Un-detecting Dynamical Dark Energy in DESI's data

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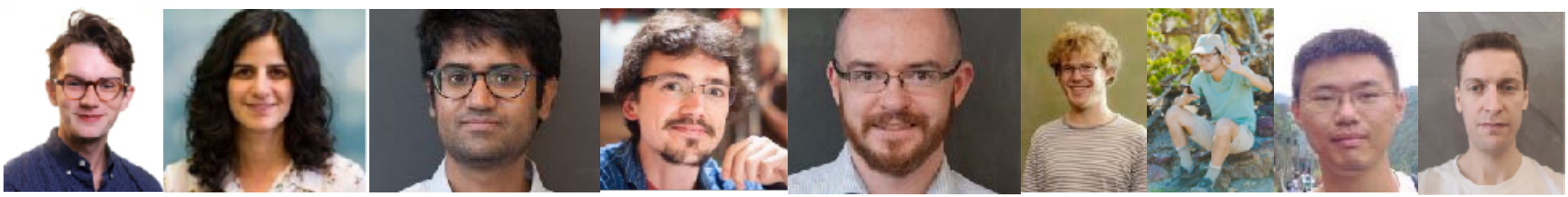


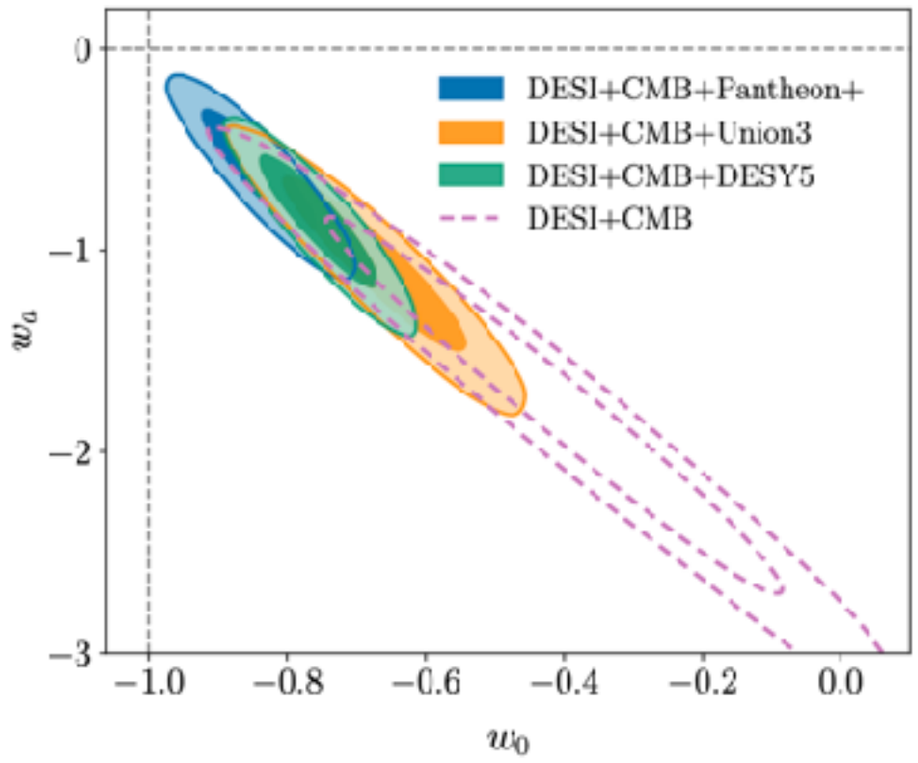
J. Sullivan, C. Cuesta-Lazaro, S. Mishra-Sharma, A. Obuljen, M. Toomey,
O. Philcox, Shi-Fan Chen, Shu-Fan Chen, A. Chudaykin, T. Bakx, Z. Vlah (sorry can't fit all the pics)

Plan:

1. DESI results on DDE
2. w0wa hunter's guide
3. DE interactions? Tau? Ok?
4. Full-shape recap
5. New tools I: Simulation-Based Priors
6. New tools II: One-Loop Bispectrum
7. Independent reanalysis of DESI DR1 FS: results
8. ???
9. Lunch !

Into and Motivation

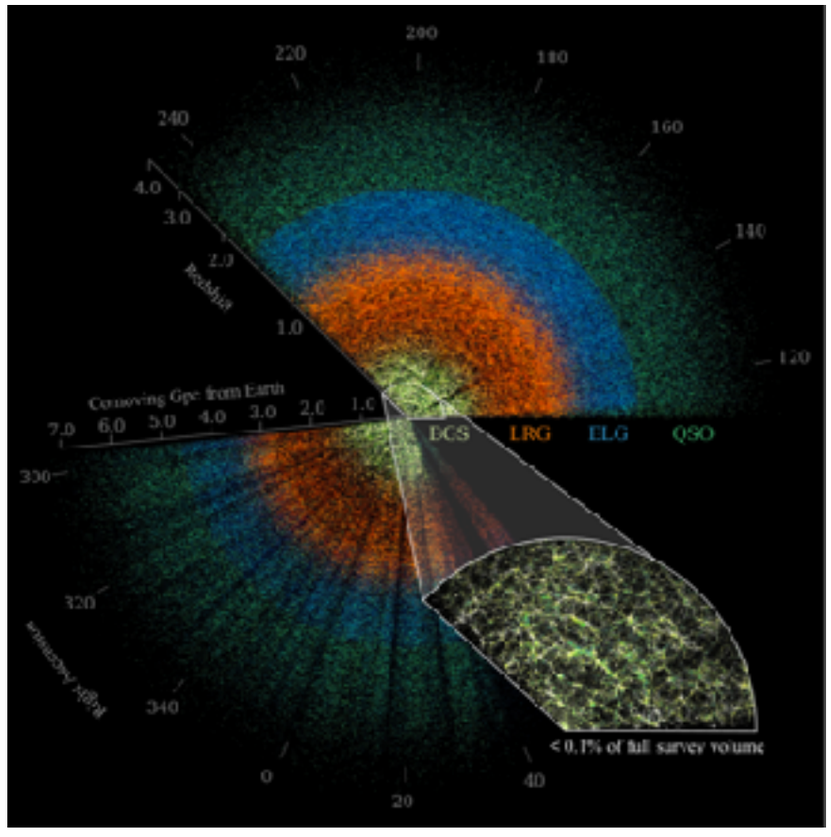
DESI reported evidence for w0wa in BAO data



Satya's talk

$$w(z) = \frac{p_{DE}}{\rho_{DE}} = w_0 + \frac{z}{1+z} w_a$$

$$\textbf{CC:} \quad = -1 + \frac{z}{1+z} \cdot 0$$



Credit: Claire Lamman

The New York Times

A Tantalizing 'Hint' That Astronomers Got Dark Energy All Wrong

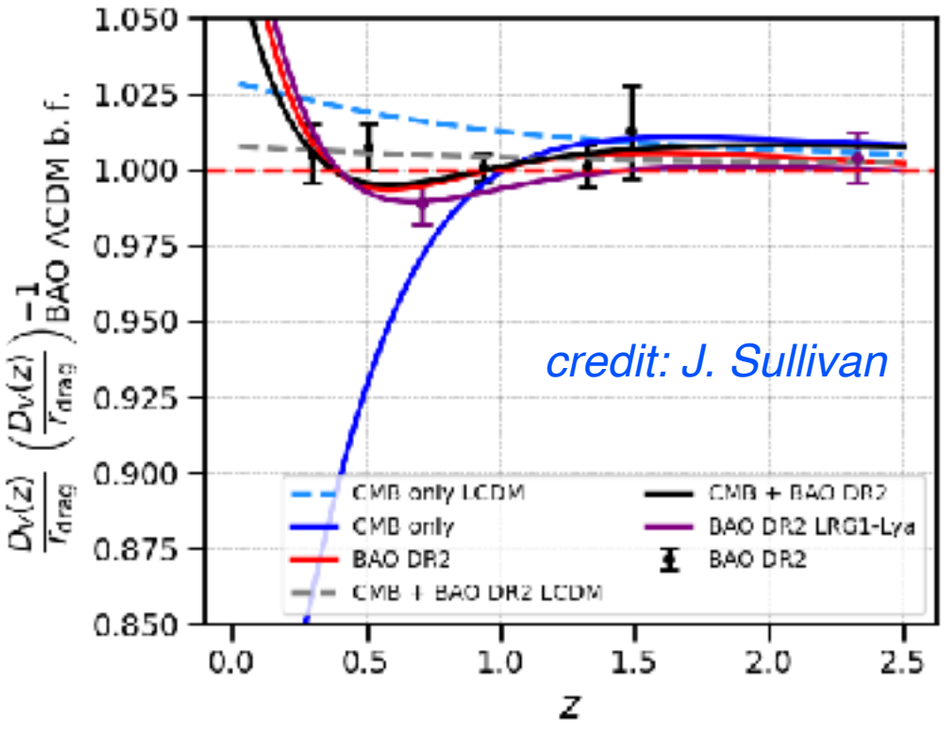
Scientists may have discovered a major flaw in their understanding of that mysterious cosmic force. That could be good news for the fate of the universe.

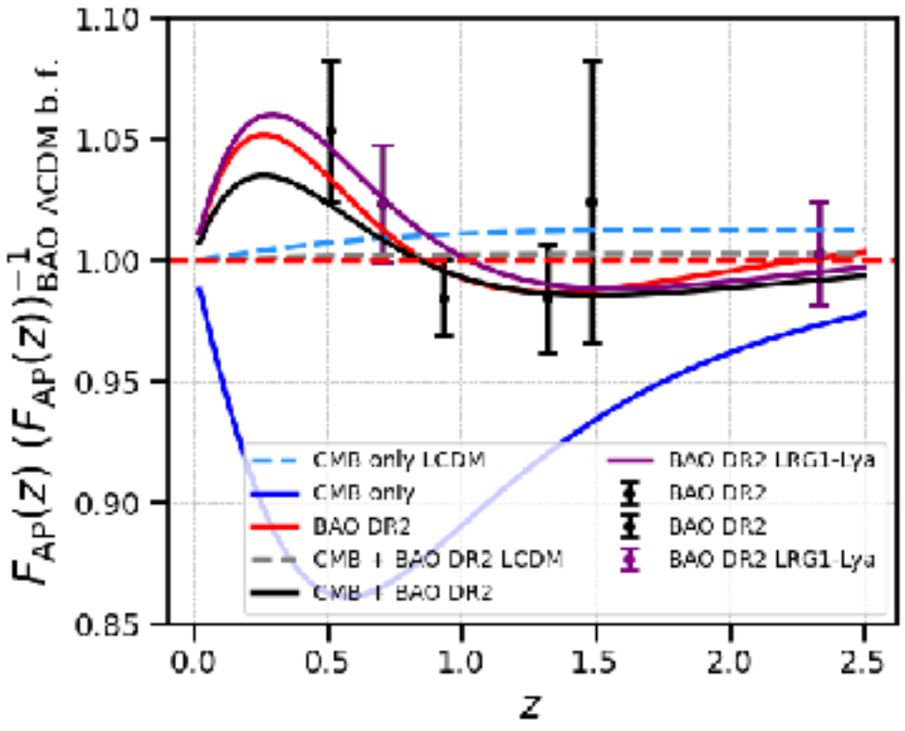
w0wa Hunter Guide

- Overall slope (Om tension w/ CMB), and the phantom crossing

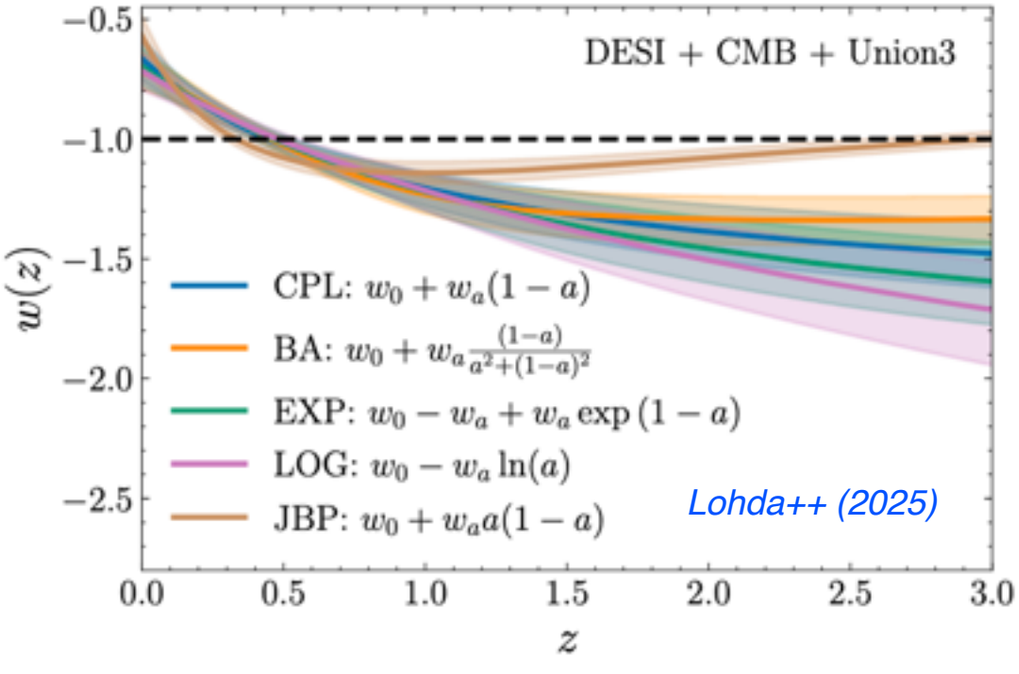
$$D_V \sim (D_A^2/H)^{1/3}$$

$$F_{\rm AP} \sim H(z) D_A(z)$$





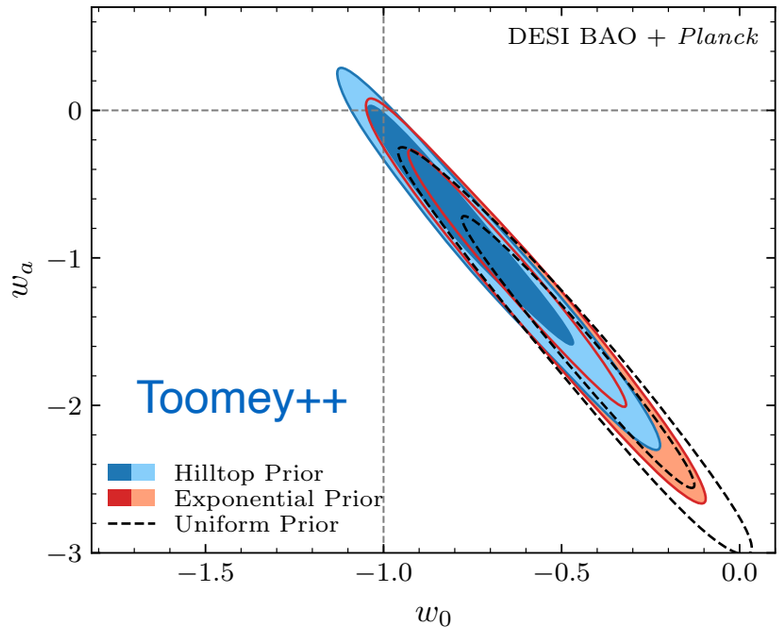
- Phantom crossing is necessary to fit the data well

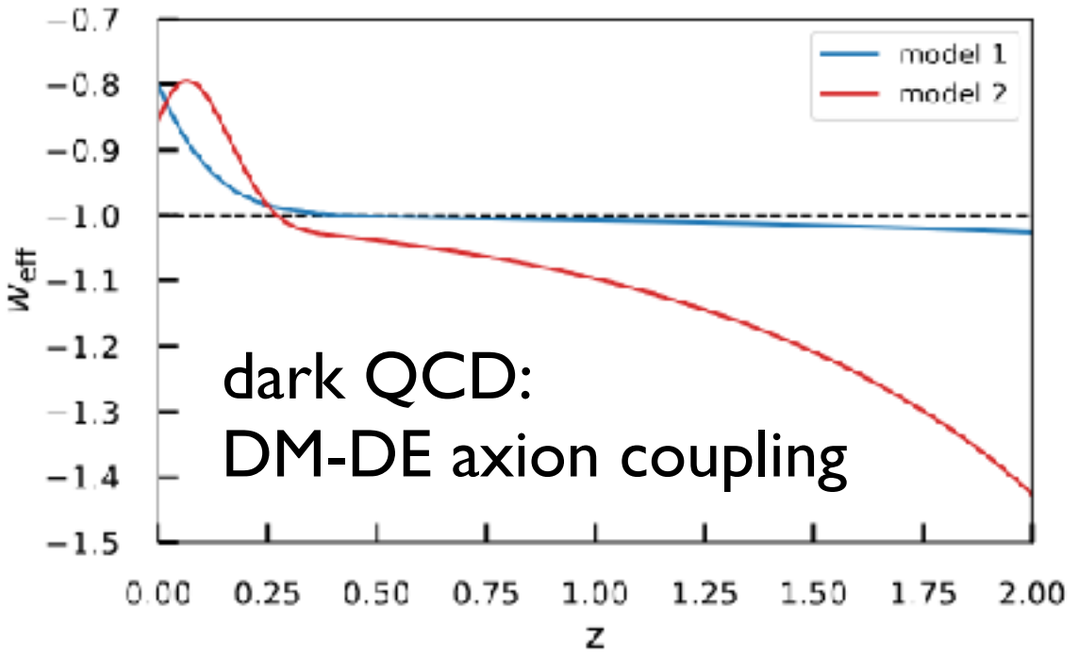


Models

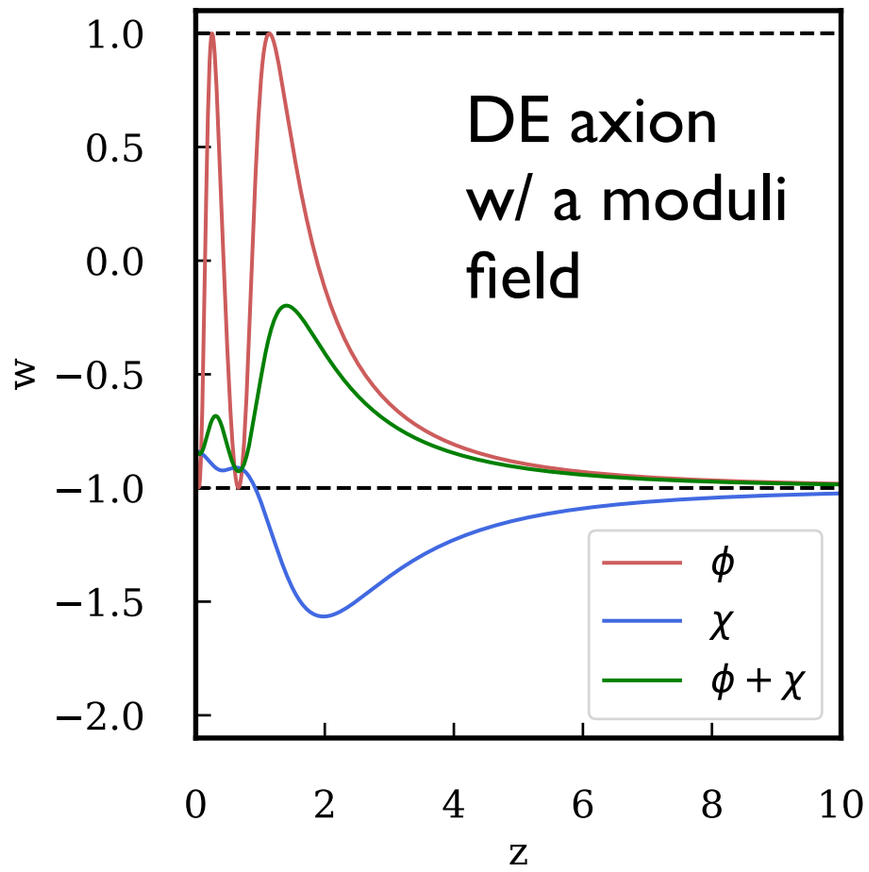
- Usual single scalar field models do not work b/c it can't be phantom

- Interacting fields work —> effective phantom behavior without violating NEC





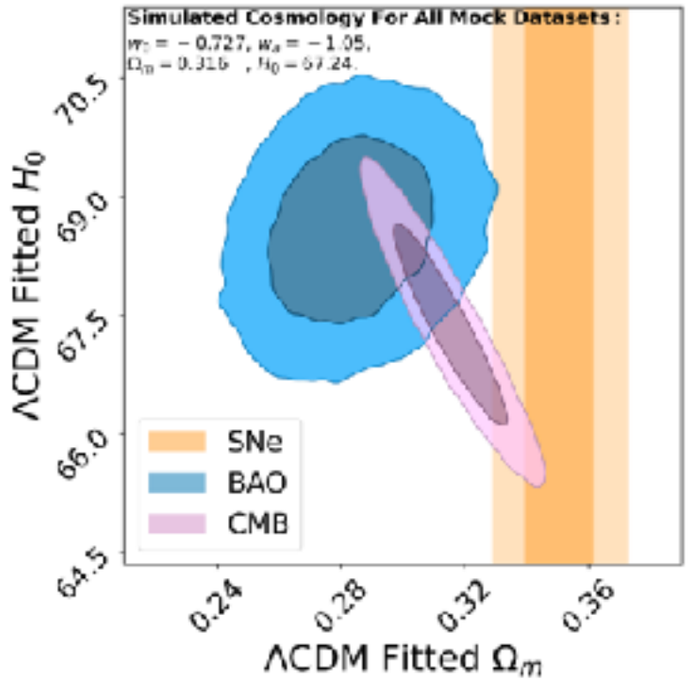
Khoury, Lin, Trodden (2025)



Toomey, Sullivan, Hughes, MI (to appear)

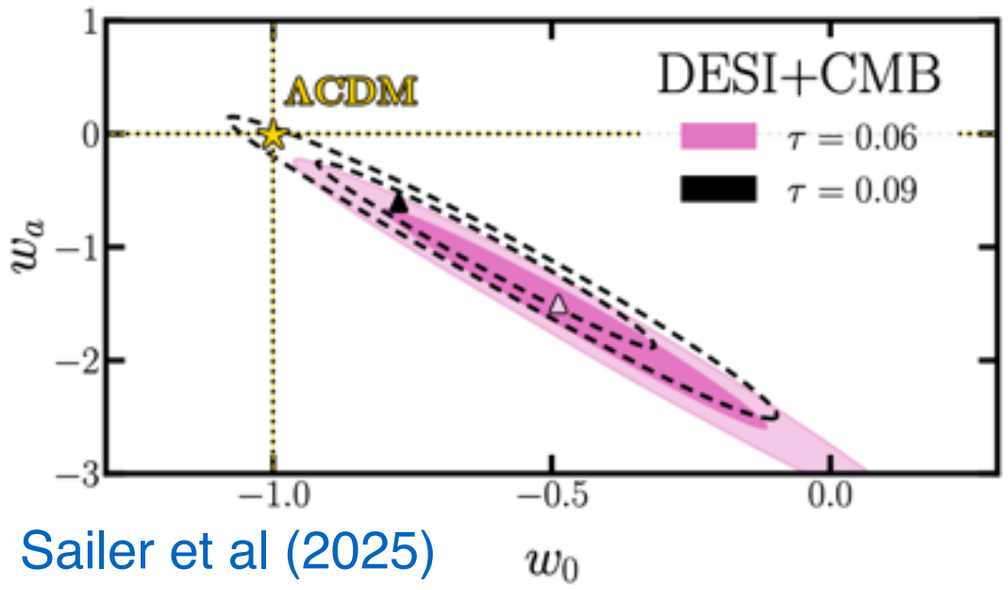
w0wa / Tau / Ok ?

- Tension in LCDM Om measurements between CMB and BAO

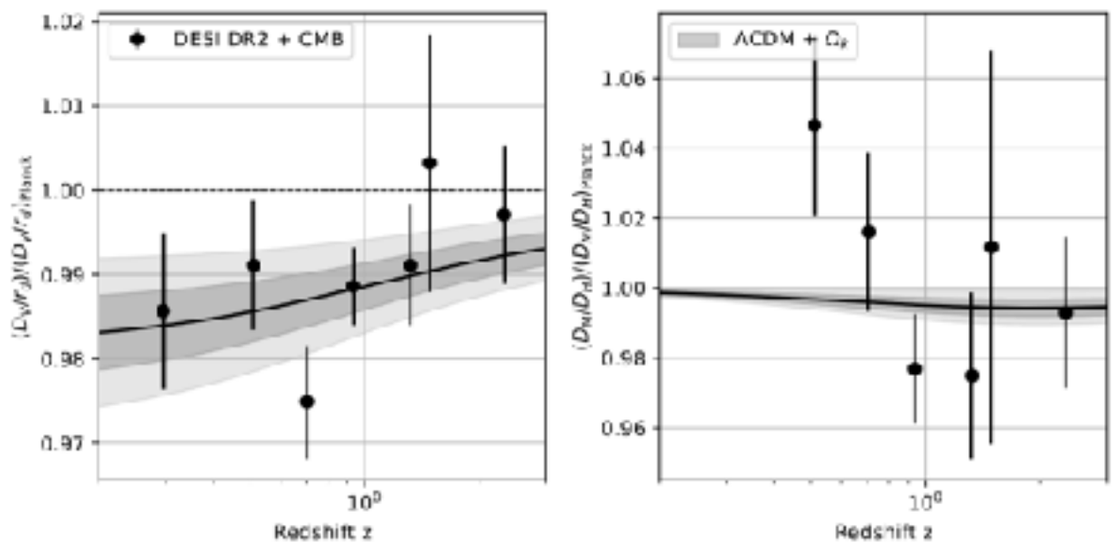


Tang et al (2025)

- Can be caused by something other than w0wa: (* no SNe)



Sailer et al (2025)

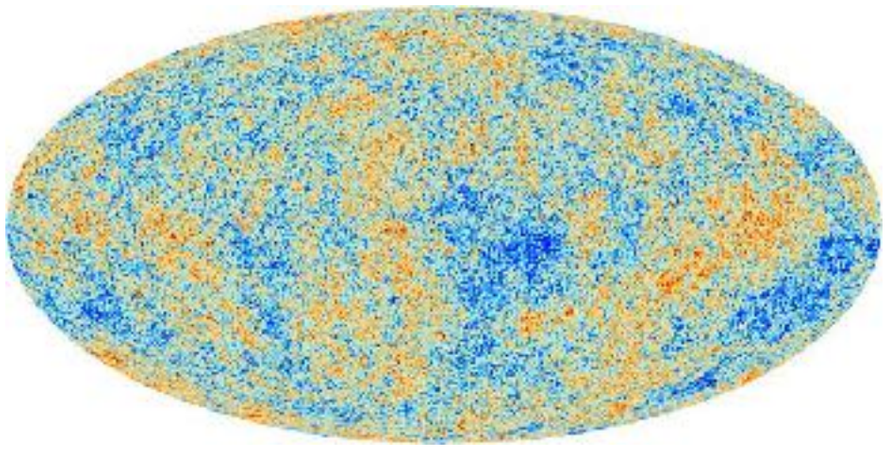


Chen, Zaldarriaga (2025)

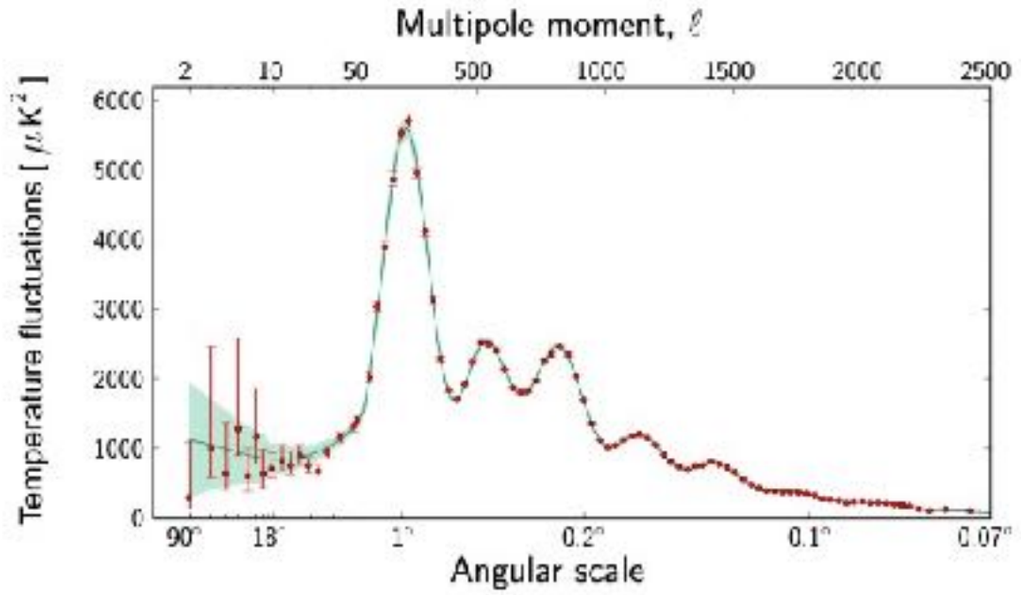
We need more information. Full Shape!

EFT-based full-shape analysis

Cosmic Microwave Background

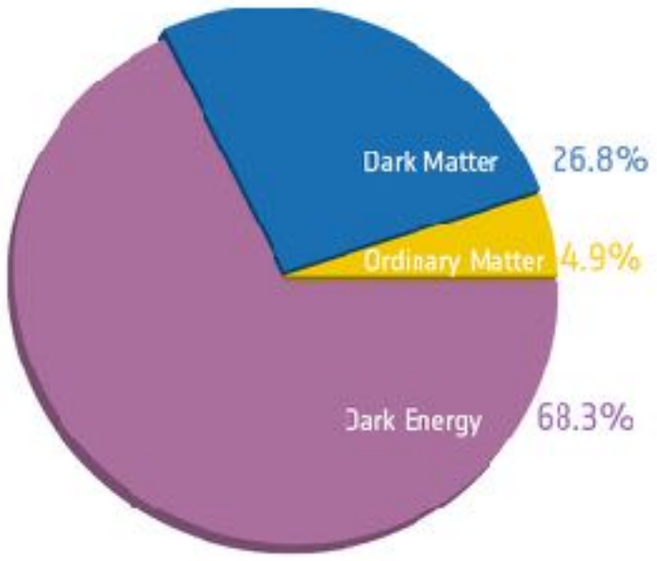


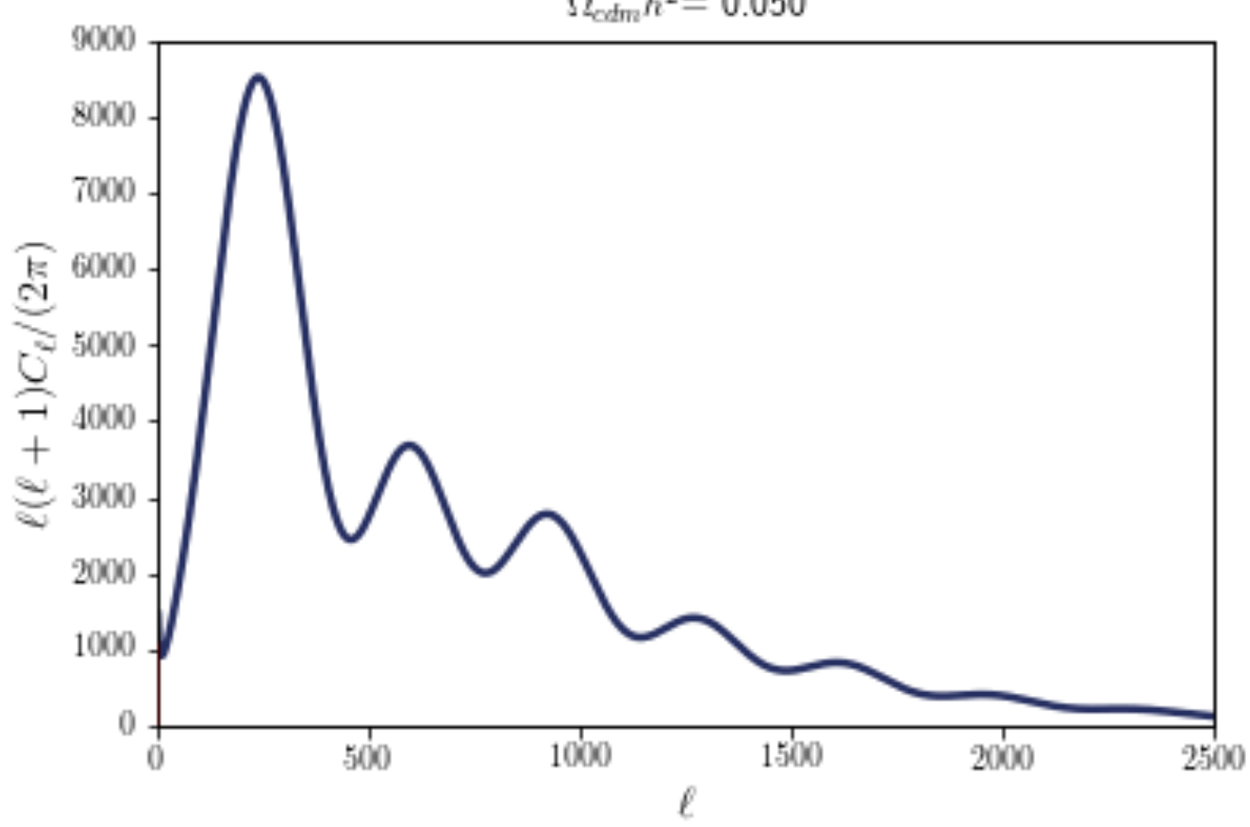
Planck'18



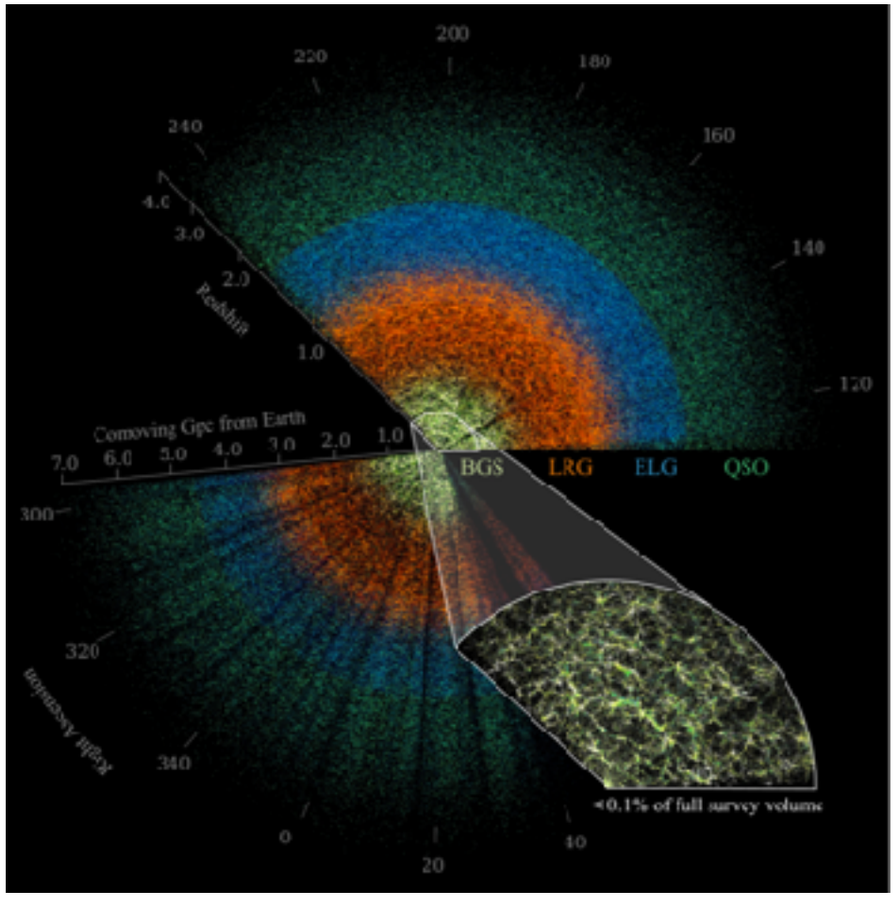
$$C_\ell \sim \left\langle \left(\frac{\delta T}{T}\right)^2 \right\rangle, \quad \ell \sim \frac{1}{\theta}$$

$$\{\Omega_m, \Omega_b, H_0, \tau, A_s, n_s\}$$





Large-Scale Structure

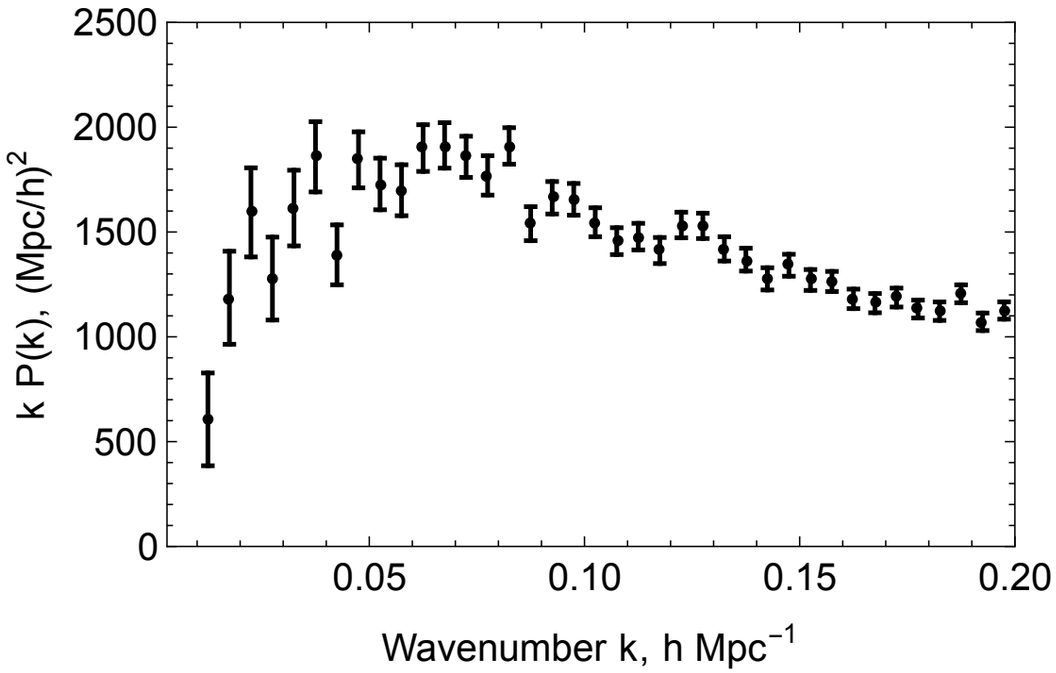


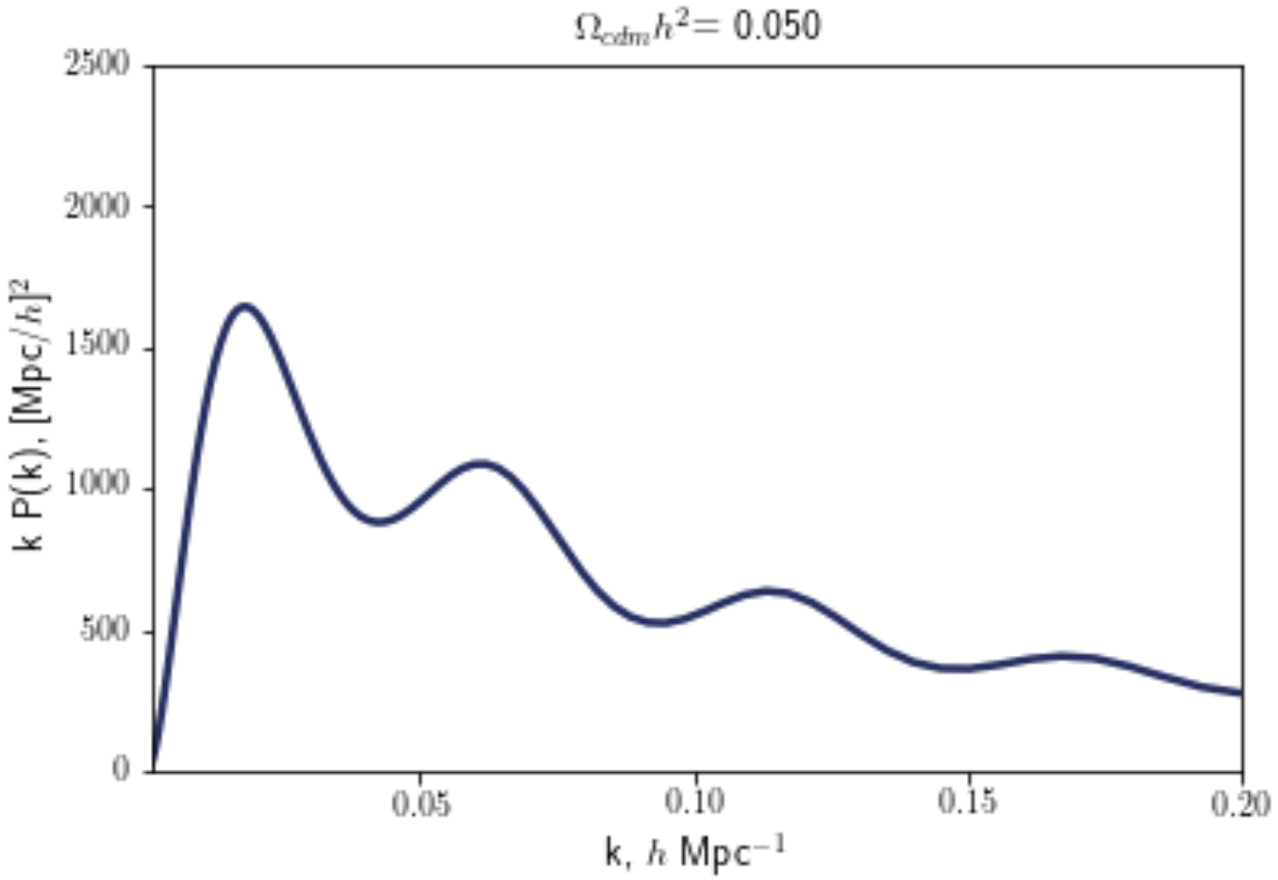
(c) DESI

$$\delta = \frac{\delta\rho}{\rho}$$

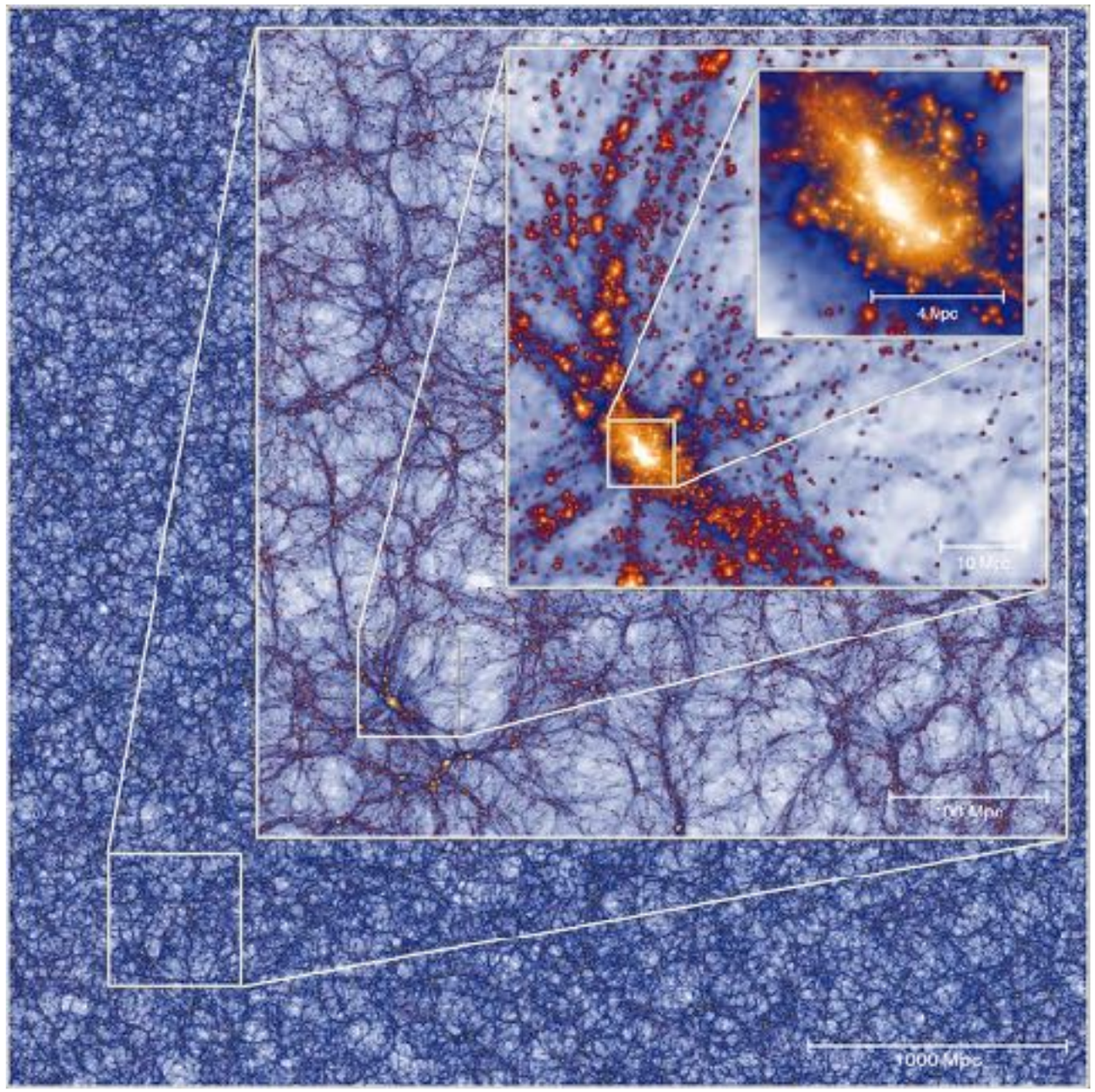
$$\langle \delta^2 \rangle \rightarrow P(k)$$
$$\langle \delta^3 \rangle, \ldots$$

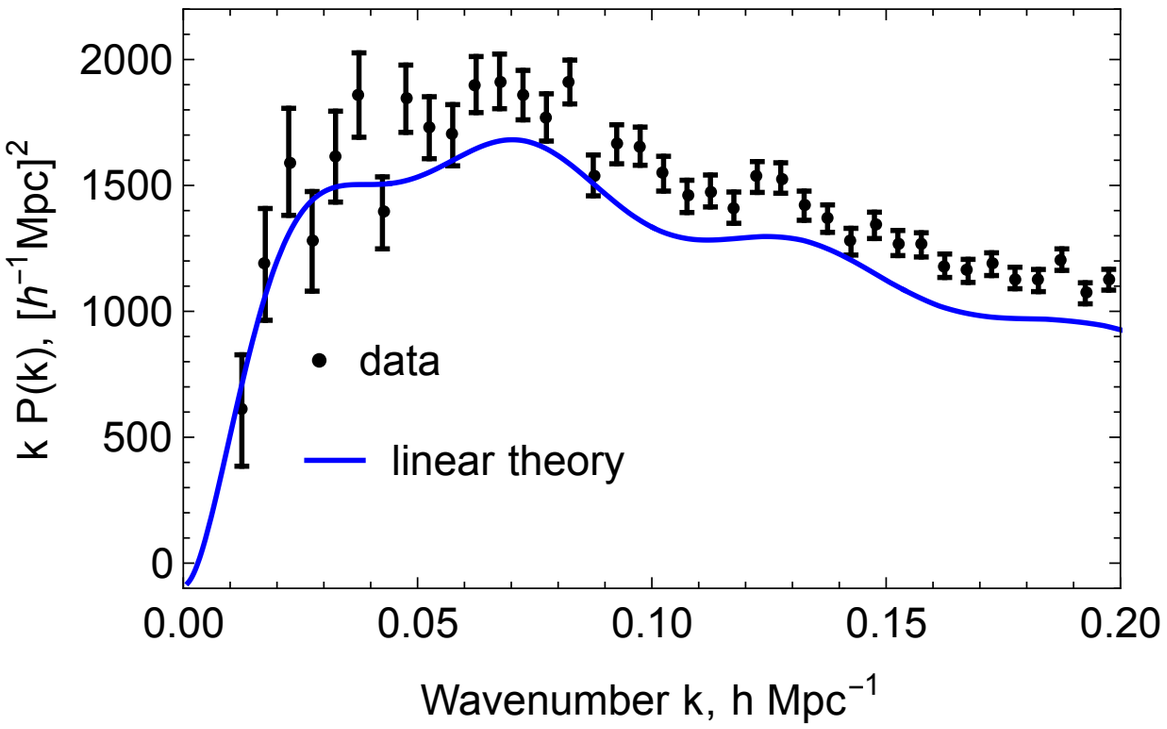
$$k = \frac{2\pi}{\lambda}$$





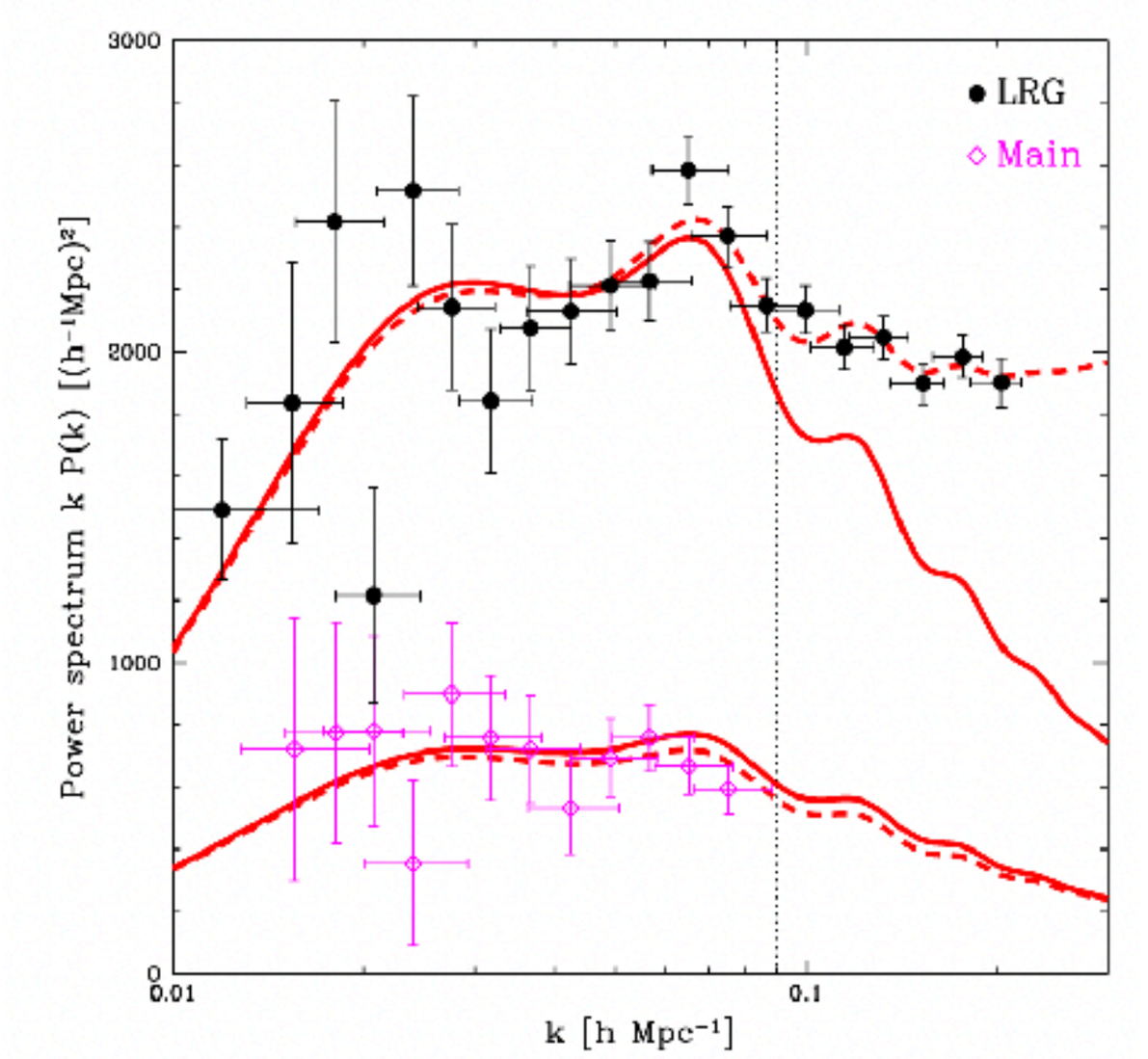
The big problem





- CMB analysis relies on linear physics
- LSS is intrinsically non-linear

Ways to analyse LSS:



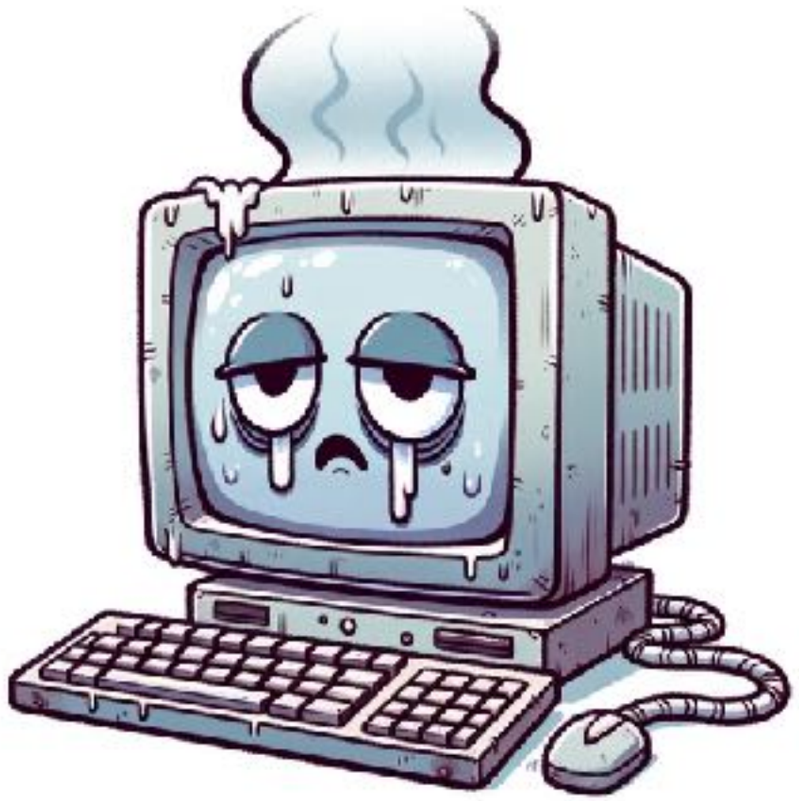
Tegmark++, SDSS analysis (2006)

- $\sigma_{\rm theory} \gg \sigma_{\rm data}$
- "standard" approach until recently:
  focus on observables that
  are approximately stable w.r.t.
  non-linear effects:
  Baryon Acoustic Oscillations + RSD
- Discard shape information
- For many models the progress
  can be made only
  with the shape information.
  I'll show today how this works
  with the Dynamical DE

Solutions

Simulations

- matter clustering
- unlimited range
- galaxy formation
- time-consuming



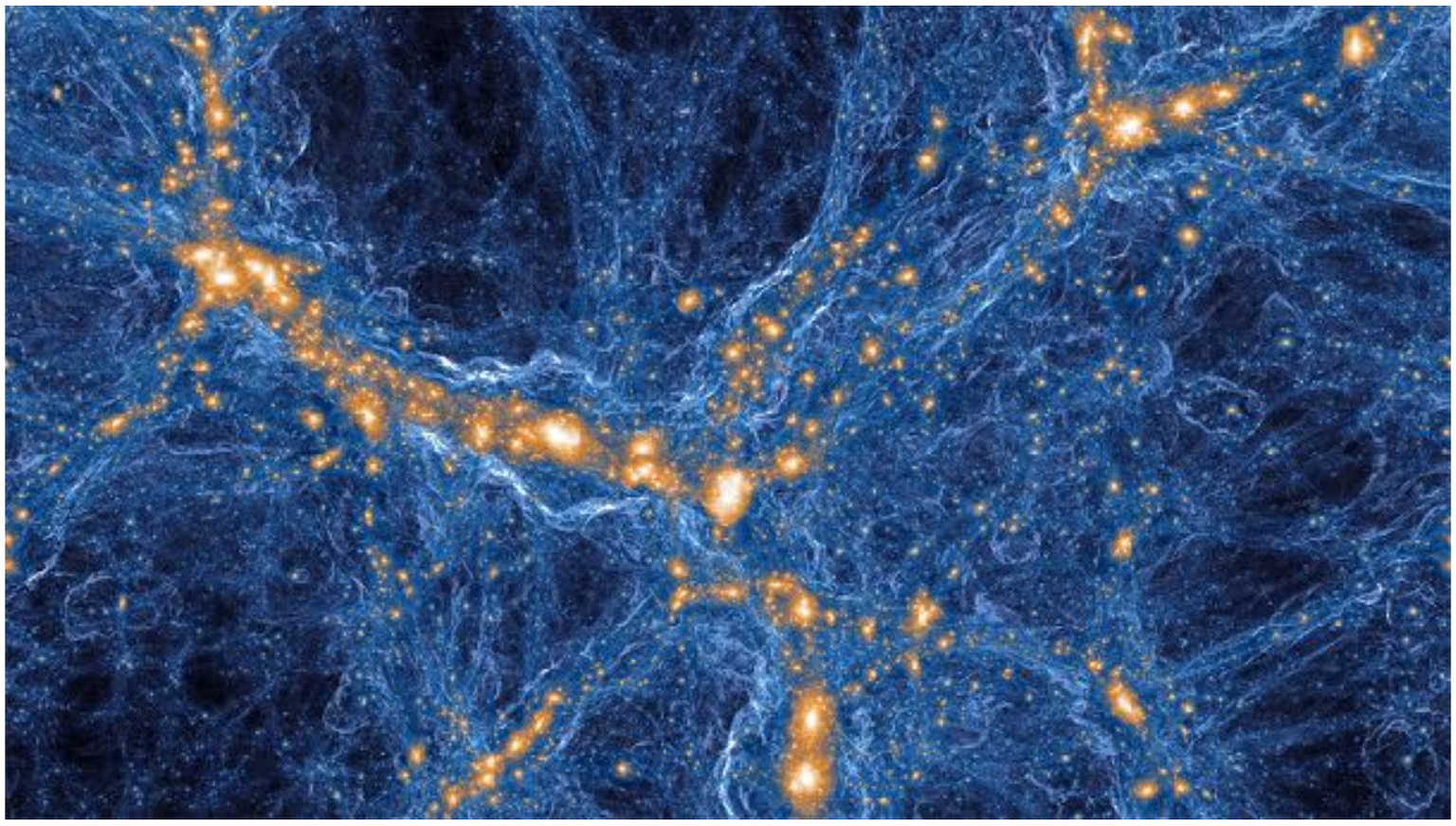
Perturbation theory (EFT)

- limited range
- precision & accuracy
- fast/ cheap - beyond LCDM
- marg. over astrophysics

State-of-the-art equipment
for a theoretical physicist

Galaxies in perturbation theory (EFT)

$$\delta = \frac{\delta\rho}{\rho}$$



- Dimensional analysis + Symmetries:

$$\delta_{\rm g} = \begin{array}{l} b_1\delta \\ + b_2\delta^2 + b_{\mathcal{G}_2}(\nabla_{\langle i}\nabla_{j\rangle}\Phi)^2 + \ldots \end{array}$$

$+\cancel{v^i}$ $+\cancel{\Phi}$

Rotation invariance (+Galilean inv)

Equivalence Principle

Roy, McDonald (2006)

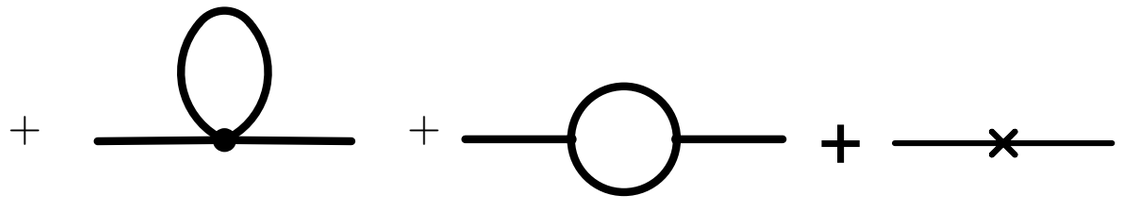
Desjacques, Jeong, Schmidt (2016)

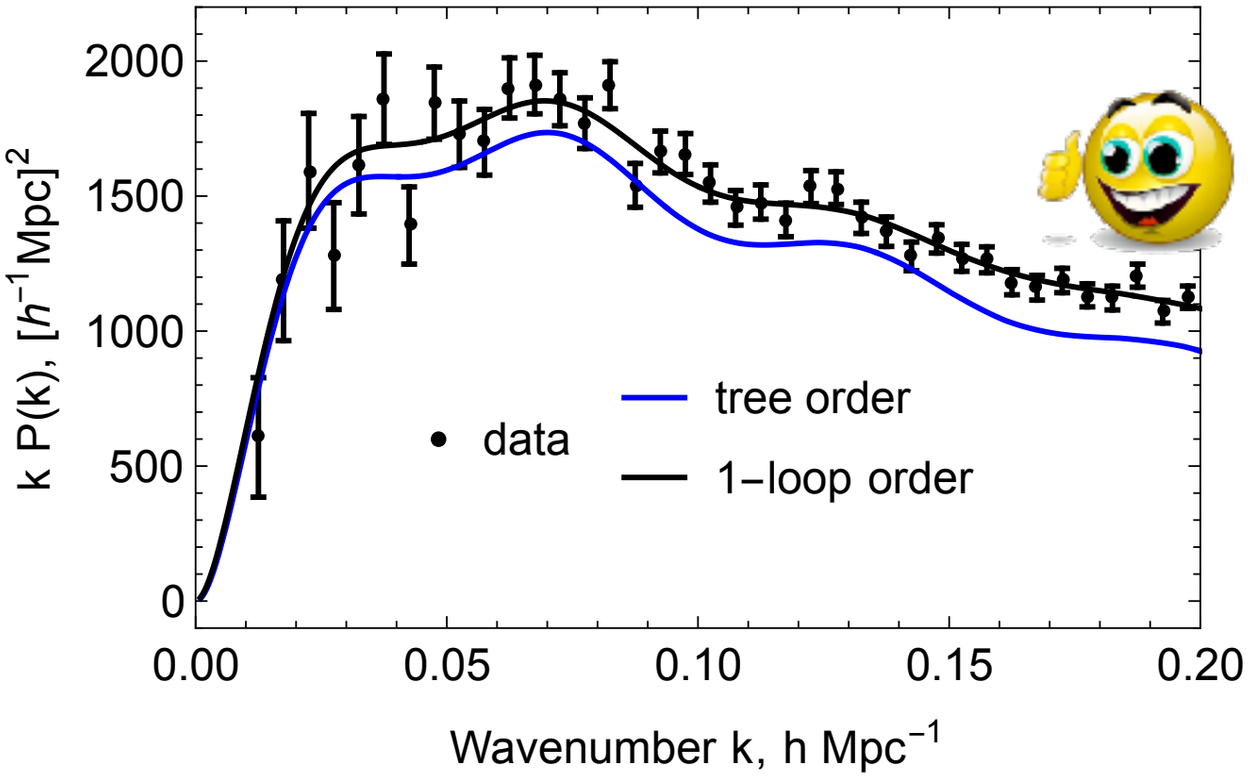
Nuisance (bias) parameters:

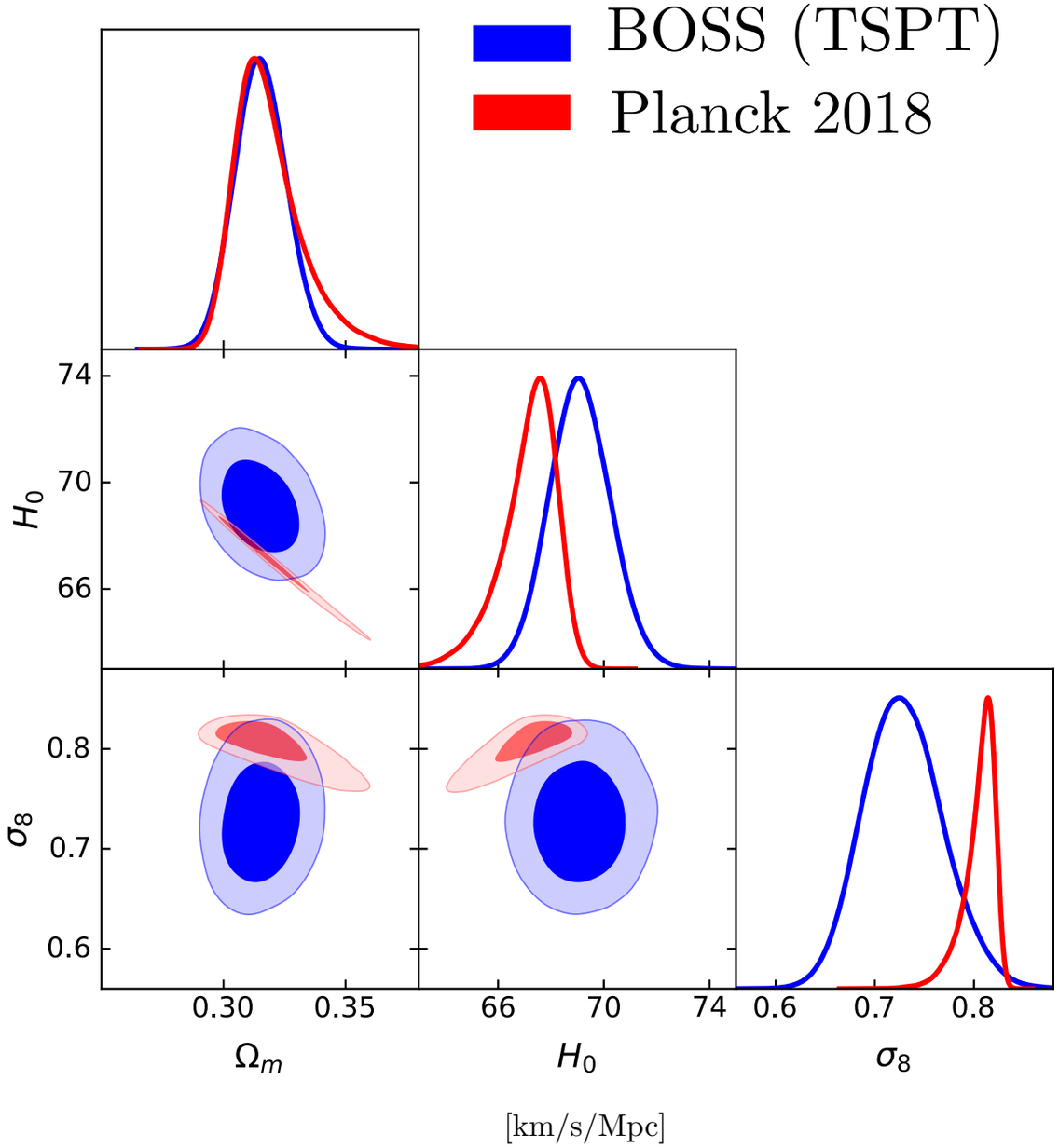
$$b_1, b_2, b_{\mathcal{G}_2}, \ldots$$

EFT program

$$\langle \delta_{\mathbf{k}} \delta_{\mathbf{k}'} \rangle \sim P(k) =$$







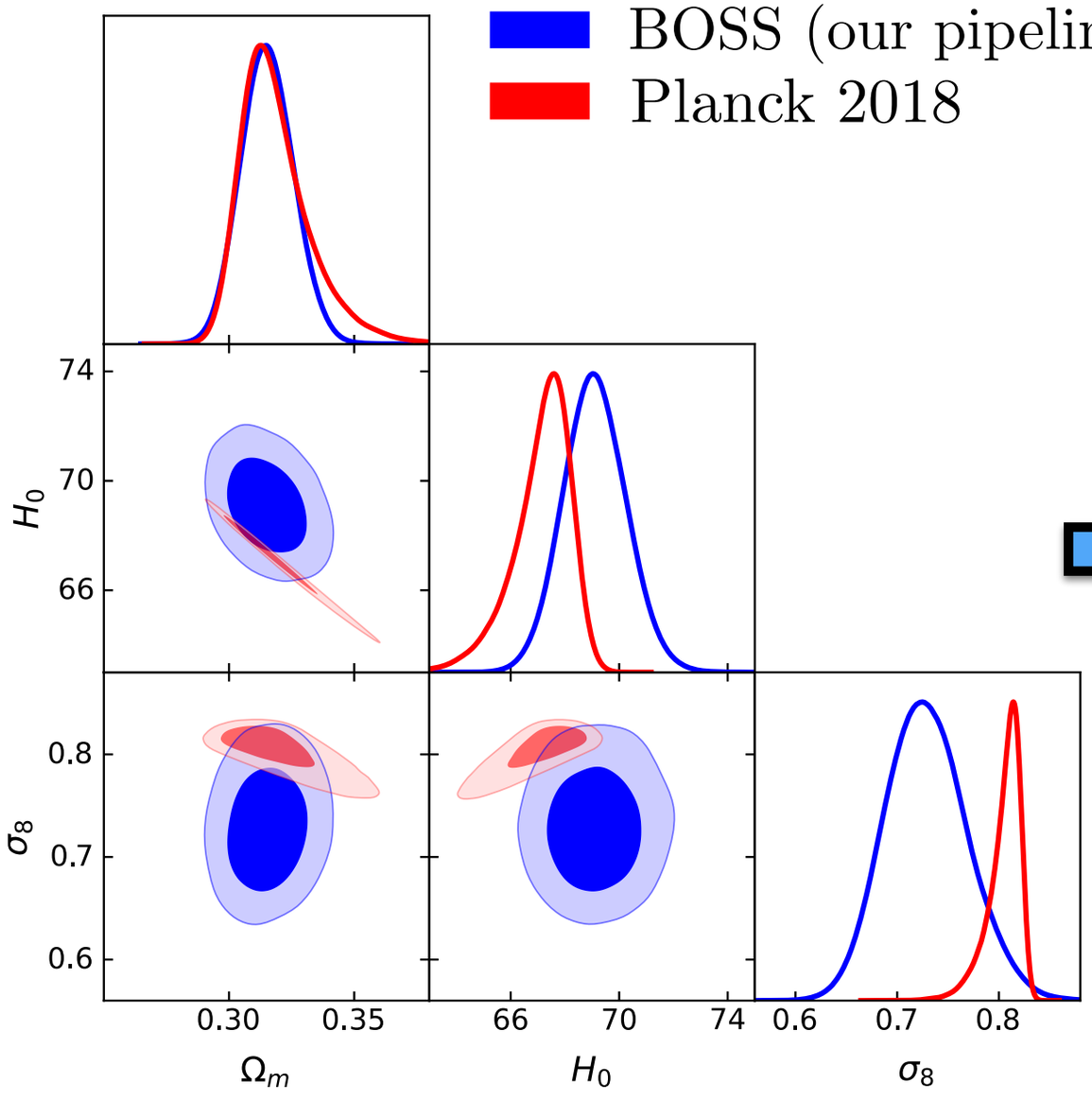
MI, Simonovic, Zaldarriaga (2019), Philcox, MI (2021) ++
D'Amico, Kokron++(2019), Chen, White, Vlah (2021)

Baumann (2012), Nicolis, Carrasco, Senatore, Zaldarriaga, Simonovic, White, Vlah, Lewandowski, ++ many more

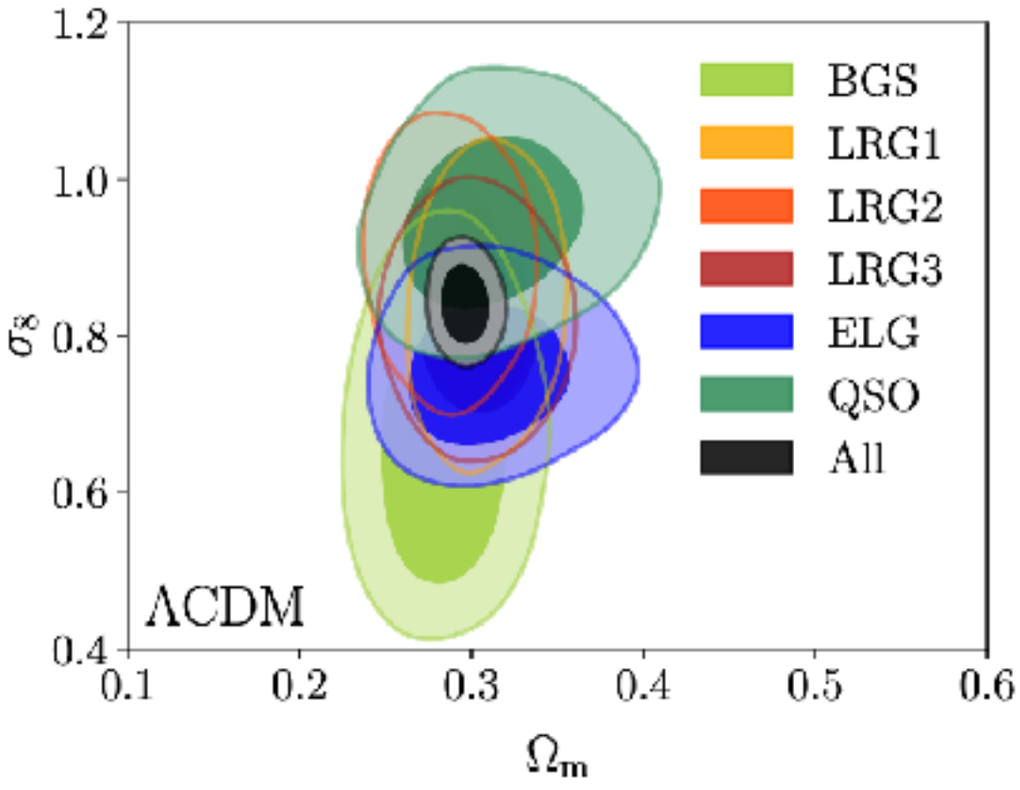
Check out CLASS-PT code

see also FAST-PT, Velocileptor, Spinosourus, PiBird, CLASS-1loop, etc.

EFT: from BOSS to DESI



DESI adopted EFT full-shape analysis as a main beyond BAO analysis



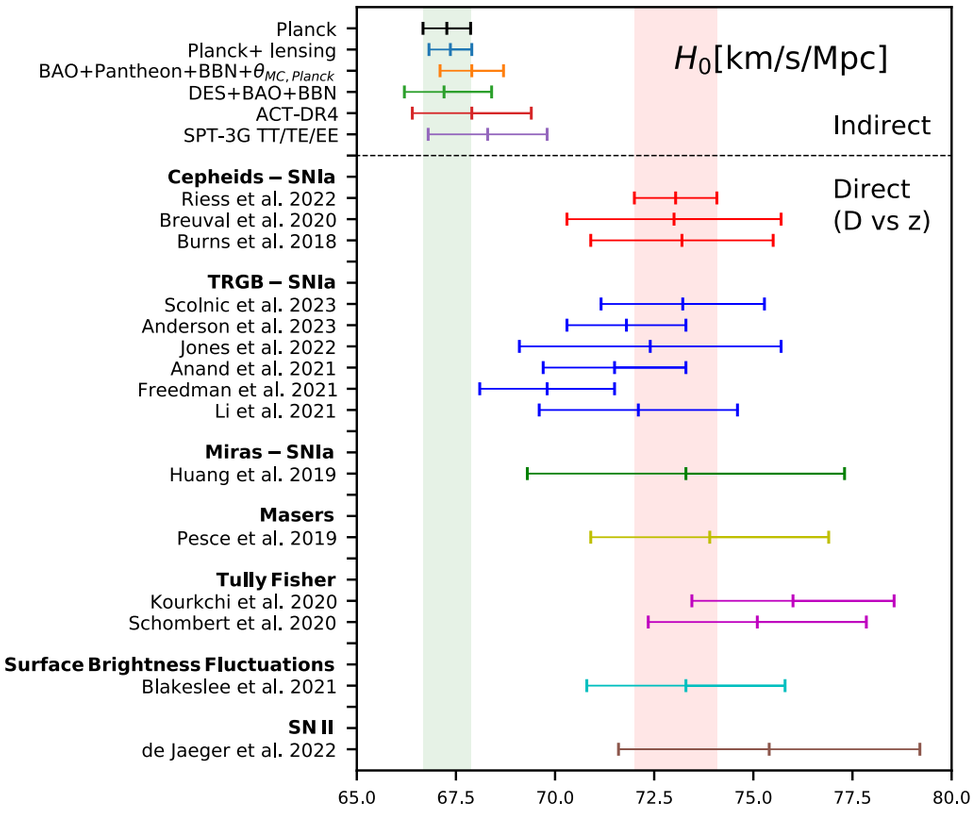
MI, Simonovic, Zaldarriaga (2019), Philcox, MI (2021) ++
D'Amico, Kokron++(2019), Chen, White, Vlah (2021)

DESI collaboration (2024)

The most complete BOSS analysis: Chen, Ivanov, Philcox, Wenzl (2024)

Applications

Hubble tension



Dark Sectors

Inflation

Ghost inflation!

O.Philcox, C. Hill, E. McDonough, M. Toomey, A. He, R. An, V. Gluscevic, K. Rogers, A. Lague, K. Akitsu, G. Cabass, C. Dvorkin, F.-Y. Cyr-Racine, D. Camarena, +++

Check out previous editions of this workshop

New tools

Limits of EFT: breakdown on small scales

- Perturbation theory does not work beyond its radius of convergence

- No matter how many loops you compute, EFT is a disaster beyond the non-linear scale:

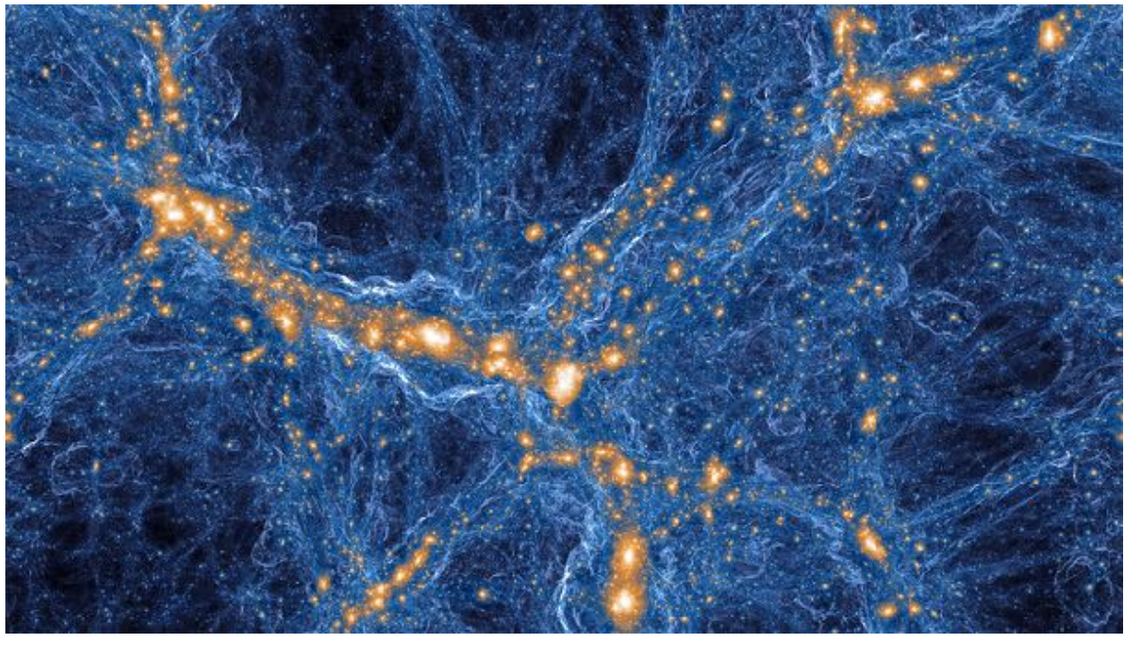
$$\delta_{lin} \sim 1 \qquad\qquad k_{\rm NL} \sim 1\ h{\rm Mpc}^{-1}$$

e.g. spherical collapse

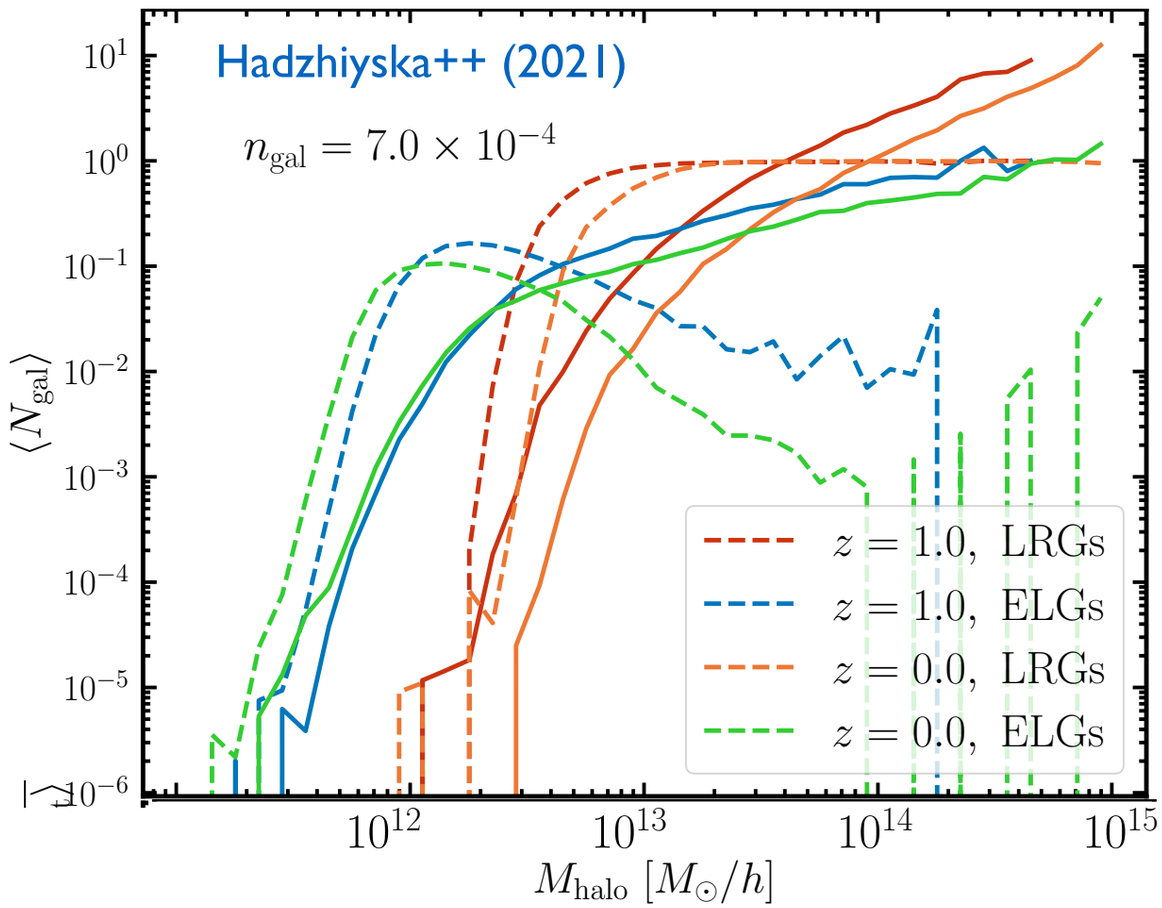
$$\delta_{NL} = \frac{1}{\left(1 - \frac{\delta_{lin}}{\nu}\right)^{\nu}} - 1\,, \quad \nu = \frac{21}{13}$$

$$\approx \delta_{lin} + \frac{17}{21}\delta_{lin}^2 + ...$$

Simulations: from hydro to HOD



- Hydro: best we can do
- But they are expensive
- Cheap alternative: Halo Occupation Distribution (HOD)



- Galaxies live in DM halos
- Take halos from N-body

& paint galaxies based on the distribution motivated by data or hydro sims, e.g.

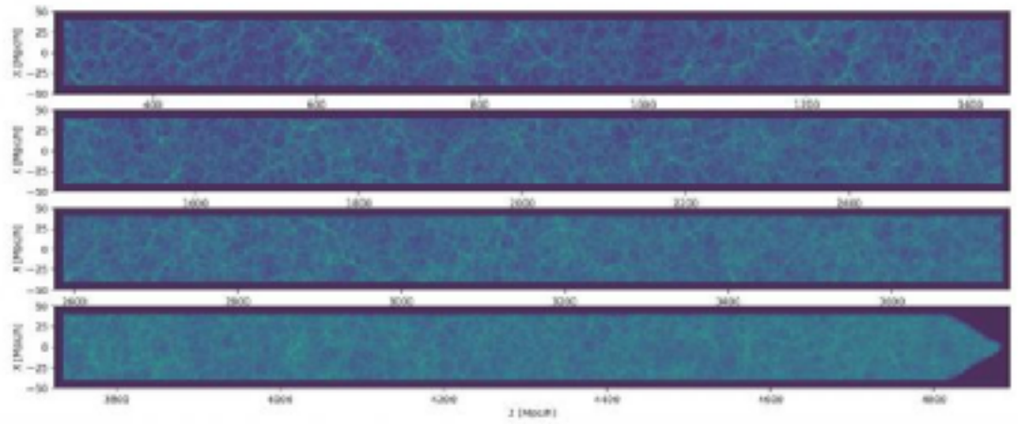
$$\langle N_{\rm cen}(M) \rangle = \frac{1}{2}\left[1 + {\rm erf}\left(\frac{\log M - \log M_{\rm min}}{\sigma_{\log M}}\right)\right],$$

$$\langle N_{\rm sat}(M) \rangle = \left(\frac{M - M_{\rm cut}}{M_1}\right)^{\alpha},$$

Simulation-based inference program

Uros' talk

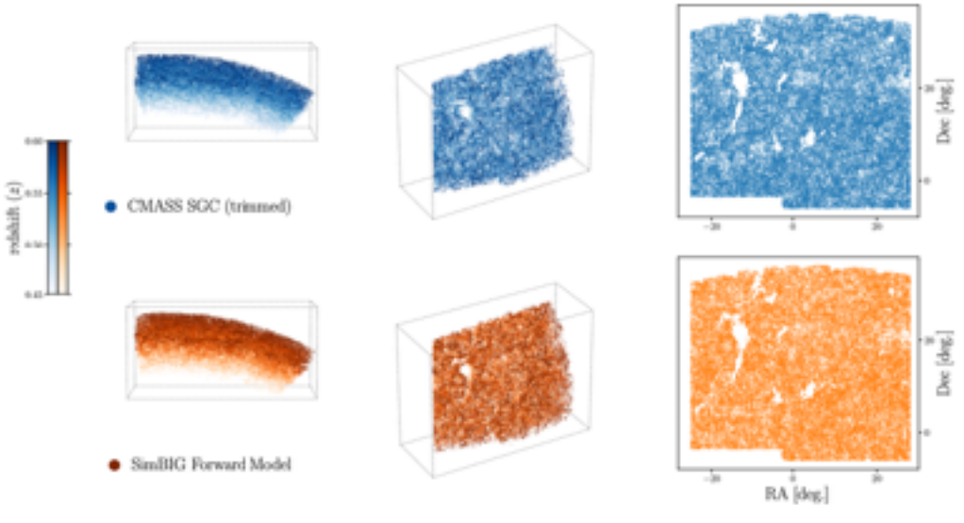
- Computational cost is a significant burden even for HOD
- Small grid of high-res high-volume simulations: e.g. AbacusSummit



© Cuesta-Lazaro ++'23

Grid too coarse (80 sims) for precision statements

- Large grid of small-volume low-res simulations: Quijote



Can analyze only small volumes ~ 1 (Gpc/h)^3

© Hanh ++'23

Beyond - 2pt Challenge

- Benchmarking EFT vs Simulation-based inference (SBI)

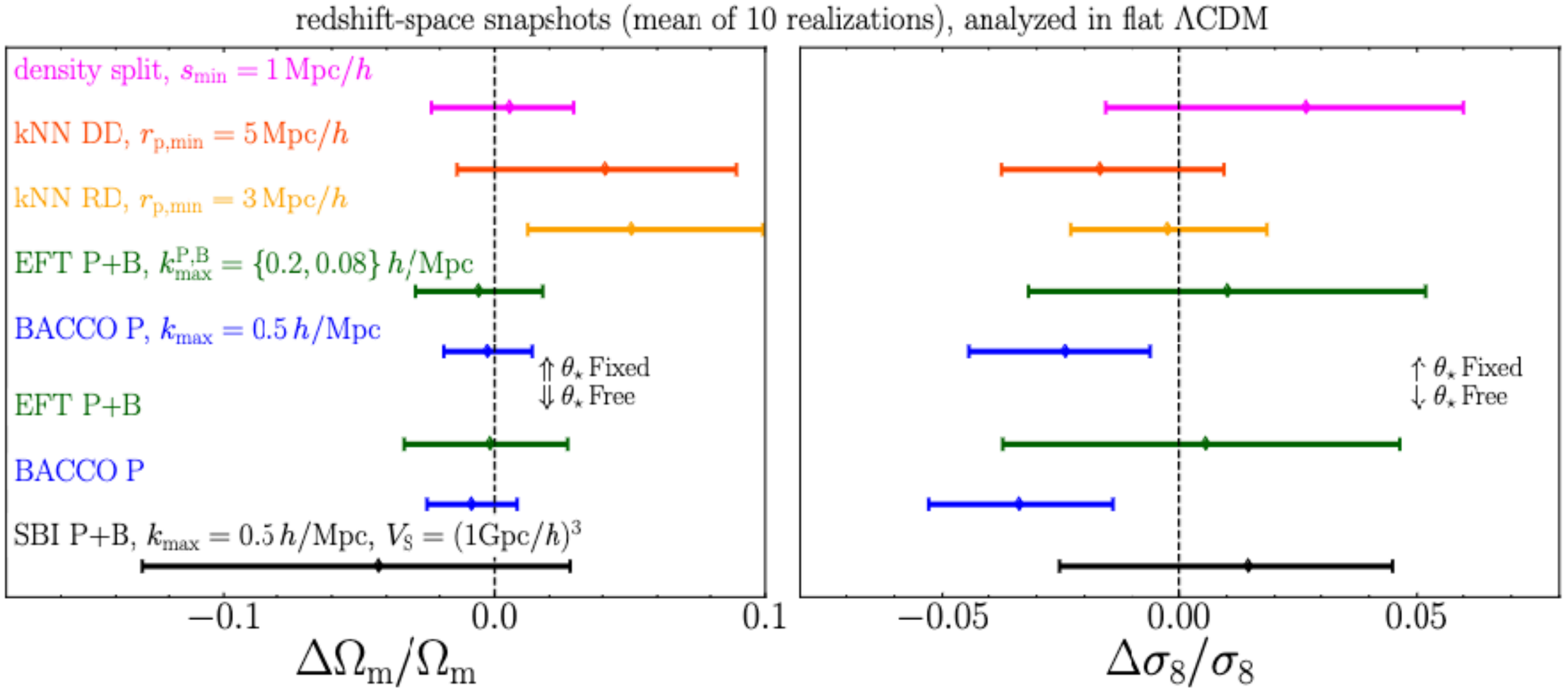
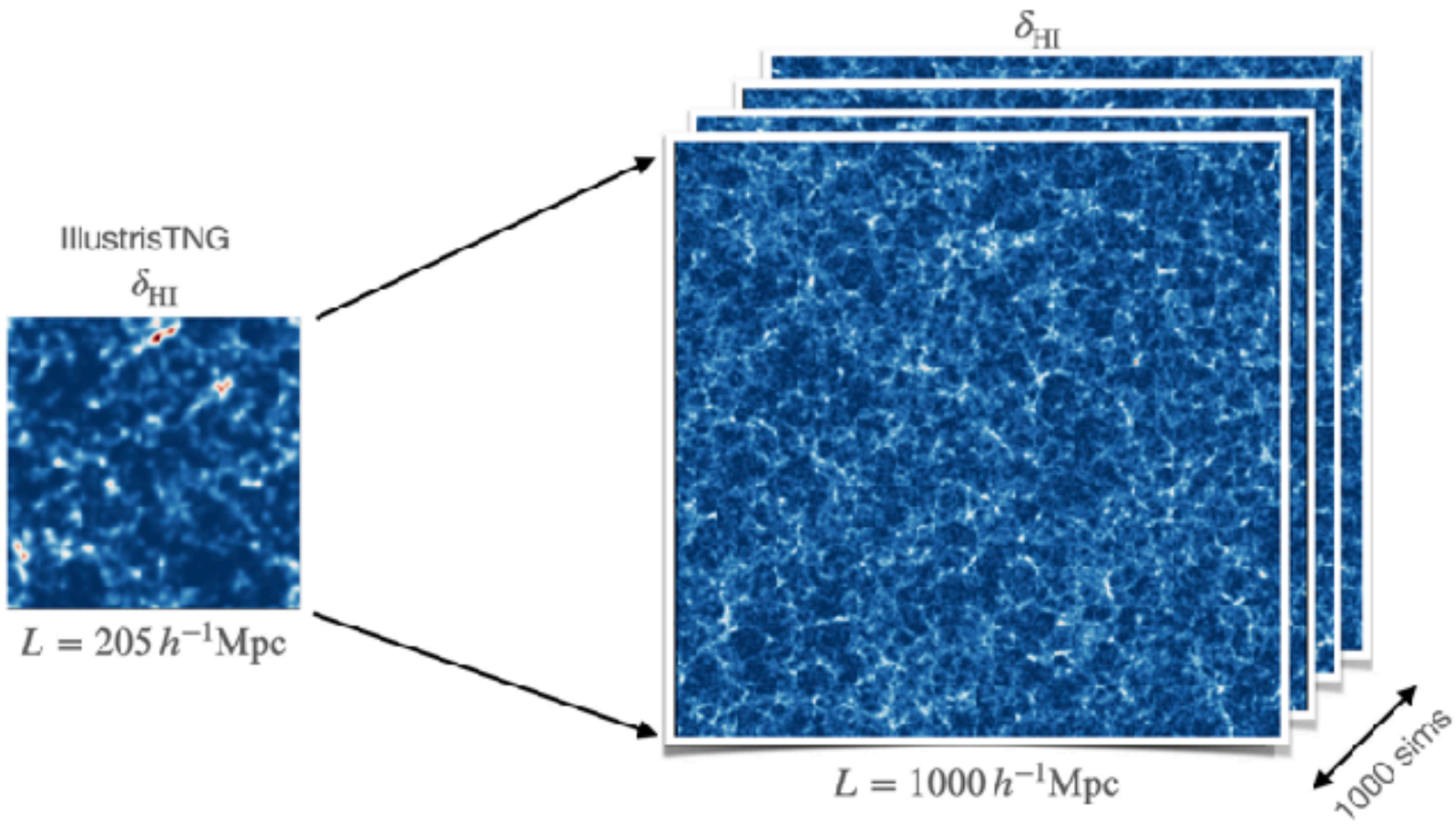


Figure 2. 1D marginalized constraints on $\Omega_{\rm m}$ and σ_8 for parameter-masked analyses of redshift-space mocks (mean of 10 realizations, errors of 1 box), marginalized over the remaining cosmological parameters of flat ΛCDM and nuisance parameters specific to each method.

E. Krause, MI ++'24

EFT (PT) vs Simulations

- Both approaches have weaknesses and merits
- Why not combine them?
- The best way: combine EFT and Sims at the field level



COLA, FastPM methods, etc., Obuljen, Simonovic ++ (2022), Modi, Philcox (2023)

EFT-based analysis with Simulation-Based priors

- The simplest way: extract priors on EFT parameters

$$b_1, b_2, b_{\mathcal{G}_2}, ...$$

From the simulations!

- Problem: need *a lot* of simulations for large “training sets"
— small volume

but small volume = large errors (cosmic variance)

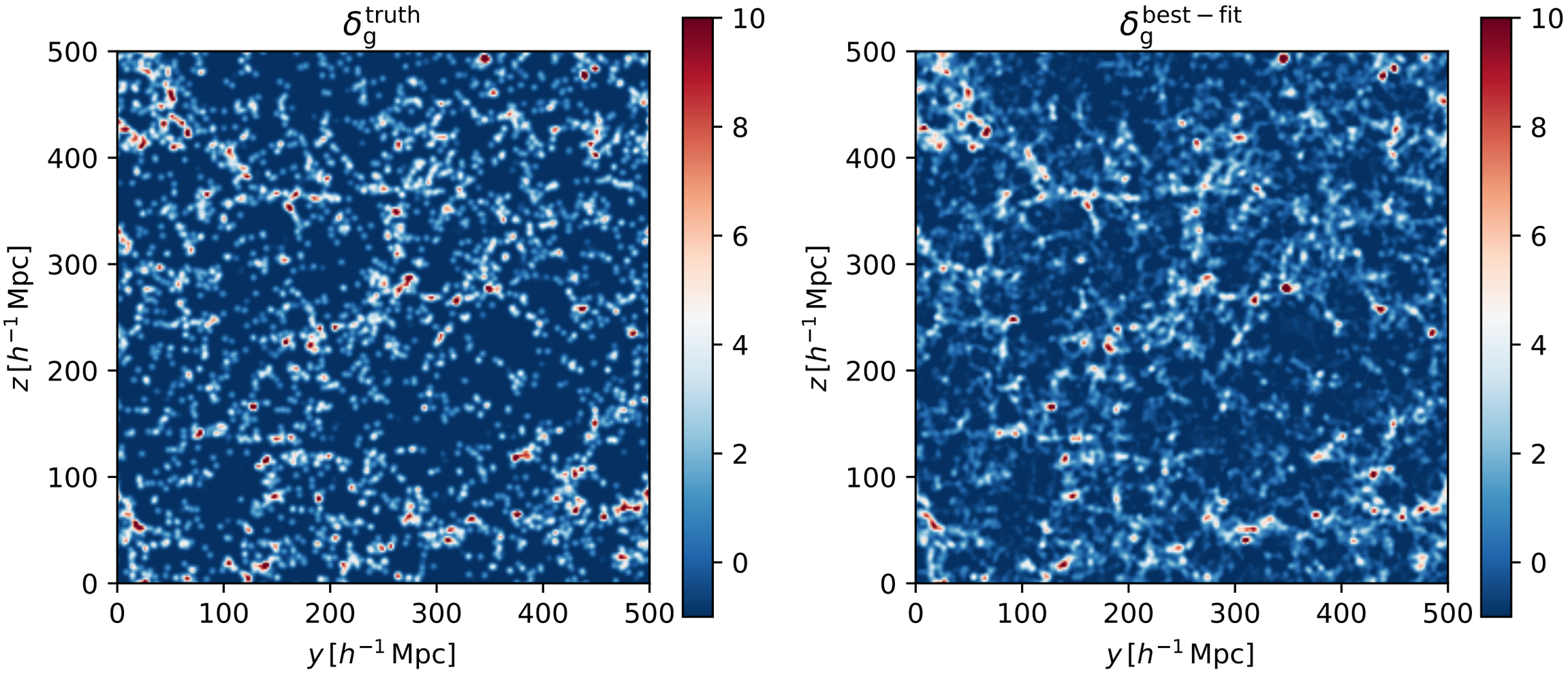
- Solution: extraction of EFT
at the field level!

Schmittfull, Simonovic, Schmidt, Nguen, …

Sullivan, Seljak, Singh’ 21

MI, Cuesta-Lazaro, Mishra-Sharma,
Obuljen, Toomey’24

Field-level comparison: MillenniumTNG

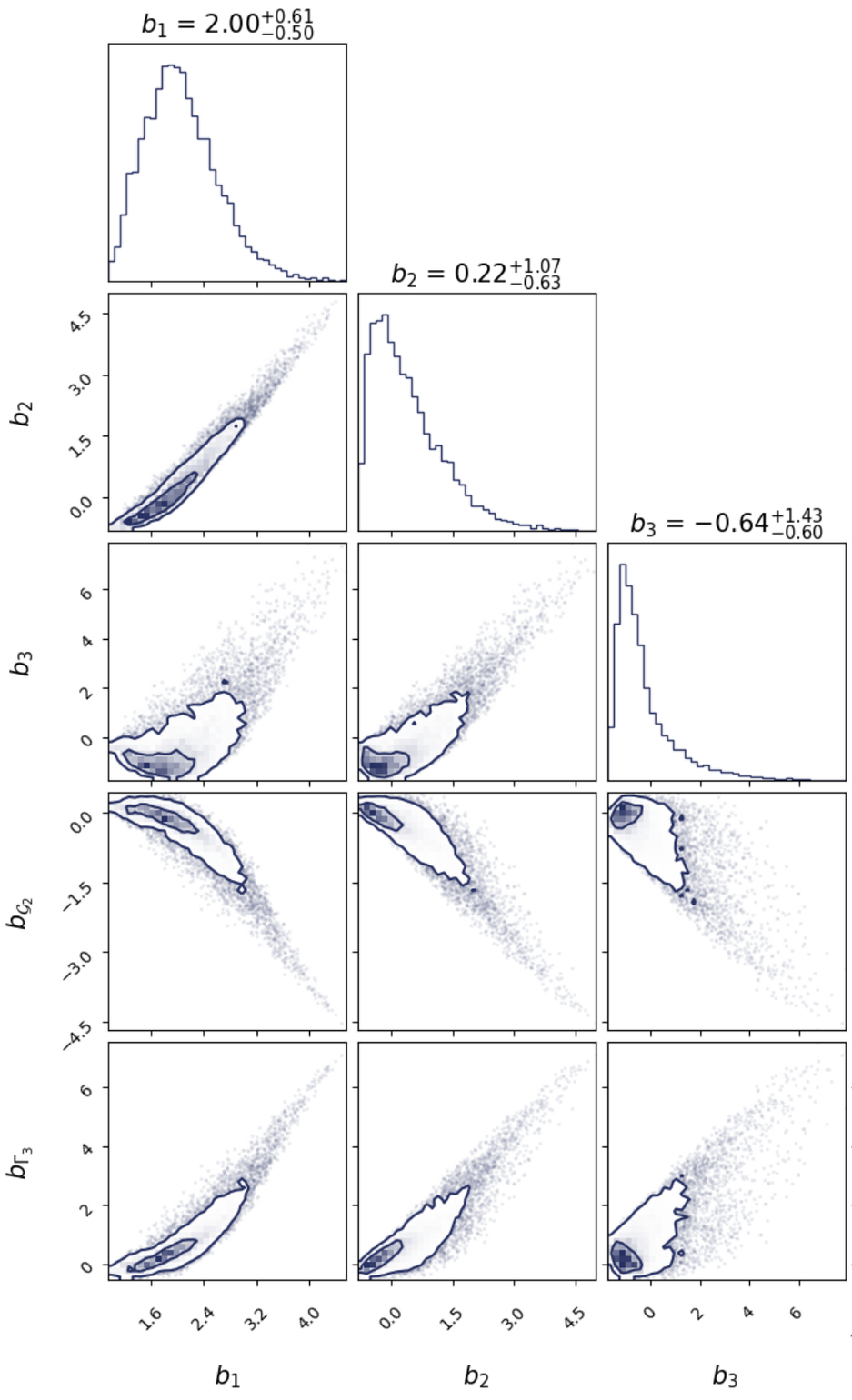


- Don't pay the price of cosmic variance because the initial conditions are known!

MI, Cuesta-Lazaro, Mishra-Sharma, Obuljen, Toomey'24

HOD-based priors

>20,000 cheap sims ⟶ Fit the distribution ⟶ Priors for EFTxFS

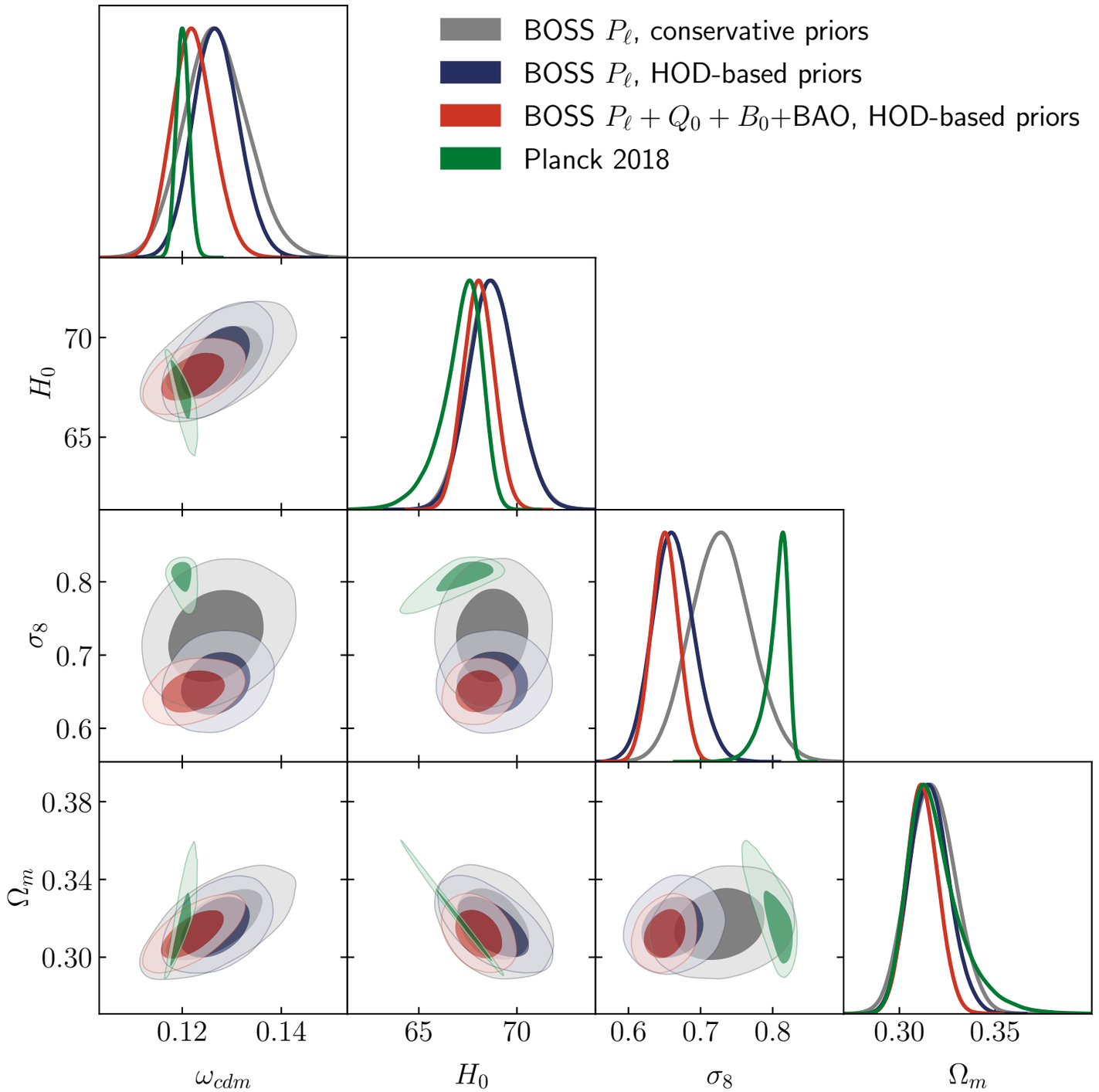


Fitting functions :
Normalizing Flows,
Gaussian Mixture Models (GMM)

MI, Cuesta-Lazaro, Mishra-Sharma, Obuljen, Toomey (2024)

Chen, MI (2025)

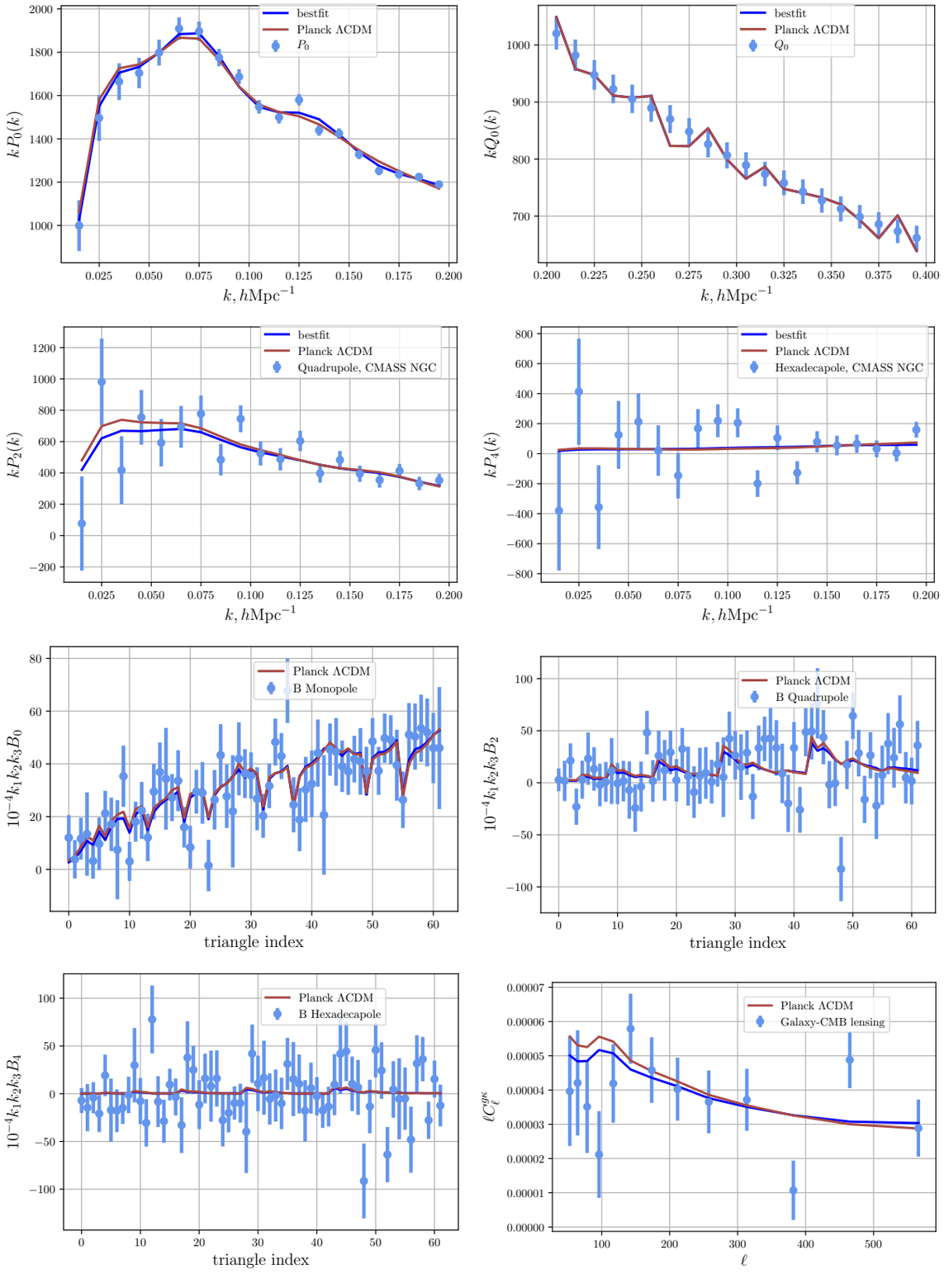
EFT with Simulation-based priors



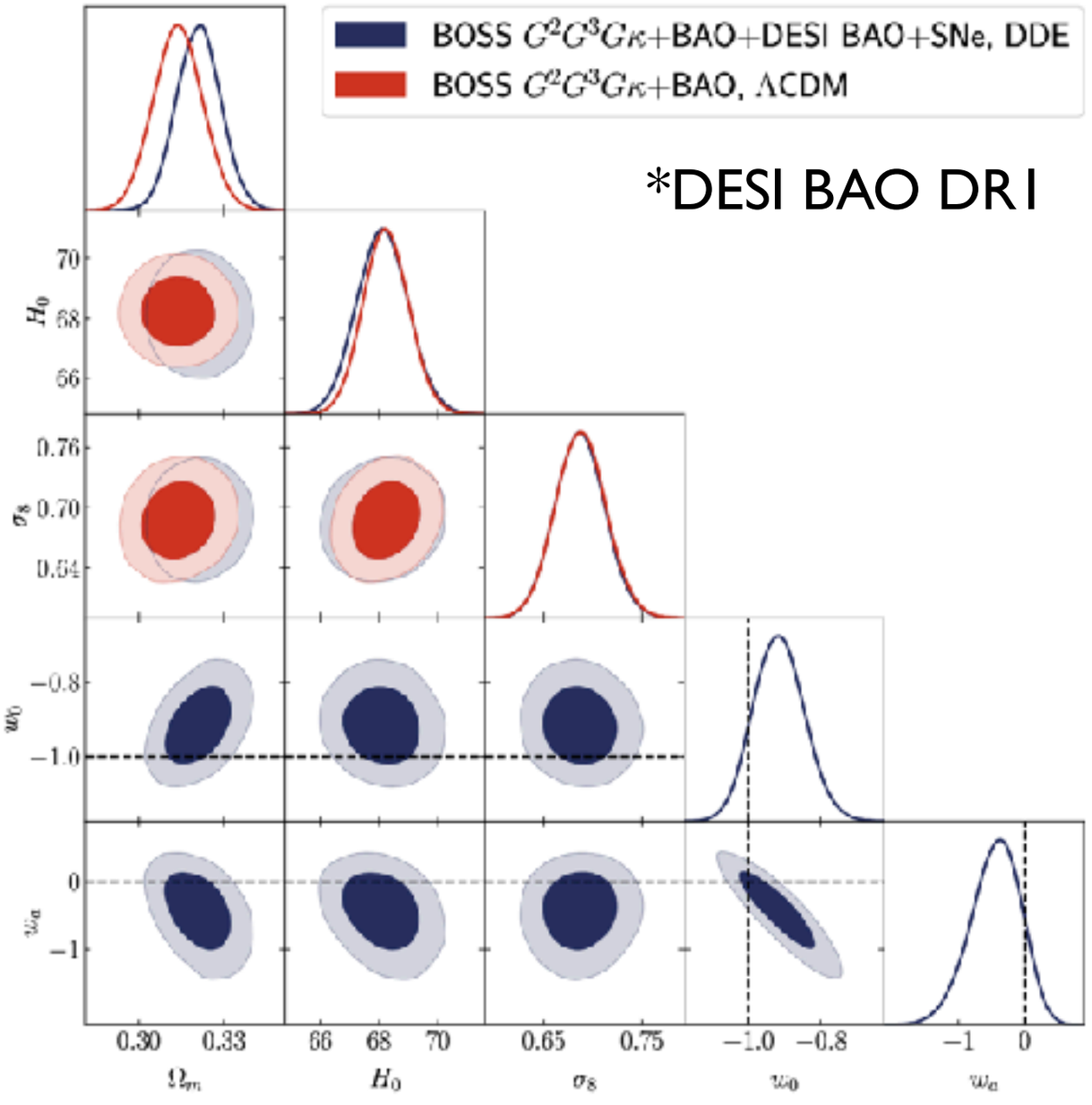
- Some of the strongest constraints ever
- Similar to the full SBI methods
- But more powerful: can be readily applied to any data, e.g. DESI
- Suggests that there's no much cosmology on small scales*

MI, Obuljen, Cuesta-Lazaro, Toomey (2409.10609)

Reanalysis of BOSS: circa 2024



$$\{P_\ell, Q_0, B_\ell, \mathrm{BAO}, C_\ell^{\kappa g}\}$$



*DESI BAO DR1

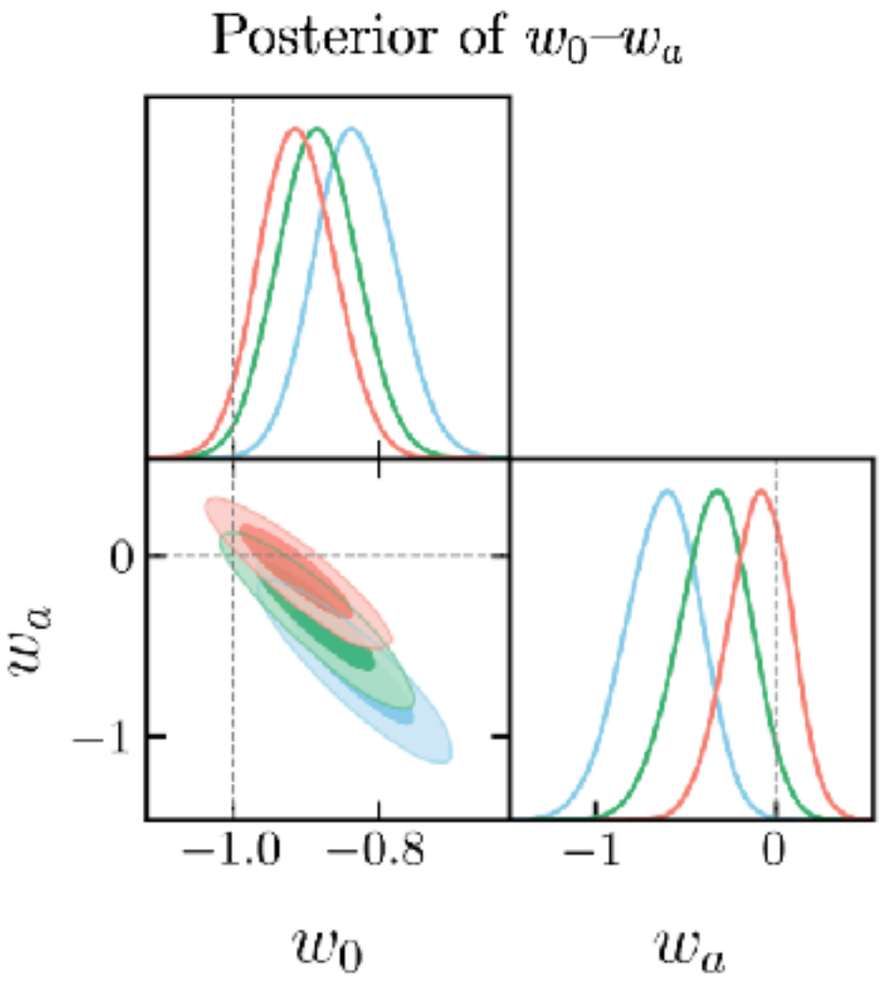
Chen, MI, Philcox, Wenzl (2024)

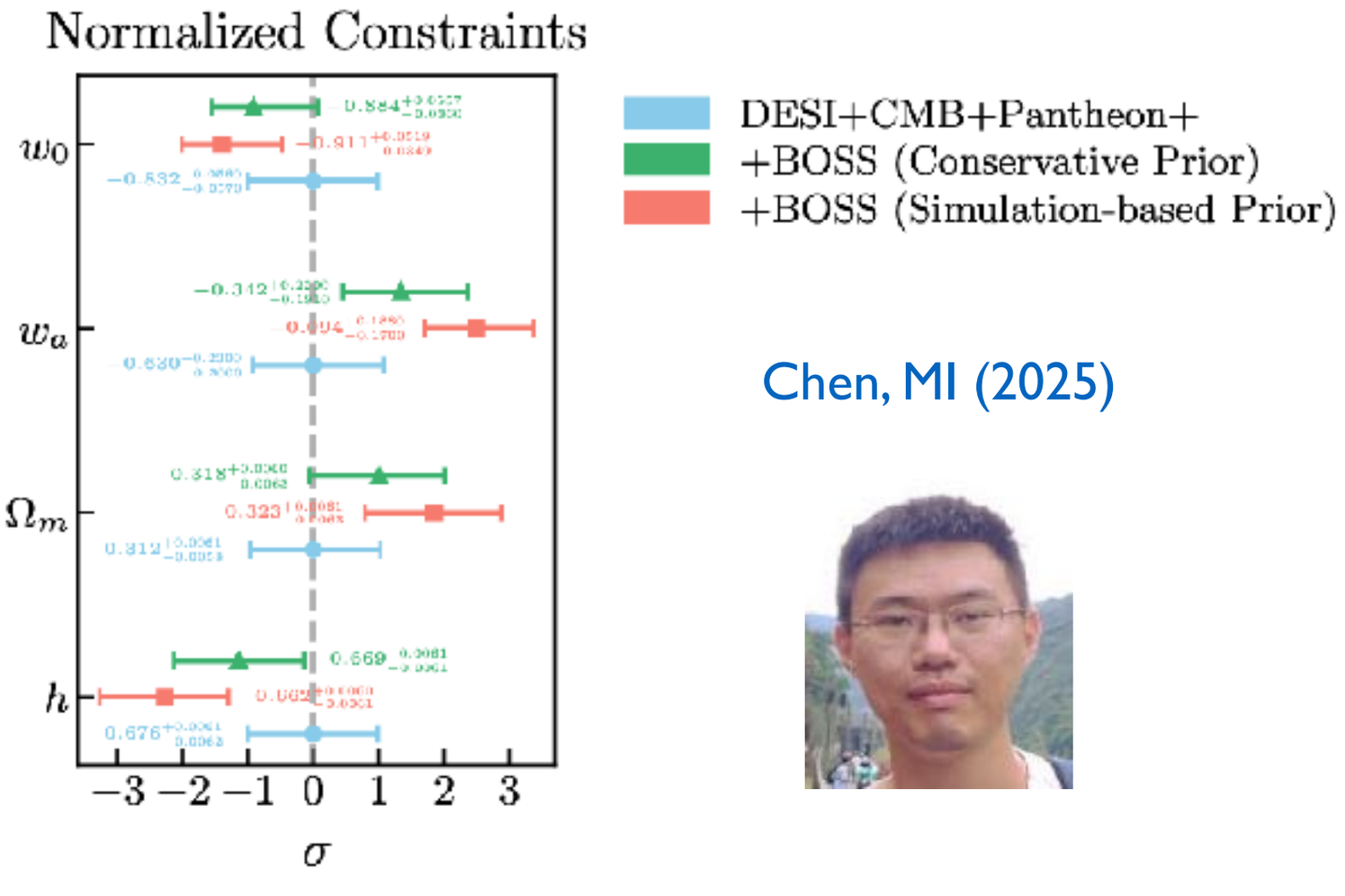
Tension w Planck (systematics)

$\approx 4\sigma$!

Un-detecting Dynamical Dark Energy: with BOSS

- the old FS data from BOSS *disfavors* w0wa even in combination with SNe, and especially so with the simulation-based priors



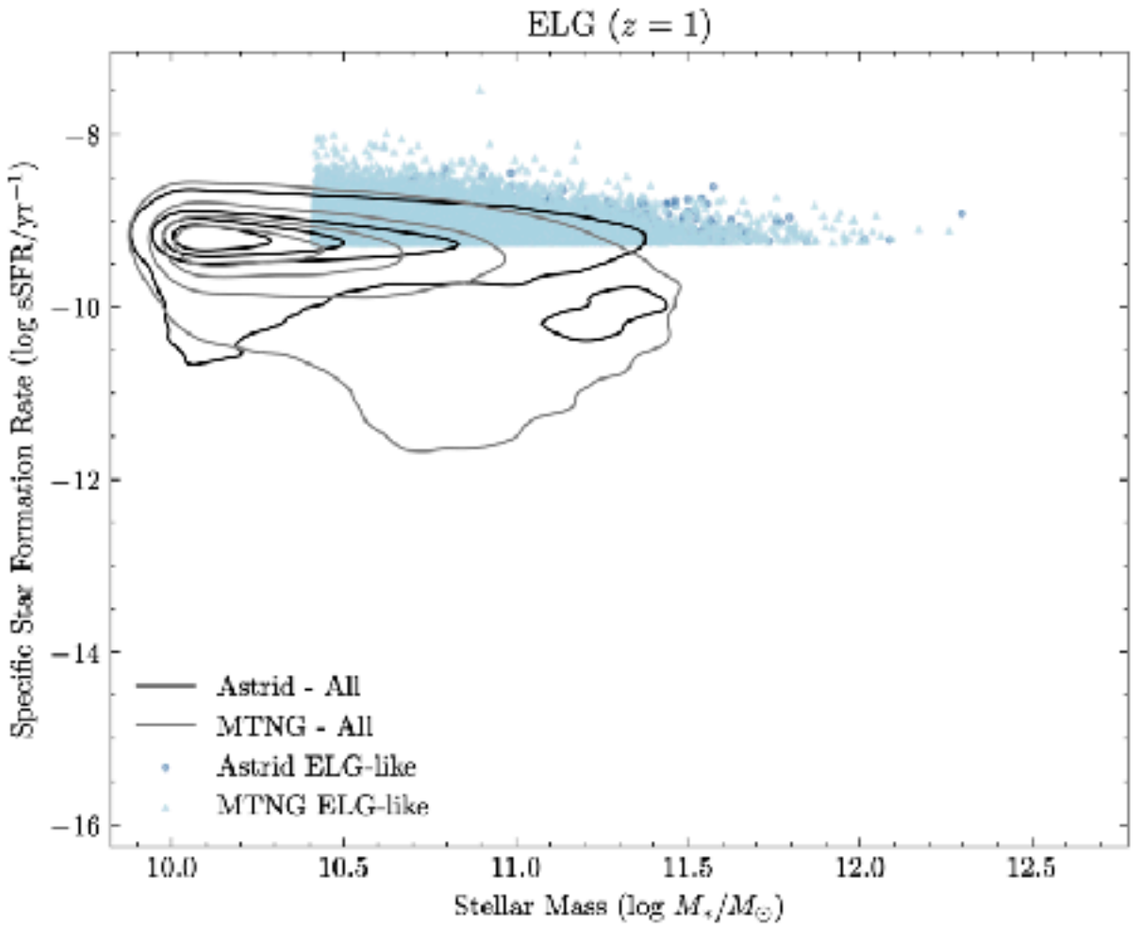


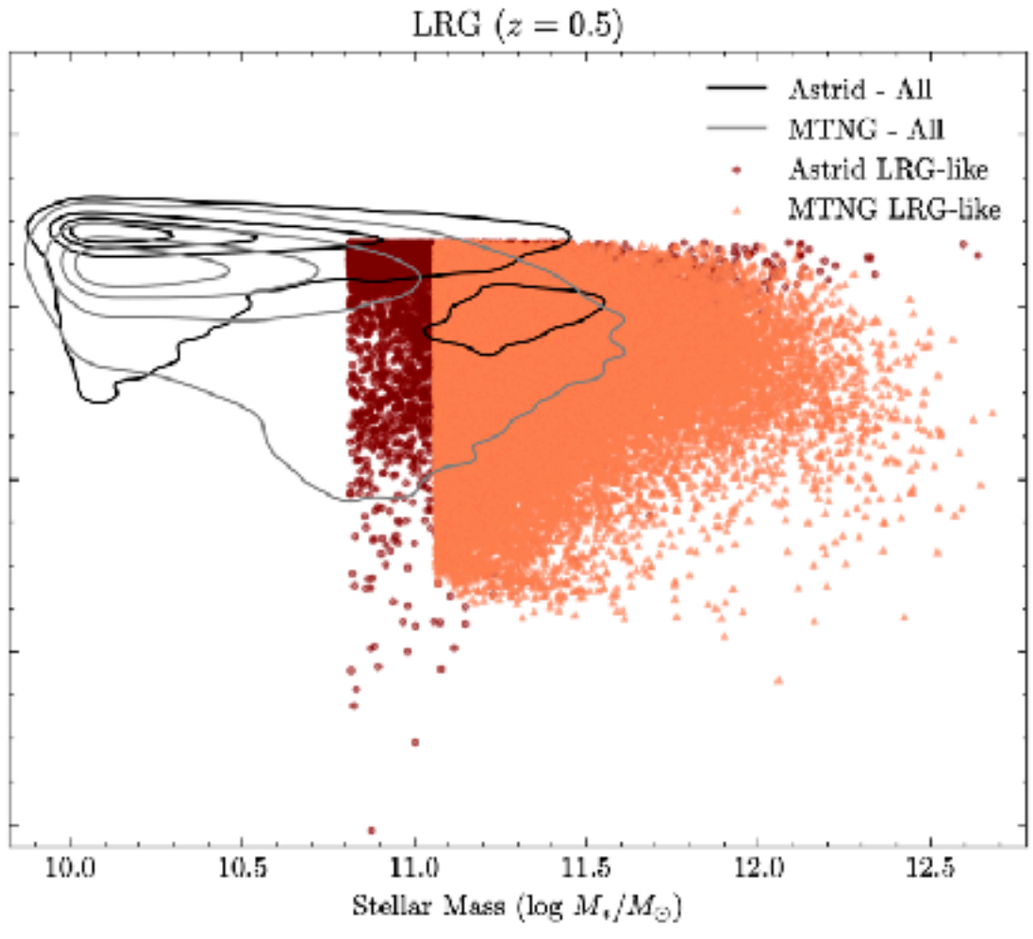
Chen, MI (2025)

Comparison with MTNG and Astrid

- One might be worried that these priors are specific to HOD models
- We validate them on full hydro simulations
- Selections matching the observed color

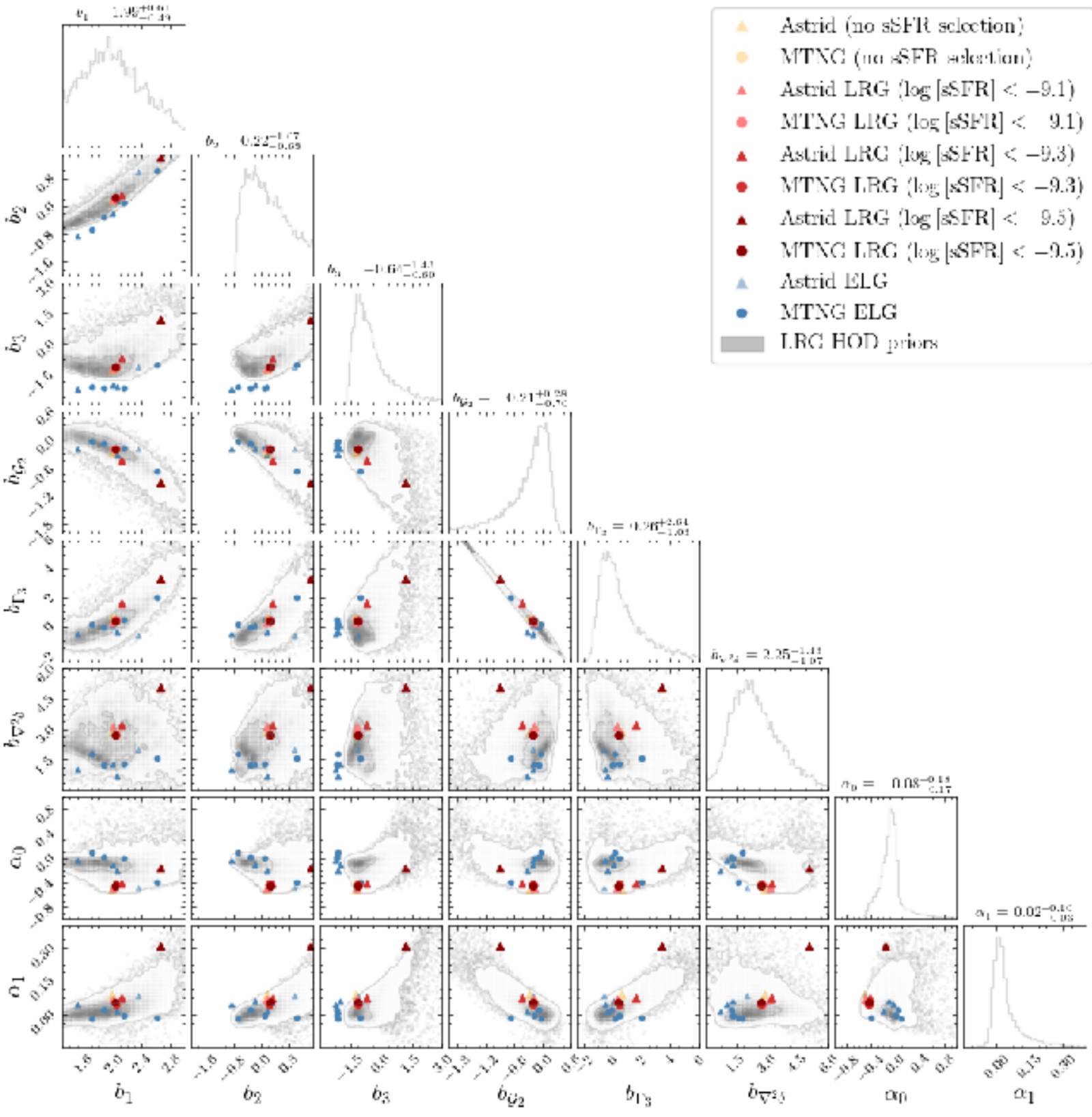
Hadzhiyska++ (2021)





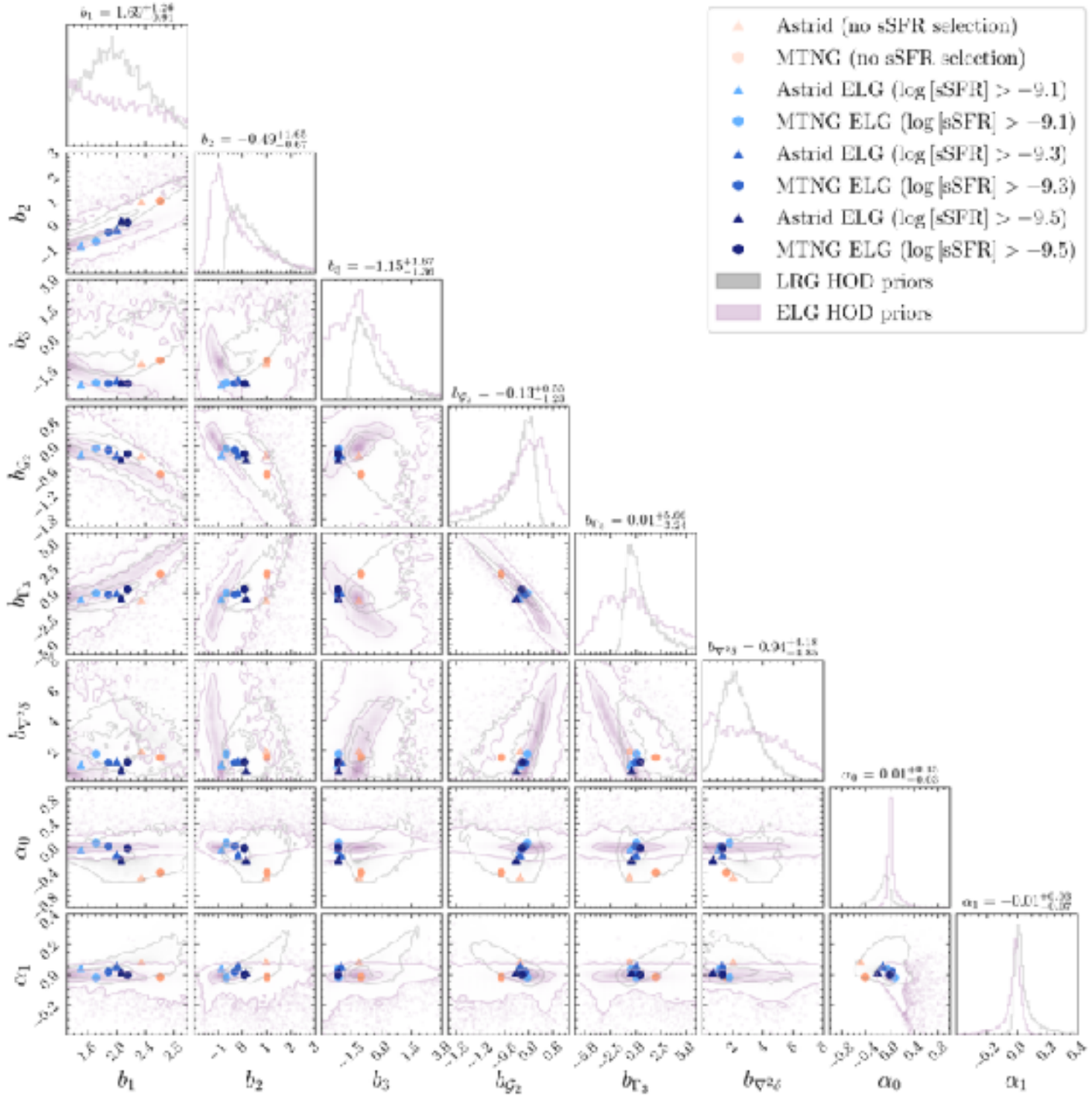
MI, Cuesta-Lazaro, Obuljen, Toomey ++ (2024)

Comparison with MTNG and Astrid

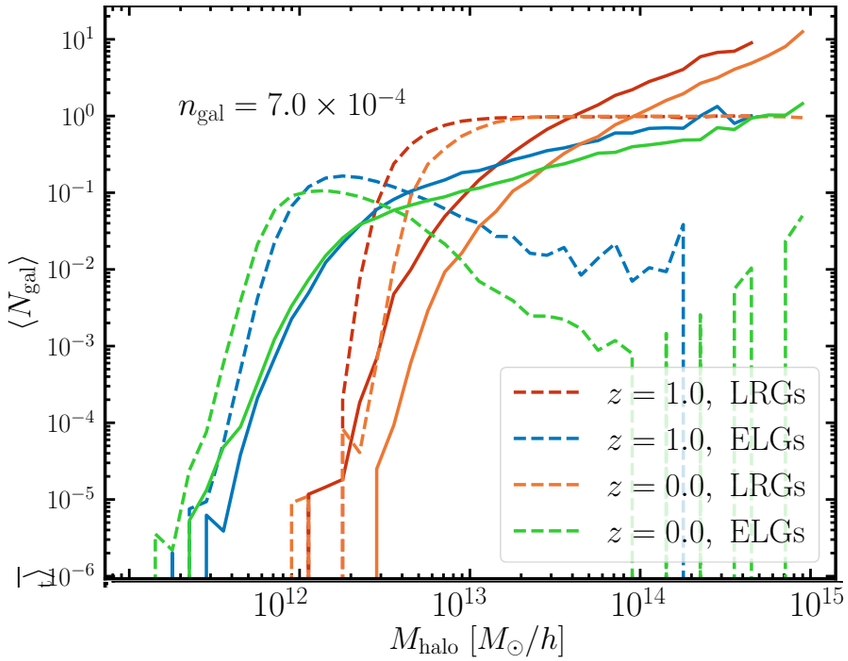


- Subgrid physics uncertainties: can't predict EFT params exactly
- Universality: correlations between EFT parameter trends and corr's seem very robust
- probably we can trust them

Hydro results for ELGs



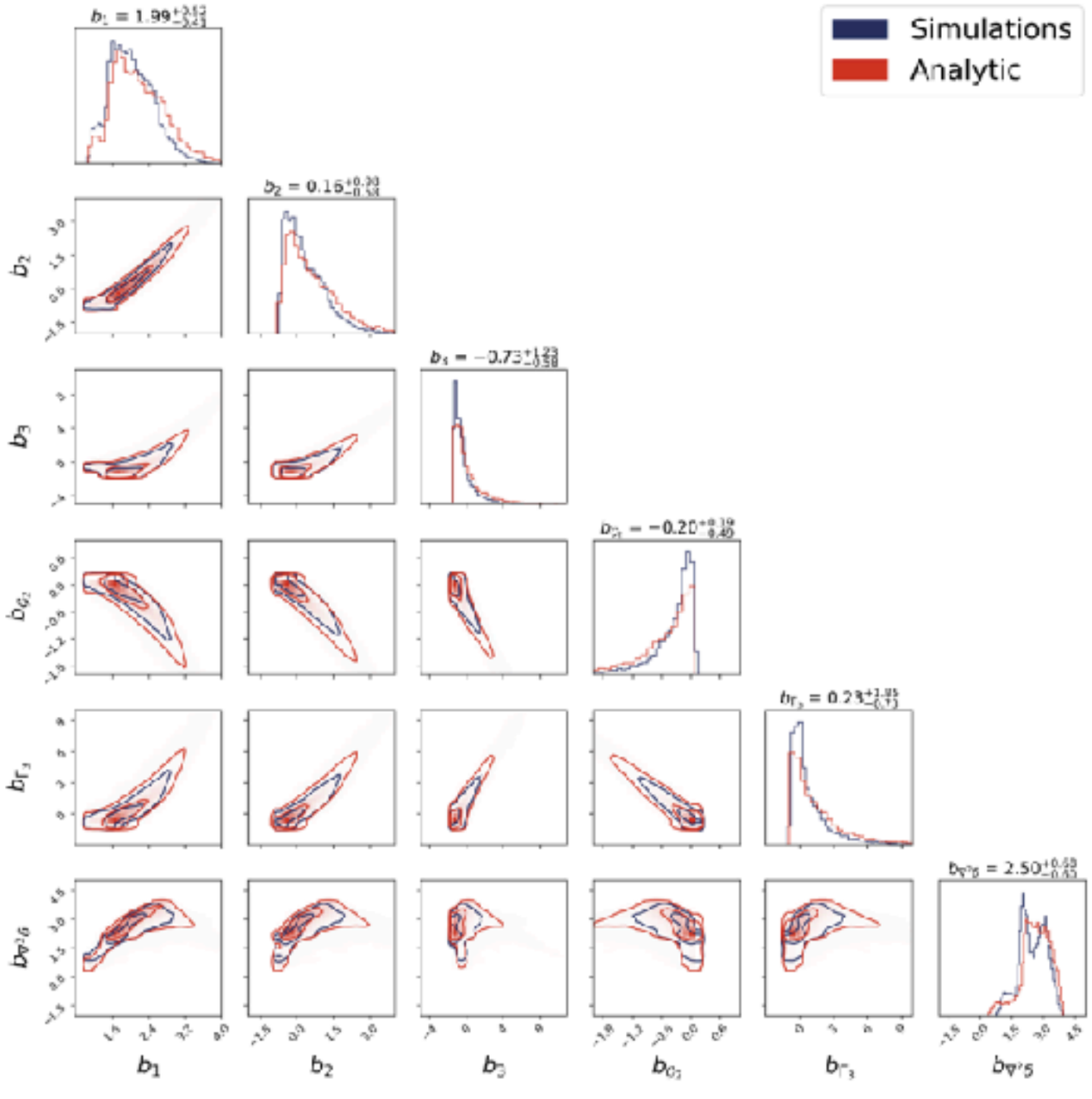
require different HOD functions:



Perfect agreement between HOD and hydro EFT parameters for this tracer as well

Analytic understanding of EFT params from halo model

$$b^g_{\mathcal{O}_a} = \underbrace{\int d\ln M \bar{n}(M)}_{\text{halo mass function}} \underbrace{\langle N_g \rangle(M)}_{\text{galaxy-DM connection}} \underbrace{b^h_{\mathcal{O}_a}(M)}_{\text{Halo bias}}$$



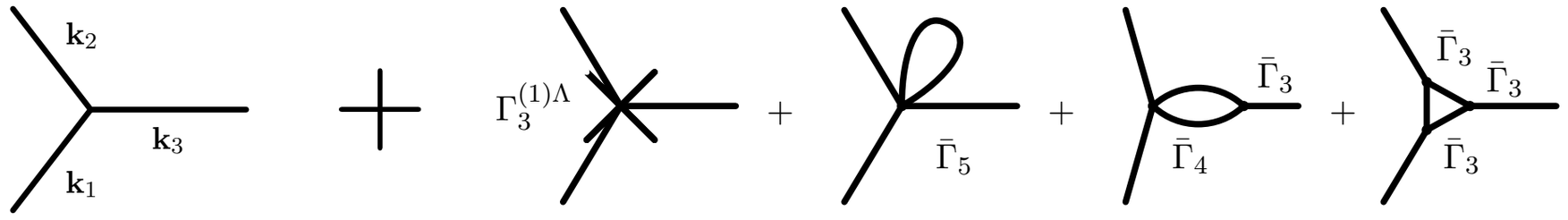
- ~10% accuracy w.r.t. simulations
- can be easily computed without simulations
- can be used in analyses Beyond SM Physics

Seljak (2000)

Akitsu (2024), Ivanov (2025)

One-loop bispectrum

$$\langle \delta_g^3 \rangle \sim$$



Scoccimarro, Eggeimeier, Senatore, D'Amico, Lewandowski, Zhang, Philcox, MI

$$P_{\rm lin} = c_i v^i(k) \qquad B_{1-{\rm loop}} \sim P_{\rm lin} P_{\rm lin} P_{\rm lin} \to C_{ijk} c^i c^j c^k$$

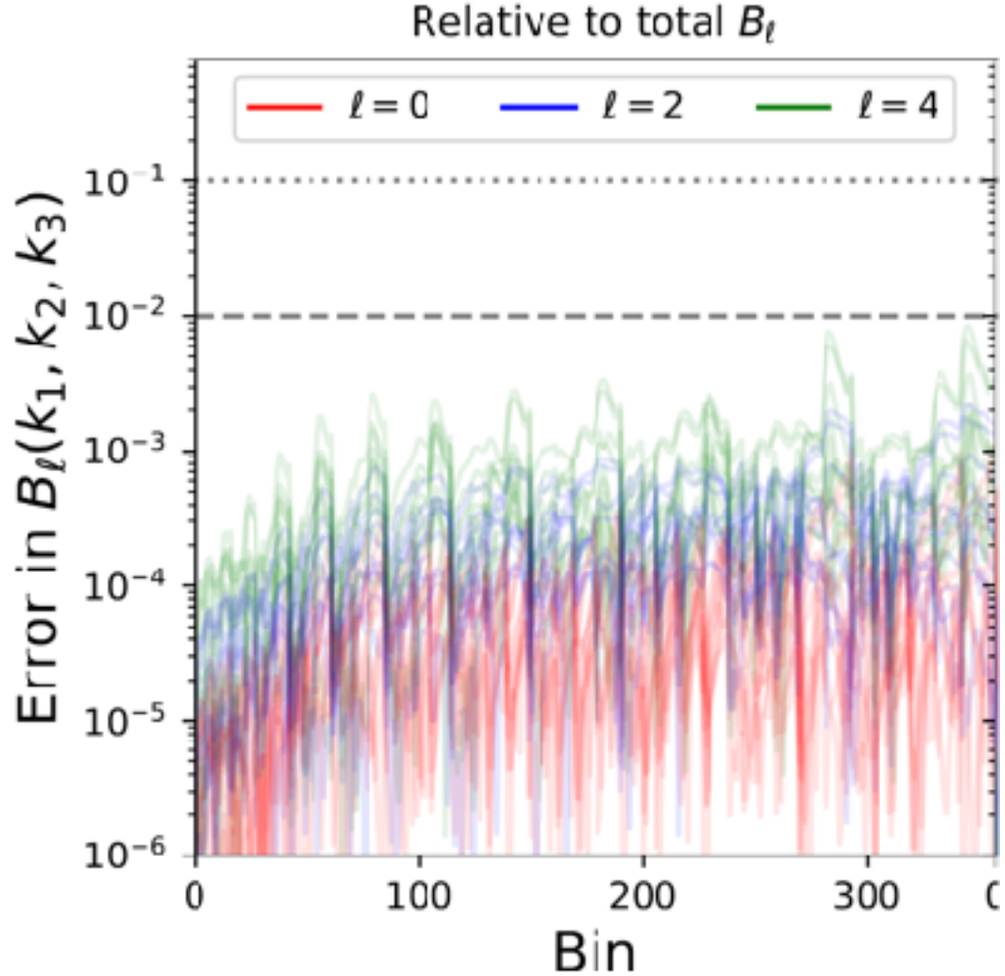
To capture BAO need around 100 elements

$$C_{ijk} \sim (10^2)^3 \sim 10^6$$

Cobra: use SV decomposition of a template bank and get the minimal number of templates: 4-8
Cosmology-dependence to 0.1% precision in <1 sec!

Fast & accurate one-loop bispectrum analysis made possible

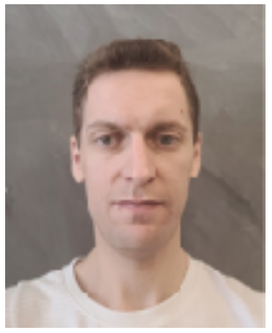
Bakx, MI, Philcox, Vlah (2025)



Back to DESI

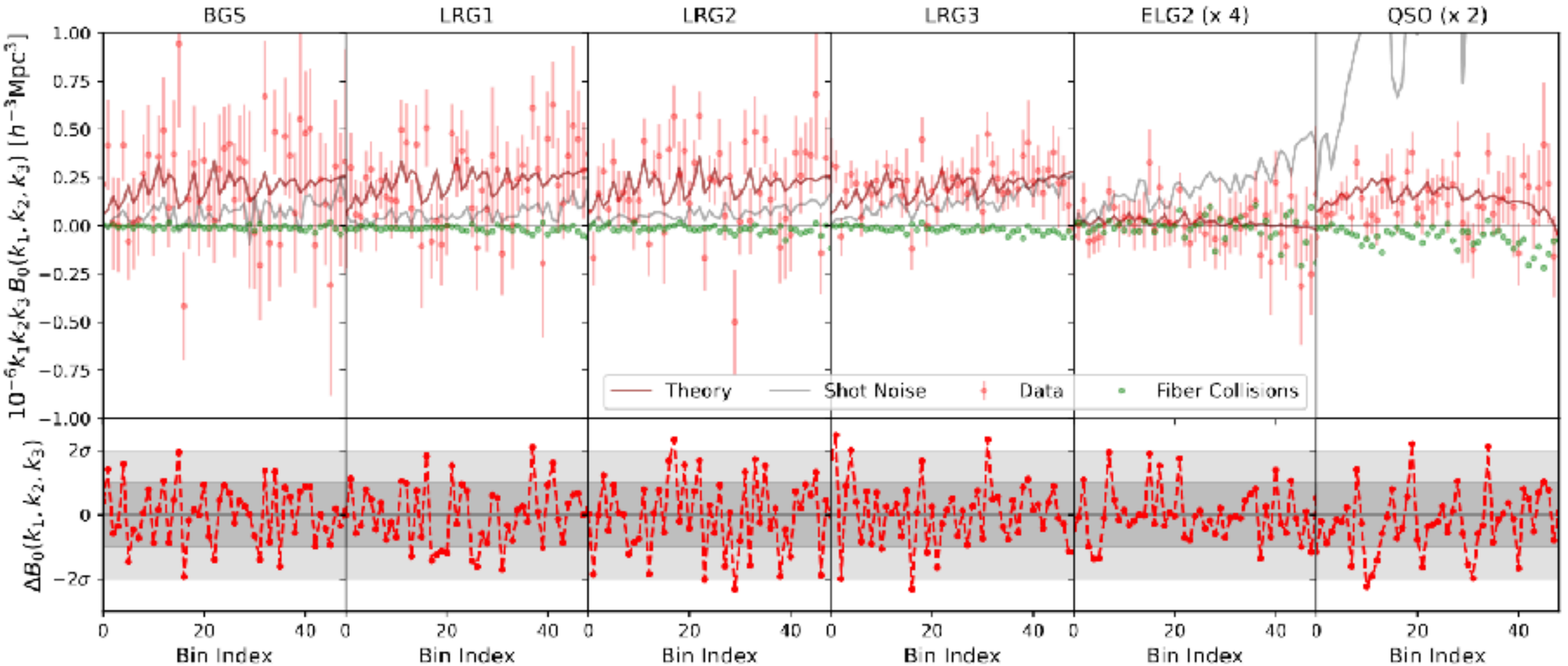
Now back to DESI

- Custom likelihood based on public FS data (DR1)
- Streamlined treatment of systematics
- Fiber collision corrections for B for the first time
- Window-free estimators for P + B



Oliver's talk on week 6 (probably)

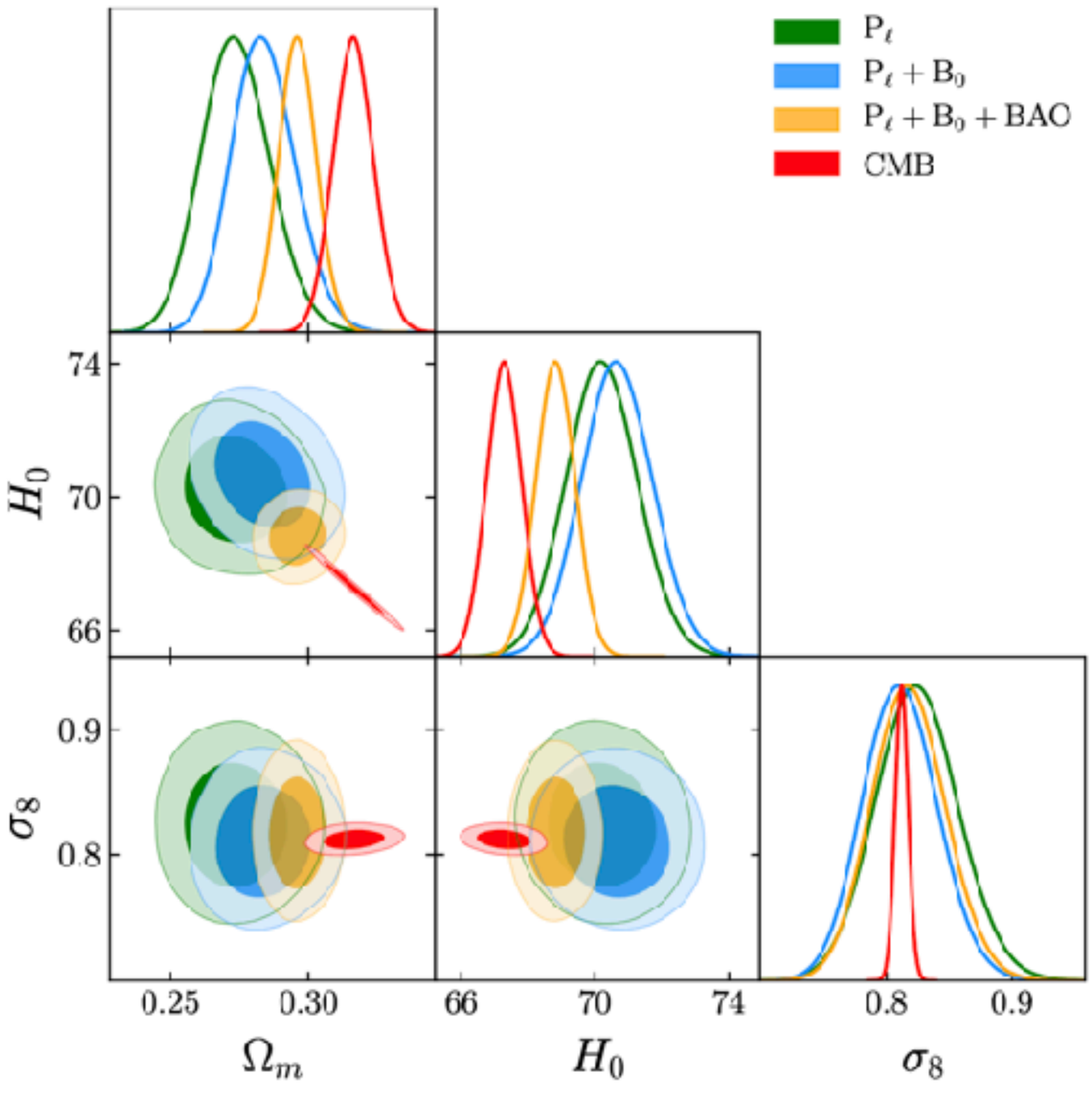
Chudaykin, MI, Philcox (2025)++



LCDM Power Spectrum + Bispectrum

- Consistent w/ DESI's P(k) FS. The bispectrum adds a bit of information and moves Om to Planck

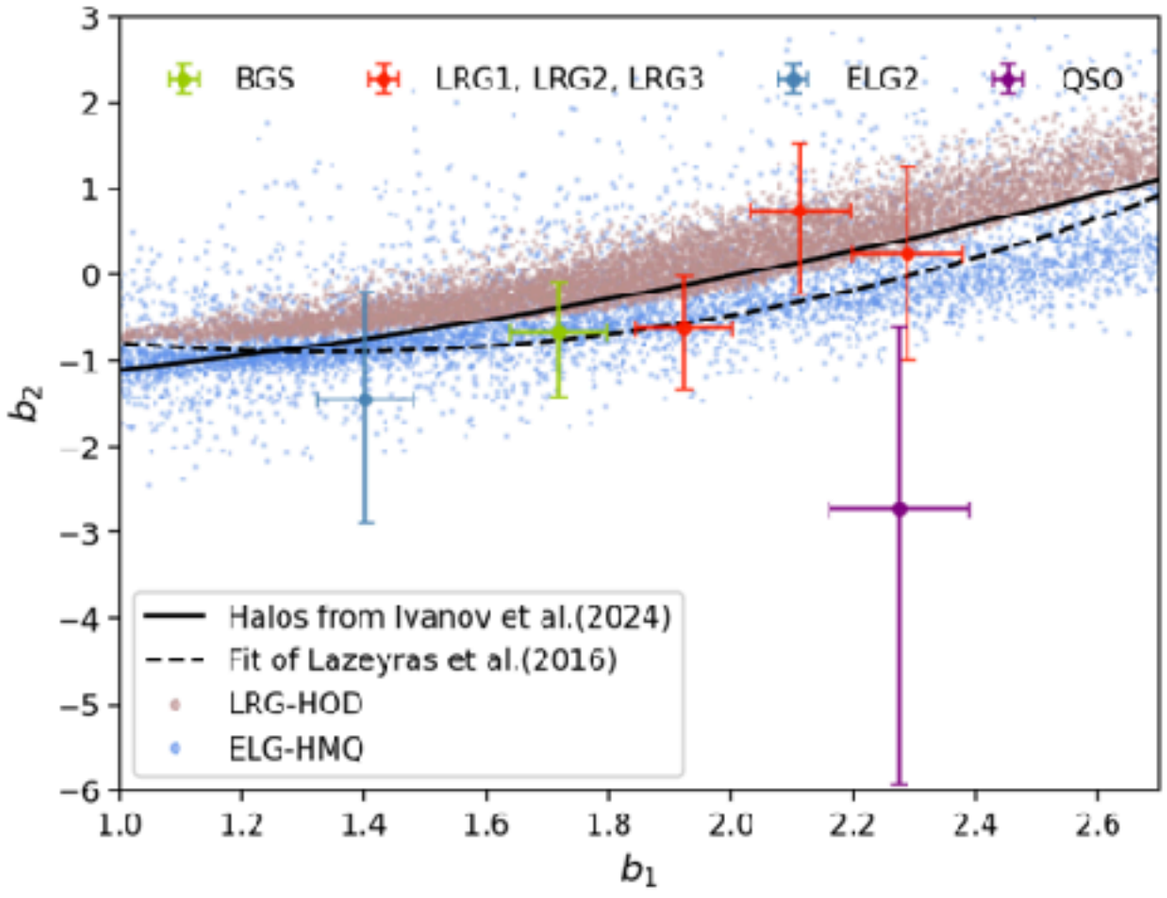
Chudaykin, MI, Philcox (2025)++



Galaxy bias

- Halo bias relations are not particularly accurate

Chudaykin, MI, Philcox (2025)++



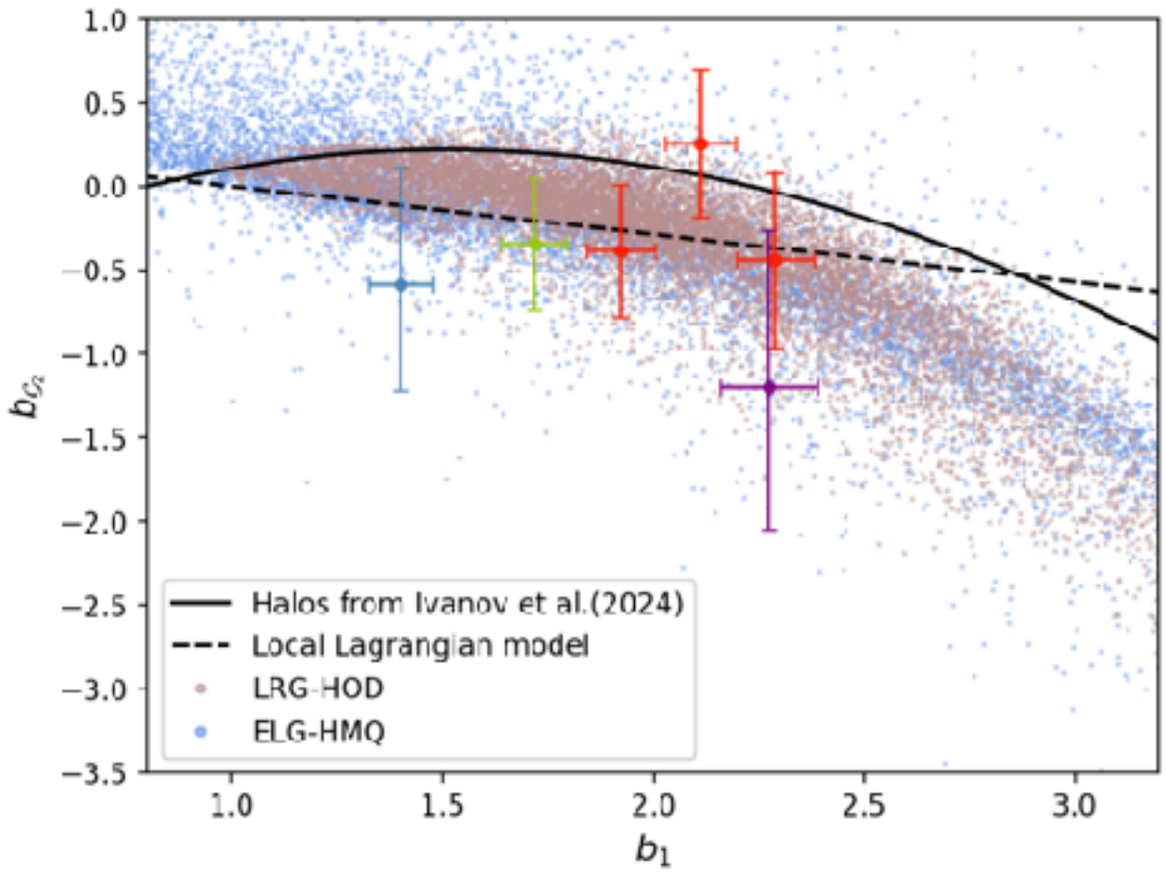
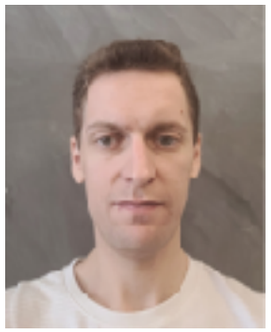
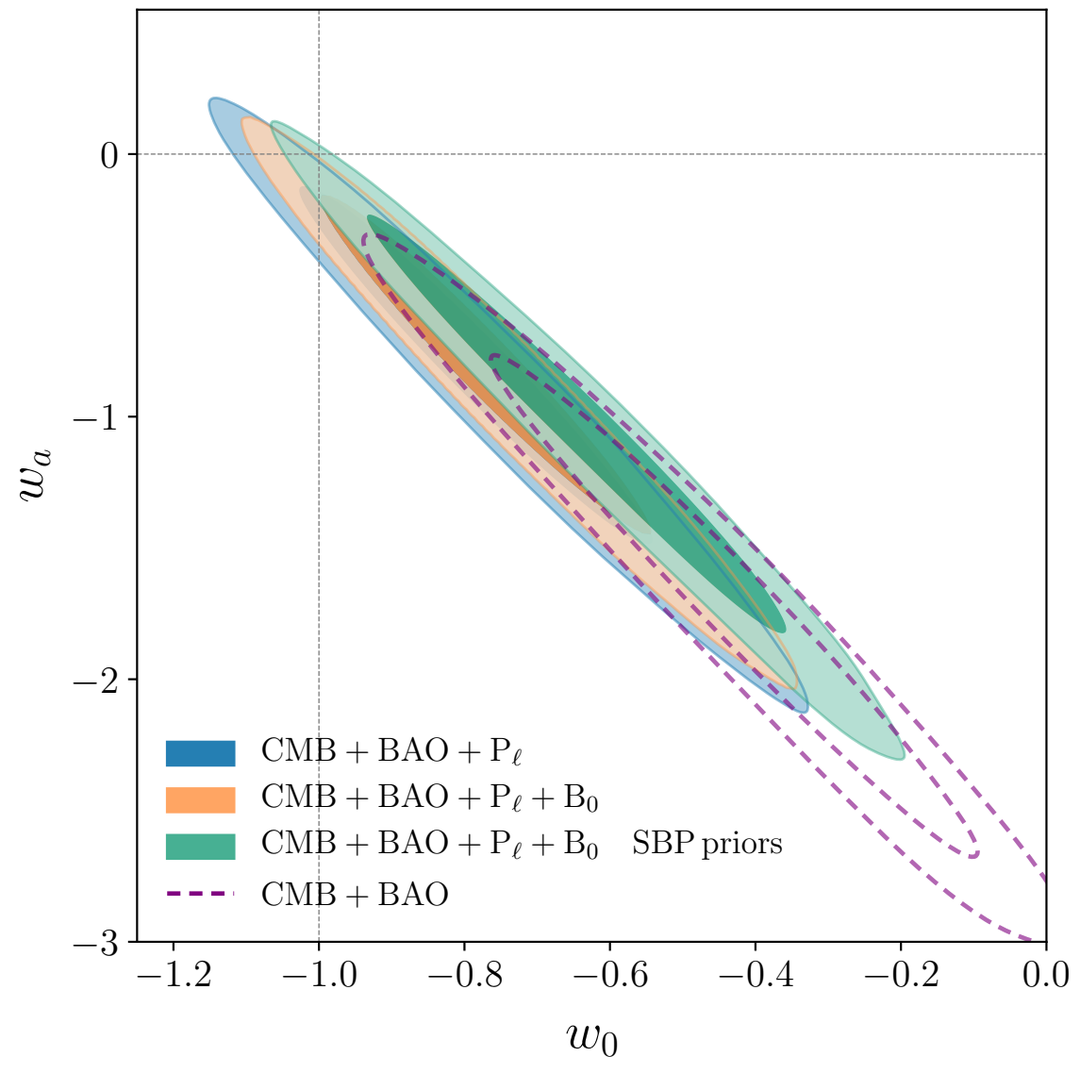


FIG. 10. **Bias Relations**: The linear, quadratic and tidal bias parameters extracted from an analysis of the $P_\ell + B_0$ data for the six DESI data chunks: BGS (green), three LRGs (red), ELG2 (blue) and QSO (purple). The black curves represent results for dark matter halos: the solid curve depicts the fit to the direct measurements from QUIJOTE halo catalogs [150], whilst the dashed curves show the peak-background split prediction for b_2 from [165] and the local Lagrangian bias model prediction for $b_{\mathcal{G}_2}$, respectively [164] The bias parameters measured from the LRG-HOD and ELG-HMQ mock catalogs [155] are shown as discrete data points.

Un-detecting Dynamical Dark Energy



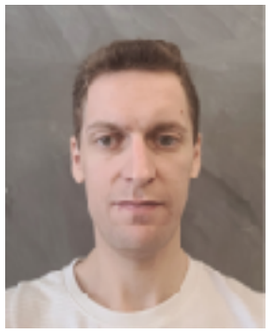

- Independent reanalysis based on public DESI FS data:



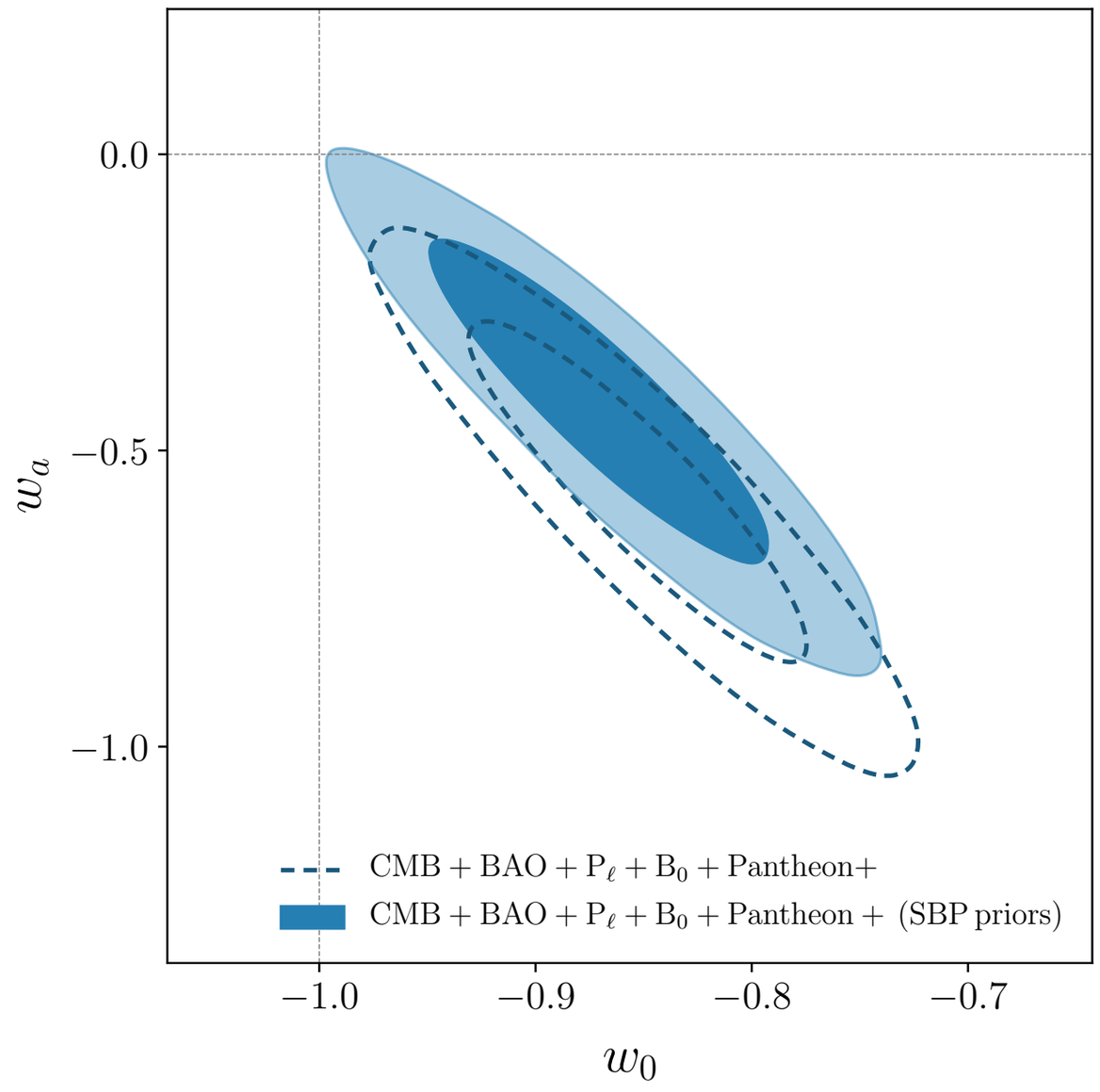
Chudaykin, MI, Philcox, to appear

* no supernovae
* tree-level bispectrum

Un-detecting Dynamical Dark Energy



- With the Supernovae!



- This suggests that w0wa is simply a statistical fluke. No new physics is required at this point

Chudaykin, MI, Philcox, to appear

* tree-level bispectrum

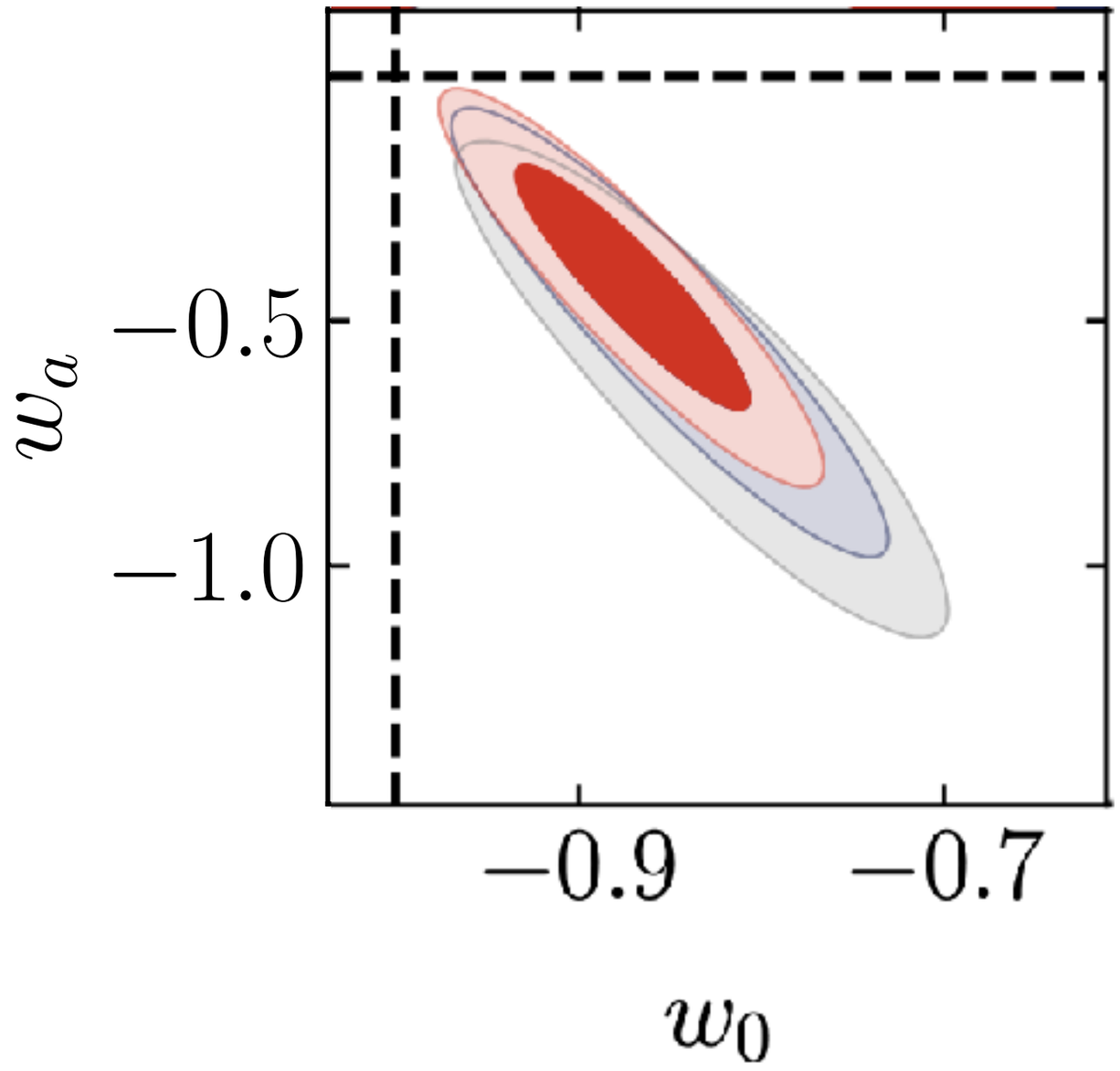
Un-detecting Dynamical Dark Energy

- Kitchen sink (preliminary):

CMB+BAO+SNe

CMB+BAO+SNe+$P_\ell + C_\ell^{g\kappa}$

CMB+BAO+SNe+$P_\ell + C_\ell^{g\kappa} + B_\ell^{1-loop}$



Chen, Chudaykin, MI, Philcox, to appear

Summary

- EFT-based FS is a highly competitive probe
- Makes a difference for BSM models
- e.g. suggests DESI's w0wa is a statistical fluctuation
- Huge improvements in the future
- Non-perturbative information, interface with simulations is key to boost constraining power

Thank you!