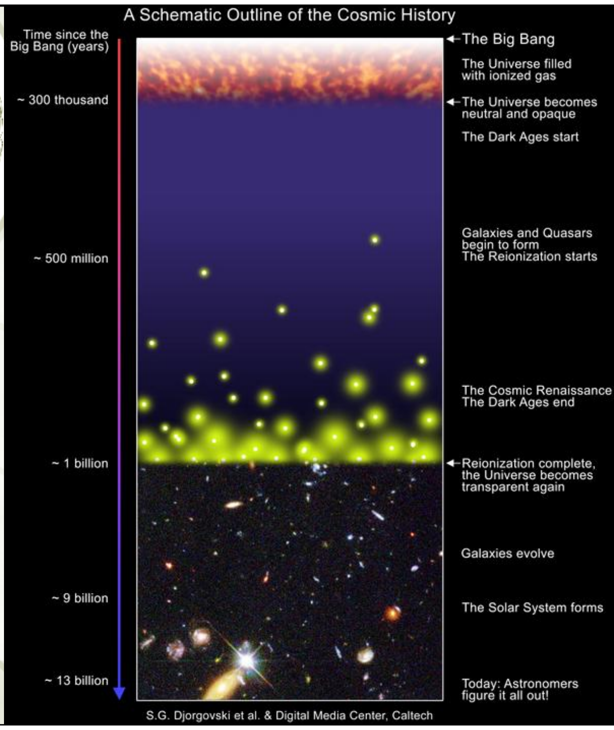
Lecture 22 : Dark Matter & Structure Formation I

- Recap
- Non-baryonic dark matter candidates
- Large scale structure in the Universe
- Origins of structure

This week: read Chapter 15



DARK MATTER: RECAP

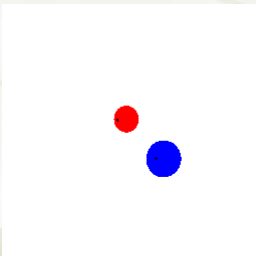
- The **density parameter** for matter is defined as

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

- 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 $\Omega_{DM} = 0.22$

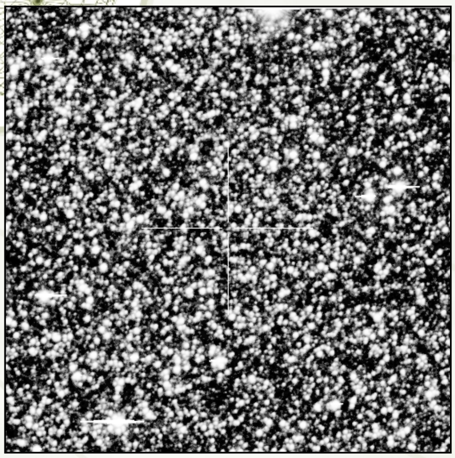
Additional limits on baryonic DM

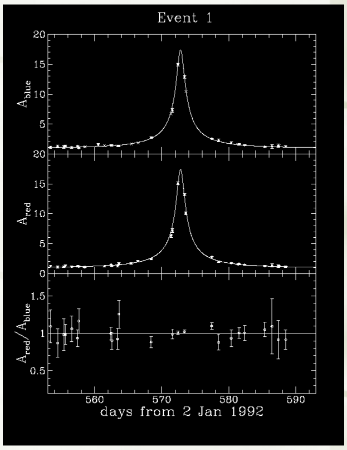
- Another candidate for dark matter that *would* be baryonic is MACHOs
- Stands for "MAssive Compact Halo Objects"
- Would consist of dark stars of some kind in the halos of galaxies
- This has been searched for using microlensing in the Milky Way



Binary microlens, from web site of Ned Wright (UCLA)

Microlensing produces temporary brightening





MACHO Project

MACHO projects

- OGLE, EROS, and MACHO projects have searched for compact objects in MW halo
- Used background of stars in Large and Small Magellanic Clouds, satellites of MW
- Result is that only 20% of halo could be in MACHOs, which are probably mostly white dwarfs
- Failure to find more MACHOs is further evidence that dark matter is non-baryonic

What is the non-baryonic dark matter?

- Basically, we have to appeal to sub-atomic particles
- Two possibilities:
  - Low-mass particles that move relativistically (near *c*)
  - Higher-mass particles that move non-relativistically
- Fast-moving particles would provide "hot" dark matter
- Slow-moving particles would provide "cold" dark matter

Hot and cold dark matter

- Whether dark matter is hot or cold will turn out to be important for how structure forms
- 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.
- Maybe the dark matter is in the form of neutrinos?
- They are known not to have large mass, but there is no requirement for it to be 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), which can occur only if they have mass
- Spread in arrival times for neutrinos from supernova SN1987a indicated mass < 17×10^{-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

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
    - 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
  - Various possibilities suggested by Particle Physics Theory…
    - Super-symmetric particles
    - Gauge bosons
  - Many experiments currently on-going
  - Large Hadron Collider at CERN may be able to detect lightest super-symmetric particle (a good candidate for WIMP)

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 superclusters
- It gravitationally binds the baryons (stars and gas) together in these systems…

… and, in fact, it is believed to have been responsible for the original condensation of cosmic structures out of nearly-uniform initial conditions!

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?

Range of cosmic structure, from small scales to large…

- 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.

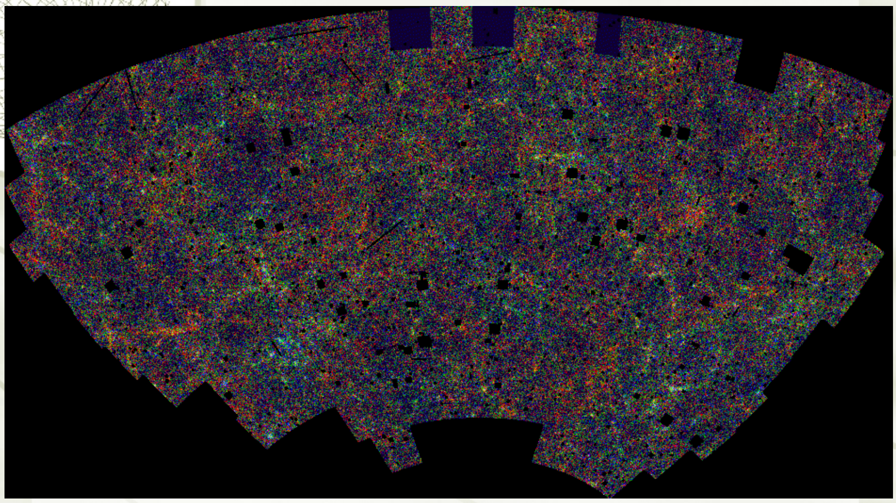
The distribution of galaxies in space

- Althought dark matter dominates, we can't see it!
- So, to trace large scale structure of the universe, we have to use galaxies
- A fundamental assumption is that there is not a strong bias in the local ratio of dark to luminous matter….

Galaxy maps on the sky

- One way to look at large scale structure is to map positions of galaxies on the sky
- Example: the APM galaxy survey, consisting of 2 million galaxies over 1/10th of the sky, surrounding Southern Galactic Pole
  - Based on scans of 185 photographic plates taken with the UK Schmidt Telescope at Siding Spring, Australia.
  - Computer processing of the data gives reliable star-galaxy classification
  - Note: there are "holes" around bright stars, clusters, etc., that were not surveyed

APM survey map



11/15/18 17

image credit: Maddox,Sutherland, Efstathiou, Loveday , Dalton (Oxford University)

Redshift surveys

- To add the "third dimension", since mid 1980's scientists have been performing redshift surveys of galaxies
- Surveys out to a distance Gpc (~1000 Mpc) have been completed
- Use map of galaxy positions on sky (like APM survey) for catalog of candidate objects
- Need to take spectrum of galaxy to obtain redshift z, hence radial velocity $v = cz$ with respect to Earth
- Can use Hubble law to get approximate distance, i.e. $D = V/H$
- Since random velocity adds or subtracts from motion due to cosmic expansion, true distance will differ somewhat from cz/H
- Random-velocity additions/subtractions have the most effect in clusters, in which radial "offset" from true distance can be large because motions in cluster can be up to 1000 km/s!

11/15/18 18

Example: 2dF Redshift survey cone diagram

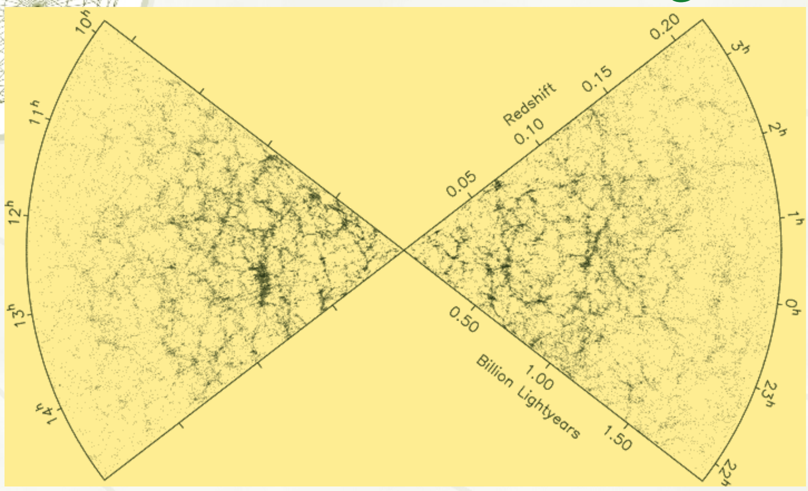


image credit: 2dF Collaboration (Anglo-Australian Observatory)

2dF GRS

- Survey can obtain spectra of up to 400 galaxies simultaneously using a fiber optical spectrograph
- Uses a robotic positioner to move fiber heads on field plate
- 2000 square degrees on sky surveyed
- 221,000 galaxy redshifts obtained over 5 years of data-taking

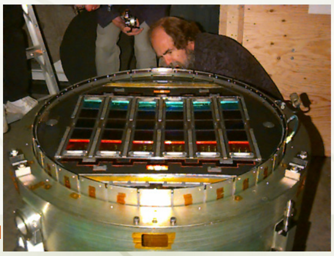
- Use 3D positions of galaxies to obtain spectrum of fluctuations of density perturbations
- This can be used to estimate Ω_M and Ω_B
- Also shows unambiguous evidence of collapse on large scales, indicating growth is due to development of gravitational instability

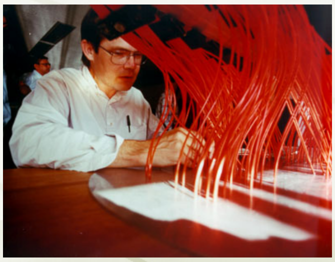
Sloan Digital Sky Survey

- Sloan Digital Sky Survey observing site, at Apache Point Observatory in the Sacramento Mountains of New Mexico. The site is 9150 feet above sea level.

SDSS

- Measuring the distance to a million of the nearest galaxies
- Total volume 100× larger than previously explored by any other survey
- Also obtain distances to 100,000 quasars, the most distant objects known
- Two stages to the process:
  - First scan with telescope equipped with complex CCD camera to obtain images in multiple colors of the sky
  - Then, for objects tagged as “interesting” based on multicolor images, follow up to obtain spectra (for redshifts) using plug plate with holes drilled for optical fibers





Images courtesy Sloan Digital Sky Survey project

11/1 23

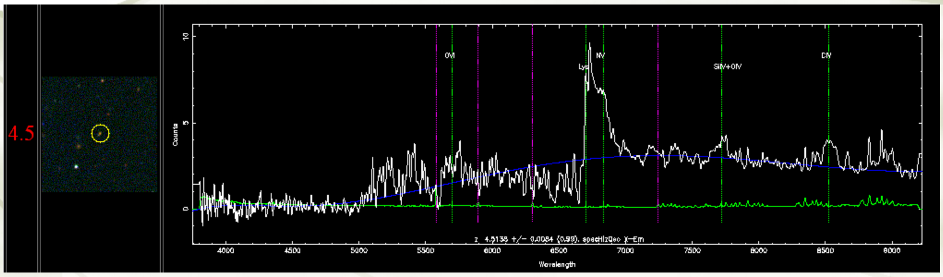
SDSS images

11/15/18 24

Images courtesy Sloan Digital Sky Survey project

SDSS: typical z = 4.5 quasar

Imaging and then spectroscopy



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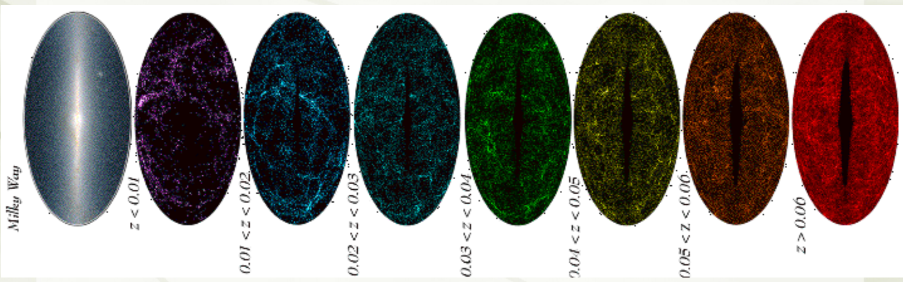
Surveys in other wavelengths: 2MASS

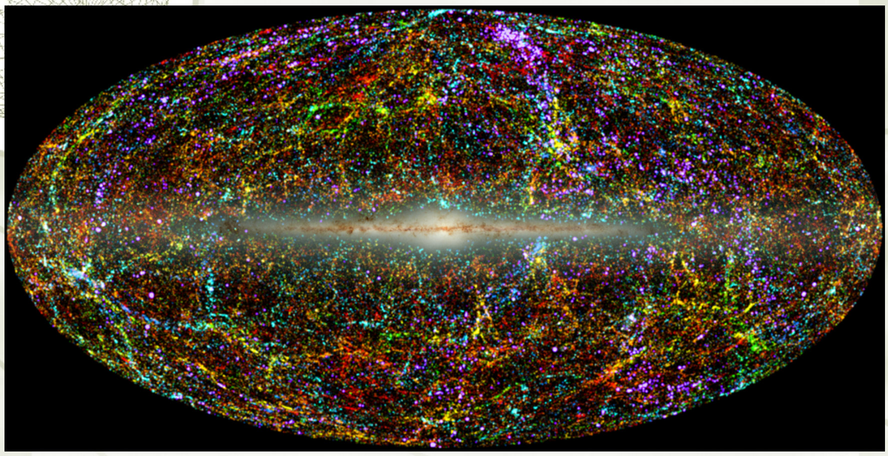
- Infrared surveys such as the **2** **M**icron **A**ll **S**ky **S**urvey (2MASS) are valuable as a complement to optical surveys
- Infrared is not biased toward actively star-forming galaxies
- Can cover more of the sky because IR passes through dust of Milky Way
- Spatial distribution of IR-selected galaxies appears consistent with distribution of optical-selected galaxies



11/15/18 26

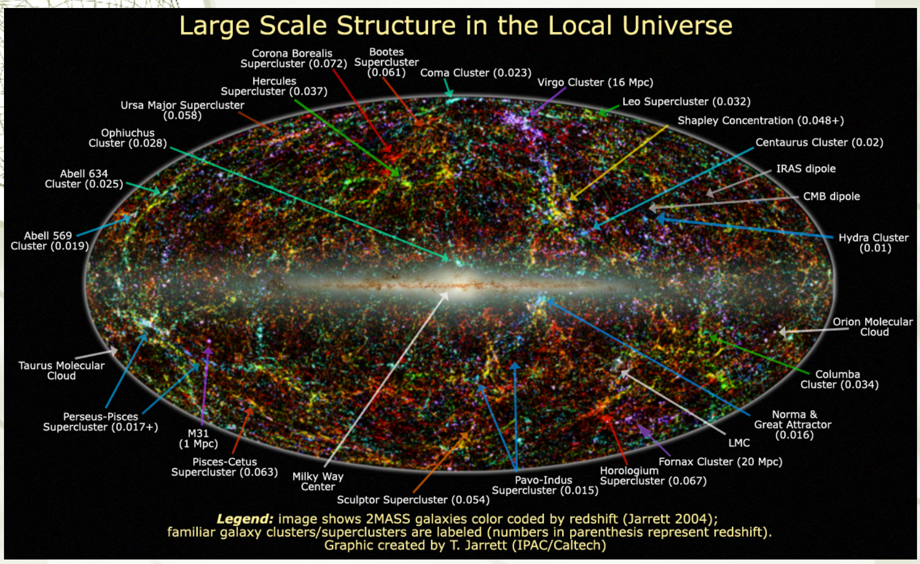
Image: T. Jarrett, Caltech

2MASS view of infrared galaxies



Blue: near; red: far

Credit: T. Jarrett, IPAC



Credit: T. Jarrett, IPAC

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

11/15/18 29

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)

11/15/18 30

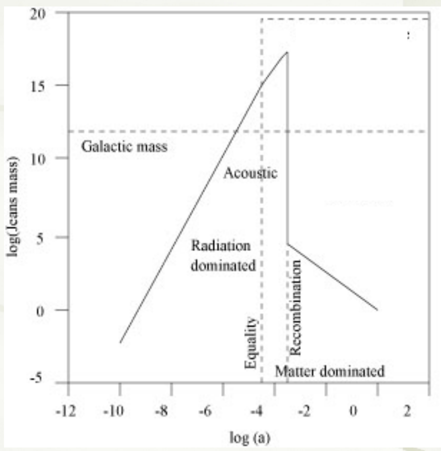
II : THE JEANS MASS AND THE ONSET OF COLLAPSE

- 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

Sir James Hopwood Jeans

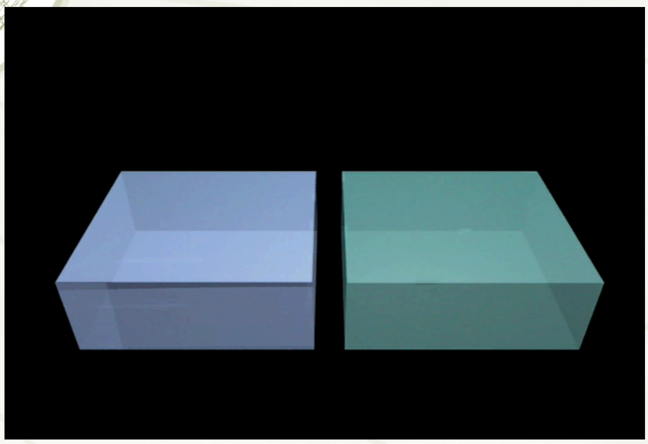
- In this diagram, cosmic scale factor is called "a" instead of *R*
- Any mass concentration that is above the solid line ($M>M_J$) would be able to grow *if not damped*
- At early times (before matter domination), growth of perturbations is damped by radiation ("photon damping")
- Jeans Mass drops sharply at recombination/decoupling
- So inhomogeneities that were previously stable to collapse ($M<M_J$), or damped by radiation, can start collapsing
- These are the seeds that turn into cosmic structure!



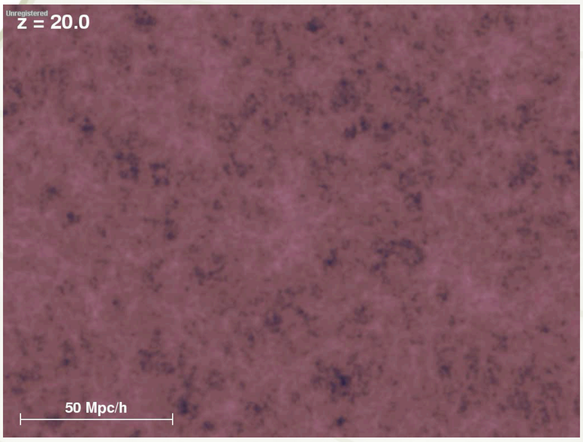
- 400,000yrs onwards…
  - After decoupling, inhomogeneities in the matter density start to grow… dense regions become denser.
  - This dense regions eventually collapse to give galaxy clusters, galaxies, stars, planets etc.
- Two general scenarios for subsequent evolution
  - **Top-down scenario:** Form big things first (galaxy superclusters), which fragment to make smaller things (clusters and galaxies)
  - **Bottom-up scenario:** Form small things first (galaxies), which collect together to make big things (clusters, superclusters)

- 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

Structure formation preview



Galaxy cluster formation



Millenium simulation, Springel et al.

Next time…

- Spectrum of initial perturbations and timing of structure formation
- Top down vs. bottom up
- Numerical simulations of structure formation
- Galaxy formation and interactions