

# Cosmology with galaxy clustering

A joint analysis of the power spectrum and bispectrum

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UK Research  
and Innovation



# From galaxy surveys to cosmology

Stage IV galaxy redshift surveys

→ unprecedented volume, high precision measurements

Neutrino mass? Modified gravity?  
Solve tensions?

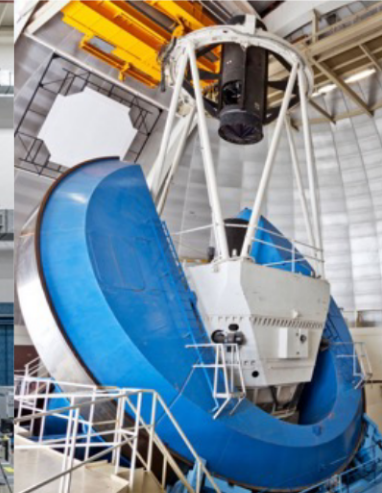
Full exploitation:

- Nonlinear regime
- Higher order statistics

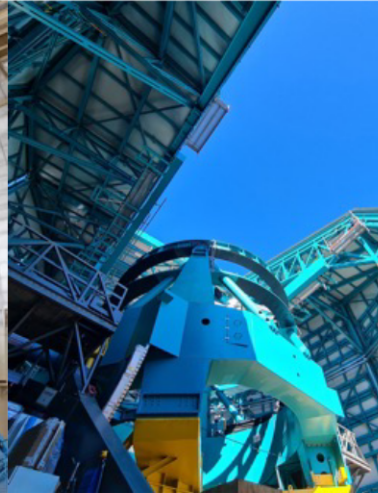
Euclid



DESI



Rubin



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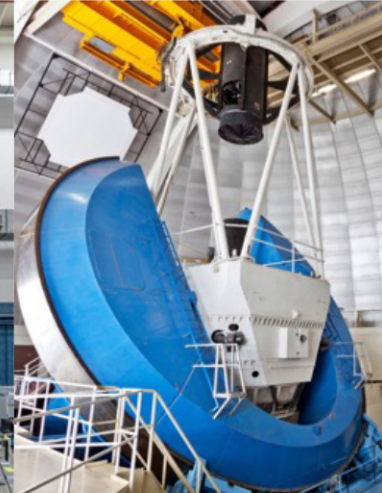
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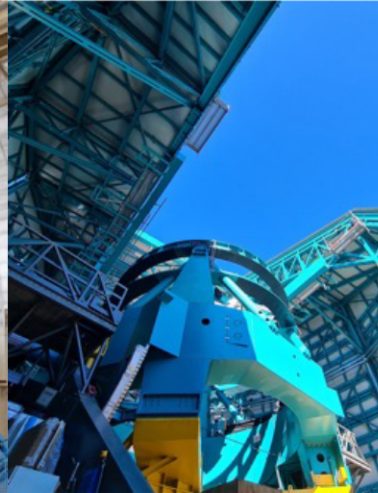
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Accurate & fast theoretical model → Likelihood analysis

# PBJ: Power spectrum & Bispectrum Joint analysis

- 1-loop power spectrum + tree-level bispectrum with non-linear galaxy bias (all in Python)
- IR-resummation routine (w – nw split)
- samplers: emcee (affine invariant & Metropolis-Hastings), Multinest (nested sampling)
- Binning effects
- Different likelihood functions for noise in the covariance matrix

CM, F. Rizzo, K. Pardede, A. Oddo, E. Sefusatti, A. Eggemeier, C. Porciani  
[1908.01774] [2108.03204] [2204.13628]

# Theoretical model – power spectrum

- EFTofLSS model (1loop + counterterms)
- Non-linear bias expansion
- Infra-red resummation routine
- FastPT → model evaluation (28 loop integrals!) in ~30 ms

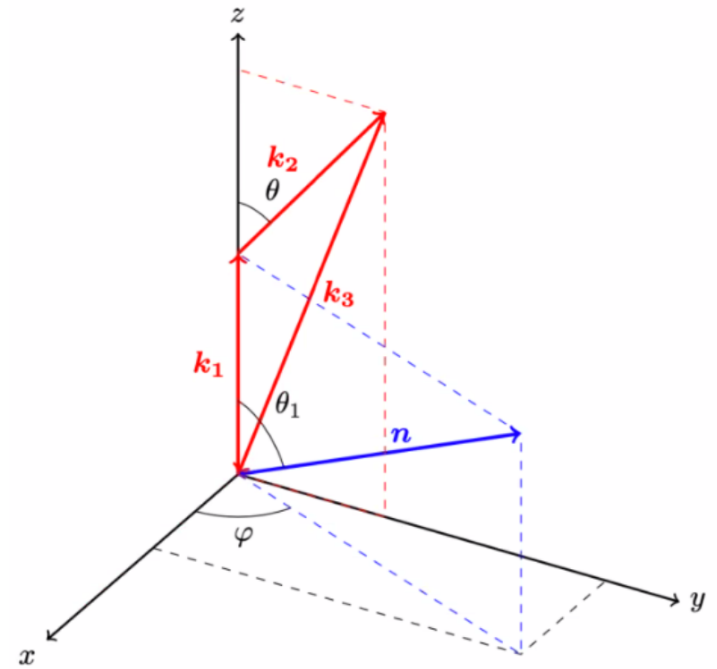
$$P_{gg}(\mathbf{k}) = Z_1^2(\mathbf{k})P_L(k) + 2 \int d^3\mathbf{q} [Z_2(\mathbf{q}, \mathbf{k} - \mathbf{q})]^2 P_L(q)P_L(|\mathbf{k} - \mathbf{q}|) \\ + 6Z_1(\mathbf{k})P_L(k) \int d^3\mathbf{q} Z_3(\mathbf{k}, \mathbf{q}, -\mathbf{q})P_L(q) + P_{\text{ctr}}(\mathbf{k}) + P_{\text{noise}}(\mathbf{k})$$

## Nuisance parameters

$b_1, b_2, b_{\gamma 2}, b_{\Gamma 3},$	bias
$\alpha_P, \epsilon_{1,k^2}, \epsilon_{2,k^2},$	noise
$c_0, c_2, c_4, c_{k^4}$	EFT counterterms

# Theoretical model – bispectrum

- Tree-level model
- Bias parameters:  $b_1, b_2, b_{\gamma_2}, \alpha_1, \alpha_2, \alpha_3$
- Higher order multipoles
- Model evaluation in  $\sim 0.1$  s

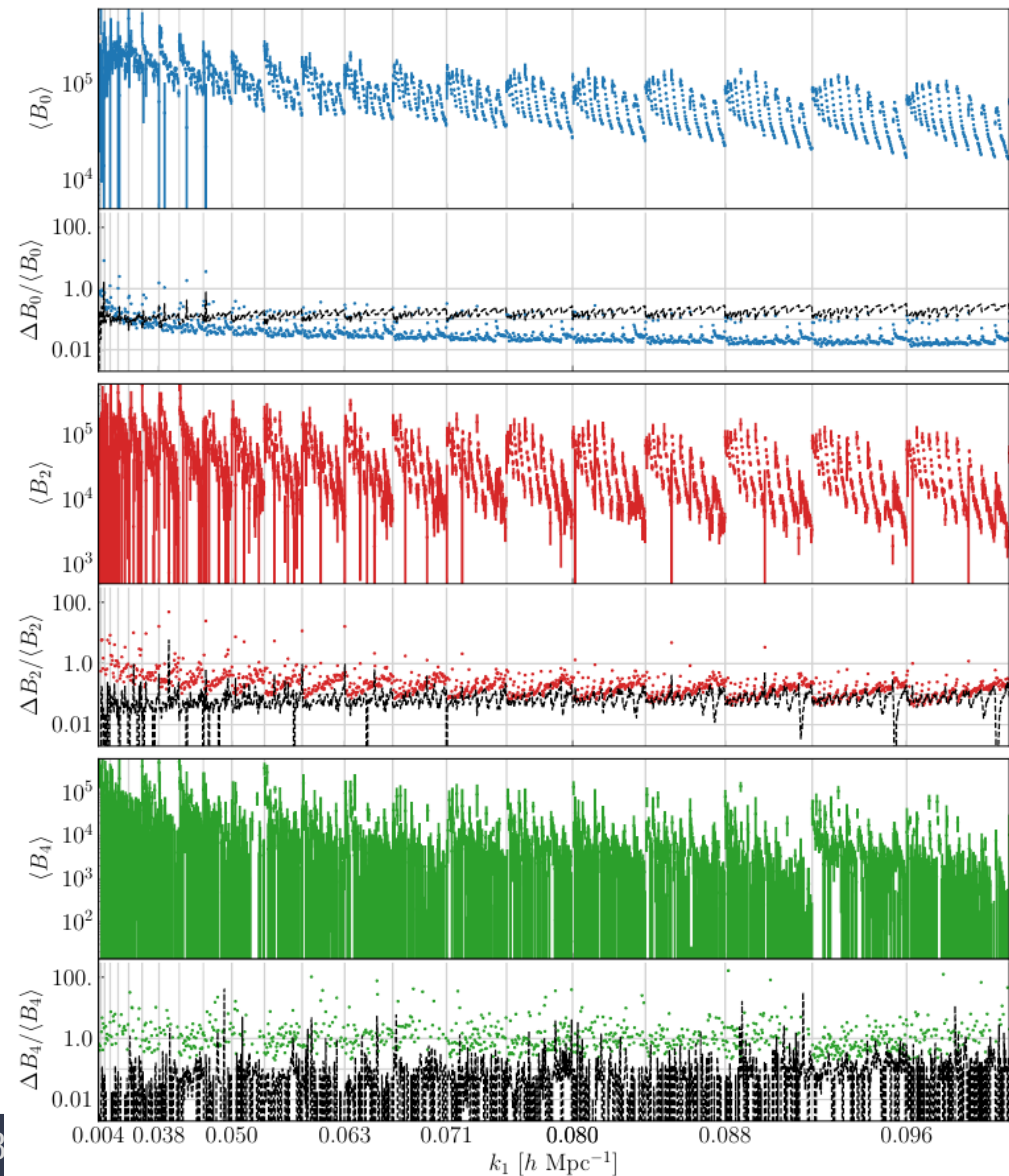


$$B_s(\vec{k}_1, \vec{k}_2, \hat{n}) = 2Z_1(\vec{k}_1)Z_1(\vec{k}_2)Z_2(\vec{k}_1, \vec{k}_2)P_L(k_1)P_L(k_2)$$

$$B_{stoch}(k_1, \vec{k}_2, \hat{n}) = \frac{1}{\bar{n}} [(1 + \alpha_1)b_1 + (1 + \alpha_3)f\mu^2] Z_1(\vec{k}_1)P_L(k_1) + \frac{1 + \alpha_2}{\bar{n}^2}$$

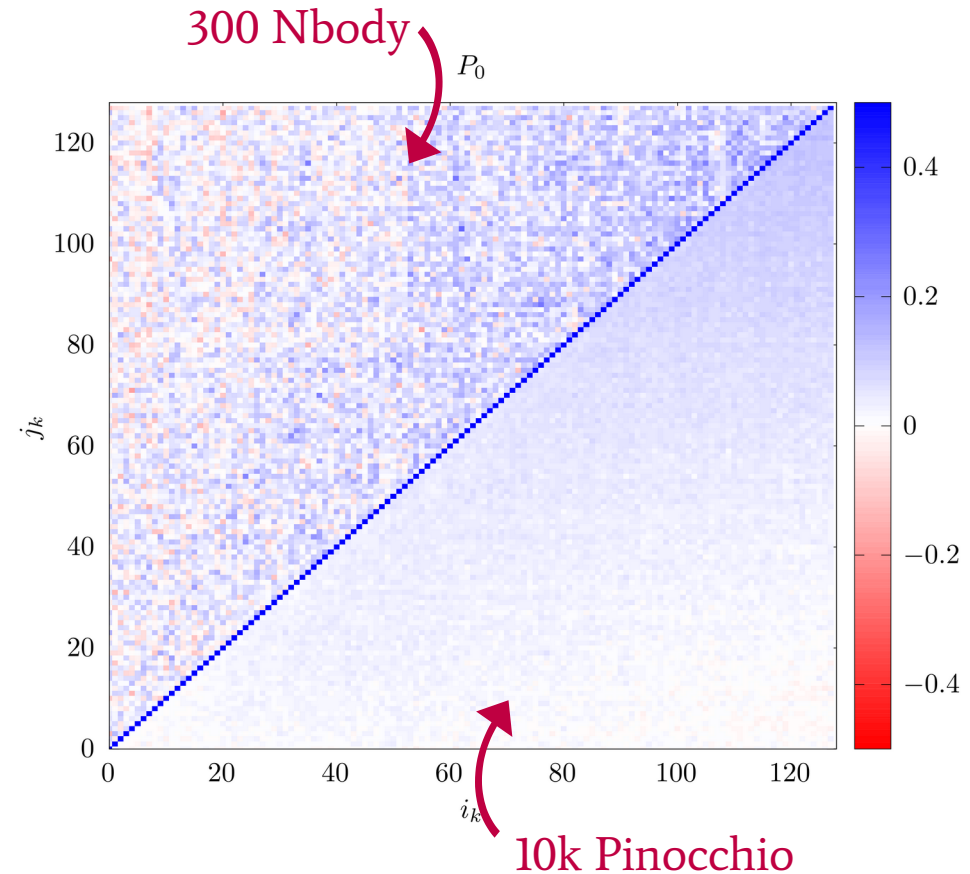
# Validation dataset

- 300 DM-only N-body simulations (Minerva),  $\Lambda$ CDM cosmology
- $L=1500 \text{ Mpc}/h \rightarrow V_{\text{tot}} \approx 1000 \text{ Gpc}^3/h^3$



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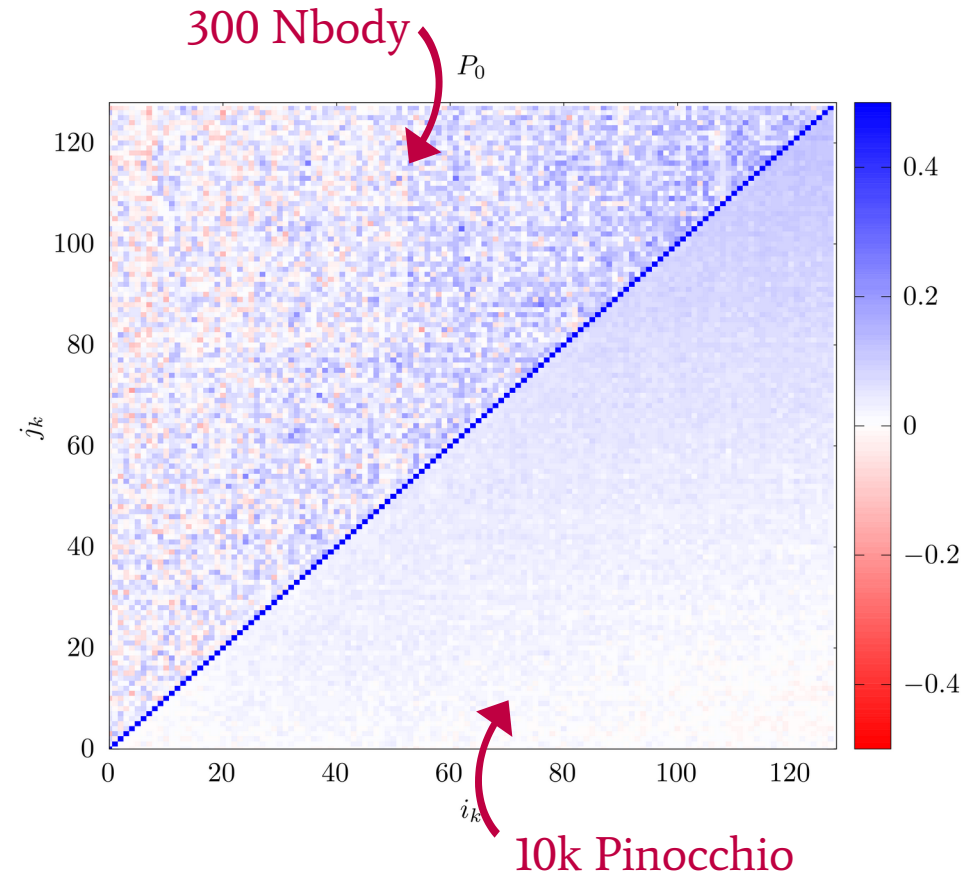




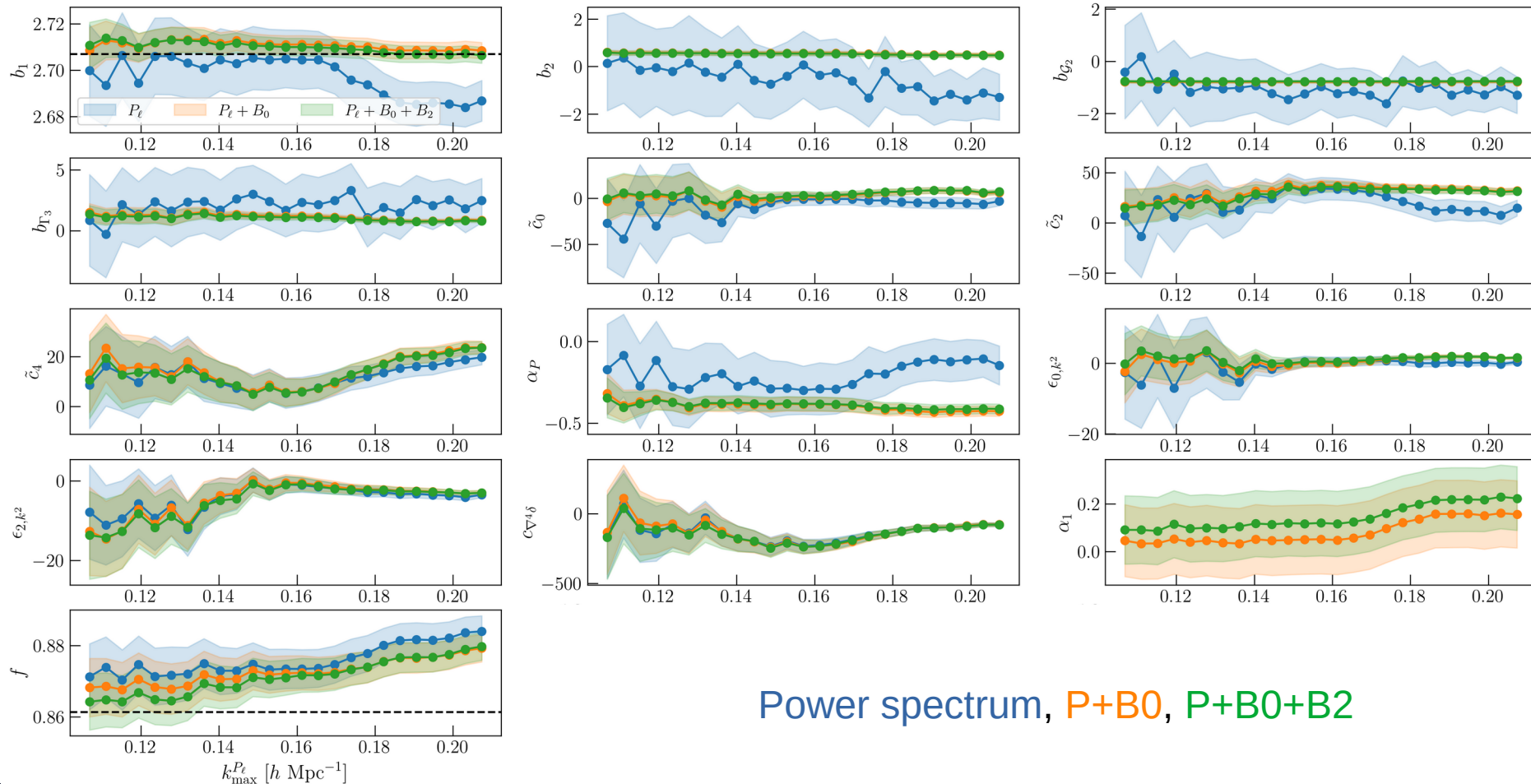
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Bispectrum multipoles analysis  
[Rizzo+2204.13628], see Kevin's  
talk!



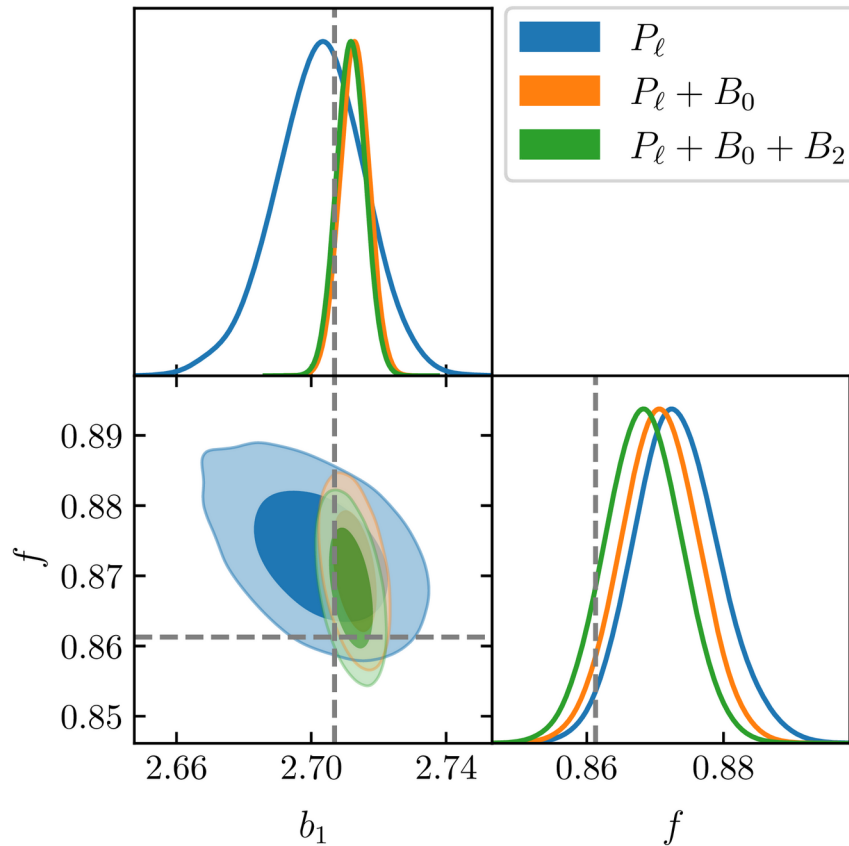
# P+B in redshift space [CM+ in prep]



Power spectrum, P+B0, P+B0+B2

# P+B in redshift space [CM+ in prep]

- Significant improvement on  $b_1 - f$  with  $B_0$
- No improvement with  $B_2$

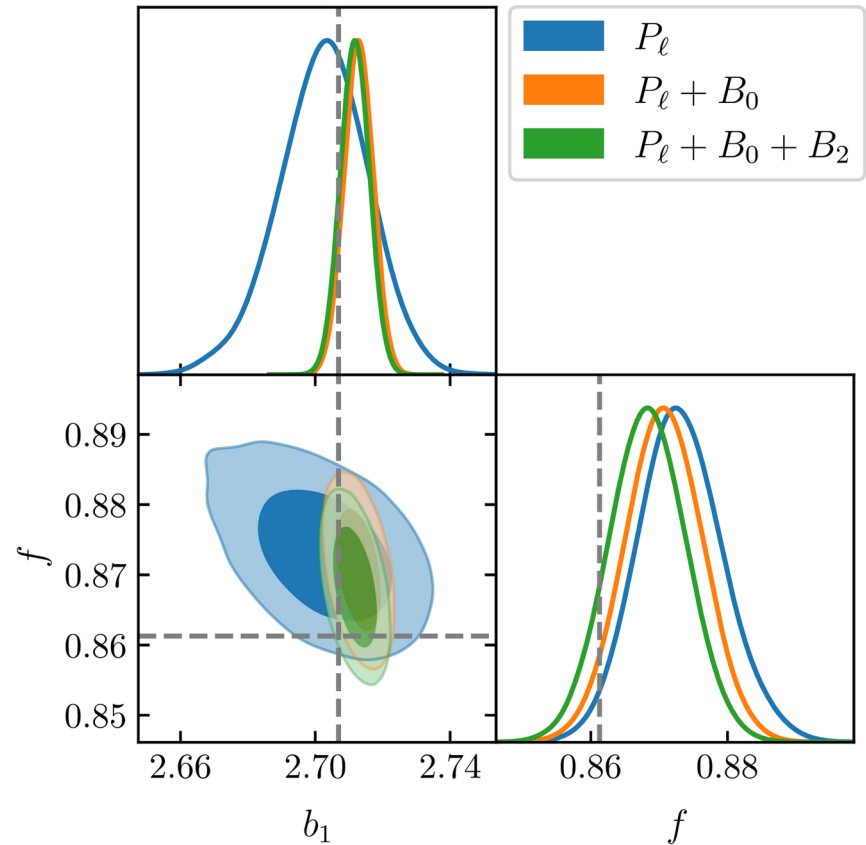


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## Ongoing:

- Reducing the parameter space
- Fits of cosmological parameters



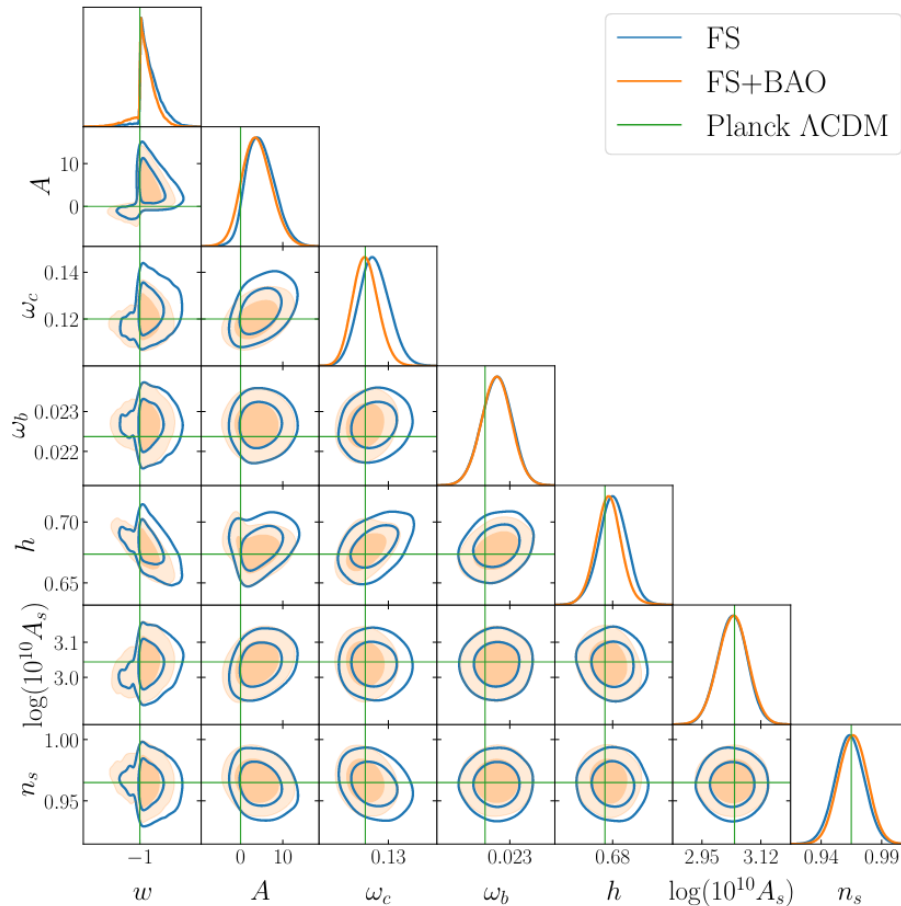
# Beyond $\Lambda$ CDM

With P. Carrilho, M. Tsedrik, A. Pourtsidou  
2207.14784, 2207.13011

- Interacting DE model (**Dark Scattering**): elastic scattering with momentum DM-DE transfer [Simpson+10]
- Interaction only affects perturbations  $\rightarrow$  Rescale  $P_L$  with appropriate growth factor
- 2 additional parameters:  $w$ ,  $A$
- Validation on simulations [2106.13163] + **BOSS analysis [Carrilho,CM+] + inclusion of bispectrum [Tsedrik,CM+]**

# Beyond LCDM

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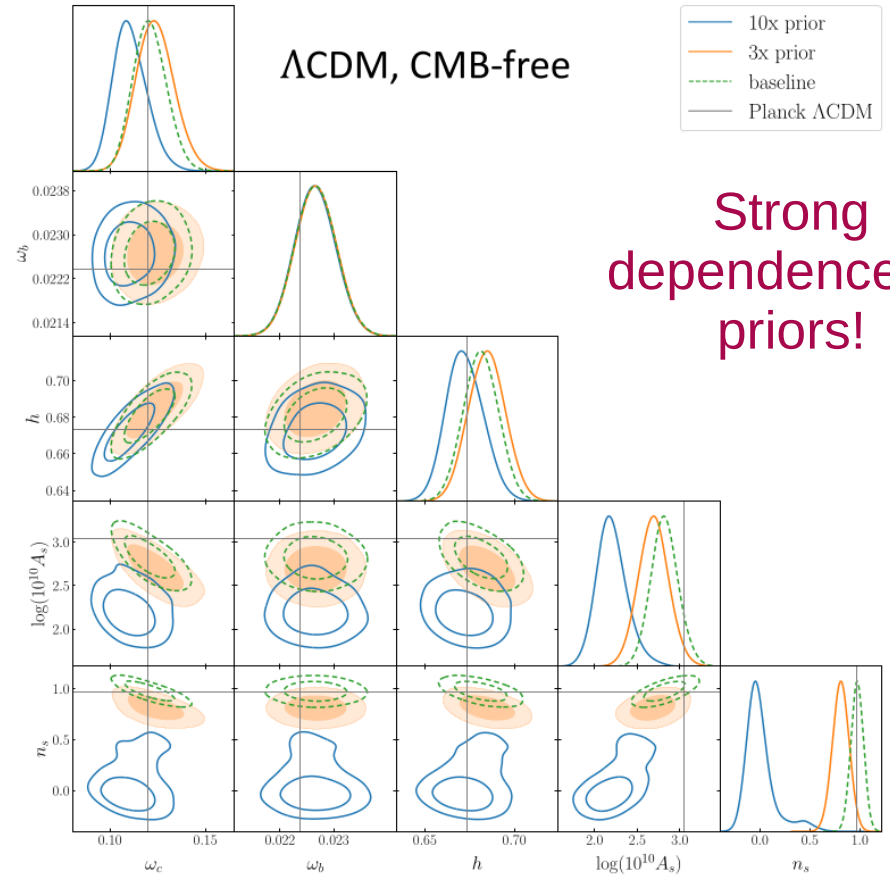
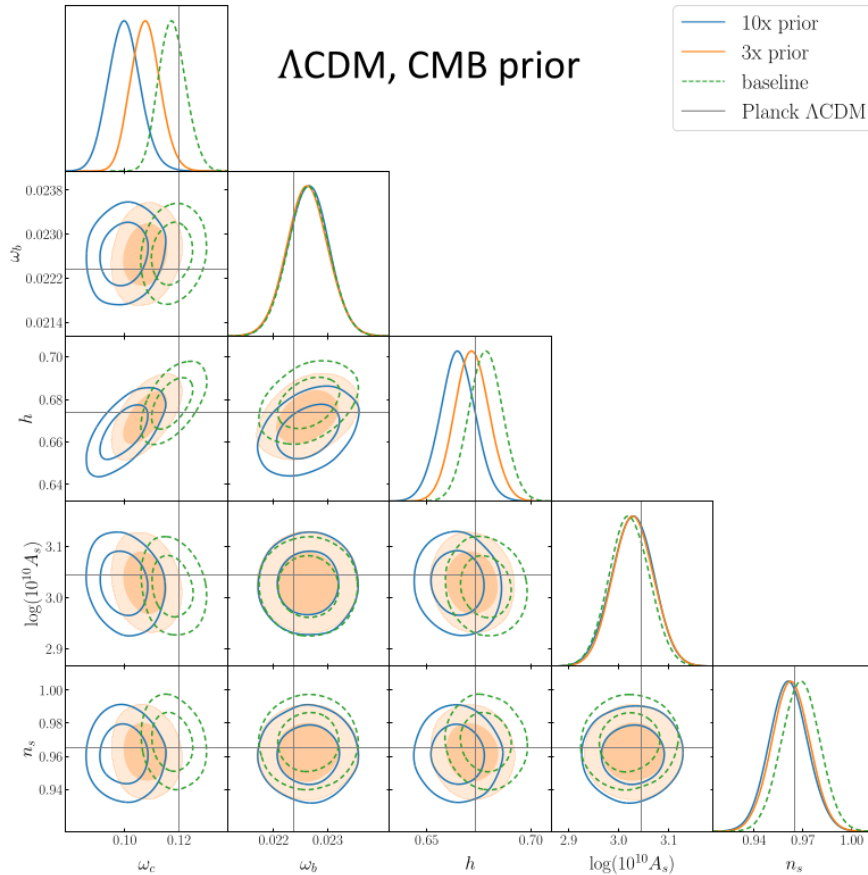


## BOSS DR12 power spectrum

- Windowless estimator [Philcox+21]
- Strong degeneracy between amplitude parameters → **bispectrum can help!**

# Beyond $\Lambda$ CDM

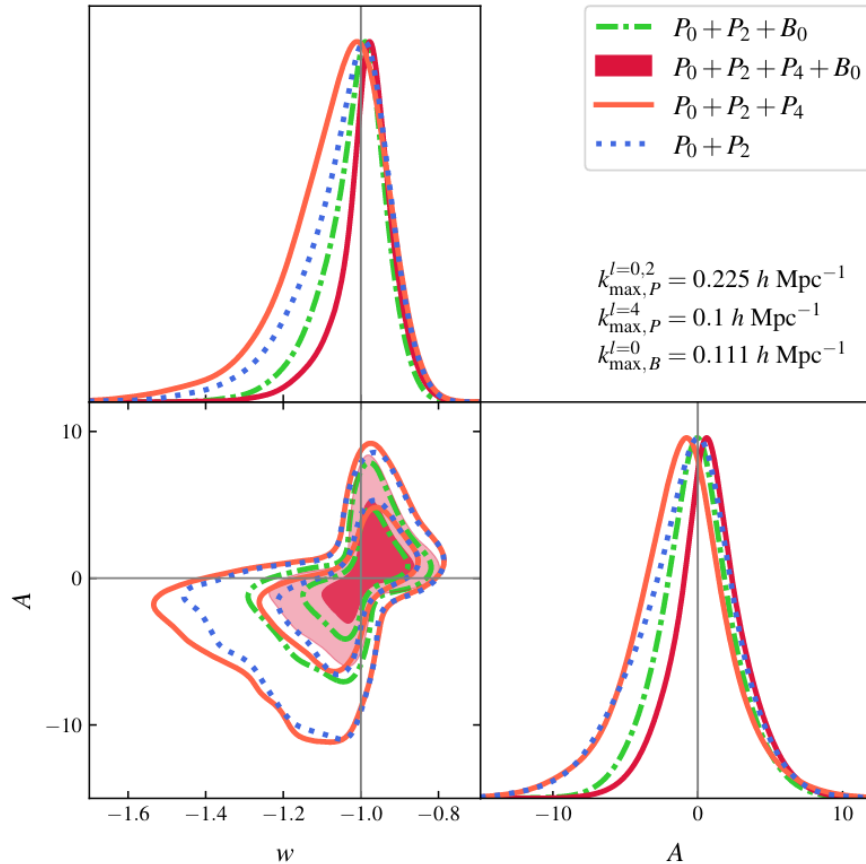
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Strong dependence on priors!

# Beyond LCDM

With P. Carrilho, M. Tsedrik, A. Pourtsidou  
2207.14784, 2207.13011



- Forecasts for P+B analysis of Dark Scattering model with Euclid errorbars
- Bispectrum breaks degeneracy between amplitude params → 30% improvement on the DS parameters
- BOSS analysis ongoing, stay tuned!



# Euclid



ESA space mission, set to launch in summer 2023

Two primary probes:

- Weak lensing
- Galaxy clustering (photometric + spectroscopic)

High precision → needs robust theoretical modelling



# Euclid



## The Flagship simulation

- $2 \times 10^{12}$  particles,  $\sim 4 \text{ (Gpc/h)}^3$
- Four snapshots  $0.9 < z < 1.8$
- HOD to populate halos with realistic galaxies

# Euclid

The Flagship simulation

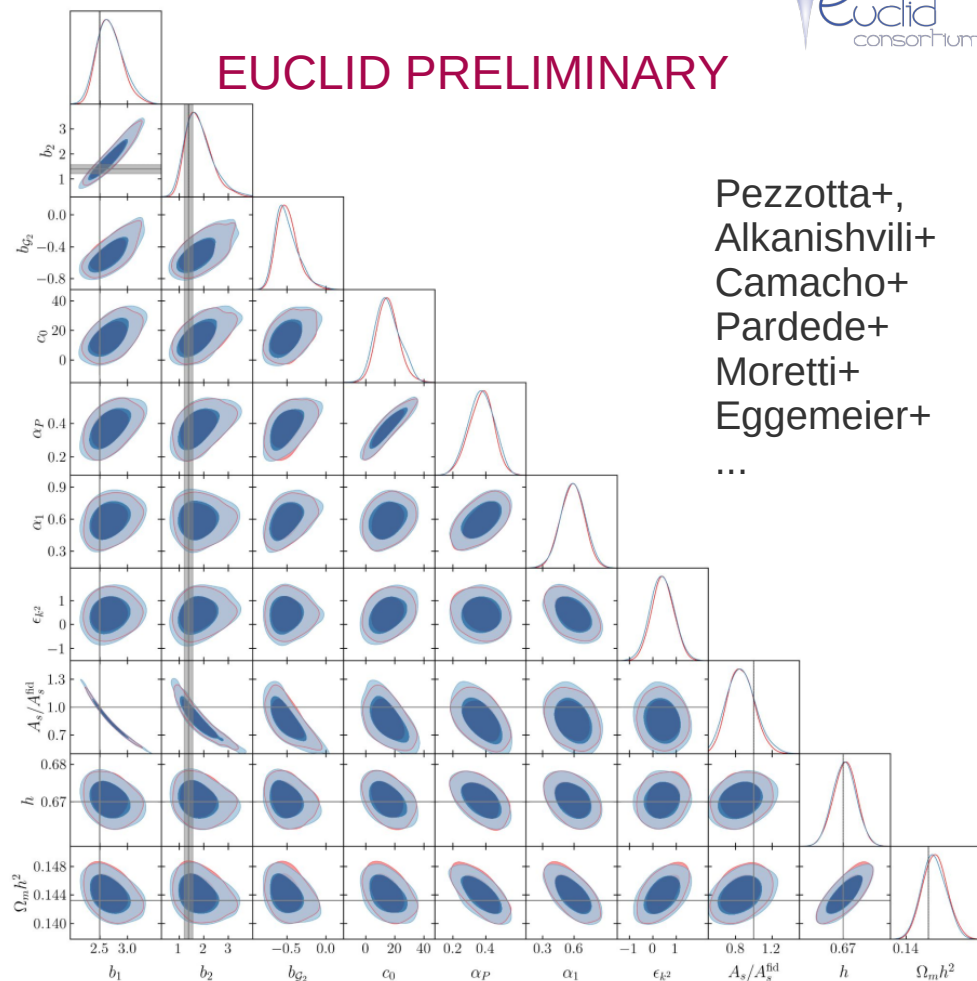
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Fits with EFTofLSS model + tree level bispectrum

- Several codes compared
- Real and redshift space, Fourier and configuration space
- **Scale cuts + model selection**



EUCLID PRELIMINARY



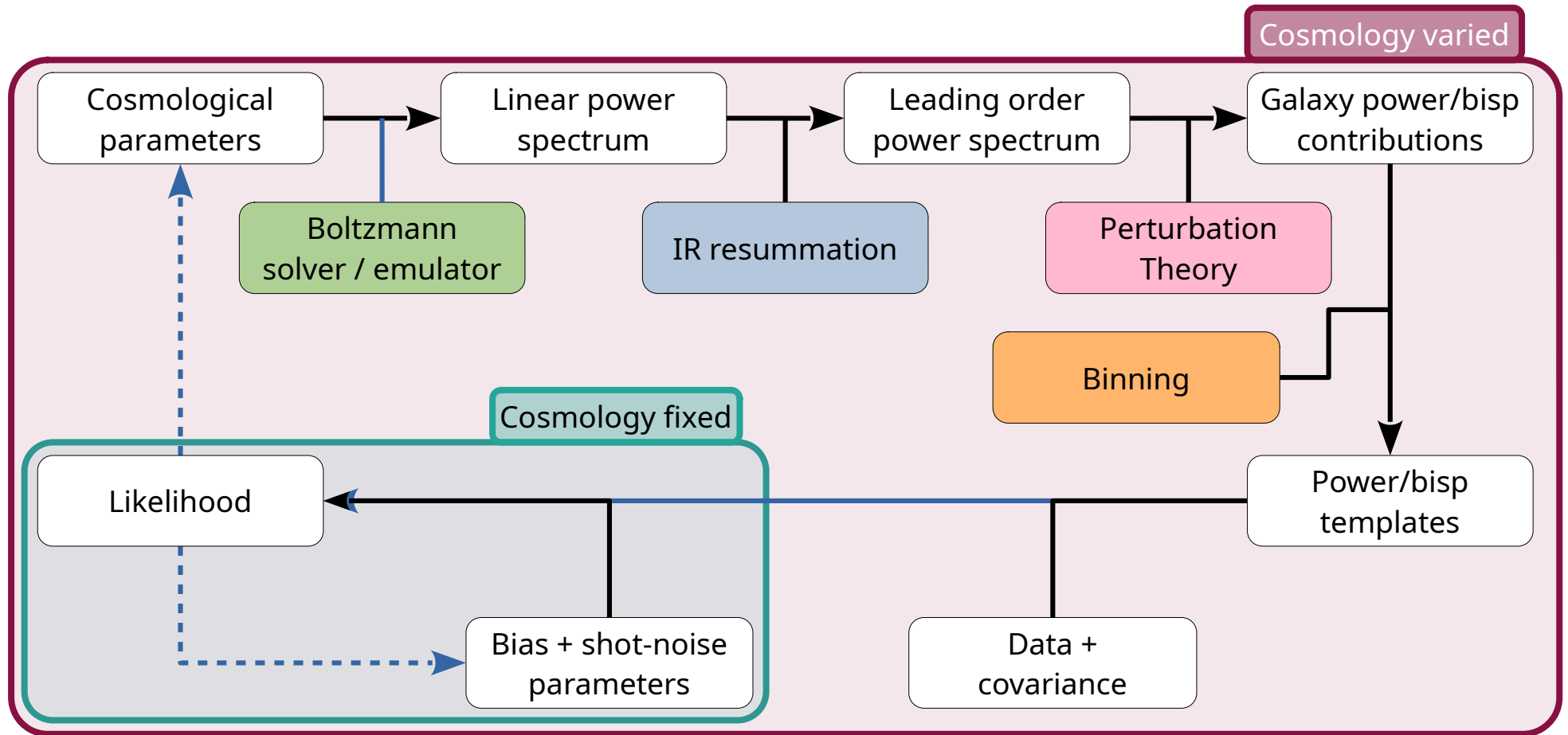
Pezzotta+,  
Alkanishvili+  
Camacho+  
Pardede+  
Moretti+  
Eggemeier+  
...

# Summary & conclusion

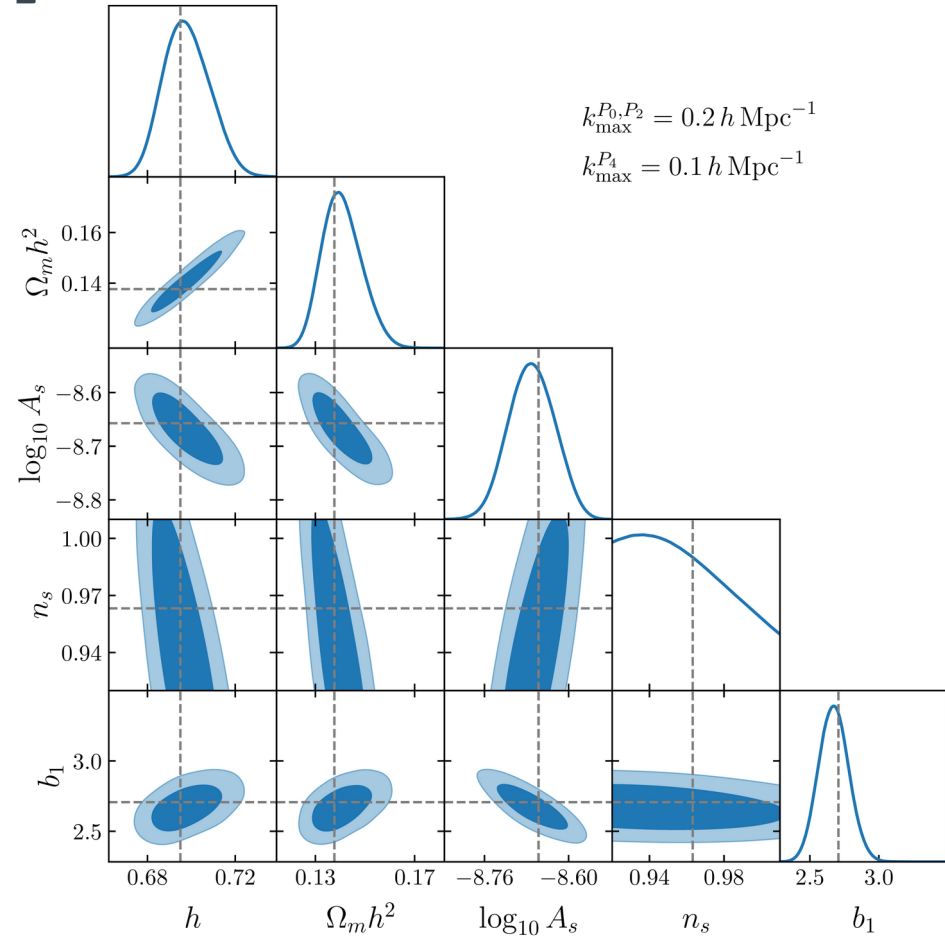
- Pipeline for the power spectrum + bispectrum joint analysis of biased tracers  
→ soon to be public
- 1-loop power spectrum + tree-level bispectrum
- **Validation on large set of sim** → robust test of theoretical model [Oddo+20,21; Pardede+22; Rizzo,CM+ 2204.13628; CM+ in prep]
- Validation and forecasts for Euclid + ported to official likelihood code
- **Beyond- $\Lambda$ CDM**: Dark Scattering constraints from BOSS [Carrilho,CM+ 2207.14784], inclusion of bispectrum [Tsedrik,CM+ 2207.13011] + Euclid preparation ongoing



# PBJ: Power spectrum & Bispectrum Joint analysis



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