Cosmological Parameter Estimation with Large Scale Structure Observations

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in collaboration with
Francesco Montanari, Ruth Durrer and Julien Lesgourgues

arXiv:1307.1459
arXiv:1308.6186

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Center for Astroparticle Physics
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Outline

Introduction

Galaxy number counts

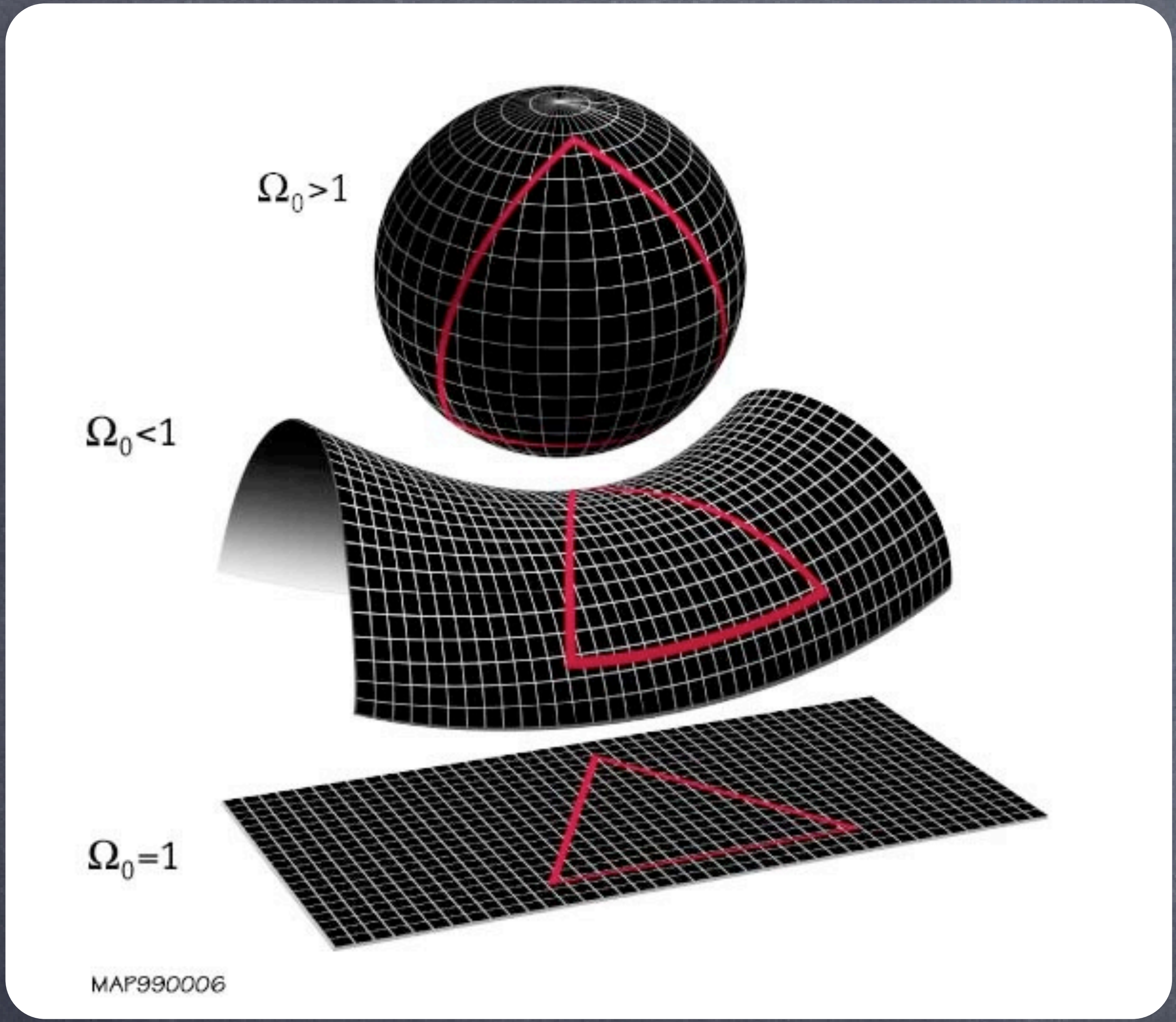
2D redshift dependent power spectra

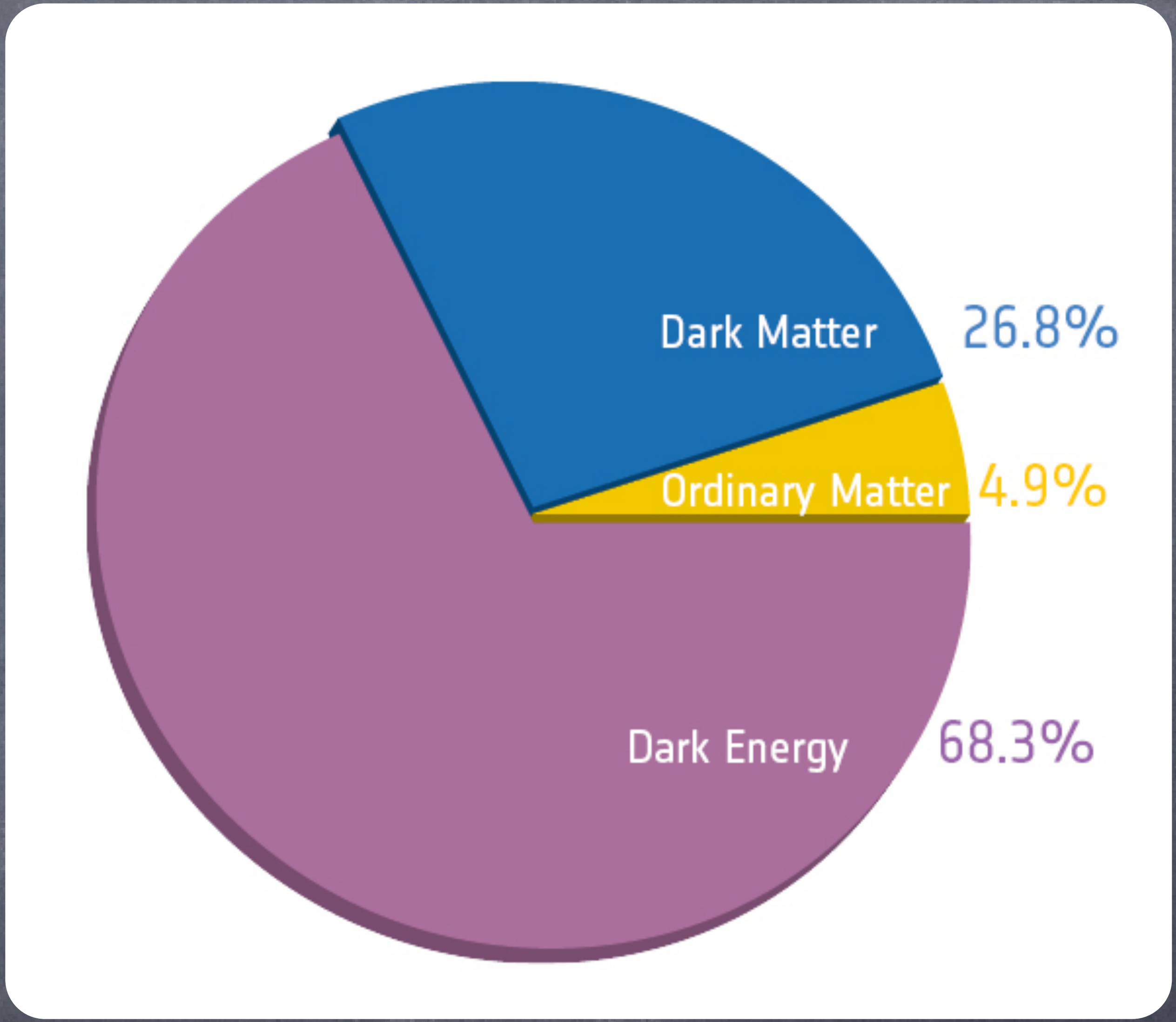
Fisher matrix analysis

Lensing Potential

CLASSgal

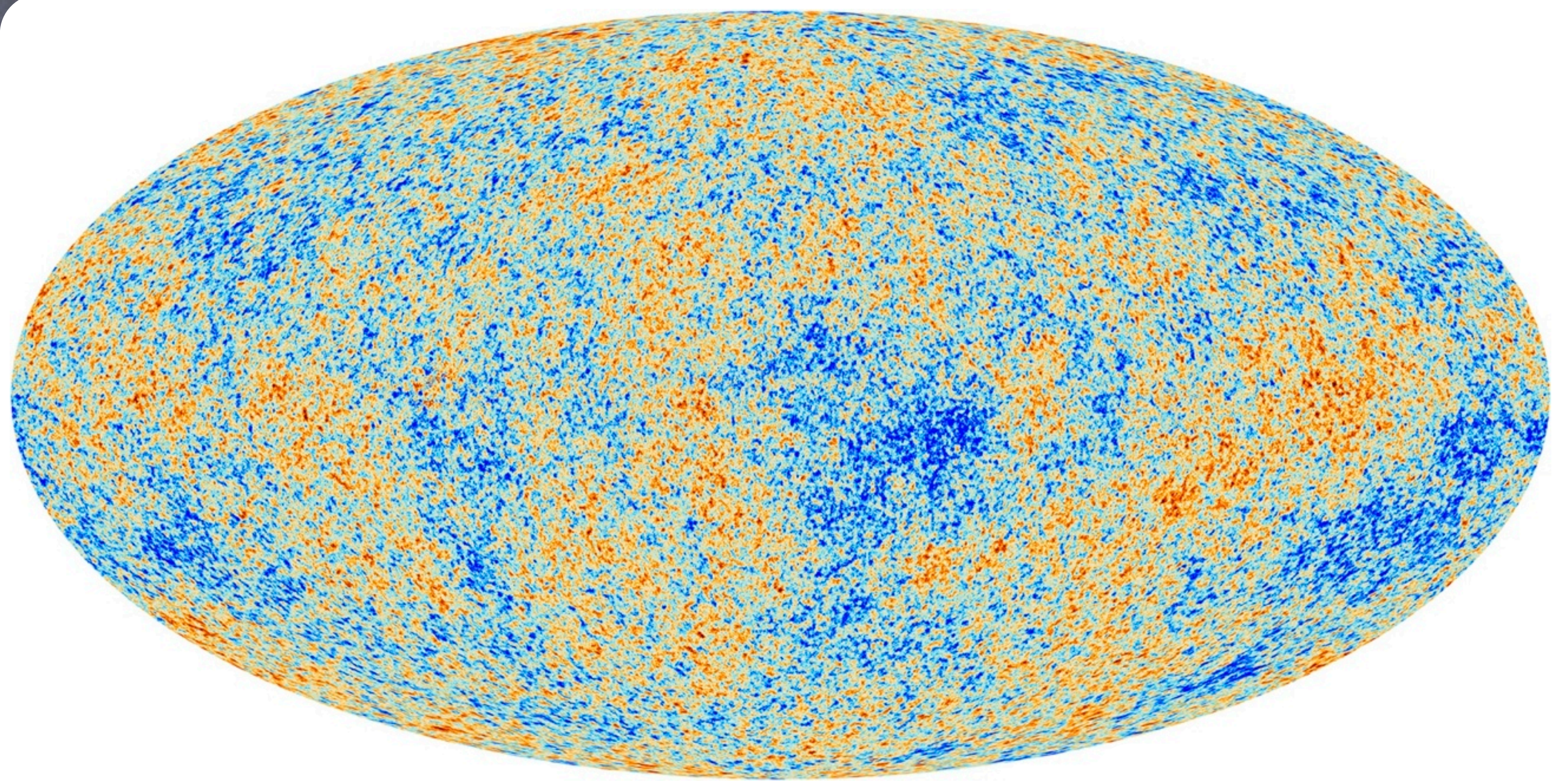
Standard Cosmological Model



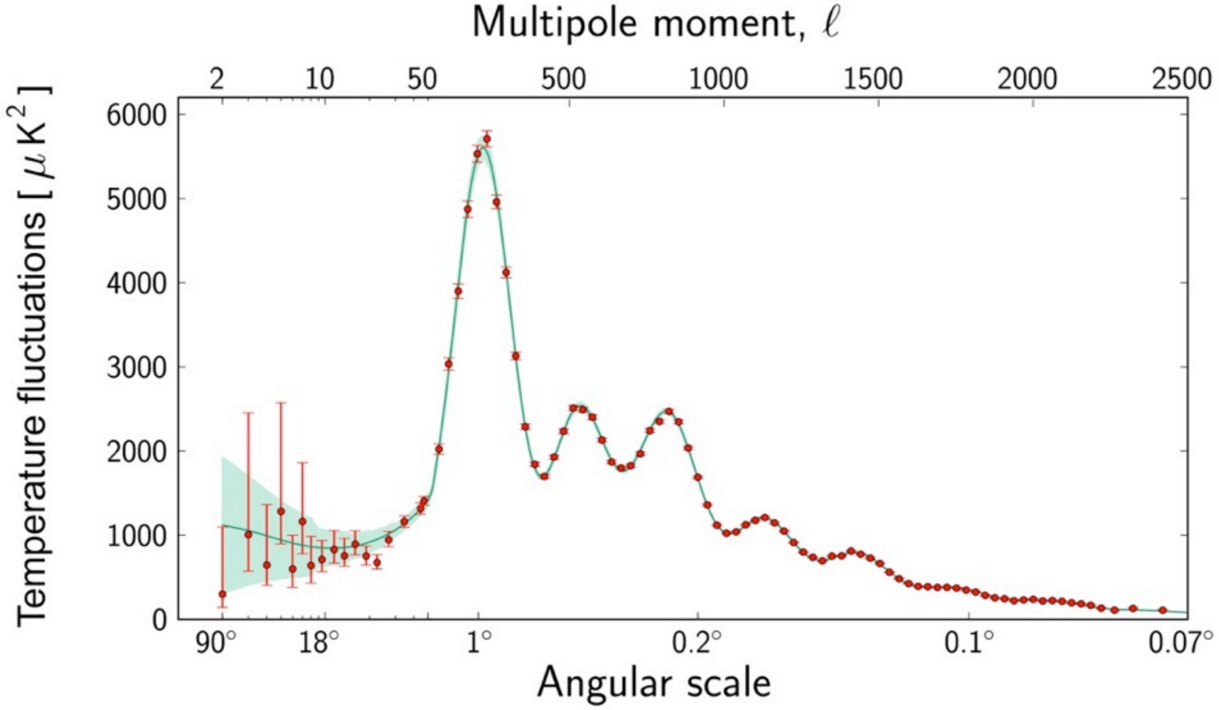


$$G_{\mu\nu} = \kappa T_{\mu\nu}$$

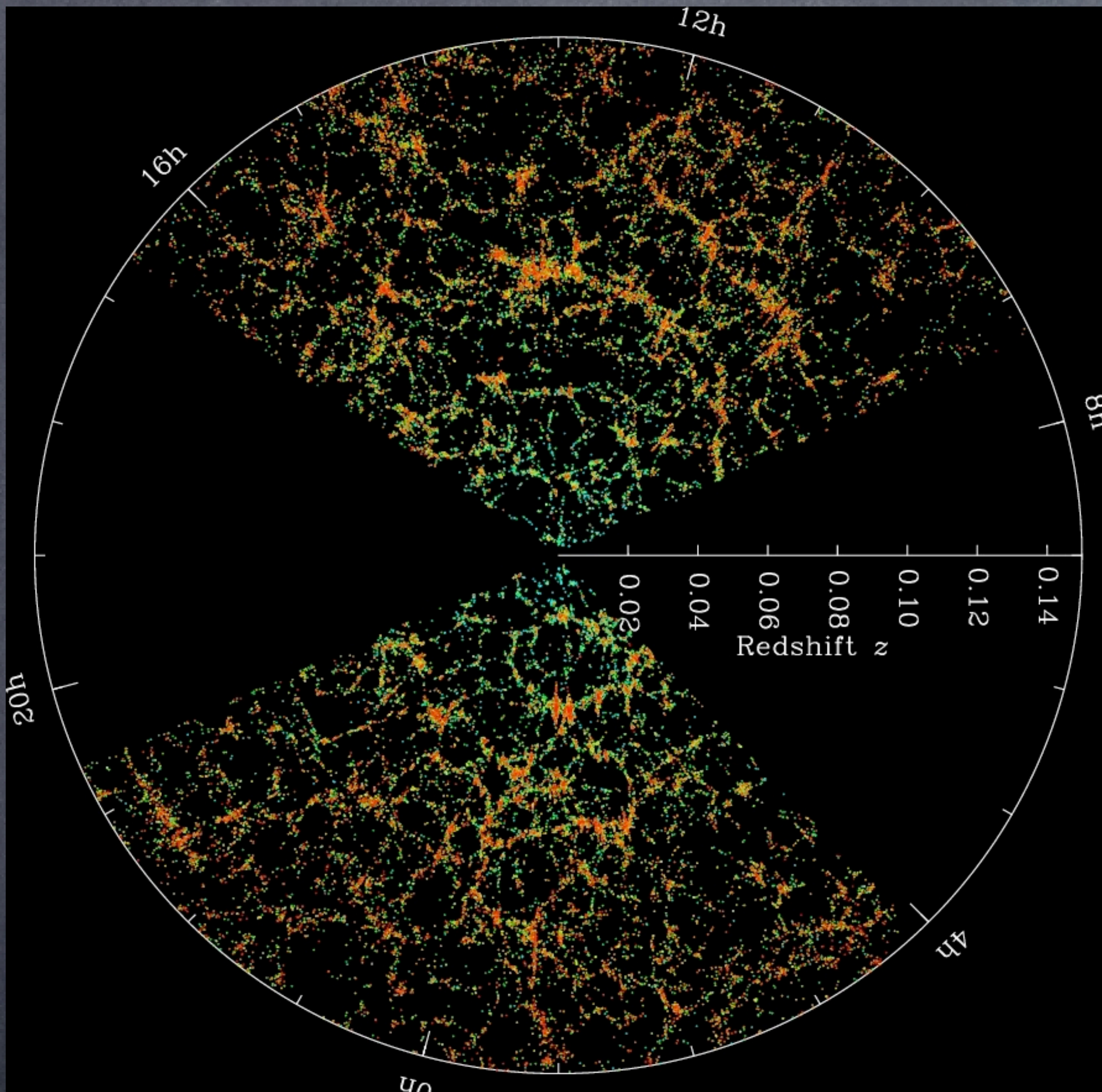
CMB

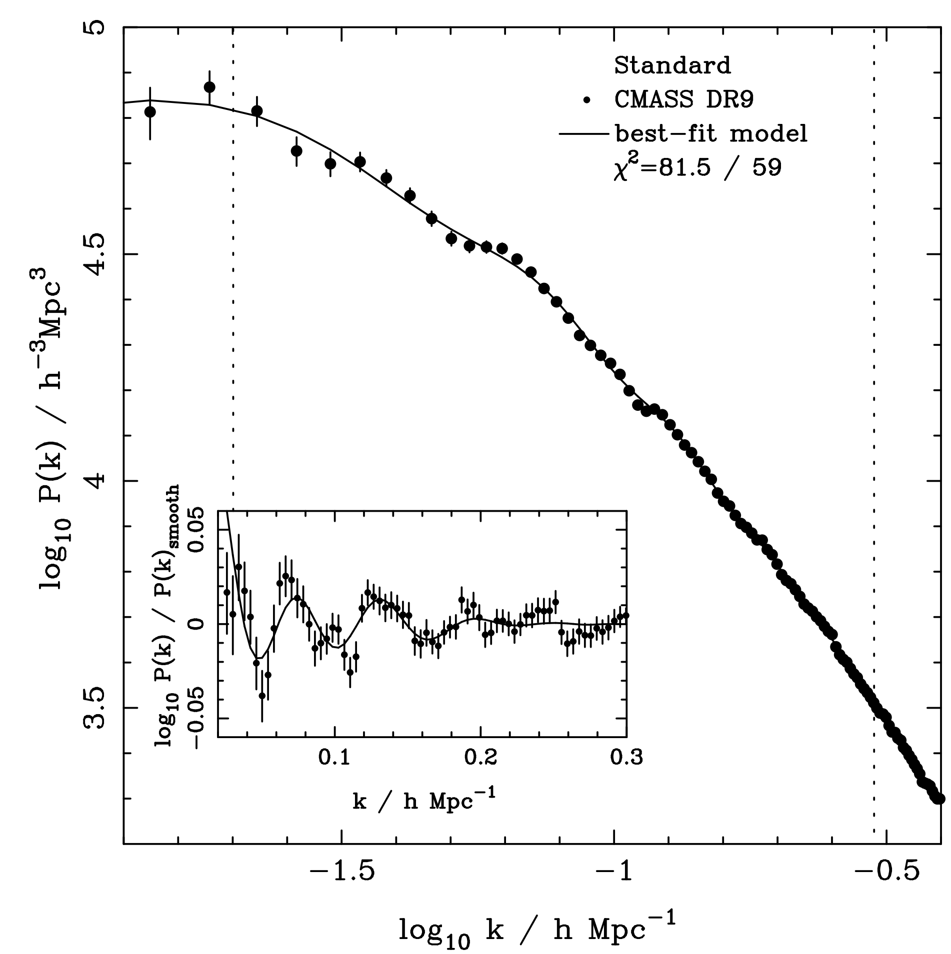


Planck Collaboration



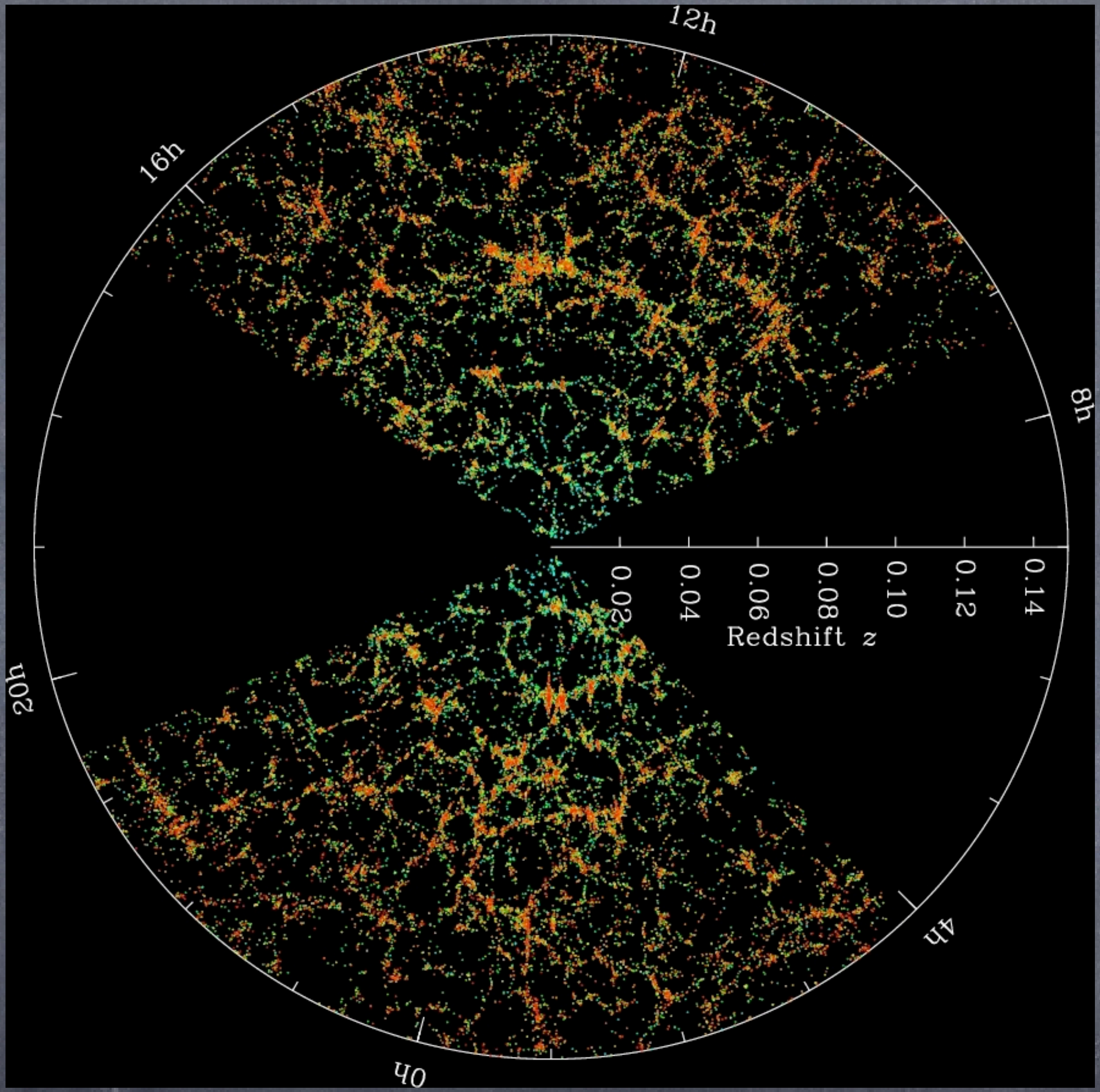
Large Scale Structures





Anderson et al ’12 [arXiv:1203.6594]

What do we really observe?



Angular position $\mathbf{n}$ Redshift z

$$N\left(\mathbf{n}, z\right) d\Omega_{\mathbf{n}} dz$$

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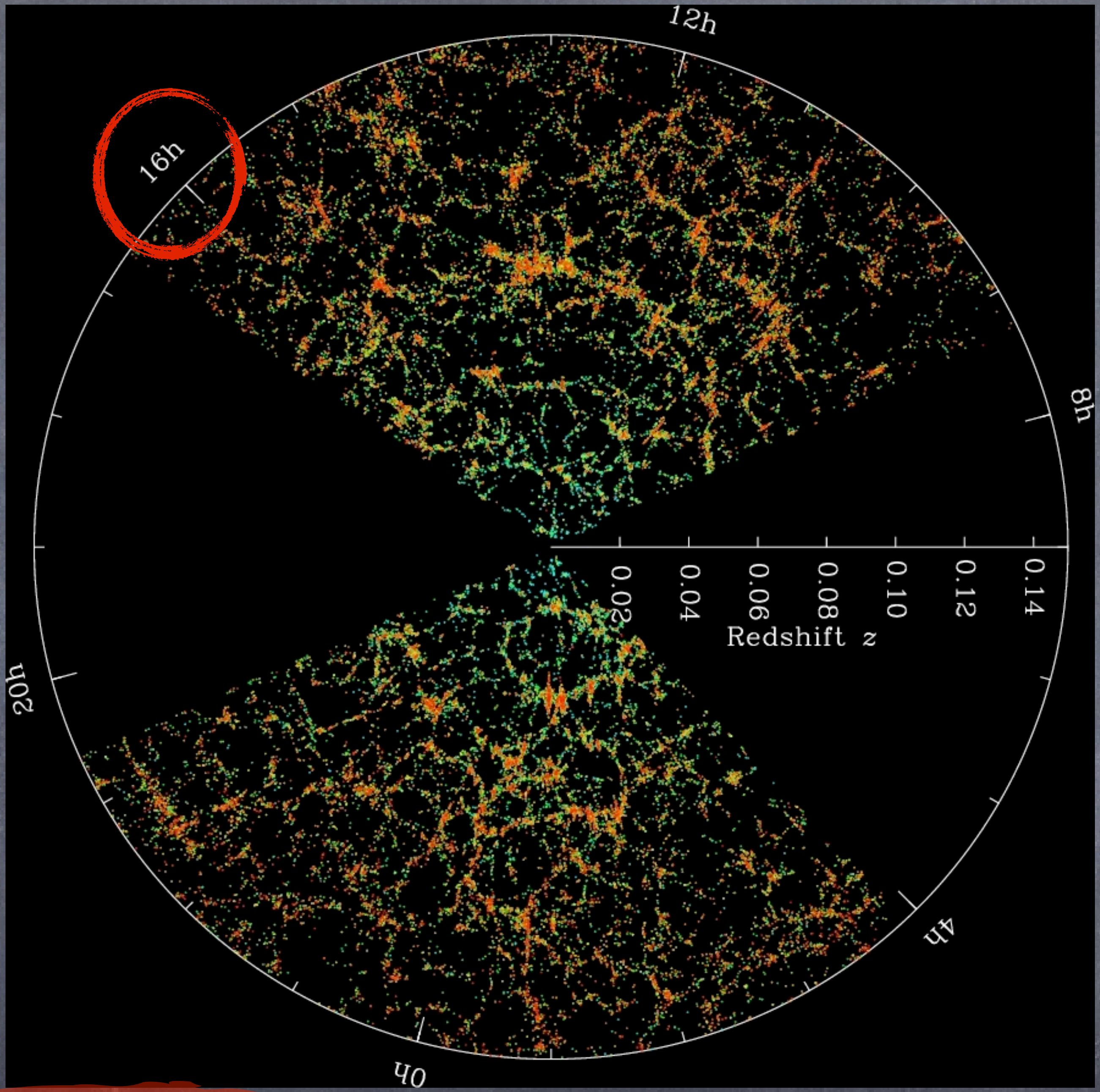

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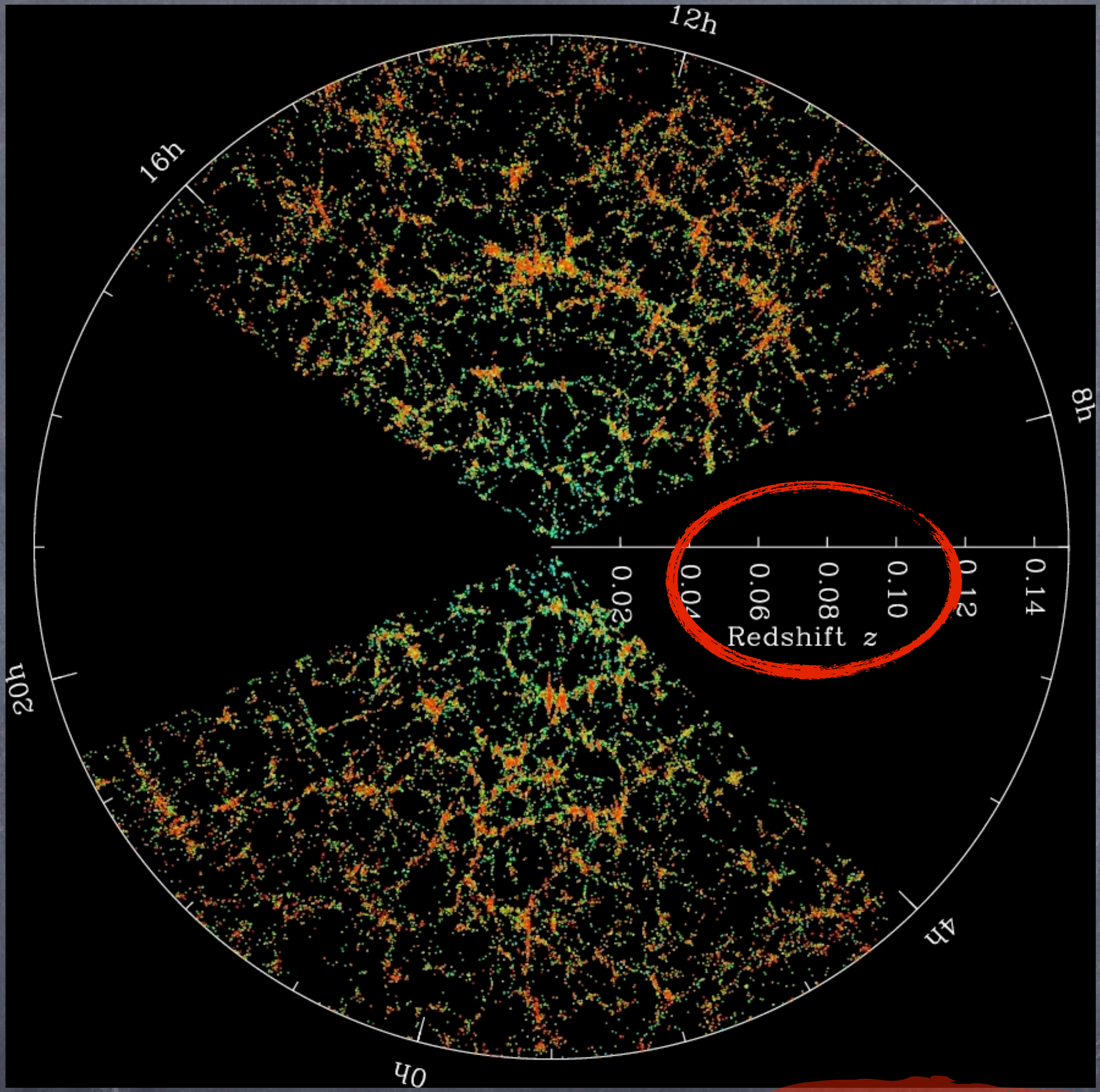

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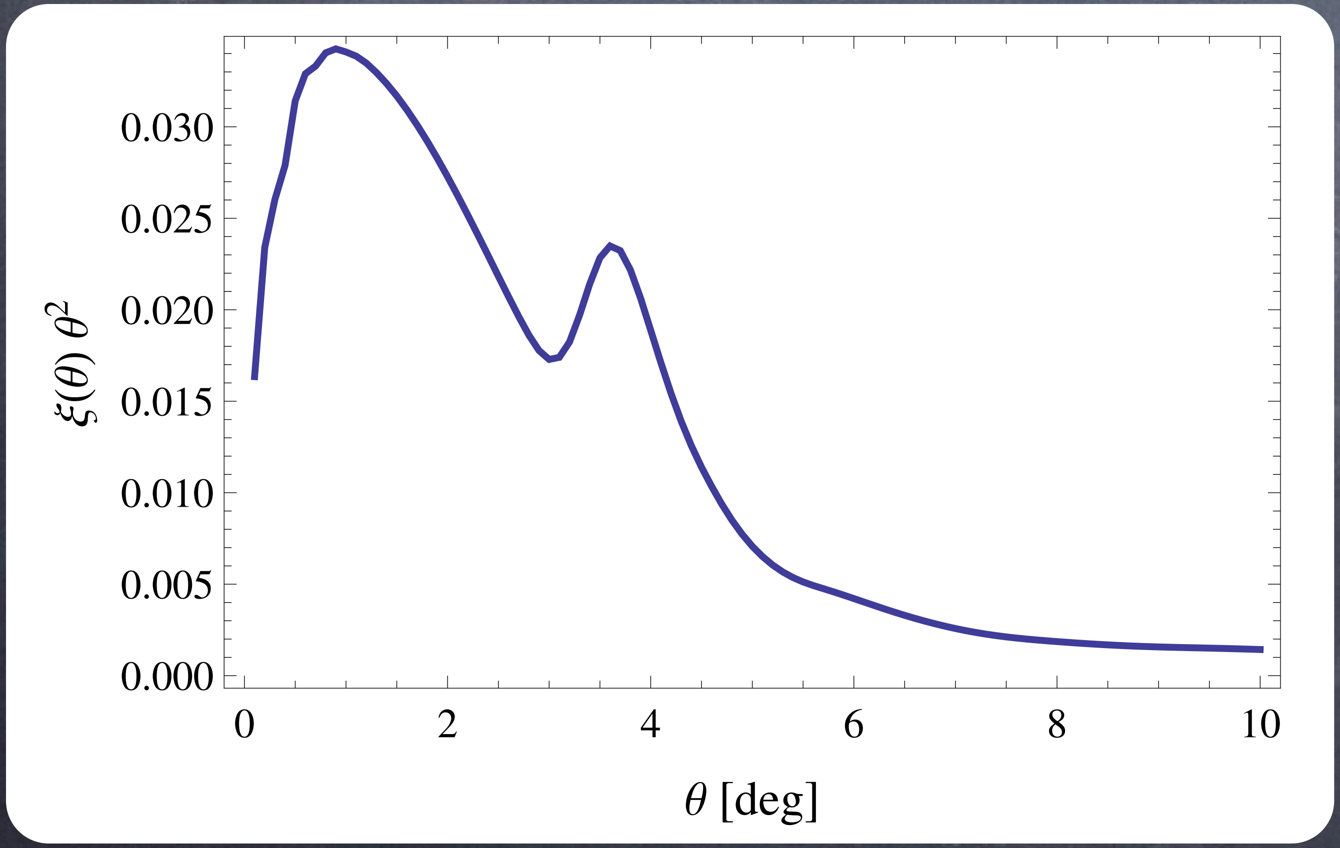
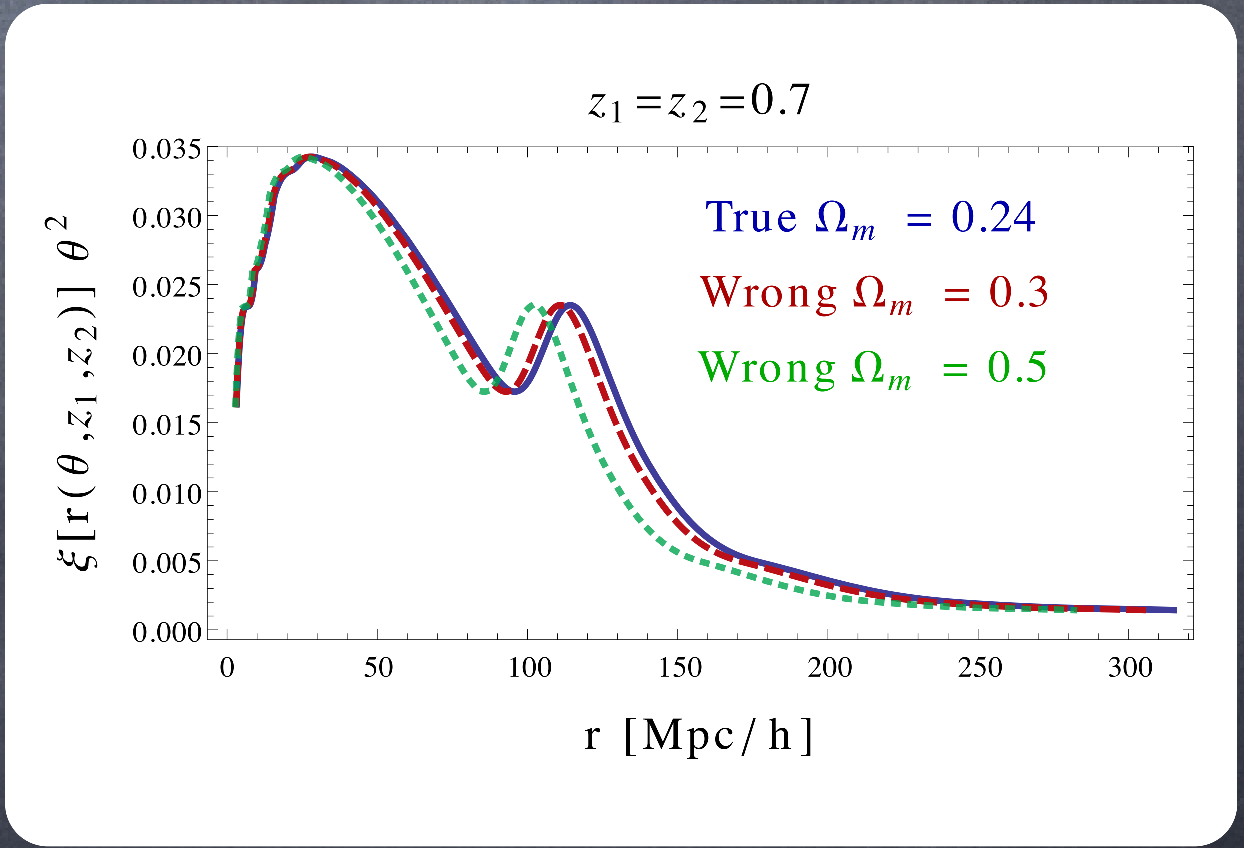
In 3D analysis we need to convert a redshift and angles into length scales

$$r(z_1, z_2, \theta) = \sqrt{\chi^2(z_1) + \chi^2(z_2) - 2\chi(z_1)\chi(z_2)\cos\theta}$$

We need to assume a cosmology!





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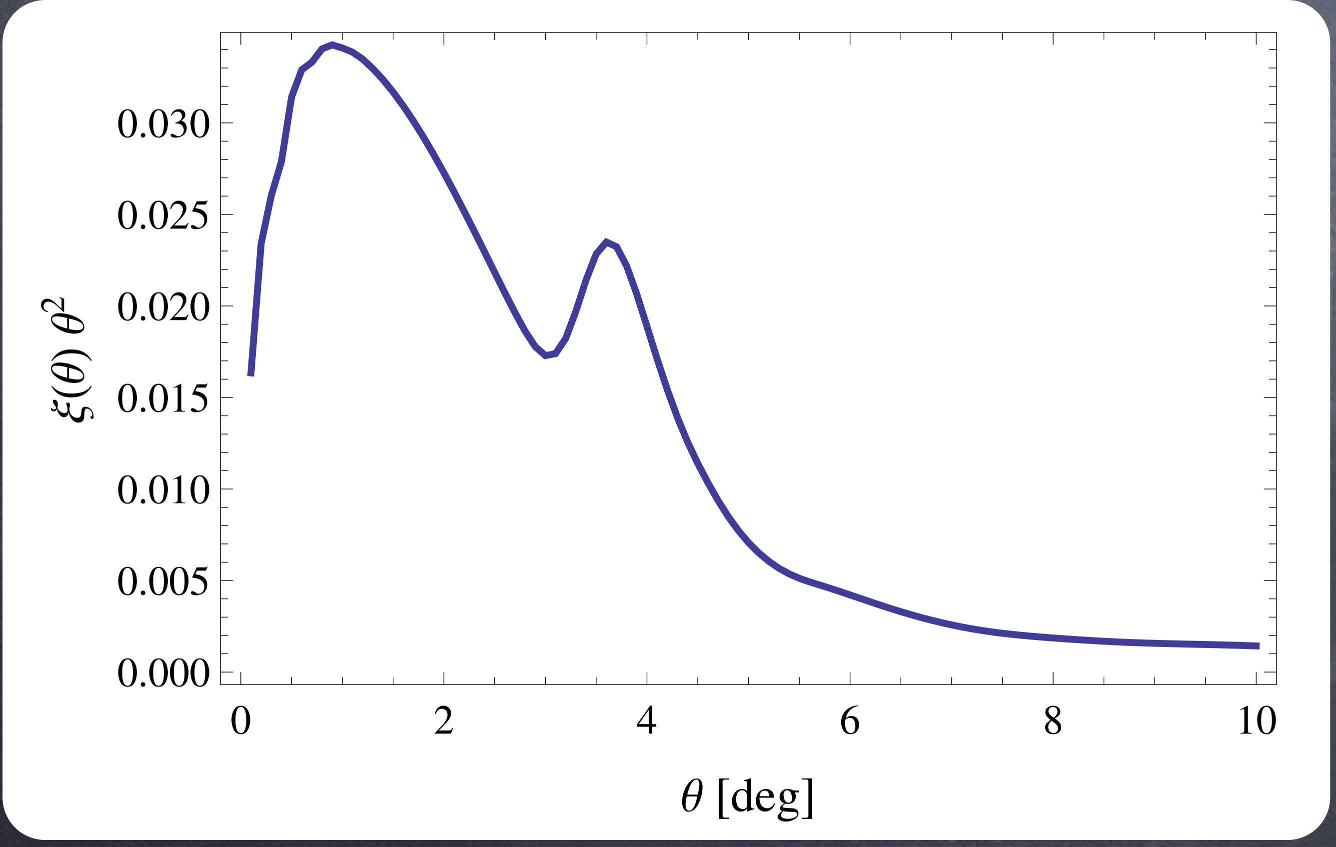

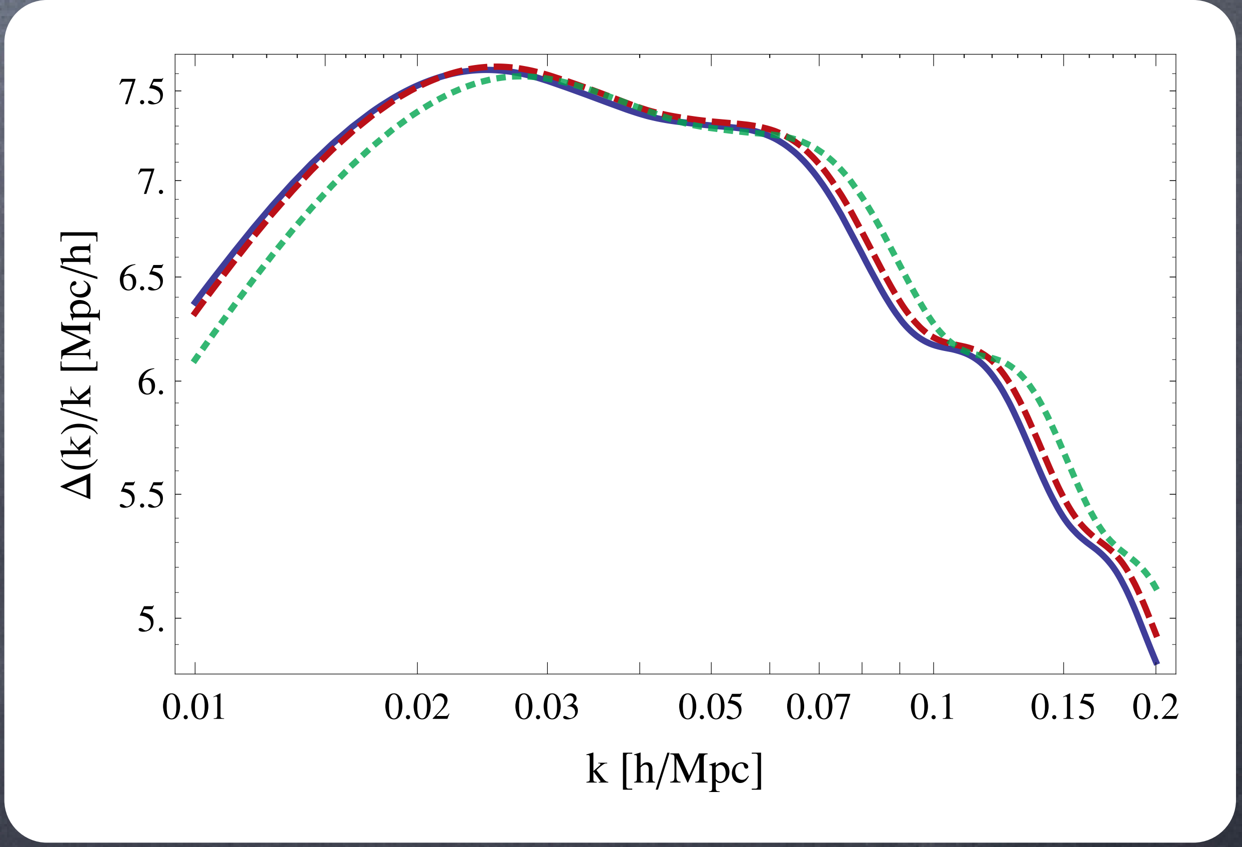

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To compute $\Delta(\mathbf{n}, z) \equiv \dfrac{N(\mathbf{n}, z) - <N>(z)}{<N>(z)}$
we have to consider:

- observation on the past lightcone
- redshift perturbed by peculiar velocity
- light deflection
- volume distortion

$$\begin{aligned}
\Delta(\mathbf{n}, z) \;\; &= \;\; D_g + \Phi + \Psi + \frac{1}{\mathcal{H}}\left[\Phi' + \partial_r(\mathbf{V}\cdot\mathbf{n})\right] \\
&+ \left(\frac{\mathcal{H}'}{\mathcal{H}^2} + \frac{2}{r_S\mathcal{H}}\right)\left(\Psi + \mathbf{V}\cdot\mathbf{n} + \int_0^{r_S} dr(\Phi' + \Psi')\right) \\
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\end{aligned}$$

Bonvin & Durrer [arXiv:1105.5280],
Challinor & Lewis [arXiv:1105.5292],
Yoo [arXiv:1009.3021]

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Density

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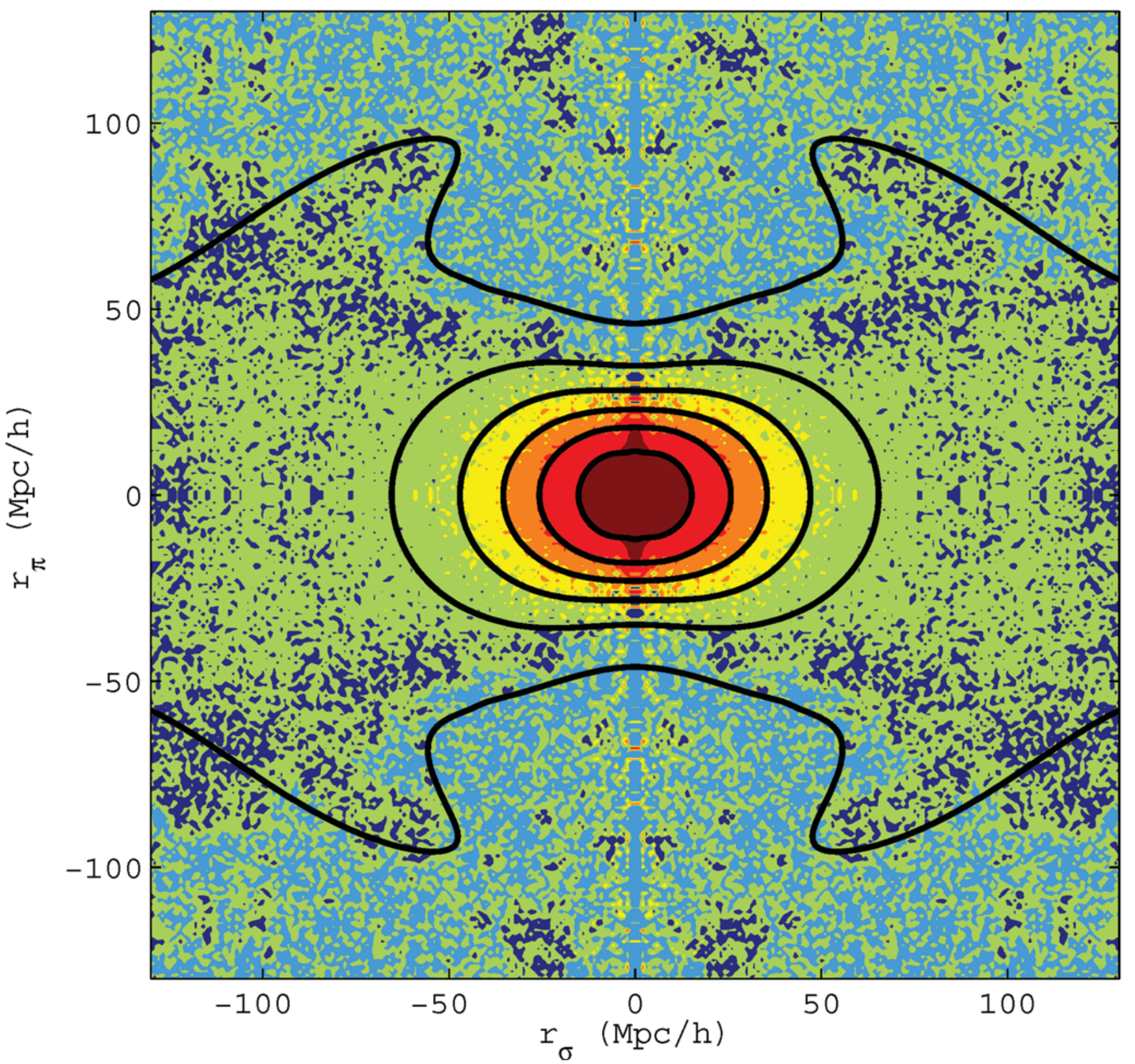
Wha ... erve?

To co ... $V > (z)$

we ha ...

- obs ... e
- reds ... ocity
- light
- volu



Reid et al ’12 [arXiv:1203.6641]

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Additional effects

galaxy bias | magnification bias | galaxy evolution

$$
\begin{aligned}
\Delta^{(N)}(\mathbf{n}, z, m_*) \quad = \quad & bD_g(L > \bar{L}_*) + (1+5s)\Phi + \Psi + \frac{1}{\mathcal{H}}\left[\Phi' + \partial_r(\mathbf{V}\cdot\mathbf{n})\right] \\
& + \left(\frac{\mathcal{H}'}{\mathcal{H}^2} + \frac{2-5s}{r_S\mathcal{H}} + 5s - f^N_{\mathrm{evo}}\right)\left(\Psi + \mathbf{V}\cdot\mathbf{n} + \int_0^{r_S} dr(\Phi' + \Psi')\right) \\
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Challinor & Lewis [arXiv:1105.5292]

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$$s(z, m_*) \equiv \frac{\partial \log_{10} \bar{N}(z, m < m_*)}{\partial m_*},$$

$$\bar{N}(z, L_S < \bar{L}_*) = \int_{F_*}^{\infty} \bar{n}_S(z, \ln F) d \ln F$$

$$\begin{aligned} \Delta^{(N)}(\mathbf{n}, z, m_*) \quad = \quad & bD_g(L > \bar{L}_*) + (1 - 5s)\Phi + \Psi + \frac{1}{\mathcal{H}}\left[\Phi' + \partial_r(\mathbf{V} \cdot \mathbf{n})\right] \\ & + \left(\frac{\mathcal{H}'}{\mathcal{H}^2} + \frac{2 - 5s}{r_S \mathcal{H}} + 5s - f_{\mathrm{evo}}^N\right)\left(\Psi + \mathbf{V} \cdot \mathbf{n} + \int_0^{r_S} dr(\Phi' + \Psi')\right) \\ & + \frac{2 - 5s}{2r_S} \int_0^{r_S} dr \left[2 - \frac{r_S - r}{r}\Delta_\Omega\right](\Phi + \Psi) \end{aligned}$$

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$$f_{\rm evo}^N = \frac{\partial \ln(a^3 \bar{N}(z, L > \bar{L}_*))}{\mathcal{H}\partial \tau_S}$$

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z-dependent angular power spectrum

Multipole expansion

$$\Delta(\mathbf{n}, z) = \sum_{\ell m} a_{\ell m}(z) Y_{\ell m}(\mathbf{n})$$

Power spectrum

$$c_\ell(z, z') =< a_{\ell m}(z) a^*_{\ell m}(z') >$$

$$c_\ell(z_1, z_2) =< a_{lm}(z_1) a_{lm}(z_2) >= 4\pi \int \frac{dk}{k} \mathcal{P}(k) \Delta_\ell\left(z_1, k\right) \Delta_\ell\left(z_2, k\right)$$

Correlation function

$$\xi(z, z', \theta) =< \Delta(\mathbf{n}, z) \Delta(\mathbf{n}', z') >= \sum_\ell \frac{2\ell + 1}{4\pi} c_\ell(z, z') P_\ell(\cos\theta)$$

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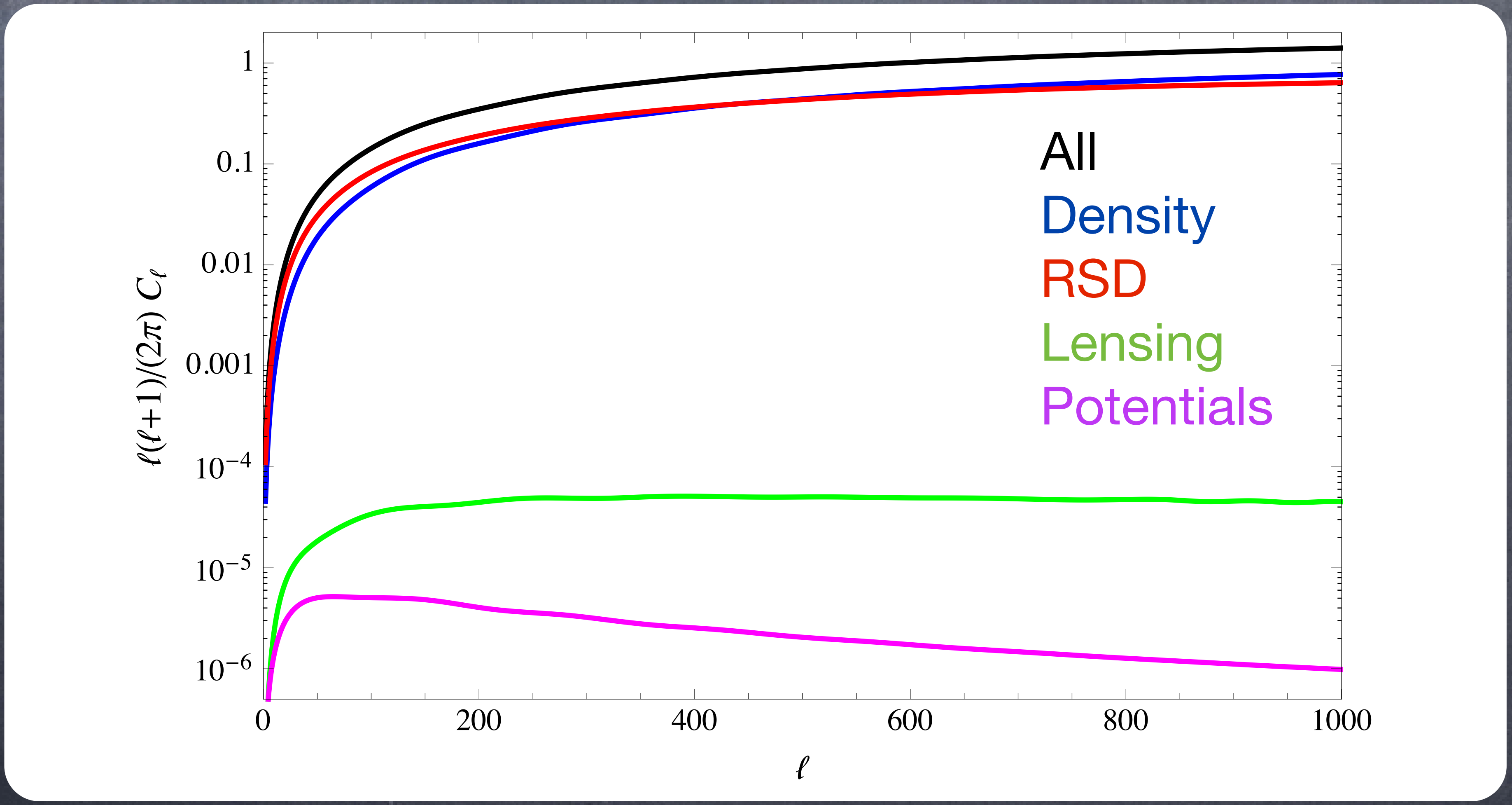


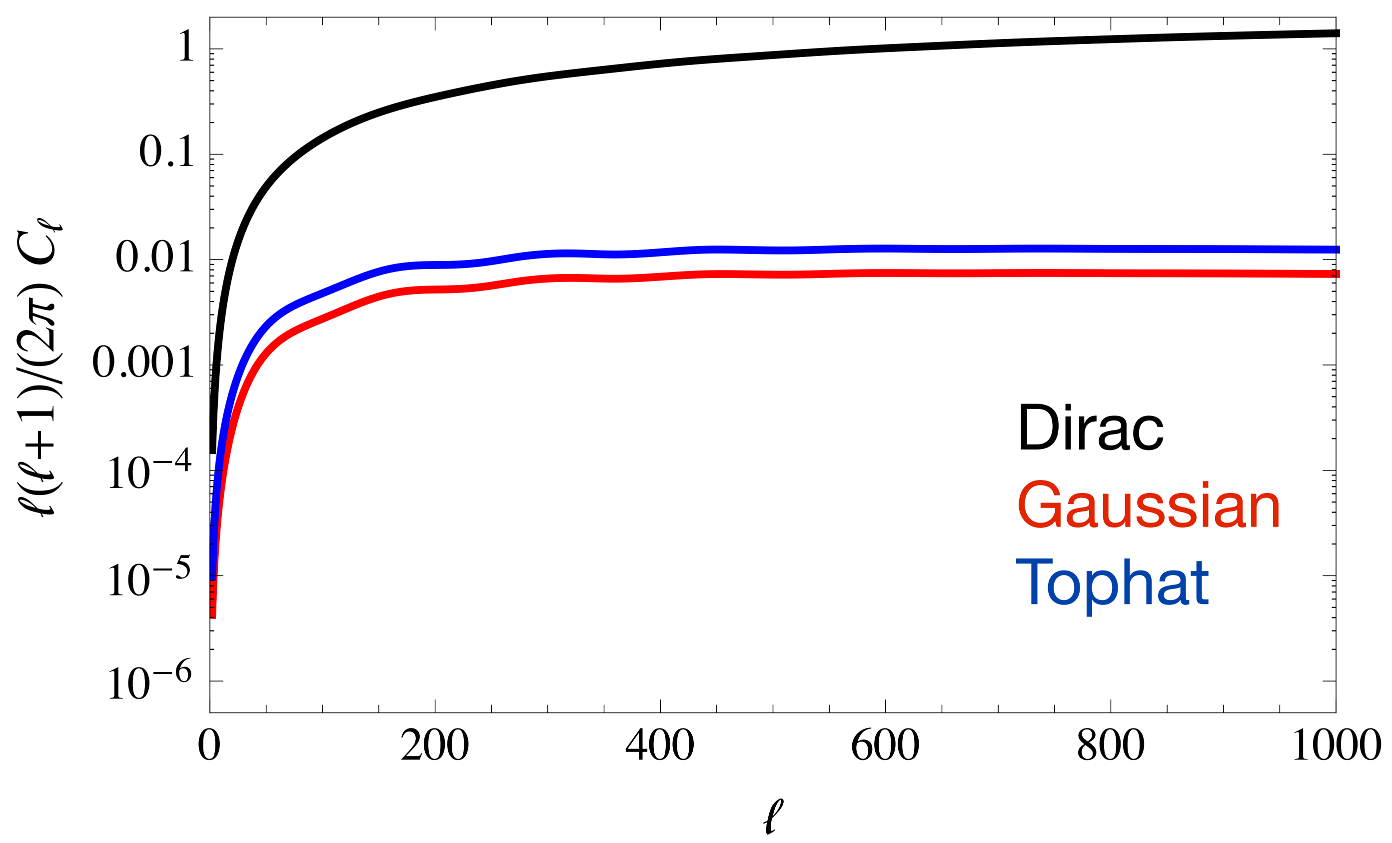
z-dependent angular power spectrum

Window Function

$$\Delta_\ell^i(k) = \int dz \frac{dN}{dz} W_i(z) \Delta_\ell(z,k) \qquad c_\ell^{ij} = 4\pi \int \frac{dk}{k} \mathcal{P}(k) \Delta_\ell^i(k) \Delta_\ell^j(k)$$

$i = j$ Auto-Correlation

$i \neq j$ Cross-Correlation



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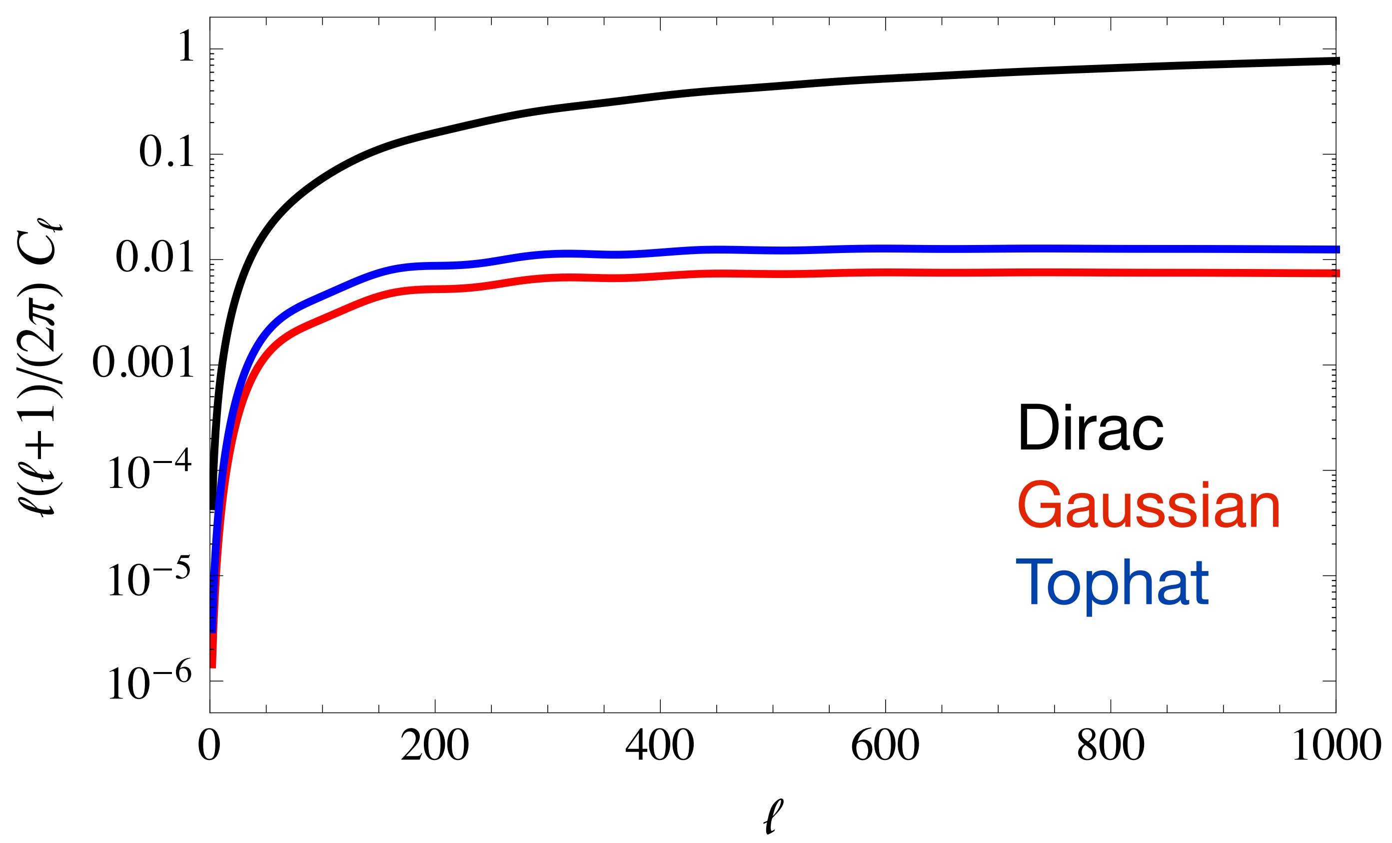

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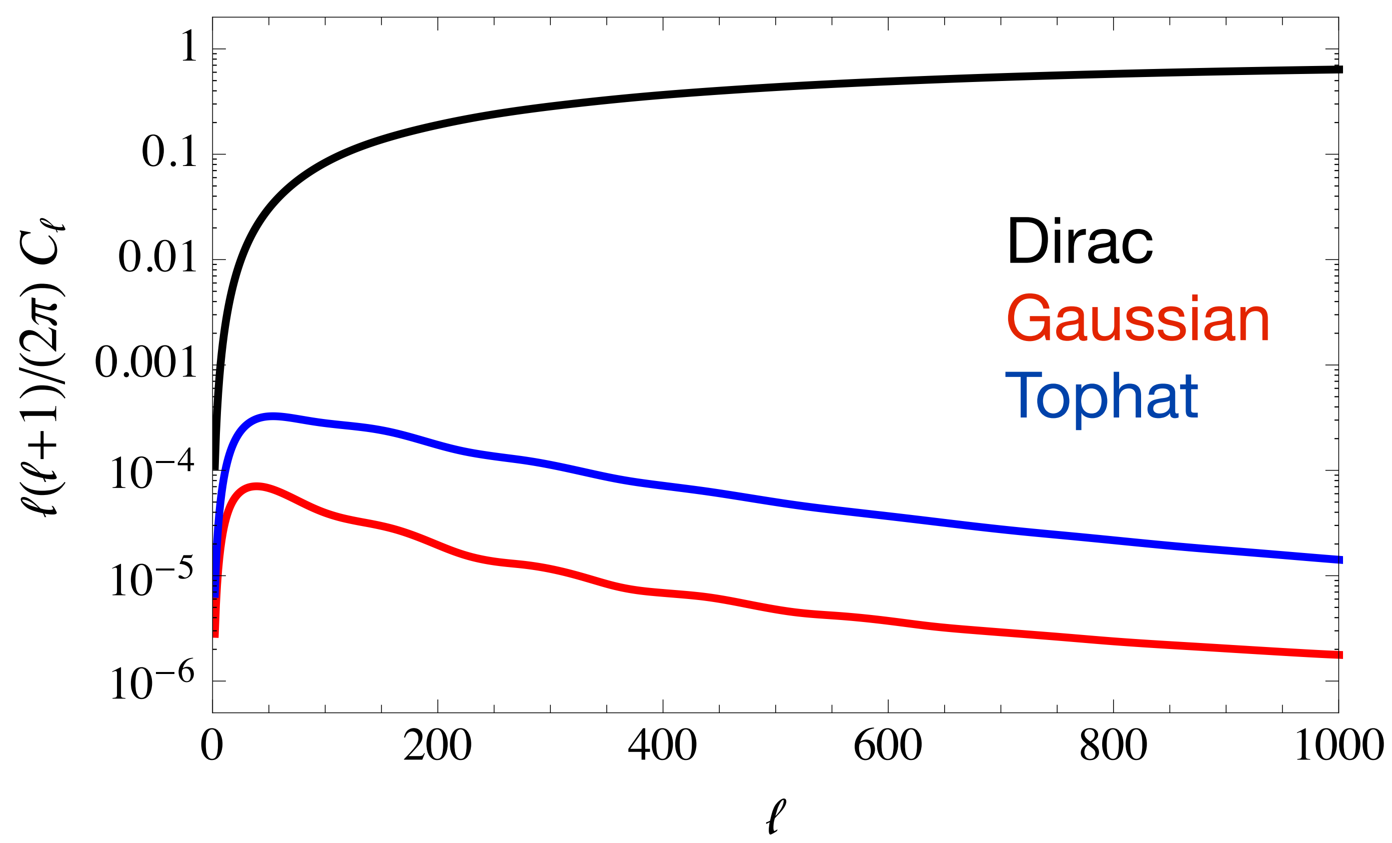
RSD



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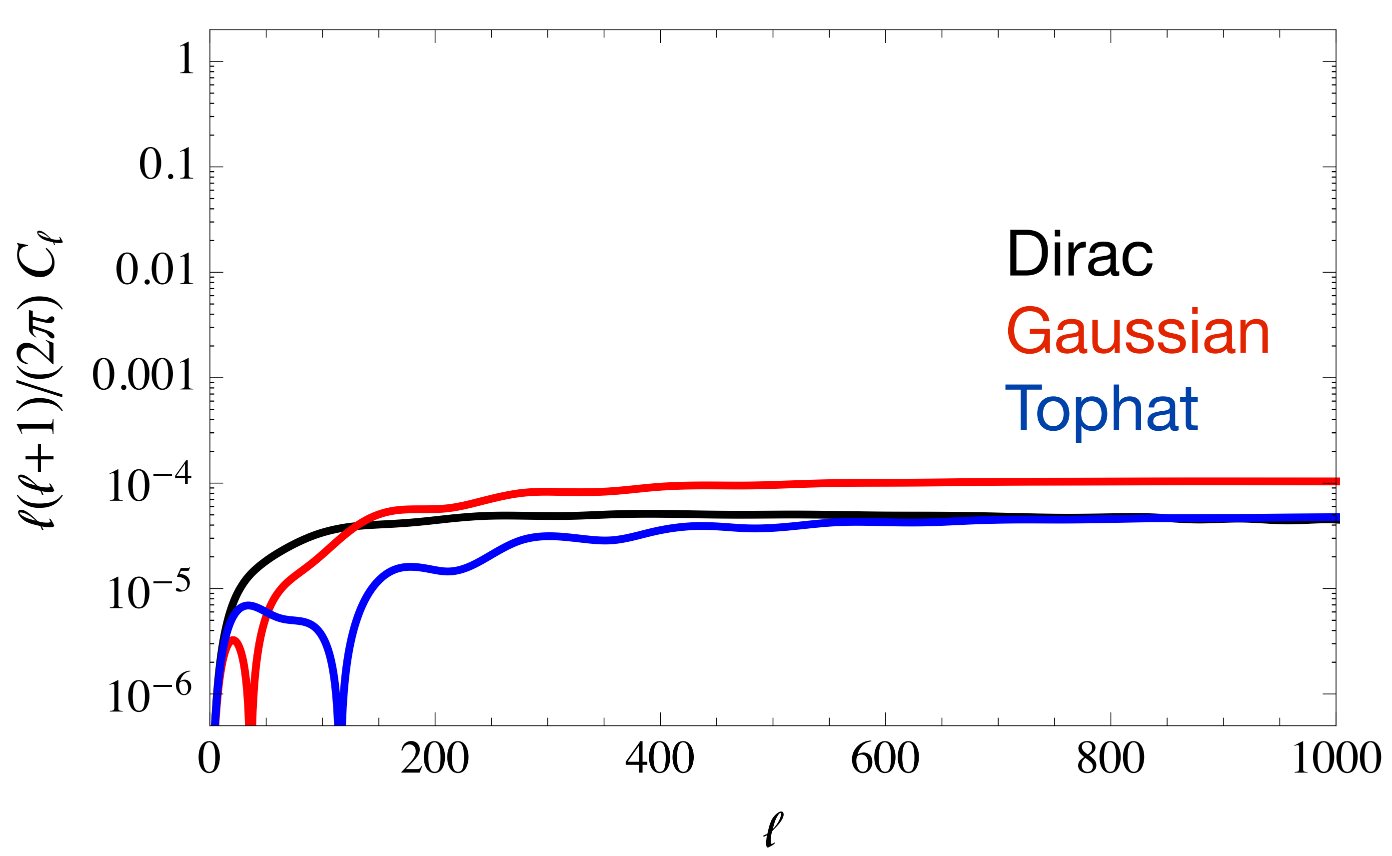

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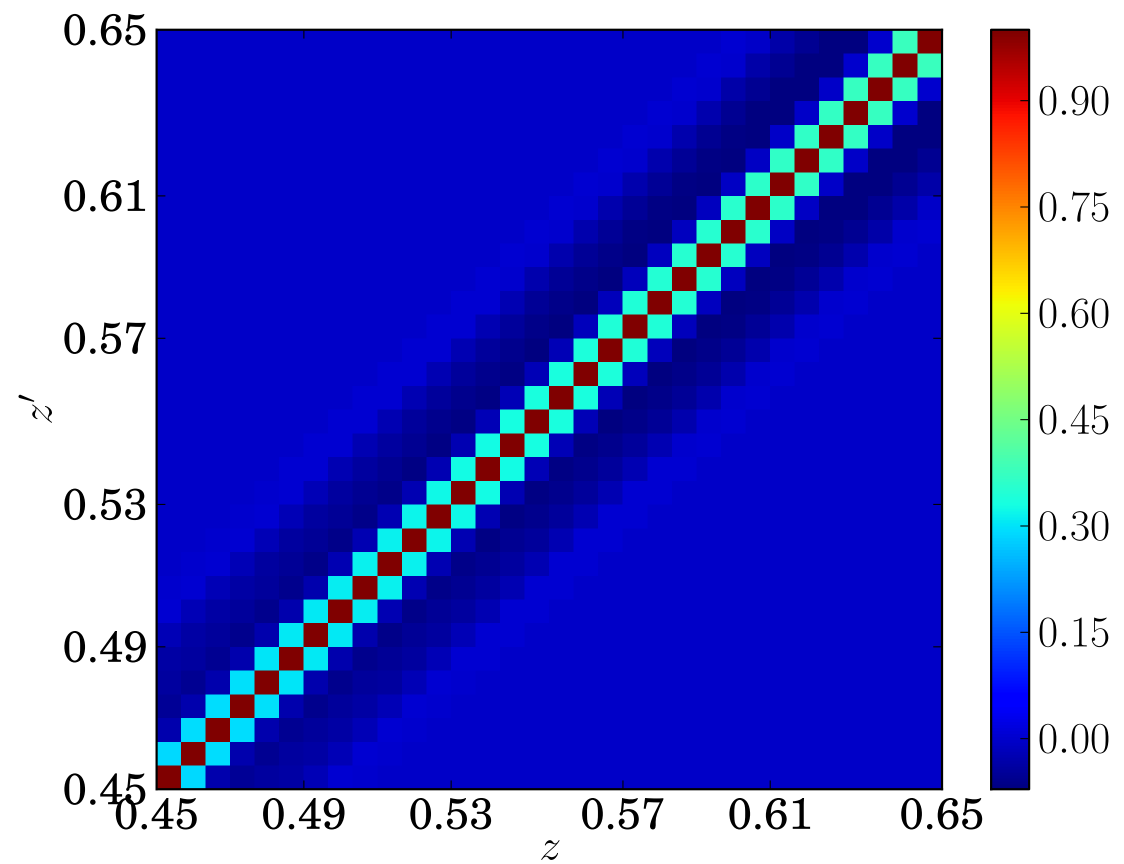
$\ell = 71$



Fisher Matrix Analysis

How good can a future survey determine the cosmological parameters?

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$$F_{\alpha\beta} = \sum_{\ell,(ij),(pq)} \frac{\partial c_\ell^{ij}}{\partial \lambda_\alpha} \frac{\partial c_\ell^{pq}}{\partial \lambda_\beta} \mathrm{Cov}^{-1}_{\ell,(ij),(pq)}$$

(assuming gaussian likelihood)

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Covariance matrix

$$\mathrm{Cov}_{[\ell,\ell'][(ij),(pq)]} = \delta_{\ell,\ell'} \frac{C_\ell^{\mathrm{obs},ip} C_\ell^{\mathrm{obs},jq} + C_\ell^{\mathrm{obs},iq} C_\ell^{\mathrm{obs},jp}}{f_{\mathrm{sky}}\,(2\ell+1)}$$

Asorey, Crocce, Gaztañaga, Lewis [arXiv:1207.6487]

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$n(i)$ number of galaxies per steradian in the i-th redshift bin

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Shot-noise

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Figure of Merit

$$\mathrm{FoM} = \left[\det(F^{-1})\right]^{-1/2}$$

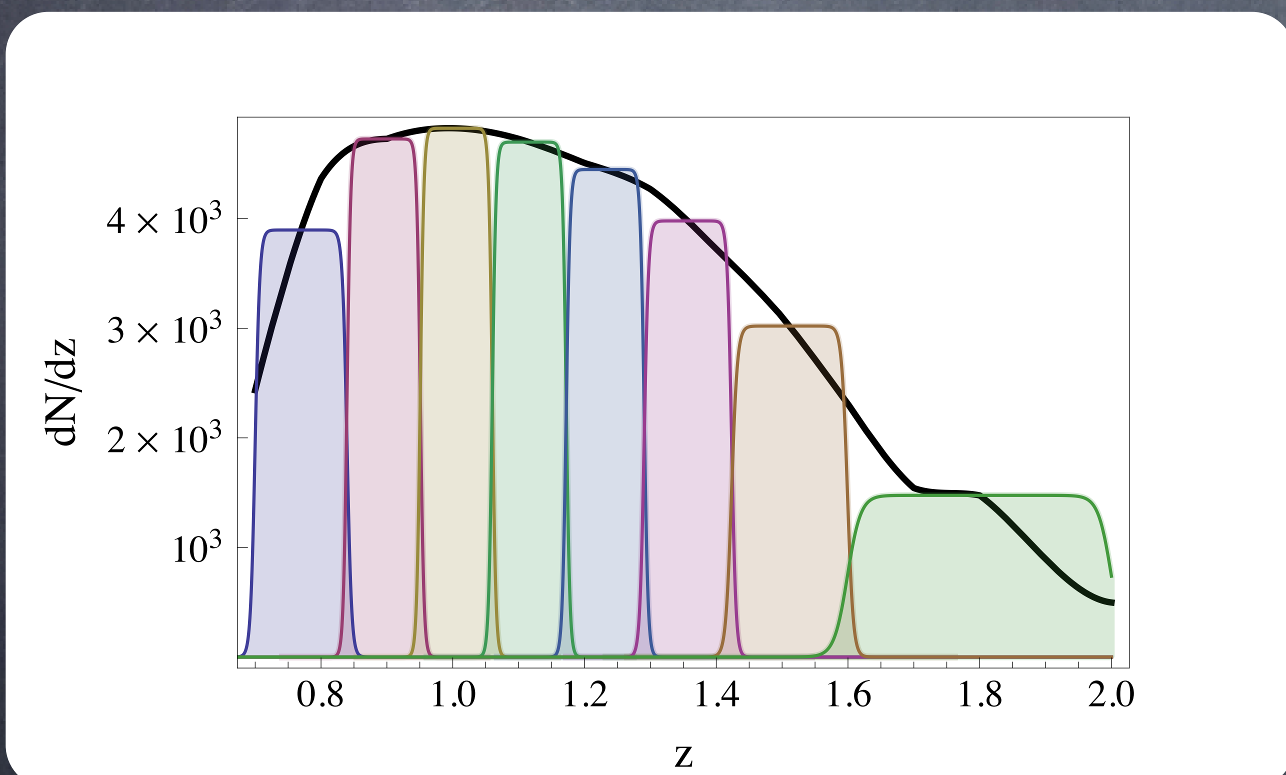
$$\mathrm{FoM}_{\mathrm{fixed}} = \left[\det(\hat{F}^{-1})\right]^{-1/2}$$

$$\mathrm{FoM}_{\mathrm{marginalized}} = \left[\det(\widehat{F^{-1}})\right]^{-1/2}$$

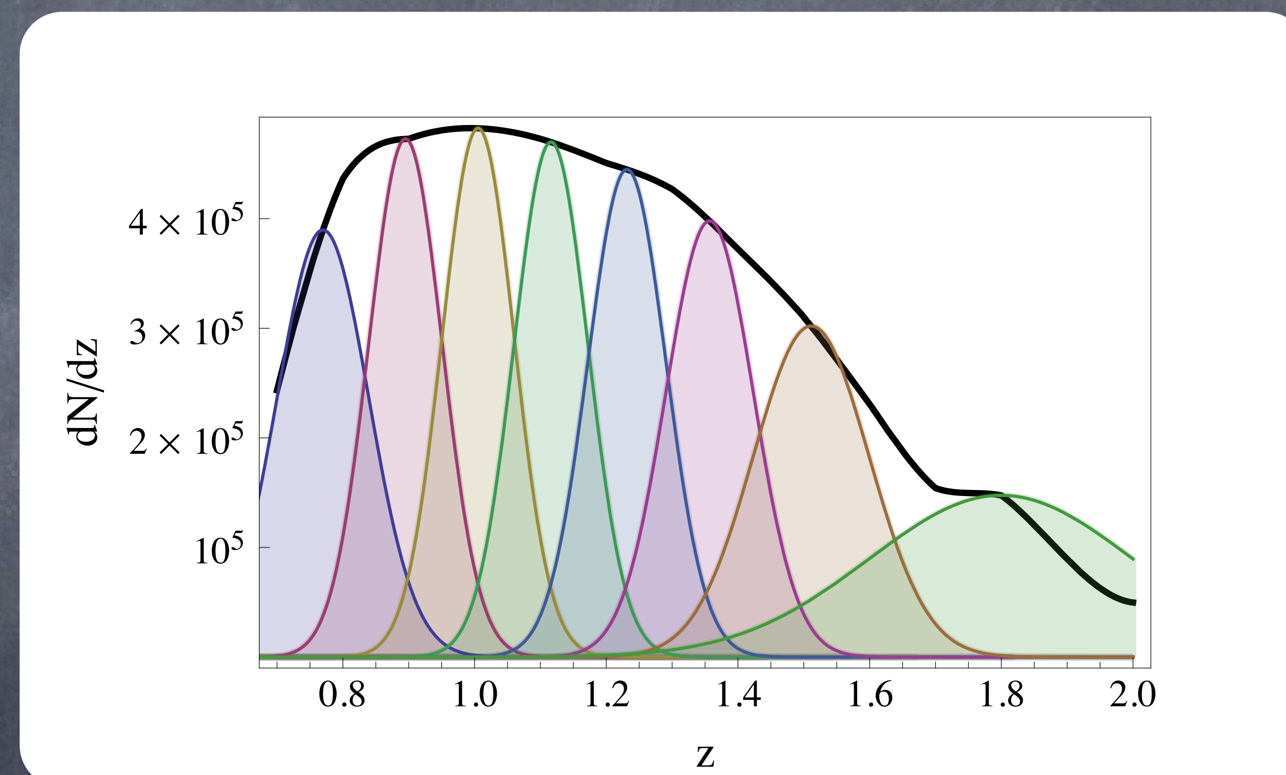
Binning Strategy

To recover the 3D information we need to split the redshift range in many bins and to consider the cross-correlations between different redshift bins.

Spectroscopic Survey



Photometric Survey



The redshift bins are chosen such that there is the same number of galaxy for each bin.

Non-linearity scales

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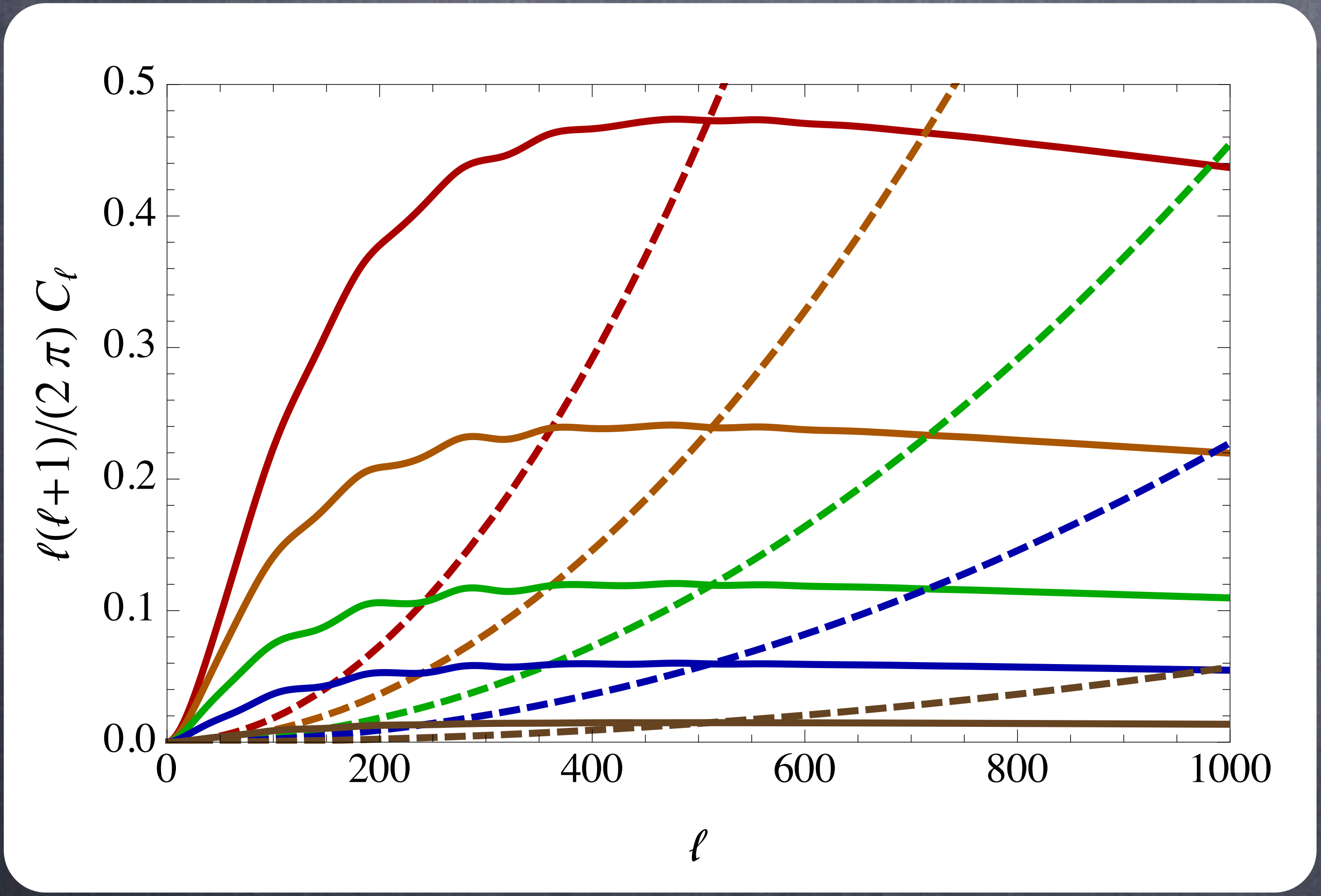
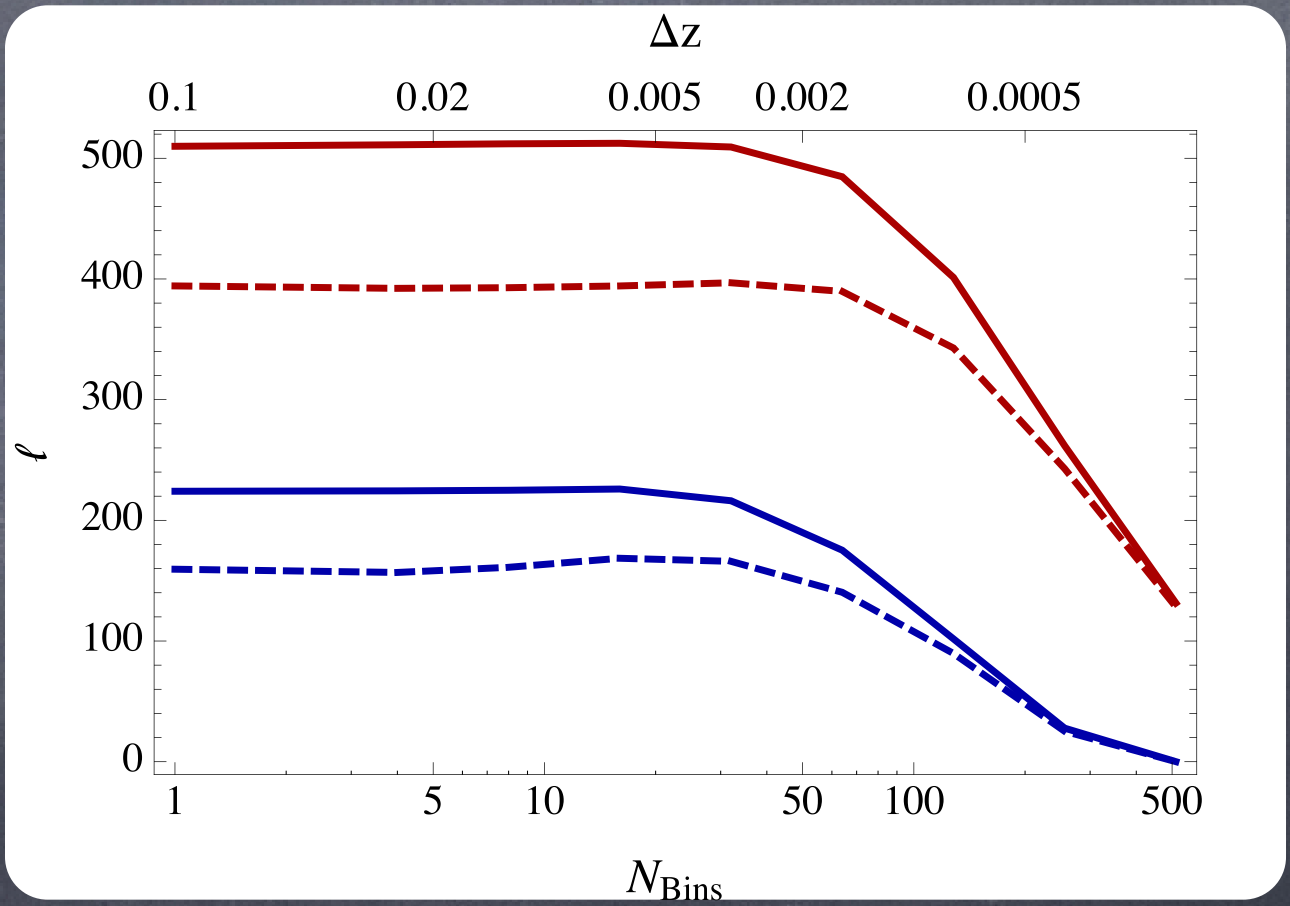
Longitudinal distance $\quad \dfrac{z_i - z_j}{H(\bar{z})}$

$$\ell^{ij}_{\max} = \begin{cases} 2\pi d(\bar{z})/\lambda_{\min} & \text{if } \delta z_{ij} \leq 0\,, \\ \dfrac{2\pi d(\bar{z})}{\sqrt{\lambda^2_{\min} - \left(\frac{\delta z_{ij}}{H(\bar{z})}\right)^2}} & \text{if } 0 < \frac{\delta z_{ij}}{H(\bar{z})} < \lambda_{\min}\,, \\ \infty & \text{otherwise.} \end{cases}$$

Cosmological Parameter Forecast

Increasing the number of bins, we get a better redshift resolution.
But shot-noise increases too.



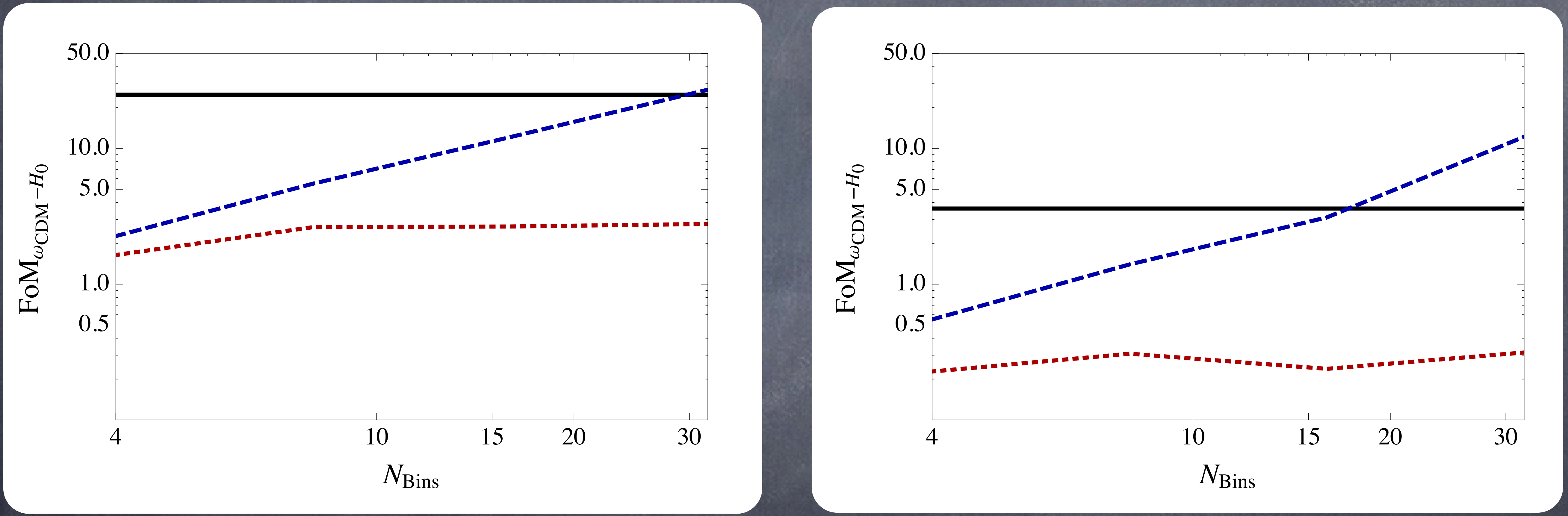


Since also the signal increases, shot-noise starts dominating for smaller bin size than naively expected.

Cosmological Parameter Forecast

spectroscopic DES-like

$\lambda_{\min} = 34\ \mathrm{Mpc}/h$ $\lambda_{\min} = 68\ \mathrm{Mpc}/h$

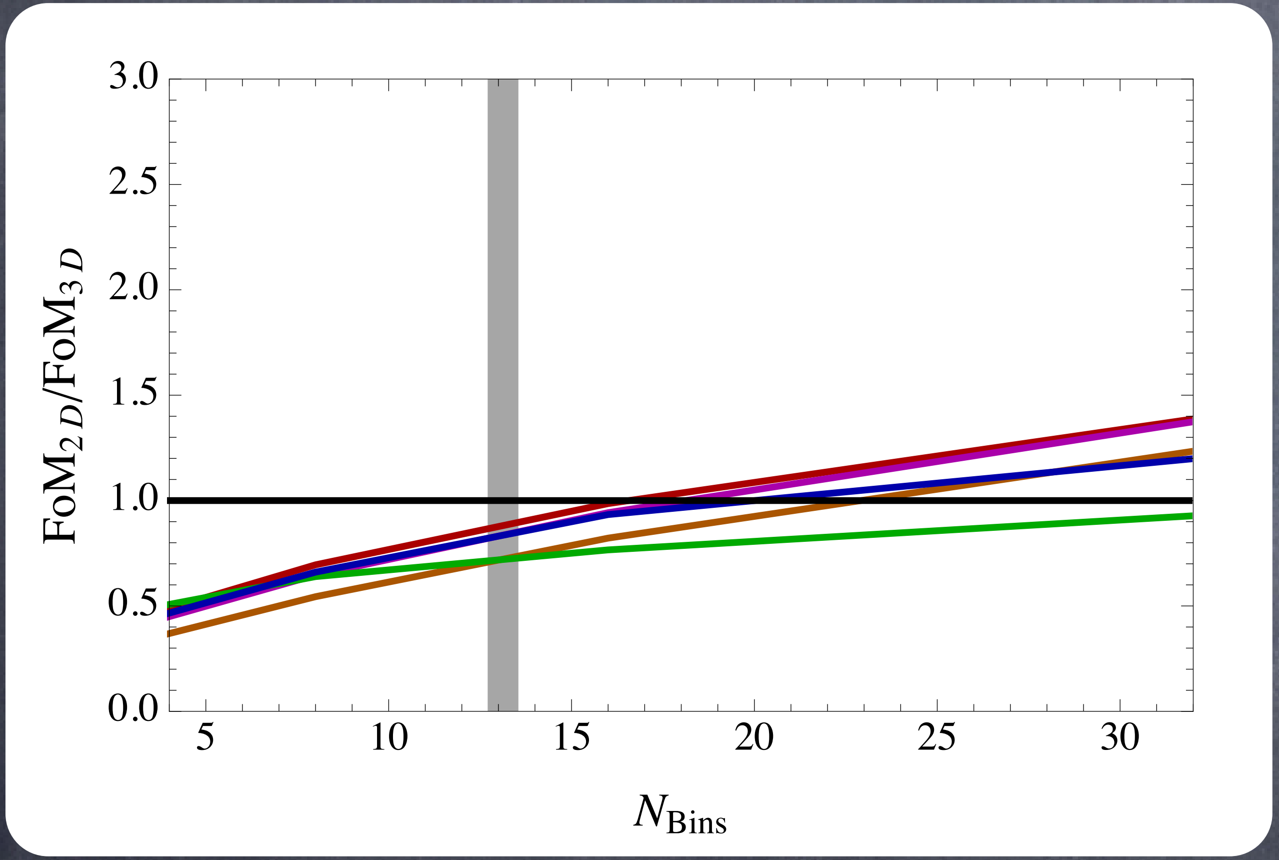


only redshift bins auto-correlations
with redshift bins cross-correlations

Cosmological Parameter Forecast

2D vs 3D

$\lambda_{\rm min} = 34\ {\rm Mpc}/h$



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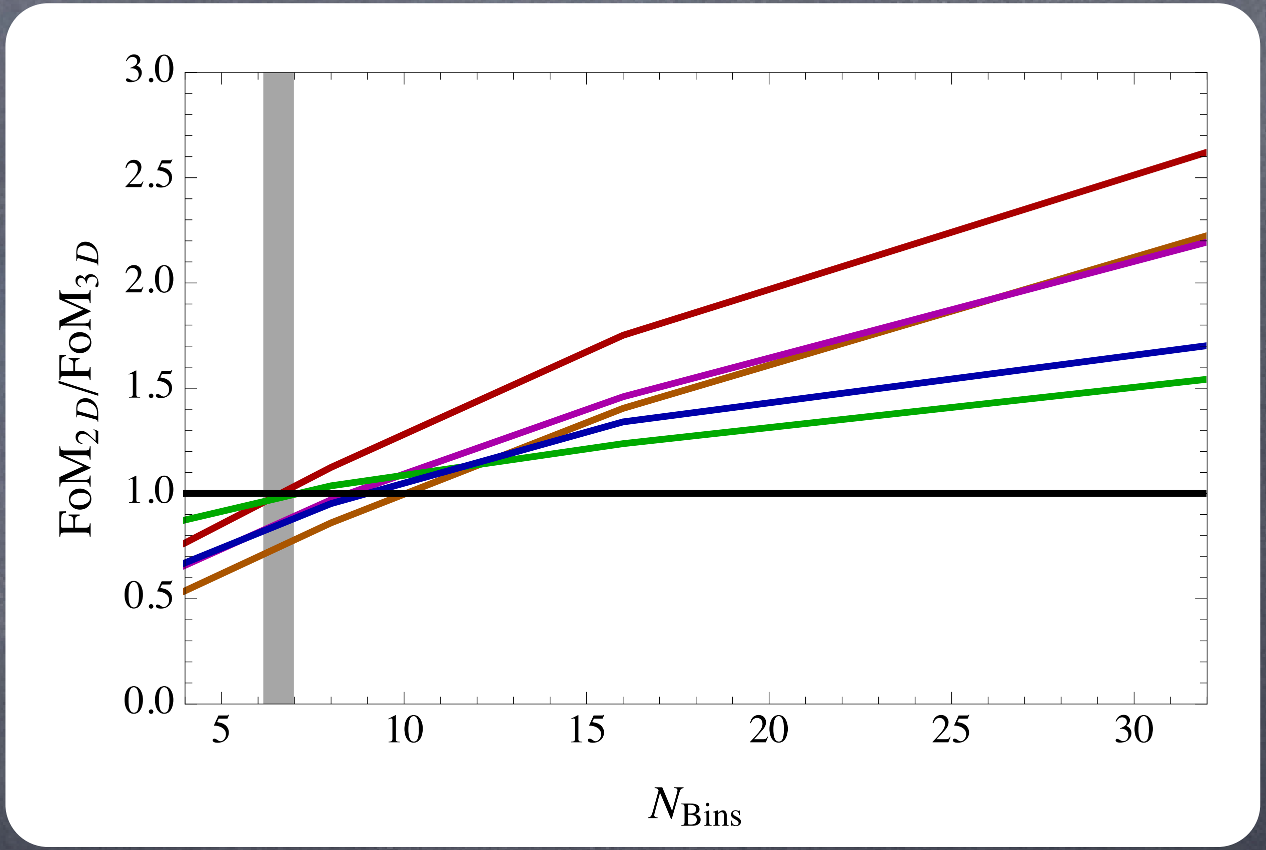
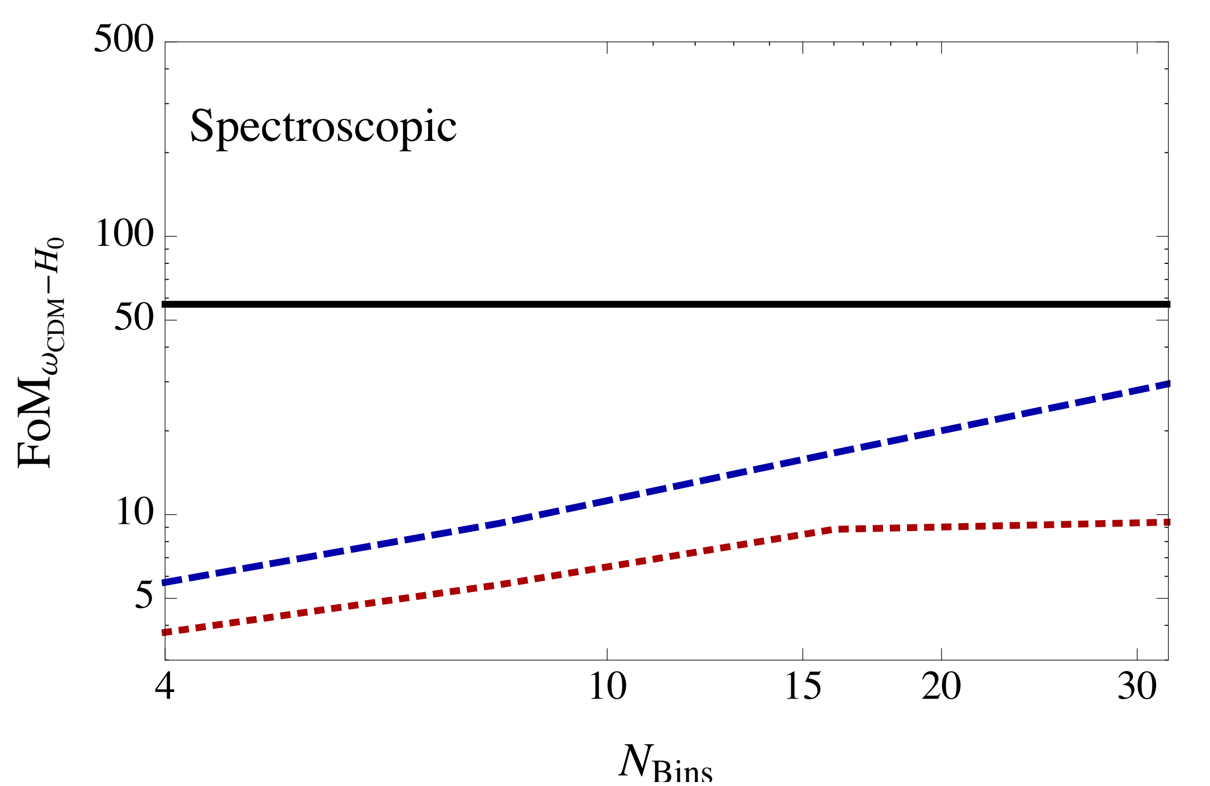


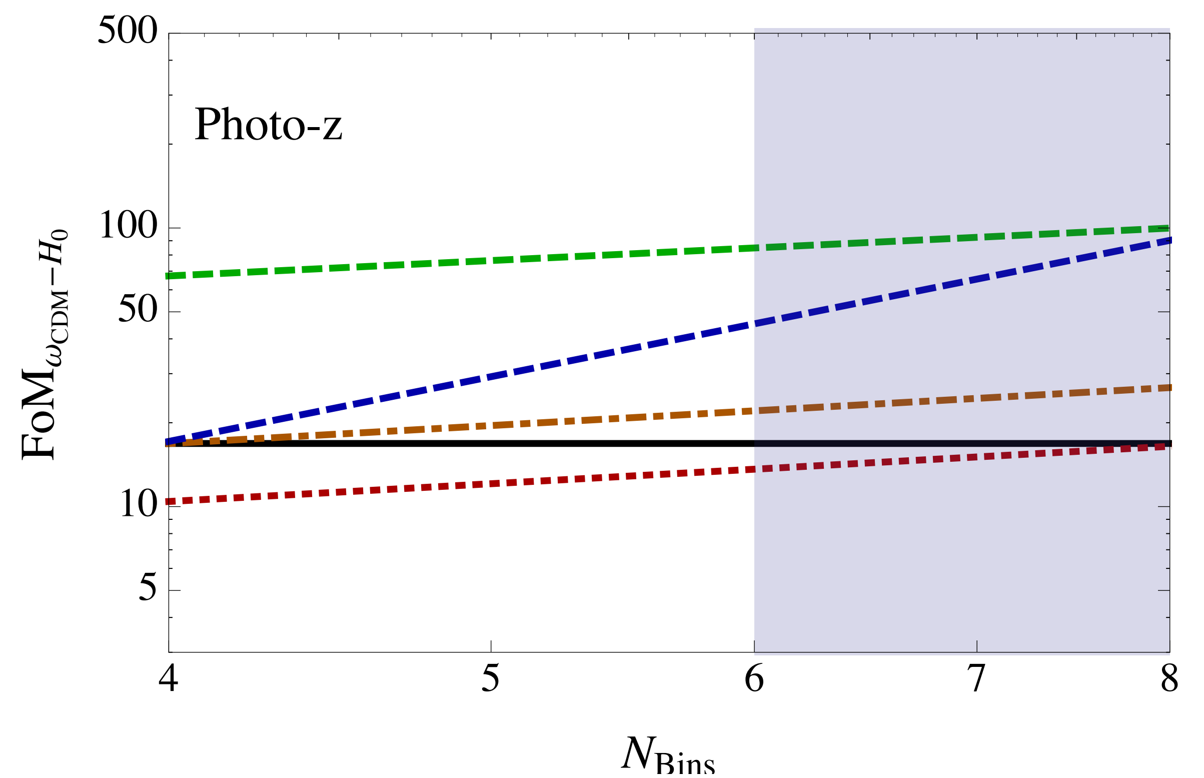
Cosmological Parameter Forecast

Euclid

Spectroscopic Survey



Photometric Survey



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Cosmological Parameter Forecast

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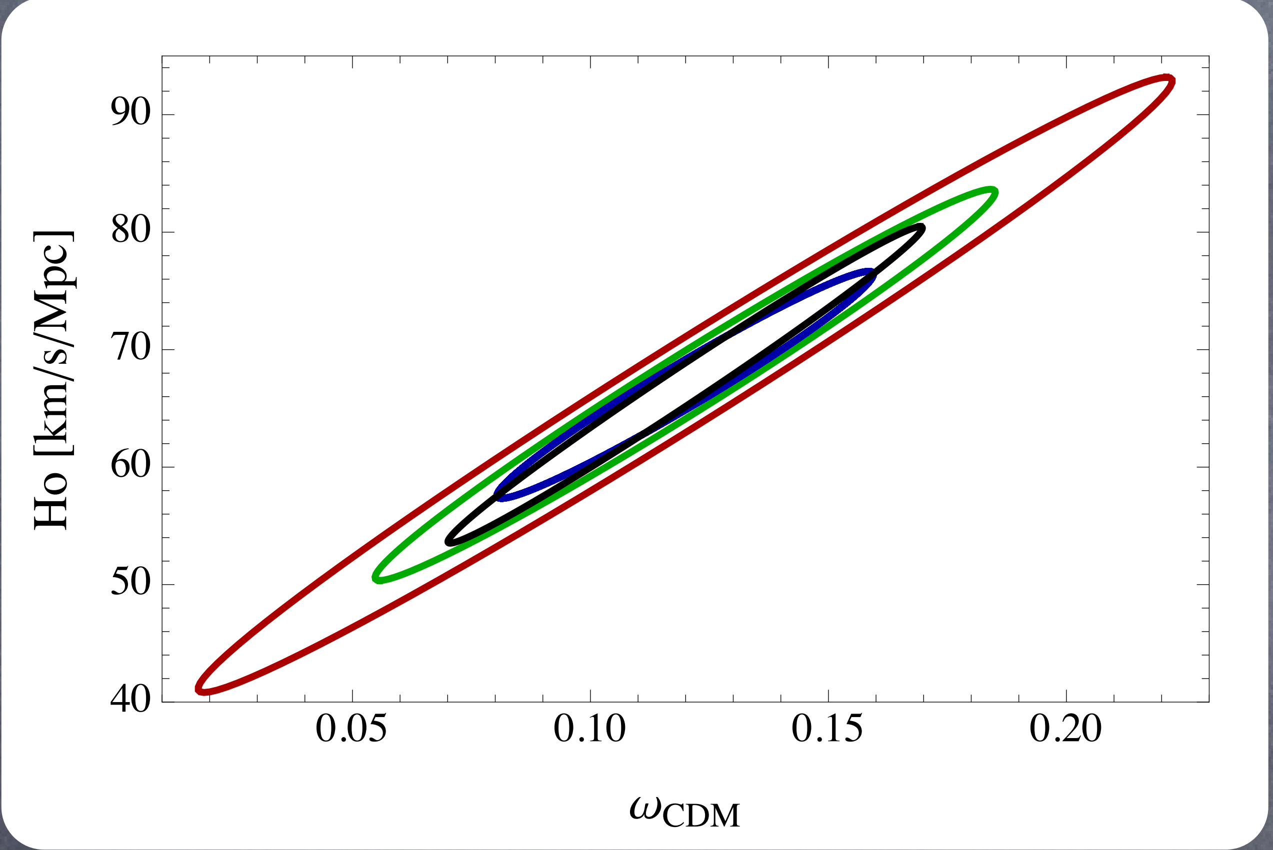

4 bins, 8 bins, 16 bins, 32 bins

Cosmological Parameter Forecast

Euclid

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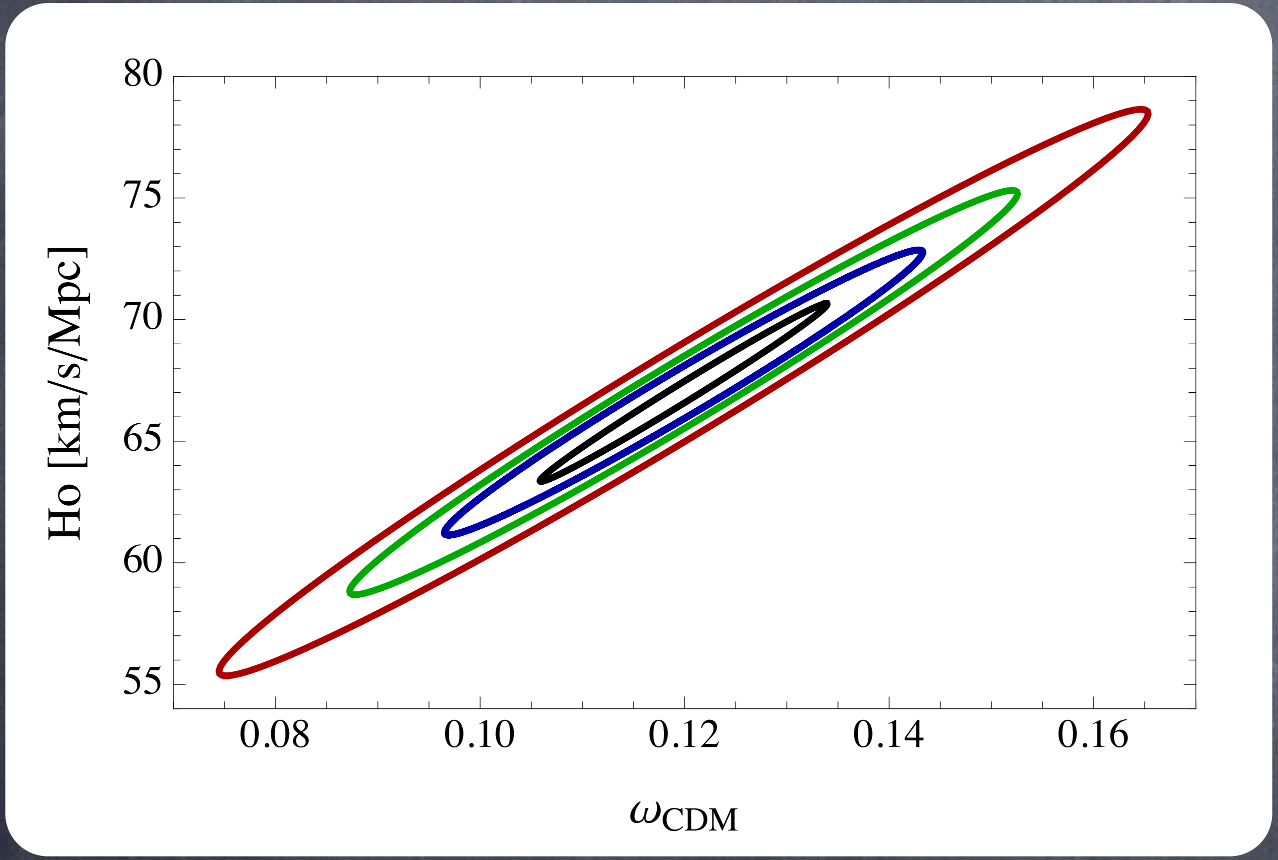

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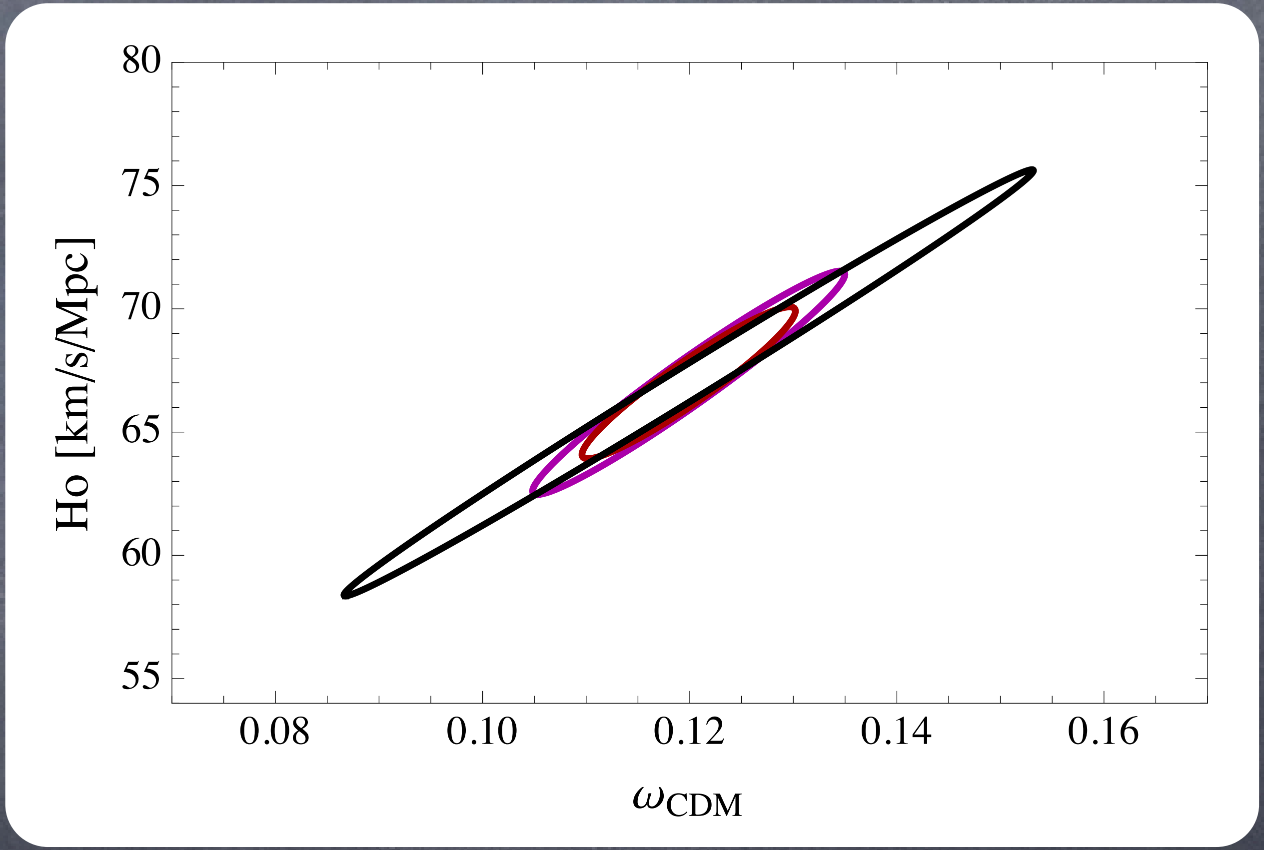

4 bins, 8 bins, 16 bins, 32 bins

Signal to Noise for different effects

Different terms encode different information

Density

Redshift-space distortion

Lensing

Potential

Signal to Noise for different effects

Different terms encode different information

Large scale matter distribution

Density

Redshift-space distortion

Lensing

Potential

Signal to Noise for different effects

Different terms encode different information

Cosmic velocity field

Density

Redshift-space distortion

Lensing

Potential

Signal to Noise for different effects

Different terms encode different information

Geometry of the universe

Density

Redshift-space distortion

Lensing

Potential

Signal to Noise for different effects

Different terms encode different information

Density

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Lensing

Potential

Signal to Noise

$$\left(\frac{S}{N}\right)_\ell = \frac{C_\ell - \tilde{C}_\ell}{\sigma_\ell}$$

$$\sigma_\ell = \sqrt{\frac{2}{(2\ell+1)\, f_{\rm sky}}}\left(C_\ell + \frac{1}{n}\right)$$

Lensing Potential

Signal to Noise $\left(\frac{S}{N}\right)_\ell = \frac{C_\ell - \tilde{C}_\ell}{\sigma_\ell}$

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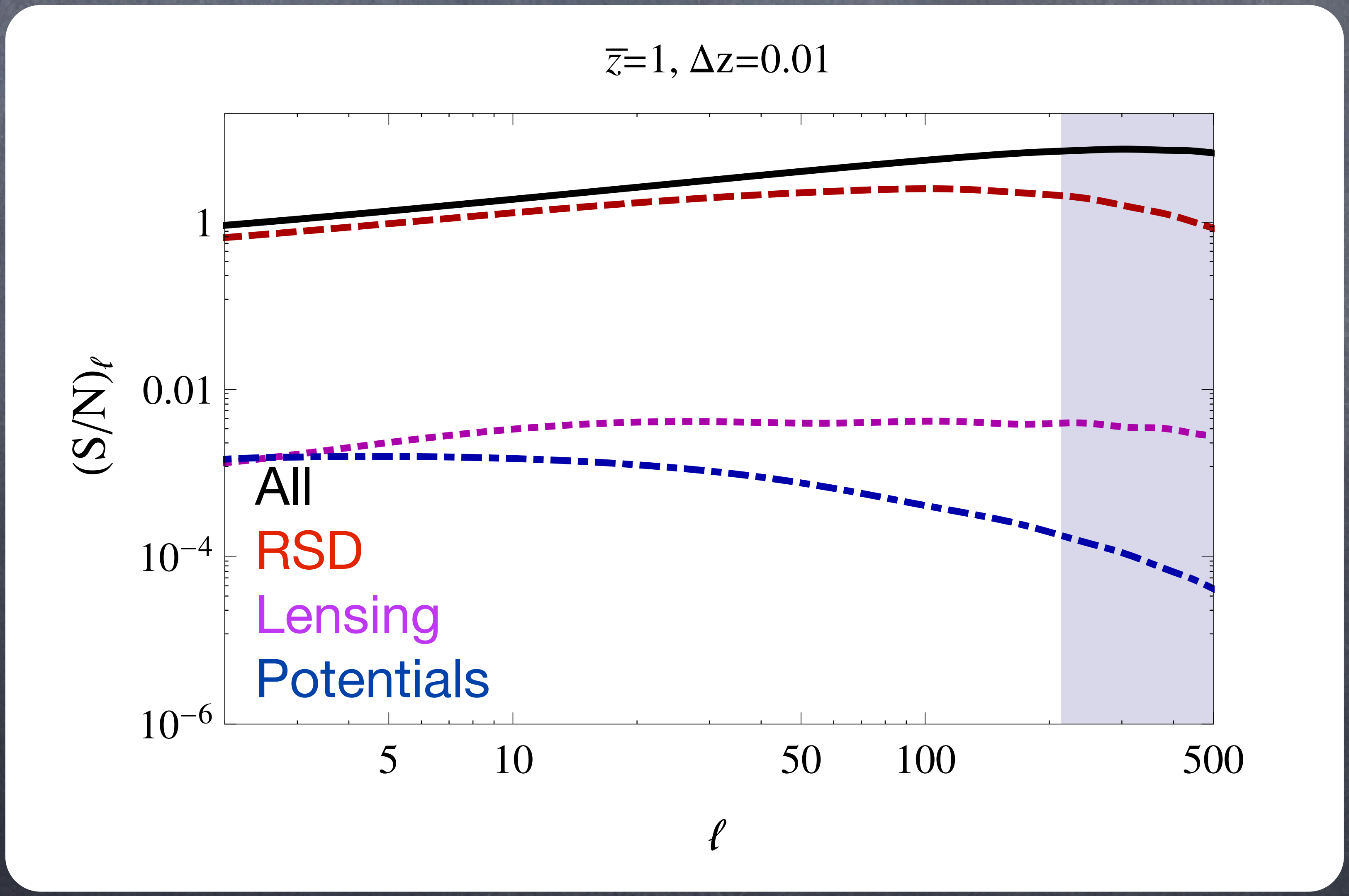

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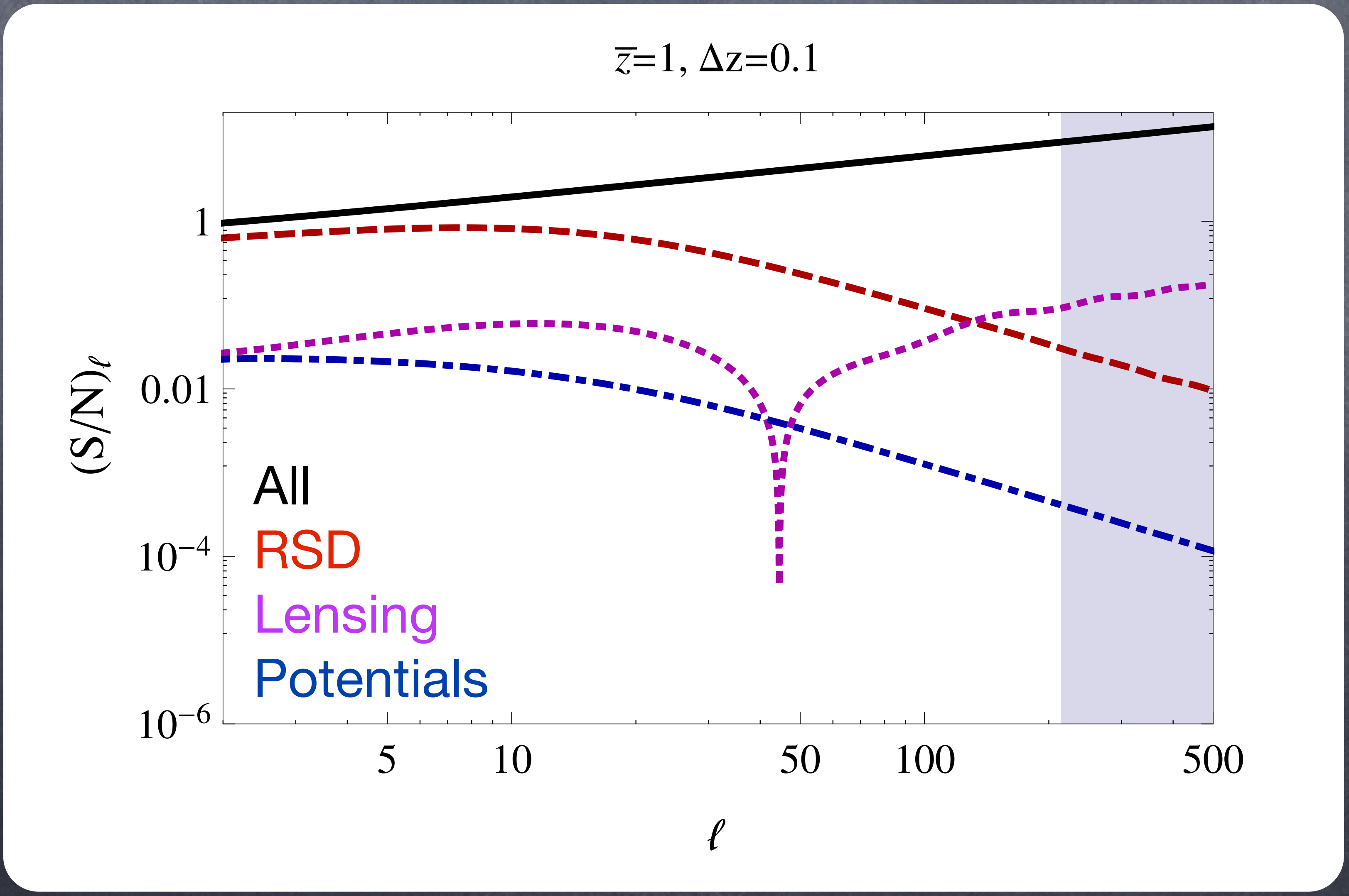

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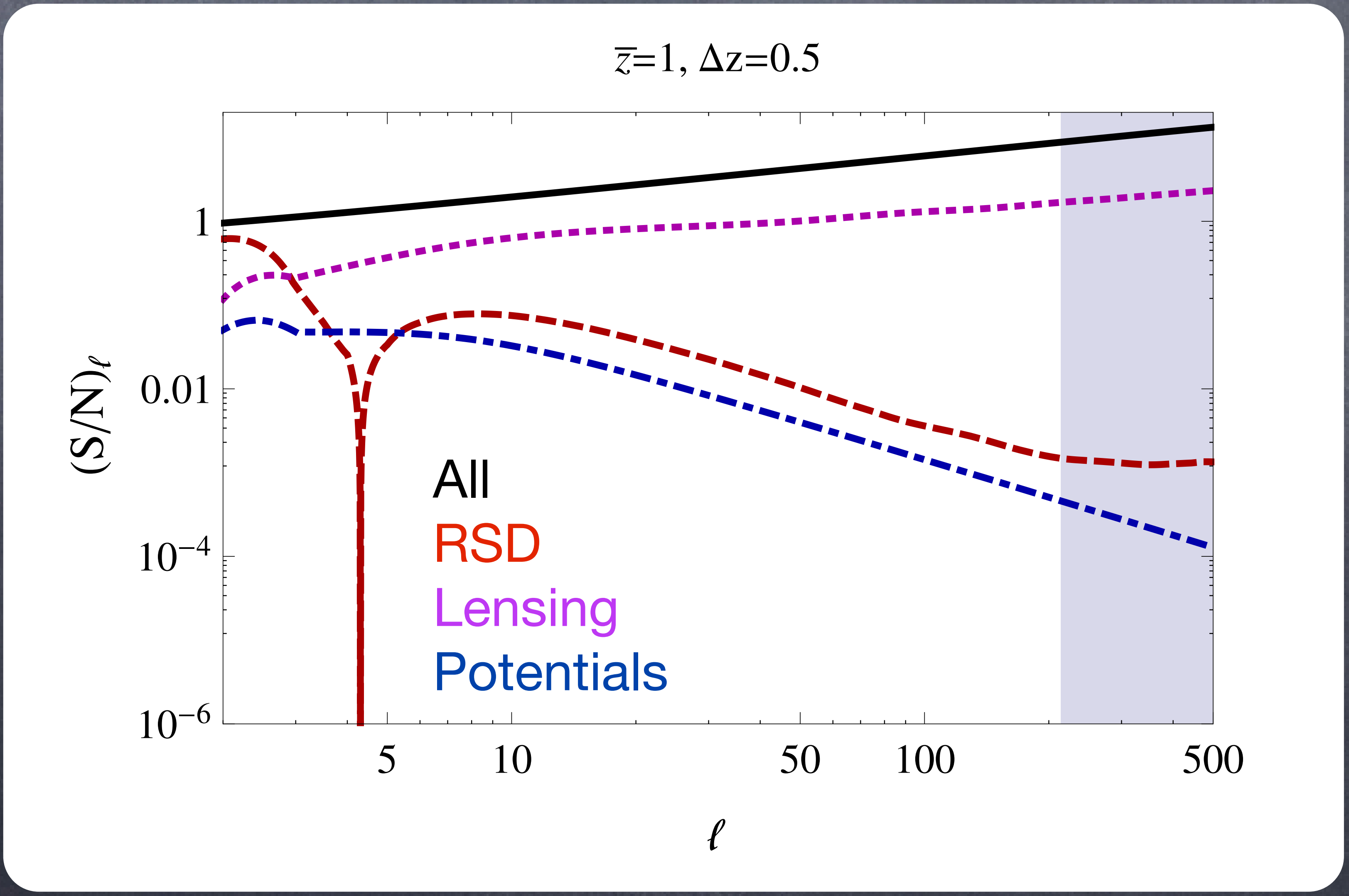

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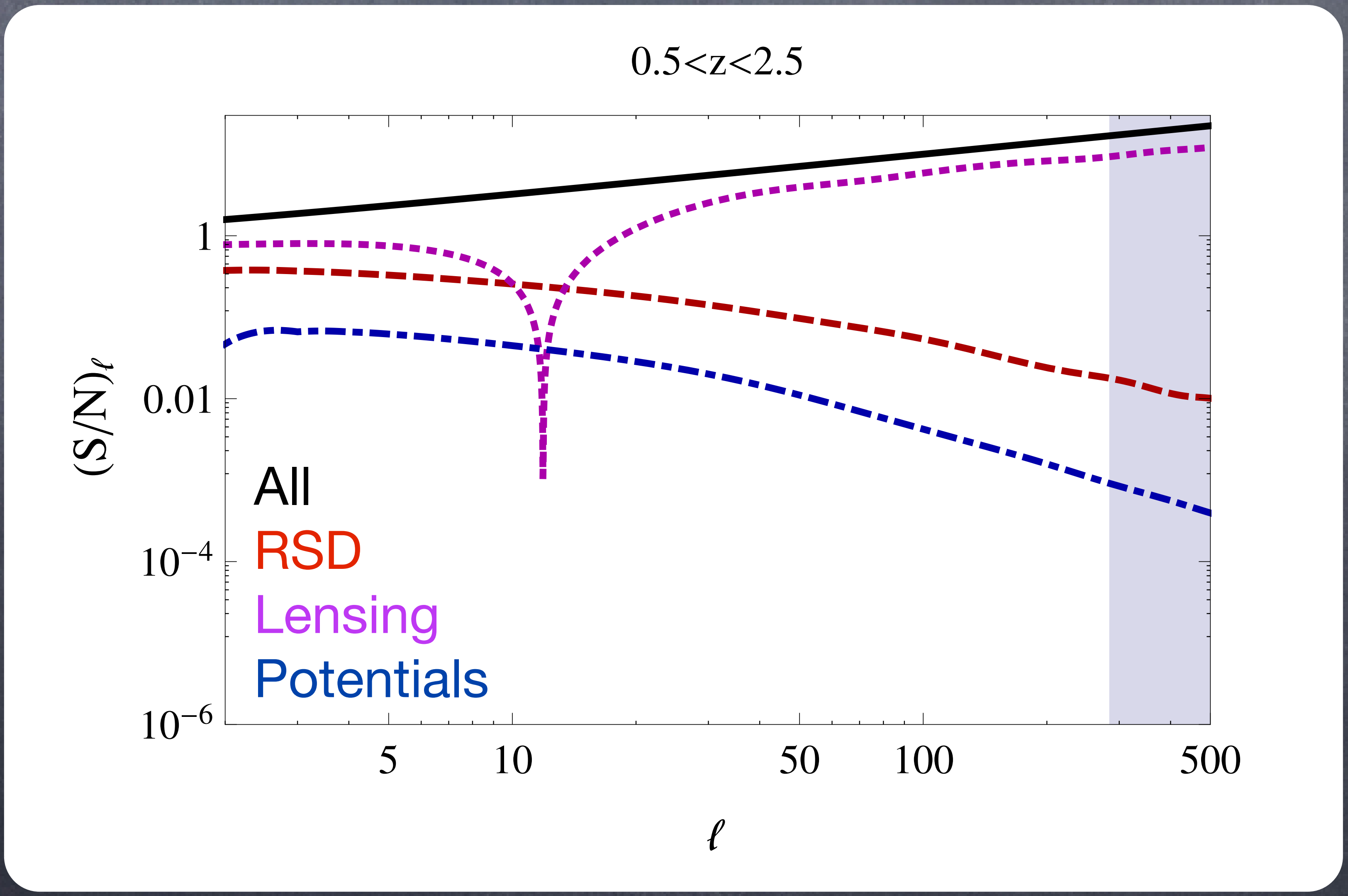
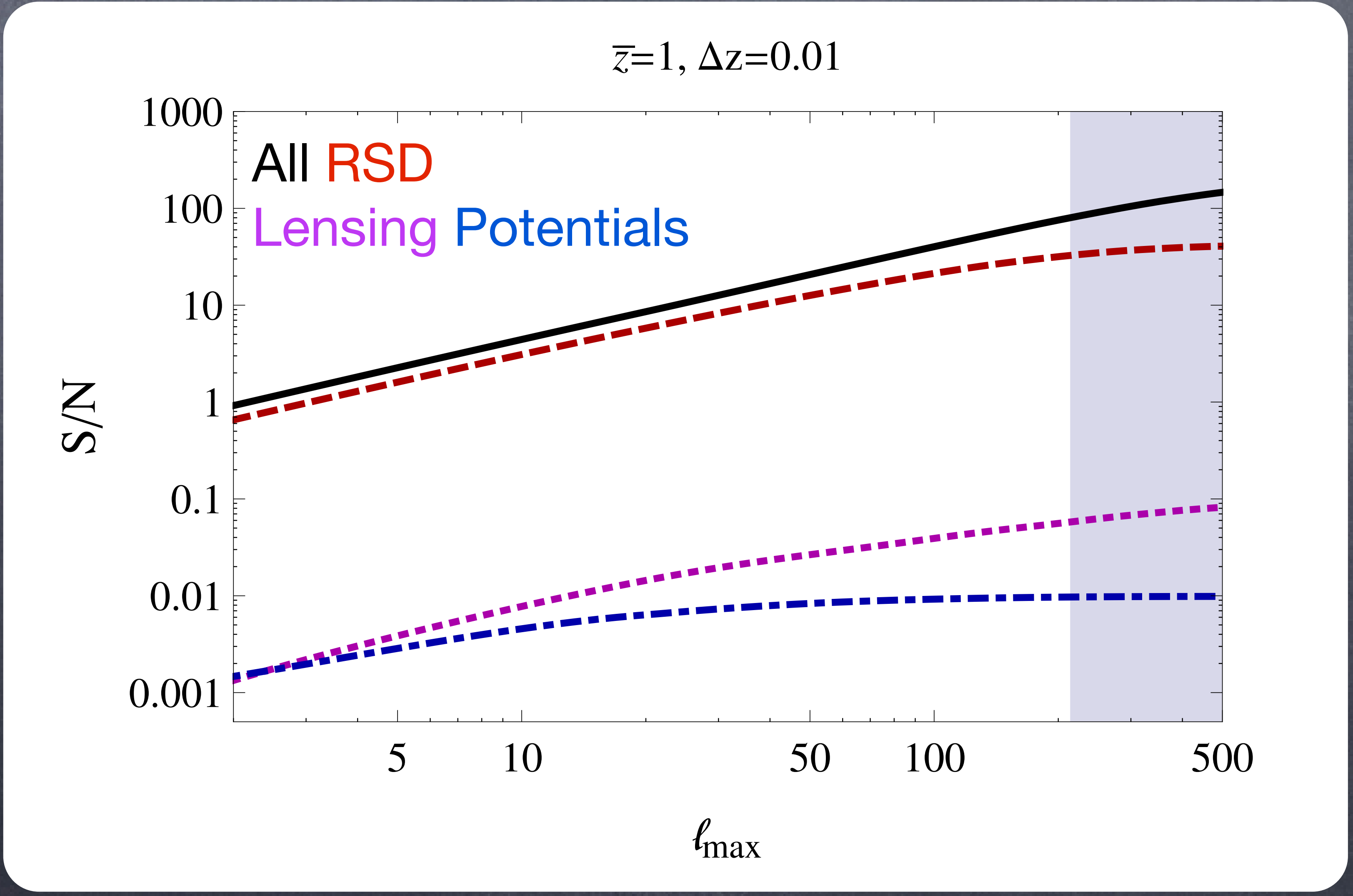


Lensing Potential

Cumulative Signal to Noise

$$\left(\frac{S}{N}\right)^2 = \sum_{\ell=2}^{\ell_{\max}} \left(\frac{C_\ell - \tilde{C}_\ell}{\sigma_\ell}\right)^2$$

Euclid



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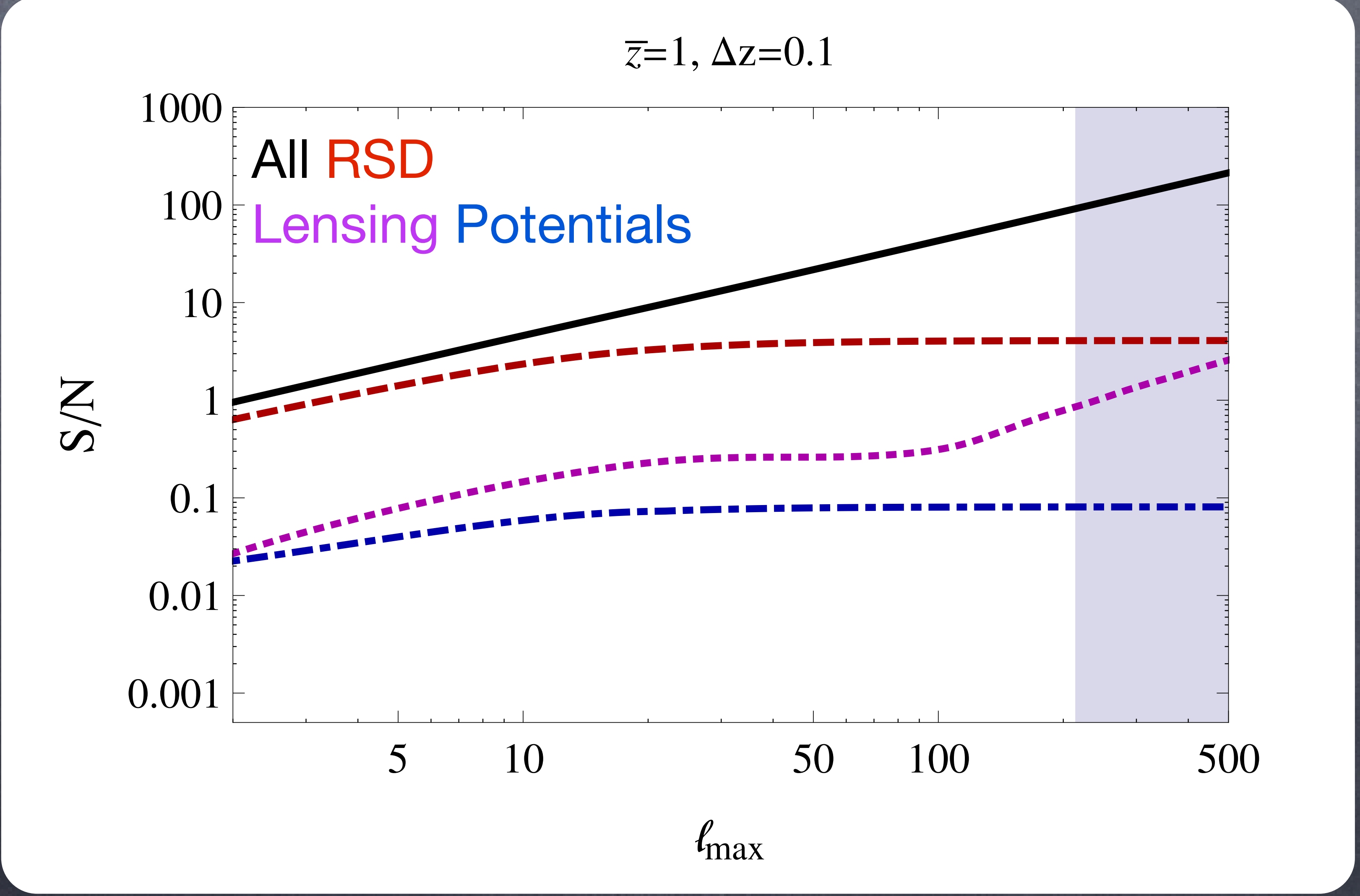

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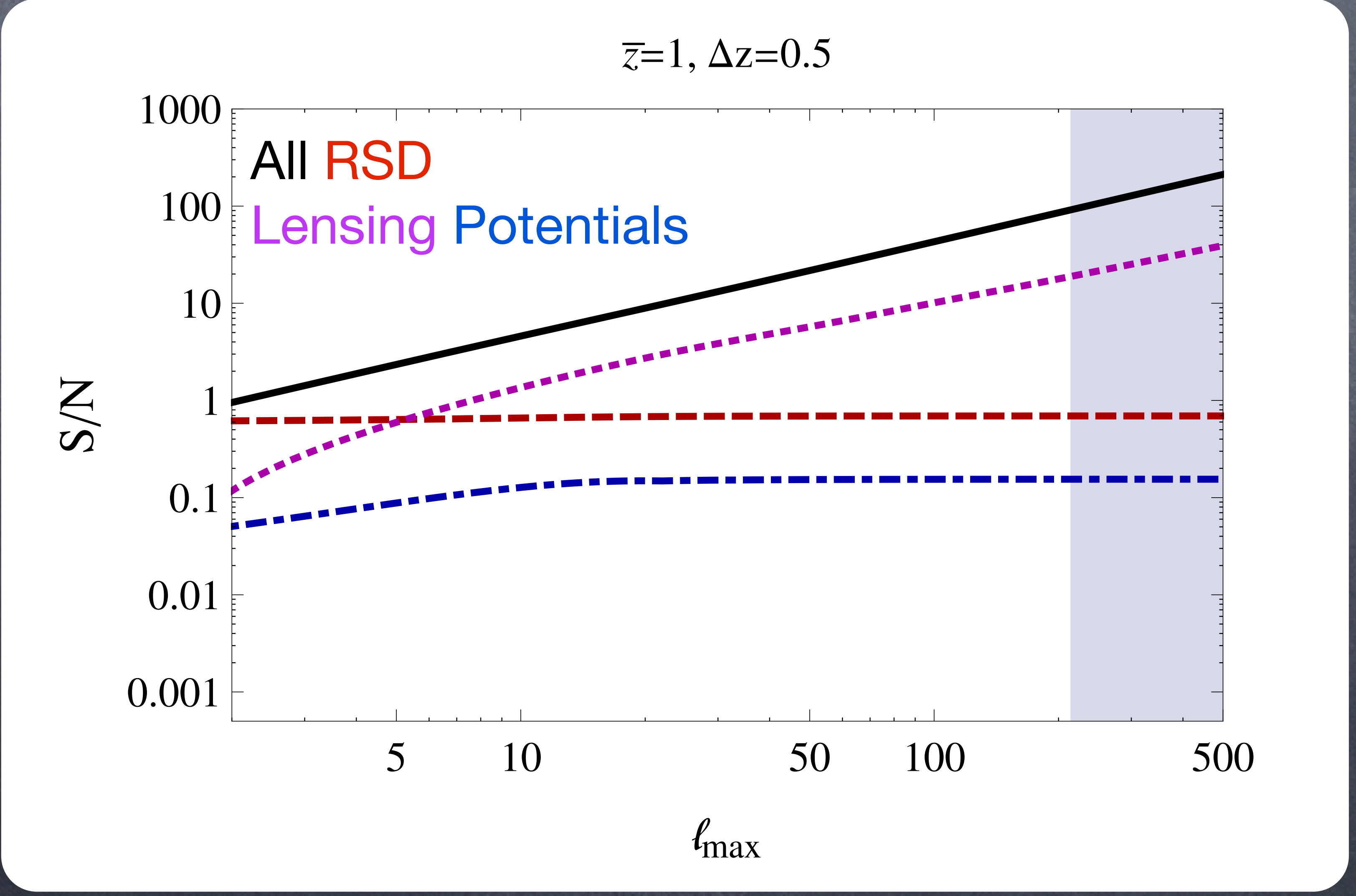

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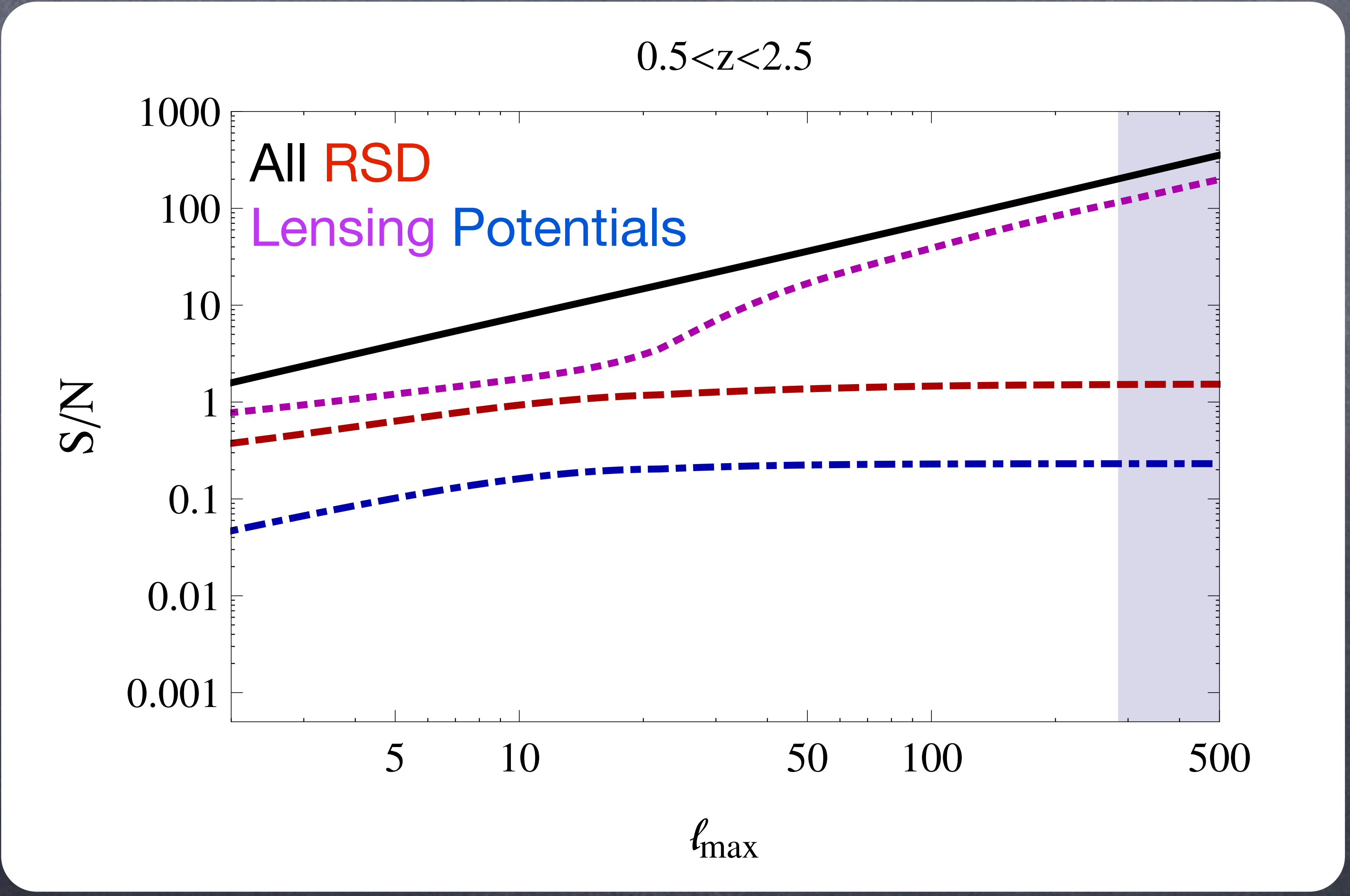

CLASSgal

Modified version of CLASS code to compute the redshift dependent angular power spectra $c_\ell(z_1, z_2)$

CLASSgal

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All the relativistic effects:
- Redshift space distortion
- Lensing
- Potential (GR) terms

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MontePython

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CLASSgal
Next..

Main parts of CLASSgal will be merged with CLASS (v2.1):
- cross-correlation with CMB
- implementation for non-flat universe

http://cosmology.unige.ch/tools

For CLASS
http://class-code.net

Conclusion

So far galaxy surveys have mainly determined P(k). Easy to measure it, but requires a fiducial model.

Future surveys (like Euclid) will be able to measure the spectra $C_\ell(z, z')$ directly from the data.

These spectra contain information about the matter distribution (density), the velocity (redshift space distortion) and the spacetime geometry (lensing).

The spectra depend sensitively and in several different ways on dark energy, on the matter and baryon densities, bias, etc. Their measurements provide a new estimation of cosmological parameters.

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