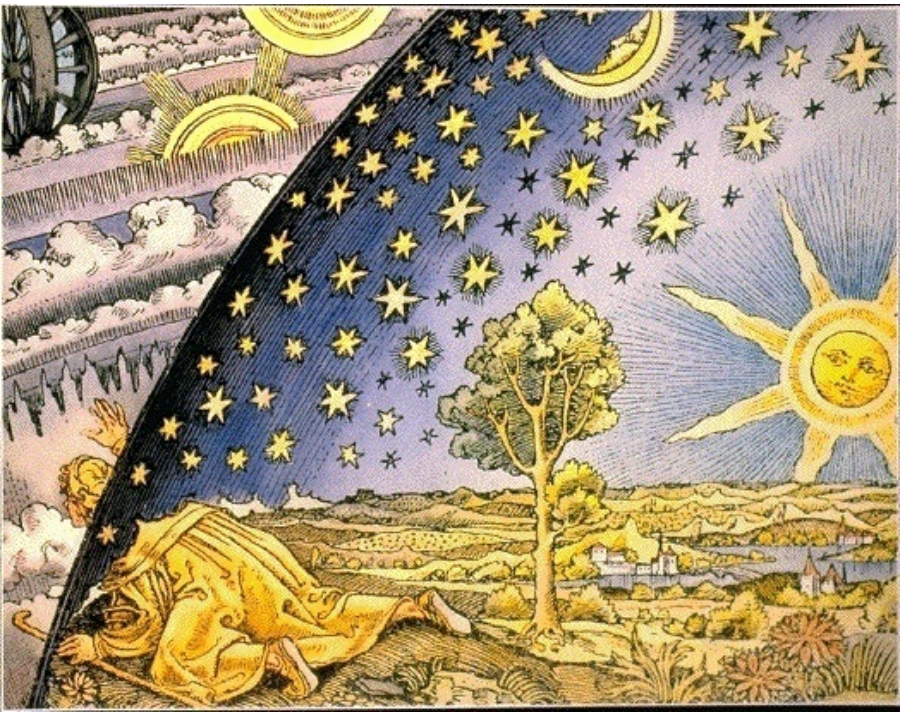
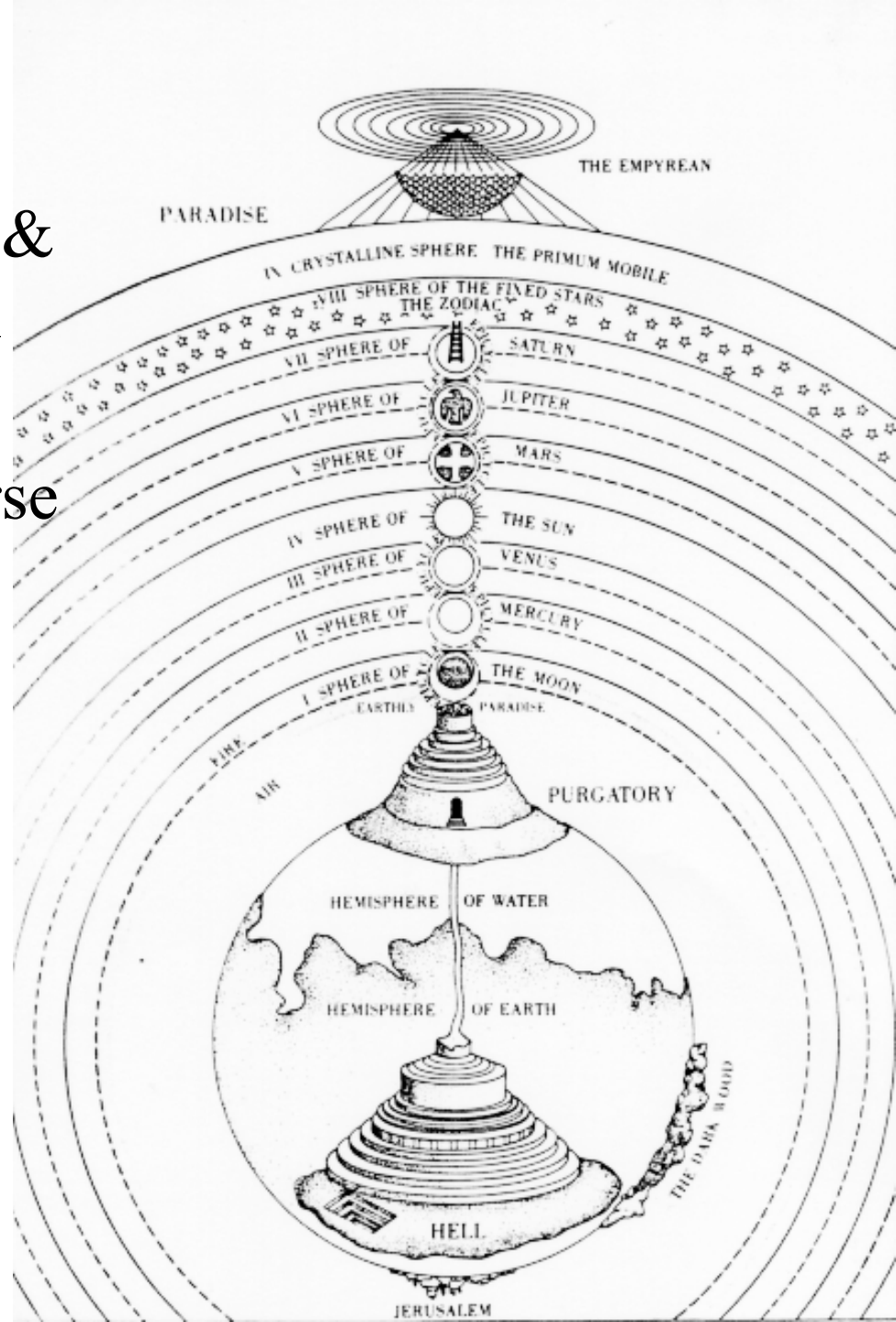
Cosmology

- **Universe**: All of space/time & everything contained therein
- **Cosmology**: Study of the nature & evolution of universe
- Medieval/Dante





Field Test Version (Jan. 2003) Contact: epepeduc@cpepw

THE HISTORY AND FATE OF THE UNIVERSE

Eight major stages in the evolution of the universe are illustrated below.

The Big Bang occured everywhere in the universe. Here one region has been illuminated and followed through time. The expansion is far greater than can be shown here.

Time

ERA 1

10^{-44} s — unknown

10^{-43} s — photon

10^{-31} meters

Inflation
(sometime between 10^{-43} and 10^{-12} s)

10^{-12} s — antiquark, muon, tau, antielectron, quark, gluon, neutrino, electron, W- boson

10^{-1} meters

ERA 2

Nucleons form: 10^{-4} s — antinucleon, nucleon, meson, photon

10^{3} meters

Nuclei form: 10^{2} s — photon, electron, nucleus (ion), ion

10^{10} meters

ERA 3

Atoms form: 3×10^{5} yr — atom, neutrino, photon

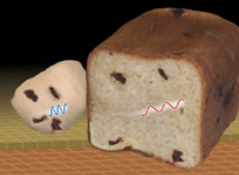
10^{21} meters

First Stars and Galaxies form: 3×10^{8} yr

10^{24} meters

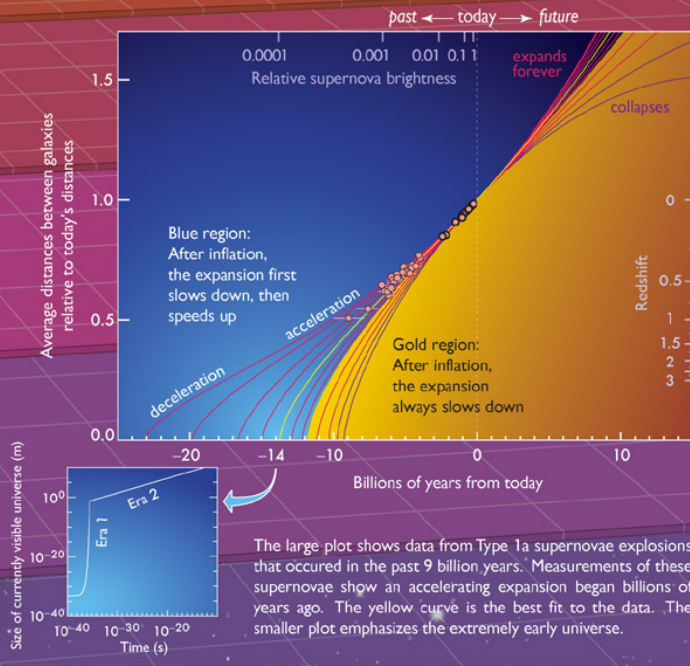
Redshifts and Expansion

Lightwaves stretch with the expansion of space. As the wavelength of visible light increases, it becomes redder (as shown for the photons in the central figure). Measuring this redshift tells us the velocity of the source. In 1929, Hubble observed that all distant objects are receding with a velocity proportional to their distance. This information and modern telescope observations show that the universe is expanding uniformly in all directions. Objects that are bound together (such as galaxies and atoms) do not expand as space expands.



The raisin bread represents a portion of t universe, and the raisins represent galaxi Due to the rising of the bread (the expansion space), wavelength increases and raisins mo apart, but raisins do not expand.

Expansion History of the Universe



The large plot shows data from Type 1a supernovae explosions that occured in the past 9 billion years. Measurements of these supernovae show an accelerating expansion began billions of years ago. The yellow curve is the best fit to the data. The smaller plot emphasizes the extremely early universe.

Fate of the Universe

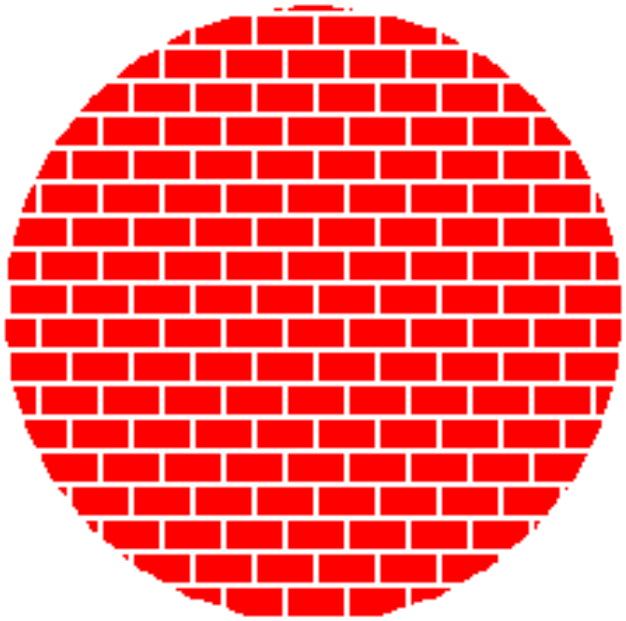
Whether the expansion of the universe will speed up, slow down, or even possibly reverse into collapse depends through gravity on the amount and types of matter and energy in it.

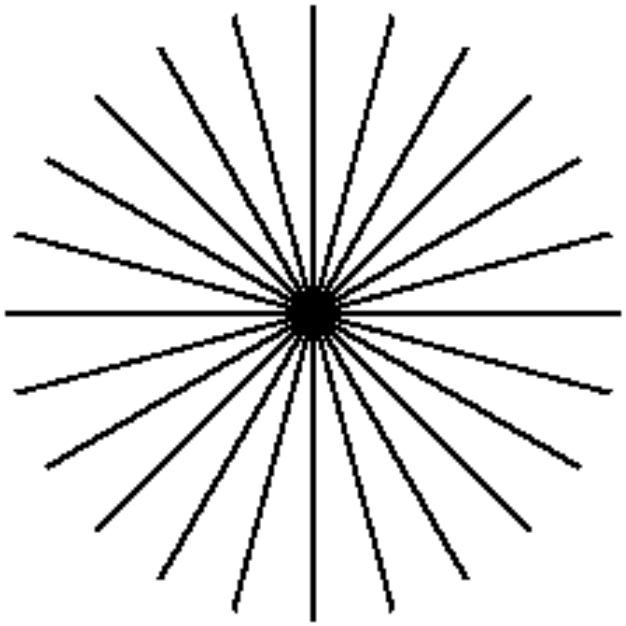
The ordinary matter – atoms and nuclei – that formed in the early universe can account for the visible mass in galaxies and clusters. But it falls far short of the total mass needed to bind them together gravitationally and explain their internal motions. So an extraordinary new type of matter, not made of atoms or nuclei, must exist; it is called ***dark matter*** because it is not directly visible.

Even stranger, recent observations of supernovae in distant galaxies show that the expansion of th universe is in fact ***accelerating***. An exotic ***dark energy*** may be causing this acceleration throug

Cosmological Principle

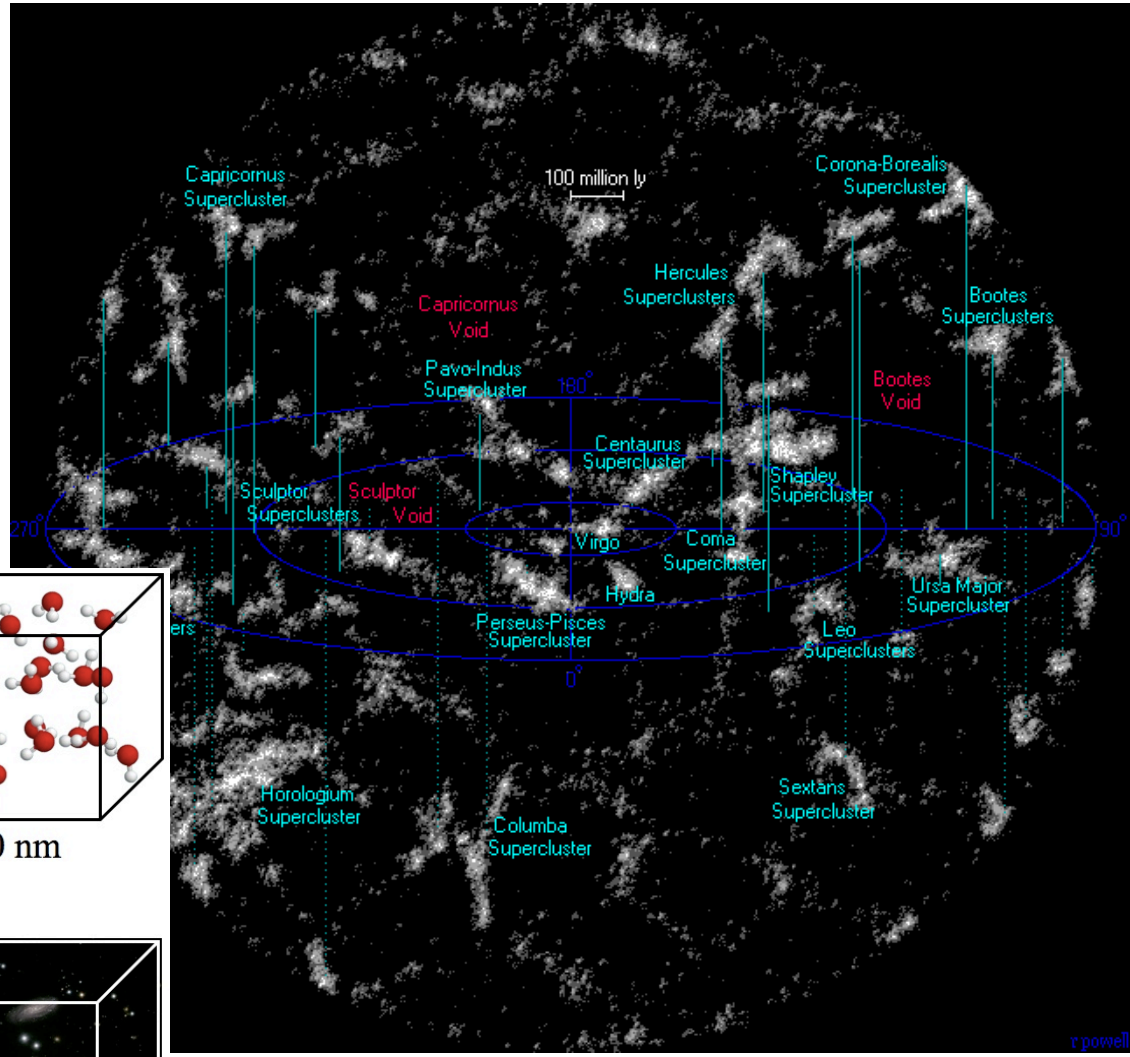
- Universality = Copernican principle: "No special observer/place"
- Physical laws are the same everywhere
- **Homogeneous** means matter is uniformly spread – all see same thing
- **Isotropic** means that it looks the same in any direction
- Bricks are homogeneous but not isotropic (too long)
- Wheel is isotropic but not homogeneous
- Homogeneous & isotropic imply no center and no edge

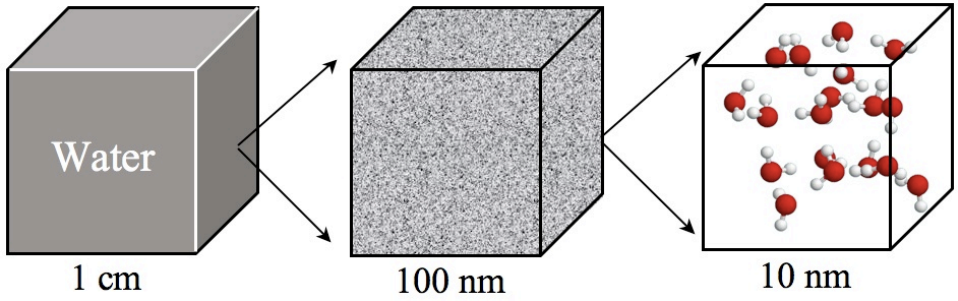


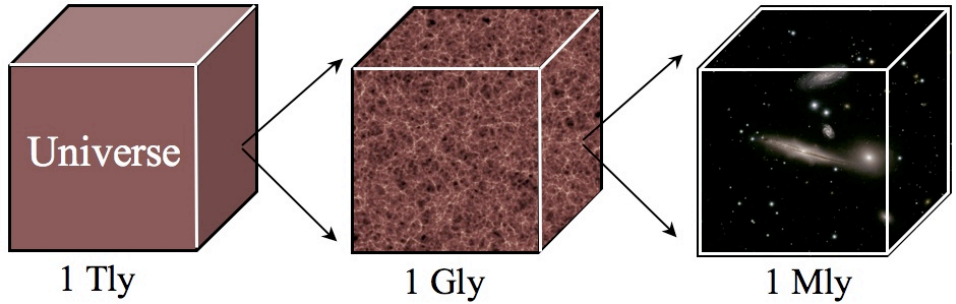


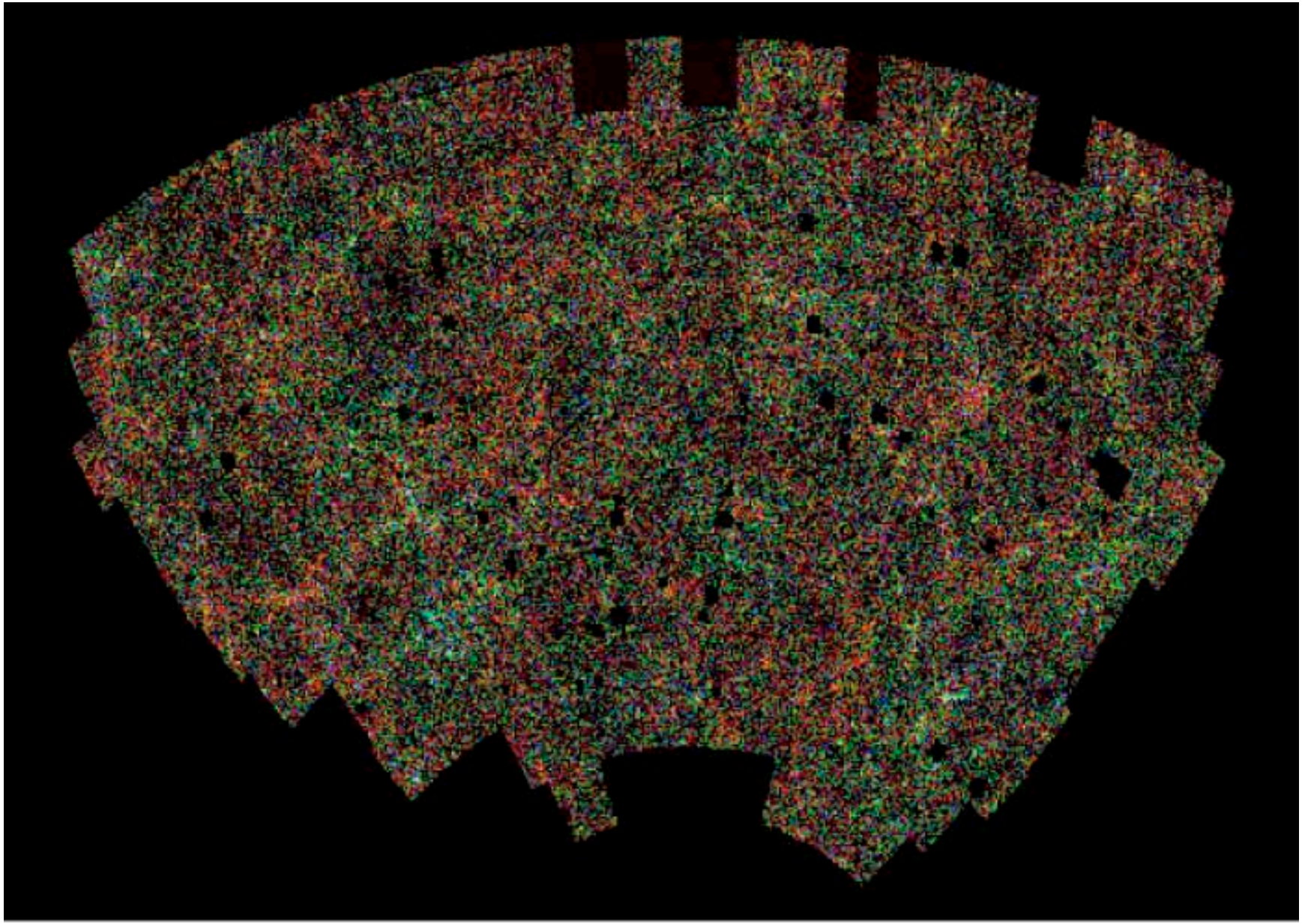
Universe is Not Homogeneous

- On the small scales
- Stars, Galaxies, Clusters of Galaxies
- Within a Hundred Million light years







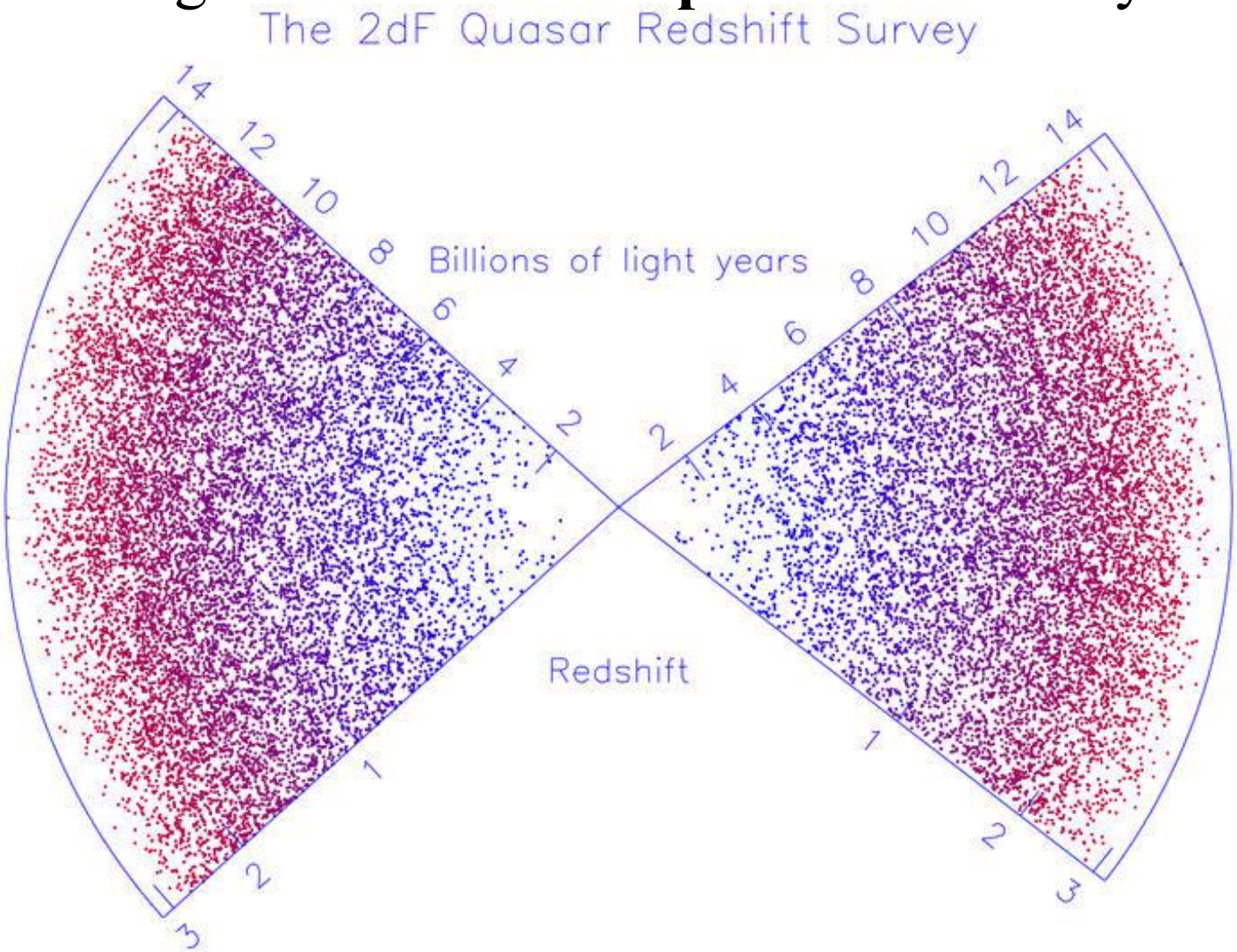


APM Survey picture of a large part of the sky, about 30 degrees across, showing almost a million galaxies out to a distance of about 2 billion light years.

MAP990047

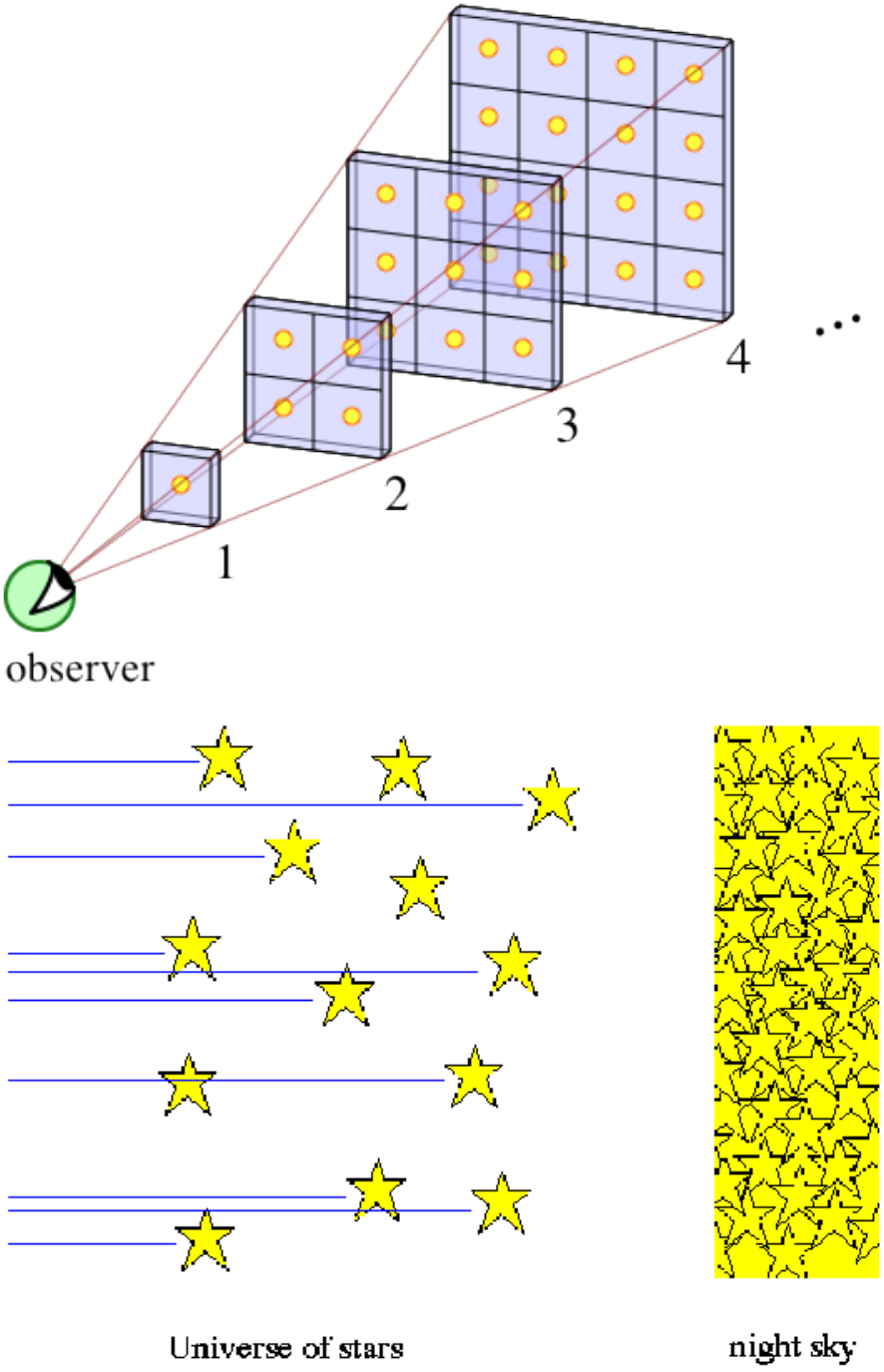
2dF Quasar Survey - **Homogenous**

- 2dF survey found thousands of quasars distributed uniformly
- No clusters so homogeneous and **isotropic** over billion lys

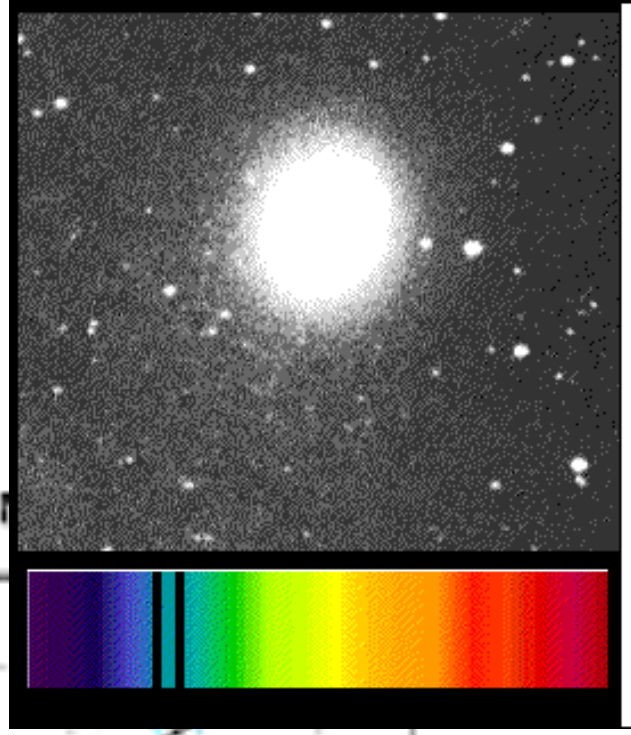


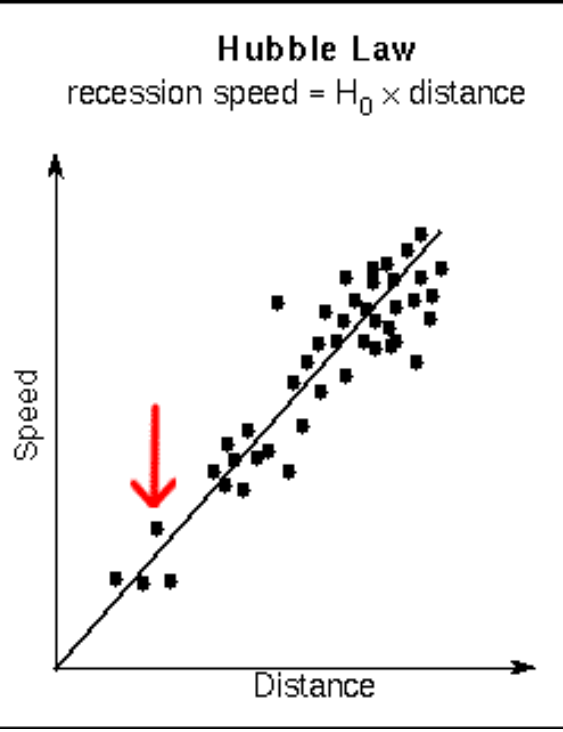
Olbers's Paradox

- As we go further away the stars/galaxies become fainter but more numerous
- If universe is infinite then eventually all lines of sight end on the surface of a star
- Sky is dark at night so the universe is not infinite
- There is an edge in time not space????



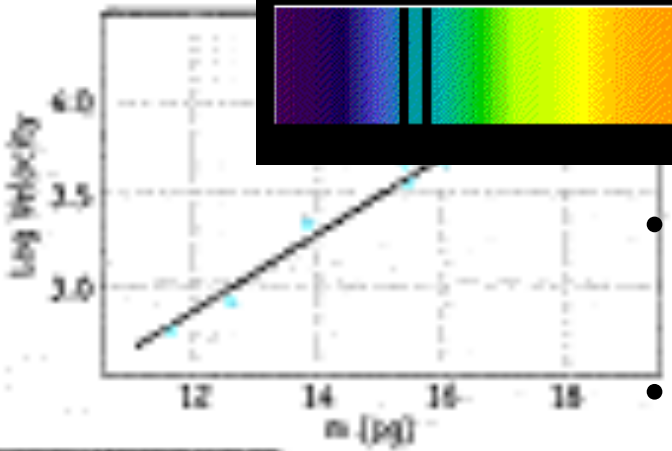
Hubble with 100 inch Telescope





Discovery of Expandi

Edwin Hubble

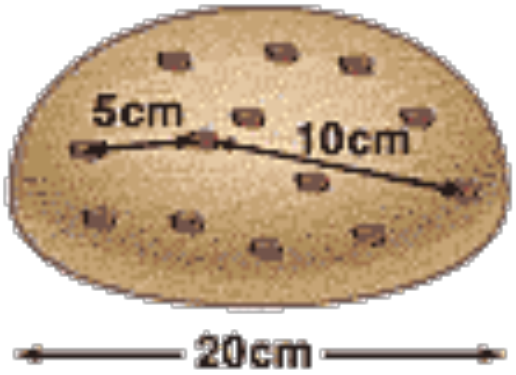


Mt. Wilson 100 Inch Telescope

- All the galaxies are moving away from us
- The Farther the Faster
- Linear Relation
- Slope= Hubble constant H_0
- Are we a bad neighbor? Isotropic but not homogeneous – unless …

Raisin Bread Model is Homogeneous

- Space between galaxies/clusters expands – No center
- Earth, Milky Way, local group does not expand
- Twice as far, twice as much space expanding
- Linear relationship between distance and velocity

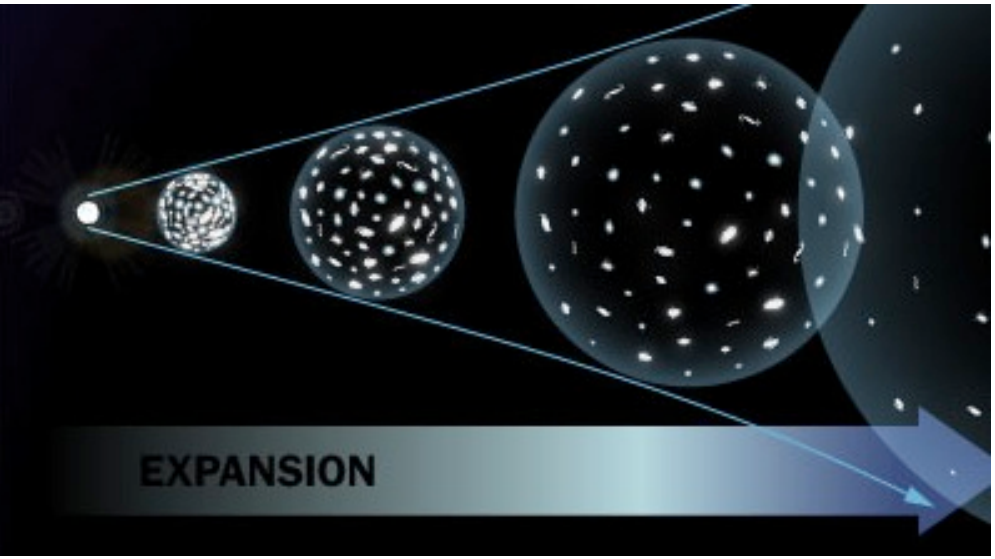


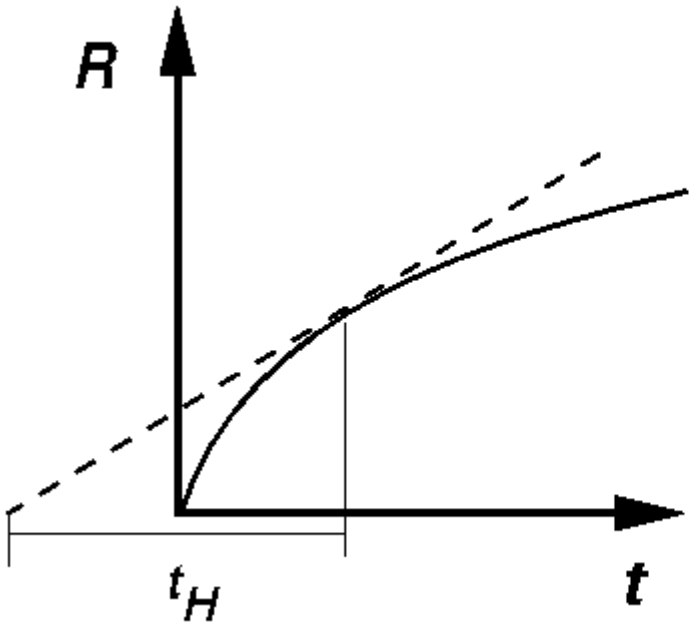
Cosmological Redshift

- Not velocity thru space
- Expansion of space
- Photons within space become stretched and redshifted
- $Z=(\lambda' - \lambda)/\lambda$
- $\lambda'/\lambda = Z+1$: factor a photon = universe has increased in size since its emission

Big Bang of **Primeval Fireball**

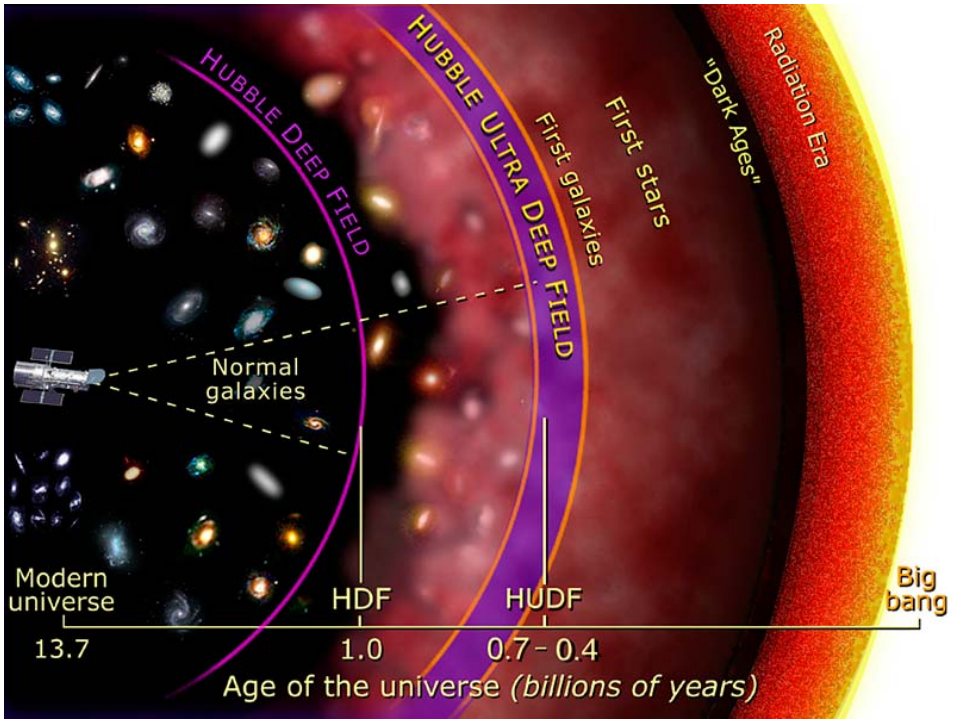
- Space between galaxies R was smaller yesterday
- We can extrapolate backwards to when **Primeval Fireball** exploded as the **Big Bang**
- Age of Universe=$1000/H_0$ Billion years=13.8 Billion years





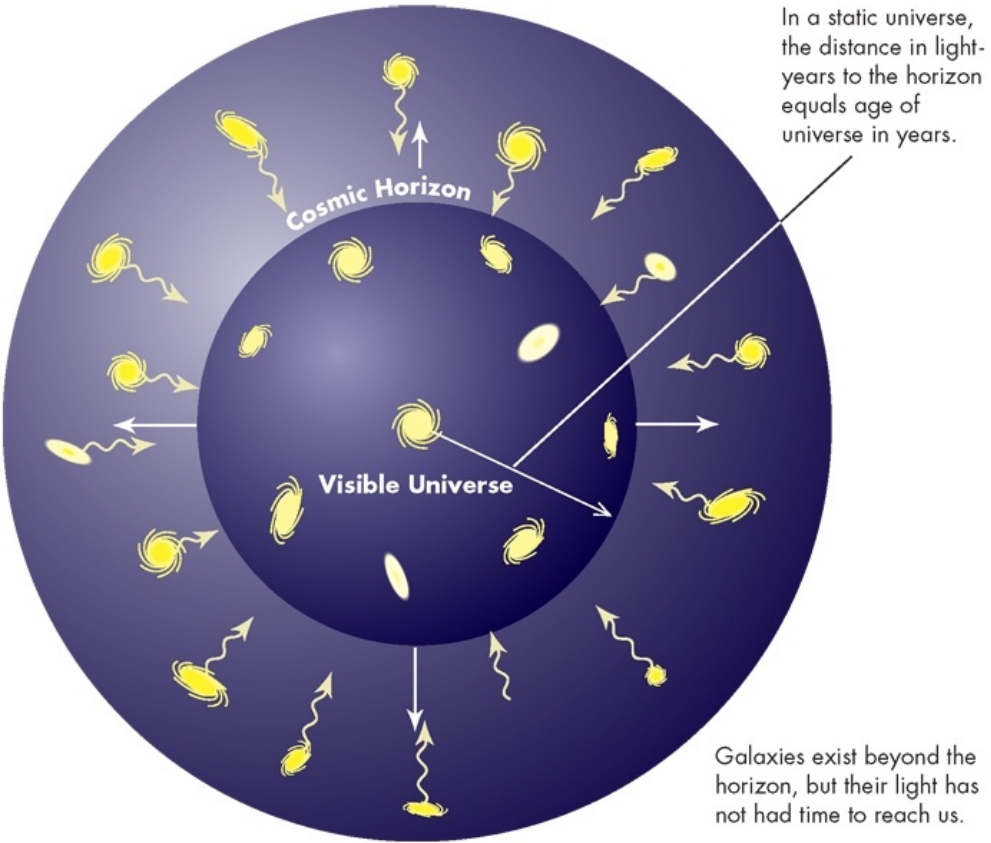
Cosmic Horizon

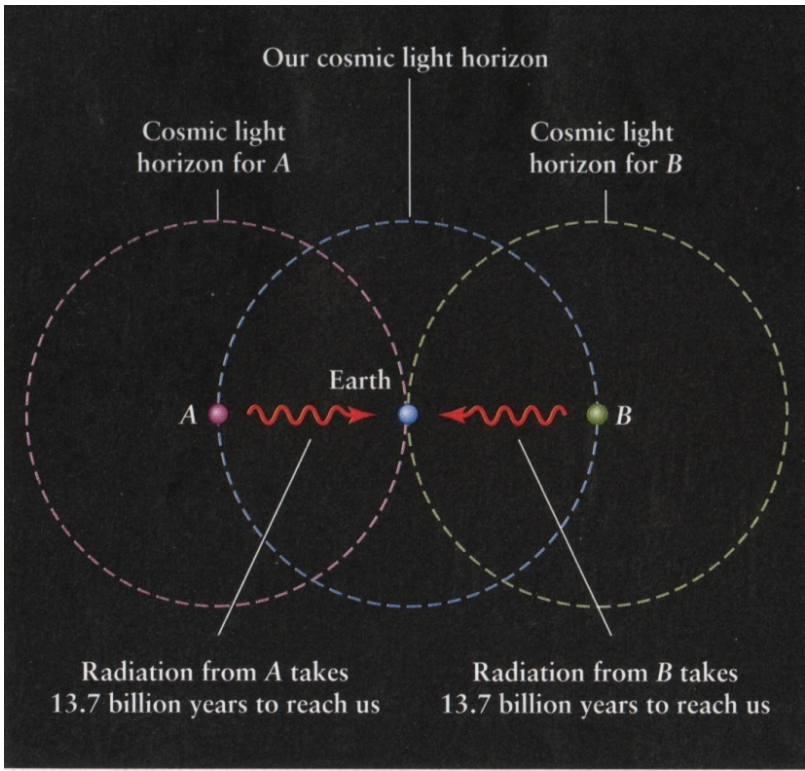
- Can NOT look back before Big Bang so there is a Cosmic horizon at 13.8Billion light years from me
- Cosmological redshift is infinite at Cosmic Horizon
- Olbers's Paradox – there is an edge in time and space



Observable universe is Part of Universe

- Each galaxy has its own **cosmic horizon** – Each person has their own
- Galaxies beyond those we can see; beyond **observable universe**
- If the BIG Universe is infinite there is a copy of you $10^{10^{29}}$m away





Which of the following is incorrect?

a. Universe: “Totality of space, time, matter & energy”
b. Isotropic: “Looks the same in every direction”
c. Homogeneous means “the same everywhere”
d. Observable universe: “The part of the universe that is visible from the Earth’s location in space and time”
e. All of these are correct

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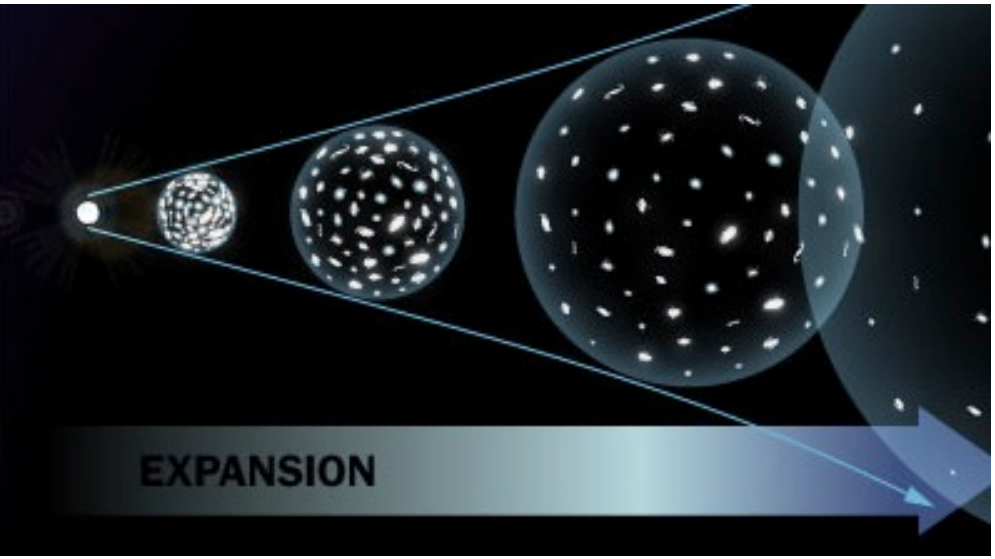
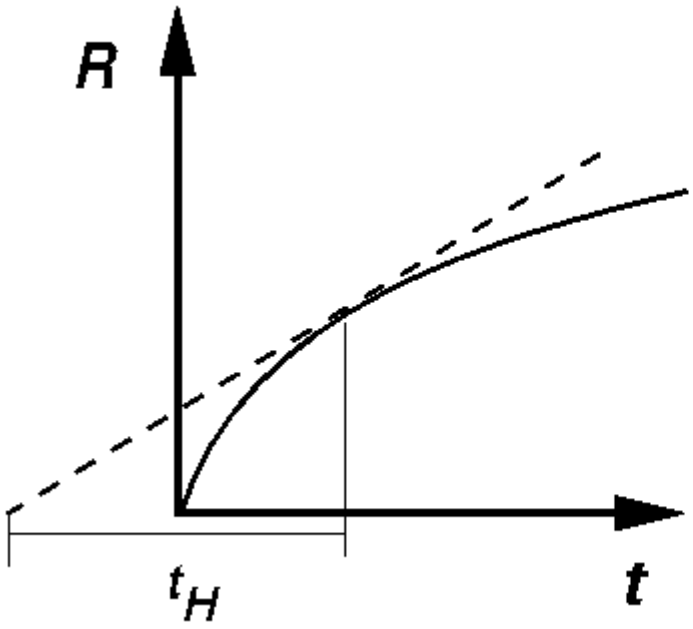
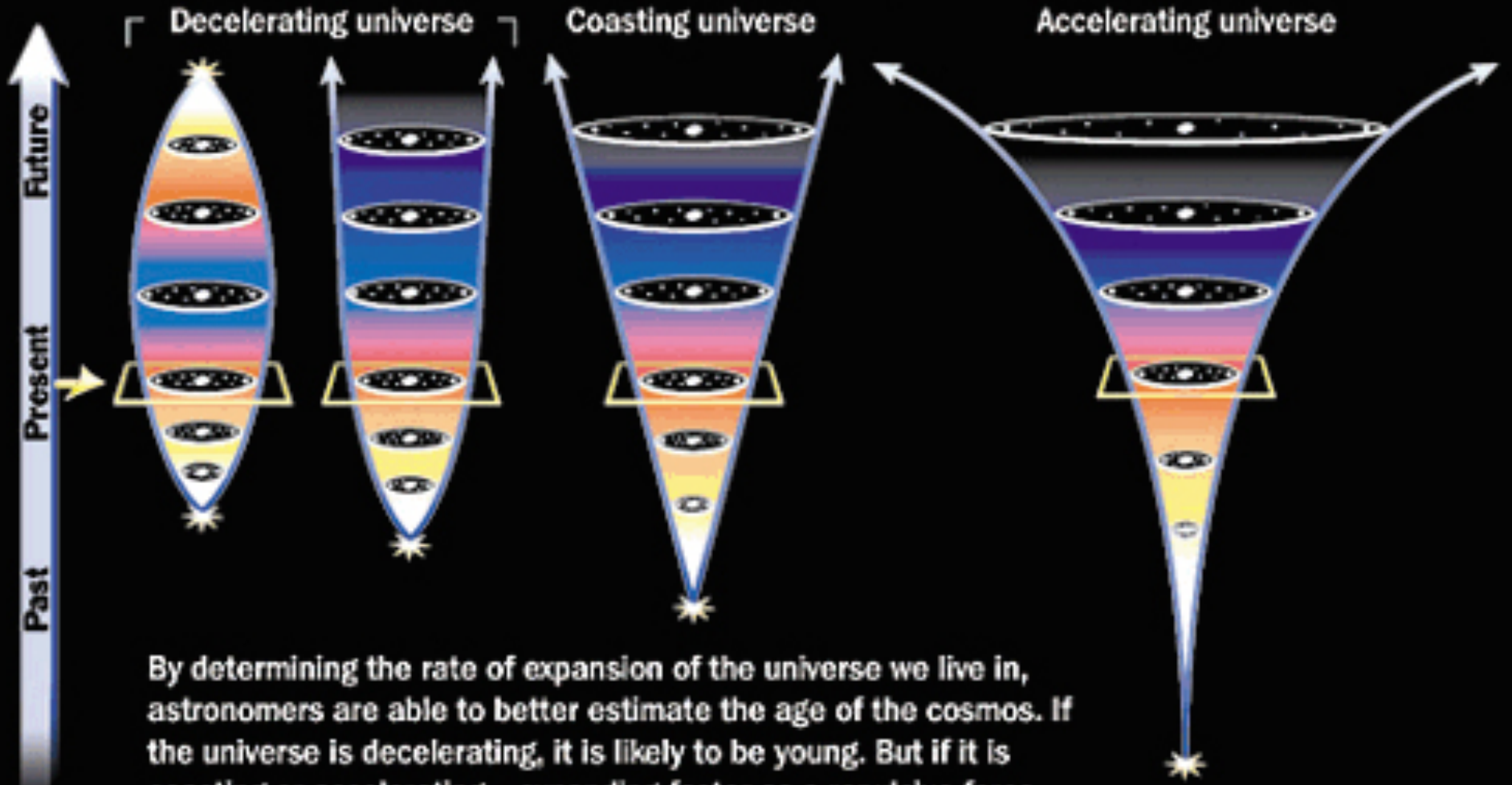


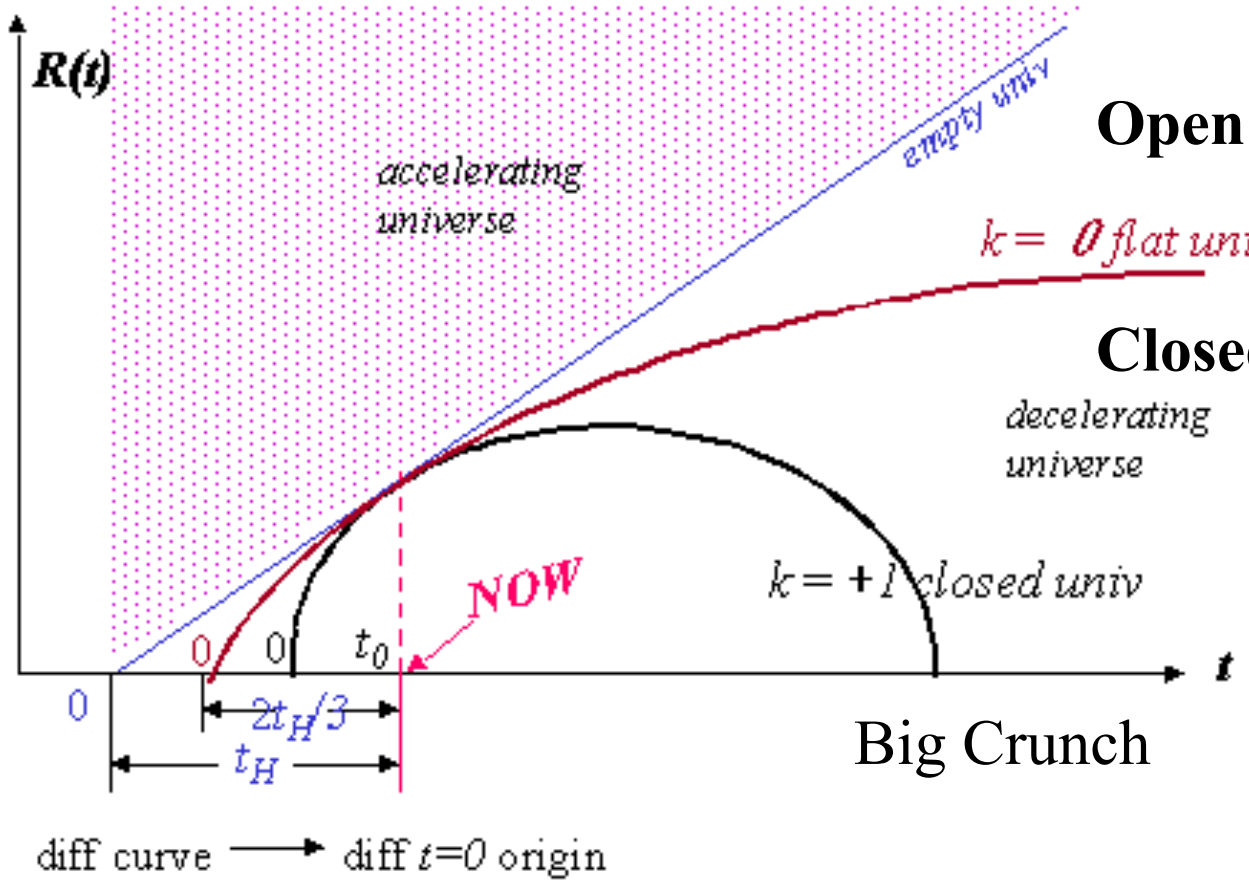


Possible models of the expanding universe



By determining the rate of expansion of the universe we live in, astronomers are able to better estimate the age of the cosmos. If the universe is decelerating, it is likely to be young. But if it is coasting or accelerating – expanding faster as a repulsive force pushes galaxies apart – it is probably older.

Time evolution of the universe



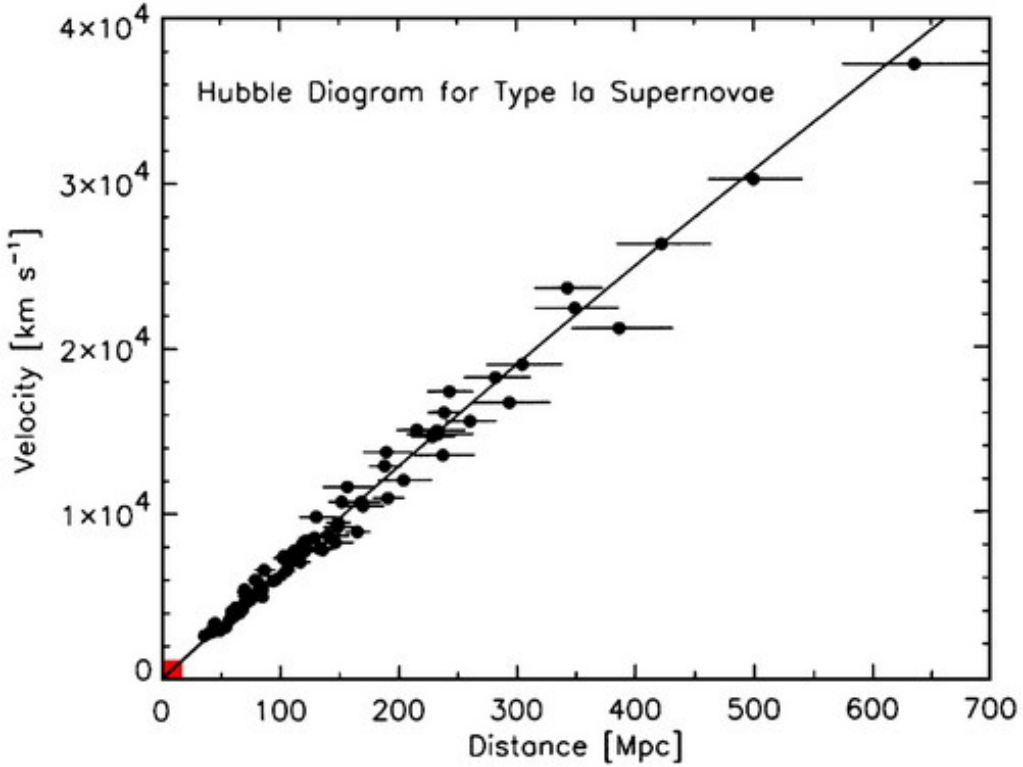
- Mass/Gravity slowed the expansion
- **Open Universe**=Low density; **Closed Universe** =High Density;
- **Flat Space=Critical Density** – very unlikely –

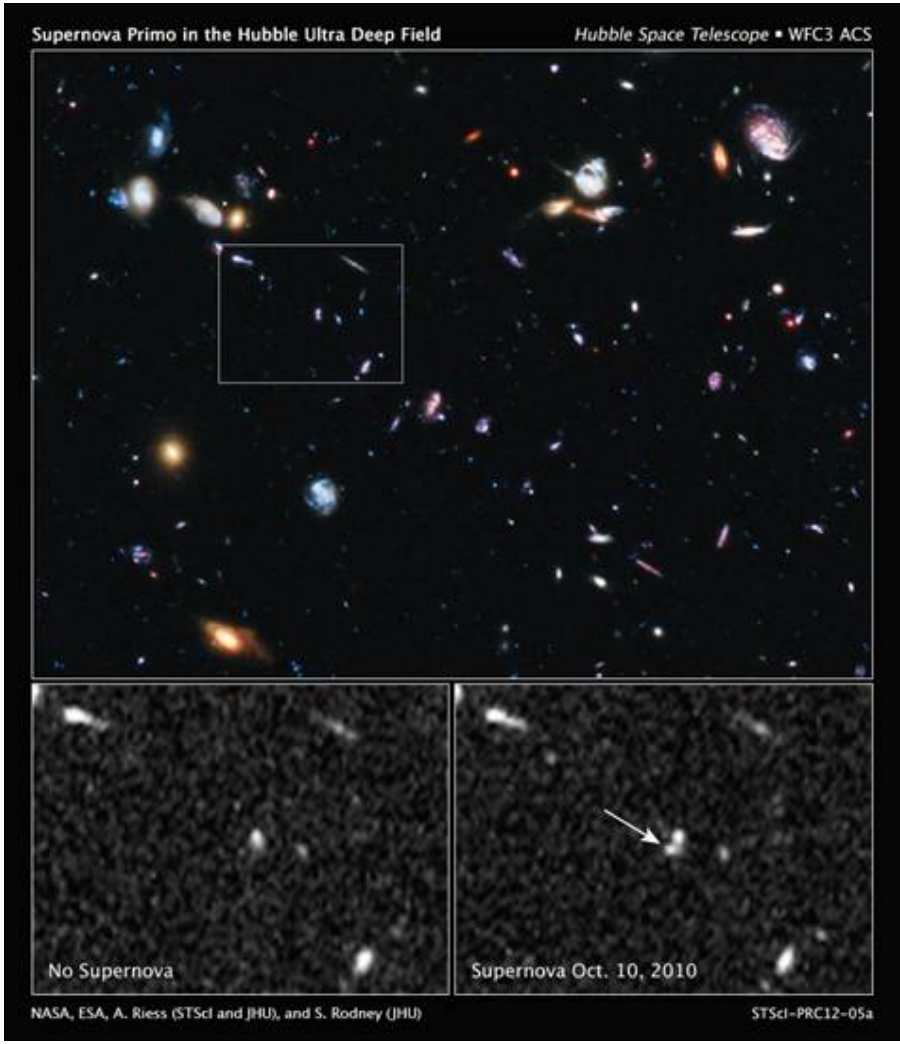
Critical Density = Critical Universe

- Galaxy cluster Abell 1689; 2.2 Billion ly; 2 Million ly across
- Add up all the mass
- 10^{11} galaxies made of 10^{11} stars made of 10^{33} grams containing 10^{23} hydrogen atoms = 10^{78} protons
- = 0.1% critical density
- Velocity Dispersion & Gravitational lenses
- Includes dark matter shows more mass
- But~15%critical density

Use Supernovae to Measure Deceleration/Mass/Density

- All SN Type Ia's have same intrinsic brightness so measure distances/velocities & get change in expansion rate





Expansion Accelerating

- Most distant supernovae show universe presently Accelerating NOT Decelerating
- 2011 Nobel prize in physics to two teams who discovered it independently (1998)

Photo: Lawrence Berkeley National Lab

Saul Perlmutter

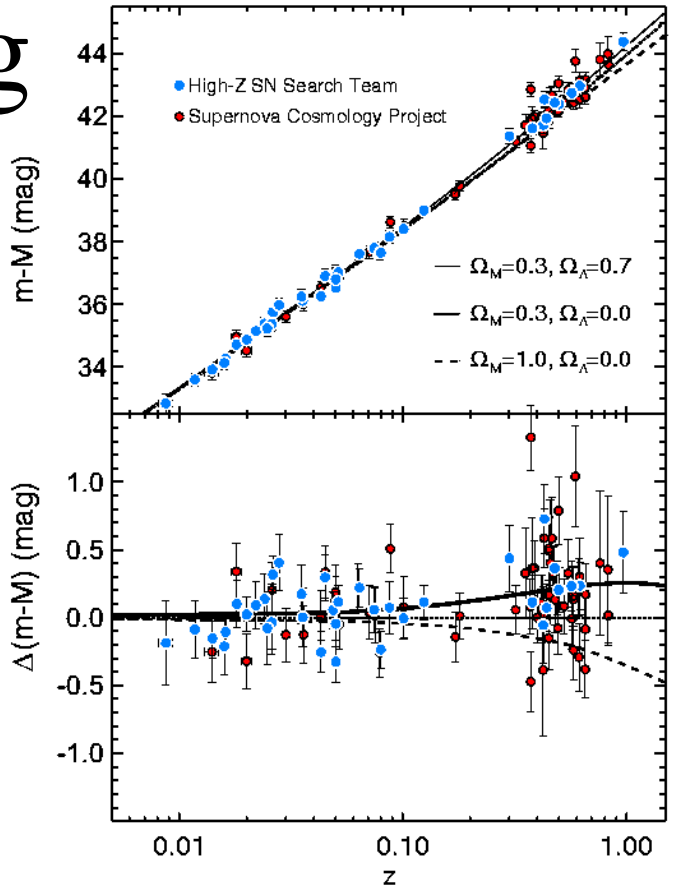
Photo: Belinda Pratten, Australian National University

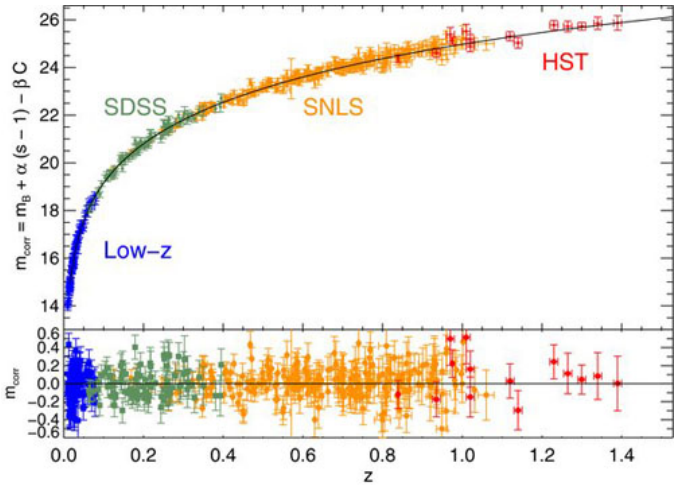
Brian P. Schmidt

Photo: Scanpix/AFP

Adam G. Riess

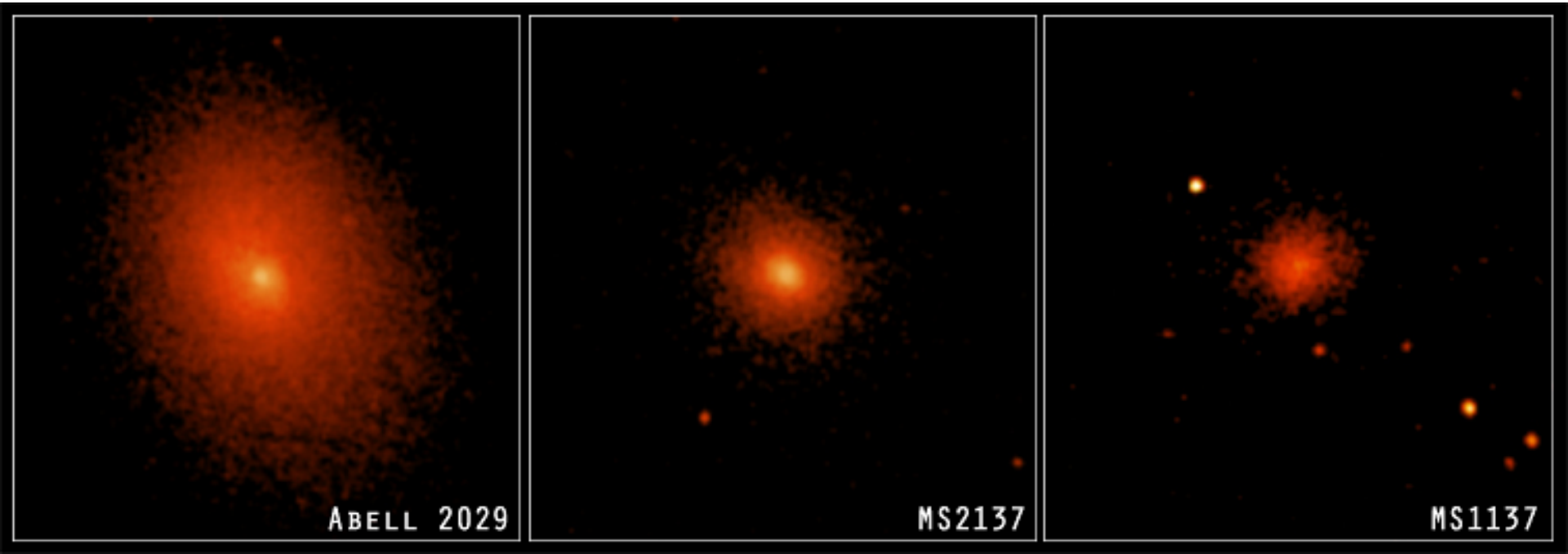
The Nobel Prize in Physics 2011 was awarded *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"* with one half to Saul Perlmutter and the other half jointly to Brian P. Schmidt and Adam G. Riess.





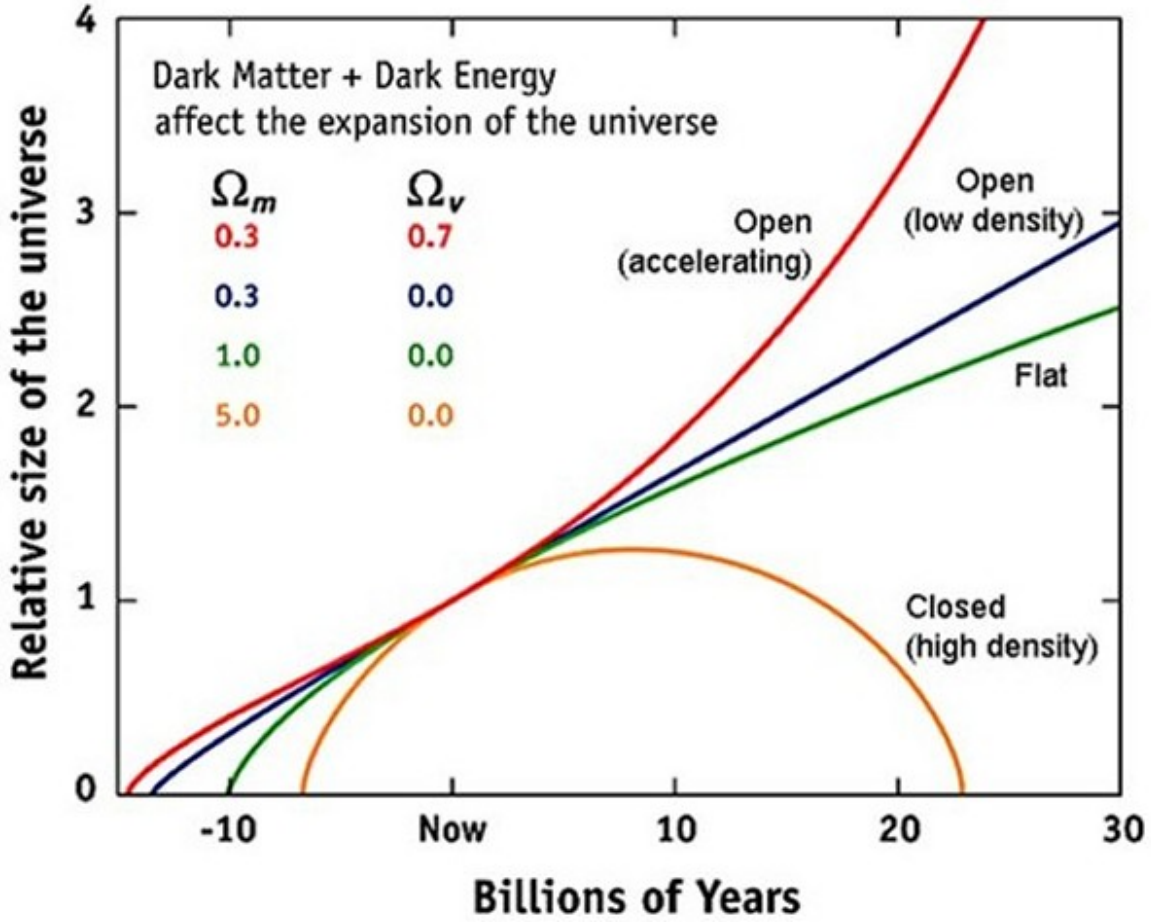
Acceleration of Expansion: X-Ray Gas → Distance & Velocity

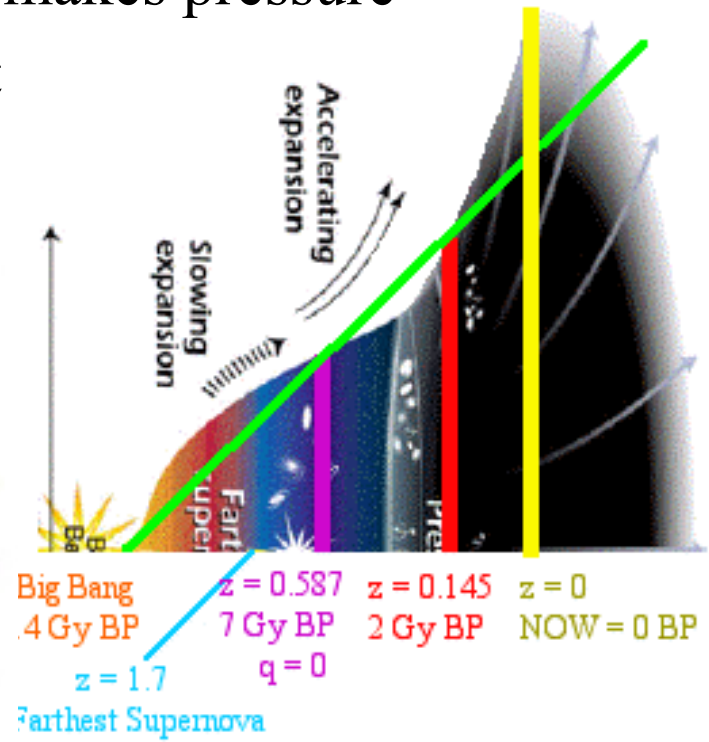
- Ratio of X-ray gas mass to dark matter mass should be constant for homogeneous universe (galaxy cluster sized)
- Gas mass measured by temperature of gas &
- Intrinsic brightness depends on gas mass and temperature
- Plus Apparent brightness gives the distance



Accelerating Expansion=**Dark Energy**

- Dark energy in vacuum between galaxies makes pressure
- Pressure/antigravity pushes galaxies apart
- Galaxies move apart faster and faster

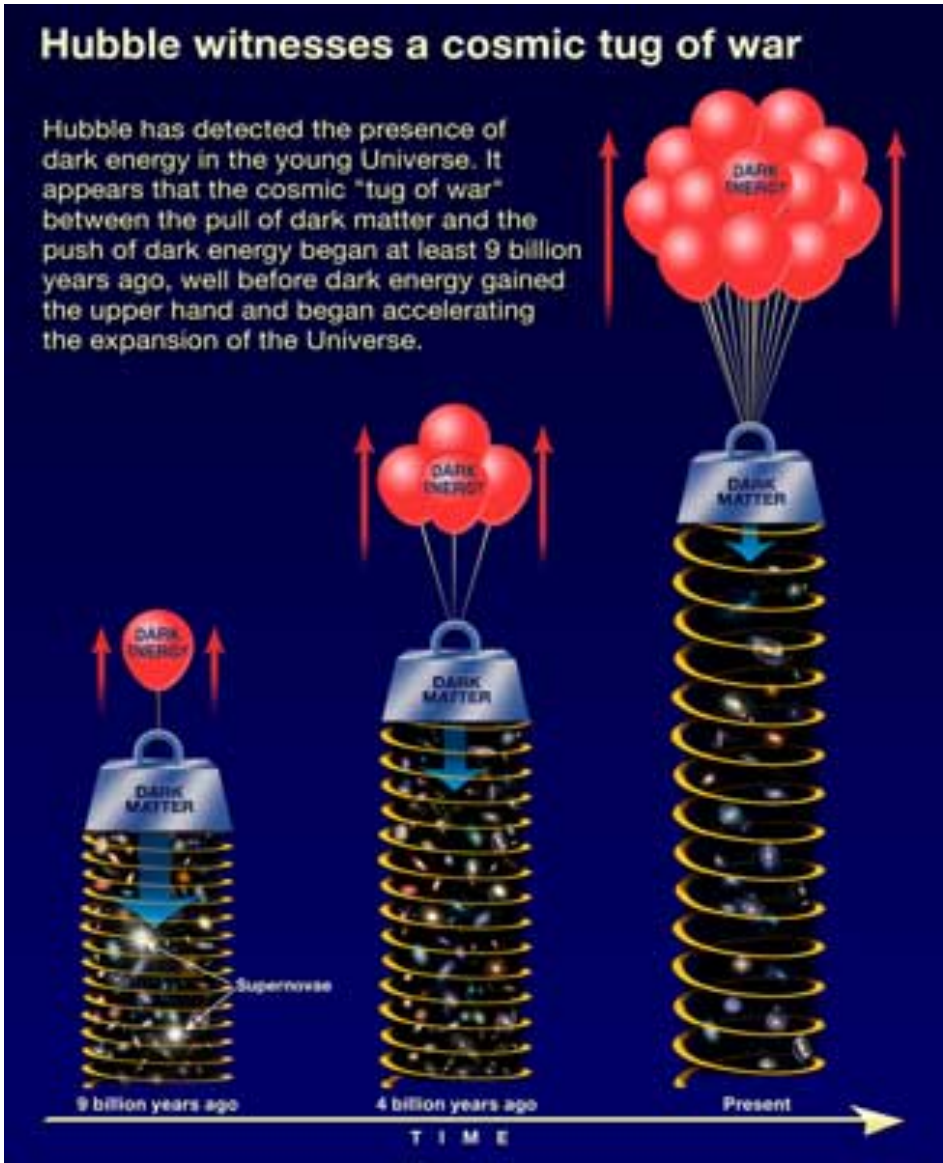




Dark Energy=Cosmological Constant

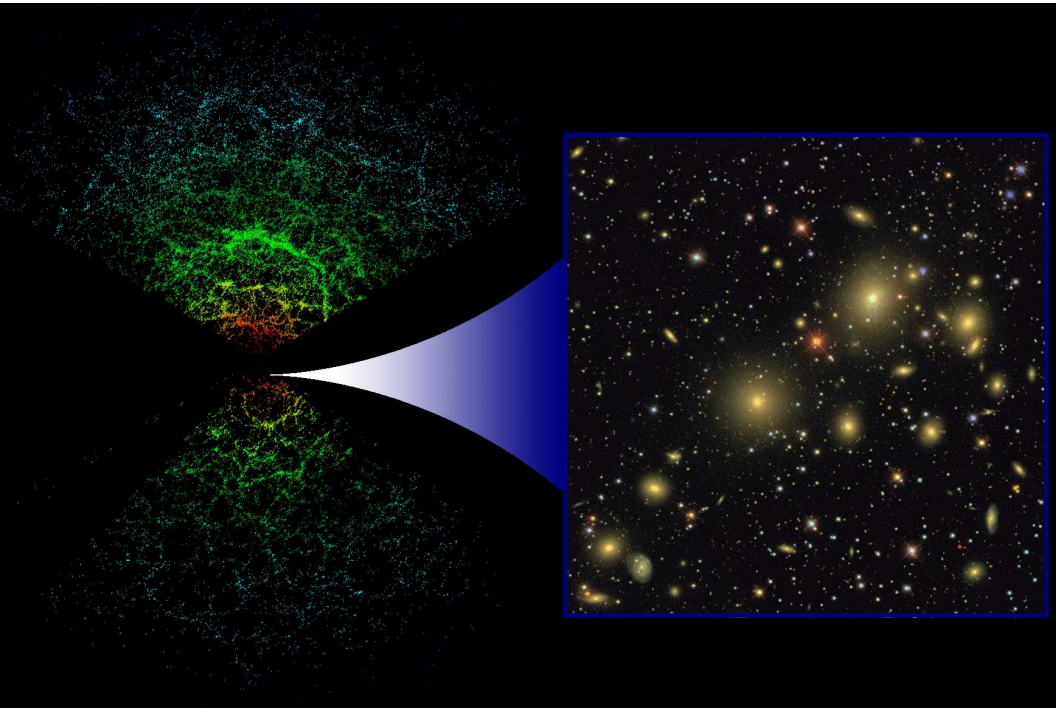
- Constant with time & volume
- More space=More pressure
- So Einstein's "Greatest Blunder" **Cosmological Constant** Λ = Dark Energy
- Is correct

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu},$$

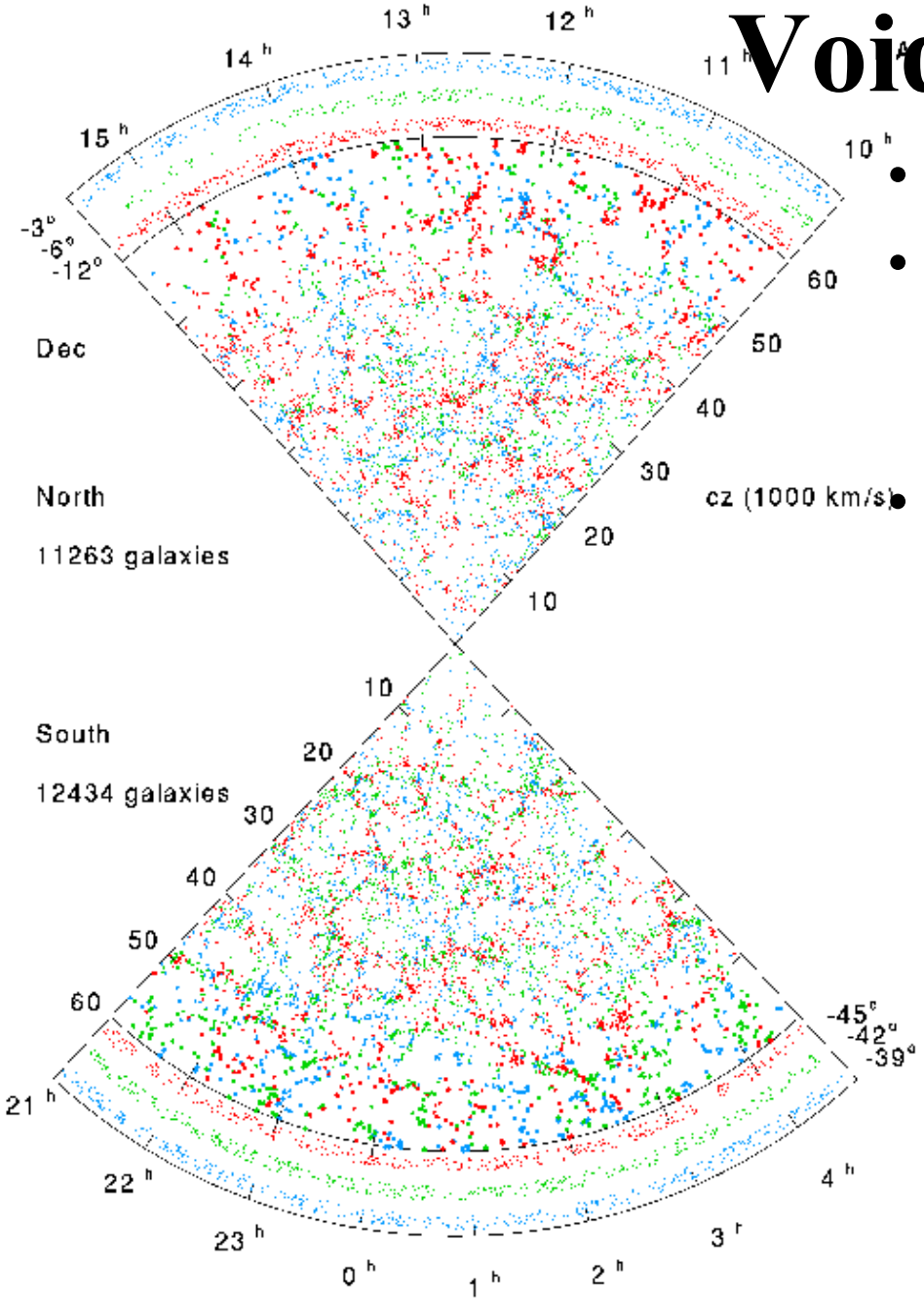


Large-Scale Structure: Observations

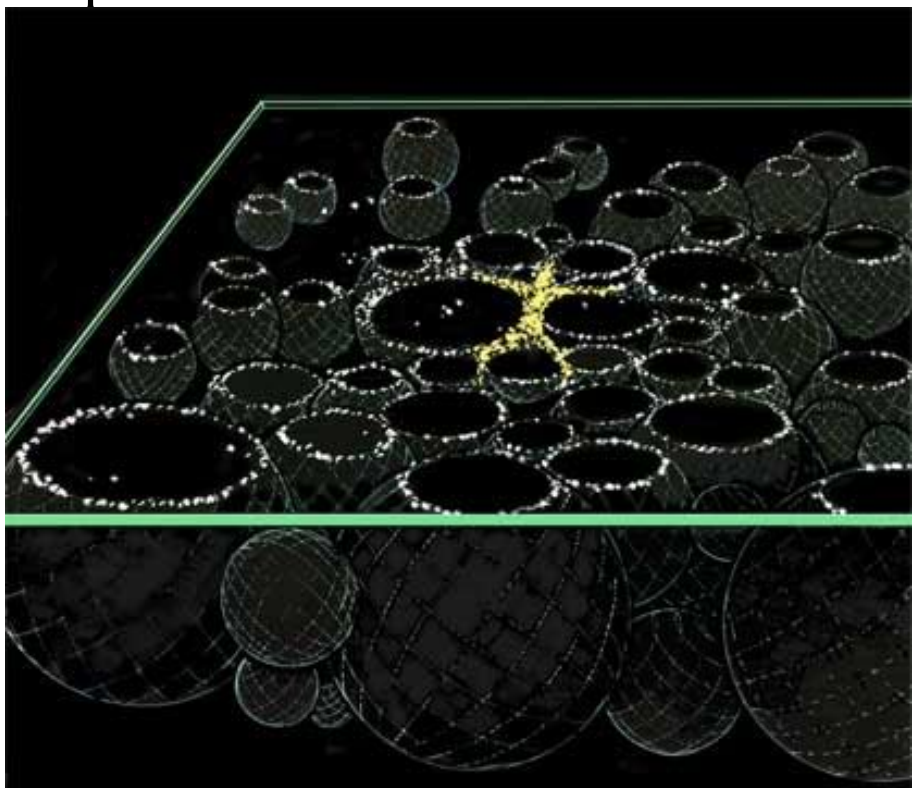
- In the 1980's Margaret Geller measured redshifts of galaxies passing overhead and plotted them according to distance and direction in space
- SLOAN Great Wall: 1Billion ly distant &1Billion ly across
- Not isotropic & homogeneous



Voids & Superclusters

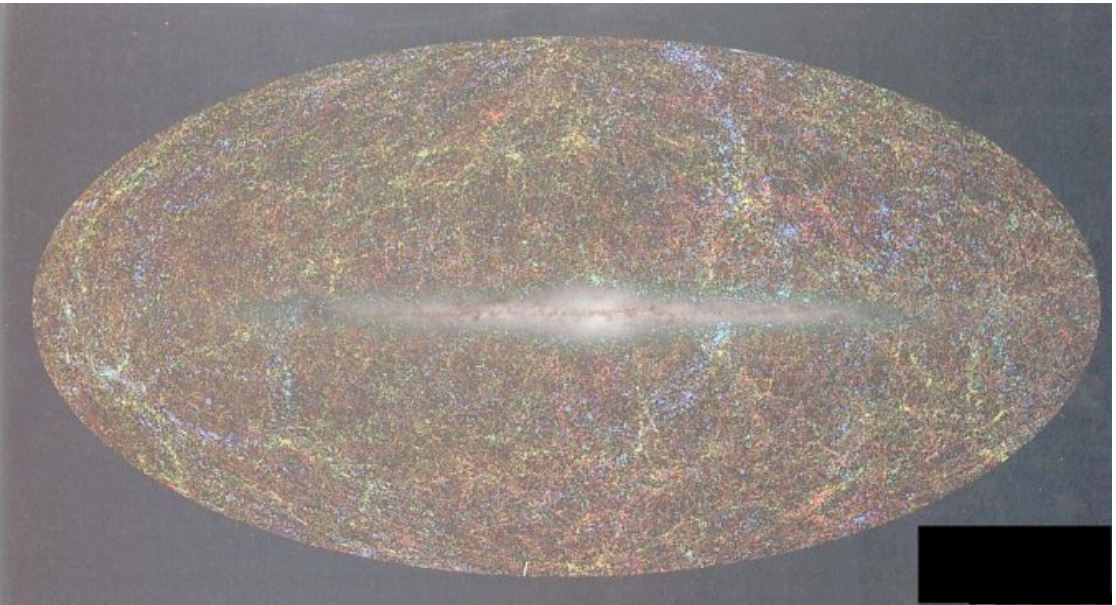


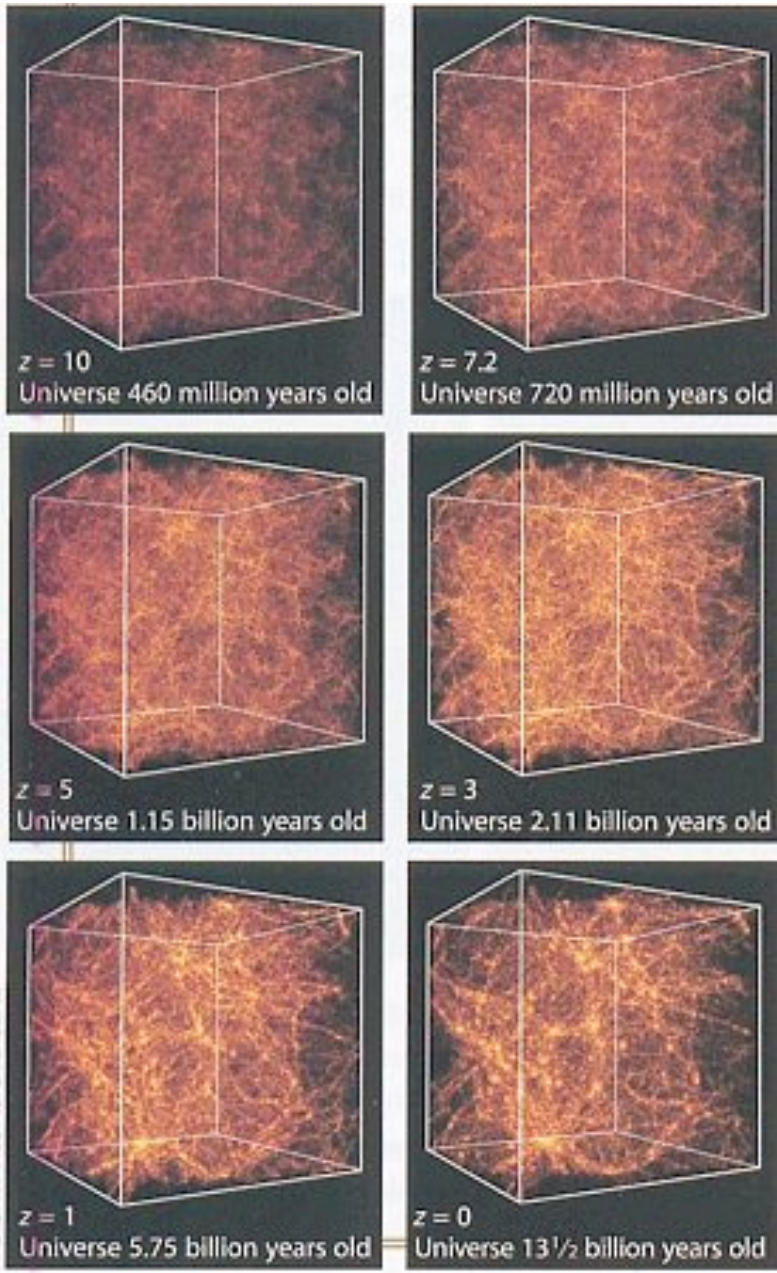
- Las Campanas redshift survey
- Galaxy distribution shows large-scale structure = **superclusters & voids,** filaments
- Like a sponge, beer bubbles or soap bubbles



Large-Scale Structure: Formation

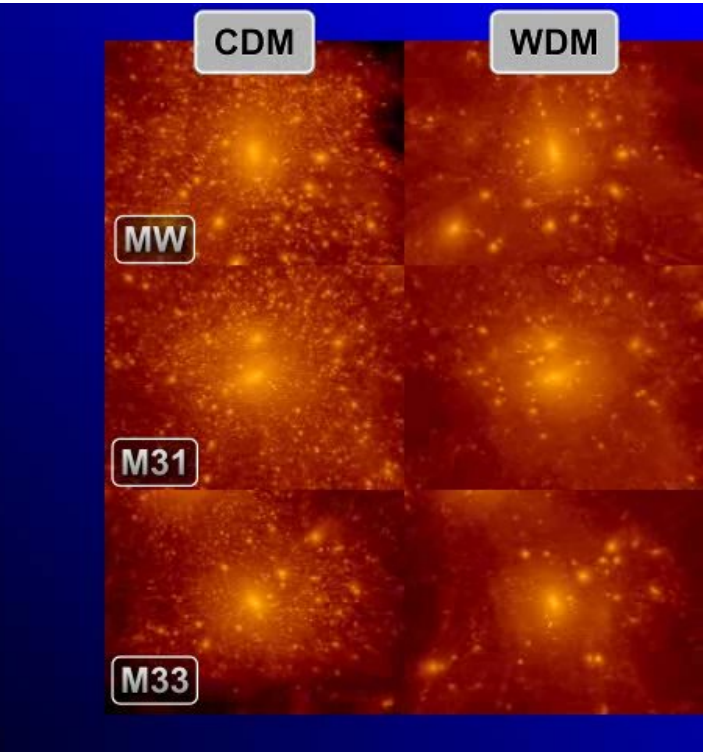
- Initially matter smooth, at z=1100
- Seeds of structure: quantum fluctuations expanded by inflation
- Gravity from all matter pulling dark & ordinary matter together
- Dark energy pushes clusters apart

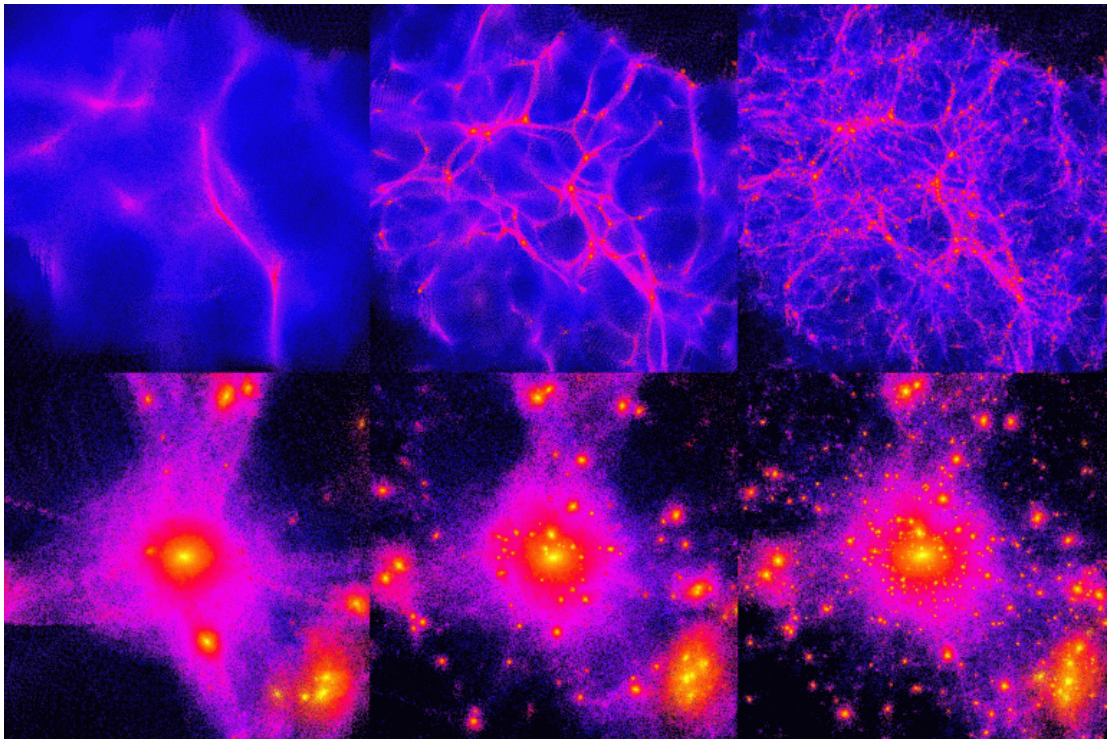




Hot and **Cold Dark Matter**

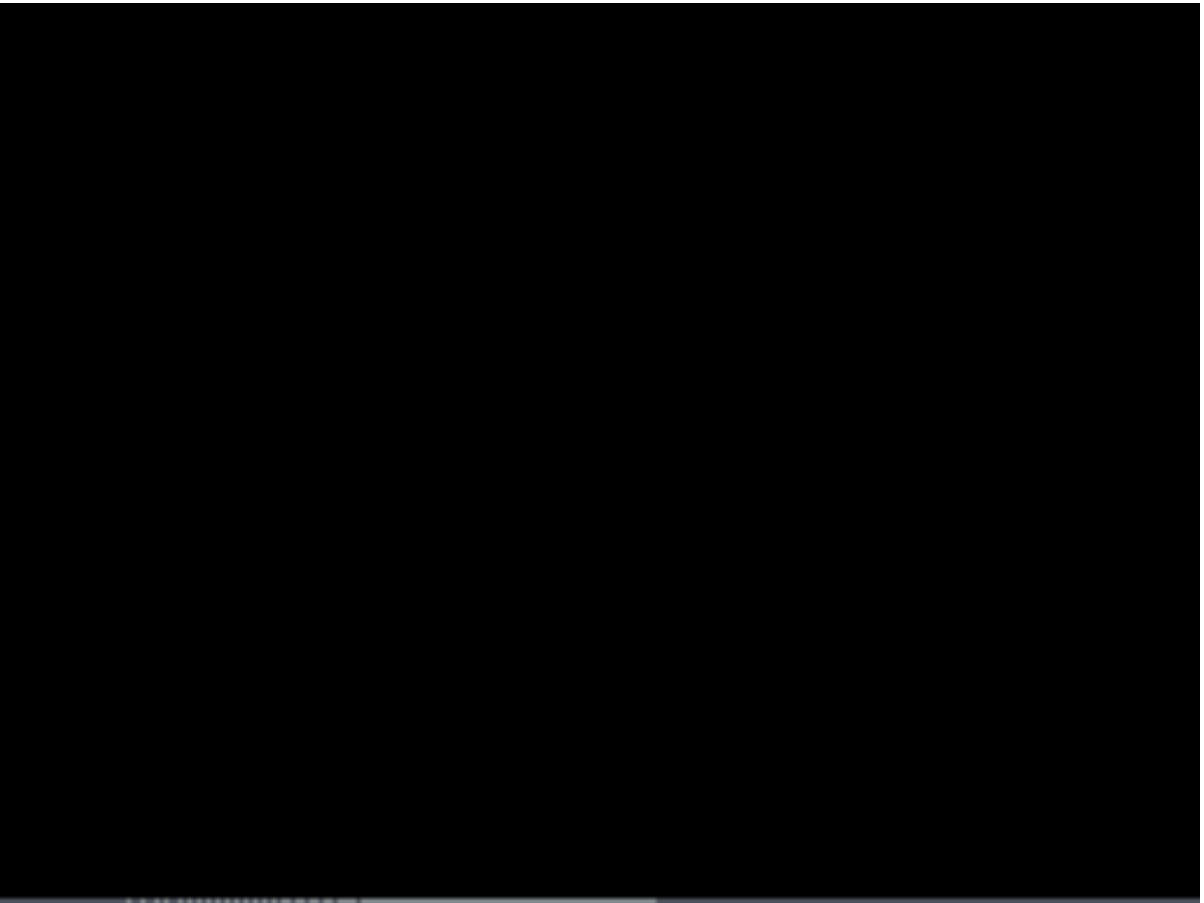
- **Cold Dark Matter**: massive slow moving WIMPs predicts too many dwarf galaxies??
- **Hot Dark Matter**: small mass + moving at/near speed of light (=neutrinos) smears out small structures
- Dark matter must be cool (slow moving) but not too cold

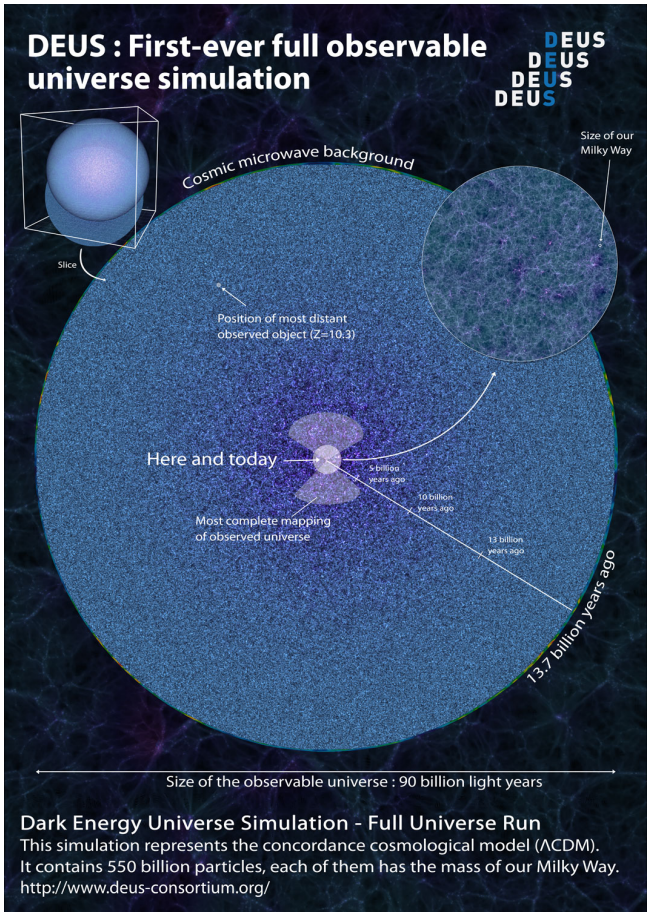




Large-Scale Structure: Simulations

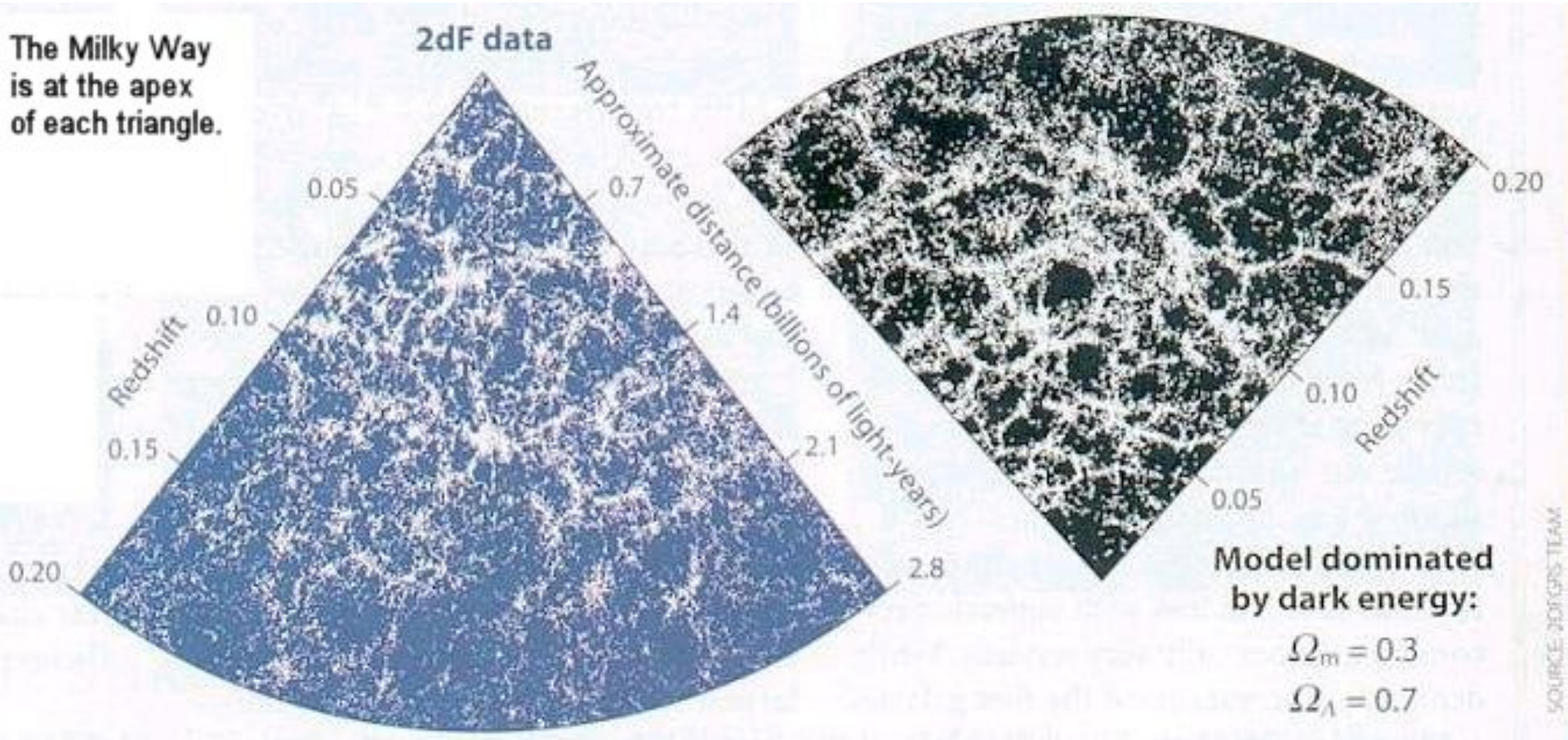
- Andrey Kravtsov: Box expands at same rate as universe
- First stars at ~500million years, Quasars by z~7 & Galaxies ~z=10





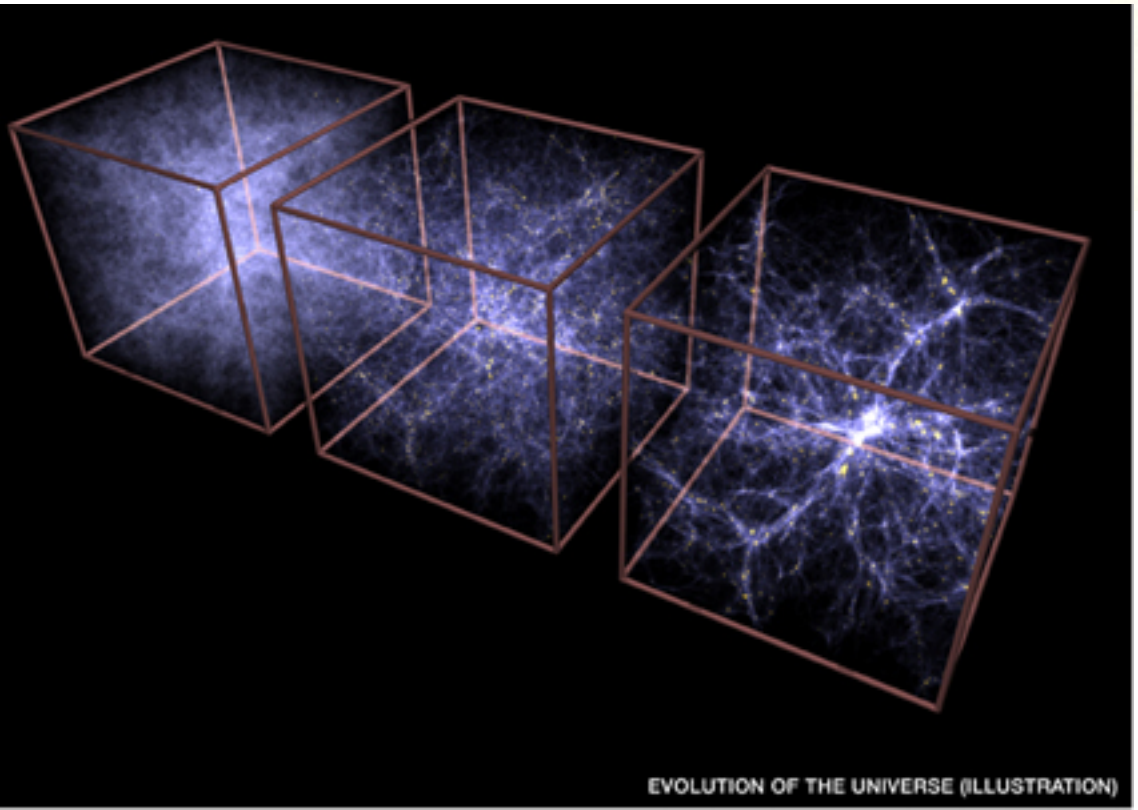
Large-Scale Structure Simulations

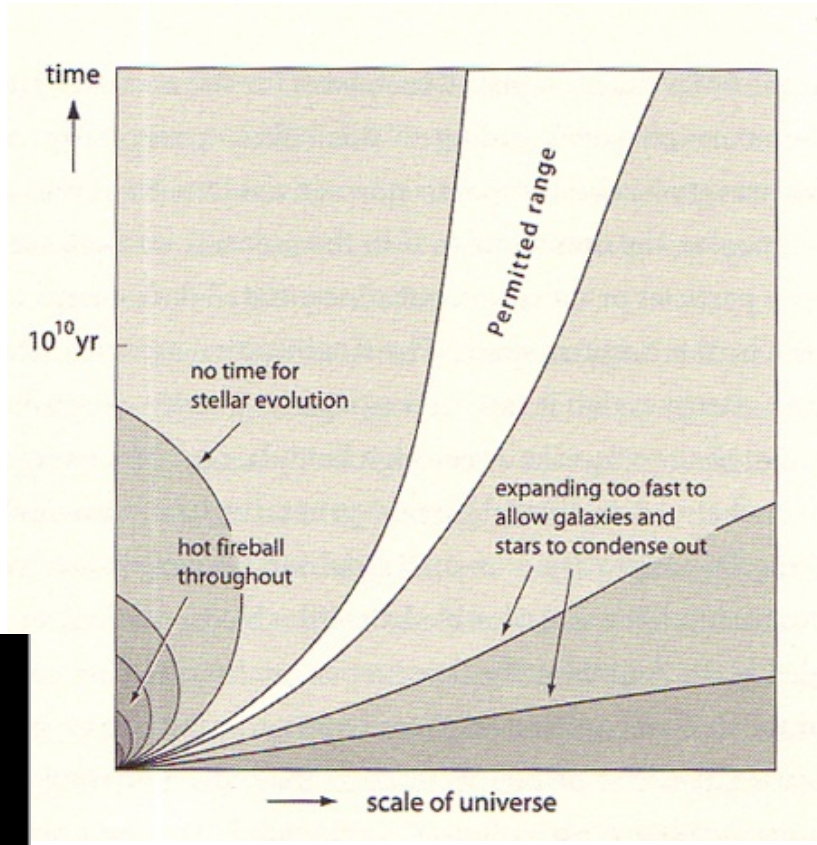
- Too much matter and all mass goes into black holes
- Too much **Dark energy:**Universe expands too fast-no stars
- Simulation with WMAP parameters-similar to real Universe



What if?

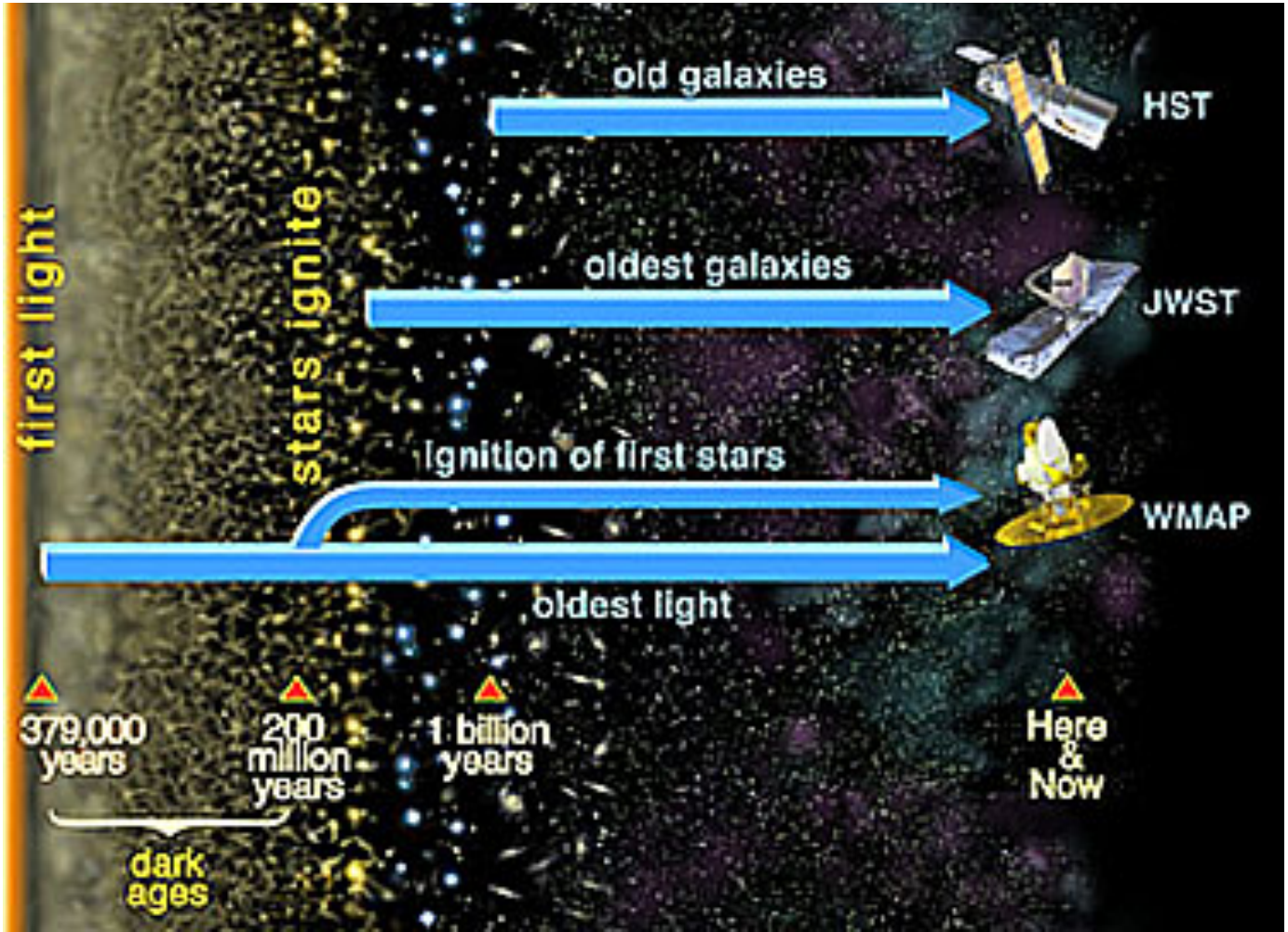
- More Dark Matter?
- More Dark Energy?





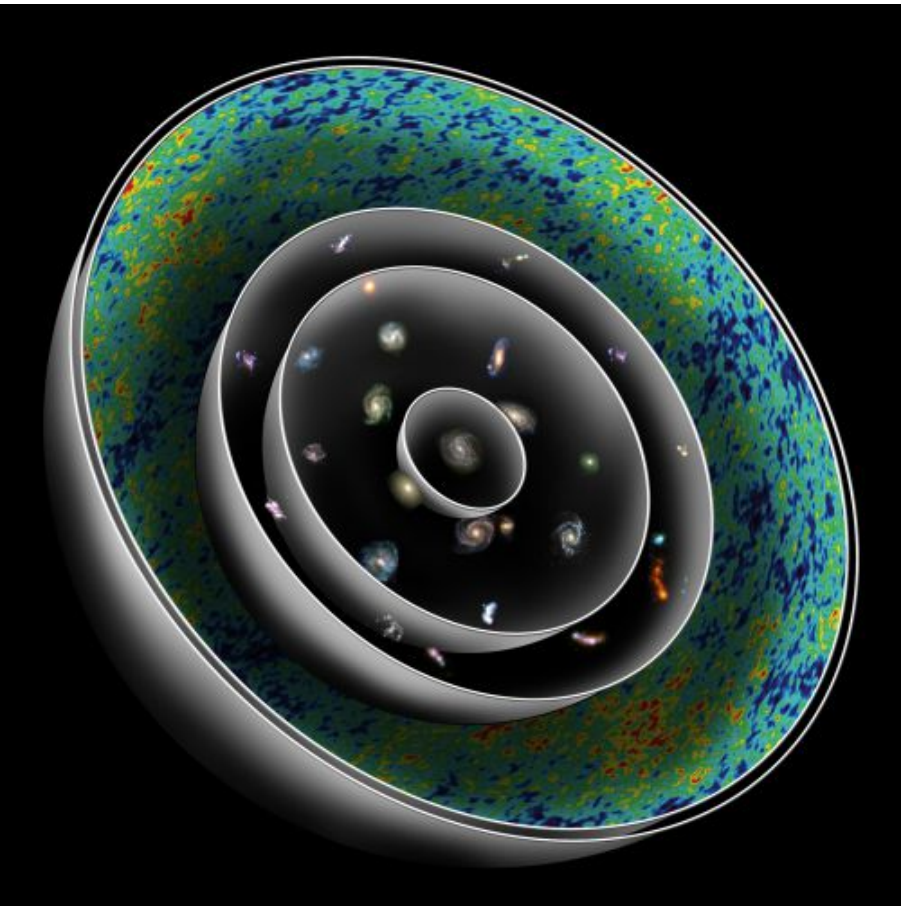
The Dark Ages

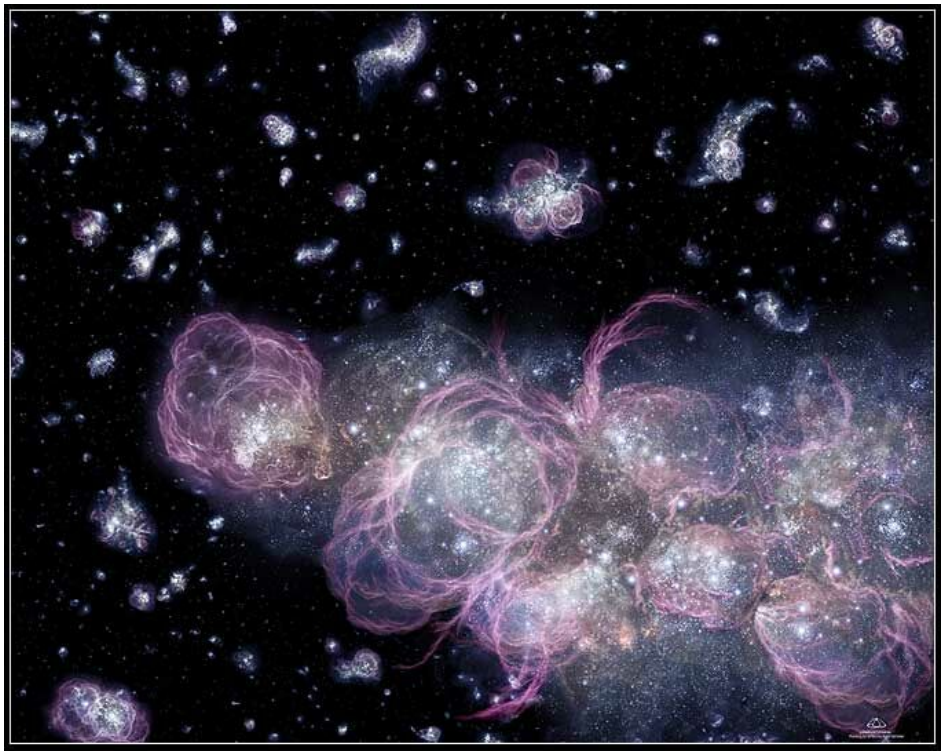
- From CMB at 380,000years to First Stars at 400 Million years



Population III

- First stars formed from only hydrogen & helium
- Not yet observed – None seen near the sun? or in Halo?
- Maybe 100's of solar masses; temp~100,000K



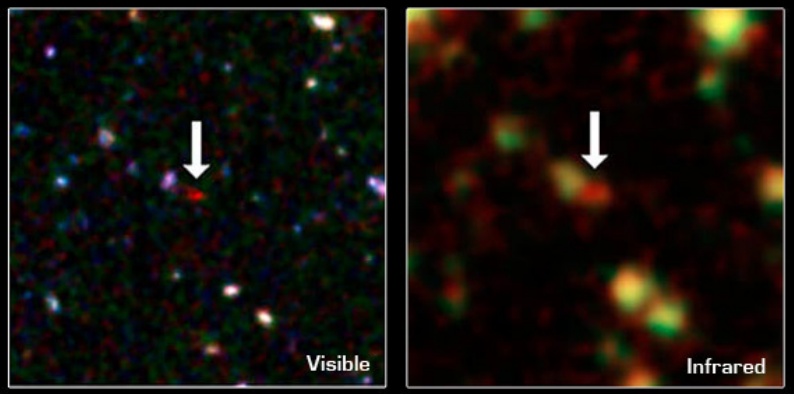


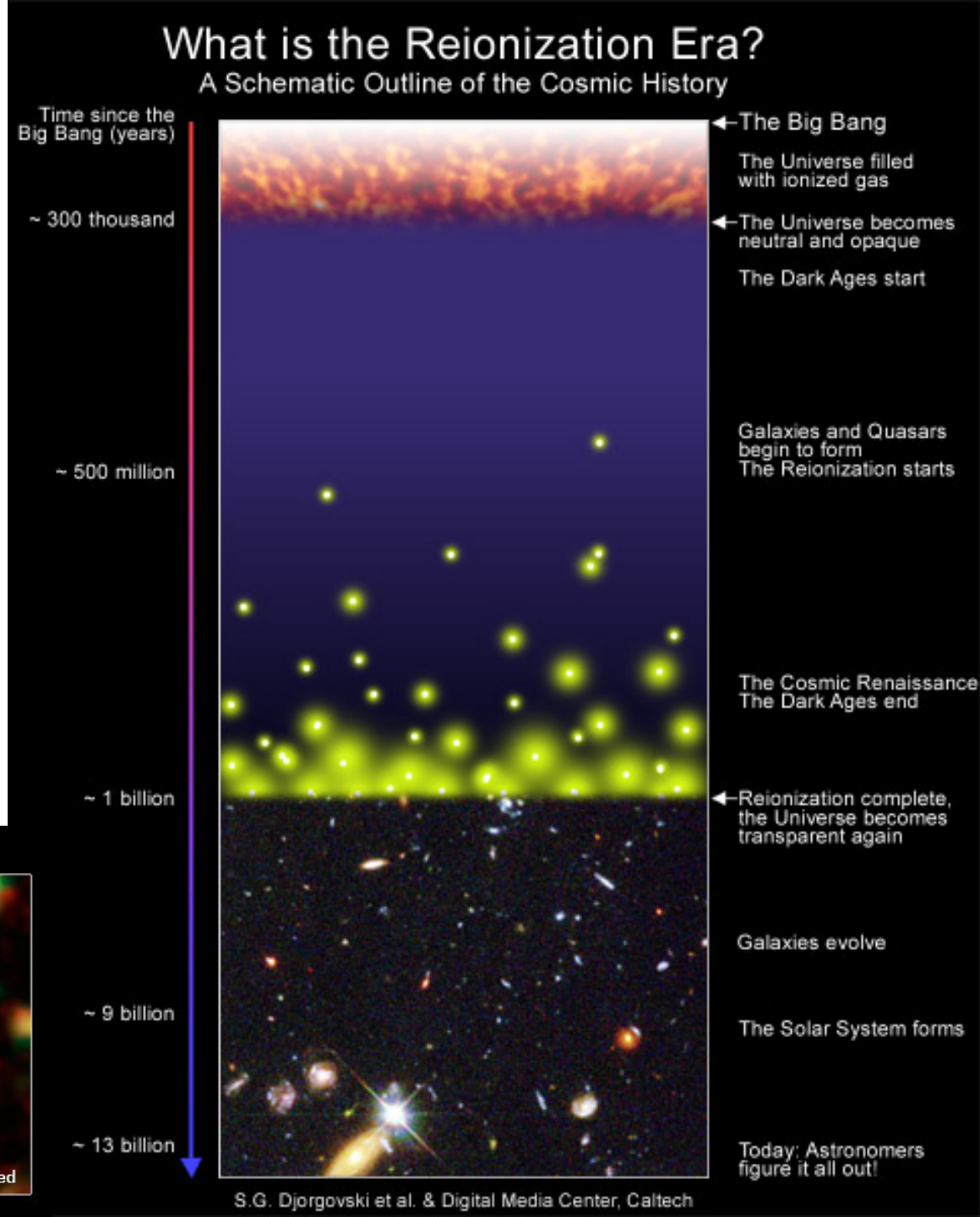
Artist's View of Star Formation in the Early Universe

Painting by Adolf Schaller • STScI-PRC02-02

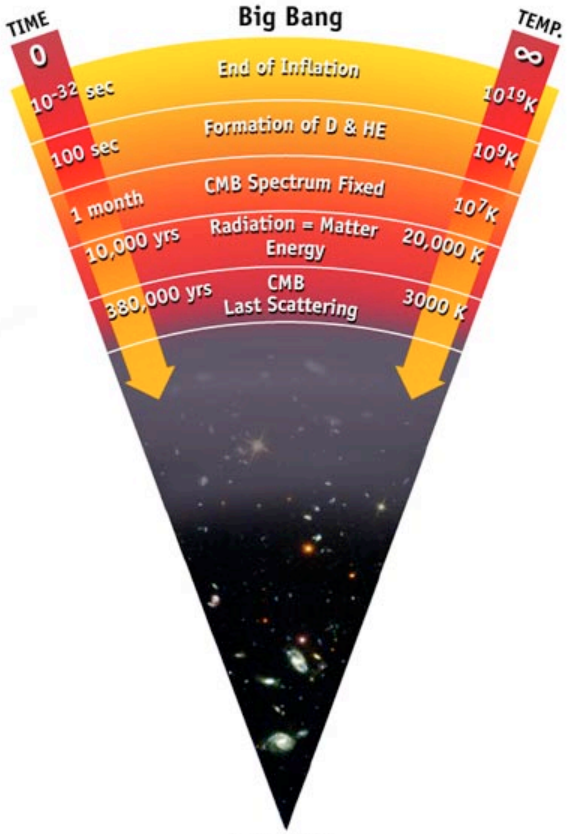
Reionization

- UV from hot Pop III stars
- Re-ionized the nearby clouds of Hydrogen
- Starburst galaxy from z=7.2 =12.9 billion years ago.

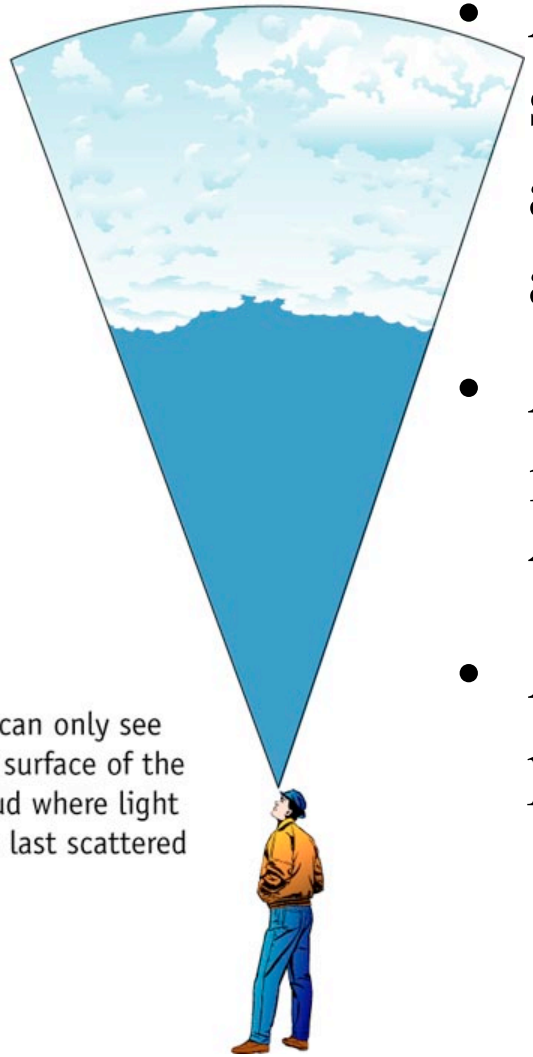




Cosmic Microwave Background = Cosmic Background Radiation



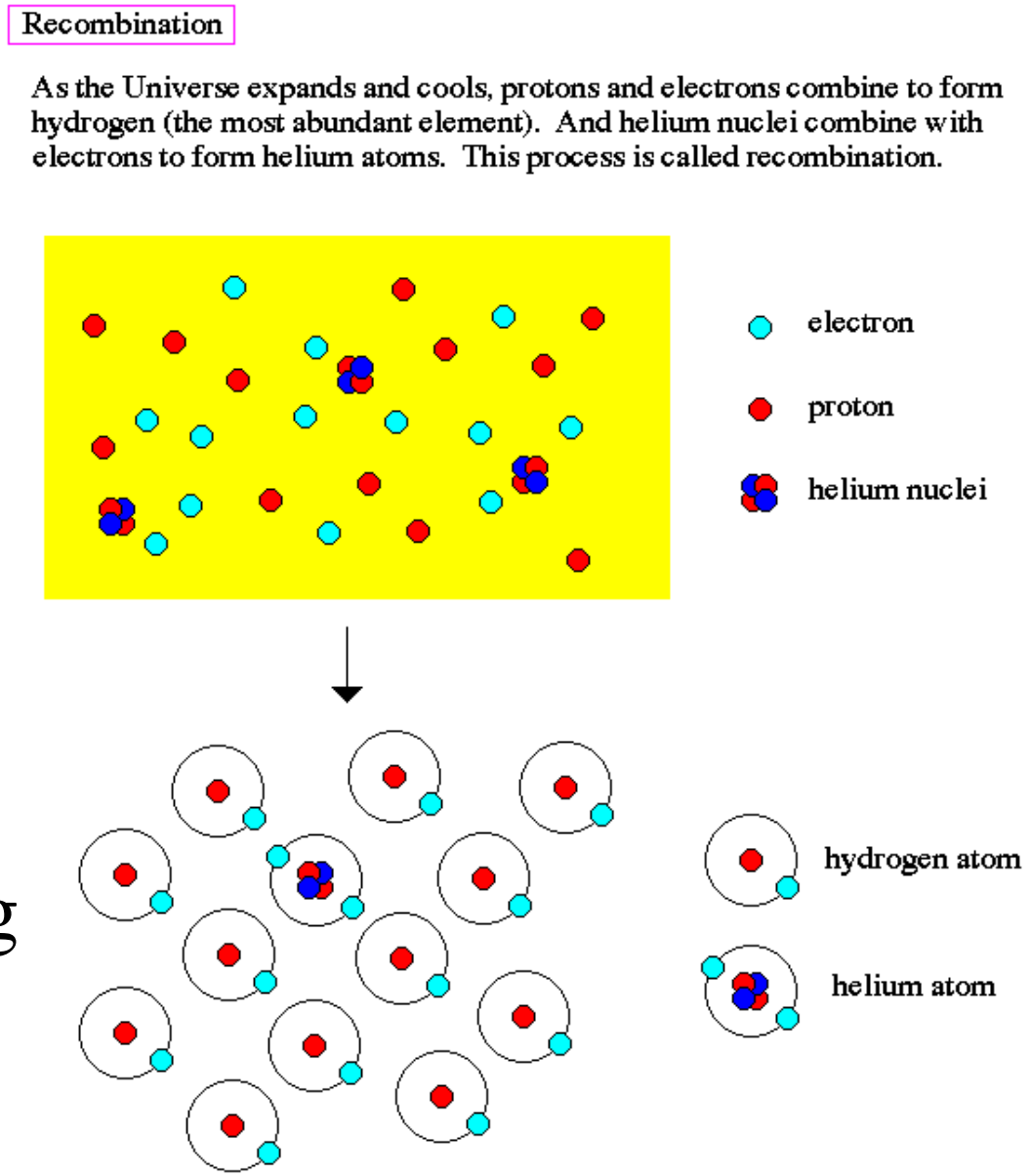
The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



- As we look back we see the universe denser and denser & hotter and hotter
- At some point/time it is too dense to see through
- Alpher, Bethe, Gamow predicted CMB 1948

Decoupled = Recombination

- The Big Bang produced extremely hot gas called the **Primeval Fireball**
- Which cooled for 380,000years to ~3000Kelvin
- Protons combined with electrons making neutral hydrogen

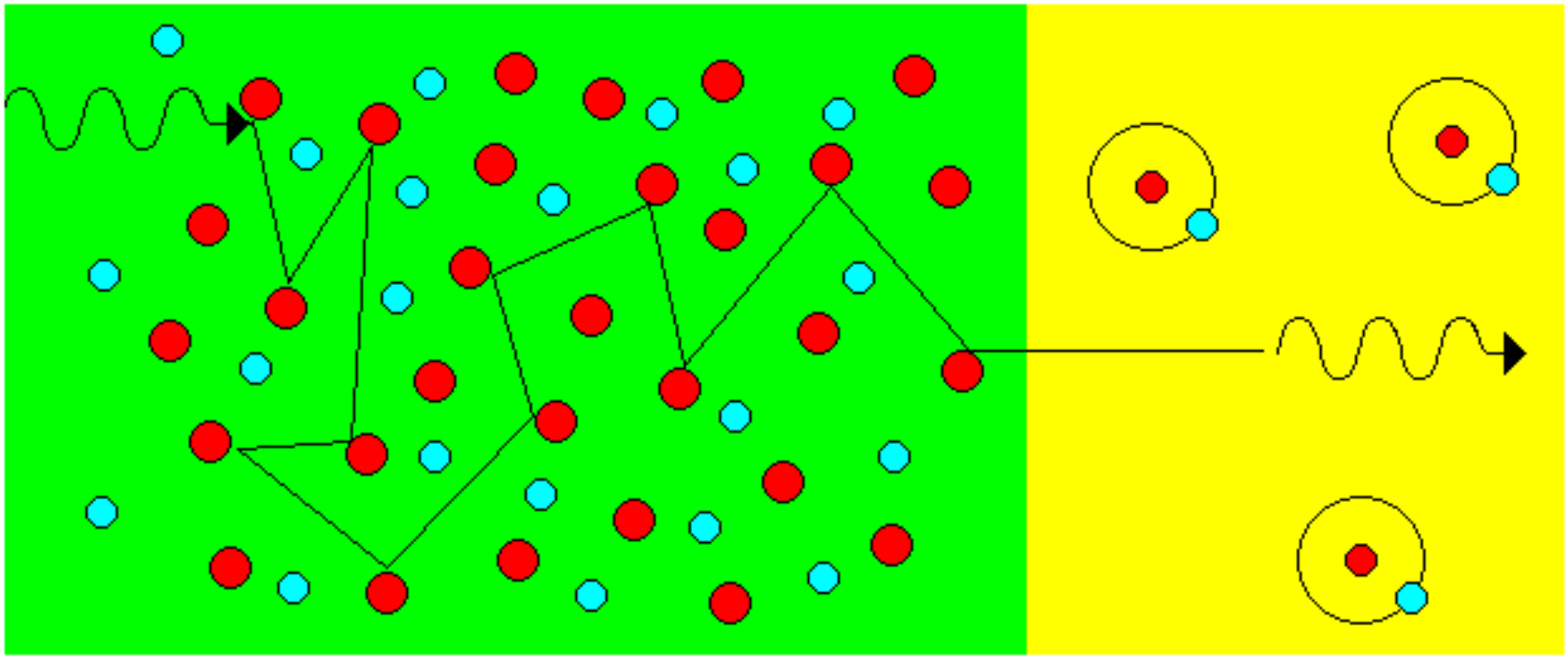


Last Scattering

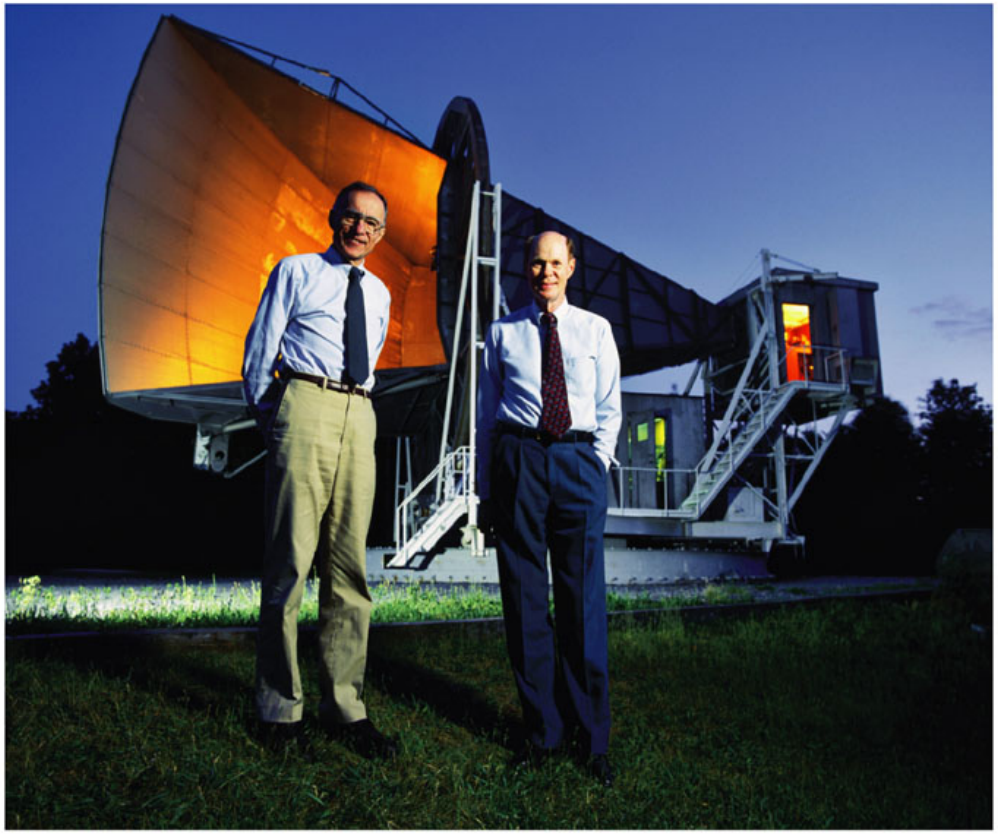
Universe became transparent and photons traveled unimpeded through the Universe

Last Scattering Epoch

As the Universe cooled, the free electrons and protons could finally bond togther to form hydrogen atoms. At the same time, the Universe went from a rich plasma to a gas of neutral hydrogen.



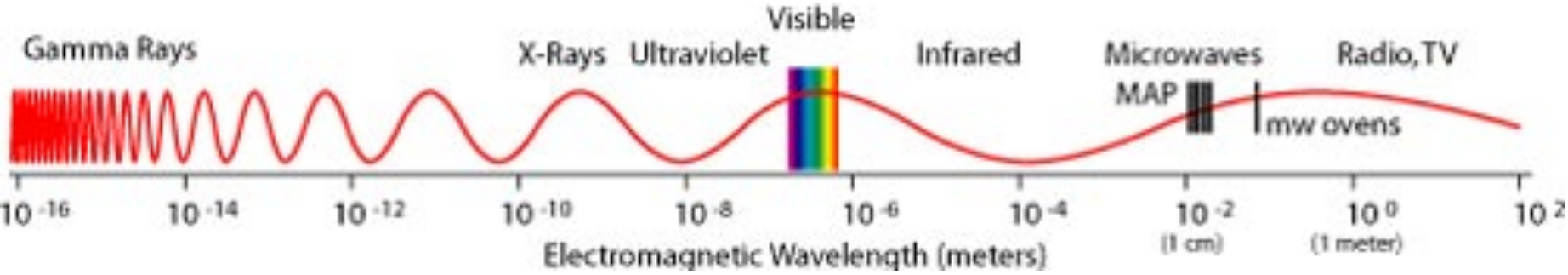
Penzias and Wilson Discover **Cosmic Microwave Background Radiation**

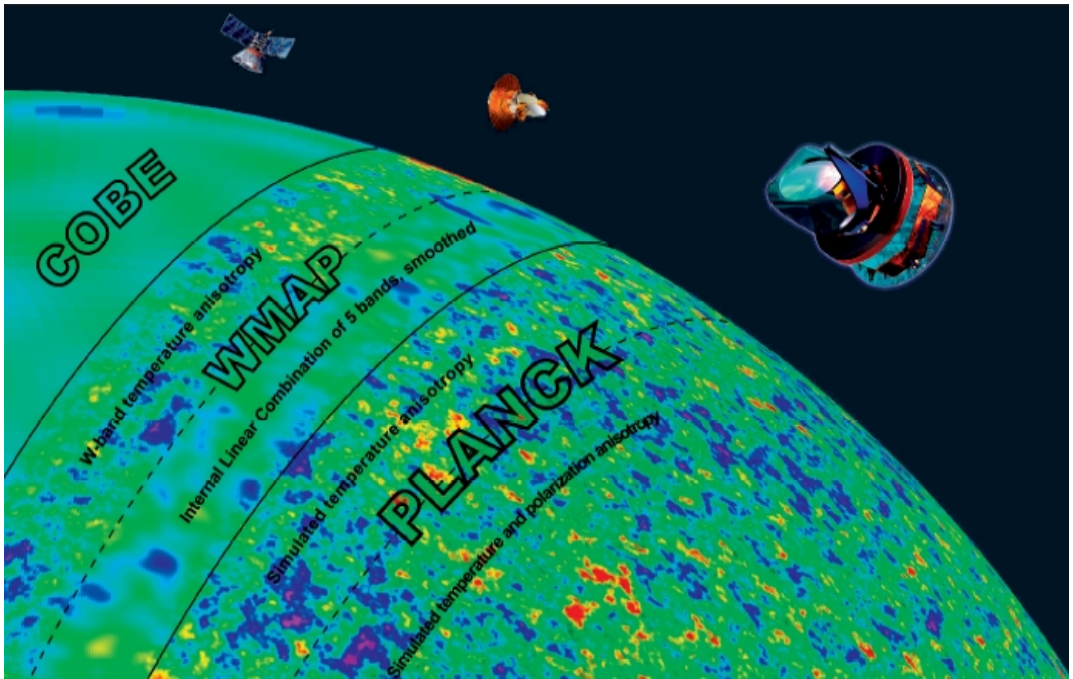


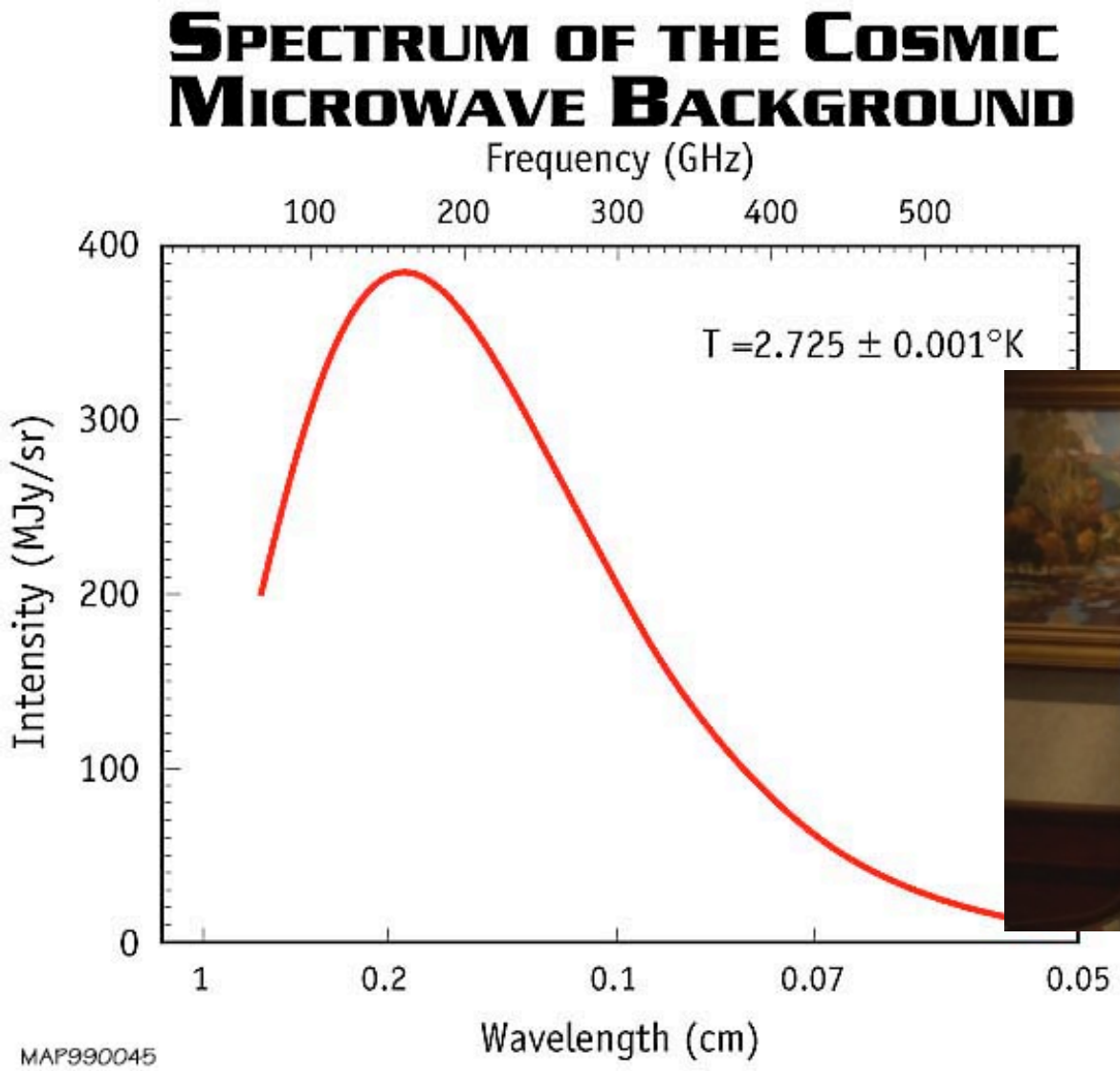
- First observed in 1965 & Nobel prize 1978
- Sky was of uniform brightness in microwaves
- End of the "Steady State Theory"
- Since temperature/density were different at this time/distance
- ~1% of static on TV is from CMBR

Satellite Measurements

- Earth's atmosphere is opaque to most microwaves so
- First COBE, then WMAP and now PLANCK

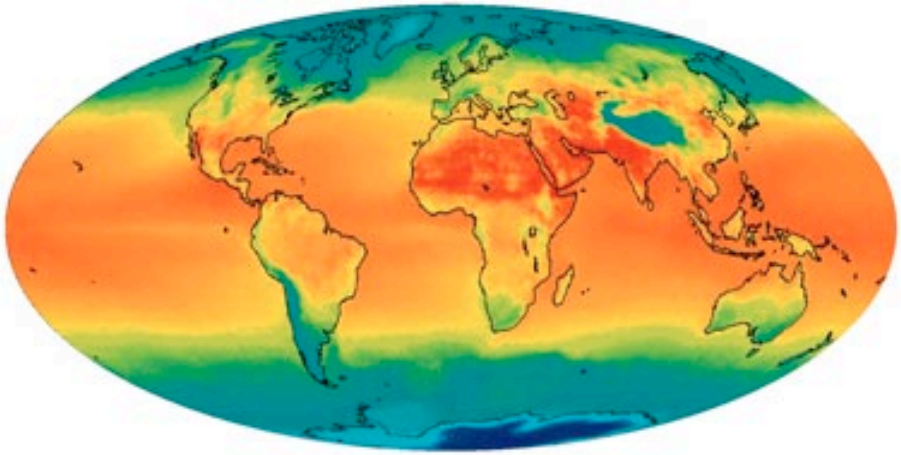






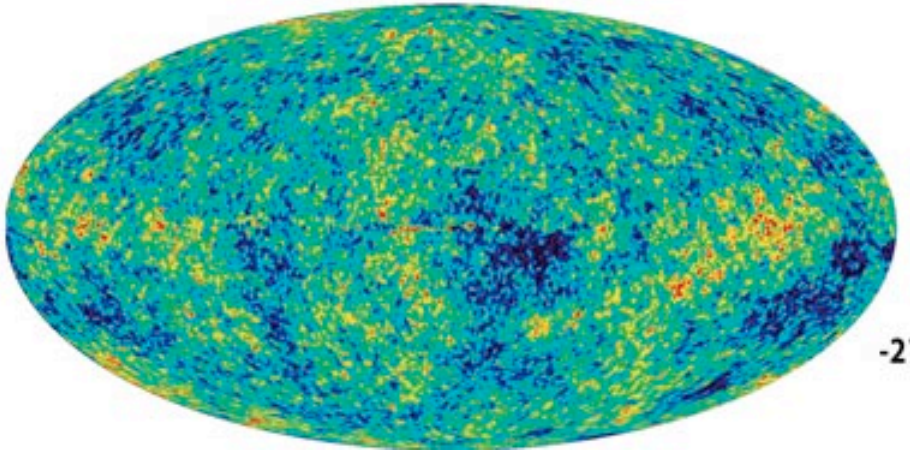
- Perfect Blackbody shape
- Was 3000K but is now redshifted with z of 1100 to 3K
- George Smoot won Nobel prize in 2006 for COBE

Temperature Map of Earth and Sky



Earth
Temperatures

-63° -13° 37°
Centigrade
June 1992

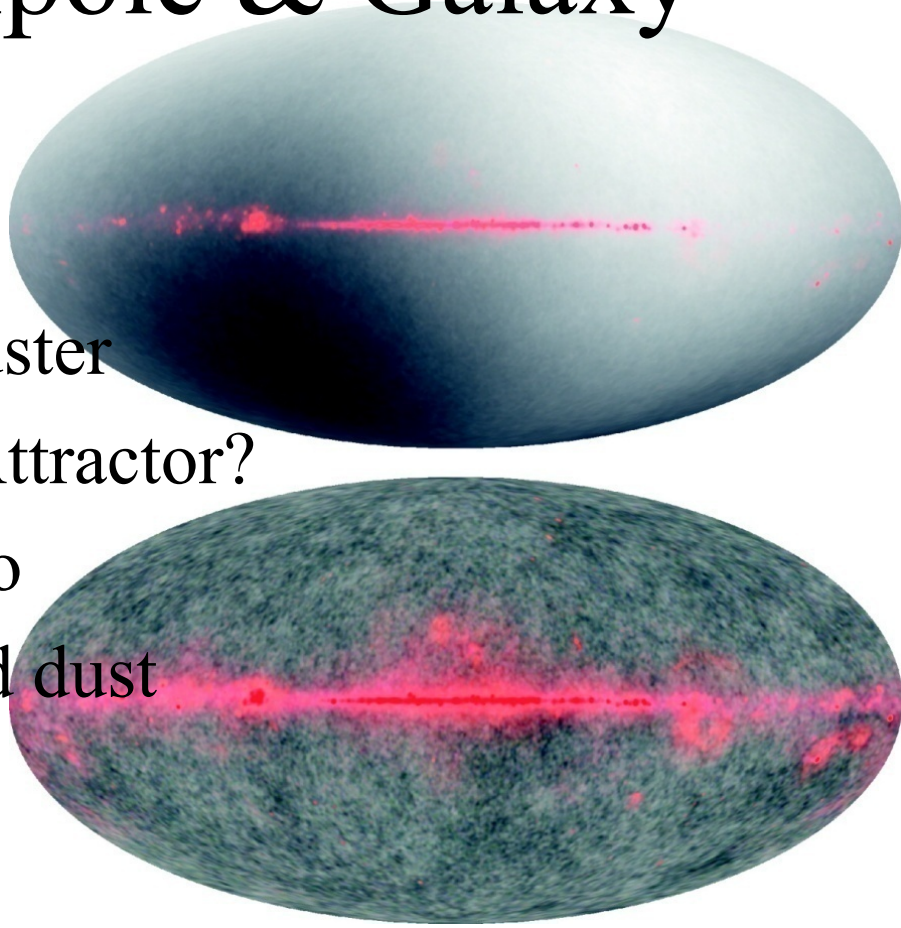


Microwave Sky
Temperatures

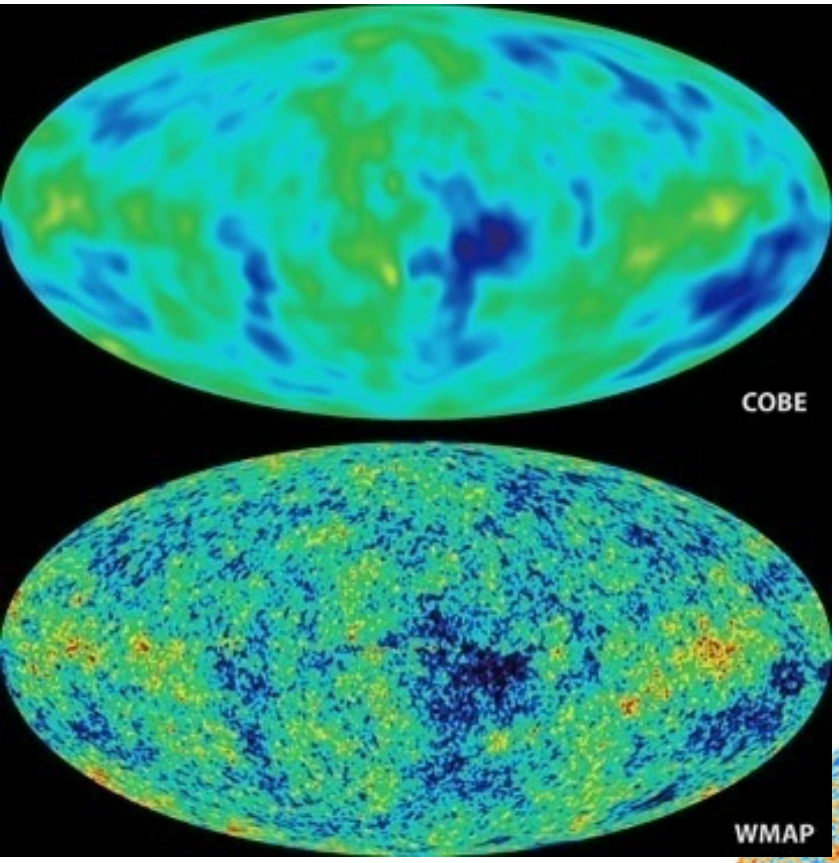
-270.4252° -270.4250° -270.4248°
Centigrade
380,000 Years after Big Bang

Background = Dipole & Galaxy

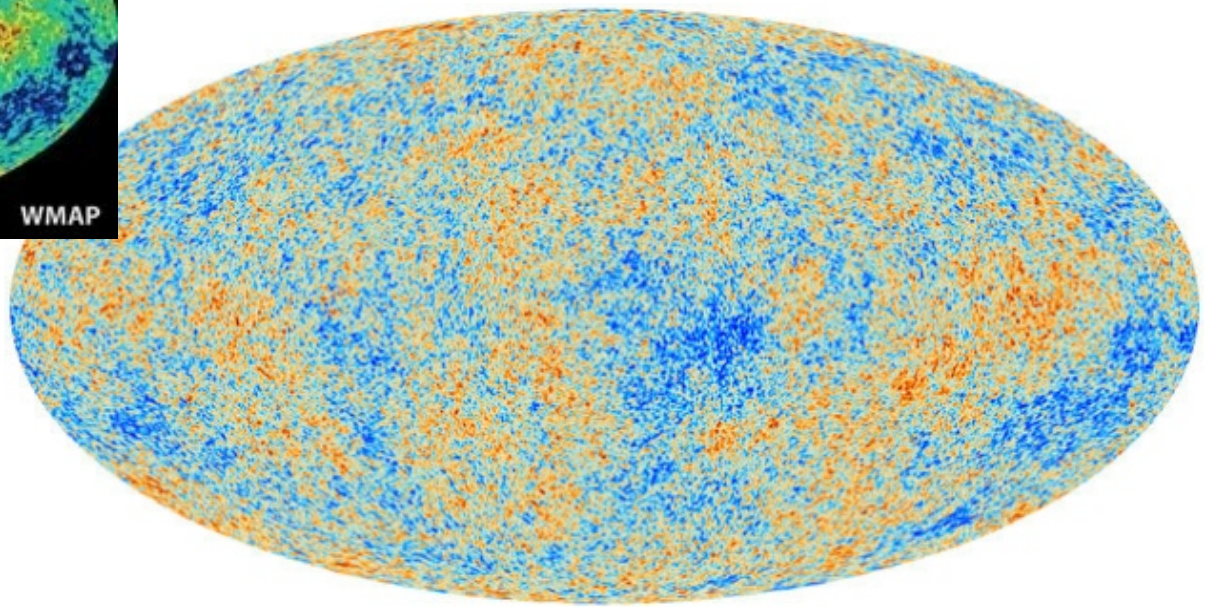
- Earth moves around Sun
- Sun moves around Milky Way
- Milky Way falls into Virgo cluster
- Virgo cluster falls into Great Attractor?
- Sums to 370km/sec toward Leo
- Stars in galaxy heat foreground dust



WMAP/COBE Results

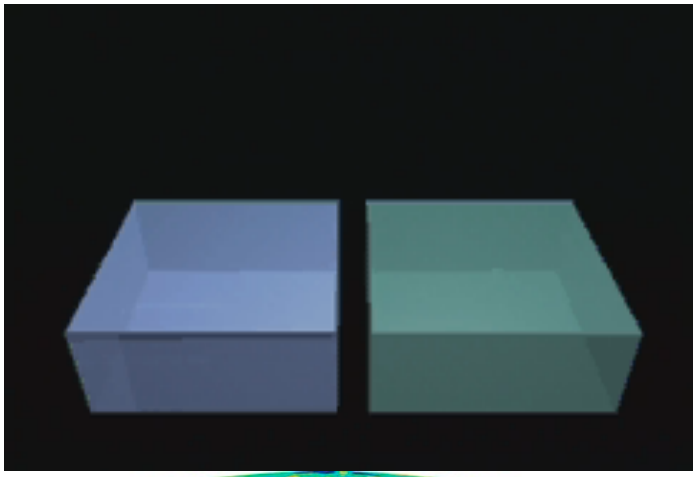


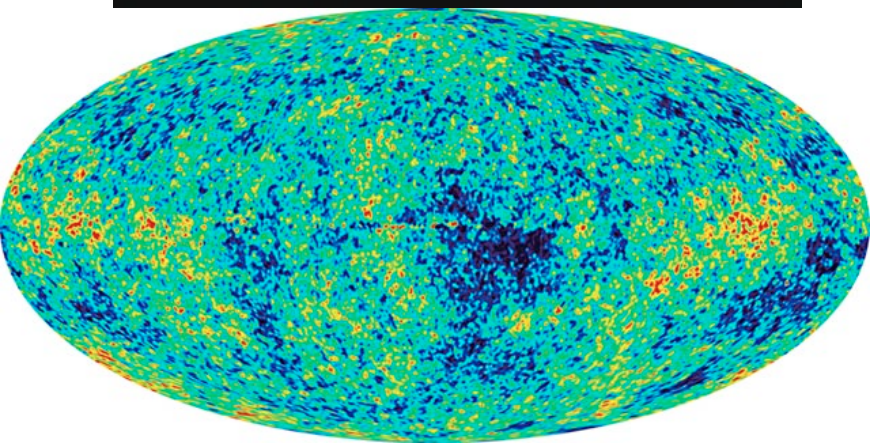
- COBE has less resolution than WMAP
- PLANCK has highest resolution
- Hubble Constant 68.3km/Mpc
- Age 13.81 Billion years

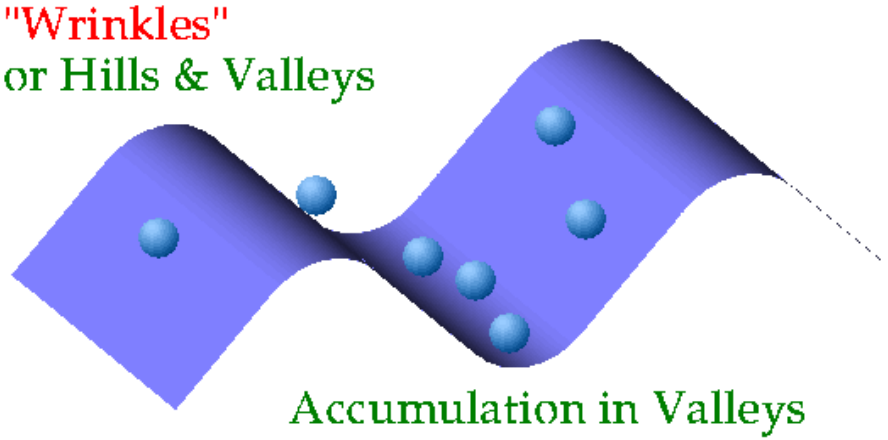


Density Fluctuations in CMB

- Slight irregularities/ripples in background at 1/100,000 level
- Hot temperature makes gas expand, rarefaction, but
- Gravity, including dark matter, pulls gas together, compression
- Acoustic/Pressure waves in gas (Speed of Sound) = known size

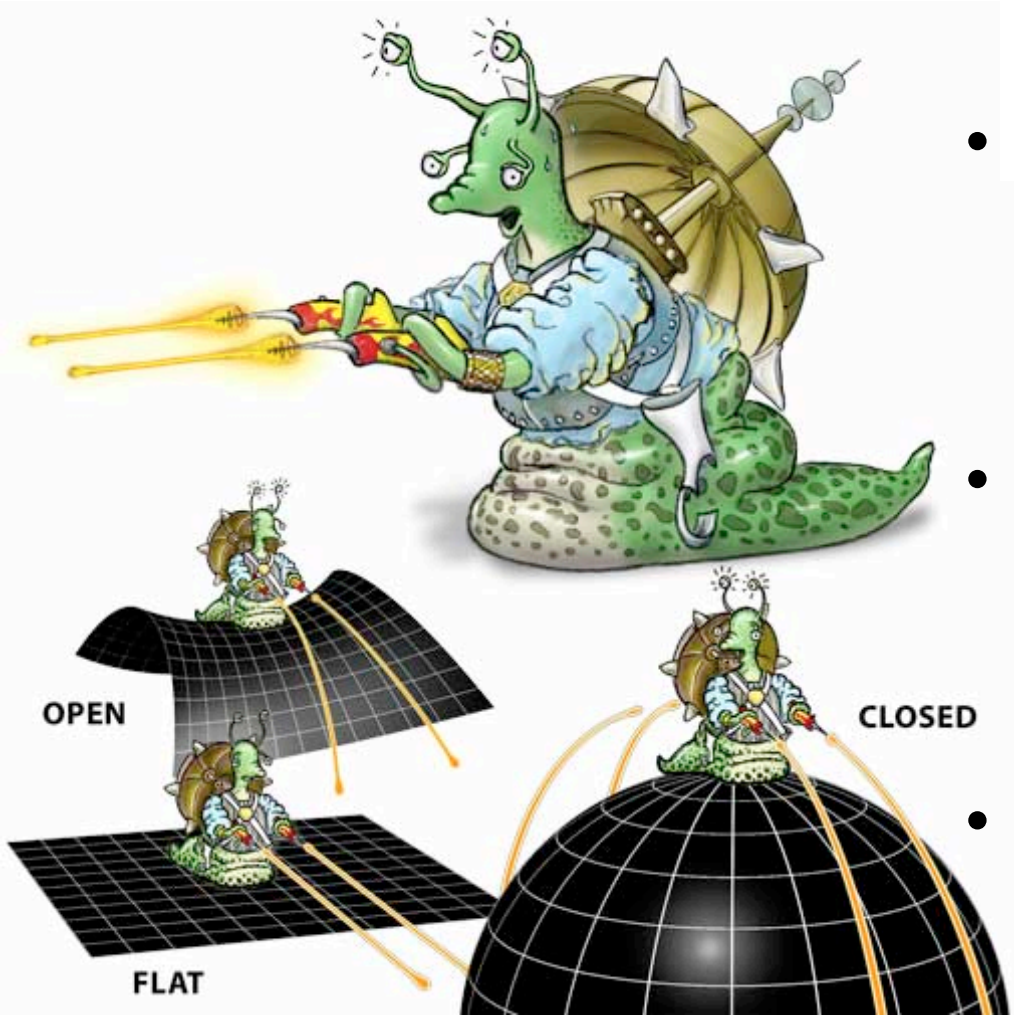


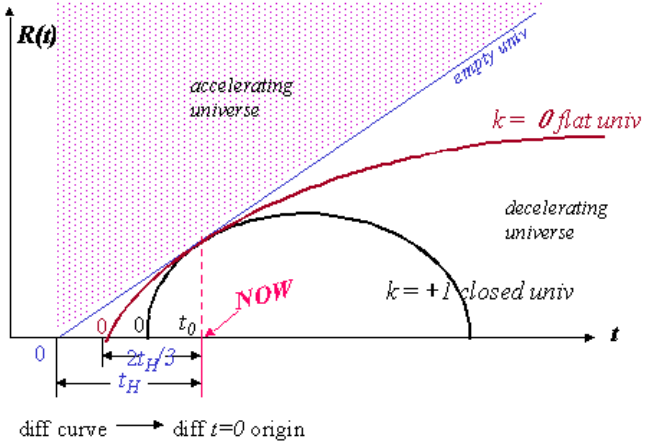




"Top View"

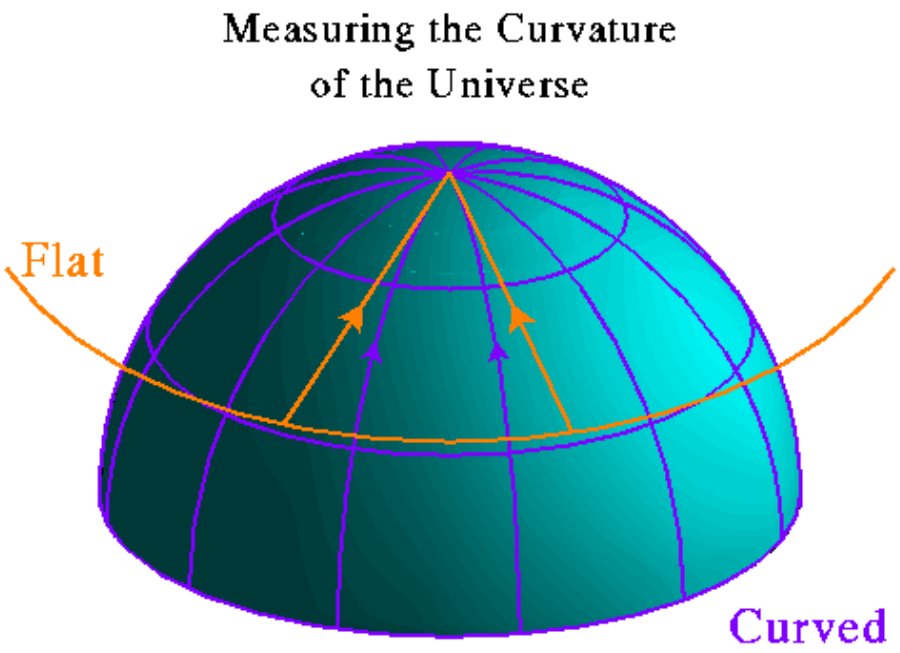
Mass/Density: Curvature of Space





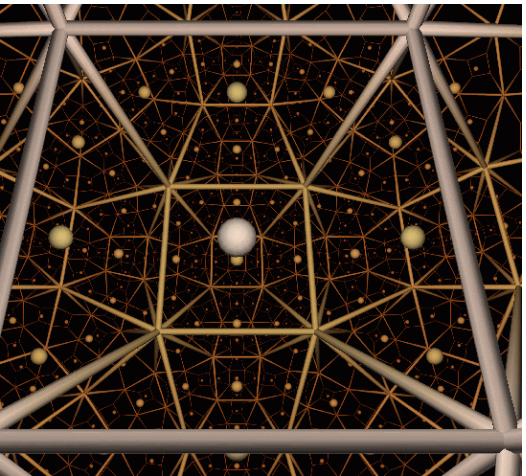
- Enough mass will cause universe to contract again: **closed=positive curvature** =finite but unbounded-globe
- Not enough mass and universe expands forever: **open=negative curvature, -**pringle chip-
- **Critical density universe** expands; slower & slower: **flat space,** -blackboard-

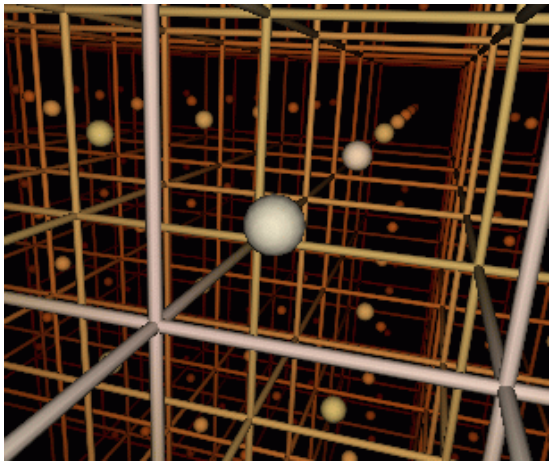
Angular Size Depends on Geometry

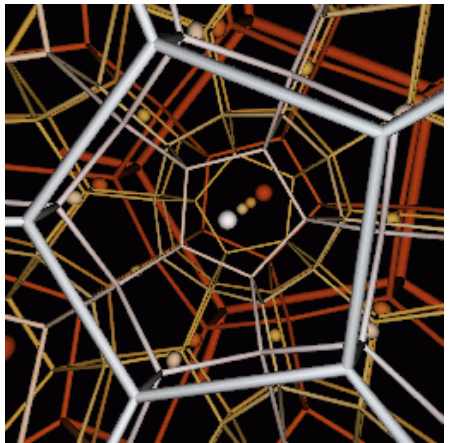


- Distant objects will appear larger in a positively curved space than in a flat space
- Spots in CMB will not be the "correct" size
- Open, Flat, Closed Universes

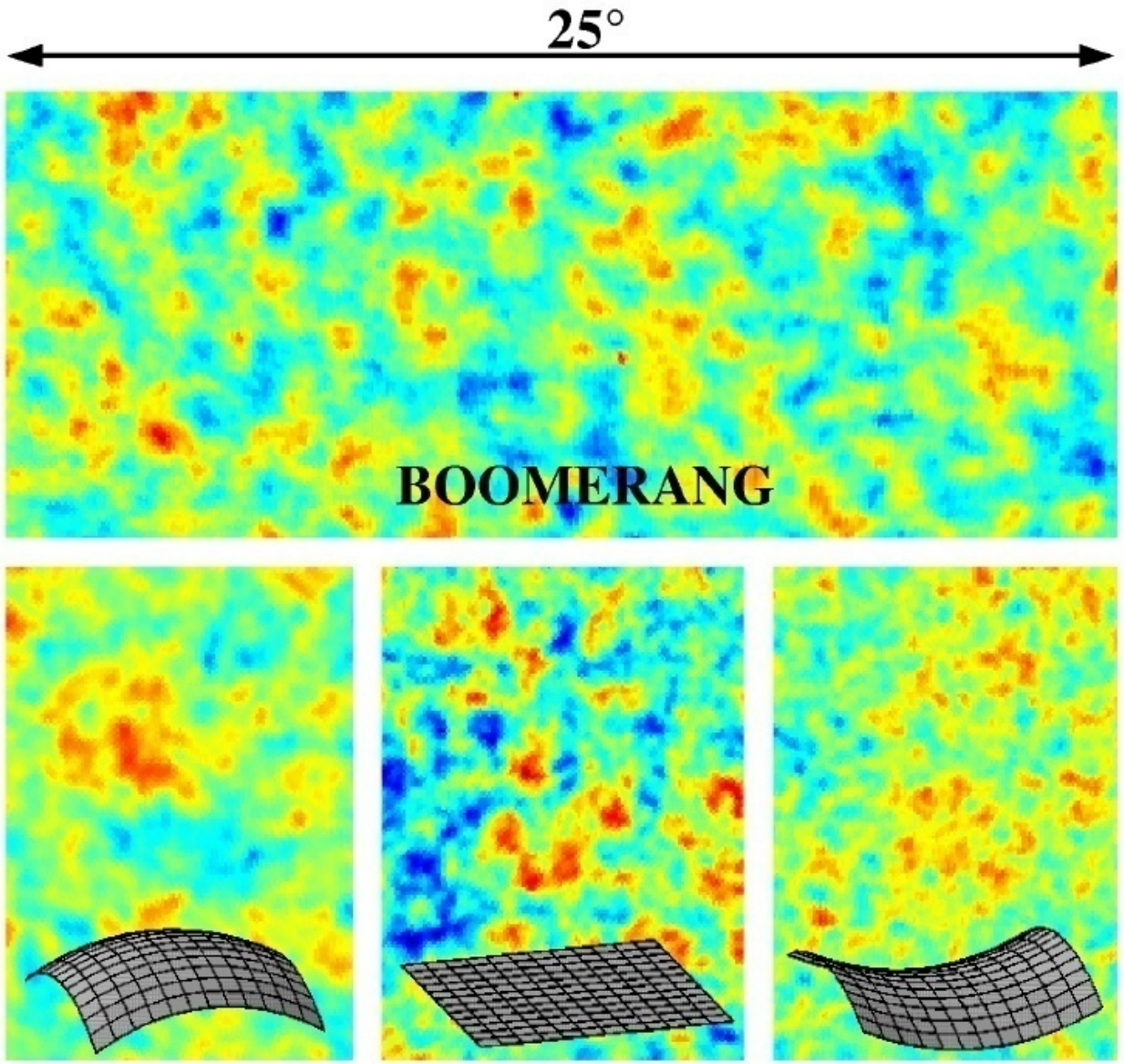
from Stuart Levy of the University of Illinois, Urbana-Champaign and by Tamara Munzer of Stanford University

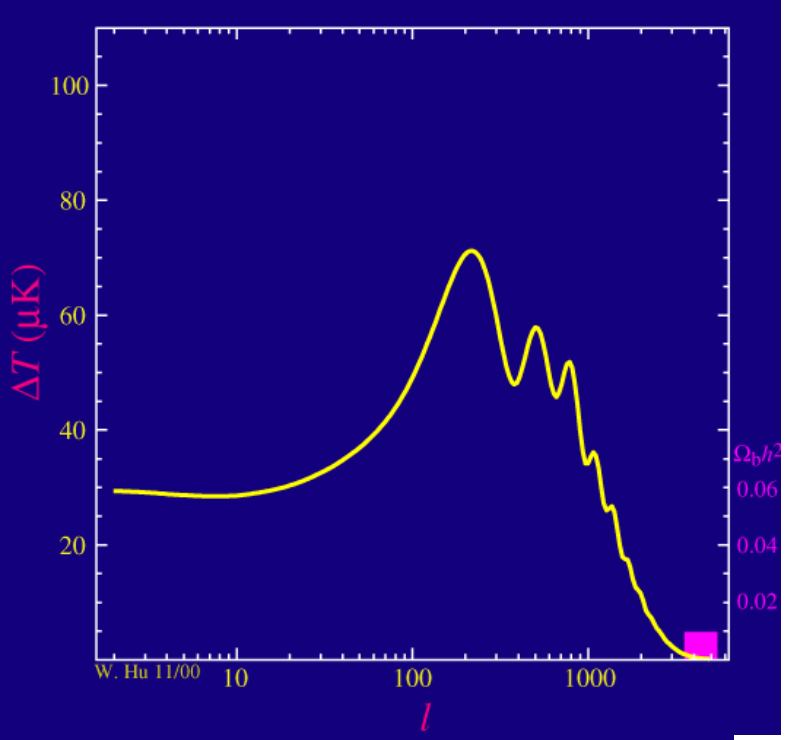


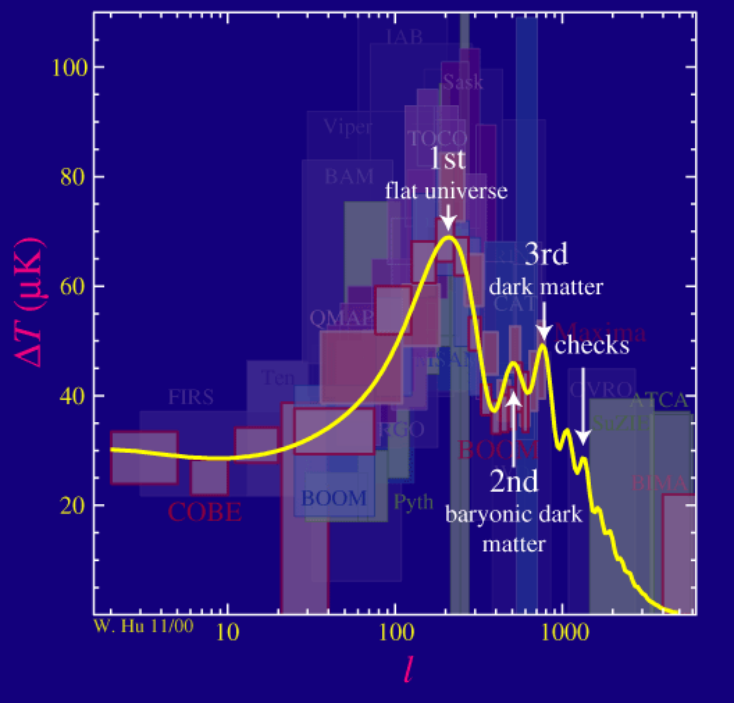




Geometry of the Universe





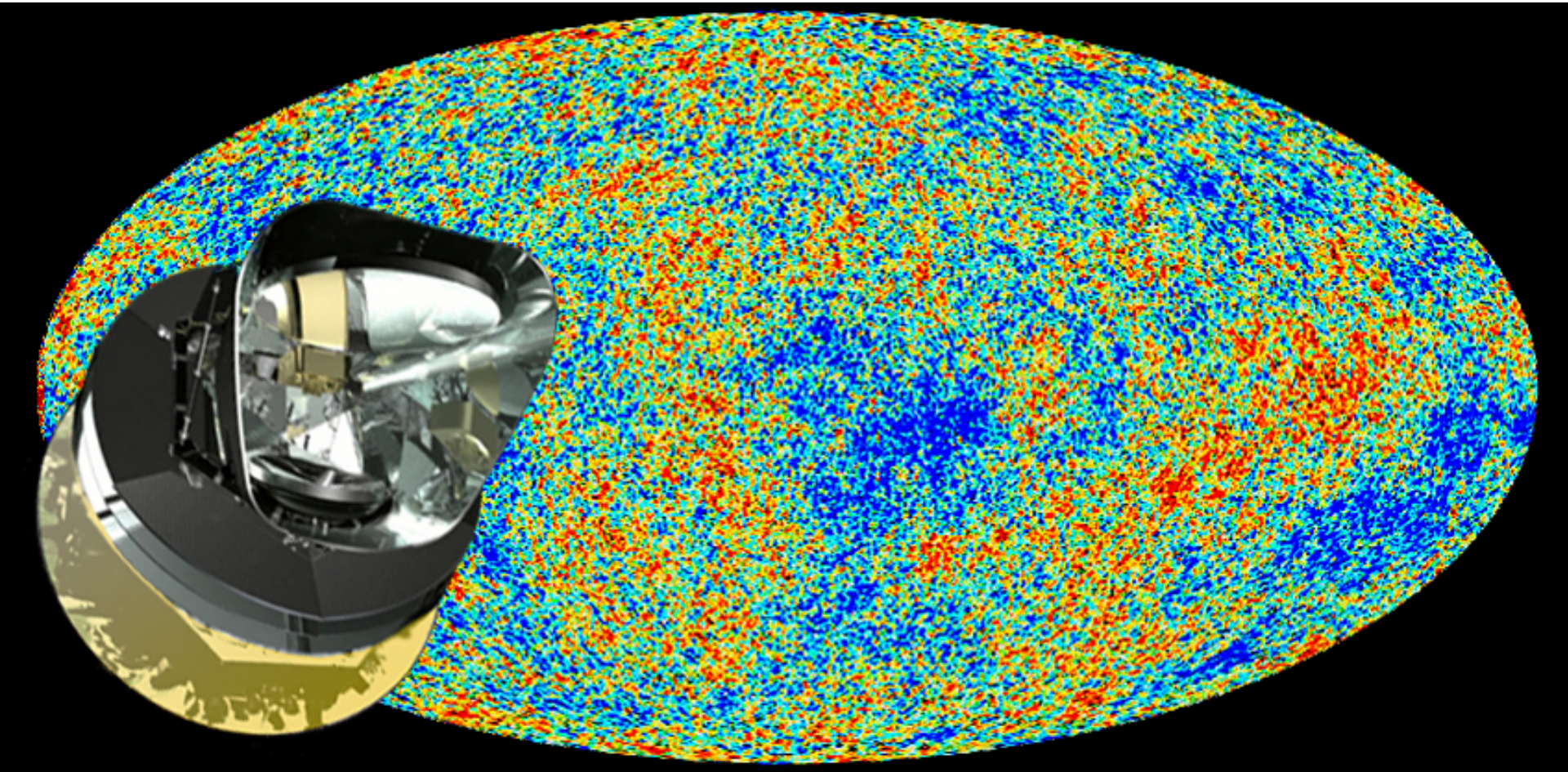


Smaller Density Fluctuations in CMB

- Measure small bumps as well
- Changing the fraction of the universe that is in baryons changes the intensity of the smaller bumps
- Ordinary matter (baryons) add inertia & gravitational mass to slow & dampen Density Fluctuations (=ripples)
- Dark matter=Nonbaryonic matter does not interact with the photons so it does not get smoothed by the photons

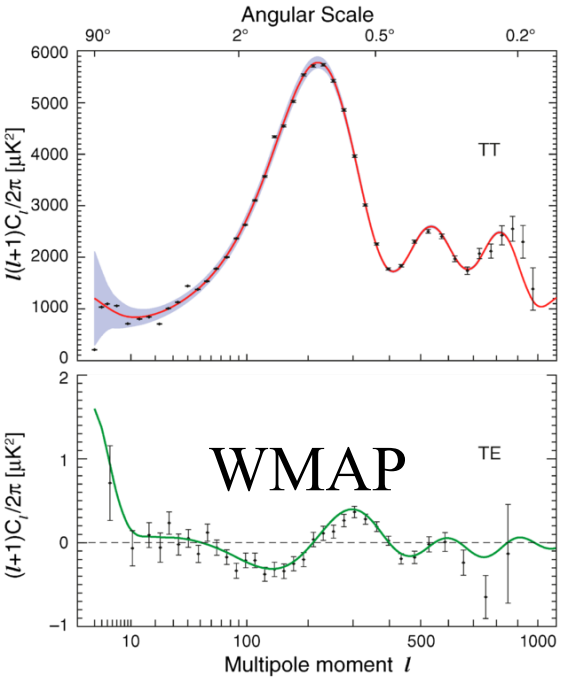
Planck's Observations of Cosmic Microwave Background Radiation

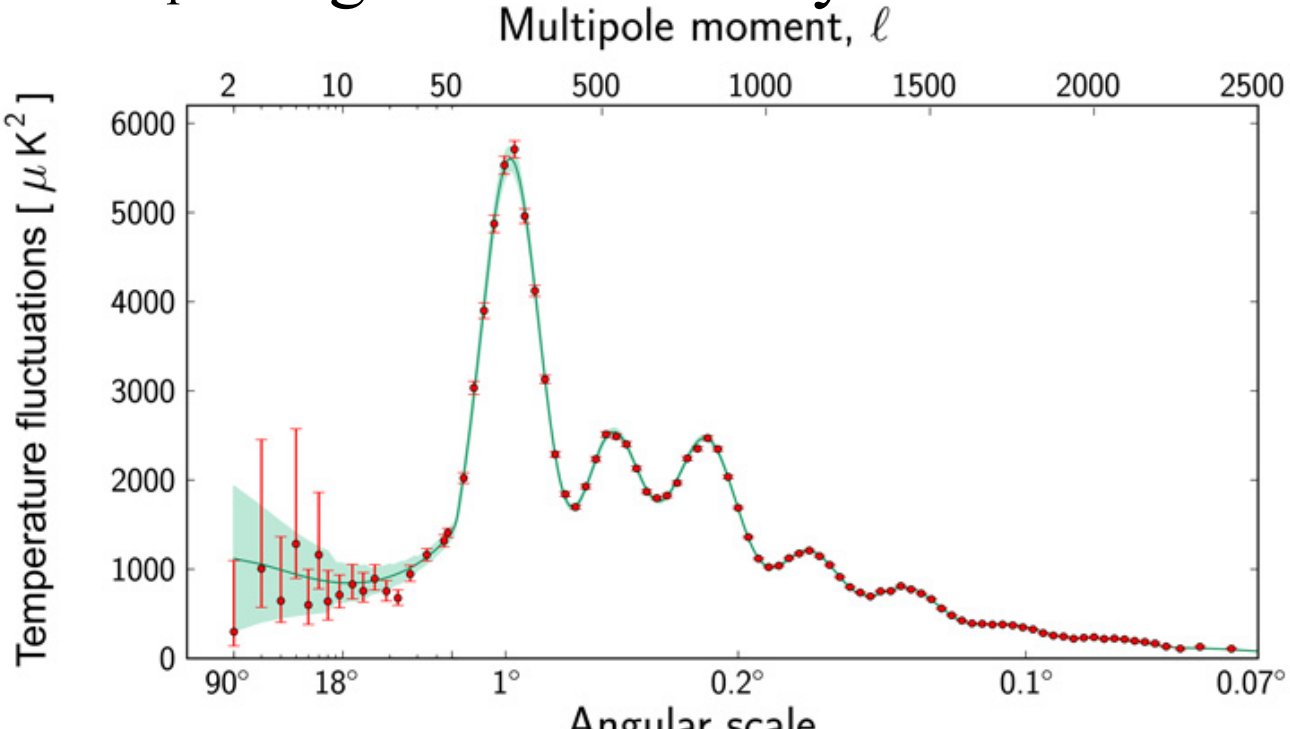
- Tiny density fluctuations measured more precisely



Precision Cosmology

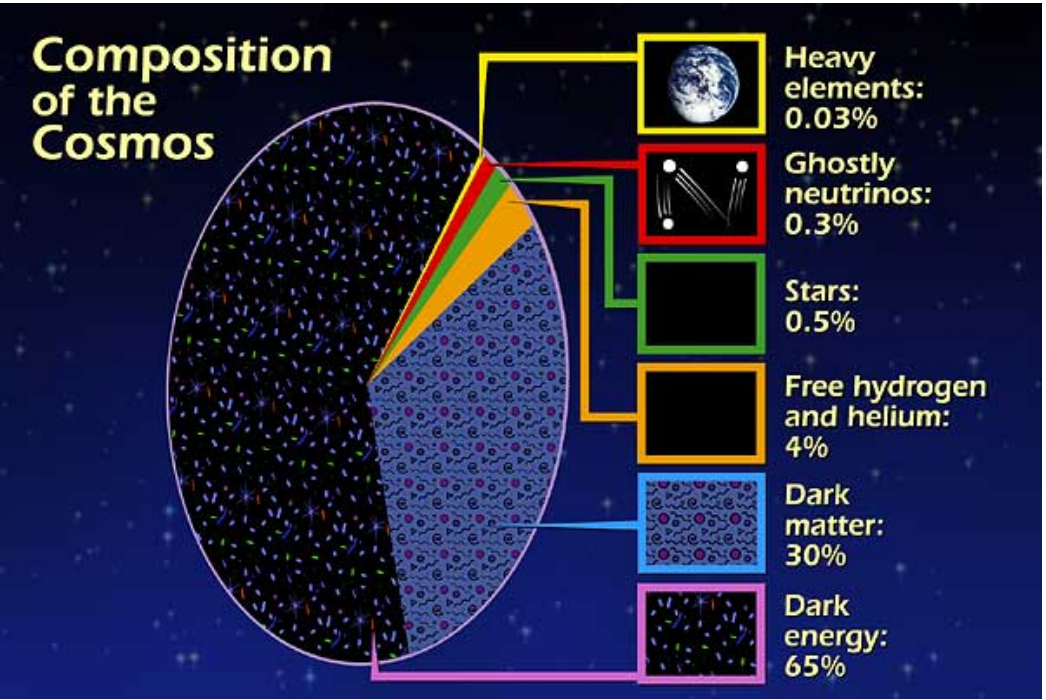
- Planck results (2013) – more frequencies, more precise amplitudes, better background subtraction, polarizations
- Sound of Big Bang from 0-760,000yrs shifted to human frequencies. Notice sound more bass notes due to expansion of universe
- Hubble cnst=67km/sec/mpc - Age 13.82Billion yrs

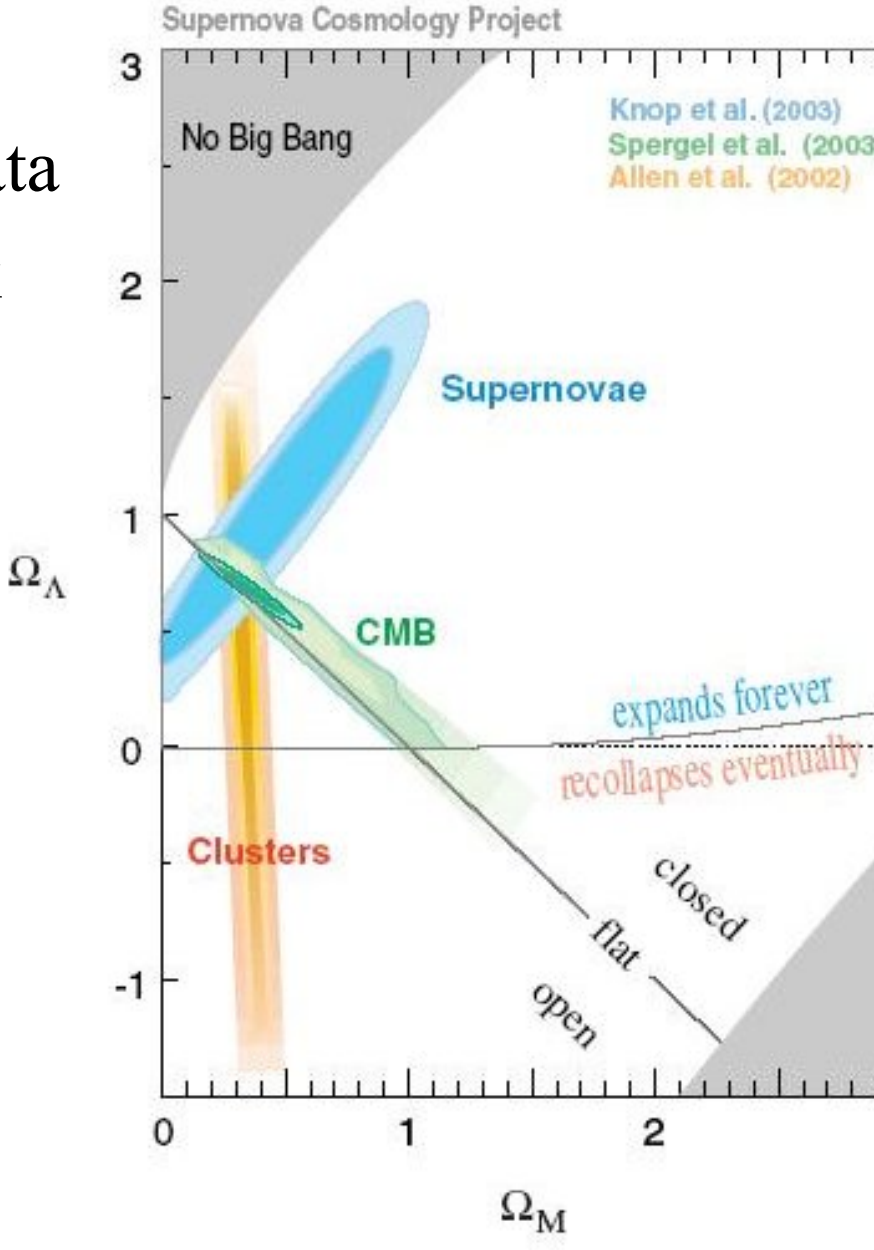




The Basic Cosmological Parameters

- Universe is Flat
- Combined with Supernovae data
- Gives Dark Energy 68%, Dark Matter 27%, Atoms 5%



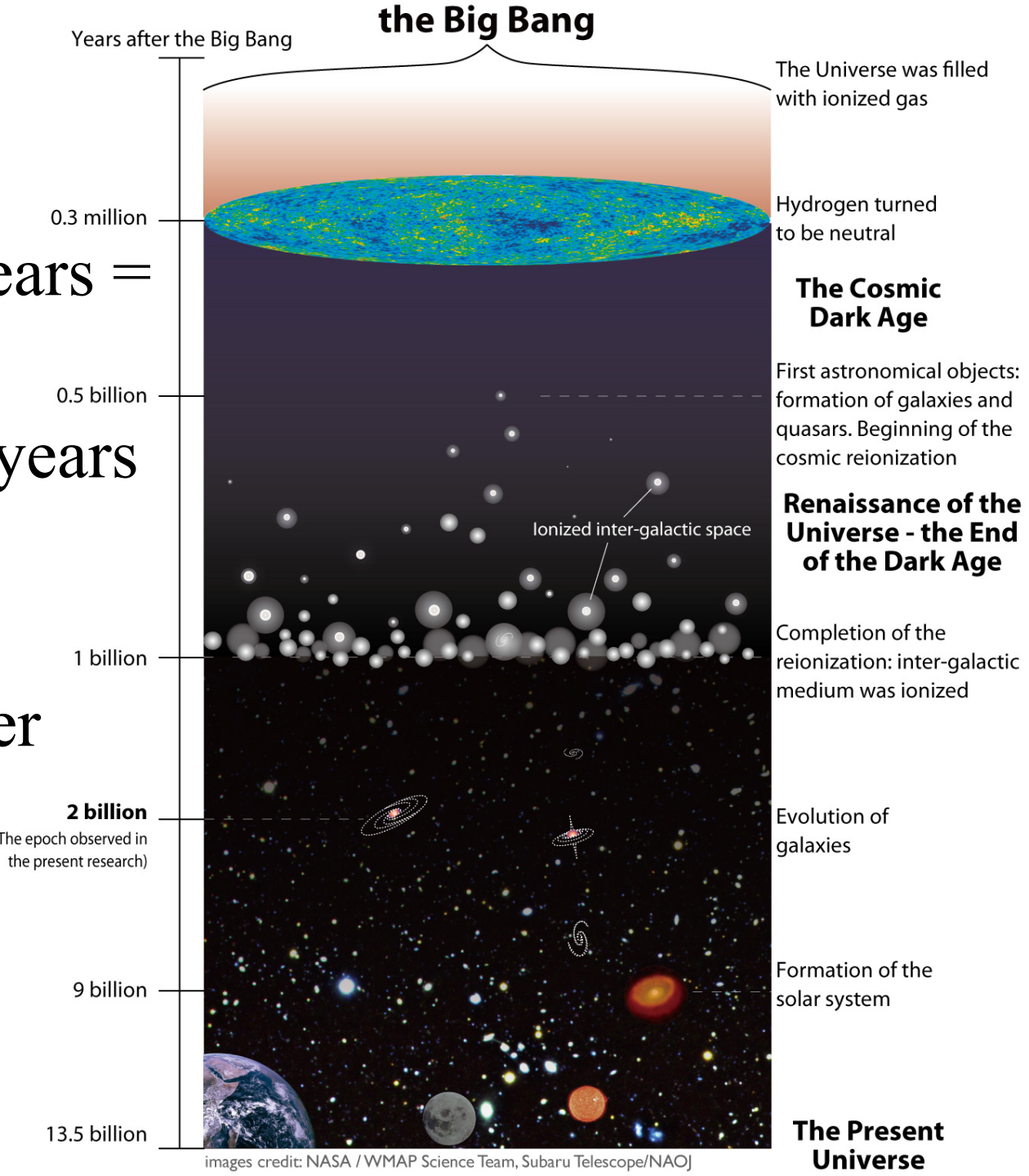


Which of the following statements are NOT correct?

a. Open and Critical=Flat universe will expand forever and a Closed universe will collapse
b. Large scale structure like the voids & superclusters of galaxies is caused by cold dark matter's gravity
c. The cosmic microwave background (CMB)is light given off by the Big Bang
d. Ripples in the CMB indicate that the universe is flat, 13.8Billion years old, 5% ordinary matter
e. All of these are correct

Dark Ages

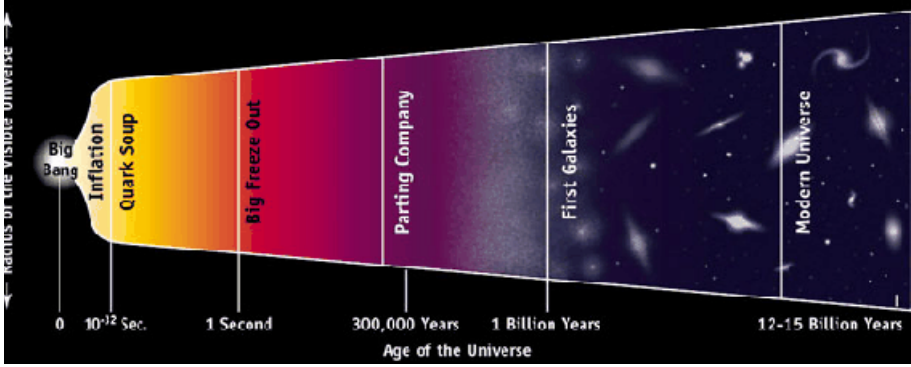
- From 380,000 years = Recombination
- To ~400million years =Reionization
- Gravity of Dark &Baryonic matter pulls Hydrogen together

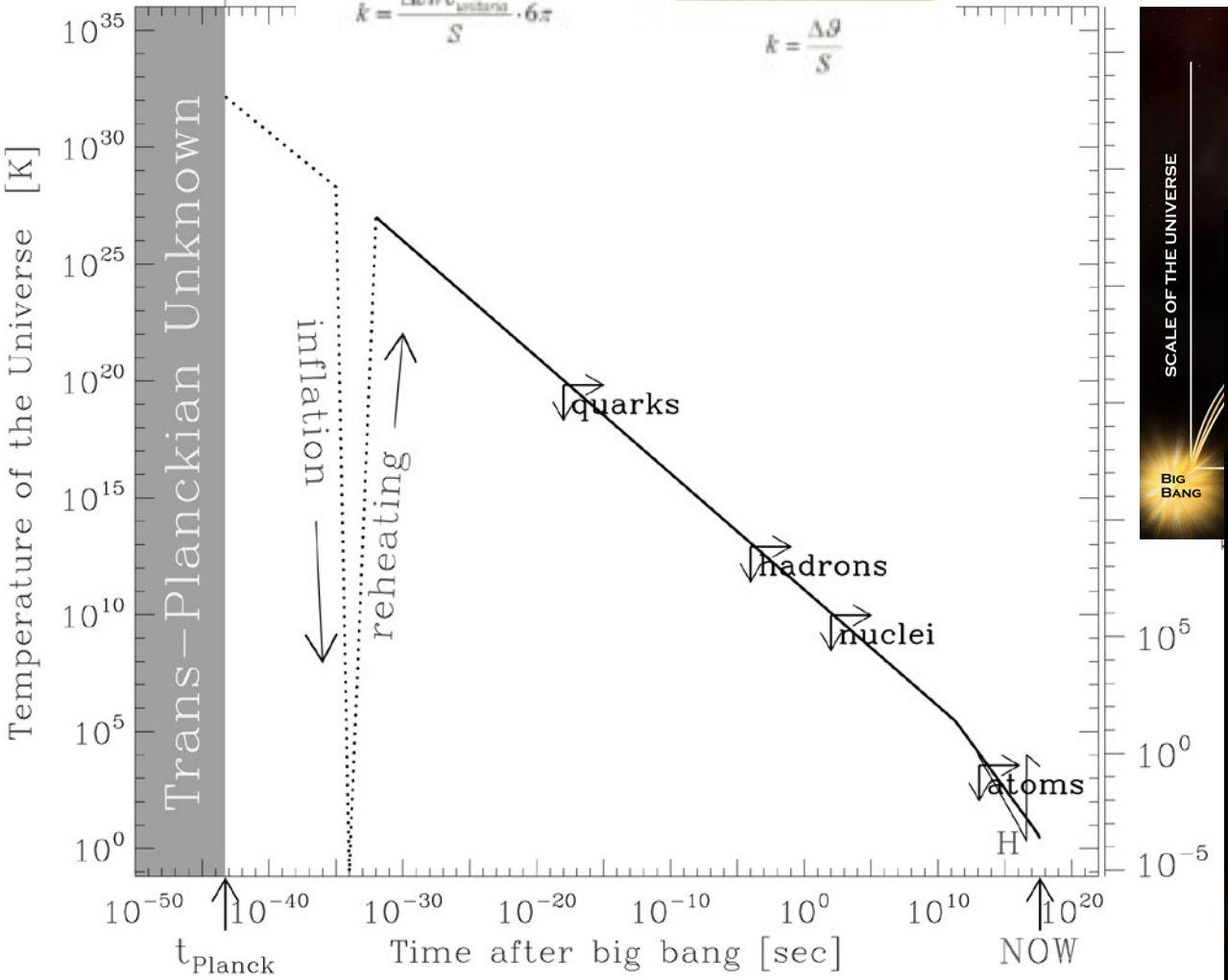


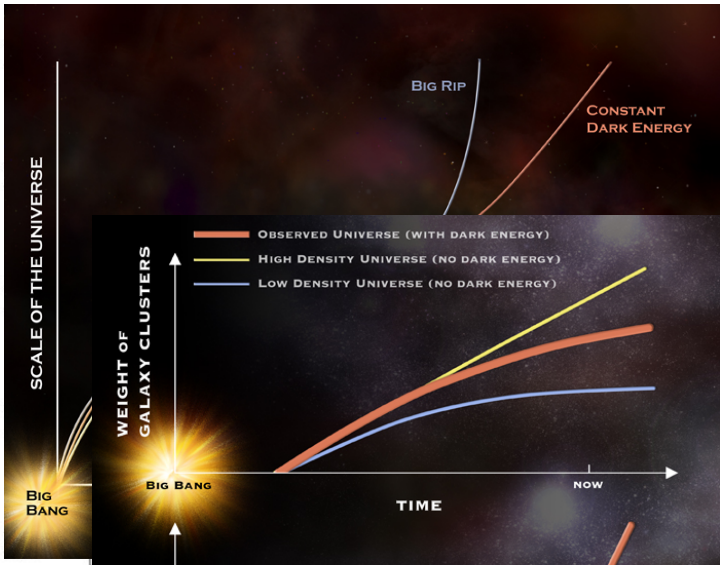
LA MISURAZIONE "INTERNA" DELLA CURVATURA

$$k = \frac{\Delta circ_{sinistra}}{S} \cdot 6\pi$$

$$k = \frac{\Delta\vartheta}{S}$$

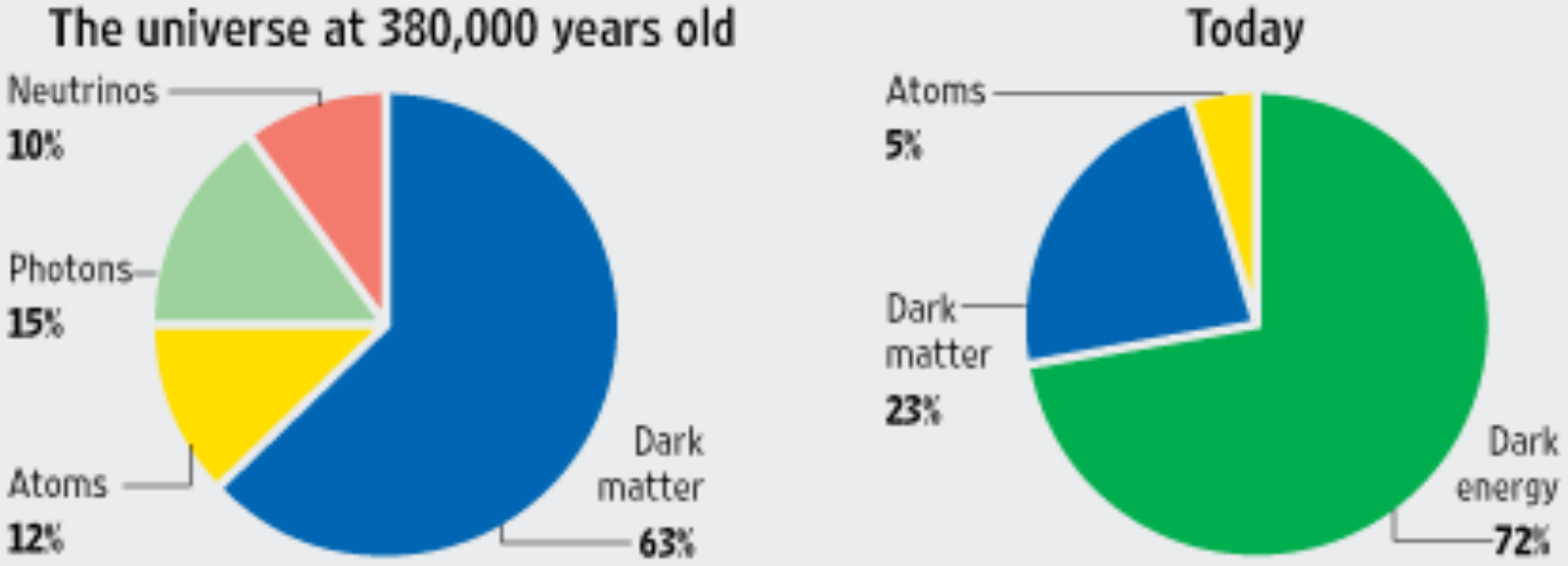




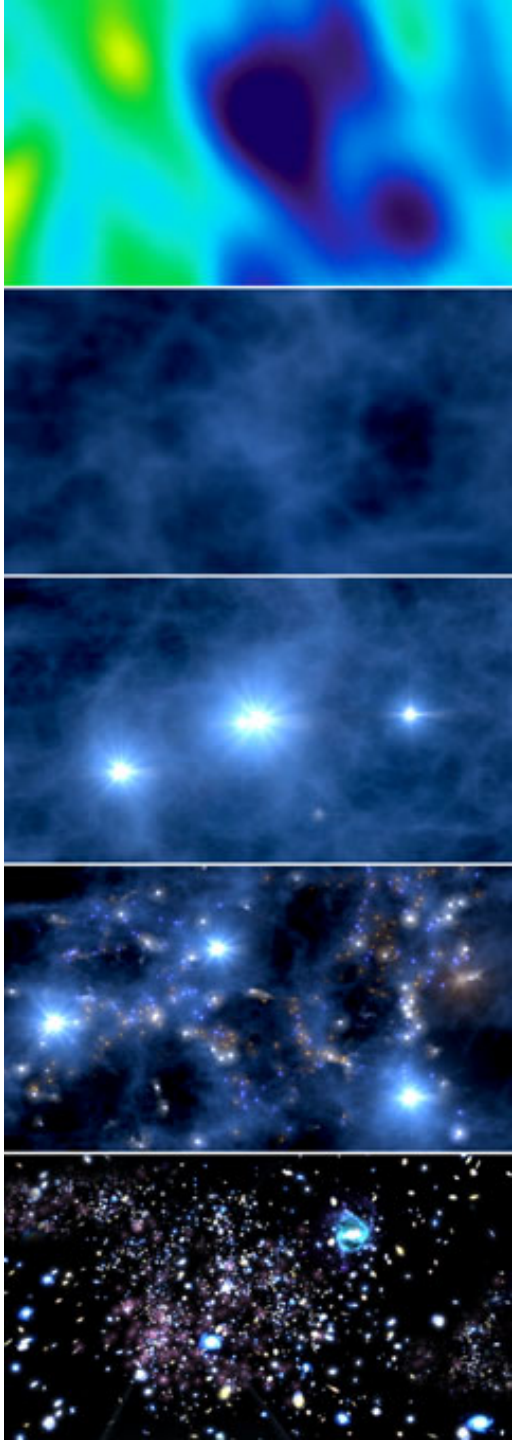


When We Were Young

How the composition of the universe today compares with its origins:

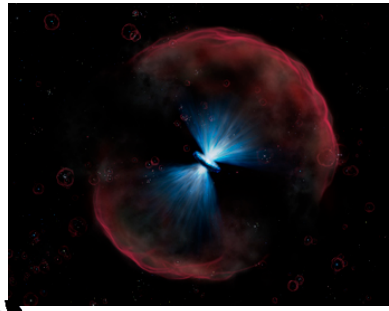


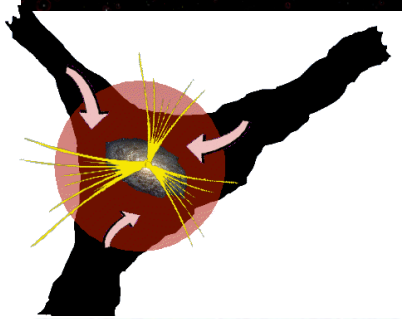
Source: NASA

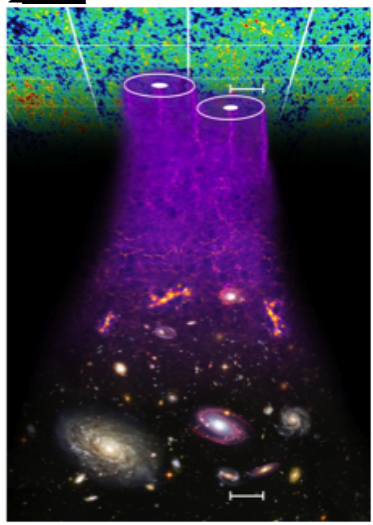


First Star Formation

- Universe started very hot and dense
- During **Dark Age** gravity pulls material from less dense regions
- Dark Age ends when first huge **Population III** stars form at ~200 million years
- **Reionization** = First stars reionize gas between galaxies
- Modern era with billions of galaxies
- Each made of billions of stars







Large Scale Structure

- 250,000 2dF galaxies with spectra out to redshift z=0.2
- Random distribution of galaxies & Actual distribution
- Universe expands
- Gravity pulled galaxies together = merging