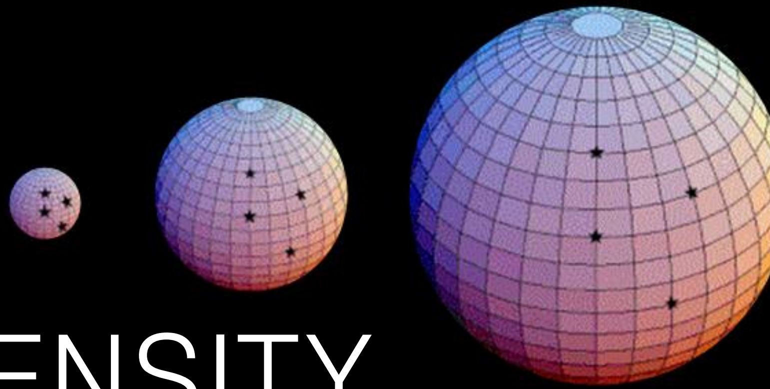
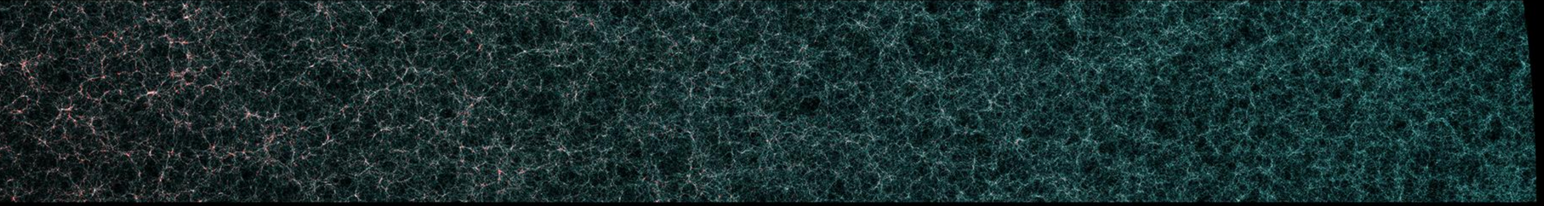


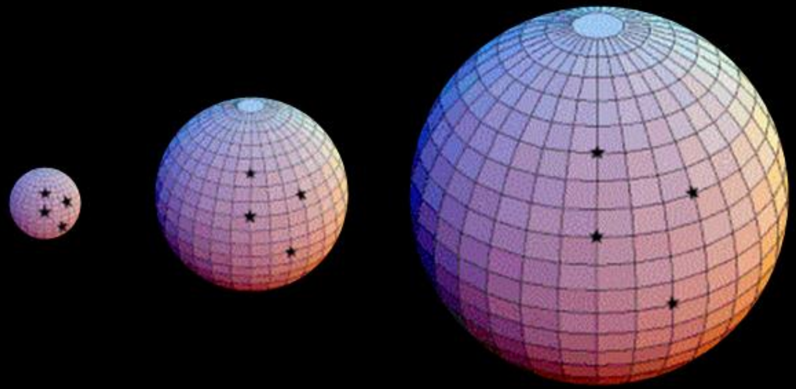
SPLITTING THE MATTER DENSITY PARAMETER Ω_m INTO THREE REGIMES: GEOMETRY, GROWTH AND EARLY–UNIVERSE

FELICITAS KEIL (IRAP TOULOUSE)
SUPERVISORS: ISAAC TUTUSAUS, ALAIN BLANCHARD

SYNERGISTIC POWER OF COMBINED COSMOLOGICAL OBSERVABLES
LPNHE, OCTOBER 2025

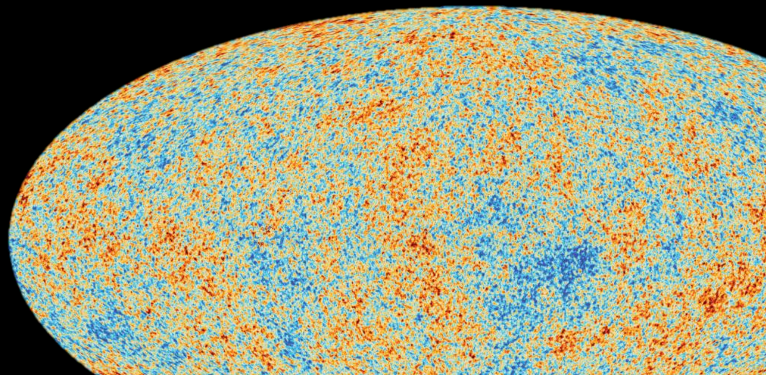
Université de Toulouse





OUTLINE

1. Consistency Tests
2. Matter Density Split
3. Previous Results (DES, KiDS)
4. Probe Modelling (3x2pt, CMB, BAO, SNIa, RSD)
5. Results
6. Euclid Preparation
7. Conclusion



CONSISTENCY TESTS

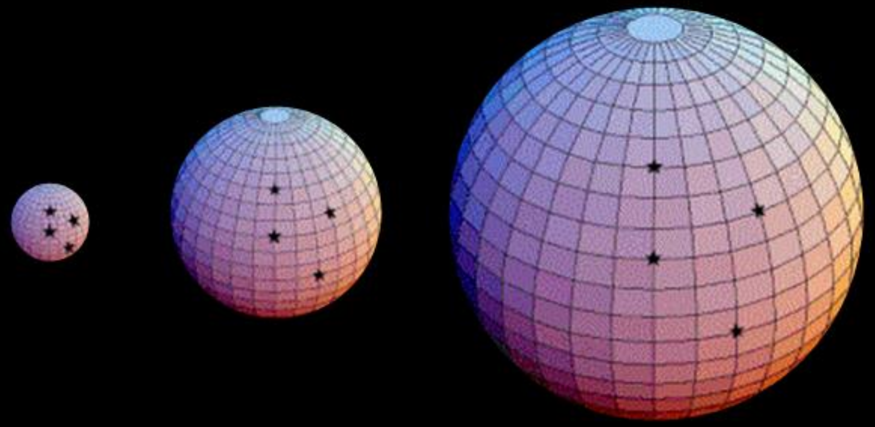
- Test the robustness of ΛCDM
- More general way to test the model with data without focusing on only one theoretical model
- Examples: Tests on Isotropy, Homogeneity, Om–statistic for dark energy, other "null tests" to see if the data deviate from ΛCDM

MATTER DENSITY SPLIT

- From cosmological surveys, we receive information from different sources
- Separating information coming from the geometry vs. the structure growth vs. early-time physics of the universe
- Predict three values for the matter density Ω_m, compare them
- If ΛCDM is correct, the values should all agree

GEOMETRICAL BACKGROUND EVOLUTION

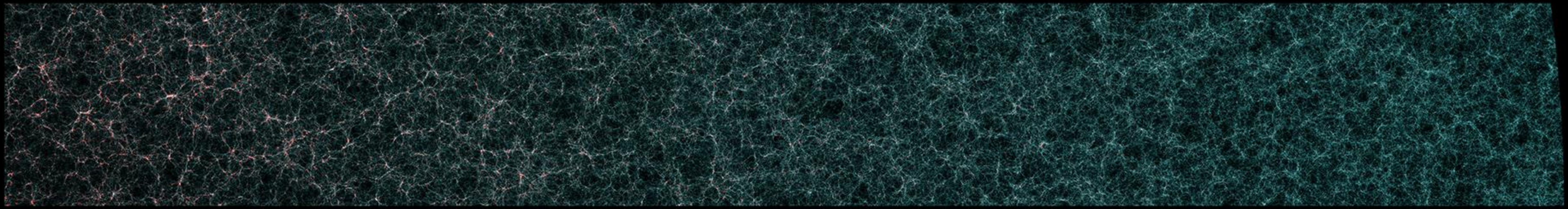
- **Geometry:** Background evolution including the expansion and curvature history of the universe
- Related to cosmological distances, e.g. luminosity and angular diameter distances (SN, BAO)



Geometric Universe Expansion

STRUCTURE GROWTH

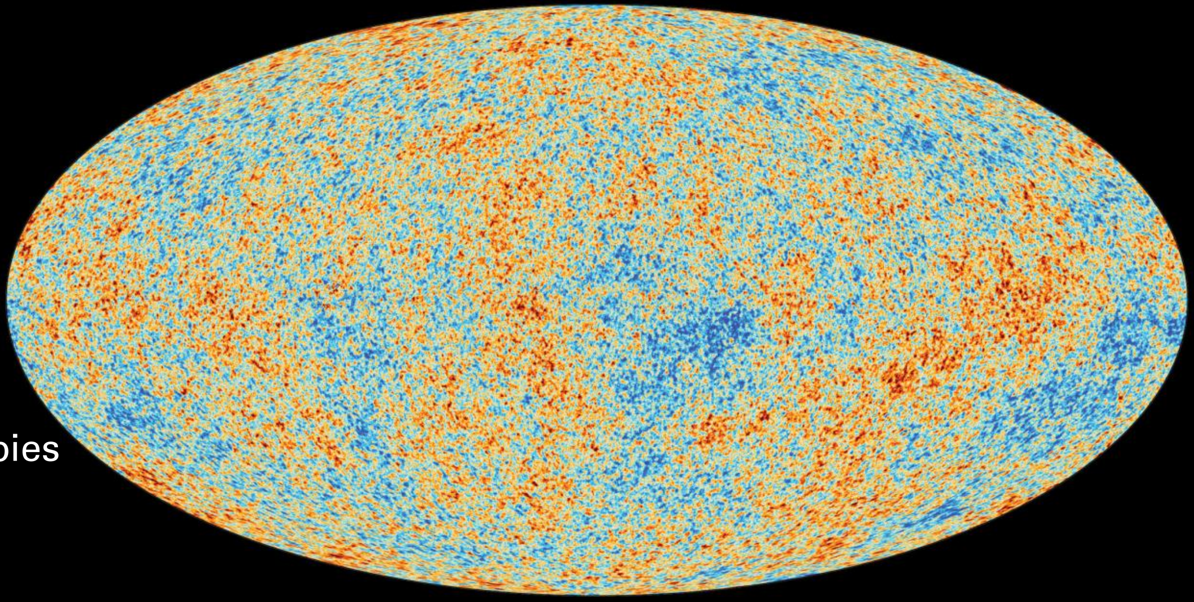
- Growth: Fluctuations originating in the early universe
- More structures form with time, leading to clusters, voids and filaments
- Information about structures embedded in the power spectrum
  - Through the growth factor, non-linear corrections, …



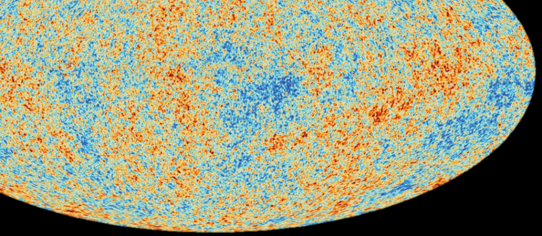
Flagship Simulation, from late to early times
J. Carretero (PIC), P. Tallada (PIC), S. Serrano (ICE) and the Euclid Cosmological Simulations SWG

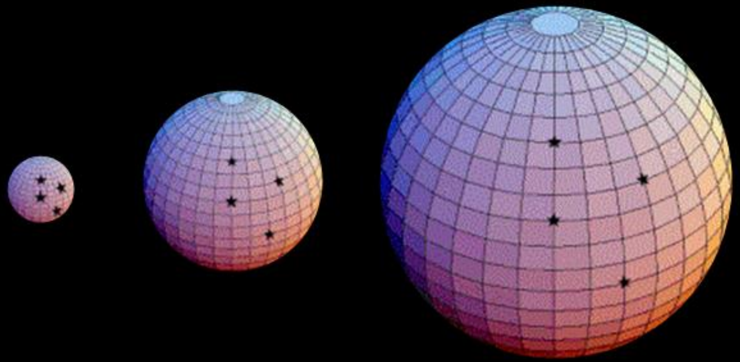
EARLY-TIME PHYSICS

- Early: Universe until recombination/decoupling
- Reflected e.g. in the CMB, primordial power spectrum (A_s, n_s)
- Parts of other probes also depend on this (e.g. BAO)



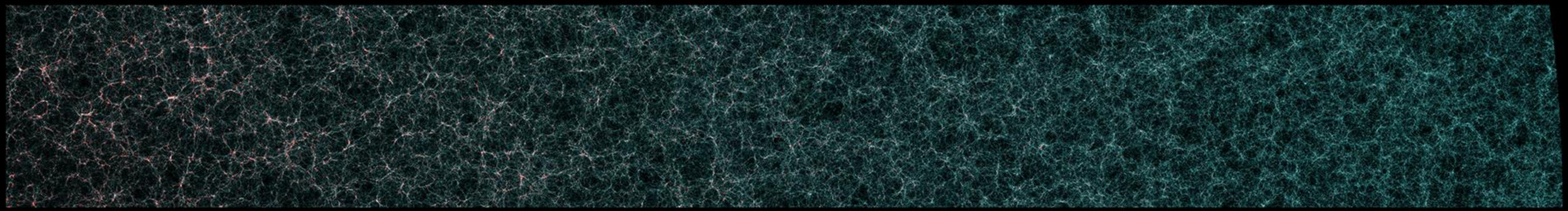
Planck CMB Anisotropies

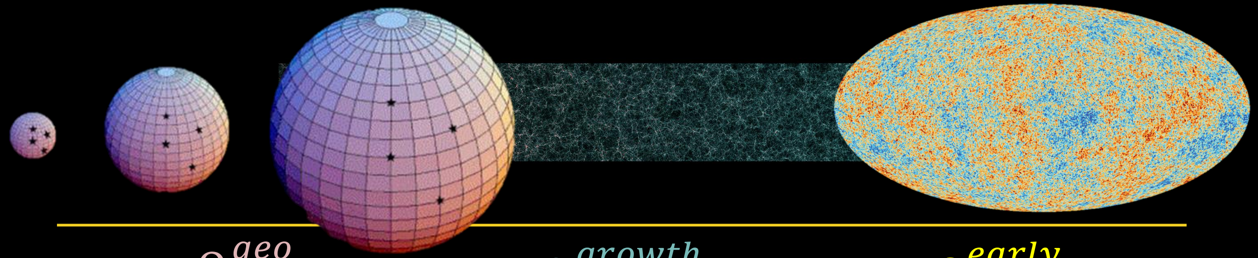




MATTER DENSITY SPLIT

- Differentiate a geometry, a growth and an early regime for parameter estimation
- Split the matter density parameter Ω_m
- Classify each parameter instance in the likelihood into one regime
- Phenomenological approach, different possible choices



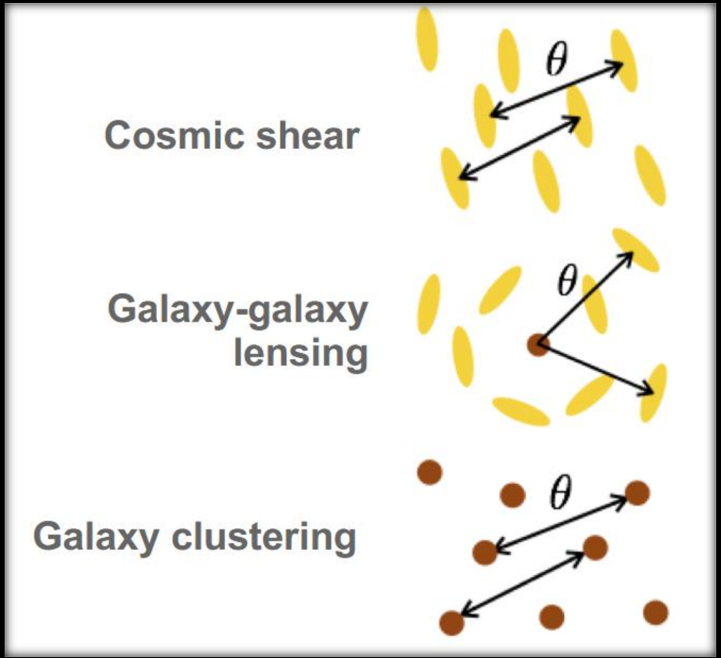


PROBE SENSITIVITIES

	Ω_m^{geo}	Ω_m^{growth}	Ω_m^{early}
• 3x2pt (galaxy clustering & weak lensing)	✓	✓	✓
• Cosmic microwave background	✓		✓
• Baryon acoustic oscillations	✓		✓
• Redshift-space distortions		✓	
• Type Ia Supernovae	✓		

3 X 2 POINT PROBE

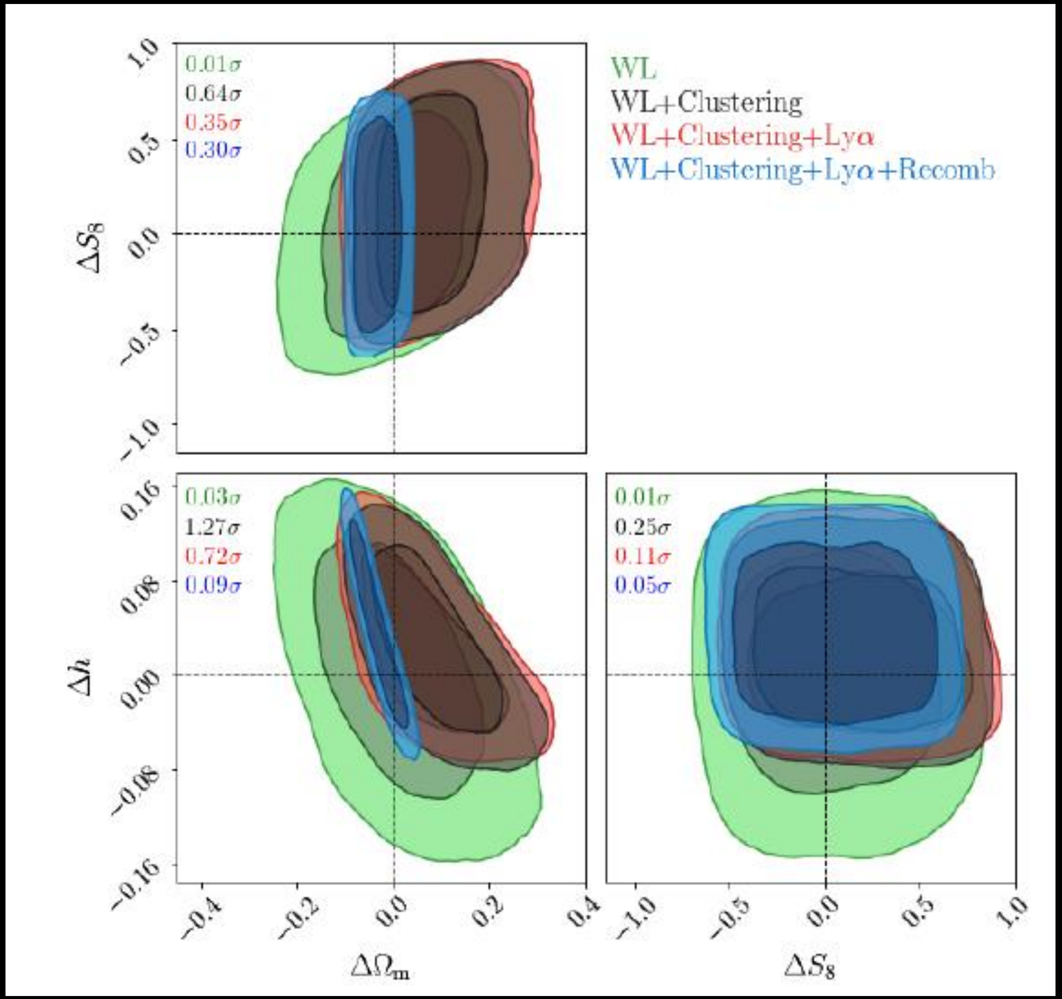
- Calculate 2–point correlation functions
  - For galaxy clustering (GC) and weak lensing (WL)
- Galaxies are distributed in redshift bins for tomographic analysis
- Correlate either GC–GC, WL–WL or GC–WL
  - Final observable are three 2–point correlation functions



Schema of the 3 x 2 point Probe

PREVIOUS RESULTS FROM KIDS-1000

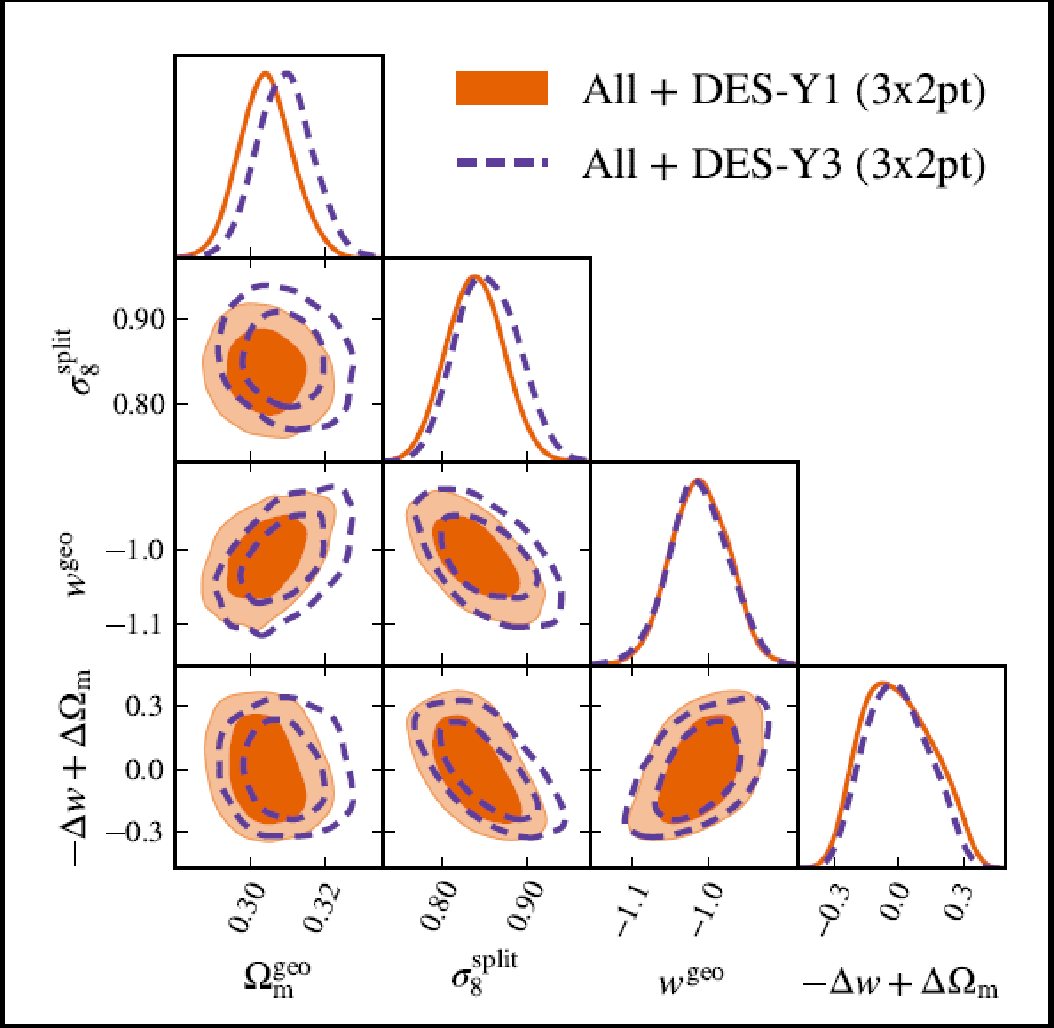
- Ruiz-Zapatero et al. 2021 considers geometry vs. growth
- Analysis relies on splitting external data
- All cosmological parameters are duplicated
  - The difference Δ between regimes is computed
- The differences are consistent with 0 (black dotted line) with comparatively large errors



KiDS-1000 split posteriors, [Ruiz-Zapatero et al. arXiv:2105.09545]

PREVIOUS RESULTS FROM DES–Y3

- Zhong et al. 2023: also considers geometry vs. growth
- Duplication of Ω_m and w
- Measure of the combination $-\Delta w + \Delta\Omega_m$
- No tension between geometry & growth for the 3x2pt + external (CMB, SN, BAO, BBN)
- The 2x2pt + external $\Delta\Omega_m$ diverges from 0 (not shown here): Attributed to systematics



DES split posteriors [Zhong et al., arXiv:2301.03694]

THEORETICAL RECIPE FOR 3X2POINT DATA

- Adapted from Zhong et al. 2023 for DES, adding the early regime
- The growth quantifies matter overdensities independently of scale

$$G(z) = (1+z)\frac{\delta_m(z)}{\delta_m(z_{ini})}$$

- The linear matter power spectrum depends on $G(z)$

$$P_{lin}(k,z) \propto \mathrm{G(z)}^2$$

THEORETICAL RECIPE FOR 3X2POINT DATA

- Calculate the growth using the differential equation

Either early or growth

$$G'' + \left(4 + \frac{H'}{H}\right) G' + \left(3 + \frac{H'}{H} \frac{3}{2} \boldsymbol{\Omega_m}(\mathbf{z})\right) G = 0$$

Geometry

- Calculate this using either the Ω_m from early times or from growth

THEORETICAL RECIPE FOR 3X2POINT DATA

- We call the Einstein–Boltzmann solver (EBS) using Ω_m^{early}
- Use the growth equation to rescale the power spectrum from the EBS
- This new split power spectrum will then be used in the analysis

$$P_{split}^{lin}(k,z) = P_{EBS}^{lin}(k,z)\left(\frac{G_{growth}^{ODE}(z)}{G_{early}^{ODE}(z)}\right)^2$$

THEORETICAL RECIPE FOR 3X2POINT DATA

- We compute σ_8 with the rescaled power spectrum

$$\left(\sigma_8^{split}\right)^2(z) = \frac{1}{2\pi^2}\int dln(k) P_{split}^{lin}(k,z) k^3 W^2(kR)$$

$$\Longrightarrow \sigma_8^{split}(z) = \sigma_8^{EBS}(z)\frac{G_{growth}^{ODE}(z)}{G_{early}^{ODE}(z)}$$

- We will sample over A_s and then derive σ_8^{split}

THEORETICAL RECIPE FOR 3X2POINT DATA

- The non-linear corrections are computed in the growth regime

- We compute the boost factor using an emulator (EuclidEmulator 2) and Ω_m^{growth}

$$B(k,\mathrm{z}) = \frac{P^{NL}(k,z)}{P^{lin}(k,z)}$$

- Then, we add this boost to the split power spectrum

$$P_{split}(k,z) = P_{split}^{lin}(k,z)\mathrm{B}^{\mathrm{growth}}(\mathrm{k},\mathrm{z})$$

THEORETICAL RECIPE FOR 3X2POINT DATA

- Consider the window function for the angular power spectrum

  for probes A,B in bins i,j

  - Projection of the power spectrum along the line of sight

- The window functions weight the observable in each redshift bin
  - Related to geometry

$$C_{ij}^{AB}(\ell) = \int_0^\infty d\chi \, \frac{W_i^A(\chi) W_j^B(\chi)}{\chi^2} \mathrm{P}_{\mathrm{split}}\big(\mathrm{k}(\ell,\chi), z(\chi)\big)$$

Comoving distance

THEORETICAL RECIPE FOR 3X2PT DATA

- The distances are in the geometry regime
- The matter density comes from the Poisson equation
  - Classified as a geometric parameter

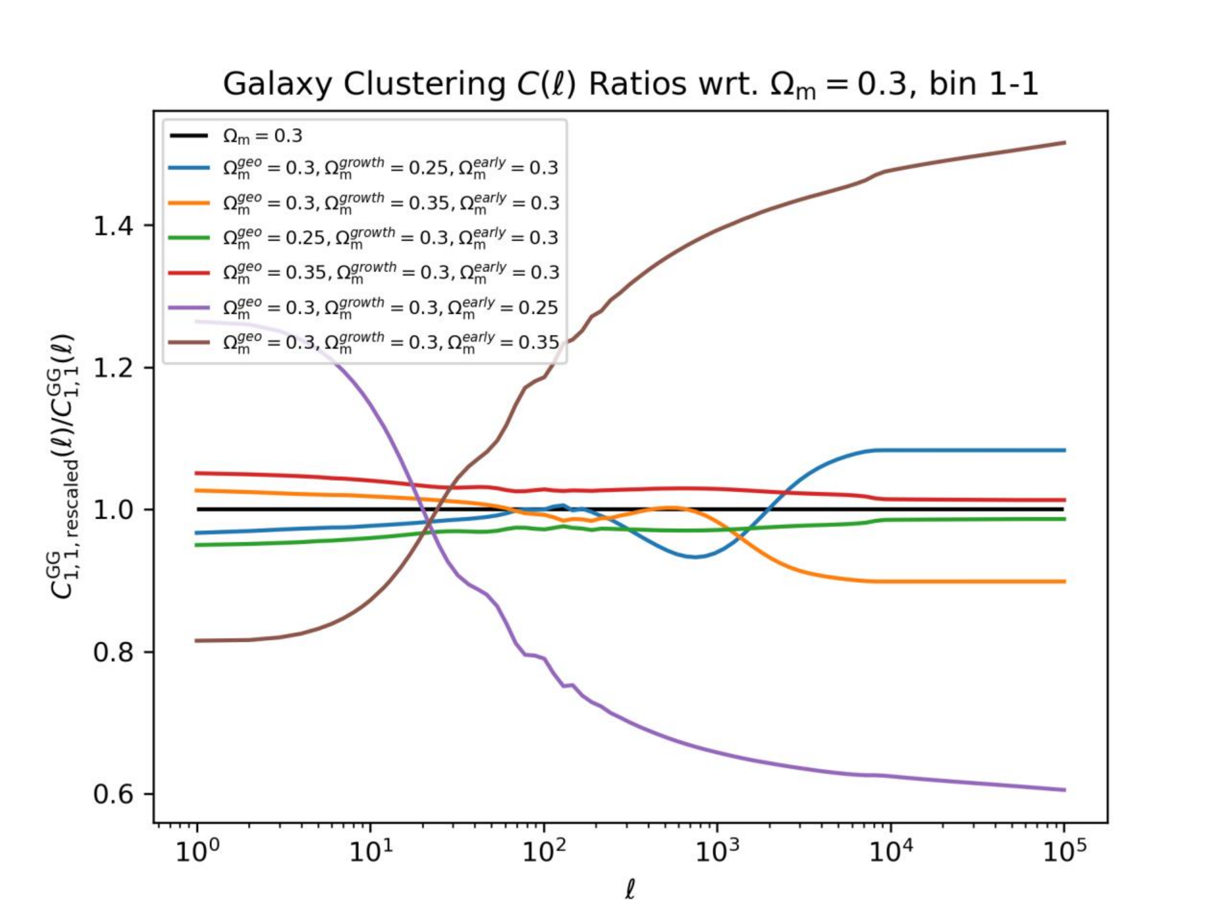
Comoving distance

$$W_i^{\kappa}(\chi) = \frac{3\Omega_m^{geo} H_0^2}{2c^2} \frac{\chi}{a(\chi)} \int_{\chi}^{\infty} d\chi' \frac{n_i^{\kappa}\big(z(\chi')\big) dz/d\chi'}{\bar{n}_{\kappa}^{i}} \frac{\chi' - \chi}{\chi}$$

$$W_i^{\delta_g}(\chi) = b_i(z(\chi)) \frac{n_i^{g}\big(z(\chi)\big) dz/d\chi'}{\bar{n}_i^{g}}$$

CLUSTERING ANGULAR POWER SPECTRUM

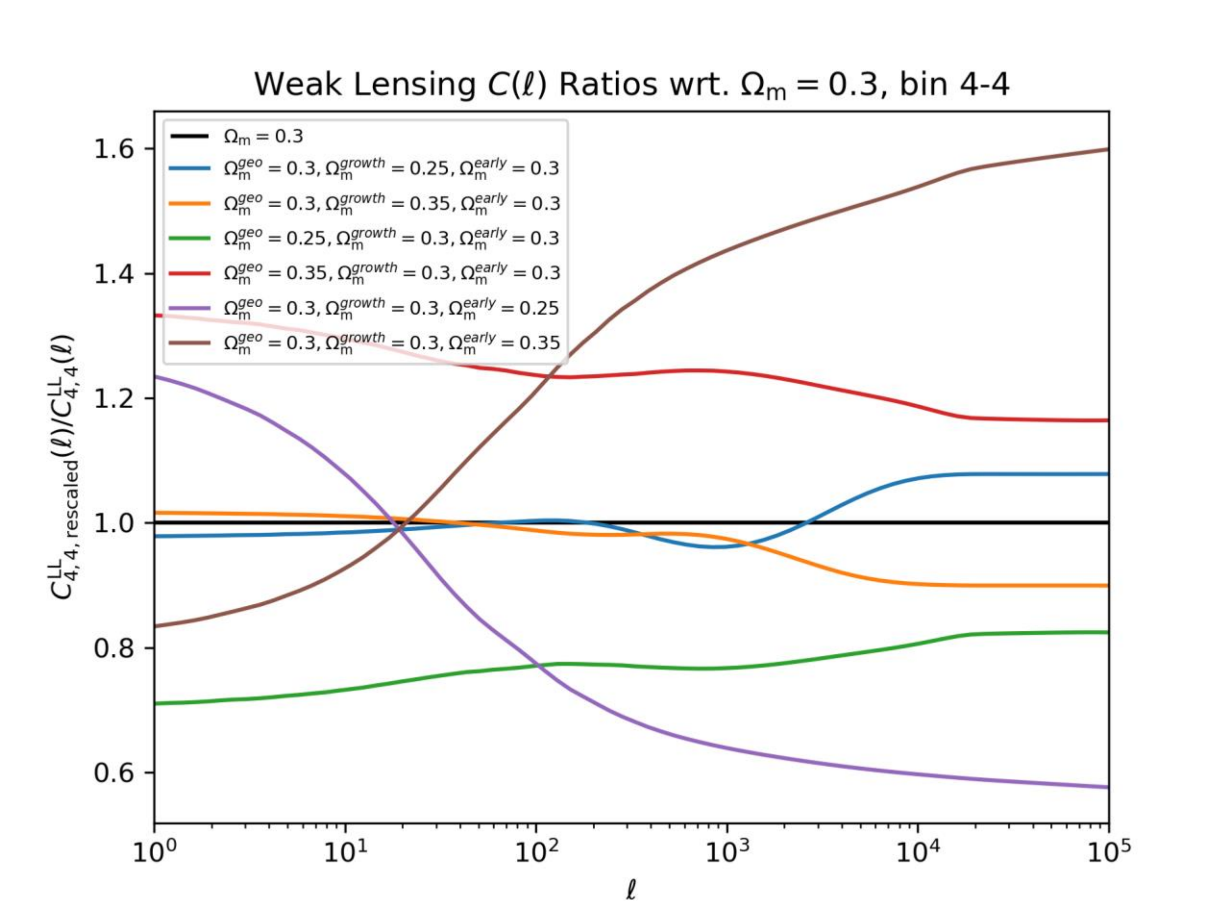
- Ratio of the C_ℓ using different Ω_m values wrt. $\Omega_m = 0.3$, bin 1–1
- Ω_m^{early} influences the EBS (while A_s is fixed) and the rescaling
- Ω_m^{growth} influences the rescaling and the non-linear corrections
- Ω_m^{geo} influences the distances in the window function



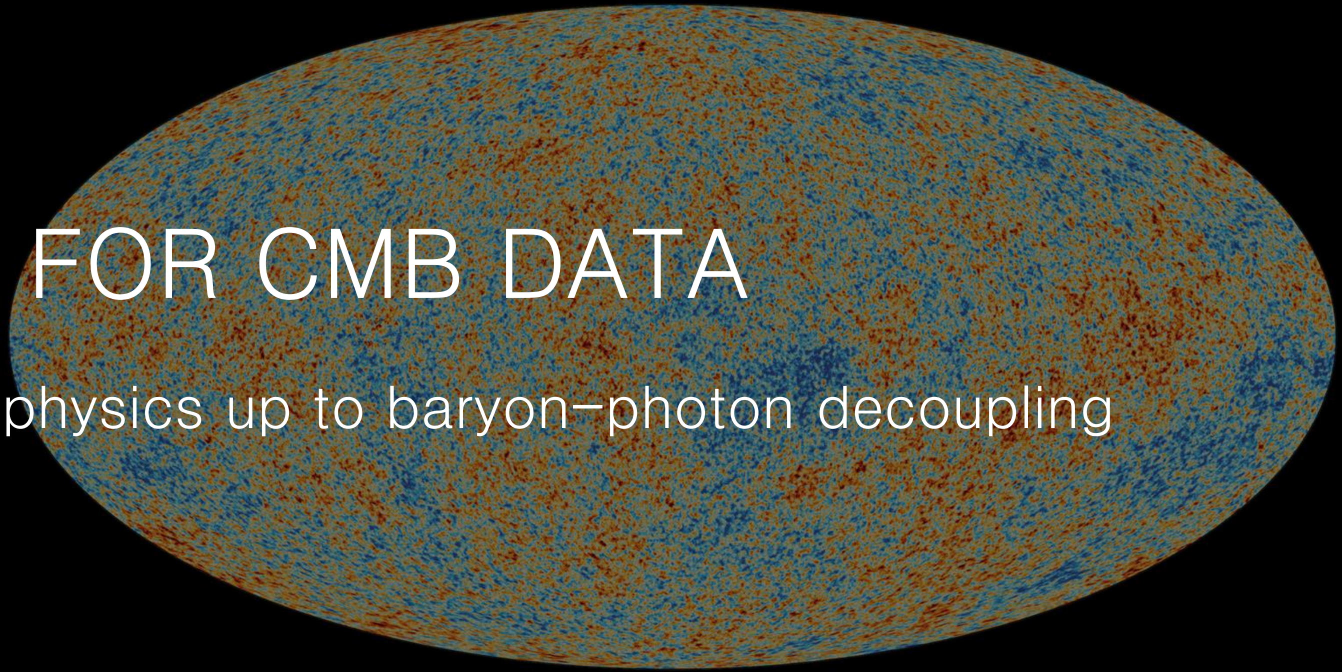
DES Split Non-linear P(k), Zhong et al.

WEAK LENSING ANGULAR POWER SPECTRUM

- Ratio of the C_ℓ using different Ω_m values wrt. $\Omega_m = 0.3$, bin 4–4
- Ω_m^{early} influences the EBS (while A_s is fixed) and the rescaling
- Ω_m^{growth} influences the rescaling and the non-linear corrections
- Ω_m^{geo} influences the prefactor and distances in the window function



DES Split Non-linear P(k) Zhong et al.



THEORETICAL RECIPE FOR CMB DATA

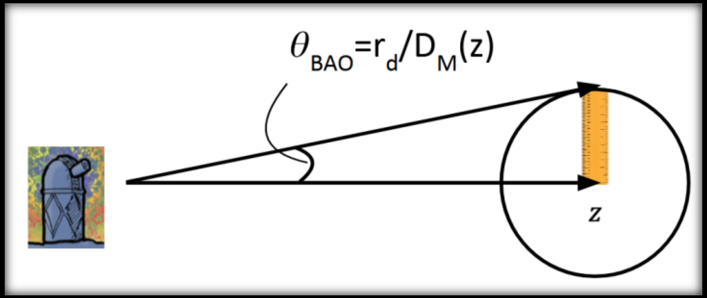
- Constrains mostly the early regime: physics up to baryon-photon decoupling
  - Call CAMB with Ω_m^{early}
- Angular scale of the acoustic peaks
  - Rescaling with the geometric angular diameter distance

$$\theta_s = \frac{\pi}{\ell} = \frac{r_s(\eta_{dec})}{d_A(\eta_{dec})} = \frac{\int_0^{\eta_{dec}} d\eta \; c_s(\eta)}{\int_{\eta_{dec}}^{\eta_0} d\eta}$$

$$\mathrm{C}^{\mathrm{TT/TE/EE}}(\ell_{scaled}) = \mathrm{C}^{\mathrm{TT/TE/EE}}\left(\ell_{CAMB}\frac{d_A^{geo}}{d_A^{early}}\right)$$

CMB Anisotropies measured by Planck

THEORETICAL RECIPE FOR BAO



- BAO constrain $\frac{D_M}{r_d}, \frac{D_H}{r_d}$ or $\frac{D_V}{r_d}$ through the observed angle θ_{BAO}
  - Distances $D_M, D_H, \& D_V$ are in the geometry regime
- r_d is the sound horizon of the universe at the drag epoch (shortly after decoupling)

Sound Speed

$$r_d = r_s(\mathrm{z_{drag}}) = \int_{z_{drag}}^{\infty} \frac{c_s(z)}{H(z)} dz$$

- Calculate with approximation (Brieden et al. 2023) and model this Ω_m as early

$$r_d = 147.05\, Mpc \left(\frac{\omega_m}{0.1432}\right)^{-0.23} \left(\frac{N_{eff}}{3.04}\right)^{-0.1} \left(\frac{\omega_b}{0.02236}\right)^{0.13}$$

THEORETICAL RECIPE FOR SUPERNOVAE

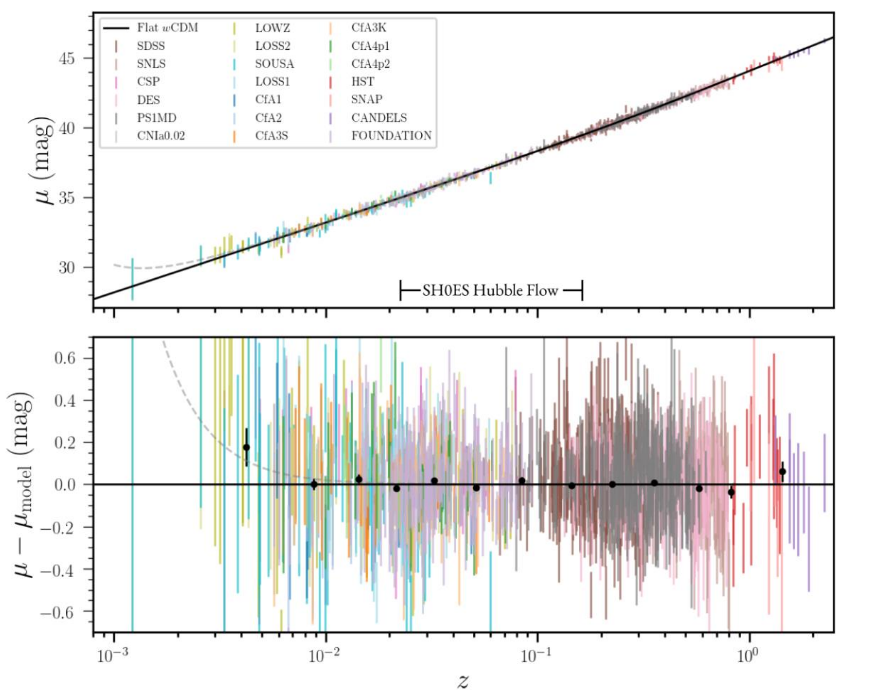
- Supernovae Type Ia are standard candles
- Measures the apparent SN magnitudes as a function of redshift
- Likelihood compares the measured apparent magnitude with the one using d_L

$$m(z) = M_0 + 5\log_{10}\left(\frac{d_L(z)}{Mpc}\right) + 25$$

- Luminosity distance is a geometric quantity
- No cepheid calibration (i.e. SH0ES)

  → We can combine with the CMB data

Pantheon+ data [Brout et al., arXiv:2202.04077]



THEORETICAL RECIPE FOR RSD DATA

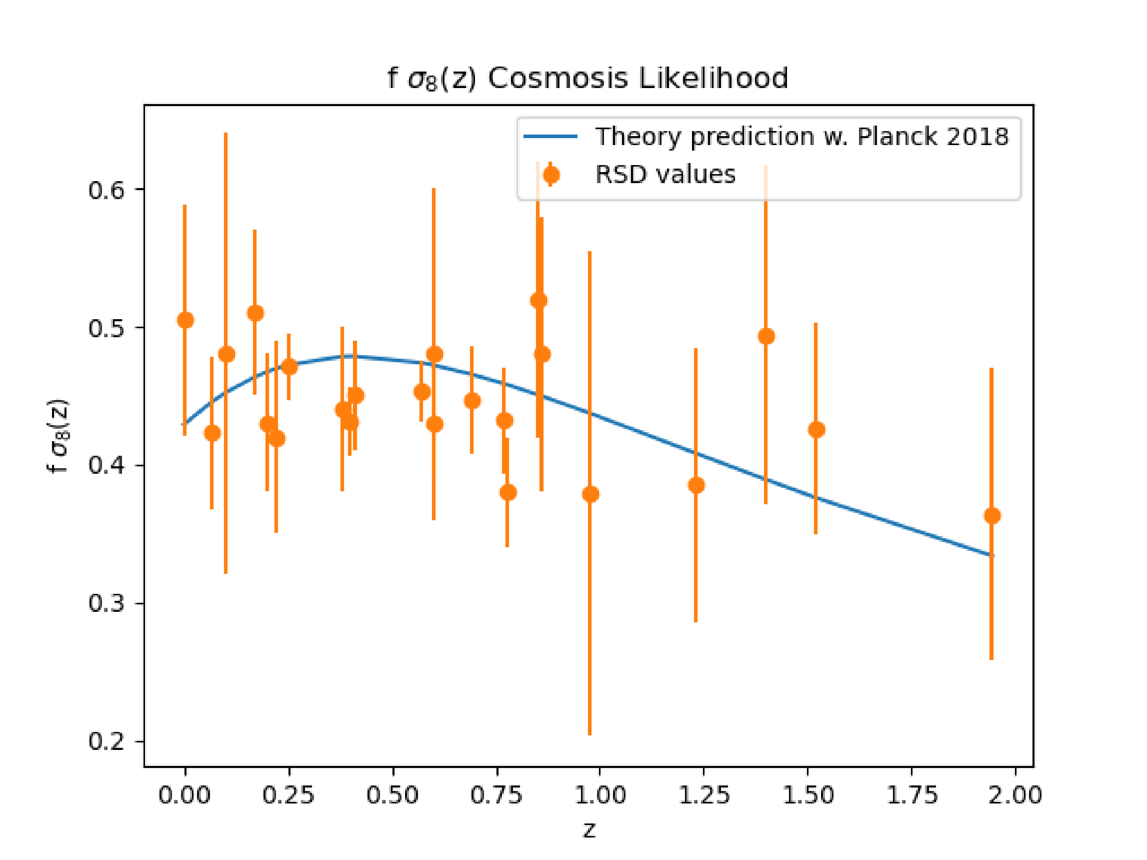
- Measure $(f \cdot \sigma_8)(z)$ from redshift-space distortions (RSD) in spectroscopic galaxy surveys
- Constrains growth
- Calculate $f(z)$ with the ODE and Ω_m^{growth}

$$G'' + \left(4 + \frac{H'}{H}\right)G' + \left(3 + \frac{H'}{H}\frac{3}{2}\Omega_m^{growth}(z)\right)G = 0$$

Geometry

REDSHIFT SPACE DISTORTION DATA

- Different possibilities to combine data points from spectroscopic surveys (e.g. SDSS)
- Sample from Blanchard et al. 2022
- Added likelihood from this data to CosmoSIS
- Either use RSD or BAO when combining due to unknown covariance

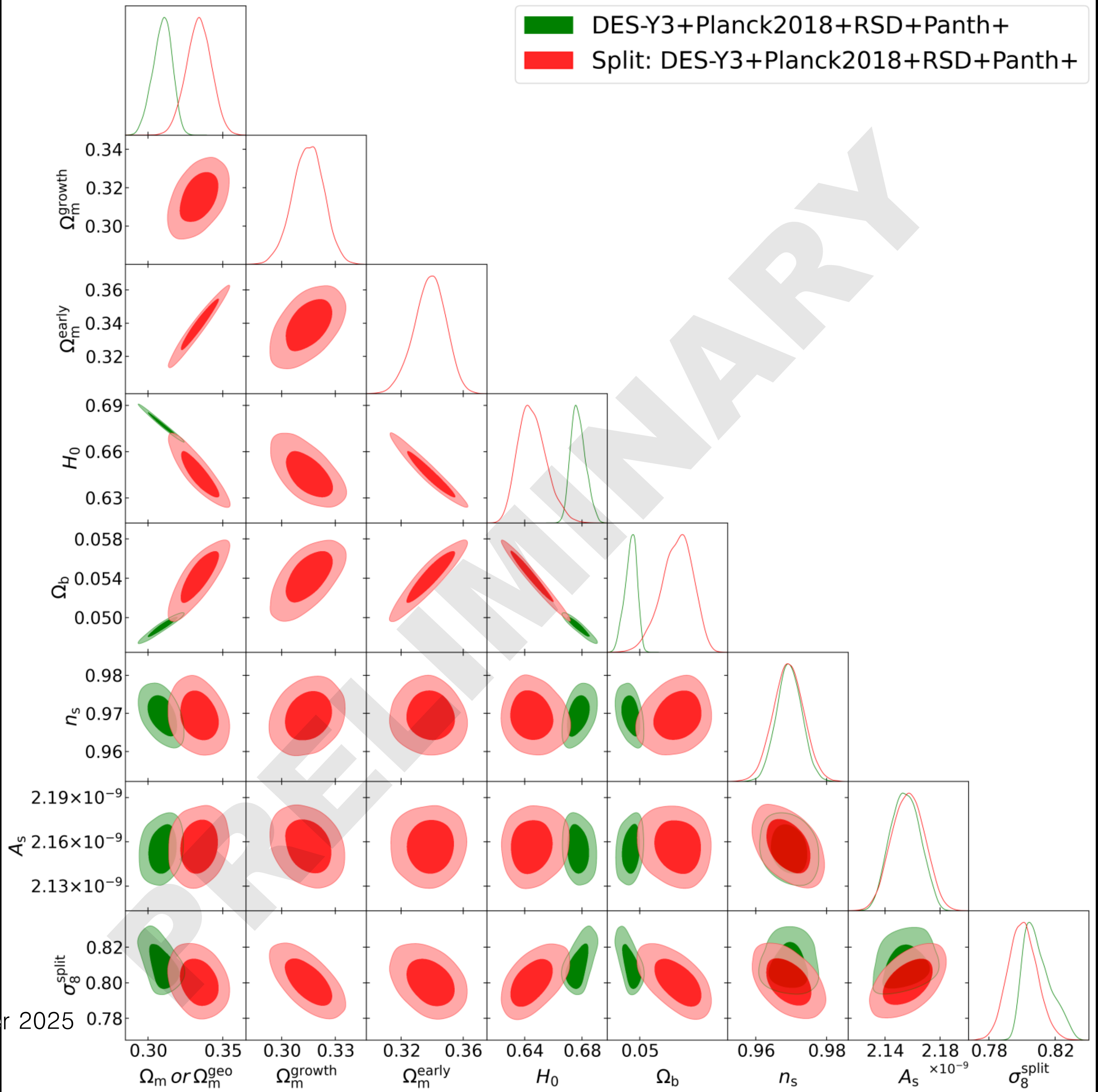


CosmoSIS Likelihood based on these measures

RESULTS

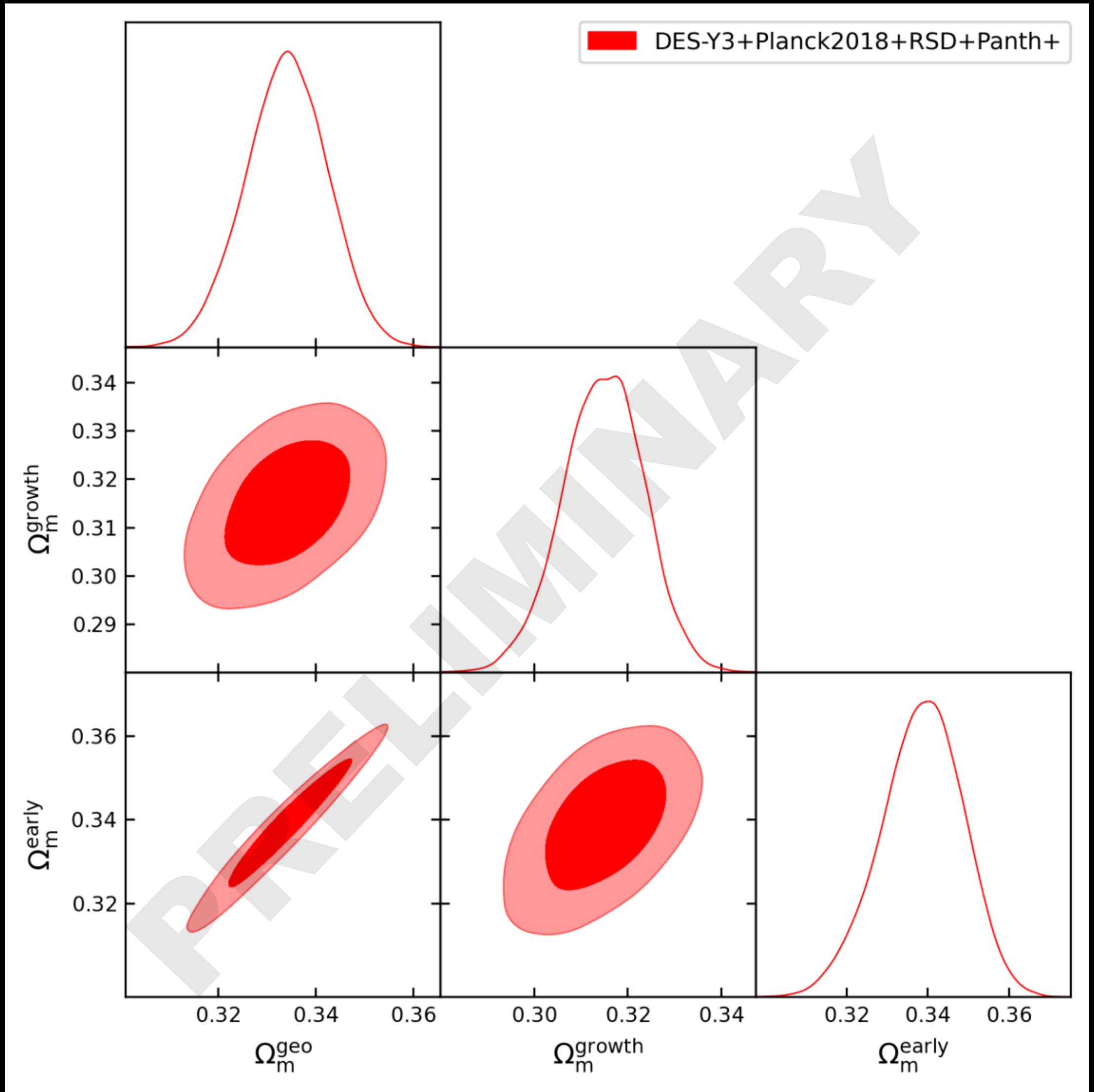
- DES+Planck+Pantheon++RSD
- σ_8^{split} correlated w. Ω_m^{growth}
  - Less correlation w. Ω_m^{geo}, Ω_m^{early}
- Lower value of H_0
  - Due to high Ω_m^{early}
    (CMB measures ω_m)

→ Higher value of Ω_b



RESULTS

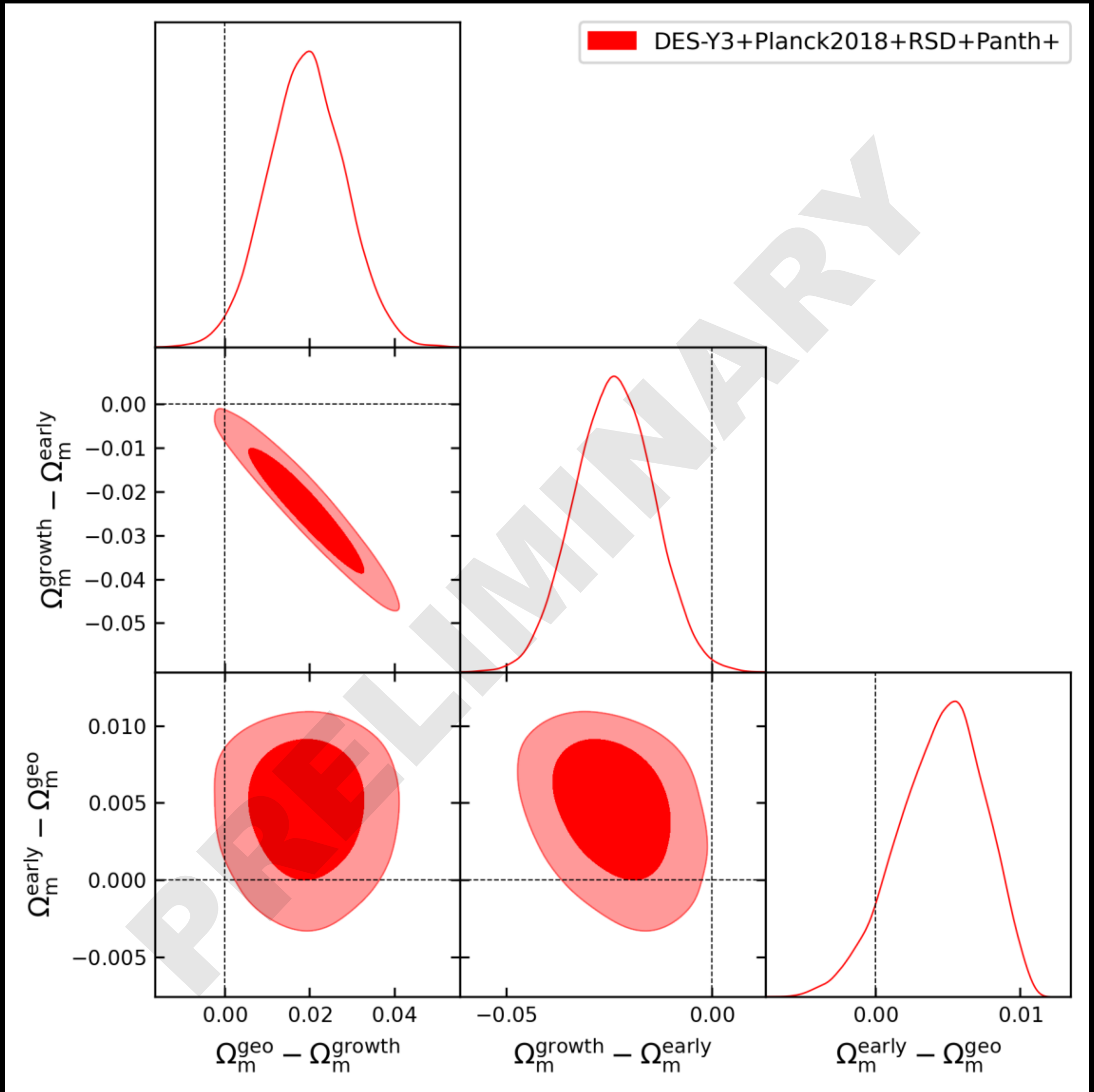
- Geometry and early regime very correlated
- The growth regime is less correlated with the other two
- The errors are remarkably similar



Correlations between the regimes

RESULTS

- Differences between the Ω_m
- The geometry and the early regime agree within 1σ
- Mild tension between these vs. growth (2.3σ)



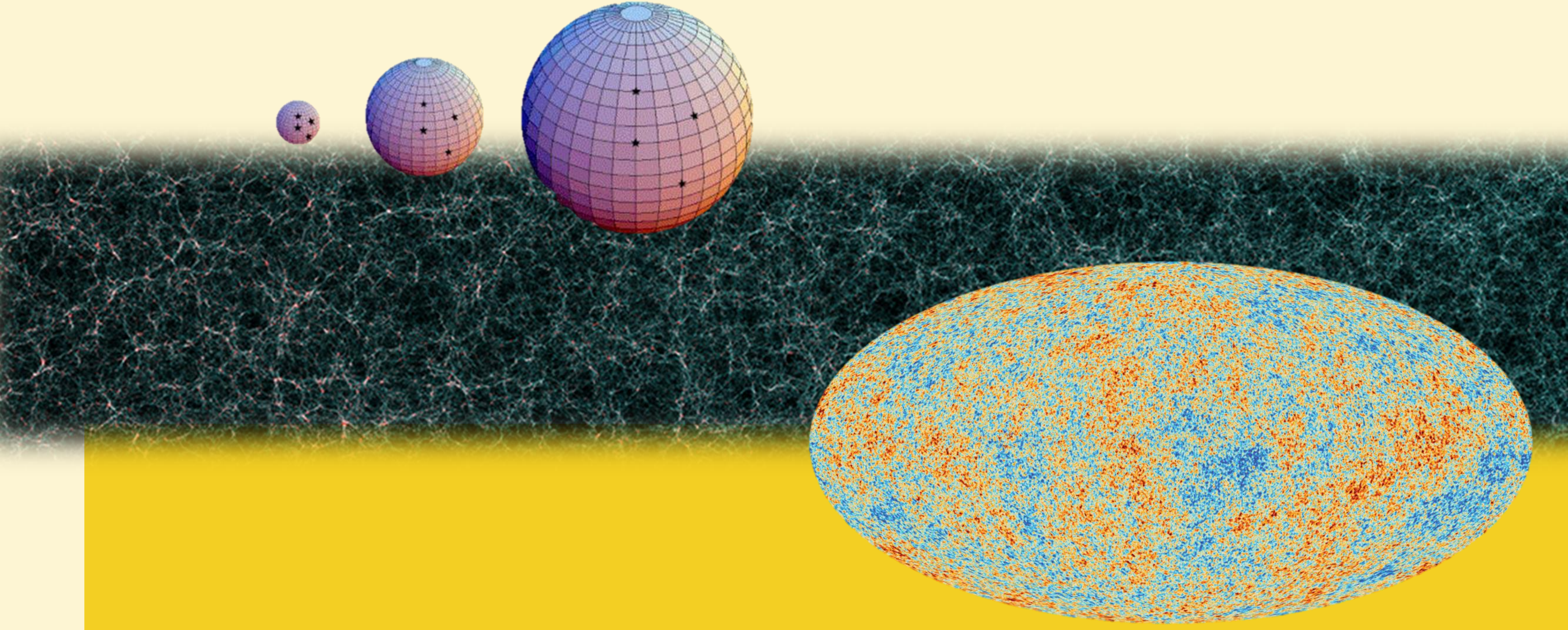
Differences between the regimes

PREPARATION FOR EUCLID DR1

- Part of the Euclid Theory Group: Homogeneity, Isotropy and Consistency Tests
- Members: Felicitas Keil, Ziad Sakr, Isaac Tutusaus, Alain Blanchard,
  Sefa Pamuk, Matteo Martinelli
- Project on the split between geometry and growth (without early-universe)
- Data sets: Euclid 3x2pt, Euclid spectroscopic BAO (geo.), Planck θ^* (geo.)
- Planned modification of the Euclid CLOE code, preparation done in CosmoSIS
  - Future validation with CosmoSIS

CONCLUSION

- Separate the influence of geometry vs. growth vs. early-times for Ω_m
- Geometry regime for distances, growth regime for structures, early regime for early-time physics
- Consistency test of ΛCDM
- Combinations of already existing data: DES+Planck+RSD+Pantheon+
- Preparation for Euclid DR1
- Geometry and early regime are similar, growth regime in mild tension (2.3σ) – preliminary



THANK YOU FOR YOUR ATTENTION

BACKUP

CEPHEID CALIBRATION

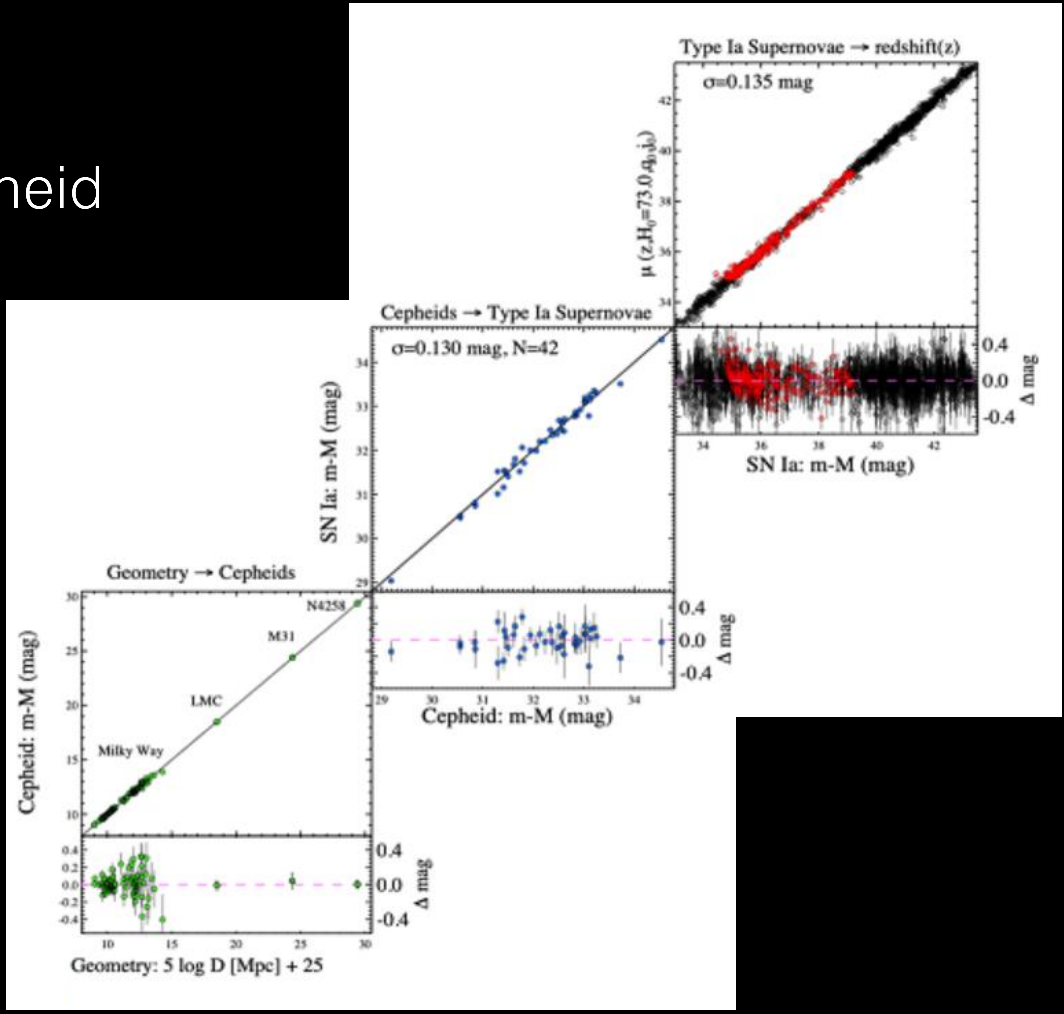
- Case distinction when computing $\chi 2$
- Apparent magnitude for SN w. associated cepheid

$$m(z) = M_0 + d_{abs,SH0ES}$$

- On all other points, standard equation holds

$$m(z) = M_0 + 5\log_{10}\left(\frac{d_L(z)}{Mpc}\right) + 25$$

- Now likelihood on both sides depends on H_0



Distance ladder, Pantheon+ collaboration

SPLIT AS CONSISTENCY CHECK

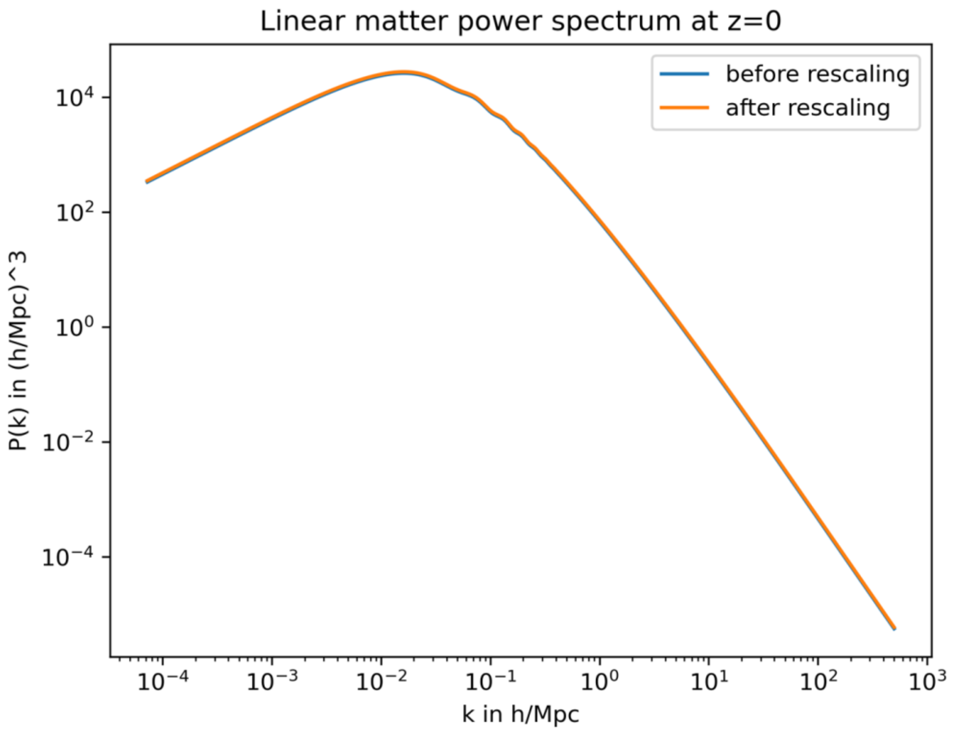
- Splitting and comparing the two regimes is a consistency check for the model
  - Both parameter sets should predict the same value
- Preparation of the pipeline for the Euclid data
  - At the same time, develop general pipeline using CosmoSIS, to analyse existing data

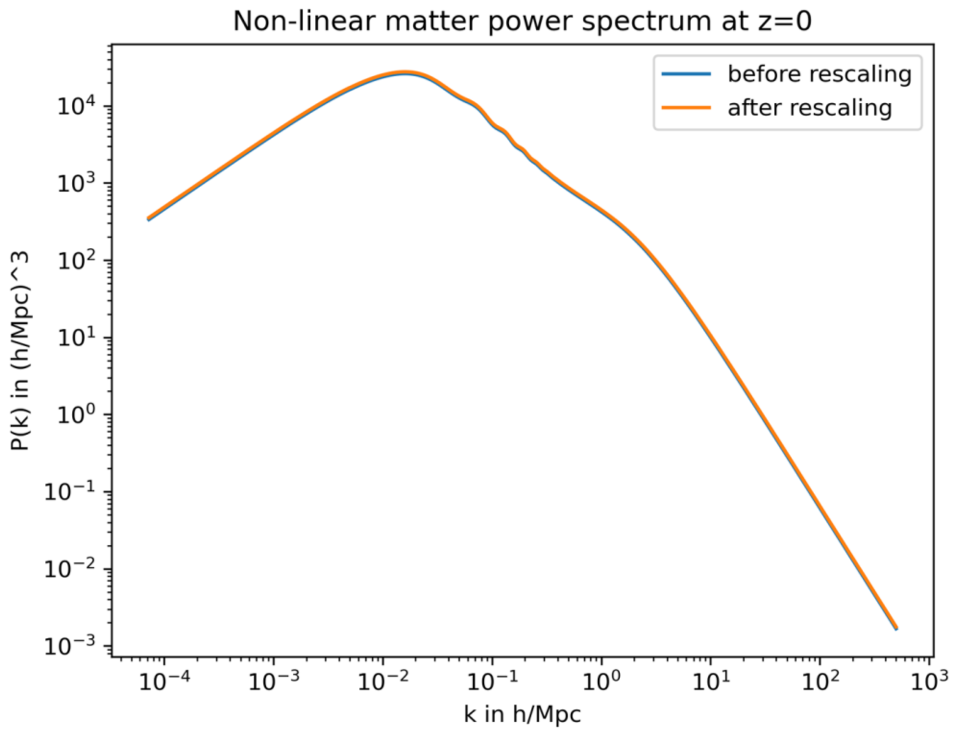
PREVIOUS RESULTS FROM KIDS-1000

- Analysis relies heavily on splitting external data:
- Geometry: BAO, Weak lensing (WL) window functions, CMB acoustic peak
- Growth: Growth rate from redshift space distortions, WL & CMB power spectrum
- All cosmological parameters are duplicated

POWER SPECTRUM RESCALING

$$P^{lin}_{split}(k,z) = P^{lin}_{EBS}(k,z)\left(\frac{G^{ODE}_{growth}(z)}{G^{ODE}_{geo}(z)}\right)^2$$





POWER SPECTRUM RESCALING

$$P^{lin}_{split}(k,z) = P^{lin}_{EBS}(k,z)\left(\frac{G^{ODE}_{growth}(z)}{G^{ODE}_{geo}(z)}\right)^2$$