# *Lecture 21+22+23 : Where did the galaxies come from*

- From homogeneity to structure…
  - Gravitational evolution of dark matter
  - Formation of dark matter halos
- Galaxy formation


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# *O.Measurements of the matter content of the Universe (recap)*

- Primordial nucleosynthesis+ CMB Peaks
  - Theory predicts how present light element abundances ($^4$He, $^3$He, D, $^7$Li) depend on mean baryon density
  - Observed abundances $\Rightarrow \Omega_B \approx 0.04$
- Galaxy/galaxy-cluster dynamics
  - Look at motions of stars in galaxies, or galaxies in galaxy clusters… $\Omega_M \approx 0.3$
  - Infer presence of large quantities of "non-baryonic dark matter" ($\Omega_{DM} \approx 0.25$)- that is matter that causes things to move (gravity) but cannot be baryonic

## *Recap: WHAT IS THE GEOMETRY OF OUR UNIVERSE?*

- Recall that universe with different curvature has different geometric properties
- Adding up the angles in a triangle,
  - Flat universe($k = 0$): angles sum to 180°
  - Spherical universe ($k = +1$): angles sum to >180°
  - Hyperbolic universe ($k = -1$): angles sum to <180°
- Similarly, for a known length $L$ at a given distance $D$, the angular size on the sky varies depending on the curvature of space
  - Flat universe ($k = 0$): angular size $\theta = L/D$
  - Spherical universe ($k = +1$): angular size $\theta > L/D$
  - Hyperbolic universe ($k = -1$): angular size $\theta < L/D$

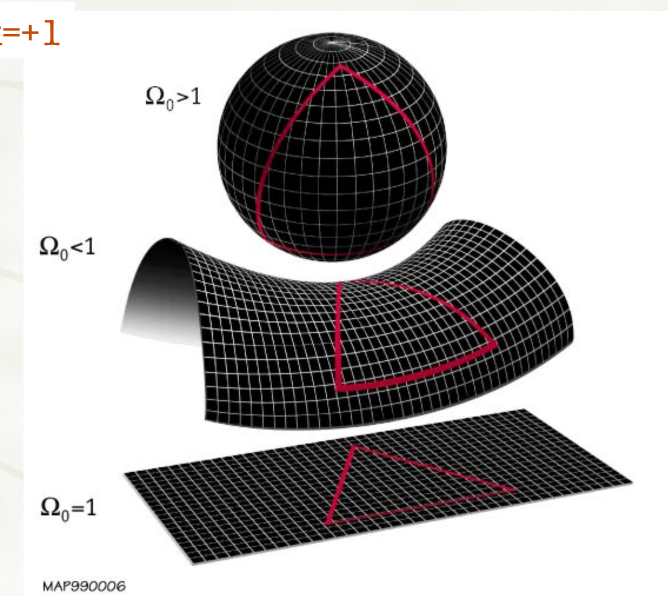


Graphics: NASA WMAP project

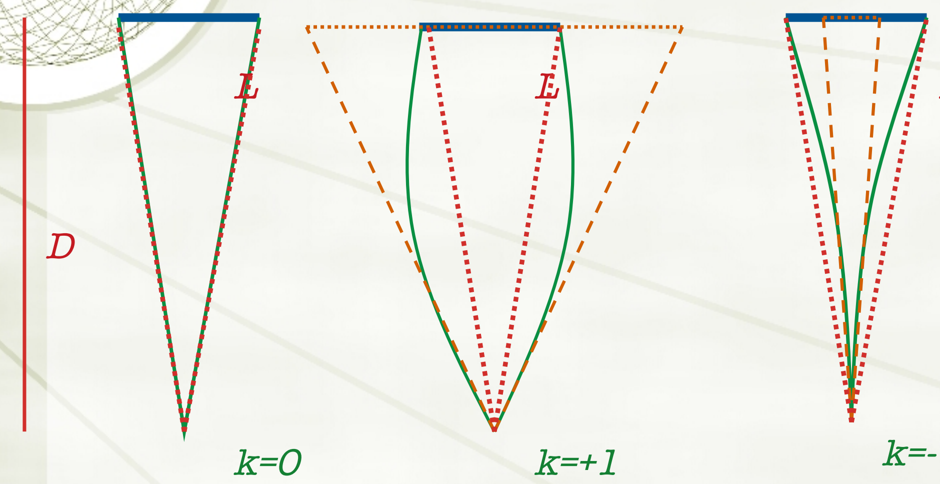
k=+1

k=-1

k=0



# Curvature affects apparent size or field of view



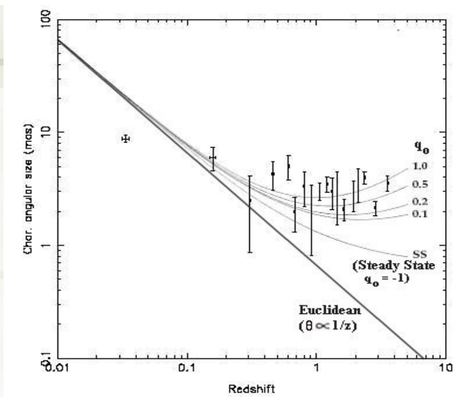



- in the simplest models,
- $q_0 < 0.5$ corresponds to the case where the Universe will expand for ever,
- $q_0 > 0.5$ to closed models which will ultimately stop expanding and contract
- $q_0 = 0.5$ corresponds to the critical case – Universes which will just be able to expand to infinity without re-contracting.

$q_0=\Omega/2$

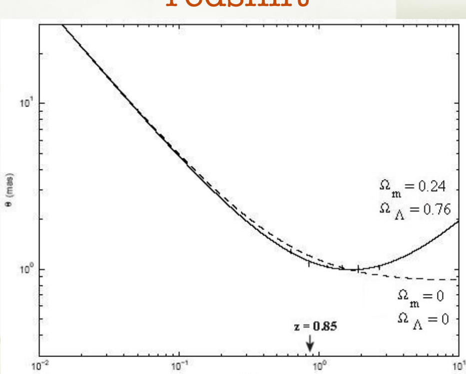
- $\Lambda$ cosmologies are different

angular size of a fixed rod




redshift

angular size of a fixed rod




redshift

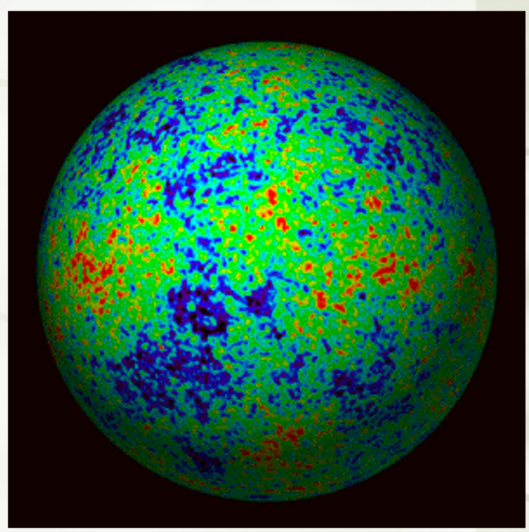
# Power spectrum peaks and valleys

- Angular scale of first (large) peak corresponds to wavelength of sound wave that would have completed half an oscillation within 300,000 years
- This is the “fundamental” peak, at about 1° angular scale
- At larger scales, waves would have completed less than half an oscillation and no large densities were introduced on those scales
- Peaks at scales <1° are higher harmonics

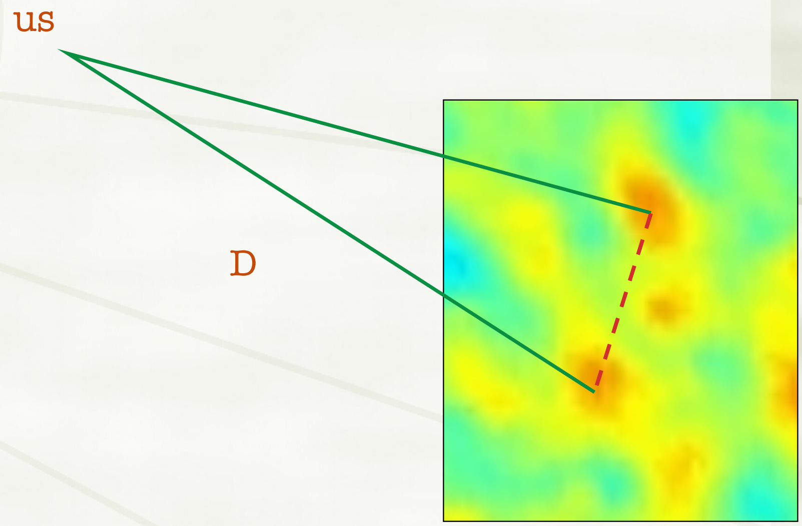


# Angular size of fluctuations in the CMB

- Remember the cosmic microwave background…
- It has fluctuations,
  - Average scale of fluctuations is known (associated with sound waves in early Universe)
  - Distance *D* to this “surface of last scattering” is also known
- Can use apparent angular separations of fluctuations compared to *L*/*D* to infer geometry of Universe



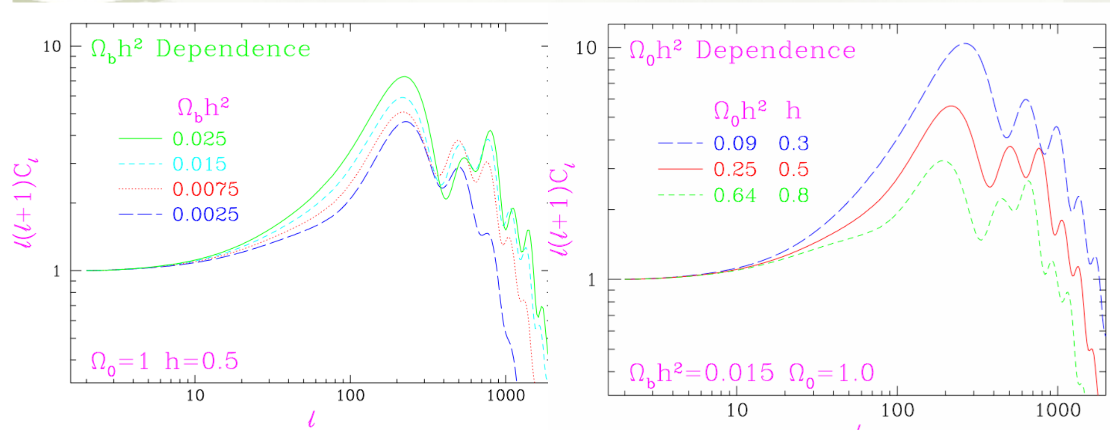
Graphics: NASA WMAP project



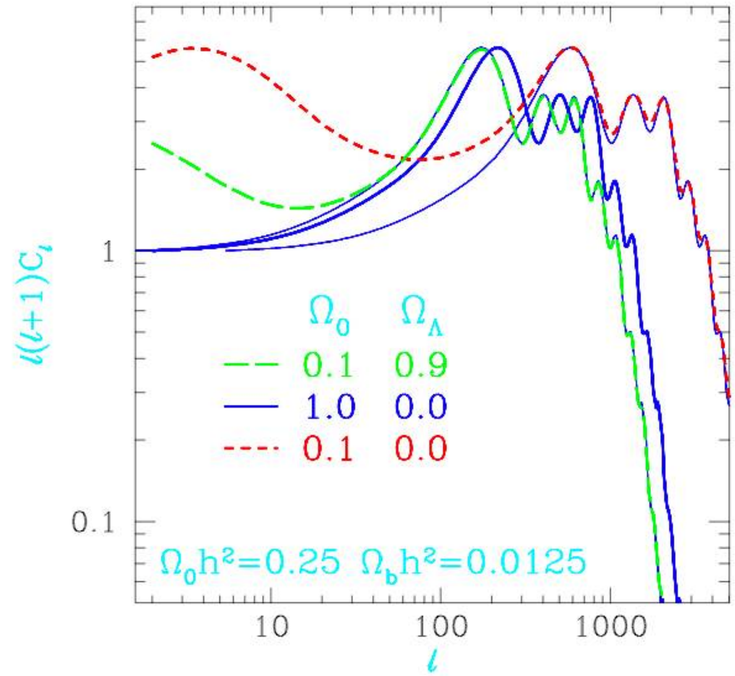



## *Spectral changes for varying parameters*

- Spectra from CBR maps also constrain other parameters such as $\Omega_B$ and $H_0$…



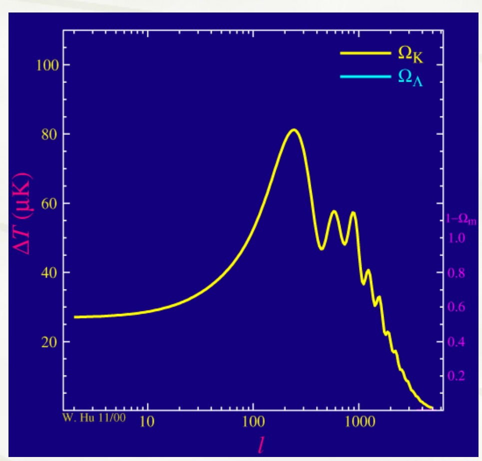

*Images: W. Hu, U.Chicago*






# *How Curvature Effects the Position of the Peaks in the CMB*

- The position of the peaks in the CMB are very sensitive to curvature



# Flat universe!

- Result:
  - The universe is **flat**
  - But, the sum of all known matter gives $\Omega_M = 0.3$
    - Surely, this implies an open/hyperbolic universe???
  - We must be missing something…
- Remember Einstein's cosmological constant?
  - Cosmological constant corresponds to an energy field that fills space… it is NOT matter, but still contributes to the curvature of the Universe
  - We can get a flat Universe if $\Omega_M + \Omega_\Lambda \approx 1$
  - So, we can reconcile the measurement of mass with flatness of Universe if $\Omega_\Lambda \approx 0.7$
  - What additional effect would this have?
  - This dark energy acts to **accelerate** the Universe!



# Flat universe!

- Result:
  - The universe is **flat**
  - In terms of omega curvature parameter,
  $k = 0$ means $\Omega_k = 0$
  - Recall that the sum of all three omega parameters as measured at present time must be 1 for the universe to be flat:

$$1 = \Omega_M + \Omega_\Lambda + \Omega_k$$

  - How do we reconcile $\Omega_k = 0$ with our measurement of the matter density, which indicates $\Omega_M = 0.26$?
  - There must be a nonzero cosmological constant, $\Omega_\Lambda = 0.74$!

$$\Omega_M \equiv \frac{\rho_0}{\rho_{crit}} \equiv \frac{\rho_0}{(3H_0^2/8\pi G)} \qquad \Omega_\Lambda \equiv \frac{\Lambda}{3H_0^2} \qquad \Omega_k \equiv -\frac{kc^2}{R_0^2 H_0^2}$$

# *EINSTEIN STILL IN THE NEWS*

The Washington Post

# HEALTH&SCIENCE

E

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

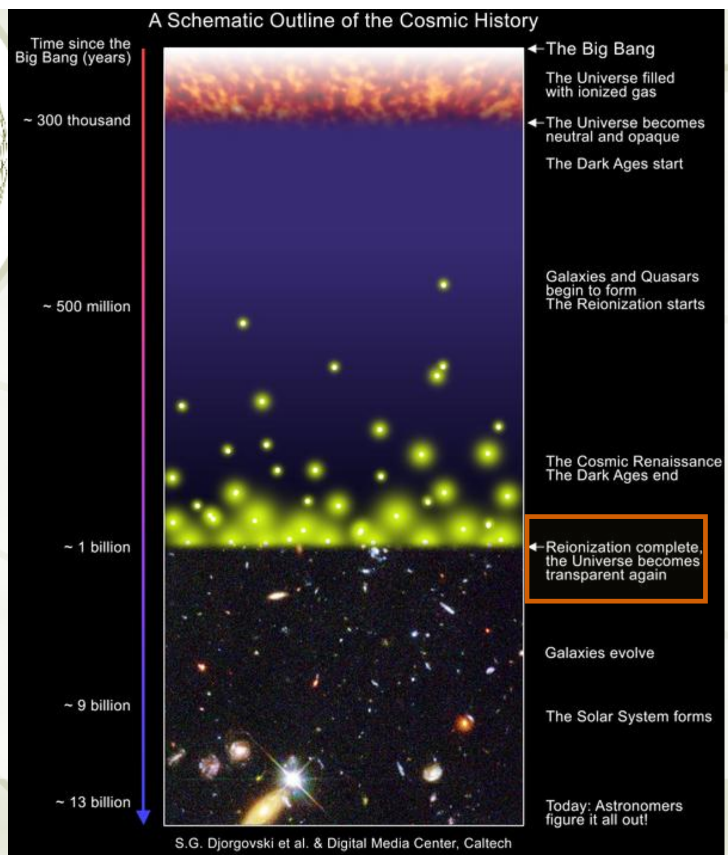
## Einstein, the sky is falling! Or not.

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.



# DARK MATTER: RECAP

- The **density parameter** for matter is defined as

$$\Omega_M = \frac{\rho_{matter}}{\rho_{crit}} = \frac{\rho_{matter}}{3H_0^{\ 2}/(8\pi G)}$$

- Nucleosynthesis arguments constrain the density of baryons (ordinary matter) to $\Omega_B \approx 0.04$
- But there seems to be much more mass in galaxy and cluster halos: total $\Omega_{Matter} = 0.26$
- So, most of the matter in the Universe appears to be non-baryonic!
- This is also supported by evidence from power spectrum of CBR fluctuations and gravitational lensing in galaxy clusters
- "Cosmic concordance" value is $\Omega_{DM} = 0.22$



# What is dark matter

*-while we do not know we can constrain some of its properties*

- Whether dark matter is hot or cold is important for how structure forms
- Hot dark matter is composed of particles that have zero or near-zero mass (neutrinos are a prime example).

  Special Relativity tells us that nearly massless particles move at nearly the speed of light. Thus, such very low mass particles must move at very high velocities and thus are called 'hot'.
- clumpy structure to set a lower limit on the dark-matter particle mass (low mass ➔high speed ➔ large distance traveled ➔ scale on which density perturbations are washed out
- Cold dark matter is composed of objects sufficiently massive that they move at sub-relativistic velocities.
- The difference between cold dark matter and hot dark matter is significant in the formation of structure, because the high velocities of hot dark matter cause it to wipe out structure on 'small' scales

  Hot dark matter resists clumping up by gravity more than cold dark matter

# Neutrinos as dark matter

- Already came across neutrinos when talking about nuclear reactions
- Neutrinos are leptons, in same family as electrons
- They are part of the "standard model" of particle physics… they have been detected and studied.
- They are known to have a small mass, but it is NOT zero
- Because neutrinos only interact very weakly with other particles, they are very hard to study!



- Evidence that neutrinos have nonzero mass comes from theory & experiments that show Solar electron neutrinos are changing into some other form of neutrino (tau or muon) on their from the sun and from nuclear reactors to detectors 100's of miles away, this can occur only if they have mass
- Spread in arrival times for neutrinos from supernova SN1987a indicated mass < $17\times10^{-9}$ times mass of proton
- Other direct evidence for neutrino masses comes from measurements of energy in decay of tritium
  - Mass is <$0.5$-$5\times10^{-9}$ times mass of proton
- **Overall conclusion:** neutrinos have very small mass, and there are not enough of them to account for all the dark matter
- Any dark matter contribution from neutrinos is **hot**, since they move relativistically

# Why Neutrinos are Not All the Dark Matter

- The number of neutrinos created in the early universe can be calculated
- $(n = (3/4)(4\pi)\Gamma(3)Z(3)\ (kT/hc)^3$ = 53 $\times 10^6$ neutrinos per cubic m for each type of neutrino
- There are ~3 types of neutrino and their anti-neutrino and to account for <u>all</u> the dark matter they would need a mass of ~10eV (=$1.8\times10^{-35}$ kg)
- Experimental upper limit are ~2 eV and upper limits from cosmology are ~1/3 eV so neutrinos make up <1/30 of the dark matter.
- If neutrinos had a mass of 10ev they would move at a velocity of ~3,000 (1+z) km/sec - so they would not be able to be contained in clusters when they formed at z~1

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- Neutrinos have two important effects in the early universe. 1) as an additional radiation component they affect the timing of the epoch of matter-radiation equality. 2) the process of neutrinos becoming non-relativistic imprints a characteristic scale in the power spectra of fluctuations. This is termed the 'free-streaming scale' and is roughly equal to the distance a typical neutrino has traveled while it is relativistic.
- Fluctuations on smaller scales are suppressed by a non-negligible amount, of the order of a few percent. This allows us to put limits on the neutrino masses and thus the contribution of neutrinos to dark matter.

# Cold dark matter candidates

- WIMPs
  - Weakly Interacting Massive Particles
  - Generic name for any particle that has a lot of mass, but interacts weakly with normal matter-through the weak nuclear force and gravity
    - Must be massive, to give required mass
    - If particles have high mass, they would be moving slowly ⇒ "cold"
    - Must be weakly interacting, in order to have avoided detection
  - BUT no known stable particles within the standard model of particle physics that have all the properties of WIMPs. Various possibilities suggested by Particle Physics Theory…
    - Super-symmetric particles
    - Gauge bosons

What does this mean - physics beyond the Standard Model - very uncertain



- Wimp class of particles are created thermally
- In thermal creation one imagines that early on, when the Universe was at very high temperature, thermal equilibrium obtained, and the number density of Wimps (or any other particle species) was roughly equal to the number density of photons.
- As the Universe cooled the number of Wimps and photons would decrease together as long as the temperature remained higher than the Wimp mass.
- When the temperature finally dropped below the Wimp mass, creation of Wimps would stop
- But as opposed to Photons Wimps are their own anti-particle so when a Wimp finds another it annihilates
- At some point the Wimp density drops low enough that the chances of a Wimp finding another to annihilate is small.
- The Wimp number density would ``freeze-out'' at this point and we would be left with a substantial number of Wimps today.

•any stable particle which annihilates with an electroweak scale cross section is bound to contribute to the dark matter of the Universe.

• theories such as supersymmetry, invented for entirely different reasons, typically predict just such a particle.

The fact that thermally created dark matter has weak scale interactions also means that it may be within reach of accelerators
•Thus many accelerator searches for exotic particles are also searches for the dark matter of the Universe.

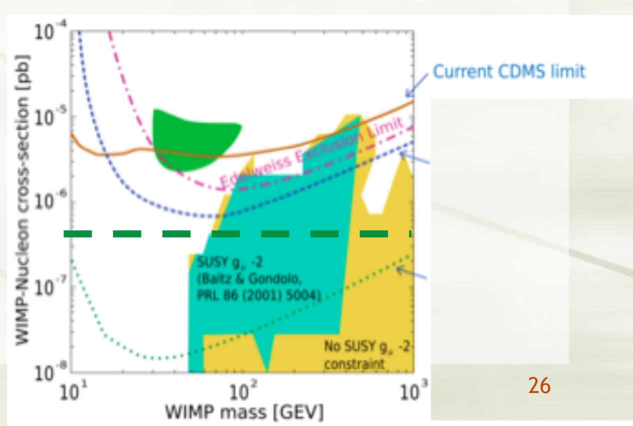
•Also, due to the weak scale interactions, Wimp-nuclear interaction rates are within reach of many direct and indirect detection method

from The Nature of the Dark Matter by Kim Griest, 1996
The Net Advance of Physics: GATEWAY REVIEWS, No. 2

# Cold dark matter candidates

- Many experiments currently on-going
  - All hope of proving WIMPs exist rest on the theory that, on occasion, a WIMP will interact with ordinary matter. Because WIMPs pass easily through ordinary matter, only a rare WIMP interaction will take place inside a solid object. The trick to detecting a WIMP is to witness one of these interactions.
  - to give an indication of how hard this is the mean free path of a neutrino is about a light-year of lead.

- Large Hadron Collider at CERN may be able to detect lightest super-symmetric particle



# How did all this structure arise

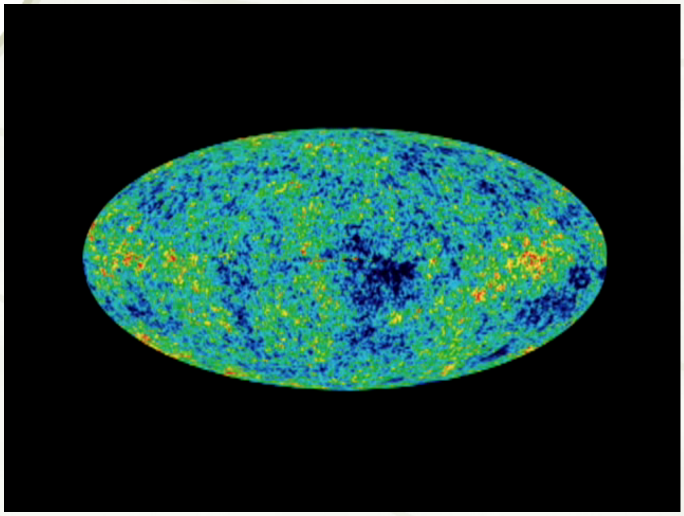
- Early universe was extremely homogeneous:
  - At z = 1100 (surface of last scattering), local fluctuations in density were only about 1 part in $10^5$
  - Fluctuations at varying scales had varying amplitudes (as seen e.g. in CBR power spectrum)
  - During radiation era, there was strong interaction 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

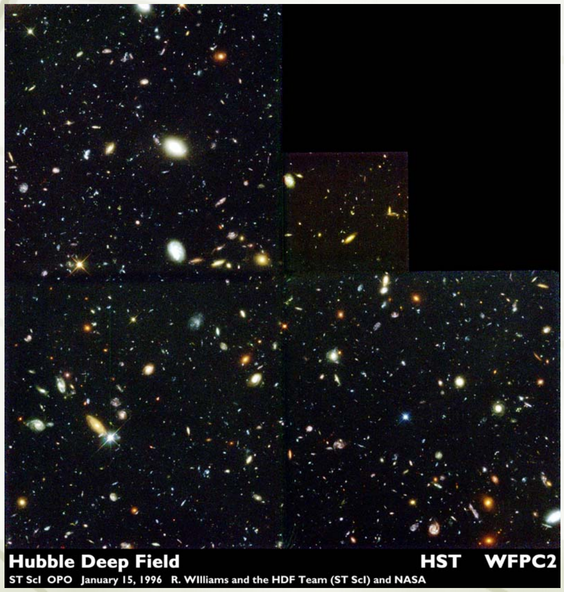




# RECAP: Homogeneity

- 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.

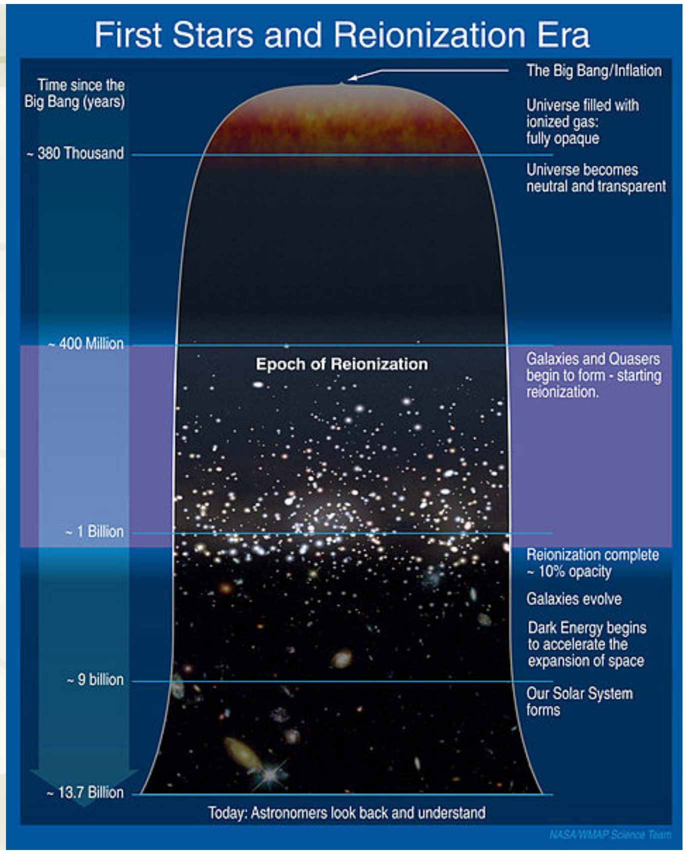
# I.Timeline for structure formation

- 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 CBR
  - 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 ($z \sim 1100$) 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 $z \sim 7$ (~$8 \times 10^8$ yrs after Big Bang) the universe re-ionizes- energy from star formation or quasars ionizes the intergalactic medium (IGM)

- After the first 400,000yrs onwards…
  - After decoupling, inhomogeneities in the matter density start to grow… dense regions become denser.
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  - at z~7(~8x$10^8$ yrs after Big Bang) the universe re-ionizes- energy from star formation or quasars ionizes the intergalactic medium (IGM)

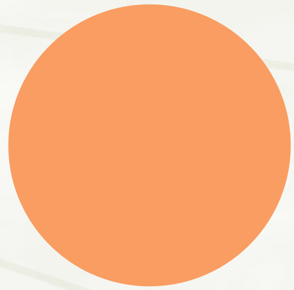
- Two general scenarios for subsequent evolution
  - **Top-down scenario -**big things form first (galaxy superclusters), which fragment to make smaller things (clusters and galaxies)
  - **Bottom-up scenario**: small things form first (small galaxies), which collect together to make big things (bigger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

# 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



# 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*

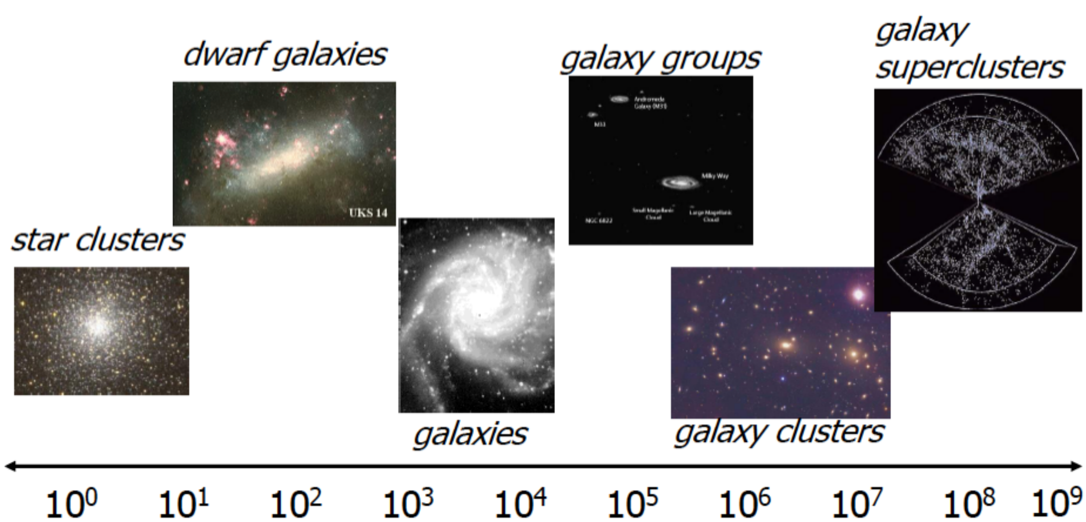
- *the original condensation of cosmic structures out of nearly-uniform initial conditions and*
- *the growth of structure.*

# 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



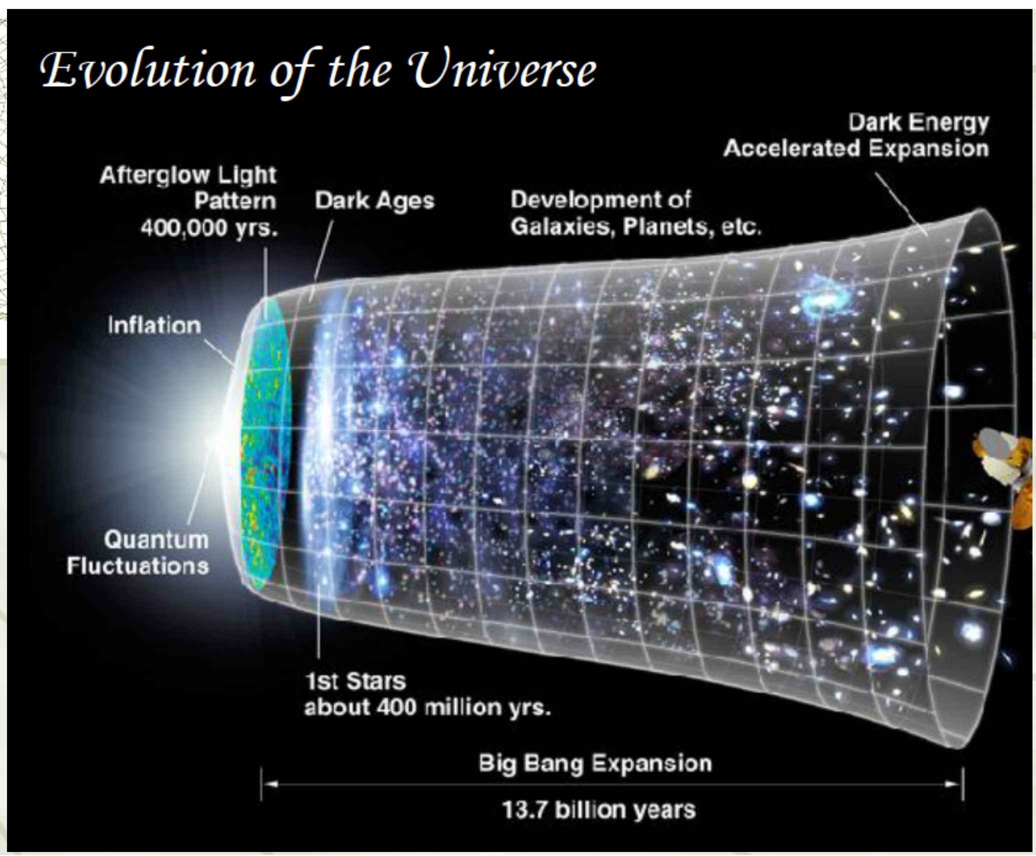

Size in light years

# *Range of cosmic structure, from small scales to large…*

**Not DM dominated** (applies to the first three items):

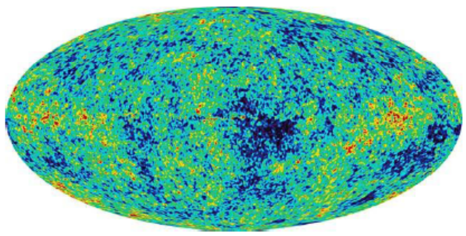
- Tiny scale: planets around stars
- Very small scale: stars in clusters
- Small scale: stars and star clusters in galaxies
- Medium scale: galaxies in groups and clusters
- Large scale: sheets and filaments of galaxies, hot gas, + dark matter; voids in between
- Very large scale: "Hubble volume" containing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





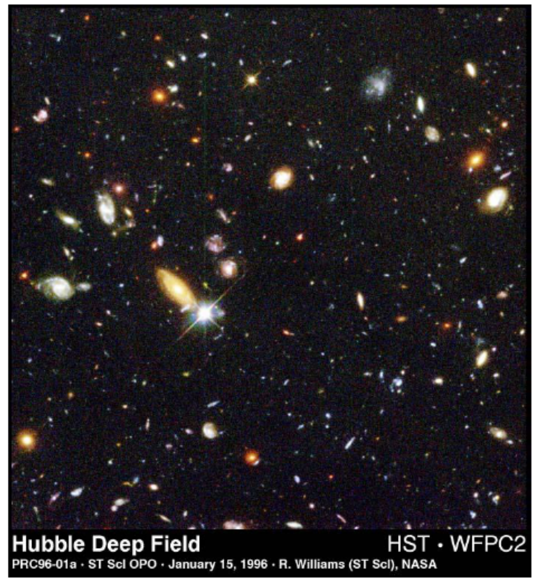
# Our universe then and now

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



Wilkinson MAP (NASA)

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

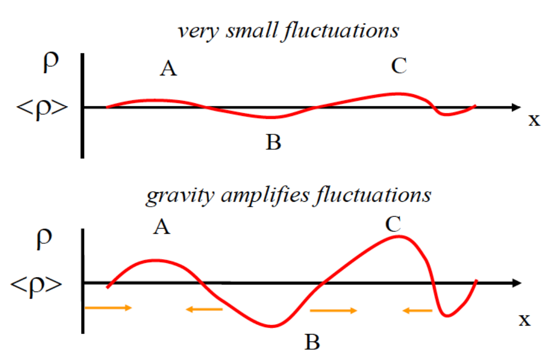



M.Norman

# 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 build 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!

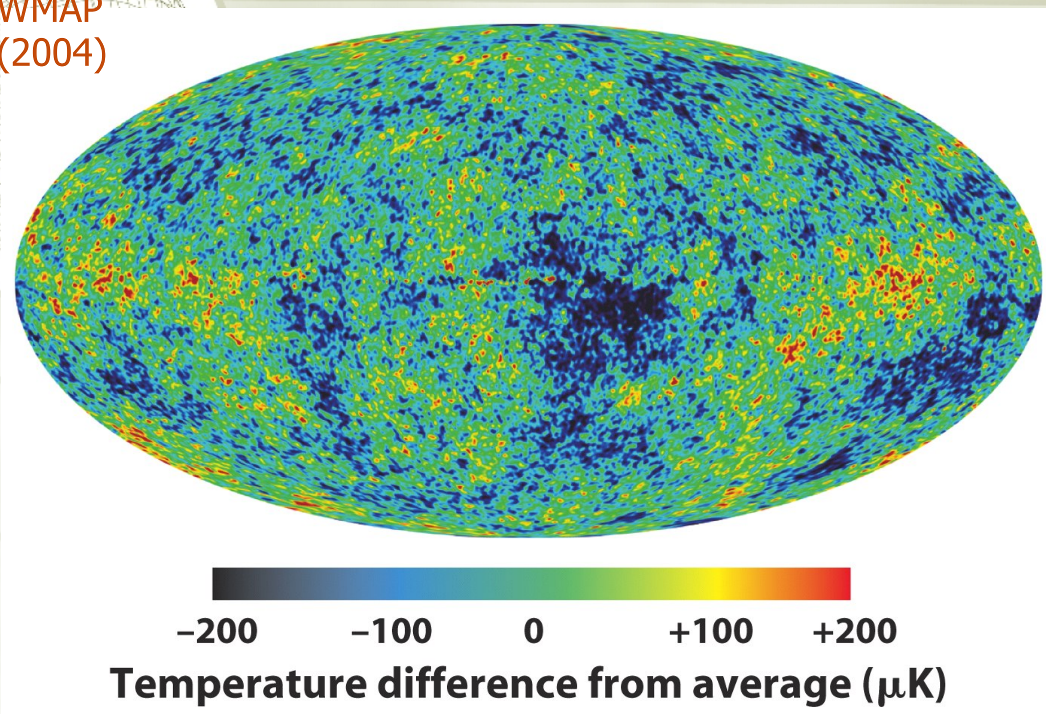
## *I : Formation of structure*

- 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)

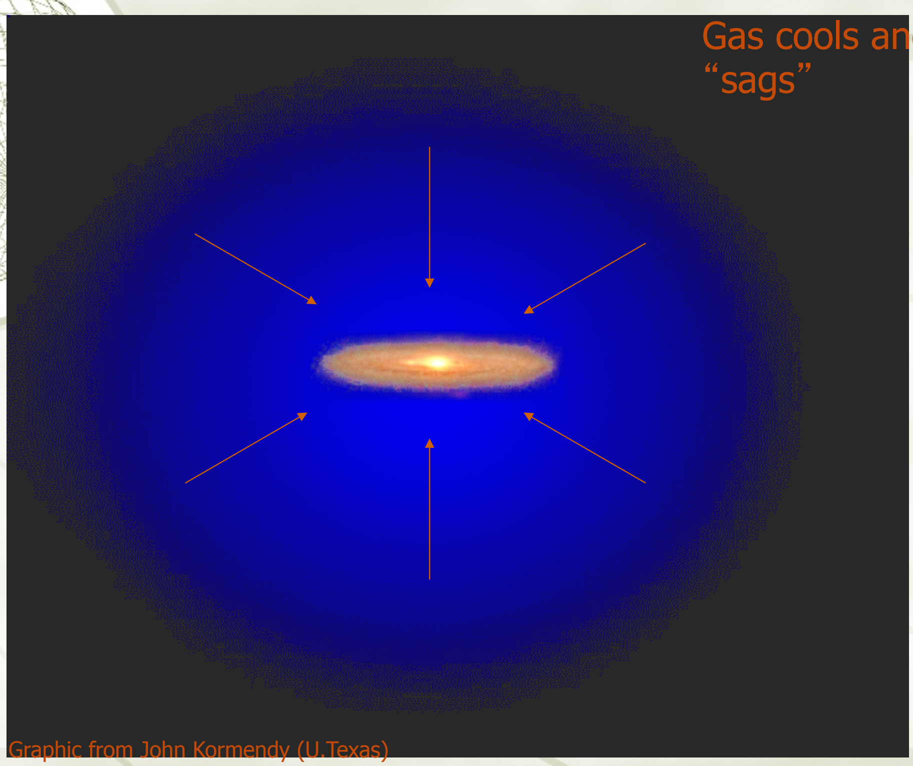


WMAP (2004)



# 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




Graphic from John Kormendy (U.Texas)

# *Numerical Simulations of Structure formation*

## *How Do They do This*

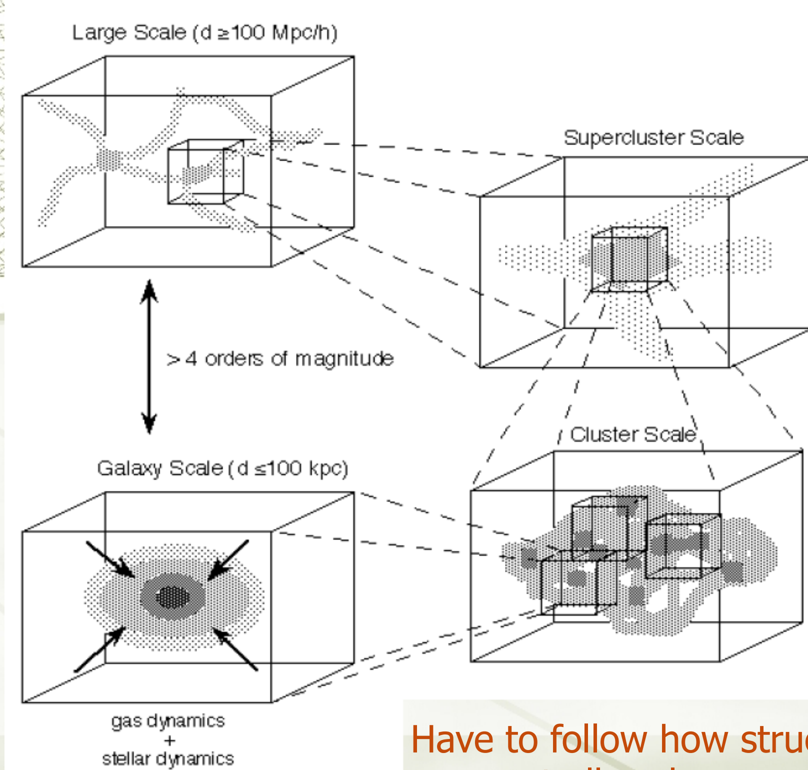
- *Globally*, the universe evolves according to the Friedmann equation

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

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

- *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

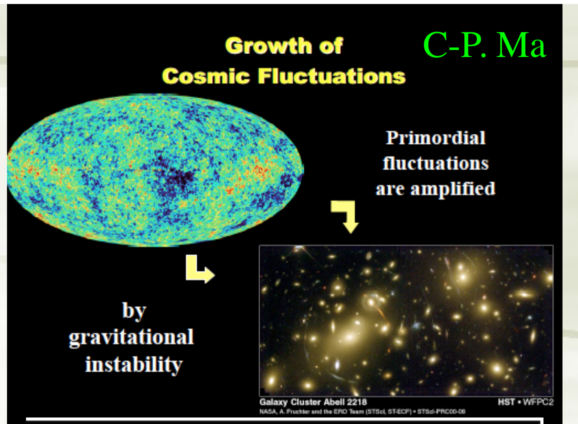
- $4096^3$ particle/cell hydrodynamic cosmology simulation
- NICS Kraken (XT5)
  - 16,384 cores

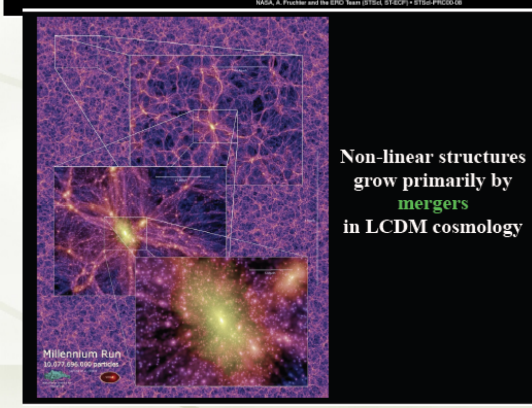



Have to follow how structure grows at all scales

# 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

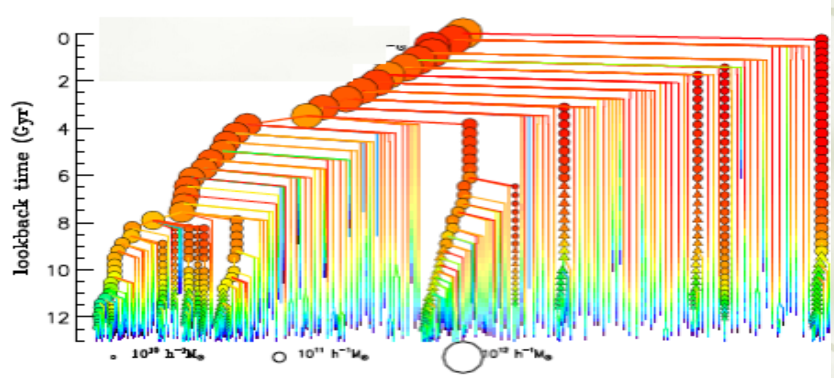
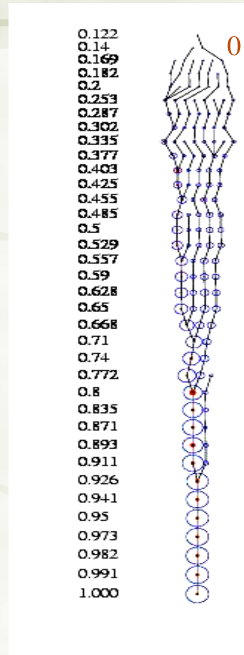



**Figure 1.** BCG merger tree. Symbols are colour-coded as a function of B - V colour and their area scales with the stellar progenitors more massive than $10^{10}$ $M_\odot$ $h^{-1}$ are shown with symbols. Circles are used for galaxies that reside in the FOF gro by the main branch. Triangles show galaxies 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)

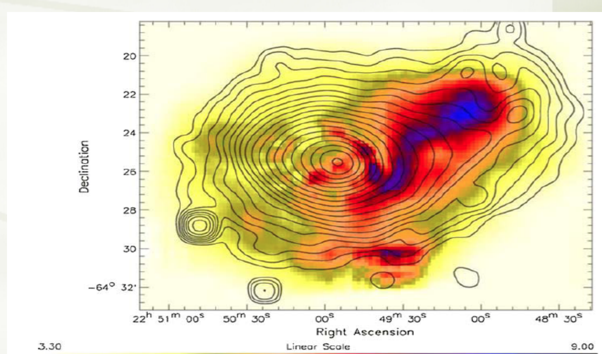



Fig. 15 Temperature map of the merging cluster A3921 by Belsole et al. (2005). The temperature map has

# *Extreme Merger*

- Bullet cluster (1E0657)
- Allen and Million

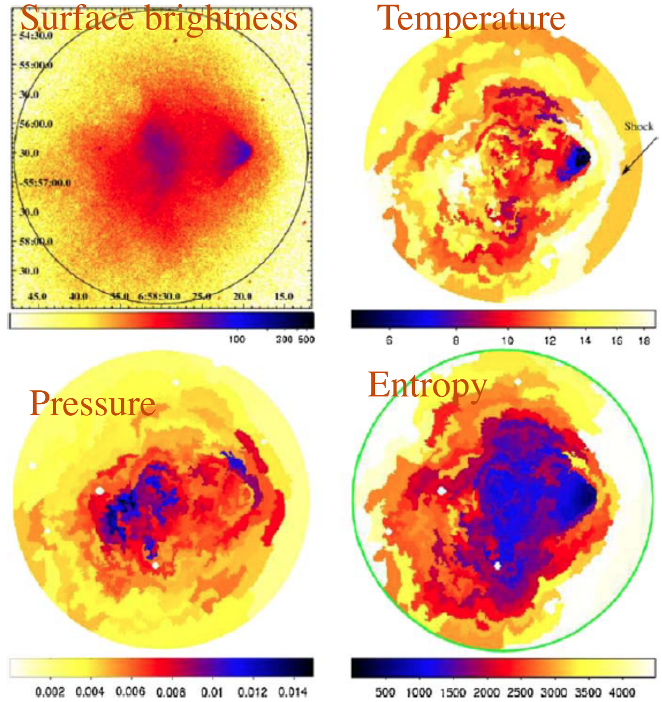



**Fig. 16** Thermodynamic maps for the ICM of the "bullet cluster", 1E0657-56 (Million and Allen 2008)

# *Hierarchical Formation of Structure*

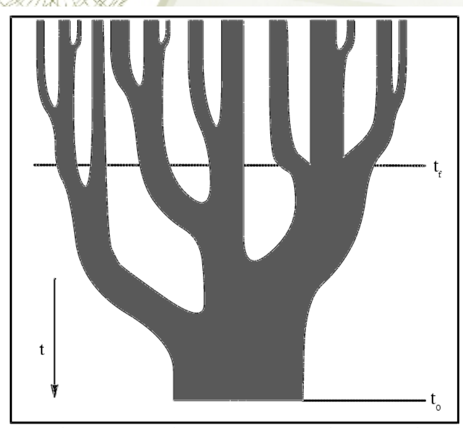
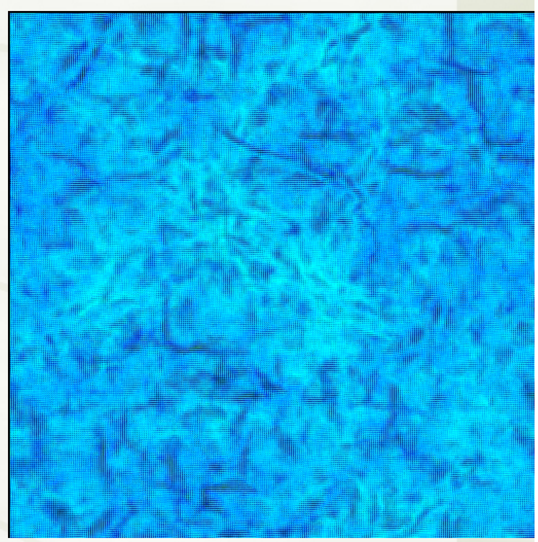
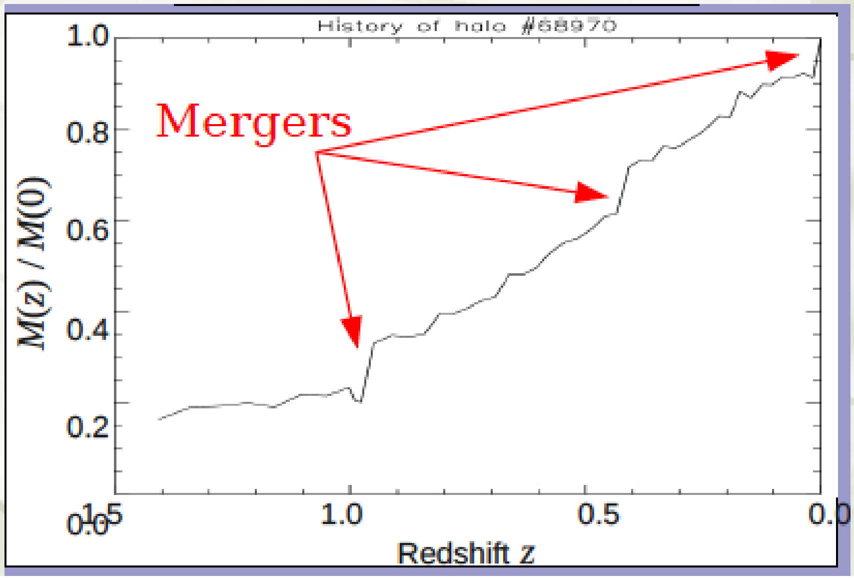



**Figure 6.** A schematic representation of a "merger tree" depicting the growth of a halo as the result of a series of mergers. Time increases from top to bottom in this figure and the widths of the branches of the tree represent the masses of the individual parent halos. Slicing through the tree horizontally 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.

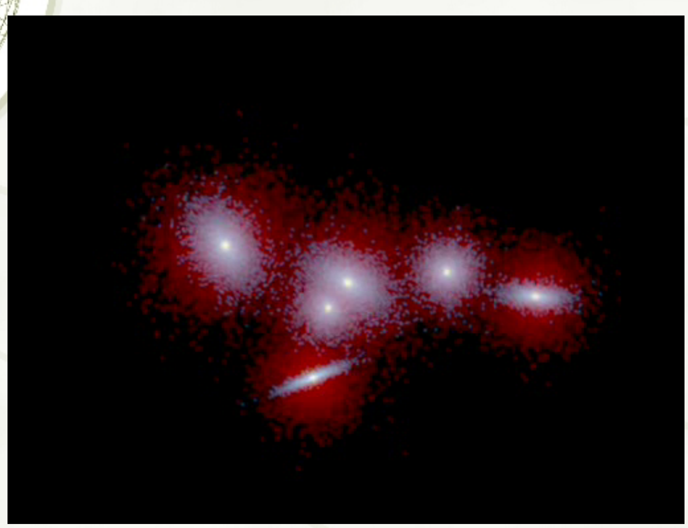


Bode

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




*Computer simulation of galaxy collisions that make a big elliptical*



J. Barnes, UH