Large Scale Structure / Baryon Acoustic Oscillations
+
Enigma of Dark Energy
+
Observational Cosmology from Galaxy Clusters

Layout of the Course

Feb 5: Introduction / Overview / General Concepts
Feb 12: Age of Universe / Distance Ladder / Hubble Constant
Feb 19: Distance Ladder / Hubble Constant / Distance Measures
Feb 26: Distance Measures / SNe science / Baryonic Content
Mar 4: Baryon Content / Dark Matter Content of Universe
Mar 11: Cosmic Microwave Background
Mar 18: Cosmic Microwave Background / Large Scale Structure
Mar 25: Baryon Acoustic Oscillations / Dark Energy / Clusters
Apr 1: No Class
Apr 8: Cosmic Shear / Dark Energy Missions
Apr 15: Dark Energy Missions / Open Questions / Review for Final Exam

May 13: Final Exam

This Week

Problem Set 2 is due by March 28 (one extra day!)

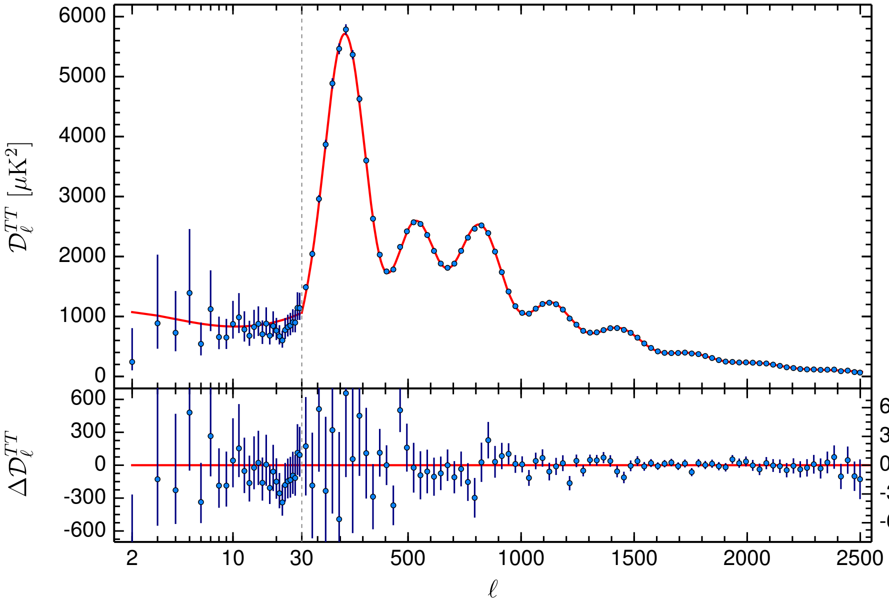
Will Distribute Problem Set 3 on Thursday/Friday of this week…

Will be due April 14th…

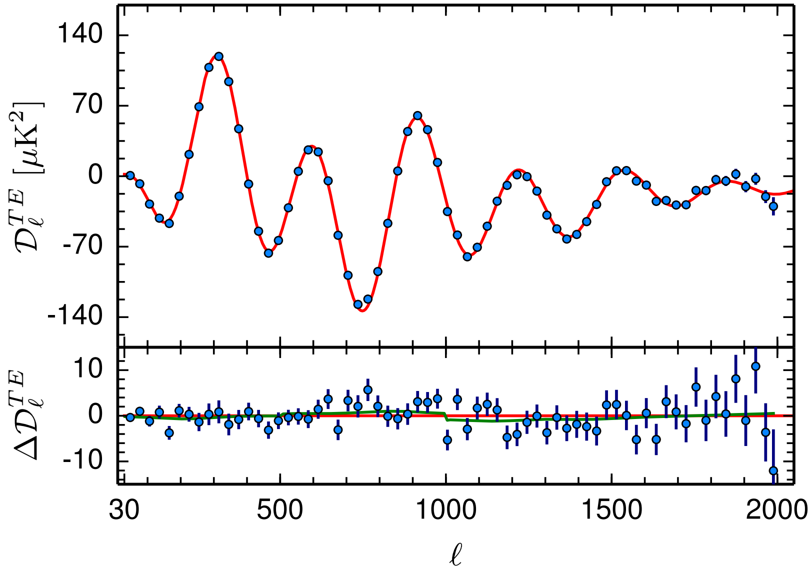
Review Material from Last Week

Cosmic Microwave Background

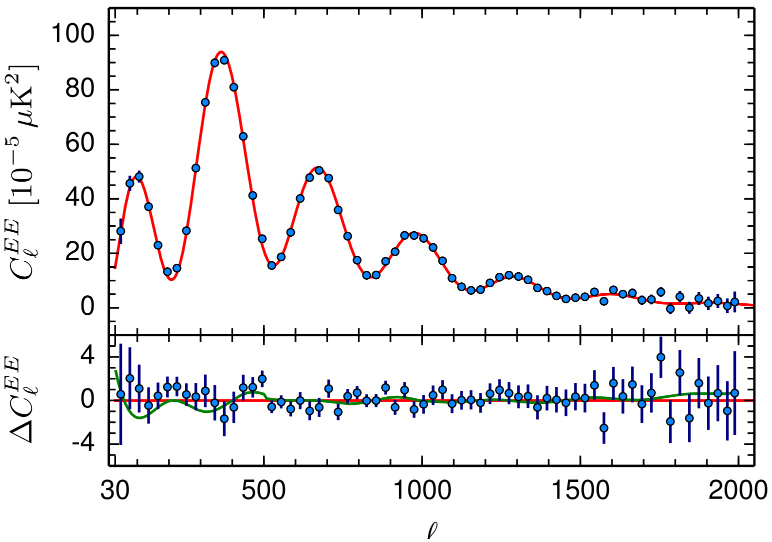
TT spectrum



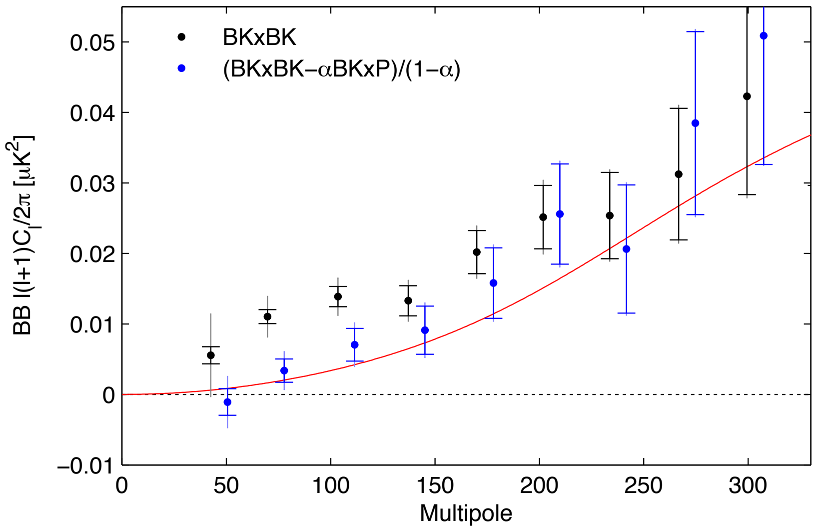
TE spectrum



EE spectrum

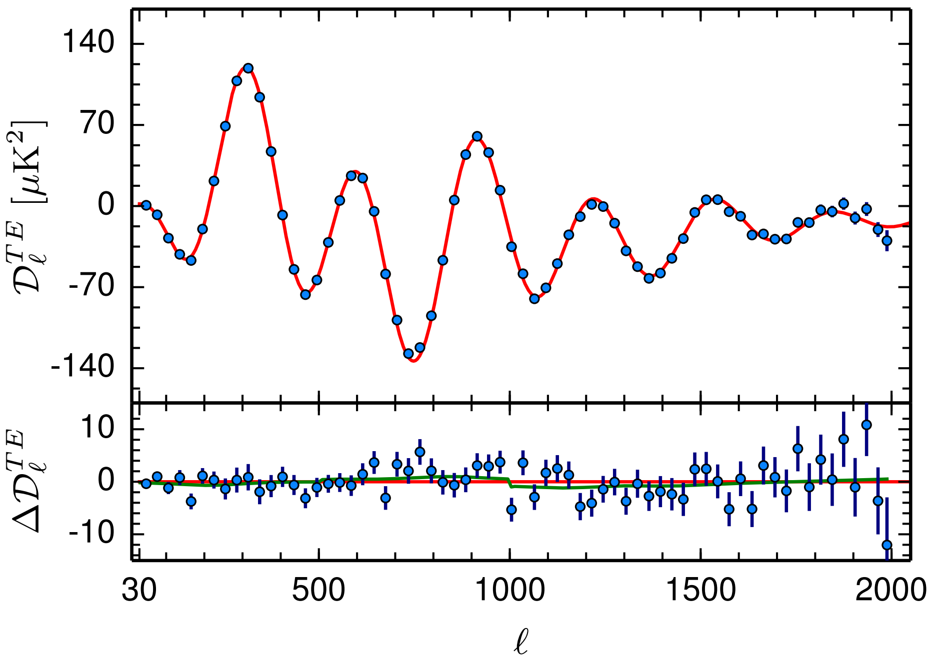


BB spectrum

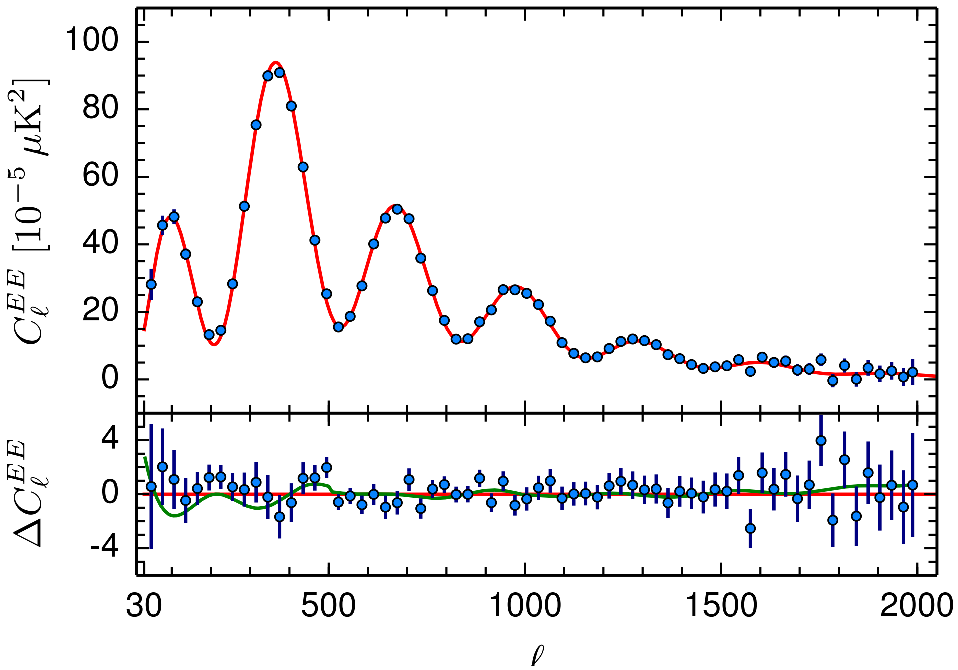


TE/EE Power Spectra

TE spectra



EE spectra



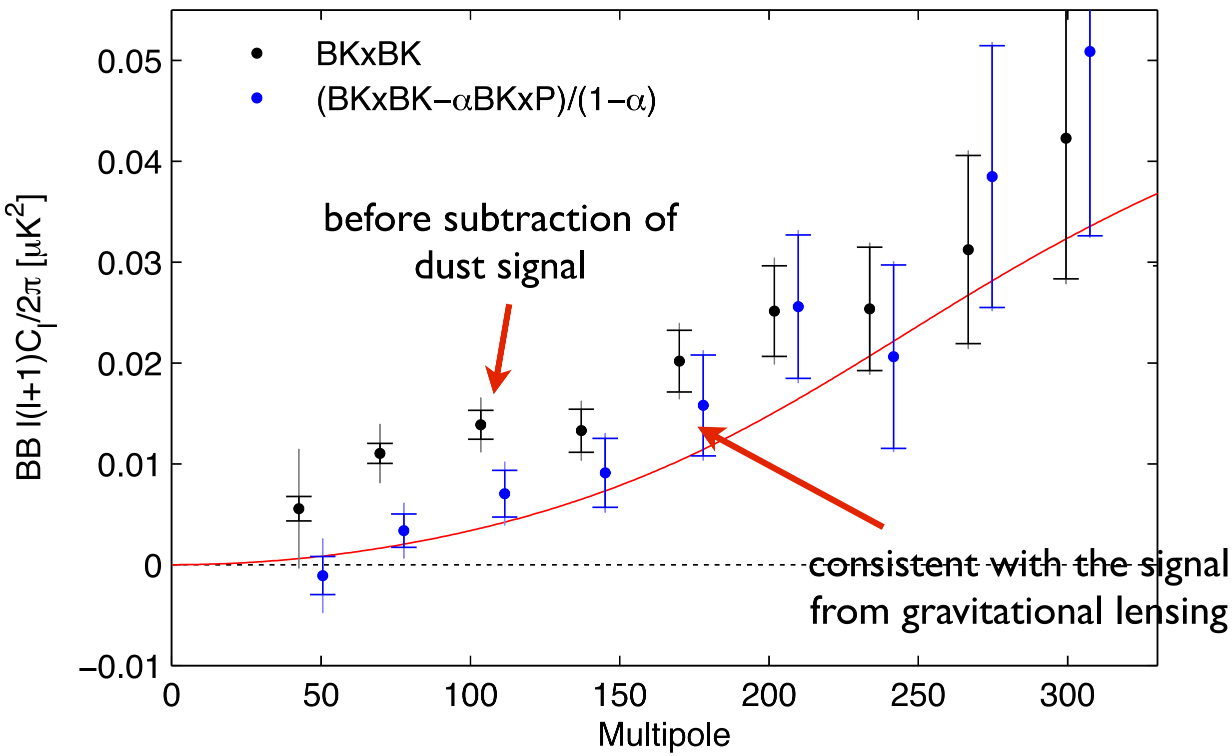
Contains Very Similar Information to that Present in TT Power Spectrum...

Allows us to verify that we understand the physics correctly...

Expect some difference from TT power spectrum -- depending on the ionization history of universe

Cosmic Microwave Background

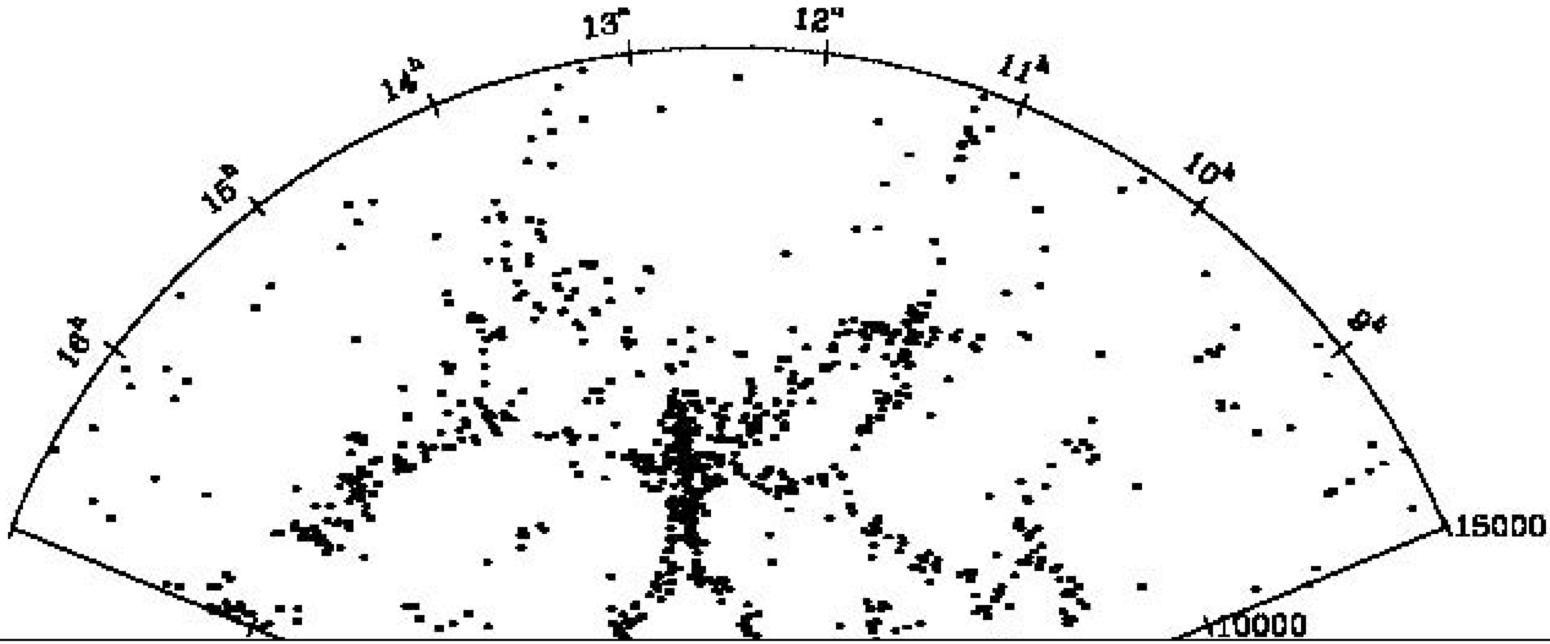
BB spectra



Signal arises from (1) gravity waves from inflation and (2) the impact of gravitational lensing on CMB...

Detection first reported in 2014 by BICEP II, but most of the signal likely from dust emission in our own galaxy

So what can we learn from the spatial distribution of galaxies on the sky?



Spatial Distribution of Galaxies on some part of sky

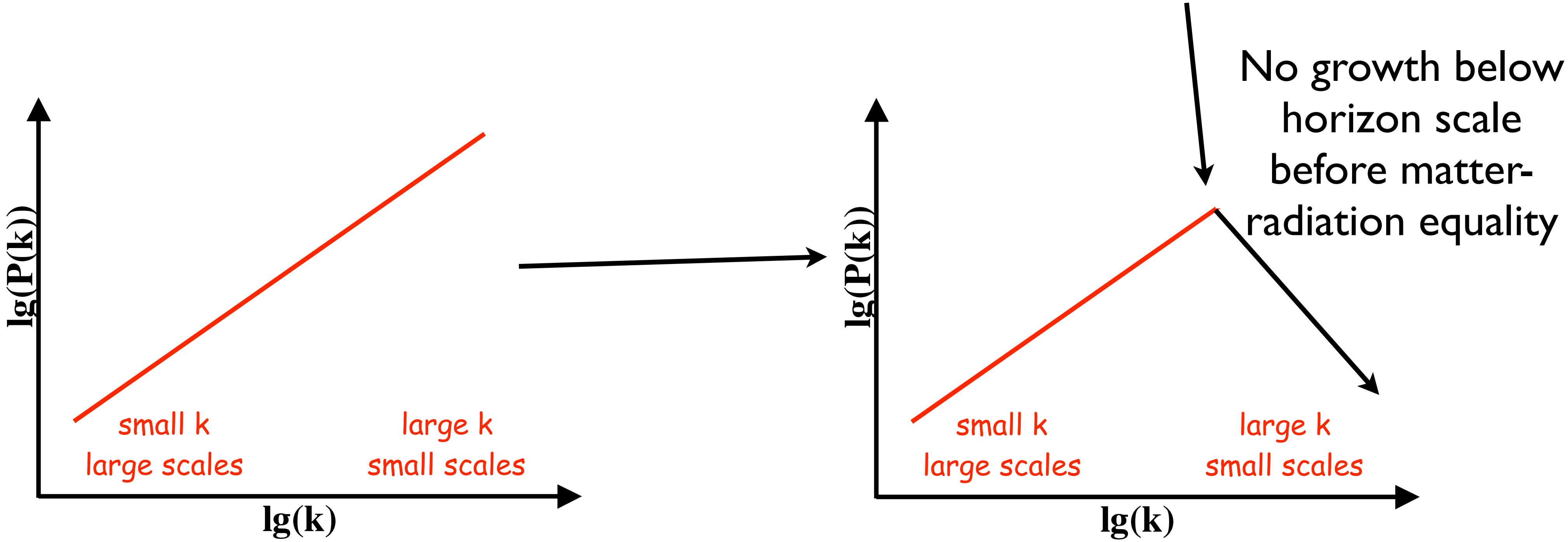
→ We can derive the matter power spectrum

How does the matter power spectrum take on its shape?

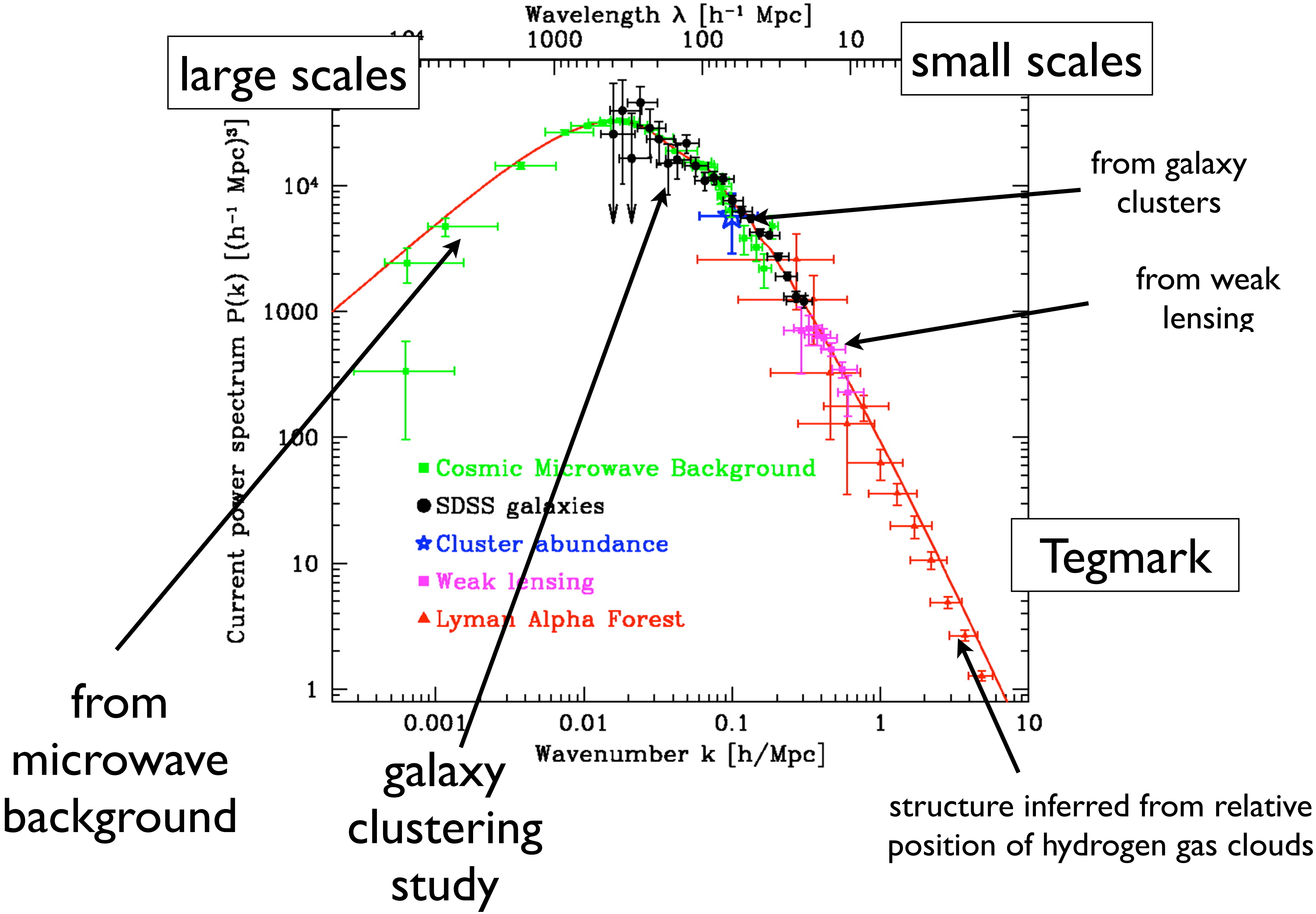
The initial power spectrum of fluctuations is the following:

$$P_0(k) = A\, k^{n_s}$$

Position of turn-over determined by horizon size @ matter-radiation equality



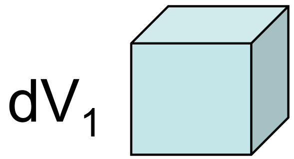
Different techniques/sources probe different regimes in matter power spectrum

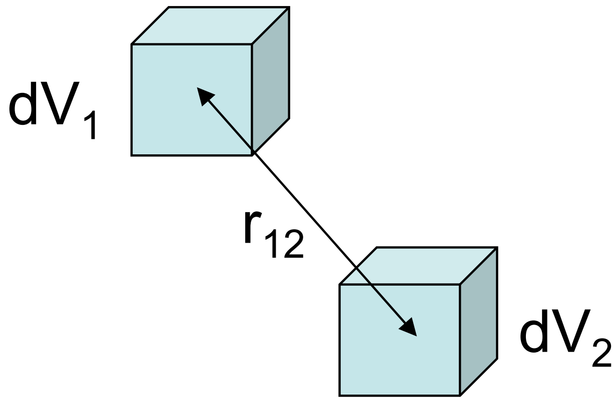


How do we quantify structure in the distribution of galaxies on the sky?

==> in terms correlation functions

The Correlation function ξ is not equal to zero -- since the presence of a galaxy at some place in space makes it more likely another one will be close by....





$$dP_1 = n\, dV_1$$

$$dP_{12} = n^2\, (1 + \xi(r_{12}))\, dV_1\, dV_2$$

n = average density of galaxies

Why do we care? The matter power spectrum is the Fourier transform of the correlation function ξ

$$P(k) = \int \xi(r) e^{ik \bullet r} d^3r \equiv \int \xi(r) \frac{\sin(kr)}{kr}\, r^2 \cdot dr$$

What does the power spectrum teach about various cosmological parameters?

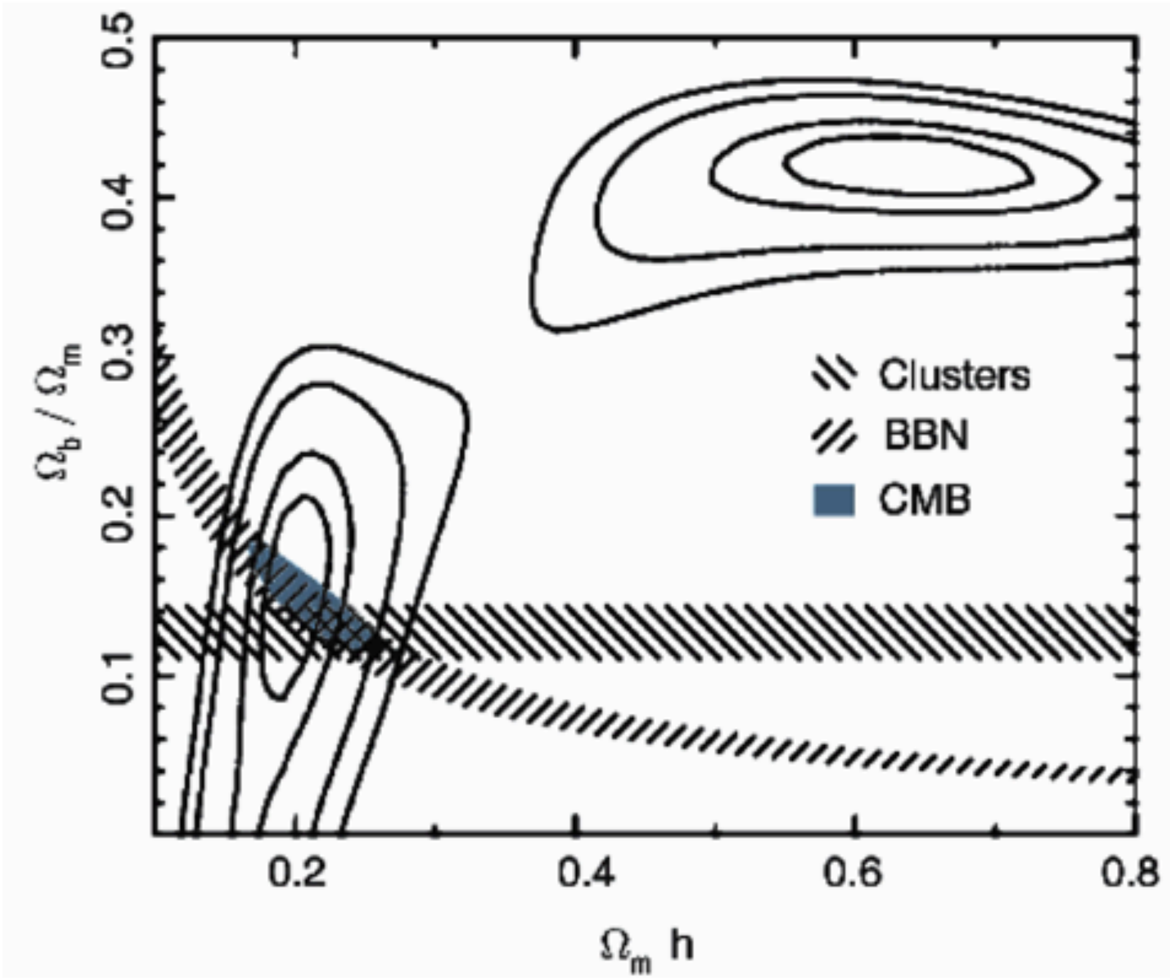
Teach us mostly about $\Omega_m h$ (and z_{eq}) and Ω_b

Here is one example from an early study using the 2DF survey in 2003

$\Omega_m h = 0.2$
$\Rightarrow \Omega_m = 0.3$

$\Omega_b = 0.04$

Yet another constraint on the baryonic density of universe!



Peacock 2003, astro-ph/0309240 and Peacock 2001, astro-ph/0105450.

New Material

How do we normalize the power spectrum?

We parameterize this using the σ_8 parameter

While deriving correlation function and Power spectrum from galaxy survey, one thing we are particularly interested in is the normalization of the power spectrum

$$P_0(k) = A\, k^{n_s}$$

(related to the A parameter here)
($n_s = 1$)

This is defined using this parameter σ_8 (intended to represent the root-mean-squared fluctuations in a 8 h^{-1}Mpc volume):

$$\sigma_{8,\mathrm{g}}^2 := \left\langle \left(\frac{\Delta n}{\bar{n}} \right)^2 \right\rangle_8 \approx 1$$

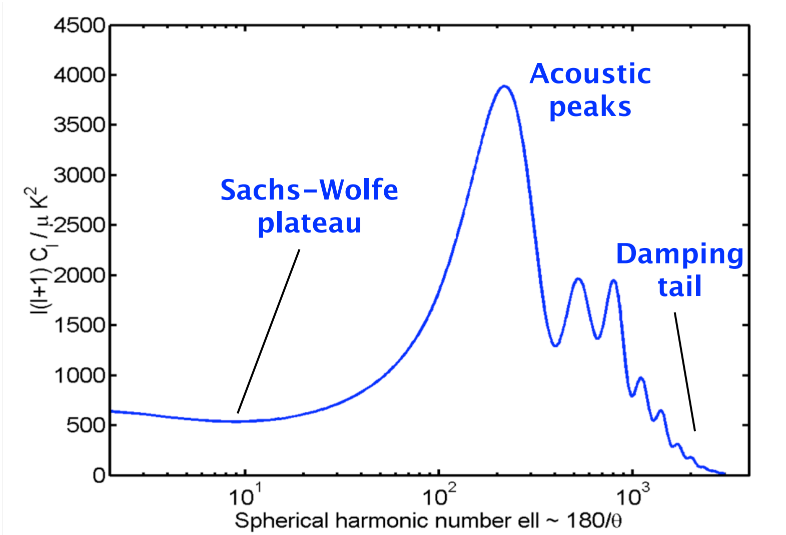
(8 h^{-1} Mpc was chosen because appeared close to 1)

Size of density fluctuations in a volume really defines the amplitude of power spectrum

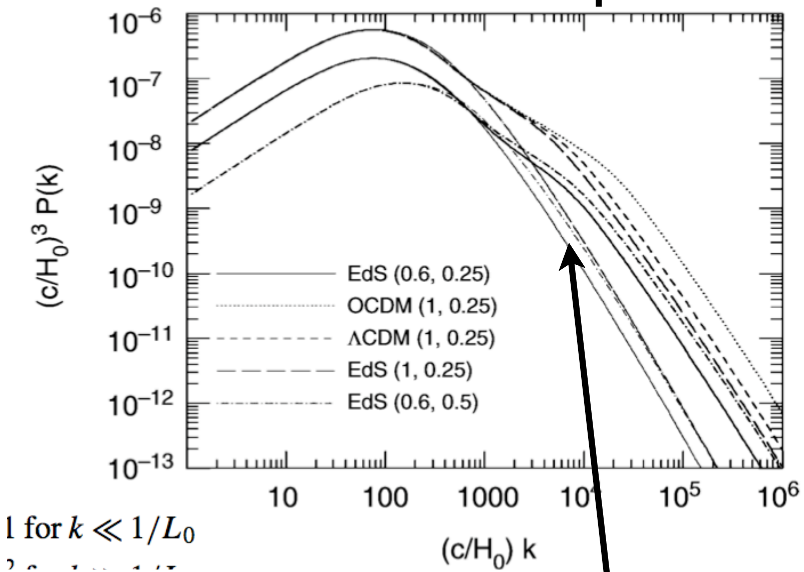
What effect do baryons have on the matter power spectrum?

Just like in the CMB, baryons impart acoustic oscillations on matter power spectrum

CMB Power Spectrum

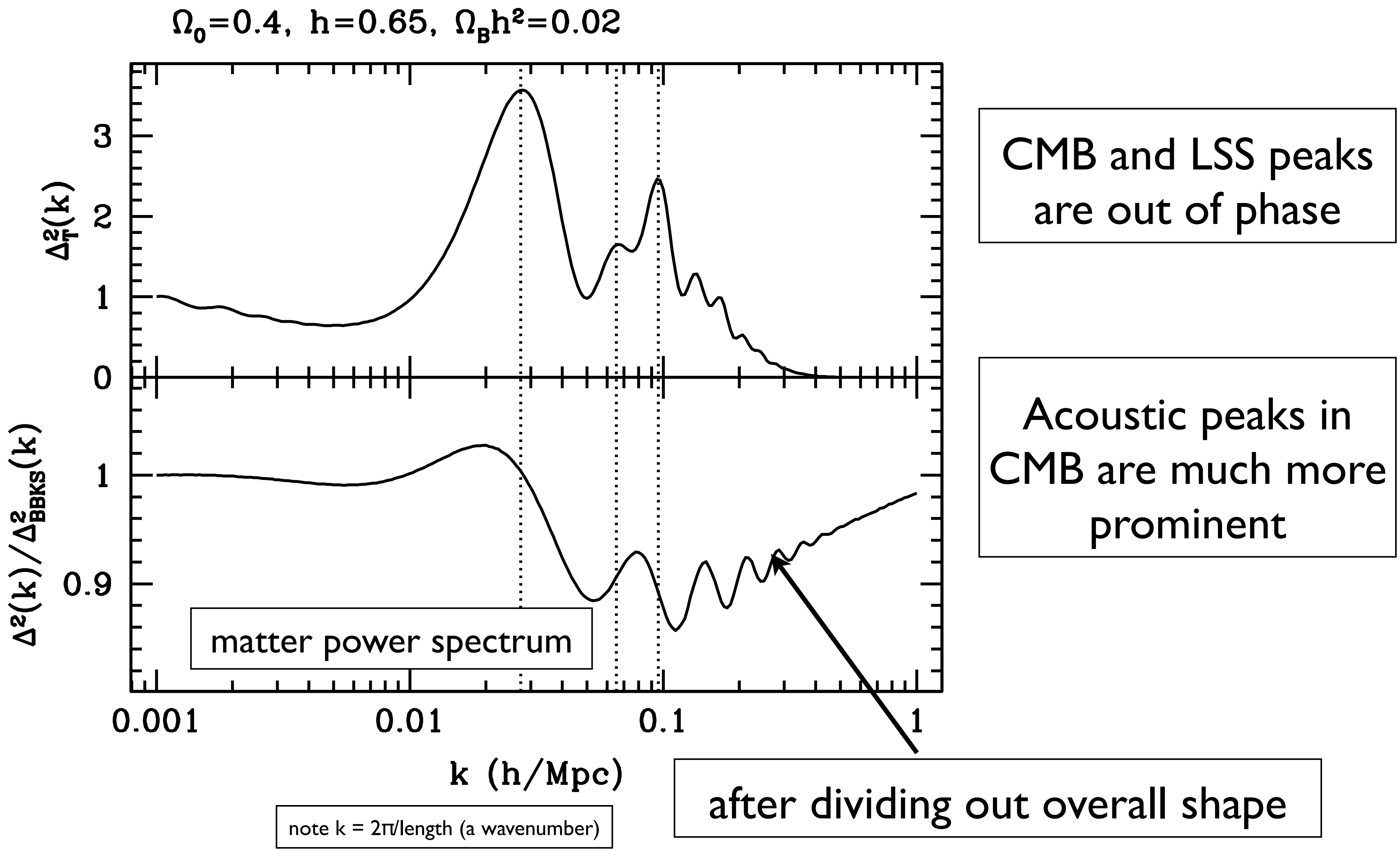


Matter Power Spectrum



Has small acoustic oscillations in the matter power spectrum

Here are the CMB and matter power spectrum overlaid one over top of the other



This makes the acoustic peaks more obvious

Meiksin et al. 1999

But where do these acoustic peaks come from?

Between $z = 3500$ (when universe became matter dominated) and $z = 1080$ (photons and baryons decoupled):

Perturbations in baryonic material cannot grow (being coupled to radiation) and will just oscillate

baryonic material $\Rightarrow$ no growth

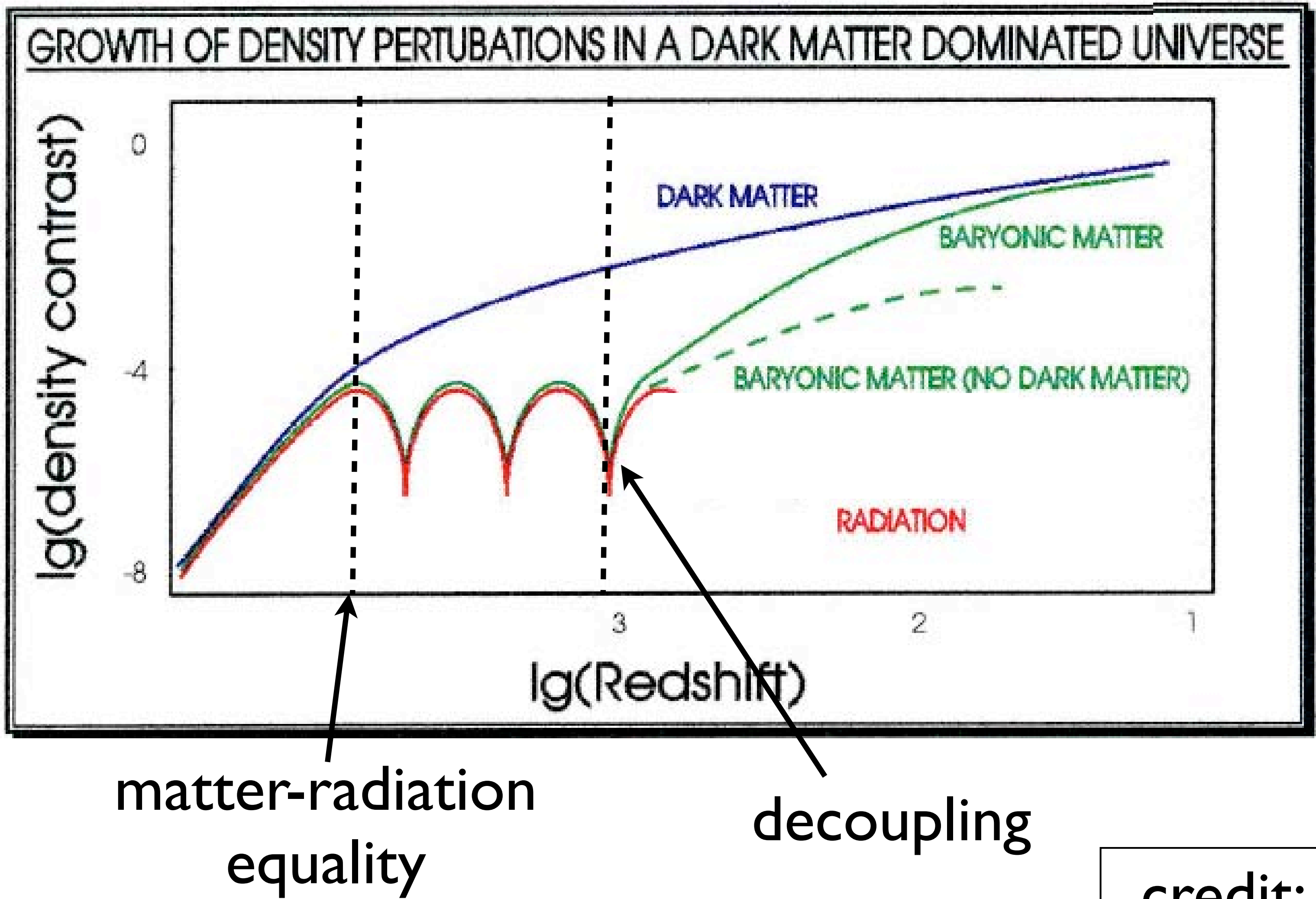
Perturbations in dark material can grow (not being coupled to the radiation)

dark matter $\Rightarrow$ growth

As a result, perturbations in dark matter get a head start

But where do these acoustic peaks come from?

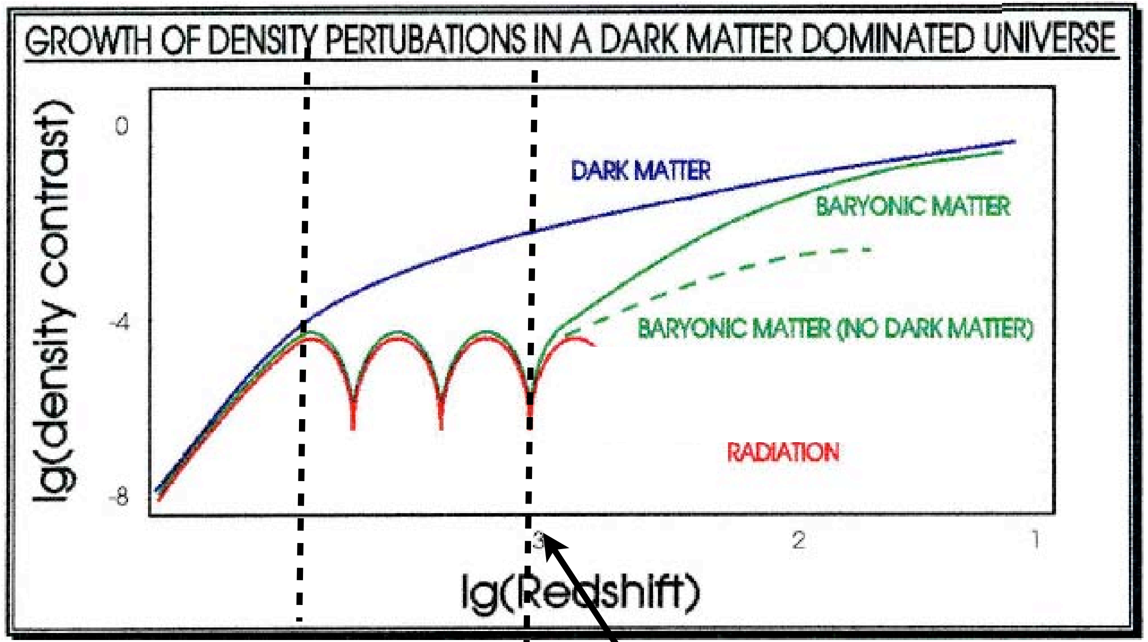
here's an illustration (notice difference between dark matter and baryonic matter)



credit: Pearson

But where do these acoustic peaks come from?

here's an illustration (notice difference between dark matter and baryonic matter)



Before decoupling, perturbations in dark matter are able to grow, but perturbations in baryons are not.

After decoupling, baryons fall into overdensities from dark matter.

matter-radiation equality

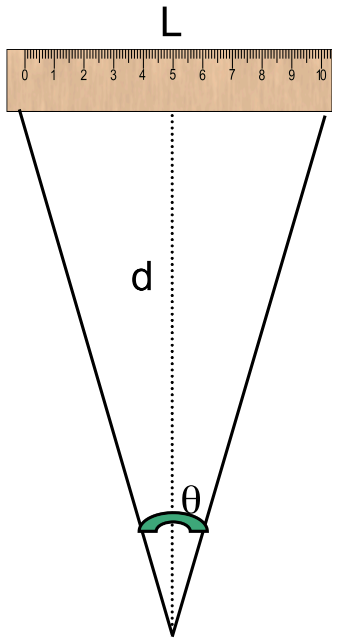
decoupling

But, in doing so, they affect the dark matter; they add the oscillatory ringing structure to larger perturbations defined by dark matter

Why do we care about these small oscillations in matter power spectrum caused by baryons?

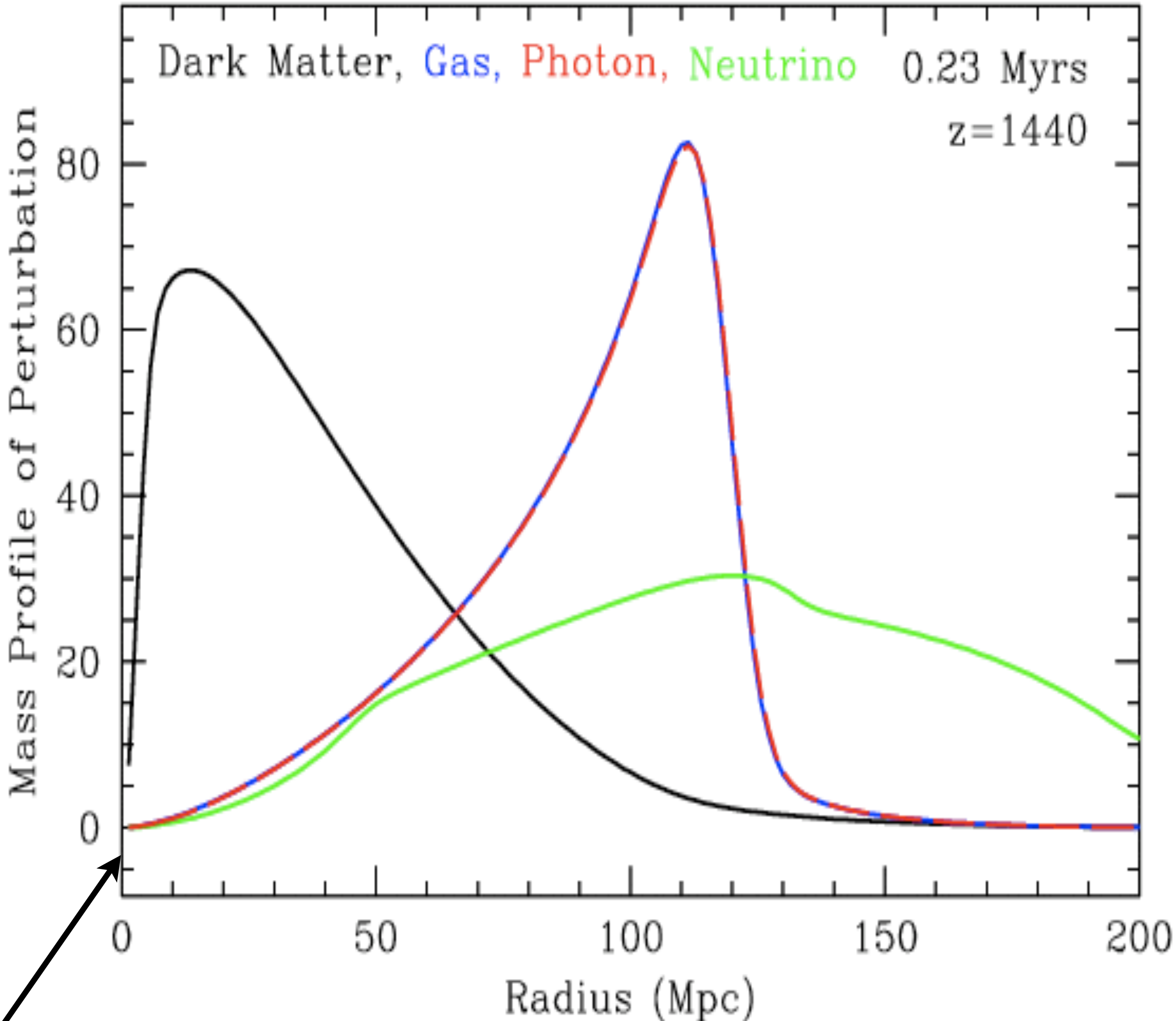
These oscillations cause there to be preferential structure at a certain comoving physical scale!

It provides us with a standard rod again that we can use to learn about the universe!



We can therefore do a galaxy survey at any epoch or redshift, measure the power spectrum, and look for the acoustic peak from baryons!

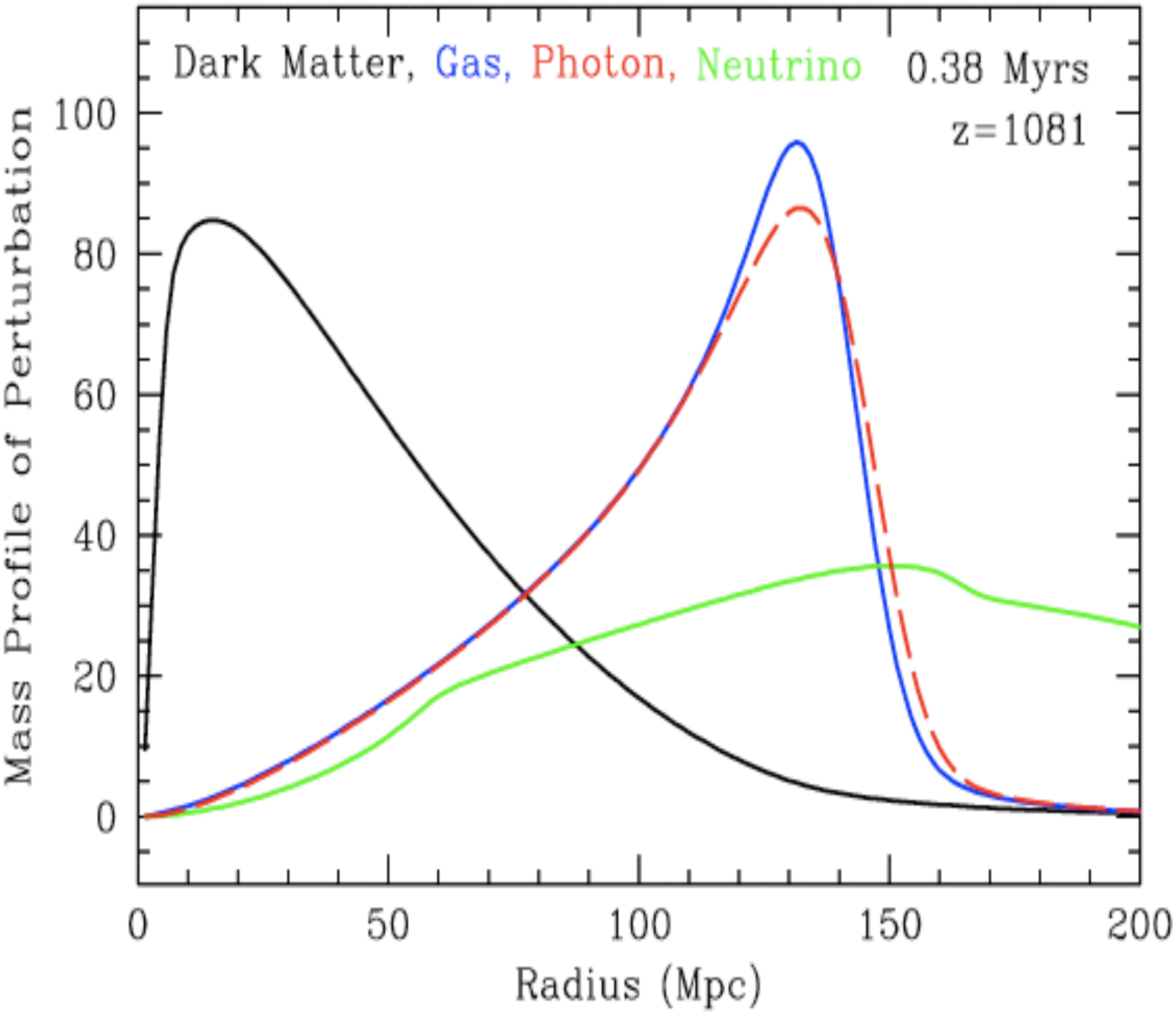
It will define same comoving scale at all epochs!



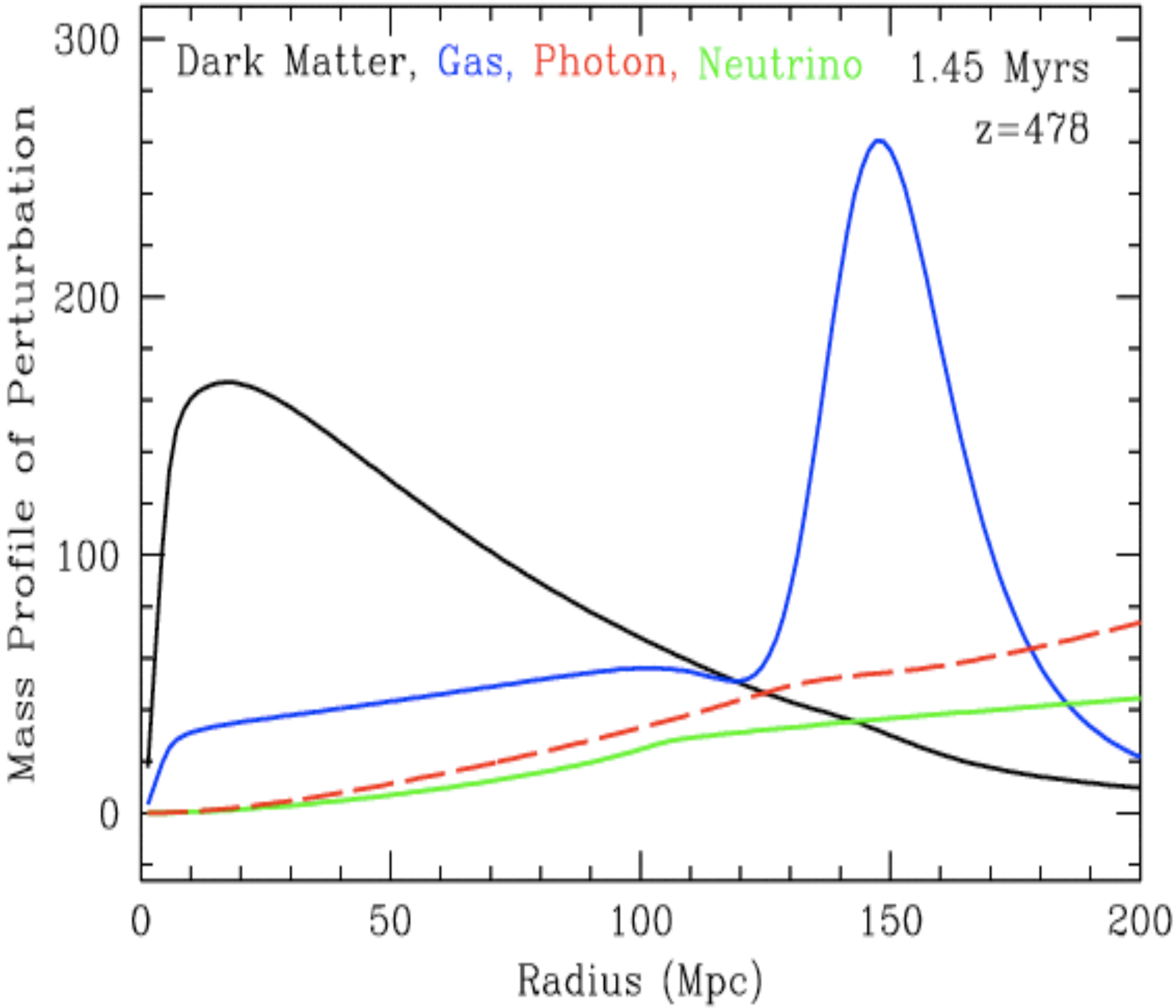
imagine we have a overdensity here at time t = 0

dark matter will fall towards it

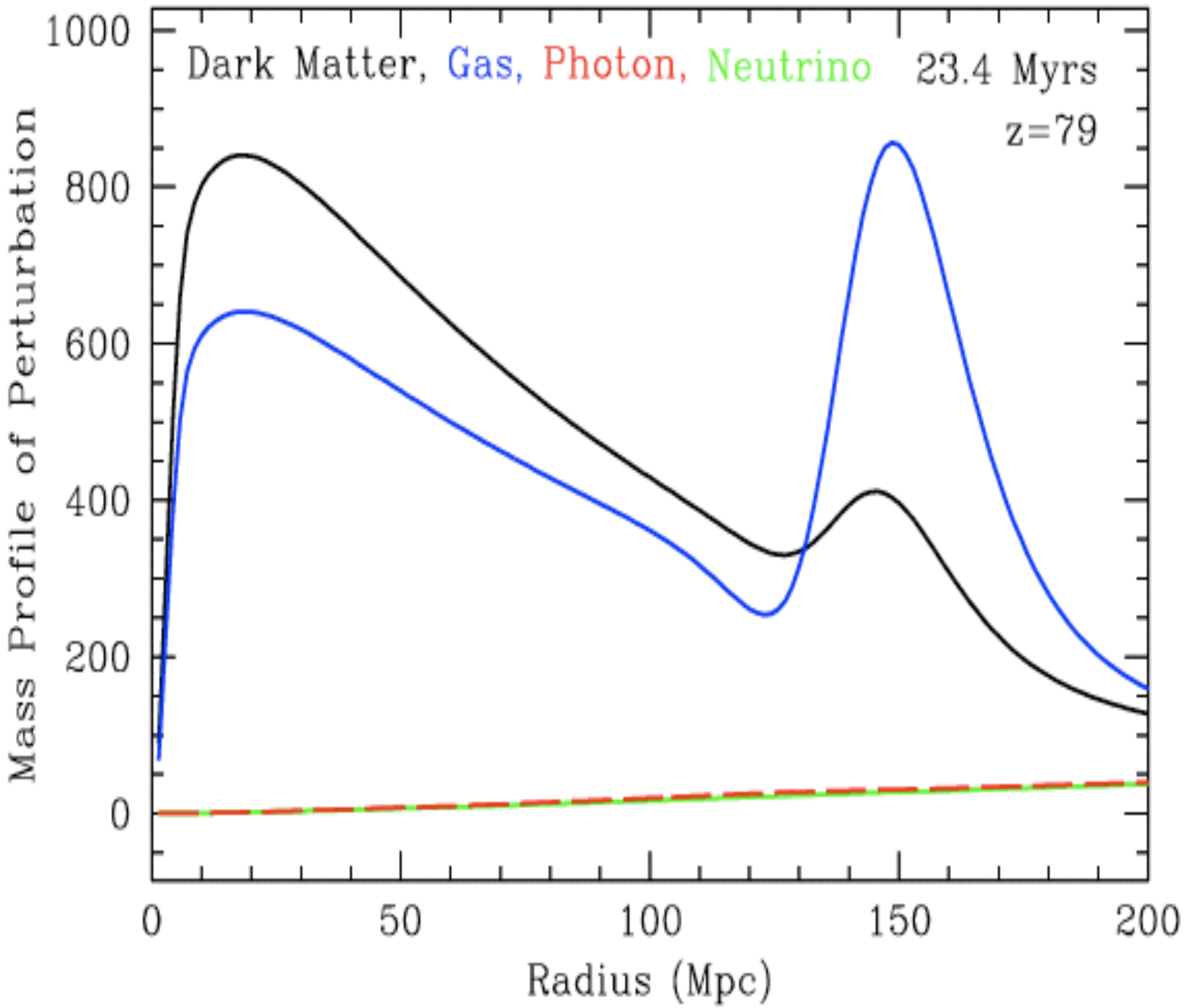
but baryons and radiation will bounce



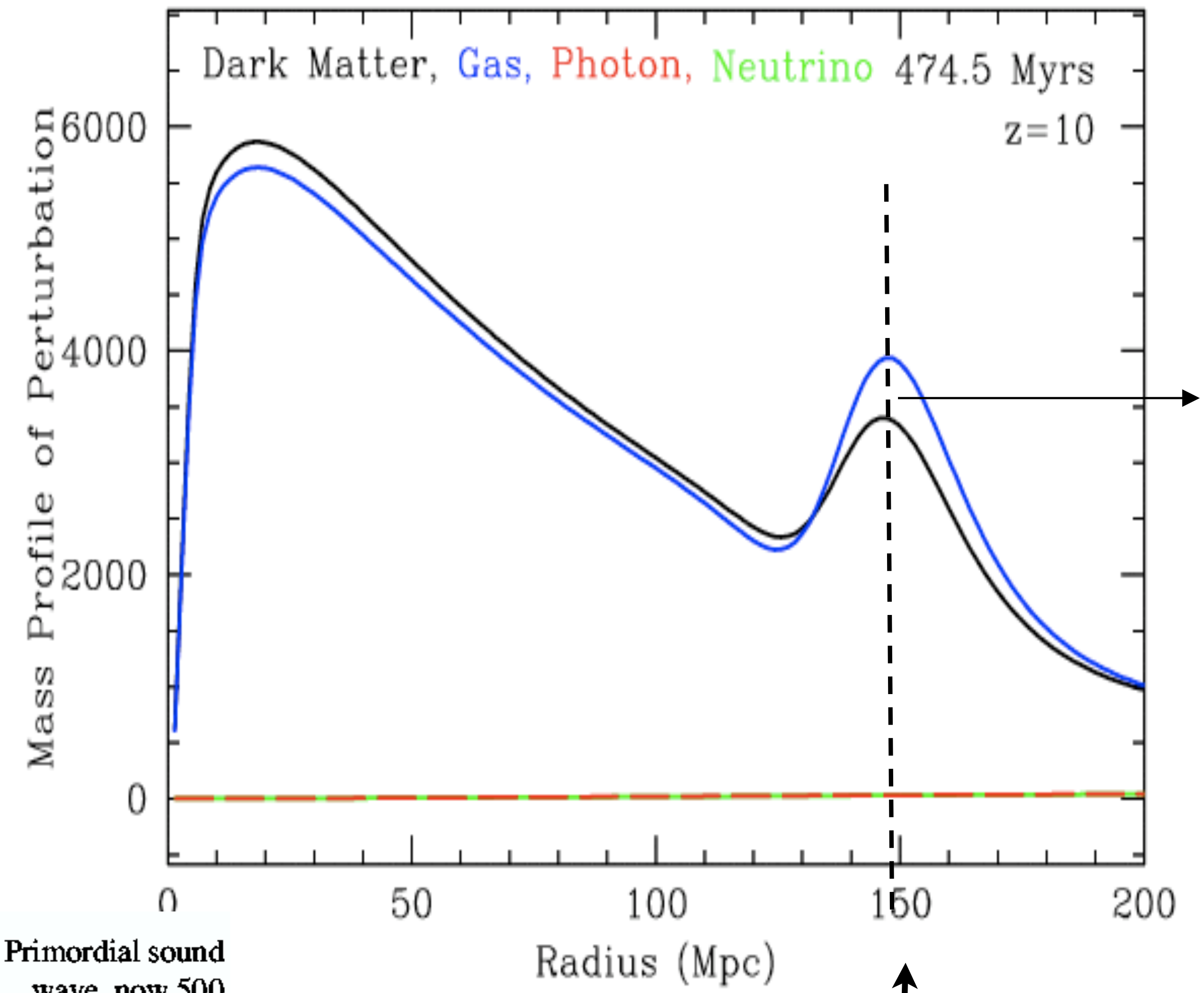
Dark Matter, Gas, Photon, Neutrino
0.38 Myrs
z=1081
Mass Profile of Perturbation
Radius (Mpc)
0
20
40
60
80
100
0
50
100
150
200



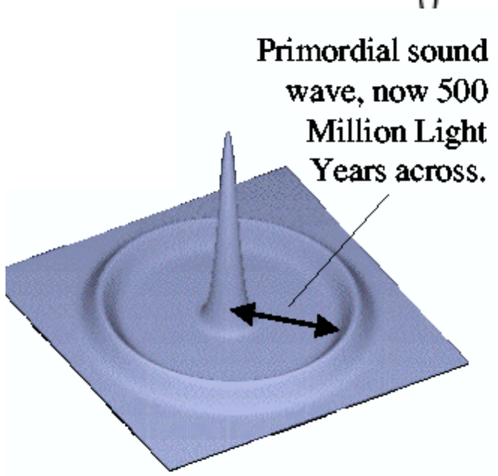
Dark Matter, Gas, Photon, Neutrino
1.45 Myrs
z=478
Mass Profile of Perturbation
Radius (Mpc)
0
100
200
300
0
50
100
150
200



Dark Matter, Gas, Photon, Neutrino
23.4 Myrs
z=79
Mass Profile of Perturbation
Radius (Mpc)
1000
800
600
400
200
0
0
50
100
150
200



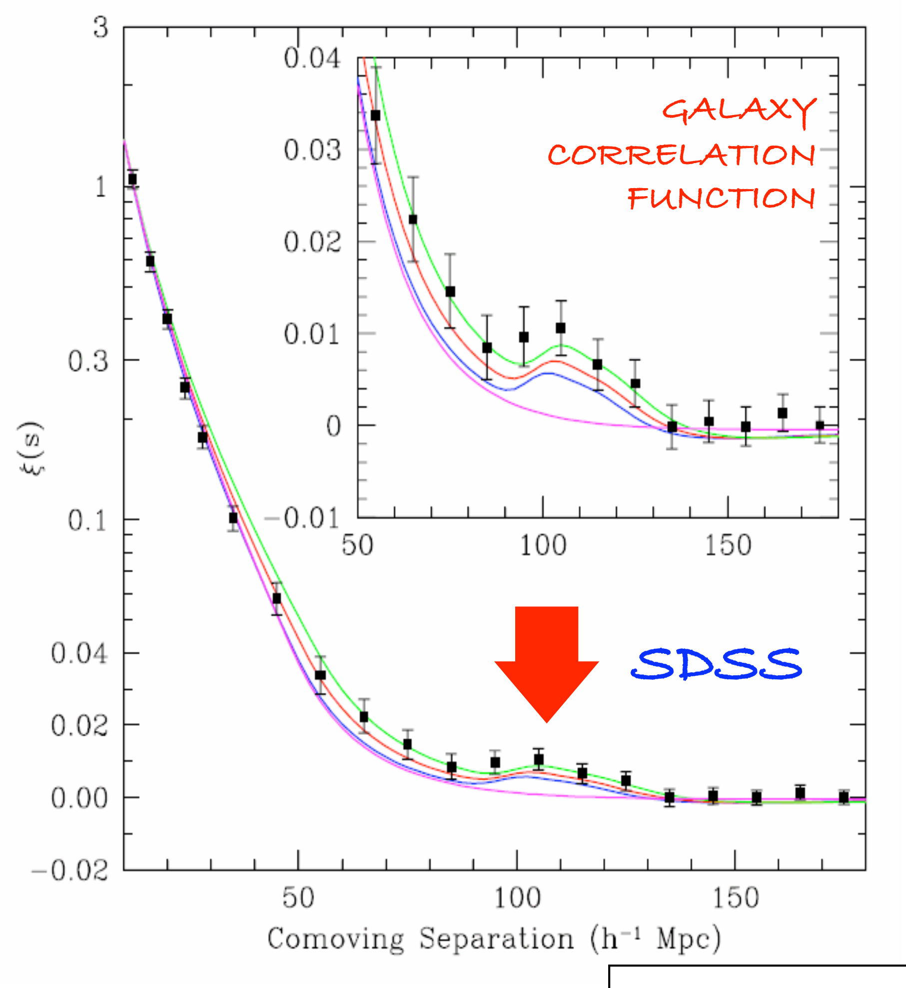
Sound horizon at matter-radiation decoupling



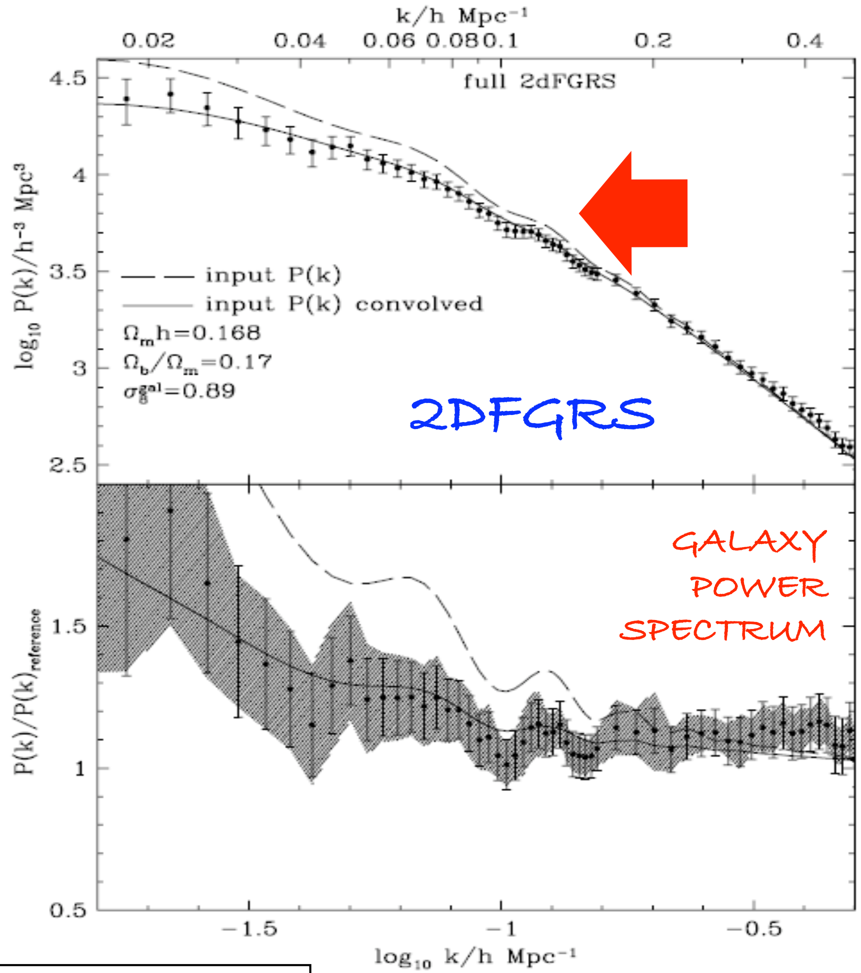
this bump is at 150 Mpc!

By measuring the correlation function for a galaxy survey we can look for this bump (from baryon acoustic oscillations)

SDSS: EISENSTEIN ET AL. (2005)



2DFGRS: COLE ET AL. (2005)



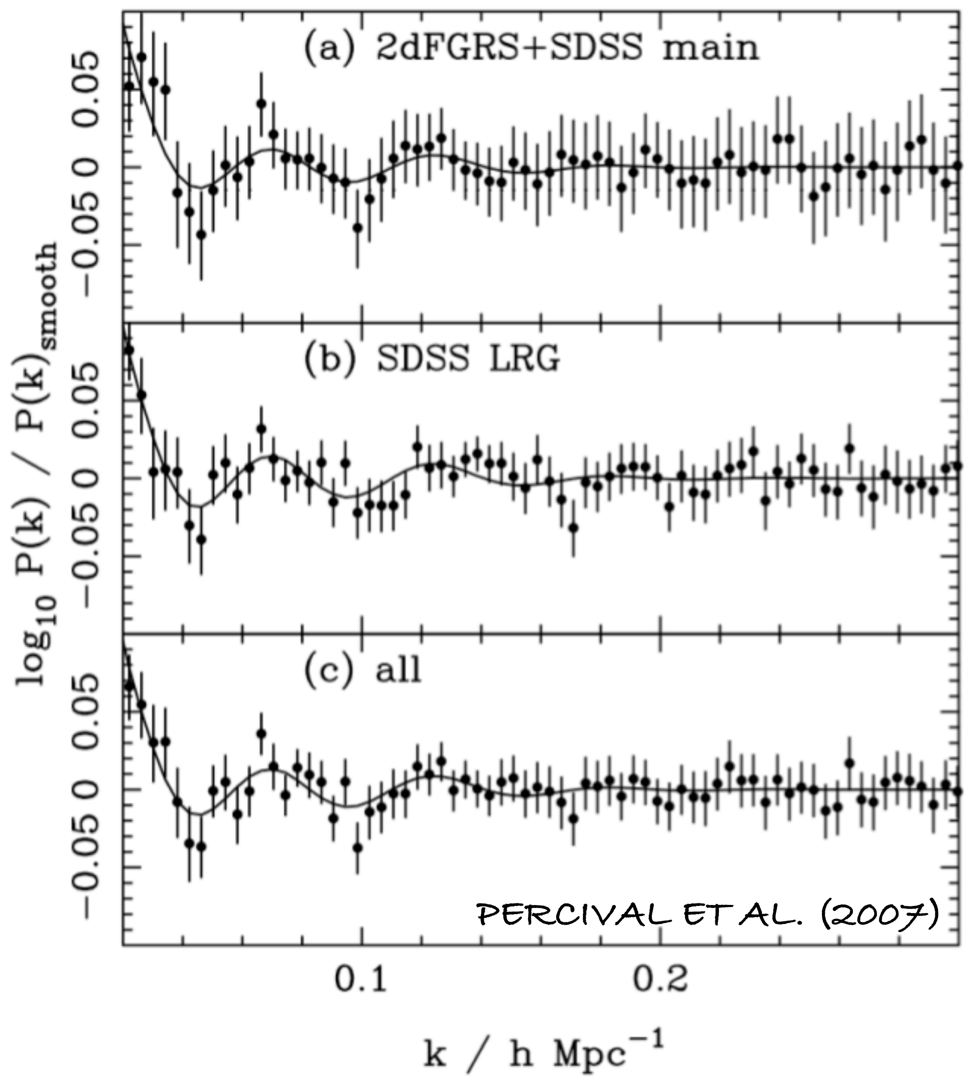
First Measurements

More recent State-of-the-art measurements of the baryonic acoustic oscillations

Detected at 99.74% confidence!

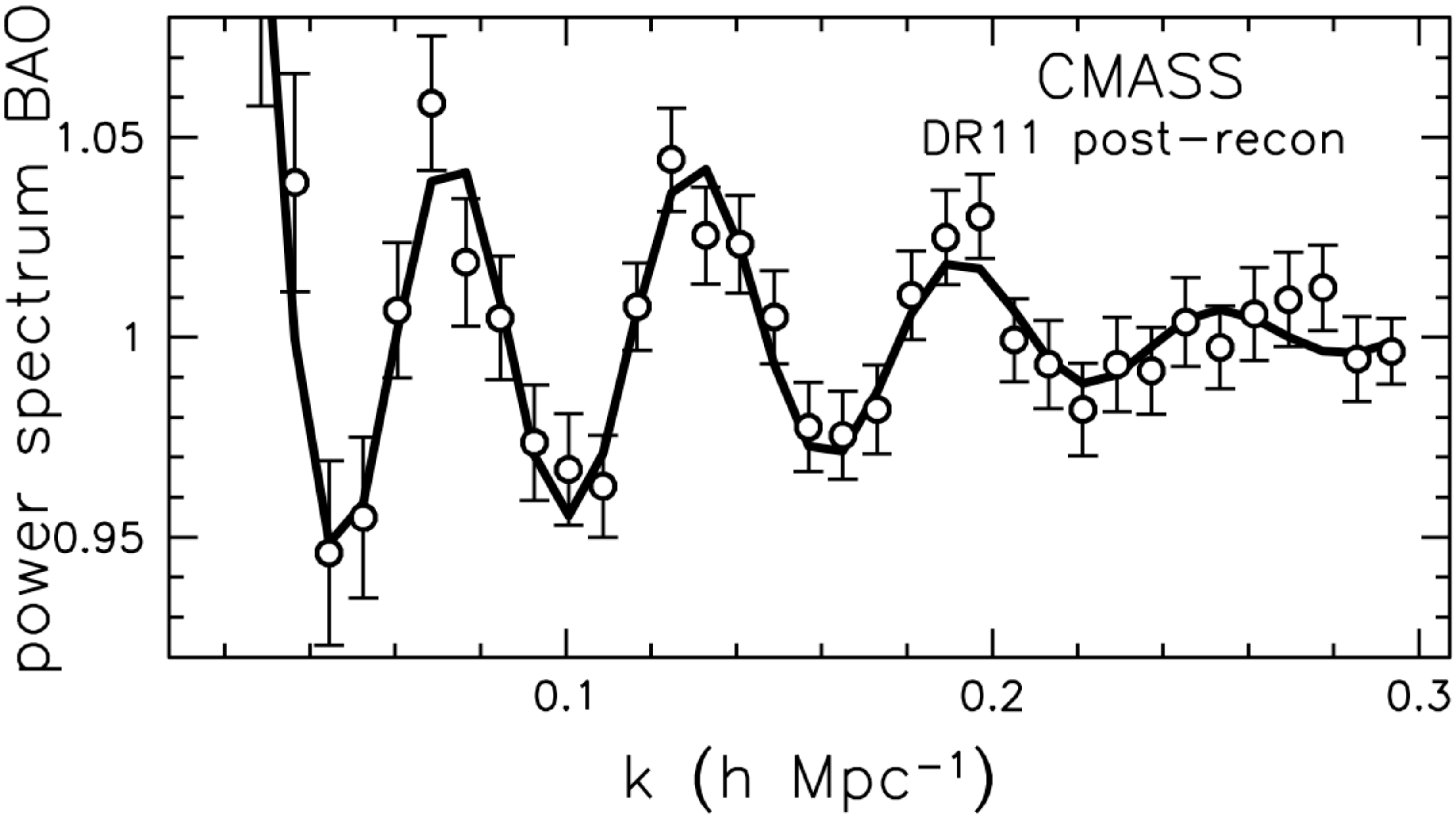
$\Omega_m = 0.256 \pm 0.027$

Allows us to examine same basic standard rod at both z = 0.35 and z = 1100 (CMB)



Now the BAO technique has been used out to z>~0.6...

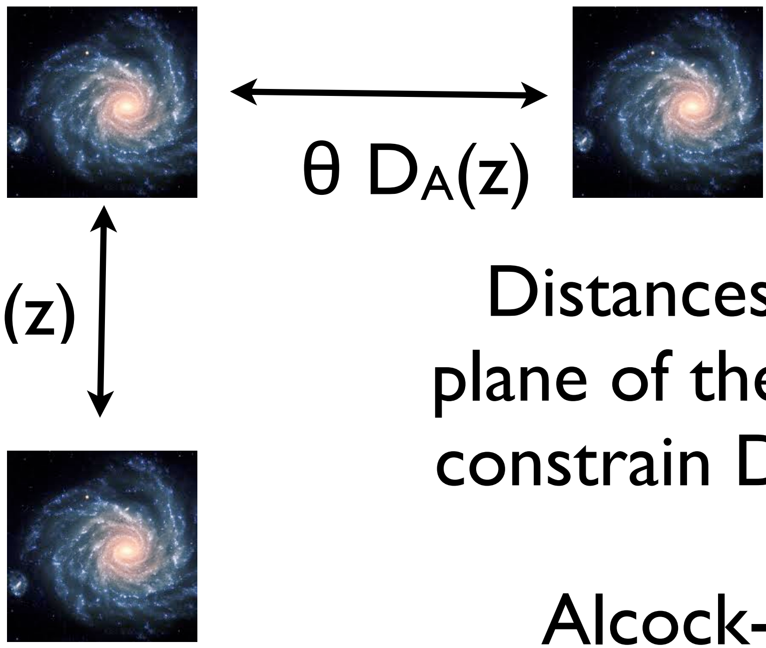
Results of BOSS survey at z~0.55



Anderson+2013

The Baryon Acoustic Oscillation Method can be used to look for structure in the plane of the sky, but also along the line of sight

Observables of interest for constraining the cosmology: $D_A(z)$, $H(z)$



$c(\Delta z)/H(z)$

Distances in plane of the sky constrain $D_A(z)$

Distances along line of sight constrain $H(z)$

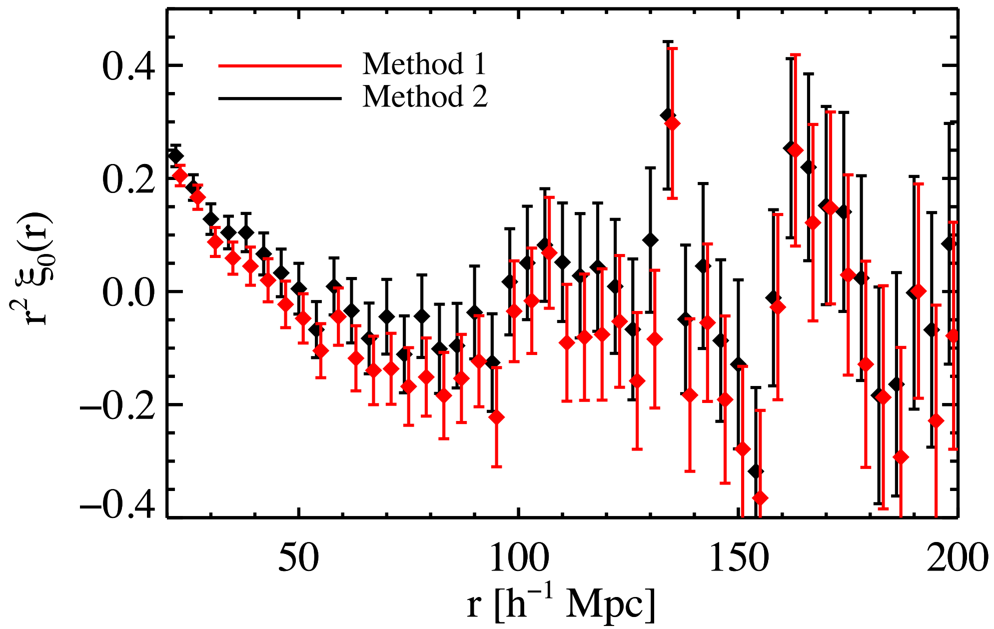
Alcock-Paczynski constraints

both length scales must be the same

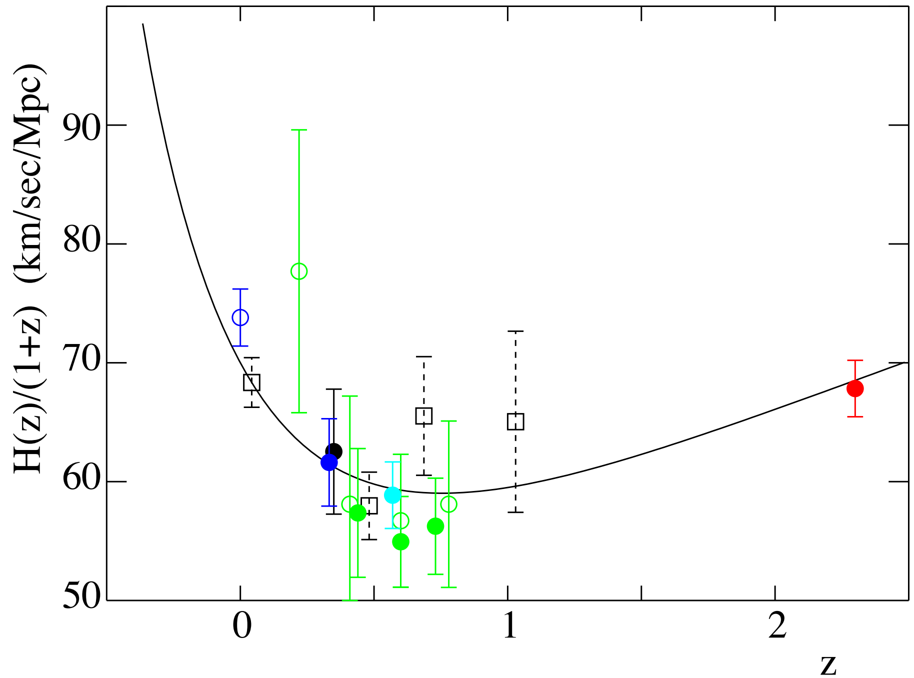
telescope

BAO have also been used to constrain H(z)... amazing out to z~2.3...

Power spectrum measured for absorption lines from gas at z~2.3 in z~2.5 quasars



Constraints on the evolution of the Hubble parameter to z~2.3



Busca+2013

Baryonic Acoustic Oscillations are one of the four main techniques being used for dark energy experiments at present.

The other three are the following:

1. Galaxy Clusters
2. Cosmic Shear
3. Supernovae Ia Search Experiments

Enigma of Dark Energy

Already up to this point in the course, you have already seen many different pieces of evidence for some form of dark energy, which we have expressed as $\Omega_\Lambda > 0$

There is an overwhelming amount of evidence for its existence

→ SNe Search Experiments

Observed SNe in distant galaxies are observed to be fainter than they would otherwise be without dark energy

→ Late Integrated Sachs-Wolfe Effect

Dark Energy Affects the Differential Redshifting of CMB photons as they move in and out of gravitational potential. By cross correlating known galaxy clusters with CMB, we can observe this effect.

→ First Acoustic Peak of CMB Implies Universe is Flat, while other evidence indicates $\Omega_M \sim 0.3$ (Large Scale Flows, Kaiser Effect, Ratio of Baryons and Total Matter in Galaxy Clusters, Large Scale Structure, Baryon Acoustic Oscillations)

Enigma of Dark Energy

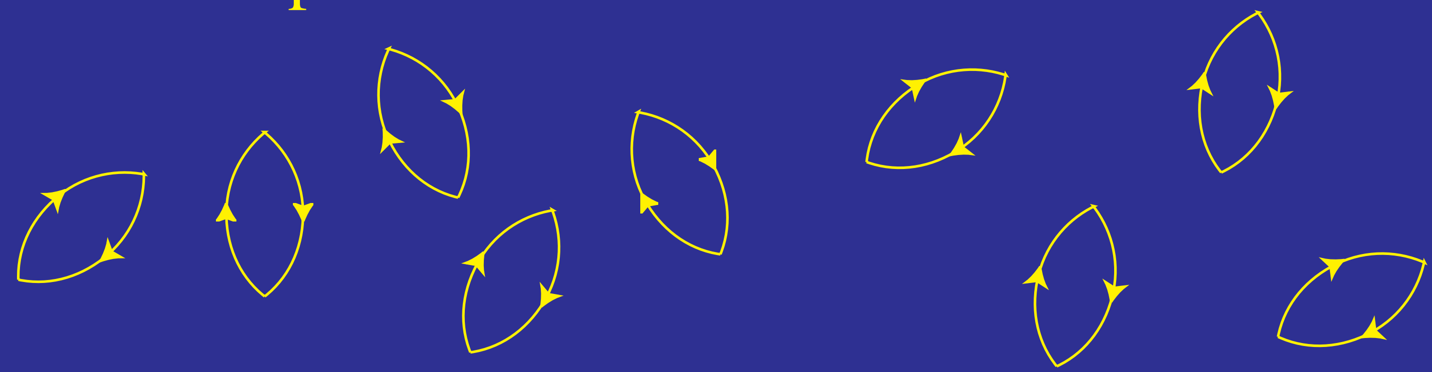
As you all know, a key component of universe is dark energy. Very roughly, it exerts a repulsive force on the space fabric -- increasing its acceleration.

There is an overwhelming amount of evidence for its existence

However, its nature remains an enigma

Enigma of Dark Energy

- Constant energy density, hence increasing net energy as universe expands consistent with data
- Quantum mechanics allows/predicts such phenomena in the form vacuum energy: empty space is alive with virtual particles



- Naive prediction is 10^{120} times too big and more sophisticated models still 10^{60} off

Credit Hu

→ Possibly more natural to explain dark energy as a scalar field that evolves with cosmic time...

Enigma of Dark Energy

As a result of there is a lot of interest in exploring forms of dark energy that are not constant, but evolve with cosmic time

Quote from Dark Energy Task Force

VI. A Dark Energy Primer

In General Relativity (GR), the growth of the Universe is described by a scale factor $a(t)$, defined so that at the present time t_0, $a(t_0) = 1$. The time evolution of the expansion in GR obeys

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}, \quad > 0$$

This implies that

1. The Universe is dominated by some particle or field (*dark energy*) that has negative pressure, in particular $w = P/\rho < -1/3$; ***or***
2. There is in fact a non-zero cosmological constant; ***or***
3. The theoretical basis for this equation, GR or the standard cosmological model, is incorrect.

Enigma of Dark Energy

In order to ascertain the form of dark energy, we parameterize its effects in terms as the w parameter:

$$P = w\rho c^2$$

Typically take c = 1

There are a few important cases:

Type dark energy	w	redshift scaling of DE density	dynamical significance
Cosmological Constant λ	-1	Constant	z<1
Quintessence	$-1 < w < -1/3$	$(1+z)^{+1}$ for w=-2/3	earlier
Phantom Energy	$w < -1$	$(1+z)^{-1}$ for w=-4/3	later

Enigma of Dark Energy

In the case of quintessence or phantom energy (w < -1 or w > -1), the dark energy density evolves with cosmic time.

How does it evolve?

Friedmann's equations:

$$\dot{a}^2 = \frac{8\pi G}{3}\rho a^2 + k \qquad \ddot{a} = -\frac{4\pi G}{3}\rho(1+3w)a \qquad (\text{for } w = \text{const.})$$

w = P/ρ

differentiate with respect to time

$$2\dot{a}\ddot{a} = \frac{8\pi G}{3}\frac{d}{dt}\left(\rho a^2\right) \qquad \dot{a}\ddot{a} = -\frac{4\pi G}{3}\rho(1+3w)a\dot{a}$$

multiply by da/dt

$$\frac{d}{dt}\left(\rho a^2\right) = -\rho(1+3w)a\dot{a}$$

$$\frac{d}{dt}\left(\rho a^2\right)a + \rho a^2\dot{a} = -\rho(3w)a^2\dot{a}$$

$$\frac{d}{dt}\left(\rho a^3\right) = -\rho(3w)a^2\dot{a}$$

$$\dot{\rho}a^3 + 3\rho\dot{a}a^2 = -3w\rho a^2\dot{a}$$

$$\frac{d\log\rho}{dt} = -3(1+w)\frac{d\log a}{dt} \qquad \Rightarrow \qquad \rho \propto a^{-3(1+w)}$$

For w = -1 the density is constant.

Enigma of Dark Energy

Given this evolution in the energy density of dark energy, the second Friedmann equation can be rewritten as follows:

$$H^2(a) \equiv \left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_k a^{-2} + \Omega_X a^{-3(1+w)}\right],$$

The term Ω_X represents the cosmological constant if $w = -1$. Otherwise, it represents dark energy with constant w.

Based on the above equation, we can derive all the standard formulas for the distances, evolution of the Hubble constant, growth factors, etc., but let us before doing this, let us consider another case first.

Time Varying Dark Energy

the most generic model for Dark Energy allows for a time variation in the equation of state parameter: $w = w(z)$

common parameterizations: $w(z) = w_0 + w_1 z$

$w(z) = w_0 + w_a(1-a) = w_0 + w_a\, z/(1+z)$

For this parameterization, we can rewrite the $a^{-3(1+w)}$ factor in the second term of the Friedmann equation in the following manner:

$$a^{-3(1+w)} \to \exp\left(3\int_a^1 \frac{da'}{a'}\left[1+w(a')\right]\right).$$

for a time-independent w(a), this just reduces to $a^{-3(1+w)}$

$$H^2(a) \equiv \left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_k a^{-2} + \Omega_X a^{-3(1+w)}\right],$$

How does the energy density in dark energy evolve relative to other components of universe for these more generic models?

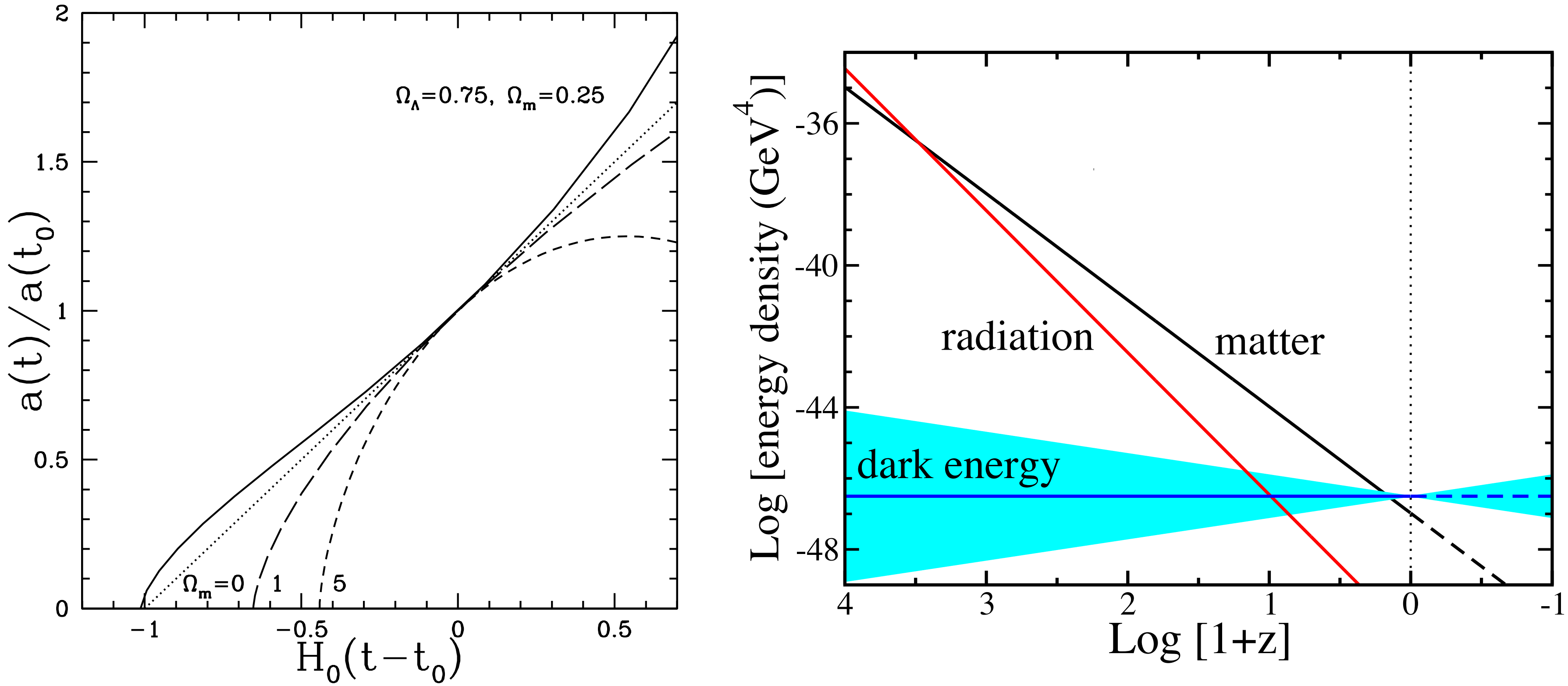
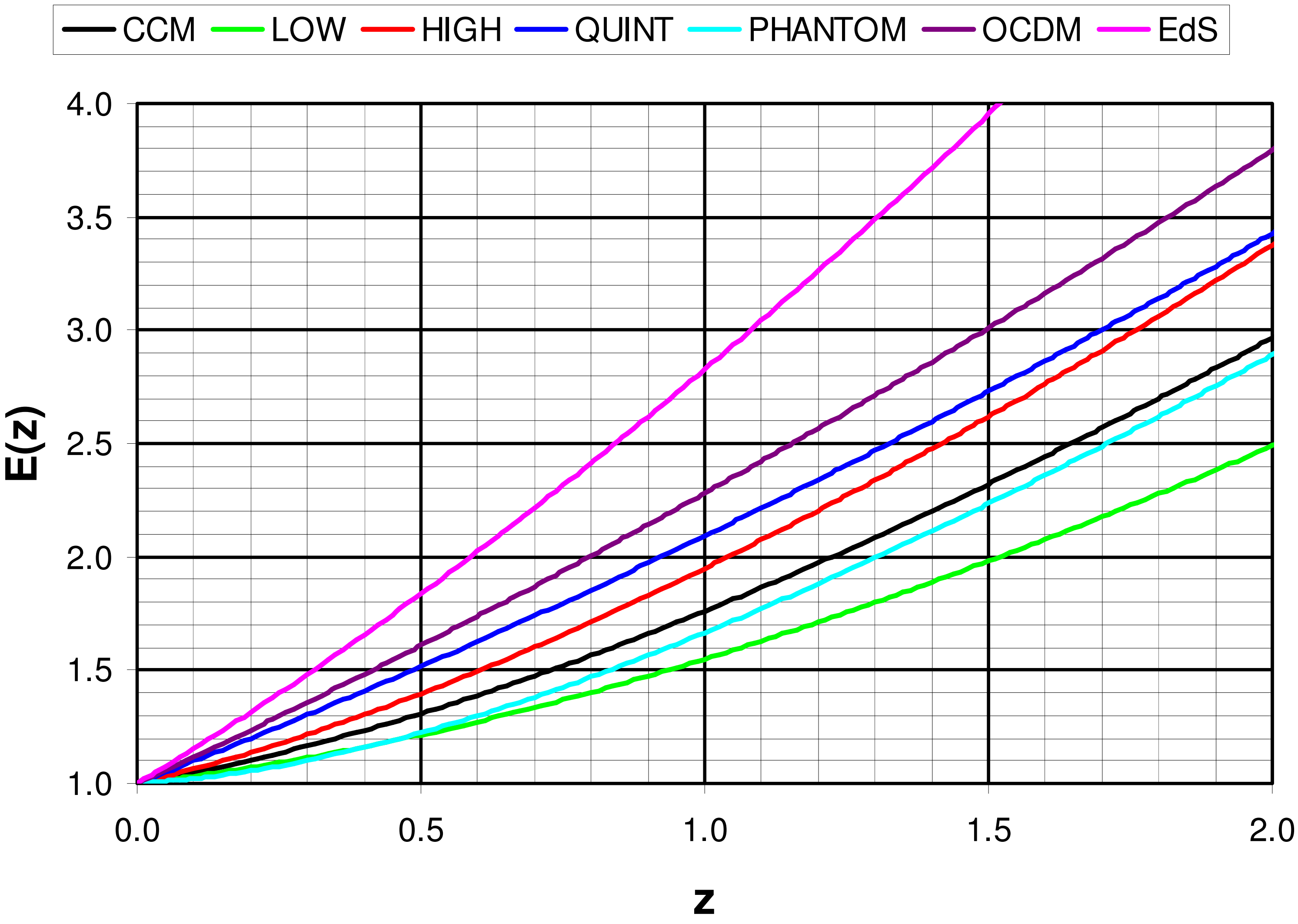


FIGURE 1. Left panel (a): Evolution of the scale factor vs. time for four cosmological models: three matter-dominated models with $\Omega_0 = \Omega_m = 0, 1, 5$, and one with $\Omega_\Lambda = 0.75, \Omega_m = 0.25$. Right panel (b): Evolution of radiation, matter, and dark energy densities with redshift. For dark energy, the band represents $w = -1 \pm 0.2$. From Frieman et al. [13].

How does this change the behavior of quantities we calculated before?

Evolution Function E(z)

$H(z) = H_0\, E(z)$



$[\Omega_m, \Omega_{DE}, w]$

EdS [1.0,0,0]

OCDM [0.3,0,0]

QUINT [0.3,0.7,-0.5]

HIGH [0.4,0.6,-1]

CCM [0.3,0.7,-1]

PHANTOM [0.3,0.7,-1.3]

LOW [0.2,0.8,-1]

for flat and open geometries, E(z) is a monotonic function of z

Credit: Fassbender

We can also apply this modified E(z) factor to our calculation of distances.....

Comoving Distance :

$$D(z) = R_0 \cdot r = \begin{cases} \dfrac{d_H}{\sqrt{|\Omega_k|}} \sin\left(\sqrt{|\Omega_k|} \displaystyle\int_0^z \frac{dz}{E(z)} \right) & \text{closed Universe } k=1,\ \Omega_k<0 \\ d_H \displaystyle\int_0^z \frac{dz}{E(z)} & \textbf{flat geometry } \mathbf{k=0,\ \Omega_k=0} \\ \dfrac{d_H}{\sqrt{|\Omega_k|}} \sinh\left(\sqrt{|\Omega_k|} \displaystyle\int_0^z \frac{dz}{E(z)} \right) & \text{open Universe } k=-1,\ \Omega_k>0 \end{cases}$$

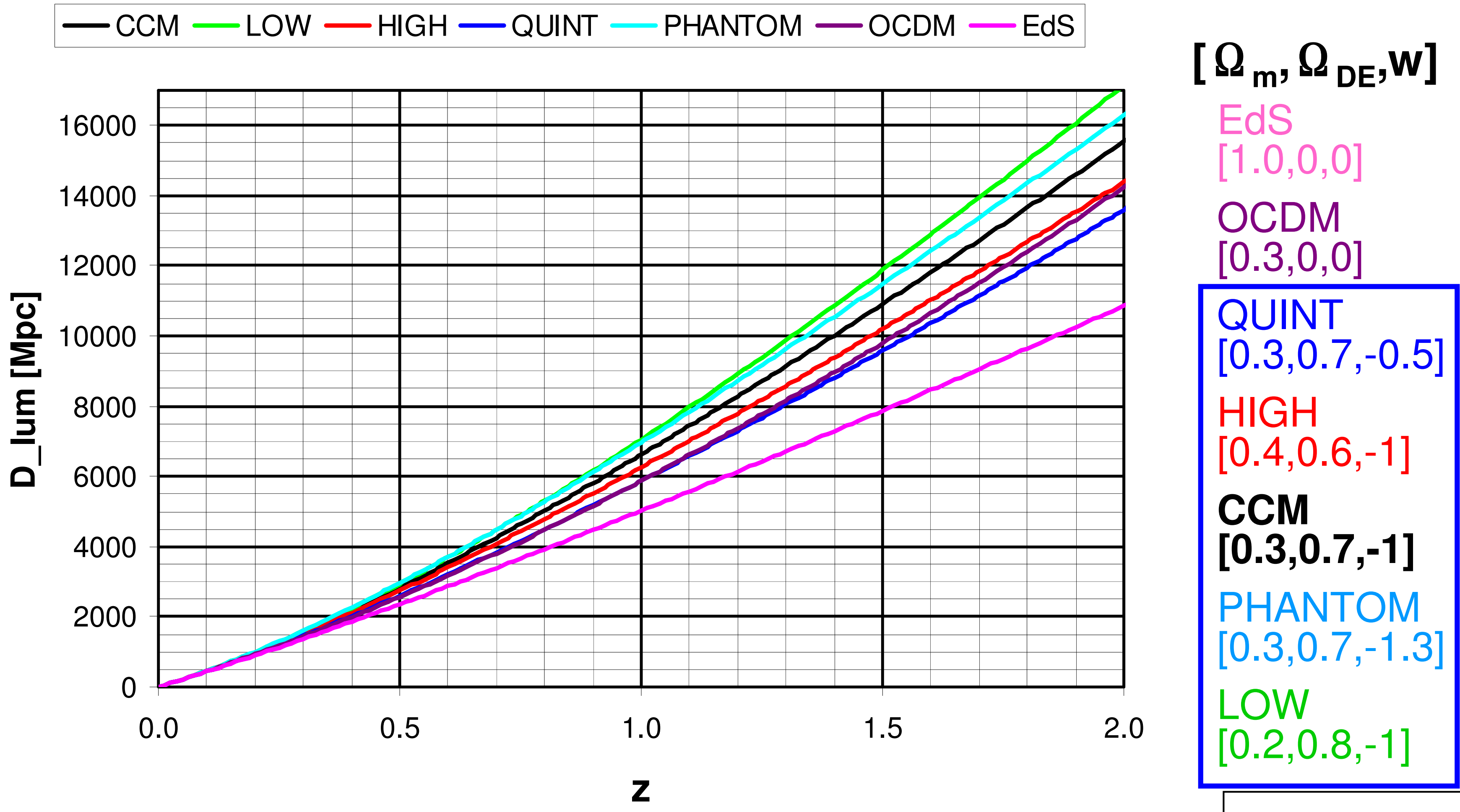
$$\text{mit:} \quad \Omega_k \equiv 1 - \Omega_m - \Omega_\Lambda \quad \& \quad d_H = 4280 h_{70}^{-1}\,\text{Mpc}$$

Luminosity Distance : $$D_L(z) = (1+z) \cdot D(z)$$

Angular Diameter Distance : $$D_A(z) = \xi(z) = \frac{D(z)}{1+z}$$

What is the effect on the Luminosity Distance D_L?

- cosmic distances are proportional to the integral over 1/E(z), i.e. the area under this function out to redshift z
- higher expansion rates in the past, i.e. larger values for the evolution function E(z), translate into shorter cosmic distances D(z) [for flat geometries]
- the larger the influence of Dark Energy, the larger the cosmic distances



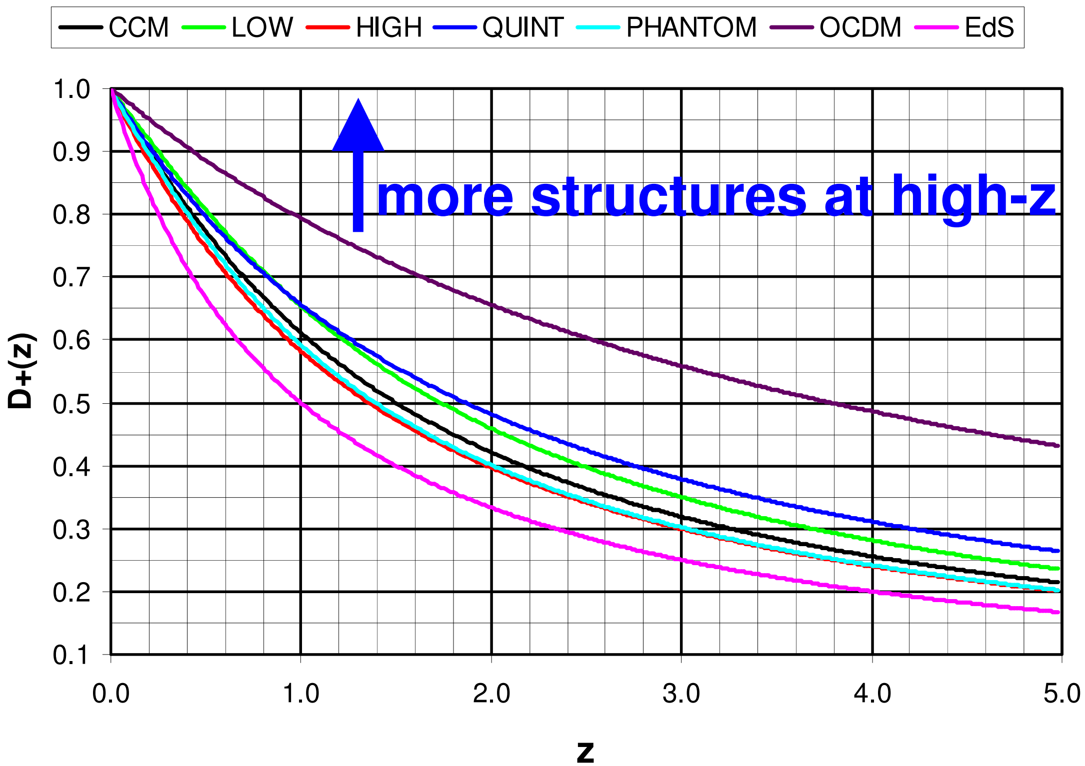
Credit: Fassbender

What is the effect on the Growth Factor?

- the linear structure growth function D+(z) is a solution to the density perturbation growth equation for the linear regime (L3) $\delta(\mathbf{x},t) = D_+(t) \cdot \delta_{i+}(\mathbf{x},t_i)$

$$D_+(z) = \frac{5}{2}\Omega_\mathrm{m} E(z) \cdot \int_z^\infty \frac{1+z'}{E(z')^3} dz'$$

- flat cosmologies with a dark energy component exhibit structure growth in between the Einstein-de Sitter (EdS) case of $D_+=(1+z)^{-1}$ and the slow structure growth of a low density open Universe (OCDM)



[Ω_m, Ω_{DE}, w]

EdS
[1.0,0,0]

OCDM
[0.3,0,0]

QUINT
[0.3,0.7,-0.5]

HIGH
[0.4,0.6,-1]

CCM
[0.3,0.7,-1]

PHANTOM
[0.3,0.7,-1.3]

LOW
[0.2,0.8,-1]

Credit: Fassbender

How can we constrain the w parameter?

Generally, we constrain the w parameter in the same way we constrain many other cosmological parameters.

We constrain it by looking at the following quantities versus redshift (cosmic time, see earlier lecture):

Useful in computing distances along the line of sight

$H(z) = H_0 E(z)$

Distances

Volume Element

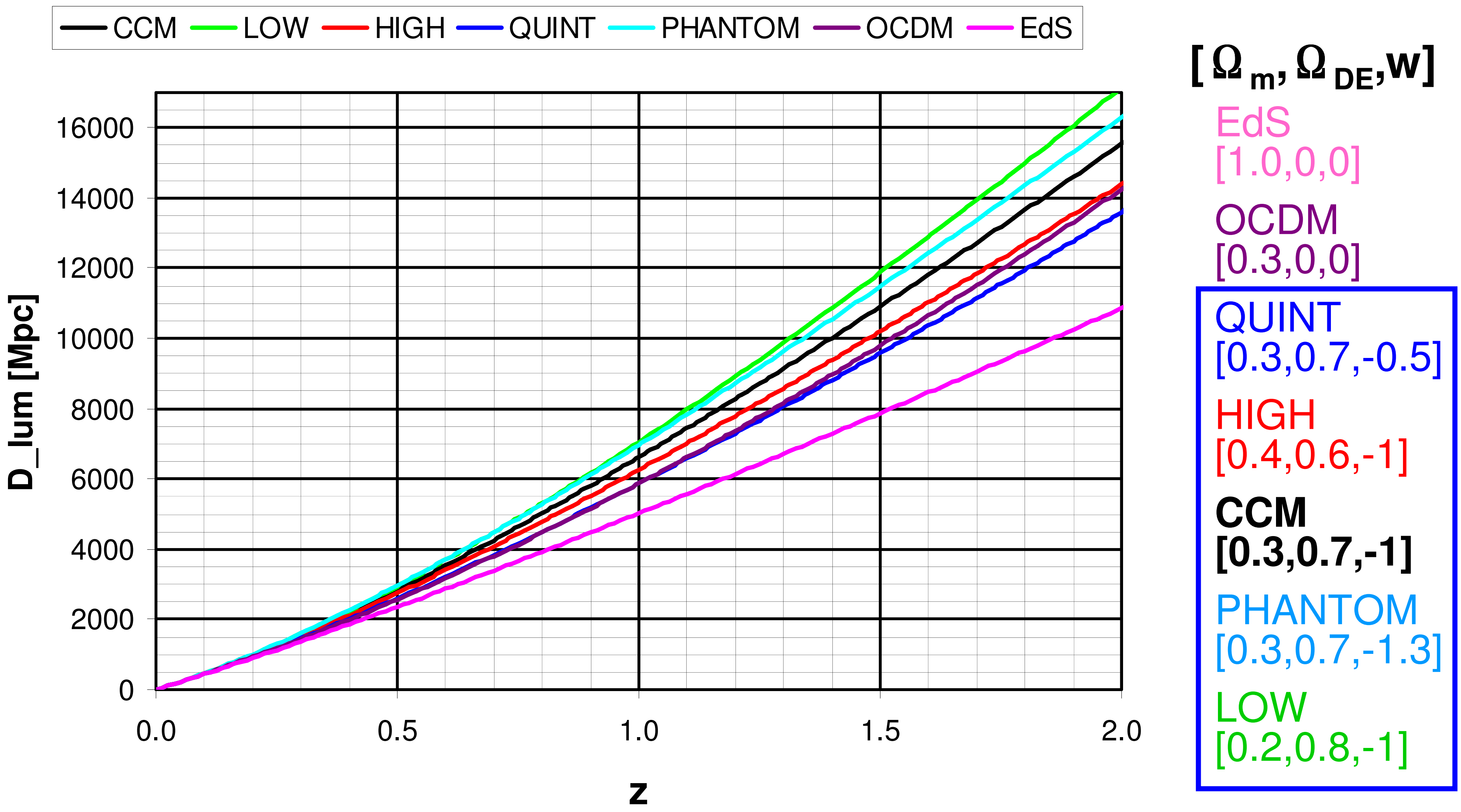
$E(z)$

Geometrical Tests

Growth Factor (Rate at which structures in Universe Grow)

How can we probe this?

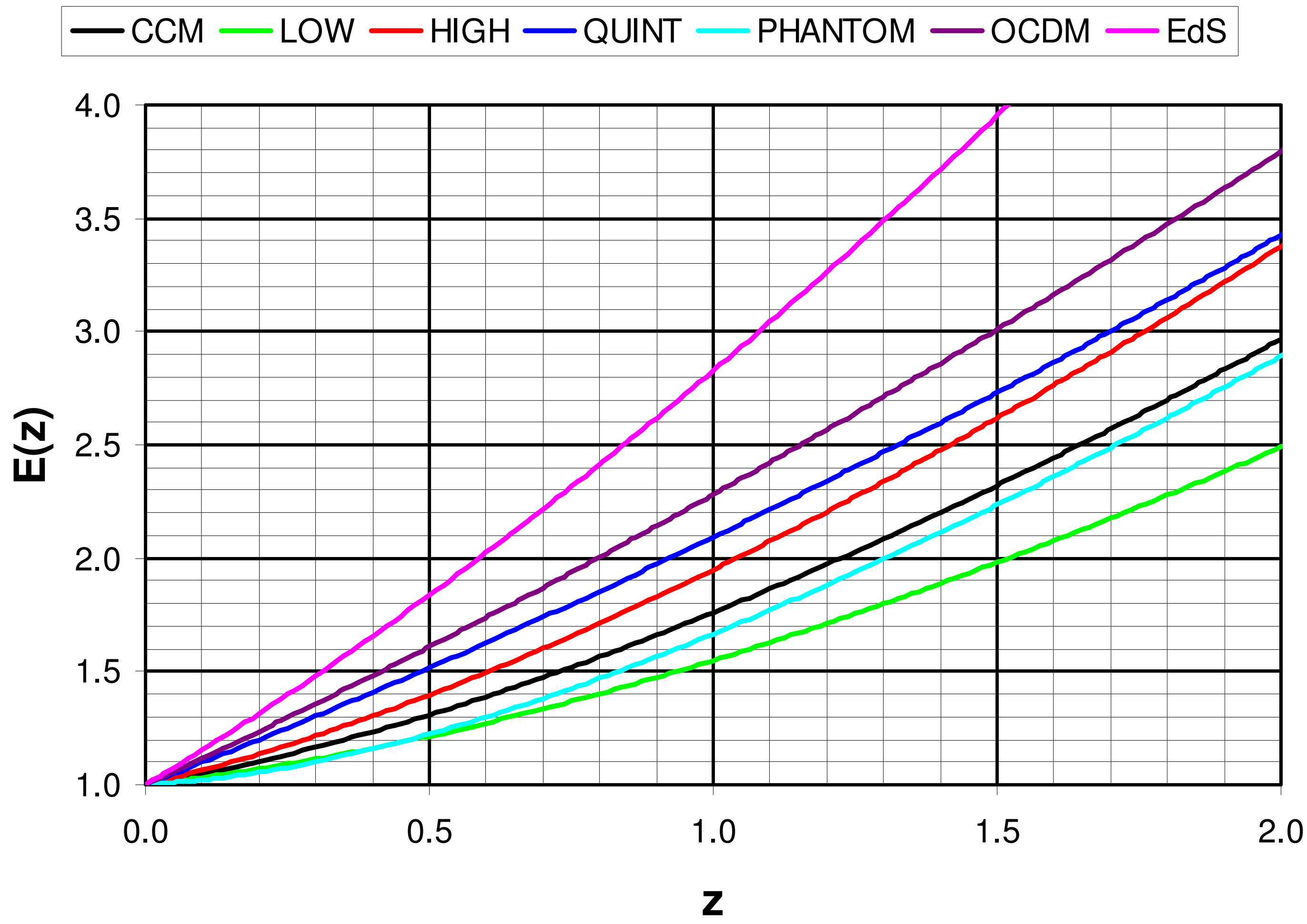
Luminosity Distance



Credit: Fassbender

How can we probe this?

The Evolution Function E(z)



$[\Omega_m, \Omega_{DE}, w]$

EdS
[1.0,0,0]

OCDM
[0.3,0,0]

QUINT
[0.3,0.7,-0.5]

HIGH
[0.4,0.6,-1]

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[0.3,0.7,-1]

PHANTOM
[0.3,0.7,-1.3]

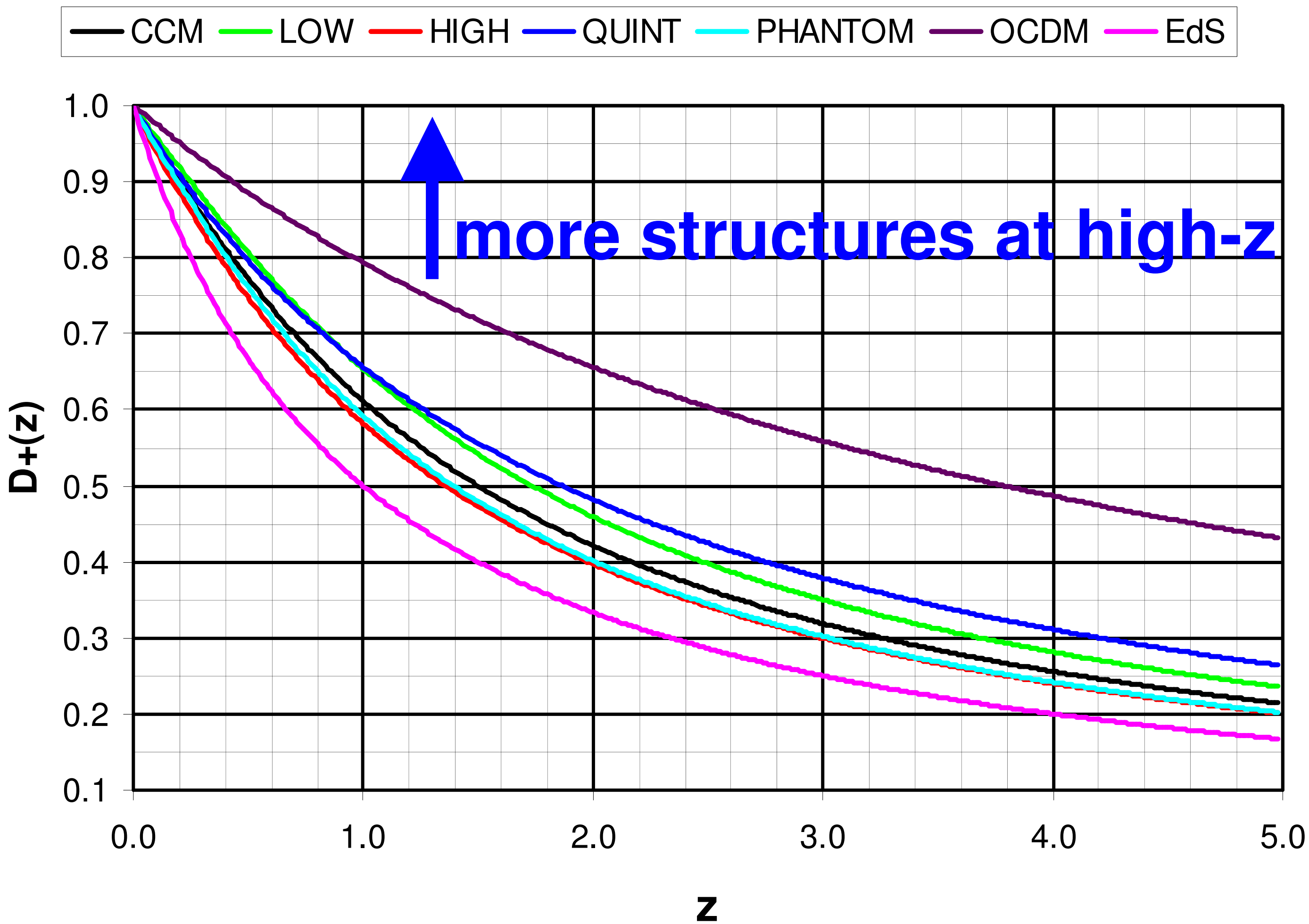
LOW
[0.2,0.8,-1]

for flat and open geometries, E(z) is a monotonic function of z

Credit: Fassbender

How can we probe this?

Growth Factor



[Ω_m, Ω_{DE},w]

EdS
[1.0,0,0]

OCDM
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CCM
[0.3,0.7,-1]

PHANTOM
[0.3,0.7,-1.3]

LOW
[0.2,0.8,-1]

structure grow efficiently when $\Omega = 1$ (since density is clos
where slight overdensities cause collapse)

Credit: Fassbender

Here's an alternate set of plots:

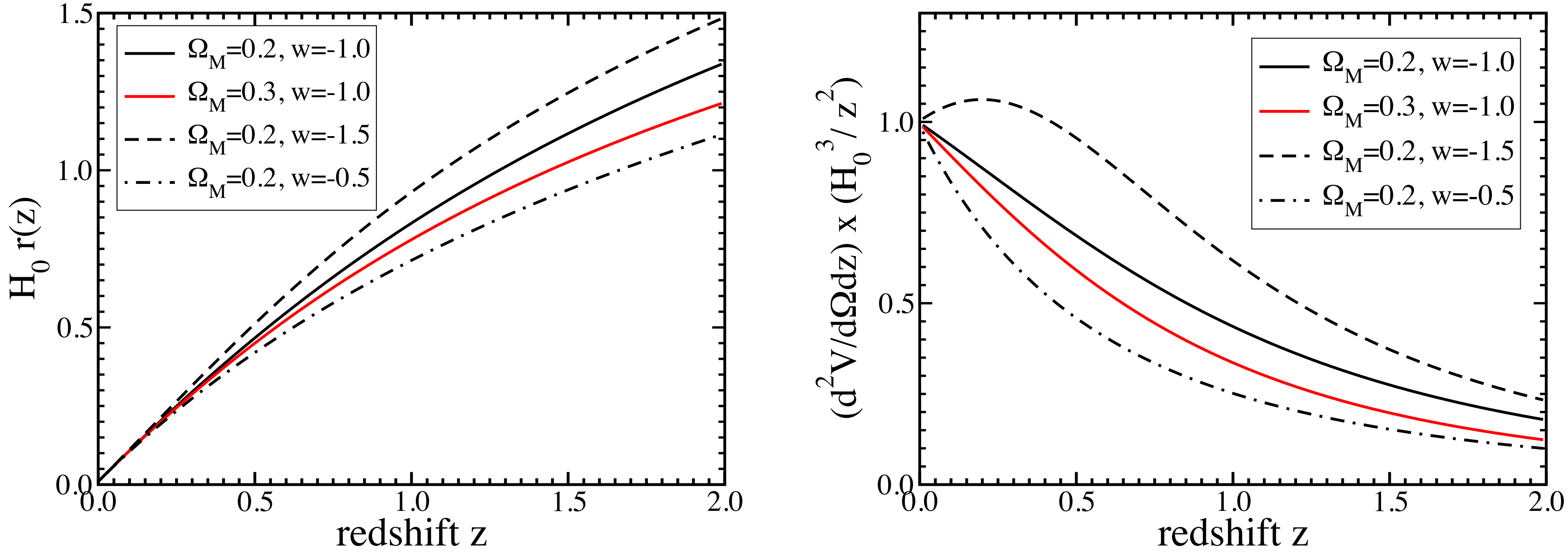
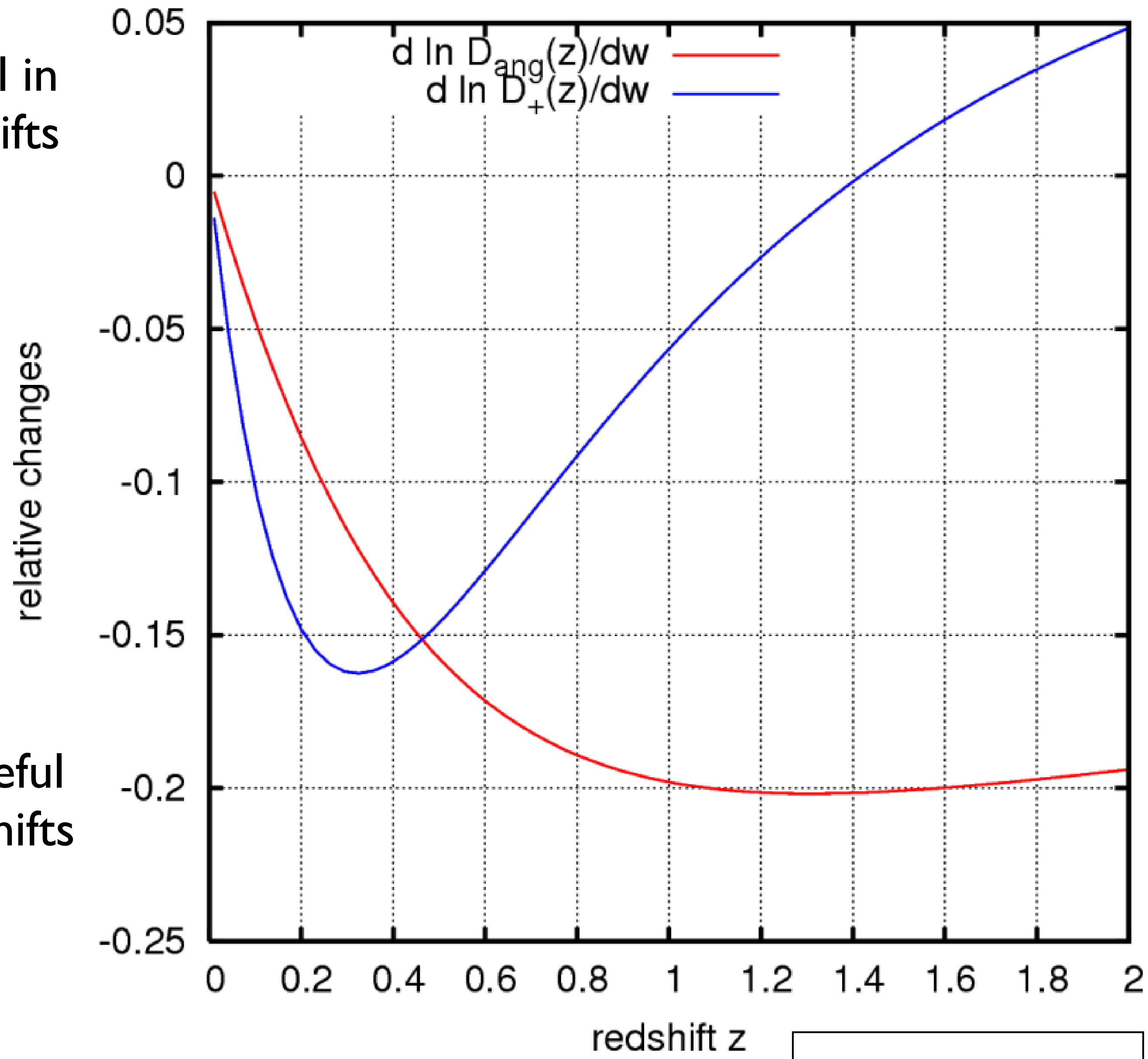


FIGURE 2. Left: Distance vs. redshift in a flat Universe with different values of the cosmological parameters Ω_m and w. Right: volume element vs. redshift for same models. From Frieman et al. [13].

Where do they provide the strongest constraints?

growth factor most useful in examining w at low redshifts

distance measures most useful in examining w at high redshifts



Credit: Bartelmann

So the game is to determine the w parameter and how it depends on redshift

There are four standard methods:

1. Supernovae Ia (lecture 4)
   - -- use of standard candles to establish distance-redshift relation
   - -- first established existence of dark energy >20 years ago
2. Baryonic Acoustic Oscillations (This lecture)
   - -- gives us a standard rod to establish distance-redshift relation with low systematics
3. Galaxy Clusters (This lecture)
   - -- provide us with sensitive probe of growth of structure
   - -- early evidence for low Ω_m
4. Weak Gravitational Lensing (Next Lecture)
   - -- provide us with sensitive probe of growth of structure
   - -- powerful technique still in process of realizing full potential

Now let's discuss what we can learn about the universe and the cosmological parameters from galaxy clusters

Galaxy Clusters

Galaxy clusters are large regions of the universe that have collapsed (due to gravity)

mass > 10^{14} M_{sol}

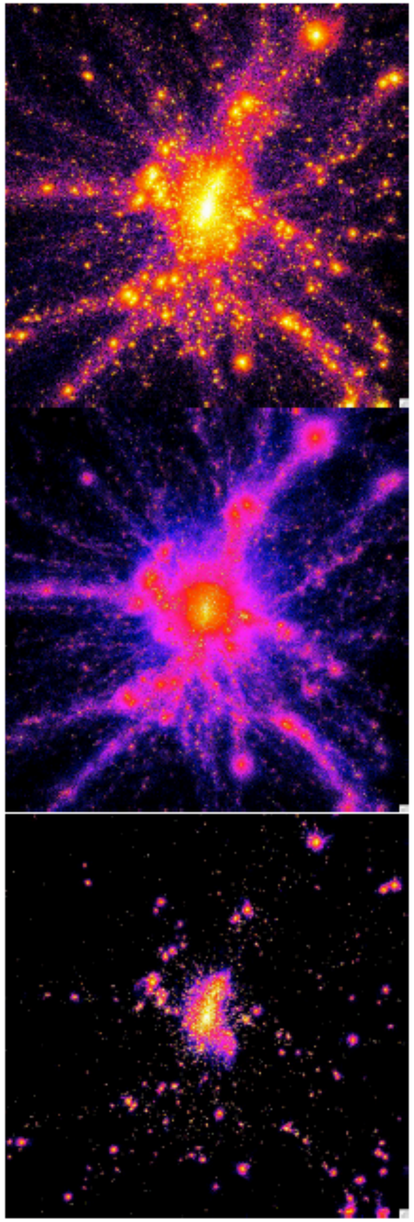
Approximate mass budget:

~2% galaxies

~13% in a very hot ionized gas

~85% in dark matter

Most of the baryons are in the ionized gas!



Credit: Porciani

Intra-Cluster Medium (ICM)

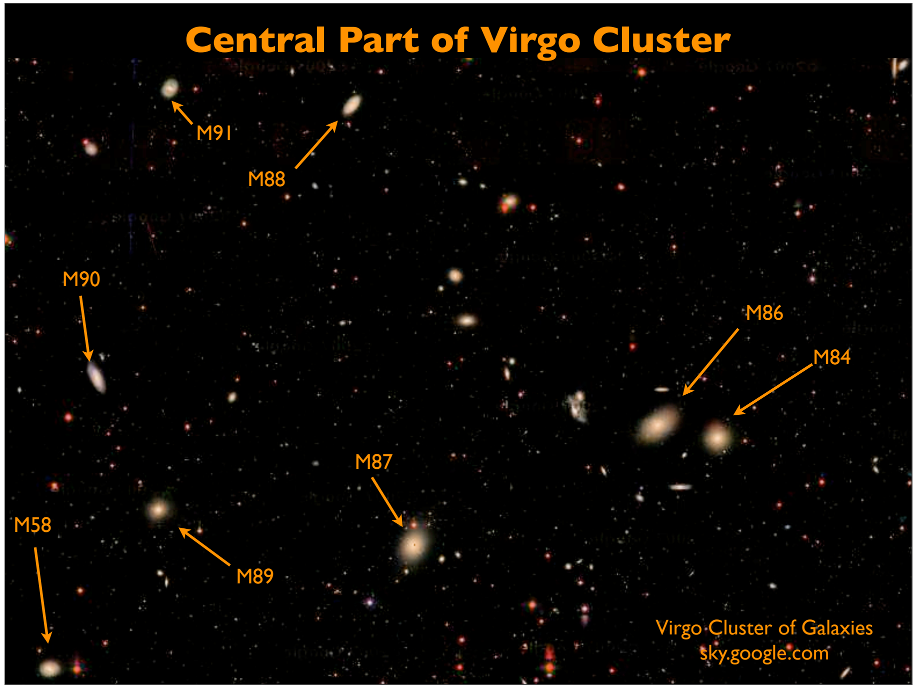
- Majority of observable cluster mass (majority of baryons) is hot gas
- Temperature $T \sim 10^8$ K ~ 10 keV (heated by gravitational potential)
- Electron number density $n_e \sim 10^{-3}$ cm^{-3}
- Mainly H, He, but with heavy elements (O, Fe, ..)
- Mainly emits X-rays (but also radio and gamma rays)
- $L_X \sim 10^{45}$ erg/s, most luminous extended X-ray sources in Universe
- Causes the Sunyaev-Zel'dovich effect (SZE) by inverse Compton scattering the background CMB photons

Credit: Porciani

Two of the most well known near-by galaxy clusters are the Virgo cluster and the Coma cluster

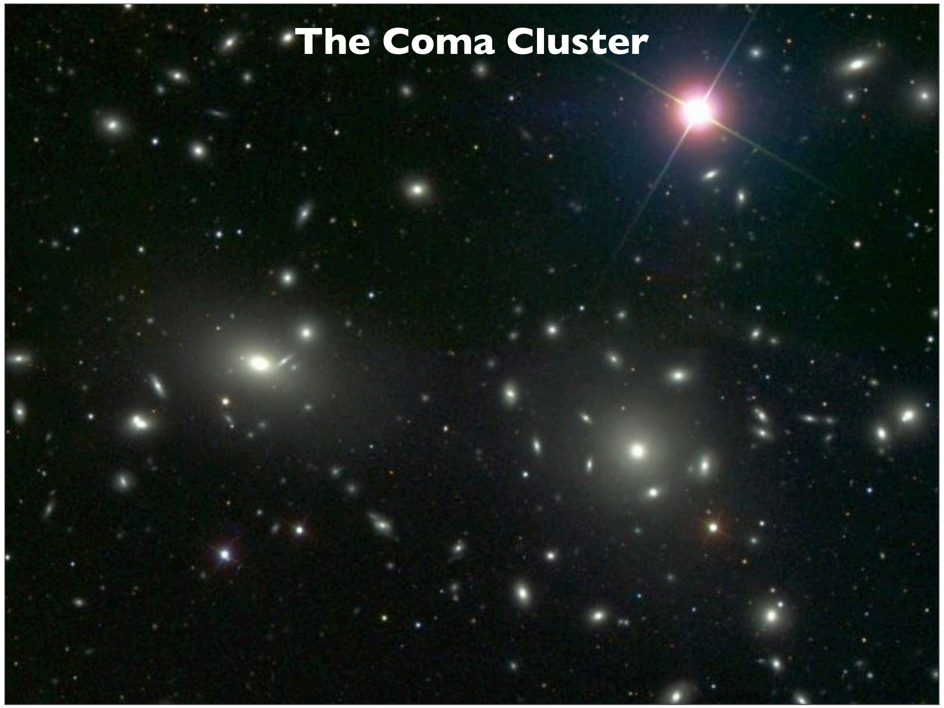
Virgo cluster

- contains >250 large galaxies
- contains 2000 smaller galaxies
- covers 10 x 10 degrees on sky
- 18 Mpc away
- 3 Mpc diameter



Coma cluster

- contains >1000 large galaxies
- contains 10000 smaller galaxies
- 90 Mpc away
- 6 Mpc diameter
- largest galaxies are giant ellipticals



Credit: Papovich

Galaxy clusters also provide us with important constraints on cosmology!

Why?

1. Density perturbations in universe grow in a regular, well-defined way.
2. Galaxy clusters are clear end result of the growth of density perturbations in universe
3. One can model the build-up of galaxy clusters primarily through gravitation, and so it is much simpler to model than lower mass (i.e., galaxy) systems.
4. Mass function of clusters depends sensitively on Ω_m the matter density and σ_8 the amplitude of density fluctuations
5. Clusters are relatively straightforward to identify in observable surveys

What can we learn from galaxy clusters?

1. Probe σ_8 and Ω_m through measured mass function of galaxy clusters (clusters probed mass function of collapsed structures)

2. Probe cosmological parameters by examining how the apparent volume density of clusters evolve

3. Derive Ω_m based on relative mass in gas and dark matter in clusters

4. Probe matter power spectrum and Ω_m from the observed clustering of galaxy clusters

Interlude: Halo Mass Function

Mass build-up in universe quantified with halo mass function

Through gravitation, overdensities in the early universe grow until they collapse. As time goes on, the mass of these collapsed objects become larger and larger. The volume density of the collapsed sources vs. mass is the **halo mass function**.

How is the Halo Mass Function modelled?

It is modelled using the functions below:

Press–Schechter (1974)

$$\frac{dn_M}{d\ln\sigma^{-1}} = \sqrt{\frac{2}{\pi}}\frac{\Omega_M\rho_{cr0}}{M}\frac{\delta_c}{\sigma}\exp\left[-\frac{\delta_c^2}{2\sigma^2}\right].$$

Jenkins et al. (2001)

$$\frac{dn_M}{d\ln\sigma^{-1}} = A_J\frac{\Omega_M\rho_{cr0}}{M}\exp[-|\ln\sigma^{-1} + B_J|^{\epsilon_J}]$$

δ_c = 1.67 (equivalent linear growth rate where source would collapse)

n_M = volume density of collapsed sources with mass M

σ in the above formula is the expected 1 fluctuations in the overdensity of regions of the universe with mass M.

Cosmology predicts the variance on mass scale M:

$$\sigma^2(M,z) = \frac{D^2(z)}{(2\pi)^3}\int P(k)|W_k(M)|^2 d^3k,$$

1. Probe σ_8 and Ω_m through measured mass function of galaxy clusters (clusters probed mass function of collapsed structures)

Can we derive a mass function from the observations using galaxy clusters?

Yes -- 1) Do a survey

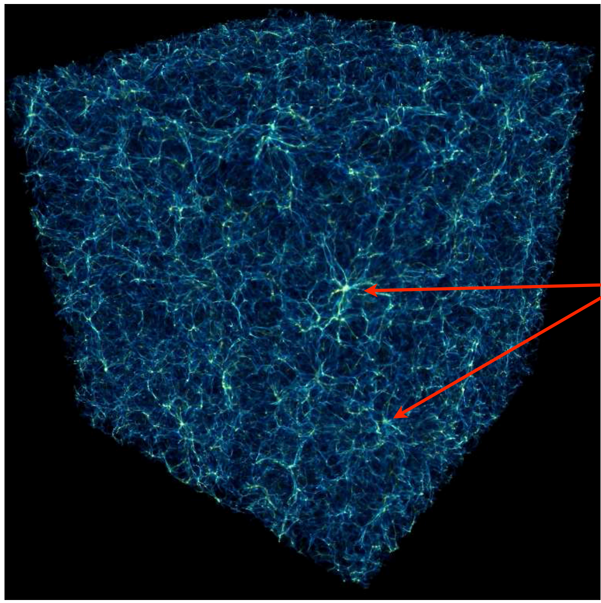
2) Have method to derive masses for clusters found in surveys

3) By comparing with theoretical mass functions, infer cosmological parameters

How do we find galaxy clusters?

This is an interesting question -- since galaxy clusters are quite rare -- and so one will not often find very massive ones even in large galaxy surveys.

volume density of $>10^{14}$ M_{sol} clusters in z=0 universe is ~7×10^{-5} Mpc^{-3}



700 Mpc comoving cube

Galaxy clusters: rare peaks in the density field

Credit: Porciani

How do we find galaxy clusters?

This is an interesting question -- since galaxy clusters are quite rare -- and so one will not often find very massive ones even in large galaxy surveys.

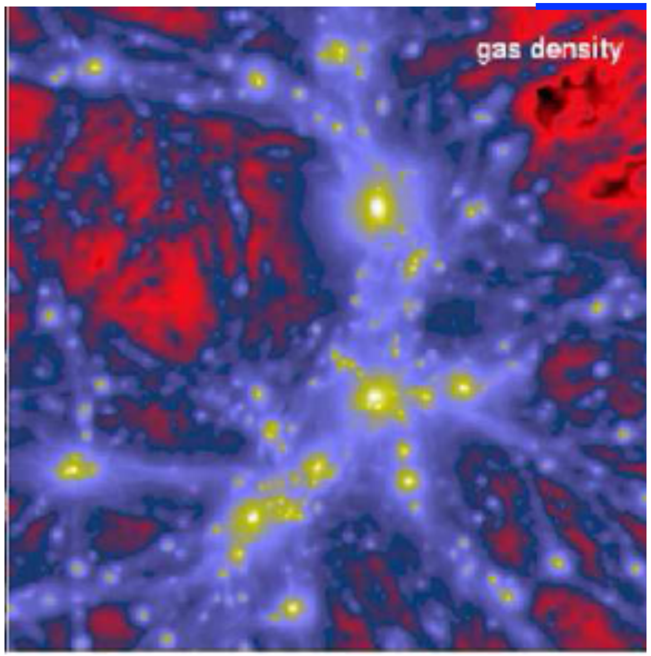
(one exception to the above point is in sky surveys that cover large parts of the sky like the Sloan Digital Sky Survey or the 2DF)

So, it often takes a dedicated endeavor to find large numbers of them

How do we find galaxy clusters?

1. By surveying the sky at x-ray wavelengths

Galaxy clusters are bright in the x-ray due to the fact that they contain very hot (10^8 K) ionized gas -- which produces significant thermal bremstrahlung



main observational limitation = surface brightness dimming

surface brightness is proportional to $(1+z)^{-4}$ (this is the generic cosmological dimming effect)

How do we find galaxy clusters?

1. By surveying the sky at x-ray wavelengths

To the right are the typical facilities that are used for these x-ray surveys

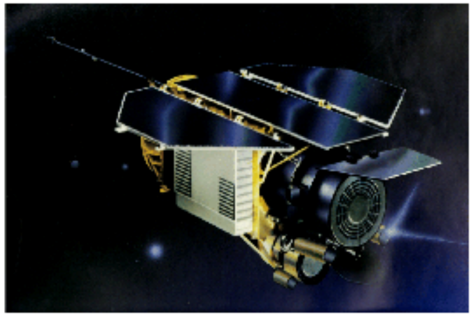
Essentially all extended x-ray sources are galaxy clusters, so straightforward to find.

Main other x-ray sources out in the universe is AGN which are 20x more numerous but those x-ray sources are not extended

In deep XMM exposures, galaxy clusters can be identified to z>1.

X-ray observatories

ROSAT



- German Survey-Satellite
- 1990-1998
- first All-Sky X-ray survey
- detection of ~2000 clusters
- census of the local cluster population (REFLEX+NORAS)
- 5 GC at z>1

XMM-Newton

- European X-ray Observatory
- 1999-201x
- 5"-10" resolution
- dozens of clusters z>1 (ongoing)

eROSITA

- German survey-instrument (MPE)
- start 2019
- ~20" resolution
- all-Sky Survey
- goal: ~100,000 clusters

Credit: Porciani

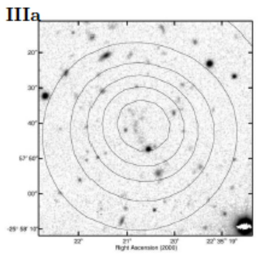
How do we find galaxy clusters?

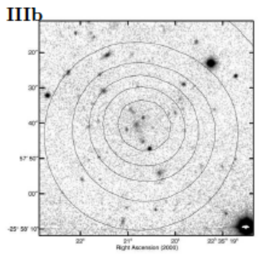
1. By surveying the sky at x-ray wavelengths

1. Start by identifying weak, extended x-ray sources in wide-area surveys

2. Follow up clusters and look for overdensity of red galaxies

VLT R-band image with X-ray contours

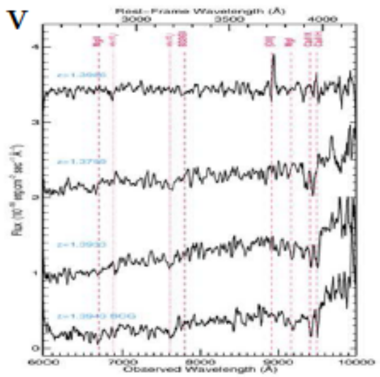




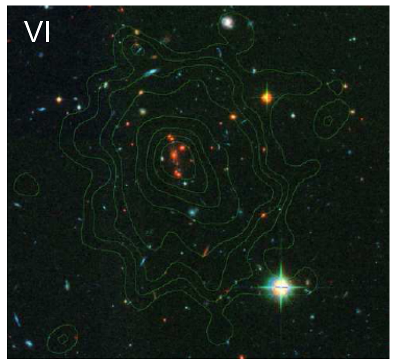
VLT z-band image with X-ray contour

3. Estimate redshift of cluster from position of spectral breaks in the red galaxies

4. Obtain spectra of red galaxies to confirm that a galaxy cluster has been found.



VLT spectra of 4 cluster member galaxies at z=1.39



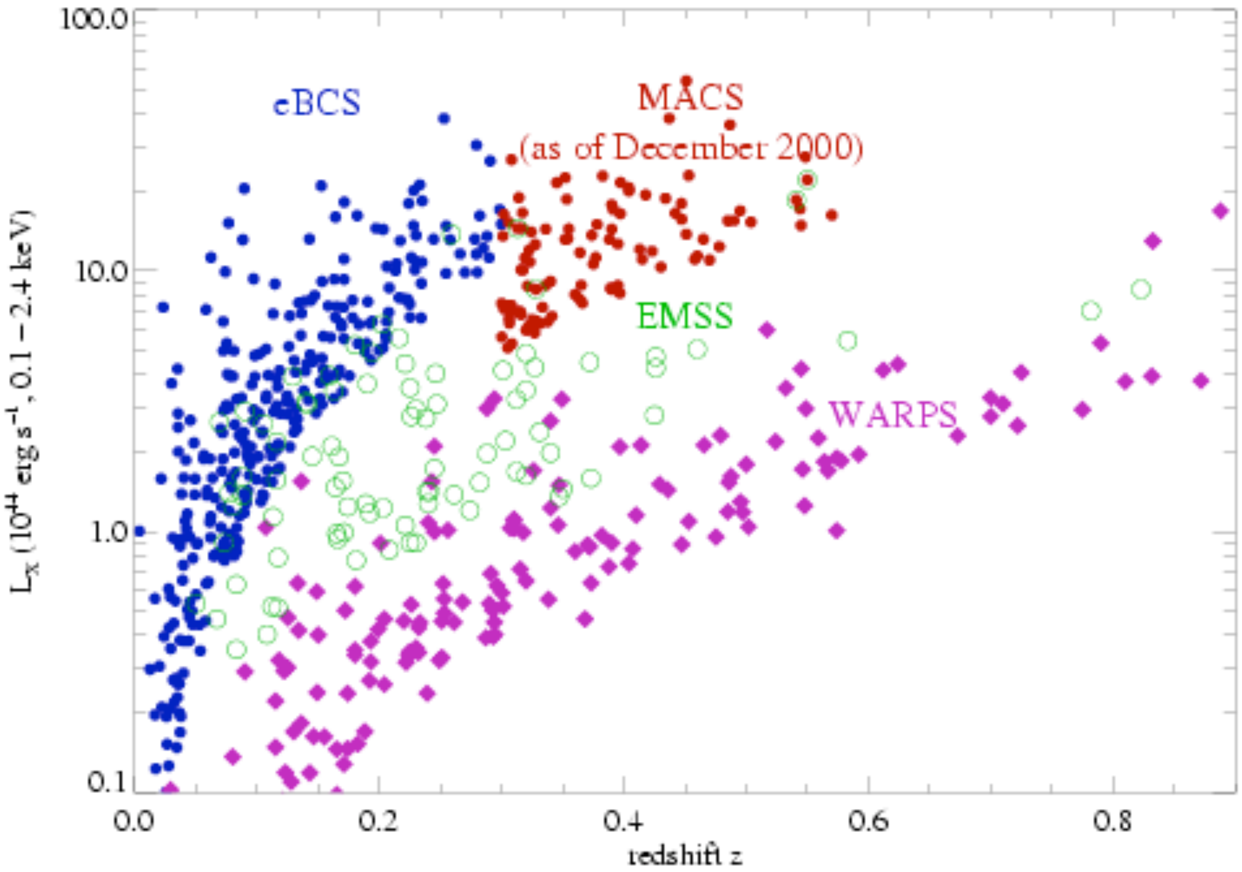
HST i+z + VLT K-band color image with Chandra contours of XMMU J2235.3-2557

Credit: Fassbender

How do we find galaxy clusters?

1. By surveying the sky at x-ray wavelengths

Here are a few X-ray cluster samples:



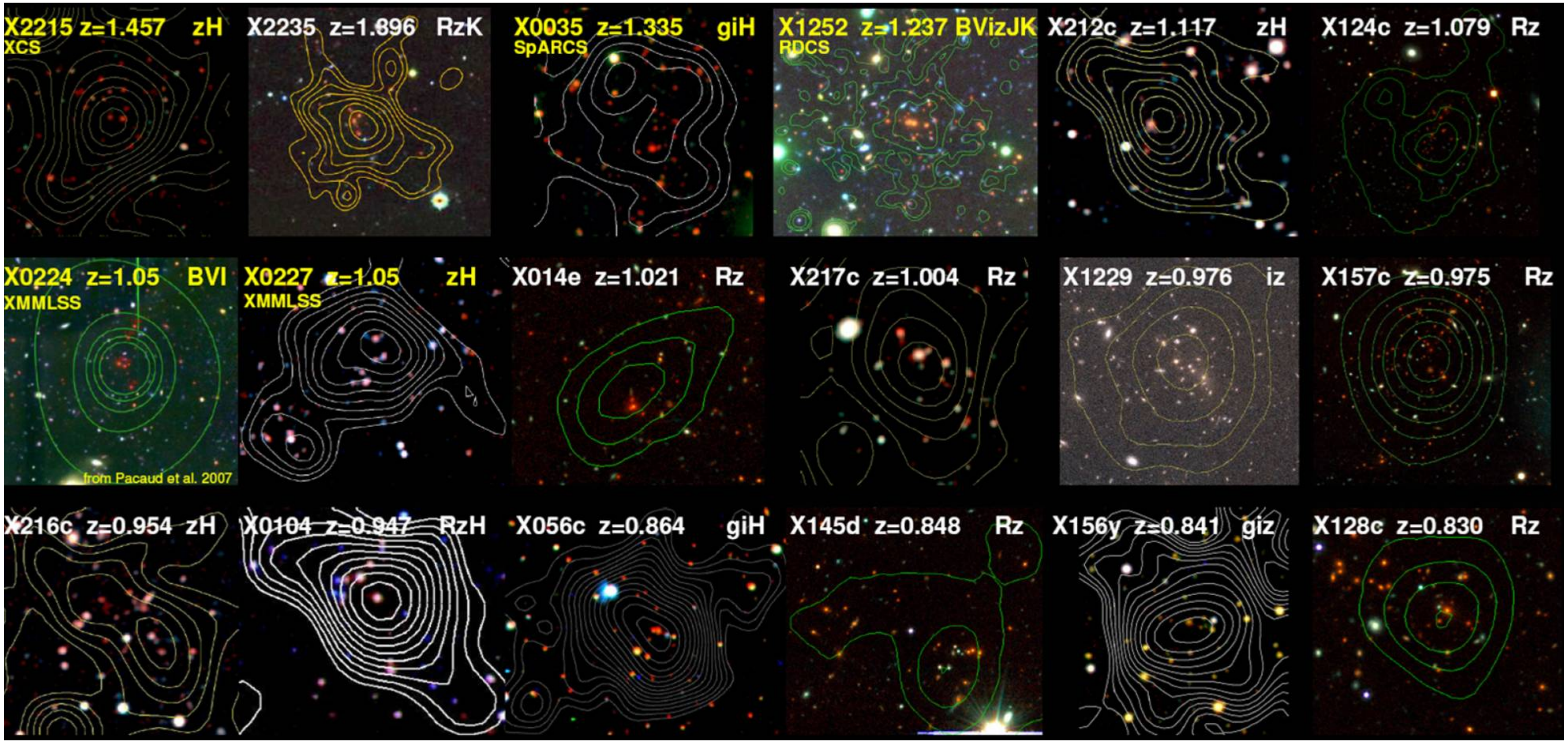
(largely defined by x-ray flux limit and search area)

Credit: Porciani

How do we find galaxy clusters?

1. By surveying the sky at x-ray wavelengths

Examples of few clusters found in the XMM-Newton Distant Cluster Project



Optical Images shown (red galaxies are likely cluster galaxies), overlaid contours are from x-ray light

Credit: Fassbender

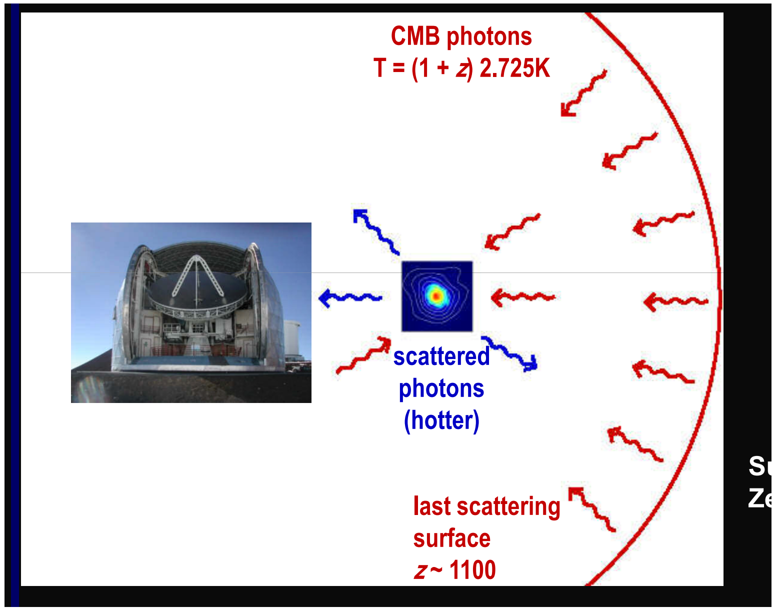
How do we find galaxy clusters?

2. By using the Sunyaev-Zeldovich effect

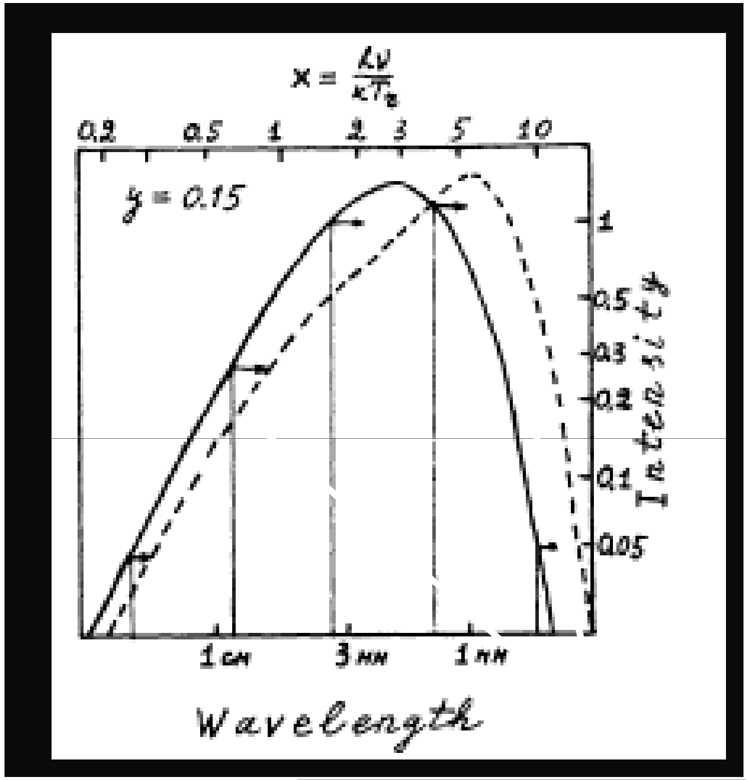
- Hot ionized gas in galaxy clusters inverse Compton scatter light from the cosmic microwave background (shifting CMB light to higher energies)

- Galaxy clusters can be seen as a bright spot or a hole in the CMB background depending on the wavelength in which one looks

As CMB photons pass through hot cluster, 1% of the photons are subject to Compton scattering



This serves to increase the energy of individual photons, but preserves their overall number



Credit: Abdalla

How do we find galaxy clusters?

2. By using the Sunyaev-Zeldovich effect

The effective change in temperature in the CMB photons is described by the following formula (no need to remember):

$$\boxed{\frac{\Delta T_{SZE}}{T_{CMB}} = f(x)\, y = f(x) \int n_e \frac{k_B T_e}{m_e c^2} \sigma_T \, d\ell,}$$

Important point is that the change is proportional to $n_e T_e$ integrated along the line of sight

Individual photon energies are boosted by $(kT_e/m_e c^2)$

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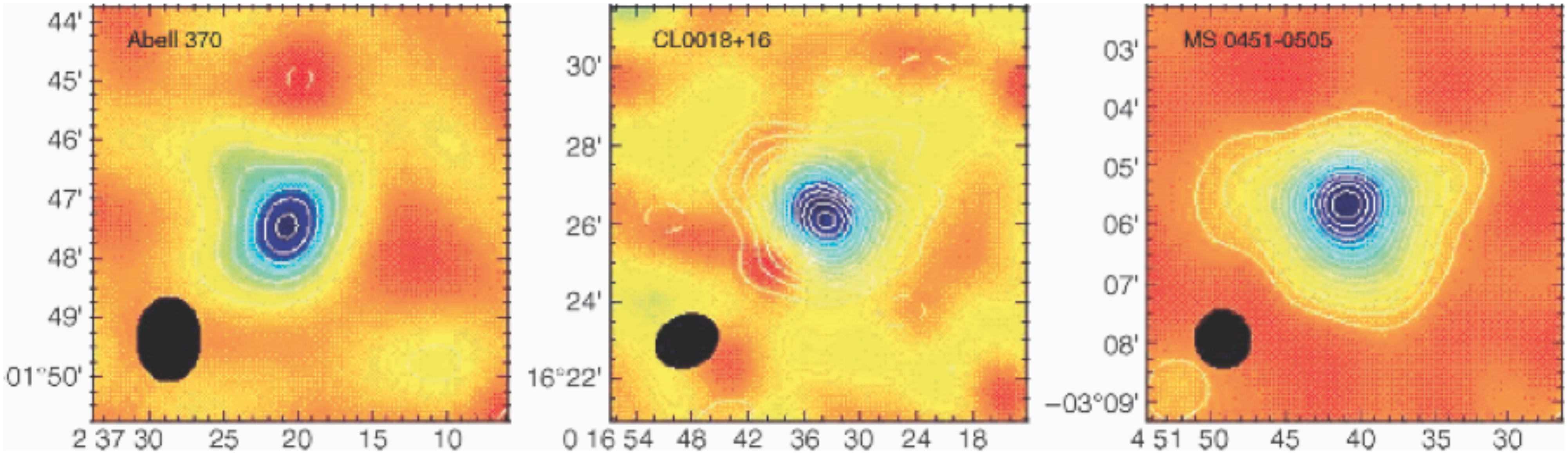
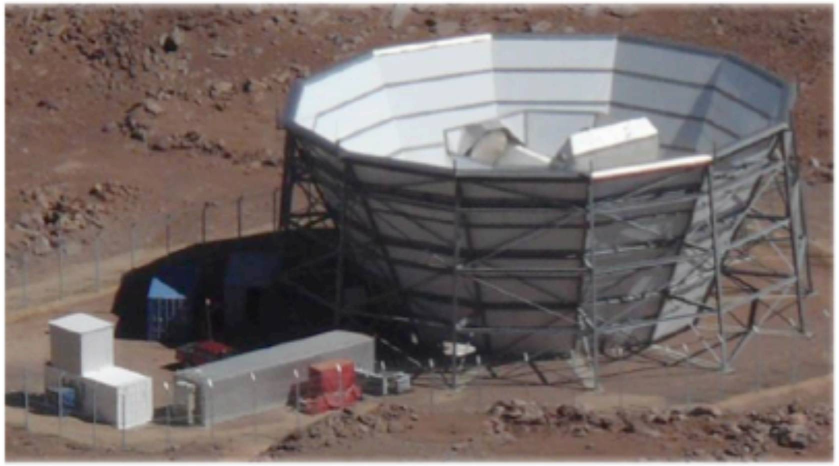


main observational limitation = instrumental sensitivity

SZ Experiments



Atacama Cosmology Telescope (ACT)

Location: Cerro Toco (5200m), Chile
Size: 6m
Frequencies: 148, 218, 277 GHz
Resolution: ~1 arcmin
ACT Cluster Survey: ~1000 deg^2

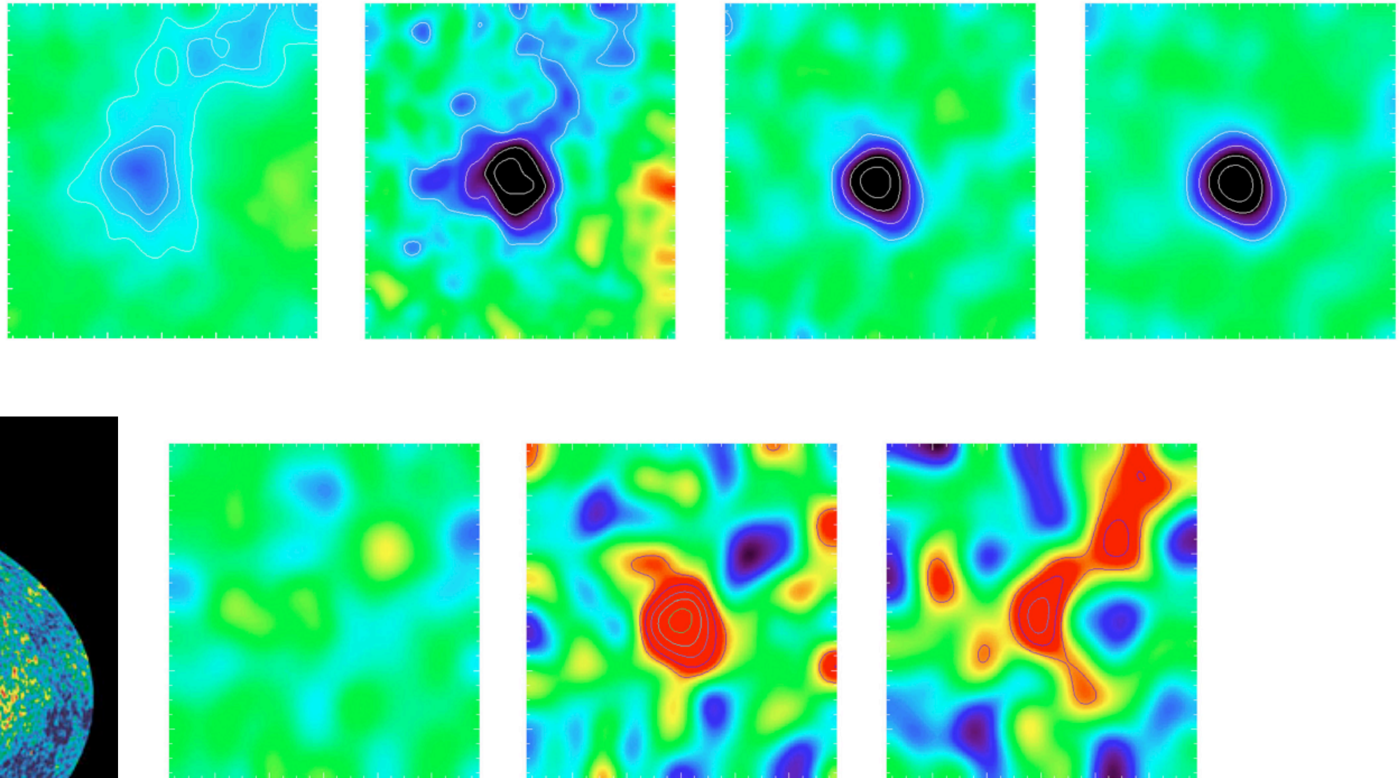
South Pole Telescope (SPT)

Location: SP (2800m), Antarctica
Size: 10m
Frequencies: 90, 150, 220 GHz
Resolution: ~1 arcmin
SPT Cluster Survey: ~2000 deg^2

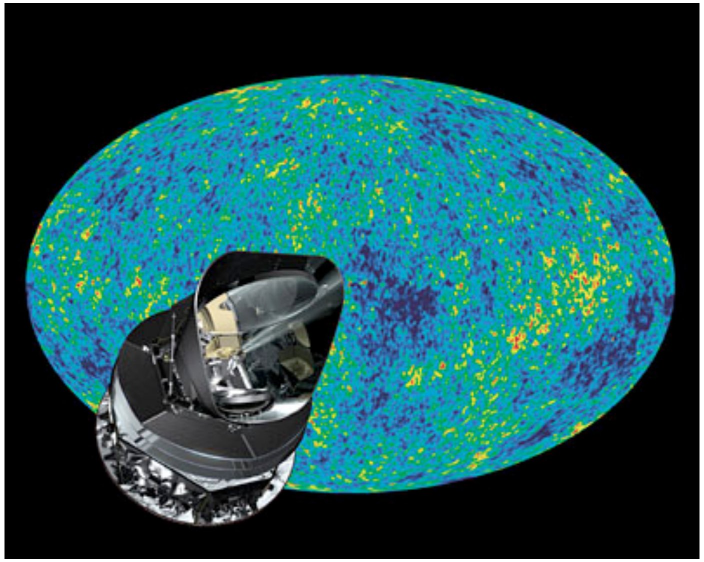
Credit: Porciani

SZ Experiments

Source: http://planck.cf.ac.uk/results/abell-2319



Planck satellite



Abell 2319 with PLANCK
Top row: 44, 70, 100, 143 GHz
Bottom row: 217, 353,545 GHz

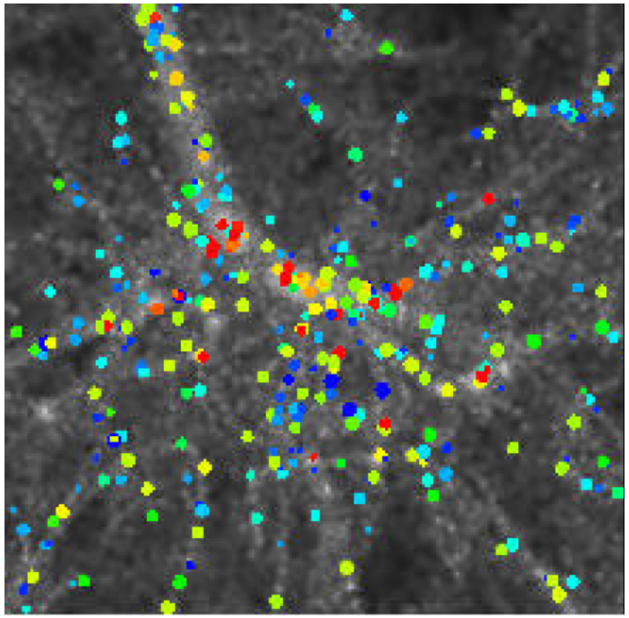
Credit: Porciani

How do we find galaxy clusters?

3. By identifying red sequence galaxies that make up the galaxy clusters

- galaxy clusters contain large numbers of very red elliptical galaxies

- possible galaxy clusters can be identified by measuring the colors for large number of galaxies in a field



Since elliptical galaxies are red, require deep near-IR / mid-IR data to find distant galaxy clusters.

Value of optical data is more limited

How do we find galaxy clusters?

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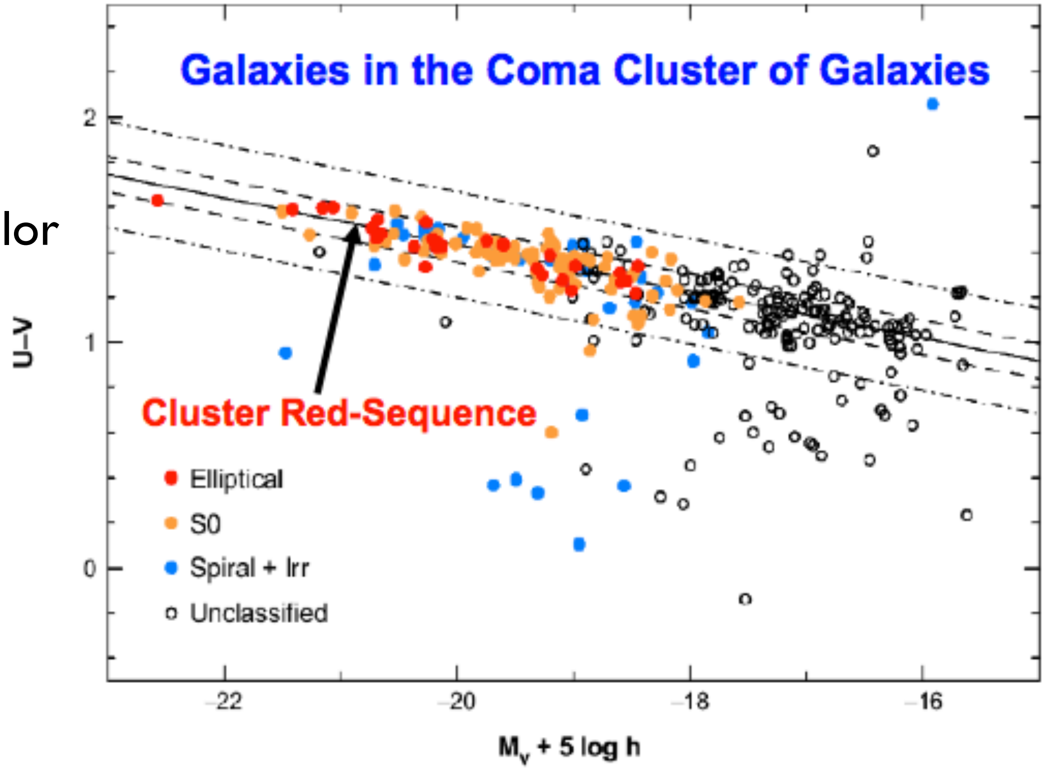
Color



Luminosity

Credit: Barrientos et al., RCS survey

Figure 2: IJK colour composite image of the field centred on RCS0439.6-2905. North is up and East to the left. This image shows approximately the central 1.1 × 1.1 Mpc.

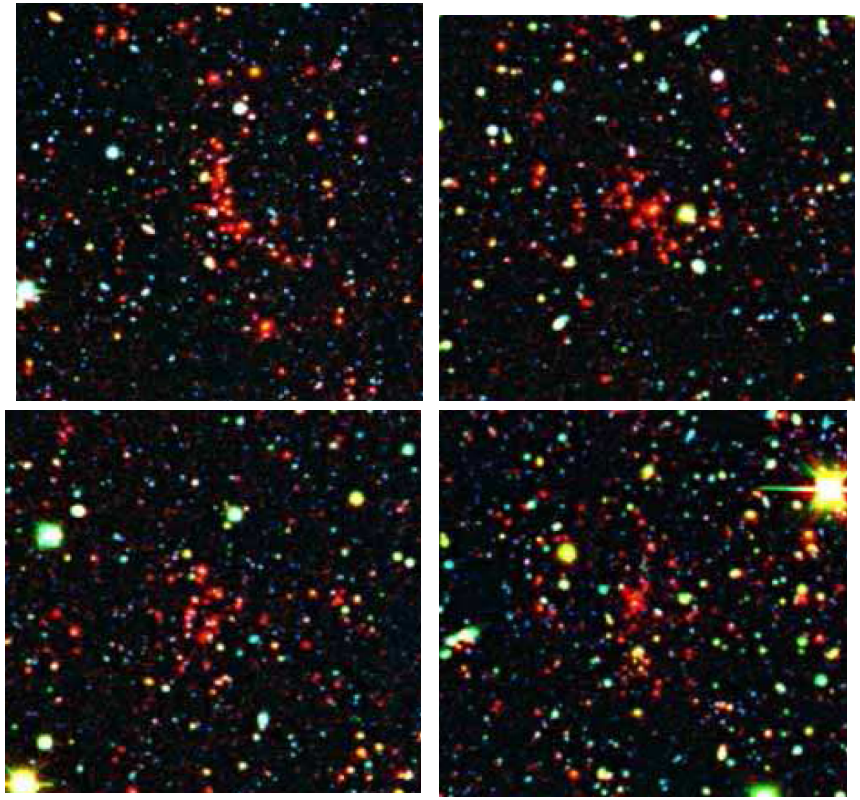
Useful to follow up overdensities of red galaxies with spectroscopy to ensure that the overdensity is not a chance projection on the sky and that all the red galaxies are part of the same cluster

How do we find galaxy clusters?

3. By identifying red sequence galaxies that make up the galaxy clusters

Such a search is particularly efficient including observations at performing search at > 4 microns with the Spitzer Space Telescope

ISCS J1434.5+3427 at $\langle z_{\rm sp} \rangle = 1.243$. ISCS J1429.3+3437 at $\langle z_{\rm sp} \rangle = 1.258$.



ISCS J1434.7+3519 at $\langle z_{\rm sp} \rangle = 1.373$. ISCS J1438.1+3414 at $\langle z_{\rm sp} \rangle = 1.413$

3x3 arcmin color composite images in B+I+[4.5μm]

about 20 spectroscopically confirmed IR-selected z>1 clusters are currently known (without X-ray data)

Source: Eisenhard et al., 2008

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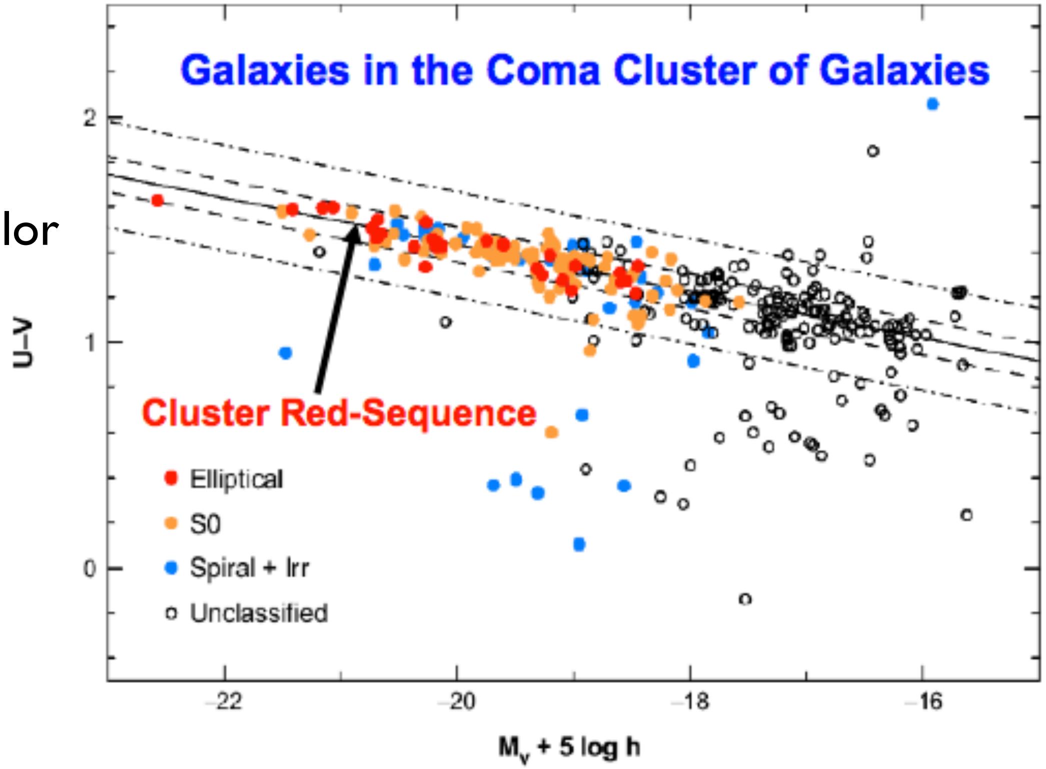

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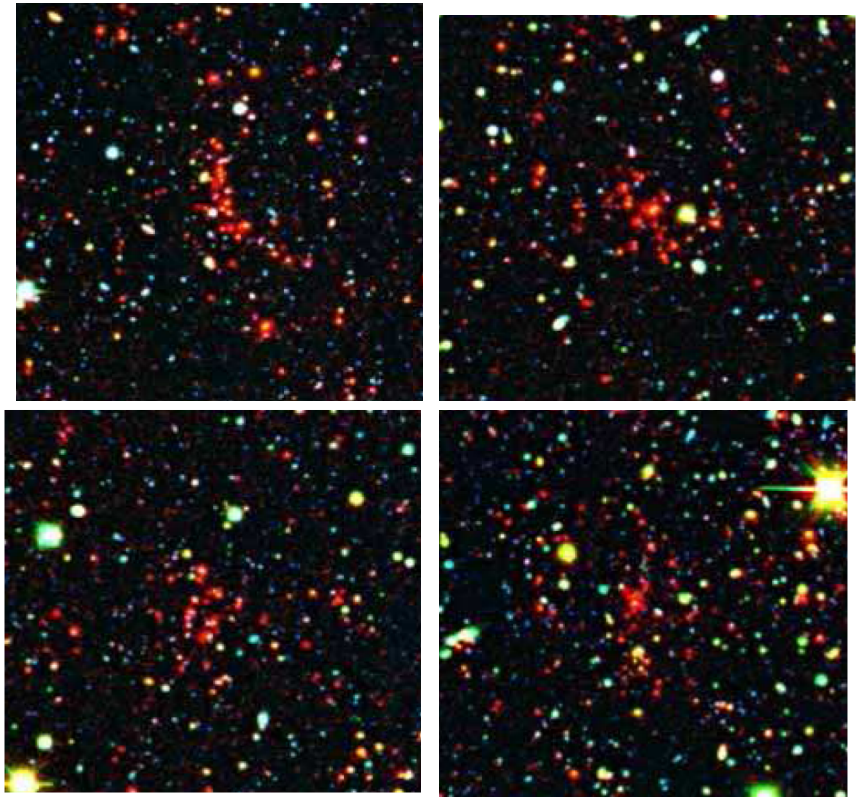

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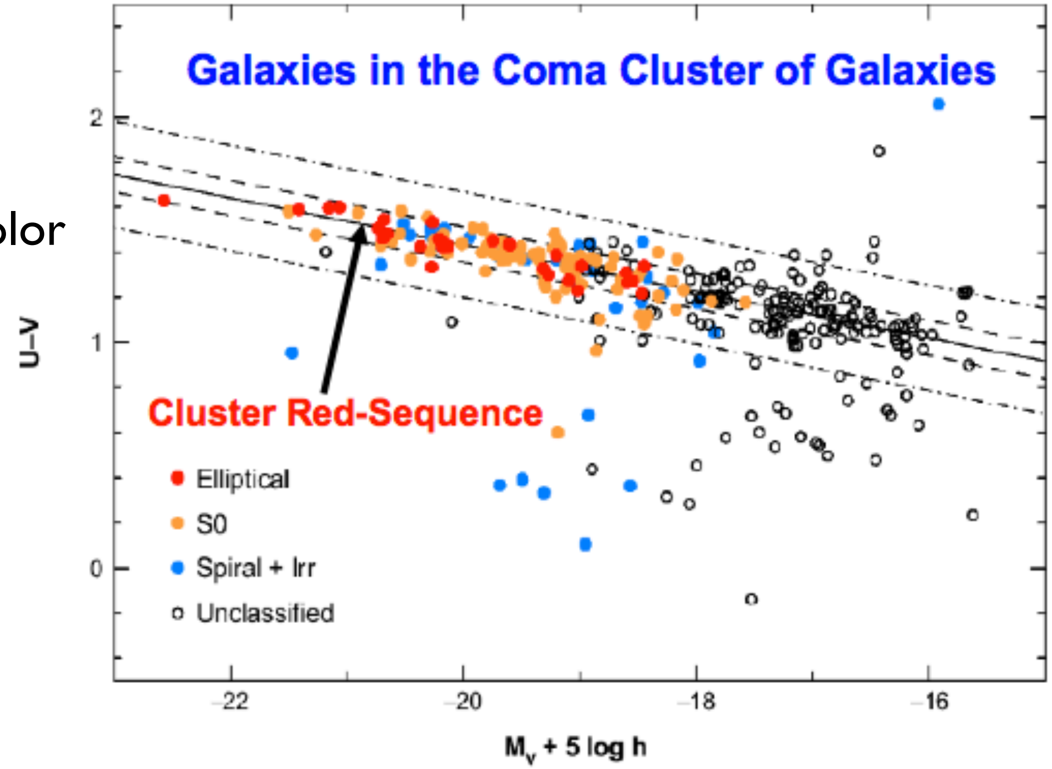

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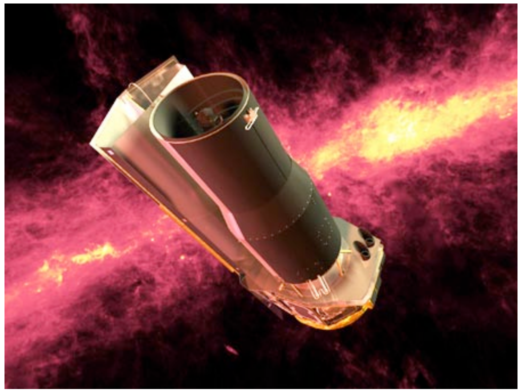
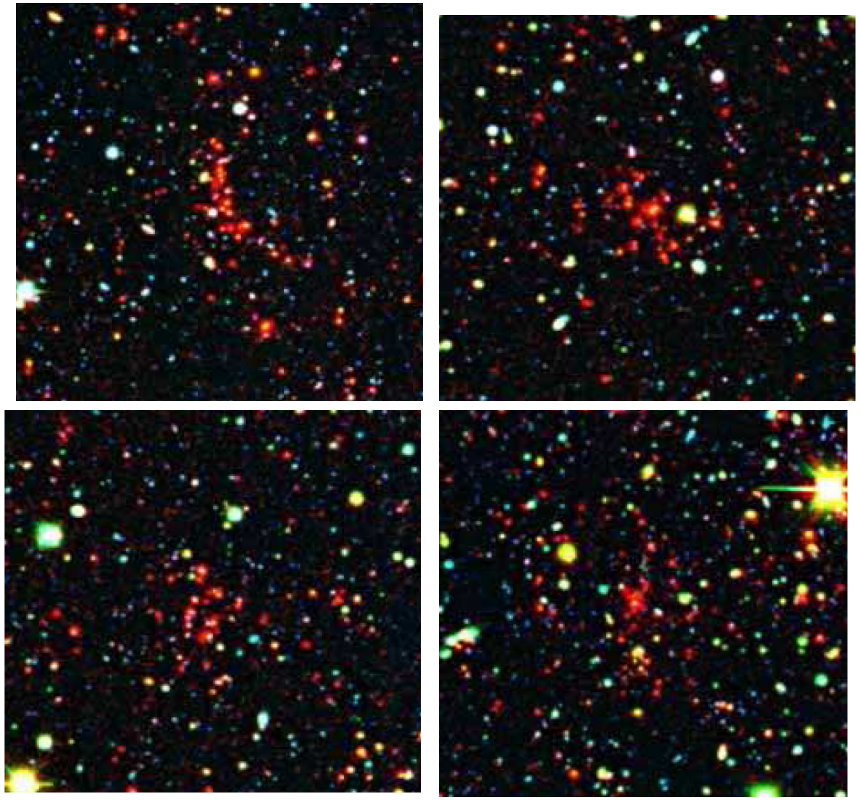


ISCS J1434.5+3427 at $\langle z_{sp} \rangle = 1.243$. ISCS J1429.3+3437 at $\langle z_{sp} \rangle = 1.258$.



ISCS J1434.7+3519 at $\langle z_{sp} \rangle = 1.373$. ISCS J1438.1+3414 at $\langle z_{sp} \rangle = 1.413$

3x3 arcmin color composite images in B+I+[4.5μm]

about 20 spectroscopically confirmed IR-selected z>1 clusters are currently known (without X-ray data)

Source: Eisenhard et al., 2008

View of Same Galaxy Cluster at Several Different Wavelengths:

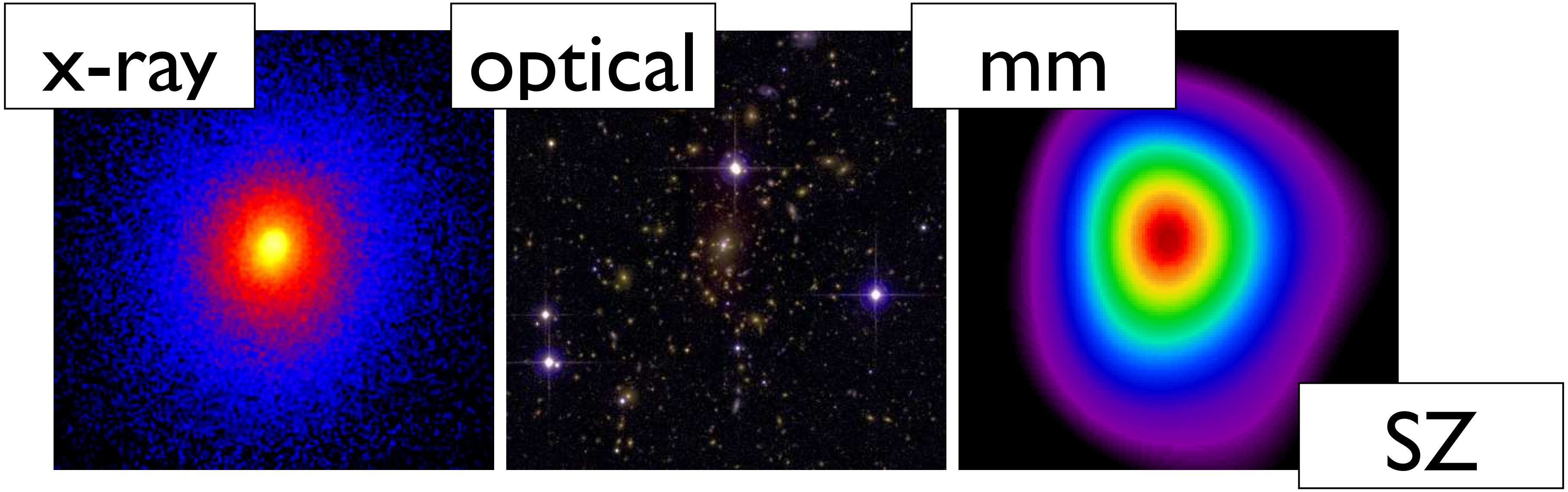


Figure 7: Images of Abell 1835 ($z = 0.25$) at X-ray, optical and mm wavelengths, exemplifying the regular multi-wavelength morphology of a massive, dynamically relaxed cluster. All three images are centered on the X-ray peak position and have the same spatial scale, 5.2 arcmin or $\sim 1.2\,\mathrm{Mpc}$ on a side (extending out to $\sim r_{2500}$; Mantz et al. 2010a). Figure credits: *Left*: X-ray: Chandra X-ray Observatory/A. Mantz; *Center*, Optical: Canada France Hawaii Telescope/A. von der Linden et al.; *Right*, SZ: Sunyaev Zel'dovich Array/D. Marrone.

Allen et al. 2011

1. Probe σ_8 and Ω_m through measured mass function of galaxy clusters (clusters probed mass function of collapsed structures)

Can we derive a mass function from the observations using galaxy clusters?

Yes -- 1) Do a survey

2) Have method to derive masses for clusters found in surveys

Fortunately, galaxy clusters appear to be self-similar, with nice scaling relations between mass, x-ray luminosity, and temperature, so it is possible to convert the temperature T of the cluster gas or x-ray luminosity into a mass for the cluster

The basic idea is that all of the properties of gas in a cluster are determined based on gravity and gas is in hydrostatic equilibrium

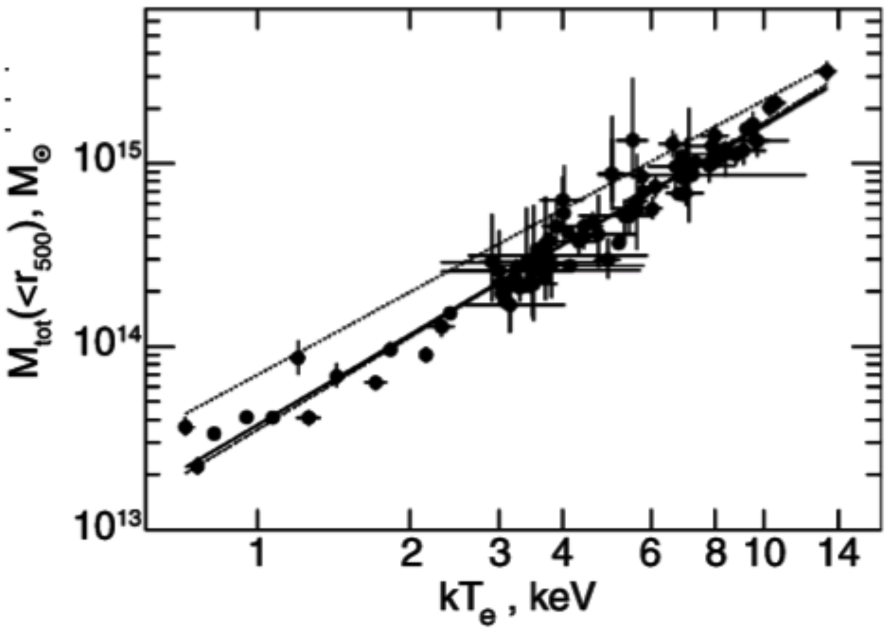
$$M_{200} = \frac{4\pi}{3}\Delta_c \rho_{\mathrm{crit}} r_{200}^3$$

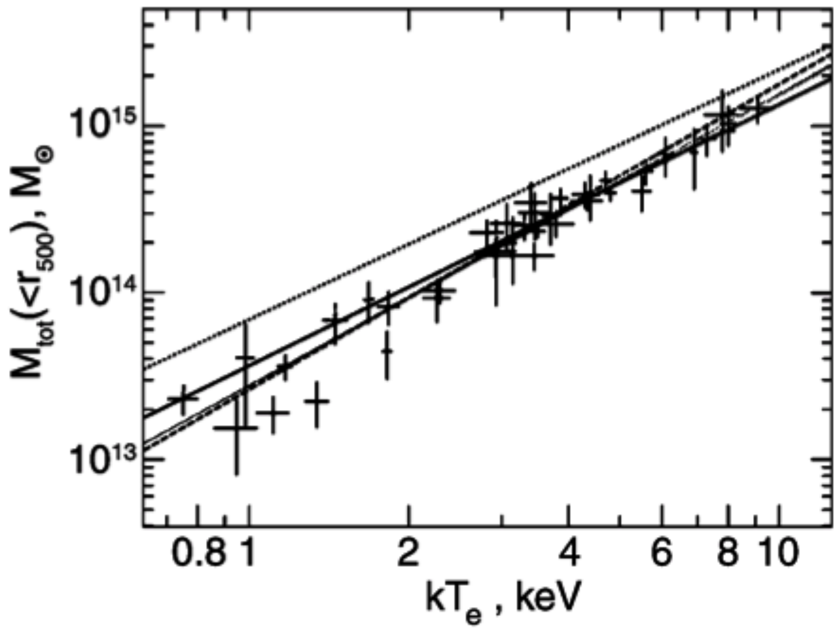
$$T \propto= \frac{M_{200}}{r_{200}} \propto r_{200}^2 \propto M^{2/3}$$

M_{200} and r_{200} refer to the total mass and radius of the collapsed object, Δ_c is the typical overdensity of a collapsed object relative to the average mass density of universe (typically ~200), and ρ_c is the critical density of the universe

Relationship between temperature and mass of cluster

$$T \propto = \frac{M_{200}}{r_{200}} \propto r_{200}^2 \propto M^{2/3}$$





$$M_{500} = 3.57 \times 10^{13}\, M_\odot \left(\frac{kT}{1\, keV} \right)^{1.58}$$

X-ray temperature is good measure of virial mass (better than velocity dispersion).

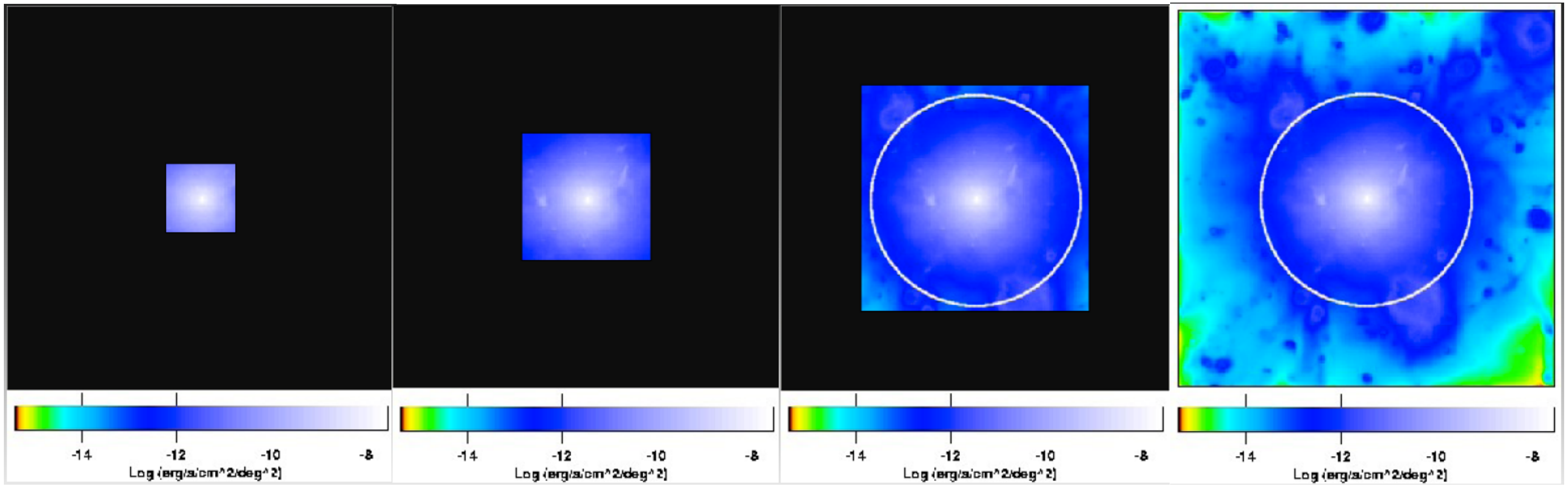
How do we measure mass of clusters?

-- from x-ray profile
-- from SZ effect
-- from gravitational lensing

X−ray
strong lensing

X−ray
SZE
weak lensing

SZE
weak lensing



Roncarelli, Ettori et al. 2006

R_{2500}
~ 0.3 R_{200}
~ 0.5 Mpc

R_{500}
~ 0.7 R_{200}
~ 1 Mpc

R_{200}
~ 1.5 Mpc

1. Probe σ_8 and Ω_m through measured mass function of galaxy clusters (clusters probed mass function of collapsed structures)

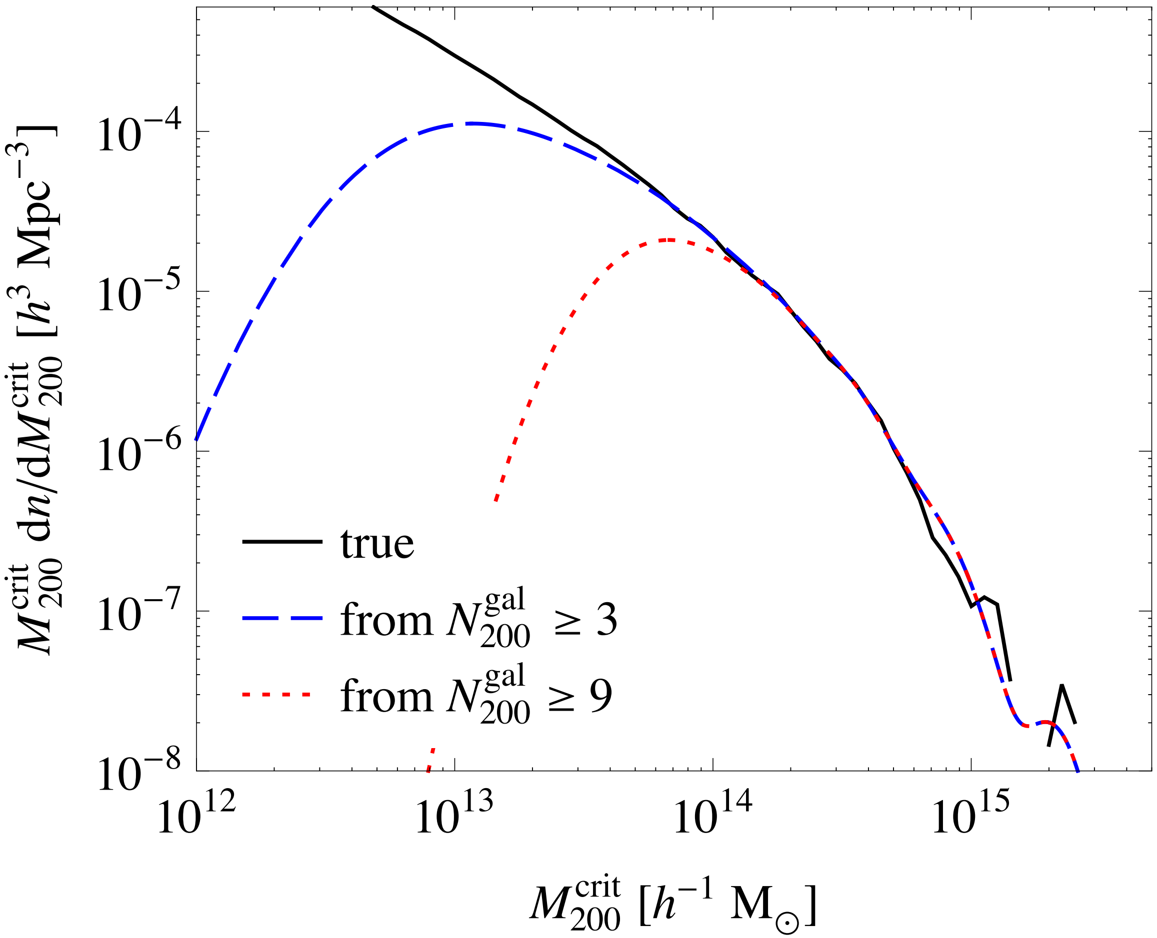
Can we derive a mass function from the observations using galaxy clusters?

Yes -- 1) Do a survey

2) Have method to derive masses for clusters found in surveys

3) By comparing with theoretical mass functions, infer cosmological parameters

The volume density of massive structures like clusters in nearby universe provide sensitive probe of mass function



MaxBCG Sample

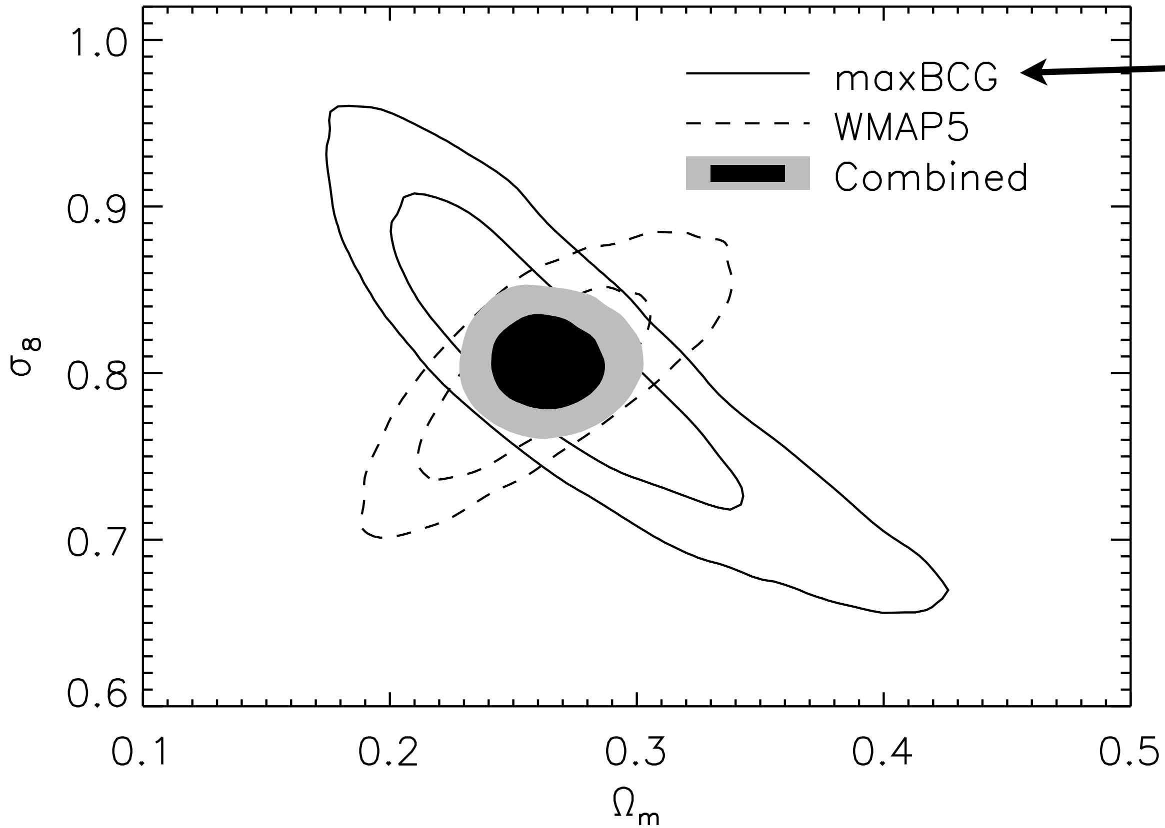
Identified from the SDSS (Sloan Digital Sky Survey) using Optical Red Cluster Member Selection Technique

Hilbert et al. 2010

Implications for Cosmological Parameters

The Abundance of Galaxy Clusters with Various Masses Provides Strong Constraints on the Total Mass Density in the Universe and Normalization of the Power Spectrum

Normalization of power spectrum



cluster survey

There's a degeneracy here:

Cluster Mass Function Constrains: $\sigma_8(\Omega_M)^{1/2}$

Rozo et al. 2010

So a higher σ_8, lower Ω_M and lower σ_8, higher Ω_M both match observations

Last week we spoke about how we normalize the Matter Power Spectrum

It is through this σ_8 parameter

While deriving correlation function and Power spectrum from galaxy survey, one thing we are particularly interested in is the normalization of the power spectrum

$$P_0(k) = A\,k^{n_s}$$

(related to the A parameter here)
($n_s = 1$)

This is defined using this parameter σ_8 (intended to represent the root-mean-squared fluctuations in a 8 h^{-1}Mpc volume):

$$\sigma^2_{8,\mathrm{g}} := \left\langle \left(\frac{\Delta n}{\bar{n}} \right)^2 \right\rangle_8 \approx 1$$

(8 h^{-1} Mpc was chosen because appeared close to 1)

Size of density fluctuations in a volume really defines the amplitude of power spectrum

We may see more discussion of σ_8 later today in this week's lecture on weak lensing and cosmic shear

What can we learn from galaxy clusters?

1. Probe σ_8 and Ω_m through measured mass function of galaxy clusters (clusters probed mass function of collapsed structures)

2. Probe cosmological parameters by examining how the apparent volume density of clusters evolve

3. Derive Ω_m based on relative mass in gas and dark matter in clusters

4. Probe matter power spectrum and Ω_m from the observed clustering of galaxy clusters

Of course, we are not simply interested in using clusters to learn about mass function of $z=0$ universe

We also want to see how the mass function for clusters evolves with cosmic time...

So, we can use searches for clusters at higher redshift to constrain the cosmological parameters

Different cosmological parameters imply different growth rates for clusters...

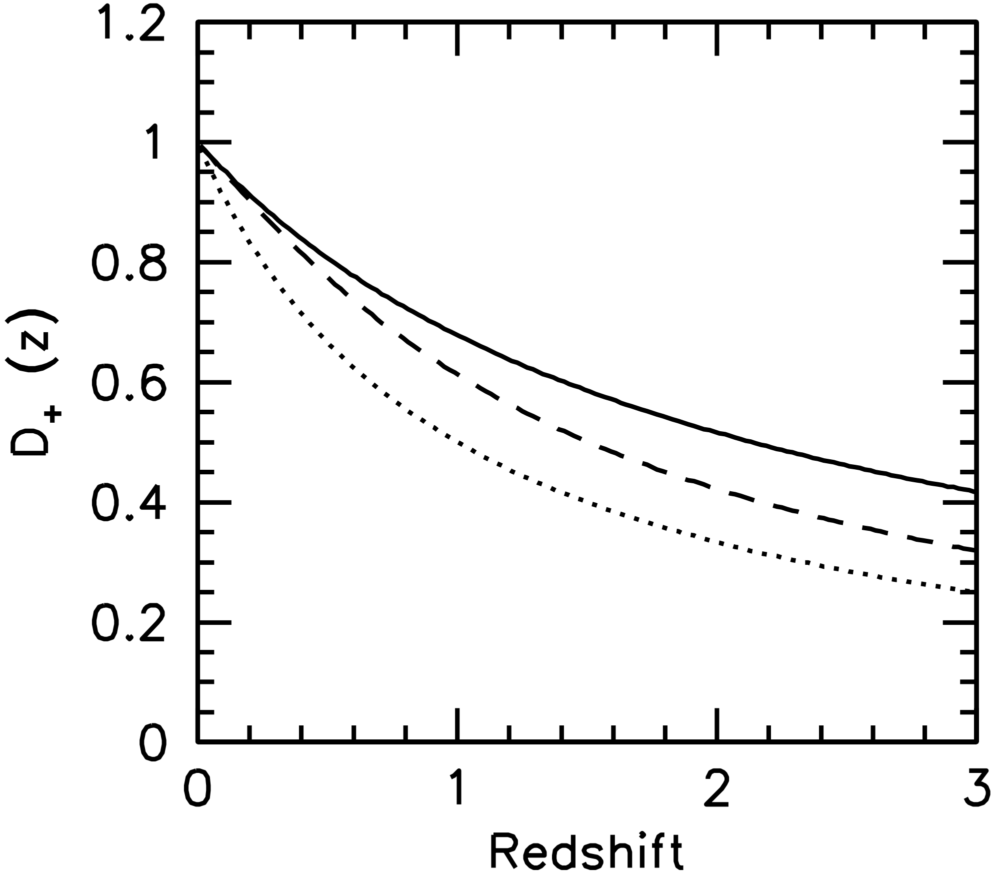
The rate at which structures grow in the universe depends upon the cosmological parameters:

Depend upon the growth factor (linear regime):

$$D_+(a) = \frac{5a}{2}\Omega_\mathrm{m}\left[\Omega_\mathrm{m}^{4/7} - \Omega_\Lambda + \left(1 + \frac{1}{2}\Omega_\mathrm{m}\right)\left(1 + \frac{1}{70}\Omega_\Lambda\right)\right]^{-1}$$

where a is size of universe and Ω_m, Ω_Λ are all evaluated in the past

Growth factor



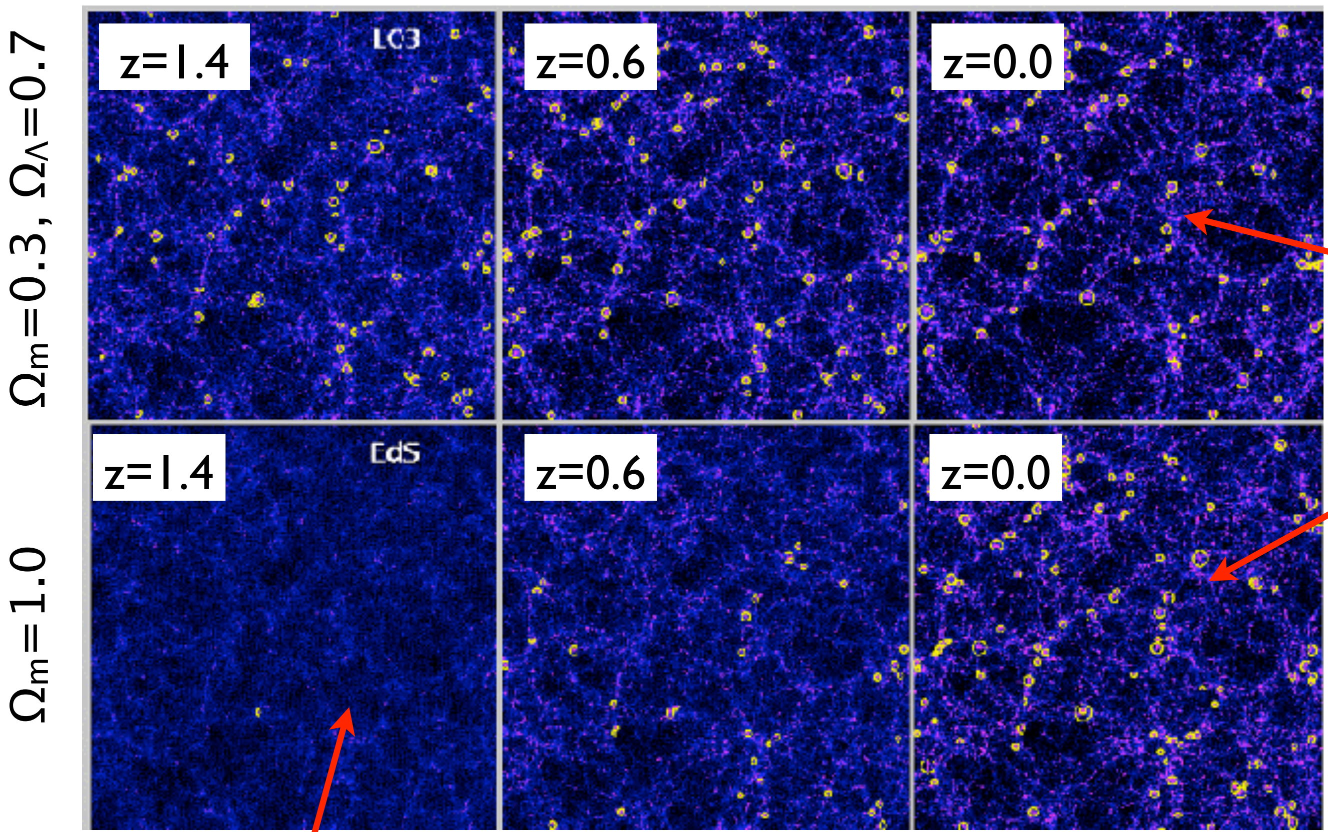
Ω_m=0.3, Ω_Λ=0.0

Ω_m=0.3, Ω_Λ=0.7

Ω_m=1.0, Ω_Λ=0.0

structure grow efficiently when $\Omega = 1$ (since density is closer to 1 where slight overdensities cause collapse)

Different cosmological parameters imply different growth rates for clusters...



Borgani & Guzzo, Nature, 2001

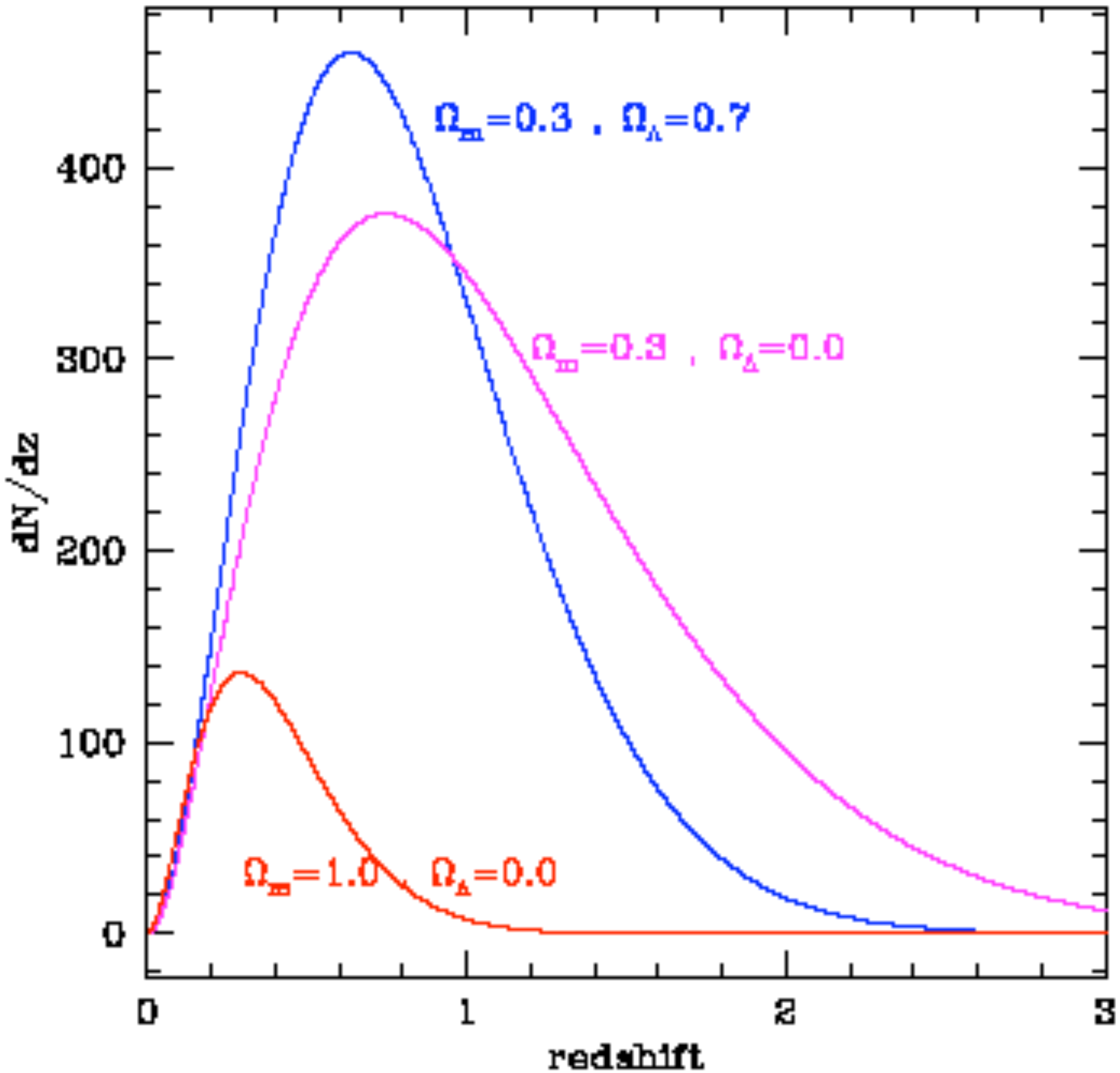
Note that the two cluster models agree at redshift z=0 (the present day) by construction.

However, there are large differences between these models in the past.

Different cosmological parameters imply different growth rates for clusters...

Simple Illustration of how many clusters one would expect to find in various cosmological models as a function of redshift

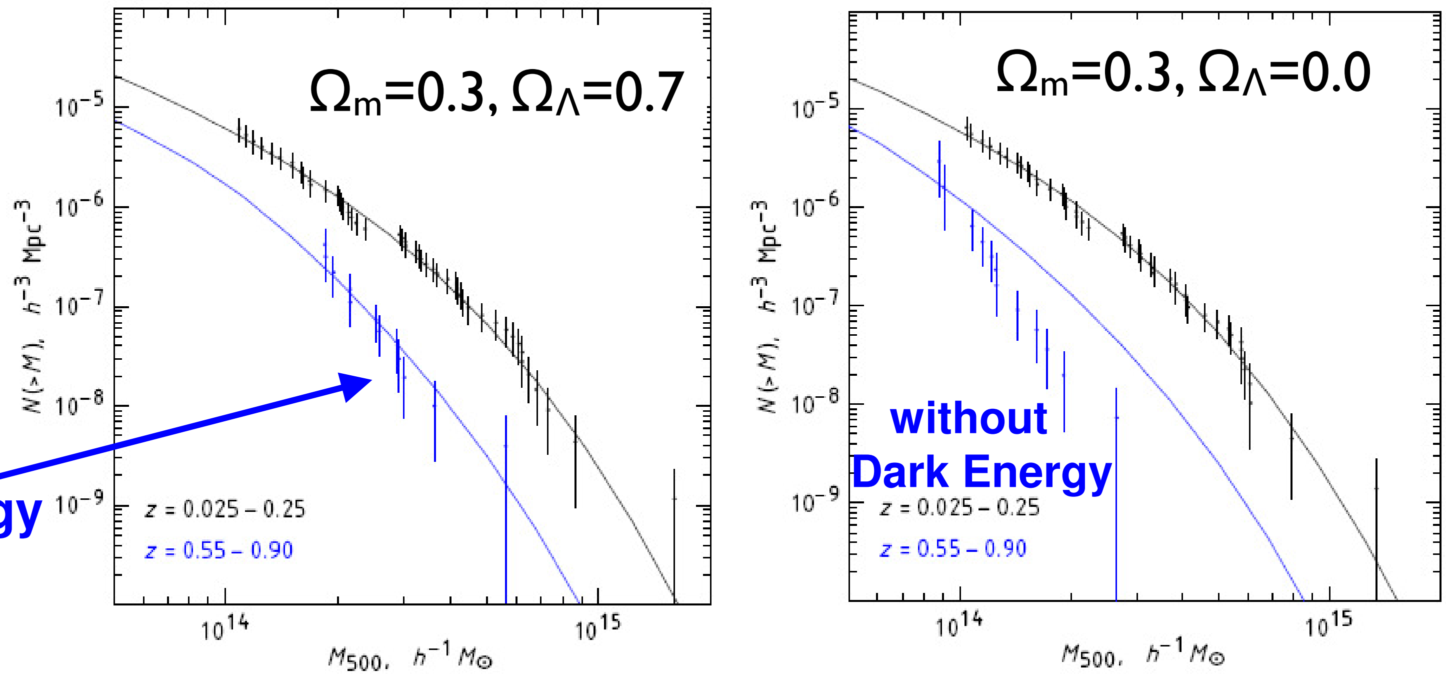
Note that there are essentially no clusters at high redshift in the Ω_m=1.0, Ω_Λ=0.0 model



Different cosmological parameters imply different growth rates for clusters...

5 σ detection of Dark Energy from Clusters alone

observed mass function **with Dark Energy**



Vikhlinin et al. 2009 (Chandra Cluster Cosmology Project)

Here we exploit differences in the rates of structure growth, volume element, and luminosity distance D_L

The evolution of the cluster mass function also breaks degeneracy between σ_8 and Ω_M

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4. Probe matter power spectrum and Ω_m from the observed clustering of galaxy clusters

Use fractional composition of cluster in baryons and dark matter to infer composition of universe

$$\frac{\text{(total baryonic mass in gas + stars)}}{\text{(total mass of cluster)}} = \frac{\Omega_b}{\Omega_m} = f_{gas}$$

Total baryonic mass in gas + stars:

-- use x-ray light profile and spectrum to infer mass in gas

-- use optical light to infer mass in stars

Total mass in cluster:

-- use x-ray light profile, gravitational lensing properties

Use fractional composition of cluster in baryons and dark matter to infer composition of universe

$$\frac{\text{(total baryonic mass in gas + stars)}}{\text{(total mass of cluster)}} = \frac{\Omega_b}{\Omega_m} = f_{gas}$$

Tot

As we showed in the dark matter lecture, we can use this to demonstrate that $\Omega_m \sim 0.3$

mass in gas

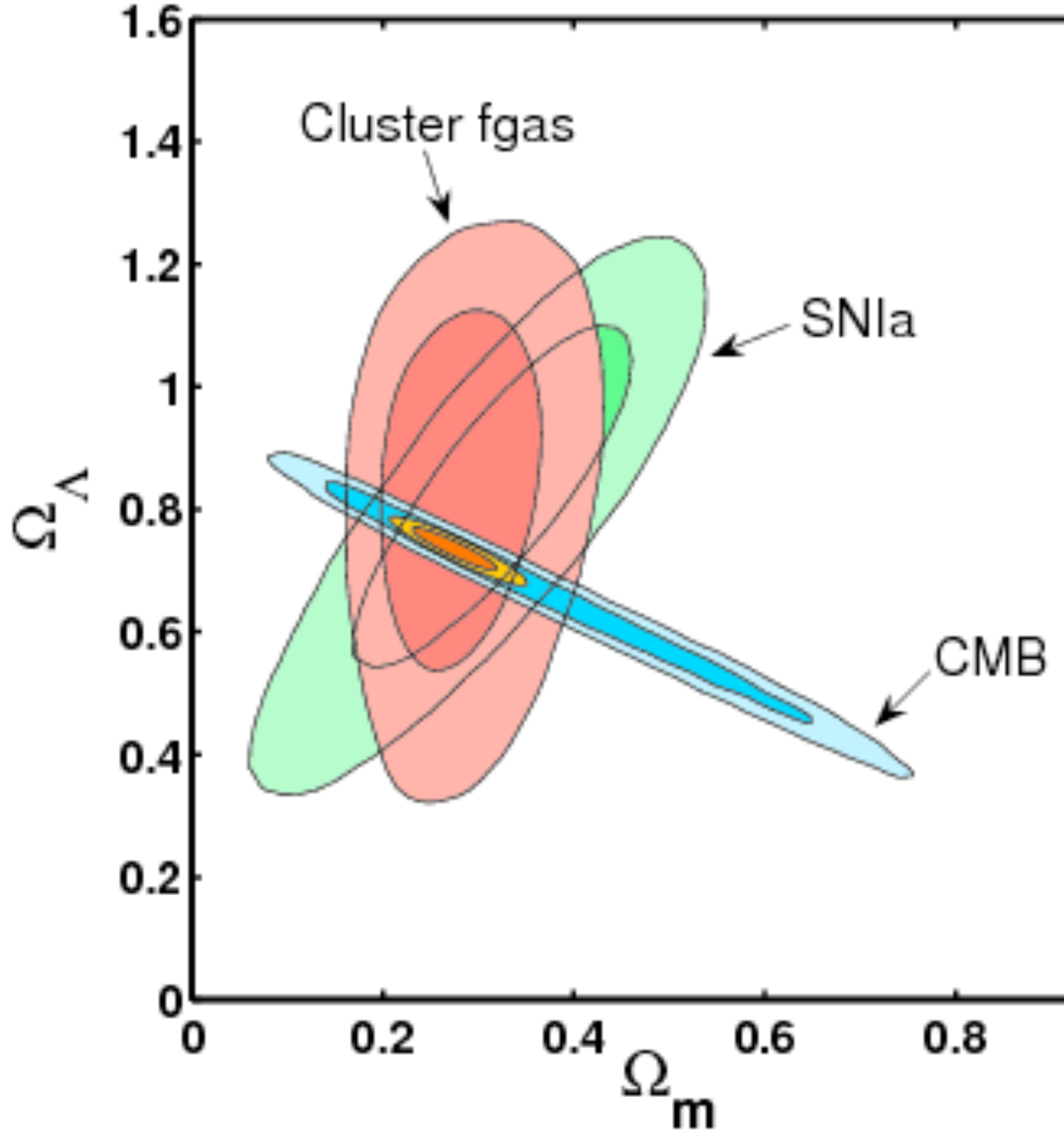
-- use optical light to infer mass in stars

Total mass in cluster:

-- use x-ray light profile, gravitational lensing properties

From the lecture on the dark matter content of the universe:

Mantz, Allen et al.



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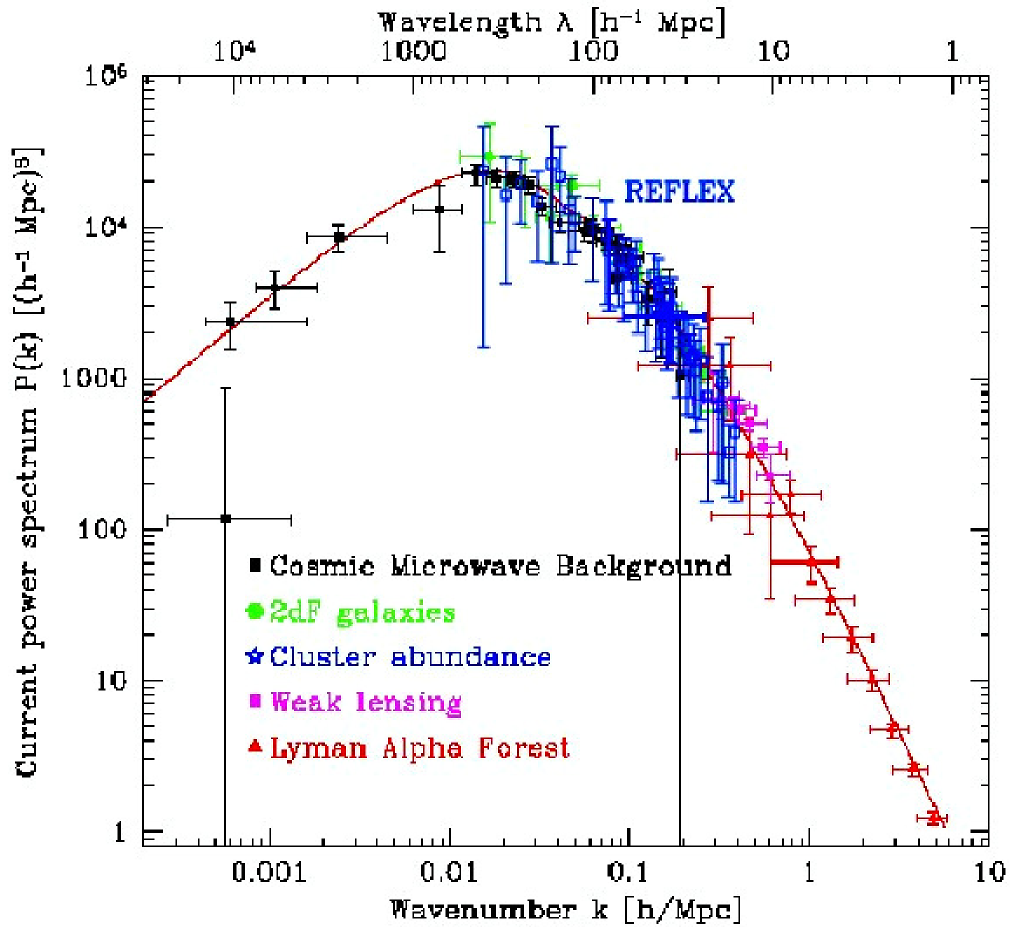
We can also galaxy clusters to probe clustering on large scales in the same way we use galaxies to do this

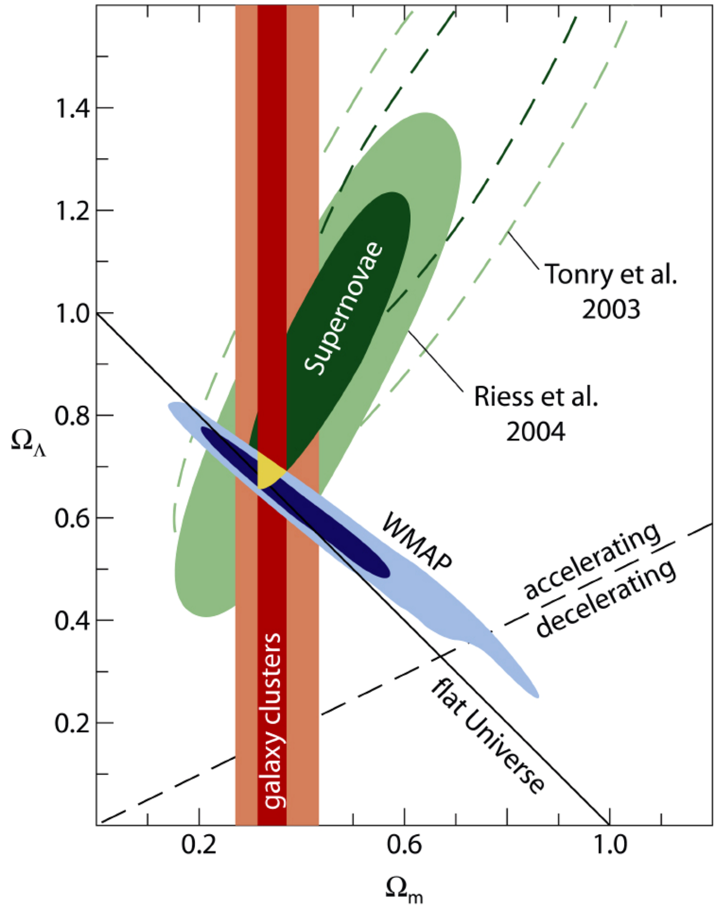
Observations:

REFLEX survey + other measures of the matter power spectrum



Schuecker et al. 2001

We can also use galaxy clusters to probe clustering on large scales in the same way we use galaxies to do this



Constraining the Cosmological Parametres

combined results from
CMB, SN Ia, and Galaxy Clusters

different methods have different degeneracies, combining them provides strong constraints

strong need for Dark Energy component with Ω_{DE}~0.7

very similar to results I showed you last week for galaxy clustering studies

So the game is to determine the w parameter and how it depends on redshift

There are four standard methods:

1. Supernovae Ia (lecture 4)
   -- use of standard candles to establish distance-redshift relation
   -- first established existence of dark energy >20 years ago
2. Baryonic Acoustic Oscillations (last lecture)
   -- gives us a standard rod to establish distance-redshift relation with low systematics
3. Galaxy Clusters (this lecture)
   -- provide us with sensitive probe of growth of structure
   -- early evidence for low Ω_m
4. Weak Gravitational Lensing (this lecture)
   -- provide us with sensitive probe of growth of structure
   -- powerful technique still in process of realizing full potential