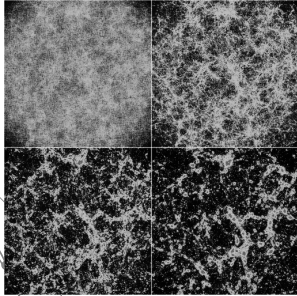


Cosmology AS7009, 2009 Lecture 10



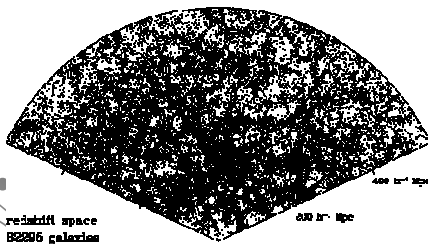
Outline

- Structure formation
 - Jeans length, Jeans mass
 - Structure formation with and without dark matter
 - Cold versus hot dark matter
 - Dissipation
 - The matter power spectrum
 - Baryon acoustic oscillations
- Reionization and high- z objects
 - When did reionization take place?
 - Caused by what?

Covers chapter 12 in Ryden + extra stuff

Walls, Filaments, Voids

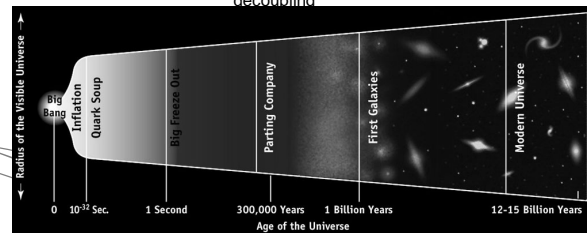
$r' < 17.56$, $d > 2'$, θ_{Alice}



- Voids ~ 70 Mpc

Cosmic epochs

Matter-radiation
decoupling



Likely seeds of galaxy formation: Quantum fluctuations expanded to macroscopic scales by inflation

Jeans length I

Which baryonic objects will collapse under the force of gravity?

- Two time scales:
 - Dynamical collapse time, t_{dyn}
 - Characteristic time scale for pressure buildup, t_{pre}
- $t_{\text{pre}} > t_{\text{dyn}} \rightarrow$ Object collapses
- $t_{\text{pre}} < t_{\text{dyn}} \rightarrow$ Hydrostatic equilibrium attained; collapse prevented

Jeans length II

Jeans length λ_J : Size of overdense regions for which $t_{\text{pre}} = t_{\text{dyn}} \rightarrow$

Regions of size $> \lambda_J$ will collapse

Regions of size $< \lambda_J$ will not

$$\lambda_J = \sqrt{\frac{\pi c_s^2}{G \bar{\epsilon}}}$$

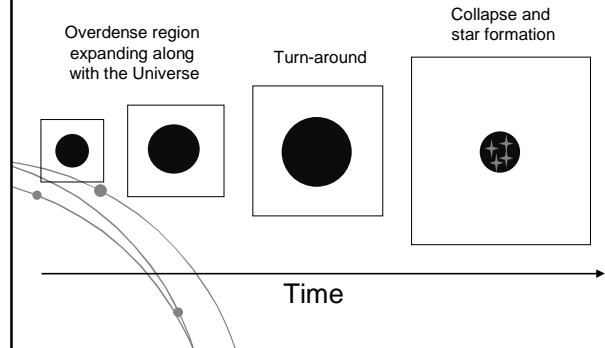
Sound speed in overdense region

Mean density of overdense region

Jeans mass

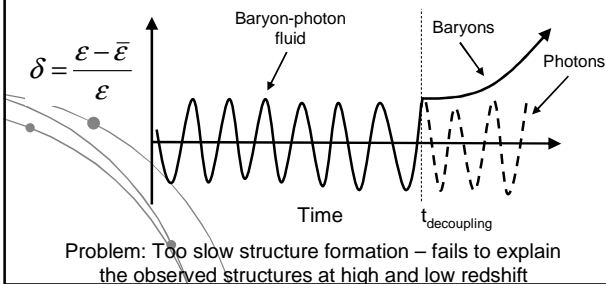
- Jeans mass M_J : Mass of baryons inside sphere of radius λ_J
 - $M > M_J \rightarrow$ Collapse
- Before decoupling: photon-baryon fluid with very high M_J ($\sim 10^{19} M_{\text{solar}}$)
- After decoupling: M_J drops to ($\sim 10^4$ - $10^5 M_{\text{solar}}$) in baryon fluid \rightarrow Baryons lose pressure support

Collapse in an expanding Universe



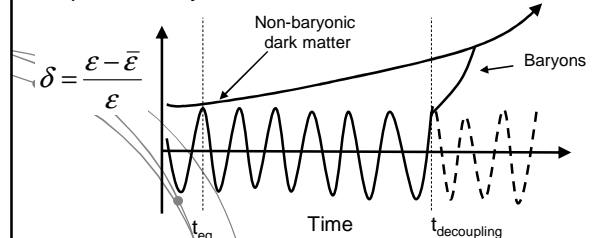
Structure Formation *Without* Non-Baryonic Dark Matter

- Density perturbations that will eventually form galaxies and galaxy clusters cannot start to grow until after decoupling ($t \approx 0.35$ Myr)



Structure Formation *With* Non-Baryonic Dark Matter

- Density perturbations will start to grow at the epoch of matter-radiation equality ($t \approx 0.047$ Myr)
- Baryons will fall into the potential wells already produced by the dark matter

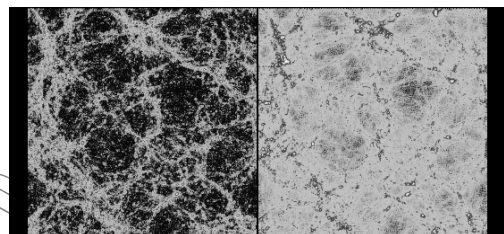


Hot & cold dark matter I

- Hot dark matter (HDM): Relativistic velocities at decoupling
- Cold dark matter (CDM): Non-relativistic velocities at decoupling
- Warm dark matter (WDM): Intermediate velocities at decoupling

Velocities of the dark matter particles regulate how massive the first collapsing objects are

Hot & cold dark matter II



Cold dark matter

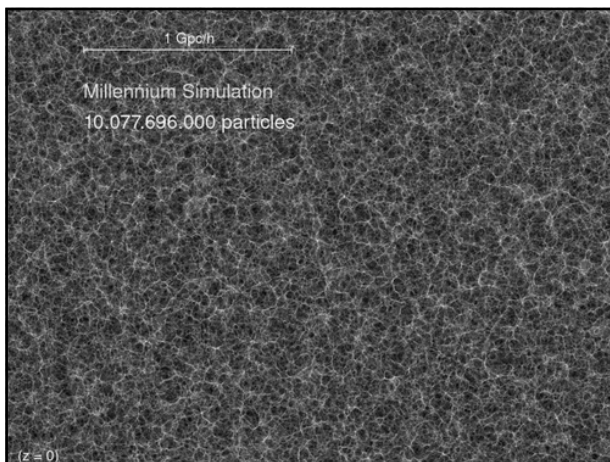
Cold + hot dark matter

HDM → Top-down structure formation

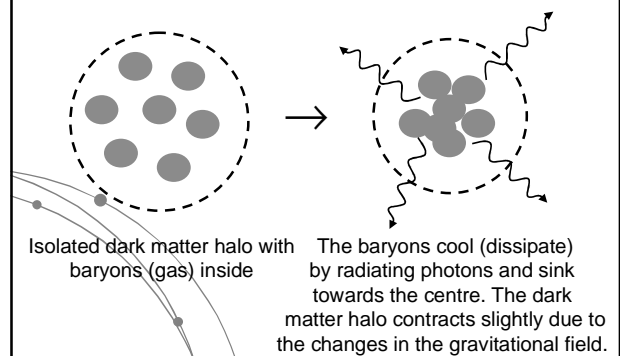
- Free-streaming wipes prevents growth of density perturbations on small scales
- Top-down: Big structures form first, small ones later
- Overdensities of galaxy cluster mass collapse before the galaxies inside are formed
- Massive galaxies form before dwarf galaxies

CDM → Bottom-up structure formation

- Bottom-up = Small structures form first, big ones later
- Potential wells in non-baryonic CDM form before decoupling, into which baryons may fall after decoupling
- Small objects form first, galaxy clusters last (some are still collapsing)



Dissipation inside dark matter halos



The Matter Power Spectrum

Most inflation models predict an adiabatic, power-law spectrum of Gaussian perturbations

Amplitude Wave number

$$P \propto k^n$$

Corresponding potential fluctuations:

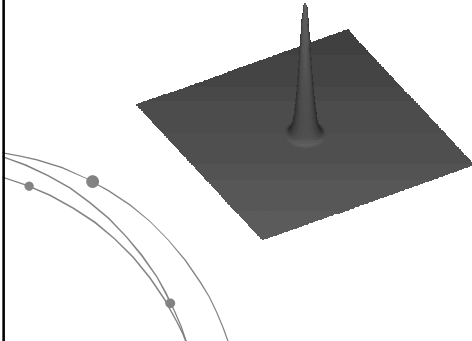
$$\delta\Phi \propto M^{(1-n)/6}$$

$n = 1 \Rightarrow$ Harrison - Zeldovich spectrum
(scale - free)

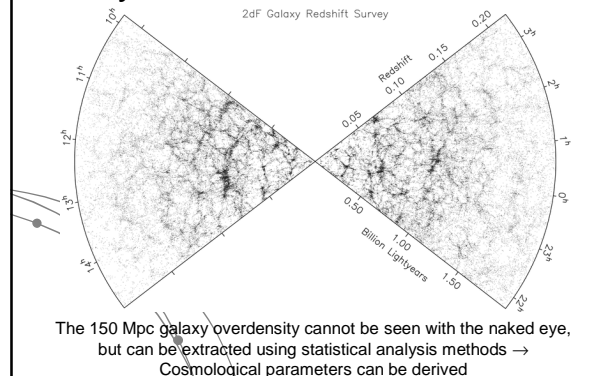
Baryon Acoustic Oscillations

- Overdensities (in baryons and dark matter), eject spherical sound waves
- Sound speed $\sim 0.5 c$
- Photons decouple \rightarrow Sound speed drops
- Wave stalls at $R \sim 150$ Mpc
- This overdensity of gas acts as seed for galaxy formation and can be detected in large galaxy surveys
- The 150 Mpc radius serves as a standard ruler

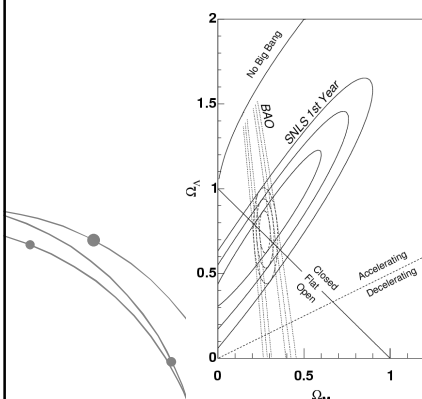
Baryon Acoustic Oscillations II



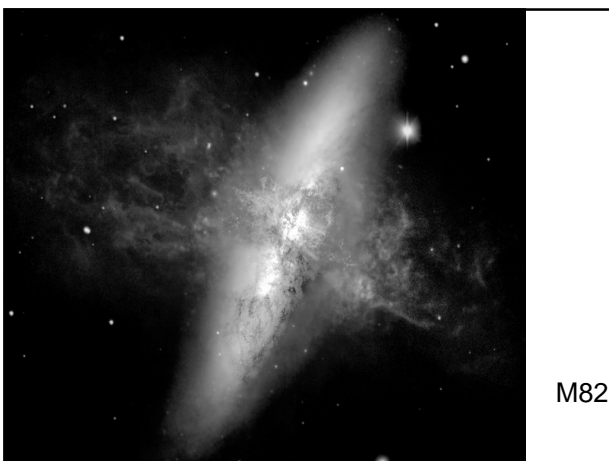
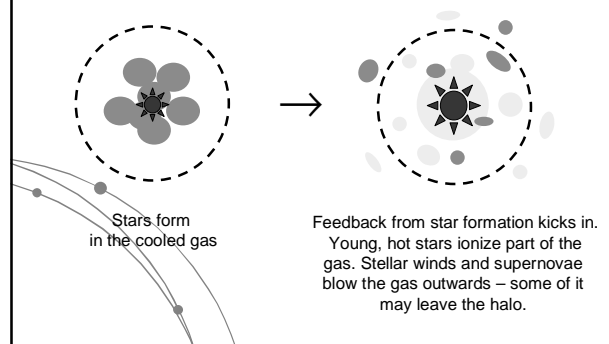
Baryon Acoustic Oscillations III



Baryon Acoustic Oscillations IV



Star Formation and Feedback

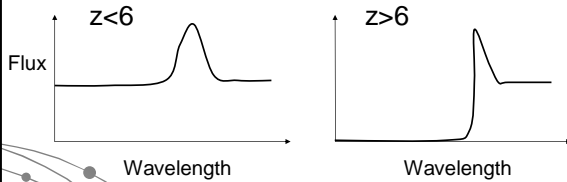


Reionization

- The Universe cooled and becomes neutral at the epoch of recombination
- But most of the gas in the local Universe is ionized → Somewhere along the way the Universe must have experienced reionization
- Conjecture: Reionization is caused by the formation of astronomical objects (sources of Lyman continuum photons)
- The first astronomical light sources are expected to light up at around $z = 30-15$ (100–300 Myr after the Big Bang)

When did reionization take place?

Quasar Ly α spectra (The Gunn—Peterson test)

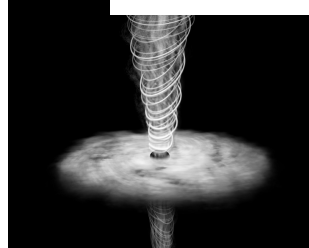
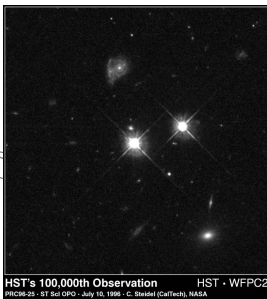


- Gunn-Peterson test \rightarrow Reionization at $z \approx 6$
- But WMAP \rightarrow Reionization at $z \approx 11$
- What is going on?!?
- Prolonged reionization ($z=20-6$)?
- Reionization happened twice?

What caused reionization?

- Quasars? \leftarrow
- Starburst galaxies? \leftarrow
- Population III stars? \leftarrow
- Evaporating primordial black holes?
- Decaying dark matter?

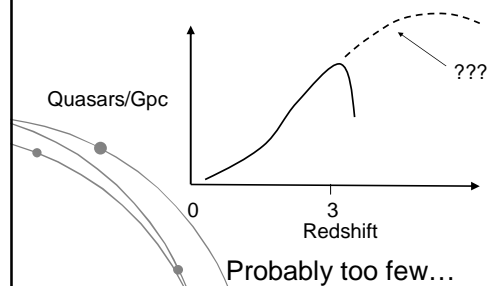
Quasars



HST's 100,000th Observation
PRC98-23 - ST Sci OPO - July 15, 1998 - C. Beaulieu (CalTech), NASA

HST - WFPC2

Quasars as Sources of Lyman Continuum Radiation at High Redshift

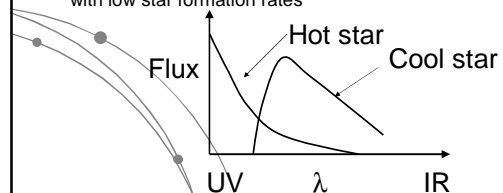


Starburst Galaxies



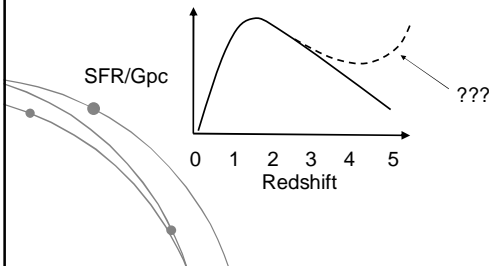
Why Do Starburst Galaxies Produce Lots of Lyman Continuum Photons?

- Stars are born in the mass range $\sim 0.08-120$ solar masses
- The highest-mass stars have the shortest lifetimes (a few Myr)
- \rightarrow Large numbers of high-mass stars are only found in galaxies that actively form stars
- High-mass stars are typically hotter than low-mass stars
- Hot stars emit more UV radiation (stars are almost black bodies)
- \rightarrow Starbursts emit more Lyman continuum radiation than galaxies with low star formation rates



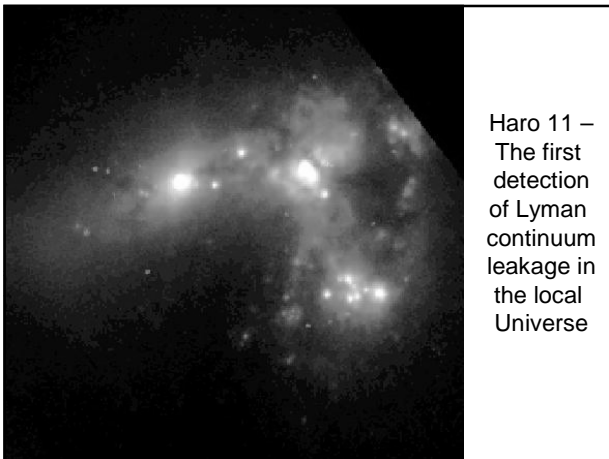
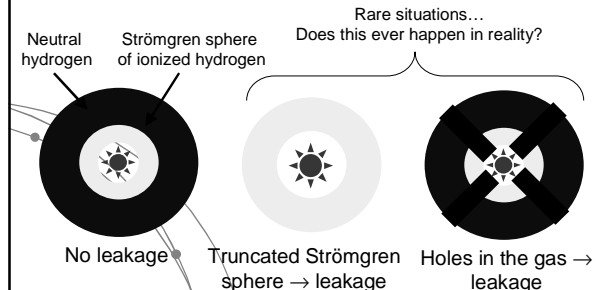
Starburst galaxies II

Cosmic SFR (in galaxies) probably too low...



Starburst galaxies III

Additional caveat: Starburst galaxies must have significant Lyman continuum escape fractions to contribute to reionization



Haro 11 –
The first detection
of Lyman
continuum
leakage in
the local
Universe

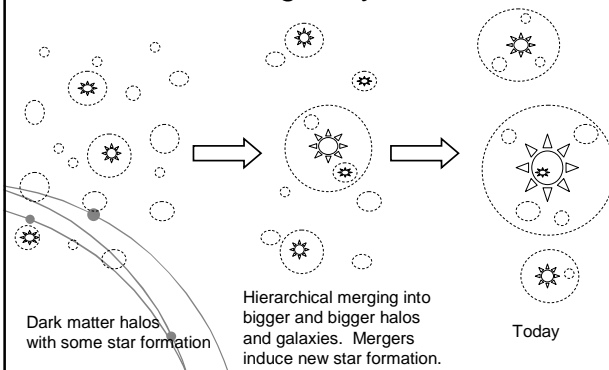
Population III stars?

- Population I stars (young, metal-rich, disk)
- Population II stars (old, metal-poor, stellar halo)
- Population III stars (the oldest stars, metal-free)

Population III stars may have been very Massive (> 100 — 200 solar masses)

→ Short-lived, but produce a lot of Lyman continuum emission during their lifetimes

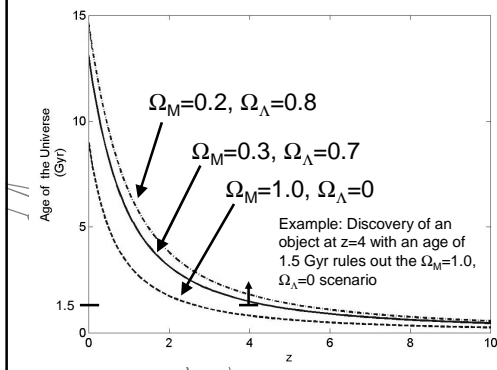
Cold Dark Matter → Hierarchical galaxy formation



The Hubble Ultra Deep Field



High-Redshift Objects as Probes of Cosmology: Ages



Spectroscopic Age Determinations of Galaxies

Stars typically become redder when they grow older →
The shape of the spectrum of a galaxy (containing billions of stars) is indicative of the age

