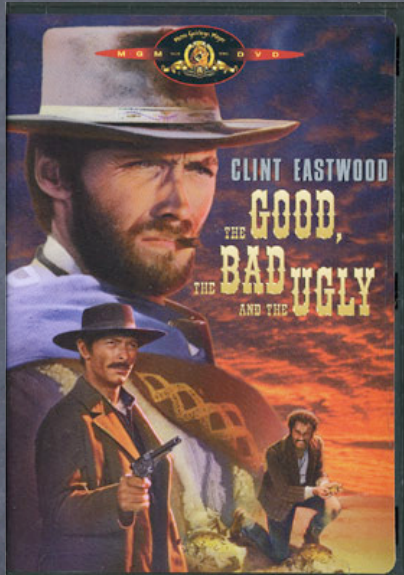


Cosmic Analogies: the good, the bad, and the ugly



Dragan Huterer, Randy Landsberg,
Hiranya Peiris, Andrew Zentner
Kavli Institute for Cosmological Physics
University of Chicago

Outline

Outline

- Part I: A few basic facts about our Universe

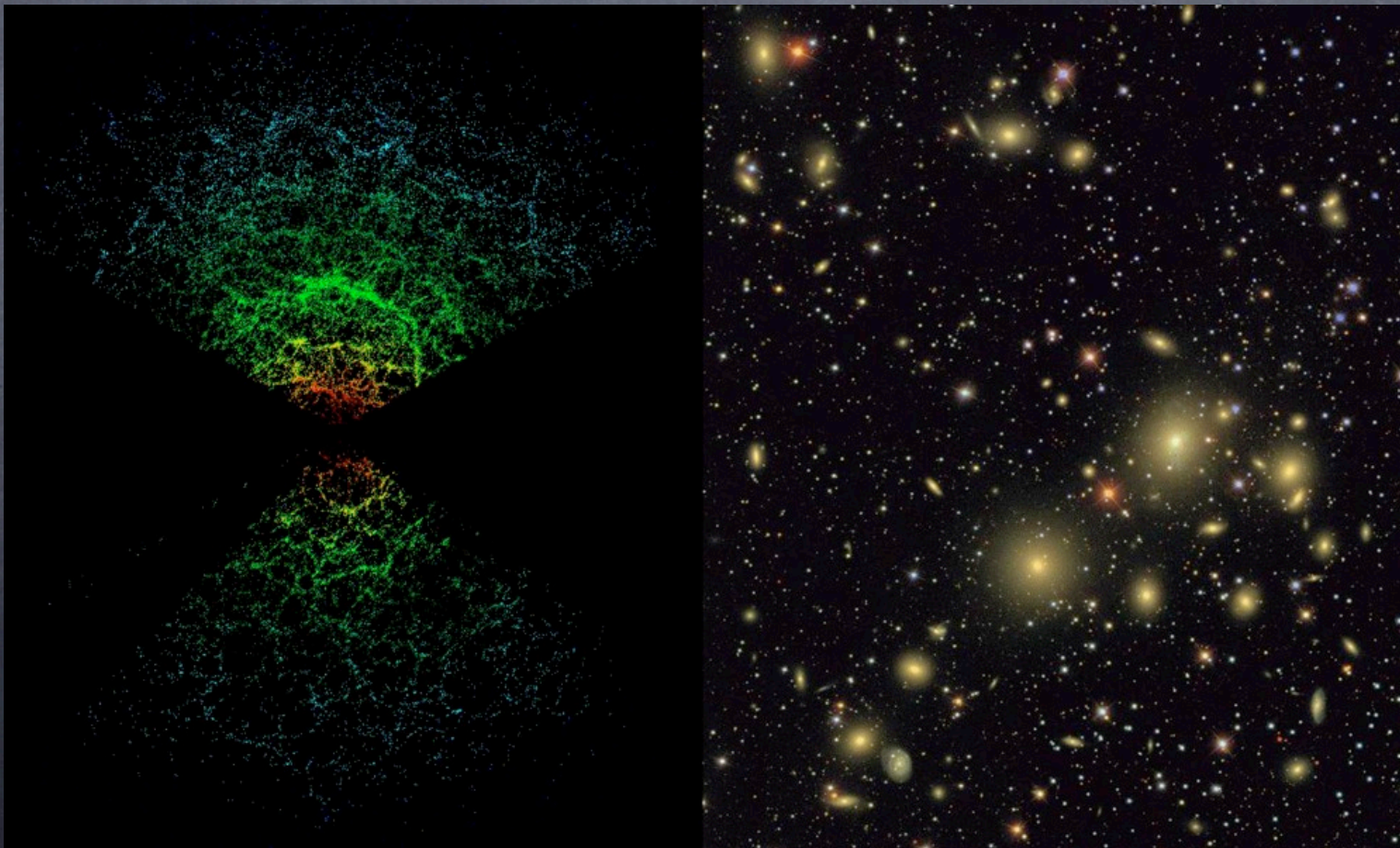
Outline

- Part I: A few basic facts about our Universe
- Part II: The Universe through ANALOGY!

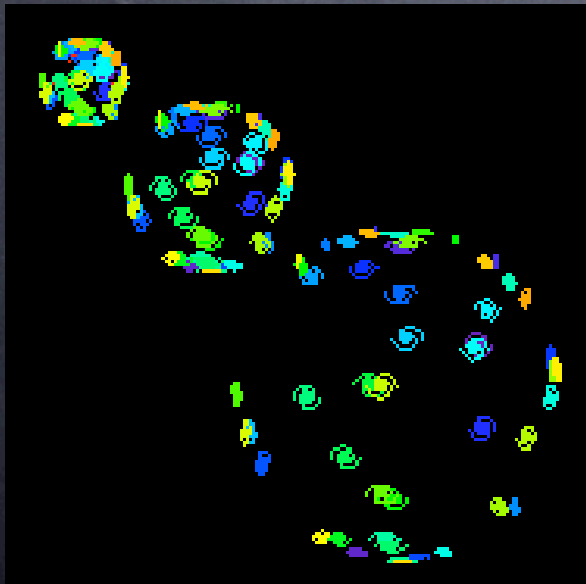
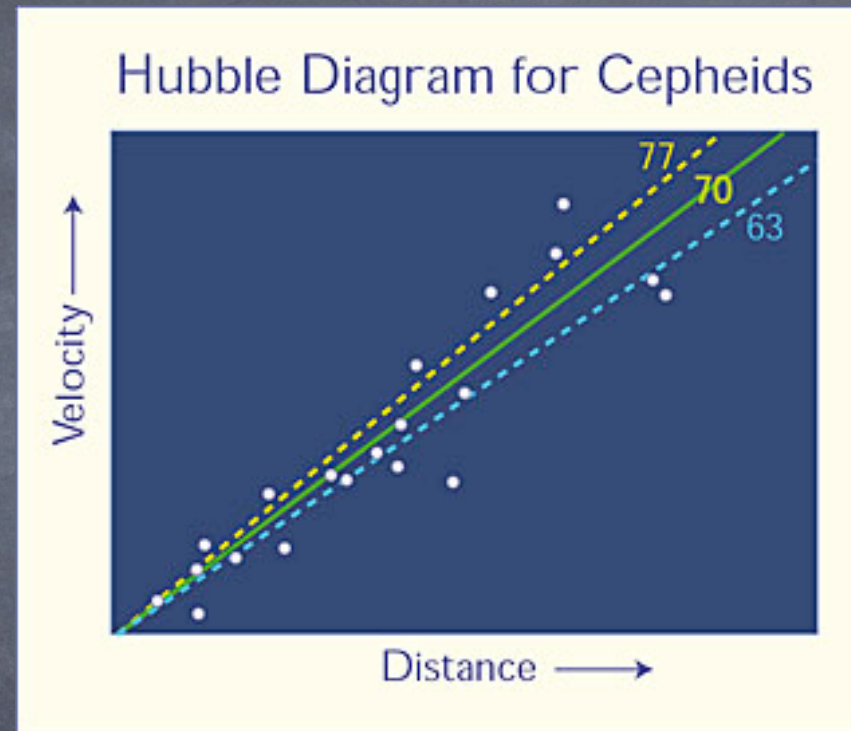
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The universe is homogeneous and isotropic

- **Homogeneous**: appears the same everywhere in space
- **Isotropic**: appears the same in every direction

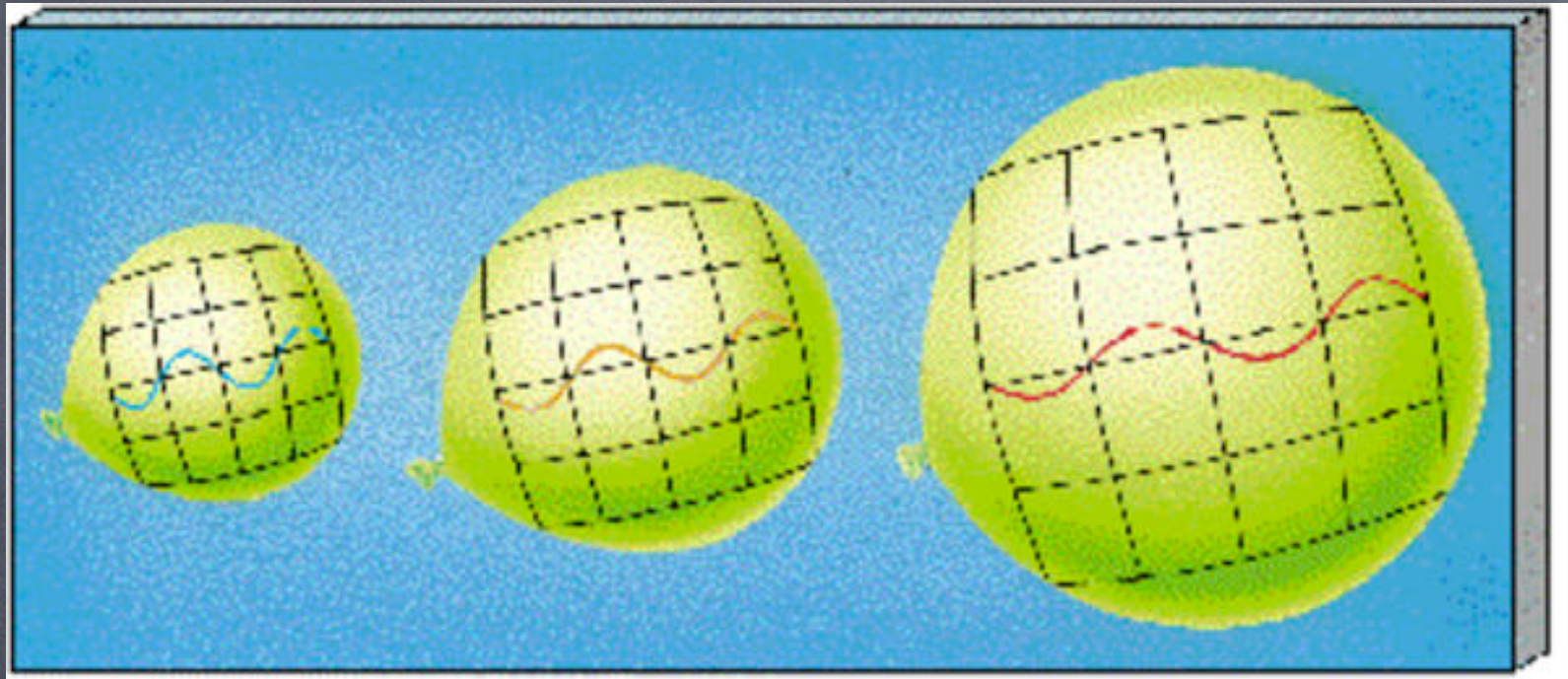


The universe is expanding!



Edwin Hubble

The Cosmological Redshift



- Wavelengths of light stretch as the Universe expands
- Spectra have features that encode the amount of wavelength expansion

Can measure distances using
standard candles
(Cepheids, Type Ia Supernovae)



flux $\rightarrow 1/\text{distance}^2$



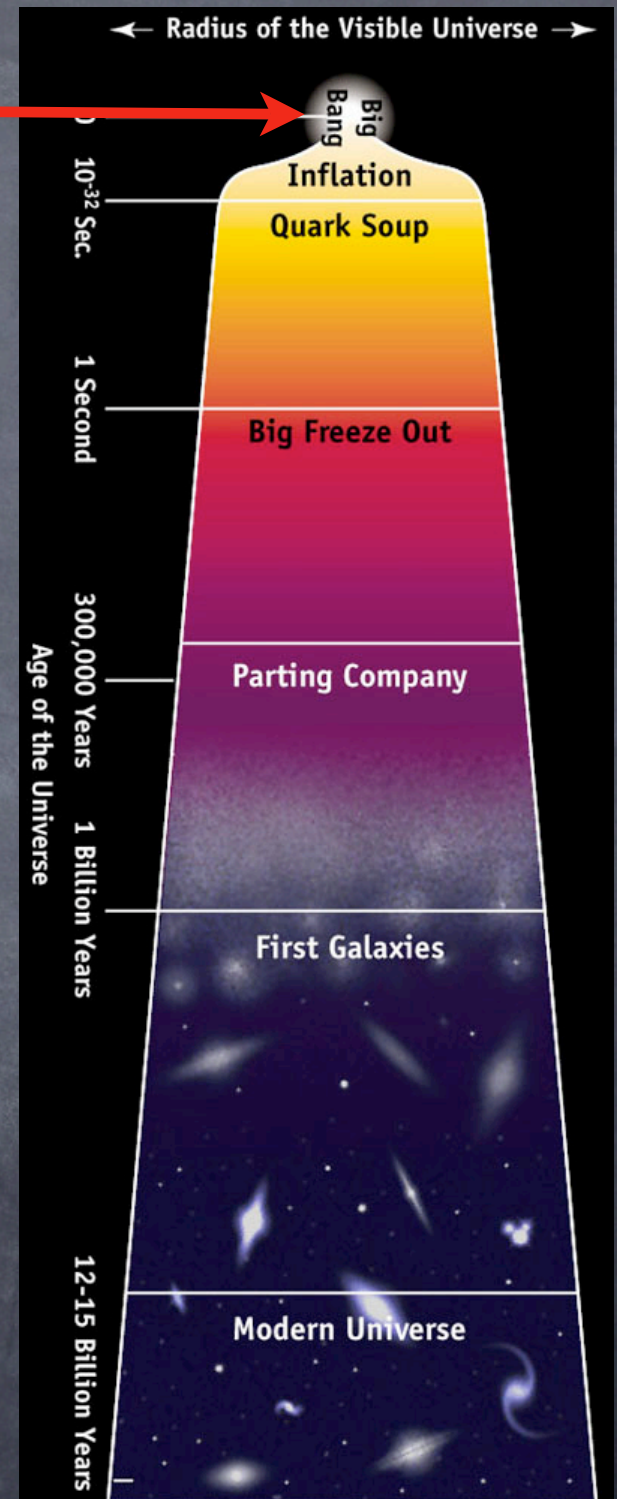
By measuring the flux,
you can determine the **distance**,
which is one of hardest things in astronomy

History of the universe from $t=0$ to $t=13.7$ Gyr

A Brief Overview...

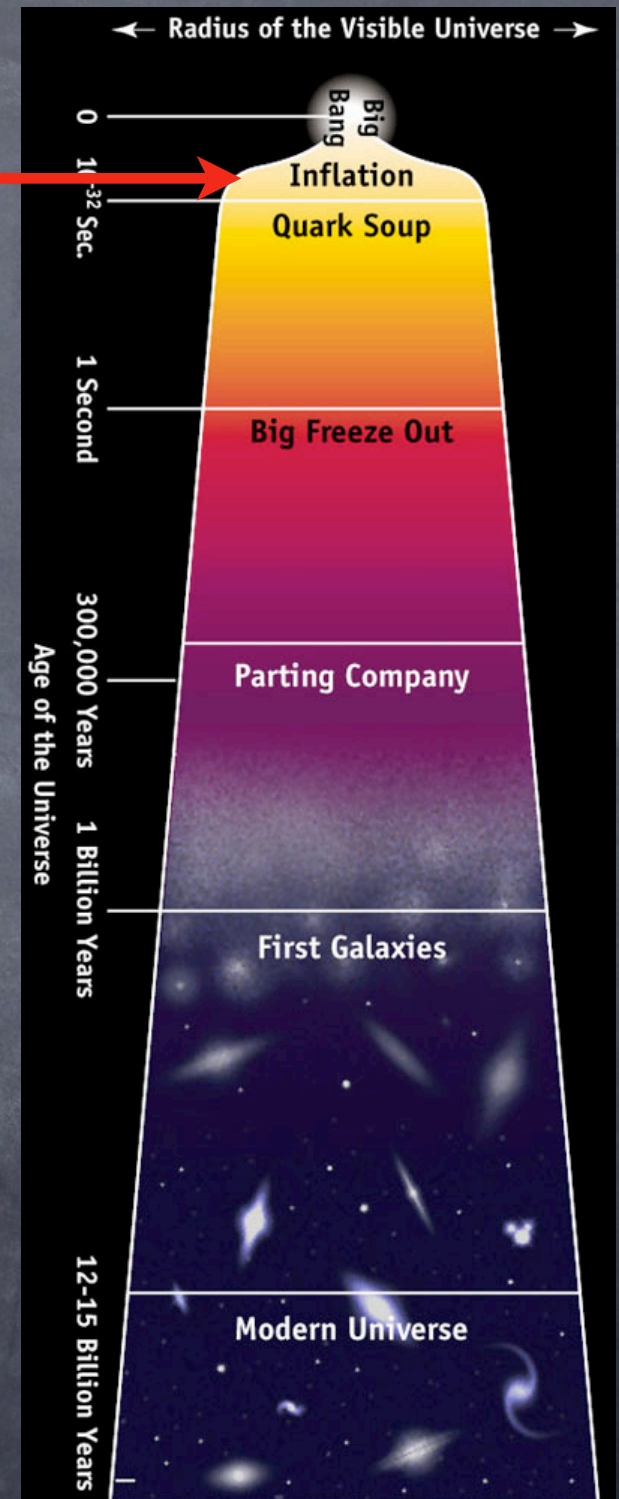
Big Bang ($t=0$)

- Expansion starts
- Happened “everywhere”
- Details not well known
- Currently beyond reach of any cosmological probe



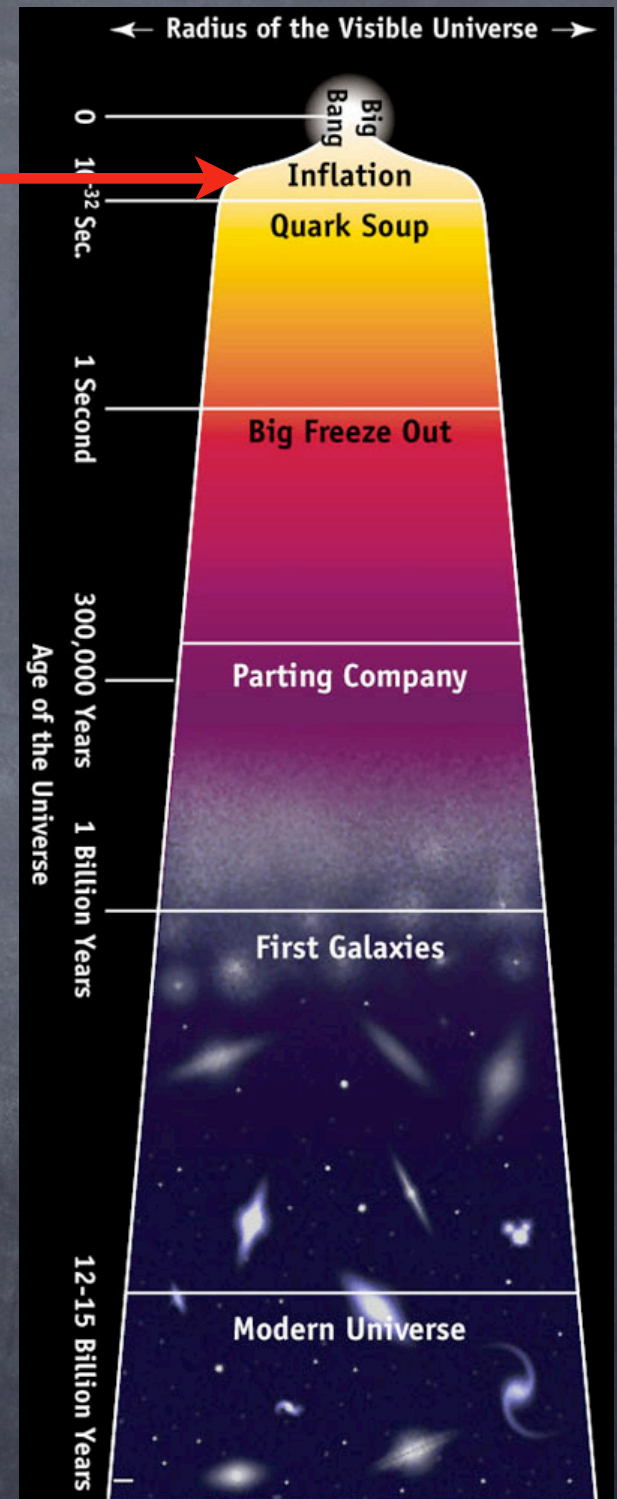
Very early Universe (t =tiny moments after BB)

- High energies
- Exotic physics
- Grand Unified Theory? (all forces united)
- Inflation - a period of rapid expansion
- Density fluctuations laid out



Very early Universe (t=tiny moments after BB)

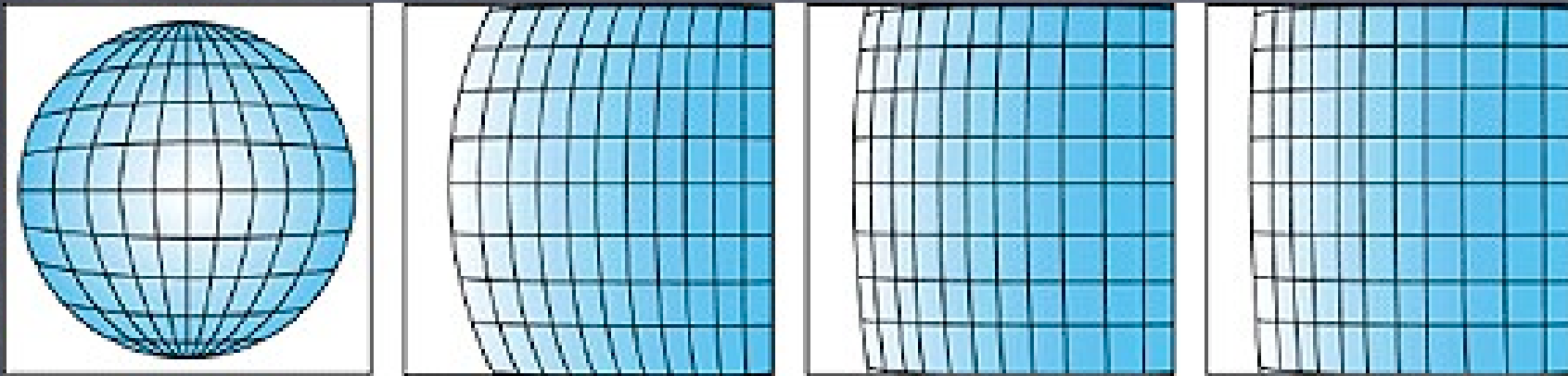
- The Universe experienced an epoch of extremely rapid expansion called INFLATION



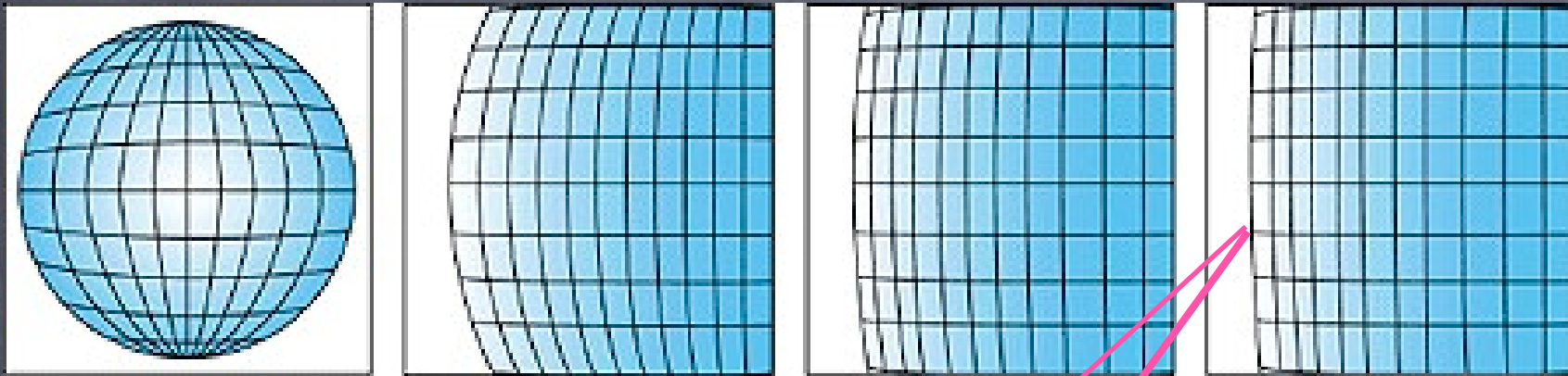
Cosmic Inflation Addresses Two Big Problems

- The Horizon Problem: How can different parts of the Universe, separated by a distance greater than light could have traveled, know to be the same?
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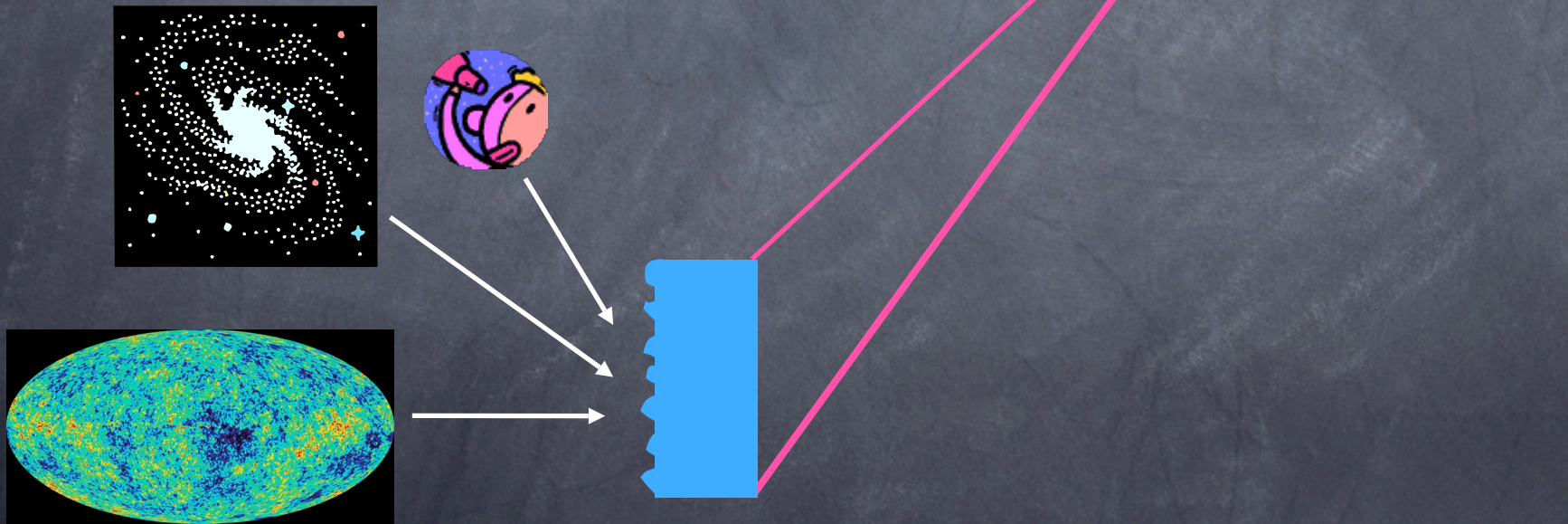
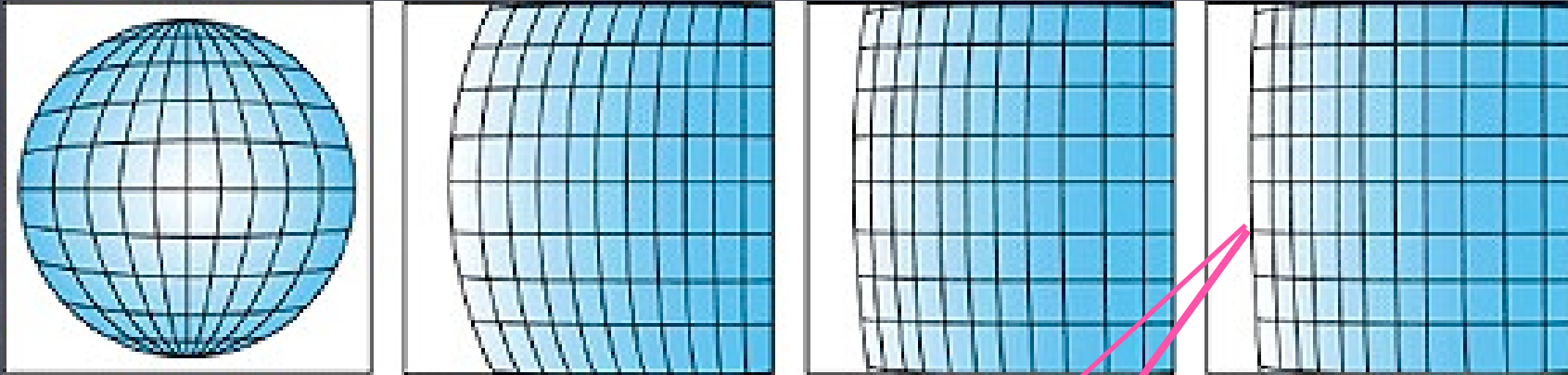
Inflation creates quantum ripples



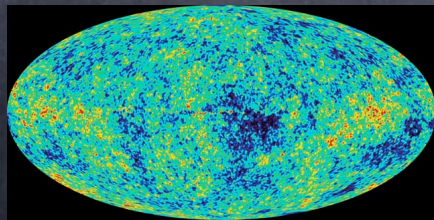
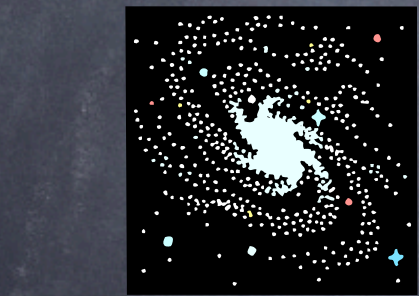
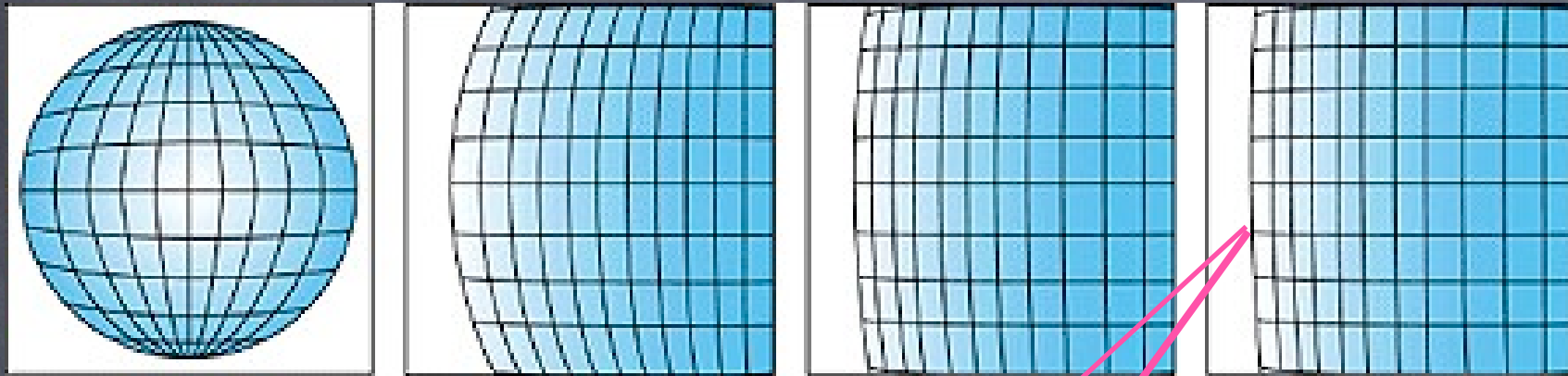
Inflation creates quantum ripples



Inflation creates quantum ripples



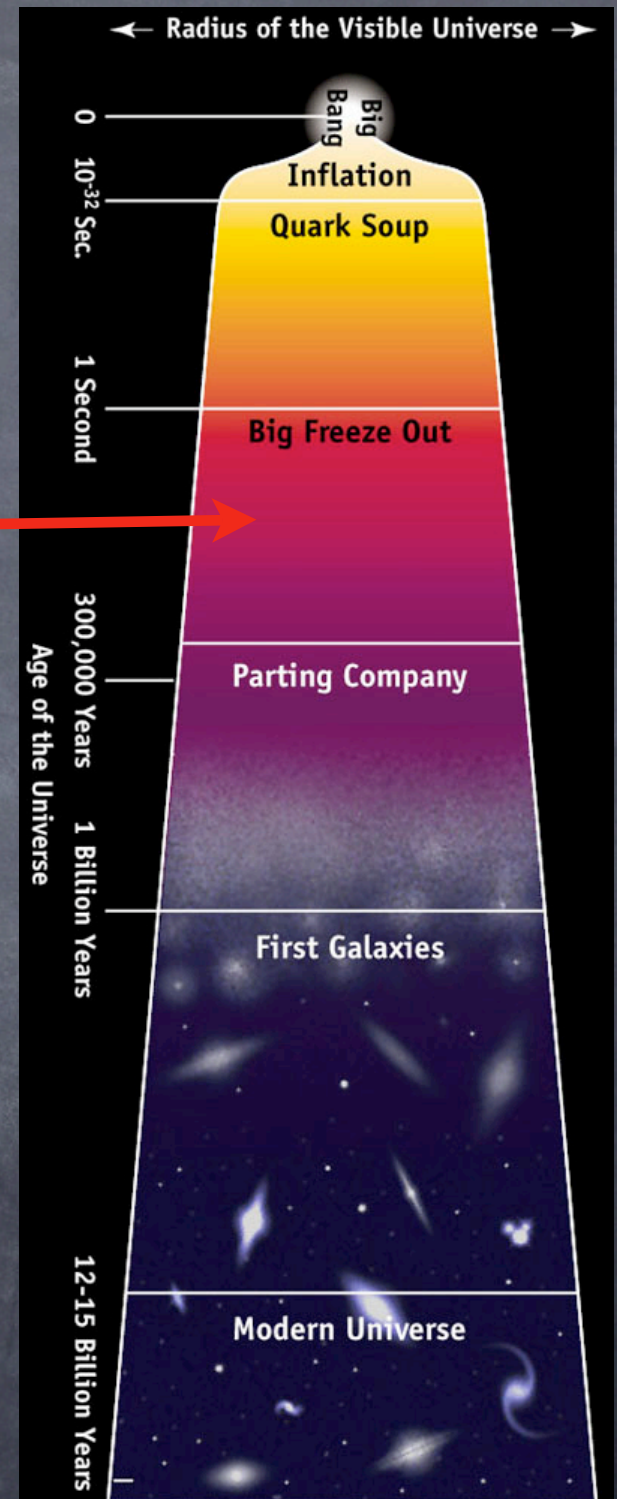
Inflation creates quantum ripples



Inflation creates quantum ripples that grow to become all the structures in the Universe!

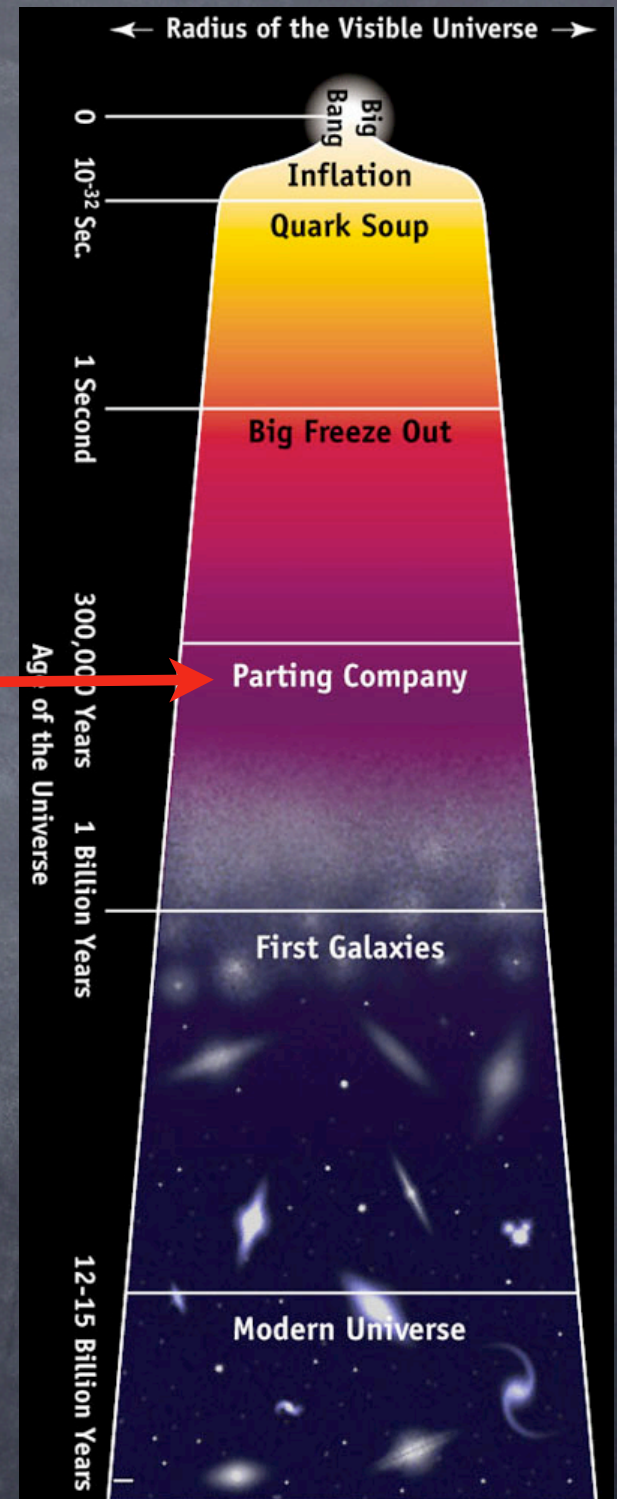
Nucleosynthesis ($t=3$ minutes)

- Atomic nuclei form!
- out of neutrons, protons, electrons...
- Hydrogen, Helium, small quantities of others
- Universe is still dominated by radiation (photons)
- Universe is still opaque - photons do not propagate far

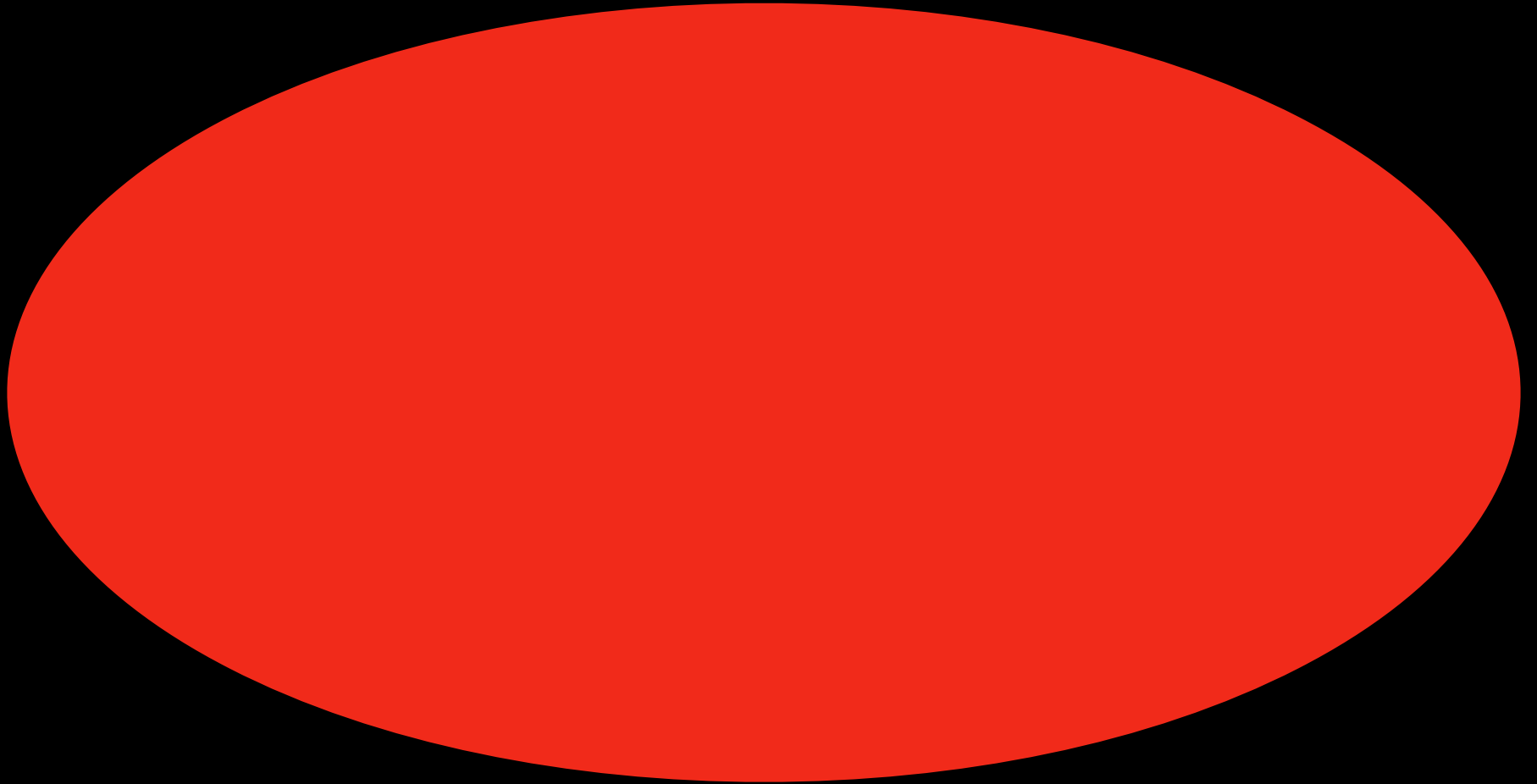


Universe becomes transparent ($t=380,000$ yrs)

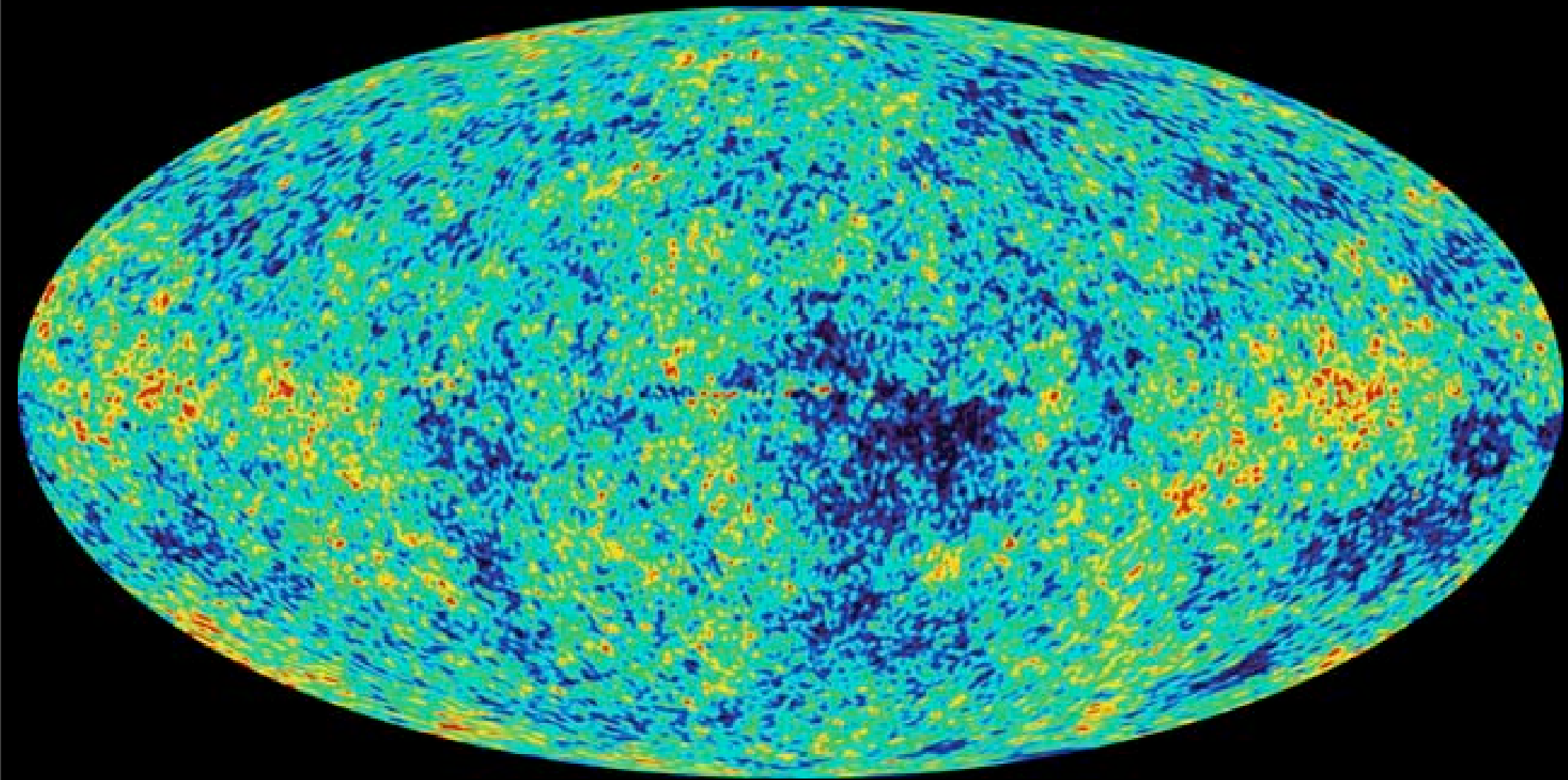
- Radiation finally free to propagate - universe has become cool enough for atoms to form
- The **Cosmic Microwave Background** radiation we observe has been released at this time
- Temp = 3000 Kelvin (2.725 Kelvin today)
- Uniform to one part in 100,000



T=2.725 Kelvin

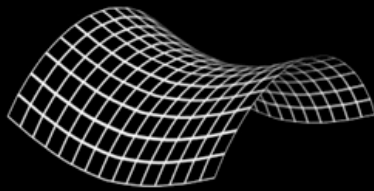
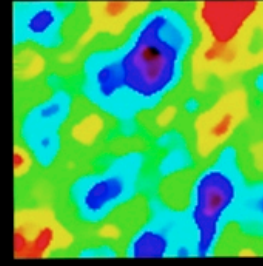
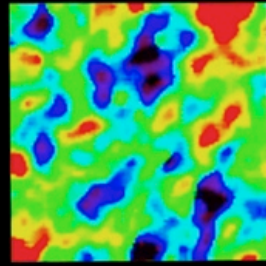
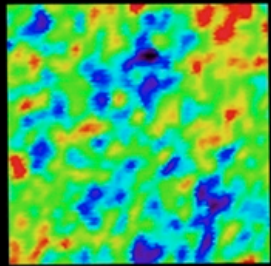


Fluctuations 1 part in 100,000 (of 2.725 Kelvin)

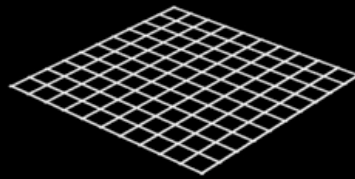


The CMB Spot Sizes Are A "Standard Ruler"

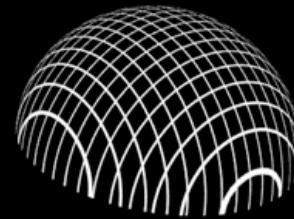
GEOMETRY OF THE UNIVERSE



OPEN

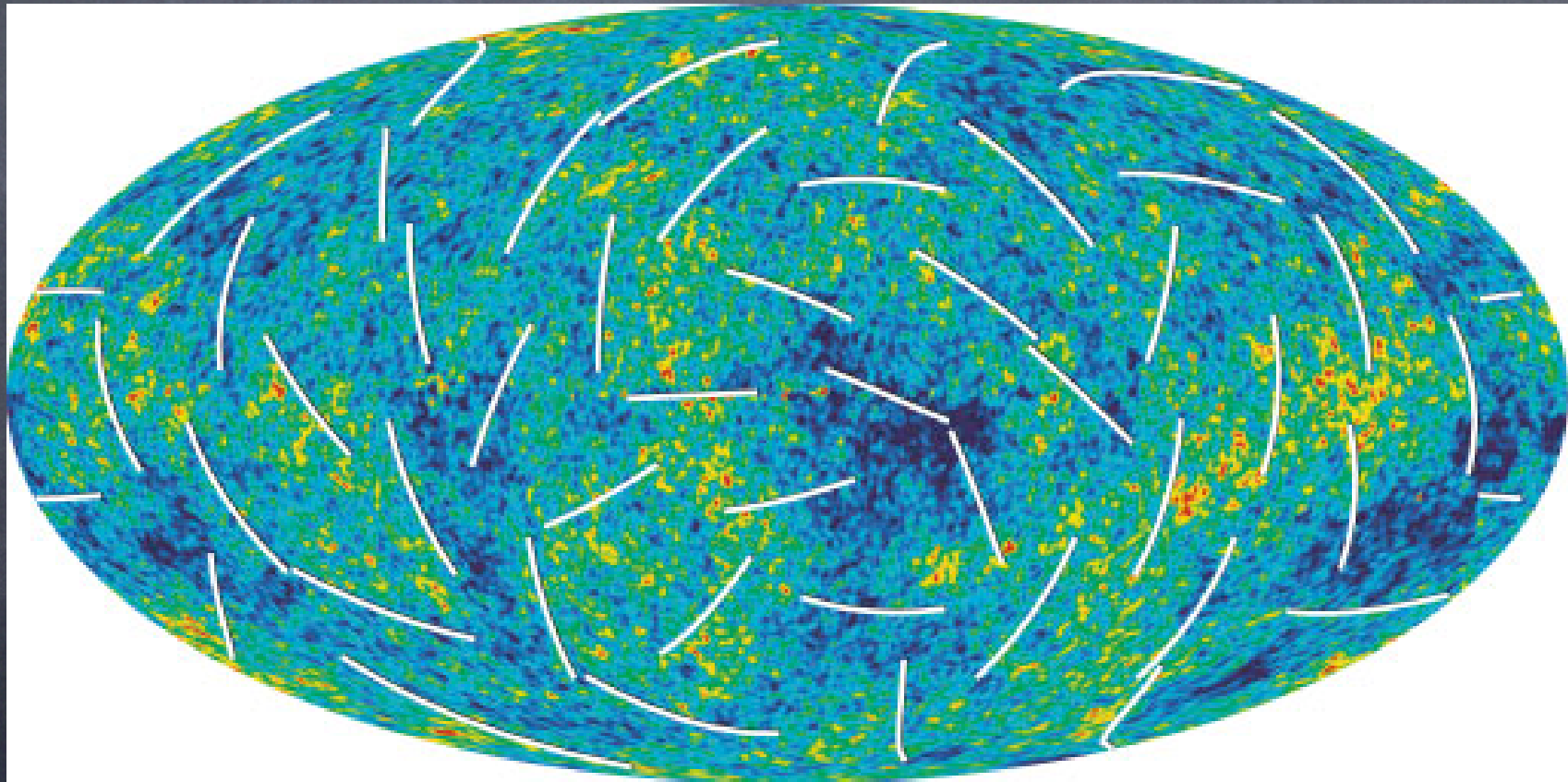


FLAT



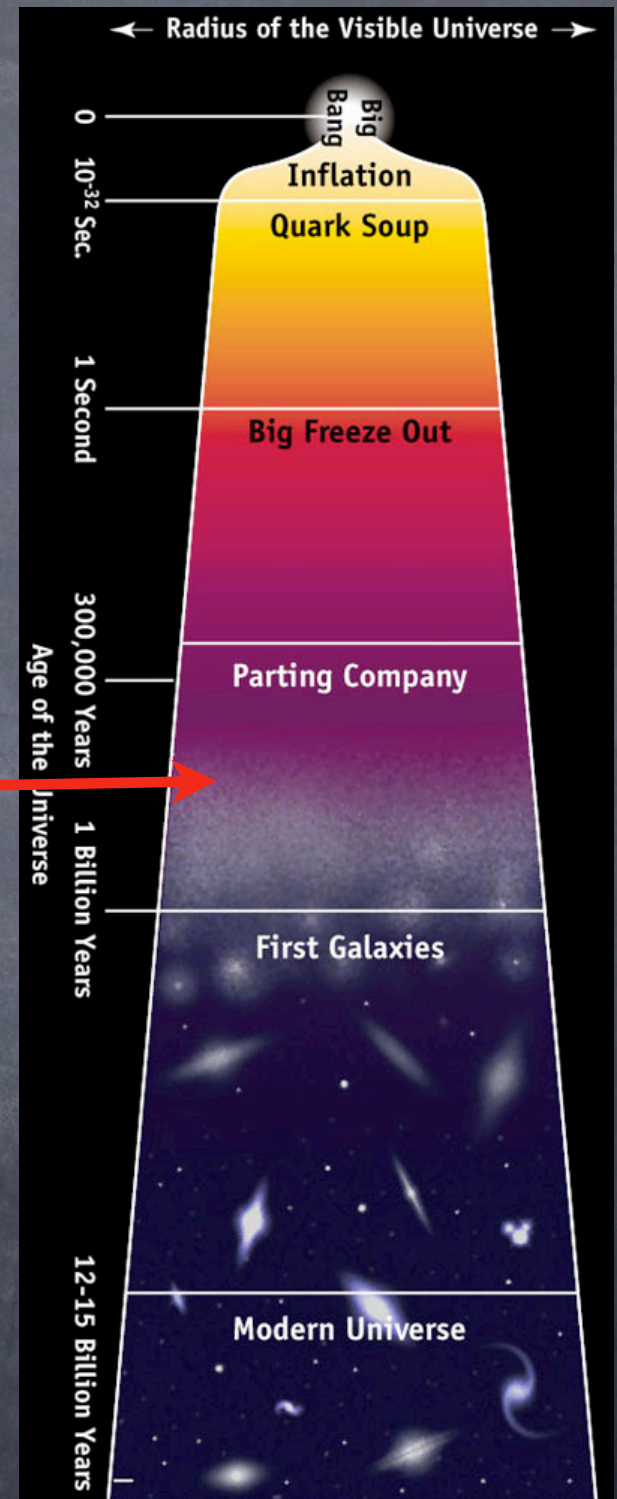
CLOSED

The Cosmic Background Radiation is Polarized



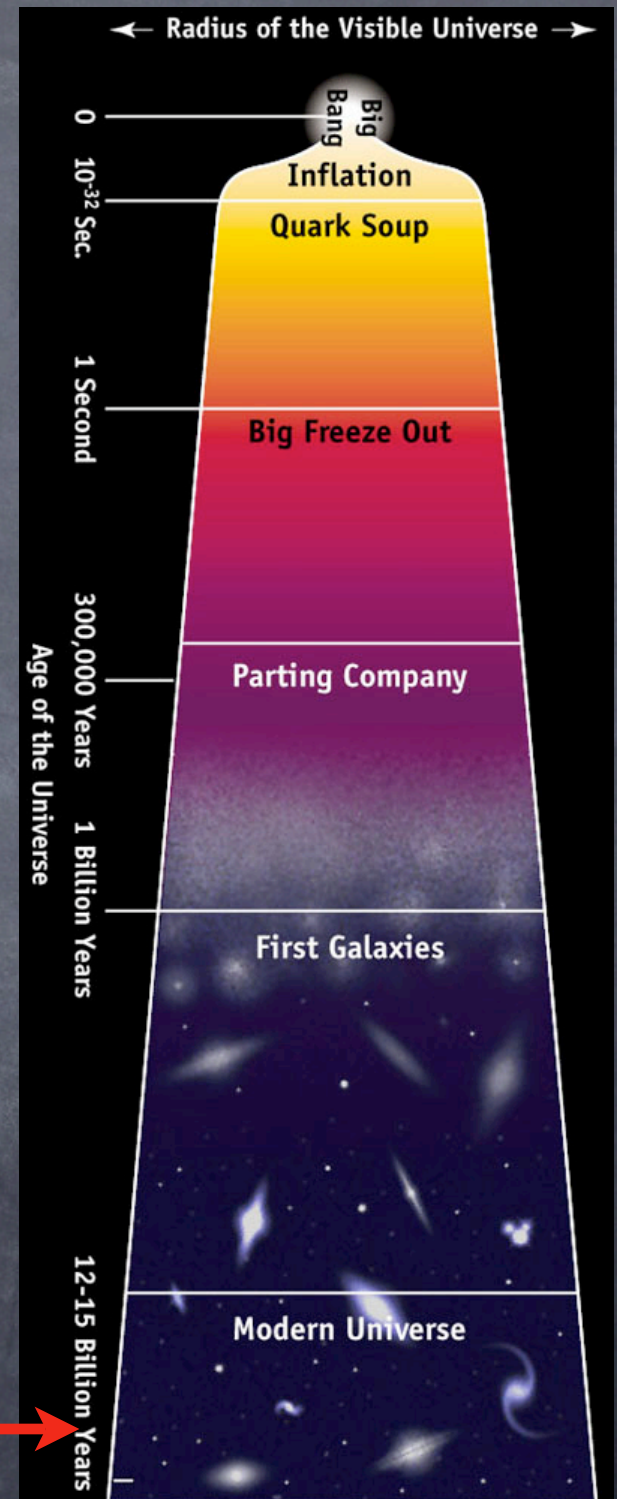
The dark ages ($t < 1$ billion yrs)

- Universe is dark, slowly becomes matter dominated
- First stars ionize the hydrogen atoms
- First stars and first galaxies eventually form



Modern Universe ($t=13.7$ billion yrs)

- Stars, Galaxies, Clusters of galaxies everywhere
- A lot more Dark Matter that we cannot directly see
- Even more mysterious Dark Energy takes over (a few billion years ago)



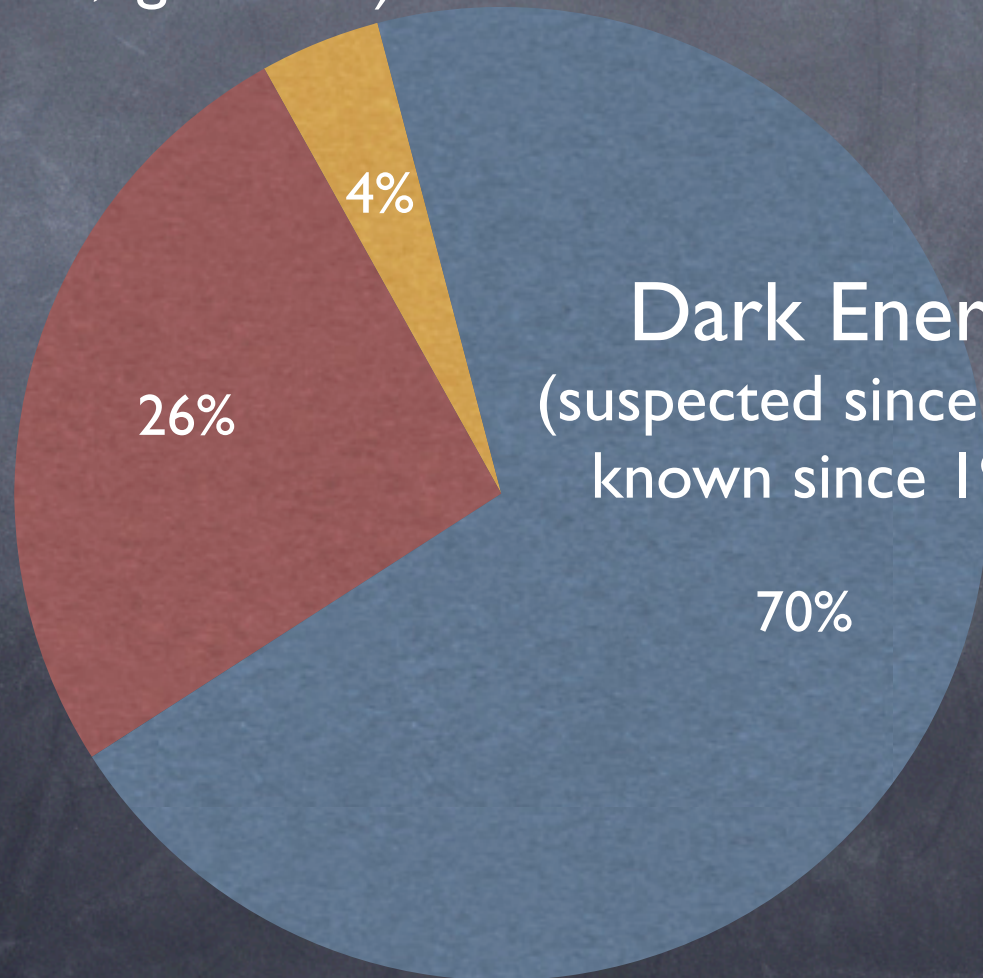
Makeup of universe today

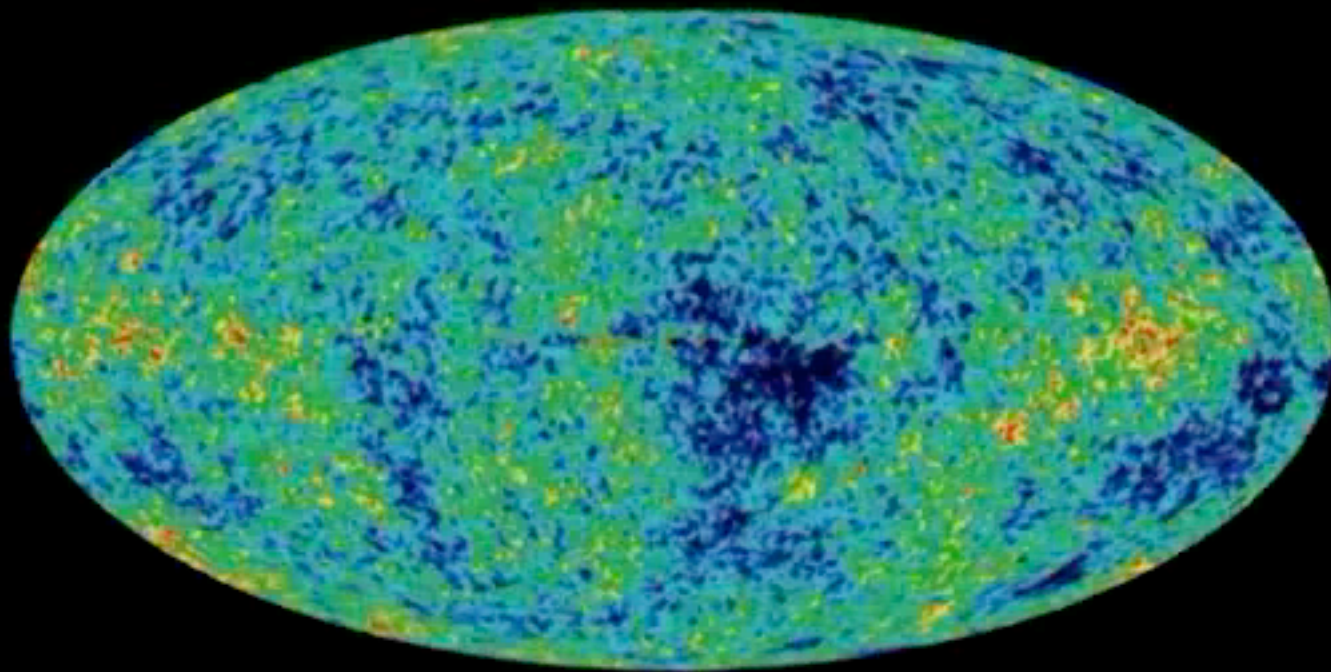
Visible Matter
(stars 0.4%, gas 3.6%)

Dark Matter
(suspected since 1930s
known since 1970s)

Dark Energy
(suspected since 1980s
known since 1998)

Also:
radiation (0.01%)

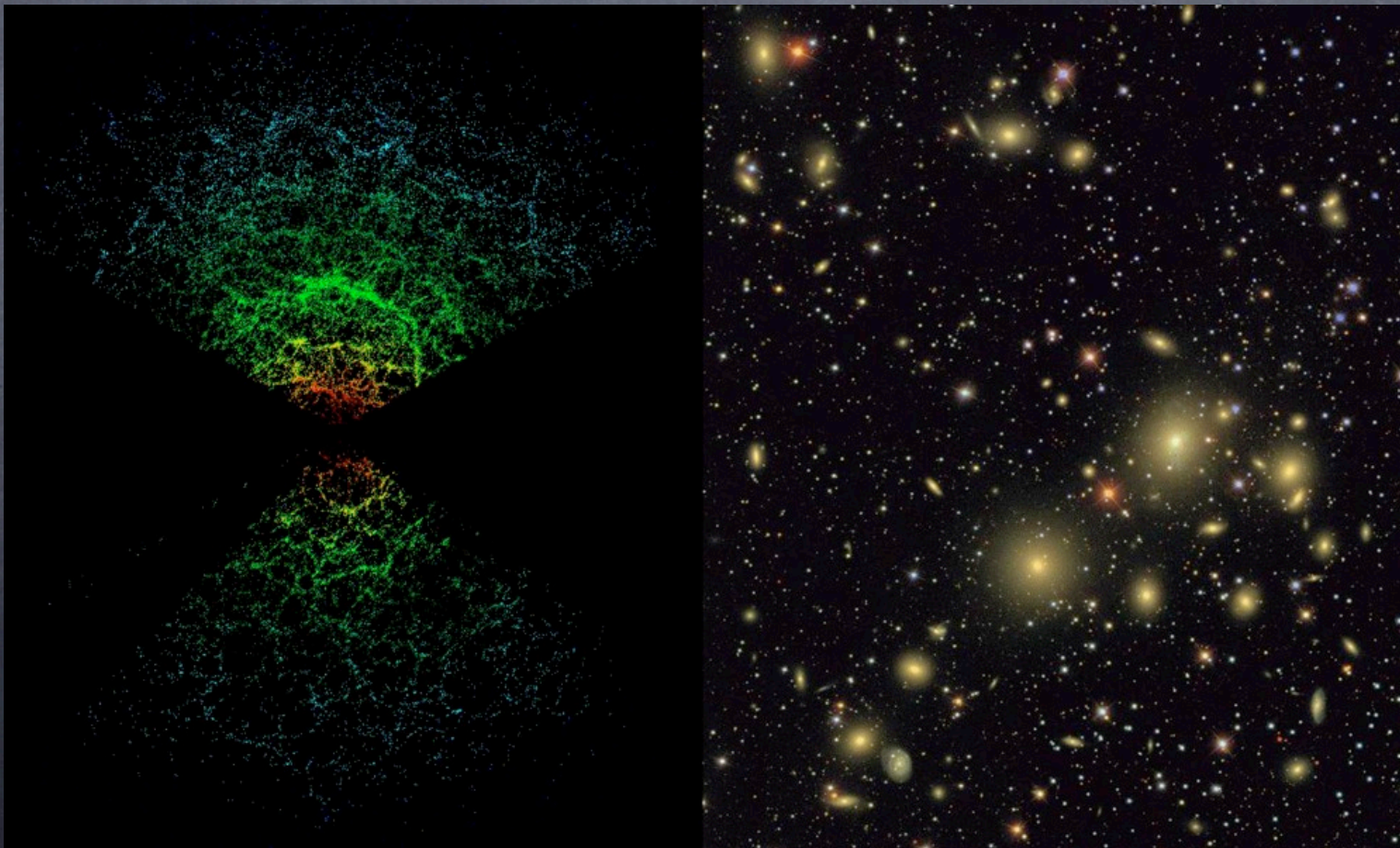




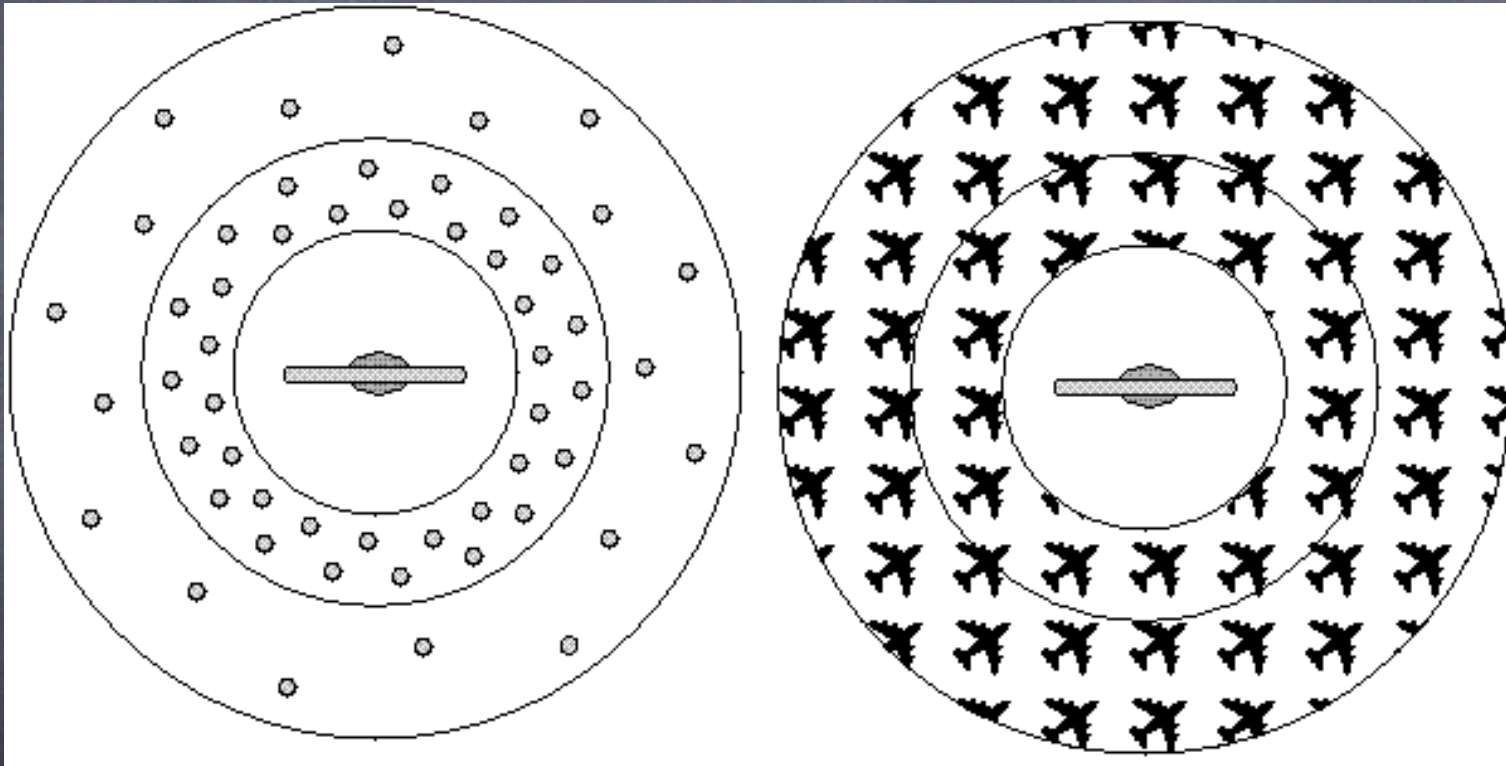
Part II: The Universe Through Analogy

The universe is homogeneous and isotropic

- **Homogeneous**: appears the same everywhere in space
- **Isotropic**: appears the same in every direction



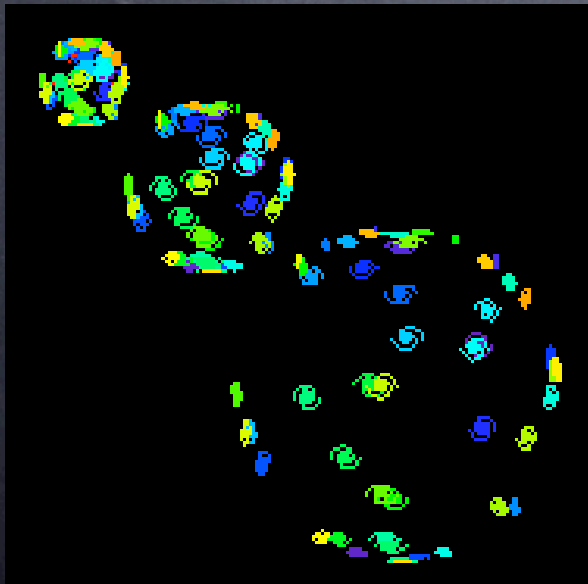
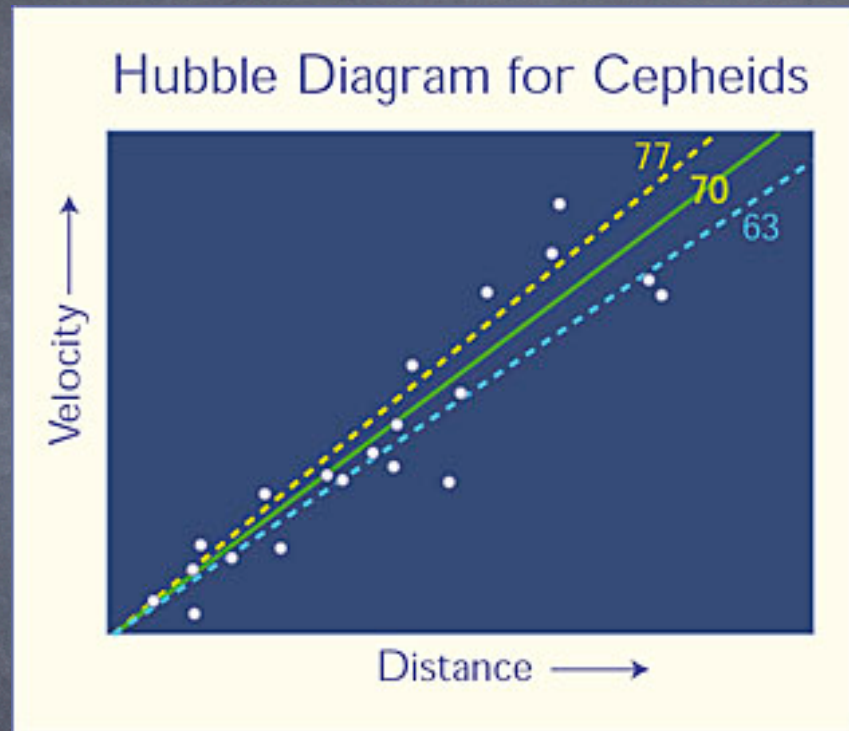
Homogeneity and Isotropy



Not Homogeneous

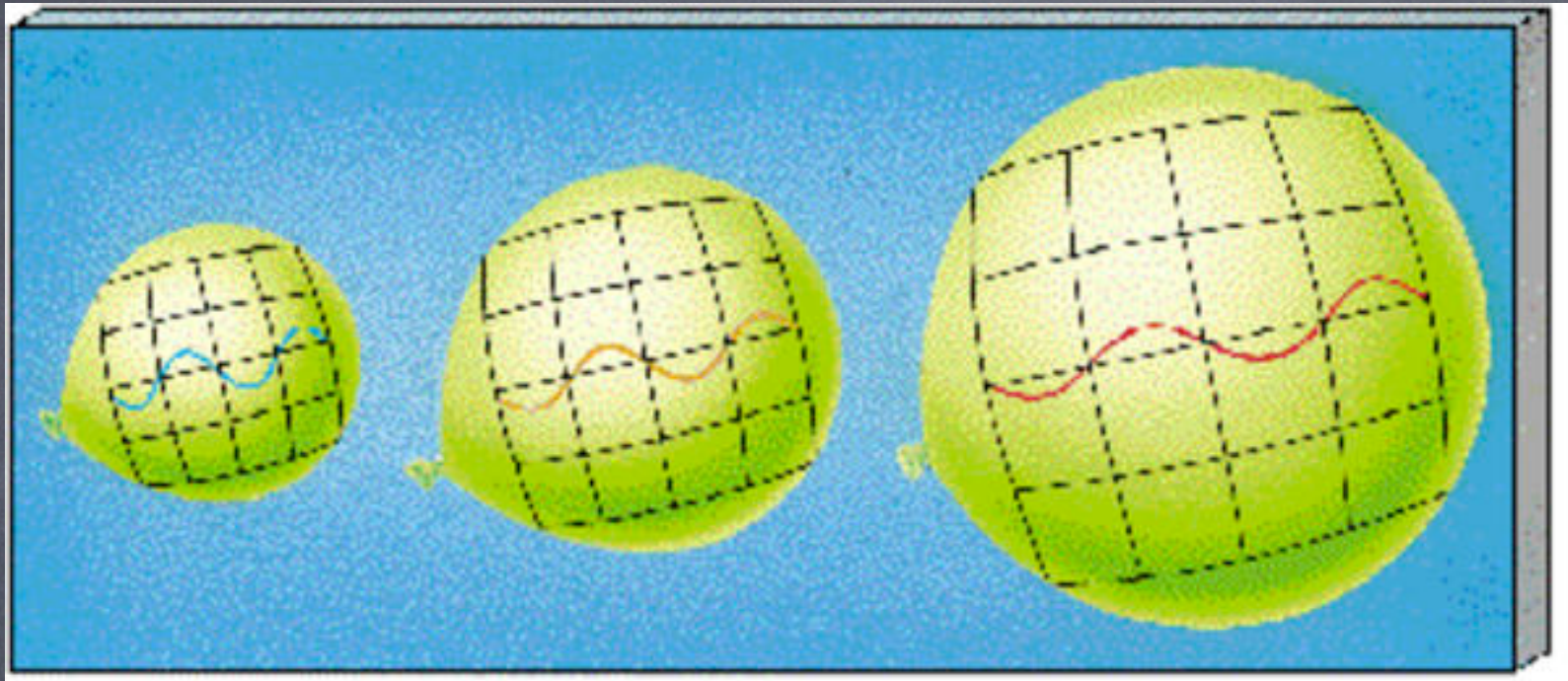
Not isotropic

Expansion of Universe



Edwin Hubble

Expansion analogy: Blowing up the balloon

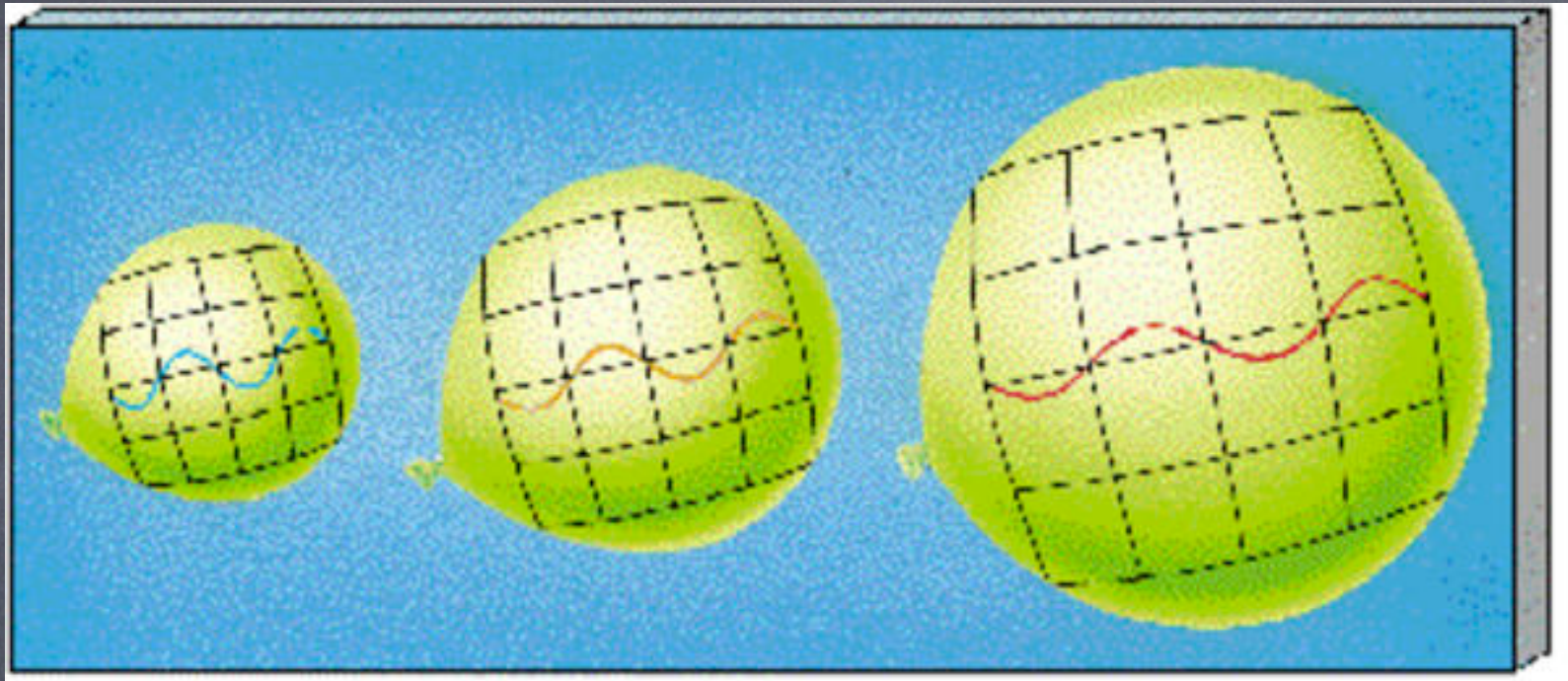


- The Good:

- It is expanding

- all points recede from all other points

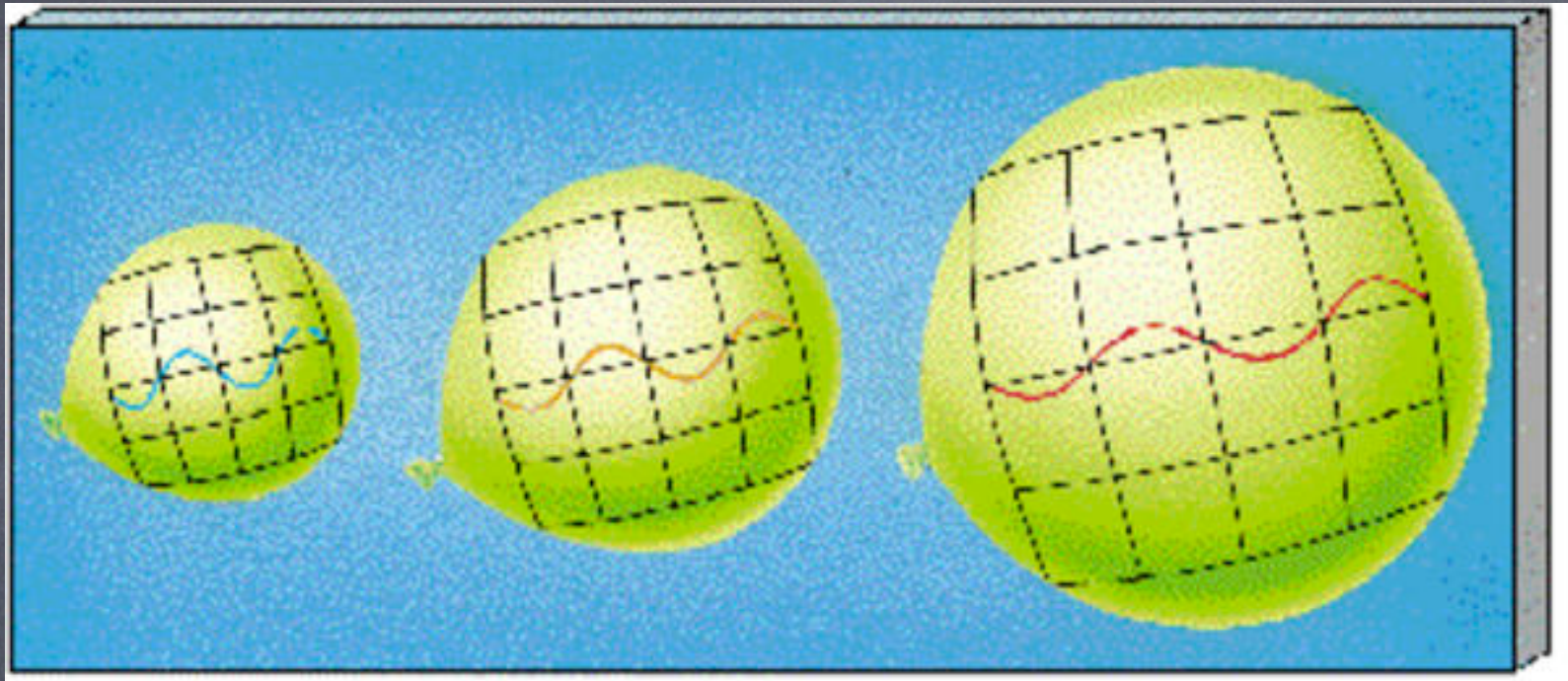
Expansion analogy: Blowing up the balloon



• The Bad:

- It is two dimensional and one must envision a three dimensional situation
- Points representing galaxies must not expand

Expansion analogy: Blowing up the balloon



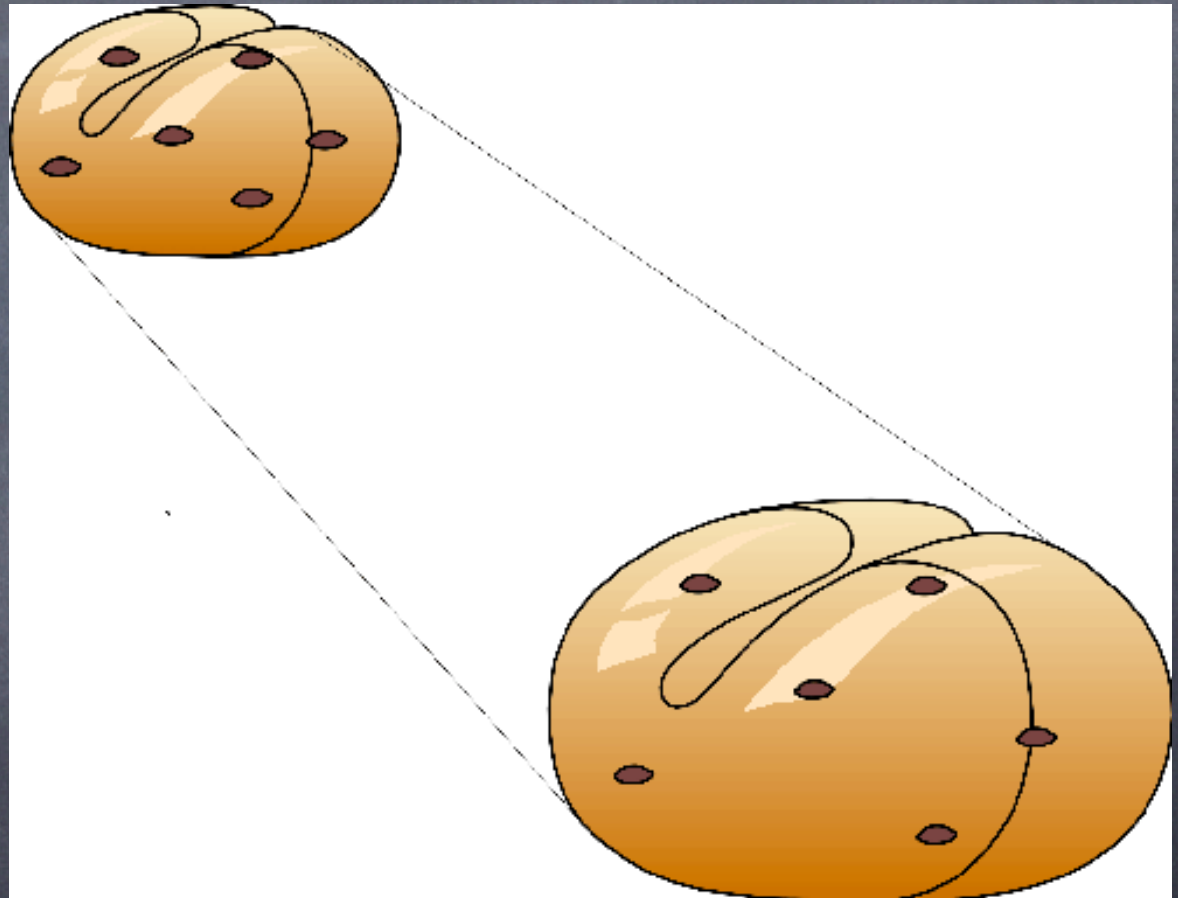
• The Ugly:

• What does the Universe expand into?

Expansion Analogy II: Raisin bread

- The Good:

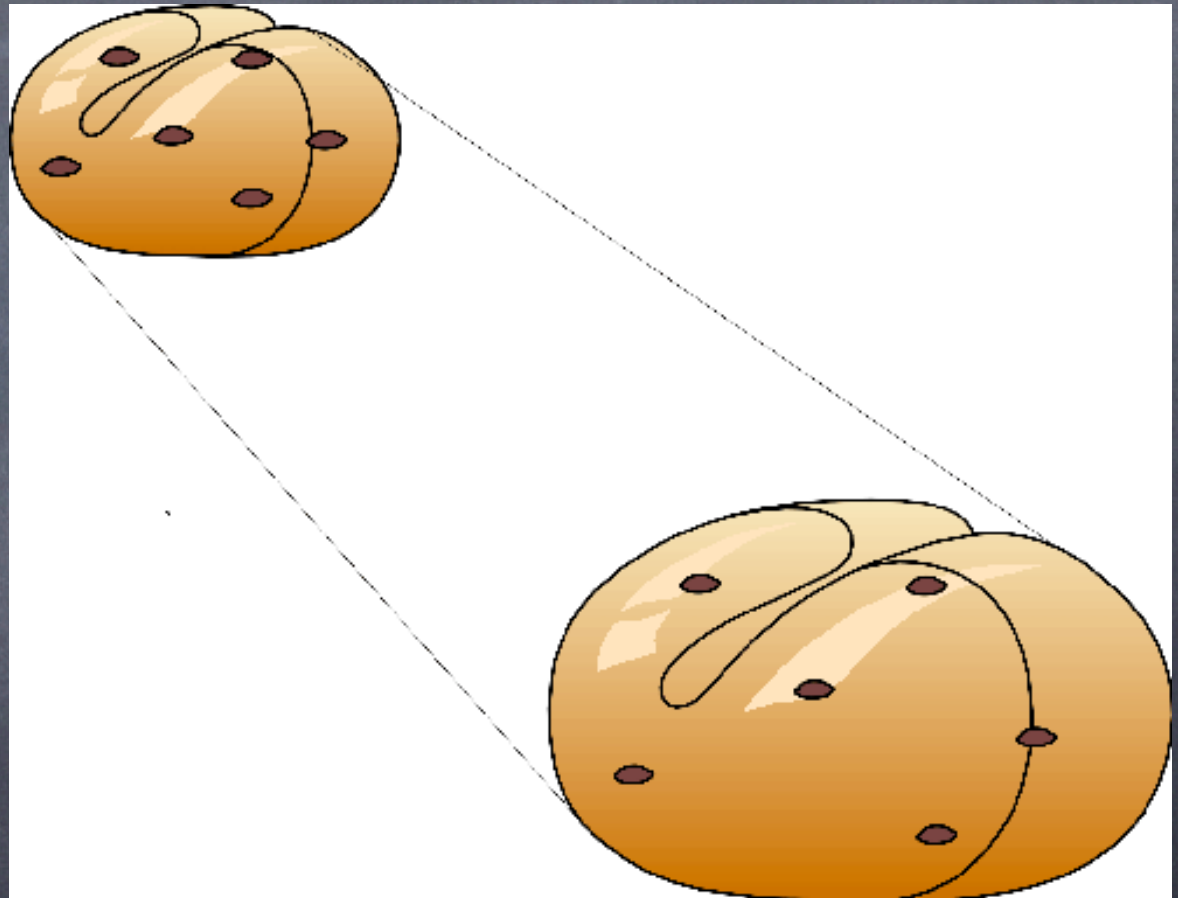
- This example is Three dimensional
- The raisins retain their sizes



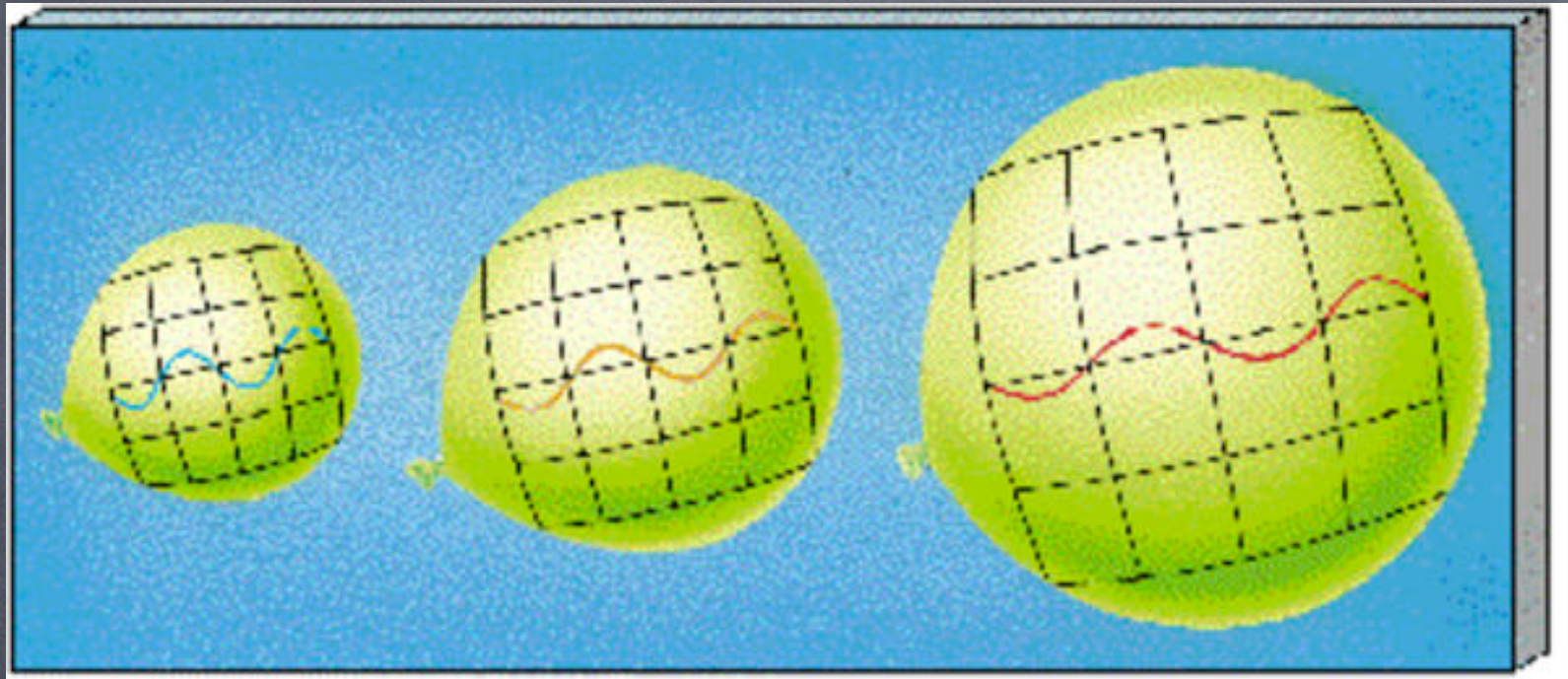
Expansion Analogy II: Raisin bread

- The Ugly:

- Still gives a sense of the Universe expanding into something else
- What's beyond the Universe?

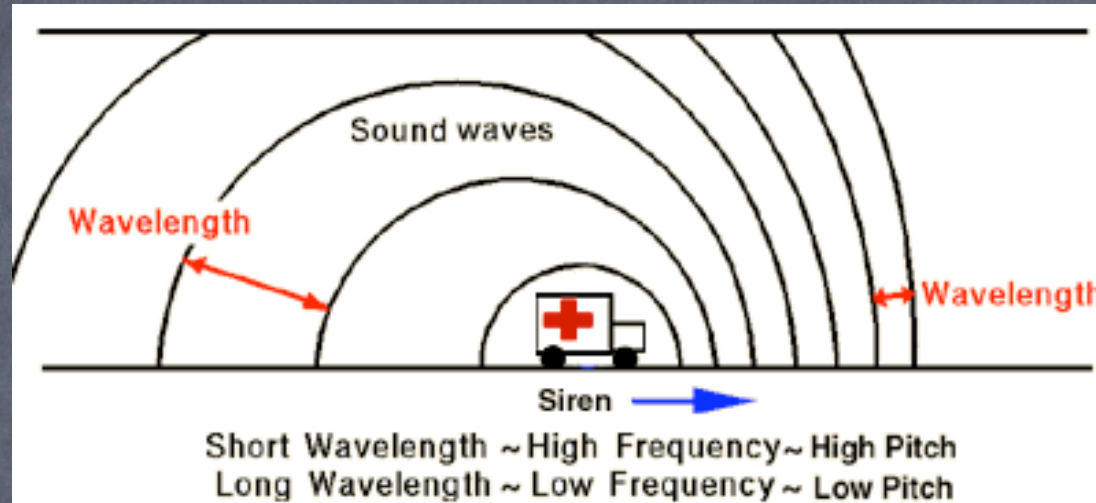


The Cosmological Redshift



- Wavelengths of light stretch as the Universe expands
- Spectra have features that encode the amount of wavelength expansion

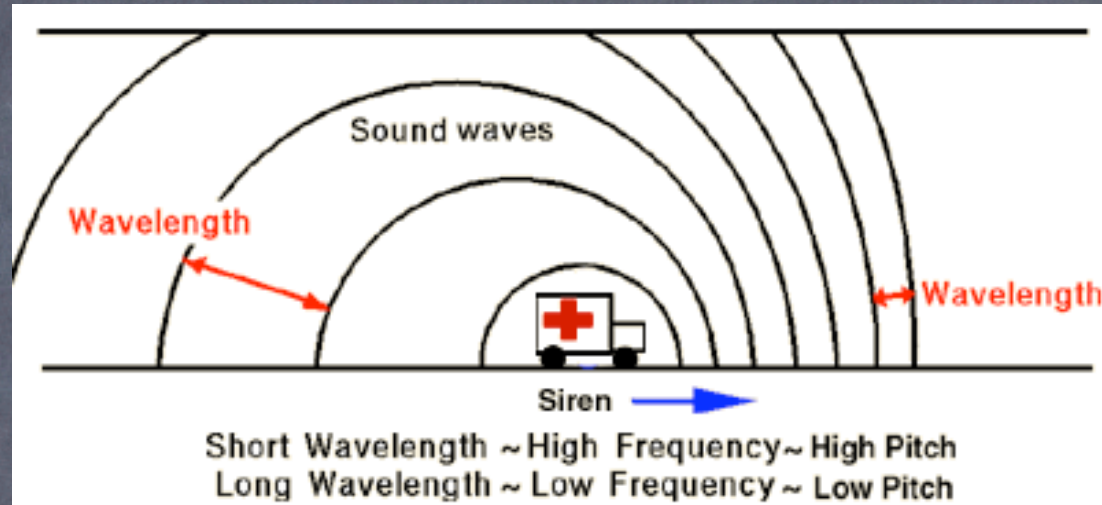
The Cosmological Redshift



• The Good:

- This is a very familiar phenomenon
- An excellent description of the Doppler Effect

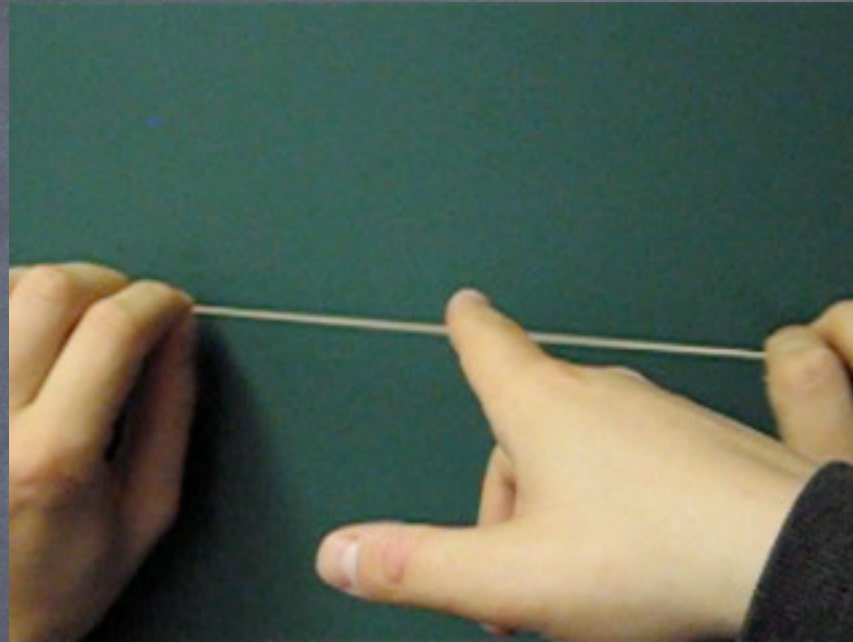
The Cosmological Redshift



• The Bad:

- Technically, Cosmological Redshift is not a Doppler Shift

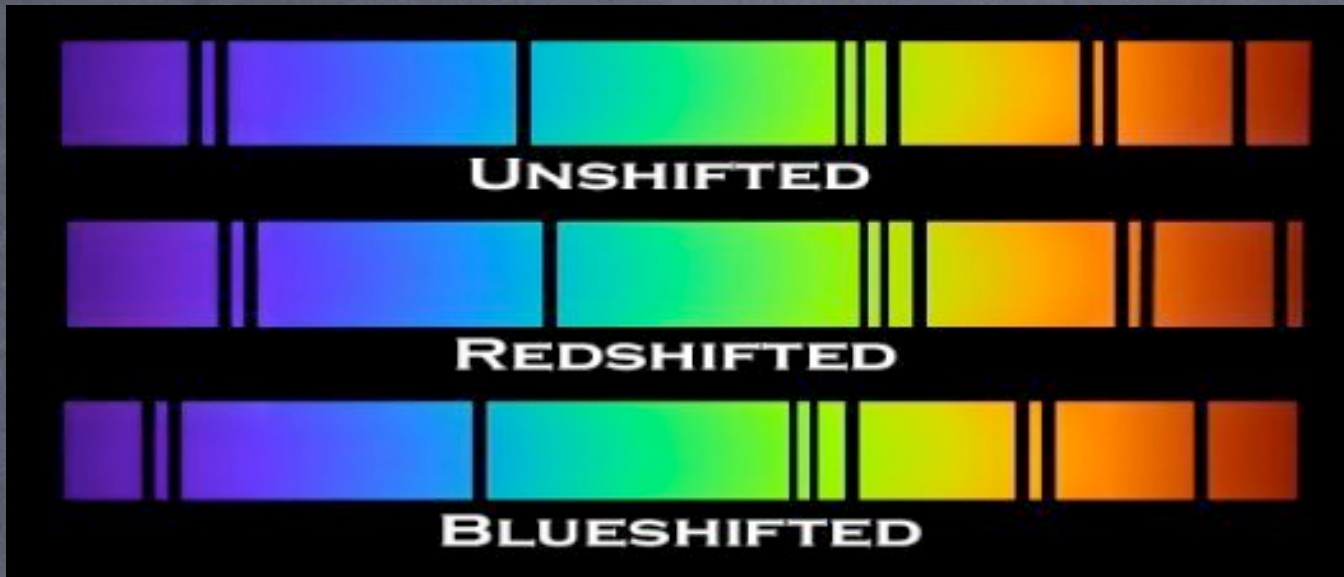
The Cosmological Redshift



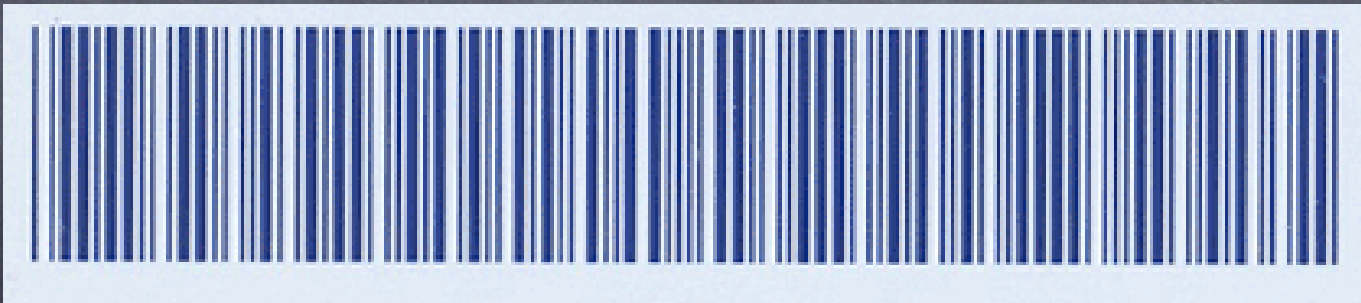
- Wavelengths Expand As Space Expands
- Good Analogy: A Rubber Band Stretched Between Your Hands!

The Cosmological Redshift

← short
wavelength

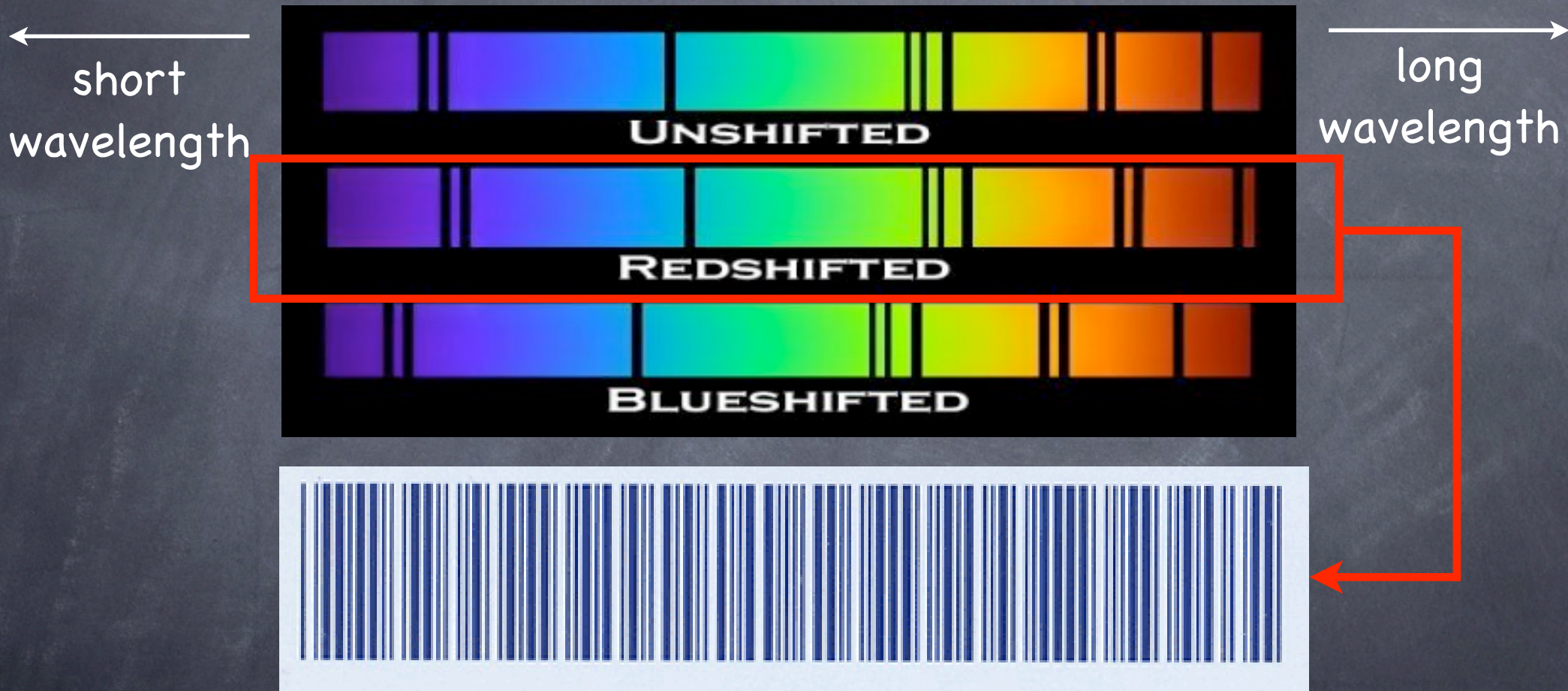


→ long
wavelength



- Like a barcode, spectral lines give the amount of wavelength expansion, or redshift

The Cosmological Redshift



- Like a barcode, spectral lines give the amount of wavelength expansion, or redshift

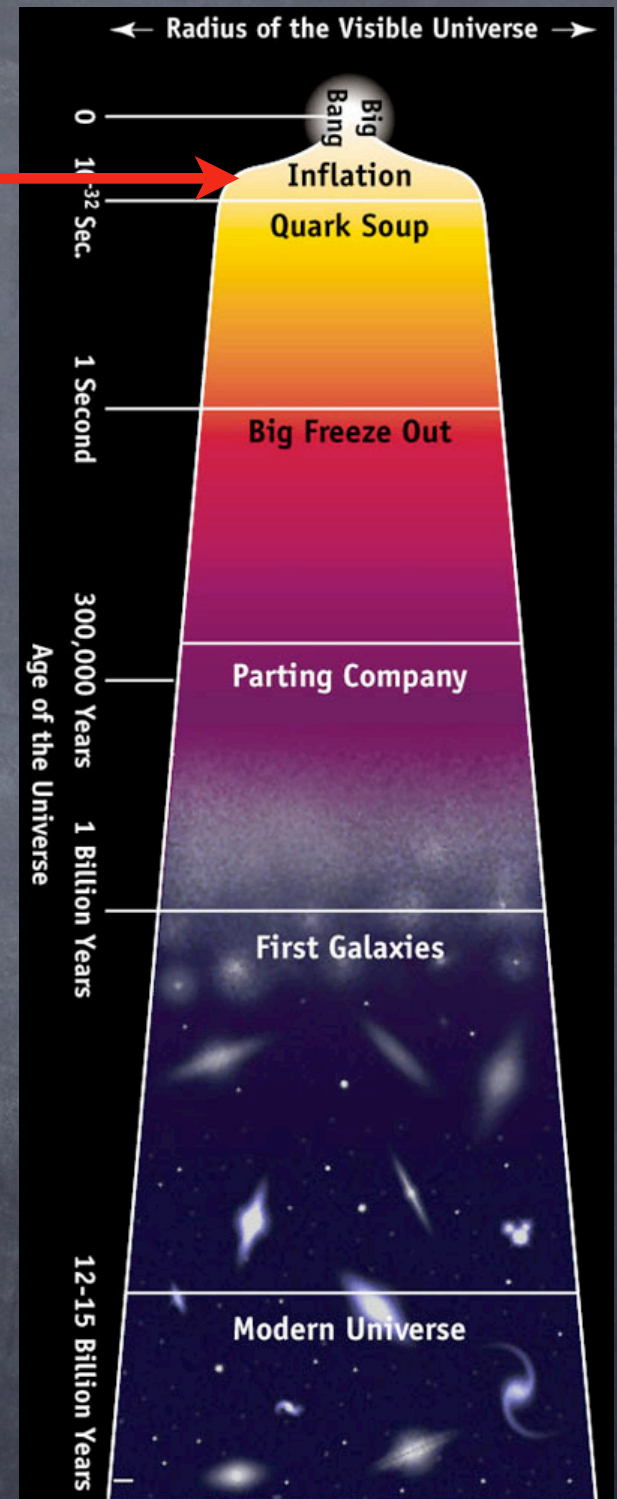
Looking Out Is Equivalent To Looking Back In Time



Demonstration: looking back at a baby universe

Very early Universe (t=tiny moments after BB)

- The Universe experienced an epoch of extremely rapid expansion called INFLATION



Cosmic Inflation Addresses Two Big Problems

- The Horizon Problem: How can different parts of the Universe, separated by a distance greater than light could have traveled, know to be the same?
- The Flatness Problem: Why is the geometry of the Universe so close to being the flat, Euclidean geometry we are familiar with?

The Horizon Problem: An Analogy



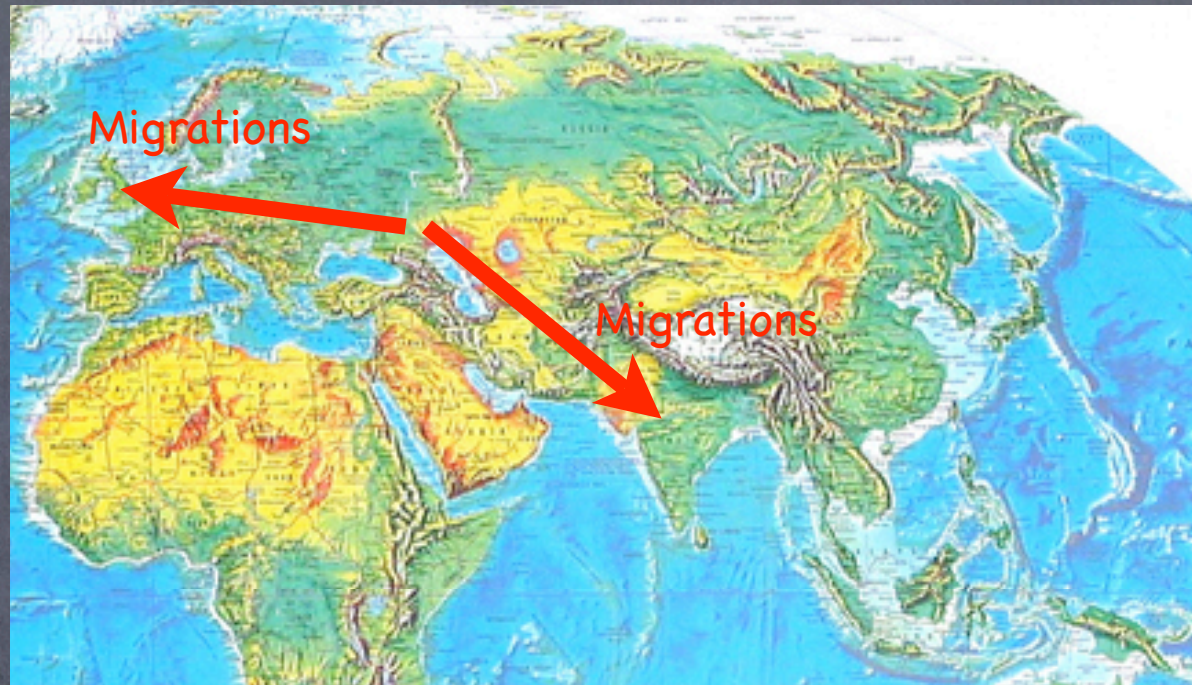
- Why are there similarities in language in widely separated cultures?

The Horizon Problem: An Analogy



- Some degree of common ancestry is believed to be the reason.

The Horizon Problem: An Analogy



- Migration plays the role of inflation, moving groups vast distances apart at which point they lose contact

The Horizon Problem: An Analogy



- Groups are isolated by desert, mountain etc.

The Horizon Problem: An Analogy



- Eventually, these cultures communicate and notice the similarity, this is analogous to observing uniform CMB temperatures across the sky.

The Horizon Problem Analogy



- The Bad:

- Fails to convey the sheer degree of uniformity in the Universe, 1 part in 100000!

The Classroom Analogy



- Imagine a large class taking an exam
- At the end they all hand in the same exam
- You **know** there has to have been communication between them!

The Flatness Problem



- The Good:

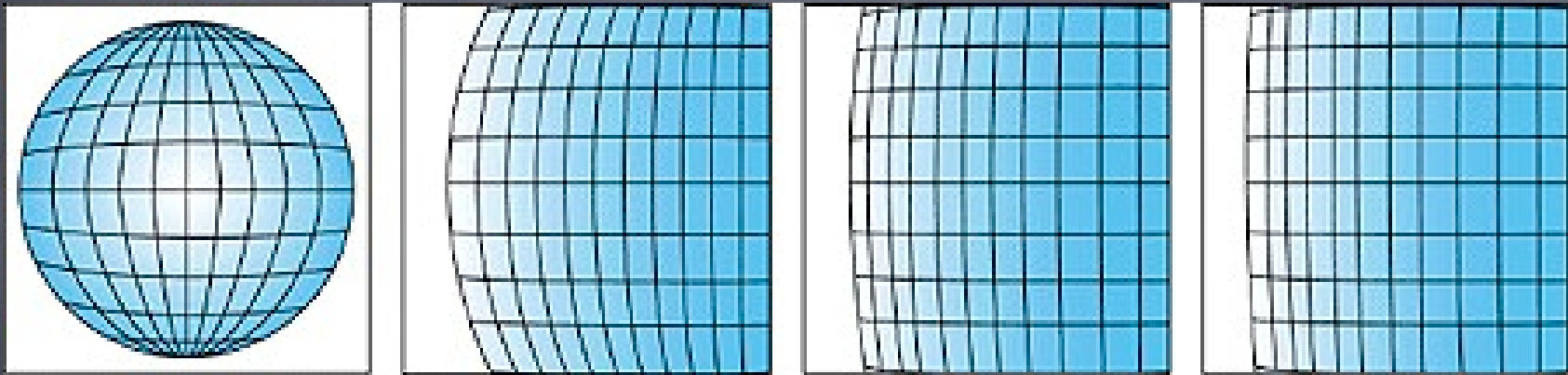
- Represents an unstable equilibrium akin to the spatial flatness of the Universe

The Flatness Problem



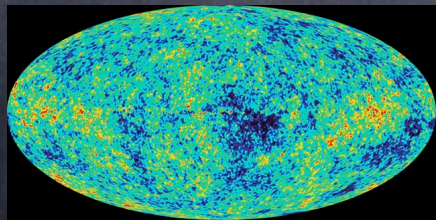
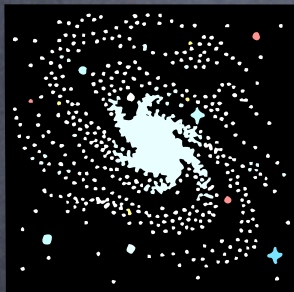
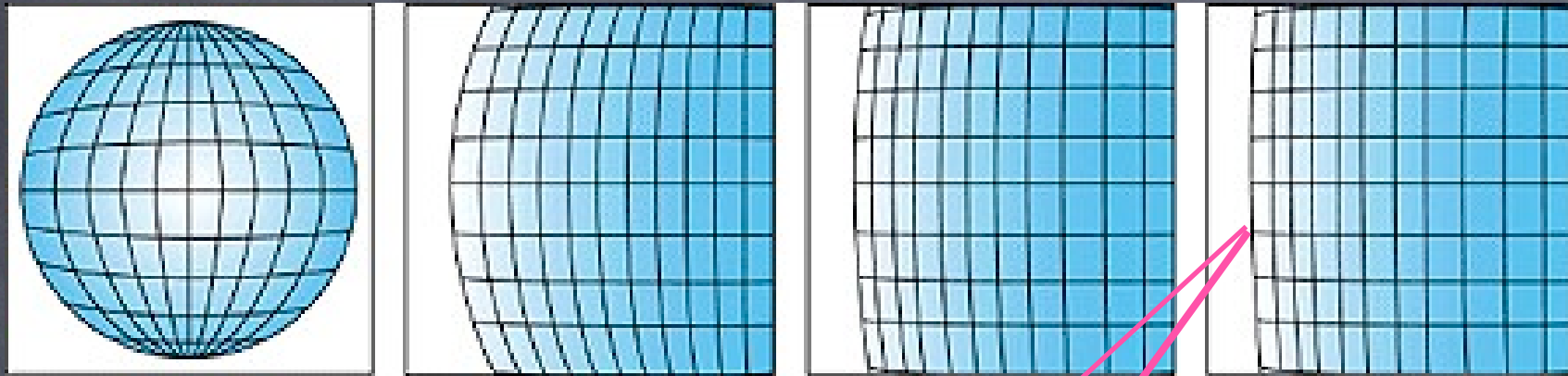
- The Ugly:
 - What is the Pencil?
 - The pencil plays the role of the Universe and the connection between the two is difficult.

Inflationary solution to The Flatness Problem



Inflation expands the universe so much that
the part around us appears exactly flat

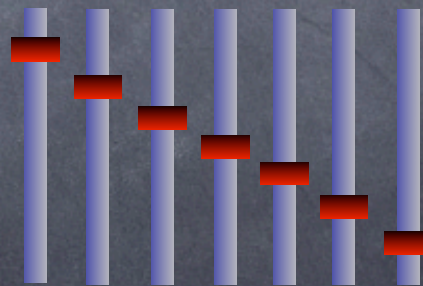
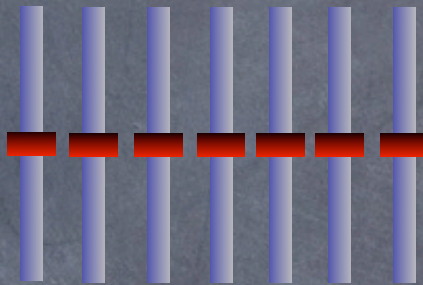
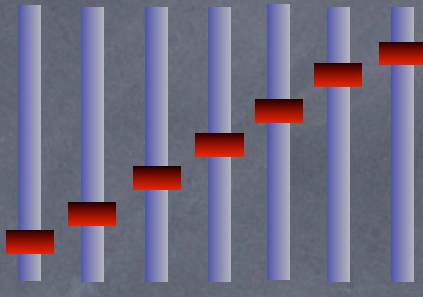
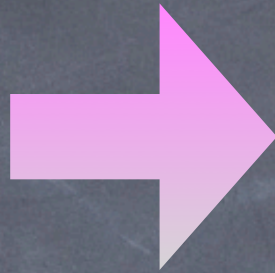
Inflation creates quantum ripples



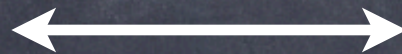
Inflation creates quantum ripples that forms all the structures in the Universe!

The Universal Graphic Equalizer!

More power on
small scales

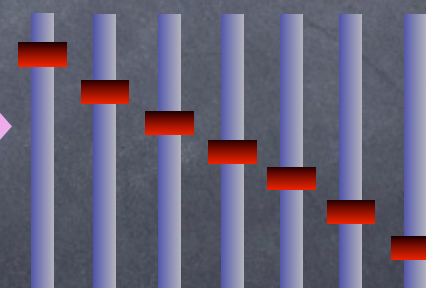
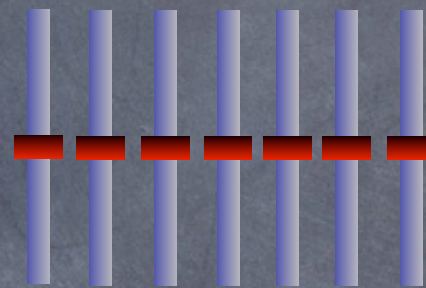
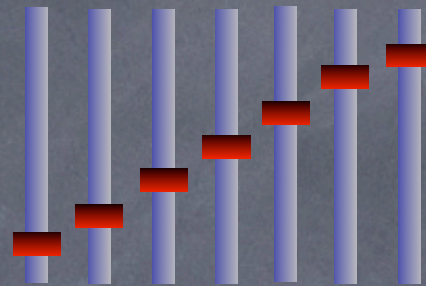


Large scales = Bass



Small scales = Treble

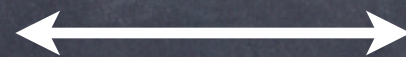
The Universal Graphic Equalizer!



More power on
large scales



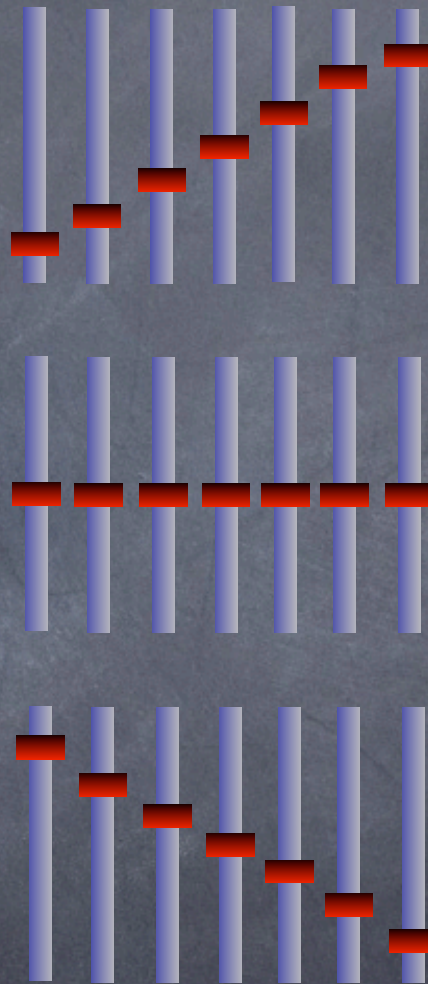
Large scales = Bass



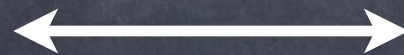
Small scales = Treble

The Universal Graphic Equalizer!

Inflation predicts
roughly equal
power on all
scales – this is
observed!



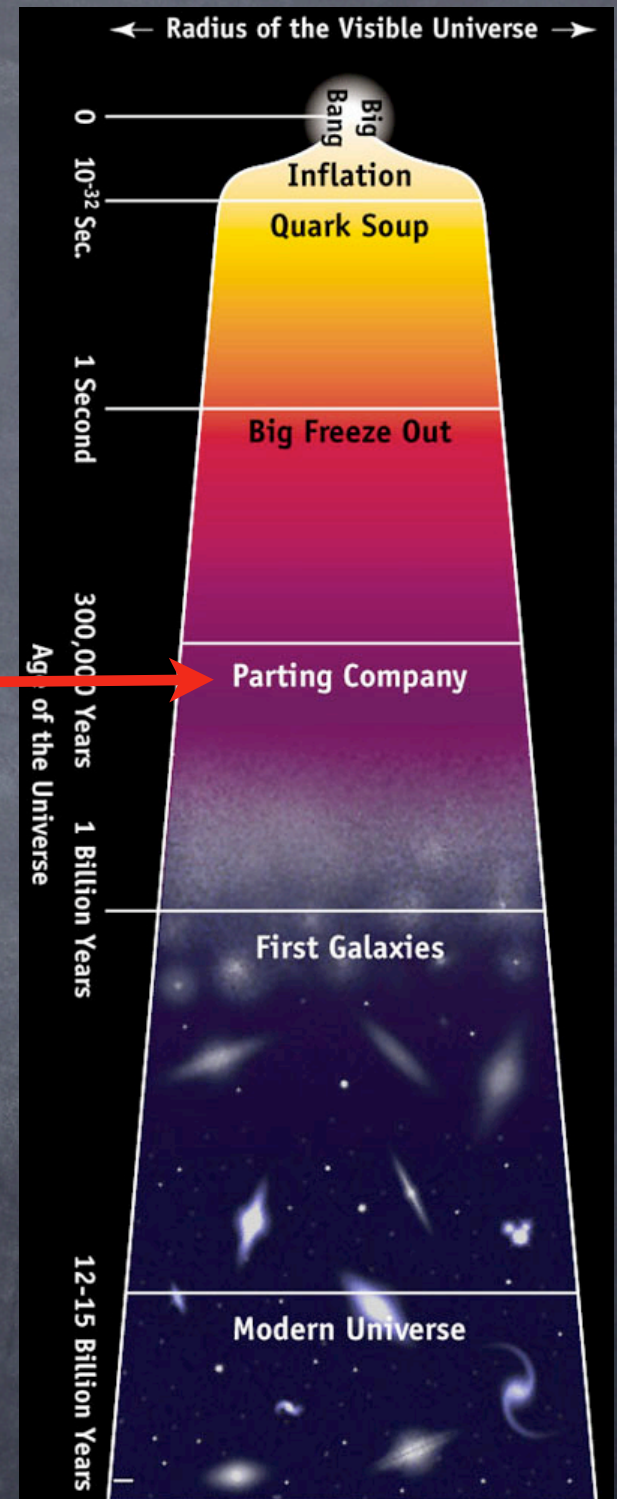
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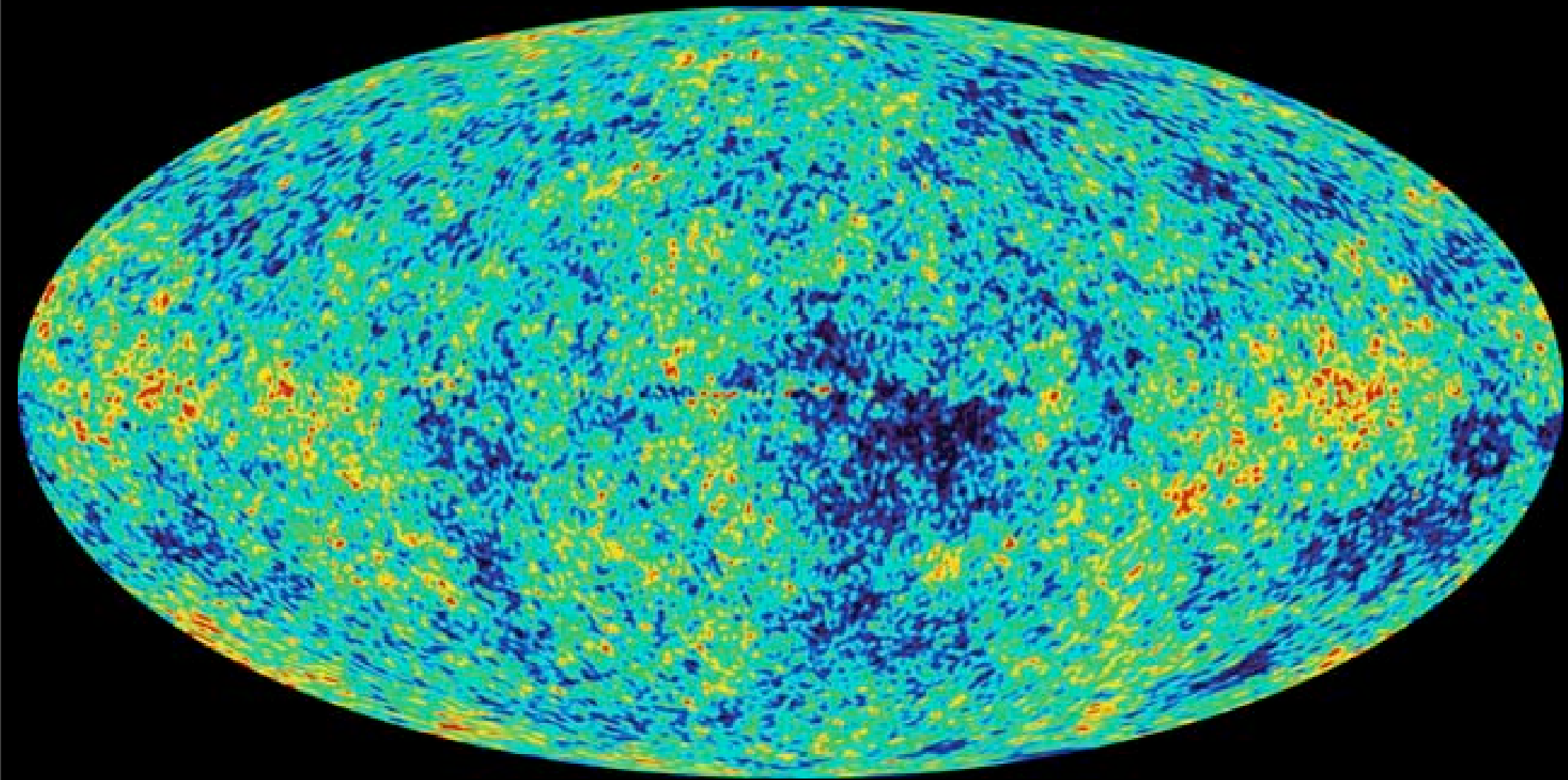
Small scales = Treble

Universe becomes transparent ($t=380,000$ yrs)

- Radiation finally free to propagate - universe has become cool enough for atoms to form
- The **Cosmic Microwave Background** radiation we observe has been released at this time
- Temp = 3000 Kelvin (2.725 Kelvin today)
- Uniform to one part in 100,000

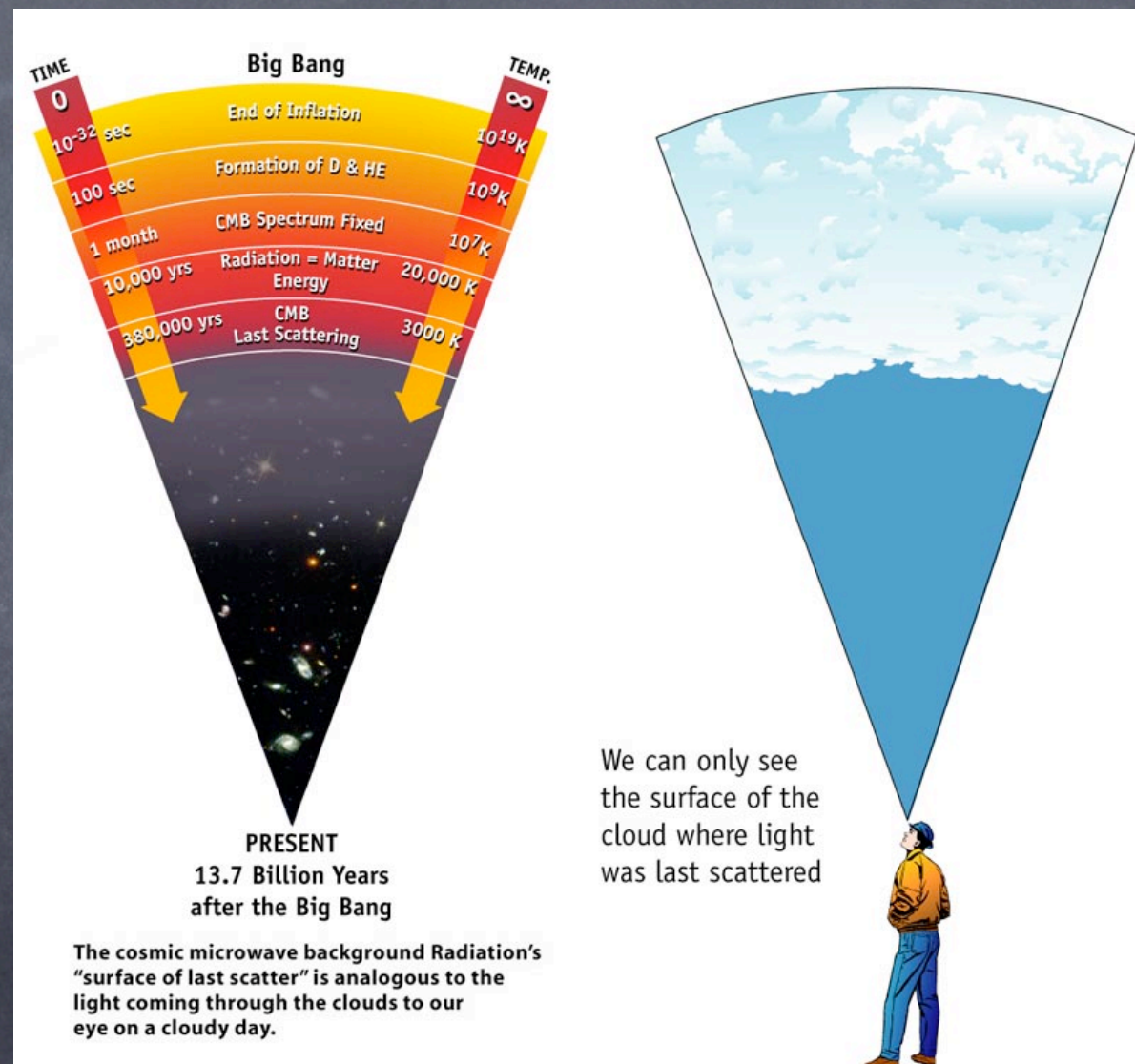


Fluctuations 1 part in 100,000 (of 2.725 Kelvin)



The CMB: The Surface of Last Scattering

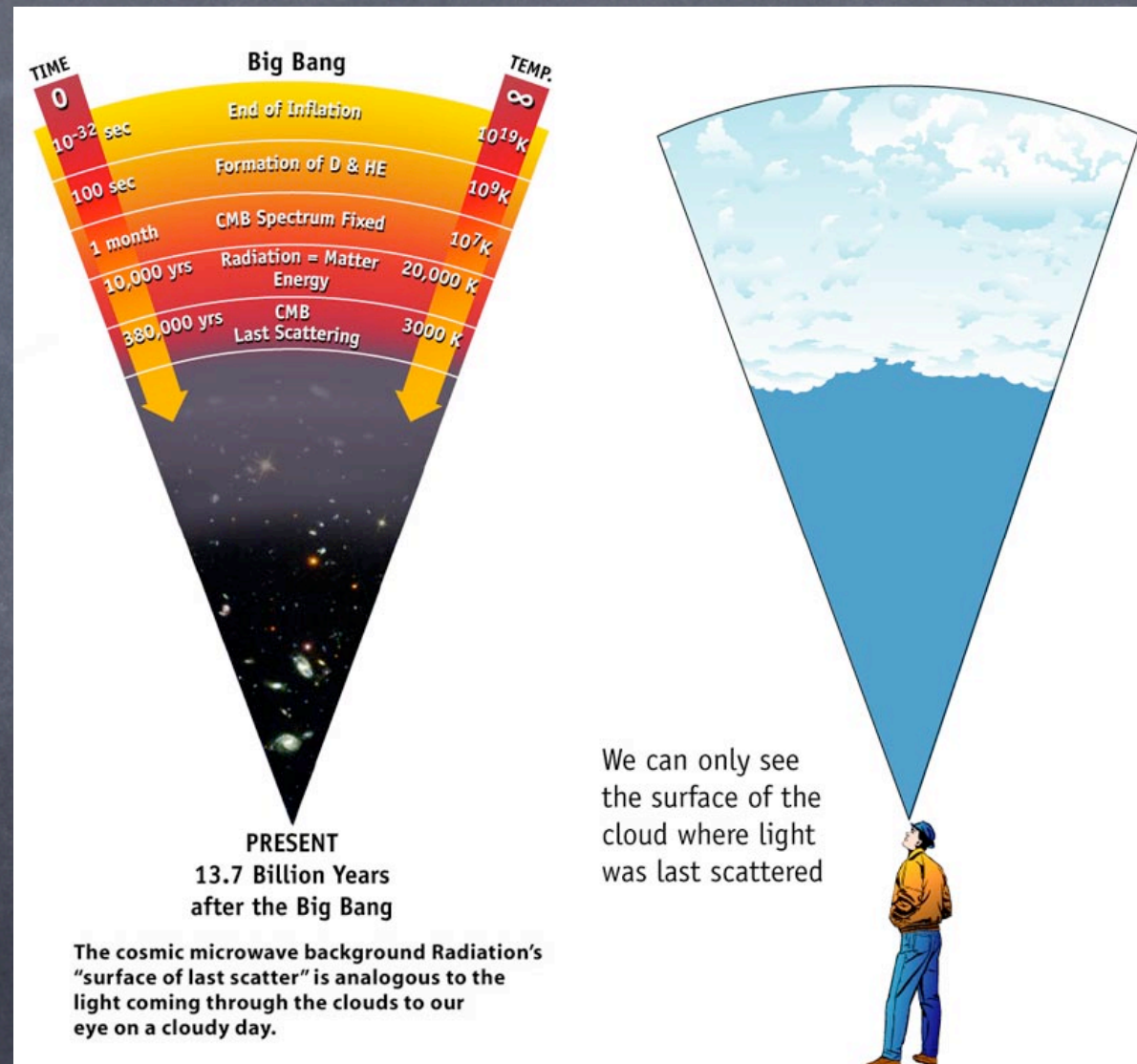
- The Good:
 - Cannot see beyond scattering
 - CMB travels to us from the point of scattering



The CMB: The Surface of Last Scattering

The Bad:

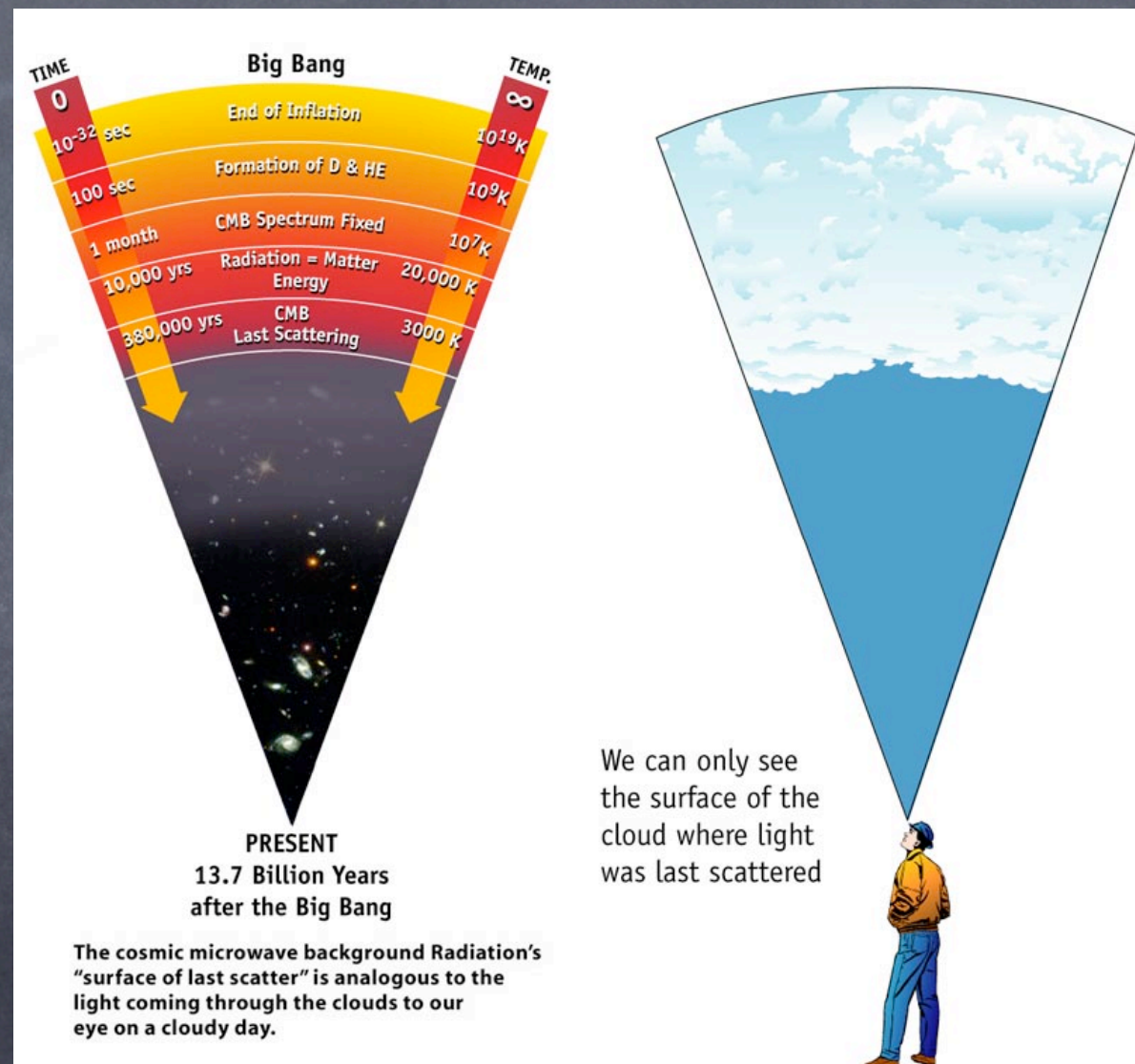
- Nothing Plays the role of the Sun in the Universe



The CMB: The Surface of Last Scattering

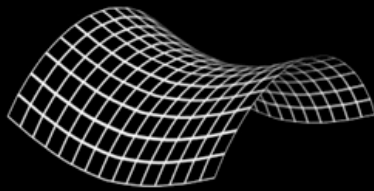
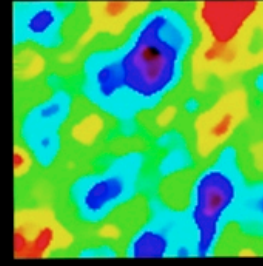
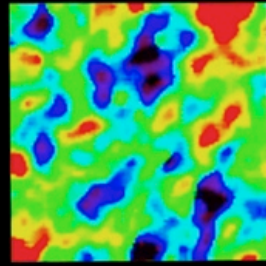
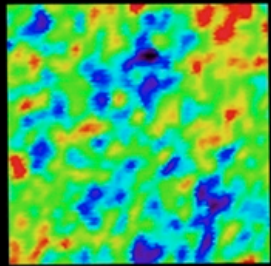
The Ugly:

- Possible conceptual difficulty because is it difficult to comprehend the vast amount of time we are looking back to

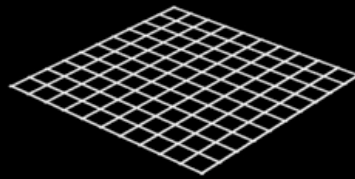


The CMB Spot Sizes Are A "Standard Ruler"

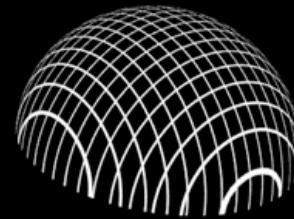
GEOMETRY OF THE UNIVERSE



OPEN



FLAT



CLOSED

A "Standard Ruler": The Headlights of a Car



If you know the intrinsic separation of the headlights, you can estimate how far away the car is

A "Standard Ruler": The Headlights of a Car



If you know the intrinsic separation of the headlights, you can estimate how far away the car is

Good: The analogy is completely correct

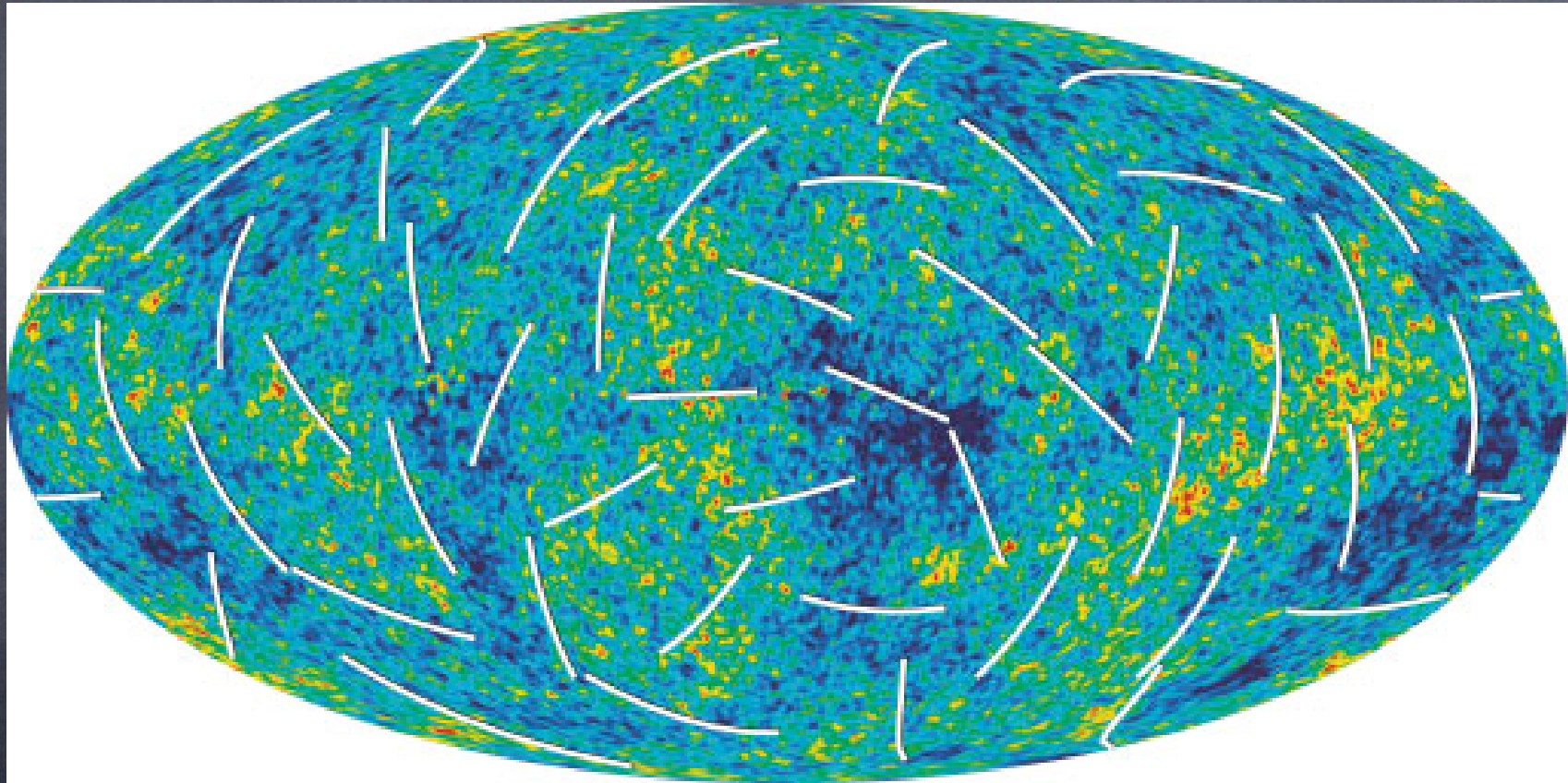
A "Standard Ruler": The Headlights of a Car



If you know the intrinsic separation of the headlights, you can estimate how far away the car is

Bad: we are used to knowing the intrinsic separation of headlights and take this whole process for granted

The Cosmic Background Radiation is Polarized



The Cosmic Background Radiation is Polarized

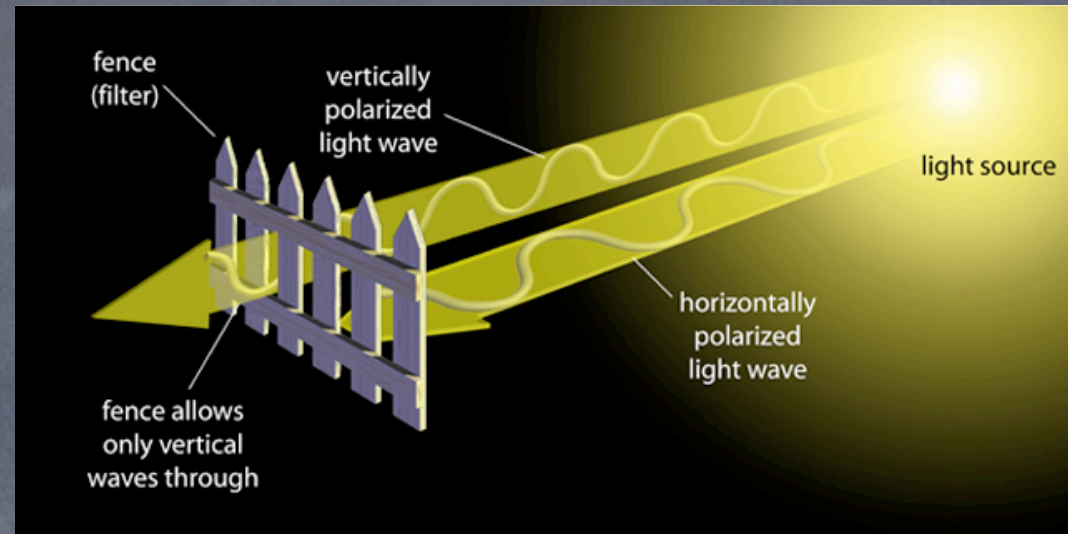
The fence analogy:
imagine light passing
through slits in the
fence

• Good:

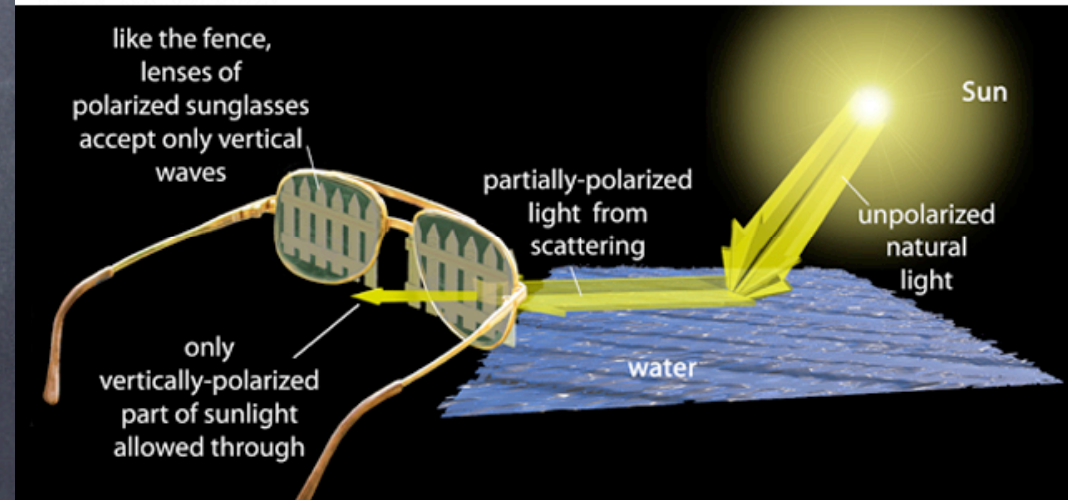
• Easy to visualize

• Ugly:

• Fence slits are usually too wide

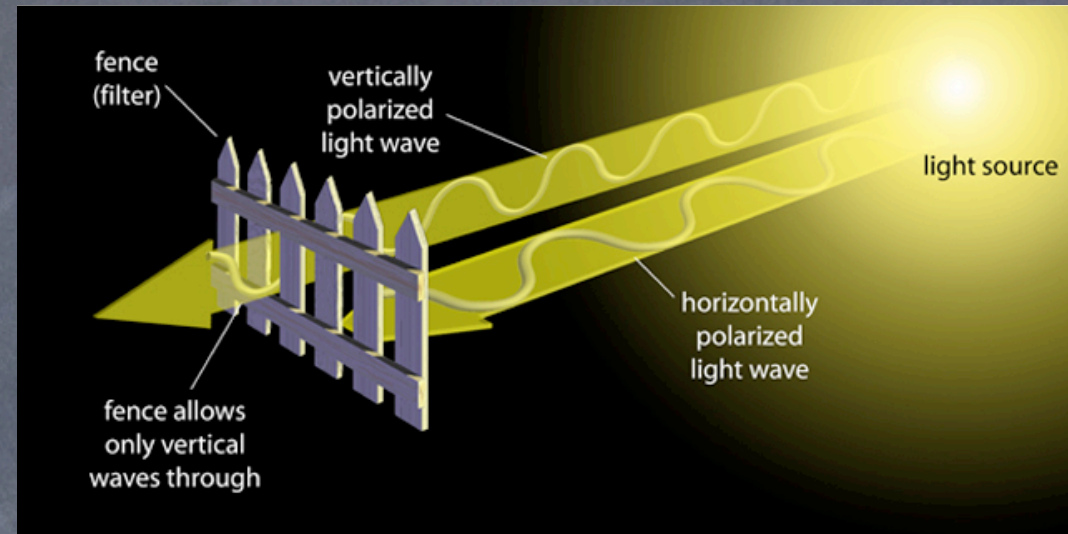


how we see it...

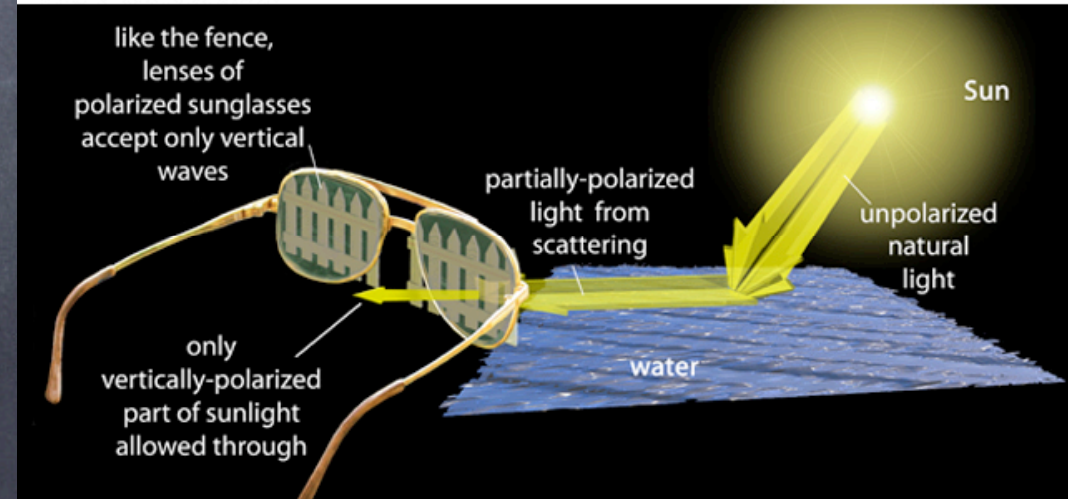


The Cosmic Background Radiation is Polarized

The polarized sunglasses analogy



how we see it...

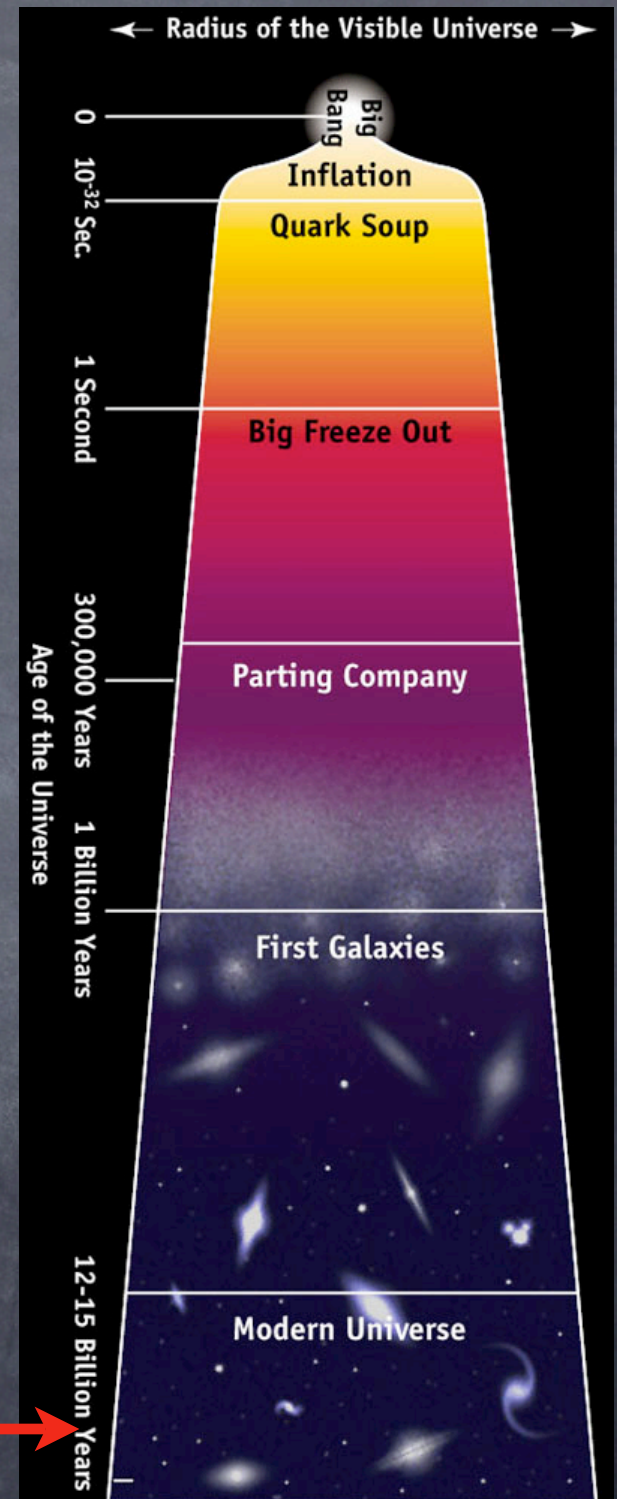


👁️ Good:

👁️ In everyday use

Modern Universe ($t=13.7$ billion yrs)

- Stars, Galaxies, Clusters of galaxies everywhere
- A lot more Dark Matter that we cannot directly see
- Even more mysterious Dark Energy takes over (a few billion years ago)



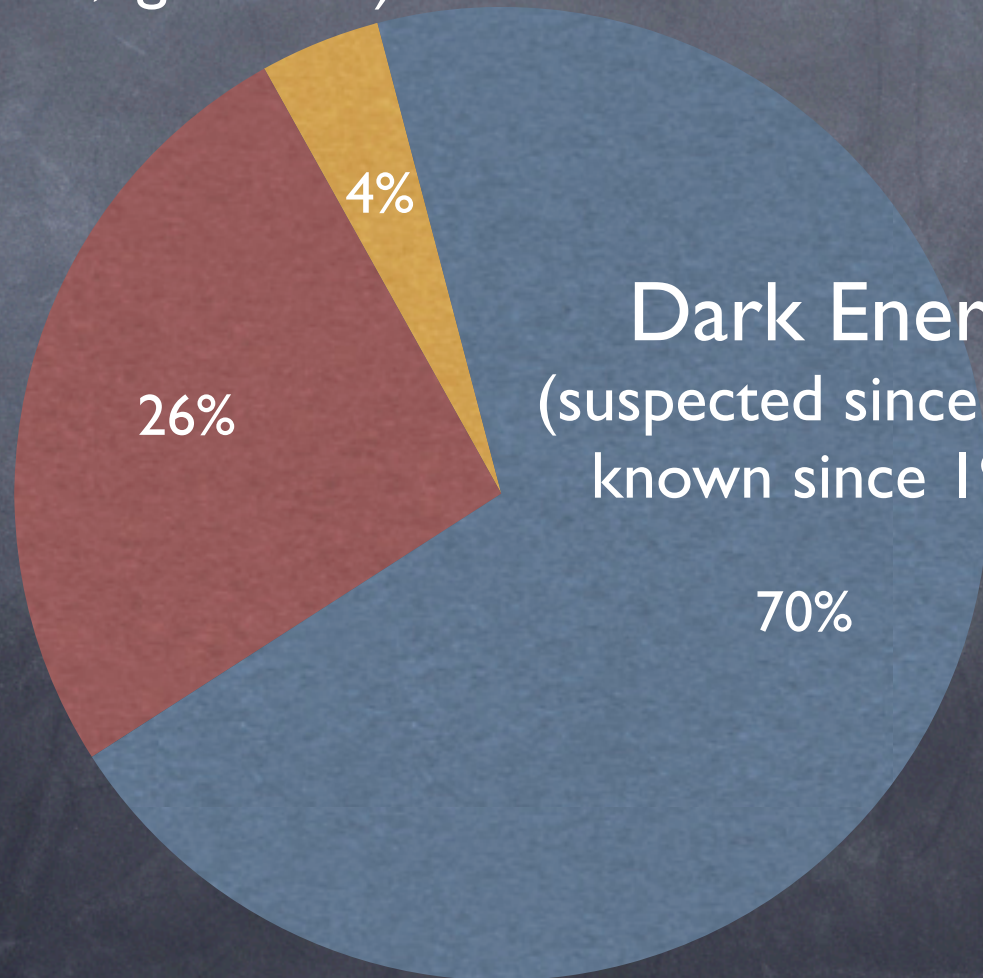
Makeup of universe today

Visible Matter
(stars 0.4%, gas 3.6%)

Dark Matter
(suspected since 1930s
known since 1970s)

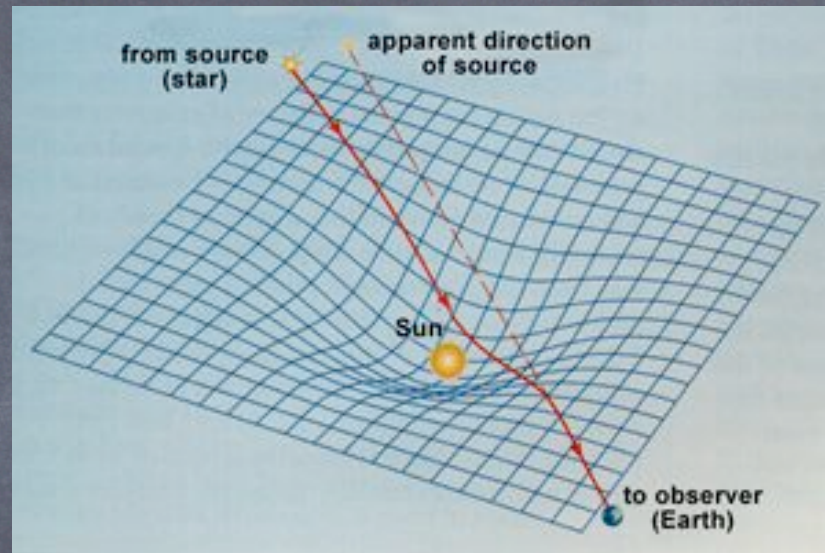
Dark Energy
(suspected since 1980s
known since 1998)

Also:
radiation (0.01%)



Dark matter can be “seen” because it curves space!

Curved space analogy: Elastic membrane

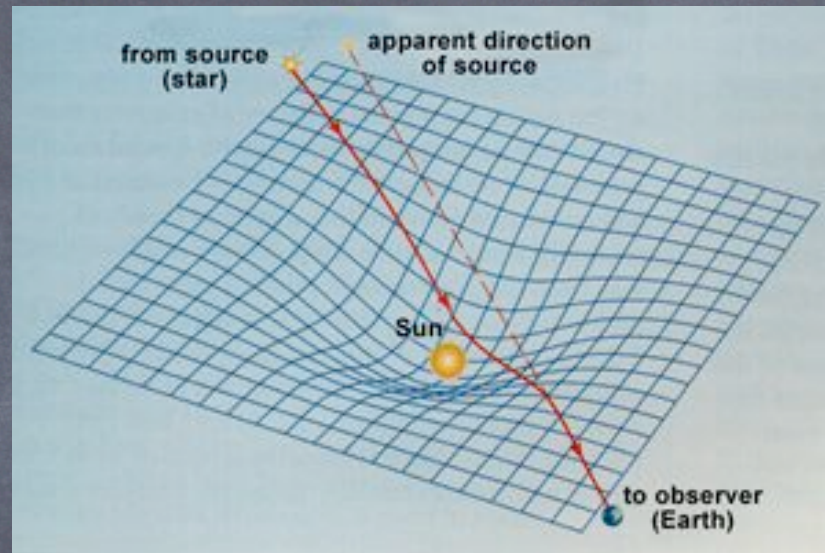


• The Good:

• Good illustration of the curving of spacetime by mass and energy

Dark matter can be “seen” because it curves space!

Curved space analogy: Elastic membrane

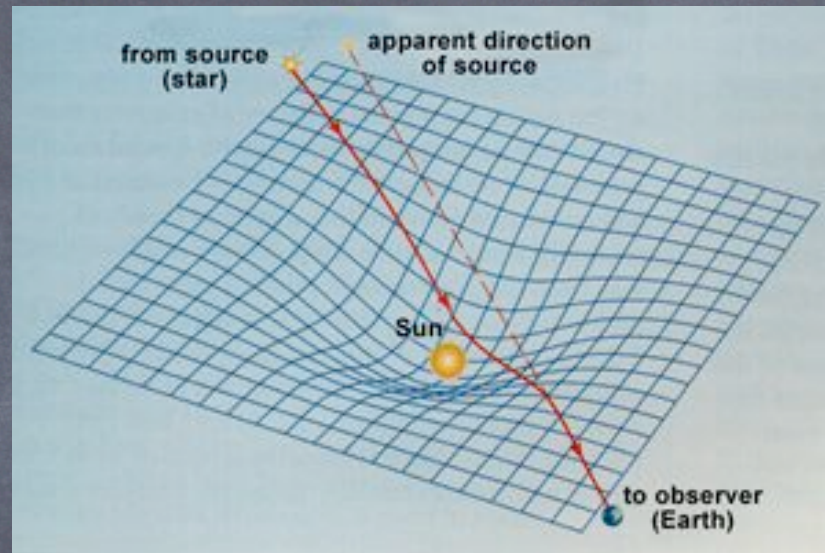


👁️ The Bad:

- 👁️ The representation of space is two-dimensional
- 👁️ The sun should reside in a space of the same dimensionality

Dark matter can be “seen” because it curves space!

Curved space analogy: Elastic membrane



👁️ The Ugly:

- 👁️ People project their every day experience by considering frictional forces and the earth “falling in to the sun”.

Key property of SNe Ia and Cepheids:
Their intrinsic luminosity is (nearly) constant
=> They are **standard candles**



flux $\rightarrow 1/\text{distance}^2$



By measuring the flux,
you can determine the **distance**,
which is one of hardest things in astronomy

A "Standard Candle": The Headlights of a Car



If you know the
intrinsic brightness
of the headlights,
you can estimate
how far away the
car is

A "Standard Candle": The Headlights of a Car



If you know the intrinsic brightness of the headlights, you can estimate how far away the car is

Good: The analogy is completely correct

A "Standard Candle": The Headlights of a Car



If you know the intrinsic brightness of the headlights, you can estimate how far away the car is

Bad: we are used to knowing the intrinsic brightness of headlights and take this whole process for granted

Summary

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- Analogies can be good, bad or ugly...

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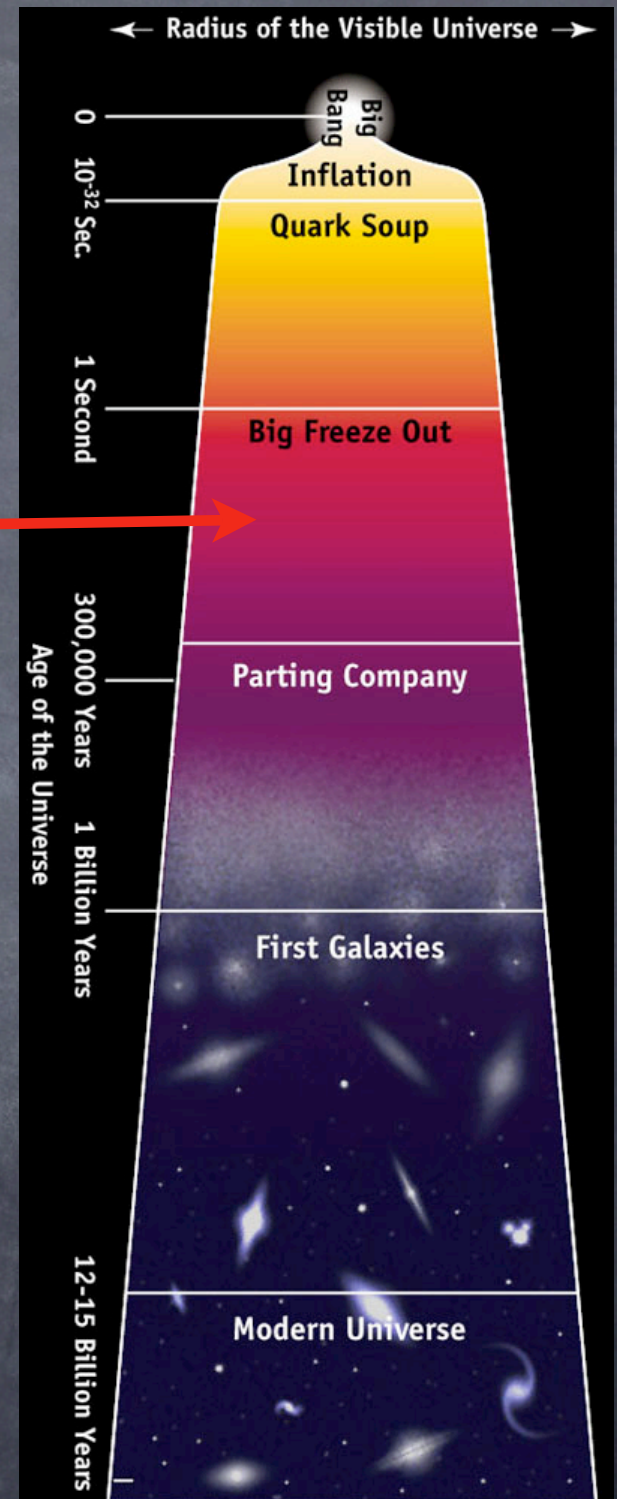
- Analogies can be good, bad or ugly...
- ...but the universe is a strange place...
- ...and you can be sure that **any** analogy will eventually **break down**...
- the key is to know **where** it breaks down!

Outtakes

Things that could serve as useful analogies, but have not (yet) been approved by The Committee

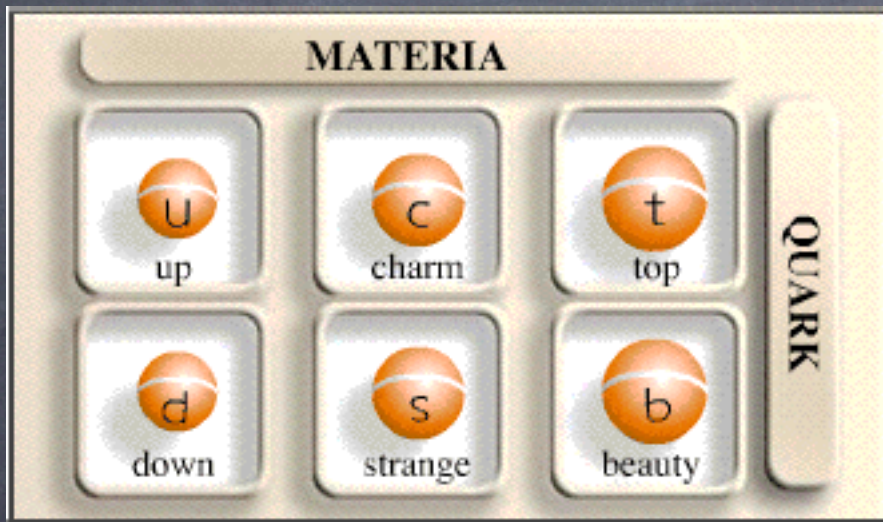
Nucleosynthesis ($t=3$ minutes)

- Atoms form!
- out of neutrons, protons, electrons...
- Hydrogen, Helium, small quantities of others
- Universe is still dominated by radiation (photons)
- Universe is still opaque - photons do not propagate far

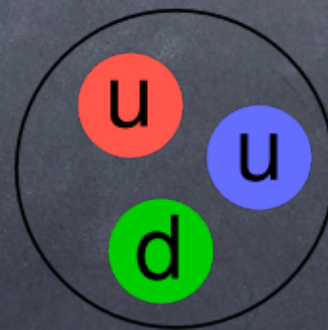


Quark Soup ($t < 1$ sec)

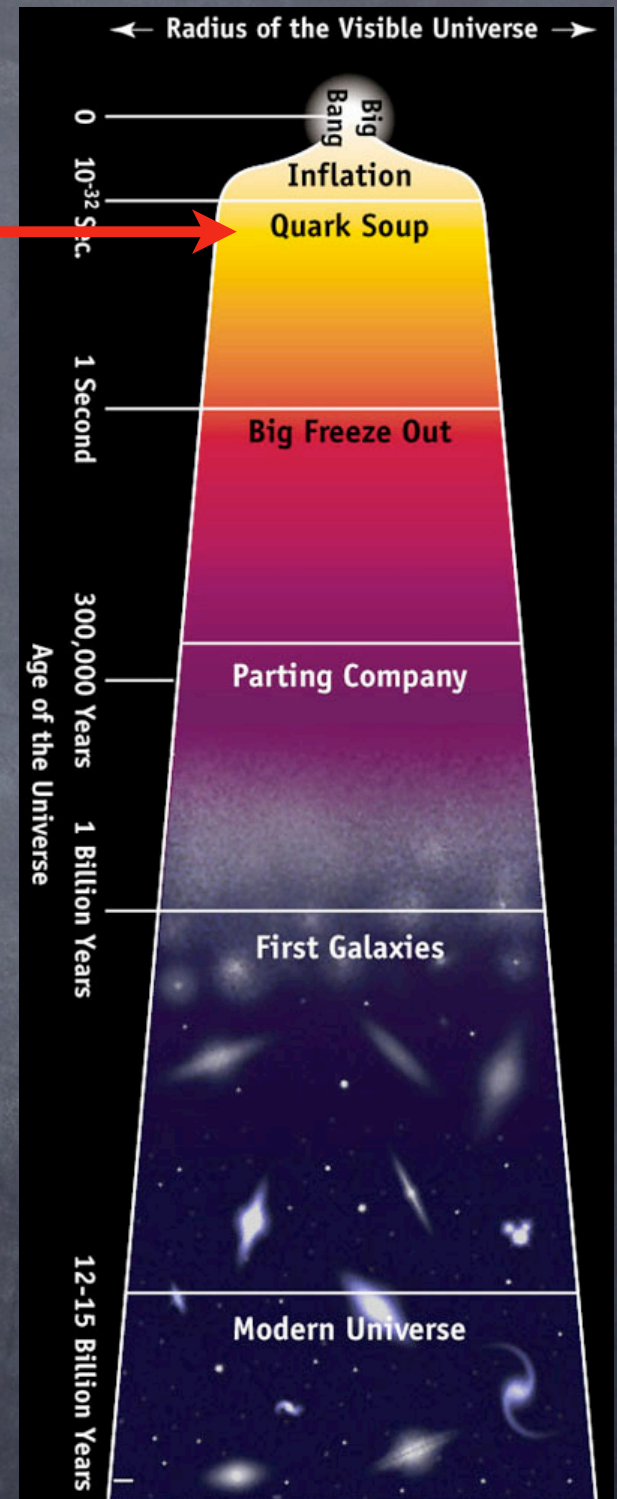
Quarks are free, floating around



Later, they are bound



PROTON

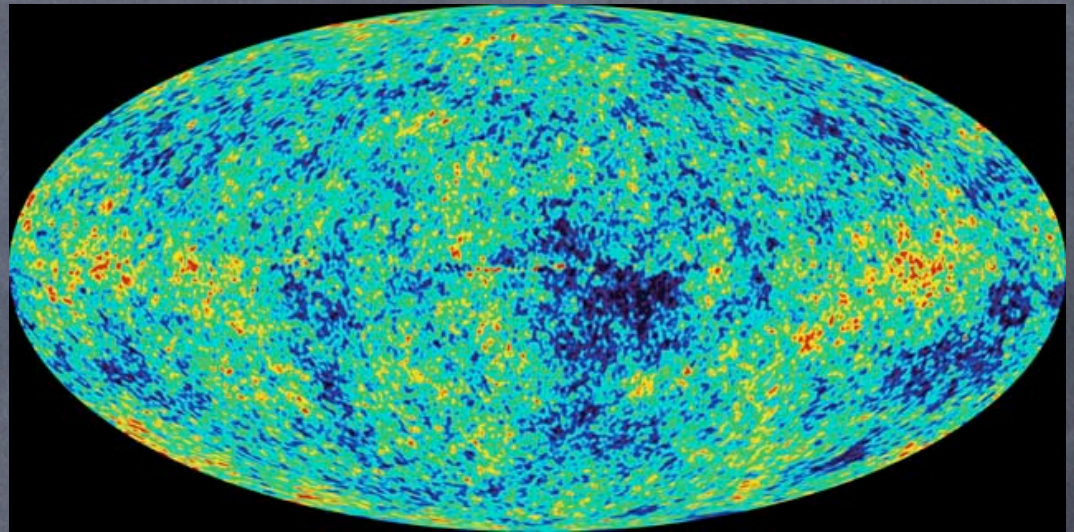
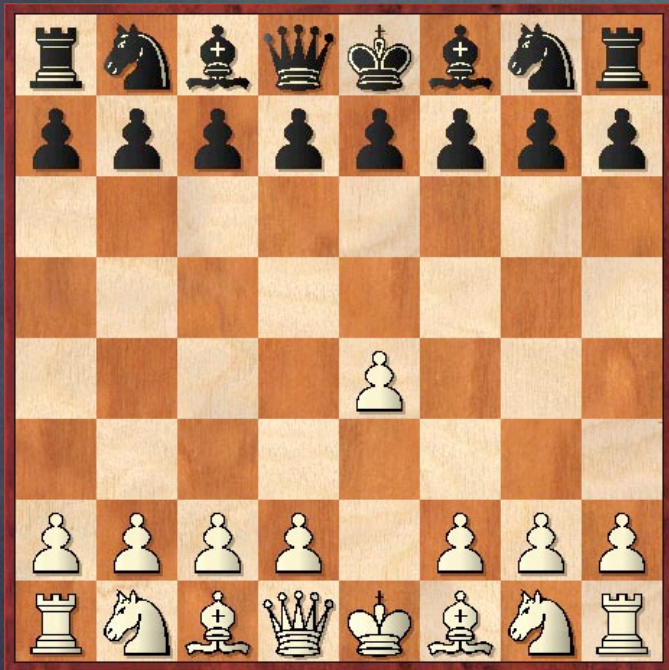


Phase transitions analogy - phases of water

(for phase transitions in early universe:
quarks + gluons \rightarrow nuclei
nuclei + electrons \rightarrow atoms...)

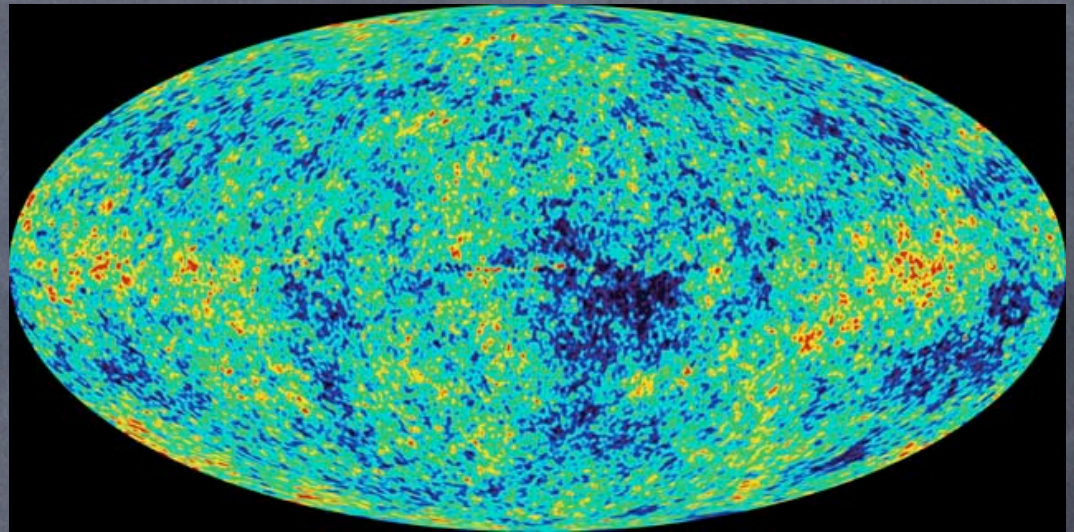
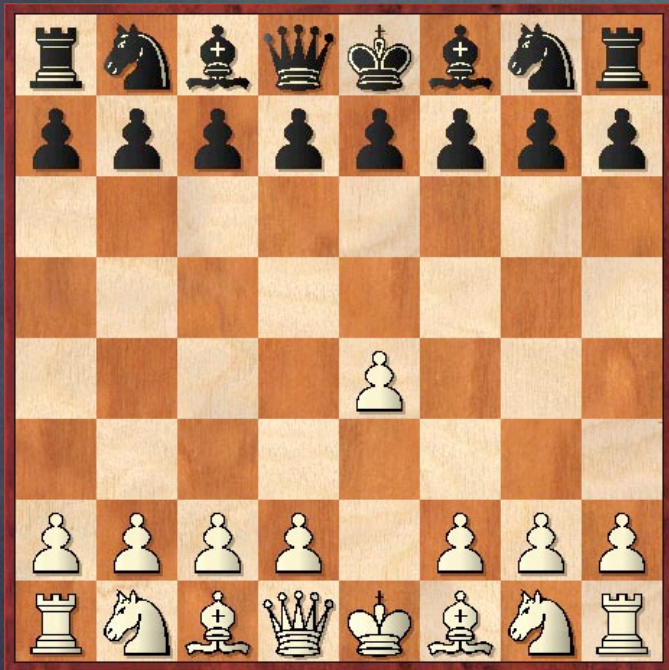
- Good: the analogy is a true one, and intuitive as well
- Ugly: does not really illustrate why such phase transitions are important and why we should care

“Typical” spot size is a standard ruler



Most spots are roughly 1 degree in size

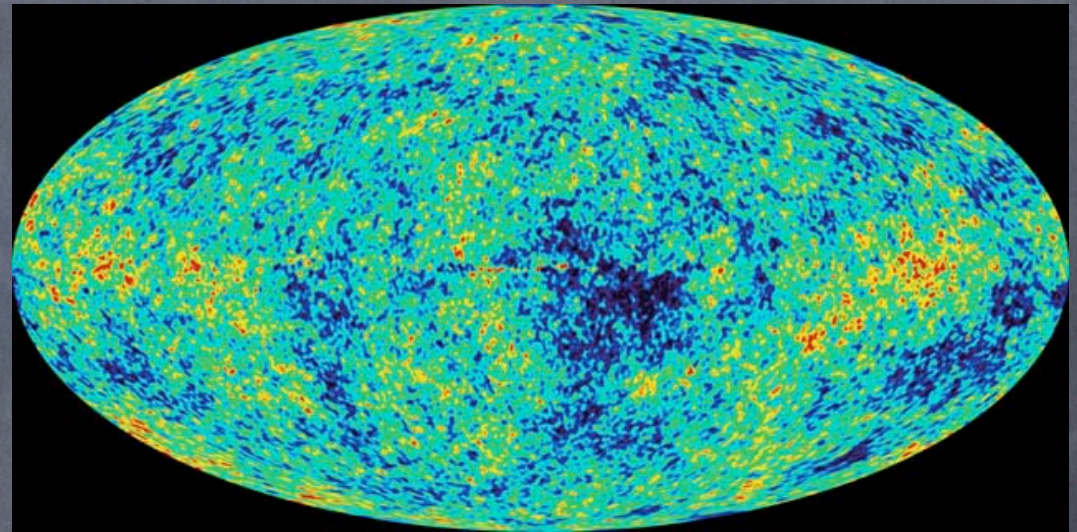
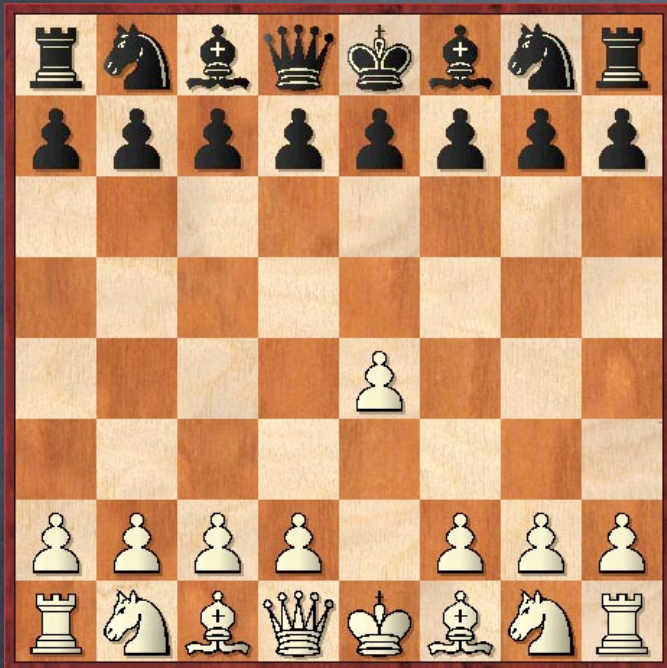
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Most spots are roughly 1 degree in size

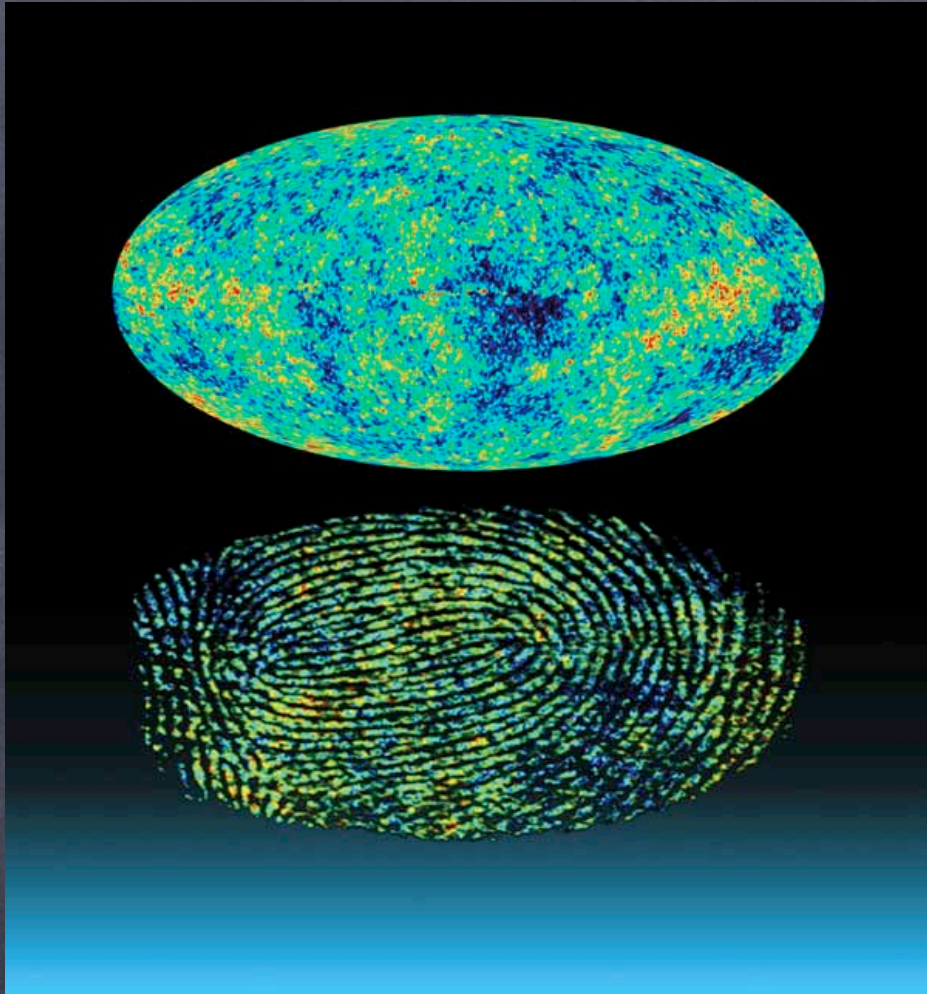
Good: The analogy is completely correct

“Typical” spot size is a standard ruler



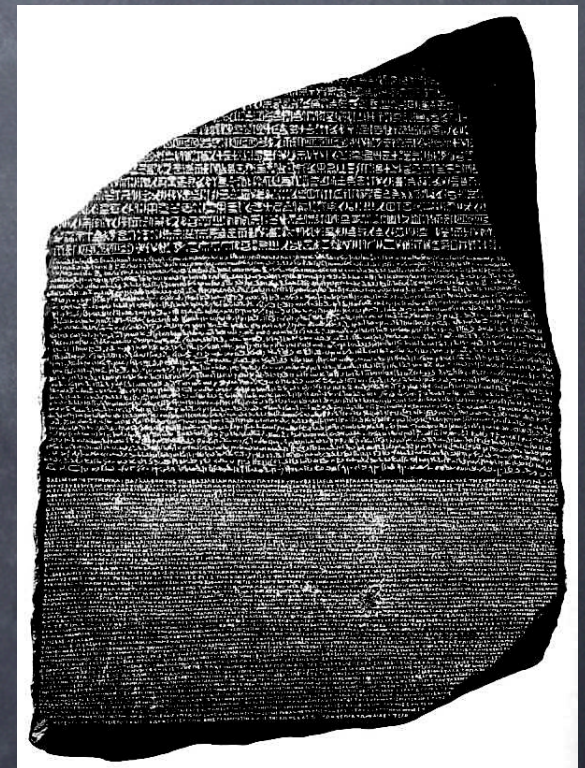
Most spots are roughly 1 degree in size

Bad: we are used to knowing the intrinsic size of chessboard squares and take this whole process for granted



CMB Map provides a
fingerprint of the
cosmological model

A "Cosmological
Rosetta Stone"



CMB Map = a fingerprint or a Rosetta Stone of cosmology

- Good:

- both analogies are completely correct that you can read off a huge amount of information about our universe from the CMB

- Bad:

- Doesn't really explain the mechanism of how that works

The dark ages ($t < 1$ billion yrs)

- Universe is dark, slowly becomes matter dominated
- First stars ionize the hydrogen atoms
- First stars and first galaxies eventually form

