EINSTEIN STILL IN THE NEWS

The Washington Post

HEALTH&SCIENCE

TUESDAY, NOVEMBER 15, 2011

2% Proportion of hospitals offering alternative care, in a recent survey. **Insuring Your Health, E3**

THREATENED SPECIES

Genome identifies culprit in frog deaths

Trade threatens the last untainted habitats on Earth. **E2**

URBAN JUNGLE?

That's no retiree, that's a real snowbird

Dark-eyed juncos fly down from the hills to D.C. for the winter. **E2**

COLD, WET

Einstein, the sky is falling! Or not.

Physicists juggle fear and glee: Maybe everything they've believed is wrong.

BY JOEL ACHENBACH

It's been an interesting and awkward autumn for physicists. They've been presented with an experimental finding that threatens to blow their vision of the universe to smithereens. A team of scientists in Europe announced in September that they'd clocked tiny particles called neutrinos traveling faster than the speed of light.

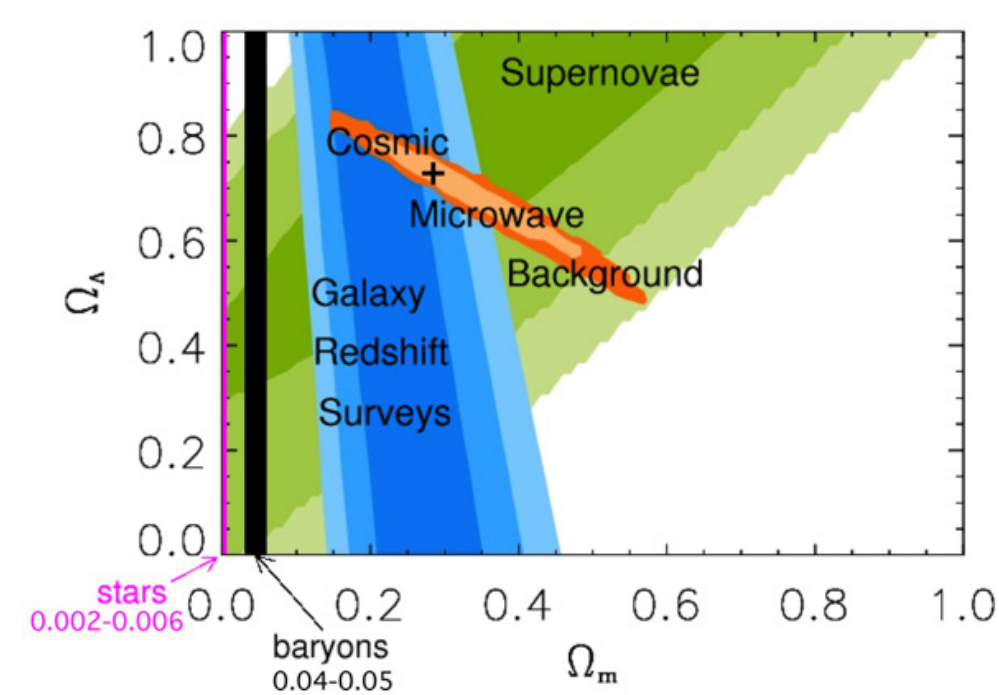
Which is heresy. Nothing goes faster than light. Einstein said so; a century of experiments have backed him up.

Concordance model

In summary, the parameters for our Universe, using best available data…

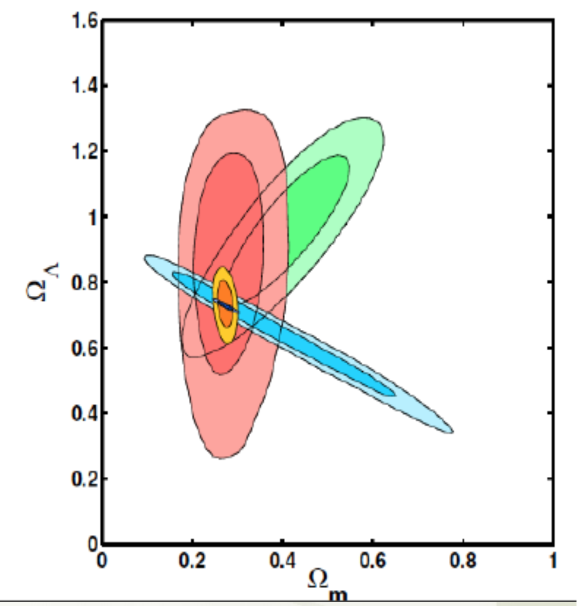
- Hubble constant: H_0 = 72 km/s/Mpc
- Geometry: Flat!
- Baryon density: $\Omega_B = 0.04$
- Dark matter density: $\Omega_{DM} = 0.22$
- Cosmological constant: $\Omega_\Lambda = 0.74$
- Age: t_0 = 13.7 billion years

…although we are far from understanding all the properties of the Universe, recent observations are bringing us to the "era of precision cosmology!"



Evidence for 'Dark Energy '

- No one technique definitely 'proves' the existence of dark energy
- The best indicator requires combining different measures
- Physics of clusters (pink) measures Ω_m very well
- CMB measures a combination of Ω_m and Ω_Λ
- and the brightness of type IA Sn a different combination of Ω_m and Ω_Λ



the contours represent the probability that the values lie inside them at the 68 and 90% confidence

What is "dark energy"?

- An "energy" that is an inherent component of space…
- Consider a region of vacuum

  Take away all of the radiation

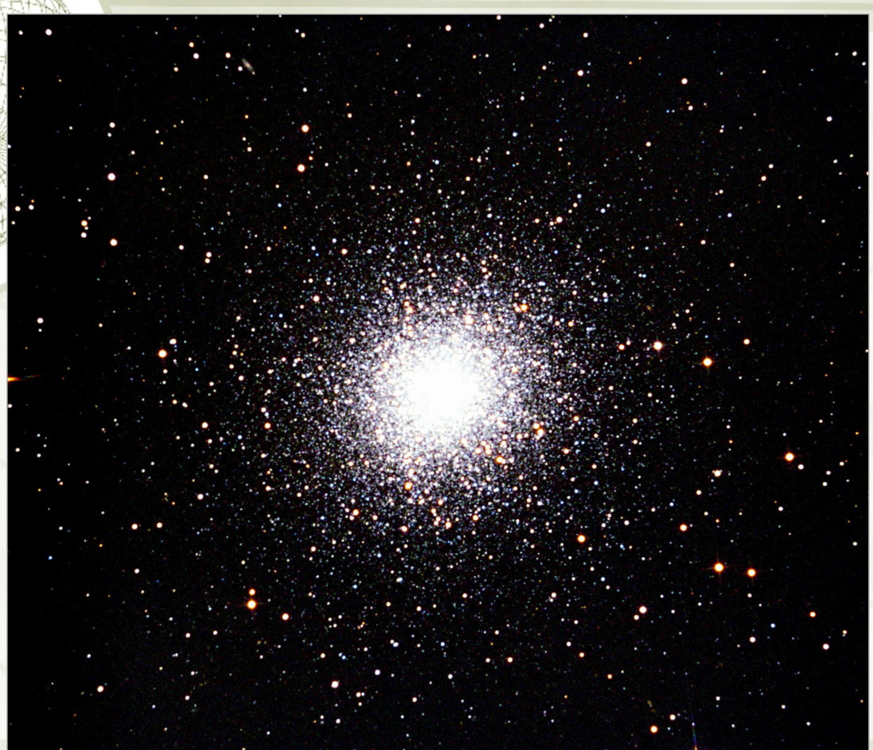
  Take away all of the matter

What's left? Dark energy!

- But we have little idea what it is…

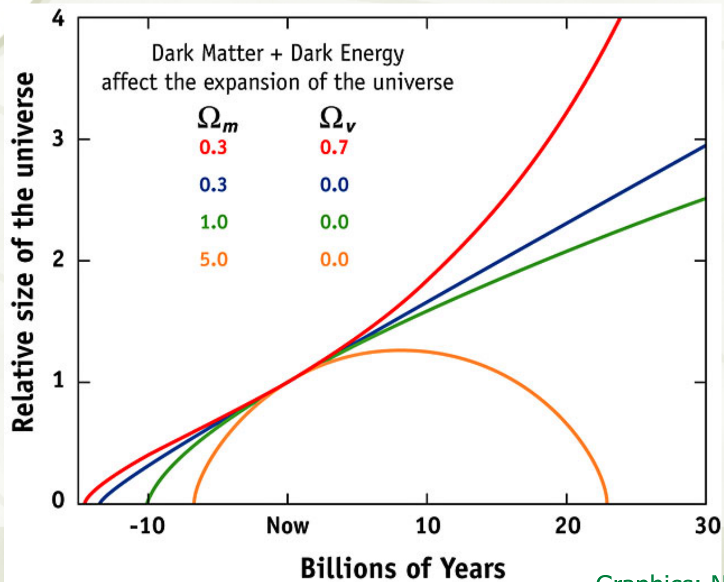
The Age of the Universe

- Using this cosmological model, we can figure out the age of the Universe.
  - Answer – 13.7 billion years
- Prediction…
  - There should be no object in the Universe that is older than 13.7 Gyr.
  - This agrees with what's seen!
  - **This was a big problem with old cosmological models that didn't include dark energy:**
    - e.g age of the universe **in** $\Omega_M = 1$, $\Omega_k = 0$, $\Omega_\Lambda = 0$ model is 9 billion years
    - But there are globular star clusters whose estimated ages are 12-14 billion years!
    - This was troubling since universe must be at least as old as the oldest stars it contains!

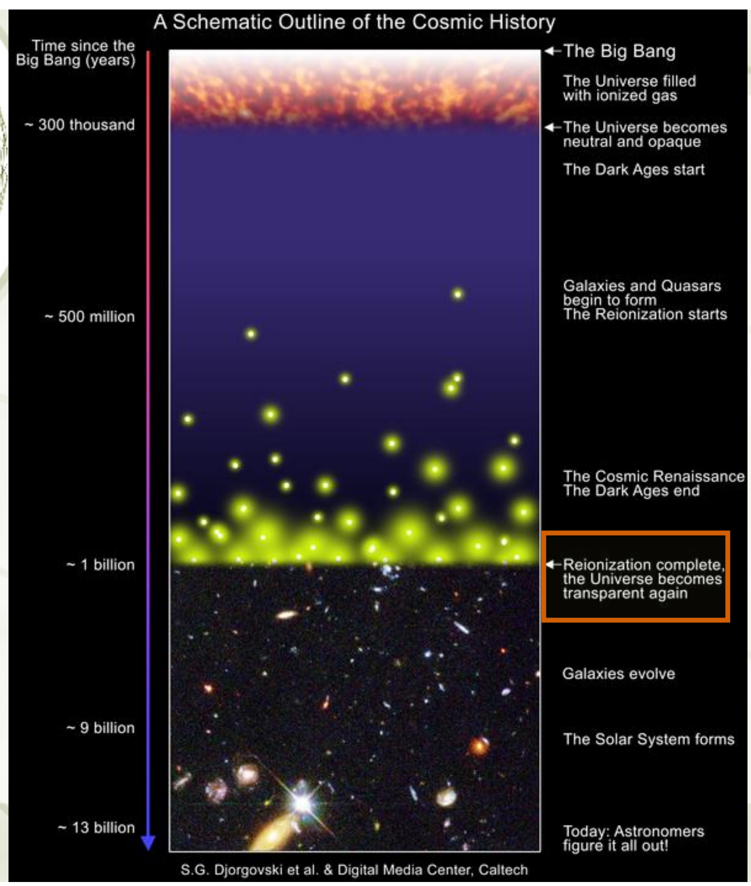


Non-zero Λ

- Recall that with a non-zero, positive value of Λ (red curve) the universe expands more rapidly than it would if it contained just matter (blue curve)



Graphics: NASA WMAP project



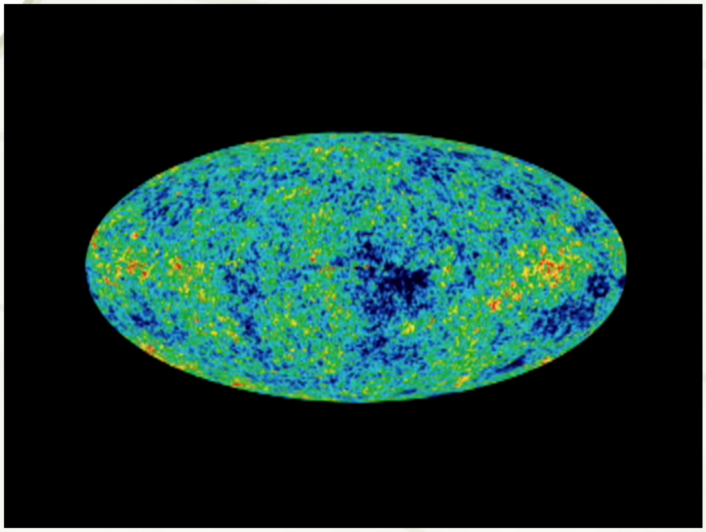
How did all this structure arise

- Early universe was extremely homogeneous:
  - At z = 1100 (surface of last scattering), local fluctuations in density were only about 1 part in 10^5
  - Fluctuations at varying scales had varying amplitudes (as seen e.g. in CBR power spectrum)
  - During radiation era, there was strong interaction between radiation and matter
    - Photons diffusing in space move matter and heat around; this **photon damping** prevented the perturbations that were present from growing at early times

After decoupling…

- When matter decouples from radiation, it becomes possible for perturbations to grow
- What would make them grow- GRAVITY !
- How does this work
  - Overdense region attracts surrounding matter toward its center
  - Matter flows away from underdense regions to nearby overdense regions
  - This can occur over a large range of scales
  - Which scales collapse when depend on the amplitude of the initial perturbations on that scale, and the kind of dark matter (cold or hot)

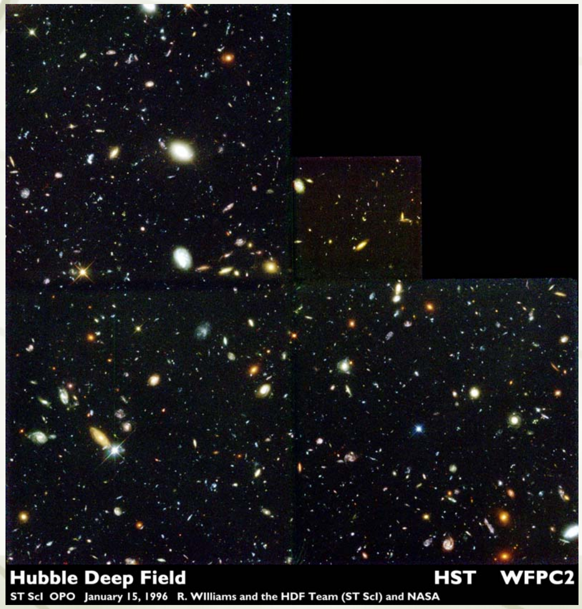
Structure formation preview



Homogeneity

- We've discussed homogeneity… the assumption that the Universe is the same from one point to another
- We've actually been talking about homogeneity in two ways…
  - The near-perfect homogeneity that the Universe possessed soon after the big bang
  - The homogeneity of the present Universe once we've averaged over very large scales.

But, on smaller scales, the present Universe is not homogeneous!!



The big question…

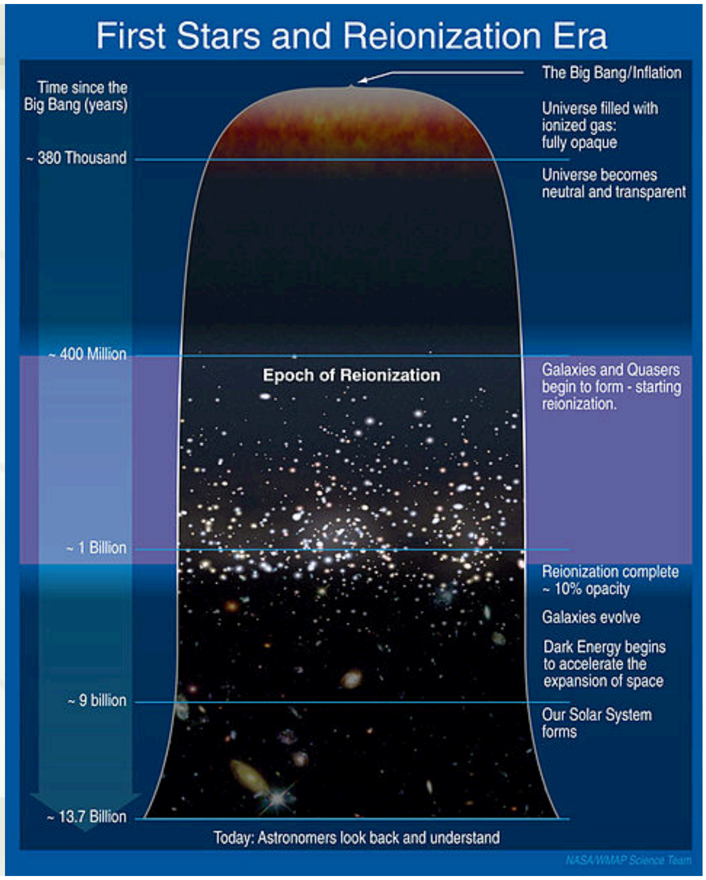
- How did we get from the almost perfect homogeneity just after the big bang to the "lumpy" situation in the Universe now
- Basic answer: gravitational collapse.

Timeline for structure formation
Read Chapter 15

- t = 0 : THE BIG BANG!
  - Everything is created…
  - Soon after this time, Universe is very smooth… there are only the tiniest ripples in the smooth distribution of matter.
- t = 3min–10 min : NUCLEOSYNTHESIS
  - Universe has expanded and cooled to the point where bound nuclei can survive
  - Ripples in the Universe are still tiny.

- The next 400,000 yrs
  - Universe continues to expand
  - Matter and radiation are tightly coupled together (i.e., matter is opaque to radiation)
  - Ripples in density grow only very slowly -- photon damping (acts like cosmic jello) prevents growth of perturbations
- t=400,000yrs;z~1000 : RECOMBINATION
  - Matter and radiation "de-couple" (radiation starts streaming freely)
  - Remant of that radiation is now seen as CMB
  - The universe was opaque before recombination because photons scatter off free electrons (and, to a significantly lesser extent, free protons), but it became transparent as more and more electrons and protons combined to form hydrogen atom
  - Small ripples at de-coupling give the CBR anisotropies observed by COBE and WMAP

- Objects started to form in the early universe energetic enough to ionize neutral hydrogen.
- As these objects formed and radiated energy, the universe went from being neutral back to being an ionized plasma, between 150 million and one billion years after the Big Bang (at a redshift $6 < z < 20$).
- However, matter has been diluted by the expansion of the universe, and scattering interactions were much less frequent than before recombination.
- Thus a universe full of low density ionized hydrogen will remain transparent, as is the case today.



- After the first (z~1100) 400,000yrs onwards…
  - After decoupling, inhomogeneities in the matter density start to grow… dense regions become denser- but nothing is 'shining': the Dark Ages
  - This dense regions eventually collapse to give the first objects (stars in very small galaxies) and then later galaxy clusters, galaxies, stars, planets etc.
  - at z~7(~8×10^8 yrs after Big Bang) the universe re-ionizes- energy from star formation or quasars ionizes the intergalactic medium (IGM)

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- Two general scenarios for subsequent evolution
  - **Top-down scenario -**big things form first (galaxy superclusters), which fragment to make smaller things (clusters and galaxies)
  - **Bottom-up scenario**: small things form first (small galaxies), which collect together to make big things (bigger galaxies, clusters, superclusters)

- Know almost nothing about what dark matter is- have 2 big possibilities - hot or cold
- Expect:
  - Top-down if dark matter is hot
  - Bottom-up if dark matter is cold
- Why
  - Because hot dark matter particles would have large random motions that would tend to smooth out smaller-scale perturbations- so big things are the first to collapse

What dark matter does…

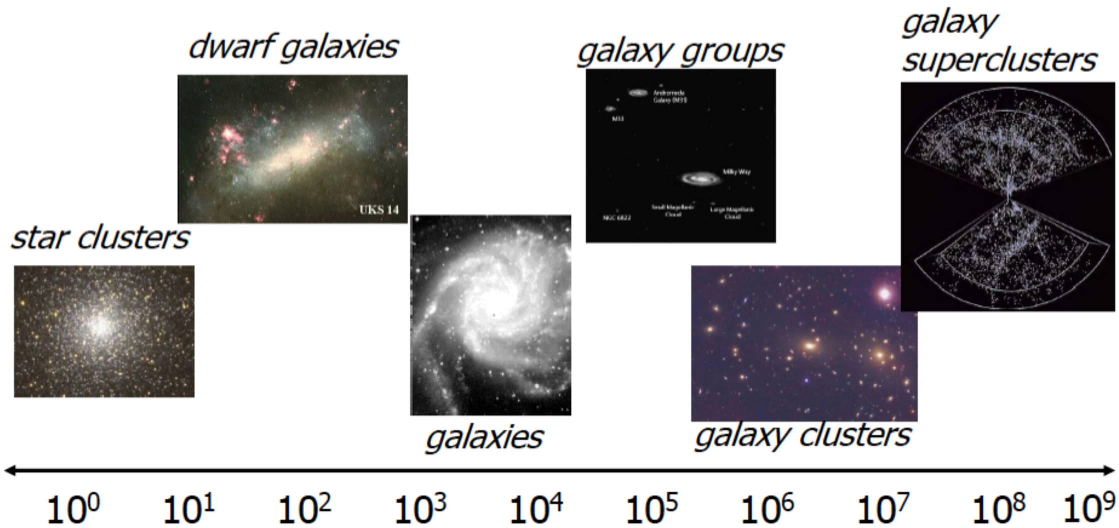
- We don't [yet] know what dark matter consists of, but we do know a great deal about **where it is and what it does**
- It surrounds galaxies, galaxy clusters, and is a major component of the universe as a whole
- It gravitationally binds the baryons (stars and gas) together in these systems…

  … and, it was responsible for
- *the original condensation of cosmic structures out of nearly-uniform initial conditions and*
- *the growth of structure.*

Structure in the Universe

- What structure is there, at varying scales
- How is cosmic "structure" observed and quantified
- How did the structure grow and evolve over time

Universe Has a Hierarchy of Structures
All Objects
Larger than Star Clusters are Dominated by Dark Matter

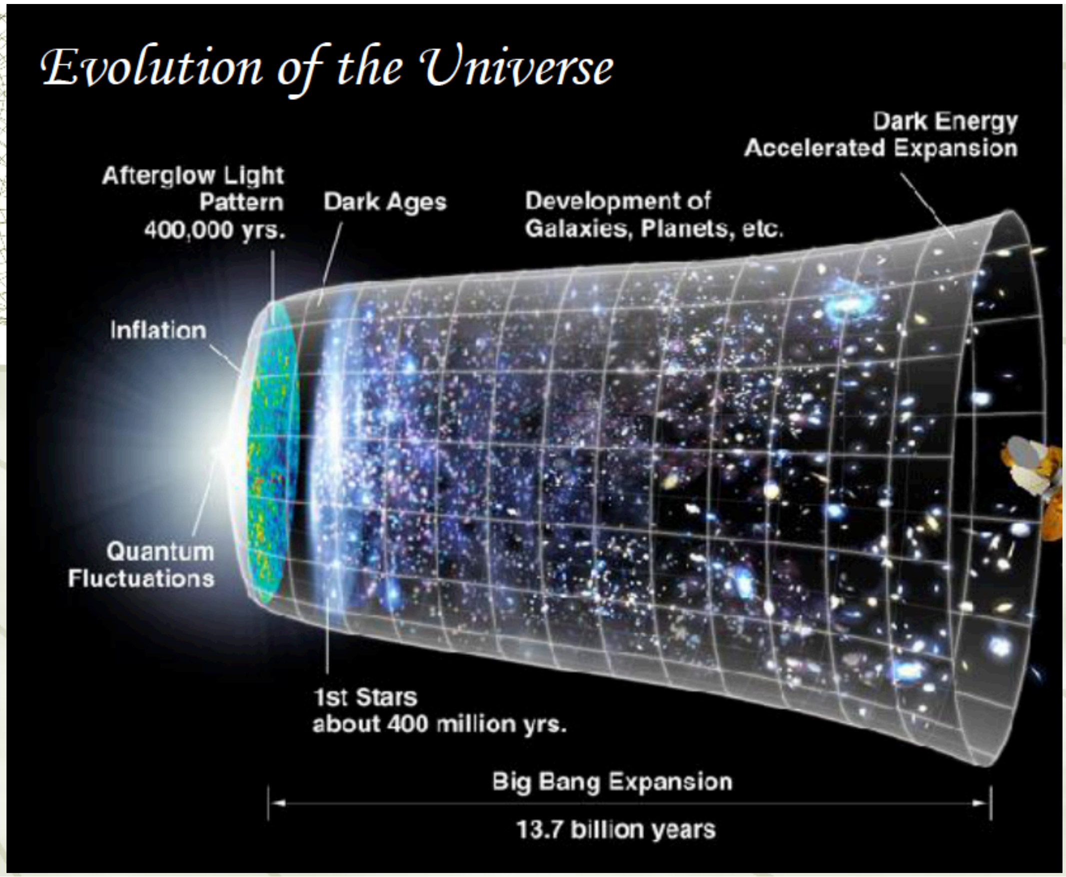


Size in light years

Range of cosmic structure, from small scales to large…

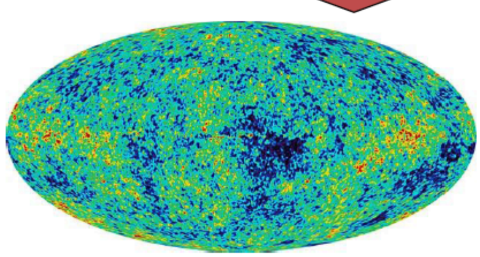
Not DM dominated

- Tiny scale: planets around stars
- Very small scale: stars in clusters
- Small scale: stars and star clusters in galaxies
- Medium scale: galaxies in groups and clusters
- Large scale: sheets and filaments of galaxies, hot gas, + dark matter; voids in between
- Very large scale: "Hubble volume" containing many statistically similar collections of filaments, voids, etc.



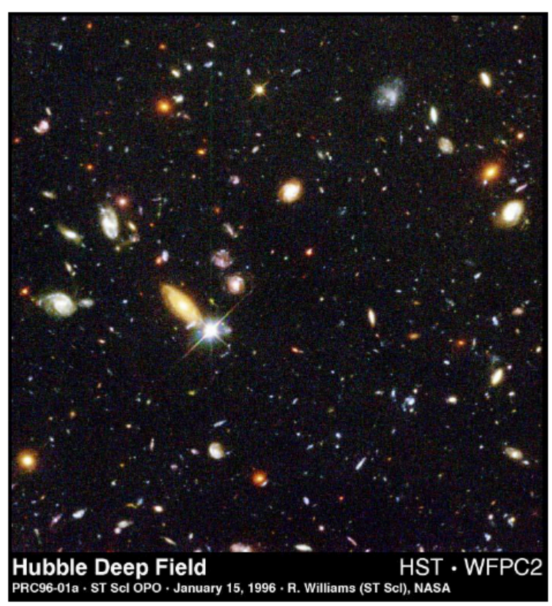
Our universe then and now

Recombination (~380,000 yr)
$\delta\rho/\langle\rho\rangle \sim 10^{-4}$



Wilkinson MAP (NASA)

Present (~14x10^{9} yr)
$\delta\rho/\langle\rho\rangle \sim 10^{6}$

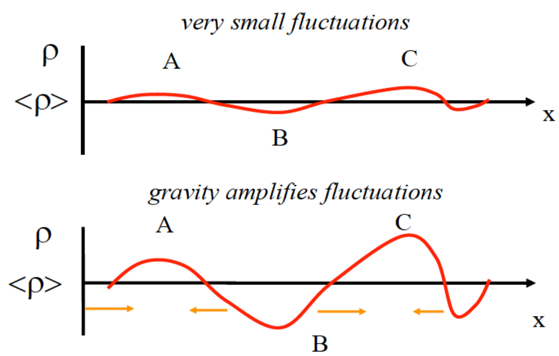


M.Norman

Generic Idea Behind Structure Formation

- Unlike dark matter, normal ("baryonic") matter can emit radiation and cool down
- Normal matter falls into halo, cools, settles to center
- Once cool dense clouds form, can get star formation
- Through this process, a galaxy is built up

Gravitational Instability: Origin of Cosmic Structure



M. Norman

Formation of structure-*how does the Universe go from being homogeneous to being full of structure*

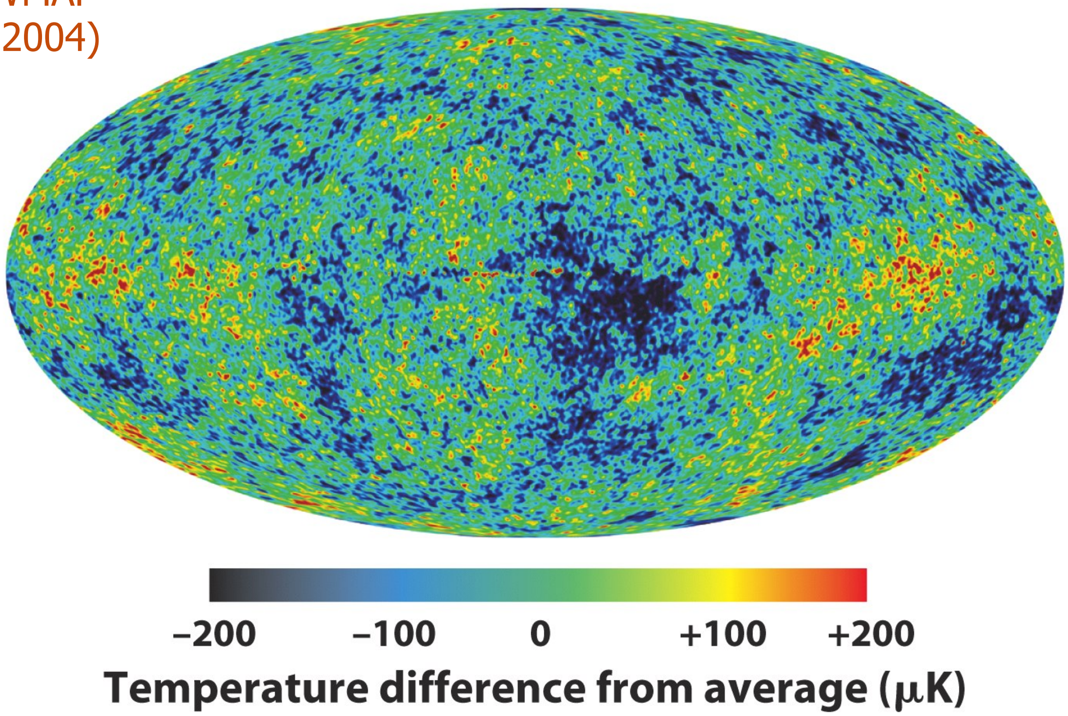
- Basic idea : Something introduced very small disturbances into the Universe at very early time.
- Those small disturbances then grew due to the action of gravity
- These Initial disturbances ("seed perturbations") were due to quantum fluctuations introduced during the "epoch of inflation" ($t \sim 10^{-35}$ s)
- The perturbations grow very slowly due to action of gravity until matter starts to dominate the energy density of the Universe (t~70,000ys)… they then start to grow faster
- Perturbations are at level of 1 part in 10^4 at epoch of recombination… this produces observed anisotropies in CMB.
- They continue to grow after that… eventually forming a filamentary structure of Dark Matter. This is the "skeleton" for galaxy formation!

I : Formation of structure

- Slightly more detail of the standard model:
  - Initial disturbance (“seed perturbations”) were quantum fluctuations introduced during the “epoch of inflation” ($t \sim 10^{-35}$s)
  - The perturbations grow very slowly due to action of gravity until matter starts to dominate the energy density of the Universe (t~70,000ys)… they then start to grow faster
  - Perturbations are at level of 1 part in 10^5 at epoch of recombination (300,000 yrs)… this produces observed anisotropies in CMB.
  - They continue to grow after that… eventually forming a filamentary structure of Dark Matter. This is the “skeleton” for galaxy formation!
  - http://map.gsfc.nasa.gov/universe/bb_cosmo_struct.html

- 400,000yrs onwards…after recombination
  - inhomogeneities in the matter density start to grow… dense regions become denser.
  - This dense regions eventually collapse to give galaxy clusters, galaxies, stars, planets etc.
- When the universe was .001 its present size (~ 500,000 years after the Big Bang), the density of matter in the region of space that now contains the Milky Way, was only 0.5% higher than in adjacent regions. Because its density was higher, this region of space expanded more slowly than surrounding regions.
- As a result of this slower expansion, its relative over-density grew. When the universe was .01 its present size (roughly 15 million years after the Big Bang), our region of space was ~ 5% denser than the surrounding regions.
- This gradual growth continued as the universe expanded. When the universe was .2 its present size (roughly 1.2 billion years after the Big Bang), our region of space was probably twice as dense as neighboring regions. Cosmologists speculate that the inner portions of our Galaxy (and similar galaxies) were assembled at this time)

WMAP
(2004)

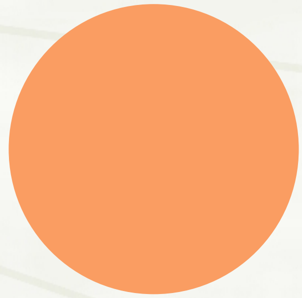


II : Galaxy formation

- Gravitational collapse forms "dark matter halos"- 2 lectures ago
- Dark matter halos have range of
  - Masses (range from $<10^8 M_{sun}$ to $10^{15} M_{sun}$)
  - Wide range of Angular momenta (barely spinning to rapidly spinning halos)
- Unlike dark matter, normal ("baryonic") matter can emit radiation and ***cool down***
  - Normal matter falls into halo, cools, settles to center
  - Once cool dense clouds form, can get star formation
  - Through this process, a galaxy is build up
  - What determines whether a galaxy is a disk/spiral or an elliptical

II : THE JEANS MASS AND THE ONSET OF COLLAPSE

- Imagine an overdense clump of mass M.
- If clump is very small, sound waves will smooth it out.
- If clump is very big, it will gravitationally collapse.
- The threshold mass separating "small" and "big" is called the Jeans Mass, M_J (after Sir James Jeans)

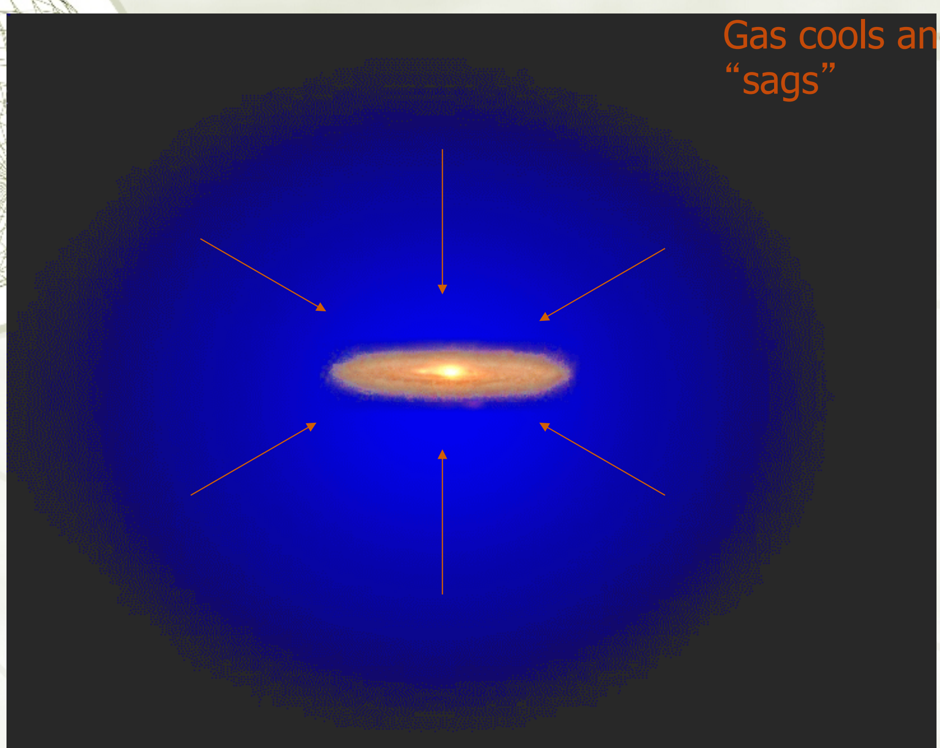


Collapsing force: gravity
Restoring force: pressure, operating through sound waves

$$M_J = \frac{(\text{sound speed})^3}{\sqrt{G^3 \rho}}$$

Sir James Hopwood Jeans

Gas cools and "sags"



Graphic from John Kormendy (U.Texas)

Numerical Simulations of Structure formation

How Do They do This

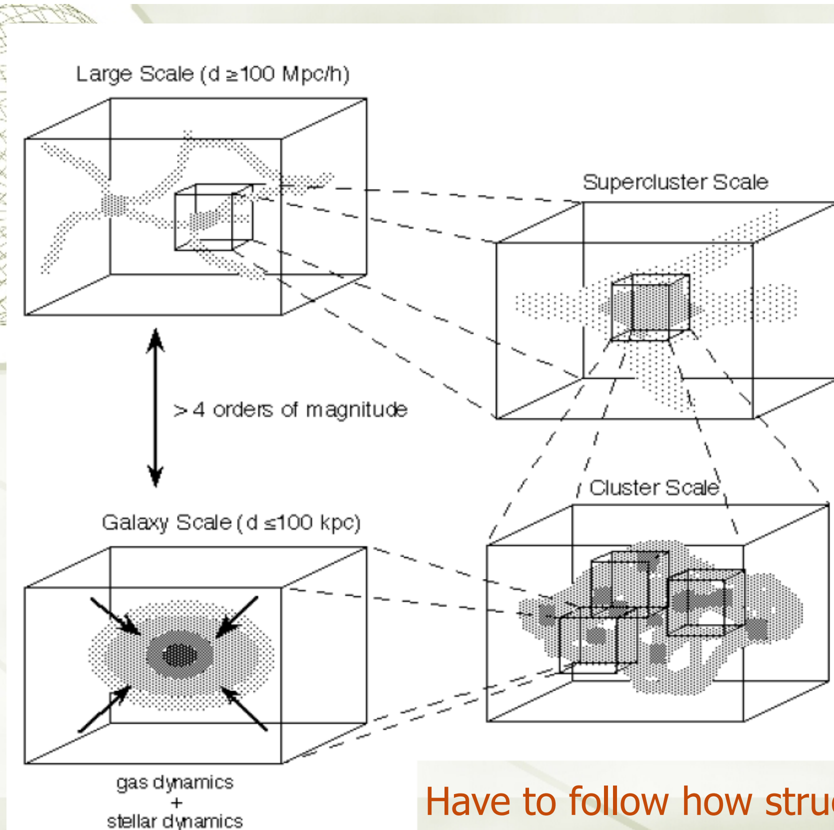
- *Locally* its contents obey:
- -Newton's laws of gravitational for stars and cold dark matter (CDM)
- -Physics equations for gas
- -Atomic, molecular, and radiative processes important for the condensation of stars and galaxies from diffuse gas

- *Globally*, the universe evolves according to the Friedmann equation

$$H(t)^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} + \frac{\Lambda}{3}$$

Hubble parameter; scale factor a(t); mass-energy density; spacetime curvature; cosmological constant

- 4096^3 particle/cell hydrodynamic cosmology simulation
- NICS Kraken (XT5)
  - 16,384 cores



Have to follow how structure grows at all scales

Formation

- Galaxies, clusters form through gravitational collapse, driven by dark matter (~80% of their total mass)
- In the hierarchical scenario more massive objects form at later times: clusters of galaxies are produced by the gravitational merger of smaller systems, such as groups and sub-clusters

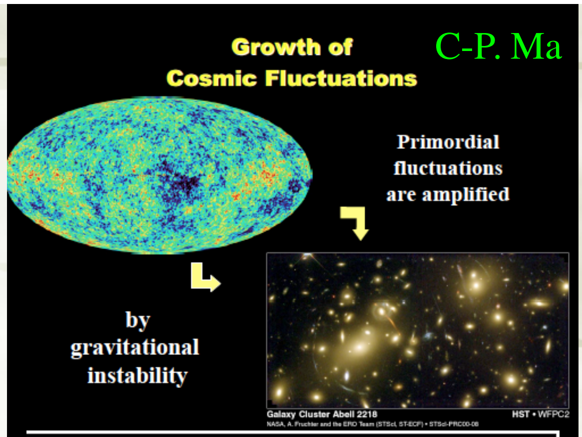
Millenium Simulation

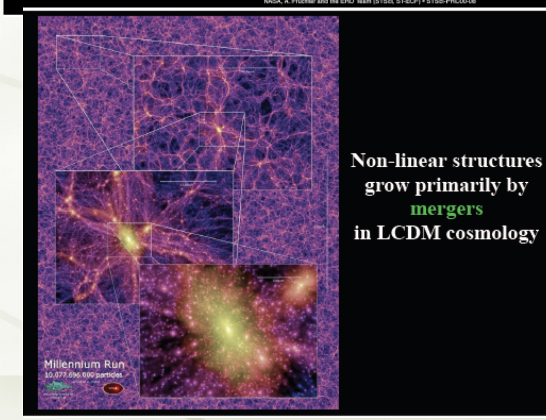
It used 6 million cpu-hours of time on the Pleiades supercomputer at NASA Ames Research Center, 2 racks (64 nodes total) enhanced with NVIDIA graphics processing unit (GPU): 52 teraflops total

Total cores: 112,896 (32,768 additional GPU cores)

Total memory: 191 TB.

not enough timesteps to smoothly visualize the evolution of the simulation.





How does Structure Form- Mergers

- As time progresses more and more objects come together- merge and get bigger and more massive

Now

10^{10} yrs ago

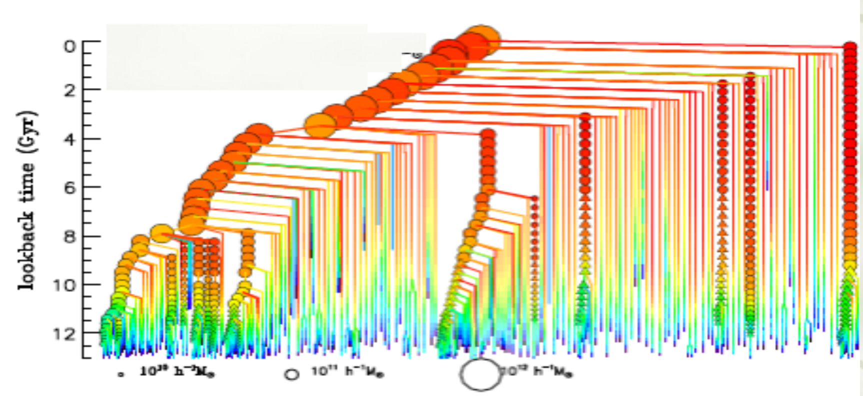
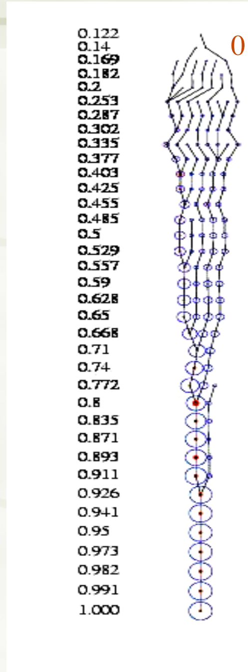


Figure 1. BCG merger tree. Symbols are colour-coded as a function of B - V colour and their area scales with the stellar progenitors more massive than 10^{10} $M_\odot$ h^{-1} are shown with symbols. Circles are used for galaxies that reside in the FOF gro by the main branch. Triangles show galaxies that have not yet joined this FOF group.

What is a Merger Tree

- In LCDM cosmology structure grows by the merging of bound systems + infall of small stuff
- The fraction of contribution of each component depends on time and mass.



0.12 age of universe

Millenium simulation

today

R. Wechsler

Mergers

- Temperature map (in color) and intensity map (contours) for a merging cluster (Abell 3921, Belsole et al 2005)
- The X-ray emitting gas is shocked as the clusters merge (movie 2 lectures ago)

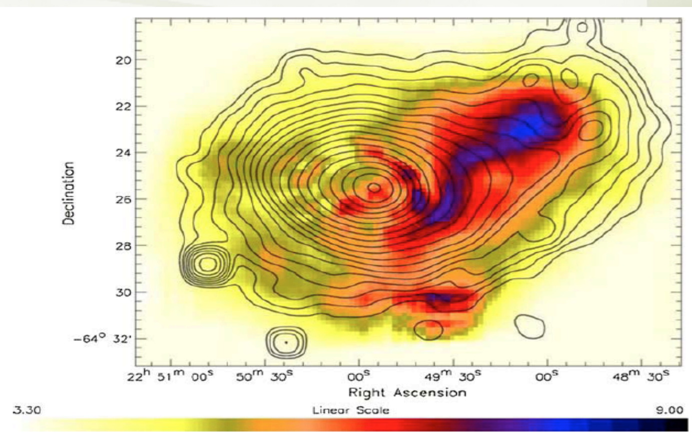


Fig. 15 Temperature map of the merging cluster A3921 by Belsole et al. (2005). The temperature map has

Extreme Merger

- Bullet cluster (1E0657)
- Allen and Million

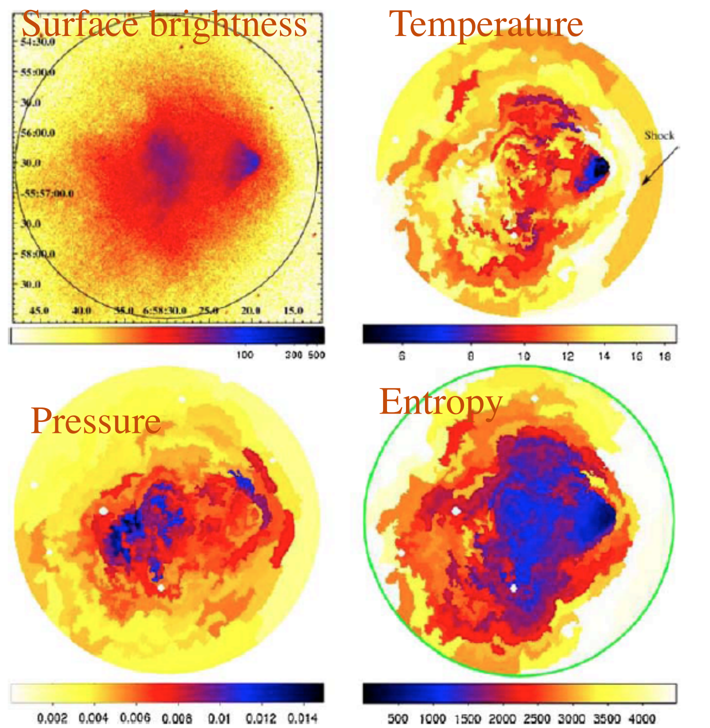


Fig. 16 Thermodynamic maps for the ICM of the "bullet cluster", 1E0657-56 (Million and Allen 2008)

Hierarchical Formation of Structure

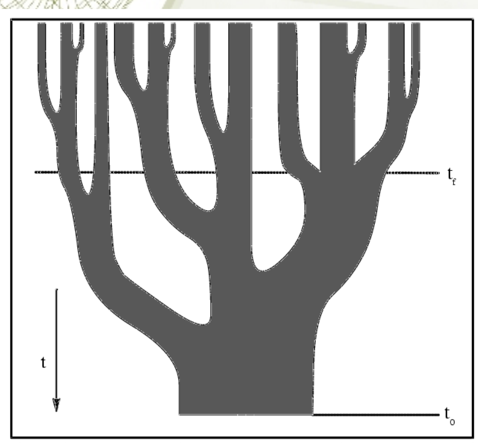
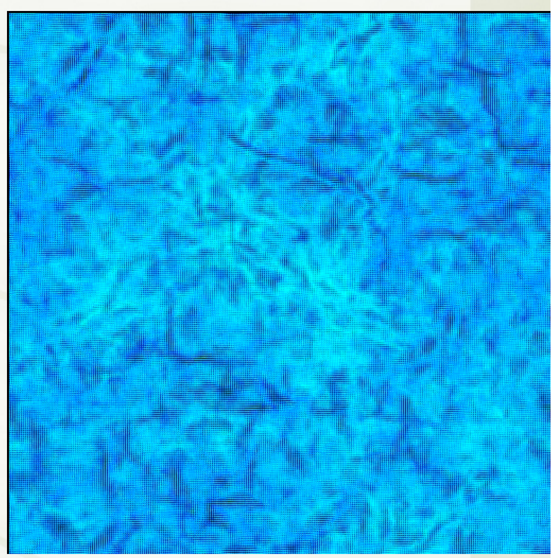
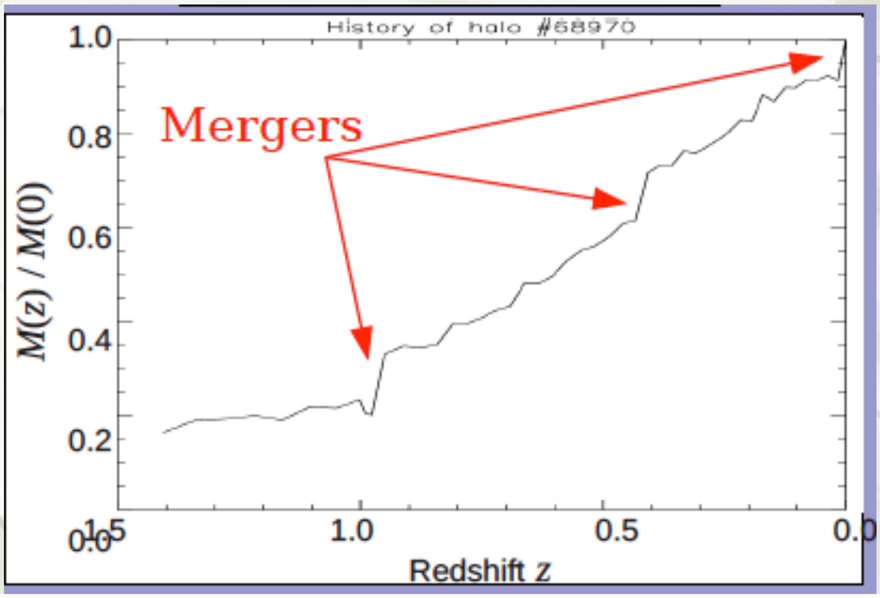


Figure 6. A schematic representation of a "merger tree" depicting the growth of a halo as the result of a series of mergers. Time increases from top to bottom in this figure and the widths of the branches of the tree represent the masses of the individual parent halos. Slicing through the tree horizontally gives the distribution of masses in the parent halos at a given time. The present time t_0 and the formation time t_f are marked by horizontal lines, where the formation time is defined as the time at which a parent halo containing in excess of half of the mass of the final halo was first created.

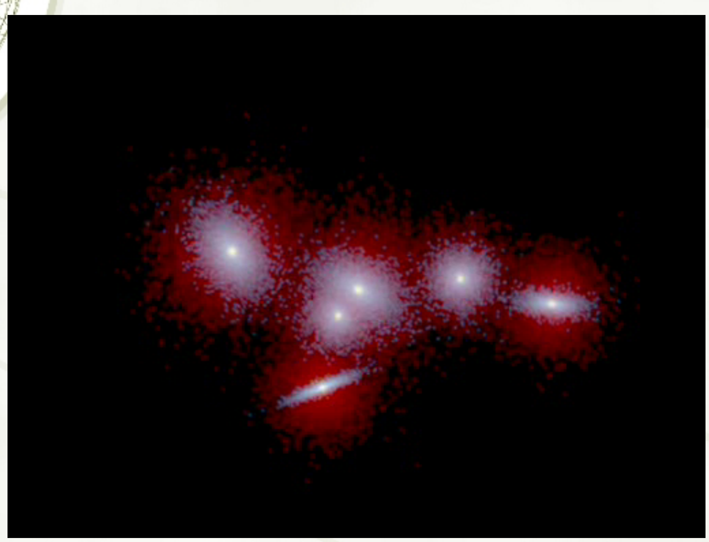


Bode

- Big mergers are rare, but increase the mass a lot



Computer simulation of galaxy collisions that make a big elliptical



J. Barnes, UH