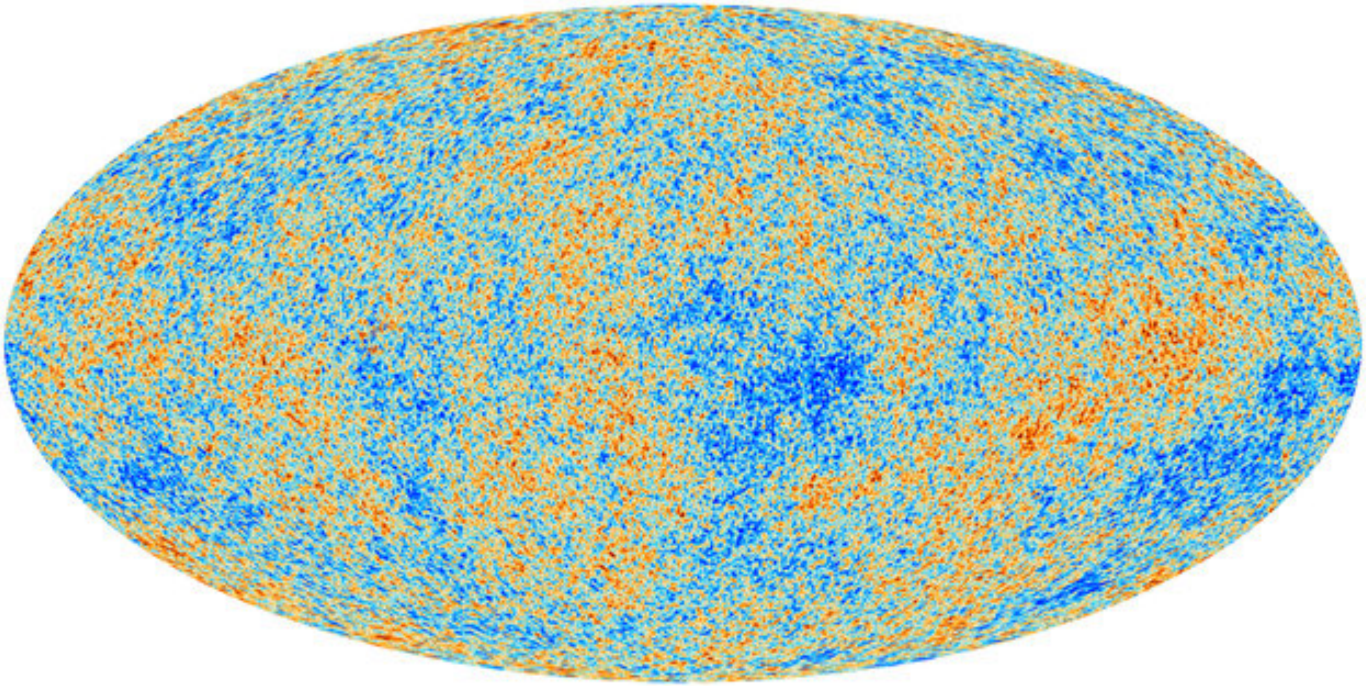
Astronomy 120



Little Bumps in the CMB & Curvature of Space

Class 23

(next to last…)

Prof J. Kenney

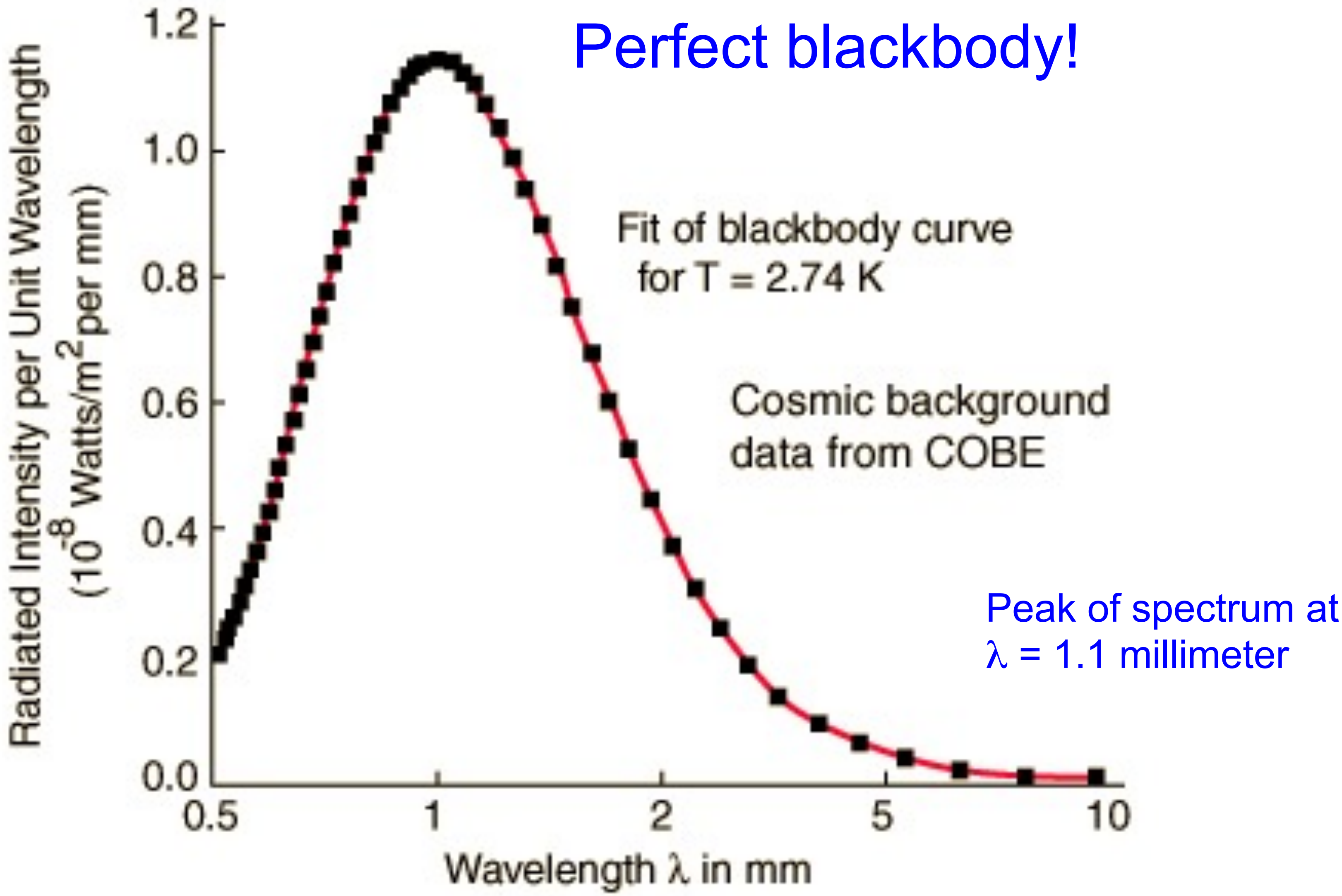
June 28, 2018

Homeworks

- all HWs must be handed in by tomorrow Thursday June 28!

- so I can post solutions to help you prepare for Final Exam on Friday

Spectrum of cosmic microwave background



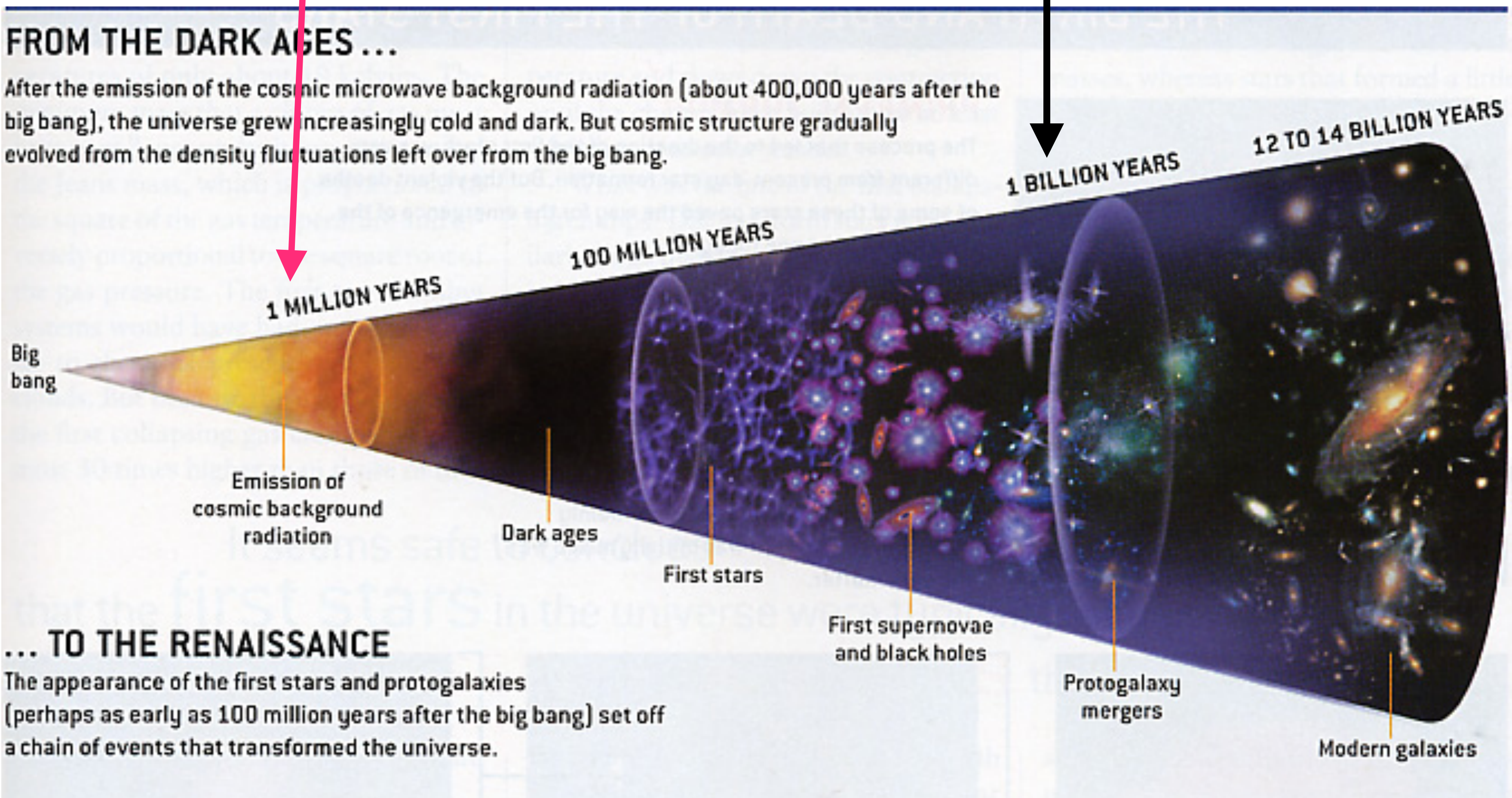
Isotropy of the Cosmic Microwave Background

Intensity of CMB radiation over whole sky:

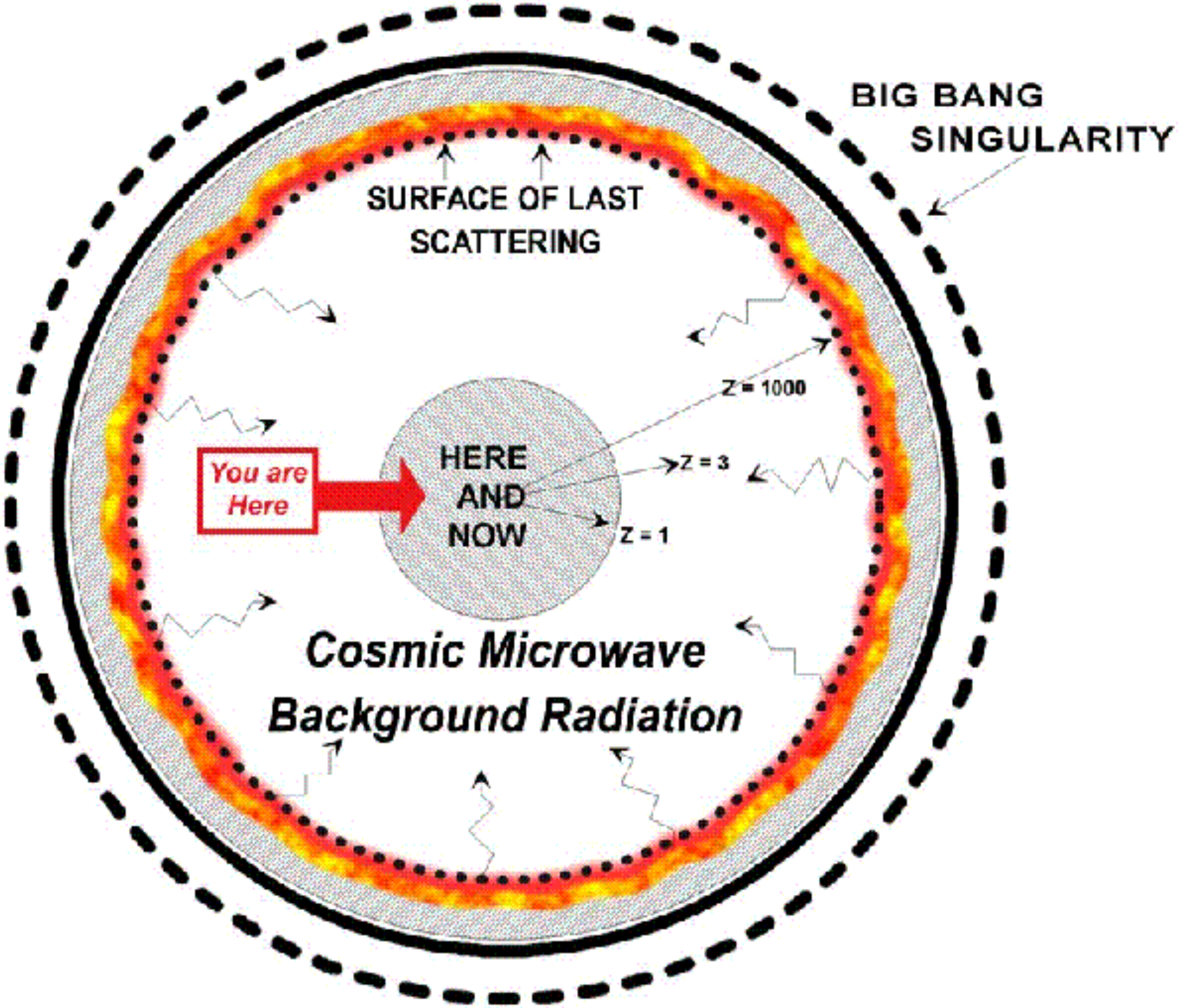
Nearly the same in every direction!

Emission of cosmic background radiation
(380,000 yrs ABB)

Era of Peak star, galaxy & black hole formation
(~ 1-4 Byrs ABB)

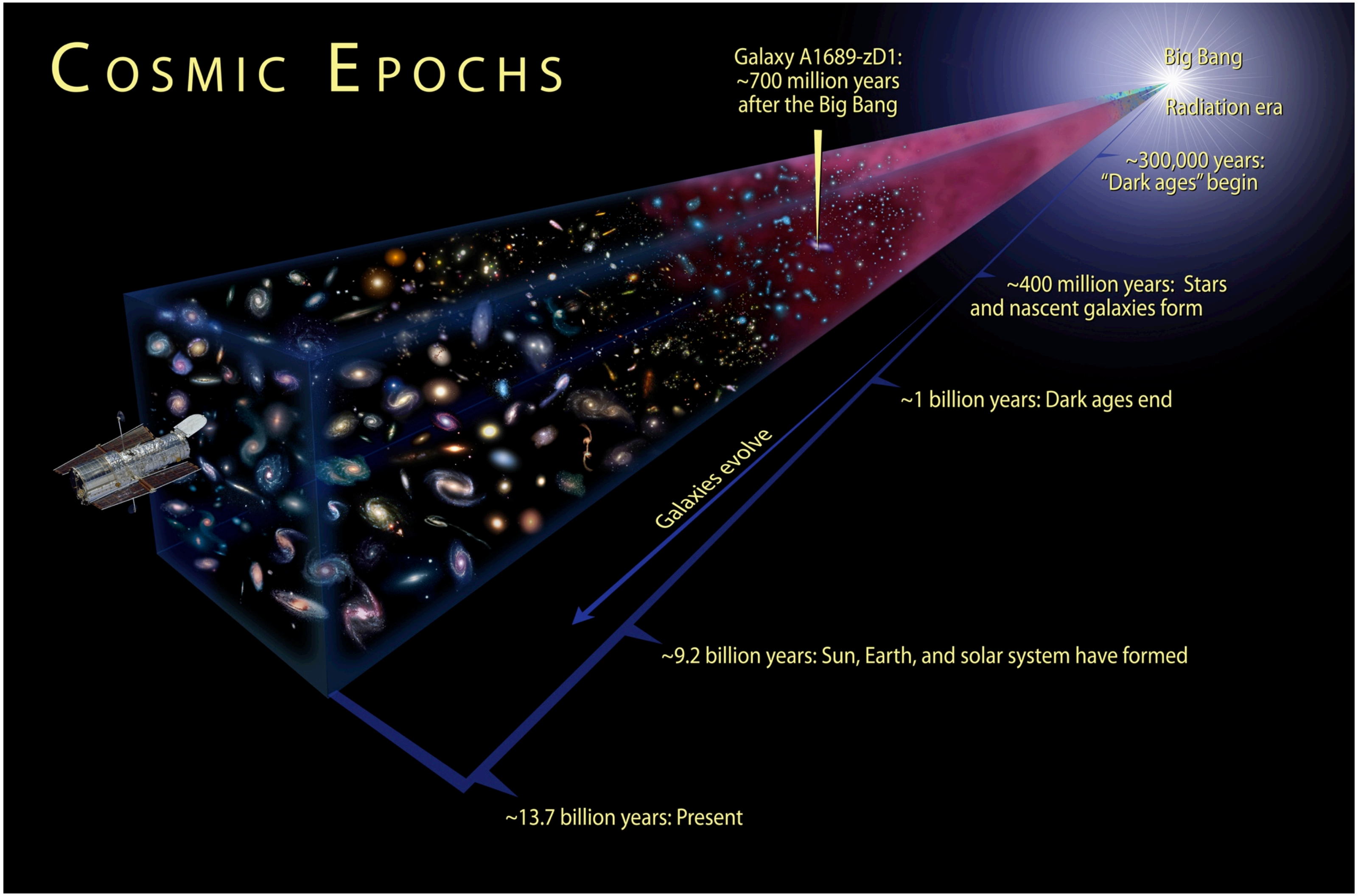


BIG BANG Cosmic Time NOW


BIG BANG
SINGULARITY
SURFACE OF LAST
SCATTERING
Z = 1000
Z = 3
Z = 1
You are
Here
HERE
AND
NOW
Cosmic Microwave
Background Radiation

Things we learn from CMB

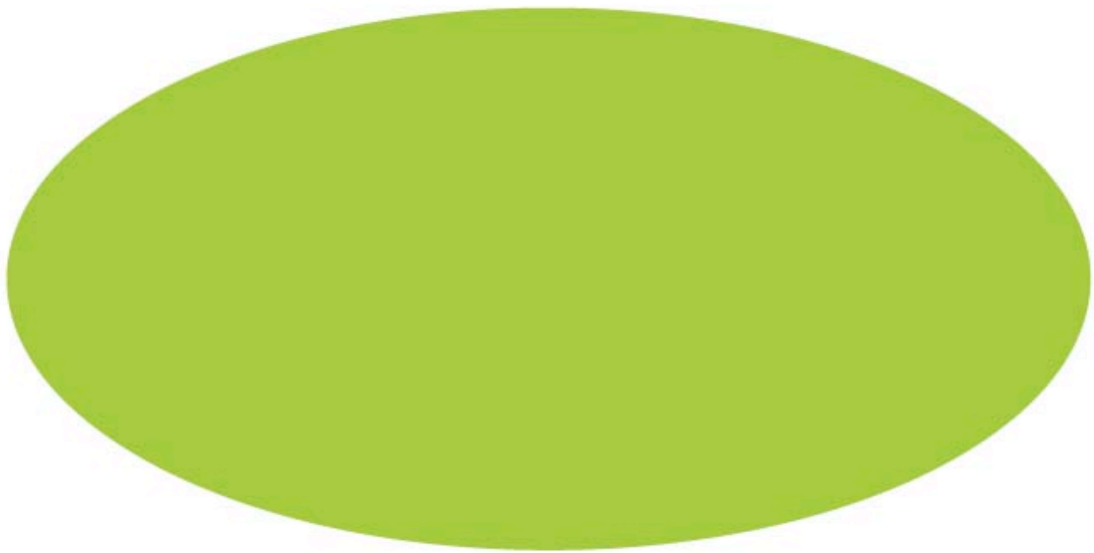
Universe was once much hotter and denser than now (evidence for BIG BANG)



Things we learn from CMB

We are not in special location in universe

ISOTROPY OF THE COSMIC MICROWAVE BACKGROUND

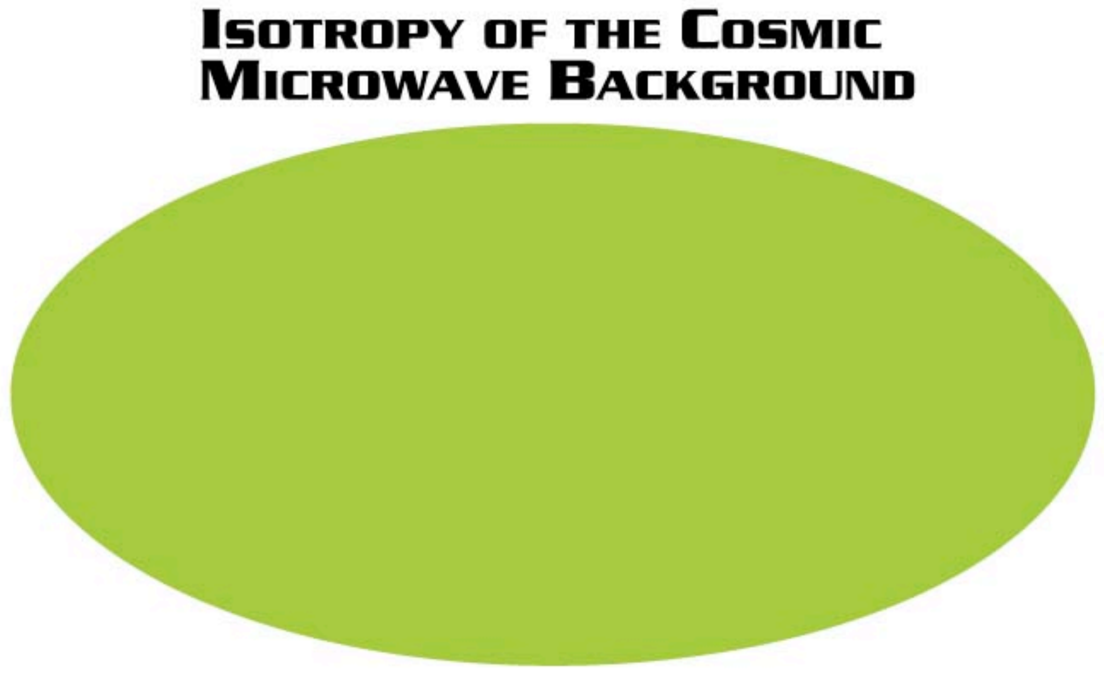


Where is the center???

NO CENTER of expansion at any one location in space --> Big Bang occurred in all of space at the same time with same intensity (what Einstein says in GR)

Things we learn from CMB

Universe was once much more uniform than now

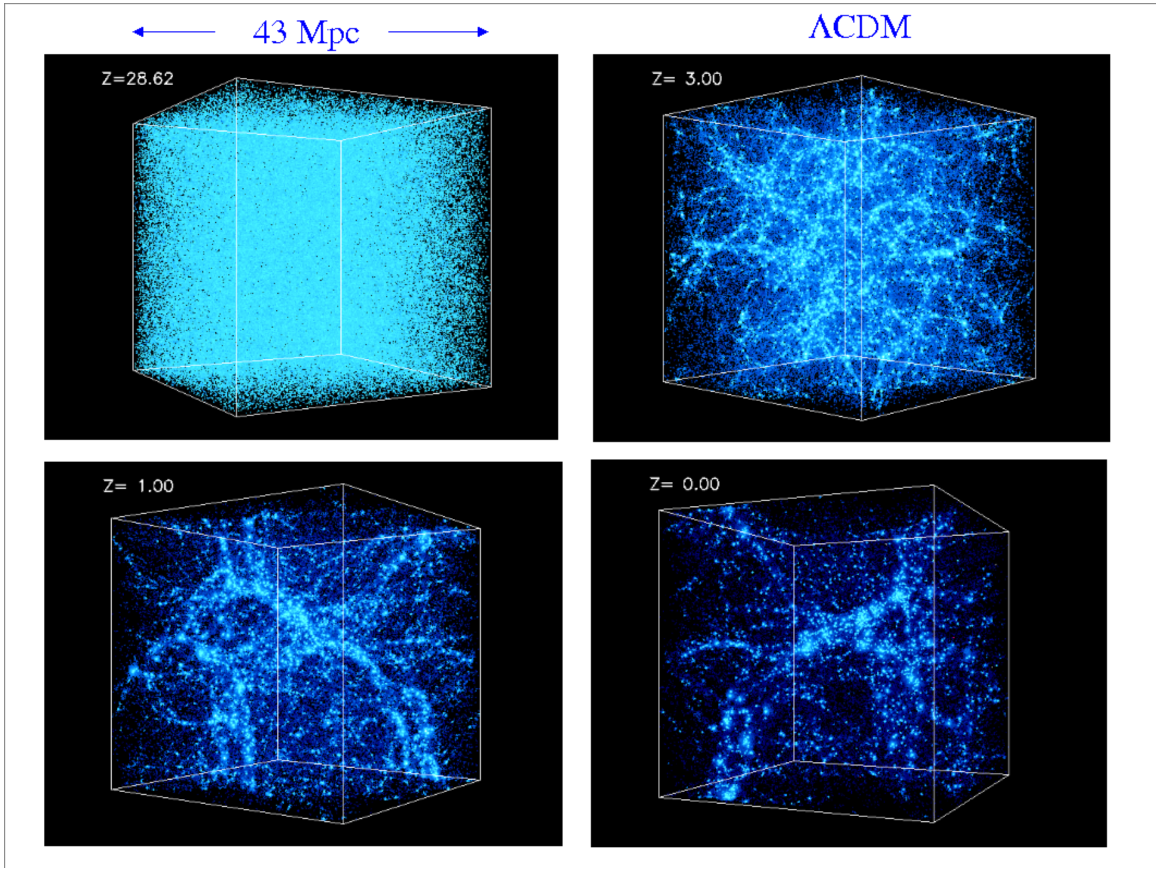


(almost) no substructure in universe at early times

Things we learn from CMB

Universe was once much more uniform than now.

So when did stars, planets, galaxies, clusters, black holes ("structure") begin to form?



Growth of structure (stars, galaxies, clusters…) in universe began in earnest only after decoupling (when CMB photons were made)

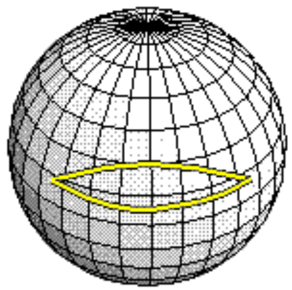
Things we learn from CMB

Evidence for dark energy & inflation

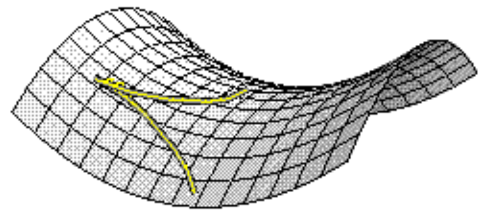
Things we learn from CMB

How space of universe is curved

Positive (spherical)

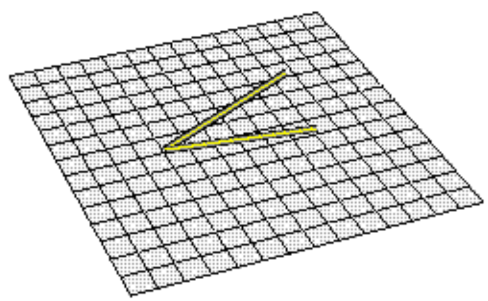


A *closed* universe curves "back on itself". Lines that were diverging apart come back together. Density > critical density.



An *open* universe curves "away from itself". Diverging lines curve at increasing angles away from each other. Density < critical density.

Negative (saddle)



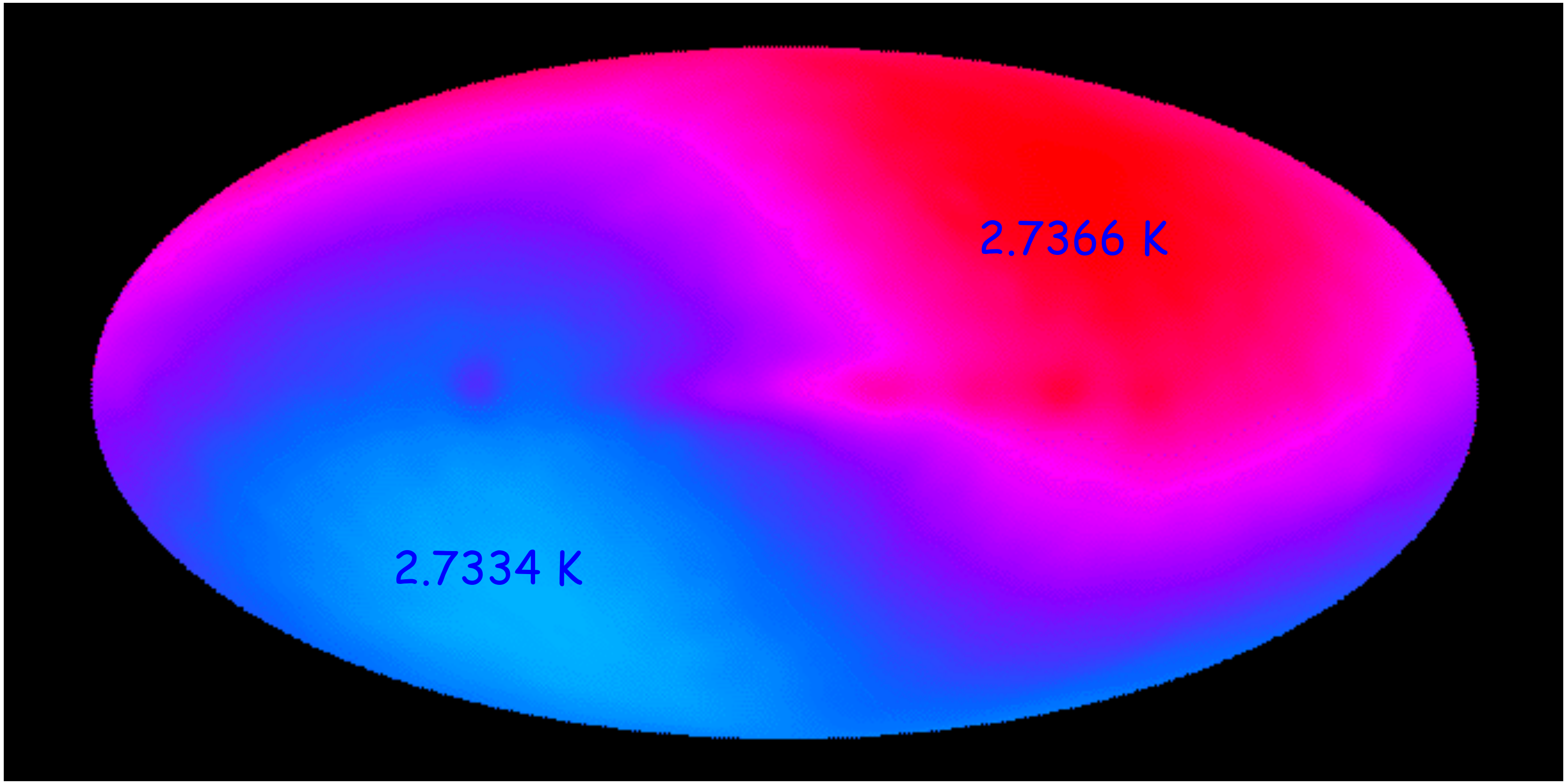
A *flat* universe has no curvature. Diverging lines remain at a constant angle with respect to each other. Density = critical density.

Zero curvature (flat)

Types of possible curvatures for universe in General Relativity

Things we learn from CMB

- Universe was once much hotter and denser than now (evidence for BIG BANG)
- Universe was once much more uniform than now
- When structure (stars, galaxies, clusters…) in universe began to form
- Evidence for dark energy
- Evidence for inflation
- We are not in special location in universe (BIG BANG occurred in all of space at same time)
- How space of universe is curved

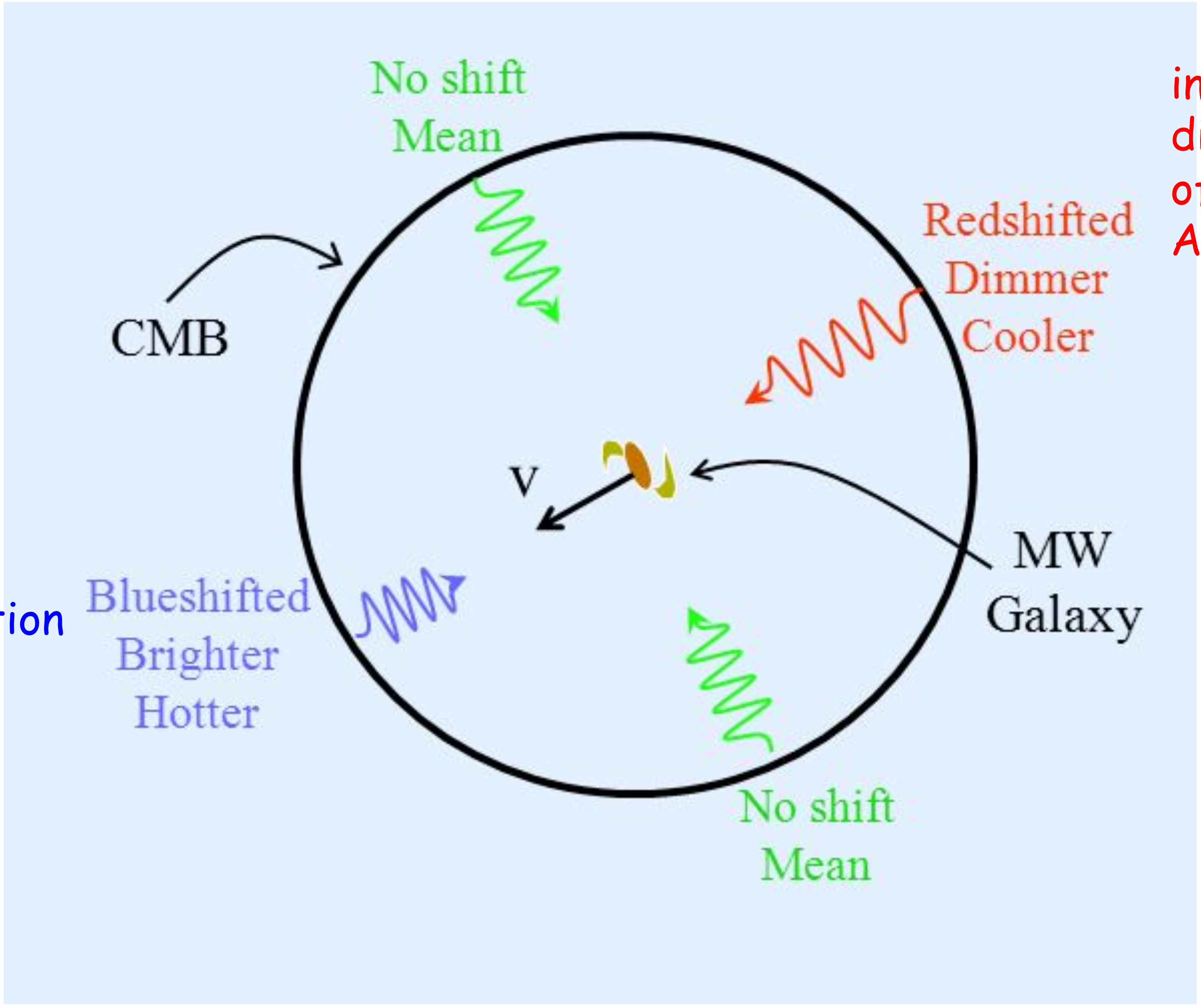


99.9% of average signal removed
…a "Dipole" pattern remains!!

99.9% of average signal removed
…a "Dipole" pattern remains!!

(all of sky shown)

Doppler shift origin of the dipole pattern in the CMB



in direction of Aquarius

in direction of Leo

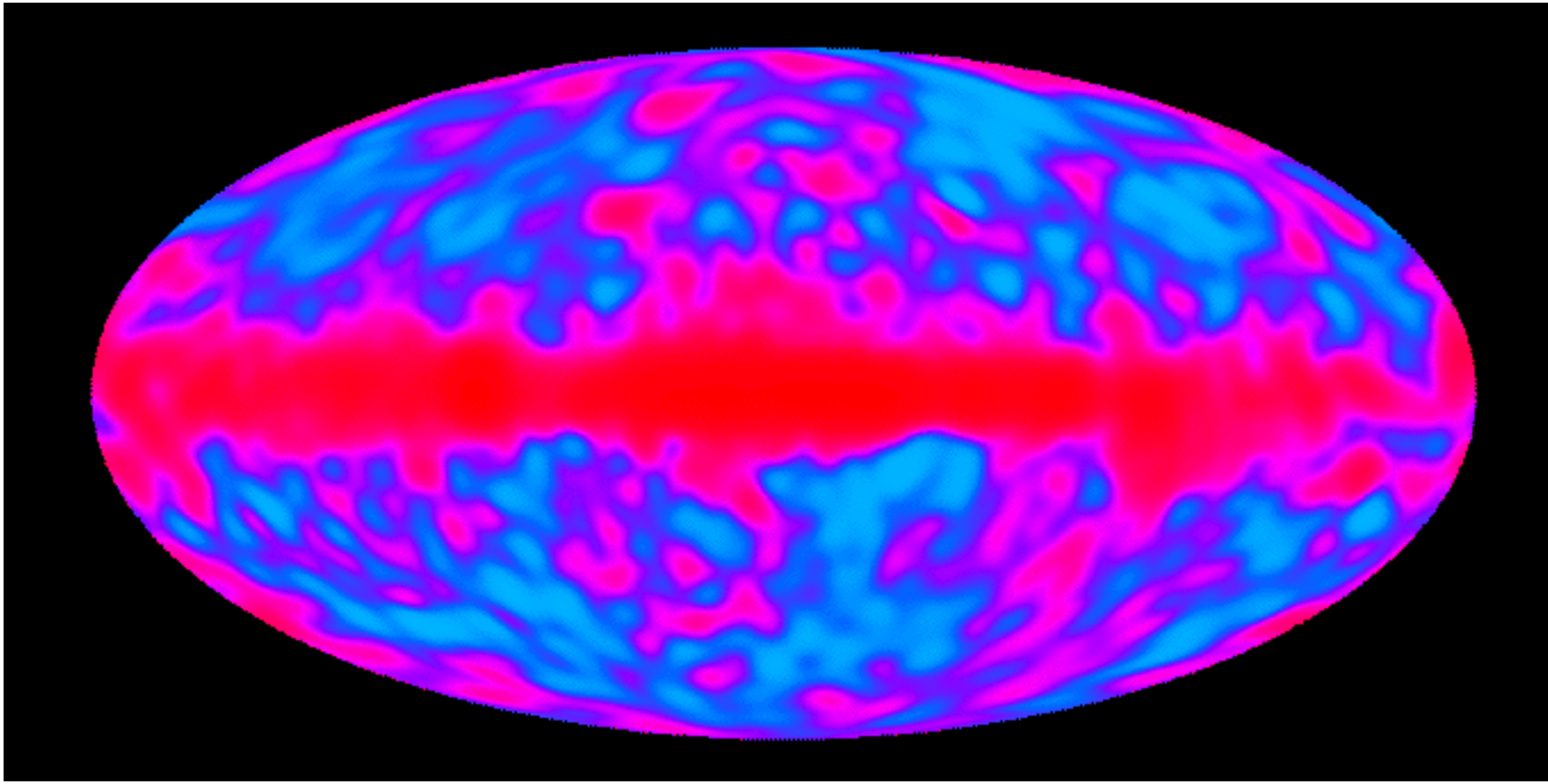
Dipole Anisotropy in CMB arises from earth's motion caused by gravitational pull of different objects

• Earth around sun	30 km/s
• Sun around center of MW	220 km/s
• MW toward Virgo cluster	350 km/s
• MW+VC toward Great Attractor	620 km/s

Pulls are in different directions so
net motion is 370 km/s toward Leo
(in between Virgo & Great Attractor)

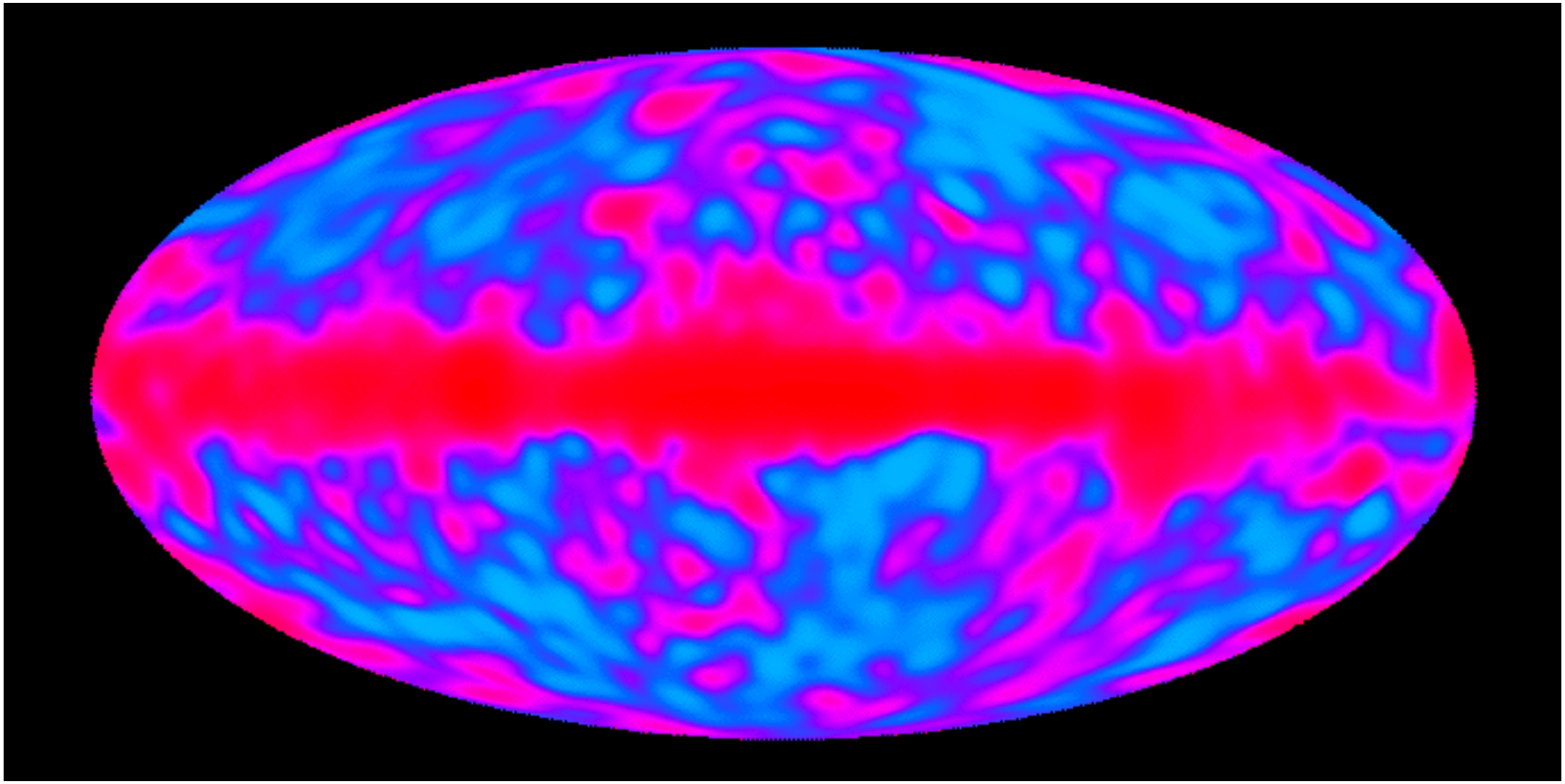
Dipole Anisotropy in CMB

- Perfect "dipole" pattern (sinusodial variation) across sky tells us this is due to our motion w.r.t. CMB
- Caused by our galaxy being pulled by gravity of nearby clusters & superclusters
- Provide us with a way to measure our motion with respect to the absolute frame of reference of expanding space itself



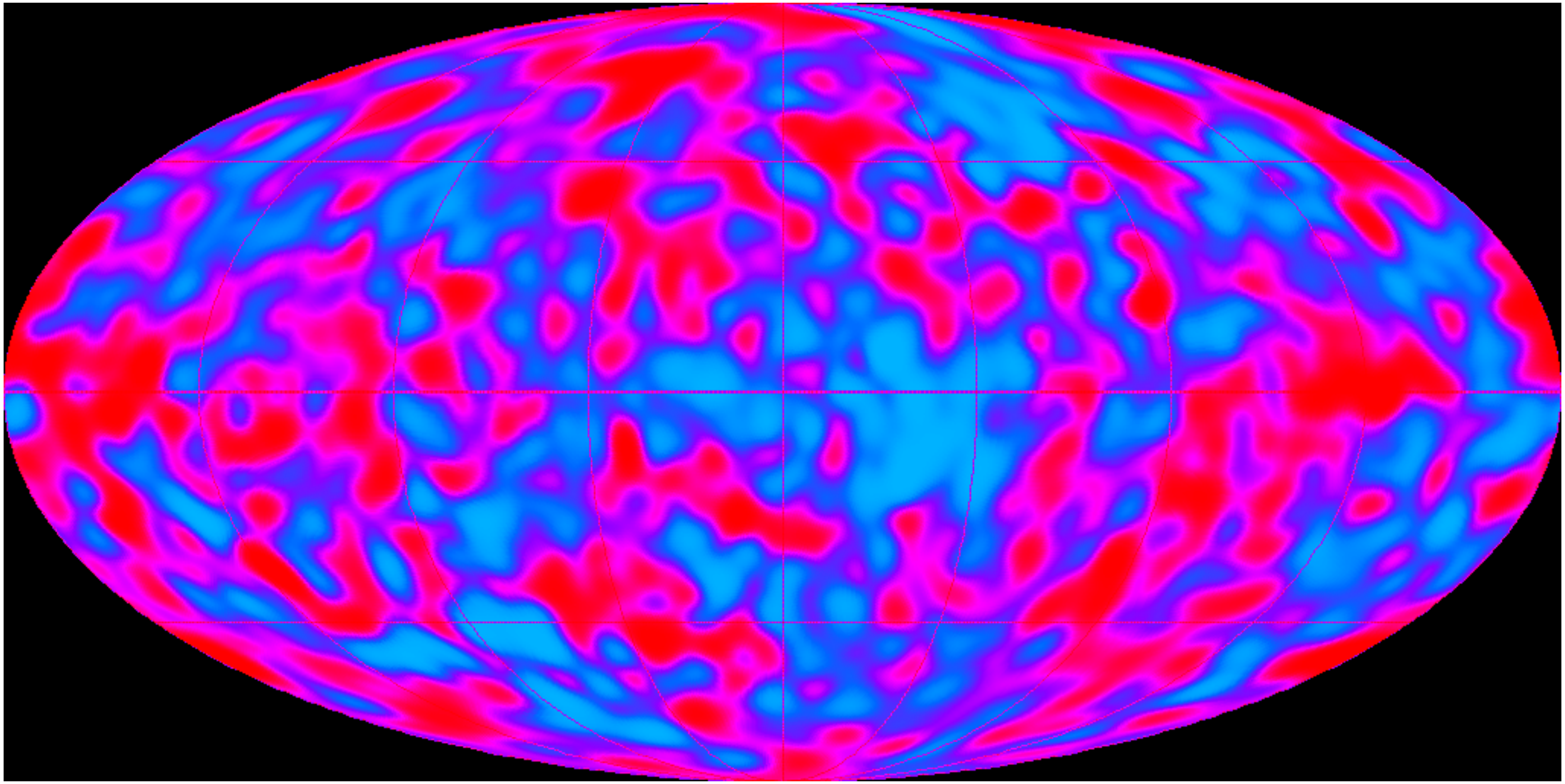
99.999% of average signal and
Dipole signal removed

Our Milky Way Galaxy



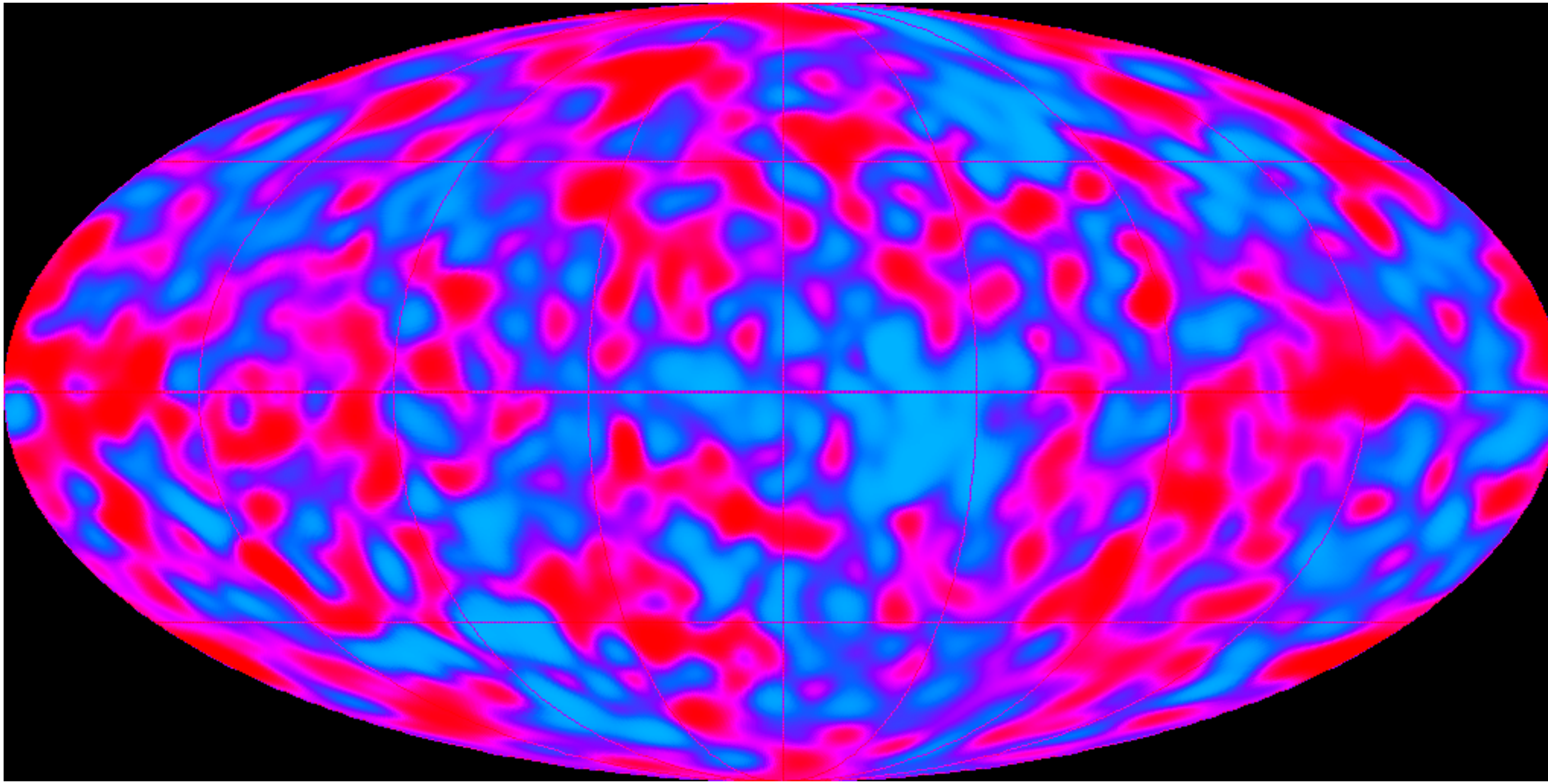
99.999% of average signal and
Dipole signal removed

COBE 1992



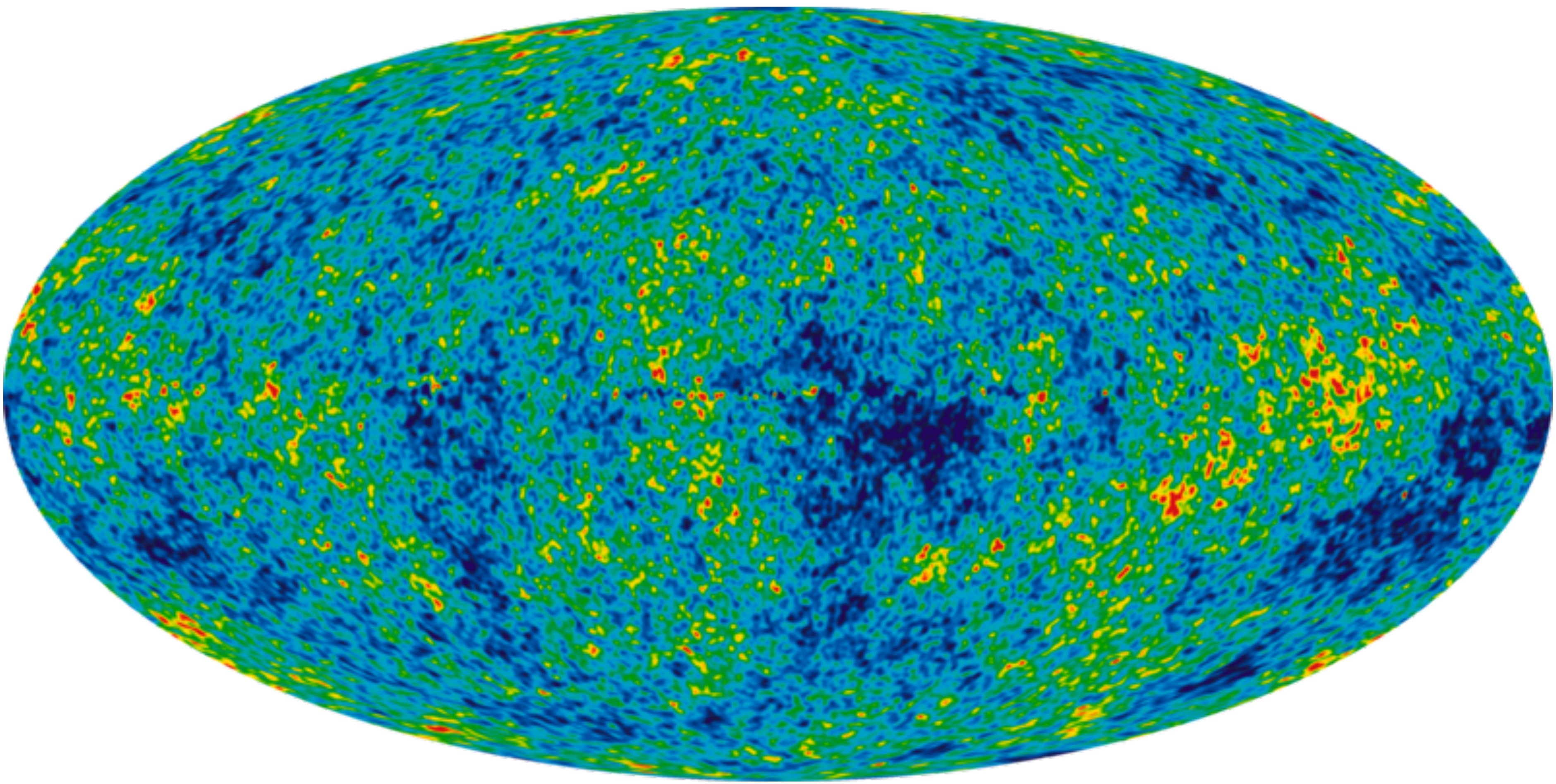
99.999% of average signal & Dipole pattern & Milky Way signal removed

CMB Map from COBE Satellite 1992

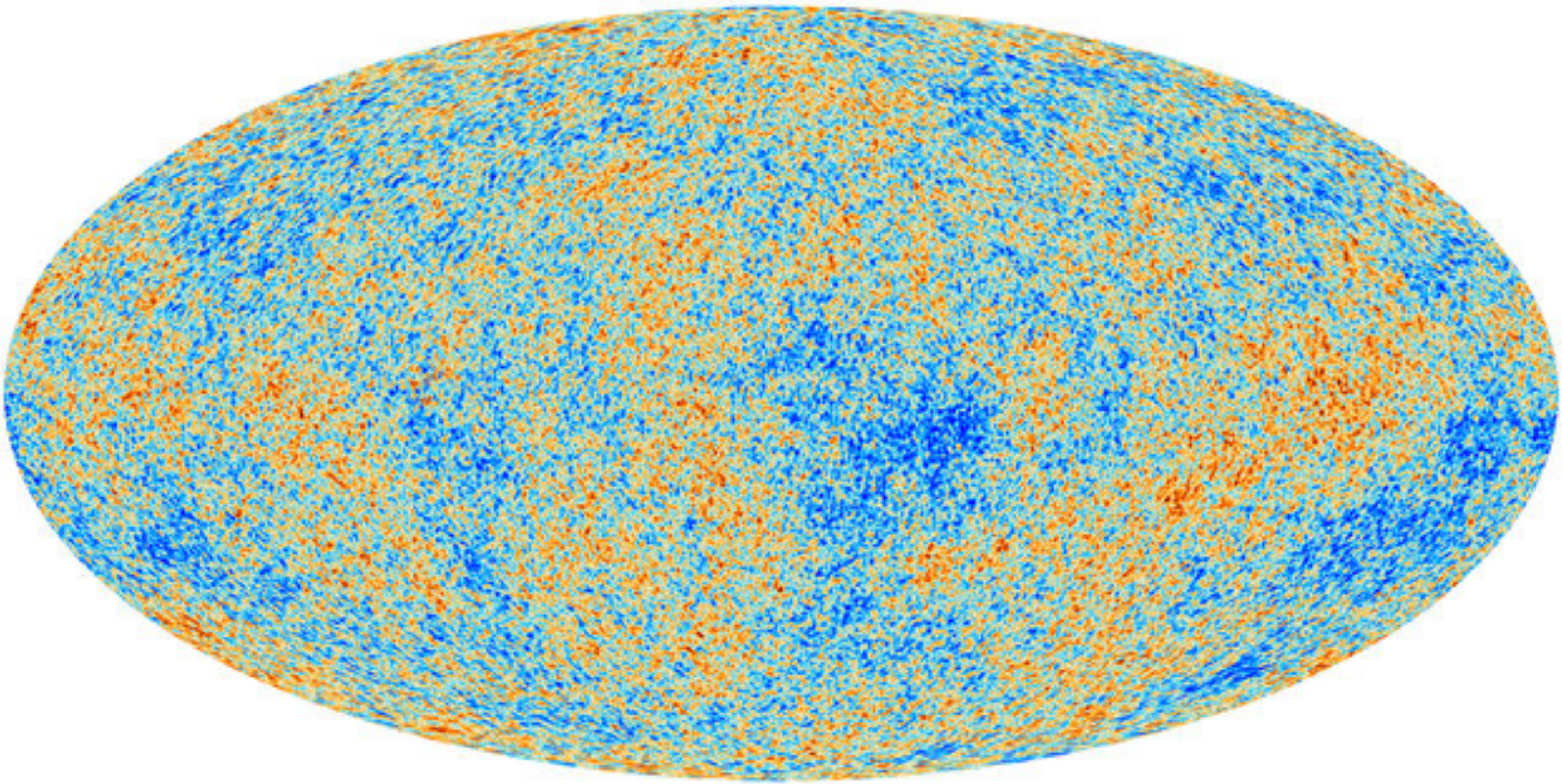


Nobel Prize in Physics in 2006 "the COBE-project can be regarded as the starting point for cosmology as a precision science".

CMB map from WMAP satellite 2001

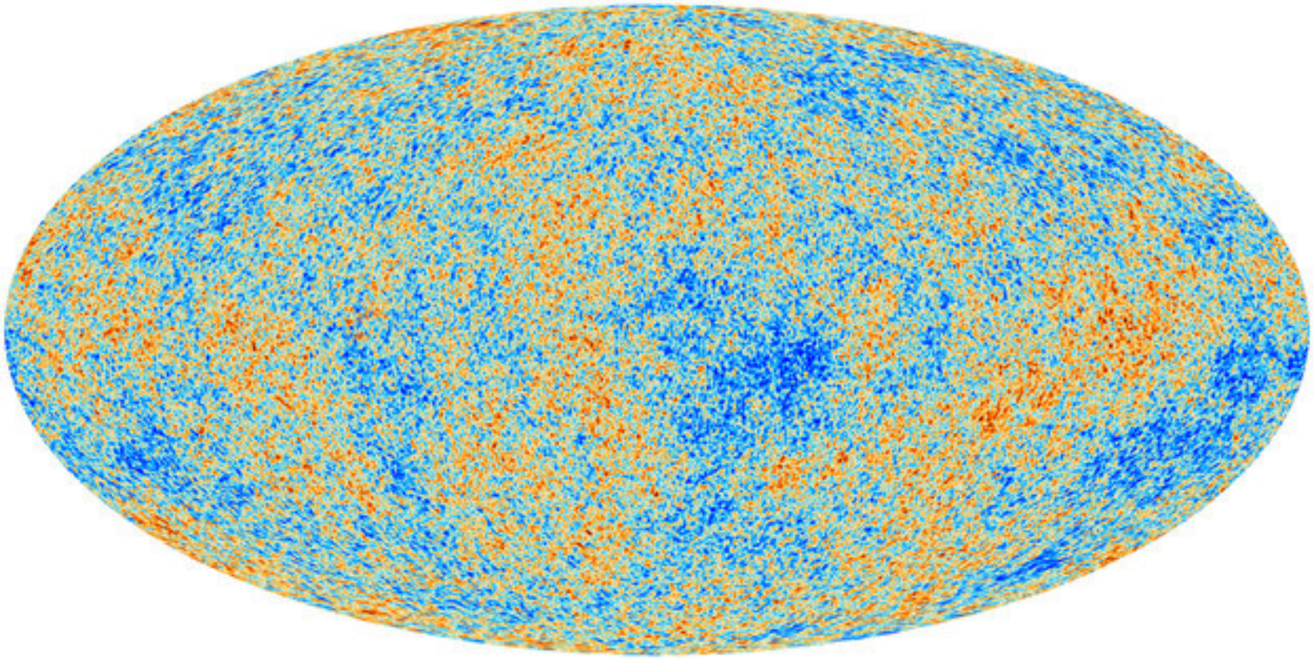


CMB map from PLANCK satellite March 2013



What is CMB? It is "snapshot" of early universe!

when it cooled enough after the Big Bang to allow protons and electrons to combine to make (long-lived) atoms for the first time, making the universe transparent to cosmic photons



at t_{ABB}=380,000 yrs

like "baby picture" …

380,000 yr/13.8 Byr is like 1 day/80 years

Although CMB is pretty isotropic (uniform to 99.9%), there are 2 small but important anisotropies

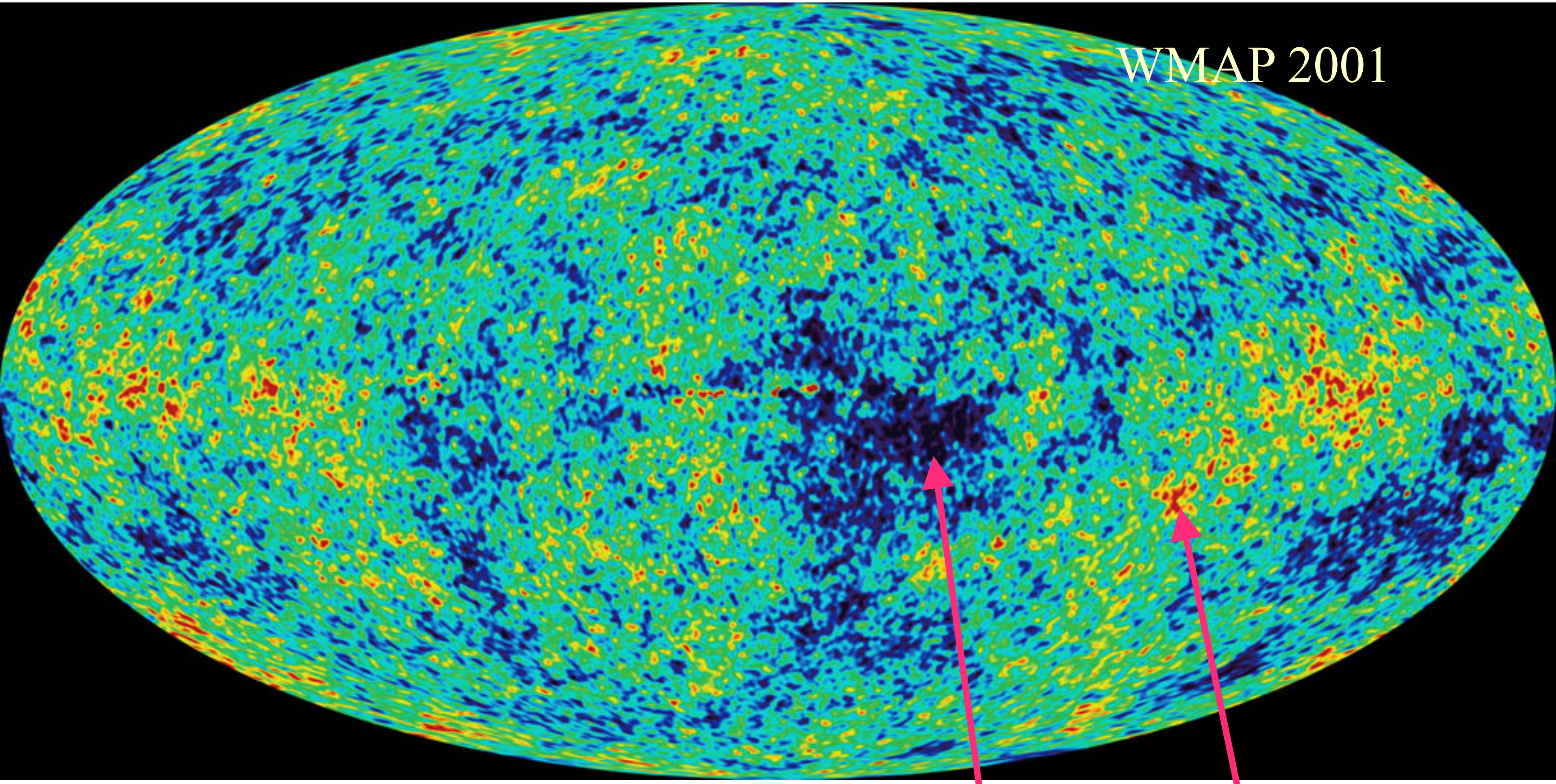
b. small scale fluctuations (smaller, more irregular variations)

small shifts in peaks of CMB spectra from one spot to another, corresponding to temperature differences of $\Delta T/T_{av} = 6x10^{-6}$

these are true temperature differences, not Doppler shifts

The dipole anisotropy tells us about our motion wrt the universe, but not much about the universe itself!

These fluctuations tell us about the early universe. They are a way to directly study the “primordial fireball” which was the universe 380,000 years ABB.



Cold spot T_2

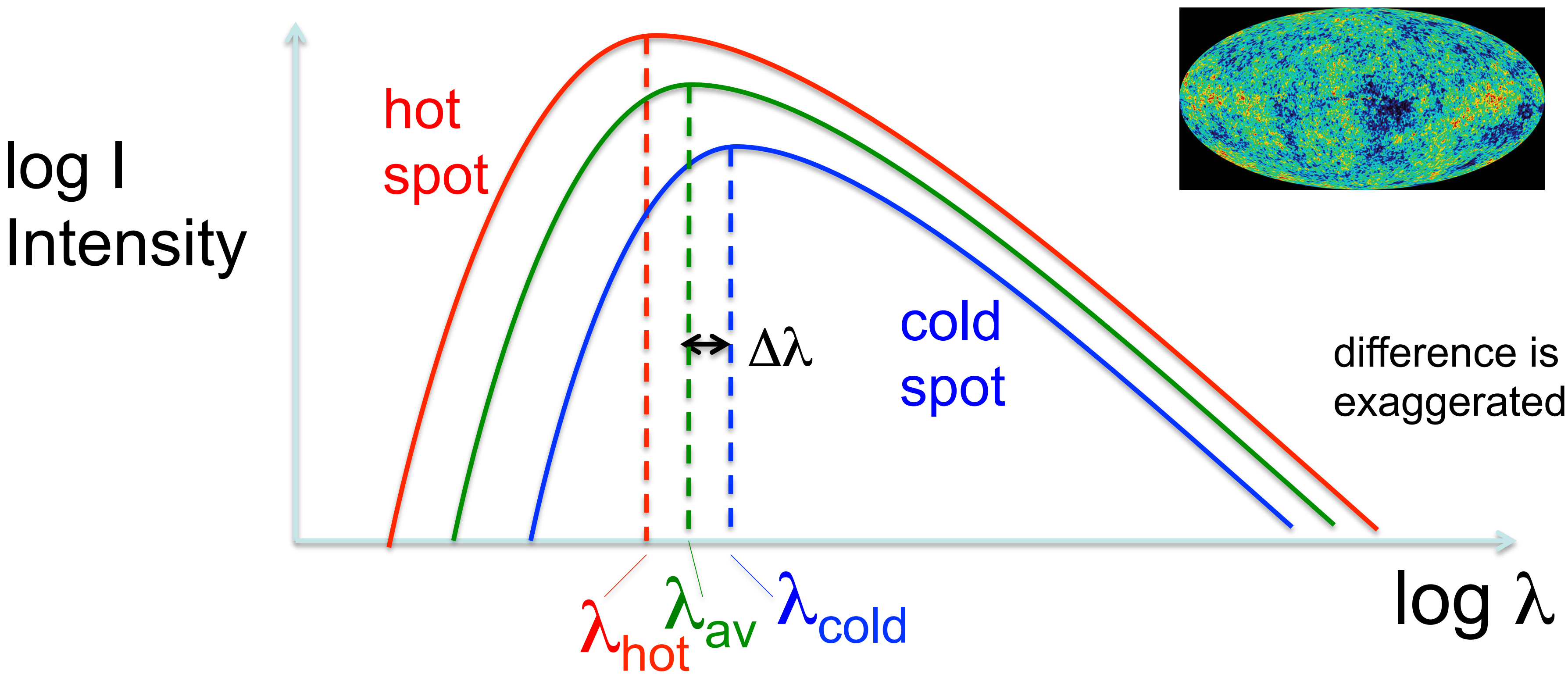
Hot spot T_1

$$\Delta T = (T_1 - T_2)/2$$

$$T_{av} = 2.725K$$

$$\Delta T/T_{av} = 6x10^{-6}$$

CMB has hot spots and cold spots

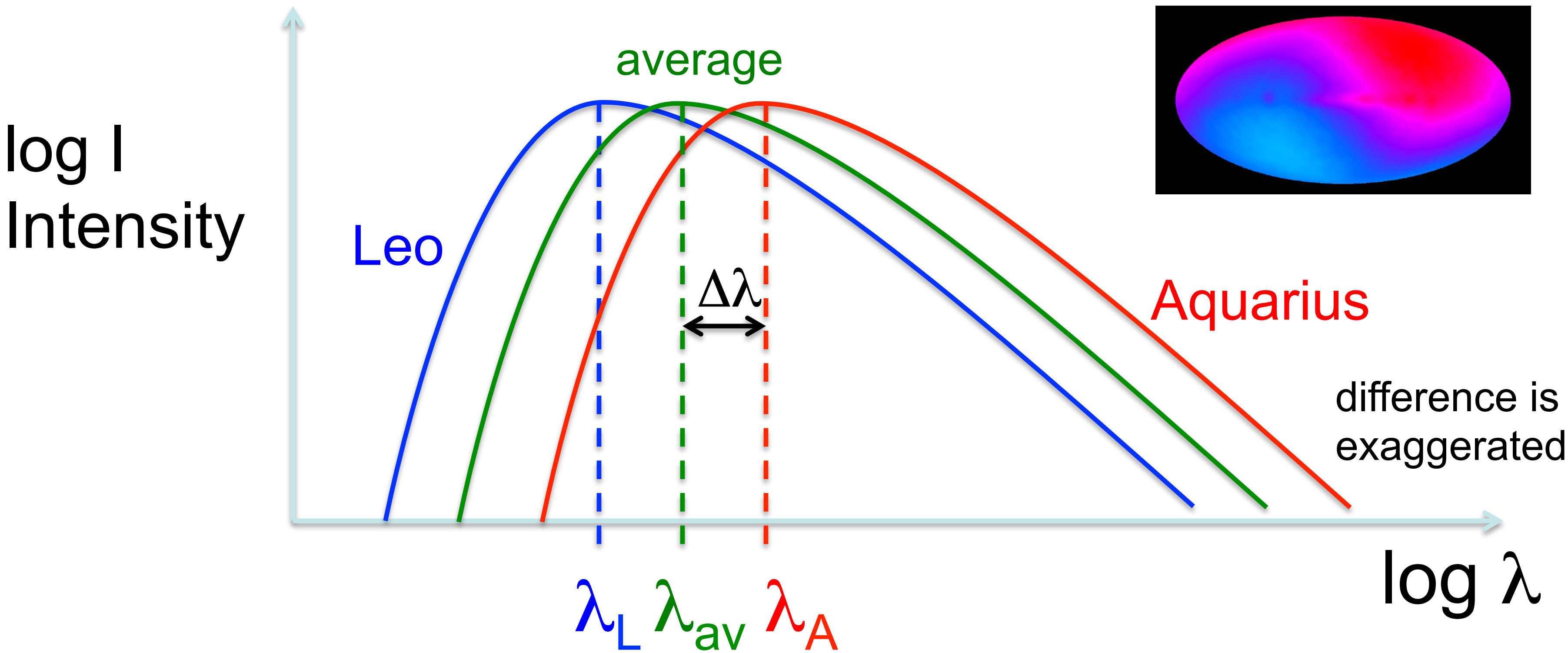


these are temperature variations
(curves don't cross)

$$\Delta\lambda / \lambda_{avg} = \Delta T / T_{avg} = 6 \times 10^{-6}$$

i.e. few parts per million

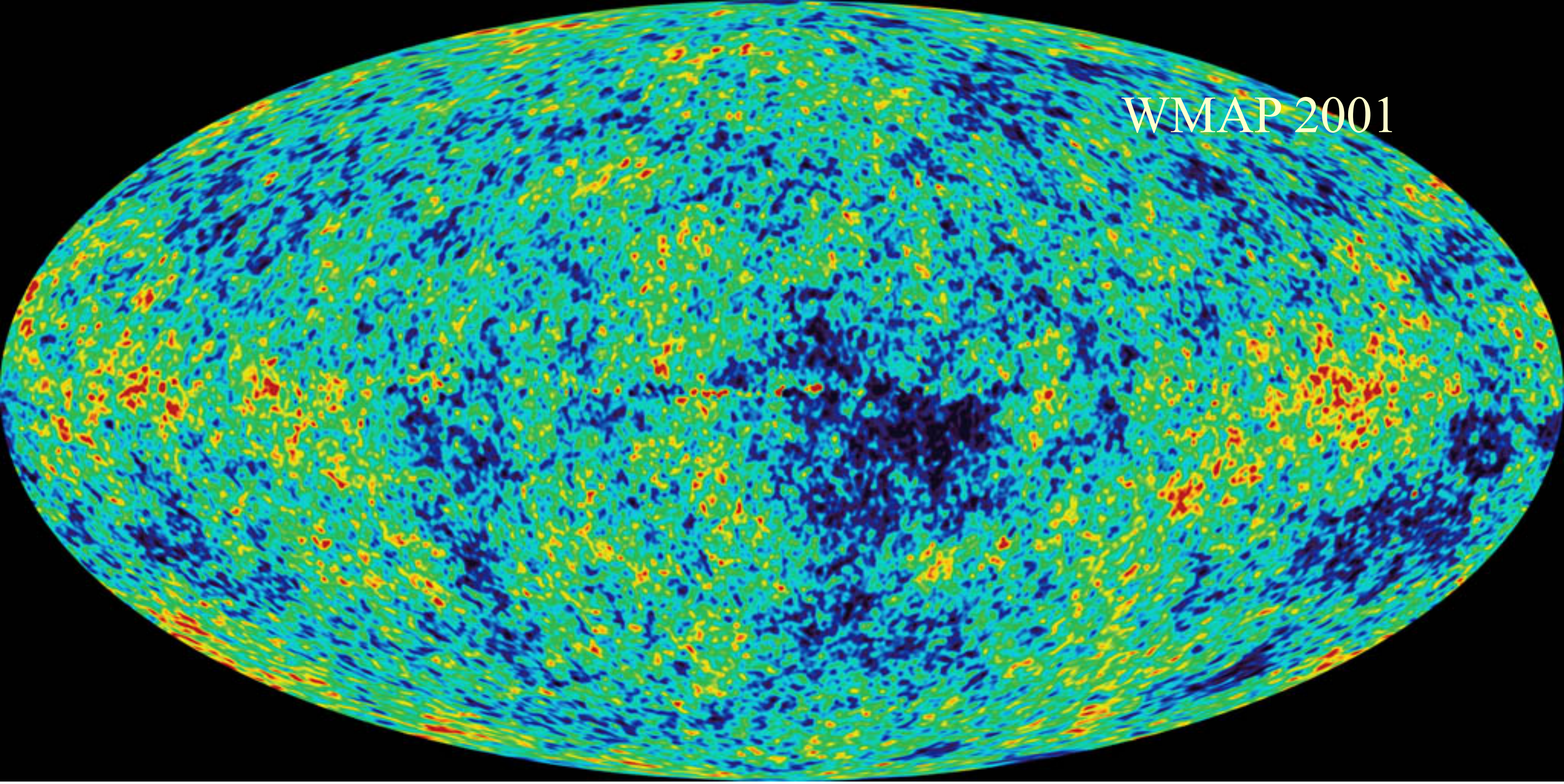
CMB spectrum slightly blueshifted toward Leo
CMB spectrum slightly redshifted toward Aquarius



this is Doppler shift caused by motion of earth wrt CMB
(curves cross)

$$\Delta\lambda / \lambda_{avg} = v / c = 0.0012 = 1.2\text{x}10^{-3}$$

$$V_{earth,CMB} = 0.0012c = 370 \text{ km/sec}$$



Small fluctuations in cosmic background radiation trace the

1. Seeds of large-scale structure in universe and tell us
2. How space in the Universe is curved &
3. Contents of Universe (how much matter & energy)!

1.seeds of structure

Gravity acts to make things collapse and make universe lumpier

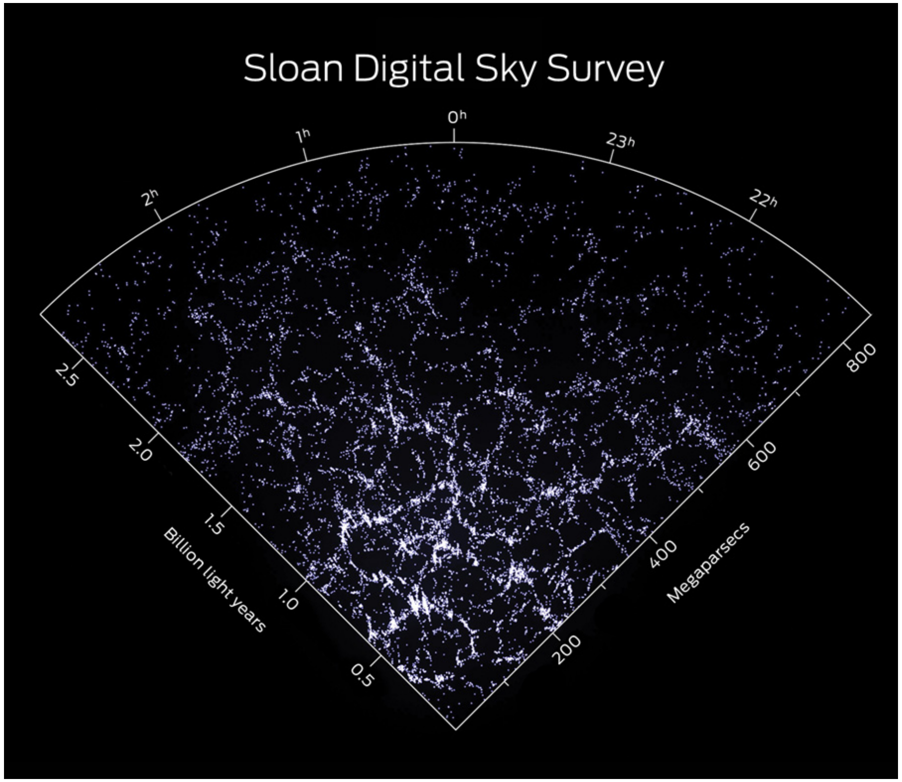
Now the matter distribution is very lumpy ..

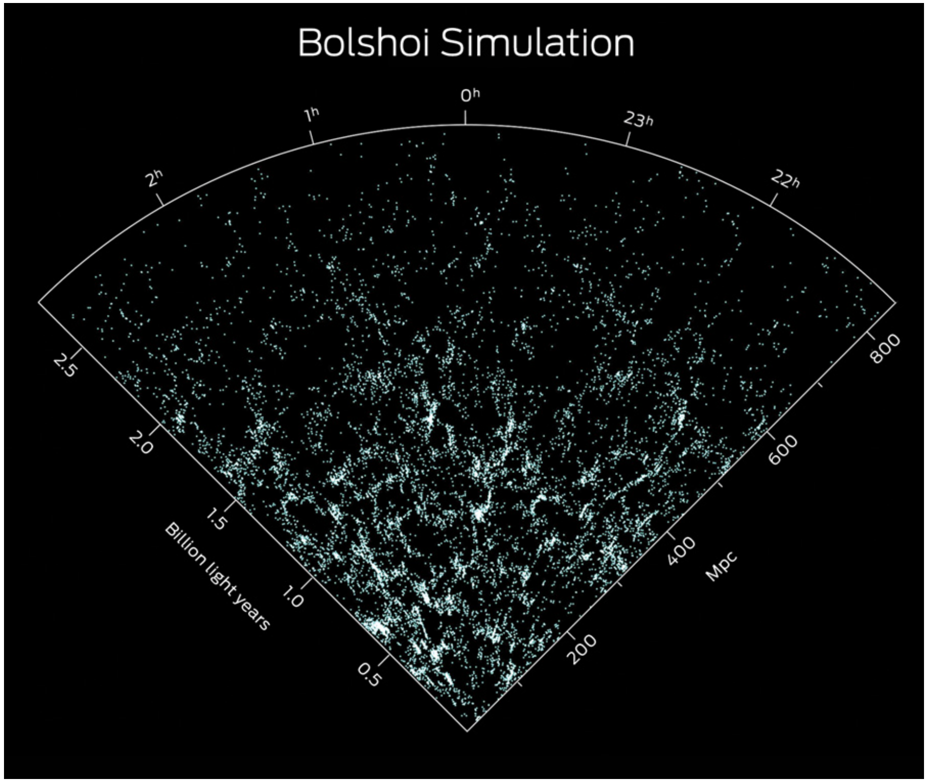
But how & when did “structure” in the universe form?

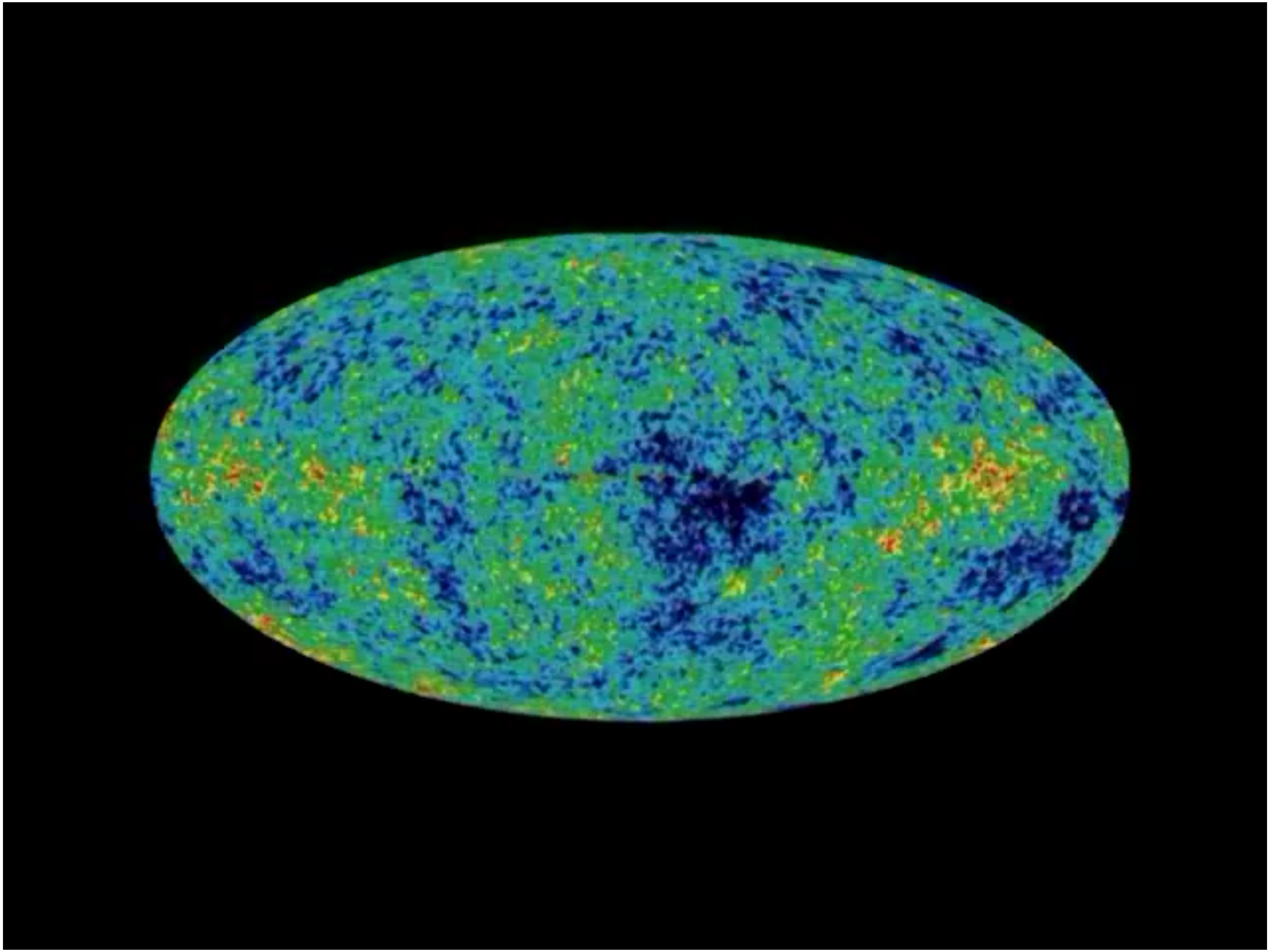
structure = concentrations of matter like superclusters, clusters, galaxies, stars

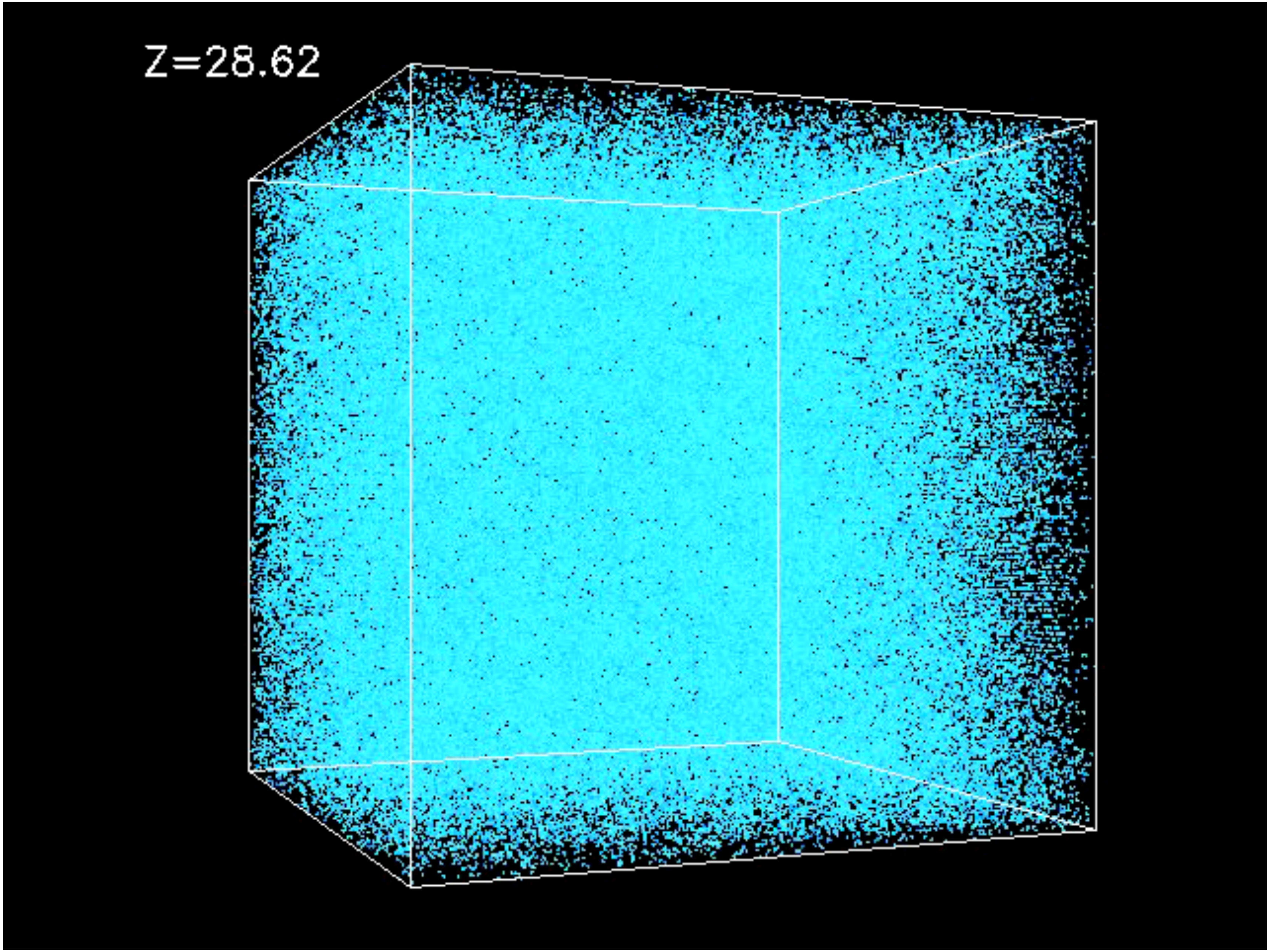
Large-scale structure in universe TODAY

Data vs. Simulation







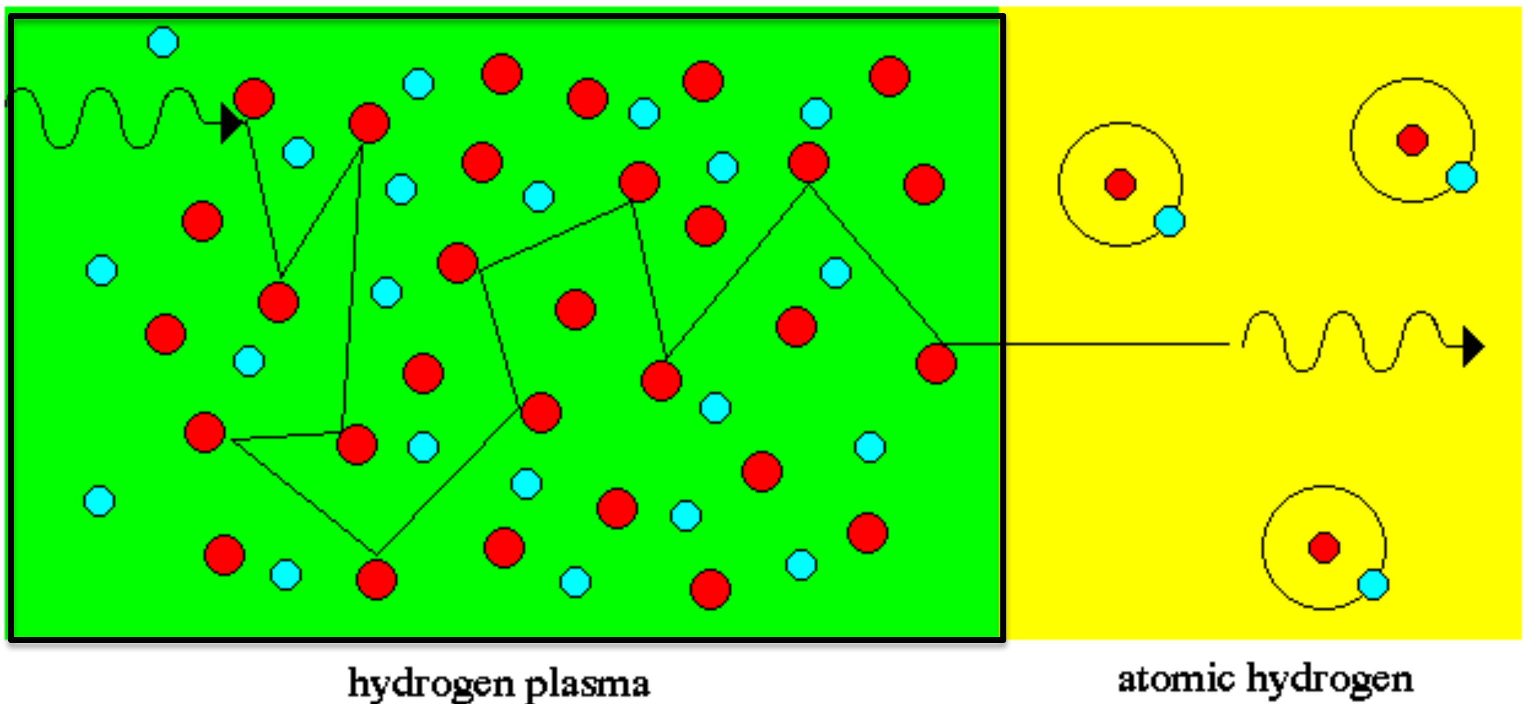

Z=28.62

Why didn’t lumps of matter form before recombination?

A. The matter was too hot for gravity to form lumps
B. Gravity was too weak compared to dark energy
C. Radiation was coupled to matter, preventing lumps from cooling
D. Radiation was the main source of mass-energy and gravity until recombination
E. Not enough time for gravity to form lumps
F. Just hard to get going so early in the morning

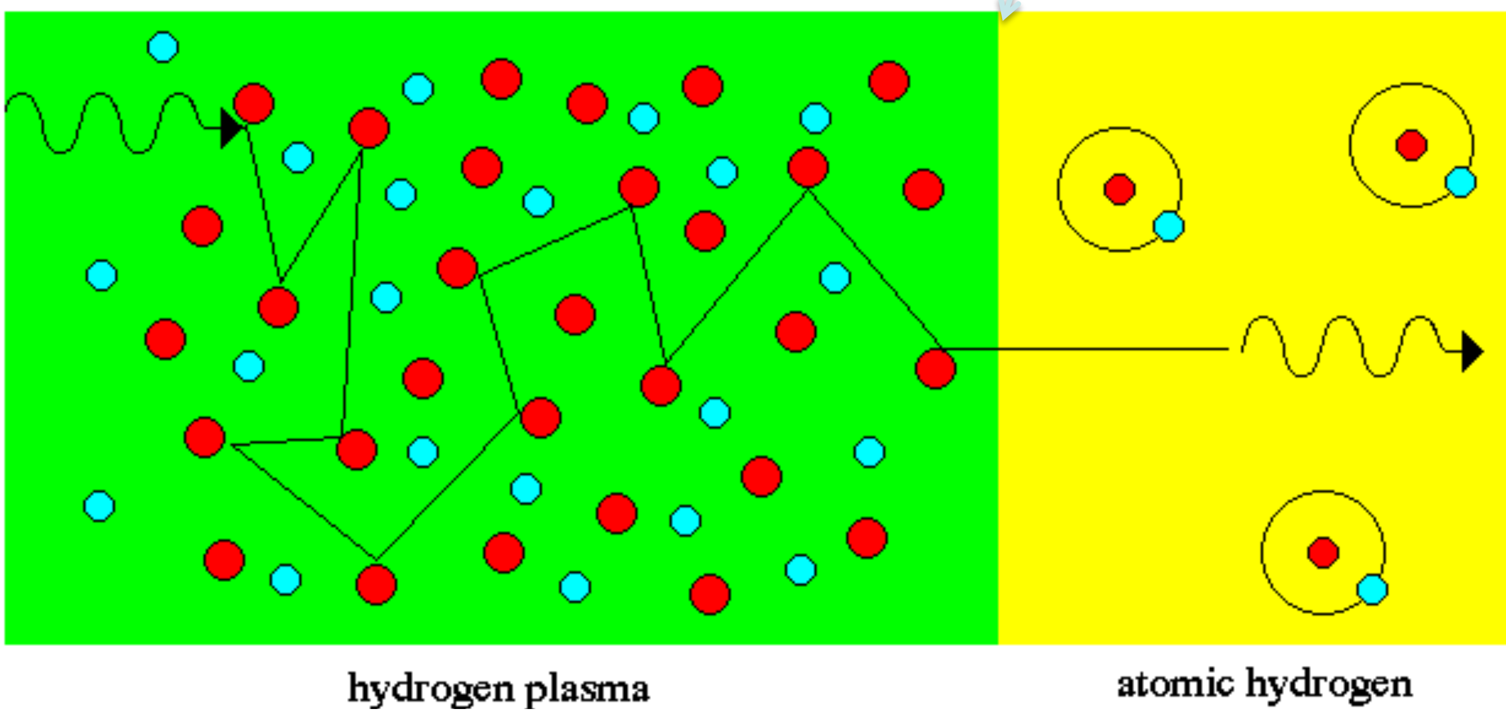
Before recombination

- Matter is in the form of plasma (p's & e's)
- Cosmic photons collide with p's and e's, scattering them – changing energy & direction
- Atoms can form but are quickly destroyed (ionized) by cosmic photons
- Cosmic photons had enough energy to ionize atoms
- Universe opaque to cosmic photons
- ***Matter & energy (cosmic photons) tightly coupled***

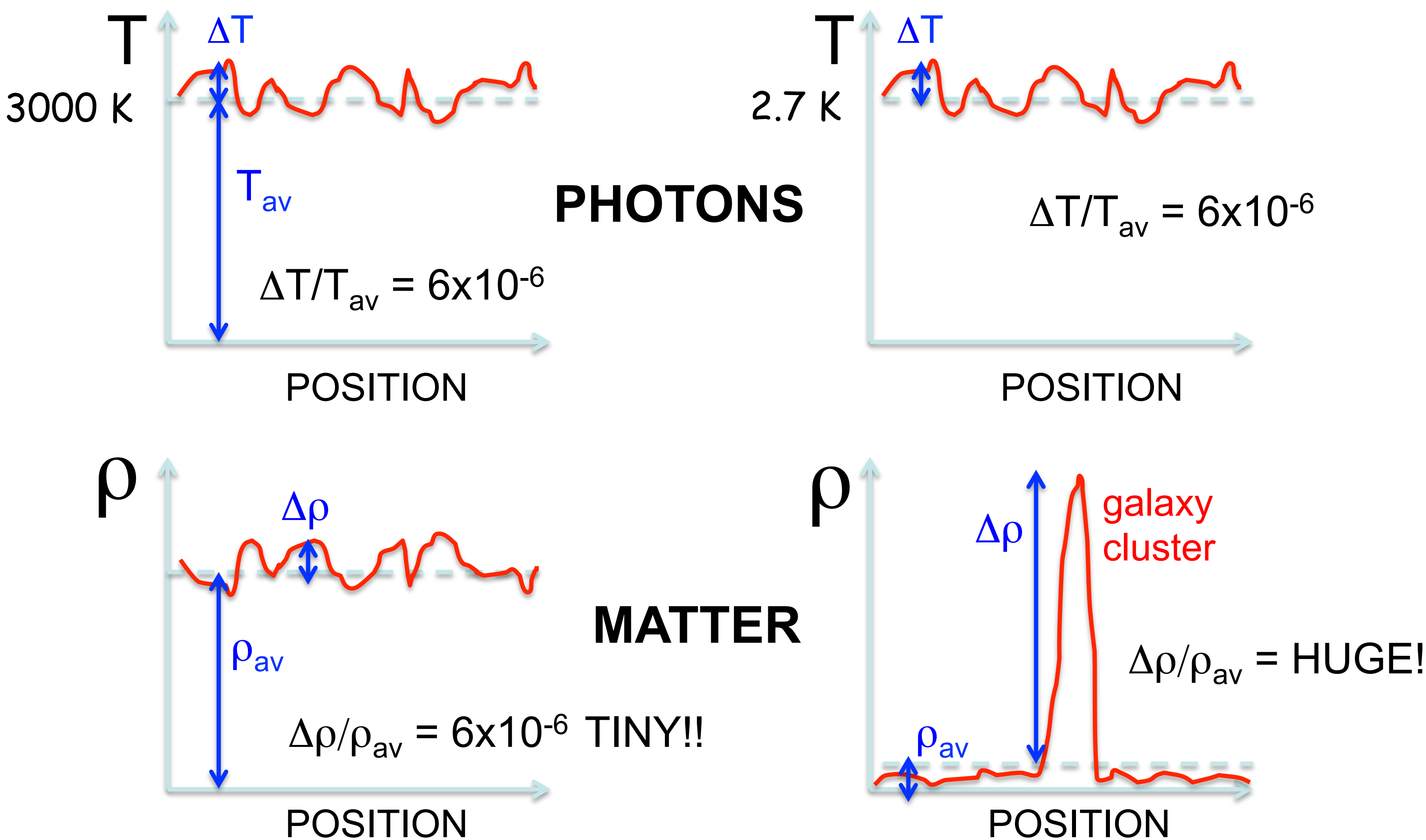


Universe AT z=1100, T=3000K, t_{ABB}=380,000 yr

- Cosmic photons suddenly no longer have enough energy to ionize atoms (due to expansion)
- p's & e's combine to form atoms (not ionized)
- "era of recombination" (combination?)
- ***"era of decoupling" (of matter & cosmic photons)***
- Moment when universe changed from being opaque to transparent (for cosmic photons)
- all cosmic photons we see now were created or last scattered (direction or energy changed) at this time



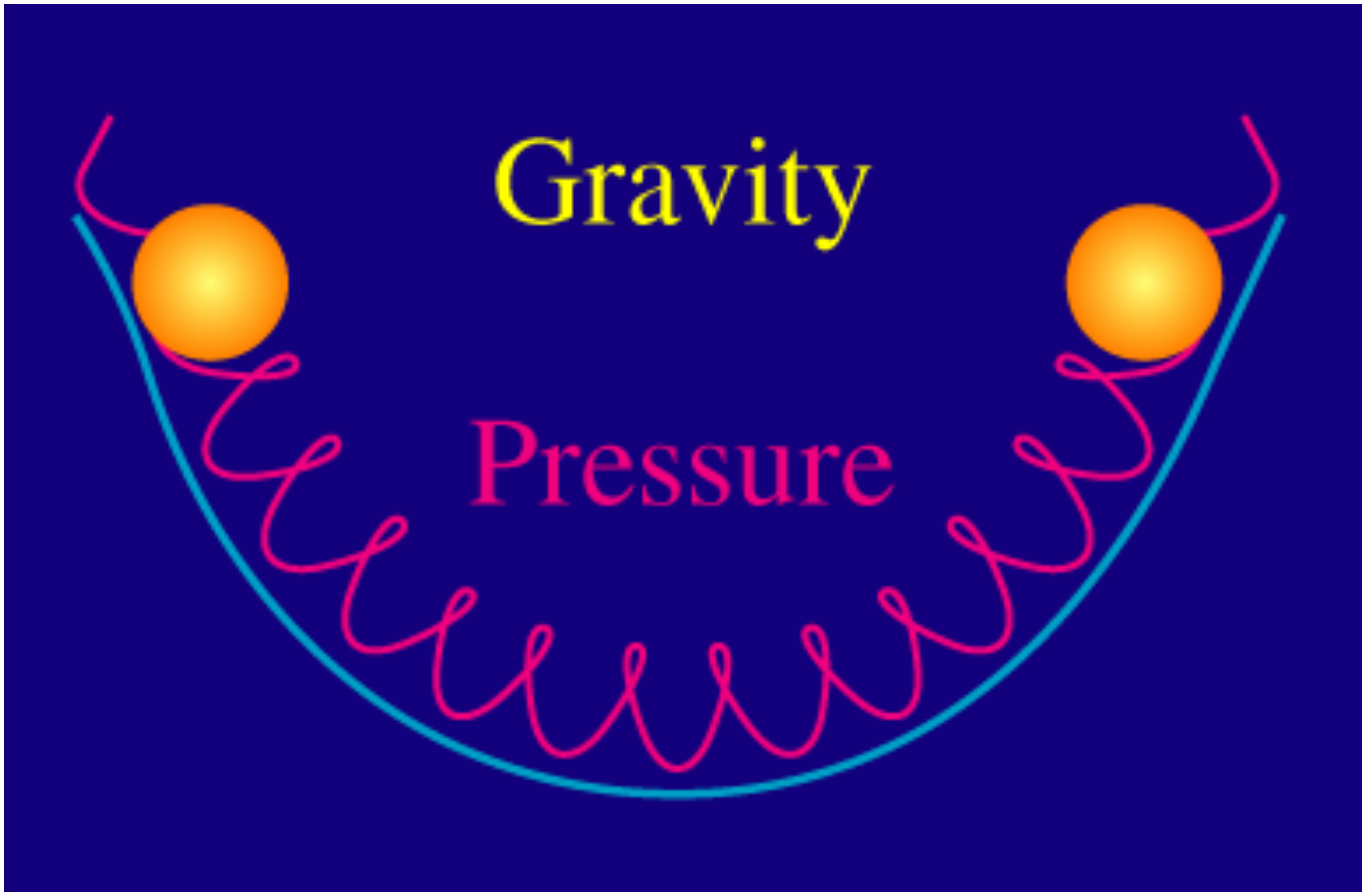
THEN t = 380,000 yr ABB   NOW t = 13.8 Byr ABB



before recombination, matter & photons coupled so structure can't form

structure really grows after recombination, once matter decoupled from cosmic photons

Why gravitational collapse doesn't happen before "recombination"



The pressure exerted by cosmic photons resists gravitational collapse

Dense lumps form from gravity if photons can escape & thereby release energy from the lump

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- If lump starts to collapse due to self-gravity, it can only continue to collapse if it can release “gravitational binding energy”, e.g. in the form of photons

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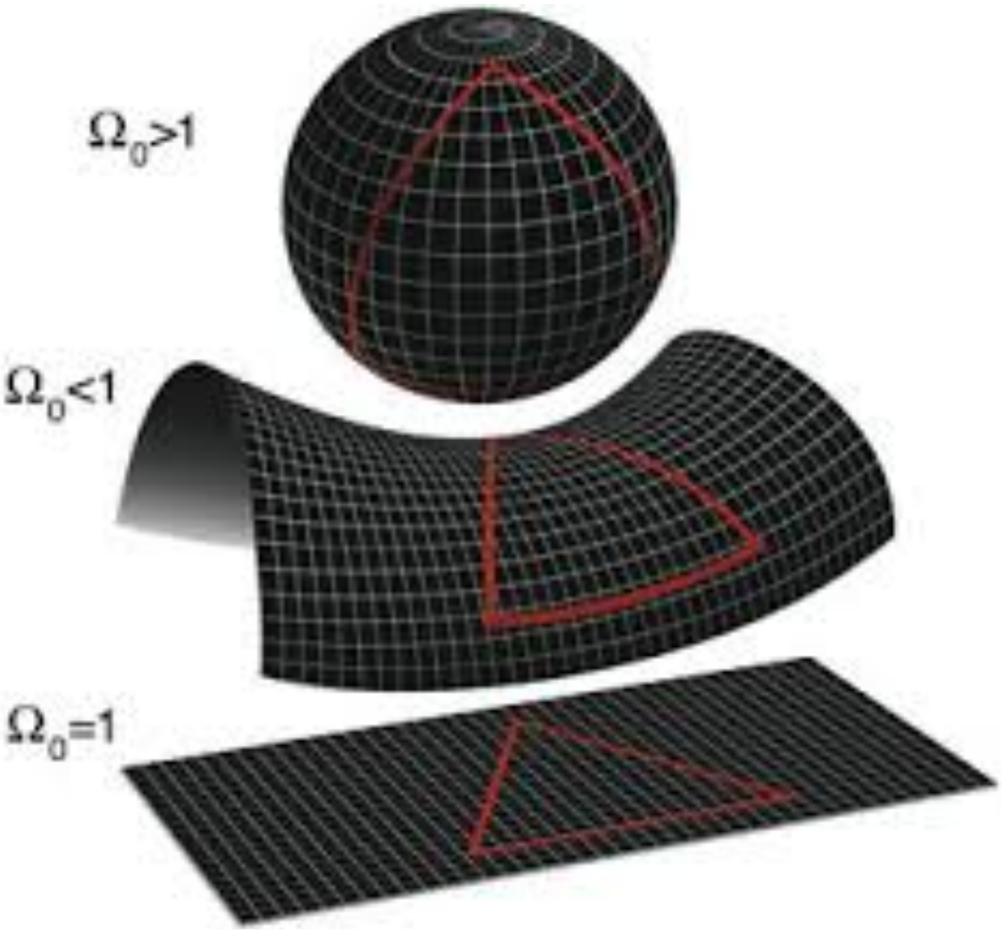
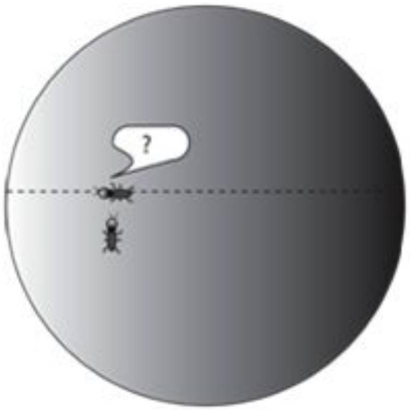
- If lump starts to collapse due to self-gravity, it can only continue to collapse if it can release "gravitational binding energy", e.g. in the form of photons
- If energy can't be released, lump will not collapse (before "decoupling")
- If energy can be released, lump will collapse (after "decoupling")

curvature of space in universe



The Ant Universe



- Ants on surface of a balloon are a good model – the ants can "traverse" the surface of the balloon and never run into a boundary

What does it mean for space in universe to be curved?

- If space were positively curved (spherical geometry, closed) and you could travel infinitely fast, you could circumnavigate the universe!!

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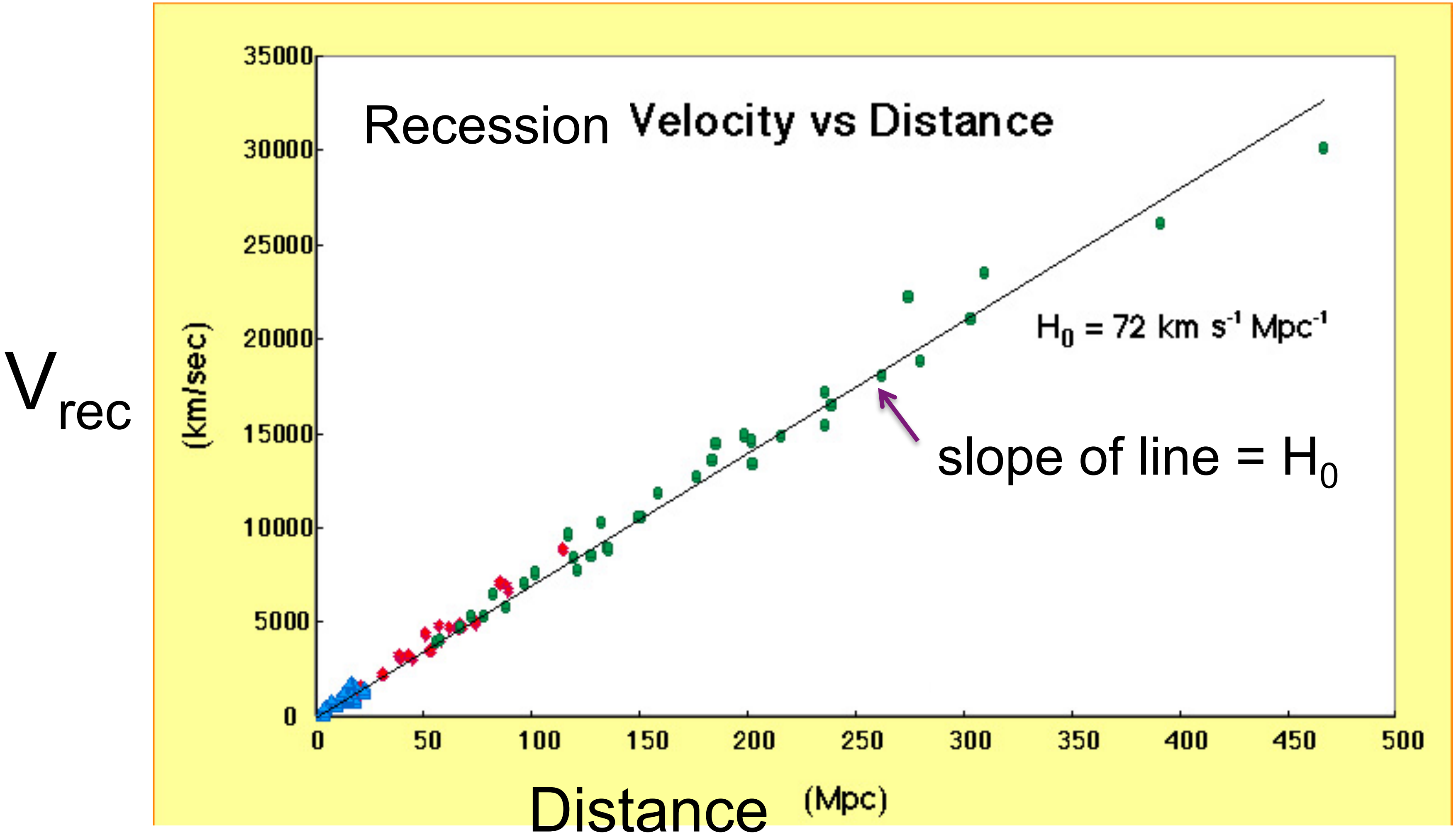
- If space were positively curved (spherical geometry, closed) and you could travel infinitely fast, you could circumnavigate the universe!!
- But… since universe is expanding and fastest possible speed *through* space is c, this is not quite possible

Hubble Law

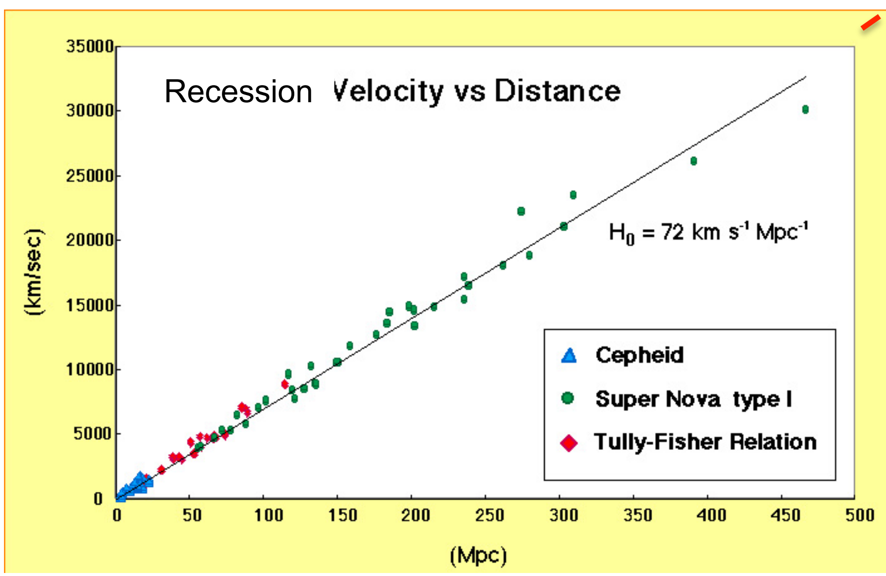


Recession Velocity vs Distance
V_{rec}
(km/sec)
35000
30000
25000
20000
15000
10000
5000
0
0
50
100
150
200
250
300
350
400
450
500
Distance (Mpc)
H_0 = 72 km s^{-1} Mpc^{-1}
slope of line = H_0

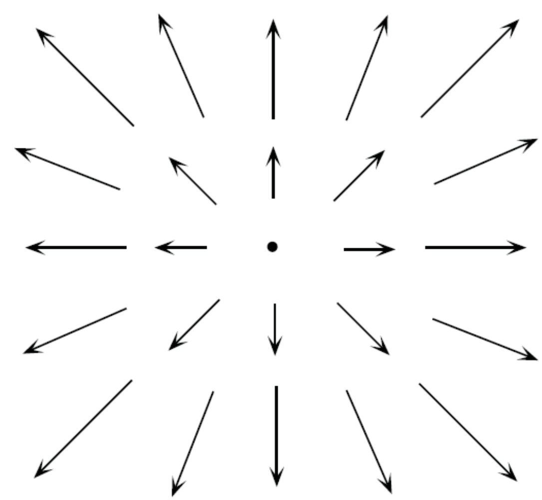
Hubble Law

eventually at some distance the recession speed becomes > c

V_{rec}



Distance

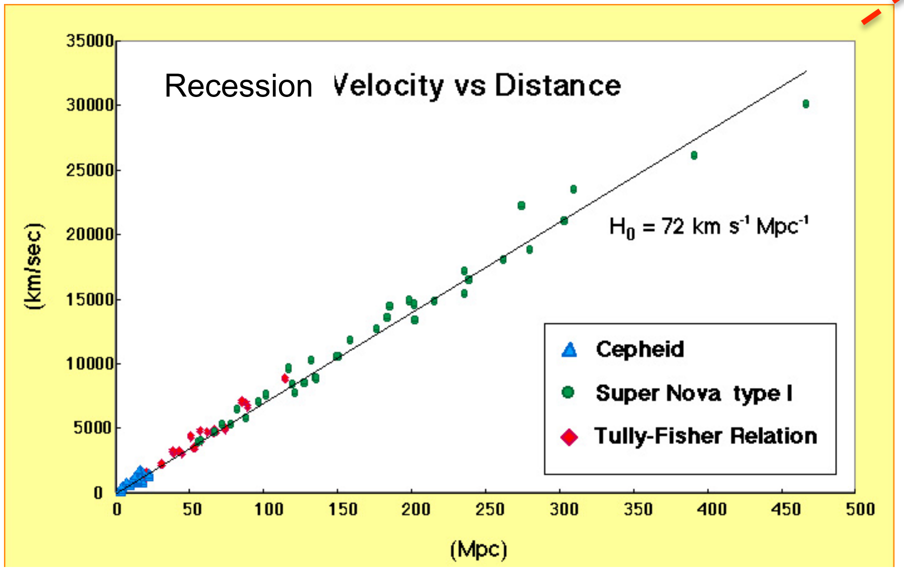


Hubble Law

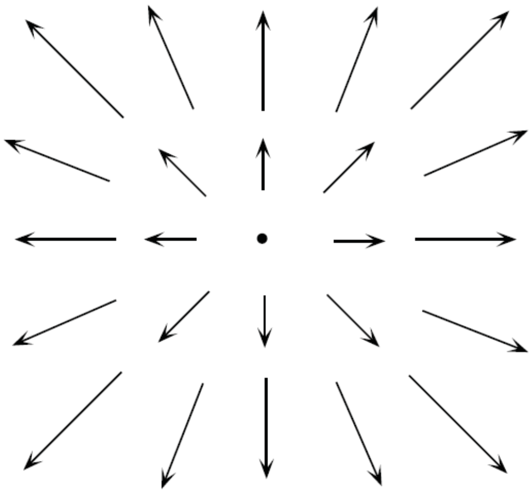
eventually at some distance the recession speed becomes > c

space can expand faster than the speed of light!

V_{rec}



Distance



Space can expand at >c

- General Relativity says: distant regions of space can separate from each other at speeds > c

- Special Relativity says: things cannot move *through* space at speeds > c

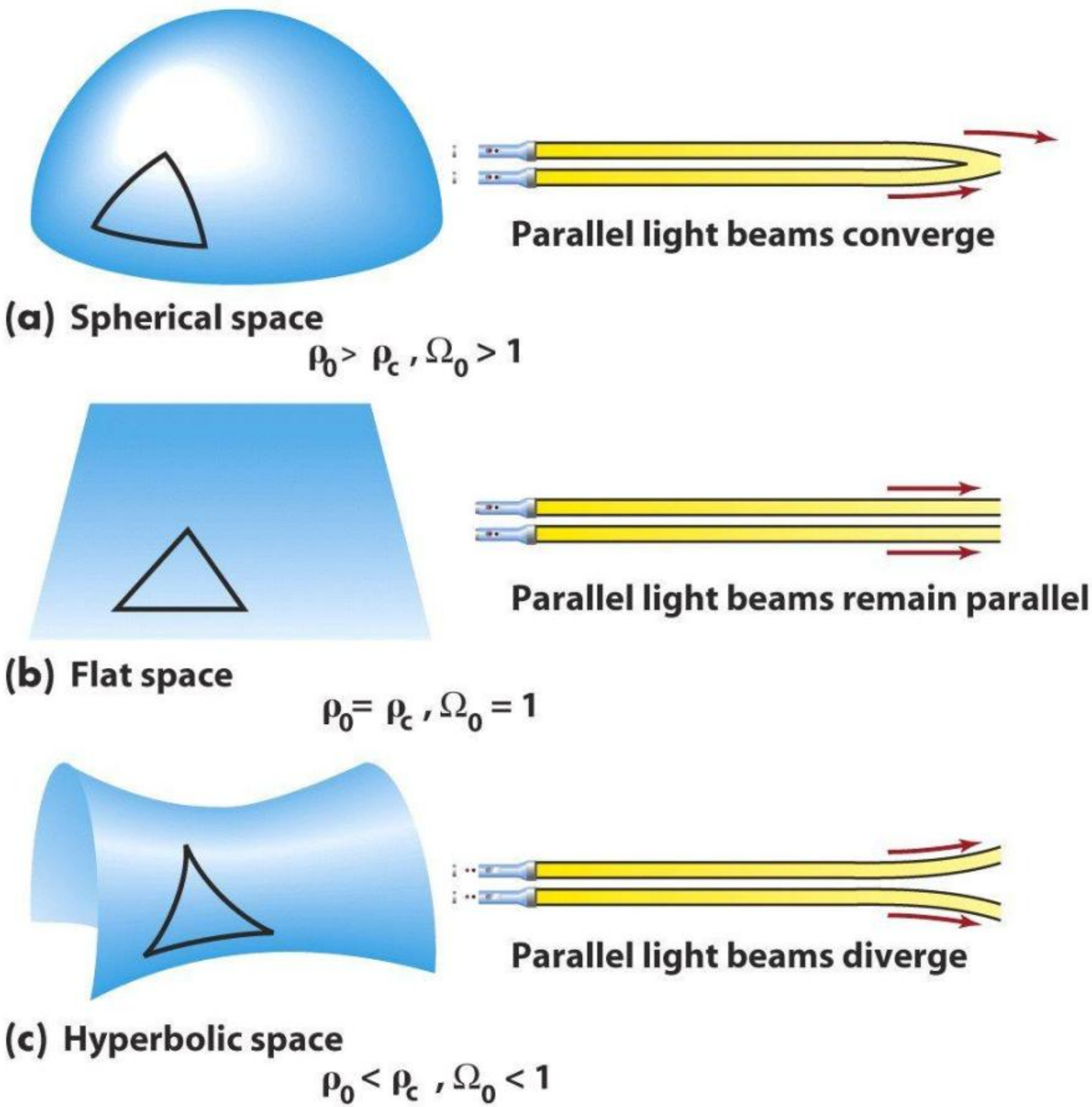
What does it mean for space in universe to be curved?

- If space were positively curved (spherical geometry, closed) and you could travel infinitely fast, you could circumnavigate the universe!!
- But… since universe is expanding and fastest possible speed *through* space is c, this is not quite possible
- As universe expands, photons have further to travel – and distant regions of space are expanding away from us at faster than the speed of light (allowed by GR) – so photons can never catch up

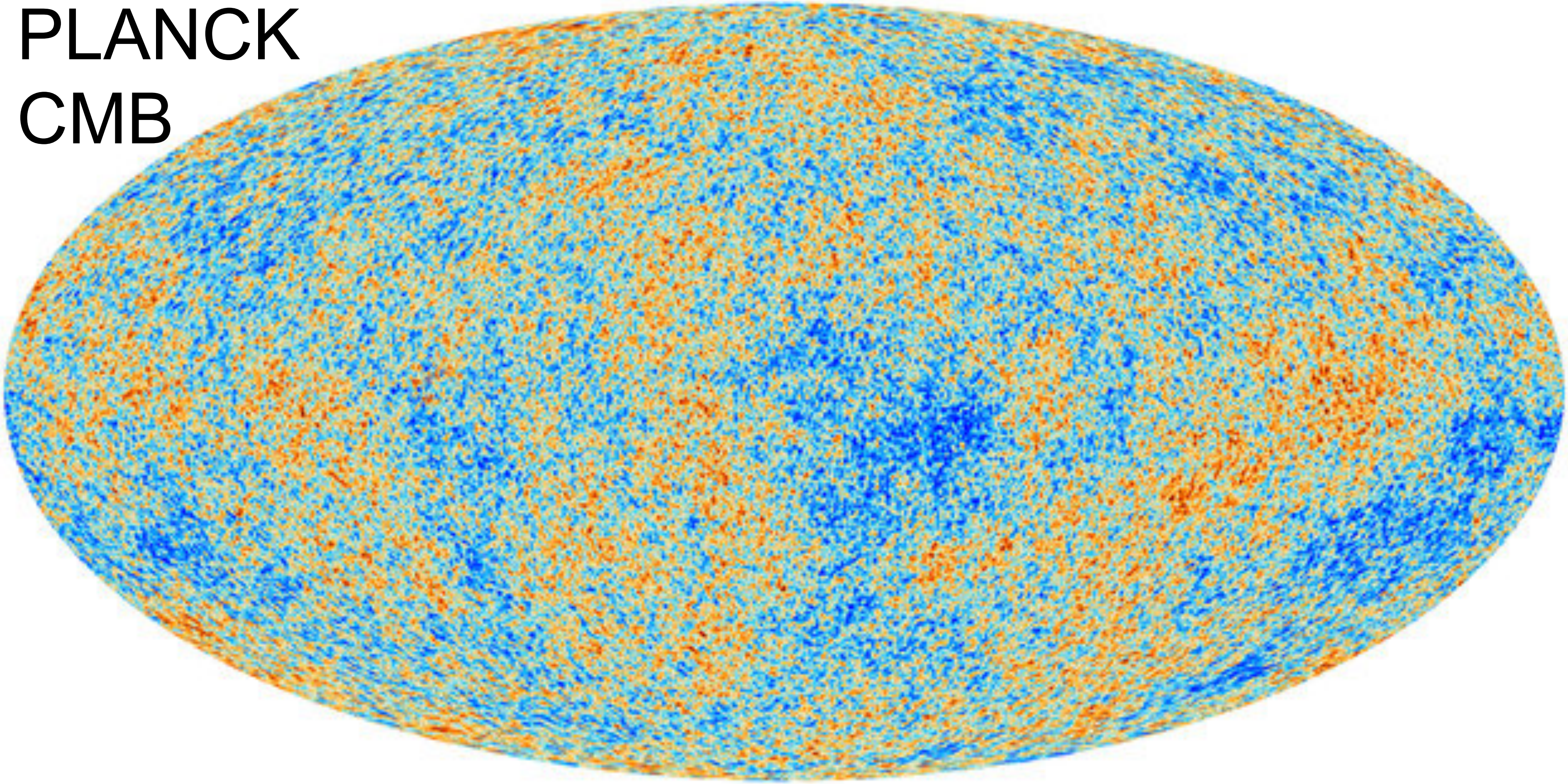
What does it mean for space in universe to be curved?

- If space were positively curved (spherical geometry, closed) and you could travel infinitely fast, you could circumnavigate the universe!!
- But… since universe is expanding and fastest possible speed *through* space is c, this is not quite possible
- As universe expands, photons have further to travel – and distant regions of space are expanding away from us at faster than the speed of light (allowed by GR) – so photons can never catch up
- Only in *closed* and *contracting* universe would photons have enough time to circumnavigate the universe (and our universe is neither…)

Possible space curvatures



PLANCK
CMB



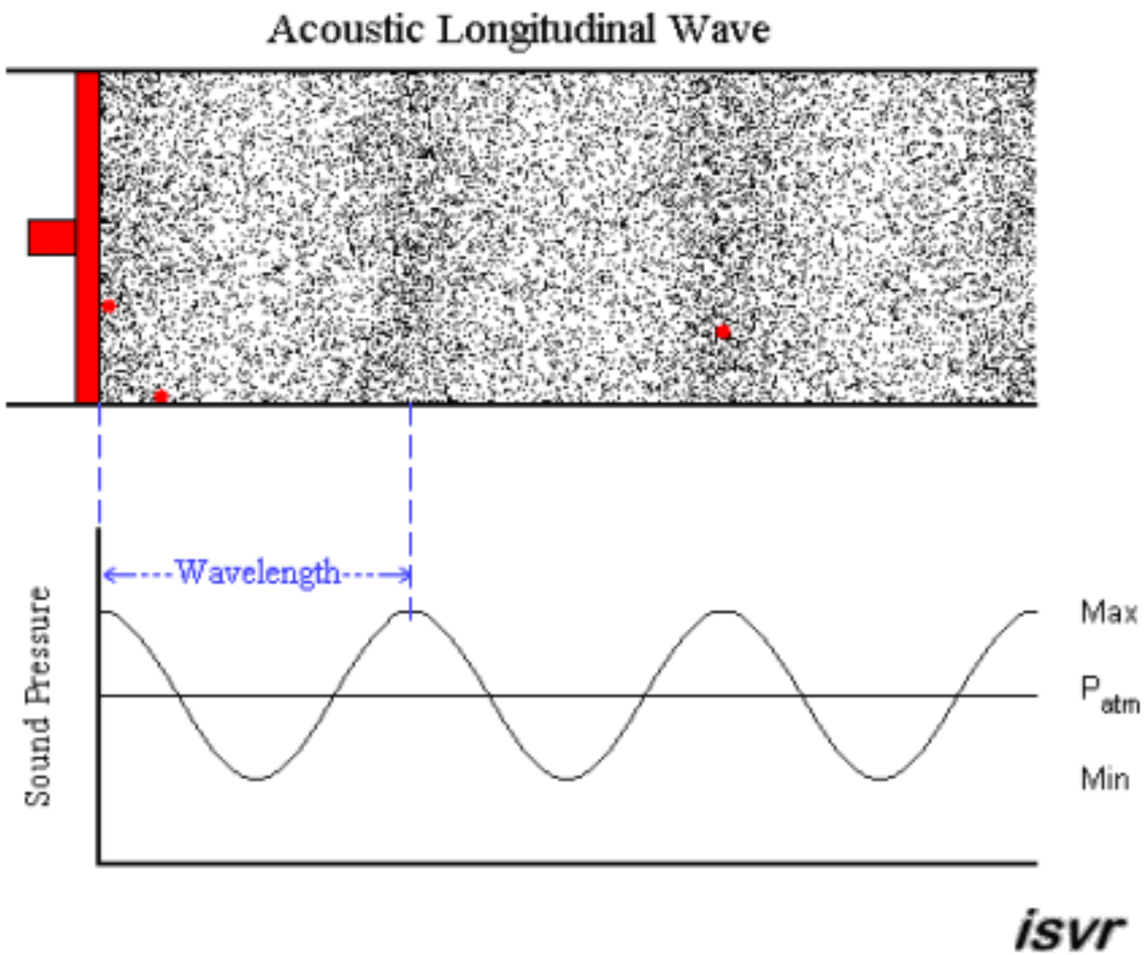
Small fluctuations in cosmic background radiation tell us

2. how space in the Universe is curved

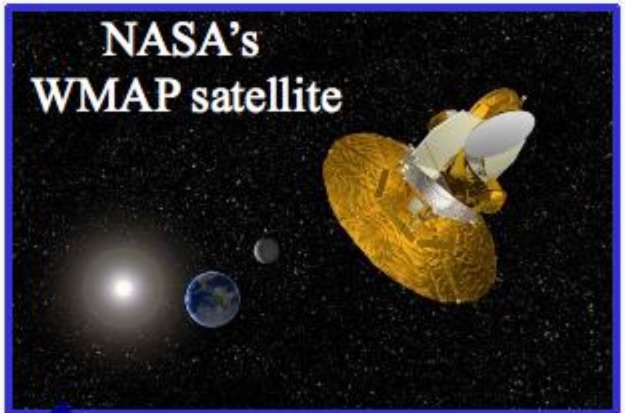
What are these fluctuations in CMB?

Fluctuations arise in very early universe (t_{ABB} < 1 sec) (as quantum fluctuations) – small non-uniformities which disturb the universe, causing sound waves

Most CMB fluctuations are ***sound waves***



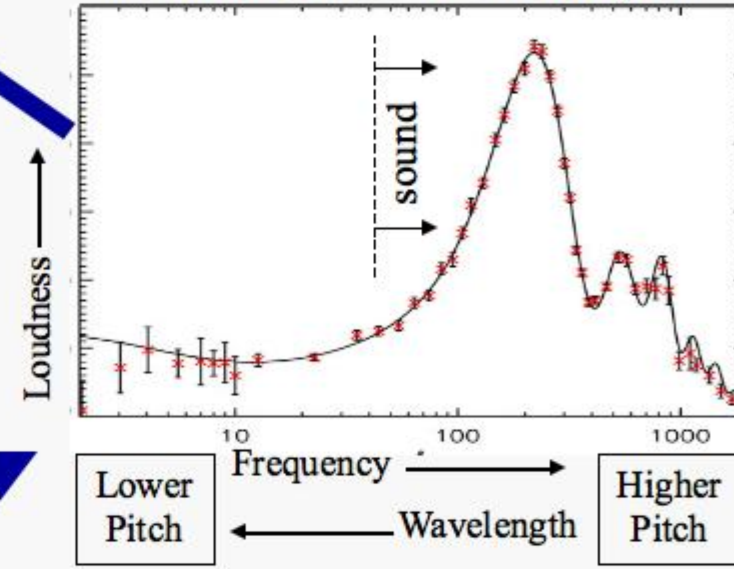
Sound Waves in the Sky



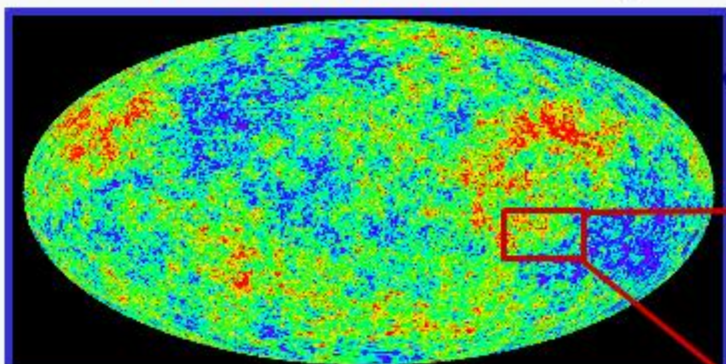
Loudspeaker

The CMB Power Spectrum

Relative loudness at different pitch

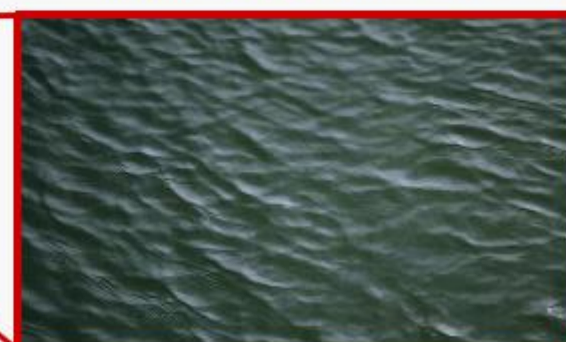


The Full Microwave Sky



Microwave brightness, greatly contrast stretched.
Brightness differences are also pressure differences
Patches smaller than 2° are sound waves

Water waves on the ocean surface illustrate sound waves on the CMB "surface"



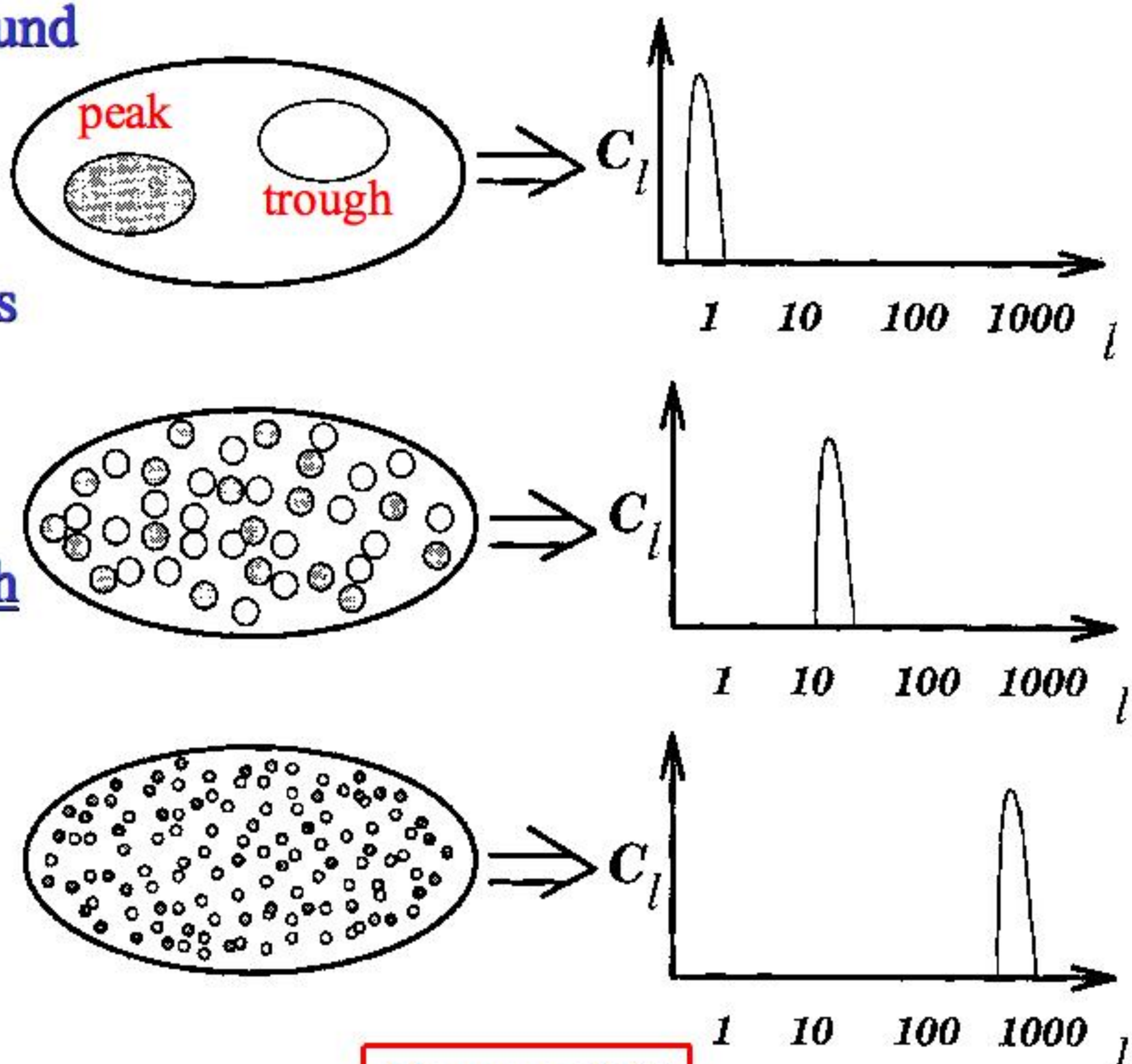
short
plus
medium
plus
long
all
mixed
together

Sky Maps → Power Spectra

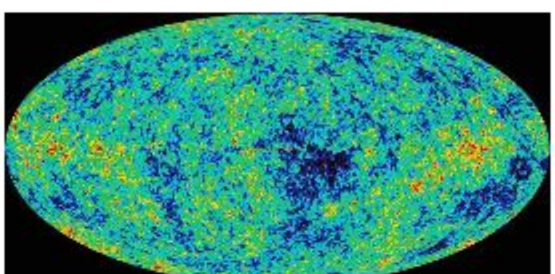
We "see" the CMB sound as waves on the sky.

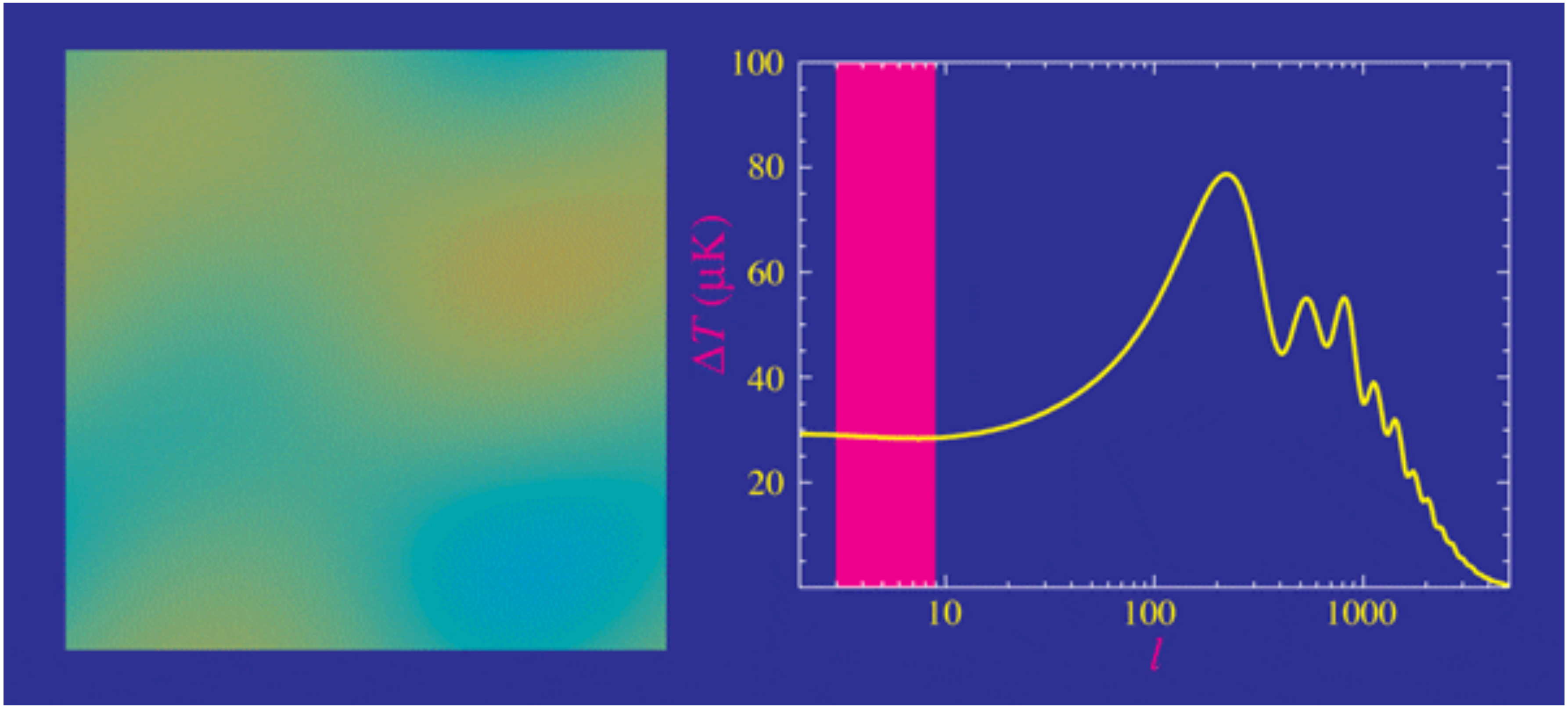
Shorter wavelengths are smaller frequencies are higher pitches

Use special methods to measure the strength of each wavelength.



Lineweaver 1997





100
80
60
40
20
ΔT (μK)
10
100
1000
l

What are these fluctuations in CMB?

Fluctuations arise in very early universe (t_{ABB} < 1 sec) (as quantum fluctuations) – small non-uniformities which disturb the universe, causing sound waves

These sound waves survive and grow in size (linear scale) due to expansion. But they do not grow in amplitude for first 380,000 yrs, since photons were coupled to matter, preventing matter from collapsing

What is the furthest distance a signal could have traveled in the universe at the time when the CMB photons were produced?

A. Infinite
B. 13.7 BLY
C. 380,000 LY
D. 0 LY
E. It depends on how the space in the universe is curved
F. It depends on speed of CMB photons

The largest blobs in CMB are the largest causally connected regions

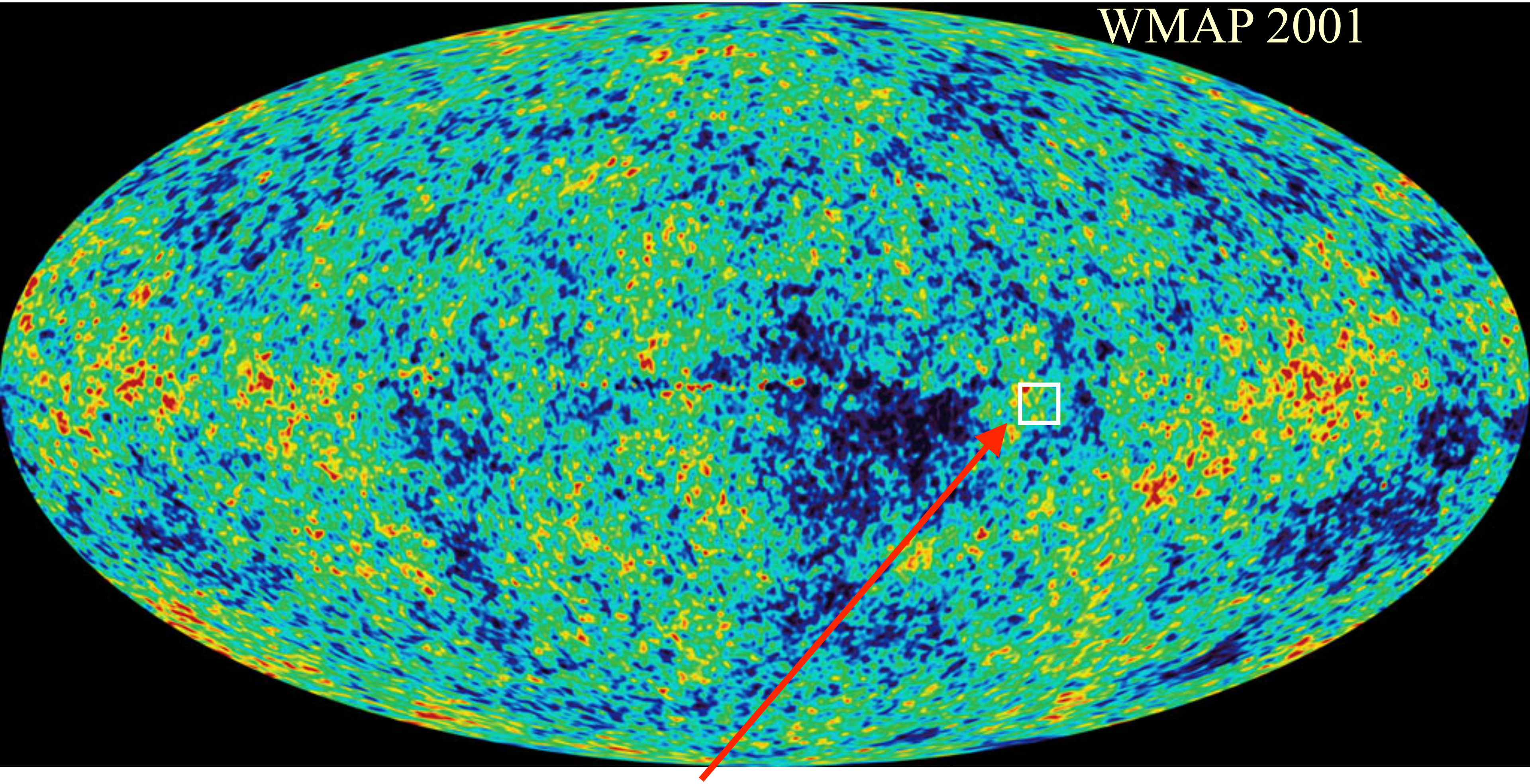
- How far could the fastest signal go through space during the entire history of the universe?
- This is the *Cosmic Light Horizon*

$$d_{CLH} = c\ t_{ABB}$$

- At age of t_{ABB} =380,000 yrs

  the largest causally connected region is

  d_{CLH} = 380,000 LY in size



Examine small patch of CMB

13.3 BLY (distance to CMB)

380,000 LY
(size of biggest
blobs in CMB)

Use "cosmological version" of small angle formula

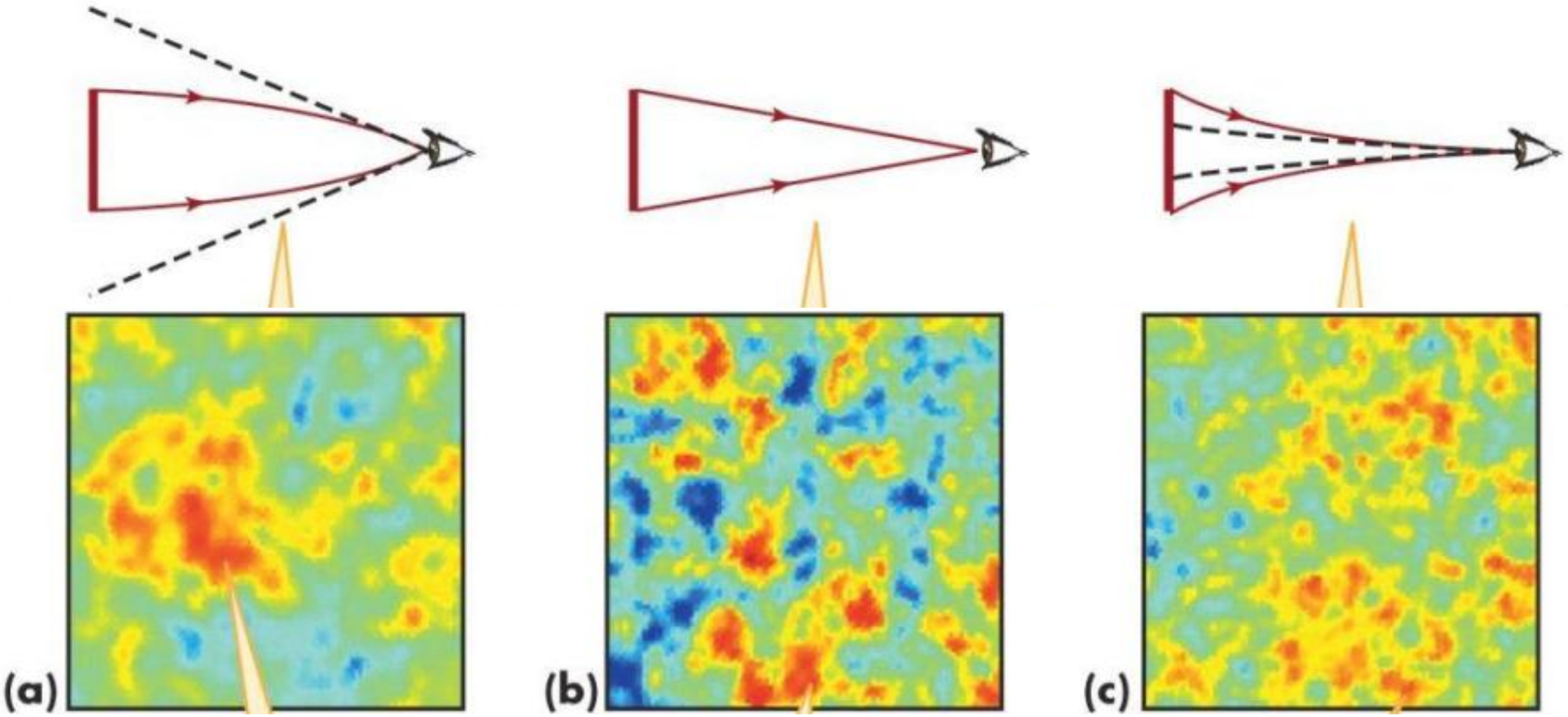
(diagram shows case of ***flat space***)

If space in the universe is:

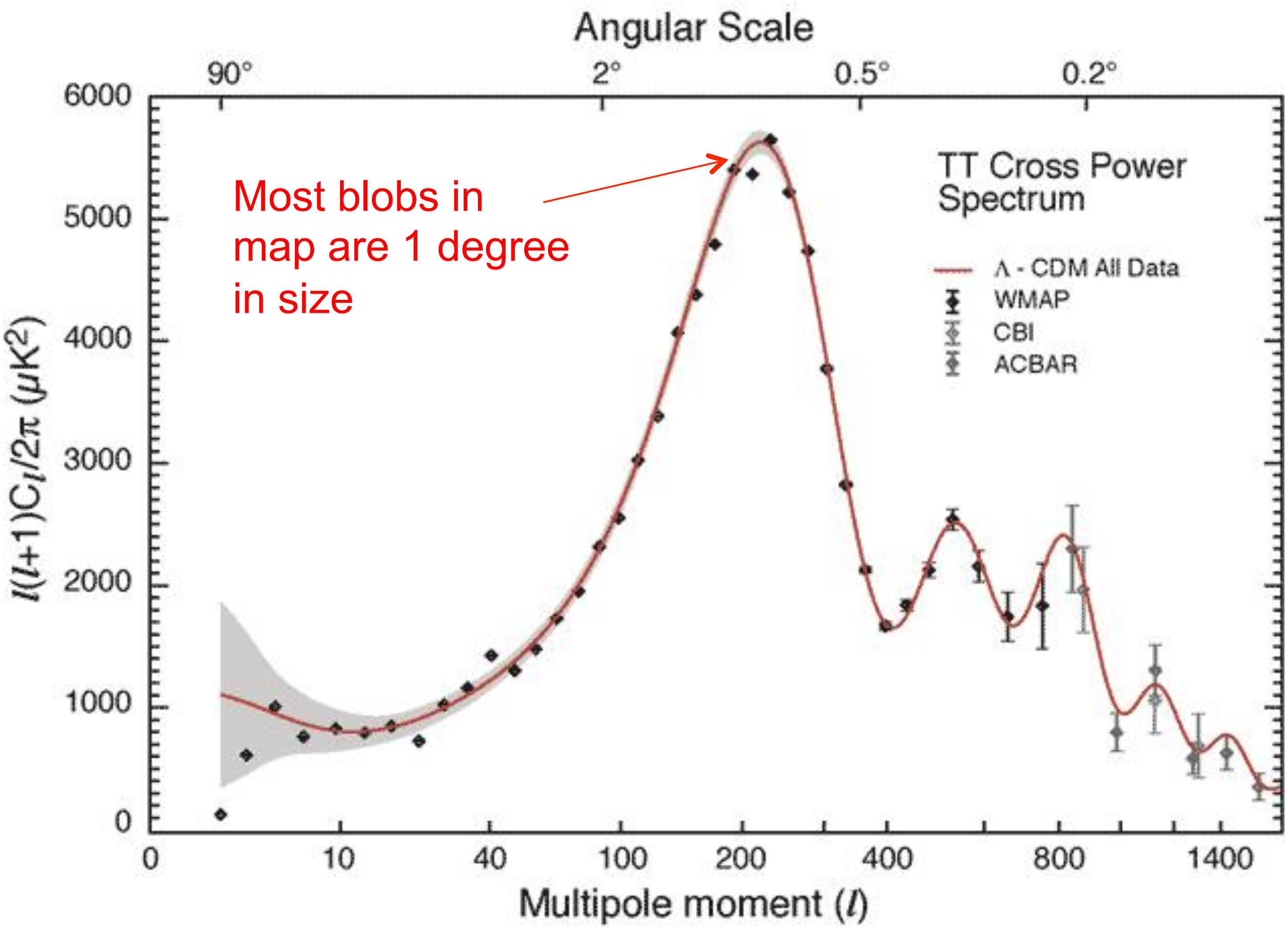
Spherical | Flat | Hyperbolic

Then the biggest blobs in the CMB appear to be:

More than 1 deg | 1 degree | Less than 1 deg



The structure in CMB map is not random!



Use "cosmological version" of small angle formula

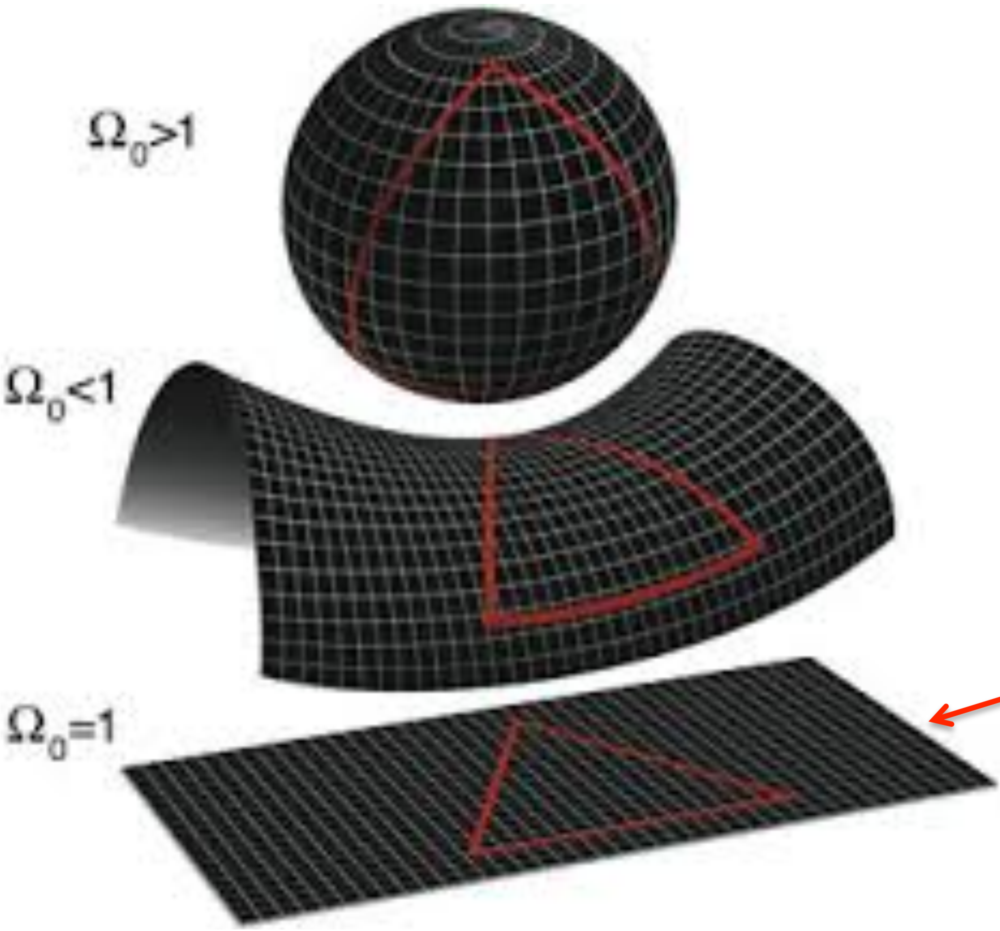
(diagram shows case of ***flat space***)

What do we find?

- Biggest blobs are 1 degree in size

→ *space in universe appears flat !*

curvature of space



our observable universe is closest to this curvature

What do we find?

- Biggest blobs are 1 degree in size

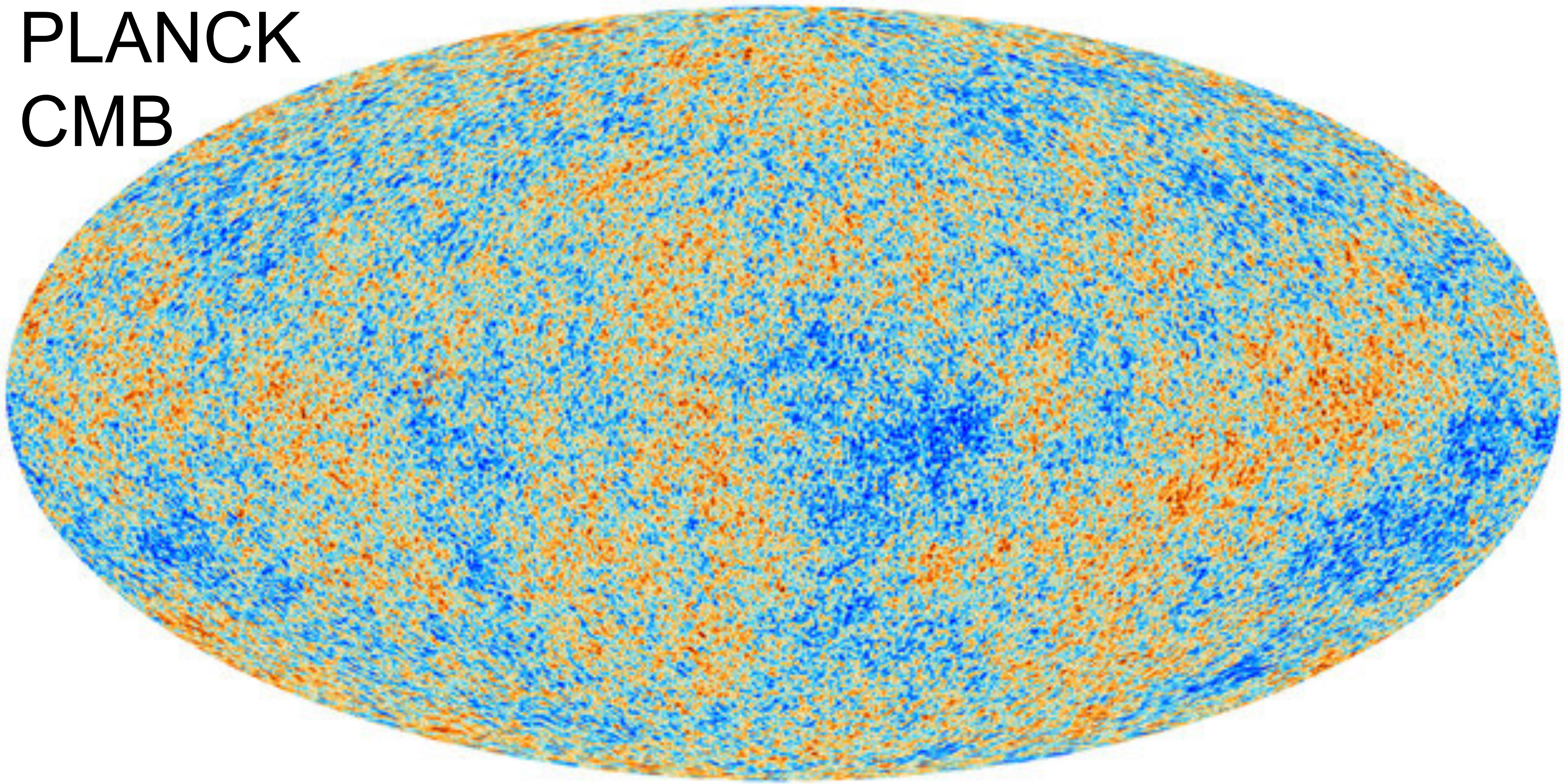
  → *space in universe appears flat !*

- This has implications for

  mass & energy content of universe

  including evidence for **Dark Energy**

PLANCK
CMB



Small fluctuations in cosmic background radiation tell us

2. how space in the Universe is curved &

3. contents of Universe!

Curvature of space & dark energy

Total amount (density) of matter, radiation & dark energy

$\rho_0 = \rho_m + \rho_{rad} + \rho_\Lambda$ **total density**

$\Omega_m = \rho_m / \rho_{crit}$ matter (baryonic and dark matter)

$\Omega_{rad} = \rho_{rad} / \rho_{crit}$ radiation (cosmic background & other photons)

$\Omega_\Lambda = \rho_\Lambda / \rho_{crit}$ dark energy

$\Omega_o = \Omega_m + \Omega_{rad} + \Omega_\Lambda$ **total density parameter**

$\Omega_o = \rho_0 / \rho_{crit}$; $\rho_{crit} = 3 H_o^2 / 8 \pi G$

Curvature of space & dark energy

$\Omega_o = \Omega_m + \Omega_{rad} + \Omega_\Lambda = \rho_0 / \rho_{crit}$ total density parameter

$\rho_{crit} = 3 H_o^2 / 8 \pi G$

introduced previously in discussing FATE of universe

but in general ρ_0 / ρ_{crit} gives ***curvature of space***

Contents of universe determine its curvature!

Curvature of space & dark energy

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Contents of universe determine its curvature!

CMB fluctuations indicate:

$\Omega_o = 1$ i.e., flat universe

We know $\Omega_m = 0.27$

$\Omega_{rad} = 0.00005$ (nearly zero!)

Curvature of space & dark energy

$\Omega_o = \Omega_m + \Omega_{rad} + \Omega_\Lambda = \rho_0 / \rho_{crit}$ total density parameter

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CMB fluctuations indicate:

$\Omega_o = 1$ i.e., flat universe

We know $\Omega_m = 0.27$

$\Omega_{rad} = 0.00005$ (nearly zero!)

➔ $\Omega_\Lambda = 0.73$

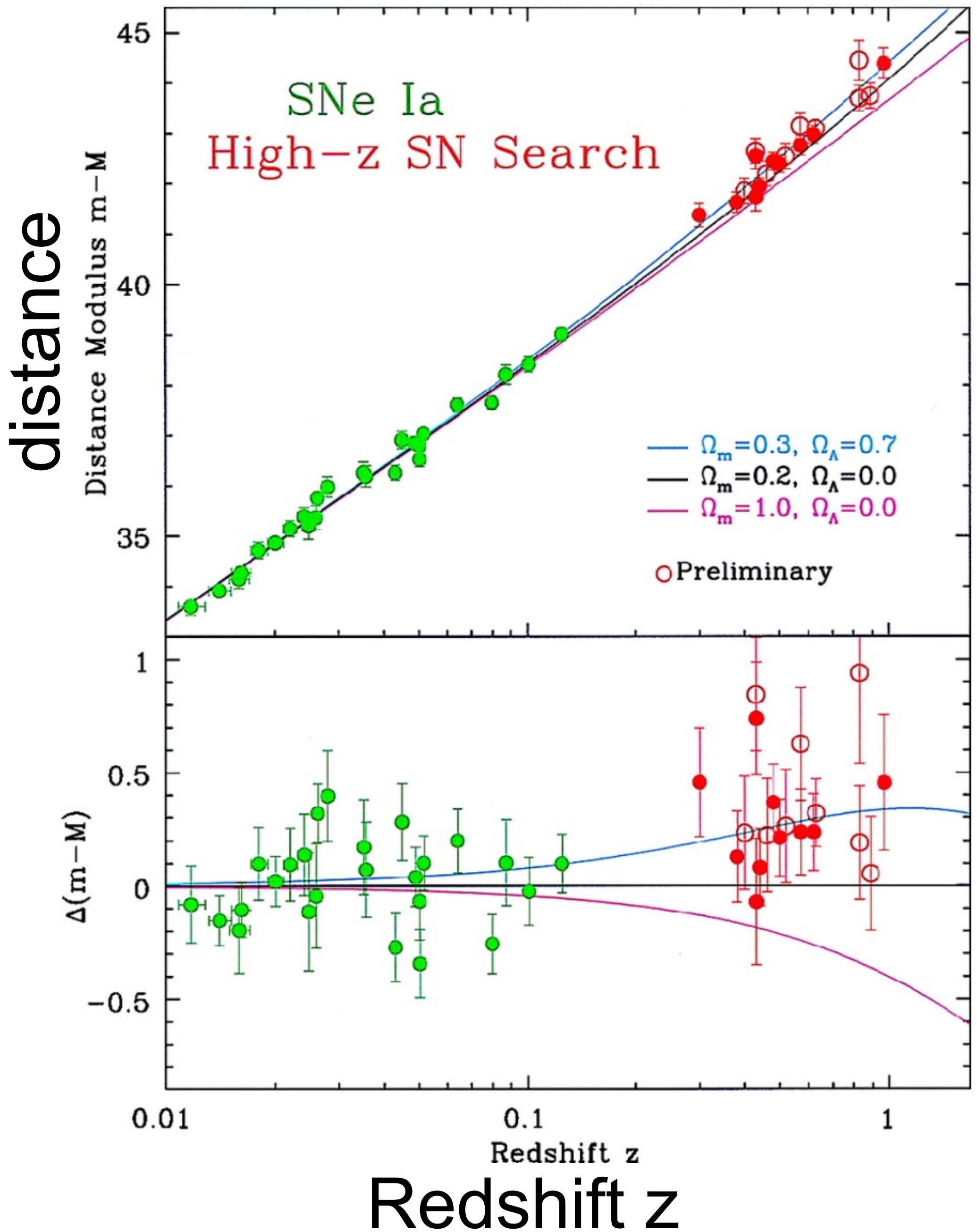
i.e. dark energy must exist and is important component of universe!

Type Ia supernova in nearby spiral galaxy

HST image of NGC 4526 in Virgo Cluster, distance ~ 50 MLY

Type Ia supernovae are standard candles!

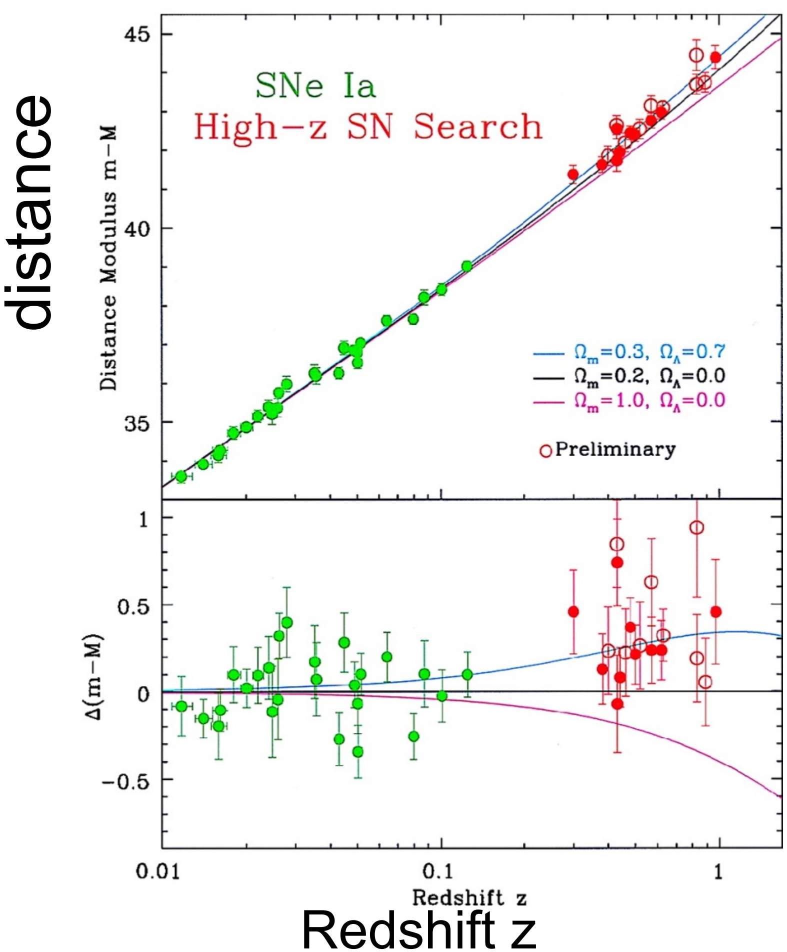
Evidence for ***acceleration*** in expansion of universe

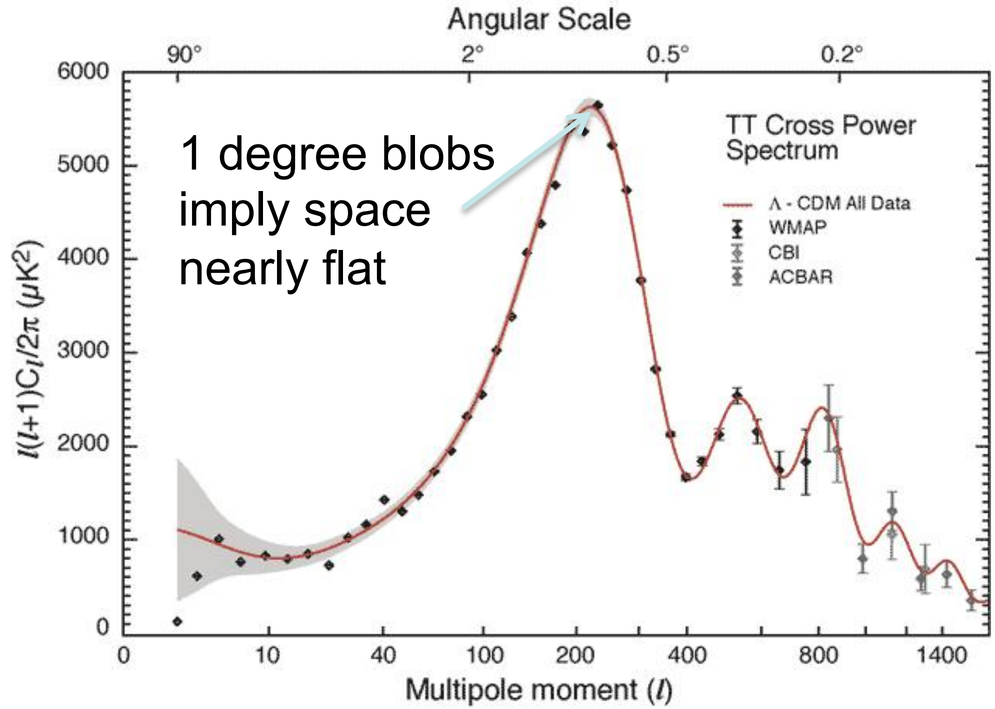


Distant supernovae at a given distance have ***smaller*** redshifts than they would if expansion was constant or slowing down (decelerating)

This wins Nobel Prize in Physics in 2011 !!

Two forms of evidence for Dark Energy



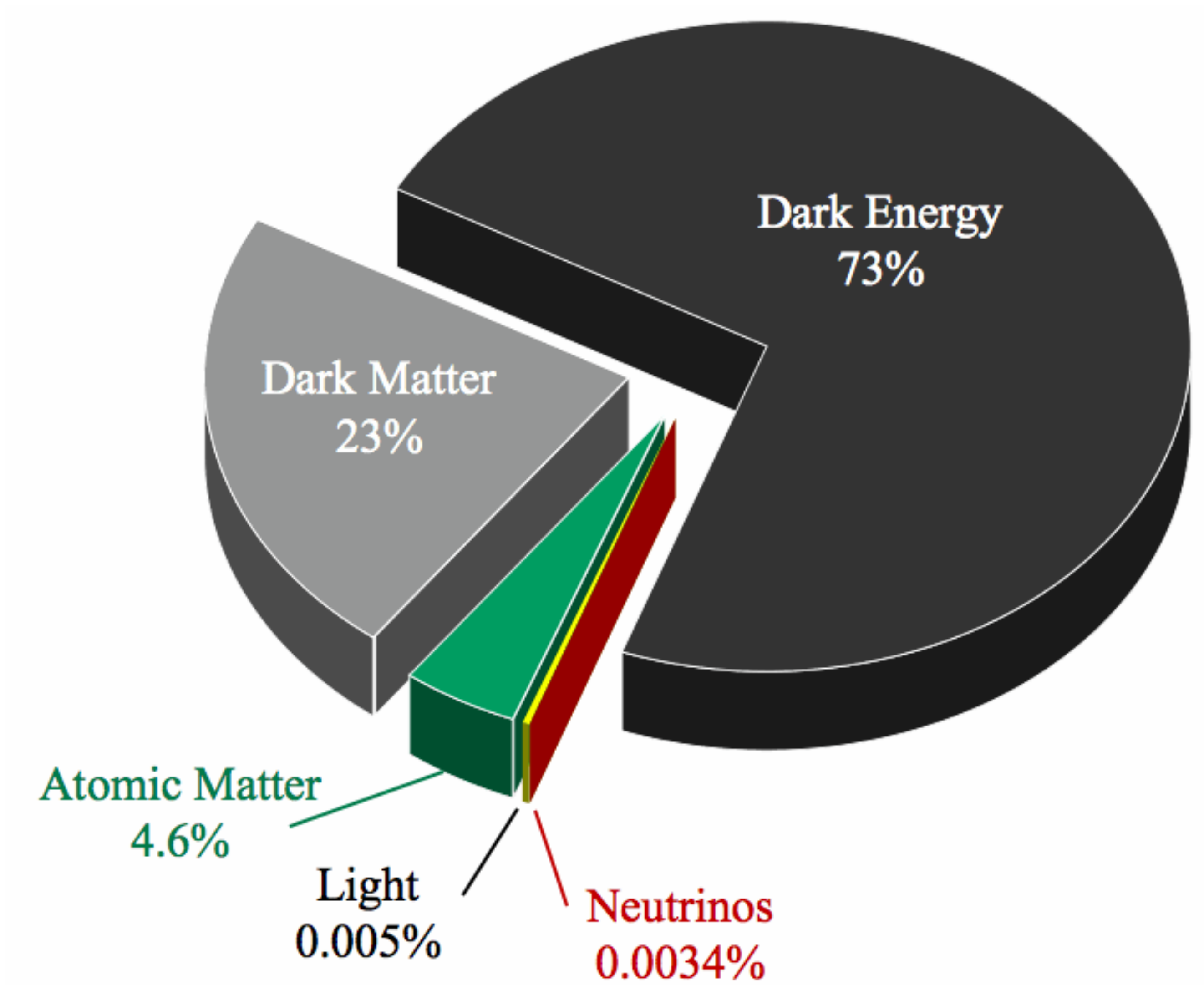


amount of Dark Energy needed to account for acceleration of expansion (Ω_Λ = 0.73) is same amount needed to account for nearly flat space (Ω_o = 1 -> Ω_Λ=0.73) in observable universe

Evidence for Dark Energy from distant standard candles (Type Ia SN)

1. For SN at given (large & known) distance, redshift is smaller than in case of constant expansion
2. Thus photons from large distances have been stretched less than constant expansion case
3. Which implies less rapid expansion in past
4. Which implies expansion rate has accelerated
5. Something must have caused acceleration; that something given name "Dark Energy"

Mass-energy budget of present universe



What is Dark Energy?

A. the energy associated with dark matter $E_{DARK}=M_{DARK}c^2$
B. the mass-energy needed to balance the effect that gravity has on the expansion of the universe
C. the mass-energy needed to bridge the gap between the mass we know exists and what is needed to make the universe flat
D. the mass-energy which is causing the expansion to decelerate
E. Putin's REAL secret plan