New Strategies for Extracting Cosmology from Galaxy Surveys @ Sesto, 2024

Enhancing Galaxy Clustering Analyses with Non-Perturbative Pairwise Velocities

Image credit: Euclid Flagship simulation

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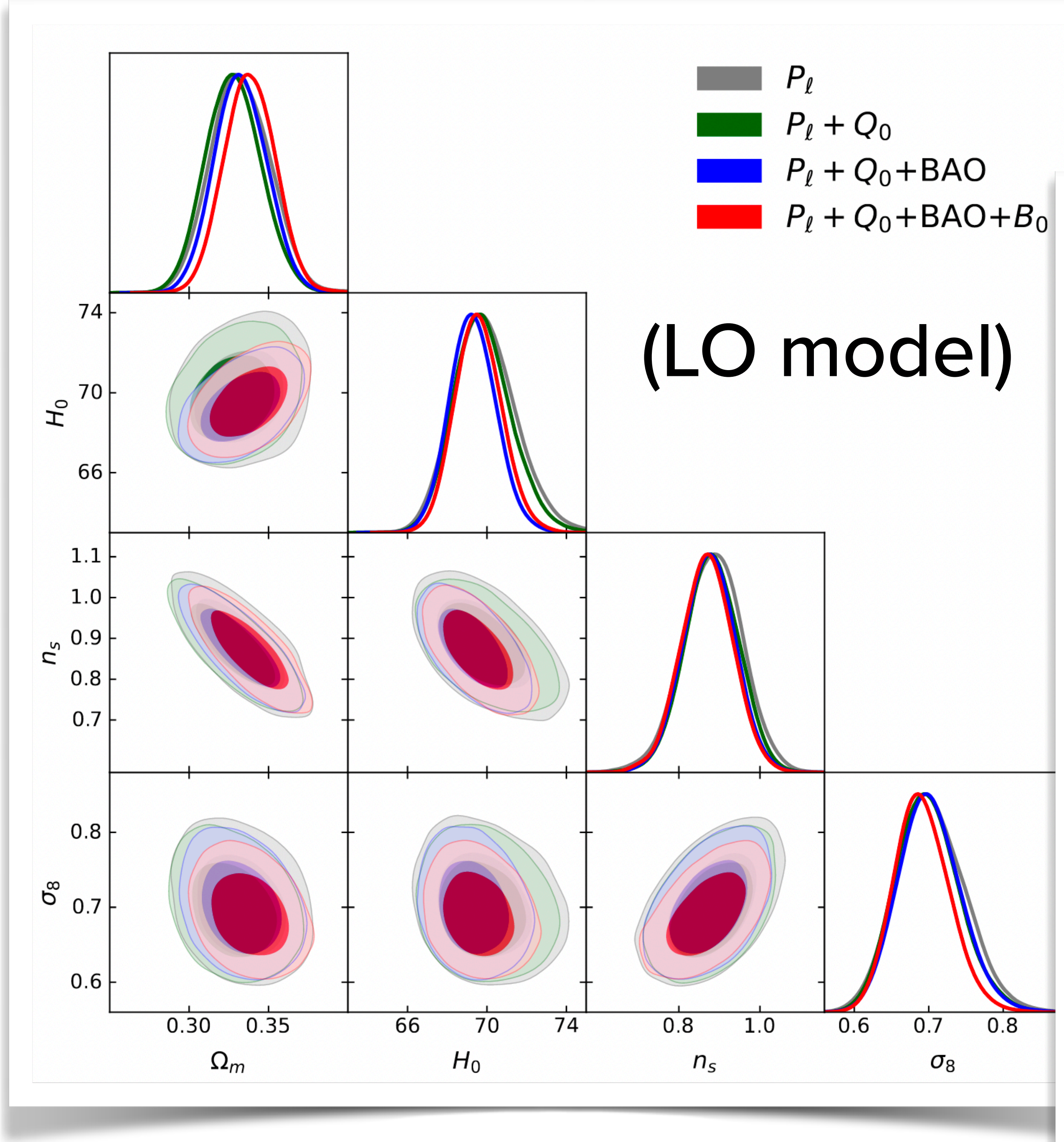
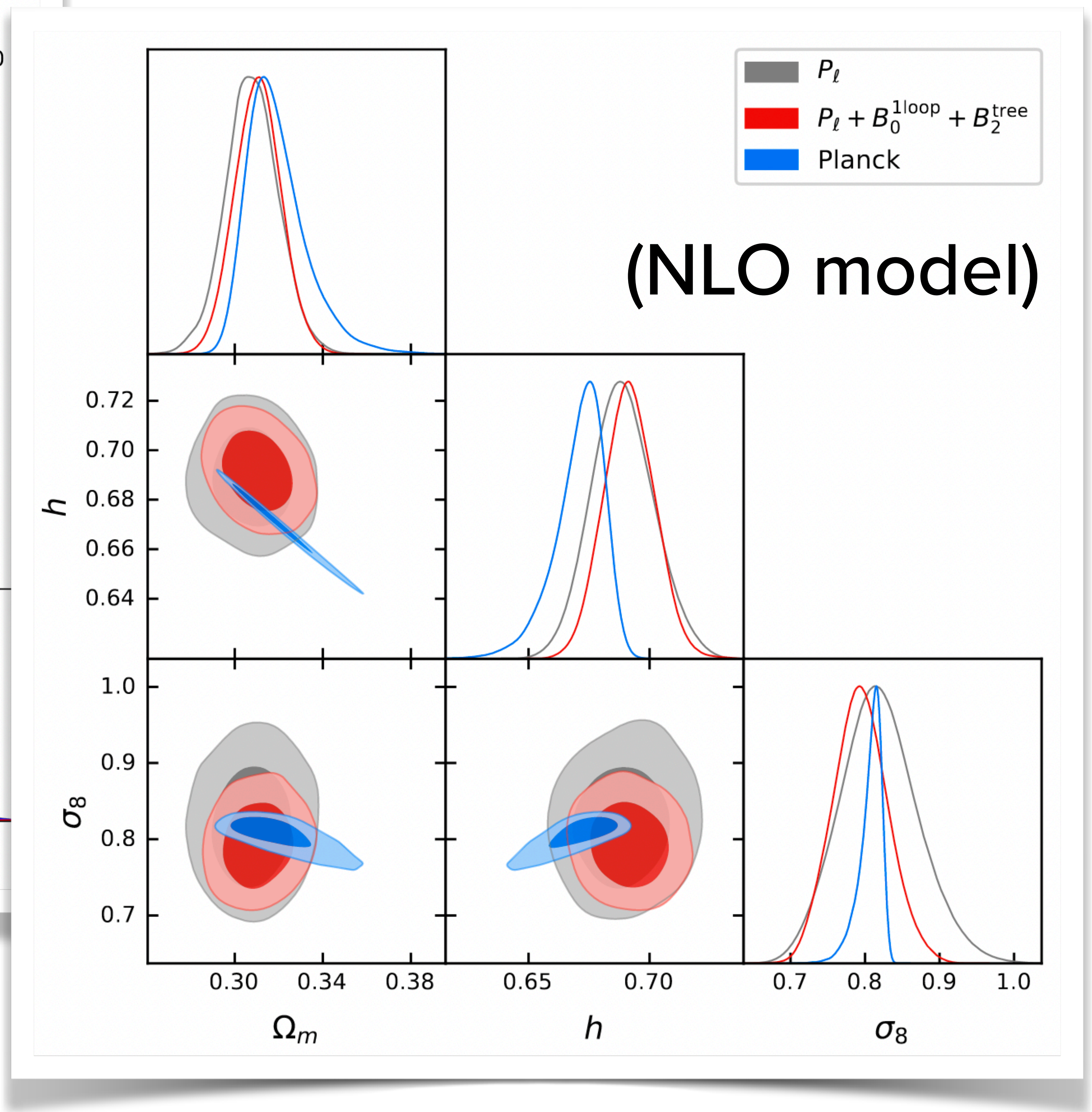
LIMITATIONS IN RECENT BISPECTRUM ANALYSES



Philcox & Ivanov 22
(also Ivanov+ 21)



D'Amico+ 22

➡ $\sim 10 - 15\,\%$ **improvement over power spectrum** by including bispectrum with leading order model, potentially more with next-to-leading-order model

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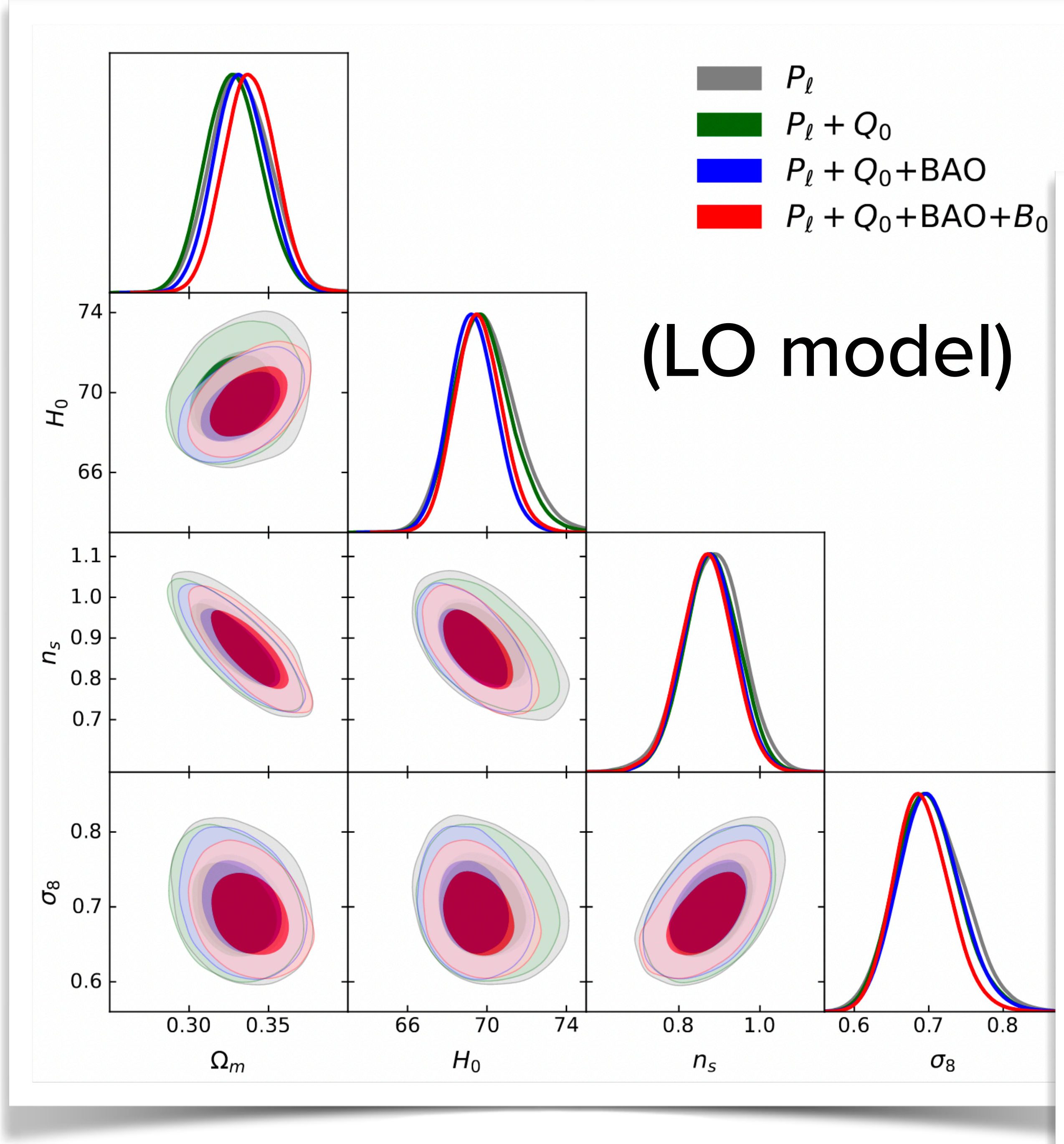

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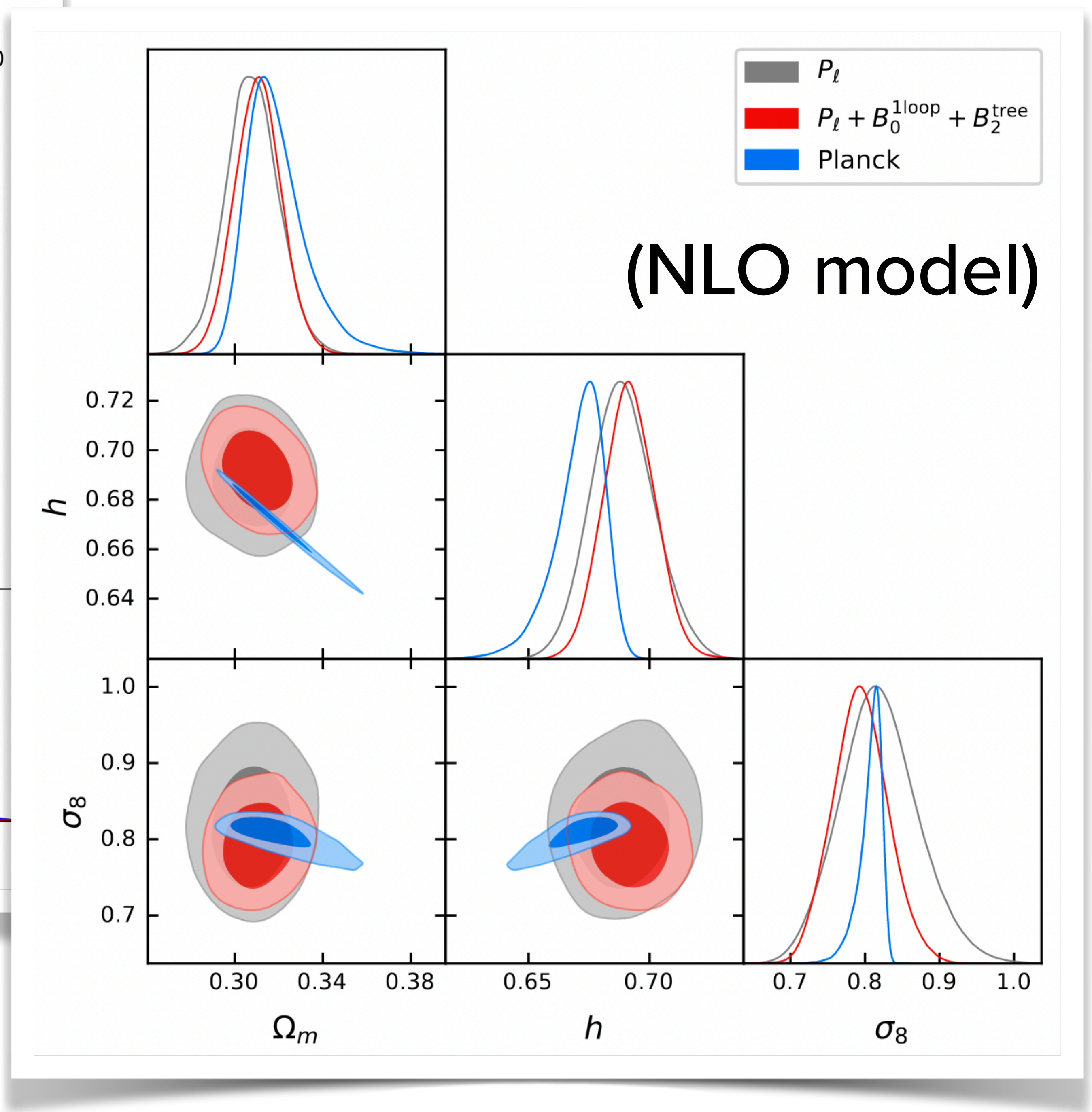
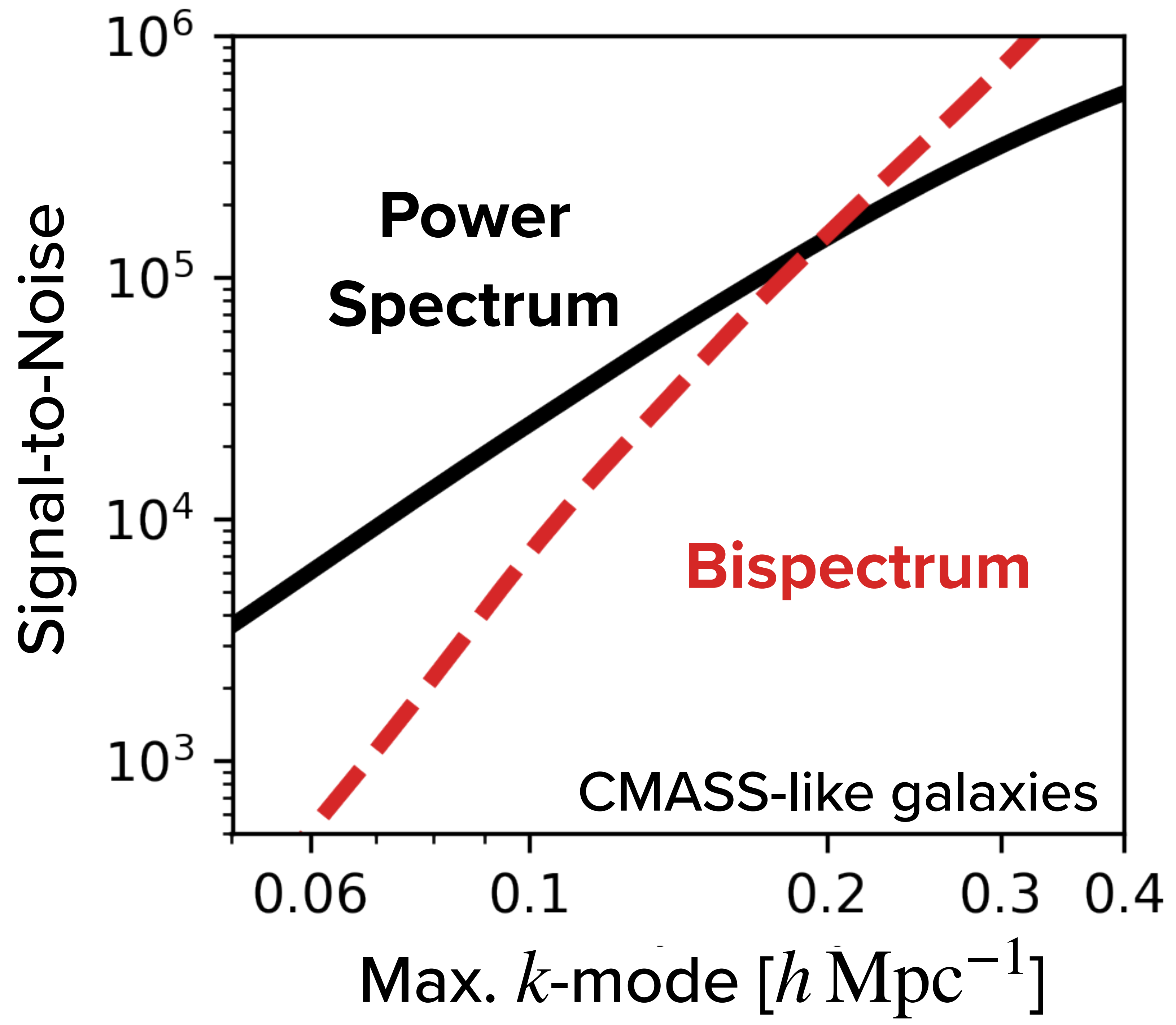


D'Amico+ 22

$\sim 10-15\,\%$ **improvement over power spectrum** by including bispectrum with leading order model, potentially more with next-to-leading-order model

Why such "little" improvements??

→ conservative scale cuts necessary, 0.08 $h\,\mathrm{Mpc}^{-1}$ for leading order model



THE REDSHIFT SPACE MAPPING

$$\boxed{\boldsymbol{s} = \boldsymbol{x} + v_{\|}\,\hat{\boldsymbol{n}}}$$

Why is it difficult to model redshift space distortions in perturbation theory?

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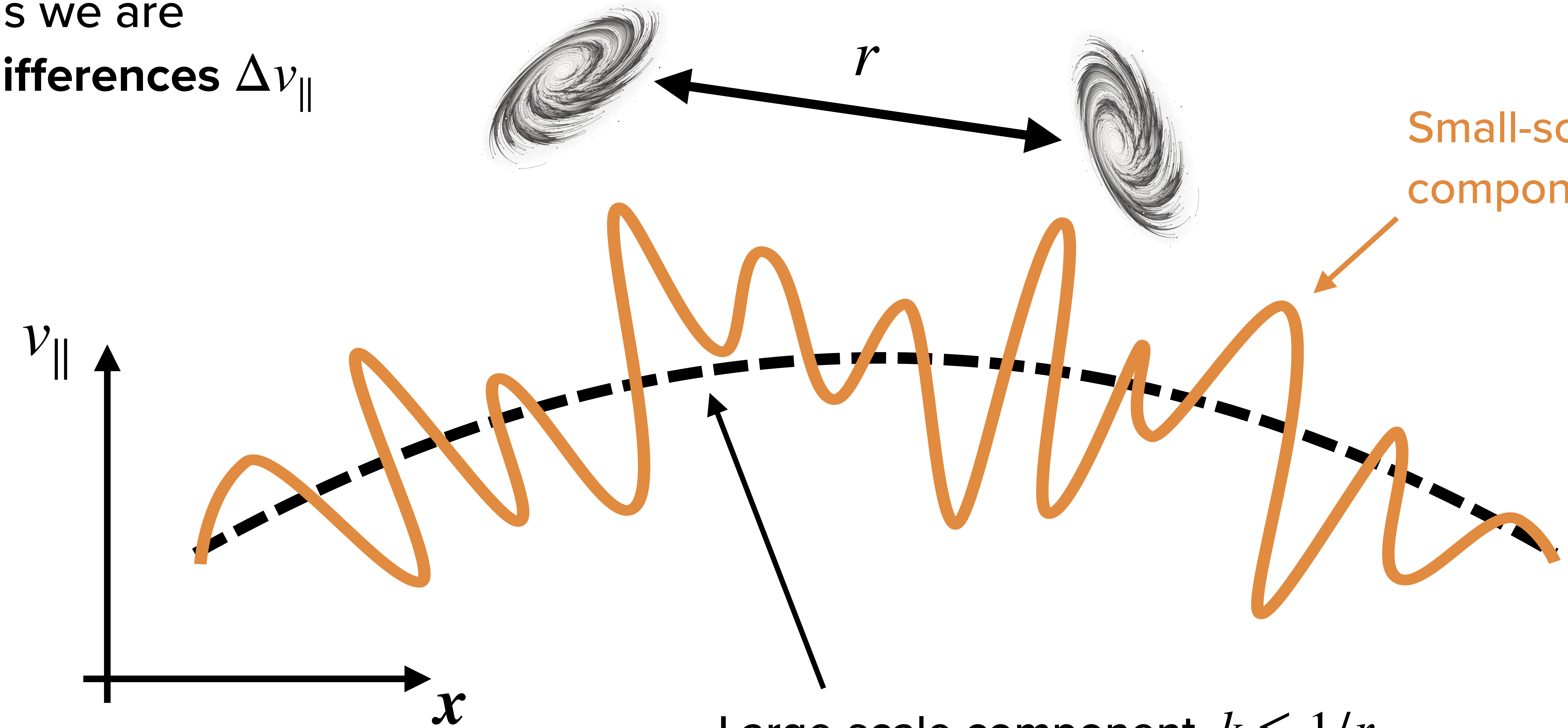
In correlation functions we are sensitive to **velocity differences** $\Delta v_{\parallel}$



Small-scale component

Large-scale component, $k \lesssim 1/r$

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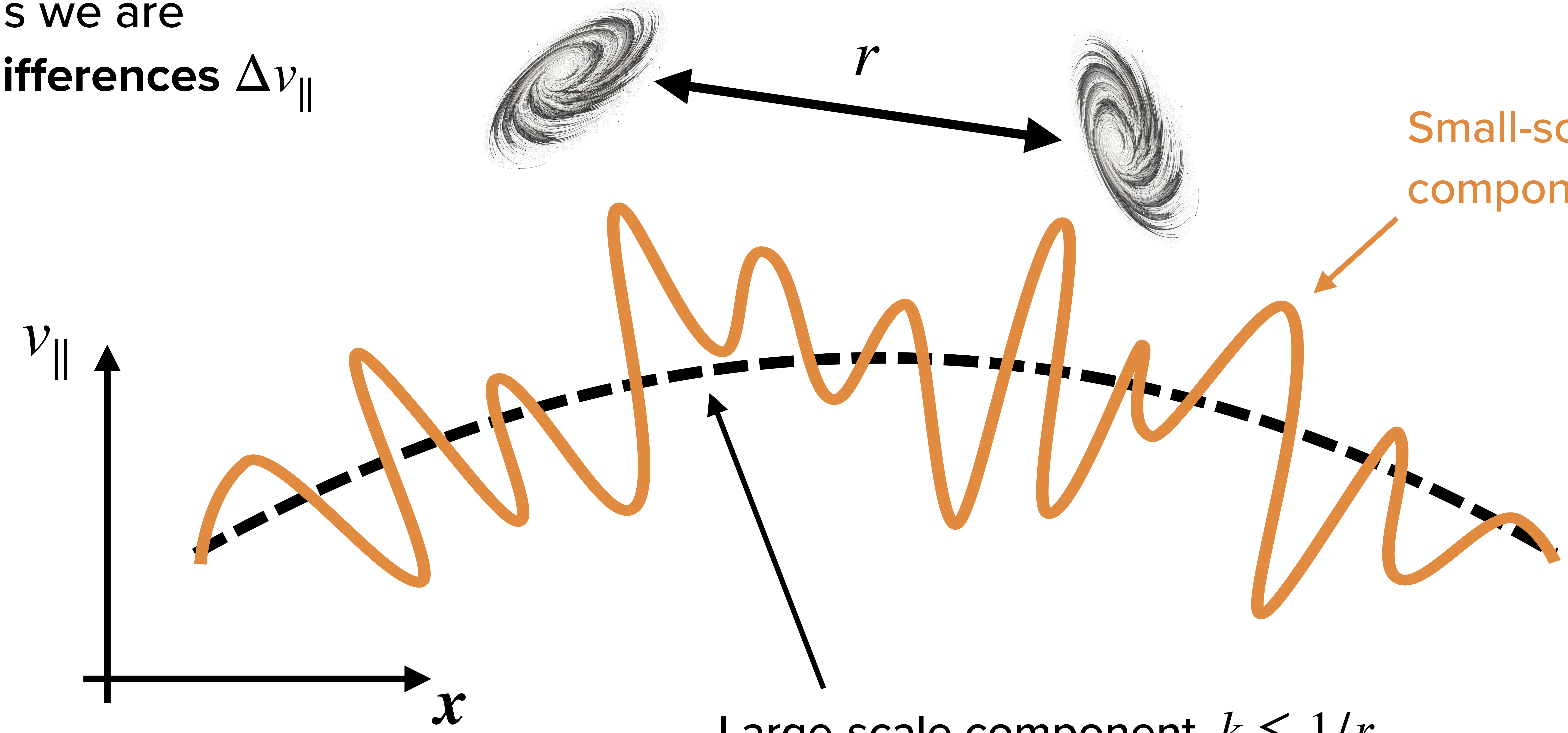
Why is it difficult to model redshift space distortions in perturbation theory?

↳ In correlation functions we are sensitive to **velocity differences** $\Delta v_{\|}$

Large-scale component cancels out in $\Delta v_{\|}$

⬇

Velocity differences are **always** sensitive to non-linearities!



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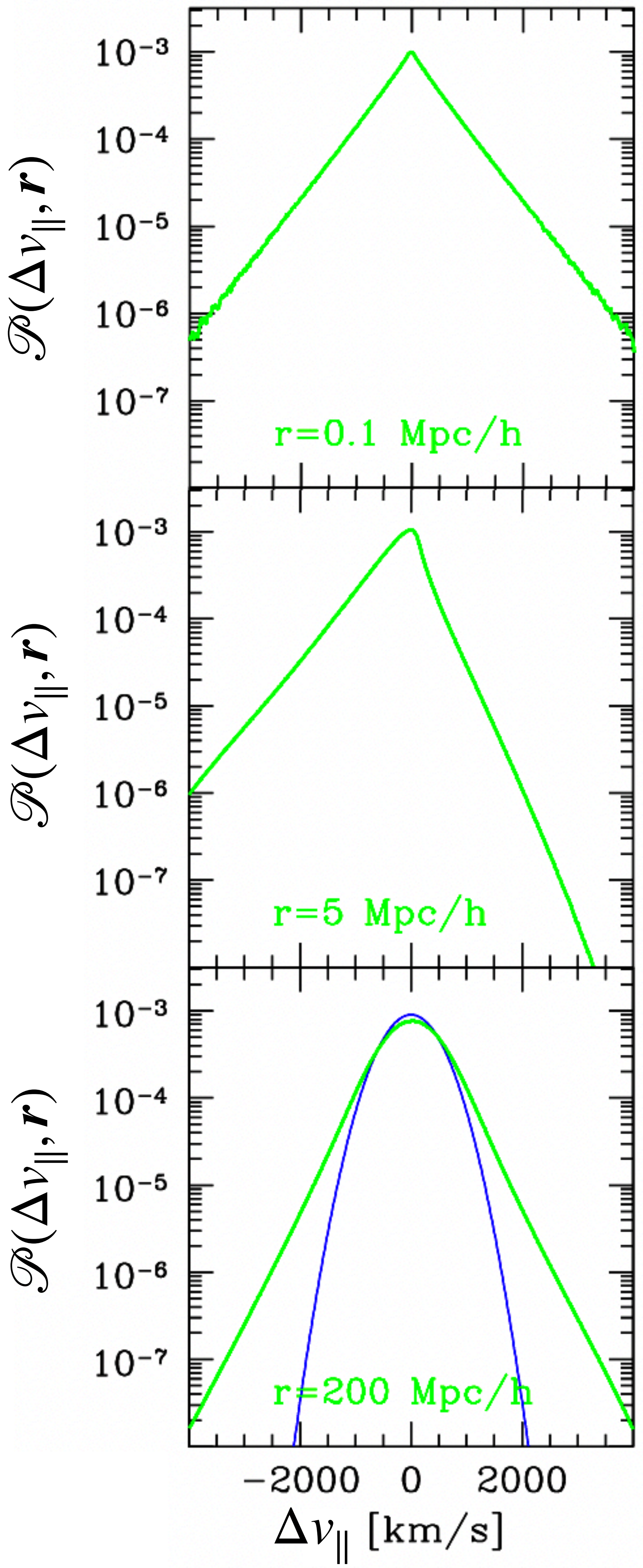
THE PAIRWISE VELOCITY DISTRIBUTION

Scoccimarro 04



THE PAIRWISE VELOCITY DISTRIBUTION

"Streaming model"

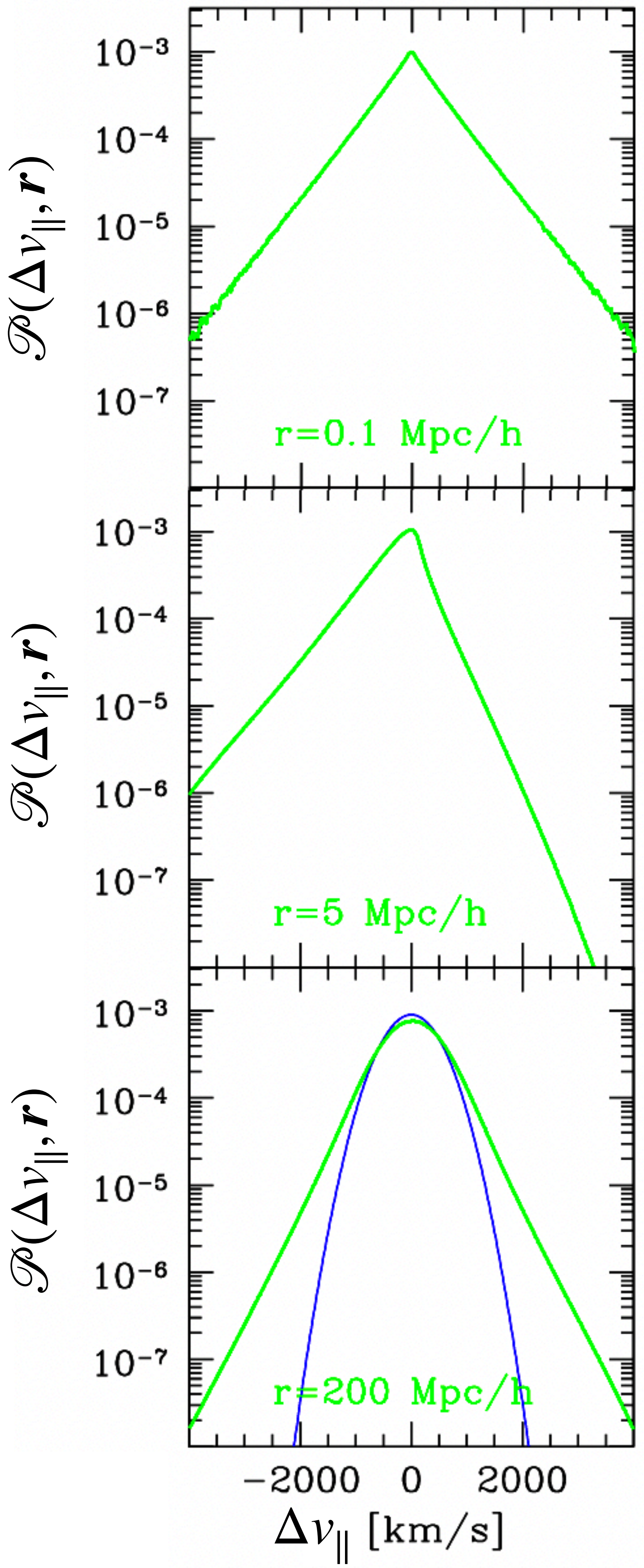
Fisher 95
Scoccimarro 04

$$\overbrace{P_s(k,\mu)}^{\text{Redshift-space power spectrum}} = \int \mathrm{d}^3r\, \mathrm{e}^{i\boldsymbol{k}\cdot\boldsymbol{r}} \left\{ \underbrace{[1+\xi(r)]}_{\text{Real-space correlation function}} \overset{\text{Moment generating function of mass weighted velocities}}{\mathscr{M}(k_\parallel, \boldsymbol{r})} - 1 \right\}$$

$\mu = k_\parallel / k$

Fourier transform

Scoccimarro 04



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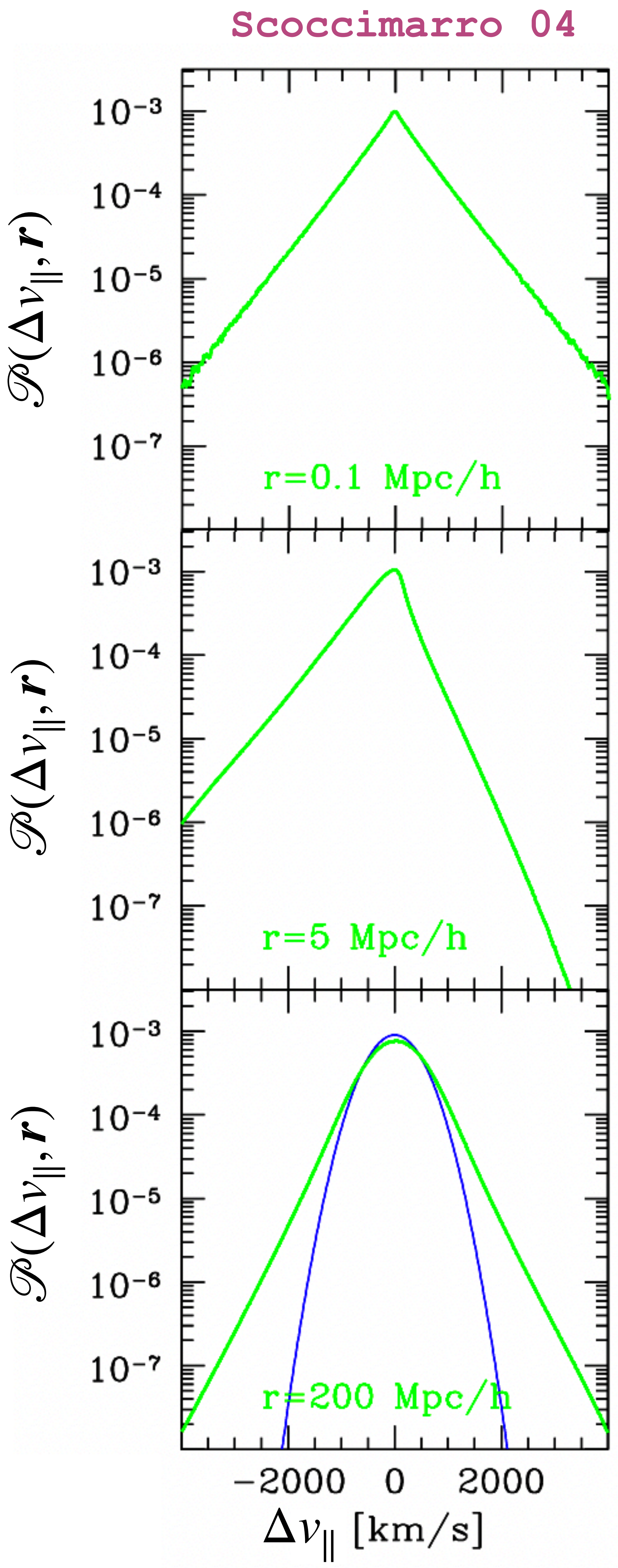

Modelling approaches:

- Assume functional form for $\mathscr{M}$: Gaussian streaming model, e.g. CLPT, CLEFT
  Reid & White 11, Wang+ 14, Vlah+ 16

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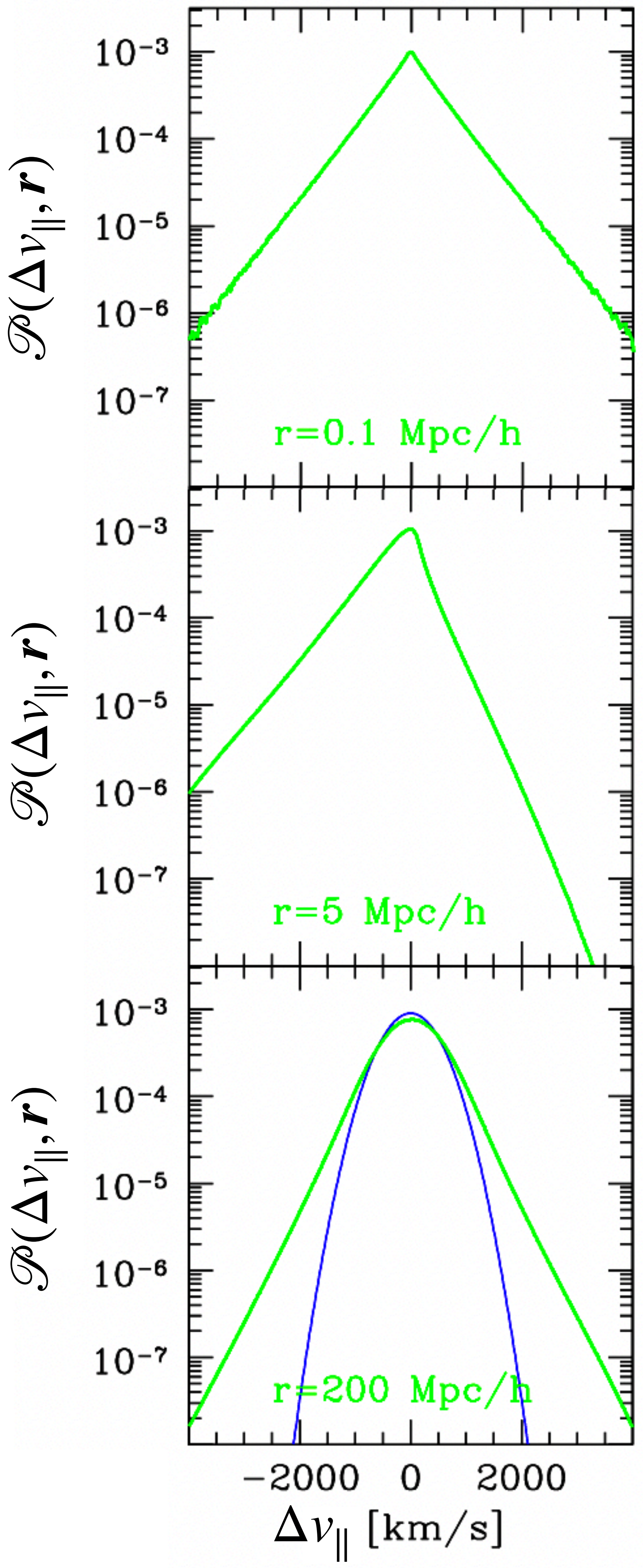

Modelling approaches:

- Assume functional form for $\mathscr{M}$: Gaussian streaming model, e.g. CLPT, CLEFT
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- Perturbative expansion of $\mathscr{M}$:

Moment generating function of unweighted (volume weighted) velocities

➡ $\mathscr{M}(k_\parallel, \boldsymbol{r}) = W(k_\parallel, \boldsymbol{r}) \times \big[$ cross-correlations between densities & velocities $\big]$

Scoccimarro 04, Taruya+ 10 (TNS)

VELOCITY DIFFERENCE GENERATING FUNCTION

In all recent Effective Field Theory (**EFT**) models the function $W(k_\parallel, \boldsymbol{r})$ is expanded perturbatively

$$W(k_\parallel, \boldsymbol{r}) \equiv \left\langle \mathrm{e}^{-\mathrm{i}k_\parallel\,\Delta v_\parallel(\boldsymbol{r})} \right\rangle \approx 1 + k_\parallel^2/2 \left\langle \Delta v_\parallel^2 \right\rangle + k_\parallel^4/8 \left\langle \Delta v_\parallel^2 \right\rangle^2 + \ldots$$

velocity dispersion,
highly sensitive to non-linearities

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➡ Motivates the introduction of **redshift space counterterms**

$$P_{\mathrm{ctr,s}}(k, \mu) = c_2 \, k^2 \mu^2 P_{\mathrm{lin}}(k) \; + \; c_4 \, k^2 \mu^4 P_{\mathrm{lin}}(k) \; + \; c_{\mathrm{nlo}} \, k^4 \mu^4 P_{\mathrm{lin}}(k)$$

`Perko+ 16, Desjacques+ 19, Ivanov+ 20, D'Amico+ 20`

VELOCITY DIFFERENCE GENERATING FUNCTION

We can also keep the velocity difference generating function non-perturbative!

→ Ad-hoc assumptions take $W(k_\parallel, \boldsymbol{r})$ as **Gaussian** or **Lorentzian**, but one can motivate a form based on PT:

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① Resumming quadratic non-linearities, ignoring skewness

Juszkiewicz+ 98, Scoccimarro 04, Scoccimarro (in prep)

$$\to \frac{1}{\sqrt{1 + k_\parallel^2 \, \sigma_{\mathrm{nl}}^2(\boldsymbol{r})}} \exp\left(- \frac{k_\parallel^2 \, \sigma_{\mathrm{lin}}^2(\boldsymbol{r})}{1 + k_\parallel^2 \, \sigma_{\mathrm{nl}}^2(\boldsymbol{r})} \right)$$

Linear velocity dispersion

Non-linear, “virialised” velocity dispersion

Velocity Difference Generator (**VDG**)

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Velocity Difference Generator (**VDG**)

Non-linear, “virialised” velocity dispersion

② In the large-scale limit, the dispersions become constant

Sánchez+ 16

$$\sigma_{\mathrm{lin}}^2(\boldsymbol{r}) \rightarrow \sigma_v^2$$

$$\sigma_{\mathrm{nl}}^2(\boldsymbol{r}) \rightarrow a_{\mathrm{vir}}^2$$

$$\Rightarrow \quad W_\infty(k_\parallel) = \frac{1}{\sqrt{1 + k_\parallel^2\,a_{\mathrm{vir}}^2}} \exp\left(-\frac{k_\parallel^2\,\sigma_v^2}{1 + k_\parallel^2\,a_{\mathrm{vir}}^2}\right)$$

TEST ENVIRONMENT: DATA & LIKELIHOOD

Minerva simulation suite:

- 300 realisations of volume $(1500\,h^{-1}\,\mathrm{Mpc})^3$ each
- Populated with HOD galaxies, matching **LOWZ** and **CMASS** galaxies at $z = 0.3,\, 0.57$

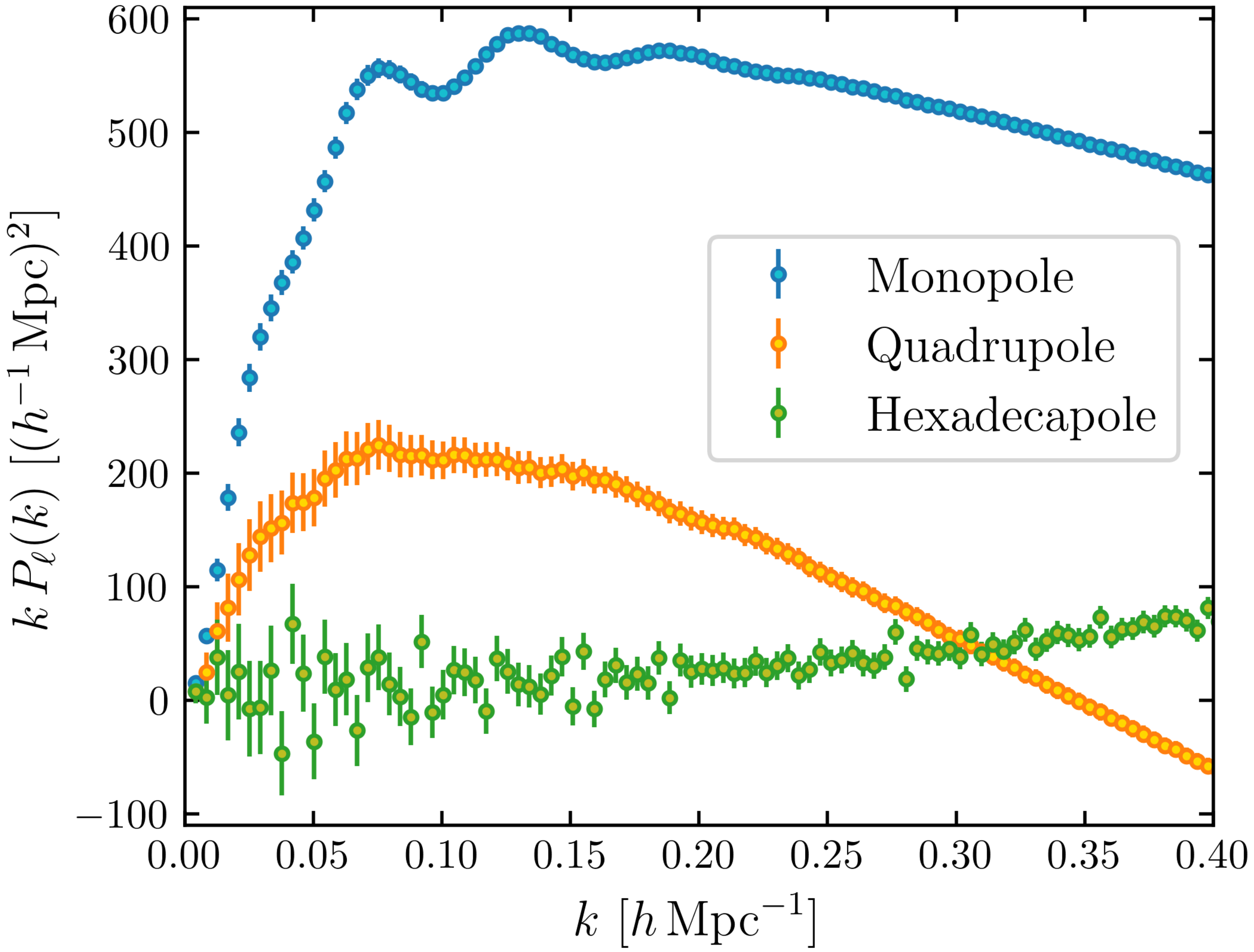
Measure **power spectrum multipoles**

➡ use mean as data vector $\boldsymbol{X}$

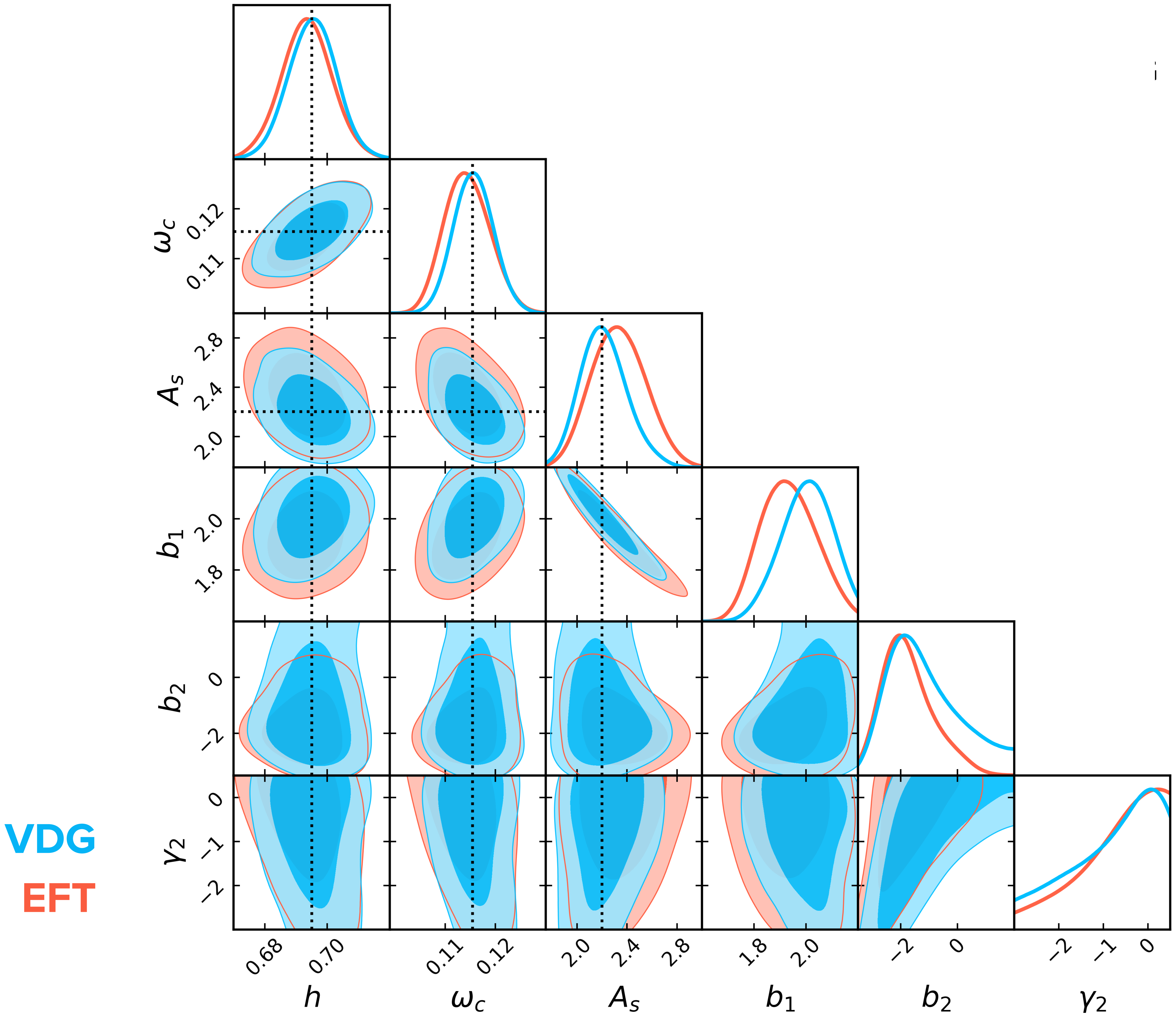
$$-\log \mathscr{L} = \frac{1}{2}\left(\boldsymbol{X}-\boldsymbol{\mu}\right)\cdot C_X^{-1}\cdot\left(\boldsymbol{X}-\boldsymbol{\mu}\right)$$

Covariance matrices:

- Gaussian predictions using best-fit bias parameters
- Tune volume to Euclid-like redshift shell:
  - ▸ $\Delta z = 0.2$ at $\bar{z} = 0.9$
  - ▸ $15{,}000\,\mathrm{deg}^2$
  - ▸ $\bar{n} \approx 2\times 10^{-3}\,(h\,\mathrm{Mpc}^{-1})^3$



QUANTIFYING MODEL PERFORMANCE



CMASS

$k_{\rm max} = 0.2\,h\,{\rm Mpc}^{-1}$ (down to ~ 30 Mpc/h)

- Analysing the power spectrum multipoles for different wavenumber cutoffs $k_{\rm max}$
- Varying three cosmological parameters (h, ω_c, A_s), in addition to 10 “nuisance” parameters
- Model predictions are obtained from **COMET** (a fast emulator of theory predictions) `AE+ 22`

`AE+ (in prep)`

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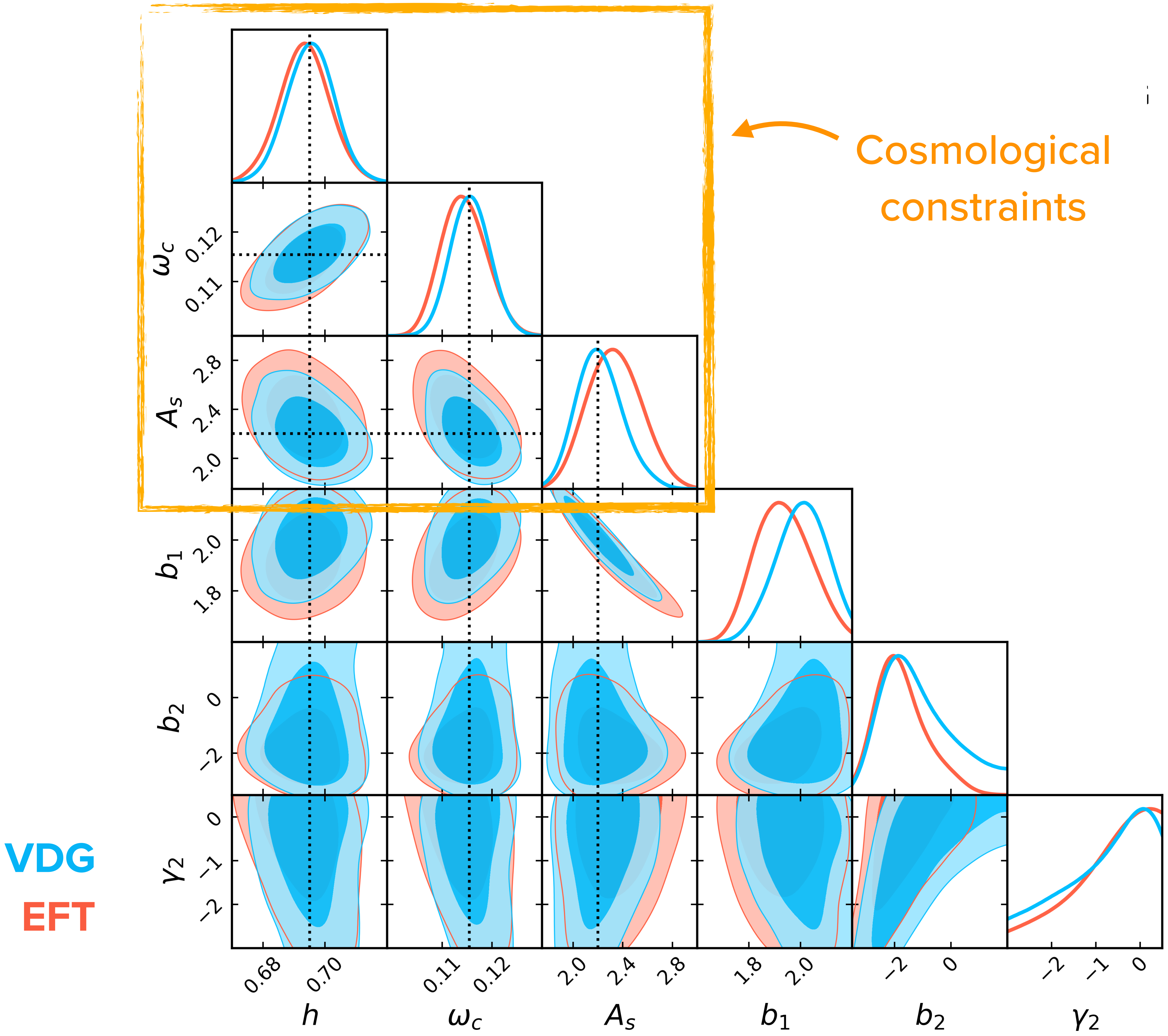

Cosmological constraints

- Analysing the power spectrum multipoles for different wavenumber cutoffs k_max
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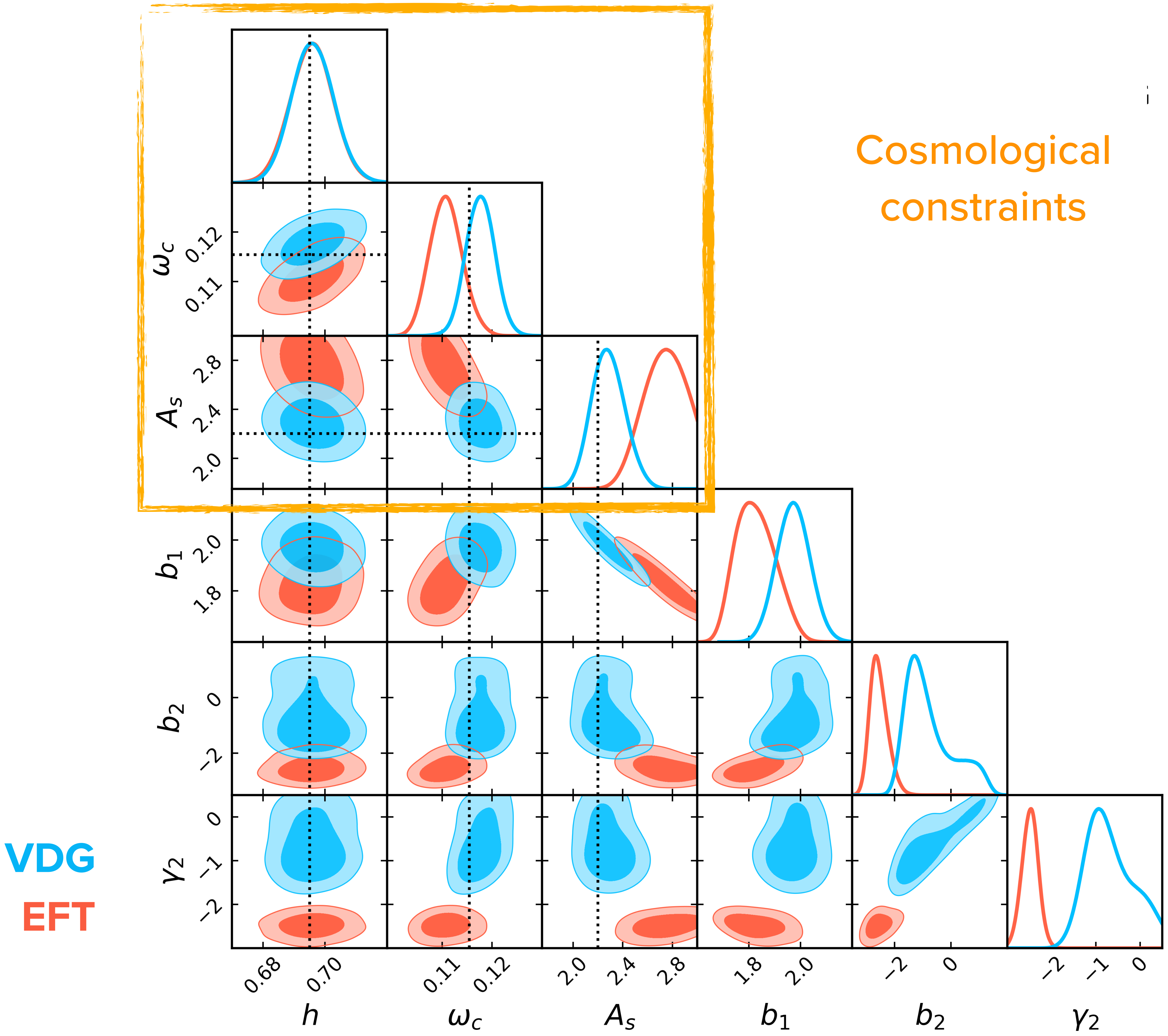

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CMASS

$k_{\mathrm{max}} = 0.35\,h\,\mathrm{Mpc}^{-1}$ (down to ~ 20 Mpc/h)

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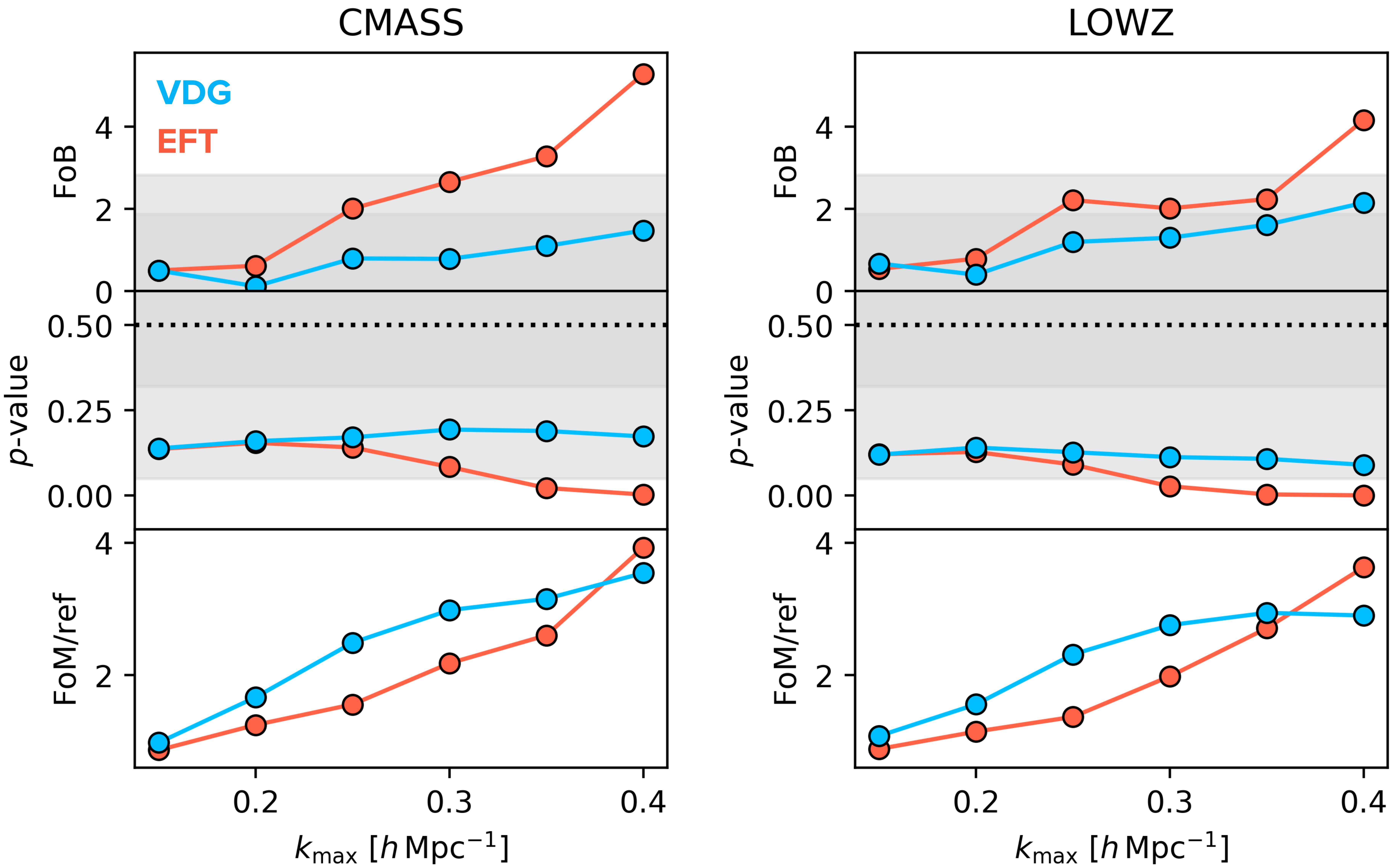

AE+ (in prep)

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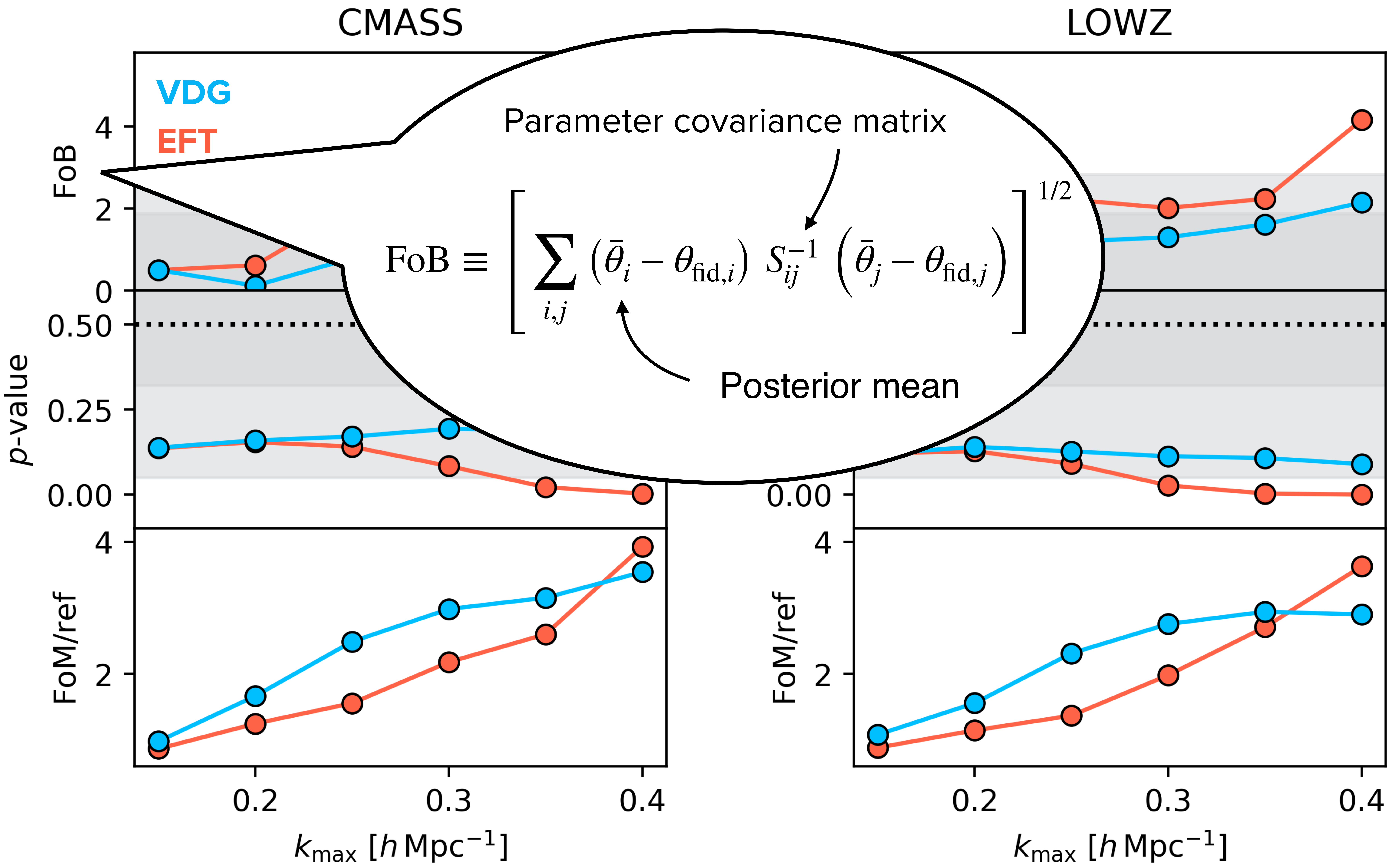

Parameter covariance matrix

$$\mathrm{FoB} \equiv \left[\sum_{i,j} \left(\bar{\theta}_i - \theta_{\mathrm{fid},i}\right) \, S^{-1}_{ij} \, \left(\bar{\theta}_j - \theta_{\mathrm{fid},j}\right) \right]^{1/2}$$

Posterior mean

AE+ (in prep)

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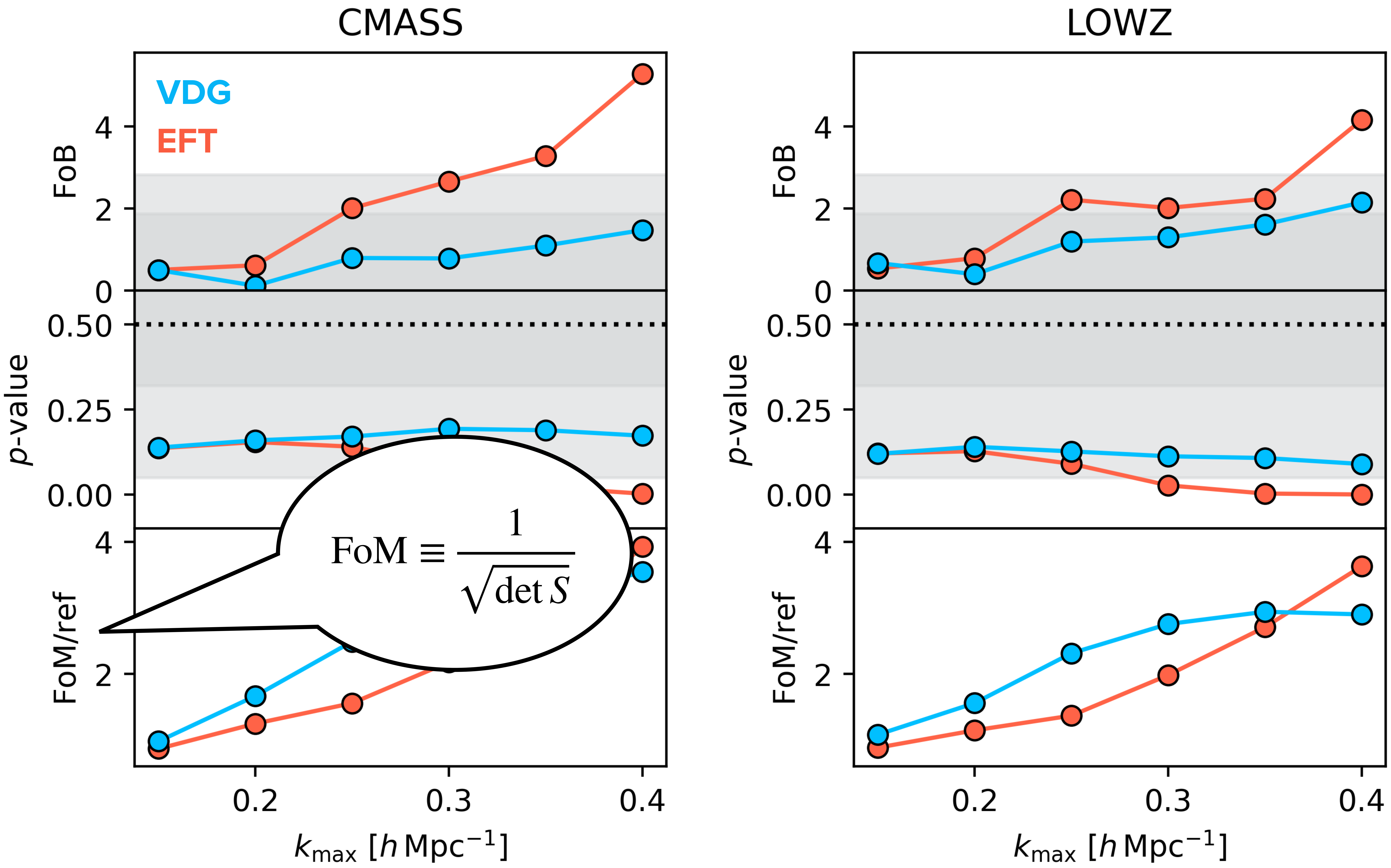

$$\mathrm{FoM} \equiv \frac{1}{\sqrt{\det S}}$$

AE+ (in prep)

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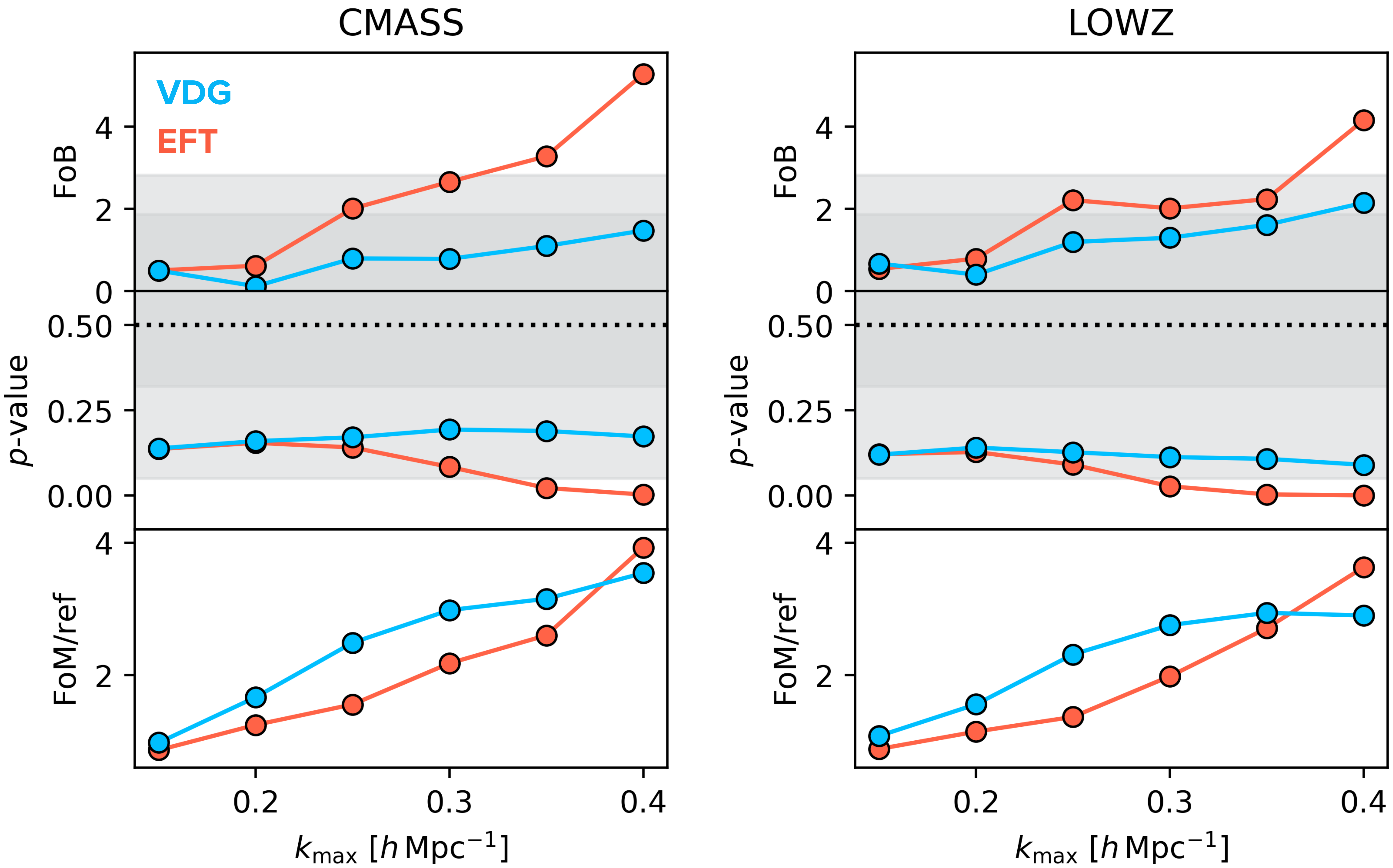

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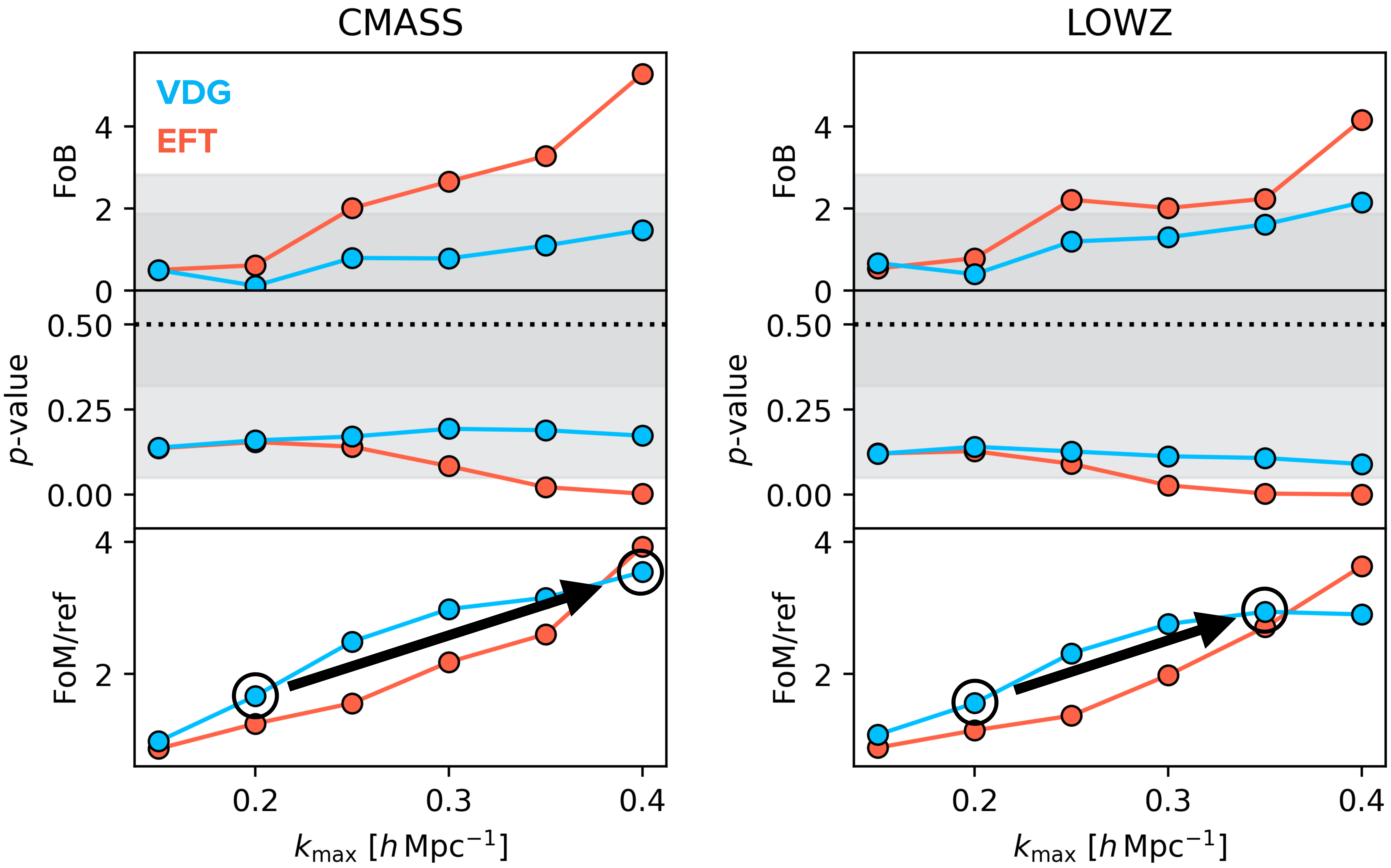
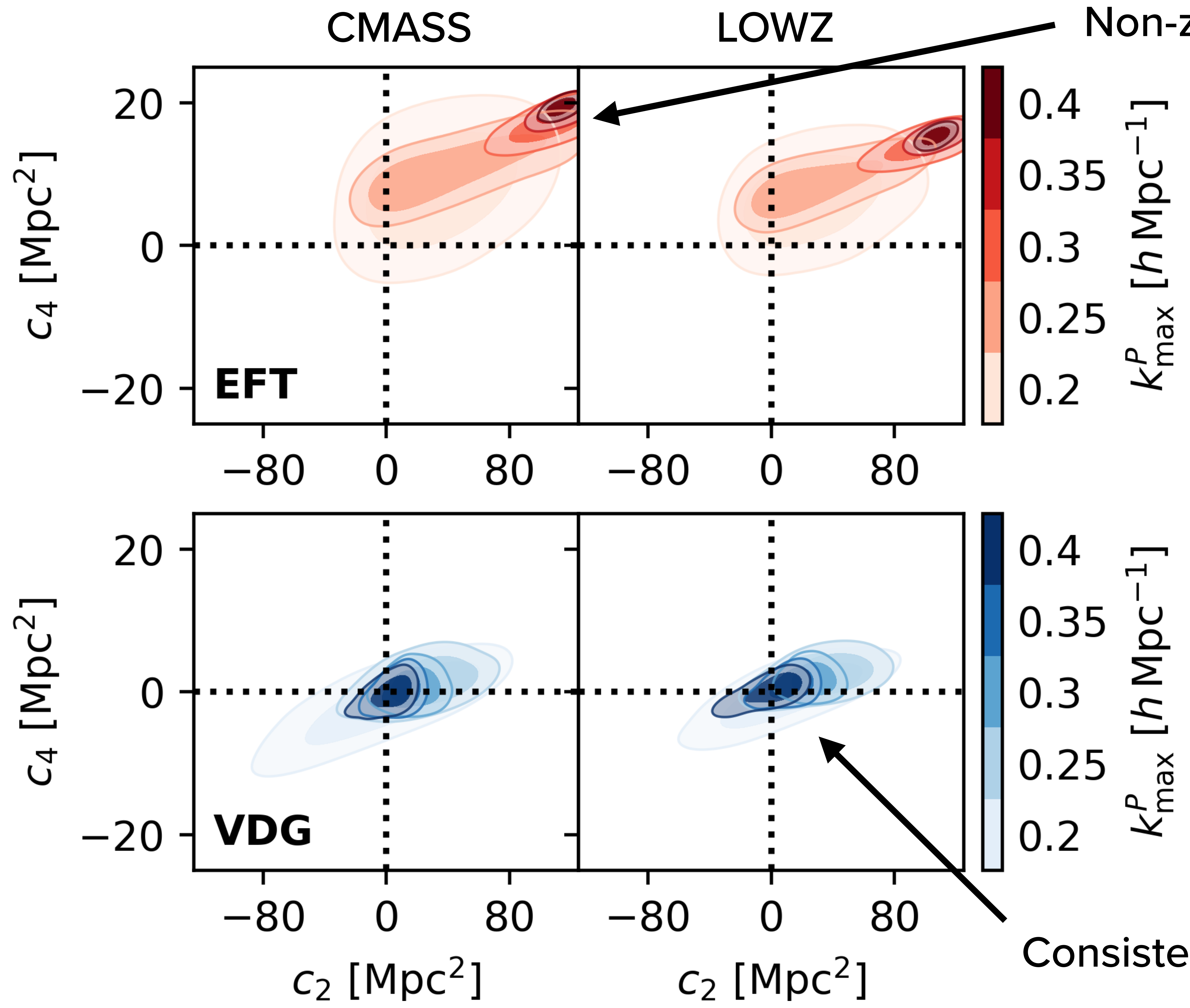


- Gains in constraining power by unlocking information from smaller scales!
- No change in model complexity (number of parameters)

`AE+ (in prep)`

REDSHIFT SPACE COUNTERTERMS



Non-zero & sample-dependent

Consistent with zero

- VDG damping function captures well non-linearities of the redshift-space mapping
- Possibility to simplify model and **reduce projection effects**?

`AE+ (in prep)`

JOINT ANALYSIS

Analysing power spectrum multipoles together with bispectrum multipoles (monopole + quadrupole)

- Adopting leading order model of Ivanov+ 21 for the EFT bispectrum, **2 additional counterterm parameters**

$$\rightarrow \; Z_{1,\mathrm{ctr}} = c_{B,1}\, k^2 \mu^2 + c_{B,2}\, k^2 \mu^4$$

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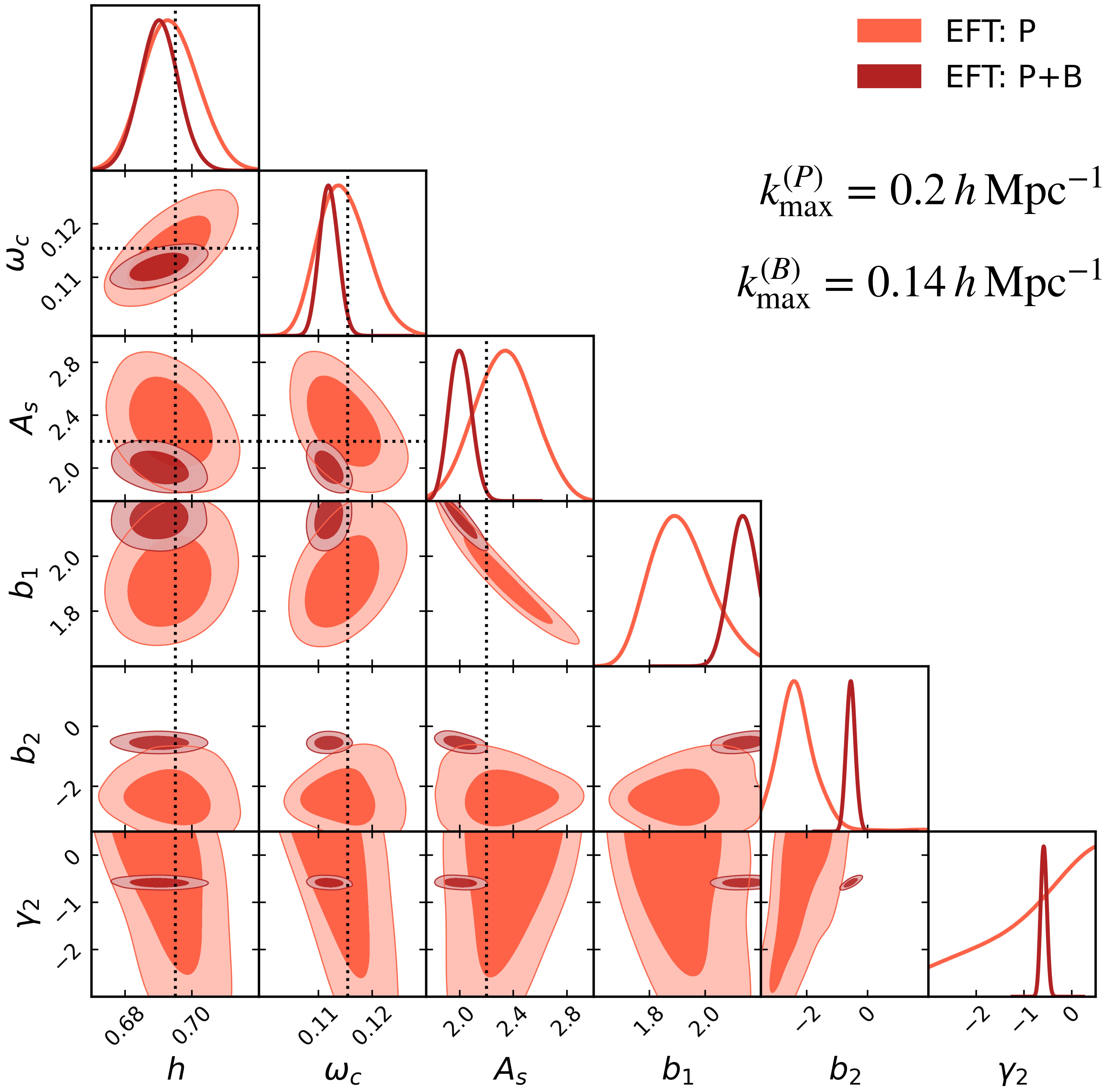

$$k_{\rm max}^{(P)} = 0.2\, h\,{\rm Mpc}^{-1}$$

$$k_{\rm max}^{(B)} = 0.14\, h\,{\rm Mpc}^{-1}$$

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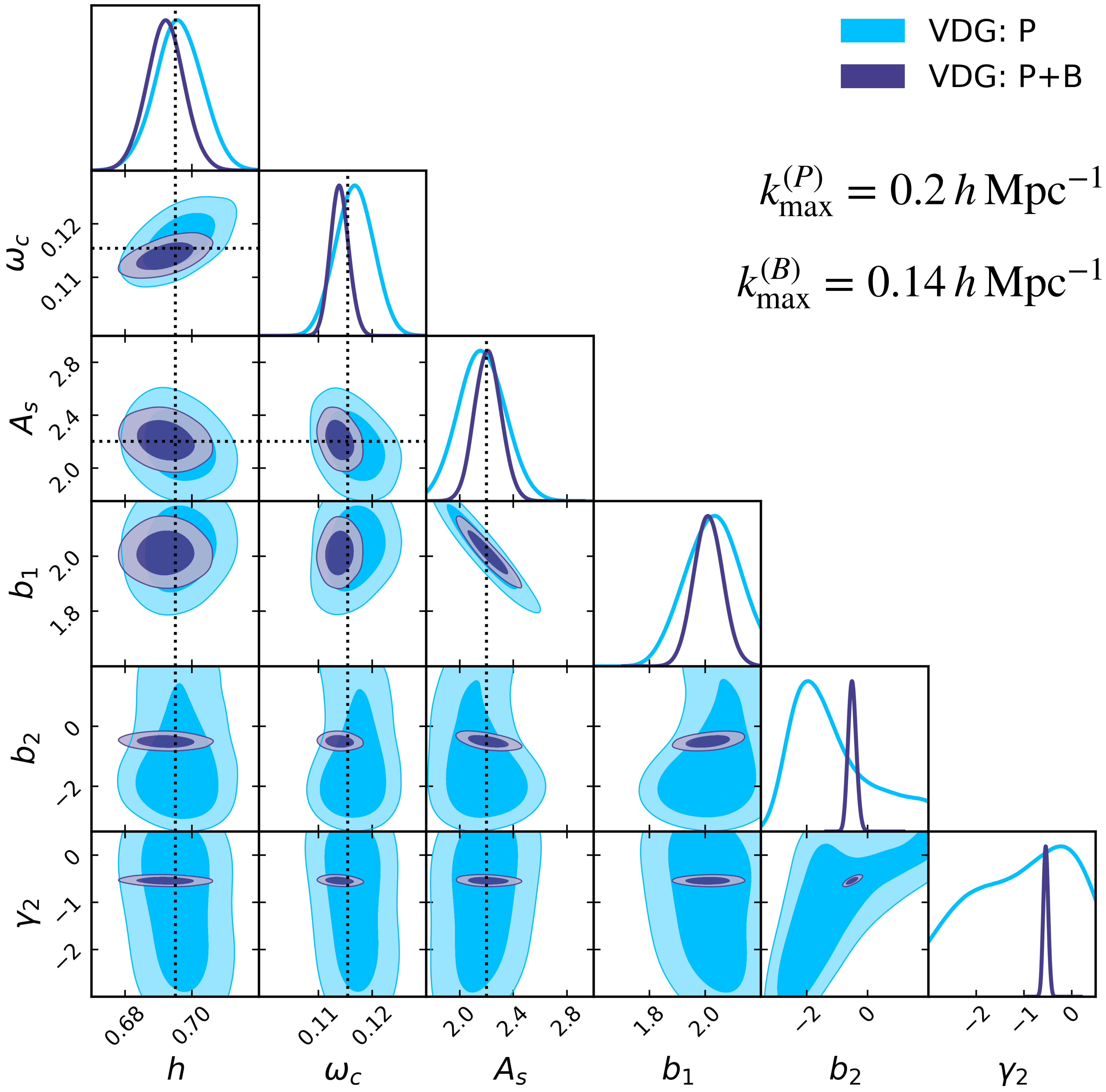

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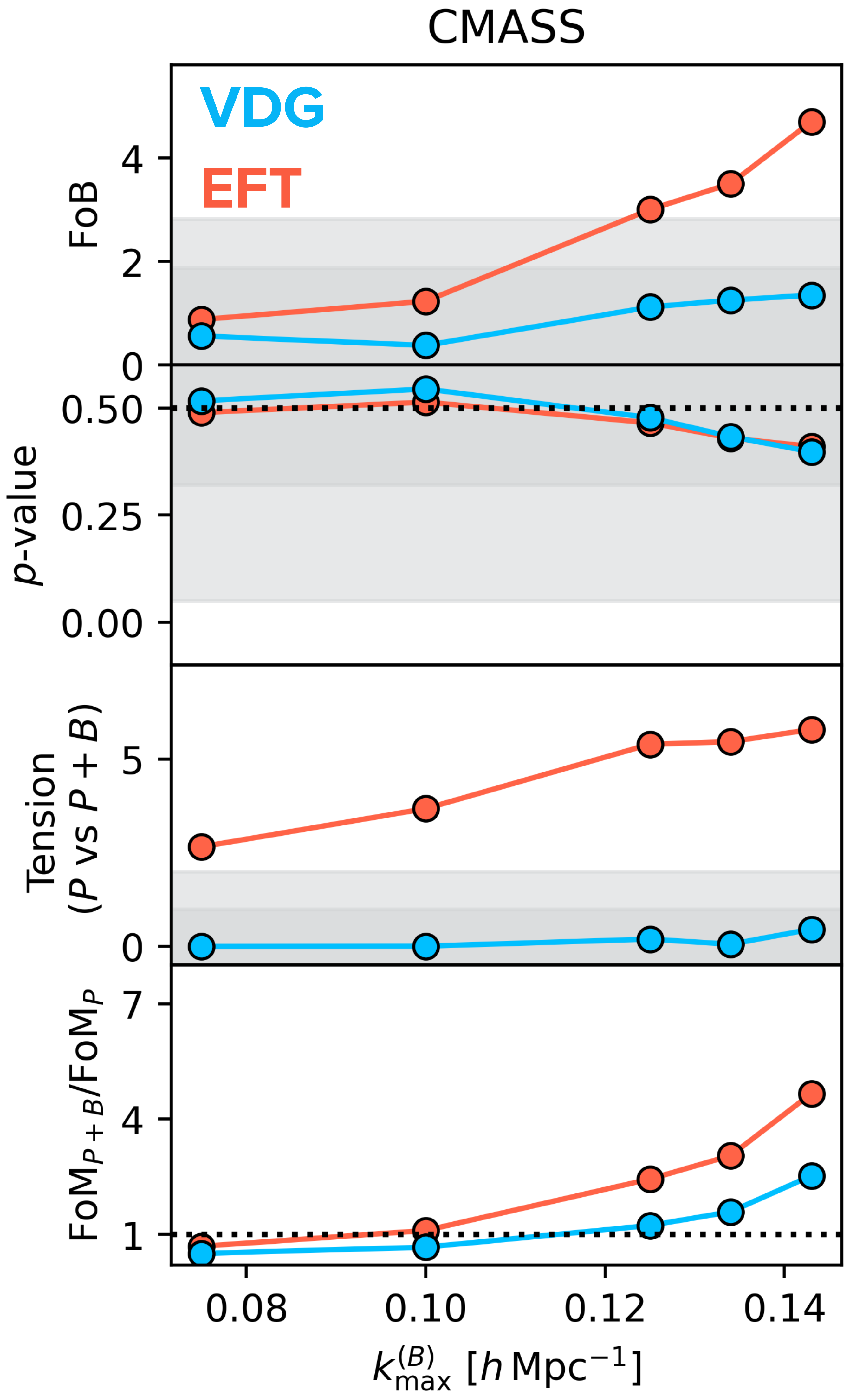
GAINS OVER THE POWER SPECTRUM



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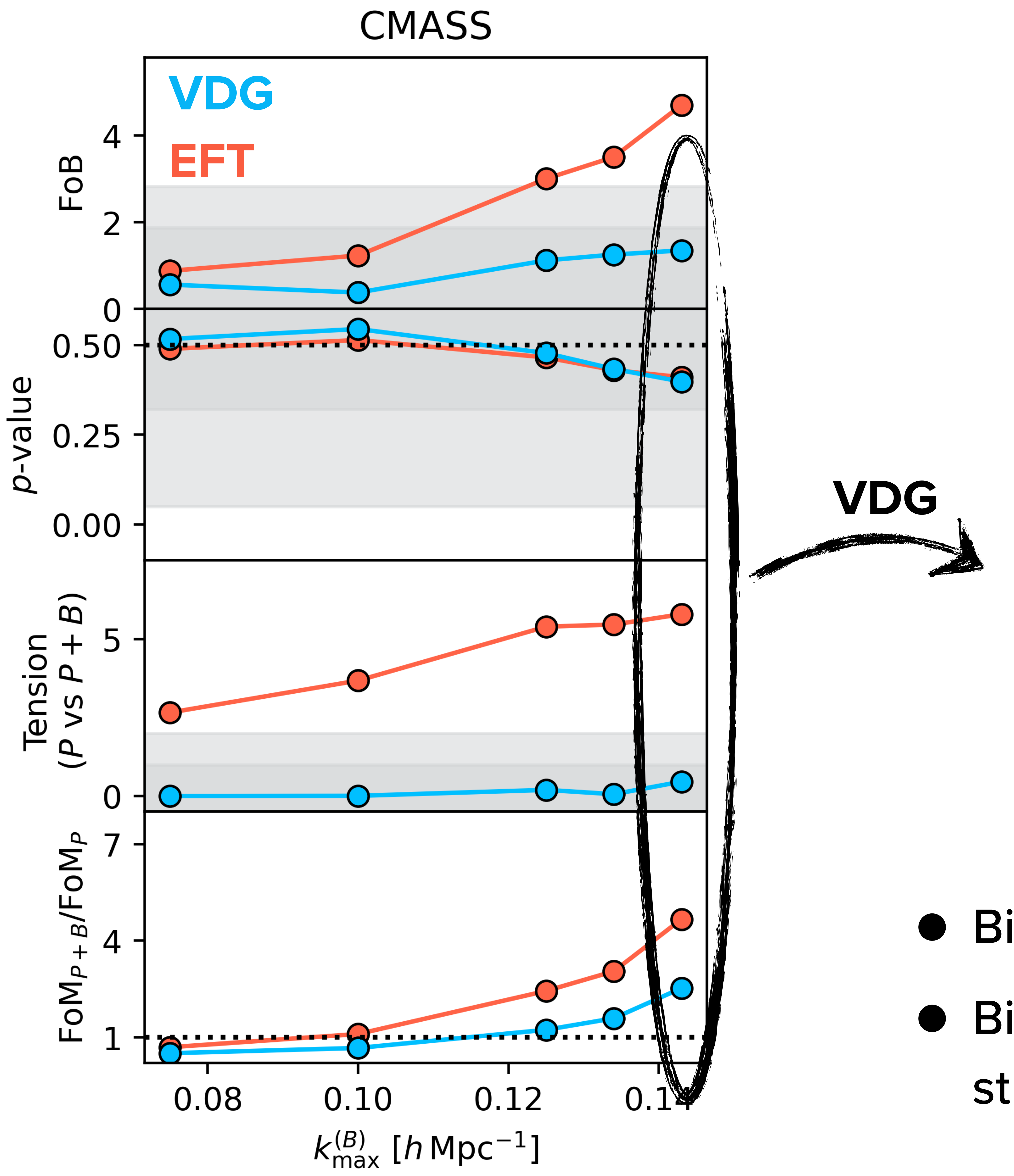
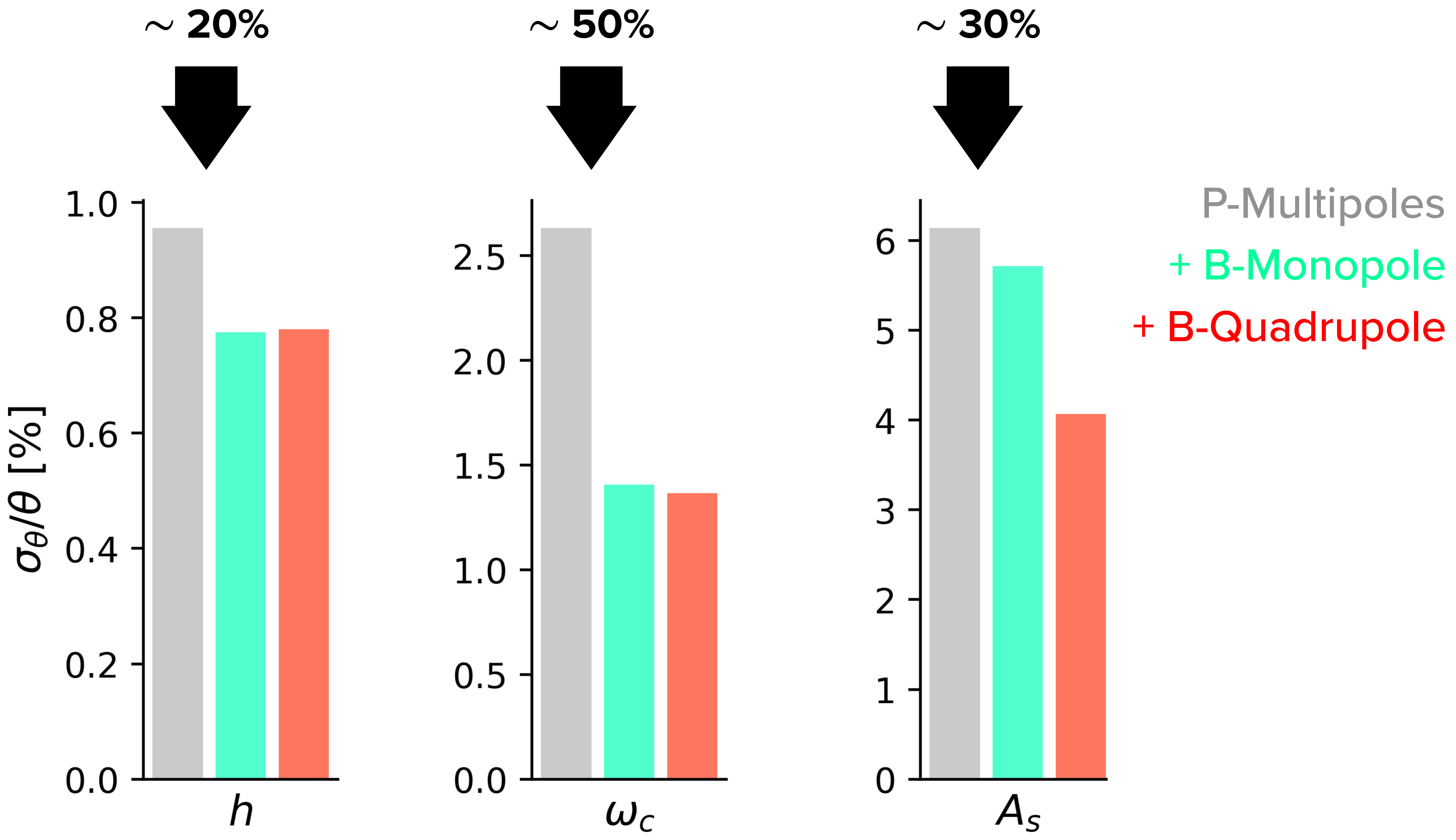




- Bispectrum **monopole** mainly improves constraints on h and ω_c
- Bispectrum **quadrupole** helps tightening posterior for A_s (due to stronger breaking of $f - \sigma_{12}$ degeneracy)

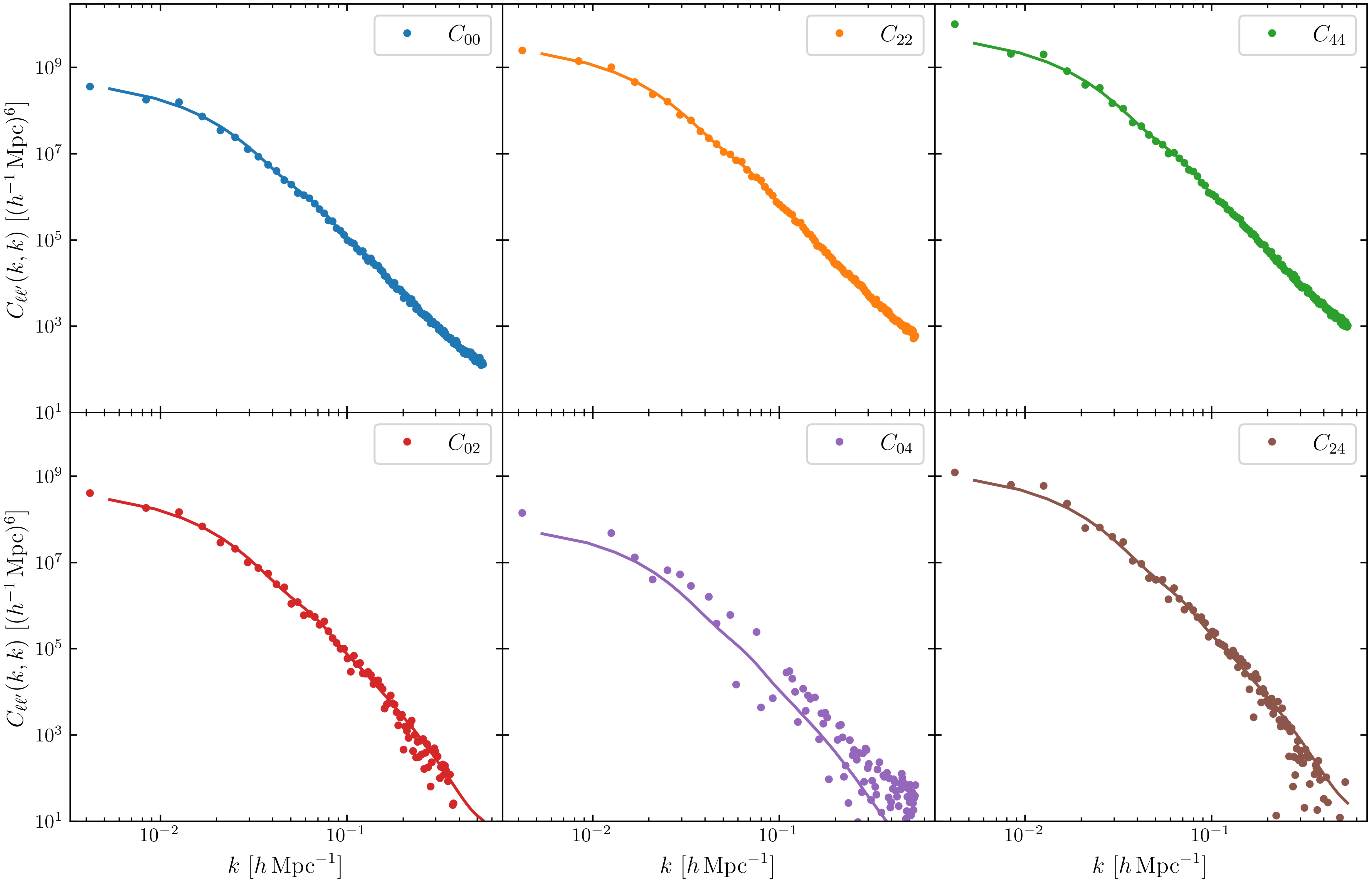
TAKE AWAY

A (partially) non-perturbative treatment of the redshift-space mapping offers significant improvements in the modelling of two- and three-point statistics

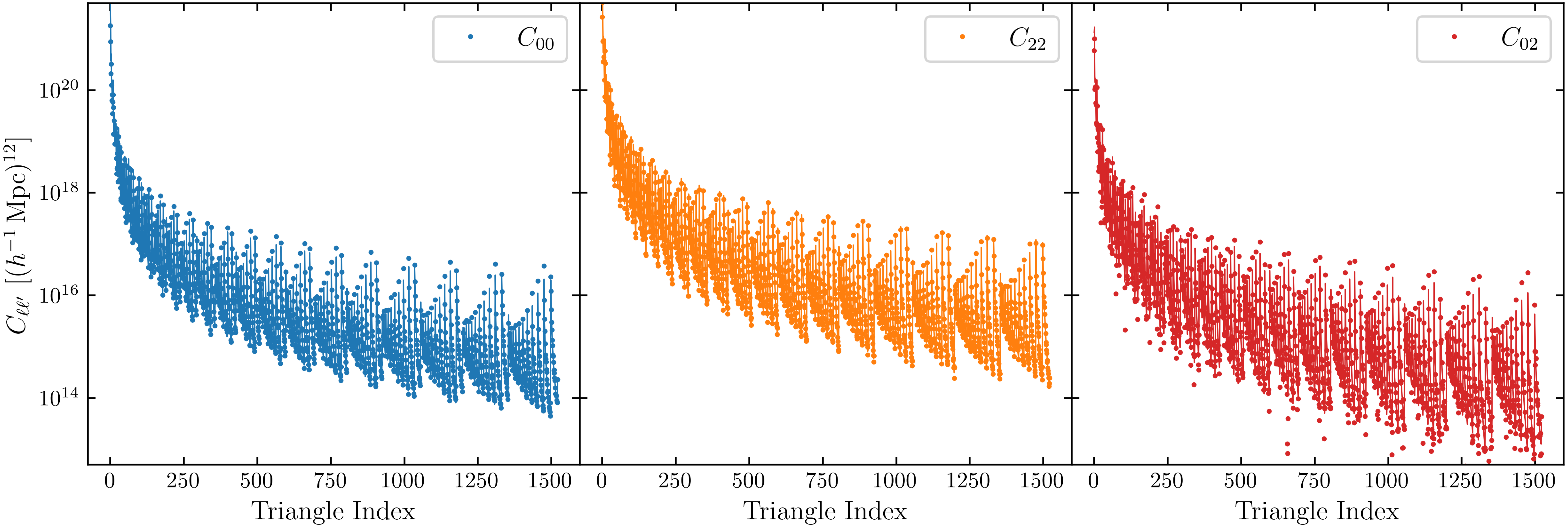
- Gains in constraining power on ΛCDM parameters from extended k-range
- Tested across various different galaxy samples (caveat: only HOD)
- Possibility to alleviate projection effects due to reduction of counterterm parameter space

Big **THANKS** to my collaborators: B. Camacho, M. Crocce, N. Lee, A. Pezzotta, C. Porciani, A. Sánchez, R. Scoccimarro, E. Sefusatti, A. Semenaite

POWER SPECTRUM COVARIANCE



BISPECTRUM COVARIANCE



POWER SPECTRUM & BISPECTRUM METRICS