ZACHARY SLEPIAN

THE BARYON-DARK MATTER RELATIVE VELOCITY AND A NEW APPROACH TO THE 3-POINT CORRELATION FUNCTION

LBNL RPM
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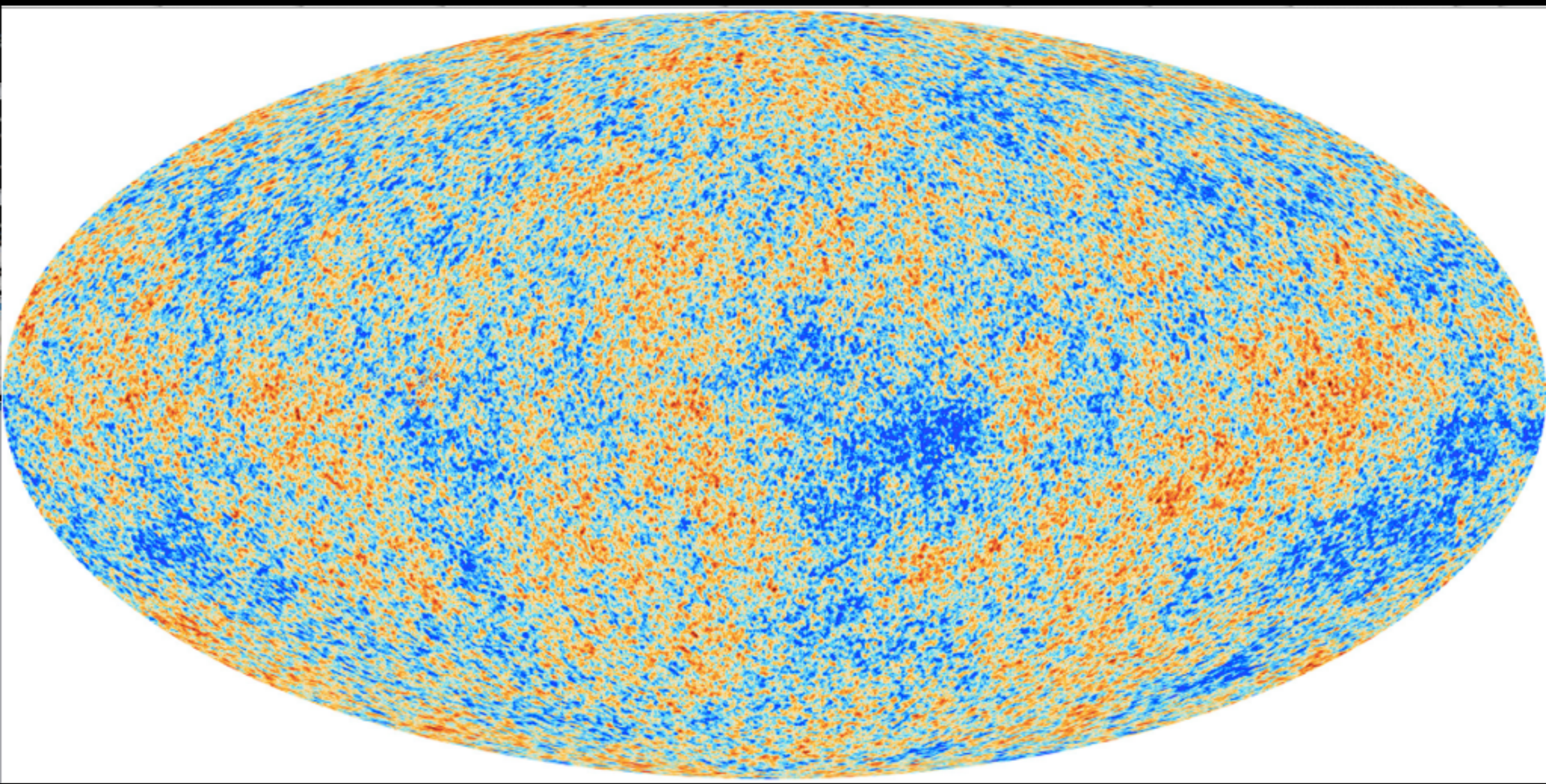
Outline

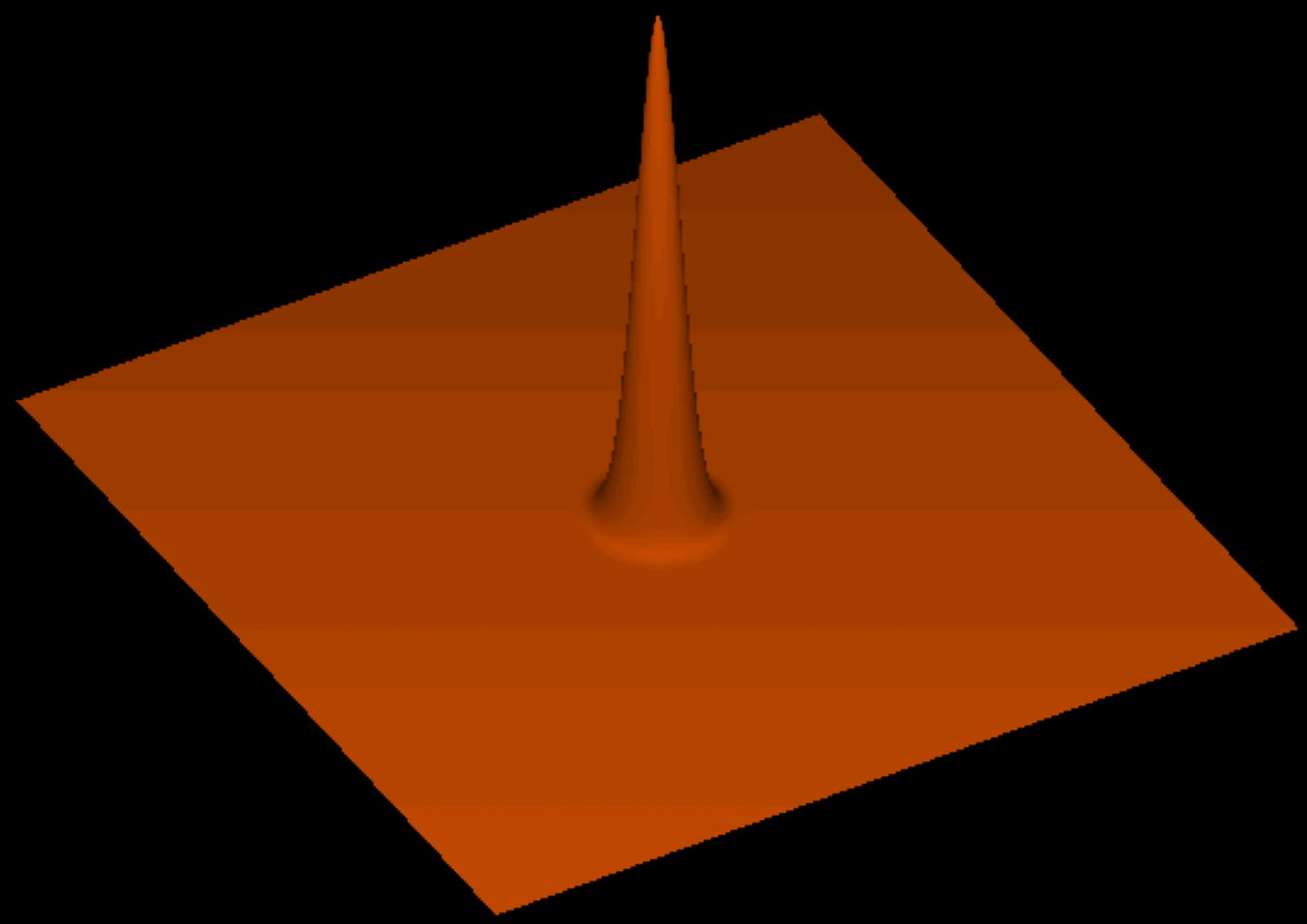
1. BAO method
2. Baryon-DM relative velocity: a possible astrophysical systematic?
3. 3-point correlation function as a diagnostic
4. Multipole basis for the 3PCF
5. RV signatures in the 3PCF
6. Reformulating the 3PCF: algorithm and all
7. BOSS CMASS results
8. Returning to the RV
9. Applications to DESI
10. Conclusions

1. BAO method

COSMIC MICROWAVE BACKGROUND

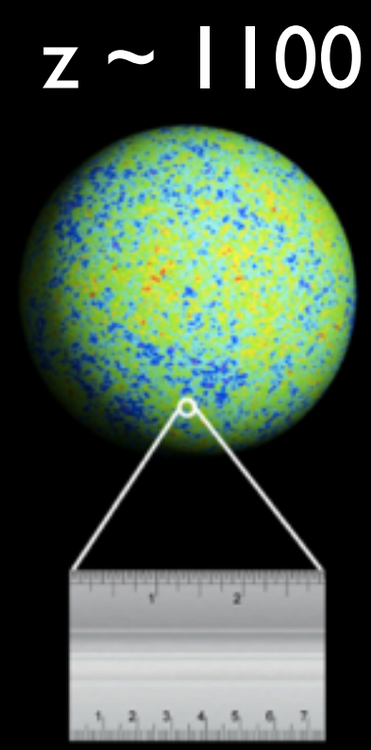


Planck collaboration 2013



Animation: Daniel Eisenstein

BAO as a standard ruler



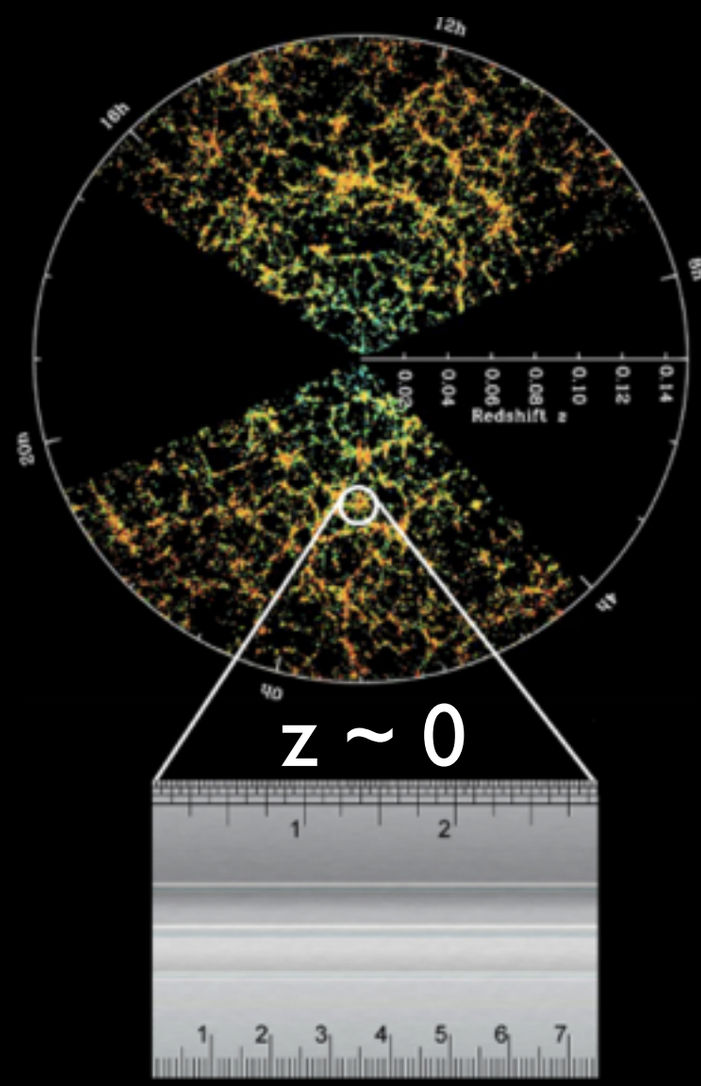
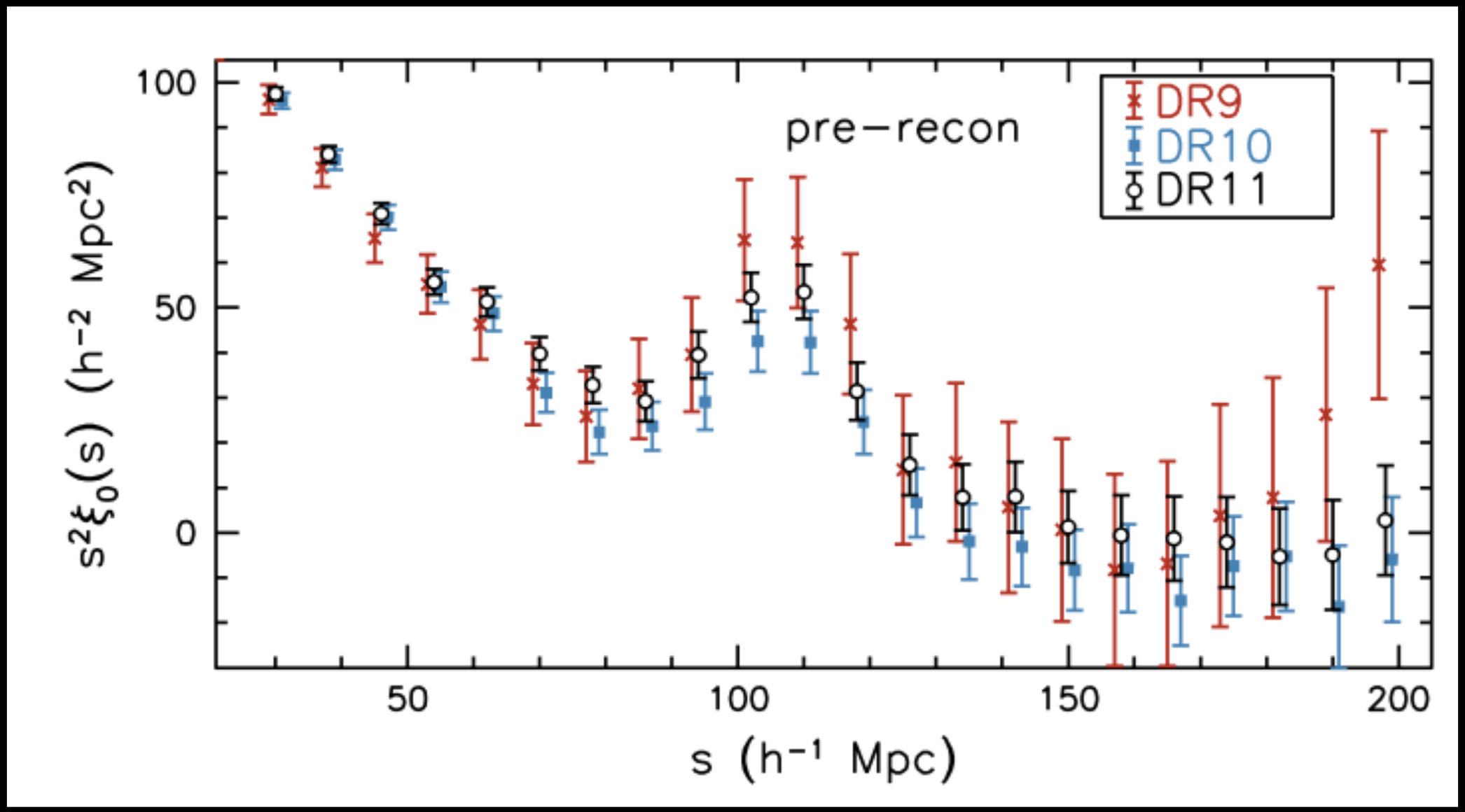


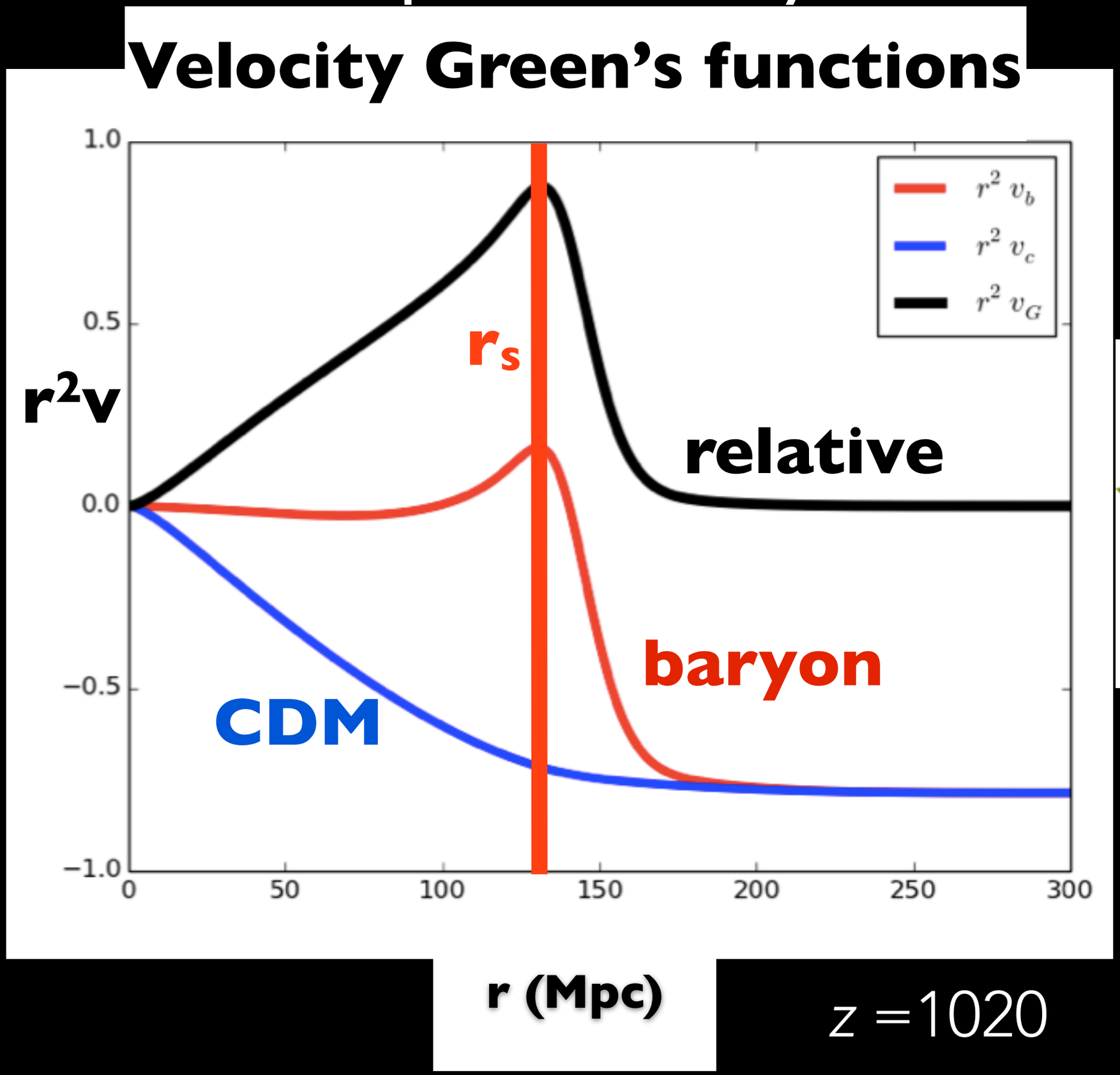
image: http://newscenter.lbl.gov/wp-content/uploads/ruler-cmb-today.jpg

Uses a bump in the galaxy-galaxy correlation function

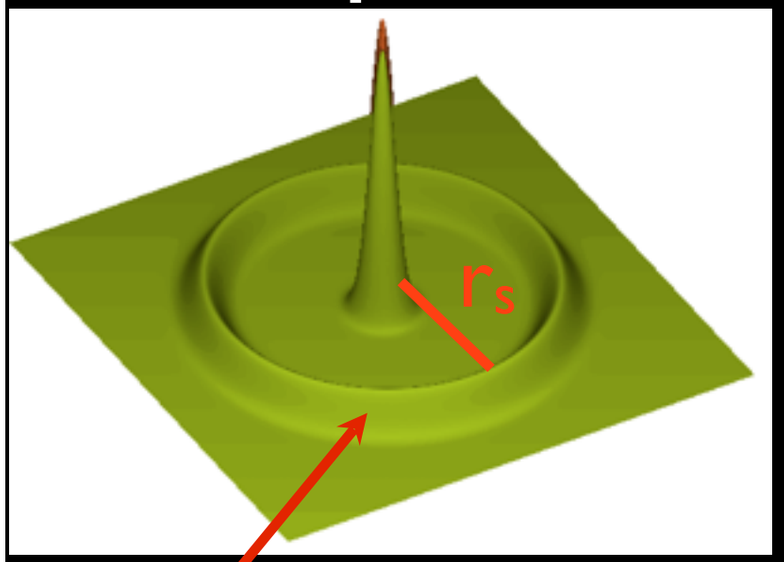


Eisenstein et al. 2005
Cole et al. 2005
Figure: Anderson et al. 2014

BAO also produce baryon-DM relative velocity



Density snapshot



Baryon-photon pulse outgoing

$z = 1020$

Green image: Daniel Eisenstein
Figure: SE2015a
RV effect: Tseliakhovich & Hirata 2010

2. Relative velocity as a possible systematic

Relative velocity is ~10% of halos' circular velocity at z~50

These are luminous red galaxies' progenitors

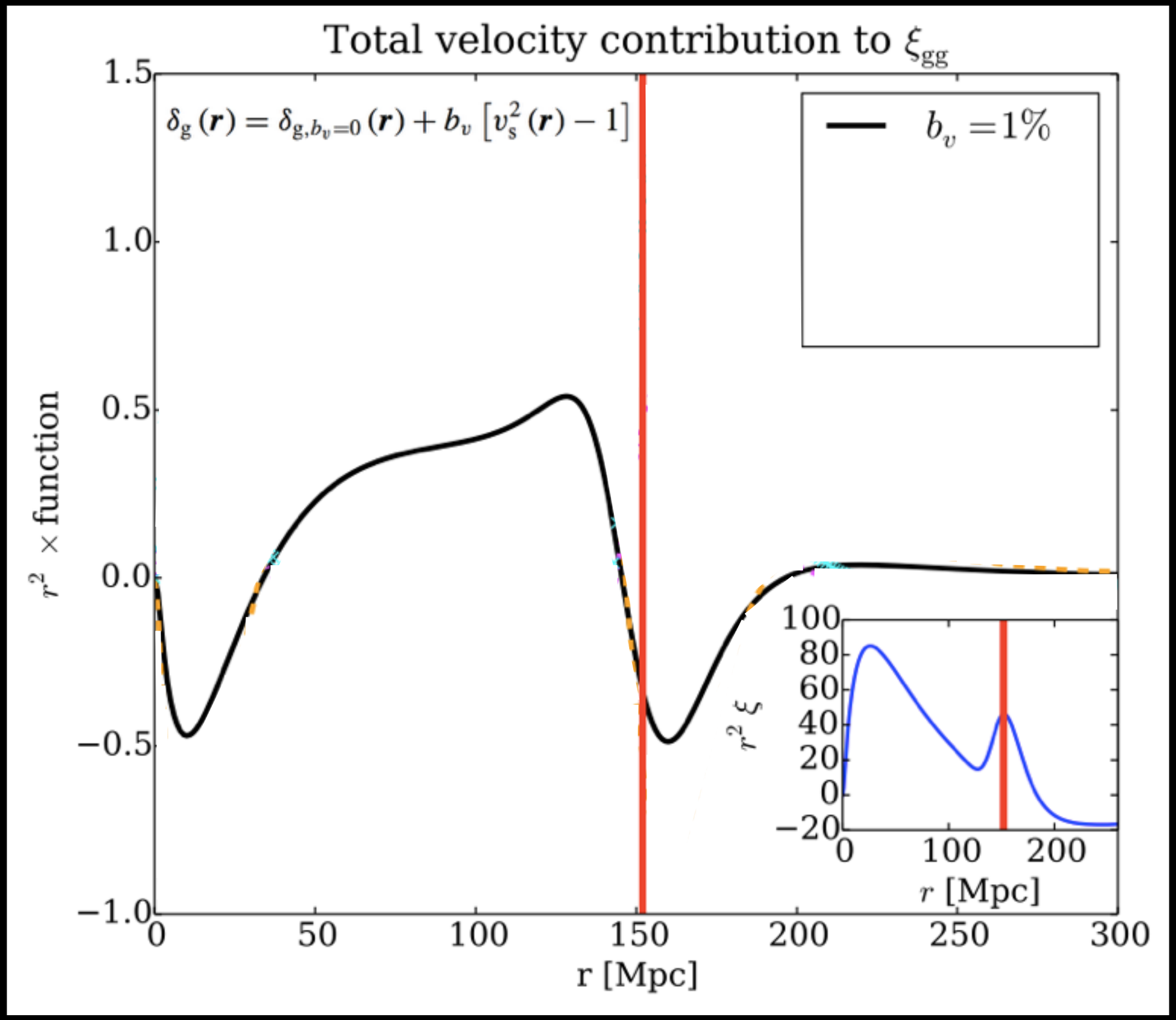
If they have a strong memory, relative velocity could introduce **correlations** on BAO scale

2. Relative velocity as a possible systematic

motivates exploring a galaxy bias model

$$\delta_{\rm g} = b_1 \delta_{\rm m} + b_2 \left[\delta_{\rm m}^2 - \left\langle \delta_{\rm m}^2 \right\rangle\right] + b_v \left[\left(v_{\rm bc}^2/\sigma_{\rm bc}^2 - 1\right)\right]$$

bias model: Yoo Dalal & Seljak 2011



using Green's function at z = 50

Figure: Slepian & Eisenstein 2015a

3. A diagnostic

3-POINT CORRELATION FUNCTION OF GALAXIES

$$\langle \delta_{\rm g}(\vec{s})\delta_{\rm g}(\vec{s}+\vec{r}_1)\delta_{\rm g}(\vec{s}+\vec{r}_2)\rangle = \zeta(r_1, r_2; \hat{r}_1 \cdot \hat{r}_2)$$

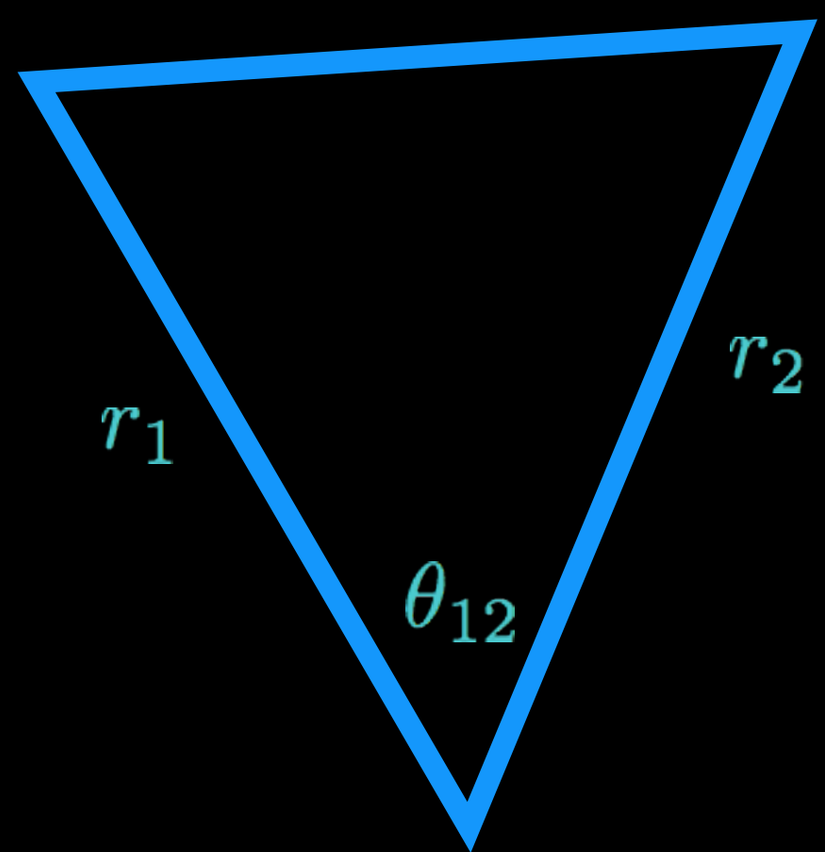
$$\delta_{\rm g} = b_1\delta_{\rm m} + b_2\left[\delta_{\rm m}^2 - \left\langle\delta_{\rm m}^2\right\rangle\right] + b_v\left[\left(v_{\rm bc}^2/\sigma_{\rm bc}^2 - 1\right)\right]$$

3PCF has a term in b_1^3, $b_1^2 b_2$, and b_v

Szapudi 2004
McBride et al. 2011; Nichol et al. 2006
Slepian & Eisenstein 2015b

THE MULTIPOLE BASIS

$$\zeta(r_1, r_2; \hat{r}_1 \cdot \hat{r}_2) = \sum_l \zeta_l(r_1, r_2) P_l(\hat{r}_1 \cdot \hat{r}_2)$$



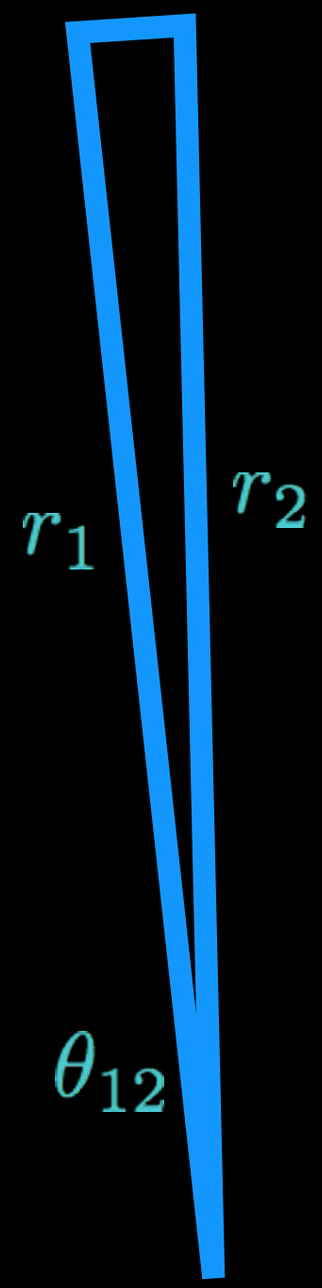
$$P_0(\cos\theta_{12}) = 1$$

$$P_1(\cos\theta_{12}) = \cos\theta_{12}$$

$$P_2(\cos\theta_{12}) = \frac{1}{2}\left(3\cos^2\theta_{12} - 1\right)$$

Szapudi 2004
Slepian & Eisenstein 2015a, b

THE SQUEEZED LIMIT



for perturbation theory to work, no triangle side can be too small

Slepian & Eisenstein 2015a

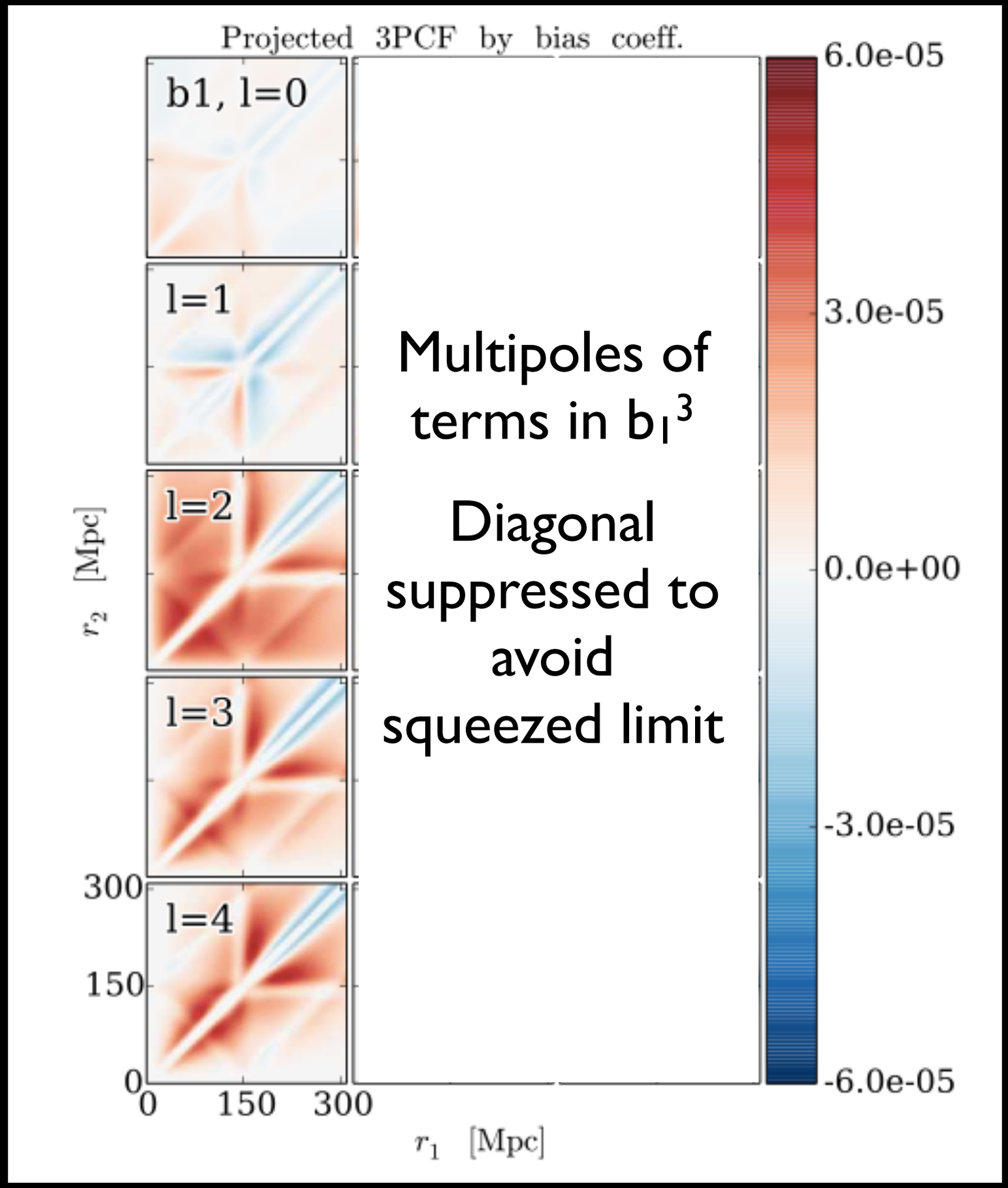


Figure: Slepian & Eisenstein 2015a

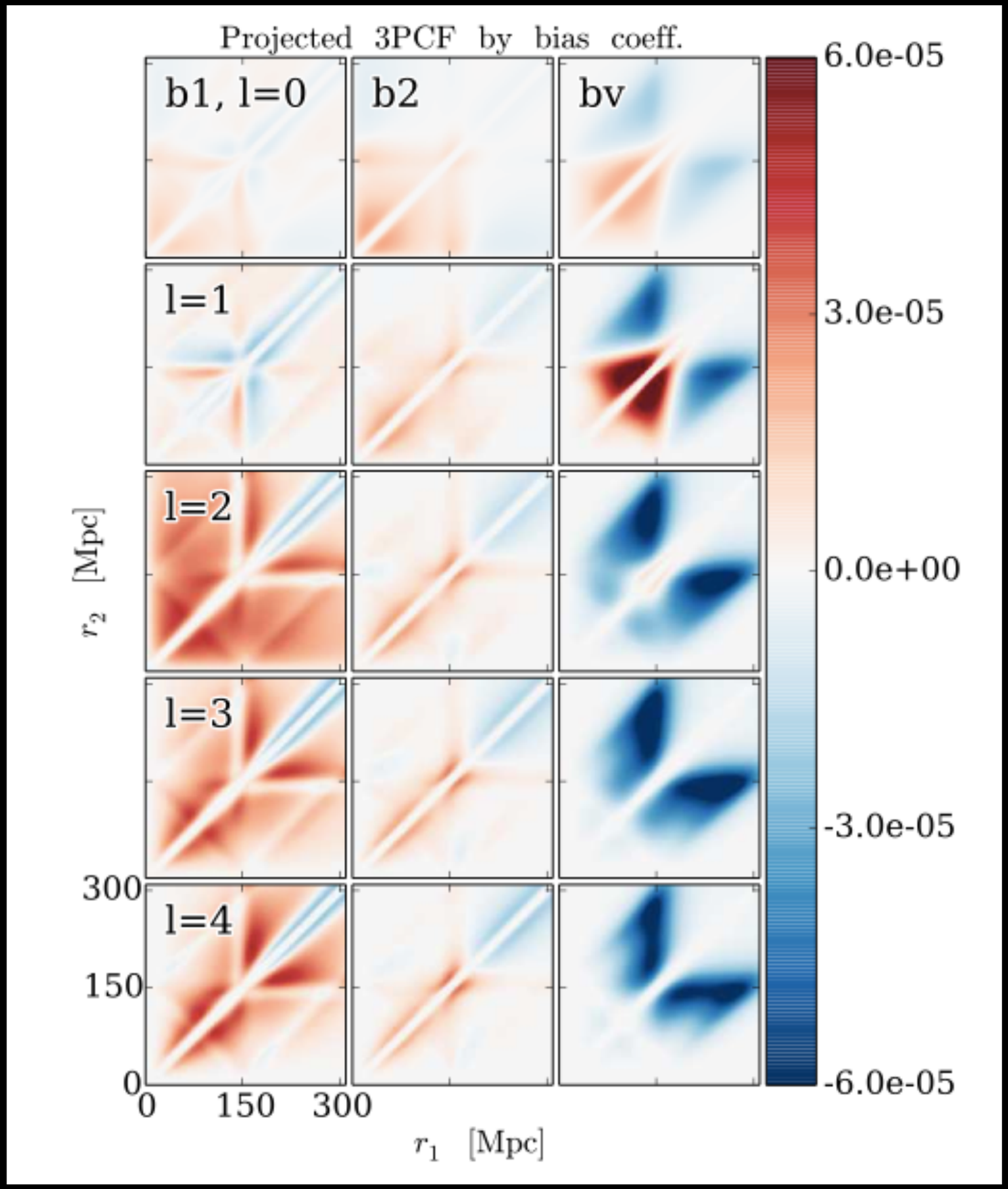


Figure: Slepian & Eisenstein 2015a

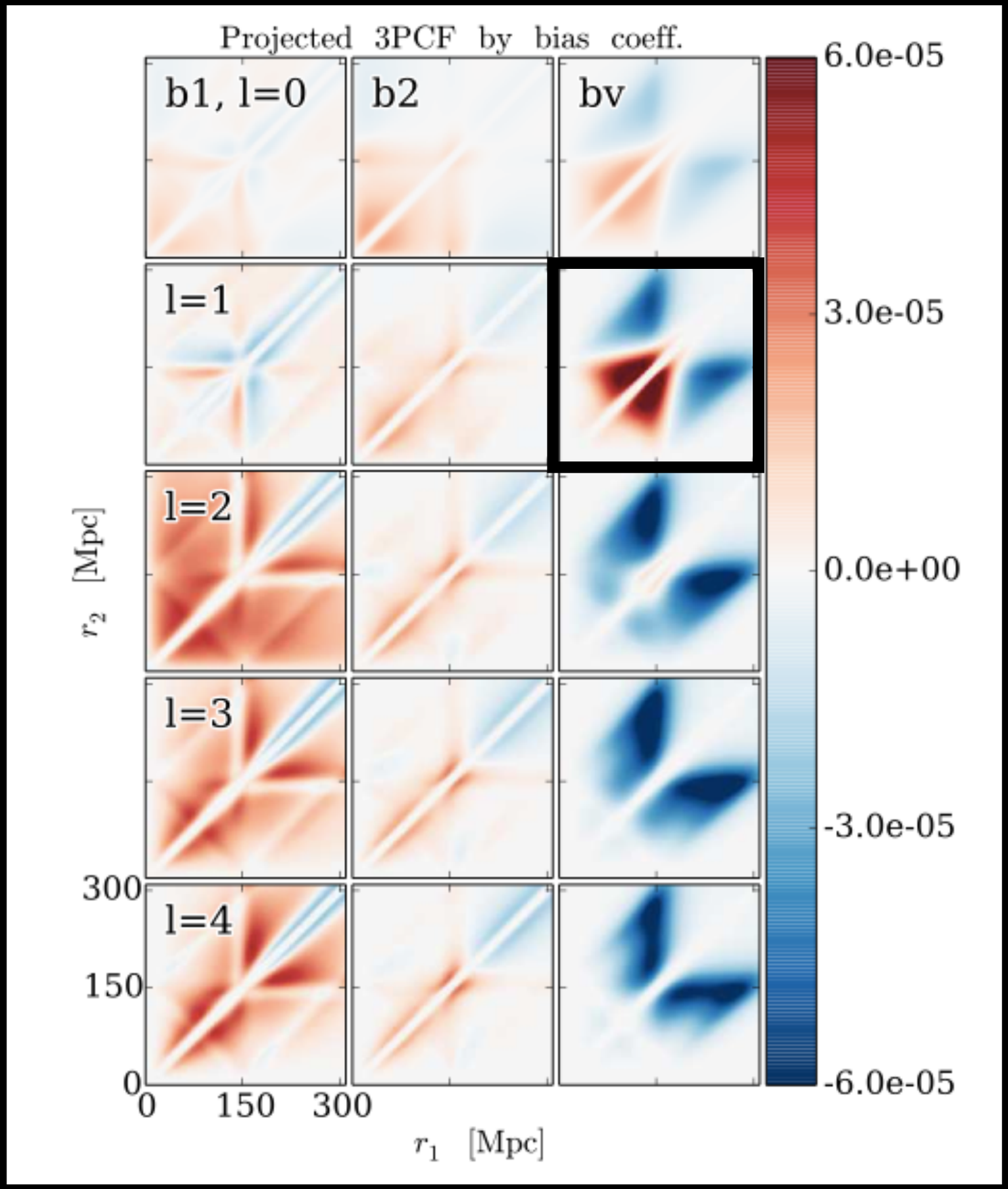
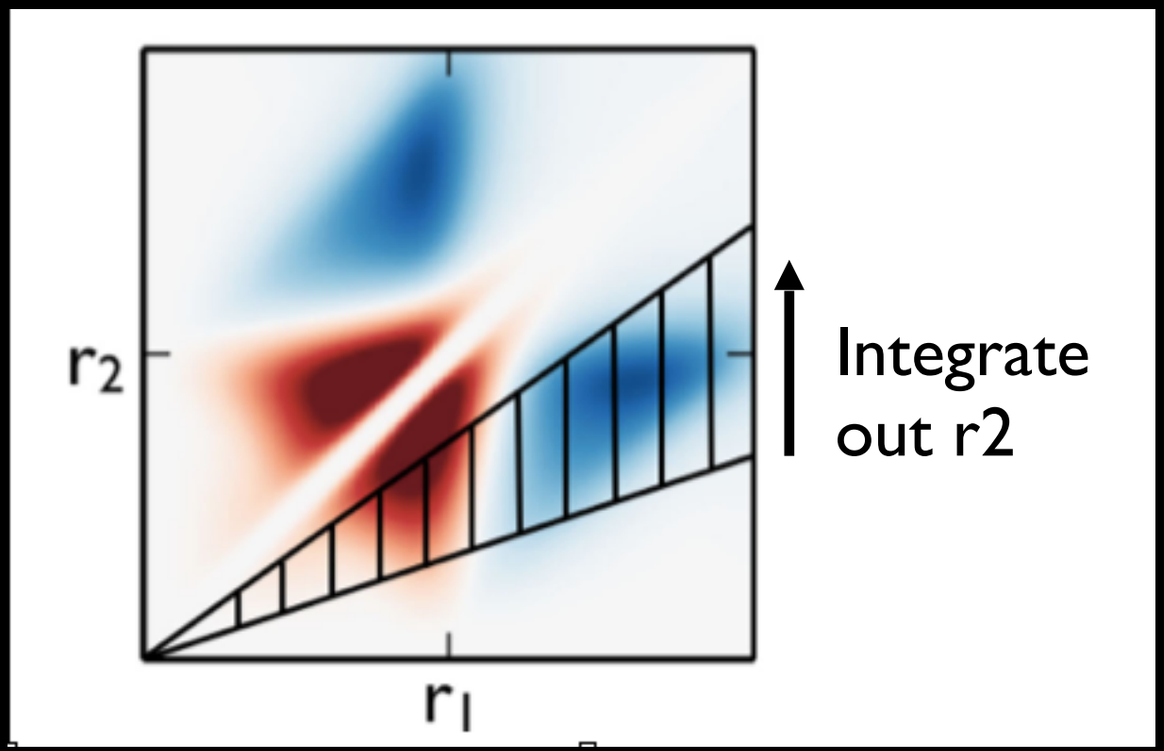
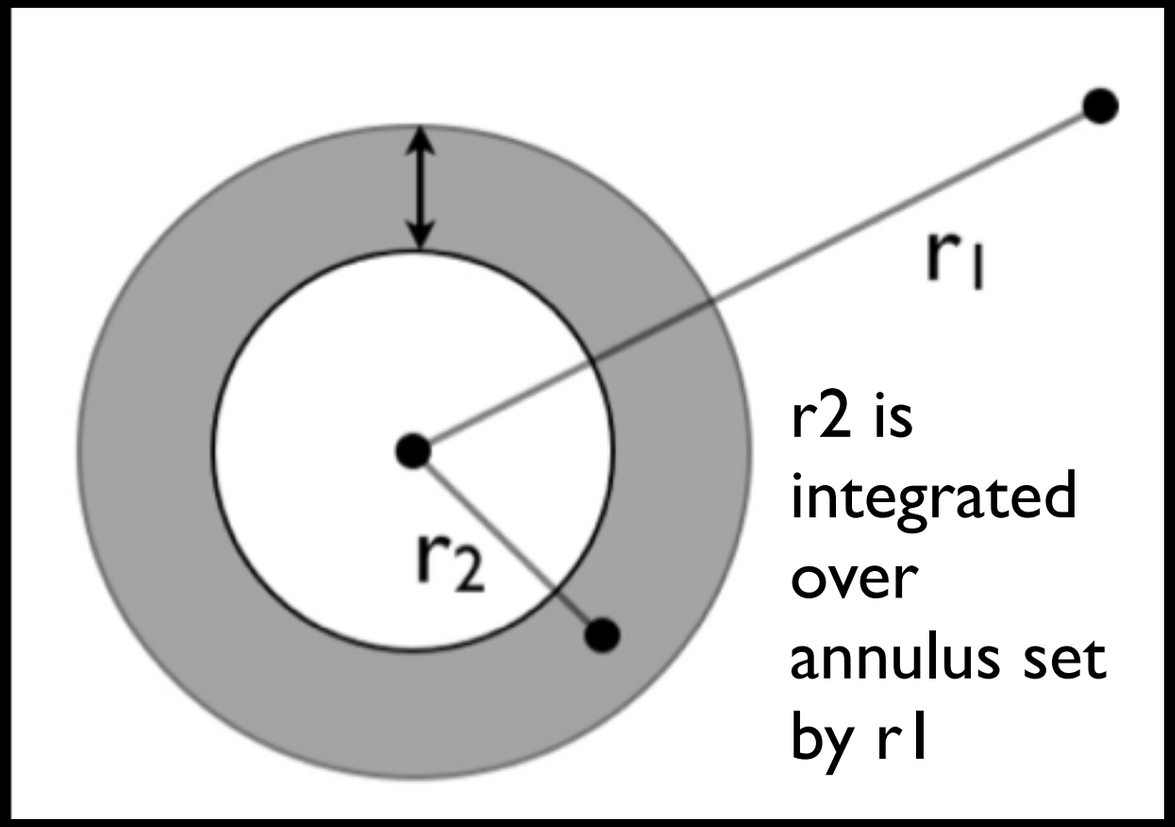


Figure: Slepian & Eisenstein 2015a

COMPRESSION

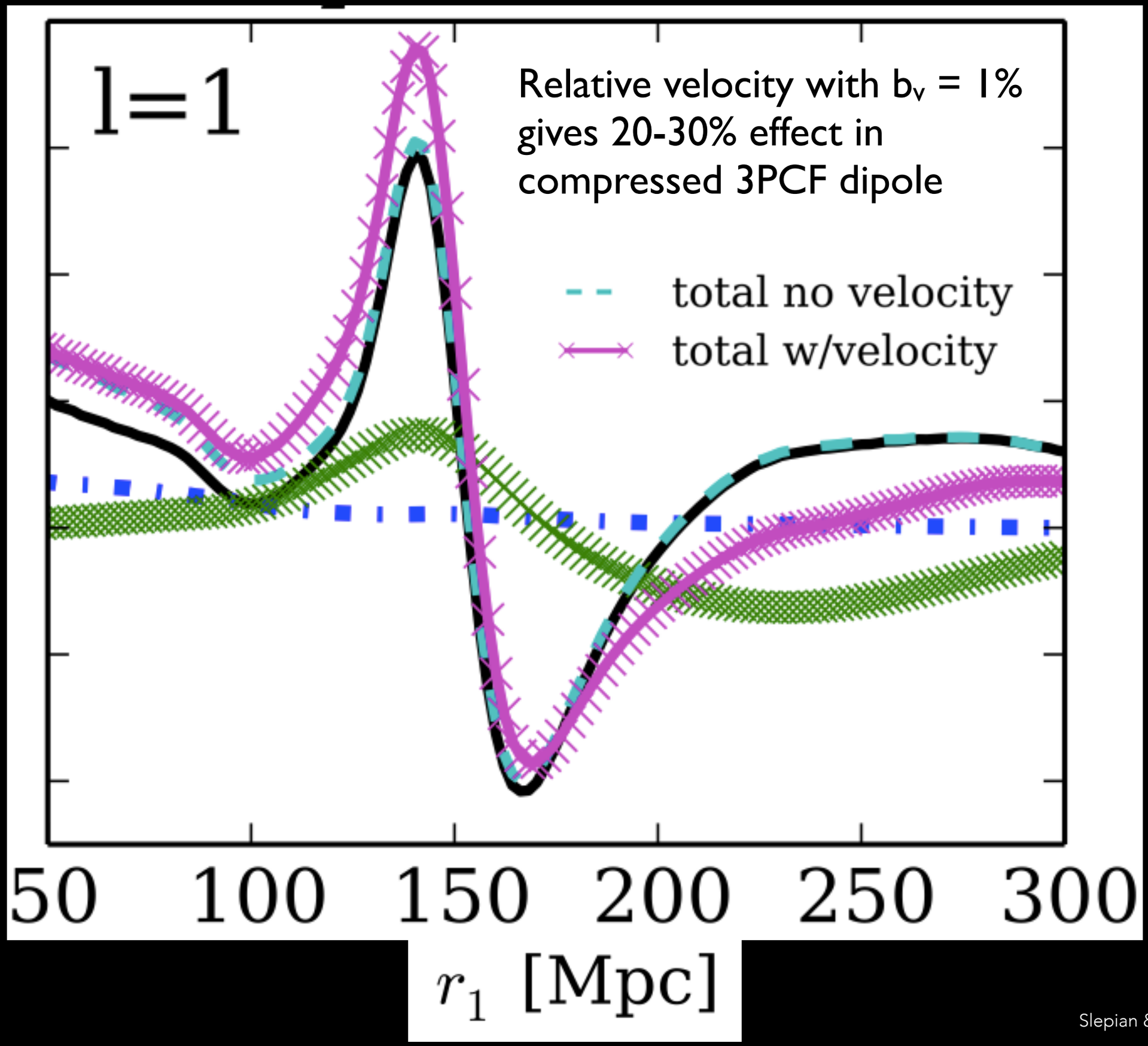




Compression is proportional to

$$\int_{r_1/3}^{2r_1/3} r_2^2 dr_2 \; \zeta_l(r_1, r_2)$$

Slepian & Eisenstein 2015a



Slepian & Eisenstein 2015a

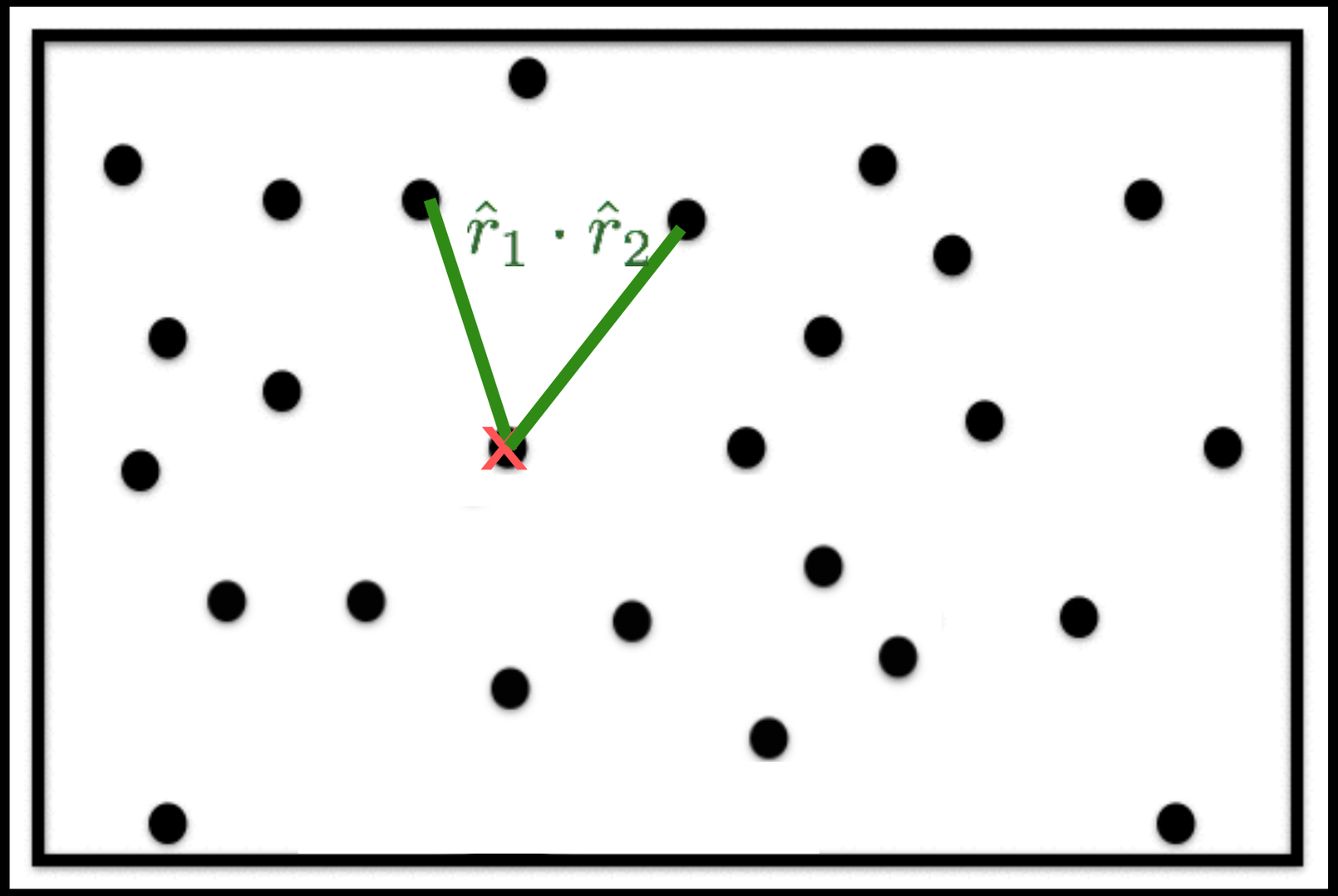
Measuring the 3PCF multipoles should allow b_v to be measured and removed from BAO method

HOW DO WE MEASURE THE 3PCF'S MULTIPOLES?

Compute about a particular galaxy given by **s** first, then average over all galaxies

$$\bar{\hat{\zeta}}_l(r_1, r_2; \vec{s}) =$$

$$\frac{2l+1}{(4\pi)^2} \int d\Omega_1 d\Omega_2 \delta(\vec{s}) \bar{\delta}(r_1; \hat{r}_1; \vec{s}) \bar{\delta}(r_2; \hat{r}_2; \vec{s}) P_l(\hat{r}_1 \cdot \hat{r}_2)$$



looks like order N^2 about **each** galaxy

so overall order N^3

Slepian & Eisenstein 2015b

$$\bar{\hat{\zeta}}_l(r_1, r_2; \vec{s}) =$$
$$\frac{2l+1}{(4\pi)^2} \int d\Omega_1 d\Omega_2 \delta(\vec{s}) \bar{\delta}(r_1; \hat{r}_1; \vec{s}) \bar{\delta}(r_2; \hat{r}_2; \vec{s}) P_l(\hat{r}_1 \cdot \hat{r}_2)$$

SECRET SAUCE

$$P_l(\hat{r}_1 \cdot \hat{r}_2) = \frac{4\pi}{2l+1} \sum_{m=-l}^{l} Y_{lm}(\hat{r}_1) Y^*_{lm}(\hat{r}_2)$$

$$\bar{\hat{\zeta}}_l(r_1, r_2; \vec{s}) = \frac{1}{4\pi} \delta(\vec{s}) \sum_{m=-l}^{l} \int d\Omega_1 \; \bar{\delta}(r_1; \hat{r}_1; \vec{s}) Y_{lm}(\hat{r}_1)$$
$$\times \int d\Omega_2 \; \bar{\delta}(r_2; \hat{r}_2; \vec{s}) Y^*_{lm}(\hat{r}_2)$$

These 2 integrals are the same up to magnitude of r-vector

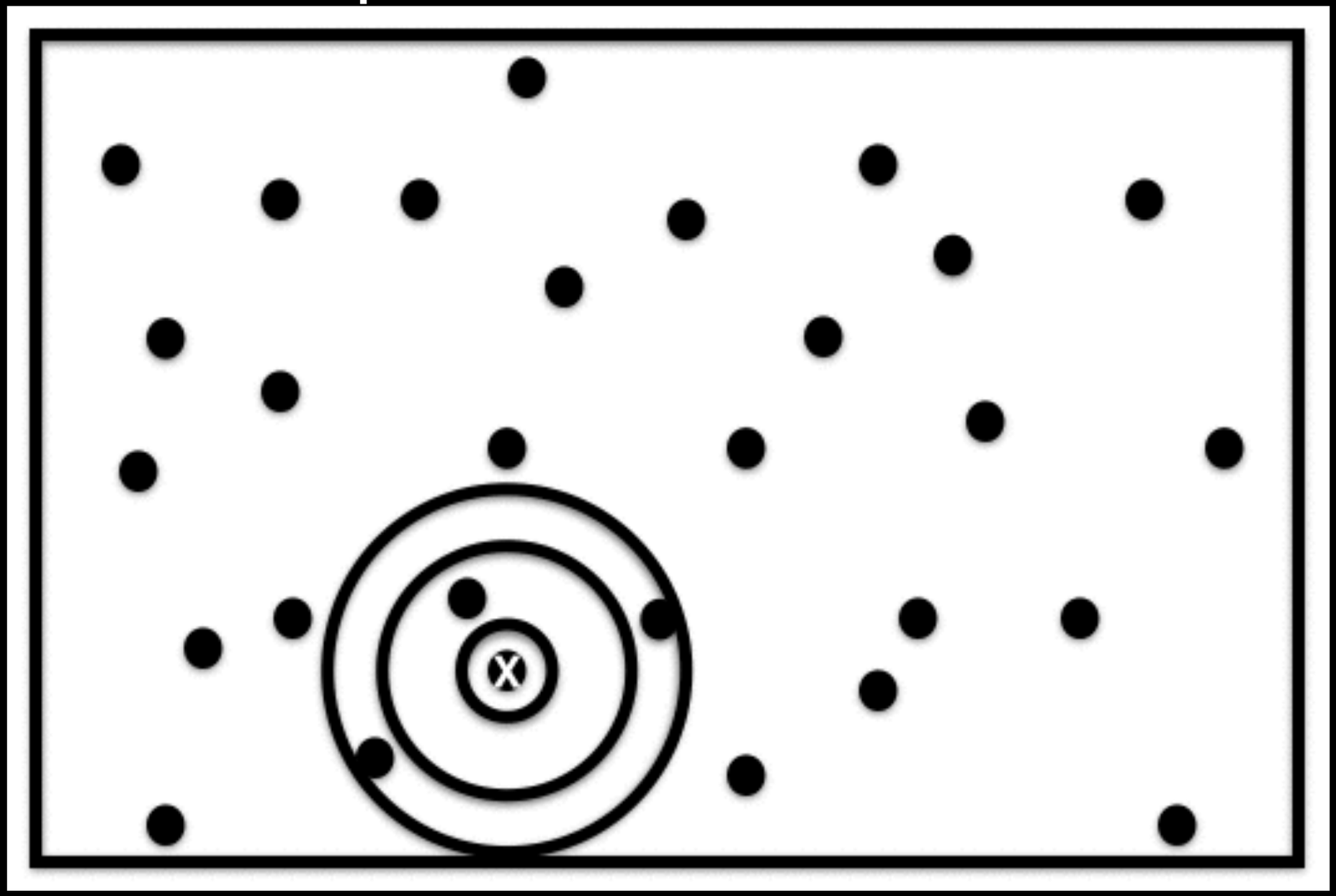
Slepian & Eisenstein 2015b

$$\bar{\hat{\zeta}}_l(r_1, r_2; \vec{s}) = \frac{1}{4\pi}\delta(\vec{s}) \sum_{m=-l}^{l} \int d\Omega_1 \; \bar{\delta}(r_1; \hat{r}_1; \vec{s}) Y_{lm}(\hat{r}_1)$$

$$\times \int \underline{d\Omega_2 \; \bar{\delta}(r_2; \hat{r}_2; \vec{s}) Y^*_{lm}(\hat{r}_2)}$$

$$a_{lm}(r; \vec{s}) = \sum_{\text{gals } j \text{ in bin}} Y^*_{lm}(\hat{r}_j)$$

Around each galaxy, compute a_{lm} in spherical shells/radial bins



$$a_{lm}(r;\vec{s}) = \sum_{\text{gals } j \text{ in bin}} Y^*_{lm}(\hat{r}_j)$$

NOW ORDER N ABOUT EACH GALAXY

Slepian & Eisenstein 2015b

COMPUTING THE A_{LM}

$$a_{lm}(r;\vec{s}) = \sum_{\text{gals } j \text{ in bin}} Y^*_{lm}(\hat{r}_j)$$

$$Y_{1-1} = \frac{1}{2}\sqrt{\frac{3}{2\pi}} \cdot \frac{x - iy}{r}$$

Pre-compute powers of x/r, y/r, z/r

Works well because don't need many multipoles

SPEED OF THE ALGORITHM

500X FASTER THAN A TRIPLET COUNT

ONLY 6X SLOWER THAN COMPUTING A 2-POINT FUNCTION

How do we now **fit parameters** to the multipoles?

Need the **covariance matrix**

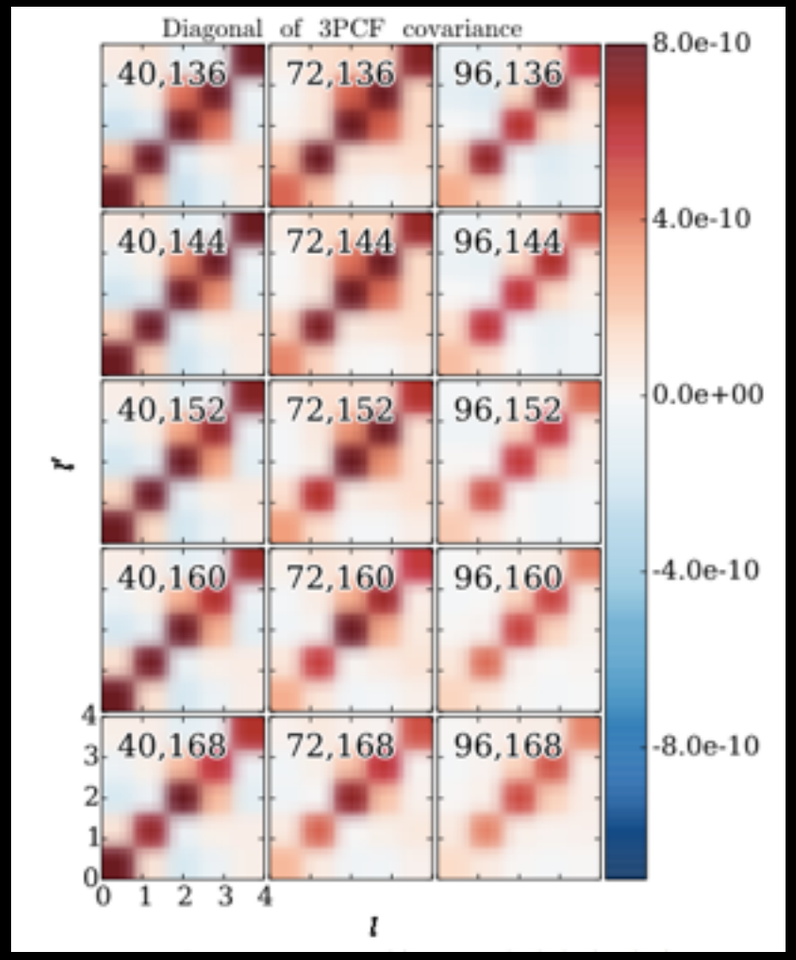
Turned out to be **hard**

Previous state of the art required 6-D integral, and not clear how to project onto multipoles

Previous state of the art: Szapudi 2001

COMPUTING THE COVARIANCE

$$\mathrm{Cov}_{ll'}(r_1, r_2; r_1', r_2') = \frac{4\pi}{V}(2l+1)(2l'+1)(-1)^{l+l'}$$
$$\times \int r^2 dr \sum_{l_2} (2l_2+1) \begin{pmatrix} l & l' & l_2 \\ 0 & 0 & 0 \end{pmatrix}^2$$
$$\times \Big\{ (-1)^{l_2} \xi_0(r) \Big[f_{l_2 ll'}(r; r_1, r_1') f_{l_2 ll'}(r; r_2, r_2')$$
$$+ f_{l_2 ll'}(r; r_2, r_1') f_{l_2 ll'}(r; r_1, r_2') \Big] + (-1)^{(l+l'+l_2)/2}$$
$$\times \Big[f_{ll}(r; r_1) f_{l'l'}(r; r_1') f_{l_2 ll'}(r; r_2, r_2')$$
$$+ f_{ll}(r; r_1) f_{l'l'}(r; r_2') f_{l_2 ll'}(r; r_2, r_1')$$
$$+ f_{ll}(r; r_2) f_{l'l'}(r; r_1') f_{l_2 ll'}(r; r_1, r_2')$$
$$+ f_{ll}(r; r_2) f_{l'l'}(r; r_2') f_{l_2 ll'}(r; r_1, r_1') \Big] \Big\}.$$



Slepian & Eisenstein 2015b

Assumes density field is Gaussian Random Field and neglects survey boundaries

Converted a linked 9-D integral into **products of 2-D** ones using techniques originally developed for nuclear physics

$$f_{ll}(r; r_1) = \int \frac{k^2 dk}{2\pi^2} P(k) j_l(kr_1) j_l(kr)$$

and

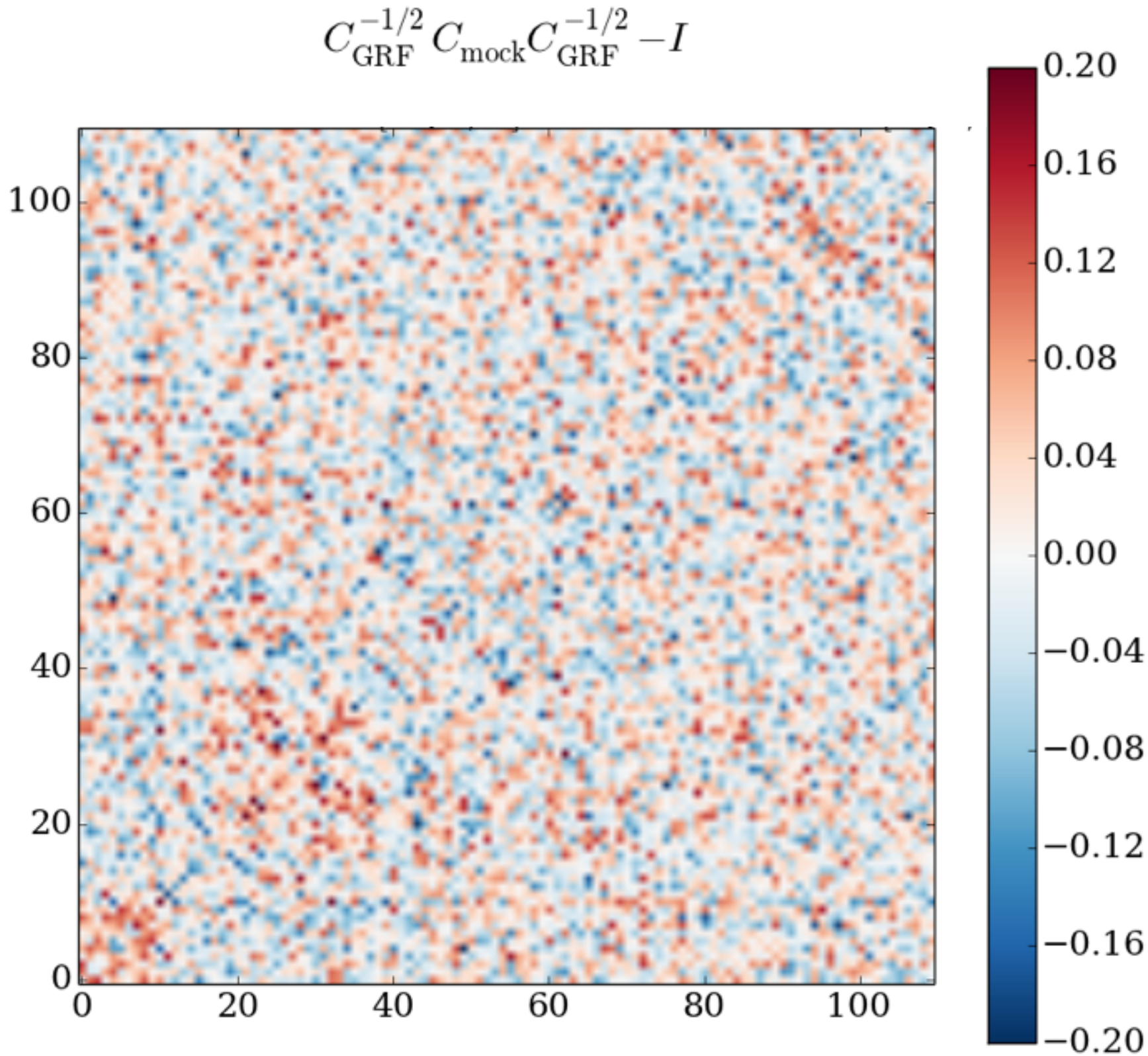
$$f_{l_2 ll'}(r; r_1, r_1') = \int \frac{k^2 dk}{2\pi^2} P(k) j_l(kr_1) j_{l'}(kr_1') j_{l_2}(kr)$$

TESTING THE COVARIANCE

Using 299 DR12 mock catalogs (PATCHY, Kitaura et al. 2015), compute empirical covariance

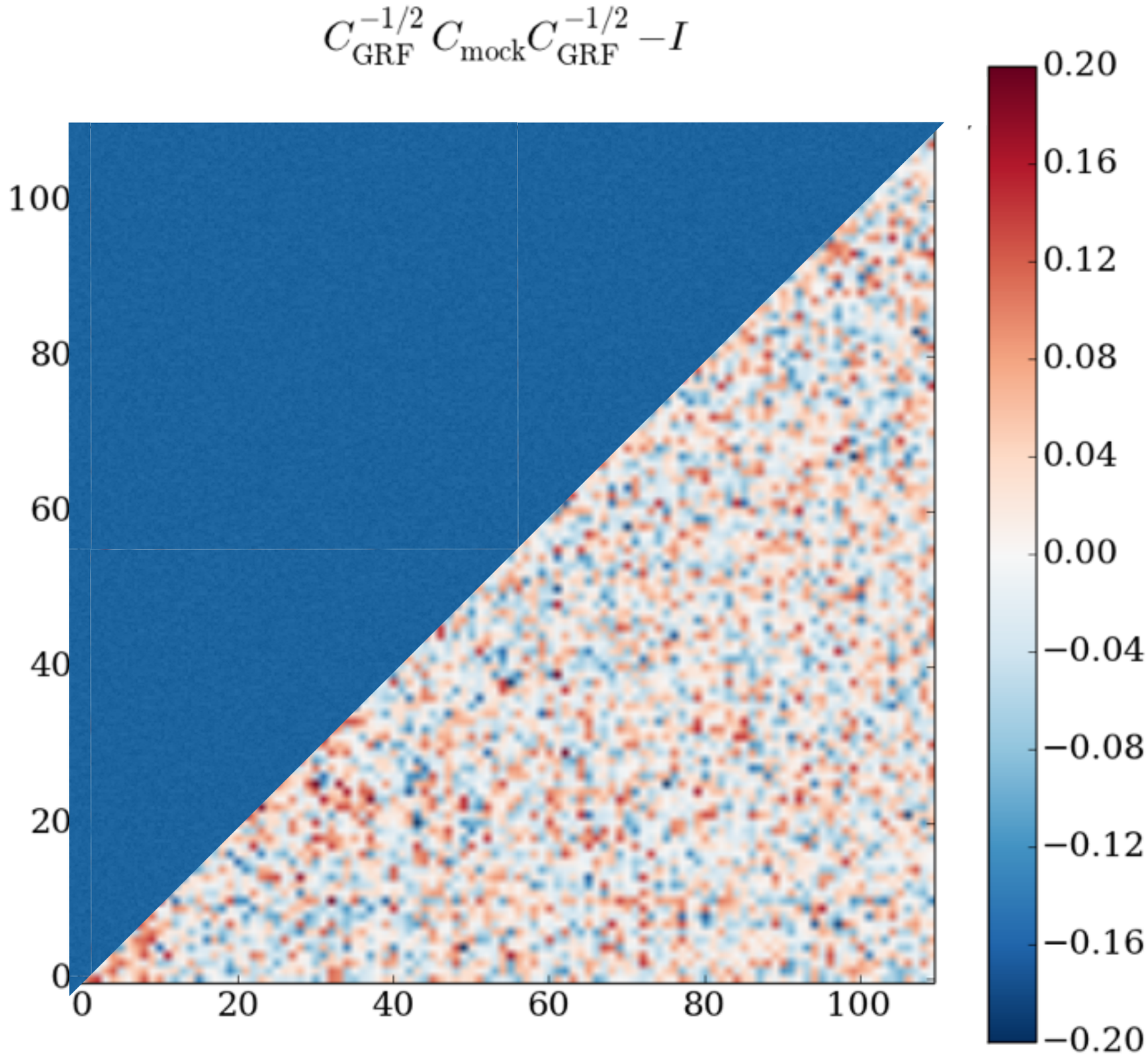
Test: apply inverse of analytic (GRF) covariance we computed to empirical covariance

Subtract identity: should get random noise



Mean is 0.6%, RMS is 6%

Slepian et al. 2015



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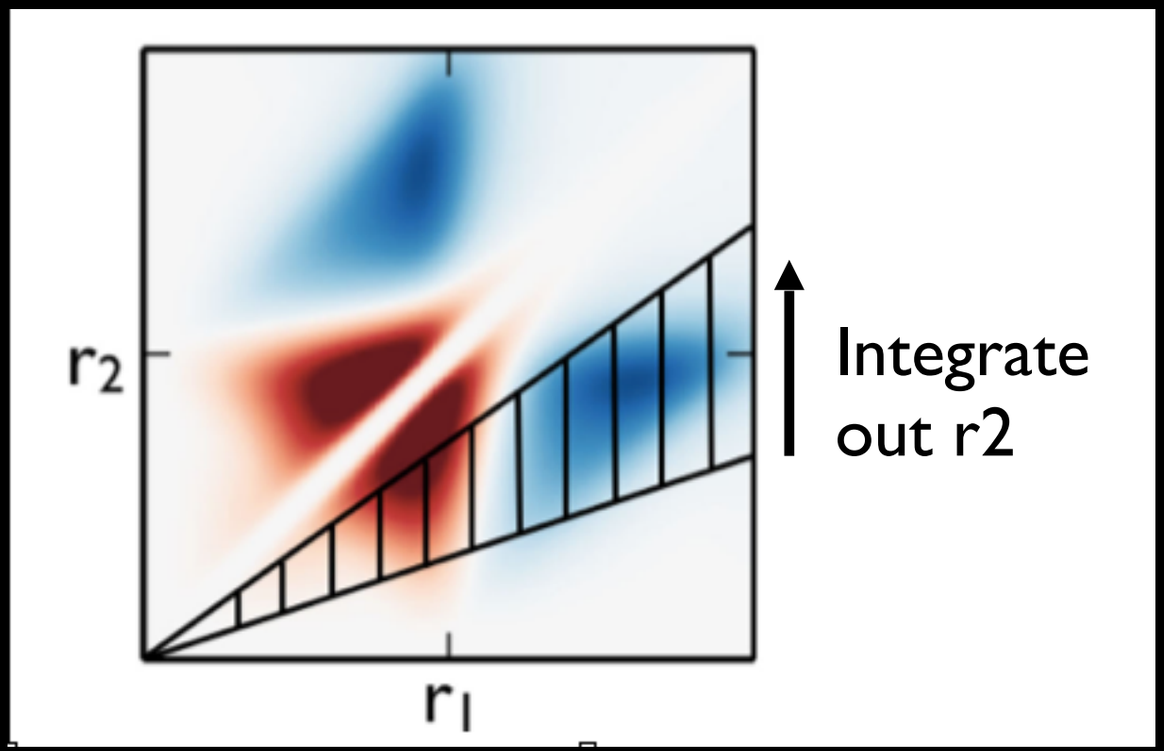
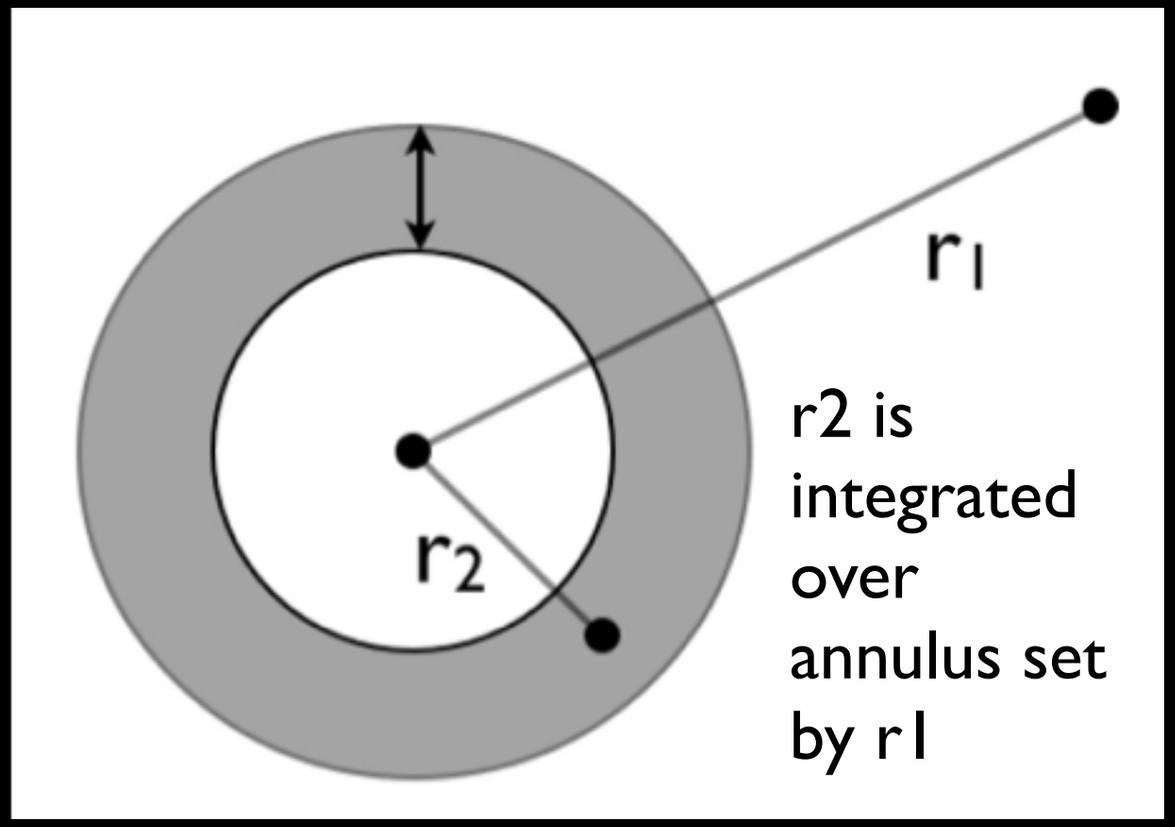
Slepian et al. 2015

NOW FOR THE MOCKS . . .

COMPRESSION



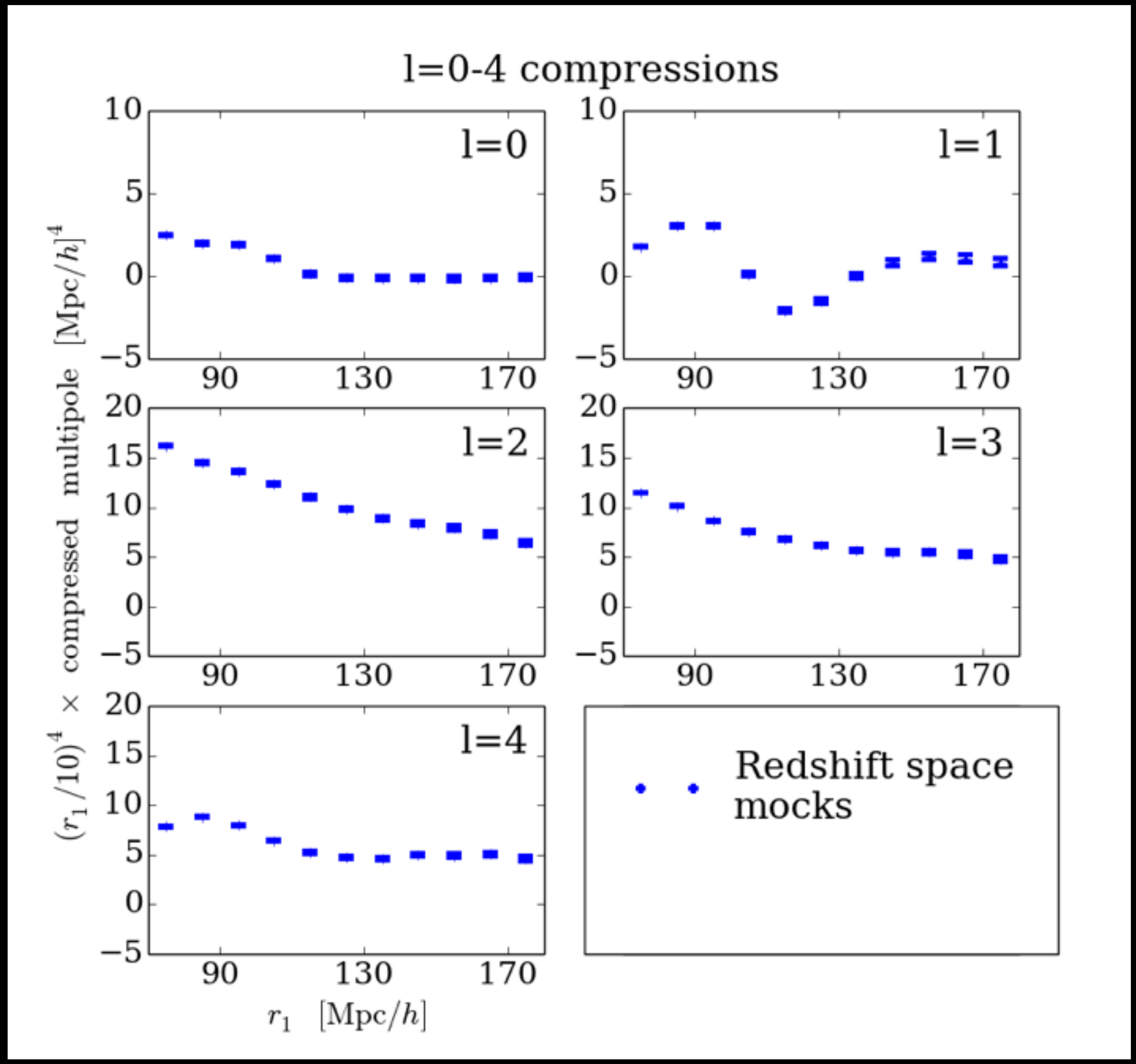


Compression is proportional to

$$\int_{r_1/3}^{2r_1/3} r_2^2 dr_2 \; \zeta_l(r_1, r_2)$$

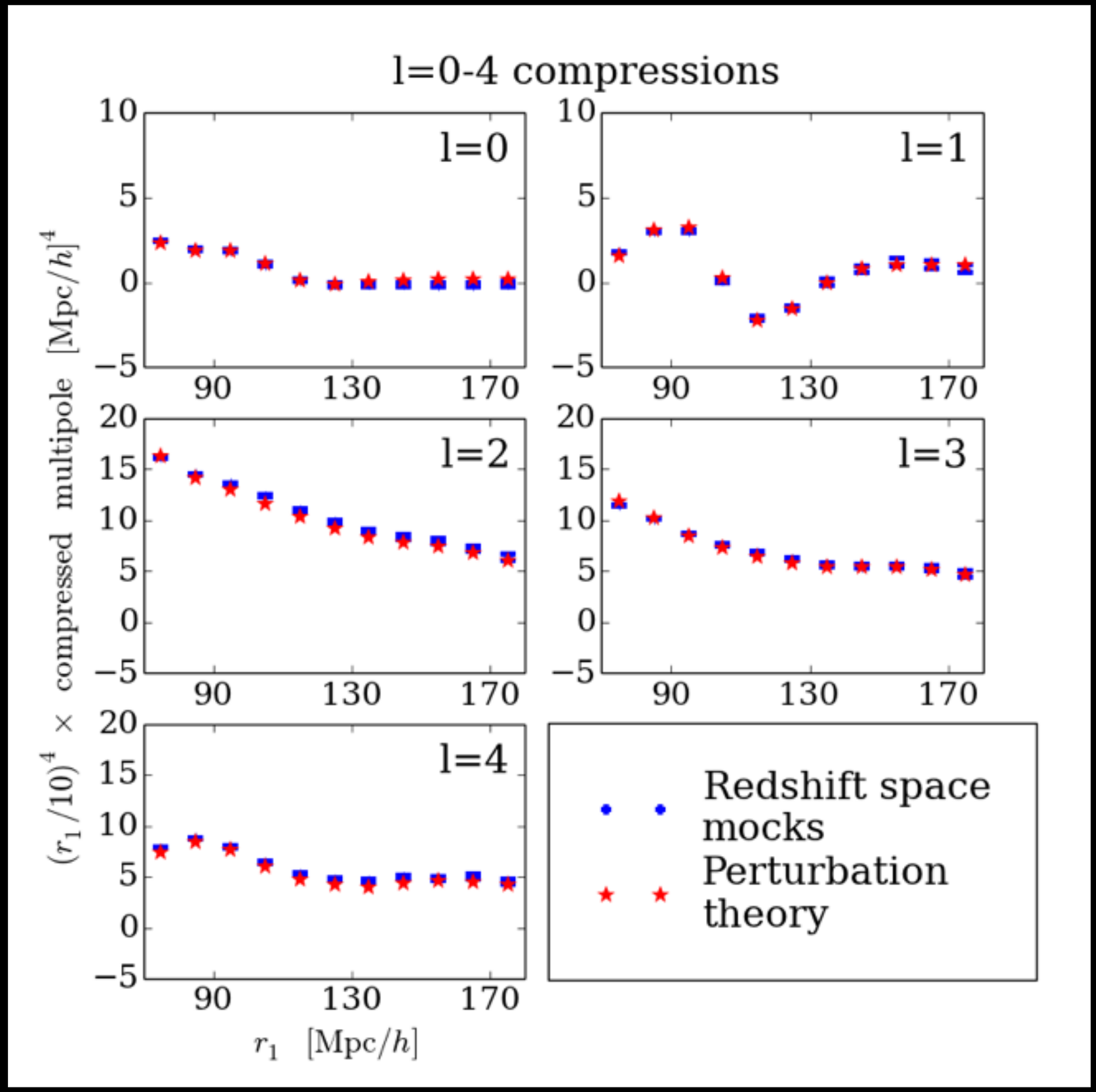
Slepian & Eisenstein 2015a

PATCHY MOCK RESULTS



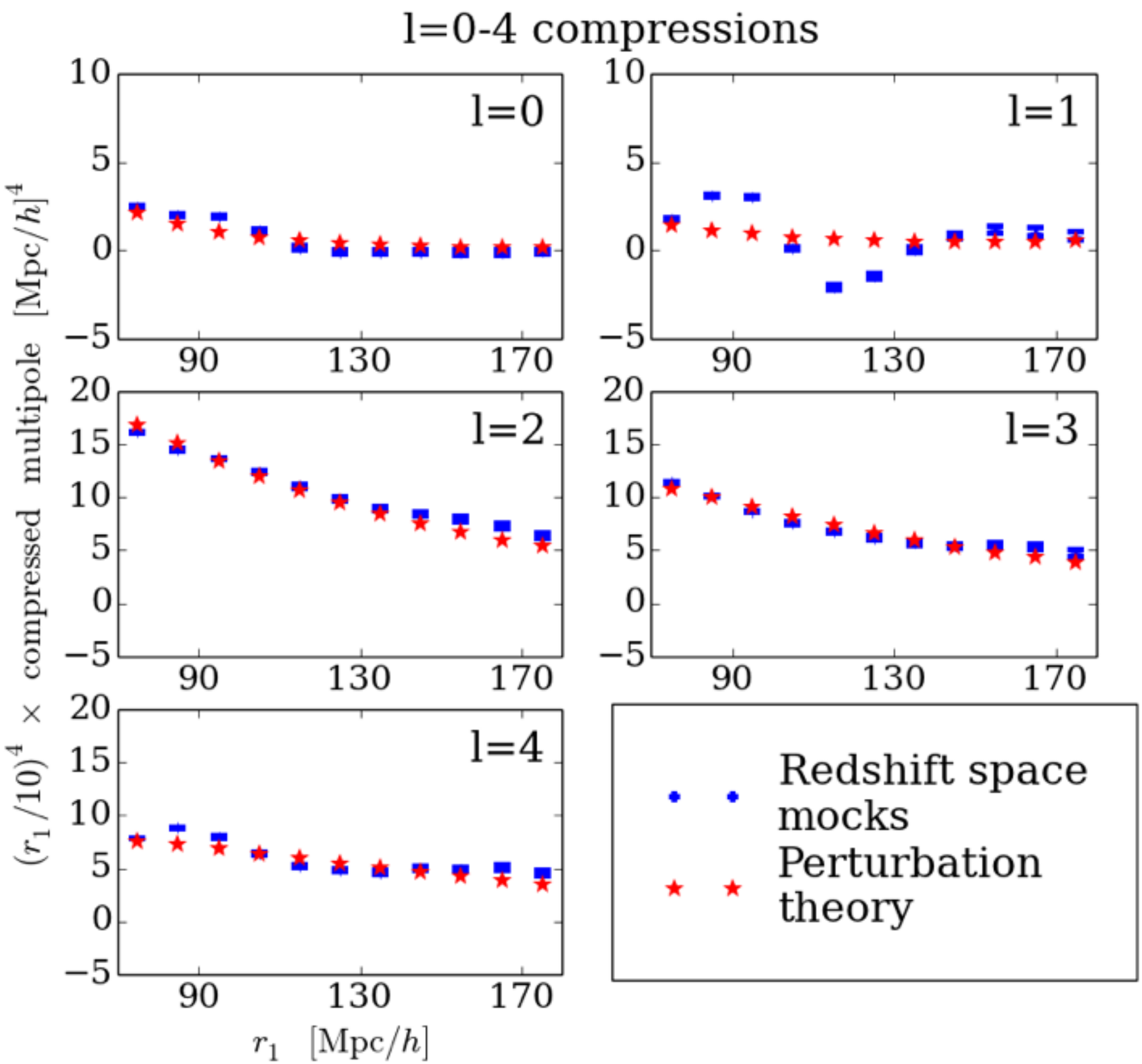
Slepian et al. 2015

PATCHY MOCK RESULTS



Slepian et al. 2015

MOCKS FIT WITHOUT BAO



$\Delta\chi^2$ is 3234 on 107 degrees of freedom: 57σ preference for BAO

Slepian et al. 2015

NOW FOR THE DATA

Apply our approach to DR12 BOSS CMASS sample

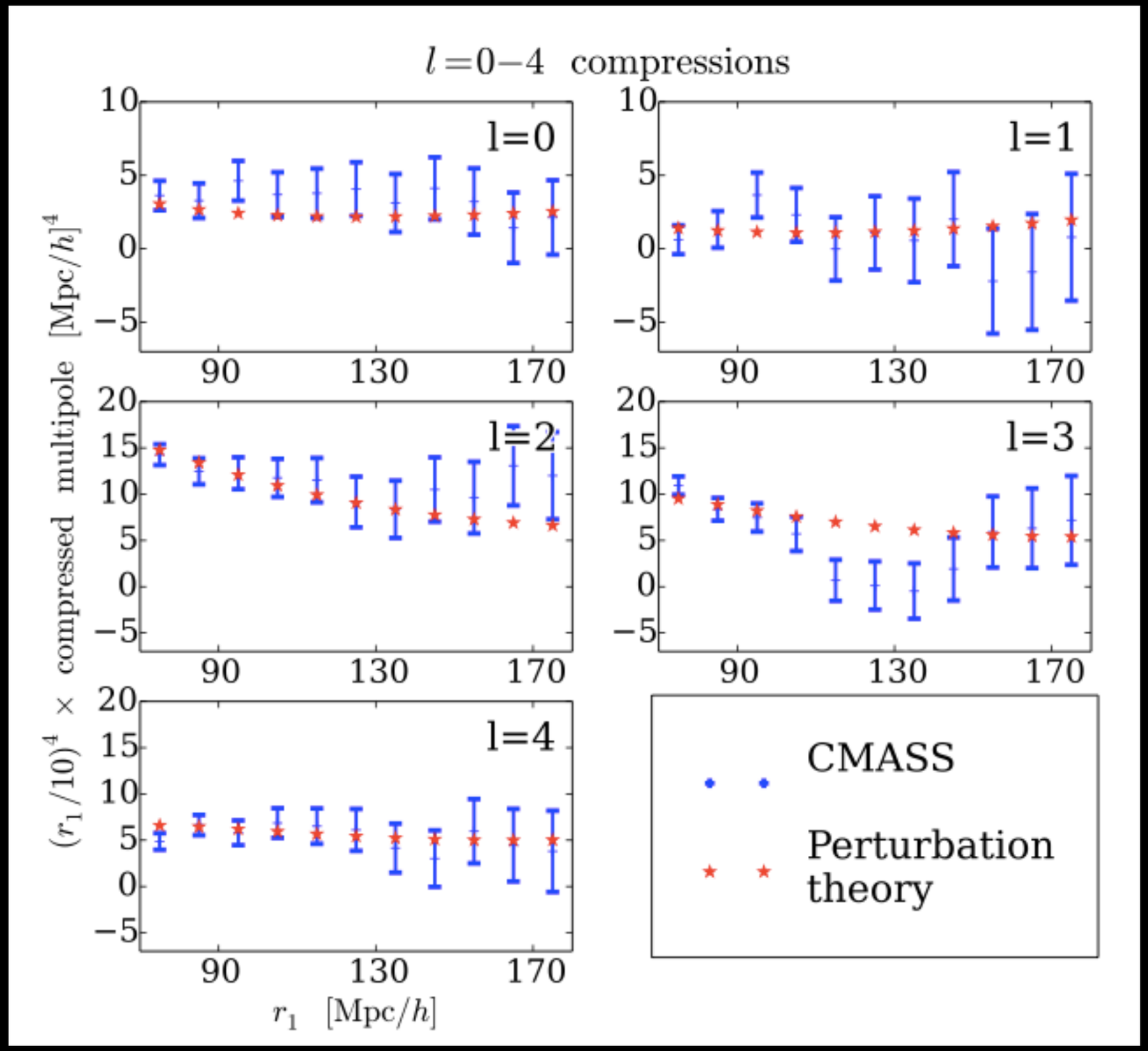
CMASS is color-selected
$0.43 < z < 0.7$

777, 202 galaxies over 9,493 sq. deg.

Completed 2014

Alam et al. 2015
Reid et al. 2016

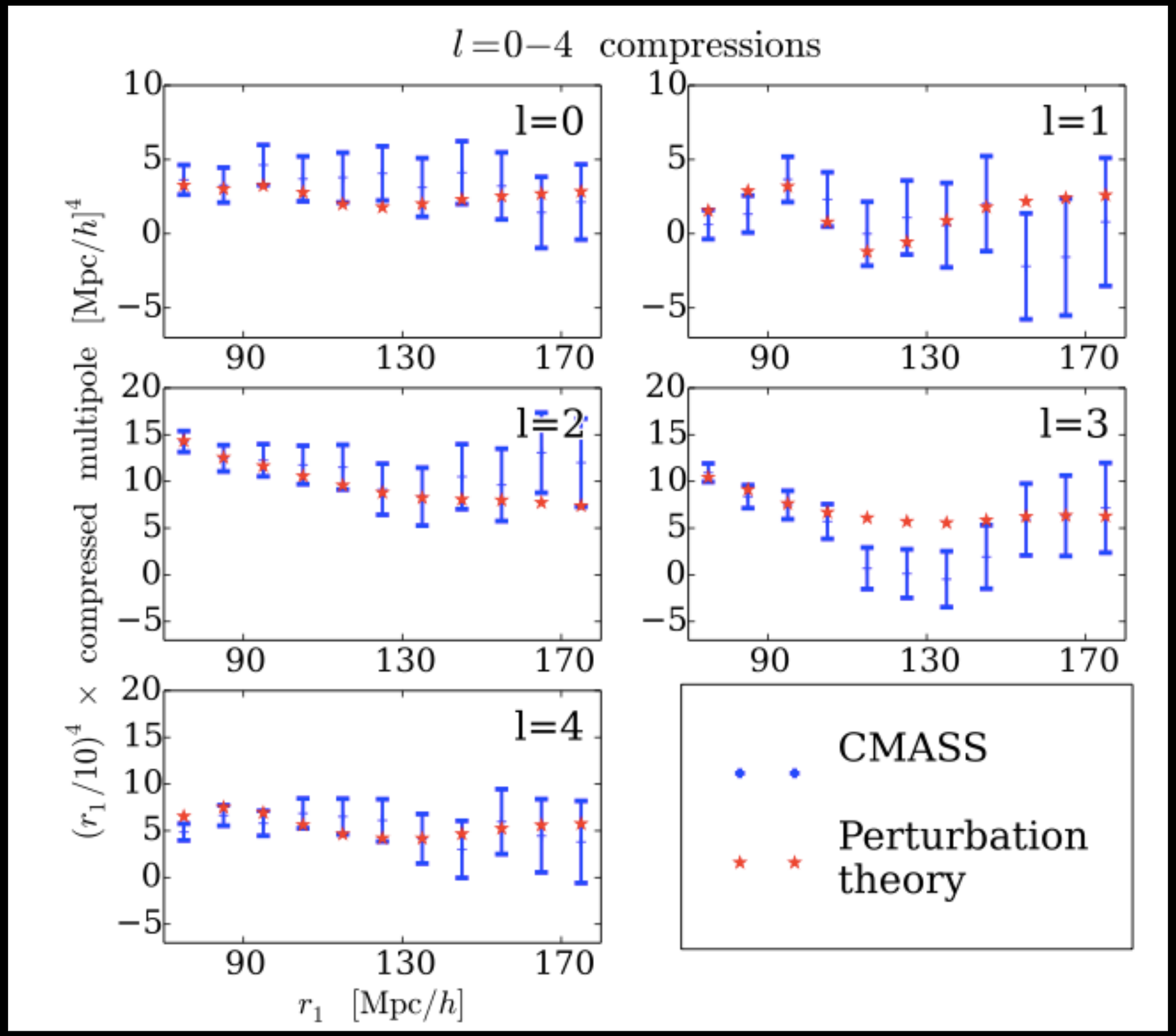
CMASS: FIT WITHOUT BAO



Error bars are diagonal of covariance matrix

Slepian et al. 2015

CMASS: FIT WITH BAO



Slepian et al. 2015

WE FIND

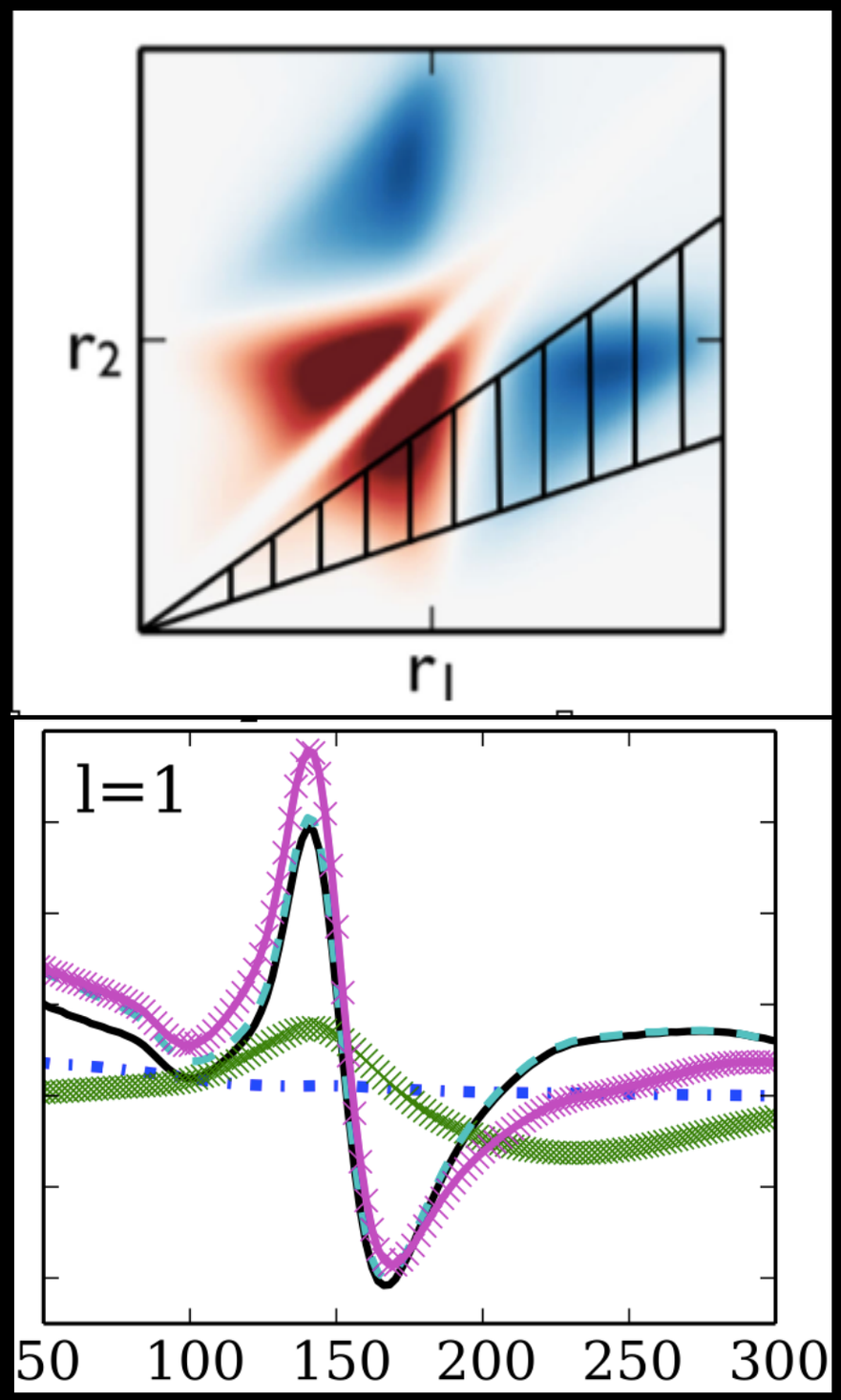
$\Delta\chi^2$ of 7.58 on 107 degrees of freedom, meaning 2.8σ preference for BAO

From scaling mocks, this is plausible

Refinements are underway

Slepian et al. 2015

RETURNING TO THE RELATIVE VELOCITY



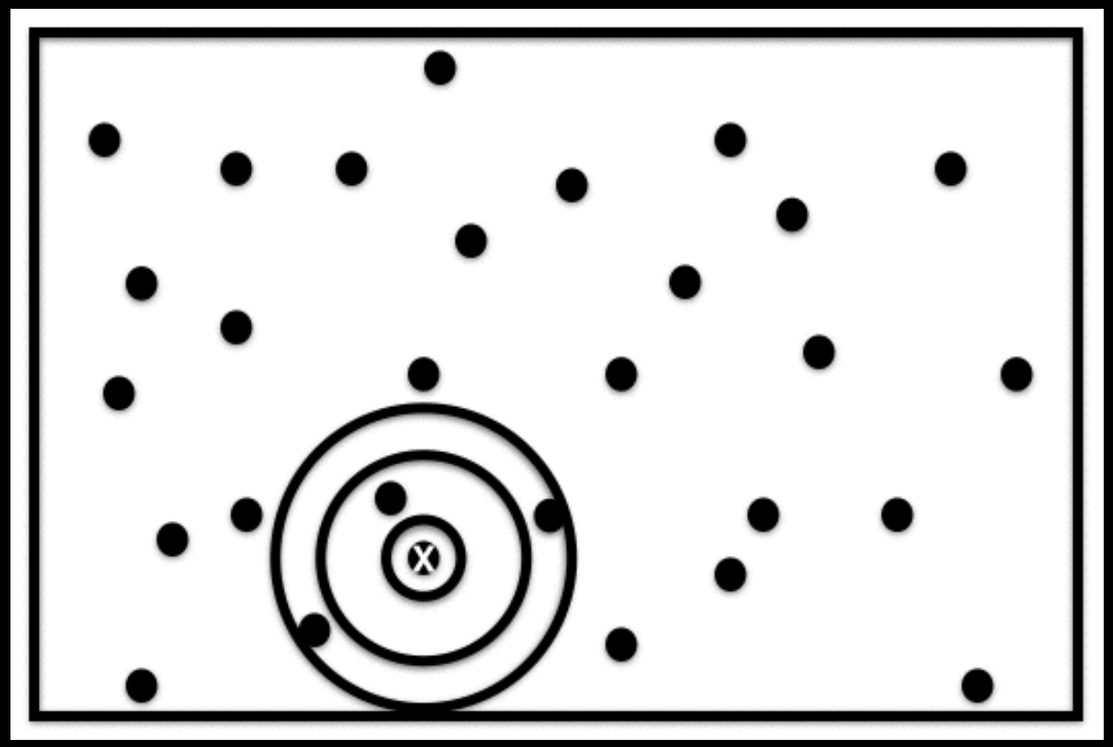
This year, thesis will use our templates to place constraint on RV

Constraining this systematic vital for DESI to reach desired precision

FURTHER APPLICATIONS TO DESI

Extract BAO information from 3PCF

Use Fourier version of algorithm (Slepian & Eisenstein 2015c)



FURTHER APPLICATIONS

Constrain Primordial Non-Gaussianity using the 3PCF + N-body sims. or EFT of LSS

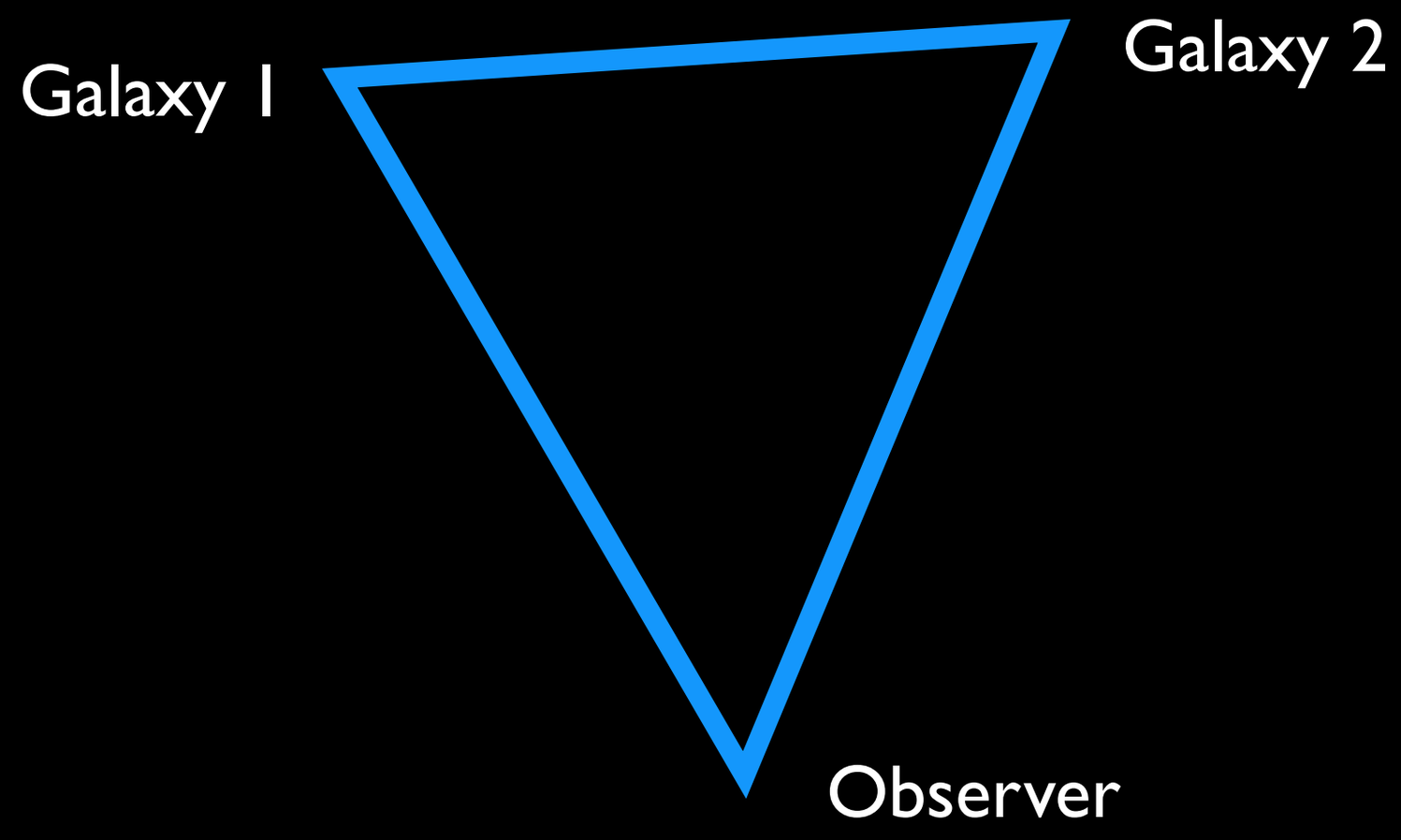
Examine redshift space distortions in the 3pcf in our multipole framework to test GR or measure growth rate

LSST, DES/DECaLS: measure projected 3PCF, optimal for photometric surveys (Slepian & Eisenstein 2015b shows how)

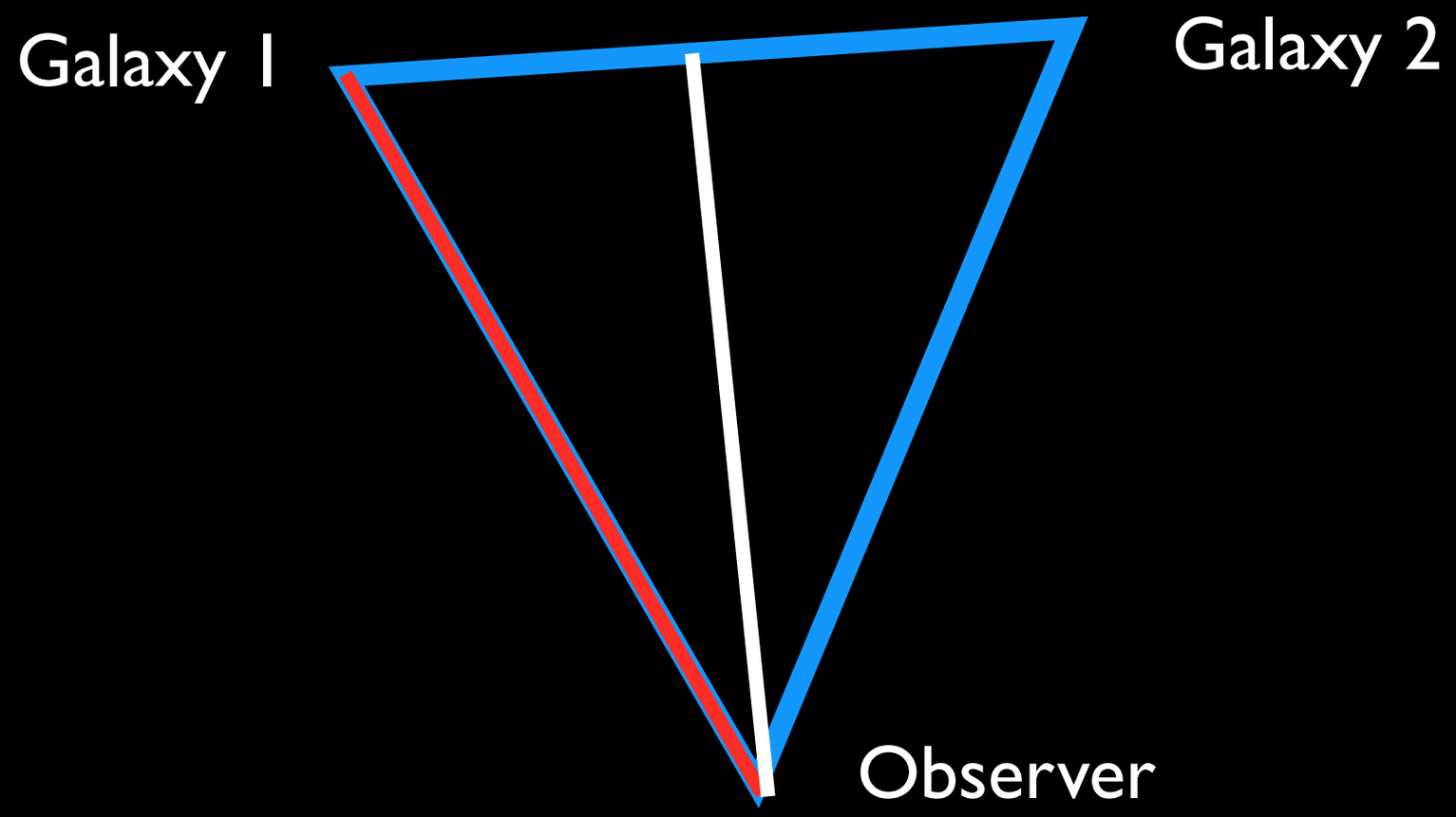
THE ANISOTROPIC 2PCF

Using Fourier transforms for this previously required single line of sight to survey

But geometry is just like 3PCF



THE ANISOTROPIC 2PCF



We show how to use red line of sight—i.e. to one pair member—with FTs (SE2015c)

Better: angle bisector (white) with FTs: Slepian & Eisenstein 2015e

CONCLUSIONS

1] Baryon-dark matter relative velocity can systematically bias BAO

2] Signature in 3PCF that should allow detection

3] Reformulation of 3PCF: transformational speed increase, simple handling of covariance

4] Preliminary results from BOSS using this framework; 2.6 sigma BAO feature

5] Anisotropic 2PCF: combines accurate l.o.s. with Fourier Transform approach