CMB lensing cross-correlations with large-scale structure surveys

David Alonso (U. Oxford) - Aug. 10th 2021. CMB-S4 Summer meeting

Probes of late-time structure

LSST
Legacy Survey of Space and Time

$$\delta_g(\hat{\mathbf{n}})$$
$$\gamma_g(\hat{\mathbf{n}})$$

$$N_c(\lambda, z)$$
$$\delta_c(\hat{\mathbf{n}}; \lambda)$$
$$v_r(\hat{\mathbf{n}})$$

$$\kappa(\hat{\mathbf{n}})$$

$$y(\hat{\mathbf{n}})$$
$$\Delta_{\mathrm{CMB}}(\hat{\mathbf{n}})$$
$$\Delta_{\mathrm{kSZ}}(\hat{\mathbf{n}})$$
$$\Delta_{\mathrm{CIB}}(\hat{\mathbf{n}})$$

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Legacy Survey of Space and Time

I'll talk about this

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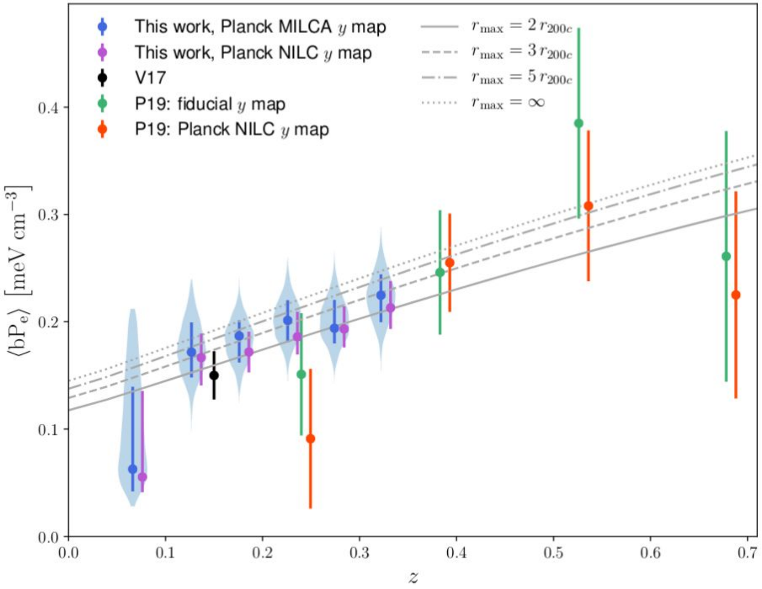
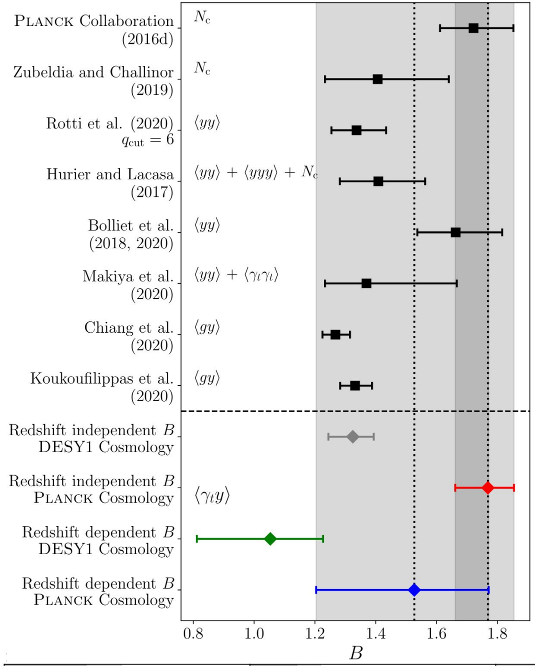
What I won’t talk about: tSZ tomography

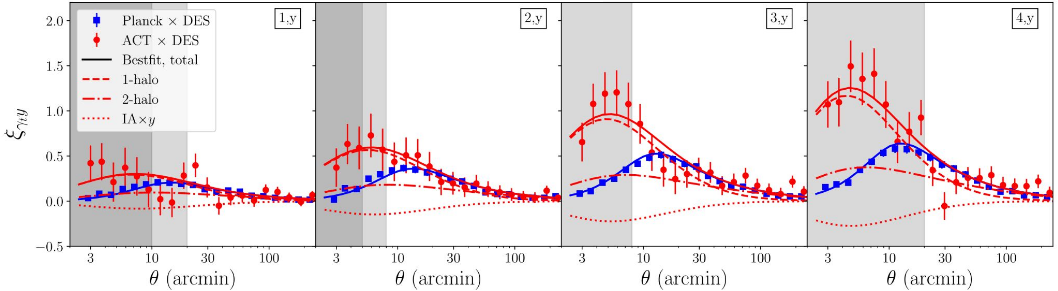
- Constrain z-evolution of gas pressure and mass bias
- Connection to gas thermodynamics.

Koukoufilippas et al. 2019

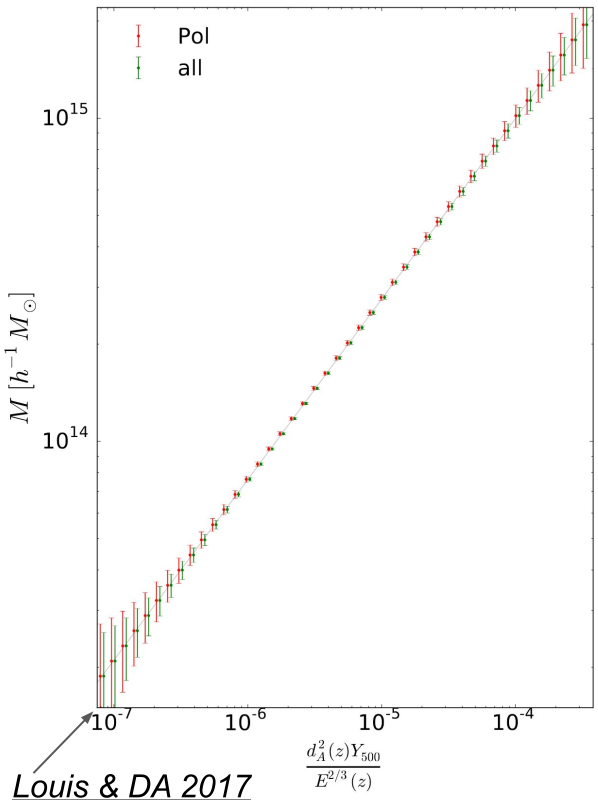


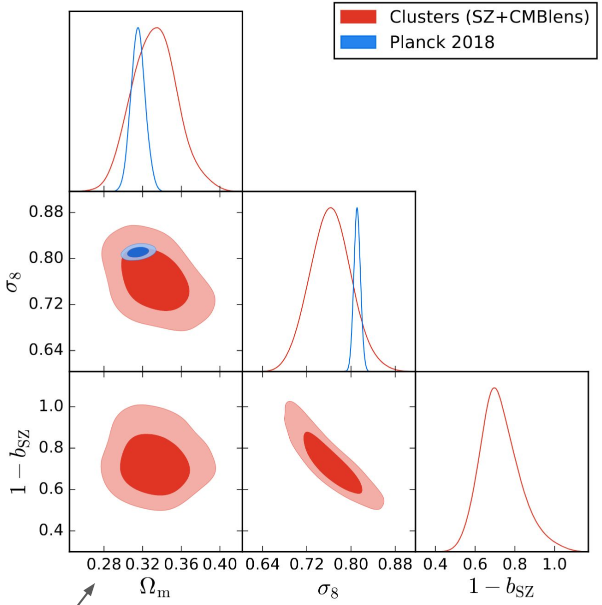


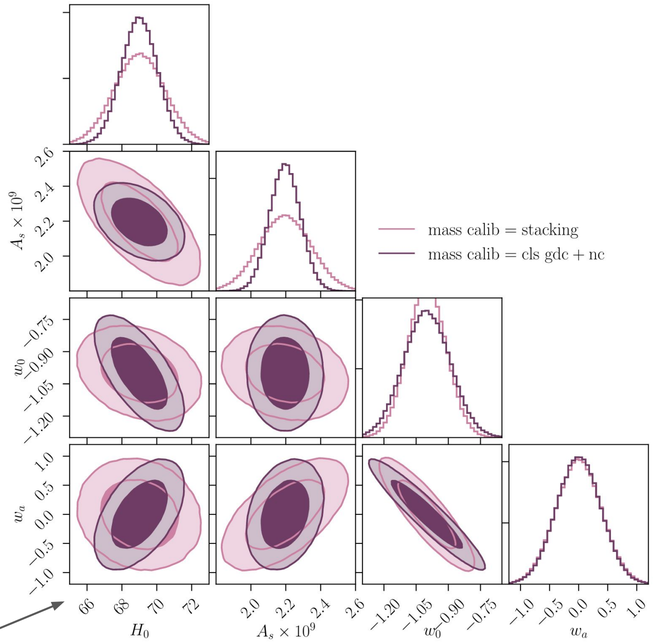
Pandey et al. 2021
Gatti et al. 2021



What I won't talk about: mass calibration







Louis & DA 2017
Bartlett & Melin 2015
Madhavacheril et al. 2018
Raghunathan et al. 2021

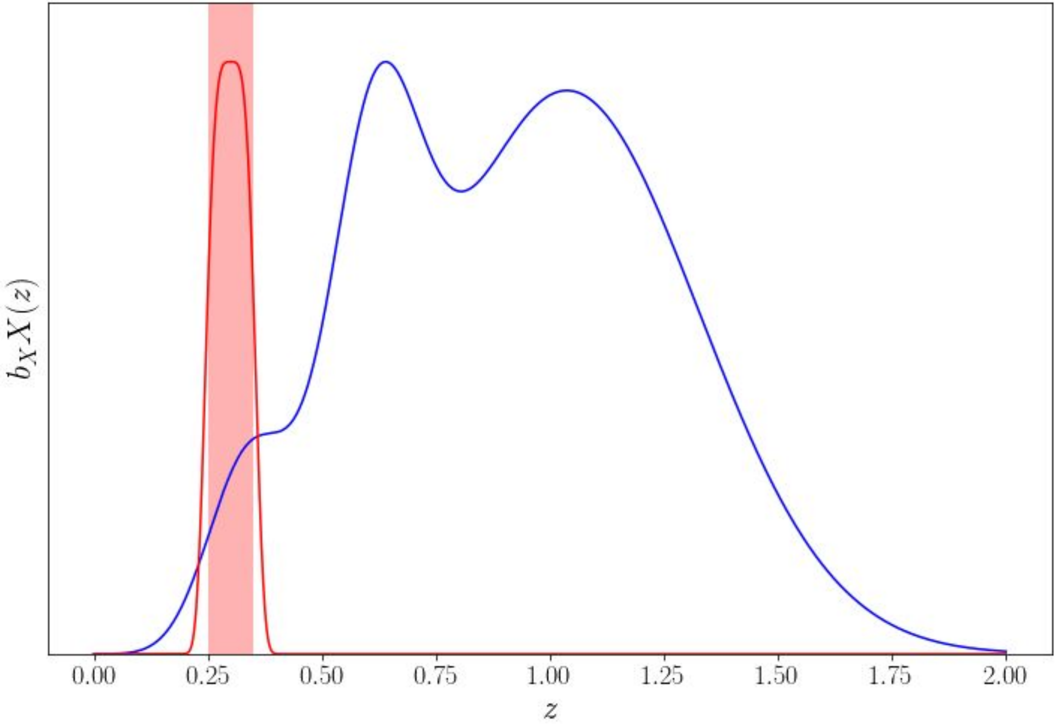
Zubeldia & Challinor 2019
Baxter et al. 2018
Nicola et al. 2020

- CMB lensing can constrain cluster masses with very high precision.
- Particularly important at high z.

What I will talk about: tomography

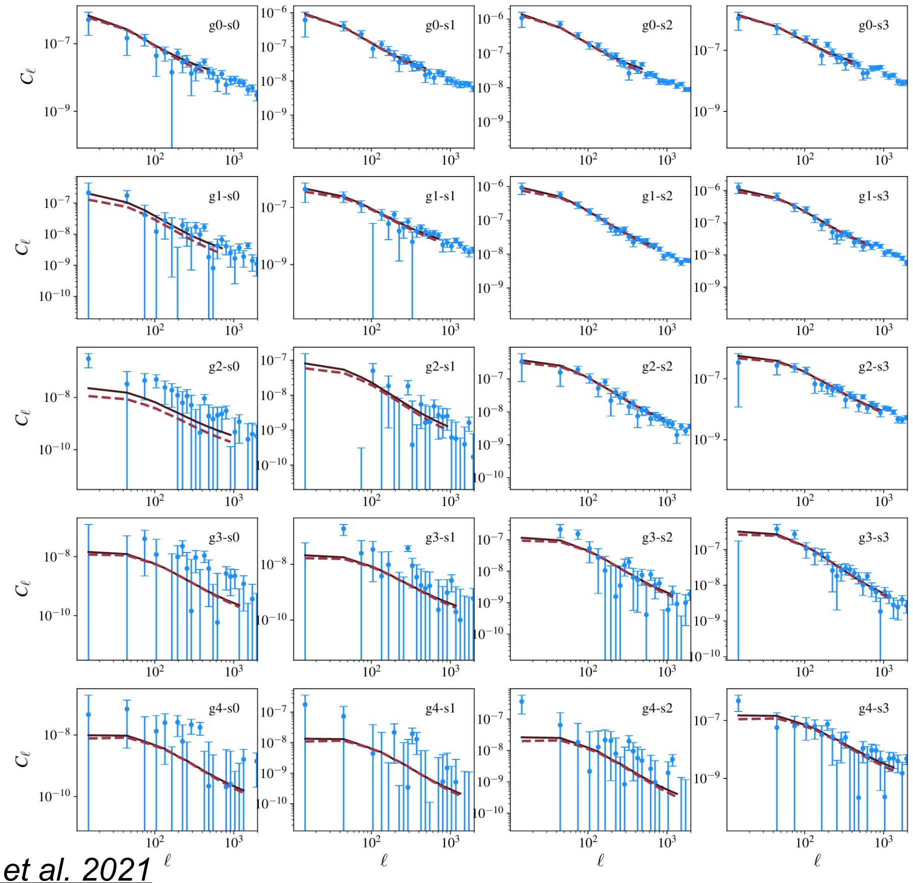
$$x(\theta,\phi) = \int dz\, \bar{X}(z)\,[1+\delta_X(\theta,\phi,z)]$$

$$\langle x\,\delta_g(z_*)\rangle \propto b_X(z_*)\bar{X}(z_*)$$



What I will talk about: tomography

Over time tomography has become synonymous with *"Nx2pt"* or *"extracting information from a combination of projected tracers of structure"*



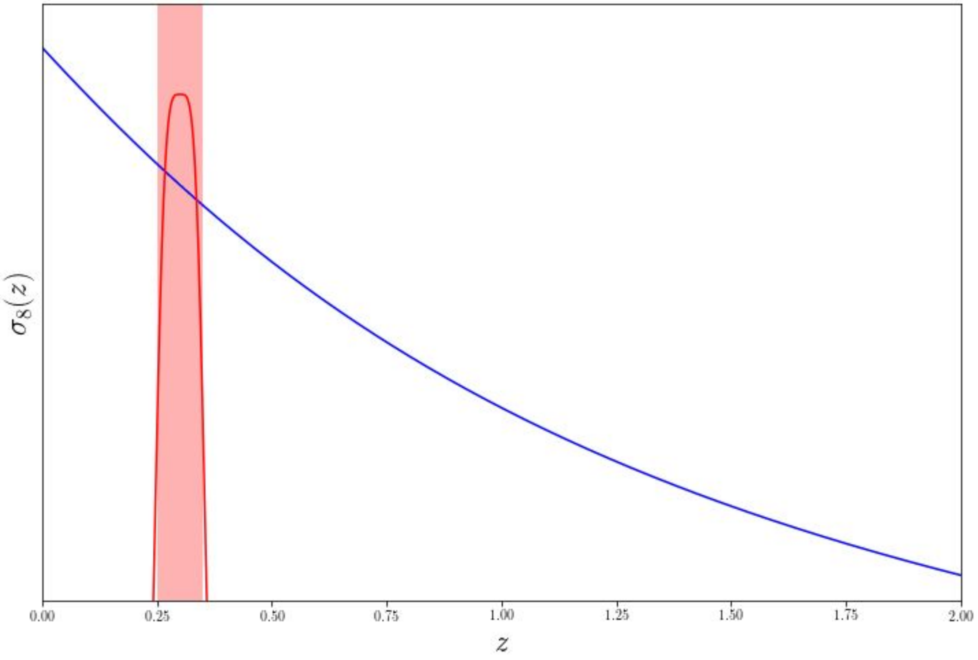
Hadziyska et al. 2021

Tomographic reconstruction: growth

- Consider CMB lensing + δ_g:

$$C_\ell^{g\kappa} \propto \sigma_8^2\, b_g \qquad C_\ell^{gg} \propto (\sigma_8\, b_g)^2$$

So you can measure $\sigma_8(z)$



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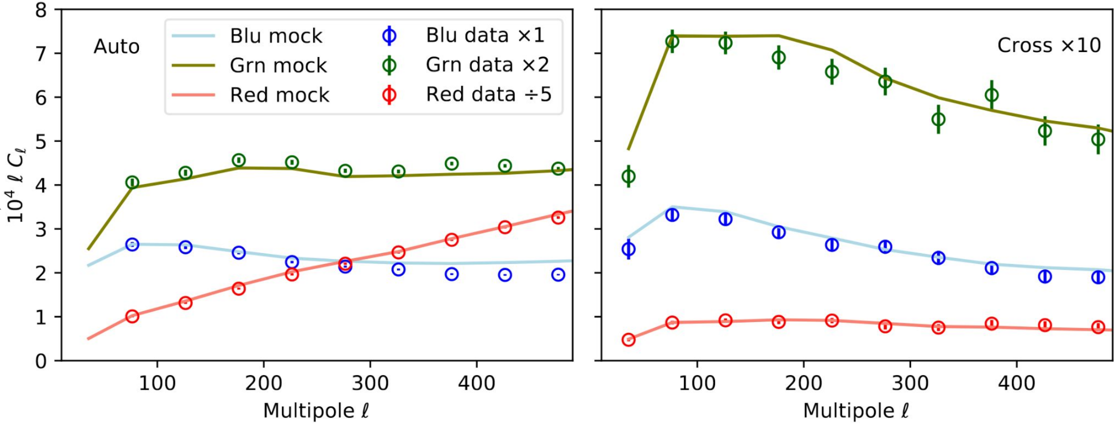

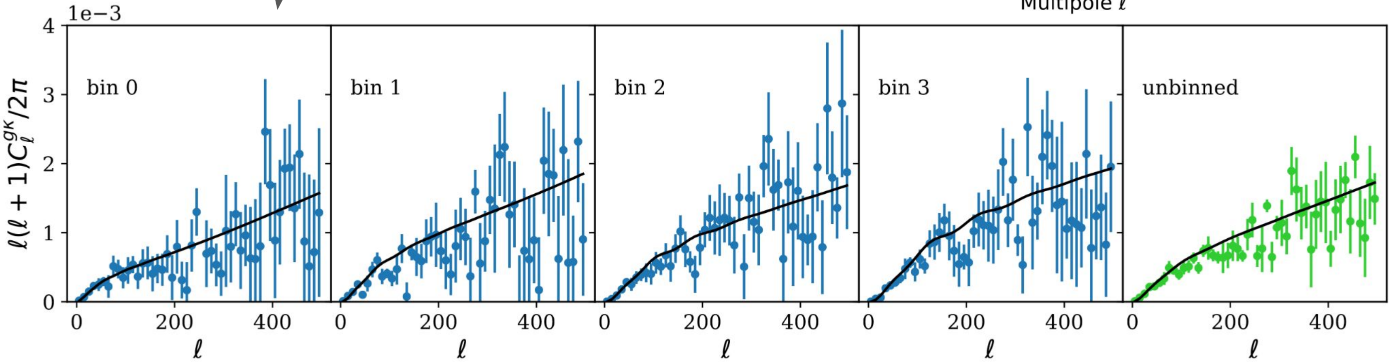

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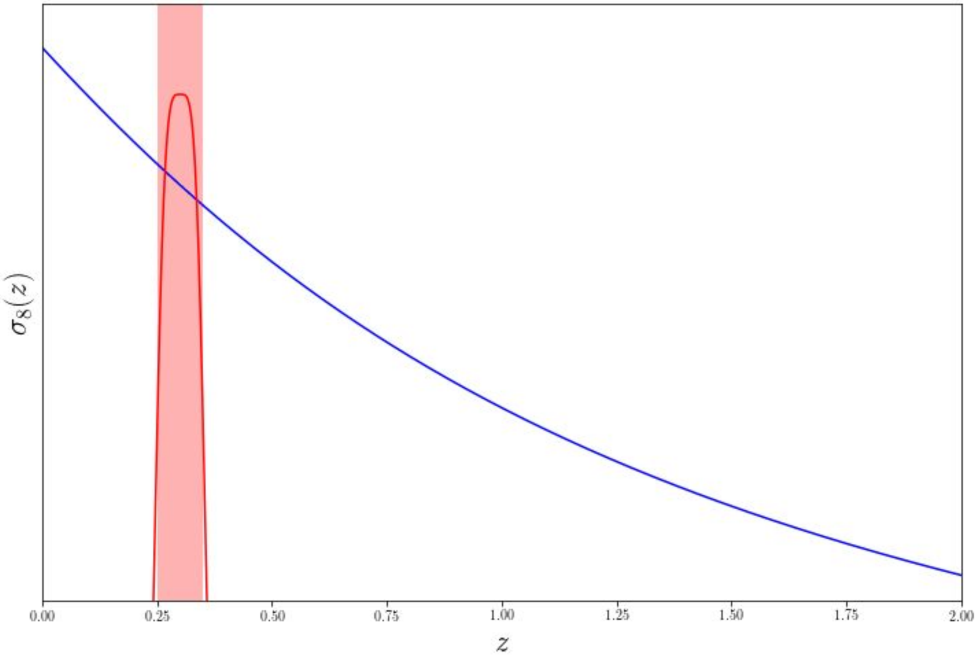
- Due to projection you are also sensitive to χ(z), and P(k).
Yu et al. 2021



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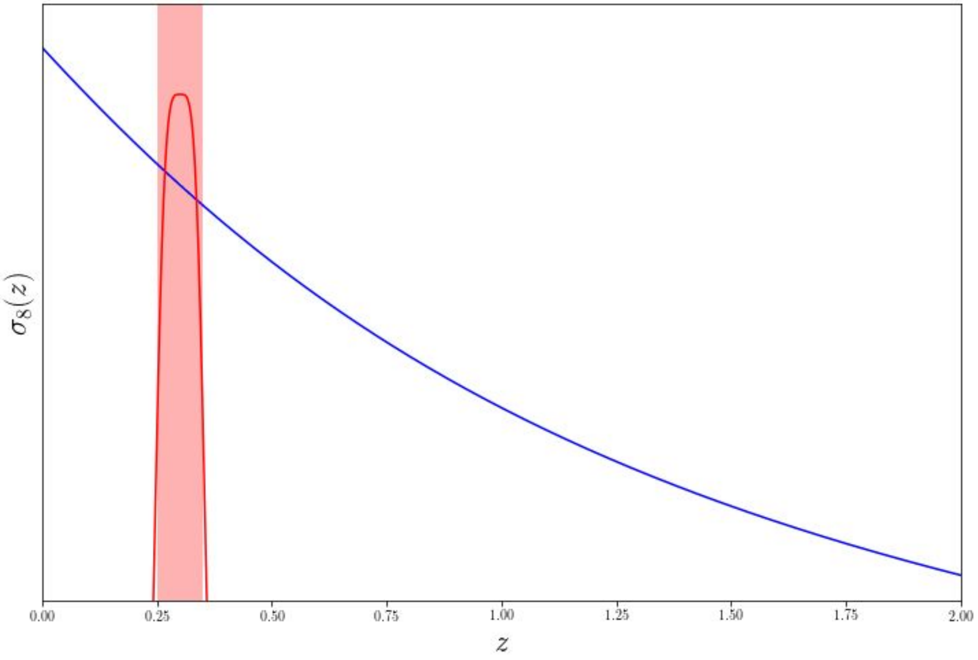
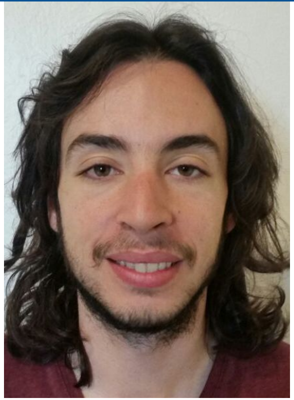
- Due to projection you are also sensitive to $\chi(z)$, and P(k).
_Yu et al. 2021_

- LSST can do this on its own via cosmic shear, but:
  1. CMB leads to significant improvements in FoM.
     Fang et al. 2021
  2. High redshifts?



Tomographic reconstruction: growth

Garcia-Garcia et al. 2021



Growth reconstruction

Idea: reconstruct the linear amplitude of fluctuations from all relevant *projected* large-scale structure data.

- Is the growth history compatible with ΛCDM?
- Do different probes agree on this growth history?
- Is the current tension coming from a specific redshift range?

+ Independent analysis of existing datasets (DES, KiDS)
+ Combined constraints on S_8

Tomographic reconstruction: growth

Garcia-Garcia et al. 2021

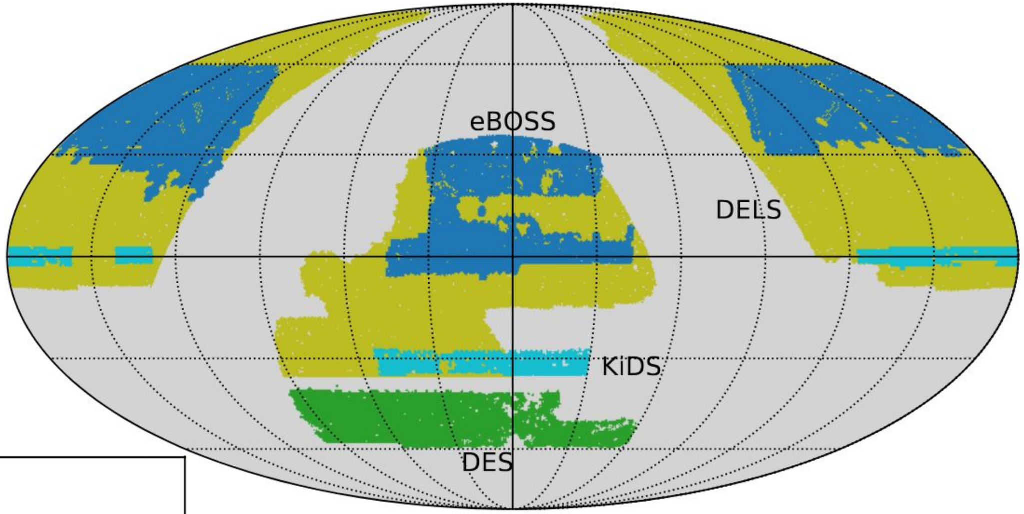
Data:

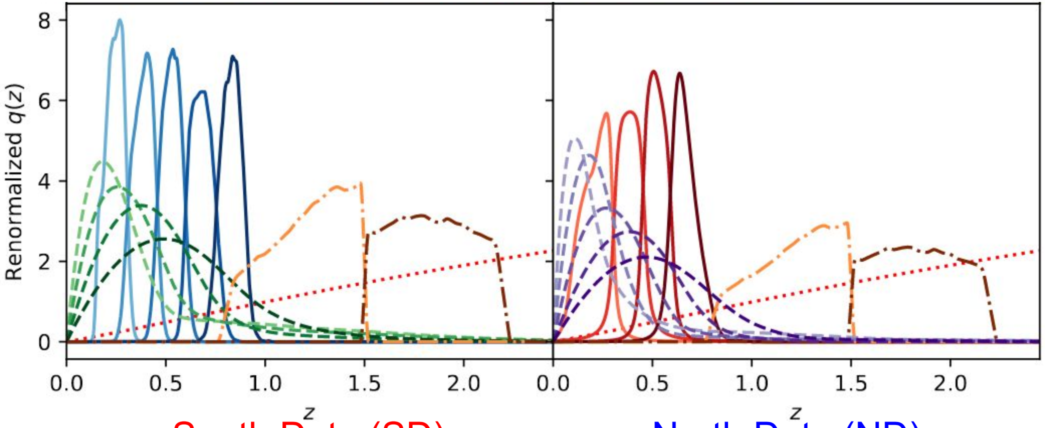
Shear:

- DES Y1
- KiDS-1000

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

Tomographic reconstruction: growth

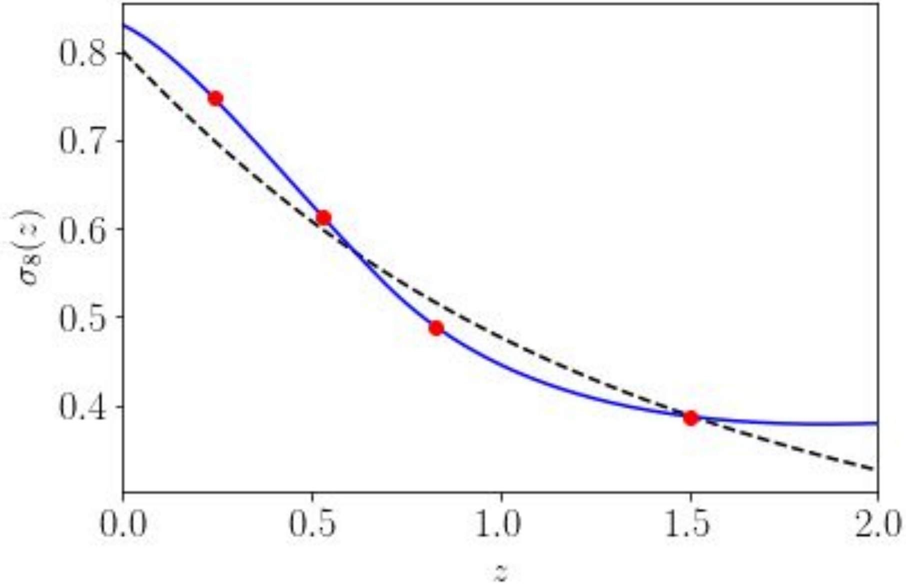
Garcia-Garcia et al. 2021

Growth reconstruction: the analysis

Model:

- Background: ΛCDM
- Power spectrum at z=0: ΛCDM
- Growth history: quadratic spline with free nodes
- Non-linear matter P_k: HALOFIT
- Galaxy bias: linear (k_{max} = 0.15 Mpc^{-1})

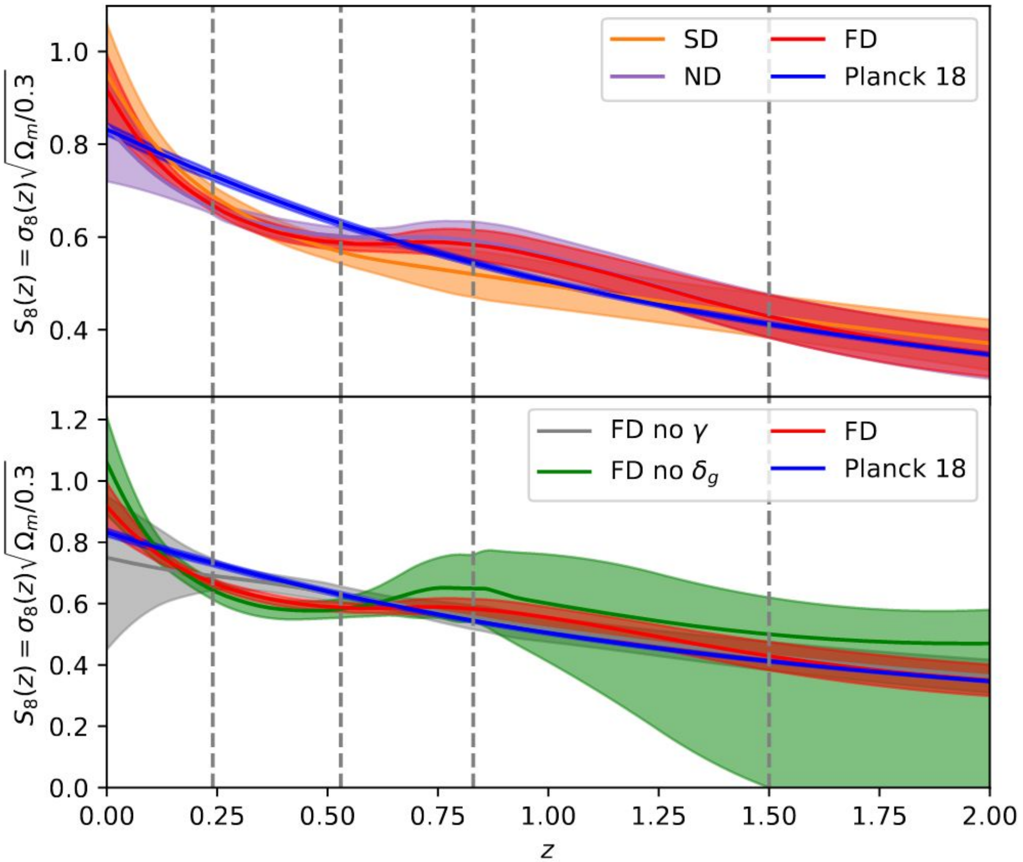
$$P_{\mathrm{L}}(k,z) = D^2(z)\, P_L(k,0)$$



Tomographic reconstruction: growth

Garcia-Garcia et al. 2021

Growth reconstruction: results

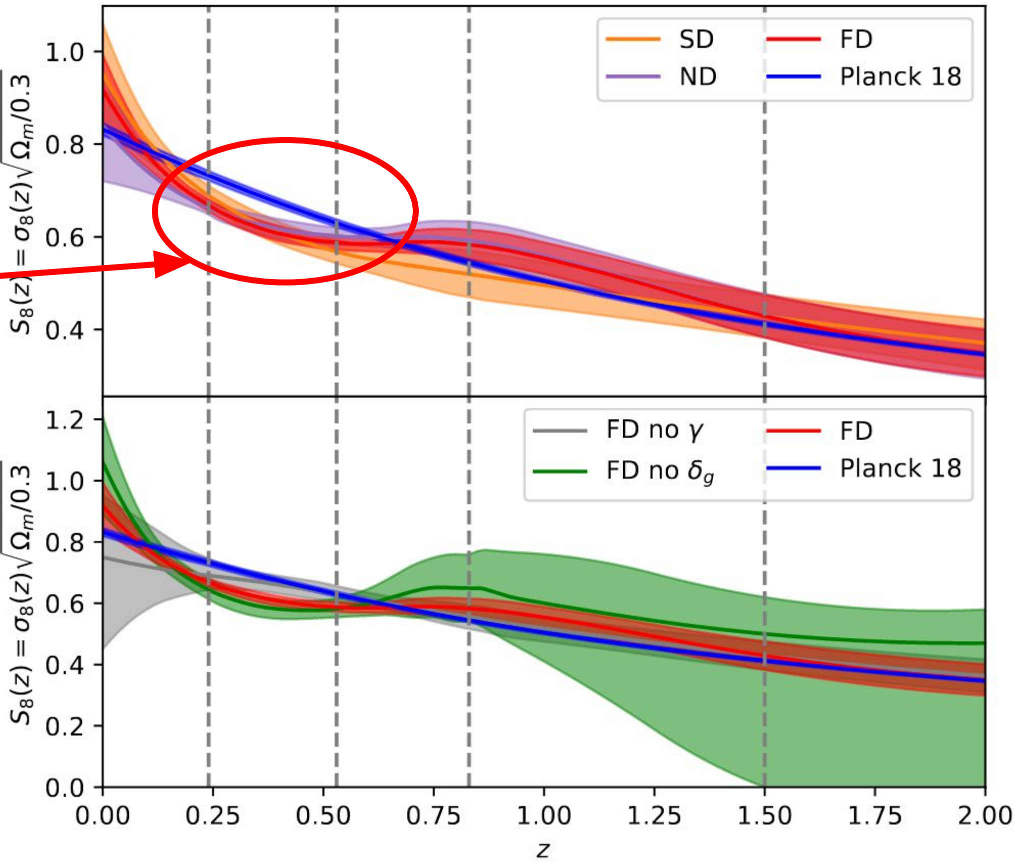


Tomographic reconstruction: growth

Garcia-Garcia et al. 2021

Growth reconstruction: results

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



Tomographic reconstruction: growth

Garcia-Garcia et al. 2021

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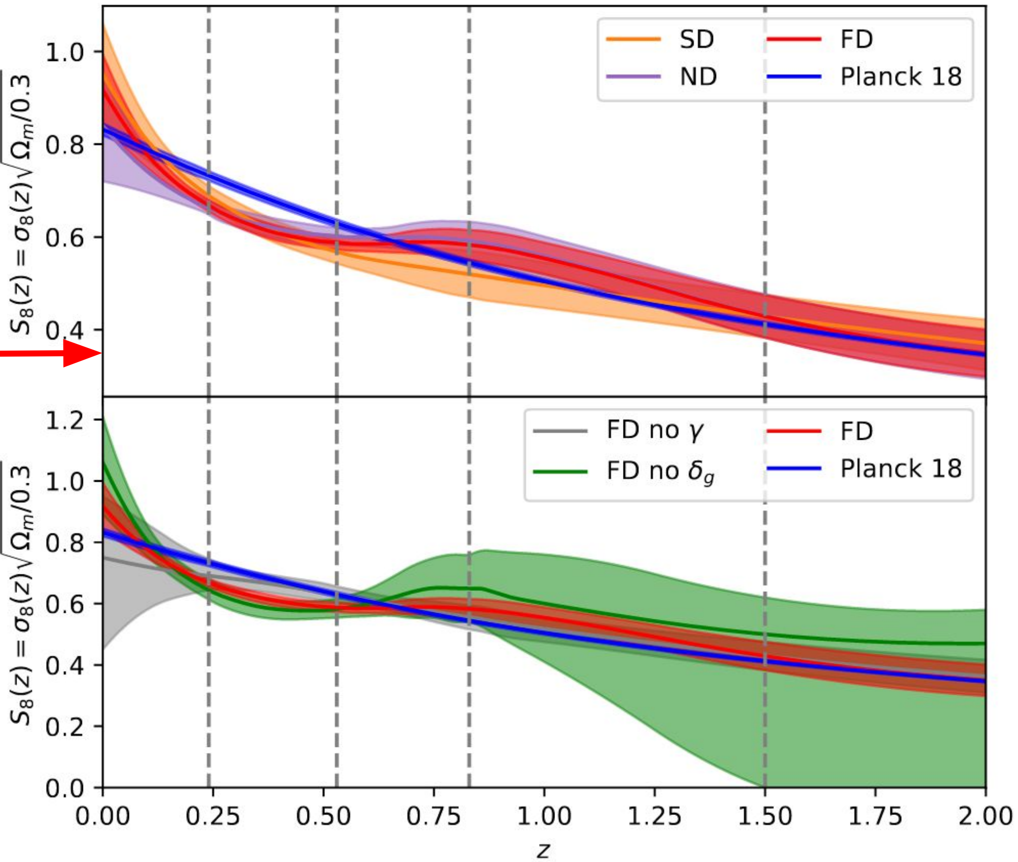

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Garcia-Garcia et al. 2021

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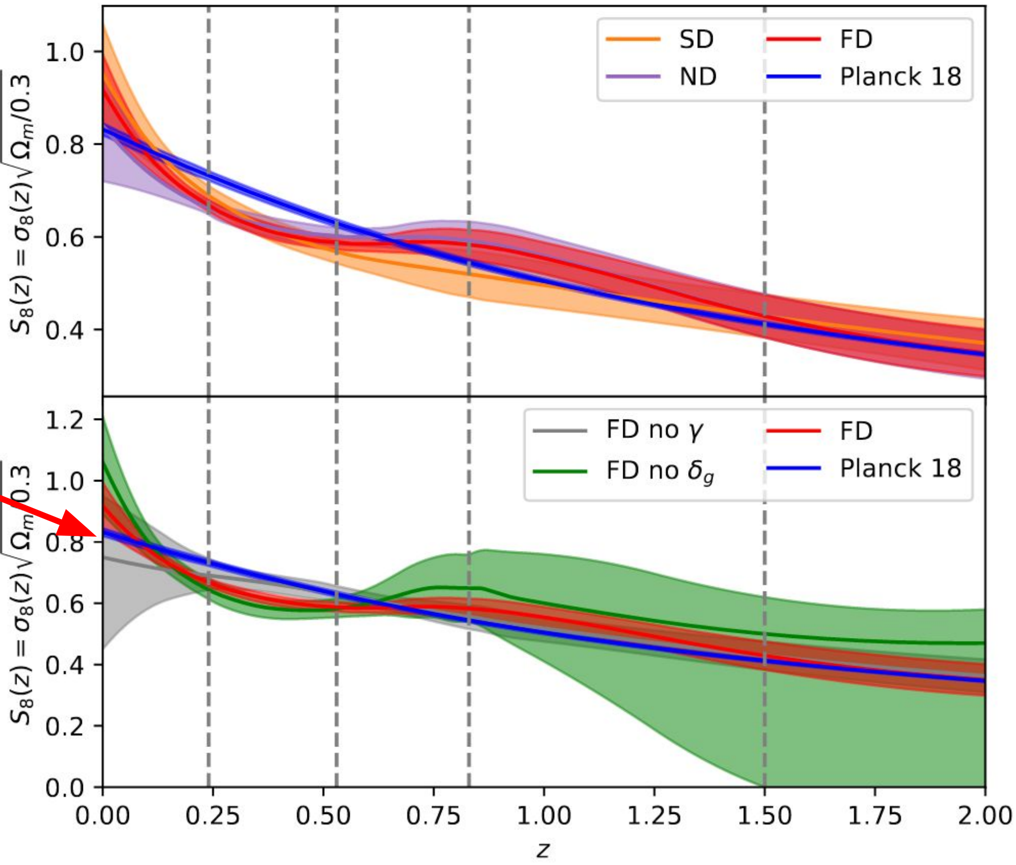

Tomographic reconstruction: growth

[Garcia-Garcia et al. 2021]

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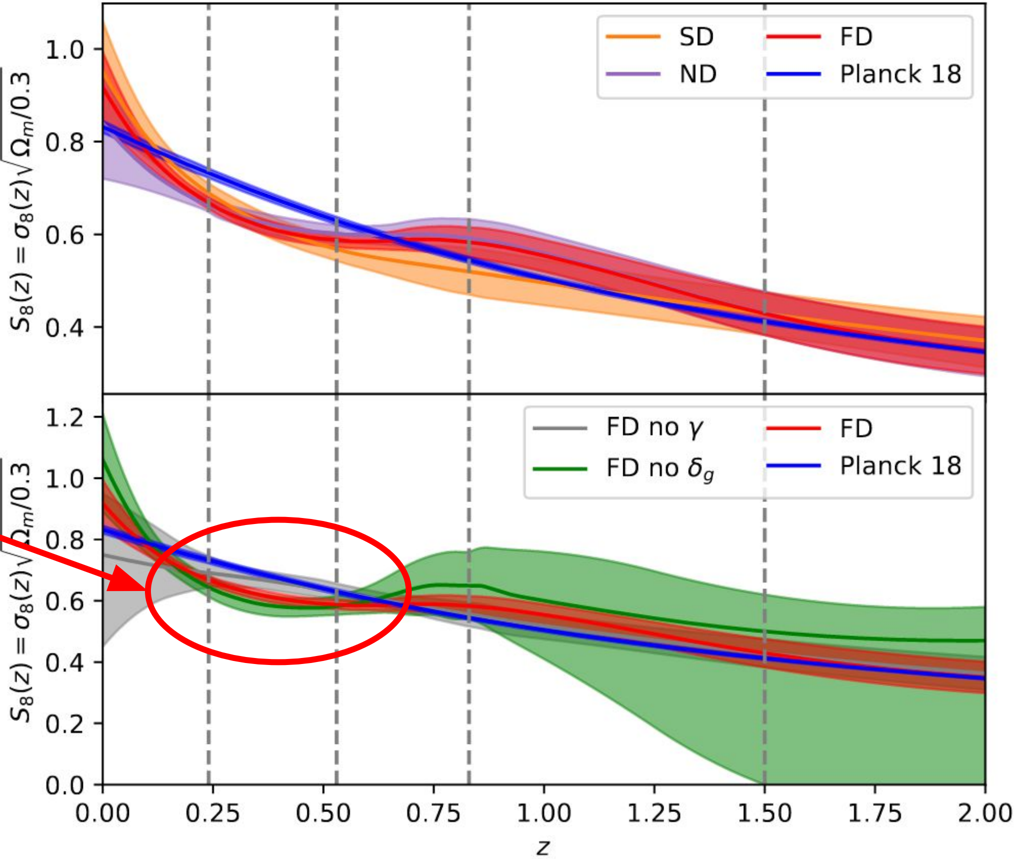

But see [Krolewski et al. 2021]!

Tomographic reconstruction: growth

[Garcia-Garcia et al. 2021]

Growth reconstruction: results

Results:

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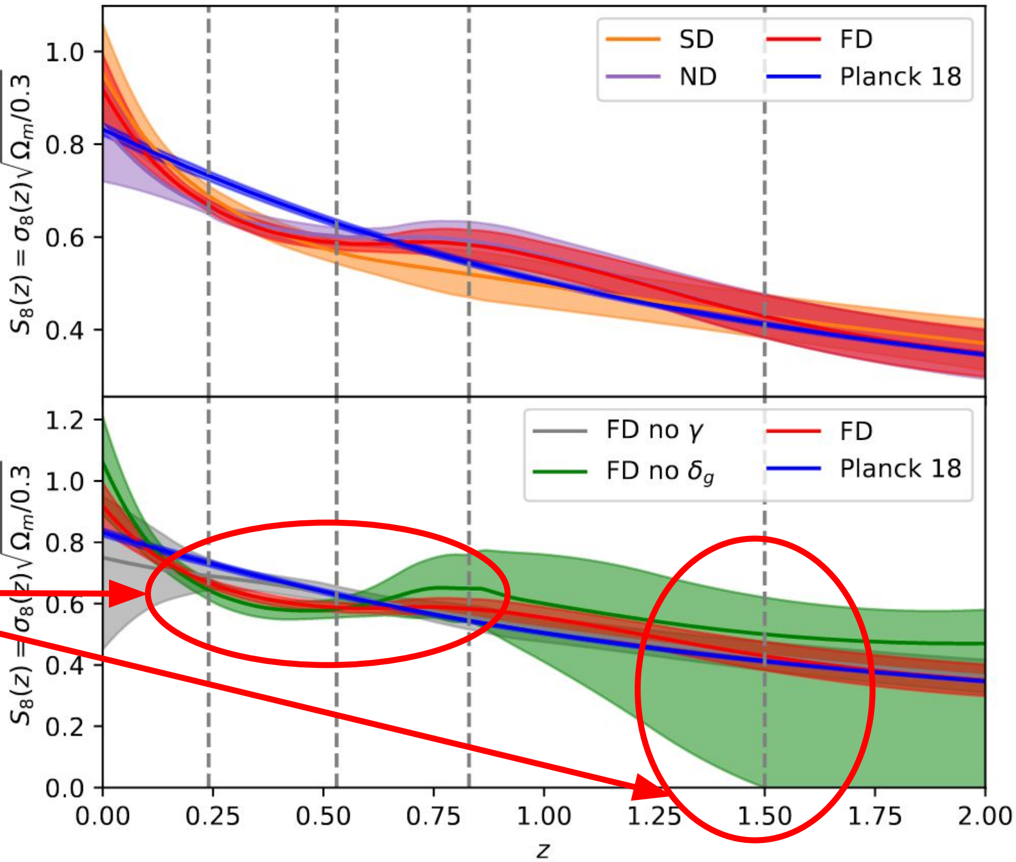
- Clustering + CMBκ compatible with planck (but also with shear).
- Most constraining power at z<0.8. QSOxκ vital for high-z growth.



Tomographic reconstruction: growth

Garcia-Garcia et al. 2021

Growth reconstruction: ΛCDM constraints

Results:

- ΛCDM is an excellent fit to the low-z data
- North and South data compatible
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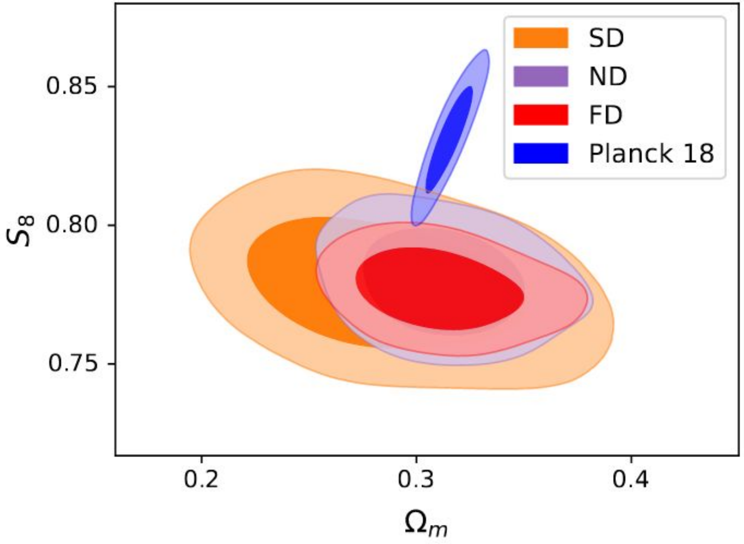

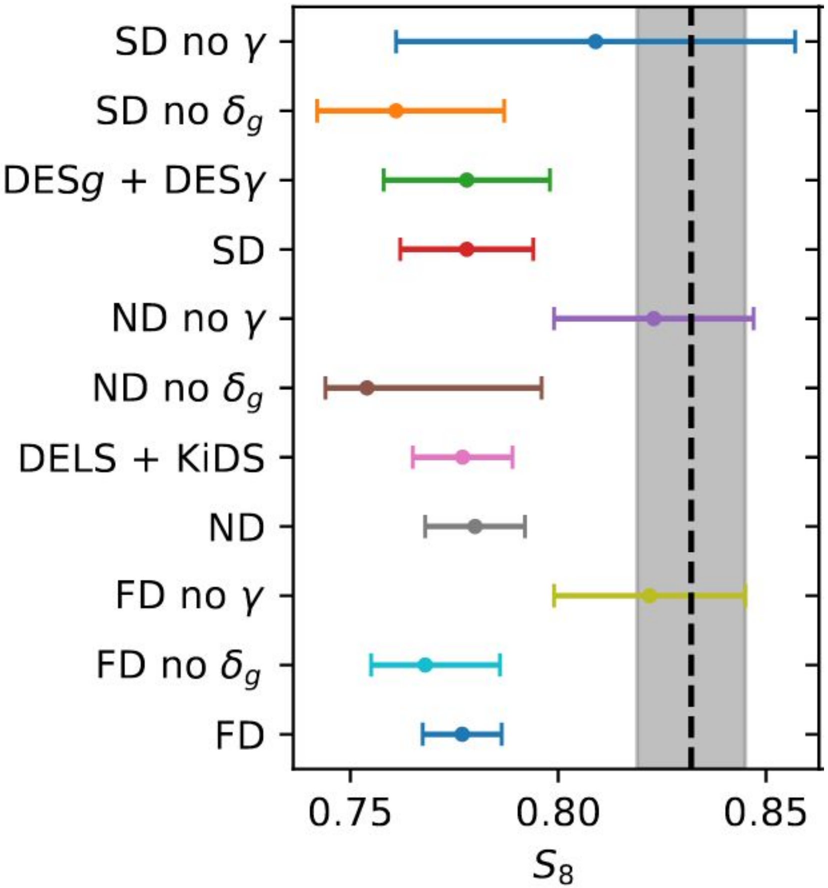

X-correlation systematics: photo-z

Arguably the most pernicious non-theoretical systematic:

- Need to characterize all modes of uncertainty in the N(z)
  Hadzhiyska et al. 2020

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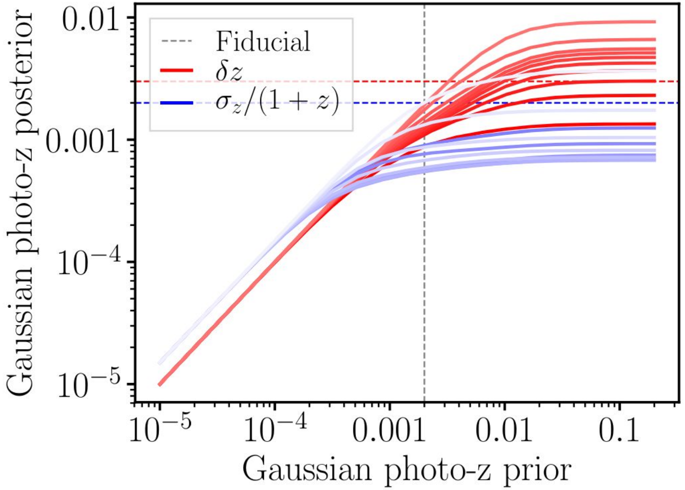
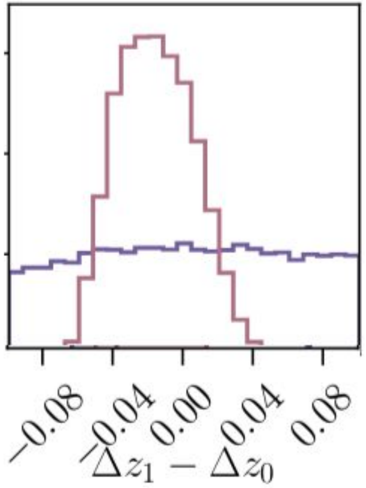
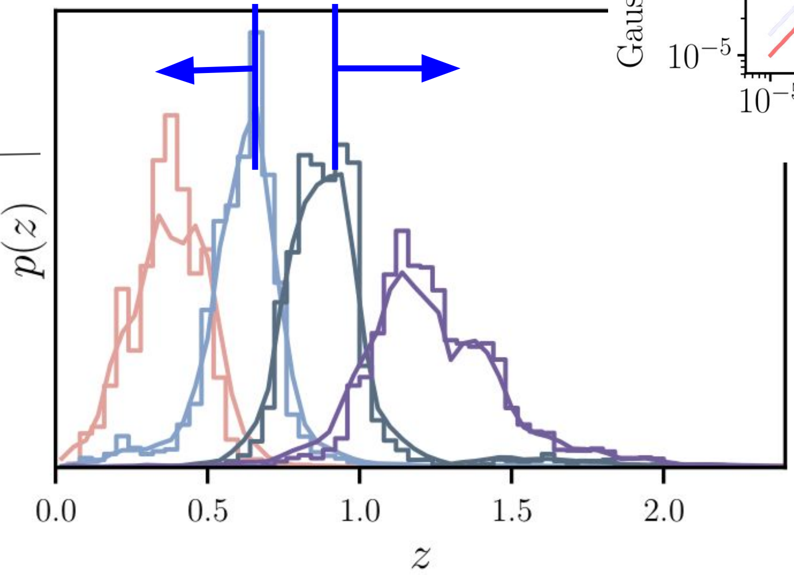
  Nicola et al. 2020, *Schaan et al. 2020*







X-correlation systematics: photo-z

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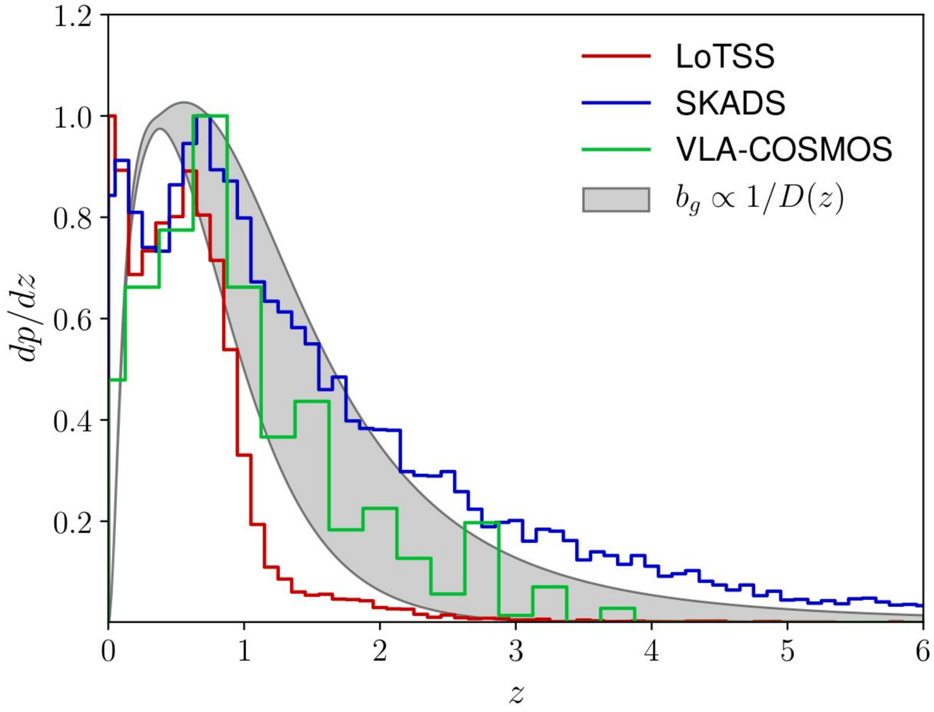
- Need to characterize all modes of uncertainty in the N(z)
  Hadzhiyska et al. 2020
- Can be self-calibrated through internal correlations (to some extent)
  Nicola et al. 2020, *Schaan et al. 2020*
- CMBκ x-corrs less sensitive to N(z) uncertainties...
- … so it can help calibrate:
  - N(z) width
  - Hight-z tail of faint samples

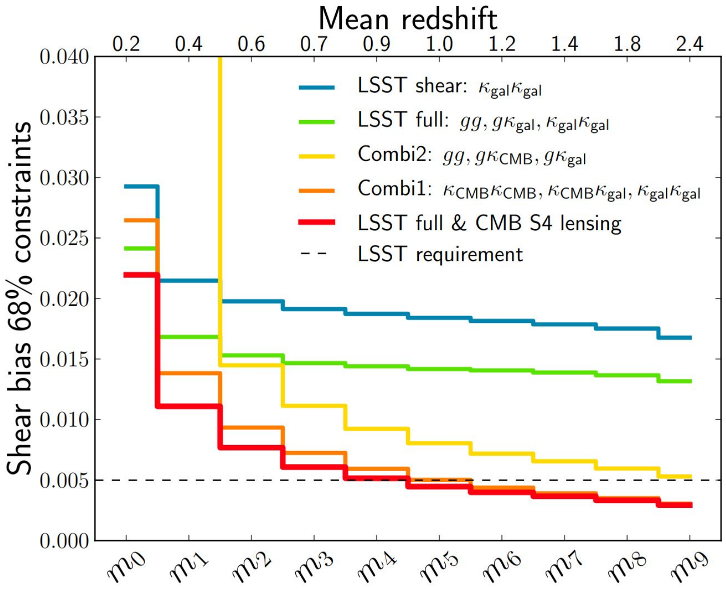
  Alonso et al. 2020

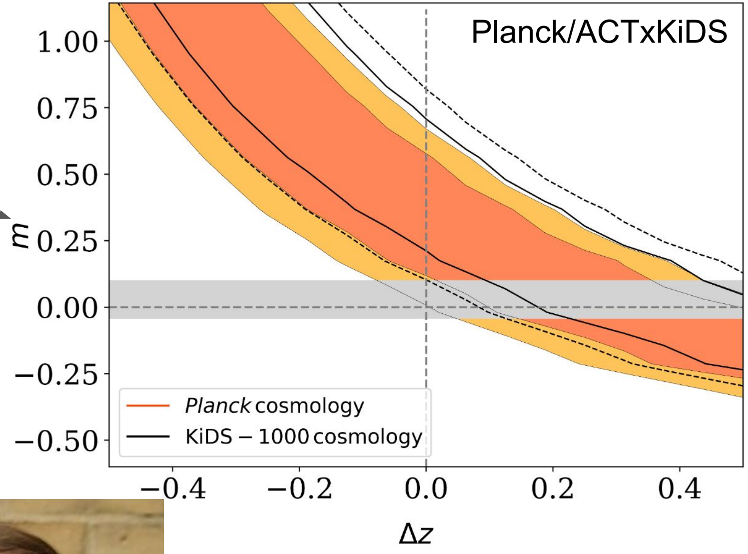


X-correlation systematics: shear calibration

Calibratable through κxγ (especially at high-z)

Schaan et al. 2016, *Robertson et al. 2021*

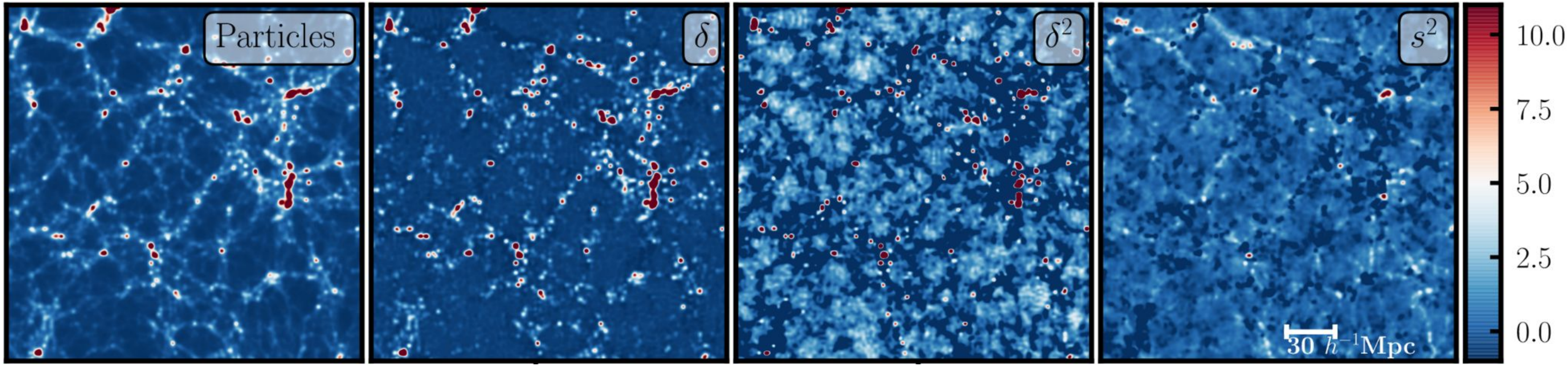




X-correlation systematics: galaxy bias

- Galaxy clustering is (by far!) the highest S/N tracer.
- Lots of data are thrown away:
  - Large-scale observational systematics (easier in x-corr)
  - **Small-scale galaxy bias**
- At LSST/S4 sensitivities we will need to go beyond linear bias (even on conservative scales).
- Promising avenue: hybrid EFT + simulations method

$$1 + \Delta_g \simeq 1 + b_1 \Delta_M + b_2 \Delta_M^2 + b_s S^2 + b_\nabla \nabla^2 \Delta_m$$



Kokron et al. 2021 Modi et al. 2020

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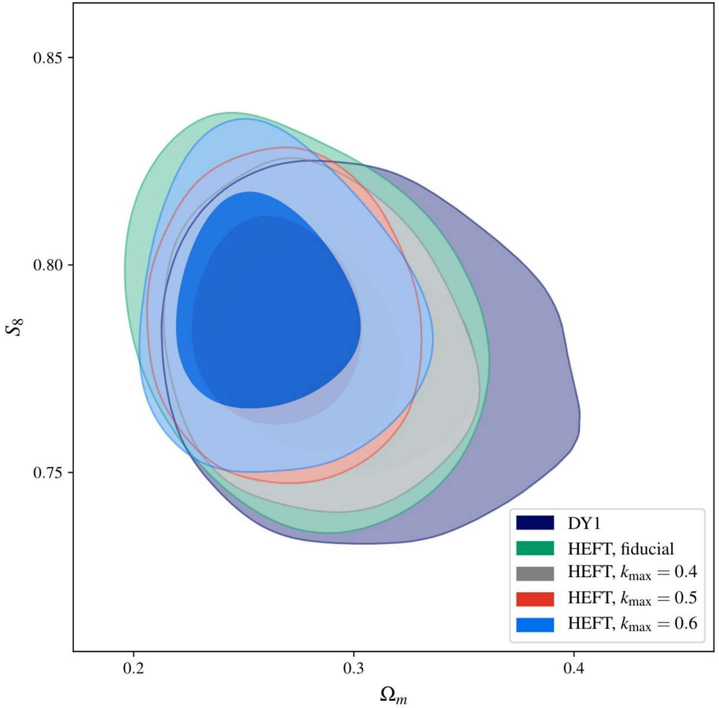
- Promising avenue: hybrid EFT + simulations method
- Demonstration on DESY1 data (*Hadzhiyska et al. 2021*)
  - Good fit up to ~k=0.6 Mpc^{-1}
  - 35% better Ω_m, 10% better S_8



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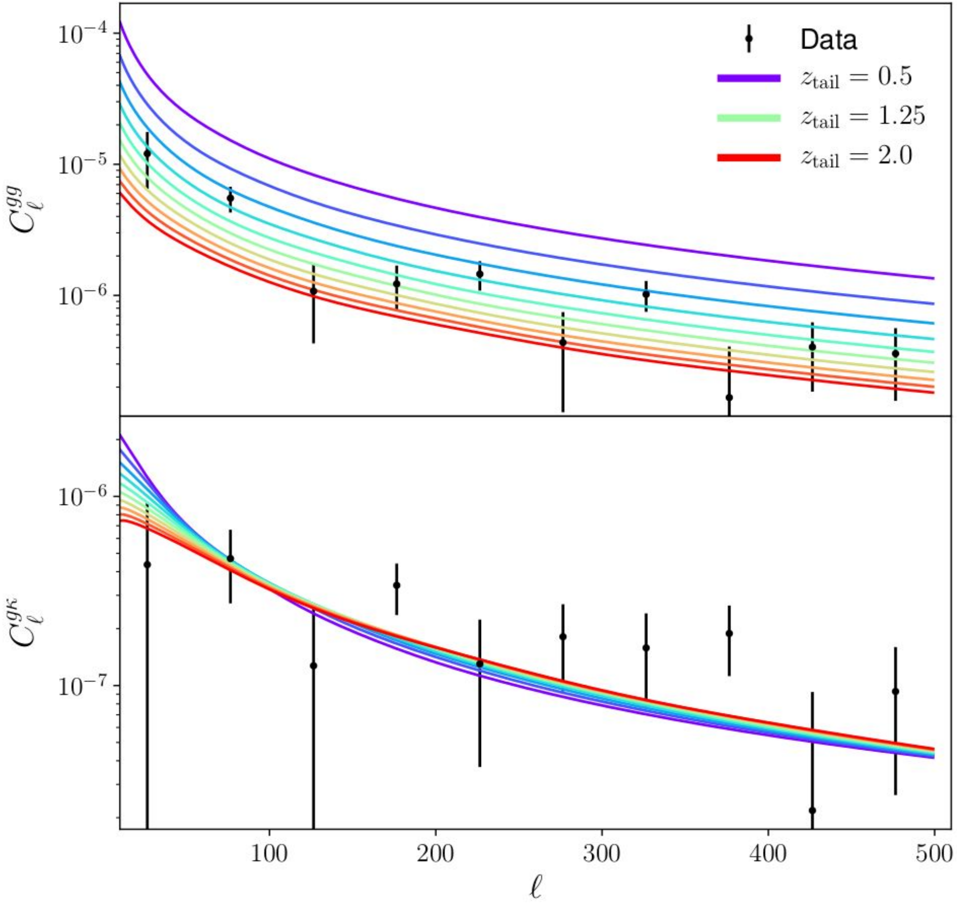


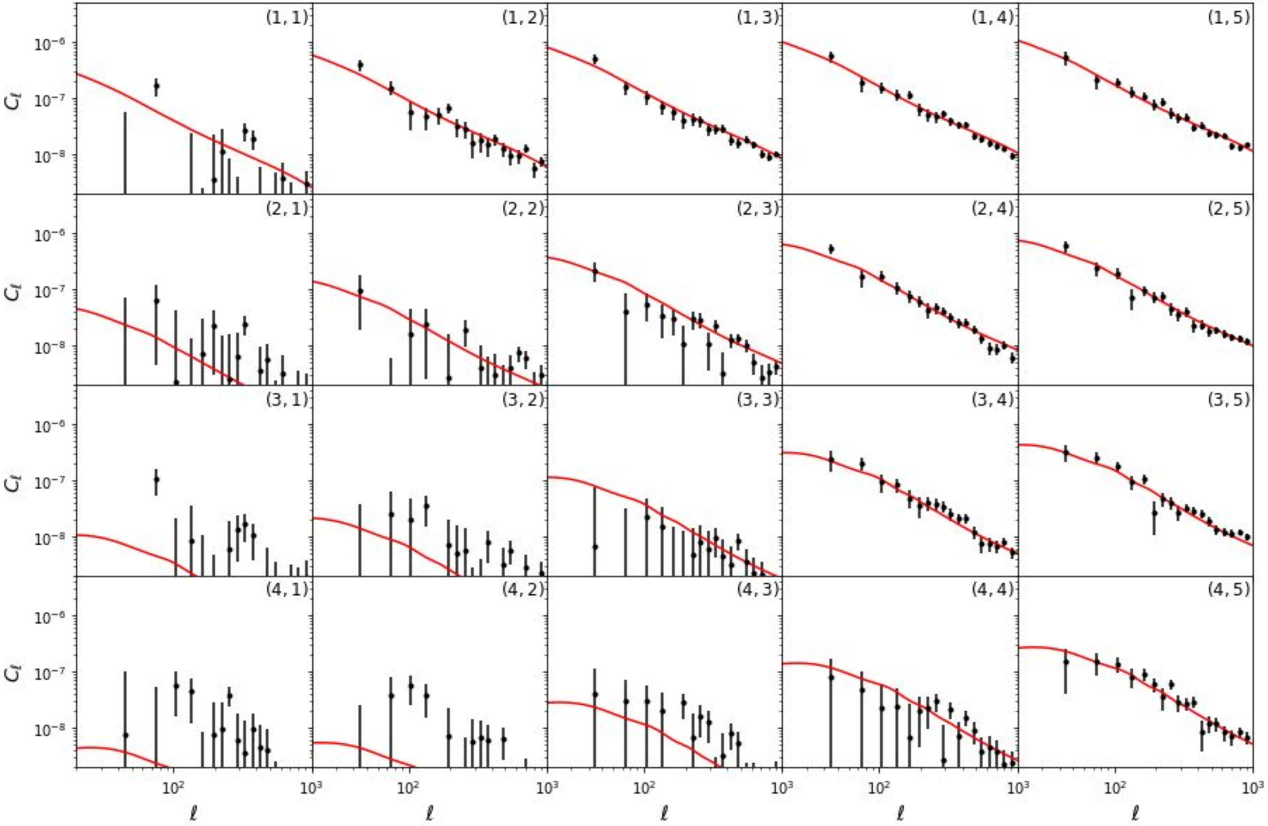
Tomographic reconstruction: growth

Garcia-Garcia et al. 2021

Growth reconstruction: the analysis

Data analysis:

- Independent C_ℓ-based analysis
- Analytical covariances inc. mode-coupling.
- N_d = 1275



Example: Legacy survey x KiDS

Tomographic reconstruction: growth

Garcia-Garcia et al. 2021

Growth reconstruction: the analysis

Data analysis:

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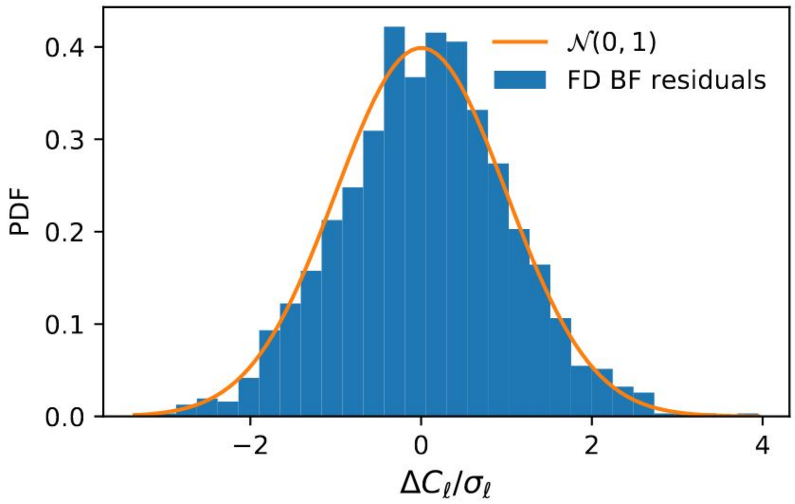
- N_d = 1275
- Sanity checks:
  * B-modes
  * Impact of GC systematics via deprojection
  * Goodness-of-fit tests



Tracer name	KiDS Bin 0	Bin 1	Bin 2	Bin 3	Bin 4	Tracer name	DES γ Bin 0	Bin 1	Bin 2	Bin 3
DELS-0	0.460	0.135	0.234	0.978	0.650	DES g-0	0.396	0.733	0.704	0.294
DELS-1	0.011	0.781	0.661	0.105	0.438	DES g-1	0.737	0.983	0.889	0.071
DELS-2	0.226	0.425	0.752	0.163	0.861	DES g-2	0.378	0.809	0.264	0.288
DELS-3	0.483	0.324	0.567	0.569	0.269	DES g-3	0.923	0.073	0.905	0.354
CMBκ	0.280	0.050	0.078	0.167	0.450	DES g-4	0.517	0.048	0.889	0.459
KiDS-0	0.949	0.604	0.463	0.586	0.761	CMBκ	0.168	0.170	0.432	0.943
KiDS-1	–	0.795	0.292	0.877	0.336	DES γ-0	0.436	0.232	0.630	0.774
KiDS-2	–	–	0.603	0.044	0.006	DES γ-1	–	0.545	0.991	0.645
KiDS-3	–	–	–	0.977	0.406	DES γ-2	–	–	0.813	0.245
KiDS-4	–	–	–	–	0.612	DES γ-3	–	–	–	0.977

Tomographic reconstruction: growth

<u>*Garcia-Garcia et al. 2021*</u>

Growth reconstruction: ΛCDM constraints

Results:

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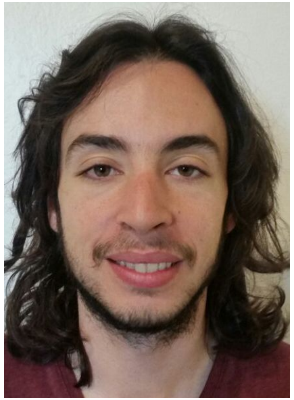
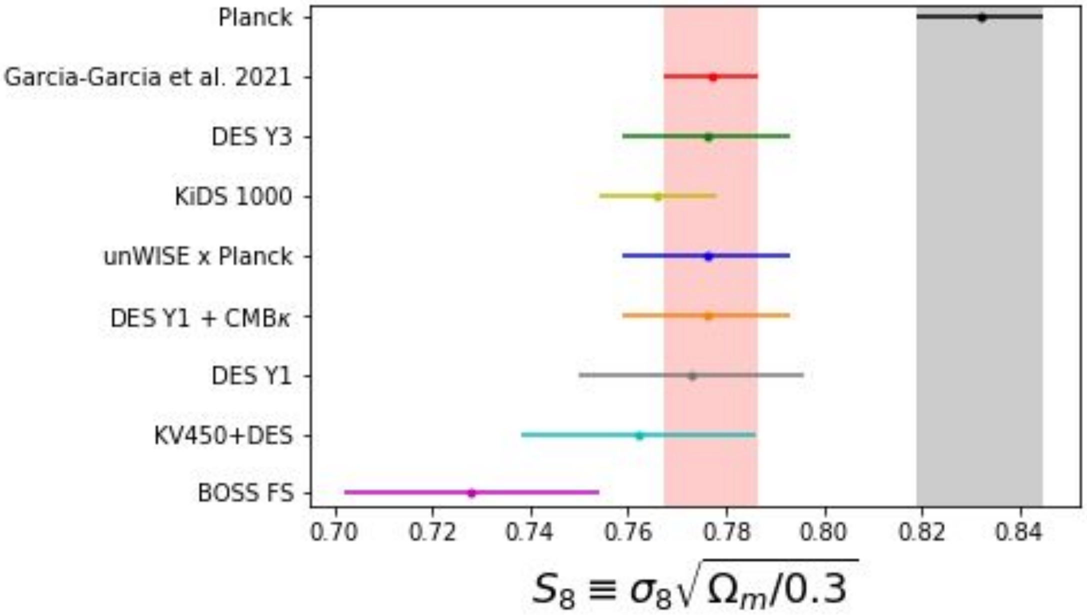
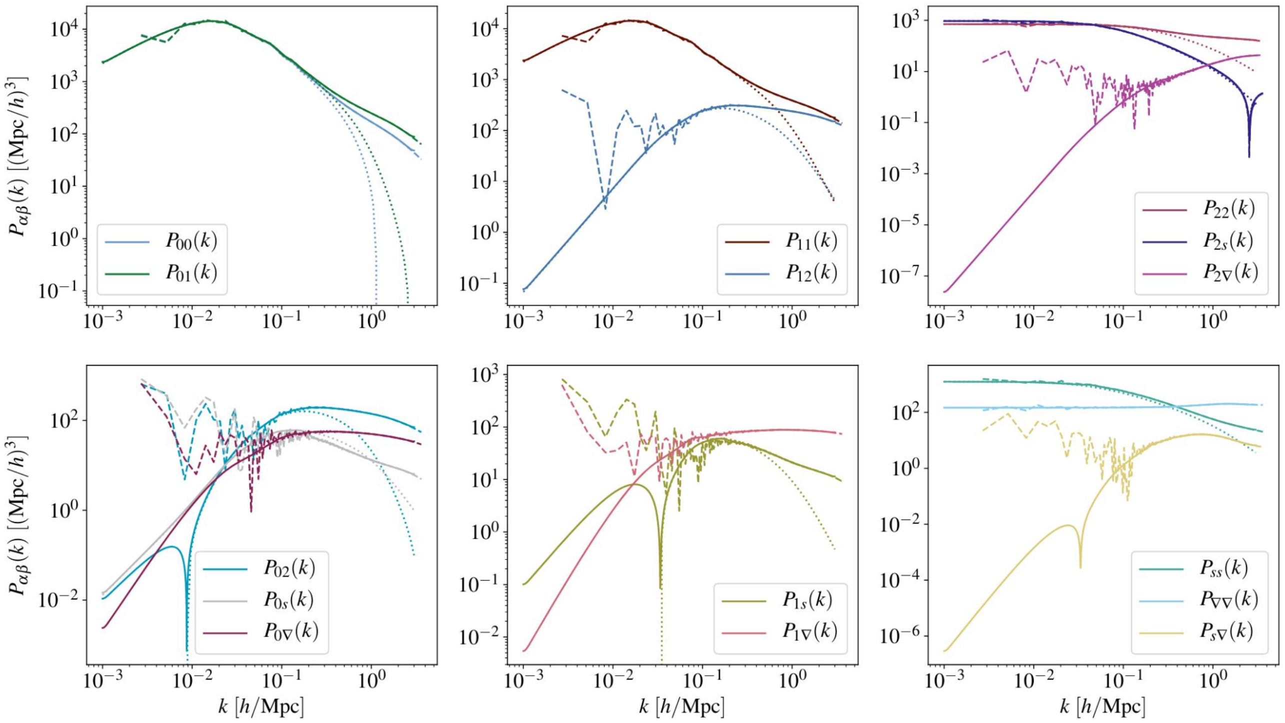




Beefing up clustering

Hadzhiyska et al. 2021

Hybrid EFT bias expansion



- Implementation based on ABACUS simulation.
- Smooth transition between LPT and sims.

Beefing up clustering

Hadzhiyska et al. 2021

Hybrid EFT bias expansion

$$P_{\alpha\beta}(k;\vec{\theta}) = P_{\alpha\beta}(k;\vec{\theta}_*) + (\vec{\theta} - \vec{\theta}_*) \cdot \nabla_\theta P_{\alpha\beta}(k)$$

$$P_{\alpha\beta}(k;\vec{\theta}) = \frac{P^{\rm HF}_{mm}(k;\vec{\theta})}{P^{\rm AB}_{11}(k;\vec{\theta})} P^{\rm AB}_{\alpha\beta}(k;\vec{\theta})$$

- Implementation based on ABACUS simulation.
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- Cosmological dependence of ratio wrt. $P_{mm}(k)$ through linear derivatives

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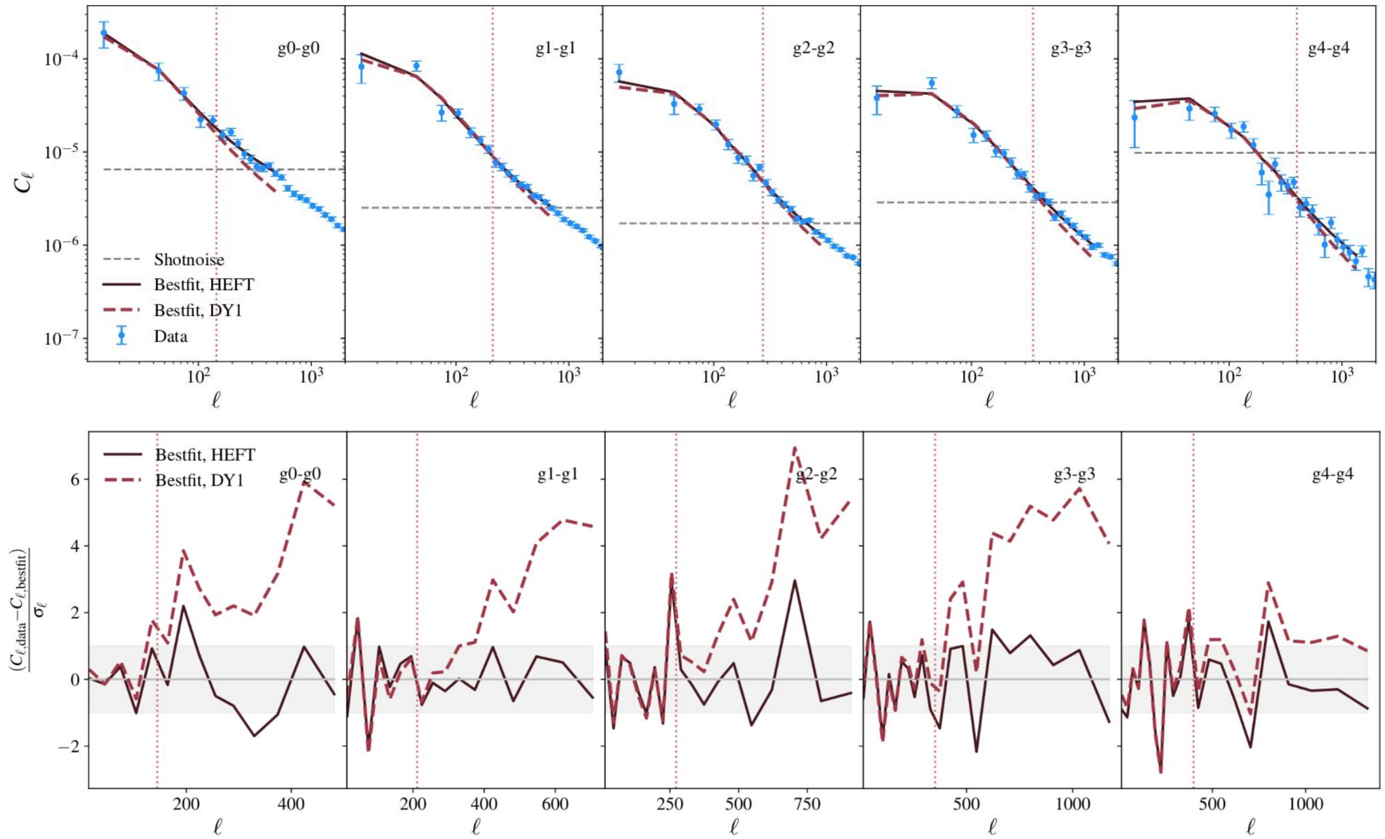
Performance on real data

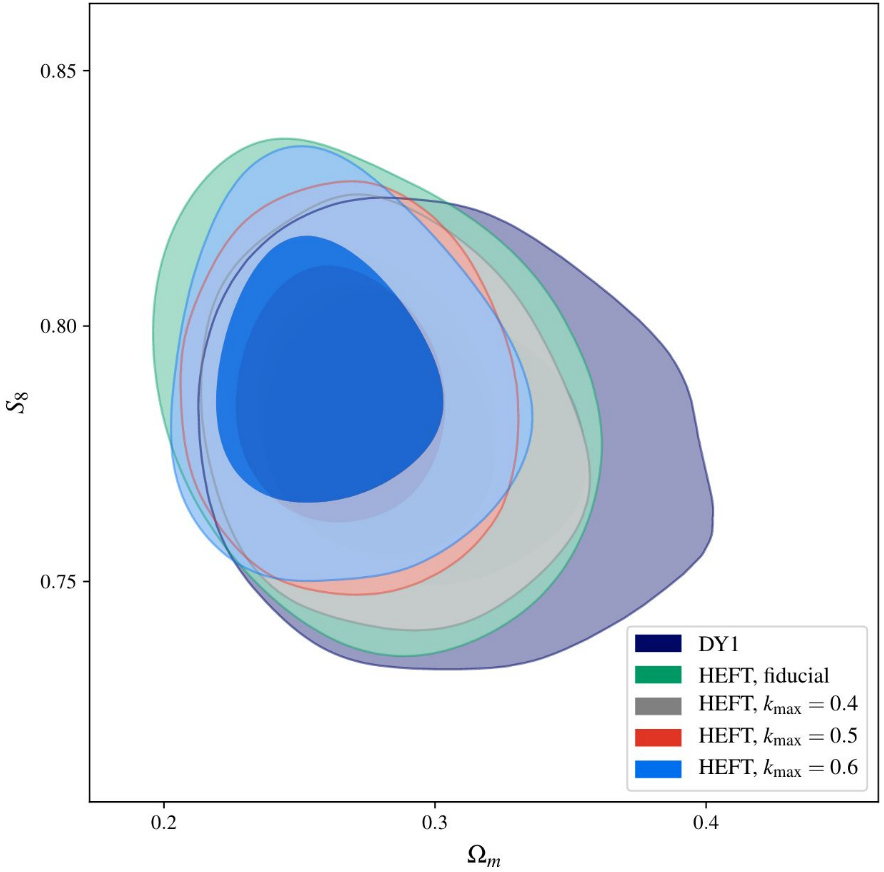


- Markedly improved performance in goodness of fit on high-k

Beefing up clustering

Hadzhiyska et al. 2021

Performance on real data



- Markedly improved performance in goodness of fit on high-k
- 35% better Ω_m
  10% better S_8
  Potential gains in H_0