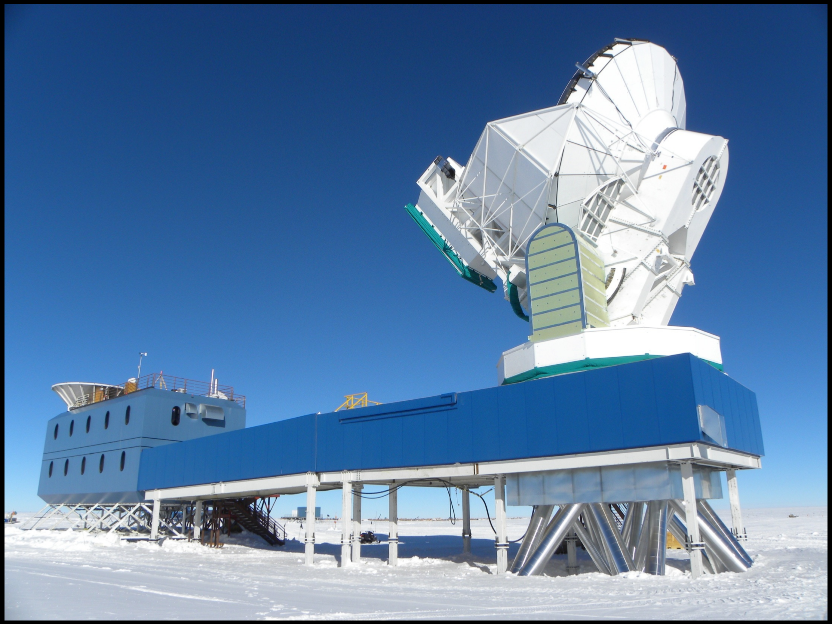
Myth-Busters:
Dark Energy Survey and South Pole Telescope



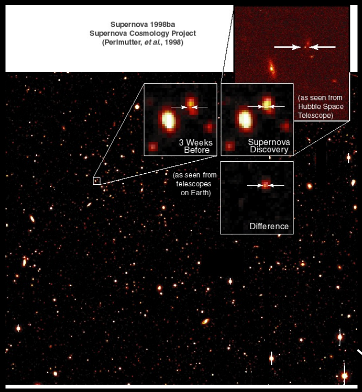
5/29/15

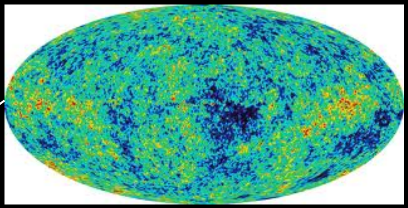
Scott Dodelson Fermilab

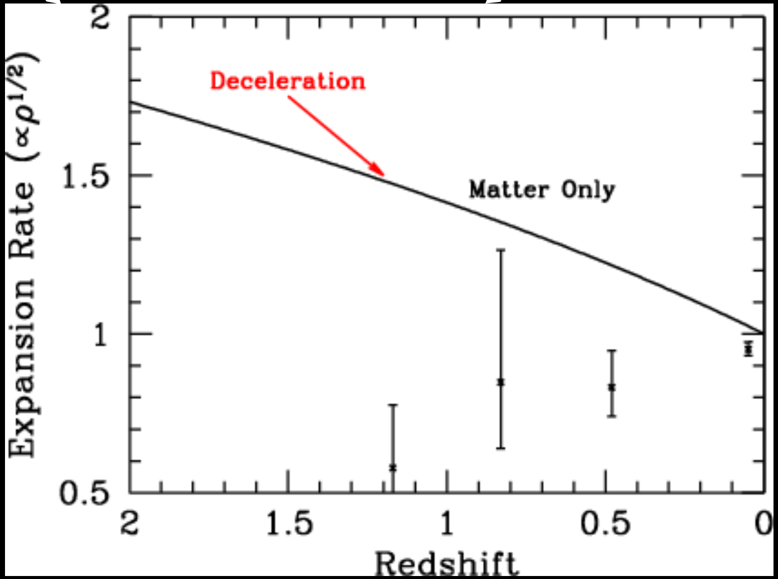
Too many collaborators/builders to acknowledge

But, thanks John!

General Relativity predicts that the expansion of the Universe should be slowing down





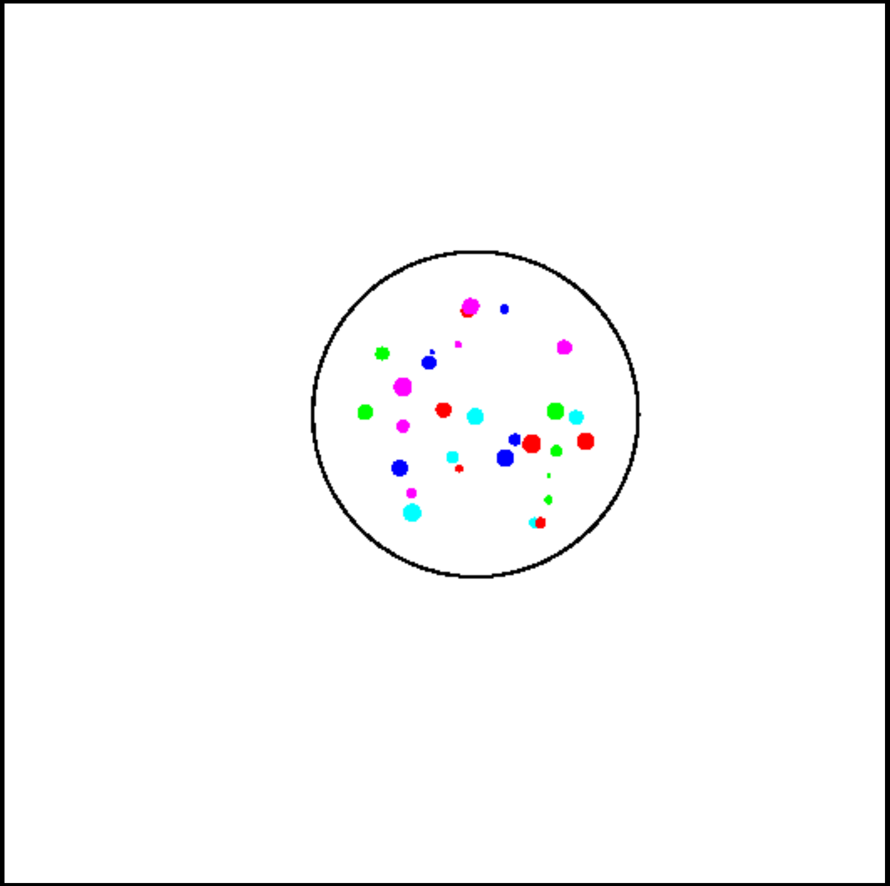


This prediction is incorrect: the Universe is accelerating

New Substance driving acceleration

- **Dark Energy** does not get diluted as universe expands
- Energy associated with empty space
- Quantum mechanics predicts zero point fluctuations even in empty space

Too large by a factor of 10^{120}!



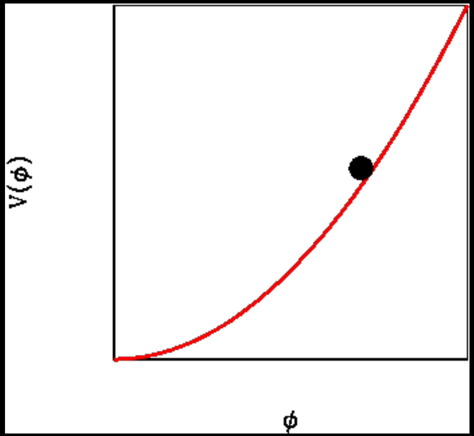
ANOTHER POSSIBILITY : SCALAR FIELD

- Require roughly constant energy density

- Potential energy larger than kinetic energy

- Mass must be very small: $m < 10^{-33}$ *eV* (Hubble rate today) or else field oscillates

- Slowly rolling field leads to non-constant energy density <--> equation of state *w* different from -1

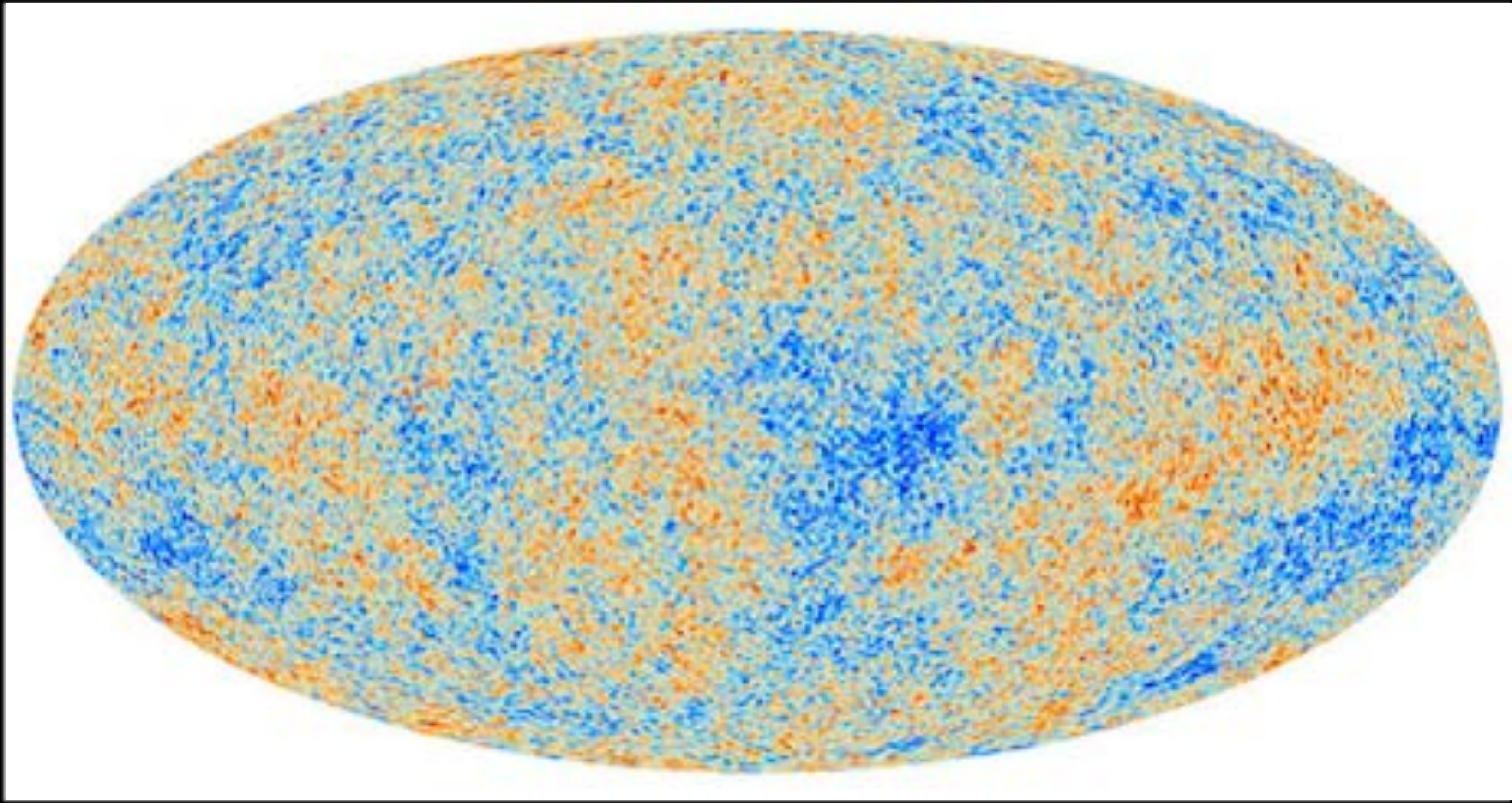


$$\ddot{\varphi} + 3H\dot{\varphi} + m^2\varphi = 0$$

Standard Lore

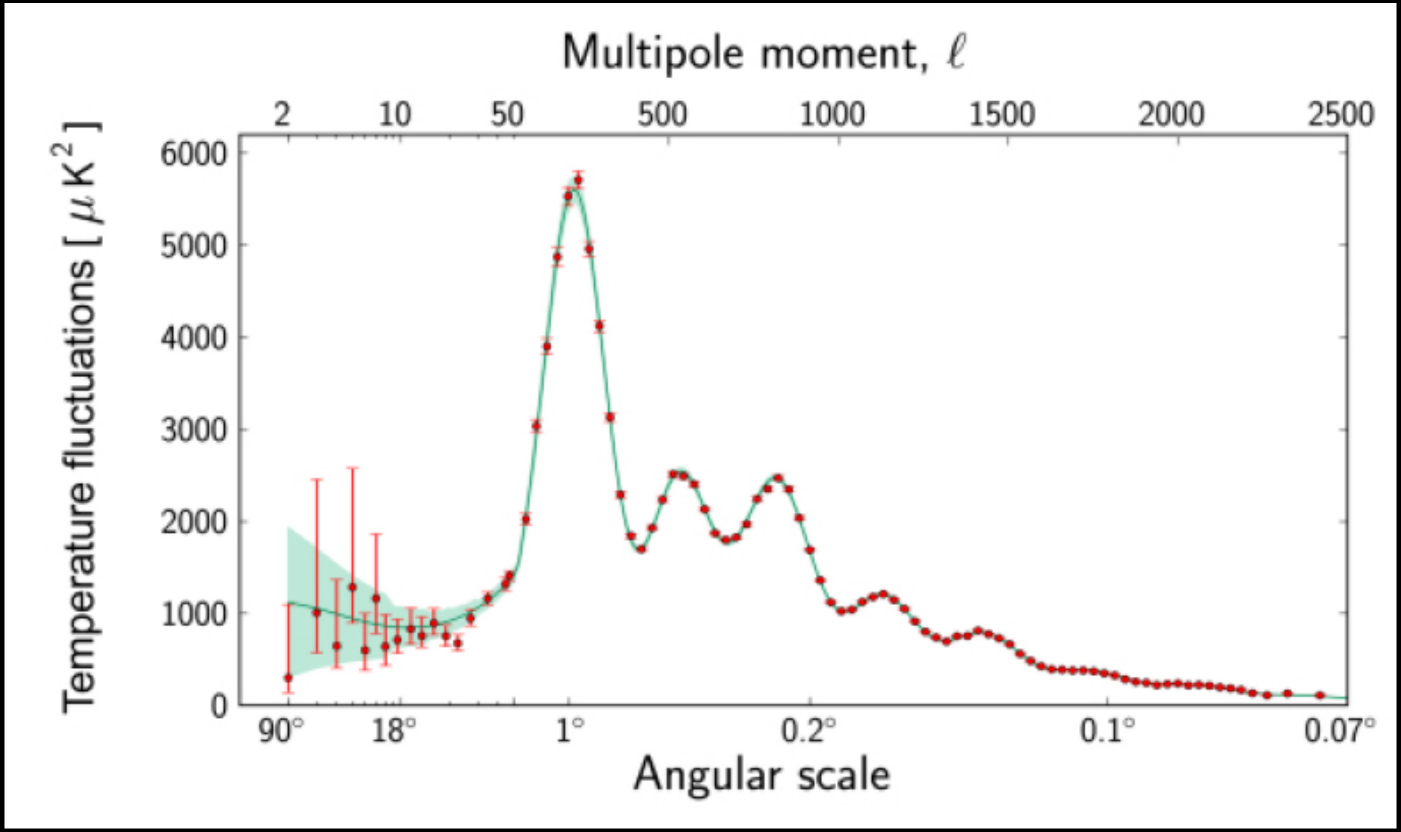
- Goal is to constrain the dark energy equation of state w
- Galaxy Surveys probe the Universe today. Armed with priors from the CMB, they constrain w with multiple independent probes
- Cosmic Microwave Background (CMB) experiments probe the Universe when it was 400,000 years old and perturbations were linear. Tightly constrain other cosmological parameters

Cosmic Microwave Background



Map of small inhomogeneities in the Universe when it was 400,000 years ol

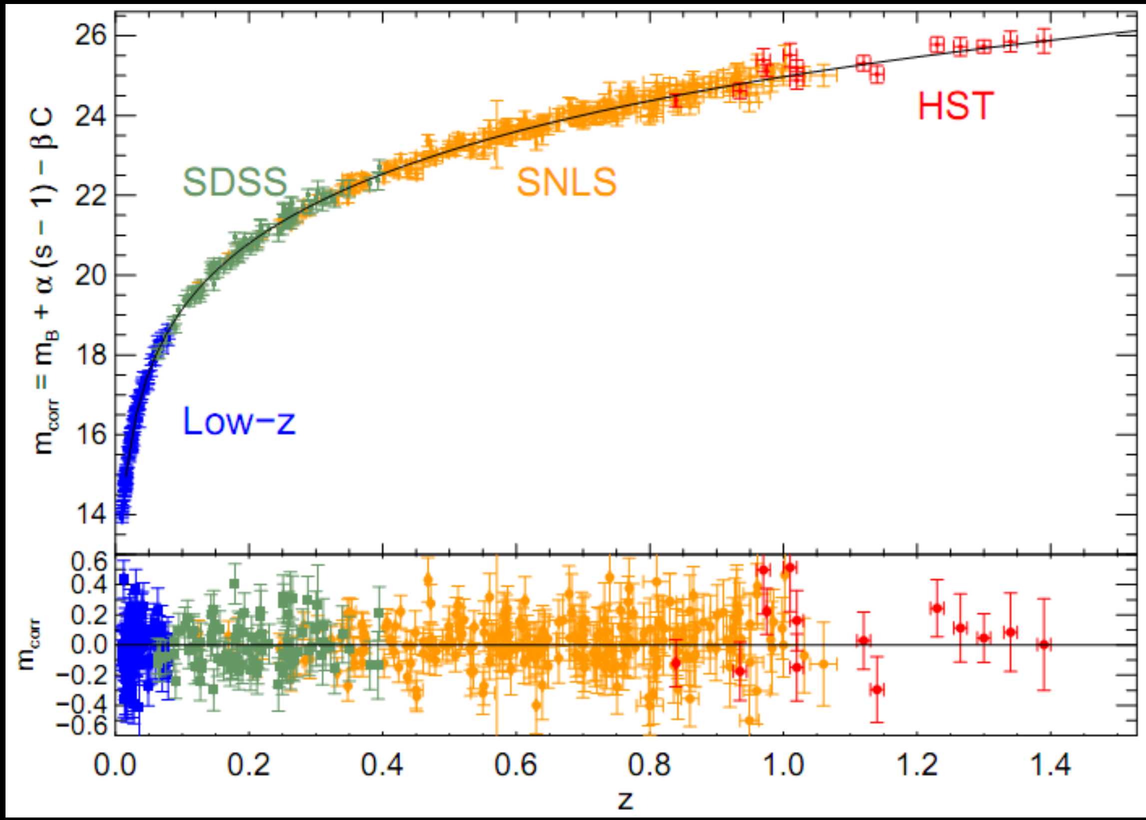
CMB Anisotropies Constrain Parameters



Pattern of harmonics pins down: baryon density, cold dark matter density, geometry of the Universe, primordial fluctuations

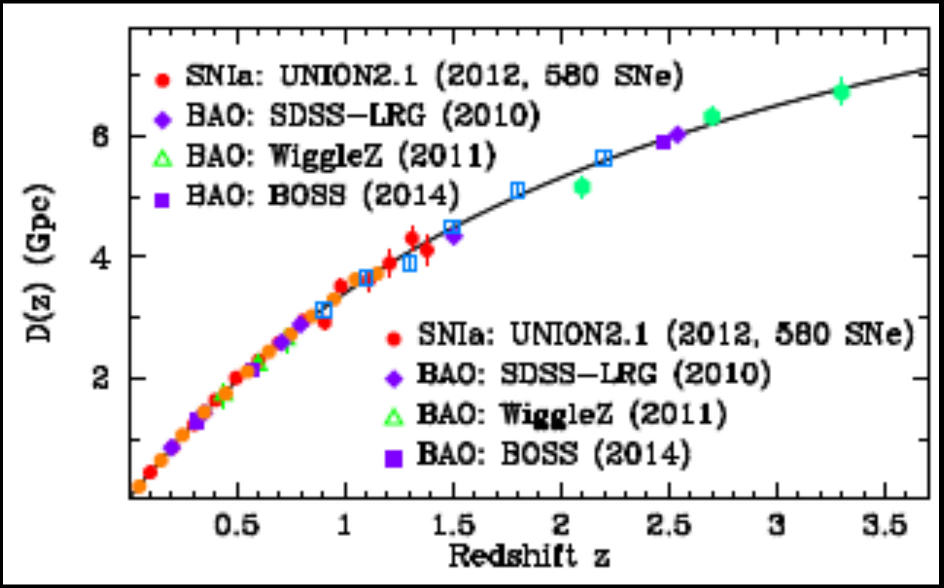
Type Ia Supernovae

- Supernova are bright (so can be seen from far away) and standardizable (so can be used as distance indicators)
- Enable us to map redshift-distance relation, i.e., the expansion history of the Universe



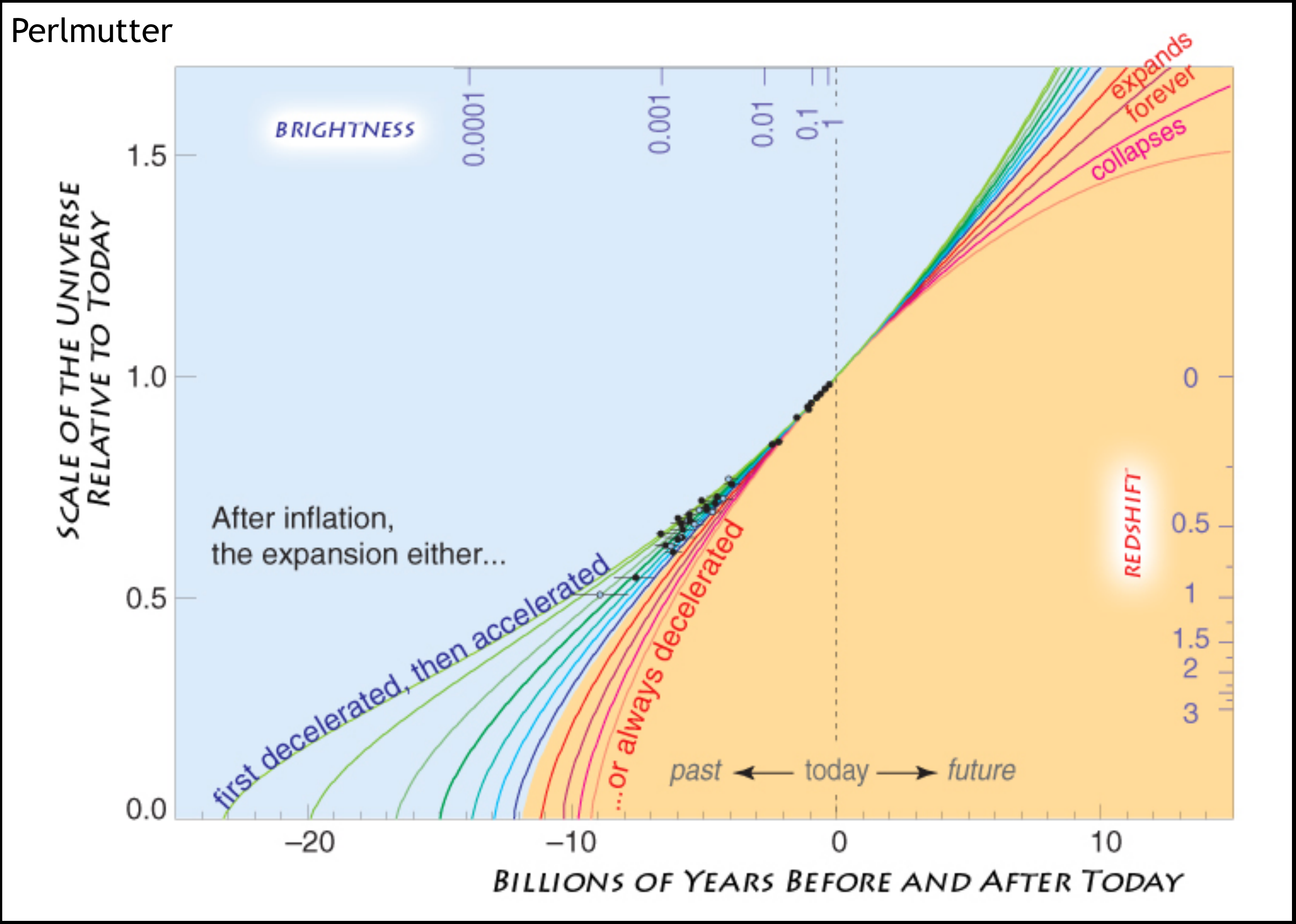
Baryon Acoustic Oscillations

- Clustering of Galaxies traces clustering of matter
- Feature of baryon-photon oscillations imprinted at physical scale of 150 Mpc.
- Location in angular space yields distance to galaxies

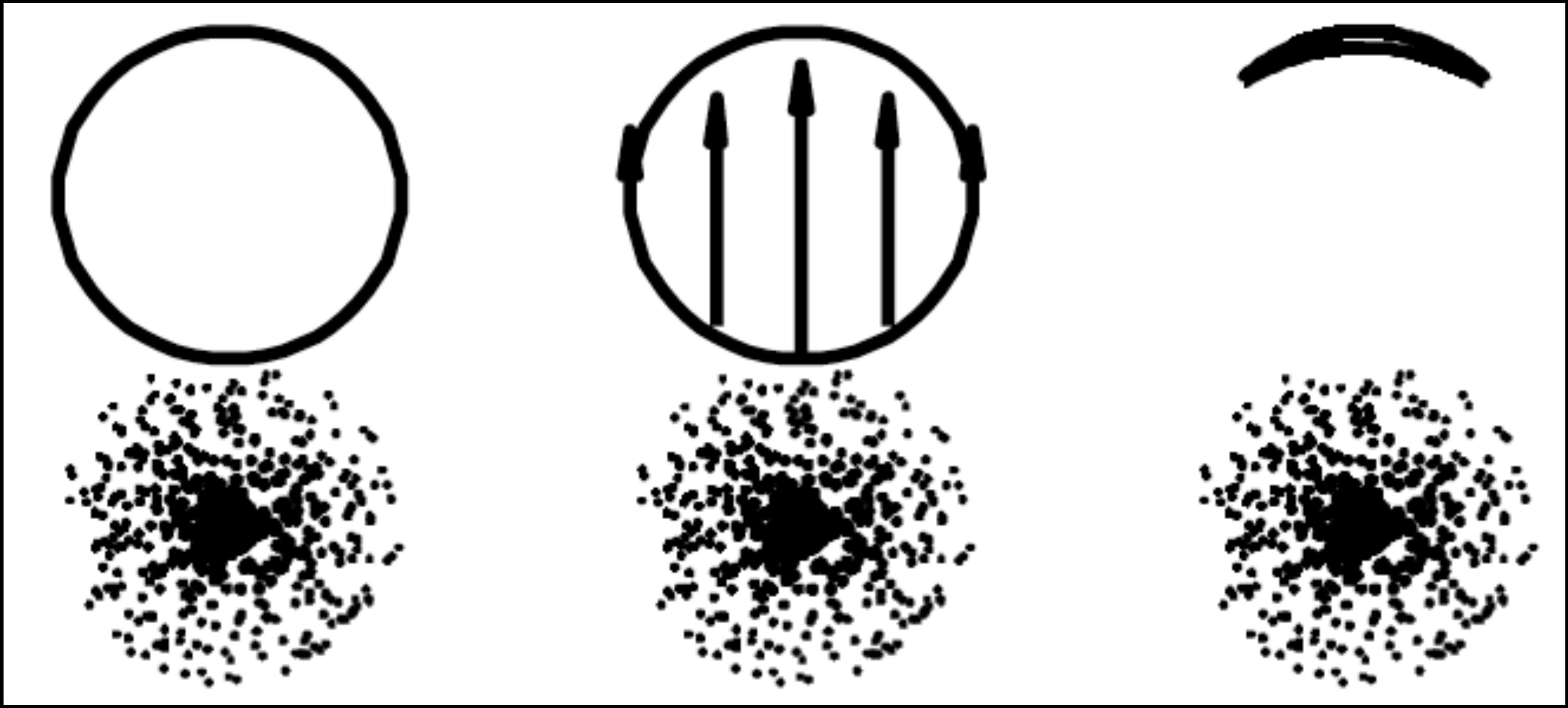


Snowmass: Kim et al 2014

Enable Chart of Expansion History, constraining *w*

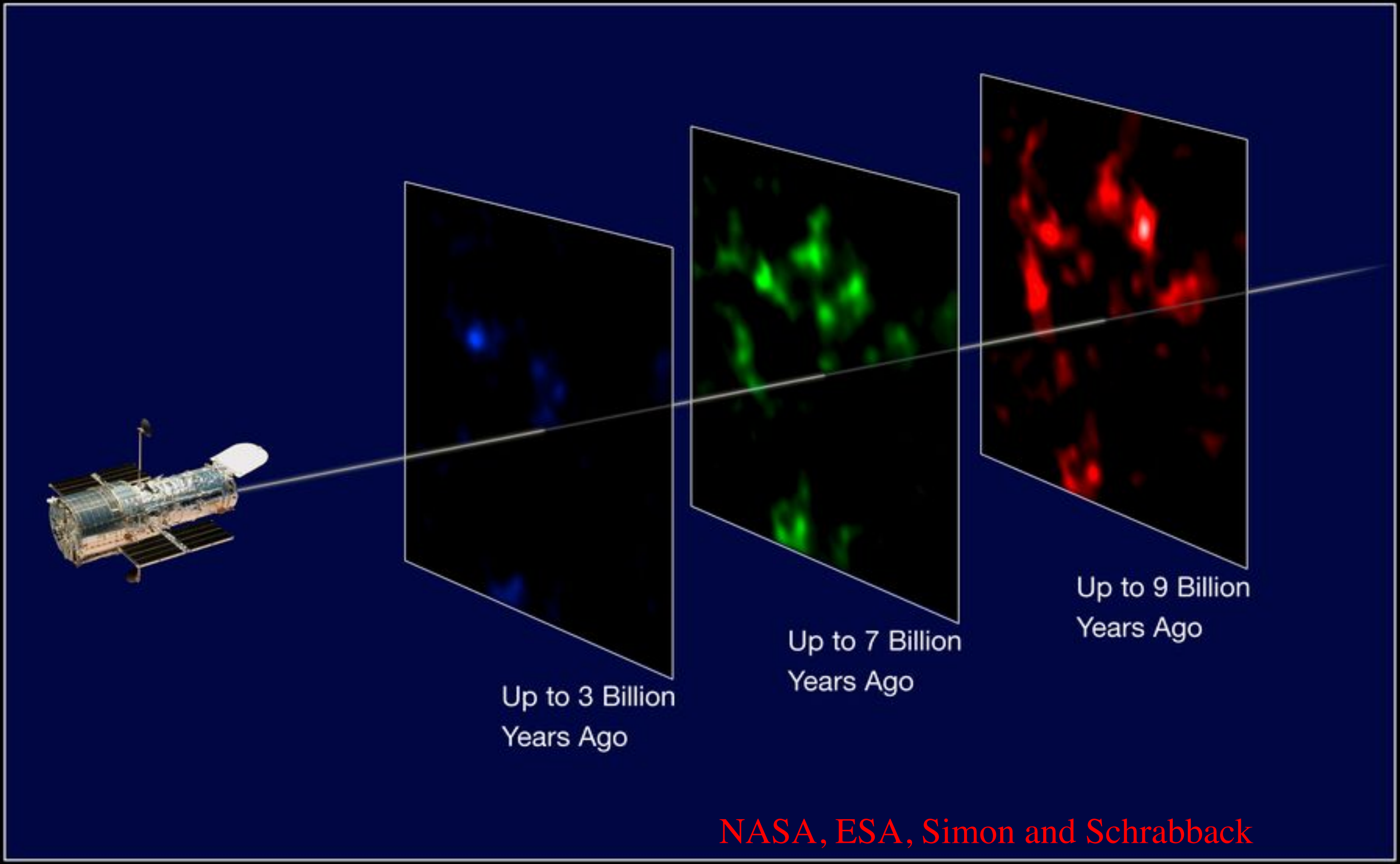


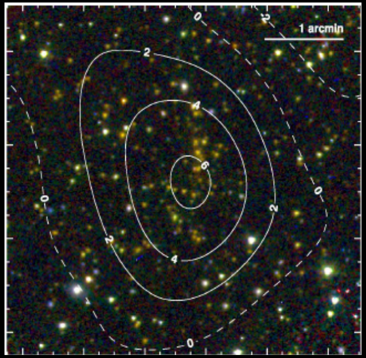
Weak Gravitational Lensing:
Galaxy Shapes are Distorted by intervening Mass



Infer *convergence* κ, mass integrated along line of sight

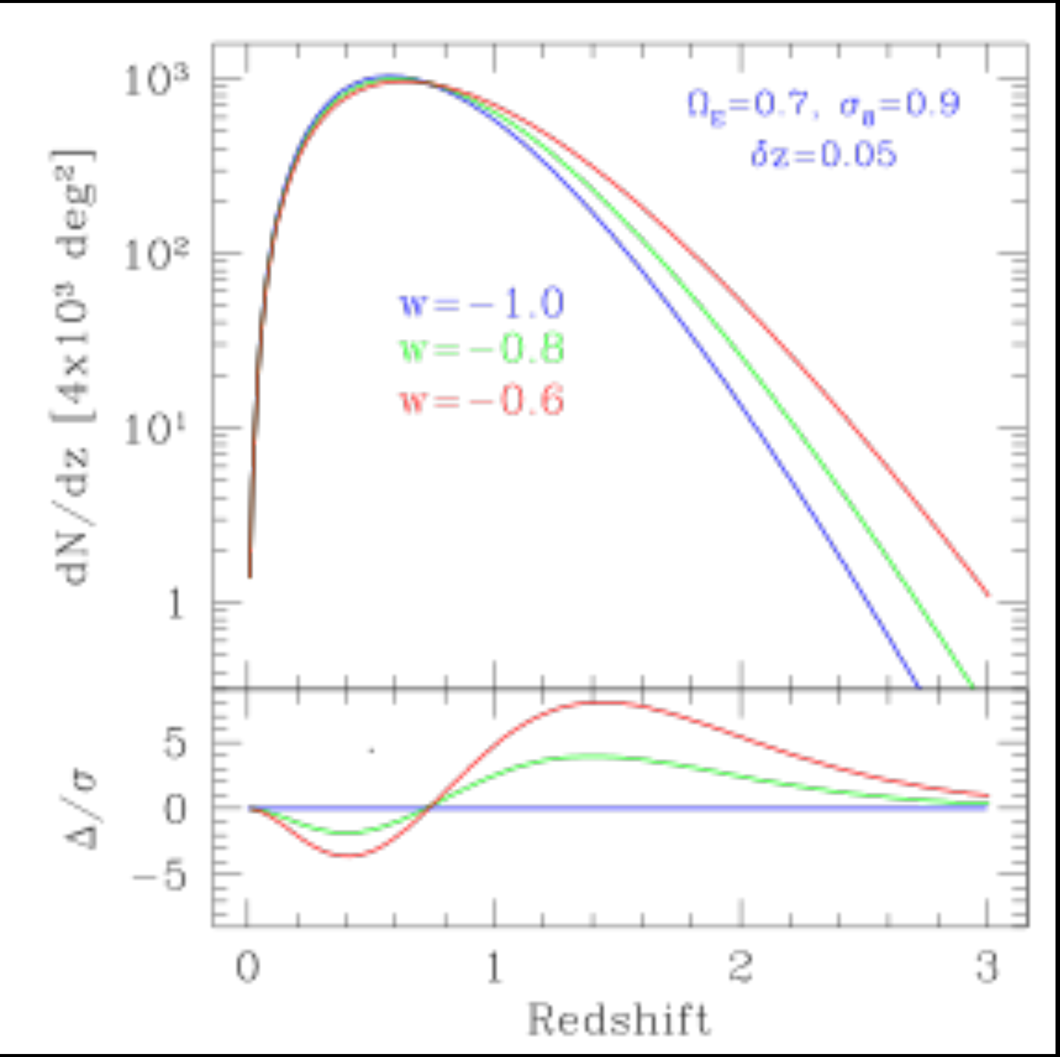
Convergence from different redshift slices depends on *w*





Galaxy Clusters

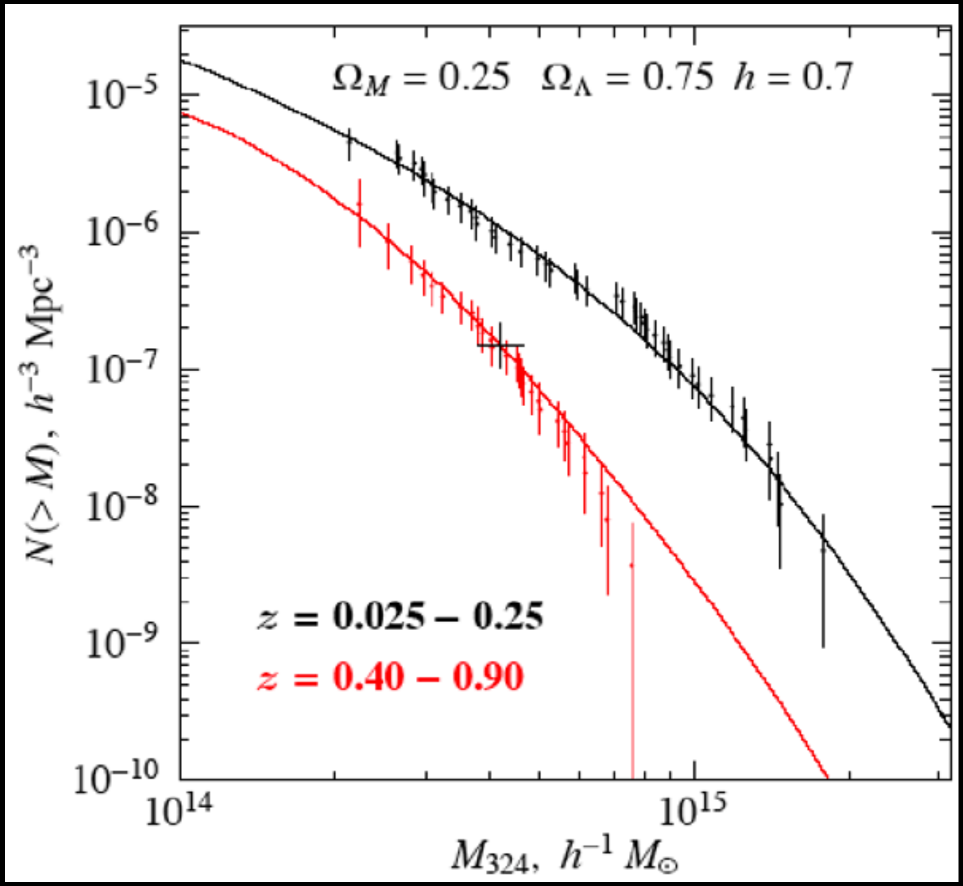
The number of large galaxy clusters as a function of redshift depends on *w*



Frieman, Turner, & Huterer 2009

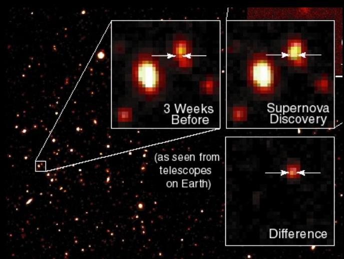
Galaxy Clusters

- Abundance probes tail of probability distribution so is exponentially sensitive to variance: (Prob ~ $\exp(-\delta_c^2/2\sigma^2)$)
- Variance as a function of redshift is measure of how fast inhomogeneities grow
- Necessary (and difficult) to determine cluster masses

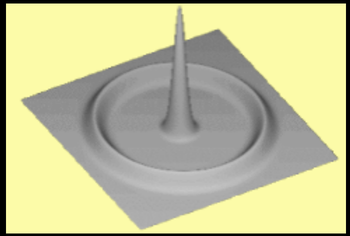


Vikhlinin et al. 2007

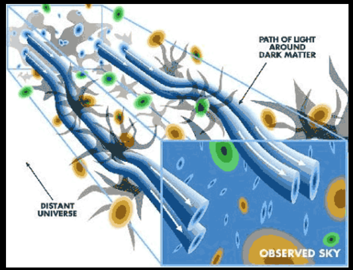
4 Independent probes plus uncorrelated CMB → Constraints on *w*



Supernova Brightness

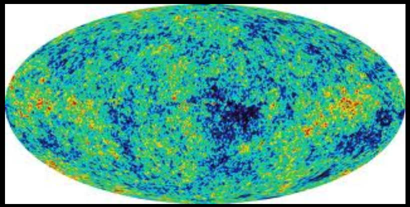


Baryon Acoustic Oscillations

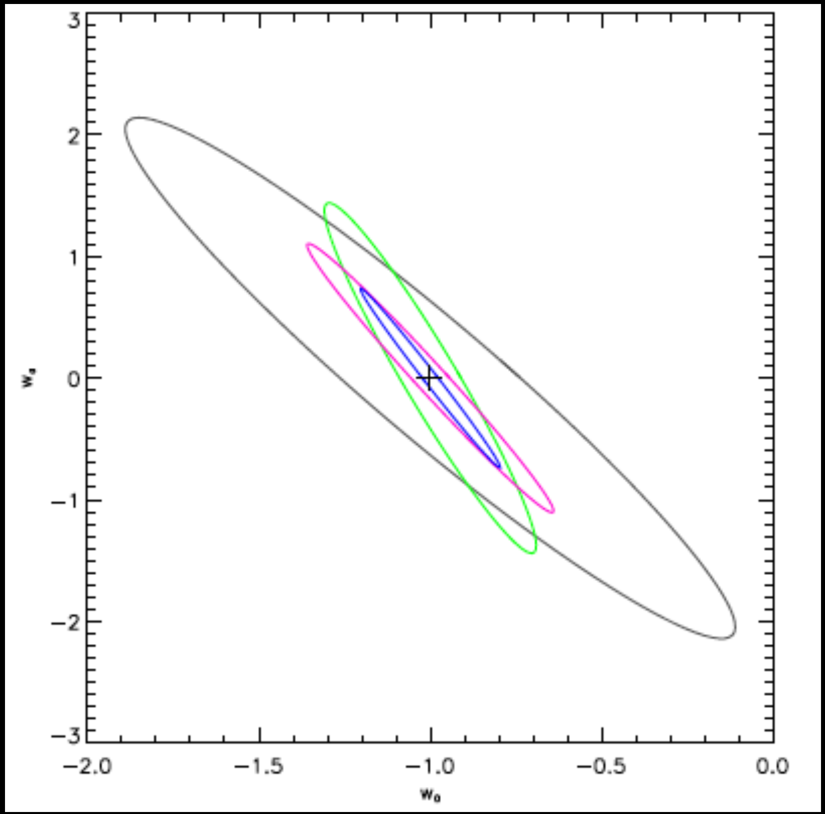


Gravitational Lensing

Galaxy Cluster Abundance



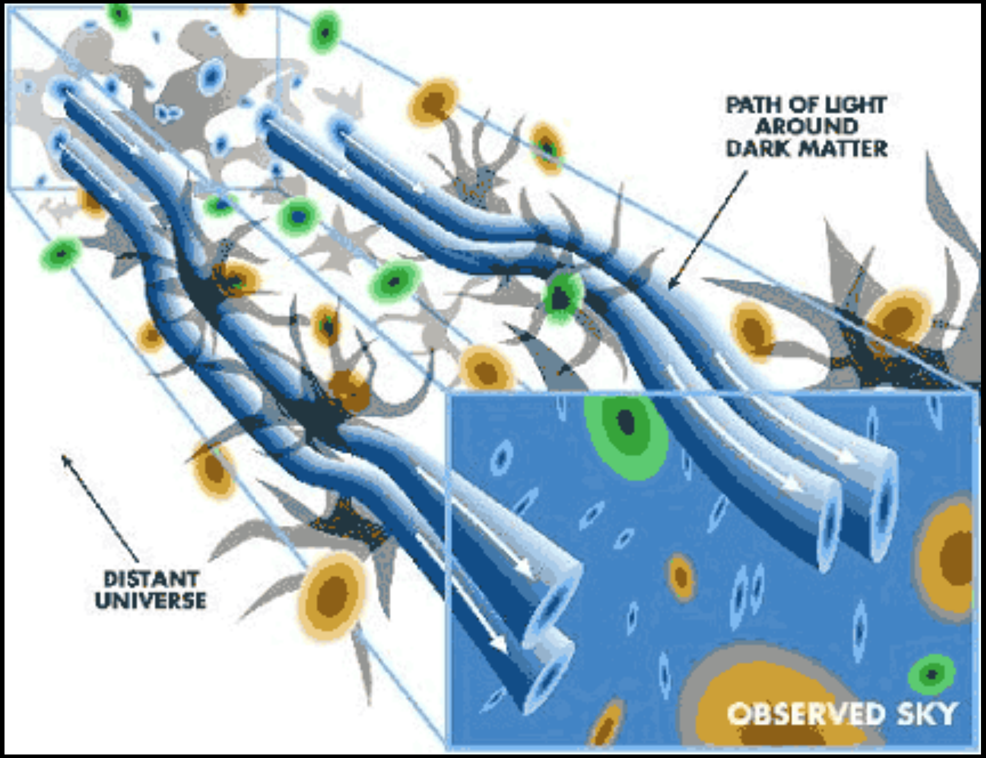
Cosmic Microwave Background



Myth I: Four probes are independent

- Simply multiplying likelihoods is incorrect: all probes are correlated with one another
- Simple example: Lensing and Clusters

-- Number of clusters obviously correlated with distortion of background galaxies
-- Cluster masses obtained via these distortions



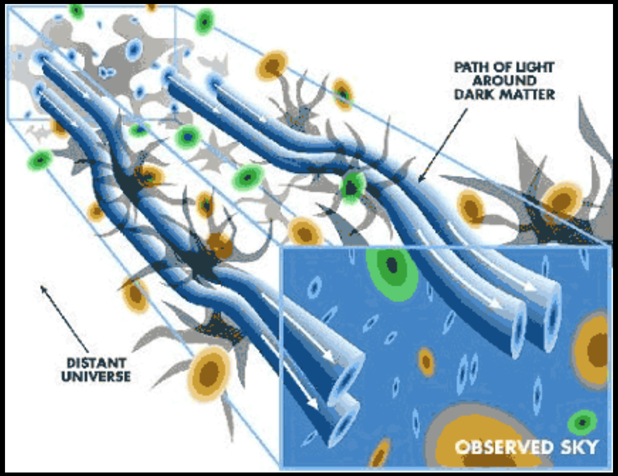
CosmoSIS: Cosmological Survey Inference System

- Designed by Theory & Combined Probes Working Group in DES (Fermilab, Manchester, Chicago) to help the collaboration work together to extract tightest constrains on dark energy
- Software Framework that empowers multiple users to develop and share code, combine analyses, and produce robust cosmological parameter constraints
- Already in use in DES, gaining traction with the broader community (breakout workshop in 2014; v1.2 recently released)

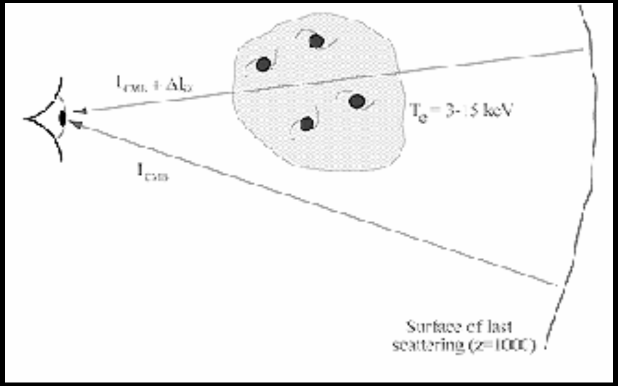
https://bitbucket.org/joezuntz/cosmosis/wiki/Home or contact me

Myth II: CMB is uncorrelated with Galaxy Surveys

- Gravitational Lensing



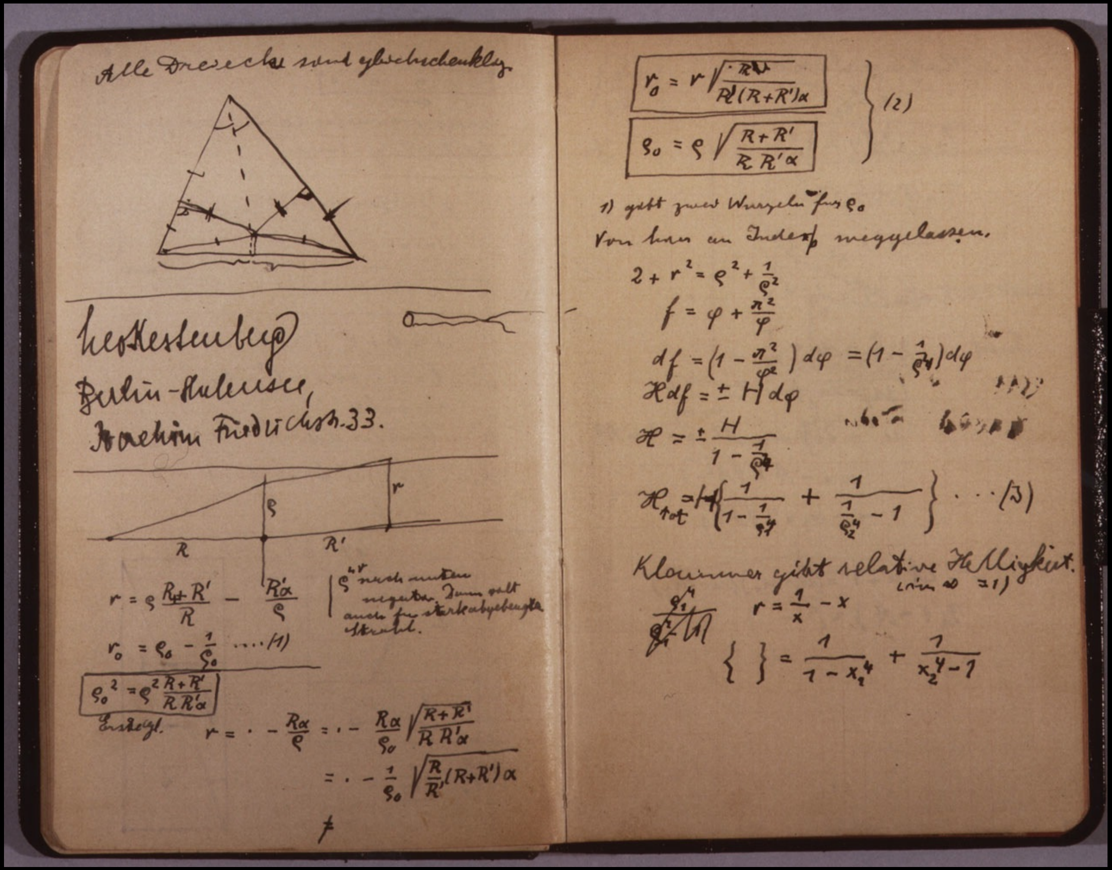
- Sunyaev-Zeldovich Effect



Gravitational Lensing

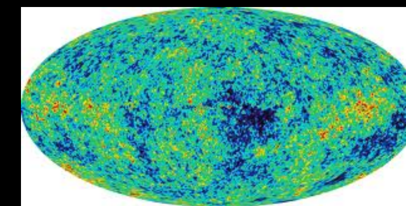
We are used to discrete objects (galaxies, QSOs) being lensed.

How do we study the lensing of the temperature (a Gaussian field) at last scattering?

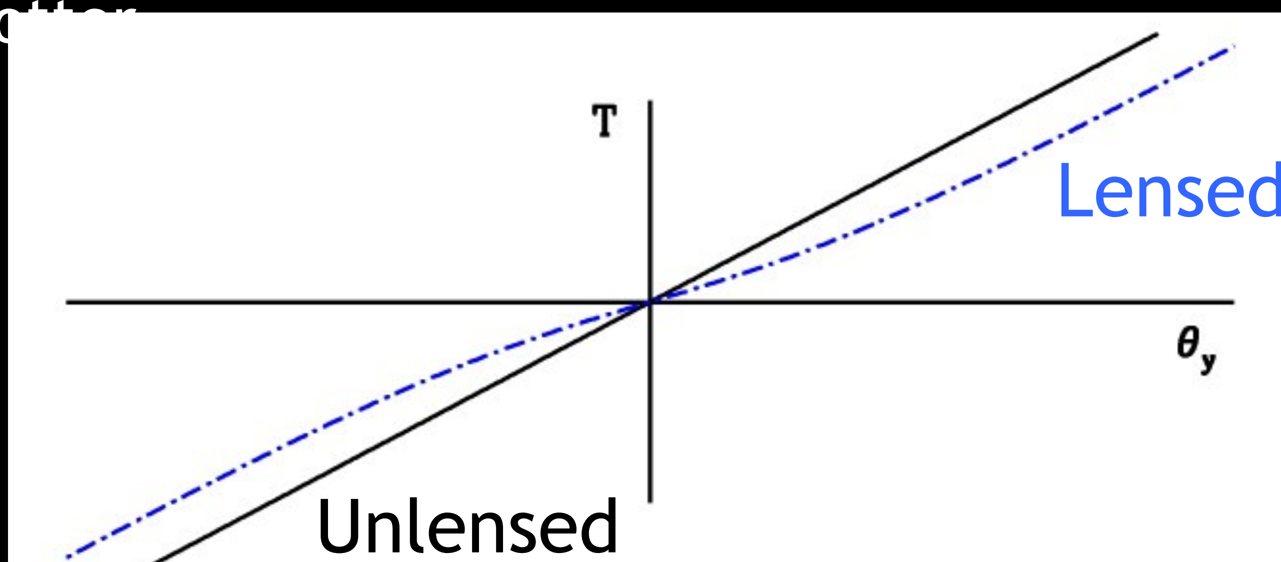


Einstein 1912!

Gravitational lensing by galaxy clusters

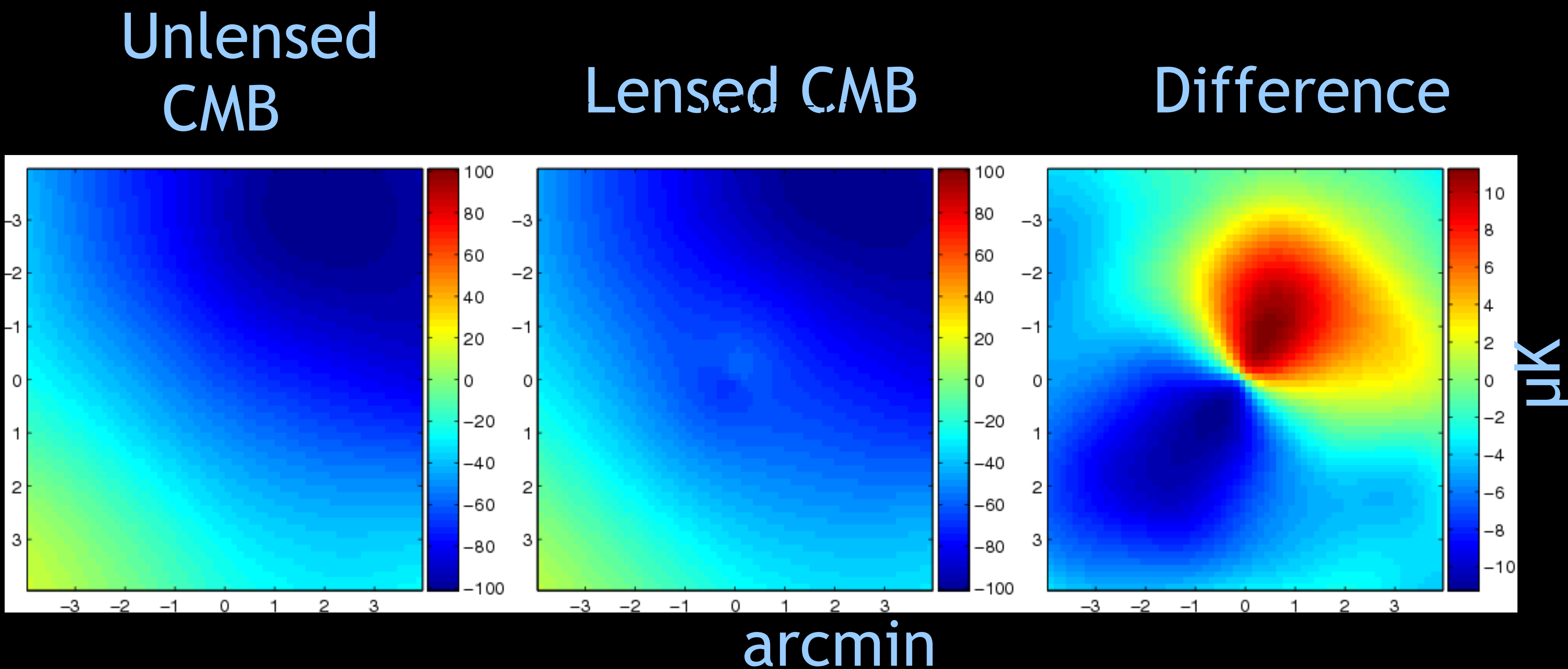


Hot spots cooler when lensed and cool spots hotter



Seljak & Zaldarriaga 2001

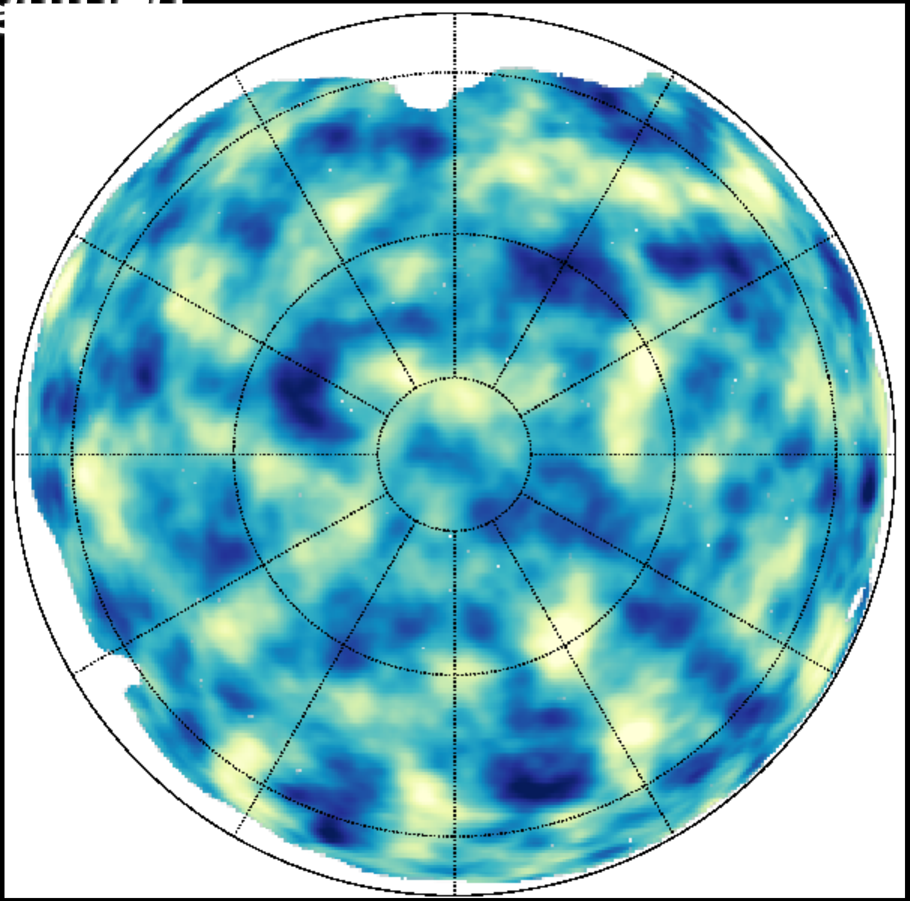
The Signal



Lewis and Challinor, 2006

More generally, can make maps of convergence

Power behind over-dense regions is magnified

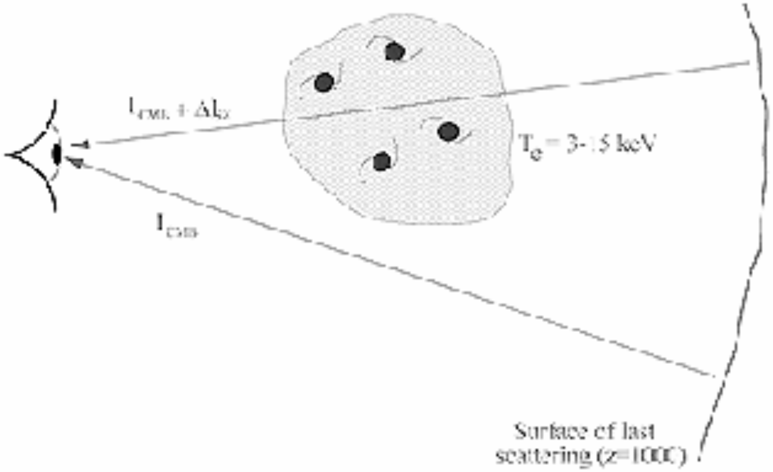


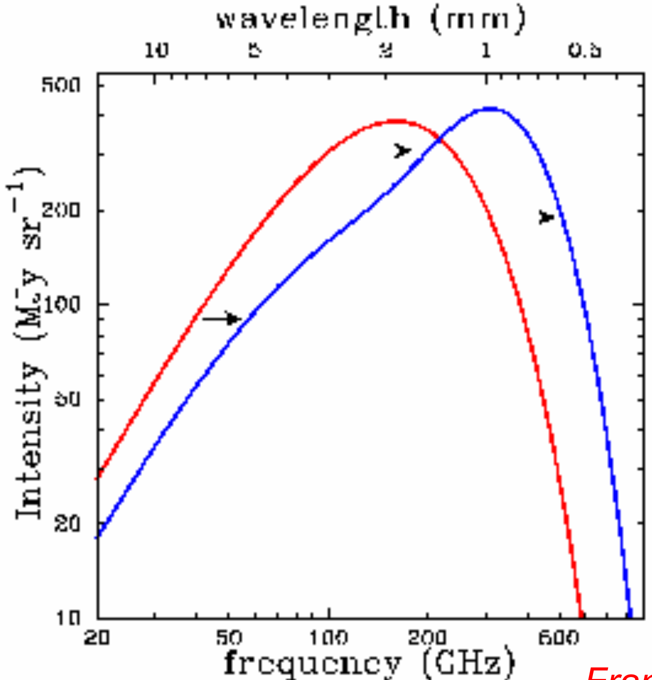
Infer κ by measuring anisotropy of power

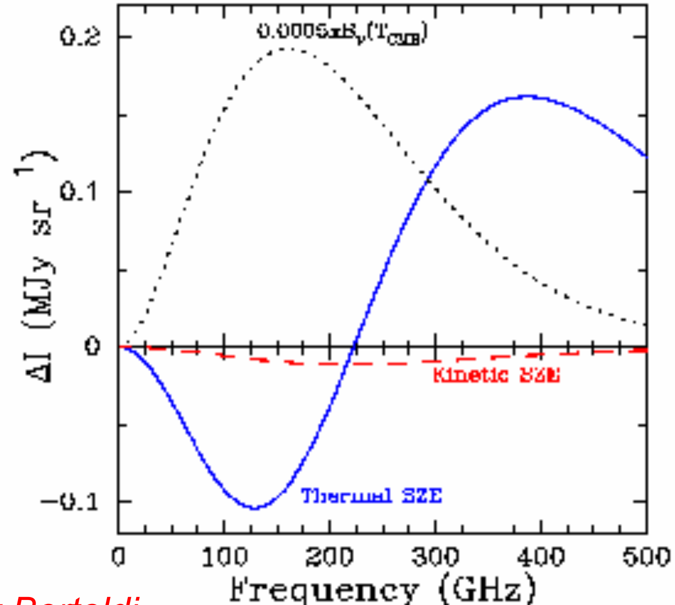
Planck

Sunyaev-Zel'dovich Effect

$$\frac{\Delta T}{T_{CMB}} = g(x) \int dl \, n_e(l) \, \frac{k_B \, T_e(l)}{m_e c^2} \, \sigma_T$$







mJy

Frank Bertoldi

Myth III: *w* is the only goal

Can explain acceleration without dark energy (w) by modifyin
GR:

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\left[R + f(R)\right] + \int d^4x\sqrt{-g}\,L_m$$

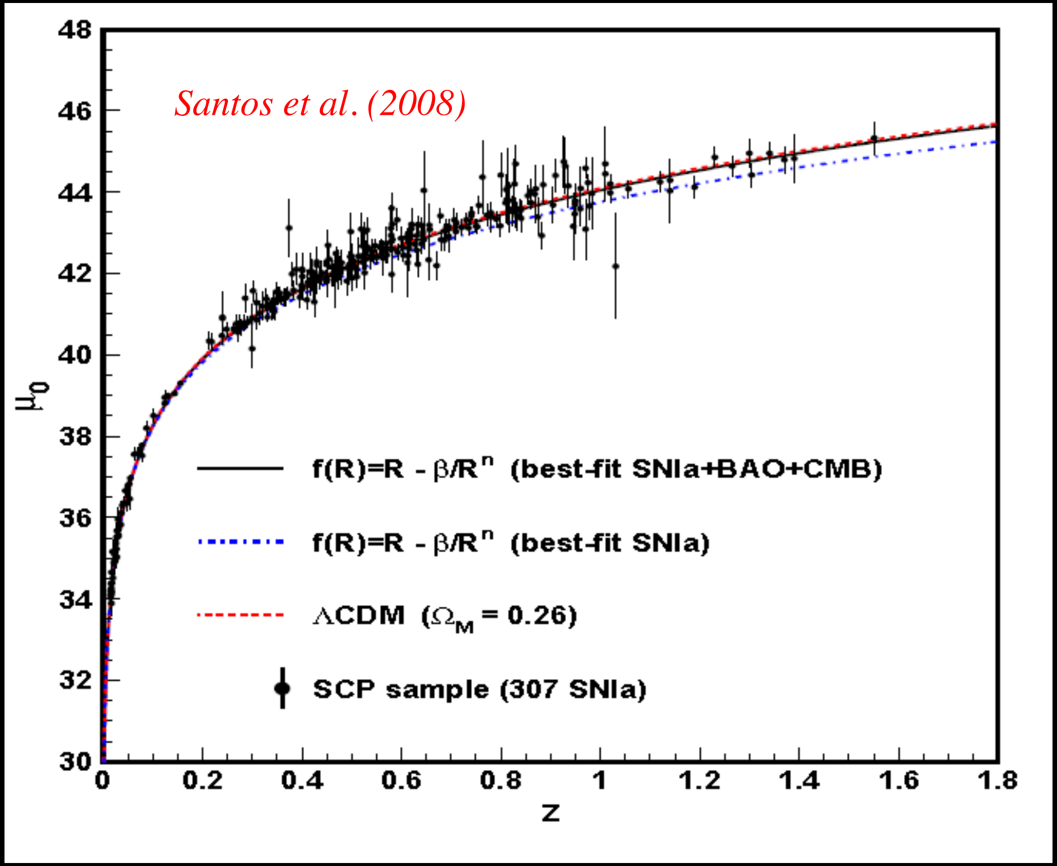
For the cosmological metric, the acceleration equation generalizes to:

Get acceleration if these terms are positive

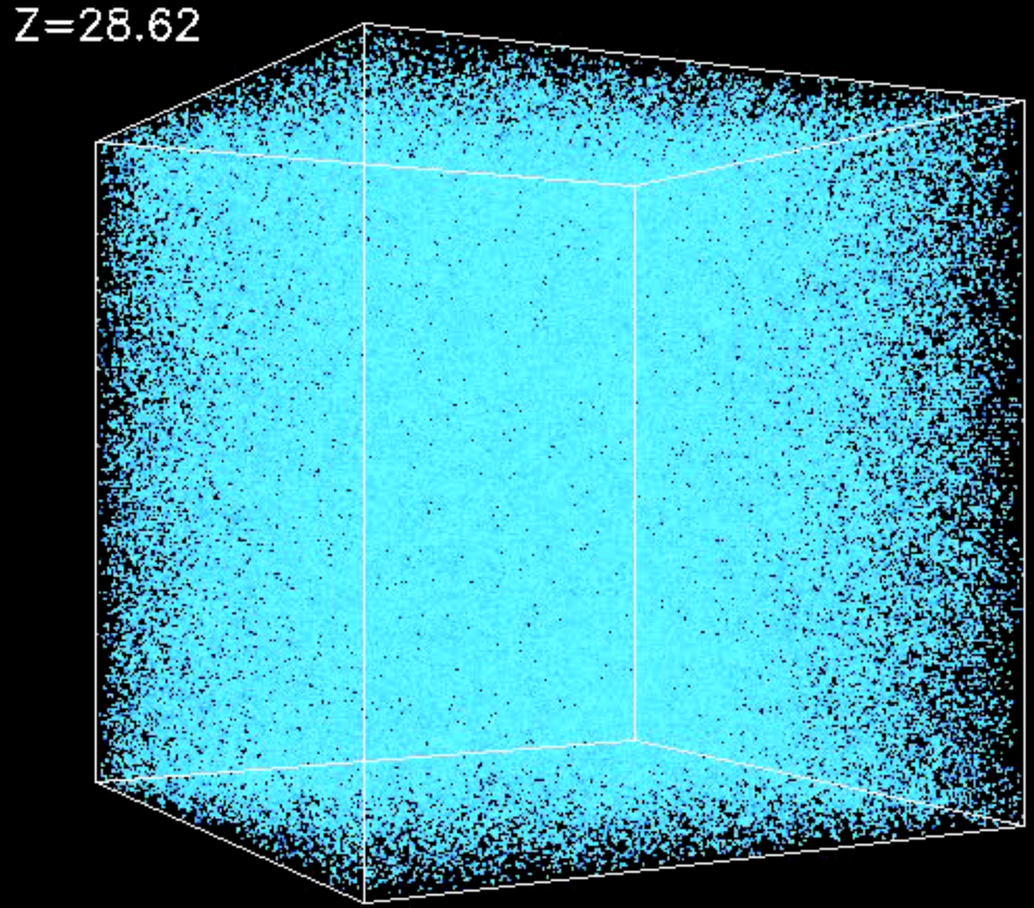
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) + \left[\frac{\partial f}{\partial R}H^2 - \frac{f}{6} - \frac{\partial [illegible] / \partial R}{2}\right]$$

Easy to fit Expansion History

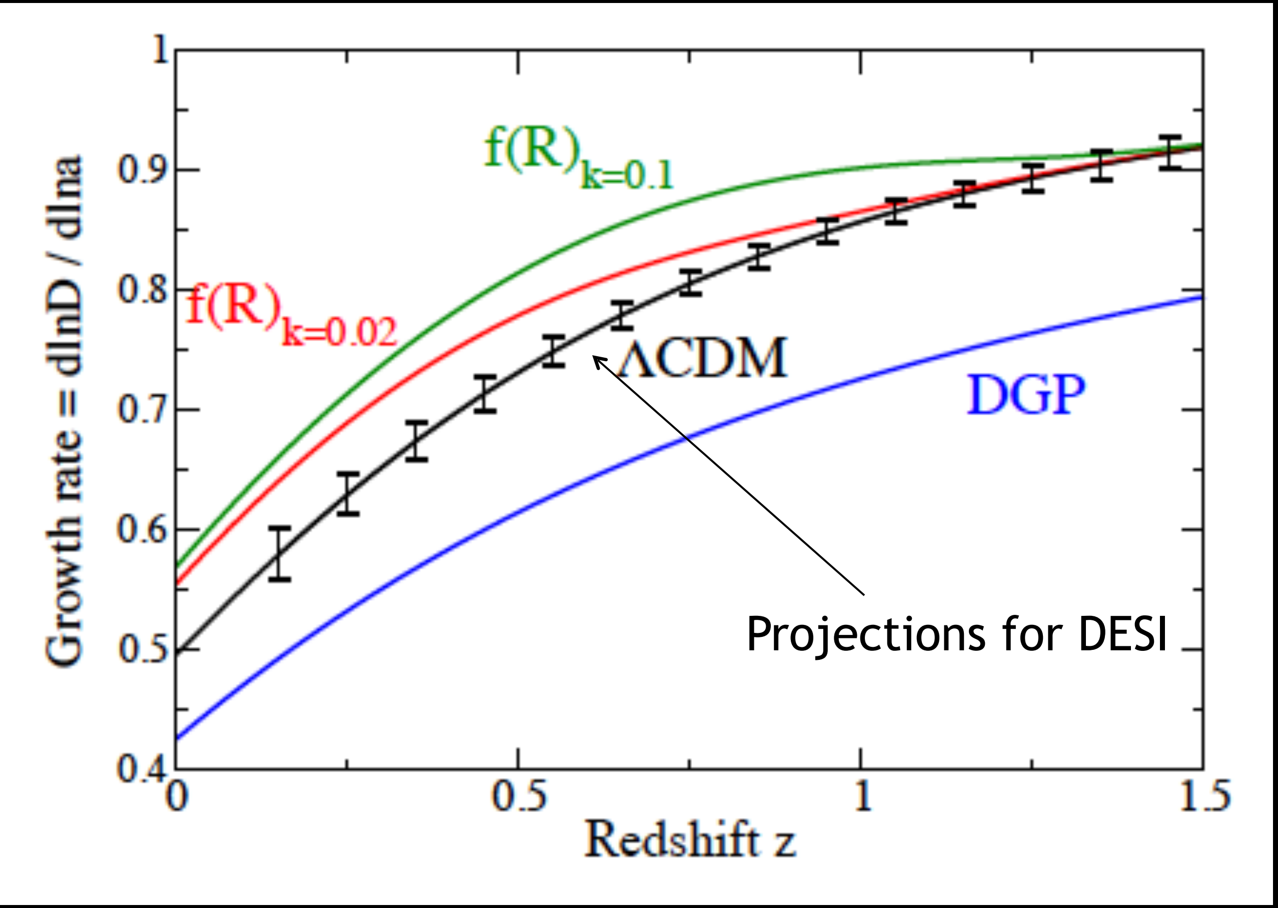
The new parameter in f(R) has dimensions of mass and is of order 10^{-33} eV



But the rate at which structure grows is a key discriminant

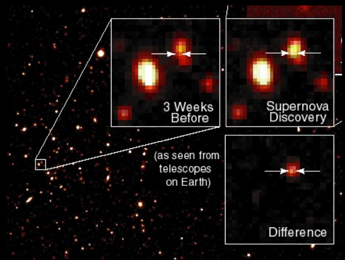


Growth differs in Modified Gravity Models

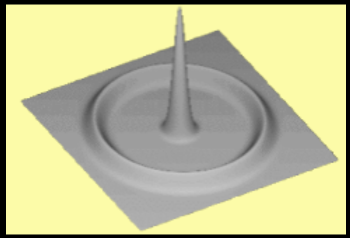


Snowmass: Huterer et al. 2014

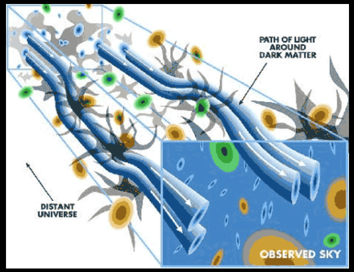
4 Independent probes plus uncorrelated CMB → Constraints on *w*



Supernova Brightness

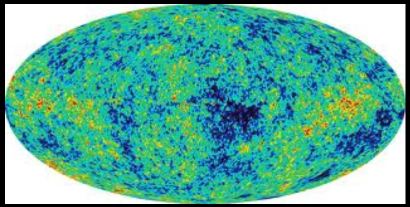


Baryon Acoustic Oscillations

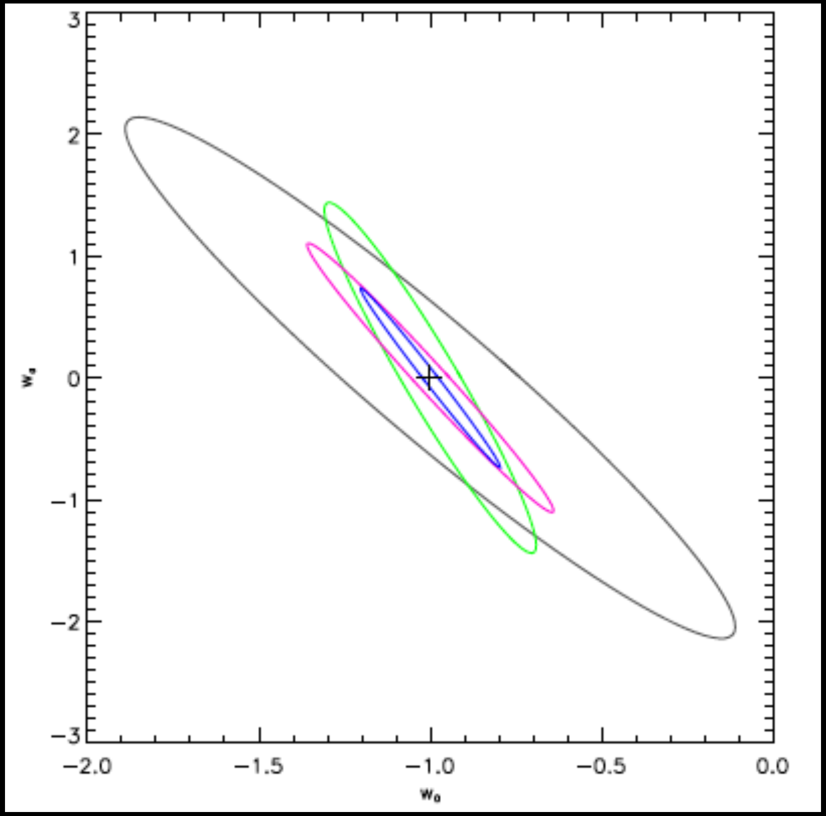


Gravitational Lensing

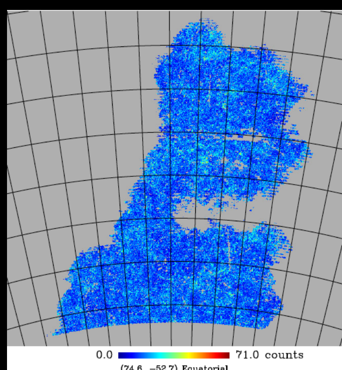
Galaxy Cluster Abundance

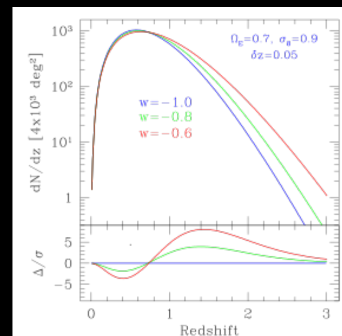


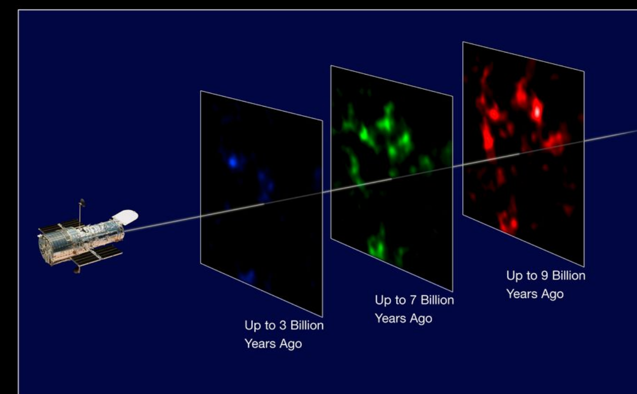
Cosmic Microwave Background

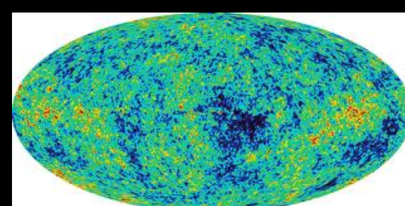


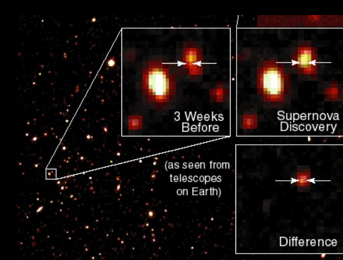
Determine what is driving the current epoch of acceleration …









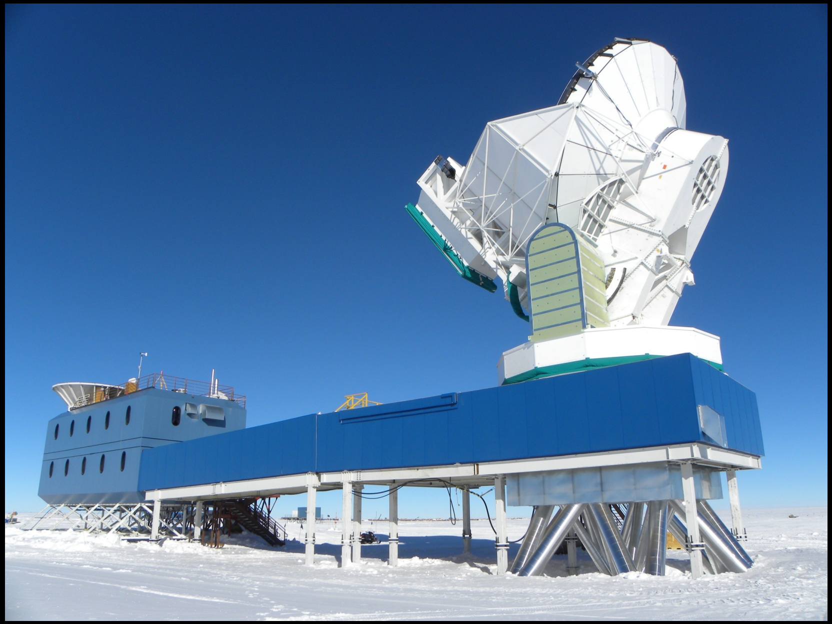


by combining all probes including CMB to measure expansion history and growth of structure

South Pole Telescope

- 10 meter telescope

- SPT-SZ survey* (2009-12)
  - 2500 sq. deg.
  - ~1 arcmin resolution
  - ~18 μK-arcmin noise
  - 3 bands: 90,150, 220 GHz

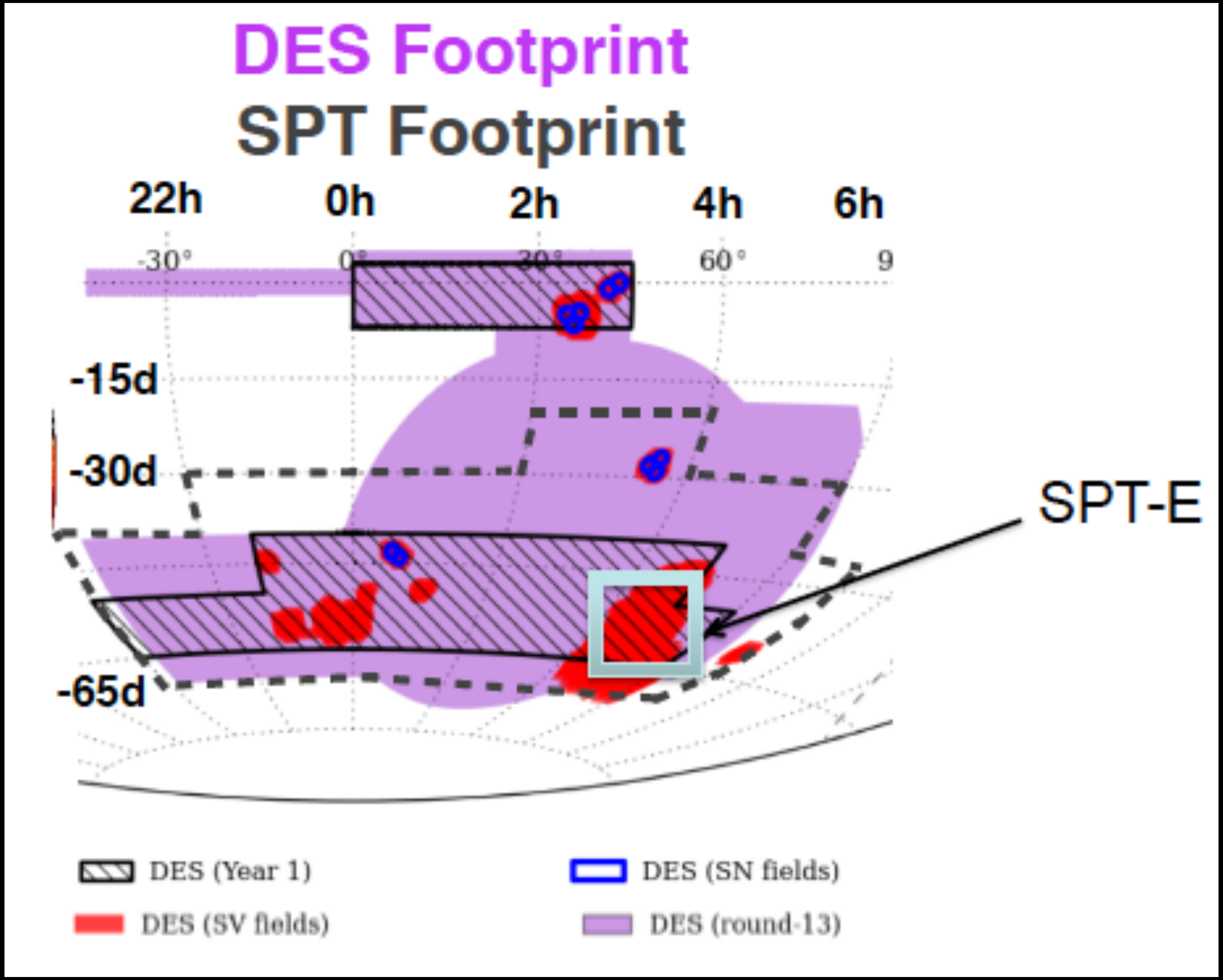


* Since then SPT-Pol, soon SPT-3G, then CMB-S4

Dark Energy Survey

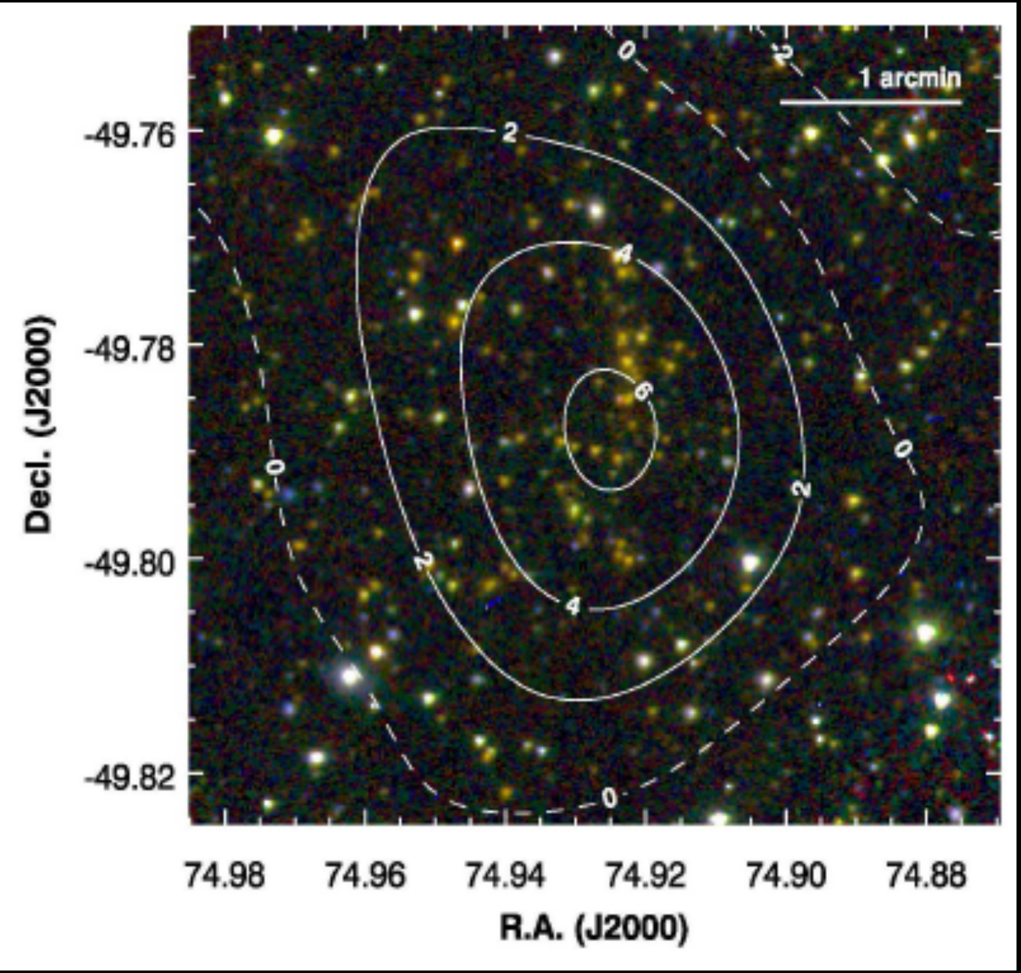
- 570 Megapixel camera built at Fermilab for the Blanco 4m telescope in Chile
- Full Survey 2013-18 *(SV 2012)*
  - 5000 sq. deg. (200)
  - 5 Bands
  - ~24^{th} magnitude
  - Sub-arcsec seeing

Overlapping Areas



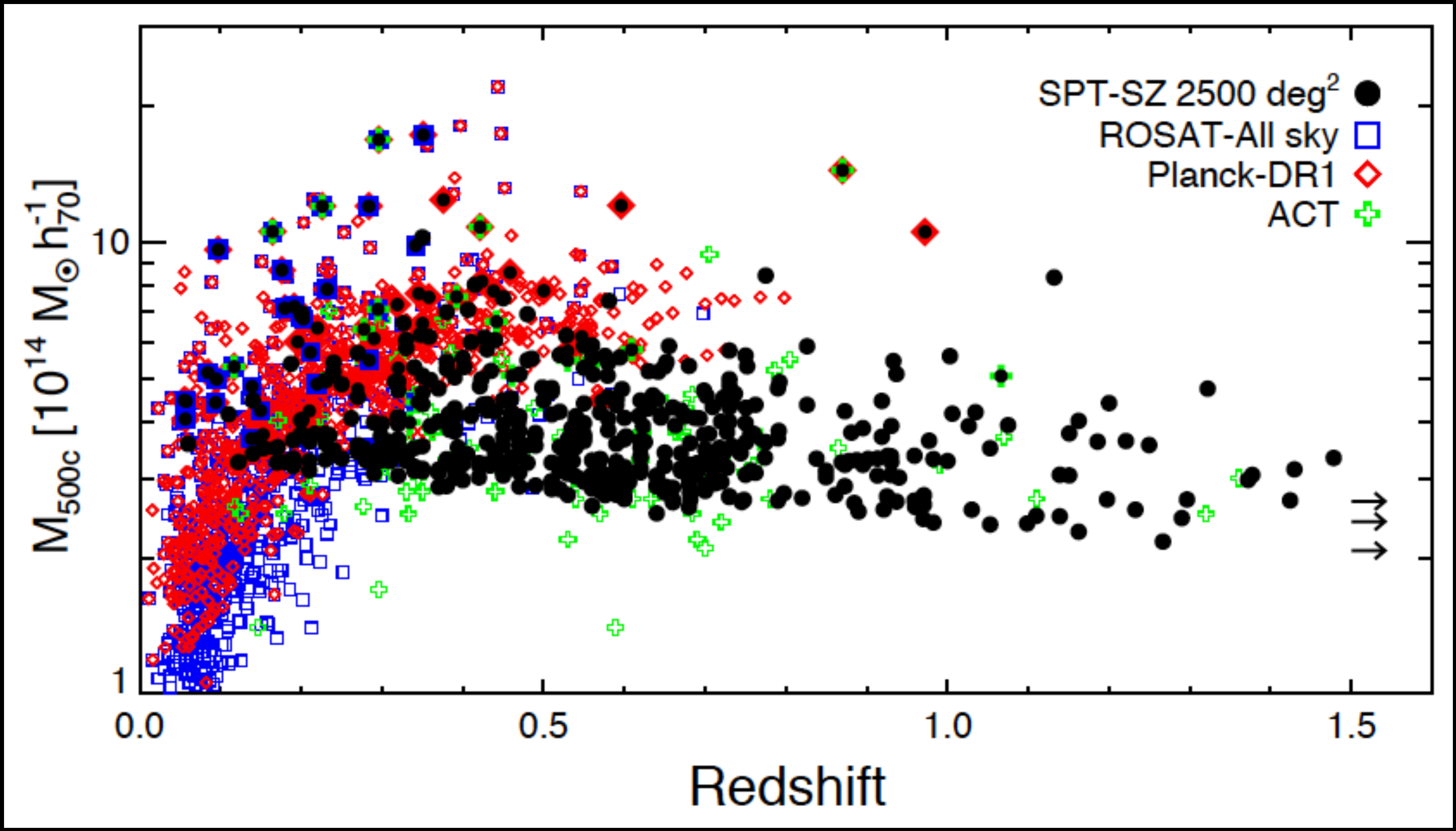
Clusters discovered with SPT-SZ

- Contours show SZ S/N
- Colors from follow-up observations (in this case Spitzer and Magellan)
- Obtain estimates of mass and redshift



Bleem et al. 2015

Clusters discovered with SPT-SZ

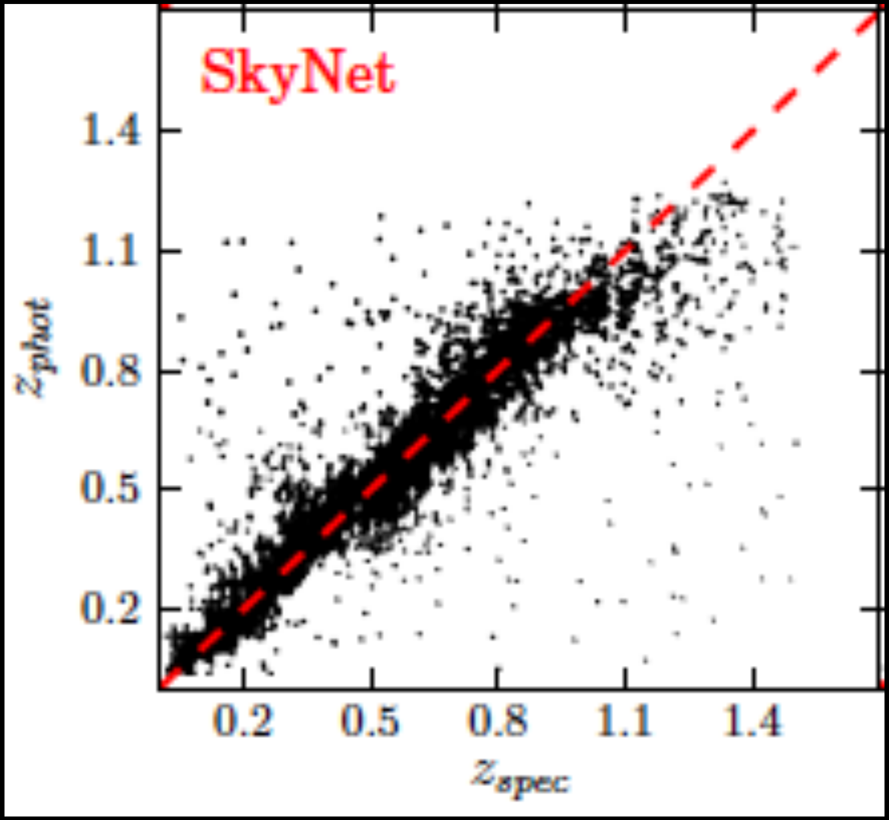


We would like to find these in DES

DES is a Photometric Survey: 2D not 3D

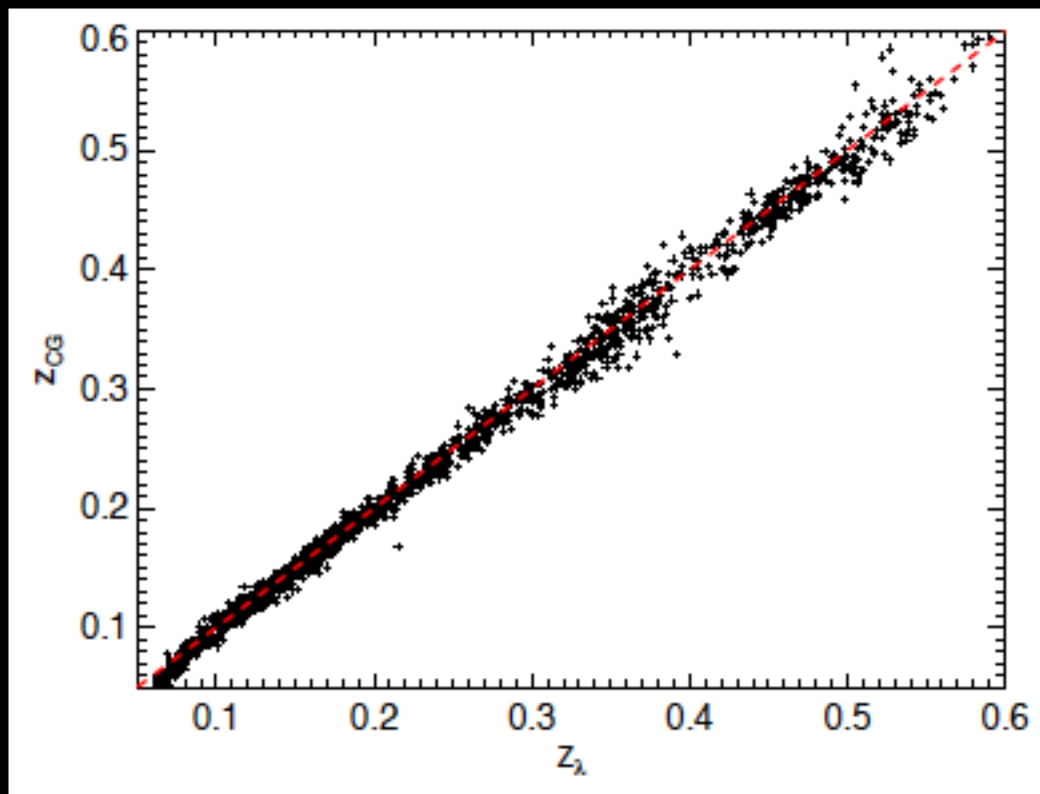
DES is a Photometric Survey: but better than 2D

Use galaxy colors to estimate *photometric* redshifts (distances)



DES: Sanchez et al. (2014)

DES is a Photometric Survey: but much better than 2D for Galaxy Clusters

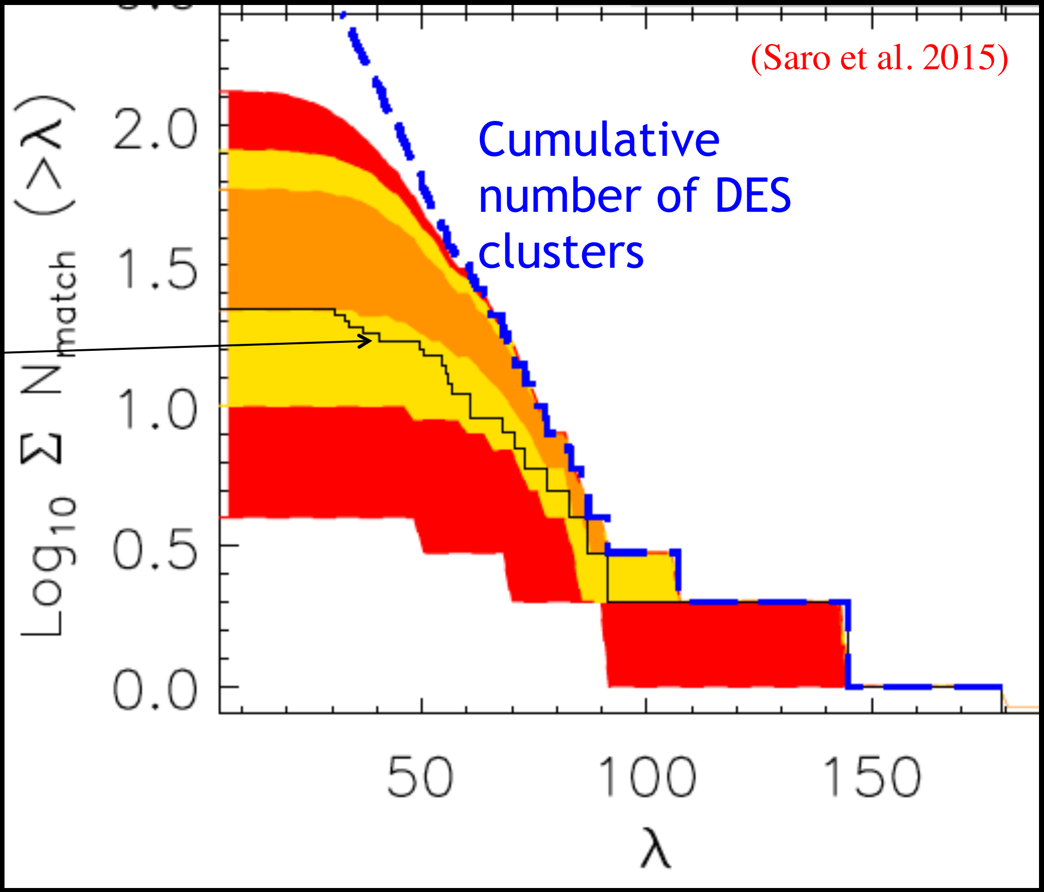


Rykoff et al. (2013)

Calibrating DES Cluster Masses with SPT

Cumulative number of SPT clusters detected by DES

Colored regions are expectations from Monte Carlo (1,2,3 sigma)

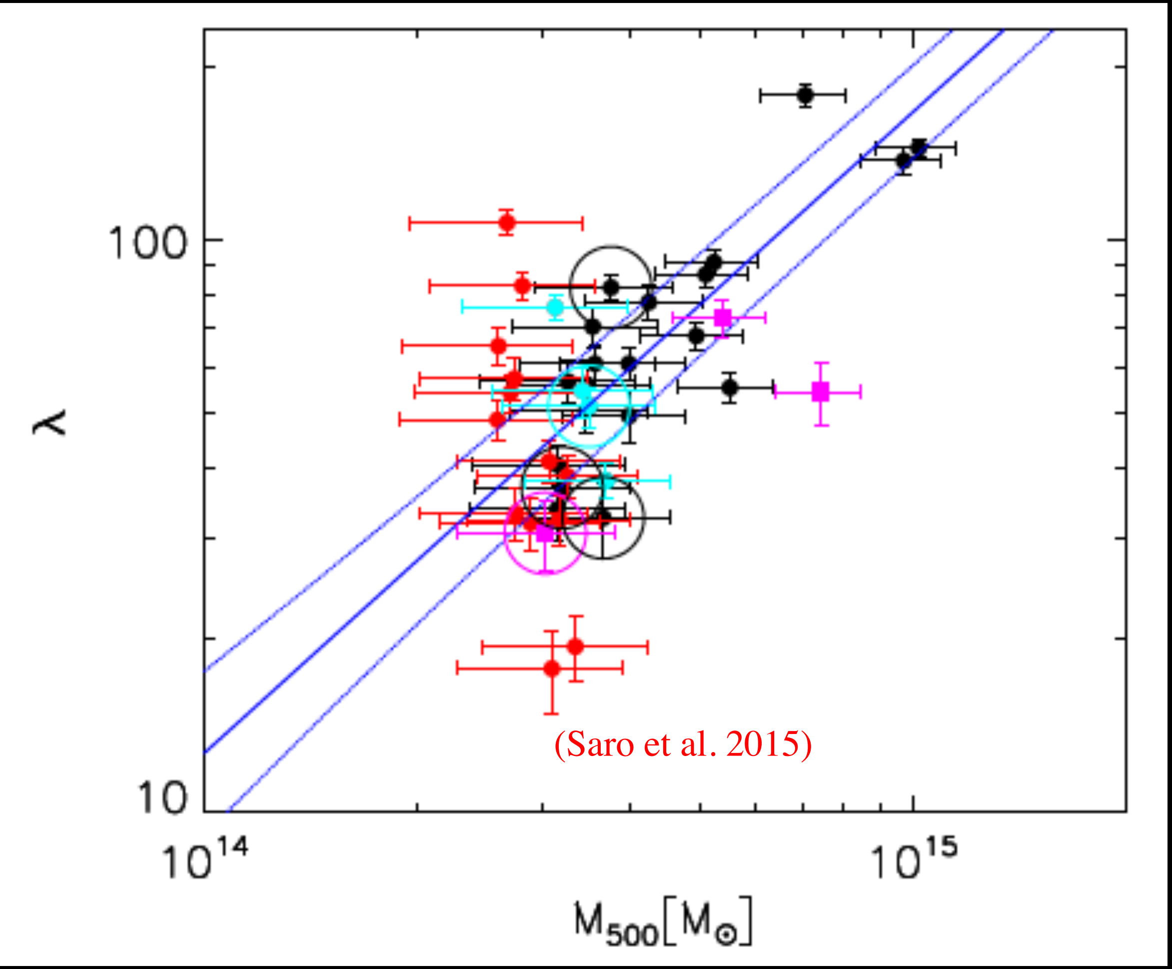


DES Richness

Calibrating DES Cluster Masses with SPT

Tools to estimate cluster masses:

- SZ signal
- X-Ray
- Weak Lensing
- *Optical Richness*

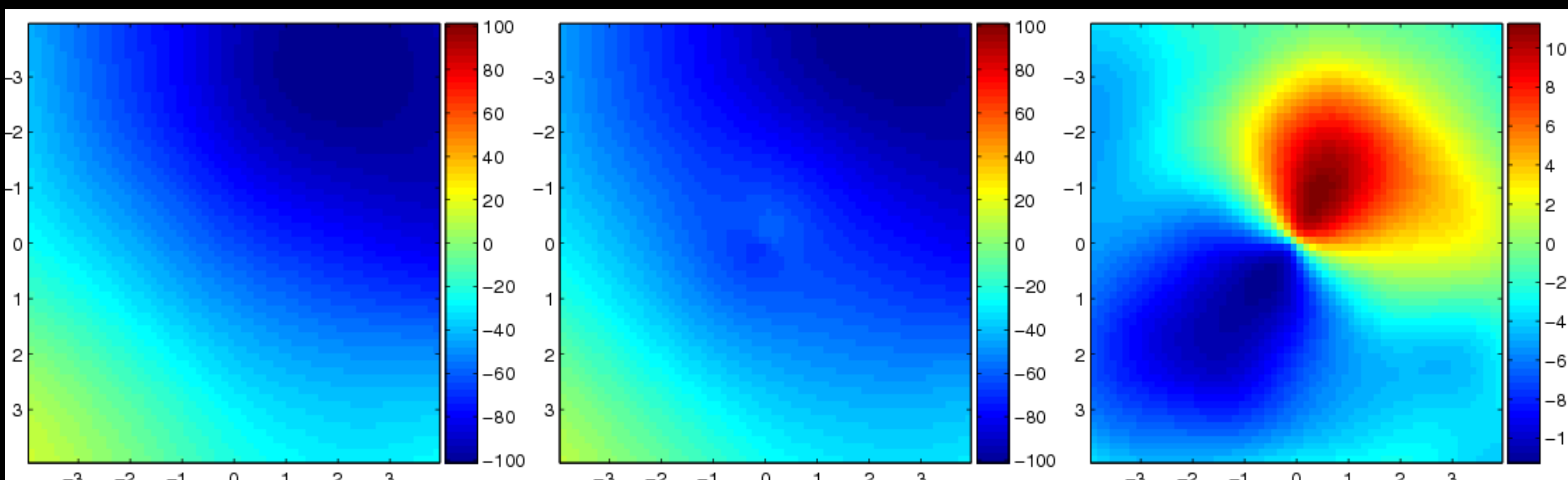


New probe: Lensing of the CMB by Galaxy Clusters

Unlensed CMB

Lensed CMB

Difference



arcmin

μK

Lewis and Challinor, 2006

Likelihood Approach

$$\mathcal{L}(\vec{d};C) = \frac{1}{(2\pi)^{N_{pix}/2}\sqrt{\det(C)}} \exp\left[-\frac{1}{2}\vec{d}^T C^{-1}\vec{d}\right]$$

- N_{pix} = number of pixels in a cutout around each cluster
- d = temperature values in these pixels
- C_{ij} = pixel-pixel covariance matrix

Baxter et al. (2015)

The Lensed CMB Covariance Matrix

Lensing changes effective separations of pixels

$$\vec{\theta}_{ij} \rightarrow \vec{\theta}_{ij} + \delta\vec{\theta}_{ij}$$

$\delta\vec{\theta}_{ij}$ depends on cluster mass distribution, redshift and position on sky

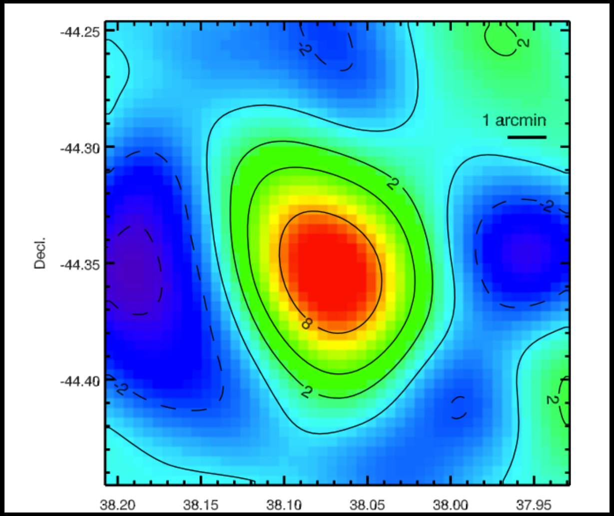
$$C_{ij} \sim \int \frac{d^2 l}{2\pi} C_l e^{i\vec{l}\cdot[\vec{\theta}_{ij}+\delta\vec{\theta}_{ij}]}$$

Parameterize the mass distribution with a single parameter *M* and obtain L(*M*)

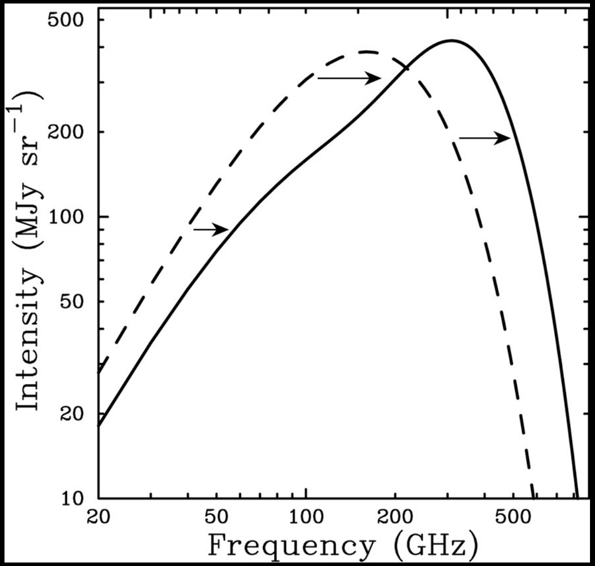
Eliminating Sunyaev-Zel'dovich Contamination

- Thermal SZ effect serious contaminant for cluster lensing measurement

- Use linear combination of 90, 150 and 220 GHz maps that cancels tSZ while preserving CMB



Williamson et al. 2011

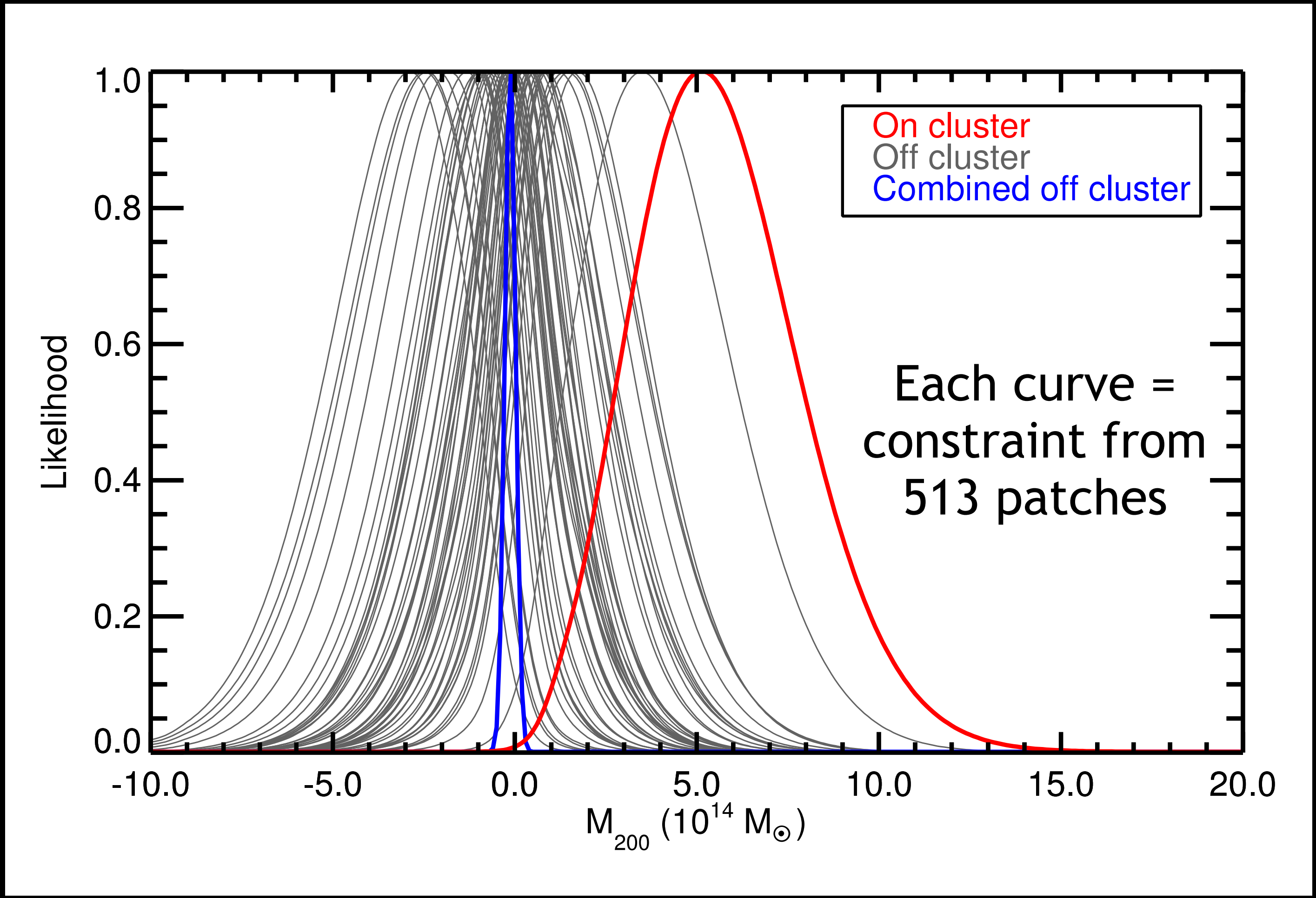


Systematic Errors

- Use mock data to determine impact of various systematic effects
- The most important of these bias the recovered cluster mass *low*:
  - Cluster mis-centering
  - Contamination from kinetic Sunyaev-Zel'dovich effect
  - Lensing of Cosmic Infrared Background
  - Expected deviation from NFW profile

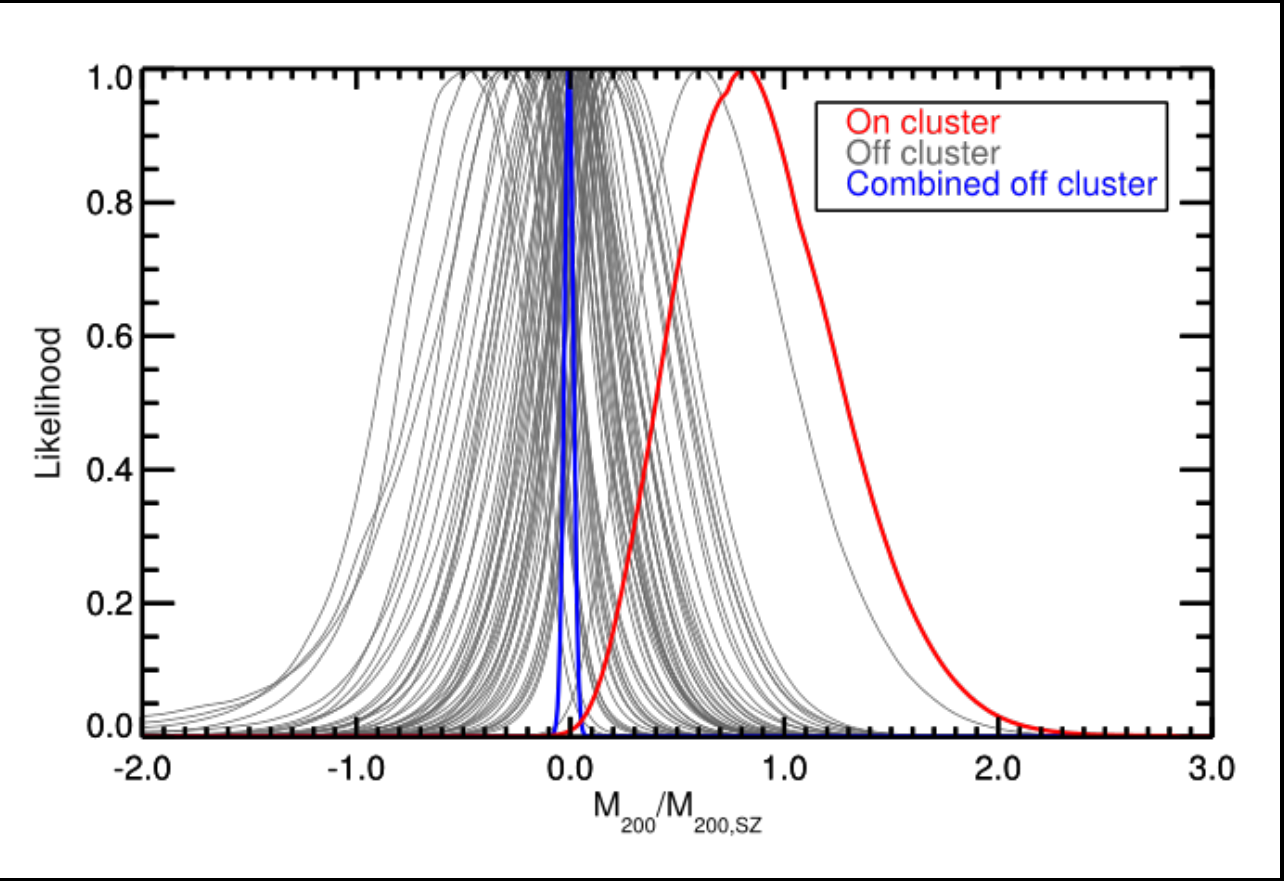
- Accounting for these biases would **increase** our detection significance

Result: constraint on mean cluster mass



Baxter et al. (2015)

Results: constraint on scaling between lensing and SZ-derived masses

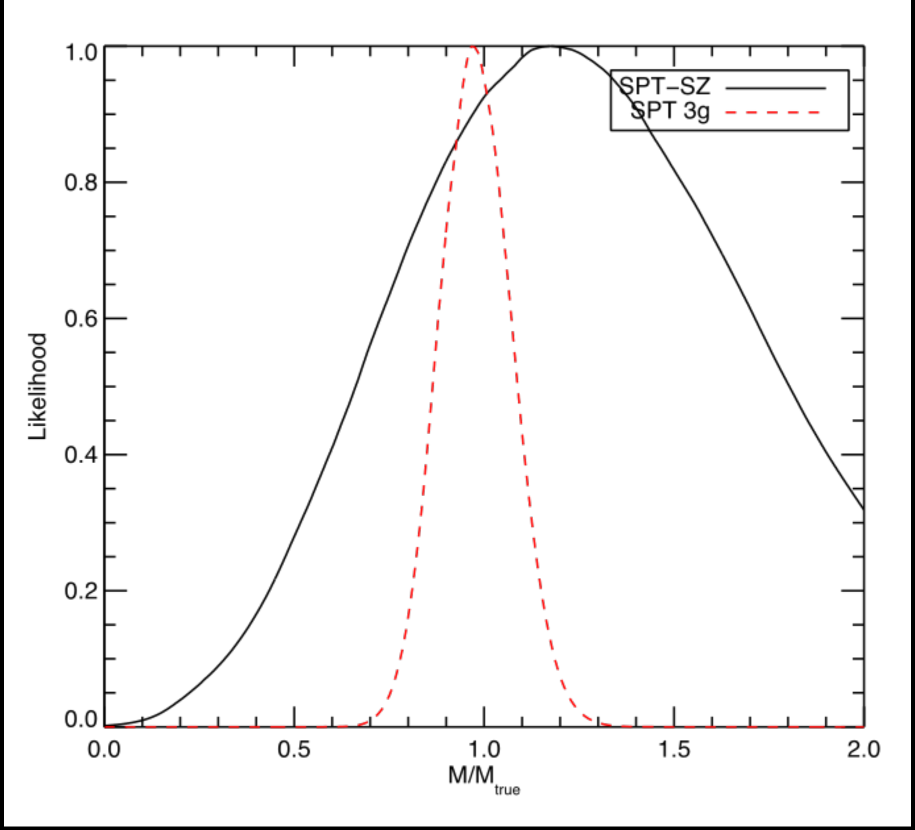


Baxter et al. (2015)

New Tool has Bright Future

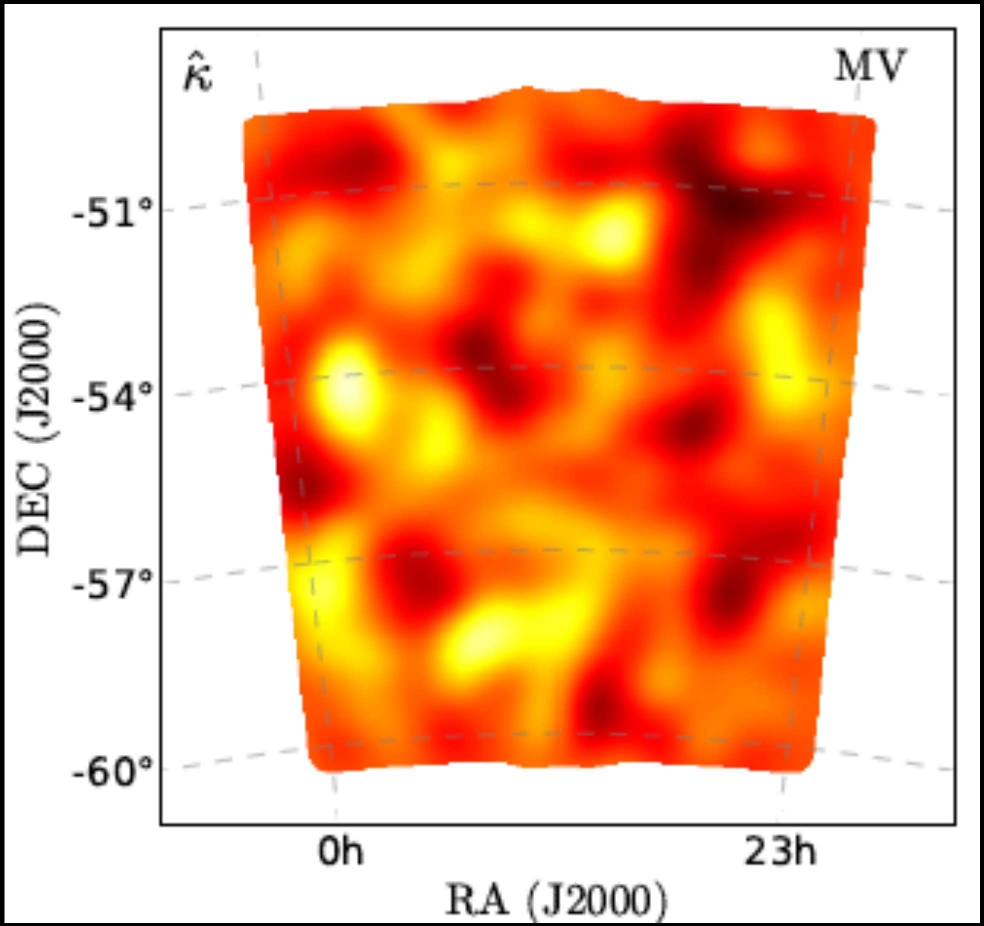
- Ongoing and upcoming CMB measurements
  - SPTpol and ACTPol have lower noise than SPT-SZ survey
  - Polarization adds more info about lensing

- Longer term experiments
  - SPT-3G
    - Factor of ~7 lower noise than SPT-SZ at 150 GHz
    - Polarization
    - More clusters
  - Stage IV goal: 1 μK-arcmin over 50% of sky



Eric Baxter

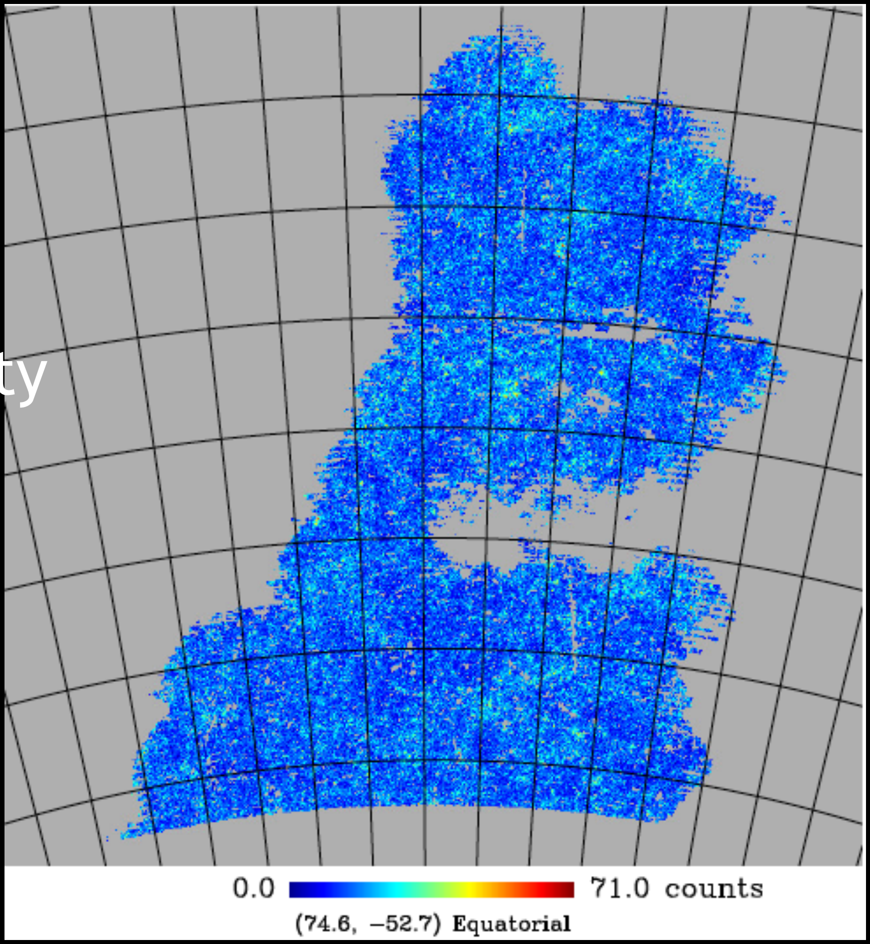
Lensing Maps from SPT



Story et al. 2015

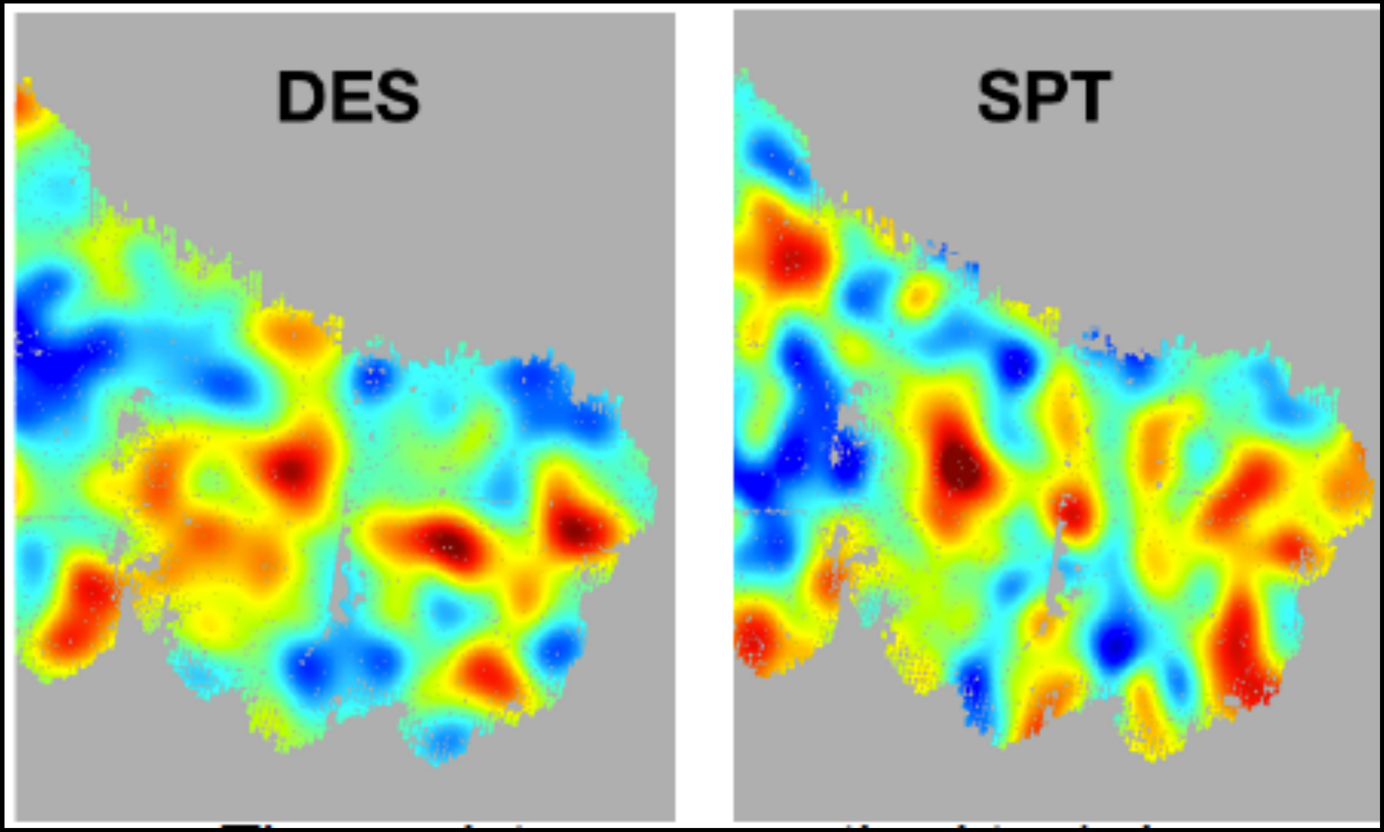
DES Science Verification Data

Map of the Galaxy Density



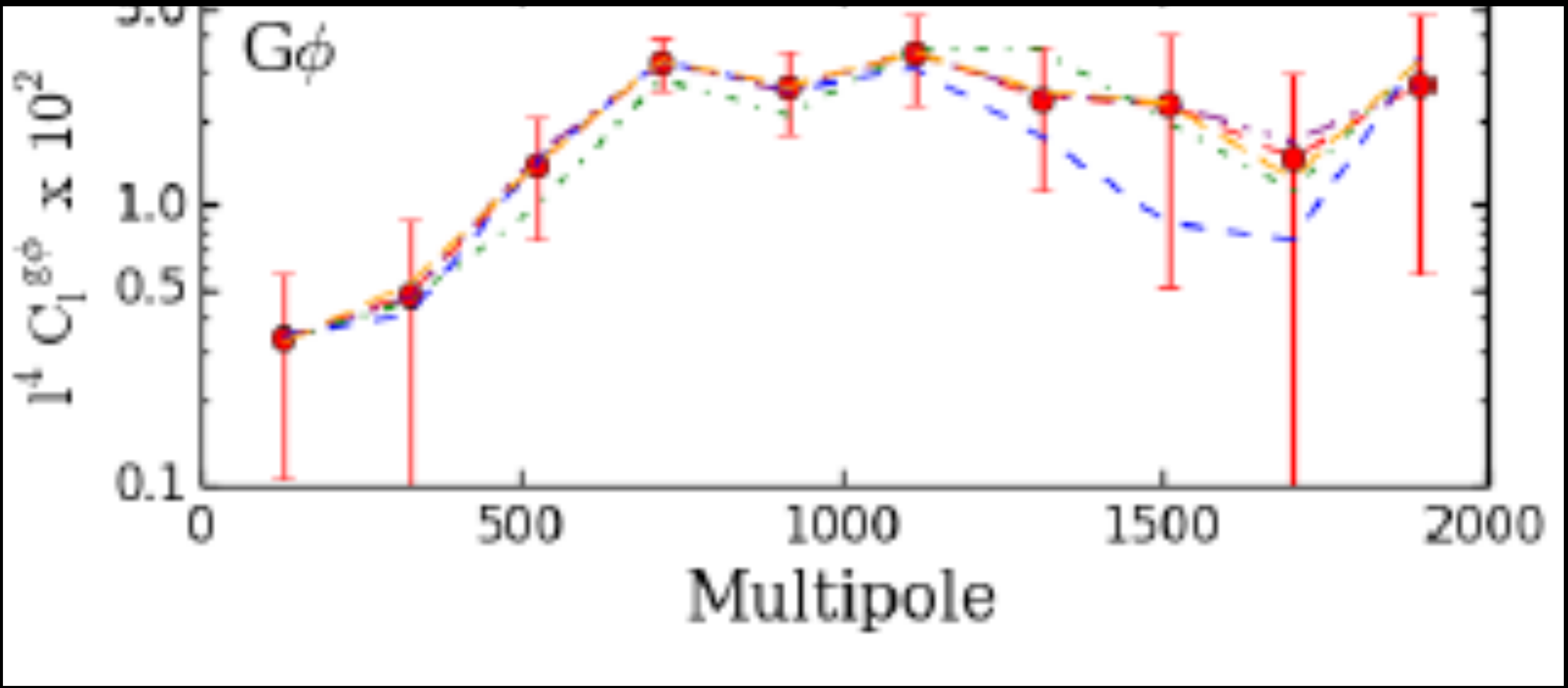
(Giannantonio et al 2015)

DES Galaxies X SPT Lensing



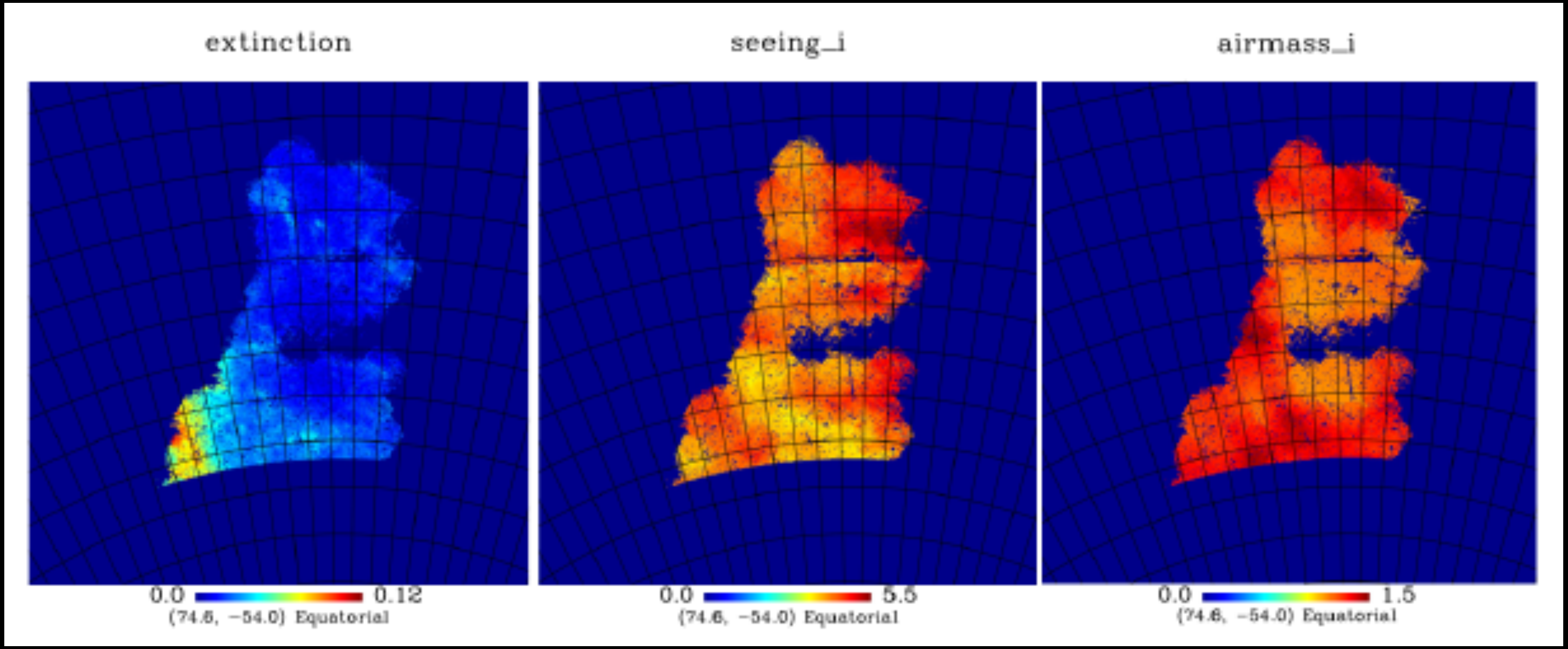
(Giannantonio et al 2015)

DES Galaxies X SPT Lensing



(Giannantonio et al 2015)

Systematics Tests



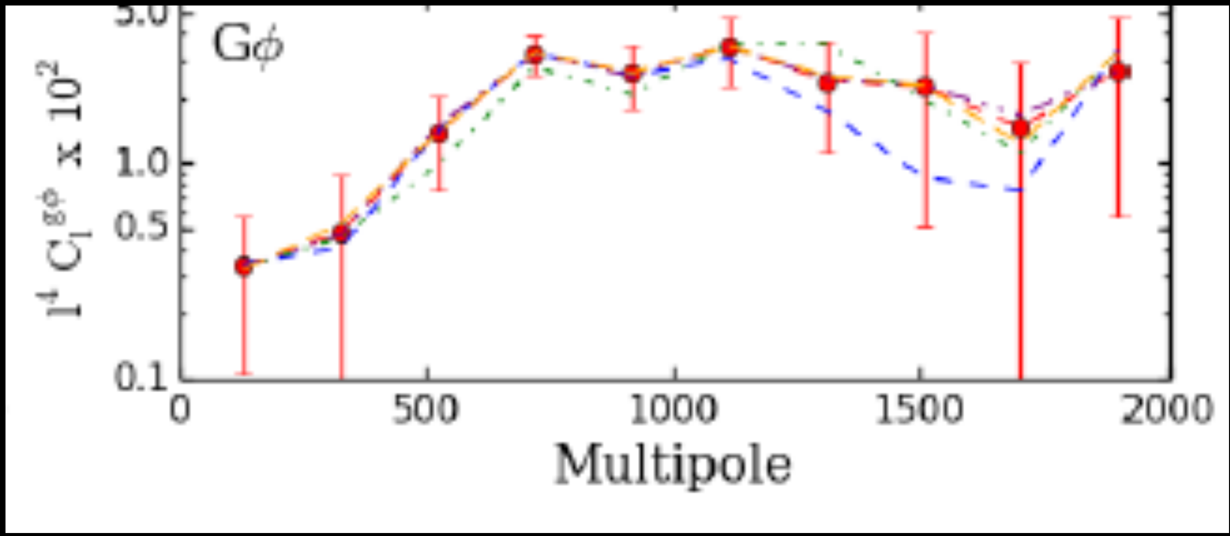
Maps of potential systematic effects

DES Galaxies X SPT Lensing

$$\delta_{g,\mathrm{obs}} = \delta_{g,\mathrm{true}} + \sum_s \alpha_i \delta_s$$

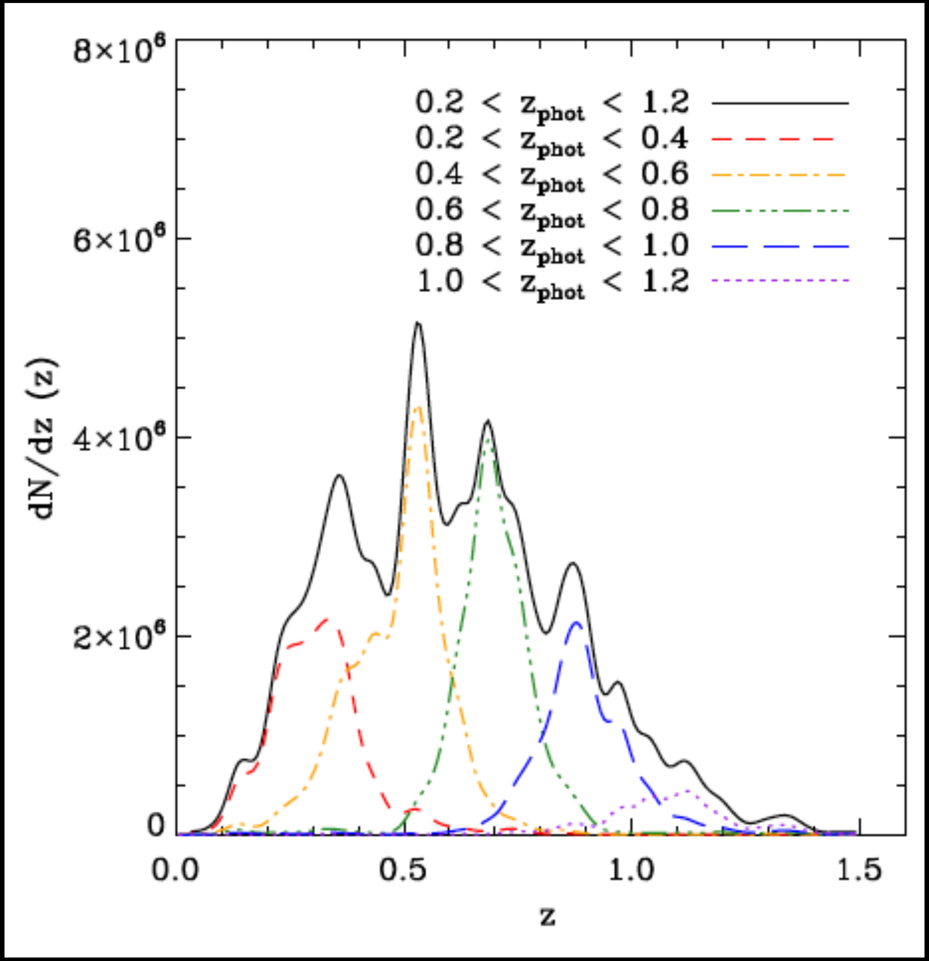
↓

$$C^{g\kappa}_{l,true} = C^{g\kappa}_{l,obs} - \frac{C^{gs}_l \, C^{\kappa s}_l}{C^{ss}_l}$$

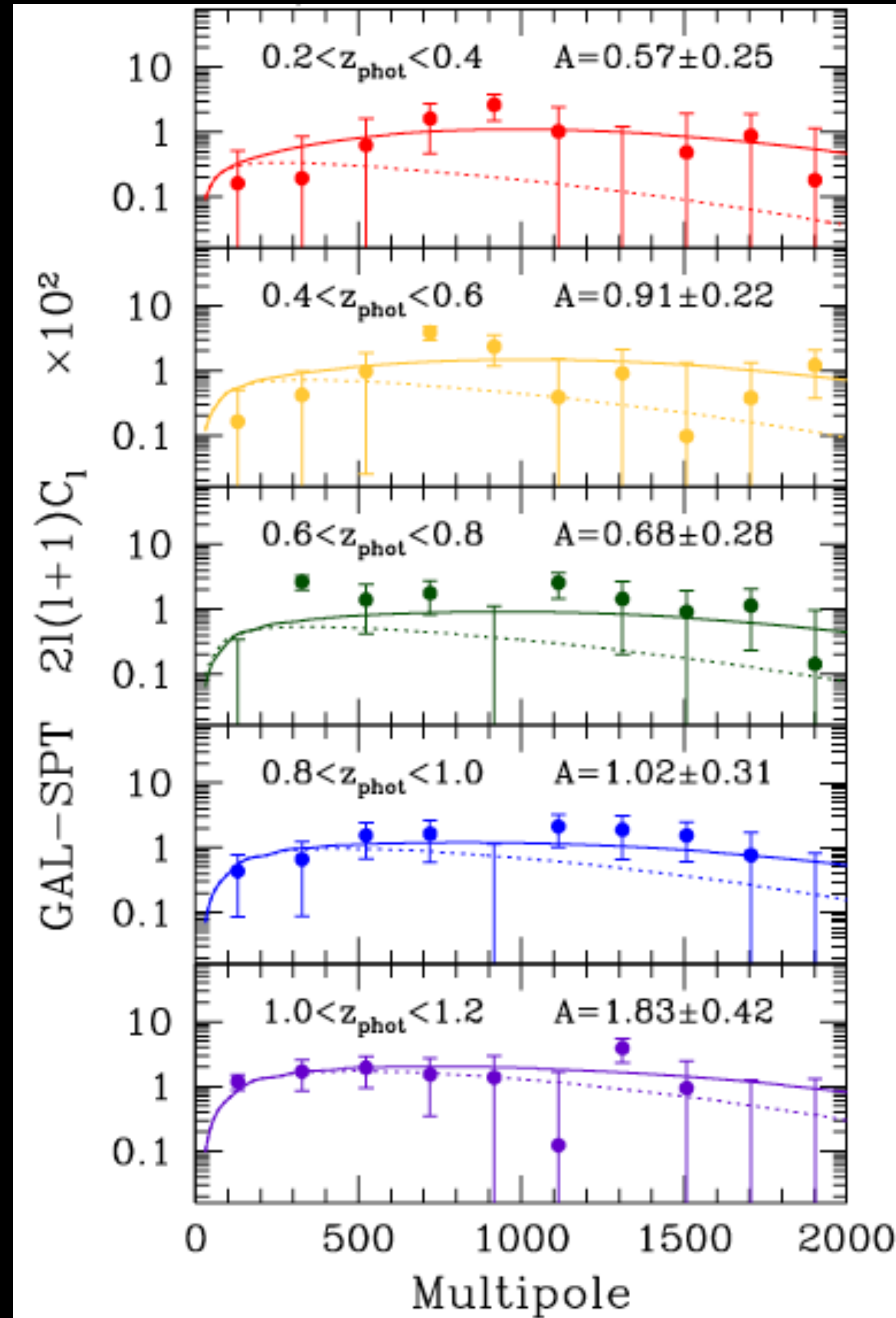


Cawthon

Convergence maps in redshift slices

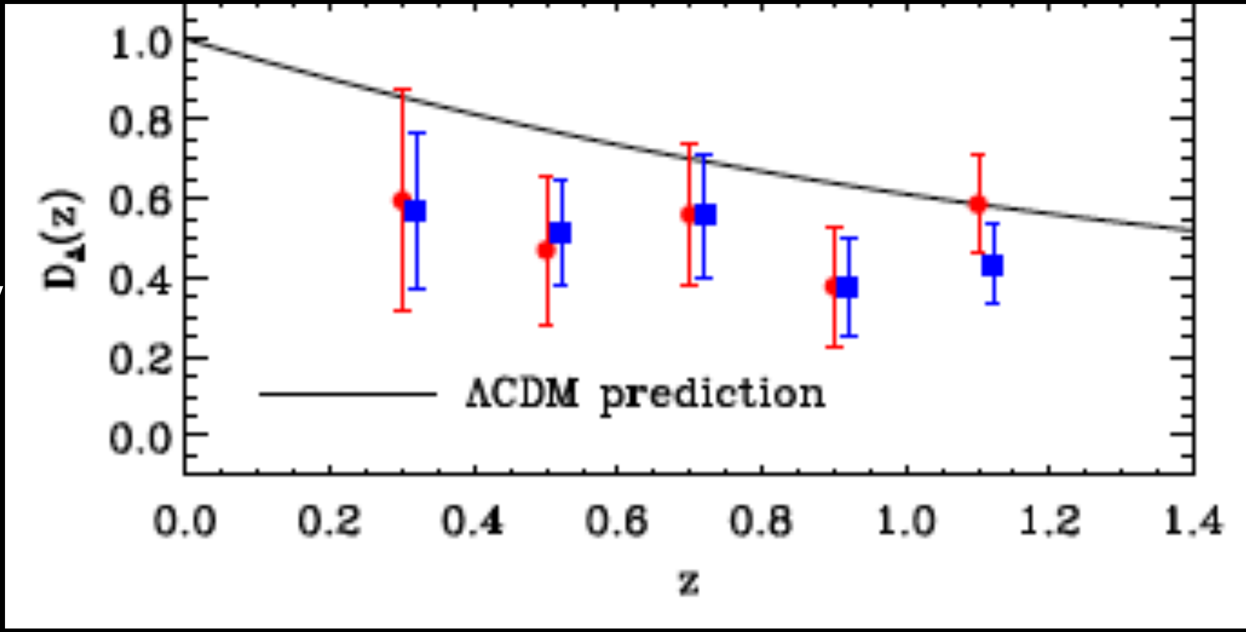


- Cross-correlation in each redshift slice picks out contribution to CMB convergence from that slice
- Can infer growth of structure



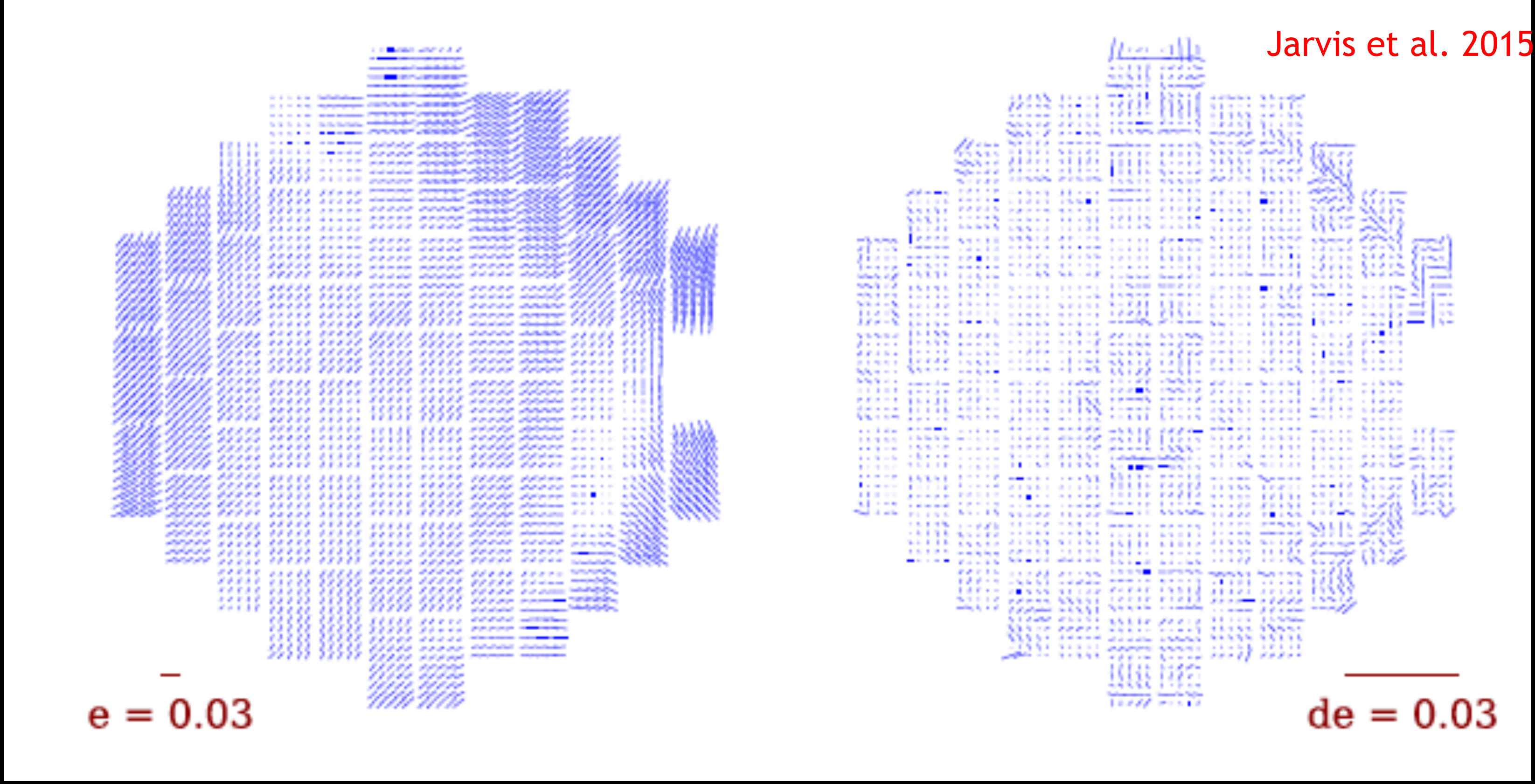
DES Galaxies X SPT Lensing

Preliminary estimate of growth function … early day



(Giannantonio et al 2015)

DES Lensing

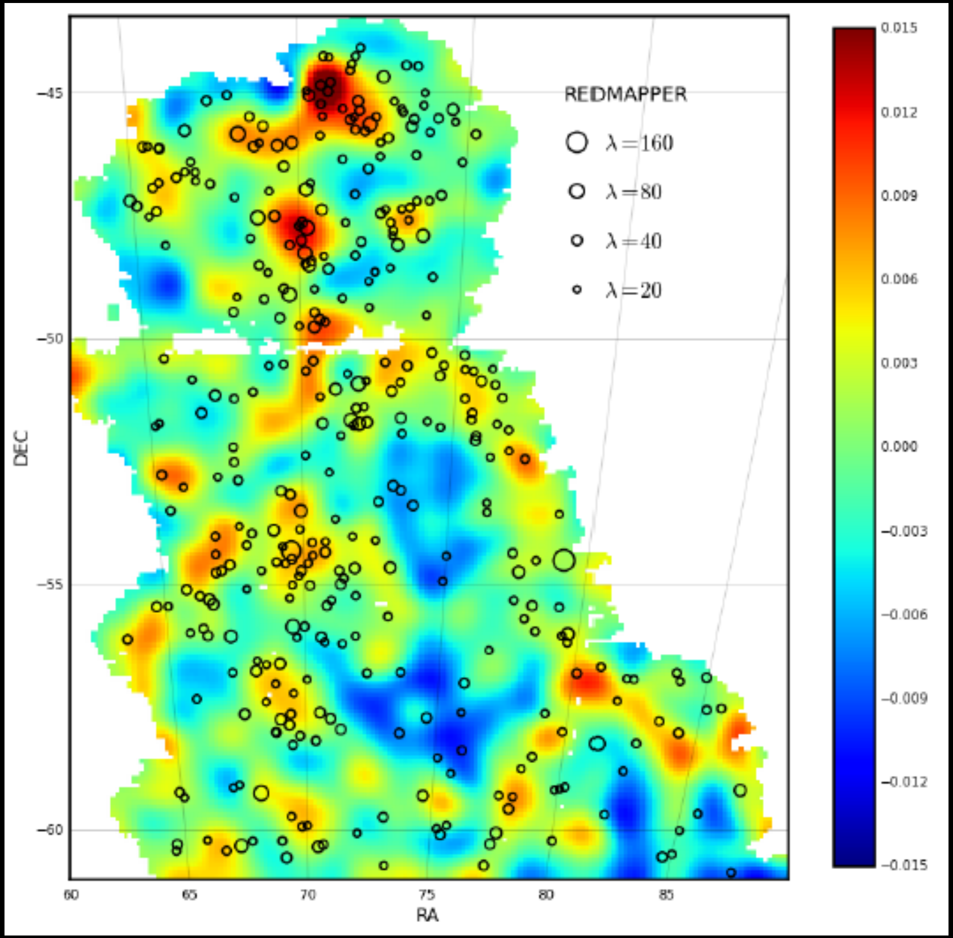


Ellipticity due to Point Spread Function

Residual Ellipticities (what we are after)

DES convergence map

inferred from measurements of shapes of background galaxies

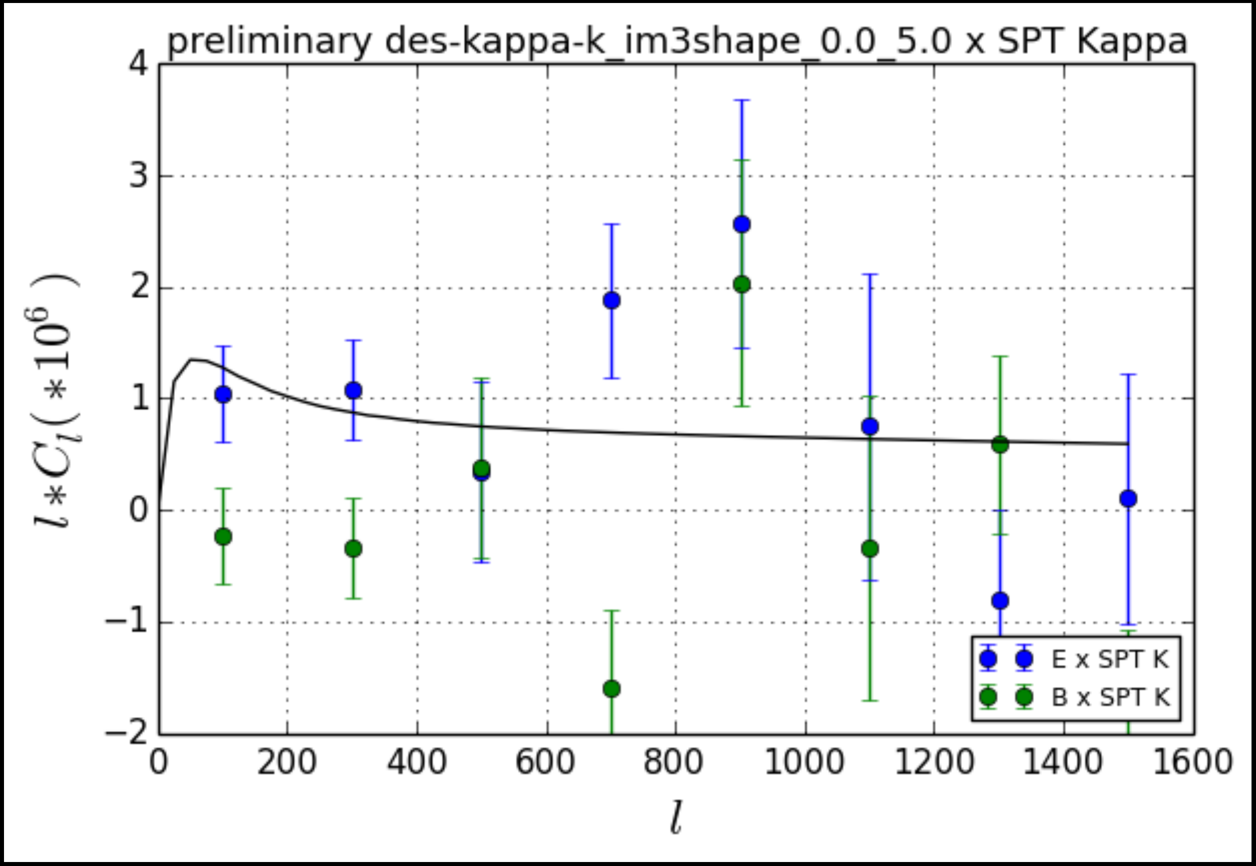


Note the clusters in overdense regions!

(Vikram et al. 1504.03002)

Why not?

Eventually, the CMB will give an additional tomographic bin to use to combine with DES bins

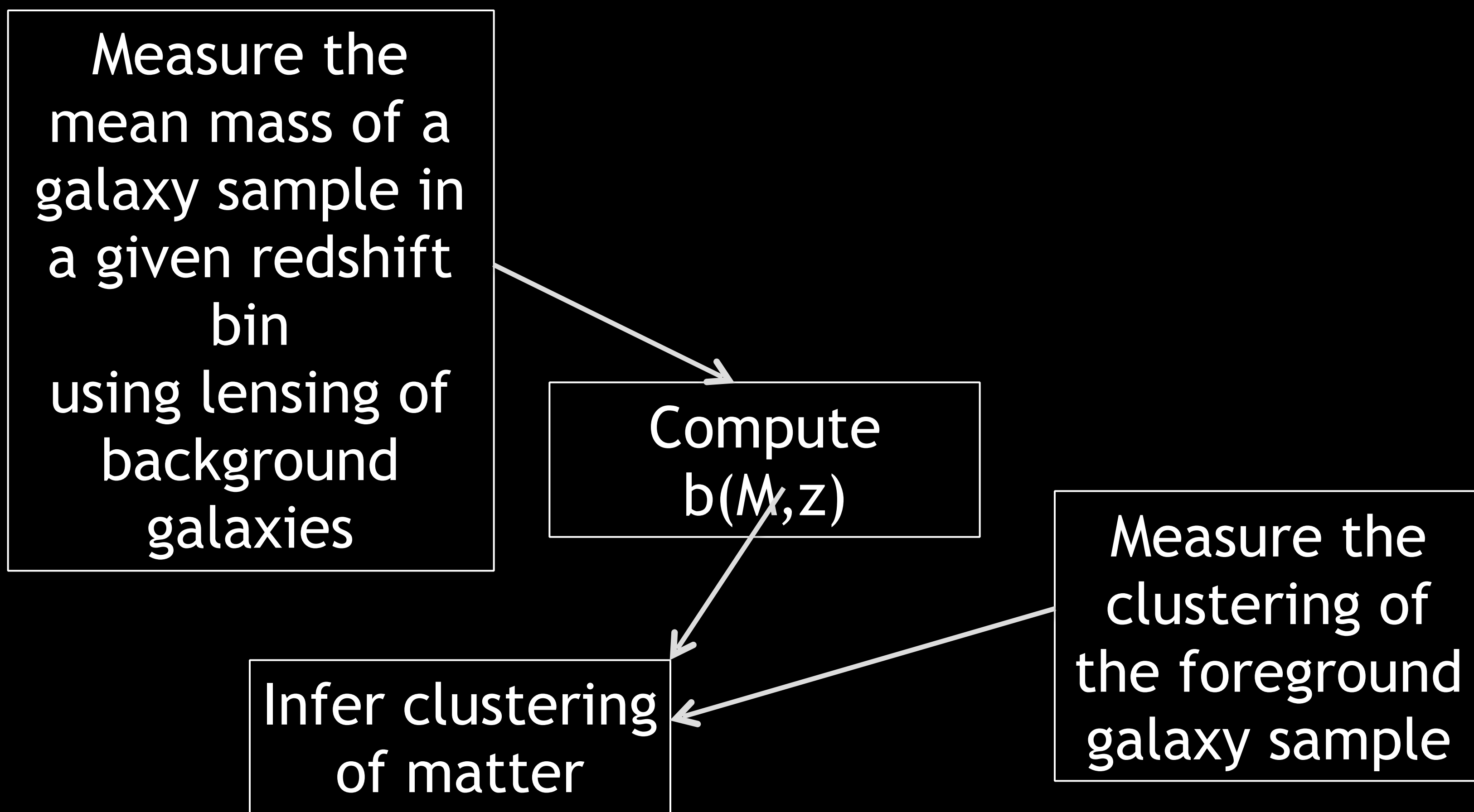


Cawthon, Kirk, Omori, Holder, …

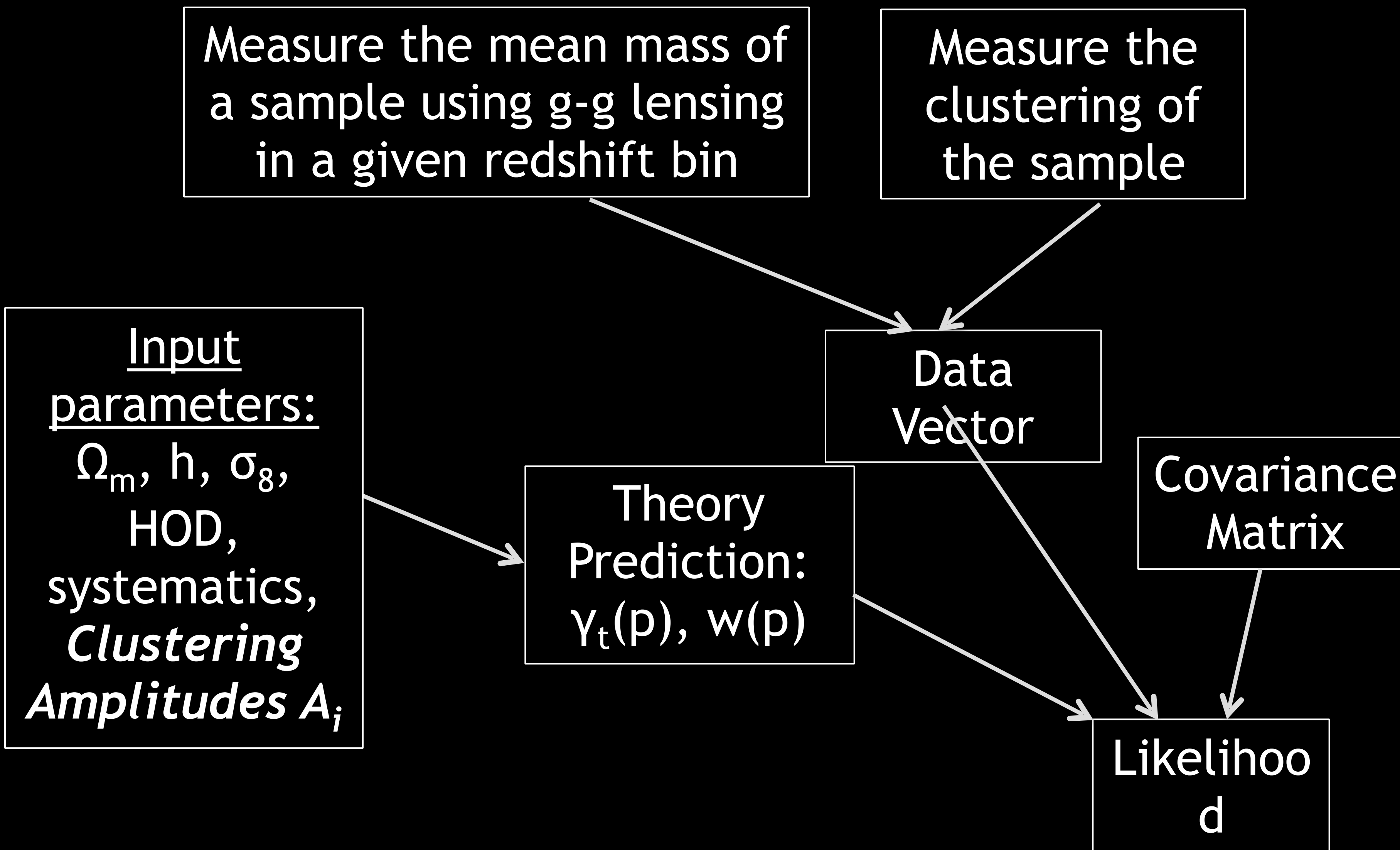
Lensing + Galaxy Distribution (Yoo & Seljak; Oguri and Takada; van den Bosch, More, Cacciato, Mo, Yang)

- Use shapes of background galaxies to estimate mass of foreground galaxies in given redshift slice
- There is a theoretical prediction, calibrated off simulations for *bias* b(M) that relates galaxy over-density to matter over-density
- Use the large scale distribution of the foreground galaxies (whose bias is now known) to infer the clustering in that redshift slice

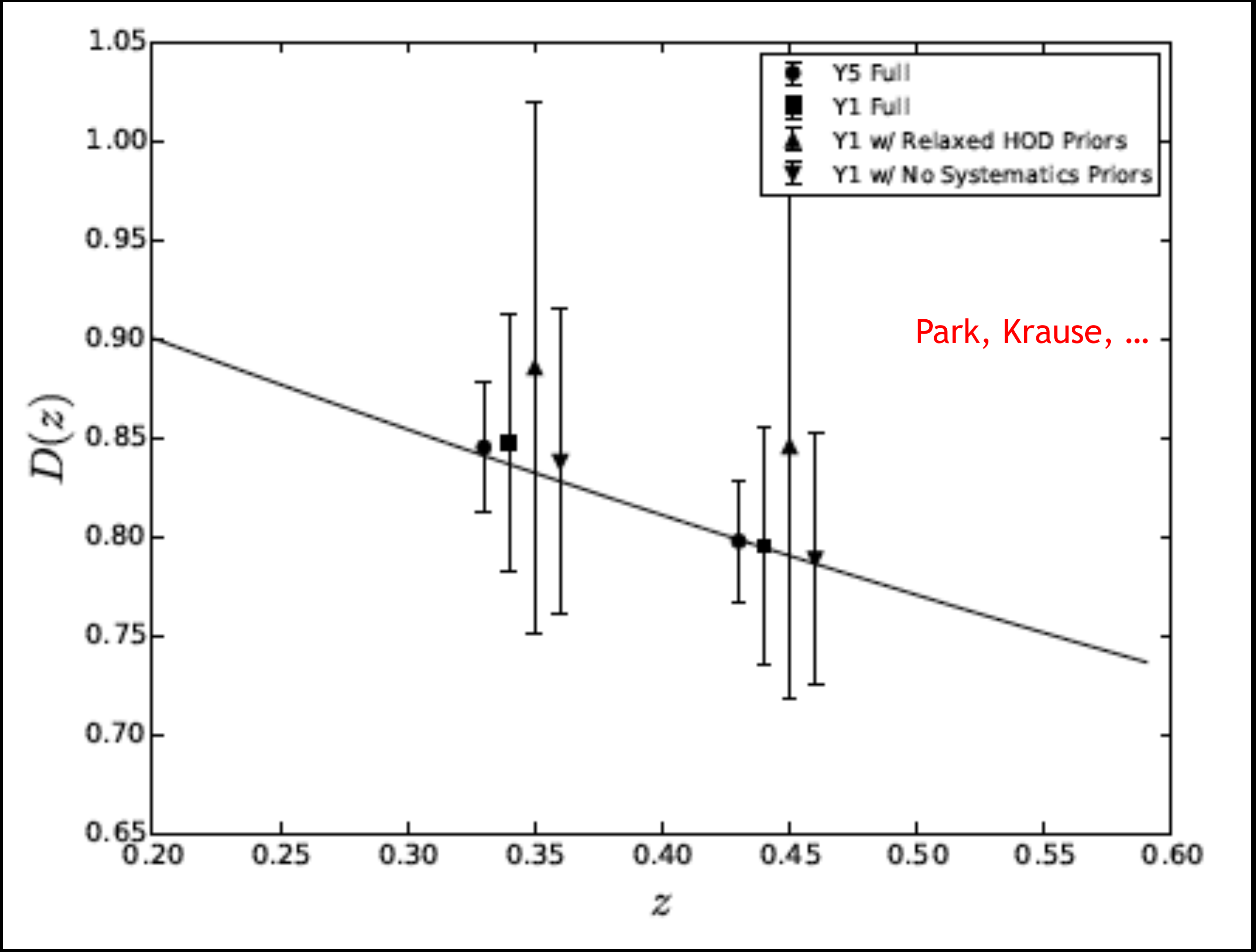
Simple Prescription



More Subtle Prescription



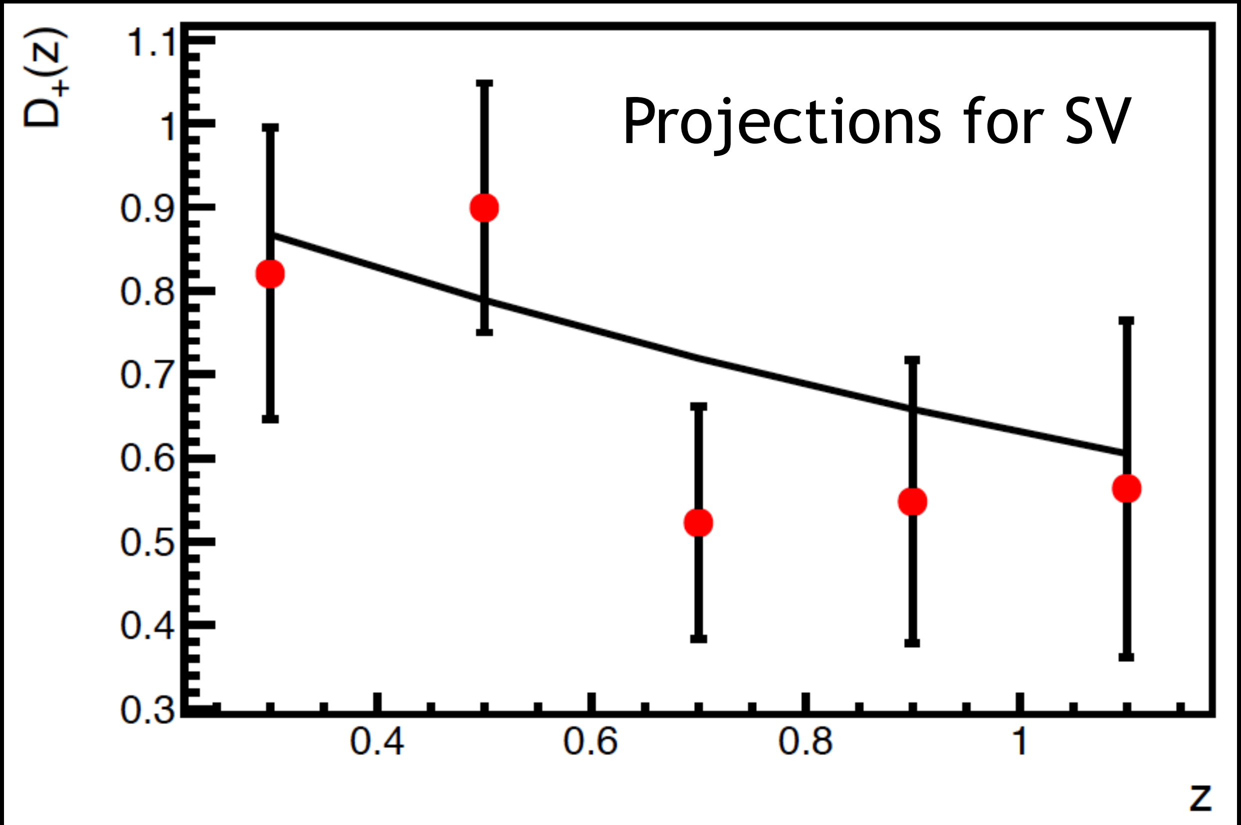
Analysis on Simulated Data Vector



Park, Krause, …

Similar idea using Clusters

- Measure cluster masses
- Cross-correlate clusters with galaxies to get galaxy bias
- Galaxy auto → matter clustering

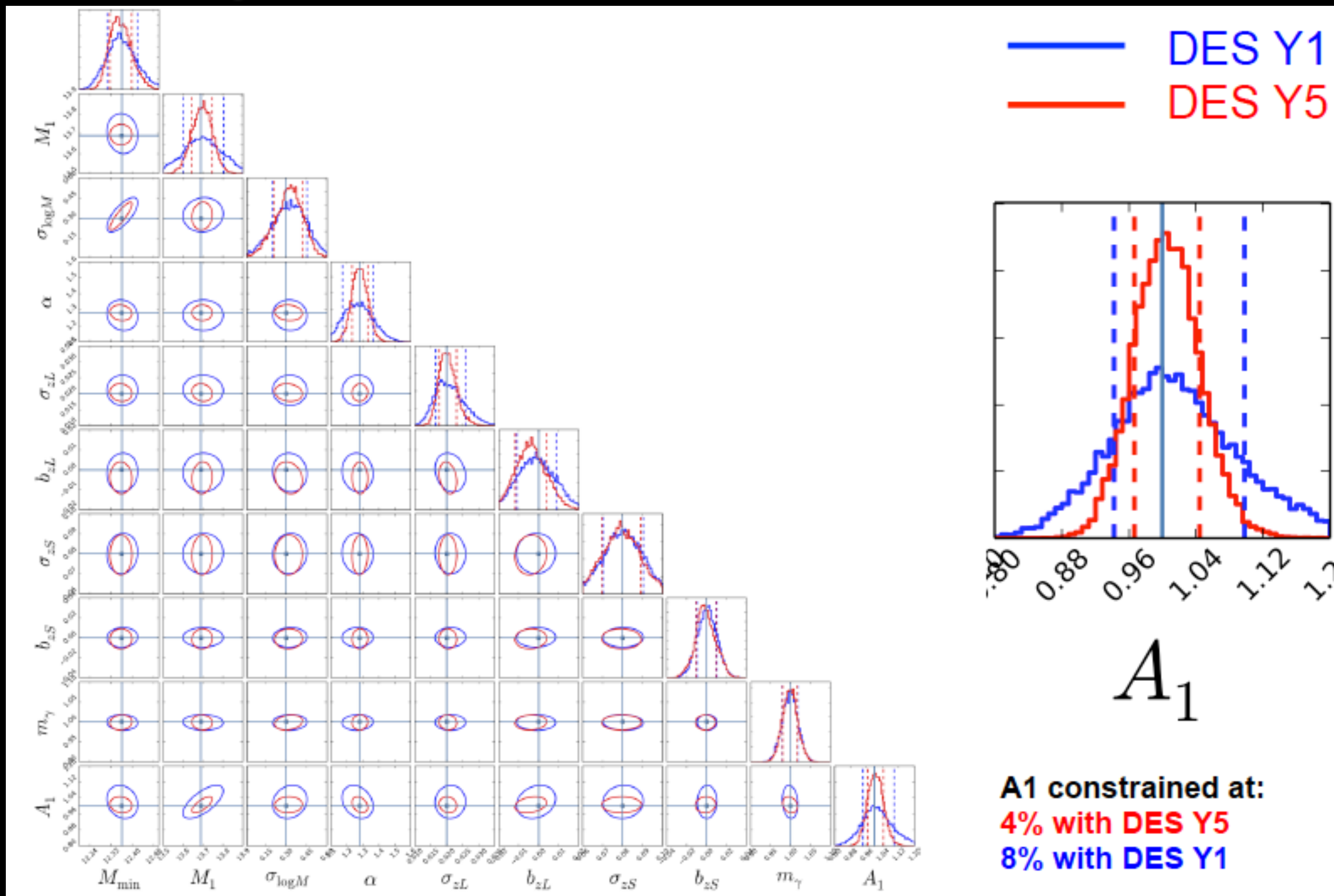


Lopez et al.

Conclusions

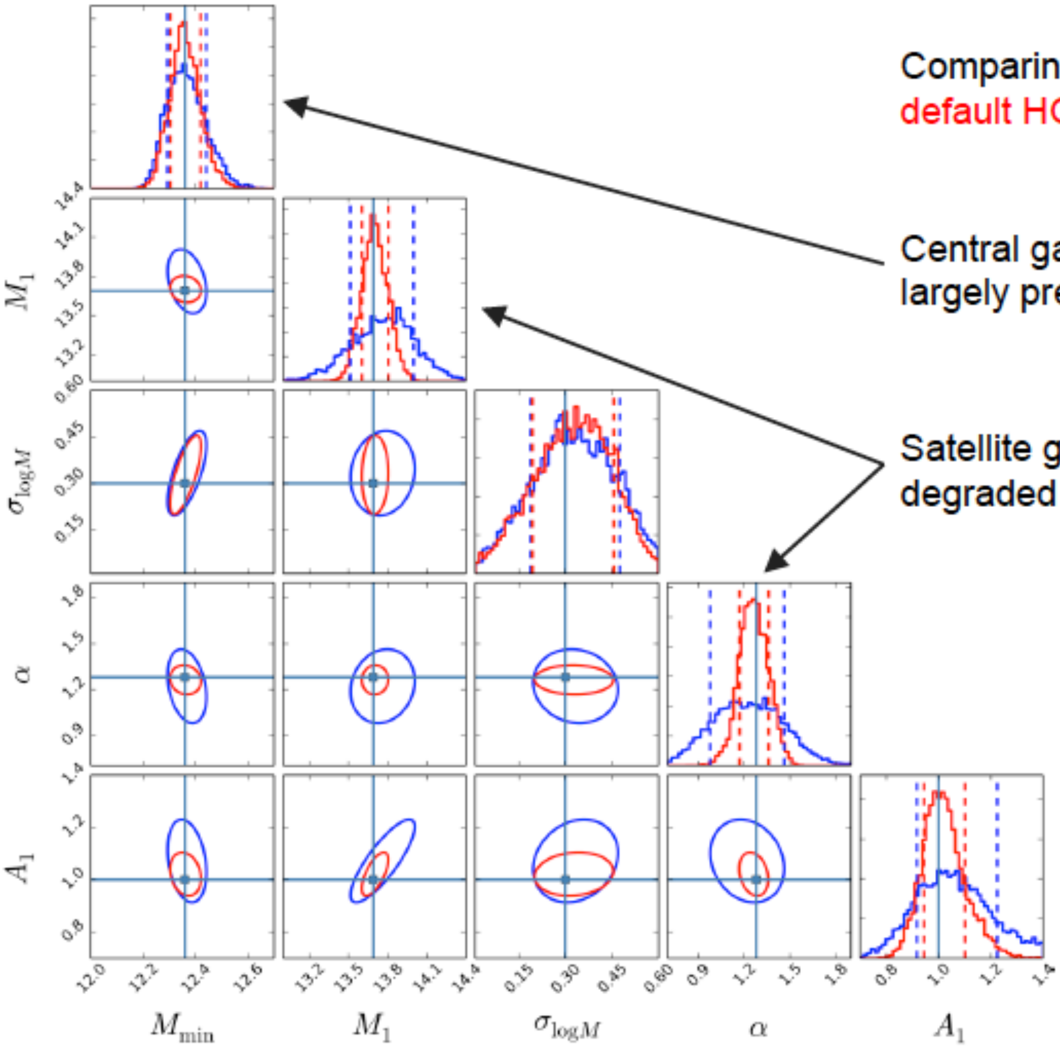
- Dark Energy Probes and CMB are highly correlated
- Just beginning to understand how to extract the most information from multiple probes about the mechanism driving cosmic acceleration
- DES has started up and early results have been released. We are working feverishly to get out more … and more

Analysis on Simulated Data Vector



Park, Krause, et al. 2015

Priors on HOD particularly important



Comparing full 20-parameter runs with default HOD priors and relaxed HOD priors

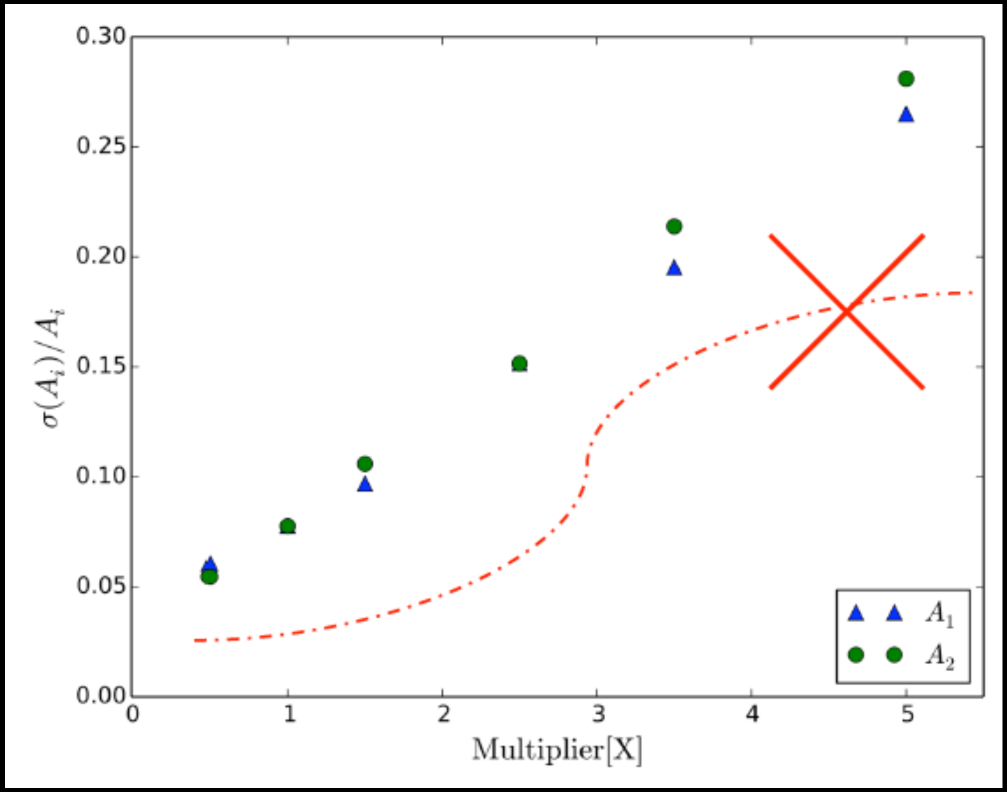
Central galaxy HOD constraints are largely preserved

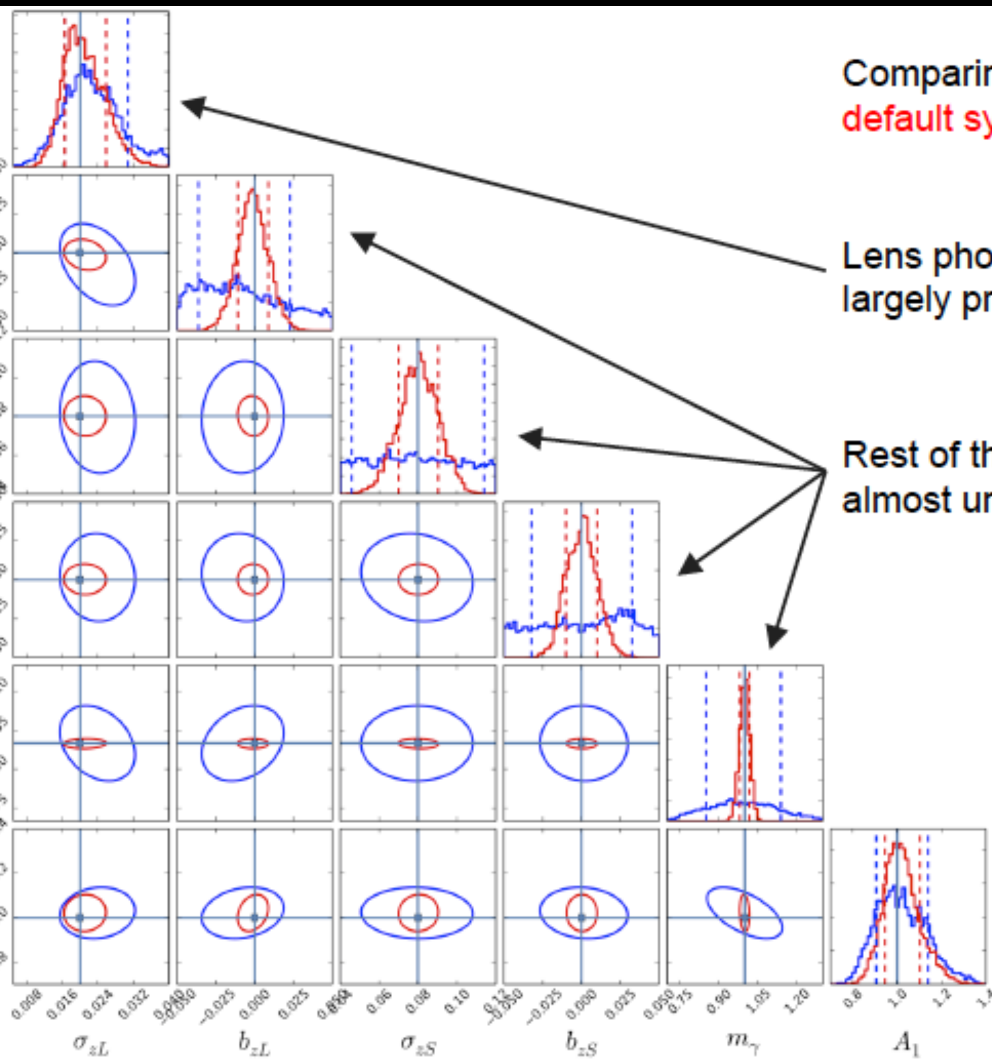
Satellite galaxy HOD constraints are degraded following relaxed priors

A1 constrained at:
8% with default priors
16% with relaxed priors

Priors on HOD particularly important

Starting to apply to data but need to supplement with small scale clustering measurements to constrain HOD





Comparing full 20-parameter runs with default sys. priors and no sys. priors

Lens photo-z scatter constraints are largely preserved

Rest of the systematics parameters are almost unconstrained without priors

A1 constrained at:
8% with default priors
11% with no priors

Gravitational Lensing of the Primordial CMB

Primordial *unlensed* temperature Θ^u is re-mapped to

$$\Theta(\vec{\theta}) = \Theta^u(\vec{\theta} + \delta\vec{\theta})$$

where the deflection angle is a weighted integral of the gravitational potential along the line of sight

$$\begin{aligned} \delta\vec{\theta}(\vec{\theta}) &= -\nabla\phi(\vec{\theta}) \\ &\equiv -\int_0^{\chi_*} d\chi W(\chi)\nabla\Psi(\chi\vec{\theta},\chi) \end{aligned}$$

Taylor expand …

$$\Theta(\vec{\theta}) \simeq \Theta^u(\vec{\theta}) + \frac{\partial \Theta^u}{\partial \vec{\theta}} \cdot \delta\vec{\theta}$$

leading to a new term

$$\Theta_{lens}(\vec{\theta}) = -\frac{\partial \Theta^u}{\partial \vec{\theta}} \bullet \nabla \varphi$$

Non-Gaussianities lead to new possibilities:

Consider the 2D Fourier transform of the temperature

$$\tilde{\Theta}(\vec{l}) = \tilde{\Theta}^u(\vec{l}) + \int d^2l' \left(\vec{l'} \cdot [\vec{l} - \vec{l'}]\right) \tilde{\Theta}^u(\vec{l'}) \tilde{\phi}(\vec{l} - \vec{l'})$$

Recall that $\langle \tilde{\Theta}^u(\vec{l}) \tilde{\Theta}^u(\vec{l}) \rangle = (2\pi)^2 \delta^2(\vec{l} + \vec{l'}) C_l$

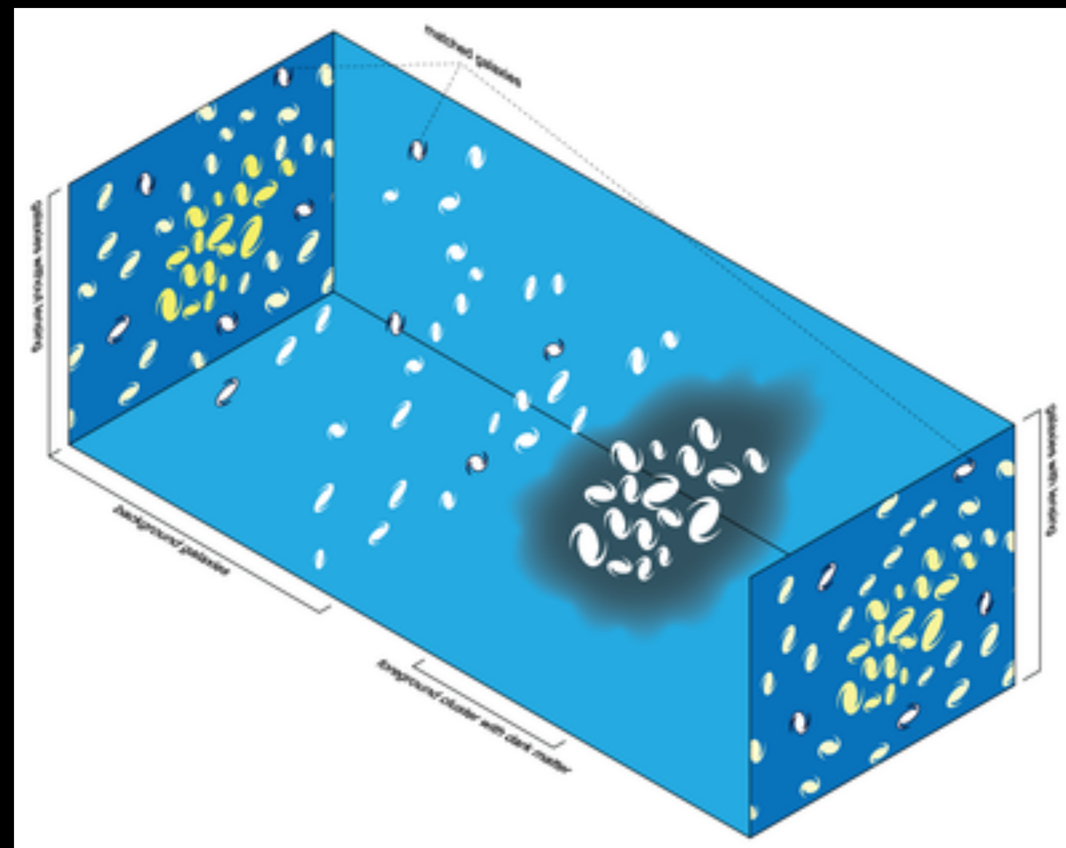
Now though different Fourier modes are coupled! The quadratic combination

$$\int d^2l_1 F(\vec{l}, \vec{l}_1) \tilde{\Theta}(\vec{l}_1) \tilde{\Theta}(\vec{l} - \vec{l}_1)$$

would vanish w/o lensing. Because of lensing, it serves as an estimator for the projected potential

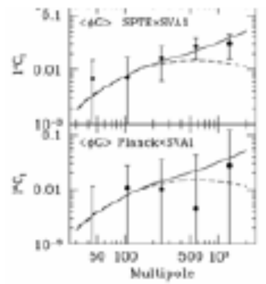
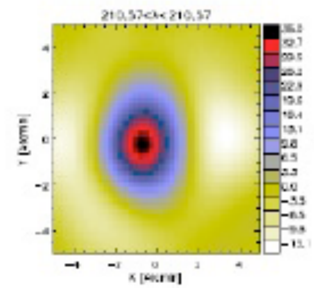
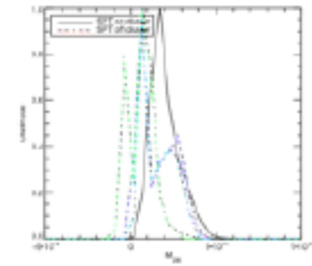
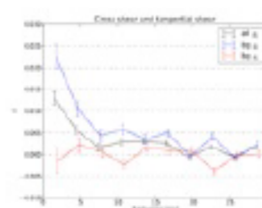
Weak Gravitational Lensing

- Galaxy shapes distorted by intervening matter over- and under-densities
- Can measure 2-point function (angular correlation function or power spectrum) of galaxy ellipticities
- Tomography yields information about both geometry and structure



Beyond *w* and 4+1 independent probes

- Modifications of General Relativity can produce cosmic acceleration and can be differentiated from GR+DE models
- CMB is correlated with galaxy surveys in ways that we are just beginning to explore
- Galaxy Survey probes are (often highly) correlated with one another

DES\SPT	Map	Temperature	SZ Source Profile	Lensing of Dipole
Galaxy Map	Galaxy over-density and CMB kappa map 	ISW and Diffuse SZ	Clusters and Non-Cluster Galaxies 	Stacked Clusters (Baxter) 
Shear Map	DES cosmic shear with CMB kappa map	ISW and Diffuse SZ	This would probe <Phi x Pressure>	
Tangential Shear [g-g lensing; cluster lensing]	"CMB kappa"-lensing OR correlate mass maps from g-g lensing with CMB kappa	Probes <\Delta\Sigma x Pressure>	Cluster lensing of SZ-detected clusters 	

Illustrate these ideas with recent results from DES and SPT

Dark energy survey

Science Verification: 2012-13
5 Year Survey: 2013-18

South pole telescope

SPT-SZ: 2008-11
SPTPOL: 2012-15
SPT-3G: 2016-19