Redshift-Space Distortions of Baryon Acoustic Oscillations

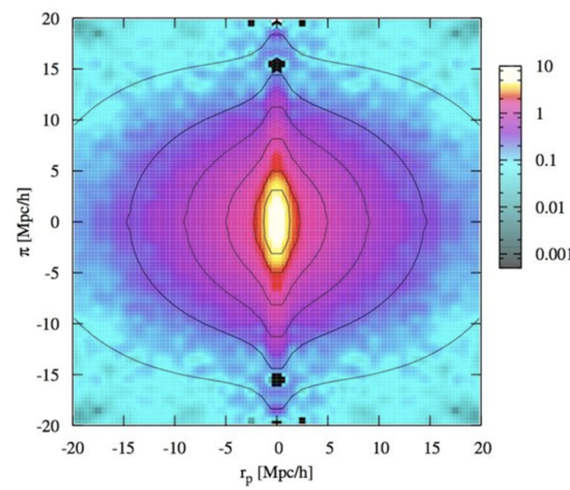
Alex Szalay
Haijun Tian
Tamas Budavari
Mark Neyrinck

Redshift Space Power Spectrum

- Expressing the power spectrum (Kaiser 1987)

$$P_s(\mathbf{k}) = P_r(k)[1 + \beta\mu^2]^2,$$

where μ is the angle between the line of sight and the wave vector
- $P(k)$ and $\xi(r)$ are duals:
  - P gets elongated
  - ξ gets compressed along the line of sight
- This is due to linear infall
- Fingers of God on the axis



Redshift Space Correlation Fn

$$\xi^{(s)}(r,\gamma) = \left(1+\frac{2\beta}{3}+\frac{\beta^2}{5}\right)\xi_0(r) - \left(\frac{4\beta}{3}+\frac{4\beta^2}{7}\right)\xi_2(r)P_2(\cos\gamma) + \frac{8\beta^2}{35}\xi_4(r)P_4(\cos\gamma)$$

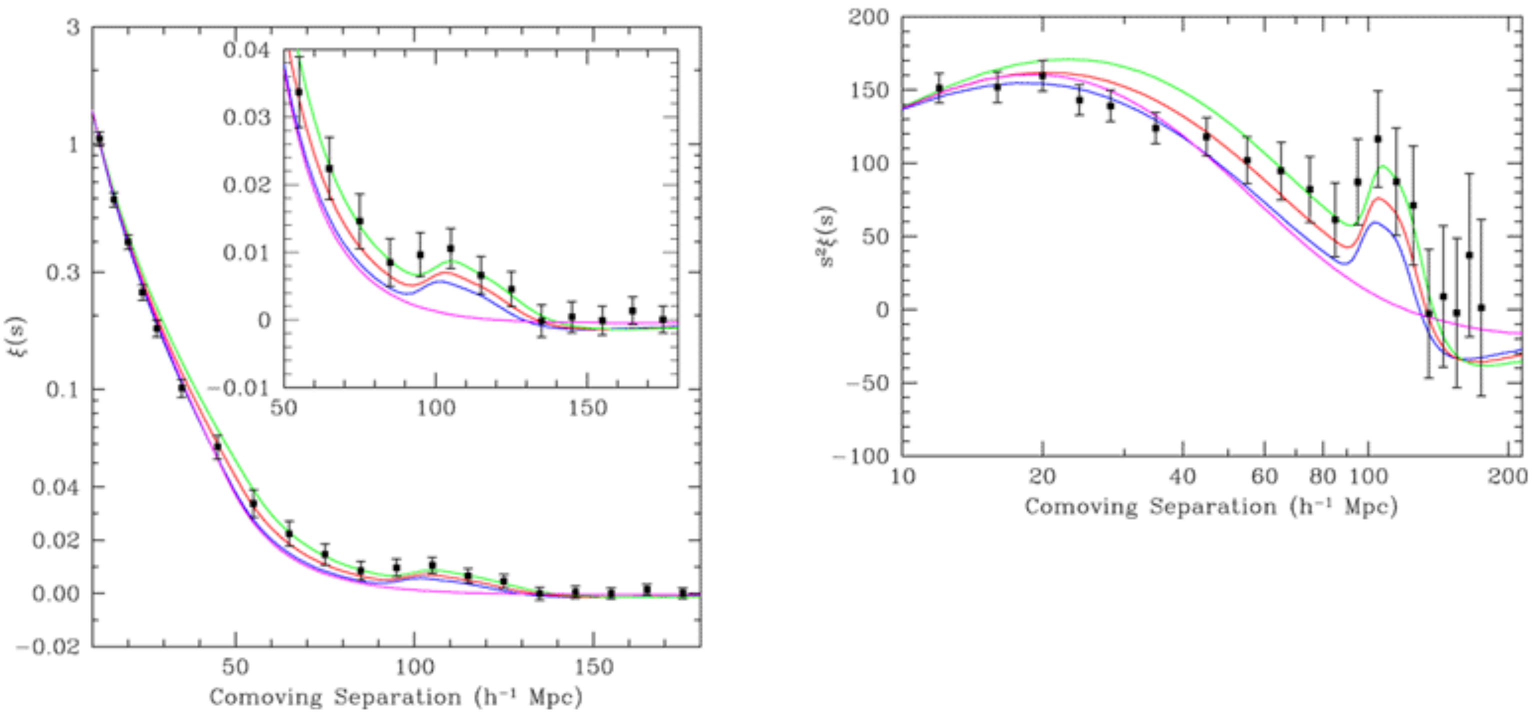
$$\xi_L^{(n)}(r) = \frac{1}{2\pi^2}\int dk\, k^2 k^{-n} j_L(kr) P(k).$$

Szalay, Matsubara, Landy (1998)

- Azimuthal average wipes out the P_2 and P_4 terms, only the real space correlation function remains
- β terms contain a second derivative (Hamilton '92)
$$\frac{2\beta}{3}\left[j_0(kr) - 2j_2(kr)\right] = -2\beta\left[j_0''(kr)\right]$$
- Interesting effect on power spectra with sharp features: redshift-space distortions make features even sharper!
- Baryon Acoustic Oscillations !!!

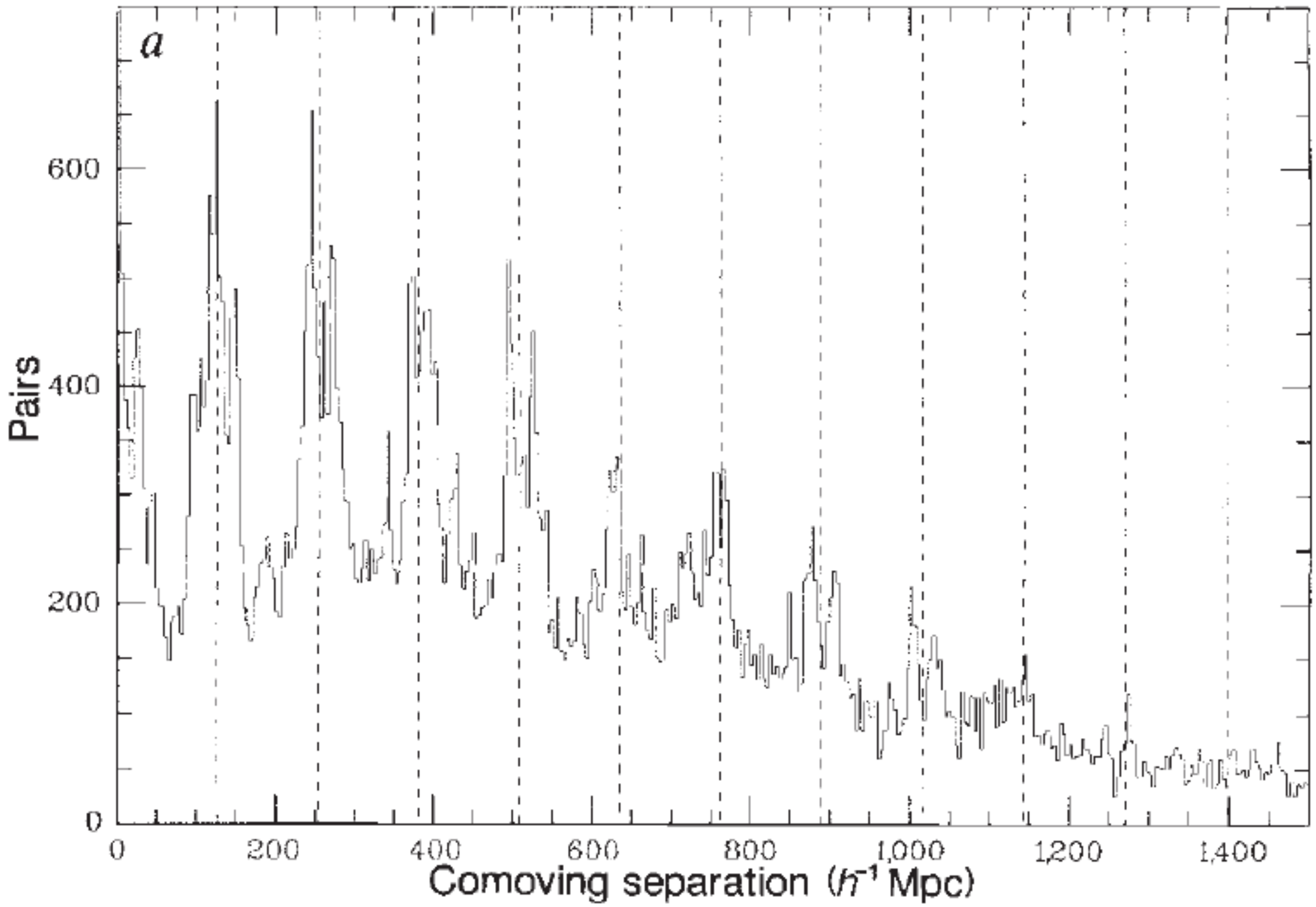
Finding the Bumps – DR4

- Eisenstein et al (2005) – LRG sample



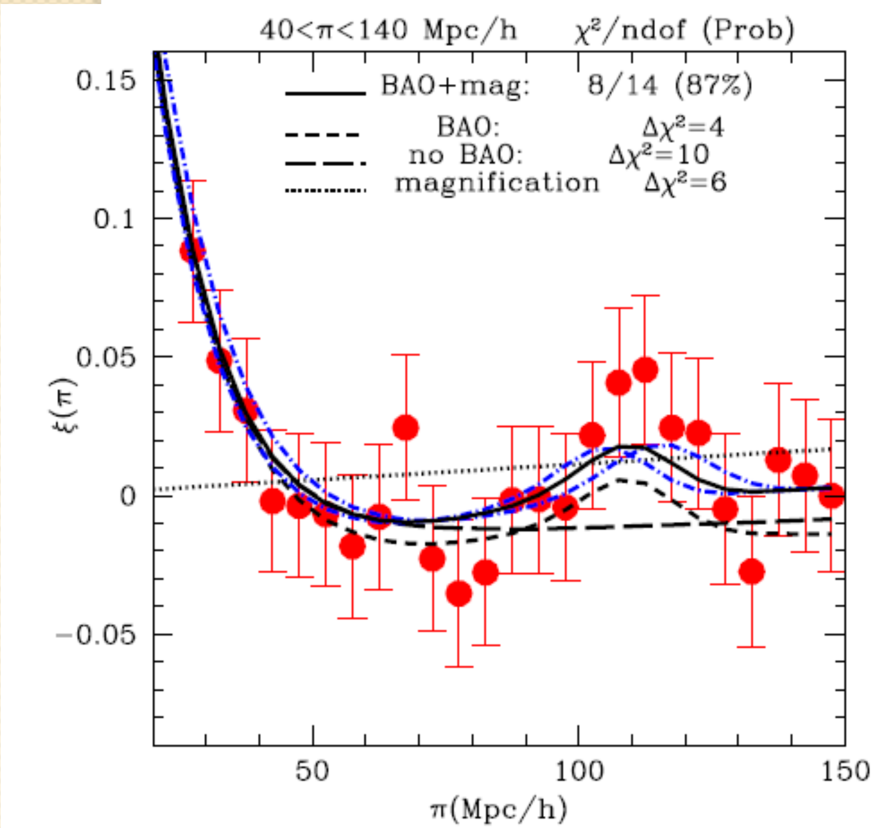
Correlation function

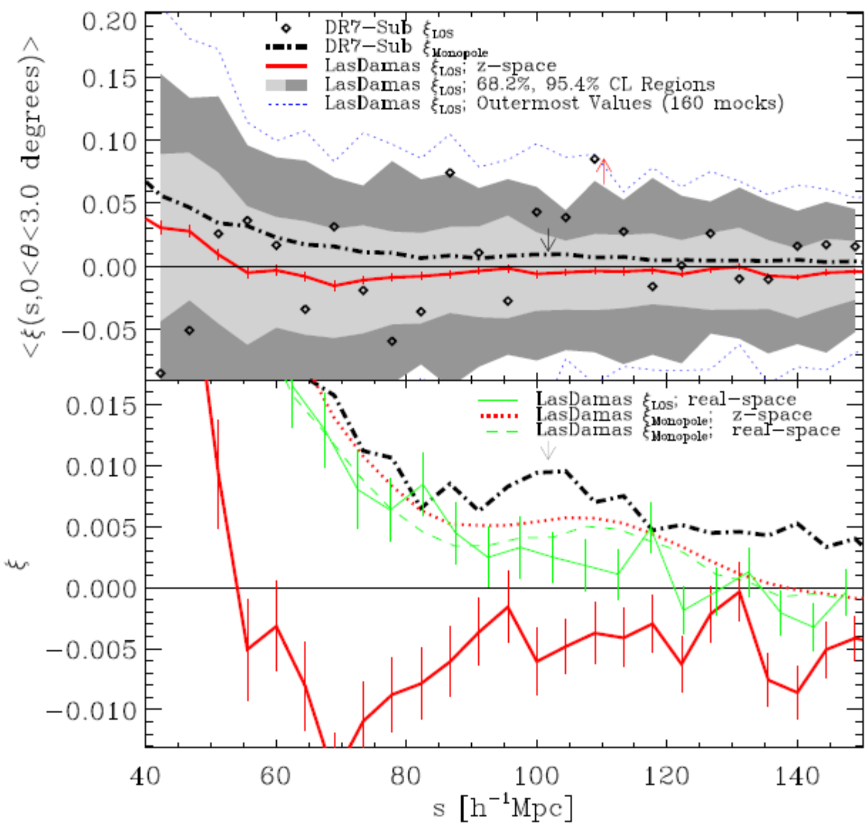
BEKS 1990 – peaks at 128 h^{-1} Mpc



A Recent Controversy: LOS Bump

SDSS LRG





Gaztanaga et al(2009)

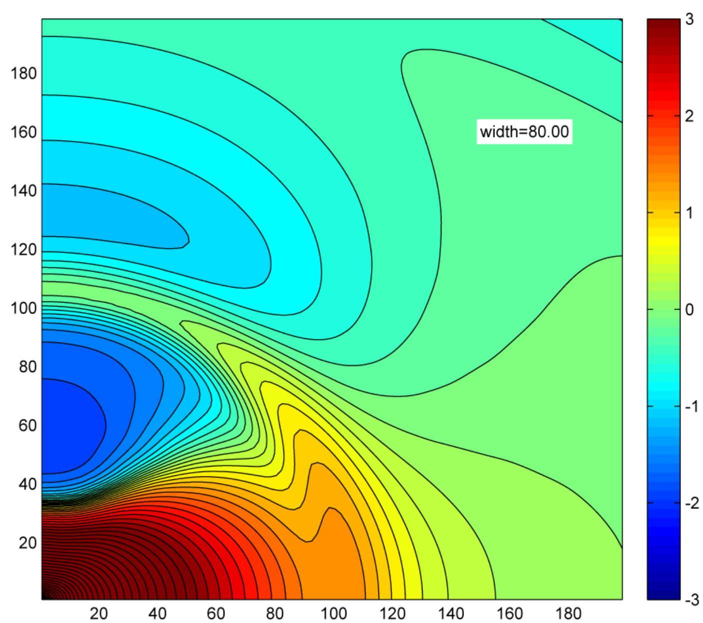
Kazin(2010)

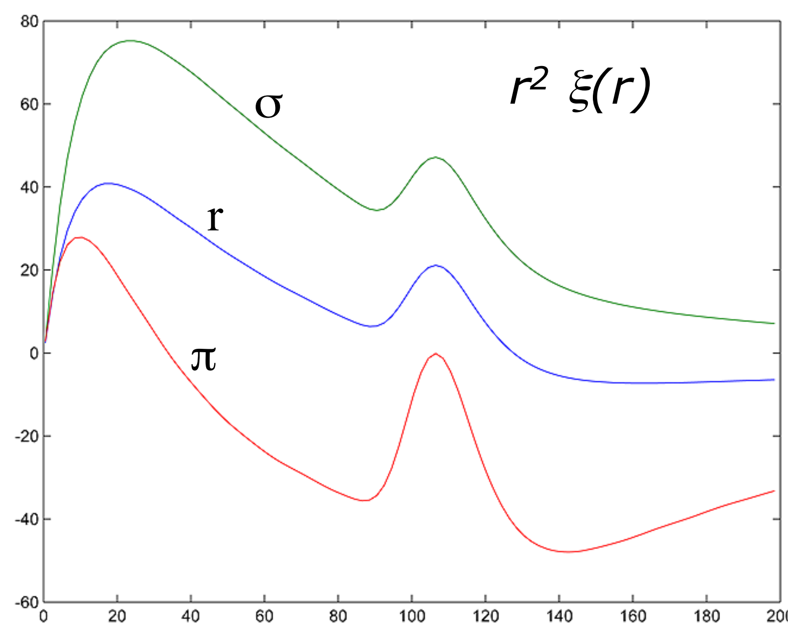
$\xi(r)$ from linear theory + BAO

- Mixing of ξ_0, ξ_2 and ξ_4
  - Along the line of sight

$$\xi_n(r) = \frac{1}{2\pi^2}\int_0^\infty dk\, k^2 j_n(kr) P(k)$$

$$\xi^{(s)}(r) = \left(1 + \frac{2\beta}{3} + \frac{\beta^2}{5}\right)\xi_0(r) - \left(\frac{4\beta}{3} + \frac{4\beta^2}{7}\right)\xi_2(r) + \frac{8\beta^2}{35}\xi_4(r)$$





2D Symmetry

- There is a planar symmetry:
  - Observer + 2 galaxies
- Thus 2D correlation of a slice is the same
- We usually average over dcosθ

$$\left(1+\frac{2\beta}{3}+\frac{\beta^2}{5}\right)\xi_0(r)$$

- Very little weight along the π axis:

$$\langle \xi(r,\theta)\rangle_\theta = \int_0^{\pi/2} d\theta \sin\theta\, \xi(r,\theta)$$

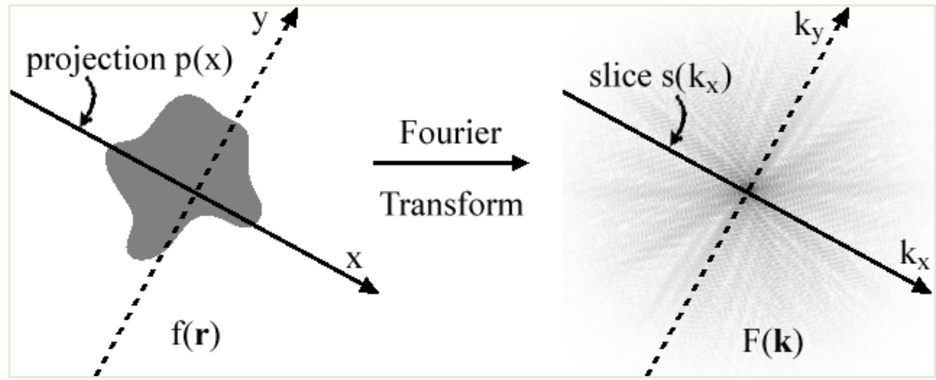
Sharp features at the line-of-sight go away with averaging!

Why correlation function?

- For a homogeneous isotropic process, the correlation function in a lower dimensional subset is identical to full
- There are subtleties:
  - With redshift space distortions the process is not fully homogeneous and isotropic
- Redshift space distortions and 'bumps'
  - Distortions already increase the 'bumps'

Projection and Slicing Theorem

$$F_m P_m = S_m F_N$$



$$p(x) = \int_{-\infty}^{\infty} f(x,y)\, dy.$$

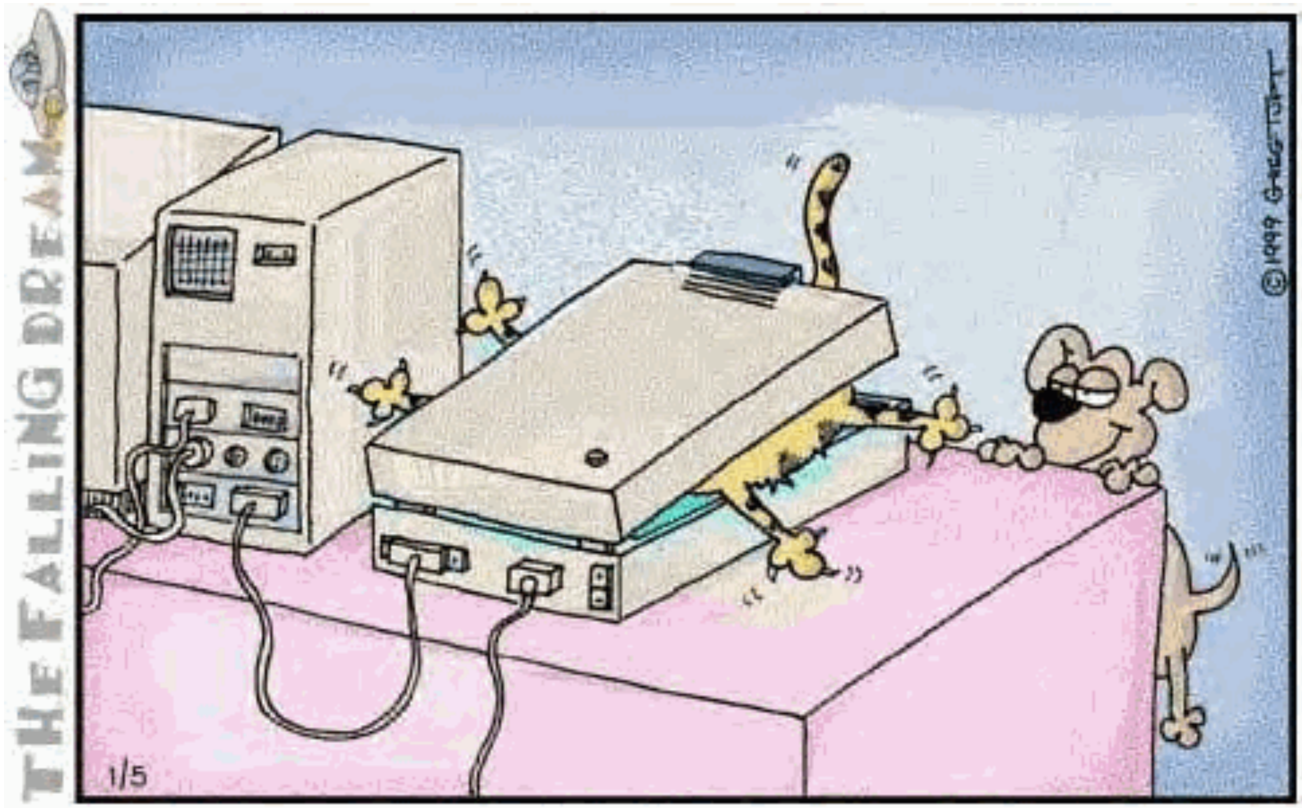
$$F(k_x, k_y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x,y)\, e^{-2\pi i (x k_x + y k_y)}\, dx dy.$$

$$s(k_x) = F(k_x, 0) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x,y)\, e^{-2\pi i x k_x}\, dx dy$$

$$= \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\infty} f(x,y)\, dy \right] e^{-2\pi i x k_x} dx$$

$$= \int_{-\infty}^{\infty} p(x)\, e^{-2\pi i x k_x} dx$$

The basis of CAT-SCAN / Radon xform



"Cat Scan"

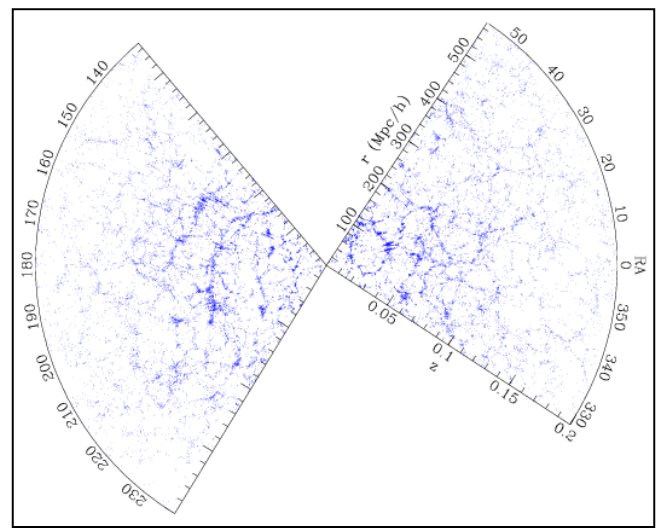
Slices and Pencilbeams

Slicing along a plane

- The isotropic correlation function is the same
- Corresponding 2D power spectrum is given by the projection onto the plane of the slice

Slicing along pencilbeams

- 1D power spectrum is the projection onto the axis of the pencilbeam

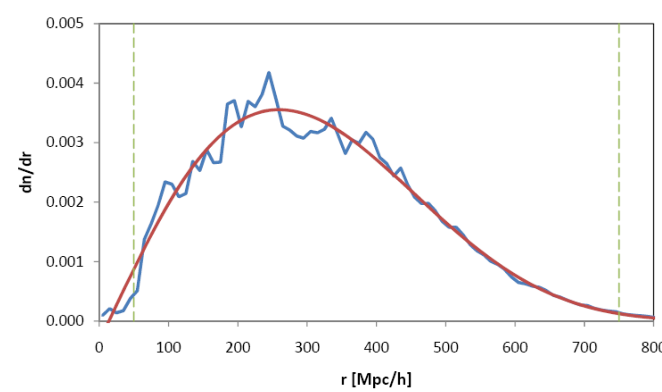


Tomography of SDSS

- SDSS DR7 Main Galaxy Sample
  - Limit distances to $100<r<750\ h^{-1}$ Mpc
- Compute 3D correlation function
- Also cut 3D data into thin angular slices
  - Project down to plane (only 2D info)
  - Different widths (2.5, 5, 10 deg)
  - Rotate slicing direction by 15 degrees
  - Ensemble of 661 slices to work with
- Analyze 2D correlation functions $\xi(\pi,\sigma)$

SDSS Sample

- SDSS DR7 MGS, Stripes 9 through 37, Northern Cap only
- 0.001<z<0.18, zConf>0.9, zErr<0.1
- Remove all the objects in the incomplete areas
- 527,362 objects
- 17M random galaxies
- Slices:

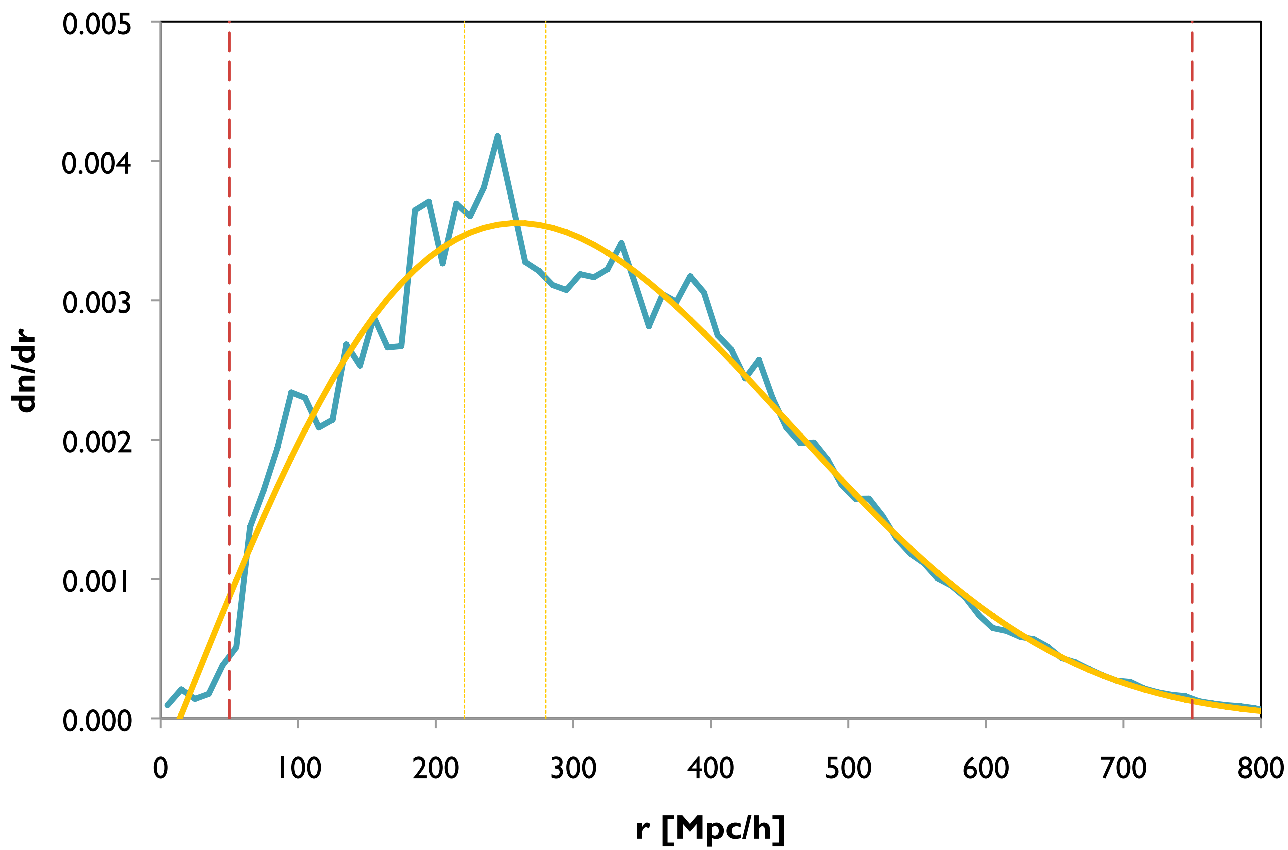


From 0 to 165°, 15° increments, 12 angular orientations, 2.5° thickness, 20°<width<80°, 661 slices total

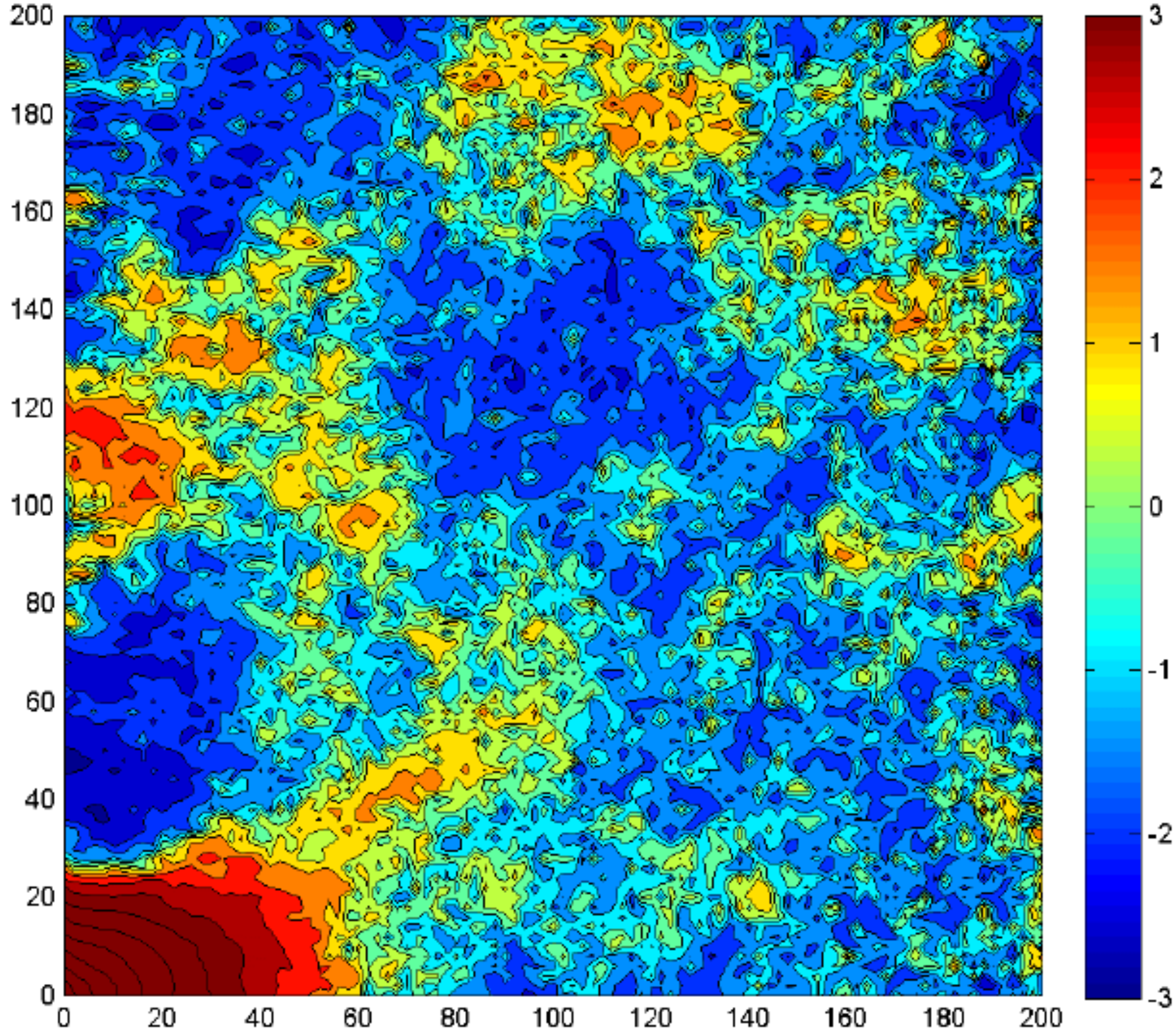
Computations on GPUs

- Generated 16M randoms with correct radial and angular selection for SDSS-N
- Done on an NVIDIA GeForce 260 card
- **600 trillion** galaxy/random pairs
- Brute force massively parallel code, much faster than tree-code for hi-res ξ
- All done inside the JHU SDSS database
- Correlation function is now DB utility

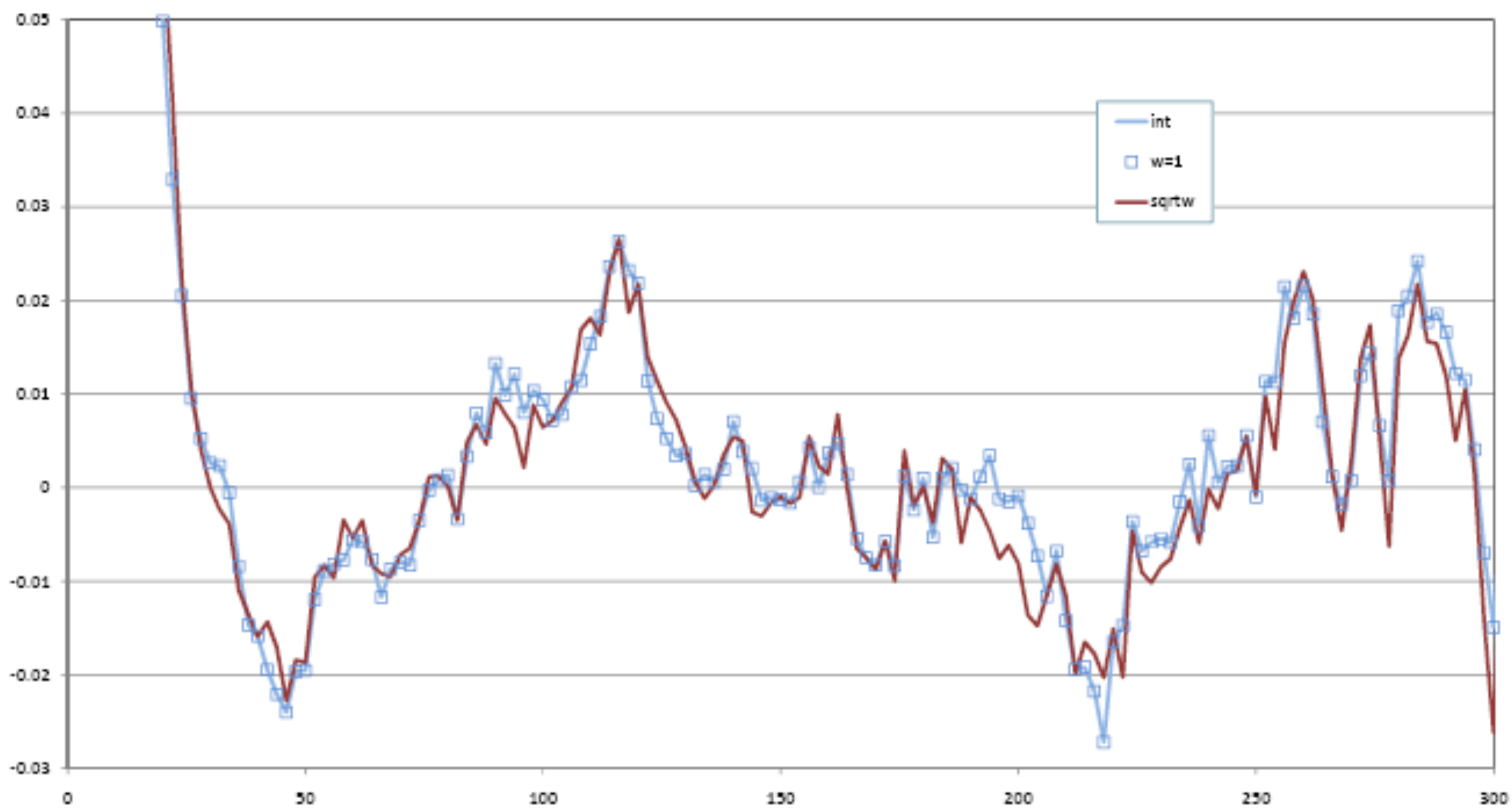
Radial Distribution



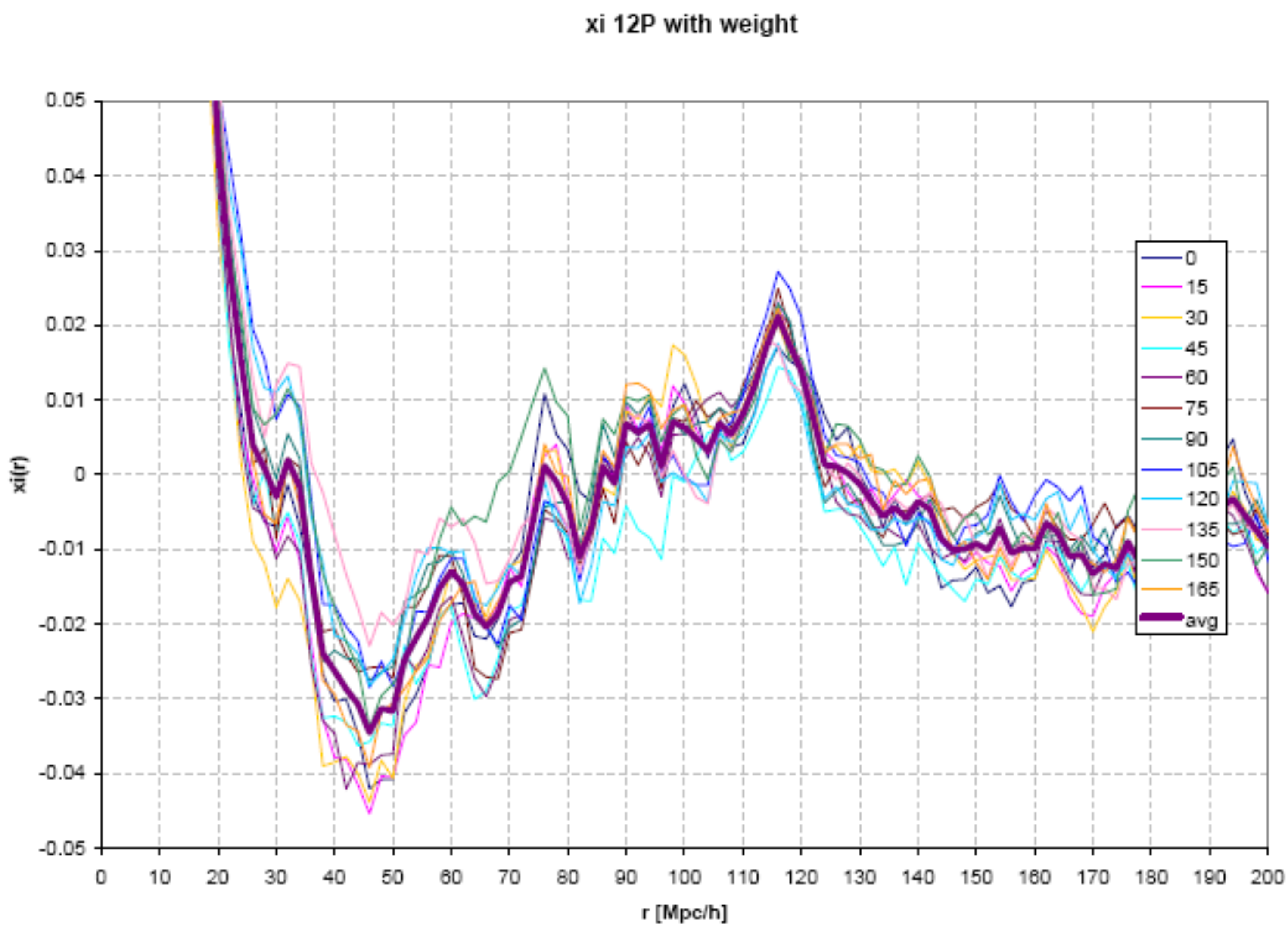
300-750 Mpc/h Cut



300-750 Mpc/h only

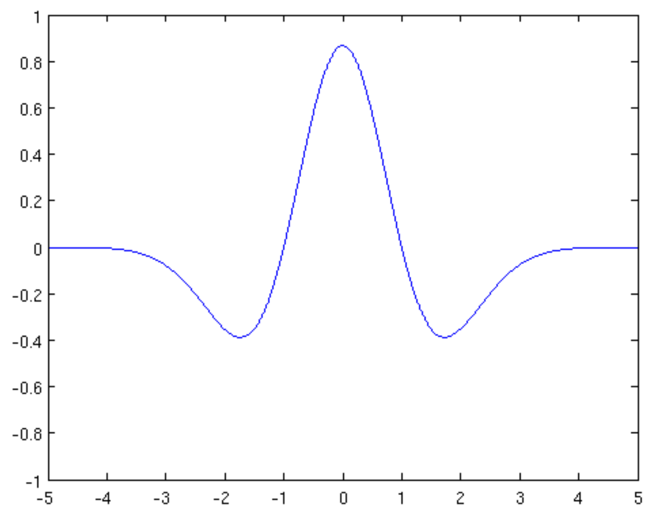


12 Slice Orientations

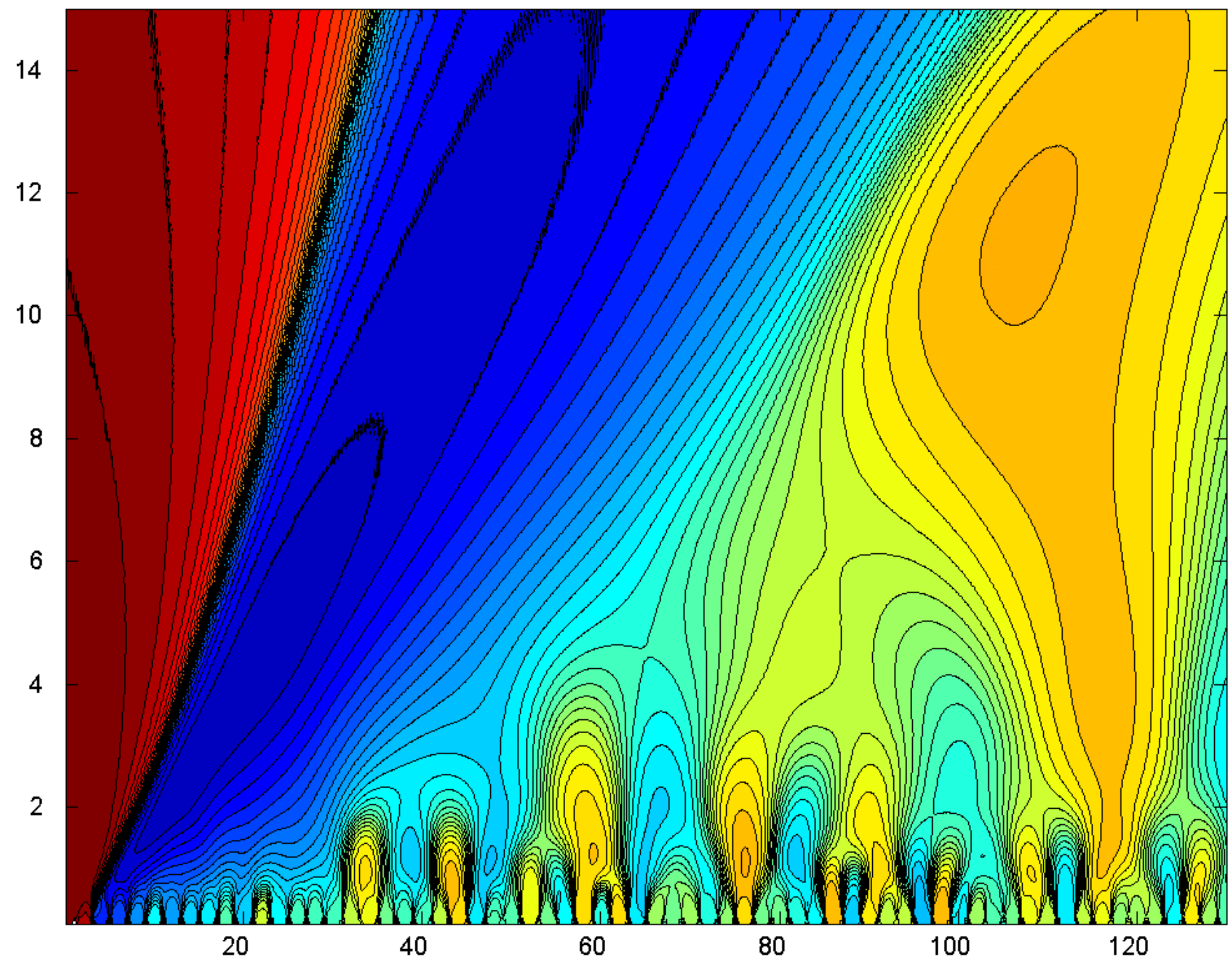


Wavelet Transform

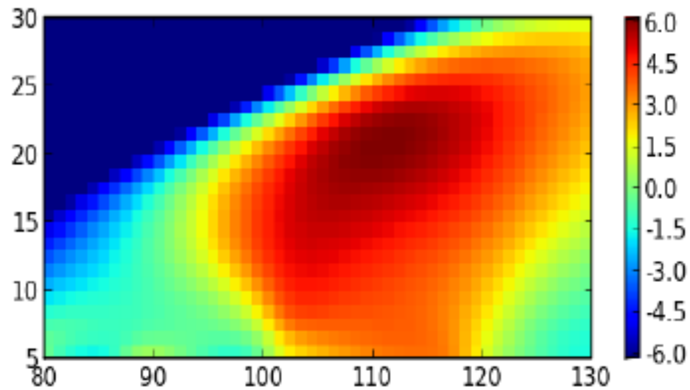
- Mexican hat wavelet transform
  - Compensated filter
  - Enhances localized "bump"
- Zero signal for constant background
- Decreases correlations among bins



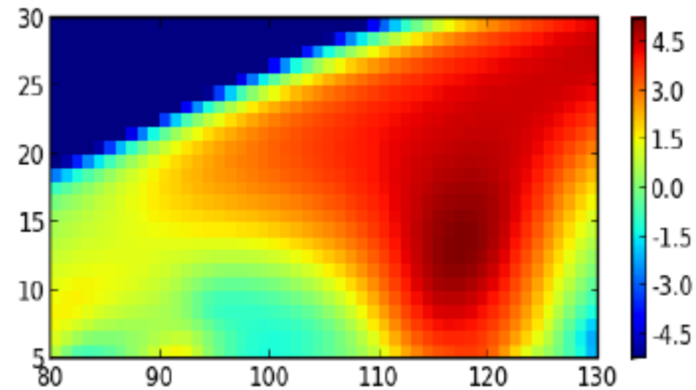
Wavelet Transform



S/N of the Wavelet Transform



Flat theta



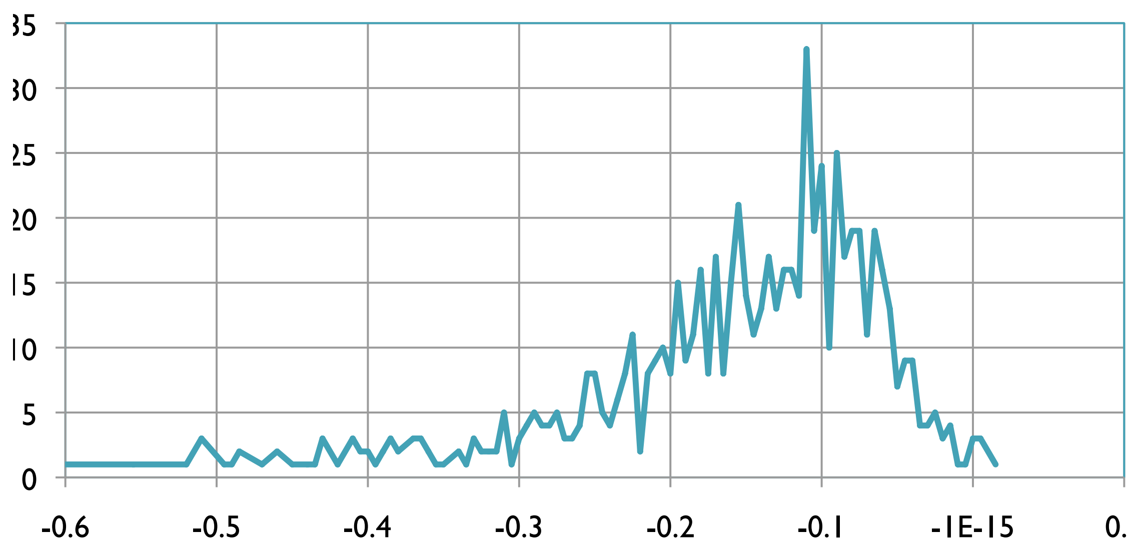
LOS(6 deg)

Noise estimated from slices, divided by 16

Strong Non-Linear Infall (55Mpc)

Distribution of LOS Mexican Hat wavelet coefficients over the 660 slices,

- Center at 55 h^{-1}Mpc, width 25 h^{-1}Mpc



Conclusion

- Redshift space distortions amplify and sharpen features along the line of sight
- Near and far side infall onto the BAO bump
- Angular averaging wipes out most of this effect
- Evidence for BAO in SDSS DR7 MGS at around 110 h^{-1}Mpc, potentially constraining the equation of state at low z $(4.5\text{-}6\sigma)$
- Trough at 55 h^{-1}Mpc indicates effects of nonlinear infall on these scales
- Nonlinearities important on ~BAO scales!

60

Happy

Birthday

David!