Astrophysical Systematics in Weak Lensing

Baryonic Effects on Matter Distribution
Intrinsic Alignment of Galaxies

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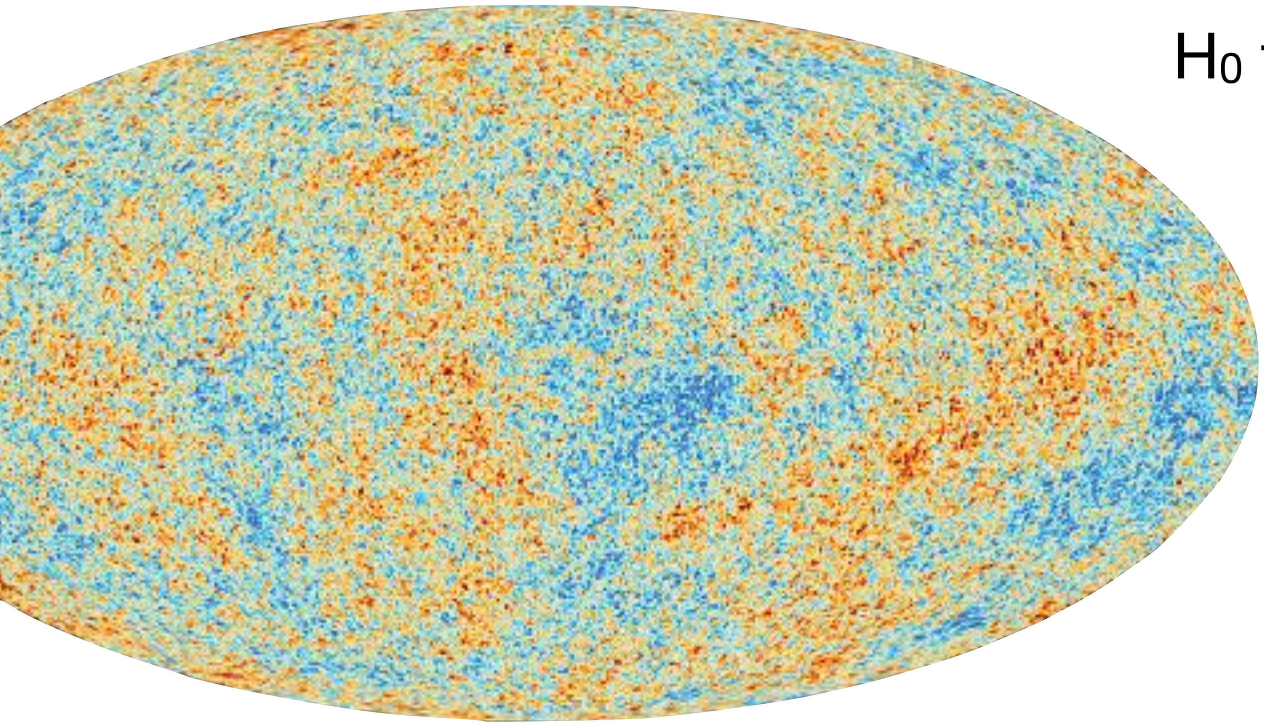
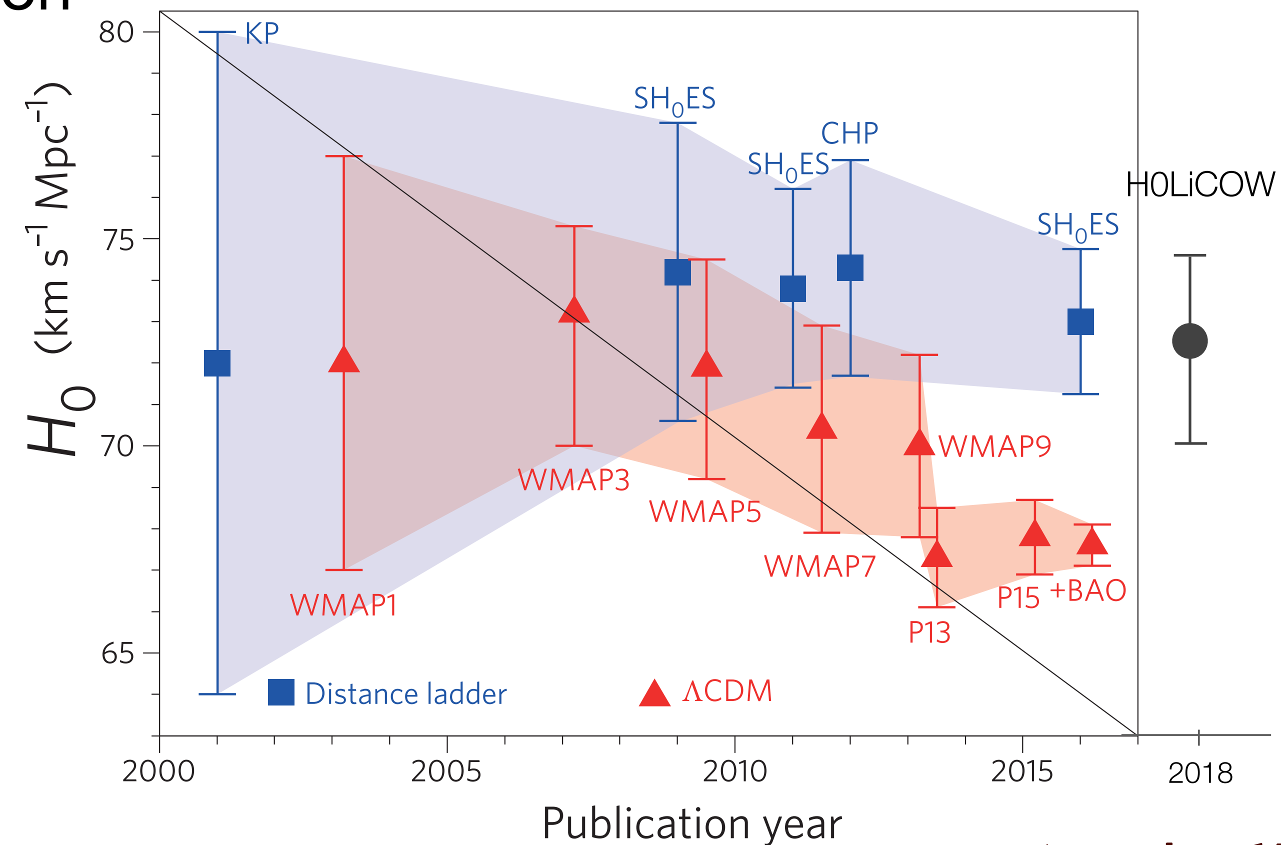
Testing ΛCDM — from CMB to late time Universe

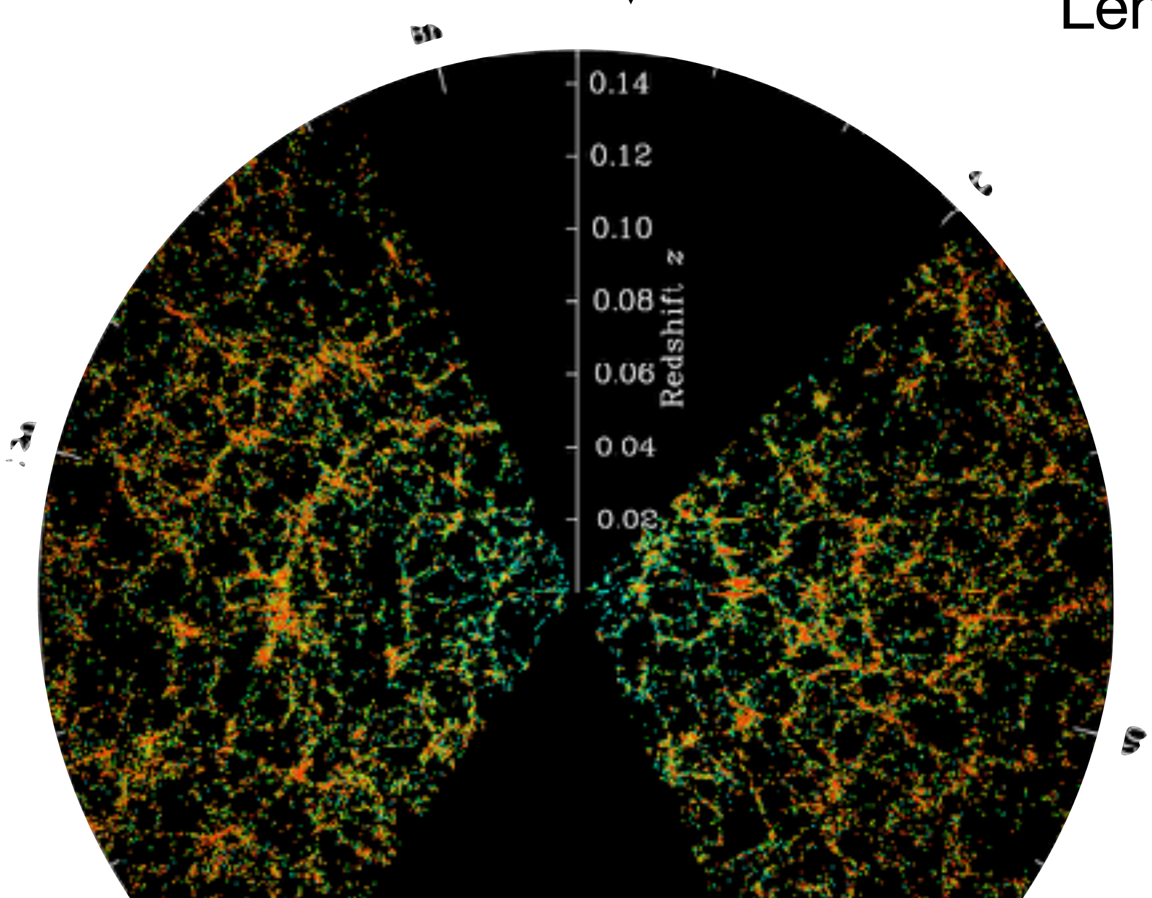


H_0 tension

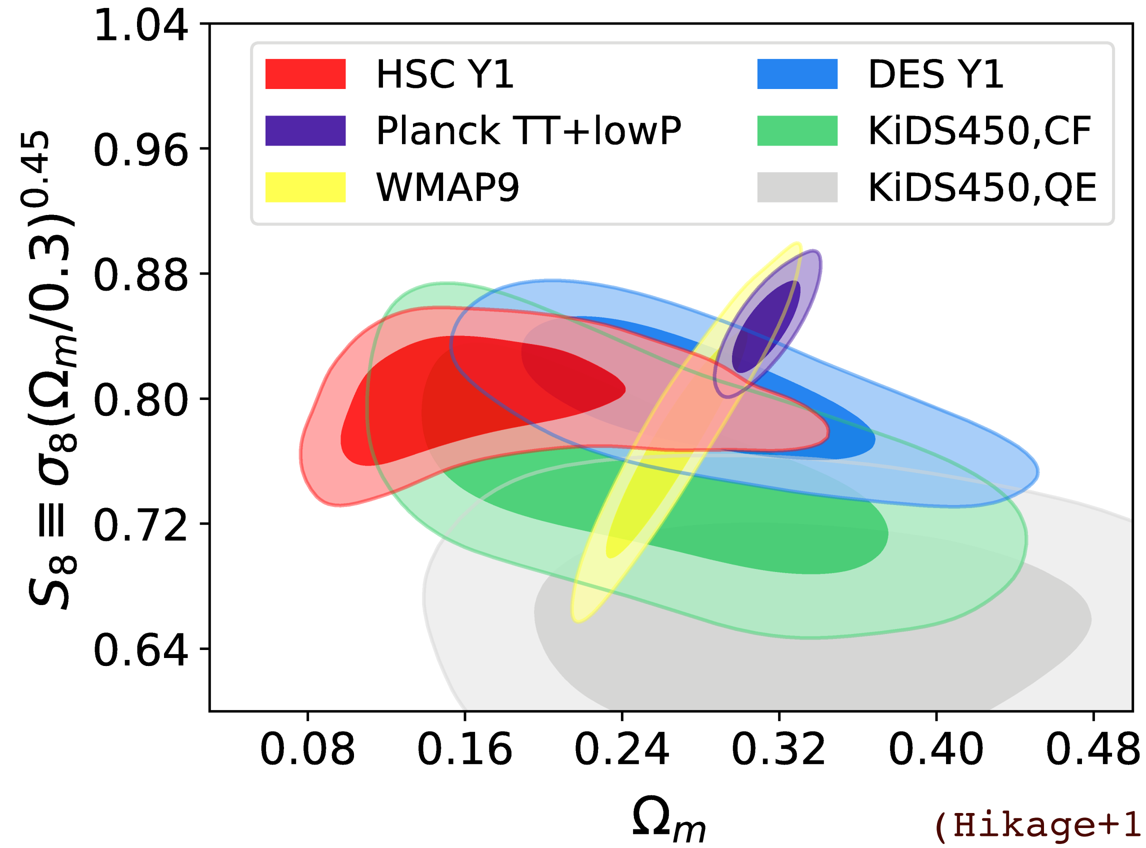


(Freedman17)

evolution of structure growth

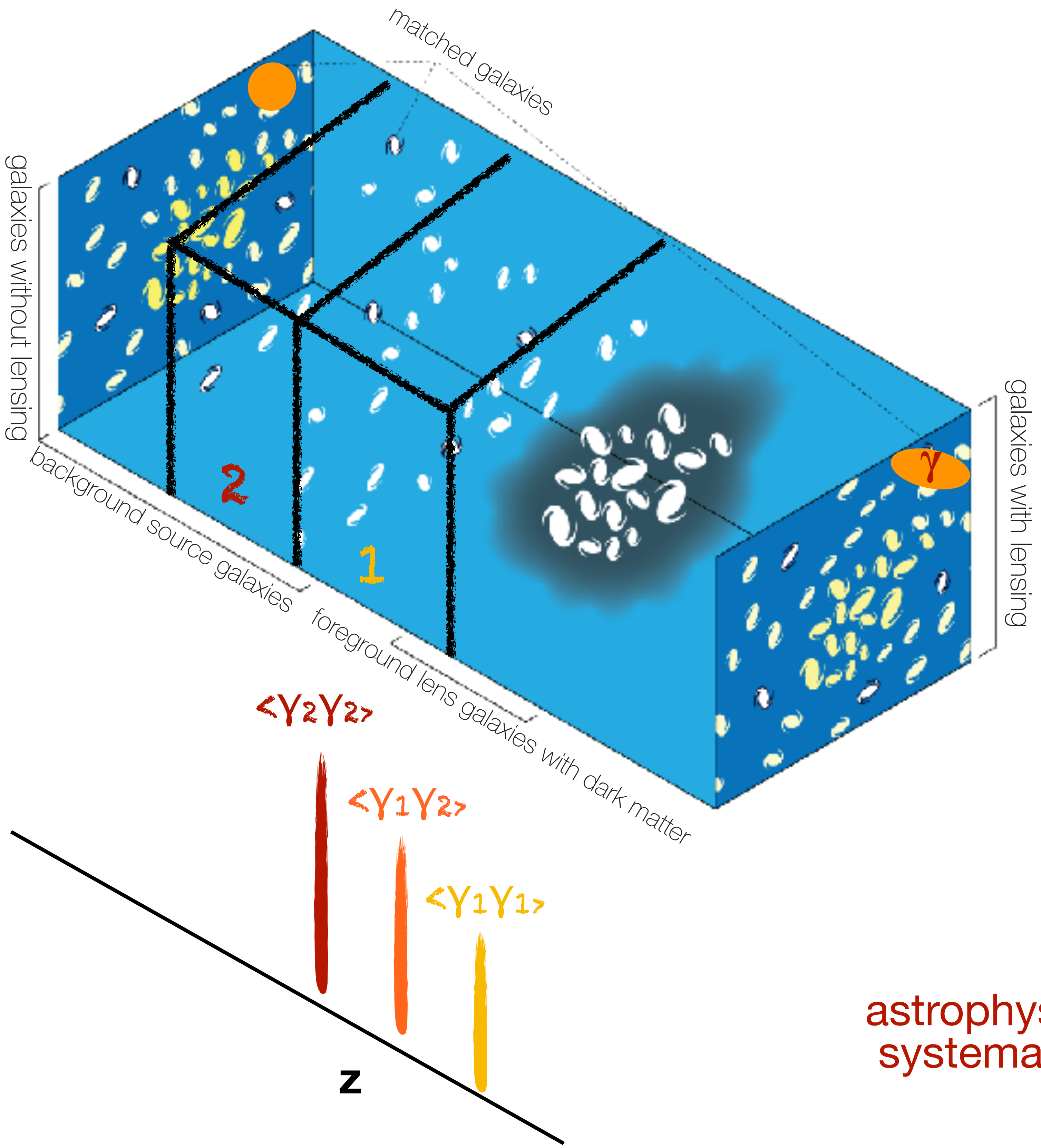


Lensing is low



(Hikage+18)

Weak Gravitational Lensing



- **Direct measurement** of the **integrated mass** content.

$$\text{lensing potential} \propto \frac{D_{SL}\, D_L}{D_S}\, \Sigma$$

- **Tomography technique** provides more information from the **evolution of structure across redshift.**

- Constrain cosmology mainly via **growth of structure**, partially via **geometry** (distance ratios).

- **Systematics** to overcome:
  - — Shear calibration
  - — Photometric redshift
  - — Intrinsic alignment
  - — Baryonic effect

astrophysical systematics (Intrinsic alignment, Baryonic effect)

Outline of this talk

1 Modeling baryonic effects in cosmic shear

with Tim Eifler, Rachel Mandelbaum, Scott Dodelson

arXiv:1809.01146

2 Intrinsic Alignment of galaxies in redMaPPer clusters

with Rachel Mandelbaum, Peter Freeman, Yen-Chi Chen
Eduardo Rozo, Eli Rykoff, Eric Baxter

arXiv:1605.01065, arXiv:1704.06273

3 Outlook

We rely on **gravity-only** simulations to interpret survey observables.

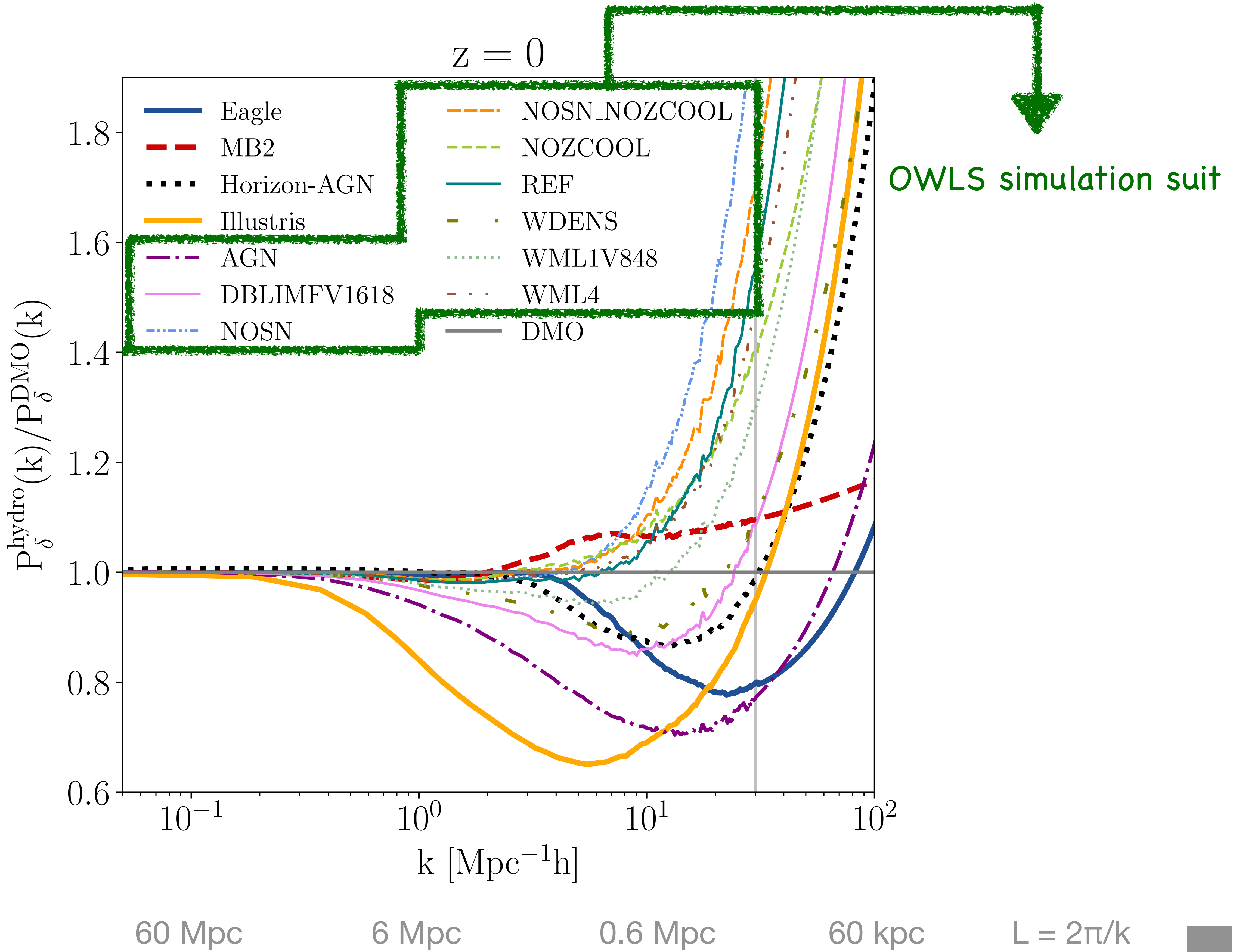
Convergence of P(k,z | cosmology) in DMO sims

		L = 2π/k: 6 Mpc	2 Mpc	0.6 Mpc
		k [h Mpc^{-1}]: 1	3	10
Halofit	(Takahashi+12)	~ 5%	~ 10%	~ 10%
HMcode	(Mead+15)	~ 5%	~ 5%	~ 5%
Emulator: COYOTE Universe	(Heitmann+10)	~ 1%	~ 5%	~ 5%
Emulator: Aemulus Project	(DeRose+18)	~ 1%	~ 1%	
Emulator: MIRA-TITAN Universe	(Heitmann+16)	~ 1%	~ 1%	~ 1%

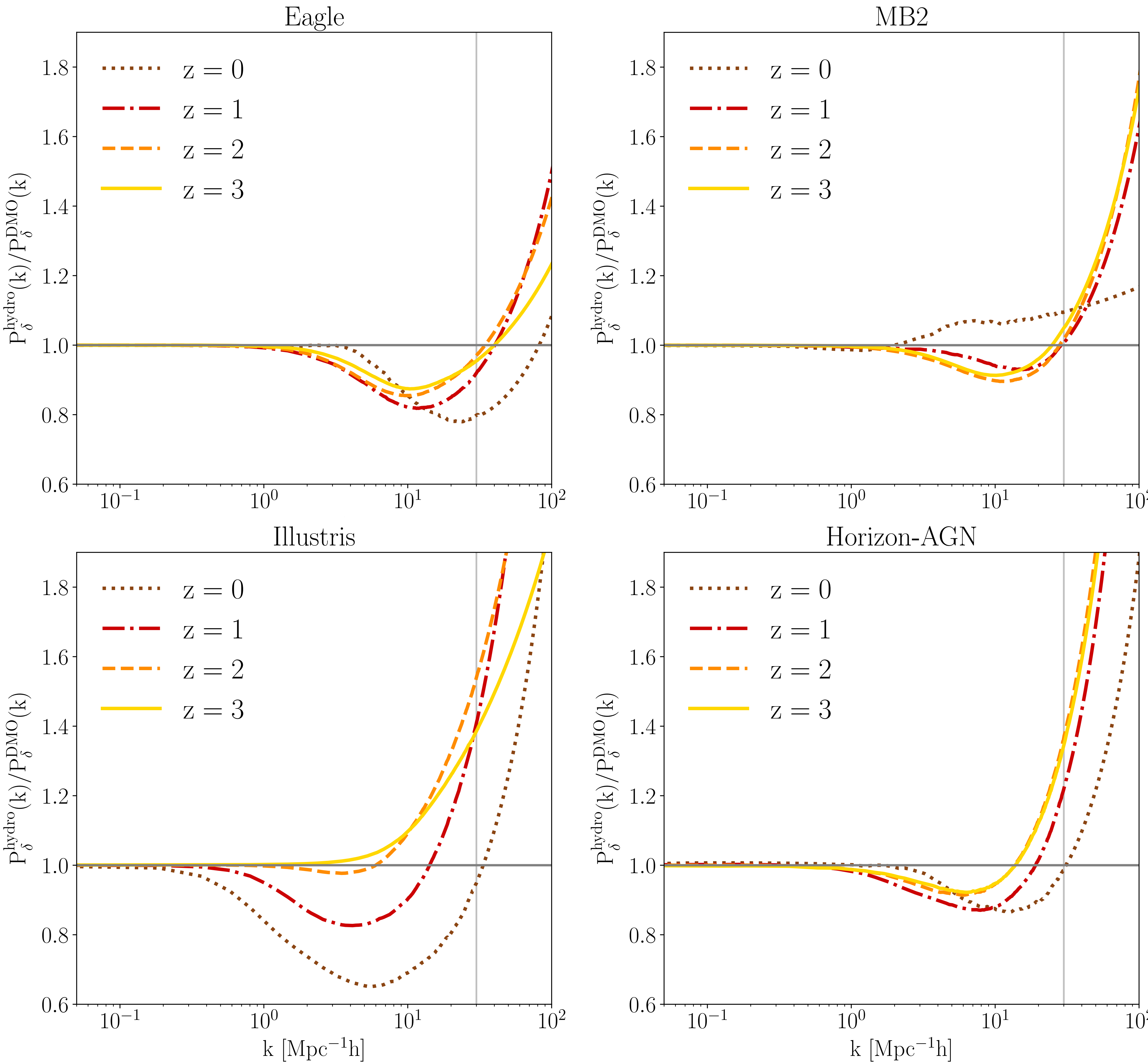
Uncertainties due to baryonic physics
~ 10-30%

The the accuracy of power spectra need to be at **1% level** out to **k~10 h Mpc^{-1}** in the era of LSST.

Hydrodynamical simulations are far from converging…



The redshift evolution on P(k) can be really different…



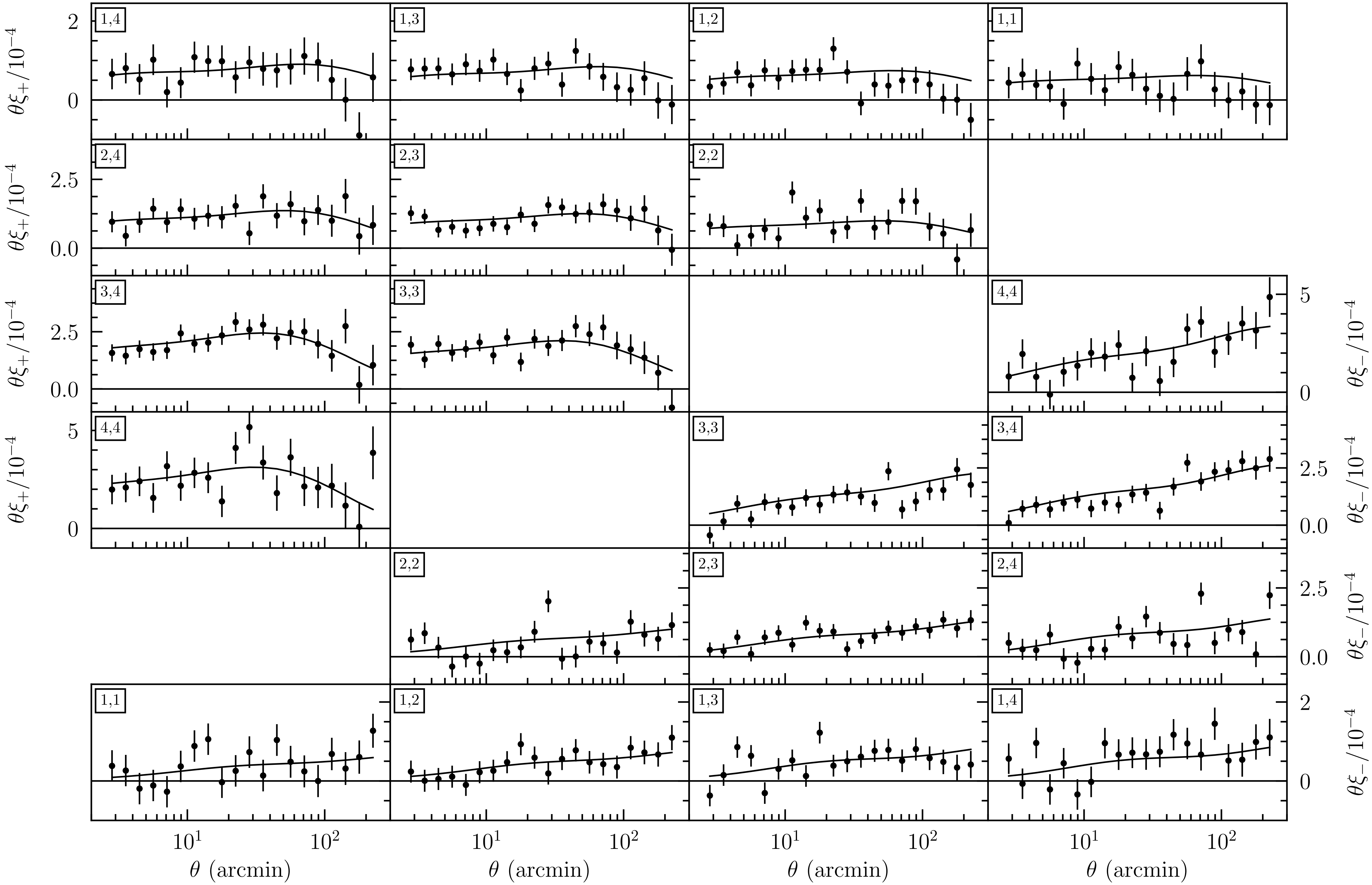
Safe small scale cut in cosmic shear analysis

DES Y1

ξ+ scale cut : 4 ~ 6 arcmin

ξ- scale cut : 30~70 arcmin

determined based on **OWLS-AGN** baryonic scenario



(Troxel+18)

Two baryon mitigation techniques — PCA & HMcode

PCA

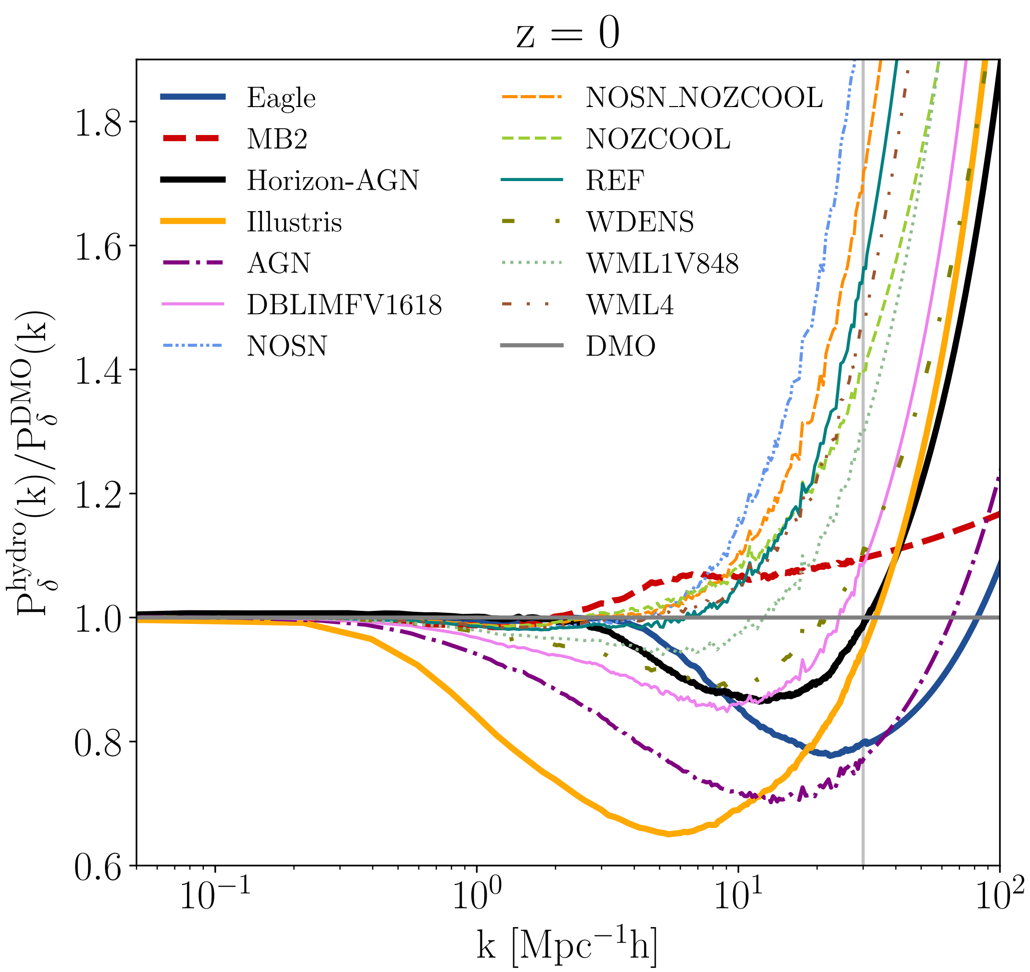
(Eifler et al. 2015)

Marginalizing over dominant PC modes

Assumption

Our Universe hydro sims

share similar baryonic feature



HMcode (halo model)

(Mead et al. 2015)

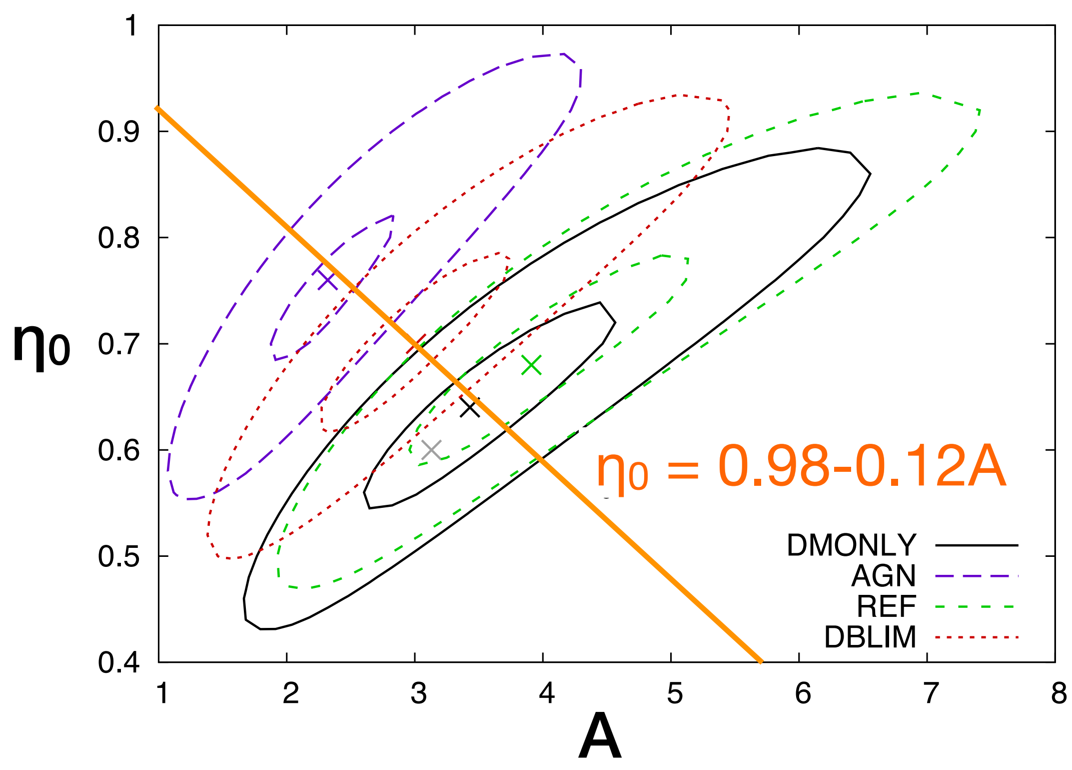
Marginalizing over halo structure parameters

A : Amplitude of concentration-mass relation

η_0 : halo bloating factor (mass dependent feedback)

Modeling options → $P(k, z \mid p_{co}, A, \eta_0)$

→ $P(k, z \mid p_{co}, A)$

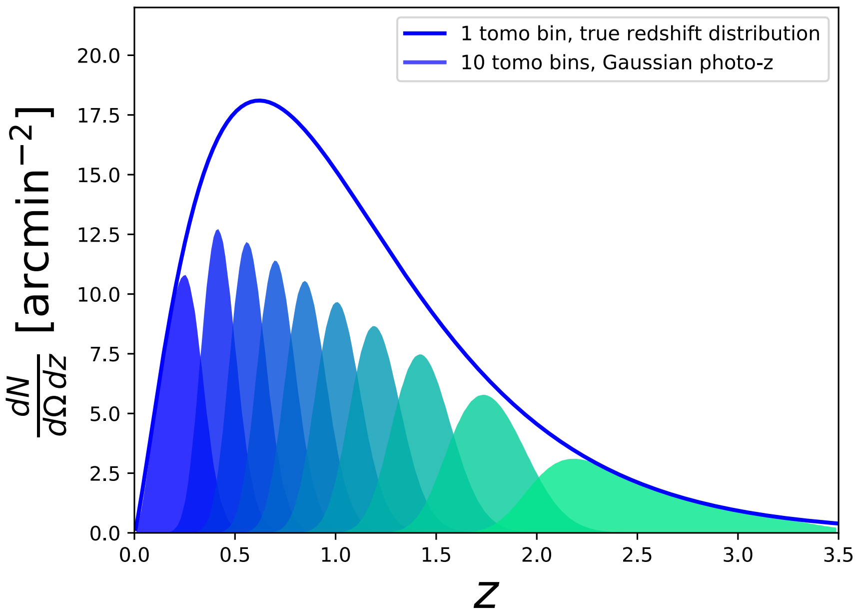


LSST Year 10 Likelihood simulation setting up

Observables

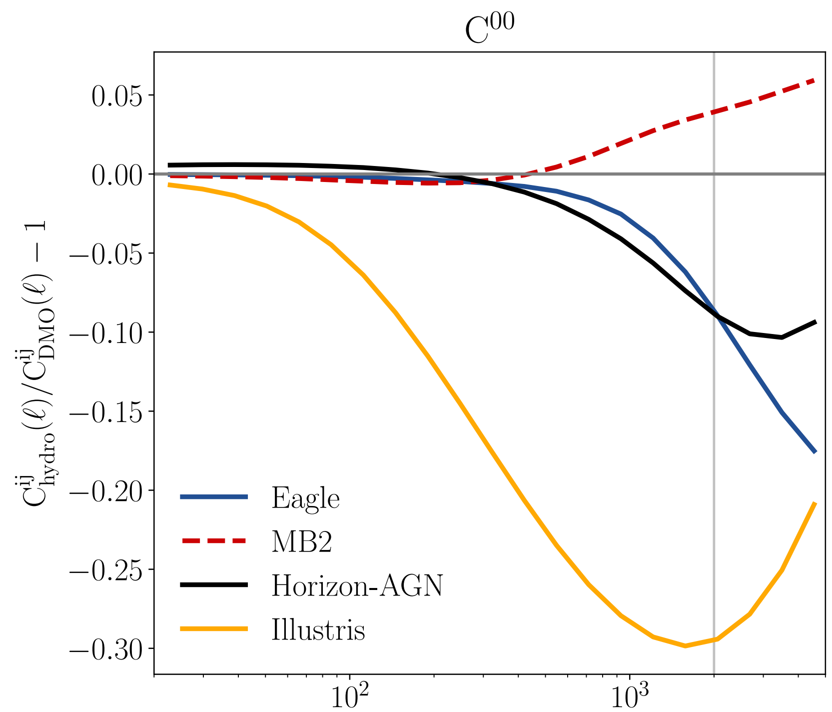
Shear tomography power spectrum $C^{ij}(\ell)$

(contaminated with baryonic scenarios of MB2/Eagle/Horizon-AGN/Illustris)



6 arcmin 2.5 arcmin

scale cut $\ell_{max} \approx$ 2000 or 5000



Θ 2° 12 arcmin

cross tomography bins

$$\begin{pmatrix} C^{00}_{bary}(30) \\ C^{00}_{bary}(50) \\ \cdots \\ C^{00}_{bary}(2000) \\ C^{01}_{bary}(30) \\ \cdots \\ \cdots \\ C^{ij}_{bary}(l) \\ \cdots \\ \cdots \\ \cdots \\ \cdots \\ \cdots \\ C^{99}_{bary}(2000) \end{pmatrix}_{990}$$

bin (0,0)

bin (i , j)

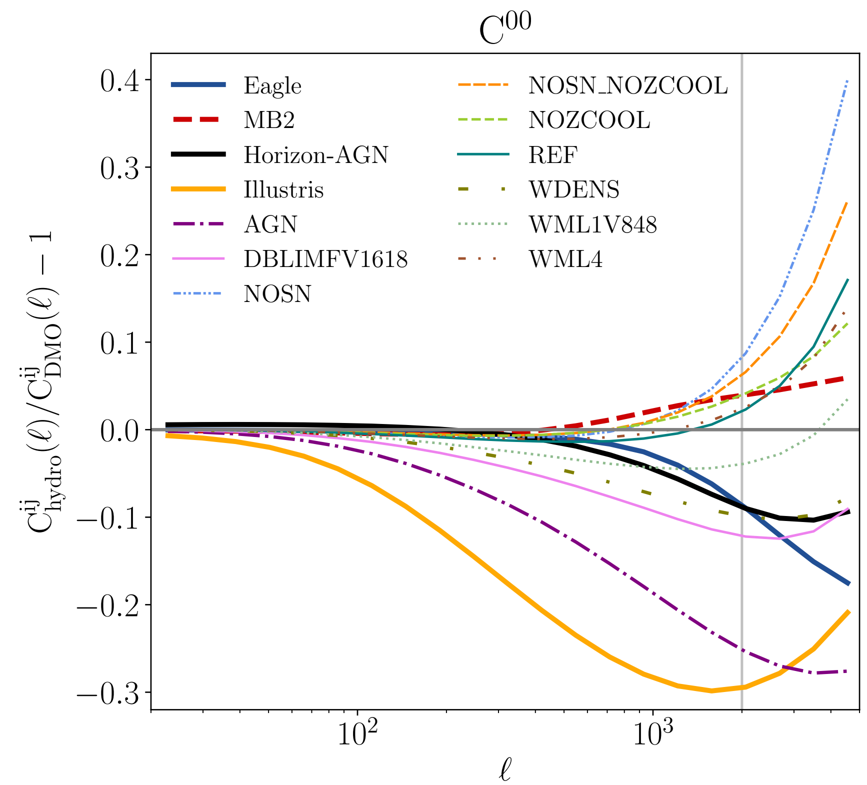
bin (9,9)

Cosmological model

wCDM : $\{\Omega_m, \sigma_8, w_0, w_a, n_s, \Omega_b, h\}$

Model vector constructed from DMO P(k)+PCA or HMcode $\{A, \eta_0\}$

Training set : OWLS



Likelihood analysis

$$\log L \propto - [\, \mathbf{D}-\mathbf{M}(\mathbf{p}_{co}) \,]^t \, C^{-1} \, [\, \mathbf{D}-\mathbf{M}(\mathbf{p}_{co}) \,]$$

Covariance Matrix:
LSST Y10 estimated from Cosmolike

Procedures of PCA — Quantify the discrepancy in terms of **weighted difference**

9 OWLS hydro sims

Step 1 Build difference matrix Δ

$$\begin{array}{cccc} \text{AGN} & \text{DBLIMFV1618} & & \text{WML4} \\ \end{array}$$
$$\Delta = \begin{pmatrix} \mathbf{B}_{sim1}-\mathbf{M} & \mathbf{B}_{sim2}-\mathbf{M} & \cdots & \mathbf{B}_{sim9}-\mathbf{M} \end{pmatrix}_{990\times 9}$$

Step 2 Apply covariance driven <u>weighting factor</u> L^{-1}

L is the square root of $C = L\,L^{t}$
(Cholesky Decomposition)

$$\begin{array}{cccc} \text{AGN} & \text{DBLIMFV1618} & & \text{WML4} \\ \end{array}$$
$$\Delta_{ch} = L^{-1}\Delta = \begin{pmatrix} \mathbf{B}_{sim1,ch}-\mathbf{M}_{ch} & \mathbf{B}_{sim2,ch}-\mathbf{M}_{ch} & \cdots & \mathbf{B}_{sim9,ch}-\mathbf{M}_{ch} \end{pmatrix}_{990\times 9}$$

$M_{ch} = L^{-1} M$
$B_{sim1,ch} = L^{-1} B_{sim1}$

Procedures of PCA — compute PC basis

Step 3 Perform PCA on Δ_{ch}

$$\Delta_{ch} = L^{-1}\Delta = \begin{array}{cccc} \text{AGN} & \text{DBLIMFV1618} & \cdots & \text{WML4} \\ \left(B_{sim1,ch}-M_{ch} \right. & B_{sim2,ch}-M_{ch} & \cdots & \left. B_{sim9,ch}-M_{ch} \right) \end{array}$$

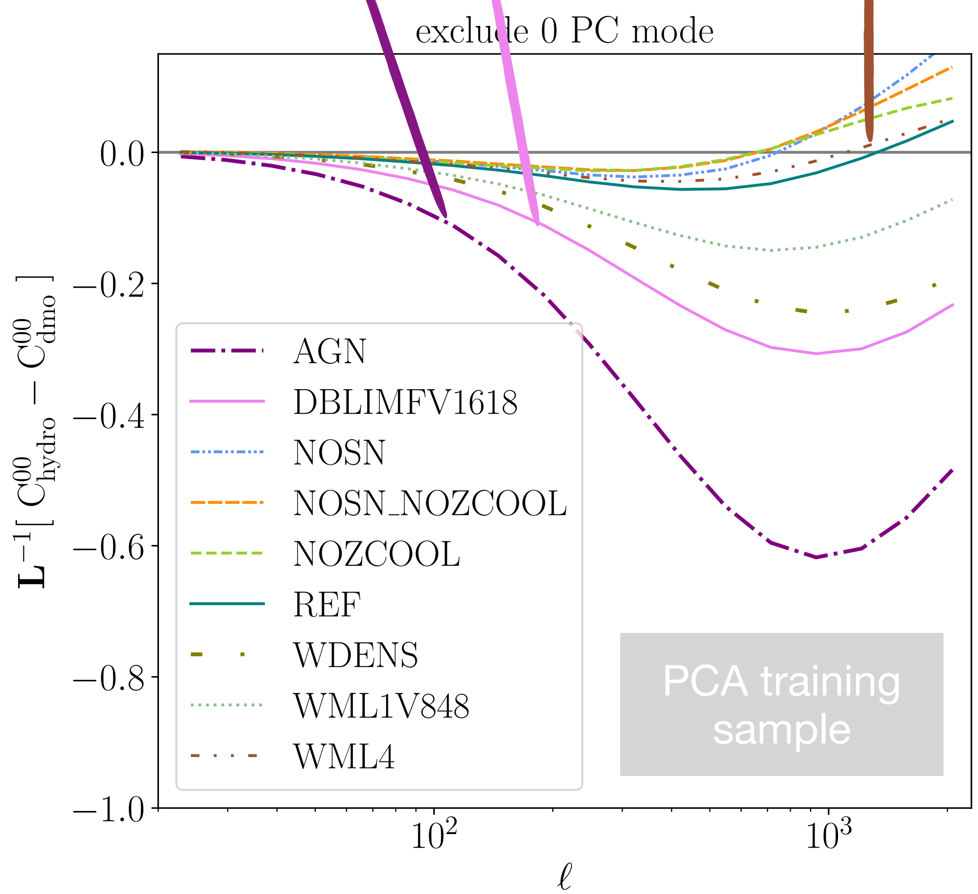
990x9

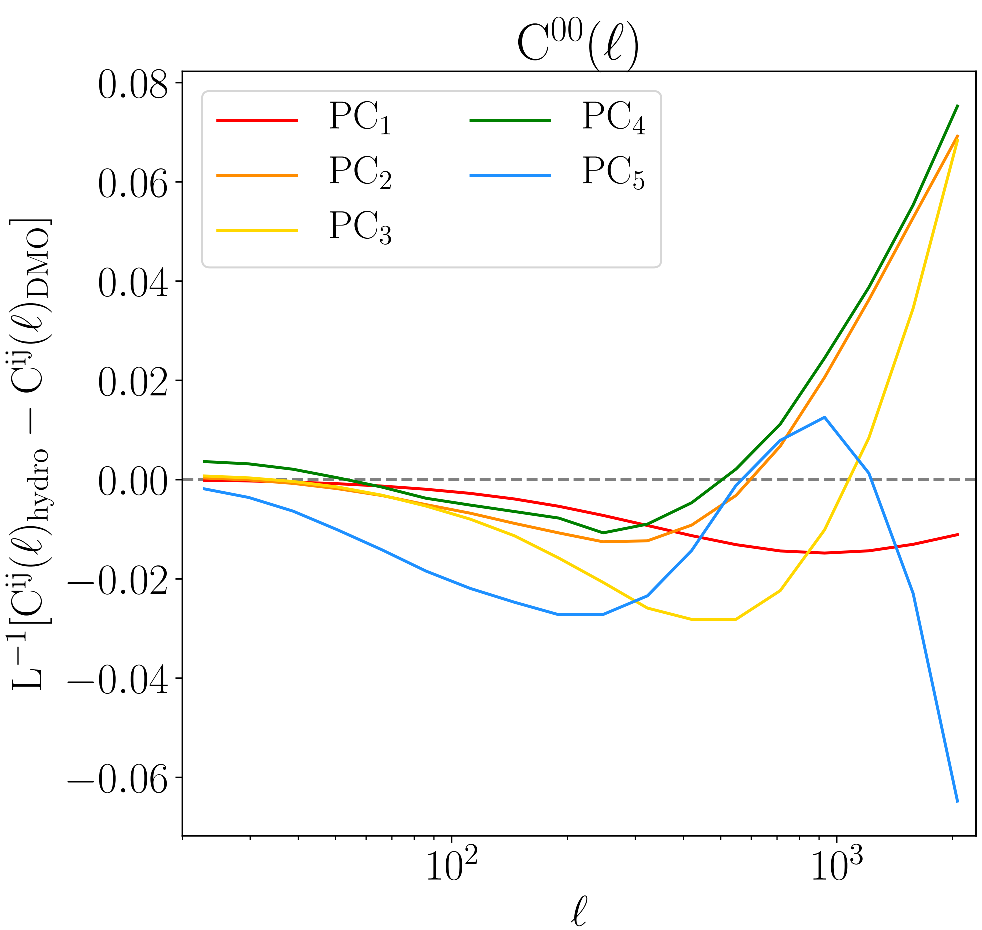
$M_{ch} = L^{-1} M$

$B_{sim1,ch} = L^{-1} B_{sim1}$

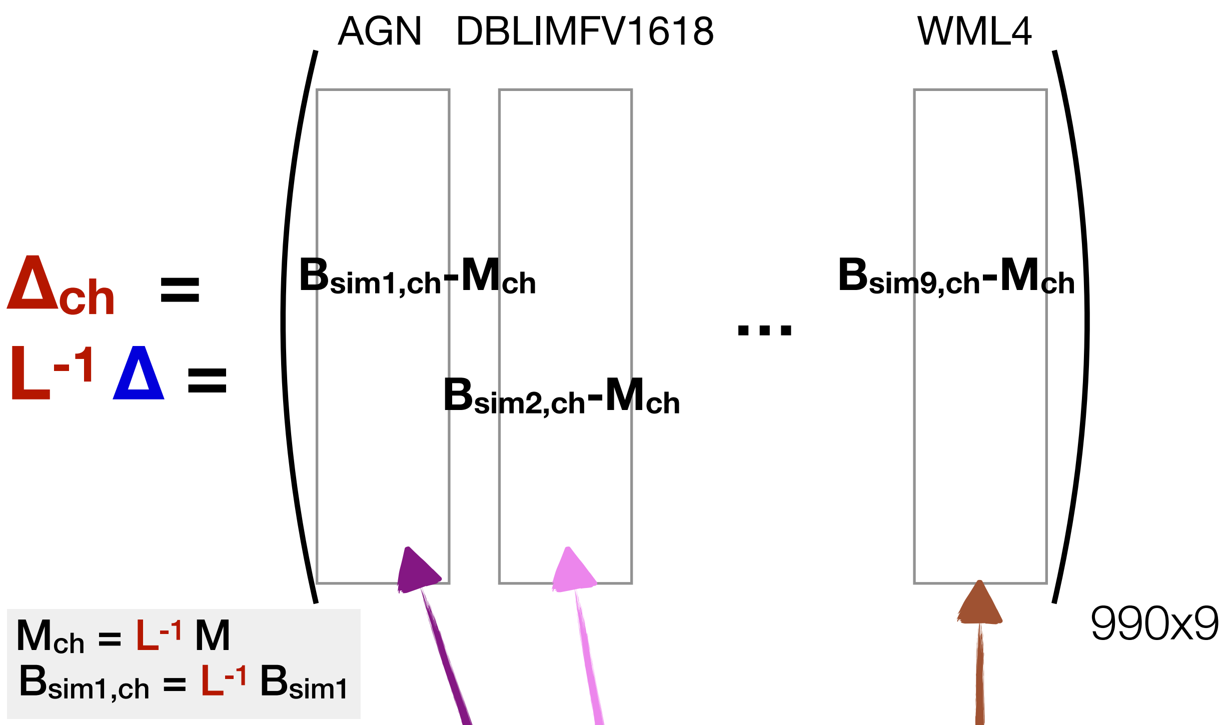
$$U = \left(PC_1 \; PC_2 \; \ldots \; PC_9 \; \ldots \; PC_{990} \right)$$

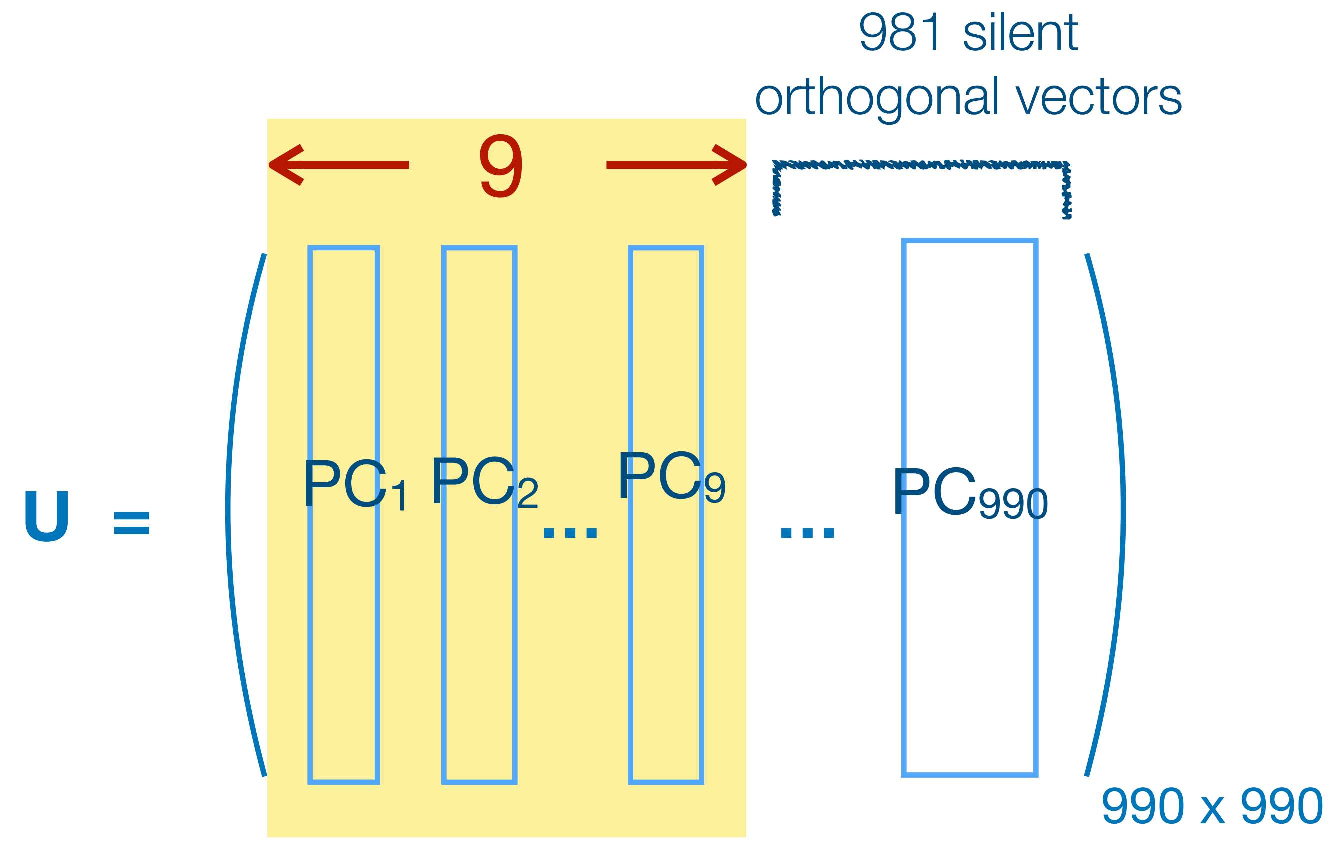
990 x 990

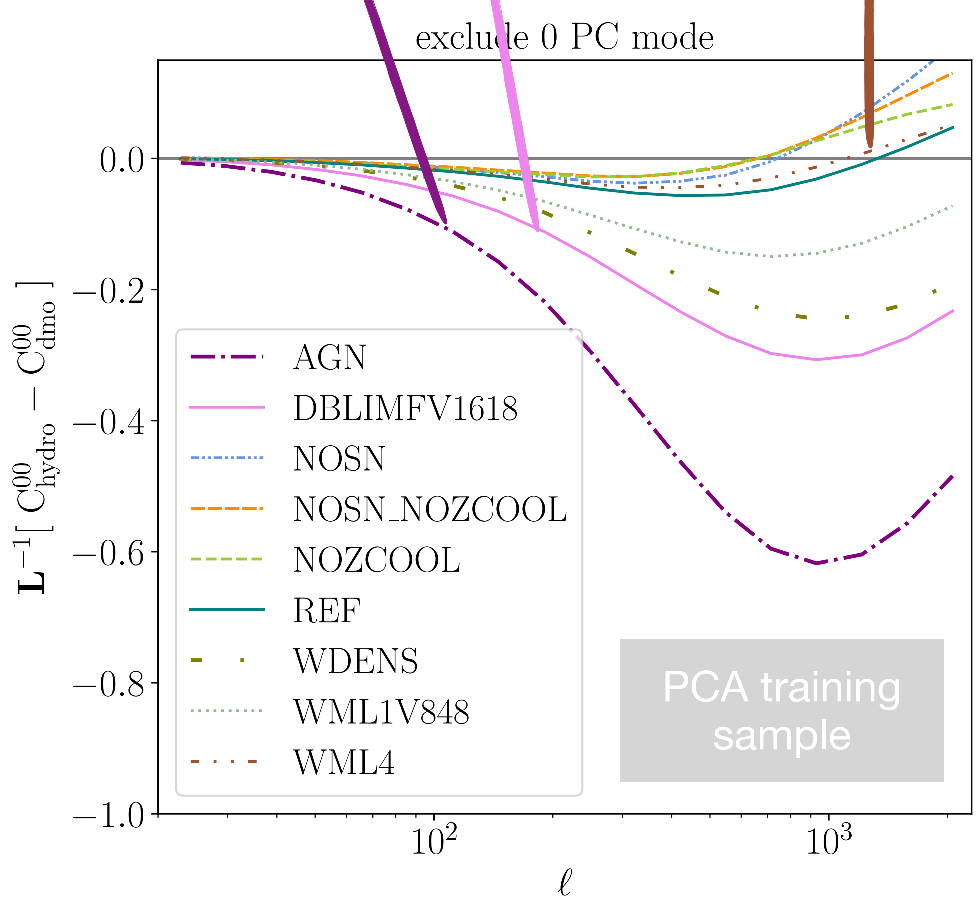


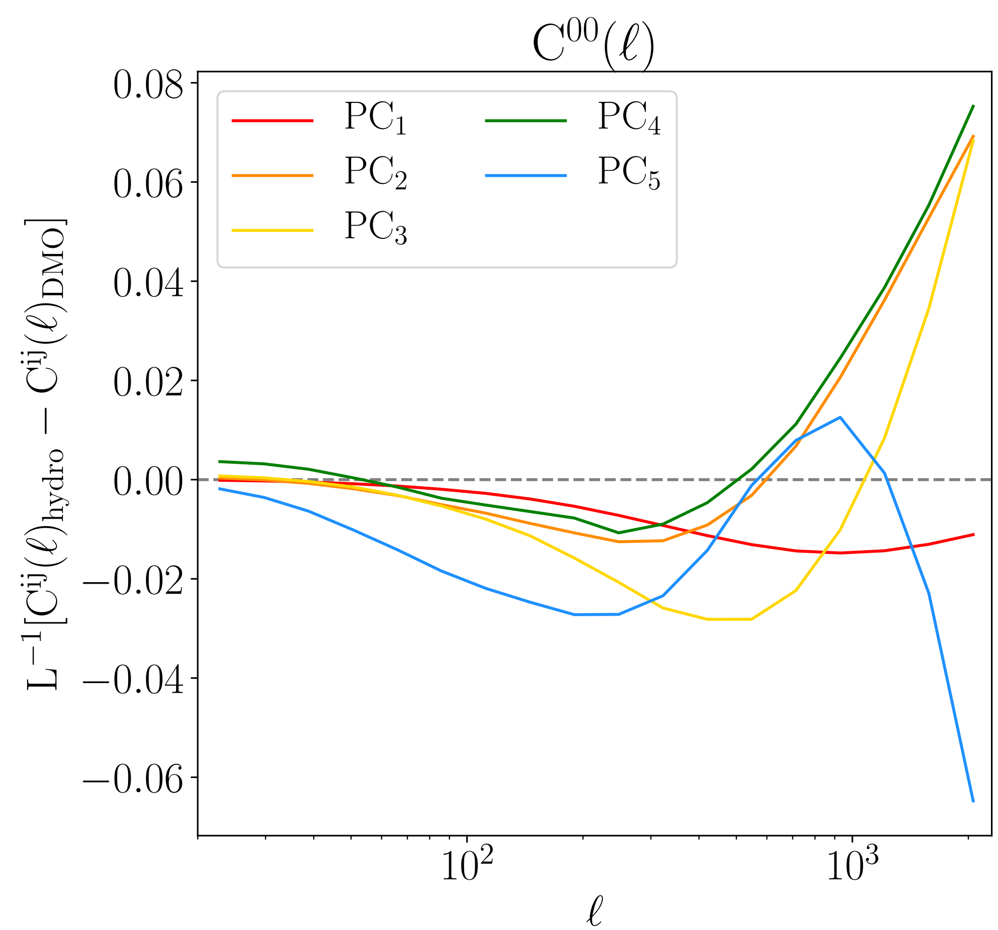


Procedures of PCA — compute PC basis









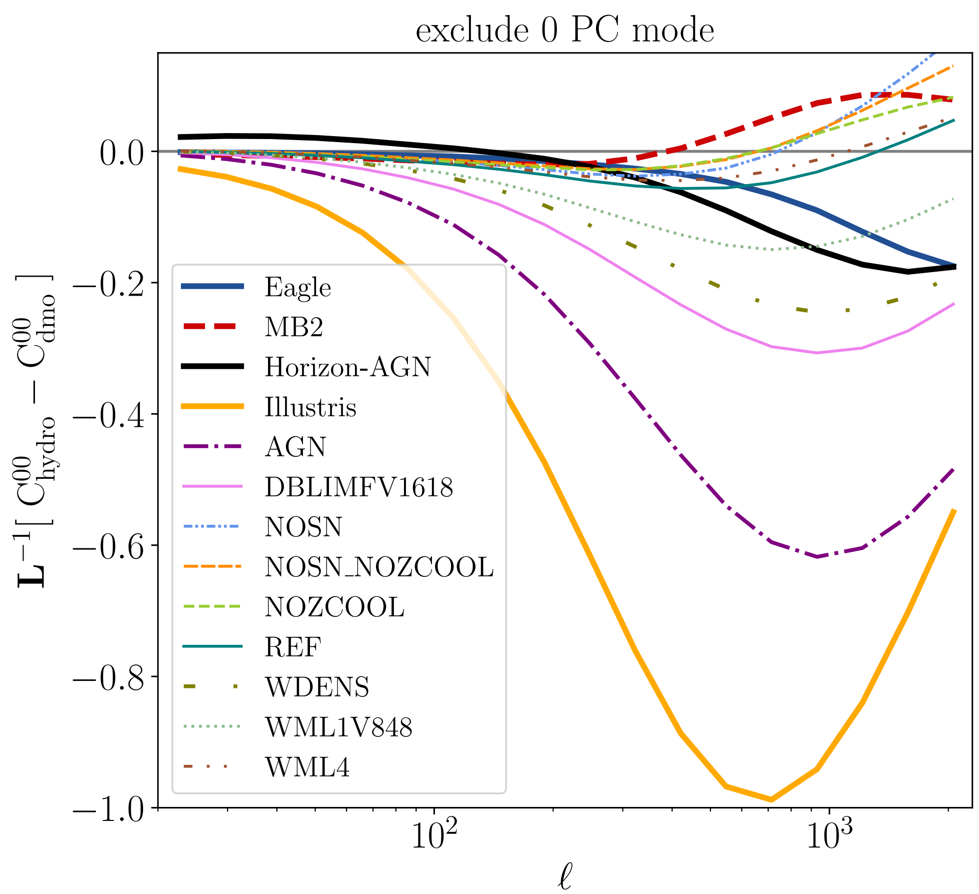
Procedures of PCA —9 PCs to span the baryonic uncertainty.

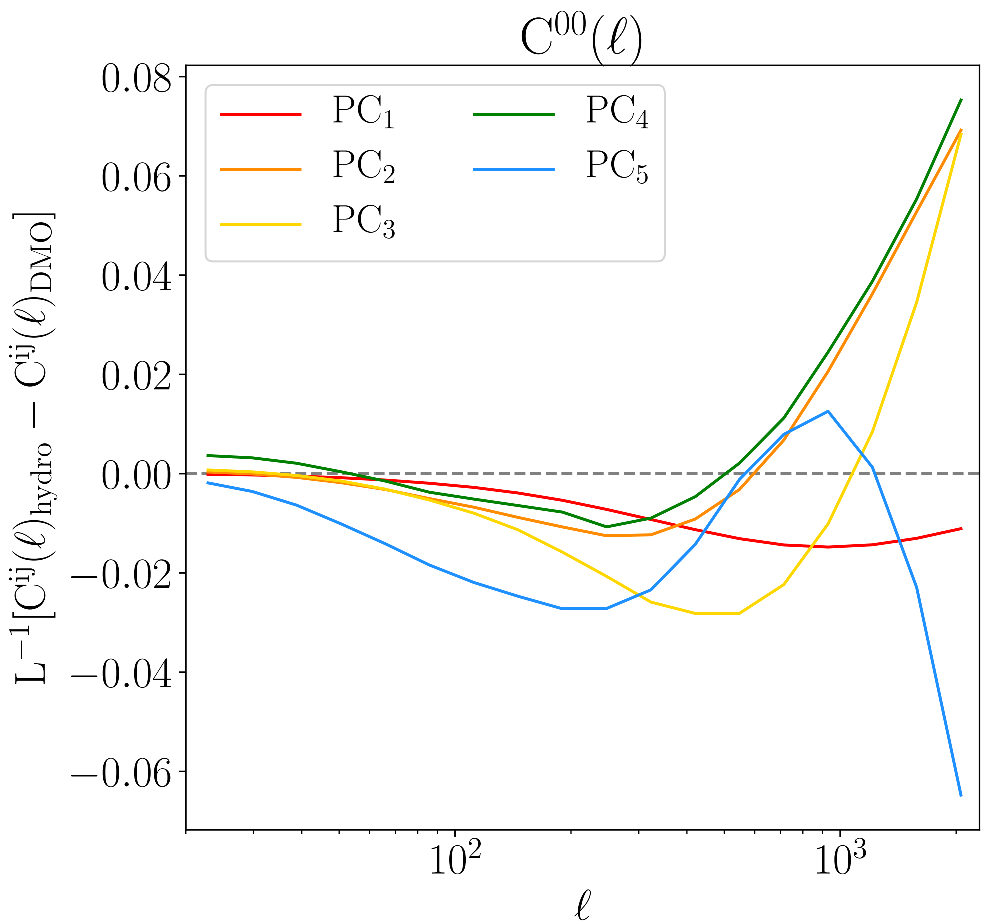
$$B_{OWLS,ch} - M_{ch} = L^{-1}\,(B_{OWLS} - M) = \sum_{i=1}^{9} Q_i\, PC_i$$

?

$$D_{MB2,ch} - M_{ch} = L^{-1}\,(D_{MB2} - M) = \sum Q_i\, PC_i$$

Eagle | Eagle
Illustris | Illustris
Horizon-AGN | Horizon-AGN





Procedures of PCA — exclude PC modes in likelihood analysis

$$\log L \propto - [\,\mathbf{D}\text{-}\mathbf{M}\,]^t \ \mathbf{C}^{-1} \ [\,\mathbf{D}\text{-}\mathbf{M}\,]$$

de-correlate
(Cholesky decomposition)

$$= - [\,\mathbf{D}\text{-}\mathbf{M}\,]^t \ (\mathbf{L}^t)^{-1} \ \underline{\mathbf{L}^{-1} \ [\,\mathbf{D}\text{-}\mathbf{M}\,]}$$

$$= - [\,\mathbf{D}_{ch}\text{-}\mathbf{M}_{ch}\,]^t \ \mathbf{I} \ \boxed{[\,\mathbf{D}_{ch}\text{-}\mathbf{M}_{ch}\,]}$$

$\mathbf{M}_{ch} = \mathbf{L}^{-1}\,\mathbf{M}$
$\mathbf{D}_{ch} = \mathbf{L}^{-1}\,\mathbf{D}$

$$\mathbf{U} = \begin{pmatrix} PC_1 & PC_2 & \cdots & PC_9 & \cdots & PC_{990} \end{pmatrix}$$

990 x 990

Step 4 Exclude PC modes

Fitting : $$[\mathbf{D}_{ch}\text{-}\mathbf{M}_{ch}(\mathbf{p}_{co})]$$

Procedures of PCA — exclude PC modes in likelihood analysis

$$\log L \propto - [\,\mathbf{D}\text{-}\mathbf{M}\,]^t \; \mathbf{C}^{-1} \; [\,\mathbf{D}\text{-}\mathbf{M}\,]$$

de-correlate
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$$= - [\,\mathbf{D}_{ch}\text{-}\mathbf{M}_{ch}\,]^t \; \mathbf{I} \; [\,\mathbf{D}_{ch}\text{-}\mathbf{M}_{ch}\,]$$

$\mathbf{M}_{ch} = \mathbf{L}^{-1}\,\mathbf{M}$
$\mathbf{D}_{ch} = \mathbf{L}^{-1}\,\mathbf{D}$

$$\mathbf{U} = \begin{pmatrix} PC_1 & PC_2 & \cdots & PC_9 & \cdots & PC_{990} \end{pmatrix}$$

990 x 990

Step 4 Exclude PC modes

Fitting : $\mathbf{U}^t\,[\mathbf{D}_{ch}\text{-}\mathbf{M}_{ch}(\mathbf{p}_{co})]$

Procedures of PCA — exclude PC modes in likelihood analysis

$$\log L \propto -\,[\,\mathbf{D}\text{-}\mathbf{M}\,]^t \; \mathbf{C}^{-1} \; [\,\mathbf{D}\text{-}\mathbf{M}\,]$$

de-correlate
(Cholesky decomposition)

$$= -\,[\,\mathbf{D}\text{-}\mathbf{M}\,]^t\,(\mathbf{L}^t)^{-1}\,\underline{\mathbf{L}^{-1}\,[\,\mathbf{D}\text{-}\mathbf{M}\,]}$$

$$= -\,[\,\mathbf{D}_{ch}\text{-}\mathbf{M}_{ch}\,]^t\;\mathbf{I}\;\boxed{[\,\mathbf{D}_{ch}\text{-}\mathbf{M}_{ch}\,]}$$

$\mathbf{M}_{ch} = \mathbf{L}^{-1}\,\mathbf{M}$
$\mathbf{D}_{ch} = \mathbf{L}^{-1}\,\mathbf{D}$

$$\mathbf{U} = \begin{pmatrix} PC_1 & PC_2 & \cdots & PC_9 & \cdots & PC_{990} \end{pmatrix}_{990 \times 990}$$

Step 4 Exclude PC modes

Fitting : $\mathbf{P}_N \mathbf{U}^t\,[\mathbf{D}_{ch}\text{-}\mathbf{M}_{ch}(\mathbf{p}_{co})]$

P: projection matrix

exclude 1 pc mode

$$\mathbf{P}_1 = \begin{pmatrix} 0 & & & & \\ & 1 & & & \\ & & 1 & & \\ & & & 1 & \\ & & & & \ddots \end{pmatrix}_{990 \times 990}$$

exclude 2 pc modes

$$\mathbf{P}_2 = \begin{pmatrix} 0 & & & & \\ & 0 & & & \\ & & 1 & & \\ & & & 1 & \\ & & & & \ddots \end{pmatrix}_{990 \times 990}$$

Procedures of PCA — exclude PC modes in likelihood analysis

$\log L \propto -[\,\mathbf{D}-\mathbf{M}\,]^t \; \mathbf{C}^{-1} \; [\,\mathbf{D}-\mathbf{M}\,]$

de-correlate
(Cholesky decomposition)

$= -[\,\mathbf{D}-\mathbf{M}\,]^t (\mathbf{L}^t)^{-1} \underline{\mathbf{L}^{-1} [\,\mathbf{D}-\mathbf{M}\,]}$

$= -[\,\mathbf{D}_{ch}-\mathbf{M}_{ch}\,]^t \; \mathbf{I} \; \boxed{[\,\mathbf{D}_{ch}-\mathbf{M}_{ch}\,]}$

$\mathbf{M}_{ch} = \mathbf{L}^{-1}\mathbf{M}$
$\mathbf{D}_{ch} = \mathbf{L}^{-1}\mathbf{D}$

$$\mathbf{U} = \begin{pmatrix} PC_1 & PC_2 & \cdots & PC_9 & \cdots & PC_{990} \end{pmatrix}_{990 \times 990}$$

Step 4 Exclude PC modes

$$\text{Fitting}: \; \mathbf{U P_N U^t} \, [\mathbf{D_{ch}} - \mathbf{M_{ch}}(\mathbf{p_{co}})]$$

P: projection matrix

exclude 1 pc mode

$$\mathbf{P_1} = \begin{pmatrix} 0 & & & & \\ & 1 & & & \\ & & 1 & & \\ & & & 1 & \\ & & & & \ddots \end{pmatrix}_{990 \times 990}$$

exclude 2 pc modes

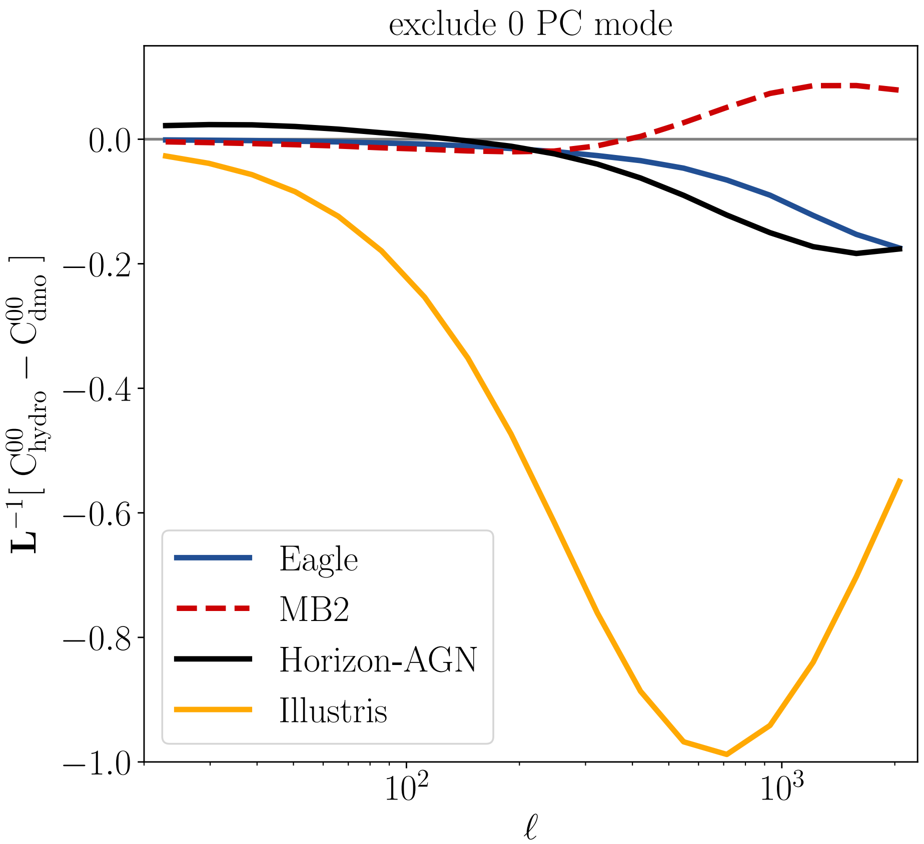
$$\mathbf{P_2} = \begin{pmatrix} 0 & & & & \\ & 0 & & & \\ & & 1 & & \\ & & & 1 & \\ & & & & \ddots \end{pmatrix}_{990 \times 990}$$

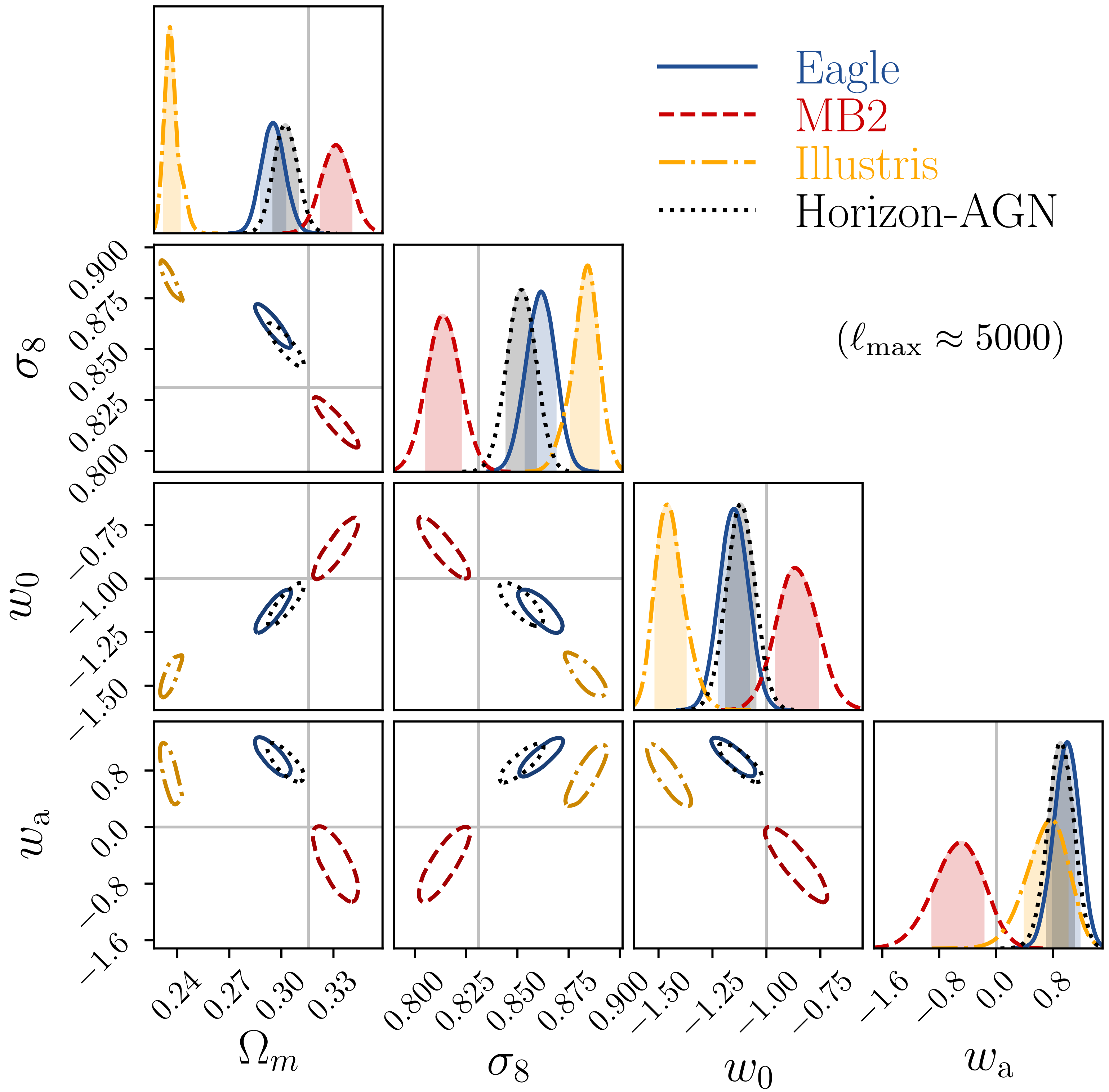
No baryonic mitigation technique applied

($\ell_{\max} \approx 5000$)

2.5 arcmin

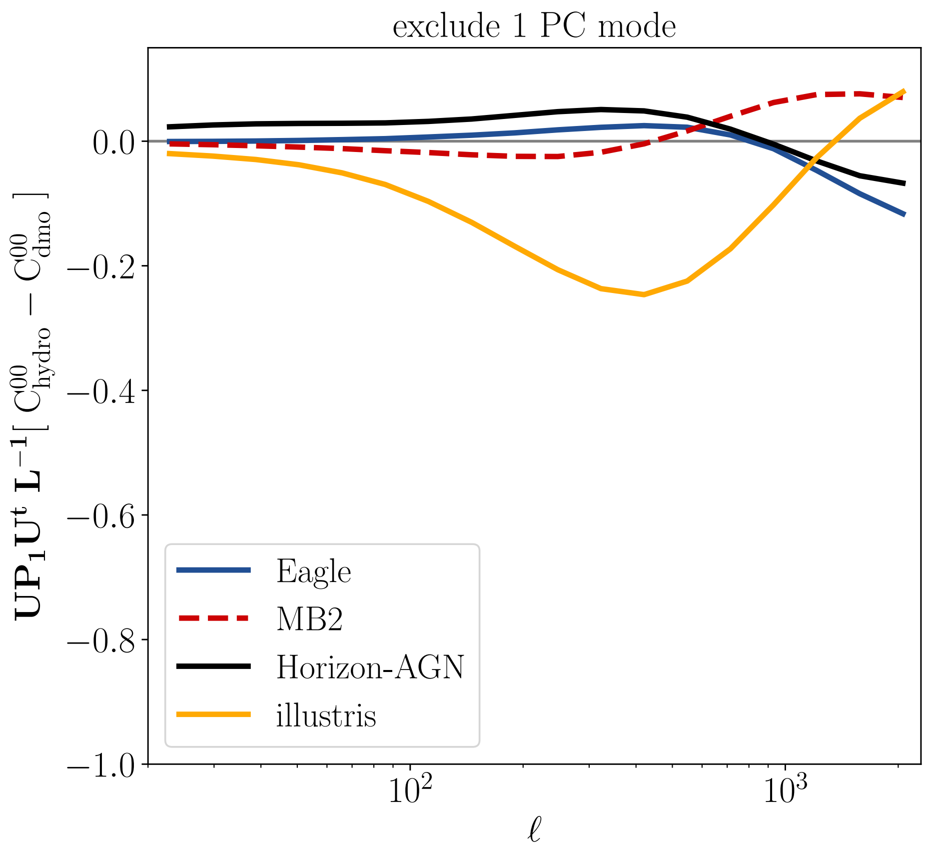
(The performance of PCA when excluding 0 PC mode)

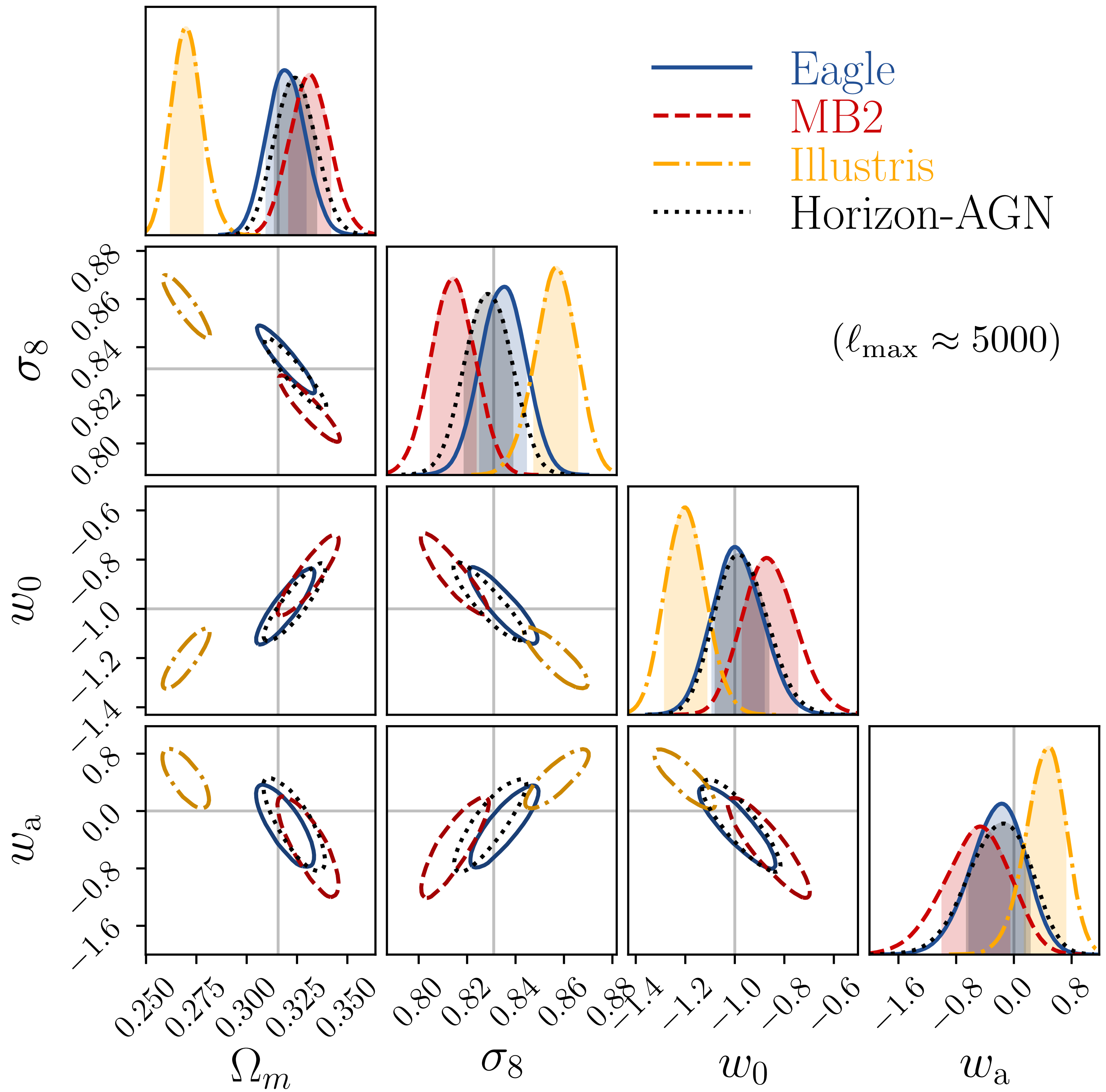




The performance of PCA after excluding 1 PC mode

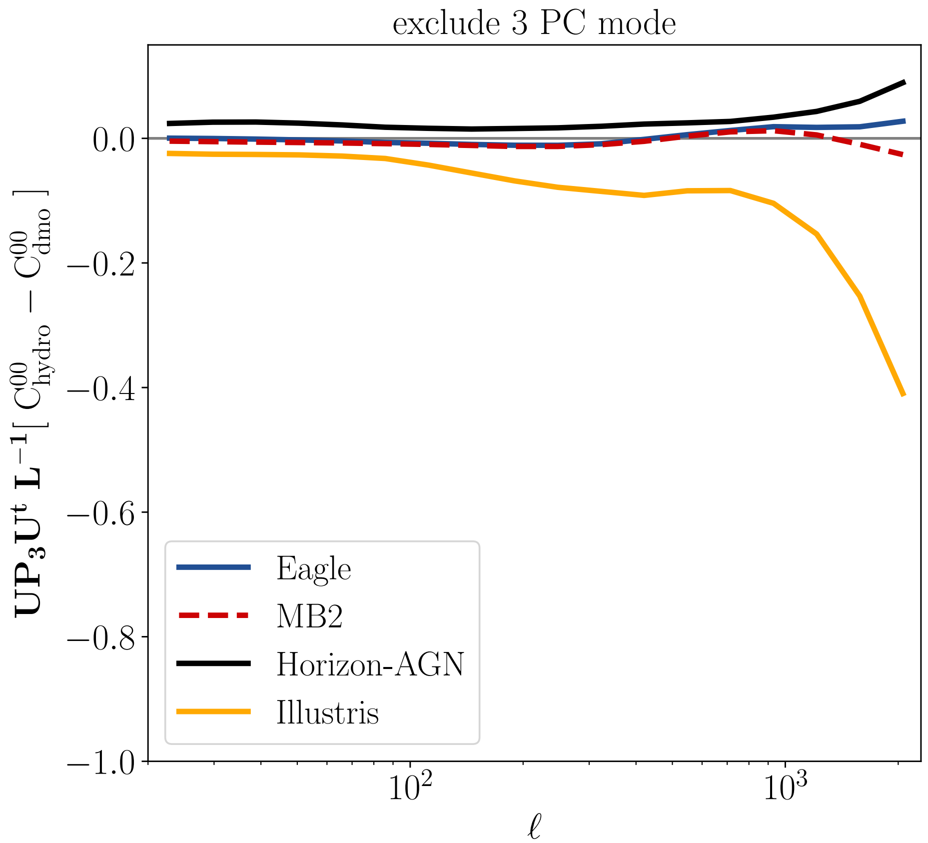
($\ell_{\max} \approx 5000$)
2.5 arcmin

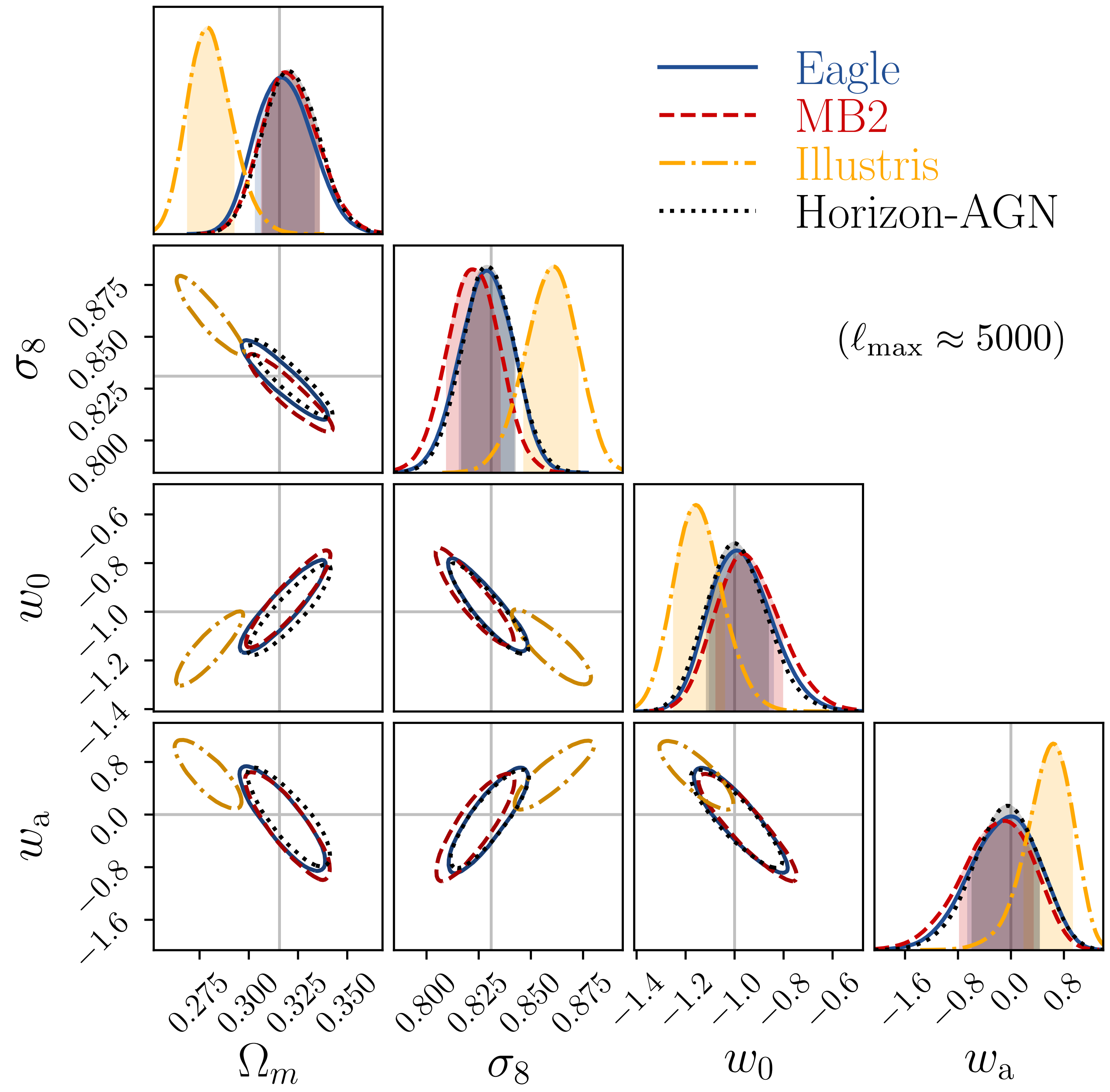




The performance of PCA after excluding 3 PC mode

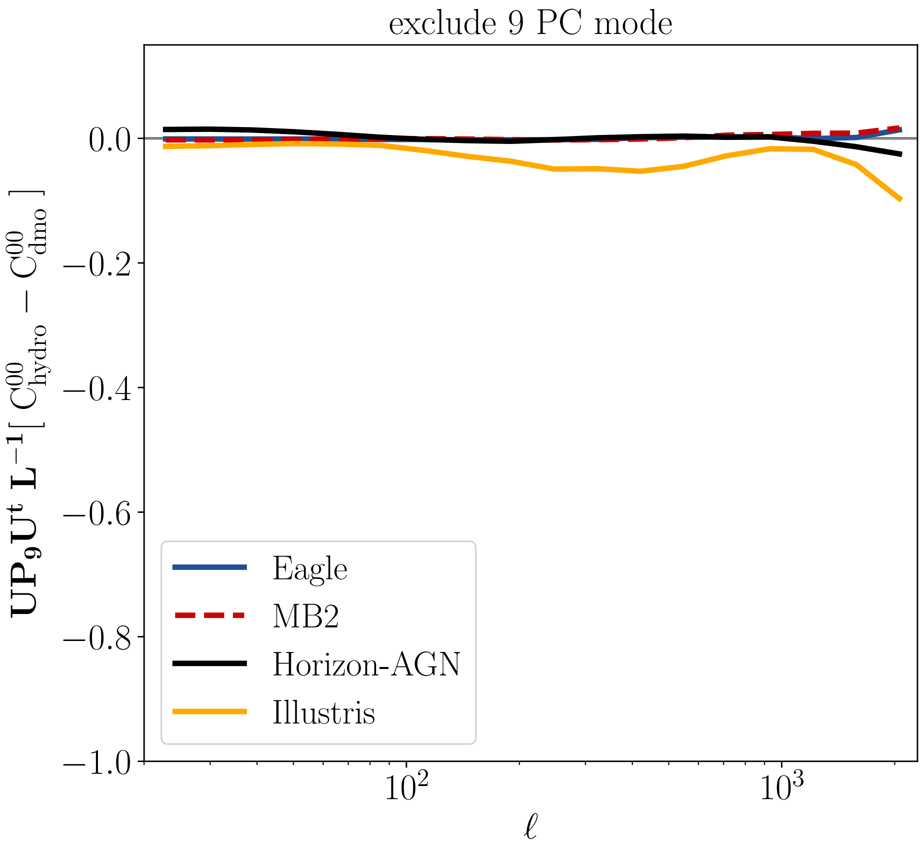
($\ell_{max} \approx 5000$)
2.5 arcmin

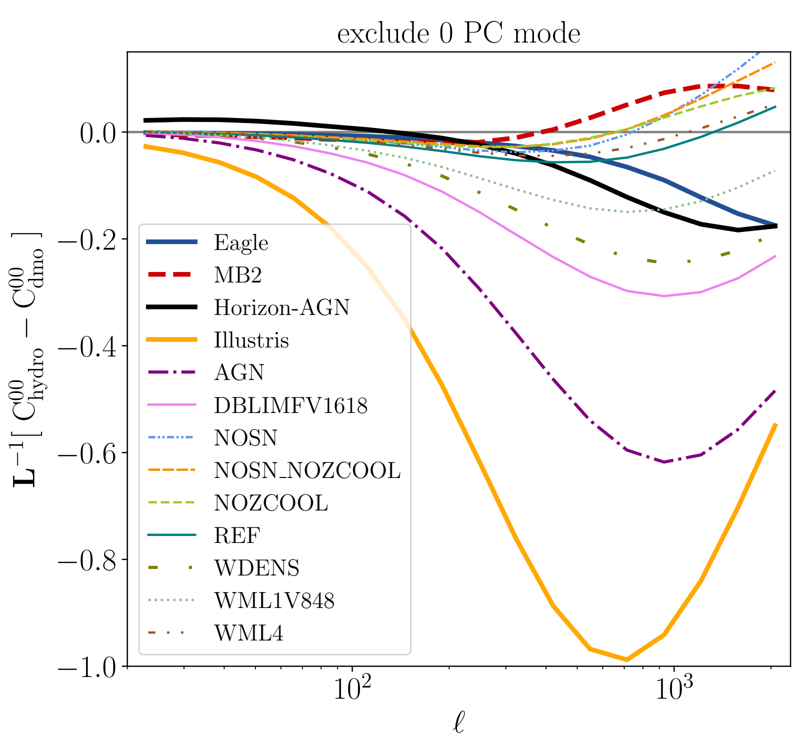


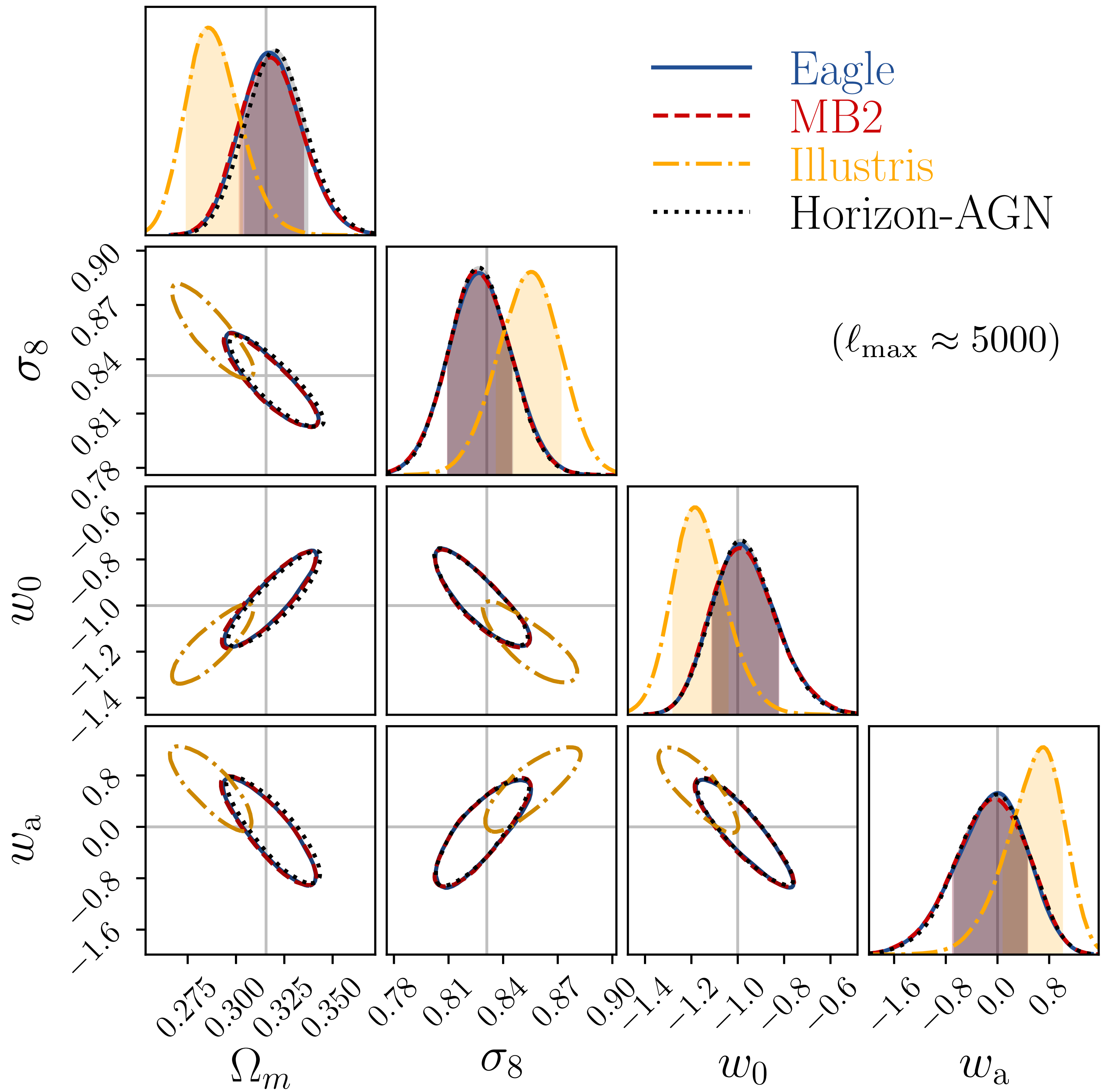


The performance of PCA after excluding 9 PC mode

($\ell_{max} \approx 5000$)
2.5 arcmin







Featured training simulations are need for PCA method to account for the strong feedback scenario like Illustris.

Performances of PCA v.s. HMcode — the criteria

A successful baryon mitigation approach :

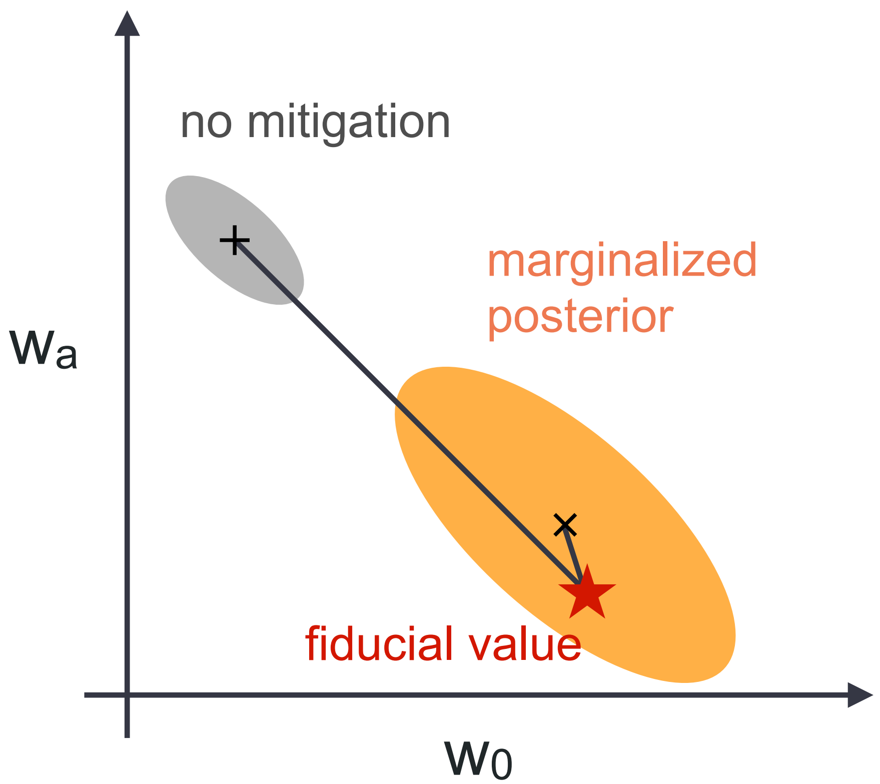
1. **Flexible** enough to cover all possible uncertainties caused by baryons

   Residual bias < 0.5 σ

   (σ: 1D marginalized error)

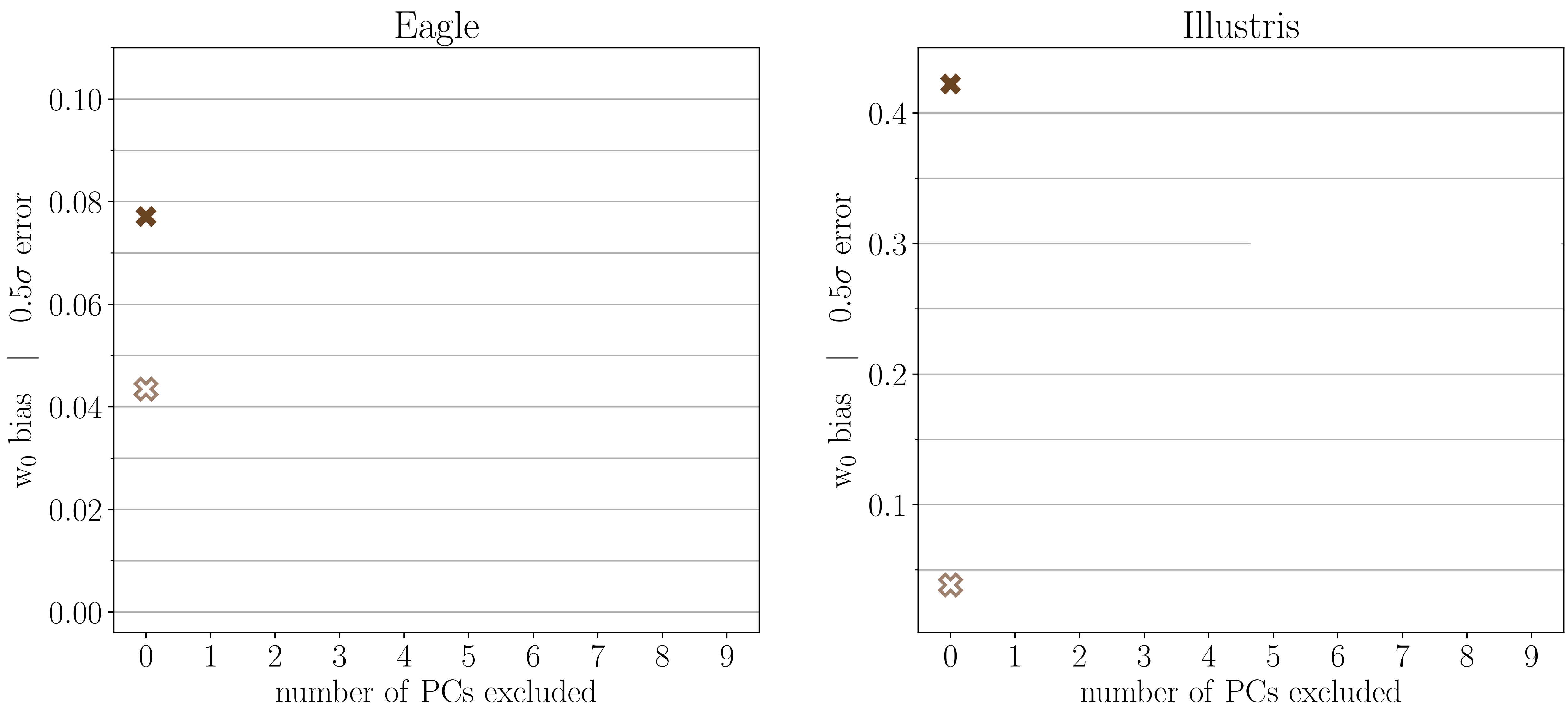
2. **Limited degrees of freedom** to preserve constraining power on cosmology

   The smaller 1σ marginalized error, the better.



Performances of PCA v.s. HMcode — the result

($\ell_{max} \approx 2000$)
6 arcmin



1. Model flexibility
   Residual bias < 0.5 σ

2. Residual constraining power

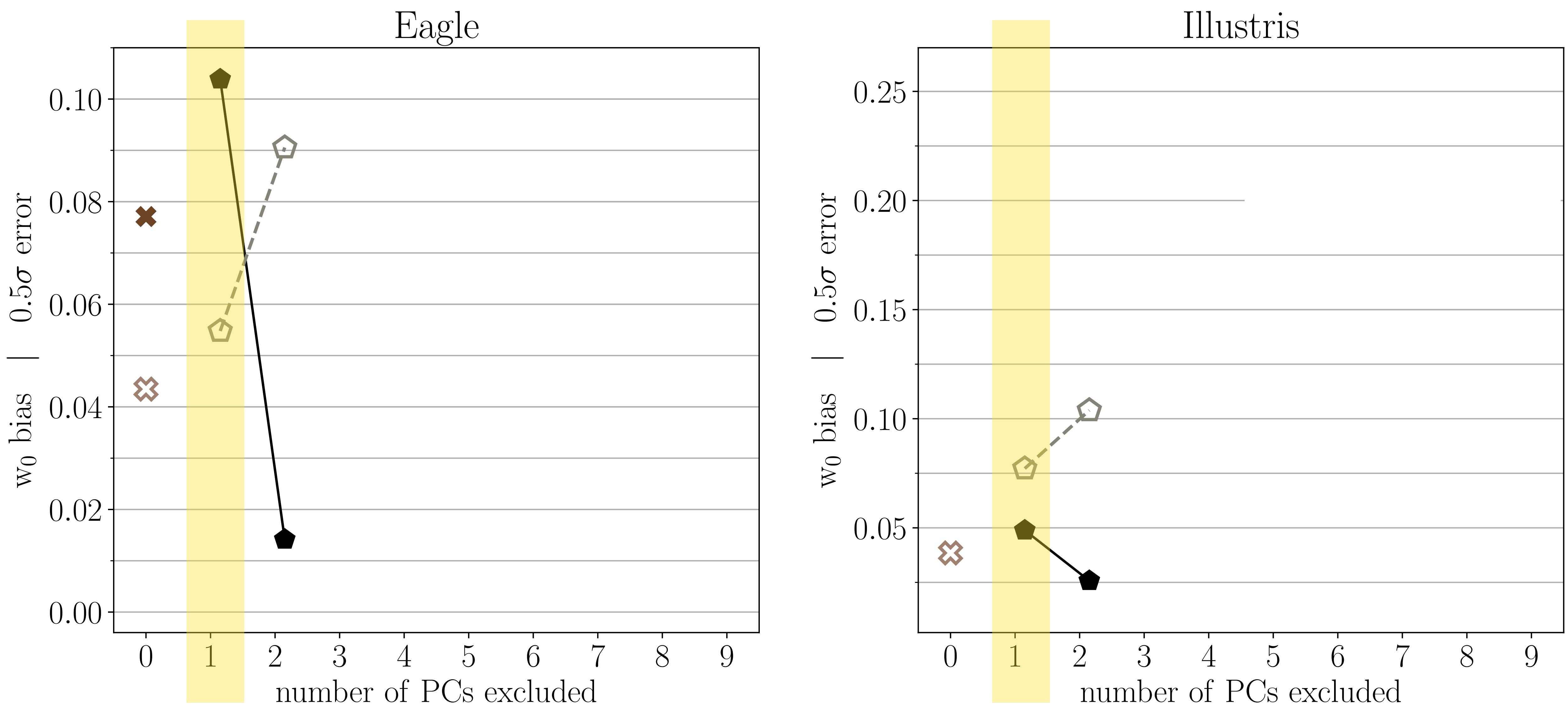
raw bias of w_0

0.5σ error w_0

without mitigation

Performances of PCA v.s. HMcode — the result

($\ell_{max} \approx 2000$)
6 arcmin



raw bias of w_0
0.5σ error w_0
without mitigation

HMcode $\langle$ $\mathbf{M}(\mathbf{p}_{co}, A, \eta_0)$ / $\mathbf{M}(\mathbf{p}_{co}, A)$

$\eta_0 = 0.98 - 0.12A$

1. Model flexibility
   Residual bias < 0.5 σ

2. Residual constraining power

residual bias of w_0

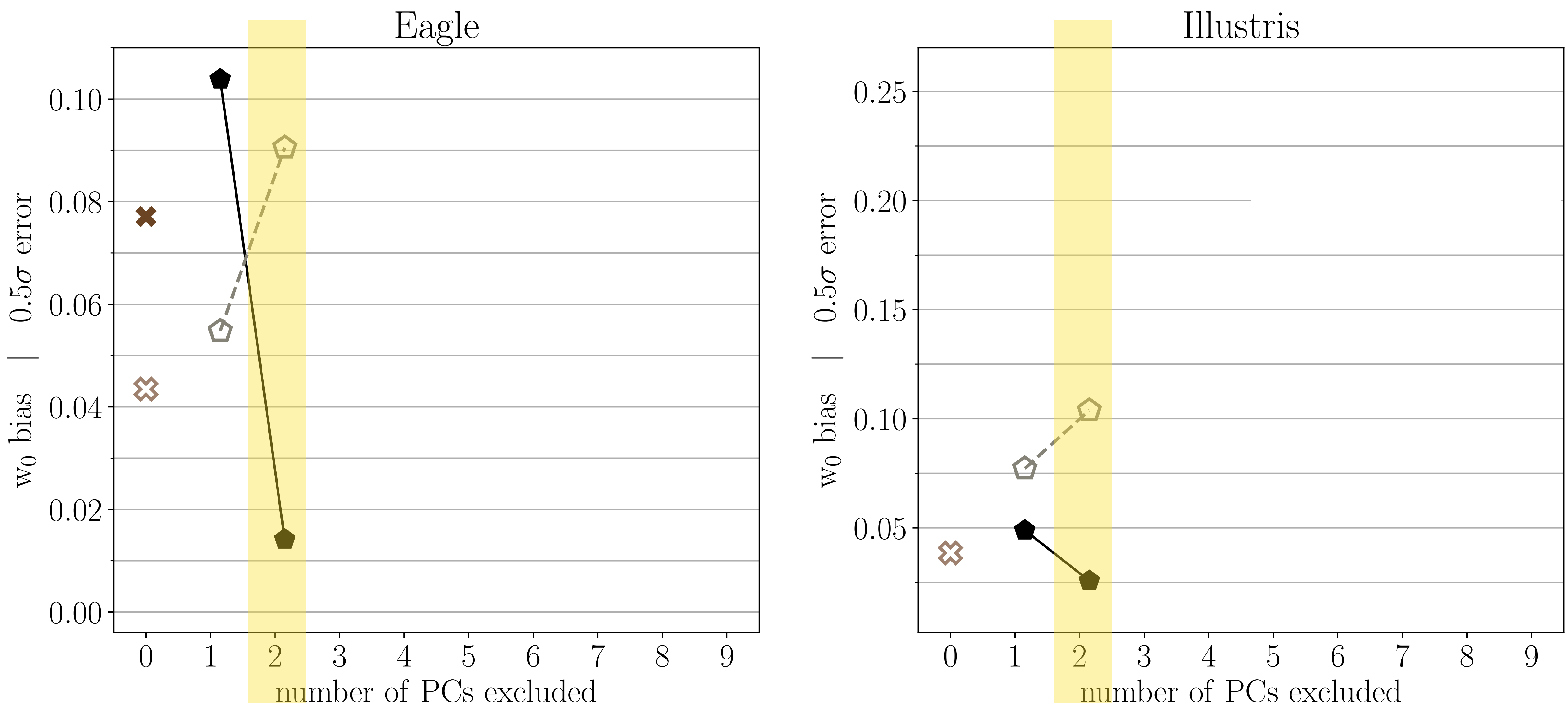
0.5σ error of w_0

after HMcode marginalization

Hope < after marginalization

Performances of PCA v.s. HMcode — the result

($\ell_{max} \approx 2000$)
6 arcmin



raw bias of w_0
0.5σ error w_0

without mitigation

HMcode $\langle$ $\mathbf{M}(\mathbf{p_{co}}, A, \eta_0)$ / $\mathbf{M}(\mathbf{p_{co}}, A)$

$\eta_0 = 0.98 - 0.12A$

1. Model flexibility
   Residual bias < $0.5\,\sigma$

2. Residual constraining power

residual bias of w_0

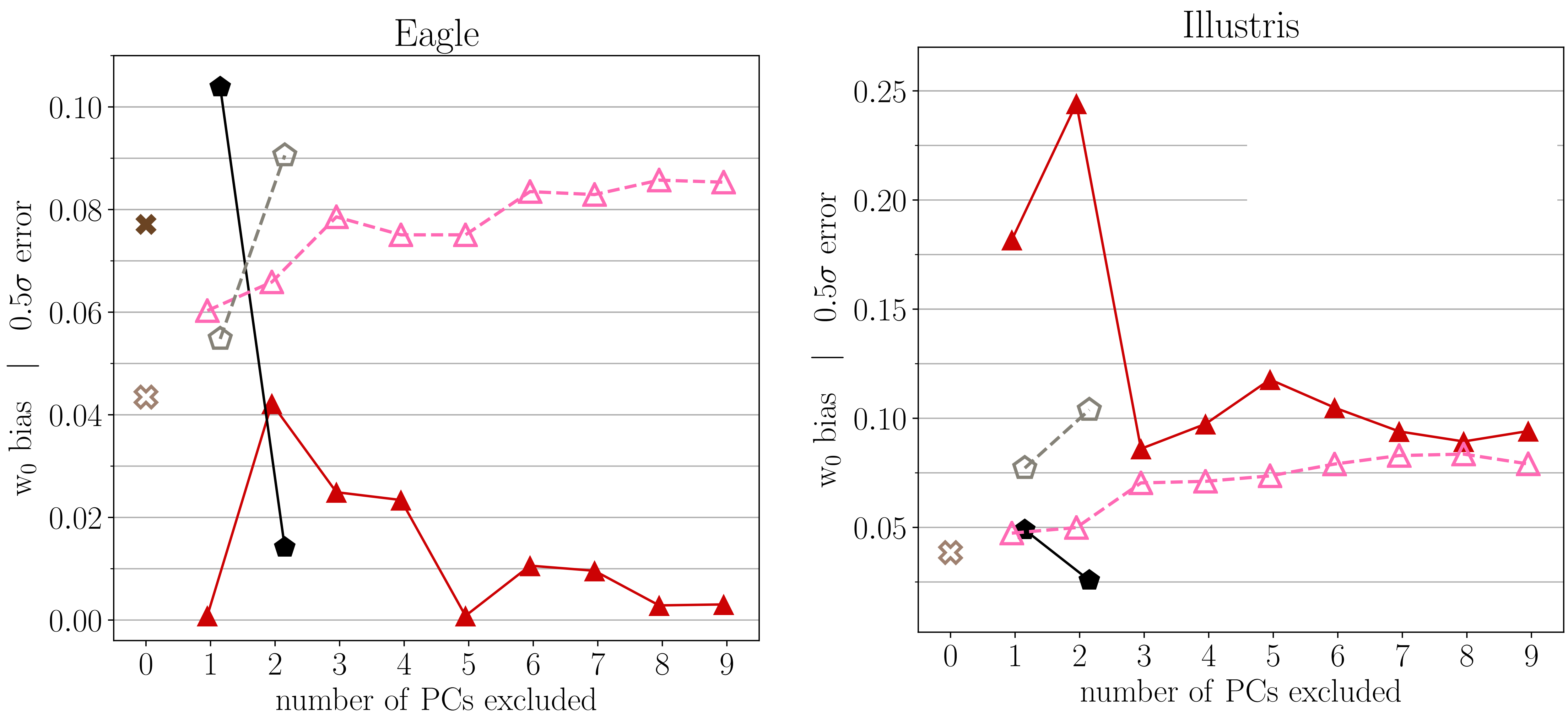
0.5σ error of w_0

after HMcode marginalization

Hope ⬠ < ⬟ after marginalization

Performances of PCA v.s. HMcode — the result

($\ell_{max} \approx 2000$)
6 arcmin



Results for MB2 and Horizon-AGN are similar as Eagle.

raw bias of w_0
0.5σ error w_0

without mitigation

residual bias of w_0
0.5σ error of w_0

HMcode marginalization

HMcode: $\mathbf{M}(\mathbf{p}_{co}, A, \eta_0)$, $\mathbf{M}(\mathbf{p}_{co}, A)$

$\eta_0 = 0.98 - 0.12A$

residual bias of w_0

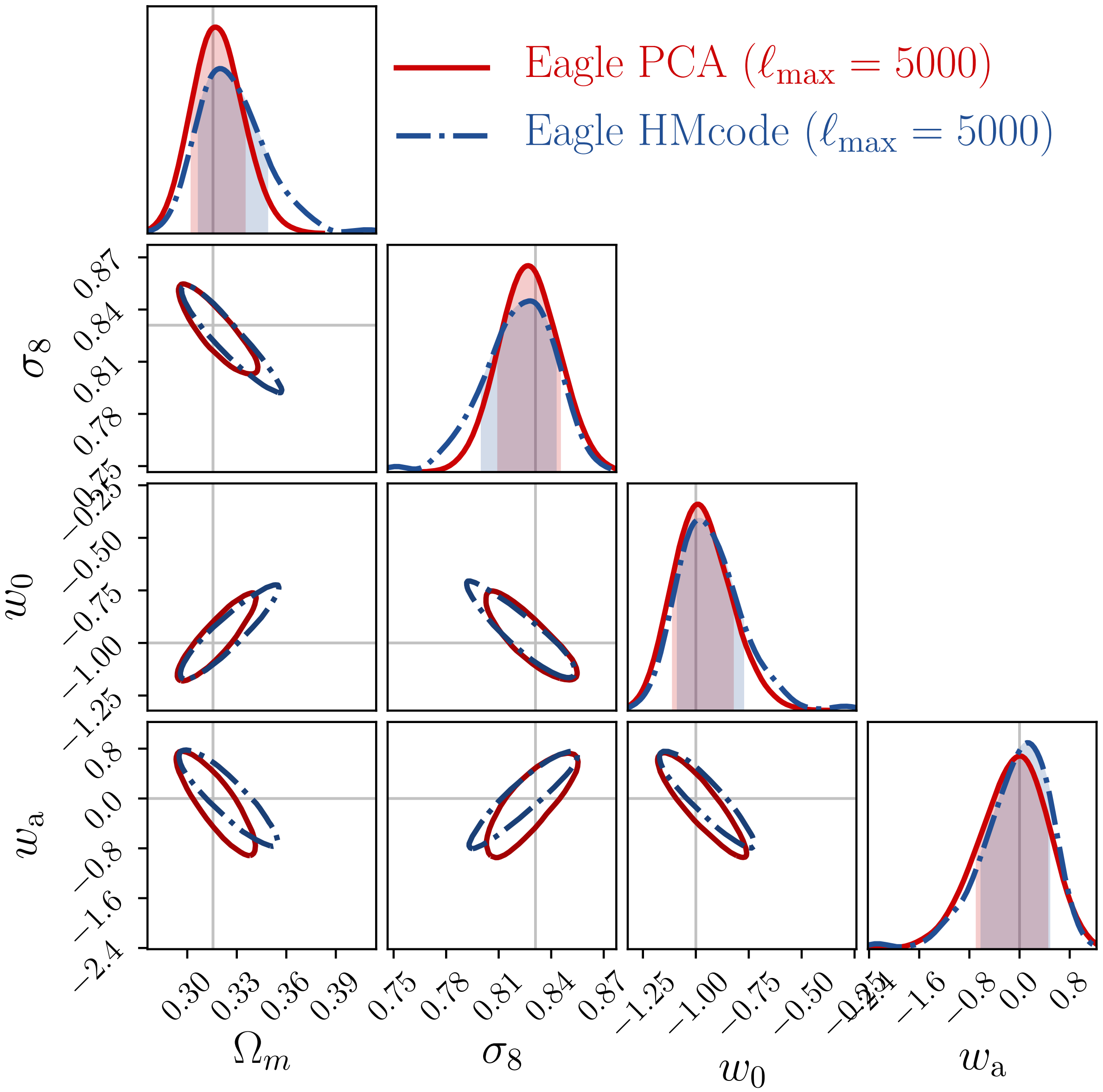
0.5σ error of w_0

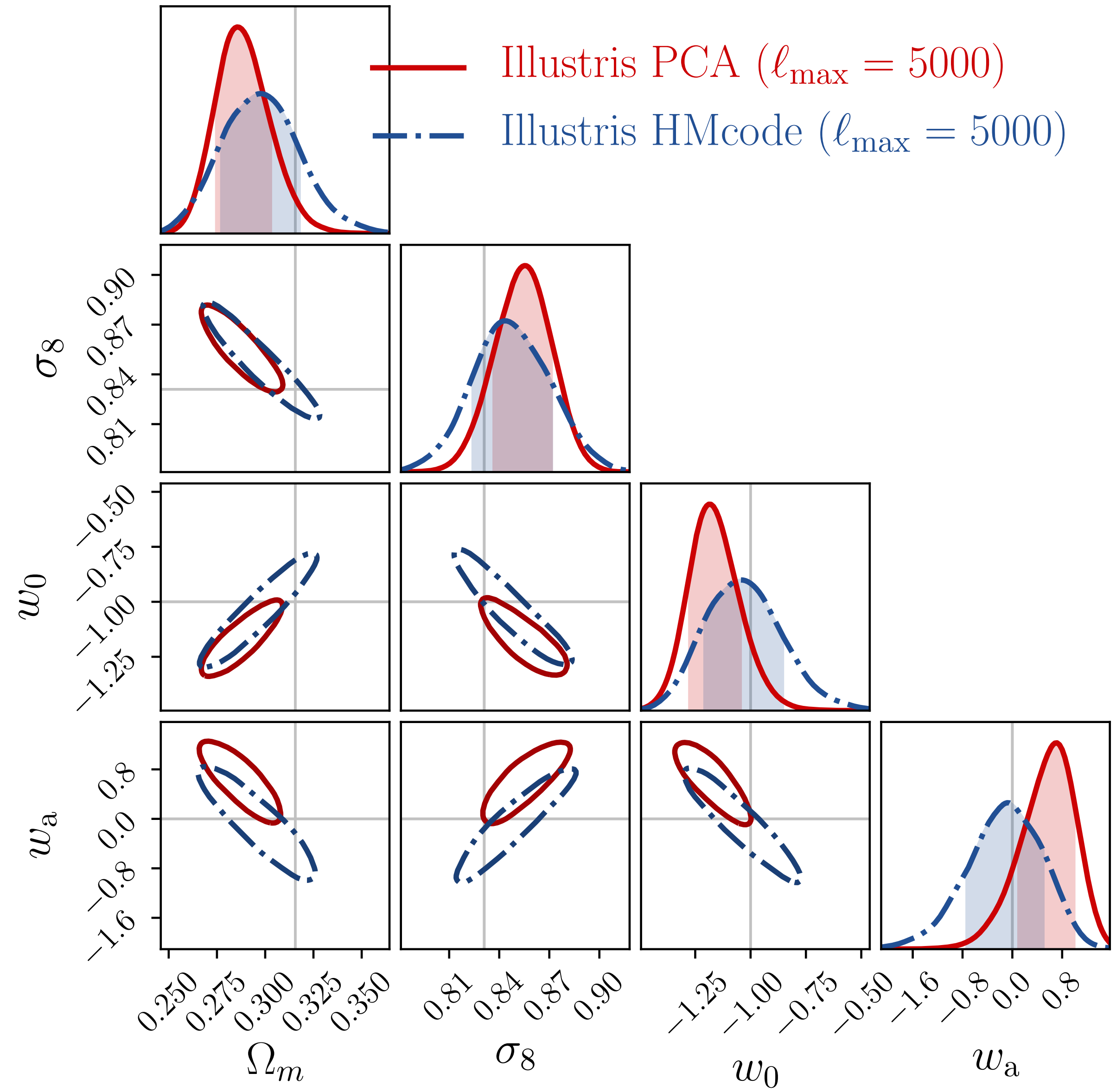
PCA marginalization

1. Model flexibility
   Residual bias < 0.5 σ

2. Residual constraining power

Performances of PCA v.s. HMcode — pushing to $\ell_{\max} \approx 5000$

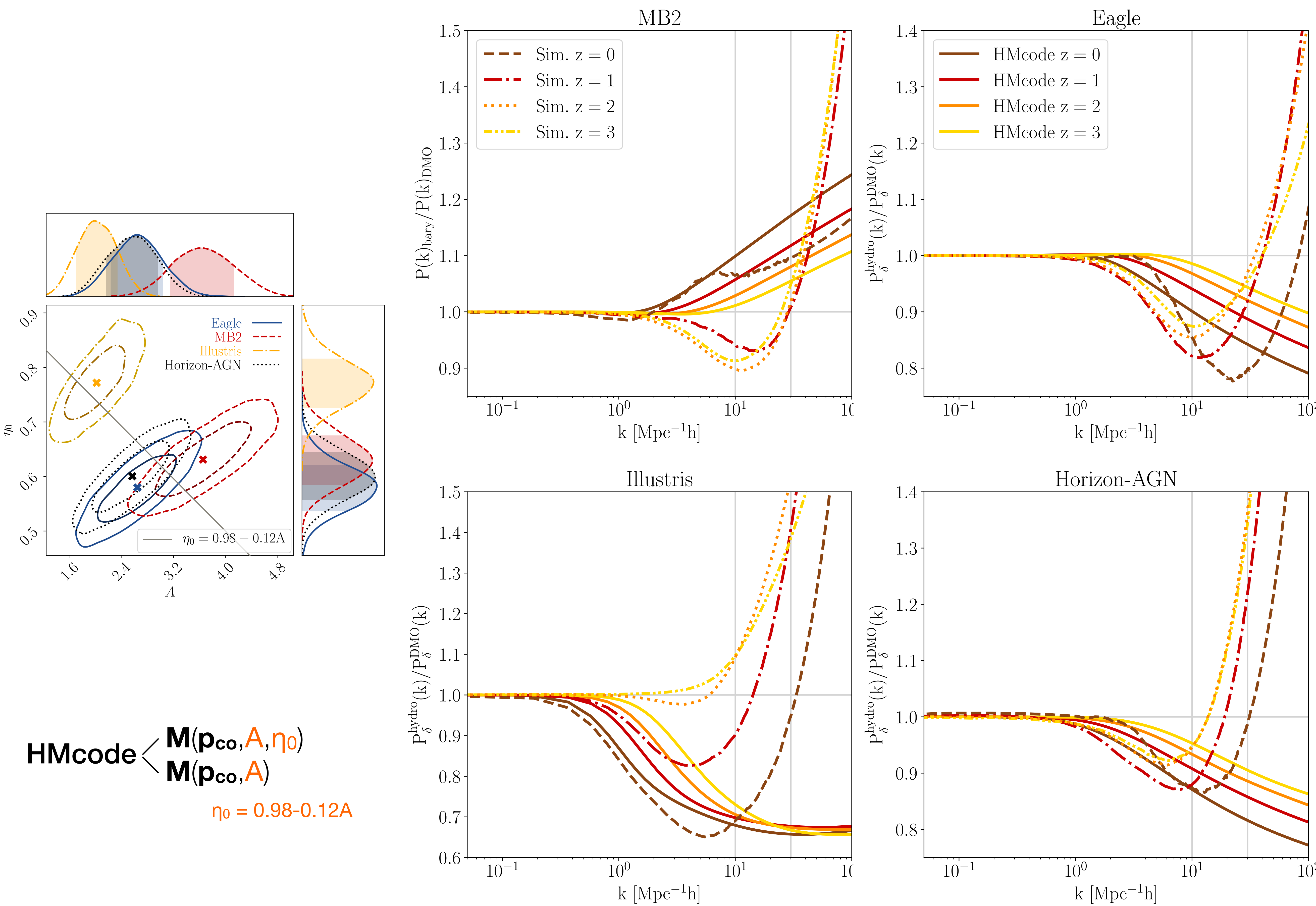




(PCA posteriors here are results when excluding 9 PC modes — the most conservative choice)

Results for MB2 and Horizon-AGN are similar as Eagle.

HMcode is designed to mitigate P(k) up to k ~ 10 *h* Mpc^{-1}

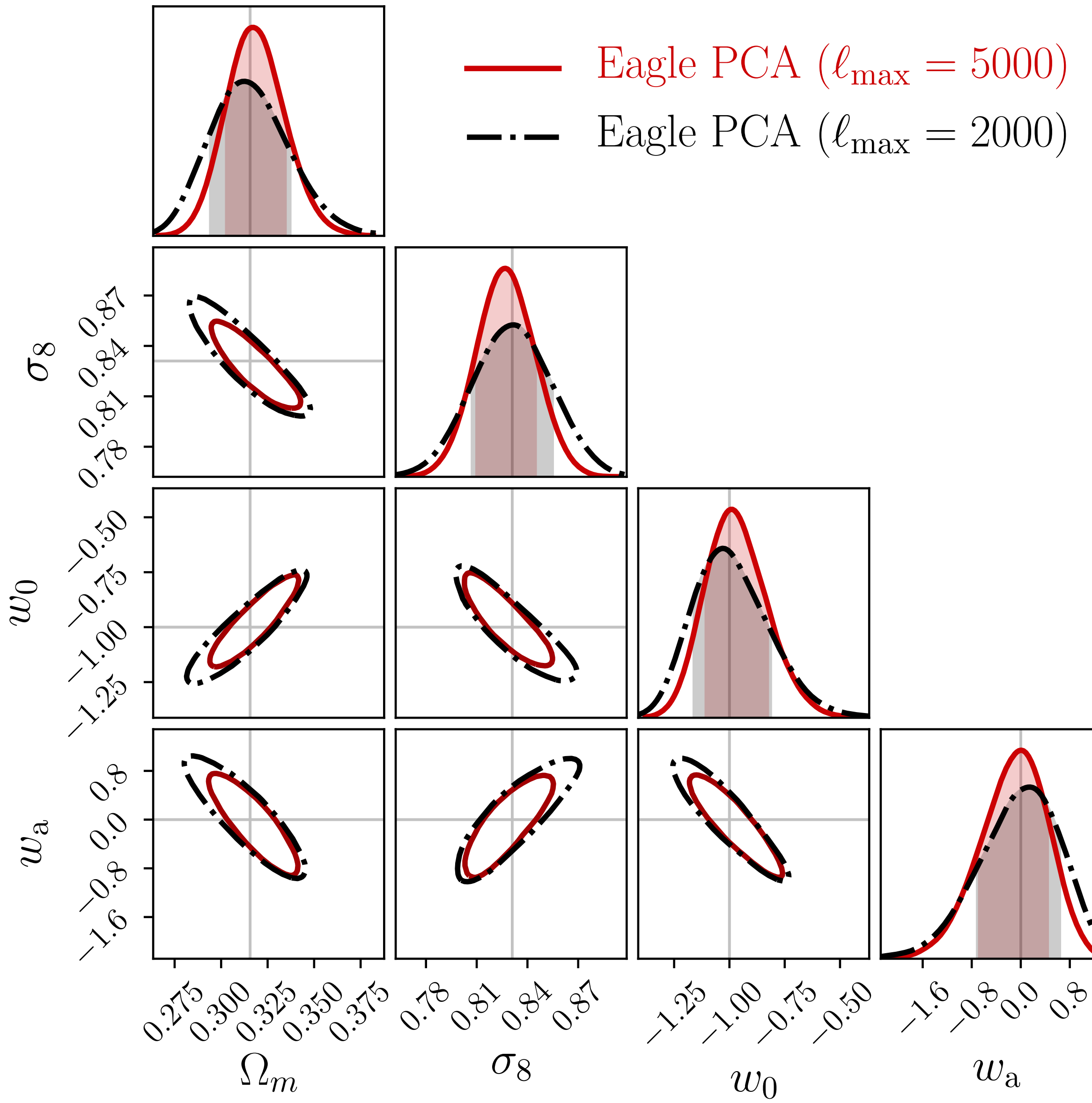


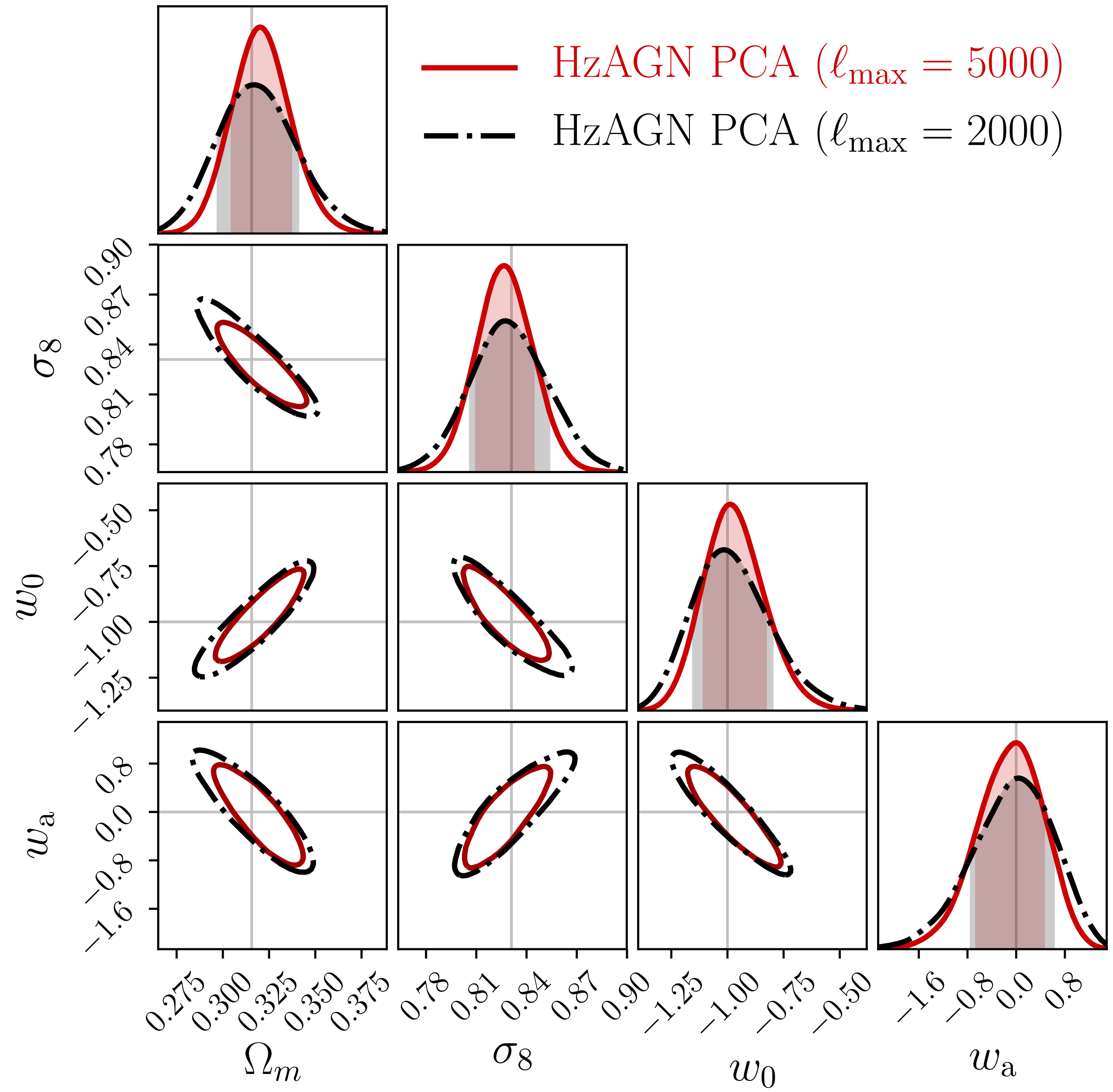
HMcode $\langle$ $\mathbf{M}(\mathbf{p}_{co}, A, \eta_0)$, $\mathbf{M}(\mathbf{p}_{co}, A)$

$\eta_0 = 0.98 - 0.12A$

Do we gain more information from $\ell_{max} \approx$ 2000 to 5000 ?

6 arcmin 2.5 arcmin

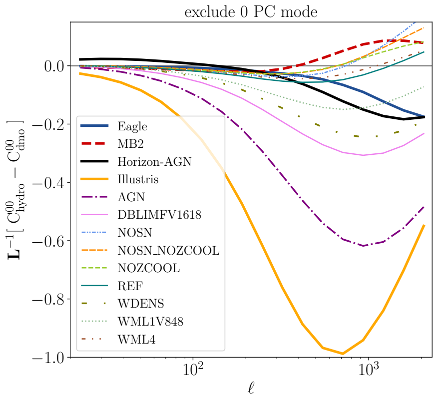




(PCA posteriors here are results when excluding 9 PC modes — the most conservative choice)

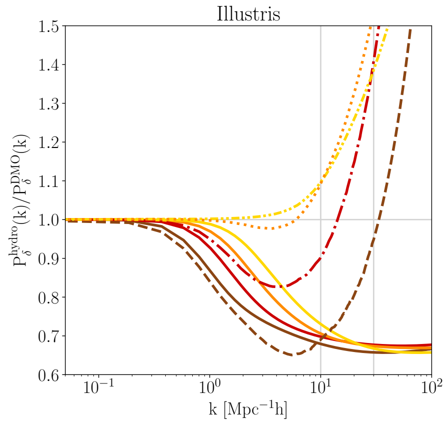
Results for MB2 and Horizon-AGN are similar as Eagle.

Summary — modeling baryonic effects for future cosmic shear



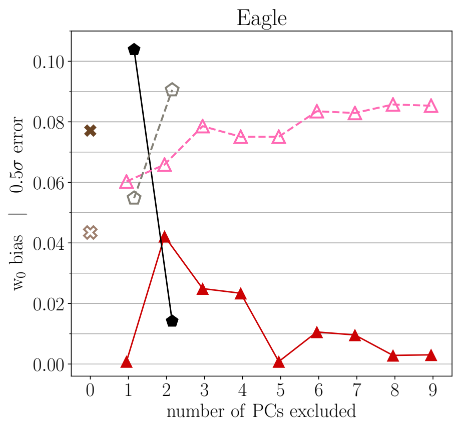
PCA method can **capture baryonic feature within few combination of PC modes.**

Distinct training simulations are needed to span the outlier baryonic scenarios.

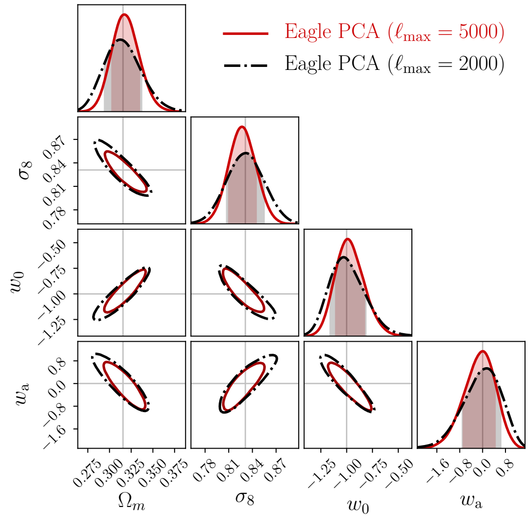


HMcode works specifically well for **Illustirs** (strong feedback suppression).

Always **marginalized over 2 parameters** for the use of **HMcode** to assure flexibility.



The **error bar converged for PCA method.**



Do we gain more information from ℓmax ≈ 2000 to 5000?

Yes, but only 15~30% improvement depending on baryonic scenarios.

Outline of this talk

1 Modeling baryonic effects in cosmic shear

with Tim Eifler, Rachel Mandelbaum, Scott Dodelson

arXiv:1809.01146

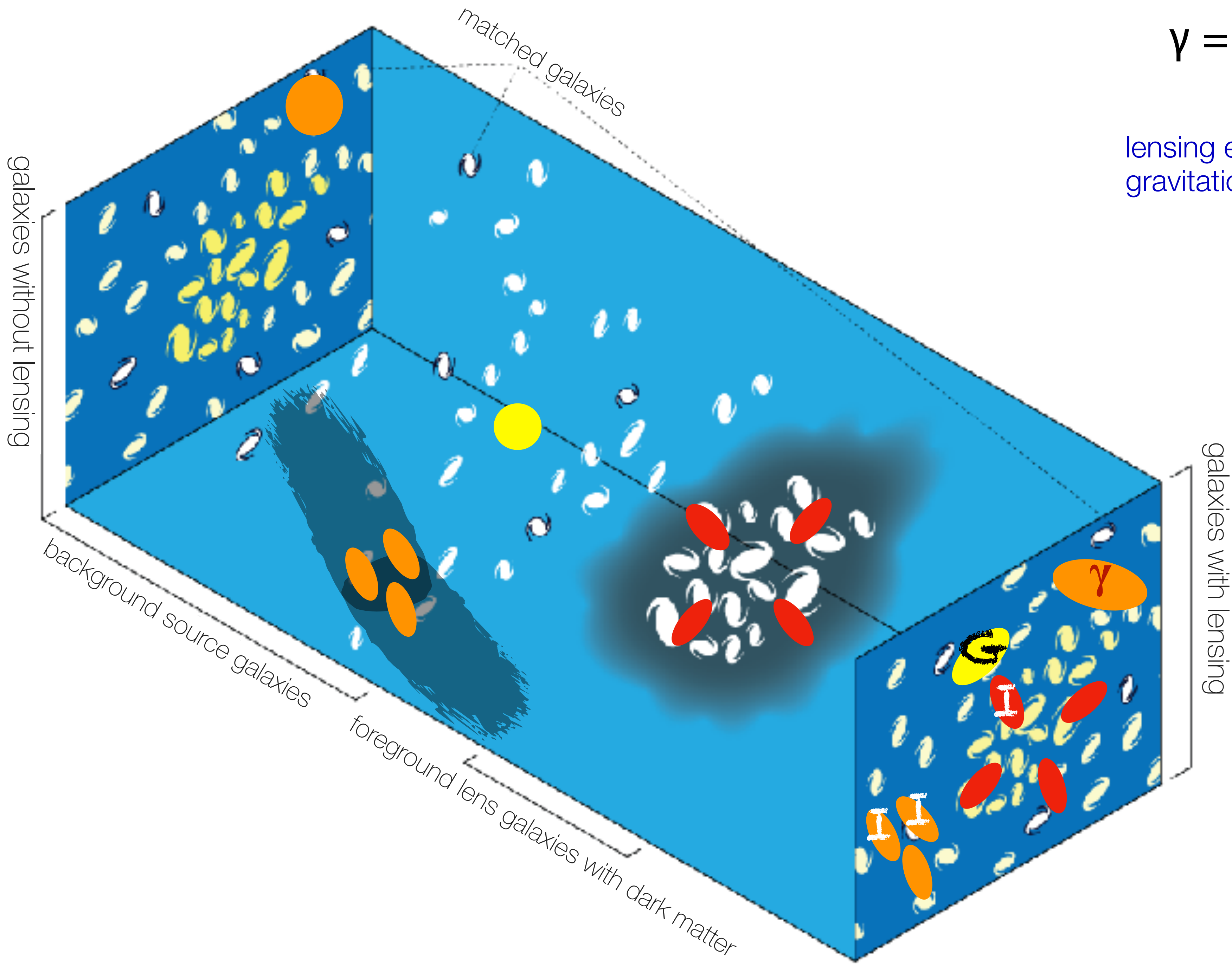
2 Intrinsic Alignment of galaxies in redMaPPer clusters

with Rachel Mandelbaum, Peter Freeman, Yen-Chi Chen
Eduardo Rozo, Eli Rykoff, Eric Baxter

arXiv:1605.01065, arXiv:1704.06273

3 Outlook

Intrinsic Alignment (IA) — violation of lensing assumption



$$\gamma = \gamma^{G} + \gamma^{I}$$

Intrinsic alignment induced by **local tidal field**

lensing effect from **foreground** gravitational potential

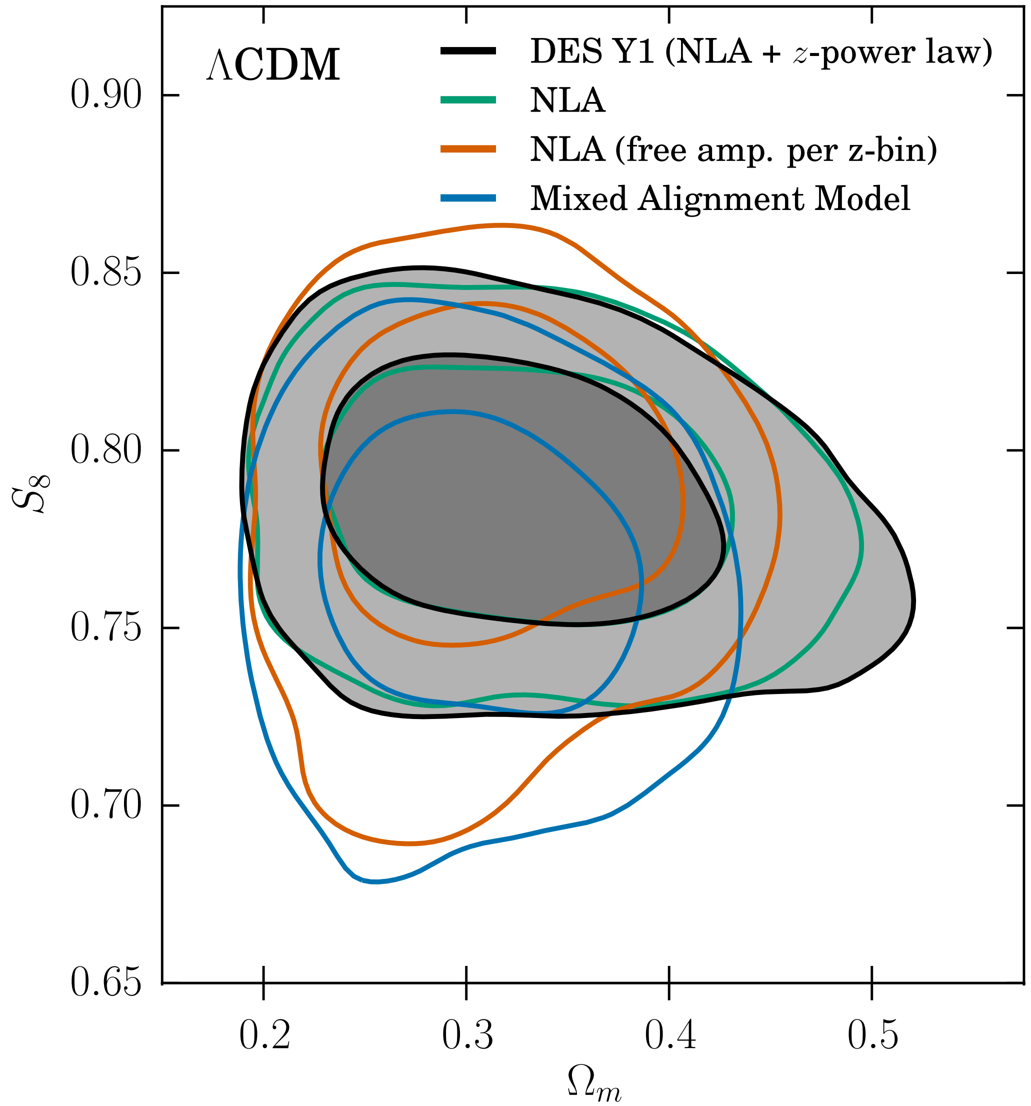
$$\langle\gamma\gamma\rangle = \langle\gamma^{G}\gamma^{G}\rangle + \langle\gamma^{I}\gamma^{I}\rangle + \langle\gamma^{G}\gamma^{I}\rangle + \langle\gamma^{I}\gamma^{G}\rangle$$

real lensing signal G I term ~zero

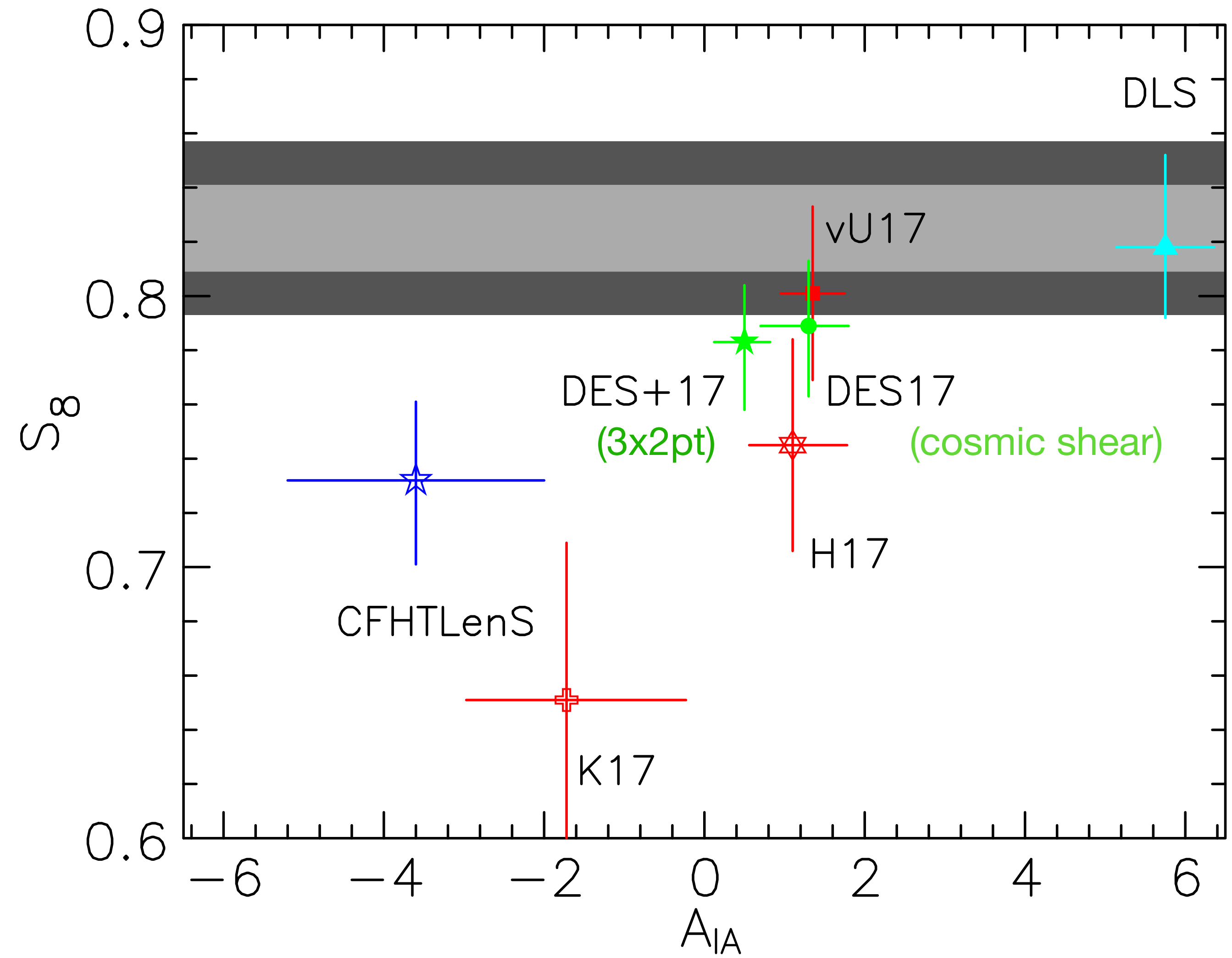
I I term

Impact of IA on cosmological parameters $S_8 = \sigma_8 \sqrt{\Omega_m / 0.3}$

DES Y1 cosmic shear



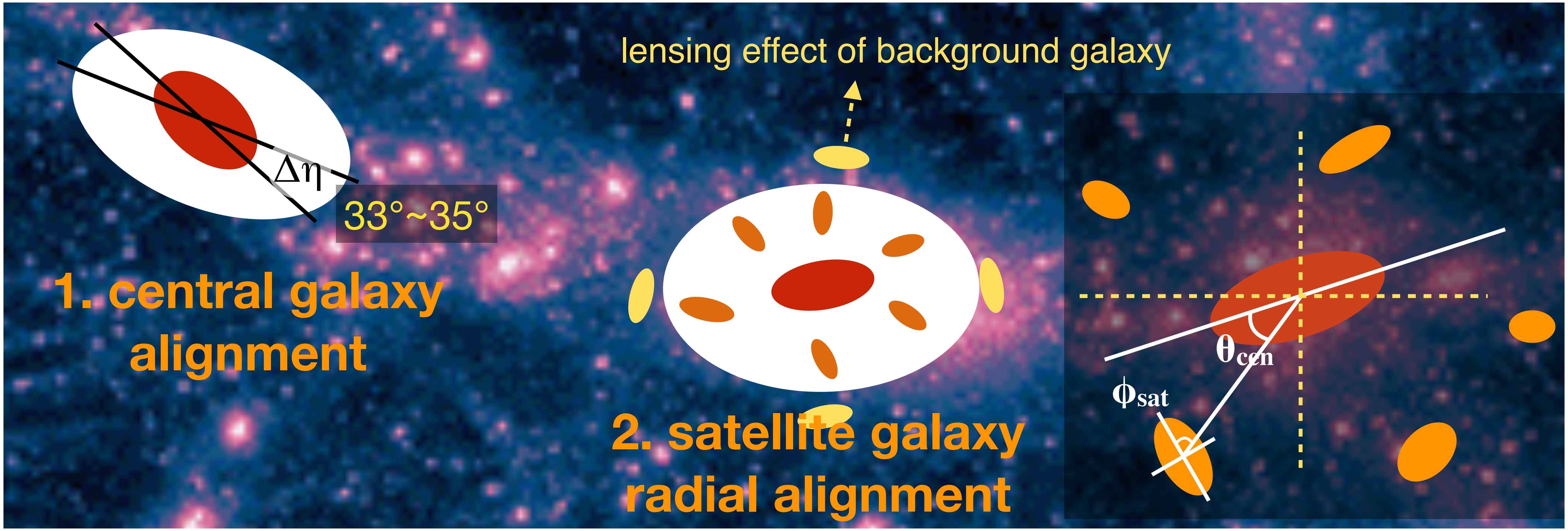
(Troxel+18)



(Efstathiou & Lemos 18)

Non-linear alignment model (NLA)
NLA model with free amplitudes per redshift bin
Mixed Alignment model (Blazek+18)

Intrinsic Alignment at small scale (1-halo)



(arXiv:1605.01065) (arXiv:1704.06273)

Sample

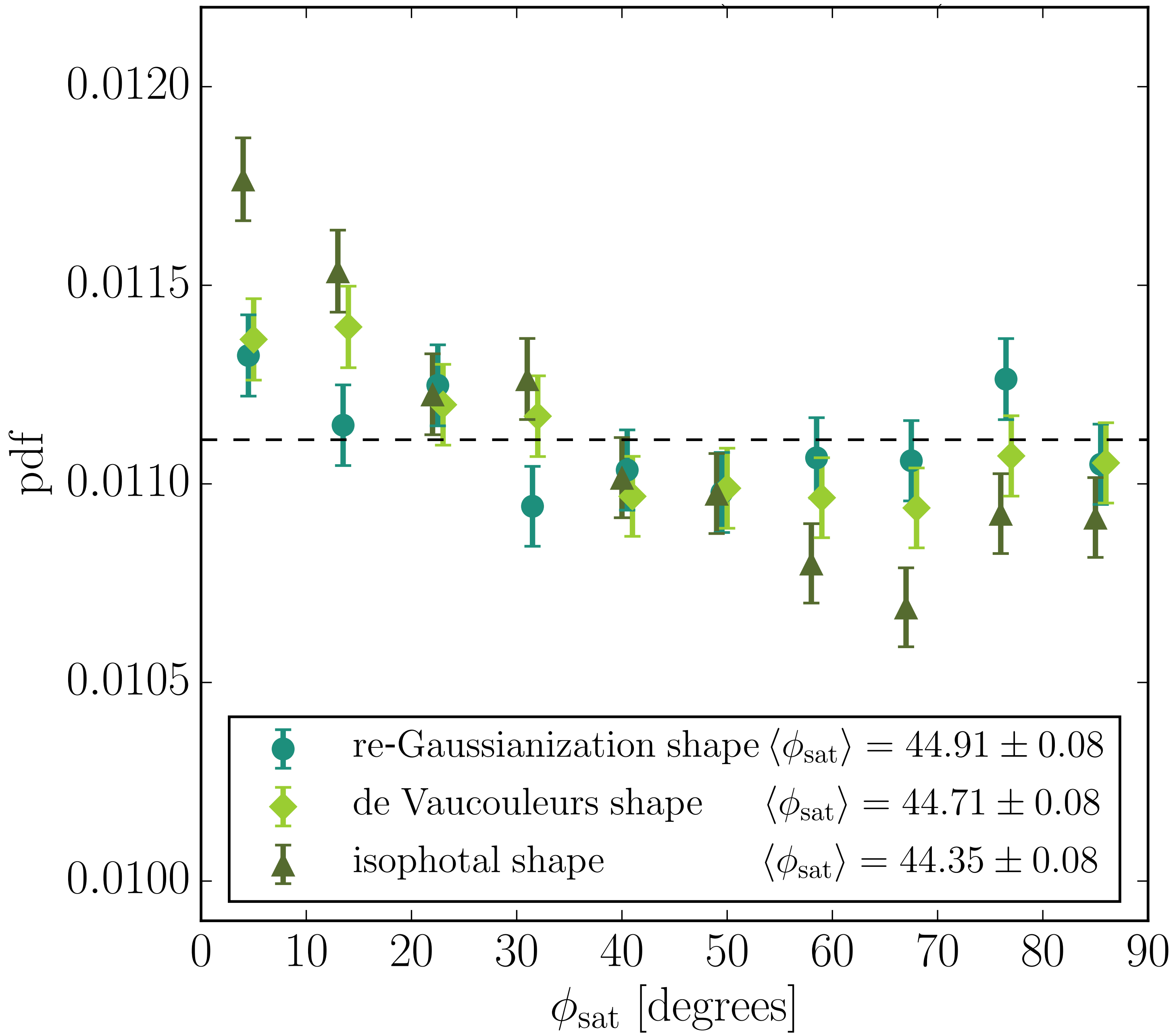
~ 8,000 **redMaPPer clusters** in $0.1 < z < 0.35$ (SDSS DR8)

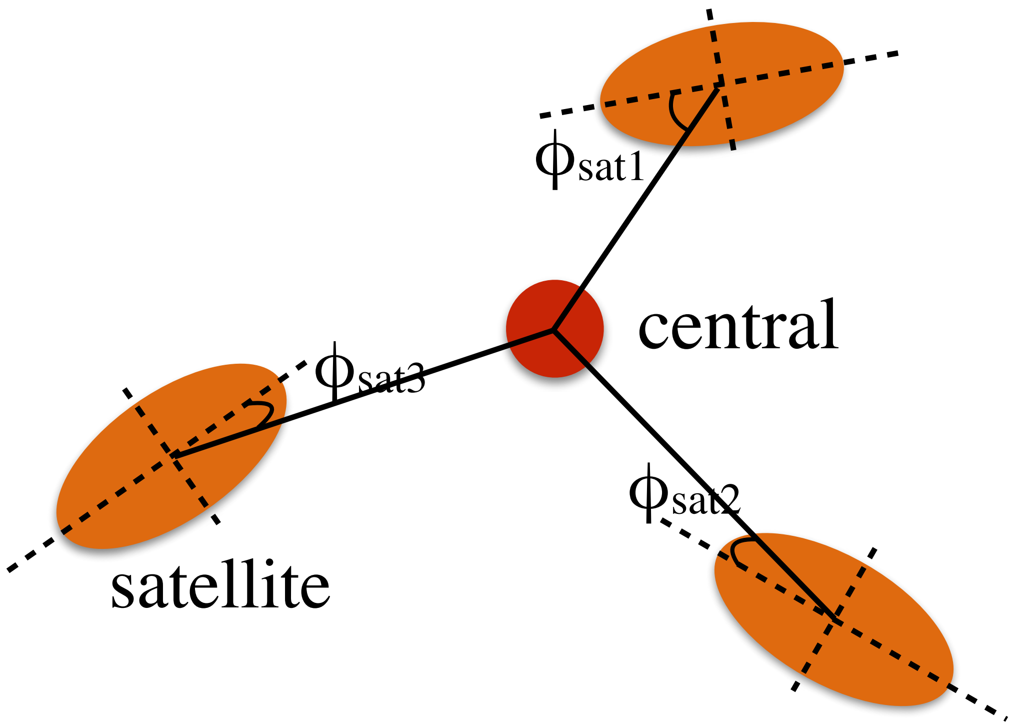
~ 120,000 effective satellites with shape measurement

IA signal depends on shape measurement method

re-Gaussianization (inner profile)
de Vaucouleurs
isophotal (outer profile)

Satellite Galaxy Radial Alignment





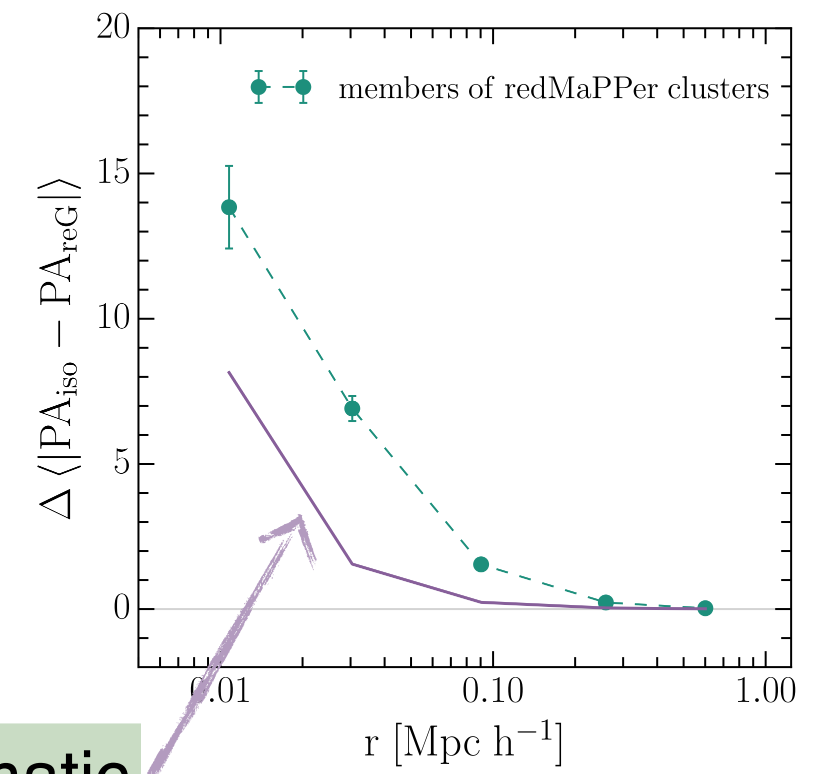
no detection

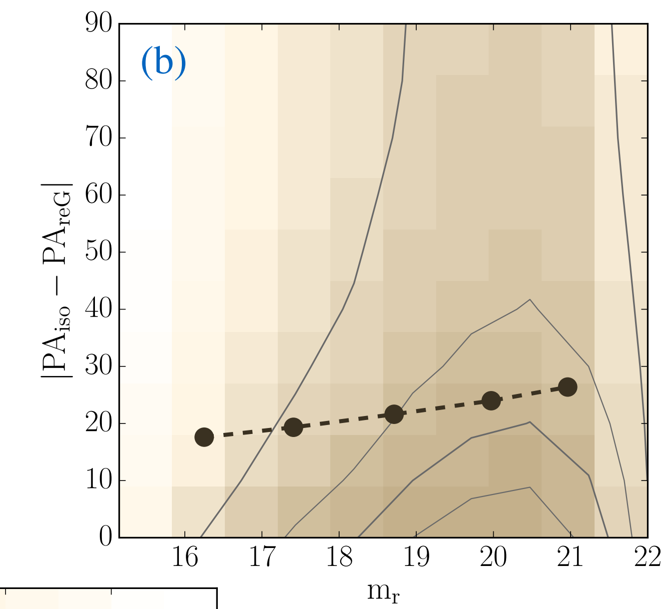
3.6σ detection

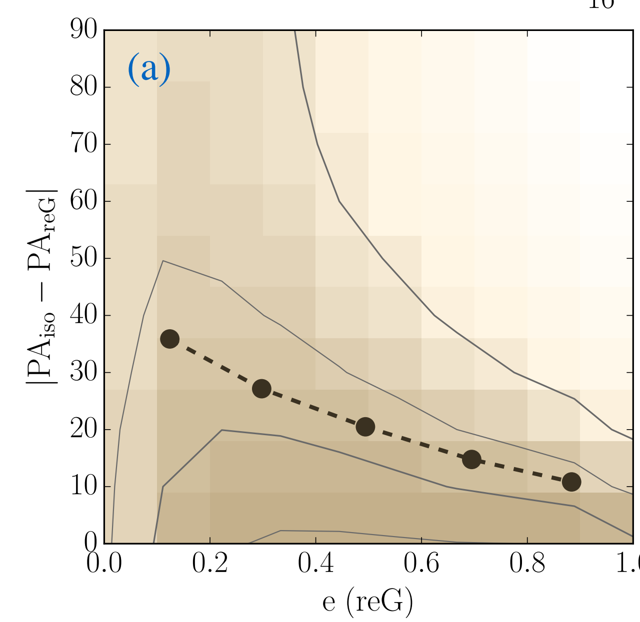
8σ detection

Origin of discrepancy in the detected IA signal

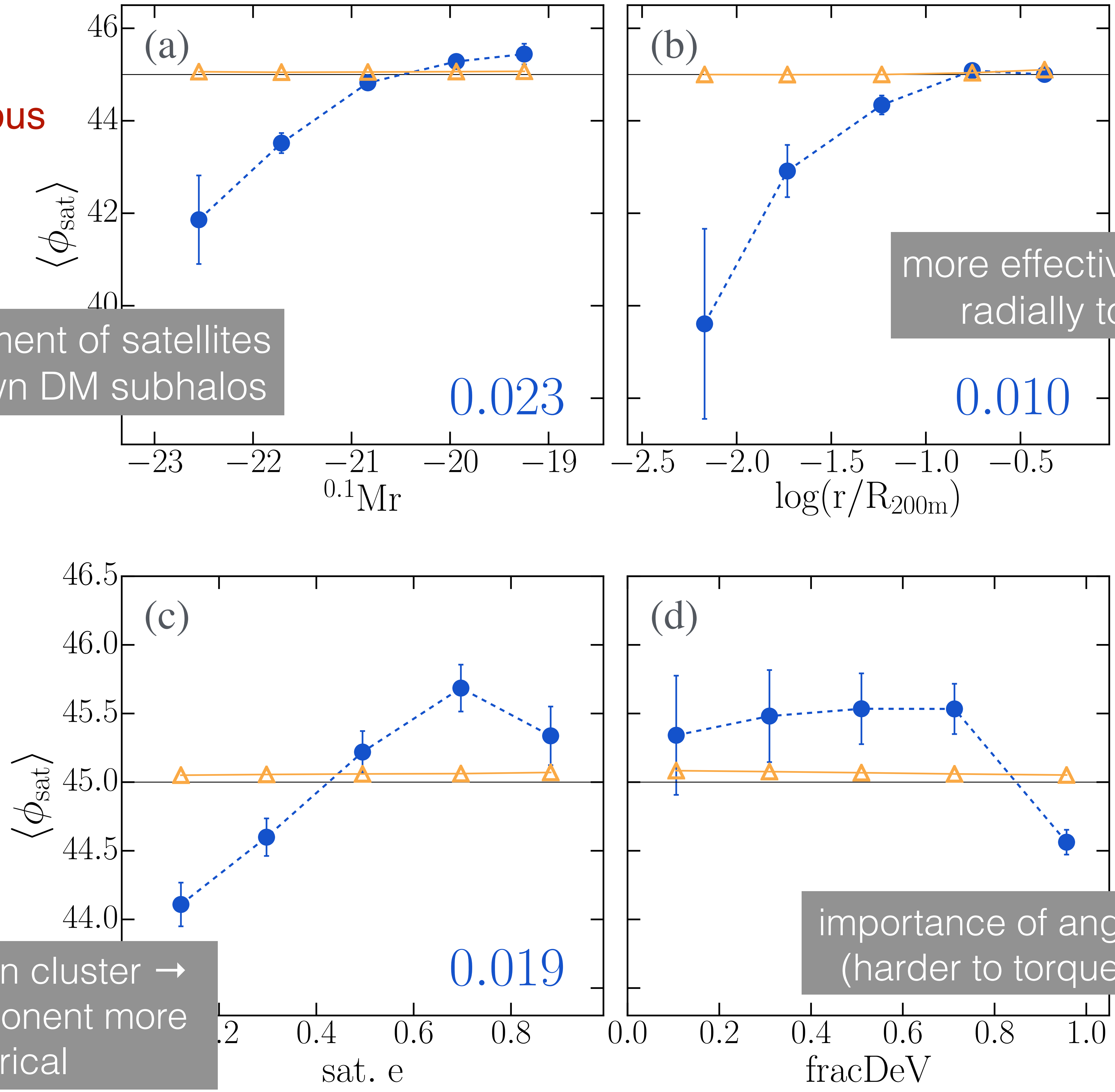
- Difference in Position Angle
  - Physical
    - Isophote twisting
  - Systematic
    - Bright neighbor systematic
    - Crowded field systematic
    - PSF systematic
  - Noise
    - Pixel noise
    - Ellipticity noise







Physical origin of satellite galaxy alignment



more luminous satellites

better alignment of satellites with their own DM subhalos

closer to cluster center

more effective to be torqued radially to halo center

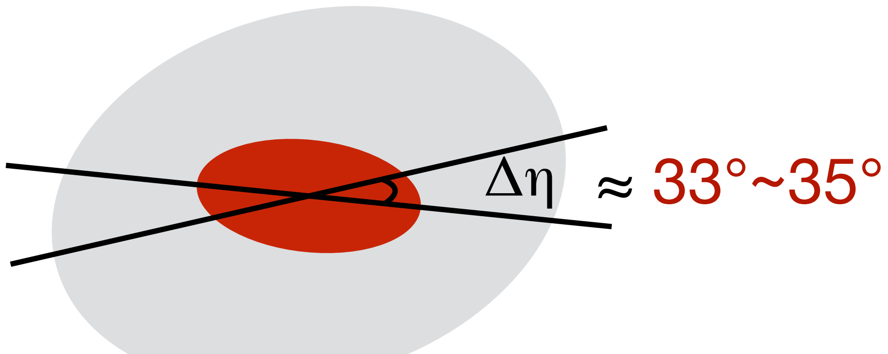
rounder in shape

longer time in cluster → stellar component more spherical

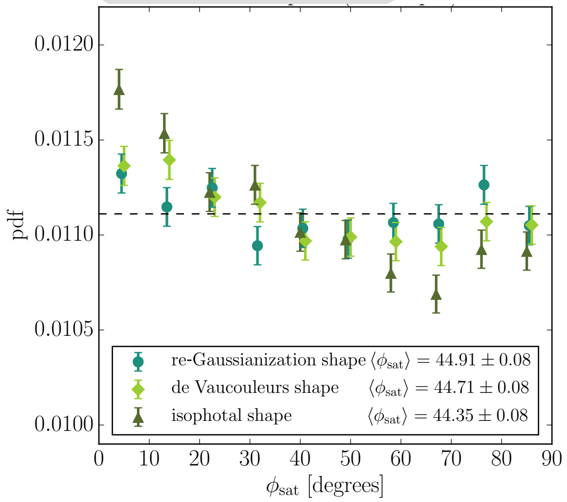
higher bulge fraction

importance of angular momentum (harder to torque disky system)

Summary — intrinsic alignment in redMaPPer clusters



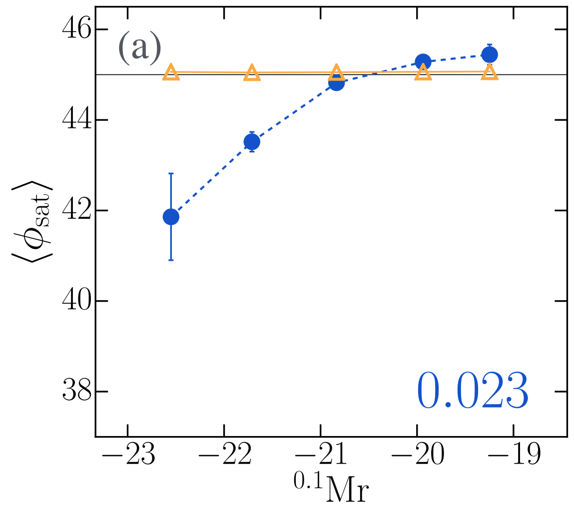
Central galaxy alignment



Satellite galaxy alignment

No significant signal detected using the most conservative shape measurement.

Complicated by noises and systematics.



We select several predictors that have significant influence on IA.

IA involves complicated physical processes during galaxy and cluster formation.

- Our results could be used to build an empirically-motivated **halo model for IA** including dependencies on galaxy or cluster properties.

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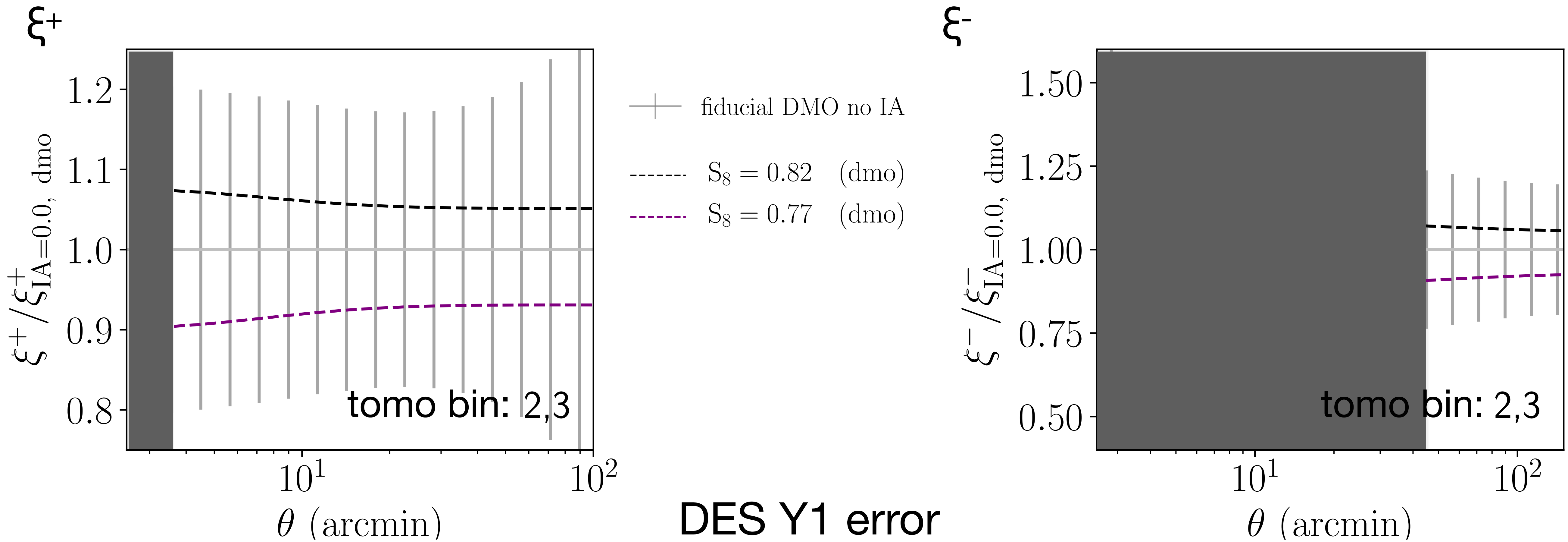
3 Outlook

Data precision is increasing, accurate physical models are necessary.



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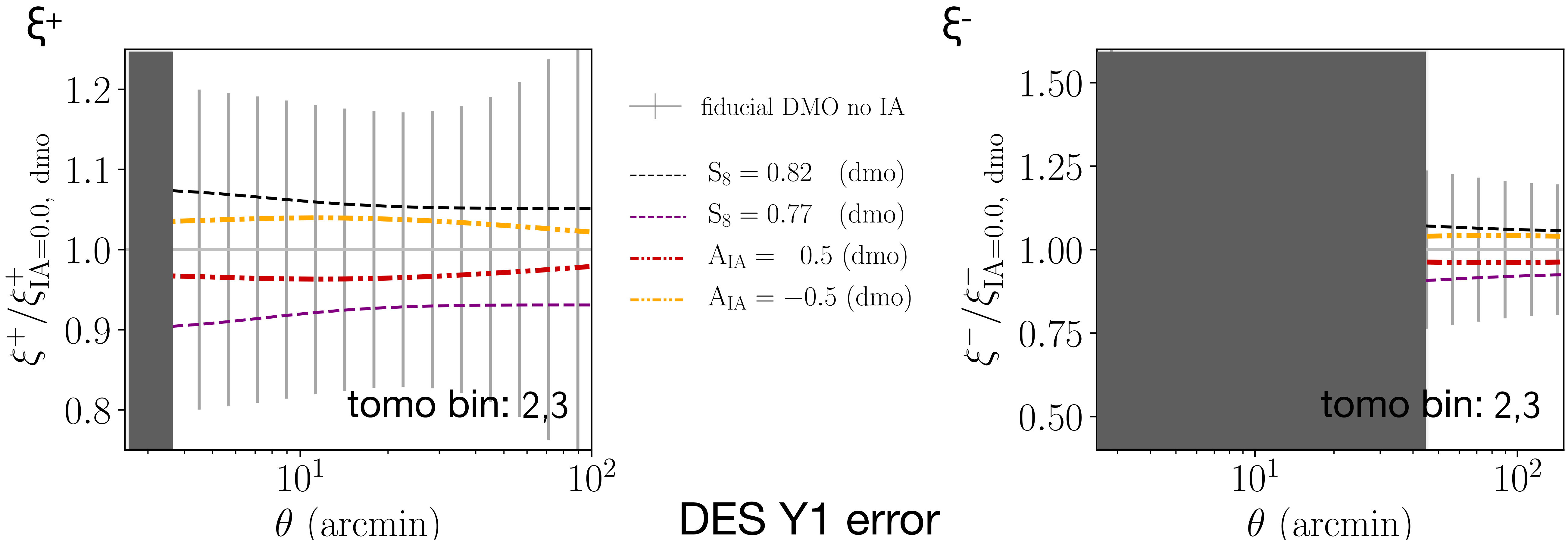

- DES Y1 **statistical error for S_8** is comparable with **IA bias.**
- **Small scale IA model** is needed to really extend cosmological analysis to small scale.

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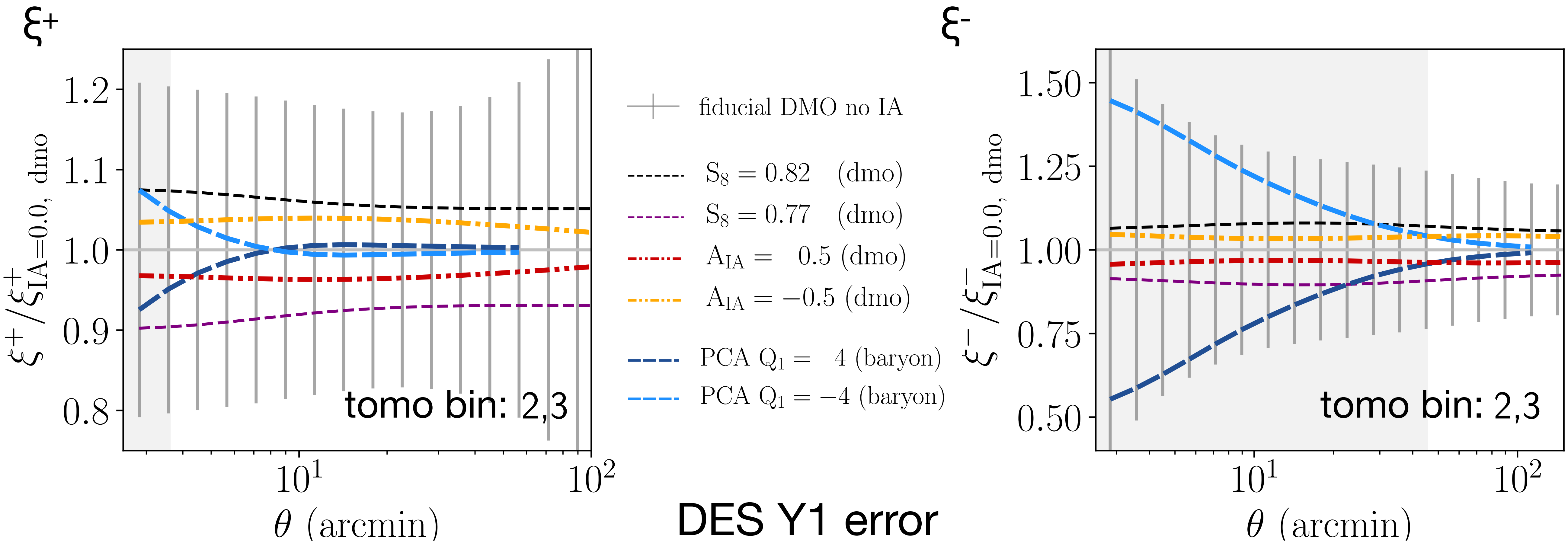

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- On going work : Extending DES Y1 cosmic shear analysis to small scale. (Huang et al. in prep.)

$$\boxed{\boldsymbol{M}_{\mathrm{bary}}(\boldsymbol{p}_{\mathrm{co}}, \boldsymbol{Q}) = \boldsymbol{M}(\boldsymbol{p}_{\mathrm{co}}) + \mathbf{L}\sum_{i=1}^{n} Q_i\, \mathbf{PC}_i}$$

- Constraining PC amplitudes Q_i to **rule out unlikely hydrodynamical scenarios** from data.

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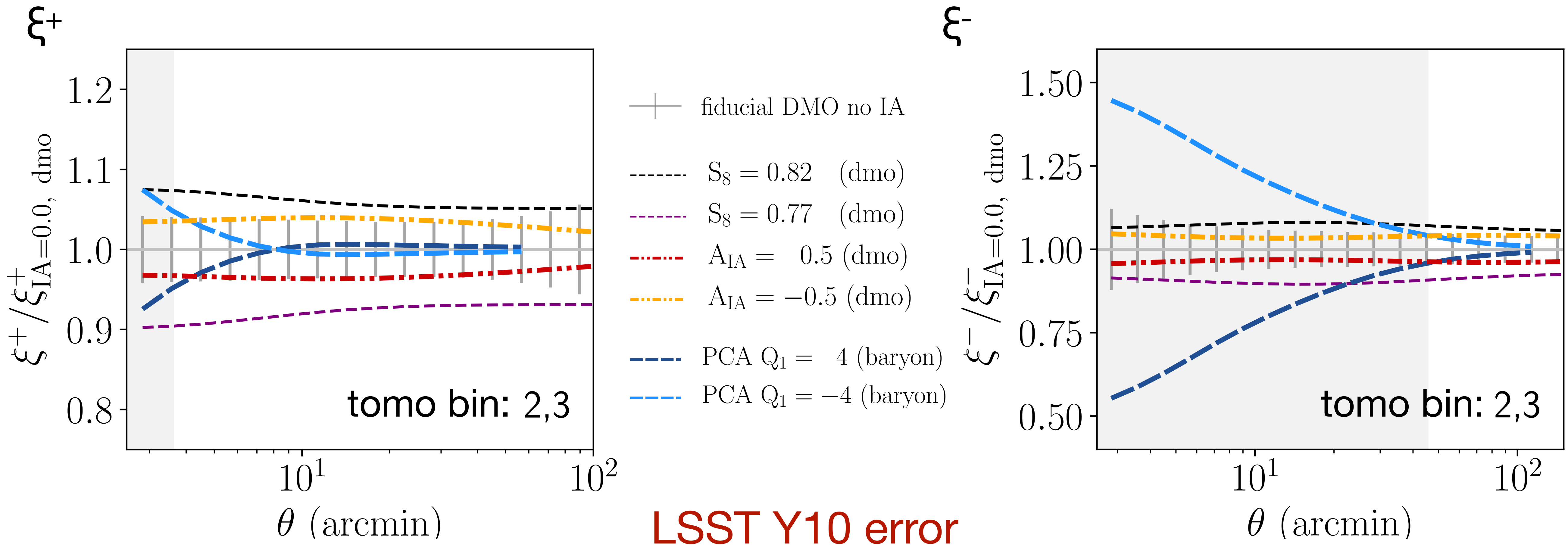

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- Constraining PC amplitudes Q_i to **rule out unlikely hydrodynamical scenarios** from data.
- **Better information on astrophysical systematics is needed** to bring the cosmological error down for future Stage IV survey.