
EDECS
Exploring Dark Energy Cosmic Structures

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# Baryon Acoustic Oscillations from the DEUS-FUR simulation

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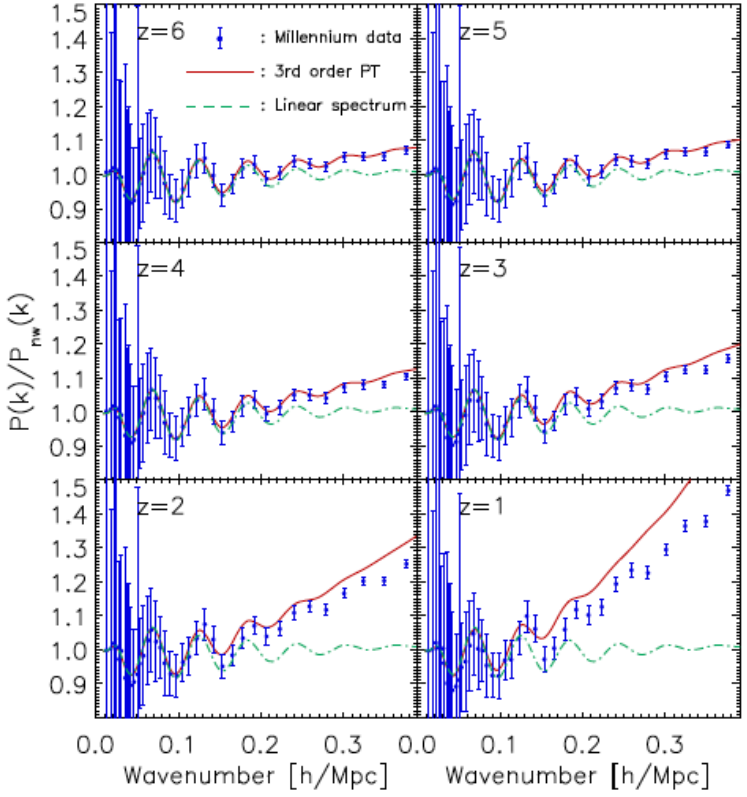
Reference:

Y. Rasera, P.S. Corasaniti, JM Alimi, V. Bouillot, V. Reverdi, I. Balmes
MNRAS, 440, 1420 (2014), arXiv:1311.5662

# Resolving the BAO Scale

**Large Dynamical Range**

- ~100 Mpc/h quasi-linear scale at z < 1
- ~1-10 Mpc/h width




**N-body Requirements**

- Large Volume (> 1 Gpc)$^3$
- High Resolution (≤$10^{12}$ $M_{sun}$)

Jeong and Komatsu 2009

# Probing Large Volumes

**Sample Variance Errors**

$$\sigma(k) = \sqrt{\frac{2}{N_k}}\left[P(k) + \frac{1}{N_p}\right] \quad \text{with} \quad N_k = \frac{k^2 \Delta k}{2\pi^2} V \qquad V = L_{box}^3 \quad , \quad \Delta k = \frac{2\pi}{L_{box}}$$

Jeong and Komatsu 2009

**Large Ensembles** e.g.

- 5000 PM-runs, $N_p=256^3$, $L_{box}$=1 Gpc/h Takahashi et al. 2009
- 12288 AMR-runs, $N_p=256^3$, $L_{box}$=656 Mpc/h
- 96 AMR-runs, $N_p=1024^3$, $L_{box}$=656 Mpc/h Blot et al. 2014

**Still..** k-sampling, Beat-coupling, Numerical Systematics

# Physicality of Newtonian Simulations

**GR Effects (?)**

- Newtonian gravity at dozens Gpc/h scales?
- On large scales at leading order in Φ, GR particle-trajectories = ZA which is Newtonian solution at leading order

  Chisari & Zaldarriaga (2011); Green & Wald (2012)

- Purely relativistic effects only at $2^{nd}$ order in Φ > Newtonian terms at $2^{nd}$ order, but suppressed compared to ZA displacements
- Corrections to $P_{lin}(k)$ are $O(10^{-5})$ at z=49 and $O(10^{-3})$ at z=0

  Rigopoulos & Valkenburg (2015)

# DEUS - Full Universe Runs

- $L_{box}$ = 21 Gpc/h
- $N_p = 8196^3$
- $\Delta x_{coarse}$ = 40 kpc/h
- $m_p = 10^{12}\ M_{sun}/h$
- RAMSES code
- Models: **LCDM-W7**, RPCDM-W7, WCDM-W7


**Curie Thin (80000 cores)**

- 1.2 Petabytes of data
- 10 Mhours

Alimi et al. (2012), Proceedings of SC'12, arXiv: 1206.2838

# Be Accurate and Precise!

## Statistical & Systematic Errors

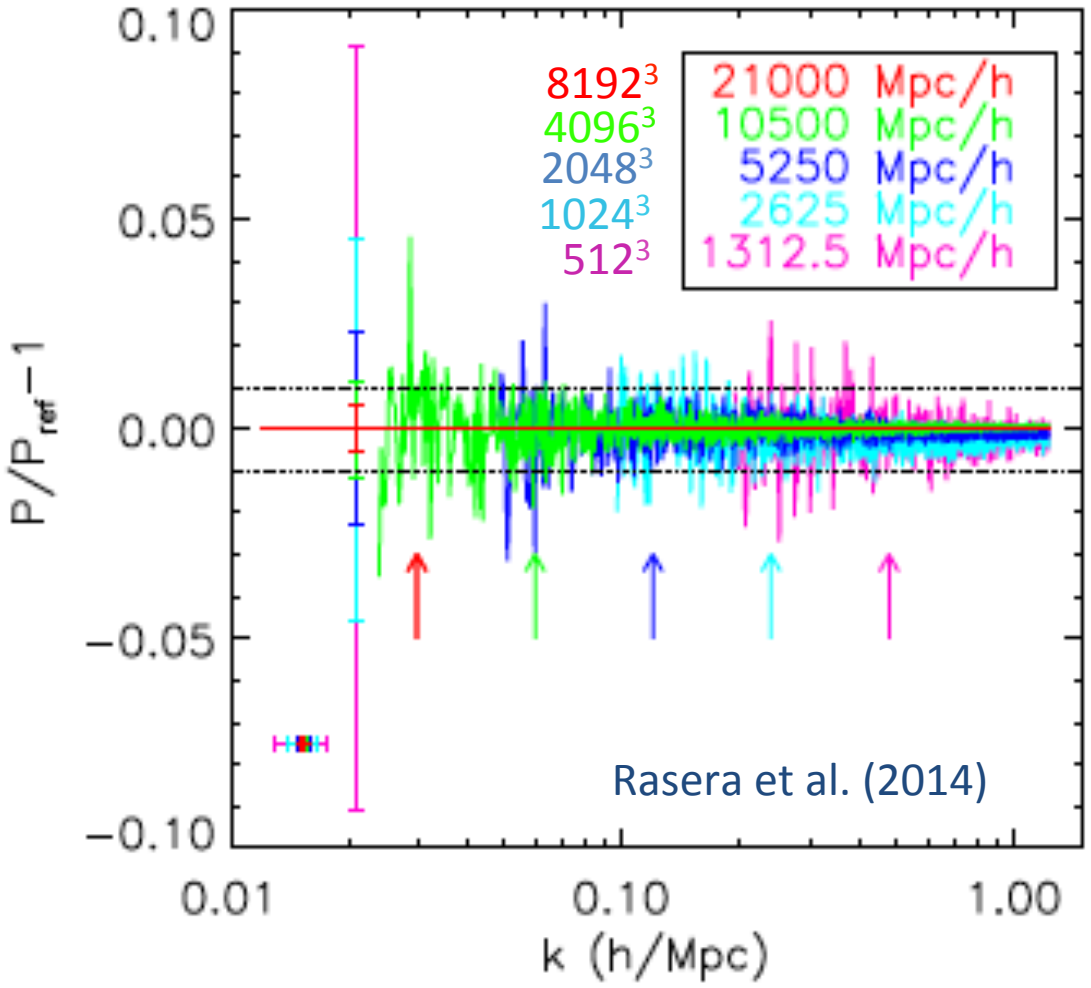
- Mass Resolution
- Refinement
- Initial Conditions
- Time Integration

## Simulation Suite

| $L_{box}$ | $n_x$ | $m_{ref}$ | $z_i$ | $C_{dt}$ |
|---|---|---|---|---|
| 10500 | 4096 | 14 | 106 | 0.2 |
| 5250 | 2048 | 14 | 106 | 0.2 |
| 2625 | 1024 | 14 | 106 | 0.2 |
| 1312 | 512 | 14 | 106 | 0.2 |
| 5250 | 2048 | 8 | 106 | 0.2 |
| 5250 | 2048 | 25 | 106 | 0.2 |
| 5250 | 2048 | 14 | 106 | 0.08 |
| 5250 | 2048 | 14 | 106 | 0.5 |
| 5250 | 2048 | 14 | 272 | 0.2 |
| 5250 | 2048 | 14 | 170 | 0.2 |

| $L_{box}$ | $n_x$ | $m_{ref}$ | $z_i$ | $C_{dt}$ |
|---|---|---|---|---|
| 5250 | 2048 | 14 | 66 | 0.2 |
| 5250 | 2048 | 14 | 41 | 0.2 |
| 2592 | 2048 | 8 | 56 | 0.5 |
| 2592 | 1024 | 8 | 56 | 0.5 |
| 648 | 1024 | 8 | 93 | 0.5 |
| 648 | 512 | 8 | 93 | 0.5 |
| 648 | 256 | 8 | 93 | 0.5 |
| 2625 | 1024 | 14 | 106* | 0.2 |
| 5250 | 2048 | 14 | 106** | 0.2 |

# Statistical Errors

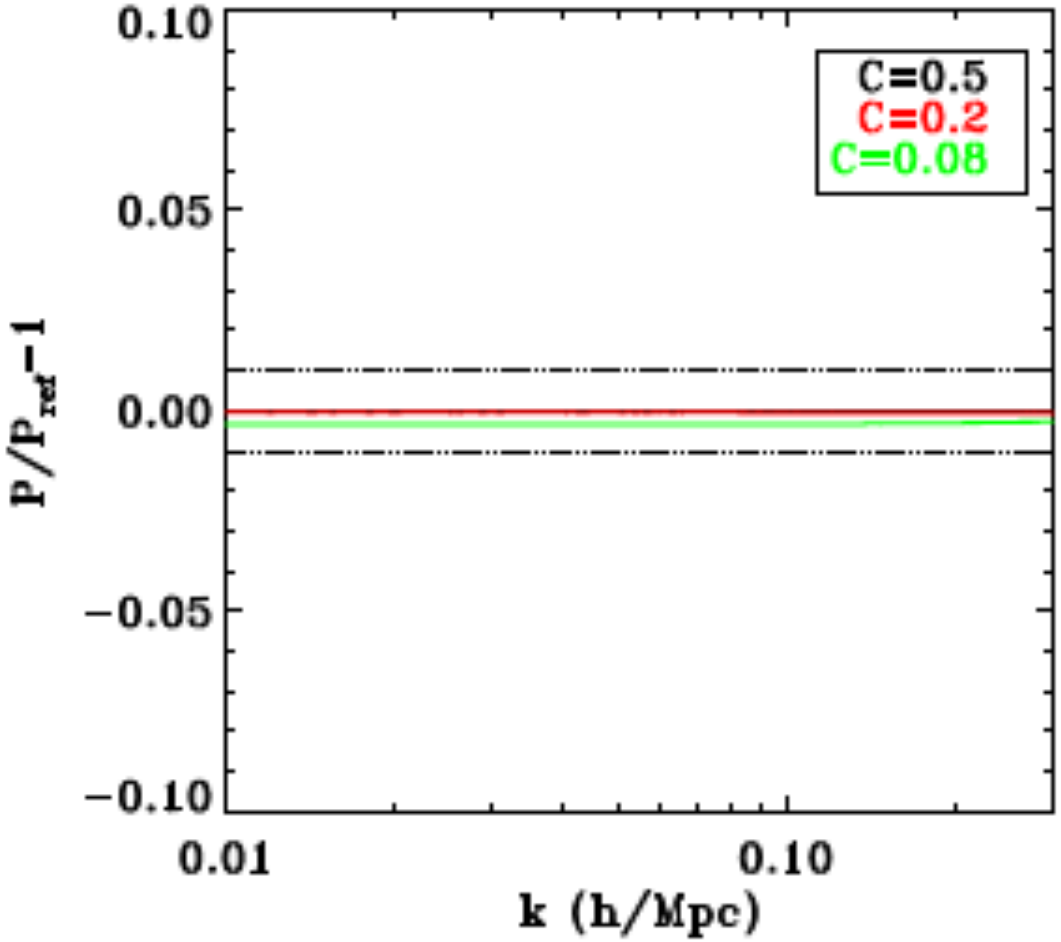



$k_{min}$ setting requirements:

- $E = \sigma_{noise}/P < 1\%$
- $dk/k < 1\%$

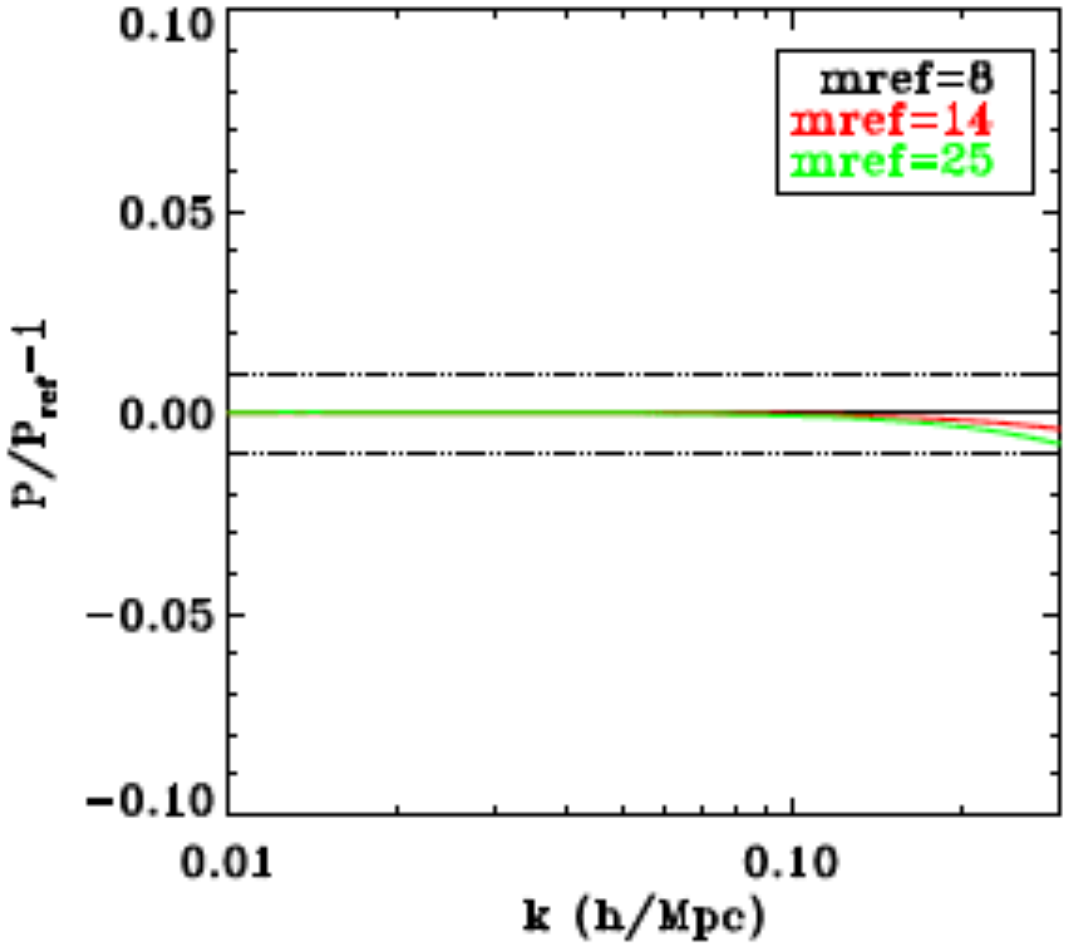
# Systematic Errors – Integration dt

$L_{box}$ = 5250 Mpc/h $N_p = 2048^3$



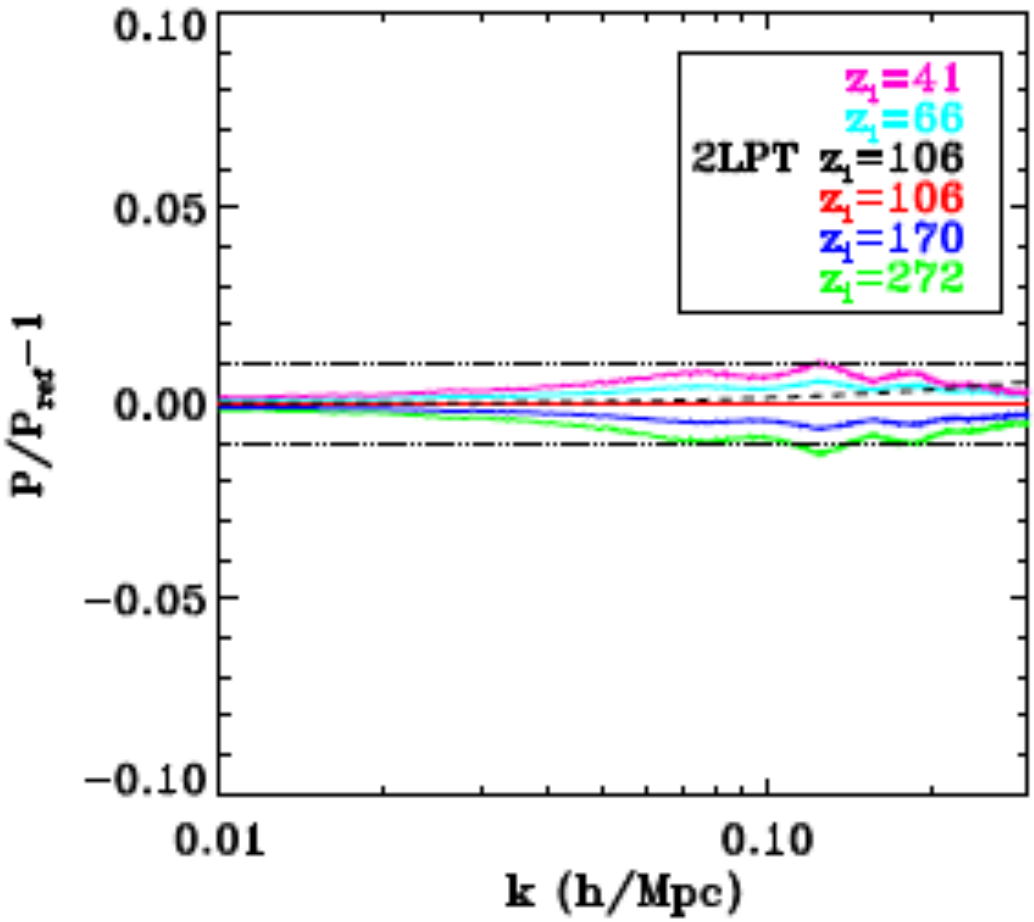
# Systematic Errors – Refinement

$L_{box}$ = 5250 Mpc/h $N_p = 2048^3$

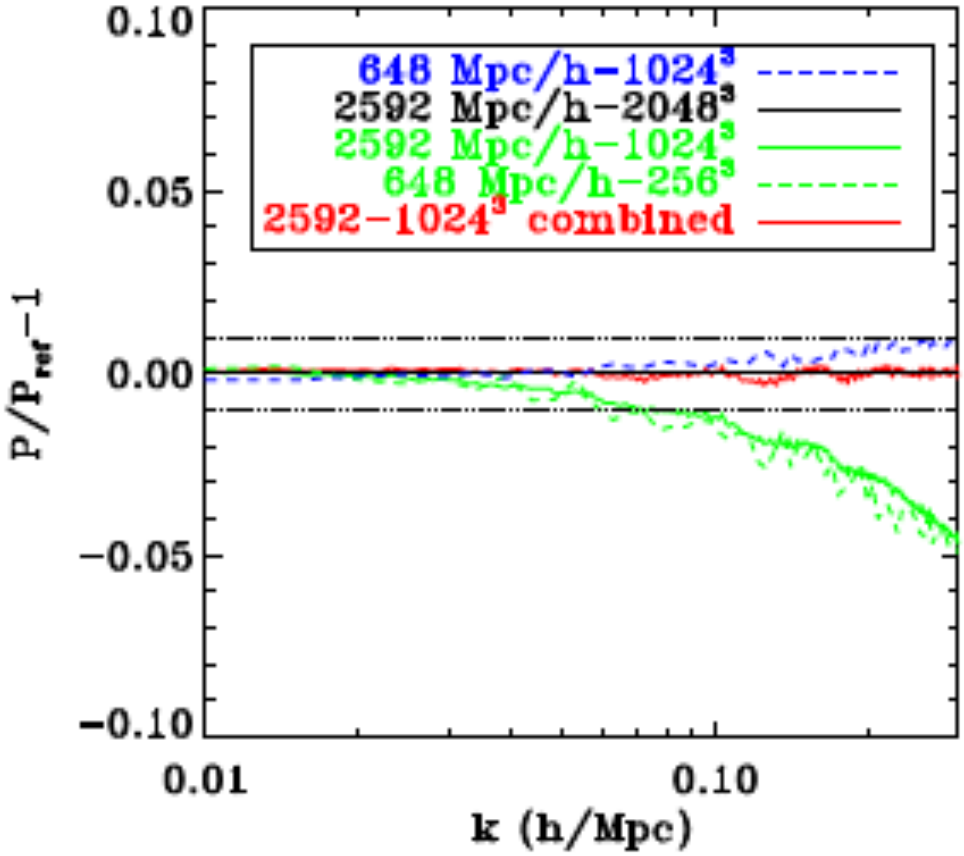


# Systematic Errors – IC

$L_{box}$ = 5250 Mpc/h $N_p = 2048^3$



# Systematic Errors – Mass Resolution




$m_p = 1.8\ 10^{10}\ h^{-1}\ M_{Sun}$

$m_p = 1.5\ 10^{11}\ h^{-1}\ M_{Sun}$

$m_p = 1.2\ 10^{12}\ h^{-1}\ M_{Sun}$

$$r^{corr}_{poly-fit}(k) = \frac{P_{256^3-648}(k)}{P_{2048^3-2592}(k)}$$

$$P^{corr}_{DEUS-FUR}(k) = \frac{\hat{P}_{DEUS-FUR}(k)}{r^{corr}_{poly-fit}(k)}$$

- 8% drop at k=0.3 for ~3 $10^{12}\ h^{-1}\ M_{sun}$ (Heitmann et al. 2010)
- ~8 cells per particle, Zeldovich wave test (Knebe, Green & Binney 2001)

# BAO Spectrum at 1%

**Interval Range** $0.03 < k < 0.3$

**Wiggle-free Spectrum**

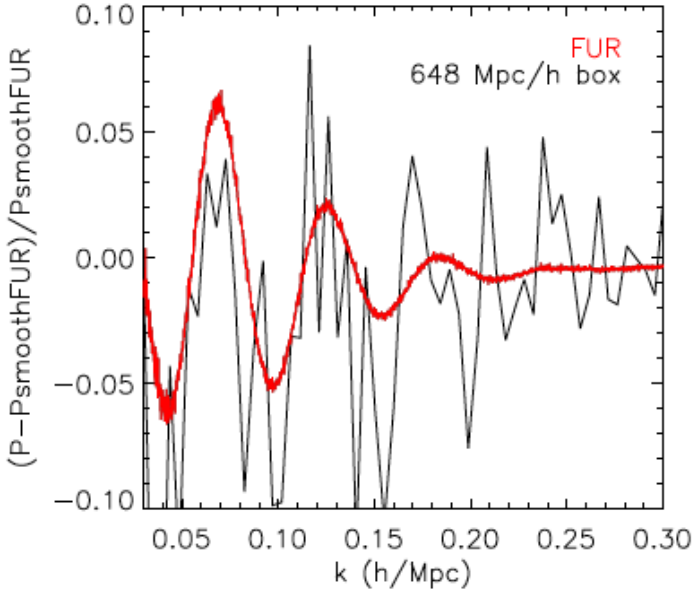
- Linear wiggle-free ? NL erase BAO at high-end interval
- Polynomial fit ?
- NL evolved wiggle-free initial spectrum

Crocce & Scoccimarro (2008)

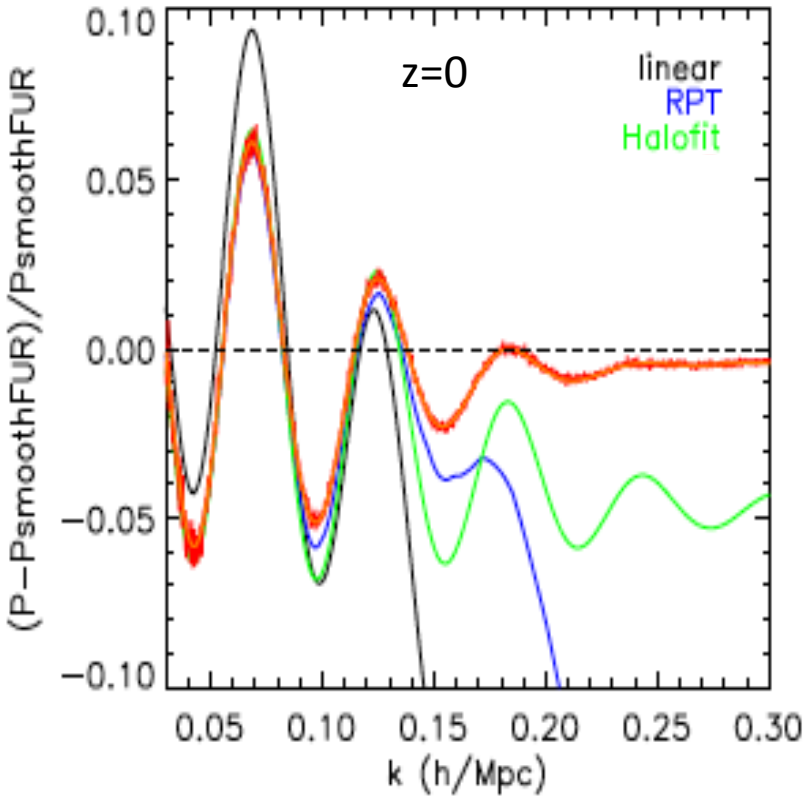
N-body evolved Hu & Eisensten wiggle-free Initial Conditions

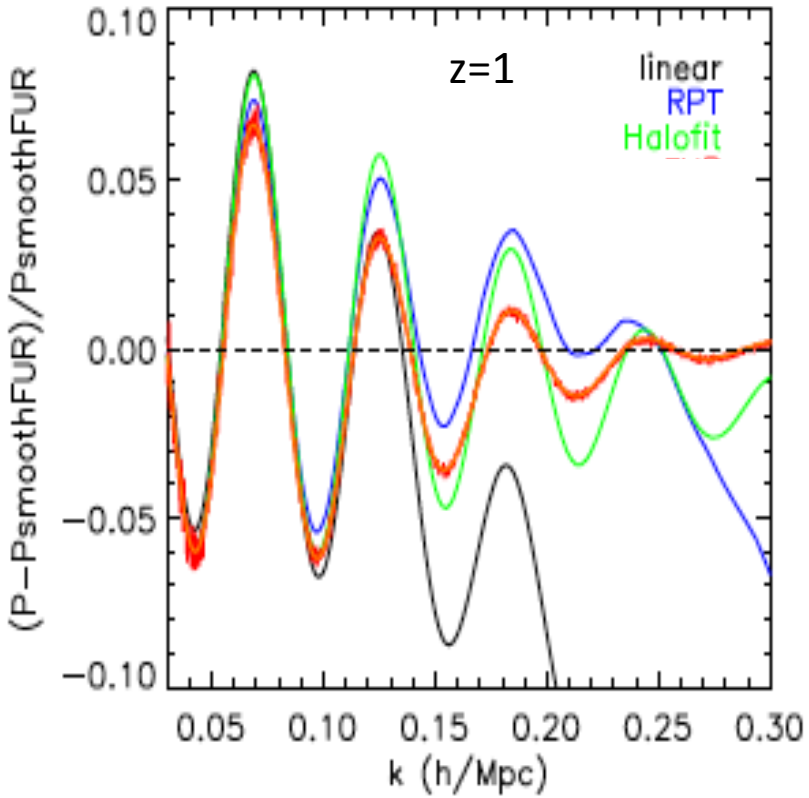
$L_{box}$ = 5250 Mpc/h $N_p = 2048^3$

$$P^{BAO}_{DEUS-FUR}(k) = P^{corr}_{DEUS-FUR}(k) - P_{smooth}(k)$$



# BAO Spectrum vs Analytics



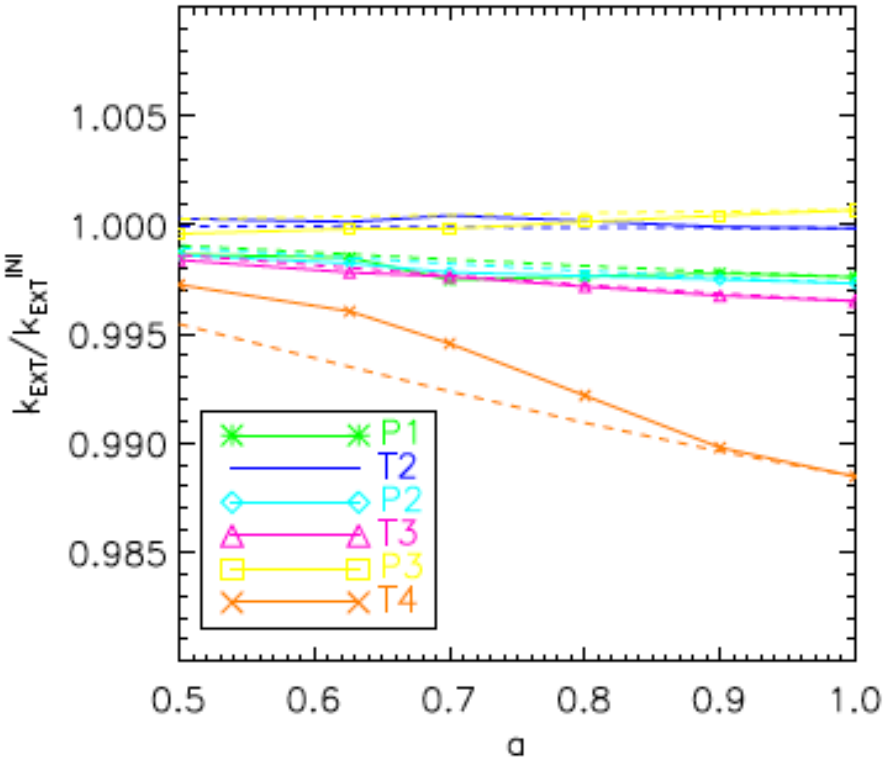



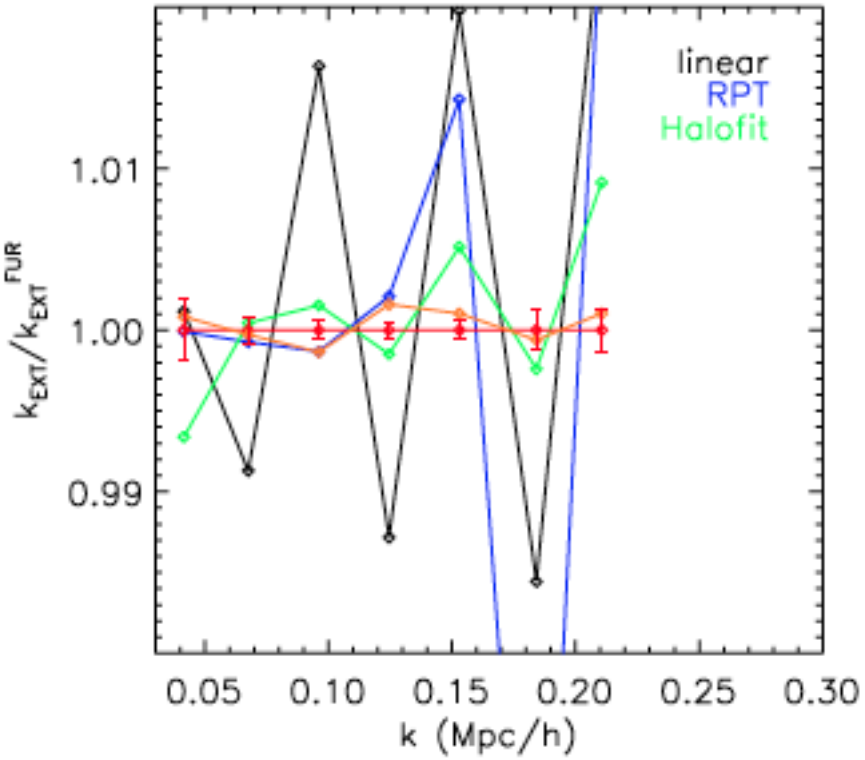

RegPT – Taruya et al. (2012)

Halofit – Smith et al. (2003,2014)

# BAO Shift & Redshift Evolution

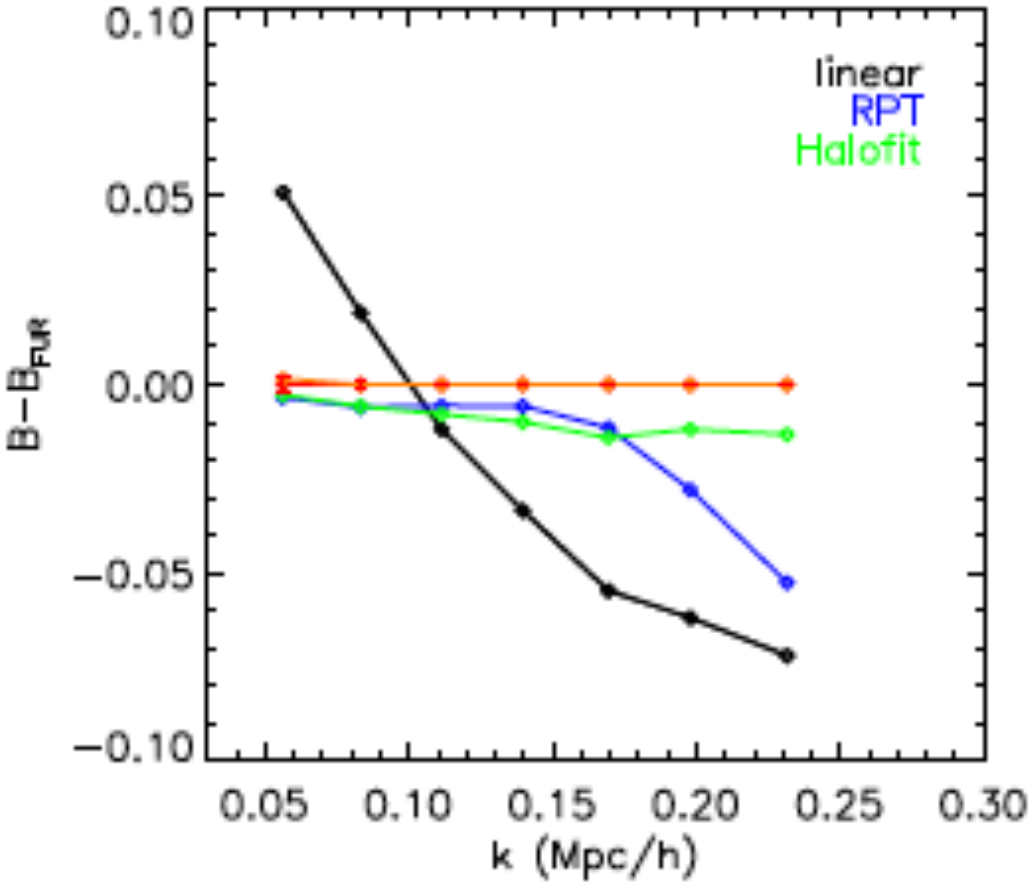
- Non-linear shifts ~1% confirming PT expectations




- z-dependence ≈ $D_+(z)^2$
- 3rd Peak & 2nd Dip unaltered

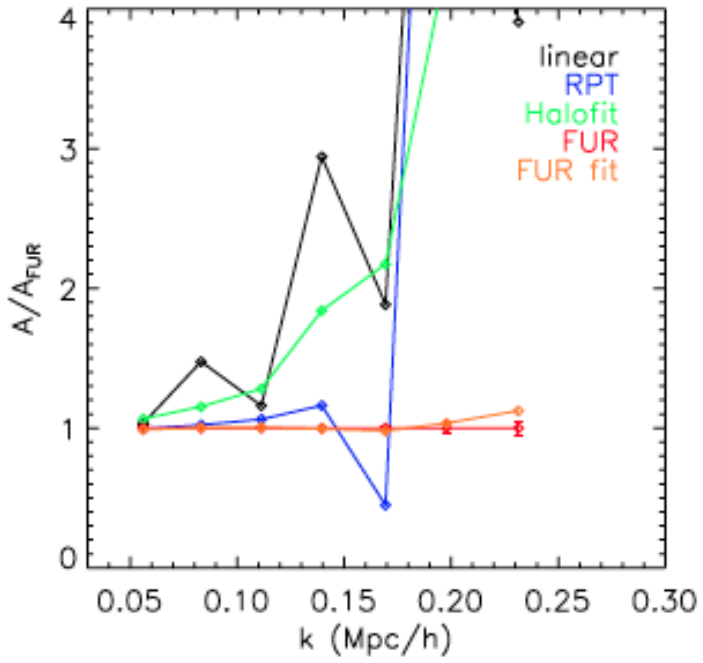
# BAO coupling to broad-band slope



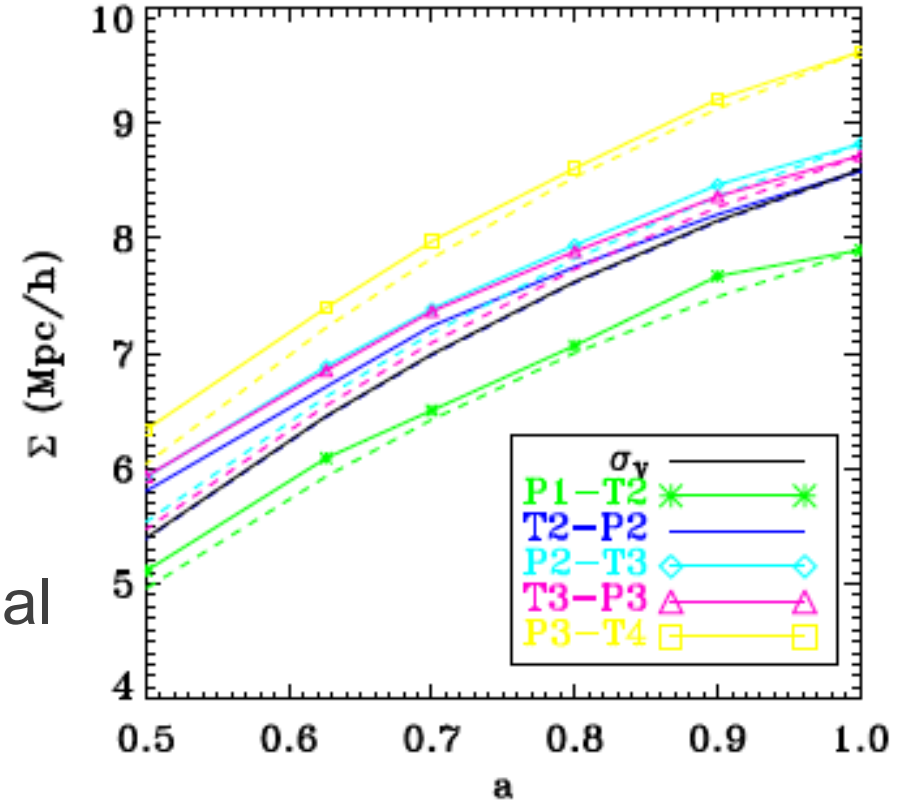

- Estimated from averaging B(k) over pairs of consecutive extrema

- RPT deviations >1% beyond 3rd peak

# BAO Damping & Redshift Evolution




- Scale-dependent damping




- z-dependence proportional to velocity dispertion
- Redshift scaling proportional to $D_+(z)$

# Conclusions

- BAO precision cosmology requires precise and accurate N-body spectra to validate model templates/theoretical predictions

- Requires very large volume simulations. Using DEUS-FUR we validated BAO spectrum LCDM-W7 to 1% stats and num sys through convergence error analysis

- Non-linearities carry cosmological information, they are not NUISSANCE!

# How about covariance?

## Non-linear Mode Correlations

$$\mathrm{cov}(k_1,k_2) = \frac{2}{N_{k_1}} P^2(k_1)\delta_{k_1k_2} + \frac{1}{V}\int_{\Delta_{k_1}}\int_{\Delta_{k_2}} \frac{d^3k_1^{`}}{V_{k_1}} \frac{d^3k_2^{`}}{V_{k_2}}\, T(k_1^{`},-k_1^{`},k_2^{`},-k_2^{`})$$

- Sourced by non-linear collapse induced non-Gaussianity
- Full trispectrum calculation not analytically viable
- Infer by numerically sampling P(k)

$$\mathrm{cov}(k_1,k_2) = \frac{1}{N_r - 1}\sum_{i=1}^{N_r}\left[\hat{P}_i(k_1) - \bar{P}(k_1)\right]\left[\hat{P}_i(k_2) - \bar{P}(k_2)\right]$$

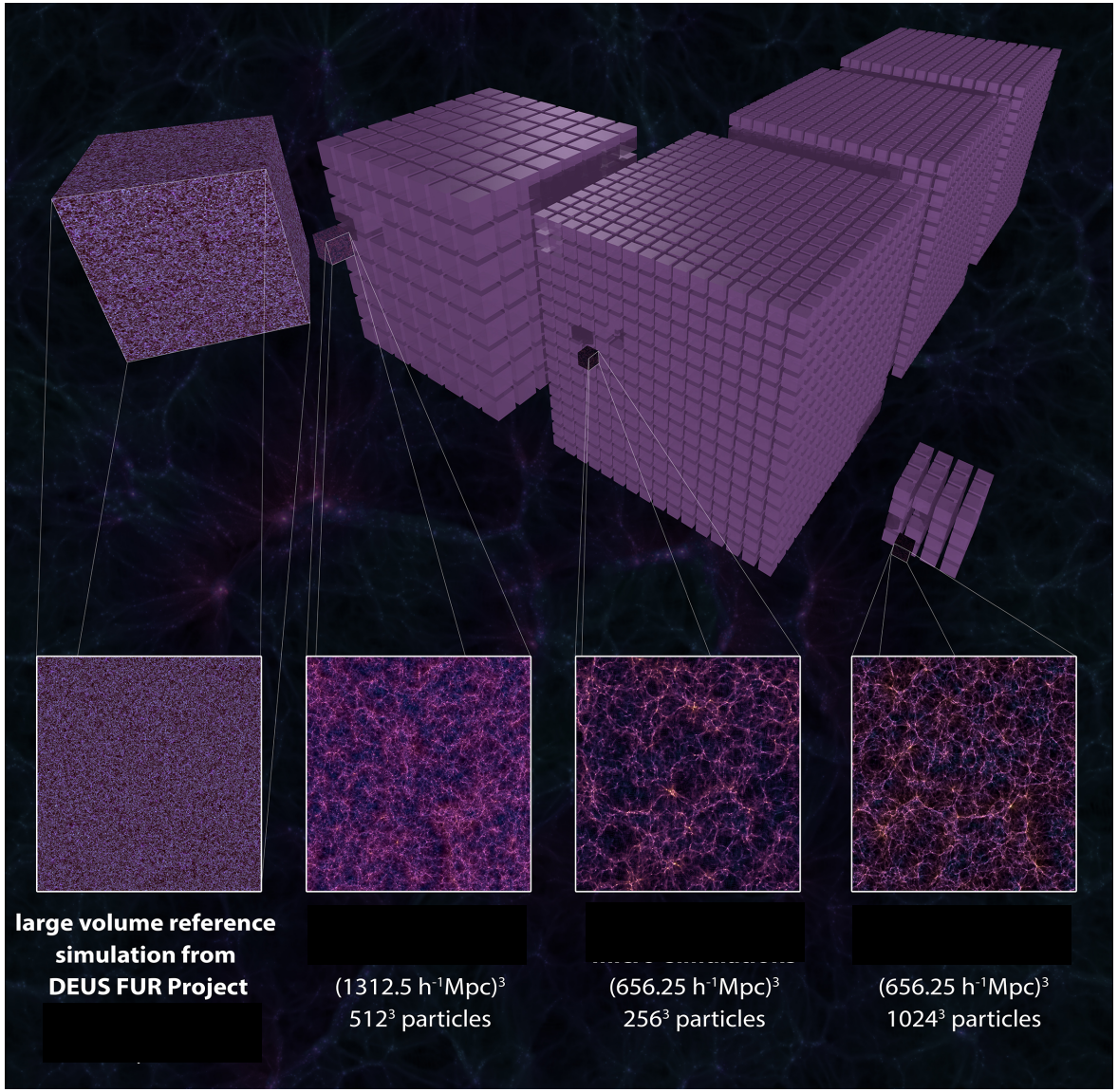
$$\bar{P}(k) = \frac{1}{N_r}\sum_{i=1}^{N_r}\hat{P}_i(k)$$

# DEUS-Parallel Universe Runs

#-12288 Simulations
$N=256^3$ L=648 Mpc/h
$m_p \sim 10^{12} M_{sun}$

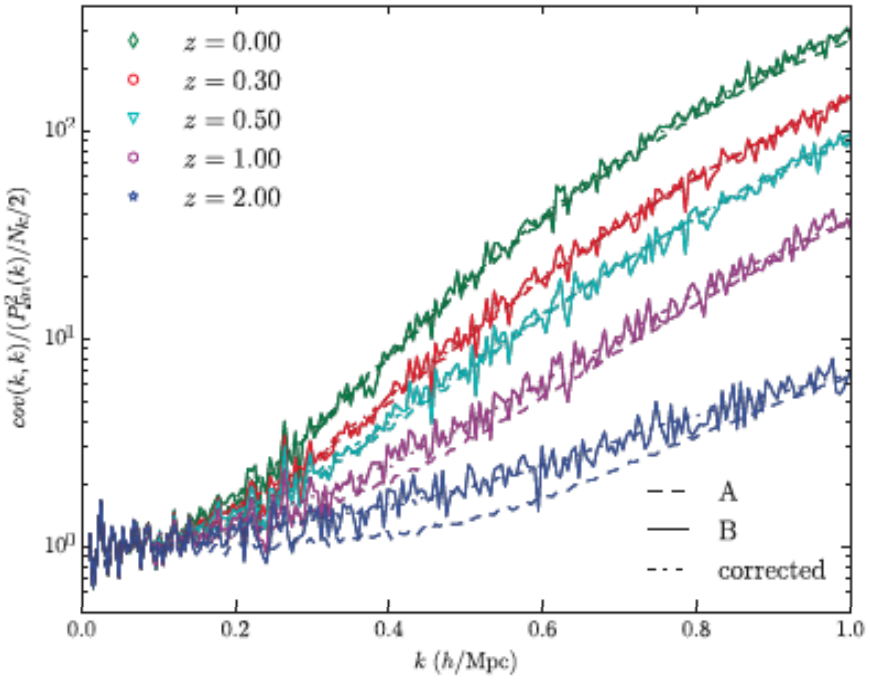
#-512 Simulations
$N=512^3$ L=1.3 Gpc/h
$m_p \sim 10^{12} M_{sun}$

#-128 Simulations
$N=1024^3$ L=648 Mpc/h
$m_p = 1.8 \times 10^{10} M_{sun}$

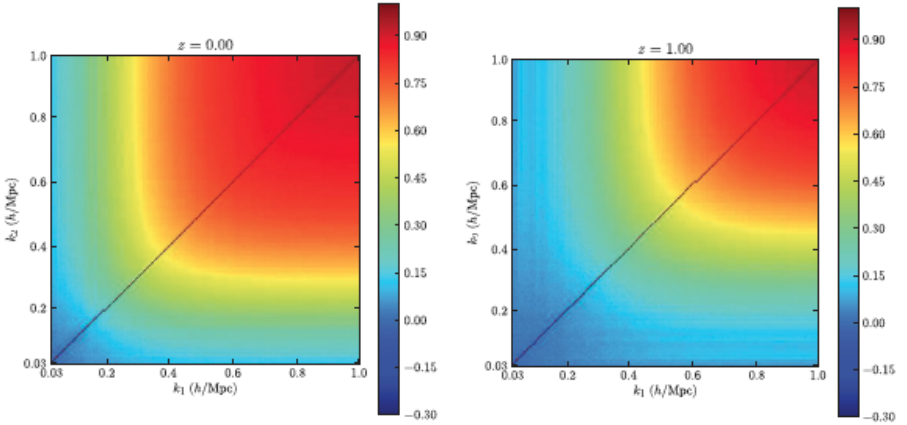


# DEUS-PUR Covariance

## Diagonal




## Off-Diagonal

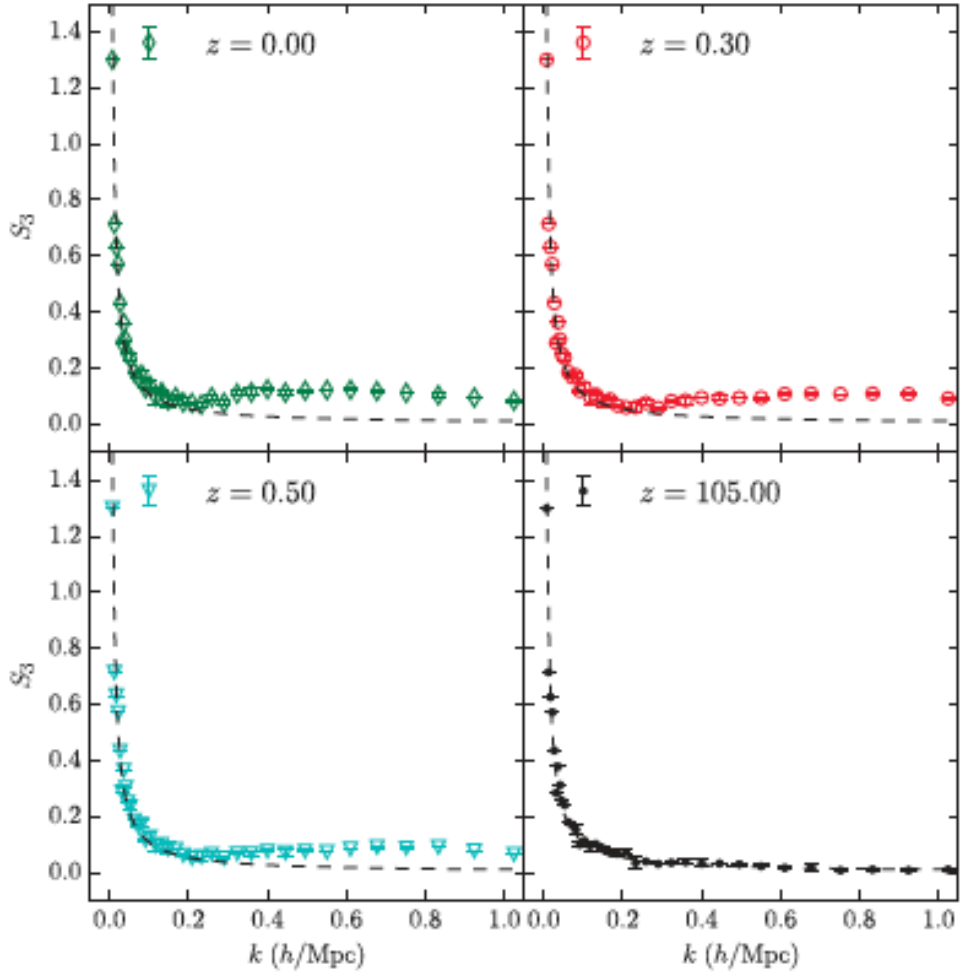



- Full covariance needs to be included
- Underestimate errors on α

Blot et al. (2015)

# Power Spectrum Distribution

## Deviations from $\chi^2$ statistics




Blot et al. (2015)

## S/N and Convergence

$$\left(\frac{S}{N}\right)^2 = \sum_{k_1, k_2 < k_{\max}} P(k_1)\, \psi(k_1, k_2)\, P(k_2),$$