Cosmology from Distance and Growth

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Justification

- For most of this talk I will directly be exploring applications of cosmic shear data, which is not the subject of this workshop.
- However, the applications I discuss can also be worked out for X-ray and SZ surveys of galaxy clusters. These surveys' sensitivity to dark energy also comes from their senstivity to distance and growth (Haiman, Mohr & Holder 2001).

Outline

- Using the CMB to control the high-z matter content and primordial power spectrum (so that low-z observations can focus on things important at late times such as dark energy).
- Tomographic Cosmic Shear
- Reconstruction of r(z) and g(z)
- Application to
  - Gravity
  - Inflation
  - Neutrino masses
- A New SZ-Shear Synergy?

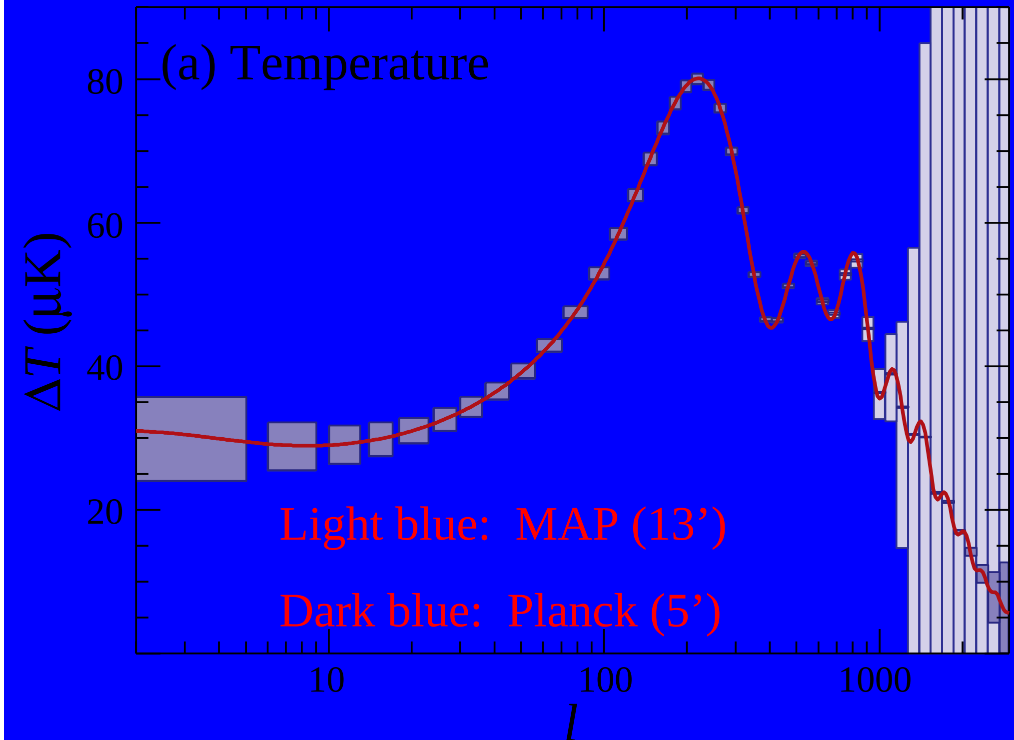
Planck can determine the matter power spectrum through the matter-dominated era

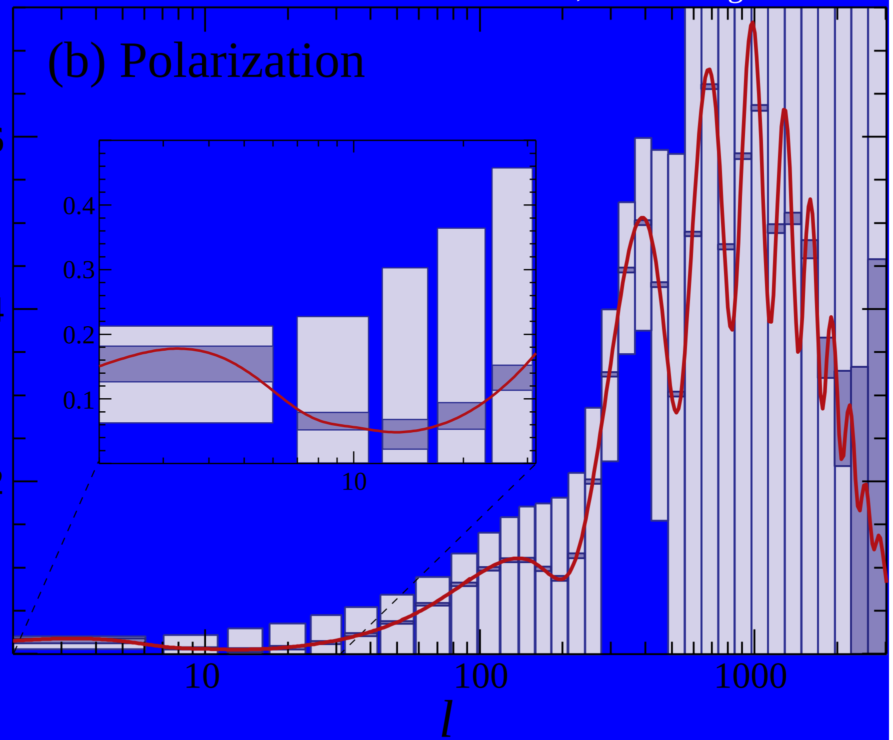
(improvement due to ang. res.) (improvement due to sensitivity)

Temperature

Polarization

Eisenstein, Hu and Tegmark 1998





🡐 Large angular scales Small angular scales 🡒

- •P amplitude about 10% of T anisotropy
- •l > 15 from last—scattering surface
- •l < 15 from reionization

Breaking the P-τ Degeneracy

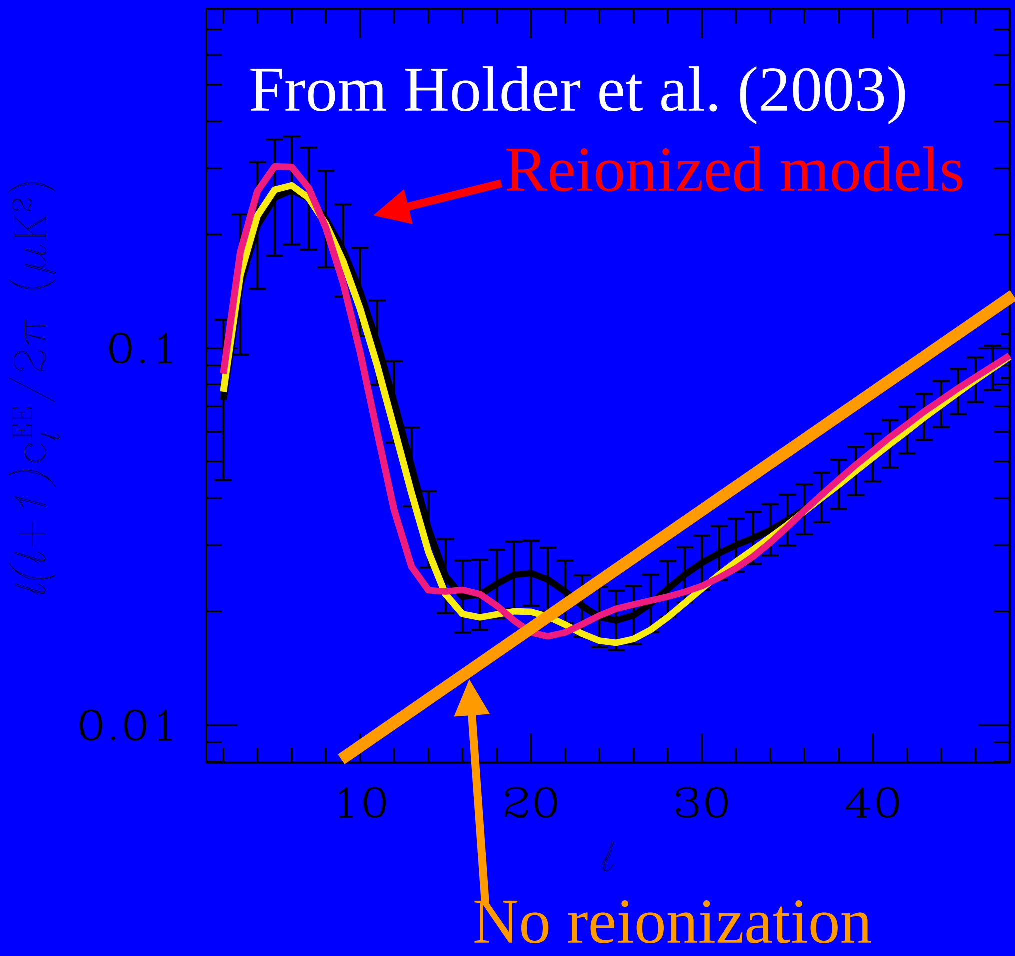
1) Reionization Uniformly suppresses power at l > about 25 by $e^{-2\tau}$

2) And creates new fluctuations at very low l

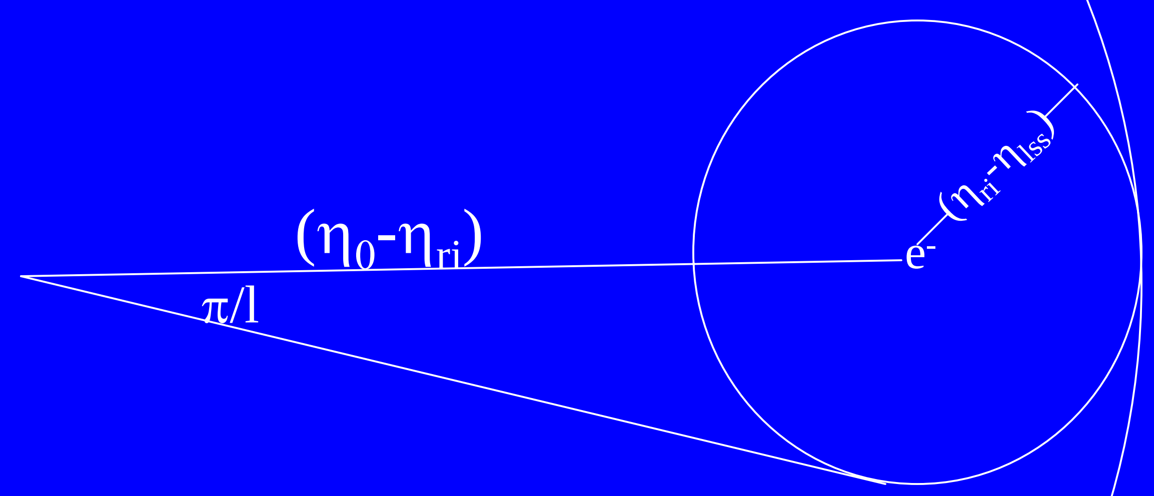
The signal is very small (0.1 μK^2).

Need the high sensitivity of Planck and nearly full -sky coverage to study this signal in any detail. WMAP is insufficient.

Cosmic variance error bars



Why are there bumps in the polarization power spectra at low l?



$l=k(\eta_0-\eta_{ri})$

$2=k(\eta_{ri}-\eta_{lss})$

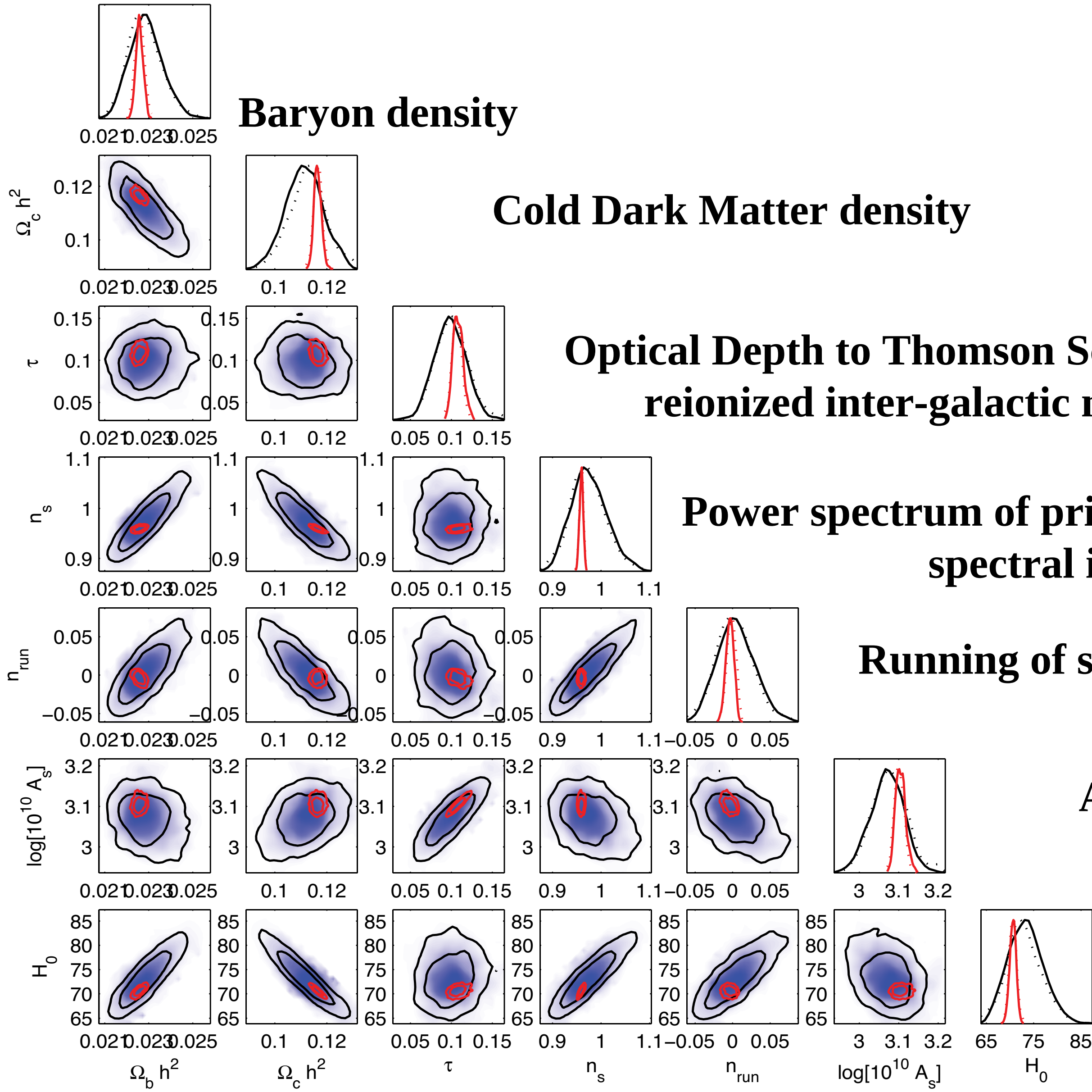
➔ $l=2\,(\eta_0-\eta_{ri})\,/(\eta_{ri}-\eta_{lss})$

$C_l^{EE} \propto \tau^2$

$C_l^{TE} \propto \tau$

Zaldarriaga 1997

Cosmological Parameter Error Forecasts



Baryon density

Cold Dark Matter density

Optical Depth to Thomson Scattering by reionized inter-galactic medium

Power spectrum of primordial perturbations spectral index (n_s)

Running of spectral index ($dn_s/dlnk$)

Amplitude of primordial perturbations

Hubble constant

Blue: WMAP 4-year

Red: Planck 1-year

Planck and the ‘high-z’ parameters

- Improve n_s and $dn_s/d\ln k$ by extending to smaller scales.
- Improve primordial power spectrum amplitude determination by using low l polarization to break P-τ degeneracy: $\sigma(P)/P = 2\sigma(\tau)$
- Improve $\omega_m = \Omega_m h^2$ to 1% determination by cosmic-variance limited measurement of 3rd peak.

➔ Determines the density power spectrum from high-z until dark energy becomes dynamically important.

All that remains to be inferred from low-z large-scale structure data are two functions: g(z) and r(z)*

If the dark matter is cold and pressureless, and we can ignore spatial density fluctuations in the dark energy itself, then

$$\delta(x,z_1) = g(z_2)/g(z_1)\ \delta(x,z_2);$$

i.e., growth is scale-independent.

How the density field influences two-dimensional images of the sky we observe today depends on the angular-diameter distance, r(z) .

*To zeroth order… there are important exceptions to this rule (e.g. due to neutrinos).

All that remains to be inferred from low-z large-scale structure data are two functions: g(z) and r(z)

It is through these two functions that large-scale structure probes

[galaxy redshift surveys, galaxy cluster surveys (SZ, optical, lensing, X-ray), shear two-point function, etc.]

are sensitive to the dark energy.

We will study how well the cosmic shear two-point function can be used to simultaneously reconstruct g(z) and r(z).

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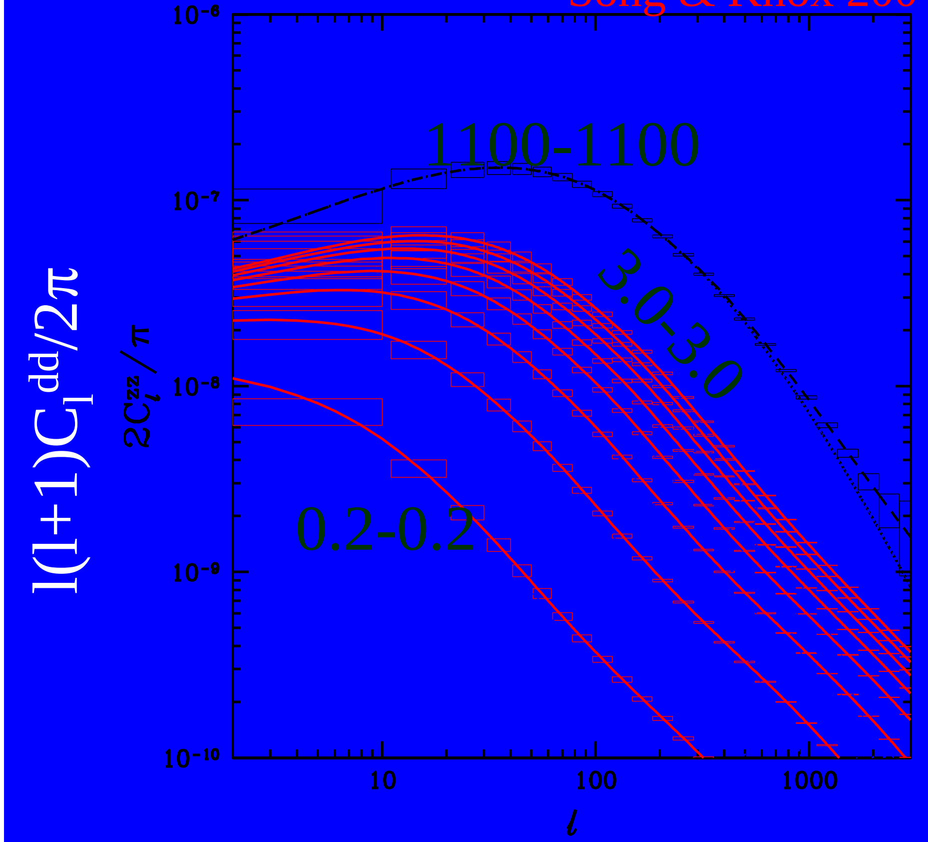
Baseline model of shear data: G2π, An Approximation to the LSST Cosmic Shear Survey

- Source redshift distribution:
  - $dn/dz \propto z^{1.3}\exp[-(z/1.2)^{1.2}]$ for $z < 1$
  - $dn/dz \propto z^{1.1}\exp[-(z/1.2)^{1.2}]$ for $z > 1$ (with 50% missing in $1.2 < z < 2.5$ range) Nagashima et al. 2002
  - n_{tot}=65/arcmin^2
- Eight photo-z bins: [0-0.4], …, [2.8-3.2]
- Sky coverage: 2π steradians
- Angular scales: $40 < l < 1000$
- No systematics (calibration errors, photo-z errors, …)

Cosmic Shear Two-Point Functions

Song & Knox 2004



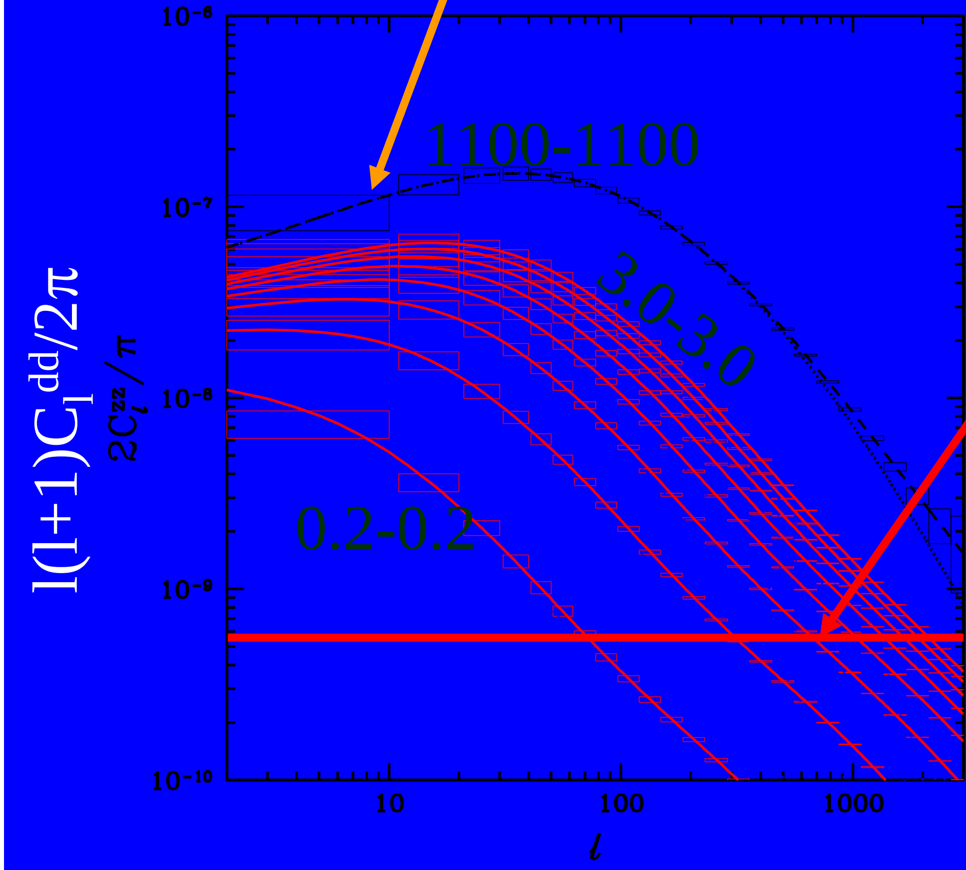
- We forecast using data with l < 1000.
- The signal is harder to calculate at l > 1000 and more sensitive to spurious psf power.
- There is a lot of information at l > 1000.
- I only use the 2-point function in this talk. No higher-order correlations (Takada & Jain 2003). No counting of mass clusters (Tyson et al. 2002, Wang et al. 2004, Hennawi and Spergel 2005). No 'cross-correlation cosmography' (Jain & Taylor 03, Bernstein & Jain 03, Song & Knox 04, Hu & Jain 04).

Some of the 9(9+1)/2=45 two-point functions

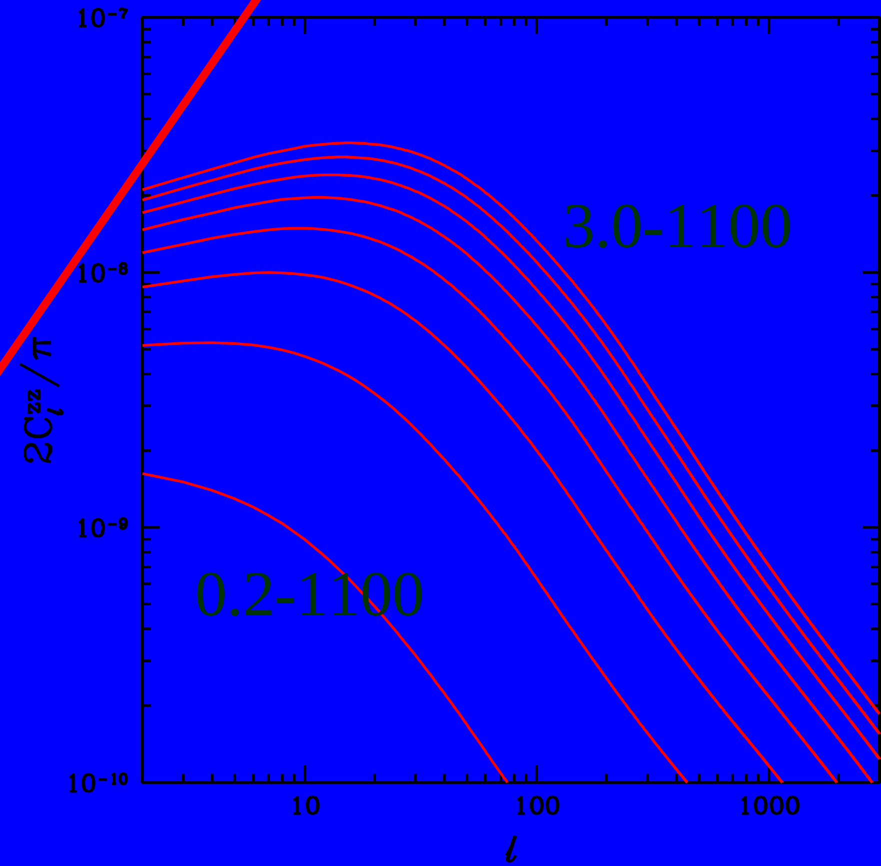
‘CMBpol’ errors shown here… but we use Planck

Shape noise power for 10 gal/arcmin^2

Redundancy provides robustness (e.g., Takada & White 2003)



auto power spectra (z-z)



cross power spectra (z-1100)

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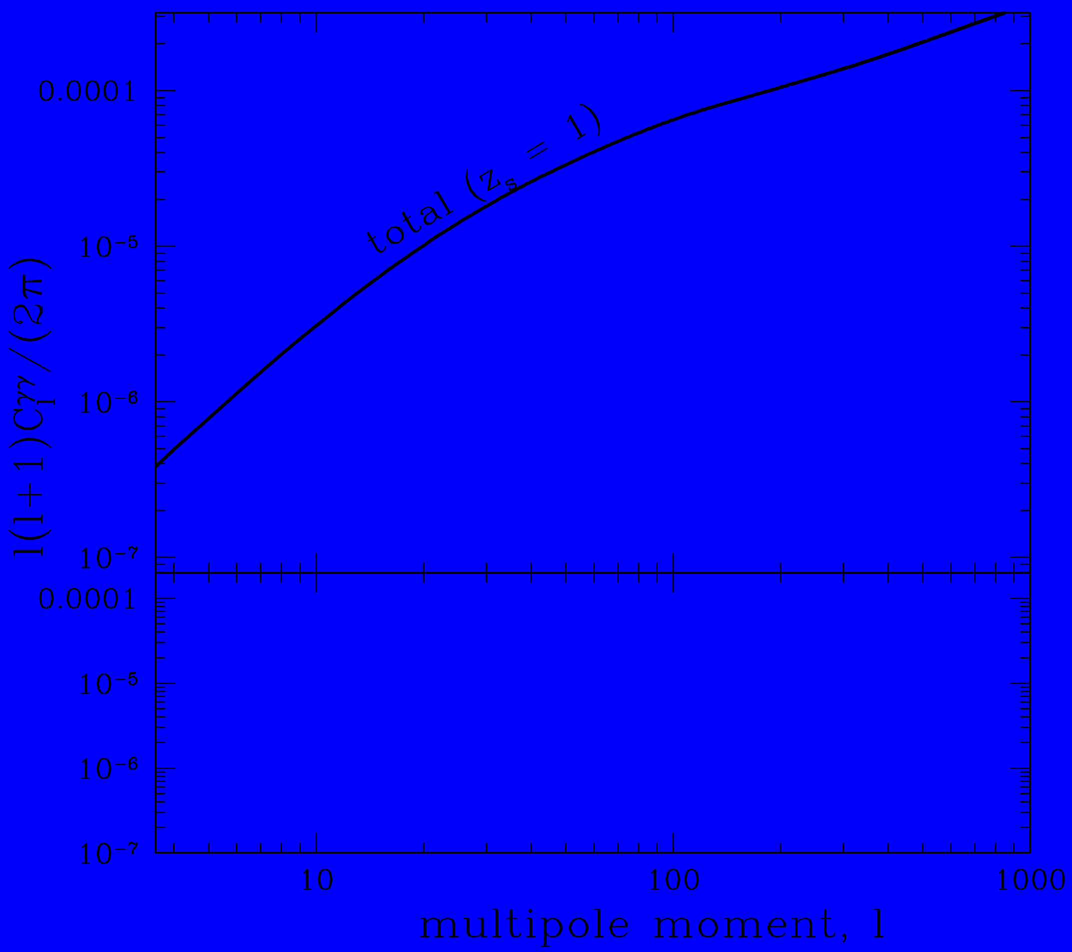
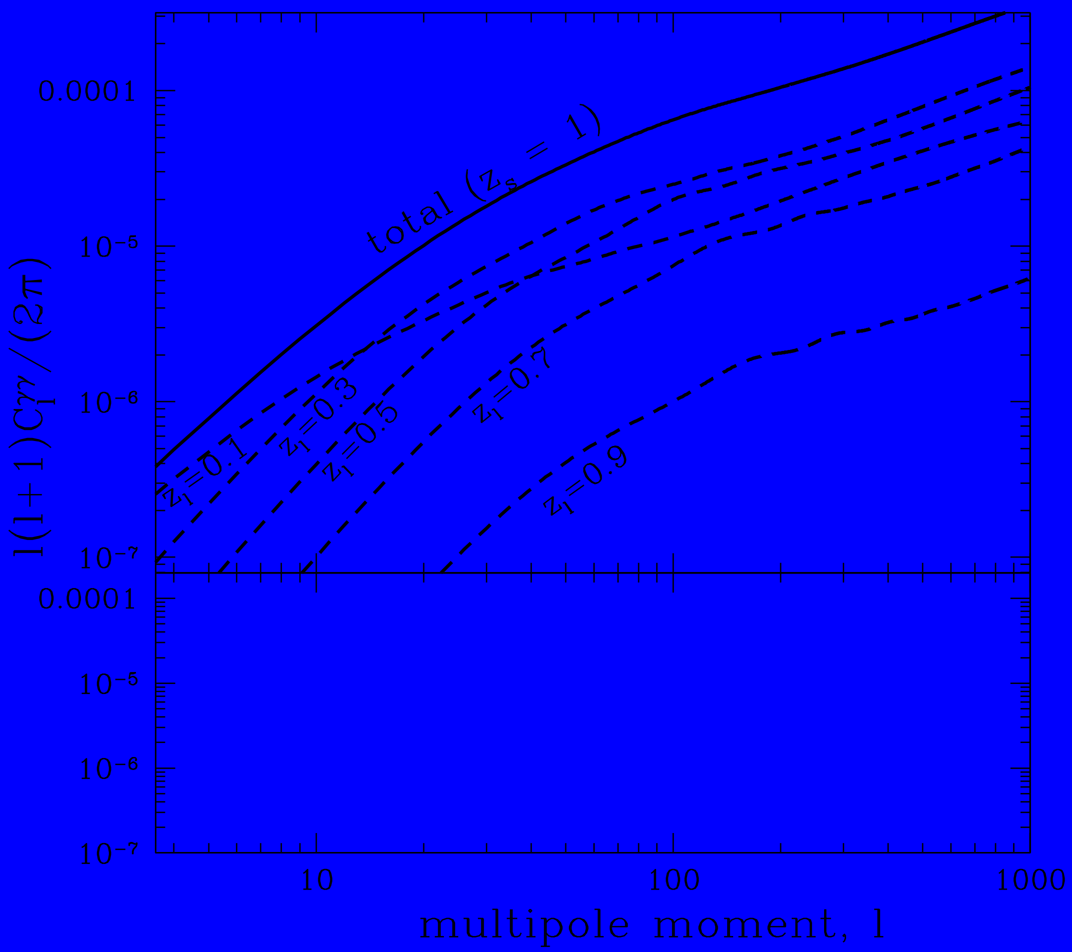
Dependence of Shear power on r(z) and g(z)

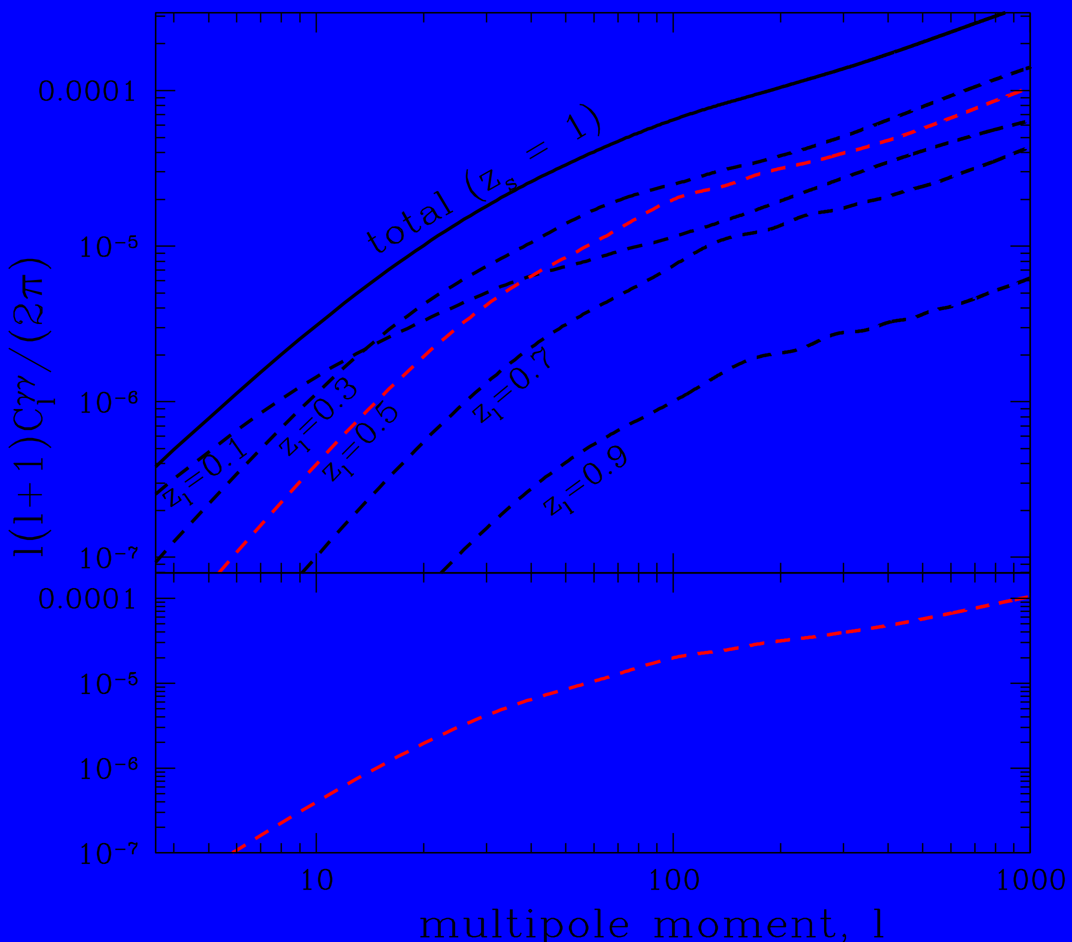
Note: switched from deflection angle power spectrum to shear power spectrum (which simply means multiplying by l(l+1)).



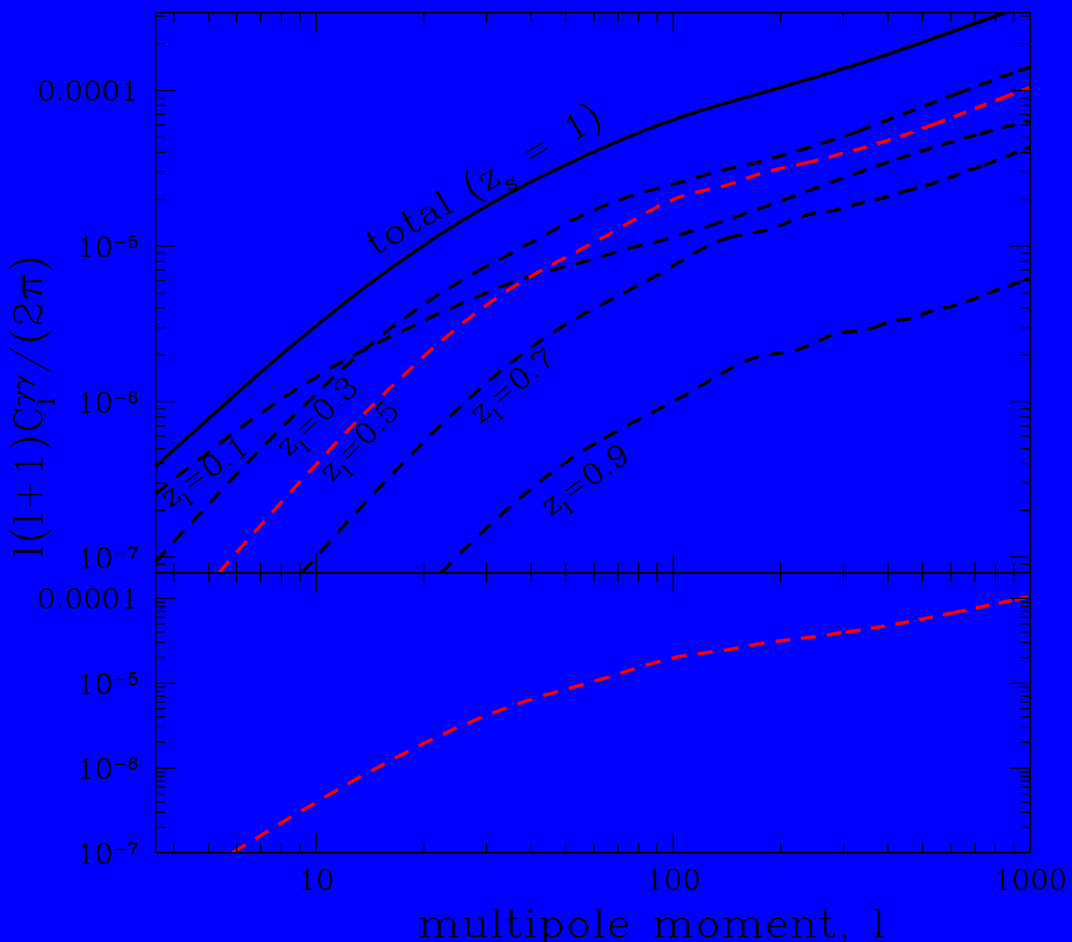
Dependence of Shear power on r(z) and g(z)



Dependence of Shear power on r(z) and g(z)

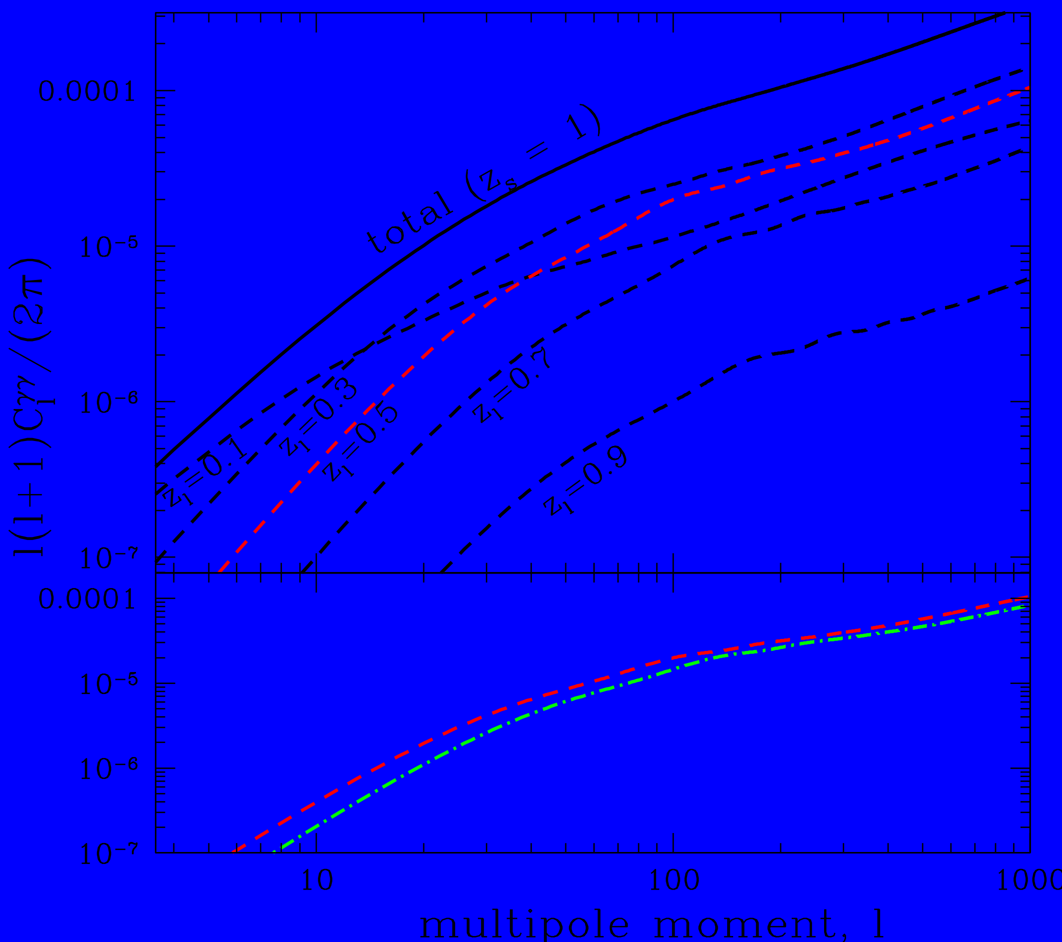


Dependence of Shear power on r(z) and g(z)



Increasing g(z=0.5) by 30%

Dependence of Shear power on r(z) and g(z)



Increasing g(z=0.5) by 30%

Increasing r(z)

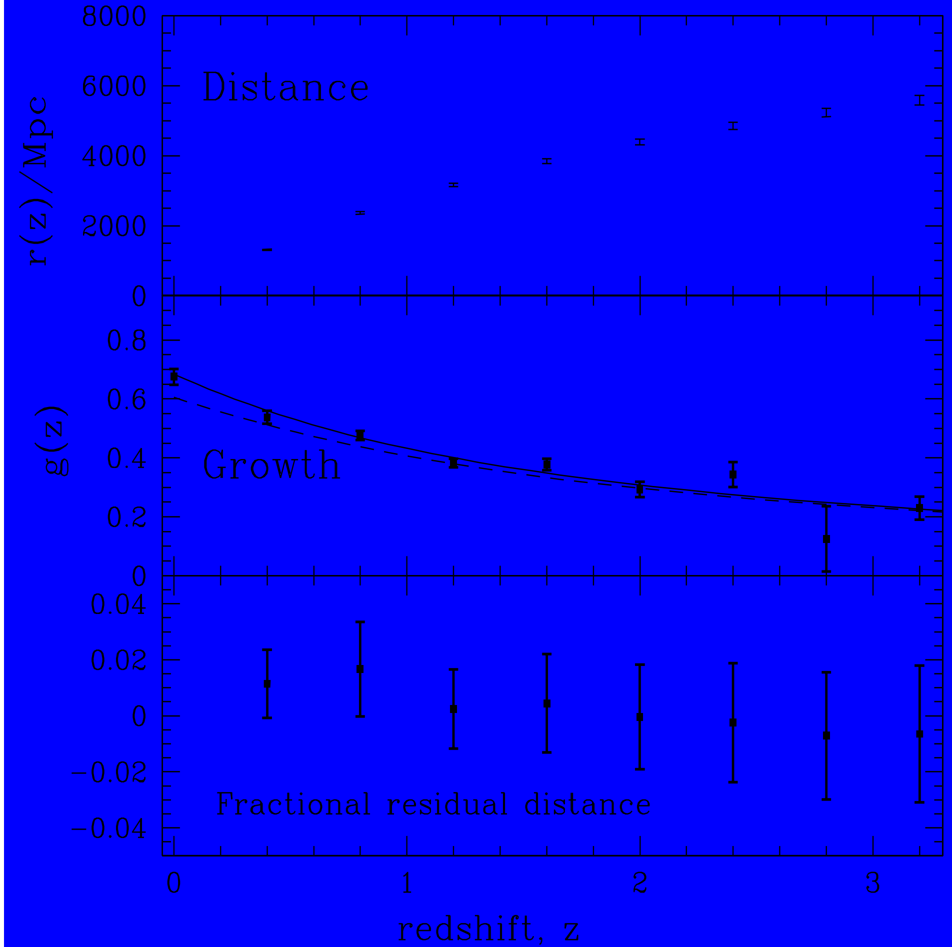
Parameterization

- Nine high-z parameters (primordial power spectrum parameters, matter density, baryon density, …)
- Eight distance parameters:
  - Distance to z=0.4i for i = 1 to 8.
  - R(z) constructed from these parameters by interpolation.
- Nine growth parameters:
  - $F(z) = g^2(z)/a^2(z)$ specified at z=0.4i for i = 0 to 8.
  - F(z) constructed from these parameters by interpolation.

From this parameterization and our modeling of the data we calculate the expected parameter error covariance matrix (assuming a linear response of power spectra to parameters; i.e. Fisher matrix approximation).

Reconstruction from LSST and Planck

Knox, Song & Tyson 2005



Scatter in points is due to one sampling of the errors from their calculated probability distribution.

- Remarkable precision, especially for distance (2% errors!)
- Errors are correlated across redshift ➔ some linear combinations are much better constrained than indicated by the error bars.
- Constraints on $w = P/\rho$ are almost entirely from r(z). [And is $\sigma(w_0) = 0.075$ (Song & Knox 2004)]
- Independent r(z) and g(z) reconstructions can be used for consistency test.

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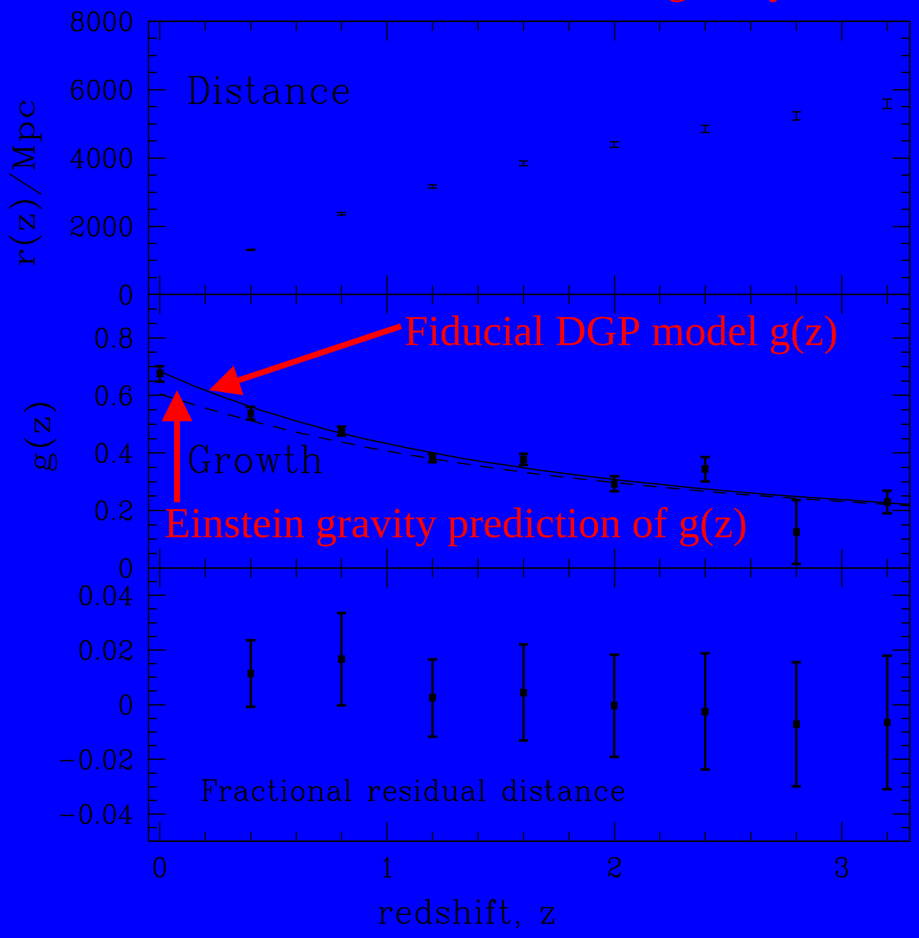
A Consistency Test

- With r(z) recovered, can adjust $\rho_x(z)$ to get right H(z) to match observed $r(z)=\int dz/H(z)$.
- With H(z) in hand, ignoring dark energy fluctuations, assuming cold dark matter and Einstein gravity, one can predict g(z).
- As an example, we took fiducial model here to be a DGP model with no dark energy. The resulting g(z) prediction for Einstein gravity + dark energy is the dashed curve. They are highly distinguishable.

Knox, Song & Tyson 2005



Curves are more than 10σ different

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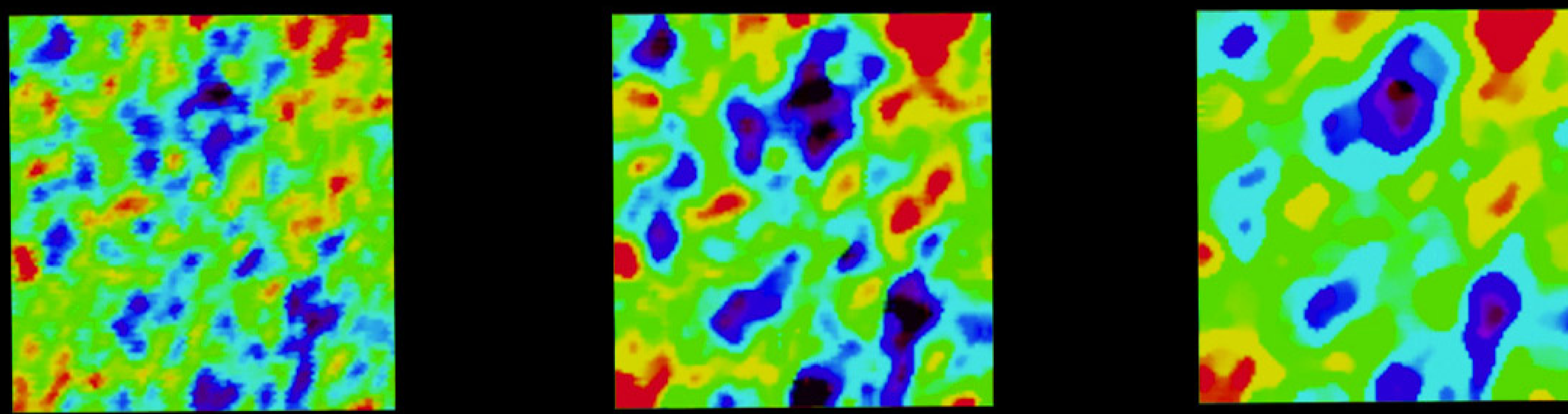
Zero Mean Curvature: The Most Robust Prediction of Inflation.

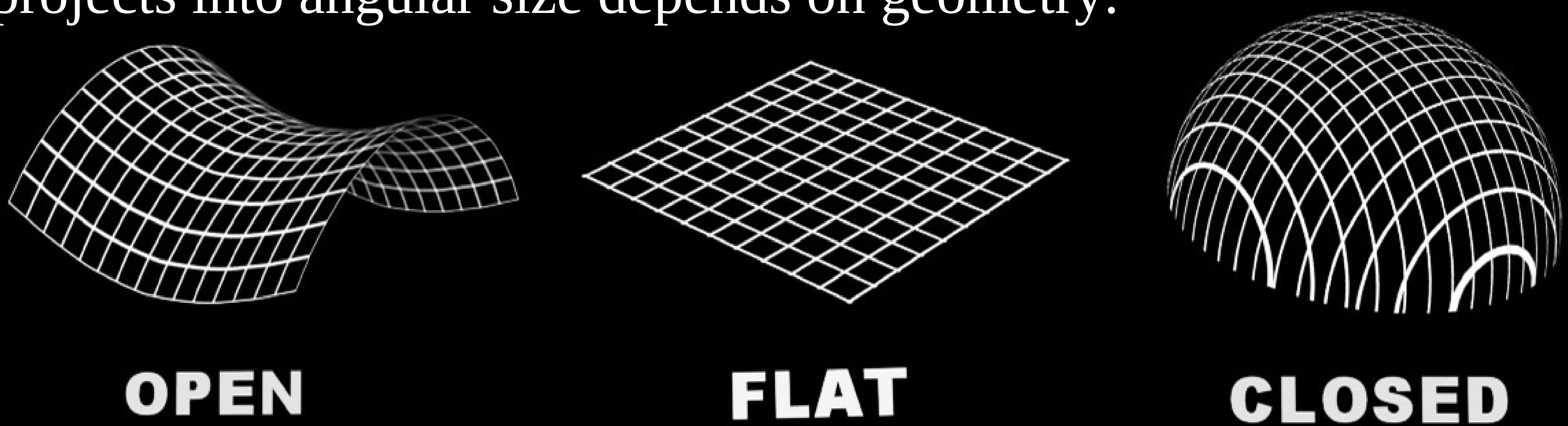
It’s worth testing to higher precision!

Measuring distances to redshifts in the matter-dominated era will help.

GEOMETRY OF THE UNIVERSE



Physical size of typical hot/cold spot can be calculated. How this projects into angular size depends on geometry.



WMAP

- Ωtotal=1 ✓

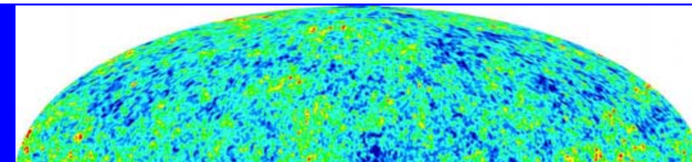
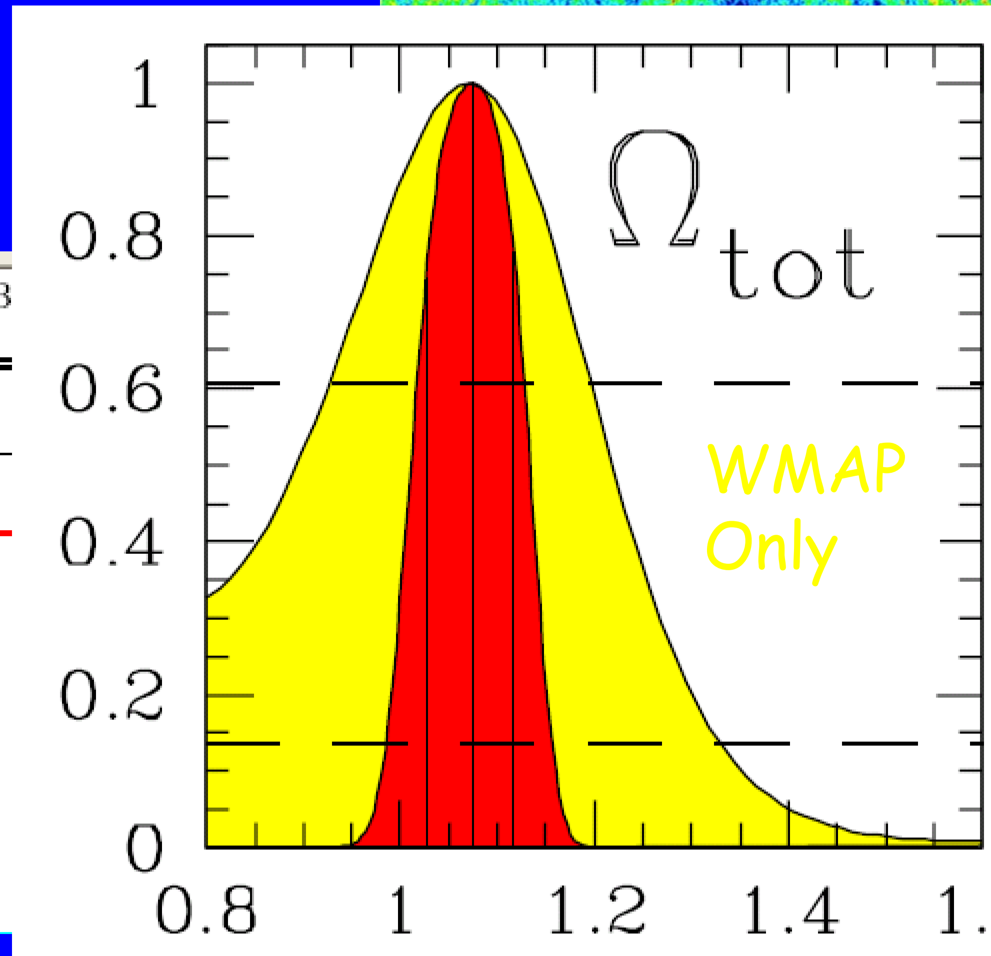


Table 3. "B

Description
Total density
Equation of state of quintessence
Dark energy density
Baryon density
Baryon density
Baryon density (cm^{-3})
Matter density
Matter density
Light neutrino density

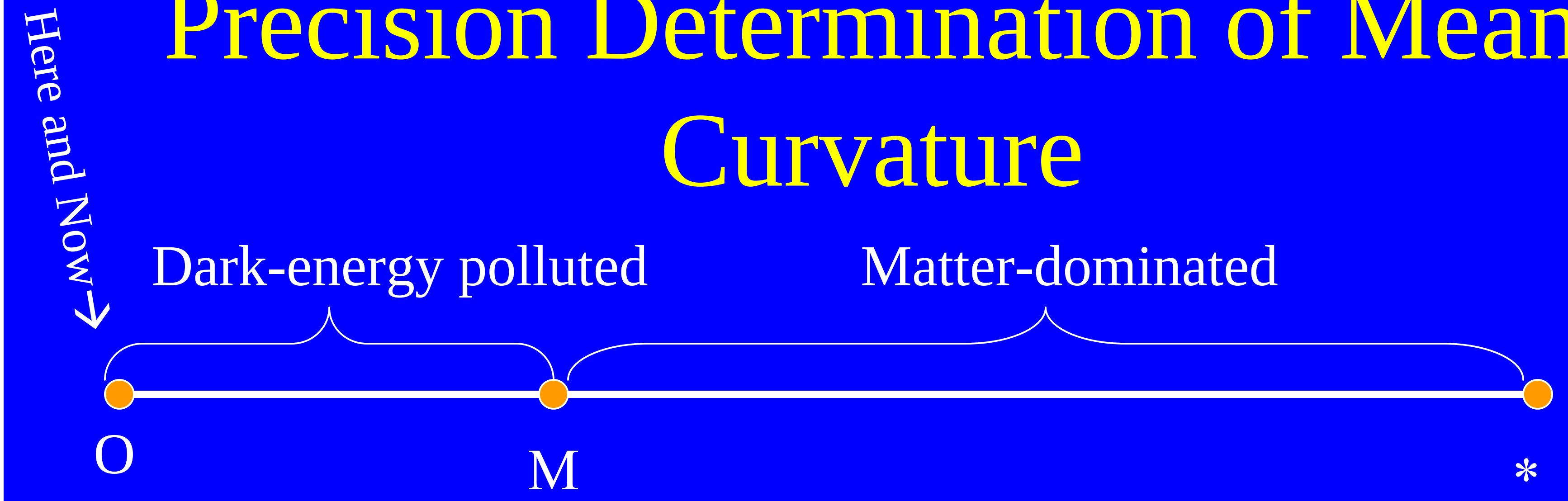


Tegmark et al astro-ph/0310723

WMAP + SDSS

Bennett et al Feb 11 '03

Precision Determination of Mean Curvature



Measure D_{O*} (with CMB) and D_{OM} (e.g., lensing)

Calculate r_{M*} (given ρ_m from CMB)*

In absence of curvature, $D_{O*}-(D_{OM}+r_{M*}) = 0$

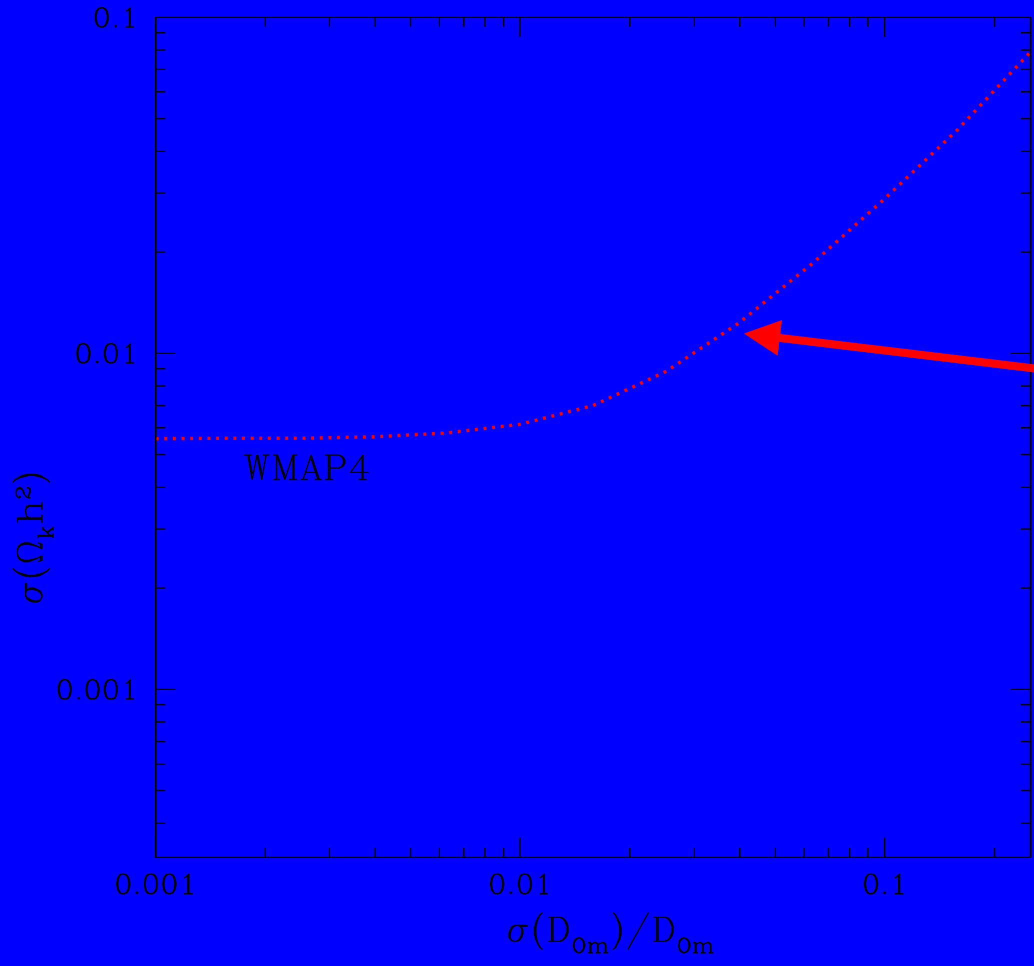
More generally (for $|\Omega_k|<<1$):

$$|D_{O*}-(D_{OM}+r_{M*})| = (|\Omega_k H_0^2|)(D_{O*}^3-D_{OM}^3)/6$$

*Note: r_{M*} is the comoving distance, equal to angular diameter distance D_{M*} if $\Omega_k = 0$.

Determining Mean Curvature

ρ_m and D_{O*} determined from CMB

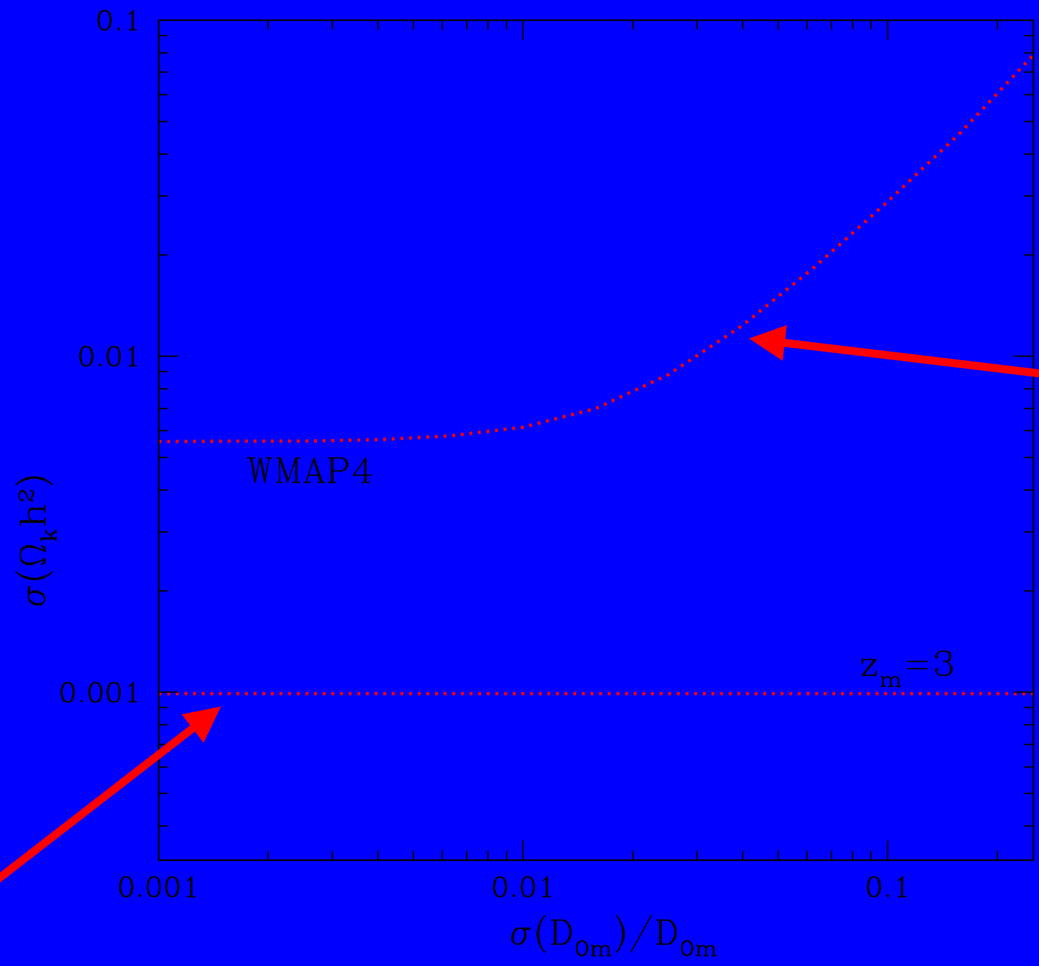


For $z_M = 3$

D_{0M} determined from something else (e.g., cosmic shear)

Determining Mean Curvature

ρ_m and D_{O*} determined from CMB

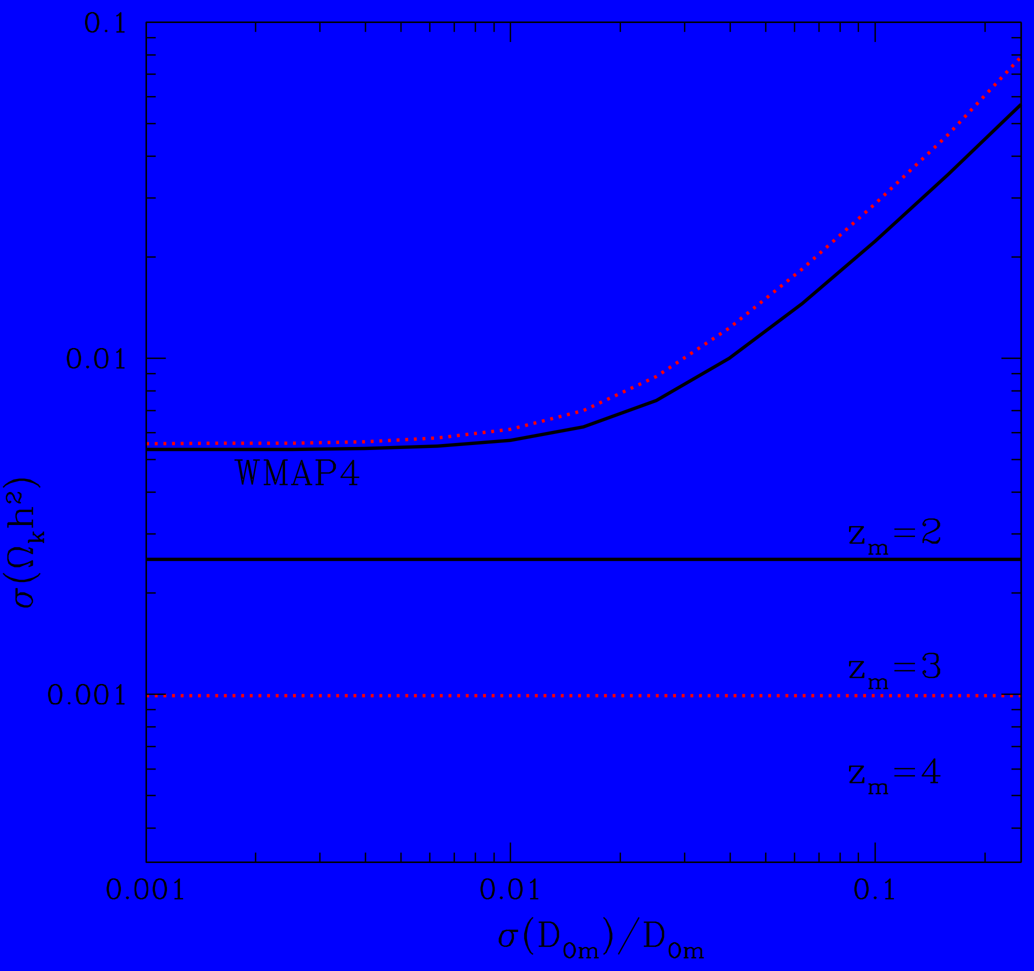


For $z_M = 3$

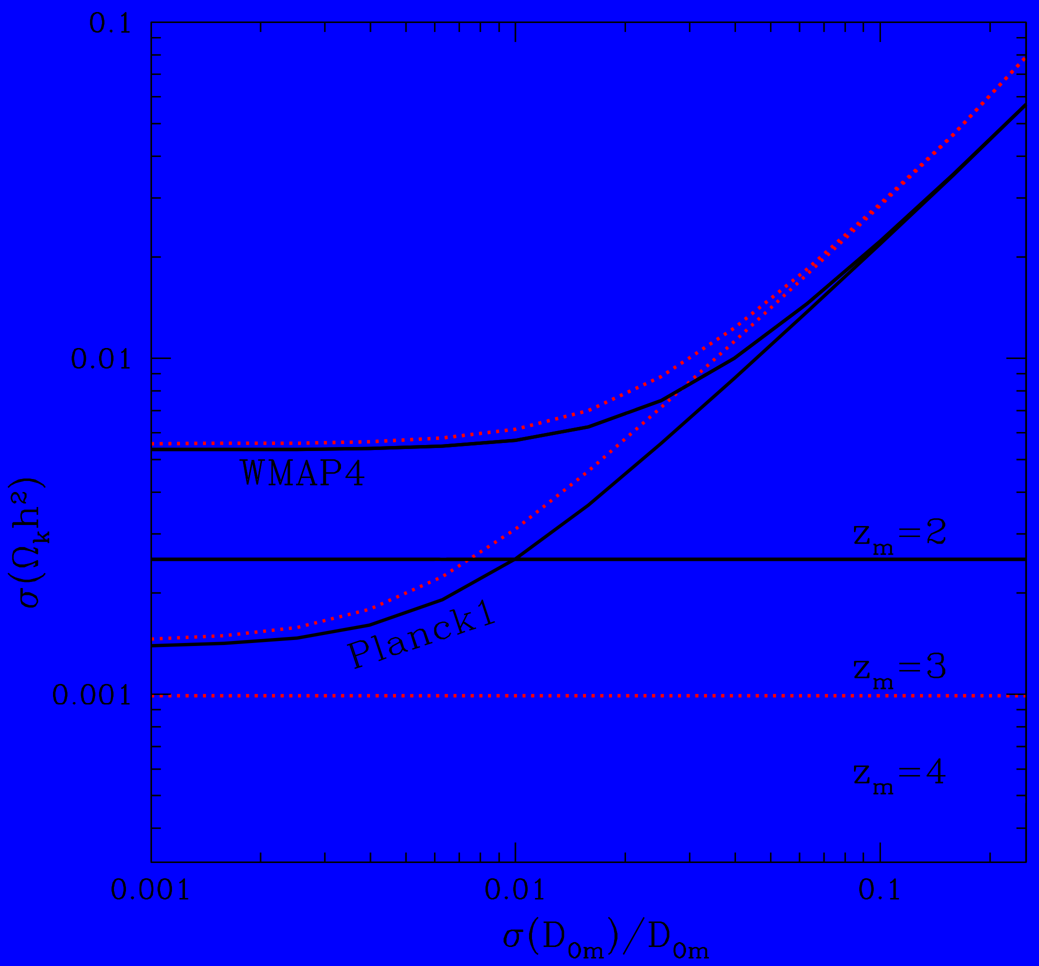
D_{0M} determined from something else (e.g., cosmic shear)

Error caused if dark energy at $z > z_M$ is neglected (assuming a cosmological constant).

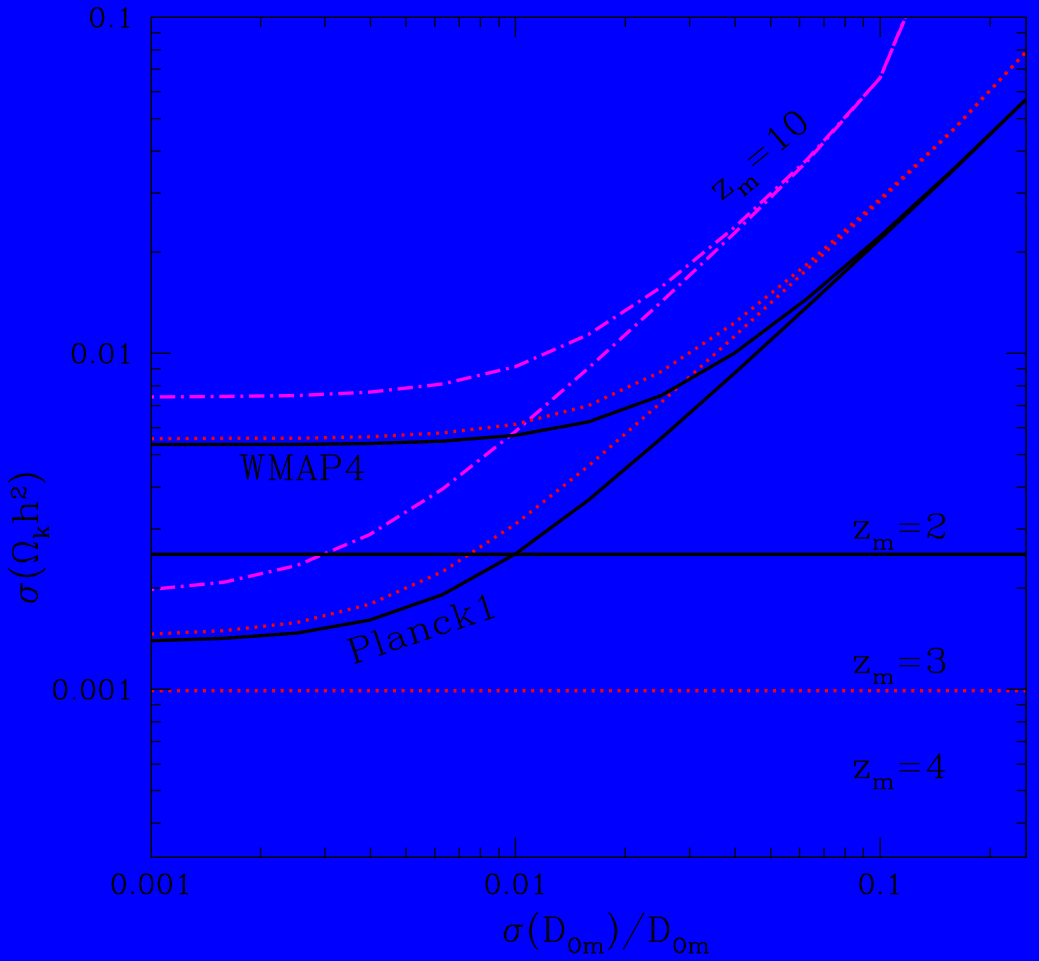
Determining Mean Curvature



Determining Mean Curvature



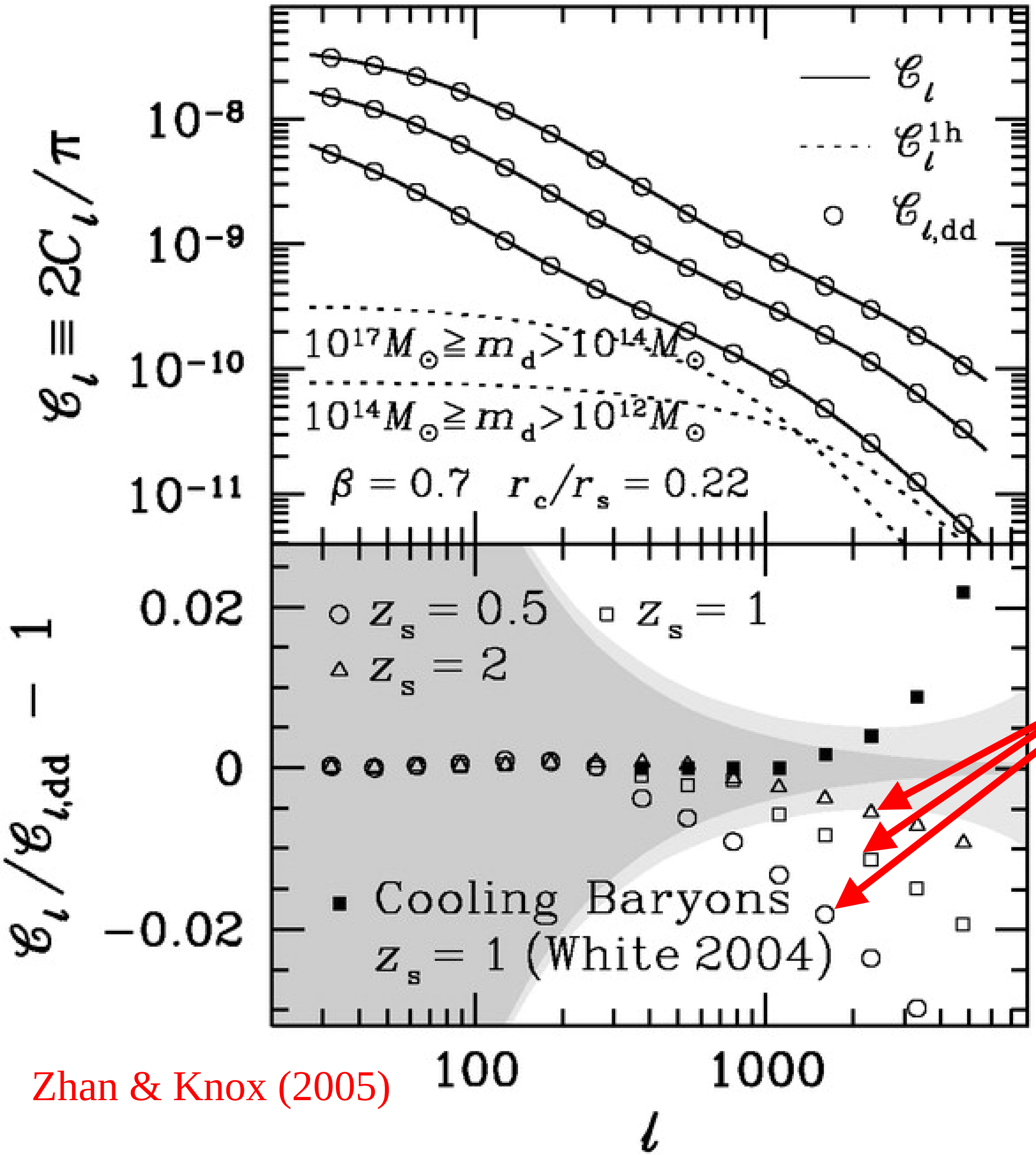
Determining Mean Curvature



Ways to get D_{OM}

- Sne Ia   (very difficult to get to z=2 or higher)
- Cosmic Shear   (as described earlier in the talk)
- Baryon oscillations (Eisenstein & Seo 2004)
- 21cm radiation
  - Alcock-Paczynski type test + H(z) from CMB
  - Baryon oscillations (Barkana & Loeb 2004)

A new SZ-Cosmic Shear synergy?

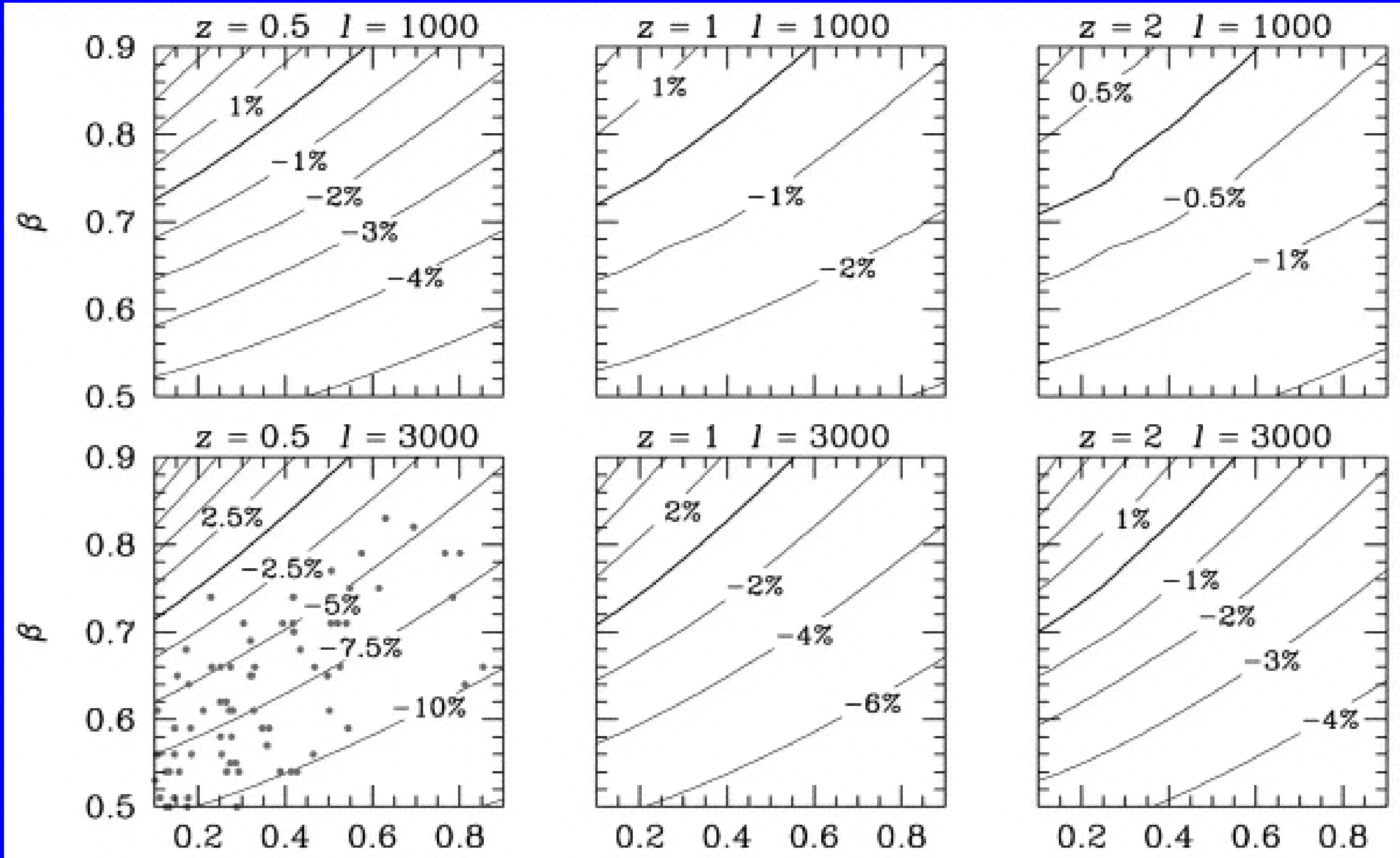


Zhan & Knox (2005)

Hot baryons suppress shear power relative to case where baryons are replaced with dark matter of same mass.

This is a highly significant effect for LSST at l > 1000.

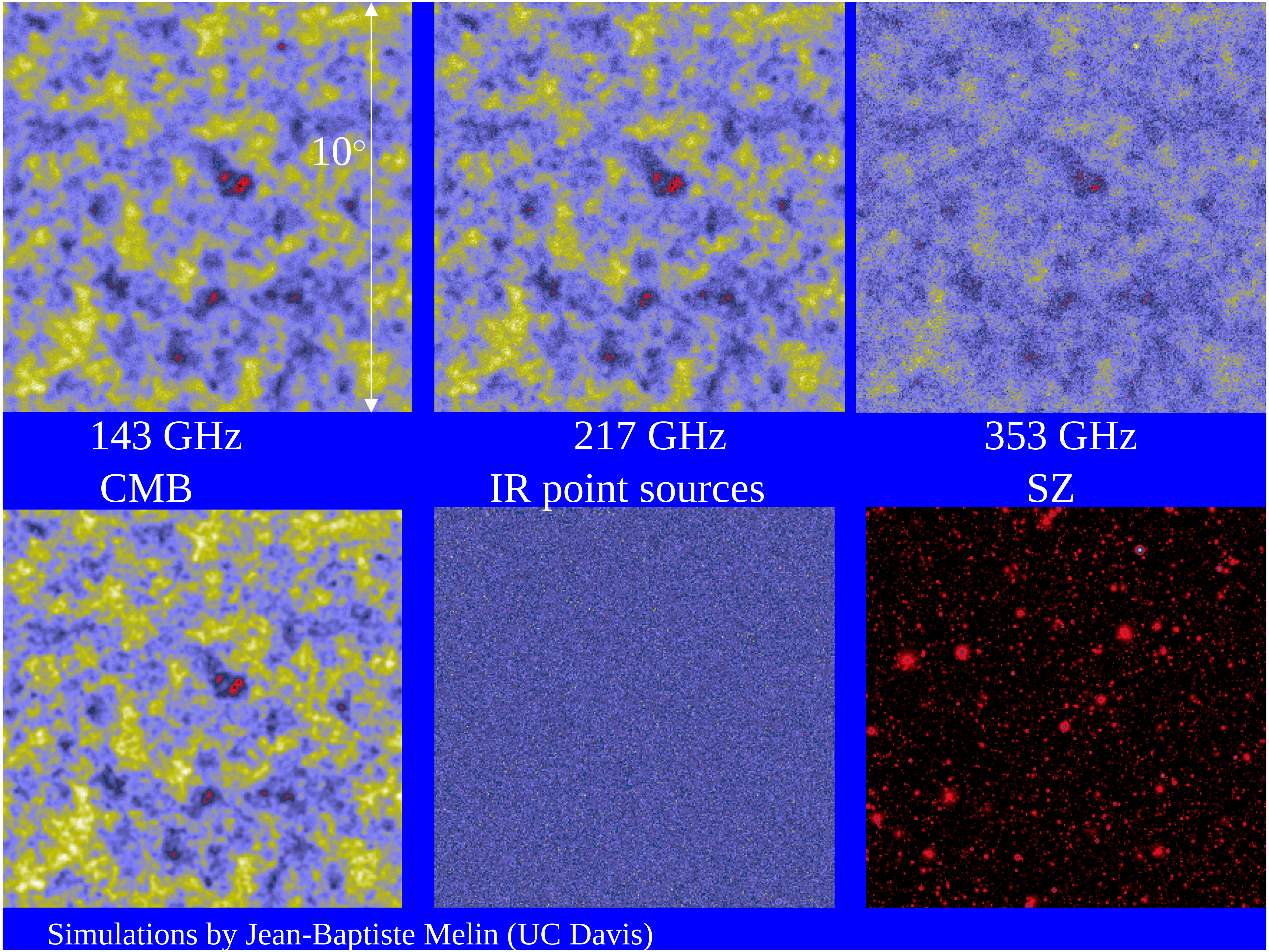
SZ observations can inform modeling of baryon profiles and thereby improve predictions for cosmic shear.

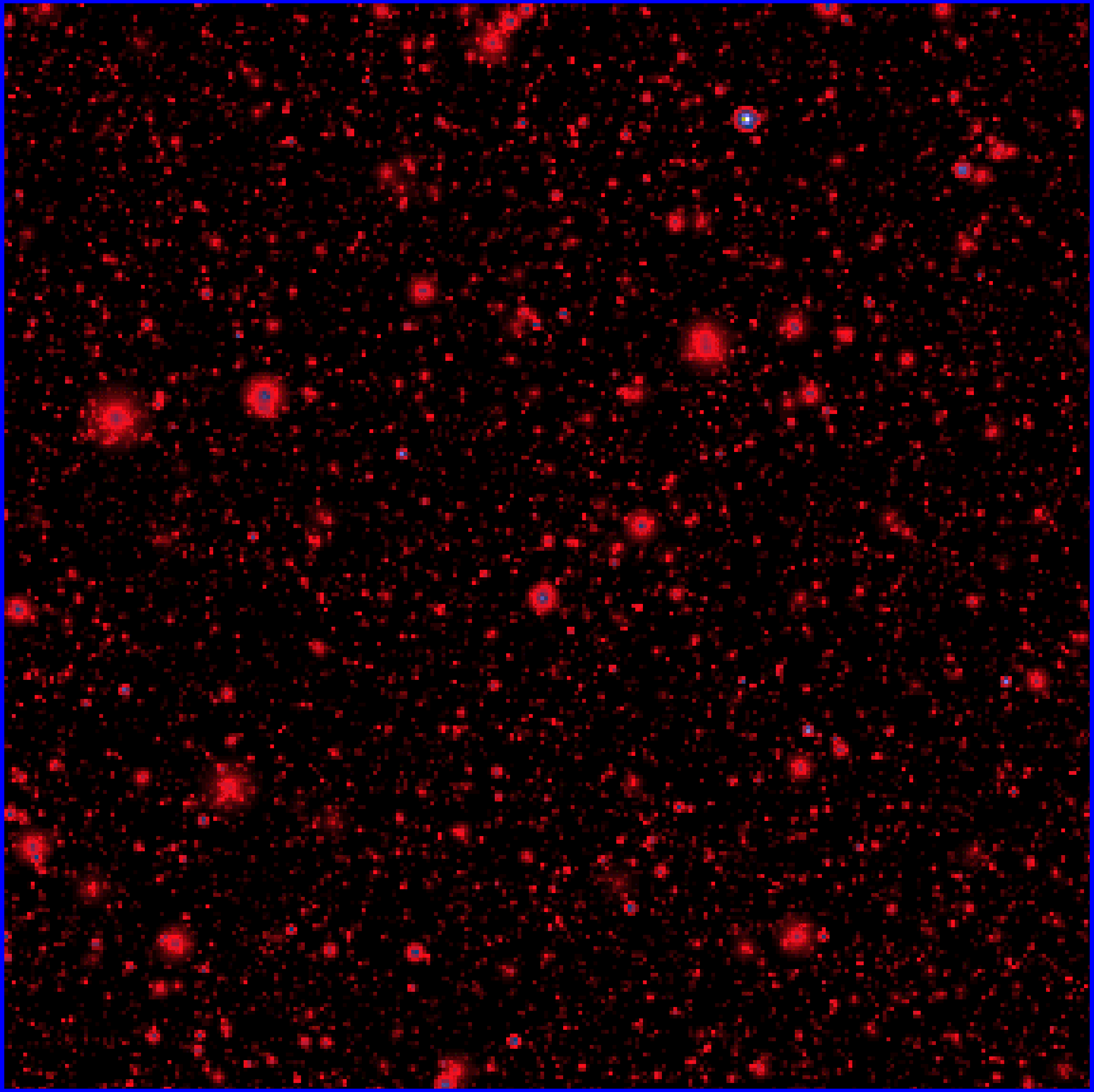


Zhan & Knox (2005)

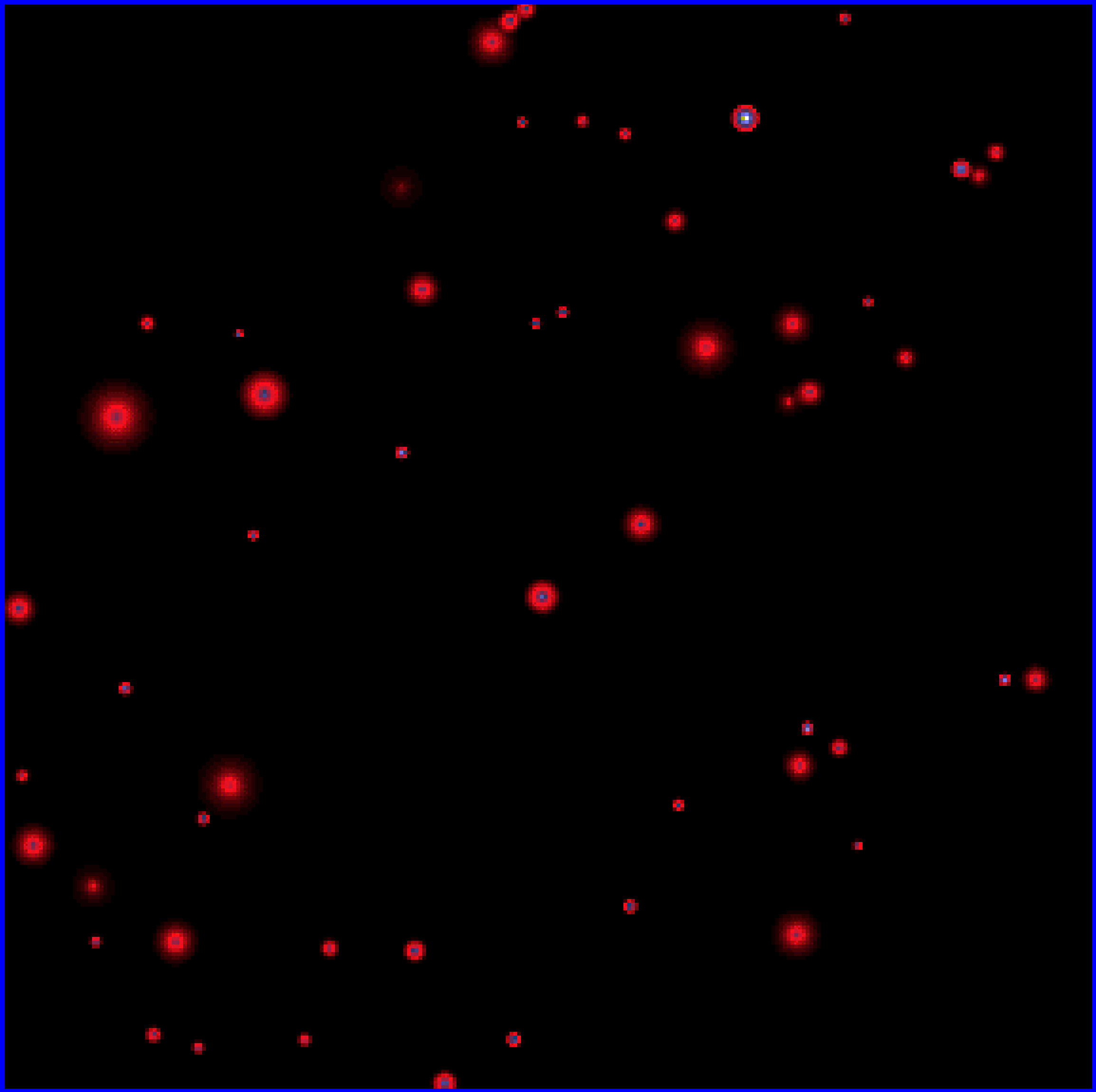
Conclusions

- With the ‘high-z’ parameters pinned down by Planck, low-z observations can concentrate on r(z) and g(z).
- These ‘two windows’ may be crucial for unraveling the mystery of the current epoch of acceleration.
- They can be measured very well with a wide and deep cosmic shear survey.
- Distances into the matter-dominate era are key for precision determination of the mean curvature, an important test of inflation.
- Baryons source gravitational potentials too: SZ observations may be critical to making full use of cosmic shear data beyond l=1000.
- Please encourage your undergraduates to apply to UC Davis for graduate school!


10°
143 GHz
217 GHz
353 GHz
CMB
IR point sources
SZ
Simulations by Jean-Baptiste Melin (UC Davis)



SZ map again



Recovered clusters