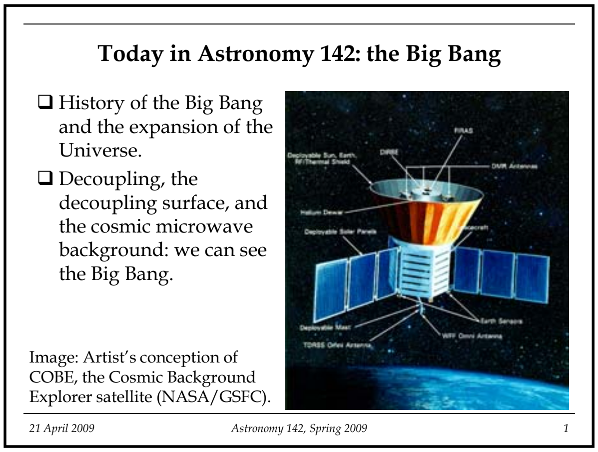
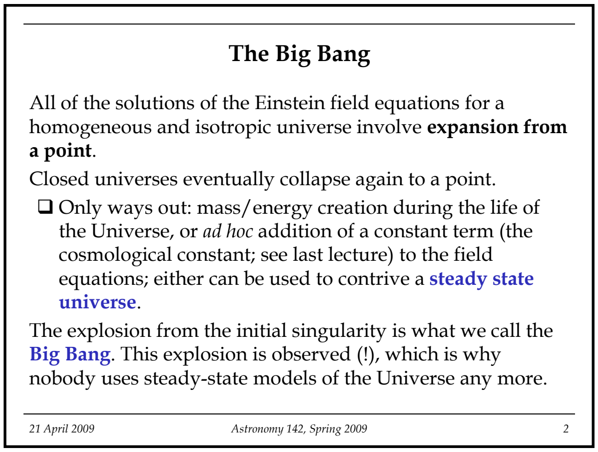


Today in Astronomy 142: the Big Bang

- ☐ History of the Big Bang and the expansion of the Universe.
- ☐ Decoupling, the decoupling surface, and the cosmic microwave background: we can see the Big Bang.

Image: Artist's conception of COBE, the Cosmic Background Explorer satellite (NASA/GSFC).



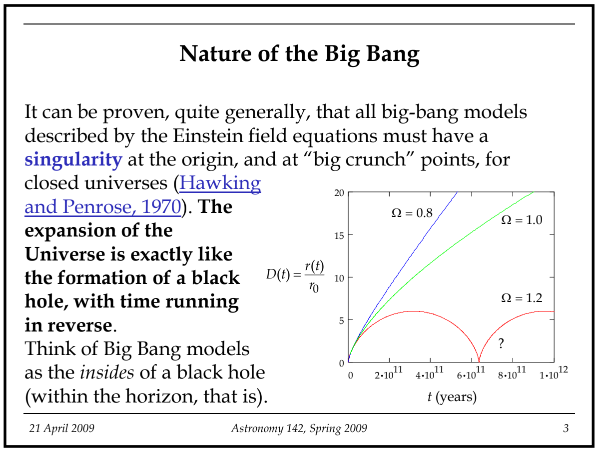
The Big Bang

All of the solutions of the Einstein field equations for a homogeneous and isotropic universe involve **expansion from a point**.

Closed universes eventually collapse again to a point.

- ☐ Only ways out: mass/energy creation during the life of the Universe, or *ad hoc* addition of a constant term (the cosmological constant; see last lecture) to the field equations; either can be used to contrive a **steady state universe**.

The explosion from the initial singularity is what we call the **Big Bang**. This explosion is observed (!), which is why nobody uses steady-state models of the Universe any more.



Nature of the Big Bang

It can be proven, quite generally, that all big-bang models described by the Einstein field equations must have a **singularity** at the origin, and at "big crunch" points, for closed universes (Hawking and Penrose, 1970). **The expansion of the Universe is exactly like the formation of a black hole, with time running in reverse.**

Think of Big Bang models as the *insides* of a black hole (within the horizon, that is).

History of the Big Bang and the expansion of the Universe

Time starts along with the expansion. At the singularity, as within any black hole, **time does not exist**, the result of the extreme mixture and warping of spacetime.

- ❑ 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 we can't get there.

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.

What do you mean, time doesn't exist close to a gravitational singularity?

- ❑ Recall the Minkowski absolute interval from special relativity (which applies to flat spacetime):

$$ds^2 = c^2 dt^2 - dx^2 - dy^2 - dz^2$$

  The spacetime coordinate that we experience as **time** enters the formula with a **plus** sign in flat spacetime. Coordinates that we experience as **space** or distance enter with **minus** signs. Same applies to Schwarzschild and Robertson-Walker absolute intervals.

- ❑ In the more complicated form for the absolute interval in field-equation solutions just outside the singularity, all coordinates enter the equation with minus signs. The four dimensions of spacetime all act like space; **there is no such thing as time at the singularity.**

History of the Big Bang and the expansion of the Universe (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,...) $\rightleftarrows$ "Matter" (particle-antiparticle pairs)

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

As the temperature fell, the highest energies available in photons, gravitons and the like decreased; therefore higher-energy particle-antiparticle pairs ceased to be created.

When it became too cold for the most massive particle-antiparticle pairs to be made, these pairs annihilated each other and turned back into photons or other massless particles.

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. We're not sure why.

History of the Big Bang and the expansion of the Universe (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 $\rightleftarrows$ Protons and neutrons and photons

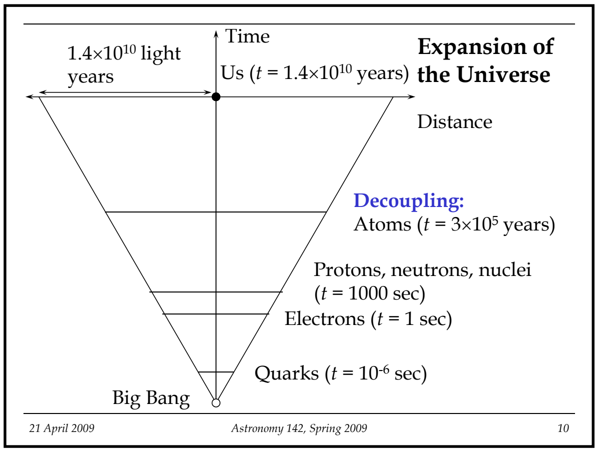
Protons and neutrons $\rightleftarrows$ Atomic nuclei and photons

Nuclei and electrons $\rightleftarrows$ Atoms and photons

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

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

Quarks and gluons	$\longrightarrow$	Protons and neutrons and photons	$T < 10^{12}$ K
Protons and neutrons	$\longrightarrow$	Atomic nuclei and photons	$< 10^{6}$ K
Nuclei and electrons	$\longrightarrow$	Atoms and photons **(Decoupling)**	< 3000 K



Expansion of the Universe

Time

1.4×10^{10} light years

Us ($t = 1.4\times10^{10}$ years)

Distance

Decoupling:
Atoms ($t = 3\times10^{5}$ years)

Protons, neutrons, nuclei ($t = 1000$ sec)

Electrons ($t = 1$ sec)

Quarks ($t = 10^{-6}$ sec)

Big Bang

Decoupling

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.

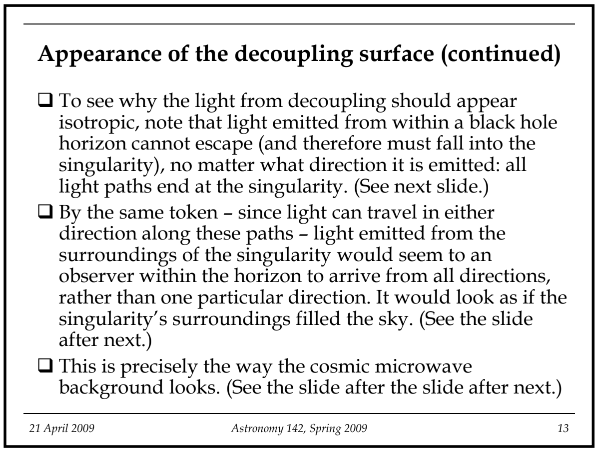
- ☐ Any photon trying to "get out" gets absorbed and re-emitted many times on the way; **the Universe is opaque before decoupling.**
- ☐ Afterwards, the average photon had insufficient energy to break up an atom. All the electrons and protons combine to form atoms and emit photons, which then lead completely separate lives. Now photons can travel without being absorbed and re-emitted constantly; **the Universe is transparent after decoupling.**

Thus the decoupling surface should look like a **blackbody**.

Appearance of the decoupling surface

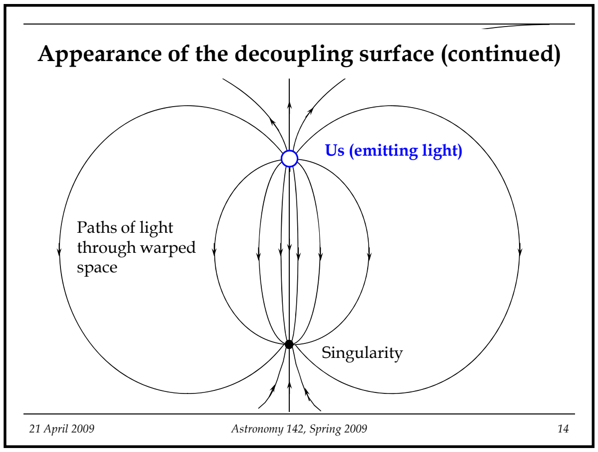
- ☐ Decoupling occurs very close (in time) to the big bang singularity, so it would appear isotropic - same brightness in all directions - to us.
- ☐ Decoupling occurs very close (in space) to the big bang singularity, so it would appear to us to be an extremely redshifted blackbody.
- ☐ We see a "background" of light at microwave wavelengths, filling the sky with uniform brightness, whose spectrum appears to be that of a blackbody. This cosmic microwave background can be nothing other than the light emitted by the decoupling surface.

Explanations and data follow...



Appearance of the decoupling surface (continued)

- ❑ To see why the light from decoupling should appear isotropic, note that light emitted from 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. (See next slide.)
- ❑ 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 an 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. (See the slide after next.)
- ❑ This is precisely the way the cosmic microwave background looks. (See the slide after the slide after next.)

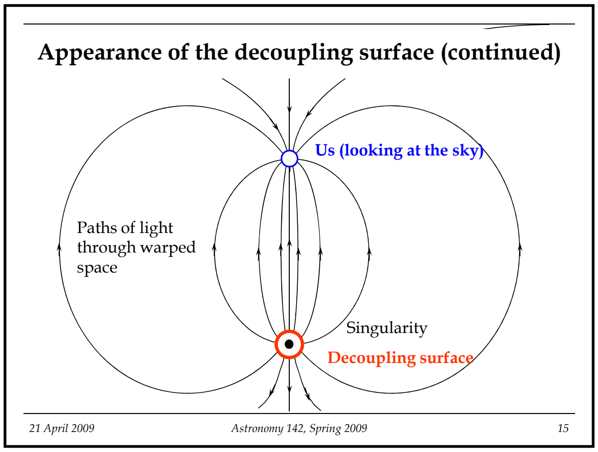


Appearance of the decoupling surface (continued)

Us (emitting light)

Paths of light through warped space

Singularity



Appearance of the decoupling surface (continued)

Us (looking at the sky)

Paths of light through warped space

Singularity

Decoupling surface

Direct observation of the Big Bang

In the 1940s, George Gamow's students, Ralph Alpher and Bob Herman, predicted that the blast from the Big Bang should be detectable someday.

- ☐ Specifically: **light emitted from the decoupling surface could be seen.**
- ☐ 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, the light should appear **isotropic**: spread uniformly across the sky.

Direct observation of the Big Bang (continued)

In 1965, Bob Wilson and Arno Penzias (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-Gamow prediction.

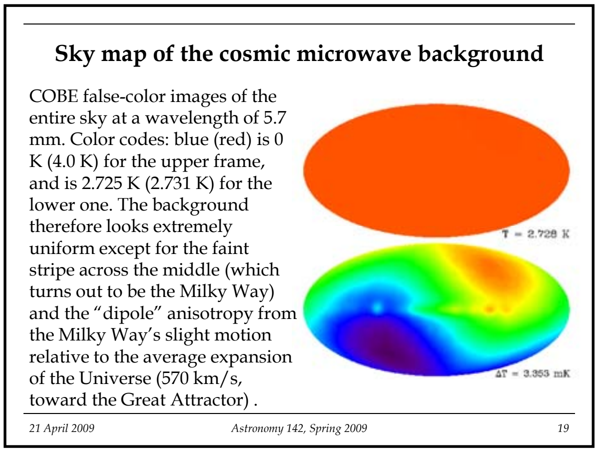
- ☐ The extra power was like that of a black body with temperature 2.7 K.
- ☐ It was the same no matter which direction they pointed their antenna. (If it comes from the sky, it's isotropic.)

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

Direct observation of the Big Bang (continued)

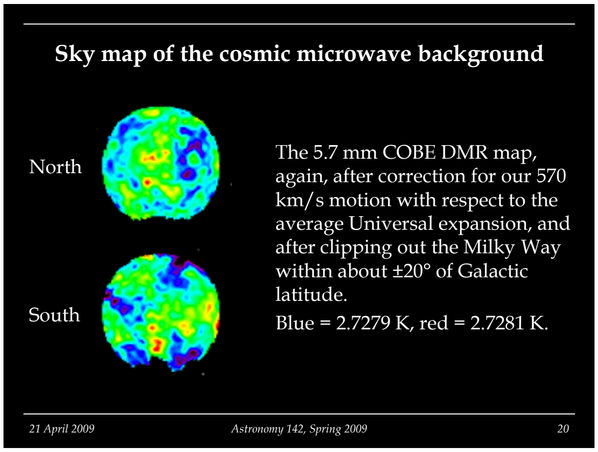
Burke knew of efforts at Princeton U. by Dicke and Peebles to build a sensitive microwave receiver and antenna to look for the Big Bang radiation predicted by the Alpher-Herman-Gamow group, but were having technical troubles. He introduced the Bell Labs group to the Princeton group.

- ☐ It was quickly noticed that Penzias and Wilson had indeed detected that relict radiation, now called the **cosmic microwave background (CMB)**.
- ☐ Thus the blast from **the Big Bang is seen directly**. This is the sturdiest support for Big Bang models of the origin of the Universe.
- ☐ For this immensely influential discovery, Penzias and Wilson shared the 1978 Nobel Prize in Physics.



Sky map of the cosmic microwave background

COBE false-color images of the entire sky at a wavelength of 5.7 mm. Color codes: blue (red) is 0 K (4.0 K) for the upper frame, and is 2.725 K (2.731 K) for the lower one. The background therefore looks extremely uniform except for the faint stripe across the middle (which turns out to be the Milky Way) and the "dipole" anisotropy from the Milky Way's slight motion relative to the average expansion of the Universe (570 km/s, toward the Great Attractor) .



Sky map of the cosmic microwave background

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 ±20° of Galactic latitude.

Blue = 2.7279 K, red = 2.7281 K.

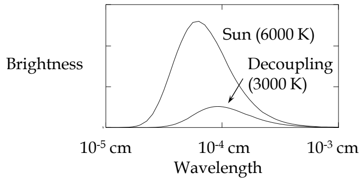
The cosmic microwave background is almost *too* isotropic.

The final image shows that no part of the cosmic microwave background differs in brightness from the average by more than 0.001%. It is hard to make gases, or their emission, that smooth or uniform. (Consider sunspots!)

- ☐ To do so would usually require that all parts of the gas be interacting with each other strongly, or that the gas be well mixed.
- ☐ This would not seem possible for different parts of the decoupling surface. We were once part of that surface, and the parts of it that we see today have been out of contact with us (and each other) since the Big Bang, since we're only now receiving light from these parts and no signal or interaction can travel faster than light.

Spectrum of the decoupling surface

The universe before decoupling is opaque, so the decoupling surface is a blackbody at a temperature of about 3000 K.



- ☐ Because it's opaque, we cannot see any closer to the singularity, using light. Neutrinos could be used to see deeper.
- ☐ However, because all particles experience a similar decoupling, nothing can be used to see the big-bang singularity itself.

Spectrum of the decoupling surface (continued)

Observed spectrum of decoupling surface:

Length of standard ruler, $\ell = R(t)r_*$, can be obtained from the Robertson-Walker interval. But wavelengths are lengths, too (see lecture, 14 April) :

$$\frac{\lambda_0}{\lambda} = \frac{R(t_0)}{R(t)} = 1+z$$

(z = redshift, sub-0 = present time)

At decoupling surface, the energy per unit time, area, solid angle and bandwidth it emits, S_λ, is given by the Planck function at the decoupling temperature T = 3000 K:

$$S_\lambda = B_\lambda(T)$$

Spectrum of the decoupling surface (continued)

Other quantities in unit bandwidth $d\lambda$:

Energy density $$du_\lambda = \frac{4\pi}{c} B_\lambda(T)\, d\lambda$$

Photon number density $$dn_\lambda = \frac{4\pi}{c}\frac{\lambda}{hc} B_\lambda(T)\, d\lambda$$

Number of photons in cube ℓ on a side $$dN_\lambda = \frac{4\pi\ell^3}{c}\frac{\lambda}{hc} B_\lambda(T)\, d\lambda$$

Same as for a present-day cube ℓ_0 on a side. $$= dN_{\lambda_0} = \frac{4\pi\ell_0^3}{c}\frac{\lambda_0}{hc} S_{\lambda_0}\, d\lambda_0$$

Thus we can obtain the present, observed spectrum of the decoupling surface, S_{λ_0}.

Spectrum of the decoupling surface (continued)

Just solve:

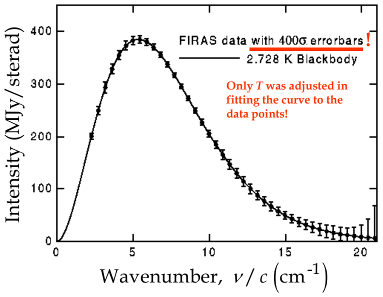
$$S_{\lambda_0} = \frac{R^3(t)}{R^3(t_0)} \frac{\lambda}{\lambda_0} \frac{d\lambda}{d\lambda_0} B_\lambda(T) = \frac{R^5(t)}{R^5(t_0)} \frac{2hc^2}{\lambda^5} \frac{1}{\exp\left(\dfrac{hc}{\lambda kT}\right) - 1}$$

$$= \frac{2hc^2}{\lambda_0^5} \frac{1}{\exp\left(\dfrac{hc}{\lambda_0 k} \dfrac{R(t_0)}{R(t)T}\right) - 1} = B_\lambda(T_0),$$

where $T_0 = TR(t)/R(t_0)$.

That is, the spectrum of the decoupling surface, as presently observed, should be a **blackbody** at temperature $T_0 = TR/R(t_0)$.

The spectrum of the cosmic microwave background



Only *T* was adjusted in fitting the curve to the data points!

COBE measurements of the background intensity as a function of frequency. (Courtesy of Ned Wright and the COBE FIRAS team.) Pretty good blackbody…

How far away is the decoupling surface?

Since decoupling happened when the Universe had only about 0.01% of its present age, it took place 13 billion years ago, and must lie 13 billion light years away (taking the matter-dominated-universe parameters from last lecture).

The redshift of decoupling can be obtained almost trivially:

$$1 + z = \frac{R(t_0)}{R(t_{\text{decoupling}})} = \frac{T_{\text{decoupling}}}{T_0} = \frac{3000 \text{ K}}{2.726 \text{ K}} \approx 1000$$

$$\Rightarrow \quad z \approx 1000 \quad .$$

The most distant galaxy hitherto detected has $z \sim 7$ (it's gravitationally lensed); the most distant quasar has $z = 6.4$.