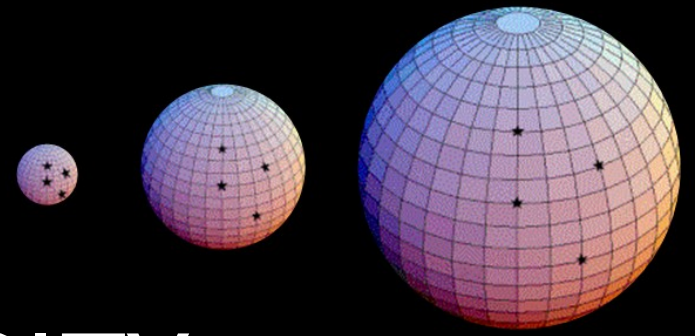
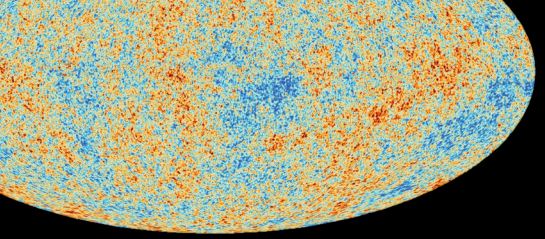


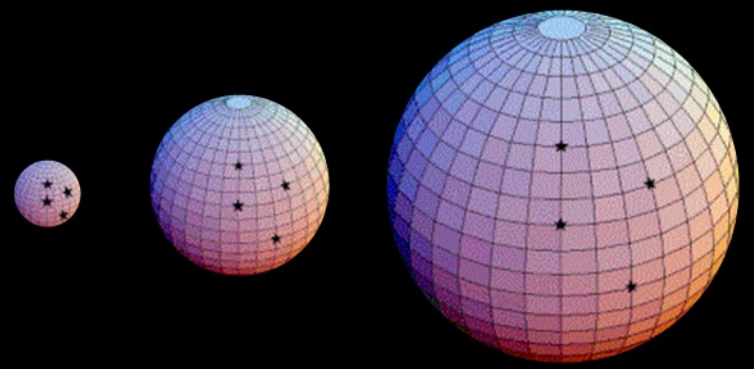
SPLITTING THE MATTER DENSITY PARAMETER Ω_m INTO THREE REGIMES: GEOMETRY, GROWTH AND EARLY-UNIVERSE

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

COLLOQUE WG DARK ENERGY 2026

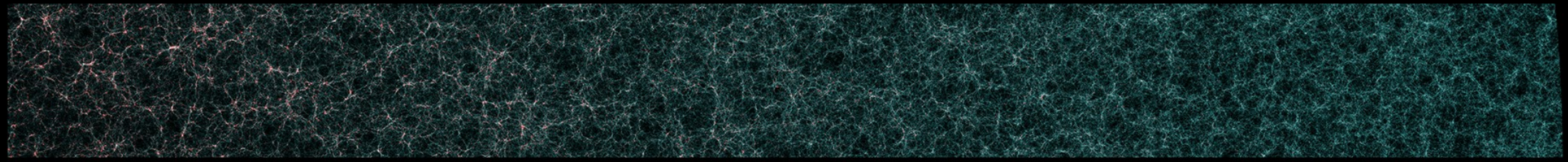


Planck 2018 CMB Temperature Anisotropies



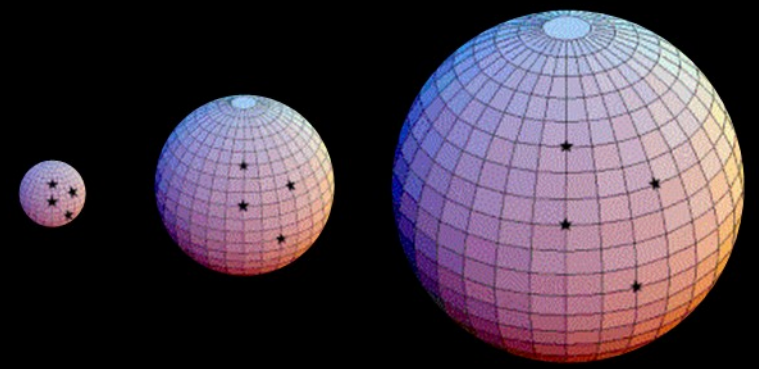
MATTER DENSITY SPLIT

- From cosmological surveys, we receive information from different sources
- Differentiate a **geometry**, a **growth** and an **early** regime for parameter estimation
- Predict three values for the matter density, compare them as a consistency test
- Earlier analyses have not found a discrepancy between geometry & growth
- Based on Keil et al. [2607.28326]

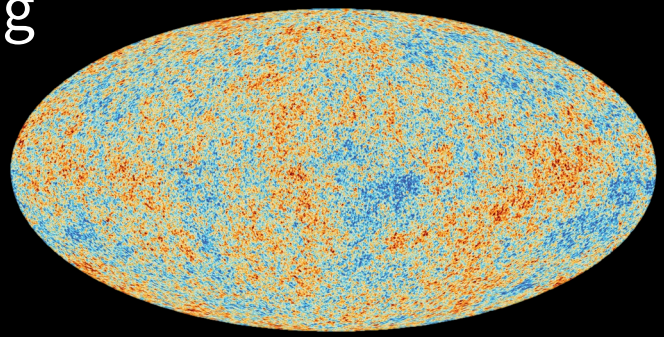


Flagship Simulation
J. Carretero, P. Tallada, S. Serrano & the *Euclid* Simulations SWG

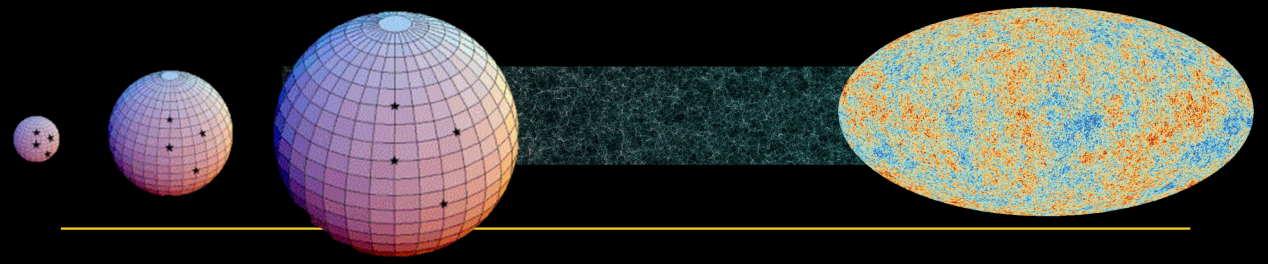
MATTER DENSITY SPLIT



- **Geometry:** Background evolution including the expansion history of the universe and distances
- **Growth:** Fluctuations leading to structure, i.e. galaxies, clusters, filaments, voids ..
- **Early:** Universe until recombination/decoupling



PROBE SENSITIVITIES

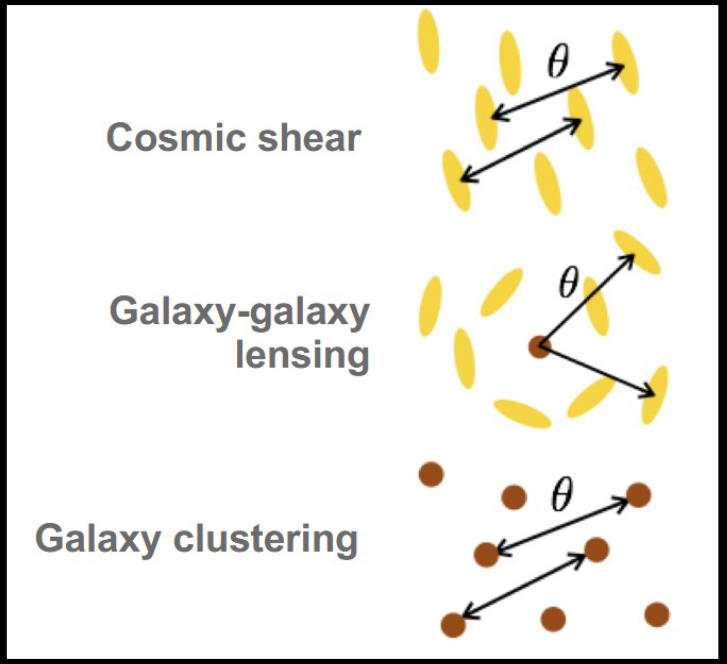


- 3x2pt (galaxy clustering, weak lensing)
- Cosmic microwave background
- Baryon acoustic oscillations
- Redshift-space distortions
- Type Ia Supernovae

Geometry	Growth	Early Universe
✓	✓	✓
✓		✓
✓		✓
(✓)	✓	(✓)
✓		

3 X 2 POINT PROBE

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



Schema of the 3x2point Probe

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

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

- Calculate the growth using the differential equation

$$G'' + \left(4 + \frac{H'}{H}\right) G' + \left(3 + \frac{H'}{H}\frac{3}{2}\Omega_m(\ln a)\right) G = 0$$

Geometry

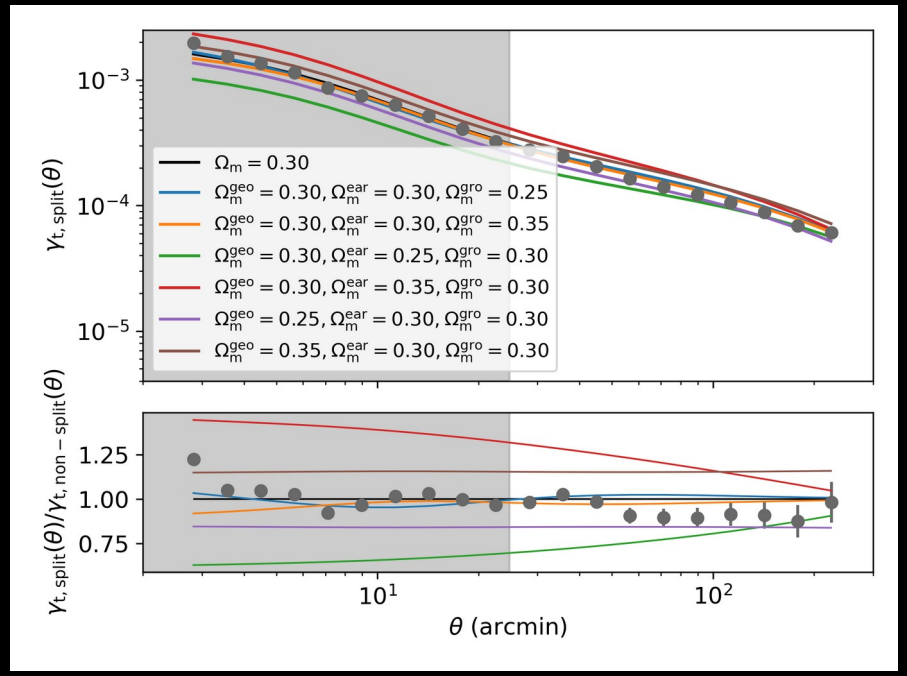
THEORETICAL RECIPE FOR 3X2POINT DATA

- Call the Einstein-Boltzmann solver (EBS) using Ω_m^{early}
- Rescale the EBS power spectrum
- This new split power spectrum

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

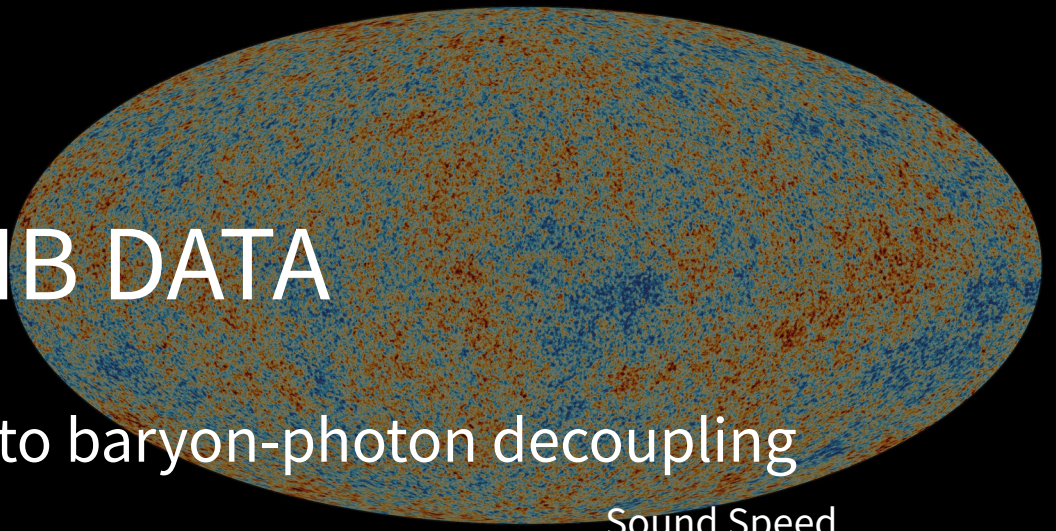
- Non-linear boost factor w. an emulator and Ω_m^{growth}

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



DES Galaxy-galaxy lensing w. split Ωm

THEORETICAL RECIPE FOR CMB DATA



- Constrains mostly the early regime: physics up to baryon-photon decoupling
  - Call EBS with Ω_m^{early}
- Angular scale of the acoustic peaks
- Rescale w. angular diameter distance

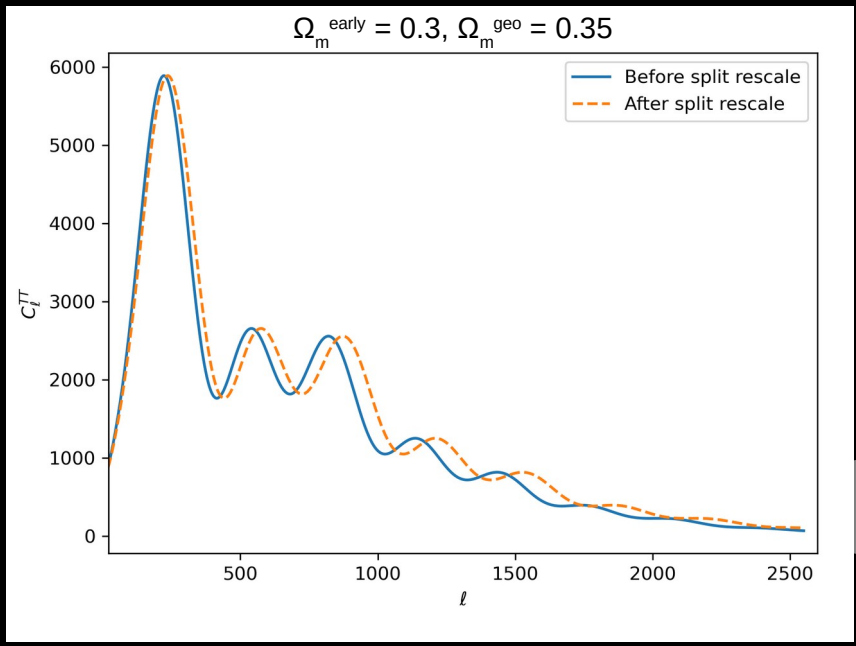
Sound Speed

$$\theta = \frac{r_s(\eta_{\rm dec})}{d_A(\eta_{\rm dec})} = \frac{\int_0^{\eta_{\rm dec}} d\eta\, c_s(\eta)}{\int_{\eta_{\rm dec}}^{\eta_0} d\eta}$$

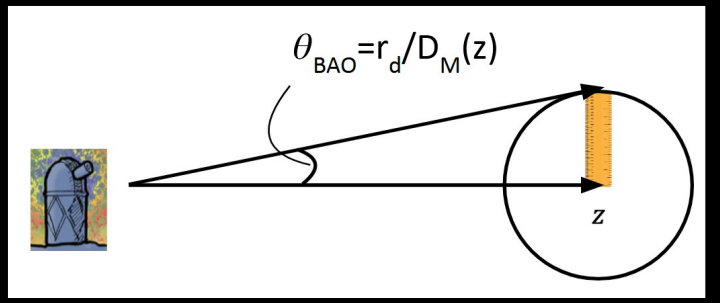
$$C^{\rm TT/TE/EE}(\ell_{\rm rescale}) = C^{\rm TT/TE/EE}\left(\ell_{\rm EBS}\frac{d_A^{\rm geo}}{d_A^{\rm early}}\right)$$

- Omit the CMB lensing that depends on growth
- Scale cuts after 1st peak at l=396 (Zhong+ 2301.03694

CMB temperature C_l w. split Ωm



THEORETICAL RECIPE FOR BAO

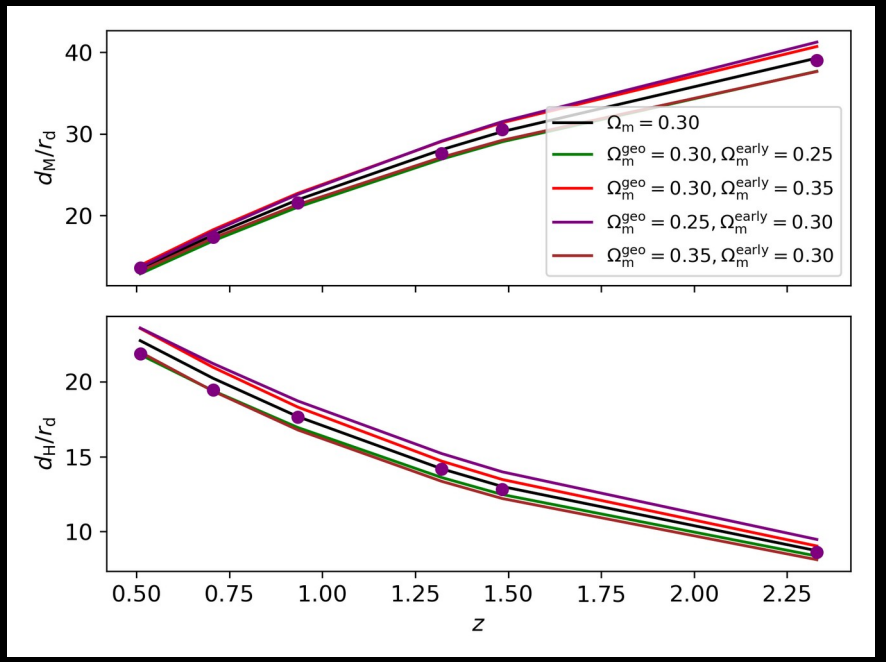


- BAO constrain $d_M(z)/r_d$ or $d_H(z)/r_d$ through the observed angle
  - Distances are in the geometry regime
- Sound horizon of the universe at the drag epoch

$$r_d = r_s(z_{drag})$$

- Approximation (Brieden et al. 2023), early Ω_m

$$r_d = 147.05\text{Mpc}\left(\frac{\Omega_m^{early}h^2}{0.1432}\right)^{-0.23}\left(\frac{N_{eff}}{3.04}\right)^{-0.1}\left(\frac{\Omega_b h^2}{0.02236}\right)^{-0.13}$$



DESI angular diameter and Hubble distances w. split Ωm

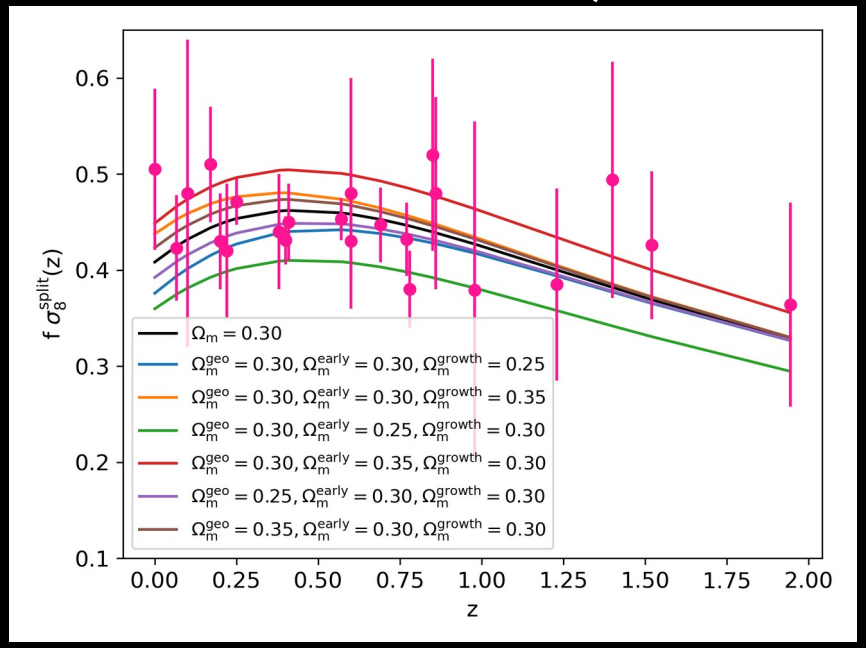
THEORETICAL RECIPE FOR RSD DATA

- $(f\,\sigma 8)(z)$ from redshift-space distortions (RSD) (Blanchard et al. 2205.05017)
- Calculate $f(z)$ with the ODE and Ω_m^{growth}

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

Geometry

$$\sigma_8^{\rm split}(z) = \sigma_{8,\rm EBS}(z)\,\frac{G_{\rm ODE}^{\rm growth}(z)}{G_{\rm ODE}^{\rm early}(z)}$$



Redshift space distortions w. split Ωm

- Not only growth-dependent, but consistent with other probes, e.g. 3x2pt

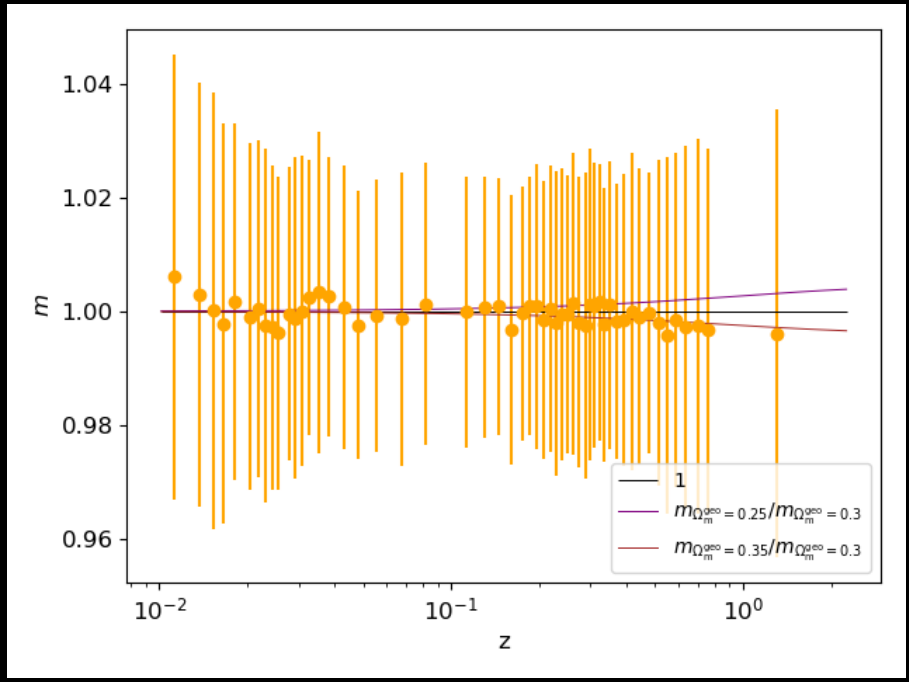
THEORETICAL RECIPE FOR SUPERNOVAE

- Supernovae Type Ia are standardisable candles
- Likelihood compares the measured SNe Ia apparent magnitude with the one using the luminosity distance

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

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

  → We can safely combine with the CMB data

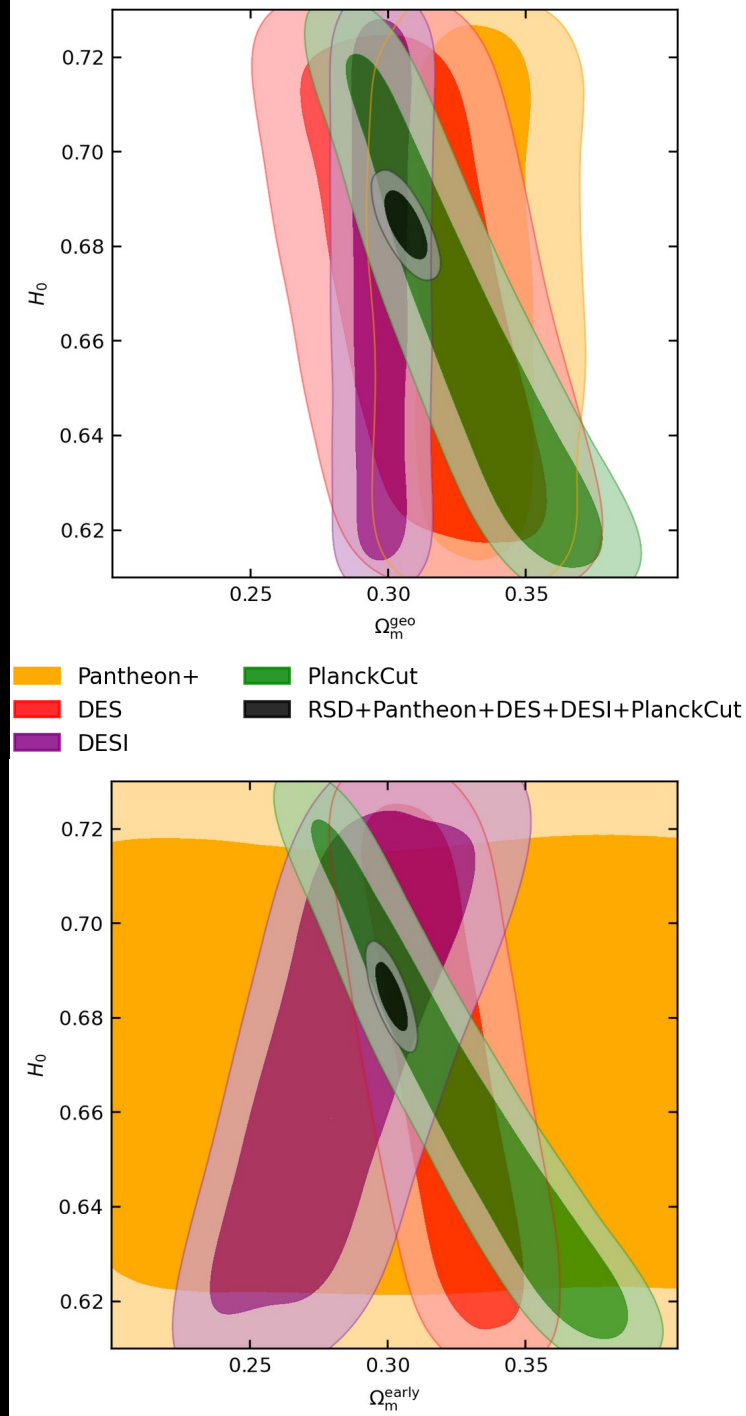


Binned Pantheon+ apparent magnitude residuals

RESULTS

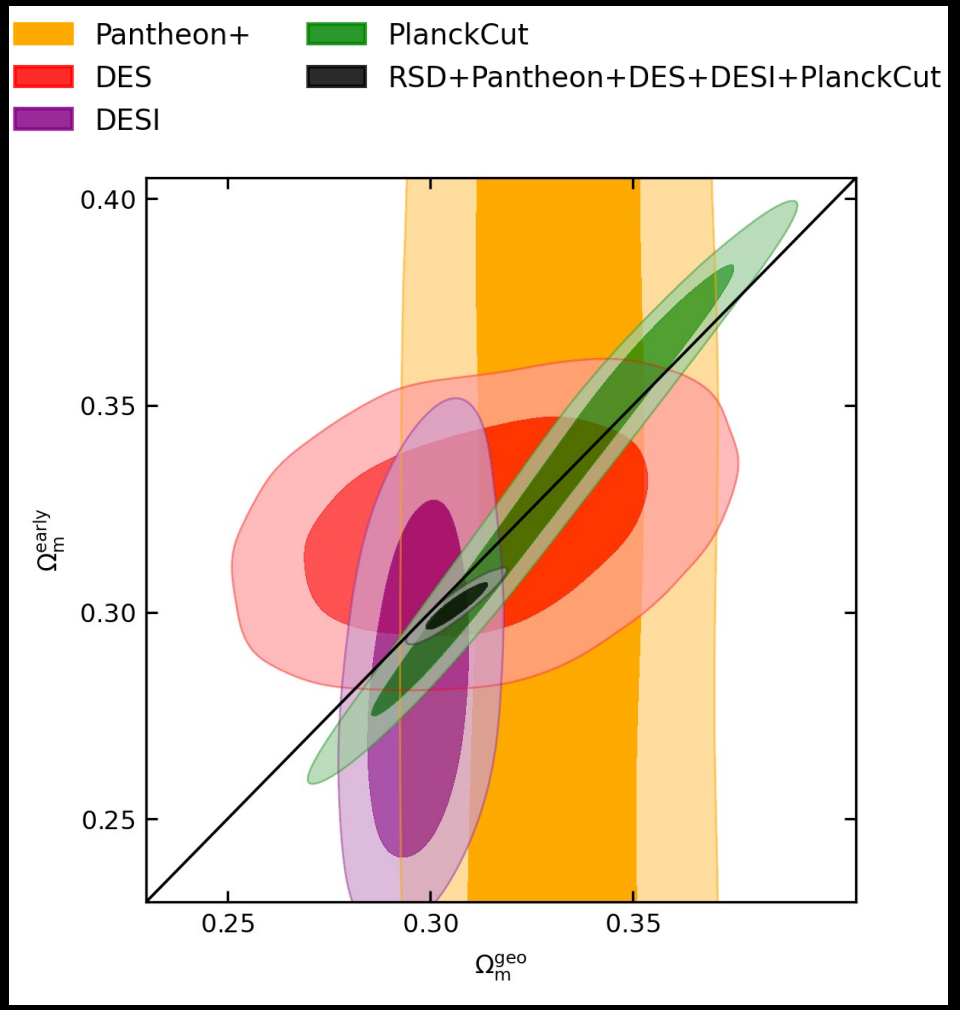
- Planck constrains $\omega_m^{geo} = \Omega_m^{geo} h^2$
- DESI does not constrain H0, only Ω_m^{geo}
- Pantheon+ (without SH0ES) as well
  - Slight discrepancy w. DESI

- Planck constrains $\omega_m^{early} = \Omega_m^{early} h^2$
- For BAO, pos. correlation from r_d
- Constraint comes from the combination



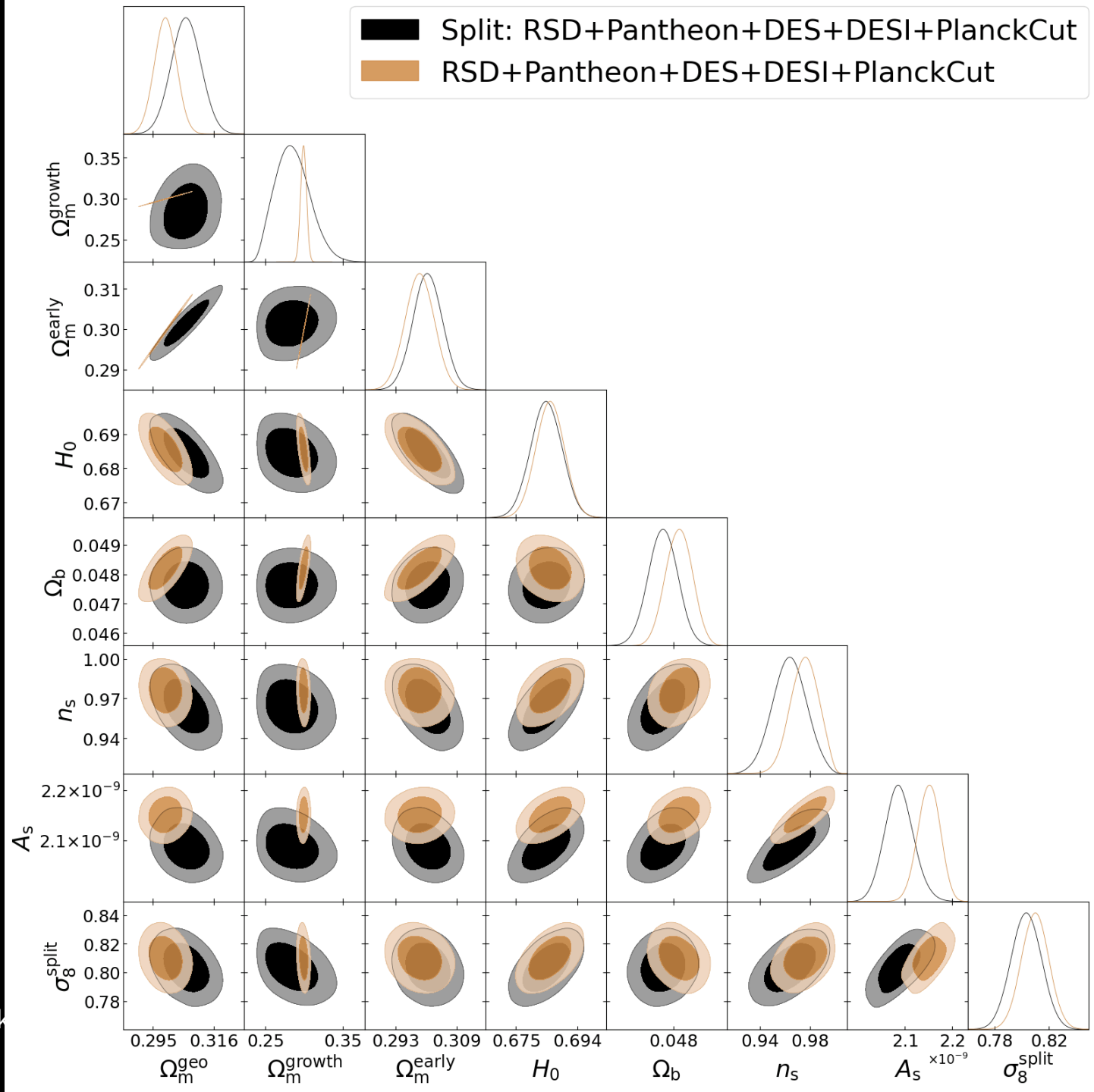
RESULTS

- Pantheon only constrains Ω_m^{geo}
- In DESI, Ω_m^{geo} much better constrained
- Planck sensitive to both
  - Strongly positively correlated
- Probes are very complementary



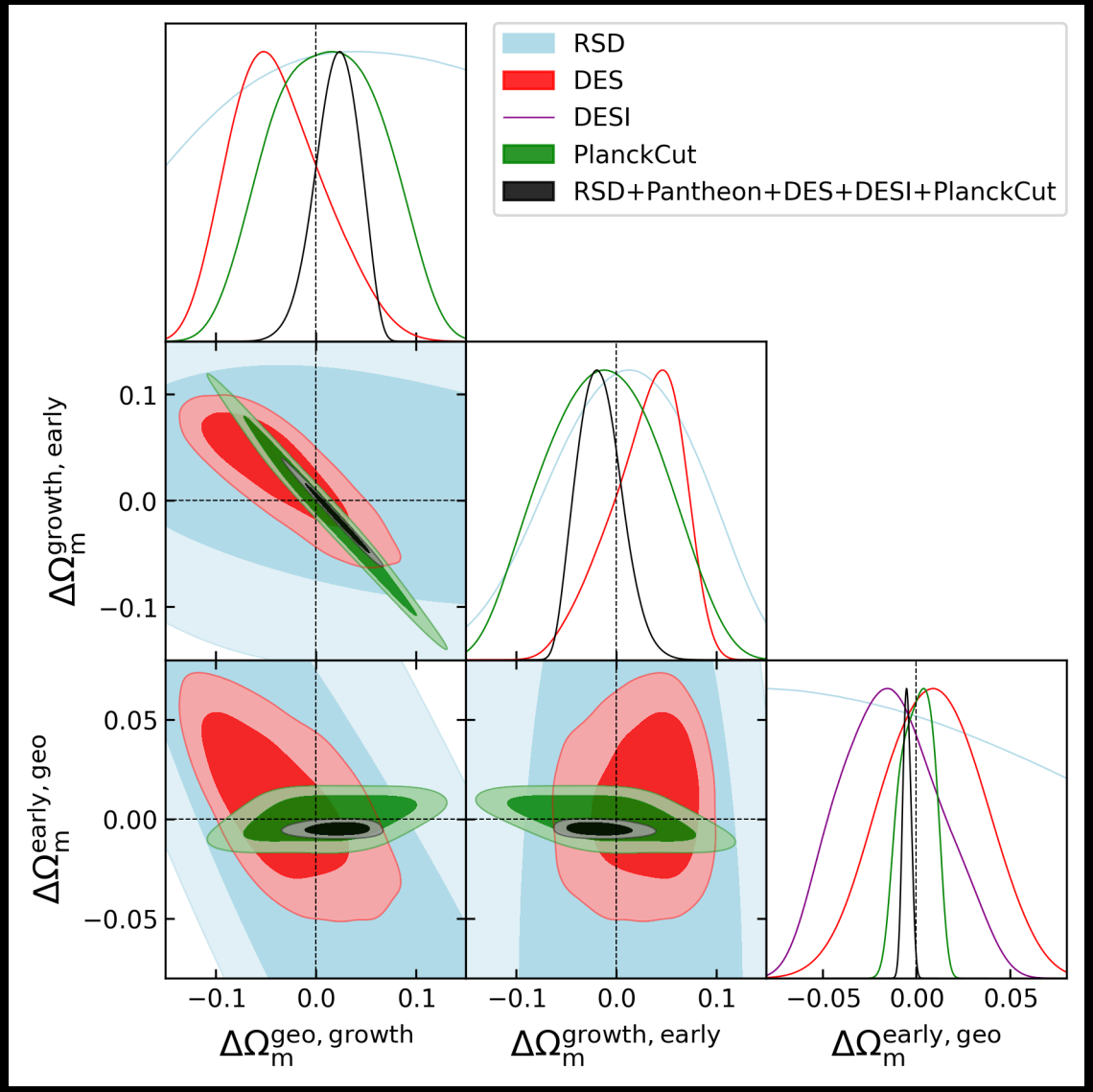
RESULTS

- RSD+Panth+DES+DESI+Planck
- Early and geom. regimes corr.
- Shifted parameters (e.g. A_s)
  - Corr. w. shifted Ω_m^{geo}
- Growth worse constrained than other regimes
- 3 regimes agree within 1σ



RESULTS

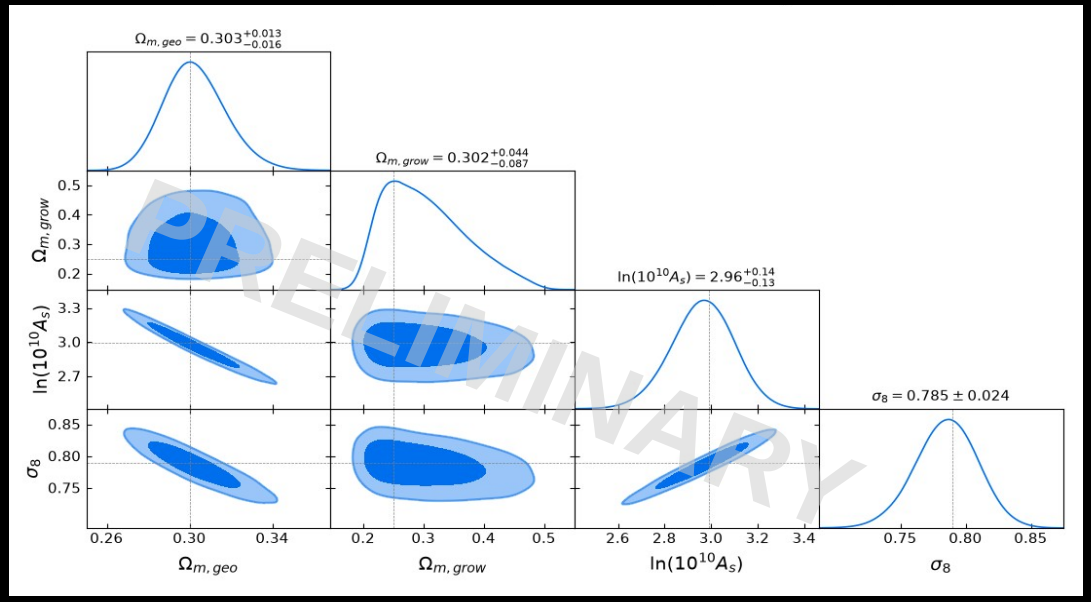
- Quantify differences between the regimes
- Differences agree with 0 broadly
- The geometry and the early regime agree within 2σ
  - Very small error



Differences between the regimes

PREPARATION FOR EUCLID DR1

- Part of the Euclid Theory Group: Homogeneity, Isotropy and Consistency Tests
- Members: F. Keil, Z. Sakr, I. Tutusaus,
  A. Blanchard, S. Pamuk, M. Martinelli
- Split between geometry and growth
- Modification of the Euclid cloe-org code

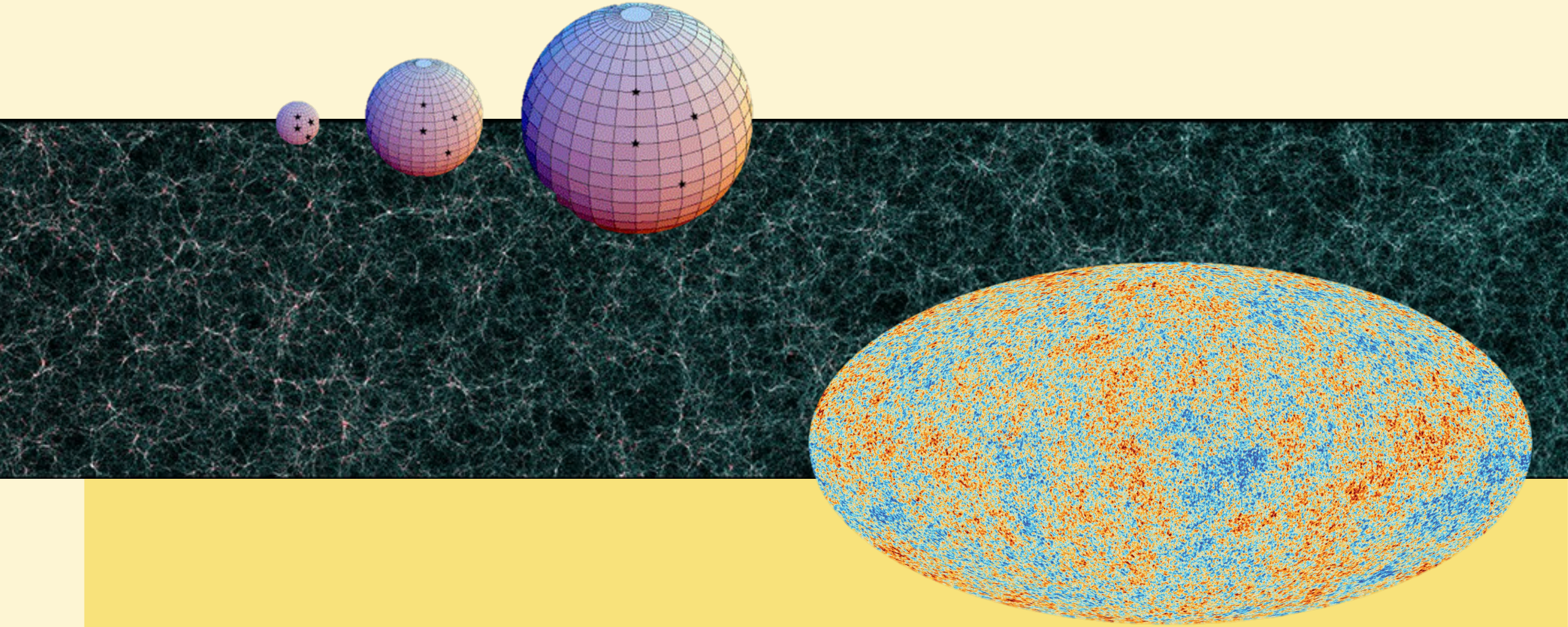


Plot by Ziad Sakr

- Preliminary tests on synthetic data: finding the input value for both Ωm ✓

CONCLUSION

- Separate the influence of geometry vs. growth vs. early-times for Ω_m
- Geometry for distances, growth for structures & early regime for early-time physics
- Consistency test of ΛCDM
- Combinations of already existing data: DES+Planck+DESI+RSD+Pantheon+
- The regimes are compatible
- Next steps: better constrain growth, i.e. with strong lensing, CMB lensing, clusters

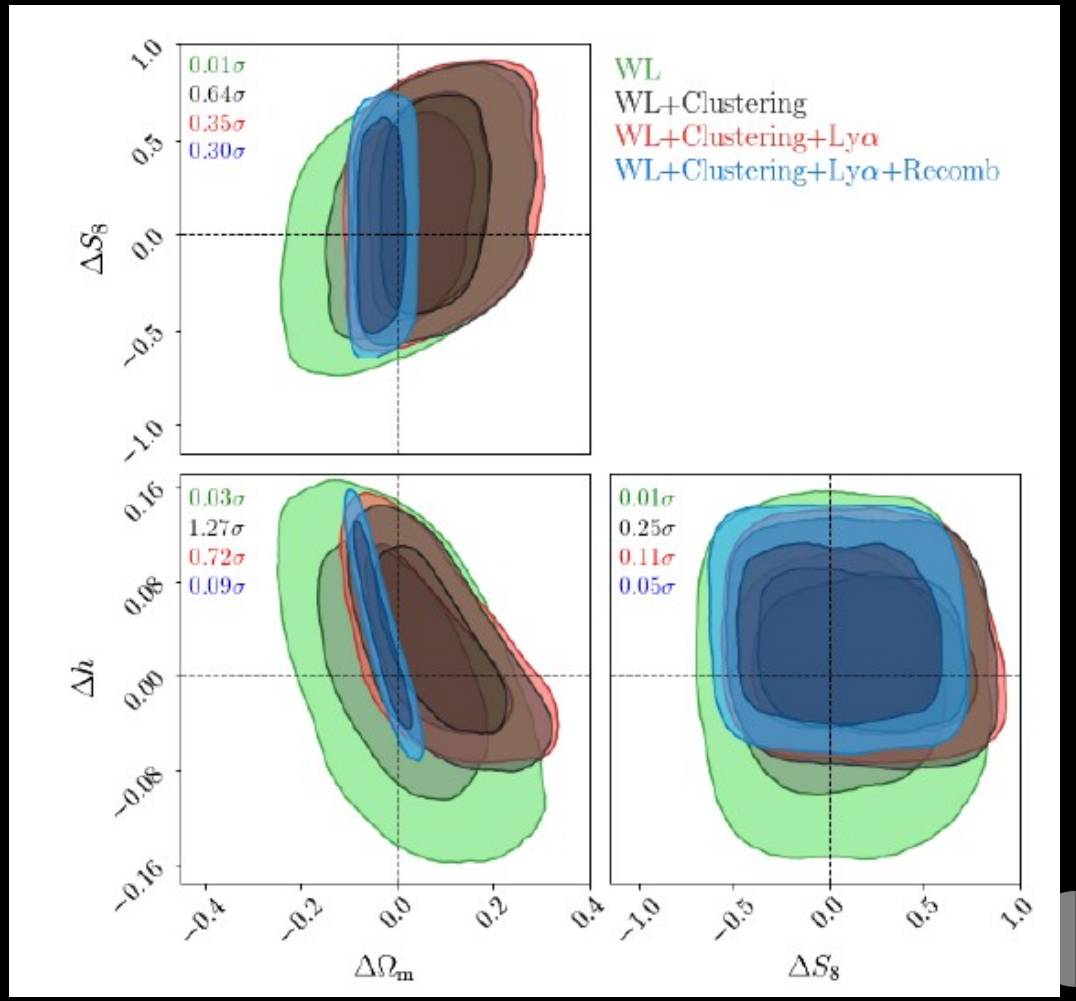


THANK YOU FOR YOUR ATTENTION

BACKUP

PREVIOUS RESULTS FROM KIDS-1000

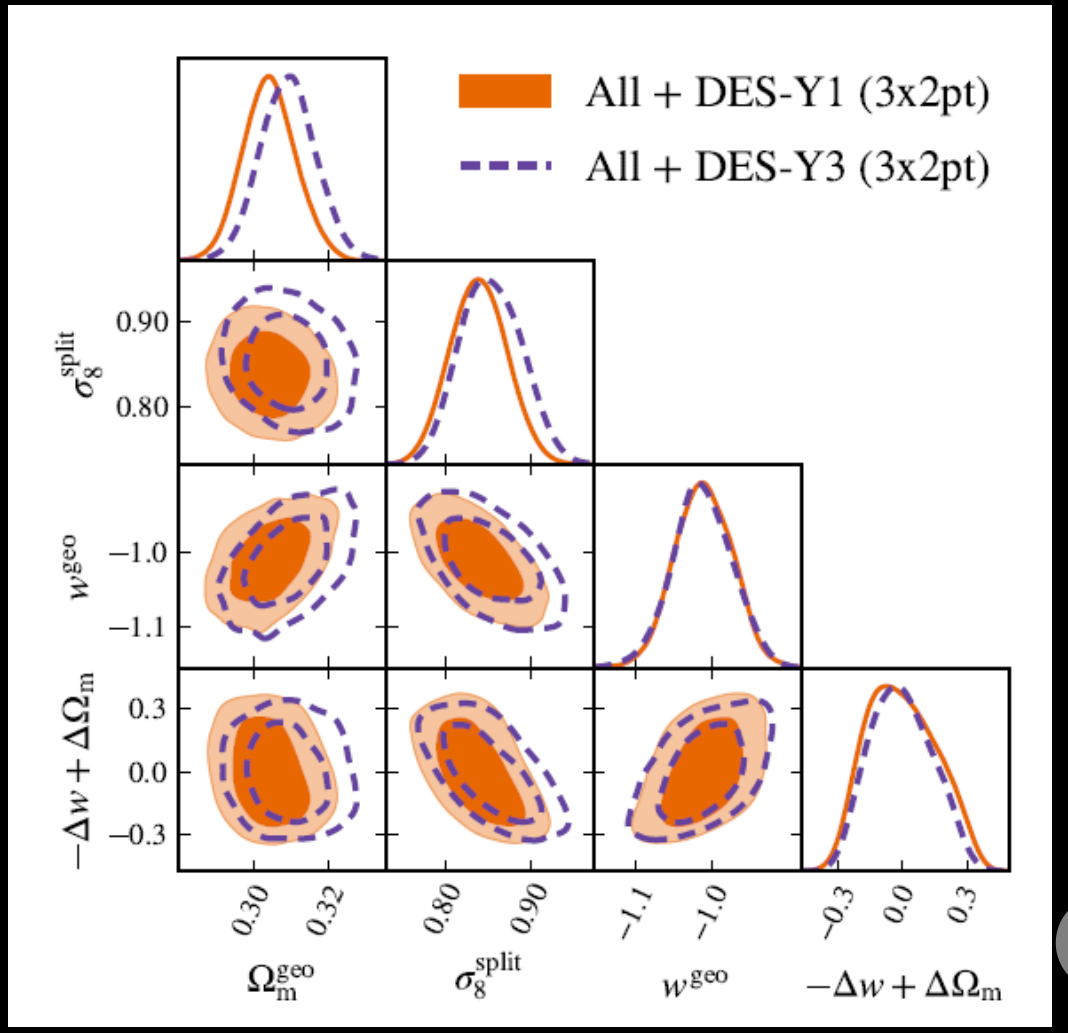
- Ruiz-Zapatero et al. 2021 considers geometry vs. growth
- Analysis relies on splitting external data
- All cosmological parameters are duplicated
  - The difference between regimes is computed
- The differences are consistent with 0 (black dotted line) with comparatively large errors



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
- No tension between geometry & growth for the 3x2pt + external (CMB, SN, BAO, BBN)
- The 2x2pt + external diverges from 0 (not shown here): Attributed to systematics



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

THEORETICAL RECIPE FOR 3X2PT DATA

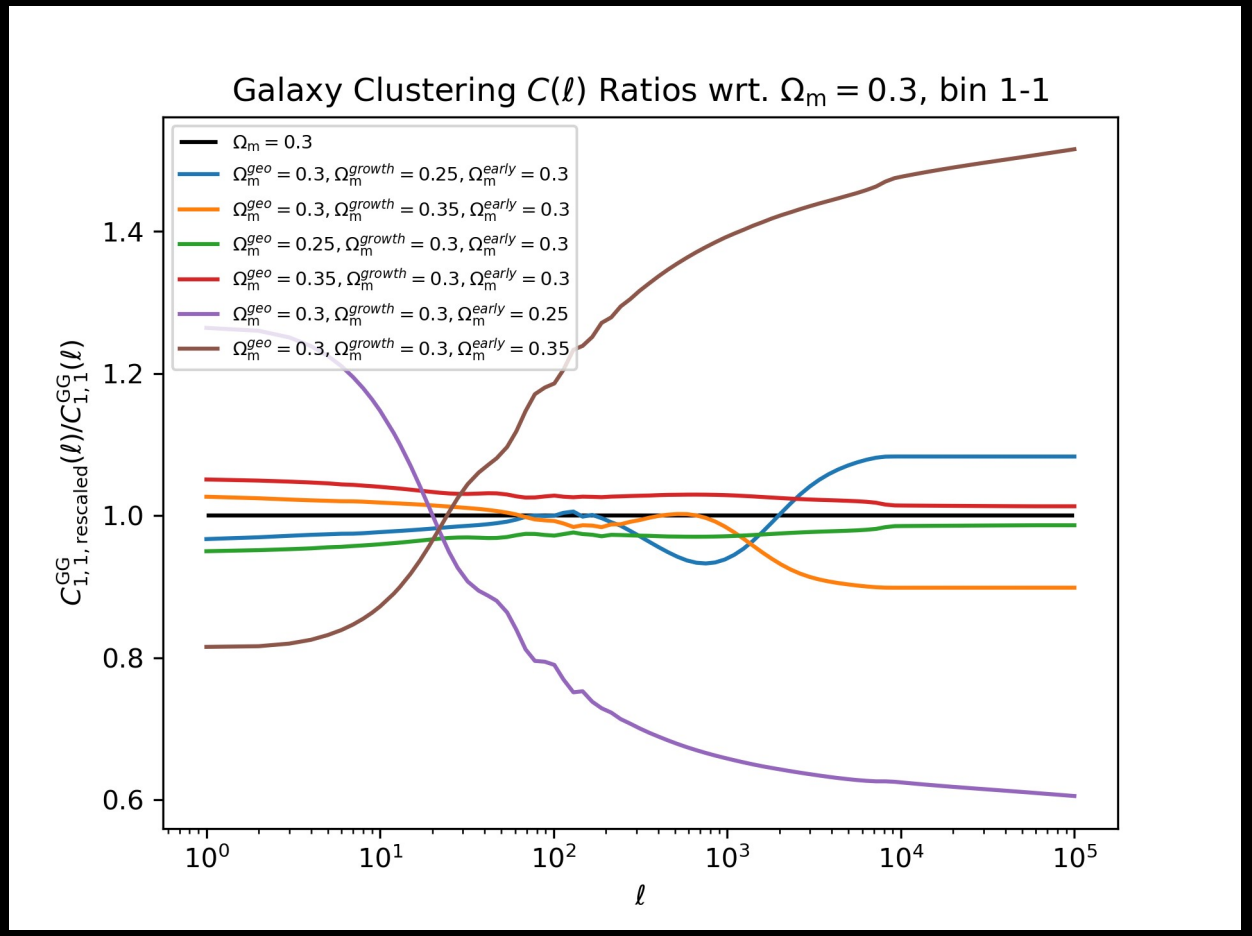
- The distances are in the geometry regime
- The matter density comes from the Poisson equation
  - Classified as a geometric parameter

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

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

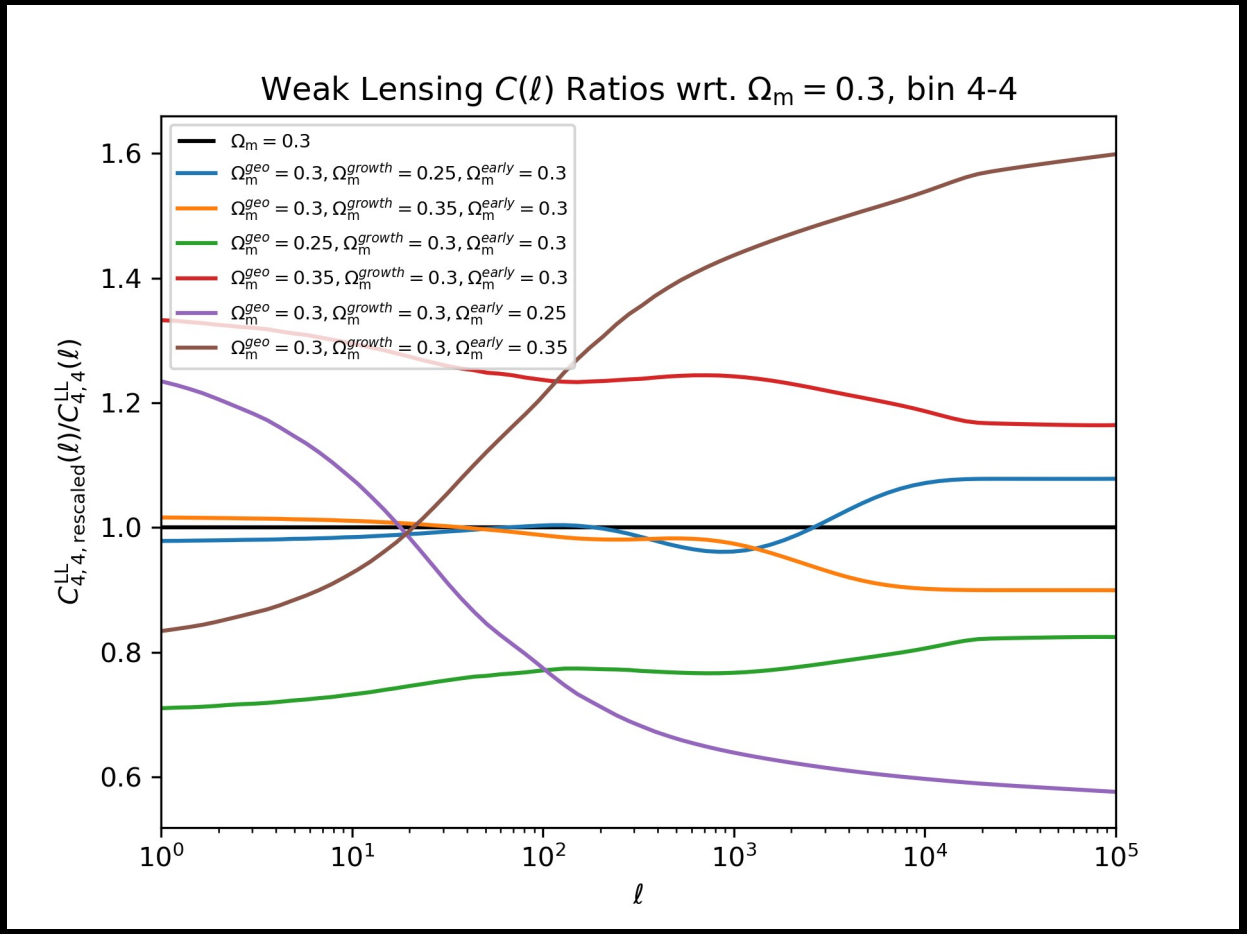
CLUSTERING ANGULAR POWER SPECTRUM

- C_l^{GG} using different Ω_m values
- Ω_m^{early} influences the EBS and the rescaling
- Ω_m^{growth} influences the rescaling and the non-linear corrections
- Ω_m^{geo} influences the distances in the window function



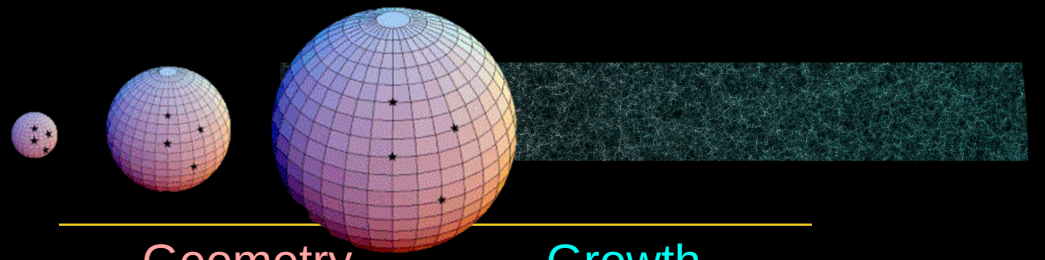
WEAK LENSING ANGULAR POWER SPECTRUM

- C_l^{LL} using different Ω_m values
- Ω_m^{early} influences the EBS and the rescaling
- Ω_m^{growth} influences the rescaling and the non-linear corrections
- Ω_m^{geo} influences the distances in the window function
-



PROBE SENSITIVITIES

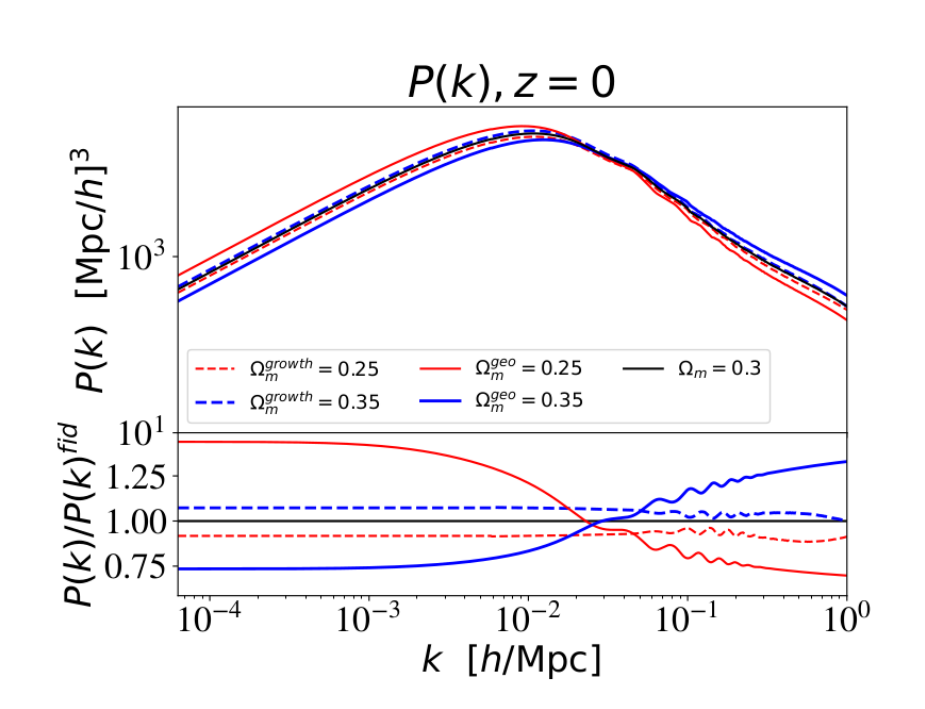
- 3x2pt (galaxy clustering & weak lensing)
- CMB acoustic angular scale θ*
- Baryon acoustic oscillations
- Redshift-space distortions

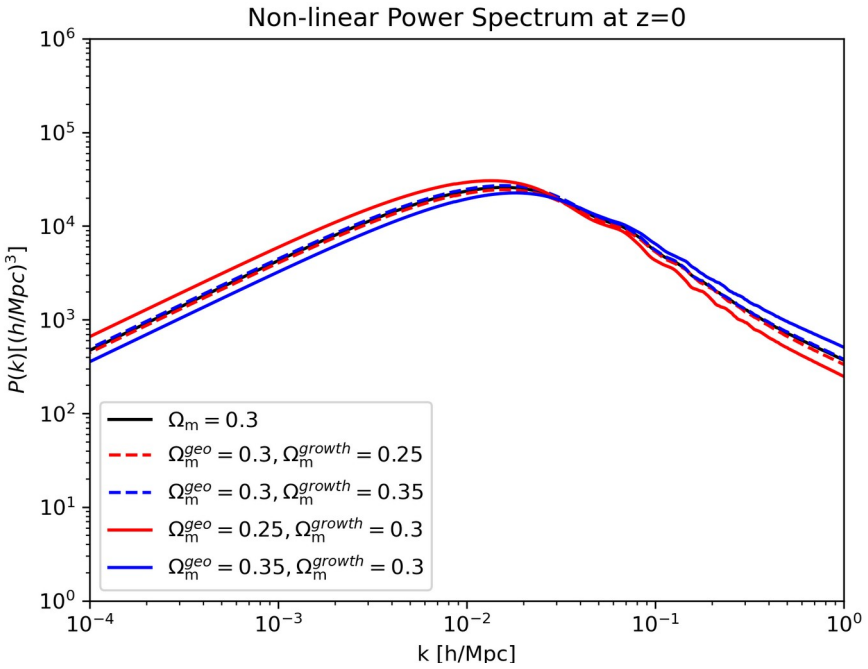


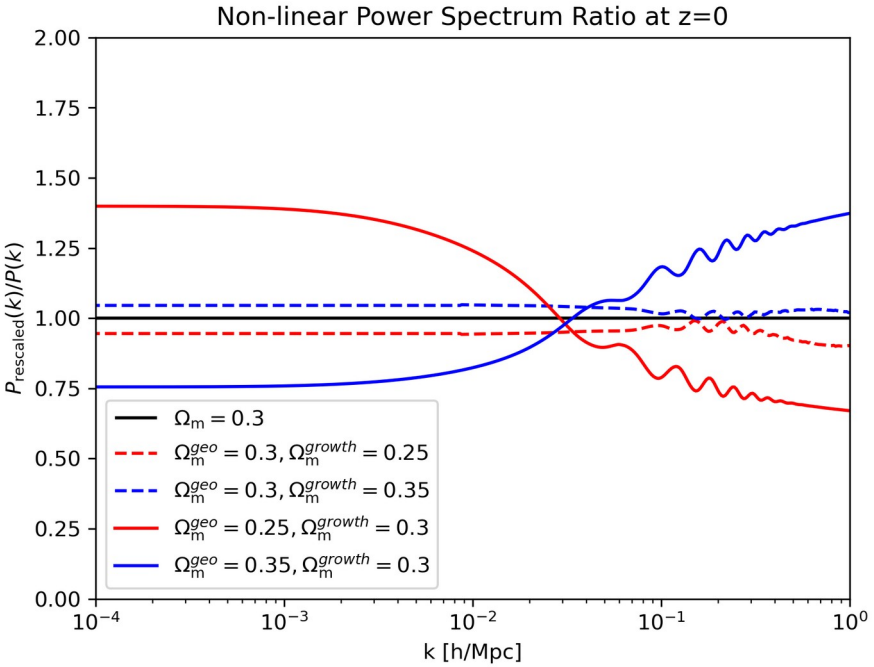
	Geometry	Growth
3x2pt (galaxy clustering & weak lensing)	✓	✓
CMB acoustic angular scale θ*	✓	
Baryon acoustic oscillations	✓	
Redshift-space distortions	(✓)	✓

COMPARISON WITH DES

- Our CosmoSIS implementation
- Matches DES figure well



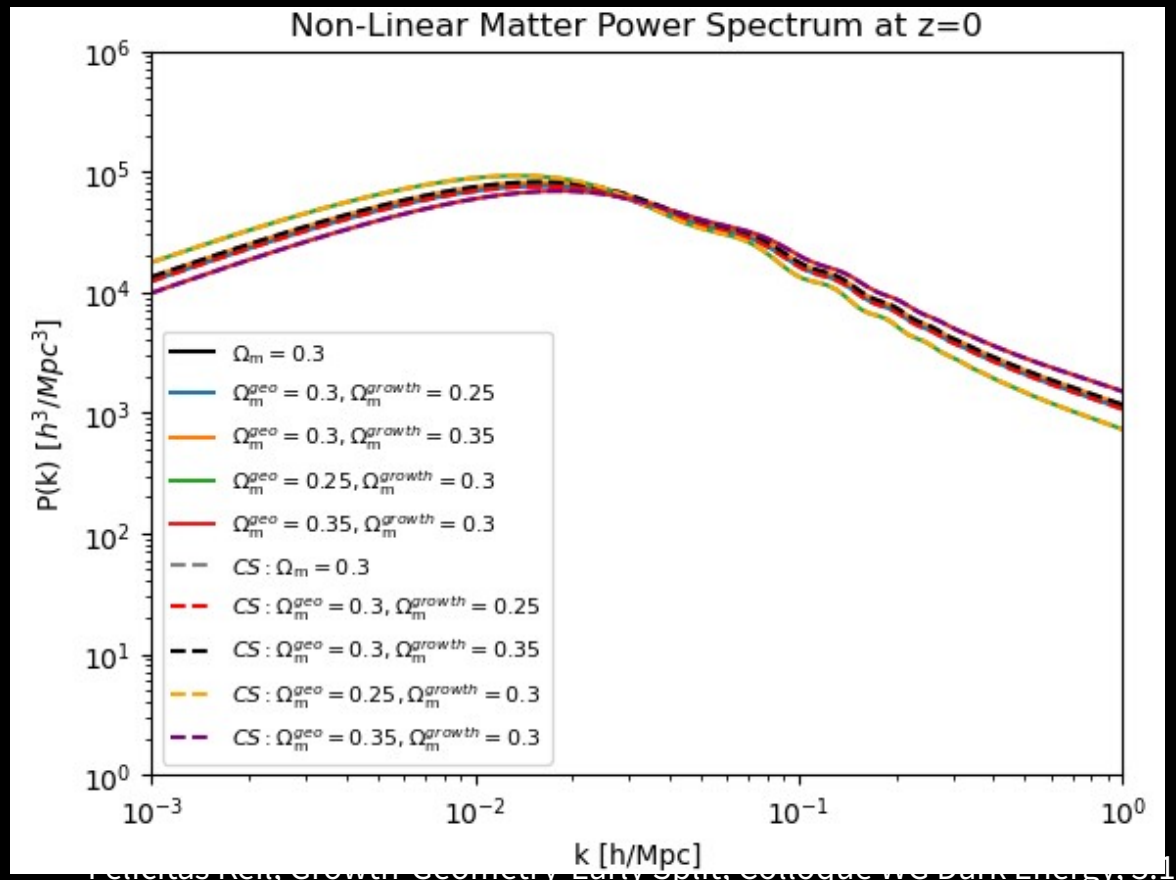


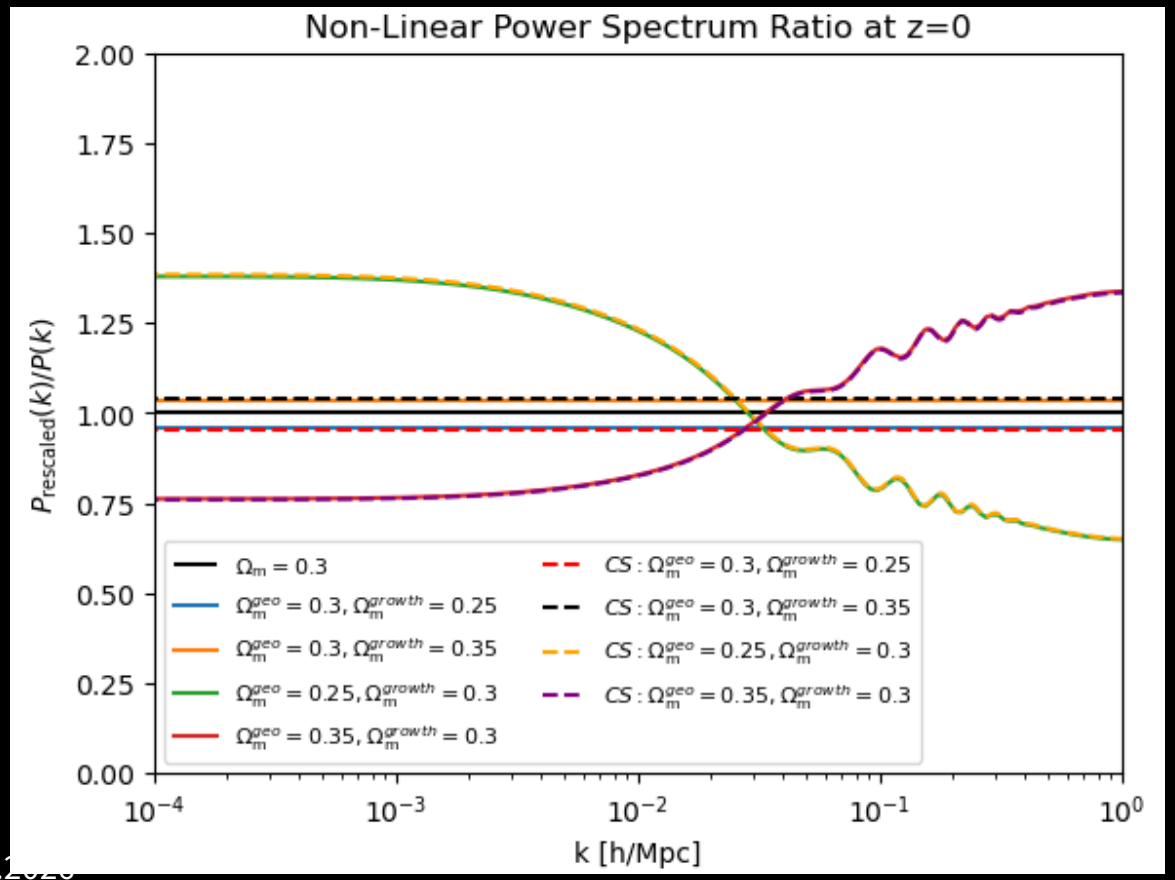


DES Split Non-linear P(k), Zhong et al.

CLOE-ORG VALIDATION WITH COSMOSIS (CS)

- Implementation of ODE and rescaling of the linear MPS





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

