Cosmology with Future Optical/NIR Surveys

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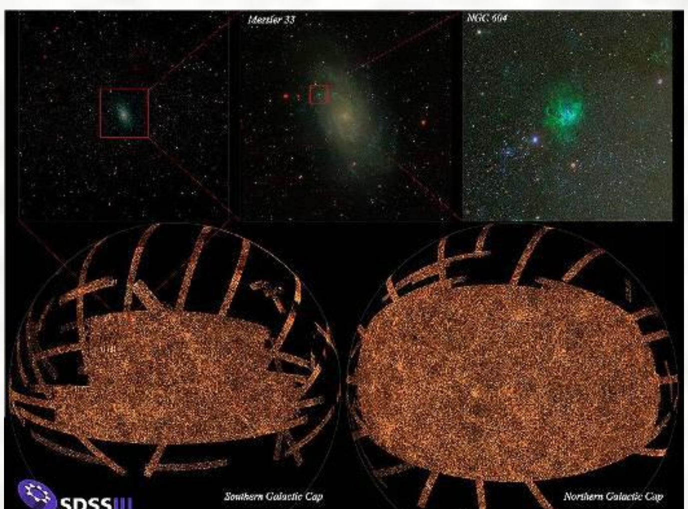
Data = Discovery Space

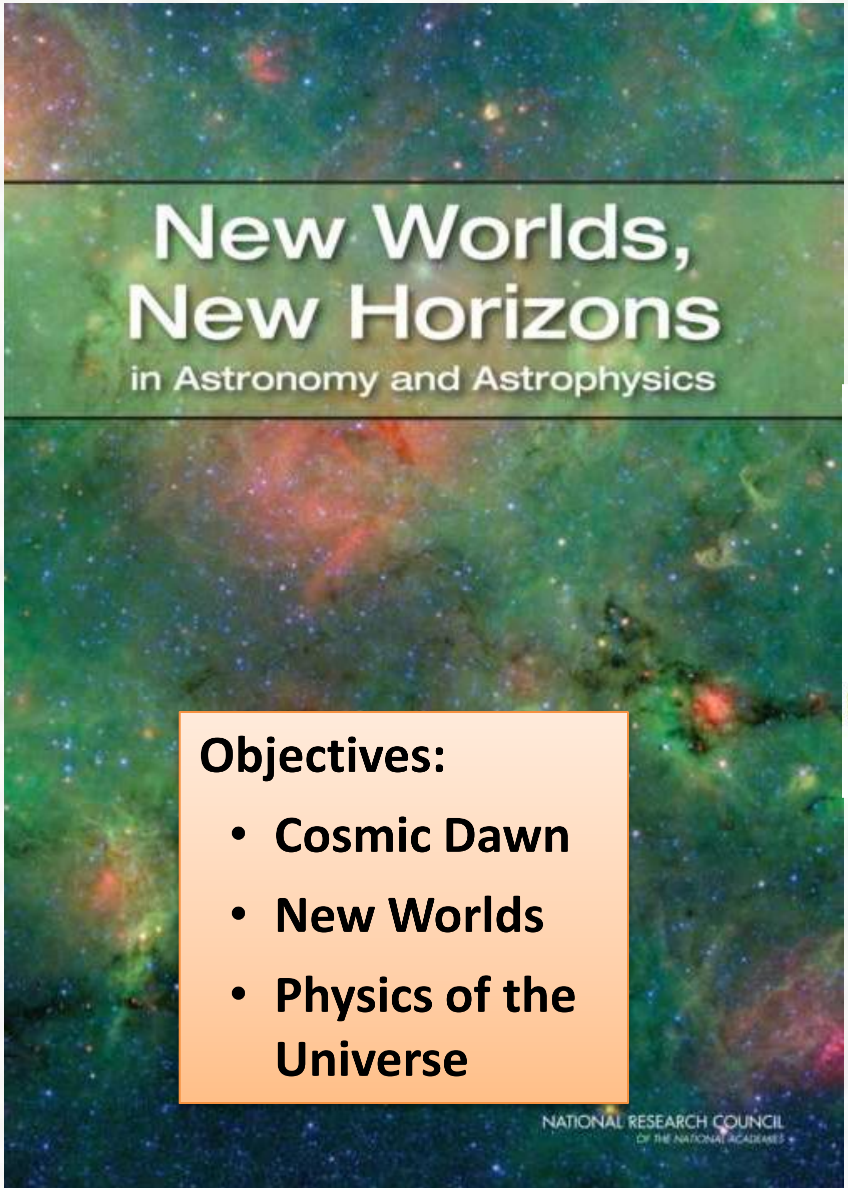
Gain of CCD survey: QE (depth), dynamical range (photometry precision), digitization (computer processing).

Top 10 telescopes 2006

Rank	Telescope	Citations	Ranking in 2004
1	Sloan Digital Sky Survey	1892	1
2	Swift	1523	N/A
3	Hubble Space Telescope	1078	3
4	European Southern Observatory	813	2
5	Keck	572	5
6	Canada–France–Hawaii Telescope	521	N/A
7	Spitzer	469	N/A
8	Chandra	381	7
9	Boomerang	376	N/A
10	High Energy Stereoscopic System	297	N/A



US Astro2010 Decadal Survey

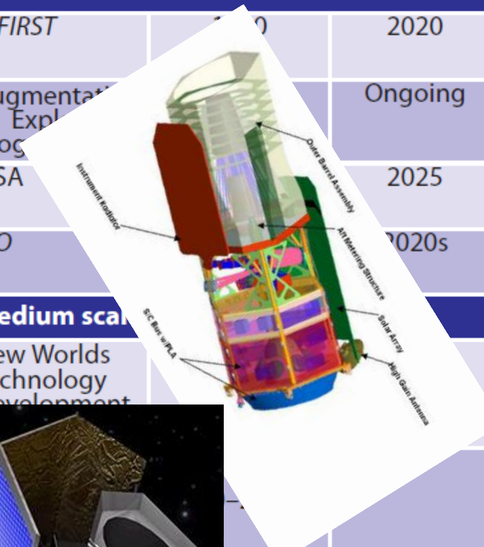


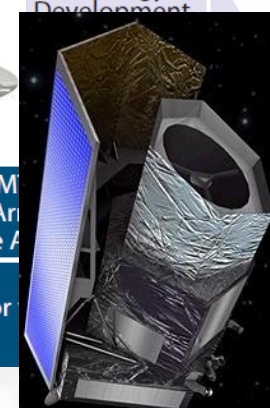
Objectives:

- Cosmic Dawn
- New Worlds
- Physics of the Universe

Ground-based priorities		
Project	Estimated cost, millions of dollars* (US federal share, 2012–21)	Estimated completion date
Large scale, ranked		
LSST	465 (421)	Late 2010s
Mid-Scale Innovations Program	93–200	Mid to late 2010s

Space-based priorities		
Project	Estimated cost, millions of dollars* (US federal share, 2012–21)	Estimated launch date
Large scale, ranked		
WFIRST		2020
Augmenta… to Expl… Prog…		Ongoing
LISA		2025
IXO		…020s
Medium scal…		
New Worlds Technology Development		





ESA Euclid

LSST, Large Synoptic Survey Telescope; GSM… …ror Telescope;
ACTA, Atmospheric Cherenkov Telescope Ar… *…Infrared Survey*
Telescope; LISA, Laser Interferometer Space A… …y.

*All estimates are in FY 2010 dollars.
†The total cost of the Explorers Program for … augmentation, exceeds $1 billion.

Priority: Large Surveys

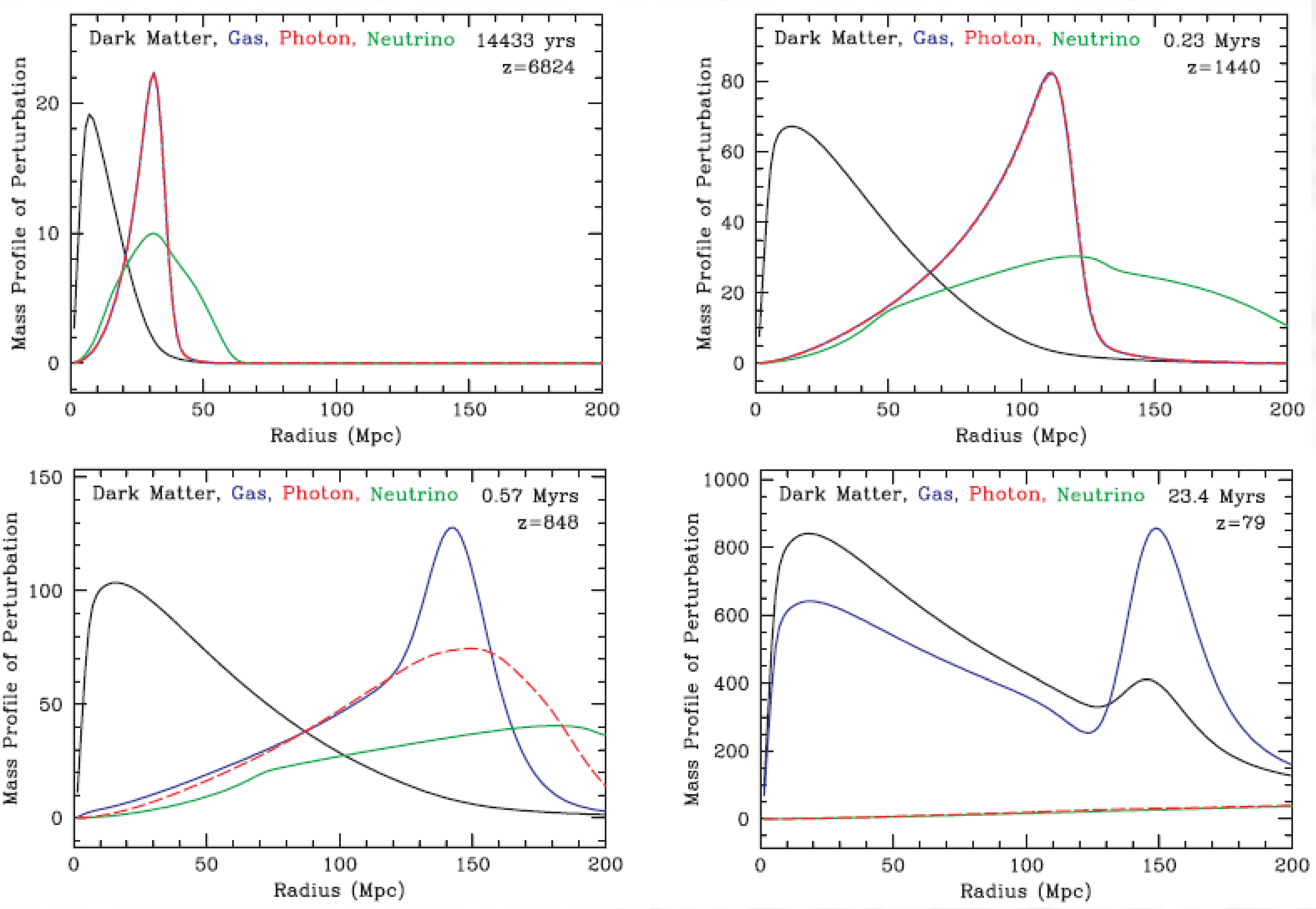
Dark Energy/Cosmology Probes

- Type Ia supernovae: luminosity distance
- Weak gravitational lensing: angular diameter distance, growth of structure, matter power spectrum
- Baryon acoustic oscillations: angular diameter distance, Hubble parameter, structure growth rate
- Cluster counting: volume/distance, growth of structure
- Strong lensing: Hubble constant, time-delay distance
- CMB: angular diameter distance, integrated Sachs-Wolfe effect

Expansion (D_A, D_L, H), growth, & power spectrum➔ Dark energy, dark matter, gravity, neutrino mass, cosmological parameters…

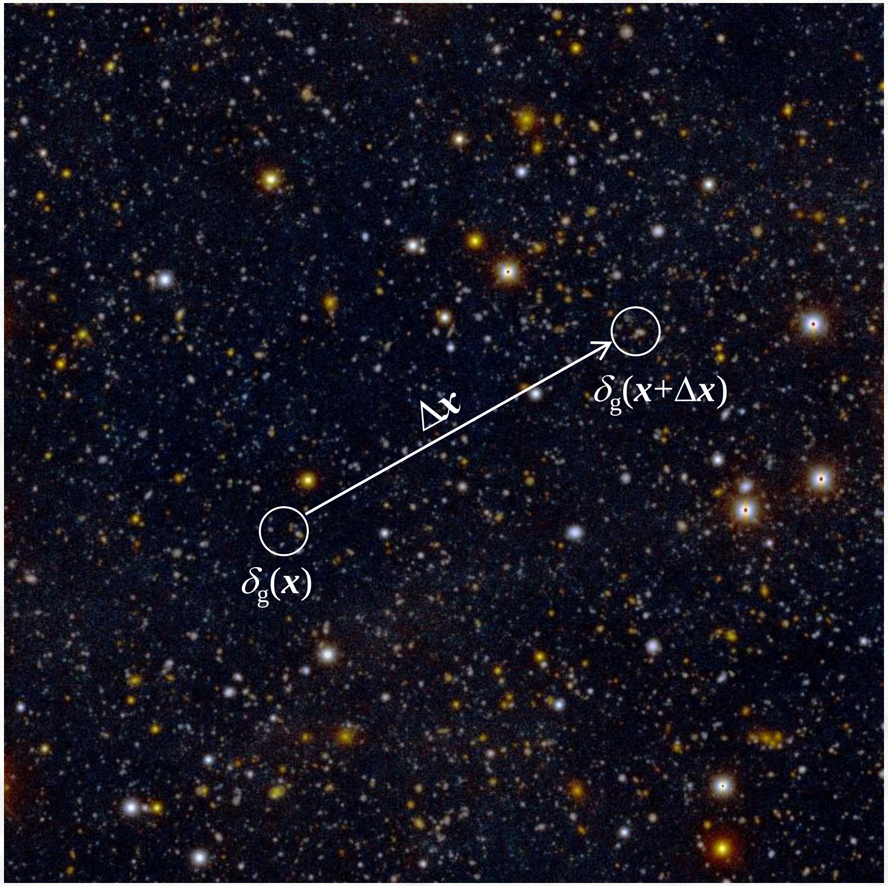
Large surveys!

Acoustic Perturbations Around Recombination



Eisenstein, Seo, & White (2007)

Galaxy 2-Point Correlation Function

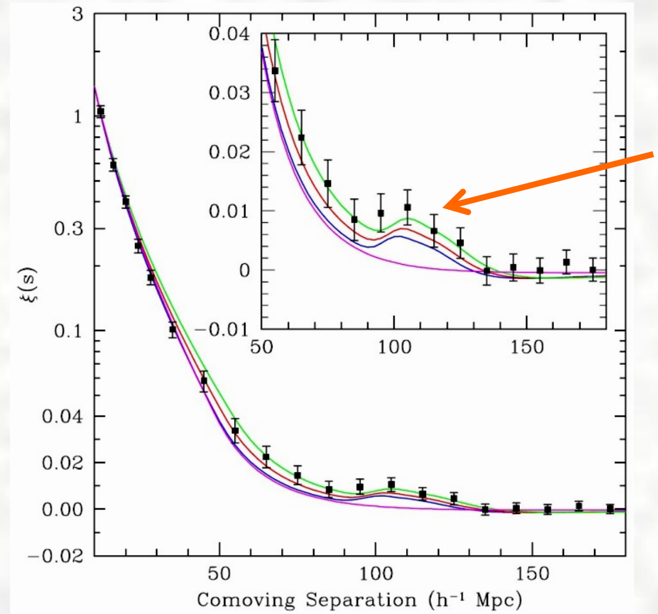


Deep Lens Survey, Tyson & Wittman

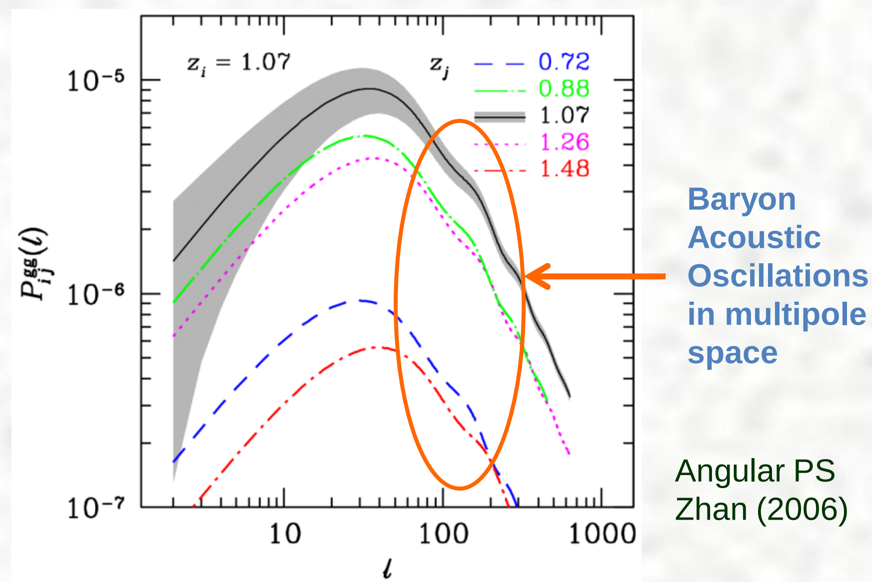
$$\delta_g(\mathbf{x}) = n_g(\mathbf{x})/\bar{n}_g - 1$$

$$\xi(\Delta x) = \xi(\Delta \mathbf{x}) = \left\langle \delta_g(\mathbf{x})\delta_g(\mathbf{x}+\Delta\mathbf{x}) \right\rangle$$ Correlation Function

$$P(k) = \text{FT } \xi(\Delta x)$$ Power Spectrum

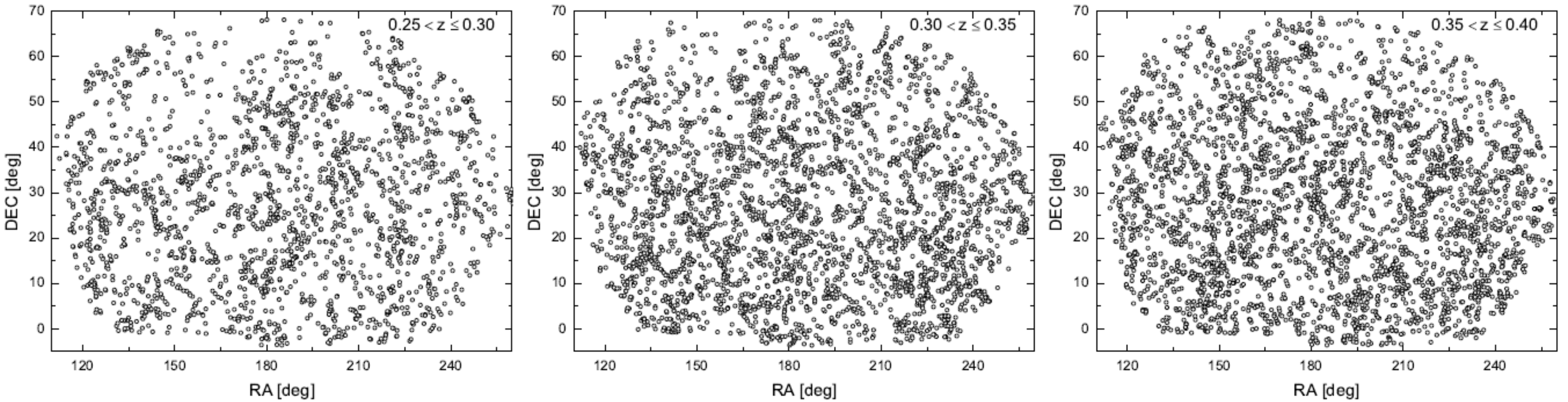


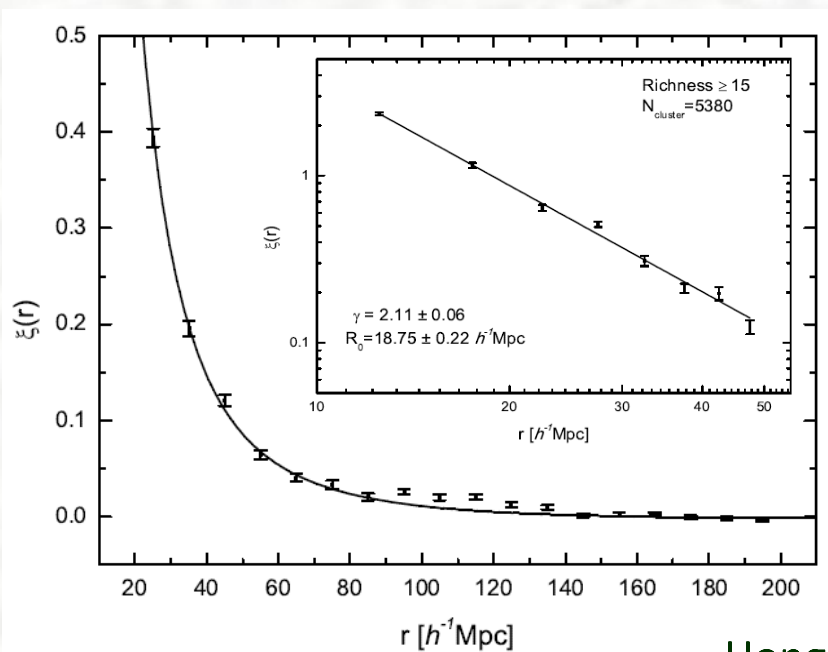
SDSS LRGs
Eisenstein et al (2005)

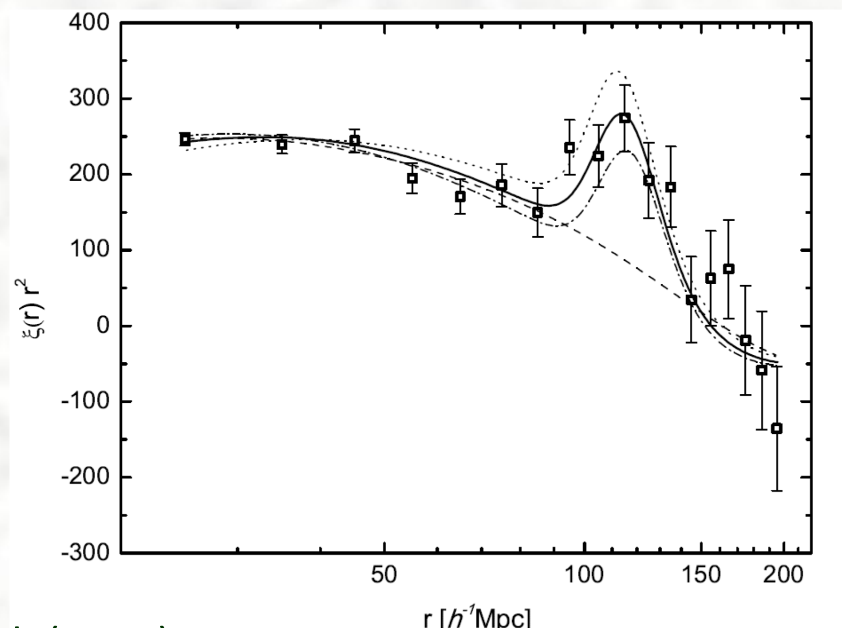


Angular PS
Zhan (2006)

BAO from Clusters in SDSS

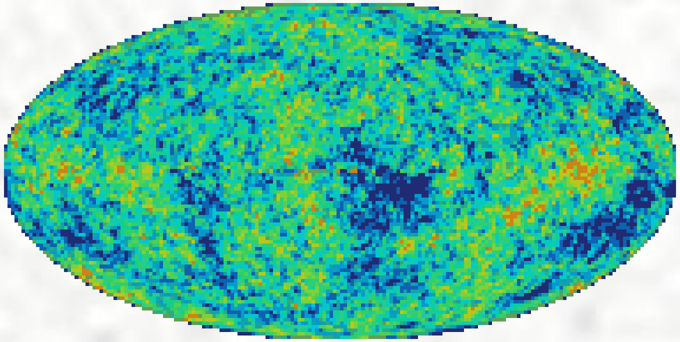




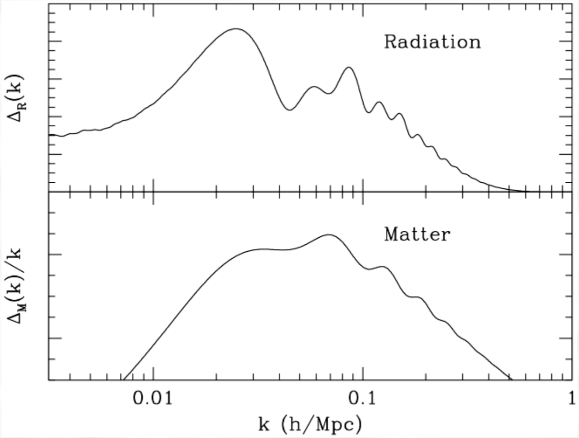


Hong et al. (2012)

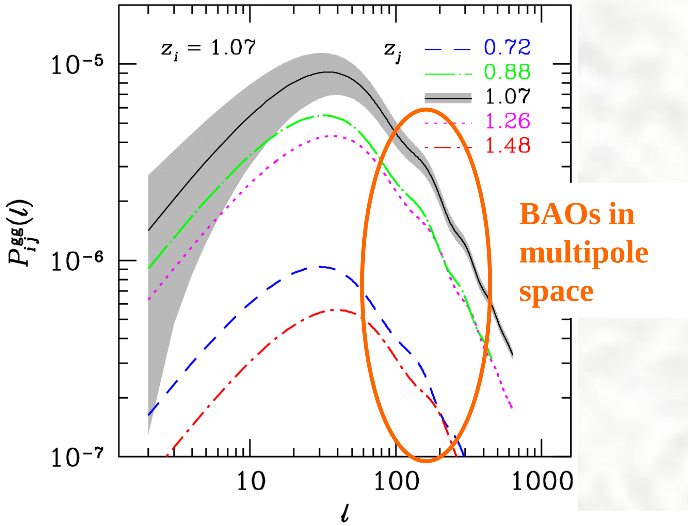
Baryon Acoustic Oscillations



CMB temp. fluctuations (WMAP)



Imprints on the matter power spectrum (White 2005)



LSST galaxy angular PS

R_S~150 Mpc

(Sound horizon at recombination)

Angular diameter distance

$$R_S = \Delta\theta D_A$$

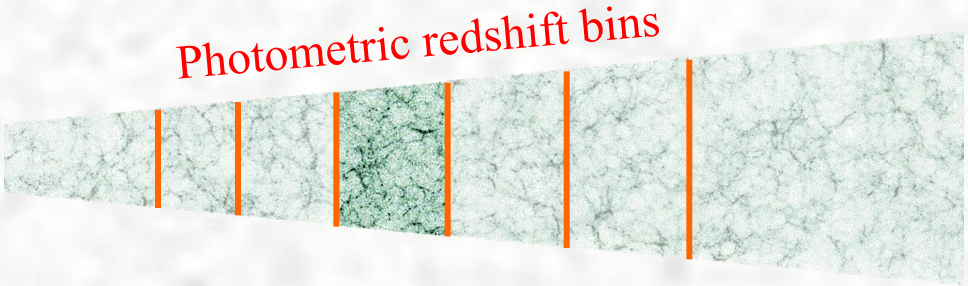
$$= c\Delta z/H$$

Redshift distortion➔

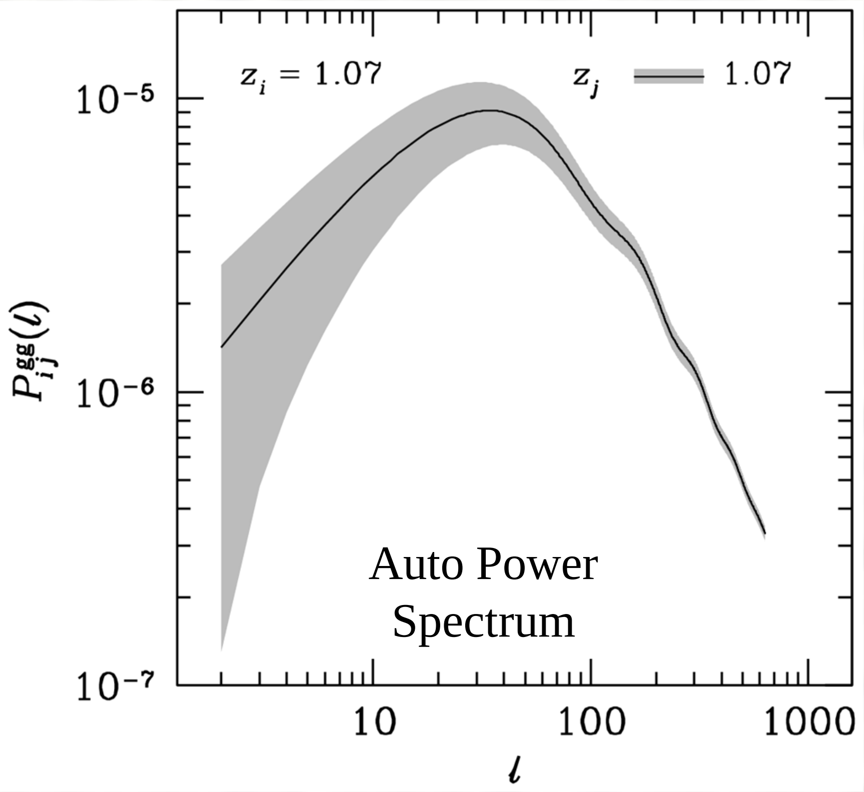
Growth rate➔

Test gravity (Zhang et al. 2008)

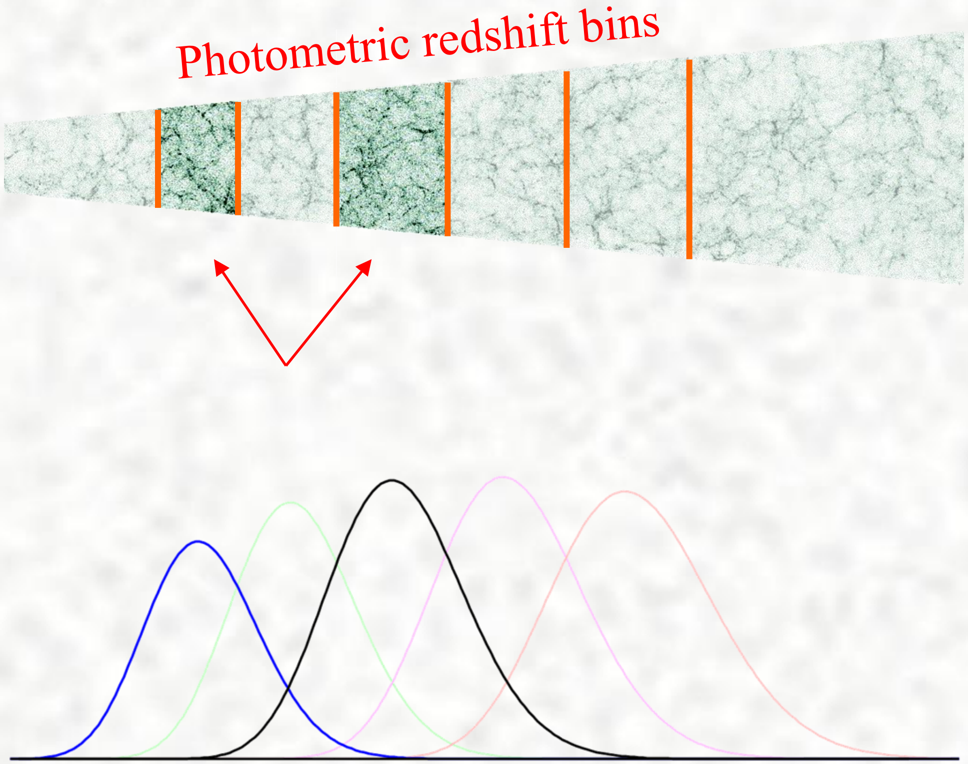
Galaxy Angular Power Spectrum



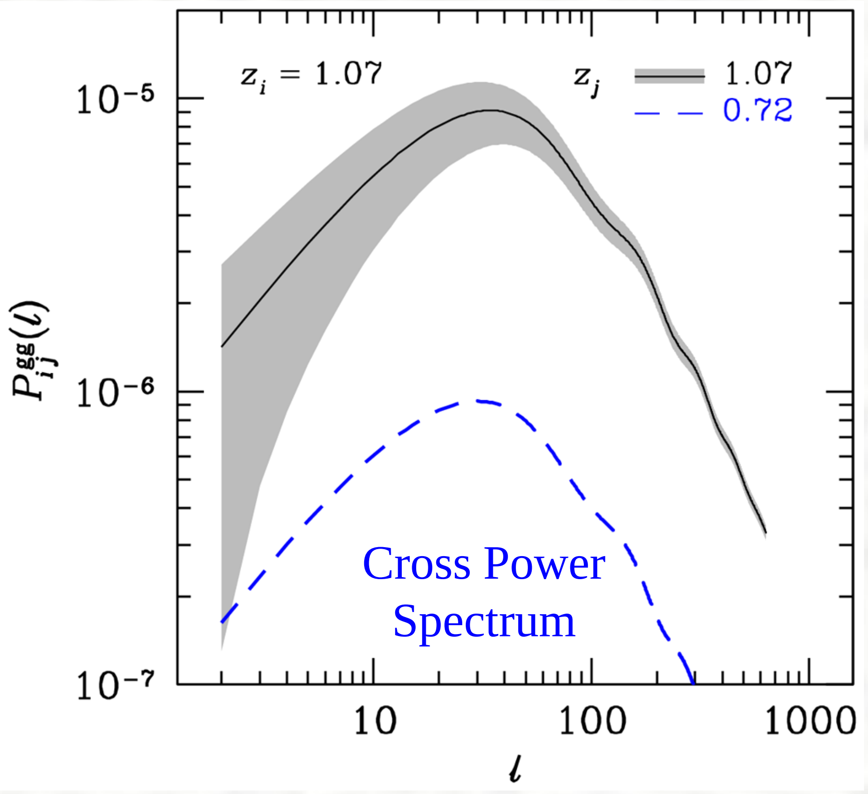
Kernel $\propto$ galaxy distribution in true-redshift space



Galaxy Angular Power Spectrum



Kernel ∝ galaxy distribution in true-redshift space

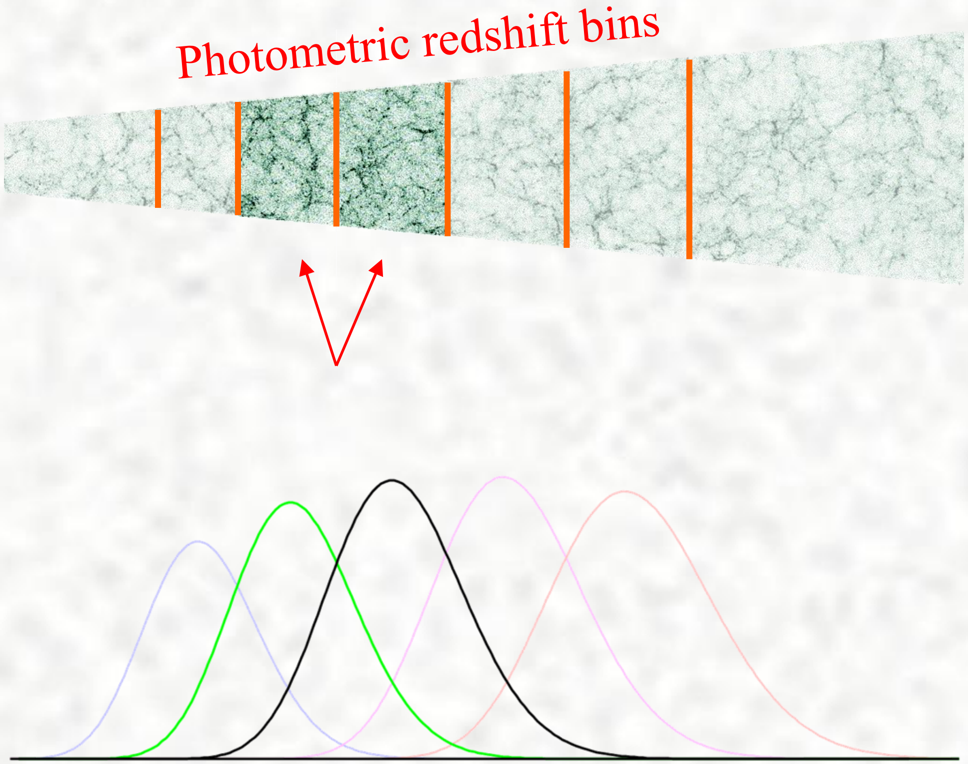


Overlap of galaxy distributions

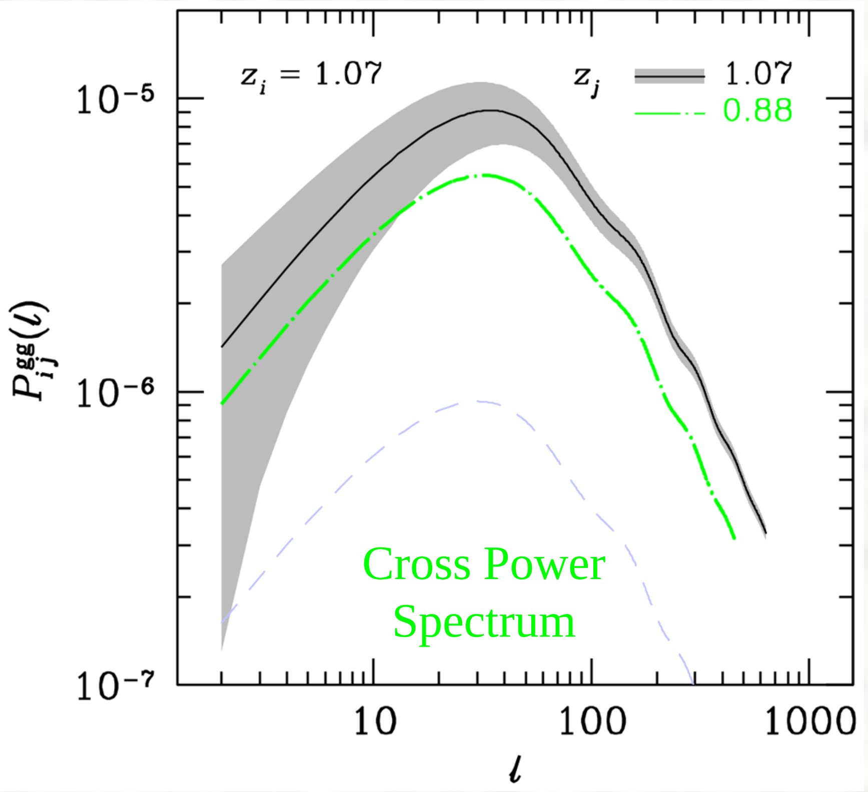
→ Cross power spectrum

(Limber approx)

Galaxy Angular Power Spectrum



Kernel ∝ galaxy distribution in true-redshift space

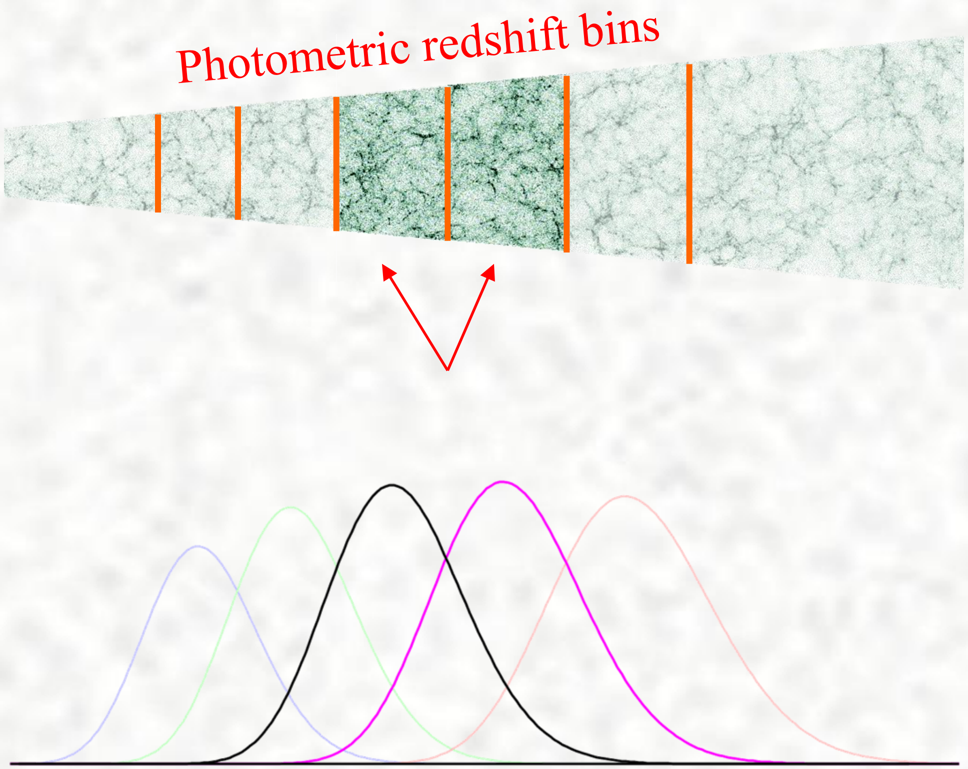


Overlap of galaxy distributions

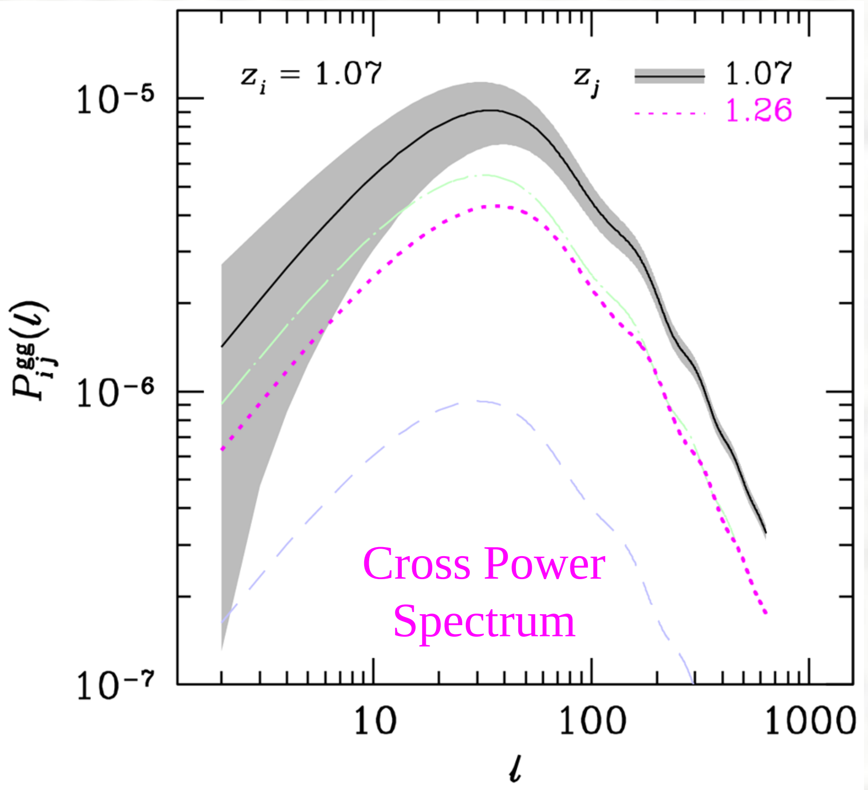
→ Cross power spectrum

(Limber approx)

Galaxy Angular Power Spectrum



Kernel ∝ galaxy distribution in true-redshift space

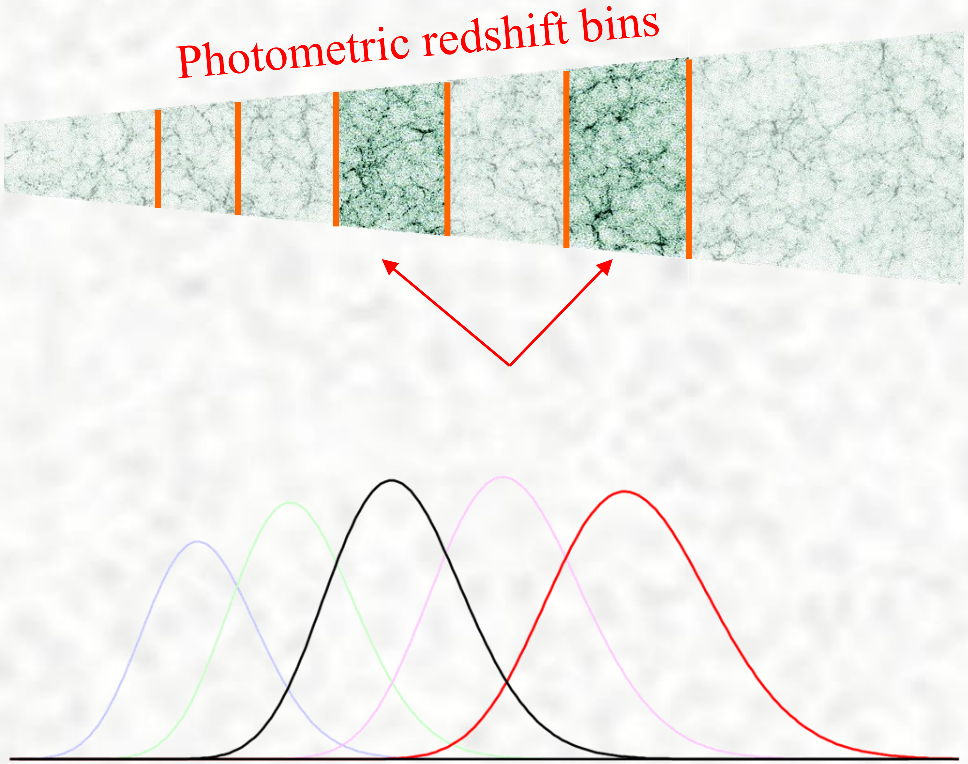


Overlap of galaxy distributions

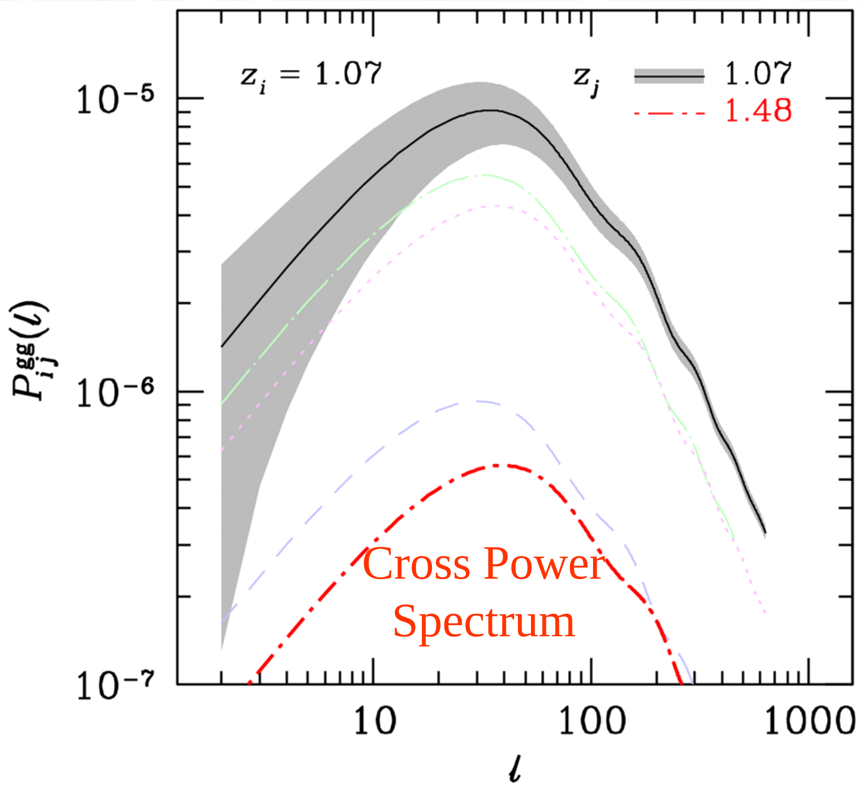
→ Cross power spectrum

(Limber approx)

Galaxy Angular Power Spectrum



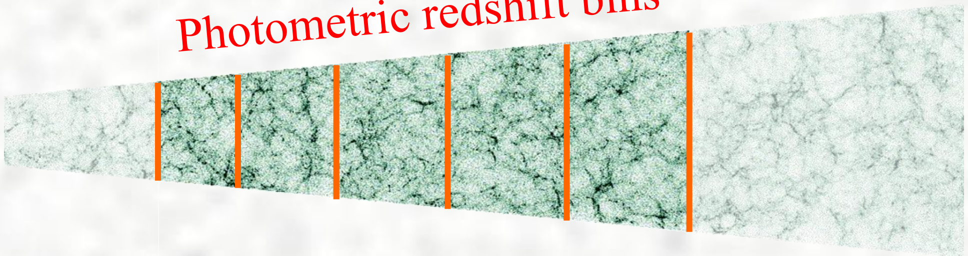
Kernel ∝ galaxy distribution in true-redshift space

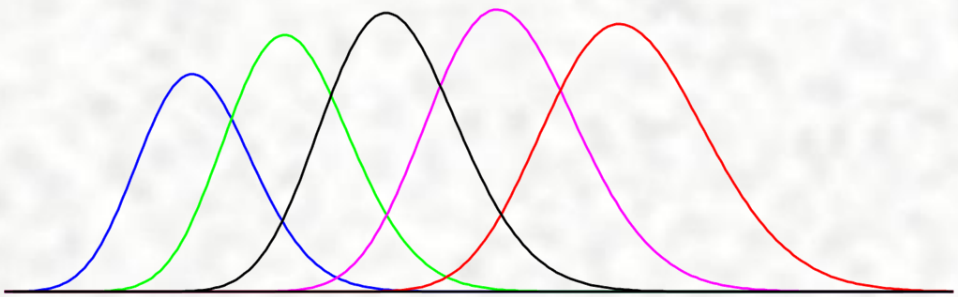


Overlap of galaxy distributions
→ Cross power spectrum
(Limber approx)

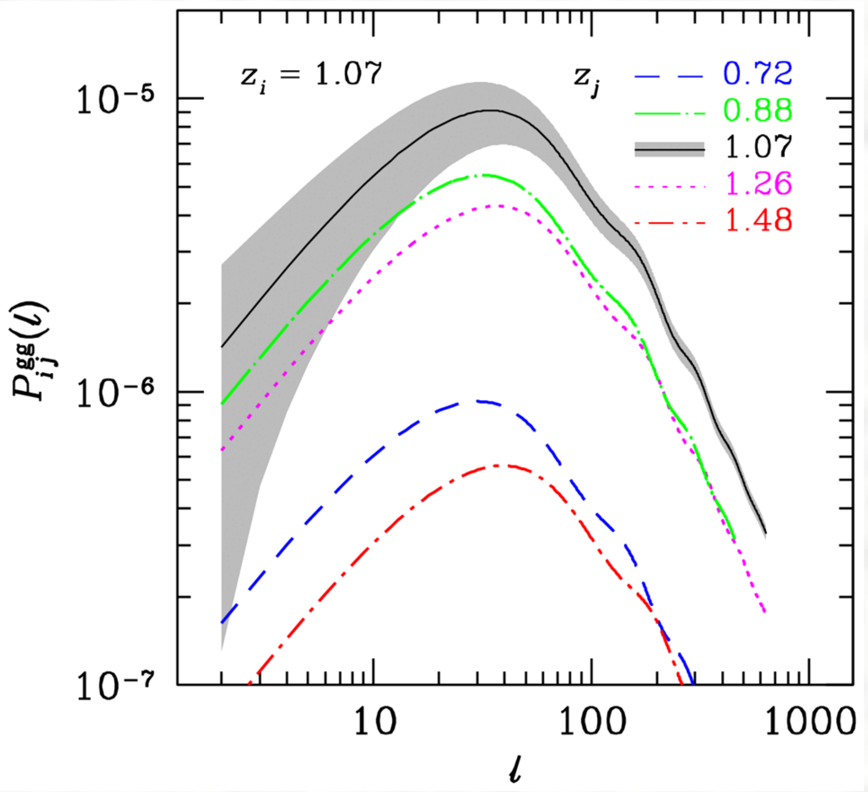
Galaxy Angular Power Spectrum

Photometric redshift bins





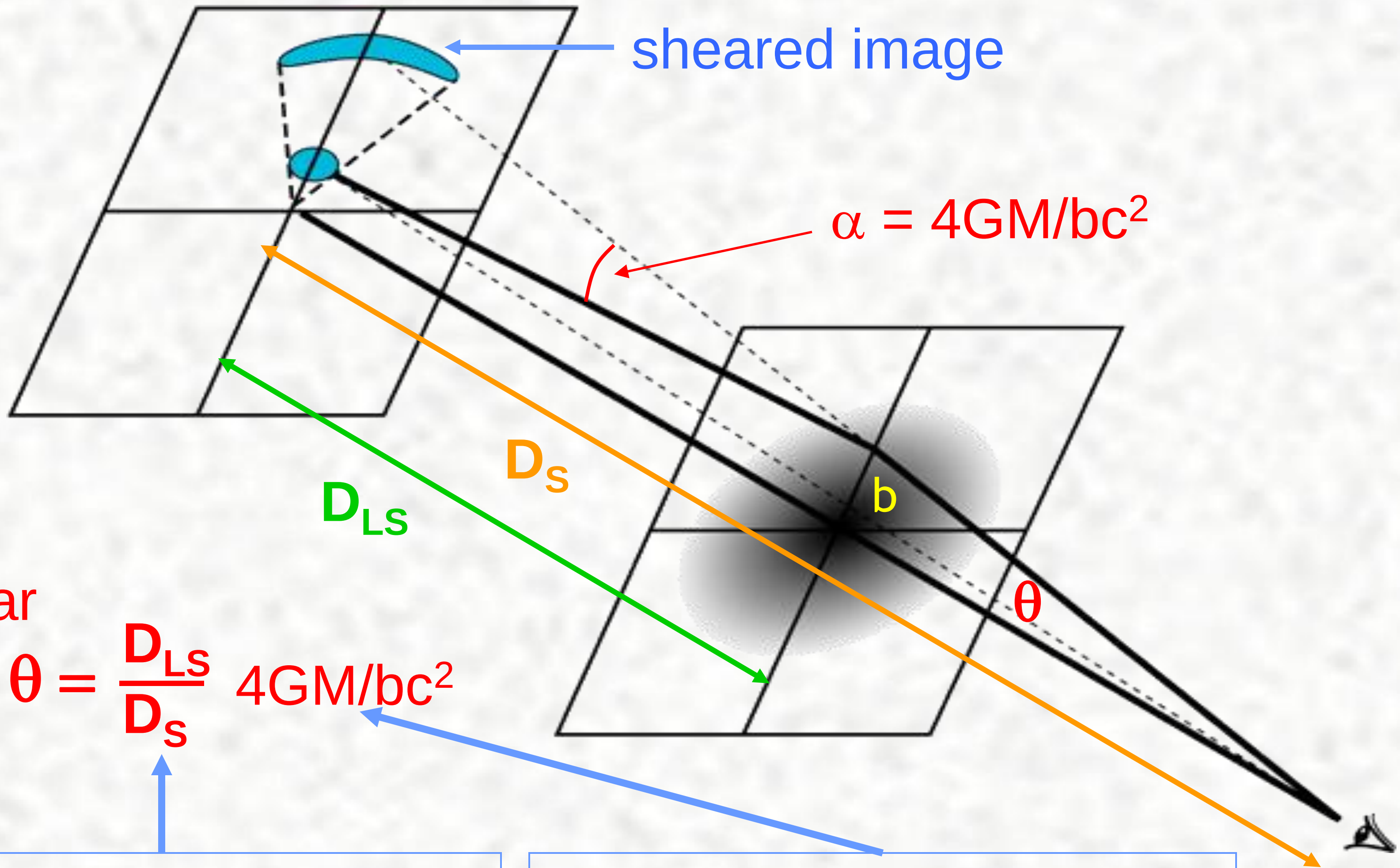
Kernel ∝ galaxy distribution in true-redshift space



$$P_{ij}^{gg}(\ell) = \frac{2\pi^2}{c\ell^3}\int dz\; H\, D_A W_i^g W_j^g \Delta_\delta^2\left(\frac{l}{D_A}\right)$$

$$W_i^g = b(z)\frac{n_i(z)}{\bar{n}_i}$$

Gravitational Lensing



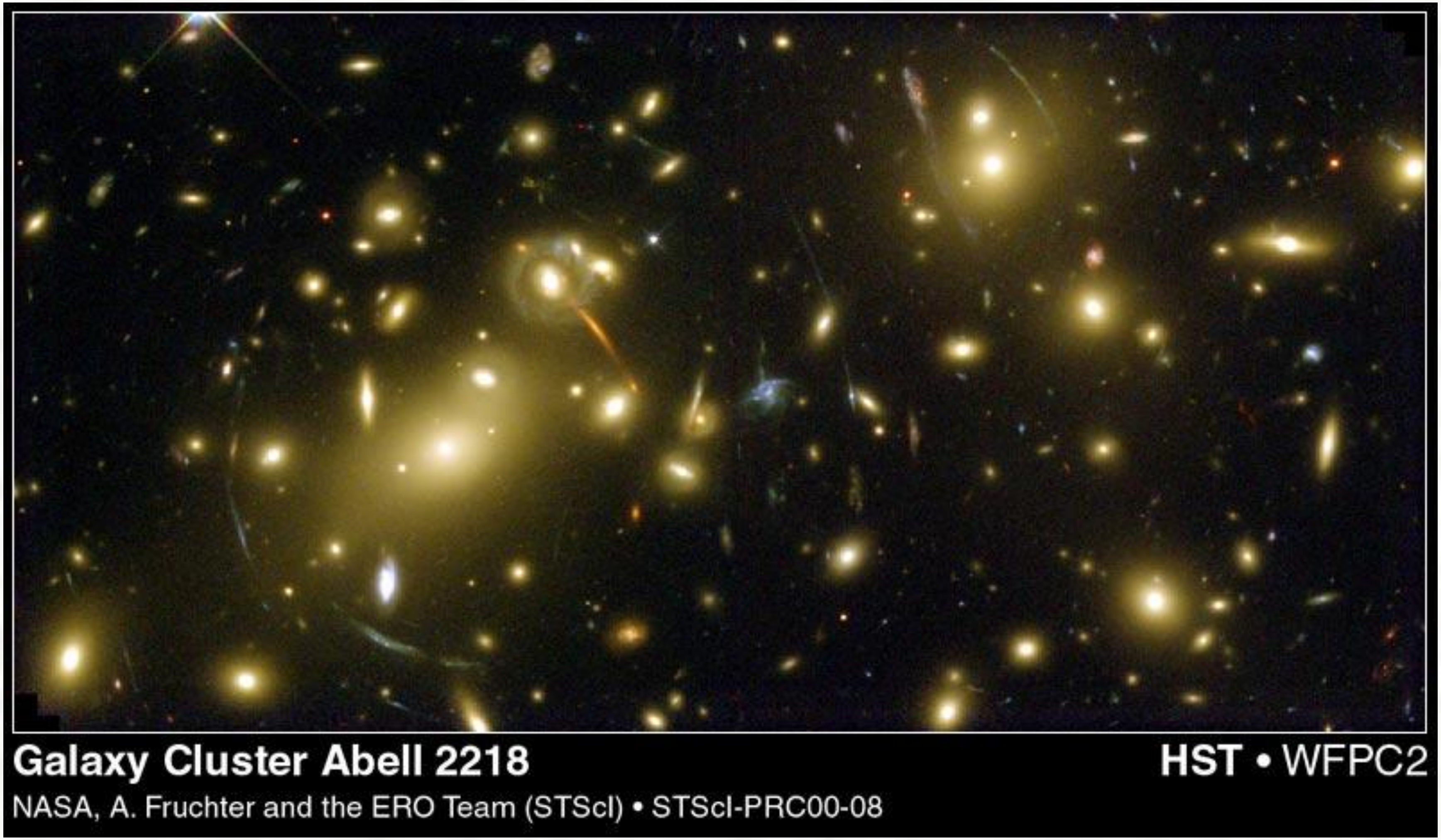
shear

$$\gamma \sim \theta = \frac{D_{LS}}{D_S} \, 4GM/bc^2$$

Cosmology changes geometric distance factors

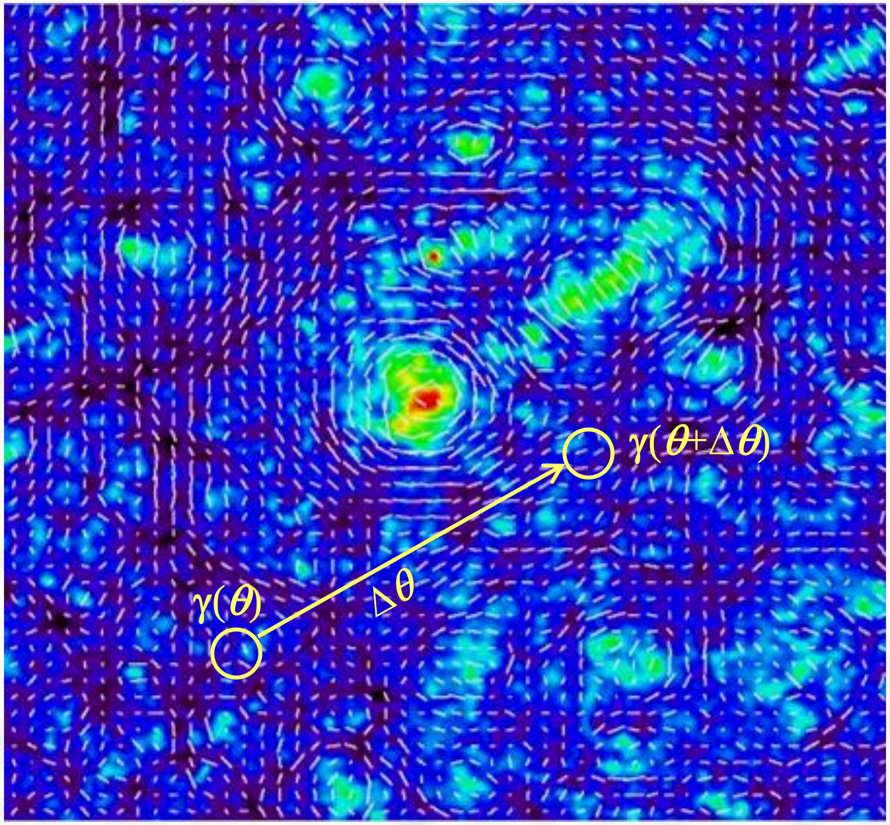
Gravity & Cosmology change the growth of mass structure

Gravitational Lensing

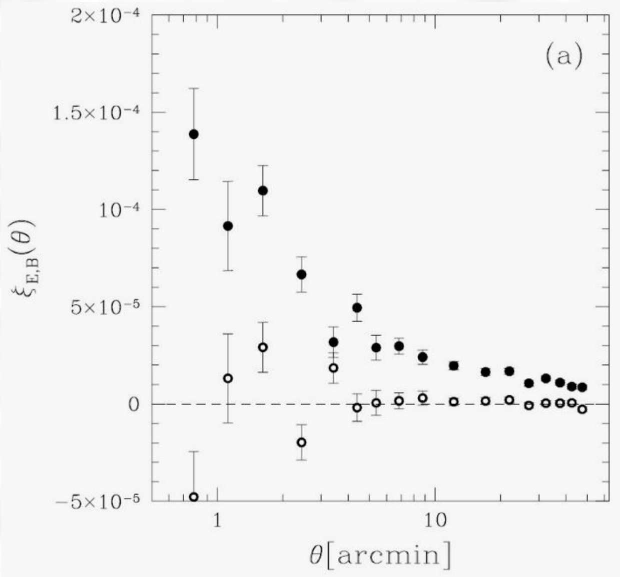


The shear correlation originates from correlation of the foreground mass.
Note: the cosmic shear, i.e., weak lensing signal, is much weaker!

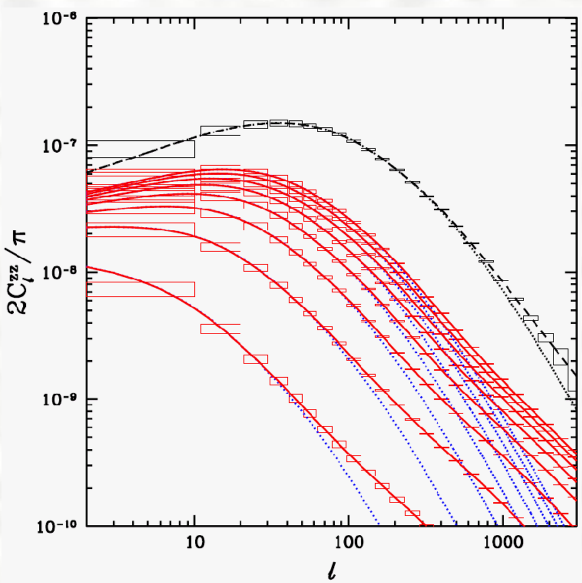
Shear 2-Point Correlation Function



1.1°×1.1° simulated shear field by Hamana



Hoekstra et al (2005)



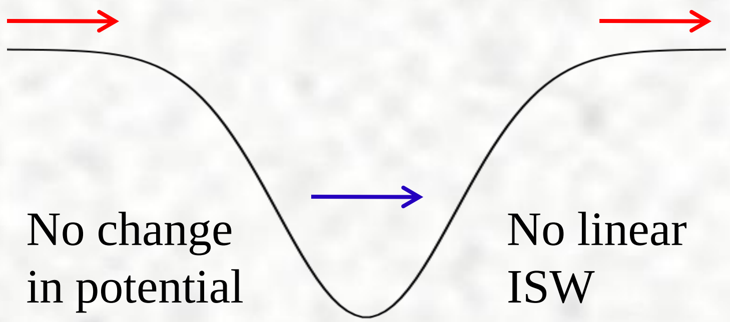
Song & Knox (2004)

$$\xi_E(\Delta\theta) = \xi_E(\Delta\boldsymbol{\theta}) = \left\langle \gamma_E(\boldsymbol{\theta})\gamma_E(\boldsymbol{\theta}+\Delta\boldsymbol{\theta}) \right\rangle$$ Correlation Function

$$\xi_B(\Delta\theta) = 0$$

$$P(\ell) = \mathrm{FT}\ \xi_E(\Delta\theta)$$ Power Spectrum

Integrated Sachs—Wolfe Effect

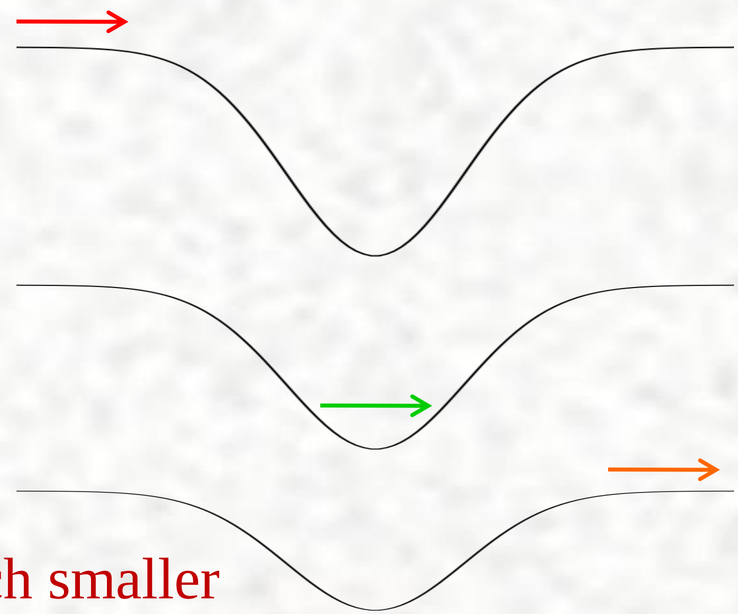


$$\Delta T_{\rm ISW} \approx \int d\tau \frac{d\phi}{d\tau}$$

$$\frac{d\phi}{d\tau} \approx a\,\phi(\mathbf{x}) \frac{d}{d\tau} \frac{D(a)}{a}$$

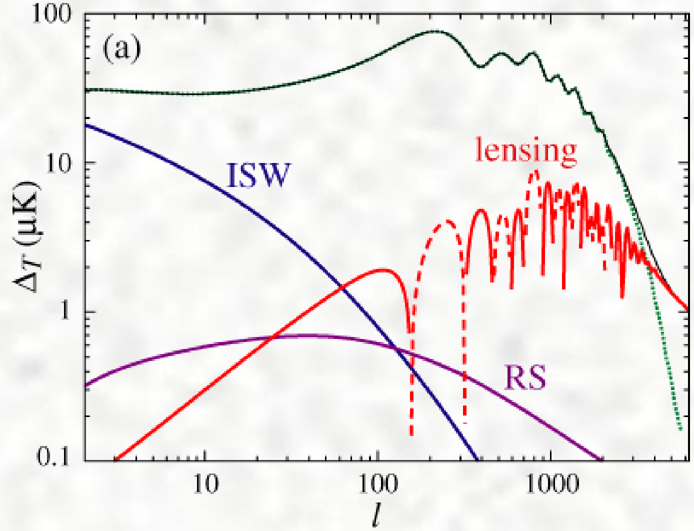
There is no linear ISW effect in an EdS universe, because $D(a)=a$. Need to break $D=a$

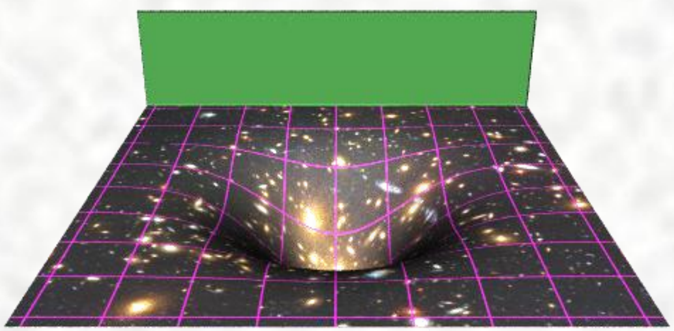
- with extra component(s) e.g., dark energy, or
- go nonlinear (Rees—Sciama effect).



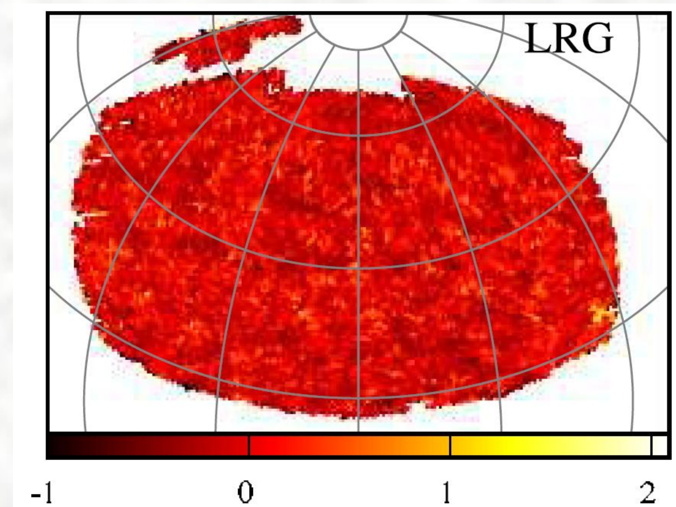
The RS effect is expected to be much smaller than the linear ISW effect in ΛCDM.

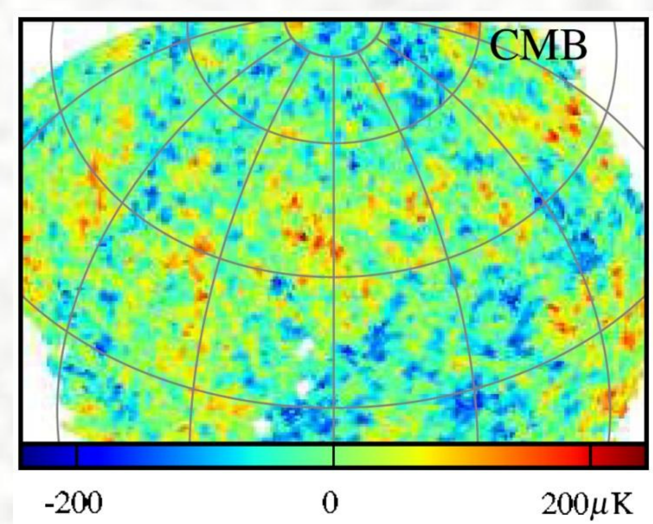
Integrated Sachs—Wolfe Effect





Supercluster





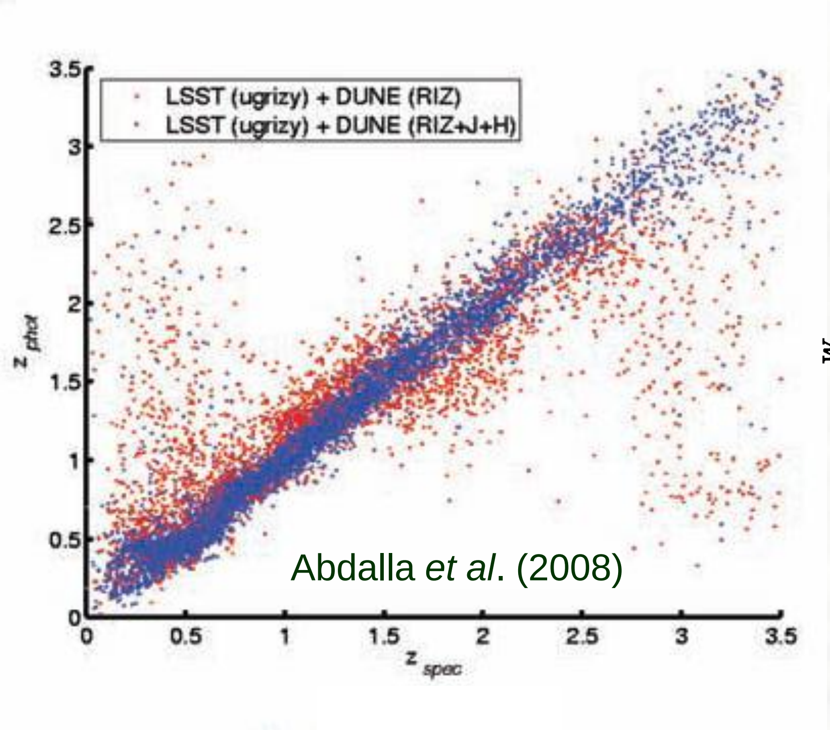
Cross correlations

Granett, Neyrinck, & Szapudi (2008, 2009)

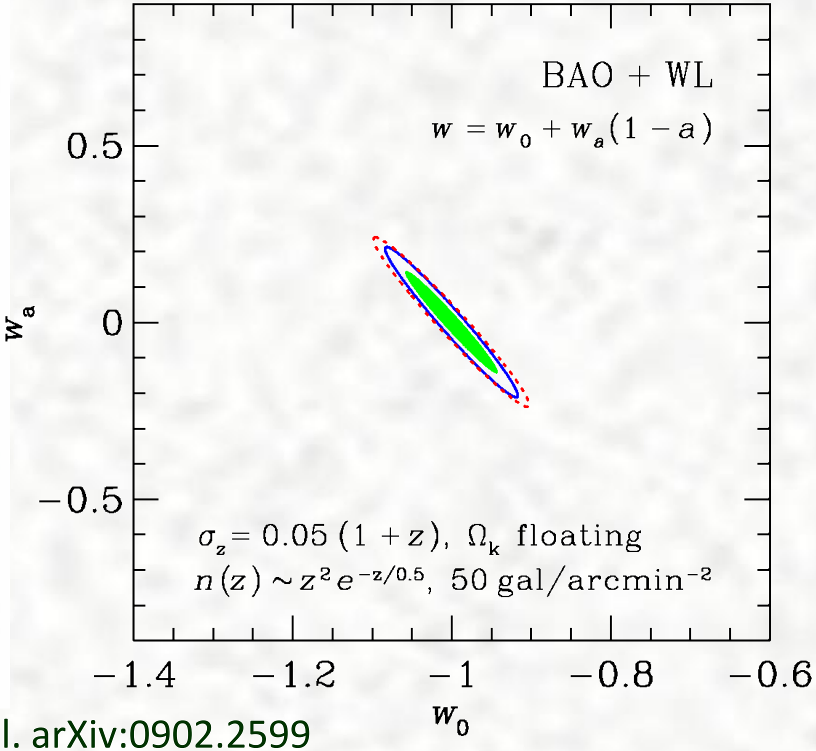
Systematic Uncertainties

- Type Ia Supernova
  Luminosity evolution, Galactic & host-galaxy dust extinction, contamination.
- Weak lensing
  Shear calibration: Properties of additive & multiplicative shear errors?
  Photo-zs: What is the error distribution function? How and how well can we calibrate it? What is the impact of non-Gaussian photo-z errors on cosmological constraints? How about catastrophic redshift errors?
  Nonlinear evolution: Percent-level calibration of the nonlinear power spectrum at $k < 1\ h$/Mpc? Baryonic influence on the dark matter distribution?
  Intrinsic alignment: Local & large-scale, intrinsic—intrinsic, gravitational—intrinsic alignments. How to remove/model the effects?
- Baryon Acoustic Oscillations
  Nonlinear evolution: Shift of the BAO scale? Higher-order statistics? Parameter estimation from non-Gaussian data?
  Galaxy bias: Scale dependence? luminosity dependence?
  Photo-zs: See WL
  Redshift distortion: Accurate calibration with N-body simulations?
- Cluster Counting
  Mass—observable relation: mean & variance?

Photo-z Sys Effects on DE Constraints



Abdalla *et al*. (2008)



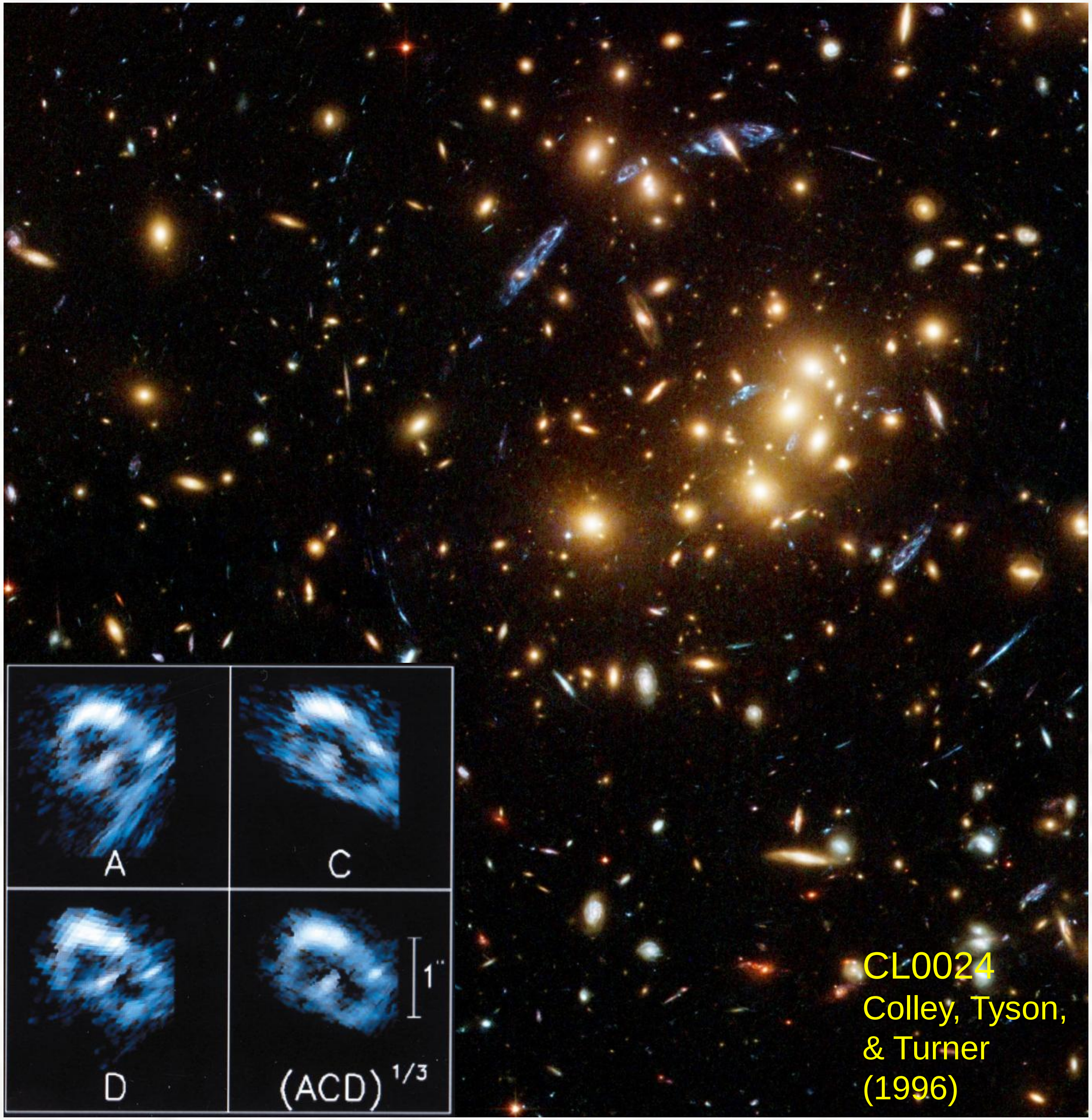
Zhan et al. arXiv:0902.2599

A joint analysis of the shear and galaxy overdensities for the same set of galaxies involves galaxy—galaxy, galaxy—shear, and shear—shear correlations, which enable some calibration of systematics that would otherwise adversely impact each probe. While the WL constraints on the dark energy equation of state (EOS, $w = p/\rho$) parameters, w_0 and w_a, as dened by $w = w_0+w_a(1-a)$, are sensitive to systematic uncertainties in the photo-z error distribution, the joint BAO and WL results remain fairly immune to these systematics.

The Big Data Challenge

- Data Reduction
- Data Management
- Simulation
- Data Analysis

Complexity of Data Reduction



Background
Detection
Deblending
PSF
Photometry
Astrometry
Stacking
Shape
Time series
Classification
Mask
Selection Func
…

OK by hand for one obj, but billions?

Simulations

End-to-end simulations are needed to develop, test and verify large projects, e.g.,

- Hardware/software specs, design, implementation, performance
- Survey strategy & optimization
- Fidelity of analysis pipelines

Challenges:

- Complex system
- Incomplete physics (simulate the universe with pieces missing or over-simplified)
- Observational effects
- Shear volume of simulations needed for analyses

Analyses

- Complex instrumental and observational effects (much stringent requirement in the big data era)
- Statistics of billions of objects over a huge volume (e.g., n-point correlations)
- Precise characterization of the likelihood of data give a model (large suite of realistic simulations)
- Exploring high dimensional parameter space (could be hundreds)