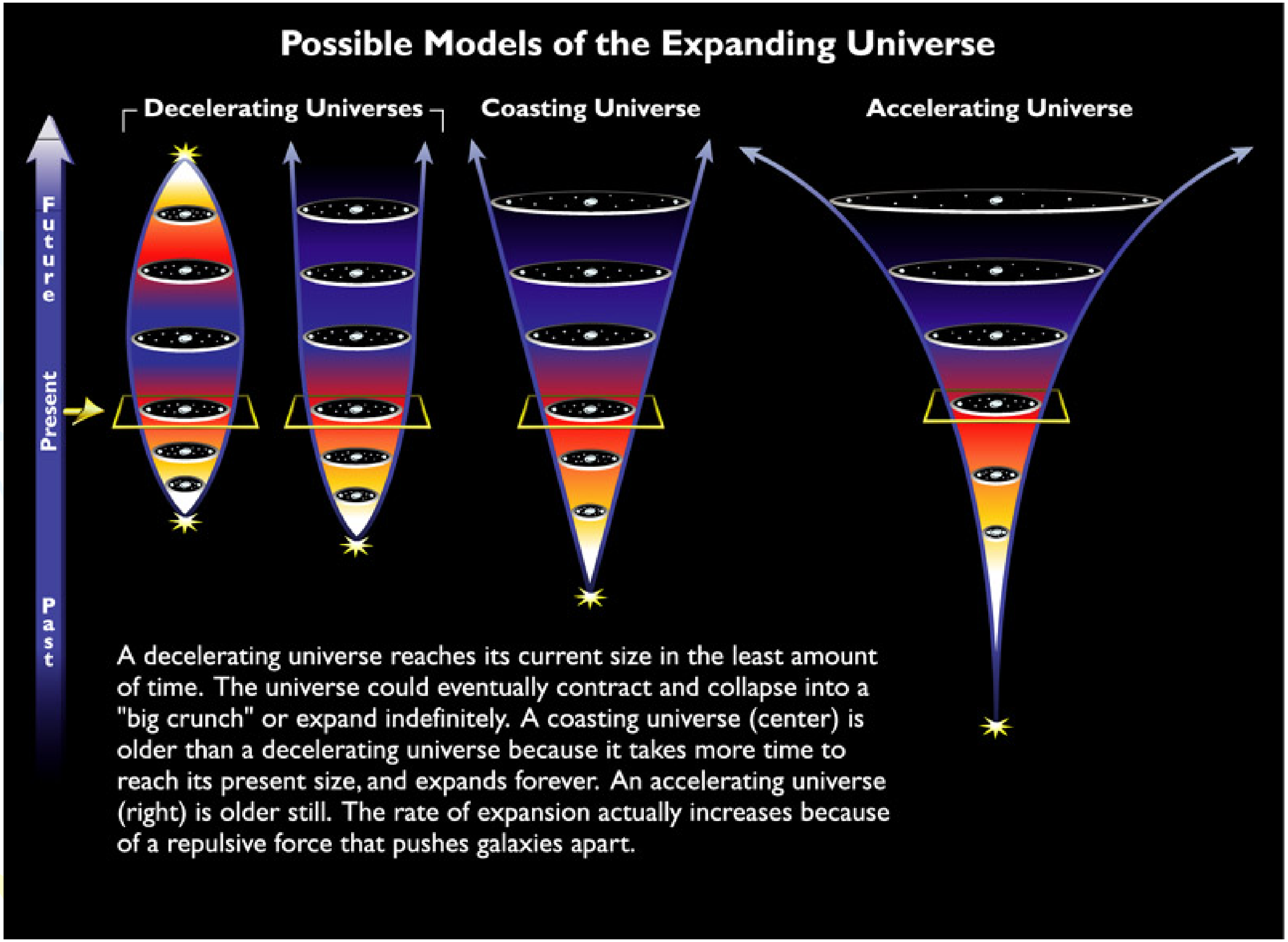
Spectrum gives amplitude of deviations at different angular scales: tones



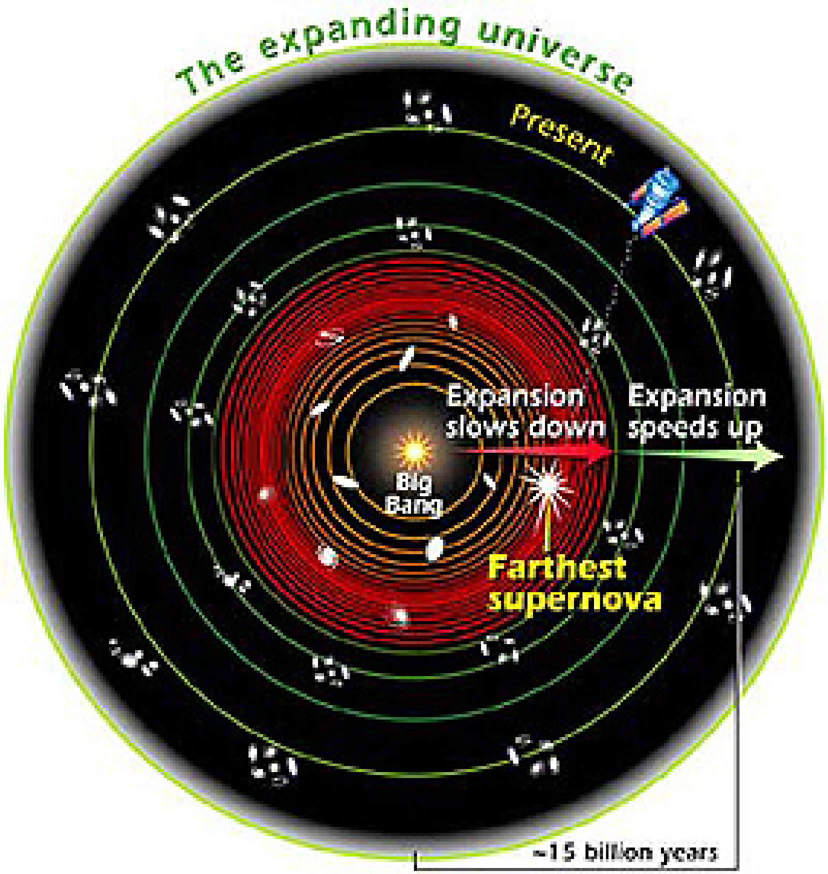
We also need to know something about the expansion rate



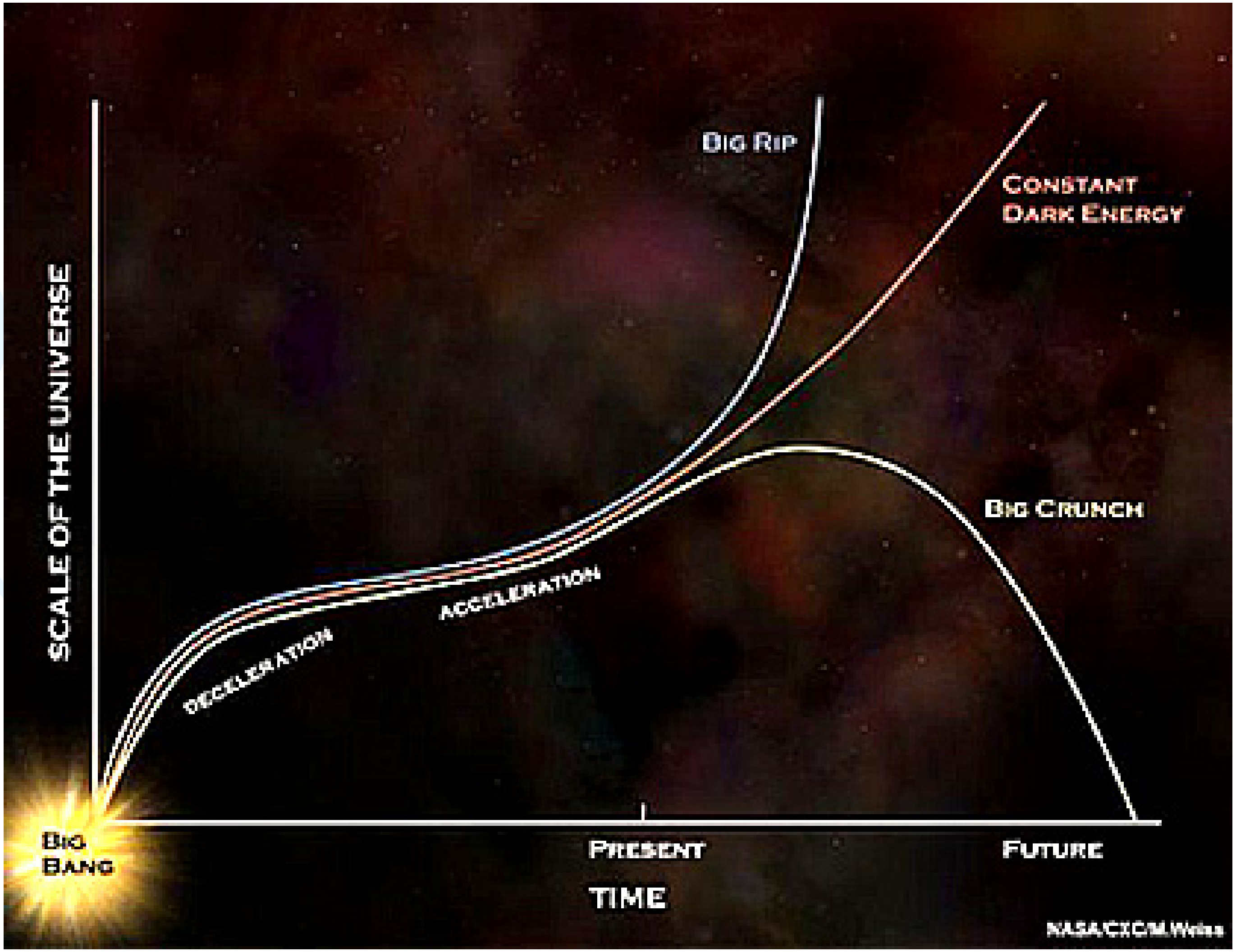
The expansion rate doesn't have to be constant throughout cosmic time…



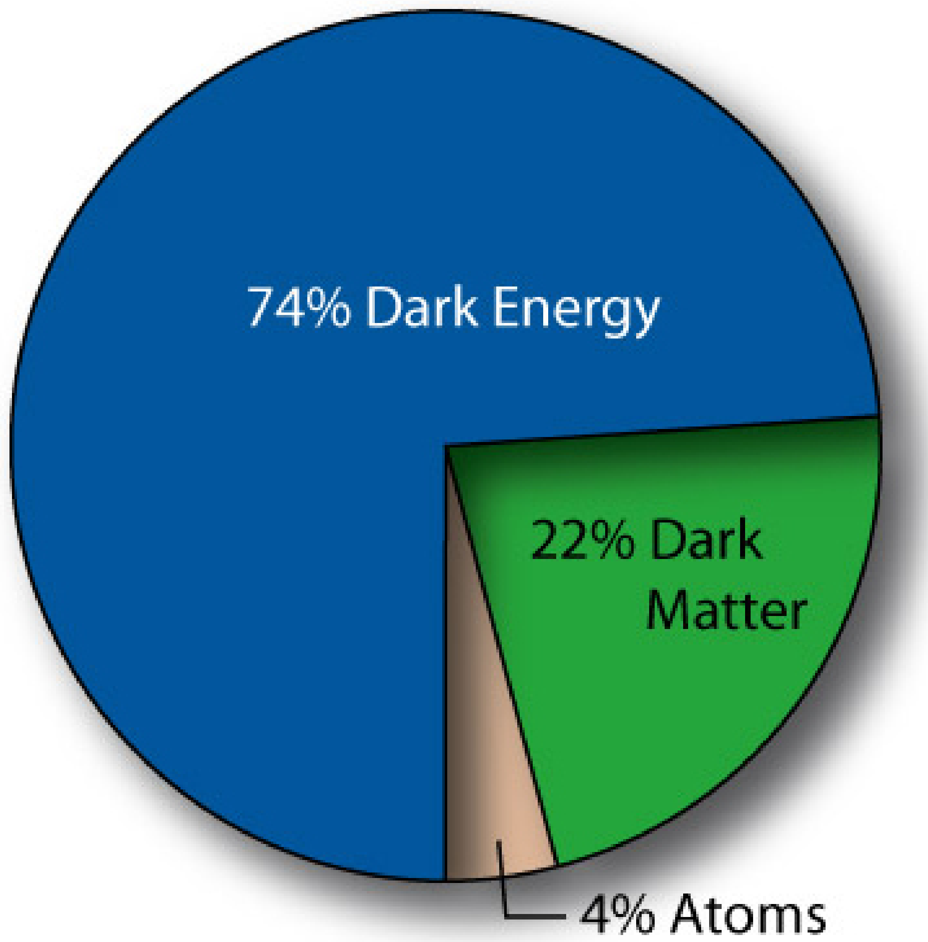
& from supernova observations it seems that expansion has not been constant



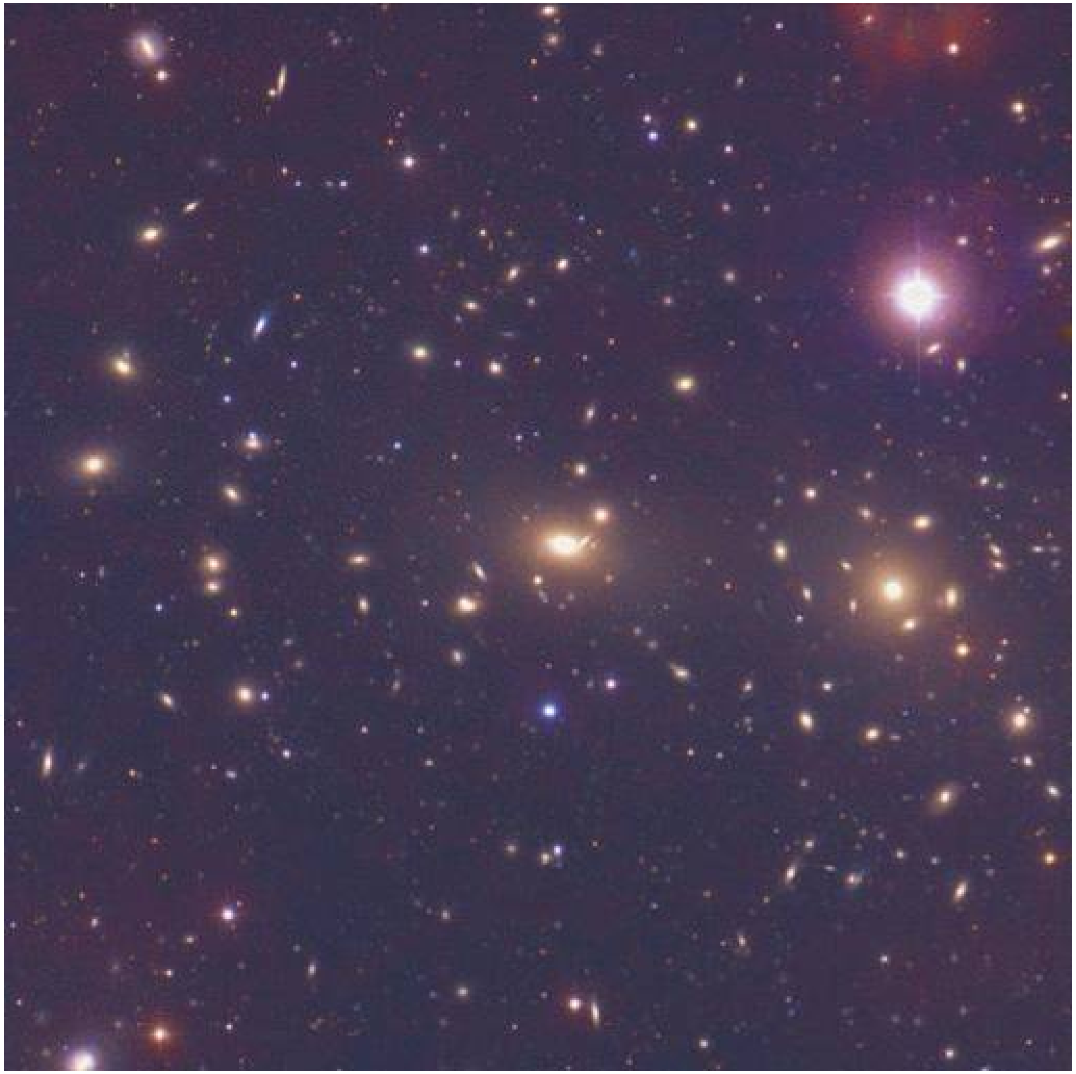
“Dark energy” is also implied



From such results, the composition of the universe can be modeled



It seems disturbing that only 4% of the universe is visible matter!



Next lecture: Search for life in the universe