Observational Cosmology Using Galaxy Clusters + Cosmic Shear

and

Dark Energy Missions

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: Clusters / Cosmic Shear / Dark Energy Missions
Apr 15: Dark Energy Missions / Review for Final Exam

May 13: Final Exam

This Week

Review Material from Last Week

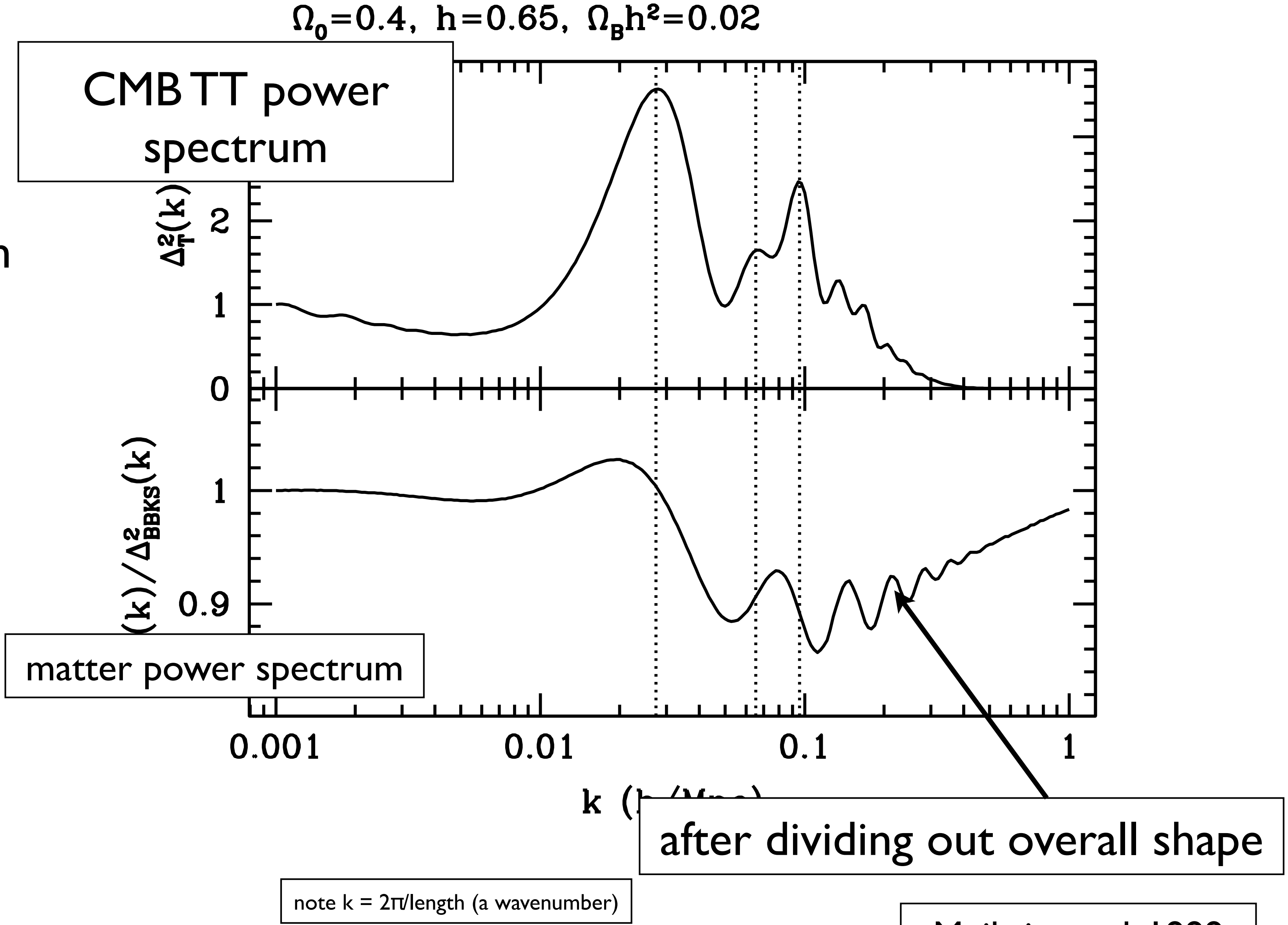
So the game is to determine the w parameter and how it depends on redshift

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 15 years ago
2. Baryonic Acoustic Oscillations (Lecture 8)
   -- gives us a standard rod to establish distance-redshift relation with low systematics
3. Galaxy Clusters (Lecture 8)
   -- provide us with sensitive probe of growth of structure
   -- early evidence for low Ω_m
4. Weak Gravitational Lensing (Lectures 9)
   -- provide us with sensitive probe of growth of structure
   -- powerful technique still in process of realizing full potential

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

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.

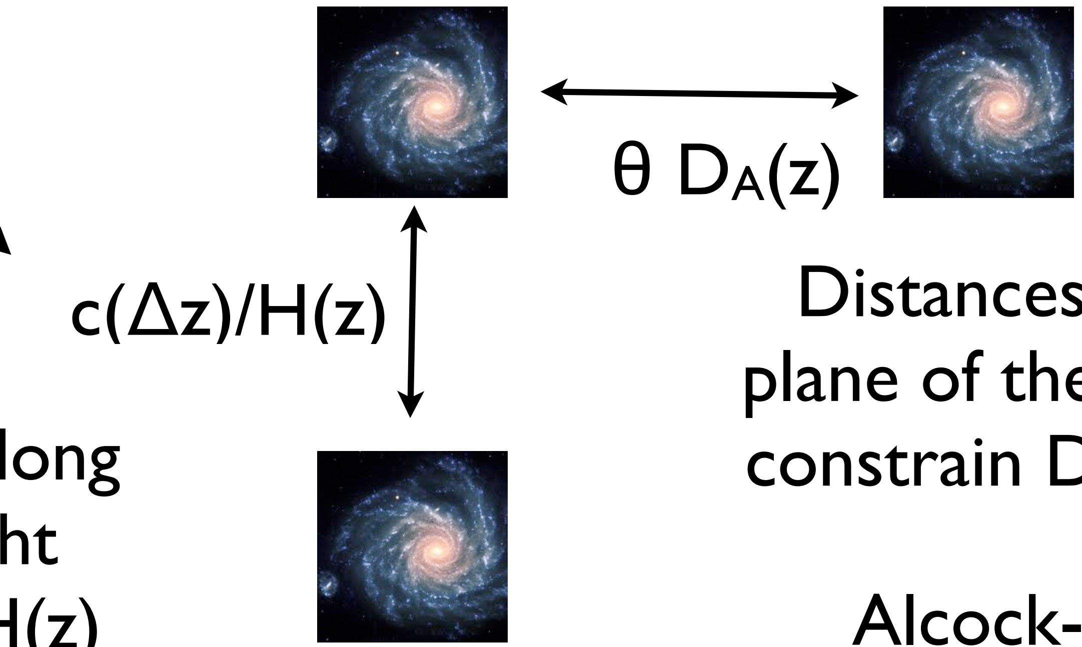


Meiksin et al. 1999

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: $D_A(z)$, $H(z)$

Recall if z~0:
$D = cz/H_0$



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

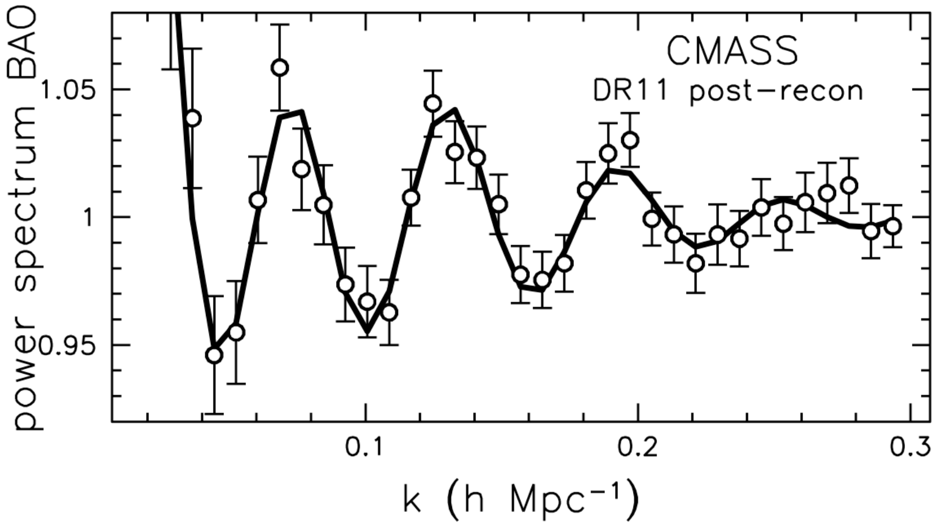
Distances along line of sight constrain $H(z)$

Alcock-Paczynski constraints

telescope

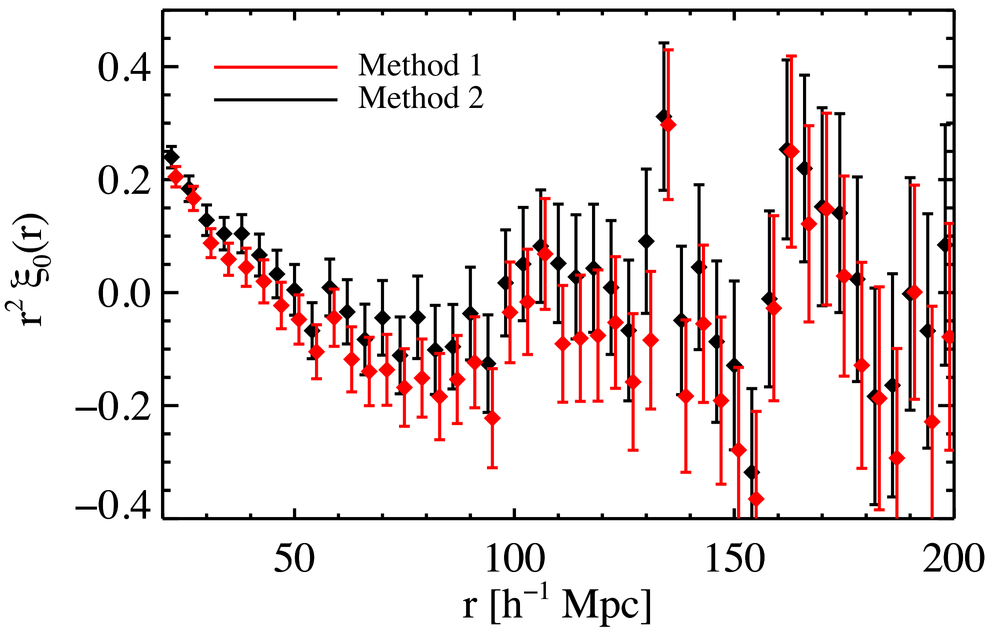
both length scales must be the same

Example of the impact BAO fluctuations have on the power spectrum for z~0.55 galaxies



Anderson+2013

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



Busca+2013

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

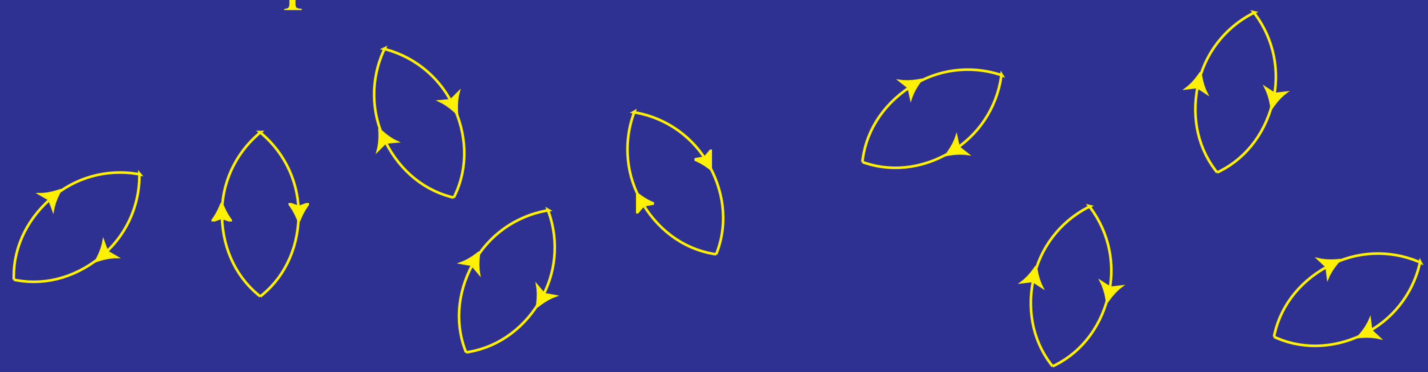
Dark Energy Affects the Differential Redshifting of CMB photons as they move in and out of gravitational potential. By cross correlating known galaxy clusters with CMB, we can observe this effect.

→ 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)

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

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

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)

Galaxy clusters also provide us with important constraints on cosmology!

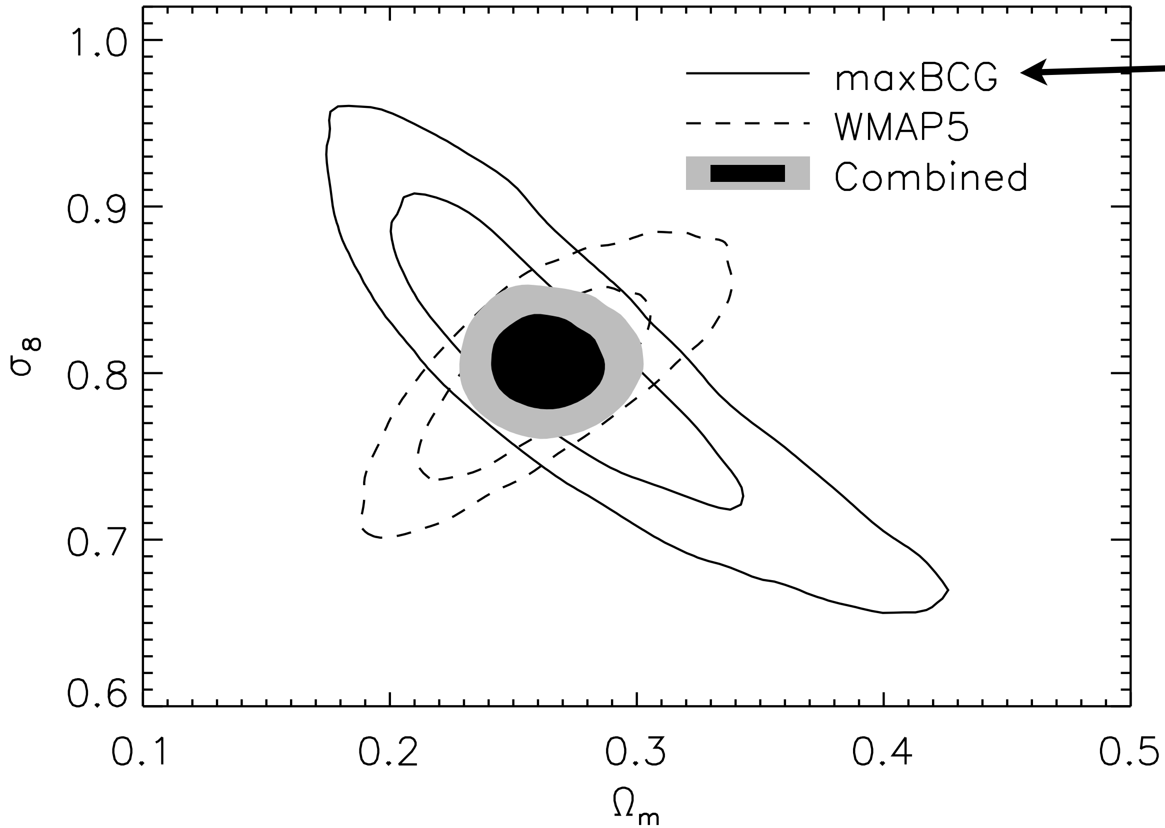
Why?

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

Value of Galaxy Clusters at z~0

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

New Material for This Week

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...

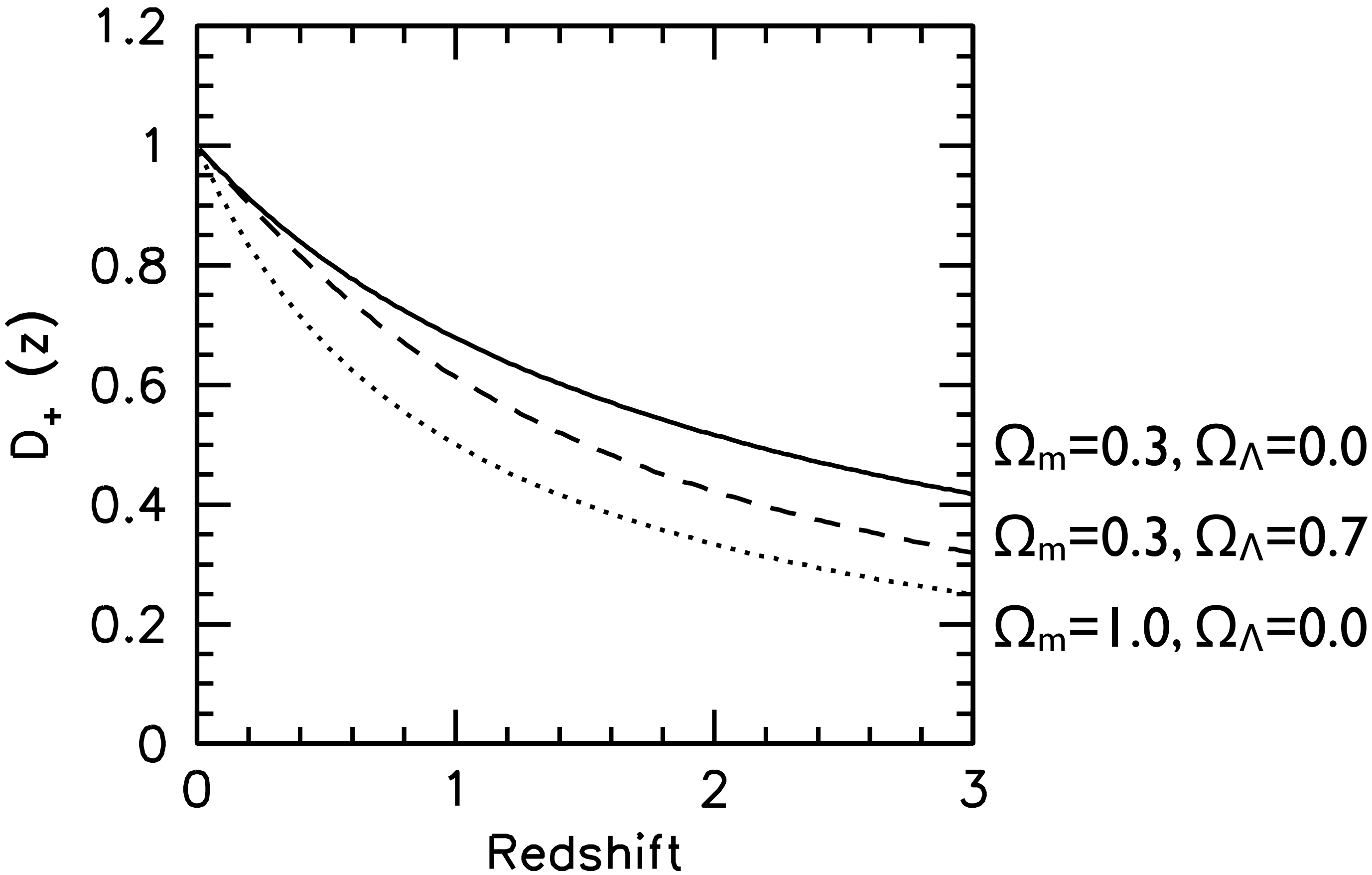
The rate at which structures grow in the universe depends upon the cosmological parameters:

Depend upon the growth factor (linear regime):

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

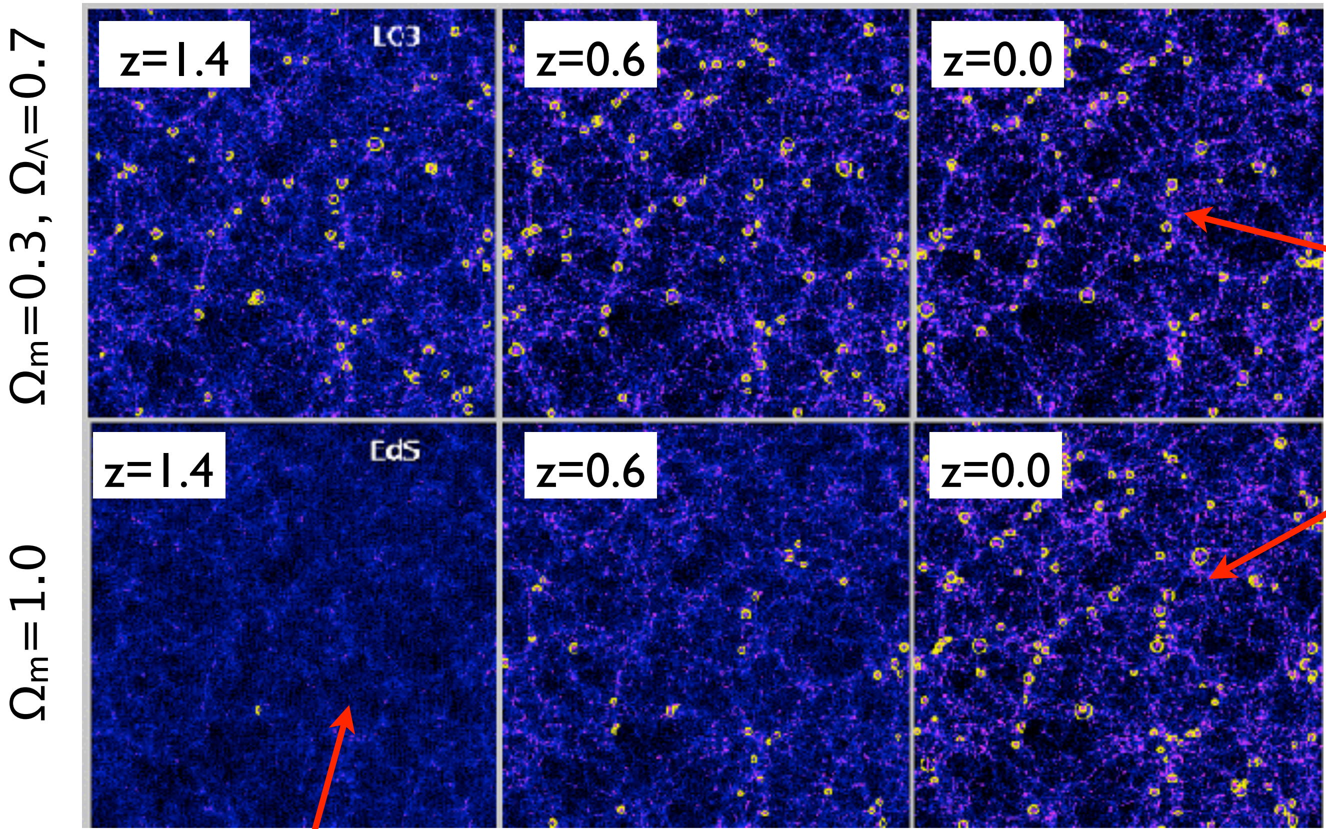
where a is size of universe and Ω_m, Ω_Λ are all evaluated in the past

Growth factor



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

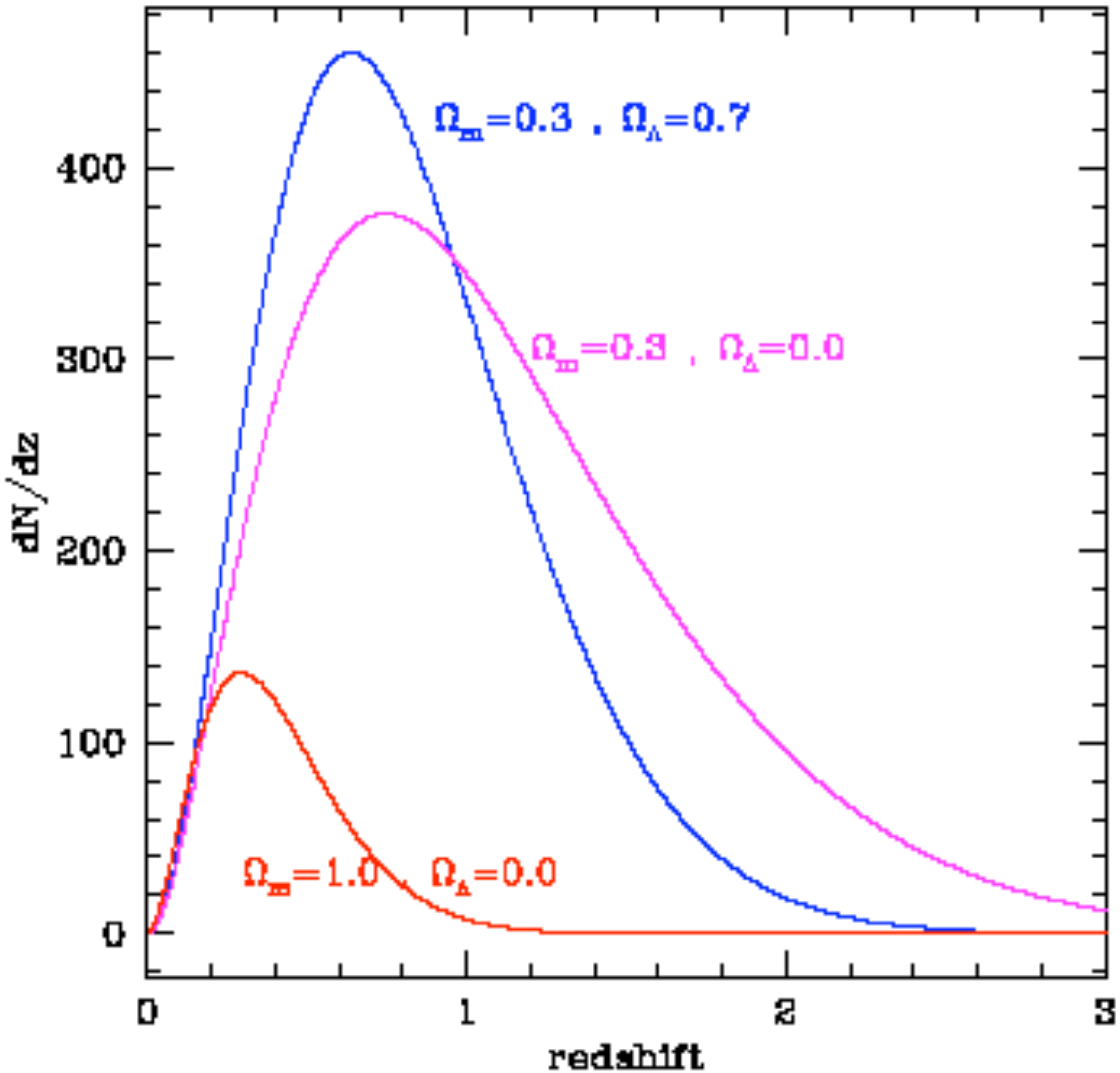
Note that the two cluster models agree at redshift z=0 (the present day) by construction.

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



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

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

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

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

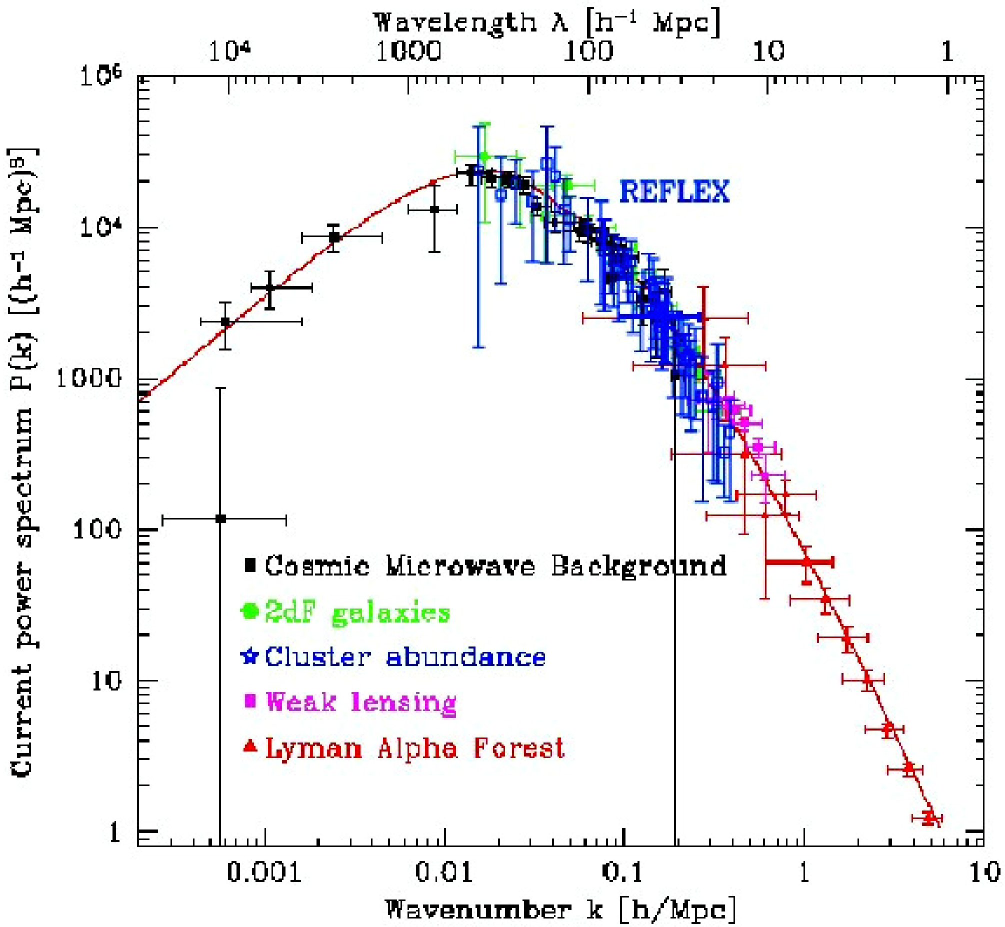
3. Derive Ω_m based on relative mass in gas and dark matter in clusters

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

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

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

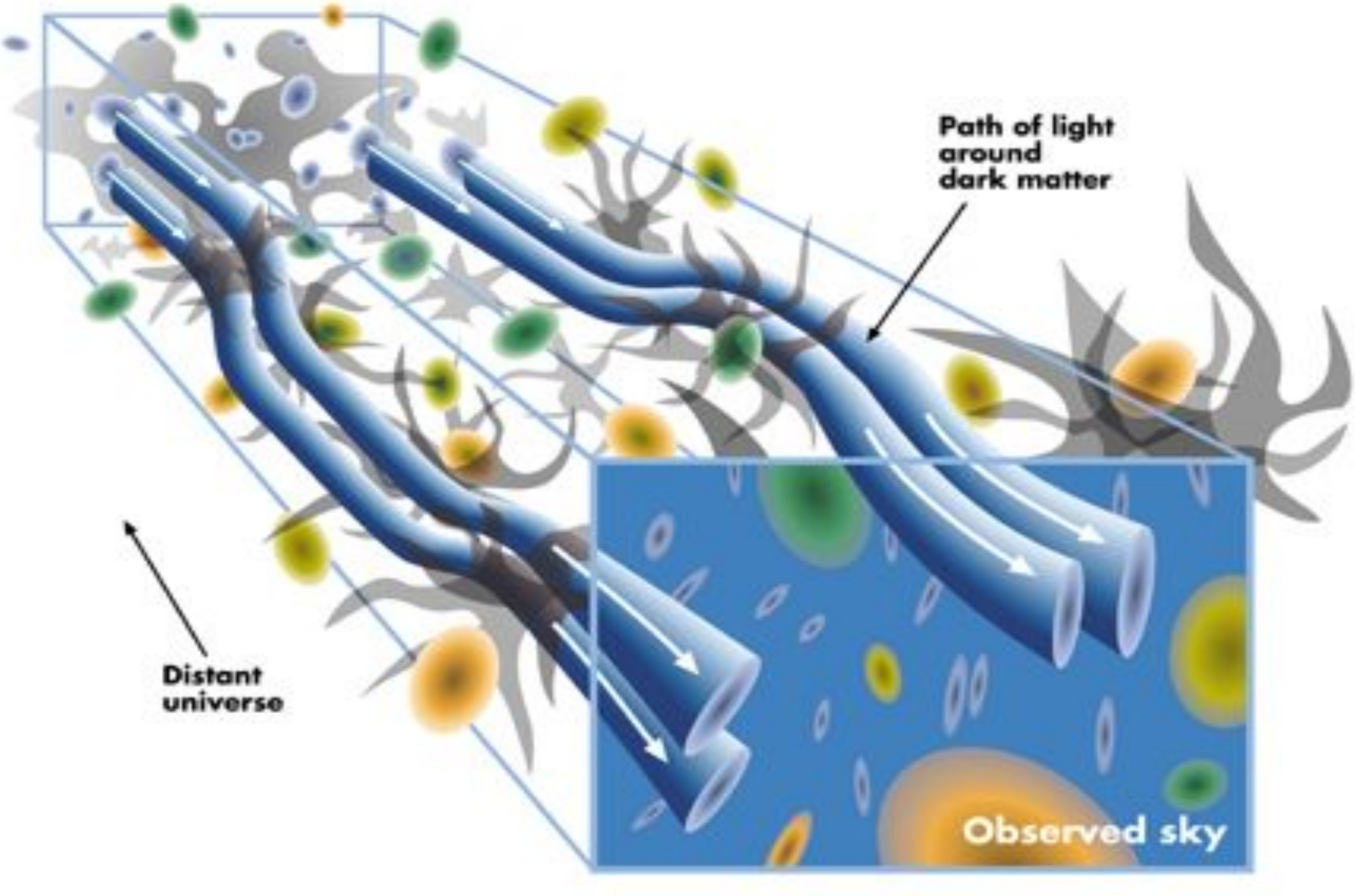
There are four standard methods:

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 (Last 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

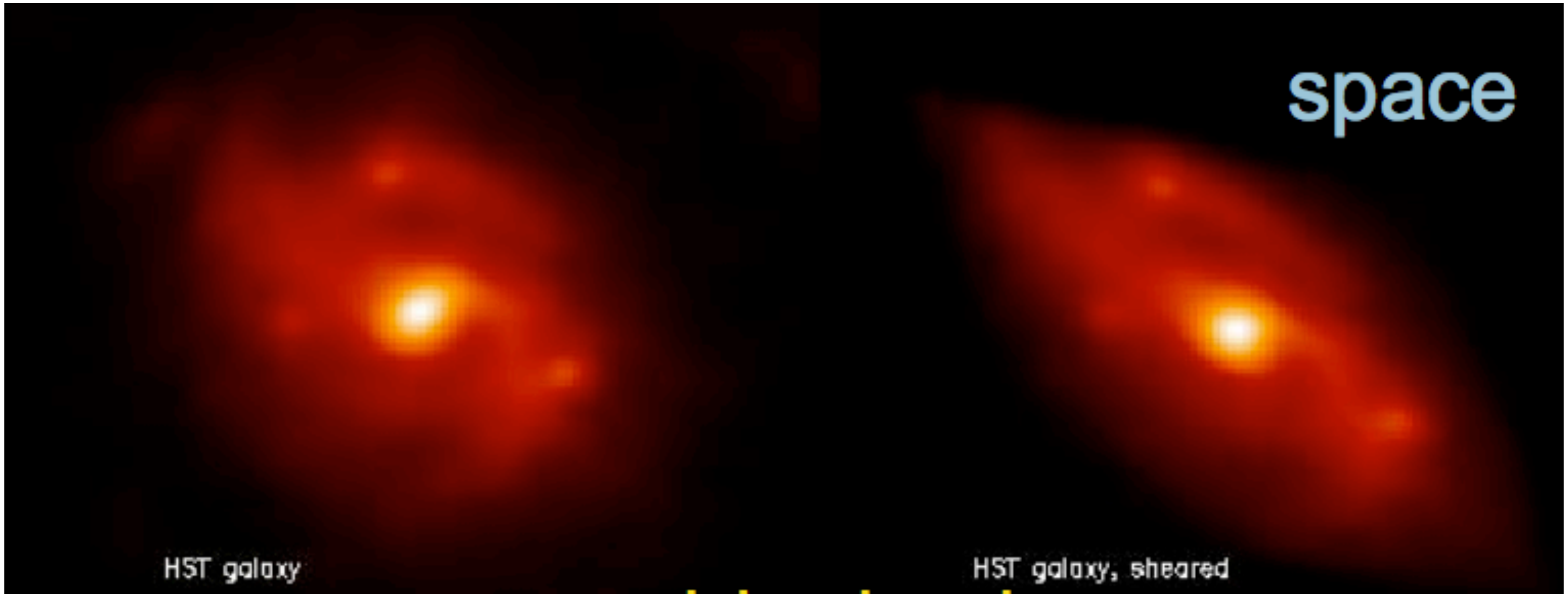
Gravitational Lensing has come up twice before:

1) measuring the total mass in galaxy clusters through gravitational lensing

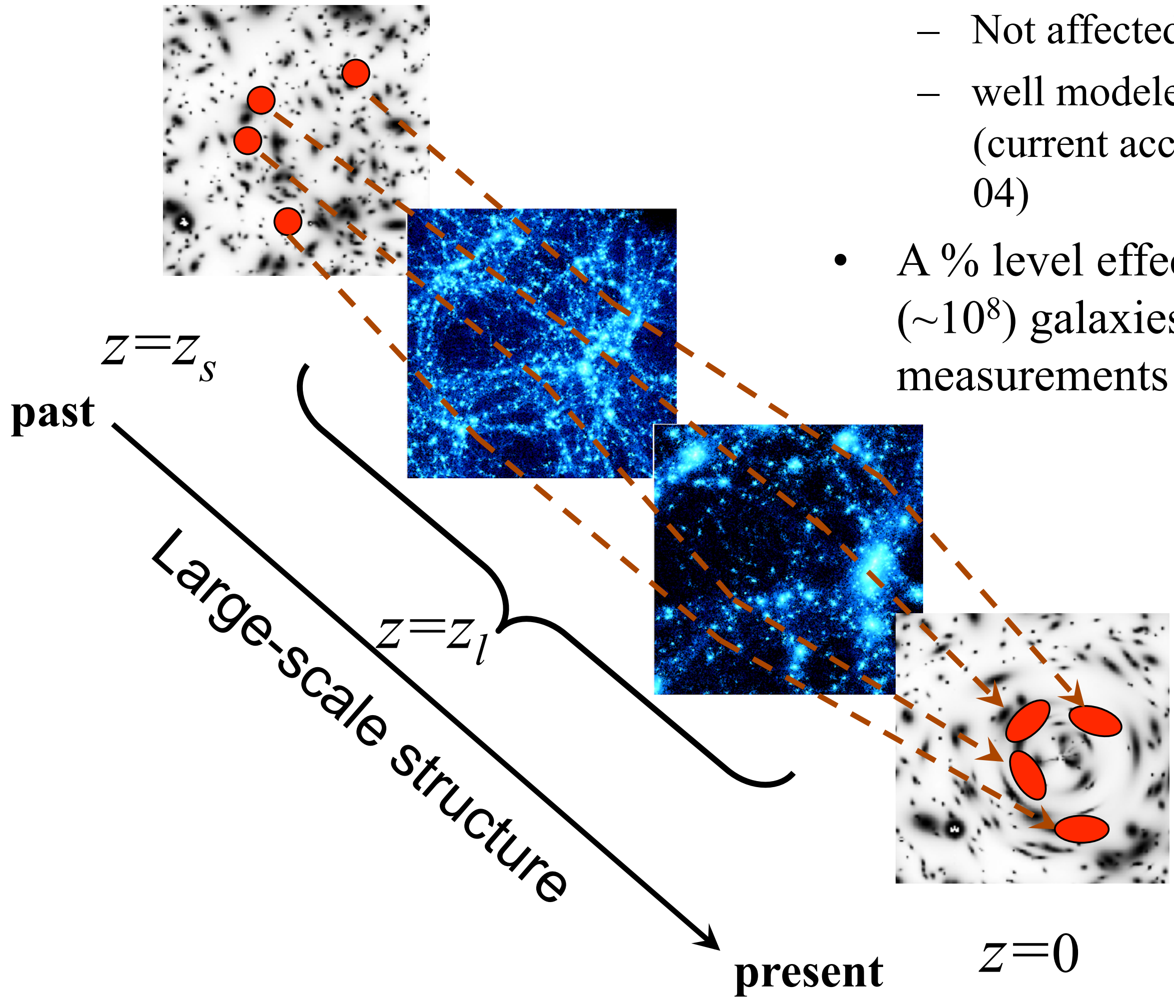
2) determining the Hubble constant by measuring the time delay between two sets of images

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

observables

$$\gamma = \frac{a-b}{a+b}$$

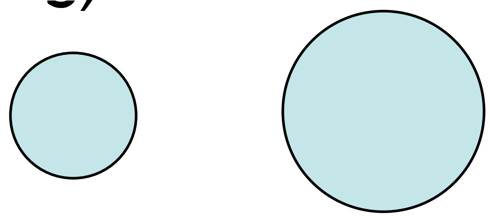
$$\gamma_1 = \gamma \cos 2\varphi$$

$$\gamma_2 = \gamma \sin 2\varphi$$

Credit: Takada

What effect does gravitational lensing have on galaxies we observe?

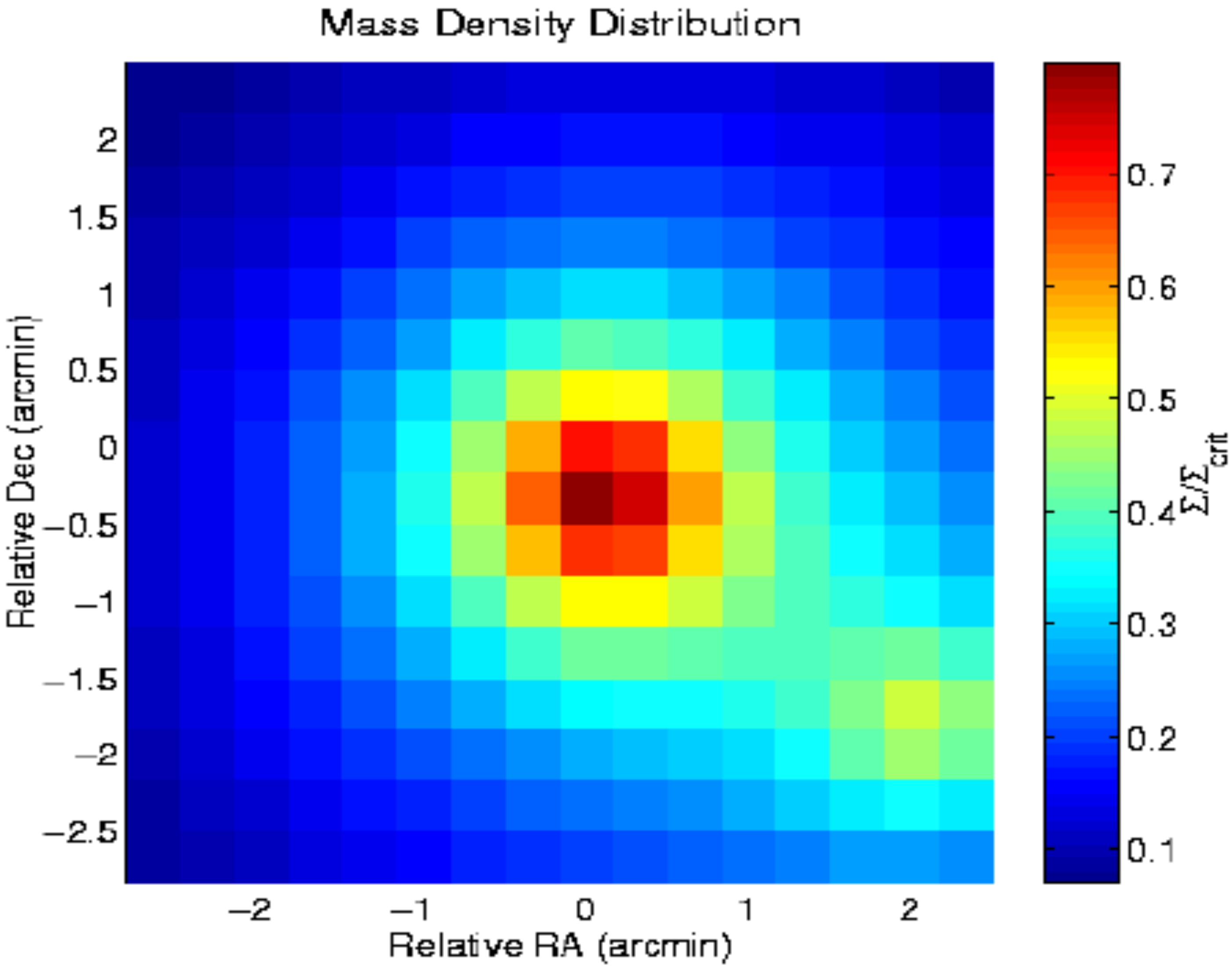
1. Magnification
   - -- expressed as κ (called convergence)
   - -- does not affect shape



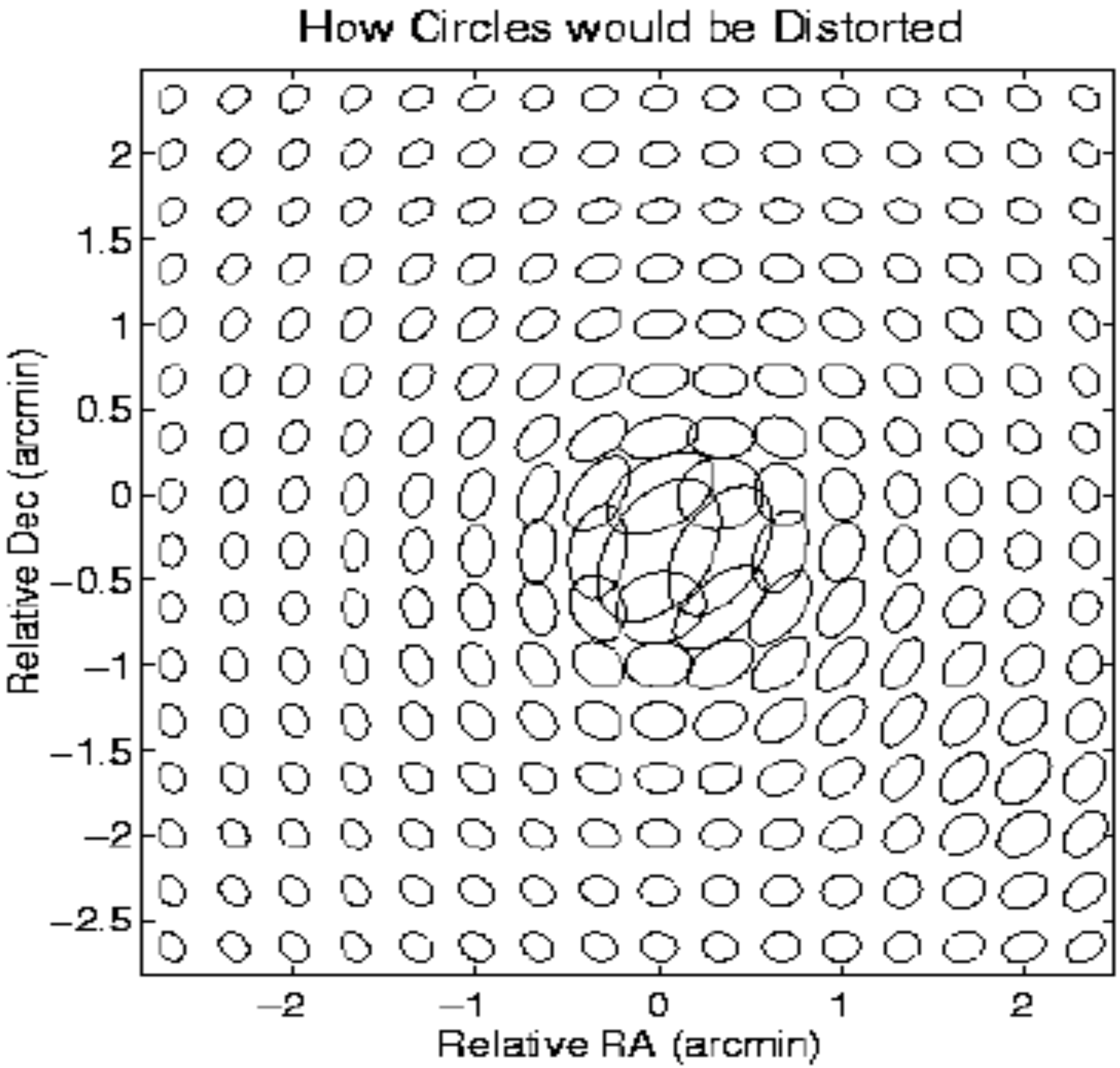
2. Shear
   - -- expressed as γ (called the shear)

$\gamma_1>0$ $\gamma_1<0$ $\gamma_2>0$ $\gamma_2<0$

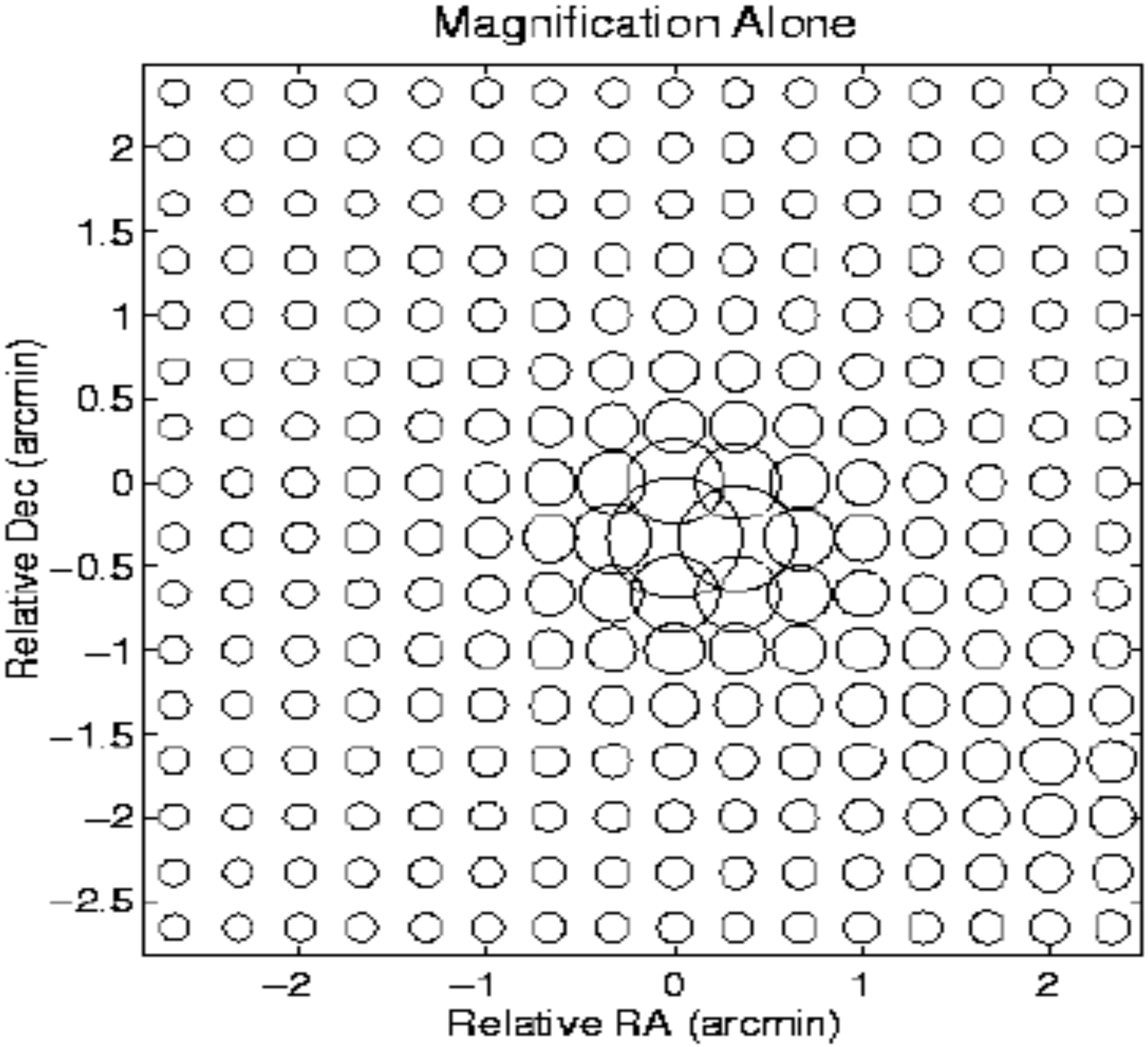
Quick illustration: let's say you have this mass distribution



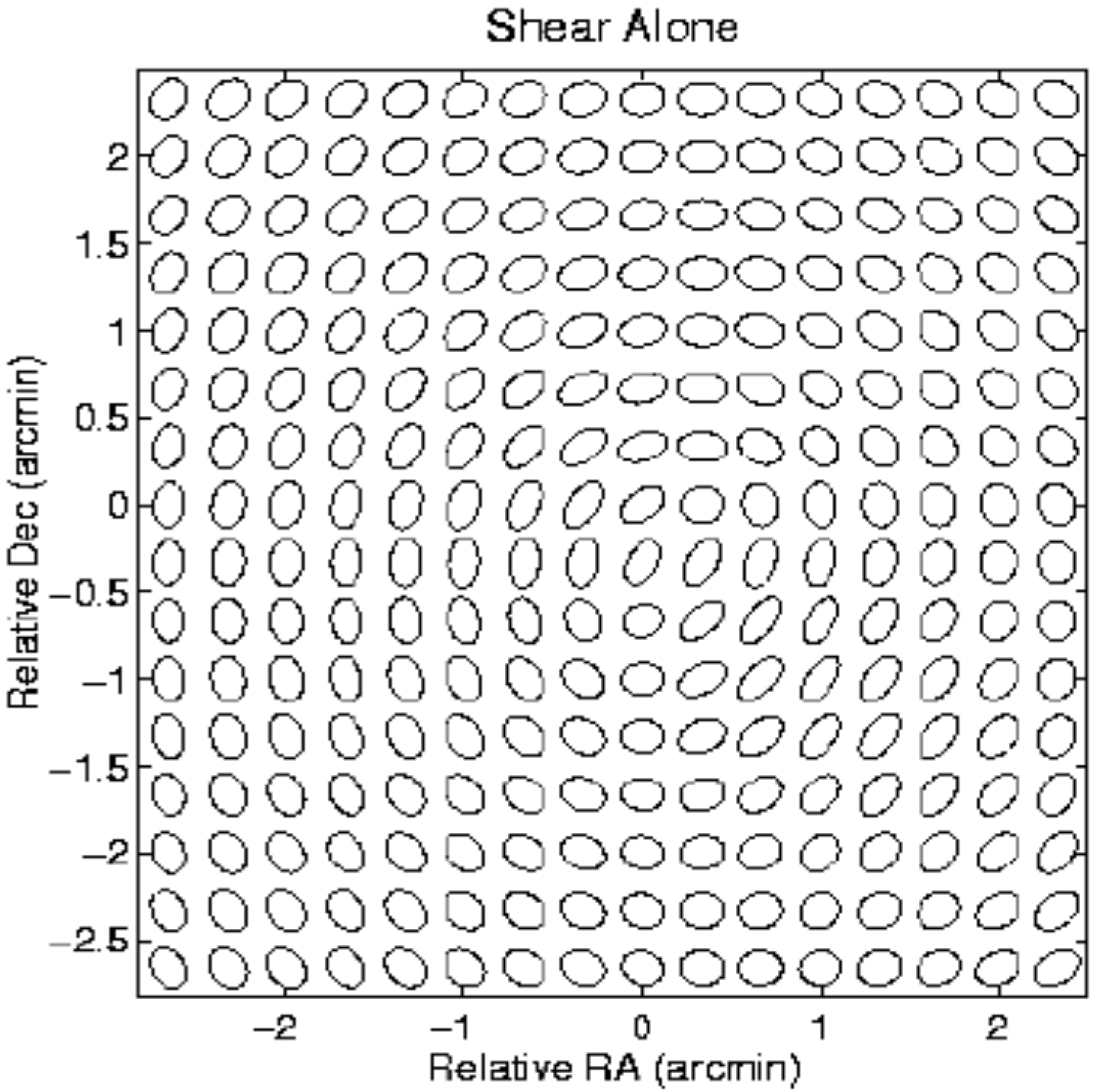
Quick illustration: then a grid of circles would be distorted as such



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:

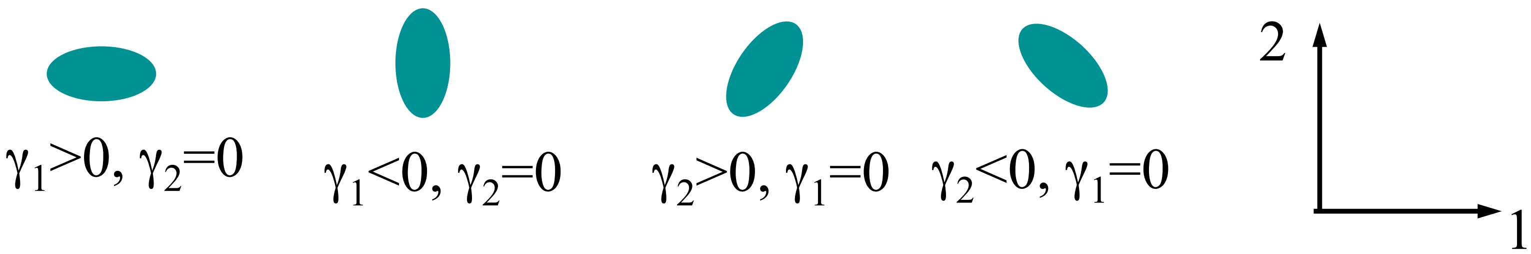
$$A_{ij} = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix} = (1-\kappa)\begin{pmatrix} 1-g_1 & -g_2 \\ -g_2 & 1+g_1 \end{pmatrix}$$

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

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

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 π/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

Credit: Takada

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(θ):

$$I_{ij} = \int d^2\theta \, I(\vec{\theta}) \; w(\vec{\theta}) \; \theta_{\mathrm{i}} \; \theta_j$$

w(θ) 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:

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

Measuring Shear

But galaxies are not perfect circles and have intrinsic orientations and ellipticities (typical ellipticities ~10-30%)

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

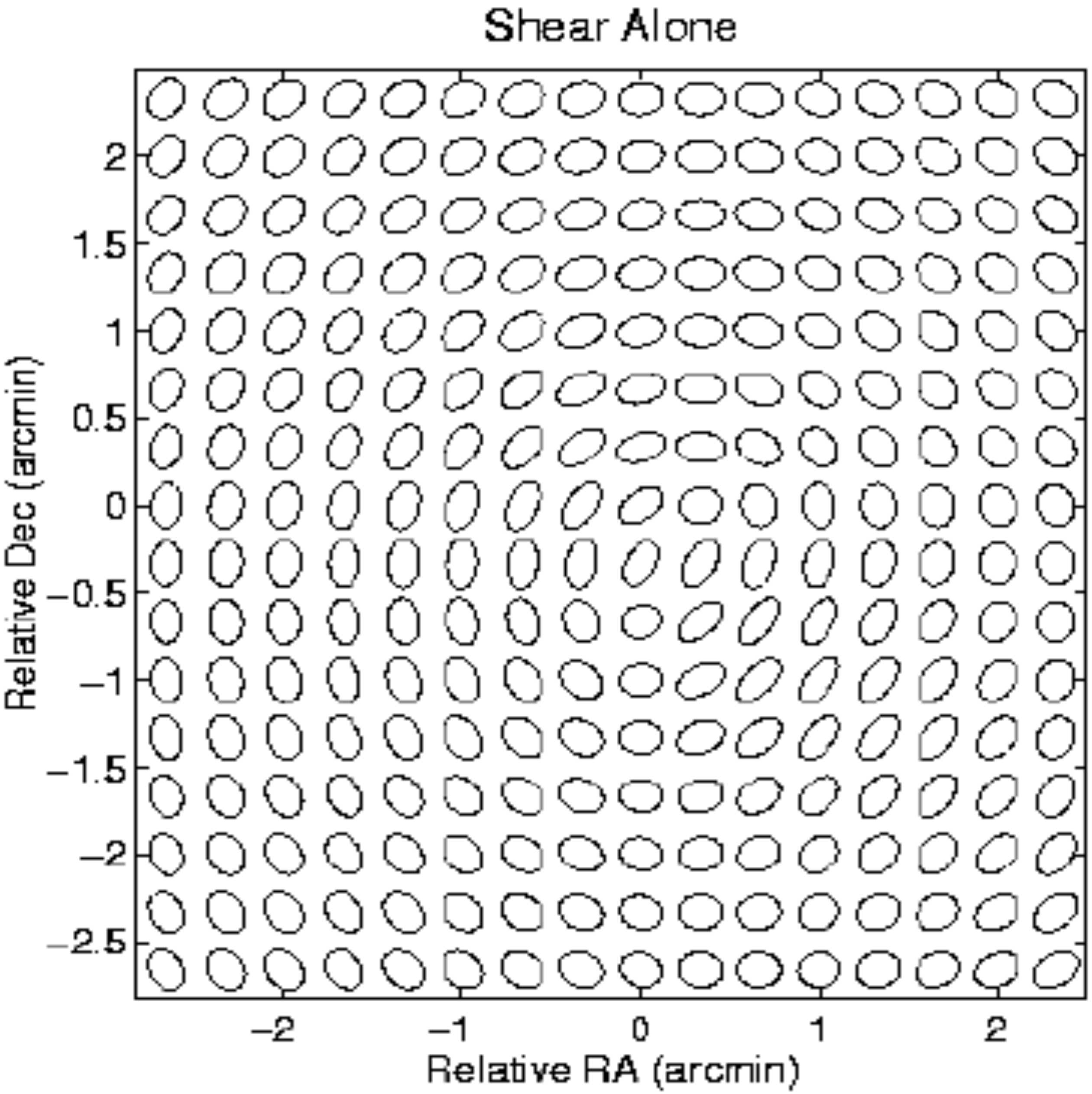
One complication in deriving the shear is that light from the galaxy is blurred by the earth's atmosphere or due to the intrinsic diffraction limit of a telescope

Procedure for Optimally Measuring Shear from Images of Galaxies is a Huge Industry!

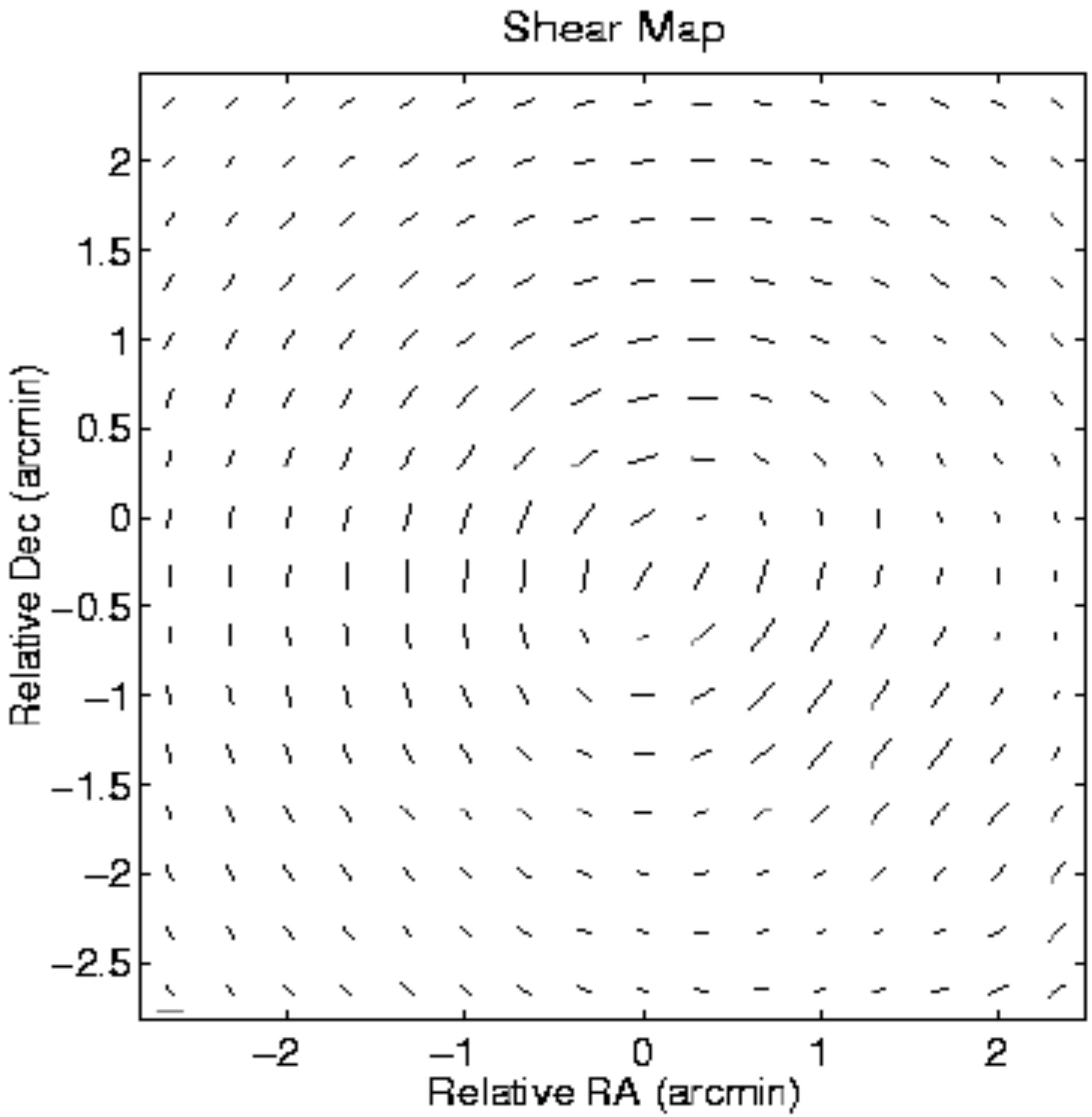
- Various groups have developed their own methods of lensing shape measurement
  - Kaiser, Squires & Broadhurst 95
  - Kuijken 99
  - Bernstein & Jarvis 02; *Nakajima* & Bernstein 04 ← *We are also working on this method*
  - …..
- There are efforts being made to test the methods using simulated images in order to assess the accuracy performance
- This is very important to refine/improve the methods, in preparation for future massive lensing surveys
- For the details, see
  - STEP (Shear TEsting Programme): Heymans et al. 06; Massey et al. 07
  - GREAT08: Bridle et al. 09
  - Next is GREAT10?

Credit: Takada

Here is just shear alone:



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



Large Numbers of Sources Needed

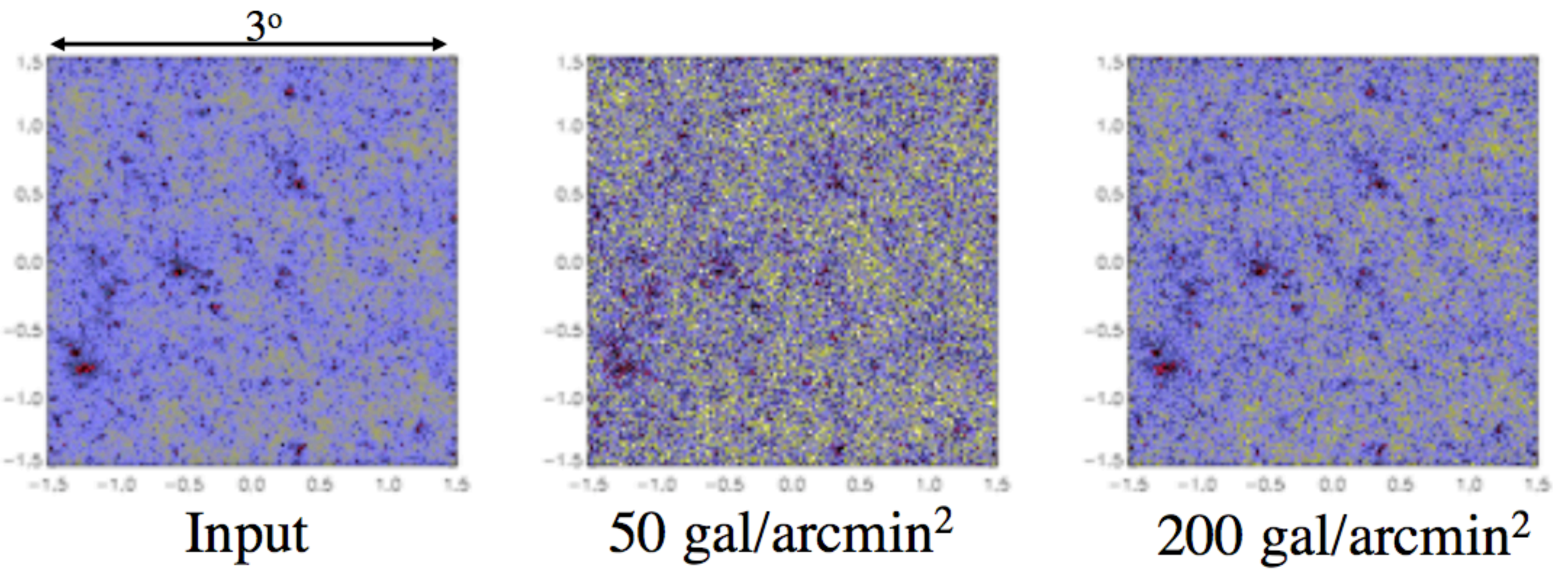
Since galaxies have approximately random orientations on the sky, we need measurements of a large number of sources per unit area to average over these effects and establish the overall effect of gravitational lensing.

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!

Large Numbers of Sources Needed

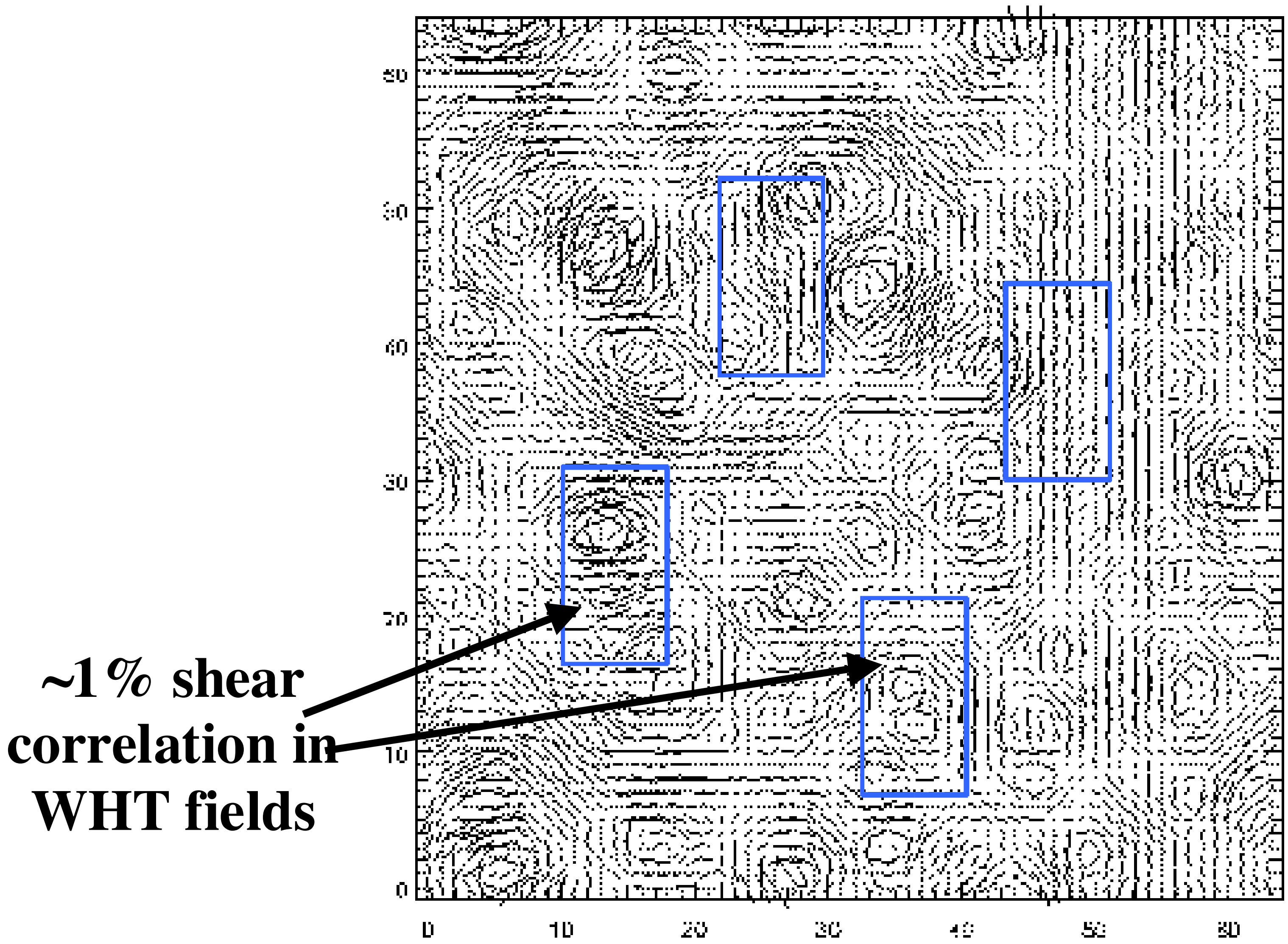
Since galaxies have approximately random orientations on the sky, we need measurements of a large number of sources per unit area to average over these effects and establish the overall effect of gravitational lensing.



A simulated convergence map and its reconstruction from mock data (courtesy of M. White)

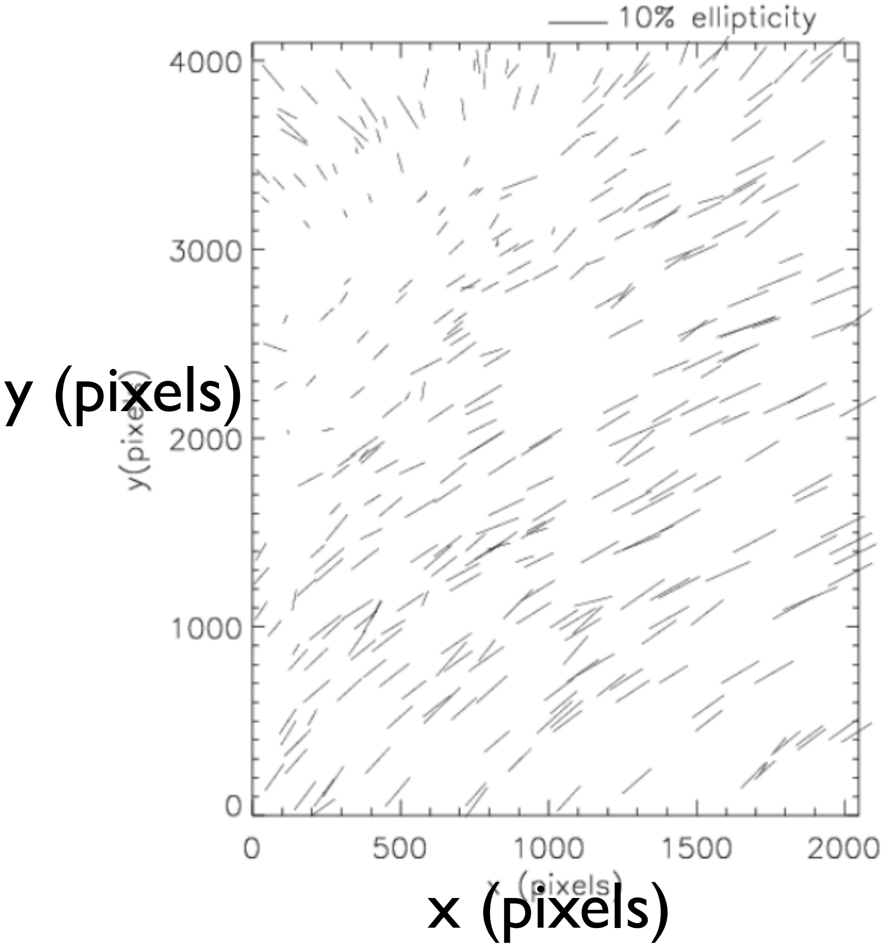
Averaging over the ellipticity in many sources, we can derive a mean shear at different positions on sky

(but signal is very weak)



PSF Anisotropies

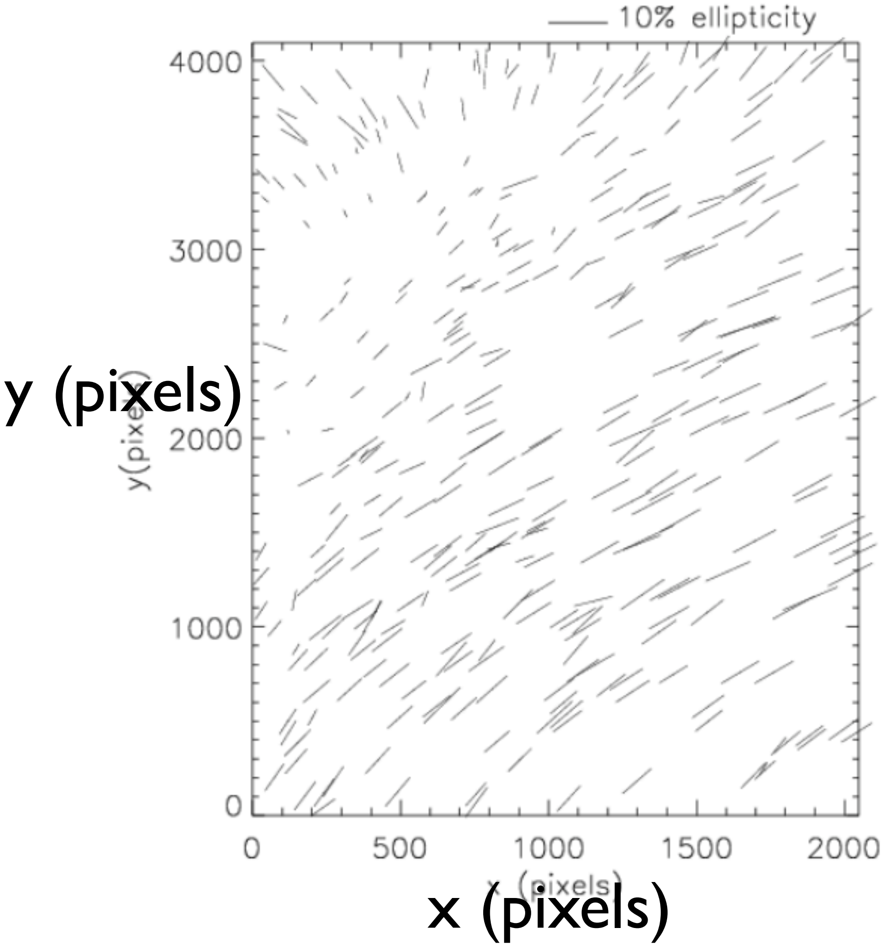
In order to measure the shear on an image, we need to understand how the PSF (point spread function) varies as a function of position on a detector or from the optics.



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.

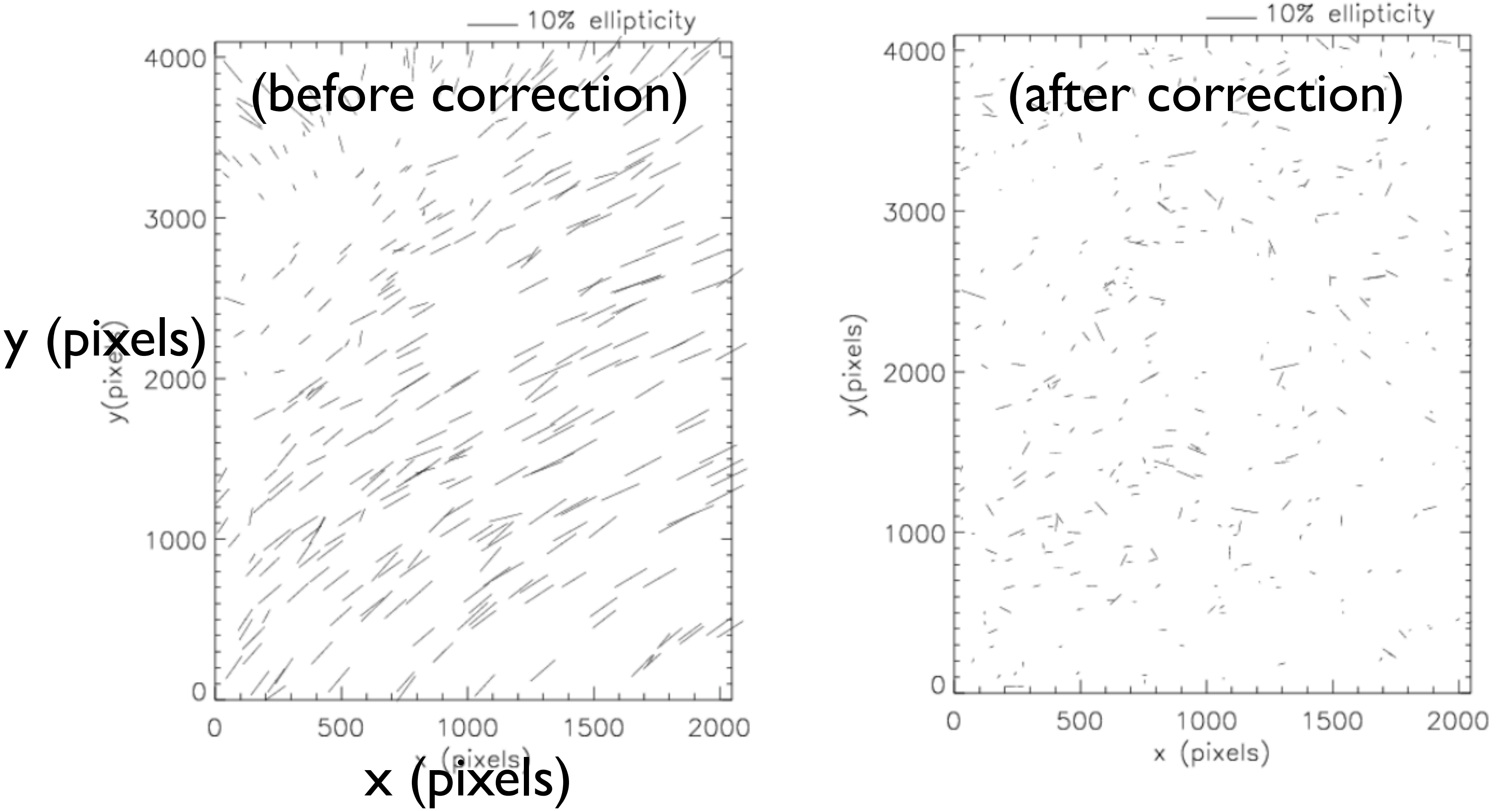


The PSF anisotropies are usually measured by observing a large number of stars with a detector and quantifying the apparent shear

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

PSF Anisotropies

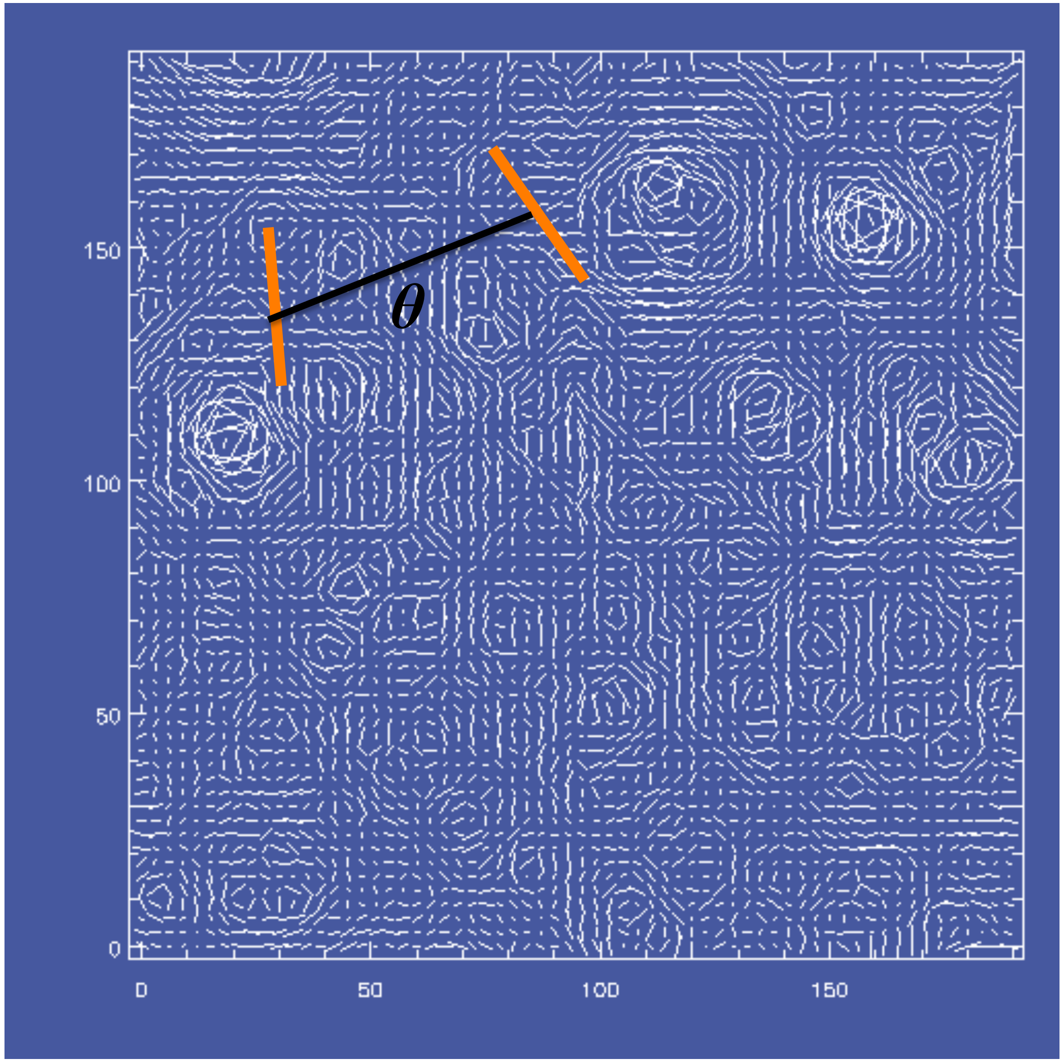
In order to measure the shear on an image, we need to understand how the PSF (point spread function) varies as a function of position on a detector or from the optics.



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

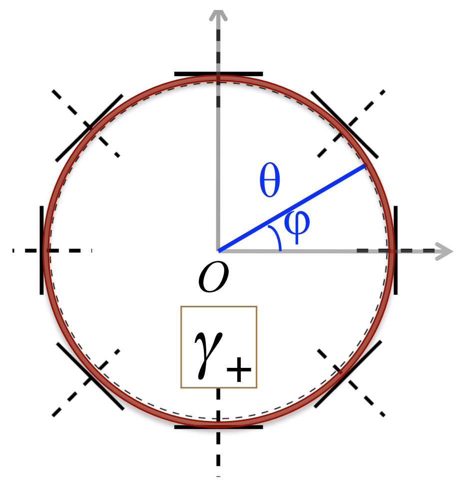


- Correlated images of distant galaxies over all angular scales
- Use images of all distant galaxies
- Correlation function method to measure the cosmic shear signals
- The lowest one is 2pt function

Credit: Takada

Determine correlation of shear measurement on different angular scales θ

E-mode



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

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

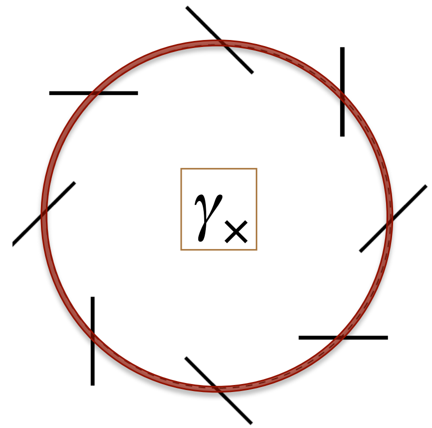
the diagram to right shows just one origin over which we can perform this averaging.

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 $\gamma_\times$

$$\langle \gamma_\times \rangle(\theta) = 0 \quad \leftarrow \textit{a monitor of systematics}$$



B-mode

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

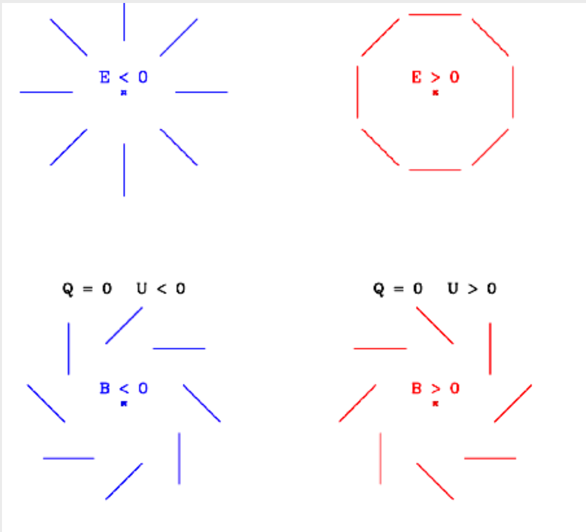
CMB lecture

One tends to break down the polarization map into two modes

(Helmholtz-Hodge theorem)

E-modes

B-modes



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

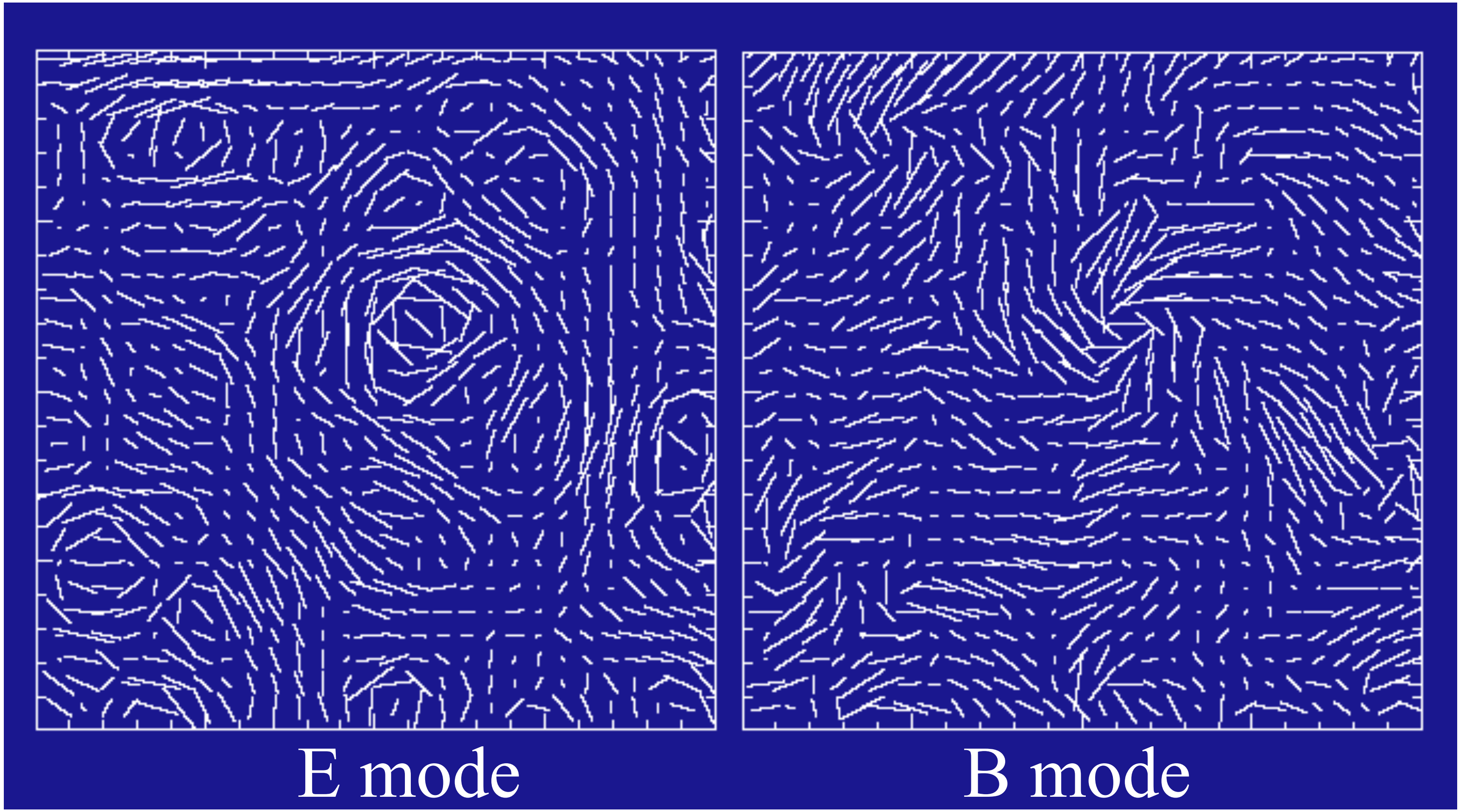
$$\nabla \times E = 0$$

B-modes have no divergence.

$$\nabla \cdot B = 0$$

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



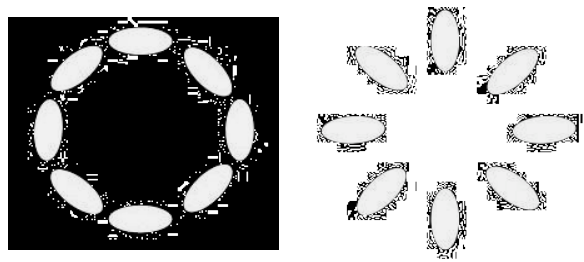
distinct different pattern

Credit: Takada

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

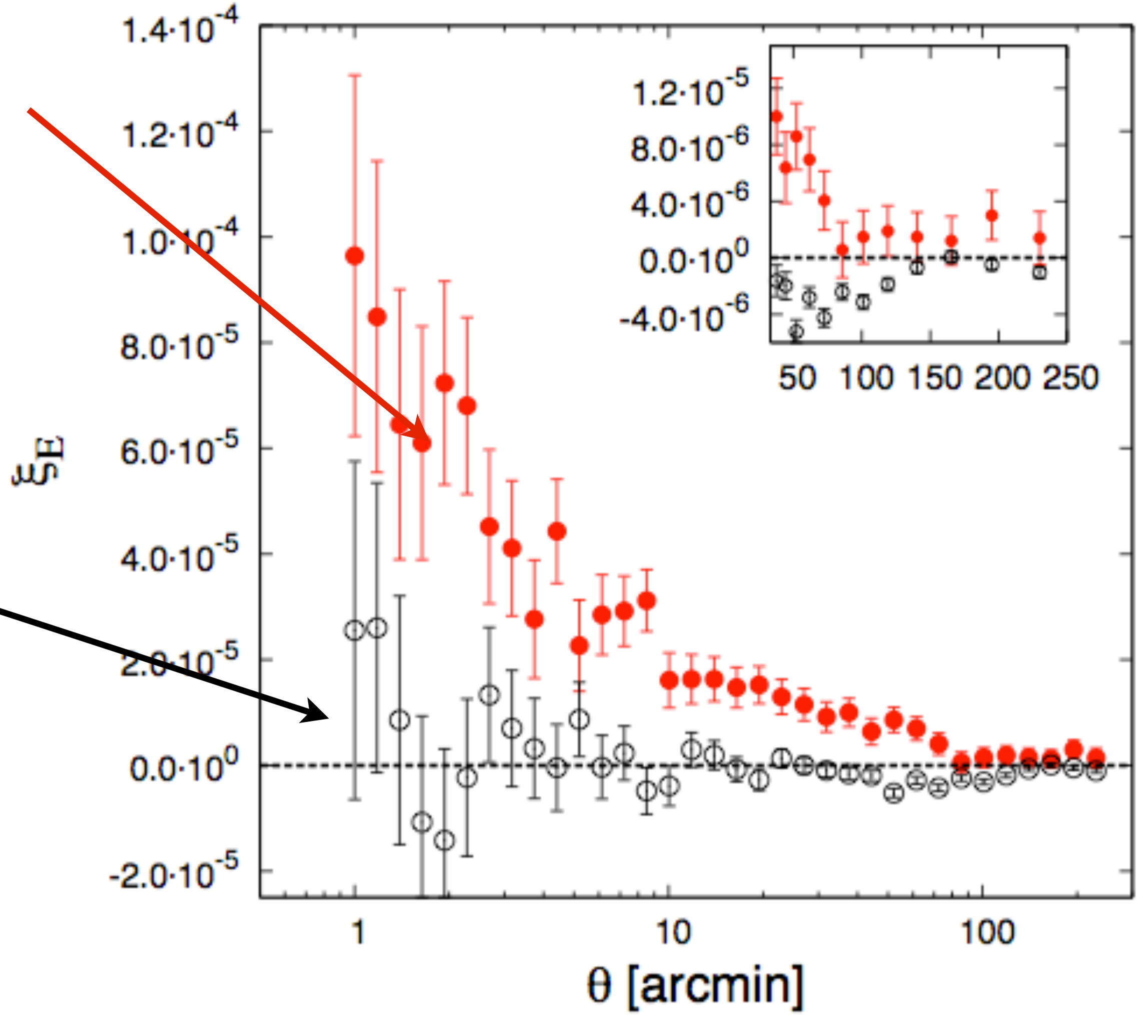


Figure 5: Ellipticity correlation function from [66]. These measurements based on the analysis of 57 $\deg^2$ of CFHTLS i' imaging data, extend out to 4 degrees, well into the linear regime. The E-modes are indicated by the red points. The B-mode (open points) is consistent with zero on most scales. 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		Power Spectrum Type Parameters
$\xi_{++}(\phi)$ $\langle\gamma_+\rangle(\theta)$	$\longleftrightarrow$	$P_\gamma(l)$ $P_\kappa(l)$ $C_{\gamma_i\gamma_j}(\ell)$

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

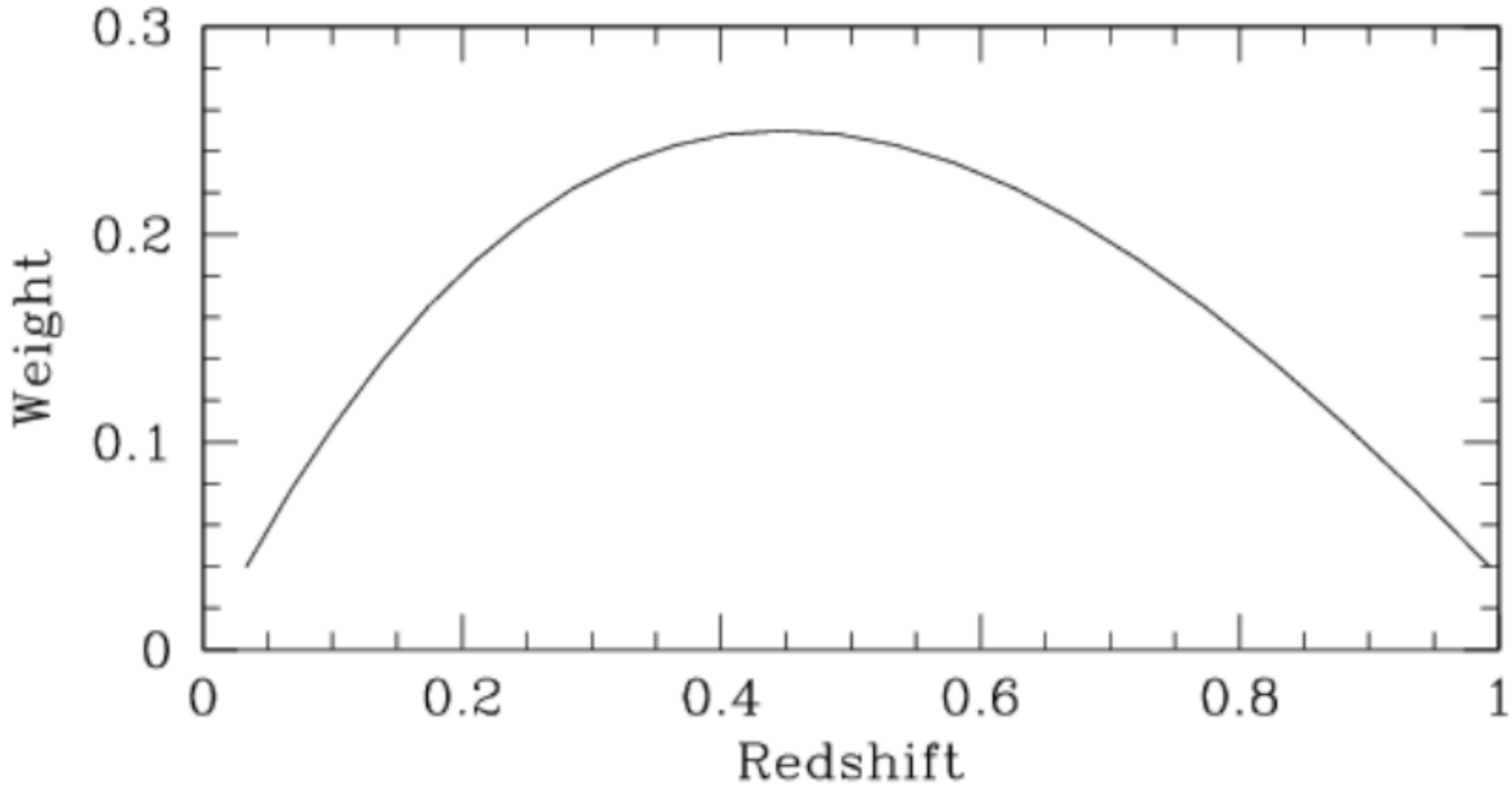
growth of mass perturbations

- Lensing efficiency function: W_{gl}
  - Overall amplitude is propotional to Ω_{m}, i.e. Ω_{de} if combined with CMB or a flat universe is *a prior* 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

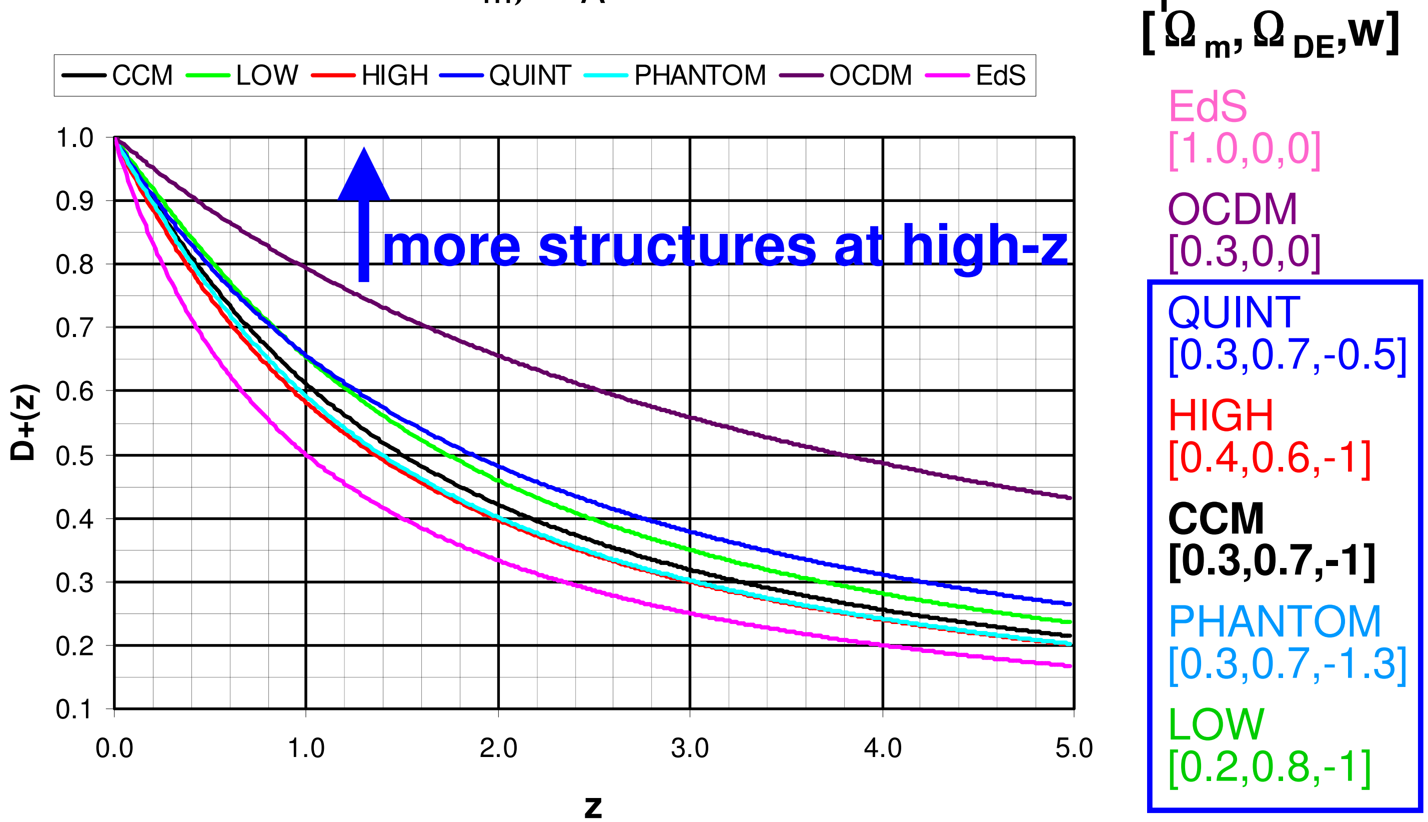
The rate at which structures grow in the universe depends upon the cosmological parameters:

Depend upon the growth factor (linear regime):

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

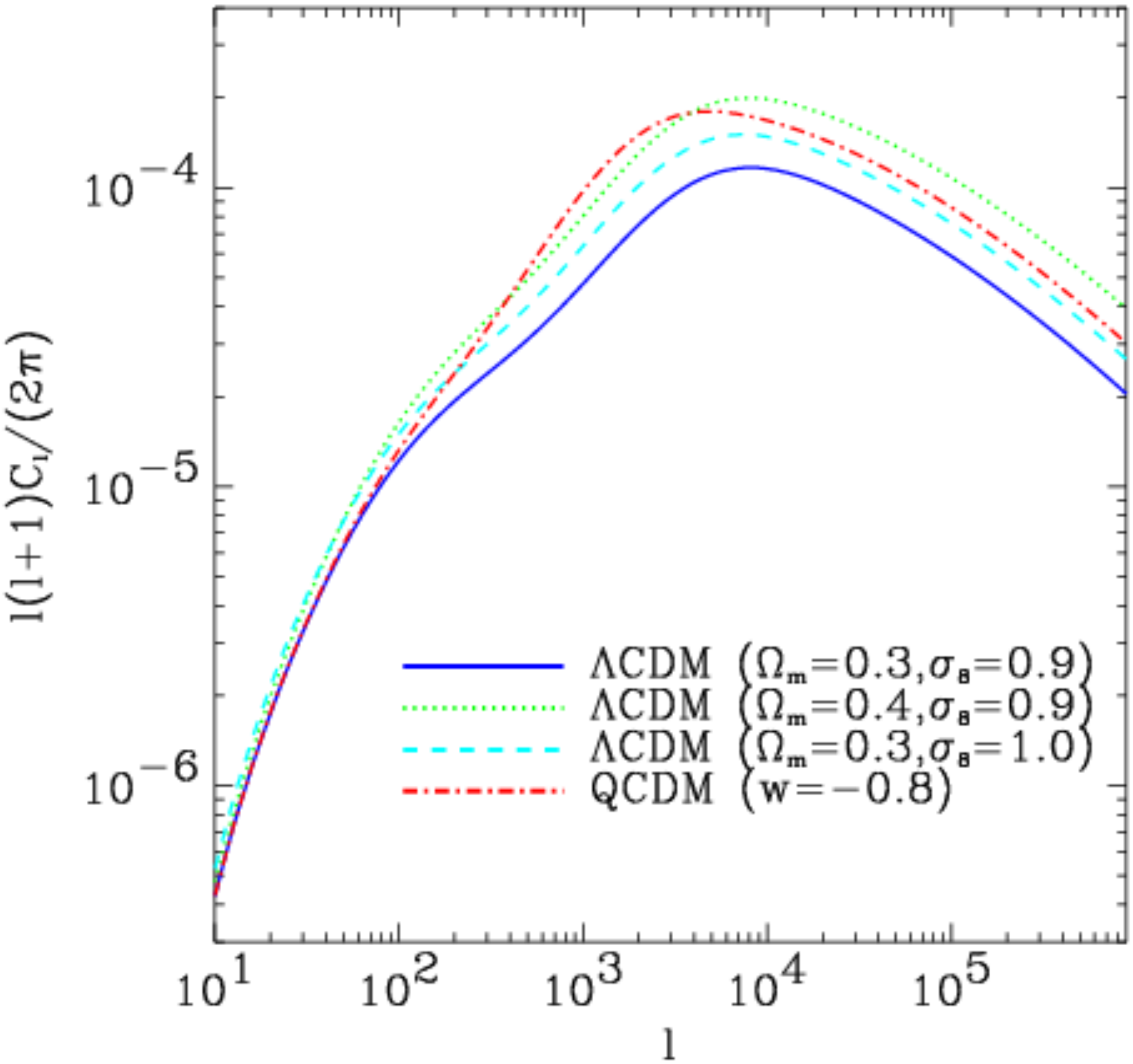
where a is size of universe and Ω_m, Ω_Λ are all evaluated in the past

Growth Factor



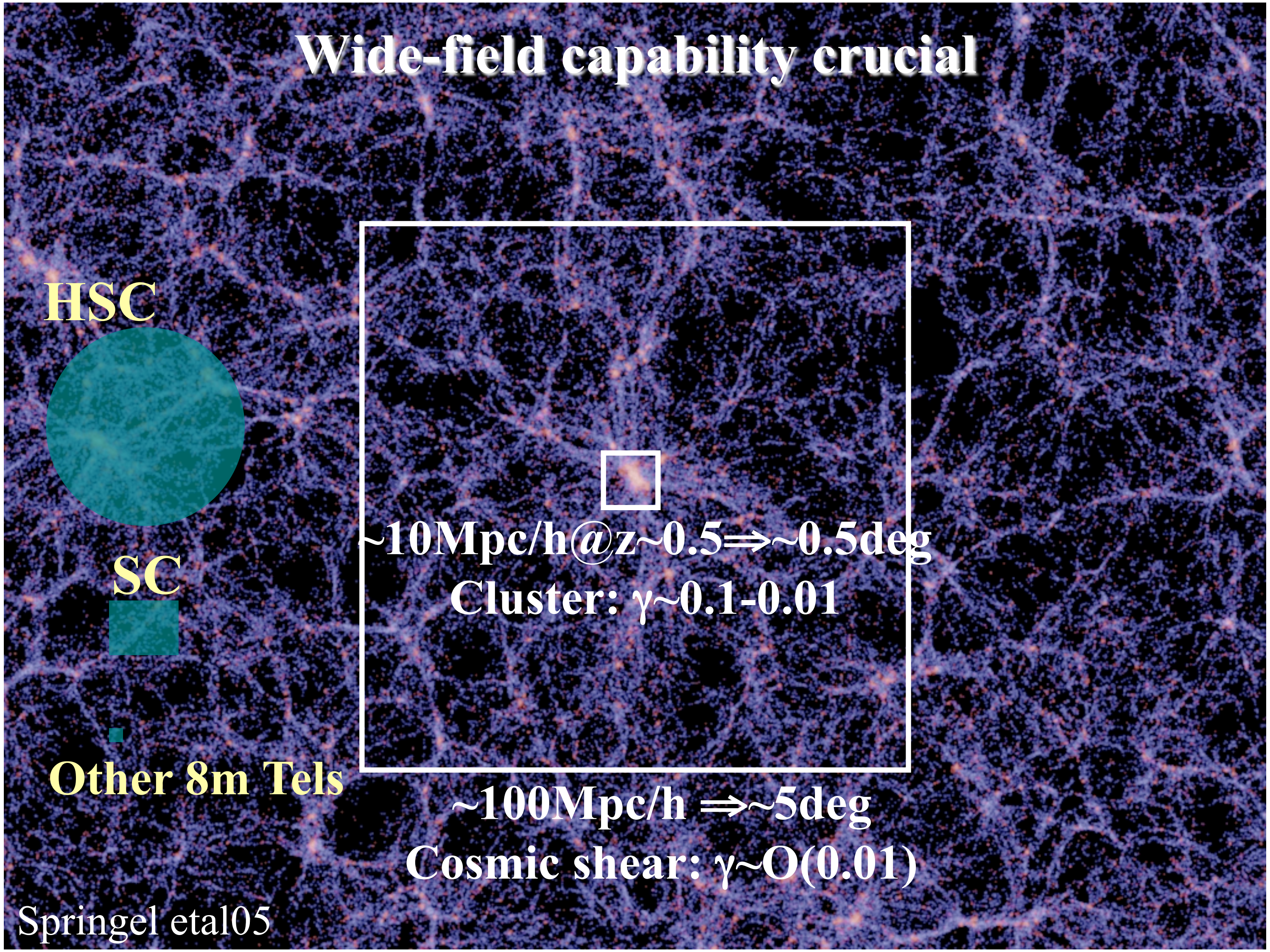
structure grow efficiently when $\Omega = 1$ (since density is closer to 1 where slight overdensities cause collapse)

What does a typical angular power spectrum look like?



Refregier et al.

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



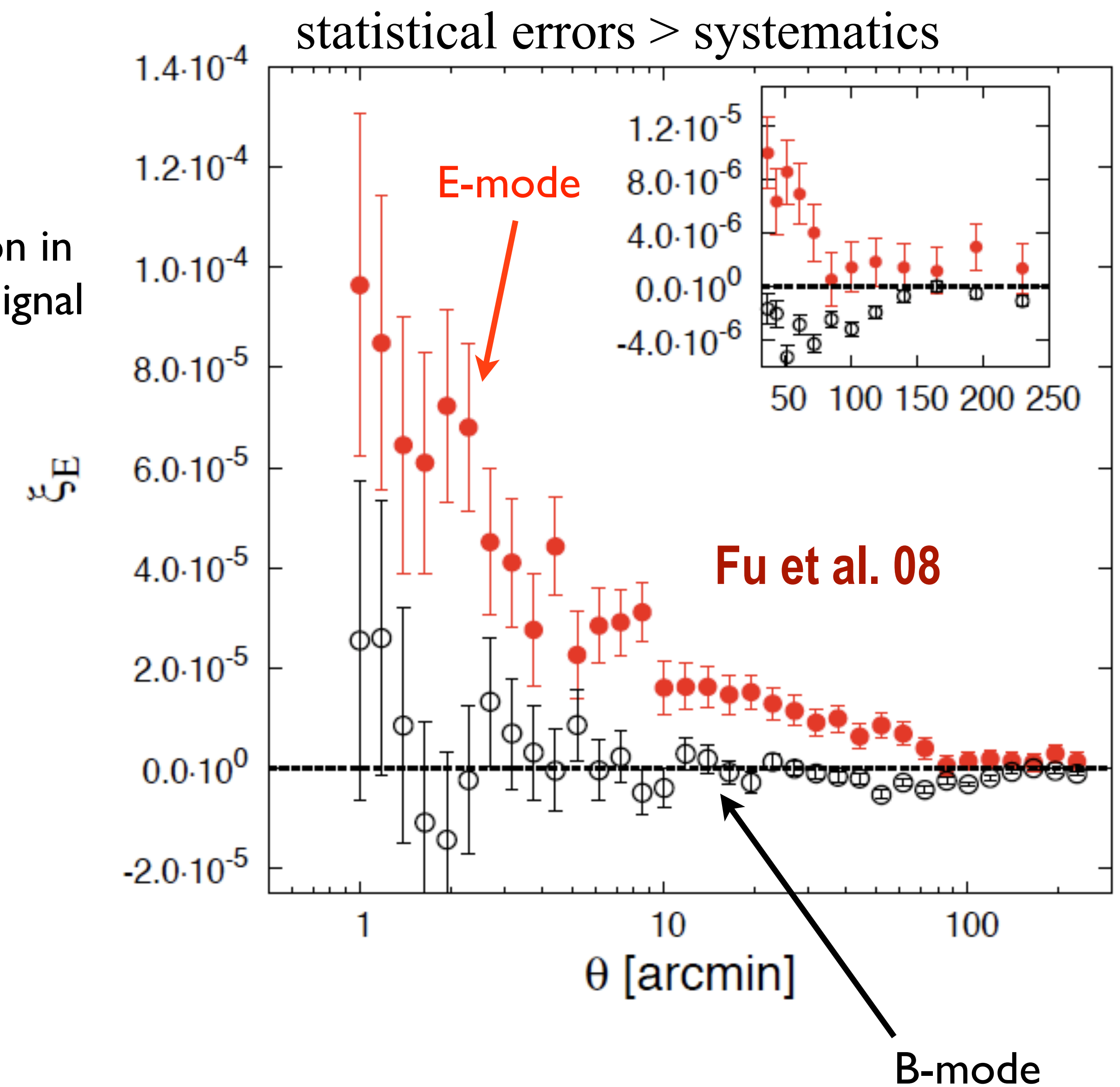
What are the typical characteristics of current wide-field weak-lensing surveys to measure cosmic shear?

Here are a few examples:

- Ongoing survey
  - CFHT Legacy Survey: Ω_s~200 deg^2, n_g~20 arcmin^-2
- Stage-III surveys (5-year time scale)
  - KIDS (2010?-): Ω_s~1500 deg^2, n_g~10 arcmin^-2
  - Pan-STARRS (2010?-): Ω_s~30000 deg^2, n_g~4 arcmin^-2
  - DES (2011-): Ω_s~5000 deg^2, n_g~10 arcmin^-2
  - Subaru (2011-): Ω_s~2000 deg^2, n_g~30 arcmin^-2
- Stage-IV surveys (10-year time scale): *ultimate surveys*
  - LSST (2016?-): Ω_s~20000 deg^2, n_g~50 arcmin^-2
  - SNAP/JEDM (20??-): Ω_s~4000 deg^2, n_g~100 arcmin^-2, +NIR
  - EUCLID (20??-): Ω_s~20000 deg^2, n_g~100 arcmin^-2, +NIR

Here is an example of state of the art work from late 2000s: CFHT WL survey

Correlation in the shear signal



- ~60 sq deg^2 (effective area: ~30 sq. deg^2)
- *i'*_AB~24.5, <z>~0.9
- Calibrate source redshift with the CFHT deep survey and the VVSD
- **~20σ detection,** over a range of few arcminutes to a few degrees
- 170 deg^2 results will be released this year?

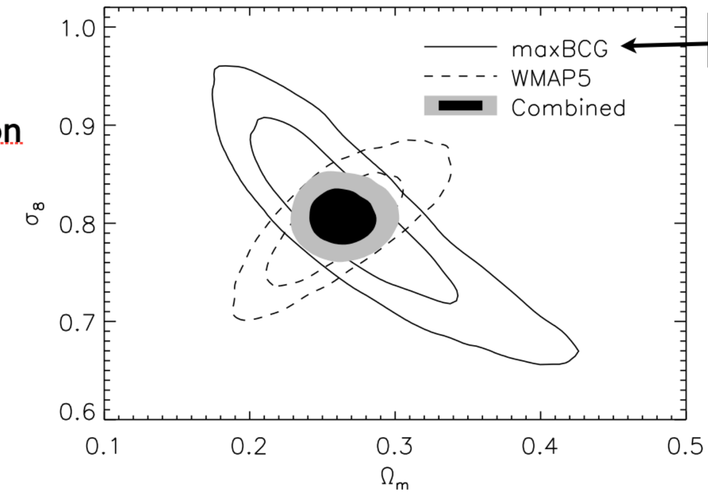
What does these teach us about various cosmological parameters?

These are similar types of constraints as we derive looking at the mass function of galaxy clusters (from last lecture)

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

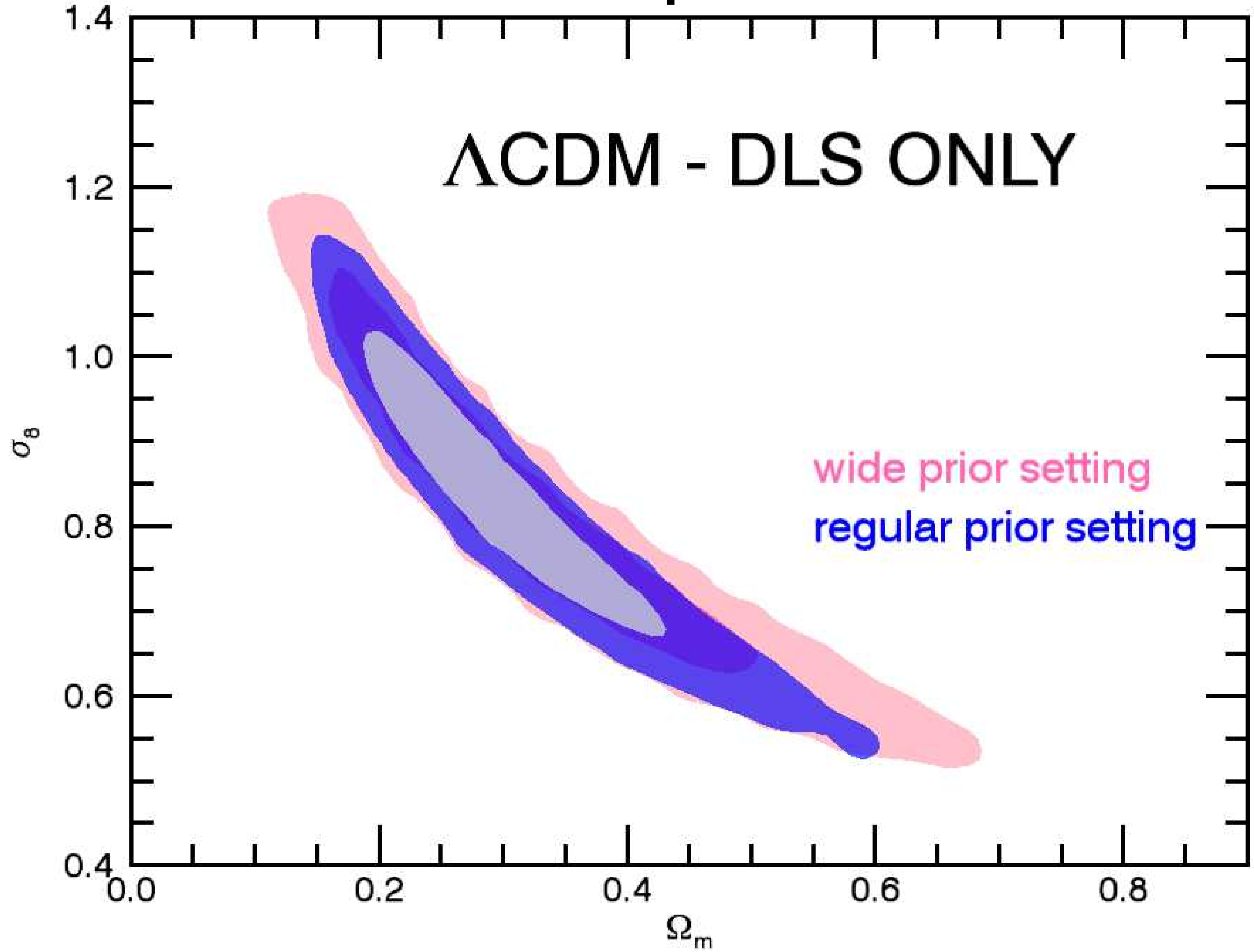
So a higher σ_8, lower Ω_M and lower σ_8, higher Ω_M both match observations

What does these teach us about various cosmological parameters?

One example

DEEP LENS SURVEY
(7 independent
4 deg^2 fields)

Constructed from
2001-2005

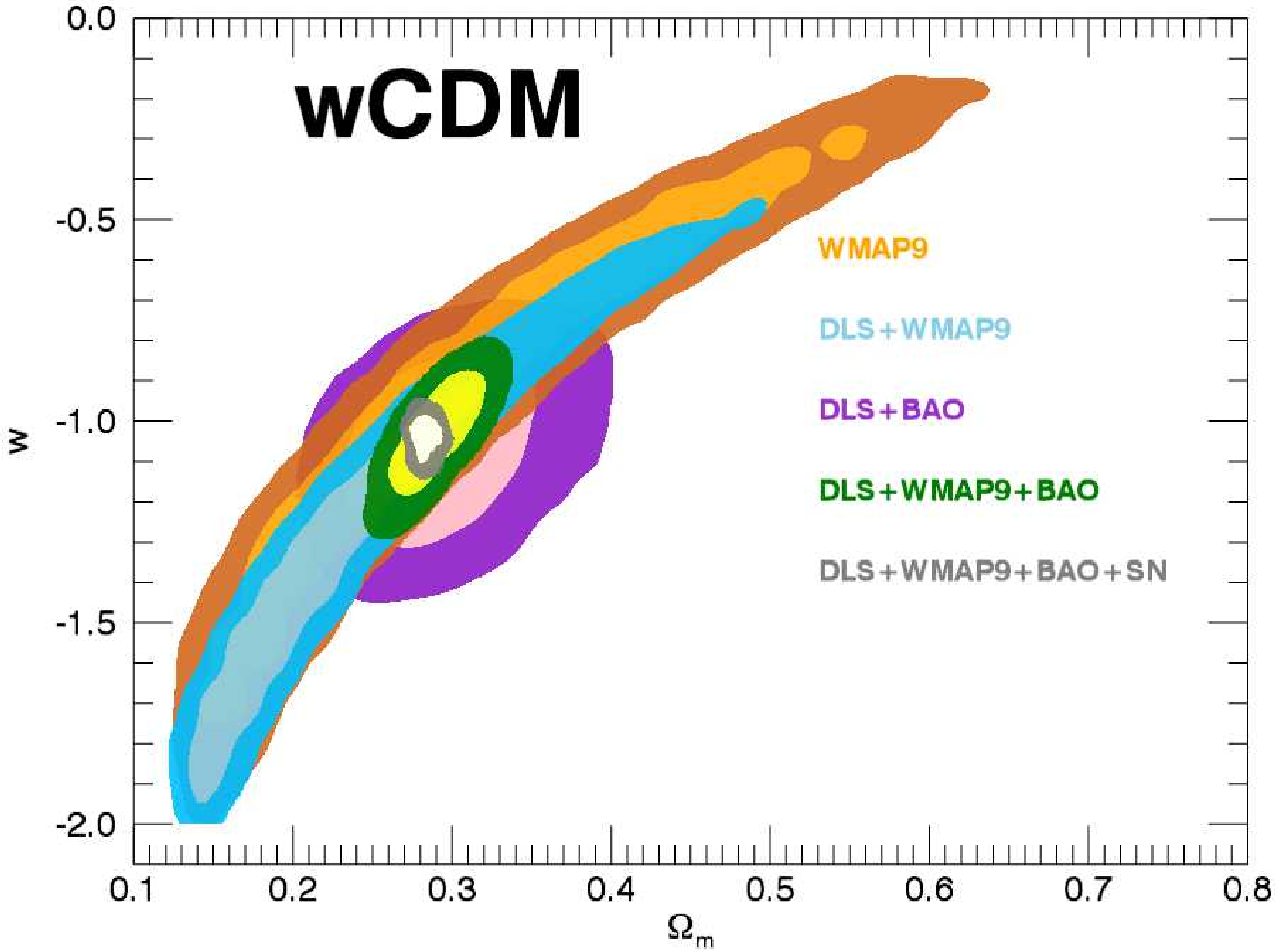


Jee+2016

What constraints can we set on w with this experiment?

DEEP LENS SURVEY
(7 independent
4 deg^2 fields)

Constructed from
2001-2005

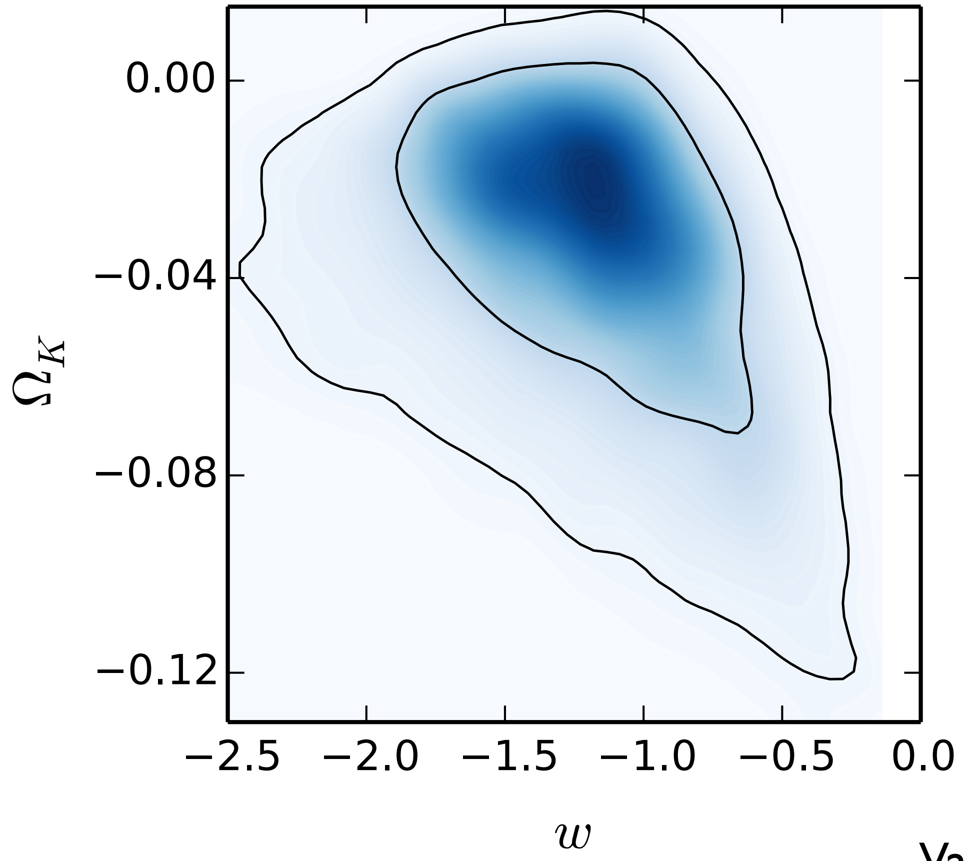


Jee+2016

How do these constraints compare with constraints from other experiments on w?

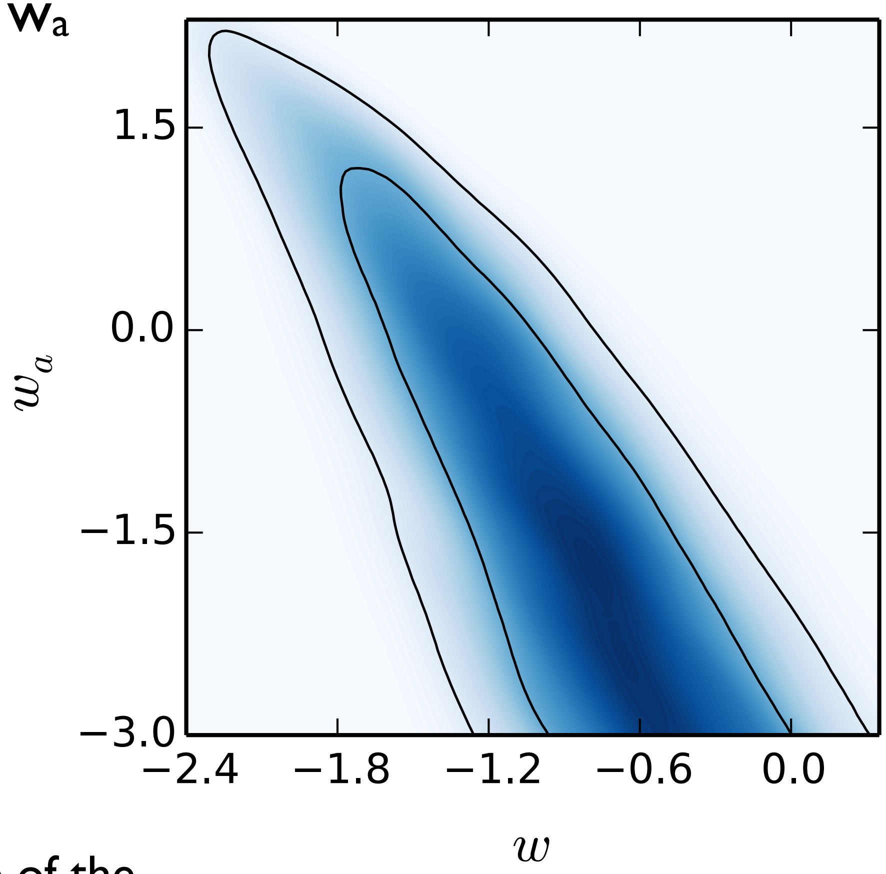
Using state of the art BAO (z~0.55) from BOSS and Planck constraints

"Curvature"



Derivative of w relative to scale factor a

w_a



Value of the w-parameter at z=0

From Gil-Marin+2015

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

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.

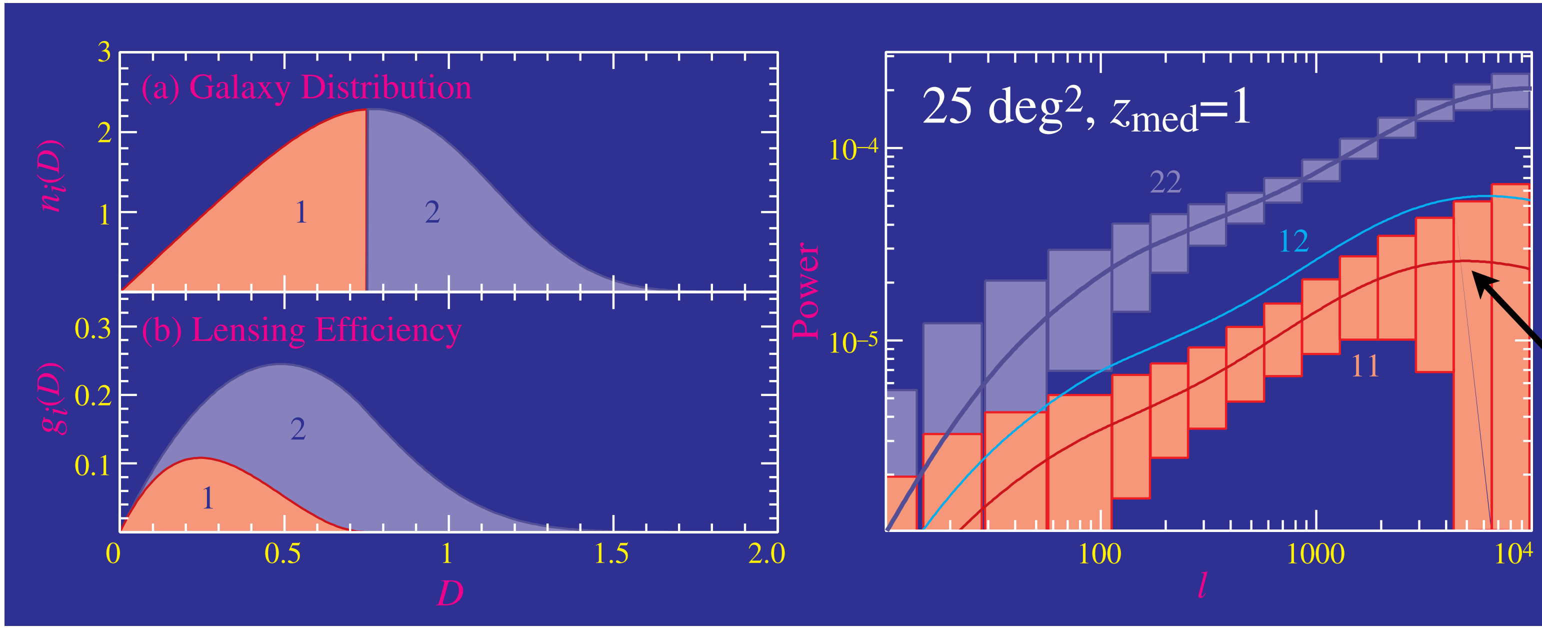
Cosmic Shear: Lots of Potential For Setting the Best Future Constraints

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



Comparing shear of sources in redshift bin #2 with sources in bin #2

Comparing shear of sources in redshift bin #1 with sources in bin #2

Comparing shear of sources in redshift bin #1 with sources in bin #1

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)

New Material for This Week

Dark Energy Experiments

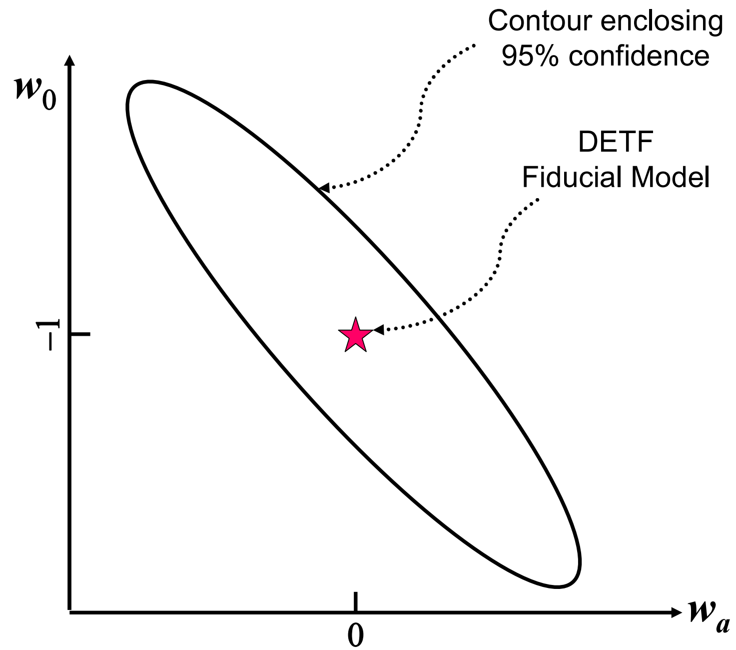
So the game is to determine the w parameter and how it depends on redshift

There are four standard methods:

1. Supernovae Ia
   -- use of standard candles to establish distance-redshift relation
   -- first established existence of dark energy 10 years ago
2. Baryonic Acoustic Oscillations
   -- gives us a standard rod to establish distance-redshift relation and Hubble parameter-redshift relation with low systematics
3. Galaxy Clusters
   -- provide us with sensitive probe of growth of structure
   -- early evidence for low Ω_m
4. Weak Gravitational Lensing
   -- provide us with sensitive probe of growth of structure
   -- powerful technique still in process of realizing full potential

Power of the techniques in constraining dark energy are quantified in terms of the "Figure of Merit"

The <u>DETF figure of merit</u> is the reciprocal of the area of the error ellipse enclosing the 95% confidence limit in the w_0–w_a plane. Larger figure of merit indicates greater accuracy.



The DETF figure of merit is defined as the reciprocal of the area of the error ellipse in the w_0–w_a plane that encloses the 95% C.L. contour. (We show in the Technical Appendix that the area enclosed in the w_0–w_a plane is the same as the area enclosed in the w_p–w_a plane.)

By combining multiple techniques, one can make huge gains in terms of the "Figure of Merit," i.e., constraining both w and w_a.

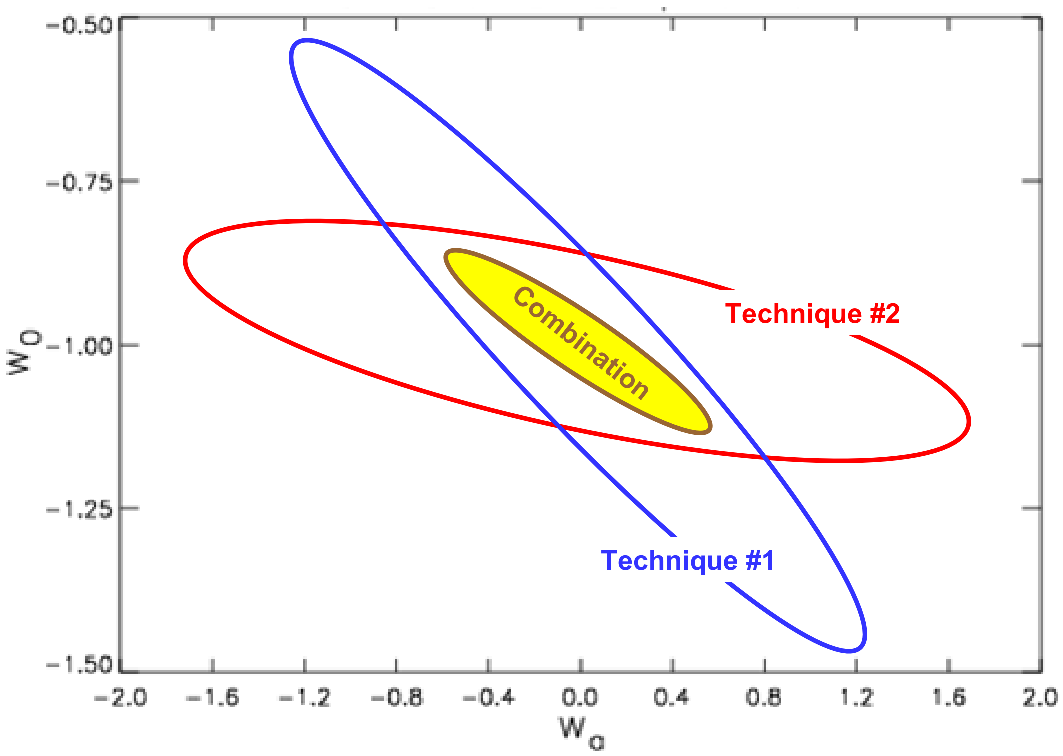


Illustration of the power of combining techniques. Technique #1 and Technique #2 have roughly equal DETF figure of merit. When results are combined, the DETF figure of merit is substantially improved.

These four methods exploit the following measurable-redshift relationships and have the following strengths and weaknesses:

Baryon Acoustic Oscillations

Extra Power in Matter Power Spectrum at Distance of First Acoustic Oscillation

Dark Energy Observables: $D_A(z)$, $H(z)$

Strengths: Least Affected by Systematics

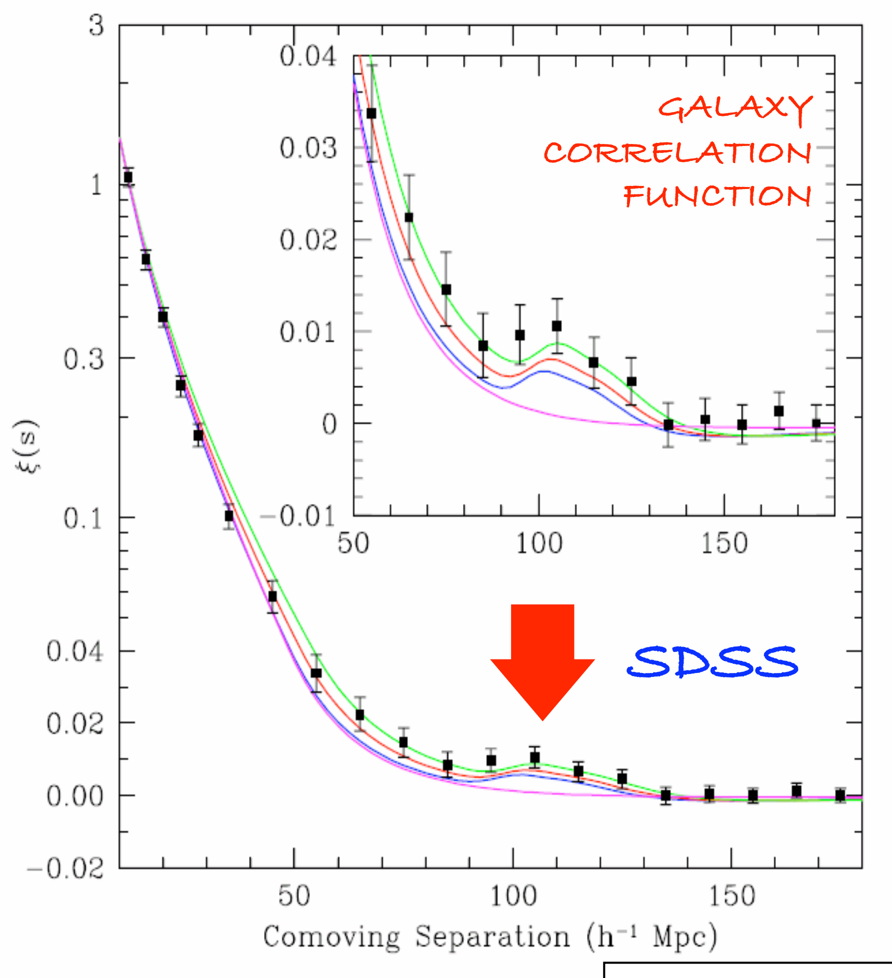
Weaknesses: Most Leverage at z>1 where changes in dark energy model have smallest effect

Sensitive to Errors in the Redshifts of the Sources Probed

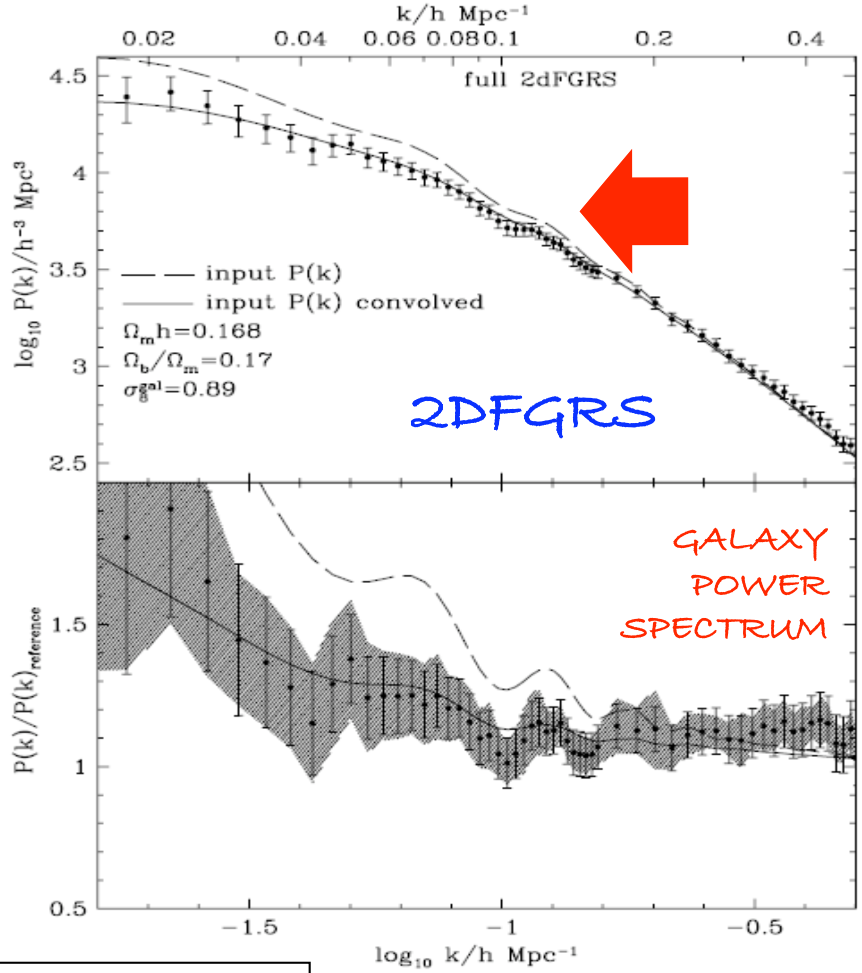
Potential in Large Area Survey: Uncertainties in the redshift estimates for individual sources can largely be overcome by covering large areas of sky

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)

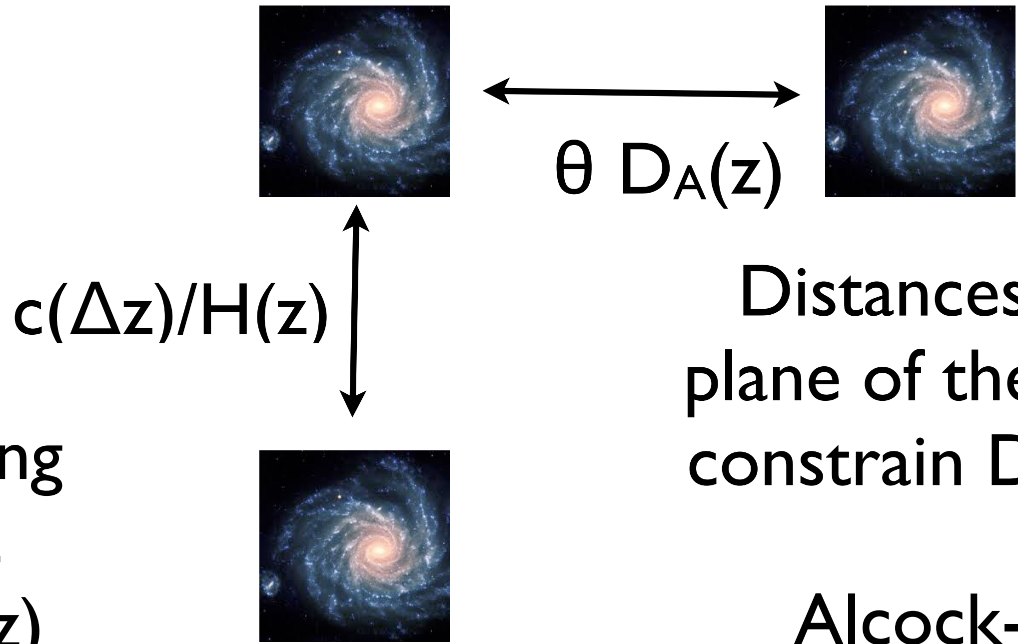


First Measurements

These four methods exploit the following measurable-redshift relationships and have the following strengths and weaknesses:

Baryon Acoustic Oscillations:

Dark Energy Observables: $D_A(z)$, $H(z)$



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

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

telescope

Alcock-Paczynski constraints

both length scales must be the same

These four methods exploit the following measurable-redshift relationships and have the following strengths and weaknesses:

Galaxy Cluster Counting:

Dark Energy Observables: Volume(z), Growth Factor (z)

Strengths: Very sensitive to Growth Factor, Many Different Techniques to Find Clusters

Weaknesses: Substantial Uncertainties in Baryonic Physics Needed to Predict x-ray, SZ, or optical signature of clusters

Potential in Large Area Survey: Useful in further calibrating cosmic shear signal

These four methods exploit the following measurable-redshift relationships and have the following strengths and weaknesses:

Supernovae (SN):

Dark Energy Observables: D_L (z)

Strengths: Most Established Technique, Very Powerful if SN are in fact a standard candle

Weaknesses: Systematic Uncertainties, Possible Evolution in SNe, Light Curve Fitting Uncertainties

Potential in Large Area Survey: Large Number of SNe found in large area surveys should allow further calibration of systematics

These four methods exploit the following measurable-redshift relationships and have the following strengths and weaknesses:

Weak Lensing:

Dark Energy Observables: D_A (z), Growth Factor (z)

Strengths: Technique with Most Power, Allows Constraints on Both Expansion and Growth Rate for Matter Perturbations

Weaknesses: Sensitive to Uncertainties in the Redshifts of the Lensed Galaxies

Need Full Knowledge of the Diversity of Spectra at Intermediate Redshift

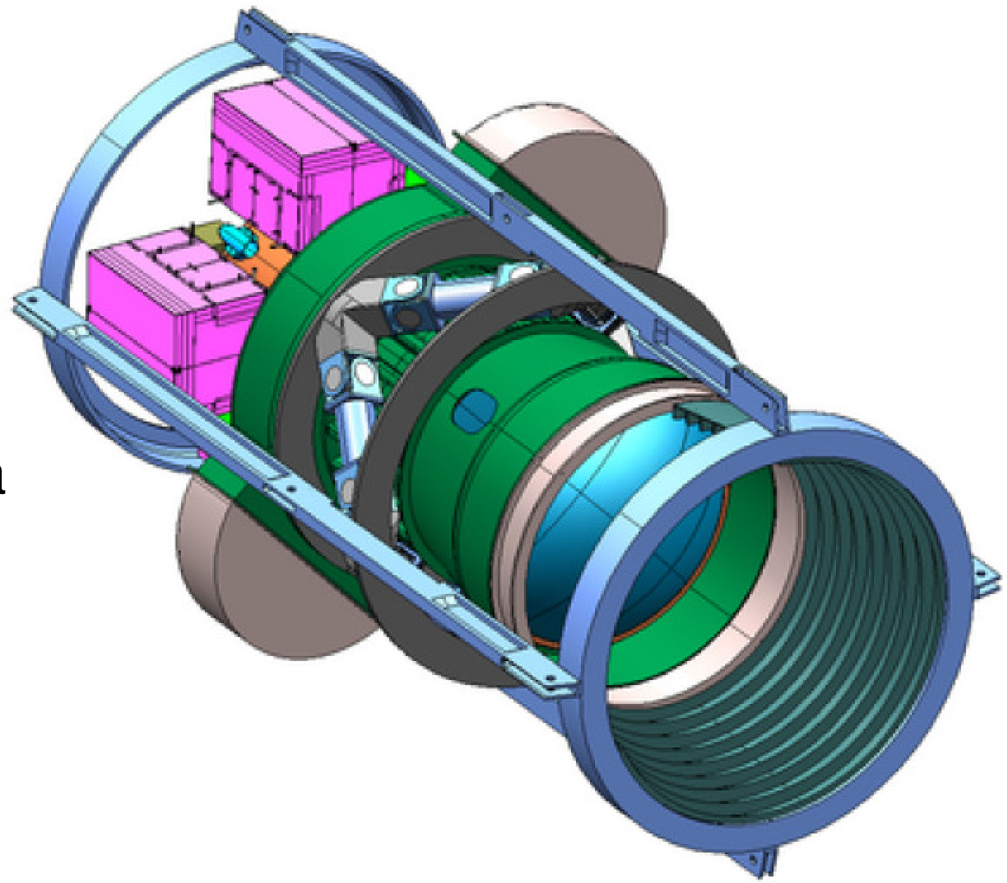
Potential in Large Area Survey: Large Area Observations Should Allow One to Calibrate Out Any Systematics

Overall of Some Important Dark Energy Experiments

Dark Energy Survey (DES)

— KIDS (led here by Koen Kuijken) is similar

- ground based imaging survey at CTIO 4m telescope of Southern region (SZE-survey overlap)
- camera: 520Mpix, 2.2deg^2 FoV
- Executed from 2013 to 2019
- 5,000deg^2 in 4bands: g r i z
- DE probes: GC, BAOs, WL, SNIa
- objects: galaxies, galaxy clusters (with photometric redshifts)
- redshift range: $0<z<1.3$
- DE constraints: σ_w~5-15%



Source: http://www.darkenergysurvey.org/

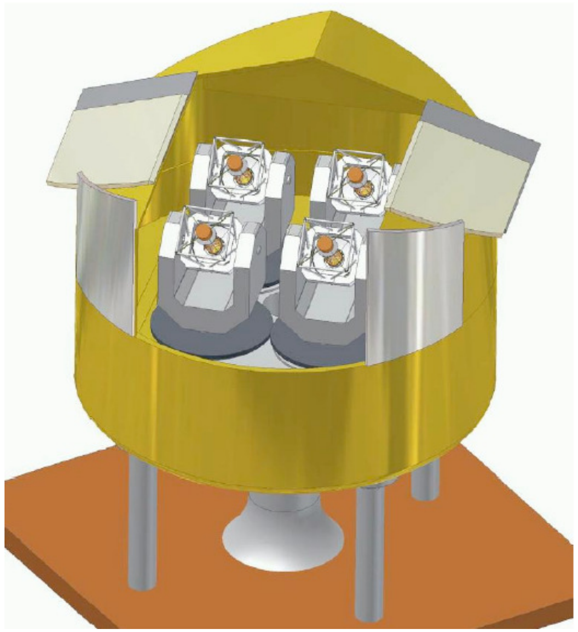
Few examples of more well known DE missions

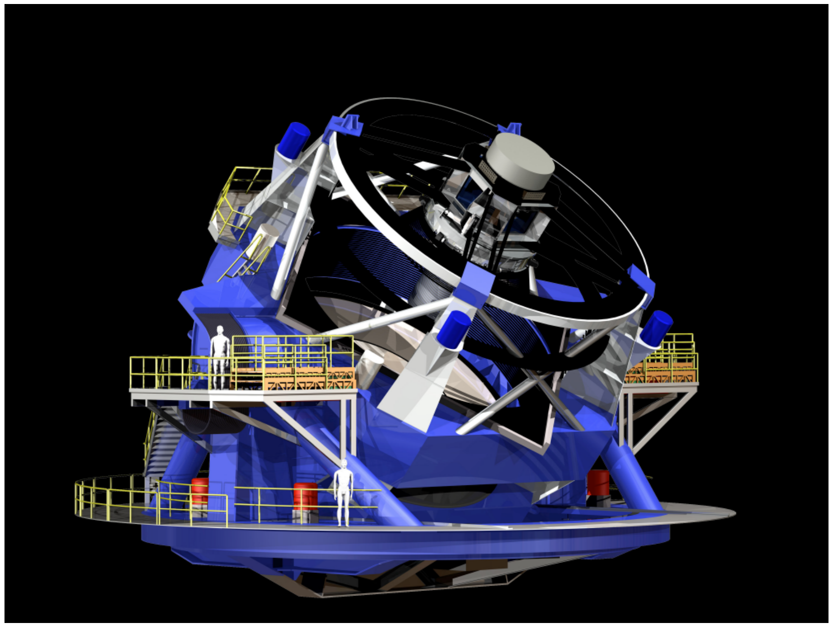
b) Deep half-sky multiband imaging surveys

PanSTARRS4: The Panoramic Survey Telescope and Rapid Response System

LSST: The Large Synoptic Survey Telescope

- start: 2025
- 20000-30,000deg^2 in 6 bands
- DE constraints: $\sigma_w \sim$ few %





Source: http://pan-starrs.ifa.hawaii.edu/public/; http://www.lsst.org/lsst

Vera Rubin Telescope

~~LSST~~ in a Nutshell

VERA C. RUBIN OBSERVATORY

- The LSST is an integrated survey system designed to conduct a decade-long, deep, wide, fast time-domain survey of the optical sky. It consists of an 8-meter class wide-field ground based telescope, a 3.2 Gpix camera, and an automated data processing system.

- Over a decade of operations the LSST survey will acquire, process, and make available a collection of over 5 million images and catalogs with more than 37 billion objects and 7 trillion sources. Tens of billions of time-domain events will be detect and alerted on in real-time.

- The LSST will enable a wide variety of complementary scientific investigations, utilizing a common database and alert stream. These range from searches for small bodies in the Solar System to precision astrometry of the outer regions of the Galaxy to systematic monitoring for transient phenomena in the optical sky. LSST will also provide crucial constraints on our understanding of the nature of dark energy and dark matter.

Summary of High Level Requirements

VERA C. RUBIN OBSERVATORY

Survey Property	Performance
Main Survey Area	18000 sq. deg.
Total visits per sky patch	825
Filter set	6 filters (ugrizy) from 320 to 1050nm
Single visit	2 x 15 second exposures
Single Visit Limiting Magnitude	u = 23.5; g = 24.8; r = 24.4; I = 23.9; z = 23.3; y = 22.1
Photometric calibration	2% absolute, 0.5% repeatability & colors
Median delivered image quality	~ 0.7 arcsec. FWHM
Transient processing latency	60 sec after last visit exposure
Data release	Full reprocessing of survey data annually

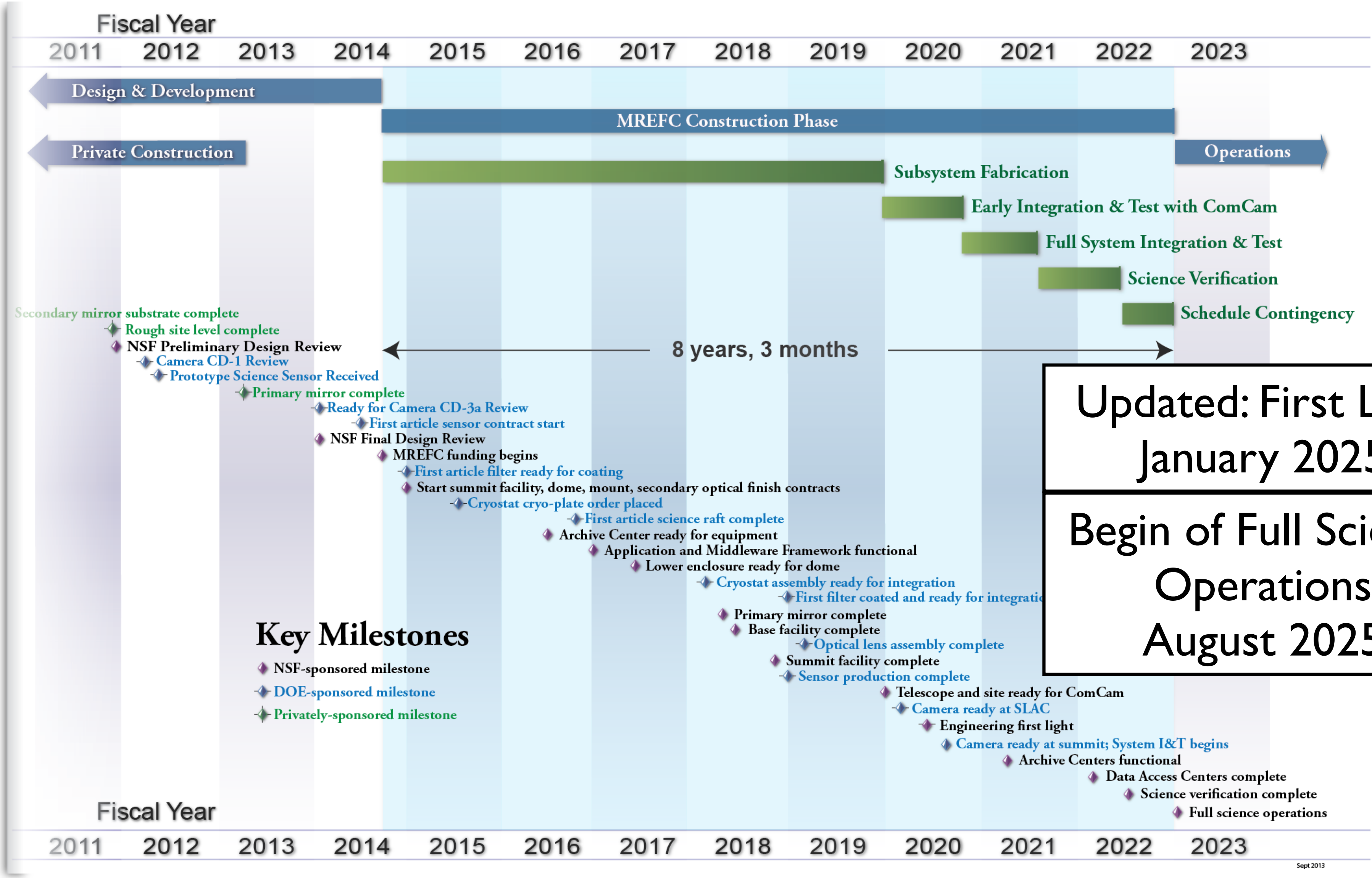
The LSST Science Book

VERA C. RUBIN OBSERVATORY

- **Contents:**
  - Introduction
  - LSST System Design
  - System Performance
  - Education and Public Outreach
  - The Solar System
  - Stellar Populations
  - Milky Way and Local Volume Structure
  - The Transient and Variable Universe
  - Galaxies
  - Active Galactic Nuclei
  - Supernovae
  - Strong Lenses
  - Large-Scale Structure
  - Weak Lensing
  - Cosmological Physics

Dark Energy

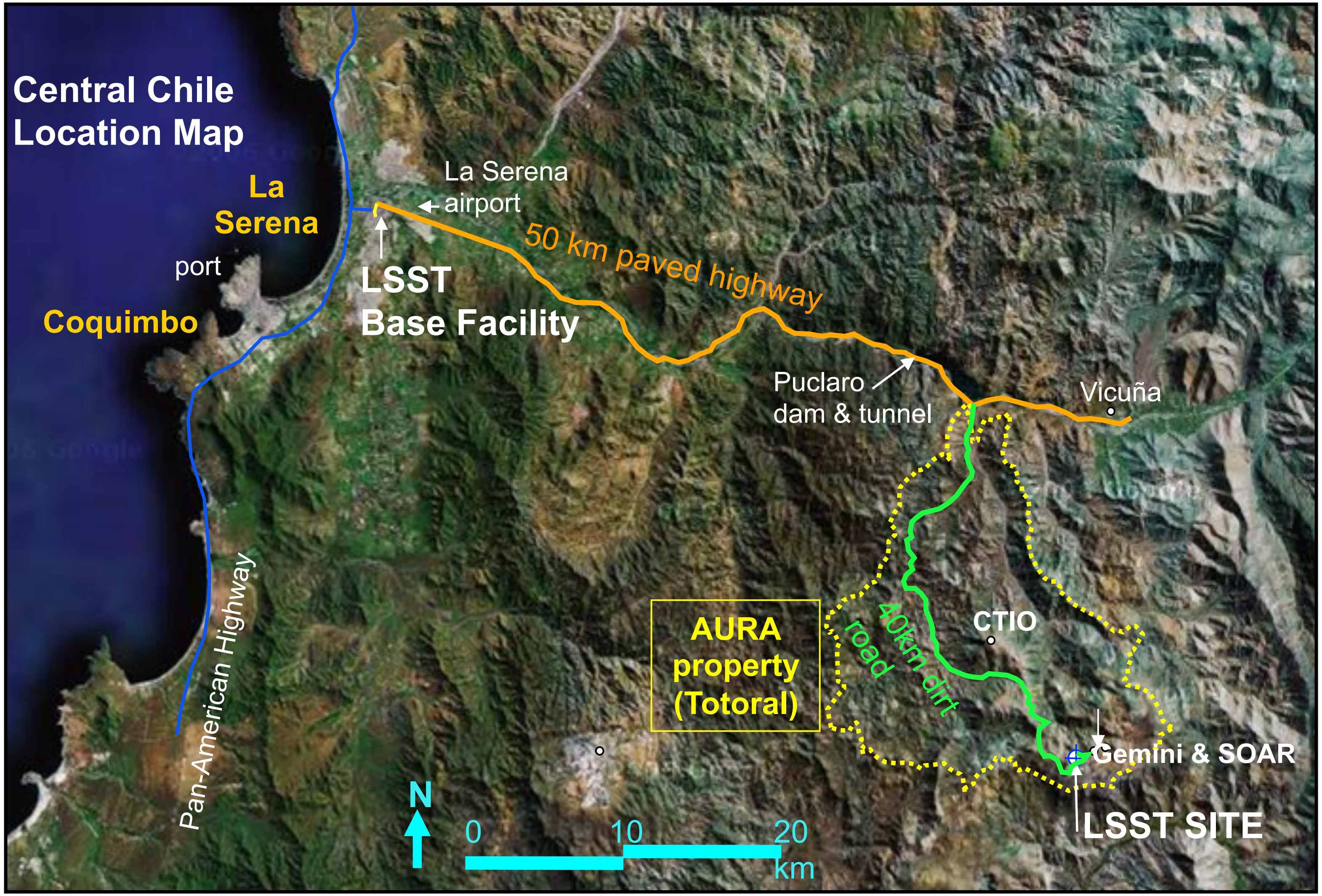
Integrated Project Schedule



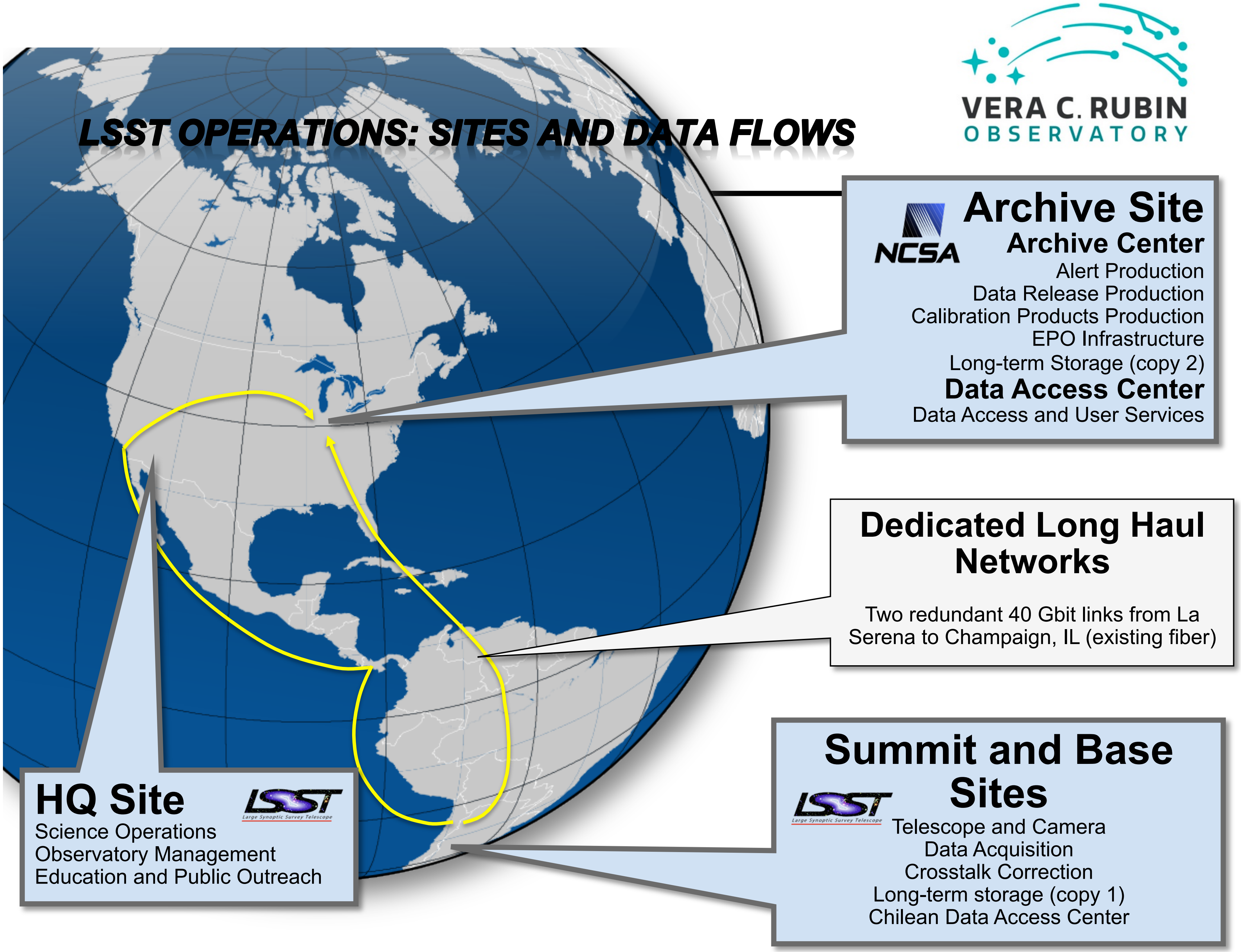
Updated: First Light January 2025

Begin of Full Science Operations August 2025

LSST Will be Sited in Central Chile

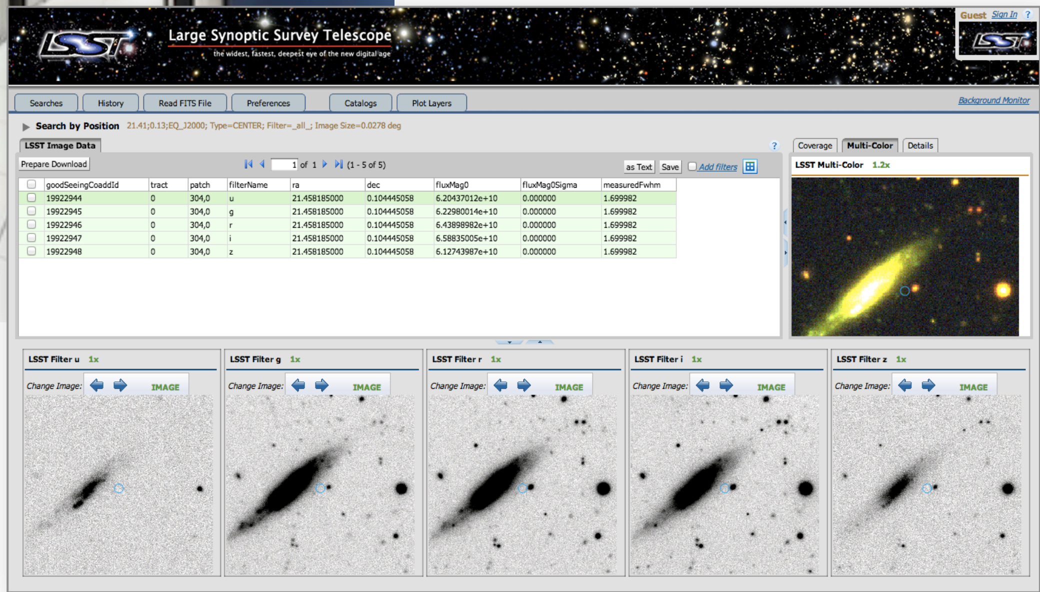


Dome and Facility Design


VERA C. RUBIN
OBSERVATORY
LSST OPERATIONS: SITES AND DATA FLOWS
Archive Site
NCSA
Archive Center
Alert Production
Data Release Production
Calibration Products Production
EPO Infrastructure
Long-term Storage (copy 2)
Data Access Center
Data Access and User Services
Dedicated Long Haul Networks
Two redundant 40 Gbit links from La Serena to Champaign, IL (existing fiber)
Summit and Base Sites
LSST
Telescope and Camera
Data Acquisition
Crosstalk Correction
Long-term storage (copy 1)
Chilean Data Access Center
HQ Site
LSST
Science Operations
Observatory Management
Education and Public Outreach

Ultimate LSST Deliverable: Reduced Data Products

*A petascale supercomputing system at the **LSST Archive** (at NCSA) will process the raw data, generating reduced image products, time-domain alerts, and catalogs.*



***Data Access Centers** in the U.S. and Chile will provide end-user analysis capabilities and serve the data products to LSST users.*

LSST From the User's Perspective

- A stream of ~10 million time-domain events per night, detected and transmitted to event distribution networks within 60 seconds of observation.
- A catalog of orbits for ~6 million bodies in the Solar System.

Level 1

- A catalog of ~37 billion objects (20B galaxies, 17B stars), ~7 trillion observations ("sources"), and ~30 trillion measurements ("forced sources"), produced annually, accessible through online databases.
- Deep co-added images.

Level 2

- Services and computing resources at the Data Access Centers to enable user-specified custom processing and analysis.
- Software and APIs enabling development of analysis codes.

Level 3

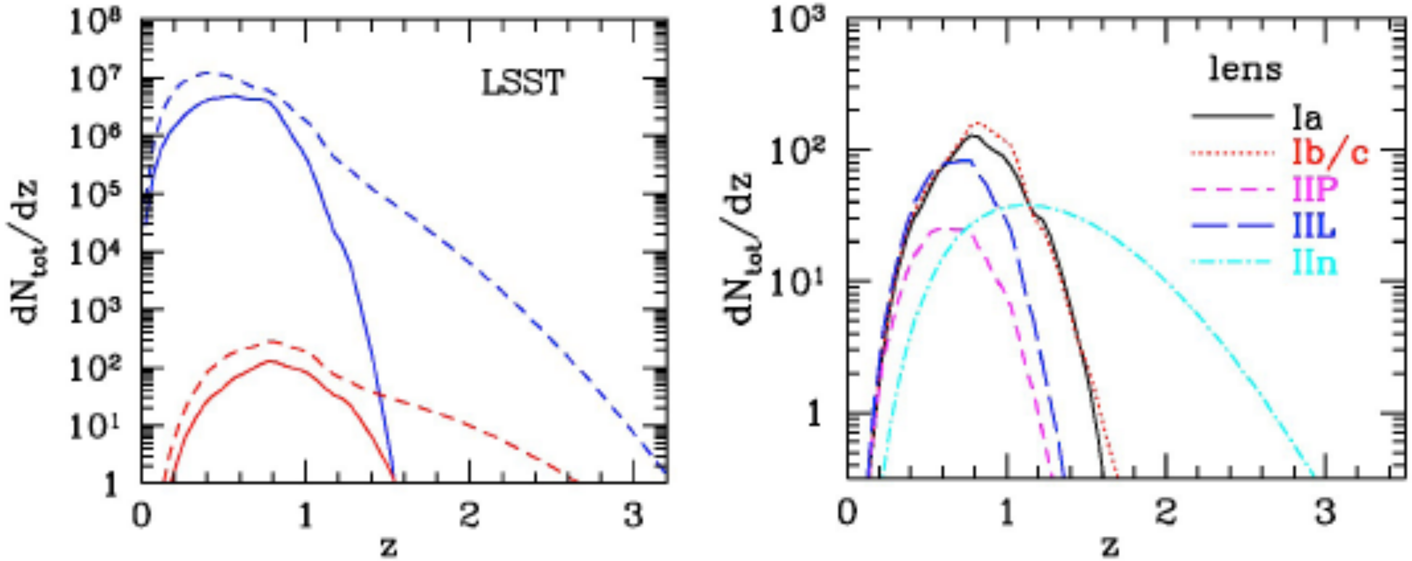
Galaxies

- LSST will be a unique tool for studies of galaxy formation and galaxy properties.
- The database will include photometry for 10^{10} galaxies from the Local Group to $z > 6$.
- We will have 6-band photometry for 4×10^9 galaxies.
- Key diagnostic tools will include:
  - Luminosity functions
  - Color-luminosity relations
  - Size-luminosity relations
  - Quantitative morphological classifications
  - Dependence on environment

Supernovae

- Roughly 10^3 supernovae have been discovered throughout the history of all astronomy.
- LSST will find > 10^7 over its ten-year duration, spanning a broad redshift range, with precise, uniform calibration.
- This will undoubtedly revolutionize the field, allowing large samples for studies of systematic effects and additional parametric dependences.
- ~ 10^5 SNe Ia will be found in the "deep drilling fields" with well-measured lightcurves in all six colors. This will be an excellent sample for precision cosmology.
- The large sample size will also allow us (for the first time) to conduct SN Ia cosmology experiments as a function of direction in the sky, providing stringent tests of the fundamental cosmological assumptions of homogeneity and isotropy.

Sample Size Estimates: Lensed SNe



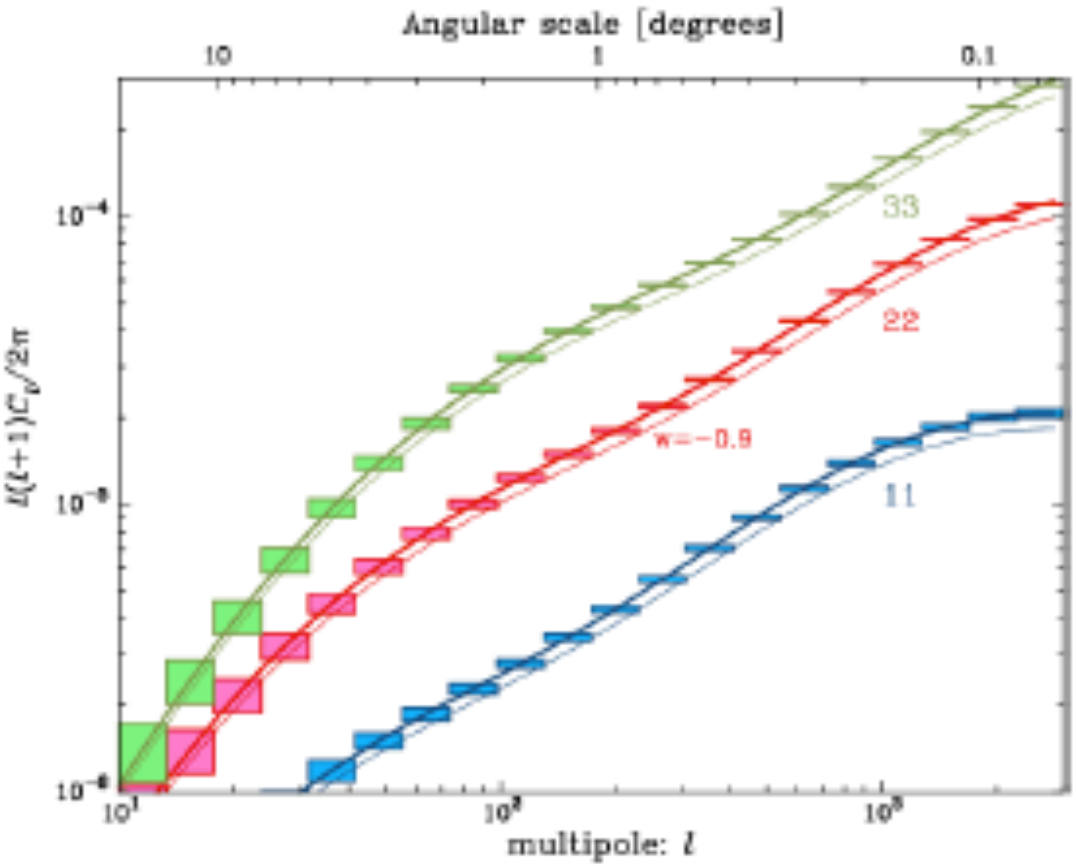
Precision Cosmology: Constraints on Dark Energy

- LSST will probe the nature of Dark Energy via a distinct set of complementary probes:
  - SNe Ia's as "standard candles"
  - Baryon acoustic oscillations as a "standard rulers"
  - Studies of growth of structure via weak gravitational lensing
  - Studies of growth of structure via clusters of galaxies

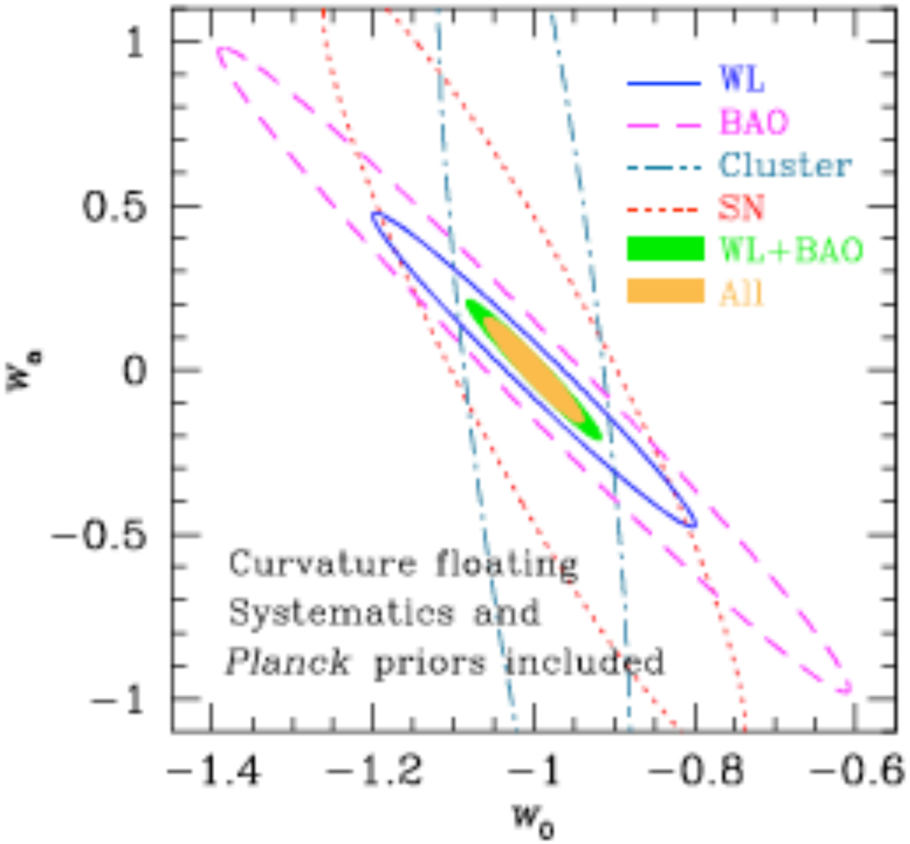
- In conjunction with one another, this rich spectrum of tests is crucial for reduction of systematics and dependence on nuisance parameters.

- These tests also provide interesting constraints on other topics in fundamental physics: the nature of inflation, modifications to GR, the masses of neutrinos.

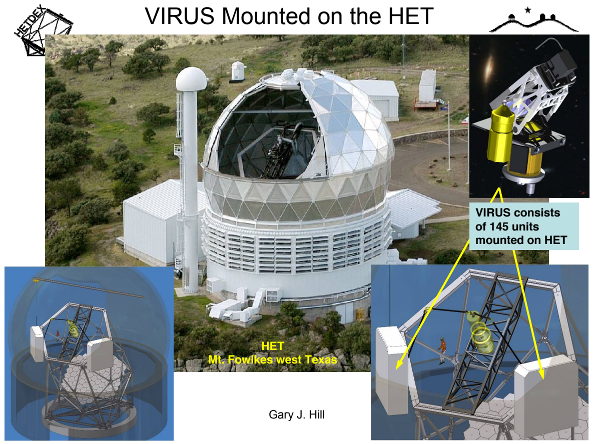
Shear Power Spectra as a Function of Redshift



Separate and Joint Constraints on the Dark Energy Equation of State



HETDEX



The Hobby-Eberly Telescope Dark Energy Experiment

Overview

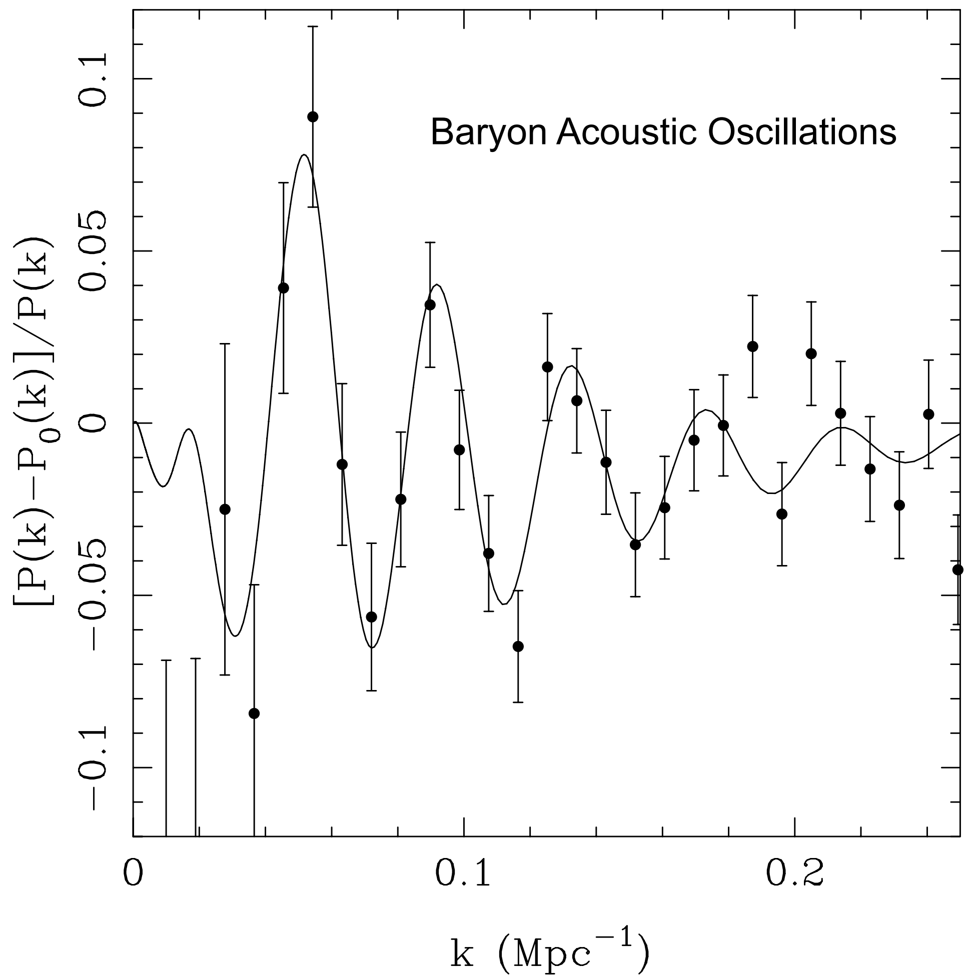
- Two observational approaches to make progress on DE
  - Get the tightest possible constraints at low redshift where effect of DE is stronger
  - Go to higher redshift where we can measure the evolution or verify that w(z) = -1
  - Both approaches are needed
- Almost all projects are focused at z<1.5
  - Due to obvious observational constraints
- Spectroscopic BAO at high redshift
  - One method to measure H(z) directly as well as $D_A(z)$
  - Only method that can be applied at z>2
  - Method with smallest systematic worries (particularly at z>1.5)
- Aims of HETDEX
  - Measure the expansion rate to percent accuracy at z>2
  - Provide a direct constraint on the density of DE at z>2
  - Provide the best measure of curvature

Executed from 2021 to 2024

HETDEX Approach

- Survey duration 3 calendar years
- 1 million tracers in 8 cubic Gpc volume
  - Total survey area 400 sq. degrees with redshift range 1.9 < z < 3.8
  - goal 1.5 million in 650 sq. deg
- Constraints (3 year)
  - H to 1.5-2%, D_A to 1-1.5%
  - Depending on tracer bias
- Ly-α emitting galaxies
  - Numerous
  - Easily detected with integral field spectrograph
- 145 integral field spectrographs, known as VIRUS
  - 42,000 spectra per exposure

Realization of HETDEX



Measuring Dark Energy Evolution

Dark energy, or its equation of state w(z), is mathematically well defined. It enters into the cosmological equations as:

$$H(z) = h\sqrt{\Omega_m(1+z)^3 + \Omega_X \exp\left[3\int_0^z \frac{1+w(z')}{1+z'}dz'\right] + \Omega_k(1+z)^2}$$

Expansion rate **Matter term** **Dark Energy term and w represents history** **Curvature term**

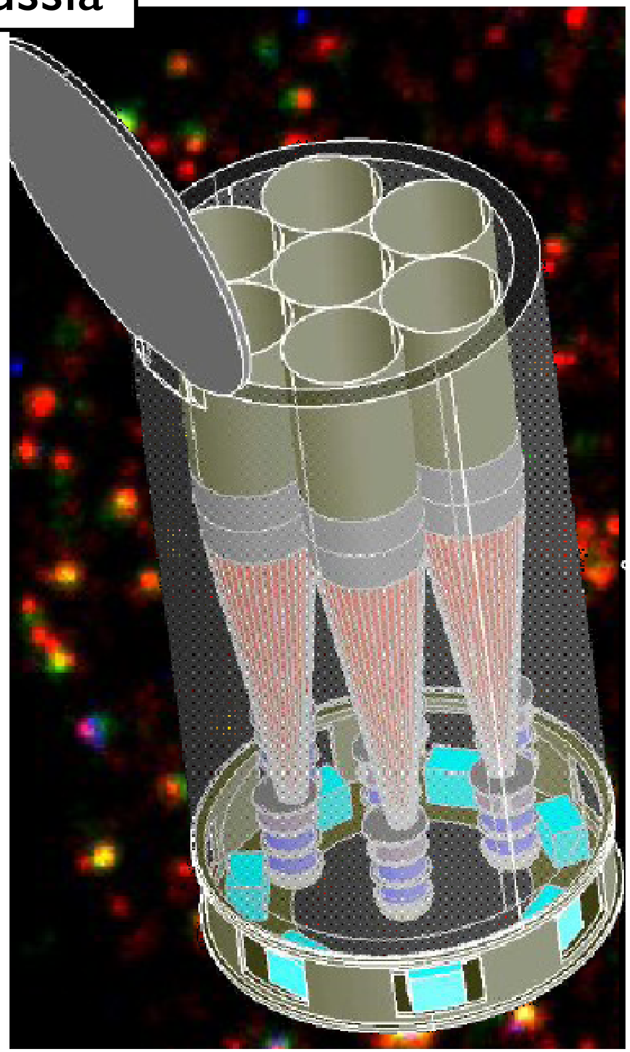
- With priors on $\Omega_M h^2$ from Planck and 3% on Ho we can achieve
  - $\sigma_H/H \sim 1\%$ at z~3 to directly detect w=-1 constant DE at 3-σ
- D_A(z=1089) will be constrained to sub-% accuracy by Planck
  - $\sigma_{DA}/D_A \sim 1\%$ at z~3 to measure curvature to 0.2% (e.g. Knox 2006)

Few examples of more well known DE missions

c) eROSITA: the next X-ray survey telescope

Collaboration between Germany / Russia

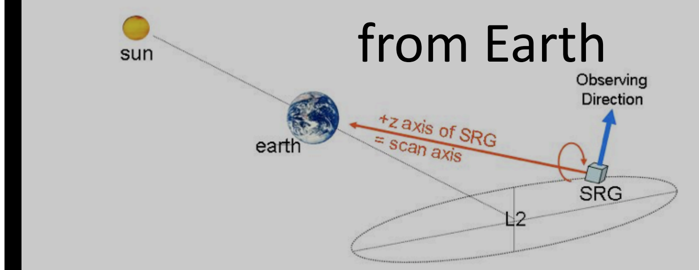
- space-based X-ray cluster survey
- currently build at MPE in Garching
- start: 2019
- all sky coverage
- DE probes: GC, BAOs
- objects: 100,000 galaxy clusters
- redshift range: $0<z<1.5$
- DE constraints: σ_w~5%
- requires large ground-based follow-up program for identification and redshifts



Note: E-ROSITA ceased operations after the beginning of the Ukraine invasion in Feb 2022. It had completed 4 of 8 all sky surveys. Analysis is ongoing.

The (Near) Future:
eROSITA ~10^5 X-Ray Clusters

1.5 million km from Earth

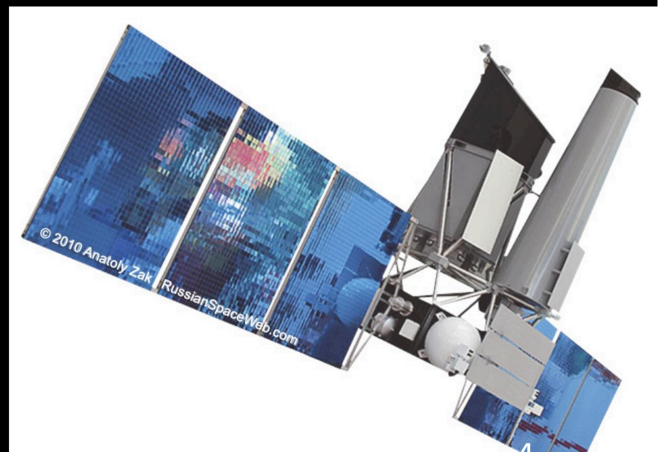


From Baikonur to L2 orbit

Zenit-2SB rocket
Fregat booster

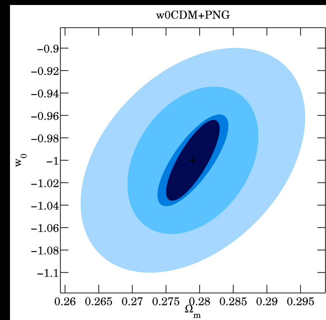
Talks P. Predehl, A. Merloni

Spektr-RG mission
Navigator platform
ART-XC / *eROSITA*

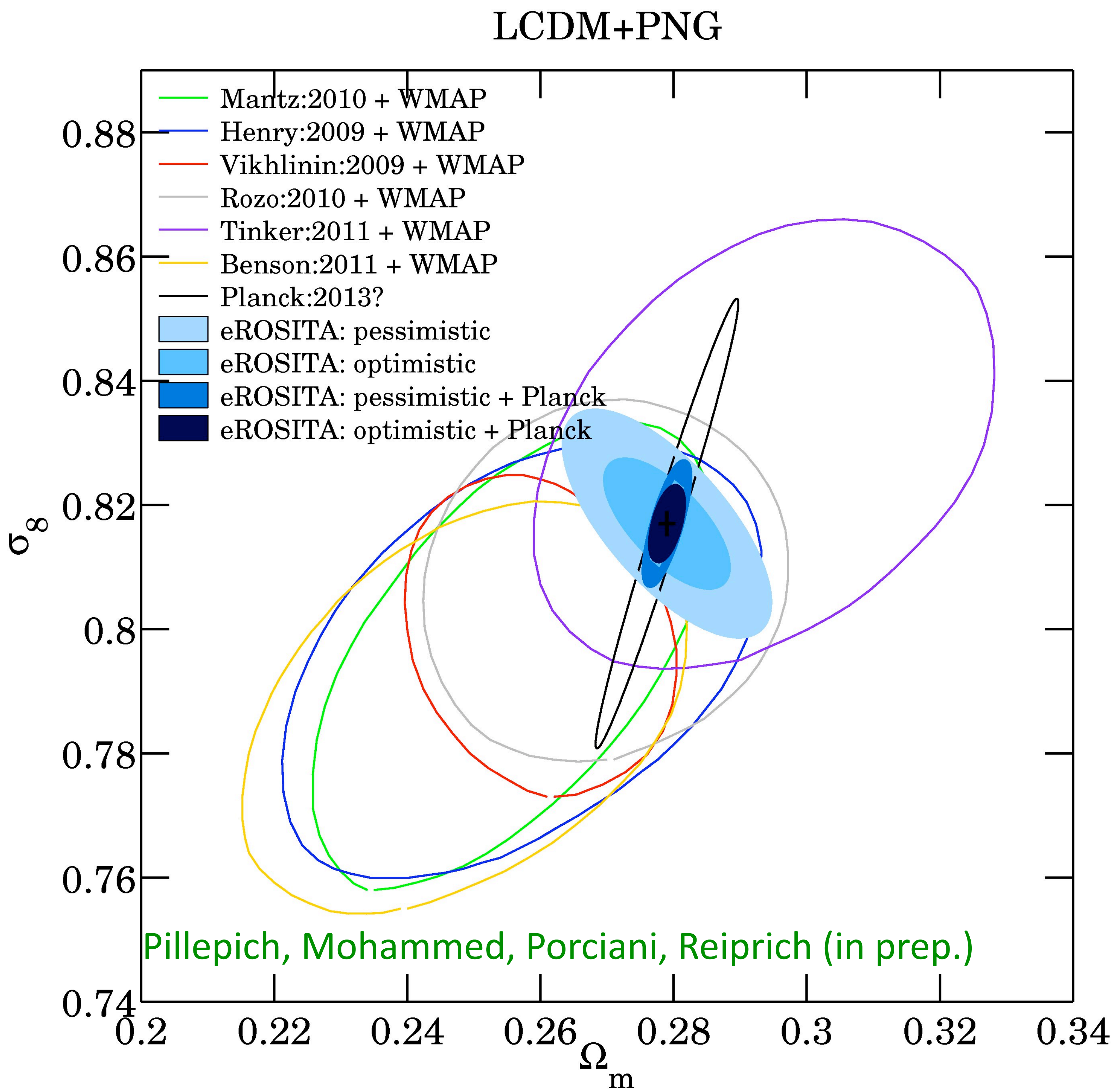


Projected Cosmological Constraints

- *eROSITA*-specific forecasts, taking into account photons registered at detector; assume that clusters get detected if at least 50 source photons received.
- Include cluster physics; scatter in L_X–M relation accounted for, fit scaling relation parameters simultaneously with cosmology ("self-cal").

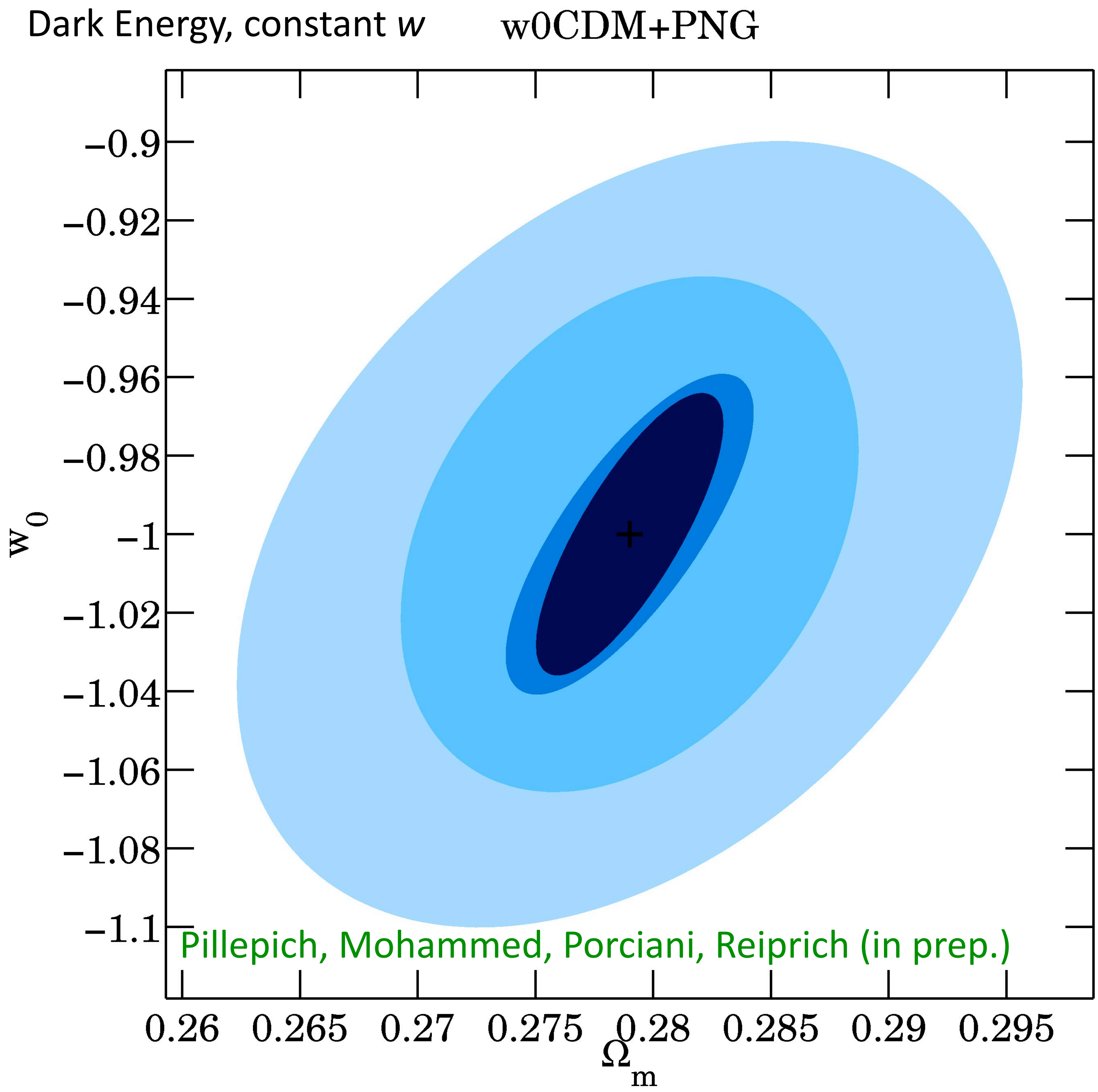


- Take into account expected redshift uncertainty.
- Apply two cosmological tests simultaneously; evolution of (i) cluster mass function and (ii) angular clustering.
- Several assumptions, e.g., hardware works, flat Universe, fiducial cosmology and L_X–M relation, redshifts, one sky for all, ….



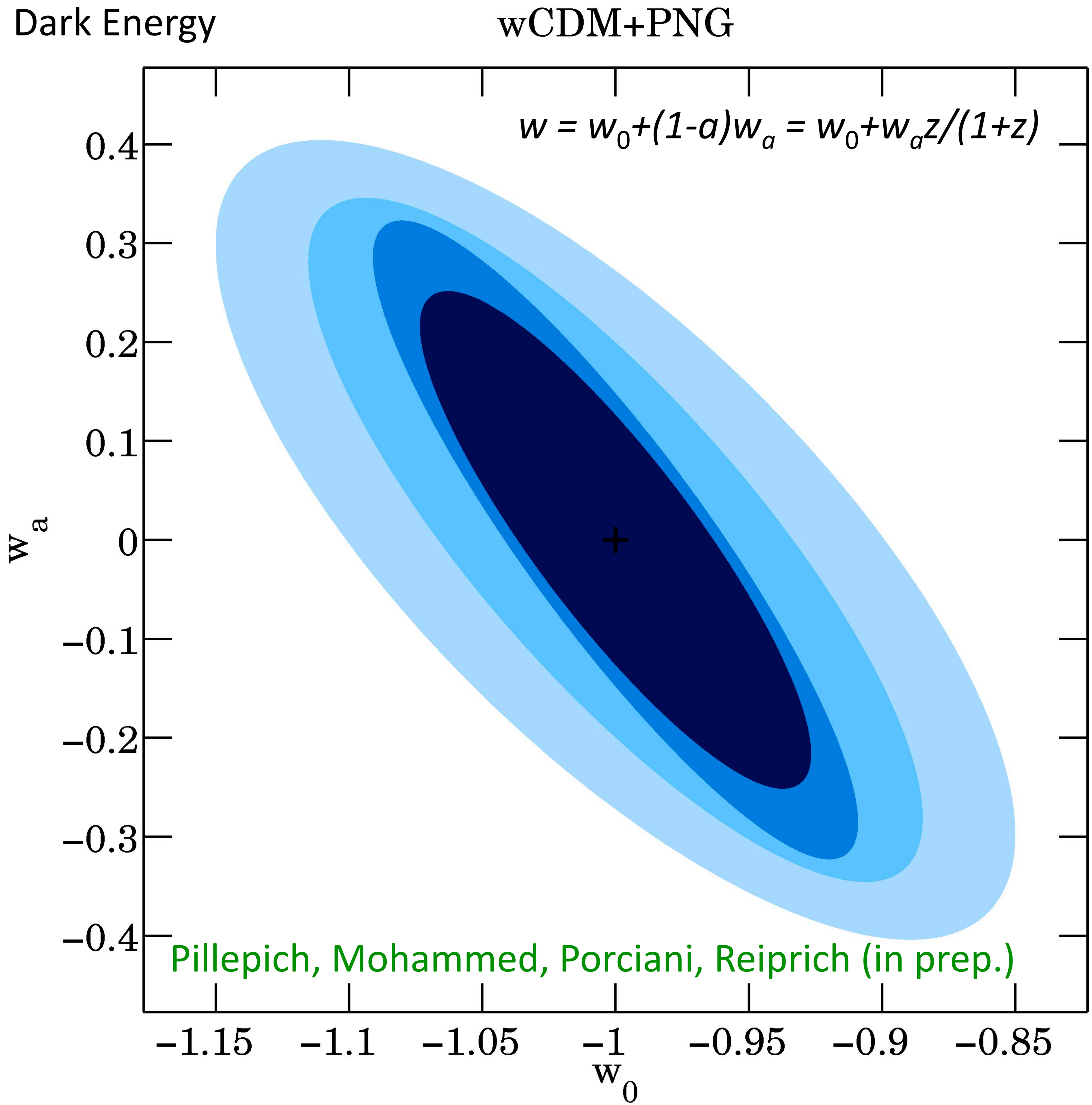
See also Pillepich et al. 2012; Merloni et al. (arXiv:1209.3114)

Dark Energy, constant *w*



See also Pillepich et al. 2012; Merloni et al. (arXiv:1209.3114)

Dark Energy



See also Pillepich et al. 2012; Merloni et al. (arXiv:1209.3114)

eROSITA Compared to DES and Euclid

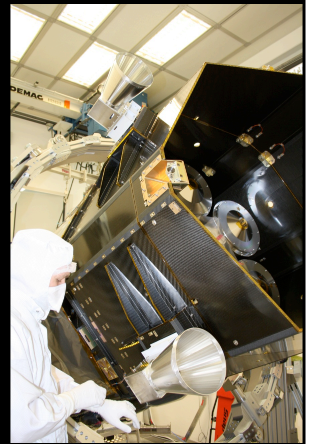
Data (Stage IV)	Redshifts	Prior Scenario	Model	$\Delta f_{\rm NL}^{\rm local}$	$\Delta\sigma_8$	$\Delta\Omega_{\rm m}$	Δw_0	Δw_a	$\text{FoM}^{\rm DEFT,1\sigma}$
eROSITA	photo-z	Pessimistic	LCDM+PNG	8.1	0.012	0.0101	-	-	-
eROSITA	spectro-z	Optimistic	LCDM+PNG	6.4	0.007	0.0060	-	-	-
eROSITA + Planck	photo-z	Pessimistic	LCDM+PNG	6.5	0.006	0.0021	-	-	-
eROSITA + Planck	spectro-z	Optimistic	LCDM+PNG	5.0	0.004	0.0015	-	-	-
eROSITA	photo-z	Pessimistic	w0CDM+PNG	8.2	0.016	0.0109	0.066	-	-
eROSITA	spectro-z	Optimistic	w0CDM+PNG	6.6	0.009	0.0063	0.043	-	-
eROSITA + Planck	photo-z	Pessimistic	w0CDM+PNG	6.9	0.007	0.0034	0.026	-	-
eROSITA + Planck	spectro-z	Optimistic	w0CDM+PNG	5.6	0.005	0.0025	0.023	<1%, <3%	-
eROSITA	photo-z	Pessimistic	wCDM+PNG	8.2	0.018	0.0120	0.098	0.27	57.4
eROSITA	spectro-z	Optimistic	wCDM+PNG	6.6	0.011	0.0066	0.075	0.23	103.1
eROSITA + Planck	photo-z	Pessimistic	wCDM+PNG	7.0	0.007	0.0036	0.059	0.21	179.4
eROSITA + Planck	spectro-z	Optimistic	wCDM+PNG	5.7	0.006	0.0026	0.048	0.16	263.3
DES (Stage III)	photo-z	WL+2D photometric	wCDM+PNG	8.6	0.009	0.0082	0.093	0.61	-
DES + Planck	photo-z	WL+2D photometric	wCDM+PNG	8.2	0.009	0.0074	0.090	0.35	-
Euclid (Stage IV)	photo-z	WL+2D photometric	wCDM + PNG	4.7	0.005	0.0048	0.054	0.32	-
Euclid	spectro-z	WL+2D spectroscopic	wCDM + PNG	5.7	0.005	0.0051	0.051	0.35	-
Euclid + Planck	photo-z	WL+2D photometric	wCDM + PNG	4.5	0.005	0.0044	0.052	0.20	-
Euclid + Planck	spectro-z	WL+2D spectroscopic	wCDM + PNG	5.3	0.005	0.0037	0.035	0.15	-

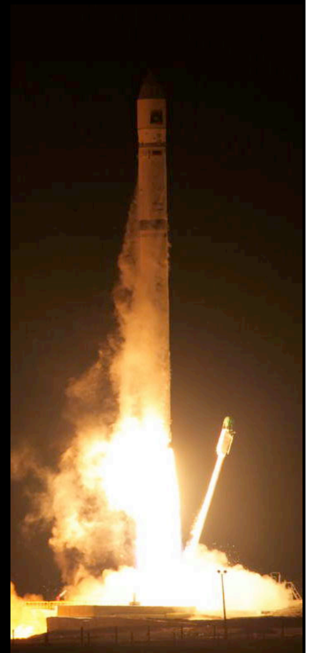
>300 for $f_{\rm NL}$=0

Pillepich, Mohammed, Porciani, Reiprich (in prep.); Merloni et al. (arXiv:1209.3114). DES and Euclid from Giannantonio et al. (2012).

Summary of Statistics/Precision

- *eROSITA* will increase statistics by 1-2 ord. of mag.
- It will discover 100k clusters, among them *all* massive ones in the observable Universe and, hopefully, many more bullet-like clusters.
- It will likely be the first "Stage IV" dark energy probe world-wide.
- It will yield competitive and complementary constraints on dark matter, e.g., $\Delta\Omega_M$<1%, dark energy, e.g., Δw_{DE}<3%, but also on modified gravity, neutrino masses, primordial non-Gaussianity, ….





eROSITA: Some Results Based on Early Data

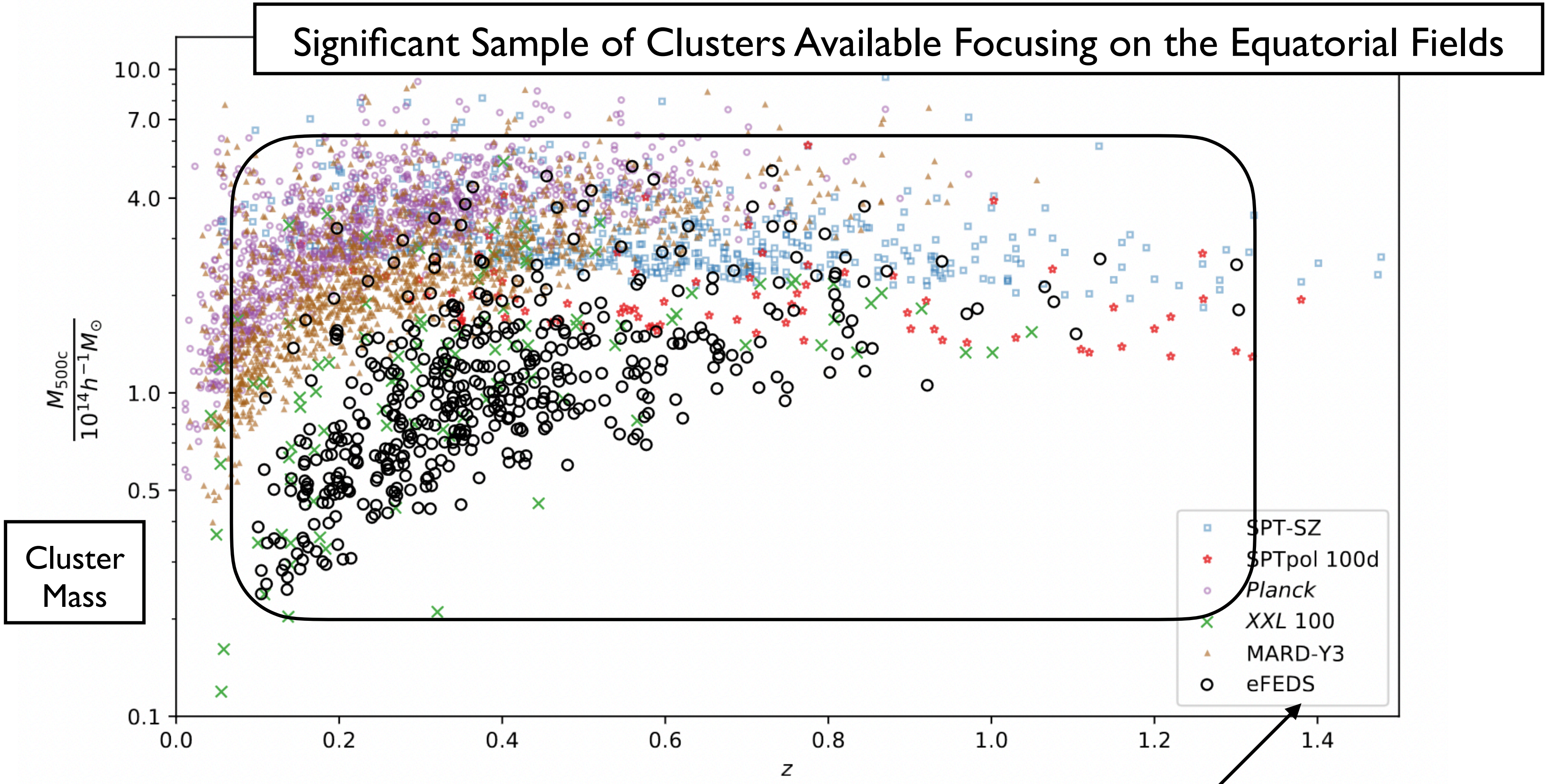


Figure 10. The mass and redshift of the eFEDS clusters (black circles), and those in the SPT-SZ survey (blue squares; Bleem et al. 2015), the SPTpol 100 degree^2 survey (red stars; Huang et al. 2020), the *Planck* mission (purple circles; Planck Collaboration et al. 2015), the brightest sample in the *XXL* survey (green crosses; Pacaud et al. 2016), and the X-ray MARD-Y3 sample (brown triangles; Klein et al. 2019). When plotting the eFEDS sample, we additionally include the two clusters at $z \approx 1.3$ that satisfy both the X-ray and optical selections.

eFEDS = e-ROSITA Final Equatorial Deep Survey

Equatorial Survey has Weak-Lensing Information Available to Calibrate Masses of Galaxy Clusters, so this is reason to focus first on them

Chiu+2023

eROSITA: Some Results Based on Early Data

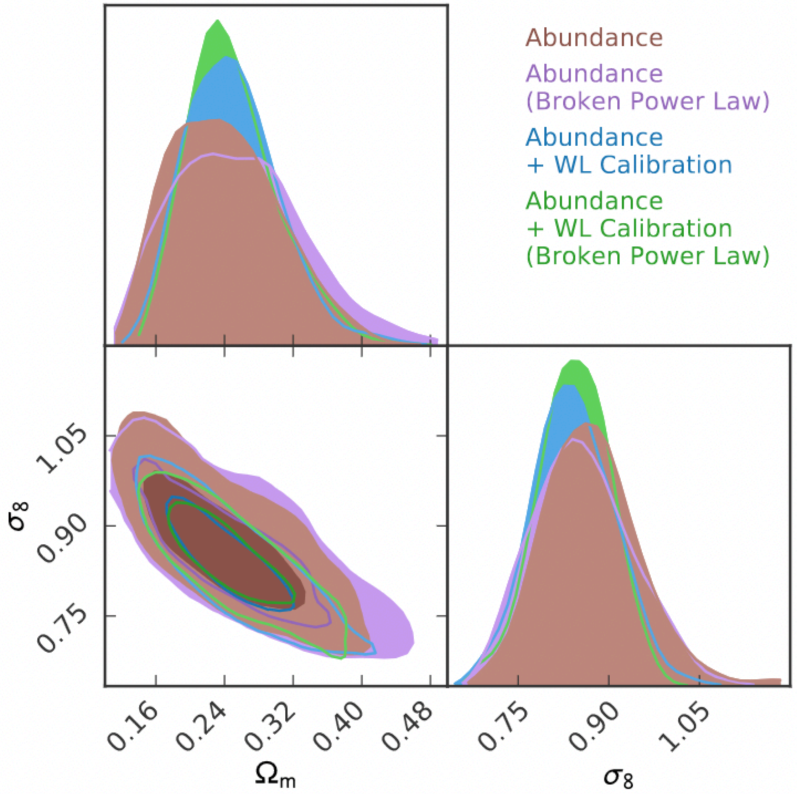


Figure 16. The constraints on Ω_m and σ_8 obtained from the modeling of the cluster abundance and that jointly with the weak-lensing mass calibration. The results based on the cluster abundance (the joint modeling) with and without the broken power-law scaling of the η–M–z relation are in purple and brown (green and blue), respectively. For the modeling of the cluster abundance (brown and purple contours), the informative priors are applied to the parameters of the η–M–z relation (see Section 4.3). The contours indicate the 68% and 95% confidence levels.

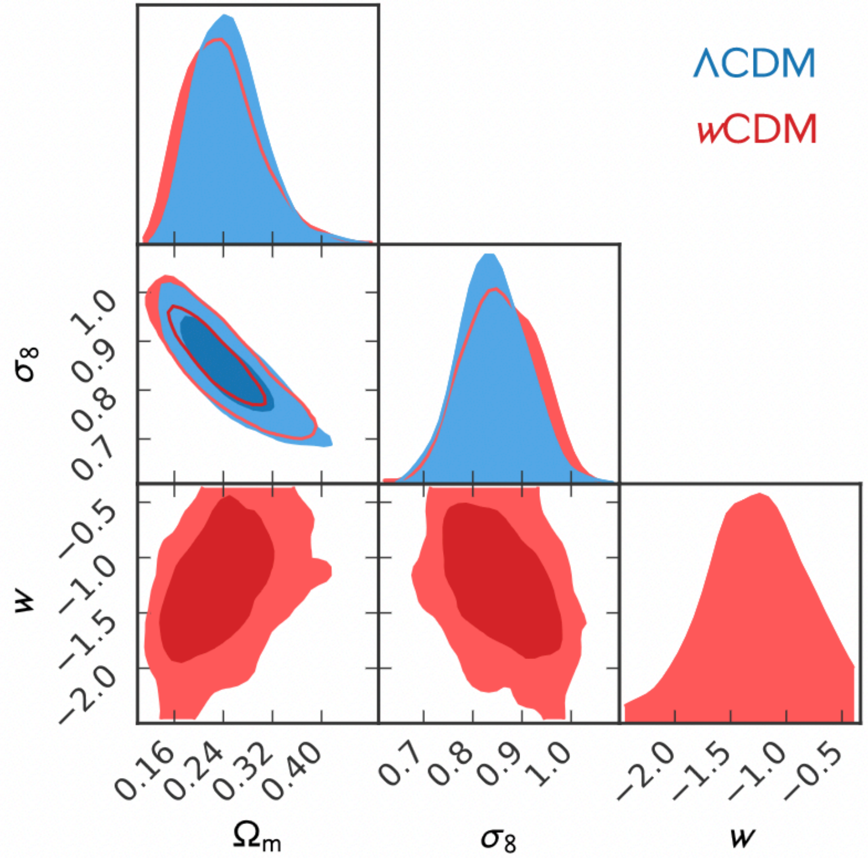


Figure 17. The cosmological constraints from the eFEDS clusters in the ΛCDM (blue) and wCDM (red) models. These constraints are obtained in the joint modeling of the weak-lensing mass calibration and the cluster abundance with the single power-law mass scaling of the count rate and with the Gaussian priors applied to the parameters of the X-ray completeness. The contours indicate the 68% and 95% confidence levels.

Chiu+2023

eROSITA: Some Results Based on Early Data

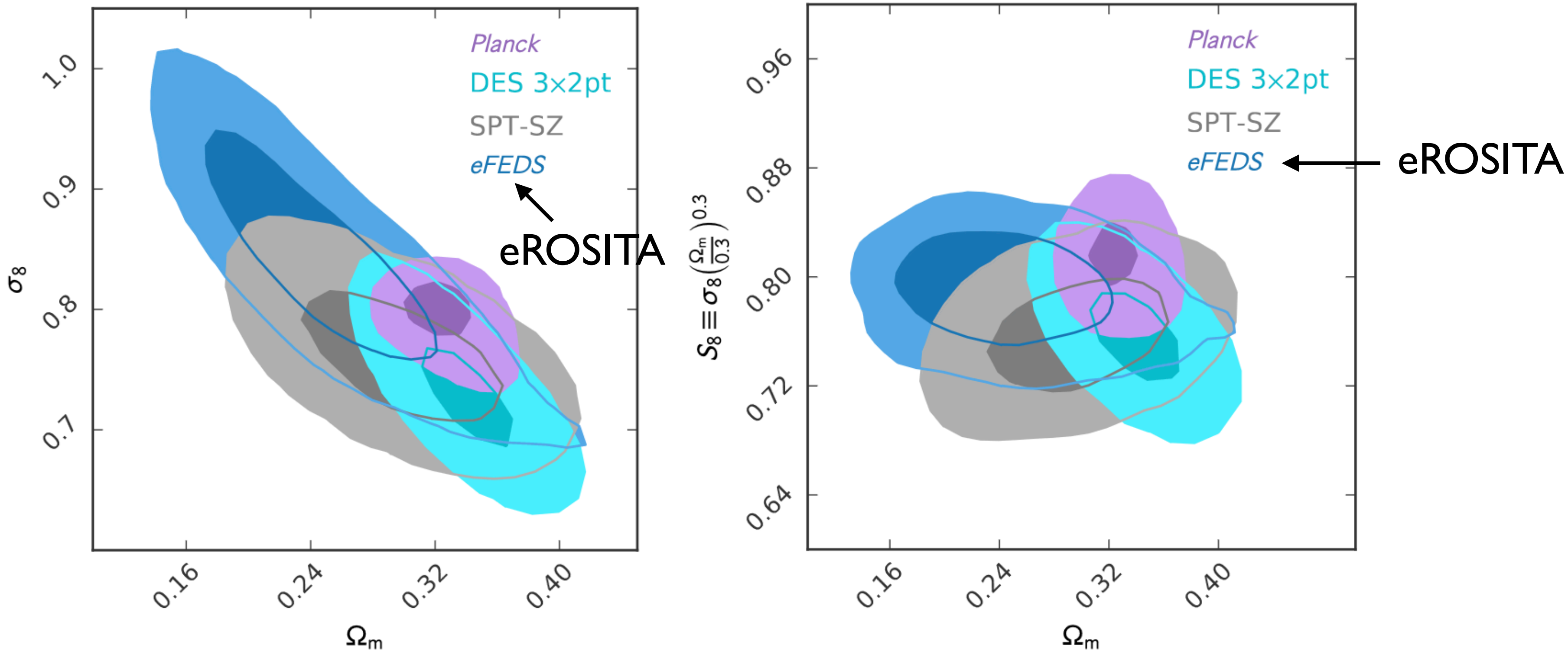


Figure 18. The comparisons of the cosmological parameters assuming the ΛCDM cosmology between the eFEDS clusters (blue) and the external results, including the anisotropy and polarization (`TTTEEE + lowE`) of CMB temperatures from *Planck* (purple; Planck Collaboration et al. 2020), the 3×2-point analysis from the Dark Energy Survey (cyan; Abbott et al. 2022), and the clusters in the SPT-SZ survey (grey; Bocquet et al. 2019). In the left (right) panel, the constraints on Ω_m and σ_8 ($S_8 \equiv \sigma_8\,(\Omega_m/0.3)^{0.3}$) are shown. The contours indicate the 68% and 95% confidence levels. The eFEDS results are in agreement with the external constraints at a level of $\lesssim 1.2\sigma$.

Chiu+2023