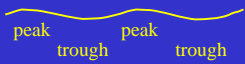
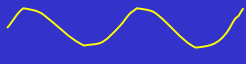
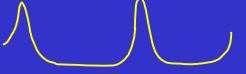



## The Growth of Structure

1. From Sound to Stars
2. A hierarchy of structures
3. The First Stars
4. The First Galaxies
5. Galaxy Clusters Form
6. The Tapestry Emerges
7. Arrival at Planet Earth

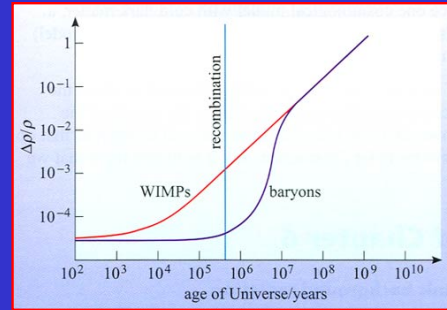
## 1. From Sound to Stars

### From Sound to Stars

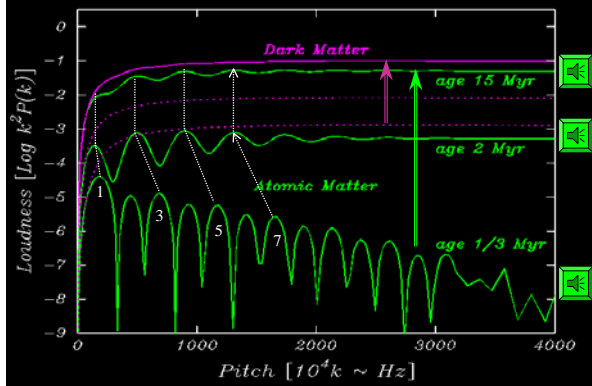
1. Sound wave 
  2. Contrast grows 
  3. Collapse begins 
  4. First stars form 
- 100 million years

### Baryons follow Dark Matter

After recombination, the baryon gas can fall into the dark matter clumps → its clumpiness quickly grows



### The Growing Hiss



### First 100 Million yrs

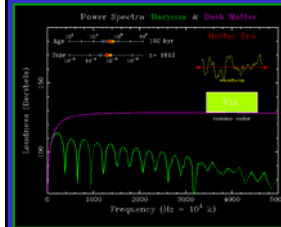
Movie time flow exponential : 2s for each 10x increase in real (cosmic) time:  
 0-2s = 10<sup>2</sup>-10<sup>3</sup> yrs; 2-4s = 10<sup>3</sup>-10<sup>4</sup> yrs etc; waveform and cosmic color also shown

Movie 5



Linear frequency x-axis  
 Log (decibel) y-axis  
 Varying (fake) volume

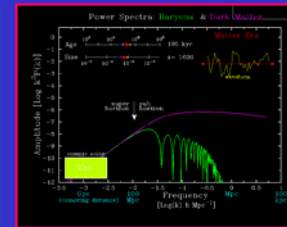
1.5 Mb



Log frequency x-axis  
 Log (decibel) y-axis  
 Constant volume

Movie 6

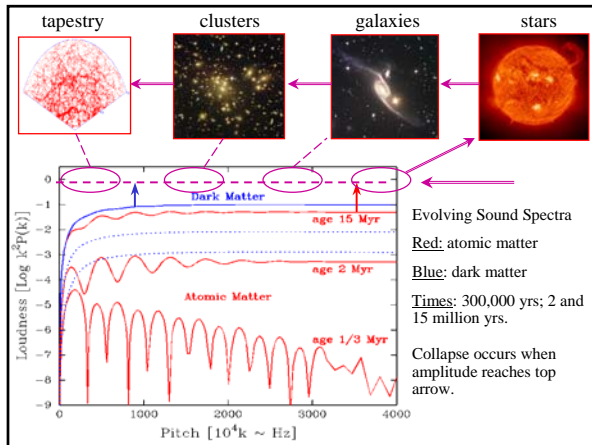
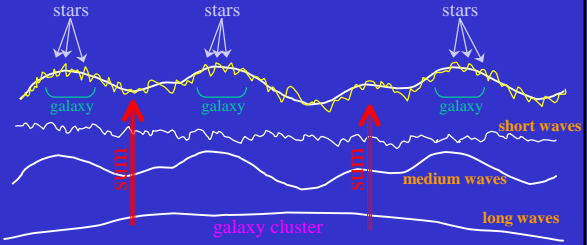
1.5 Mb



## 2. A Hierarchy of Structures

### peaks on peaks on peaks

- Dark matter clumps of all sizes are randomly distributed
- The first clumps to collapse are where all peaks coincide :  
small on top of medium on top of large  
→ stars are born in groups, which are also in groups



## 3. The First Stars

The first stars form after ~0.2 Gyr  
They are very massive → bright, blue, short lived  
They explode as supernovae → heavy elements  
Their UV radiation ionizes the whole universe

Collapse from early gas concentrations to form the first stars

Movie 7

Or click on the image  
54 Mb !!

Log Column Density [g/cm<sup>2</sup>]

Matthew Baer

### Massive Stars

Massive stars ionize surrounding gas  
→ Pink HII regions

Photons with enough energy to ionize H

Energy radiated by O6 star

Energy radiated by B1 star

Crab 10<sup>3</sup> yr

Cygnus loop - X-ray

Massive stars explode as supernovae  
→ shed new elements  
→ next generation contains these

## Universe at 1 Gyr

- Spectacular sight: proto-galaxies merging, everything closer, huge HII regions, O&B stars common, SN common



Cosmic history like fireworks display in reverse: Grand finale occurs first

Artists view of galaxy youth

## 4. The First Galaxies

Stars cluster to form sub-galaxies  
Sub-galaxies merge to build galaxies  
Significant construction within the first Gyr

Large Galaxies: form from the successive merging of smaller galaxies, star clusters and gas clouds.

See next slide for simulation.



## Merging group of galaxies

Computation: ~100 kpc region, 6 galaxies merge, 1 Gyr = 60 sec



## 5. Galaxy Clusters Form

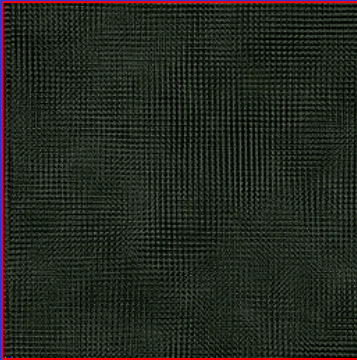
Galaxies are born in over-dense regions  
These regions collapse to form galaxy clusters  
Rich clusters are forming at ~7Gyr

## Galaxy Cluster



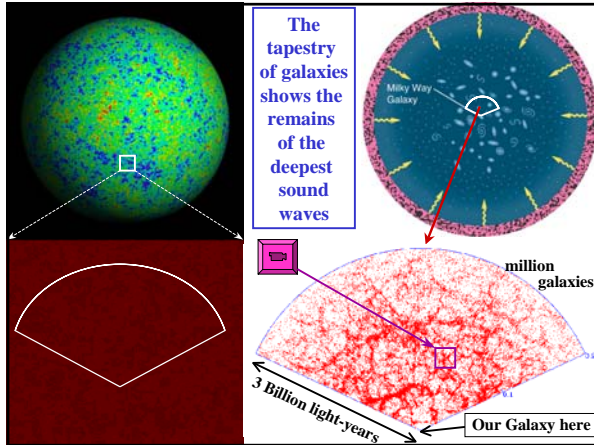
### Movie: cluster formation with a thousand galaxies

Computation: ~10 Mpc region ~10<sup>3</sup> galaxies form, 14 Gyr = 10 sec

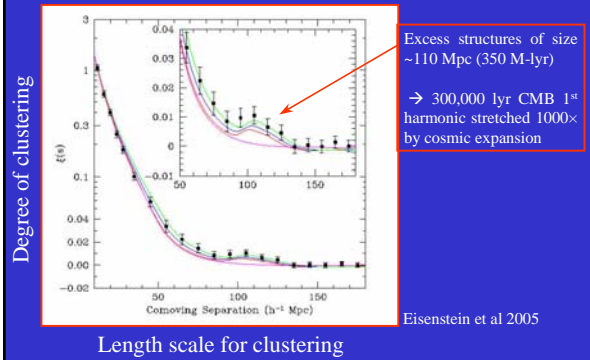


## 6. The Tapestry Emerges

- The Universe continues to Expand
- But it gets ever more “contrasty” → Tapestry grows
- The relic of the first harmonic sound wave has been discovered in this pattern of galaxies



### Acoustic peak in galaxy distributions



## 7. Arrival at Planet Earth

- After galaxies form, they continue to evolve
- Stars continue to enrich the interstellar medium
- With more heavy elements, planets can form.....

### A Path to the Solar System

- Within the galaxy, stars continue to form, evolve, and die
- With each generation, the interstellar medium gets more polluted with heavy elements. The “metallicity” continues to grow, more so in galaxy nuclei.
- Presently, galaxy disks have ~2% heavy elements (old galaxy halos are ~0.2%, galaxy nuclei ~4%)
- These help in the formation of planets..... and people!

