Connecting Probes of Dark Energy and Modified Gravity

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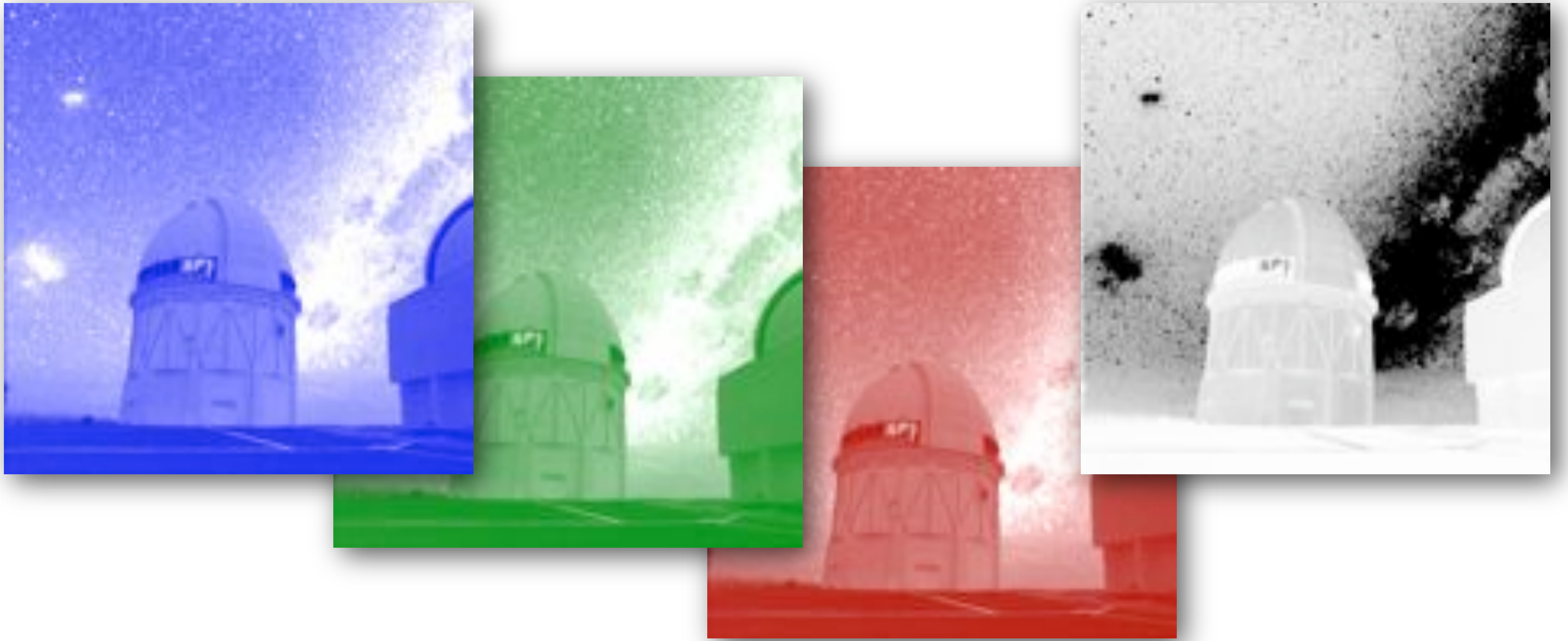
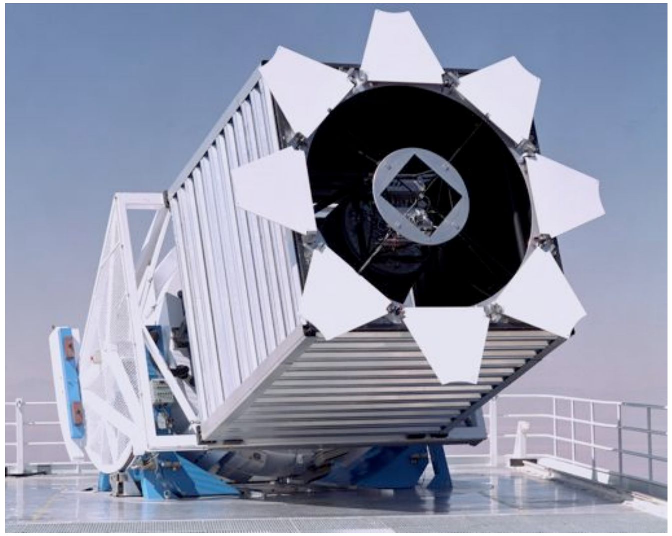


31 January 2011, Fermilab Center for Particle Astrophysics

(Some) questions I hope that large surveys will help answer:

- What is dark energy (or why is the expansion of the Universe accelerating?)
- Is General Relativity (GR) the correct description of gravity?
- What is dark matter?
- Did inflation (or something like it) happen? What caused it?
- How do galaxies form and evolve over time?
- And more!

Dark energy probes made possible by surveys



SDSS

- Type Ia Supernovae
- Baryon Acoustic Oscillations
- Weak Lensing
- Cluster Counts
- (CMB)
- Integrated Sachs-Wolfe Effect
- Redshift-space Distortions

Structure Growth

Geometry

Structure Growth *Rate*

Why think about probe combinations?

Benefits:

– Break parameter degeneracies

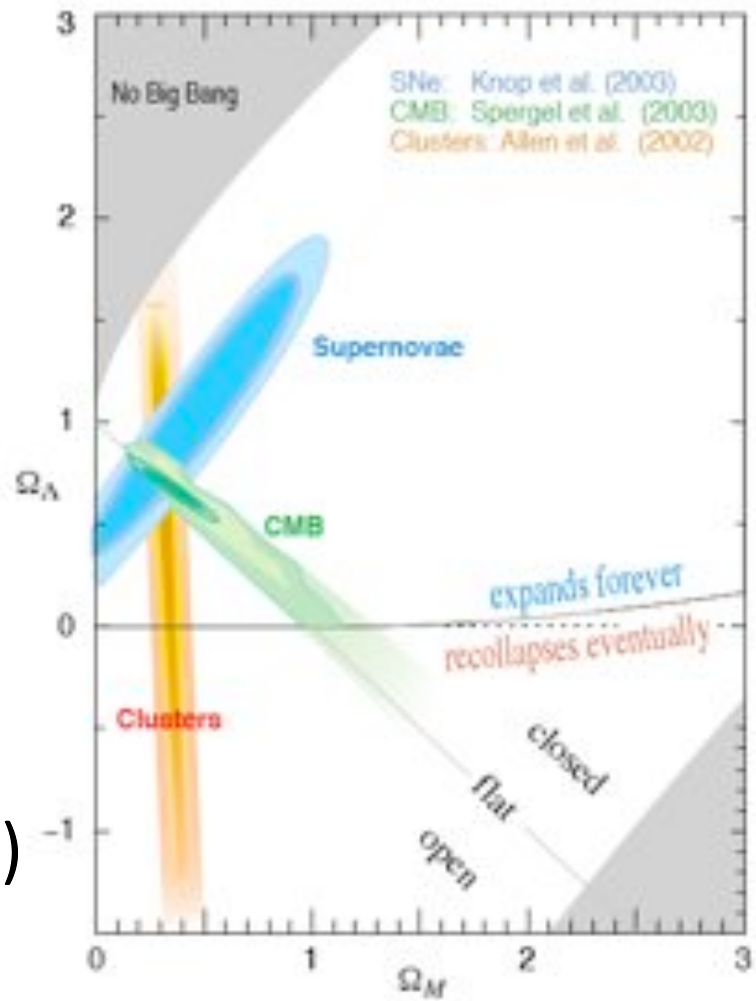
– Consistency checks

– Tests of General Relativity (GR)

Complications:

– Covariances

– Contamination (trash vs. treasure)



Outline

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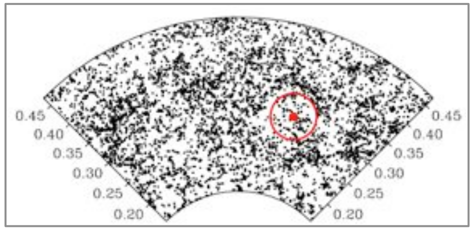
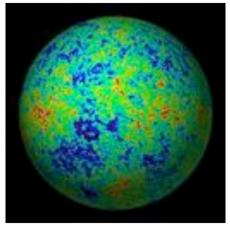
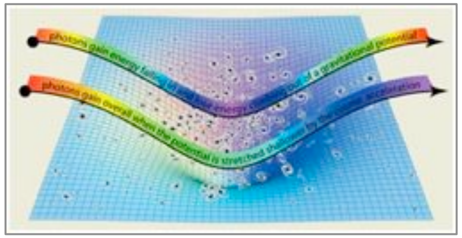
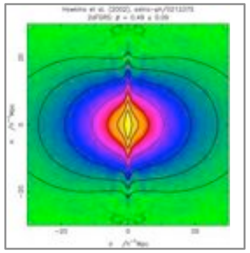
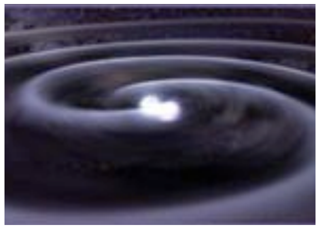
2.  + 

+  +  + 

3.  + 

4.  /  + 

Combining Cosmic Shear and Clusters including their full covariance

with S. Dodelson

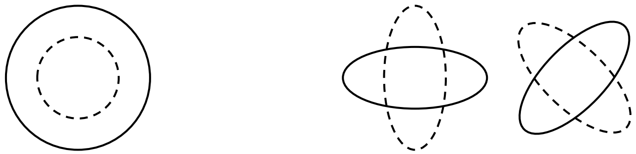
Cluster Counting

+

Lensing

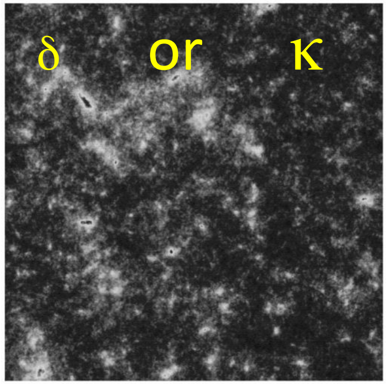
Review: Cosmic Shear

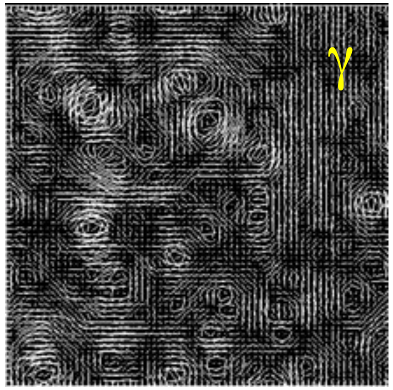
κ = convergence γ = shear



In weak lensing, shear is essentially a weighted projection of mass fluctuations δ

Jain et al. 2000





- Average over many galaxies to reduce intrinsic shape noise
- Primary probe: cosmic shear 2-point functions

$$\langle \gamma(\theta,z)\ \gamma(\theta',z') \rangle$$

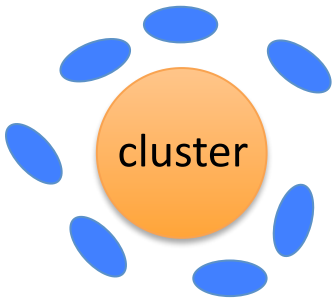
Review: Cluster Counting

- Galaxy clusters are the largest gravitationally bound structures in the Universe. ™
- Main probe: cluster mass function, $n(z,M)$
- Secondary probe: halo clustering (the clustering of clusters), $<N(r)\,N(r')>$
  - Useful for mass "self-calibration", since it depends on halo bias
  - Breaks degeneracy between mass uncertainty and w

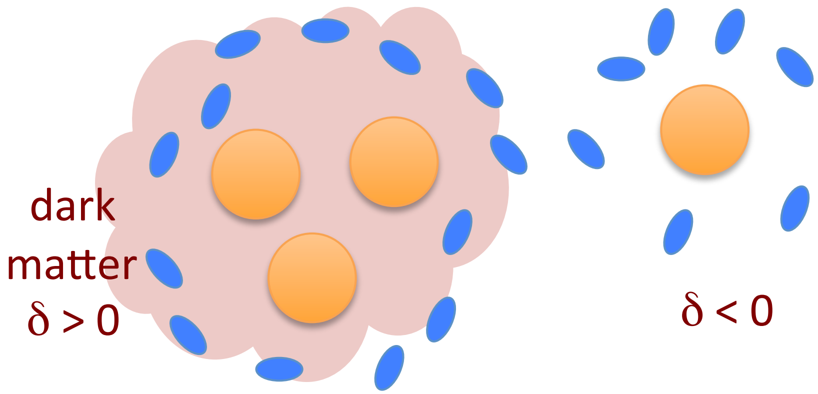
How are Cosmic Shear and Cluster Counting correlated? Halo model approach:

- A cluster causes lensing

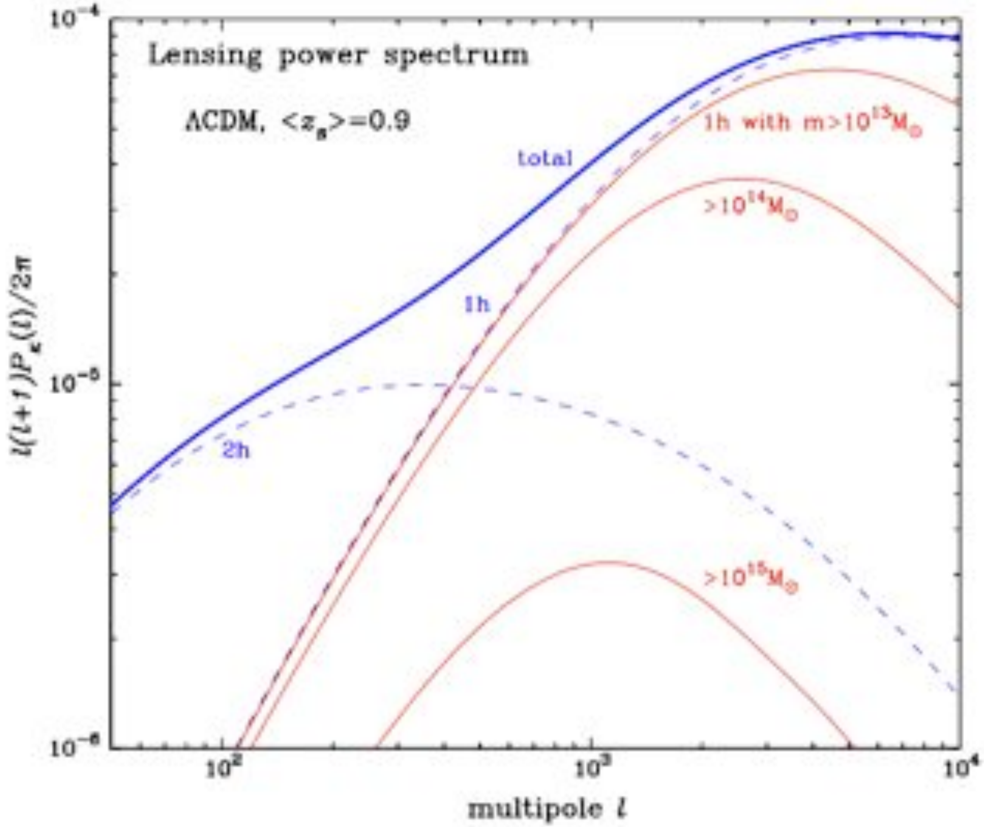
(1-halo term)



- Shear and clusters trace large matter fluctuations (2-halo term)



$$P(k) = P_{1h}(k) + P_{2h}(k)$$

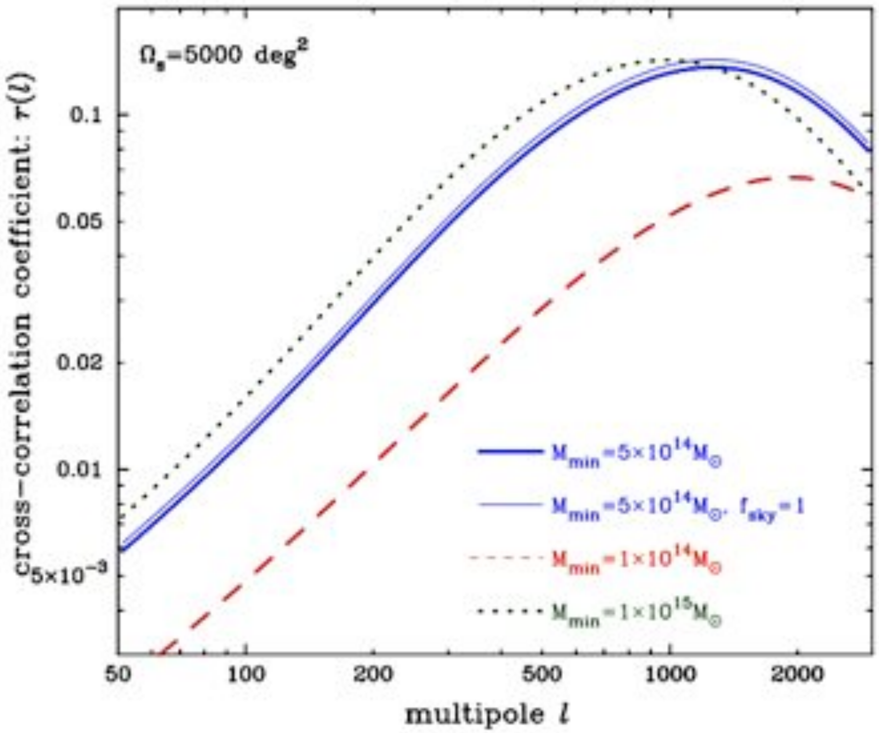


Takada & Bridle (2007)

Cross-correlation coefficients

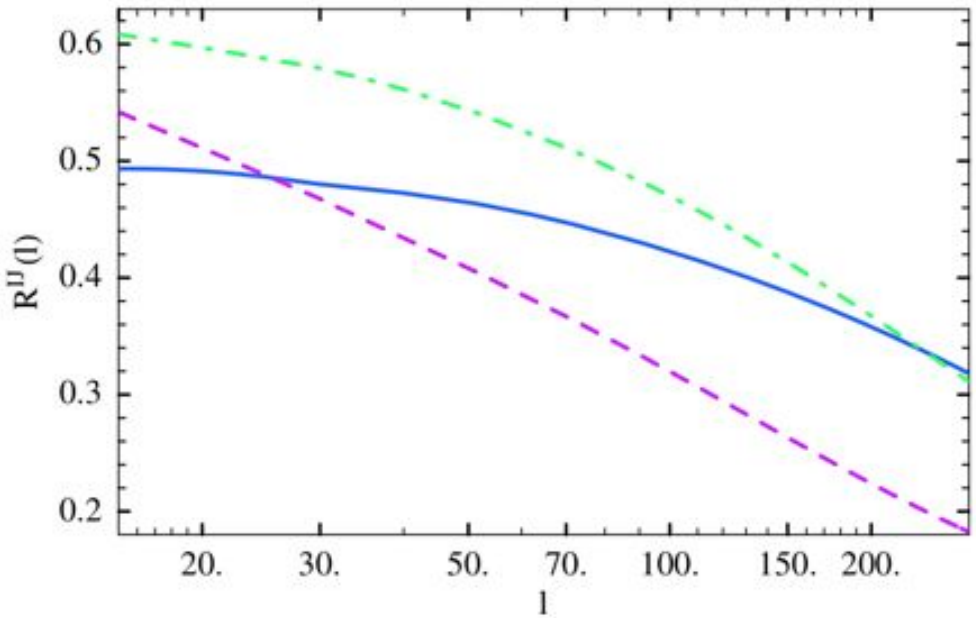
$$R = \frac{< AB >}{\sqrt{(< A^2 >< B^2 >)}}$$

A = Total # clusters $N(M>M_0)$
B = Shear power $P_\gamma(l)$



Takada & Bridle (2007)

A = Halo overdensity mode $n(l)$
B = Shear mode $\gamma(l)$



CS & Dodelson (2007)

Effects of including full covariance

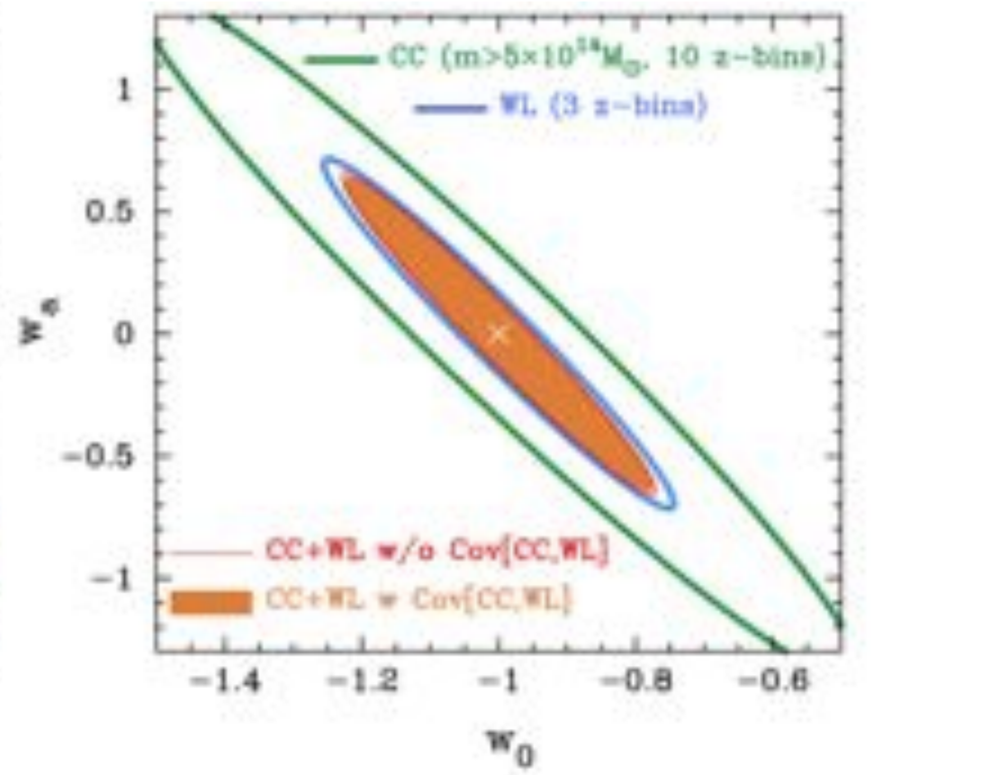
- Admiting you’re double-counting information *degrades parameter constraints*

- Measuring the cross-correlation adds new information to *improve parameter constraints*

- Which one “wins” depends on parameters of interest and survey specifications.

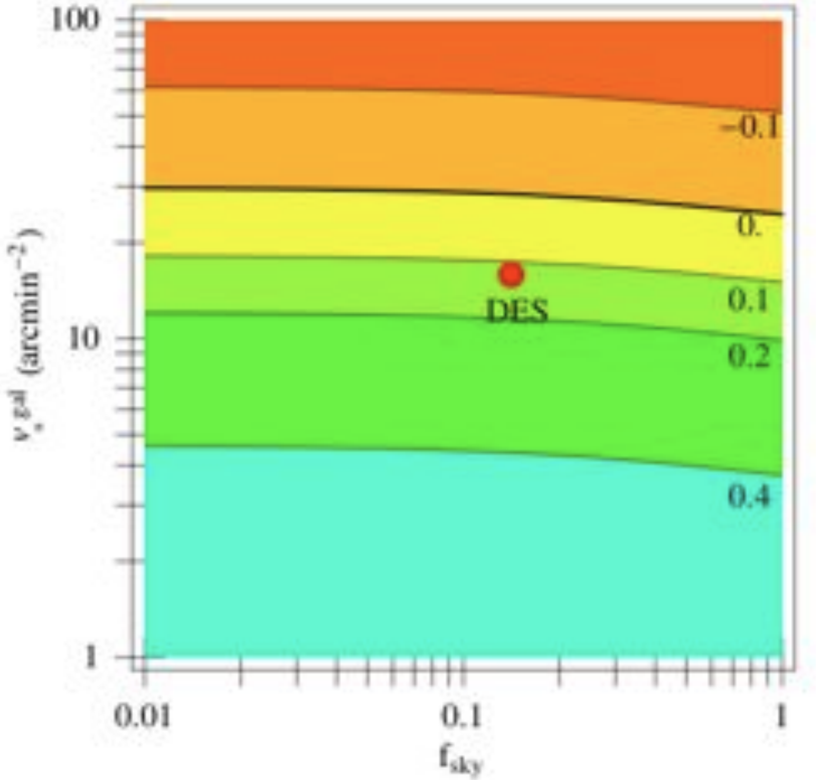
Including covariance slightly improves dark energy parameters from DES

Lensing + Cluster Counts (Takada & Bridle)



Probes	$\sigma(w_{\rm piv})$	$\sigma(w_a)$	$\sigma(w_{\rm piv})\times\sigma(w_a)$
WLT	0.039	0.47	0.019
CCM ($M_{\rm min}=5\times10^{14}\,M_\odot$)	0.085	0.95	0.081
WLT+CCM	[0.033]	[0.44]	[0.0143]
WLT+CCM (with cross-cov.)	0.032 (3%)	0.42 (3%)	0.0135 (6%)

Lensing + Halo Clustering (CS & Dodelson)



Parameter	No HC	WLT + HC Independent	WLT + HC Correlated	Difference
$\sigma(w_0)$	0.601	0.470	0.461	−2%
$\sigma(w_a)$	2.15	1.56	1.52	−2%
$\sigma(\Omega_{de})$	0.0387	0.0377	0.0362	−4%
FoM	0.485	1.01	1.15	+14%

Future Work

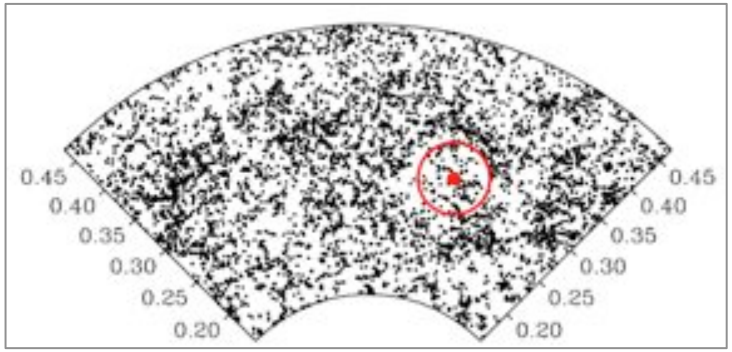
- Counts and clustering can (should!) be combined simultaneously with lensing
- Lensing and clusters share **systematics**: photo-zs, galaxy selection/detection
- These results were idealized: cross-correlation may be more beneficial after accounting for nuisance parameters
- Simulations?

A Multi-Dimensional Consistency Test for Dark Energy Surveys

with S. Dodelson, B. Hoyle, L. Samushia, & B. Flaugher

Supernovae

+



Baryon Acoustic Oscillations (BAO)

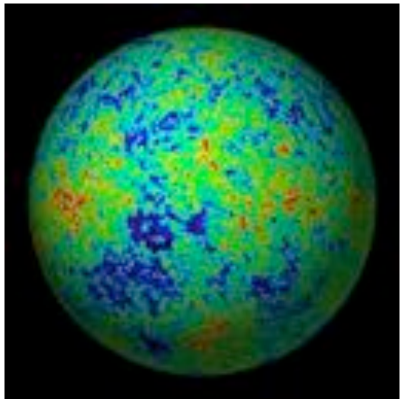
+

Lensing

+

Cluster Counting

+

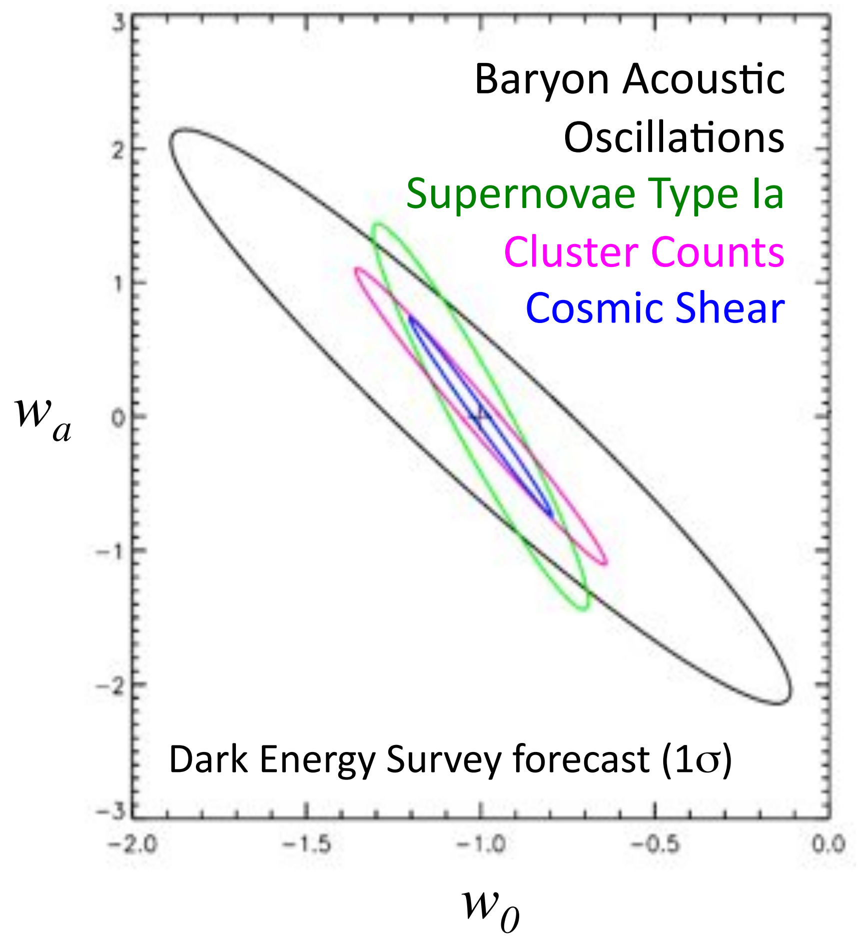


CMB

+ ...

Is there a simple, general test of GR that Dark Energy Survey can do?

- Several GR tests have been done with survey data (see e.g. Zhao et al, Reyes et al). So far GR looks good!
- Claimed detection of GR violation by Bean (false) - looked large enough to be confirmed by DES.
- Can we detect an incorrect model via **inconsistent dark energy parameters** among several probes?



- **Premise:** Suppose the Universe is described by modified gravity (MG) but we mistakenly analyze data assuming General Relativity (GR) plus a typical dark energy model,

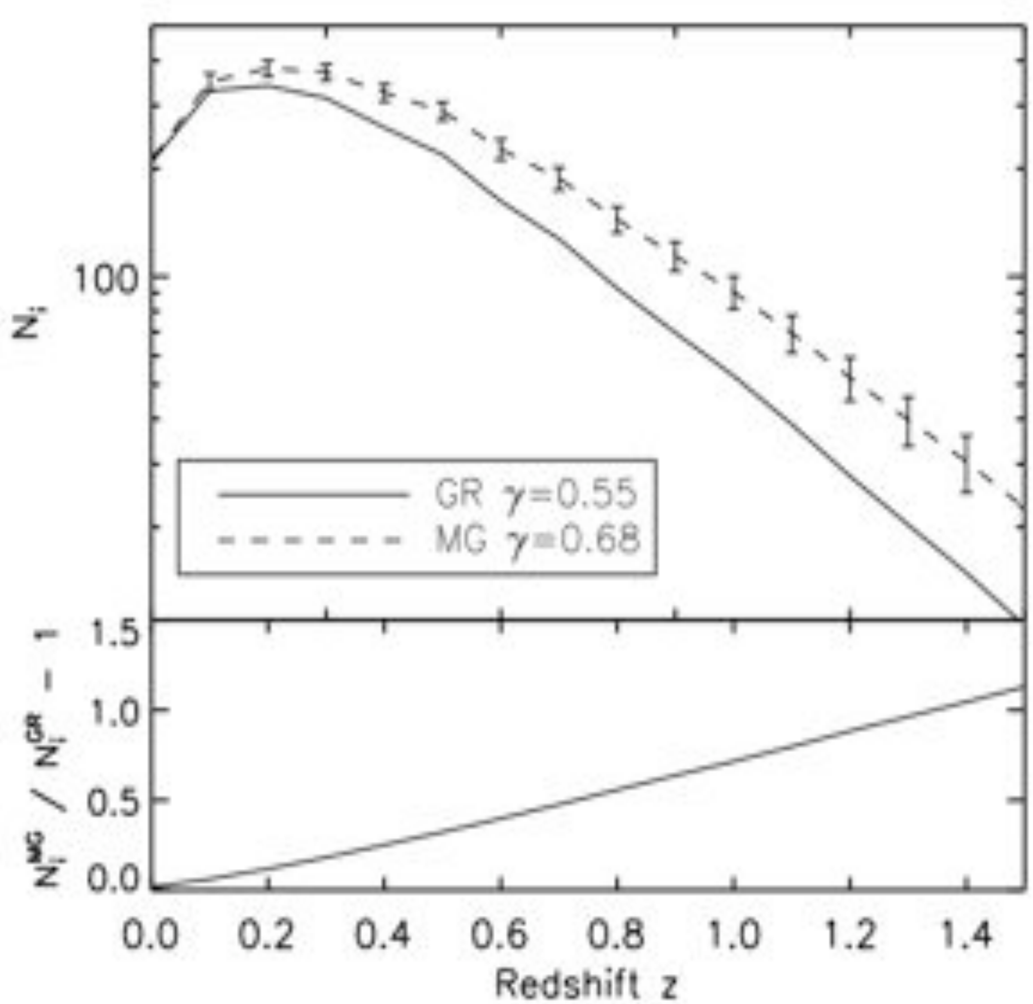
$$w = w_0 + (1 - a)w_a$$

- Our toy MG model is identical to LCDM but has a modified growth index $\gamma=0.68$ (in GR, $\gamma\sim0.55$). Matter density perturbations grow approximately as

$$f(a) \equiv \frac{d \ln \delta}{d \ln a} = \Omega_m(a)^\gamma$$

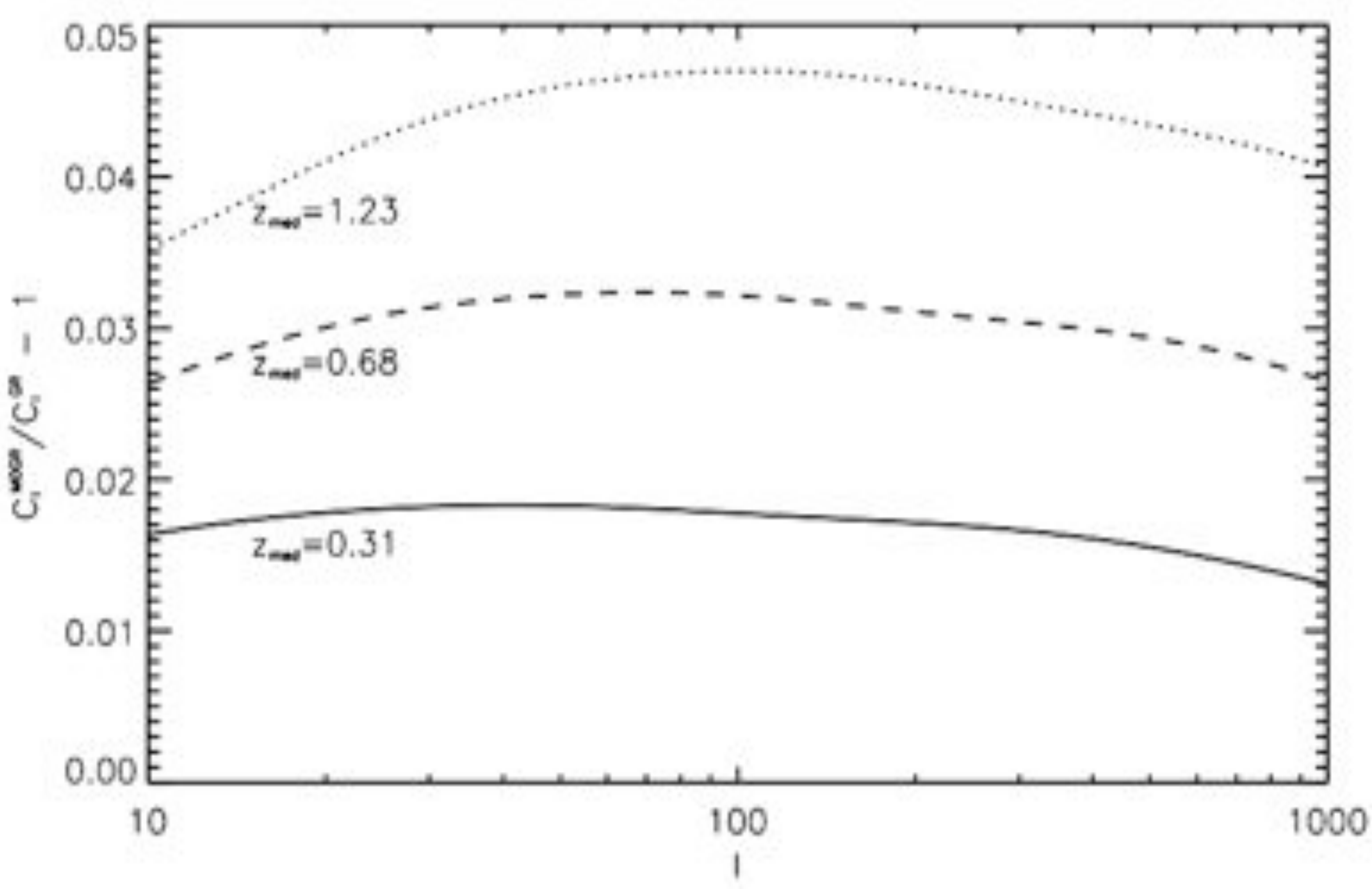
- Supernovae and BAO are unaffected by this MG model. Weak lensing and cluster predictions will be incorrect. The CMB is mostly unaffected (we ignore ISW).

Cluster counting prediction errors due to choosing an incorrect model



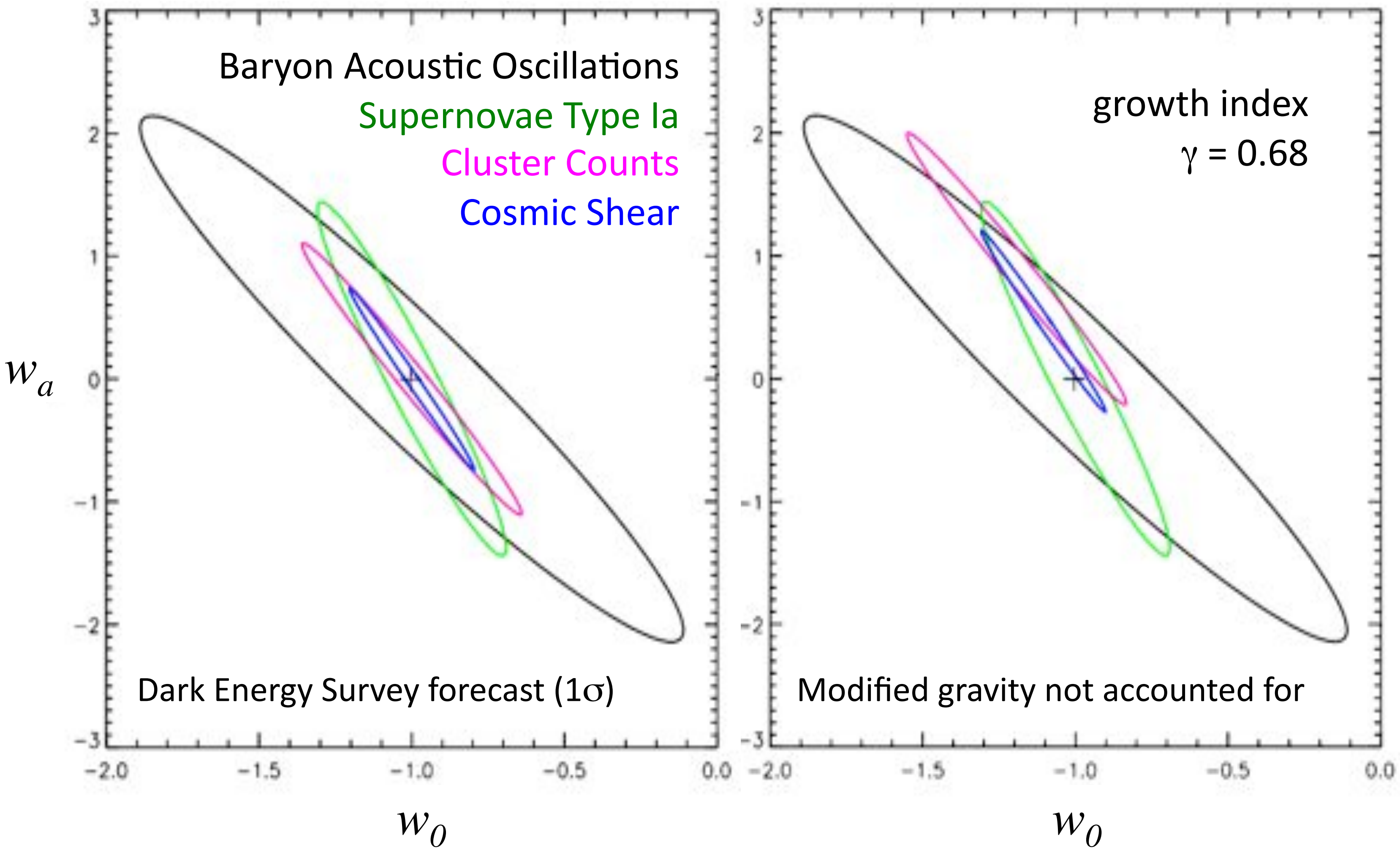
Expected number of clusters detected by DES+SPT in redshift bins of width Δz=0.1.

Cosmic shear prediction errors due to choosing an incorrect model



(Uses non-linear fitting formulae for matter power spectrum: Smith et al, Hu & Sawicki)

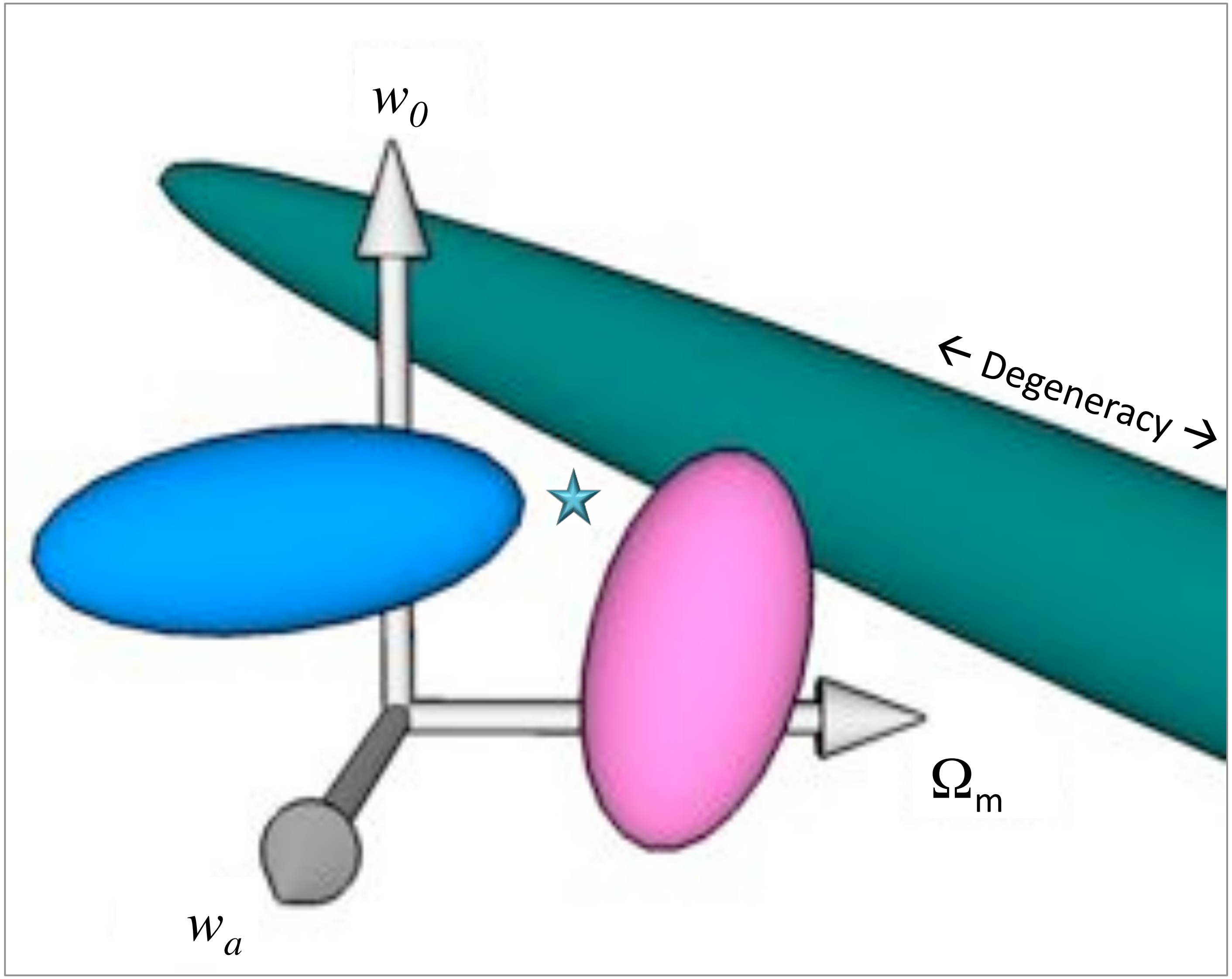
Can we detect an incorrect model via **inconsistent dark energy parameters**?



Drawbacks to glancing at the w_0-w_a plane:

- "Do the constraints overlap?" is not quantitative
- CMB data used multiple times → vague interpretation

- Parameter space can be 8-dimensional (or more). There could be inconsistency in w_0, w_a, Ω_m, Ω_k, Ω_b, H_0, n_s, σ_8



Hypothetical 1σ parameter constraints from 3 probes.
★ marks the parameter set that is most consistent with all data.

Multi-Dimensional Consistency Test

New Method:

Treat the best-fit parameter set from each experiment as a "data point" with an "error bar" (confidence region). Find the parameter set λ_α most consistent with all data by minimizing

$$\chi^2(\lambda_\alpha) = \sum_i \sum_{\alpha\beta} (\lambda_\alpha - {\lambda_\alpha}^{(i)}) \left[C^{(i)}\right]^{-1}_{\alpha\beta} (\lambda_\beta - {\lambda_\beta}^{(i)})$$

${\lambda_\alpha}^{(i)}$ = αth parameter obtained from *i*th probe

$C^{(i)}$ = covariance matrix for parameters from *i*th probe

We find that $\langle \chi^2_{\min} \rangle = (N-1)M - \sum_i S^{(i)} + B$

- M = #parameters , N = #probes , S = #degeneracies , B = "tension"

- B is a function of covariance matrices and **prediction errors** for all probes. B=0 when we expect the same parameter set from all probes.

Large B indicates non-overlapping parameter constraints. We'd interpret this as inconsistency with a goodness-of-fit given by the χ^2 probability distribution for n degrees of freedom:

$$P(\chi^2_{\min} > \nu + B; \nu) \qquad \nu = (N-1)M - \sum_i S^{(i)}$$

Result: Using a GR+dark energy model instead of our (true) MG model yields **non-overlapping 8D parameter constraints** from 4 DES probes + Planck.

WL	CL	SN	BAO	CMB	ν	B	$P(\chi^2_{\min} > \nu + B; \nu)$
	√		√	√	5	2.06	0.2164
	√	√		√	5	1.67	0.2466
	√	√	√		4	0.02	0.4030
	√	√	√	√	9	3.02	0.2121
√			√	√	6	2.08	0.2326
√		√		√	6	1.96	0.2414
√		√	√		5	0.75	0.3313
√		√	√	√	10	2.21	0.2715
√	√			√	6	6.71	0.0478
√	√		√		5	0.61	0.3462
√	√		√	√	10	8.23	0.0512
√	√	√			5	2.29	0.2003
√	√	√		√	10	9.22	0.0376
√	√	√	√		9	2.76	0.2271
√	√	√	√	√	14	15.58	0.0087

CMB and WL Fisher matrices have 3 degeneracies. SN, BAO, CL have 4.

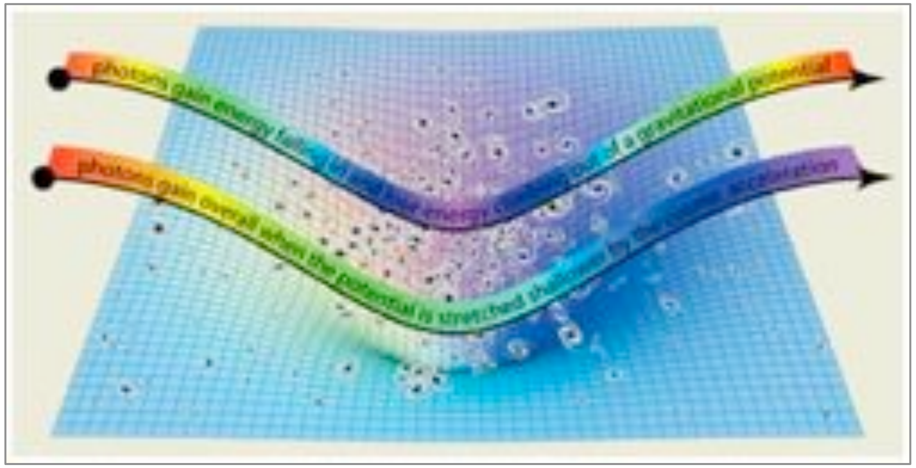
- All probes → 99% inconsistency. Need CMB, clusters and lensing for 2σ inconsistency.
- CMB is crucial, ∴ tension occurs in parameters that are well-measured by Planck.
- Tension exists despite degeneracies (infinite error bars) in each probe.

Future Work

- Generalize to non-gaussian likelihoods
- Apply to current data
- Can be appended to typical analysis
- Better visualization of inconsistencies?

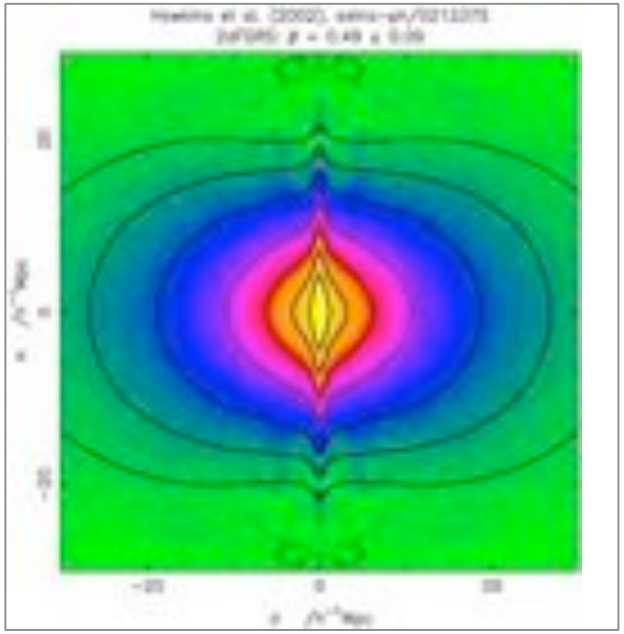
Combining the Integrated Sachs-Wolfe effect with Reshift-space distortions

Unpublished work with R. Crittenden & W. Percival



ISW

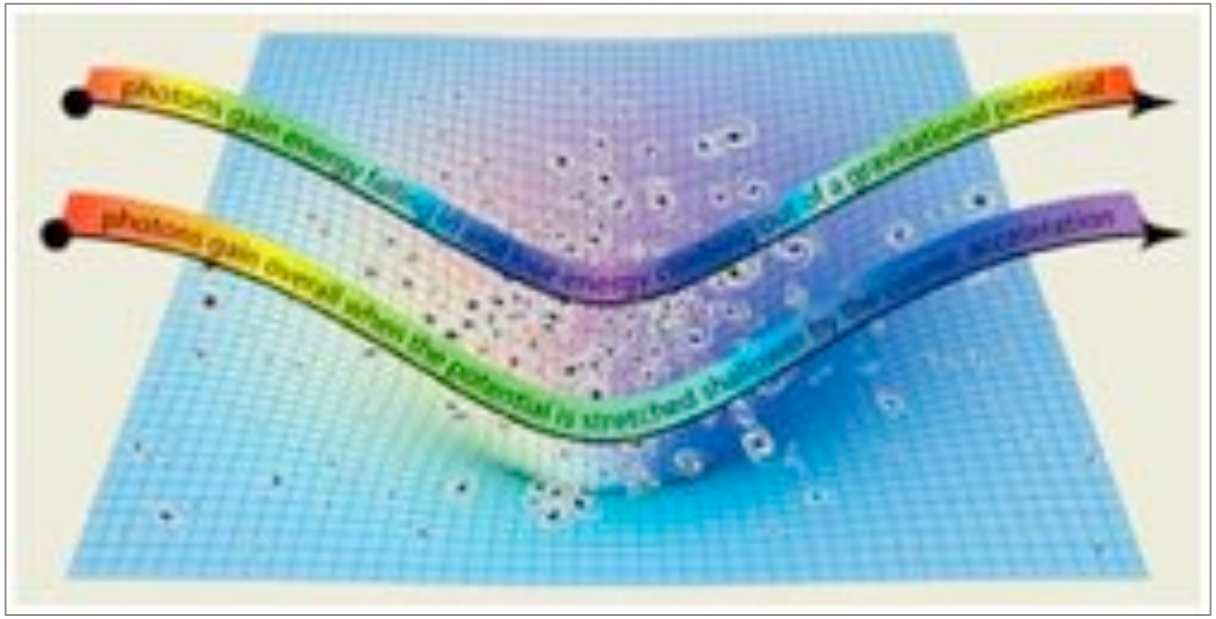
+



RSD

(BOSS + Planck)

Review: Integrated Sachs Wolfe-effect



- Imprint left on the CMB when photons traverse evolving potentials (potentials are static when Universe is matter dominated)
- Signal is a projection of $\frac{d}{dt}(\dot{\Phi} - \dot{\Psi})$ along the line of sight
- Weak signal is best detected through cross-correlations (e.g. CMB-galaxy)

Review: Redshift-space distortions (RSD)

Figure by Dodelson

$$z = H_0 x + \vec{v} \cdot \hat{x}$$ (for small z)

- Peculiar velocities *along the line of sight* cause an apparent enhancement in galaxy clustering

- Kaiser effect: $\delta^s_{\rm gal}(\vec{k}) = (1 + \beta\mu^2)\delta_{\rm gal}(\vec{k})$ $\qquad \beta \equiv \dfrac{f}{b}$

$$f(a) \equiv \frac{d\ln\delta}{d\ln a} \approx \Omega_m(a)^{0.55}$$

Under General Relativity, ISW and RSD probe similar information

$$D(z) \equiv \frac{\delta(\vec{k})}{\delta(\vec{k}; z=0)} \qquad f(a) \equiv \frac{d\ln\delta}{d\ln a} \approx \Omega_m(a)^{0.55}$$

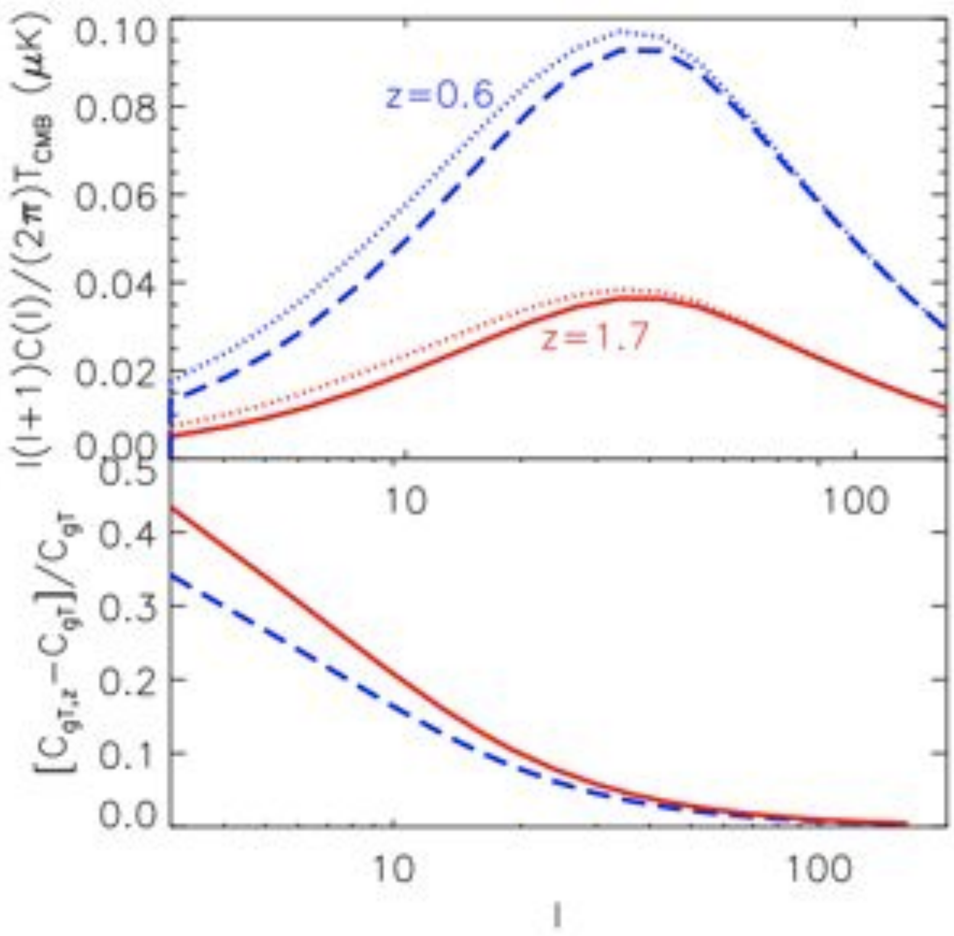
- Galaxy clustering: $D(z)\ b(z)$
- RSDs: $D(z)\ f(z)$
- ISW: $D(z)\ [1 - f(z)]$ (projected)

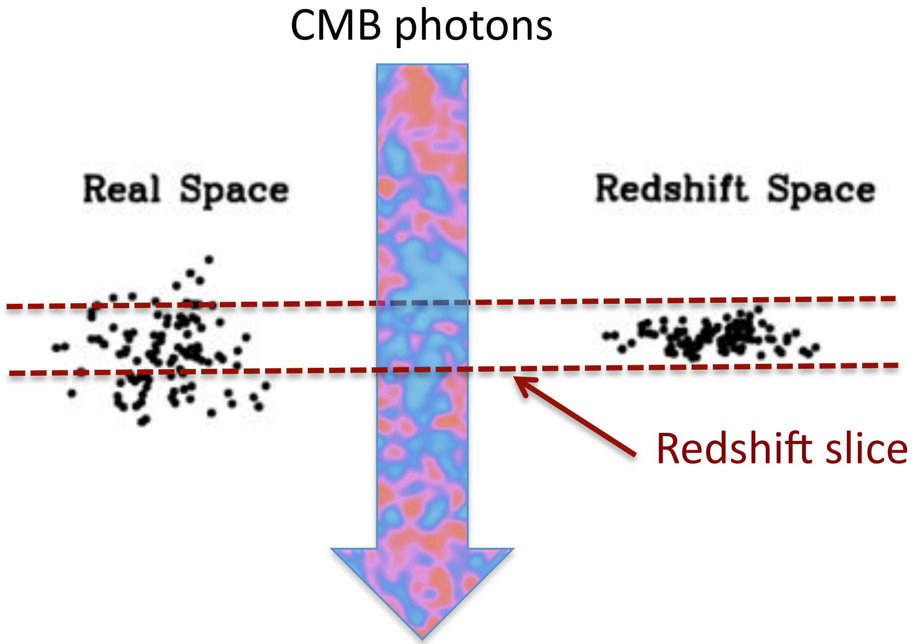
→ How complementary / redundant are ISW and RSD when combining data from e.g. BOSS and Planck?

→ How are galaxy-CMB correlations affected?

Do RSDs *boost* the ISW signal?

Rassat (2009) showed that RSD increases the ISW signal *in a single redshift slice*





This is a byproduct of the redshift binning, not a "real" correlation

Preview of upcoming paper:

- Spherical harmonic analysis of CMB and galaxies

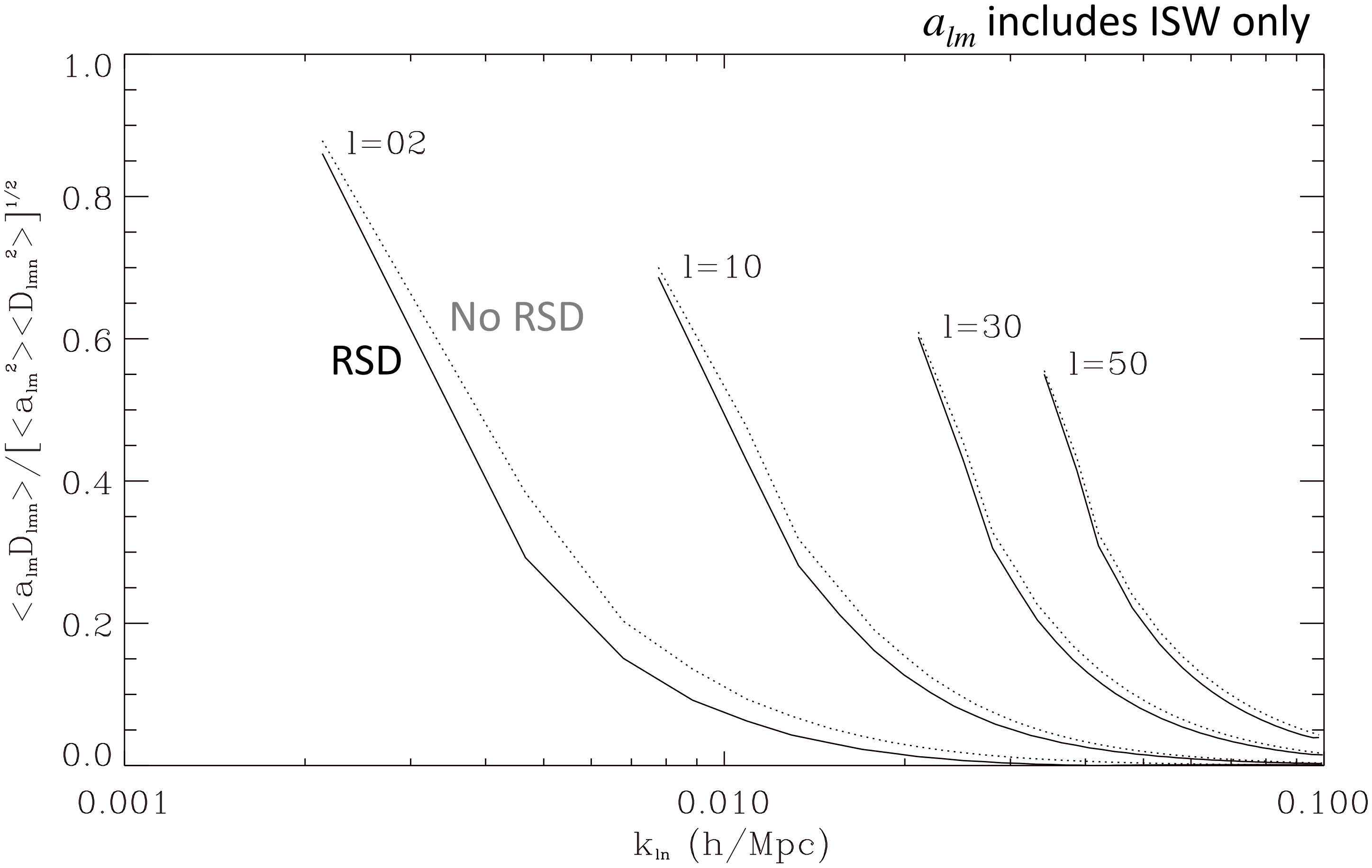
$$D_{lmn} = c_{ln} \int W(s) \rho_{\rm gal}(\vec{s}) j_l(k_{ln} s) Y^*_{lm}(\theta, \phi) d^3 s$$

s = Distance in redshift-space $\qquad$ k_{ln} = Discrete radial wavenumbers

- Allows natural computation of full covariance matrix: $\langle a_{lm}\, a_{l'm'} \rangle$, $\langle a_{lm}\, D_{l'm'n} \rangle$, $\langle D_{lmn}\, D_{l'm'n'} \rangle$

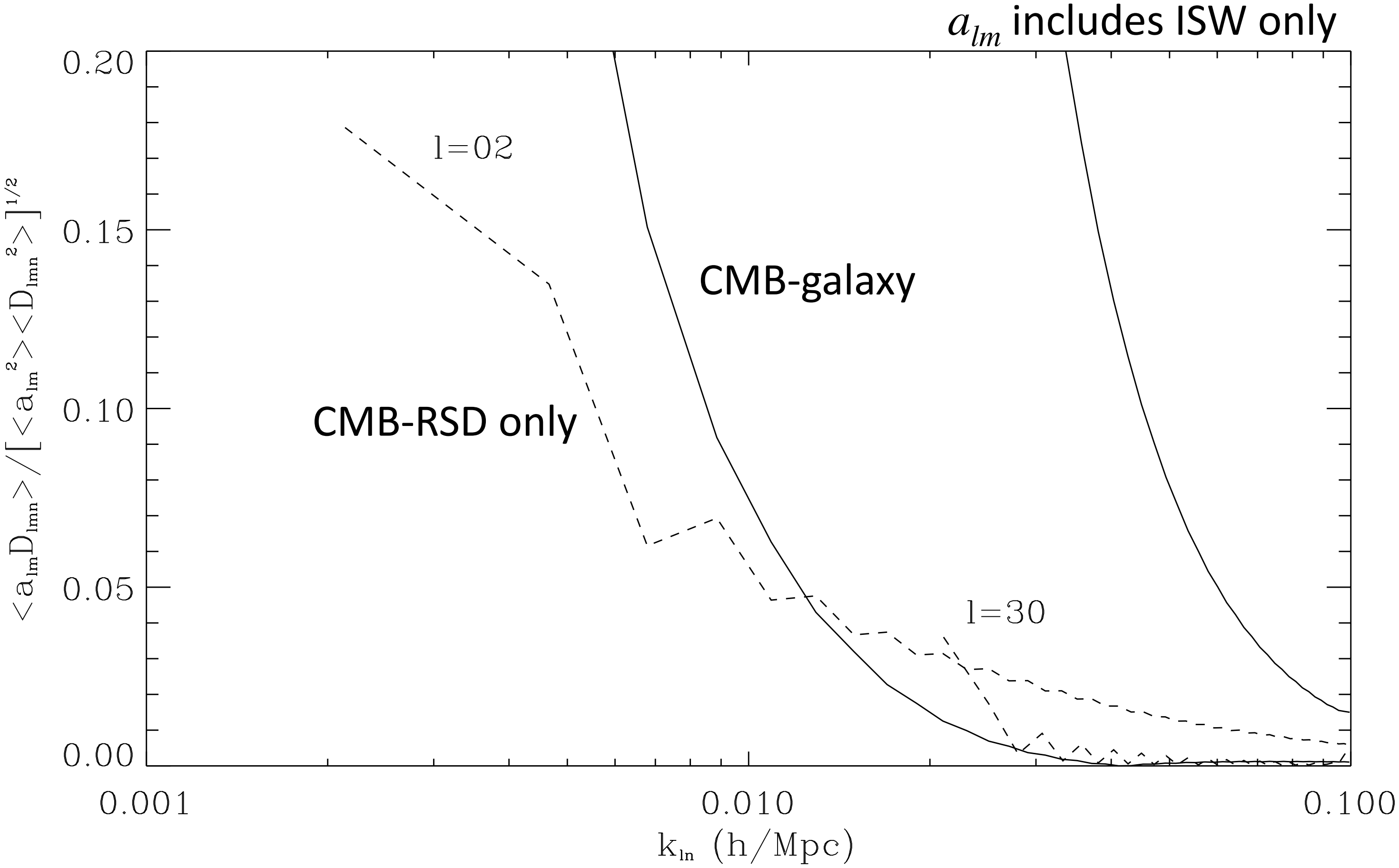
- We avoid Limber, flat-sky approximations

Result: CMB-galaxy correlations (ISW) are slightly <u>weakened</u> by RSD

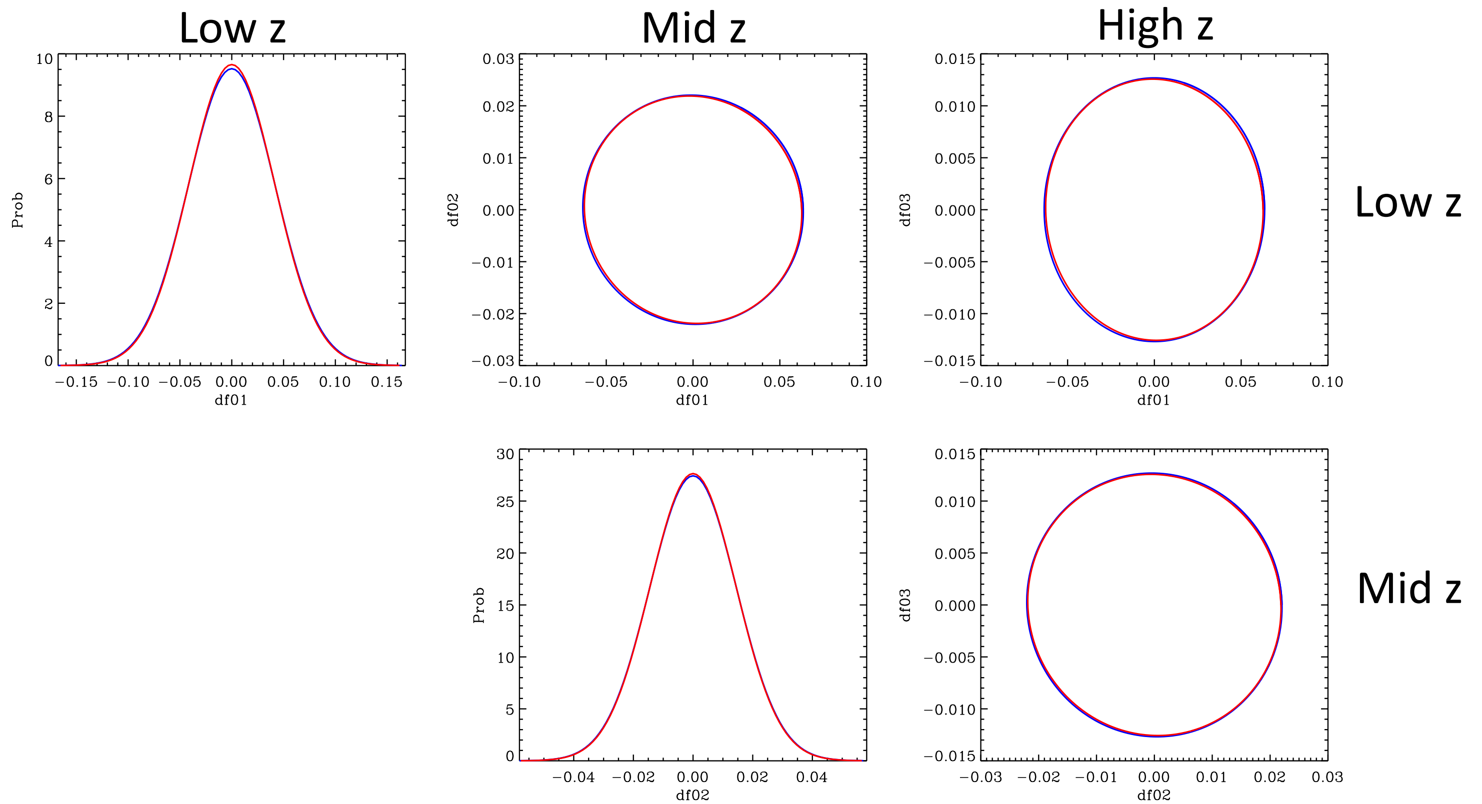


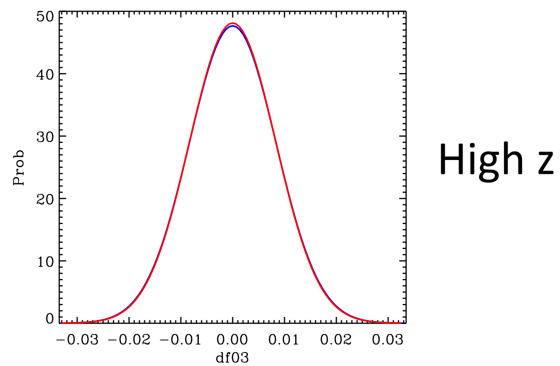
BOSS: z < 0.6 k < 0.1 h/Mpc

Result: CMB is mostly uncorrelated with "pure" RSDs



Result: ISW adds little to RSD constraint on $f(z)D(z)$

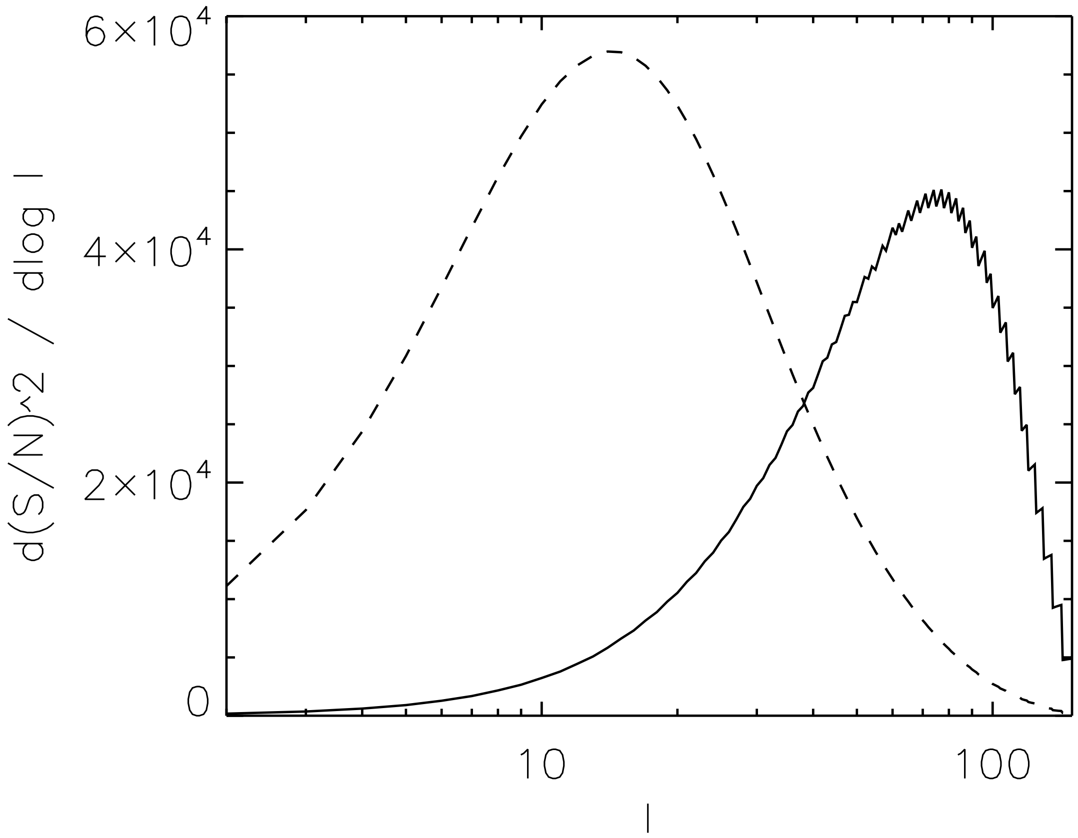




Constraining piecewise-constant changes to fD (from ΛCDM prediction) in 3 z-bins 0<z<0.6 (BOSS)

$f\,\sigma_8$ constraints = [0.031, 0.011, 0.0063]

ISW may help constrain scale-dependent growth, modified gravity, etc.



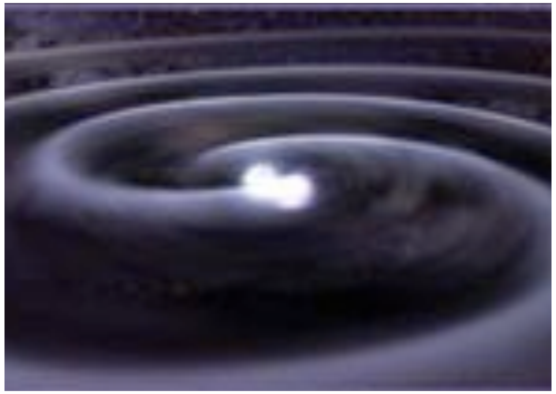
Delensing Standard Candles & Standard Sirens

with D. Bacon, B. Hoyle & M. Hendry

Supernovae

+

Lensing



Supermassive Black Hole Binaries
(LISA)

Using galaxy shears to remove random magnifications

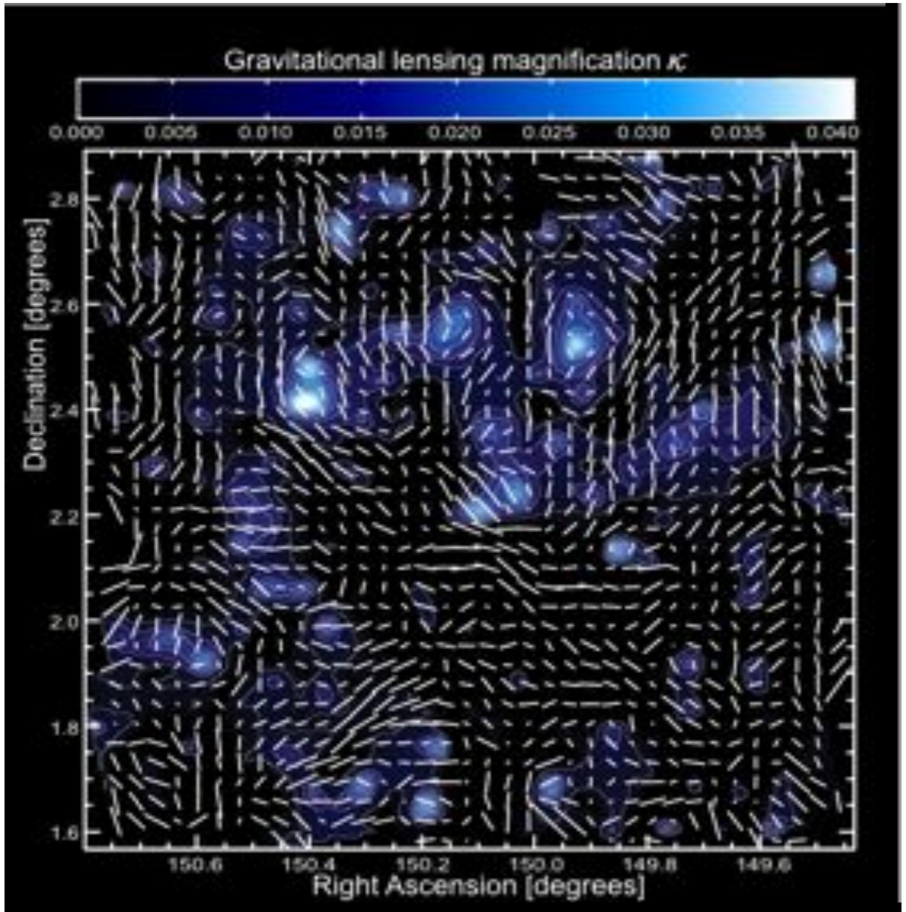
- Standard sources are randomly magnified by large-scale structure. We can only measure

$$D_L^{\text{obs}} = D_L^{\text{true}}\, \mu^{-1/2}$$

- A map of μ can be reconstructed from weakly lensed galaxy images ($\mu \approx 1\text{-}2\kappa$)

- Map will be imperfect due to
  - Intrinsic galaxy shapes
  - Smoothing/pixelization
  - Sampling Noise
  - Mass-sheet degeneracy
  - Galaxy redshift distribution

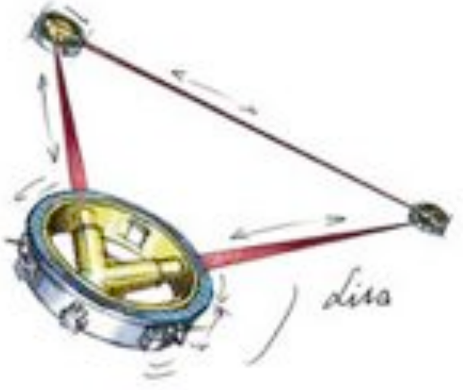
- → Decent map must be deep *and* wide *and* have high galaxy density

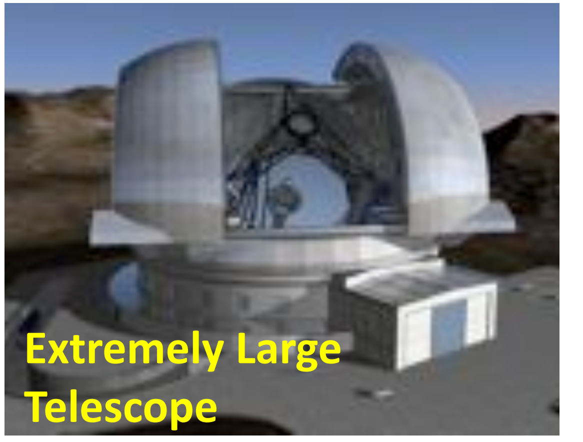


HST/COSMOS, Massey et al. (2005)

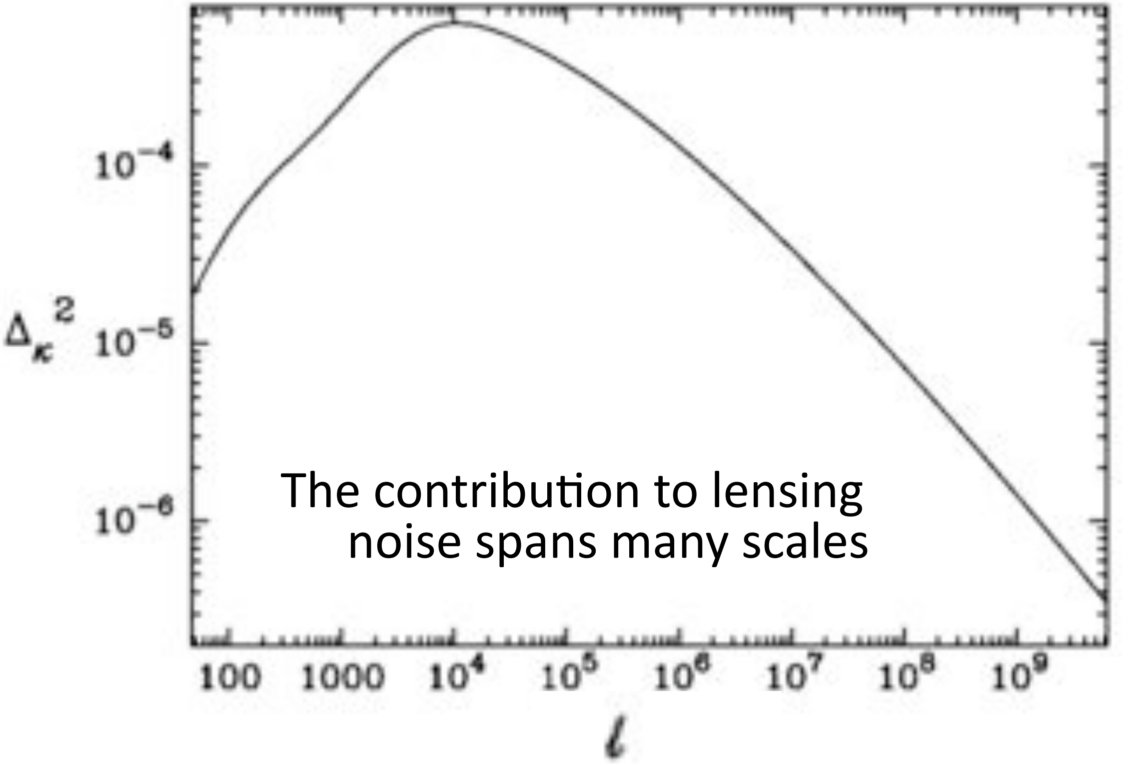
Instruments Required for Delensing

removes low-l noise

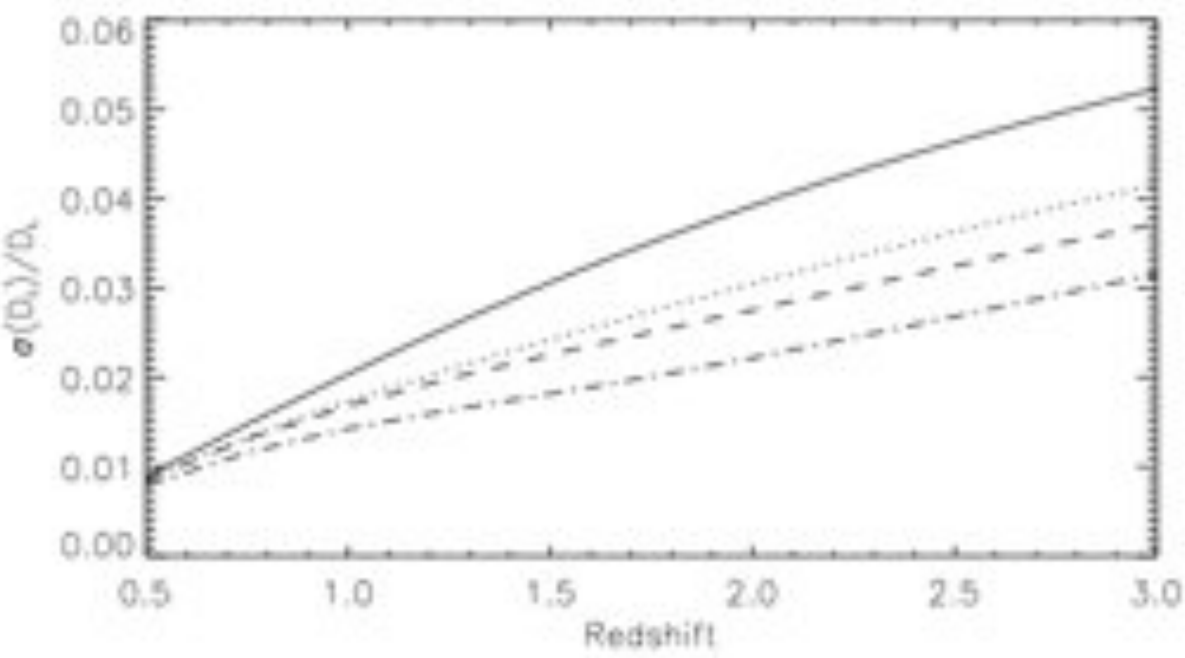




removes high-l noise



Distance error reduction (conservative guess)



Distance error from lensing

After delensing (ELT no flexion)
After delensing (ELT)
After delensing (ELT+JDEM)

30 arcmin^2 ELT image
No redshift information
Pessimistic sampling noise

Delensing this way would be more effective for SMBHBs than for supernovae:

- SMBHBs are rare (10/year?) – unlikely to get ELT to follow up on all supernovae
- Lensing could be <u>the</u> biggest source of noise for SMBHBs


Thank you!