The last 10 billion years of cosmic structure growth

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arXiv: 2105.12108

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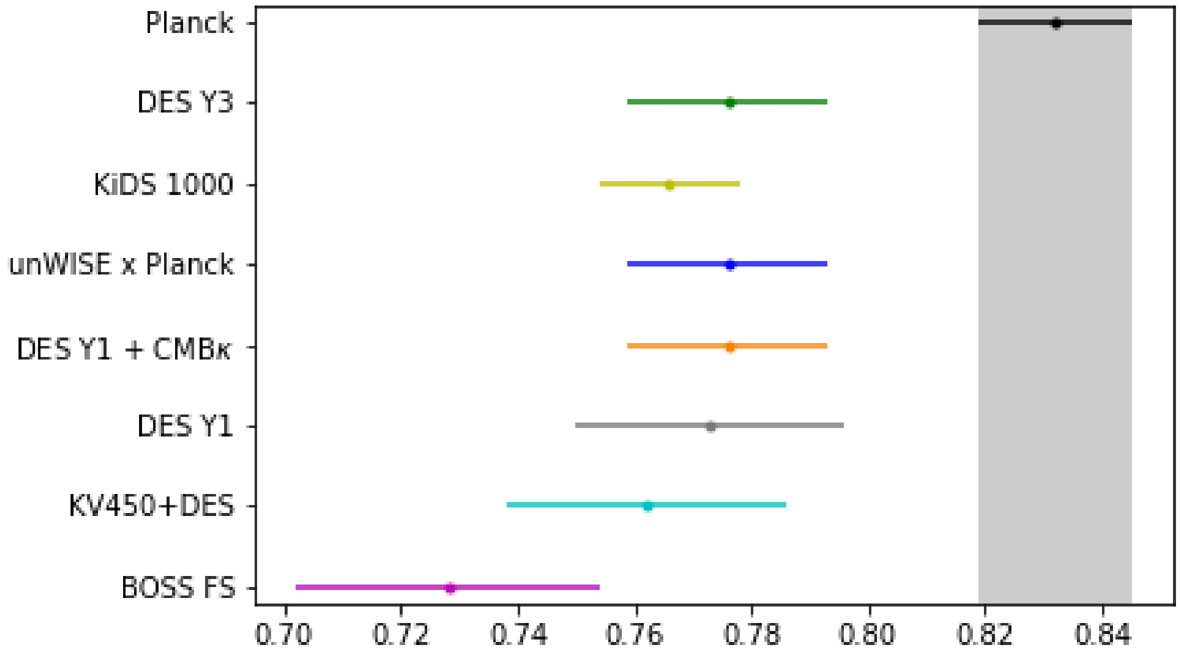
The S_8 tension

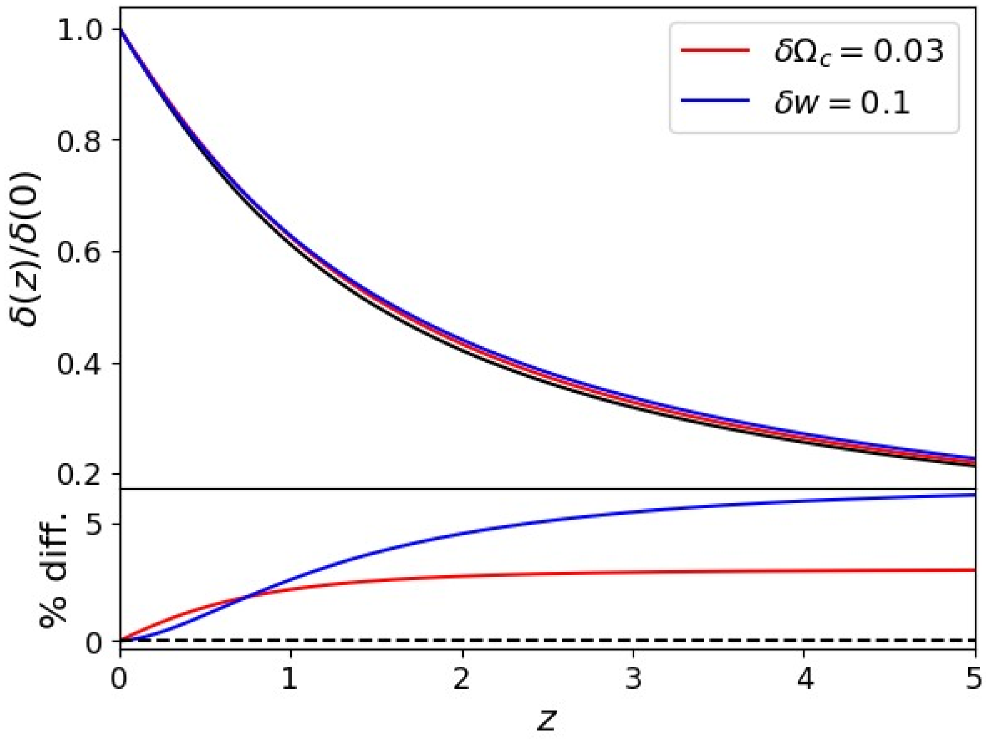


$$S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3}$$

σ_8 ~ amplitude perturbations

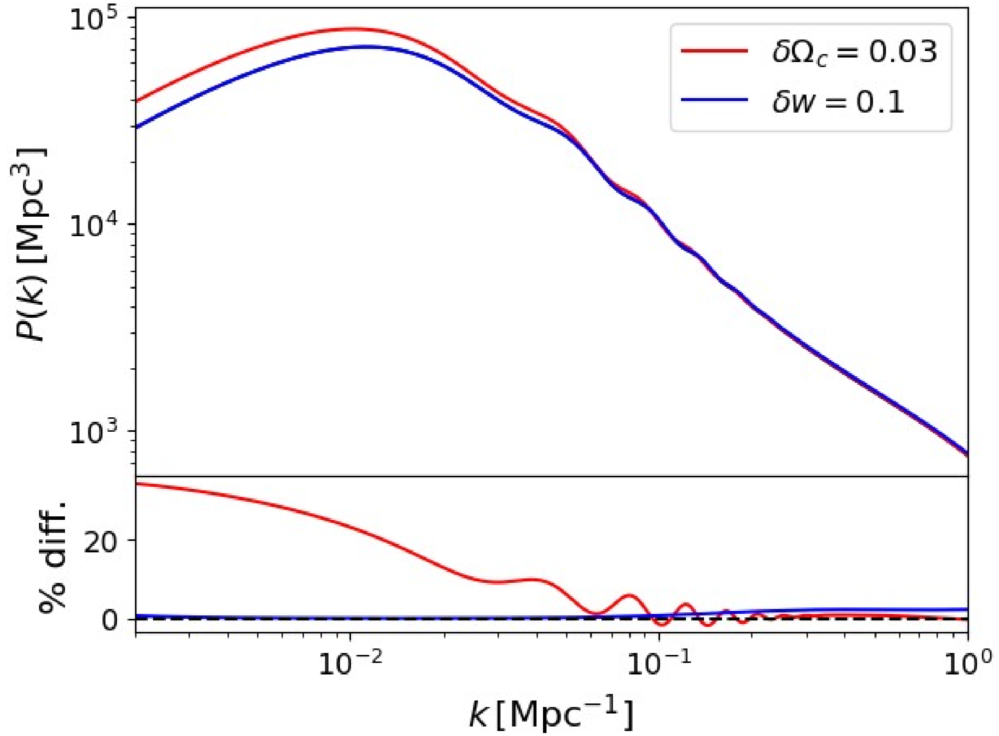
Troster et al. 2020
Abbott et al. 2017
Abbott et al. 2018
Joudaki et al. 2019

Growth of structure



$$\delta(\mathbf{x}) = \frac{\rho(\mathbf{x}) - \bar{\rho}}{\bar{\rho}}$$

The power spectrum



Theory can only predict its statistical properties:

$$P(k) \sim \langle |\delta(\mathbf{k})|^2 \rangle$$

Tracers of matter

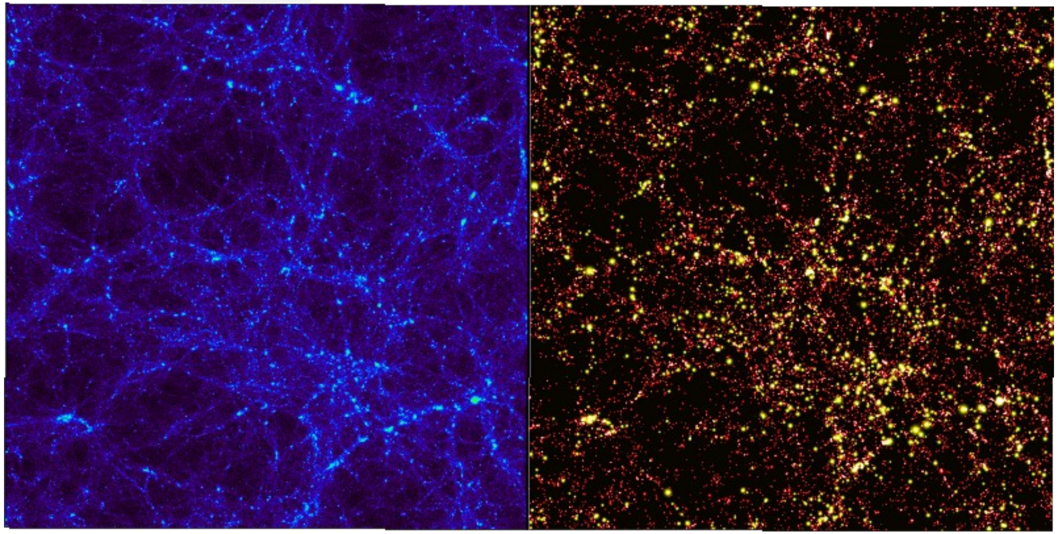
Galaxy clustering:

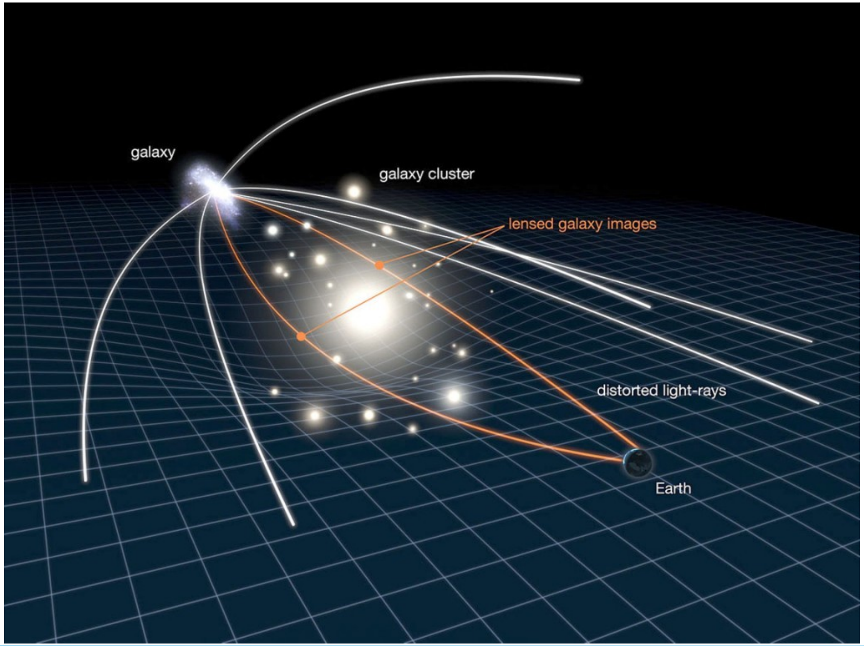
- $\delta_g = f[\delta_M] \sim b_g\, \delta_M$
- Local

Weak lensing:

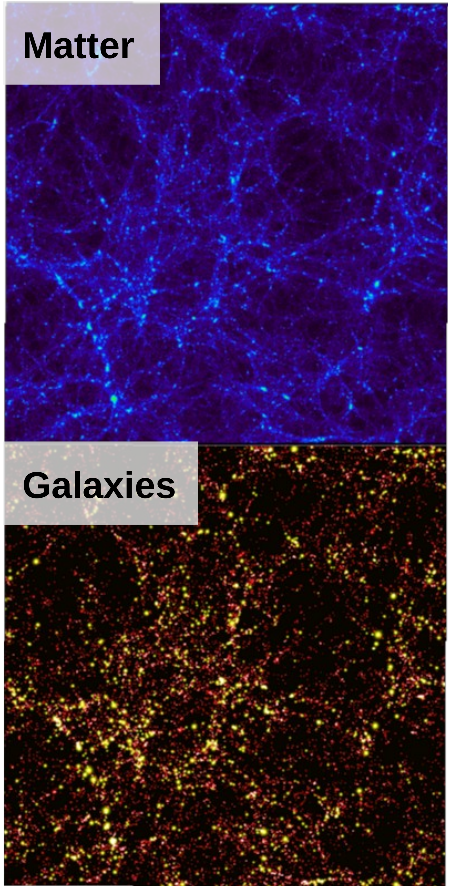
- $e_i \sim \gamma_i \sim \delta_M$
- Integrated

Matter **Galaxies**



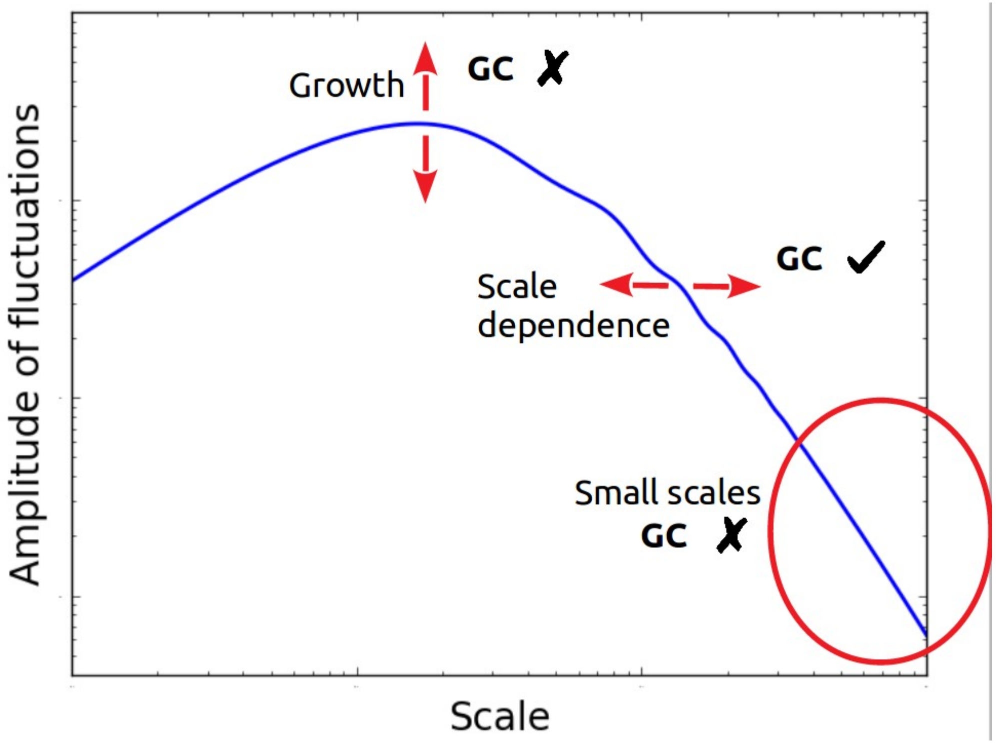


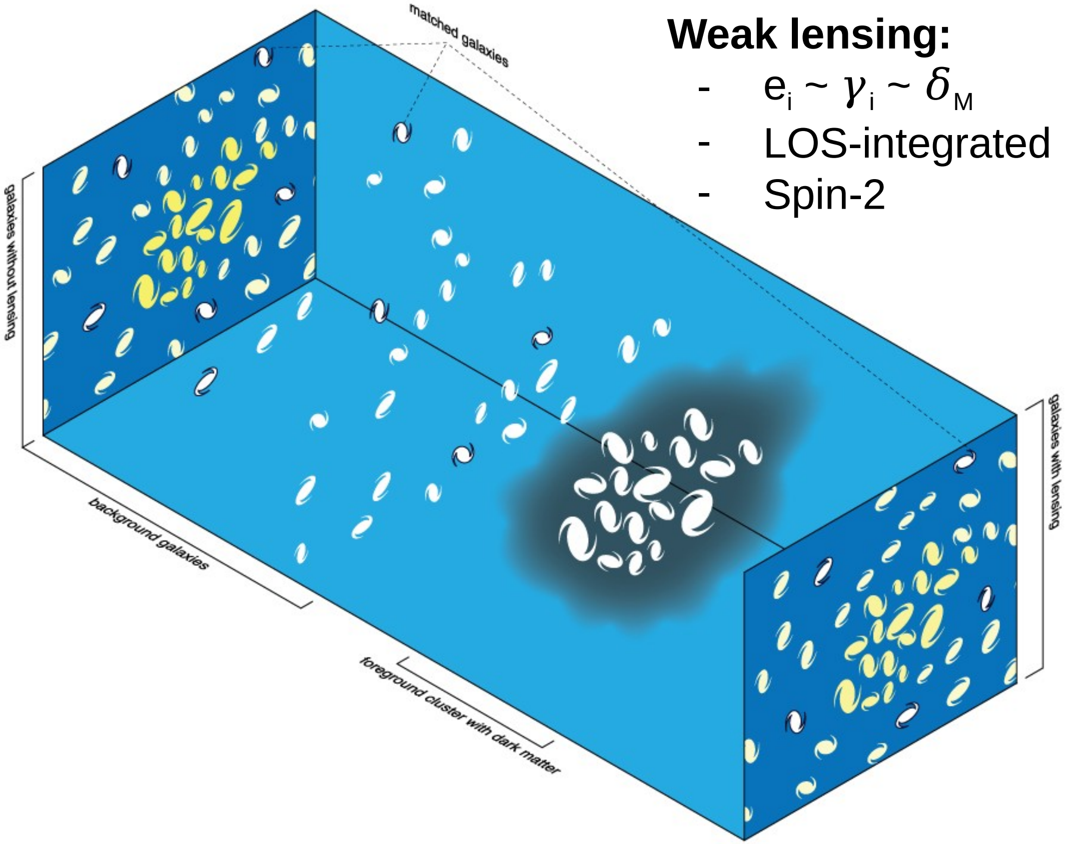
Galaxy clustering



Galaxy clustering:

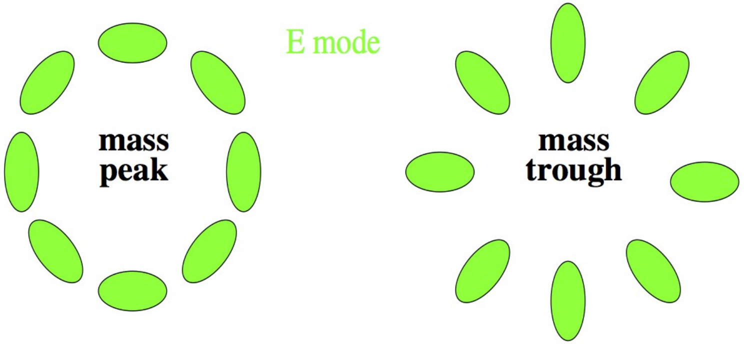
- $\delta_g = f[\delta_M] \sim b_g\ \delta_M$
- Local
- Spin-0



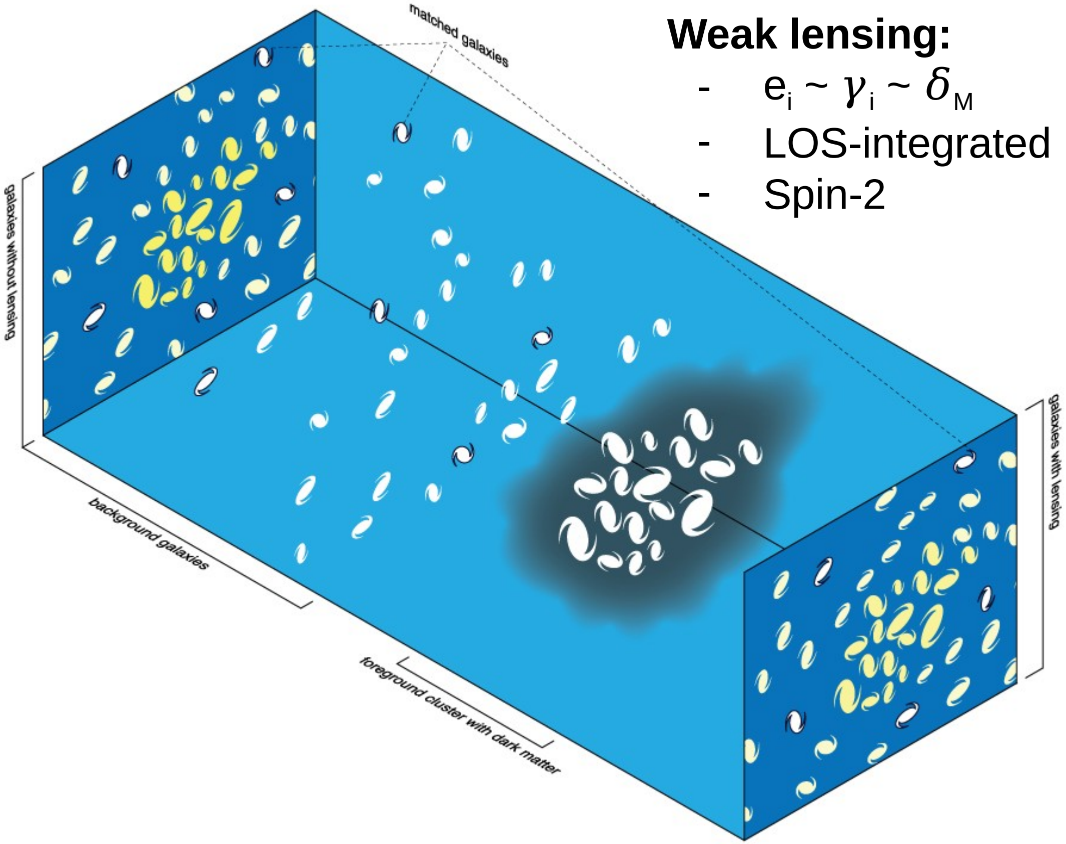


Weak lensing:

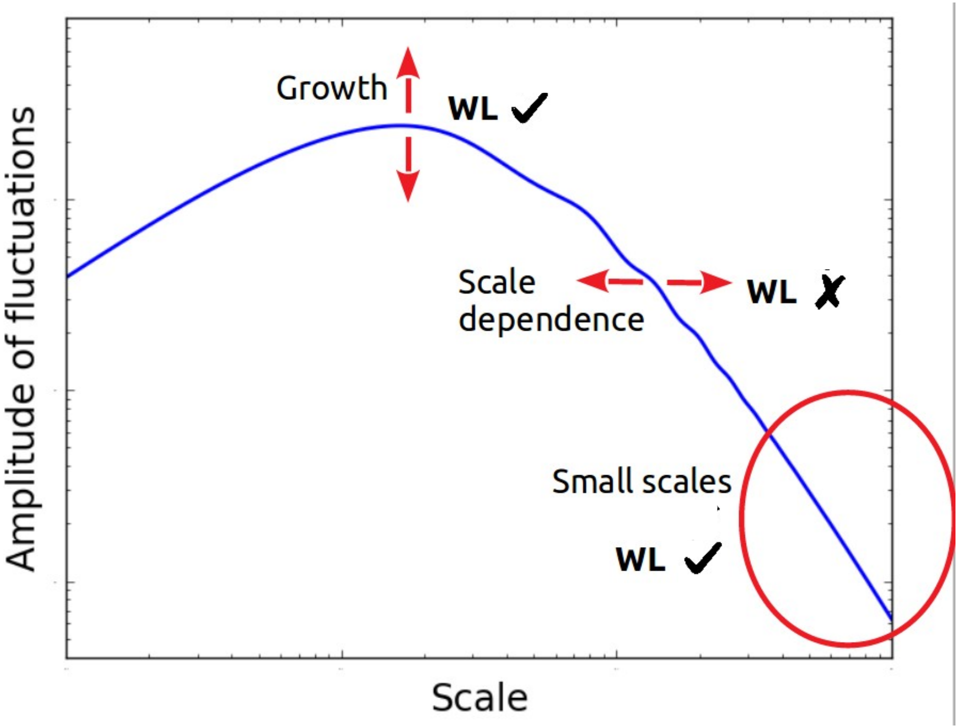
- $e_i \sim \gamma_i \sim \delta_M$
- LOS-integrated
- Spin-2



Weak lensing



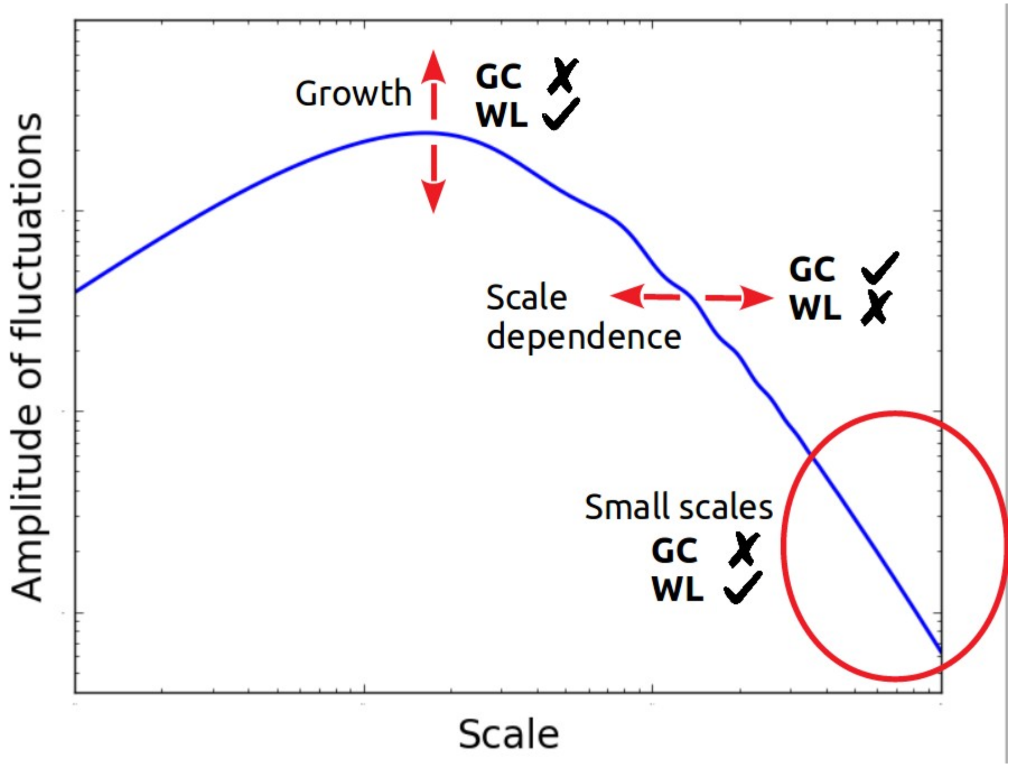
Weak lensing:
- $e_i \sim \gamma_i \sim \delta_M$
- LOS-integrated
- Spin-2



Galaxy clustering and weak lensing

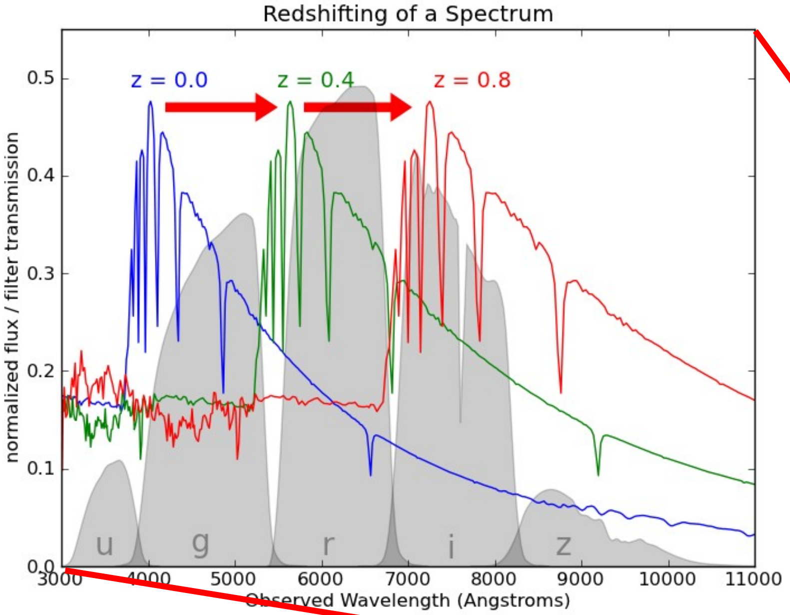
Galaxy clustering:
- $\delta_g = f[\delta_M] \sim b_g\, \delta_M$
- Local
- Spin-0

Weak lensing:
- $e_i \sim \gamma_i \sim \delta_M$
- LOS-integrated
- Spin-2



Hikage et al 2019

Photometric surveys

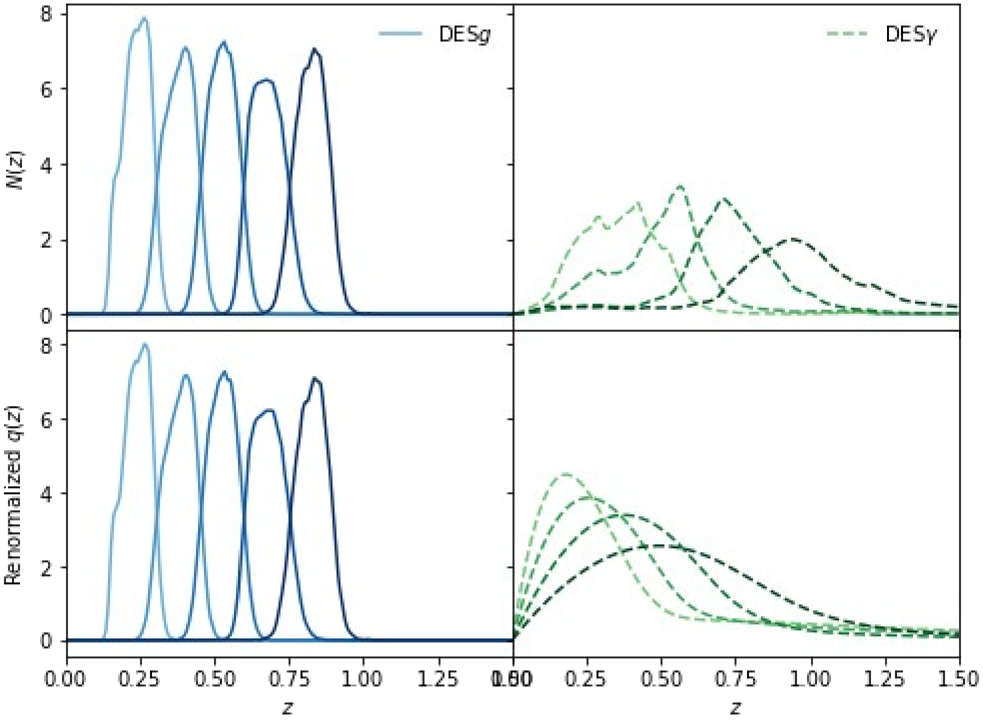


- Use all galaxies you can detect
- Good image quality
- No spectra

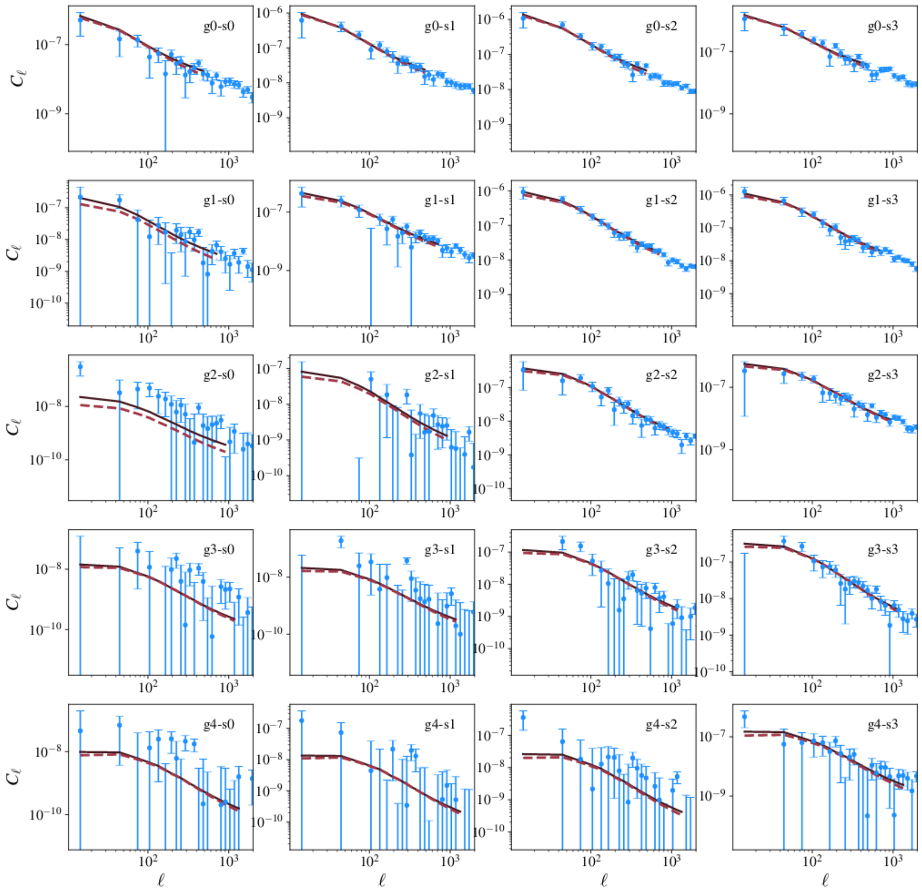
KiDS HSC

Projected clustering and shear

$$\delta_g(\hat{\mathbf{n}}) = \int dz \frac{dp}{dz} \Delta_g(\chi(z)\hat{\mathbf{n}}, z) \qquad \gamma_E(\hat{\mathbf{n}}) = \int d\chi \, q_\gamma(\chi) \, \Delta_m(\chi\hat{\mathbf{n}}), z)$$

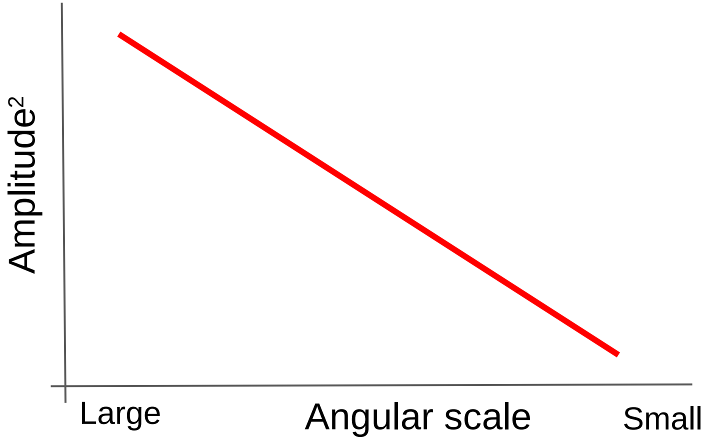


Projected angular power spectra



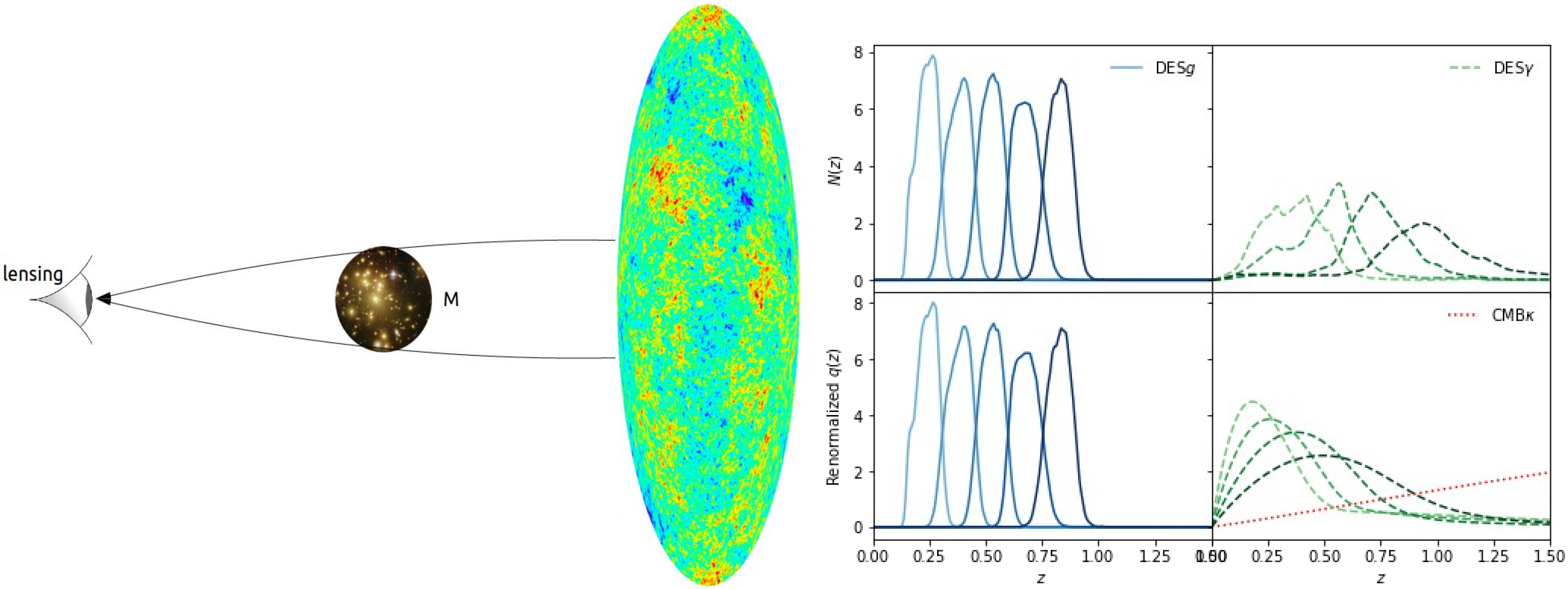
$$C_\ell^{\alpha\beta} \equiv \langle a_{\ell m}^{\alpha} a_{\ell m}^{\beta *} \rangle$$

$$C_\ell^{\alpha\beta} = \int \frac{d\chi}{\chi^2} q^\alpha(\chi) q^\beta(\chi) P_{\alpha\beta}\left(\frac{\ell + 1/2}{\chi}, z\right)$$



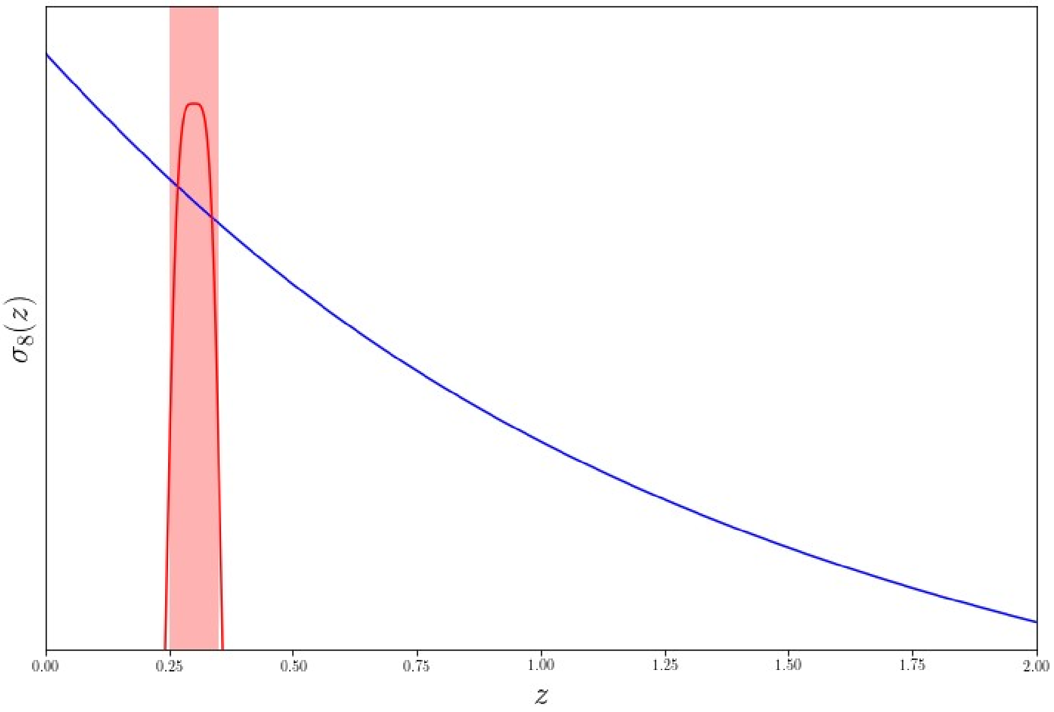
DES Y1 shear x clustering

CMB lensing



3x2pt as tomography

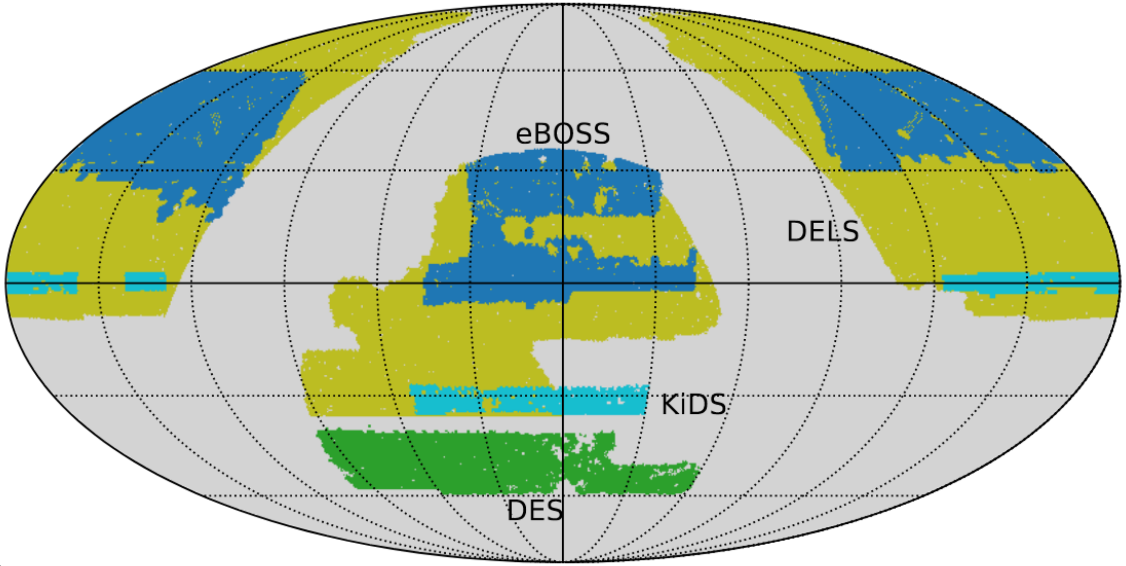
$$C_\ell^{\gamma\gamma} \propto \sigma_8^2 \qquad C_\ell^{g\gamma} \propto \sigma_8^2 b_g \qquad C_\ell^{gg} \propto \sigma_8^2 b_g^2$$

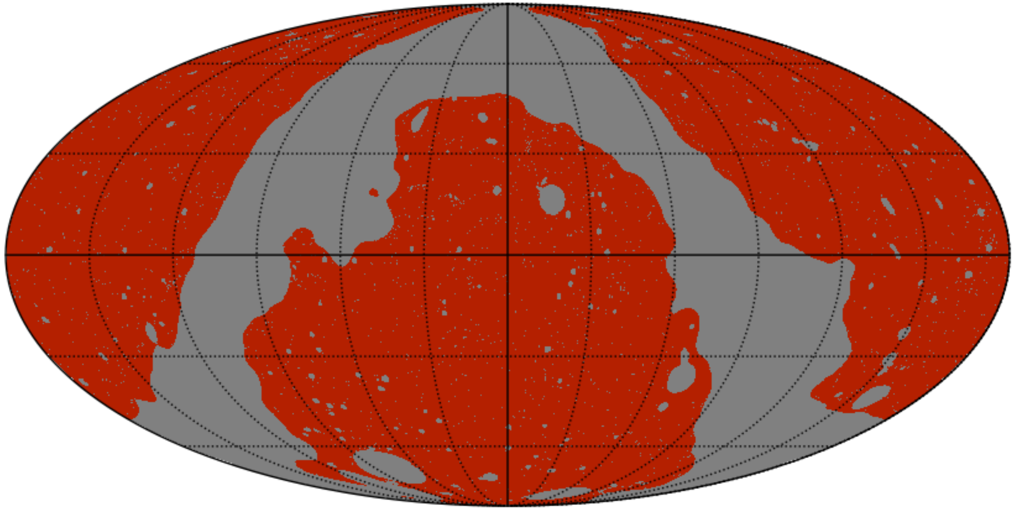


The data

Weak lensing:
- DES Y1
- KiDS-1000

Galaxy clustering:
- DES Y1 (redMaGiC)
- DESI Legacy Survey (DELS)
- eBOSS QSO





CMB lensing:
- Planck 2018 convergence map

Troxel et al. 2017; Elvin-Poole et al. 2017
Asgari et al. 2017; Hang et al. 2020
Neveux et al. 2020; Planck Coll. et al. 2018

The data

Shear:
- DES Y1
- KiDS-1000

Clustering:
- DES Y1 (redMaGiC)
- DESI Legacy Survey (DELS)
- eBOSS QSO

CMB lensing:
- Planck 2018 convergence map

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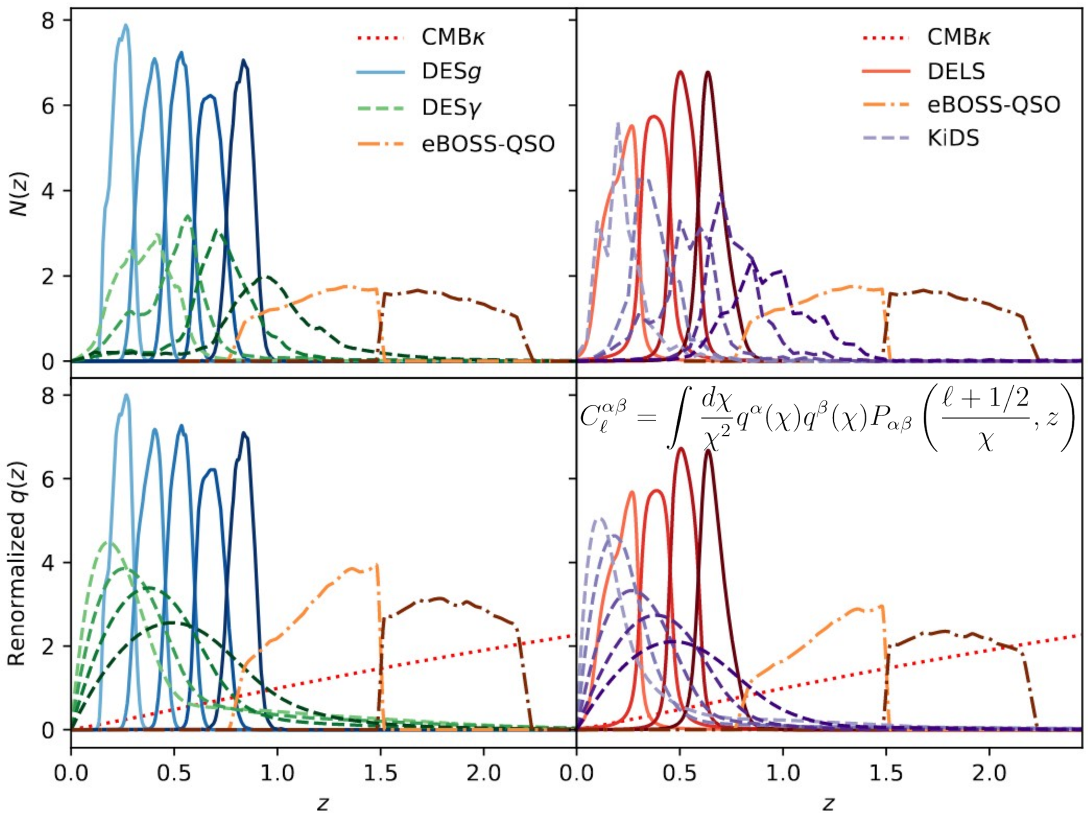
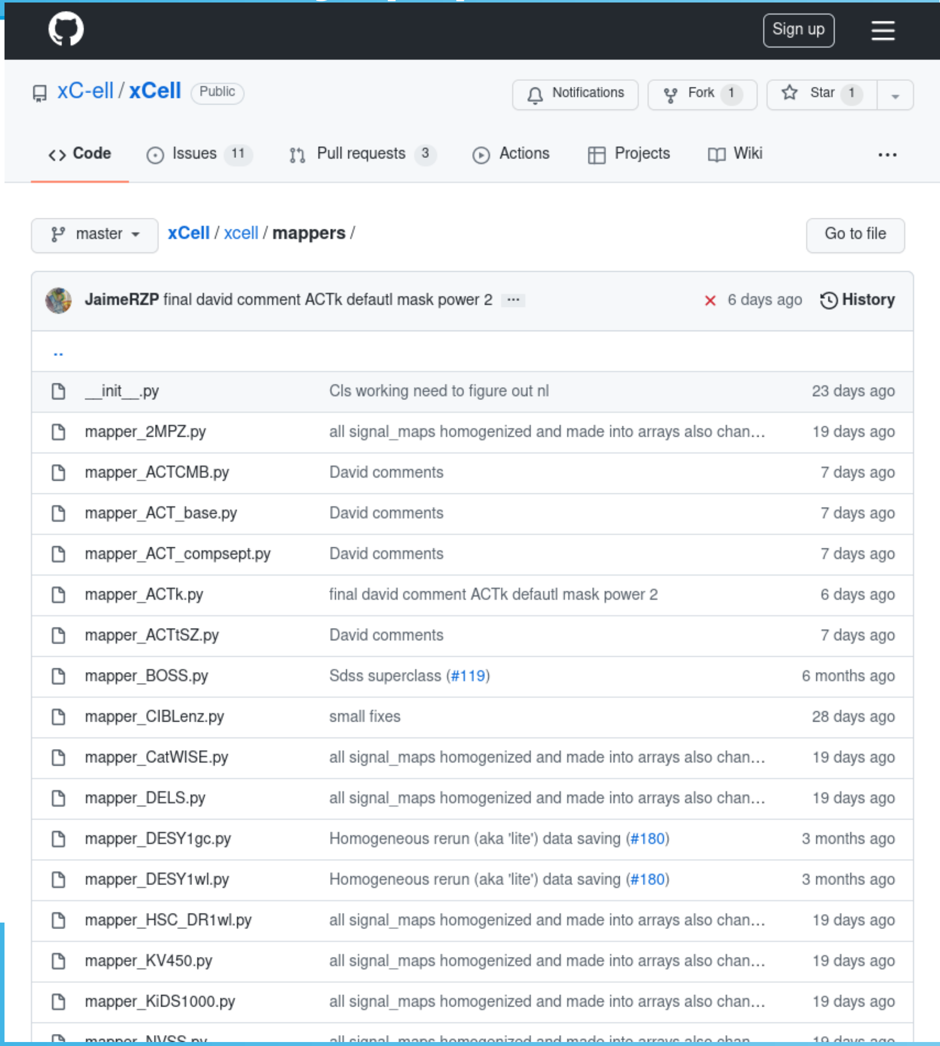


South Data (SD)   North Data (ND)

Data analysis: a new multisurvey pipeline

- Why?
  - Independent & homogeneous analysis
  - Combined in consistent way
- Pipeline:
  - Catalogs → maps → Nx2pt C_l
  - Analytical Gaussian covariance with mode coupling.
  - Optional: Marginalize noise, multiplicative bias, etc.



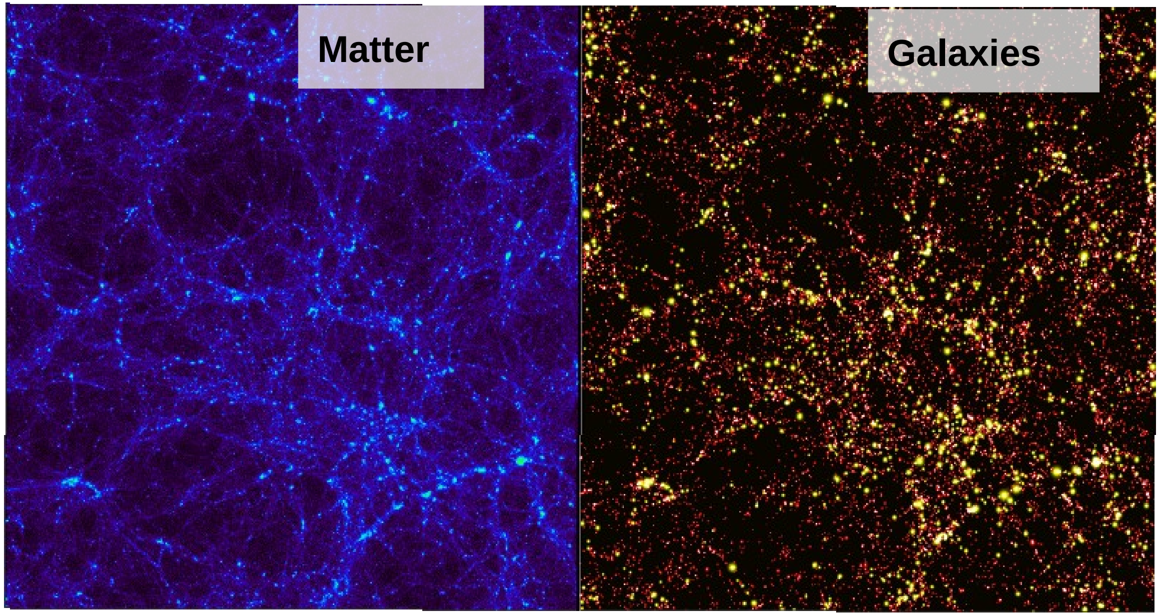
Data analysis: from catalogs to maps

Galaxy clustering

- Number overdensity
- Mask (w): Official mask
- Analytical noise (Poisson):

$$\tilde{N}_\ell = \frac{\langle w \rangle}{\bar{n}_\Omega}$$

Small differences between datasets.



$v_i \equiv$ weight of galaxy i $\quad n_p \equiv$ weighted number of galaxies

Data analysis: from catalogs to maps

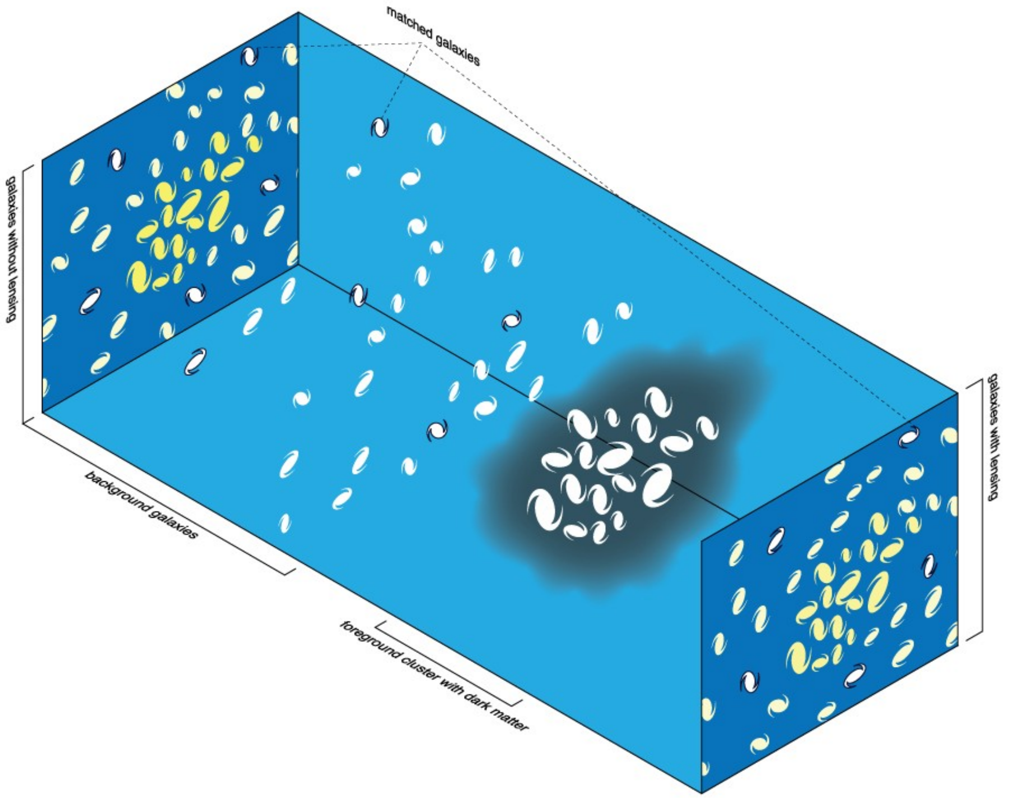
Cosmic shear

(Nicola, CGG+20)

- Shear: $\gamma_{i,p} = \langle e_{n,i} \rangle_{i \in p}$
- Mask (w): n_p
- Analytical noise:

$$\widetilde{N}_{\ell>2} = A_{\rm pix} \left\langle \sum_{i \in p} v_i^2 \sigma_{e,i}^2 \right\rangle_{\rm pix}$$

Same for KiDS and DES.



$\sigma_{e,i}^2 = (e_{i,1}^2 + e_{i,2}^2)/2$

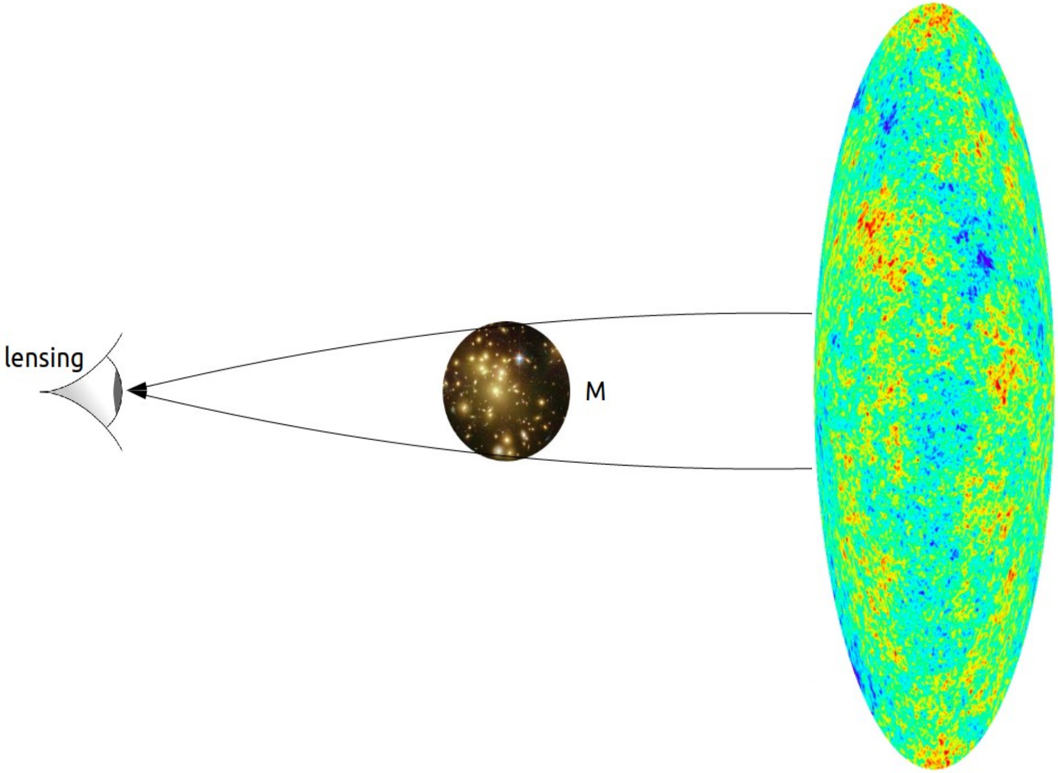
$v_i \equiv$ weight of galaxy i

$n_p \equiv$ weighted number of galaxies

Data analysis: from catalogs to maps

CMB lensing

- Convergence: κ_p from κ_{LM}
- Mask (w): Planck 2018
- Noise: Planck 2018



Data analysis: from maps to C_l

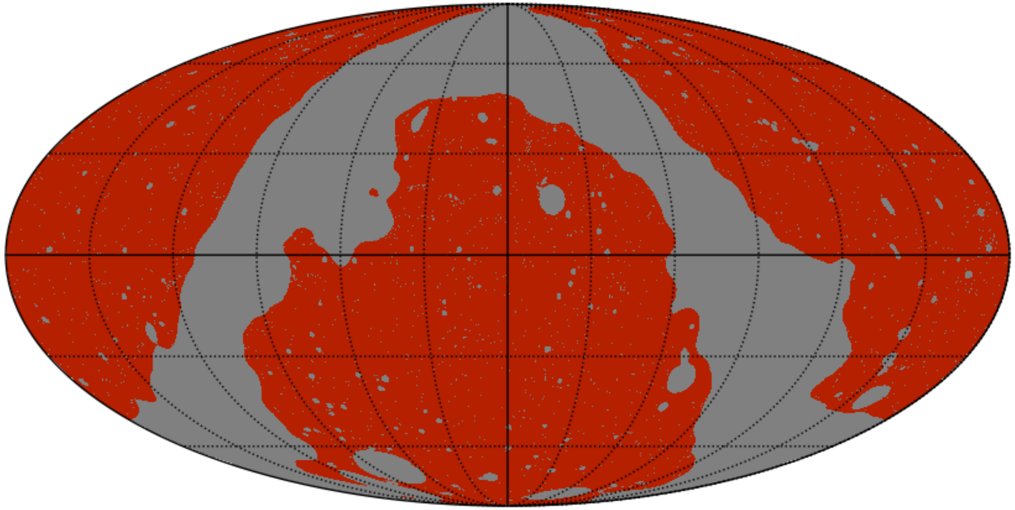
- **Problem: Mask couples scales**
  - The observed field is $\tilde{a}(\hat{\mathbf{n}}) = w(\hat{\mathbf{n}})a(\hat{\mathbf{n}})$.
  - Then, the angular power spectra

$$\langle \tilde{C}_\ell^{ab} \rangle = \sum_{\ell'} M_{\ell\ell'}^{vw} C_{\ell'}^{ab},$$

NaMaster

Solution: Pseudo-C_l estimator:

1) Bin the observed
2) Invert Mode Coupling Matrix
3) Bin-couple-decouple theory



Data analysis: from maps to C_l

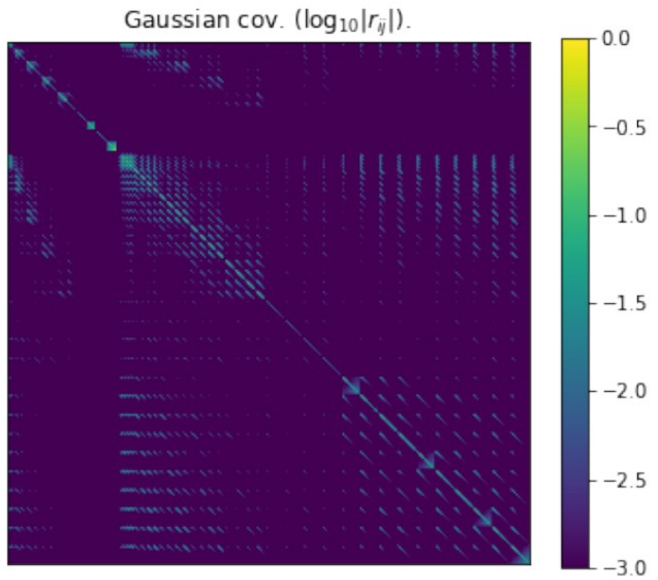
Garcia-Garcia+19, Nicola, CGG+21.

Analytical covariance matrix:

- Narrow Kernel Approximation
- Spin-0 Approximation (for KiDS)
- Efficient ($\sim l^3_{max}$ vs l^6_{max}) and accurate

Analytical marginalization:

- Noise (eBOSS)



MCMC set up: modelling

Galaxy clustering:

- Linear bias → $\delta_g = f[\delta_M] \sim b_g\, \delta_M$

$$k_{\max} = 0.15\mathrm{Mpc}^{-1}$$

- Magnification effect for QSOs (fixed)

Cosmic shear:

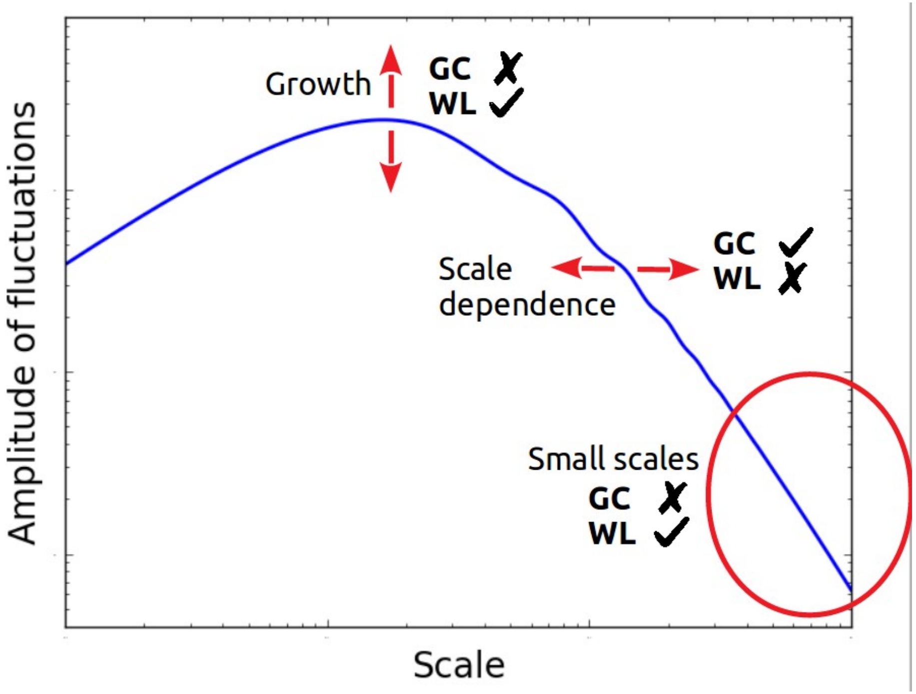
- Multiplicative bias
- Intrinsic alignments

$$q_{\gamma^i} \rightarrow (1 + m^i) q_{\gamma^i} - IA(z)$$

Redshift distributions uncertainty:

- Marginalize over z-shift

$$N(z) \rightarrow N(z + \Delta z)$$



MCMC set up: the likelihood

Gaussian likelihood

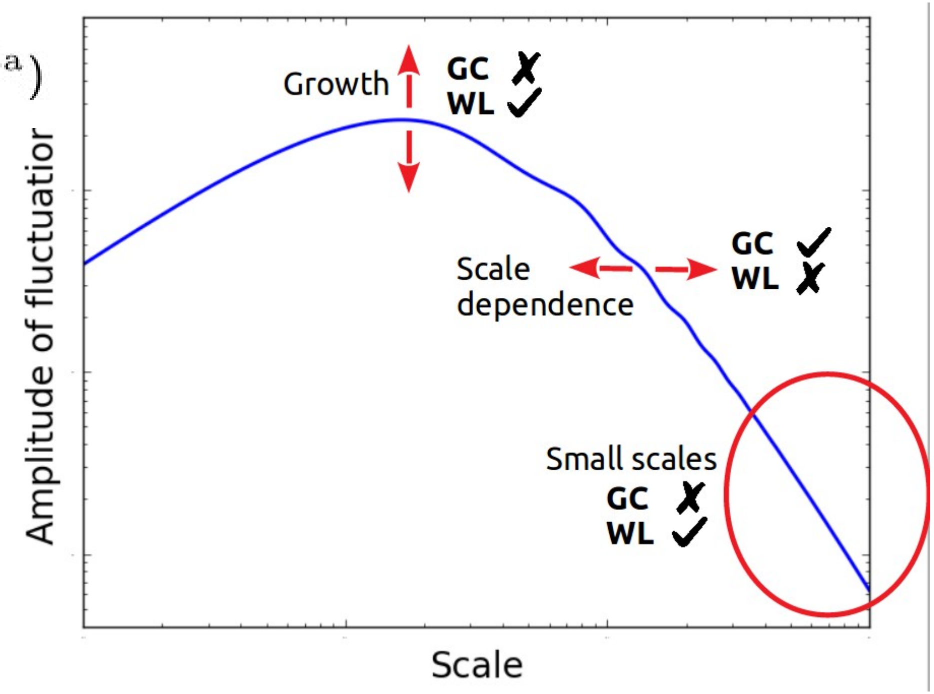
$$-2\log(\text{Likelihood}) = (C_\ell - C_\ell^{\text{data}})^T \text{Cov}^{-1} (C_\ell - C_\ell^{\text{data}})$$

Conservative scale cuts:

- Galaxy clustering: $k_{\text{max}} = 0.15\text{Mpc}^{-1}$
- Cosmic shear: $\ell_{\text{max}} = 2000$
- ℓ_{min} per dataset

45 sampled parameters

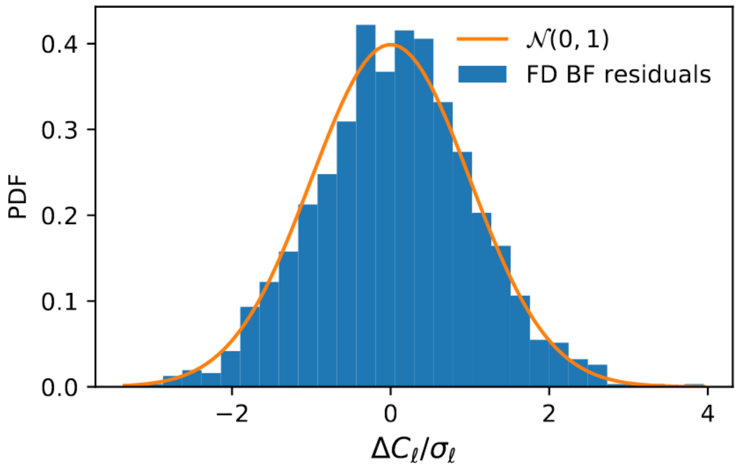
1275 data points

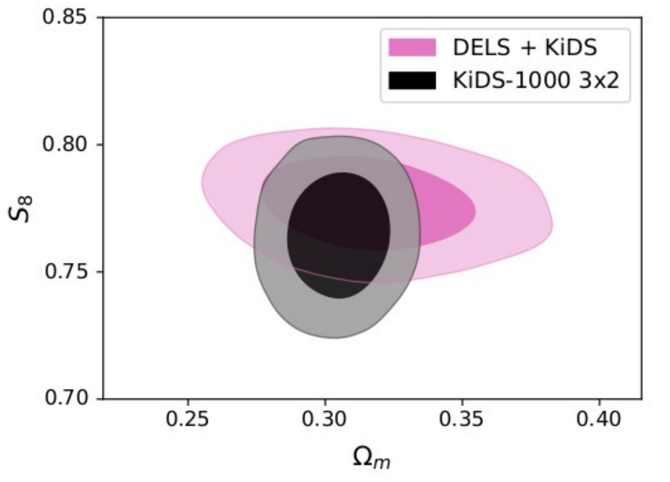


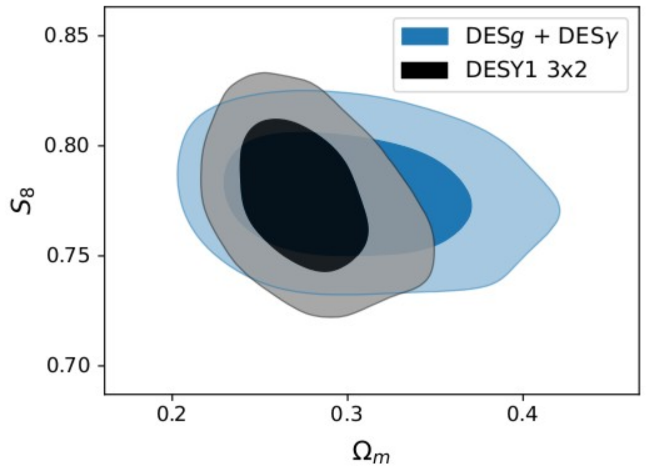
Hikage et al 2019

Data analysis: validation

- B-modes compatible with 0
- Recover official results
- Residuals ~ Gaussian
- Good fits: 0.1 < p-value < 0.9



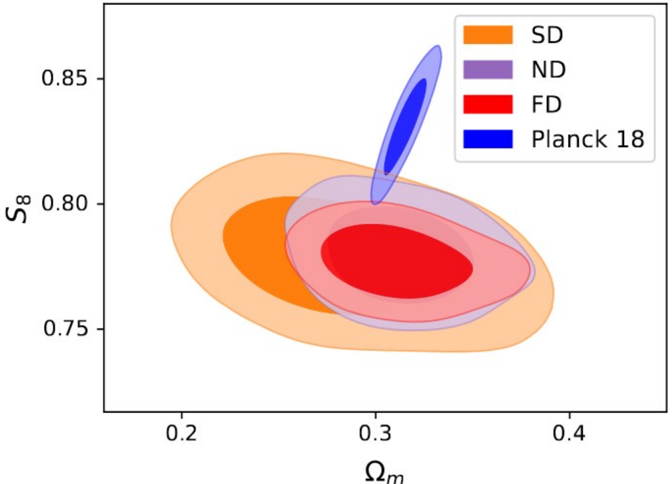


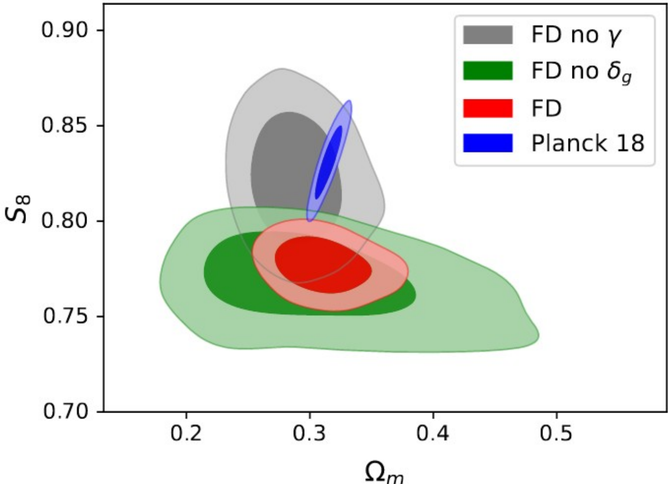


Results:

SD = DESgc + DESwl + eBOSS QSOs + CMBk
ND = DESI Legacy Survey + KiDS + eBOSS QSOS + CMBk
FD = ND + SD

- ΛCDM excellent fit
- North (~KiDS) and South (~DES) datasets compatible
- ND + SD = S_8 error reduced by $\sqrt{2}$
- 3.4σ tension with Planck
- Driven by cosmic shear

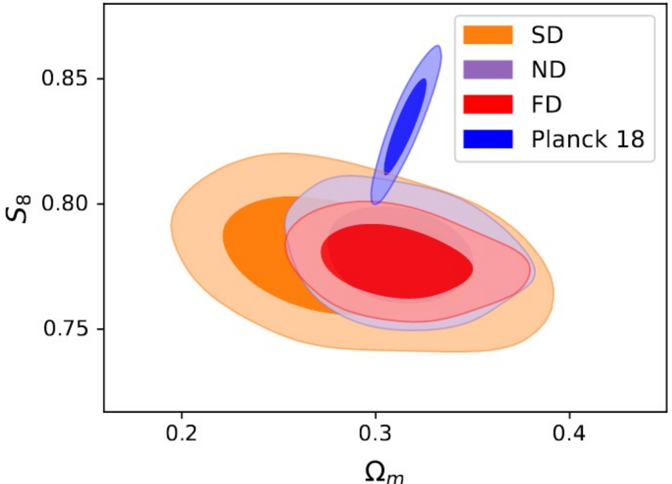


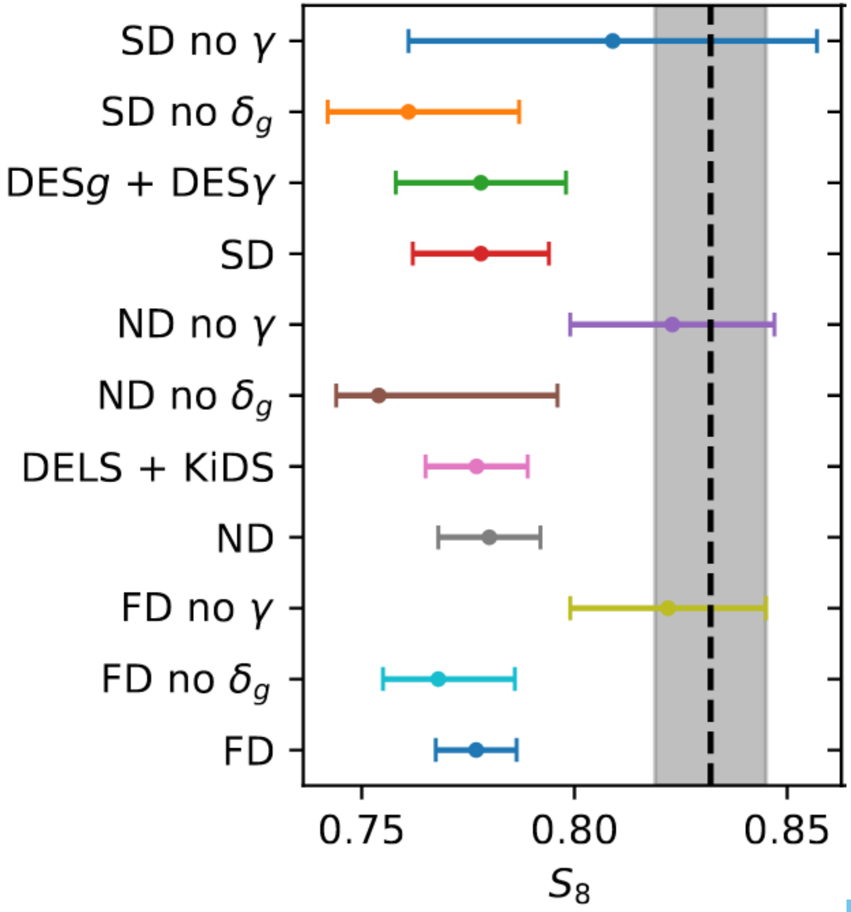


ΛCDM

Results:

- ΛCDM excellent fit
- North (~KiDS) and South (~DES) datasets compatible
- ND + SD = S_8 error reduced by $\sqrt{2}$
- 3.5σ tension with Planck
- Driven by cosmic shear

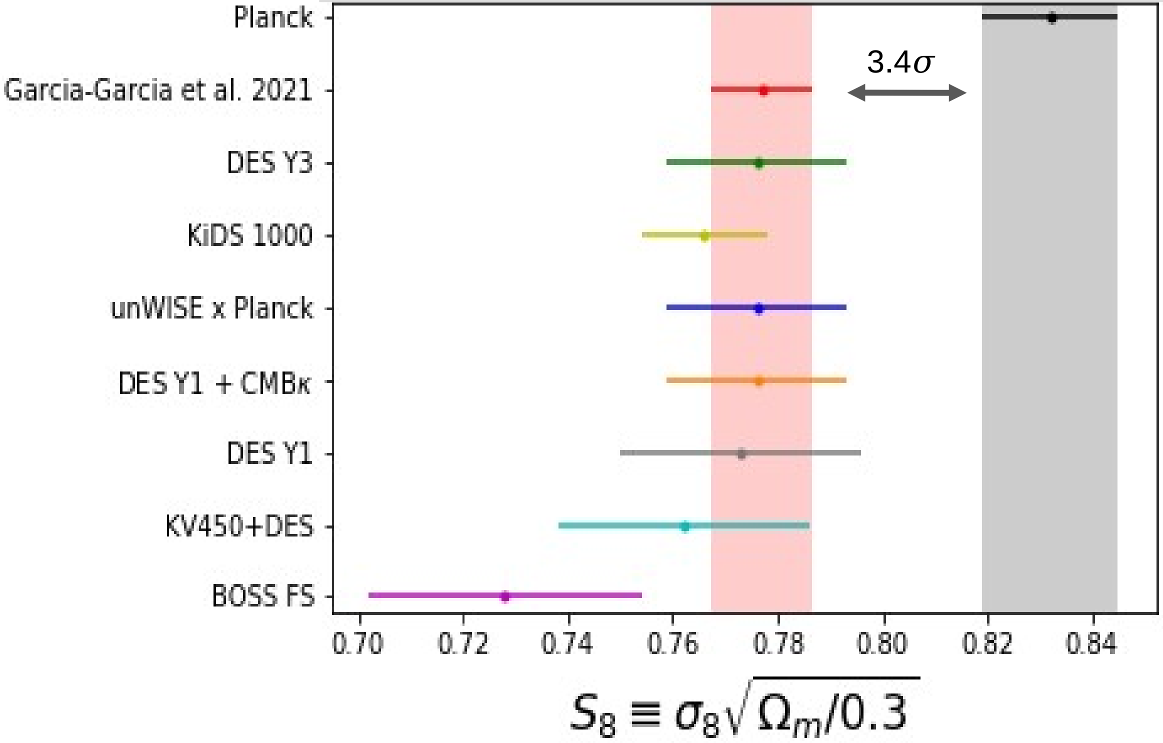




SD = DESgc + DESwl + eBOSS QSOs + CMBk
ND = DESI Legacy Survey + KiDS + eBOSS QSOS + CMBk
FD = ND + SD

ΛCDM

Best constraints at the moment



Reconstructing the growth

We constrain

$$S_8(z) = \sigma_8(z)\sqrt{\frac{\Omega_\mathrm{m}}{0.3}}$$

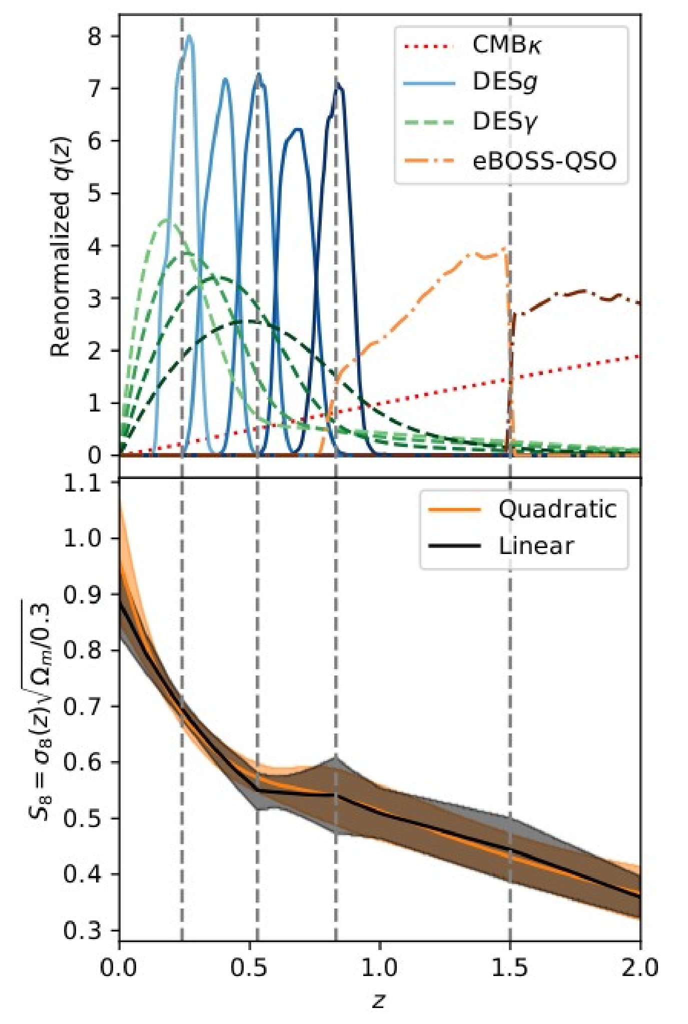
by decoupling the background and perturbations:

- Keep ΛCDM background
- Modify perturbations as

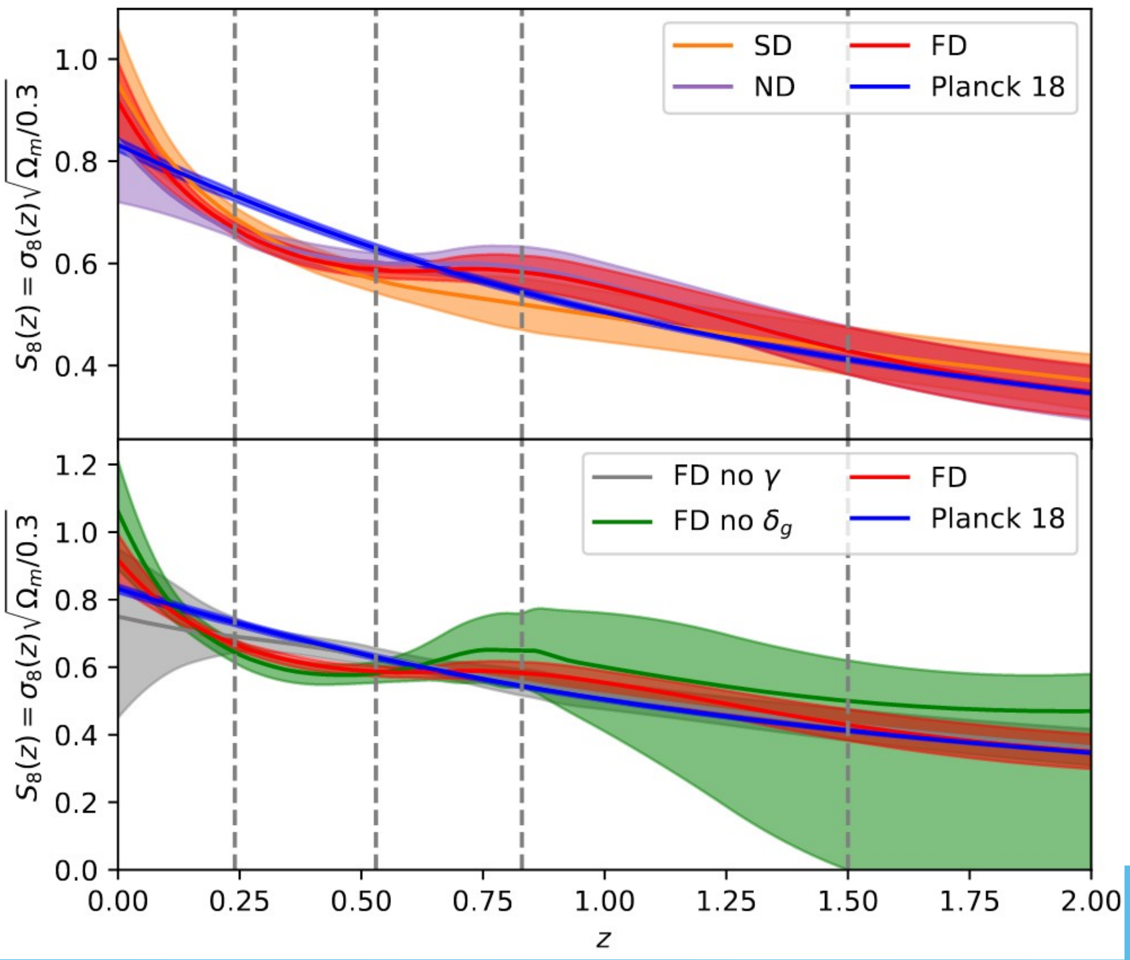
$$P_k(z) = D(z)^2 P_k^{\mathrm{P18}}(z=0)$$

with the linear growth (D(z)) as

$$D(z) = \mathrm{quadratic\_spline}(\tilde{D}_z)$$



The reconstructed growth



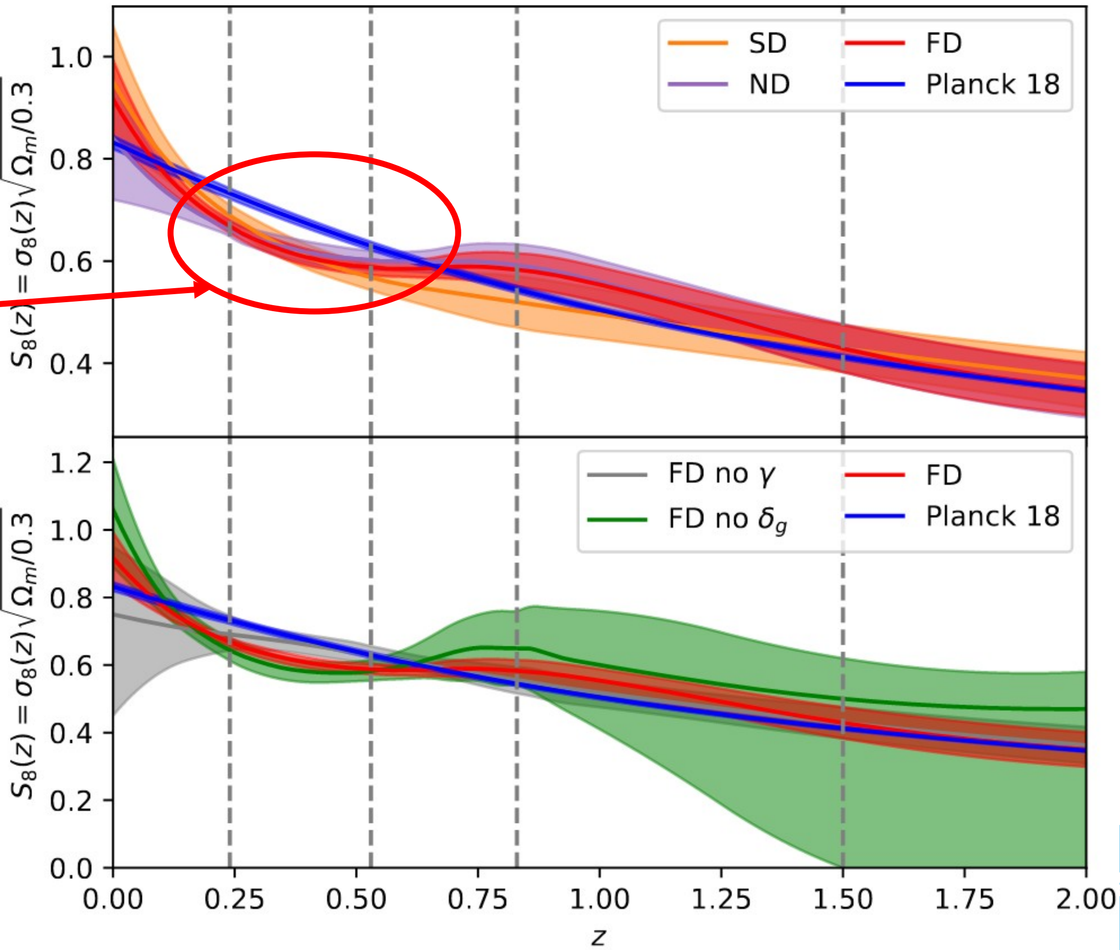
SD = DESY1 + eBOSS QSO's + CMBκ

ND = KiDS-1000 + DESI Legacy survey + eBOSS QSO's + CMBκ

FD = SD + ND

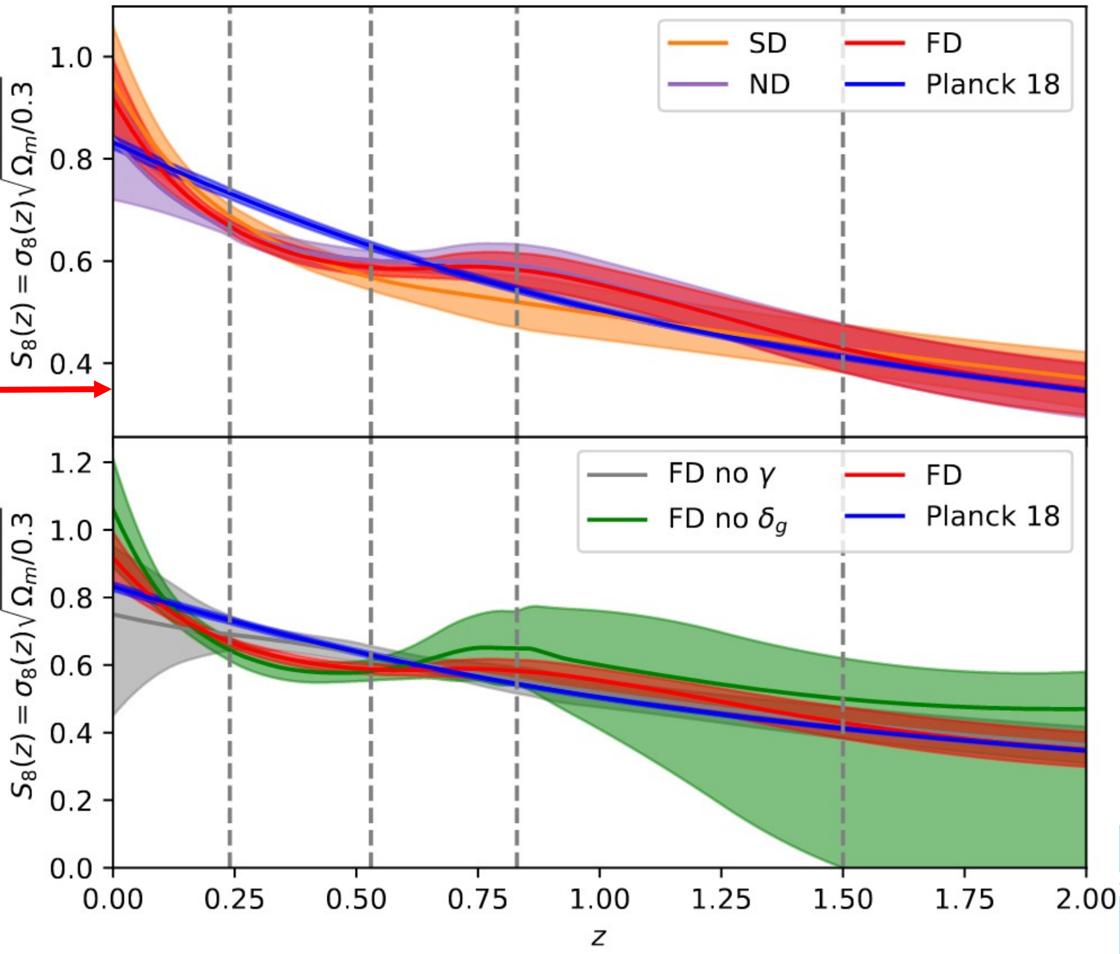
The reconstructed growth

Results:
- Lower growth (~2σ) at 0.2<z<0.6



The reconstructed growth

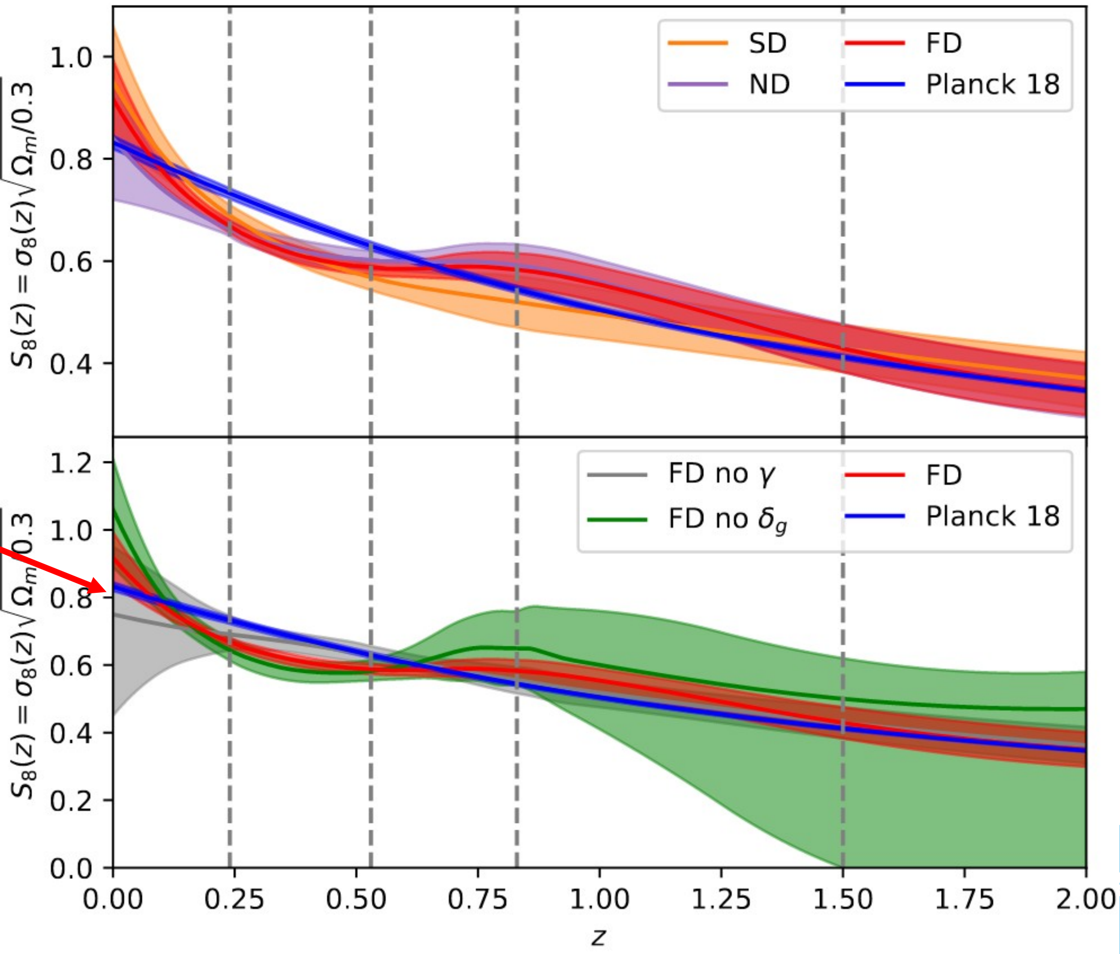
Results:
- Lower growth (~2σ) at 0.2<z<0.6
- North and South data recover compatible growth histories



The reconstructed growth

Results:

- Lower growth (~2σ) at 0.2<z<0.6
- North and South data recover compatible growth histories
- Tension driven by shear data

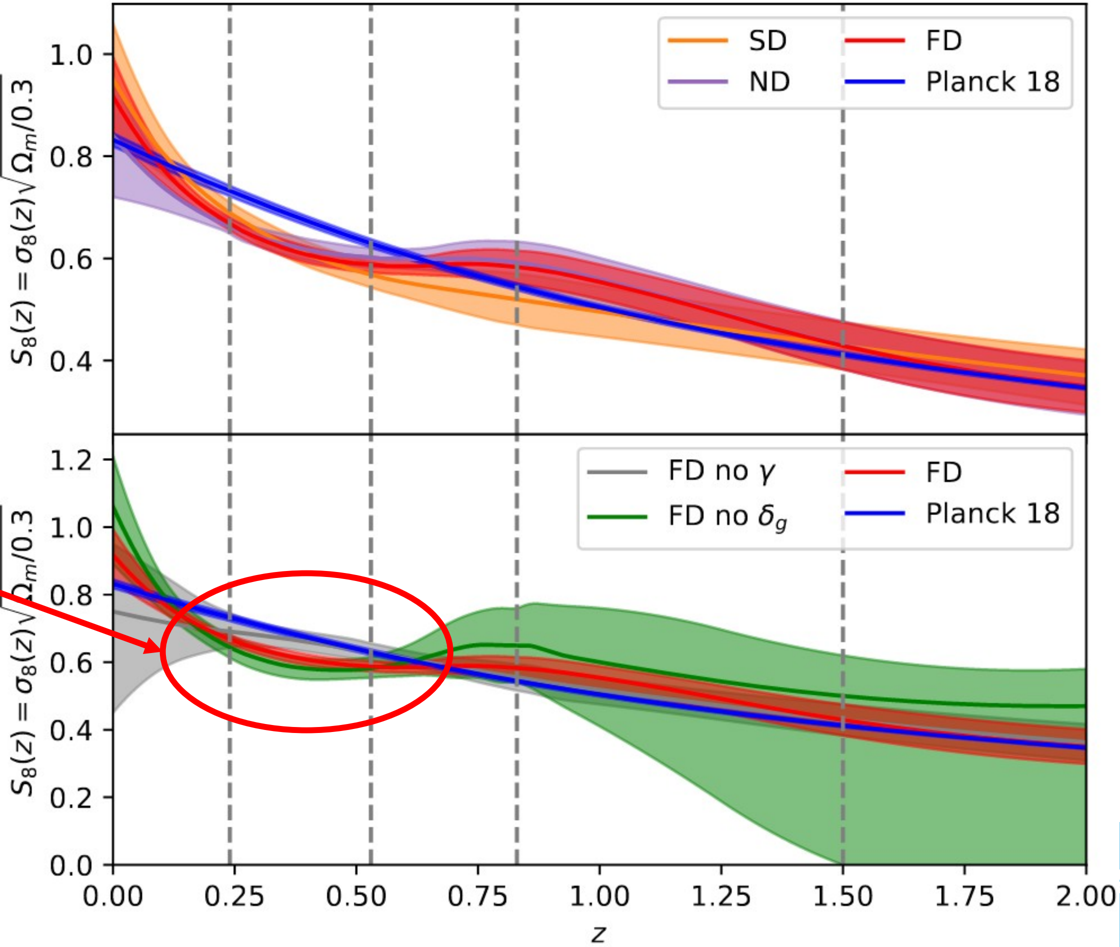


The reconstructed growth

Results:

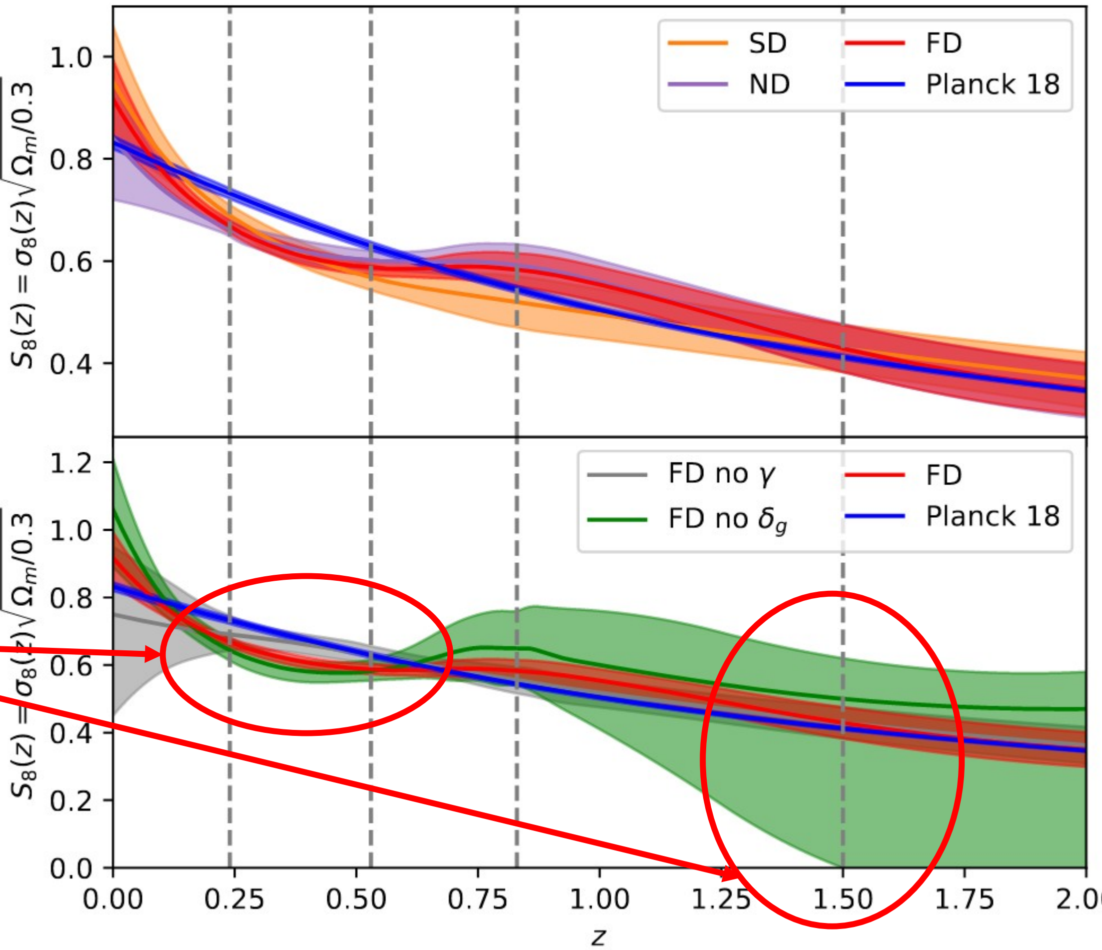
- Lower growth (~2σ) at 0.2<z<0.6
- North and South data recover compatible growth histories
- Tension driven by shear data
- Clustering + CMB κ compatible with Planck (but also with shear).

But see [Krolewski et al. 2021]() &
White et al. 2021



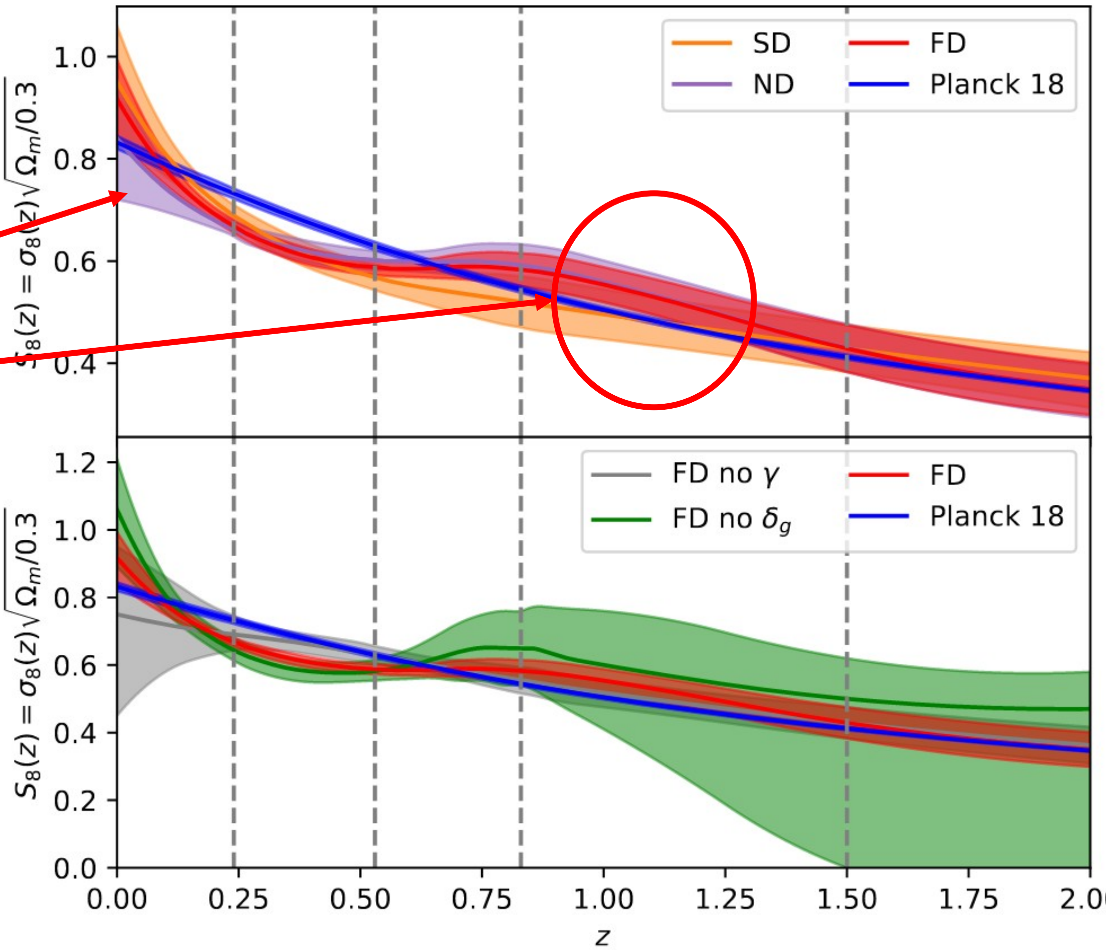
The reconstructed growth

Results:
- Lower growth (~2σ) at 0.2<z<0.6
- North and South data recover compatible growth histories
- Tension driven by shear data
- Clustering + CMB κ compatible with Planck (but also with shear).
- Most constraining power at 0.2<z<0.8. QSOs vital for high-z growth.



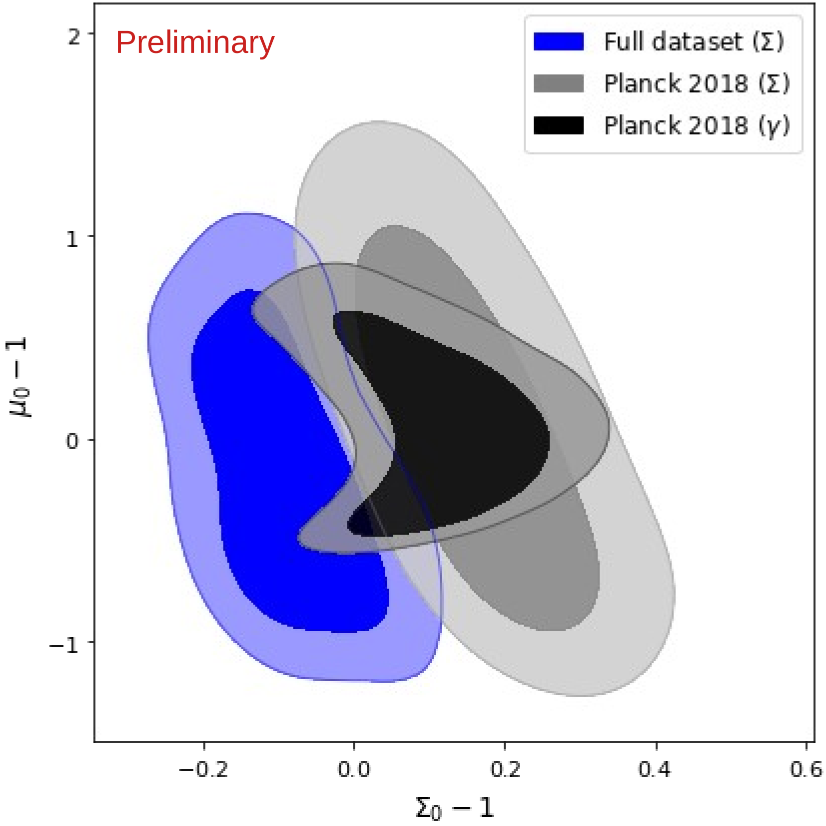
The reconstructed growth

Future work:
- Add more data:
  - z~0: 2MPZ, tSZ
  - z~1: unWISE
- $S_8(z)$ with Gaussian Processes
- Add massive neutrinos
- Improve systematics (e.g. Galaxy bias)



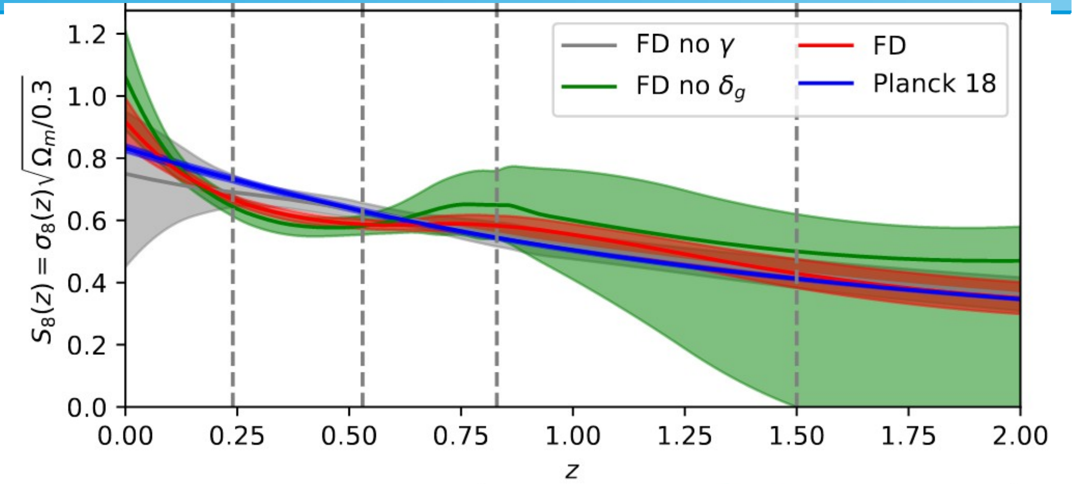
Beyond ΛCDM

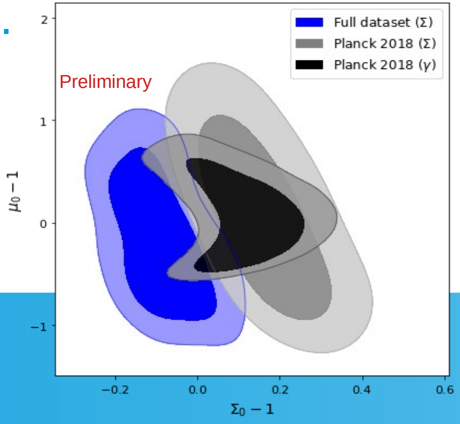
- Modify the linear pert.:
  - Growth equation: $\mu(z)$
  - Lensing: $\Sigma(z)$
- Re-calibrate HALOFIT
- Reconstruct them

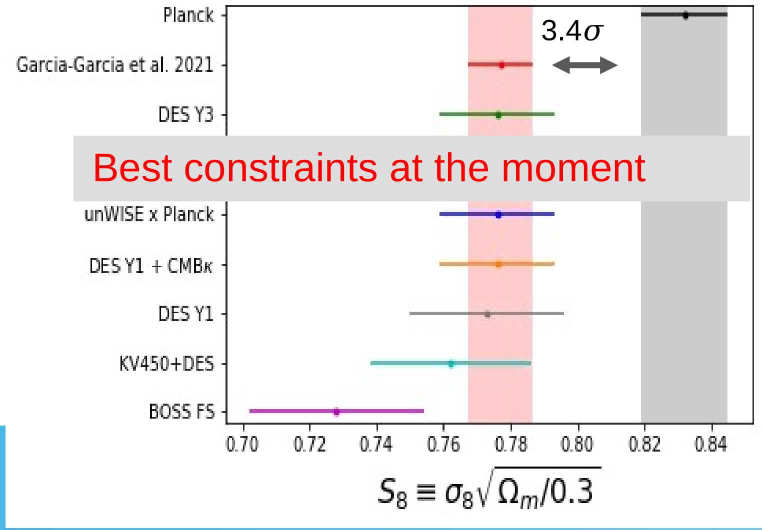


Summary

- Combination of 6 projected LSS surveys
- Reconstructed growth at z < 2
- Growth compatible with LCDM
- But in tension with Planck (~2σ)
- Constraining power at 0.2 < z < 0.7
- Future:
  - Better data at low-z (already exists) and high-z (LSST and DESI will help).
  - Beyond ΛCDM







Best constraints at the moment