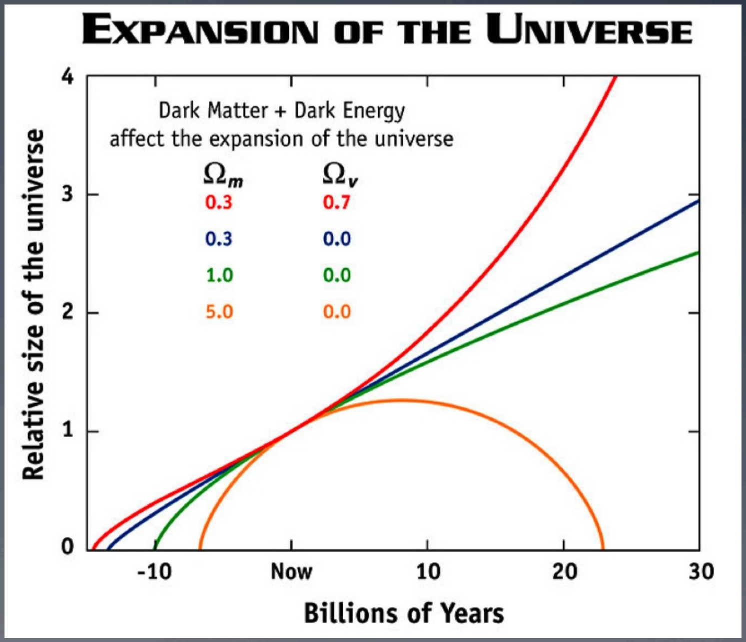
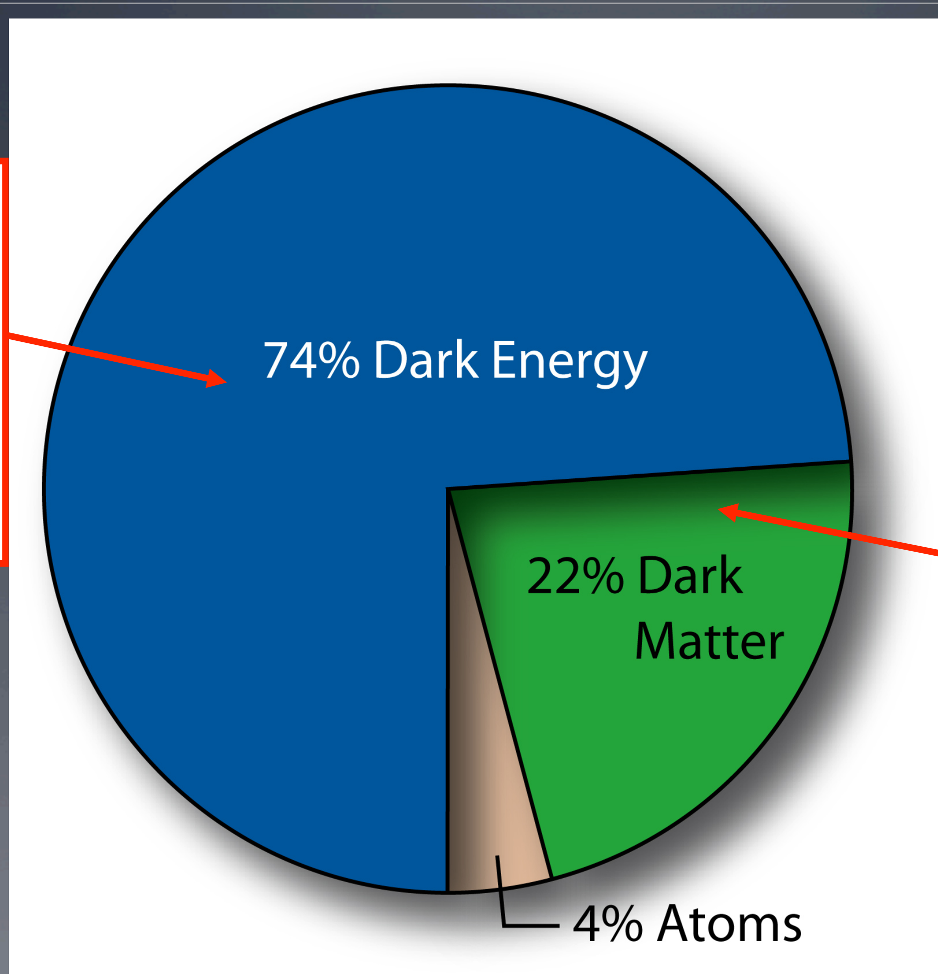
Our cosmological model

- The universe is:
  - Spatially flat
  - Homogeneous
  - Isotropic
  - Expanding at an accelerating rate (2011 Nobel prize)
- We have a basic picture of the contents of the universe
- We have a basic timeline for the history of the universe



The contents of the universe

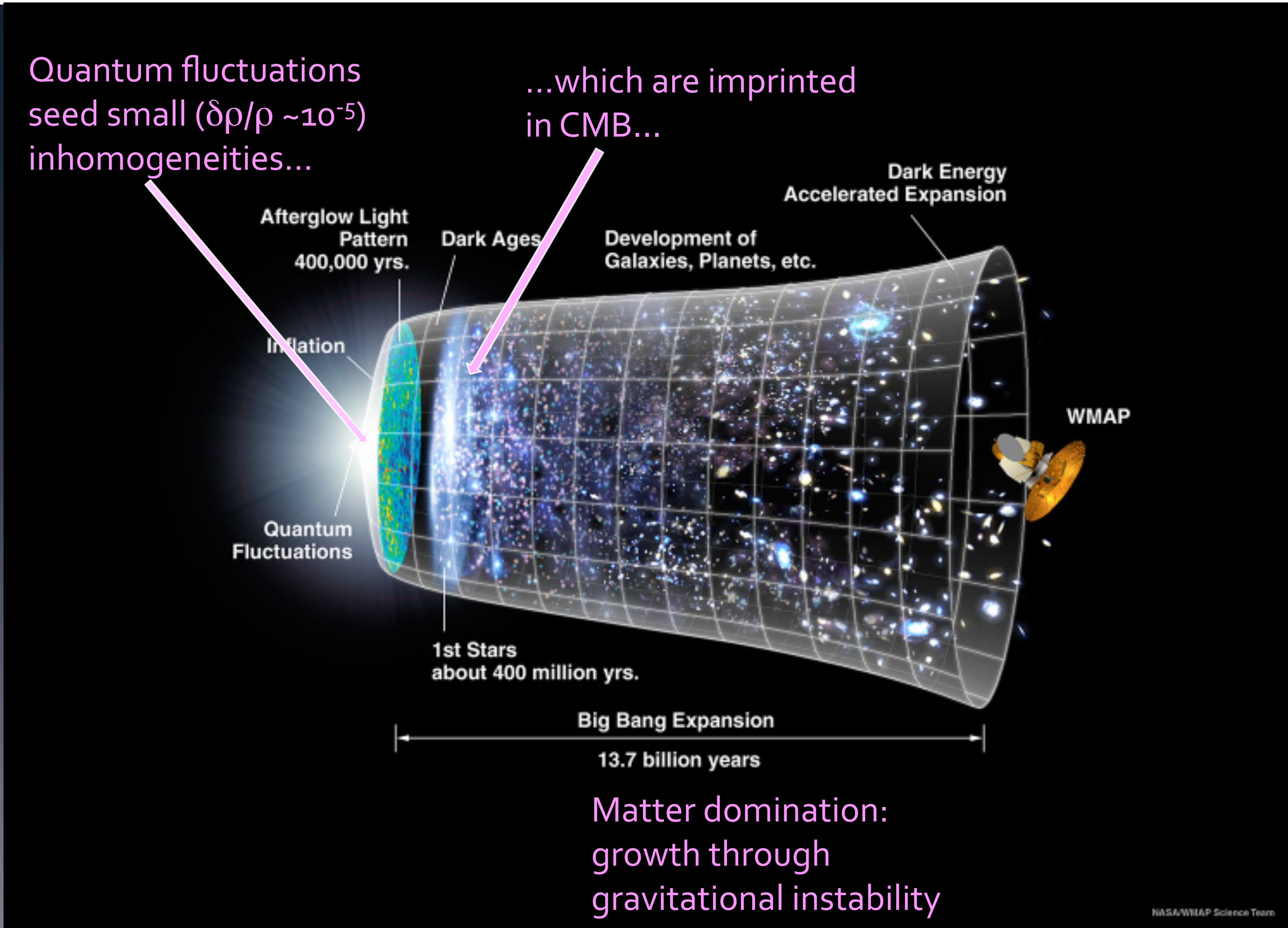
We don’t know what this is! (we only know its effects: it causes accelerated expansion)



We don’t know what this is, either! (but it’s cold = non-relativistic)

Name for model: ΛCDM

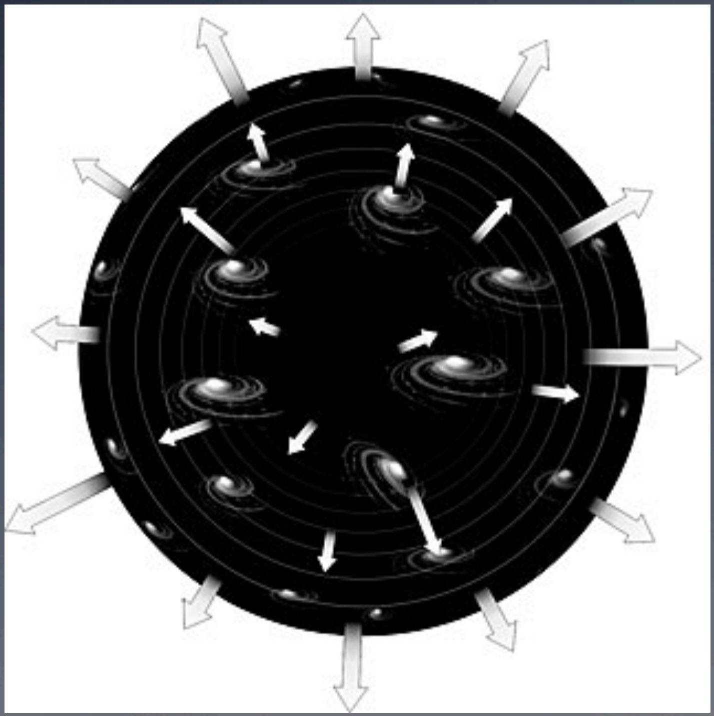
Picture courtesy of NASA/WMAP science team



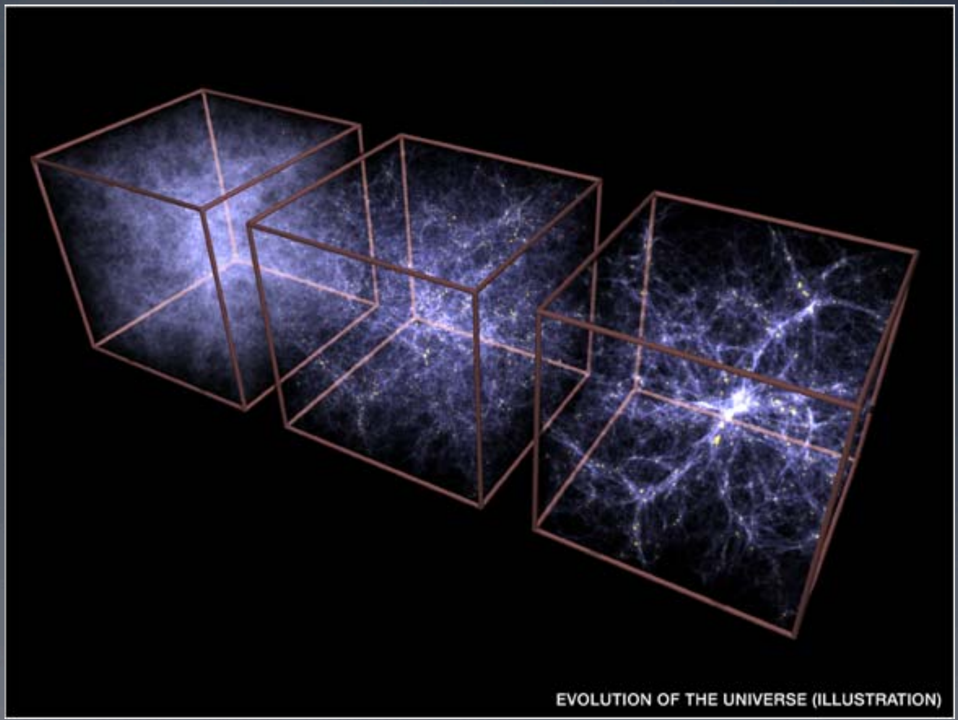
Picture courtesy of NASA/WMAP science team

Two types of cosmological measurements

Geometric



Growth of structure



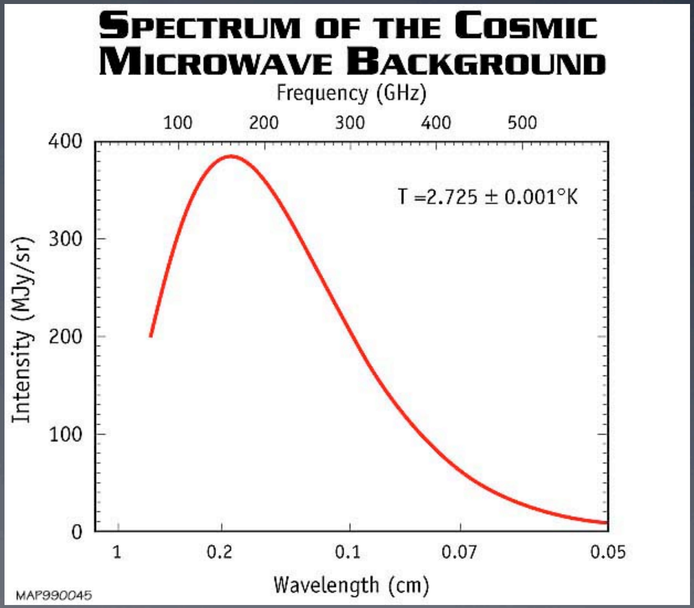
Space-time $$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$ Matter/energy

The goals of this class

- To go over the major observational methods that have led us to our current cosmological model.
  - Understand how the observations are made.
  - Understand what they teach us about cosmology.
  - Understand prospects for learning more from these methods in the future, and the major difficulties in these methods.

Cosmic Microwave Background: a view into the early universe

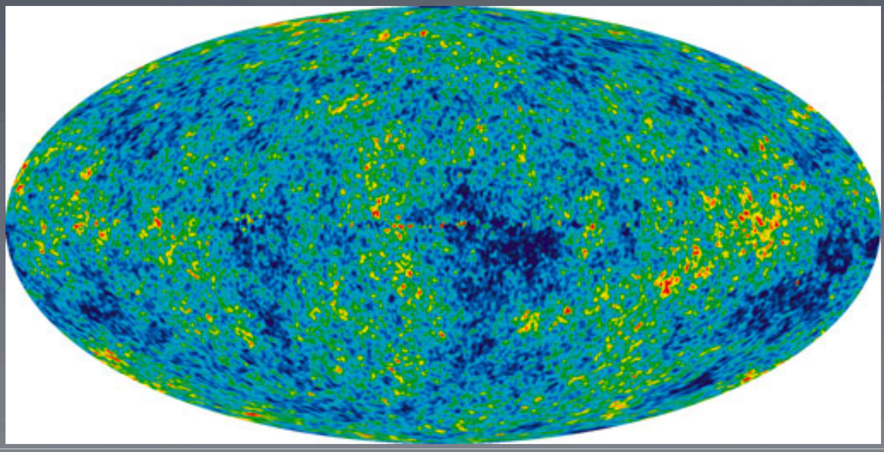
- The early universe was hot! No atoms, just electrons and nuclei.
- Photons wandered around scattering off of electrons, giving a blackbody spectrum
- Once the universe cooled enough, protons + electrons could combine to form neutral hydrogen → no more scattering!
- We see the "surface of last scattering"



Observations

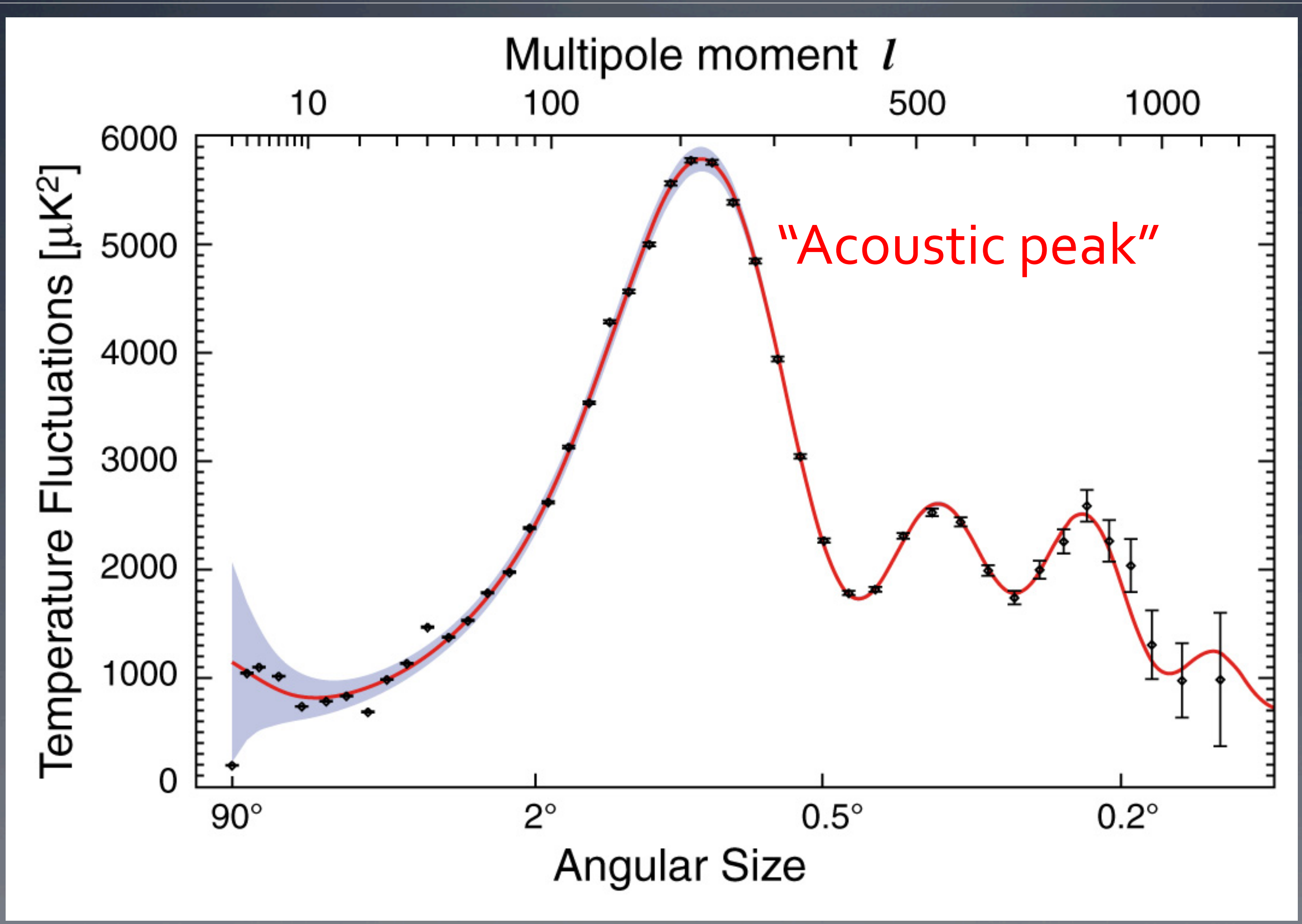
- The original observation by Penzias & Wilson: low level noise in radio receiver – is it bird droppings?
- CMB T=2.725K is uniform to better than 1 part in 1000!
- It took decades to precisely measure the low-level (10^{-5}) temperature fluctuations.

(signal from our galaxy was subtracted)



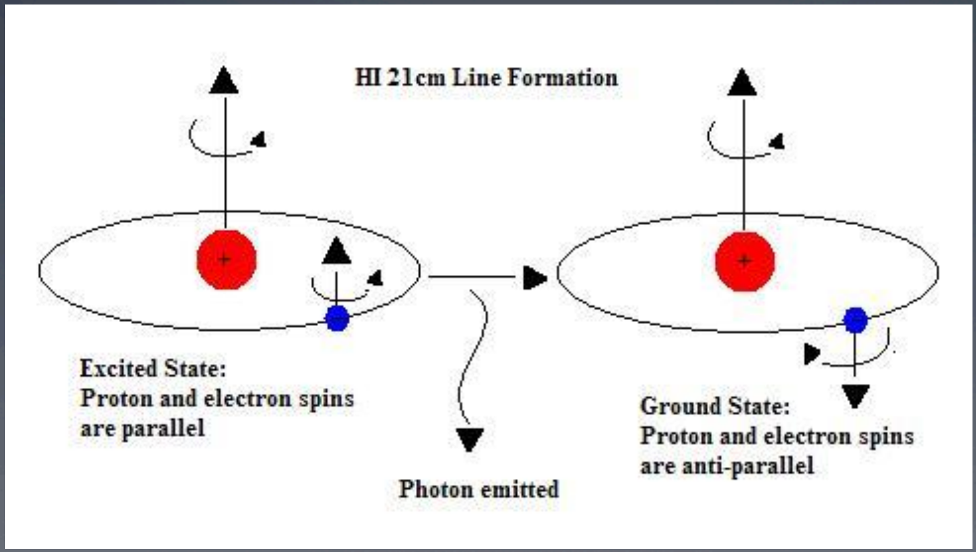
Dynamic range in T: ±200 μK

Structure in the fluctuations



Next: the Dark Ages

- After recombination and before the first galaxies (and reionization), all is dark… or is it?



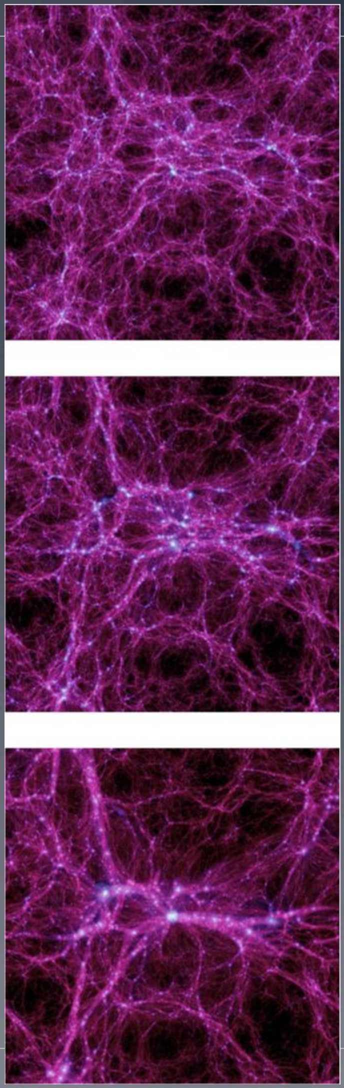
- Thanks to the hyperfine structure of the hydrogen atom, there is emission at radio wavelengths!

What can we learn from this?

- Matter distribution in the Dark Ages; structure growth
- The nature of reionization (which makes holes in the 21cm background)
- Use for test of galaxy dynamics
- Of all the probes we will discuss, this one is possibly the most challenging and is still in its infancy.

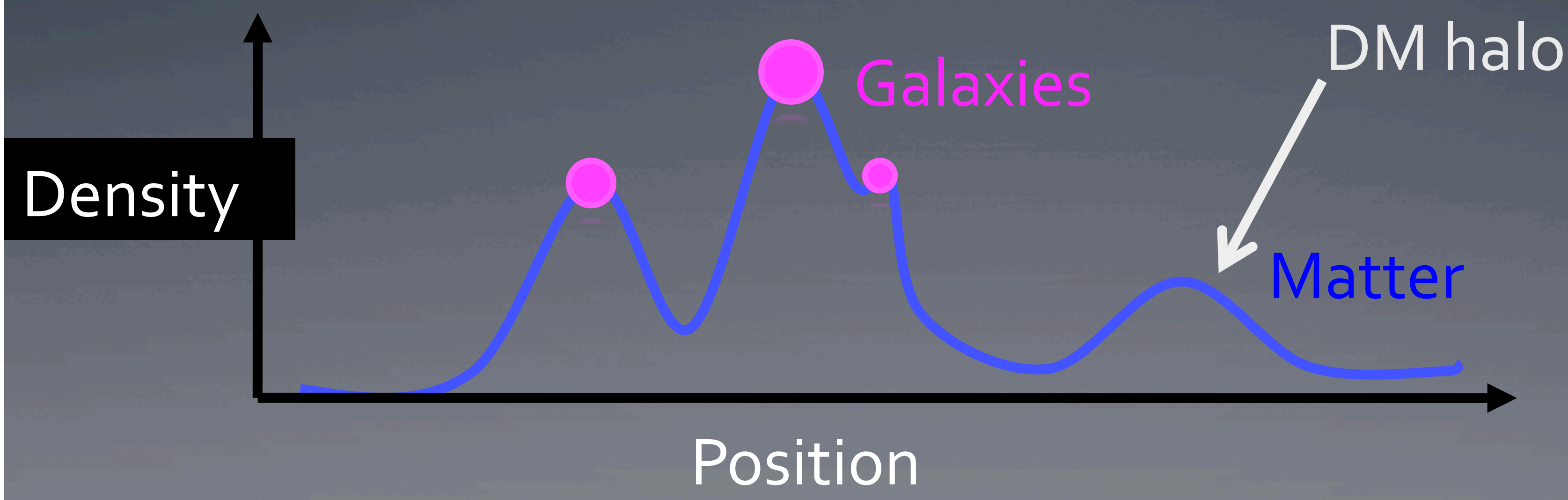
Moving from tiny perturbations to what we see today

- Beginning from tiny perturbations seen in CMB, how do we get to today?
- We can imagine that once matter is dominant, gravity can make clumps of dark matter grow (well-established, analytically and from simulations).
- But what about galaxies?



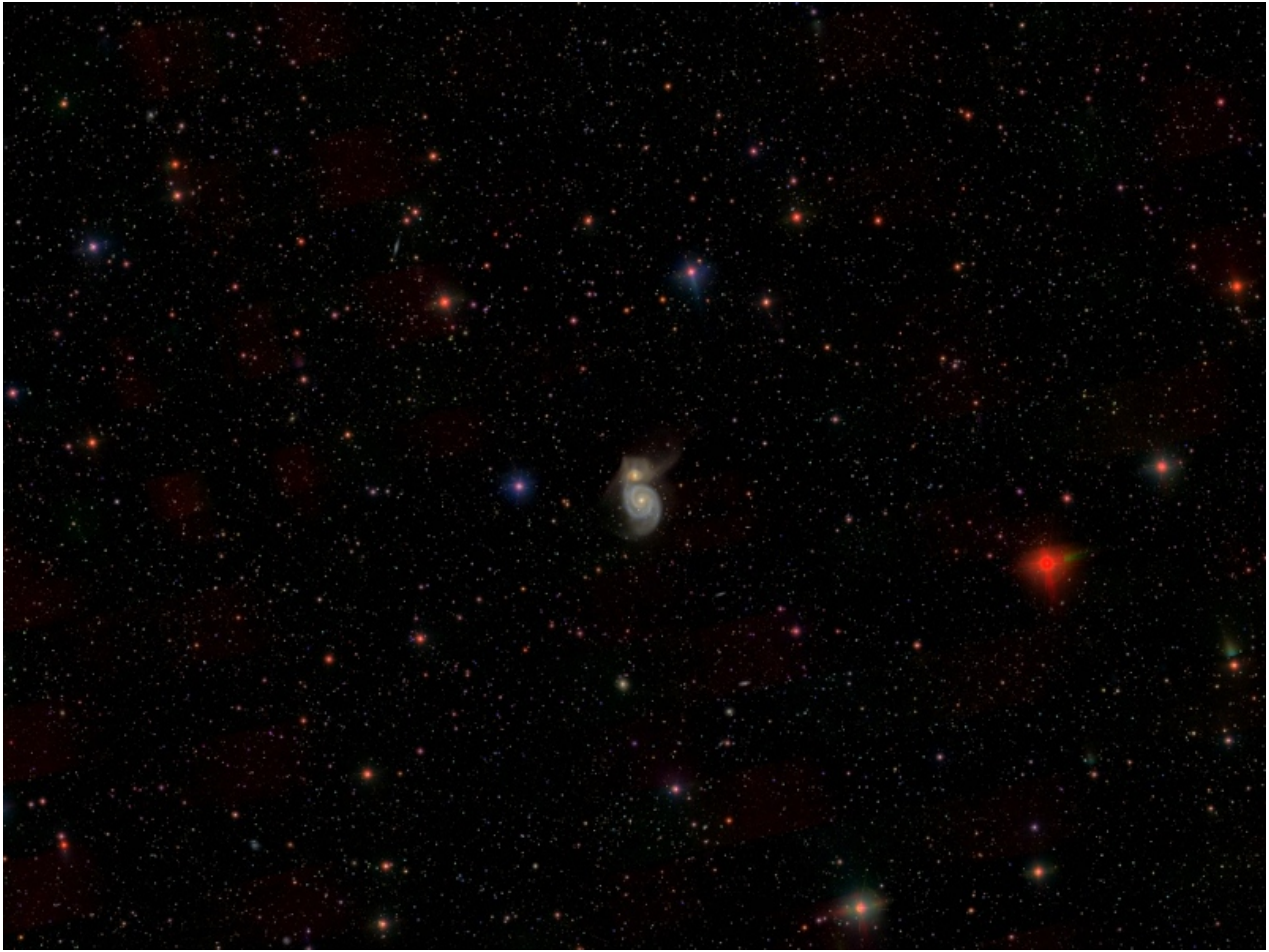
Galaxy formation theory

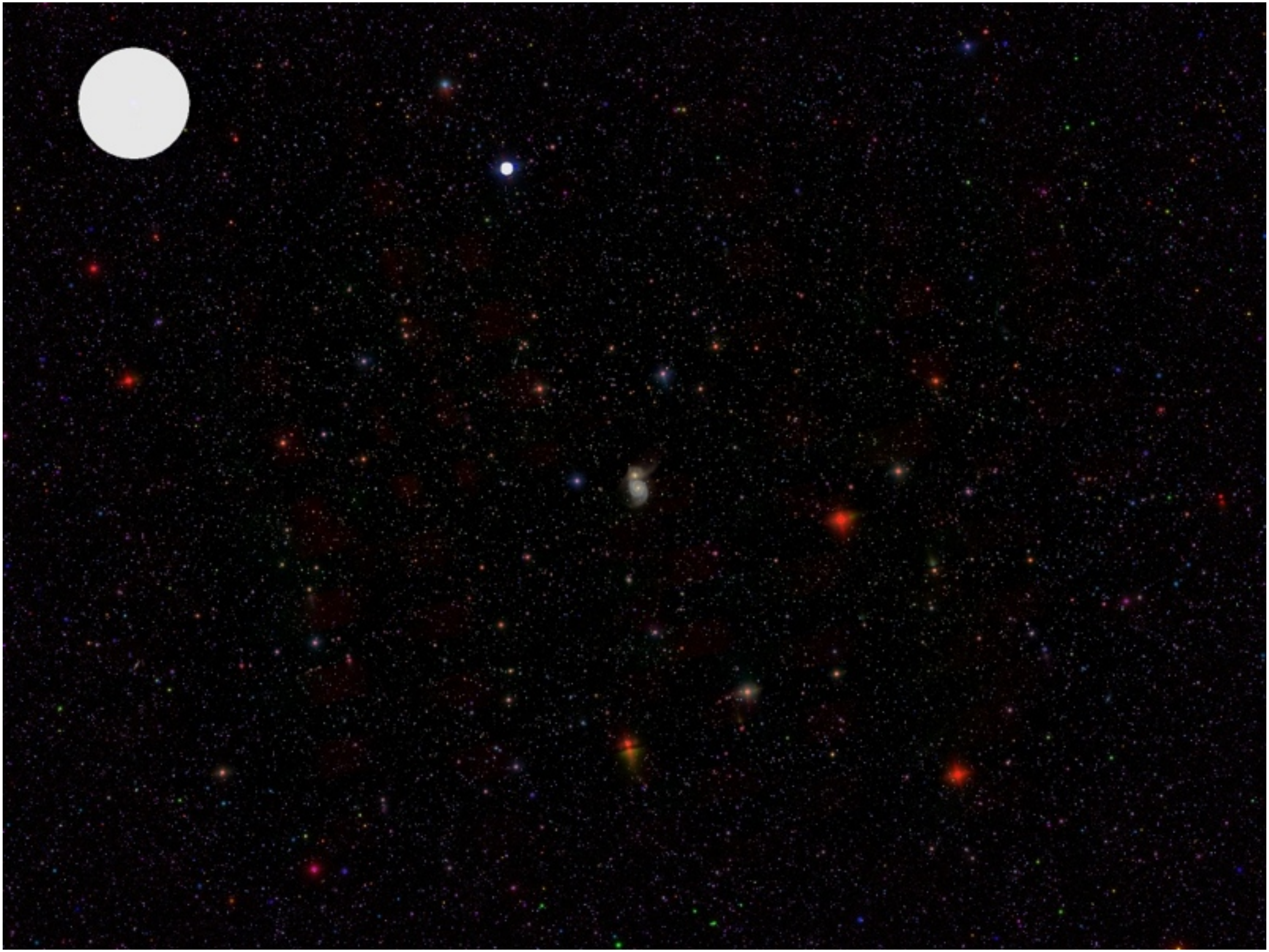
- Dark matter clumps grew until they became collapsed structures called "halos"
- The baryons cooled, condensed at the center
- Stars formed

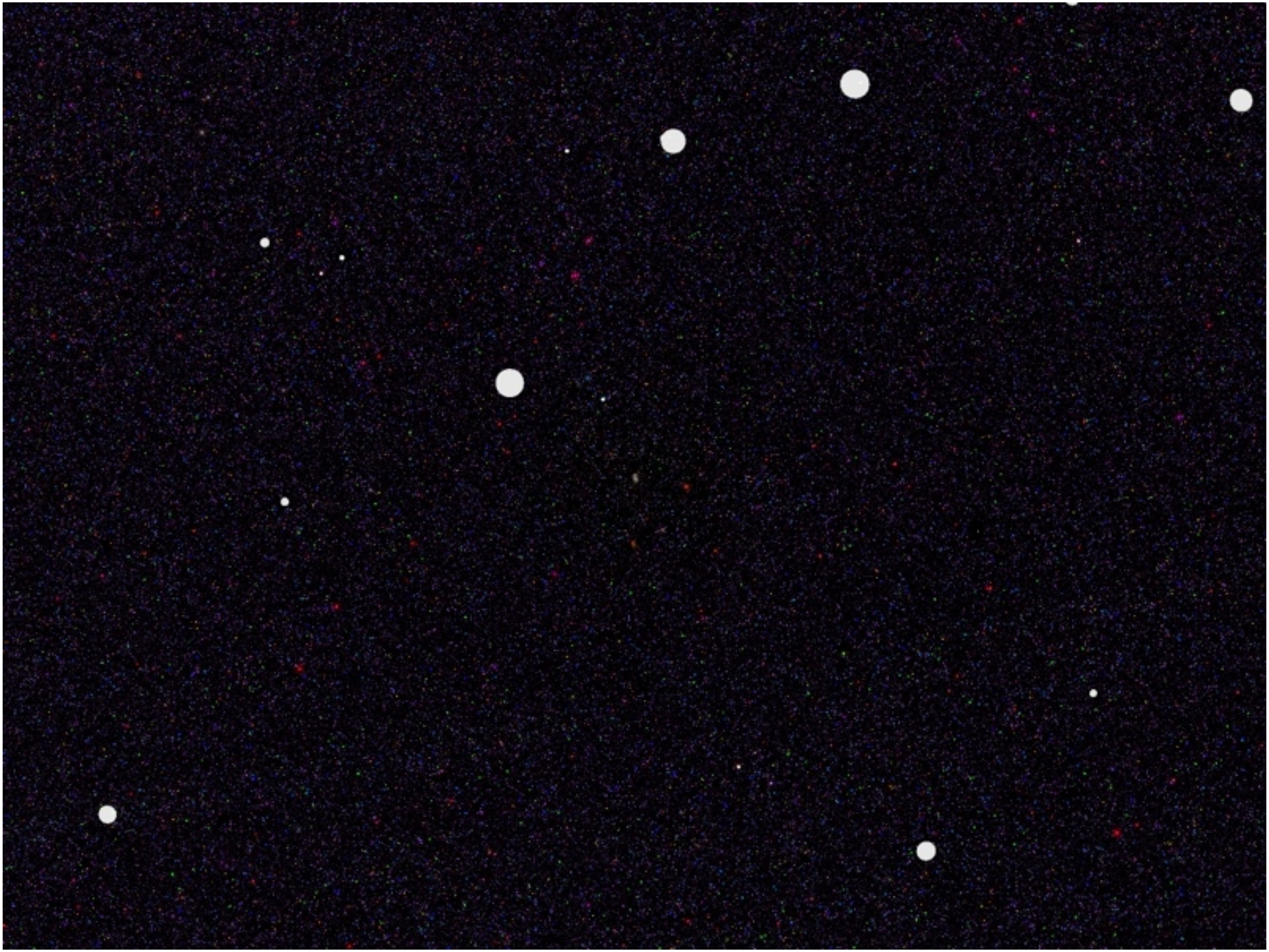


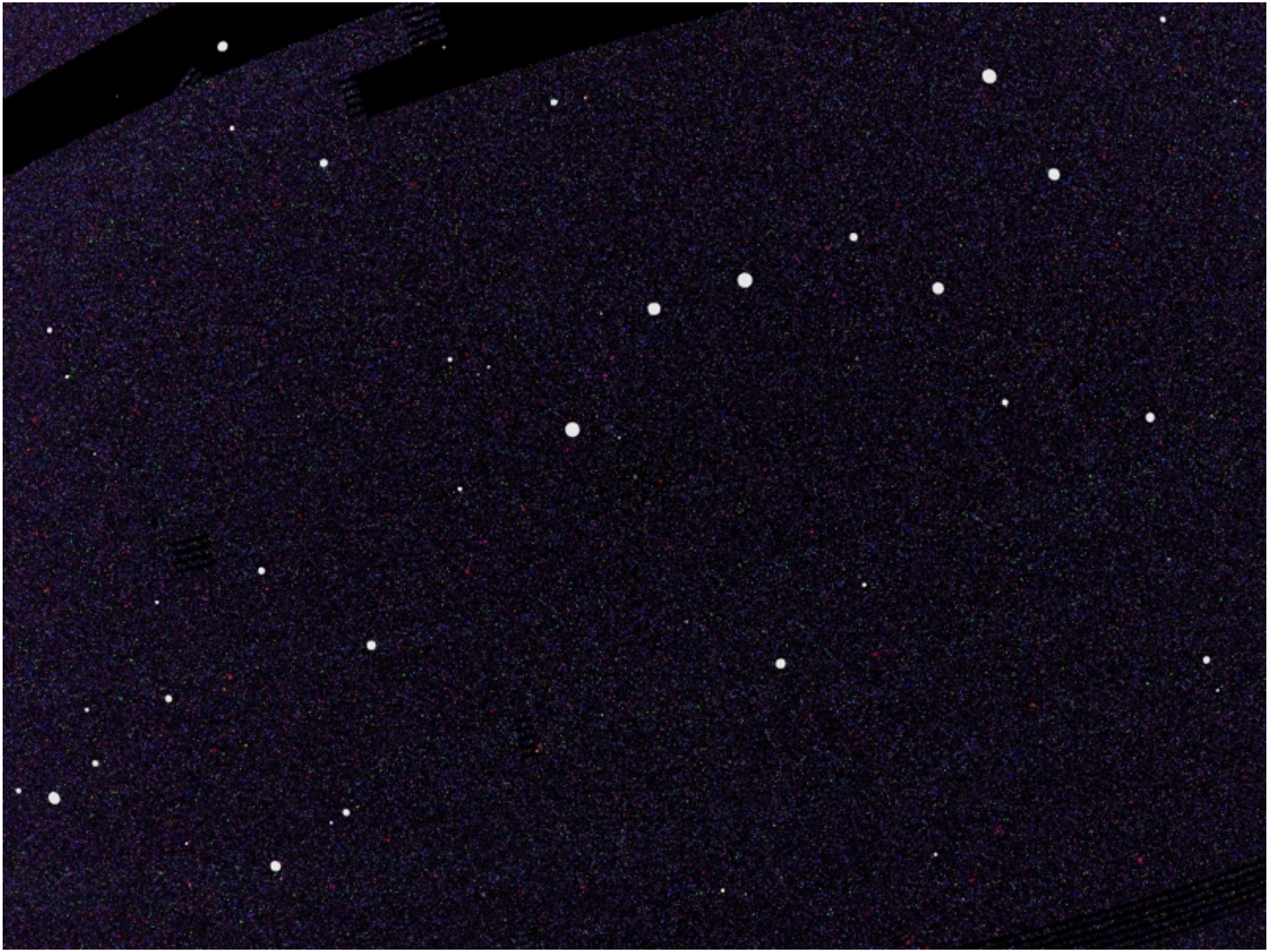
How to observe the growth of matter and/or galaxy perturbations?

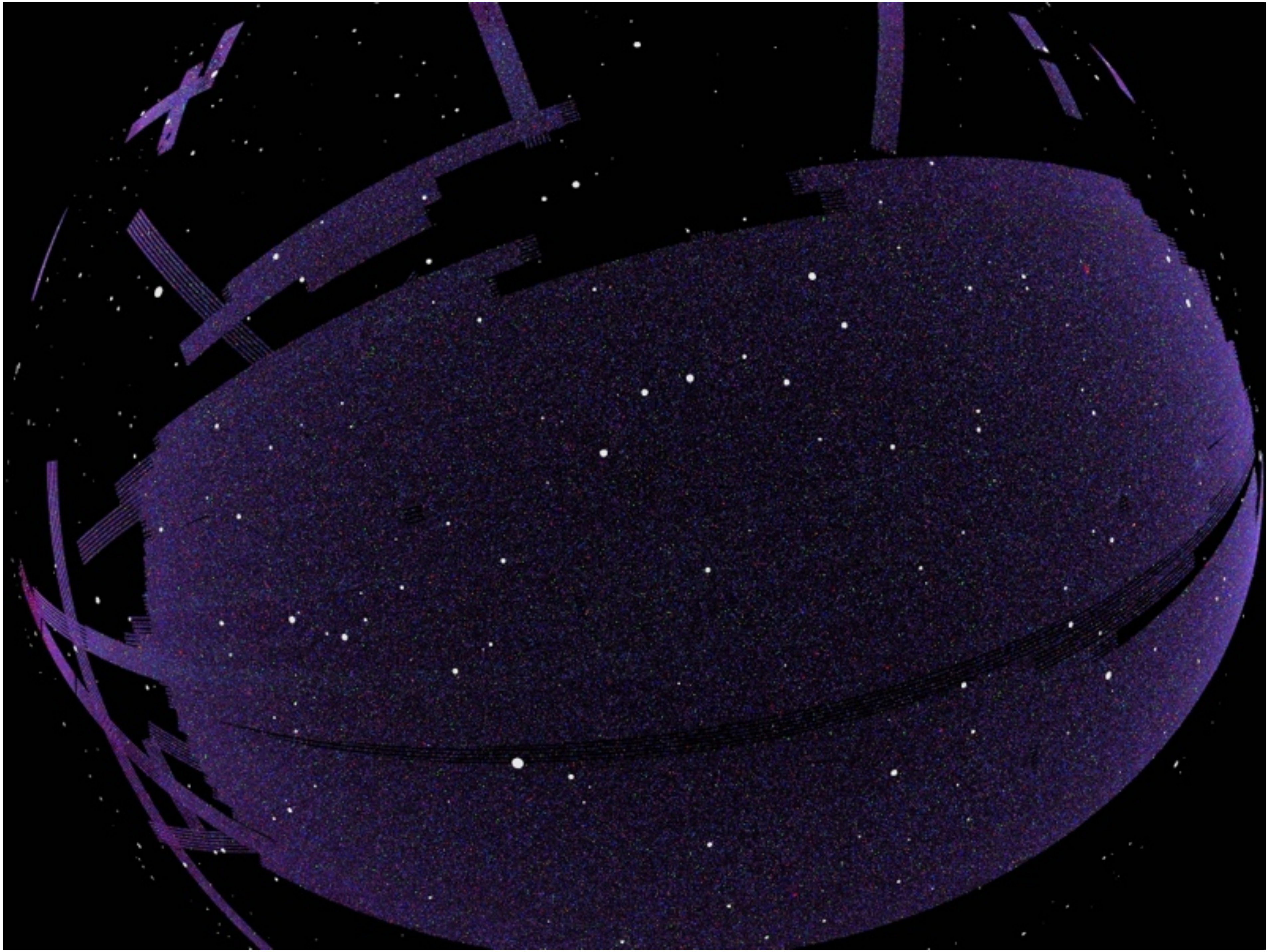
- Use a large survey of the sky to see a big cosmological volume
- What type of data?
  - Imaging: look at all light within some limited range of wavelengths
  - Spectroscopy: measure light as a function of wavelength, to precisely measure galaxy redshifts and other spectral features
- Let's get a sense of the scope of current / future surveys…

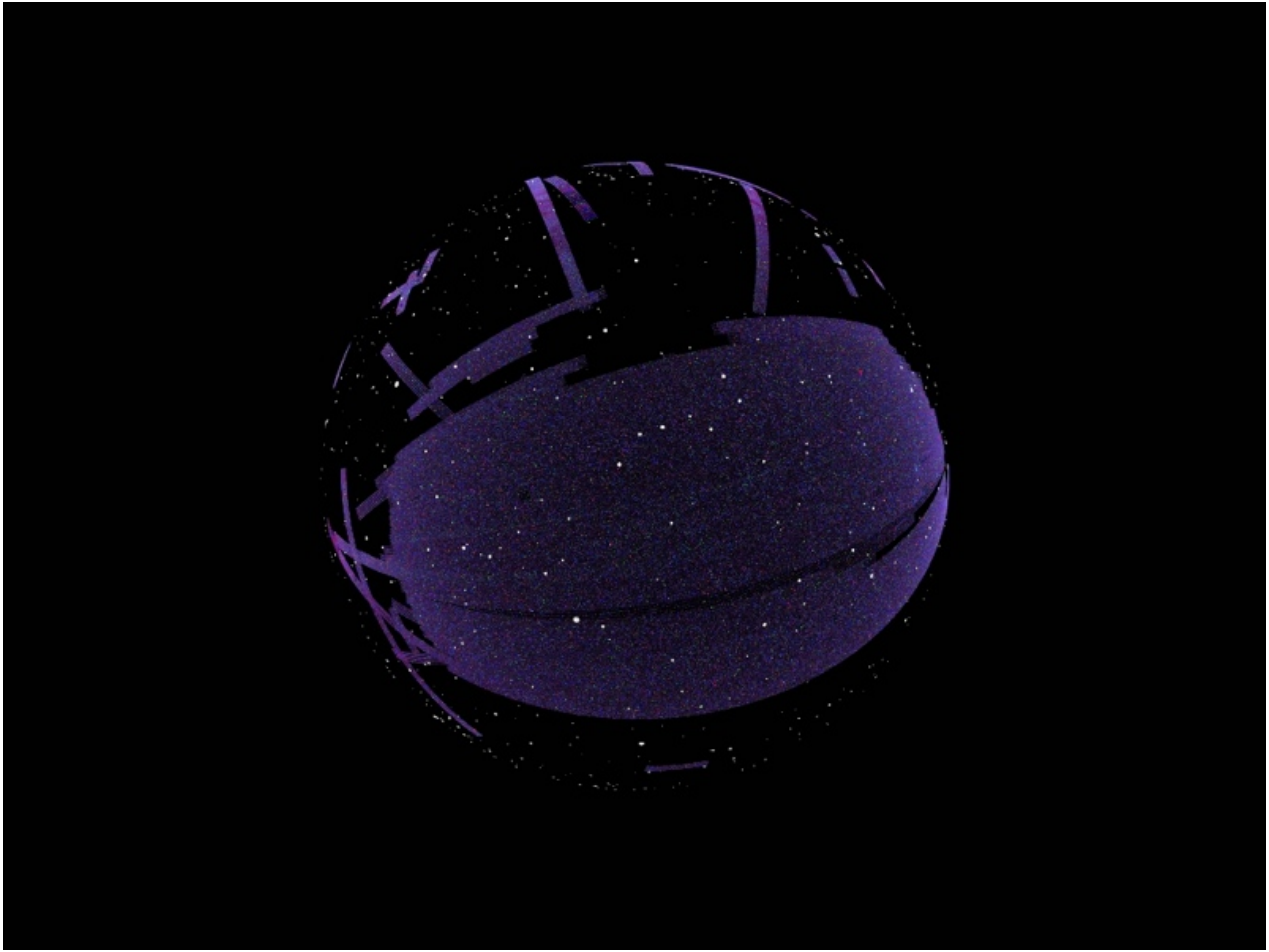












Data: Sloan Digital Sky Survey and the Bright Star Catalog

Visualization: David W. Hogg (NYU) with help from Blanton, Finkbeiner, Padmanabhan, Schlegel, Wherry

Matter clustering definitions

Given the matter density fluctuations

$$\delta_m(\vec{x}) = \frac{\rho_m(\vec{x}) - \bar{\rho}}{\bar{\rho}}$$

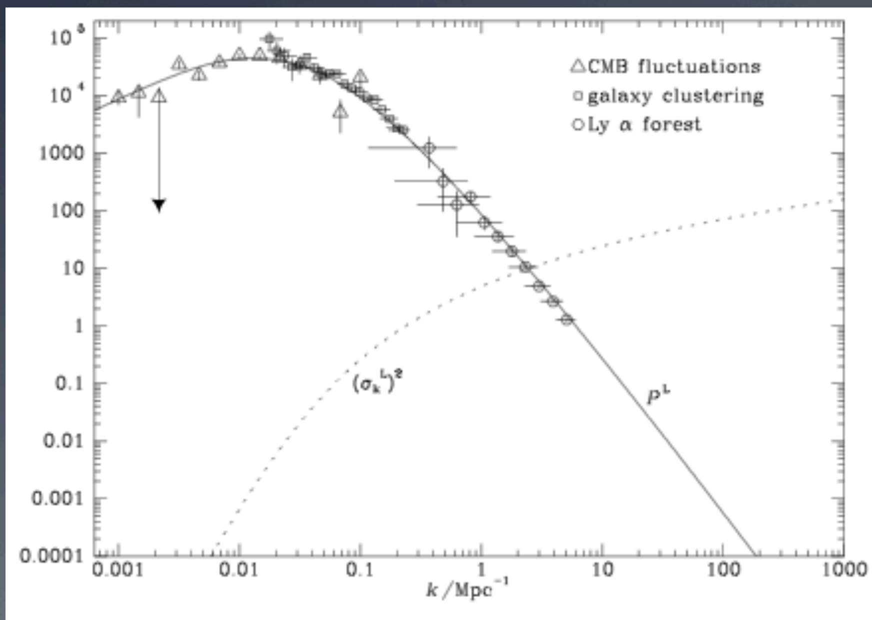
we can define their power spectrum:

$$\langle \tilde{\delta}_m(\vec{k}) \tilde{\delta}_m(\vec{k'}) \rangle = (2\pi)^3 P_{mm}(k) \delta^3(\vec{k} - \vec{k}')$$

or their correlation function:

$$\langle \delta_m(\vec{x}) \delta_m(\vec{x} + \vec{r}) \rangle = \xi_{mm}(\vec{r})$$

Power spectrum of inhomogeneities



Picture from Binney & Tremaine

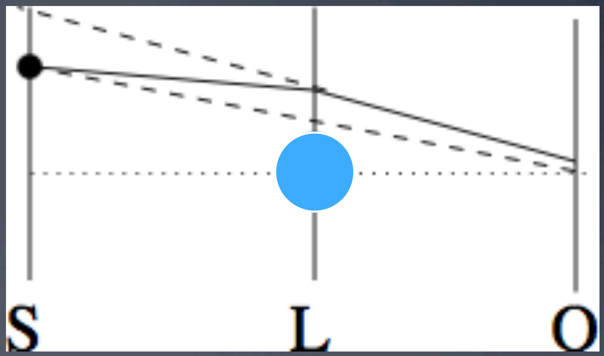
- Nearly scale-invariant spectrum on large scales
- Suppression on small scales (if entered the horizon in radiation-dominated era)
- Shape $\Rightarrow$ contents of universe, details of inflationary era (currently poorly constrained)

Be careful: galaxies vs. matter

- Gravitational theory predicts statistics of *matter* field
- Observations that include galaxies have an additional level of complication and a lot more physics!
- Galaxy bias…

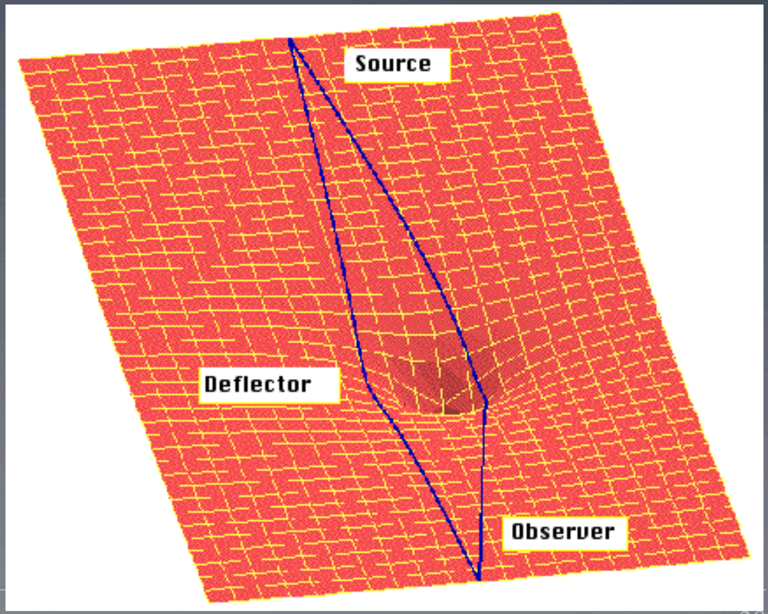
One way to measure mass

- Gravitational lensing:



Sensitive to all matter along line of sight, including dark matter!

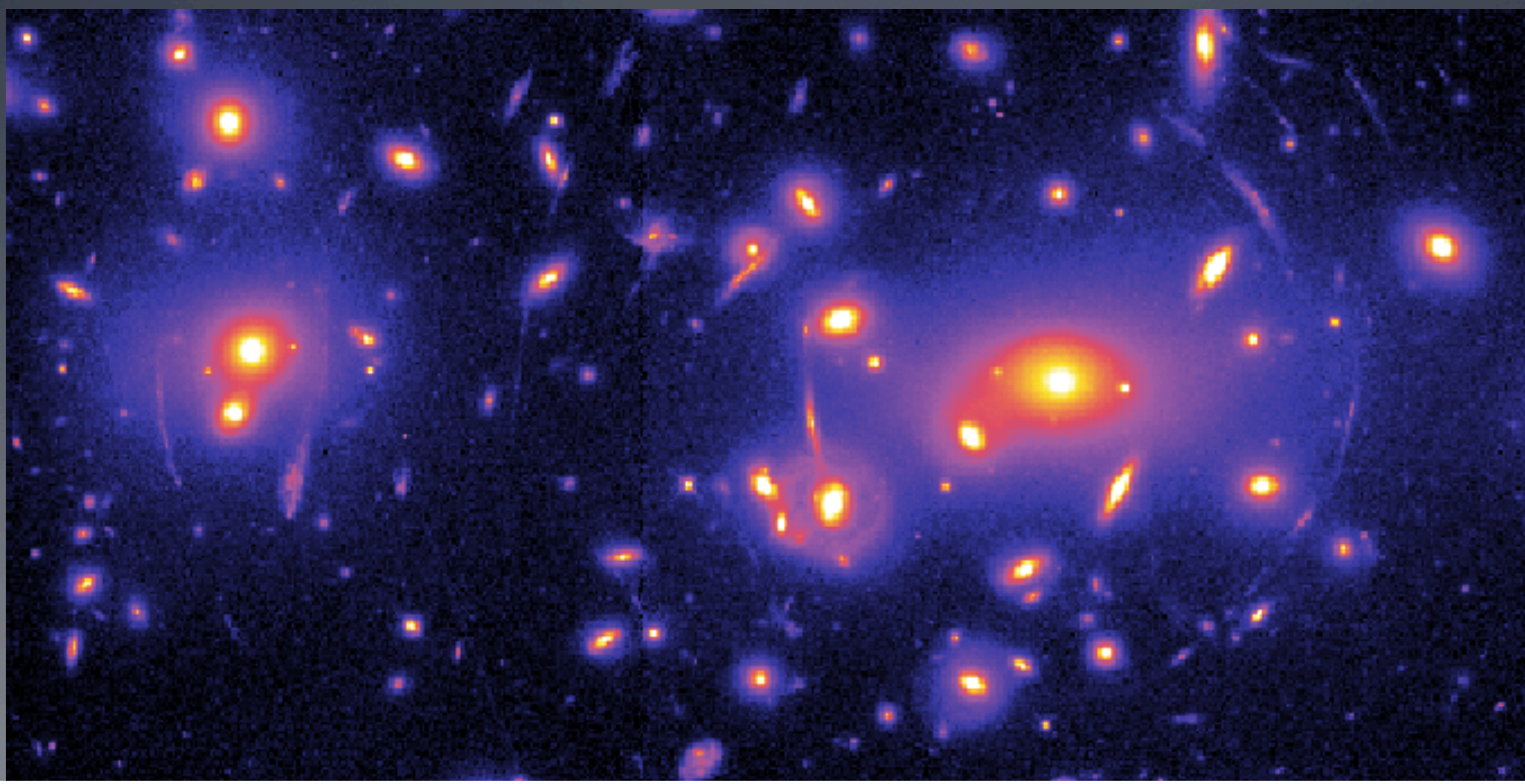
- Depends on projection along line of sight



Background

Lensing predicted by Newton, with modified predictions by Einstein:

$$\hat{\alpha} = \frac{4G}{c^2}\frac{M(<\xi)}{\xi}$$

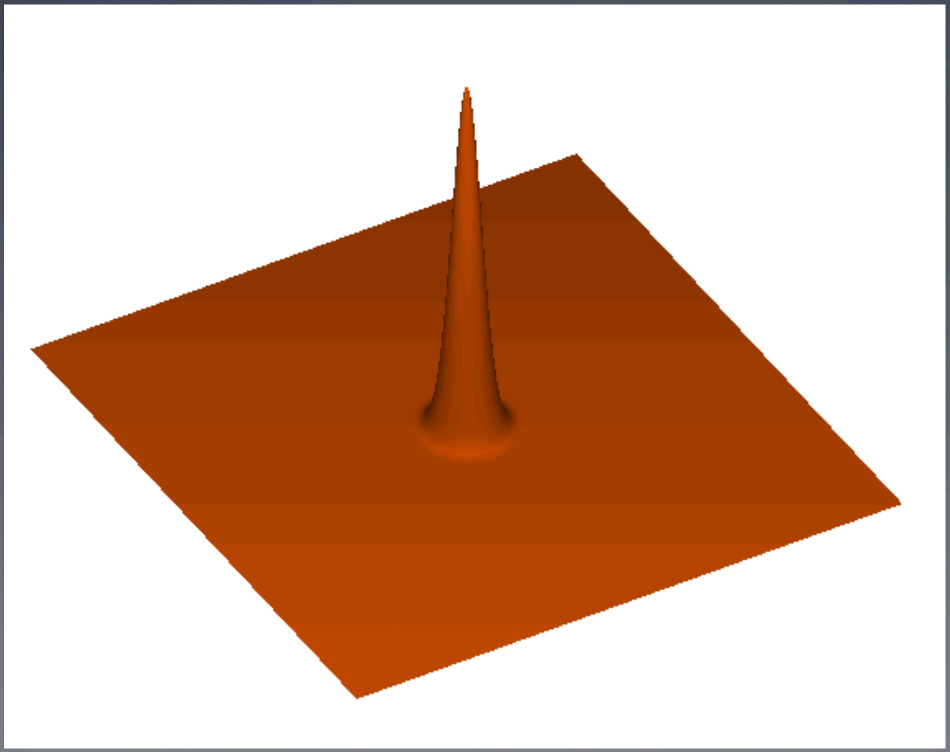


Strong and weak lensing

- Strong lensing: dramatic visual effects, but rare
- Weak lensing: very low-level coherent effects, but ubiquitous
- An important tool for studying the matter field!

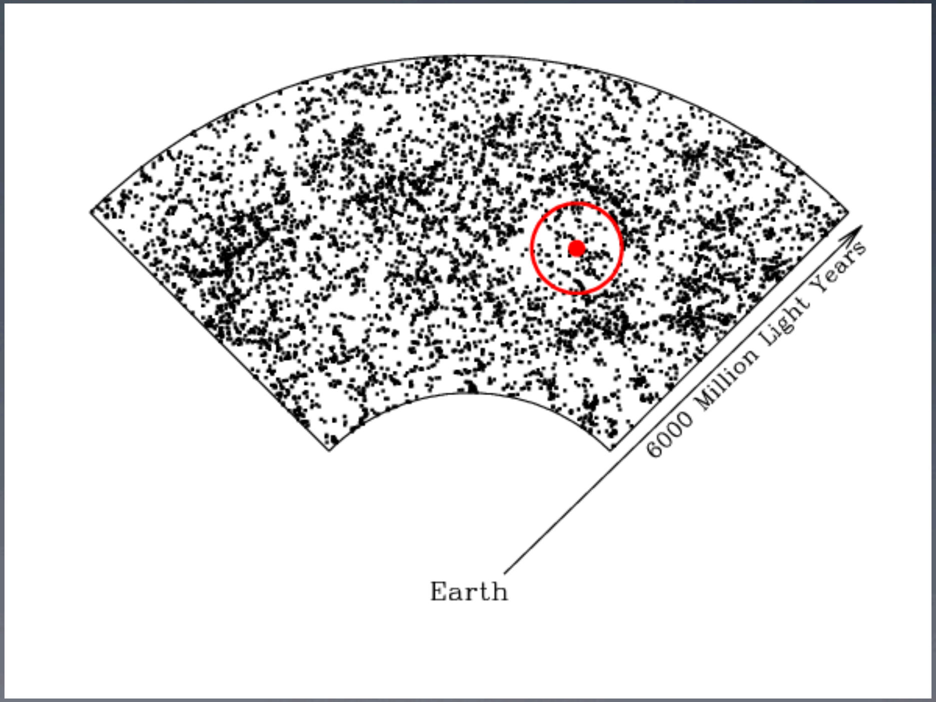
Can we use galaxies to probe geometry?? Yes!

- Remember that acoustic peak in the CMB? We see it in the galaxy distribution, too!



What does this tell us?

- A correspondence between redshift and a physical scale
- Tie it to the physical scale in the CMB
- Constrain cosmological parameters that define structure growth, e.g., matter density

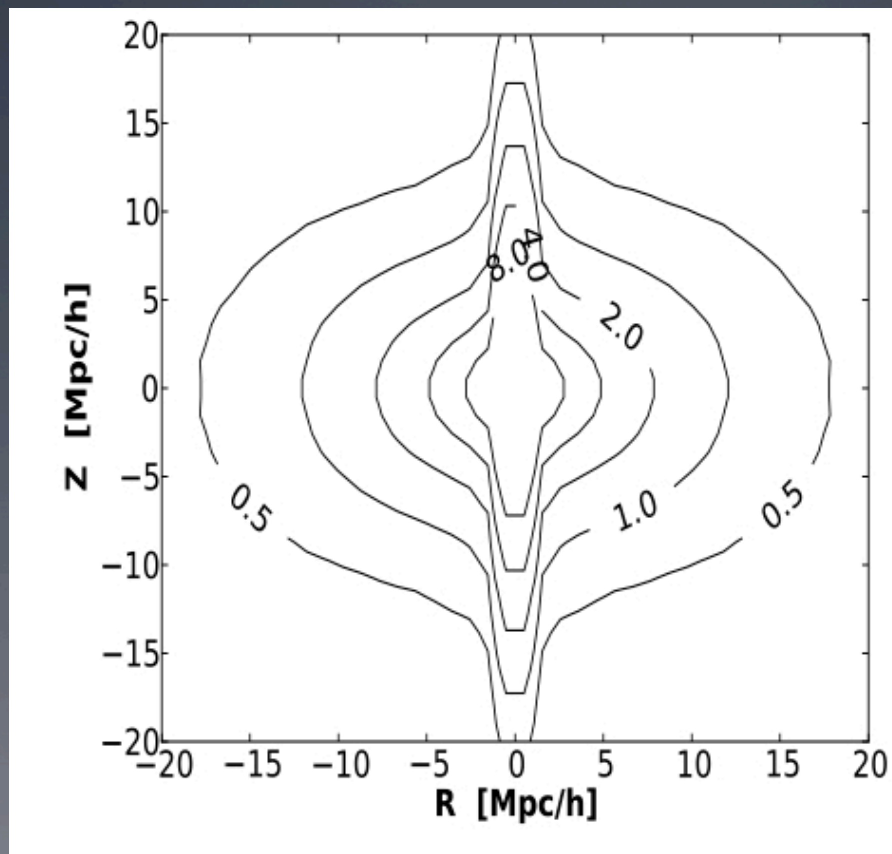


But wait: do we only measure cosmological redshift?

- The z that we measure from the galaxy spectrum includes
  - Cosmological redshift, i.e., due to expansion of universe
  - Non-cosmological velocity ("peculiar velocity")
- The redshift direction is "special" compared to the other two directions

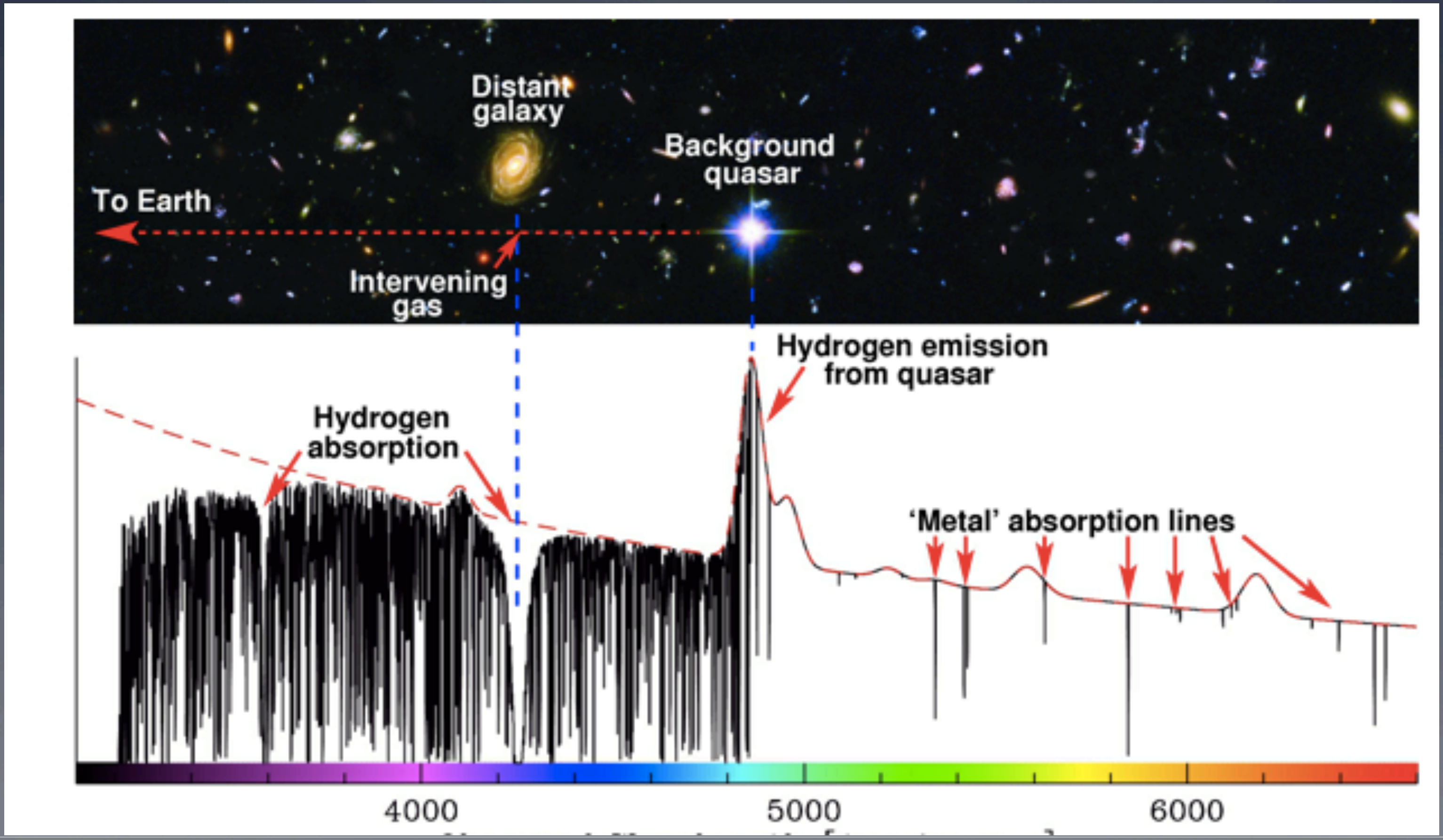
$$z_{obs} = z_{cos} + v_{pec}/c$$

Effect on measured correlations



Galaxies aren't the only interesting objects out there…

- Quasars: can we learn anything from them?



What else?

- The previous few topics constitute the bulk of the cosmological observations being done in major surveys now and for the next few decades.
- But let's not forget where the evidence for our current cosmological paradigm came from!

Original evidence for dark matter

Measure rotation speed vs. distance

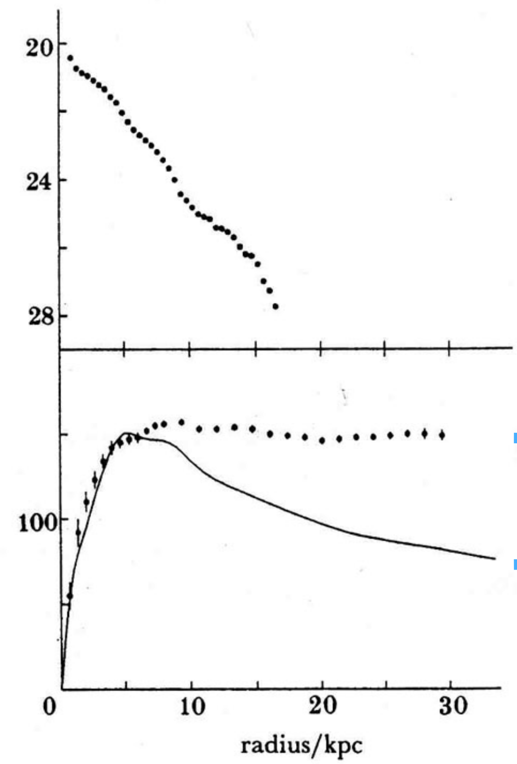
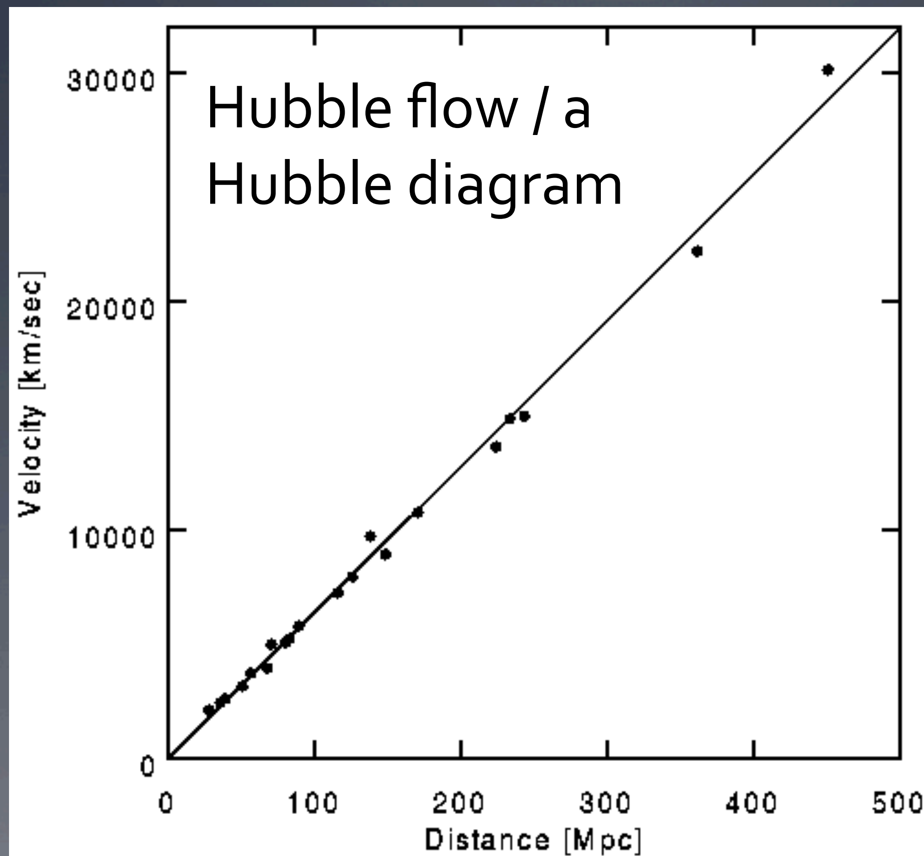


Figure 3.1. Upper panel: A logarithmic plot of surface brightness as a function of radius for the galaxy NGC 3198. Lower panel: The observed rotation curve of the galaxy (points) and the rotation speed calculated from the mass associated with the light profile only (full line) (from Albada and Sancisi 1986).

Too much mass in the outer parts of the galaxy!

What about expansion of the universe, and its acceleration?

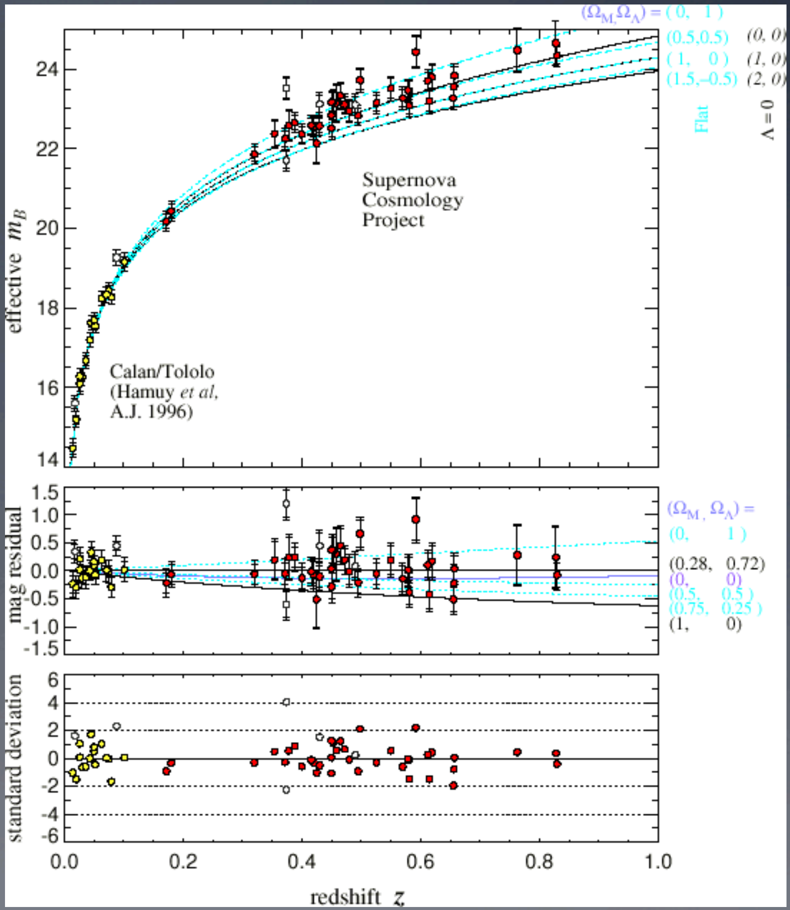


Velocity: pretty easy to measure from spectra (redshift)

Distance: really hard to measure in general

We need a "standard candle" or "standard ruler"

- "Standard ruler": BAO is an example
- In 1990s, people focused on "standard candles" – Type Ia supernovae
- Intrinsic brightness understood, so observed luminosity tells us the distance



Summary

- Many types of observations have contributed to our current cosmological understanding, and/or are still being actively used today.
- We want to help you understand how these observations are made and what exactly they teach us about the history and contents of the universe!