THE BIG BANG

PROBLEM SET #8 ON WEBWORK – DUE AFTER THANKSGIVING BREAK

THE BIG BANG

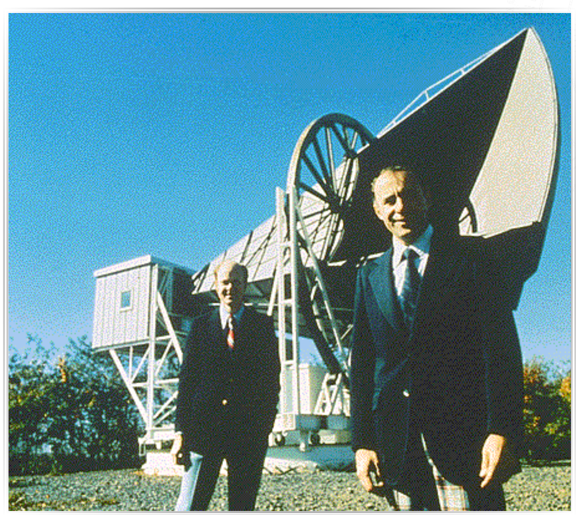
Hubble: the Universe is observed to be homogenous, isotropic, and expanding

Redshift and distance: Hubble's Law

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)

HUBBLE OBSERVES THE UNIVERSE EXPANDING

In 1929, Hubble made his third great contribution to cosmology; he observed that

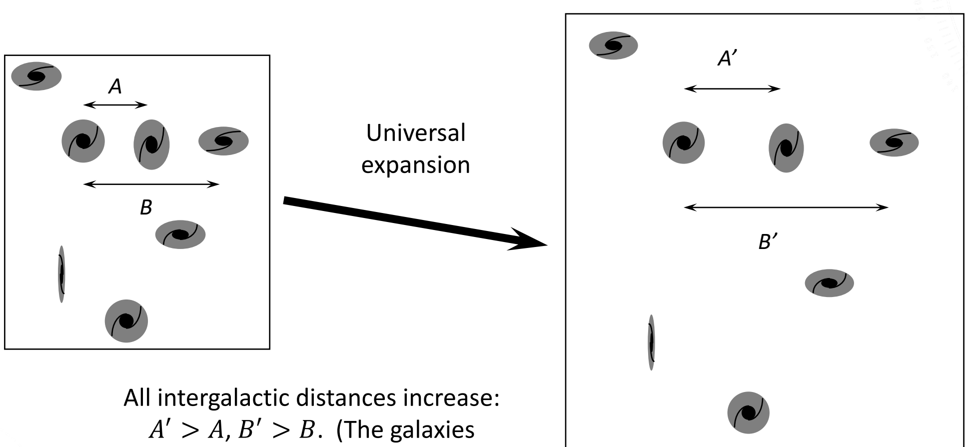
- Distant galaxies are always seen to have **redshifted** spectra. Therefore, they all **recede** from us.
- The magnitude of this Doppler shift for any given distant galaxy is in direct proportion to the distance to this galaxy: with *V* = velocity and *D* = distance to galaxy,

$$\boxed{V = H_0 D}$$ **Hubble's Law**

where $H_0 = 20$ km/s/Mly (the **Hubble constant**).

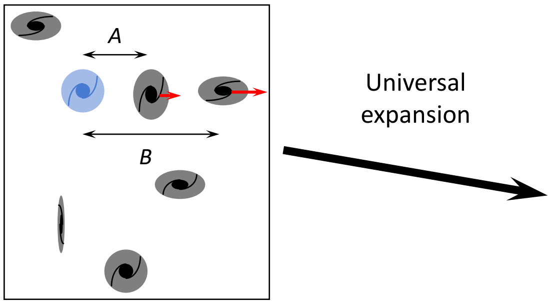
In other words, we see that **the Universe is expanding**.

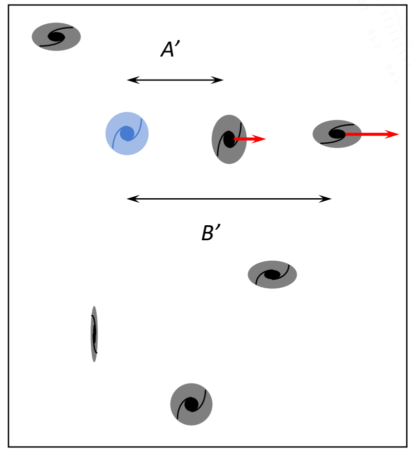
WHY GALAXIES RECEDE FROM AN OBSERVER IN AN EXPANDING UNIVERSE, NO MATTER WHERE THEY STAND



All intergalactic distances increase: $A' > A, B' > B$. (The galaxies themselves do not expand, though.)

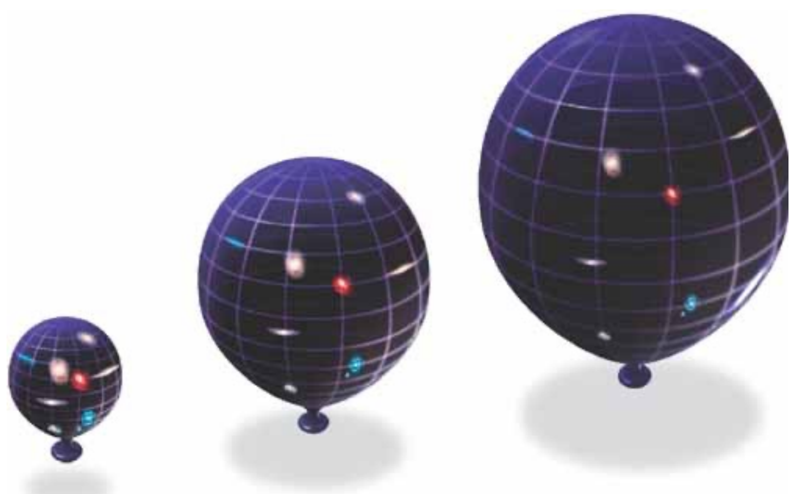
WHY GALAXIES RECEDE FROM AN OBSERVER IN AN EXPANDING UNIVERSE, NO MATTER WHERE THEY STAND





Galaxies **recede** from one another, and recede **faster** the further apart they are: $B' - B > A' - A$. Because the galaxies recede, the Doppler shifts are all redshifts.

THE EXPANDING UNIVERSE

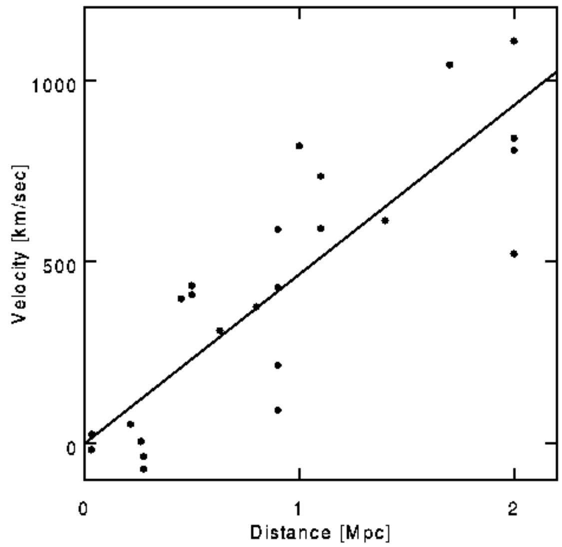


HUBBLE'S LAW

Here are Hubble's and Humason's original data and results (1929). The straight line is a reasonable fit, so

$$V = H_0 D$$

though the slope (the Hubble constant) came out much larger than the recent measurements as a result of then-unforeseen systematic distance errors.



(1 Mpc = 3.26 Mly)

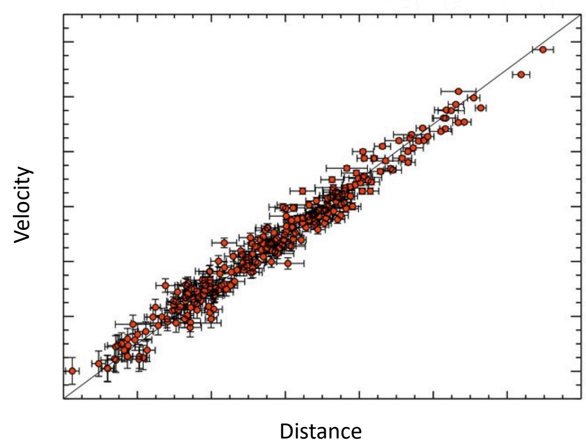
HUBBLE'S LAW

Nowadays, better distance measurements and a better fit:

$$H_0 = 22.52 \pm 0.509 \text{ km/s /Mly}$$

In ASTR 102, we will use a round number:

$$H_0 = 20 \text{ km/s /Mly}$$



DIMENSIONS OF THE HUBBLE CONSTANT

Again: the Hubble constant is

$$H_0 = 20\ \mathrm{km\ s^{-1}\ Mly^{-1}}$$

What are the dimensions of H_0?

A. Time
B. 1/Time
C. Length
D. 1/Length
E. None of the above.

MAGNITUDE OF THE HUBBLE CONSTANT

$$H_0 = 20\ \mathrm{km\ s^{-1}\ Mly^{-1}}$$
$$1\ \mathrm{year} = 3.16{\times}10^{7}\ \mathrm{s}$$

What is $1/H_0$ in years?

SIMPLE USES OF HUBBLE'S LAW

Example: The redshift of 3C 273 corresponds to a speed of 48,000 km/s. How far away is 3C 273?

$$D = \frac{V}{H_0} = \frac{48000\ \mathrm{km/s}}{20\ \mathrm{km/s\,/Mly}} = 2.4\times10^3\ \mathrm{Mly}$$

Example: The center of the nearest cluster of galaxies, the Virgo Cluster, is 70 Mly away. What is the recession speed we expect for galaxies near the center of this cluster?

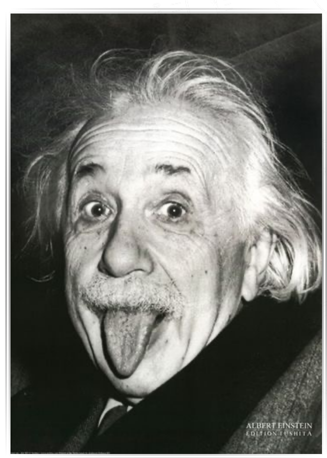
$$V = H_0 D = (20\ \mathrm{km/s/Mly})(70\ \mathrm{Mly}) = 1400\ \mathrm{km/s}$$

EINSTEIN GIVES UP

The Universe is observed to be expanding; it is not static.

- The real Universe may be described by one of the **dynamic** solutions to the original Einstein field equation. Of the four types we discussed above, the last three spend at least part of their time, if not all, expanding.
- Therefore, there appears to be no point in Einstein's cosmological constant, so he let it drop, calling it **"my greatest blunder"** in an oft-quoted elevator conversation.
- Thereafter, he began trying to show that the singularities in the dynamic solutions simply would not be realized. His effort resulted in the **steady-state** model of the Universe.

This is not the last that we will see of the cosmological constant…



WHAT IT MEANS TO BE ISOTROPIC, HOMOGENEOUS, ETC.

From our viewpoint in the Milky Way, galaxies appear to be distributed homogeneously and isotropically and be receding at the same speed at a given distance from us, no matter in which direction we look; in other words, it appears as if we are at the center of the expansion. From another, distant galaxy, galaxies would appear to be

A. Clustered around, and receding from, the Milky Way
B. Isotropically spread on the sky, but expanding away from the Milky Way
C. Clustered around the Milky Way but receding from that galaxy
D. Isotropically spread on the sky and receding from that galaxy

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.
  - Since the Universe is homogeneous, we would see the same recession no matter where we stood. That is, there is no unique center of the expansion in space, as you would find in an ordinary explosion and blast wave.

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 on 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

OBSERVATIONAL TESTS OF COSMOLOGICAL MODELS

Big Bang Universe proponents made these specific predictions based on 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, on average, be qualitatively different 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 $\lambda = \lambda_0 \left(1 + \frac{V}{c}\right)$: λ larger than λ_0.)

OBSERVATIONAL TESTS OF COSMOLOGICAL MODELS

Those studying the steady-state model predicted:

- **(I)** 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 average, everywhere in the Universe. There should be no tendency for distant galaxies to look young.

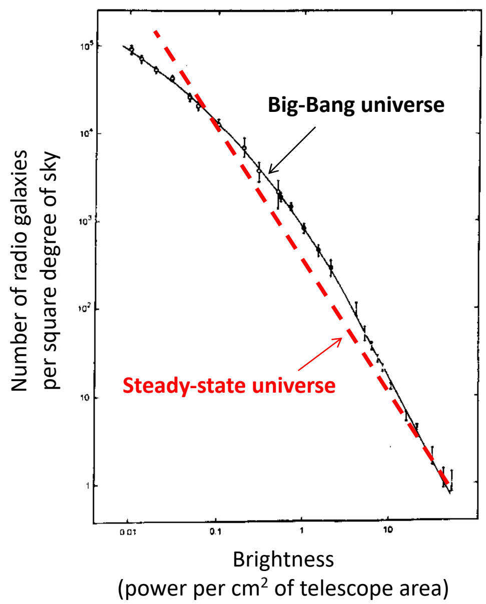
OBSERVATIONAL TESTS I: RADIO GALAXIES AT LARGE REDSHIFTS

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 further away than the faint galaxies observed by Hubble: far enough away to expect that these galaxies are closer together on average than present-day galaxies in a Big Bang model.

OBSERVATIONAL TESTS I: RADIO GALAXIES AT LARGE REDSHIFTS

Results by Pooley & Ryle (1968) (points) and a Big Bang model (curve) in , compared to a steady-state Universe model that fits the distribution of nearby galaxies in **red**.



OBSERVATIONAL TESTS I: RADIO GALAXIES AT LARGE REDSHIFTS

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

- As you look 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.
- Therefore, the entire Universe is either not homogeneous, not flat, 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 it is explicable in Big Bang models.

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 Kelvin (above absolute zero).
- Since it was close to a singularity when it was emitted, such light should appear **isotropic**: spread uniformly across the sky.

OBSERVATIONAL TESTS II: DIRECT OBSERVATION OF THE BIG BANG

In 1965, Bob Wilson and Arno Penzias (AT&T Bell Telephone Laboratories) accidentally detected this radiation, now called the **Cosmic Microwave Background (CMB)**, while working on a new microwave receiver and antenna for satellite communication.

- The blast from **the Big Bang is seen directly**. This is the strongest piece of evidence against the Steady-State universe.
- For this epochal discovery, Penzias and Wilson shared the 1978 Nobel Prize in Physics.

Increasingly accurate and detailed observations of the CMB have been made since its initial discovery. They have found that

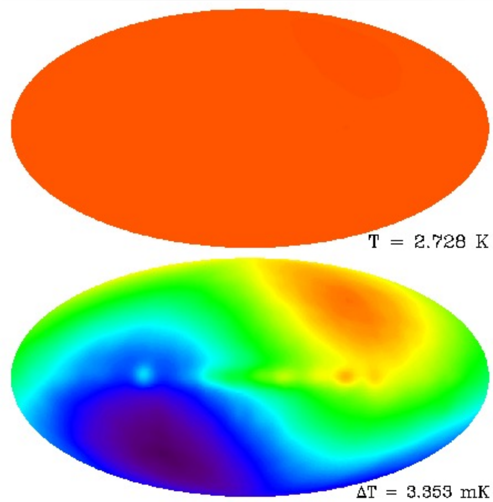
- The background is almost perfectly isotropic: the brightness at any given wavelength is the same in all directions to very high accuracy.
- The spectrum of the background – its brightness as a function of wavelength – is that of an opaque (perfectly absorbing) body at temperature 2.72548 ± 0.00057 K.
    - A perfectly absorbing body at a fixed temperature is called a **blackbody**, and the light emitted by said body 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.



WHY DOES THE BIG BANG LOOK LIKE THAT?

First, the short answers:

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 is 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 entire 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 is a prescription for blackbody radiation.

Now for the long answers.

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 the extreme mixture 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.** You would have to be outside the Universe to sensibly ask the question, and there seems to be no "outside 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.
- 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 immediately broken up.

HISTORY OF THE BIG BANG, THE EXPANSION OF THE UNIVERSE, AND DECOUPLING

- 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,…) $\longleftrightarrow$ Particle-antiparticle pairs
- 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 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.

HISTORY OF THE BIG BANG, THE EXPANSION OF THE UNIVERSE, AND DECOUPLING

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

Quarks and gluons $\longleftrightarrow$ Protons and neutrons + photons

Protons and neutrons $\longleftrightarrow$ Atomic nuclei + photons

Nuclei and electrons $\longleftrightarrow$ Atoms + photons

HISTORY OF THE BIG BANG, THE EXPANSION OF THE UNIVERSE, AND DECOUPLING

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

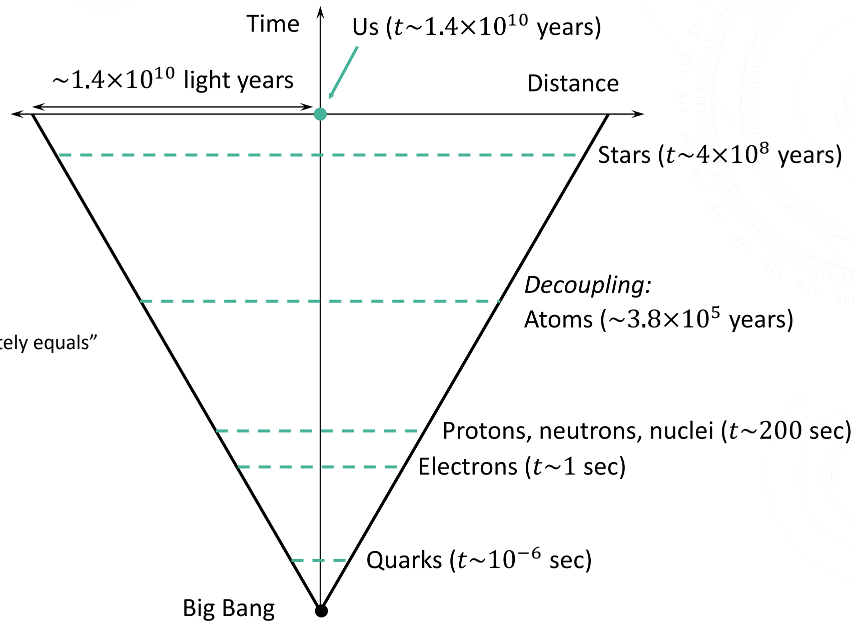
Quarks and gluons $\longleftrightarrow$ Protons and neutrons + photons $T < 10^{12}$ K

Protons and neutrons $\longleftrightarrow$ Atomic nuclei + photons $T < 10^{9}$ K

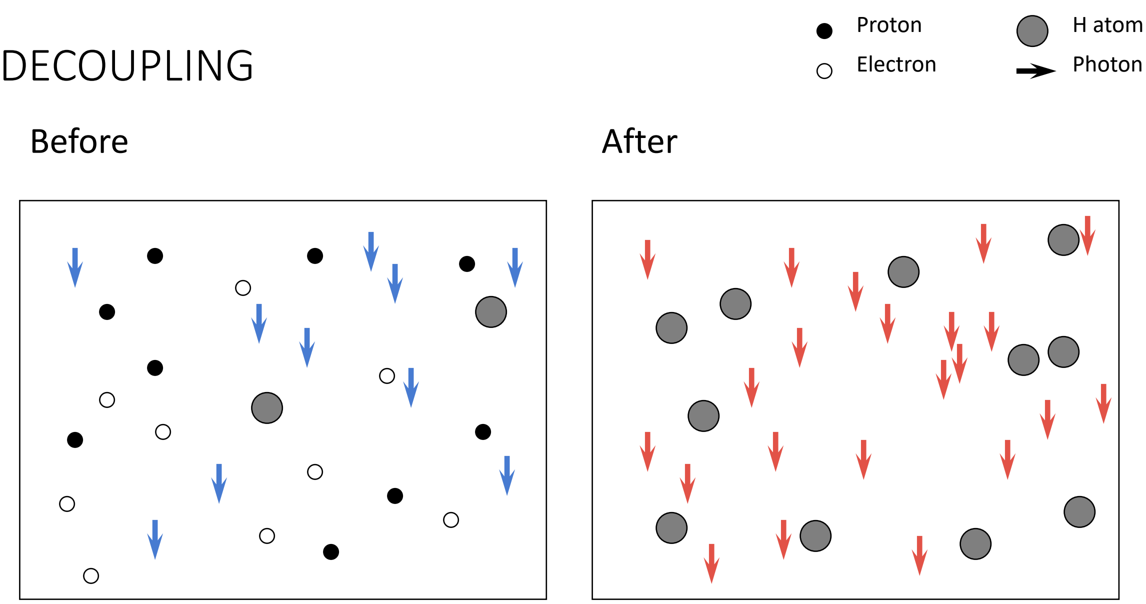
Nuclei and electrons $\longleftrightarrow$ Atoms + photons (**Decoupling**) $T < 4000$ K

EXPANSION OF THE UNIVERSE

Note: “~” means “approximately equals”



DECOUPLING



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 created and destroyed.

- Any photon trying to "get out" gets absorbed and re-emitted many times along 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 combined to form atoms and emit photons. These photons then led completely separate lives.
- Now photons can travel without being absorbed and re-emitted constantly; **the Universe is transparent after decoupling.**

DECOUPLING

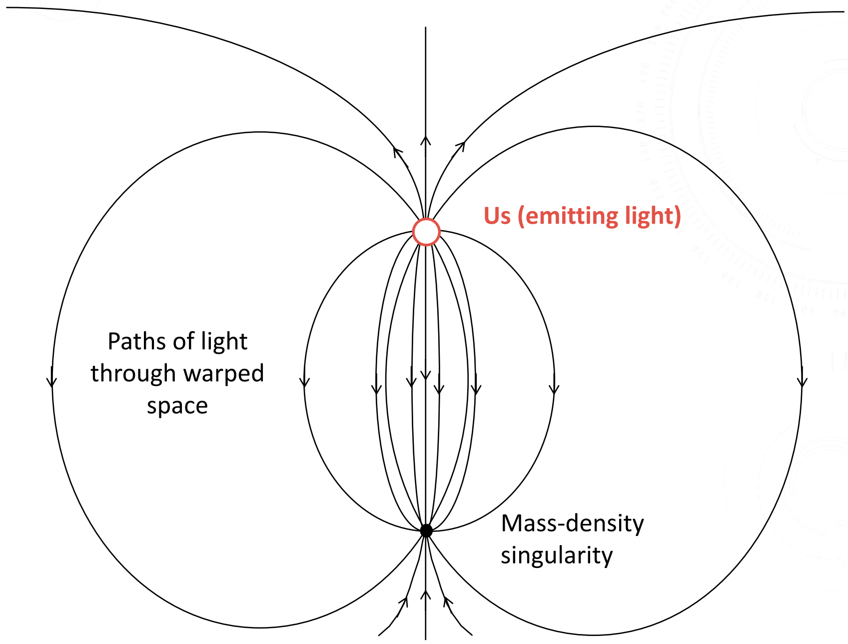
Light coming from the "surface" where decoupling occurs is the cosmic microwave background.

- Because it is 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 directly observe the mass-density singularity itself.

Why is the cosmic microwave background isotropic? Because it was emitted so close to a mass-density singularity.

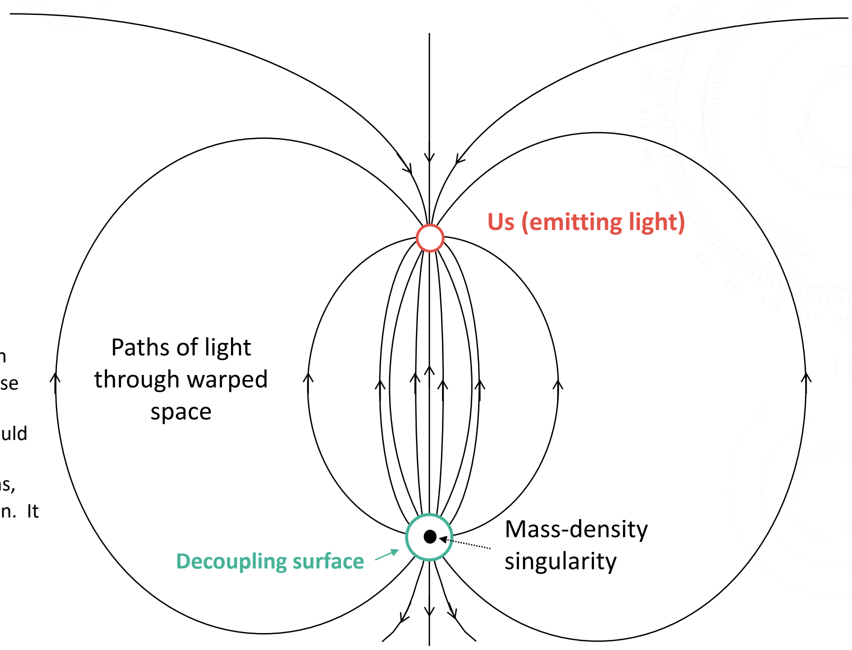
- Compare our situation to that of an observer inside a black hole. Light emitted within a black hole horizon cannot escape (and therefore must fall into the singularity), no matter in what direction it is emitted: all light paths end at the singularity.

WHY IS THE CMB ISOTROPIC?

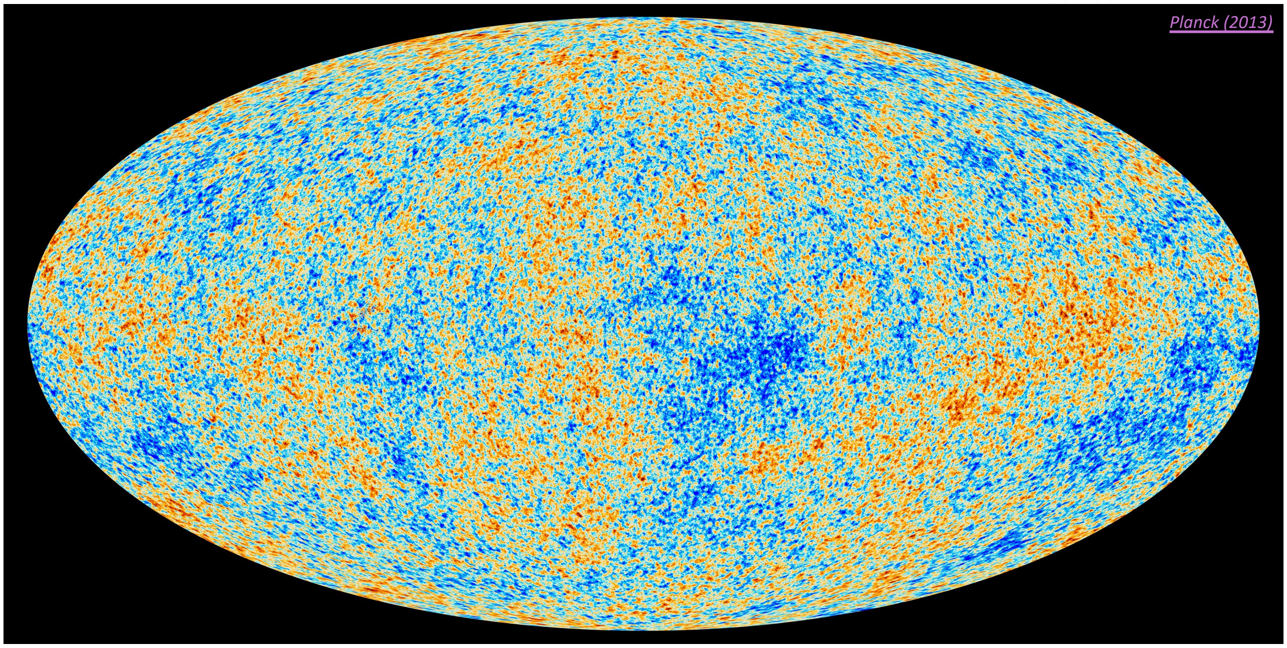


WHY IS THE CMB ISOTROPIC?

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.

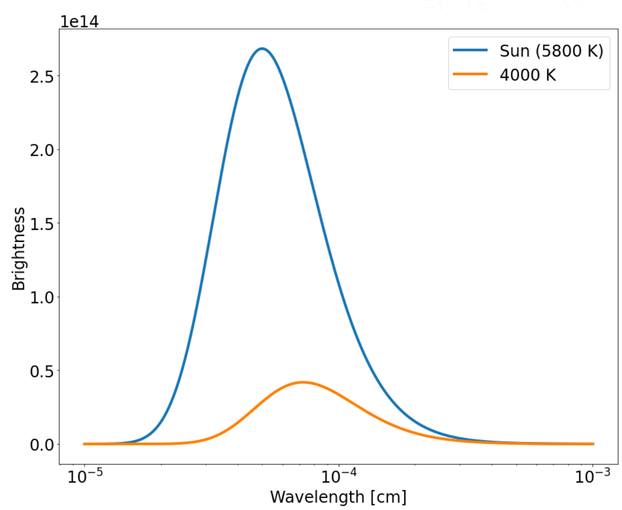


THE COSMIC MICROWAVE BACKGROUND IS ISOTROPIC



WHY DOES THE SPECTRUM OF THE CMB LOOK LIKE THAT?

Before decoupling, the Universe 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.)



APPEARANCE OF THE DECOUPLING SURFACE

- Because the decoupling surface lies so far in the past, it lies at a great distance.
- Due to 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 in the same way.

Thus, the spectrum of the cosmic microwave background should **always** look like a black body, though its temperature will decrease as the Universe expands. This is a strong prediction of all Big Bang models. And so it does.

THE CMB IS BLACKBODY RADIATION

COBE measurements of the cosmic microwave background brightness as a function of wavelength (points, with error bars blown up by a factor of 400 so that 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.