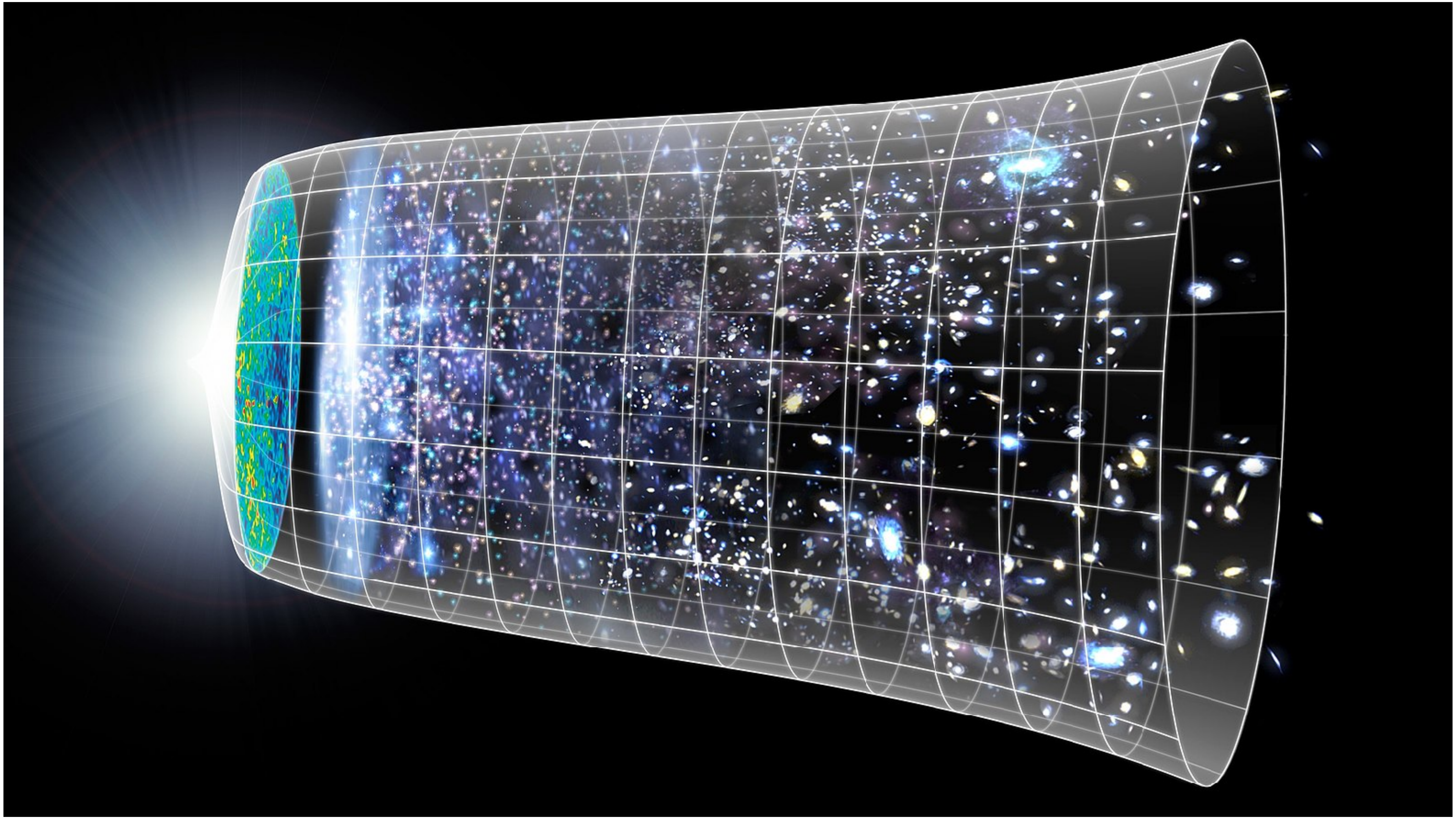
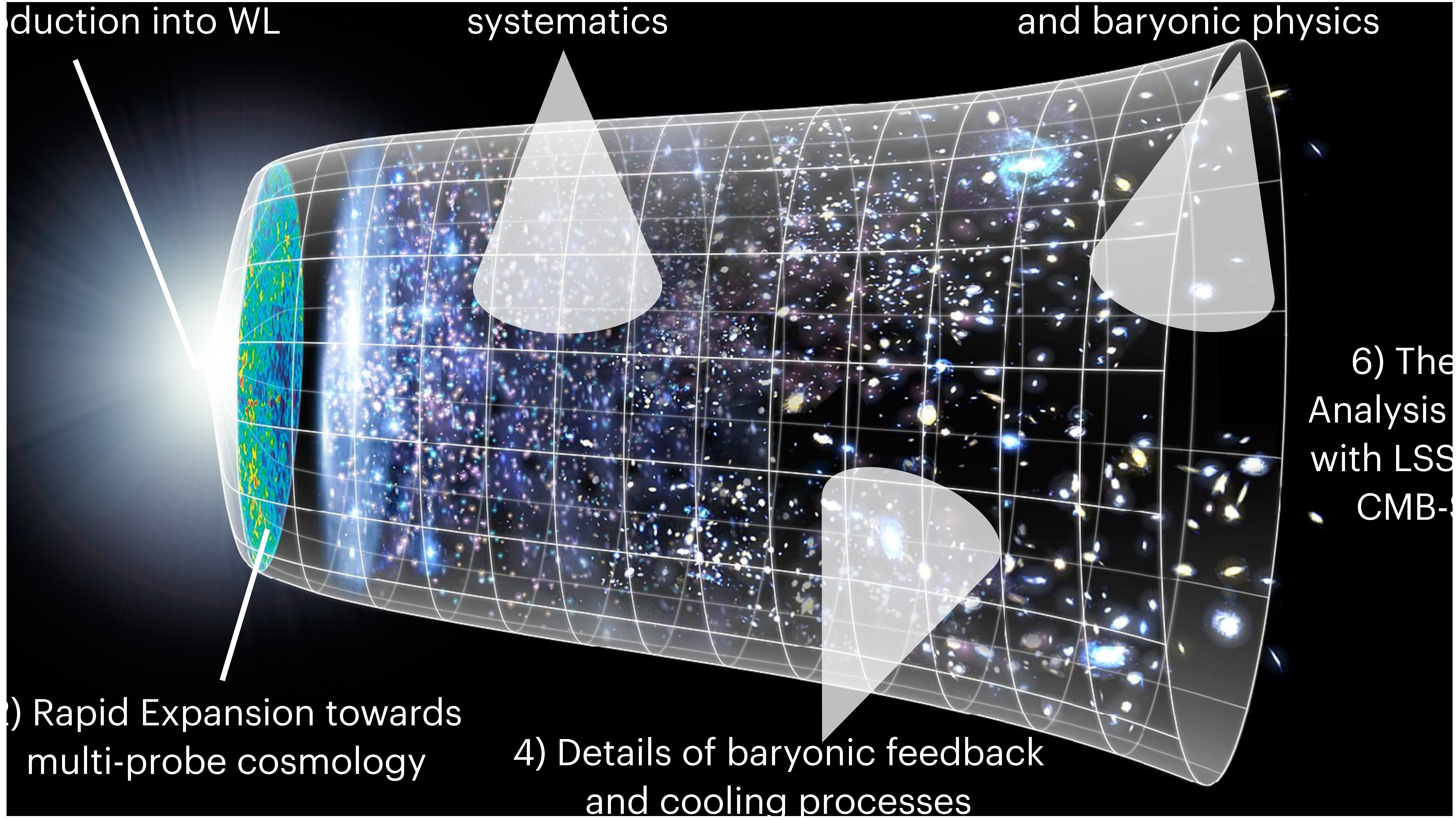
Constraining cosmology and baryonic physics with weak lensing, galaxy clustering, CMB lensing, and their cross-correlations

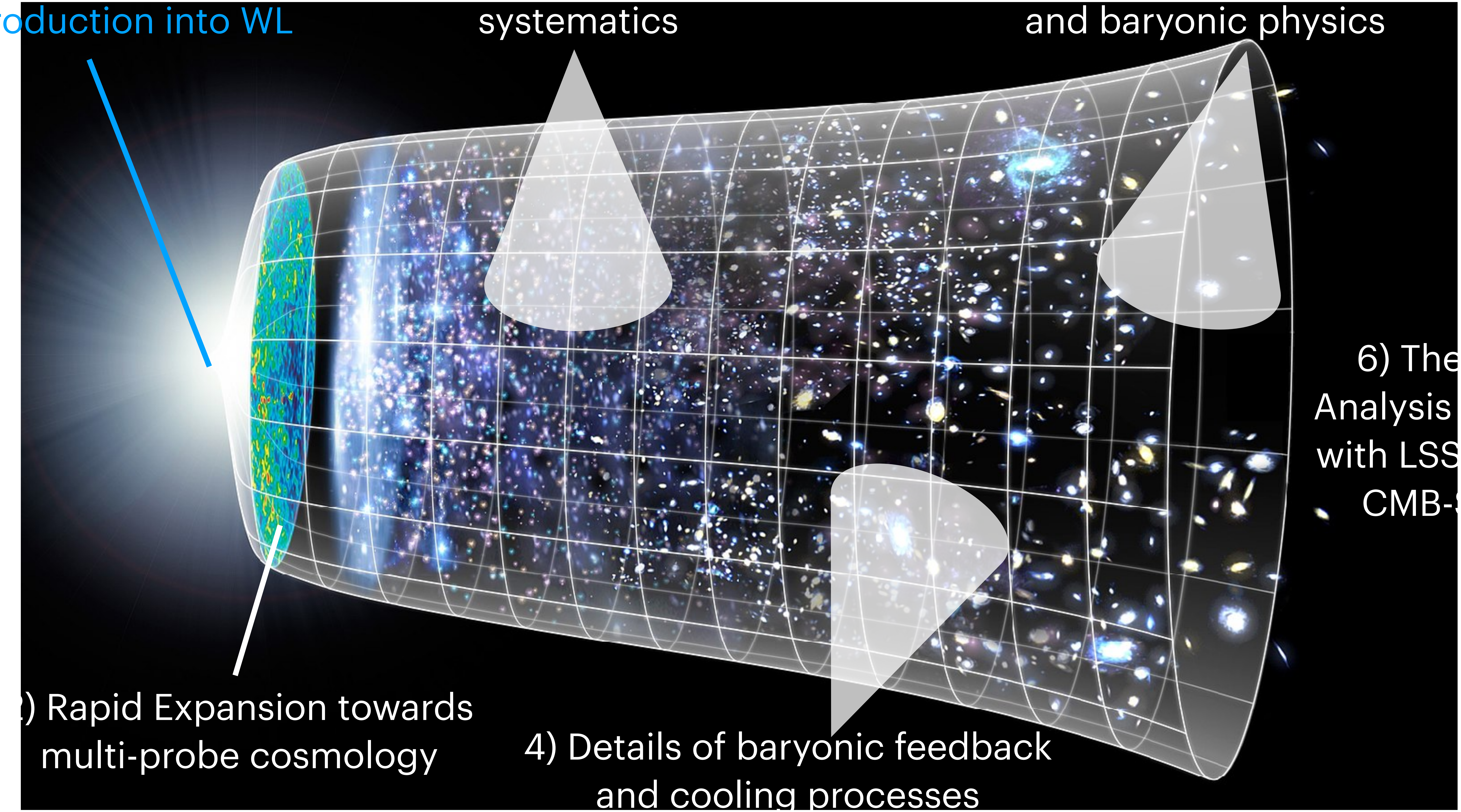
Tim Eifler, Arizona Cosmology Lab,
University of Arizona





Age of this Talk (45 mins)

1) The Beginning:
Introduction into WL



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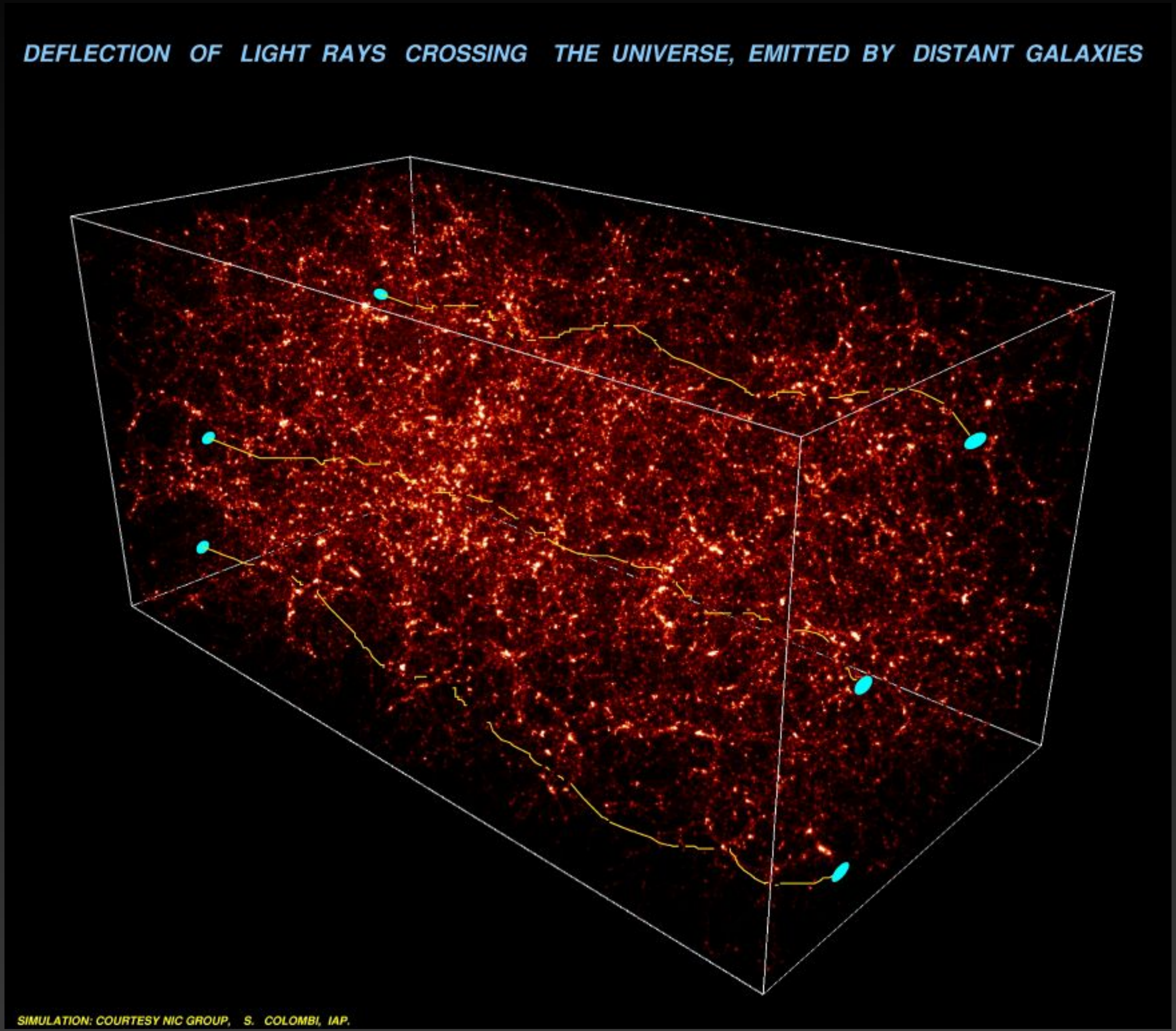
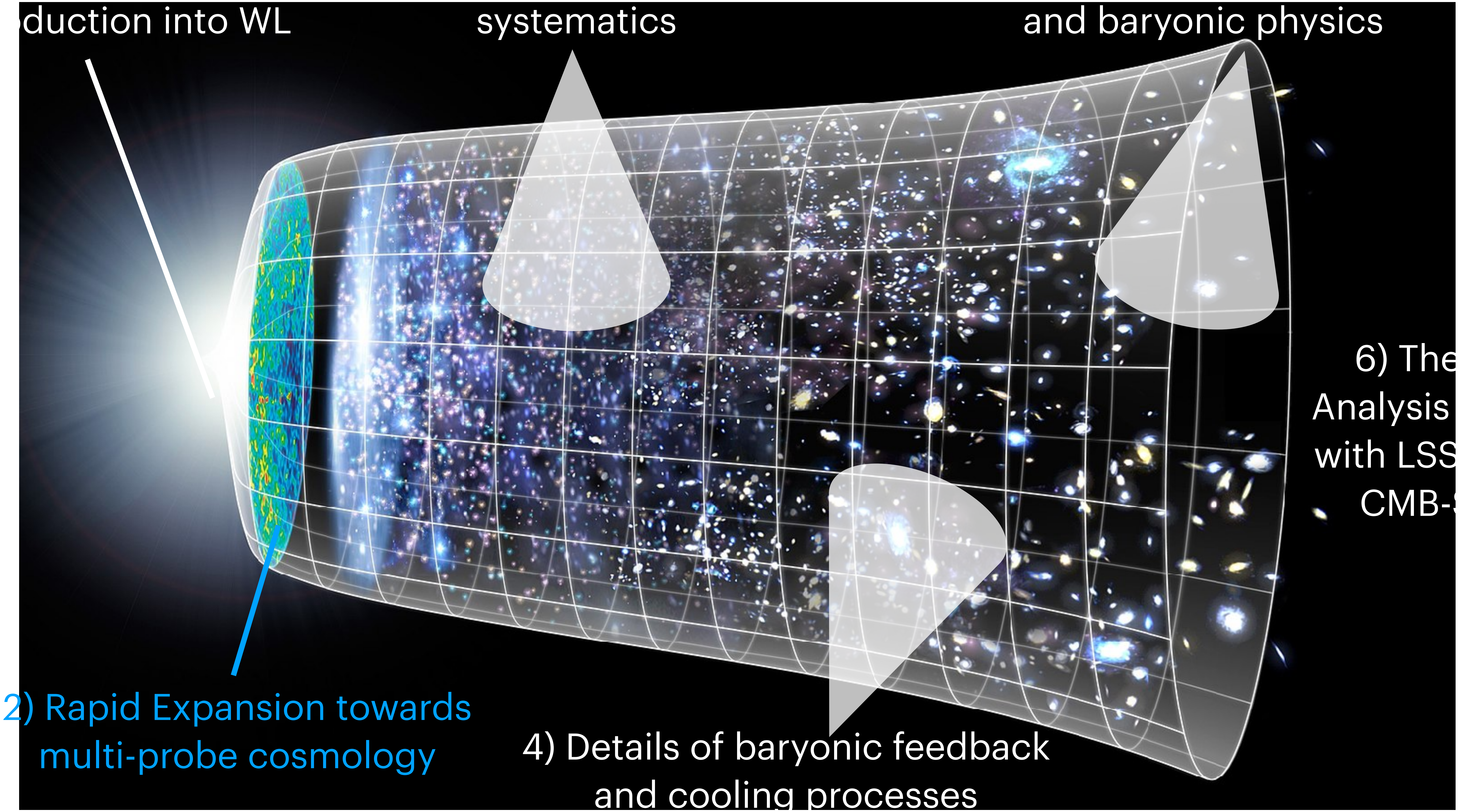
Weak Lensing



- Light rays are distorted by dark matter density field of the Universe
- Statistical properties of the distortion reflect statistical properties of the projected density field

$$C_\ell^{AB} = \int \frac{d\chi}{\chi^2} W_A(\chi) W_B(\chi)\ P_m(k = \frac{\ell + 1/2}{\chi}, \chi),$$

- Shear power spectrum is a projection of the density power spectrum with redshift dependent weight functions called “lens efficiency”



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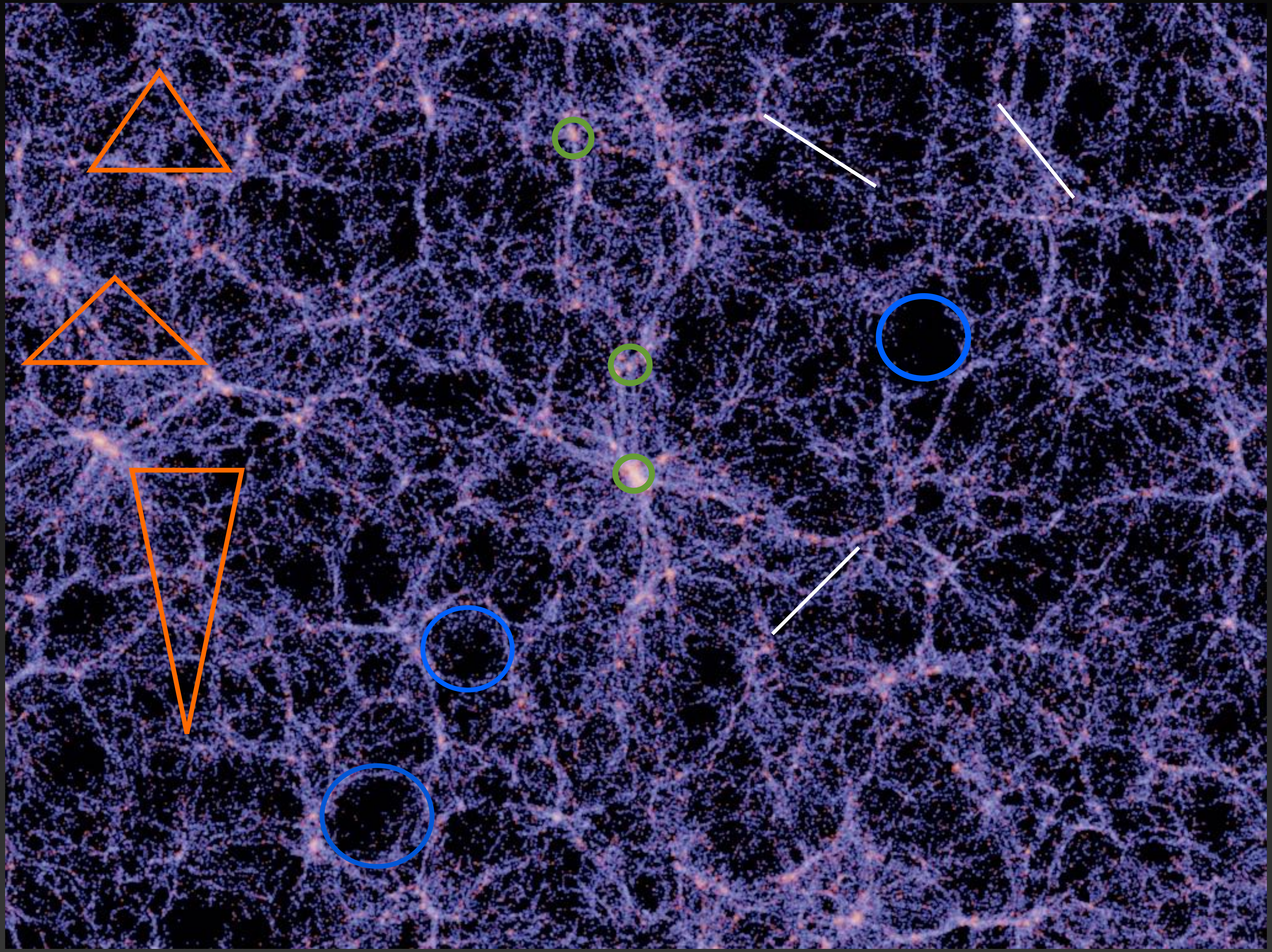
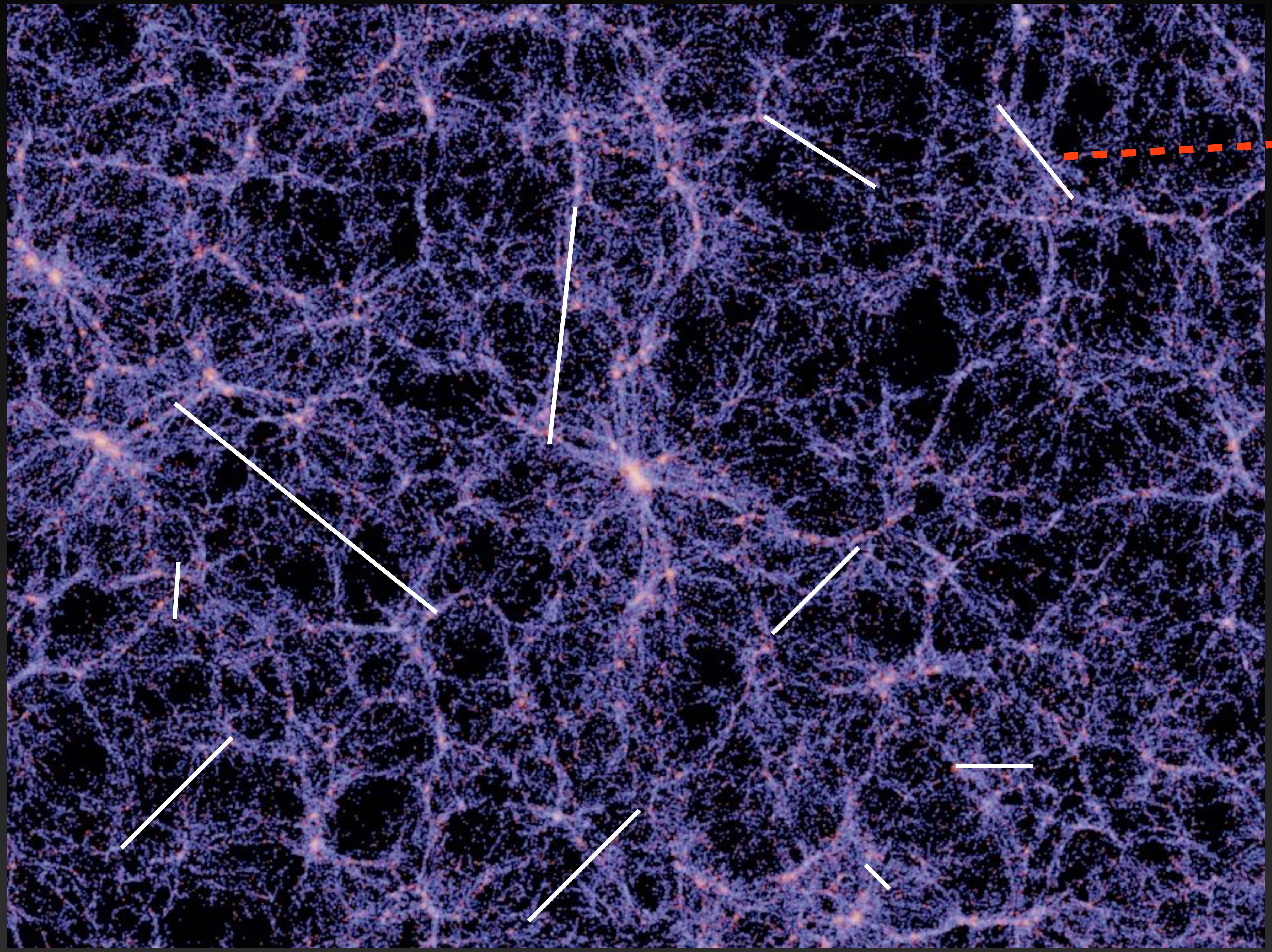
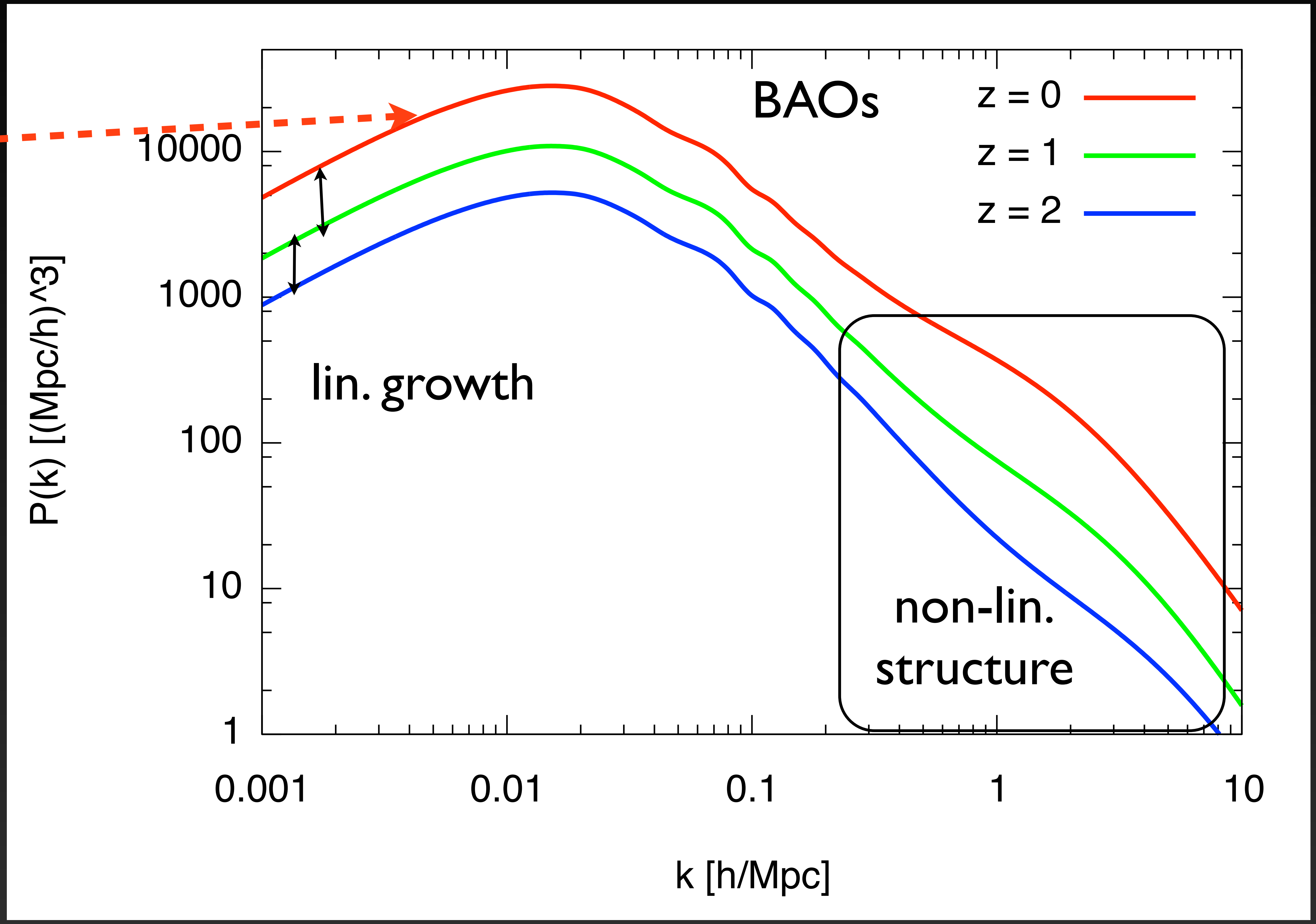
Tracers of the density field



- clusters, peaks (overdensities),
- voids (under densities)
- two-point correlations (galaxy positions, shapes)
- three-point correlations,...

Photometric galaxy clustering



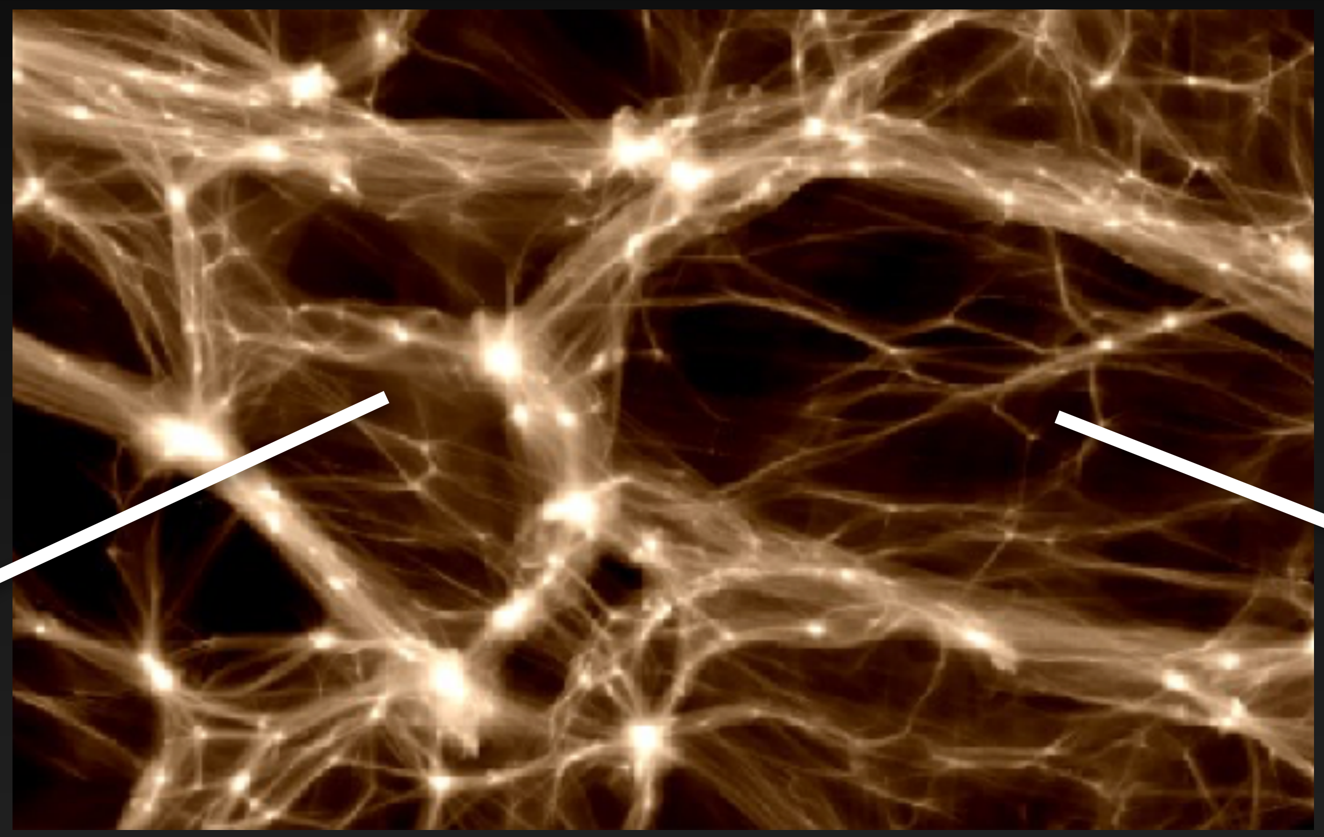


$$C_\ell^{AB} = \int \frac{d\chi}{\chi^2}\, W_A(\chi) W_B(\chi)\, P_m\!\left(k = \frac{\ell + 1/2}{\chi}, \chi\right)$$

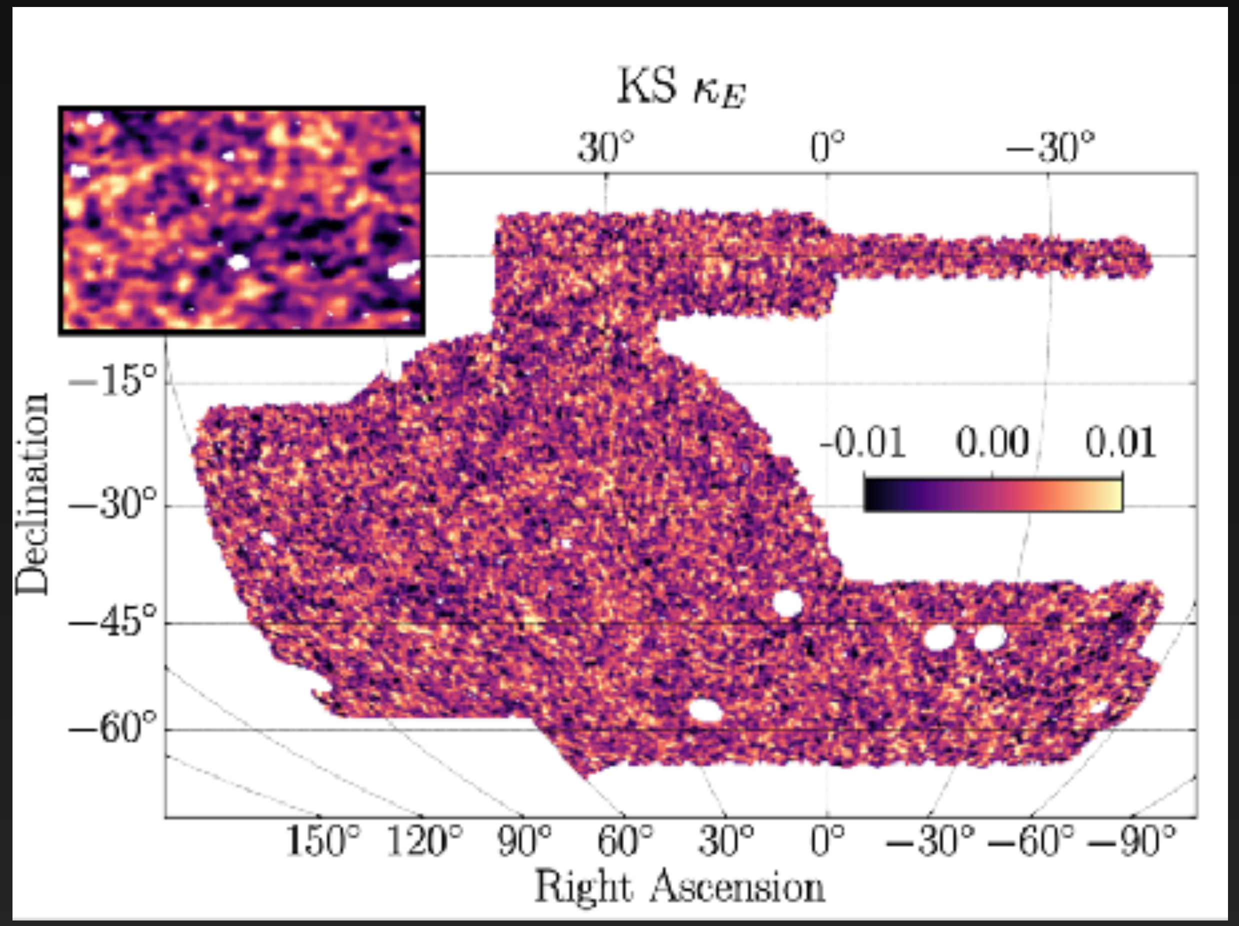
3x2pt Analysis (yes…real space)

Weak Lensing and Galaxy Clustering

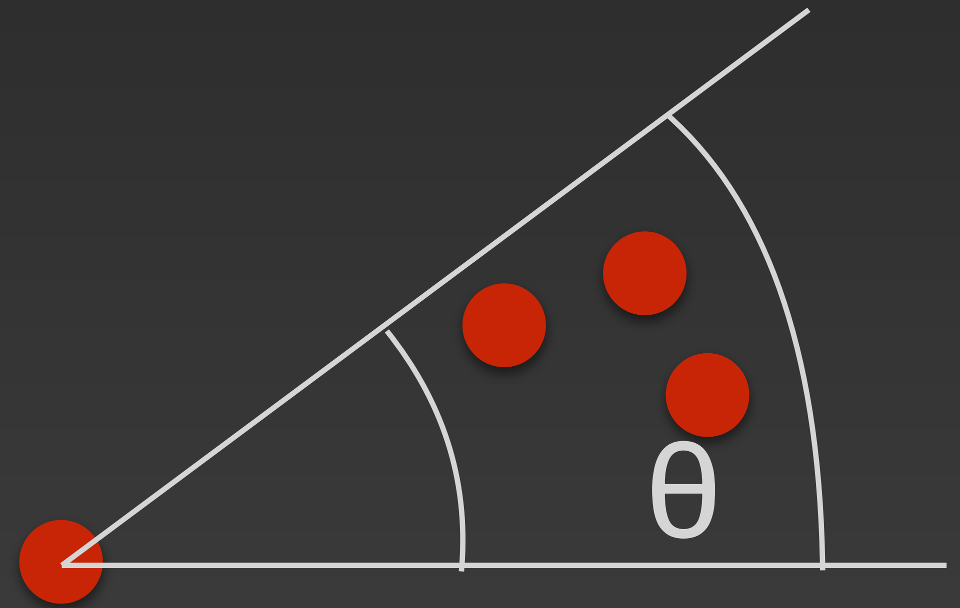
Galaxy Position Map



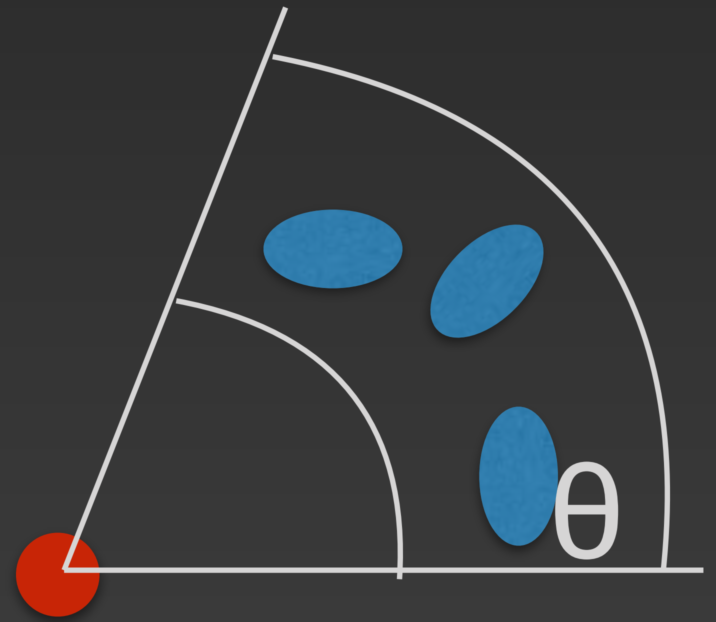
Galaxy Shear Map



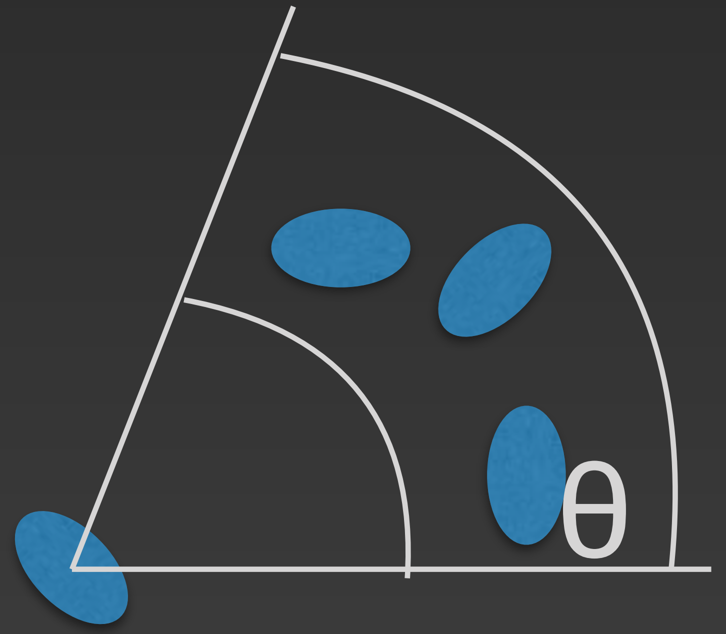
galaxies x galaxies:
angular clustering

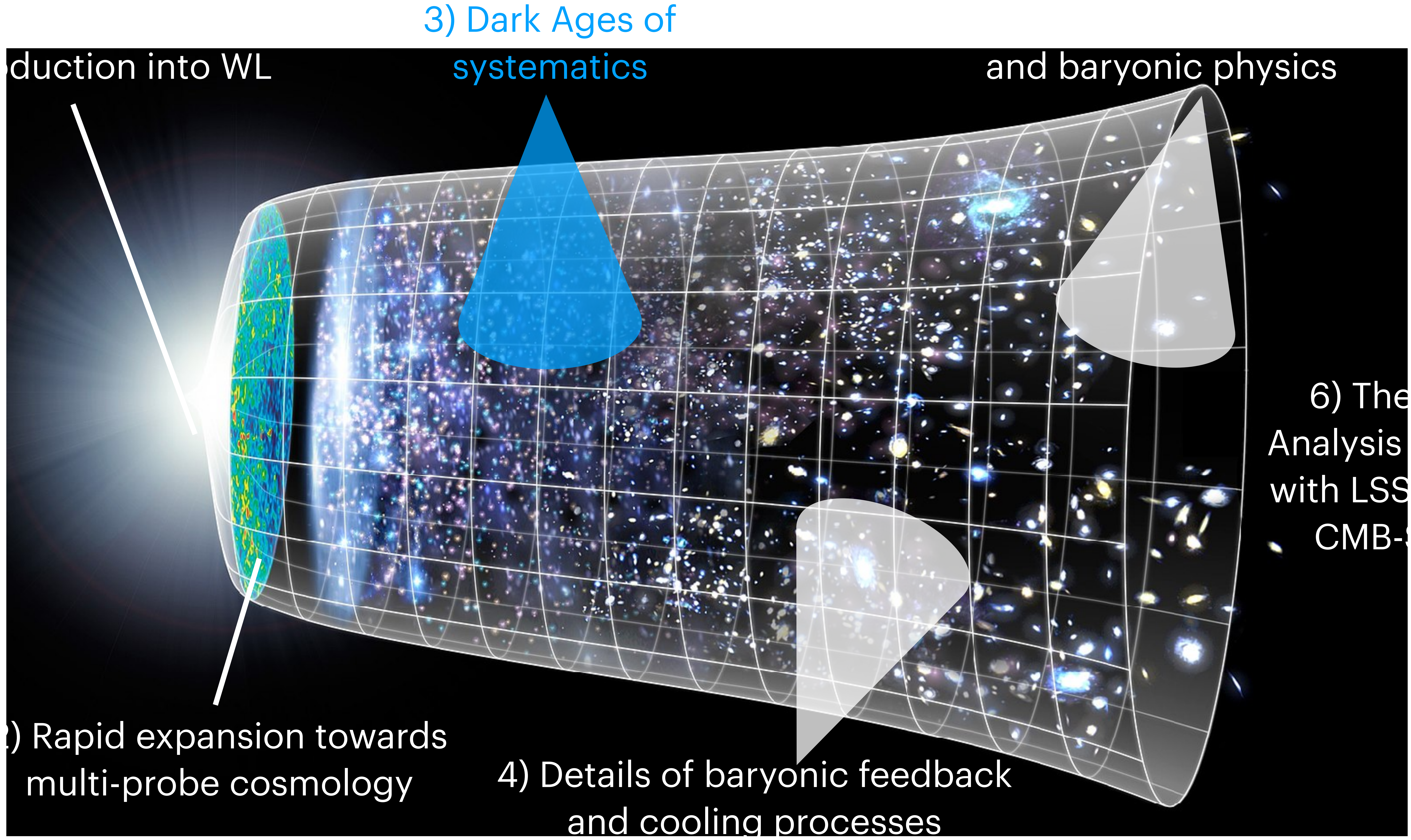


galaxies x lensing:
galaxy-galaxy lensing



lensing x lensing:
cosmic shear





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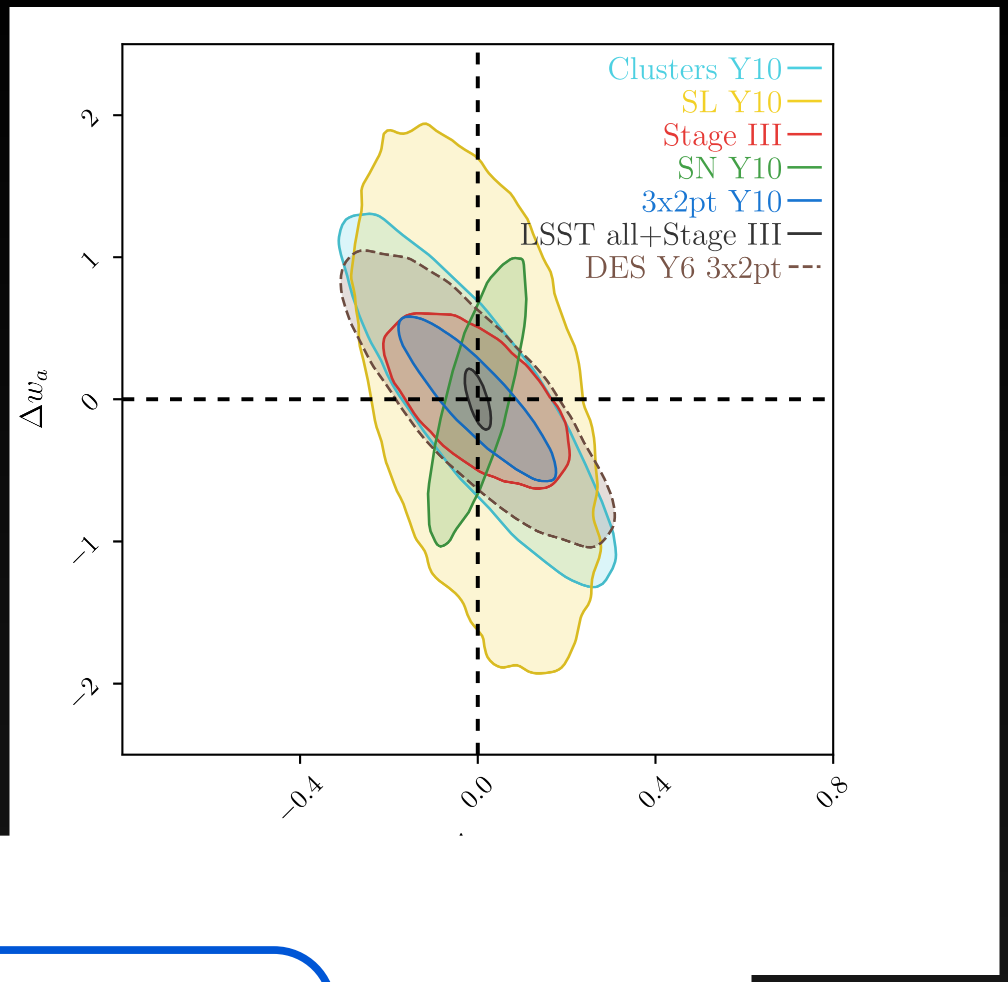
The inference challenge

→ reduced data and catalogs → summary statistics →

→



Independent probes
e.g., SN1a as priors

Large model vector (CMB+LSS)
Self-consistent modeling of all observables as a function of
1) cosmological parameters (~10)
2) nuisance parameters (XXX)

large data vector

posterior probability

$$p\left(\boldsymbol{\pi}|\hat{\mathbf{d}}\right) \propto p\left(\boldsymbol{\pi}\right) \mathcal{L}\left(\hat{\mathbf{d}}|\mathbf{m}\left(\boldsymbol{\pi}\right), C\right)$$

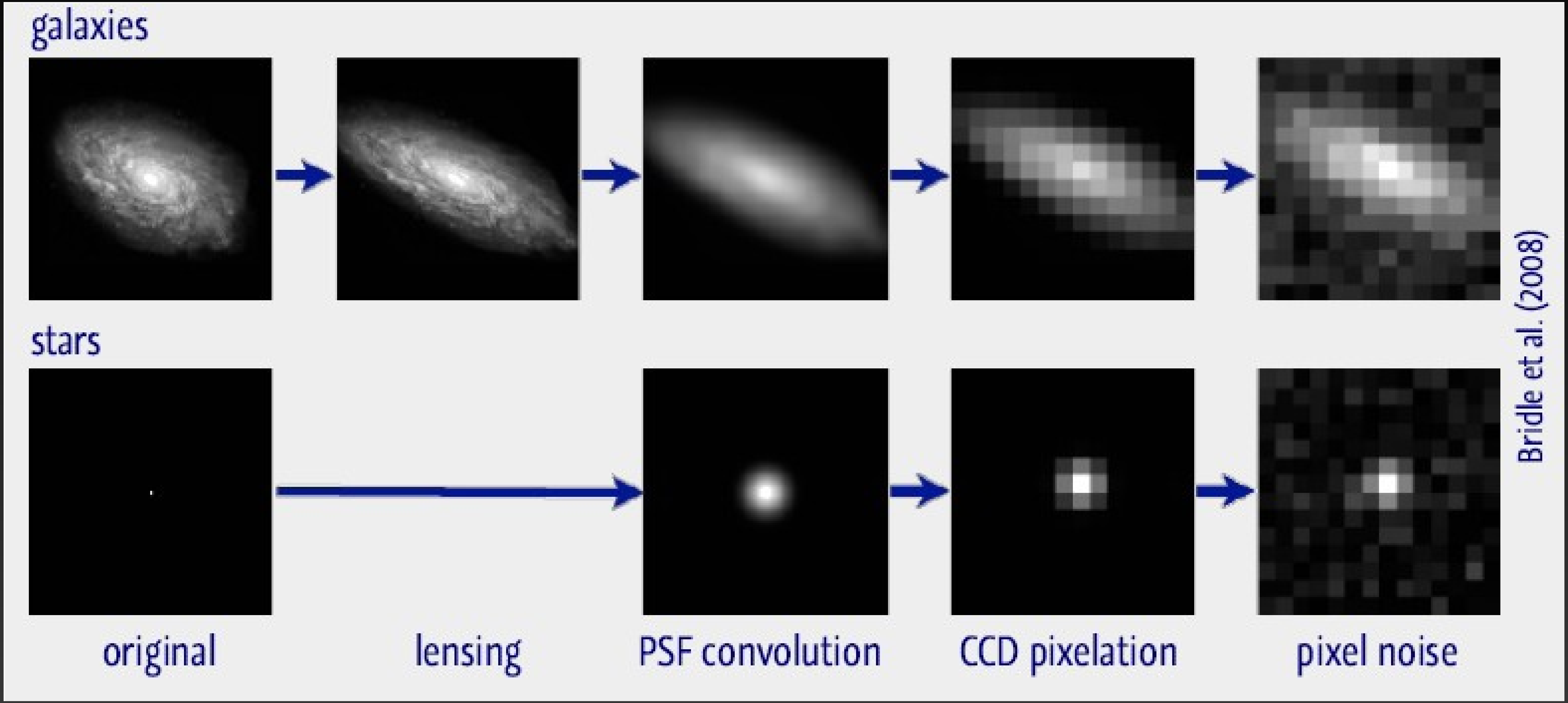
Enhanced modeling via
- Observations
- Simulations
- Theory

Statistics I - Likelihood function
- Multivariate Gaussian vs other parameterizations
- Non-parametric forms
- Approximate Bayesian Computation

Statistics II - Covariances
- cosmology dependent Signal + constant Noise
- large and complicated, non-(block) diagonal
- different methods for derivation

Shear Calibration

Shear Calibration uncertainties



Shear Calibration uncertainties

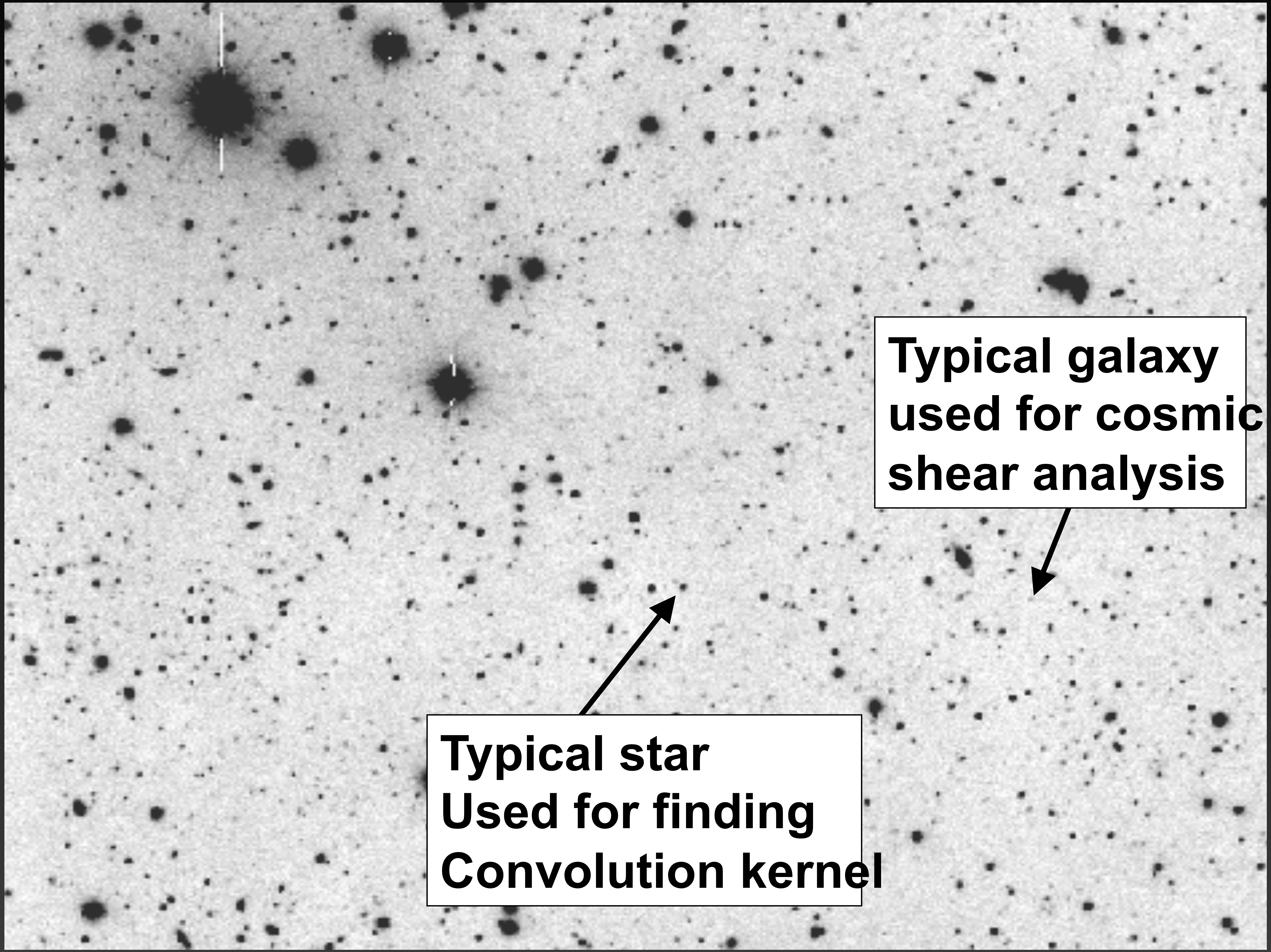
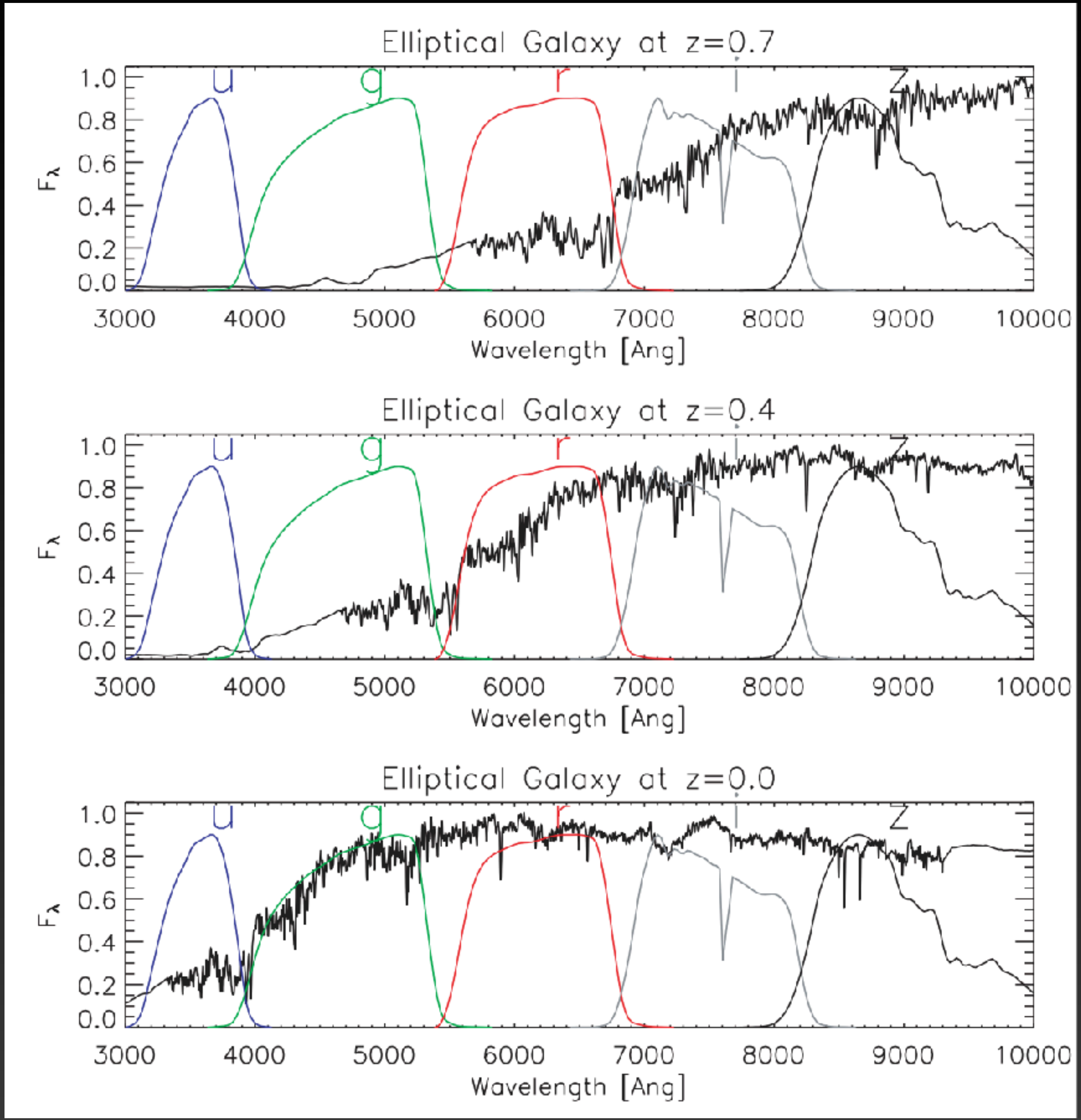


Photo-z uncertainties

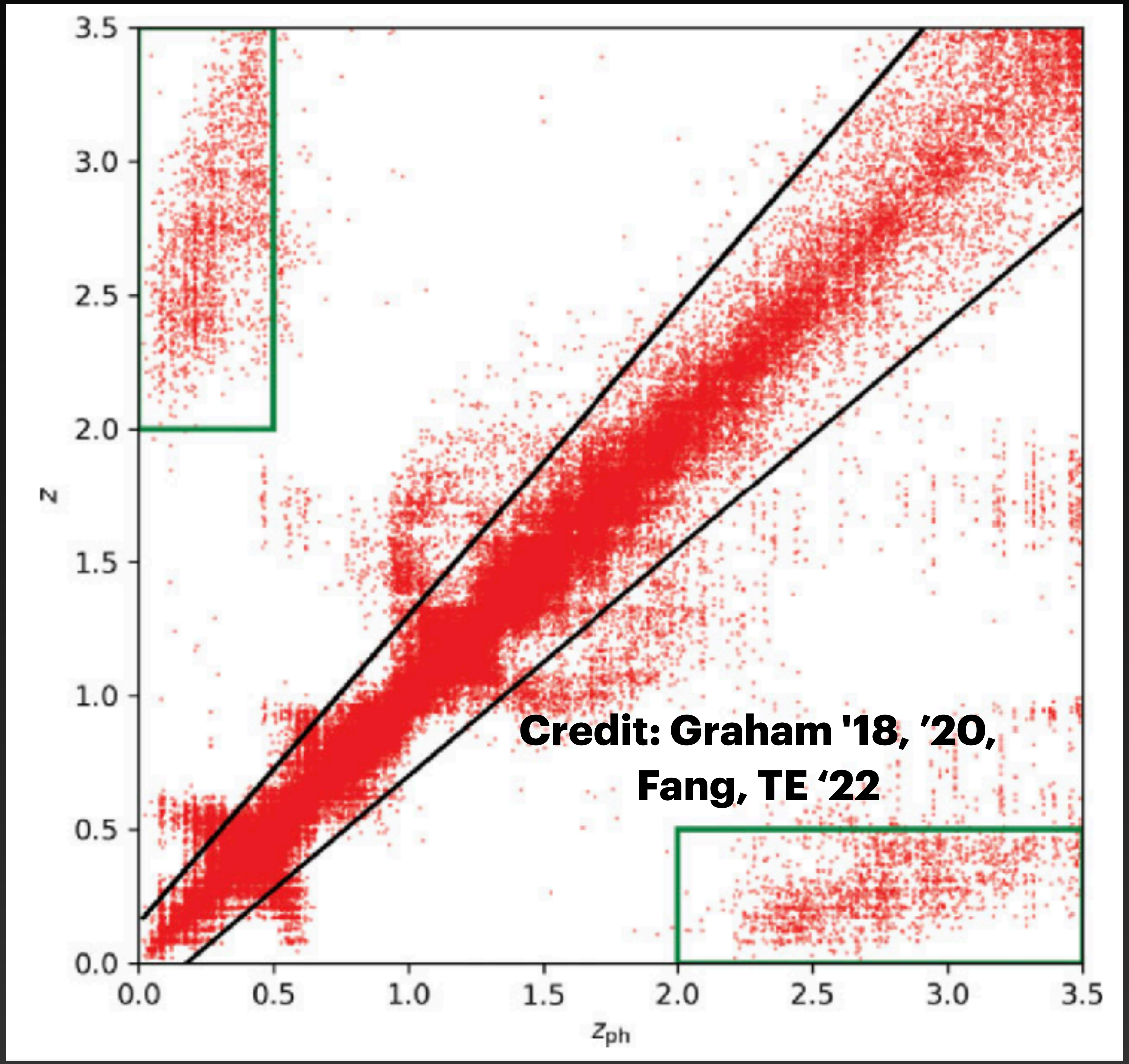
Photo-z uncertainties

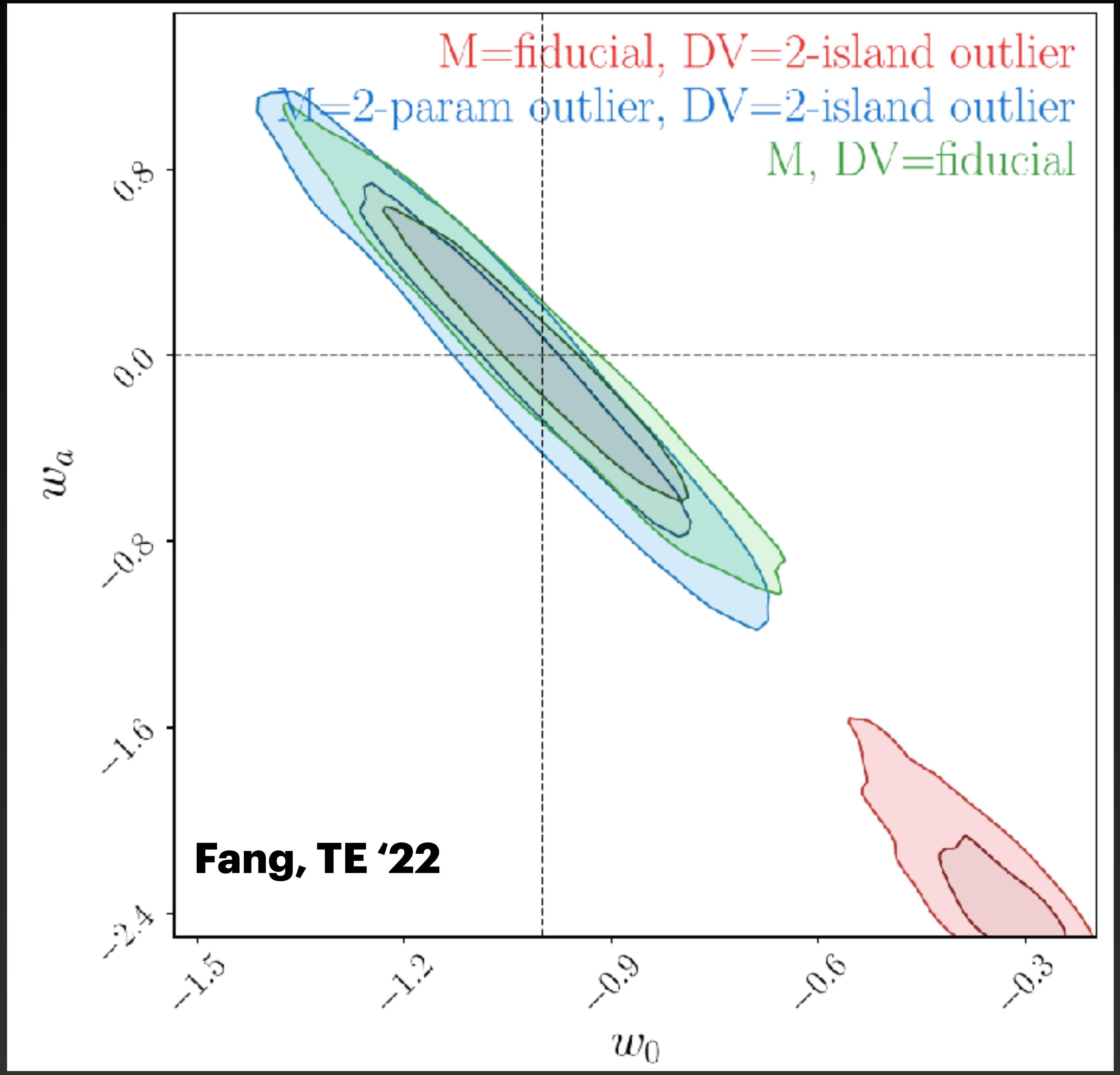


Credit: Padmanabhan+ 2007

- Measure Fluxes in many different photometric bands
- Collect spectra for representative galaxy sample
- Infer redshifts through mapping these flux measurements to galaxy spectra
- Much less accurate compared to spectroscopic redshifts

Photo-z uncertainties - catastrophic outliers

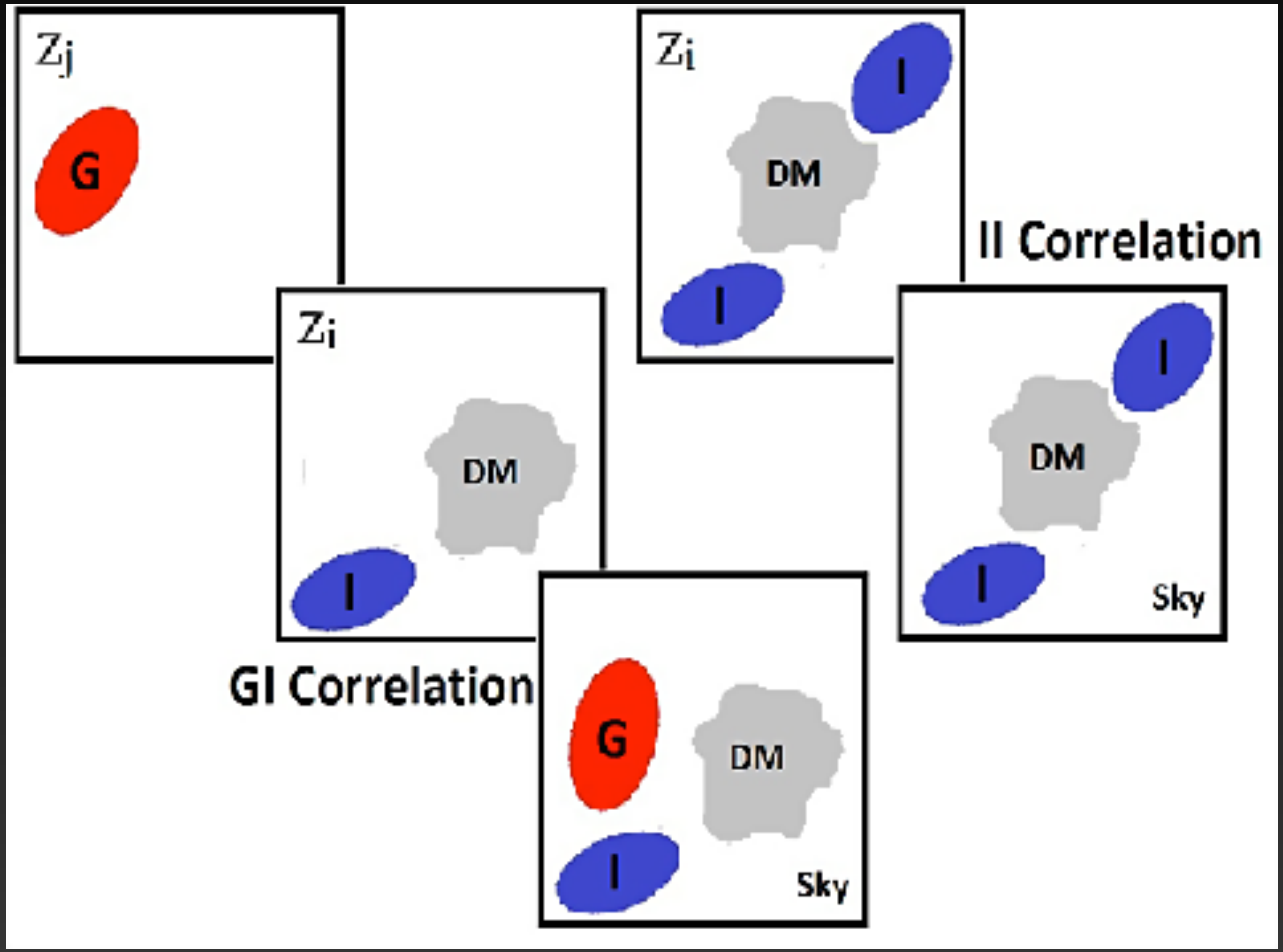




- Left: Simulated LSST PZ data showing two clear regions of outliers
- Right: We develop an 2-island model that allows for freedom in the amplitude of outlier fraction -> marginzlization over this recovers outlier-based biases nicely

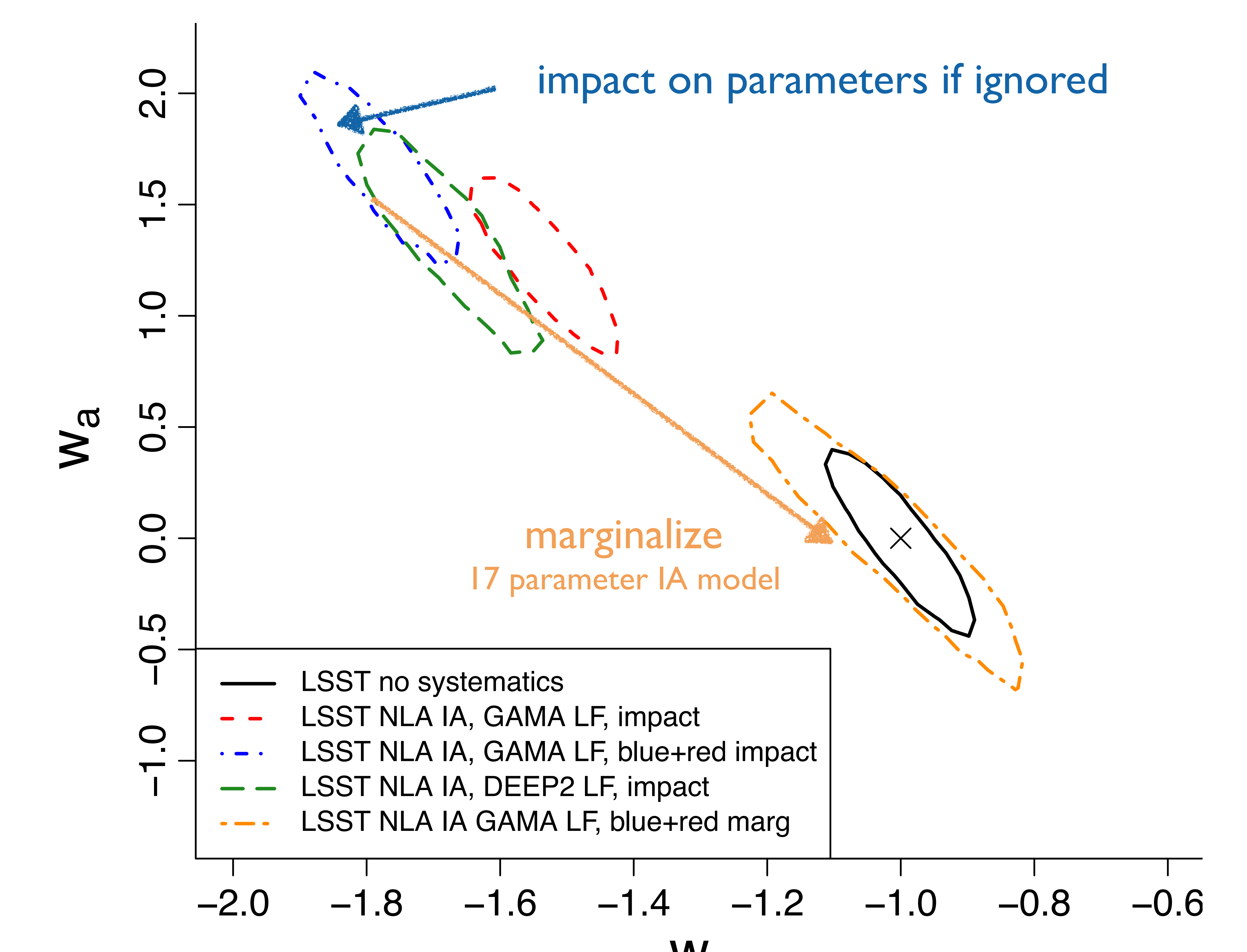
Galaxy Intrinsic Alignment

Galaxy Intrinsic Alignment (IA)



- Cosmic shear relies on the idea that galaxies are randomly oriented
- Several effects can cause alignment of galaxies with tidal field
- Two Types of IA: GI and II
- GI is more severe as a contaminant for cosmic shear

Galaxy Intrinsic Alignment (IA)



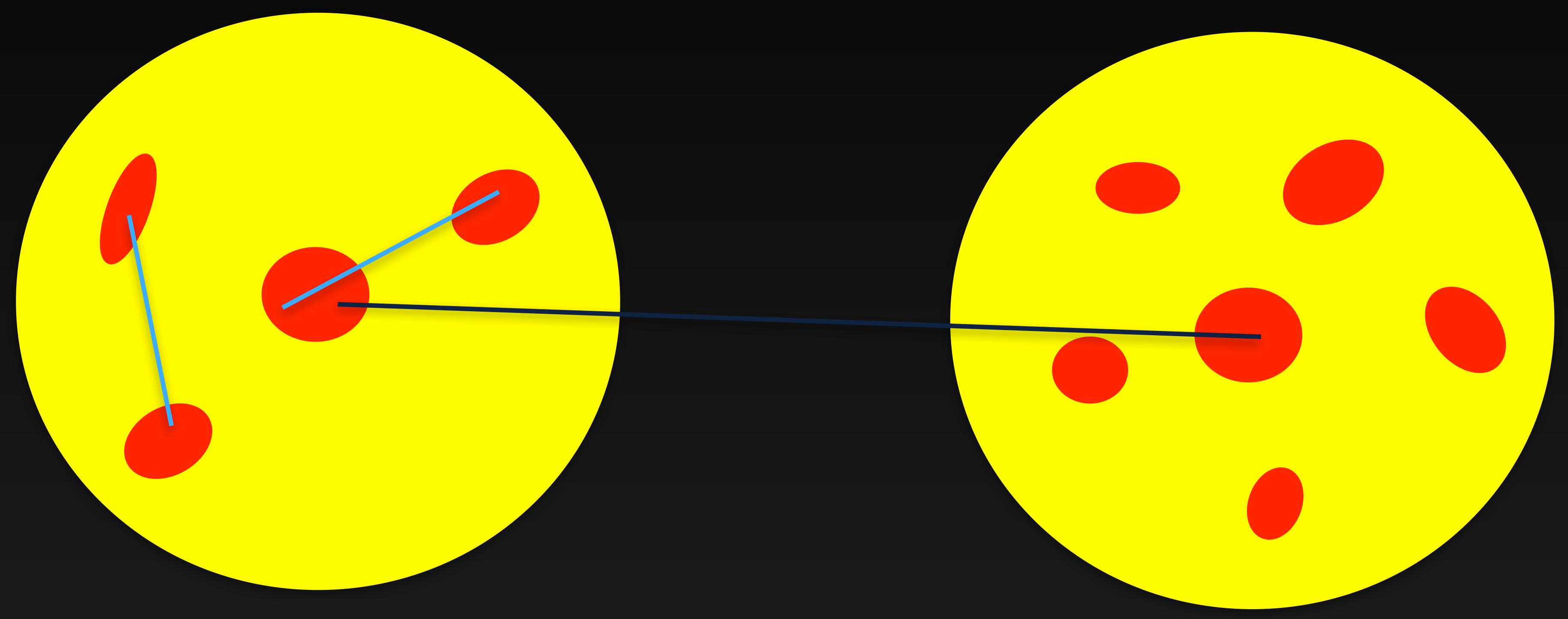
Krause, TE & Blazek'16

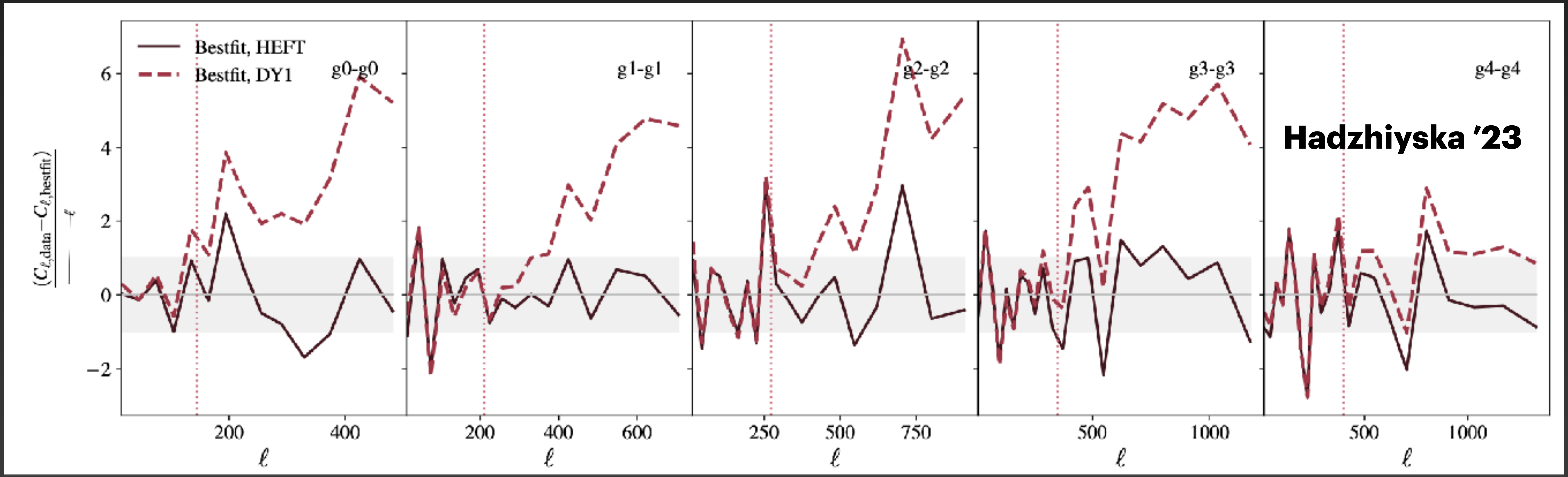
- Left shows simulated analysis for LSST Y10
- Data vectors are contaminated with nonlinear/linear alignment model
- Analysis marginalizes over 17 parameters for IA (incl luminosity function)
- Strong biases if unmitigated, significant increase in error bars if marginalized over
- **Useful:** If IA can be controlled at z<1, contamination largely vanishes

Galaxy Bias

Galaxy Bias

- Relation between a galaxy population and the matter field is the main uncertainty in clustering
- Linear relation on large scales, perturbative and HEFT methods on quasi- linear scales
- On small scales, several galaxies within massive halos: requires approximate (halo) models, or expensive sims+emulators
- All models are functions of redshift and galaxy type



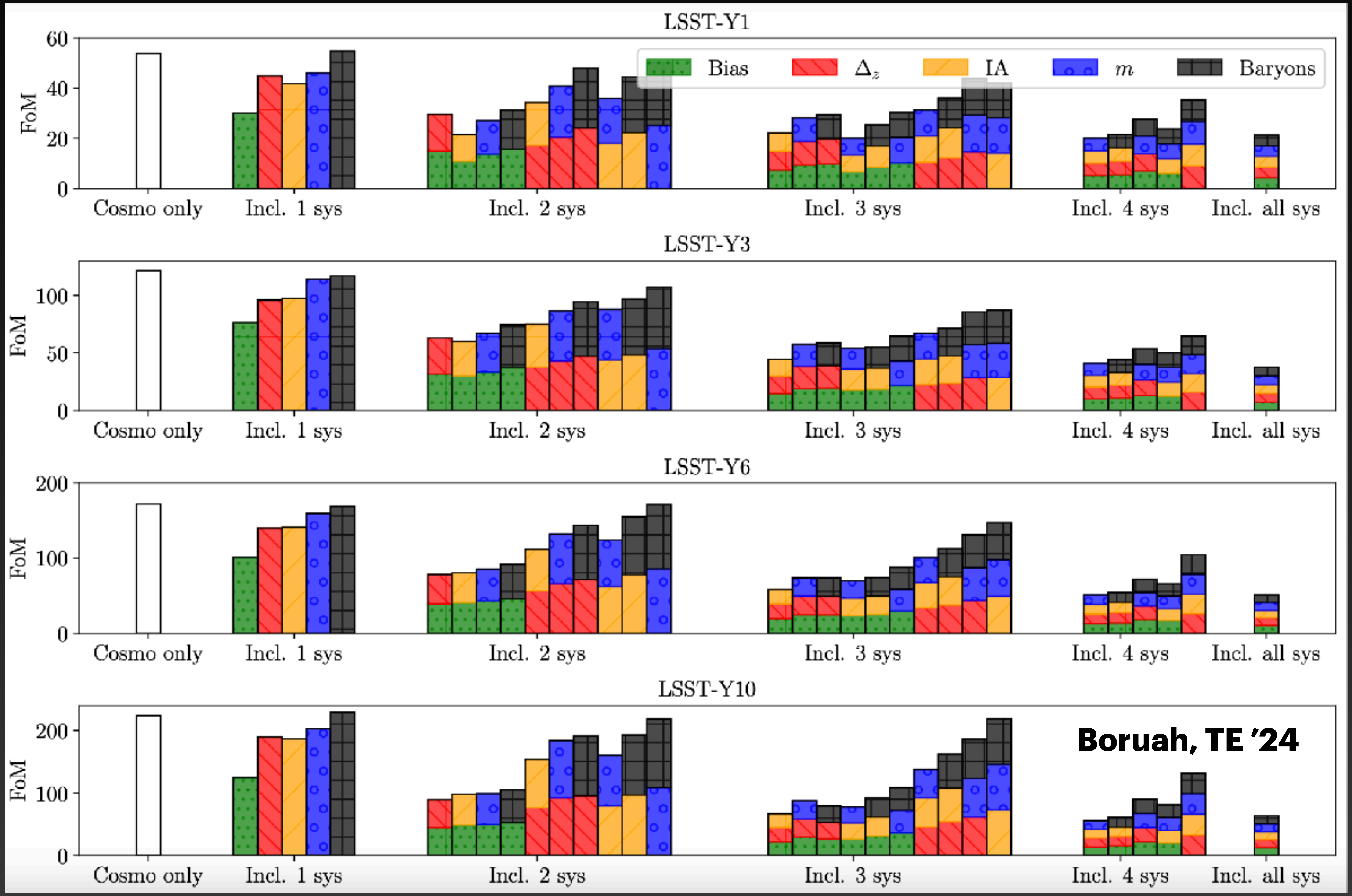


HEFT application to DES Y1 data:

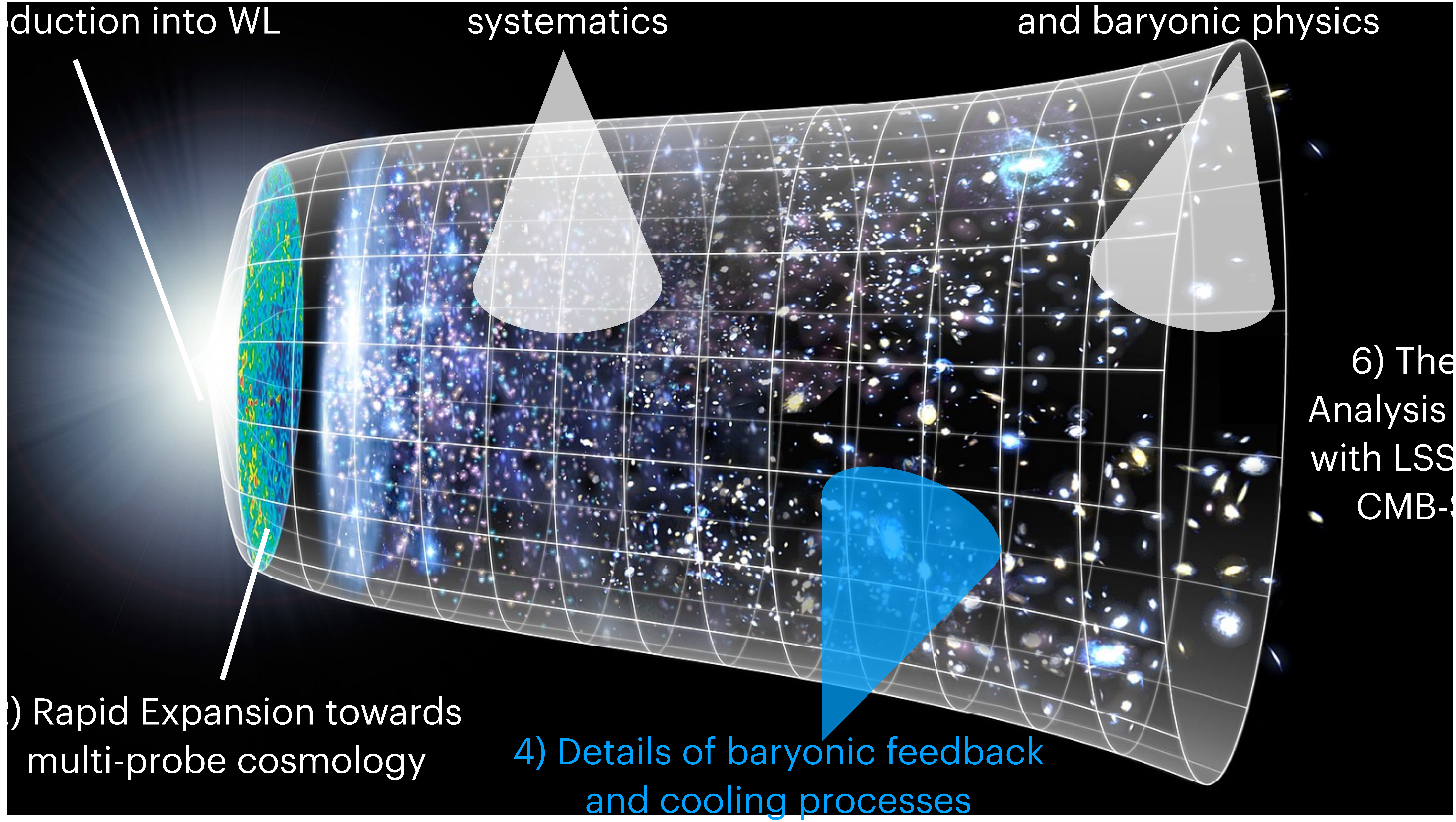
Linear approximation fails around k=0.15 Mpc^-1

Pushing to small scales yields increased constraining power

Galaxy Bias



- DESC SRD uses linear galaxy bias with scale cuts at 21 MPC/h
- Left shows the impact of different systematics on LSST Y1, Y3, Y6, Y10
- For these specific (DESC SRD) analysis settings galaxy bias is the most severe systematic affecting 3x2 LSST analyses



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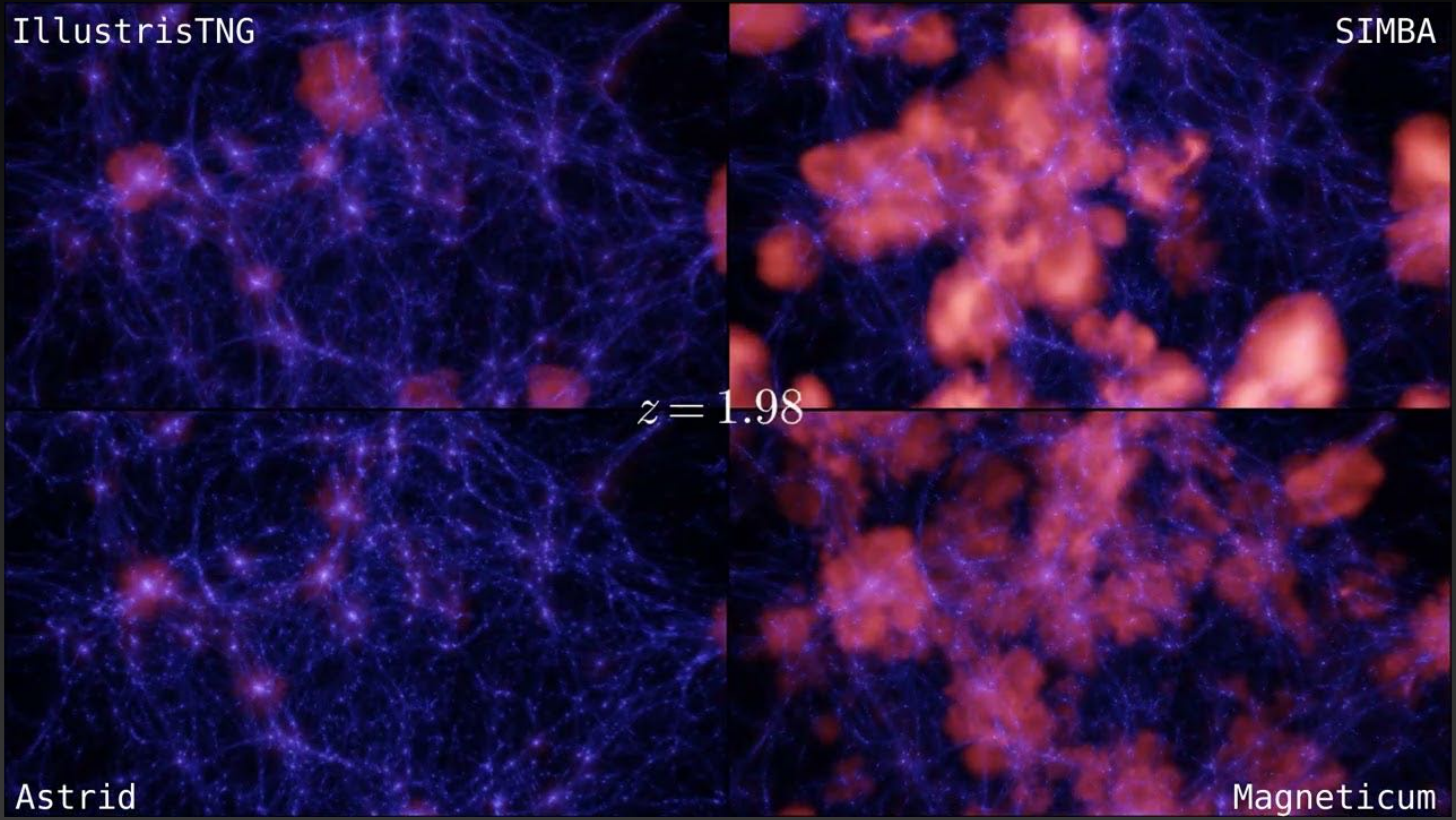
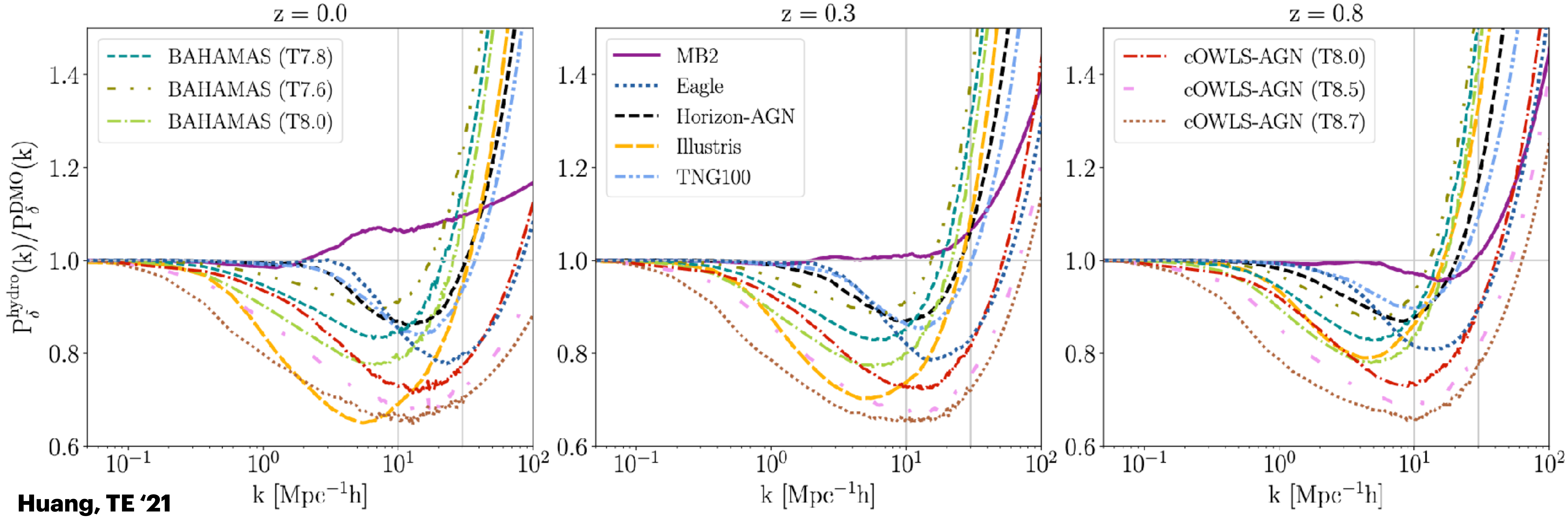
Different Feedback Scenarios

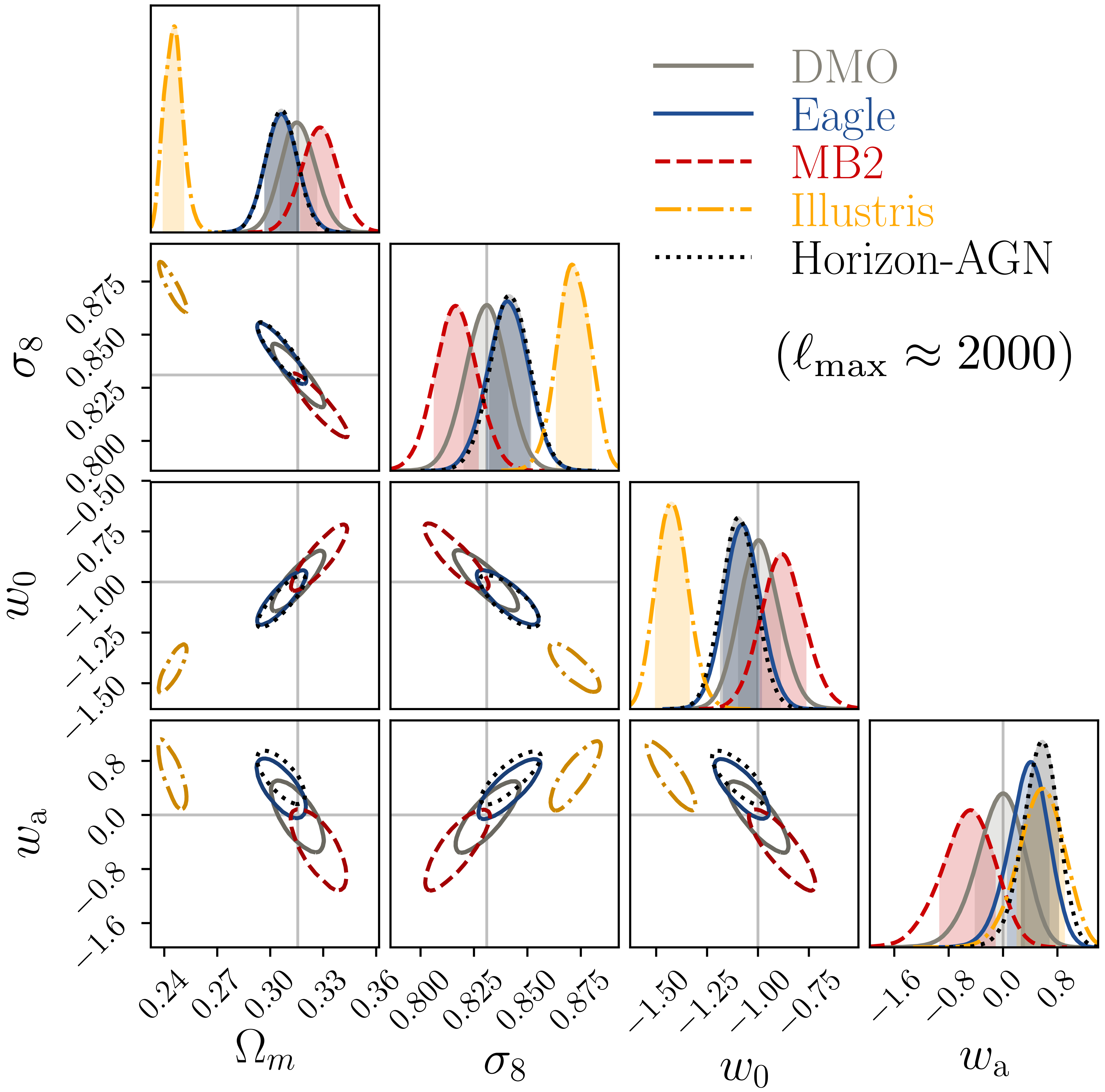


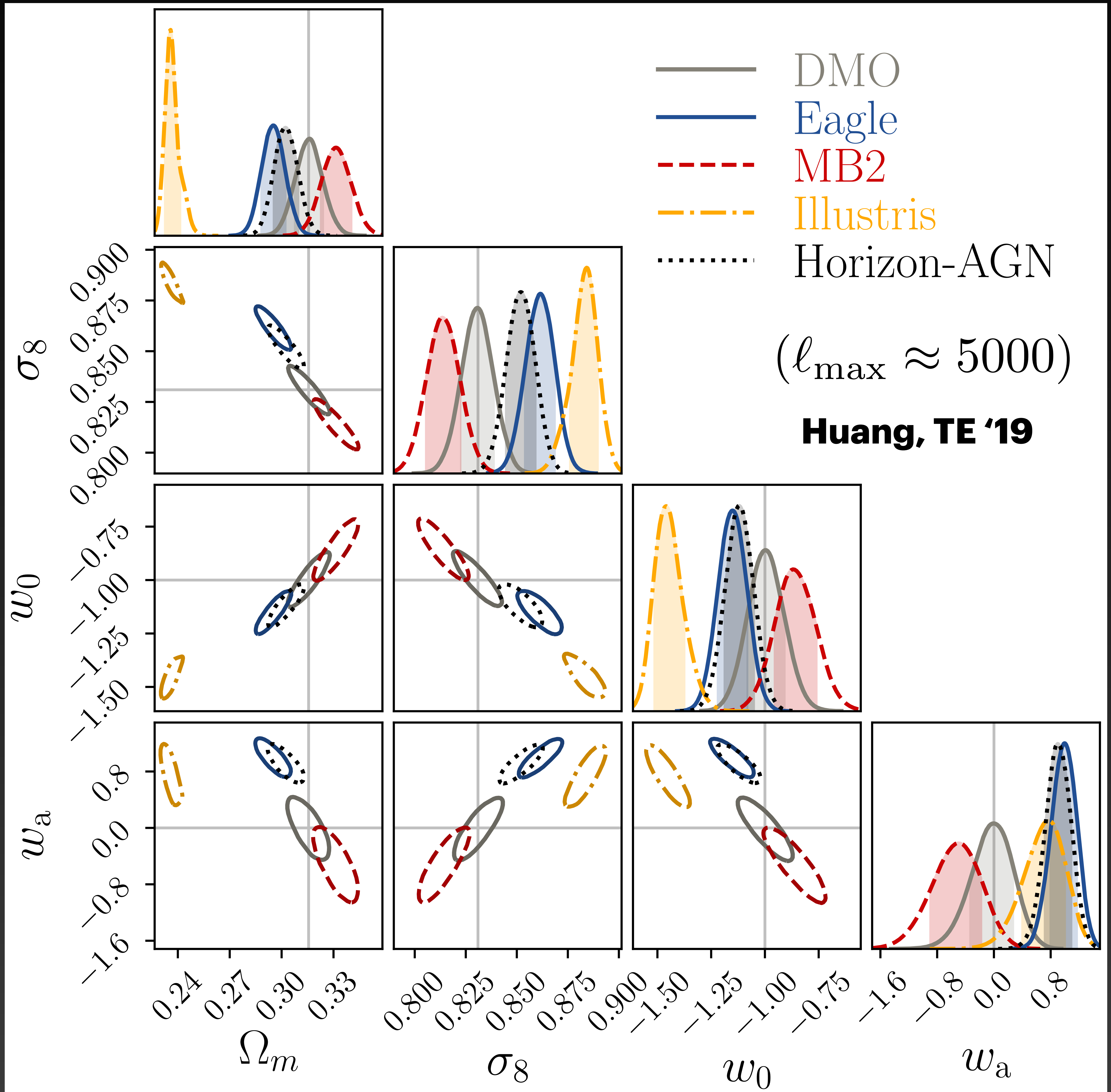
Impact on the matter power spectrum



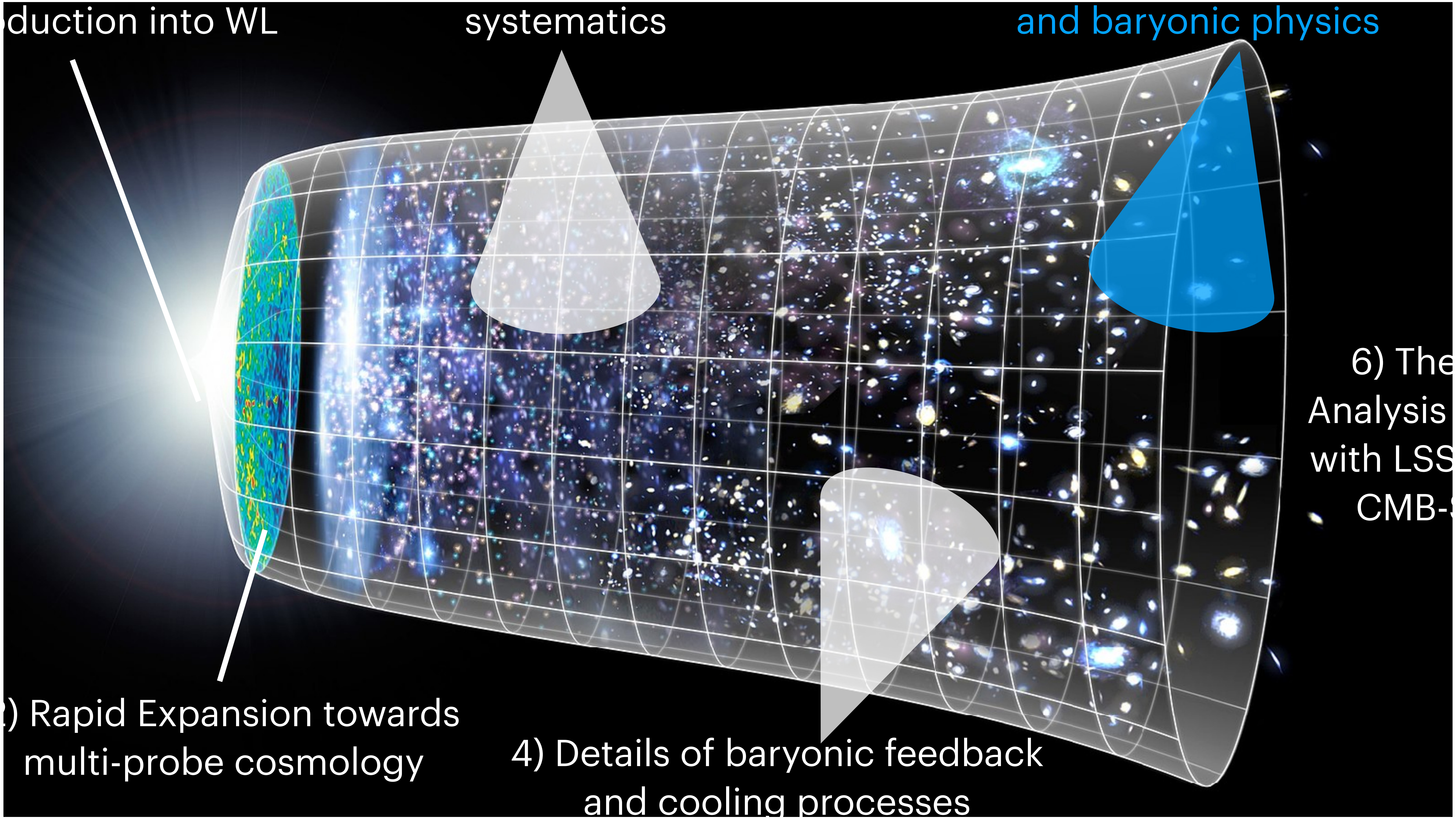
Huang, TE ‘21

Impact study: LSST Y10 simulated analysis





5) Constraints on cosmology



Age of this Talk (45 mins)

People involved

Hung-Jin Huang
PD 19-22
-> Apple Dev

Modeling baryonic physics in future weak lensing surveys

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2019

Dark Energy Survey Year 1 Results: Constraining Baryonic Physics in the Universe

Huang, TE ++ 2021

Jiachuan Xu
Grad Student

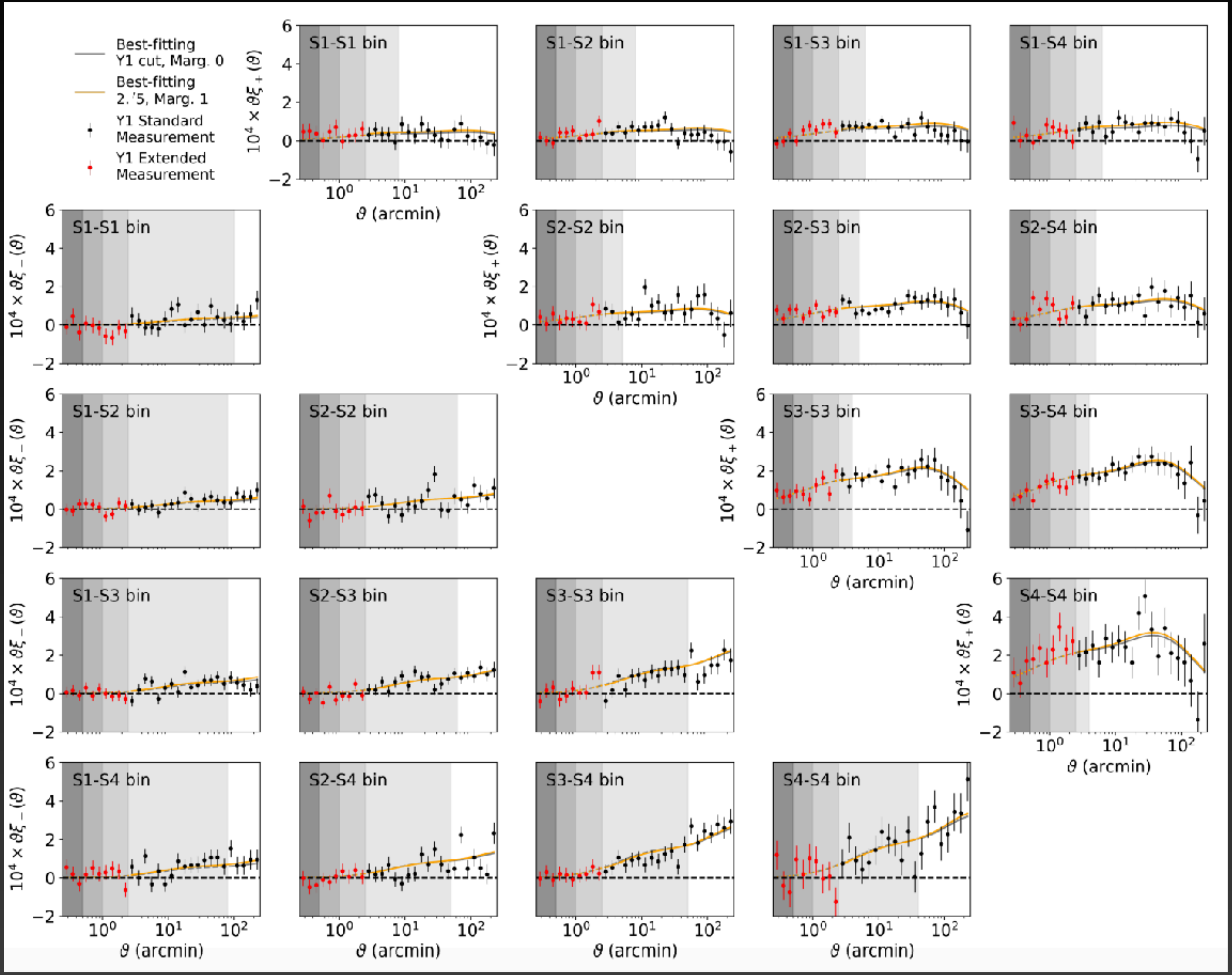
Constraining Baryonic Physics with DES Y1 and Planck data - Combining Galaxy Clustering, Weak Lensing, and CMB Lensing

Jiachuan Xu,[1] Tim Eifler,[1] Vivian Miranda,[2,3] Xiao Fang,[1,4] Evan Saraivanov,[3] Elisabeth Krause,[1,5] Hung-Jin Huang,[1] Karim Benabed,[6] and Kuniiao Ziiong[3]

2023

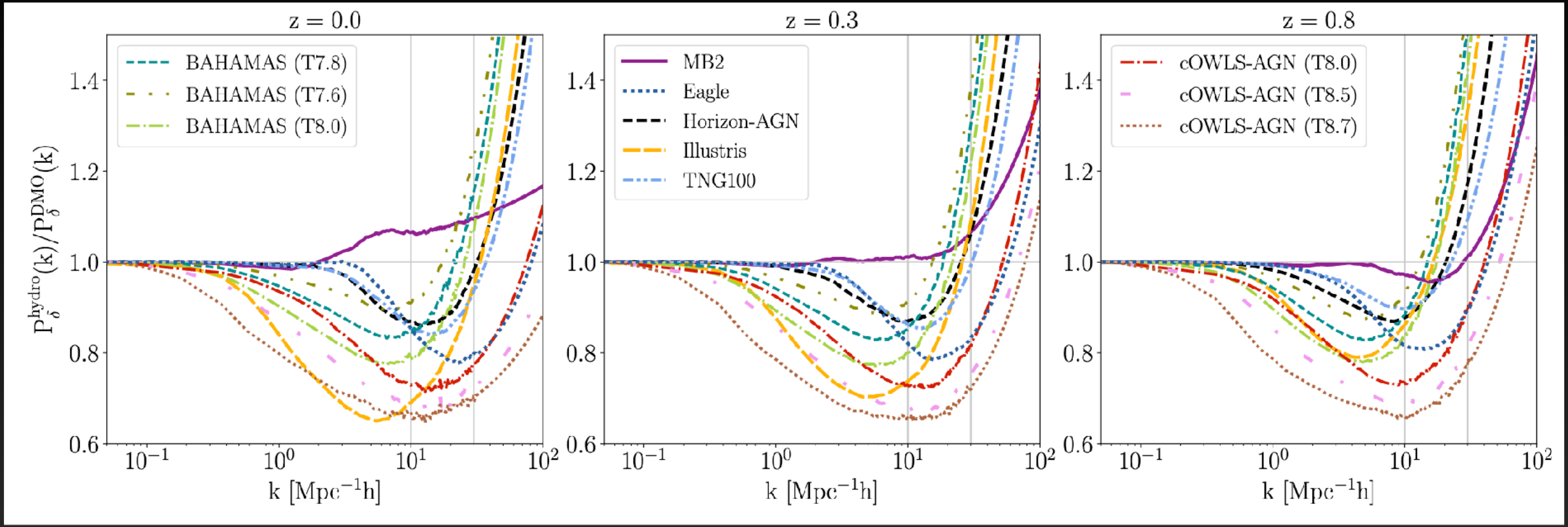
Next version with DES Y3 and Planck PR4 is coming out soon

Data Points excluded in DES Y1



- Baryonic effects severely contaminate small scale weak lensing
- All grey shaded data points were excluded from the DES Y1 analysis
- Modeling Baryons allows us to include said data points.

How do we model baryons? - Simulations



Model vector for baryonic scenario “x”

Model vector for DM scenario

Amplitude of PCs (nuisance parameter, marginalized over)

PCs containing baryonic physics (survey dependent)

$$\boldsymbol{B}_x(\boldsymbol{p}_{\rm co}) - \boldsymbol{M}(\boldsymbol{p}_{\rm co}) = \sum_{n=1}^{N} Q_n\ \mathbf{PC}_n(\boldsymbol{p}_{\rm co})$$

How do we model baryons? - Simulations

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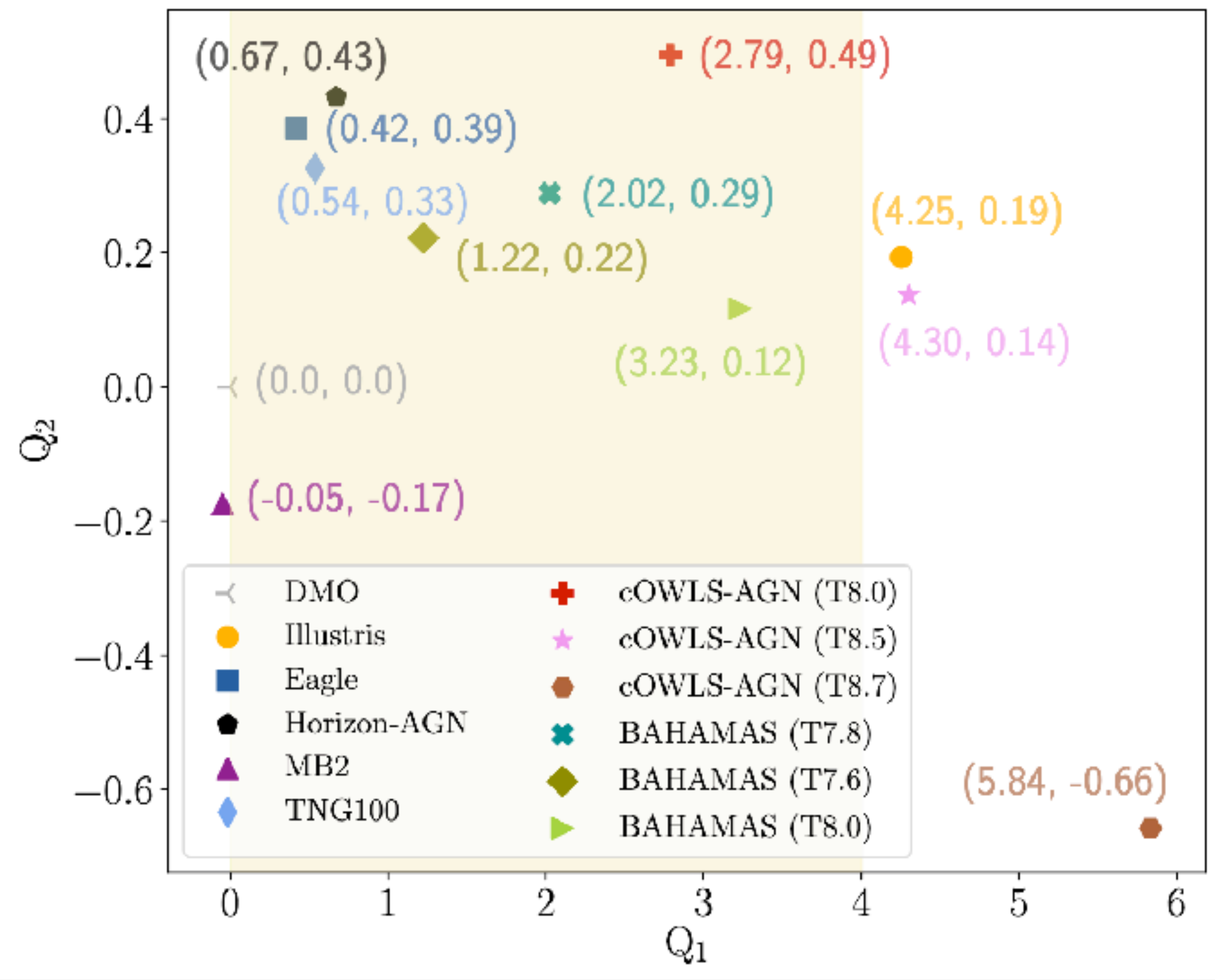
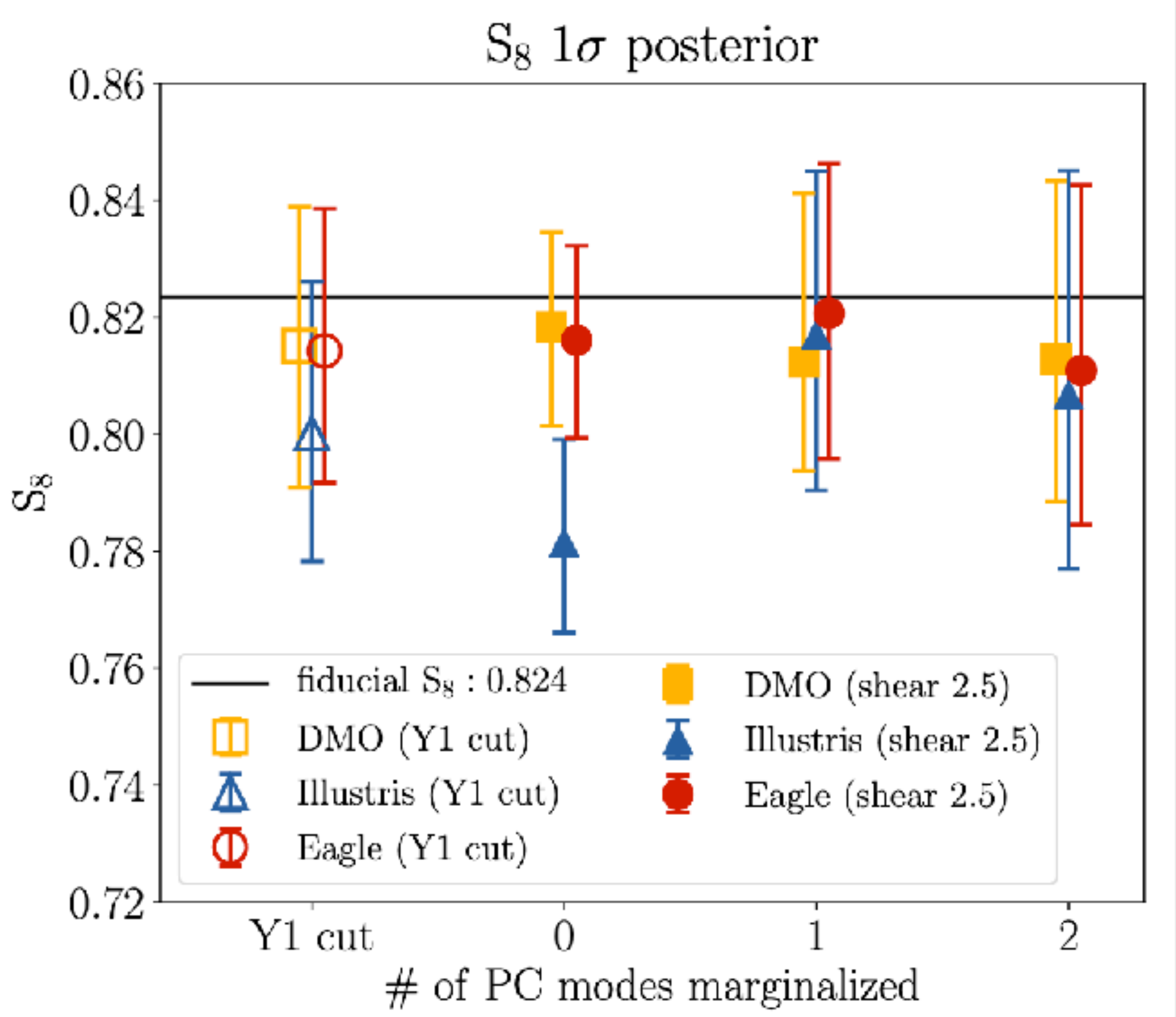


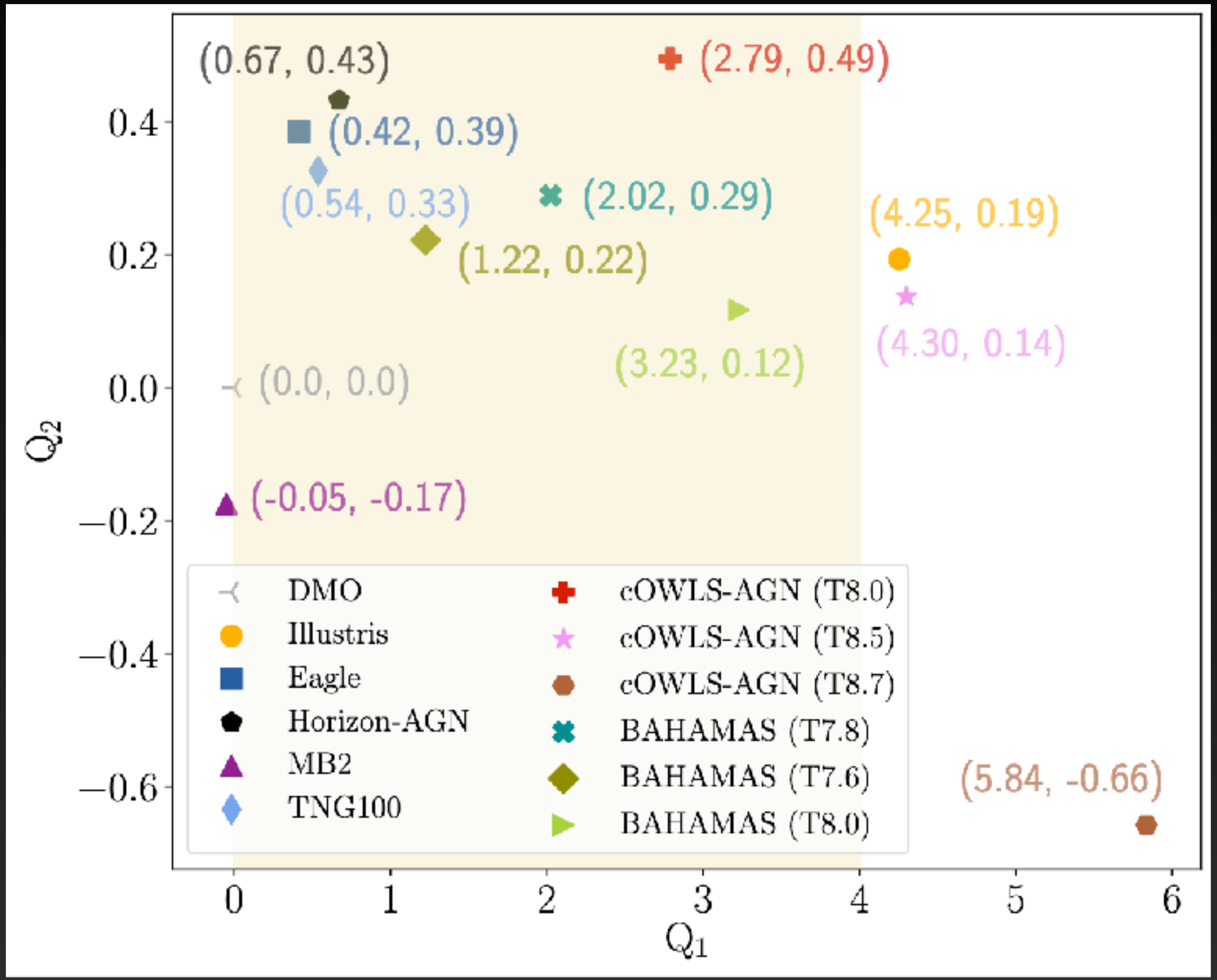


2 Games you can play now...

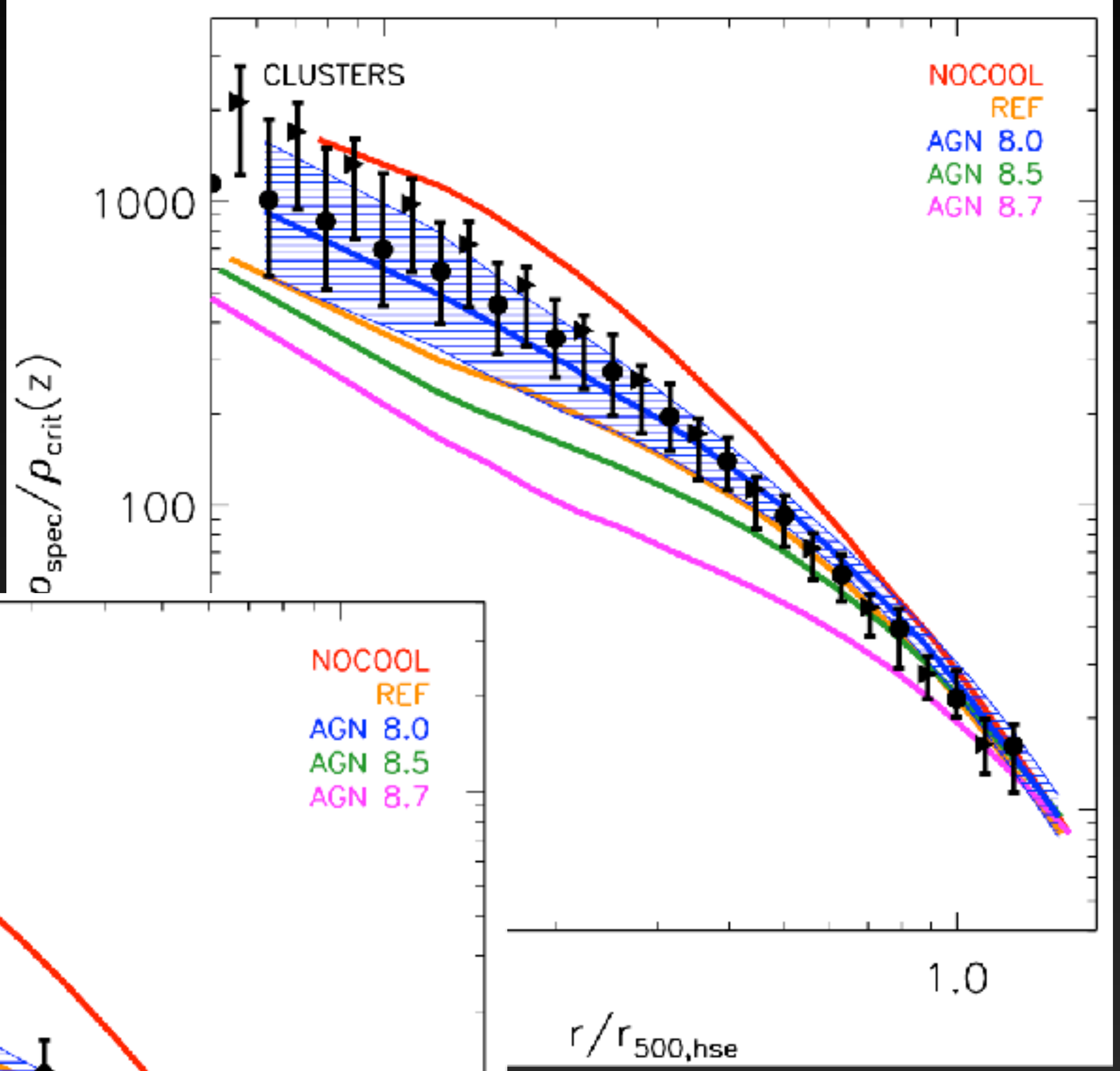
- **Game 1 - Cosmology:**
- Use info on baryonic physics info to tighten constraints on cosmology...

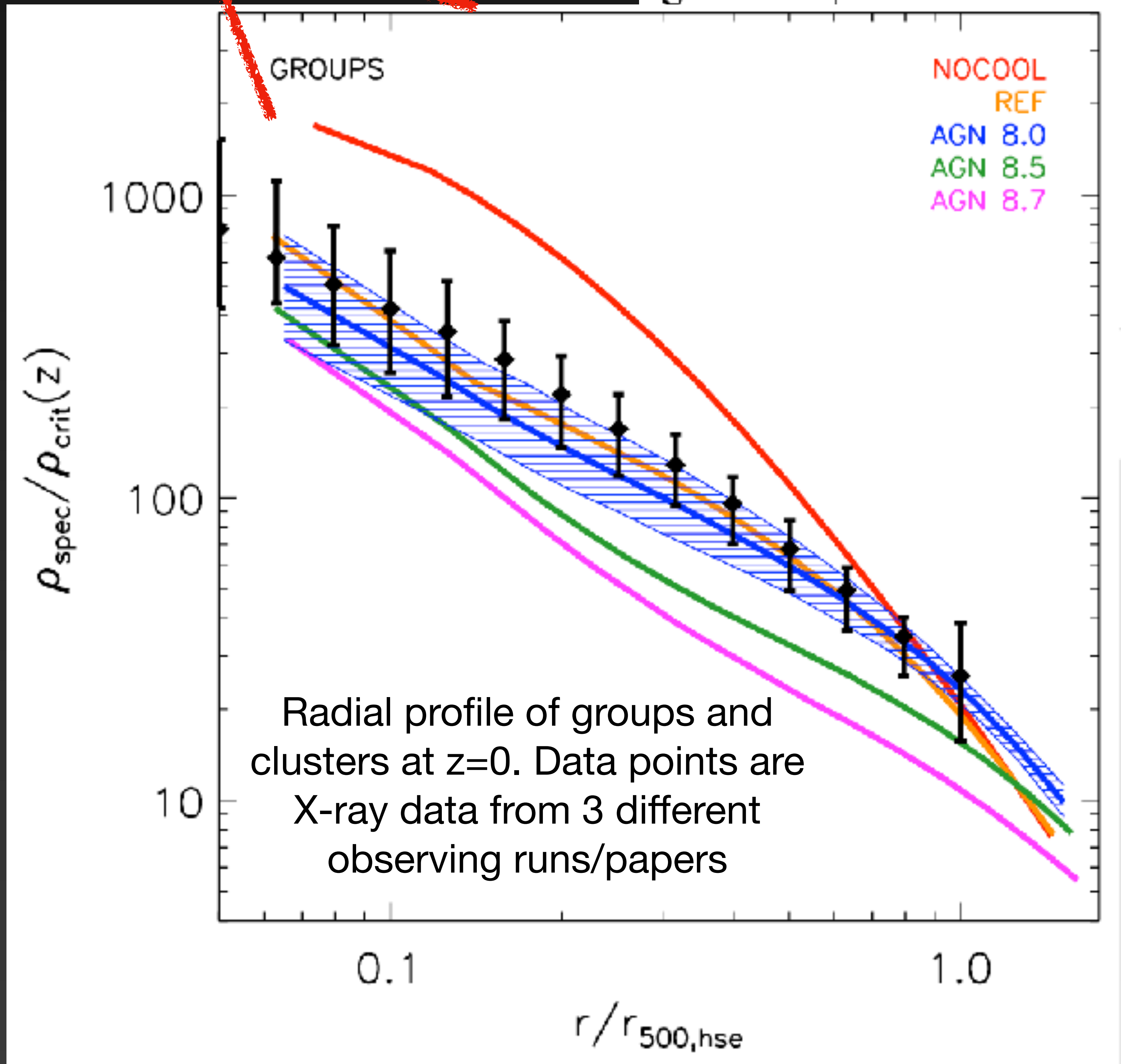
- **Game 2 - Baryons:**
  Add more information on cosmology **(consistent experiments)** to go after constraints on baryonic physics...

Game 1: Cosmology - what priors?



One of several examples for ext. constraints on baryonic scenarios



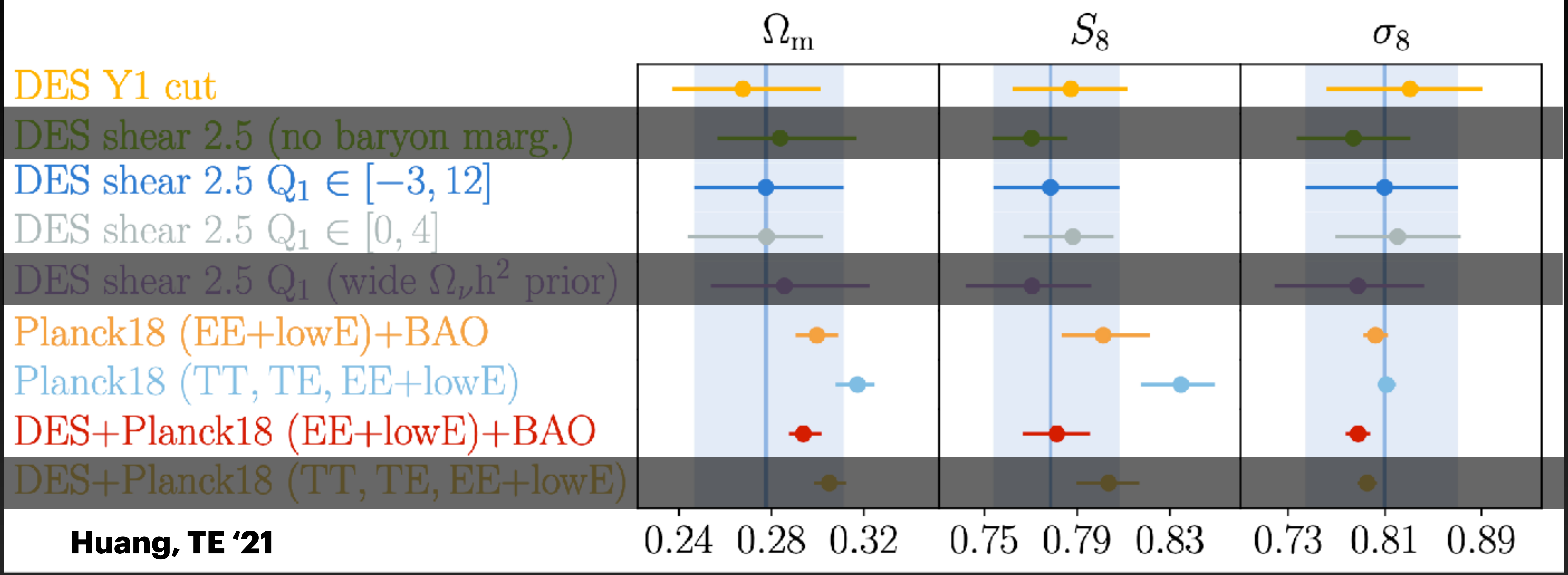


Radial profile of groups and clusters at z=0. Data points are X-ray data from 3 different observing runs/papers

Le Brun, McCarthy, Schaye, Ponman 2014

Two scenarios:
1) Q1 [-3,12] - uninformative
2) Q1 [0,4] - informative (based on X-ray, SZ, radio observations)

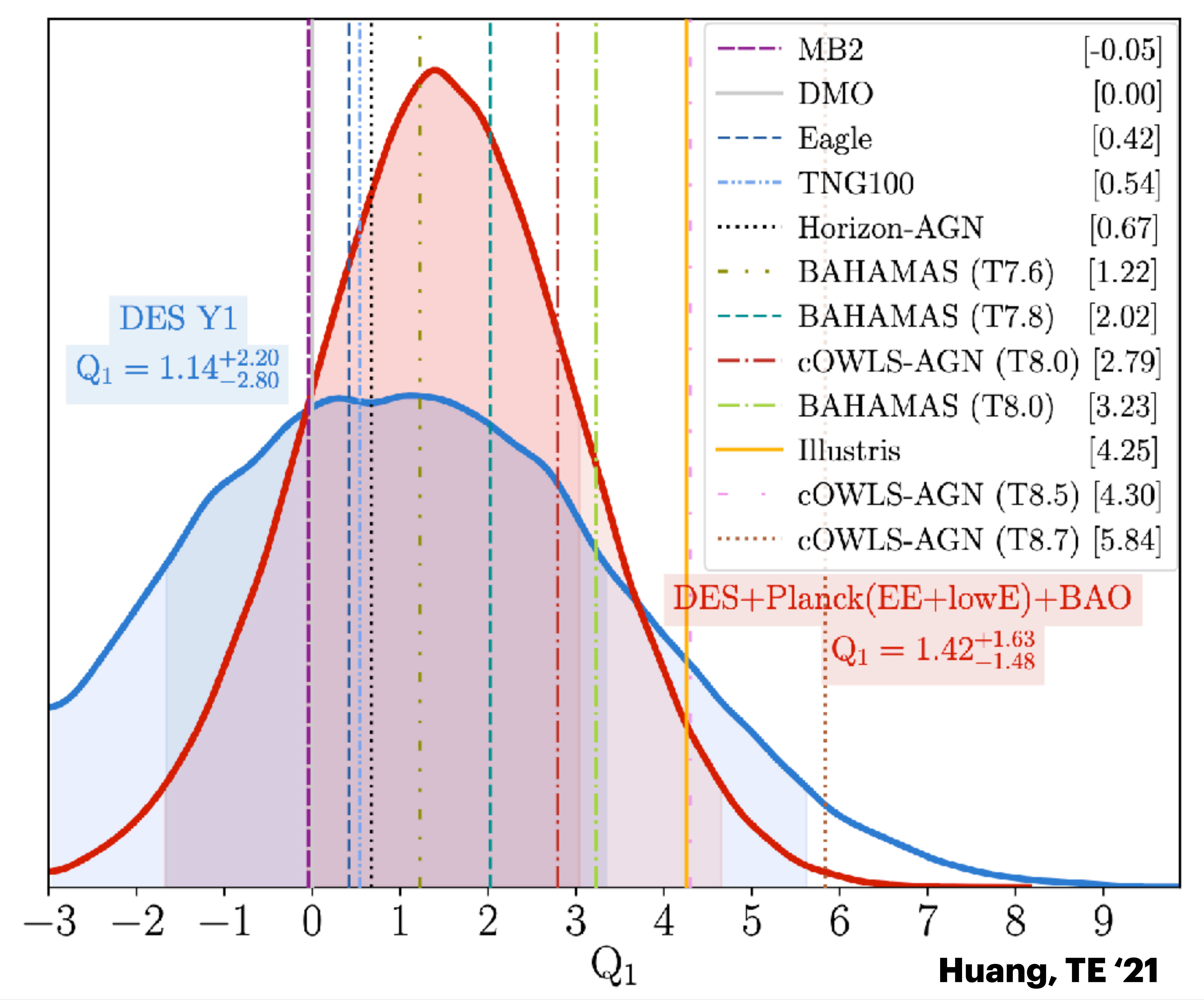
Game 1: Cosmology



DES Y1 3x2:	$0.747^{+0.027}_{-0.025}$
DES Y1 3x2(+baryons):	$0.788^{+0.018}_{-0.021}$
DES Y3 3x2:	$0.776^{+0.017}_{-0.017}$
DES Y3 shear:	$0.759^{+0.025}_{-0.023}$
KiDS 1000 shear:	$0.764^{+0.018}_{-0.017}$

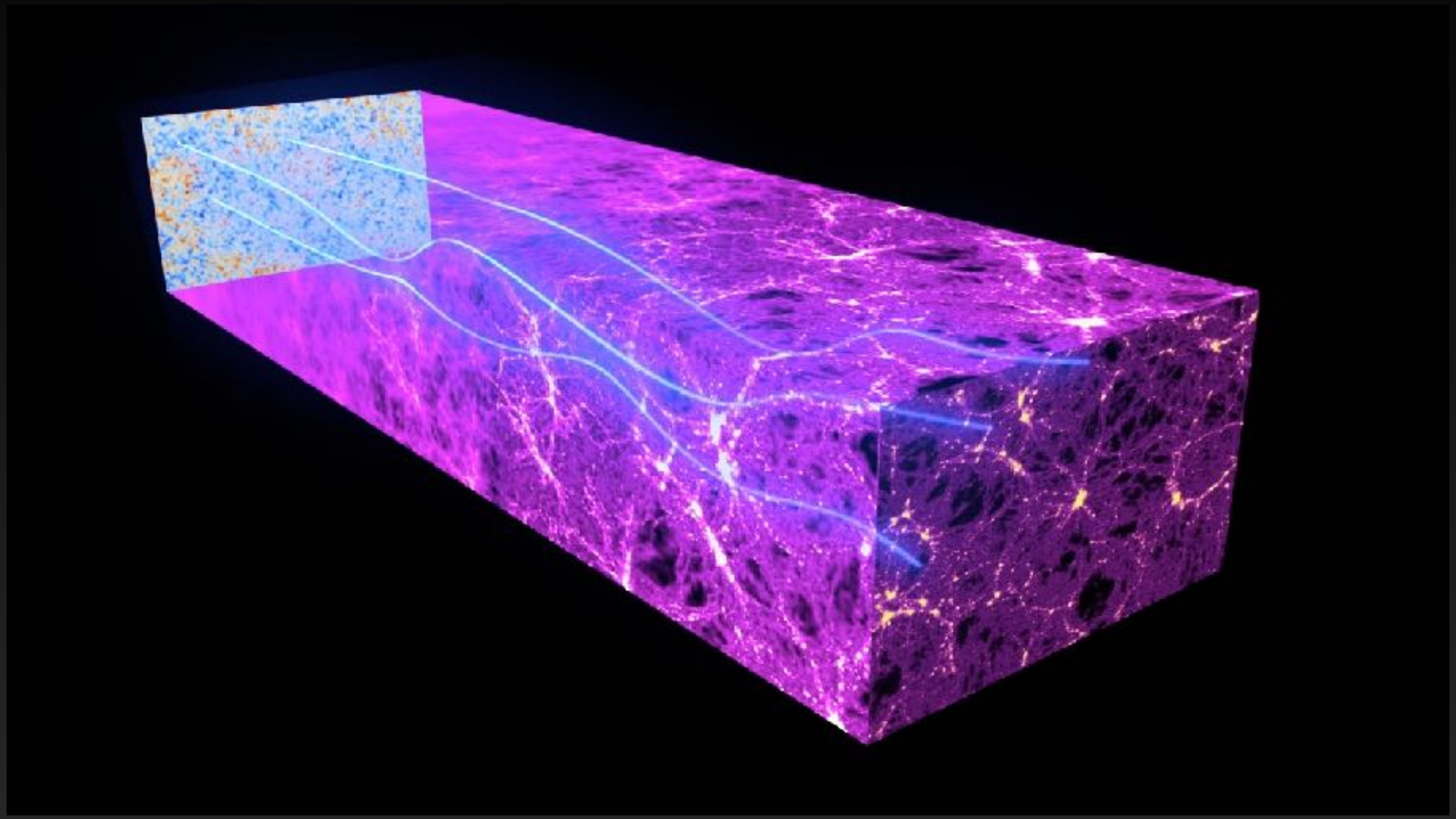
1) Inclusion of baryonic physics with conservative informative priors increases Y1 3x2 constraining power on S8 by ~20%.
2) Planck18 TT did not meet our consistency criterion -> chose Planck EE+BAO to be combined with DES for Game 2

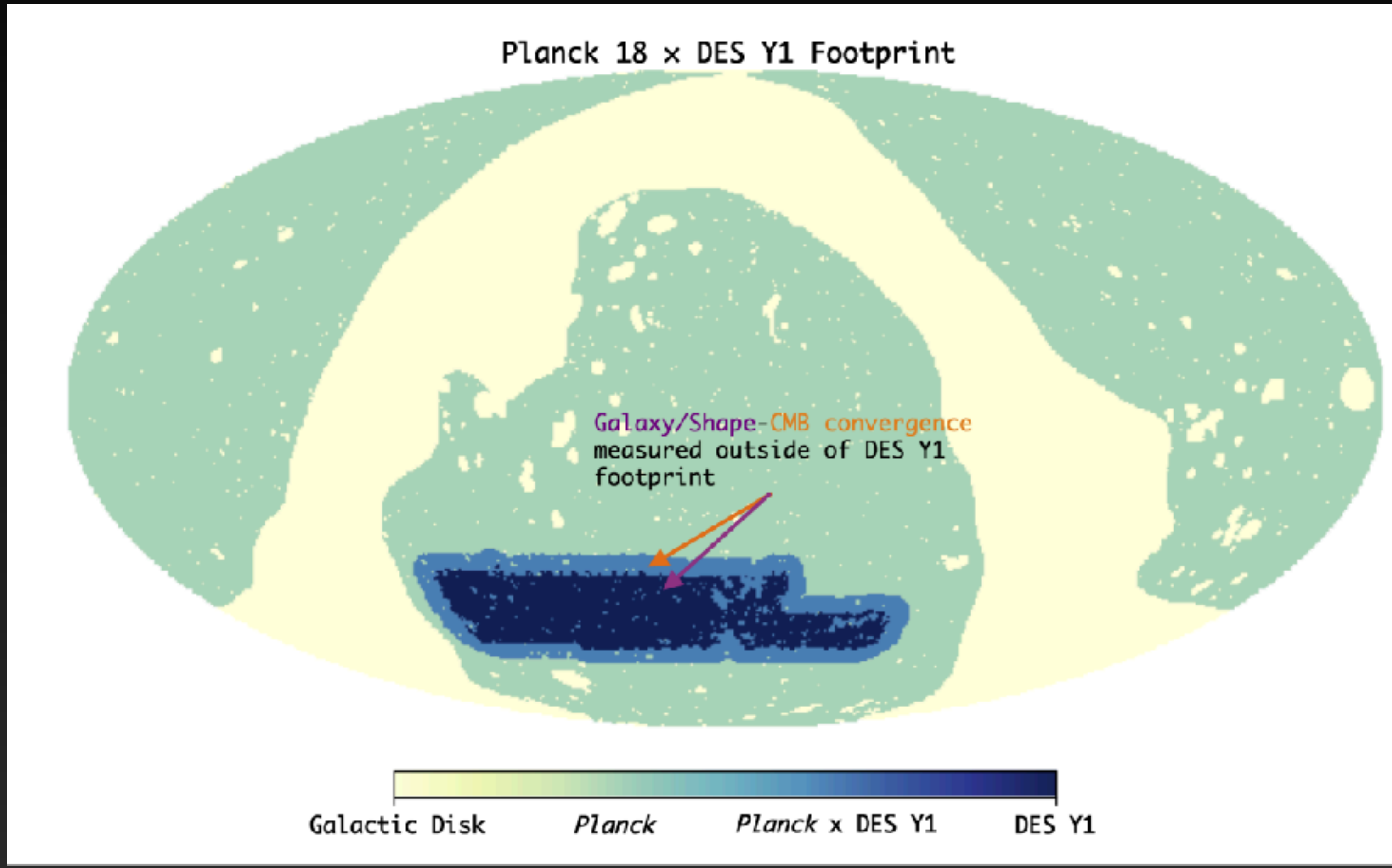
Game 2: Baryonic Physics



- DES Y1 3x2 is in tension with cOWLS T8.7 at 2.1 sigma
- Combined DESY1+ Planck EE+BAO rules out cOWLS T8.7 at 2.8 sigma
- Disclaimer: Precise sigma statements are of course rely on analysis choices
- More data and more sims needed and are underway

Now let's add CMB Lensing - Xu+ 23





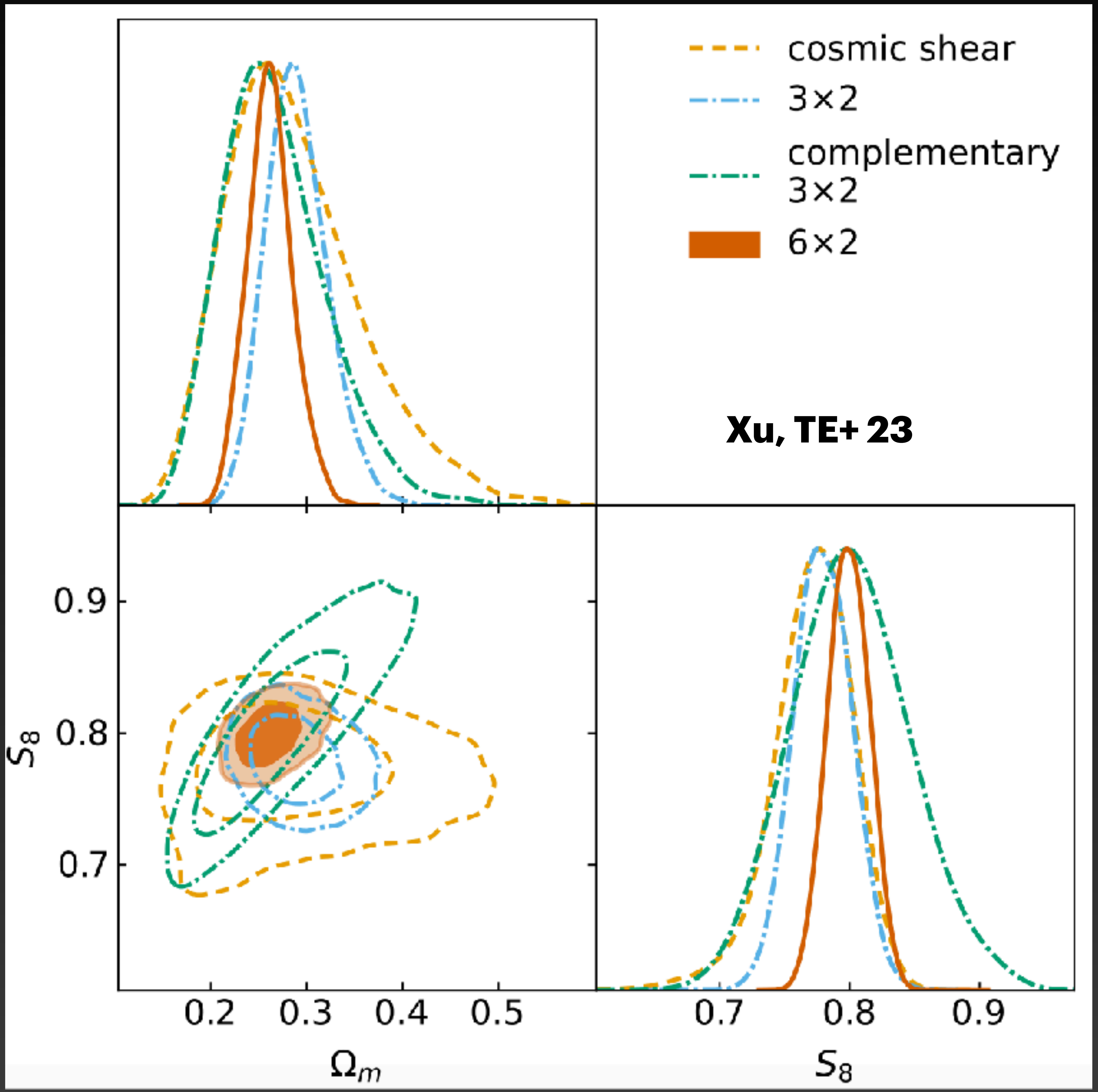
light deflected by tidal field of large-scale structure

- remapping of (primary) CMB anisotropies

CMB lensing affected by different systematics than galaxy shear estimates

- Adding CMB Lensing adds a 3rd field to the mix
- Now 6 2pt-functions, hence 6x2 analysis
- We use DES Y1 and Planck for our measurement
- Fully analytic non-Gaussian covariance that can model 3 different footprints for the different probes.

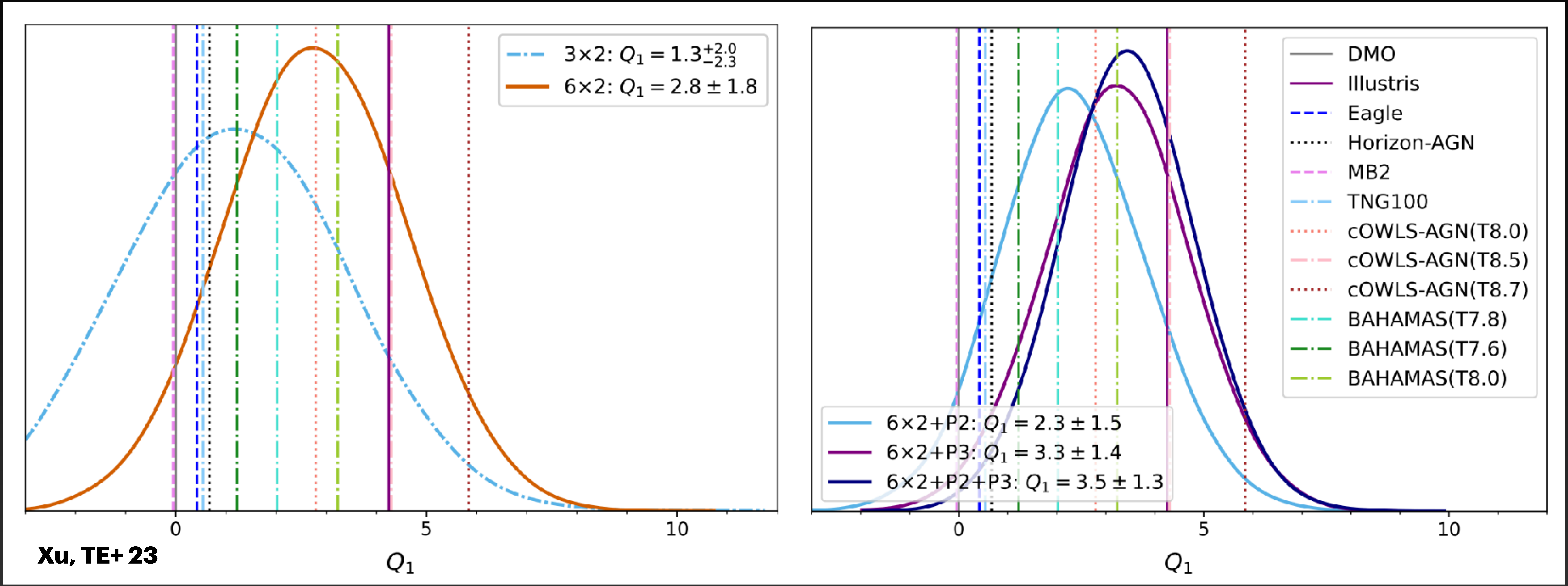
6x2 DES Y1 + PR3 cosmology results



Probes	S_8 1D Marg.	S_8 MAP	Ω_m 1D Marg.	Ω_m MAP
cosmic shear	$0.771^{+0.034}_{-0.025}$	0.797	$0.288^{+0.048}_{-0.084}$	0.301
3×2	0.779 ± 0.022	0.792	$0.290^{+0.028}_{-0.036}$	0.287
c3×2	0.801 ± 0.045	0.808	$0.267^{+0.041}_{-0.063}$	0.252
6×2	0.799 ± 0.016	0.804	$0.262^{+0.022}_{-0.025}$	0.254
6×2 + P2:BAO+BBN+SNe Ia	0.805 ± 0.016	0.805	0.288 ± 0.012	0.297
6×2 + P3:Planck EE+lowE	0.813 ± 0.014	0.814	0.3009 ± 0.0090	0.3008
6×2 + P2 + P3	0.817 ± 0.011	0.825	0.3067 ± 0.0059	0.3080

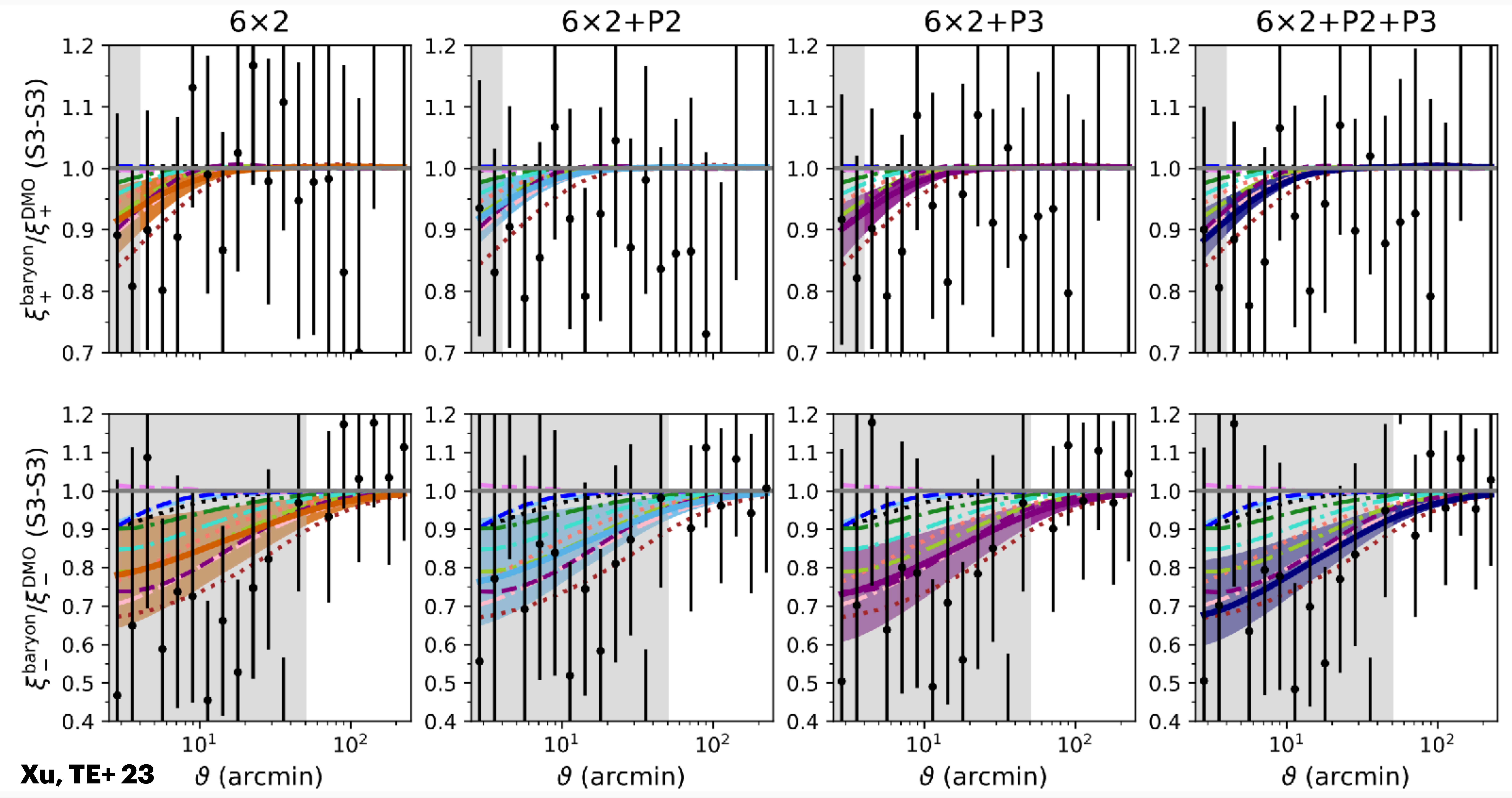
- CMB Lensing auto and cross-probes are highly complementary to 3x2
- Our 6x2 Planck+DES Y1 is more constraining than 3x2 DES Y3
- Did not combine with Planck TT since tension is too large

6x2 DES Y1+PR3 baryon physics results



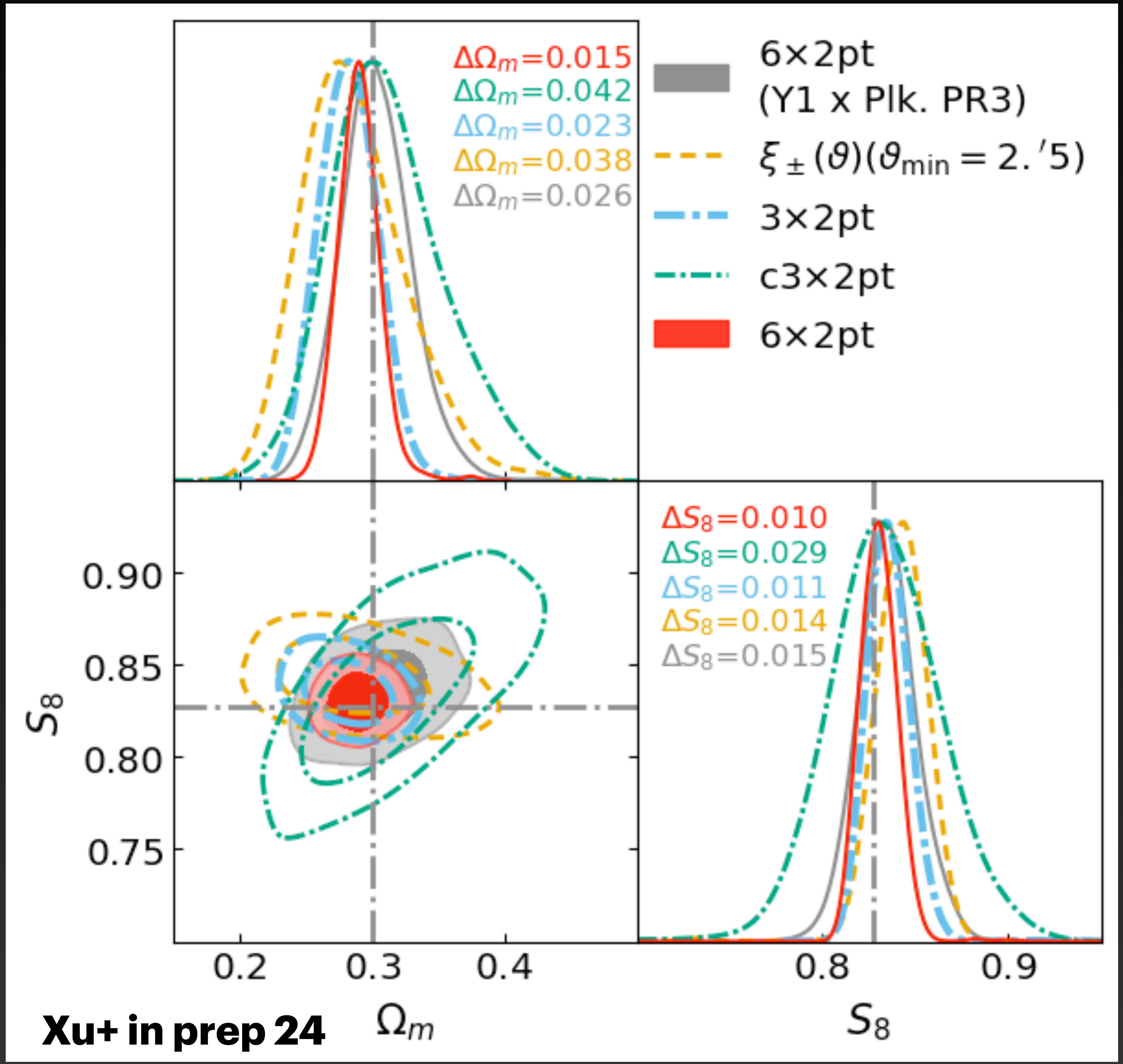
- 6x2 prefers higher feedback compared to 3x2 (Bahamas T8.0 or cOWLS T8.0 compared to Bahamas T7.6)
- Combination with priors P2, P3 tighten constraints, clear detection of baryonic physics but wide range of feedback strengths possible -> more data, stay tuned
- To fit Planck discrepancy you need feedback stronger than cOWLS T8.7

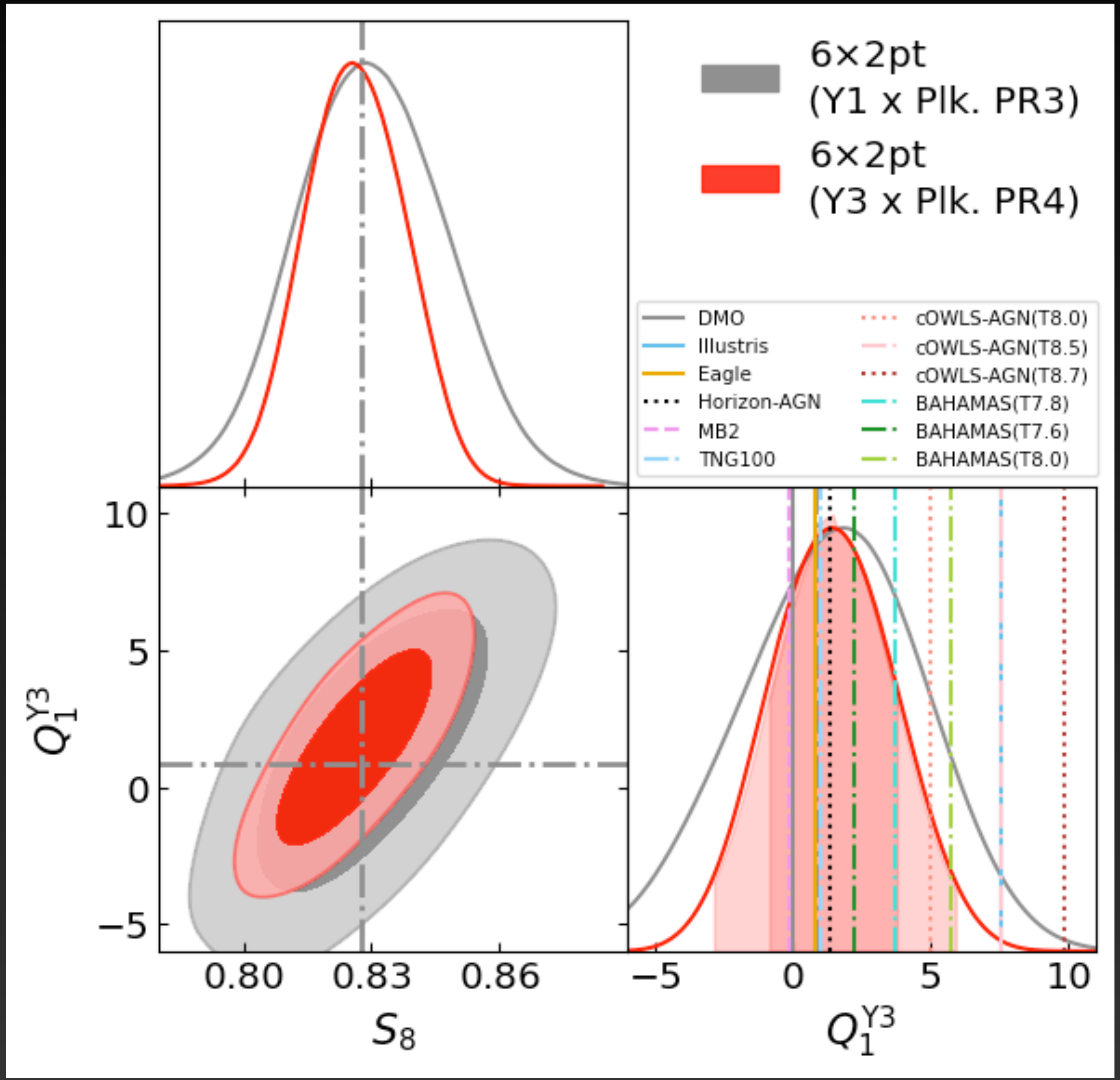
6x2 DES Y1+PR3 baryon physics results



Xu, TE+ 23

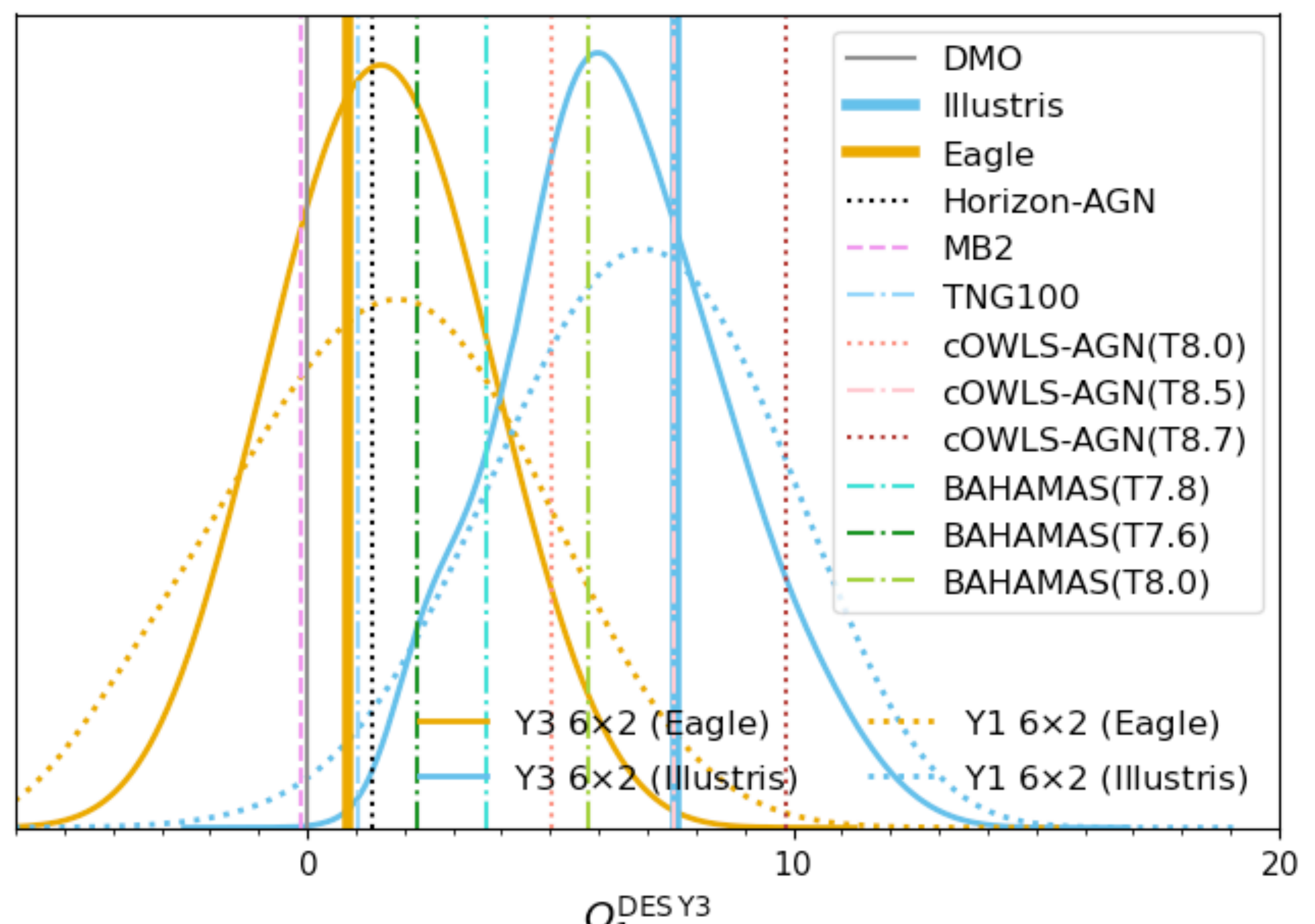
Preview: DES Y3 x PR4 (simulated)





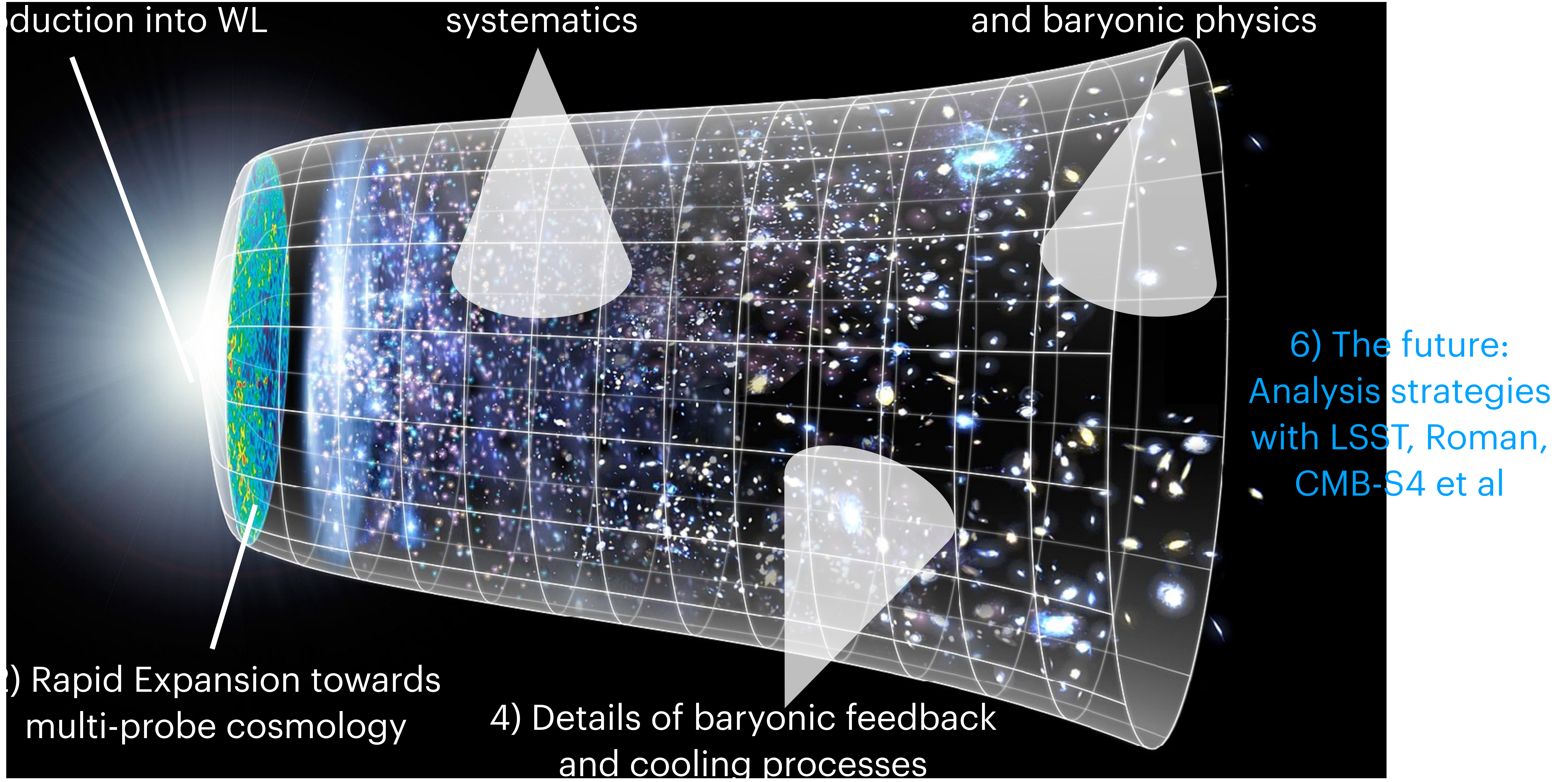
- DES Y3 + PR4 shows a significant boost in constraining power - exciting!
- May translate into 3+ sigma tension with strongest AGN feedback models in sims

Preview: DES Y3 x PR4 (simulated)



Xu+ in prep 24

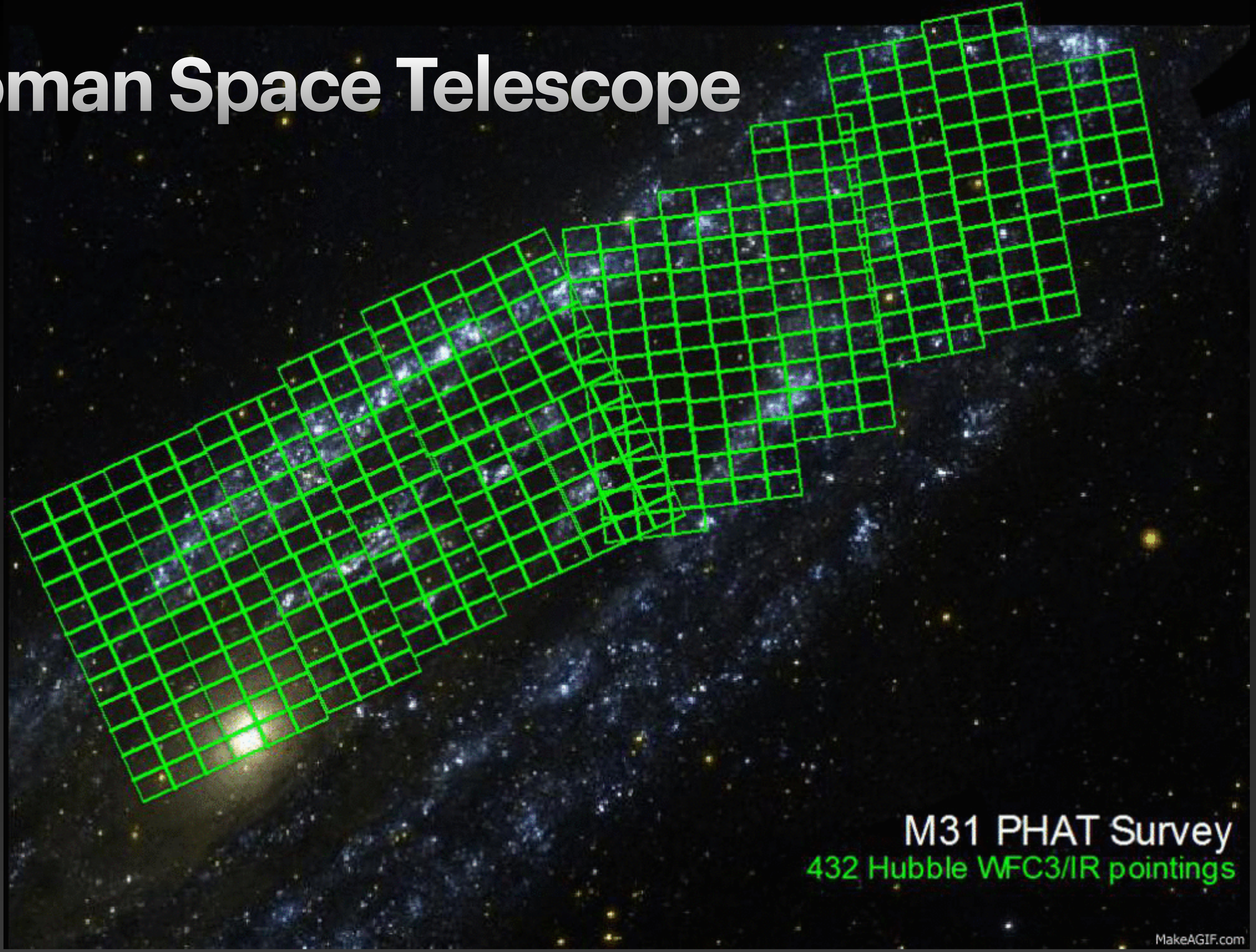
- Comparison between DES Y3 + PR3 and DES Y3 + PR4 analysis
- Data vectors are contaminated with two different scenarios (Illustrious and Eagle)



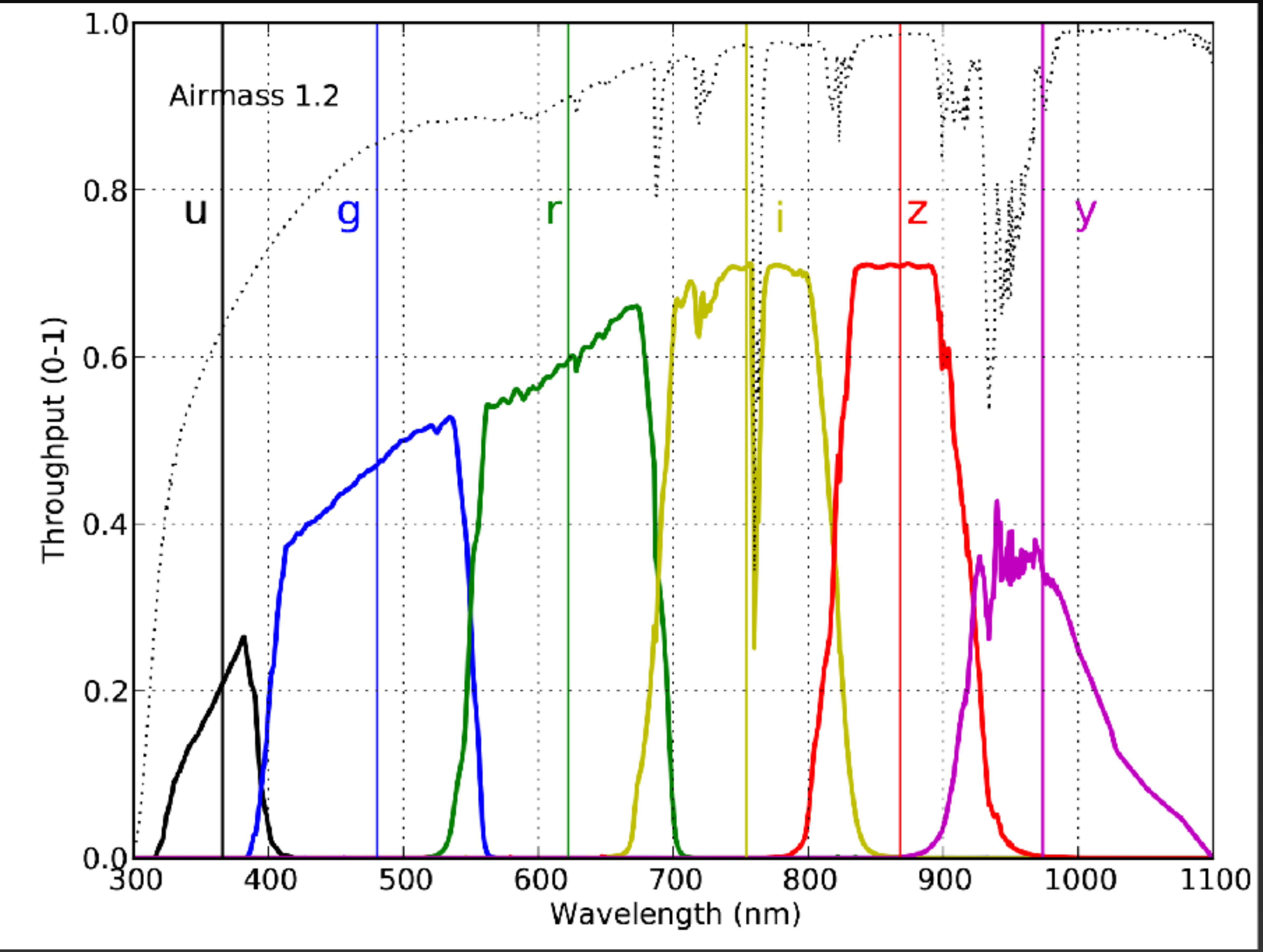
Age of this Talk (45 mins)

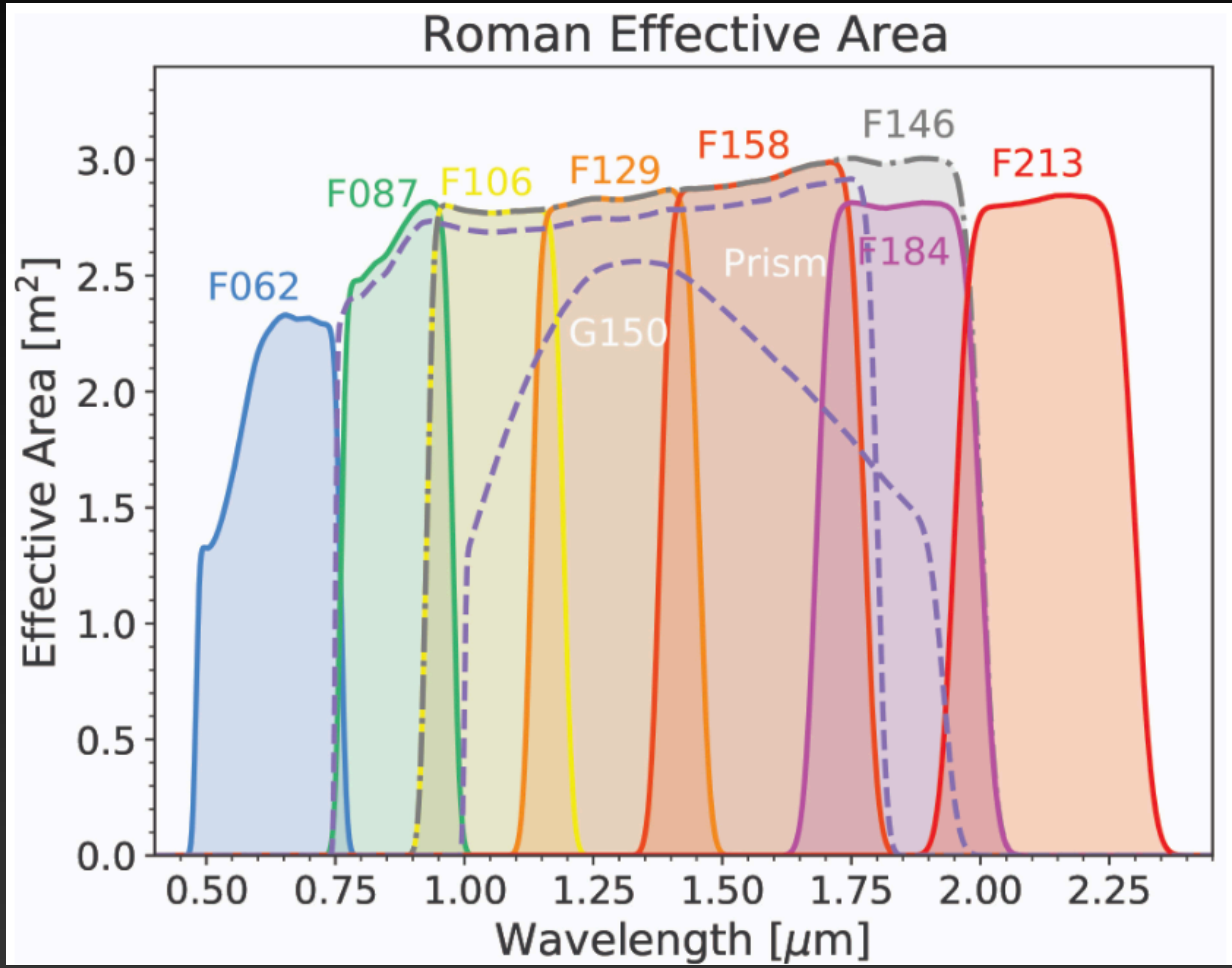
Roman Space Telescope

- Roman has a 0.3 square deg wide FoV
- Survey will overlap with LSST
- Wide area survey in the reference design is 2000 deg^2 only...
- For multi-probe synergies going wider would overlap more with CMB surveys
- Idea of a wide survey with 1 Roman band is being discussed



Roman Rubin Synergies





Looking into the future...adding CMB
Why stop at 6x2?
There's kSZ, tSZ... so many fields to add

Cosmology from weak lensing, galaxy clustering, CMB lensing and tSZ: I. 10×2pt Modelling Methodology

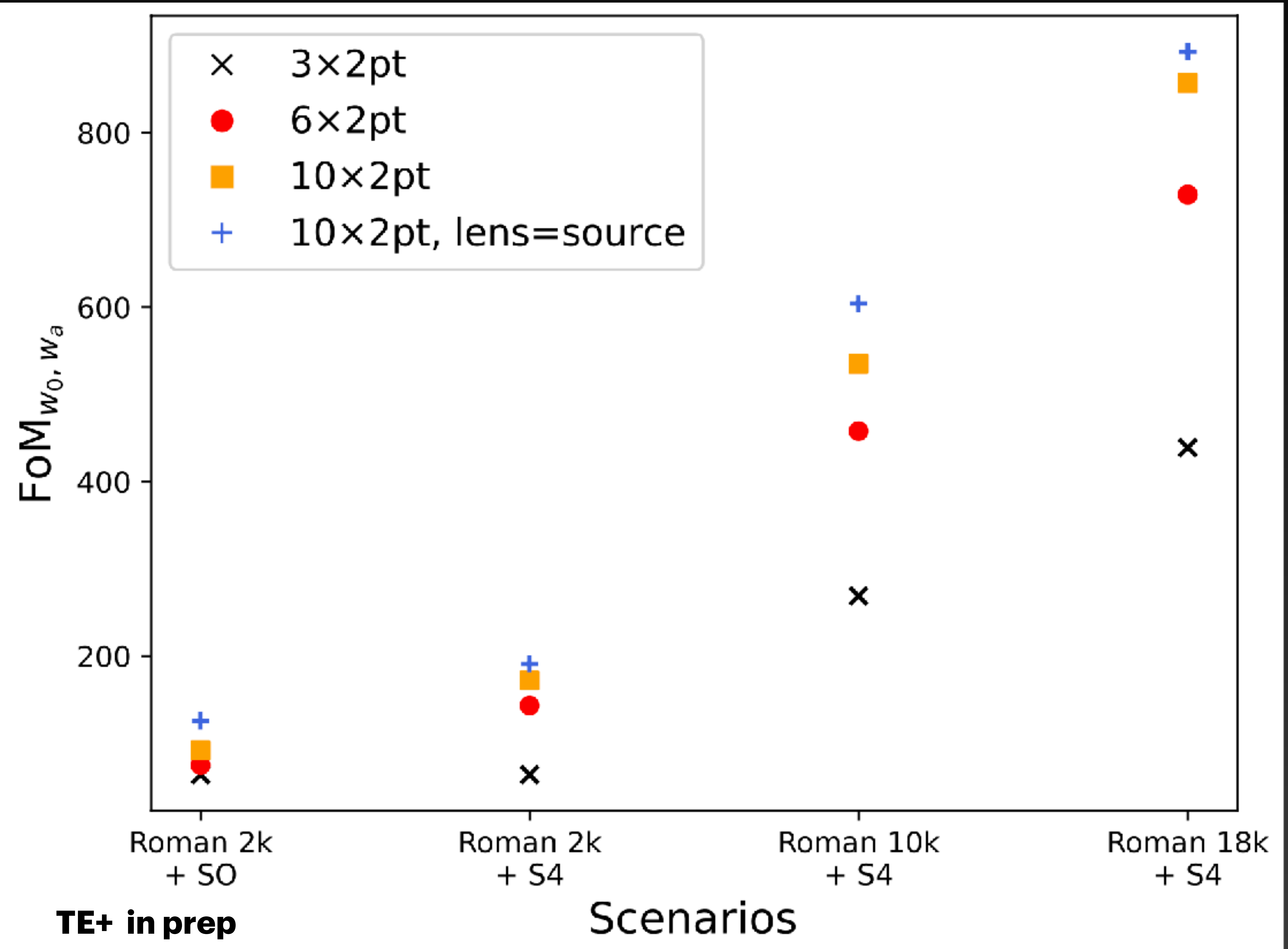
Xiao Fang★,[1,2] Elisabeth Krause,[2,3] Tim Eifler,[2] Simone Ferraro,[4,1] Karim Benabed,[5] Pranjal R. S.,[2] Emma Ayçoberry,[5] Yohan Dubois,[5] & Vivian Miranda[6]

Cosmology from weak lensing, galaxy clustering, CMB lensing and tSZ: II. Optimizing Roman survey design for CMB cross-correlation science

Tim Eifler★[1,2], Xiao Fang[1,3], Elisabeth Krause[1,2], Christopher M. Hirata[4,5,6], Karim Benabed[7], Simone Ferraro[8,3], Vivian Miranda[9], Pranjal R. S.[1], Emma Ayçoberry[7], Yohan Dubois[7]

In prep... delayed, my fault...

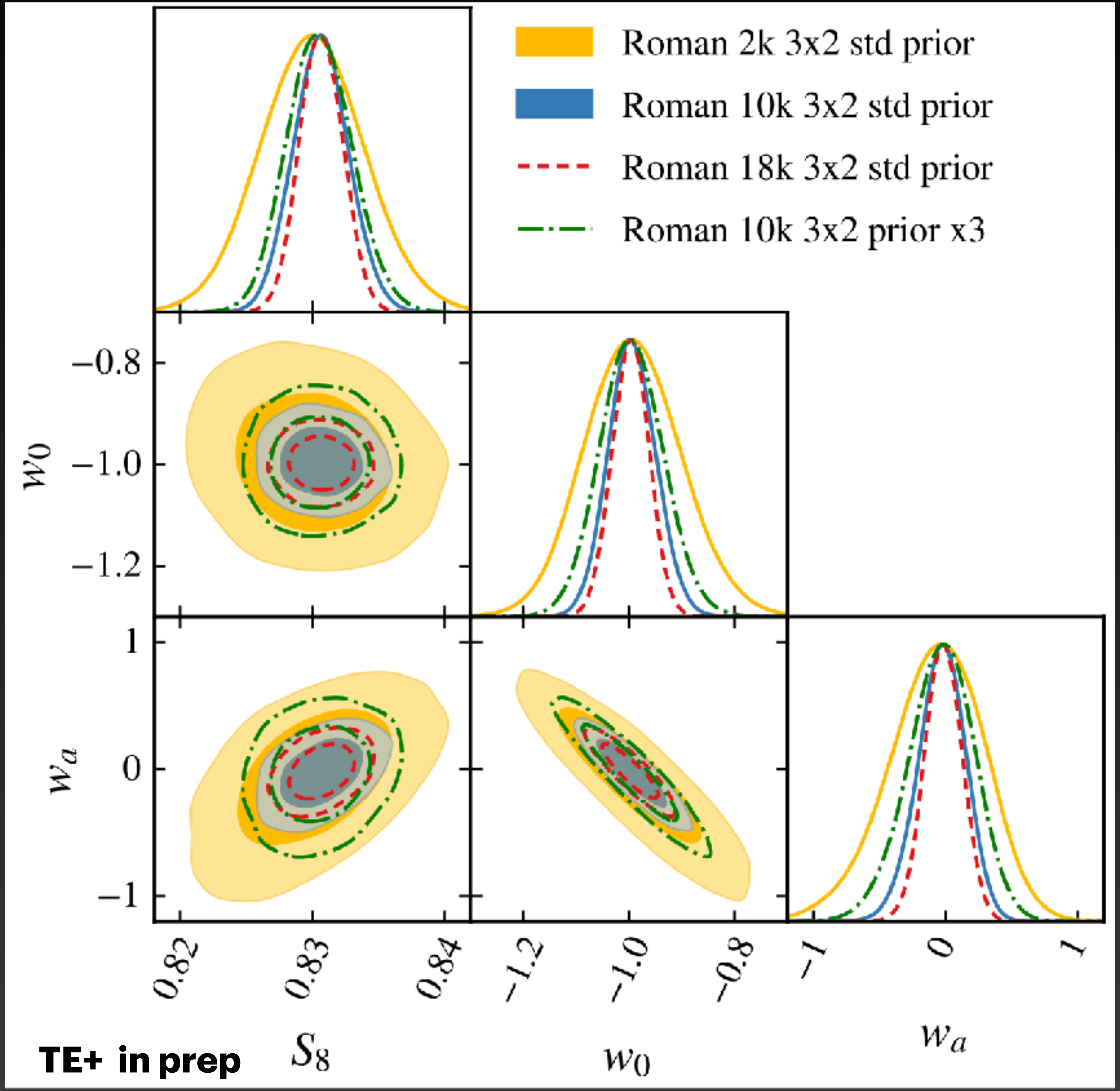
10x2 analysis Roman + CMB-S4



TE+ in prep

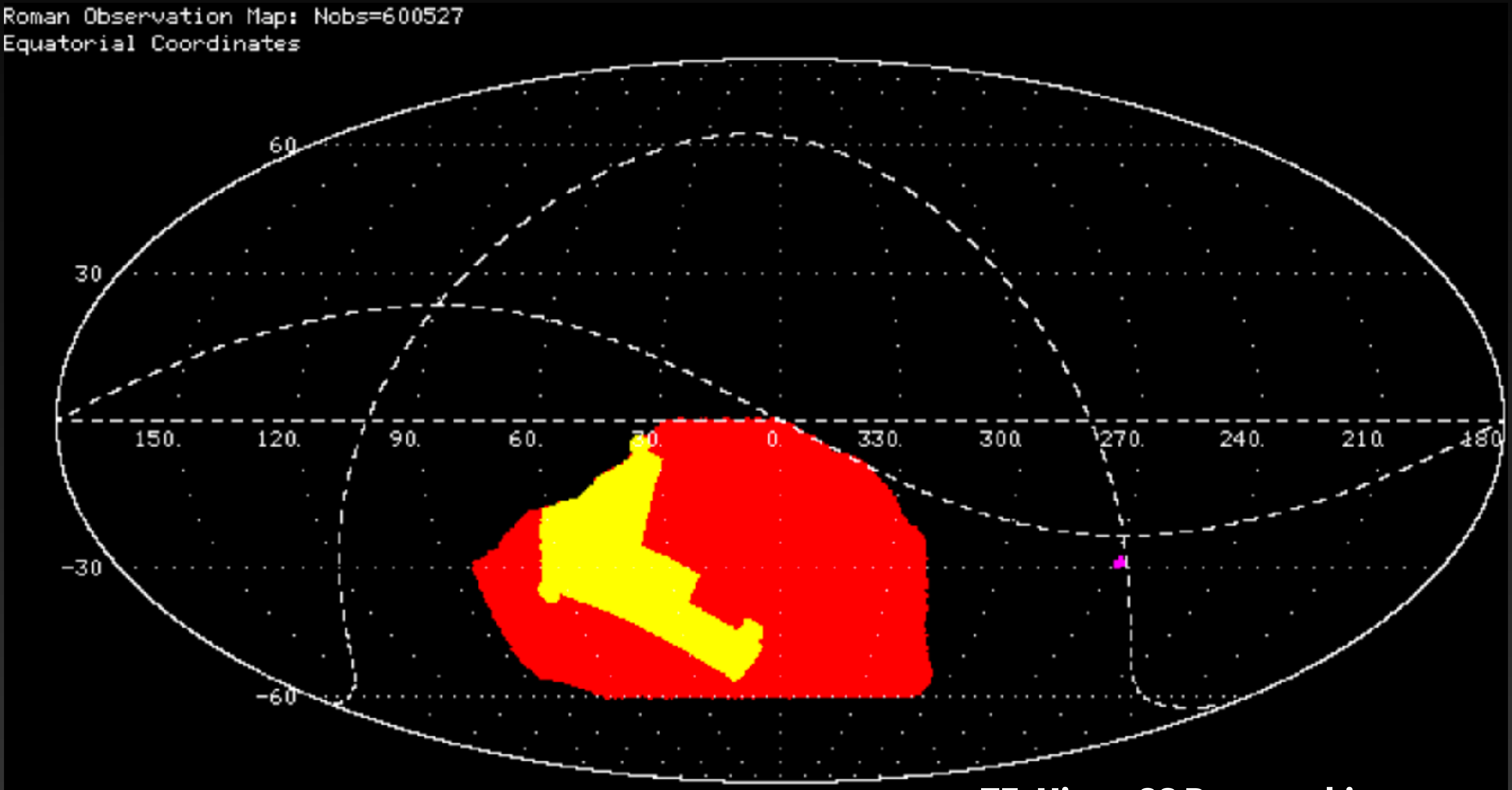
- Significant increase in FoM when pushing Roman to larger area (true for 3x2, 6x2, 10x2)
- Larger area means 1 band instead of 4 bands -> analyses include larger systematics
- Interestingly, lens=source (1 galaxy sample) idea outperforms the statistically more powerful 2 sample concept

Roman wide survey idea - systematics



- Simulated analyses for different survey areas (survey time is kept fixed)
- Reduce to 1 broad band bands to keep depth and cover more area (fewer bands means systematics danger)
- Even when increasing the observational systematics budget 3x for a Roman 10k survey, the larger area still outperforms the 2k reference survey (yellow vs green)

Idea of a 2 tier survey



TE, Hirata 23 Roman white papers

- Two tier survey idea
- One smaller area (e.g. 1000 deg^2 with 4 bands) for systematics control
- Complemented by a wide tier in just 1 band
- Between 6000-15000 deg^2 depending on depth and band chosen

Summary

- 3x2 DES Y1 prefers low baryonic feedback scenarios at the level of Bahamas T7.6 sims
- Including CMB lensing (6x2 DES Y1 x PR3) prefers medium feedback scenarios at the level of Bahamas T8.0 or cOWLS T8.0
- 3x2 and 6x2 consistent with Illustris/cOWLS T8.5 at ~1-2 sigma, cOWLS T8.7 shows mild ~2+ sigma tension
- DES Y3 + PR4 analysis is running (many upgrades incl. new sims) - stay tuned
- Somewhat unrelated: Let's make Roman a wider survey such that we can have more overlap with future CMB experiments!