Redshift-space distortion systematics and Mitigations

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Outline of the talk

- Quick introduction to RSD.
- RSD modelling.
- List of potential systematics.
  - Including overview of current RSD constraints (heavily biased towards BOSS).

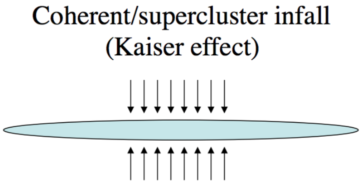
The redshift of a galaxy has two velocity components which we can't distinguish (easily)

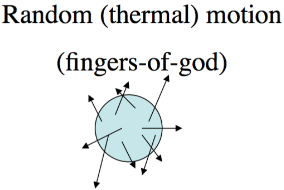
$$\vec{s} = \vec{r}\left(1 + \frac{u(\vec{r})}{r}\right).$$

On linear scales the effect is proportional to $\beta = \frac{f(z)}{b_1}$ with the growth rate

$$\frac{d(\ln D(z))}{d(\ln a)} = f(z) \approx \Omega_m^{\gamma}(z),$$

where γ depends on the theory of gravity. So we can test the matter content of the Universe and/or the underlying gravity theory.





Modelling linear galaxy clustering

- Establish a connection between the galaxy density field and the matter density field (galaxy bias, b_1).
- Model the anisotropy due to RSD as suggested by Kaiser (1987), Cole et al. (1995), Peacock & Dodds (1996)

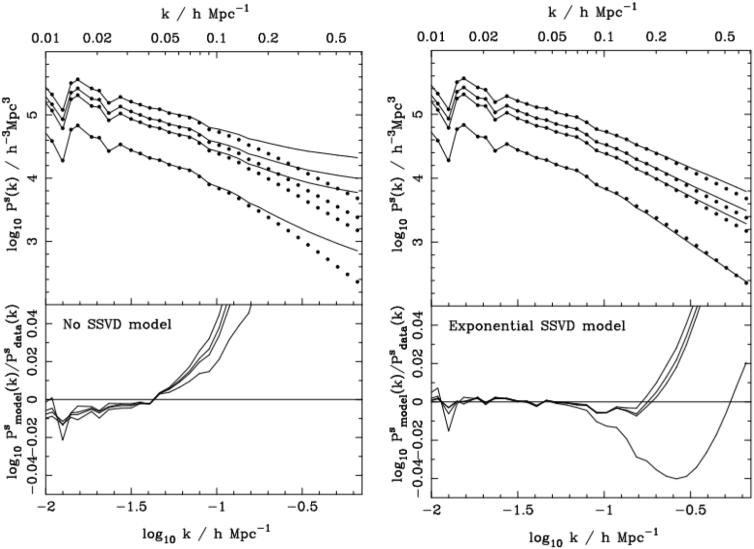
$$P^s_{\rm lin}(k,\mu) = (b_1 + f\mu^2)^2 P_{\rm lin}(k) e^{-(k\sigma_{FoG}\mu)^2}.$$

- The Alcock-Paczynski effect also introduces anisotropy

$$F(z) = (1+z)D_A(z)H(z)/c,$$

which has a different shape-dependence than RSD, if one has a large dynamic range.

- FoG are already a 10% effect by $s \sim 25h^{-1}$Mpc [$k \sim 0.15$].



Percival & White (2008)

Modelling non-linear galaxy clustering

Most of the information is on small scales, so we have to understand non-linear physics:

- Non-linear matter clustering δ_m.
- Non-linear RSD (non-linear velocity field).
- Non-linear relation between δ_m and δ_g (bias).

PT approach for non-linear effects

There have been numerous approaches to model RSD in BOSS

- Gaussian streaming models (Reid et al. 2014, Samushia et al. 2016)
- Convolution Lagrangian Perturbation Theory (Satpathy et al. 2017)
- Kaiser + pert. inspired P_{real} (Sanchez et al. 2016)
- Renormalised PT model (Beutler et al. 2016, Gil-Marin et al. 2016)
- Distribution function model (Hand et al. 2017)
- EFT (in preparation)

PT approach for non-linear effects

Based on renormalized perturbation theory (Taruya et al. 2011, McDonald & Roy 2009, Saito et al. 2014)

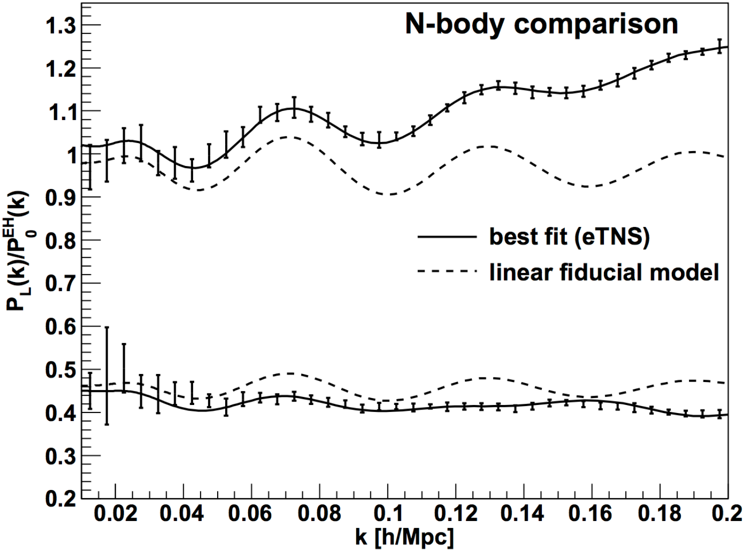
$$
\begin{aligned}
P_{\rm g}(k,\mu) = \exp\left\{-(fk\mu\sigma_v)^2\right\}\Big[&P_{{\rm g},\delta\delta}(k) \\
&+ 2f\mu^2 P_{{\rm g},\delta\theta}(k) + f^2\mu^4 P_{\theta\theta}(k) \\
&+ b_1^3 A(k,\mu,\beta) + b_1^4 B(k,\mu,\beta)\Big],
\end{aligned}
$$

with

$$
\begin{aligned}
P_{{\rm g},\delta\delta}(k) &= b_1^2 P_{\delta\delta}(k) + 2b_2 b_1 P_{b2,\delta}(k) + 2b_{s2} b_1 P_{bs2,\delta}(k) \\
&\quad + 2b_{\rm 3nl} b_1 \sigma_3^2(k) P_{\rm m}^{\rm L}(k) + b_2^2 P_{b22}(k) \\
&\quad + 2b_2 b_{s2} P_{b2s2}(k) + b_{s2}^2 P_{bs22}(k) + N, \\
P_{{\rm g},\delta\theta}(k) &= b_1 P_{\delta\theta}(k) + b_2 P_{b2,\theta}(k) + b_{s2} P_{bs2,\theta}(k) \\
&\quad + b_{\rm 3nl}\sigma_3^2(k) P_{\rm m}^{\rm lin}(k),
\end{aligned}
$$

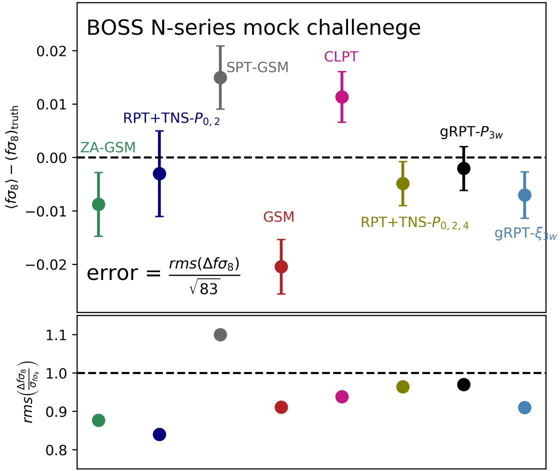
with 4 (6) free nuisance parameter

PT approach for non-linear effects



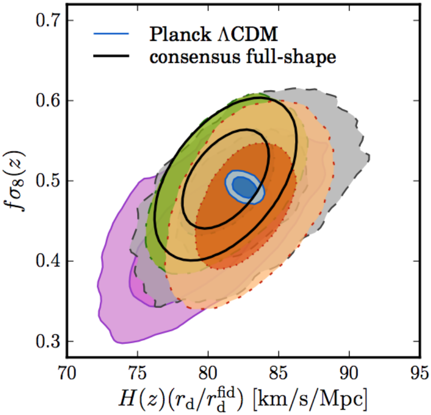
Beutler et al. (2014)

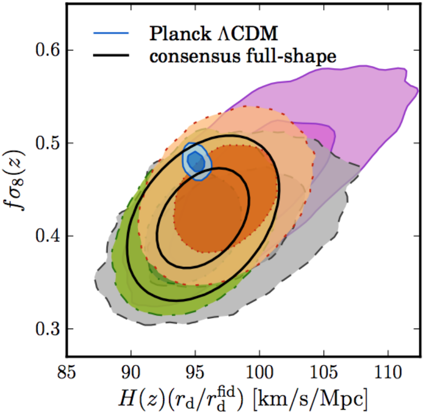
BOSS blind mock challenge



data by Jeremy Tinker

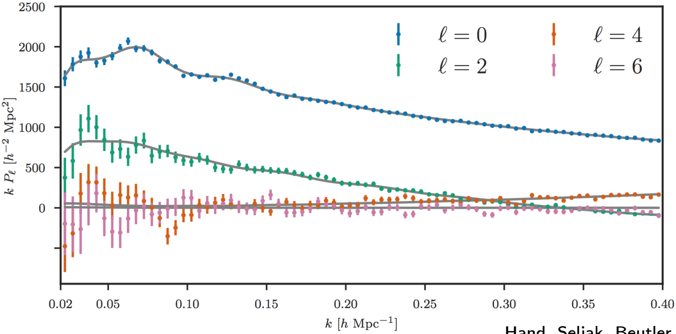
RSD in BOSS





Alam et al. (2016)

Distribution function approach



Hand, Seljak, Beutler & Vlah (2017)

- The model includes 9 (10) free nuisance parameters (based on the halo model).
- Including scales up to $k_{\max} = 0.4h^{-1}$Mpc only reduces the error on $f\sigma_8$ by 15 - 30%.
- Including the bispectrum might help constraining the PT nuisance parameters (Gil-Marin et al. 2016).

Potential systematics

- Non-linear matter clustering δ_m.
- Non-linear RSD (non-linear velocity field).
- Non-linear relation between δ_m and δ_g (bias).
- Survey geometry (window function).
- Approximations in N-point estimators (wide-angle effects etc.).
- Cosmological/theoretical assumptions (e.g. neutrino mass).
- The baryon-dark matter relative velocity (Tseliakhovich & Hirata 2010).
- Fibre collisions or in general any correlation of failure rate with the underlying density field.
- Galaxy tidal alignment (Martens et al. 2018), correlations of galaxy density and stellar density (Ross et al. 2012) or in general any correlation of selection probability with the underlying density field.
- Galaxy assembly bias.
- Non-Gaussian likelihood distributions (Hahn et al. 2018).
- The connection between the galaxy density and the matter density might be non-local (non-local bias).

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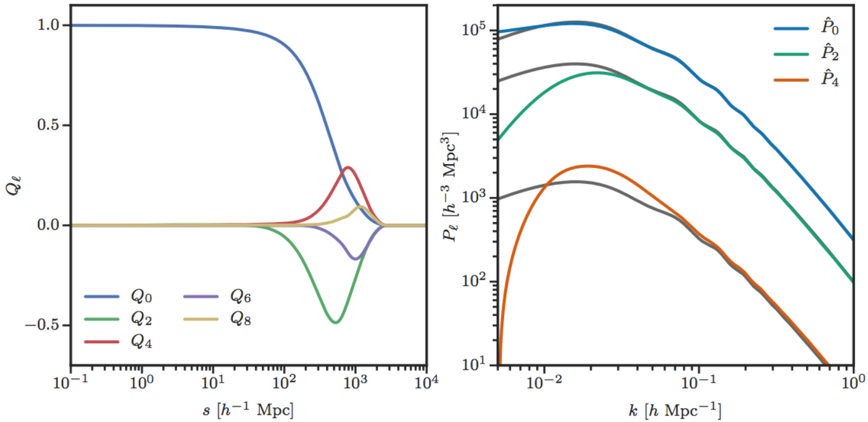
Survey geometry (window function) in BOSS



Hand, Seljak, Beutler & Vlah (2017)

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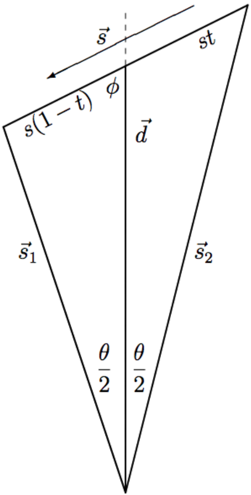
The Fourier-space FFT-based estimators use an approximation

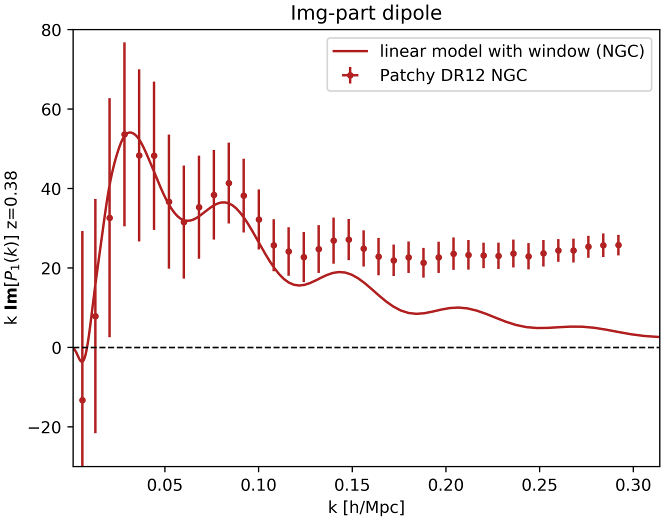
$$P_\ell(k) = (2\ell+1)\int \frac{d\Omega_k}{4\pi} \int d\vec{s}_1 d\vec{s}_2 \delta(\vec{s}_1)\delta(\vec{s}_2) e^{-i\vec{k}\cdot\vec{s}} \mathcal{L}_\ell(\hat{k}\cdot\hat{s}_1),$$

which breaks the symmetry of the pair and introduces wide-angle effects.



Castorina & White (2018)

Approximations in N-point estimators (preliminary)



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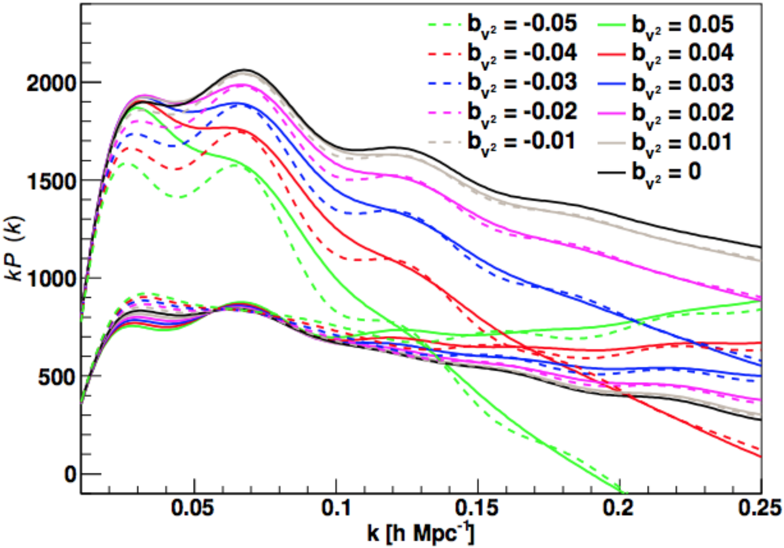
The baryon-dark matter relative velocity

Based on Yoo & Seljak (2011), Schmidt (2015) & Blazek et al. (2014)

$$
\begin{aligned}
P_g(k,\mu) = P_{\mathrm{g,NL}}(k,\mu) &+ b_{v^2}\Big[b_1 P_{\delta|v^2}(k) + b_2 P_{\delta^2|v^2}(k) \\
&+ b_s P_{s^2|v^2}(k) + b_{v^2} P_{v^2|v^2}(k)\Big] \\
&+ b_1 b_{v^2} P_{\mathrm{adv}|\delta}(k) + 2b_1 b_\delta^{\mathrm{bc}} P_{\delta|\delta_{\mathrm{bc}}} + 2b_1 b_\theta^{\mathrm{bc}} P_{\delta|\theta_{\mathrm{bc}}} \\
&- 2f\mu^2\Bigg[b_{v^2}\left(b_1 P_{\delta|v^2 v_\parallel}(k) + P_{\mathrm{adv}|\mathrm{v}_\parallel}(k)\right) \\
&- b_\theta^{\mathrm{bc}} P_{\delta|\theta_{\mathrm{bc}}} + b_\delta^{\mathrm{bc}} P_{\delta|\delta_{\mathrm{bc}}} \\
&+ b_{v^2}\left(P_{v^2|v_\parallel}(k) + P_{v^2|\delta v_\parallel}(k)\right)\Bigg] \\
&+ f^2\mu^4 b_{v^2} P_{v_\parallel|v^2 v_\parallel}(k) \\
&- f^2\mu^2 b_{v^2}\left[I_1(k) + \mu^2 I_2(k)\right],
\end{aligned}
$$

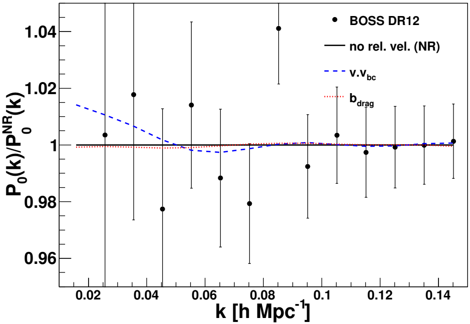
Beutler, Vlah & Seljak (2016)

The baryon-dark matter relative velocity



Beutler, Vlah & Seljak (2016)

The baryon-dark matter relative velocity

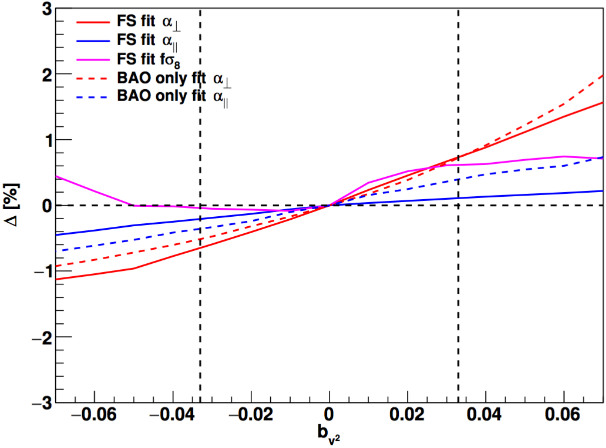


Schmidt & Beutler (2017)

BOSS, 68% (95%) confidence levels:

- $b_{v^2} = 0.012 \pm 0.015(\pm 0.031)$ (see also Slepian et al. 2016)
- $b_\delta^{\rm bc} = -1.0 \pm 2.5(\pm 6.2)$
- $b_\theta^{\rm bc} = -114 \pm 55(\pm 175)$
- $b_{\rm drag} = 140 \pm 1700(\pm 4500)$
- $b_{\rm drag,bc} = -10 \pm 10(^{+51}_{-28})$

The baryon-dark matter relative velocity



Beutler, Vlah & Seljak (2016)

Given these limits, potential shifts in the BAO measurements of BOSS are constrained to 0.53σ, 0.50σ and 0.22σ for $D_A(z)$, $H(z)$ and $f\sigma_8$, respectively

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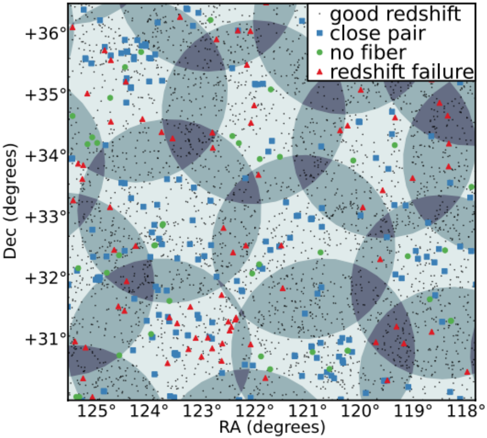
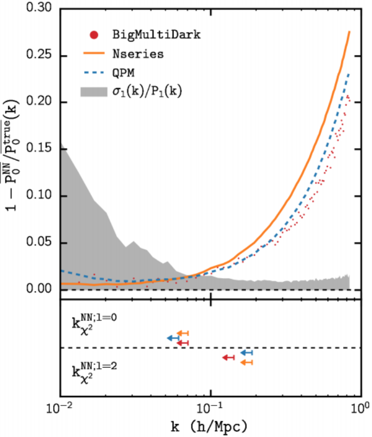
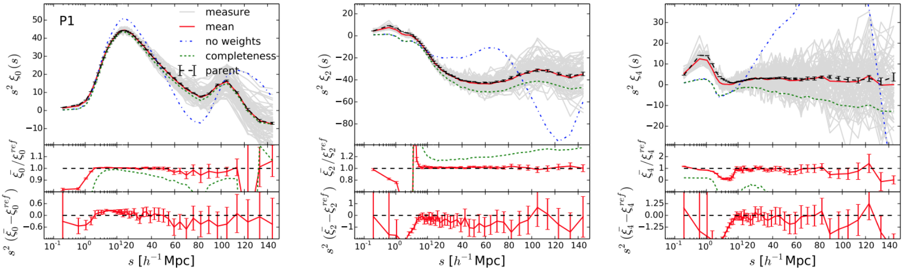
Observational systematics in BOSS





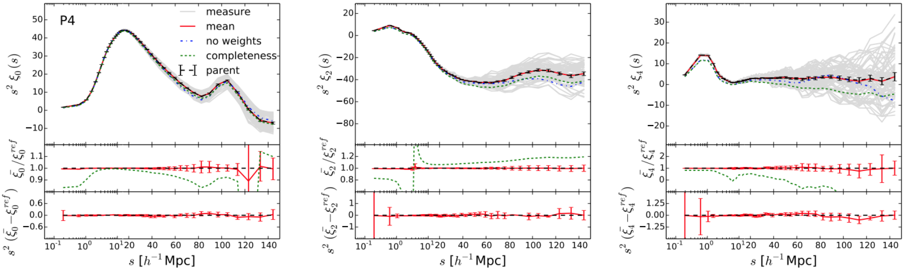
Reid et al. (2014), Hahn et al. (2016)

Observational systematics in DESI



Bianchi et al. (2017)

After 1 DESI pass (completeness 23%, worst case scenario)



Bianchi et al. (2017)

After 4 DESI passes (completeness 80%, final DESI dataset)

Mitigation strategies

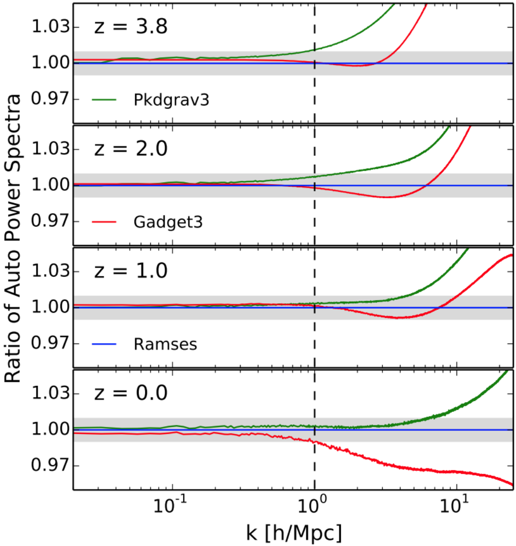
1. Modelling systematics are best handled by blind mock challenges.
   - This is becoming standard in DES/BOSS/DESI.
   - A huge amount of work!
2. Observational systematics are best handled by correlating all aspects which go into target selection or observation (e.g. seeing condition etc.).

Forward modelling approach

We can just try to model galaxy surveys using N-body simulations rather than PT:

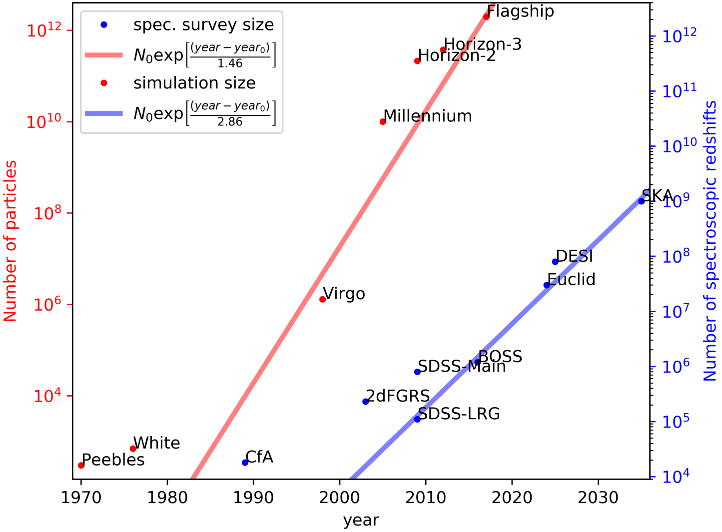
- Starting redshift, force accuracy and softening, time stepping, box size, number of particles etc.
- Running a new simulation for each MCMC step or using emulators.
- How to go from dark matter to galaxies? HOD, abundance matching... big uncertainties or many parameters.
- Observational systematics like fibre collisions or instrumental effects can be included at the level of the density field.

Precision of N-body simulations

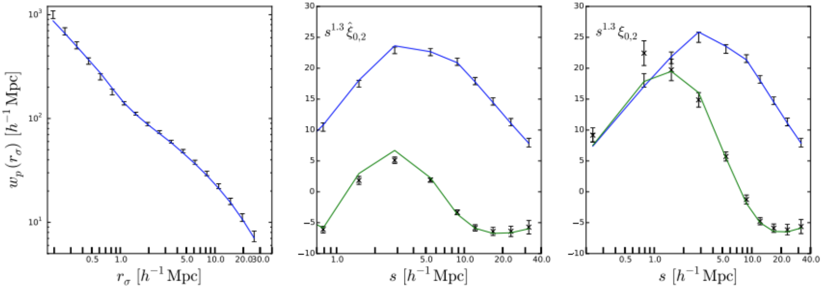


Schneider et al. (2016)

Forward modelling approach

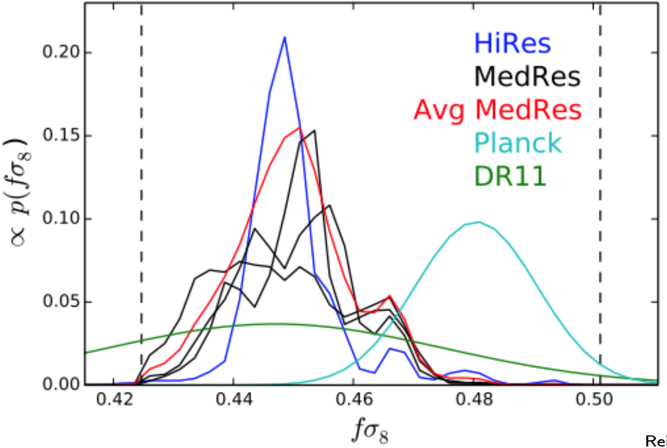


Forward modelling approach in BOSS



Reid et al. (2014)

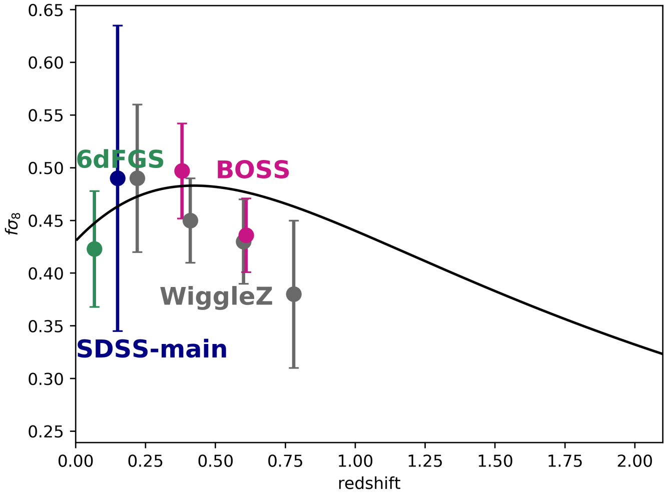
- Marginalises over HOD parameters.
- Incorporates fibre collisions using the BOSS tiling algorithm.
- Does not yet marginalised over cosmological parameters.



Reid et al. (2014)

This approach improves the constraints by a factor of ~ 2.5 compared to the PT based analysis $f\sigma_8 = 0.450 \pm 0.011$.

Look into the future



Beutler et al. (2012), Howlett et al. (2015), Blake et al. (2012), Alam et al. (2016)

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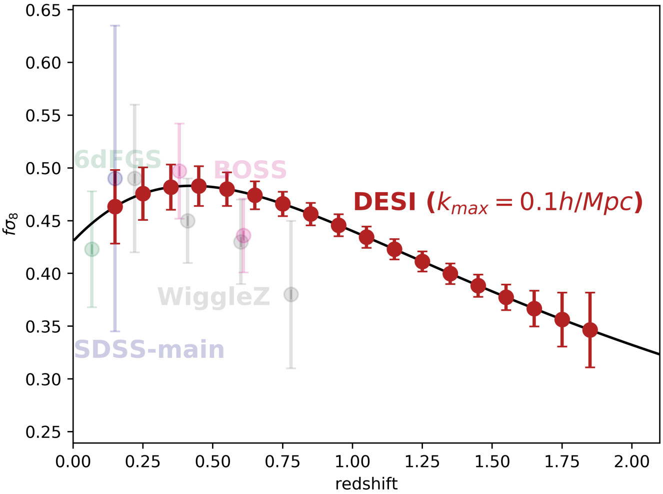

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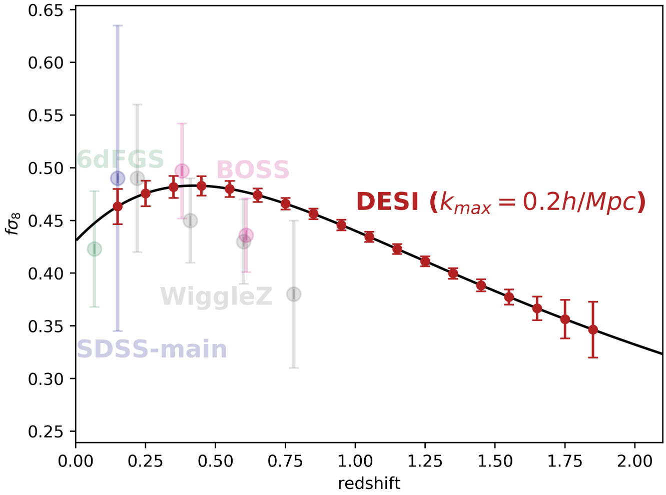

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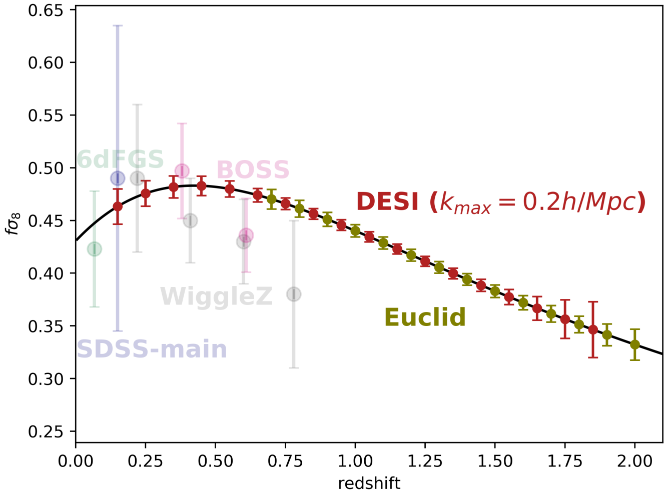
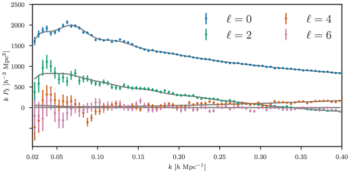
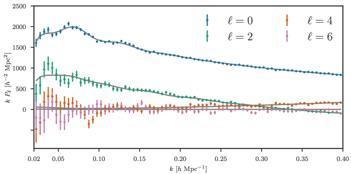
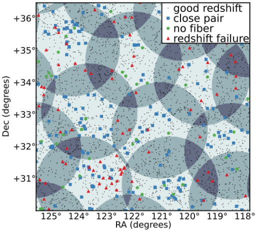


Beutler et al. (2012), Howlett et al. (2015), Blake et al. (2012), Alam et al. (2016), Font-Ribera et al. (2015), Majerotto et al. (2012)



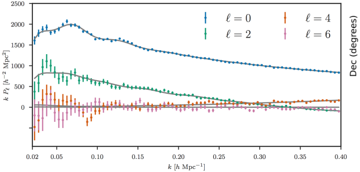
1. Modelling systematics can be handled using PT and by calibration against N-body simulations $\rightarrow$ blind mock challenges

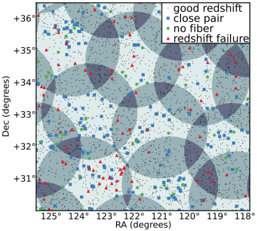


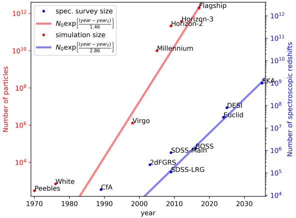


1. Modelling systematics can be handled using PT and by calibration against N-body simulations $\rightarrow$ blind mock challenges
2. Survey incompleteness (and correlations with δ) is going to be a bigger issue in DESI/Euclid compared to BOSS.

Summary







1. Modelling systematics can be handled using PT and by calibration against N-body simulations $\rightarrow$ blind mock challenges
2. Survey incompleteness (and correlations with δ) is going to be a bigger issue in DESI/Euclid compared to BOSS.
3. Forward modelling can reduce the number of nuisance parameters connected non-linear δ_m.