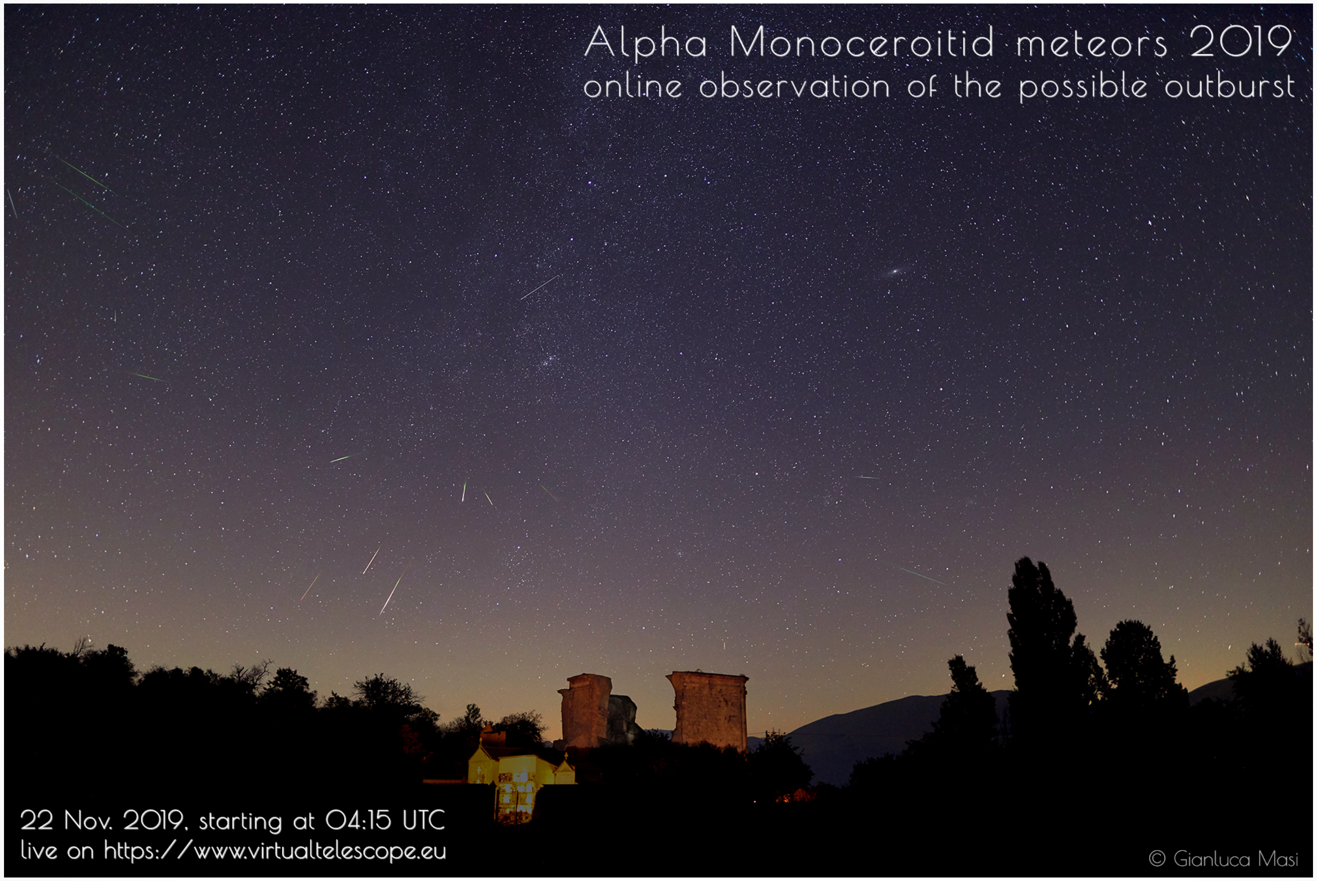
Announcements

- Quiz 4: Thursday Dec 5 (last day of class)
- Final: Dec 12 12:30pm – 3pm

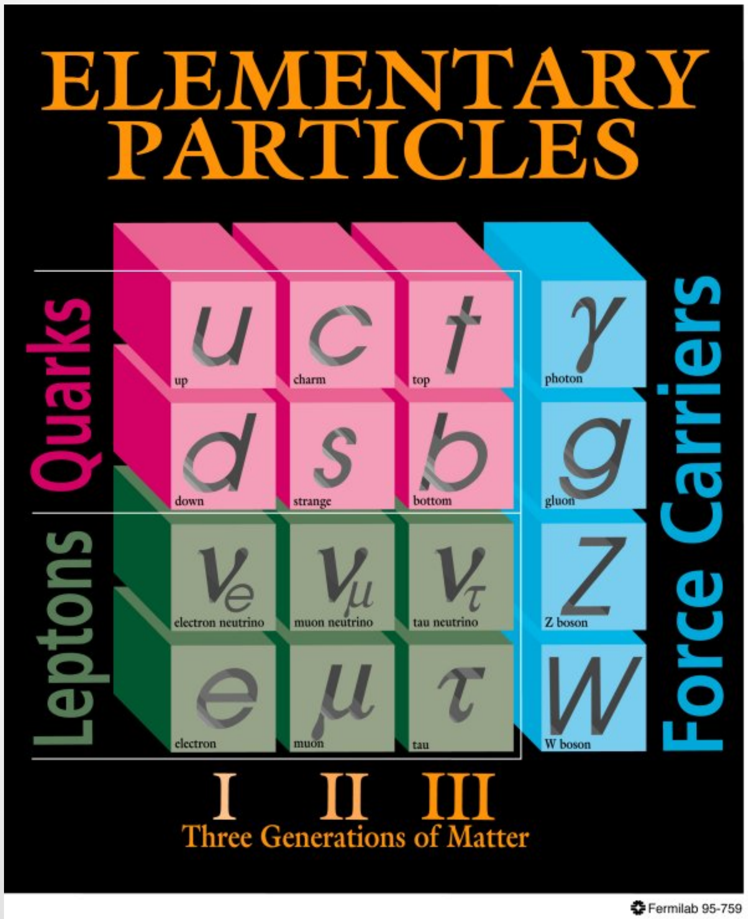
Nov 21 8:50pm



Predicted 5-400 meteors/minute, but with large uncertainty.
Unknown source of a very narrow debris stream.

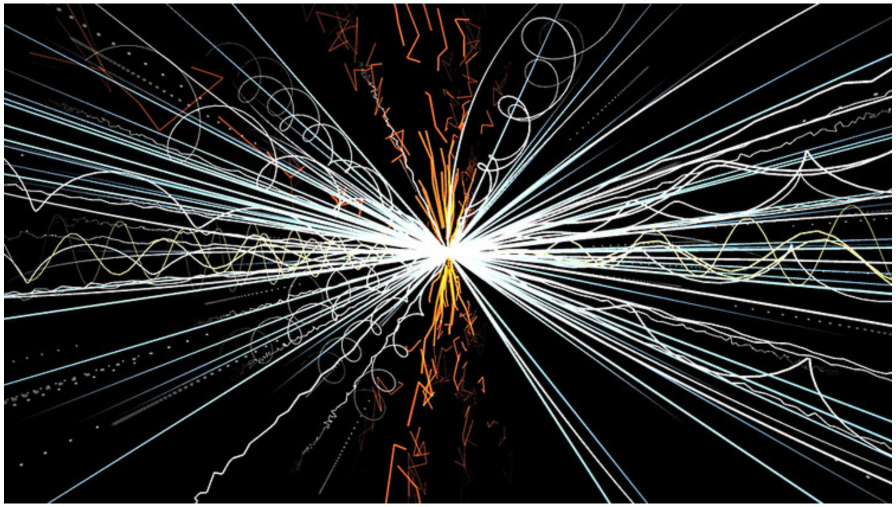
From Last Time

Table of Fundamental Building Blocks



- Fermions: fundamental particles.
  - Leptons (electron)
  - Quarks
- Hadrons: combinations of Fermions (i.e. proton, neutron)
- Bosons: particles that exchange forces

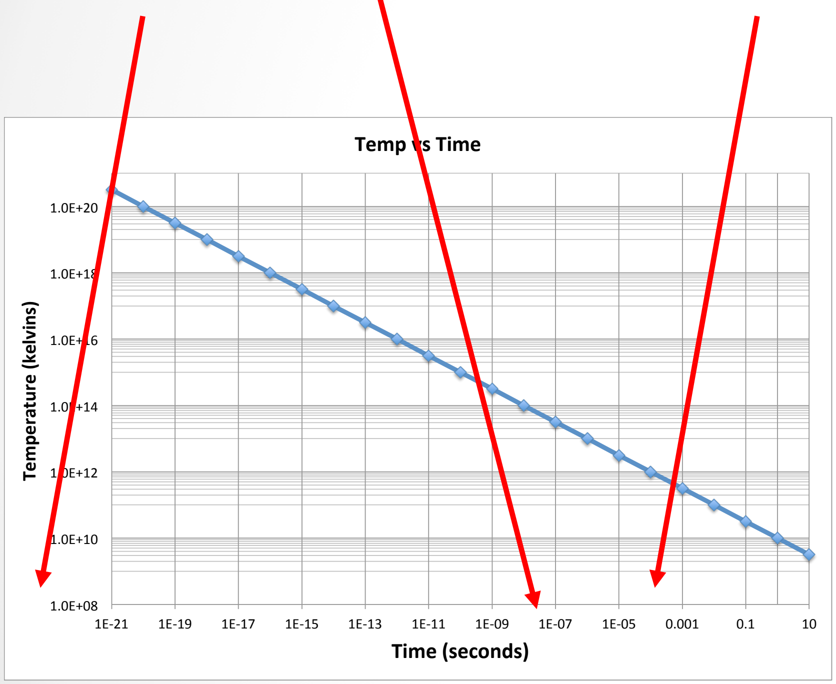
Creation of Matter



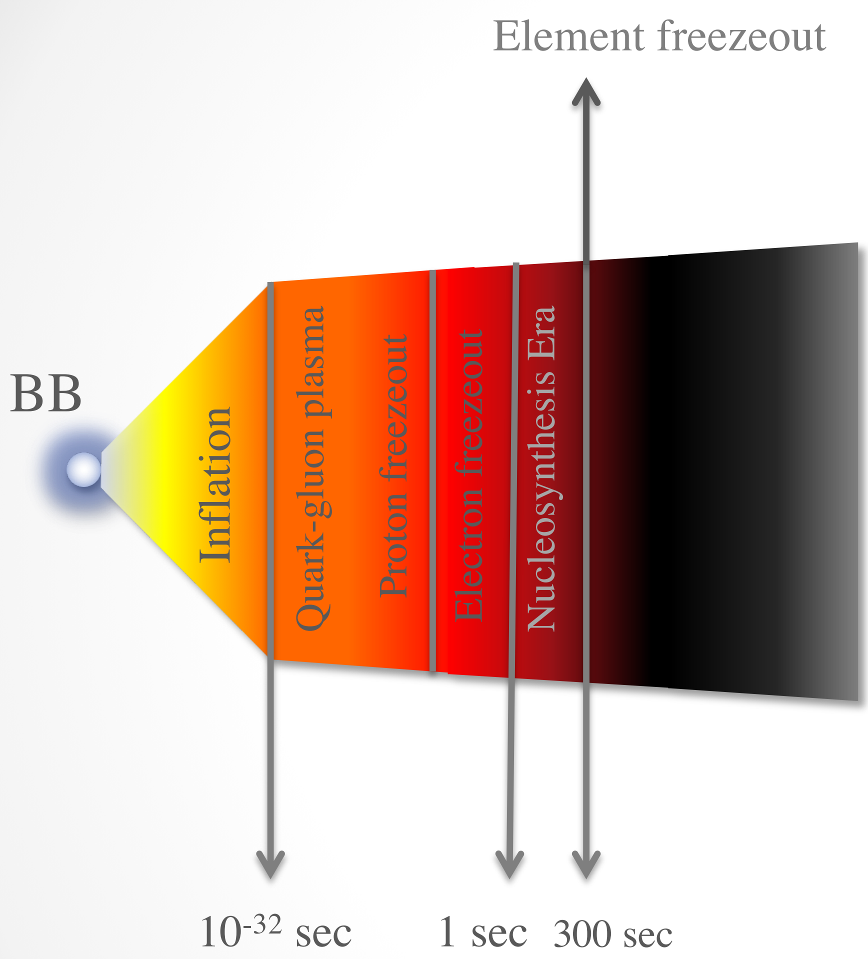
- Think about a volume of space. As the temperature goes up, the energy of photons and particles goes up
- If the average energy is equal to twice the "rest mass energy" of a particle, given by $E=mc^2$, then the particle and its anti-matter particle can be spontaneously created ("Pair production")

Pair-production in the early Universe

HBB p$^+$ freezeout e$^-$ freezeout

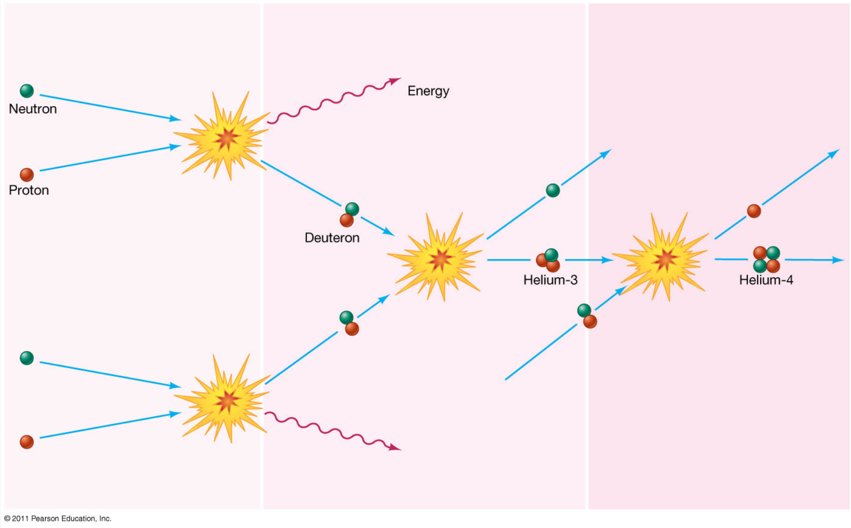


- For time < 1.84 x 10^{-7} seconds after the HBB, the average energy of a volume of the Universe was high enough that protons and anti-protons were being spontaneously produced (and destroyed): Quark-hadron-photon Soup
- As the Universe cooled, after 1.84 x 10^{-7} seconds, no more protons were made: "p$^+$ freezeout"



- Pair-production produces matter-anti-matter pairs from photon field (conservation laws)
- Hadron Era with production of p^+ and n^0 ends when energy of the photon field is < 2 x 938.3 MeV/c^2
- Lepton Era lasts longer as e^-+e^+ total mass is 2 x 0.511 MeV/c^2 and it takes the Universe longer to cool to this equivalent energy
- Nucleosynthesis starts when deuterons (p^++n^0) are no longer being blasted apart by energetic photons
- Nucleosynthesis ends when temperature is too low for fusion

Primordial Nucleosynthesis



Principle fusion chain:

- $p^+ + n^0 \rightarrow H^2$ (deuterium)
  - No electrical repulsion
- $H^2 + H^2 \rightarrow He^3 + n^0$
- $He^3 + H^2 \rightarrow He^4 + p^+$

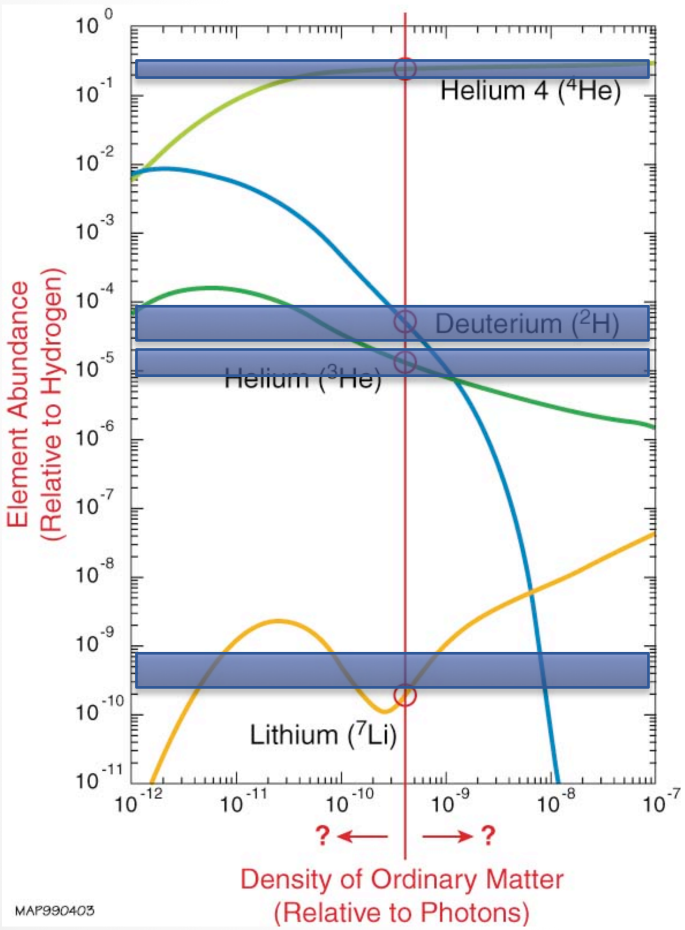
H^2 is relatively easily broken apart by energetic photons.

This is what starts the nucleosynthesis chain going: Universe cools to the point where very energetic photons are rare and H^2 is available

HBB nucleosynthesis

- After proton freeze out (1.84 x 10^{-7}s) and electron freezeout, there are protons, neutrons and electrons and many energetic photons
- Starting ~10 seconds and lasting till around 20 minutes after the HBB, the temperature and density of the Universe is right for nucleosynthesis
- Fuse Hydrogen to Helium, but because Be isotopes are unstable, heavier elements are not formed.
- HBB produced lots of hydrogen, 25% by mass of He^4, and trace amounts of H^2, $H^{3,}$ He^3, Li^7, Li^6, Be^7

Why believe in HBB?



- Observations match specific predictions for the "primordial" abundance of H, H^2, He^3, He^4 and Li^7
- Older and older stars show lower and lower abundances of elements heavier than He as does inter-galactic gas at early times

Clicker quiz

Why are electron/anti-electron pairs formed later after the HBB than proton/anti-proton pairs?

A. Because electrons are leptons and protons are made of quarks
B. Because e^- have a smaller mass than p^+
C. Because the Universe needs to cool to the point that nucleosynthesis can occur
D. Because e^- can only exist around p^+

Clicker Quiz

Why did the era of HBB nucleosynthesis end?

A. The expanding universe cooled below the minimum temperature for nuclear fusion
B. All the protons and neutrons required for nuclear fusion were used up
C. e^- freezeout occurred
D. The radiation field was so intense that photons continuously broke down heavier elements

New Material

New: Next HBB test

- Comic Microwave Background

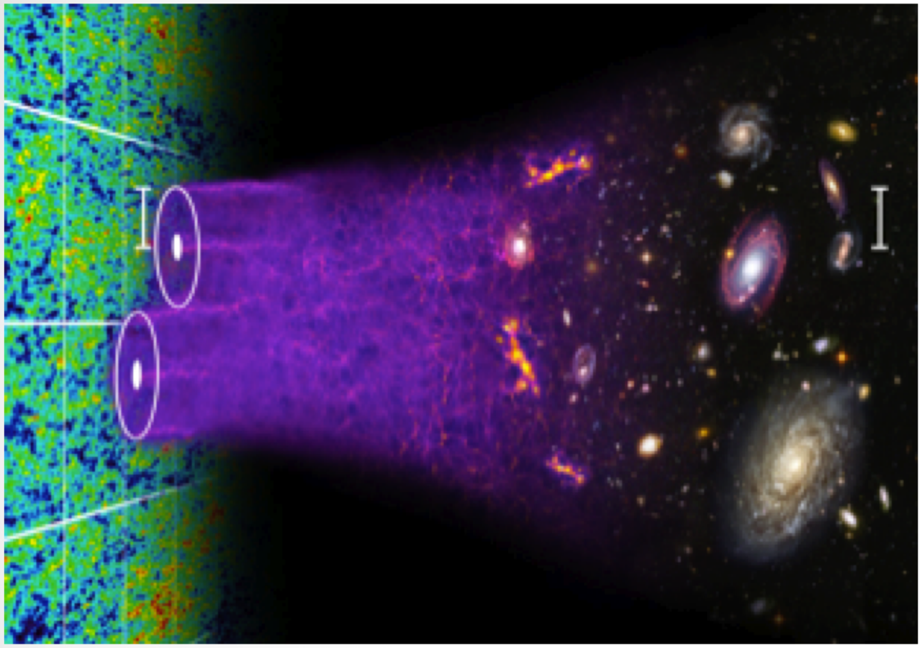
Cosmic Microwave Background

- Gamov and his collaborators continued their investigations and noted the after the era of nucleosynthesis, the Universe remained hot enough for almost 380,000 years for hydrogen atoms to be ionized
- Photons travel a very small distance before being “scattered” off electrons and protons in this plasma
- The Universe was foggy

CMB

- At 370,000 years after the Big Bang, the Universe has cooled to 3000K and electrons combined with nuclei
- Now, the vast majority of photons no longer are absorbed by atoms or scattered by free electrons: the Universe became transparent
  - As we look back in time we should see the "surface of last scattering" in every direction redshifted by a large factor
  - And/or radiation of the 3000K plasma fills the Universe and has been diluted by the subsequent expansion to look like that from a 3K object

CMB



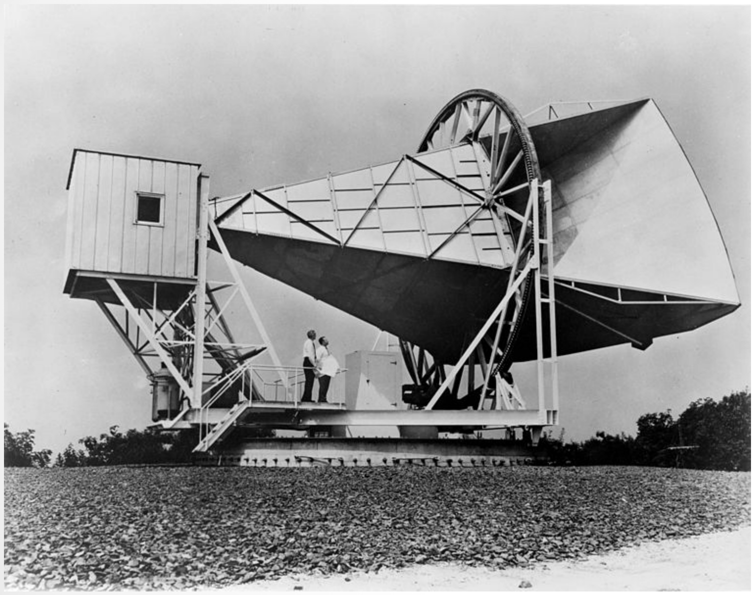
- Gamov, Alpher, Hermann work was rediscovered by Russian astronomers and Robert Dicke at Princeton in the early 1960s
- A group from Princeton started to build a radio telescope to measure the "3°" background radiation or "cosmic microwave background"

Wien's Law: $\lambda_{max}(m)=3 \times 10^{-3}/T(k)$

$\lambda_m=1\mu$ for 3000k plasma at 370,000 years

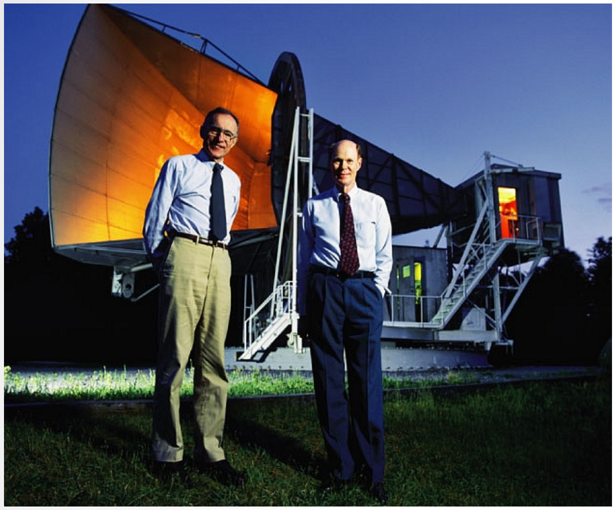
λ_m=1mm for 3k equivalent today

CMB



As the Princeton group started to build a radio telescope to test this hypothesis, two physicists at Bell Labs in 1964 had already detected the radiation without quite realizing what they were looking at

Penzias and Wilson

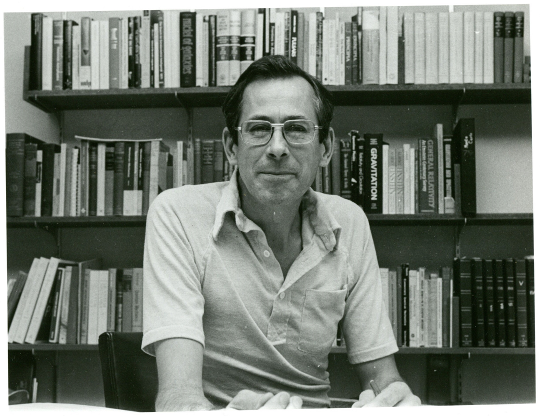


"A measurement of excess antenna temperature at 4080 Megacycles per second"

1978 Nobel Prize

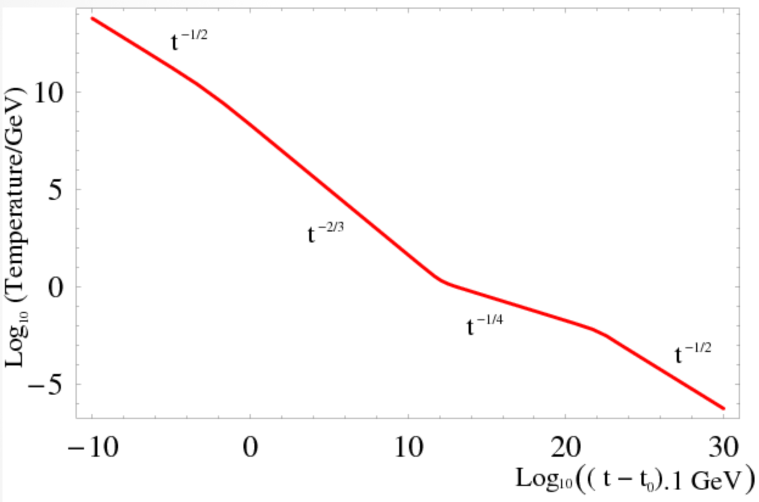
- Arno Penzias and Robert Wilson at Bell Labs developing a microwave horn antenna designed to measure reflected radio signals from Echo balloon satellites
- Background noise in the receiver was a factor of 100 higher than expected
- Saw it everywhere in the sky, day and night
- Cooled detectors to liquid-helium temperatures, removed "dialectric material" from the horn. No change.

Penzias and Wilson



- In a conversation with MIT physicist Bernie Burke, they realized it was the radiation the Princeton group was looking for
- Burke put them in touch with Jim Peebles and Robert Dicke and they realized the observations matched the noise data almost perfectly.

3-degree Microwave Background



If due to the expansion of the Universe, the temperature of the Universe is given by:

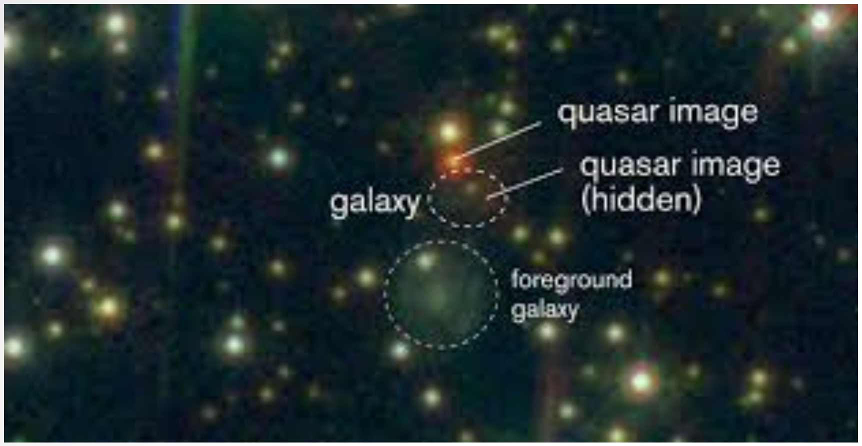
Temp= 2.725(1+z)

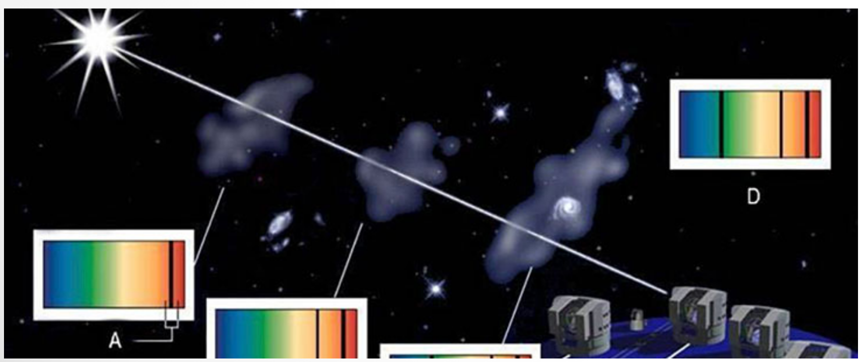
At 380,000 after the Big Bang, the redshift of the Universe is about 1100 hence the spectrum of the 3000K hot plasma is redshifted and looks like the spectrum from a 2.75K plasma

A check on the evolution of temperature

- Andrew McKellar in 1941 measured the state of the molecules CN and CH in the interstellar medium and concluded there was an ambient "temperature" of empty space of 2.75K
- He measured the excitation of the molecules by the cosmic microwave background!

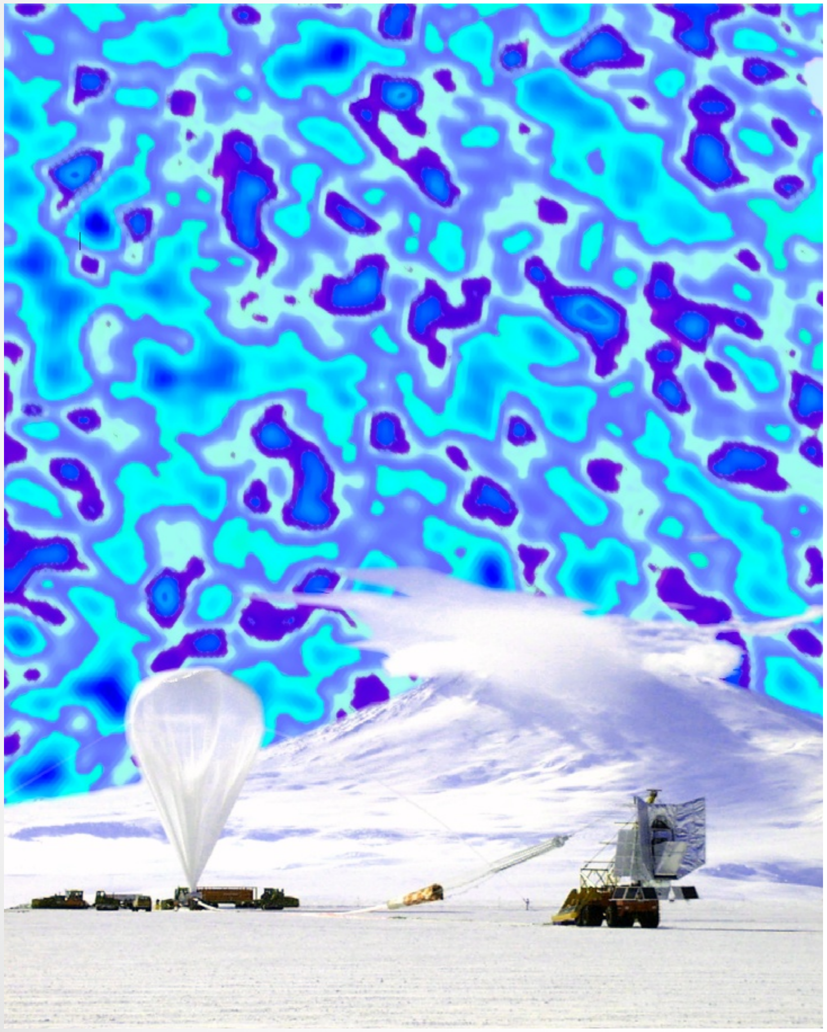
Double Check





- The baseline background temperature of the Universe has been now measured via this technique for gas as seen at 7 billion years ago and 11 billion years ago
- 7Gyr: T=5.10K (5.15K predicted
- 11Gyr: T=9.15K (9.3K predicted)

CMB Fluctuations

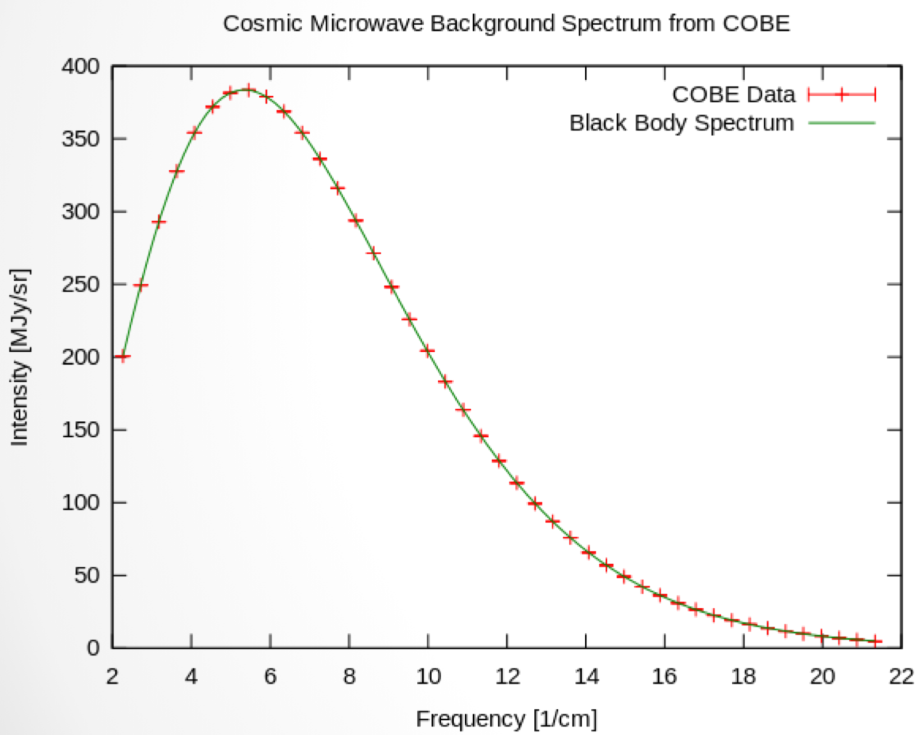


- It was recognized that the CMB could not be strictly uniform and still have the cosmic structures that we see in the Universe
- The CMB was predicted to have "hot" and "cool" spots at the level of *one part in 100,000*
- If the fluctuations existed, all competing HBB theories were finished
- This was a very hard measurement from the ground and for a decade, researchers pushed closer and closer to the 1/100,000 limit without seeing anything

CMB Fluctuations

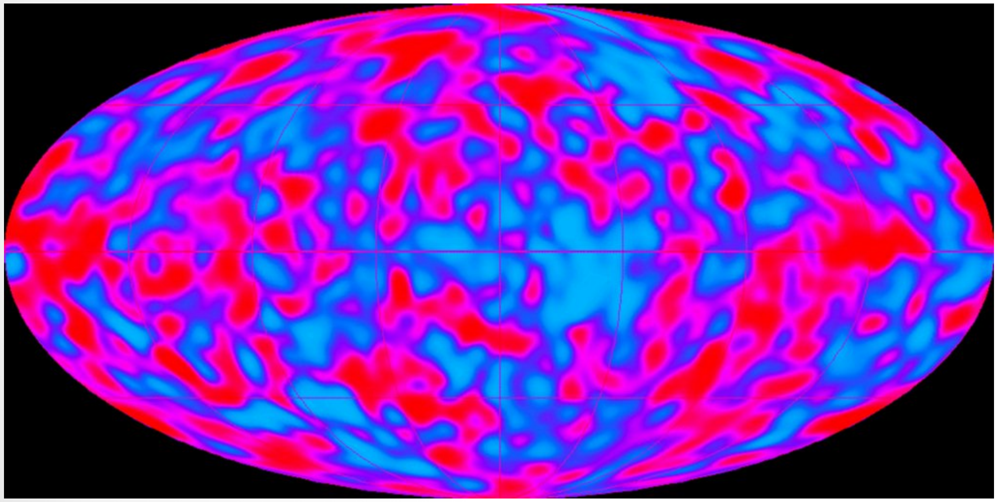
- COBE was a satellite designed specifically to measure the CMB.
- Launched on a Delta rocket in 1989
- Soviet's had launched a satellite to make the same measurement in 1983, but did not initially see fluctuations in the data

CMB Fluctuations



First COBE result was that the cosmic background radiation spectrum was spectacularly fit by a “blackbody” spectrum for a 2.725K source just as predicted by the HBB and an expansion of the Universe by a factor of ~1100 since decoupling

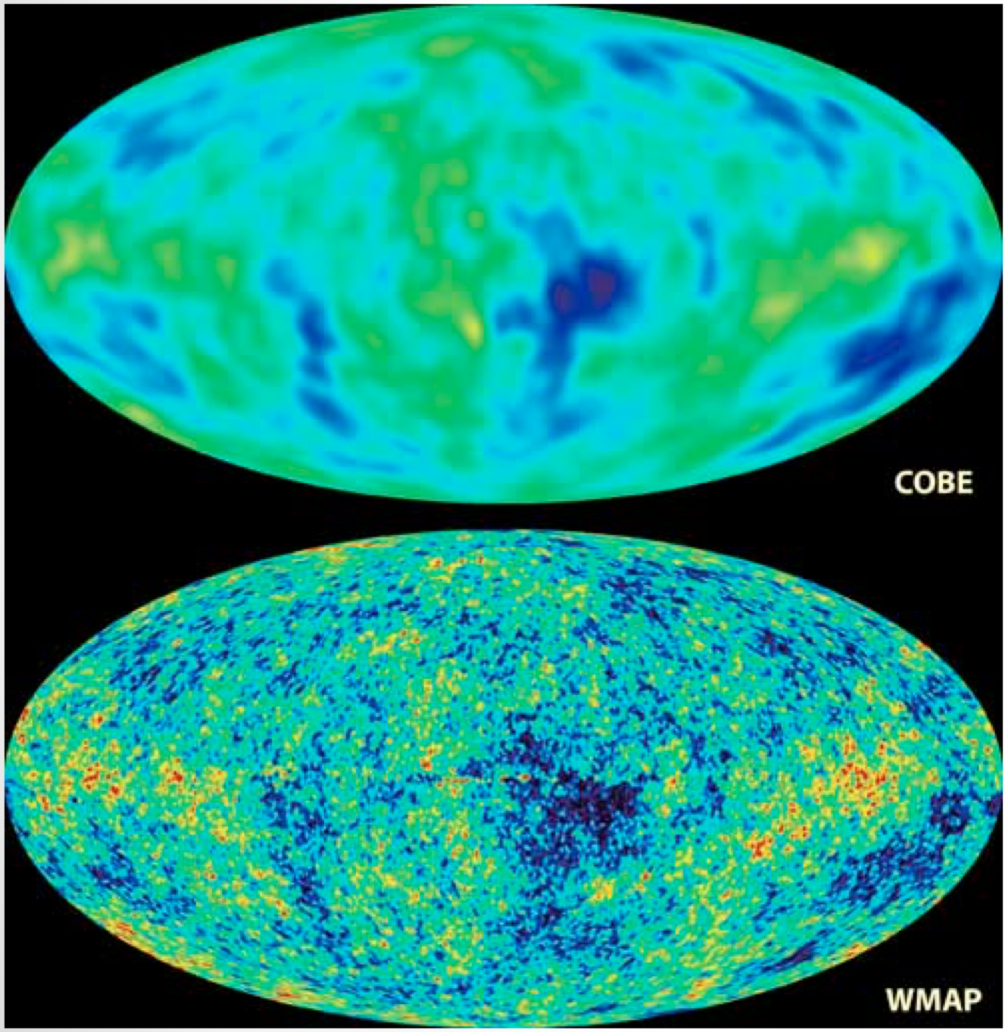
CMB Fluctuations



- Second result of COBE was the measurement of CMD fluctuations at the predicted level of 1 part in 10^5
- More Nobel Prizes! George Smoot and John Mather
- The growth of these tiny fluctuations into galaxies and clusters of galaxies today is the subject of the rest of the class
- There are ~400 microwave photons per cubic centimeter everywhere in the Universe

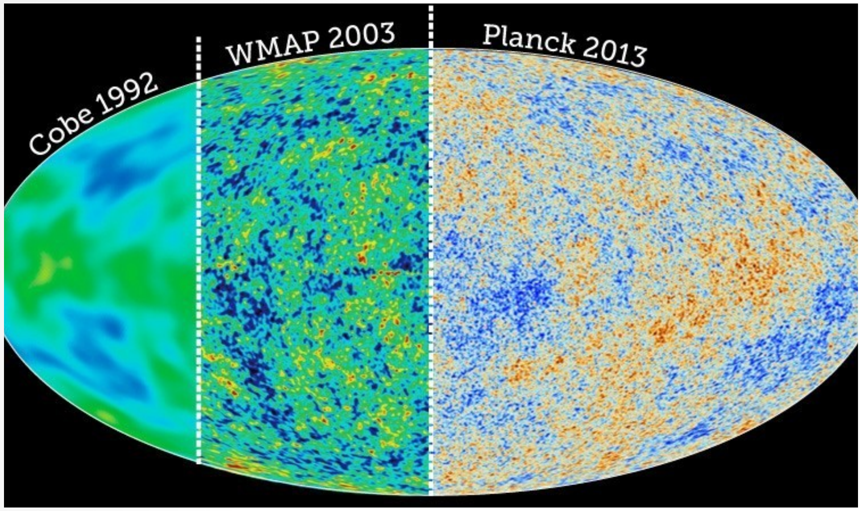
- 2006 Nobel Prize to George Smoot at UC Berkeley
  - Named parking spot at Berkeley
  - Guest appearance on the The Big Bang television show
  - Only Nobel Prize winner to receive The Rolling Wave at a UCB football game
  - $1M winner on "Are you smarter than a 5th grader?"
- Soundly trounced by MB on Science Jeopardy

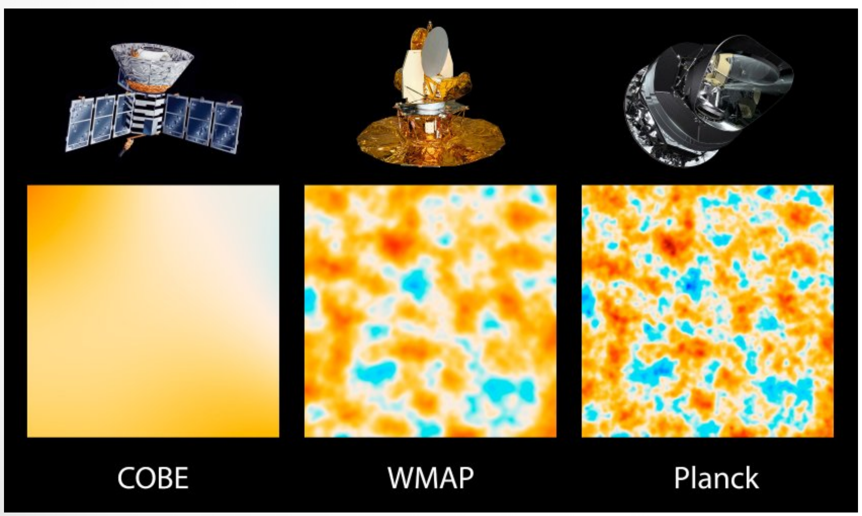
WMAP



- COBE was followed by two additional space missions with greater sensitivity and higher spatial resolution
- WMAP had 33 times better resolution and 45 times the sensitivity
- Total range in temperature is only 0.0004K

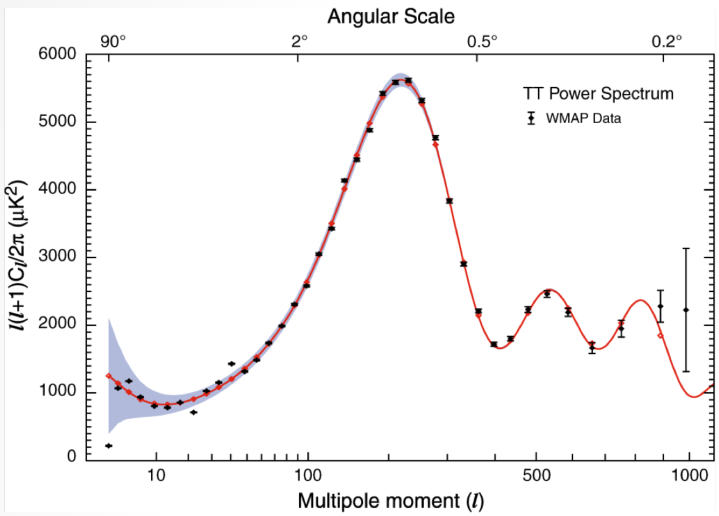
Planck

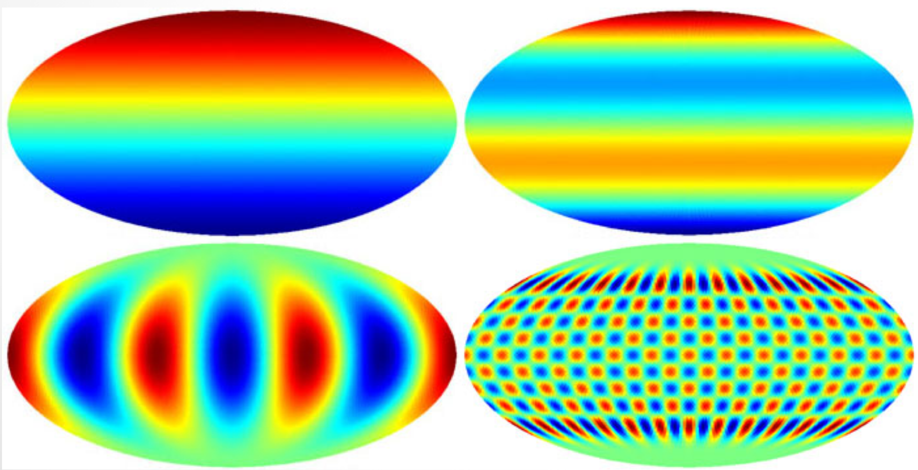




The European Space Agency launched Planck in 2013 and provided an independent measurement with even better precision that WMAP

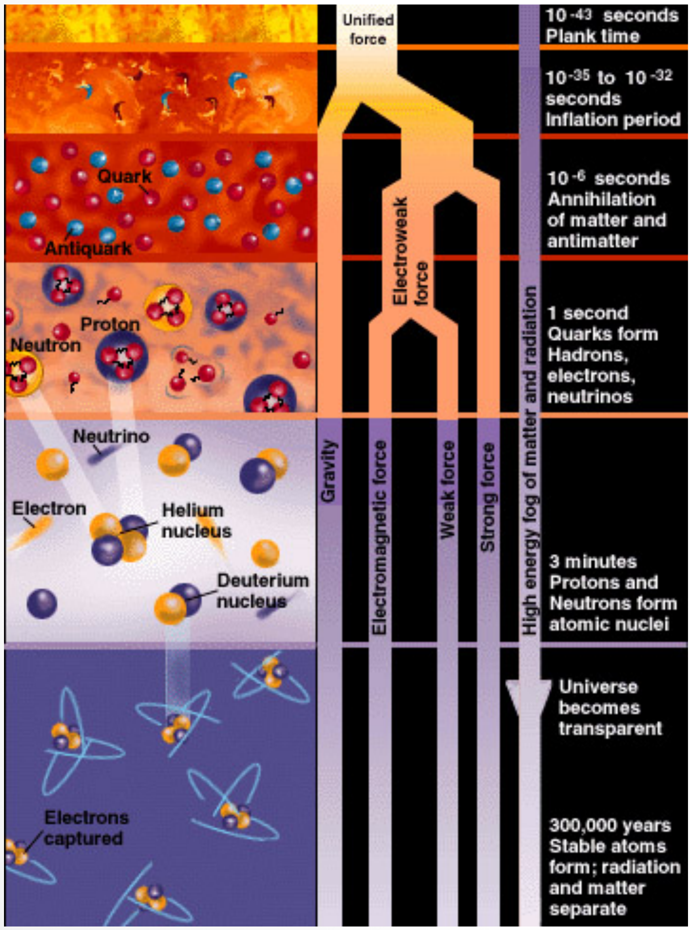
Quantifying anisotropy





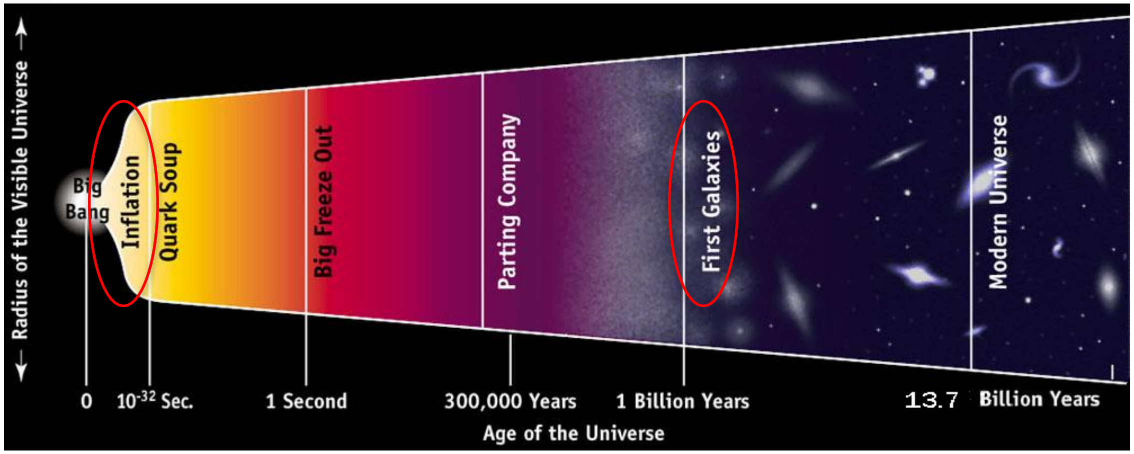
- The "power spectrum" describes the distribution of fluctuations on different spatial scales on the sky.
- The predictions for where the correlations are strong and weak depend on physical properties of the Universe at the time of decoupling

HBB test #2

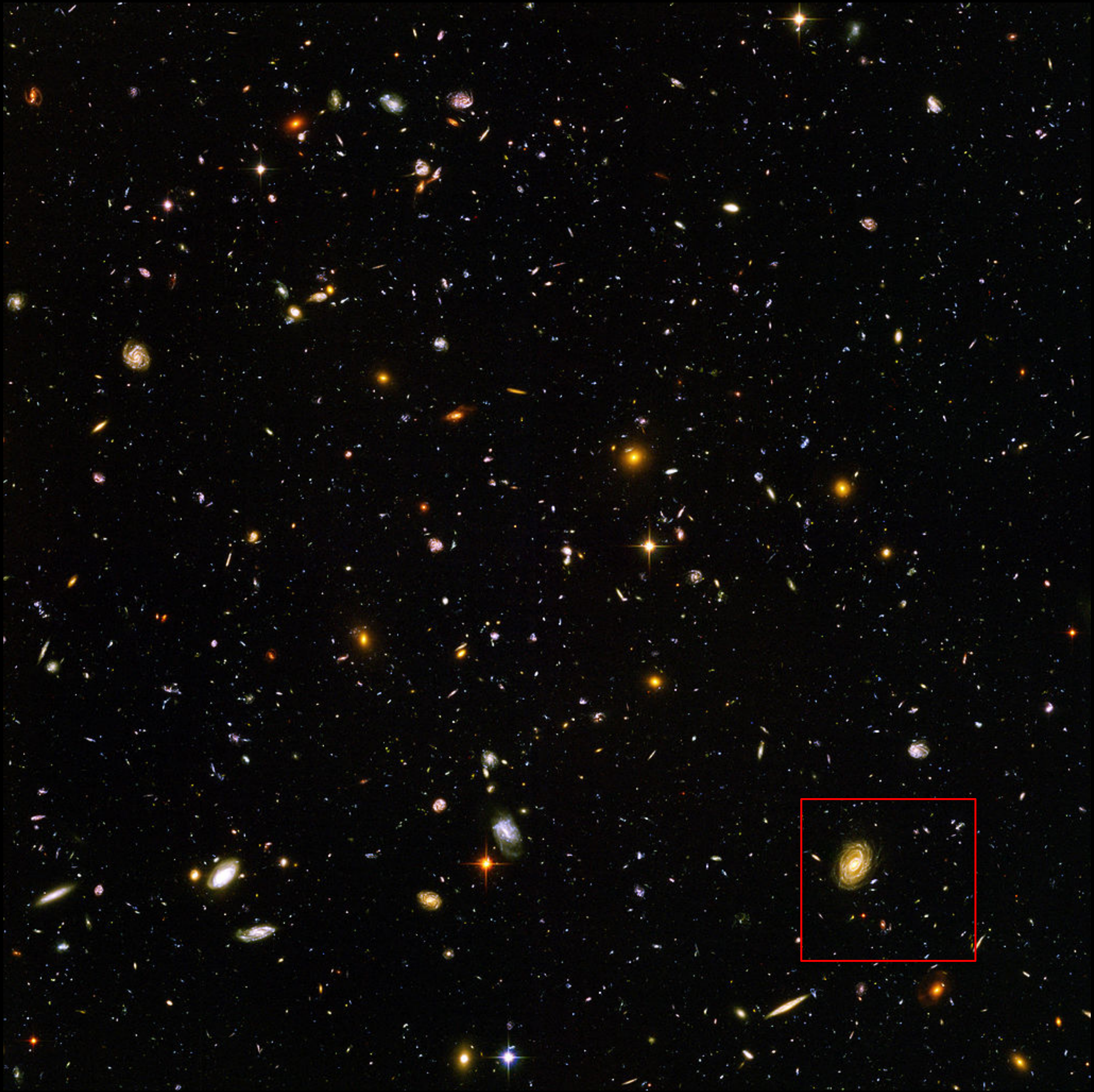


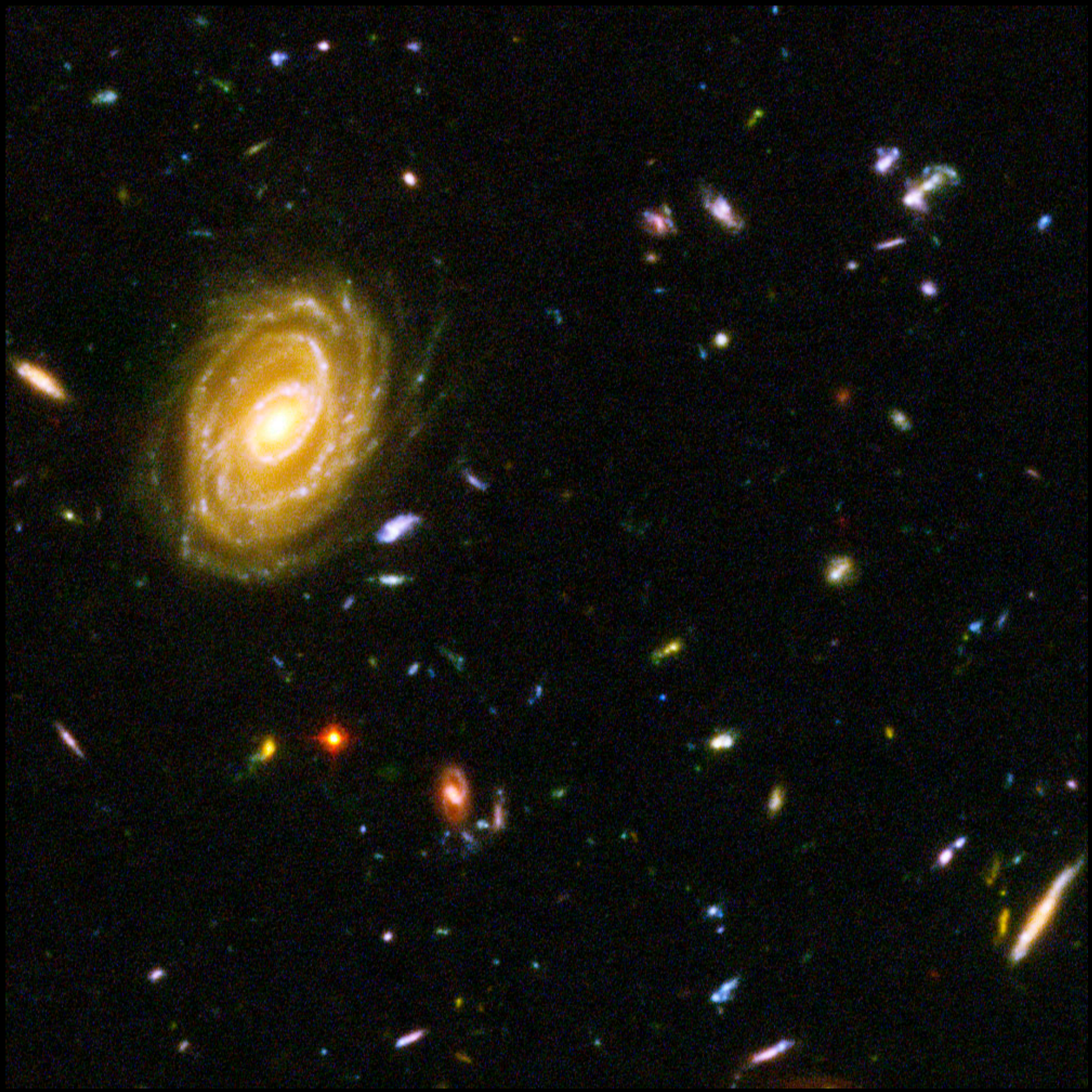
- CMB and fluctuations in the CMB are the second major test of the HBB that it passes with flying colors

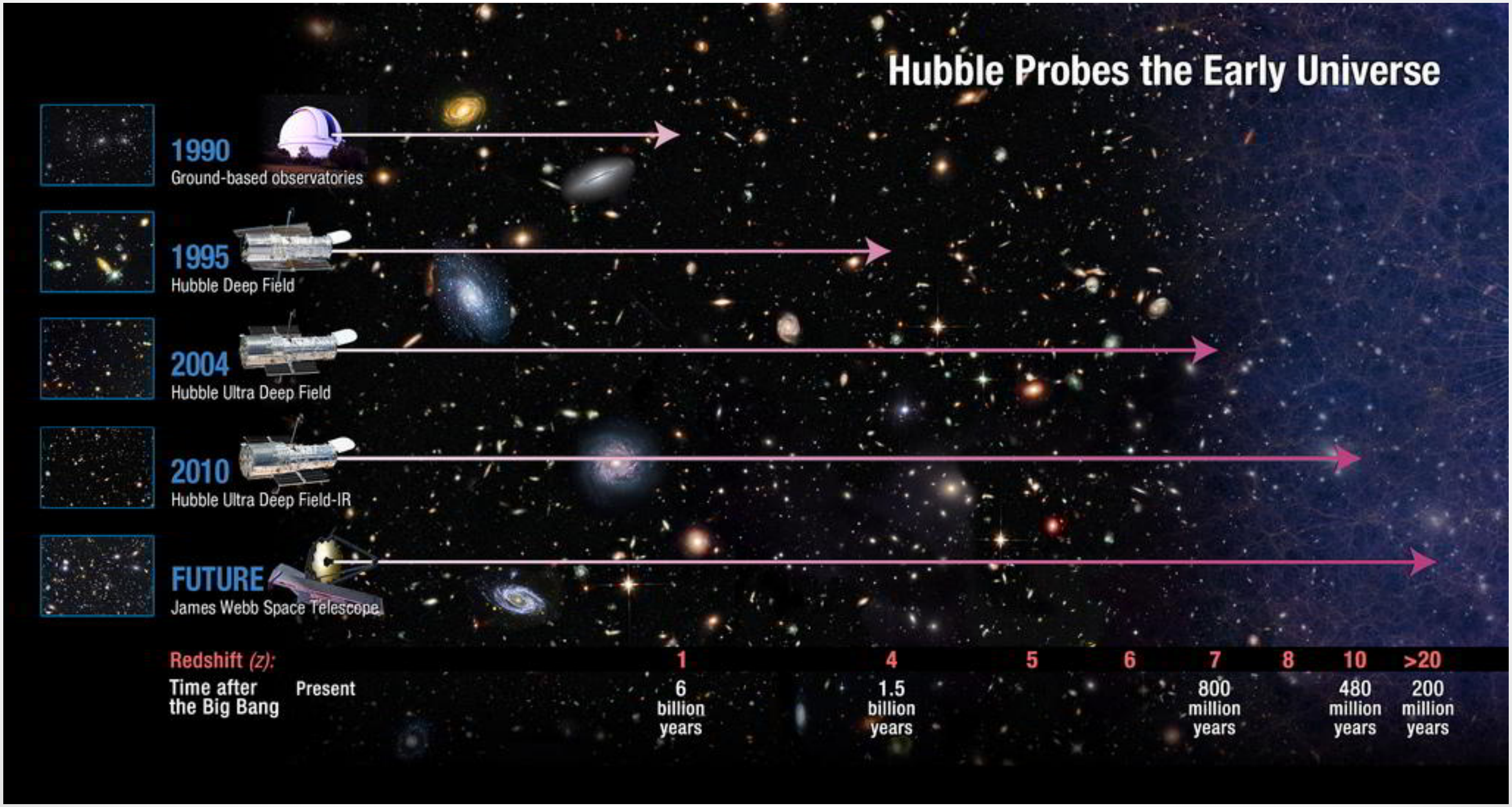
Last topics

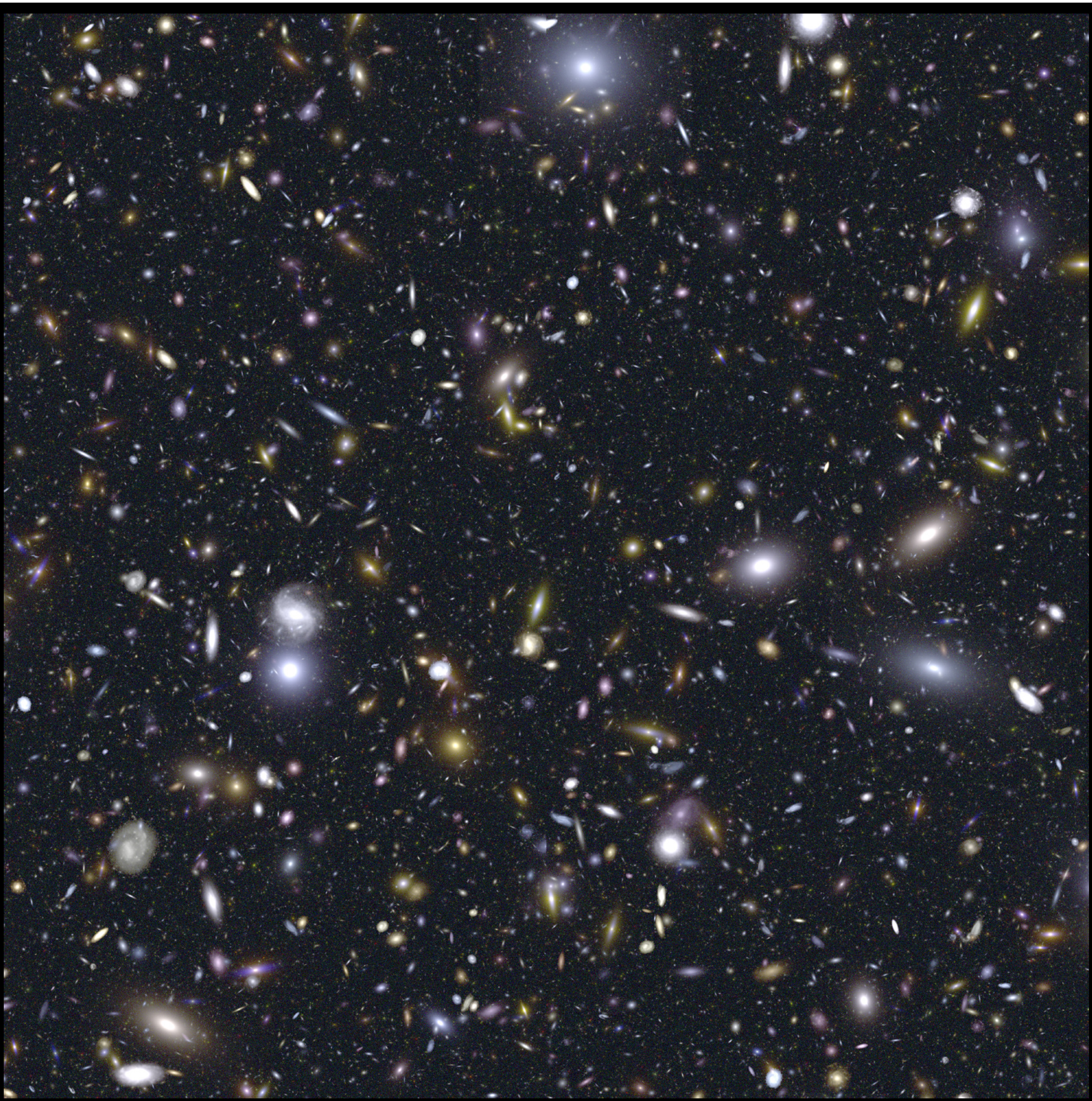


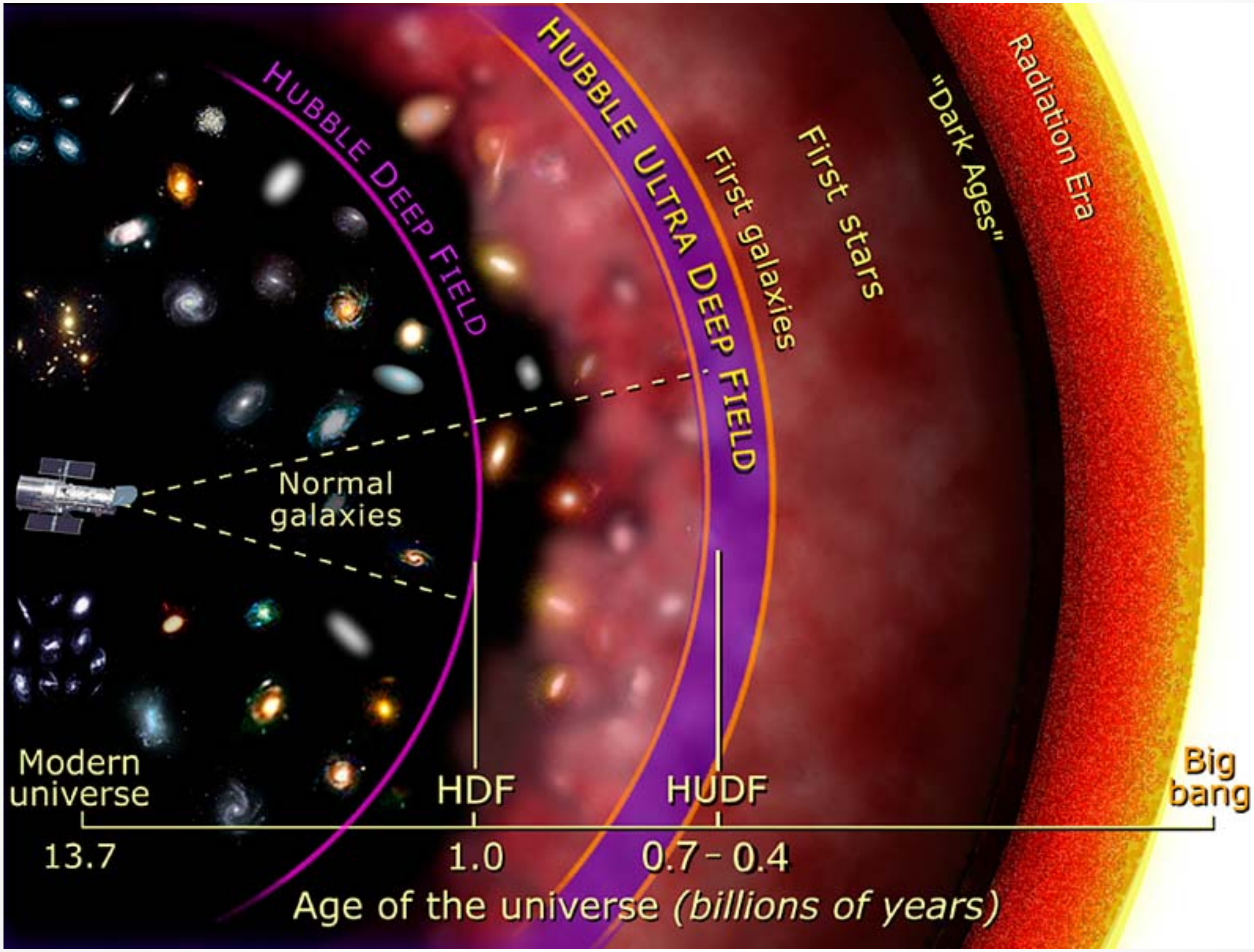
- Shape of the Universe
- Formation of structure
- Inflation
- The cold, dark future



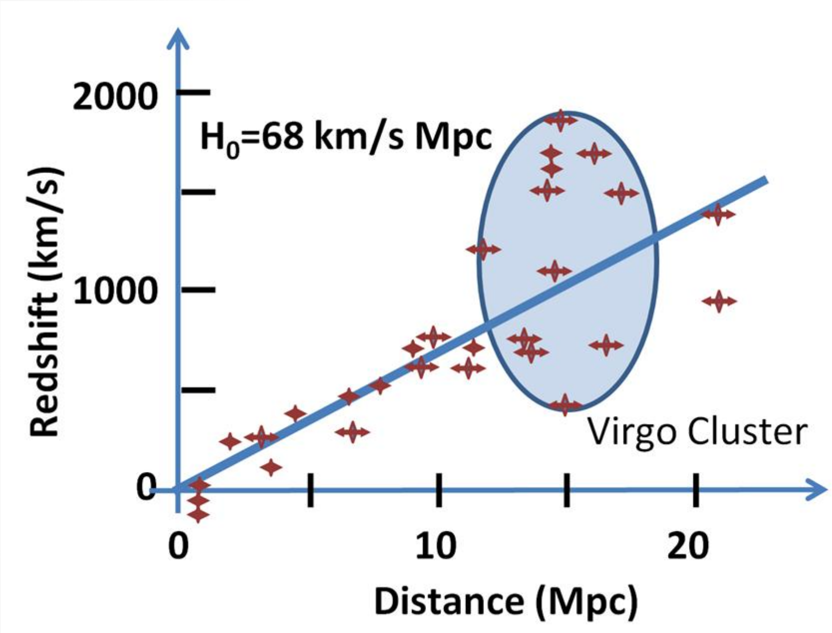



Hubble Probes the Early Universe
1990
Ground-based observatories
1995
Hubble Deep Field
2004
Hubble Ultra Deep Field
2010
Hubble Ultra Deep Field-IR
FUTURE
James Webb Space Telescope
Redshift (z):
1
4
5
6
7
8
10
>20
Time after the Big Bang
Present
6 billion years
1.5 billion years
800 million years
480 million years
200 million years



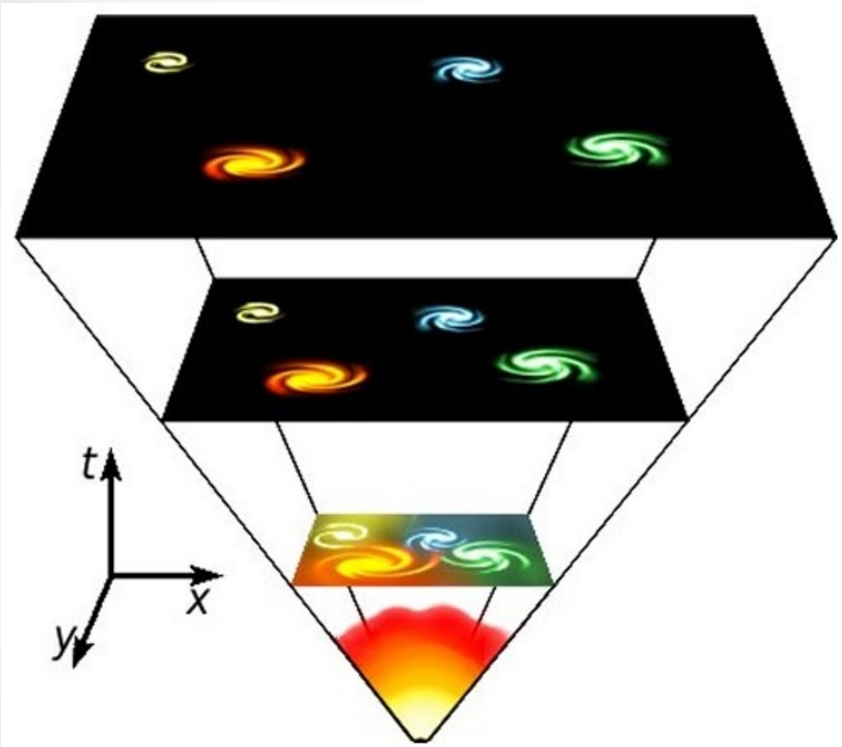

Hubble Deep Field
Hubble Ultra Deep Field
First galaxies
First stars
"Dark Ages"
Radiation Era
Normal galaxies
Modern universe
HDF
HUDF
Big bang
13.7
1.0
0.7 – 0.4
Age of the universe (billions of years)

Back to Hubble's Law



- To map the distribution of galaxies in space and time need to measure the "redshift" of galaxies
- Using Hubble's Law can use velocities to estimate distances
- Get for free information on the star formation history of the Universe, evolution of galaxies, evolution of QSOs and the distribution of matter on large scales

Redshift Measurements



- The measurement is of the change in wavelength of absorption or emission lines from a galaxy:

$$z = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{\Delta\lambda}{\lambda_0}$$

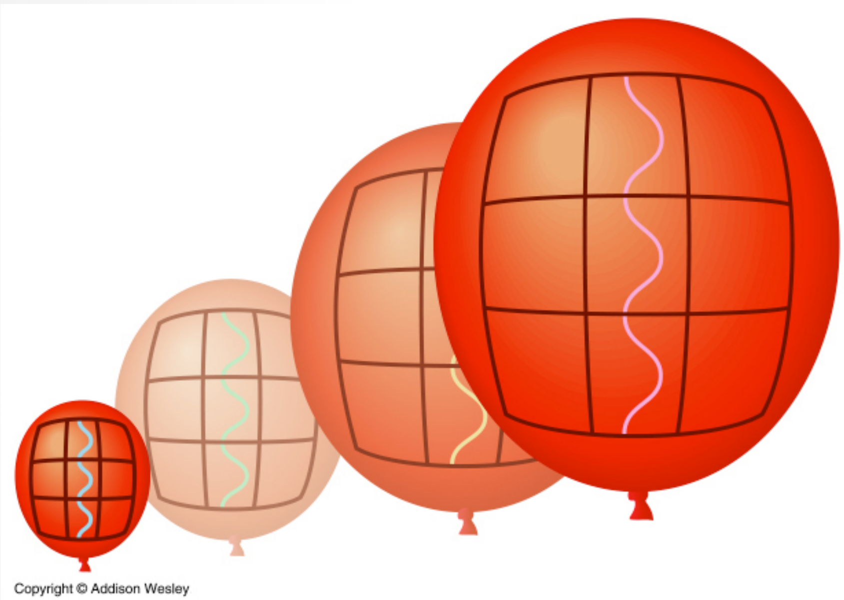
$$v = c \times \frac{\Delta\lambda}{\lambda_0}$$

If interpreted as Doppler shift

$$v = cz$$

Only holds for v<<c. Use relativistic form of Doppler shift for larger velocities

Scale Factor of the Universe



$$z = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{\lambda}{\lambda_0} - \frac{\lambda_0}{\lambda_0} = \frac{\lambda}{\lambda_0} - 1$$

$$\frac{\lambda}{\lambda_0} = 1 + z$$

(1 + z) is the ratio by which the Universe has expanded since the photons left the object

iclicker

- Suppose you take a spectrum of a distant QSO and determine that it has a redshift z = 3. How much smaller (compared to today) was the Universe when the light left the QSO? (recall $\lambda/\lambda_o=1 + z$)
  A. 1/3
  B. 3
  C. ¼
  D. 4
  E. huh?

λ/λ_o= the expansion factor = 1 + 3 =4

The Universe is 4 times larger today so it was ¼ its current size when the light left the QSO

Hubble's Law: Universe in 3-D

Aside from "peculiar motion", the Hubble constant can be used to estimate distances to galaxies:

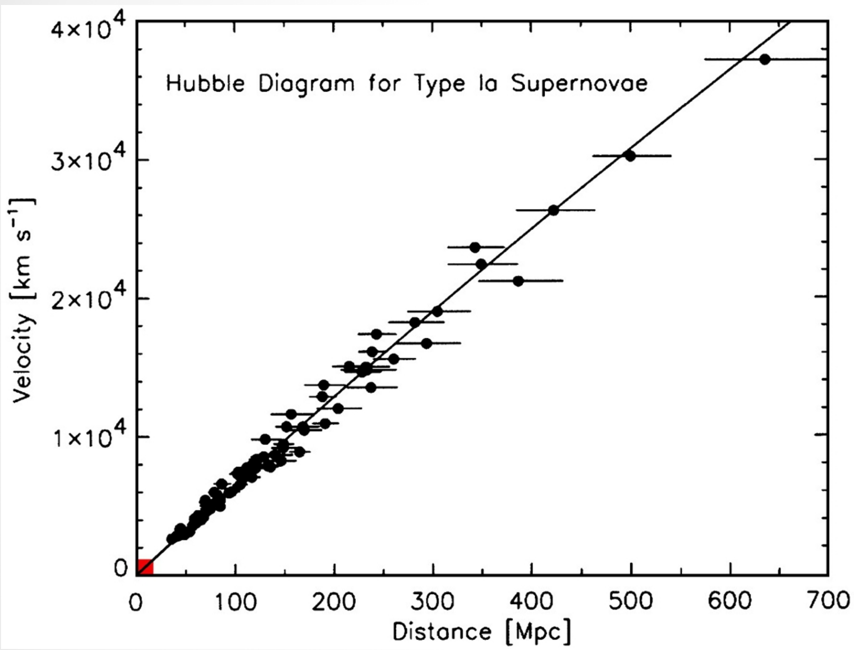
$$v = cz = H_o d$$

v= velocity measured from spectral line shifts

d=distance to the galaxy

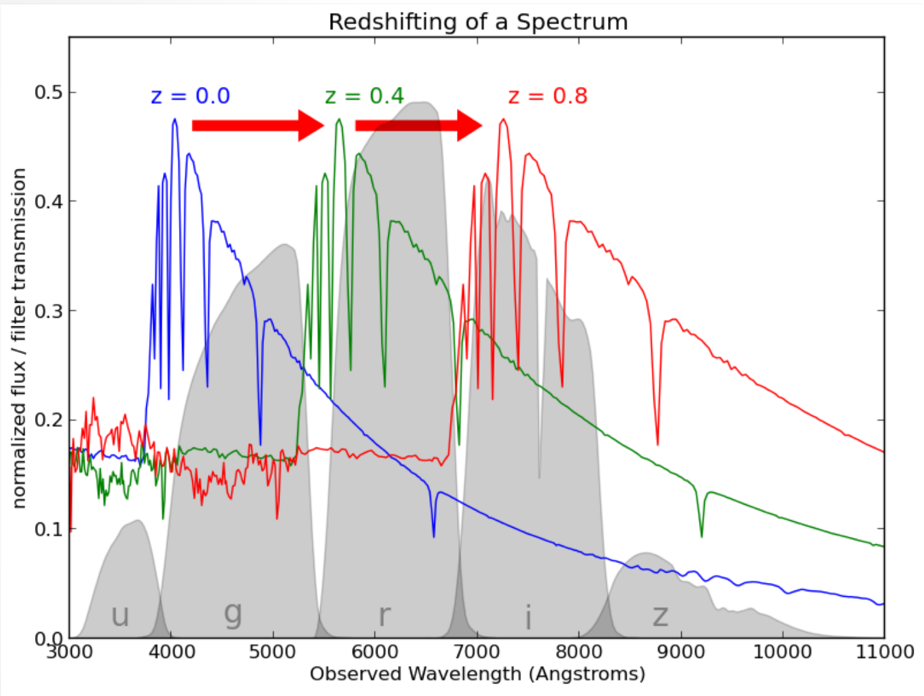
H_o= Hubble constant at current time

v in km/sec, H_o in (km/sec)/Mpc, d in Mpc



- H_o is the slope of the plot of velocity vs distance and is often in units of (km/sec)/Mpc (1/time)
- Local measurement
- Can track expansion rate at earlier times
- Deviations from a straight line tell us is the expansion is slowing down or speeding up

Galaxy Distances from z



- Take a spectrum, measure speed, s, from the shift in spectral line position.
- Suppose you measure s=18,000 km/sec:

$$d = s/H_o$$

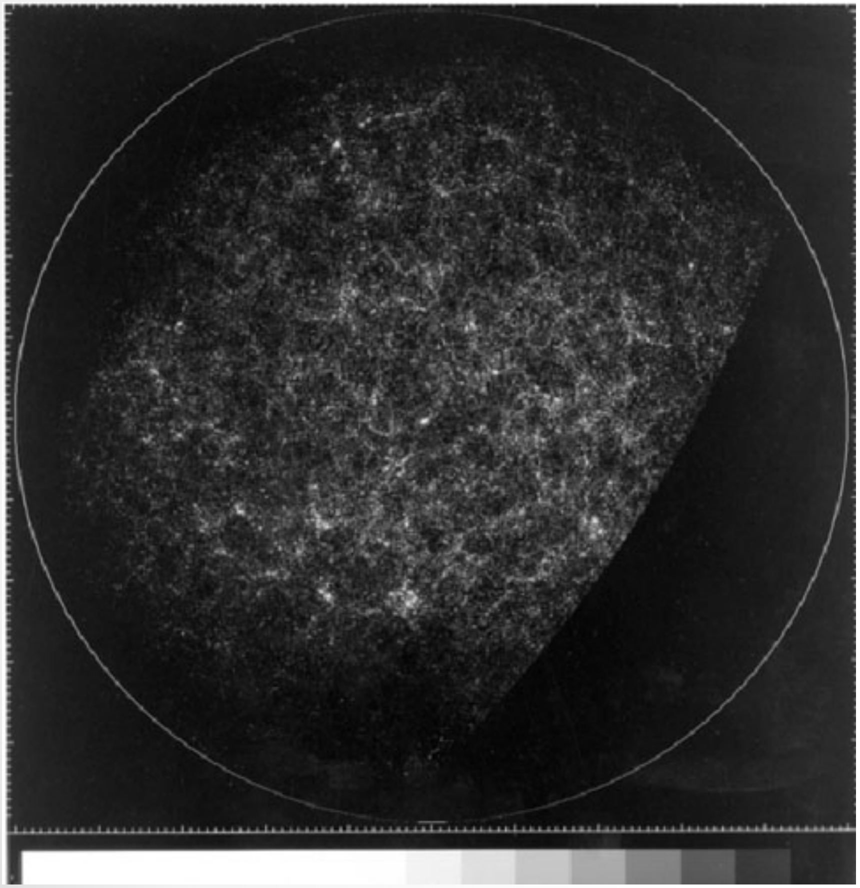
$$= 18{,}000/72 \text{ (Mpc)}$$

$$= 250 \text{ Mpc}$$

Large-scale Structure

- First hint of complex structure for the Universe was the Shane-Wirtanen survey at Lick Observatory
- Used the double astrograph to photograph the entire accessible sky (1400 photographic plates) from 1949-1957

Large-scale Structure

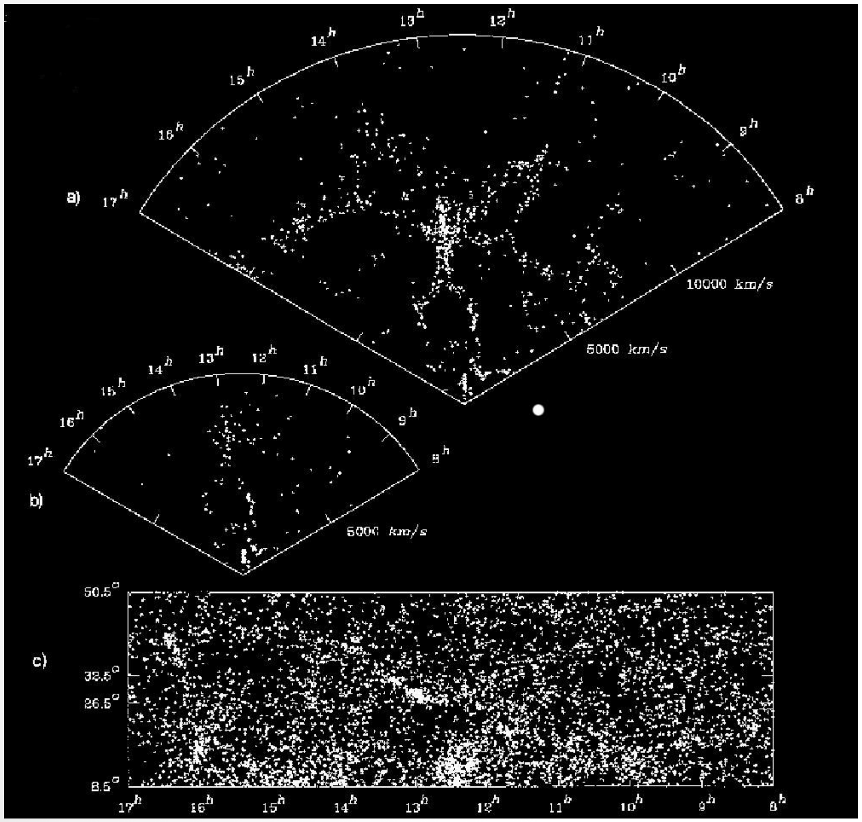


- Even without distances, the Shane-Wirtanen galaxy counts showed that galaxies were distributed in filaments and clumpy structures

Large Scale Structures

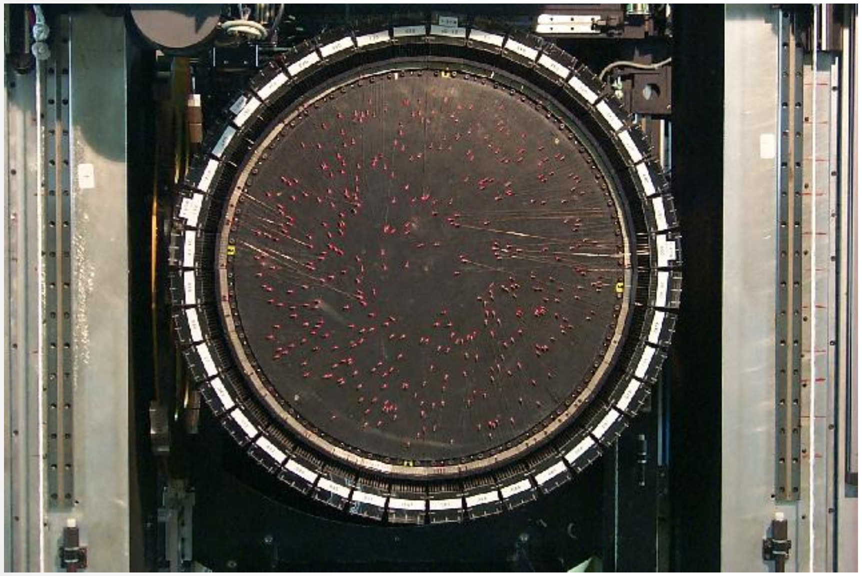
- 1980s John Huchra and Margaret Geller at Harvard started a program to map the 3-d distribution of galaxies
- The initial results took everyone by surprise
- The distribution was not uniform by filled with voids, filaments and clustering on all scales

Large Scale Structures



- These maps did not look like any of the models of the time for the expected formation of structures formed by gravitational forces
- There was some missing ingredient that was extremely important

Redshift Surveys



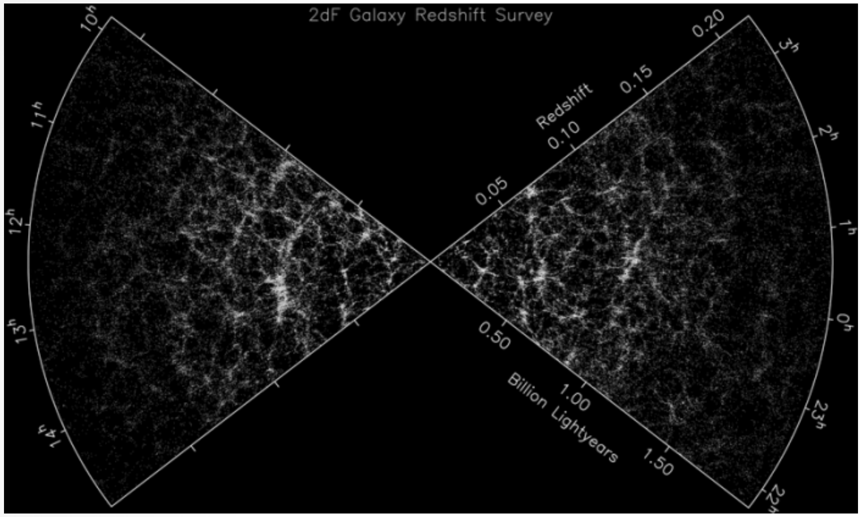
- After the Huchra/Geller survey done the old-fashioned way, special instruments and sometimes telescopes were built to obtain spectra of up to thousands of galaxies at the same time

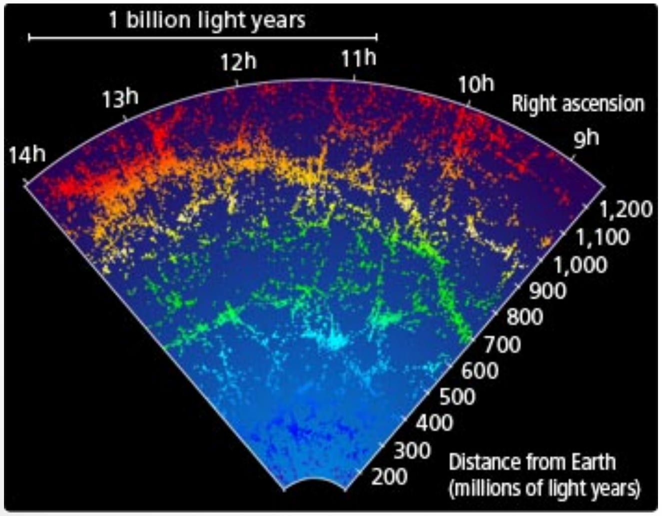
SDSS DR9 fly through

SDSS flythrough

- UCSC Connie Rockosi is one of the leaders of the SDSS
- This realization uses ~400,000 real galaxies out to z=0.1 (lookback time~1.3 billion years)

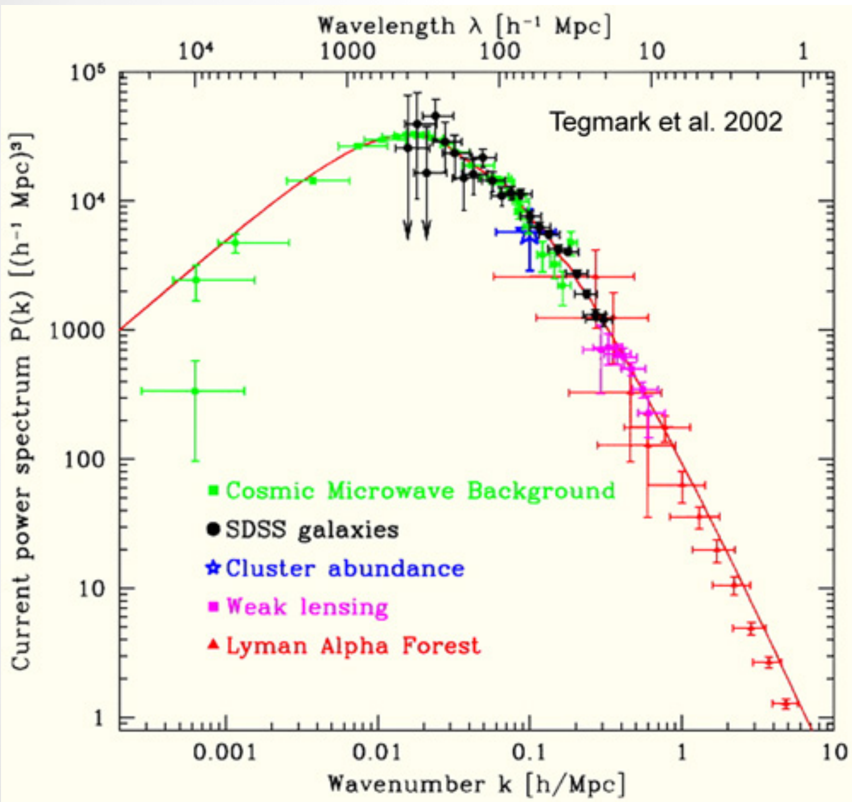
Large Scale Structure





- The result of all these studies is:
  - quantification of the nature of the distribution of galaxies in space
  - Observations of the evolution of structure with time

LSS can be quantified



- "Power Spectrum" of galaxies is a statistical representation of the "clumpiness" of the distribution in space
- Build models for the Universe with various ingredients and see if you get the same power spectrum as is measured
- Models in 1970s, 80s were way off!

review article

Nature **311**, 517 - 525 (11 October 1984); doi:10.1038/311517a0

Formation of galaxies and large-scale structure with cold dark matter

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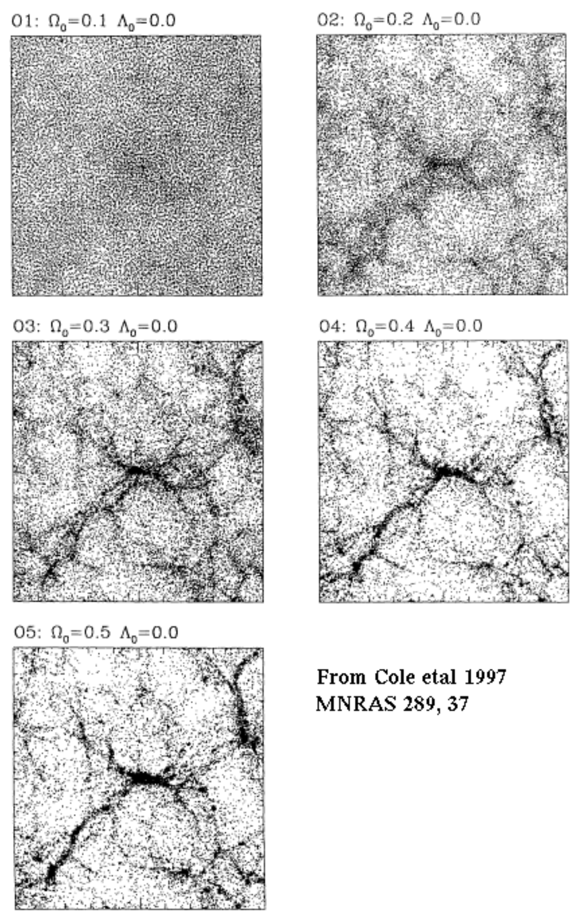
The dark matter that appears to be gravitationally dominant on all scales larger than galactic cores may consist of axions, stable photinos, or other collisionless particles whose velocity dispersion in the early Universe is so small that fluctuations of galactic size or larger are not damped by free streaming. An attractive feature of this cold dark matter hypothesis is its considerable predictive power: the post-recombination fluctuation spectrum is calculable, and it in turn governs the formation of galaxies and clusters. Good agreement with the data is obtained for a Zeldovich ($|\delta_k|^2 \propto k$) spectrum of primordial fluctuations.

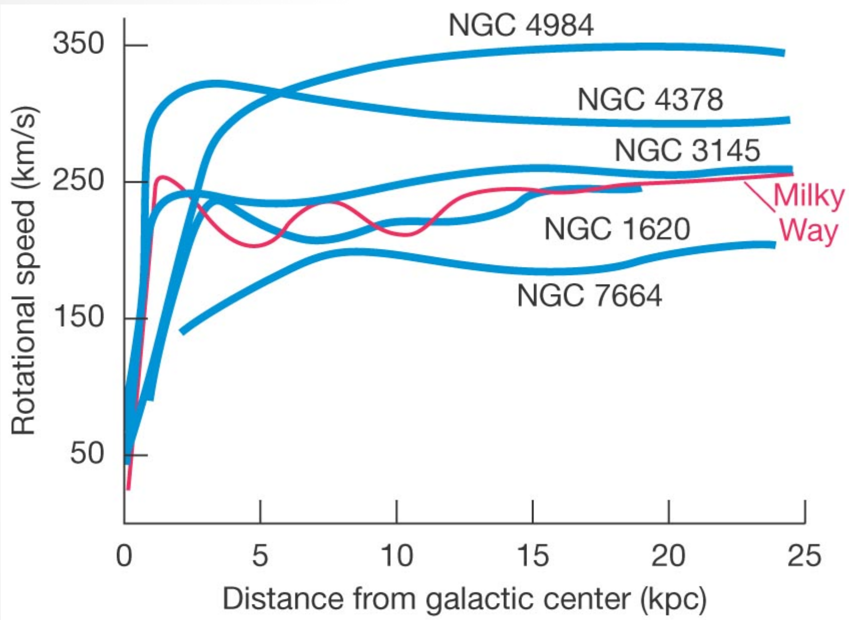
Dark Matter III



From Cole etal 1997
MNRAS 289, 37

- Blumenthal et al. did theory with pen and paper
- As computing power expanded, the same physics was put into models of the Universe
- These became great experiments
- Structure formation required lots and lots of dark matter

Dark Matter I



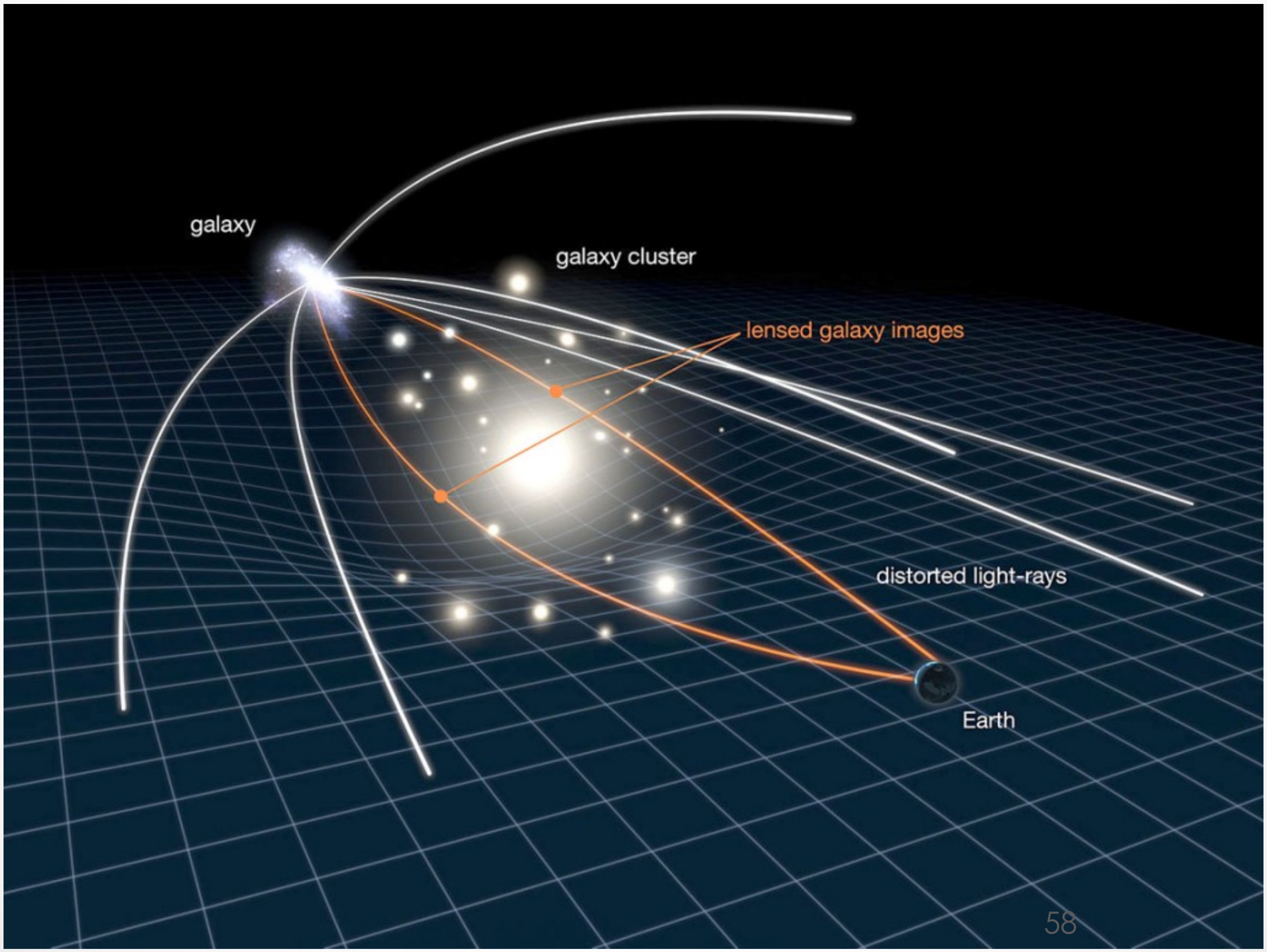
(b)

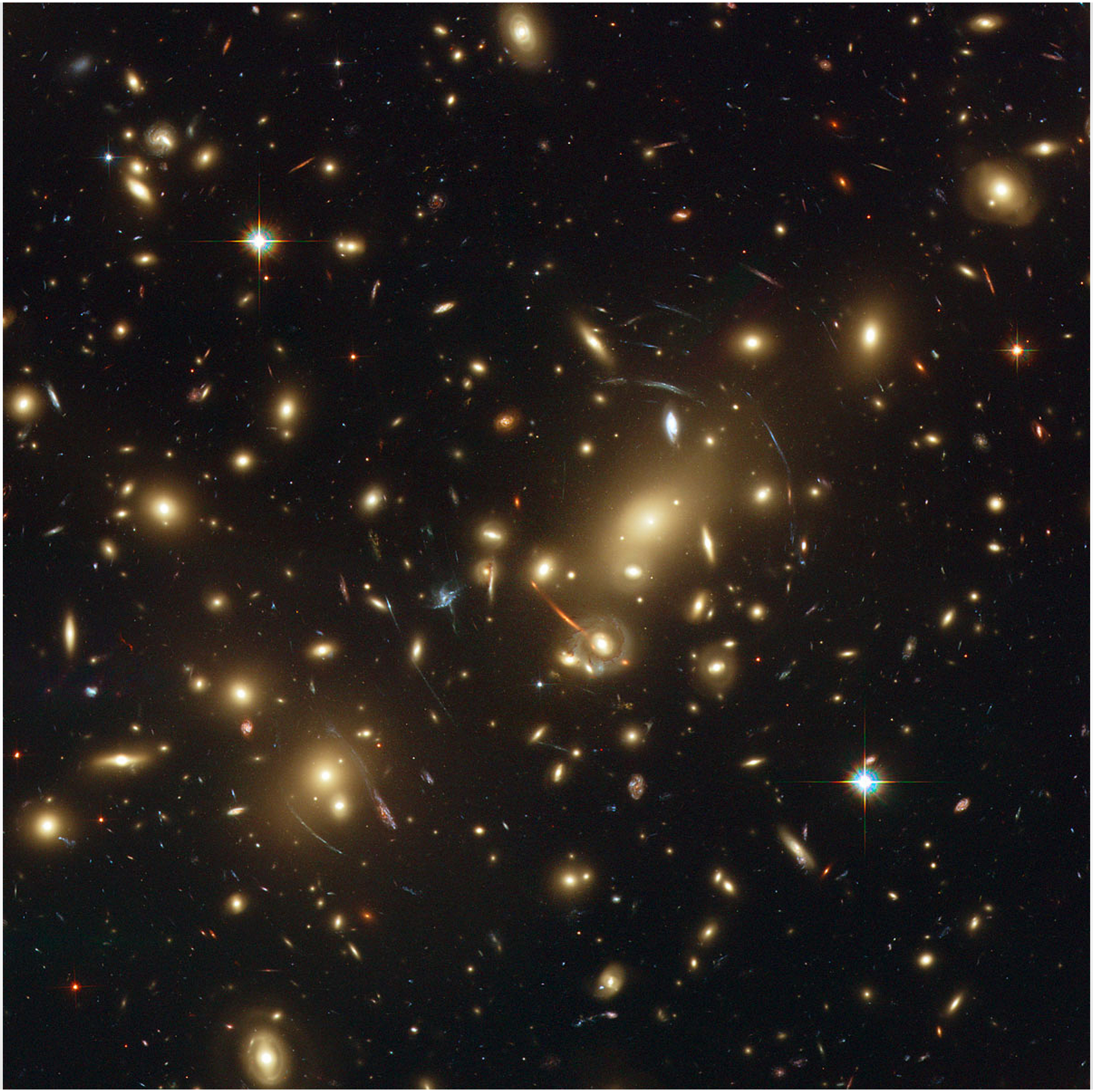
- Rotation curves of galaxies required an extended halo of non-luminous mass to keep the stars at larger radii bound to the galaxies

Dark Matter II

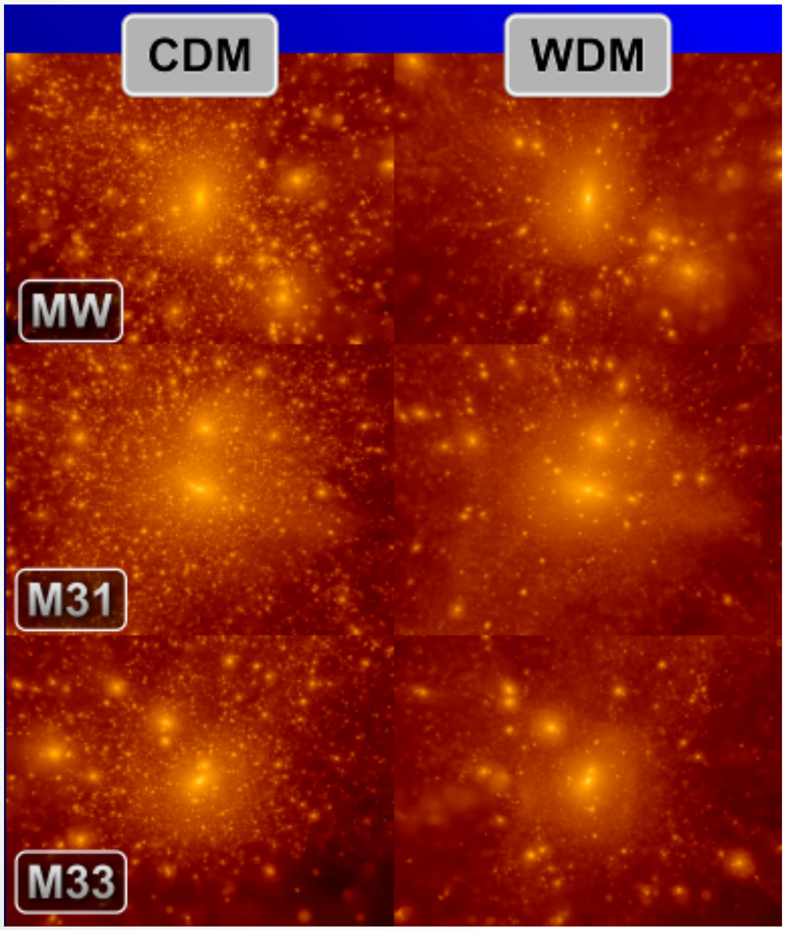
On the scale of galaxy clusters, Fritz Zwicky measured the "velocity dispersion" and inferred dark matter was required to prevent the galaxies from flying apart

Dark Matter II verified by gravitational lensing



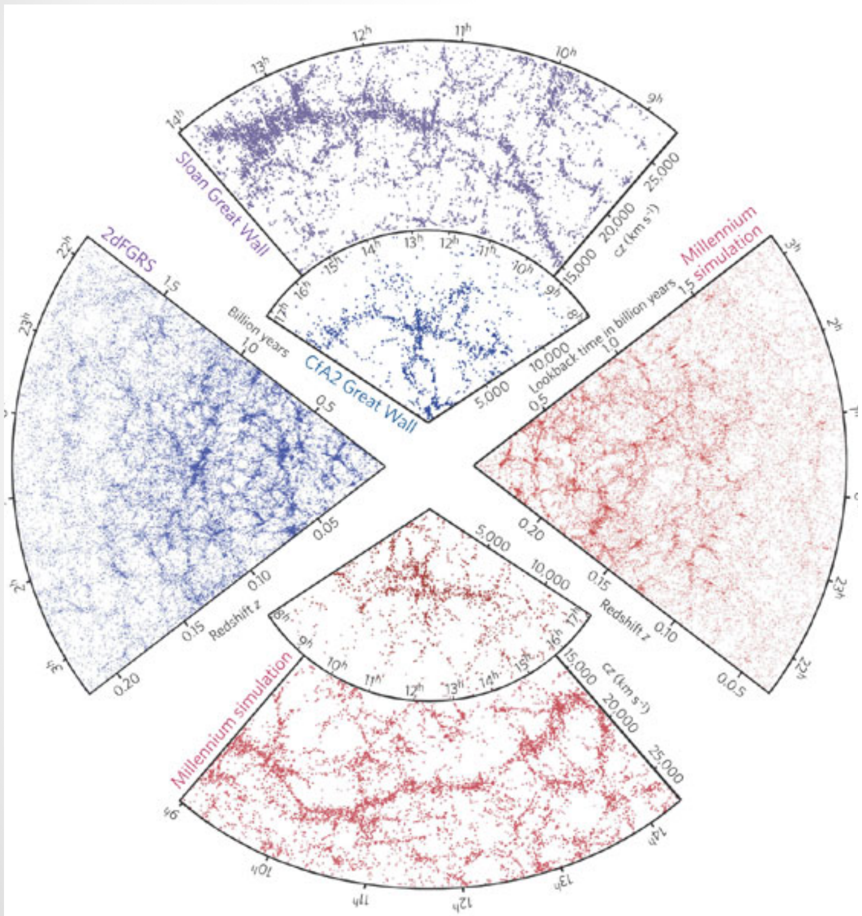


Dark Matter III return

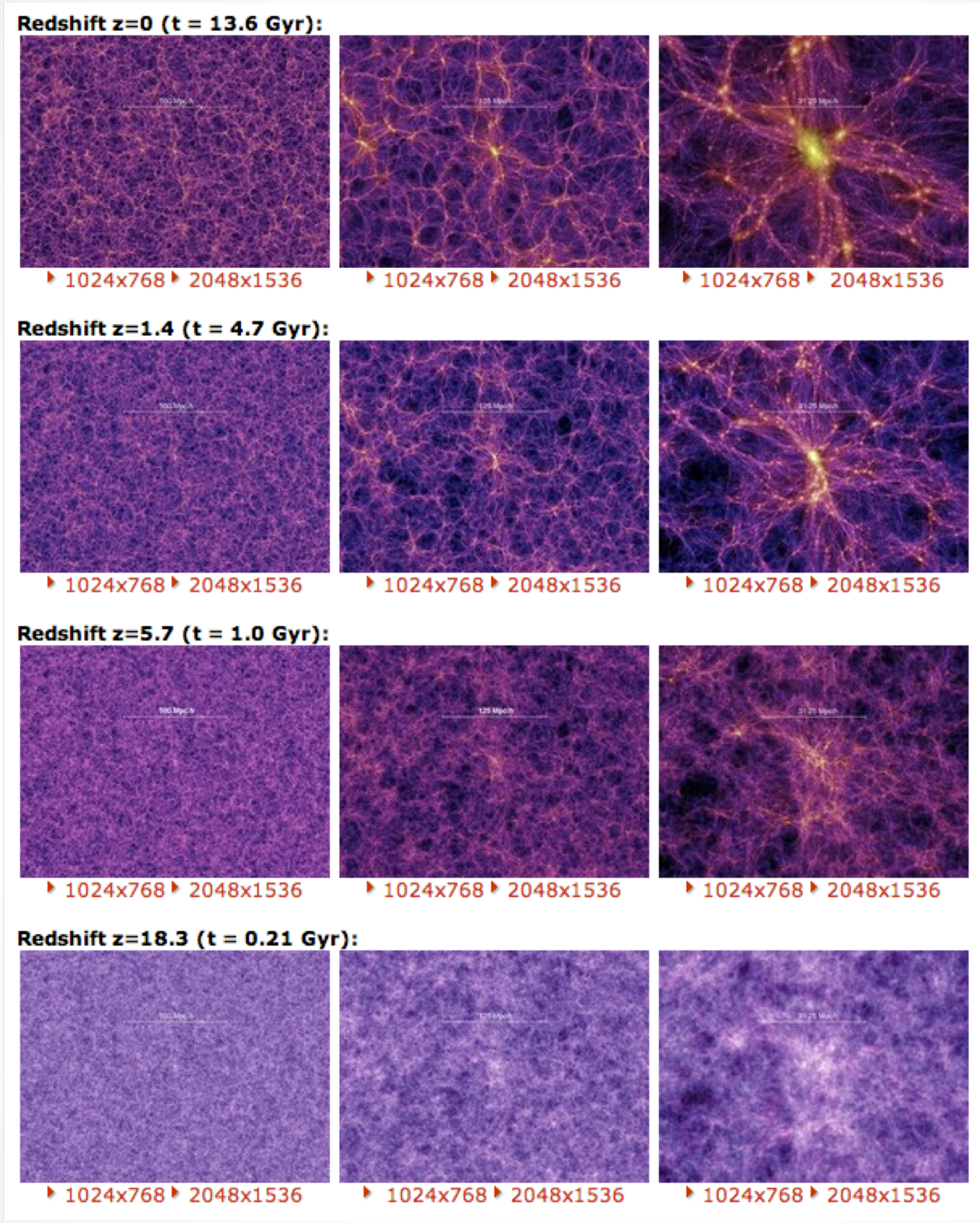


- The presence and nature of dark matter can be inferred by comparing observations to data
  - "hot" vs "cold" dark matter
  - Interaction with photons. Growth of structure depends on reaction to gravity, photon pressure and expansion of the Universe

Dark Matter



- Best match to observations for dark matter is:
  - Cold (not neutrinos) implying relatively massive
  - Weak interaction cross-section (photons and matter)
  - Does not emit or absorb radiation
  - ~30% of the mass/energy of the Universe (ordinary matter is only 4%)


Redshift z=0 (t = 13.6 Gyr):
1024x768 2048x1536
1024x768 2048x1536
1024x768 2048x1536
Redshift z=1.4 (t = 4.7 Gyr):
1024x768 2048x1536
1024x768 2048x1536
1024x768 2048x1536
Redshift z=5.7 (t = 1.0 Gyr):
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1024x768 2048x1536
1024x768 2048x1536
Redshift z=18.3 (t = 0.21 Gyr):
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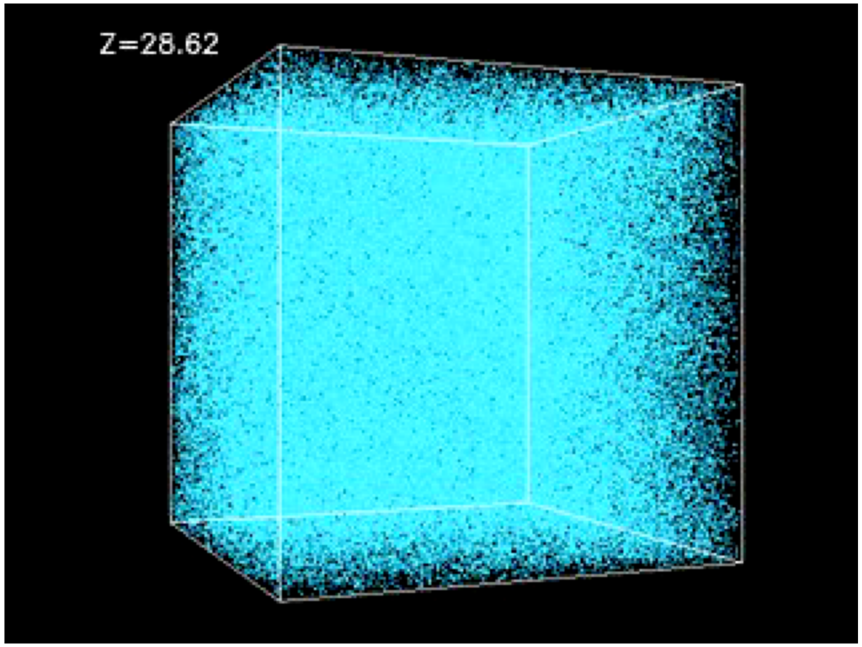
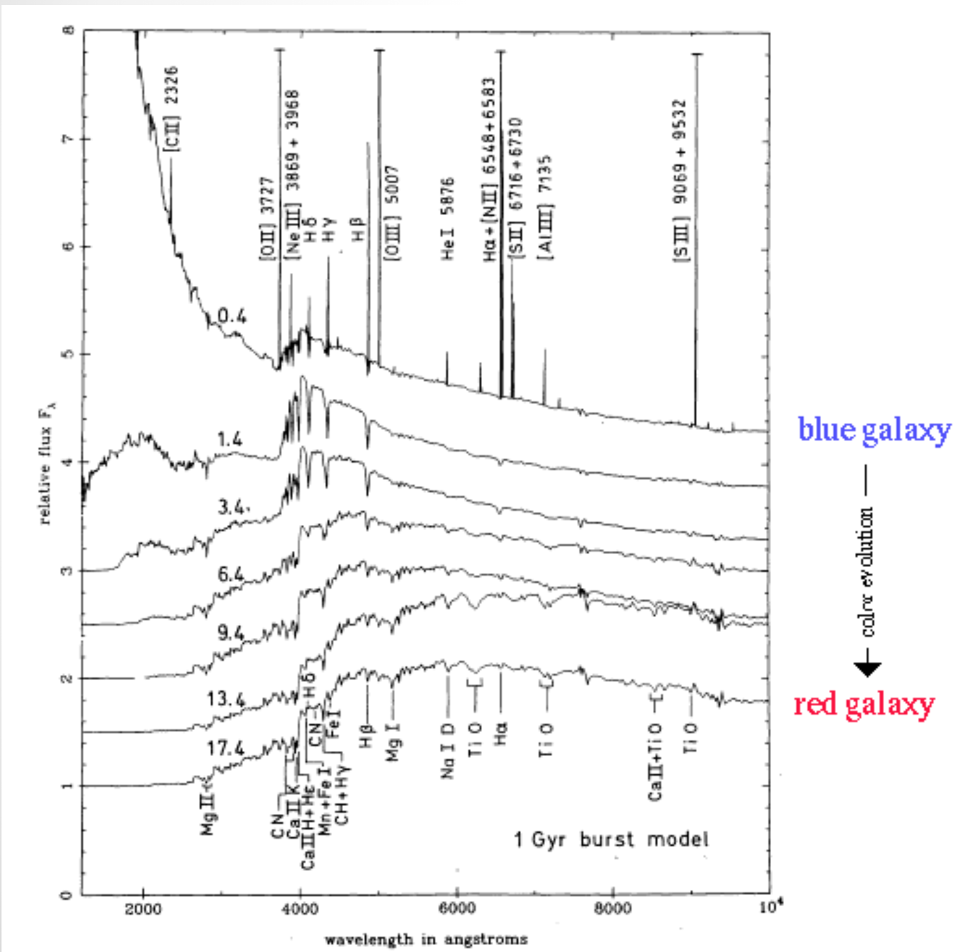
1024x768 2048x1536

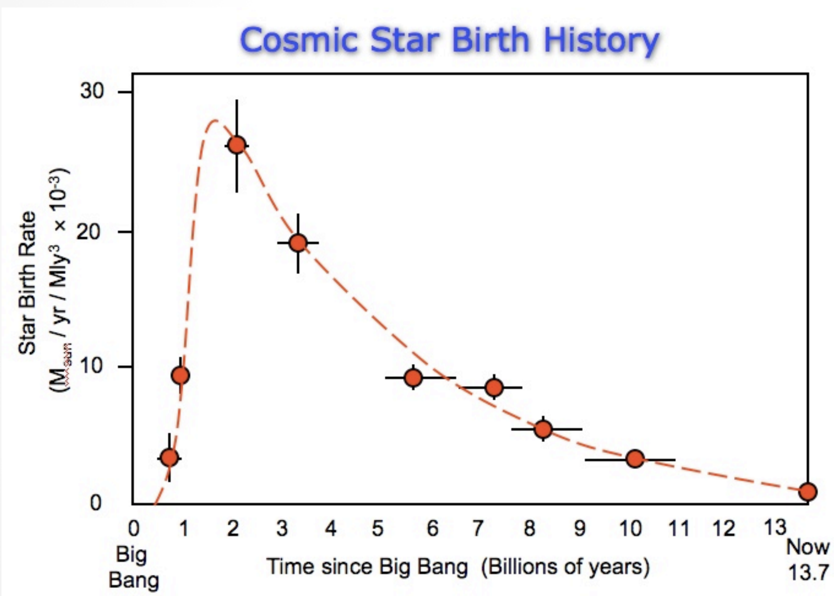

Z=28.62

Aside:History of Star Formation



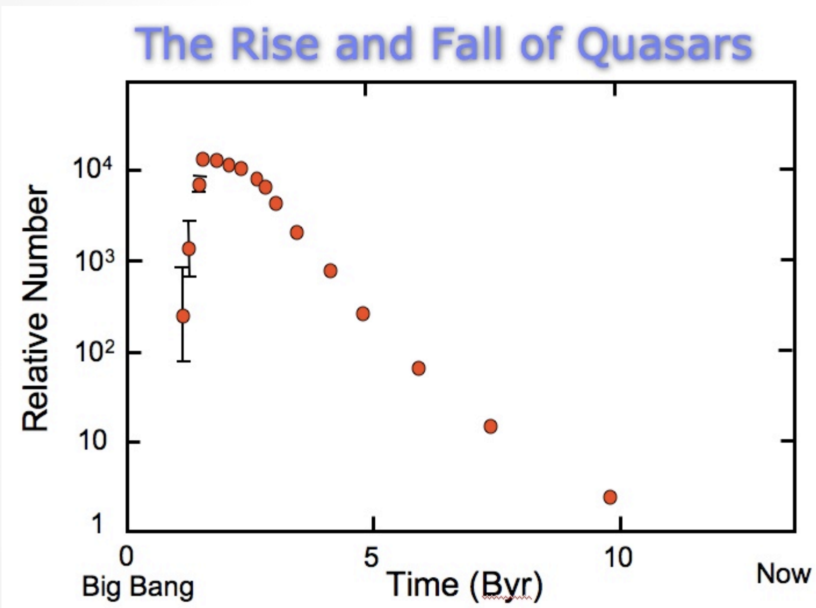
- Bonus aspect of the many spectroscopic surveys of galaxies is the star formation activity has been measured for hundreds of thousands or galaxies
- Star forming galaxies show strong emission lines from hot gas near young stars

Aside: Madau Plot



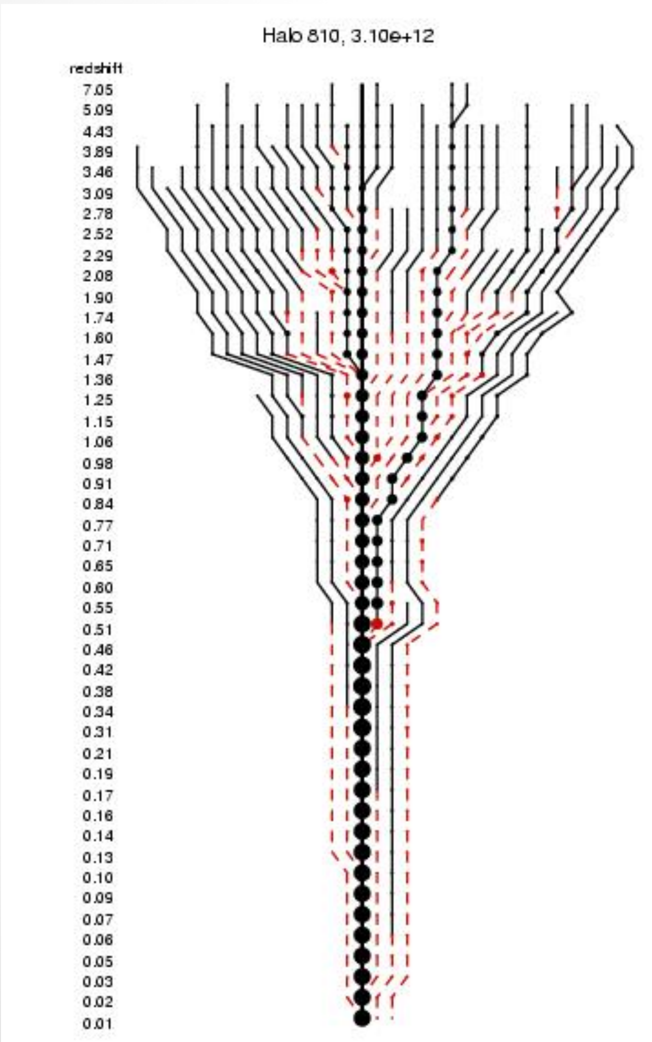
- The answer is that the main star formation epoch of the Universe has already occurred
- Fueled by lots of gas and mergers of galaxies at early times

Quasar/SMBH History of the Universe

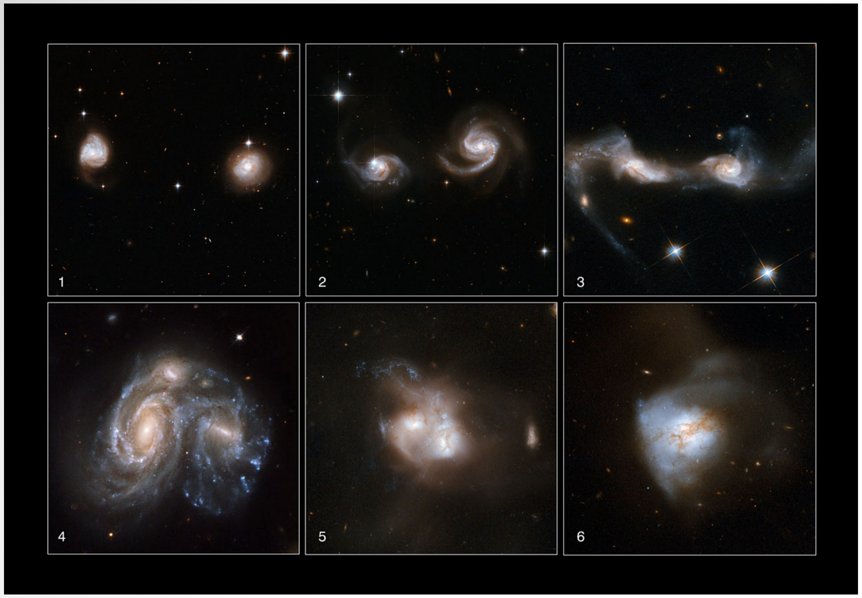


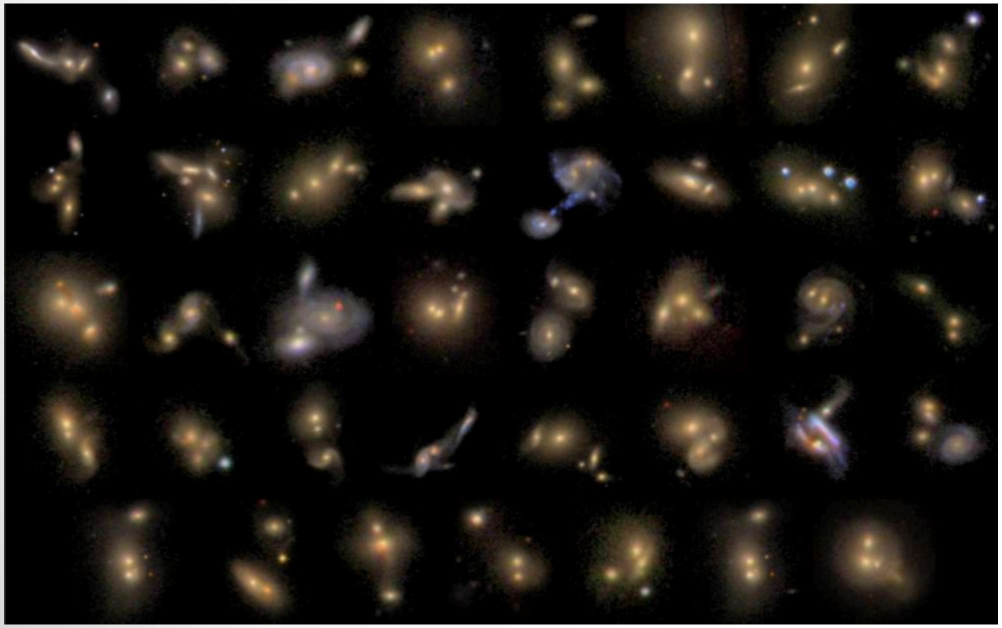
- Get a plot similar to that for star formation history (but not identical)
- Very few QSOs at times < 1billion years after the BB, strong peak between 1.7 and 3 billion years after the Big Bang

The Universe is Evolving



- We can explain the star formation and QSO histories by Star-formation history by merger history from Universe simulations
- QSO distribution in time are two examples of a Universe that is evolving in one direction





- Mergers were much more common at earlier time because the Universe was smaller and gas was falling into dark matter halos
- Mergers kick off star formation bursts and sometimes funnel gas to centers to feed super massive black holes

Age of the Universe

$$H_0 = 72\text{km}\cdot\text{s}^{-1}\cdot\text{Mpc}^{-1}$$

$$\frac{1}{H_0} = \frac{1}{72}\frac{\text{s}\cdot\text{Mpc}}{\text{km}}\times\frac{3.1\times10^{19}\text{km}}{1\text{Mpc}} = 4.3\times10^{17}\text{s}$$

$$4.3\times10^{17}\text{s}\times\frac{1\text{year}}{3.15\times10^{7}\text{s}} = 13.6\times10^{9}\text{years}$$

- If H_o was constant for all time the "expansion age" of the Universe is simply $1/H_o$
- H_o=72 (km/s)/Mpc
- km and Mpc are distance units so H_o has units of 1/seconds