Cosmology using voids in large-scale structure surveys

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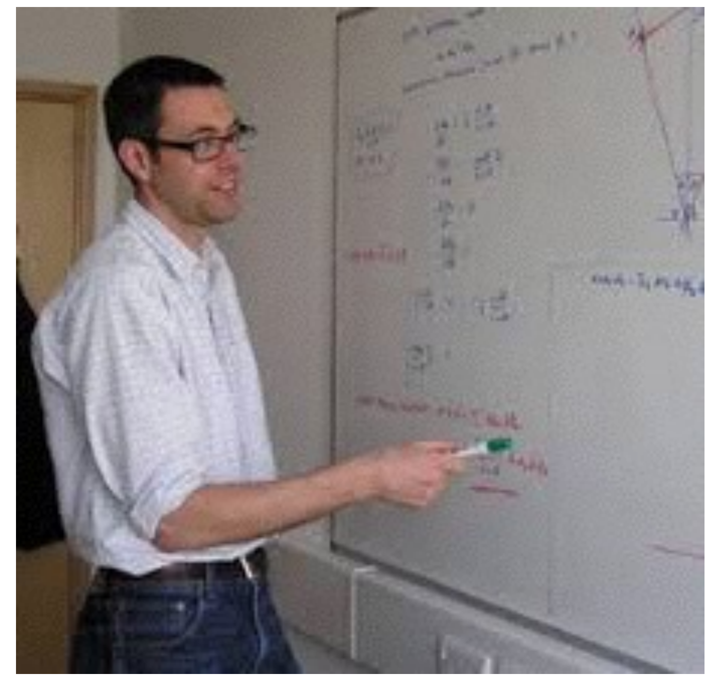
Based on work with Paul Carter and Will Percival



SN & Percival, arXiv:1712.07575

SN, Carter & Percival, due soon

Motivation

1. Voids possible tools for Alcock-Paczynski tests with future surveys

Potentially outperform BAO with Euclid? But RSD degenerate with AP!

Lavaux & Wandelt 2012

2. **Environment-dependence** of growth rate! $f = \dfrac{\mathrm{d}\ln D}{\mathrm{d}\ln a}$

density-dependent screening in modified gravity models …

3. Complementary to galaxy clustering RSD

Preliminary notes

All simulation results shown in this talk are from custom-made mock void and galaxy catalogues from the Big MultiDark simulation

The mock galaxies match **BOSS** (CMASS) galaxies, z = 0.52

Simulation volume **~** Stage IV LSS surveys (**DESI**, **Euclid**)

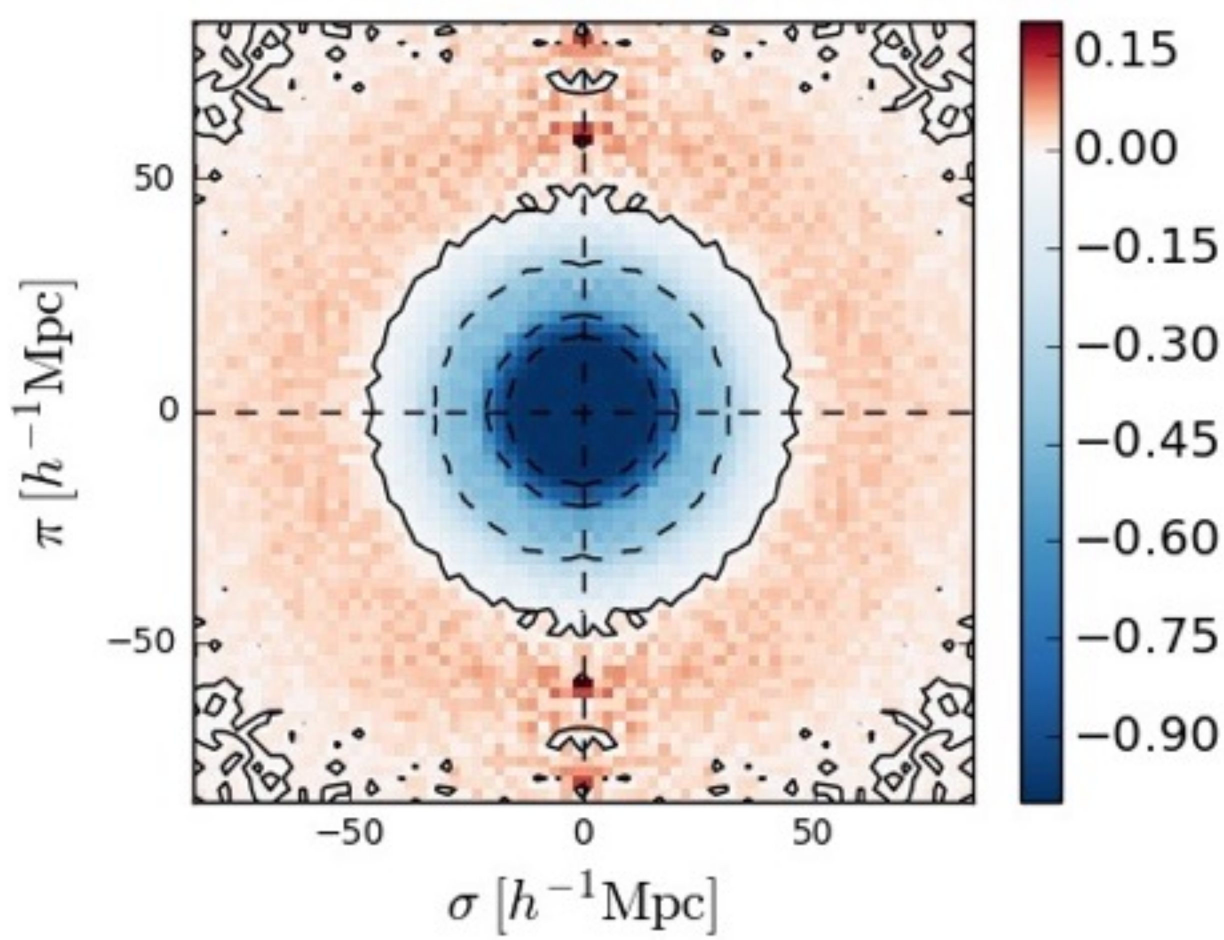
Void-finding uses **ZOBOV** algorithm – though results are quite general

Single simulation box, jackknife error estimates

The void-galaxy correlation function

$\xi_{vg}(\mathbf{r})$: cross-correlation between void and galaxy positions

(equivalent to the galaxy density profile around a void)



Real space

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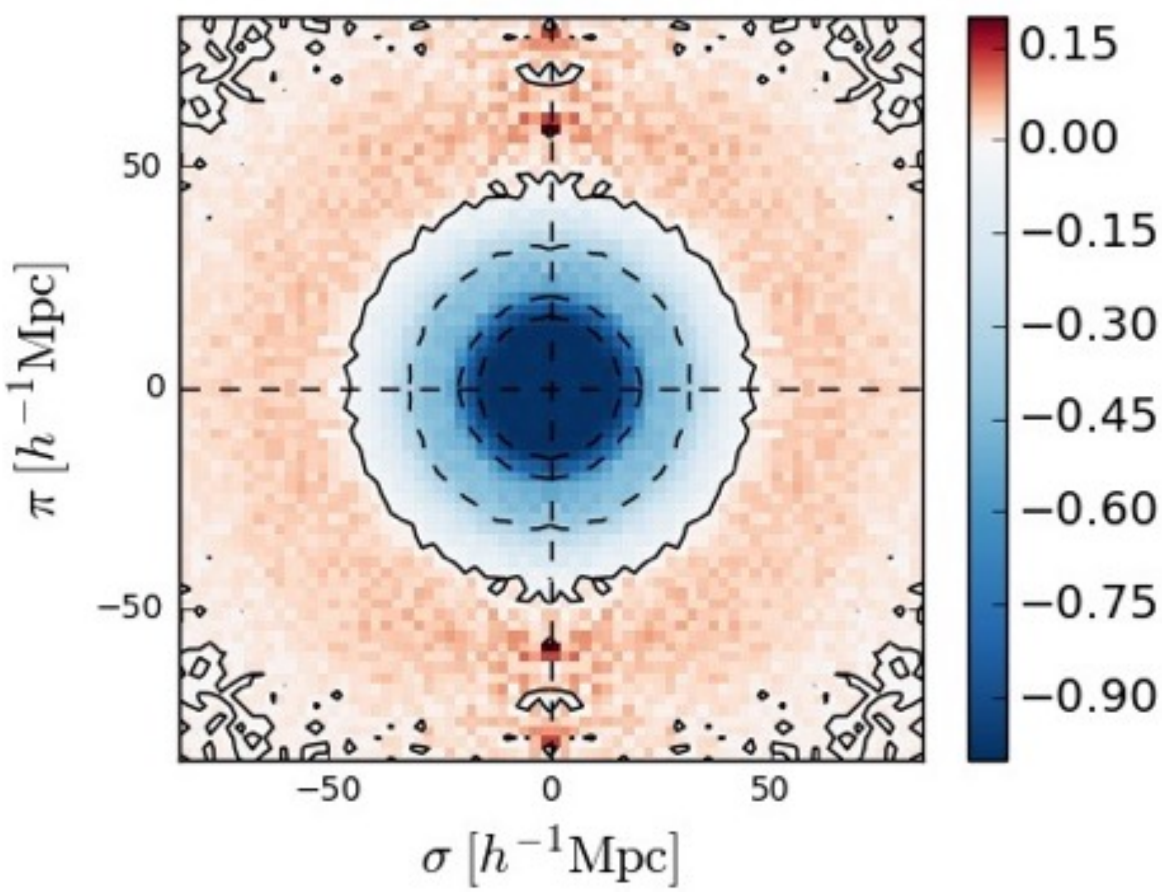
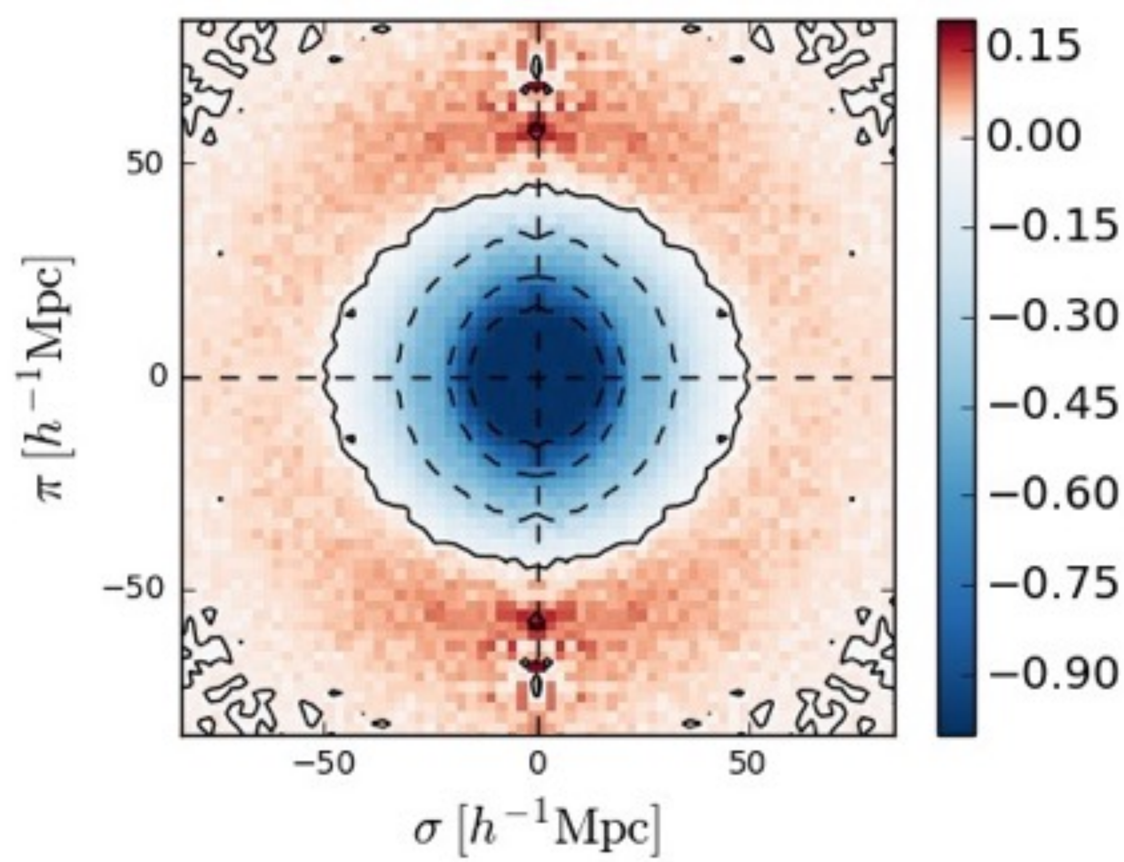


Real space

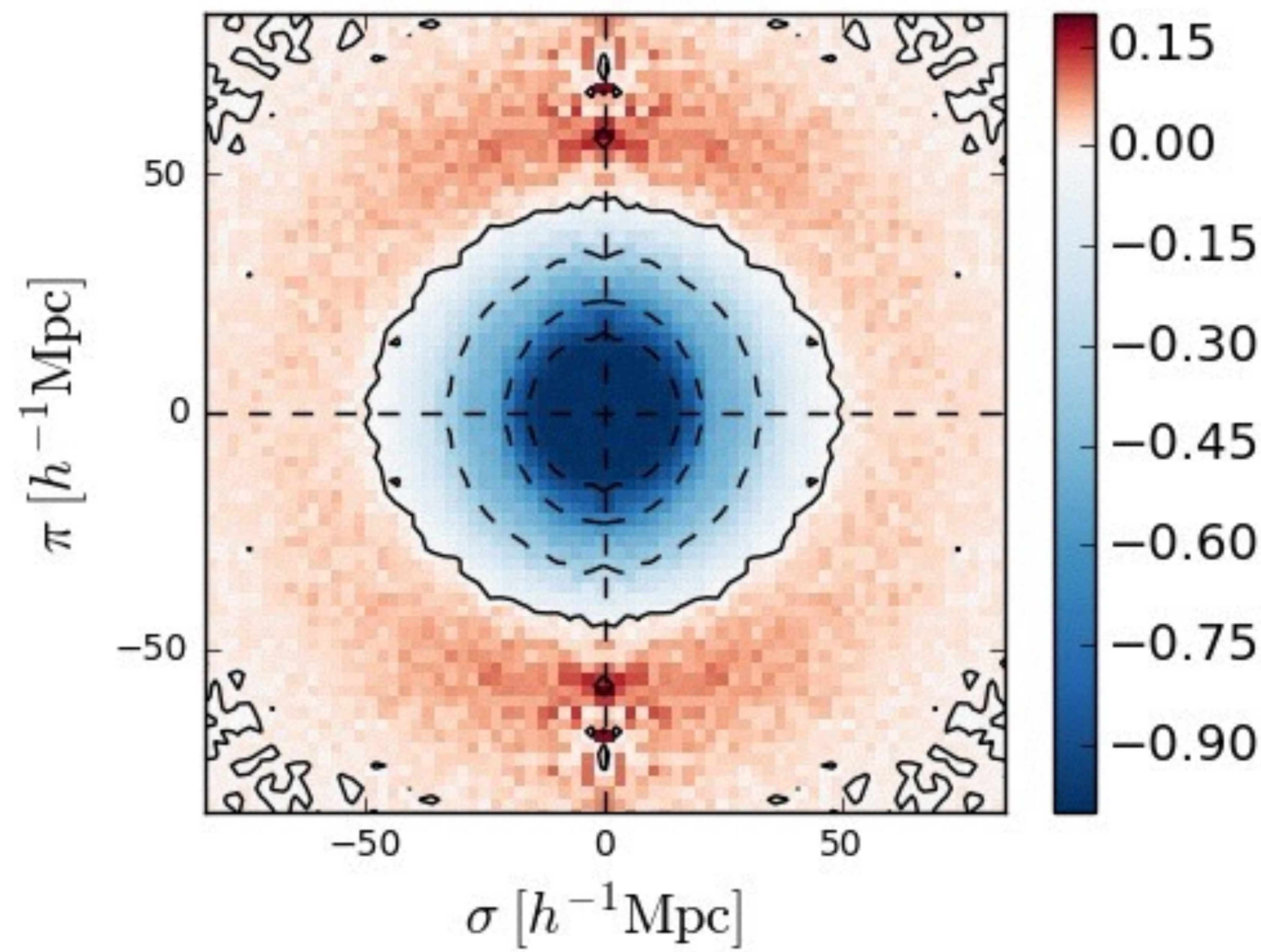


Redshift space

Void-galaxy RSD modelling

State of modelling so far:

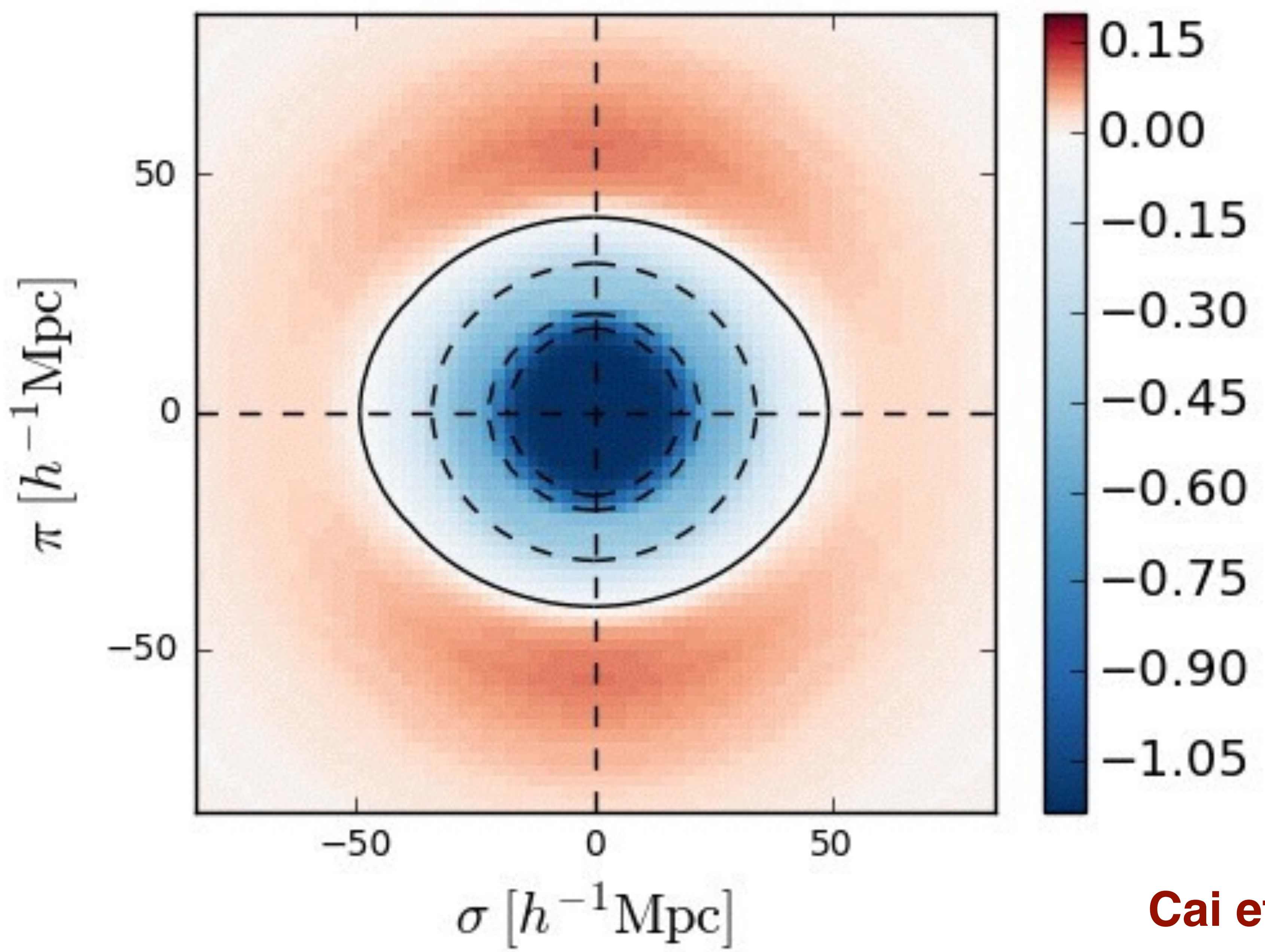
(simulation) data



Void-galaxy RSD modelling

State of modelling so far:

model



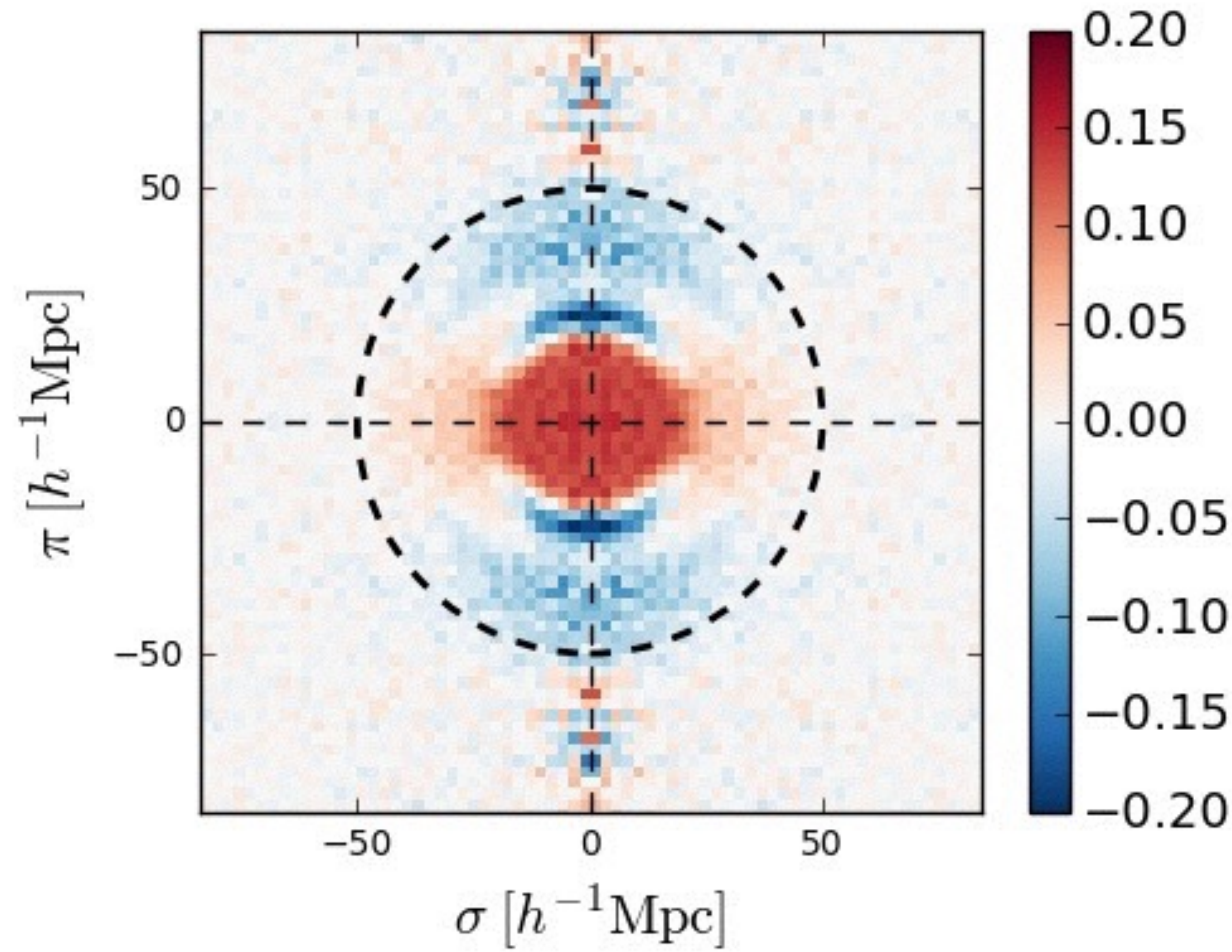
Cai et al 2016

(also used by, e.g., **Hamaus et al. 2017**)

Void-galaxy RSD modelling

State of modelling so far:

residuals



A linear model

Assumption #1: number of void-galaxy pairs conserved

$$(1+\xi^s(\mathbf{s}))\,d^3s = (1+\xi^r(\mathbf{r}))\,d^3r$$

Assumption #2: RSD due to galaxy motions only

$$\mathbf{s} = \mathbf{r} + \frac{\mathbf{v}\cdot\hat{\mathbf{X}}}{aH}\hat{\mathbf{X}}$$

Assumption #3: Linear dynamics, governed by void alone

$$\mathbf{v}(\mathbf{r}) = -\frac{1}{3}faH\Delta(r)\mathbf{r} \equiv v_r\hat{\mathbf{r}} \quad ; \quad \Delta(r) \equiv \frac{3}{r^3}\int_0^r \delta(y)y^2dy$$

A linear model

Assumption #1 **+** **Assumption #2** **+** **Assumption #3** gives

$$1+\xi^s(\mathbf{s}) = (1+\xi^r(\mathbf{r}))\left[1-\frac{f}{3}\Delta(r) - f\mu^2\left(\delta(r)-\Delta(r)\right)\right]^{-1}$$

Expand to linear order in $\delta,\ \Delta$

Deriving a linear model

$$\xi^s(s,\mu) = \xi^r(r) + \frac{f}{3}\Delta(r)\left(1+\xi^r(r)\right)$$
$$+ f\mu^2\left[\delta(r)-\Delta(r)\right]\left(1+\xi^r(r)\right)$$

SN & Percival 2017

Deriving a linear model

$$\xi^s(s,\mu) = \xi^r(r) + \frac{f}{3}\Delta(r)(1+\xi^r(r)) + f\mu^2\left[\delta(r) - \Delta(r)\right](1+\xi^r(r))$$

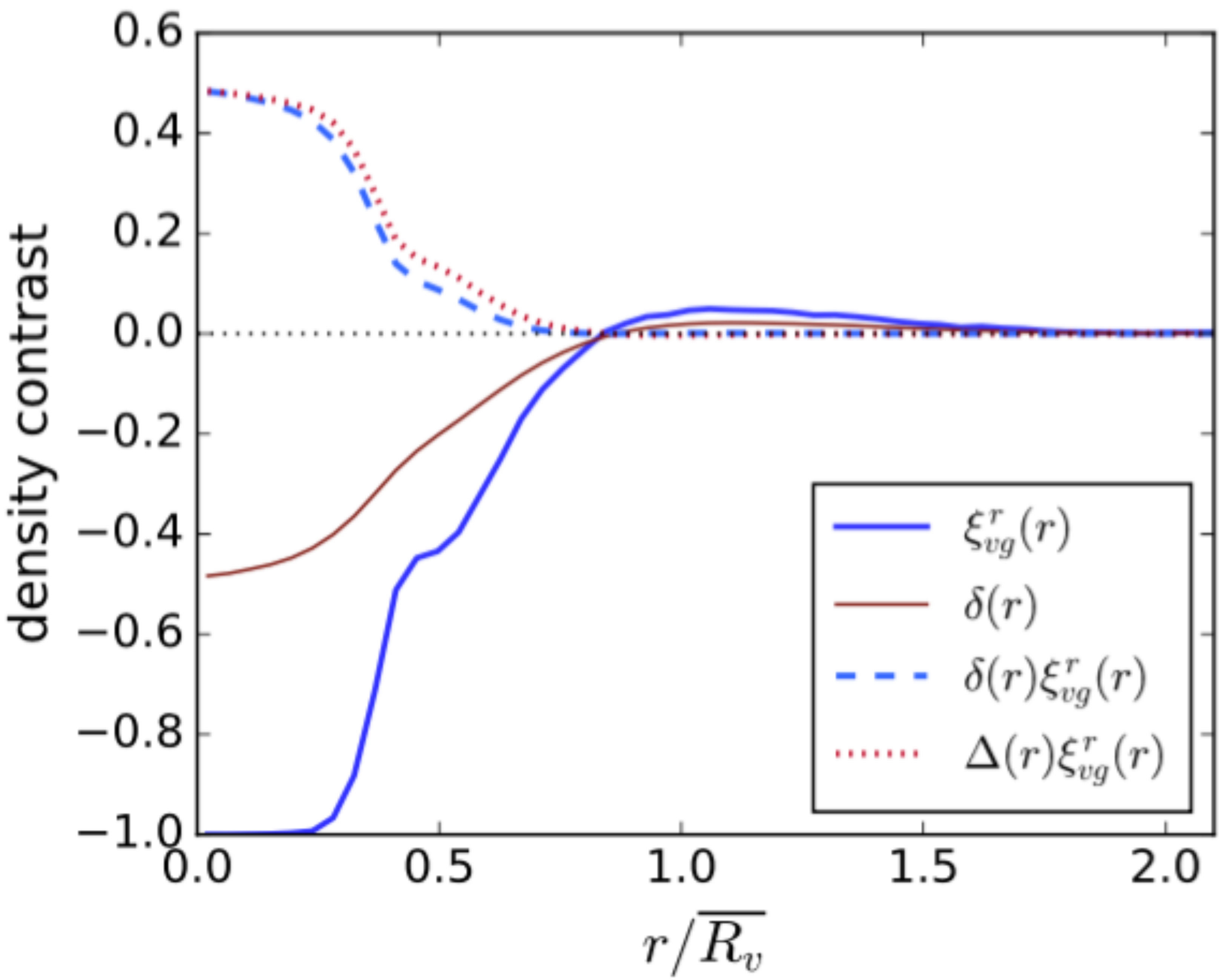
SN & Percival 2017

Key features:

- $\xi\delta,\ \xi\Delta$ are **linear order** inside voids!

Deriving a linear model

$\xi^s($



$))$

Key feat

- $\xi\delta,$

Deriving a linear model

$$\xi^s(\boldsymbol{s},\mu) = \xi^r(\boldsymbol{r}) + \frac{f}{3}\Delta(r)(1+\xi^r(r))$$
$$+f\mu^2\left[\delta(r)-\Delta(r)\right](1+\xi^r(r))$$

SN & Percival 2017

Key features:

- $\xi\delta,\ \xi\Delta$ are **linear order** inside voids!
- **Coordinate shift** important at linear order!

$$\xi(r) = \xi(s) + \xi'(s)\frac{f}{3}s\Delta(s)\mu^2 + \ldots$$

Deriving a linear model

$$\xi^s\left(\boldsymbol{s},\mu\right) = \xi^r(\boldsymbol{r}) + \frac{f}{3}\Delta(r)(1+\xi^r(r))$$
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$$\xi(r) = \xi(s) + \xi'(s)\frac{f}{3}s\Delta(s)\mu^2 + \dots$$

- Linear galaxy bias **does not hold,** $\xi(r) \neq b\delta(r)$

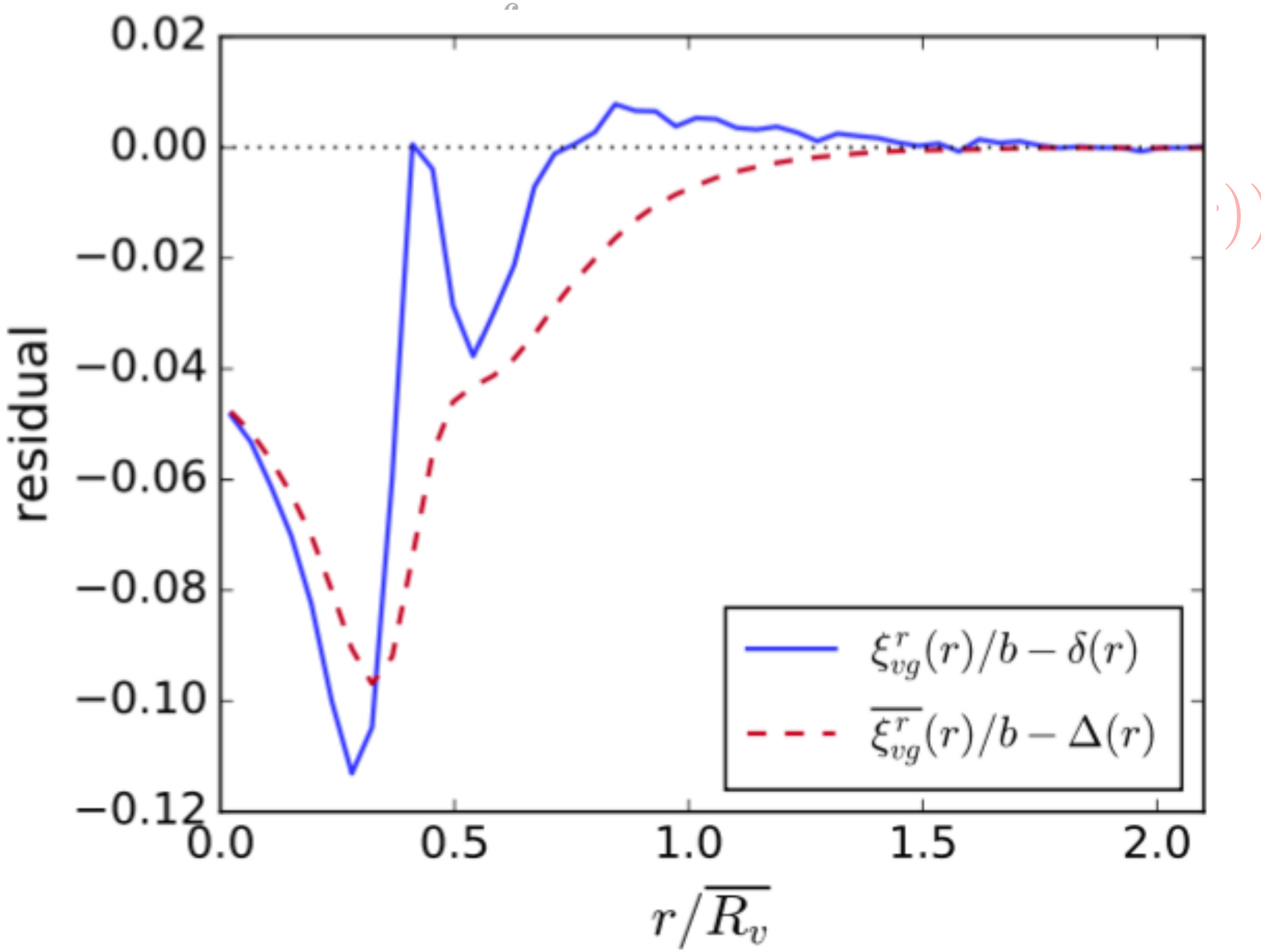
Improved linear model

ξ^s

Key fe

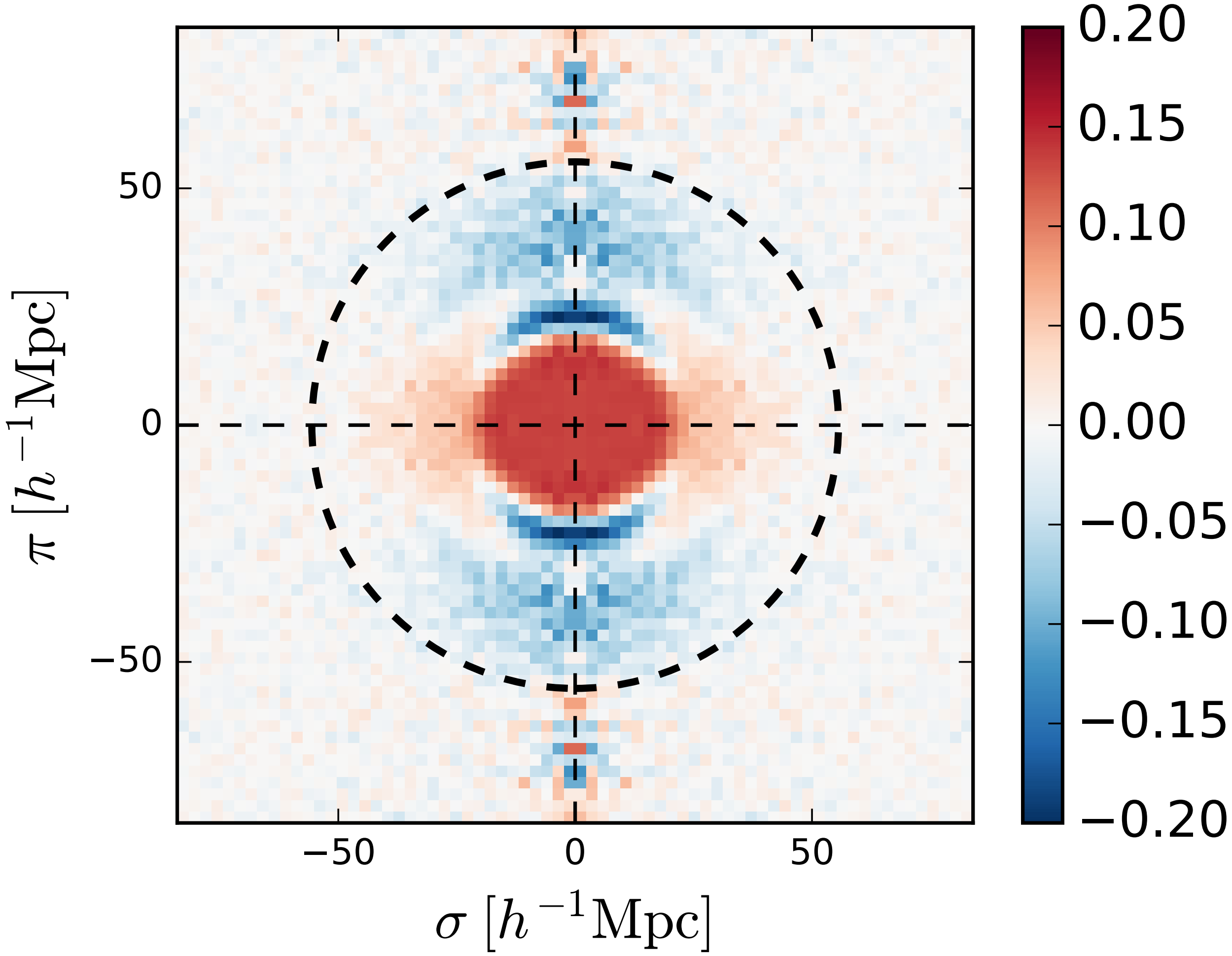
- $\xi\delta$
- Co

- Lin

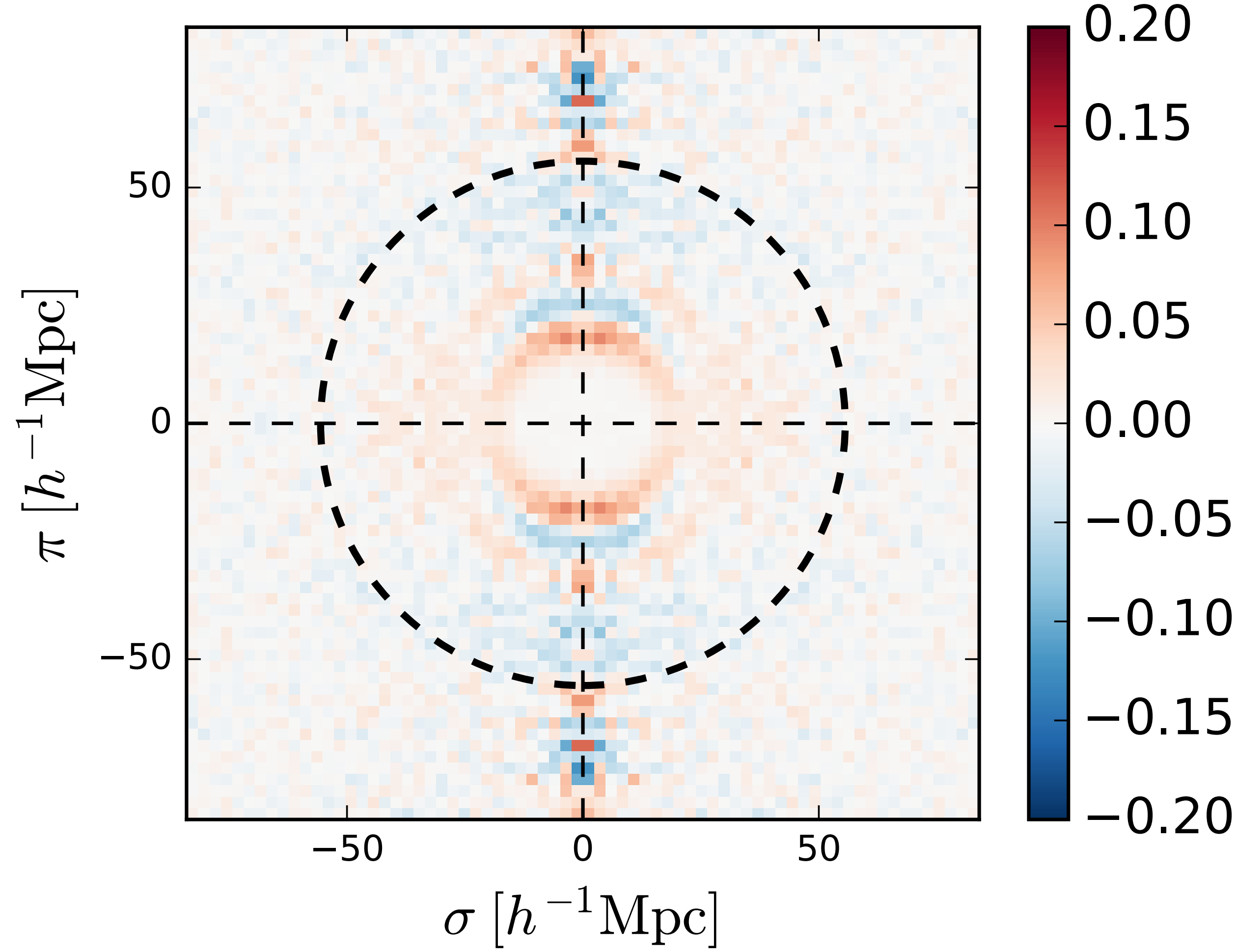


Important improvement

old model residuals

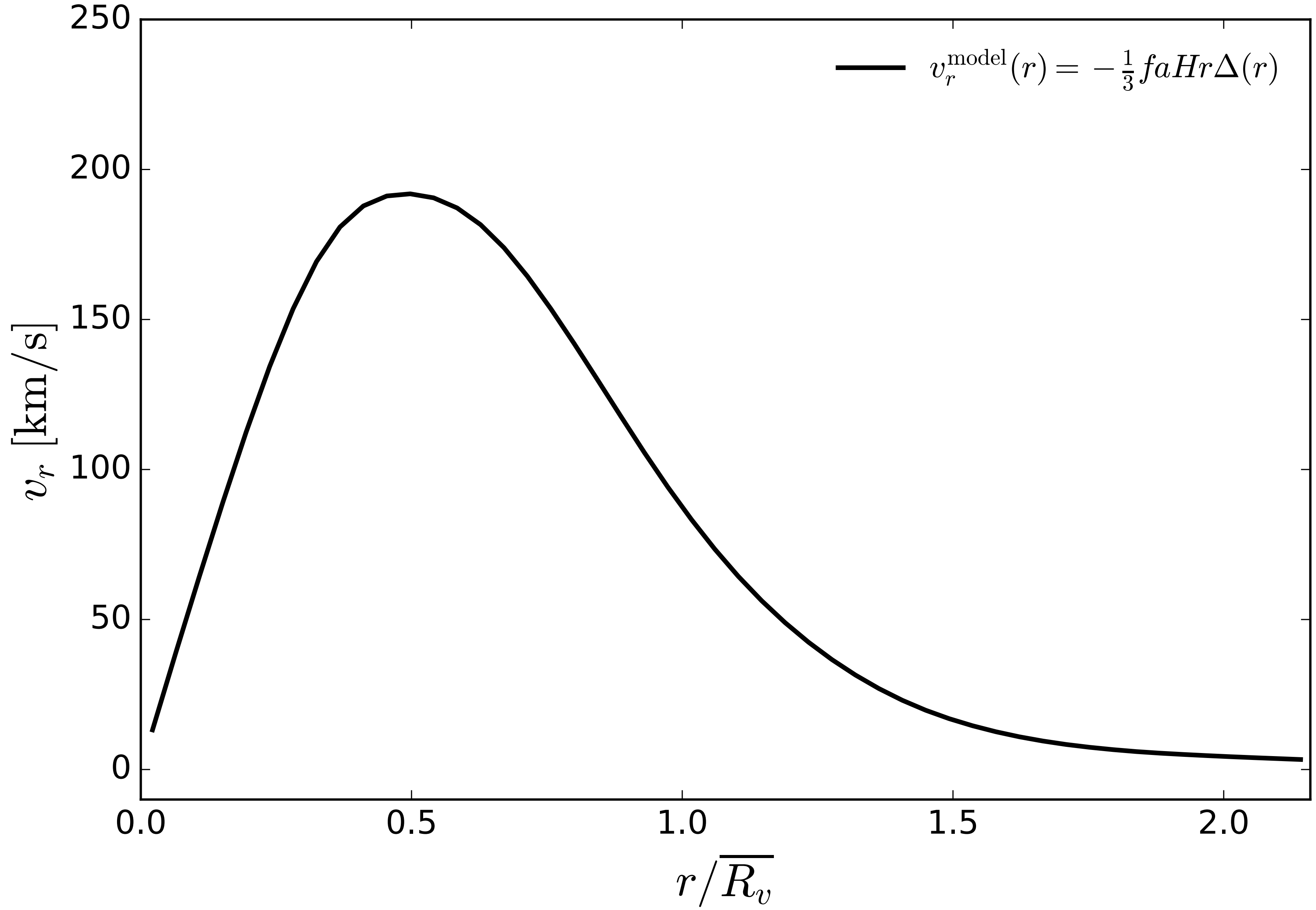


new model residuals



Performs *much* better!

Why does a linear RSD model fit so well?



SN & Percival 2017

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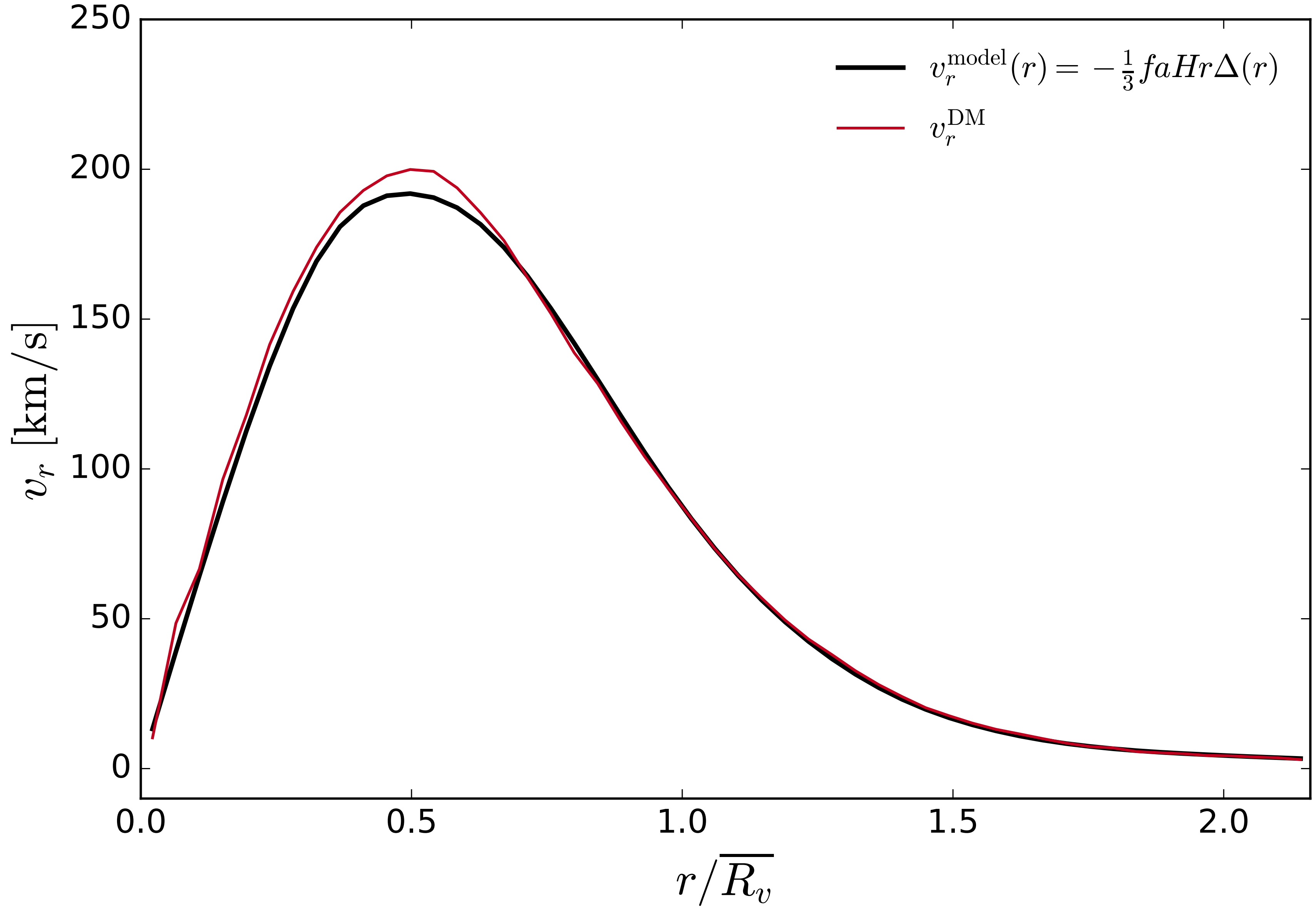

SN & Percival 2017

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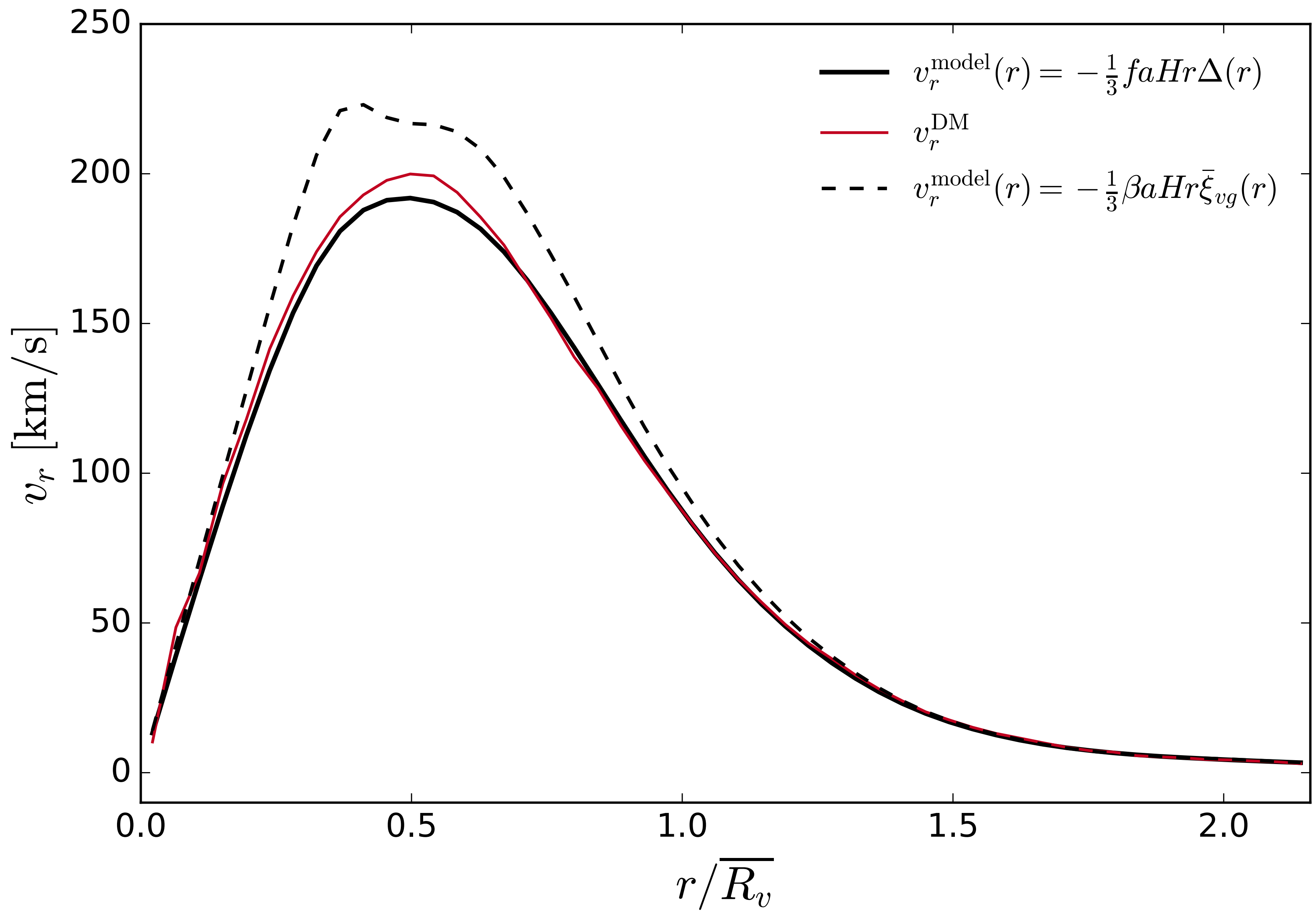

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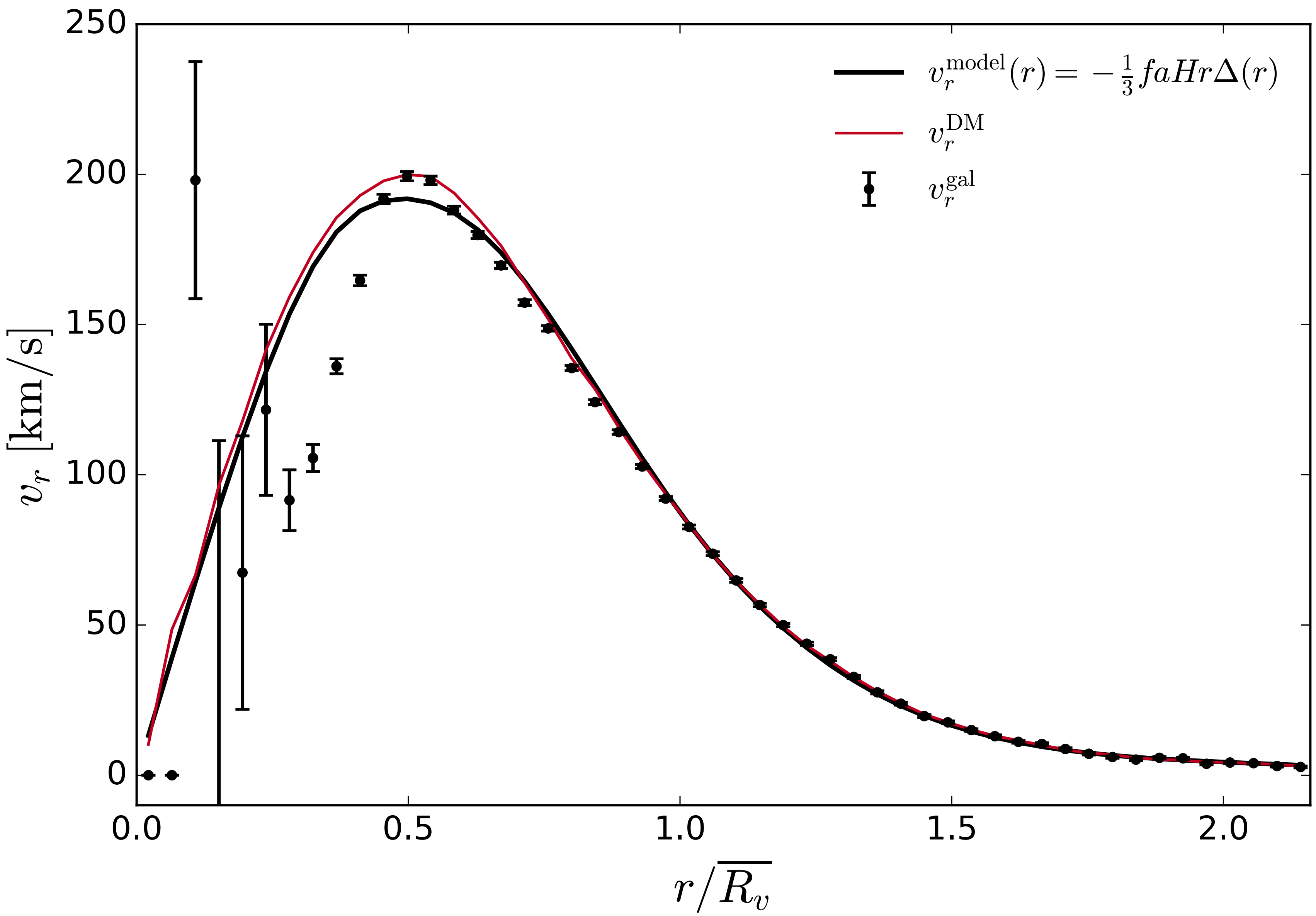

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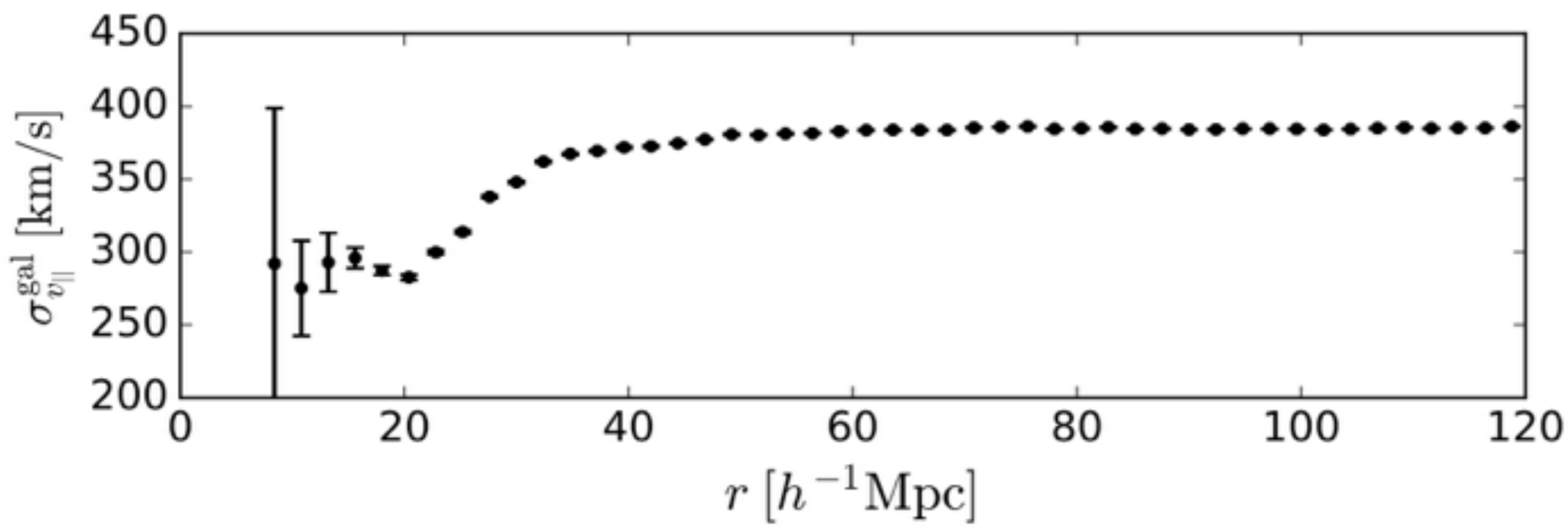
Why doesn't this RSD model fit perfectly?

Dispersion around coherent outflow is large:



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Adding velocity dispersion to the model

Allow for a dispersion in los velocities, $\mathbf{v} = v_r \hat{\mathbf{r}} + v_{||} \hat{\mathbf{X}}$, then:

$$1 + \xi^s(\sigma, \pi) = \int dv_{||} P(v_{||}) (1 + \xi^r(r)) \left| J\left(\frac{\mathbf{s}}{\mathbf{r}}\right) \right|^{-1}$$

assume Gaussian pdf,
can be scale-dependent

expand to linear
order as before

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$$1 + \xi^s(\sigma, \pi) = \int dv_{||} P(v_{||})(1 + \xi^r\,(r)) \left| J\left(\frac{\mathbf{s}}{\mathbf{r}}\right)\right|^{-1}$$

Note, **not**

$$1 + \xi^s(\sigma, \pi) = \int \frac{(1 + \xi^r(r))}{\sqrt{2\pi}\sigma_v} \exp\left(-\frac{(v_{||} - v_r(r)\mu)^2}{2\sigma_v^2}\right) dv_{||}$$

standard streaming model result **does not hold** for voids!

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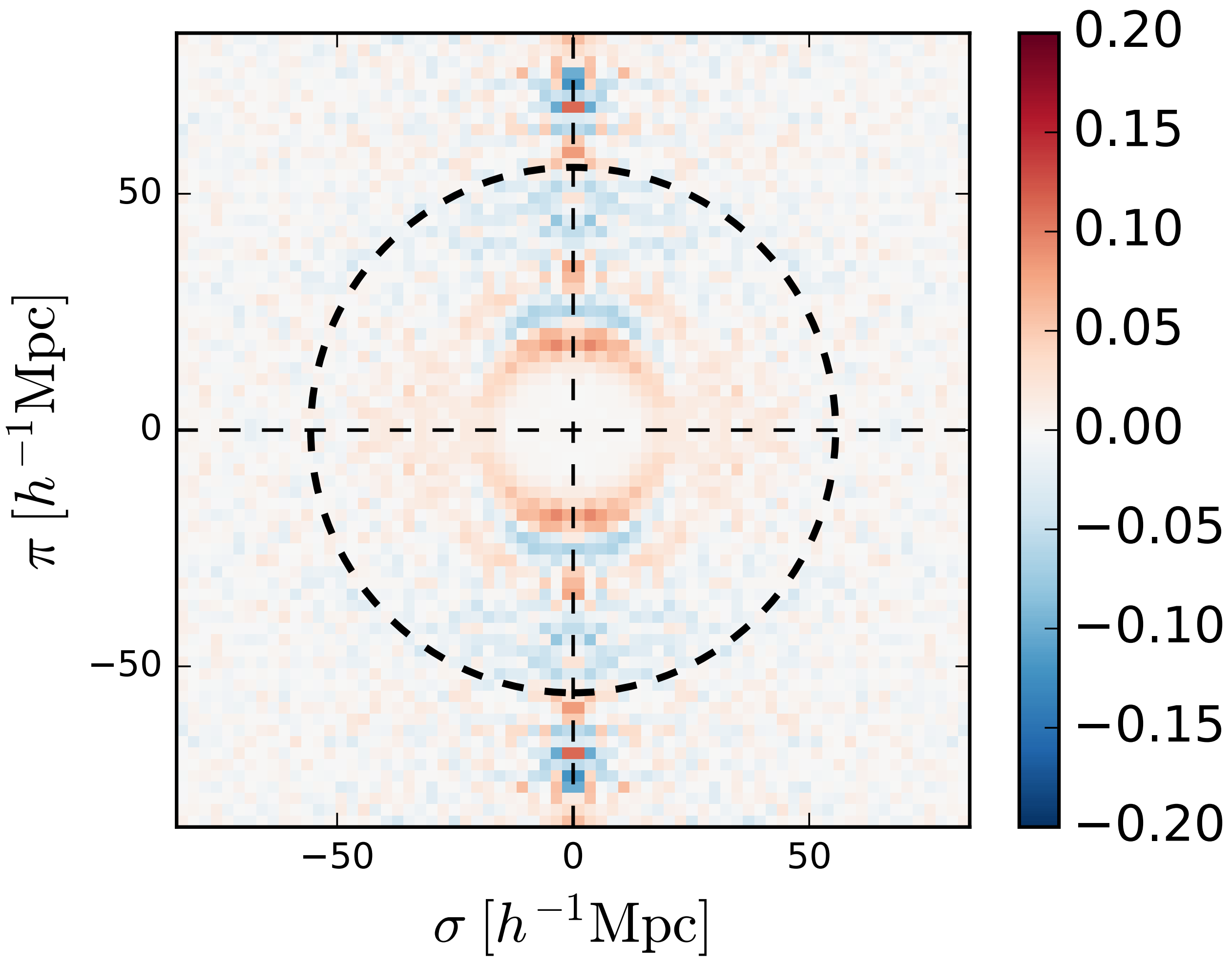
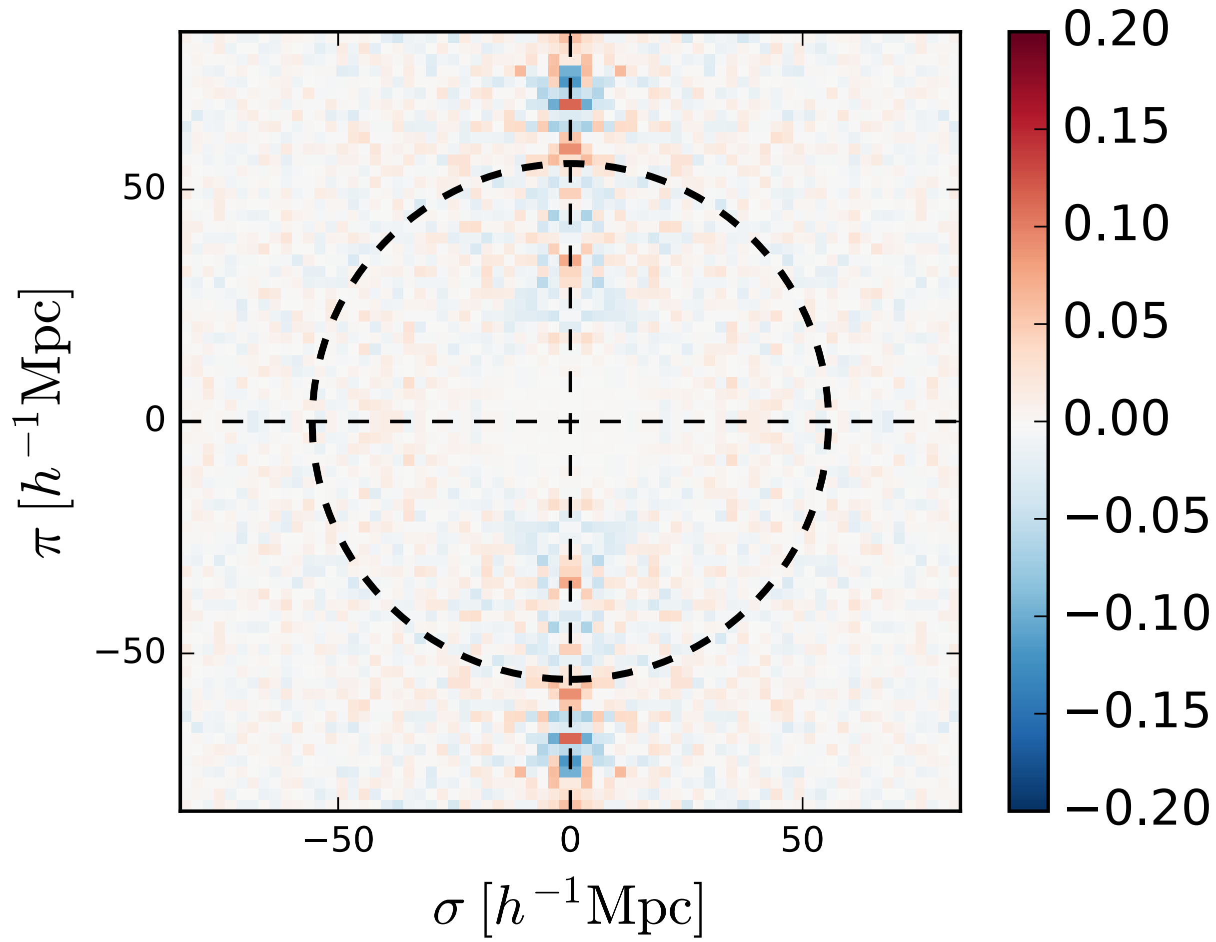
Improved linear model with dispersion

Even better residuals

without dispersion



with dispersion



Multipole expansion

For quantitative analyses, expand in terms of multipoles

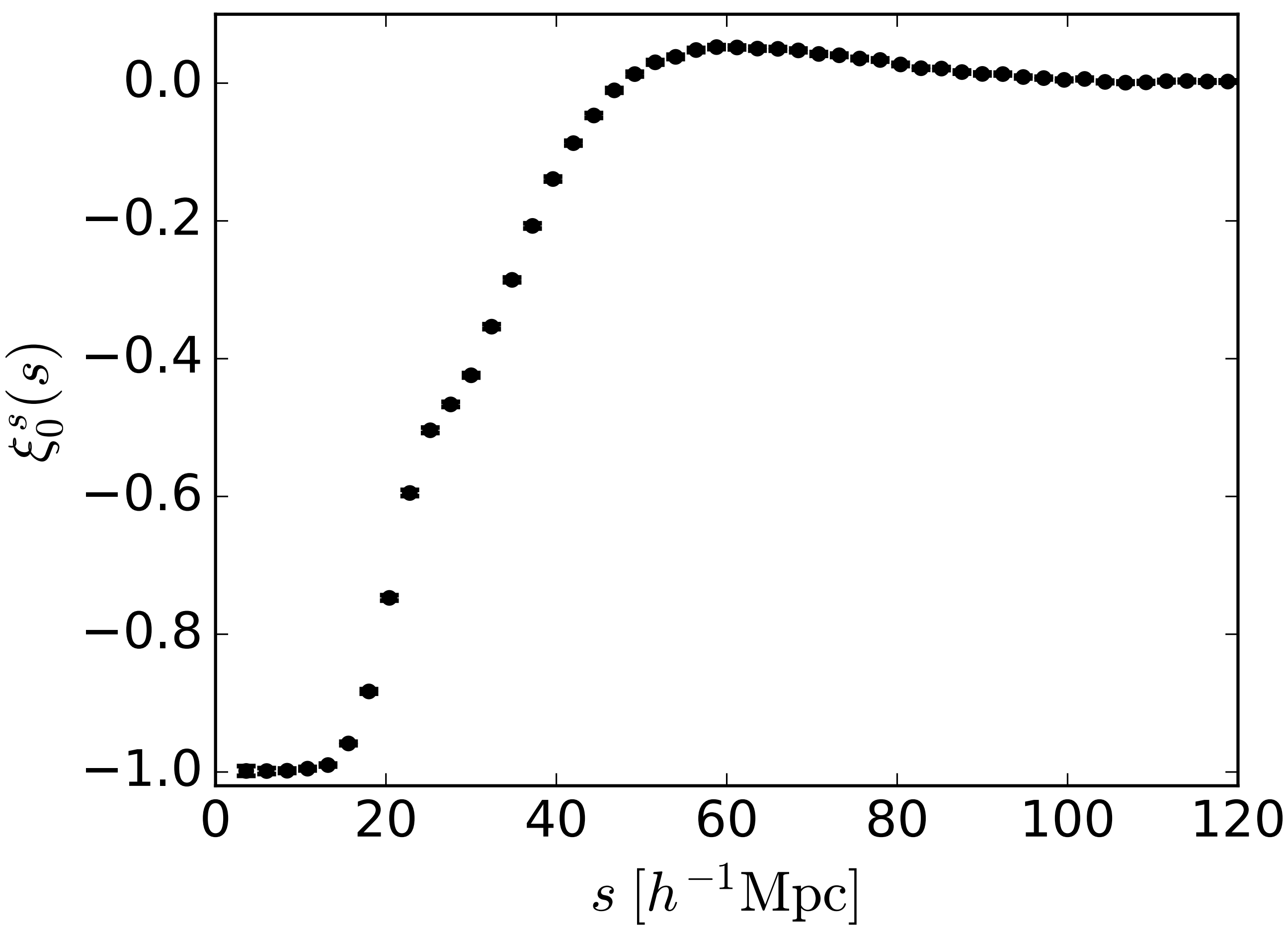
$$\xi^s_\ell(s) = \int_0^1 \xi^s(s,\mu)\,(1+2\ell)\,P_\ell(\mu)d\mu$$

Legendre polynomials

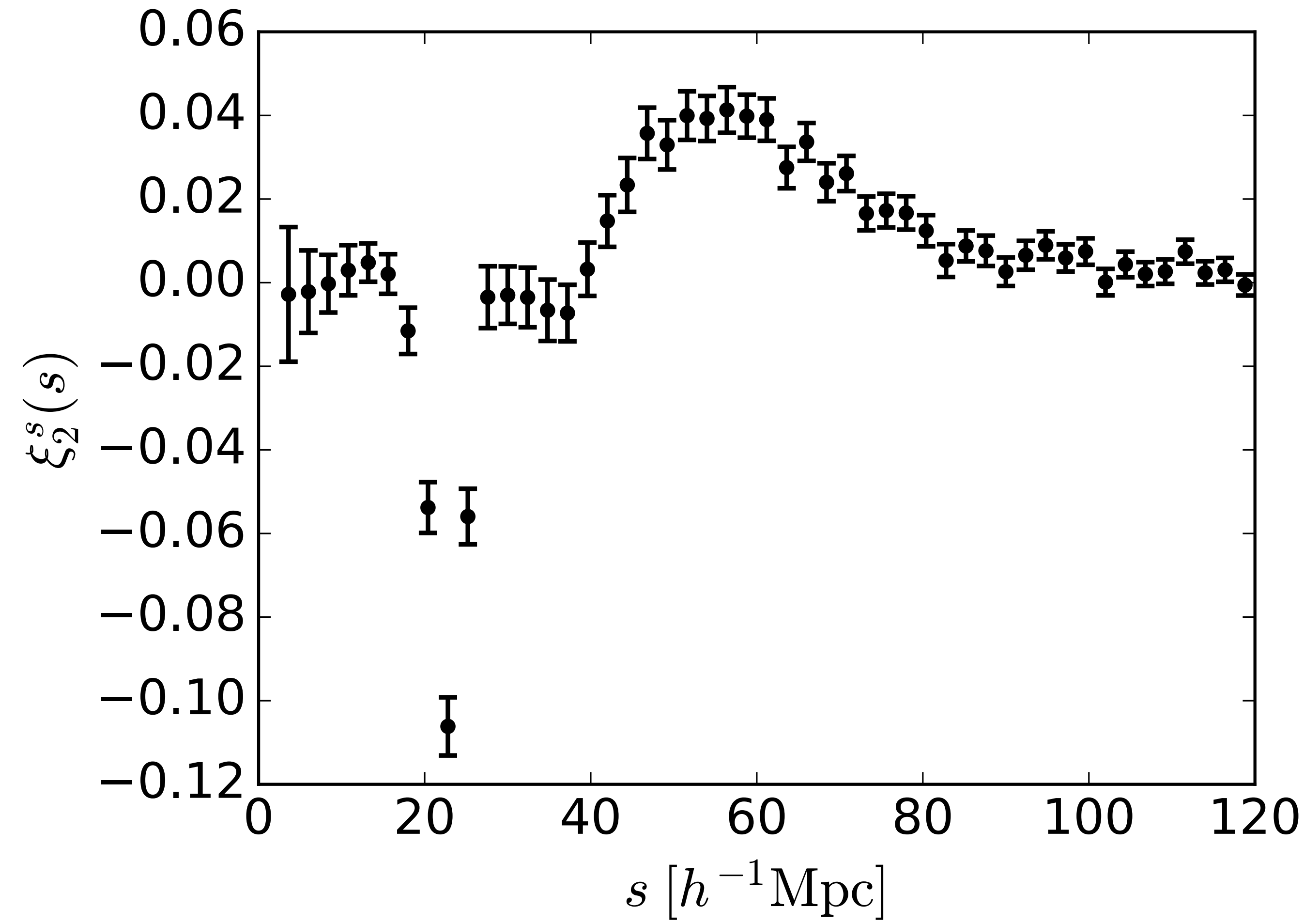
To linear order, only **monopole** and **quadrupole** are non-zero

$$\xi^s_0(s) \quad , \quad \xi^s_2(s)$$

Multipole expansion



monopole



quadrupole

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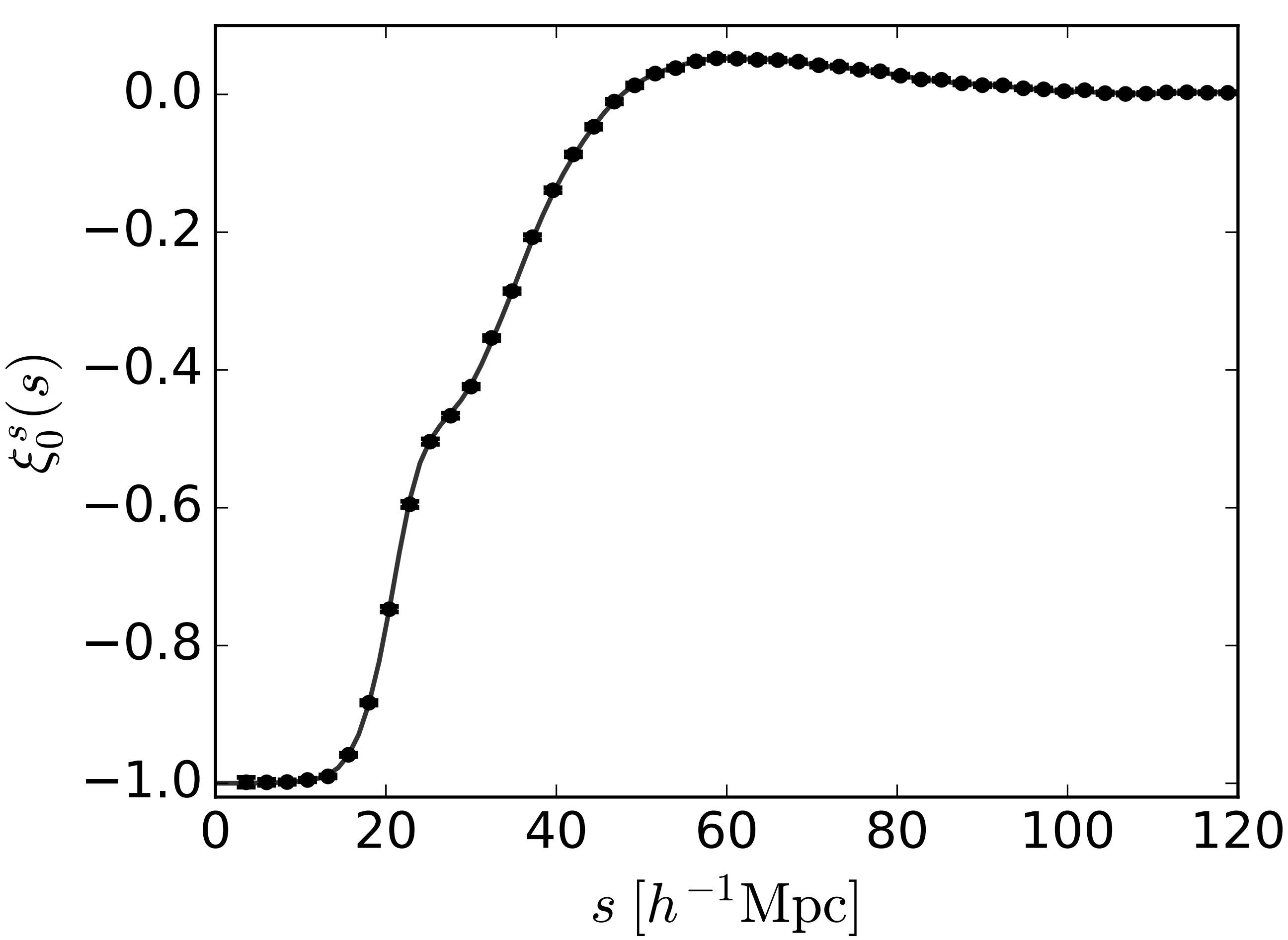
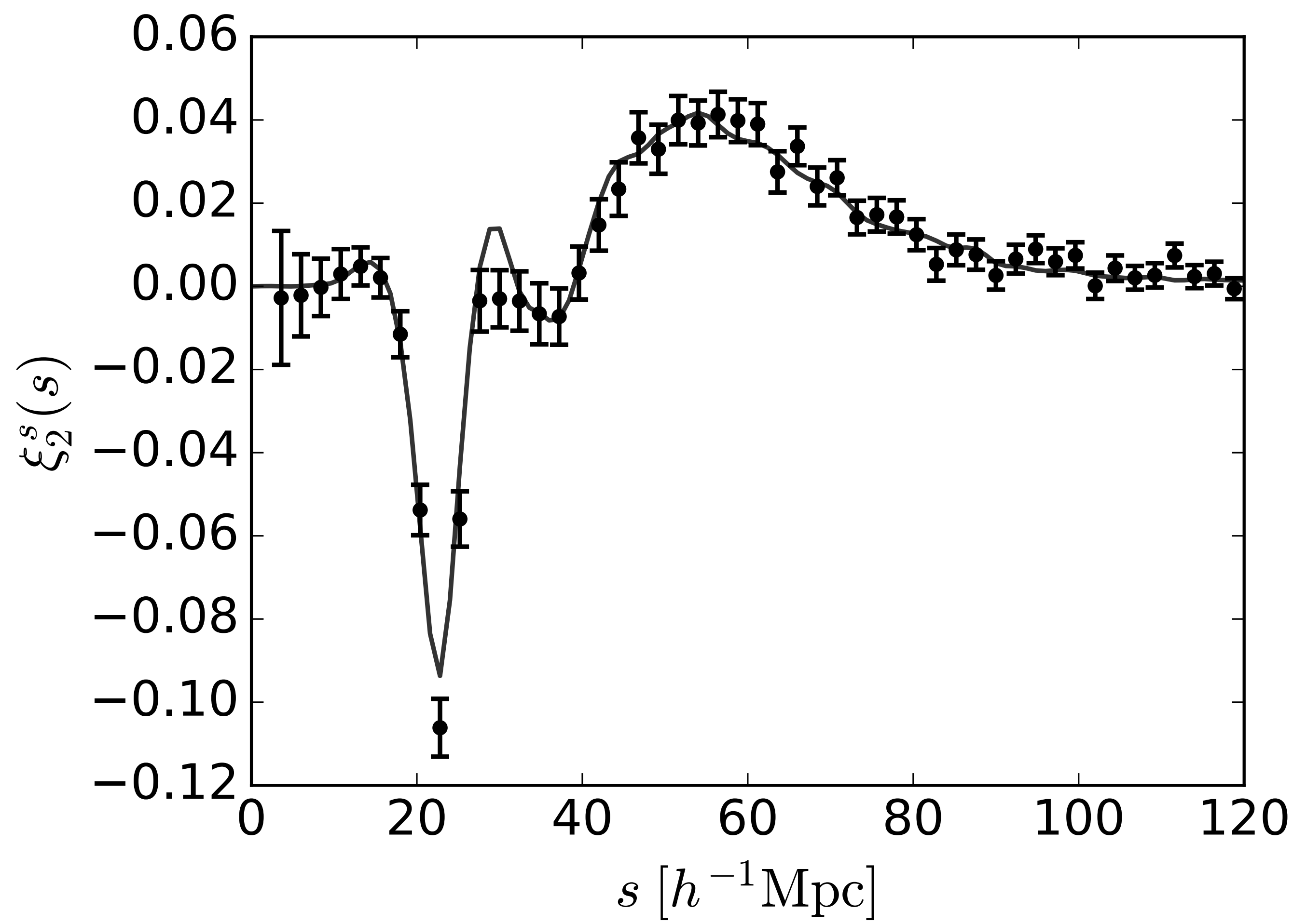
Multipole expansion



monopole



quadrupole

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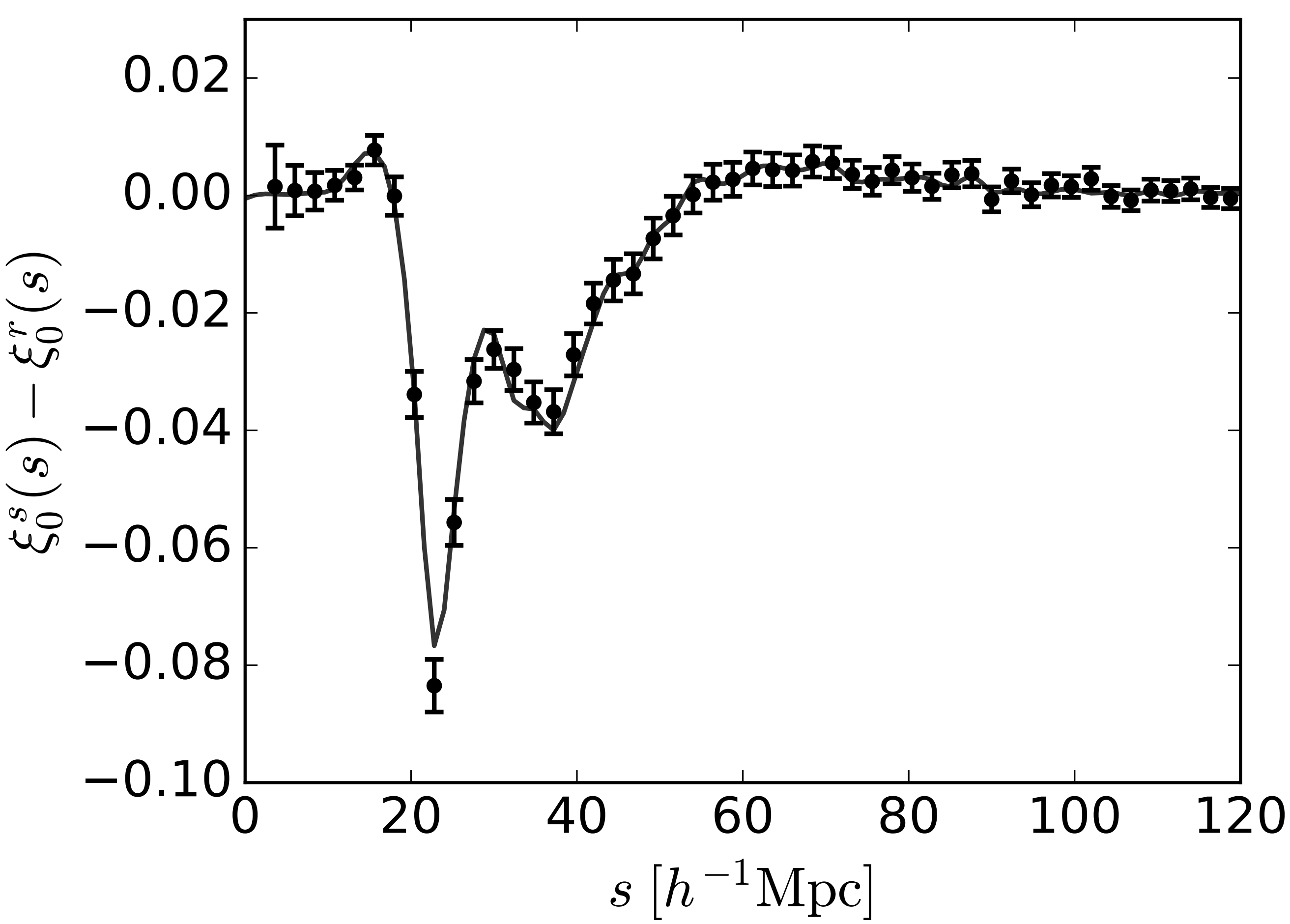
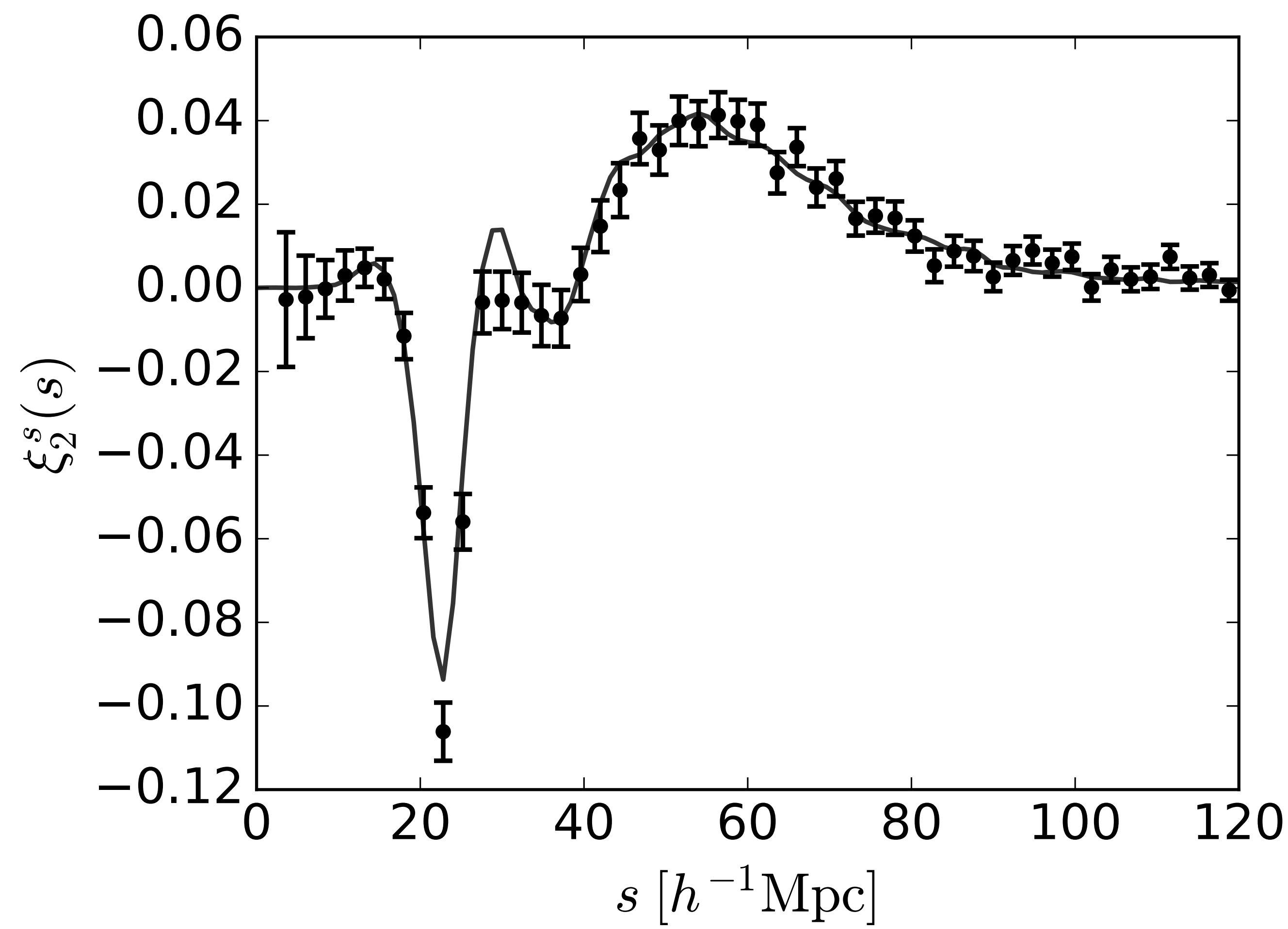
Multipole expansion



monopole difference



quadrupole

Completely linear RSD model works well **on all scales**

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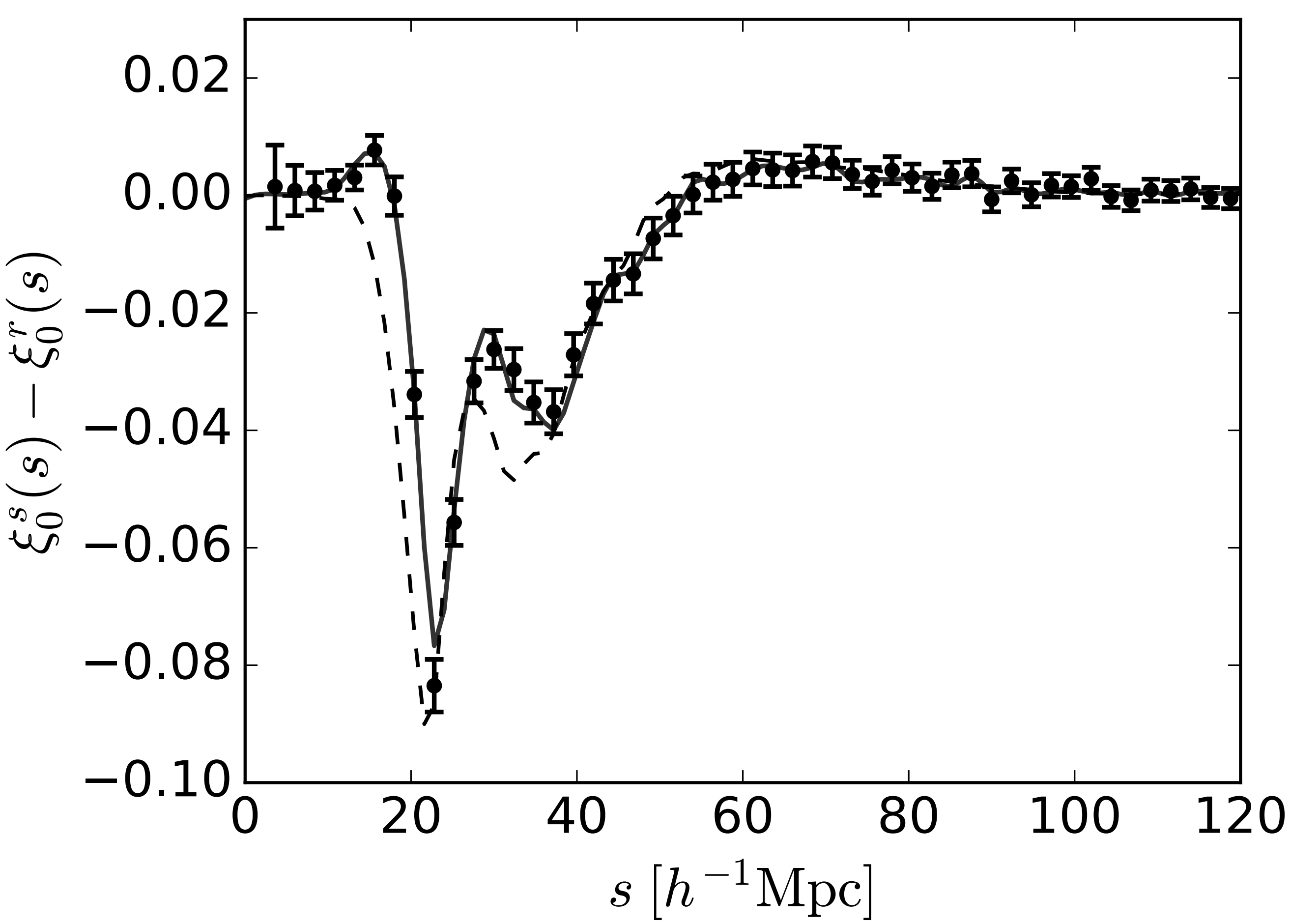
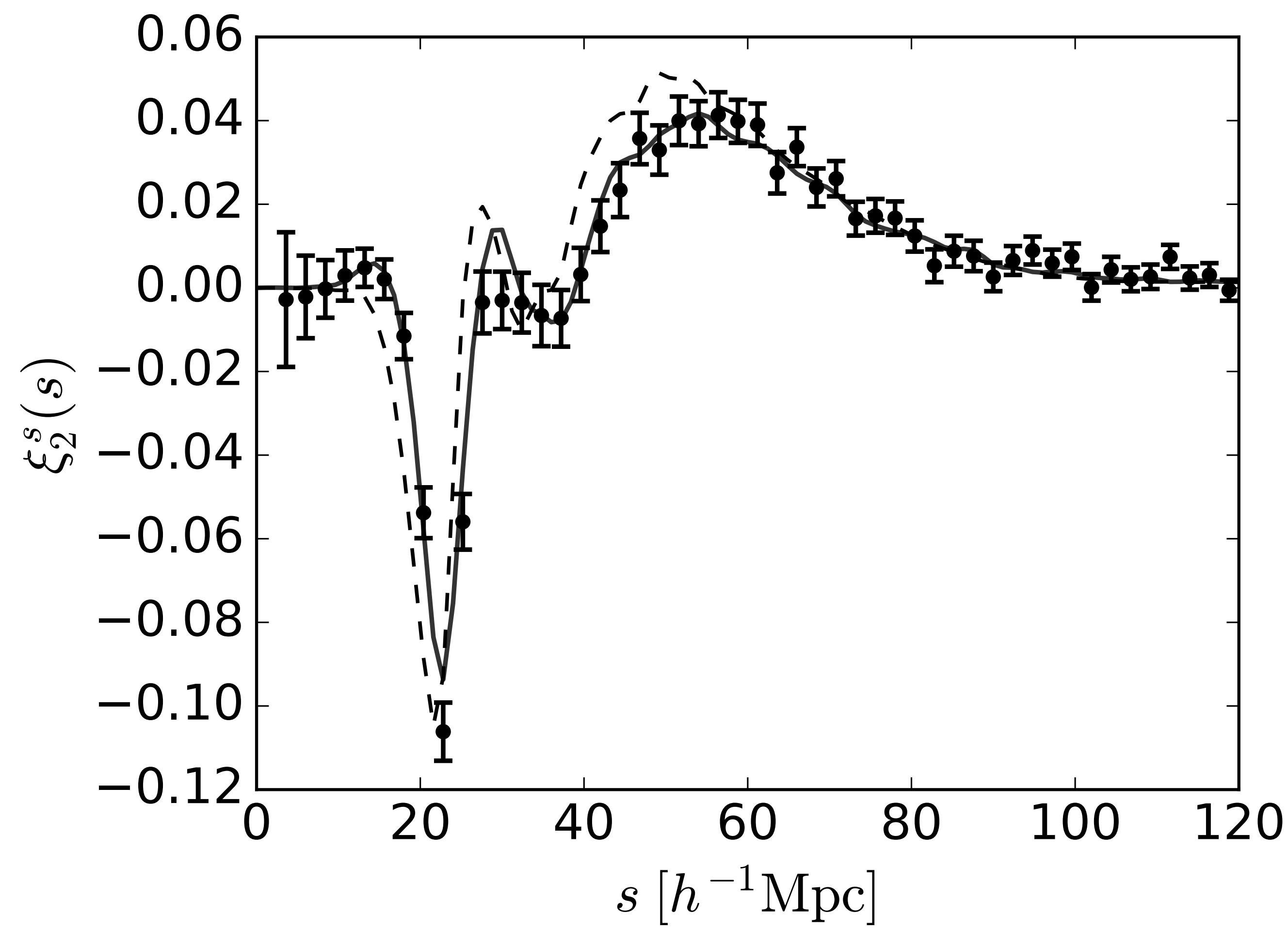
Multipole expansion



monopole difference



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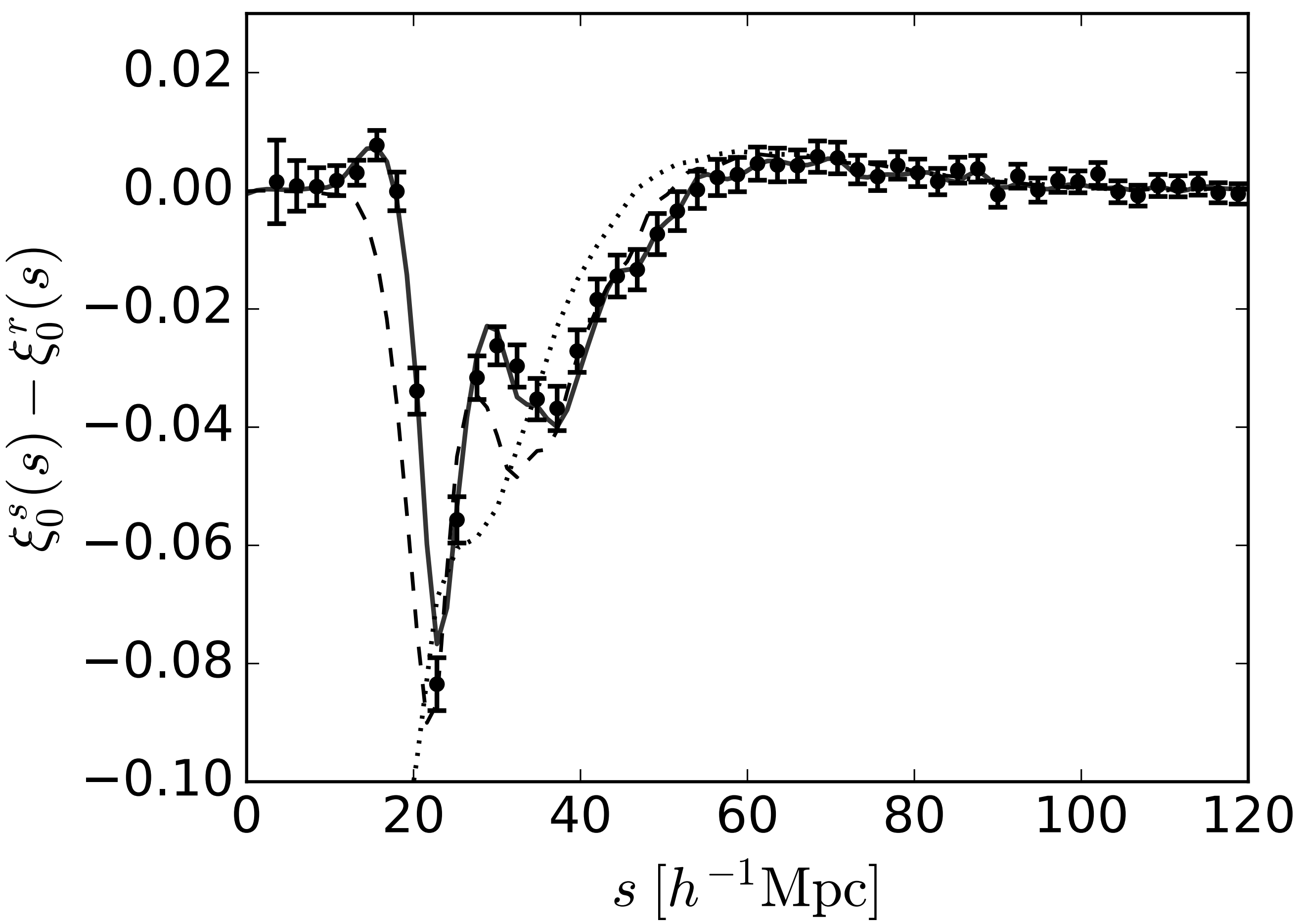
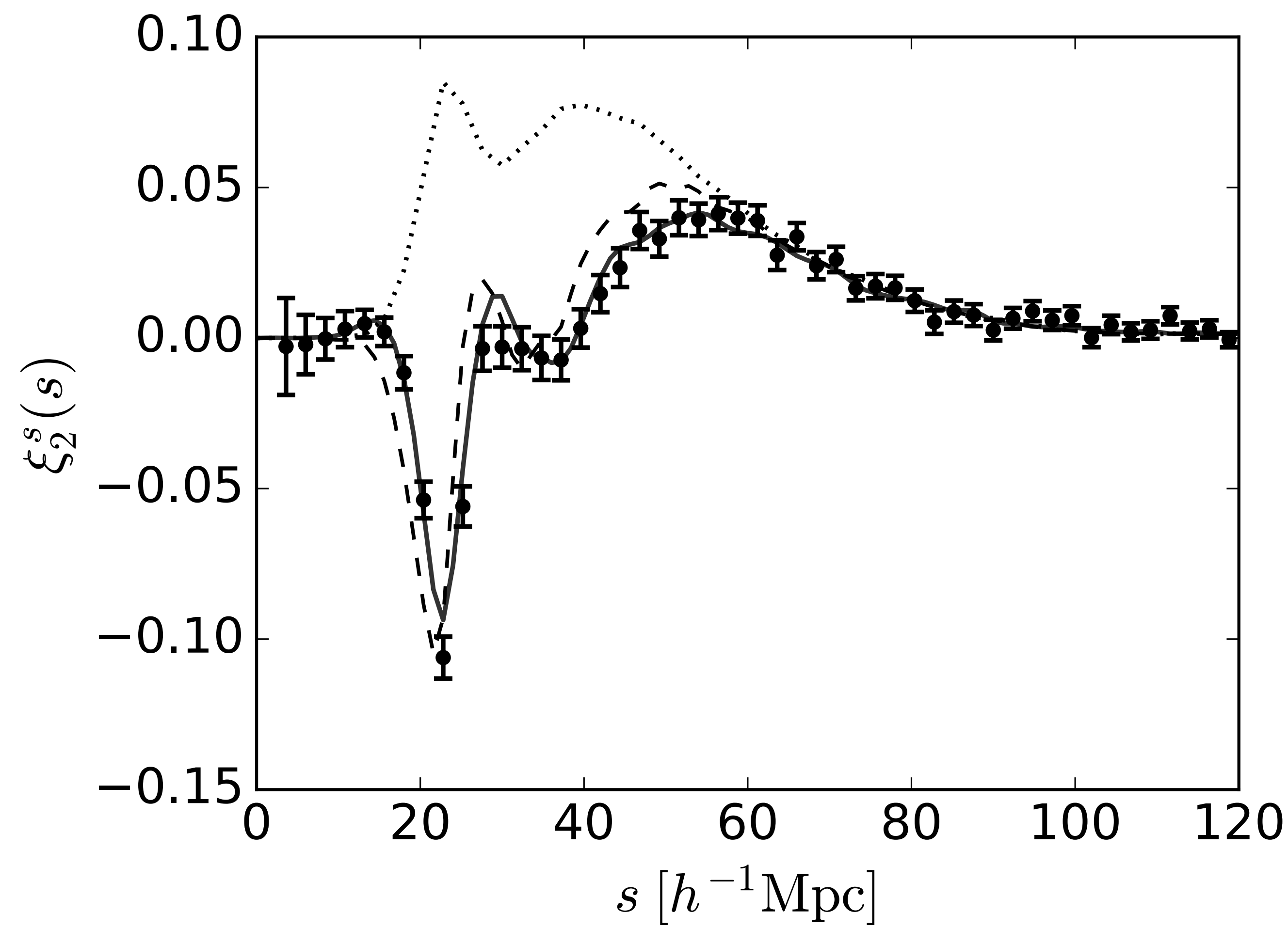


monopole difference



quadrupole

Completely linear RSD model works well **on all scales**

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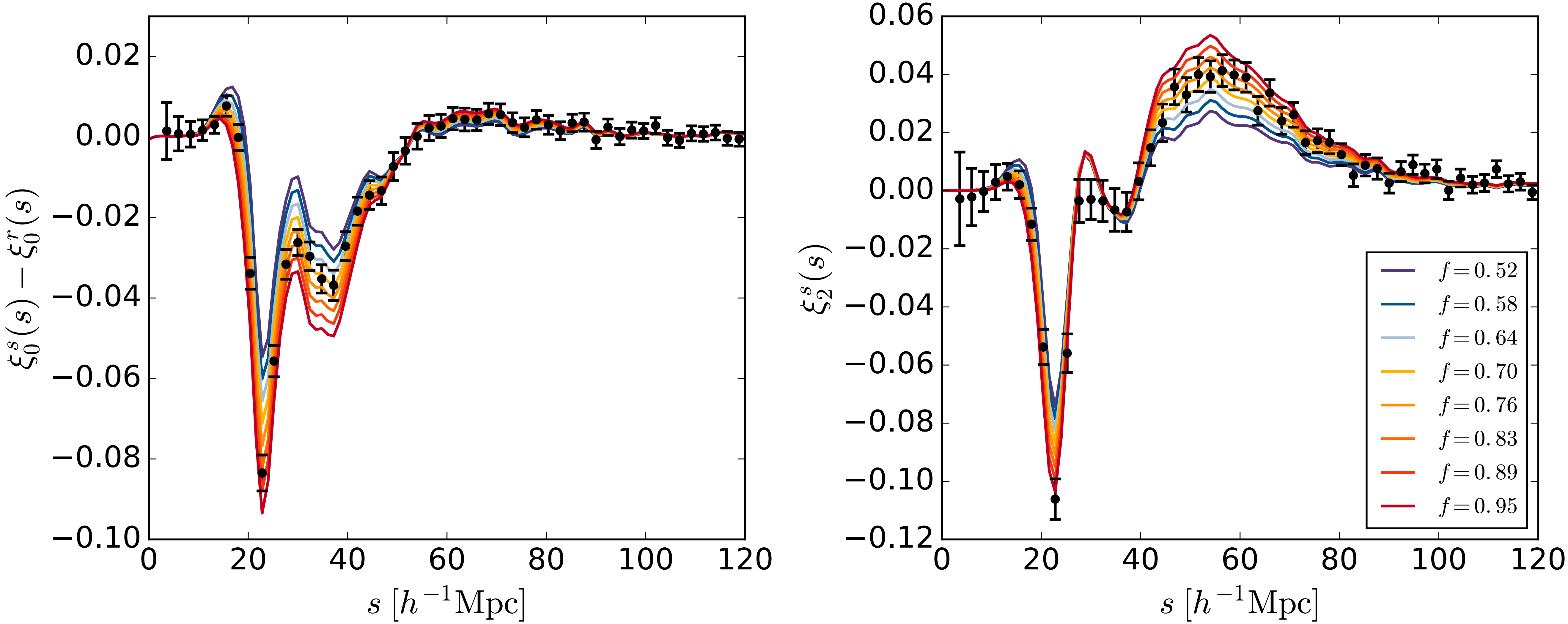
Fitting for the growth rate

Theory depends on growth rate, so can be used to fit for f



Fitting for the growth rate

Fitting requires 3 functions as input:

$$\xi^r(r)\,,\ \delta(r)\,,\ \sigma_{v_{||}}(r)$$

either from simulation OR
reconstructed from data

(must be?) calibrated from simulation

Parameter that is fit is f (not $f\sigma_8$!)

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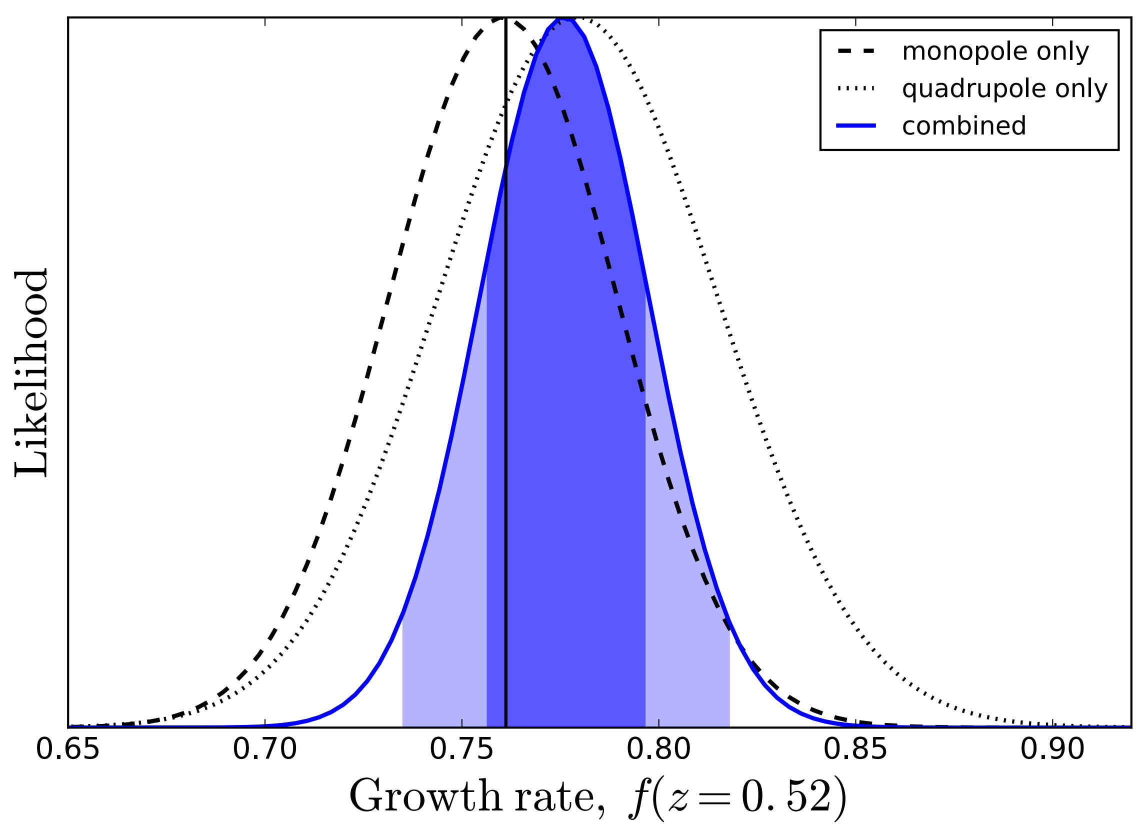

$$f = 0.78 \pm 0.02\ (2.7\%)$$

using all separation scales

$$f = 0.77 \pm 0.02\ (2.8\%)$$

using only scales within
mean void scale

$$(f_{\rm fid} = 0.761)$$

SN & Percival 2017

A major practical problem

In real data, we only have redshift-space galaxy positions

→ we only have redshift-space voids

A major practical problem

Assumption #1: number of void-galaxy pairs conserved

$$(1+\xi^s(\mathbf{s}))\,d^3s = (1+\xi^r(\mathbf{r}))\,d^3r$$

Assumption #2: RSD due to galaxy motions only

$$\mathbf{s} = \mathbf{r} + \frac{\mathbf{v}\cdot\hat{\mathbf{X}}}{aH}\hat{\mathbf{X}}$$

Assumption #3: Linear dynamics, governed by void alone

$$\mathbf{v}(\mathbf{r}) = -\frac{1}{3}faH\Delta(r)\mathbf{r} \equiv v_r\hat{\mathbf{r}} \quad ; \quad \Delta(r) \equiv \frac{3}{r^3}\int_0^r \delta(y)y^2dy$$

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Even worse than that …

e.g. void-finding

galaxy field in redshift space

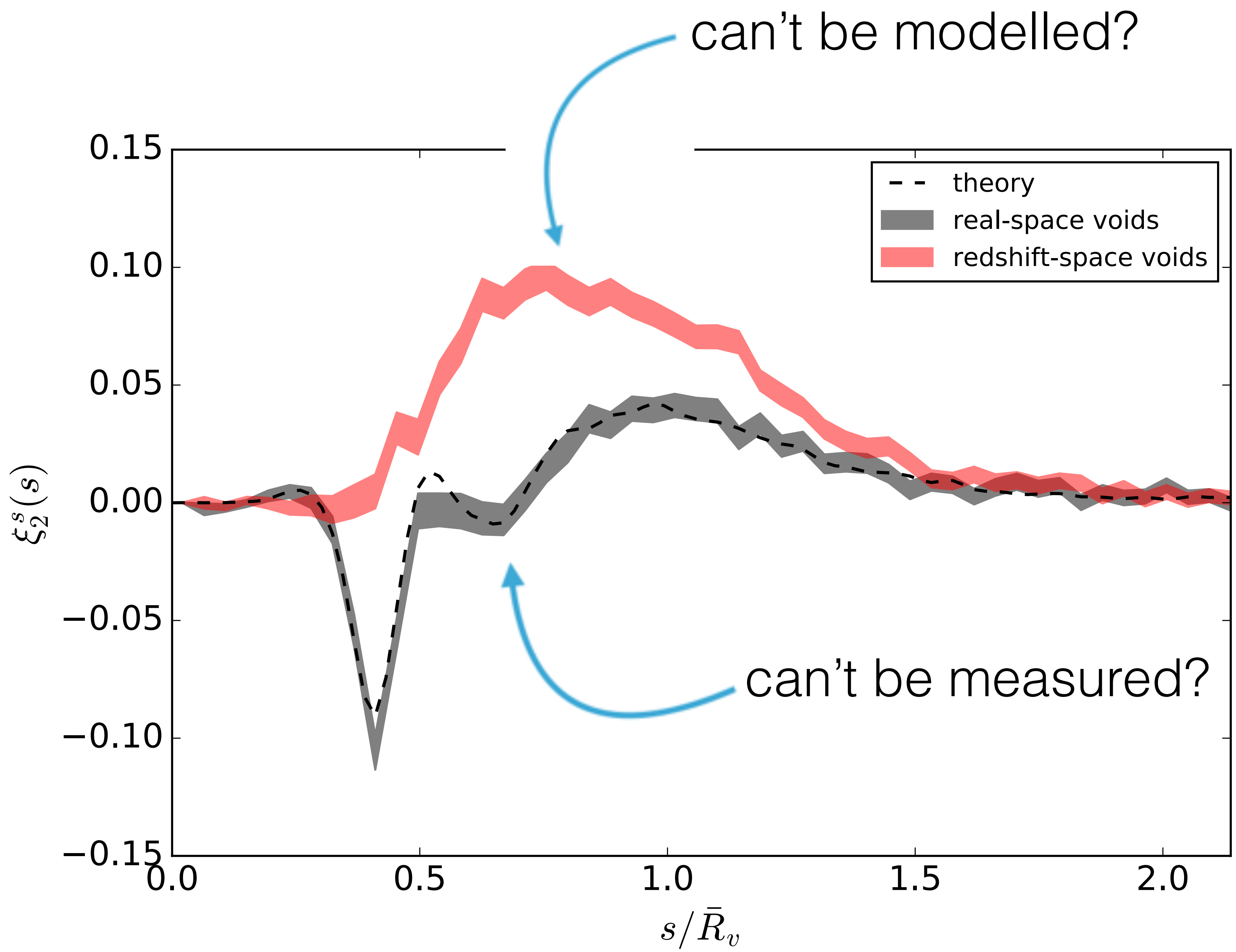
A **non-linear transformation** of a tracer density field **after RSD mapping** must have RSD itself, and also a **velocity bias**

Seljak 2012, 1201.0594

$\Longrightarrow$ Voids found in redshift-space galaxies have RSD themselves

Chuang et al 2017

A major problem



SN, Carter & Percival, in prep.

Luckily, there is a solution

Luckily, there is a solution

we can **reconstruct** the real-space galaxy field

Solution: reconstruction of real-space galaxy field

Eulerian posn. as Lagrangian posn. + displacement, $\mathbf{x}(\mathbf{q},t) = \mathbf{q} + \mathbf{\Psi}(\mathbf{q},t)$

↓

Smooth redshift-space galaxy field and solve for displacement:

$$\nabla \cdot \mathbf{\Psi} + \frac{f}{b}\nabla \cdot (\mathbf{\Psi} \cdot \hat{\mathbf{r}})\hat{\mathbf{r}} = -\frac{\delta_g}{b}$$

↓

Remove (linear, Kaiser) RSD component of displacement:

$$\Psi_{\mathrm{RSD}} = -f(\mathbf{\Psi} \cdot \hat{\mathbf{r}})\hat{\mathbf{r}}$$

↓

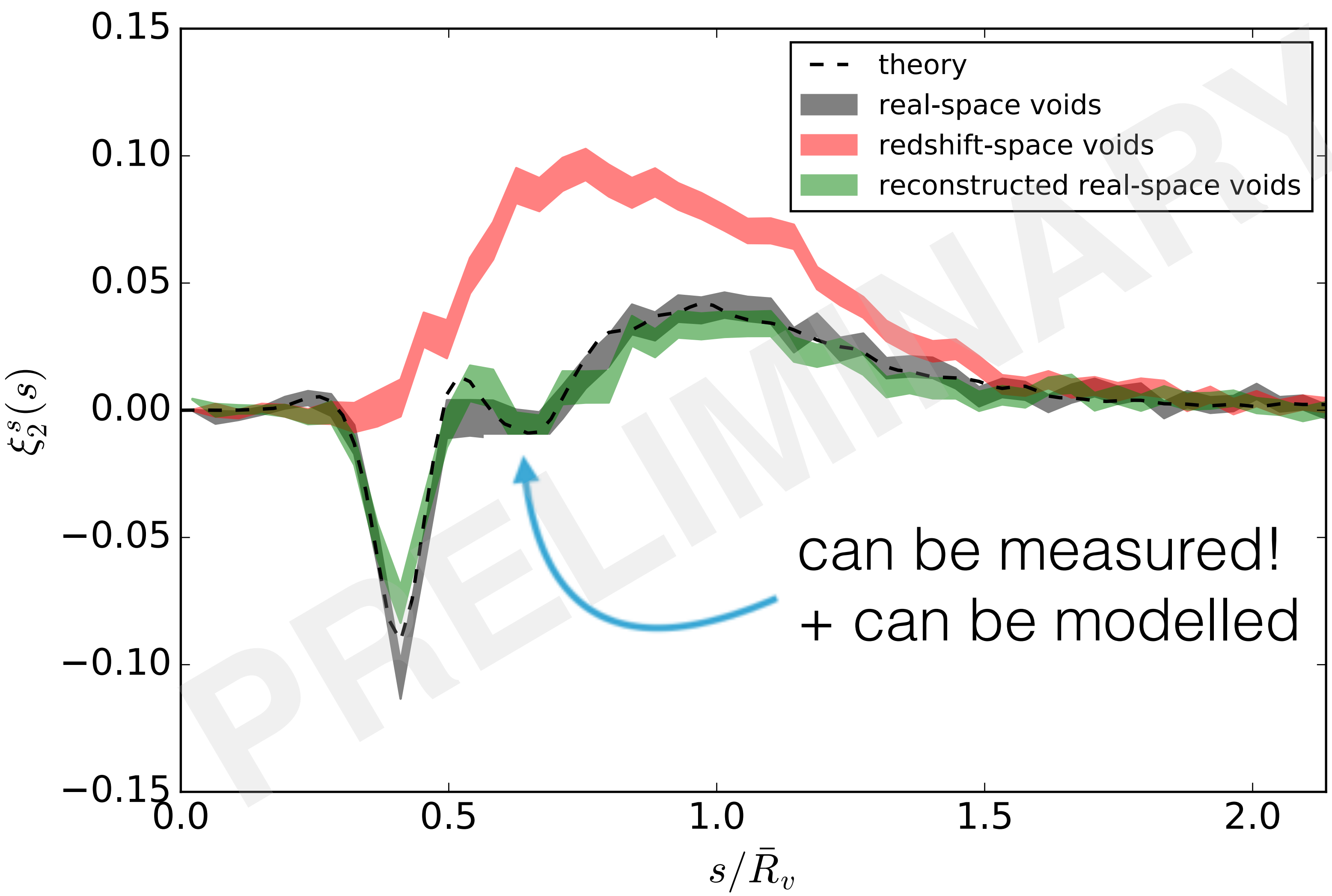
Iterate until convergence (2-3 iterations)

↓

Obtain “pseudo real-space” galaxy distribution

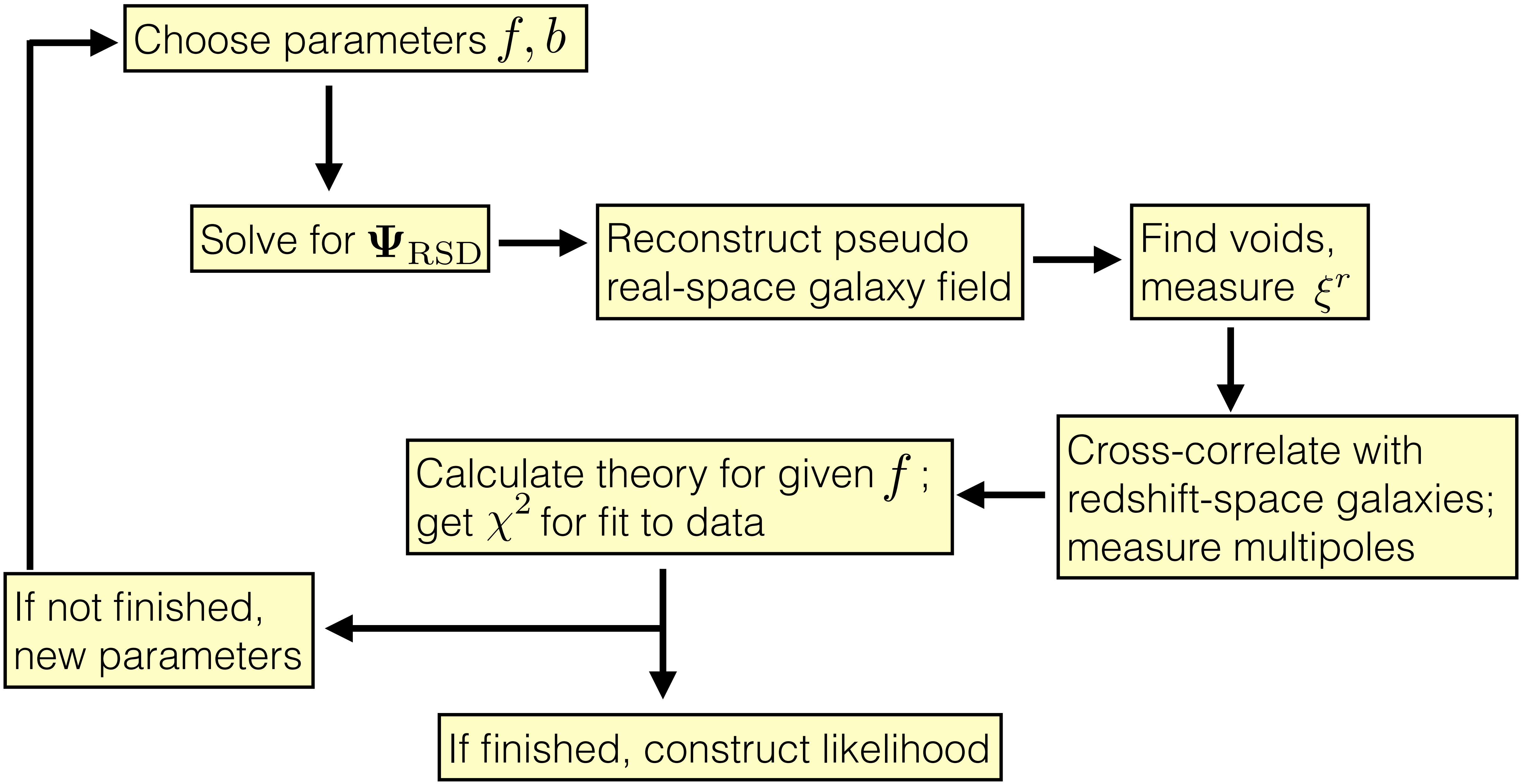
SN, Carter & Percival, in prep.

Reconstruction works



SN, Carter & Percival, in prep.

Avoiding circularity

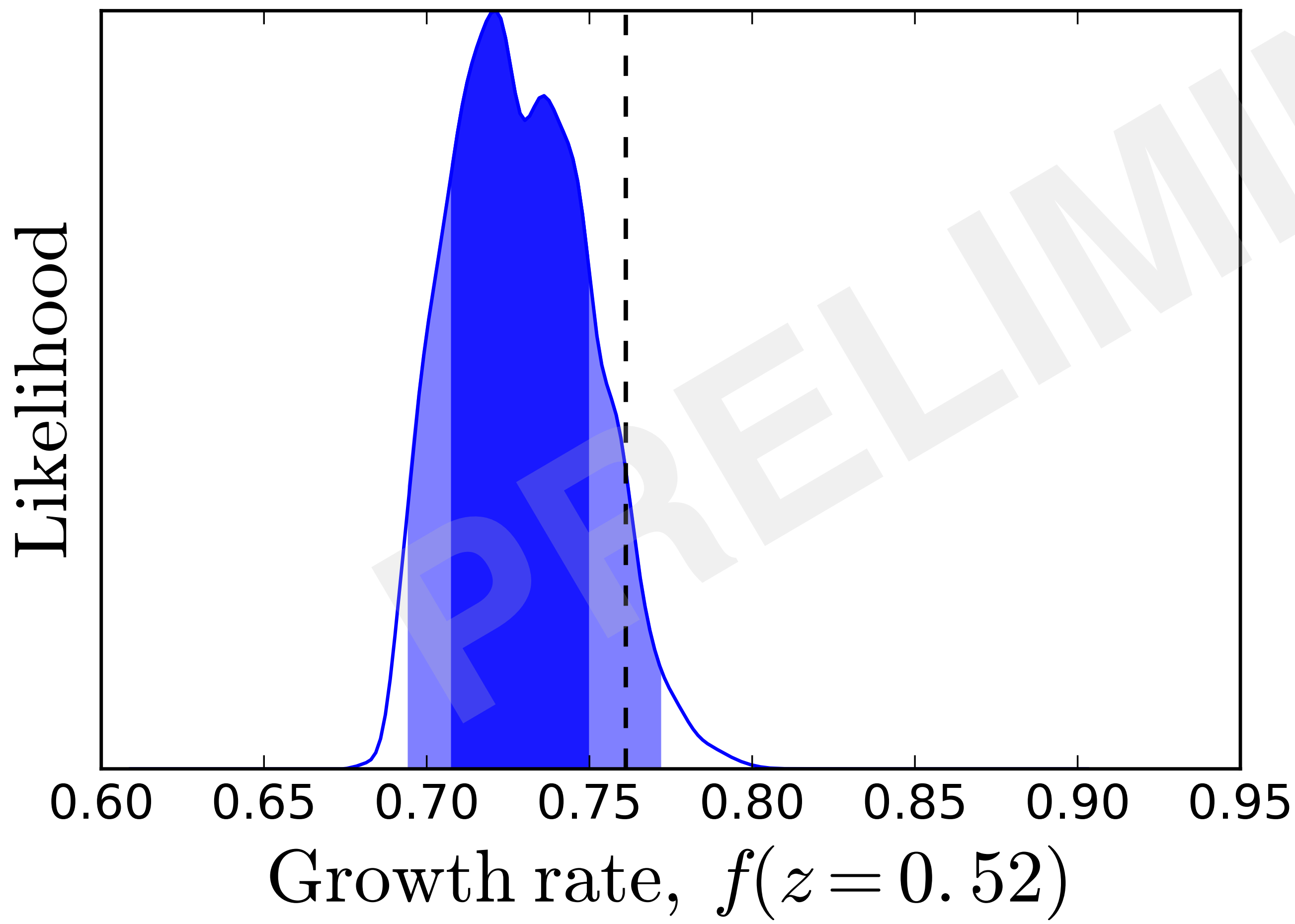


SN, Carter & Percival, in prep.

Results

Marginalising over bias, $f = 0.72^{+0.03}_{-0.01}$ (68% c.l.)

consistent with fiducial, though slightly low



$(f_{\rm fid} = 0.761)$

SN, Carter & Percival, in prep.

Summary

- Void-galaxy RSD measurements probe interesting physics, not the same as galaxy correlation
- A completely linear RSD model is sufficient on all scales!
- We made major improvements in the modelling
- The improved model allows precise constraints on growth rate *in low density regions*
- Practical issues with measurement are very important, but can be mostly solved using a reconstruction technique
- Further investigation very much required!