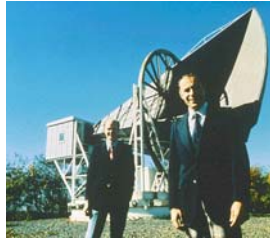


Today in Astronomy 102: the Big Bang

- ❑ Cosmological models: Big Bang and Steady State.
- ❑ Observational tests of the models, and direct observation of the Big Bang.
- ❑ The cosmic microwave background: the appearance of the decoupling surface, the closest we can see to the singularity.



Bob Wilson (left) and Arno Penzias with the horn antenna they used to discover the cosmic microwave background. (Bell Laboratories photo)

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Summary of Hubble's findings

- ❑ The Universe is **isotropic**: on large scales it looks the same in all directions, from our viewpoint.
- ❑ The Universe is **homogeneous**: it is uniform on large scales. In other words, the Universe looks the same from any viewpoint.
- ❑ The Universe is **expanding**:
 - The galaxies recede from us, faster the further away they are.
 - And since the Universe is homogeneous, we would see the same recession no matter where we stood. That is, there is no unique center in space, of the expansion, as in an ordinary explosion and blast wave.

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Cosmological models

Once Hubble's observations made it clear that the Universe is not static, two types of models remained for the structure of the Universe:

The Big Bang model: based upon non-static universes with constant total mass and energy, presently in a state of expansion, but **originating in a mass-density singularity**. Major proponents: Friedmann, Lemaitre, Robertson, Gamow, Pope Pius XII, Sandage.

The Steady-State model: in which mass-density singularities are not realized, because **steady creation of new matter** leads to a constant density on the average, expansion, and no "beginning" or "end". Major proponents: Einstein, Bondi, Gold, Hoyle, Chairman Mao, Arp.

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Observational tests of cosmological models

Big Bang Universe proponents made these specific predictions on the basis of their models:

- ❑ (I) On *very* large scales - a substantial fraction of the total size of the Universe - galaxies would be closer together on average than they are now, owing to the expansion and early curvature of the Universe. (Recall: far away = far back in time; spacetime is warped close to singularities.)
- ❑ (I) Evolution: very distant (young) galaxies should be qualitatively different on average from nearby galaxies.
- ❑ (II) **We should be able to see the blast of the Big Bang itself, by looking far enough away.** It would look like a hot, opaque body, but with its light Doppler-shifted to extremely long wavelengths because it is so far away. ($V = H_0 D$ and $\lambda = \lambda_0(1 + V/c)$: λ larger than λ_0 .)

Observational tests of cosmological models (continued)

And for their part, those studying the steady-state model predicted:

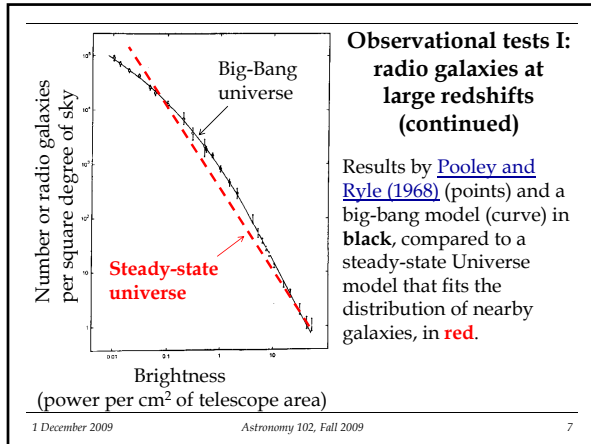
- ❑ (I) that galaxies would appear to be distributed uniformly, and spacetime would appear to be flat, no matter how far away we look.
- ❑ (I) no evolution: the internal properties of galaxies - what kinds of stars they have in them, what concentrations of heavy elements they possess, *etc.* - would be the same, on the average, everywhere in the Universe. That is, there should be no tendency for distant galaxies to look young.

A few steady-state proponents (notably Chip Arp) even predicted that galaxy redshifts would turn out not to be of cosmological origin, but instead would represent material ejected at high speeds by galaxies with small Doppler shifts.

Observational tests I: radio galaxies at large redshifts

Soon after radio galaxies were identified in the 1950s it was realized that most of the faint radio sources in the sky must be radio galaxies, mostly at distances much greater than those determined for visible galaxies.

- ❑ Counting the numbers of these faint sources as a function of their brightness basically provides a repeat of Hubble's demonstration that galaxies are distributed homogeneously on large scales.
- ❑ However, the faint radio sources should be much farther away than the faint galaxies observed by Hubble: far enough away to expect these galaxies to be closer together on average than present-day galaxies in a Big Bang model.



Observational tests I: radio galaxies at large redshifts (continued)

Implications of radio-source counts like those by Pooley and Ryle:

- As one looks back through time, the number of radio galaxies per unit volume increases (or typical separation decreases) up to very great distances.
- At the largest distances, the number of radio galaxies per unit volume decreases again.
- Thus either the Universe is not homogeneous, or is not flat, or contains galaxy populations that evolve (with radio-galaxy appearance as one phase of development), or all three.
- In any case, this is inconsistent with the predictions of the Steady State model, but explicable in Big Bang models.

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Observational tests II: direct observation of the Big Bang

In the late 1940s, two of George Gamow's students, Ralph Alpher and Bob Herman, [predicted](#) that the blast from the Big Bang should be detectable someday.

- Specifically: light would be seen that arose at the time when the Universe had cooled to the point that atoms could form.
- The light started off visible, but owing to the great distance of its source it would be [redshifted](#) into the [microwave](#) band (wavelengths of a millimeter to a few centimeters), and look like a black body with a temperature a few degrees Kelvin (above absolute zero).
- Since it was close to a singularity when emitted, such light should appear [isotropic](#): spread uniformly across the sky. (We'll explain why it should look like this, in a bit.)

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Observational tests II: direct observation of the Big Bang (continued)

In 1965, Bob Wilson and Arno Penzias (AT&T Bell Telephone Laboratories) were working on a very sensitive microwave receiver and antenna they built for satellite communication. They were trying to tune it up to reach ideal performance, but persistently found extra noise power for which they couldn't account. They knew nothing of the Alpher-Herman prediction.

- ❑ The extra power was like that of a black body with temperature only a few degrees K above absolute zero.
- ❑ It was the same no matter which direction they pointed their antenna. (If it comes from the sky, it's isotropic.)

They were grasping at straws for an explanation, when they were paid a visit by radio astronomer Bernie Burke, a professor at MIT.

Observational tests II: direct observation of the Big Bang (continued)

Burke knew of efforts at Princeton U. by Dicke and Peebles to build a sensitive microwave receiver and antenna to look for the Big Bang radiation predicted by Alpher and Herman, but were having technical troubles. He introduced the Bell Labs group to the Princeton group.

- ❑ It was quickly noticed that Penzias and Wilson had indeed **detected** that relict radiation (now called the **Cosmic Microwave Background**).
- ❑ Thus the blast from **the Big Bang is seen directly**. This is the strongest nail in the coffin of the Steady-State Universe.
- ❑ For this epochal discovery, Penzias and Wilson shared the 1978 Nobel Prize in Physics.

Appearance of the cosmic microwave background

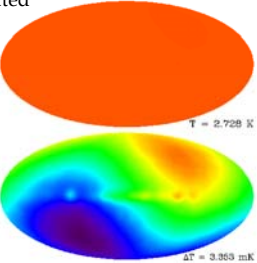
Ever since Penzias and Wilson, astronomers have been making increasingly accurate and detailed observations of the cosmic microwave background. They have found that

- ❑ the background is almost perfectly isotropic: the brightness at any given wavelength is the same in all directions, to very high accuracy.
- ❑ the spectrum of the background - its brightness as a function of wavelength - is that of an opaque (perfectly absorbing) body at temperature 2.728 K.
 - A perfectly absorbing body at a fixed temperature is what physicists call a **blackbody**, and the light one of these emits is called **blackbody radiation**. The cosmic microwave background is a virtually perfect blackbody.

The cosmic microwave background is isotropic.

COBE images of the **entire sky** at a wavelength of 5.7 mm, with brightness expressed as the blackbody temperature (in K) that would produce the detected power. (NASA/GSFC)

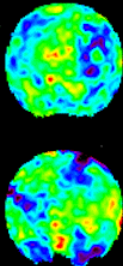
Color code: blue = 0 K, red = 4.0 K. Note how uniform (isotropic) the brightness is!



On a finer scale. Color code: blue = 2.725 K, red = 2.731 K. The maps are plotted so that the Milky Way lies horizontally across the middle.

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The cosmic microwave background is isotropic (continued).



North

South

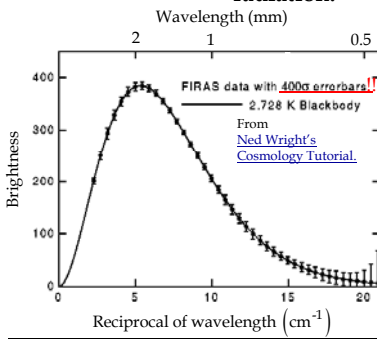
The 5.7 mm COBE DMR map, again, after correction for our 570 km/s motion with respect to the average Universal expansion, and after clipping out the Milky Way within about $\pm 20^\circ$ of Galactic latitude.

Blue = 2.7279 K, red = 2.7281 K.

George Smoot (UC Berkeley) shared the 2006 Nobel Prize in Physics for this work.

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The cosmic microwave background is blackbody radiation.



Wavelength (mm)

Reciprocal of wavelength (cm^{-1})

Brightness

FIRAS data with 400x error bars!

2.728 K Blackbody

From [Ned Wright's Cosmology Tutorial](#).

COBE measurements of the cosmic background brightness as a function of wavelength (points, with error bars blown up by a factor of 400 so they can be seen), compared to that expected from a 2.728 K blackbody (solid curve).

John Mather (NASA GSFC) shared the 2006 Nobel Prize in Physics for this work.

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Why does the Big Bang look like that?

First, quickly.

What does the cosmic background light come from? What process produced it?

- ❑ The **decoupling** of matter and light during the cooling of the expanding, early Universe.

Why is the cosmic background isotropic (spread uniformly across the sky)? That's not how explosions look in the movies.

- ❑ Because it comes from a place and time that is so **close to the mass-density singularity** in which the whole Universe used to be compressed.

Why does its spectrum look like that?

- ❑ Because before decoupling, the Universe was **opaque**, and had a nearly constant temperature: that's a prescription for blackbody radiation.


Now for the long answers.

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Mid-lecture Break

- ❑ Exam #3 is one week from Thursday, on WeBWork.
- ❑ Homework #6 is now available on WeBWork; it is due Monday at 5:30 PM.

Einstein (left) and Hubble (right), among others, by the dome of the Mt. Wilson 100-inch telescope (Institute Archives, Caltech)



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History of the Big Bang, the expansion of the Universe, and Decoupling

- ❑ **Time starts along with the expansion.** At the mass-density singularity, as in a black hole, time does not exist: only the four-dimensional space of quantum foam, the result of extreme mixture of spacetime ([lecture, 12 November 2009](#), and Thorne, pp. 476-480).
- ❑ Therefore the question "what existed before the Big Bang?" is meaningless for anyone living in the Universe; **there is no "before," because there is no such thing as time at the singularity.** One would have to be outside the universe to ask the question sensibly, and there seems to be no outside to the universe, either.
- ❑ As is the case for matter just about to form a black hole singularity, the Universe is extremely hot and dense shortly after the expansion (and time) begins. As the expansion proceeds, the Universe cools off.

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History of the Big Bang, the expansion of the Universe, and Decoupling (continued)

- ❑ The temperature of the early Universe was too high for normal matter to exist as such. It needed to cool down in the expansion before the normal constituents of matter could condense from the high-energy soup and not be broken up immediately.
- ❑ Early in the expansion, energy in the form of radiation was in equilibrium with all forms of matter and antimatter, continually producing all possible particle-antiparticle pairs, which would soon annihilate to produce radiation again.

Energy (photons, gravitons,...)	$\begin{array}{c} \longrightarrow \\ \longleftarrow \end{array}$	Particle- antiparticle pairs
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History of the Big Bang, the expansion of the Universe, and Decoupling (continued)

- ❑ As the temperature fell, the highest energies available in photons, gravitons and the like decreases; therefore higher-energy particle-antiparticle pairs cease to be created.
- ❑ When it became too cold for the most massive particle-antiparticle pairs to be made, these pairs became extinct; only the photons produced in their annihilation remained.
- ❑ However, it seems that a slight asymmetry developed early that left what we call the *particles* slightly outnumbering the *antiparticles*, so that not everything annihilated: there was still some **matter** left over, as well as lots and lots of photons.

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History of the Big Bang, the expansion of the Universe, and Decoupling (continued)

Combinations of particles, bound together by electromagnetic or nuclear forces, could also form in the early universe, but when the temperature was high enough, the combinations could be immediately broken up by the photons. Examples:

Quarks and gluons	$\begin{array}{c} \longrightarrow \\ \longleftarrow \end{array}$	Protons and neutrons and photons
Protons and neutrons	$\begin{array}{c} \longrightarrow \\ \longleftarrow \end{array}$	Atomic nuclei and photons
Nuclei and electrons	$\begin{array}{c} \longrightarrow \\ \longleftarrow \end{array}$	Atoms and photons

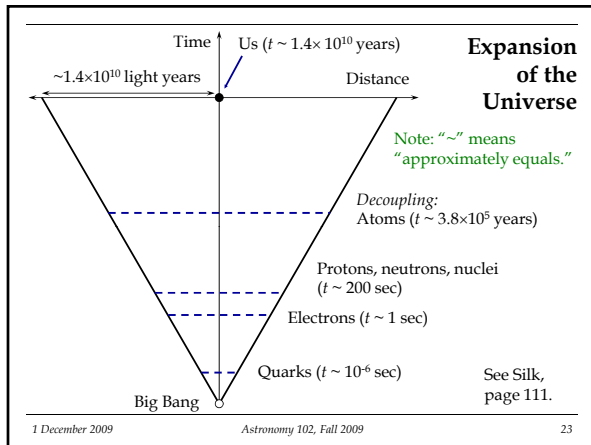
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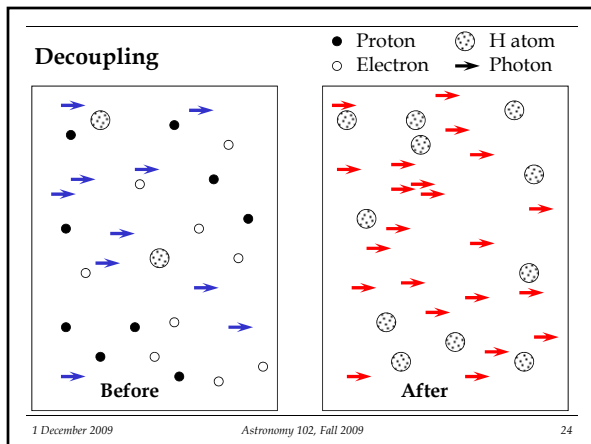
History of the Big Bang, the expansion of the Universe, and Decoupling (continued)

When the temperature gets low enough that the density of high-energy photons is small, the combinations stop being broken up.

Quarks and gluons	→	Protons and neutrons and photons	$T < 10^{12}$ K
Protons and neutrons	→	Atomic nuclei and photons	$< 10^9$ K
Nuclei and electrons	→	Atoms and photons (Decoupling)	< 4000 K

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Decoupling (continued)

Before decoupling, typical photons could destroy atoms, and so were coupled to matter in the sense that they were constantly being created and destroyed as atoms were being destroyed and created.

- ❑ Any photon trying to “get out” gets absorbed and re-emitted many times on the way; **the Universe is opaque before decoupling.**

After decoupling, the average photon had insufficient energy to break up an atom.

- ❑ All the electrons and protons combine to form atoms and emit photons, which thenceforth lead completely separate lives.

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Decoupling (continued)

- ❑ Now photons can travel without being absorbed and re-emitted constantly; **the Universe is transparent after decoupling.**

Light coming from the “surface” where decoupling occurs is the cosmic microwave background.

- ❑ Because it’s opaque before decoupling, we cannot see any closer to the mass-density singularity, using light. Neutrinos could be used to see deeper.
- ❑ However, because all particles experience a similar decoupling, nothing can be used to see directly the mass-density singularity itself.




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Appearance of the decoupling surface: why is the cosmic microwave background isotropic?

Because it was emitted so close to a mass-density singularity.

- ❑ Compare our situation to that of an observer inside a black hole. Light emitted within a black hole horizon cannot escape (and therefore must fall into the singularity), no matter what direction it is emitted: all light paths end at the singularity. 
- ❑ By the same token -- since light can travel in either direction along these paths -- light emitted from the surroundings of the singularity would seem to the observer within the horizon to arrive from all directions, rather than one particular direction. It would look as if the singularity’s surroundings filled the sky. 
- ❑ As we’ve seen, this is precisely the way the cosmic microwave background looks. 

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Why is the cosmic microwave background isotropic? (continued)

Us (emitting light)

Paths of light through warped space

Mass-density singularity

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Why is the cosmic microwave background isotropic? (continued)

Us (looking at the sky)

Paths of light through warped space

Mass-density singularity

Decoupling surface

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Why does the spectrum of the cosmic microwave background look like that?

The universe before decoupling was opaque and had a nearly constant temperature of about 4000 K, so the decoupling surface looks like a 4000 K **blackbody** from close up. (Opaque and constant temperature is the very definition of a blackbody.)

Brightness

Wavelength

Sun (6000 K)

A 4000 K blackbody

10⁻⁵ cm 10⁻⁴ cm 10⁻³ cm

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Appearance of the decoupling surface (continued)

- ❑ But because the decoupling surface lies so far in the past, it lies at a great distance.
- ❑ Because of its great distance and the Universe's expansion, the decoupling surface appears to us to be greatly redshifted. (Think of Hubble's Law, $V = H_0 D$.)
- ❑ In the expansion, all distance intervals not ruled by local gravity grow in the same proportion. This means that the cosmic microwave background's wavelengths will all be redshifted the same way.

Thus the spectrum of the cosmic microwave background should **always** look like a black body, at ever lower temperatures as the Universe expands. This is a strong prediction of all Big Bang models. And so it does, as we've seen.
