

Dark Energy,
Galaxy Cluster Searches,
and
Weak Lensing of Cosmic
Structures

Layout of the Course

Feb 3: Introduction / Overview / General Concepts

Feb 5: Age of Universe / Distance Ladder / Hubble Constant

Feb 10: Distance Ladder / Hubble Constant Distant Measures

Feb 12: SNe science / Baryonic Content / Dark Matter Content of Universe

Feb 17: Dark Matter + Cosmic Microwave Background

Feb 19: Cosmic Microwave Background + Large Scale Structure

Feb 26: Large Scale Structure / Baryon Acoustic Oscillations + Dark Energy

Mar 5: Dark Energy / Clusters / Cosmic Shear

Mar 12: Cosmic Shear / Dark Energy Missions

Mar 19: No Class

Mar 26: Other Unresolved Questions / Review for Final Exam

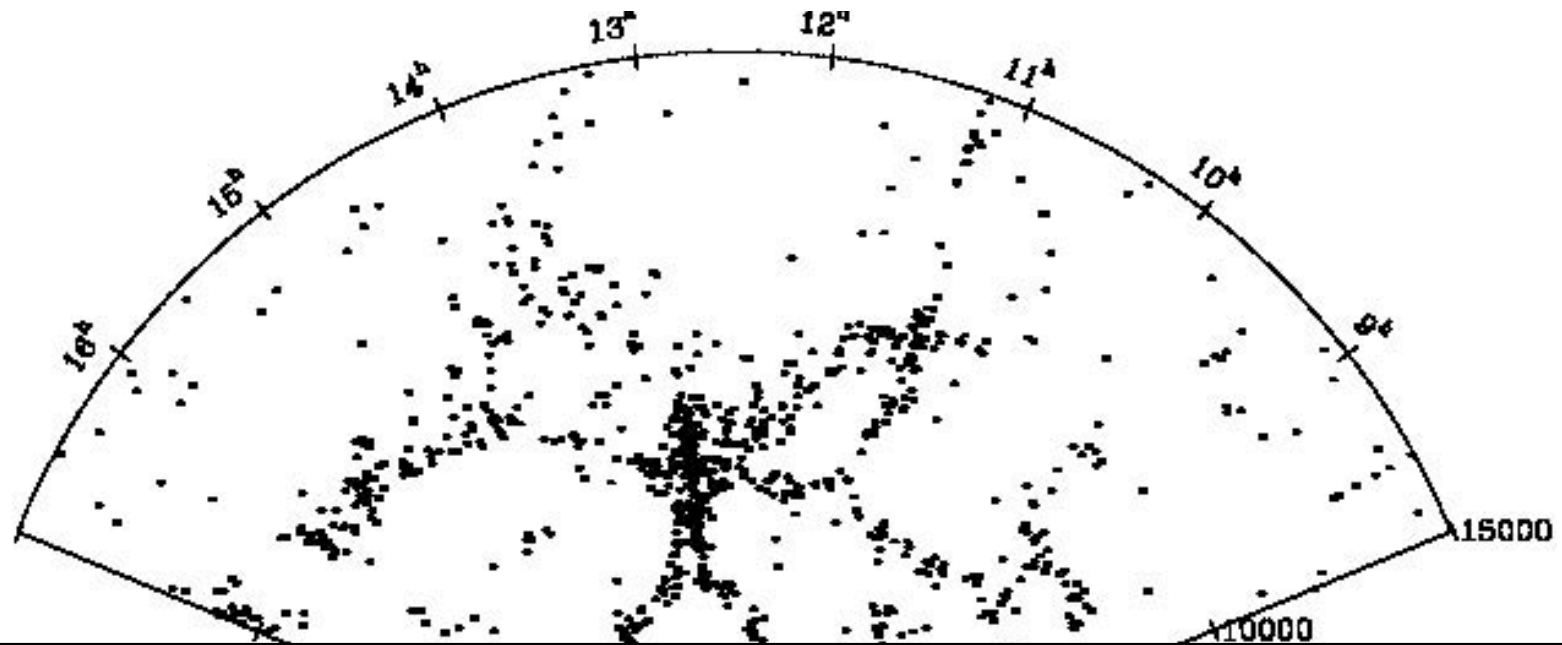
Apr 11: Final Exam



Today

Review Material from Last Week

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

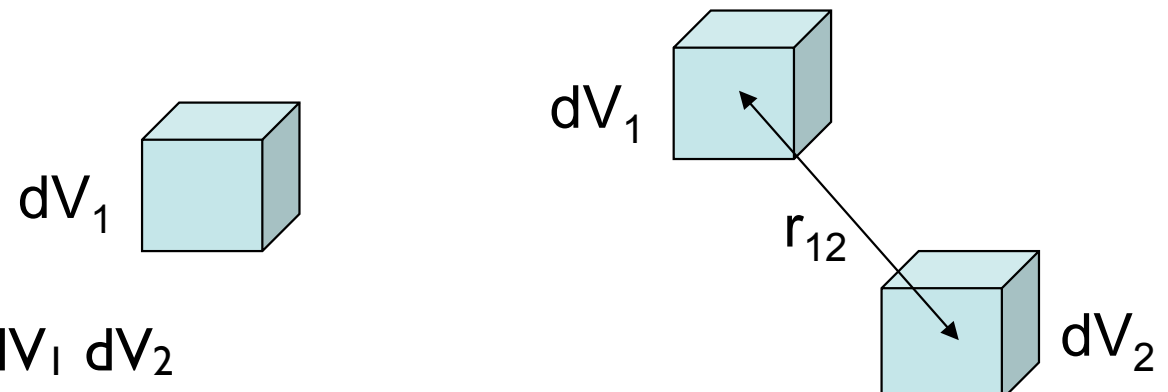
How do we quantify structure in the distribution of galaxies on the sky?

After measuring the 3D distribution of galaxies in a region of sky, determine the clustering of galaxies using 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



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

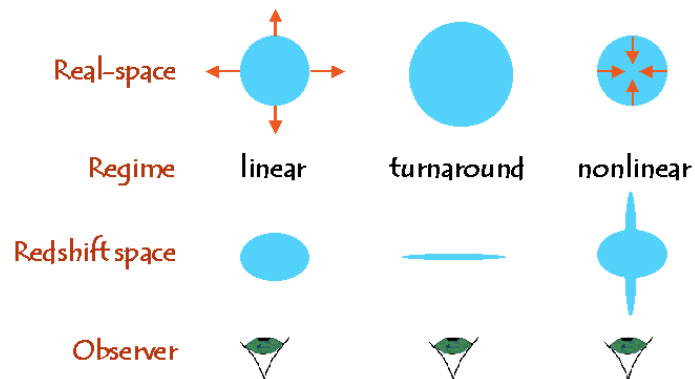
The power spectrum is the Fourier transform of the correlation function ξ

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

There are 2 key complications in interpreting clustering measurements:

Redshift Space Distortions

(Impact of peculiar velocities along line of sight)



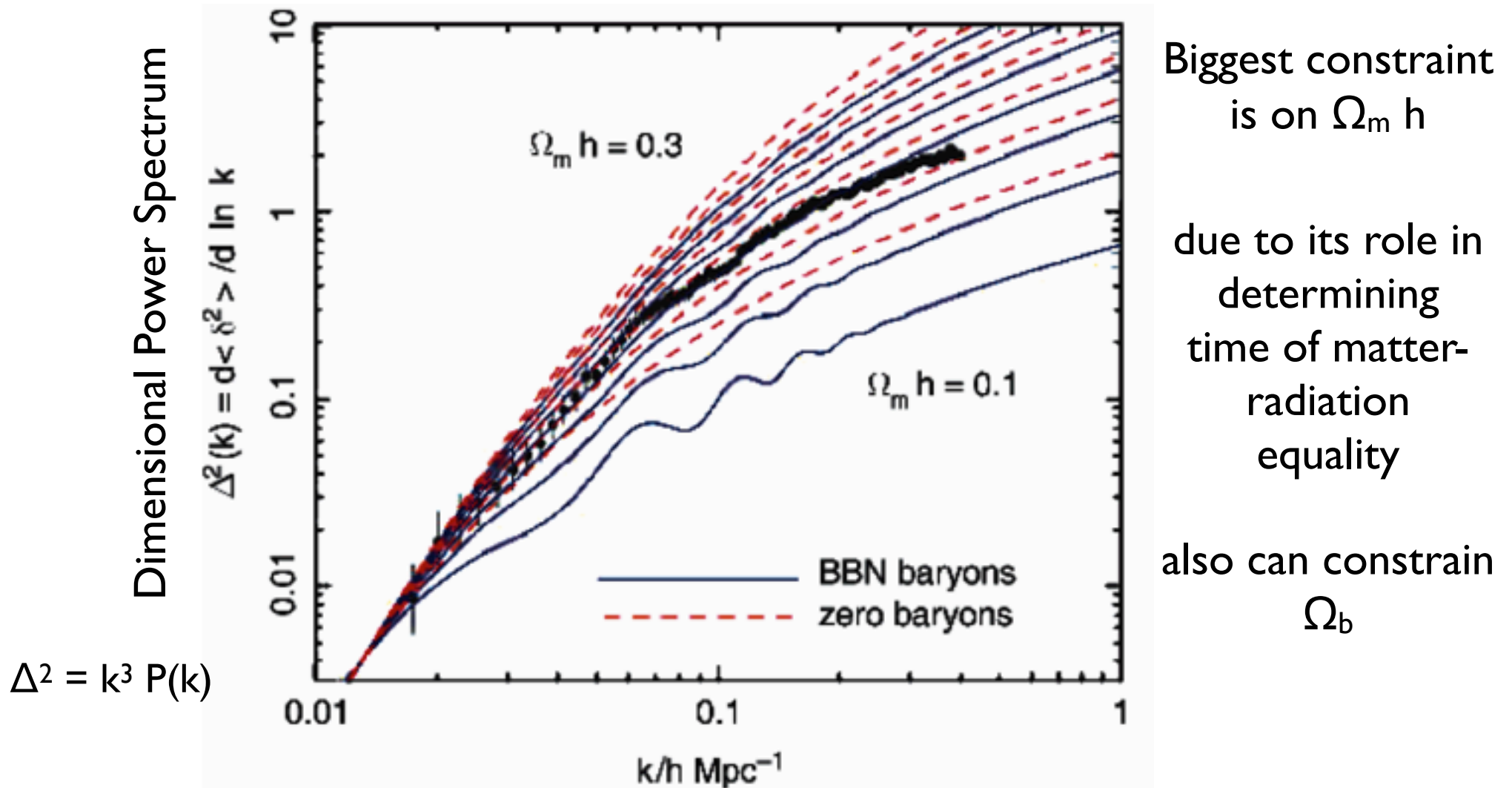
Galaxy Bias

$$\delta_g := \frac{\Delta n}{\bar{n}} = b \frac{\Delta \rho}{\bar{\rho}} = b \delta$$

Fluctuations in number density of galaxies is higher than fluctuations in the underlying mass density

What does the power spectrum teach us about the cosmological parameters?

Compare observed power spectrum with that found in simulations



Biggest constraint is on $\Omega_m h$

due to its role in determining time of matter-radiation equality

also can constrain Ω_b

Implications for Cosmological Parameters

Can use comparison to constrain cosmological parameters!

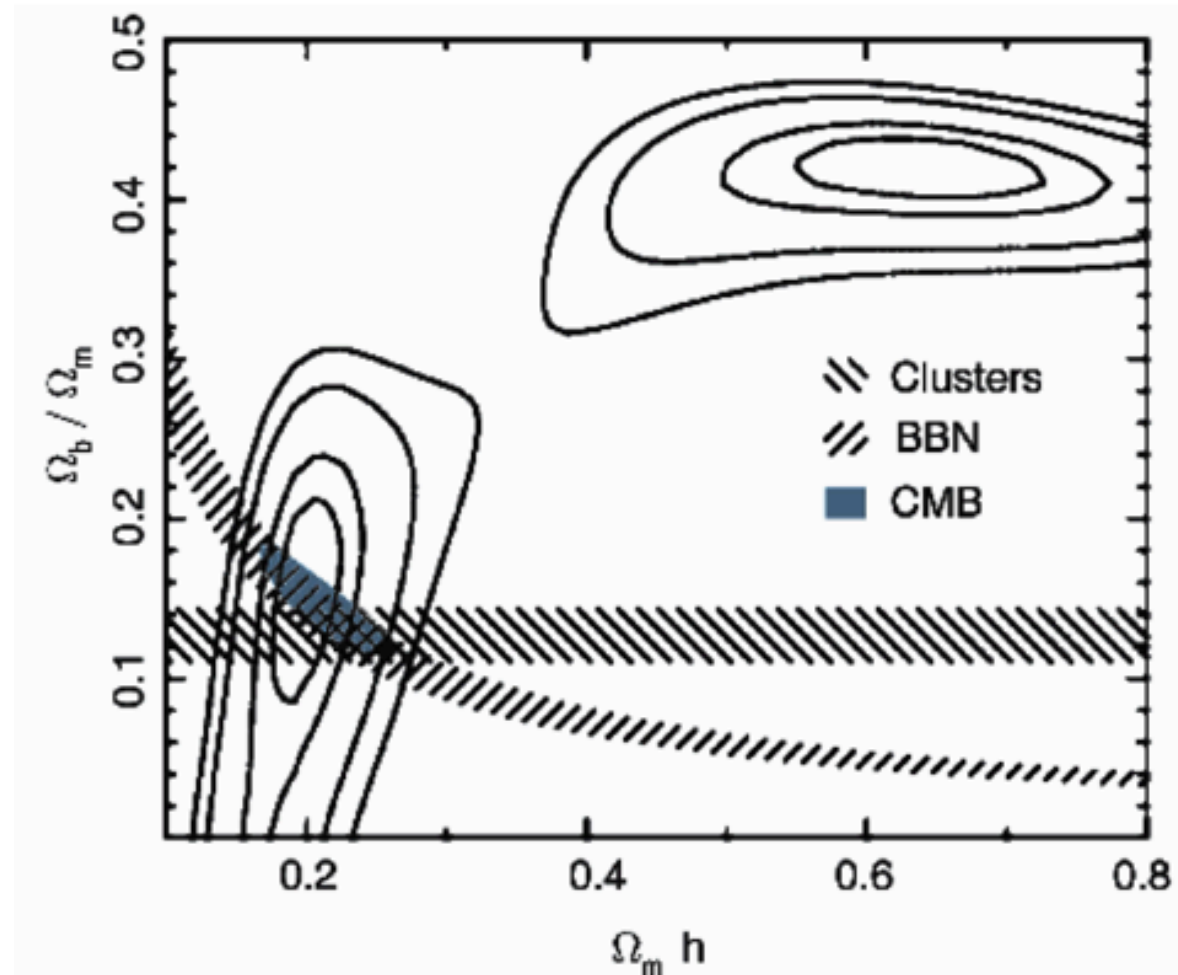
Allowed solutions are bimodal, but we can eliminate one of solutions using other constraints

$$\Omega_m h = 0.2$$

$$\Rightarrow \Omega_m = 0.3$$

$$\Omega_b = 0.04$$

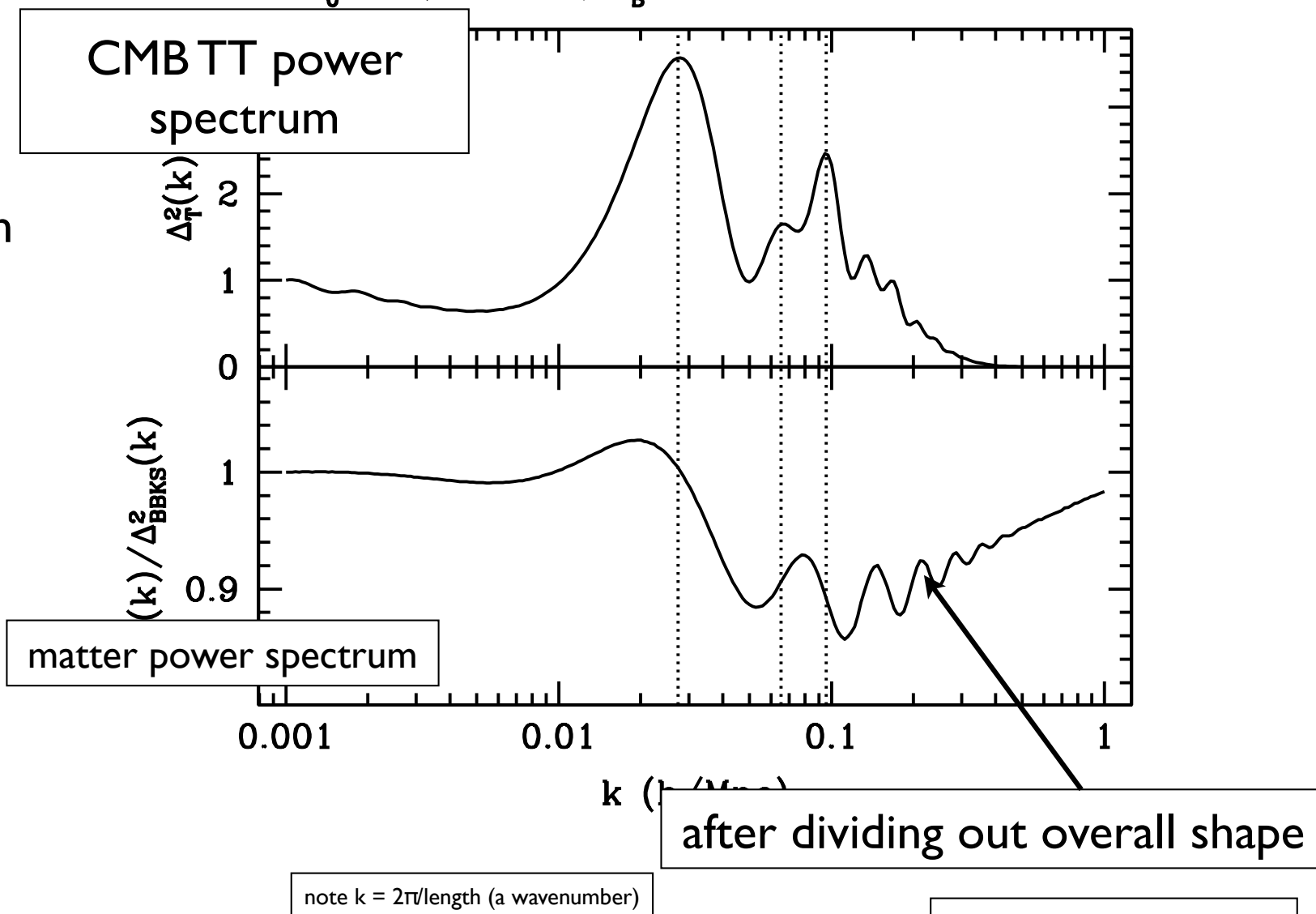
Yet another constraint on the baryonic density of universe!



Acoustic oscillations in the baryon-photon fluid imprint “ringing” in the matter power spectrum

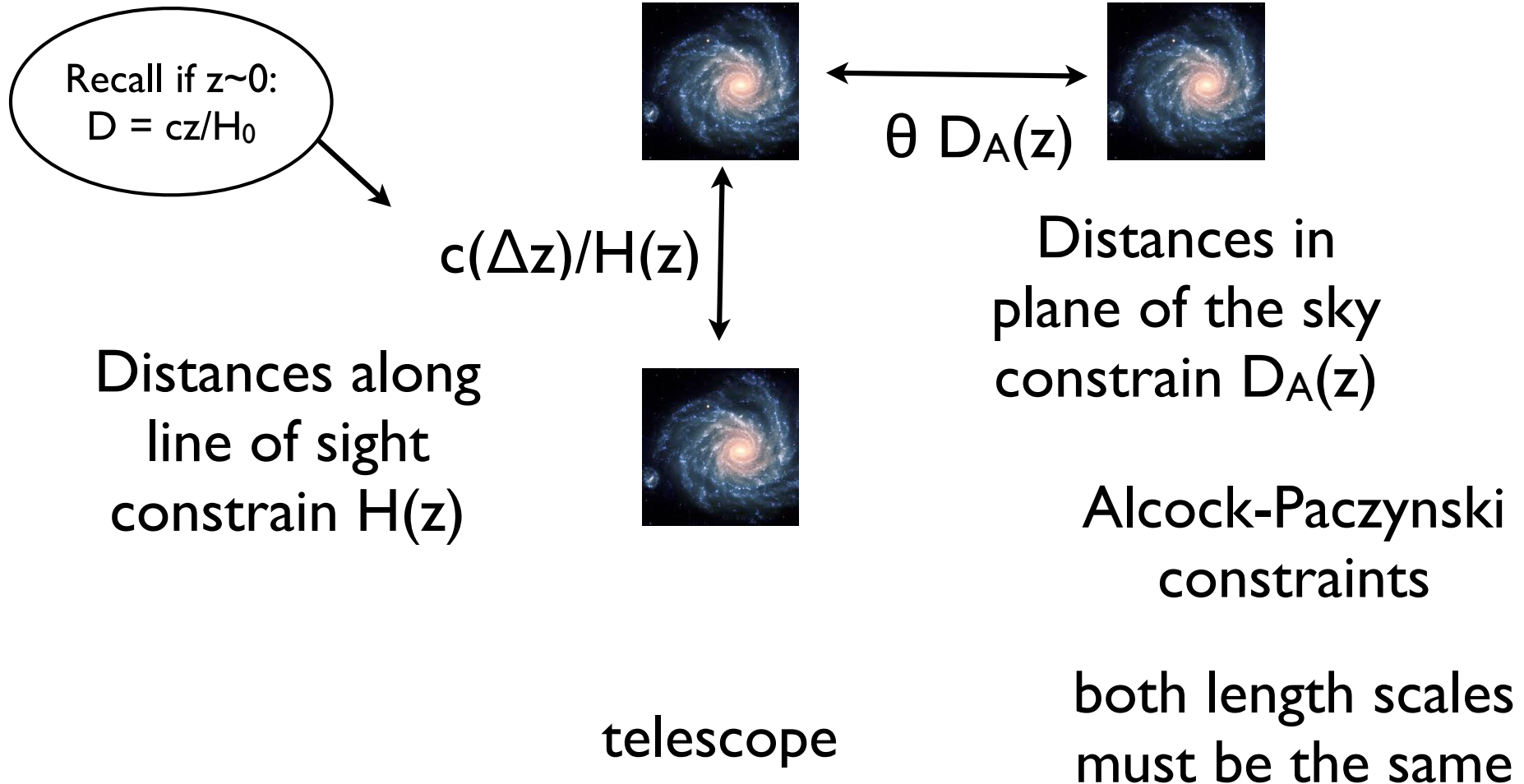
$\Omega_0=0.4, h=0.65, \Omega_b h^2=0.02$

These acoustic peaks are frozen into the power spectrum and can be used as a standard rod to measure $D_A(z)$ and $H(z)$ at all redshifts where the clustering signal can be precisely measured.

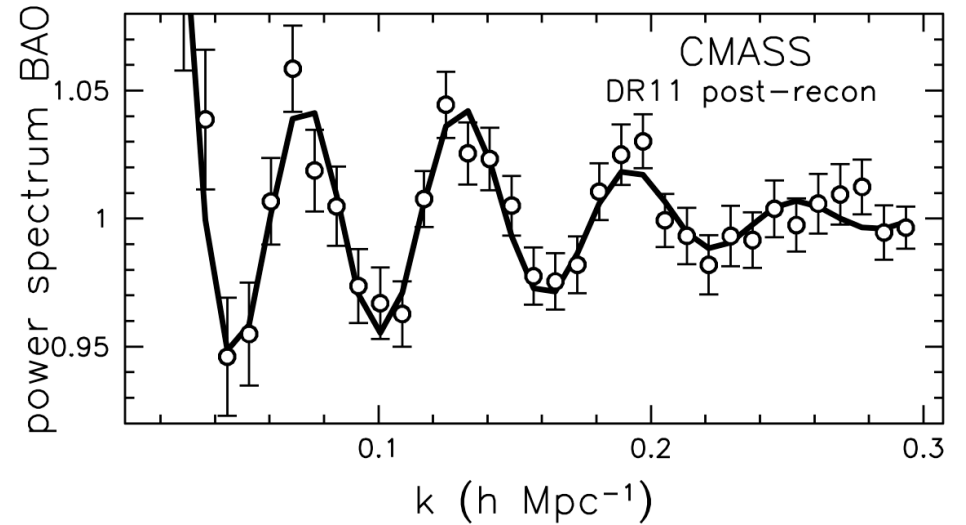


The Baryon Acoustic Oscillation Method can be used to look for structure in the plane of the sky, but also along the line of sight

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

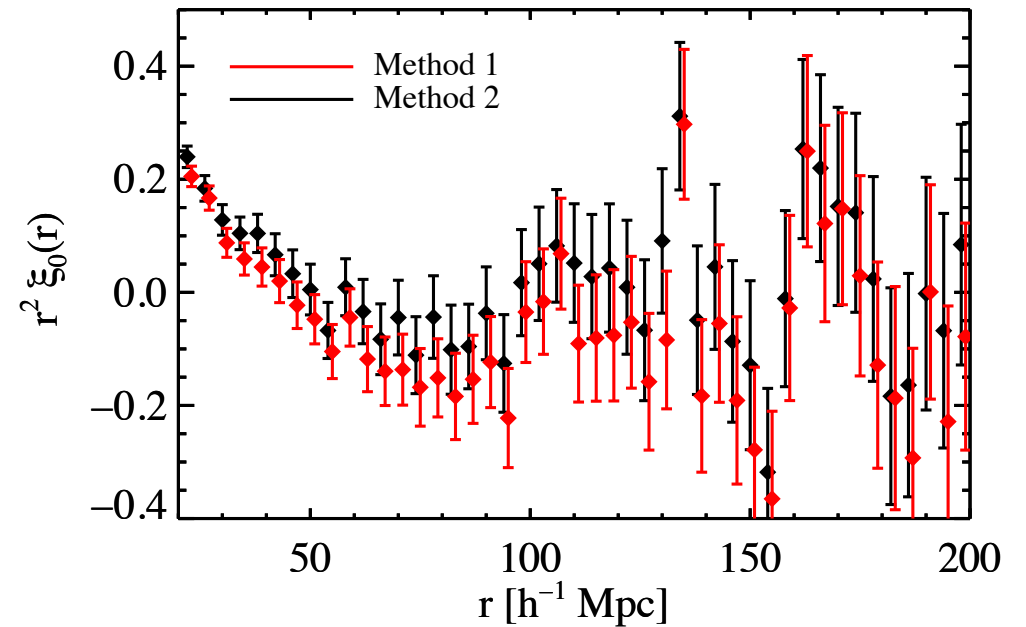


Example of the impact
BAO fluctuations have on
the power spectrum for
 $z \sim 0.55$ galaxies



Anderson+2013

Power spectrum measured
for absorption lines from
gas at $z \sim 2.3$ in $z \sim 2.5$ quasars



Busca+2013

New Material for This Week

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

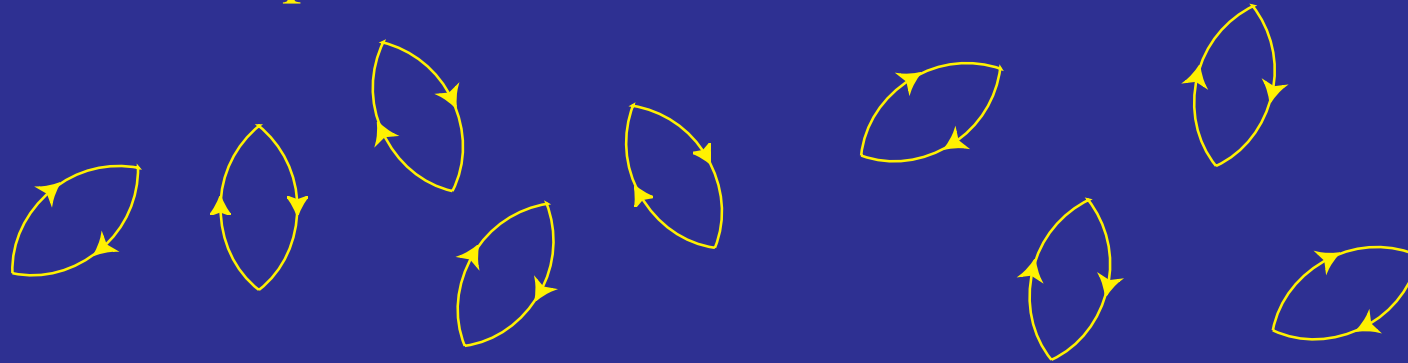
As you all know, a key component of universe is dark energy. Very roughly, it exerts a repulsive force on the space fabric -- increasing its acceleration.

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

Time Varying Dark Energy

For quintessence or phantom energy ($w < -1$ or $w > -1$), the dark energy density evolves:

How? Friedmann's equations:

differentiate with respect to time \longrightarrow

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

$$2\dot{a}\ddot{a} = \frac{8\pi G}{3} \frac{d}{dt}(\rho a^2) \qquad \ddot{a} = -\frac{4\pi G}{3} \rho(1+3w)a\dot{a} \qquad \leftarrow \text{multiply by } da/dt$$

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

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

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

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

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

$$\frac{\dot{\rho}}{\rho} = -3w\frac{\dot{a}}{a} - 3\frac{\dot{a}}{a} = -3(1+w)\frac{\dot{a}}{a}$$

For $w = -1$ the density is constant.

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

Time Varying 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:

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

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?

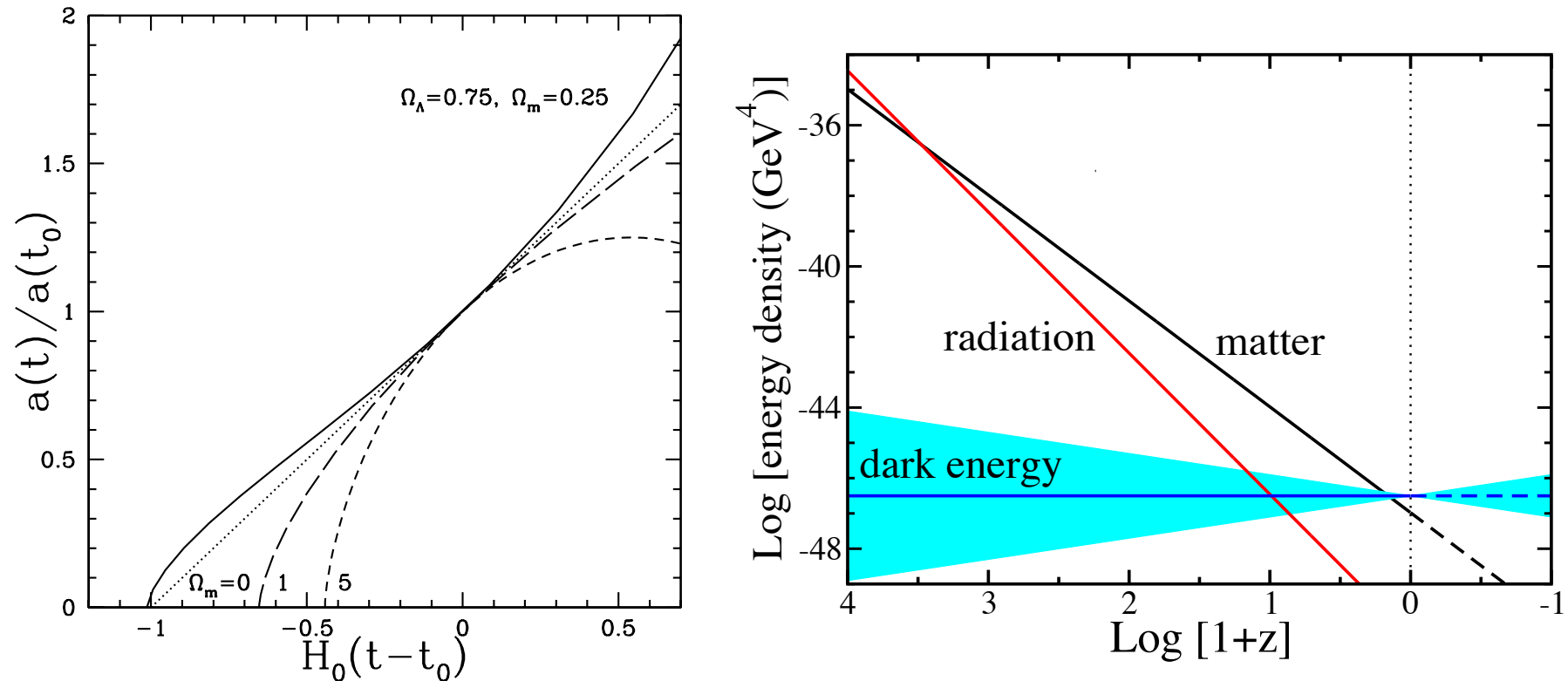
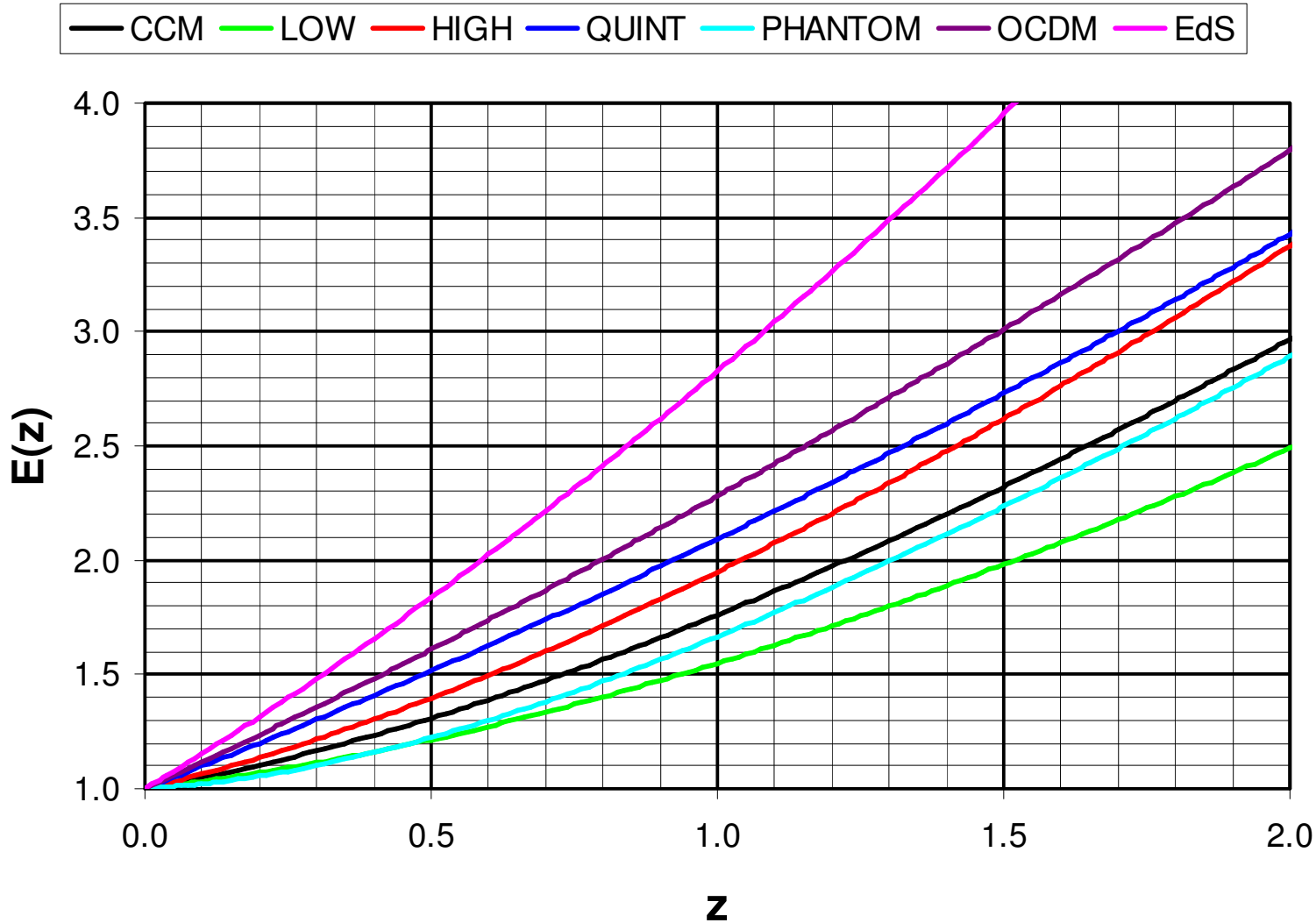


FIGURE 1. Left panel (a): Evolution of the scale factor vs. time for four cosmological models: three matter-dominated models with $\Omega_0 = \Omega_m = 0, 1, 5$, and one with $\Omega_\Lambda = 0.75, \Omega_m = 0.25$. Right panel (b): Evolution of radiation, matter, and dark energy densities with redshift. 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 :

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

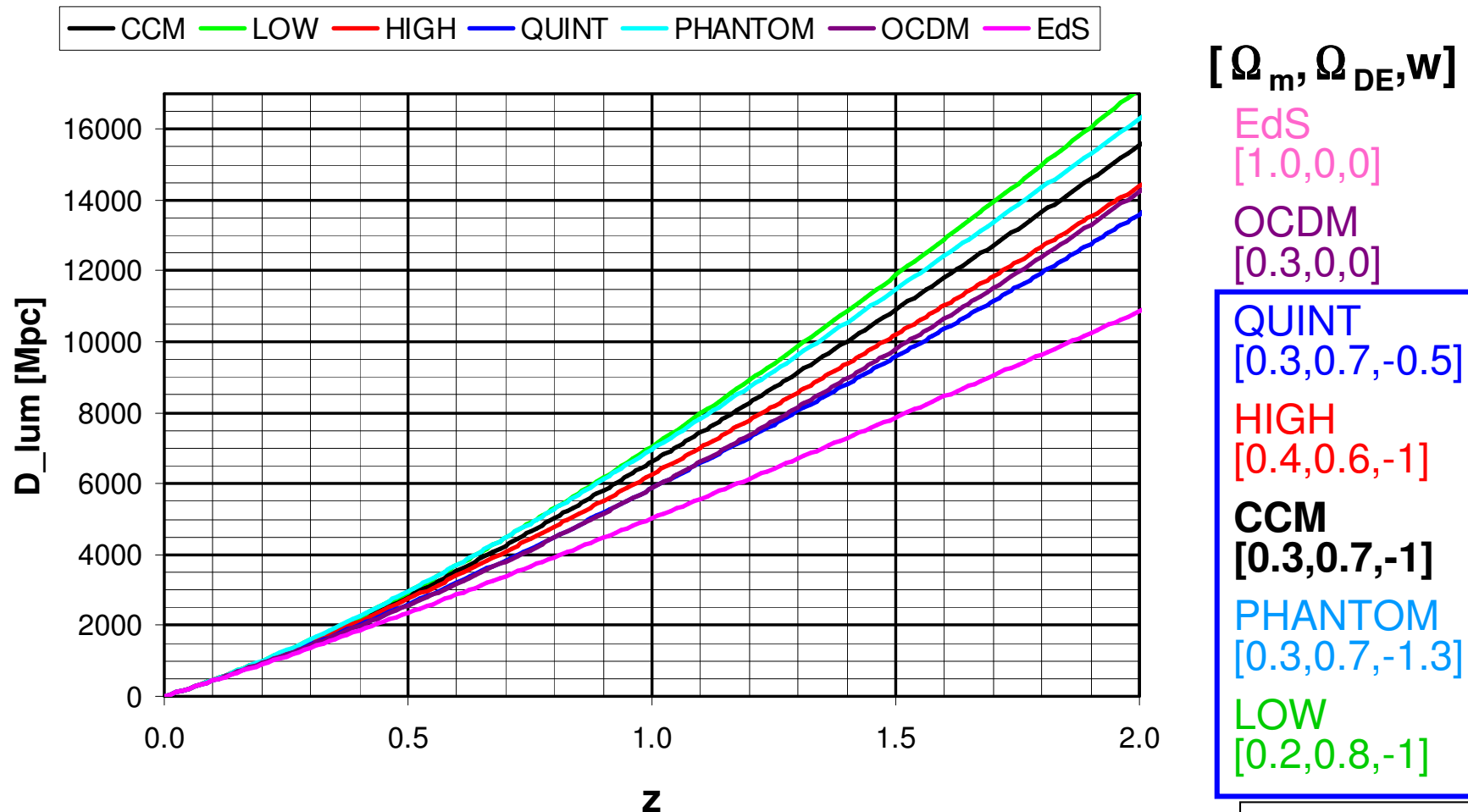
mit: $\Omega_k \equiv 1 - \Omega_m - \Omega_\Lambda$ & $d_H = 4280 h_{70}^{-1} \text{Mpc}$

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



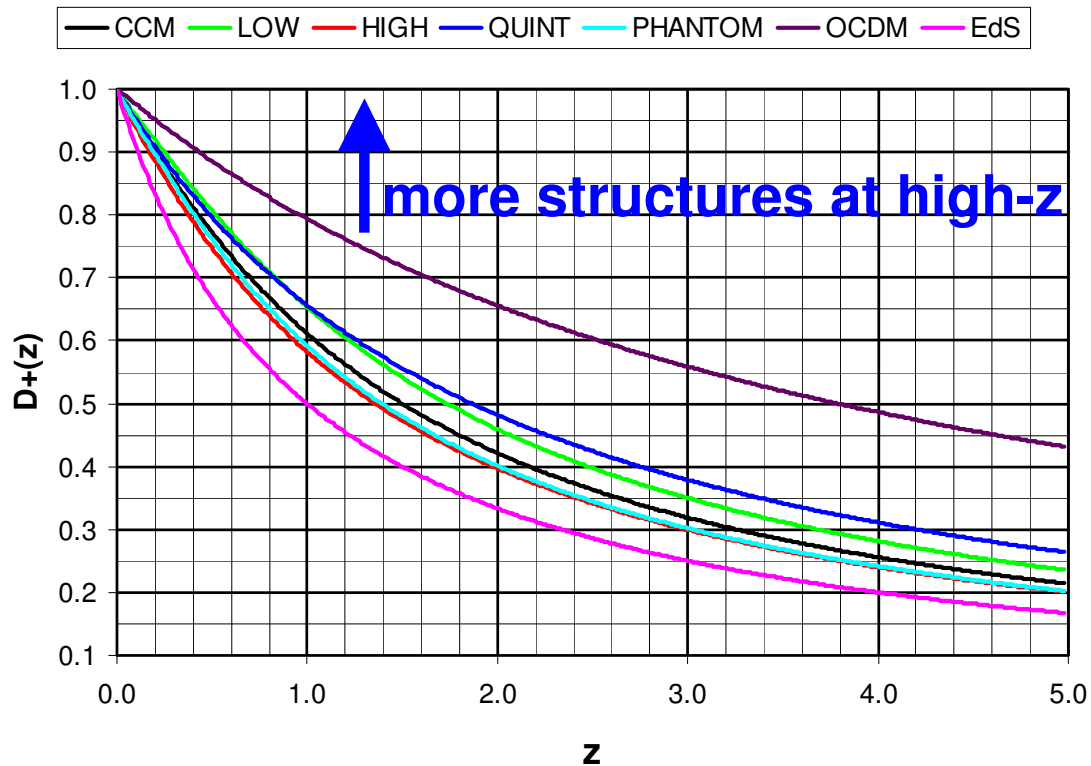
Credit: Fassbender

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) $\delta(\mathbf{x}, t) = D_+(t) \cdot \delta_{i+}(\mathbf{x}, t_i)$

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

- 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)



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

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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PHANTOM
[0.3, 0.7, -1.3]

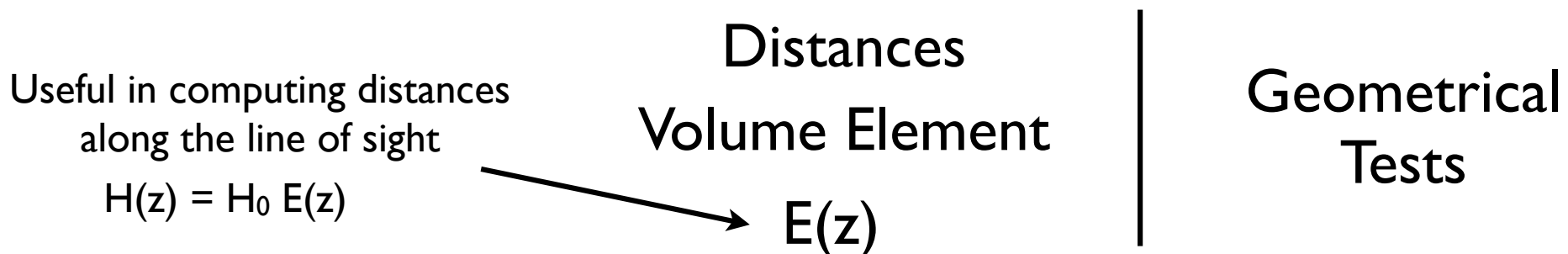
LOW
[0.2, 0.8, -1]

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How can we constrain the w parameter?

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

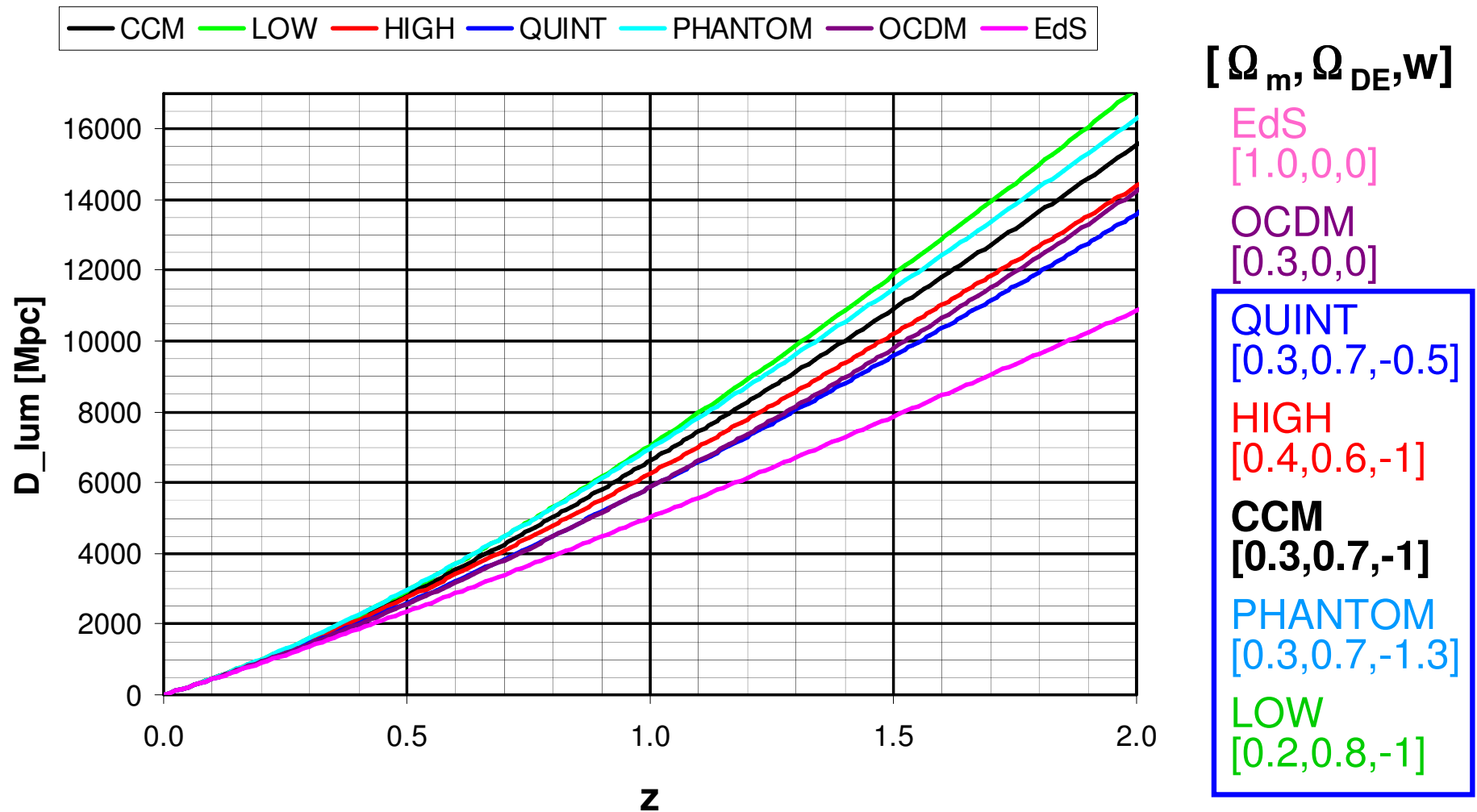
We constrain it by looking at the following quantities versus redshift (cosmic time, see earlier lecture):



Growth Factor (Rate at which structures in Universe Grow)

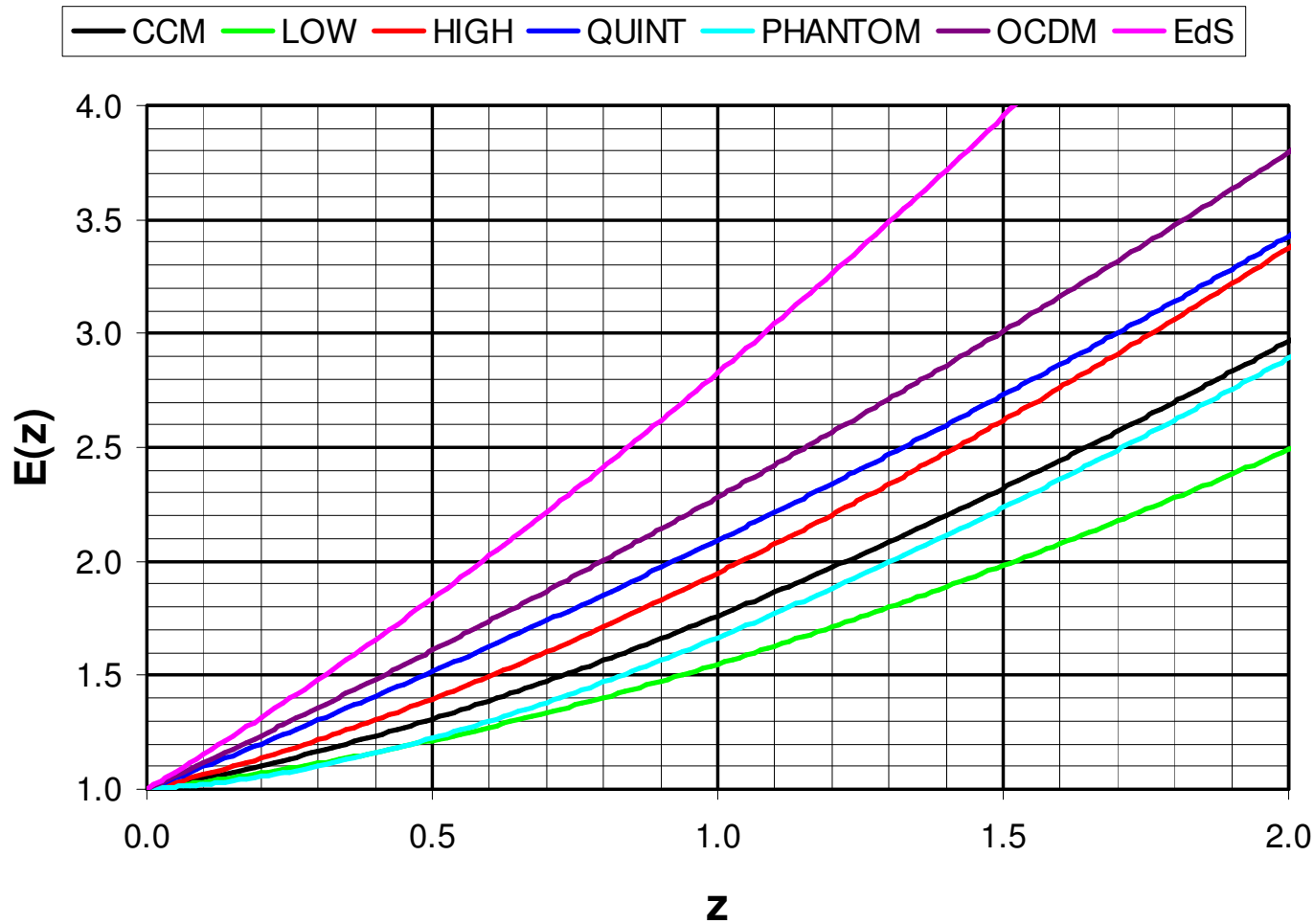
How can we probe this?

Luminosity Distance



How can we probe this?

The Evolution Function $E(z)$



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

EdS
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OCDM
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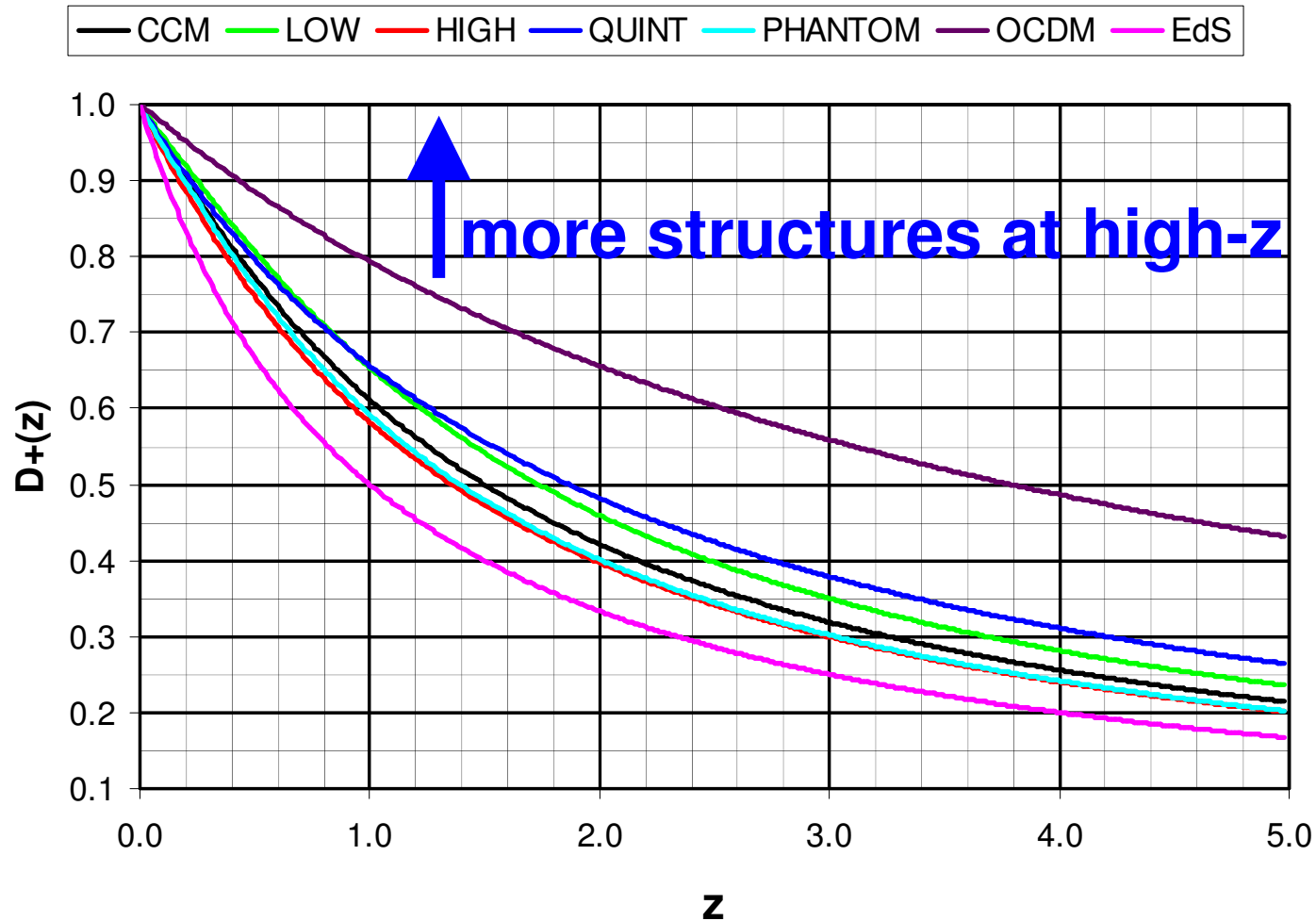
LOW
[0.2, 0.8, -1]

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

Credit: Fassbender

How can we probe this?

Growth Factor



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

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LOW
[0.2, 0.8, -1]

structure grow efficiently when $\Omega = 1$ (since density is close to ρ_{crit} where slight overdensities cause collapse)

Credit: Fassbender

Here's an alternate set of plots:

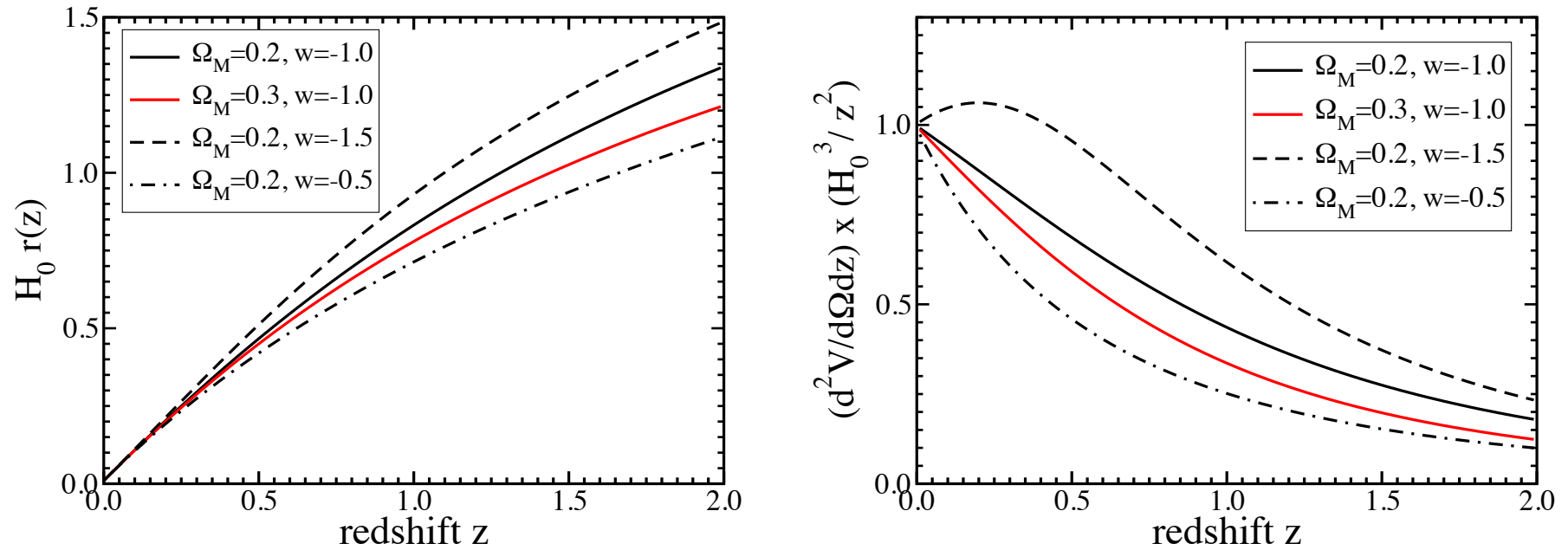
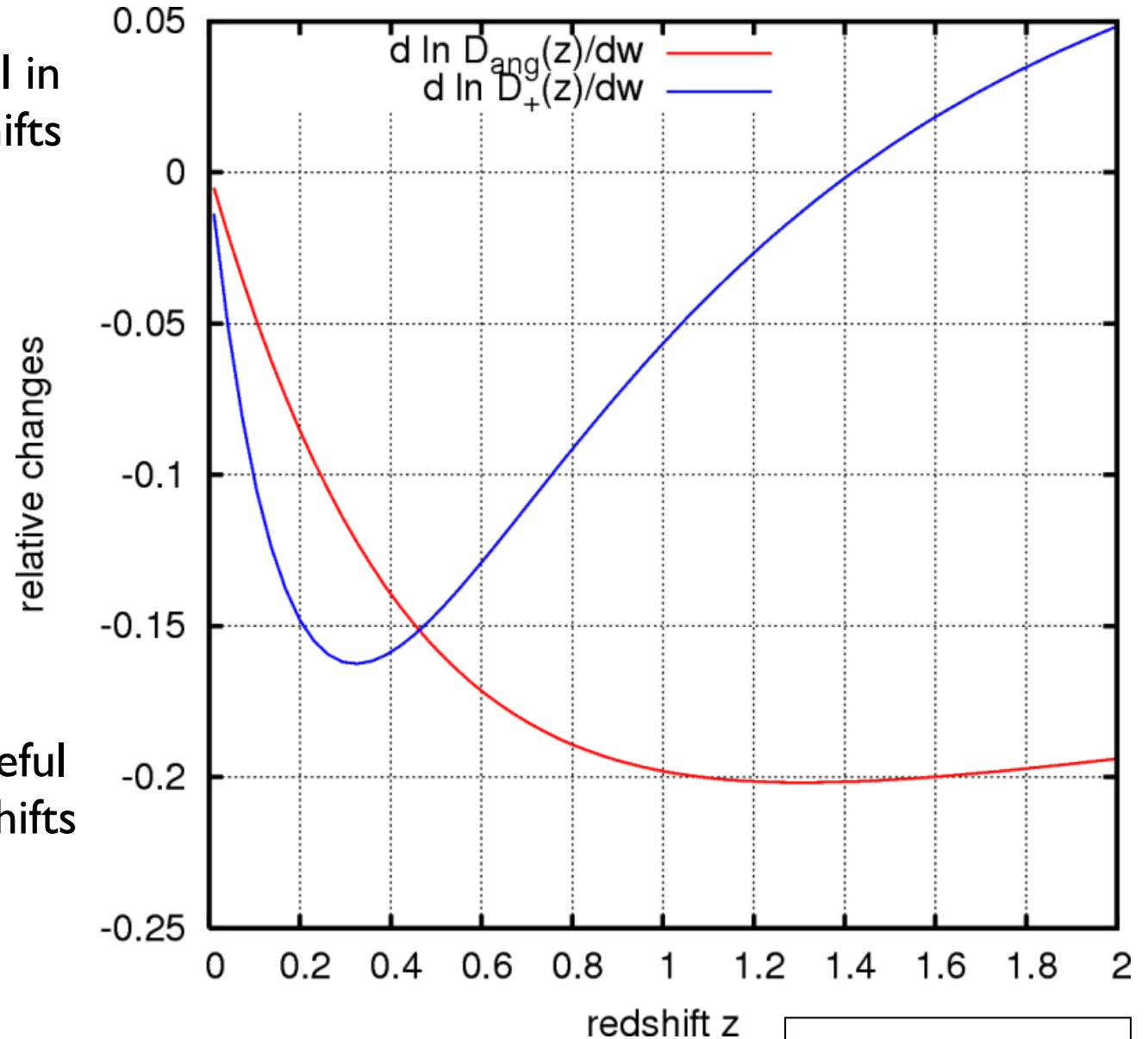


FIGURE 2. Left: Distance vs. redshift in a flat Universe with different values of the cosmological parameters Ω_m and w . Right: volume element vs. redshift for same models. From Frieman et al. [13].

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** (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

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)

$$\text{mass} > 10^{14} M_{\text{sol}}$$

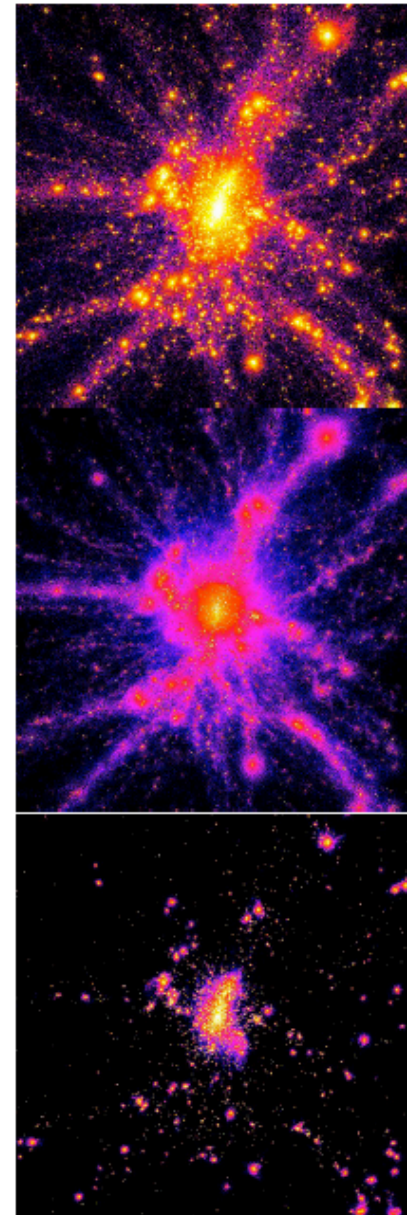
Approximate mass budget:

~2% galaxies

~13% in a very hot ionized gas

~85% in dark matter

Most of the baryons are in the ionized gas!



Dark matter

Baryons

Stellar
distribution

$z=0$

Credit: Porciani

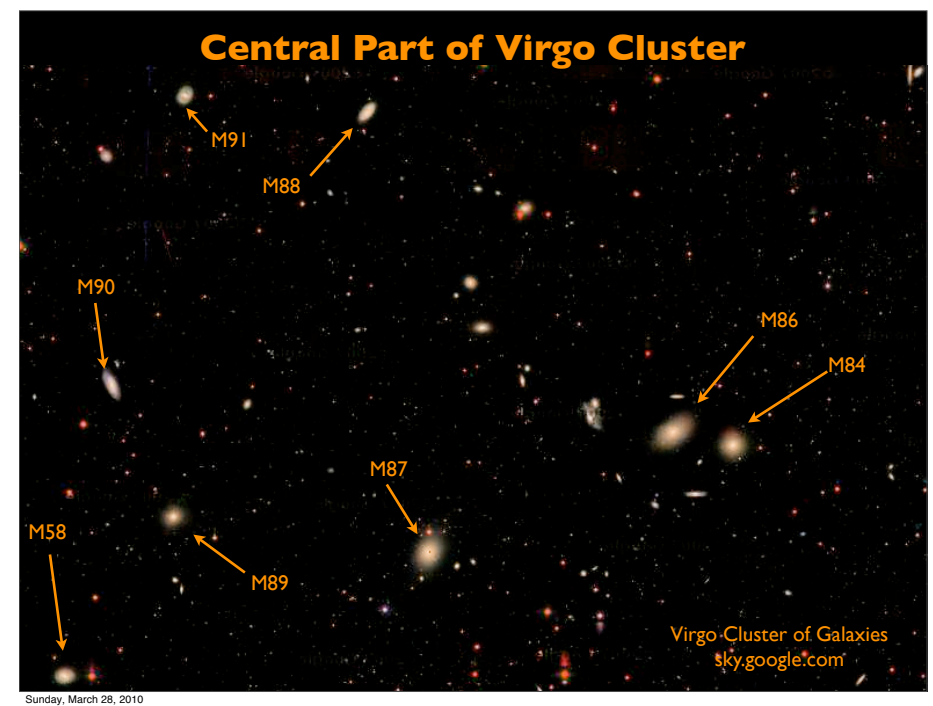
Intra-Cluster Medium (ICM)

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

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



Sunday, March 28, 2010

Coma cluster

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



Sunday, March 28, 2010

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)

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

$\delta_c = 1.67$ (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 :

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

I. 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



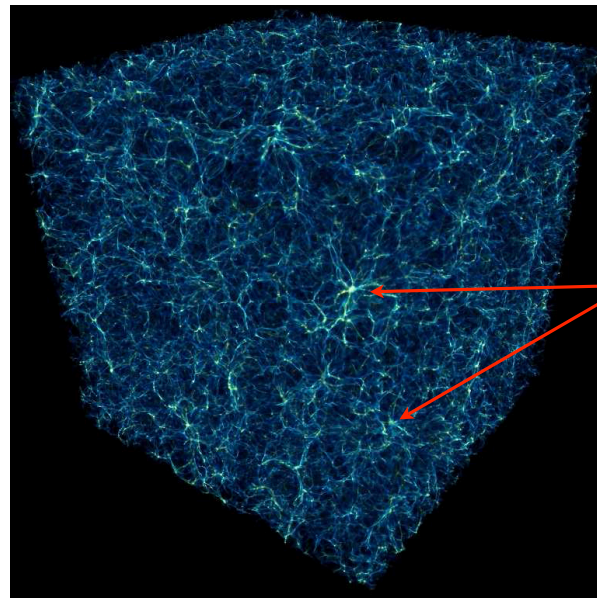
2) Have method to derive masses for clusters found in surveys

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 $>10^{14} M_{\text{sol}}$ clusters in $z=0$ universe is $\sim 7 \times 10^{-5} \text{ Mpc}^{-3}$



700 Mpc
comoving
cube

**Galaxy
clusters:**
rare peaks
in the
density
field

How do we find galaxy clusters?

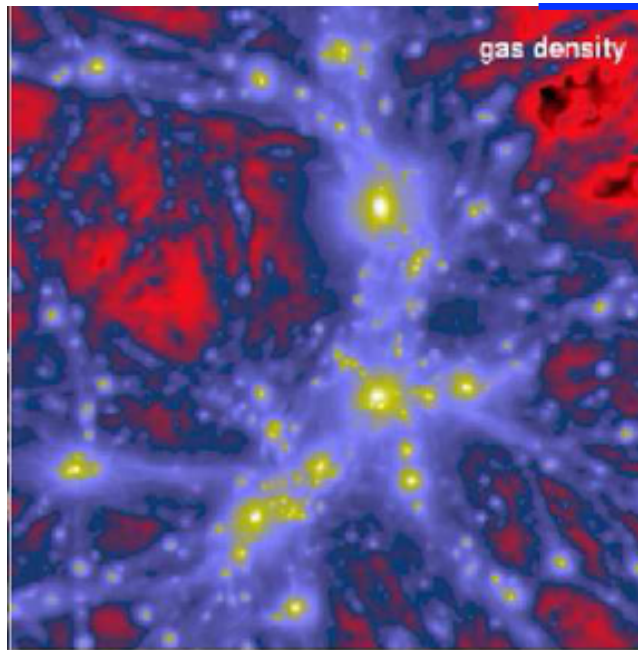
This is an interesting question -- since galaxy clusters are quite rare -- and so one will not often find very massive ones even in large galaxy surveys.

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

How do we find galaxy clusters?

I. 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 bremsstrahlung



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?

I. By surveying the sky at x-ray wavelengths

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

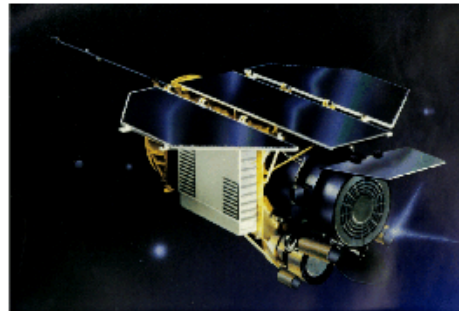
X-ray observatories

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 $z > 1$.

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

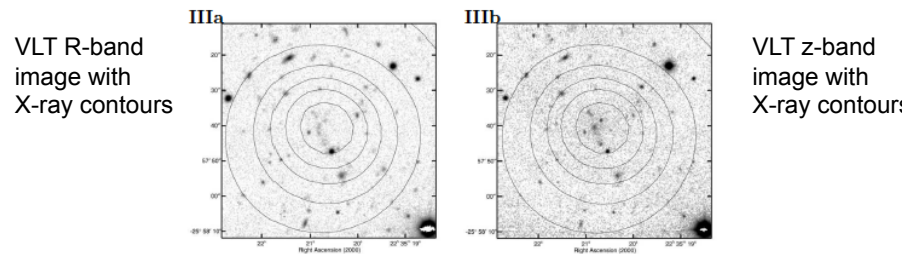


- German survey-instrument (MPE)
- start 2019
- ~20" resolution
- all-Sky Survey
- goal: ~100,000 clusters

How do we find galaxy clusters?

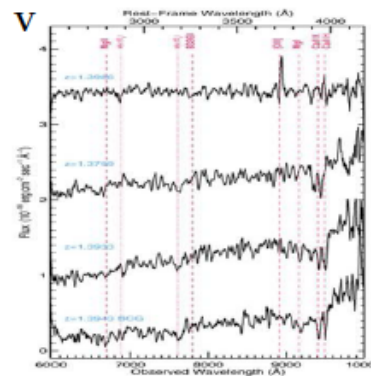
I. By surveying the sky at x-ray wavelengths

1. Start by identifying weak, extended x-ray sources in wide-area surveys
2. Follow up clusters and look for overdensity of red galaxies

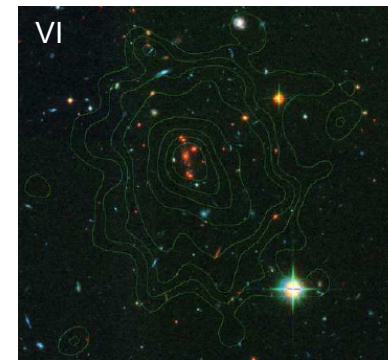


3. Estimate redshift of cluster from position of spectral breaks in the red galaxies

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



VLT spectra of 4 cluster member galaxies at $z=1.39$

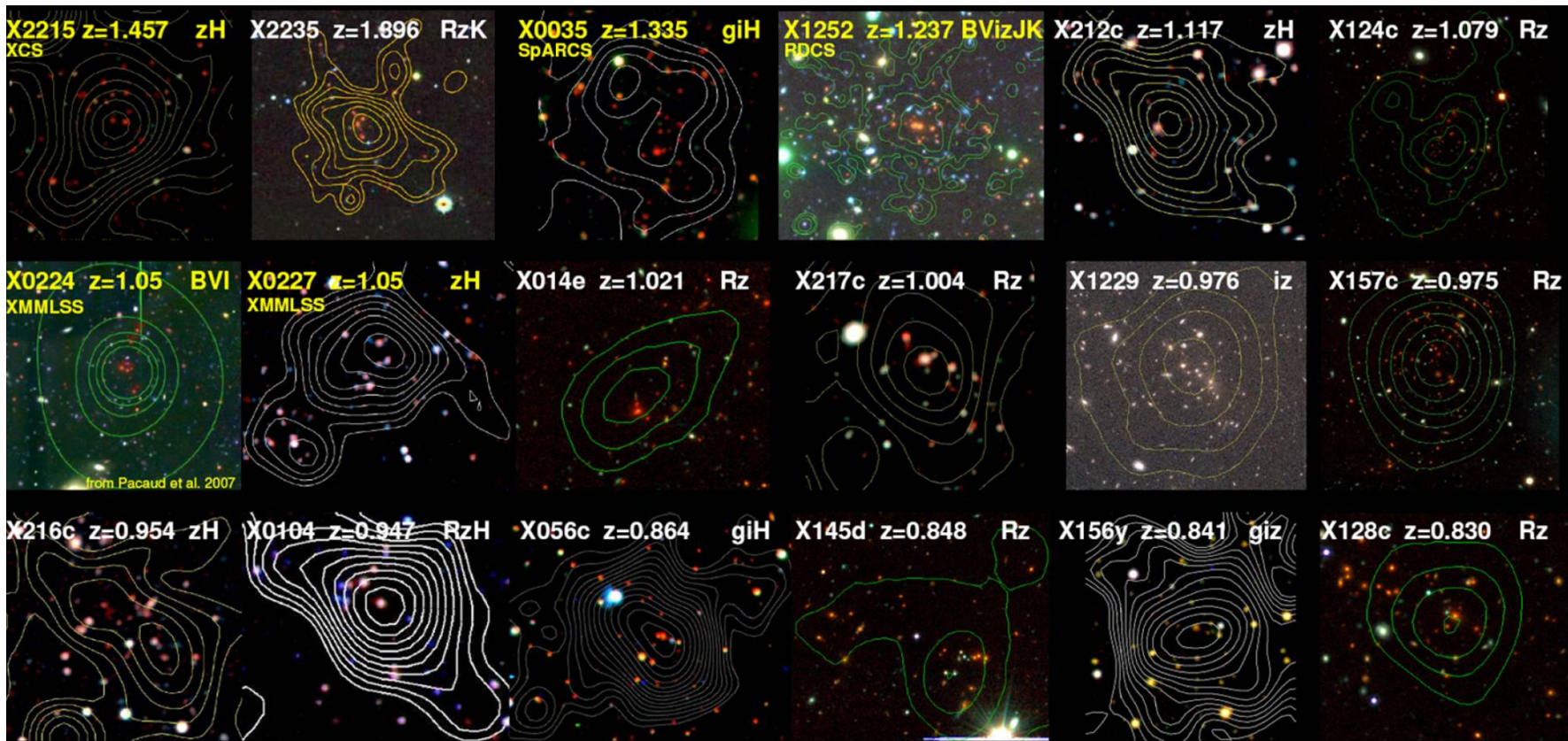


HST i+z + VLT K-band color image with Chandra contours of XMMU J2235.3-2557

How do we find galaxy clusters?

I. By surveying the sky at x-ray wavelengths

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

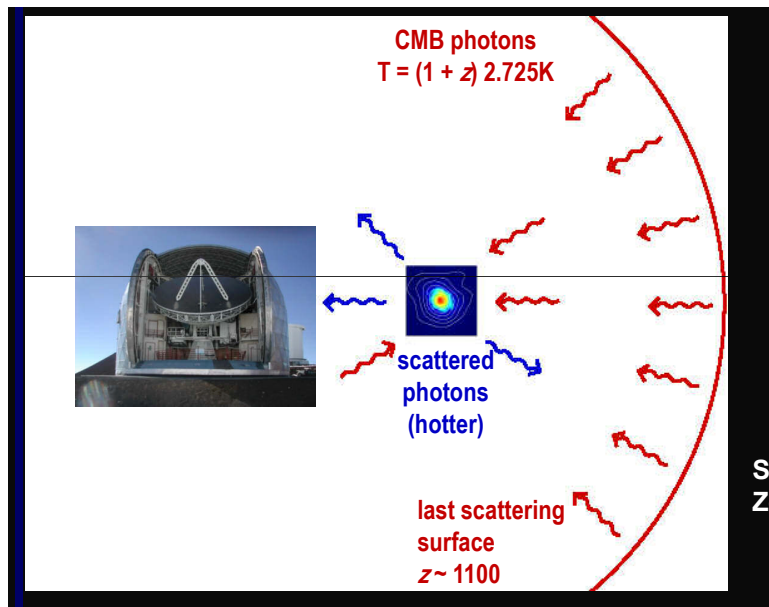


How do we find galaxy clusters?

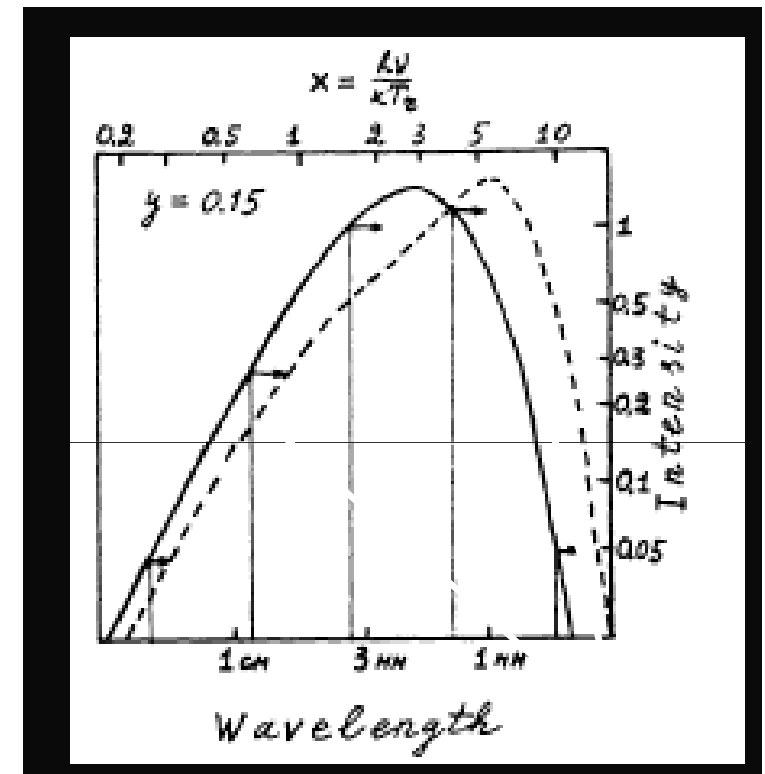
2. By using the Sunyaev-Zeldovich effect

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

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):

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

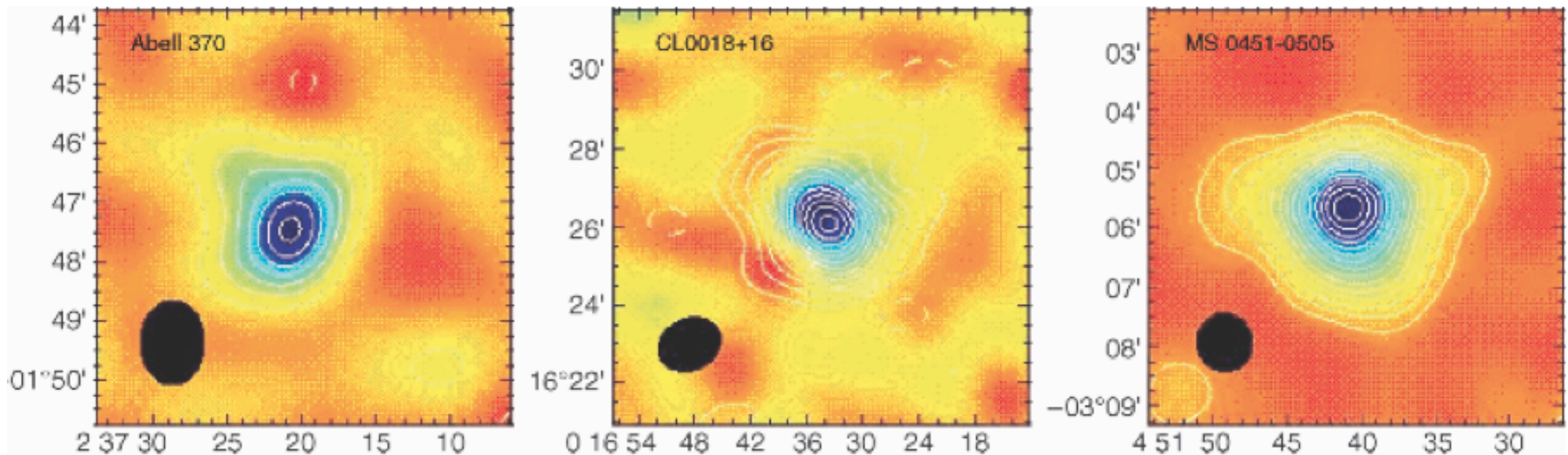
Important point is that the change is proportional to $n_e T_e$ integrated along the line of sight

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

How do we find galaxy clusters?

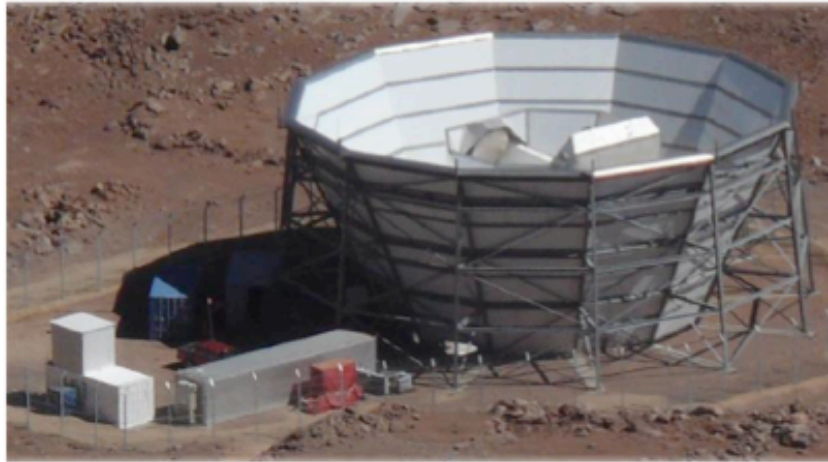
2. By using the Sunyaev-Zeldovich effect

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



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 deg²



South Pole Telescope (SPT)

Location: SP (2800m), Antarctica

Size: 10m

Frequencies: 90, 150, 220 GHz

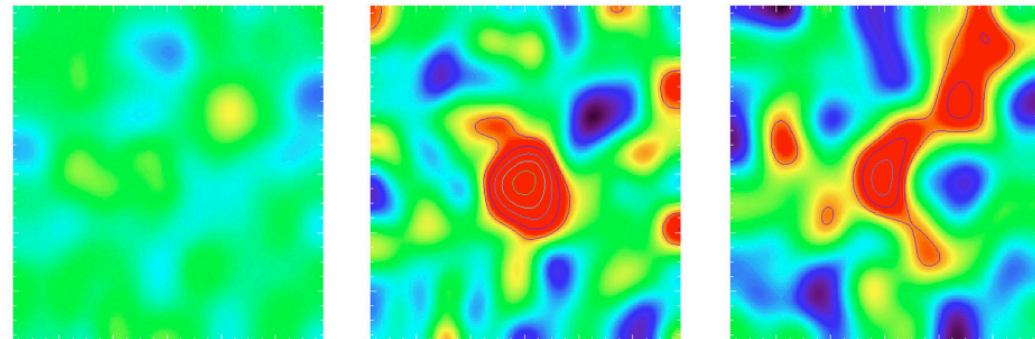
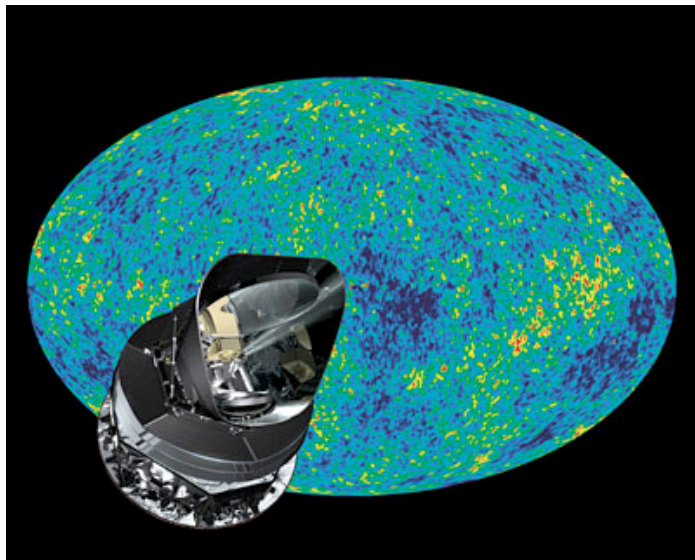
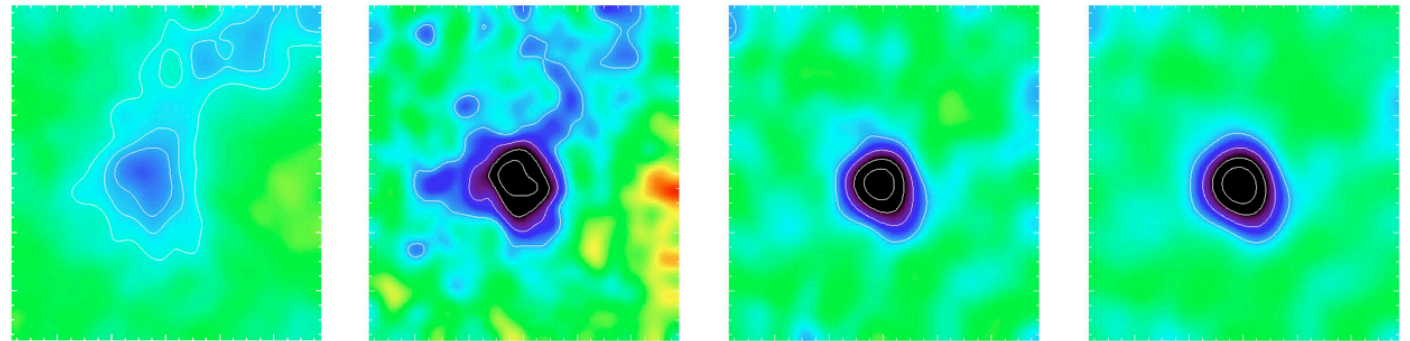
Resolution: ~ 1 arcmin

SPT Cluster Survey: ~ 2000 deg²

SZ Experiments

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

Planck satellite



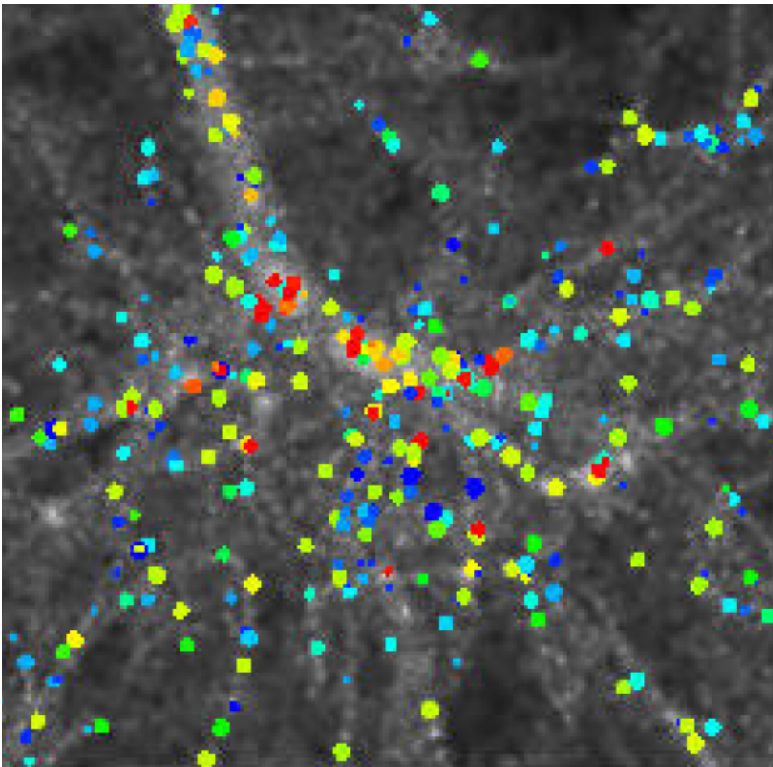
Abell 2319 with PLANCK
Top row: 44, 70, 100, 143 GHz
Bottom row: 217, 353, 545 GHz

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

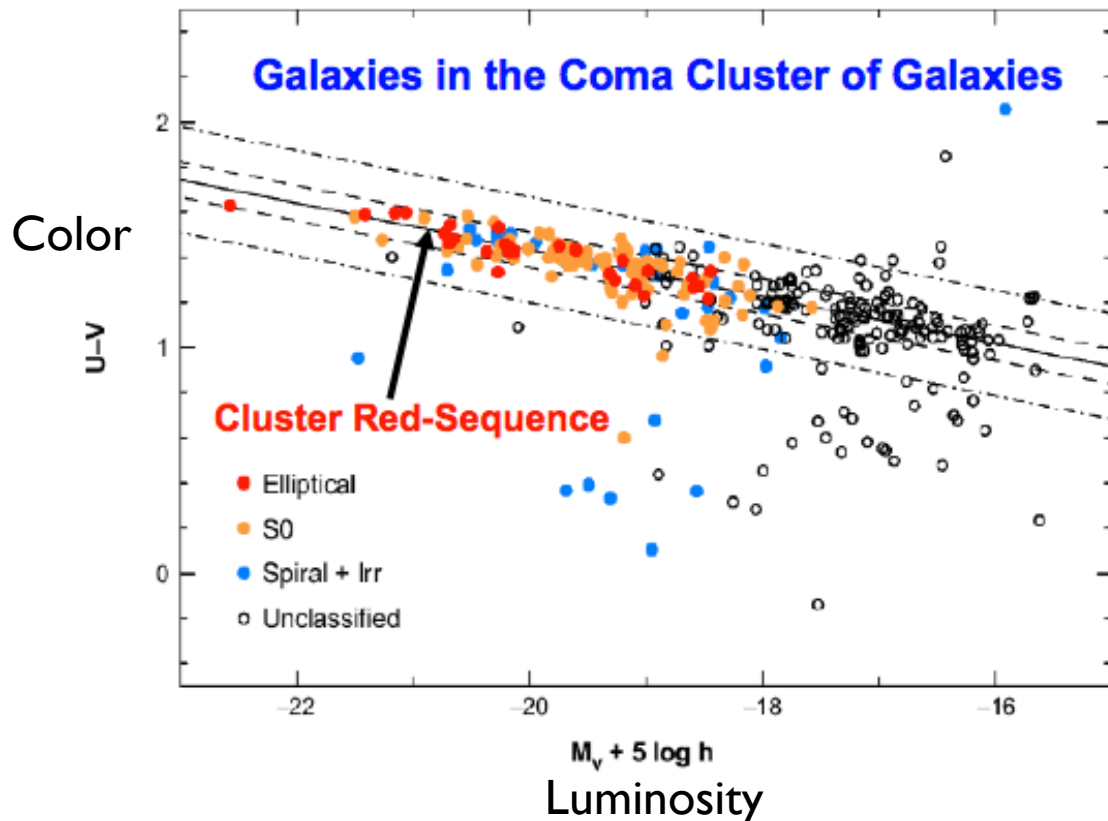


Since elliptical galaxies are red, require deep near-IR / mid-IR data to find distant galaxy clusters.

Value of optical data is more limited

How do we find galaxy clusters?

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



Credit: Barrientos et al., RCS survey



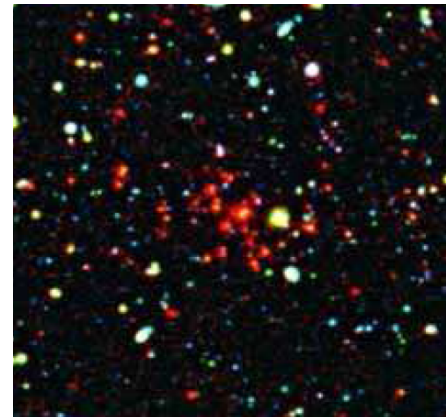
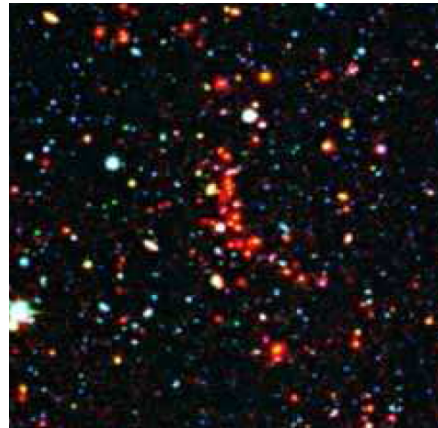
Figure 2: IJK colour composite image of the field centred on RCS0439.6-2905. North is up and East to the left. This image shows approximately the central 1.1×1.1 Mpc.

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

How do we find galaxy clusters?

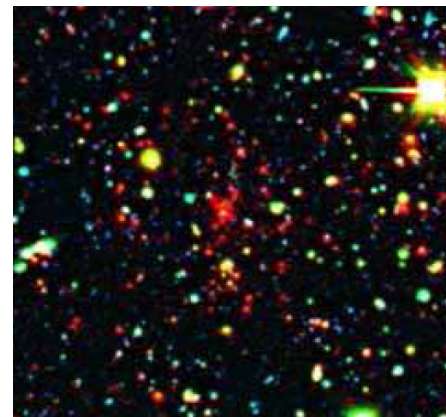
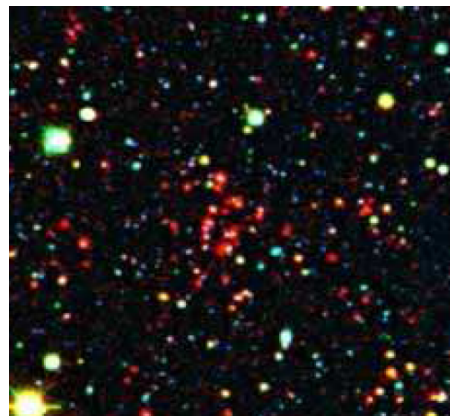
3. By identifying red sequence galaxies that make up the galaxy clusters

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



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

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



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

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

I. 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

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



Not necessary to do the same detailed modeling from lecture 5 for all clusters in cluster samples

Previous Lecture

Weighing Galaxy Clusters (from the ionized gas in clusters)

The basic idea is that:
since the ionized gas in a cluster is pressure supported and we can determine the density and temperature of gas in a cluster

From hydrostatic equilibrium:

$$\frac{1}{\rho} \frac{dp}{dr} = - \frac{GM(r)}{r^2}$$

Able to model this from observations

p = pressure
 r = radius
 ρ = density

We can infer this!

Cluster Masses Based on x-ray Observations

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

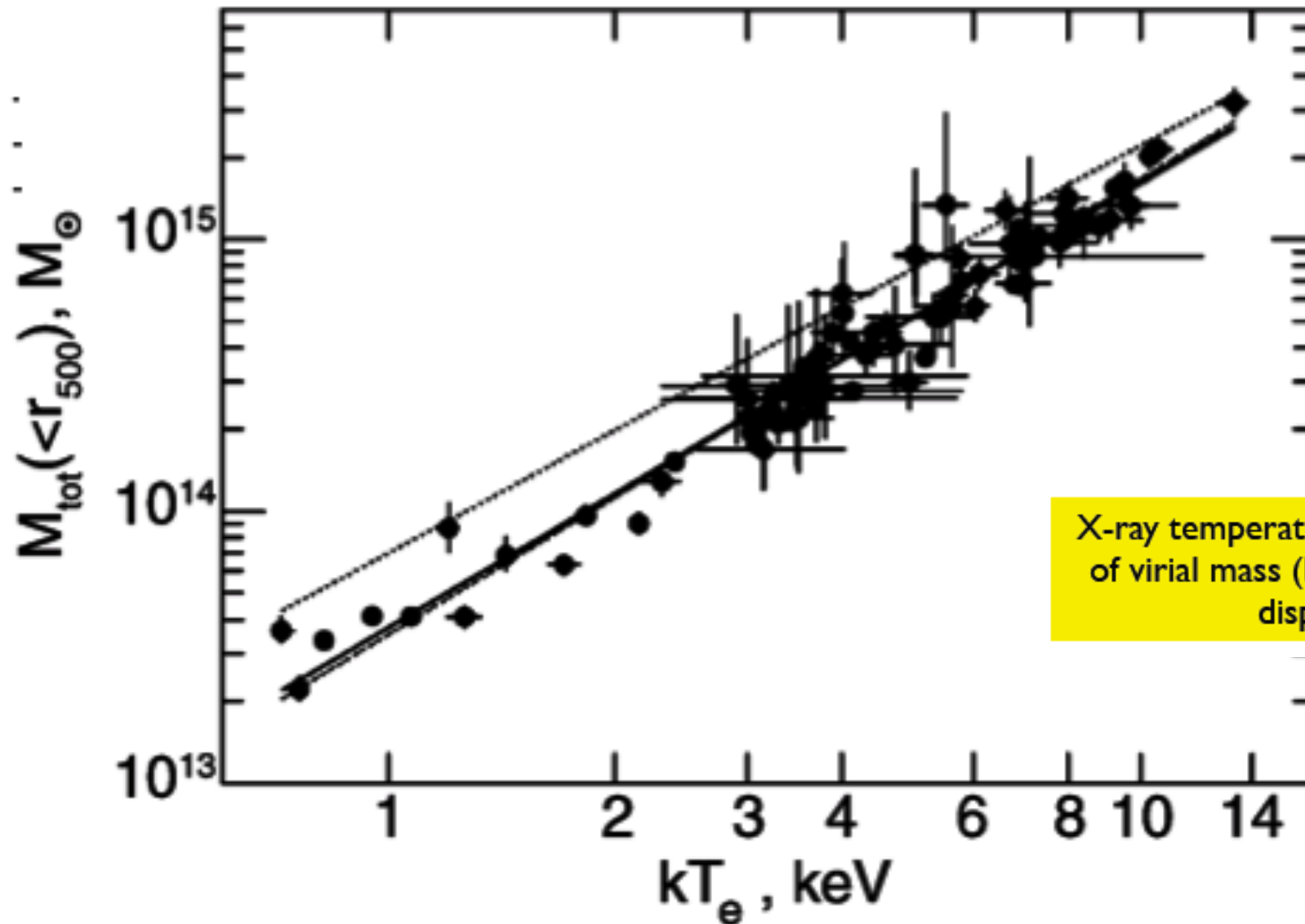
$$M_{200} = \frac{4\pi}{3} \Delta_c \rho_{\text{crit}} r_{200}^3$$

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

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

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



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

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

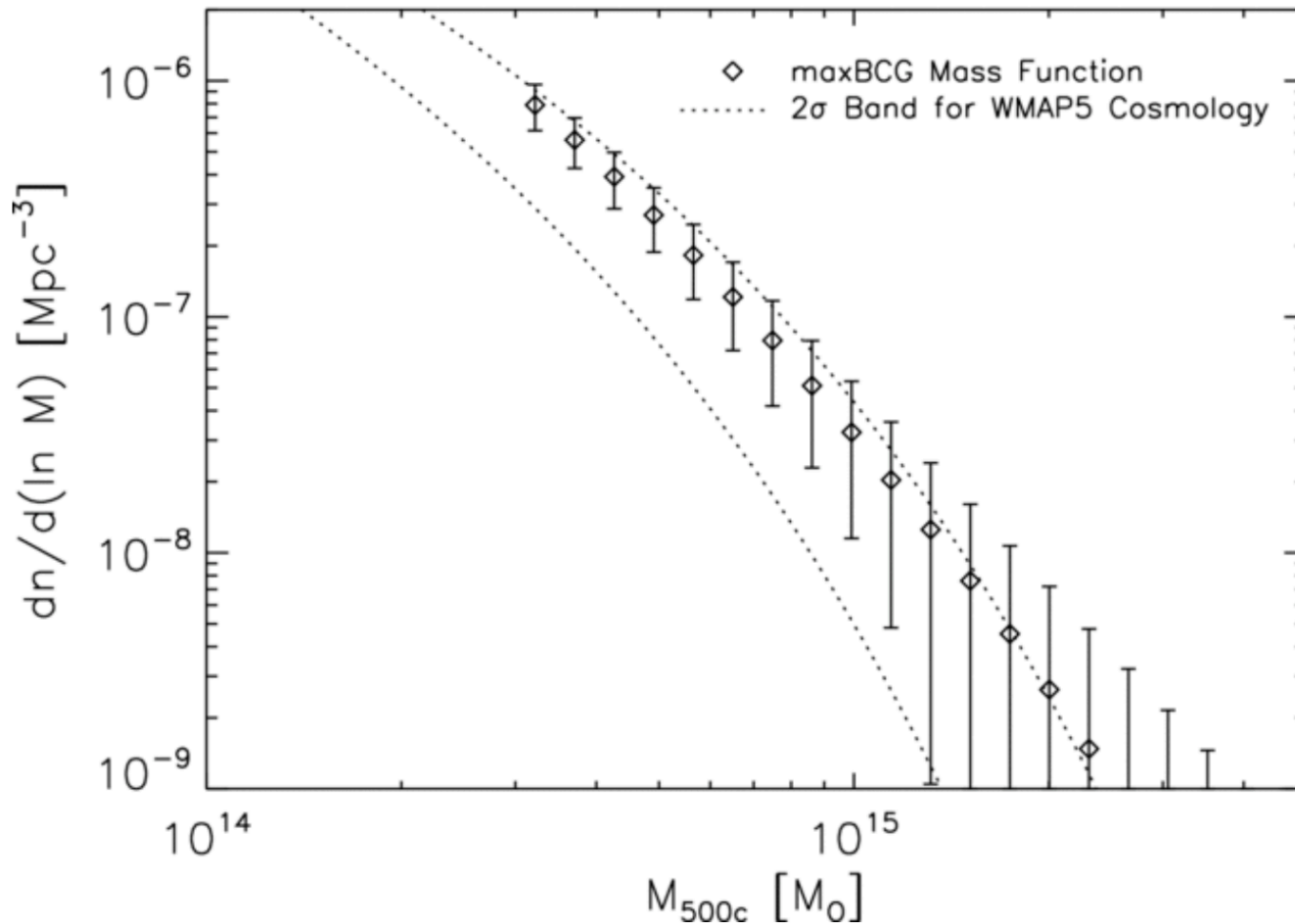
Can we derive a mass function from the observations using galaxy clusters?

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



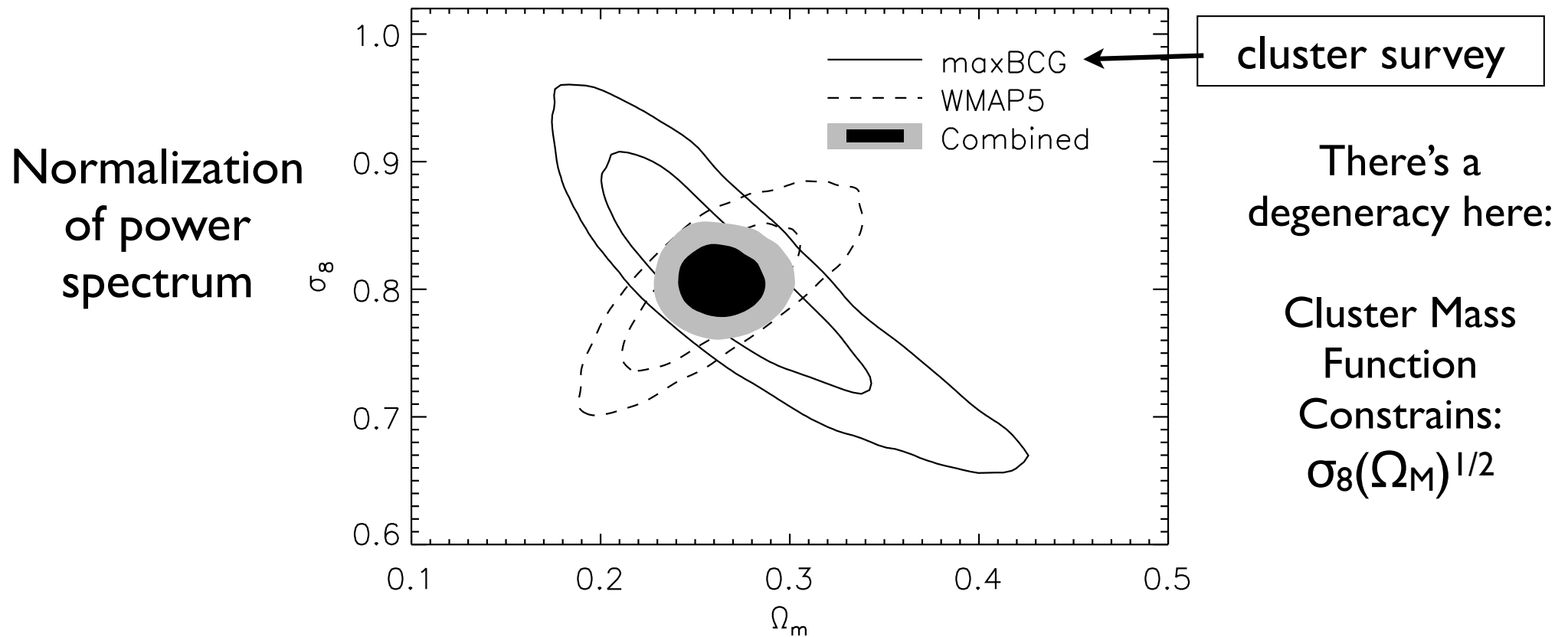
MaxBCG Sample

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

Rozo+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



Rozo et al. 2010

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

This is just one example of a probe of the cluster mass function at low redshift. Here are some other early determinations:

Paper	Observational Data Used	# Clusters	Survey Volume	Z Range	σ_8 Constraints	Ω_m Constraints
Eke, Cole & Frenk (1996)	X-ray (ROSAT)	≈ 50	Local Universe	$z < 0.1$	$\sigma_8 \approx 0.52-0.67$	$\Omega_m = 1$ assumed
Viana & Liddle (1996)	X-ray (ROSAT)	≈ 60	Small	$z < 0.1$	$\sigma_8 \approx 0.6-0.7$	$\Omega_m = 0.3-1$
Bahcall & Fan (1998)	Optical (Abell)	≈ 100	Small	$z < 0.2$	$\sigma_8 \approx 0.8$	$\Omega_m = 0.3$
Henry (2000)	X-ray (ROSAT)	≈ 60	Small	$z < 0.2$	$\sigma_8 \approx 0.56 \pm 0.1$	$\Omega_m = 1$ assumed
Seljak (2002)	X-ray + SZ	≈ 100	Intermediate	$z < 0.3$	$\sigma_8 \approx 0.7-0.8$	$\Omega_m = 0.3-0.4$
Reiprich & Böhringer (2002)	X-ray (ROSAT)	≈ 100	Intermediate	$z < 0.3$	$\sigma_8 \approx 0.7-0.9$	$\Omega_m = 0.3$
Pierpaoli et al. (2003)	X-ray (Temperature function)	≈ 100	Intermediate	$z < 0.3$	$\sigma_8 \approx 0.7-0.8$	$\Omega_m = 0.3$
Viana, Nichol & Liddle (2002)	X-ray (ROSAT)	≈ 100	Intermediate	$z < 0.3$	$\sigma_8 \approx 0.7$	$\Omega_m = 0.3-0.4$
Gladders et al. (2007)	Optical (RCS)	≈ 1000	Large	$z < 0.4$	$\sigma_8 \approx 0.7-0.8$	$\Omega_m \approx 0.3$
MaxBCG (Koester et al. 2007)	Optical (SDSS)	$\approx 13,823$	Large	$z < 0.3$	$\sigma_8 = 0.83 \pm 0.07$	$\Omega_m = 0.23 \pm 0.04$
Vikhlinin et al. (2009)	X-ray (Chandra)	≈ 200	Large	$z < 0.8$	$\sigma_8 = 0.81 \pm 0.03$	$\Omega_m = 0.25 \pm 0.04$
Rozo et al. (2010)	Optical (MaxBCG, SDSS)	$\approx 13,823$	Large	$z < 0.3$	$\sigma_8 = 0.807 \pm 0.027$	$\Omega_m = 0.265 \pm 0.016$

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

$$P_0(k) = A k^{n_s} \quad \begin{array}{l} \text{(related to the A parameter here)} \\ (n_s = 1) \end{array}$$

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

$$\sigma_{8,g}^2 := \left\langle \left(\frac{\Delta n}{\bar{n}} \right)^2 \right\rangle_8 \approx 1 \quad \begin{array}{l} \text{(8 h}^{-1} \text{ Mpc was chosen} \\ \text{because appeared close to 1)} \end{array}$$

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

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

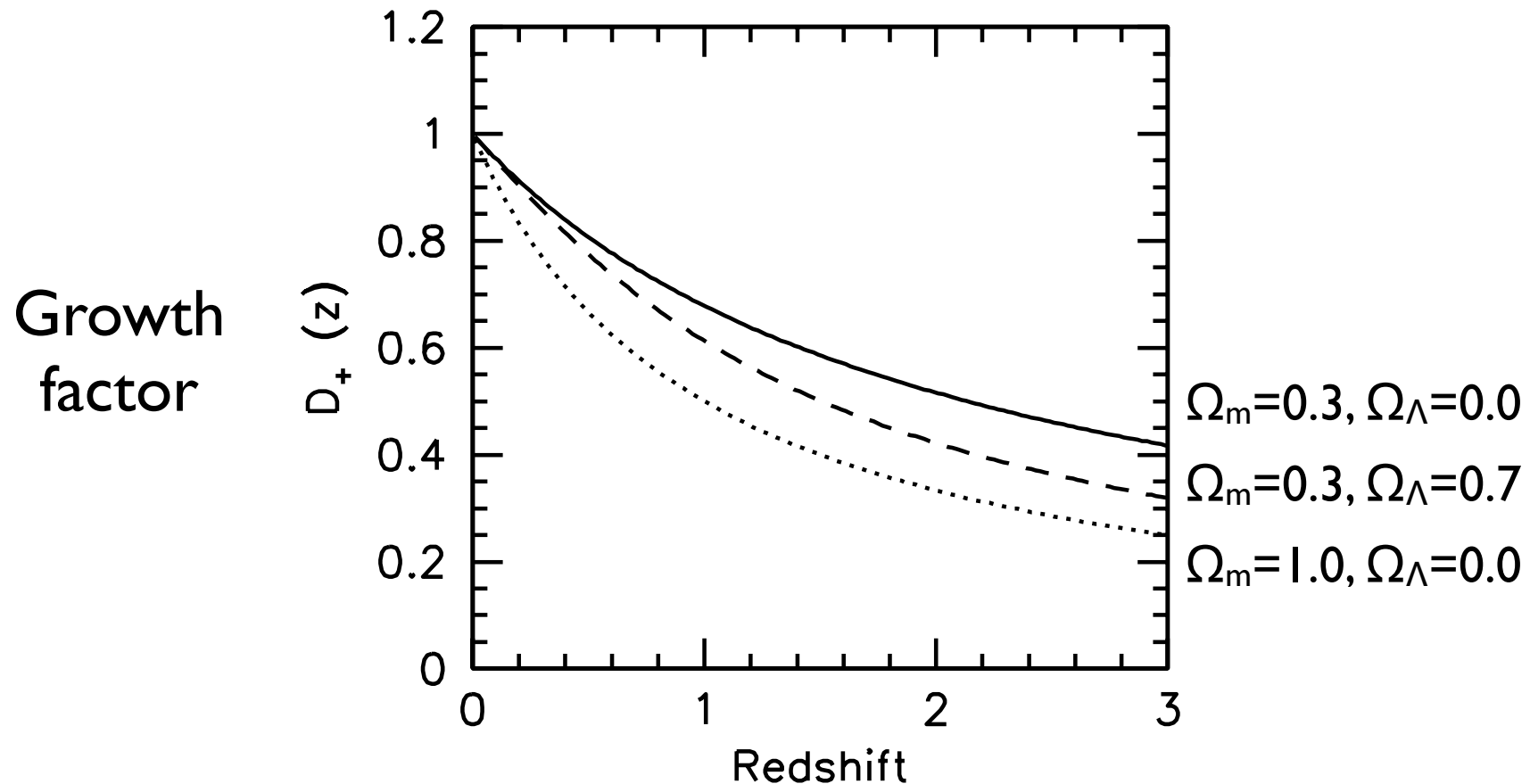
Different cosmological parameters imply different growth rates for clusters...

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

Depend upon the growth factor (linear regime):

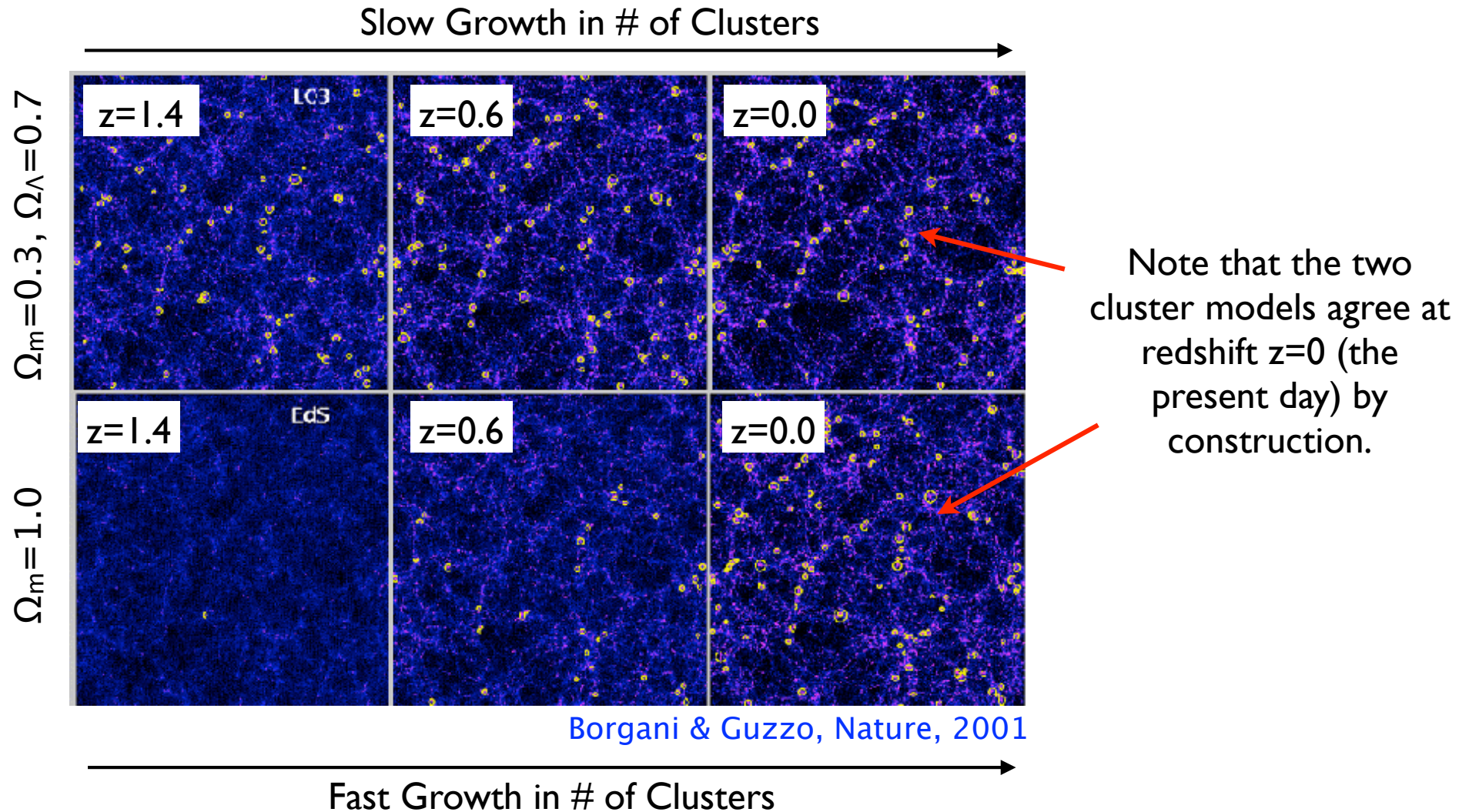
$$D_+(a) = \frac{5a}{2} \Omega_m \left[\Omega_m^{4/7} - \Omega_\Lambda + \left(1 + \frac{1}{2} \Omega_m \right) \left(1 + \frac{1}{70} \Omega_\Lambda \right) \right]^{-1}$$

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



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

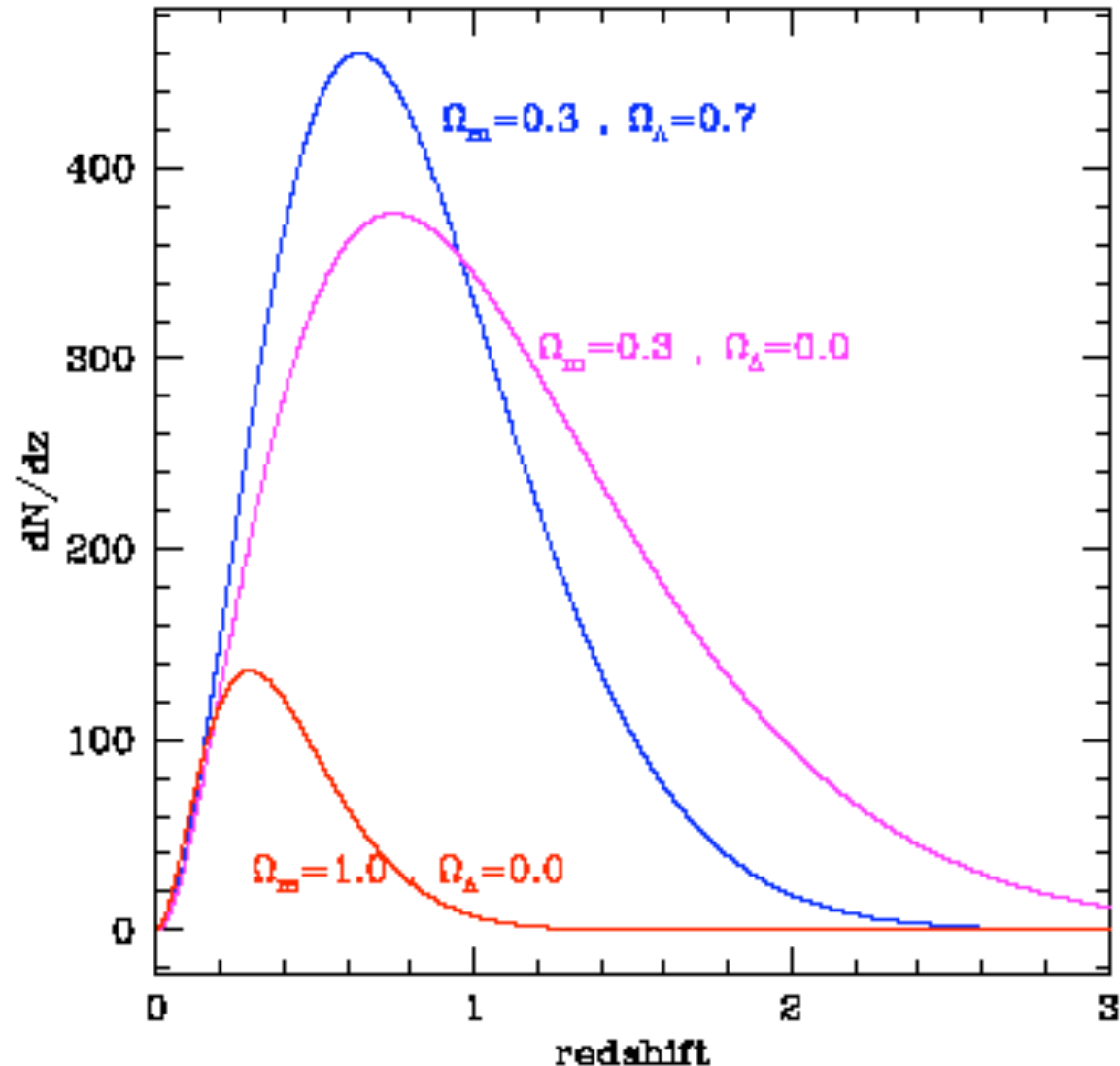
Different cosmological parameters imply different growth rates for clusters...



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

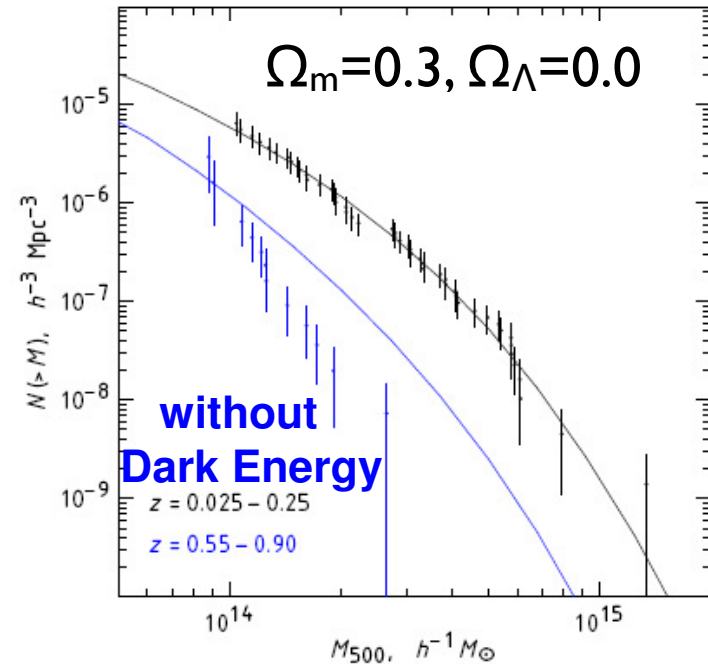
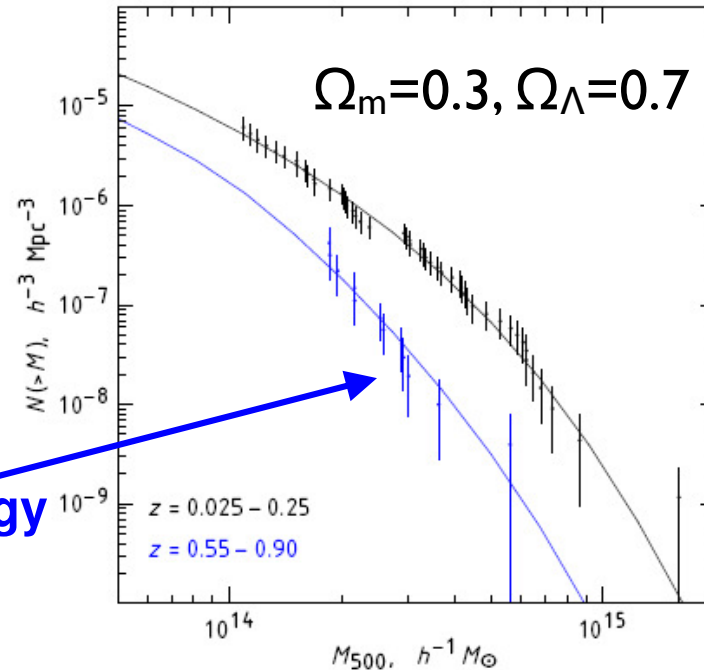
Note that there are essentially no clusters at high redshift in the $\Omega_m=1.0, \Omega_\Lambda=0.0$ model



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

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

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

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

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

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

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

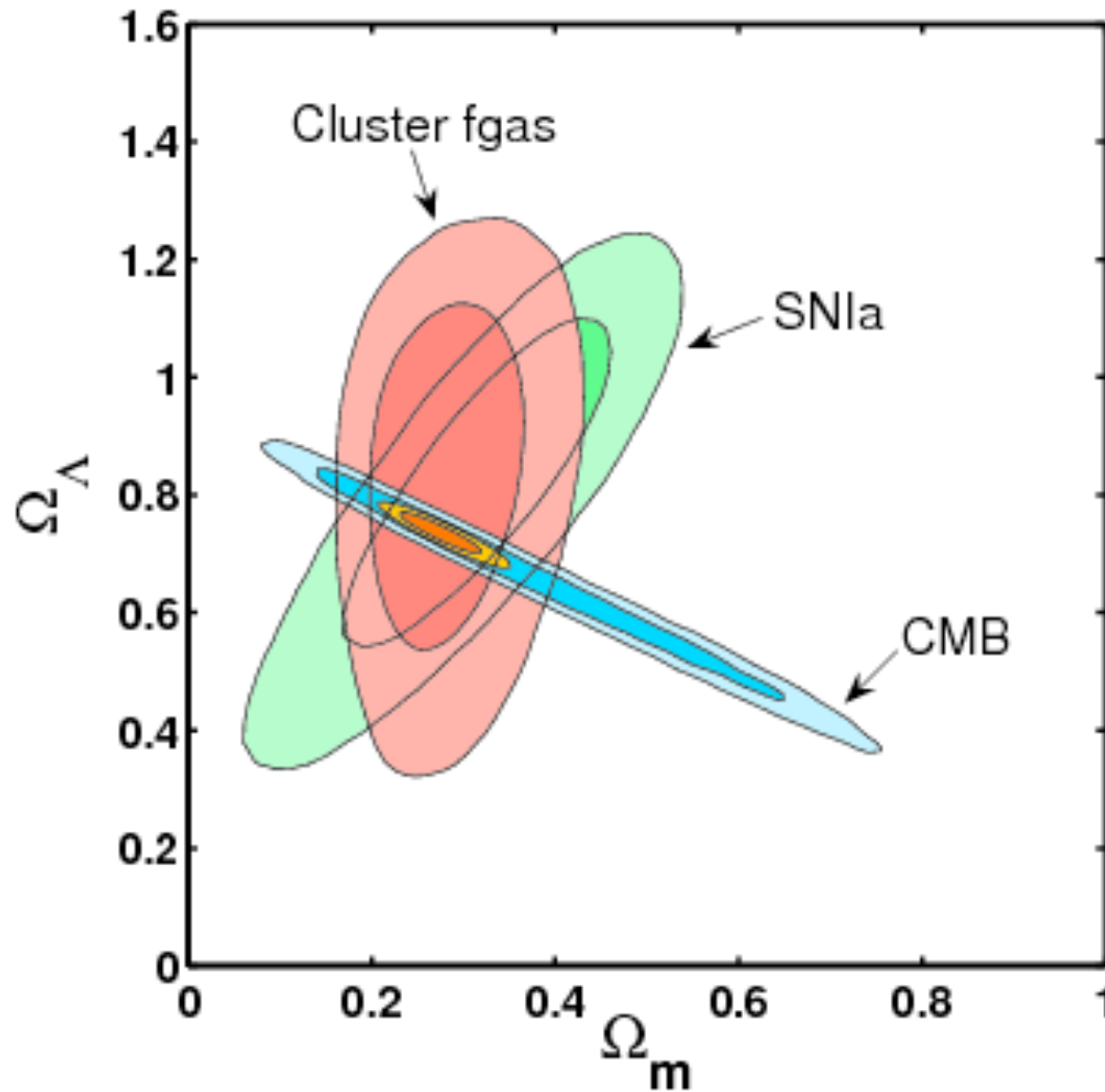
-- use optical light to infer mass in stars

Total mass in cluster:

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

Earlier lecture (#5) on the dark matter content of the universe:

Mantz, Allen et al.



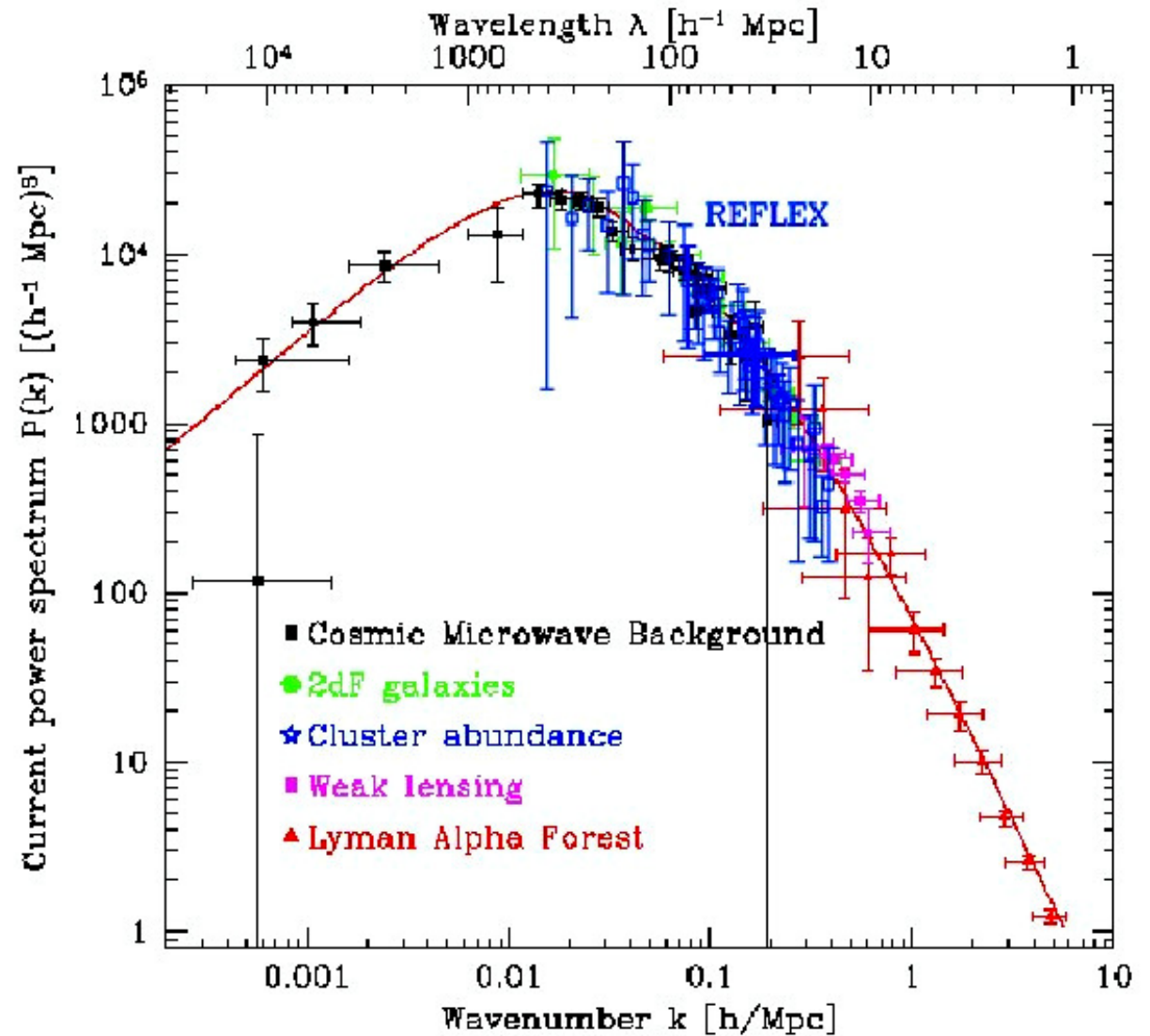
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Use galaxy clusters to probe clustering on large scales in the same way we use galaxies to do this

Observations:

REFLEX survey +
other measures of
the matter power
spectrum



Schuecker et al. 2001

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

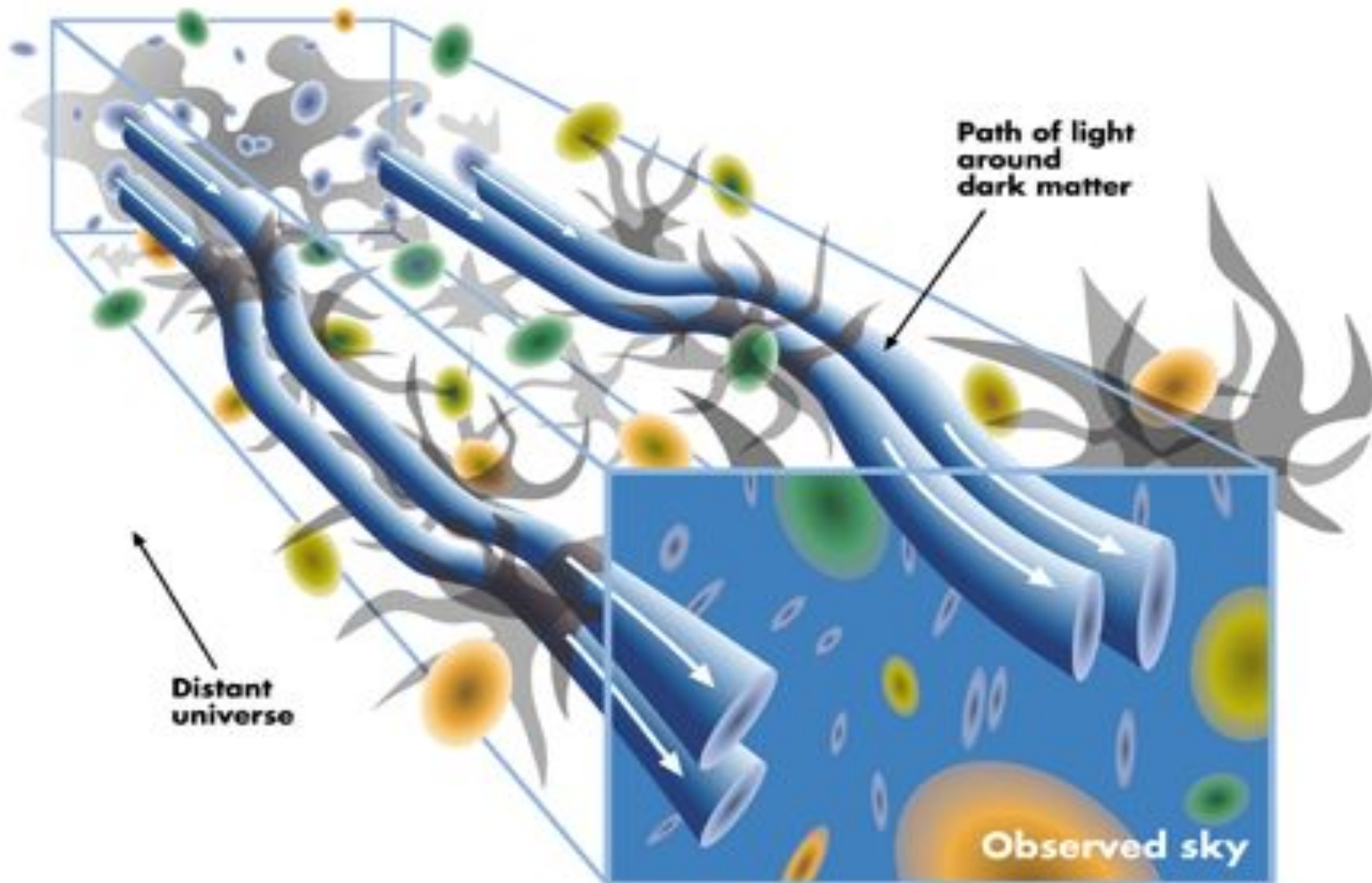
4. **Weak Gravitational Lensing (this lecture)**

- provide us with sensitive probe of growth of structure
- powerful technique still in process of realizing full potential

Let's start talking about what we
can learn from cosmic shear

Gravitational lensing from collapsed masses has a systematic imprint on the shapes of galaxies, seen over large areas of sky, i.e., cosmic shear..

Cosmic Shear



Gravitational lensing from collapsed masses has a systematic imprint on the shapes of galaxies, seen over large areas of sky, i.e., cosmic shear..

yet another case where we use gravitational lensing to learn about the cosmological properties

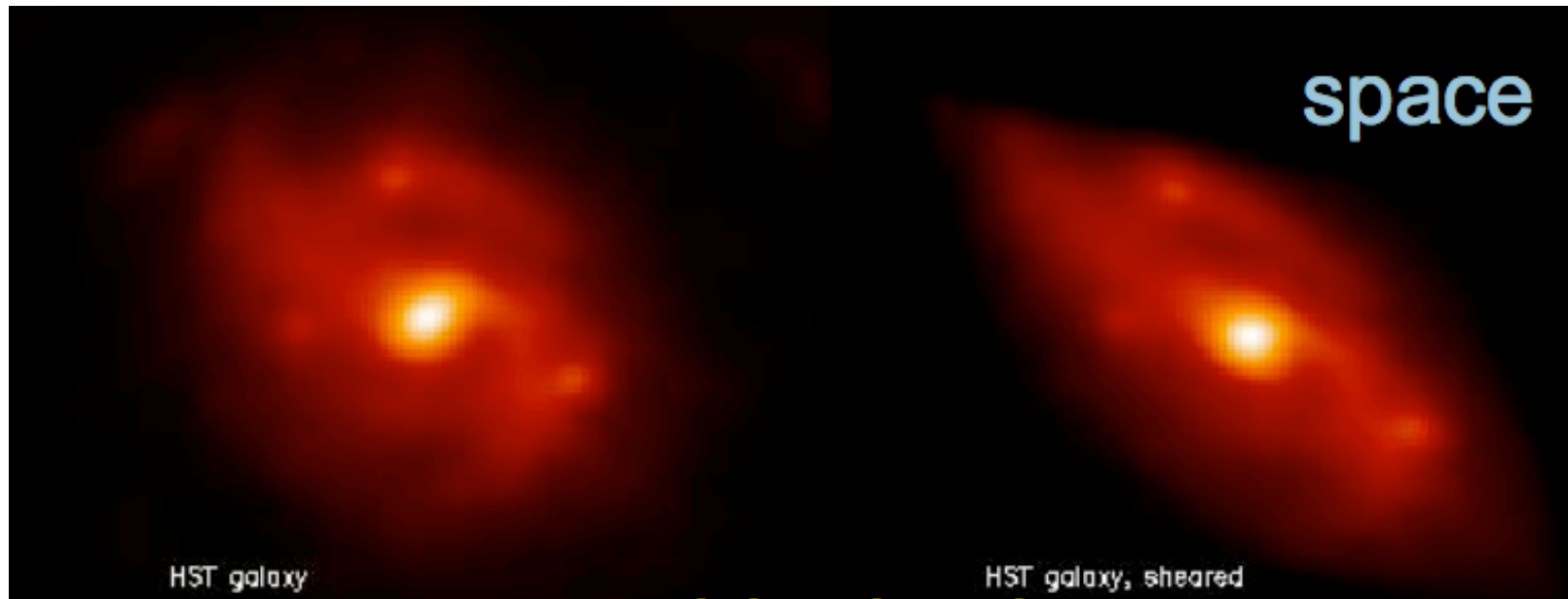
Gravitational Lensing has come up twice before:

- 1) measuring the total mass in galaxy clusters through gravitational lensing
- 2) determining the Hubble constant by measuring the time delay between two sets of images

What effect does gravitational lensing have on galaxies we observe?

Without lensing

Including lensing



Cosmic shear=cosmological weak lensing

- Arises from total matter clustering
 - Not affected by galaxy bias uncertainty
 - well modeled based on simulations (current accuracy, <10% White & Vale 04)
- A % level effect; needs numerous ($\sim 10^8$) galaxies for the precise measurements

past $z=z_s$

Large-scale structure

$z=z_l$

present $z=0$

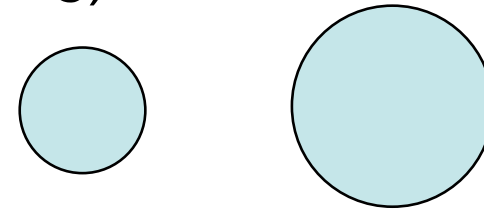
observables

$$\gamma = \frac{a-b}{a+b}$$
$$\gamma_1 = \gamma \cos 2\varphi$$
$$\gamma_2 = \gamma \sin 2\varphi$$

What effect does gravitational lensing have on galaxies we observe?

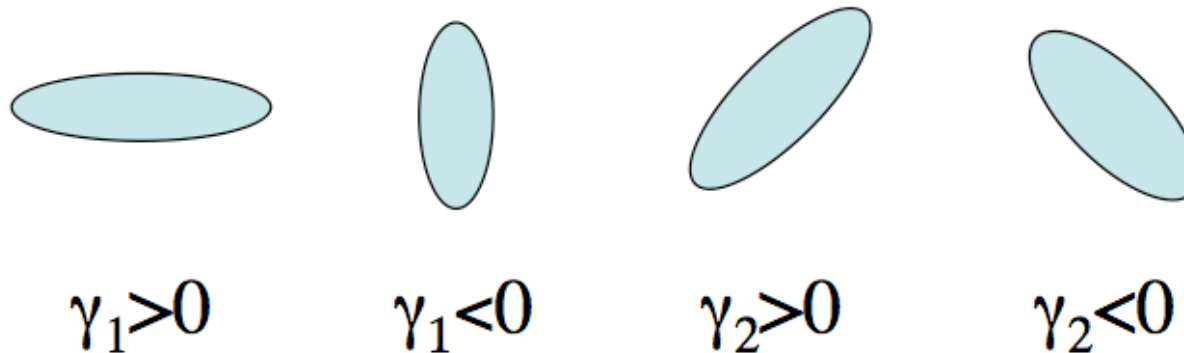
1. Magnification

- expressed as κ (called convergence)
- does not affect shape

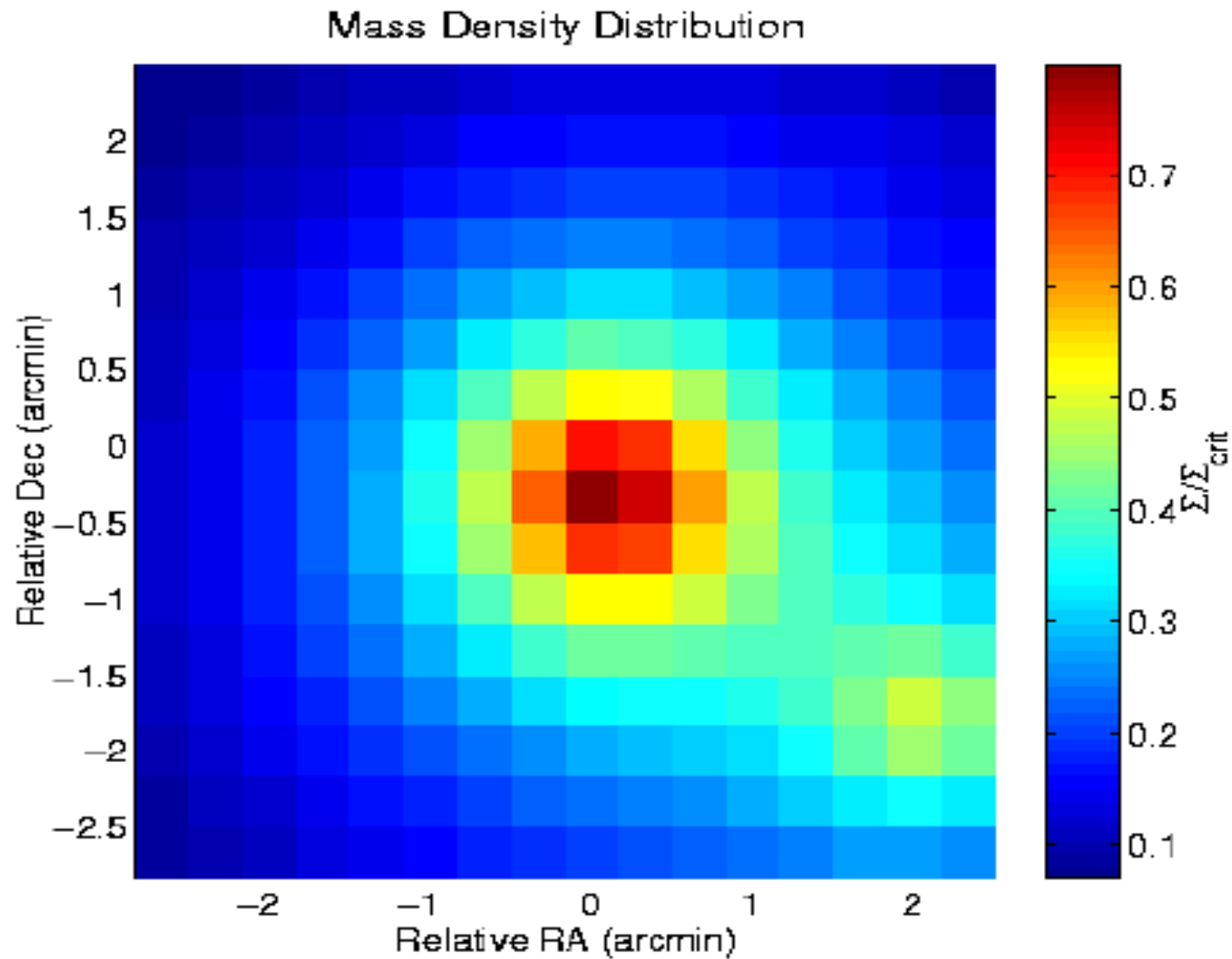


2. Shear

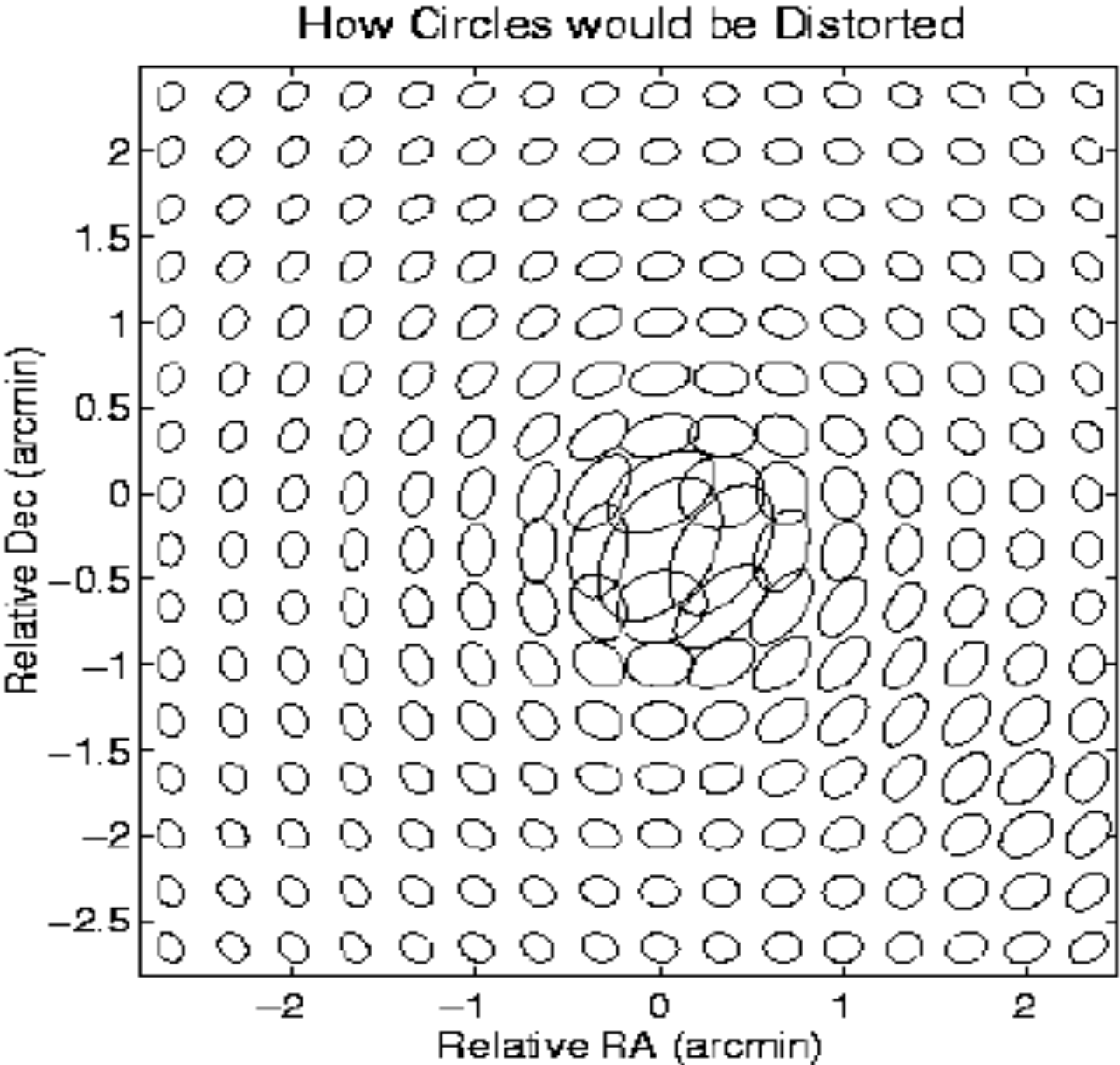
- expressed as γ (called the shear)



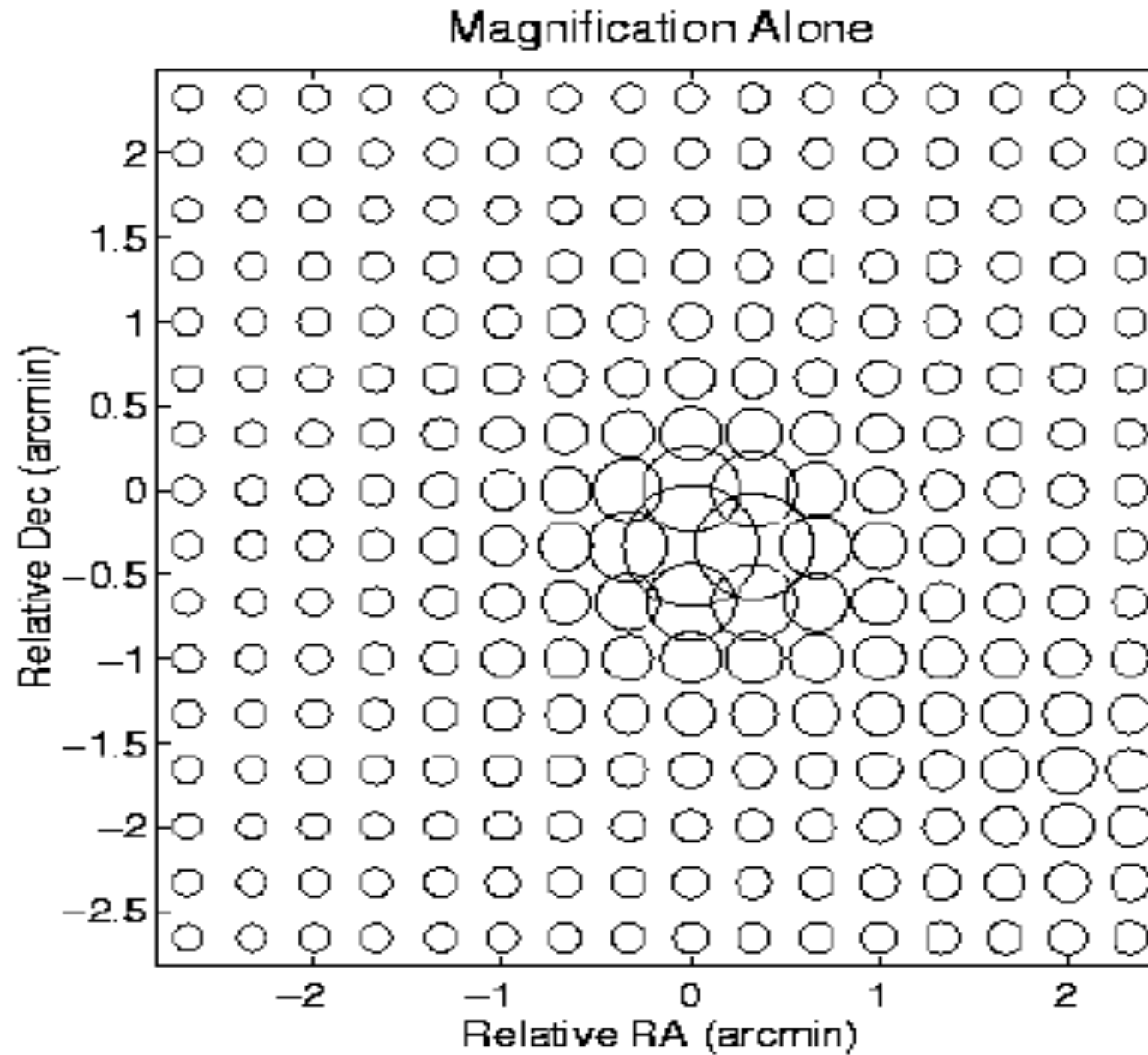
Quick illustration: let's say you have this mass distribution



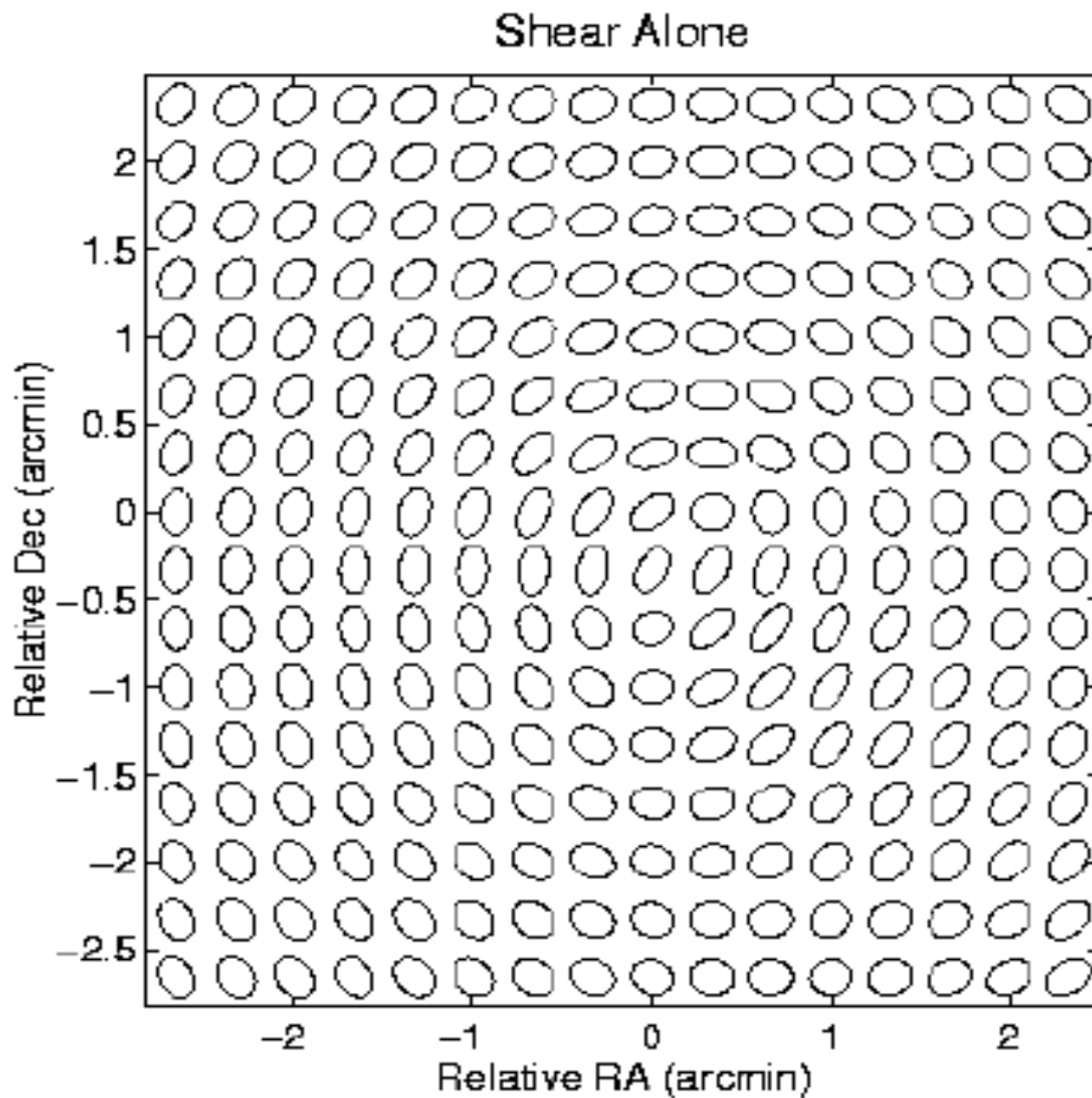
Quick illustration: then a grid of circles would be distorted as such



Here is just magnification alone:



Here is just shear alone:



Weak Lensing Basics:

(weak lensing is when the distortion of sources and background sources are not multiply lensed)

If sources are small, one can remap the surface brightness from a source f_S (without lensing) to f_{obs} (with lensing) as follows:

$$f_{obs}(\theta_i) = f_S(A_{ij}\theta_j)$$

where θ_i is position within a source or lensed image

To first order, A_{ij} is typically expressed as follows:

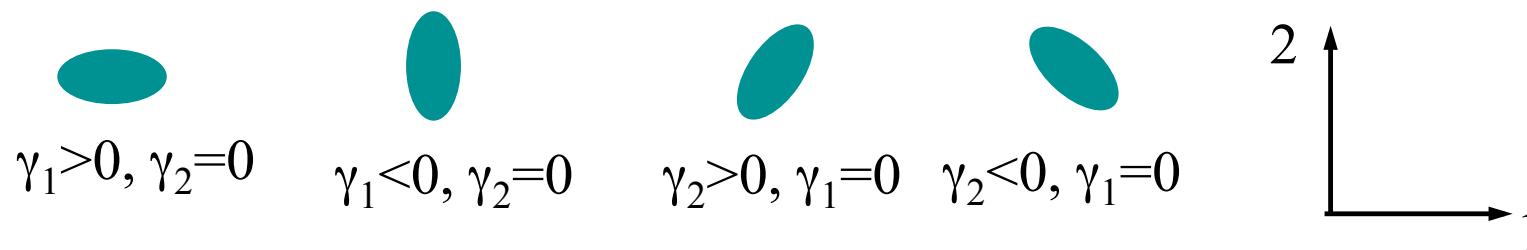
$$A_{ij} = \begin{pmatrix} 1 - \kappa - \gamma_1 & -\gamma_2 \\ -\gamma_2 & 1 - \kappa + \gamma_1 \end{pmatrix} = (1 - \kappa) \begin{pmatrix} 1 - g_1 & -g_2 \\ -g_2 & 1 + g_1 \end{pmatrix}$$

The convergence κ describe the magnifications or contractions of sources
($\kappa \ll 1$)

The shear γ (and reduced shear g) describe the distortion of the shapes of the sources ($\gamma \ll 1$)

Shear is Classified as a Spin-2 Field

- The shearing of images is a spin-2 field
- Shear has two degrees of freedom (amplitude and its position angle)



- Rotating the coordinate system by φ changes: the shear depends on the coordinate system

$$\gamma_1 + i\gamma_2 \rightarrow (\gamma_1 + i\gamma_2)e^{-2i\varphi}$$

- Under a rotation by π the field is left unchanged
- A rotation by $\pi/4$ changes γ_1 to γ_2 and γ_2 to $-\gamma_1$

Essential property of Spin-2 field is that it remains unchanged after rotation by 180 degrees

Measuring Shear

Since we do not know where sources are on the sky, we cannot directly measure the deflection of sources on the sky

However it is possible to measure the shape of galaxies.

Simplest approach is to measure the weighted second moment of the surface brightness distribution $I(\theta)$:

$$I_{ij} = \int d^2\theta I(\vec{\theta}) w(\vec{\theta}) \theta_i \theta_j$$

$w(\theta)$ is a window function that weights light from the source and gives less weight to the noisy exterior of the image

one can then derive the ellipticity from these second moments:

$$e_{obs} = \left(\frac{I_{11} - I_{22}}{I_{11} + I_{22}}, \frac{2I_{12}}{I_{11} + I_{22}} \right)$$

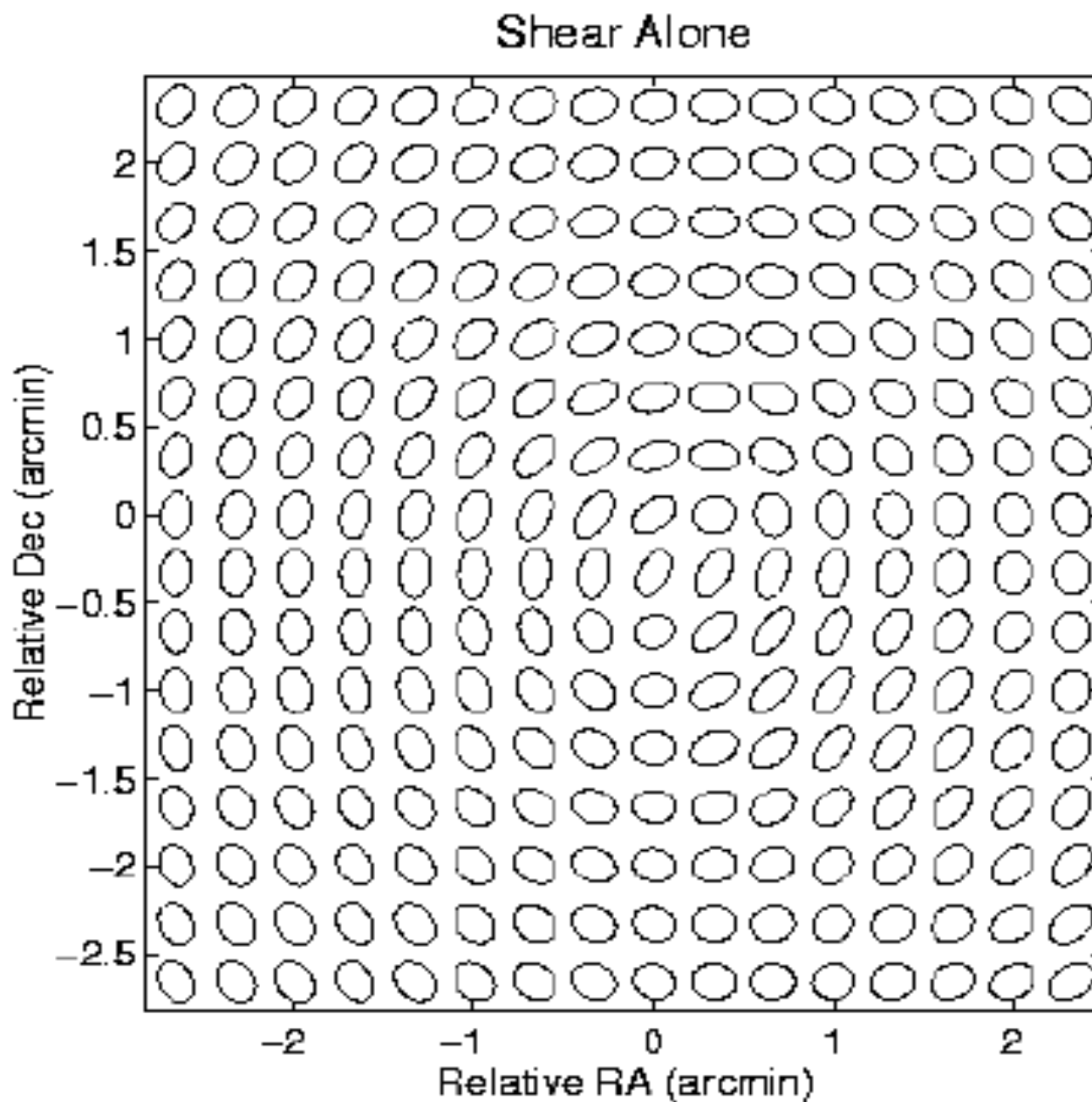
Measuring Shear

But galaxies are not perfect circles and have intrinsic orientations and ellipticities (typical ellipticities $\sim 10\text{-}30\%$)

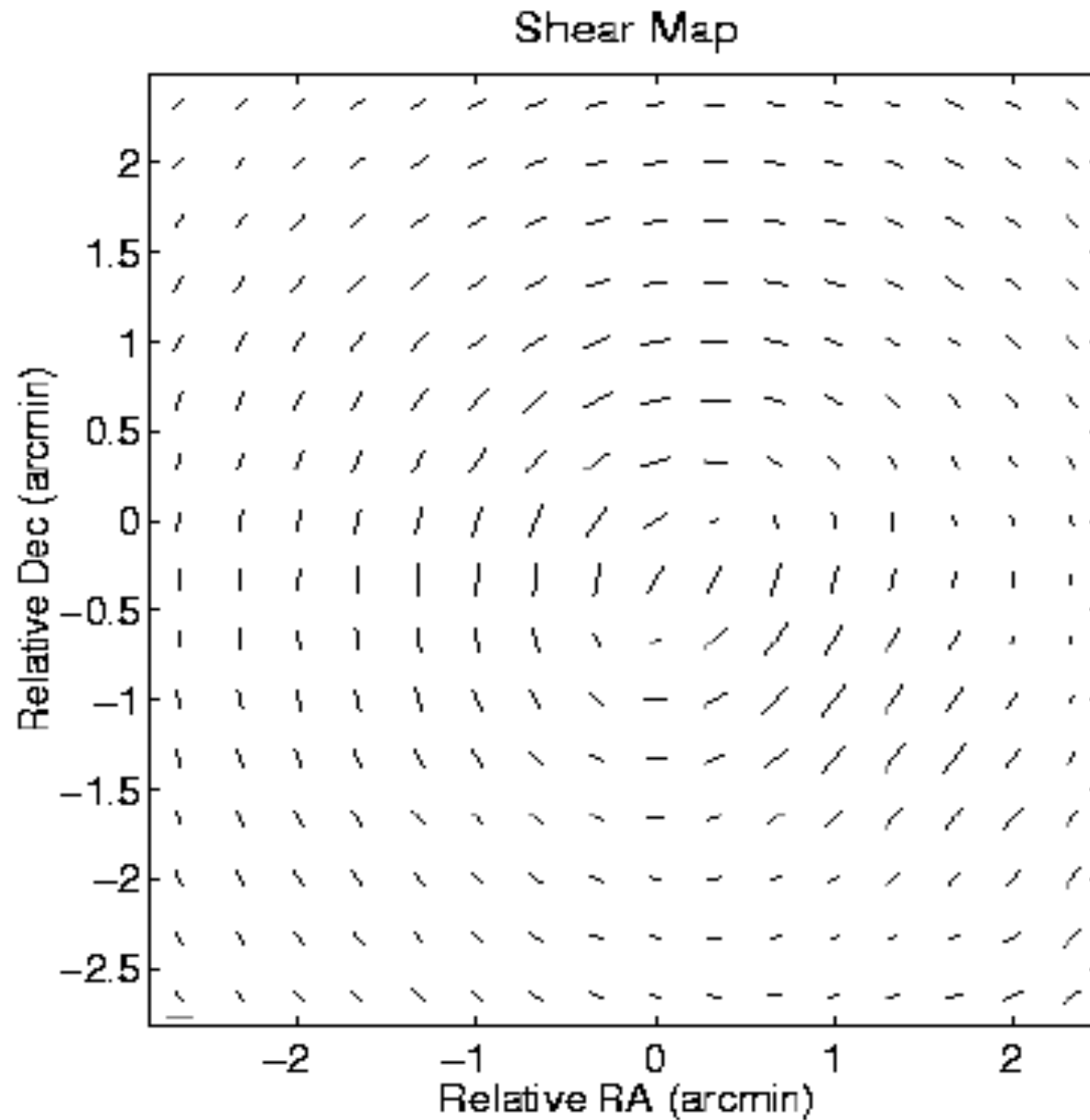
When we observe a galaxy, the shear we observe is the intrinsic value + the shear induced by gravitational lensing

One complication in deriving the shear is that light from the galaxy is blurred by the earth's atmosphere or due to the intrinsic diffraction limit of a telescope

Here is just shear alone:



The idea is to make a shear map from this distortion:



Large Numbers of Sources Needed

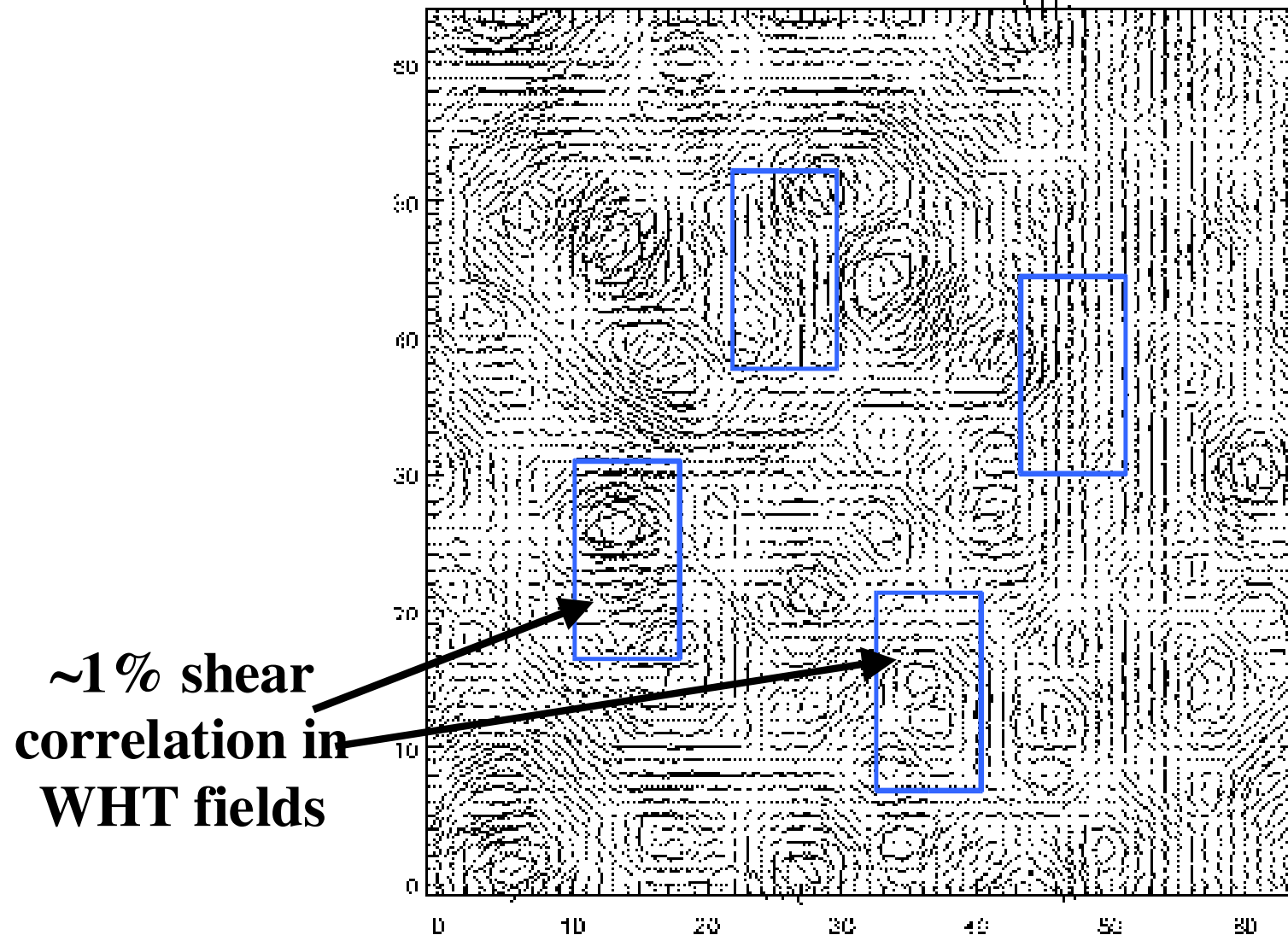
Since galaxies have approximately random orientations on the sky, we need measurements of a large number of sources per unit area to average over these effects and establish the overall effect of gravitational lensing.

We can reduce the error caused by the intrinsic ellipticity of the sources as the square root of the number of sources we examine.

Assuming that typical intrinsic ellipticity is 10% and the ellipticity caused by gravitational lensing is 1%, we need 100 sources to measure the shear with a S/N of 1. Therefore we need large numbers of sources to measure the cosmic shear accurately!

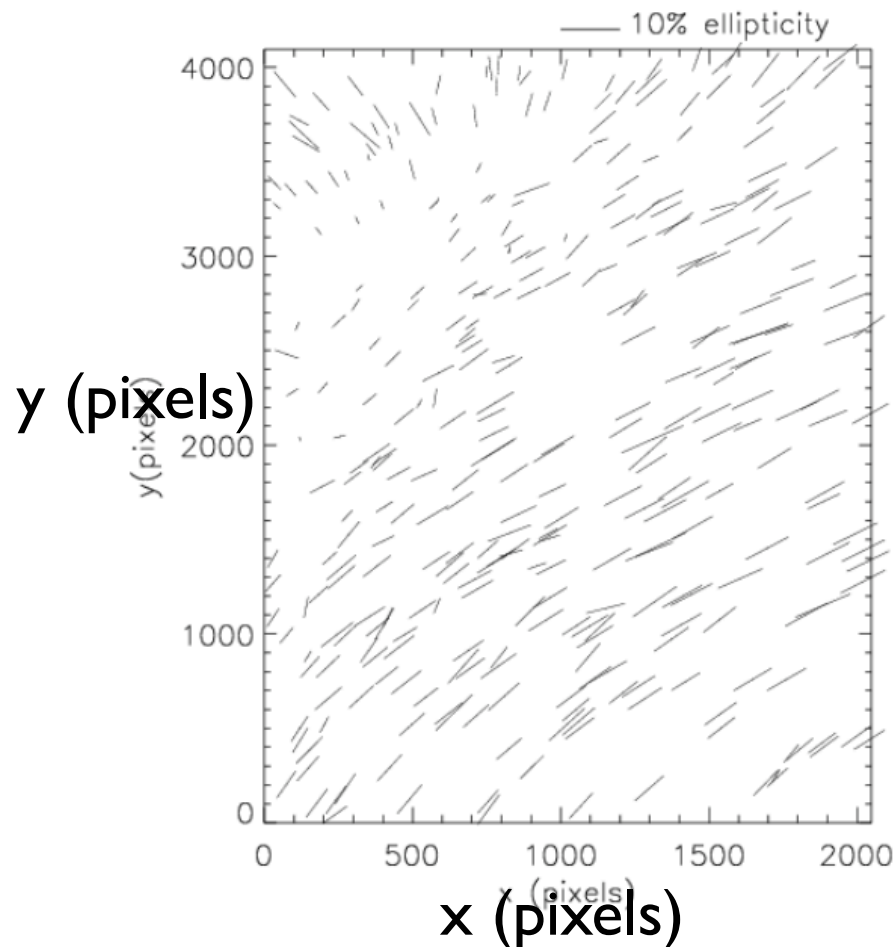
Averaging over the ellipticity in many sources, we can derive a mean shear at different positions on sky

(but signal is very weak)



PSF Anisotropies

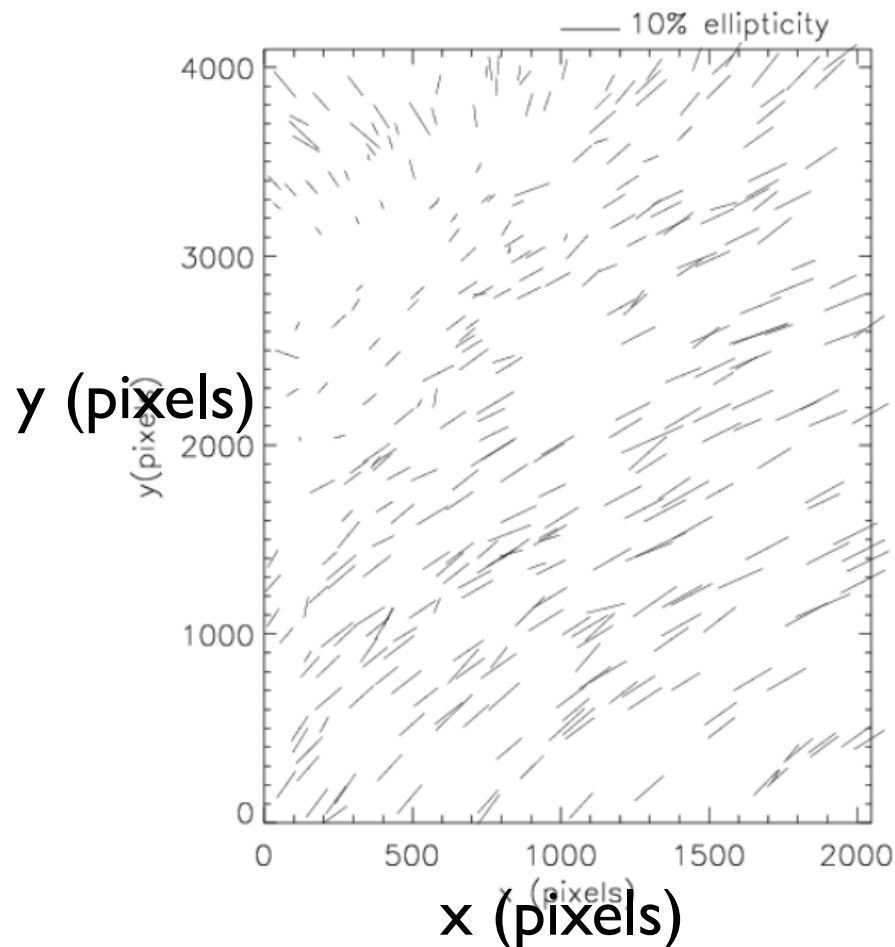
In order to measure the shear on an image, we need to understand how the PSF (point spread function) varies as a function of position on a detector or from the optics.



To the left is one example of the apparent shear that is present in the shapes of stars (which are effectively point sources)

PSF Anisotropies

In order to measure the shear on an image, we need to understand how the PSF (point spread function) varies as a function of position on a detector or from the optics.

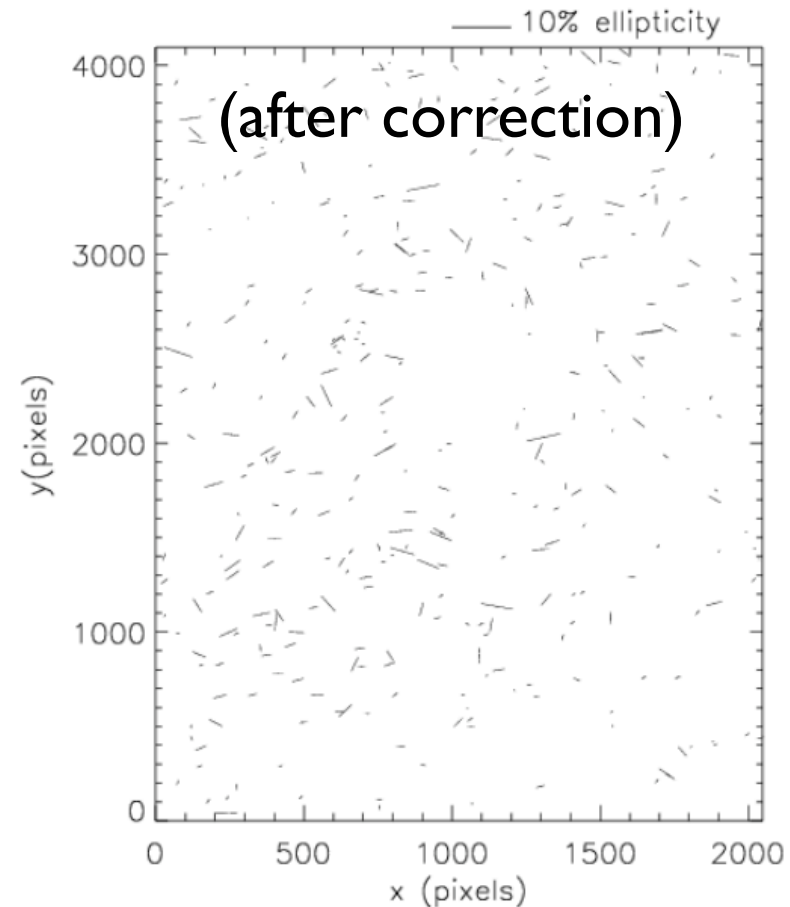
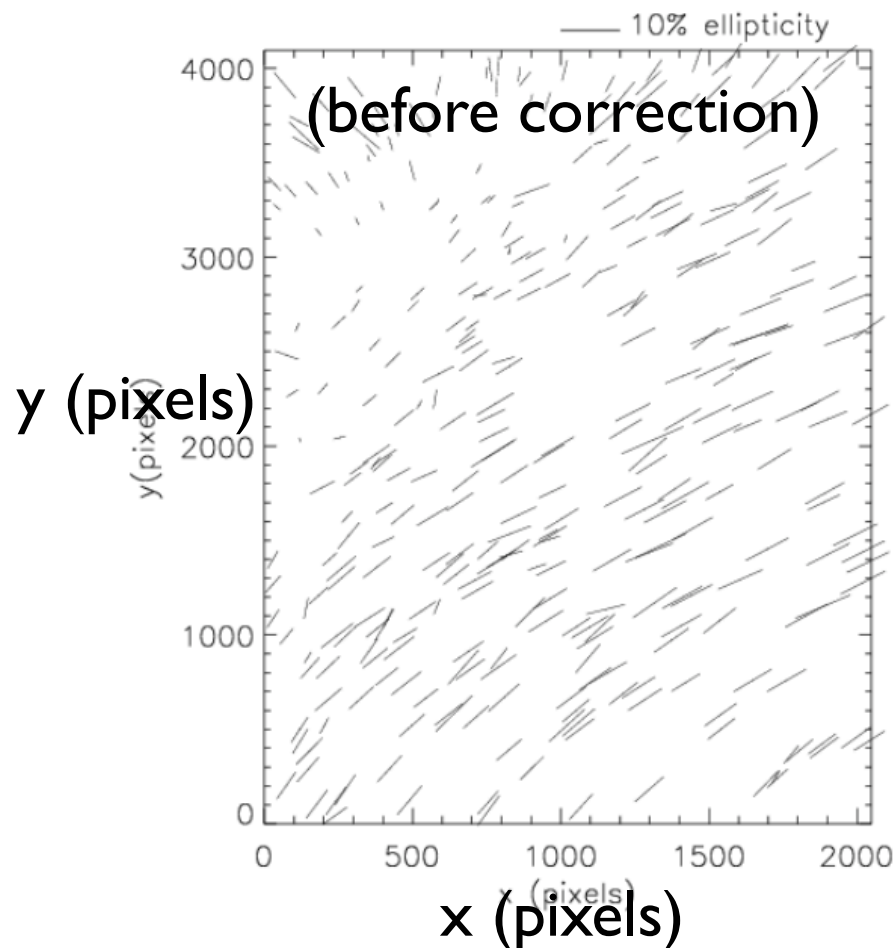


The PSF anisotropies are usually measured by observing a large number of stars with a detector and quantifying the apparent shear

One uses this shear map to apply a correction to the shear measured for galaxies on real images

PSF Anisotropies

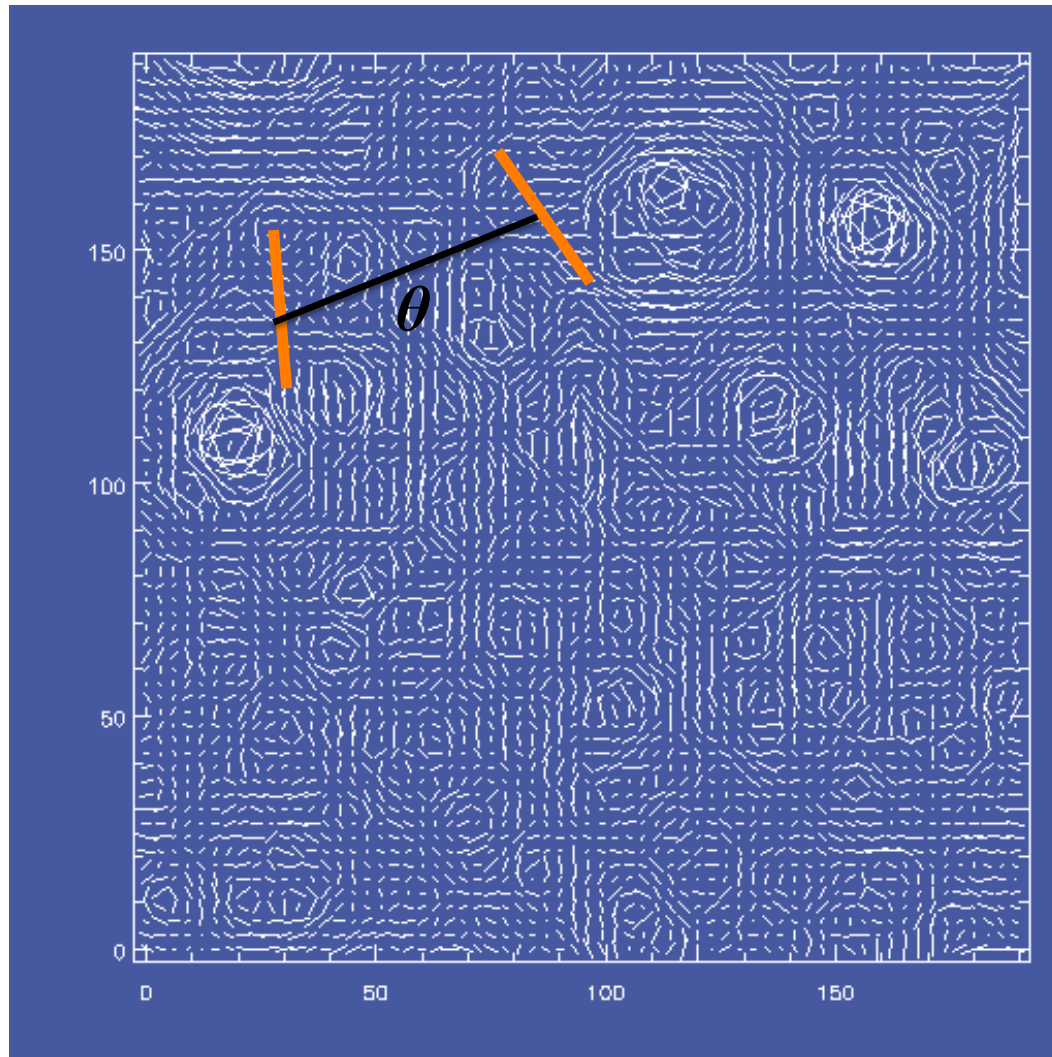
In order to measure the shear on an image, we need to understand how the PSF (point spread function) varies as a function of position on a detector or from the optics.



After measuring shear for a bunch of galaxies, how do we be sure that we have removed most of the systematics?

And how do we go about computing power spectrum for large numbers of sources?

Determine correlation of shear measurement on different angular scales θ



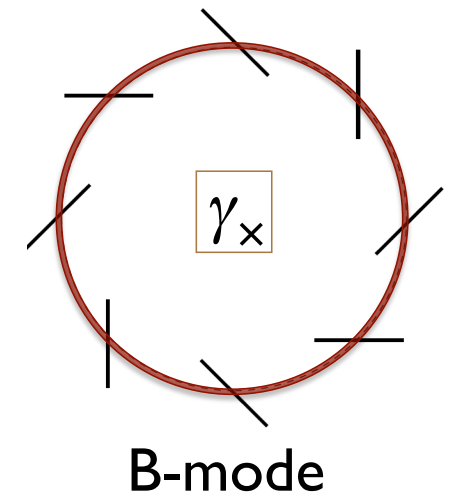
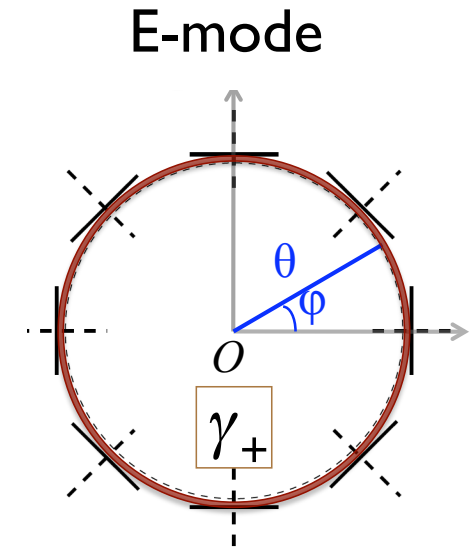
- Correlated images of distant galaxies over all angular scales
- Use images of all distant galaxies
- Correlation function method to measure the cosmic shear signals
- The lowest one is 2pt function

Determine correlation of shear measurement on different angular scales θ

similar to measures of the clustering or correlation function, determine the extent to which the shear of sources at a given separation θ is tangential

$$\langle \gamma_+ \rangle(\theta) \equiv \frac{1}{2\pi} \oint d\varphi \gamma_+(\theta, \varphi)$$

the diagram to right shows just one origin over which we can perform this averaging.



Also frequent to use ξ to represent this:

$$\xi_{++}(\theta) = \frac{1}{2\pi} \oint d\varphi \gamma_+(\theta, \varphi)$$

Can also measure in a similar way γ_x

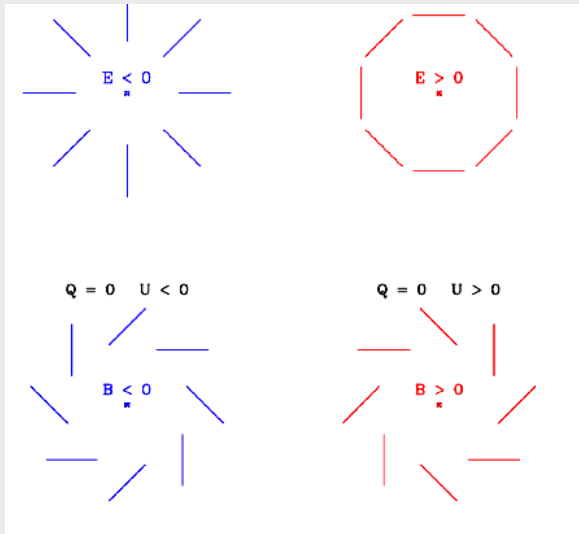
$$\langle \gamma_x \rangle(\theta) = 0 \quad \leftarrow \text{a monitor of systematics}$$

Recall E-mode and B-mode type fields from discussion of CMB polarization

CMB lecture

One tends to break down the polarization
map into two modes
(Helmholtz-Hodge theorem)

E-modes



E-modes are curl free and
can be written as the
gradient of a potential

$$\nabla \times \mathbf{E} = 0$$

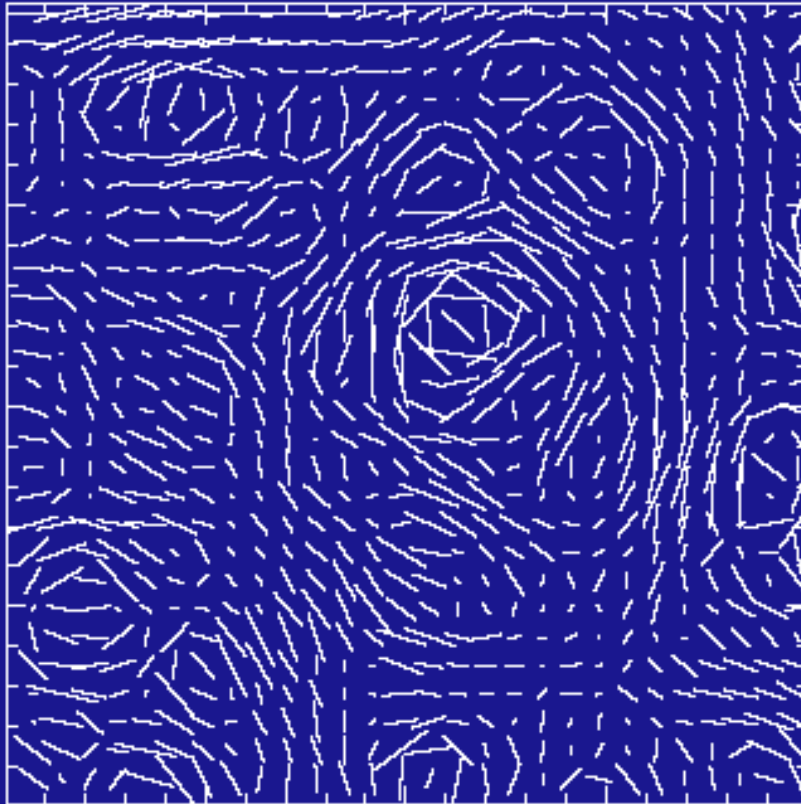
B-modes

B-modes have no
divergence.

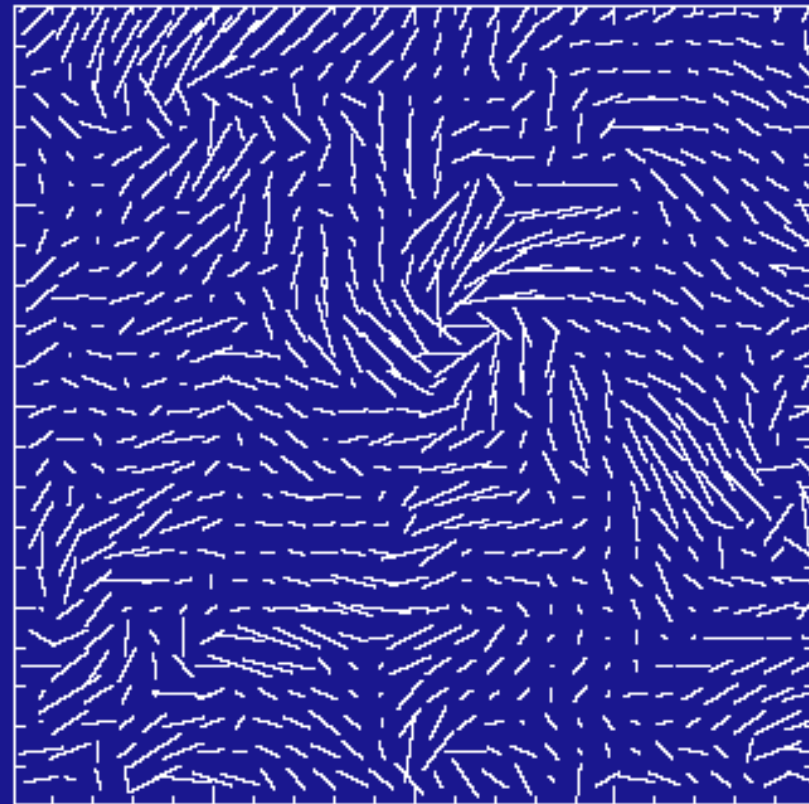
$$\nabla \cdot \mathbf{B} = 0$$

The terms E and B modes simply reflect the general form of the polarization fields and are in analogy with similar fields in electromagnetism. However, they have no direct relation with electric or magnetic fields

Examples of E-mode type and B-mode type fields



E mode



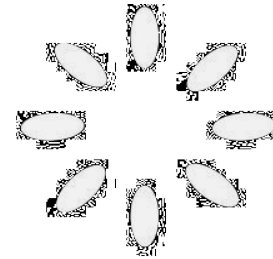
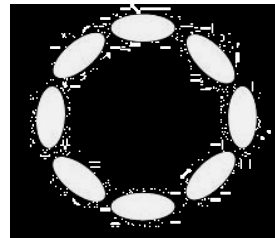
B mode

distinct different pattern

How do we check to see if we have removed the anisotropies properly?

Similar to the situation with polarization in the cosmic microwave background, we divide the field into an E-mode and B-mode

E-mode (curl-free)



B-mode (curl)



We expect only E-mode shear signal and no B-mode shear signal

An example of such a check

E-mode
shear gives a
signal

B-mode
shear gives
no signal as
expected

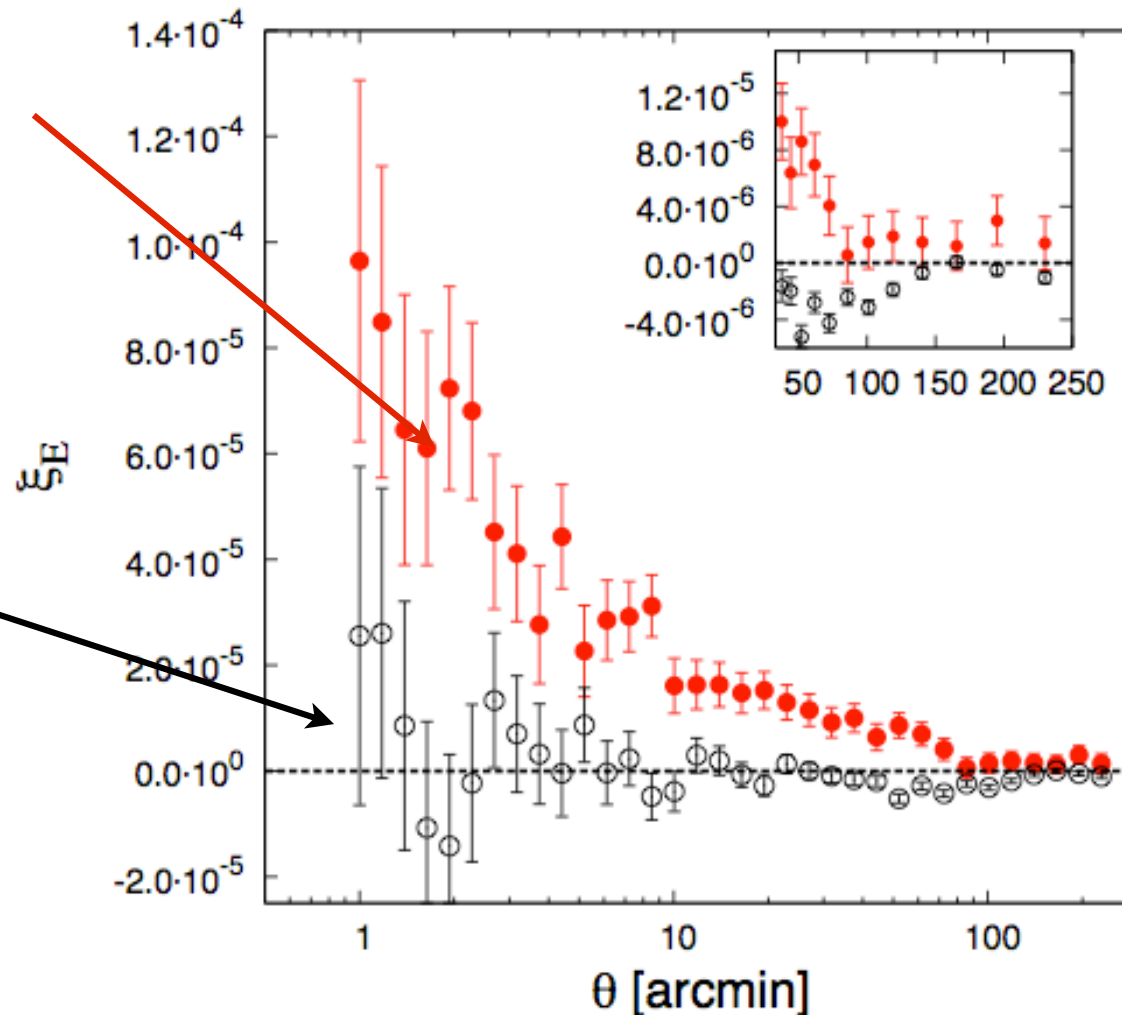


Figure 5: Ellipticity correlation function from (66). These measurements based on the analysis of 57 deg² of CFHTLS *i'* imaging data, extend out to 4 degrees, well into the linear regime. The E-modes are indicated by the red points. The B-mode (open points) is consistent with zero on most scales. As shown in the enlargement, there is an indication of residual systematics on a scale of one degree, which corresponds to the size of the camera.

And how do we go about computing power spectrum for large numbers of sources?

Convert from to angular power spectrum using
Fourier transform again:

Correlation Function
Type Parameters

$$\xi_{++}(\phi) \quad \langle \gamma_+ \rangle(\theta)$$



Power Spectrum
Type Parameters

$$P_\gamma(l) \quad P_\kappa(l) \quad C_{\gamma_i \gamma_j}(l)$$

Fourier Transform

What can we compare these angular power spectrum measurements against?

(what are the essential elements?)

Here's the equation:

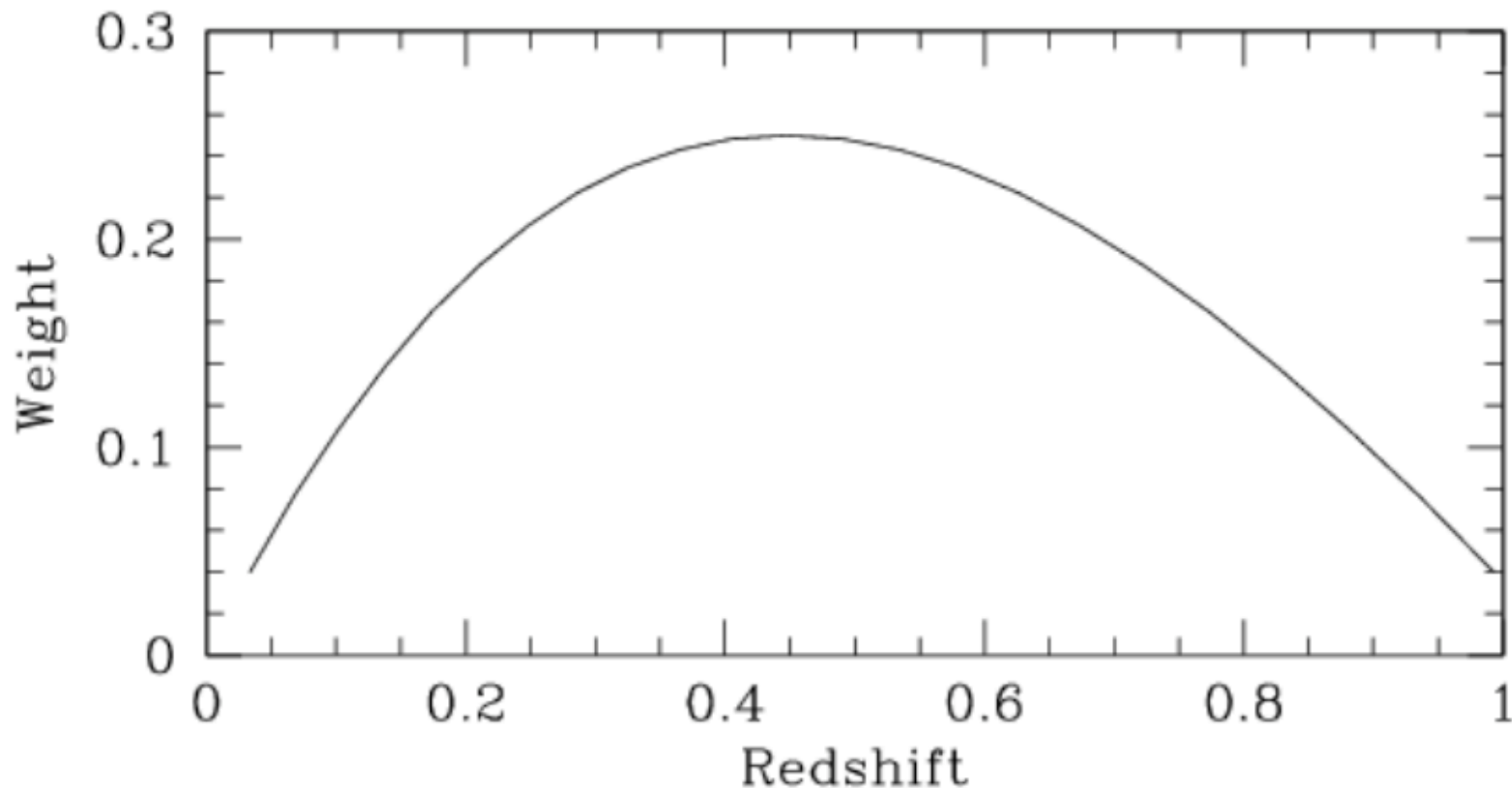
$$\gamma(\boldsymbol{\theta}) \propto \Omega_{m0} \int_0^{z_S} dz_L \frac{d_{LS}(z_L, z_S) d_L(z_L)}{d_S(z_S)} \delta(z_L, \boldsymbol{\theta})$$

lensing efficiency growth of mass perturbations

- Lensing efficiency function: W_{gl}
 - Overall amplitude is proportional to Ω_m , i.e. Ω_{de} if combined with CMB or a flat universe is *a priori* assumed
 - Sensitive to Hubble expansion through d_A , i.e. DE
 - Depends on source redshift – main uncertainty in cosmic shear measurements if redshift info is not available
- Mass clustering part: δ
 - Sensitive to primordial power spectrum (amplitude and shape)
 - Redshift history of the growth rate is sensitive to DE.

How do we weight different sources in computing power spectrum from weak lensing?

Masses “half way” in between the background source and us (the observers) have the biggest effect on the gravitational shear of the observed background sources.



Because of this dependence, very important to be able to quantify the redshift distribution of the background sources

Recall how perturbations (and collapsed structures) grow at different rates depending on the cosmology

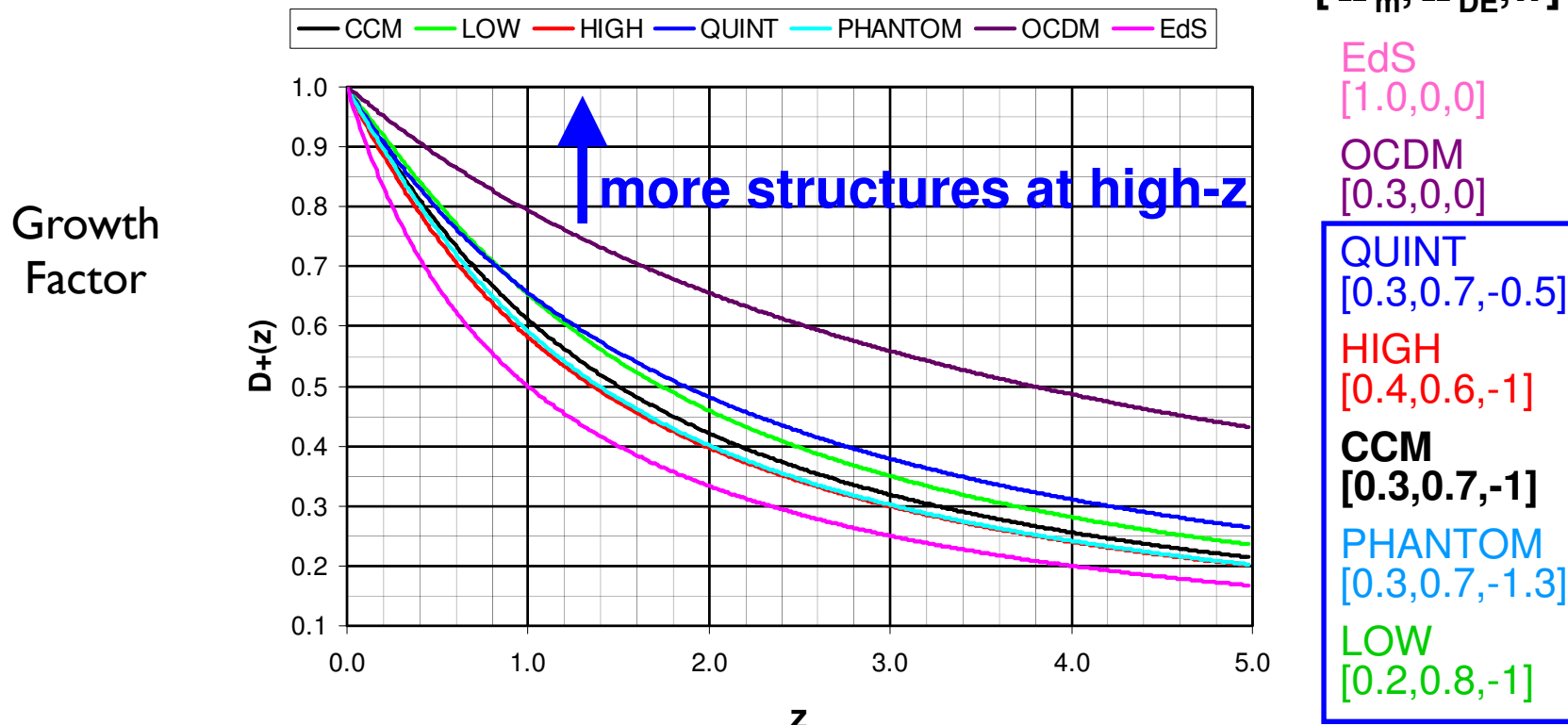
The rate at which structures grow in the universe depends upon the cosmological parameters:

Depend upon the growth factor (linear regime):

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

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

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



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

How do we expect the shear power spectrum to look?

Formula:

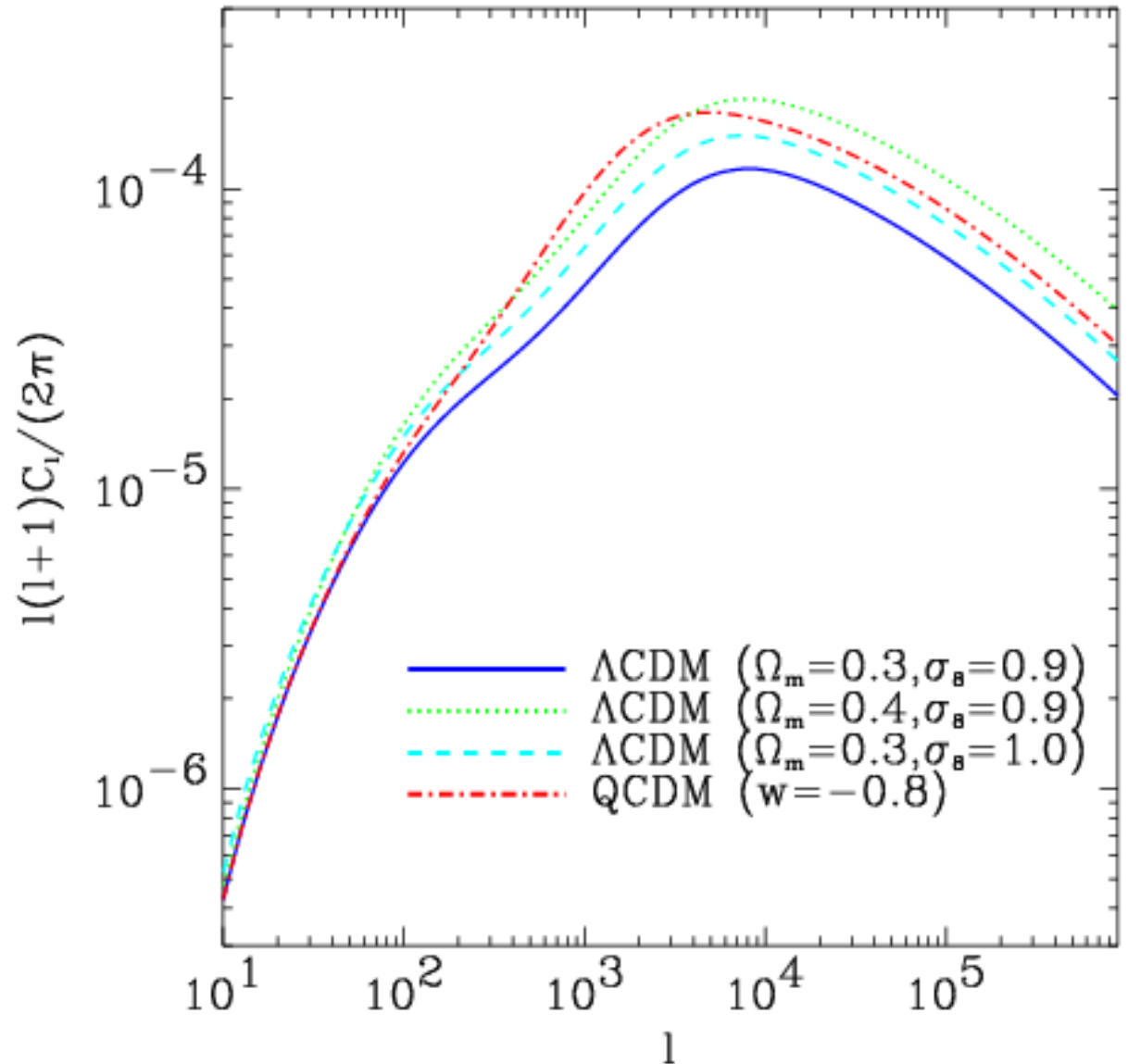
$$\gamma(\theta) \propto \Omega_{m0} \int_0^{z_S} dz_L \frac{d_{LS}(z_L, z_S) d_L(z_L)}{d_S(z_S)} \delta(z_L)$$



Fourier
Transform



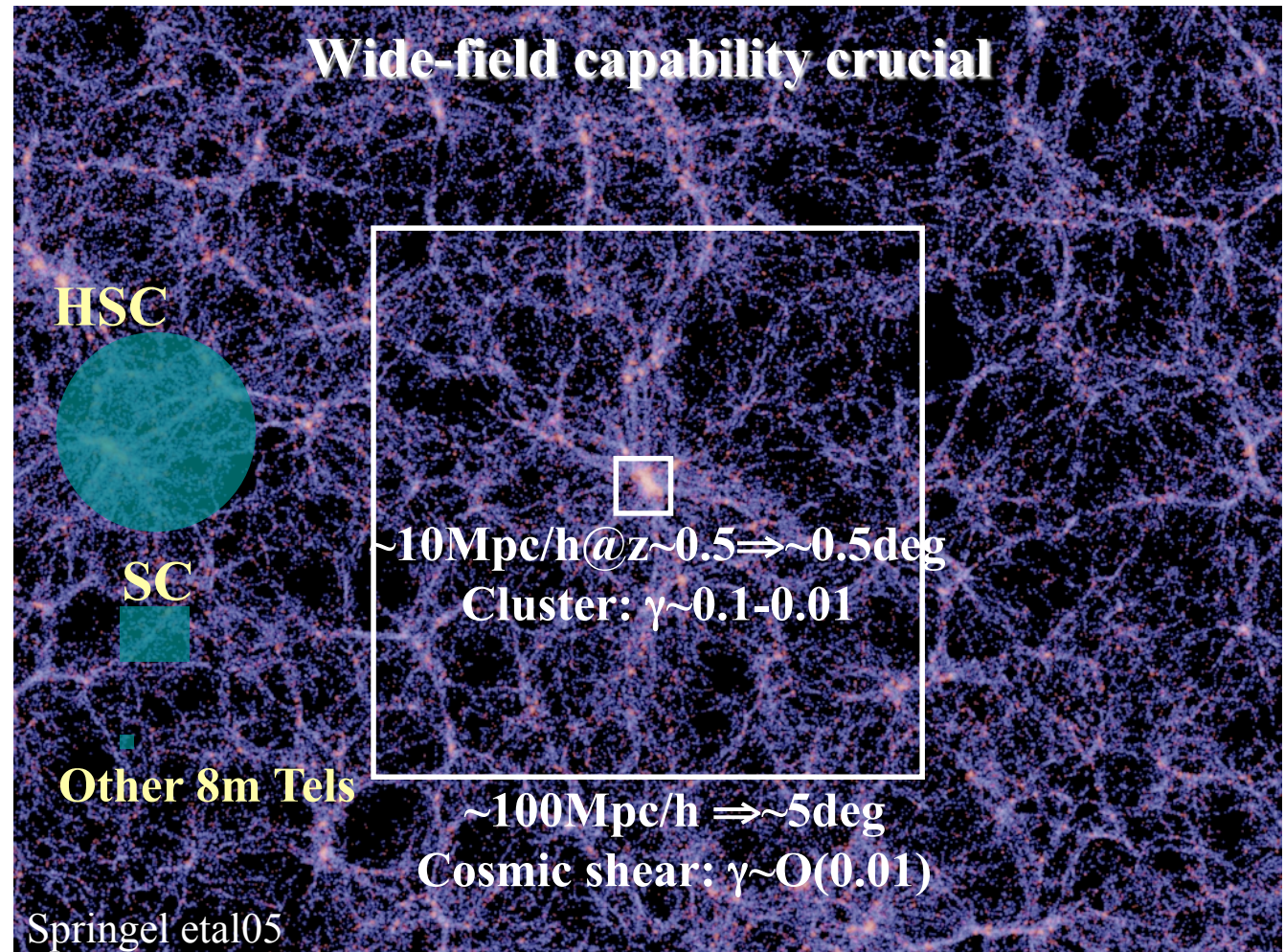
$$P_\gamma(l) \quad P_\kappa(l) \quad C_{\gamma_i \gamma_j}(\ell)$$



To measure a weak lensing signal, we need a very wide-area survey -- to probe the density fluctuations from many lines of sight

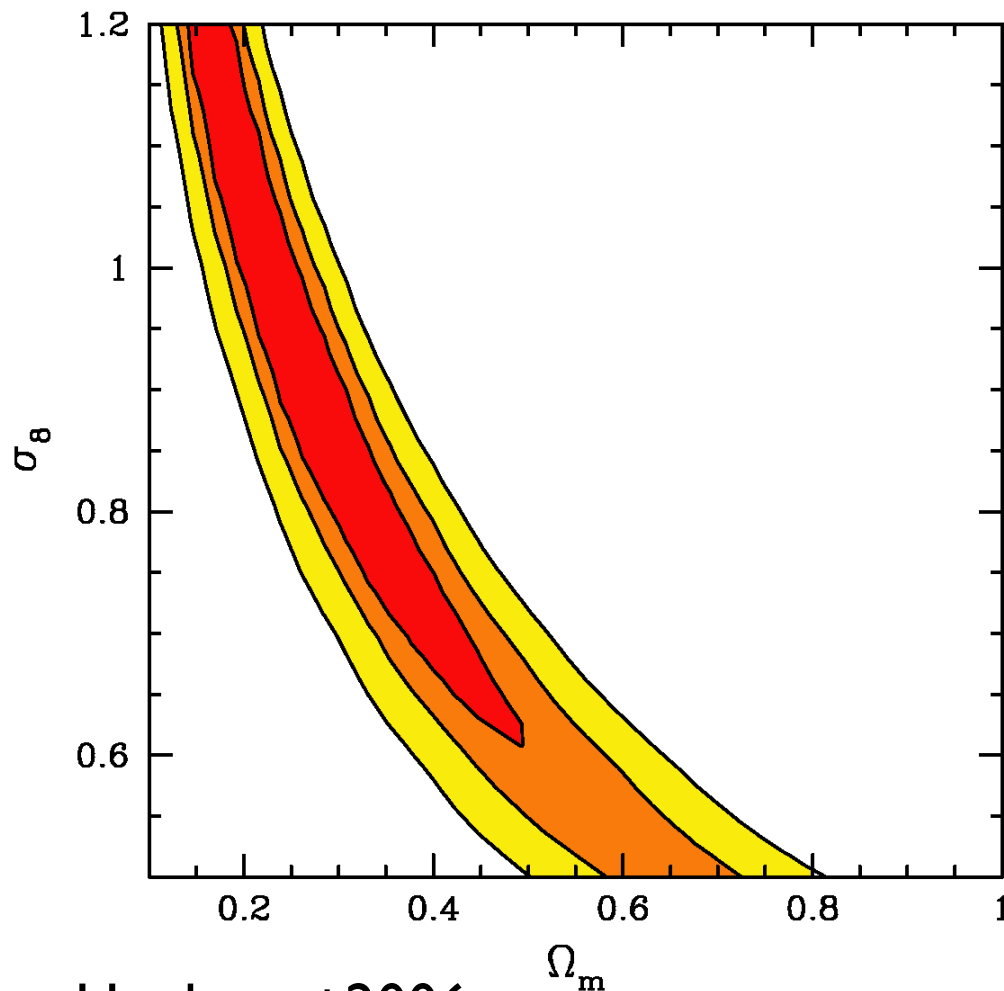
Why?

Large
Variation in
Structure in
Universe



What do these teach us about various cosmological parameters?

Consider the following example from CFHT-LS (22 deg²), one of the first significant surveys to allow for cosmic shear measurements:

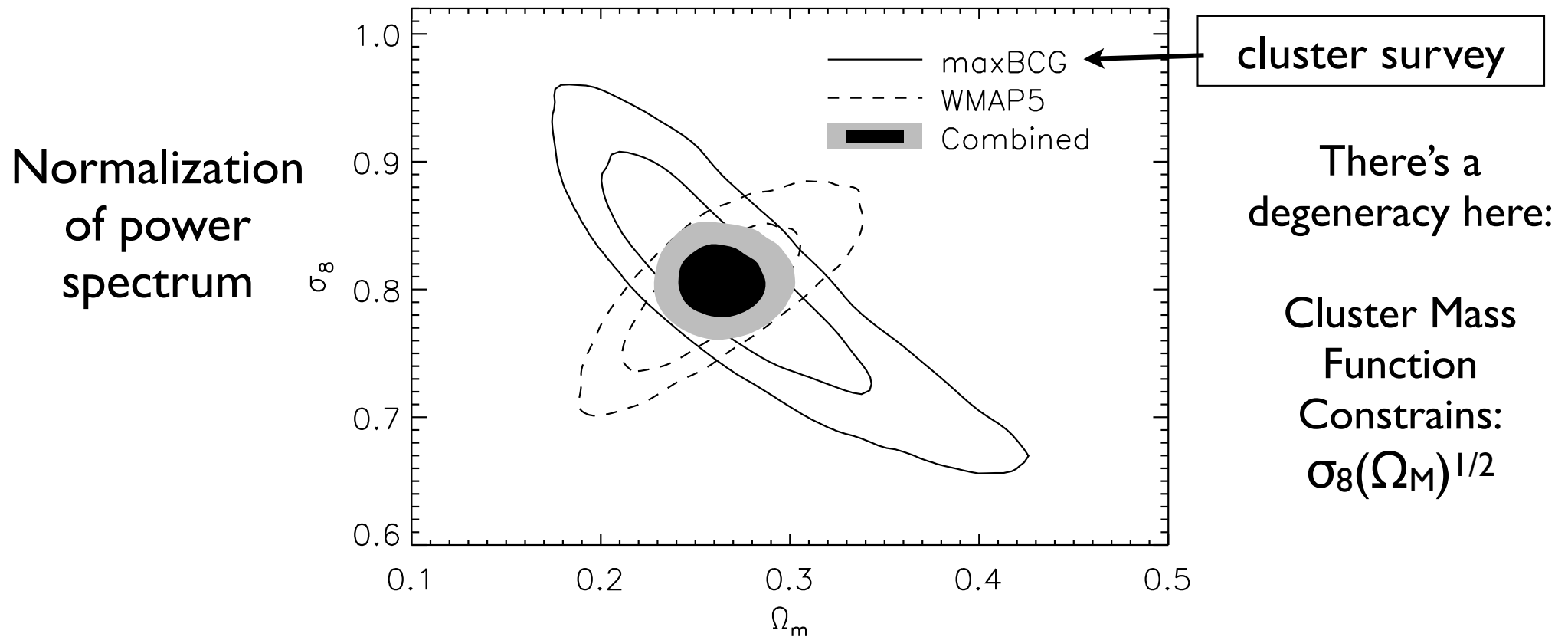


Hoekstra+2006

Constrained Quantity in Cosmic Shear Analyses:

$$\sigma_8 (\Omega_m)^{0.6}$$

These are similar types of constraints as we derive looking at the mass function of galaxy clusters (earlier in this lecture)



There's a degeneracy here:

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

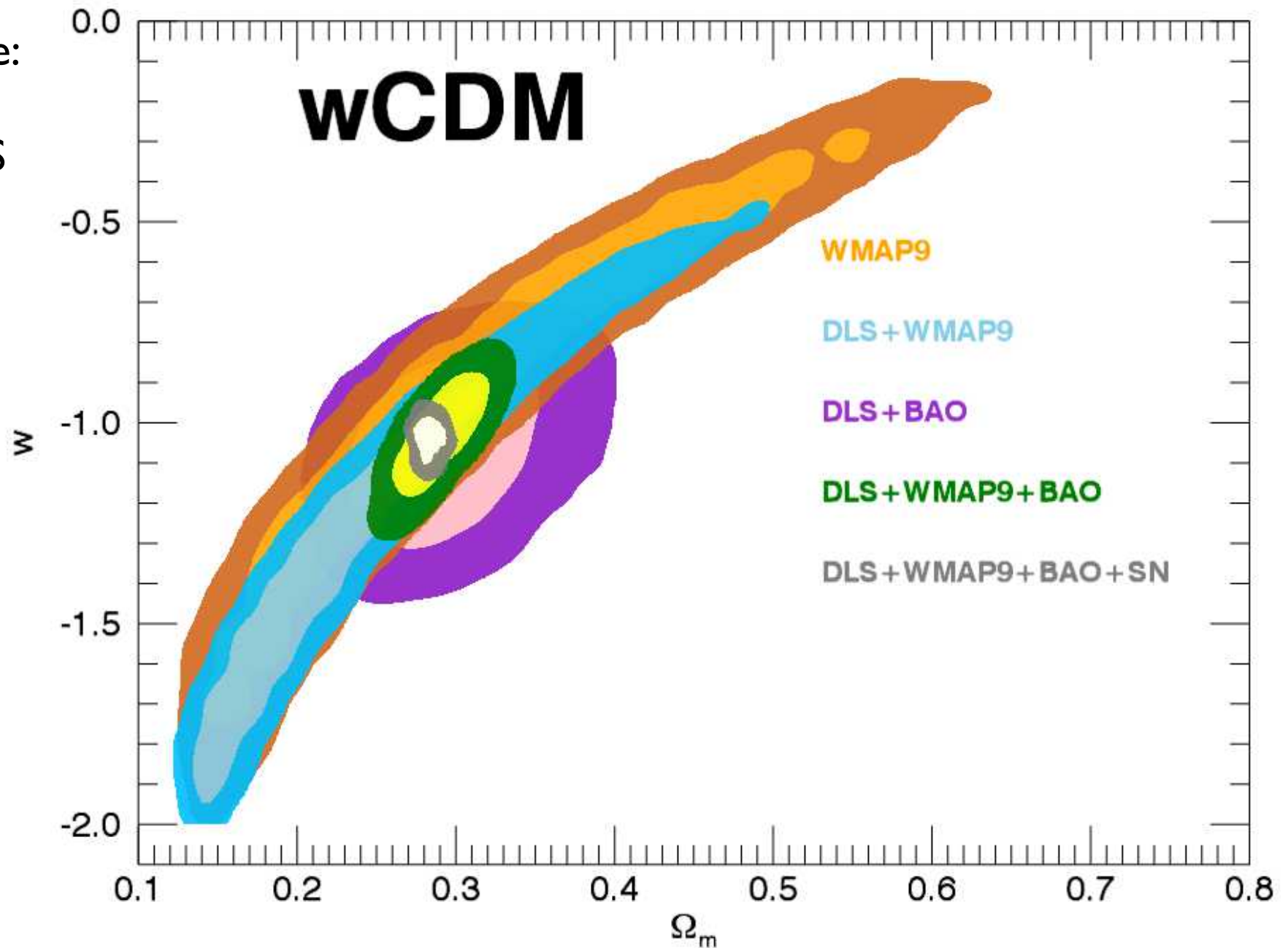
So a higher σ_8 , lower Ω_M and lower σ_8 , higher Ω_M both match observations

Rozo et al. 2010

What constraints can we set on w with these experiments?

One Example:

DEEP LENS
SURVEY



What are some of the most notable cosmic shear studies from 2000 to 2018:

Author(s)	Survey Field	Area	σ_8 Constraints	Ω_m Constraints	w Constraints
Van Waerbeke et al. (2000)	VIRMOS-Descart (CFHT)	$\approx 2.1 \text{ deg}^2$	$\sigma_8 = 0.91 \pm 0.06$	$\Omega_m = 0.3$ (assumed)	Not considered
Bacon et al. (2000)	WHT Survey	$\approx 1.5 \text{ deg}^2$	$\sigma_8 = 0.97 \pm 0.13$	$\Omega_m = 0.3$ (assumed)	Not considered
Wittman et al. (2000)	Deep Lens Survey (DLS)	$\approx 0.6 \text{ deg}^2$	$\sigma_8 = 0.8 \pm 0.2$	$\Omega_m = 0.3$ (assumed)	Not considered
Hoekstra et al. (2002)	RCS	$\approx 53 \text{ deg}^2$	$\sigma_8 = 0.86 \pm 0.04$	$\Omega_m = 0.3$ (assumed)	Not considered
Van Waerbeke et al. (2002)	VIRMOS-Descart (CFHT)	$\approx 8.5 \text{ deg}^2$	$\sigma_8 = 0.88 \pm 0.05$	$\Omega_m = 0.3$	Not considered
Jarvis et al. (2003)	CTIO Survey	$\approx 75 \text{ deg}^2$	$\sigma_8 = 0.71 \pm 0.06$	$\Omega_m = 0.3$ (assumed)	Not considered
Heymans et al. (2005)	COMBO-17	$\approx 1 \text{ deg}^2$	$\sigma_8 = 0.78 \pm 0.08$	$\Omega_m = 0.3$	Not considered
Van Waerbeke et al. (2005)	CFHTLS	$\approx 22 \text{ deg}^2$	$\sigma_8 = 0.85 \pm 0.06$	$\Omega_m = 0.3$	Not considered
Hoekstra et al. (2006)	CFHTLS	$\approx 22 \text{ deg}^2$	$\sigma_8 = 0.85 \pm 0.06$	$\Omega_m = 0.24 \pm 0.04$	Not considered
Fu et al. (2008)	CFHTLS	$\approx 57 \text{ deg}^2$	$\sigma_8 = 0.80 \pm 0.05$	$\Omega_m = 0.25$	Not considered
Schrabback et al. (2010)	COSMOS	$\approx 1.64 \text{ deg}^2$	$\sigma_8 = 0.68 \pm 0.06$	$\Omega_m = 0.3$	Not considered
Kilbinger et al. (2013)	CFHTLenS	$\approx 154 \text{ deg}^2$	$\sigma_8 = 0.79 \pm 0.03$	$\Omega_m = 0.27 \pm 0.02$	w = -1 (assumed)
Heymans et al. (2013)	CFHTLenS	$\approx 154 \text{ deg}^2$	$\sigma_8 = 0.77 \pm 0.05$	$\Omega_m = 0.3$	w = -1 (assumed)
Jee et al. (2015)	Deep Lens Survey (DLS)	$\approx 20 \text{ deg}^2$	$\sigma_8 = 0.81 \pm 0.06$	$\Omega_m = 0.26 \pm 0.05$	w = -1.13 ± 0.25
Hildebrandt et al. (2017)	KiDS-450	$\approx 450 \text{ deg}^2$	$\sigma_8 = 0.745 \pm 0.039$	$\Omega_m = 0.26 \pm 0.04$	w = -1.02 ± 0.10
Troxel et al. (2018)	DES Year 1	$\approx 1321 \text{ deg}^2$	$\sigma_8 = 0.782 \pm 0.027$	$\Omega_m = 0.267 \pm 0.017$	w = -0.82 ± 0.20

Observational Challenges — Intrinsic Alignments

In order to measure the effect that gravitational lensing has on background galaxies, we assume that the relative orientation of galaxies is random

Any alignment between the orientation of galaxies is assumed to result from gravitational lensing by intervening masses

But what if the relative orientation of galaxies is not random?

Such alignment could result from tidal interactions of galaxies on each other (if galaxies are nearby)

Seems clear that shallower surveys would be more affected than deeper surveys

Observational Challenges — Intrinsic Alignments

In fact, galaxies have been shown to exhibit some intrinsic alignments, but to first order it is not a huge concern

Good technique for ensuring that Intrinsic Alignment do not bias one's results is to exclude sources from the analysis that have similar redshifts

Other Challenges / Possible Systematic Errors

The shear signal one derives from observations is very sensitive to knowledge of the intrinsic redshift distribution of the sources (originally just used redshifts from HDF North)

In comparing with the predictions from cosmological models, the shear signal dependences on the clustering of sources at very small scales -- where the power spectrum is non-linear and baryonic physics may be important. Deficiencies in our knowledge of the latter two processes may affect weak lensing results.

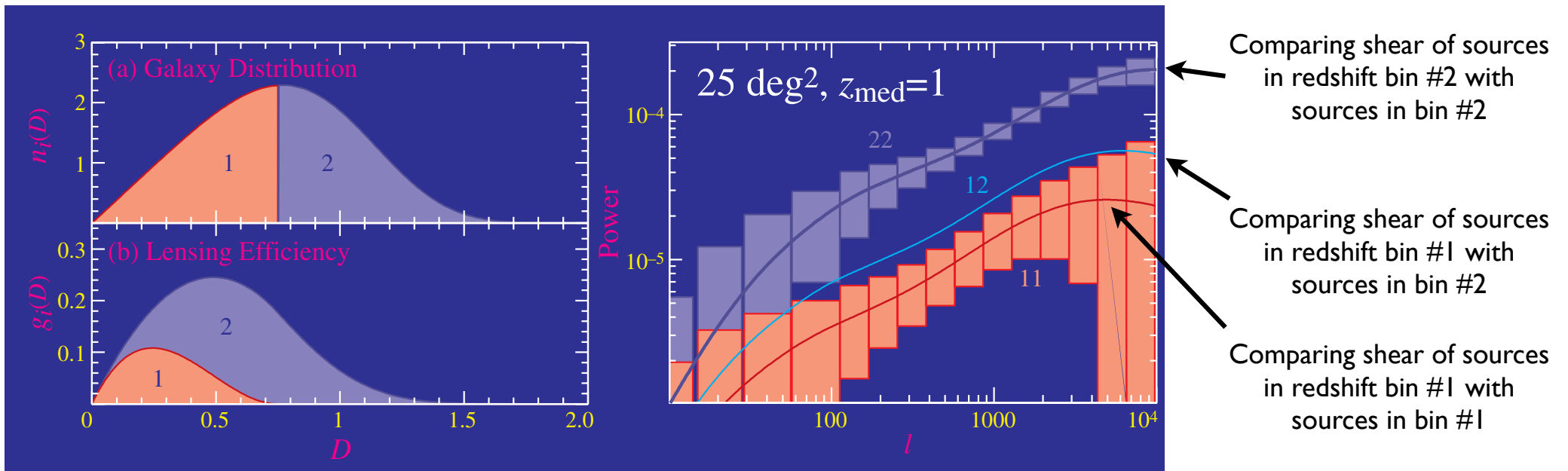
Cosmic Shear: Lots of Potential For Setting the Best Future Constraints

From the Dark Energy Task Force Report:

WL also emerging technique. Eventual accuracy will be limited by systematic errors that are difficult to predict. If the systematic errors are at or below the level proposed by the proponents, it is likely to be the most powerful individual technique and also the most powerful component in a multi-technique program.

Cosmic Shear: Lots of Potential For Setting the Best Future Constraints

One can take advantage of the redshifts one can estimate for background sources to measure the growth of structures as a function of redshift. More distant sources will pass by much more structure along the line of sight



Notice that there is much more power in the shear signal cross-correlating sources in the more distant redshift sample (#2) than the closer one (#1)