Cross-correlations and the large-scale structure

David Alonso (U. Oxford) - Dec. 11 2021, CEICO

The real heroes

Carlos Garcia-Garcia - Oxford

Caroline Guandalin - Sao Paulo -> QMUL

Nick Koukoufilippas - Oxford

Andrina Nicola - Princeton

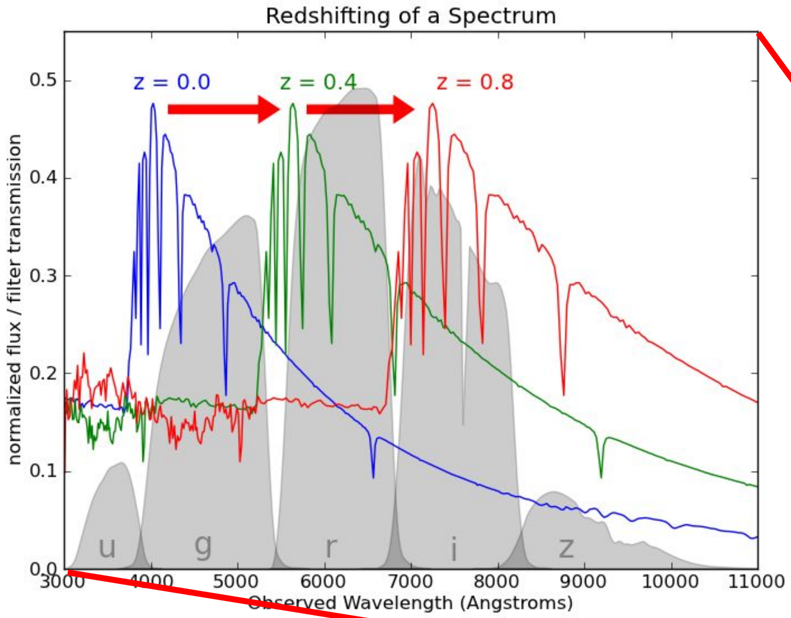
Emilio Bellini - Geneva

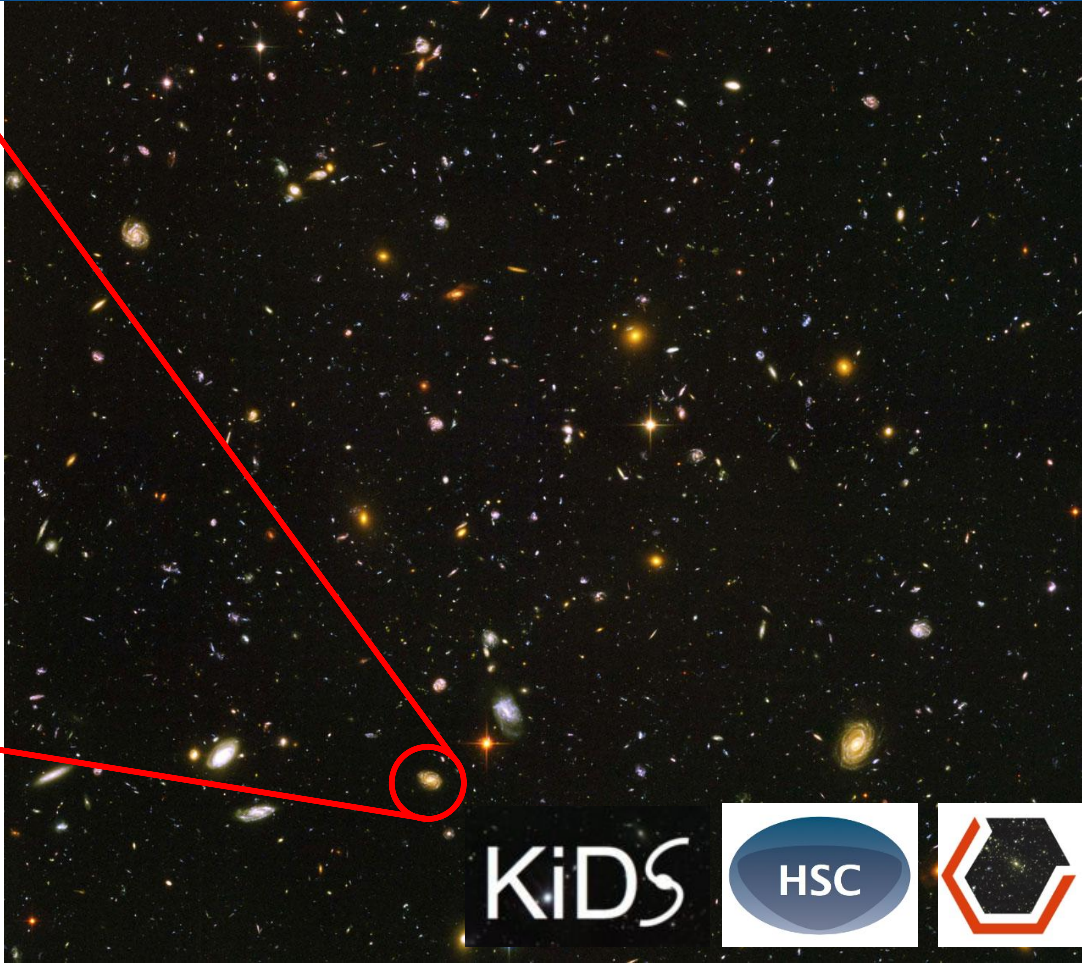
Anže Slosar - BNL

Part 0
Projected LSS tracers

$$u(\hat{\mathbf{n}}) = \int d\chi \, W_u(\chi) \, U(\chi\hat{\mathbf{n}}, z(\chi))$$

Projected tracers: photometric surveys





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

Projected tracers: photometric surveys

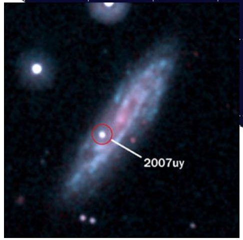
Rubin
LSST

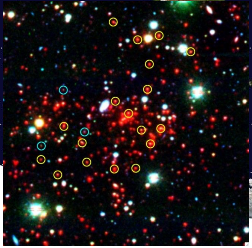
Outstanding numbers:

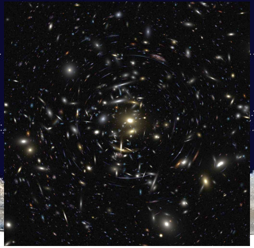
- World largest imager 8.4m, 9.6 deg^2 FOV
- Wide: 20k deg^2
- Deep: r~27
- Fast: ~100 visits/year
- Big data: ~15TB/day

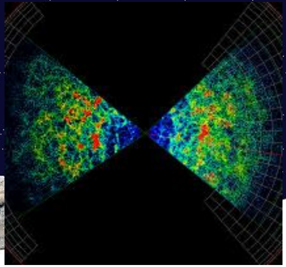
Dark Energy Science Coll.

- Supernovae
- Cluster science
- Strong lensing
- Weak lensing
- Galaxy clustering





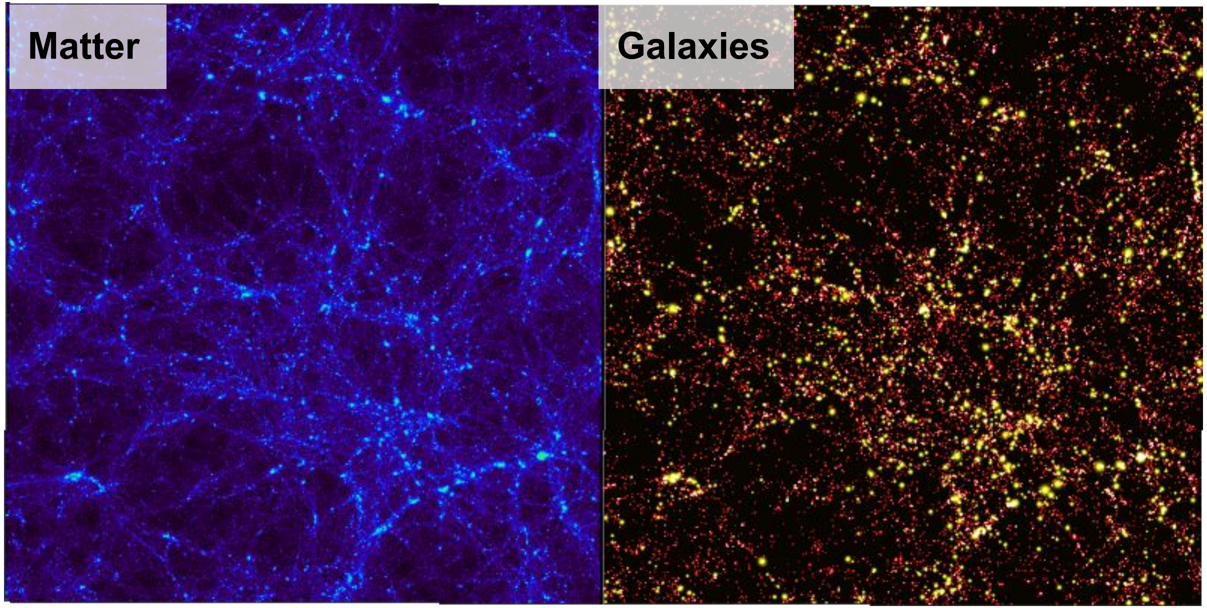




Projected tracers: galaxy clustering

Galaxy clustering:

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

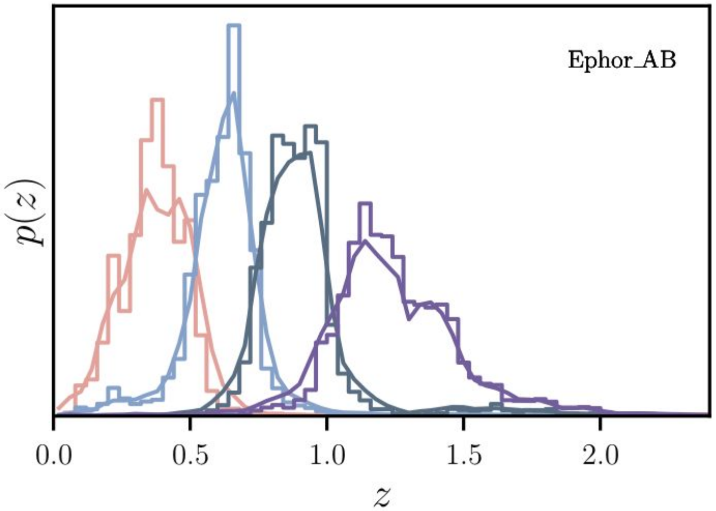


Projected tracers: galaxy clustering

Photometric clustering:

- Local probe of matter fluctuations

$$\delta_g(\hat{\mathbf{n}}) = \int dz \frac{dp}{dz} \Delta_g(\chi(z)\hat{\mathbf{n}}, z)$$

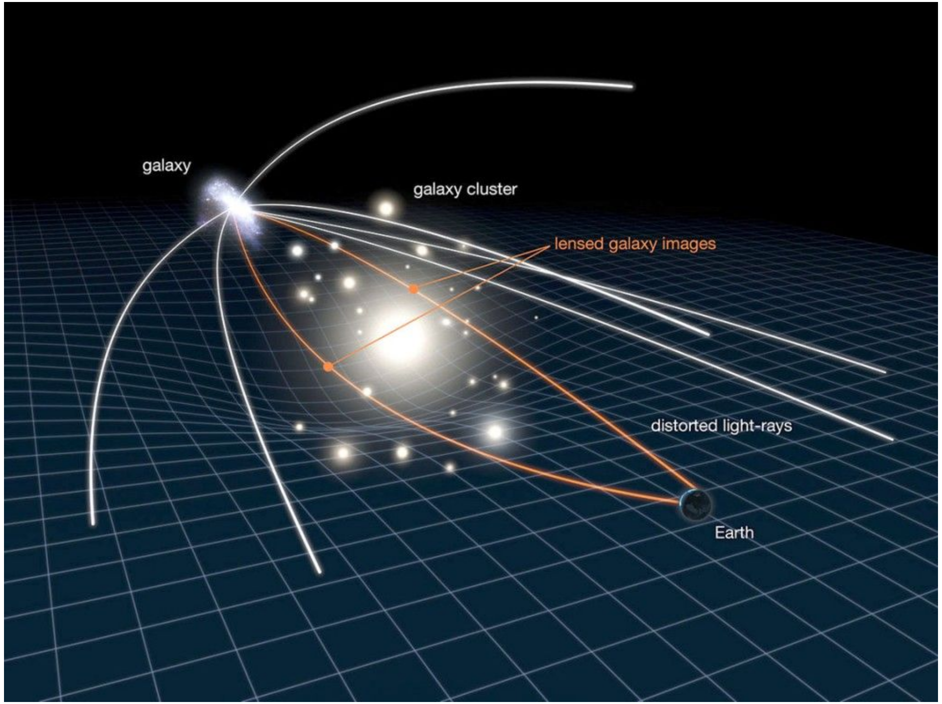


Nicola et al. 2020

Projected tracers: cosmic shear

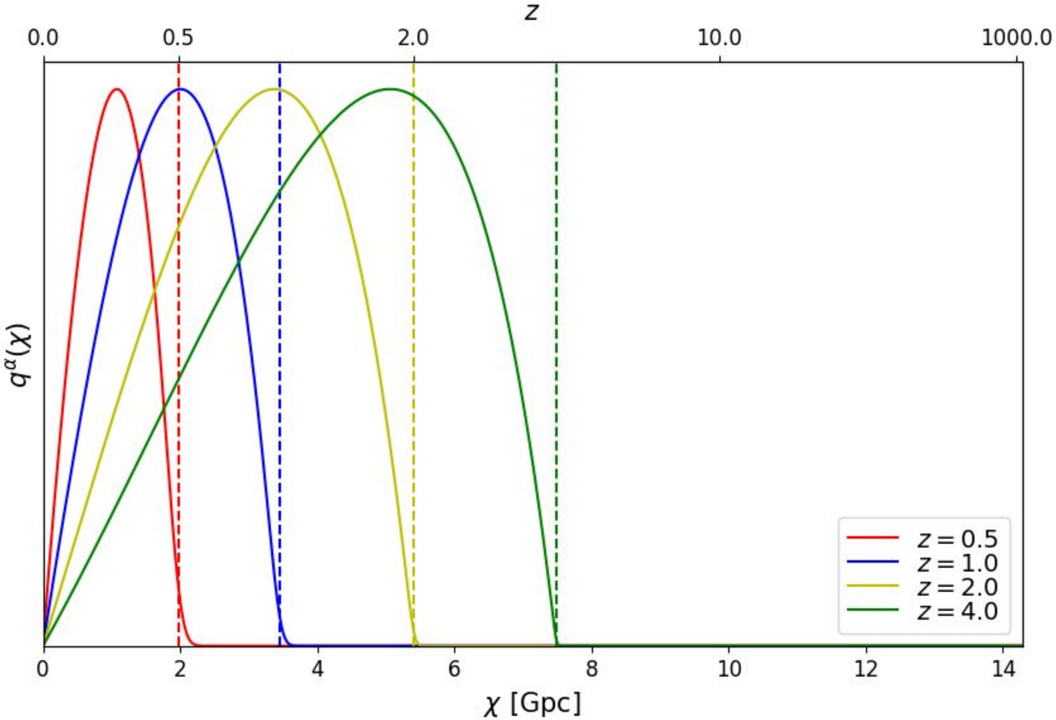
Weak lensing:

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



Projected tracers: cosmic shear

$$\gamma_E(\hat{\mathbf{n}}) = \int d\chi\, q_\gamma(\chi)\, \Delta_m(\chi\hat{\mathbf{n}}), z) \qquad q_\gamma(\chi) = \frac{3}{2} H_0^2 \Omega_m \frac{\chi}{a} \int_{z(\chi)}^{\infty} dz' \frac{dp}{dz} \frac{\chi(z') - \chi}{\chi(z')}$$



Projected tracers: “3x2-point”

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

Weak lensing:
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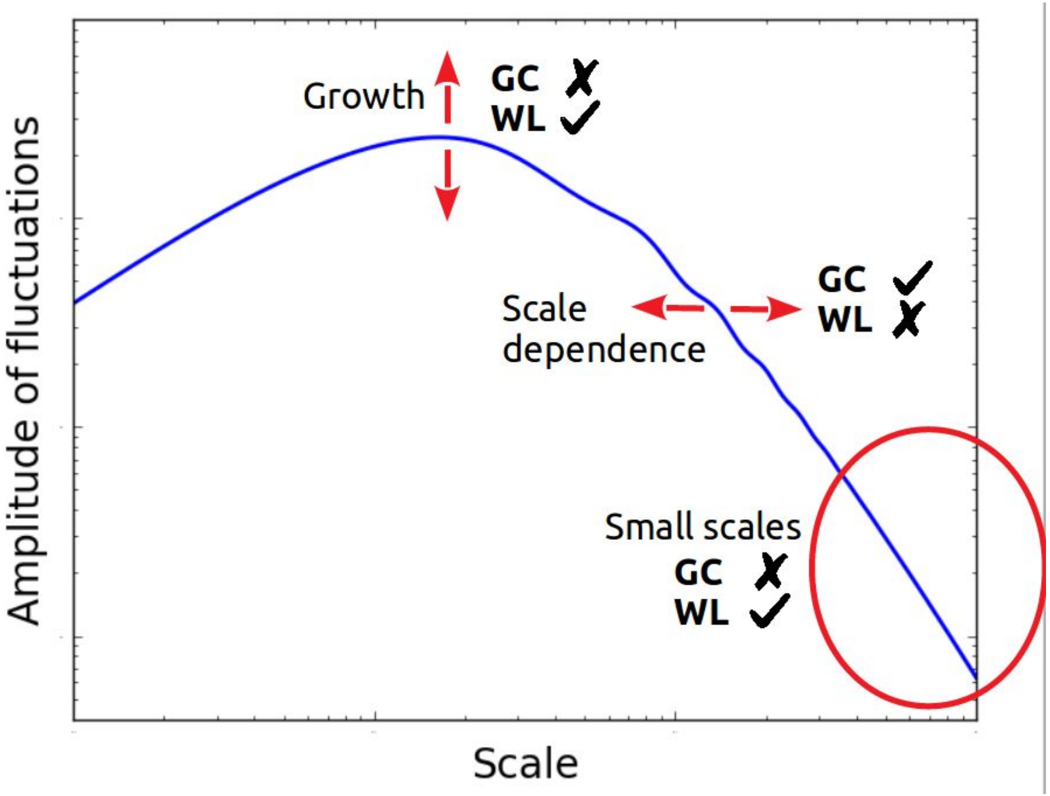
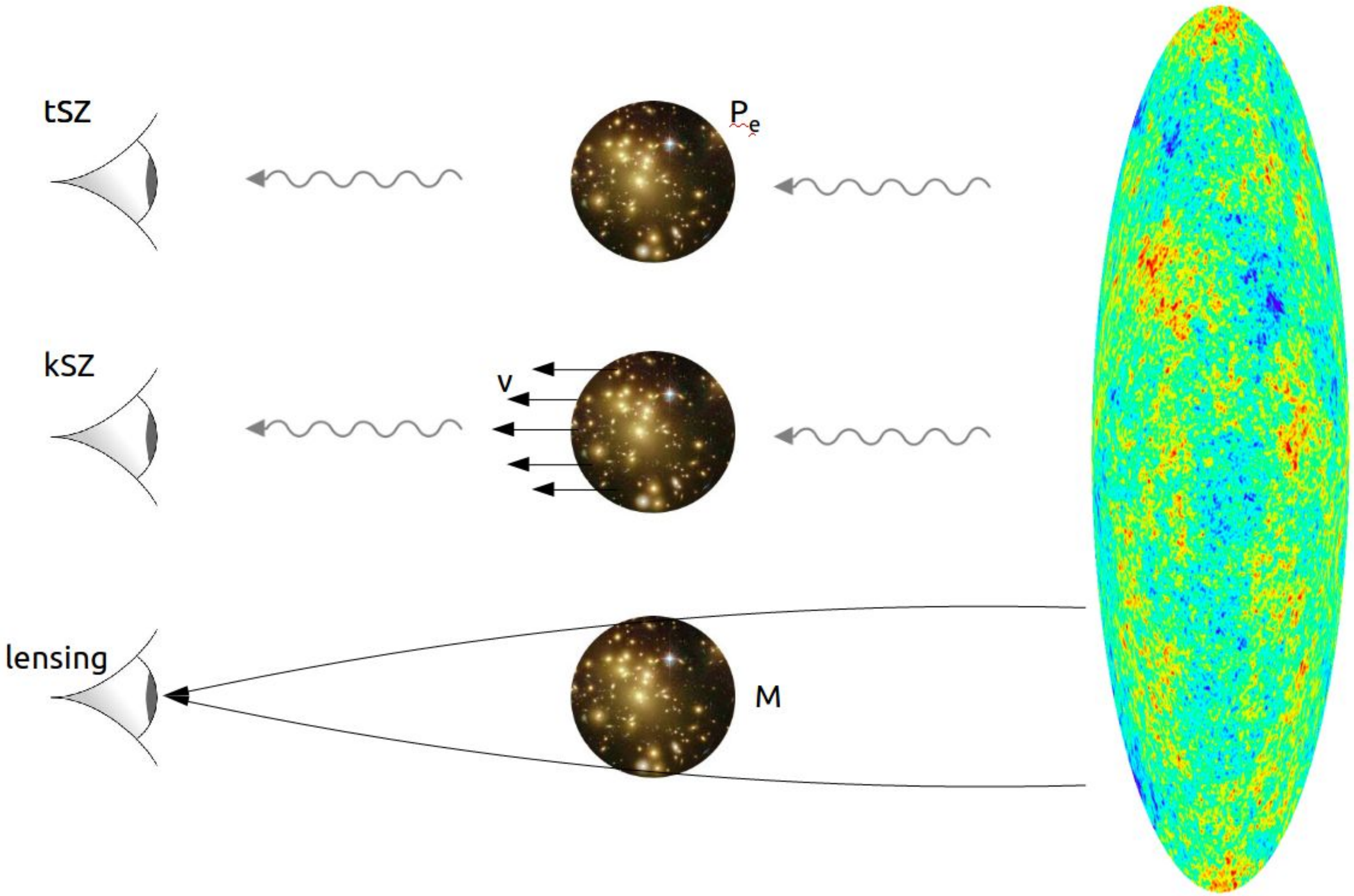
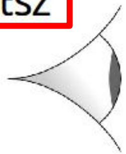


Projected tracers: CMB secondary anisotropies



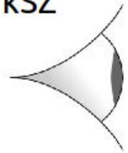
Projected tracers: CMB secondary anisotropies

tSZ



$$\left.\frac{\Delta \mathrm{T}}{\mathrm{T}}\right|_{\mathrm{tSZ}}(\nu, \hat{\mathbf{n}}) = f_{\mathrm{tSZ}}(\nu)\,\frac{\sigma_T}{m_e c^2}\int P_e(l_z, \hat{\mathbf{n}})\, dl_z$$
$$\equiv f_{\mathrm{tSZ}}(\nu)\, y(\hat{\mathbf{n}})$$

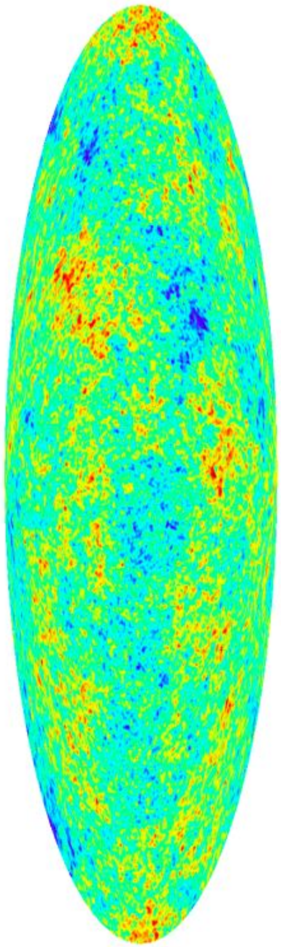
kSZ



$$\left.\frac{\Delta \mathrm{T}}{\mathrm{T}}\right|_{\mathrm{kSZ}}(\hat{\mathbf{n}}) = -\sigma_T \int (\boldsymbol{\beta}\cdot\hat{\mathbf{n}})\, n_e(l_z, \hat{\mathbf{n}})\, dl_z$$
$$\equiv -\beta_r\, \tau(\hat{\mathbf{n}}),$$

lensing

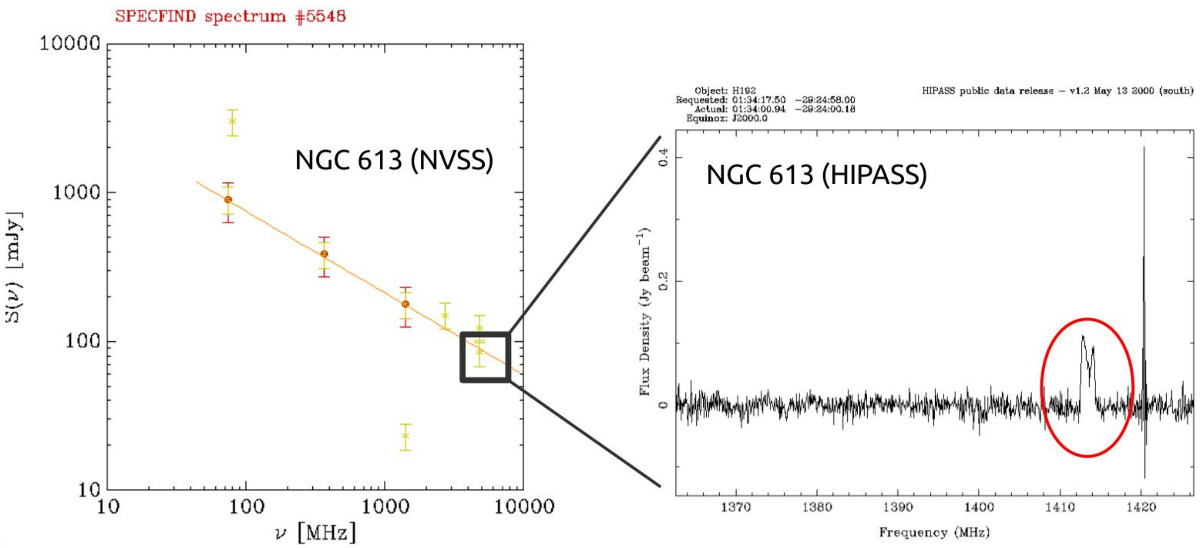
$$\kappa(\boldsymbol{x}) = \Sigma(\boldsymbol{x})/\Sigma_{\mathrm{crit}}$$
$$\Sigma(\boldsymbol{x}) \equiv \int_{-\infty}^{\infty} dl\, \rho(l, \boldsymbol{x}), \;\; \Sigma_{\mathrm{crit}} \equiv \frac{c^2 d_S}{4\pi G\, d_L\, d_{LS}}$$



Projected tracers: radio observations

Radio spectra:

- Power-law unless you're willing to resolve HI.
- <u>HI surveys</u>: spec-z but shallow.
- <u>Continuum surveys</u> (integrate over freq.): super deep, but no z!



Continuum surveys:

- Great to trace structure over huge volumes (*Siewert et al. 2019*, *Hale et al. 2017*, *Nusser et al. 2015*, *Lindsay et al. 2014*)
- Can be good for measuring f_{NL} (*Ferramacho et al. 2014*, *DA et al. 2015*)
- Good radial overlap with CMB lensing (*Allison et al. 2015*)

Projected tracers: radio observations

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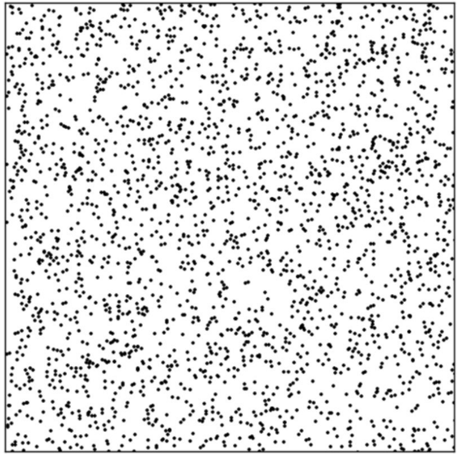
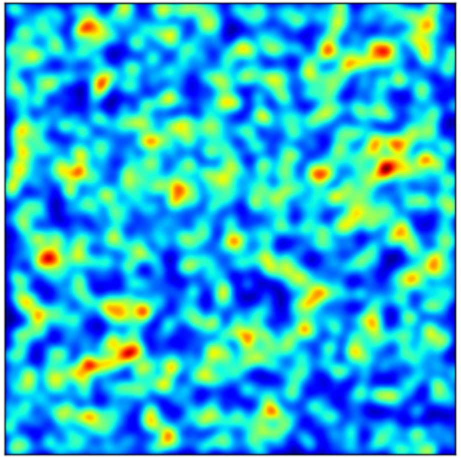
- <u>Continuum surveys</u> (integrate over freq.): super deep, but no z!
- <u>Intensity mapping</u> (integrate over area): spec-z but foregrounds.

[Battye et al. 2004](#)
[Masui et al. 2013](#)





Intensity mapping:

- Great at mapping large volumes
- But you lose all large-scale radial modes
- You also lose angular resolution, but that's OK

Projected tracers: radio observations

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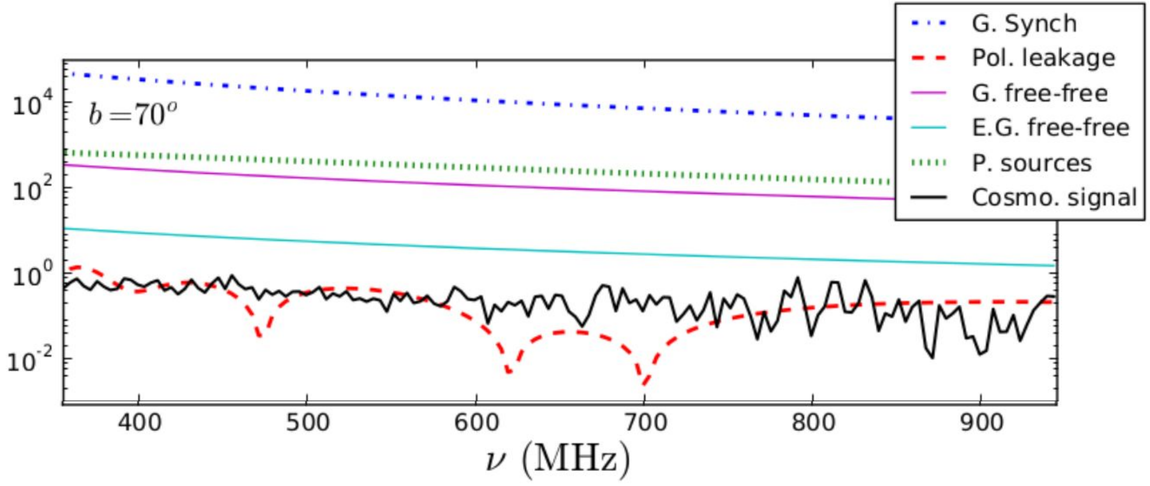

Battye et al. 2004
Masui et al. 2013

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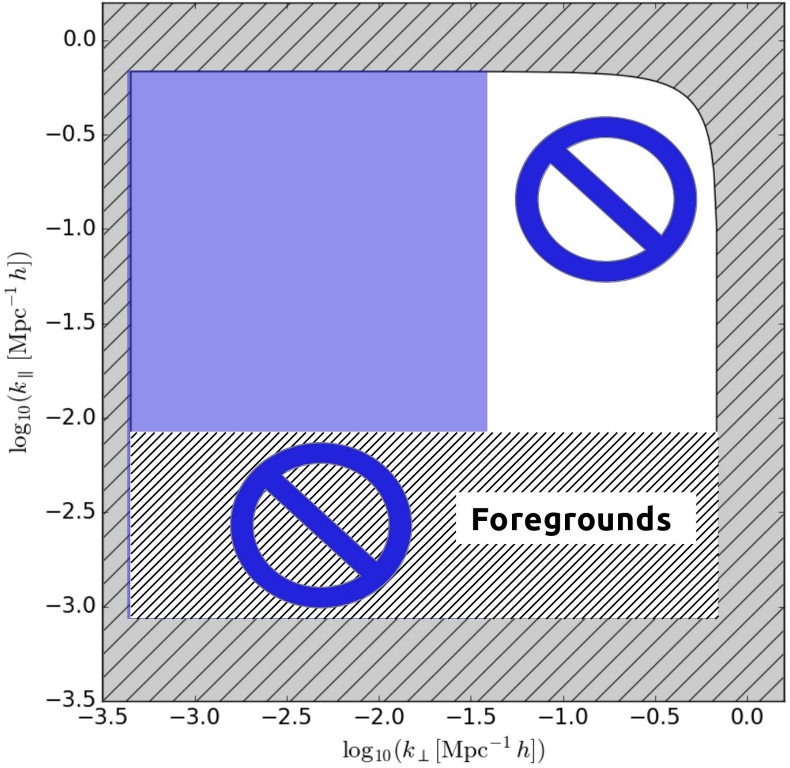

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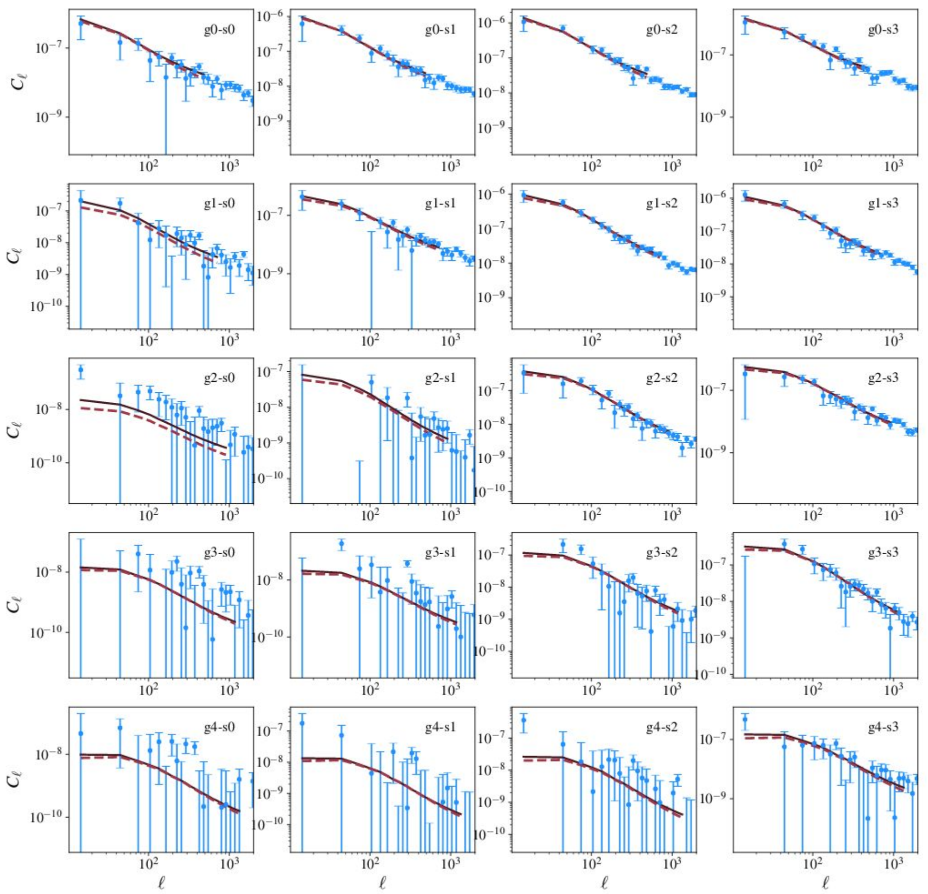
Projected tracers: power spectra



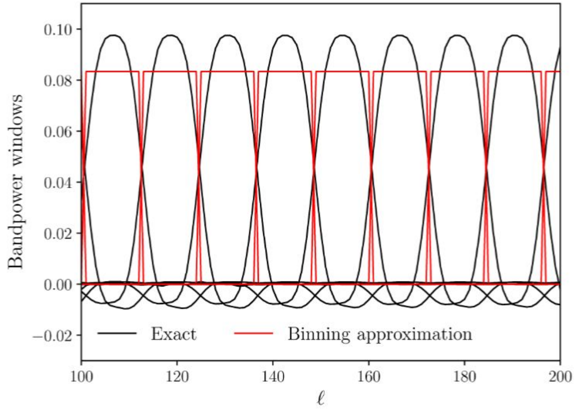
$$C_\ell^{\alpha\beta} \equiv \langle a_{\ell m}^{\alpha} a_{\ell m}^{\beta *} \rangle$$

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

DES Y1 shear x clustering

Projected tracers: power spectra

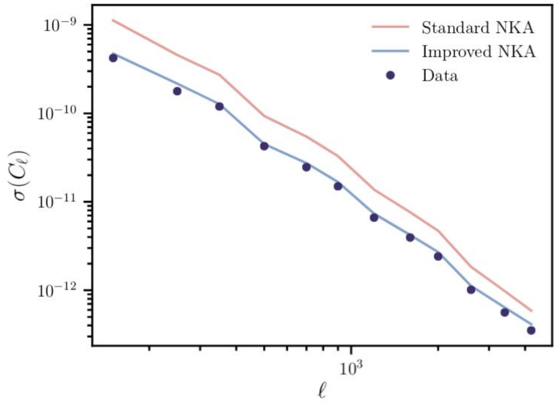
Estimation and interpretation of C_ℓs



- Estimating C_ℓs
- Mode-coupling
- Binning
- Contaminant cleaning
- Purification

Alonso et al. 2019

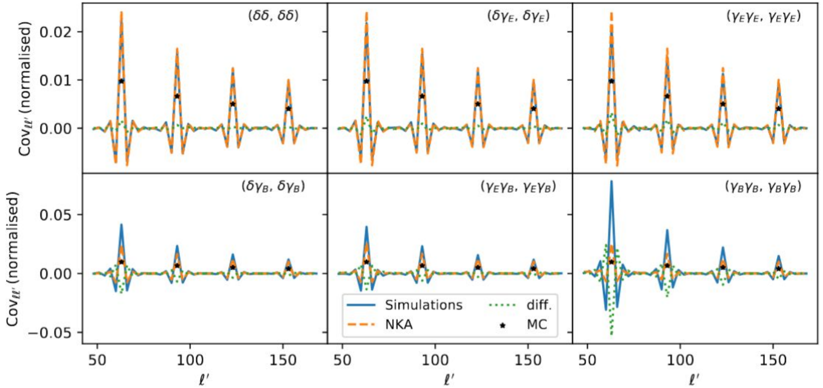
The particulars of cosmic shear



- Extreme mode-coupling.
- Inhomogeneous noise
- Noise bias
- Pixelization effects
- Improved covariances

Nicola et al. 2021

Power spectrum covariances



- Accurate/fast accounting for all forms of mode-coupling

Garcia-Garcia et al. 2019

NaMaster

build passing docs passing

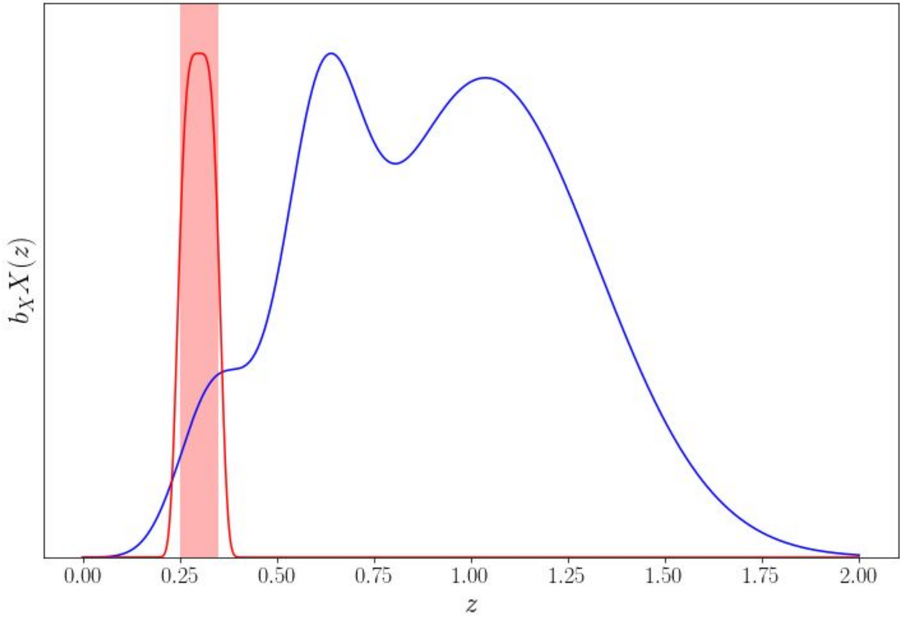
https://github.com/LSSTDESC/NaMaster

Part 1
Tomographic reconstruction

Tomographic reconstruction

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

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



Tomographic reconstruction

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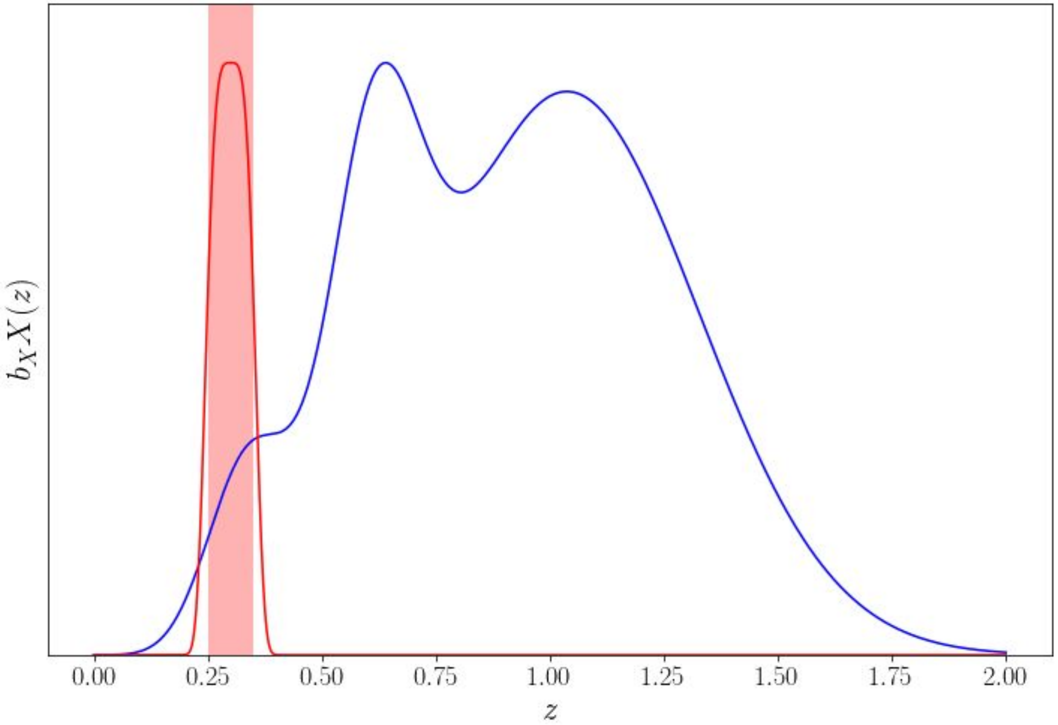
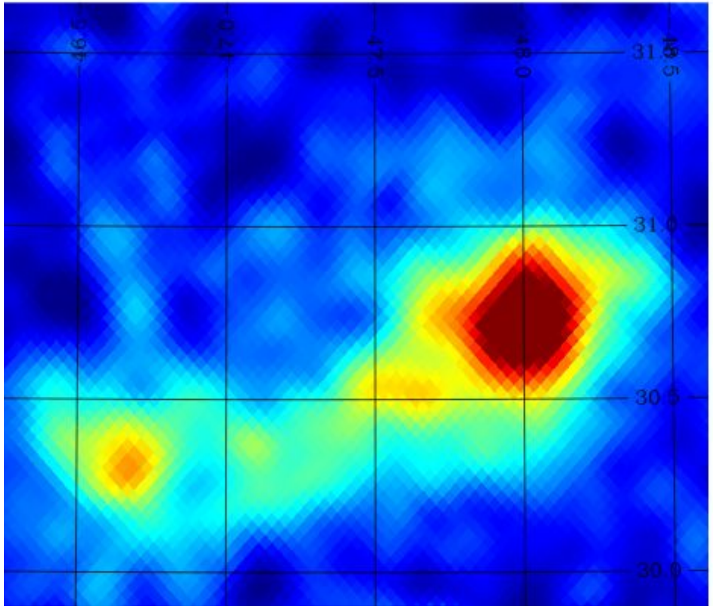


Tomographic reconstruction: tSZ

Koukoufilippas et al. 2019



Shapley supercluster Planck et al. 2015

Thermal SZ:

- Direct tracer of gas pressure.

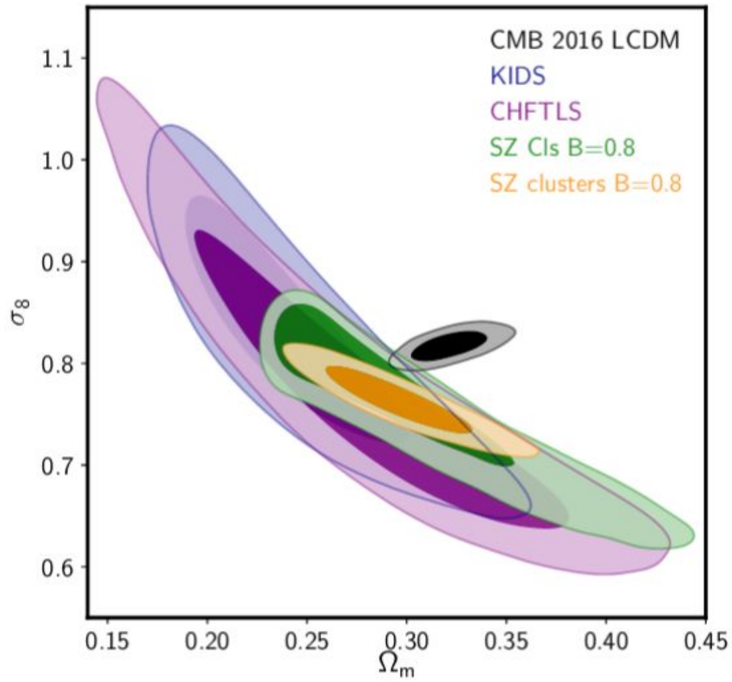
$$y(\hat{\mathbf{n}}) = \frac{\sigma_T}{m_e c^2} \int \frac{d\chi}{1+z} P_e(\chi\hat{\mathbf{n}})$$

- Projected tracer
- Indirect cluster mass proxy

Sunyaev & Zel'dovich 1970
Birkinshaw et al. 1998

1. Tomographic reconstruction

Koukoufilippas et al. 2019



Shapley supercluster

Planck et al. 2015

Thermal SZ:

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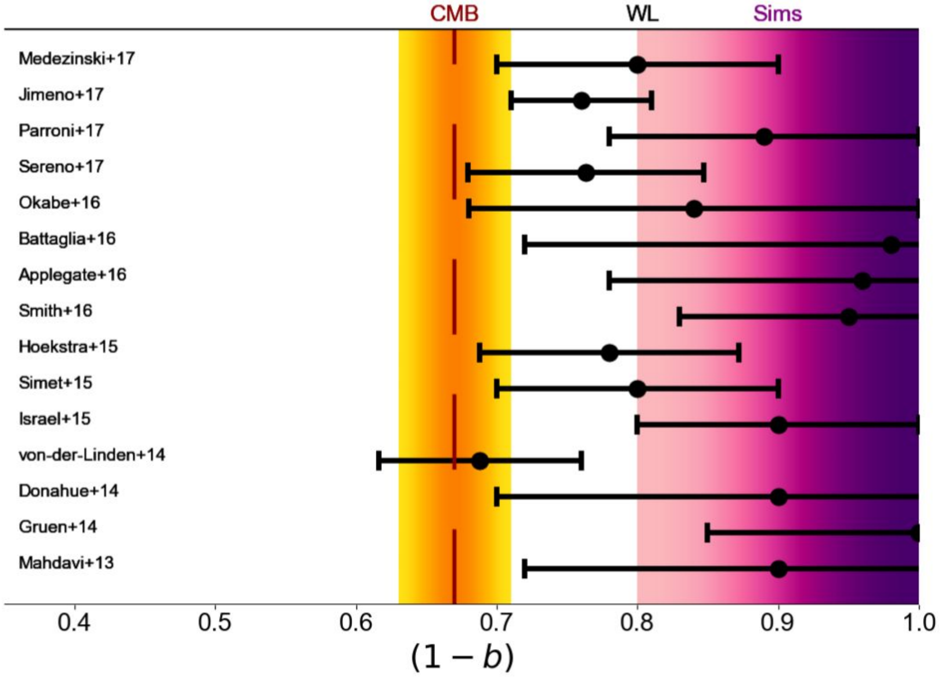
$$y(\hat{\mathbf{n}}) = \frac{\sigma_T}{m_e c^2} \int \frac{d\chi}{1+z} P_e(\chi \hat{\mathbf{n}})$$

- Projected tracer
- Indirect cluster mass proxy
- Ongoing σ_8 tension.
- Uncertainties in y(M) relation.

Sunyaev & Zel'dovich 1970
Birkinshaw et al. 1998

Tomographic reconstruction: tSZ

Koukoufilippas et al. 2019



Douspis et al. 2019

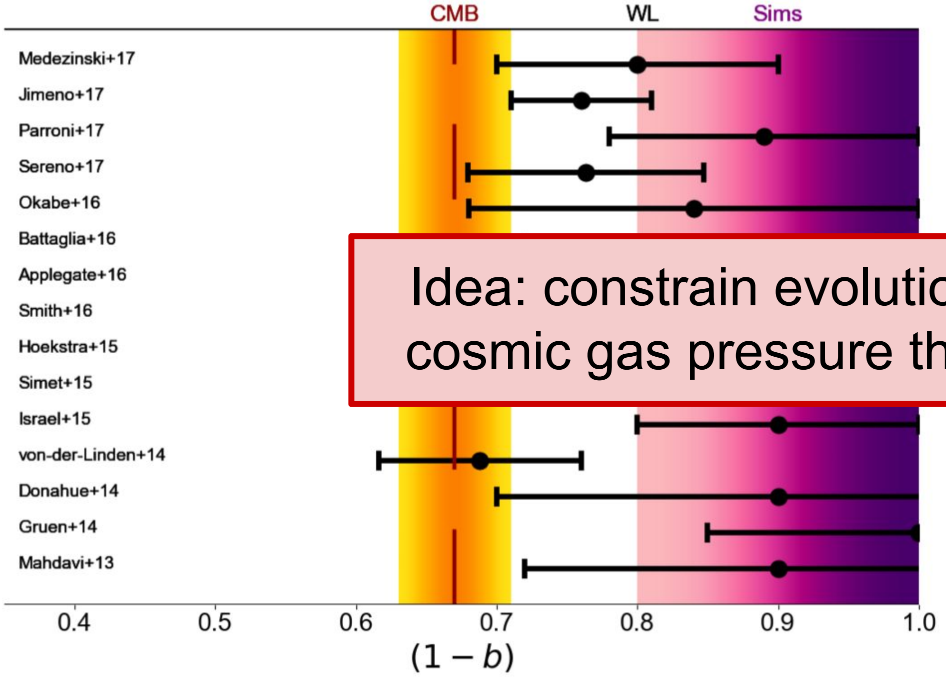
Thermal SZ:

- Direct tracer of gas pressure.
- Projected tracer
- Indirect cluster mass proxy.
- Ongoing σ_8 tension.
- Uncertainties in y(M) relation.
- Hydrostatic mass bias.

$$M_X = (1-b)M$$

Tomographic reconstruction: tSZ

Koukoufilippas et al. 2019



Douspis et al. 2019

Thermal SZ:

- Direct tracer of gas pressure.
- y.
- ion.
- Ongoing σ_8 tension.
- Hydrostatic mass bias.

Idea: constrain evolution of hydrostatic bias and cosmic gas pressure through cross-correlations.

$$M_X = (1-b)M$$

Tomographic reconstruction: tSZ

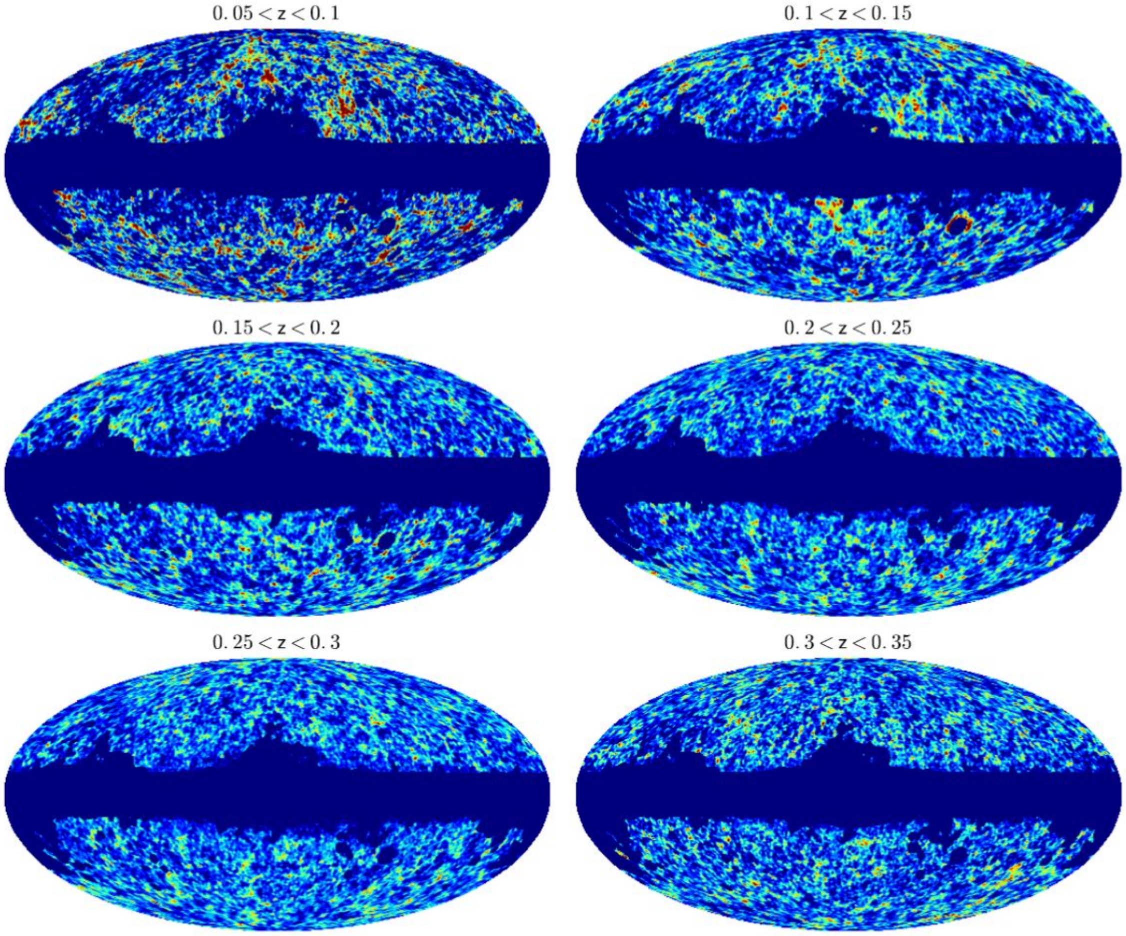
Koukoufilippas et al. 2019

2MPZ and WIxSC

- Low-z photometric surveys.
- **2MPZ**:
  2MASS+WISE+SuperCOSMOS
  ~1M sources, z~0.1, σ_z~0.013
- **WIxSC**:
  WISE+SuperCOSMOS
  ~20M sources, z<0.4, σ_z~0.03
- Super high-density (cf. redMaGiC: 700k sources at z~0.5).

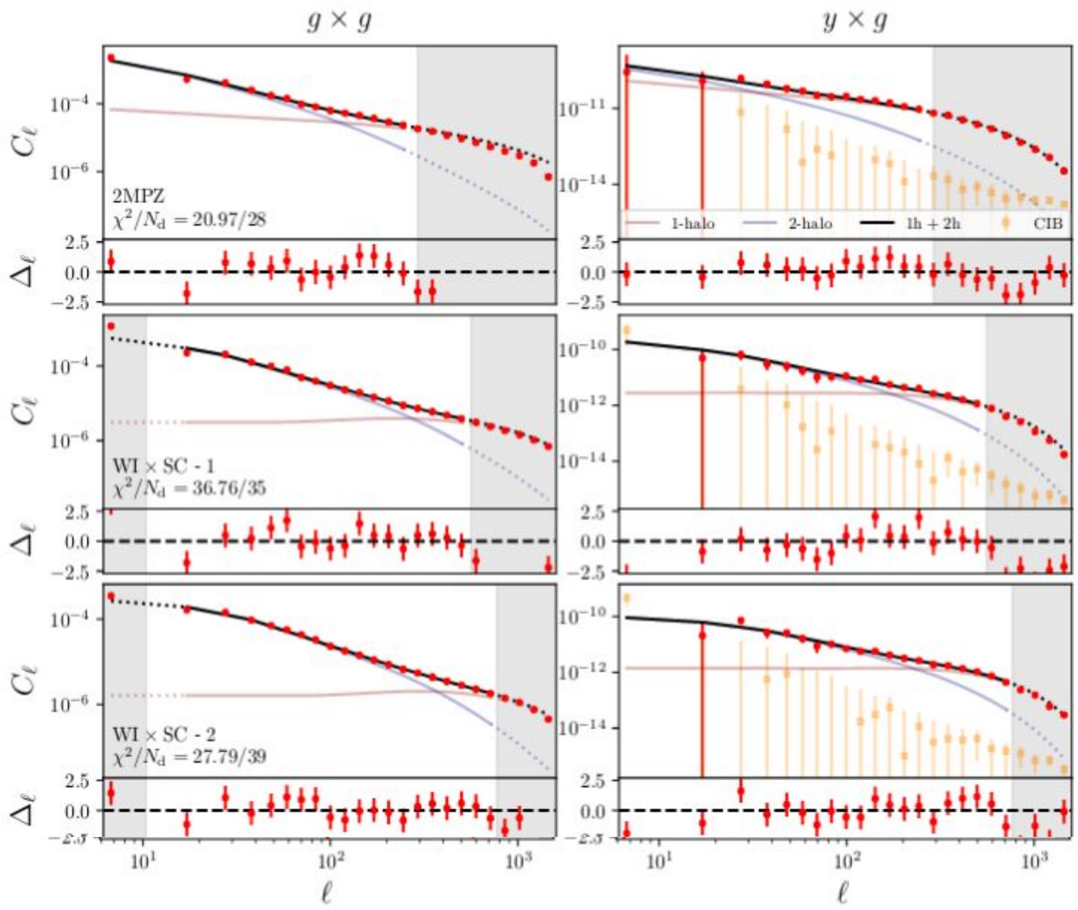
Bilicki et al. 2014
Bilicki et al. 2016
Peacock & Bilicki 2018

x-corr with **Planck** Compton-y map
Planck et al. 2015



Tomographic reconstruction: tSZ

Koukoufilippas et al. 2019



Measured and modelled g-g and g-tSZ correlations.

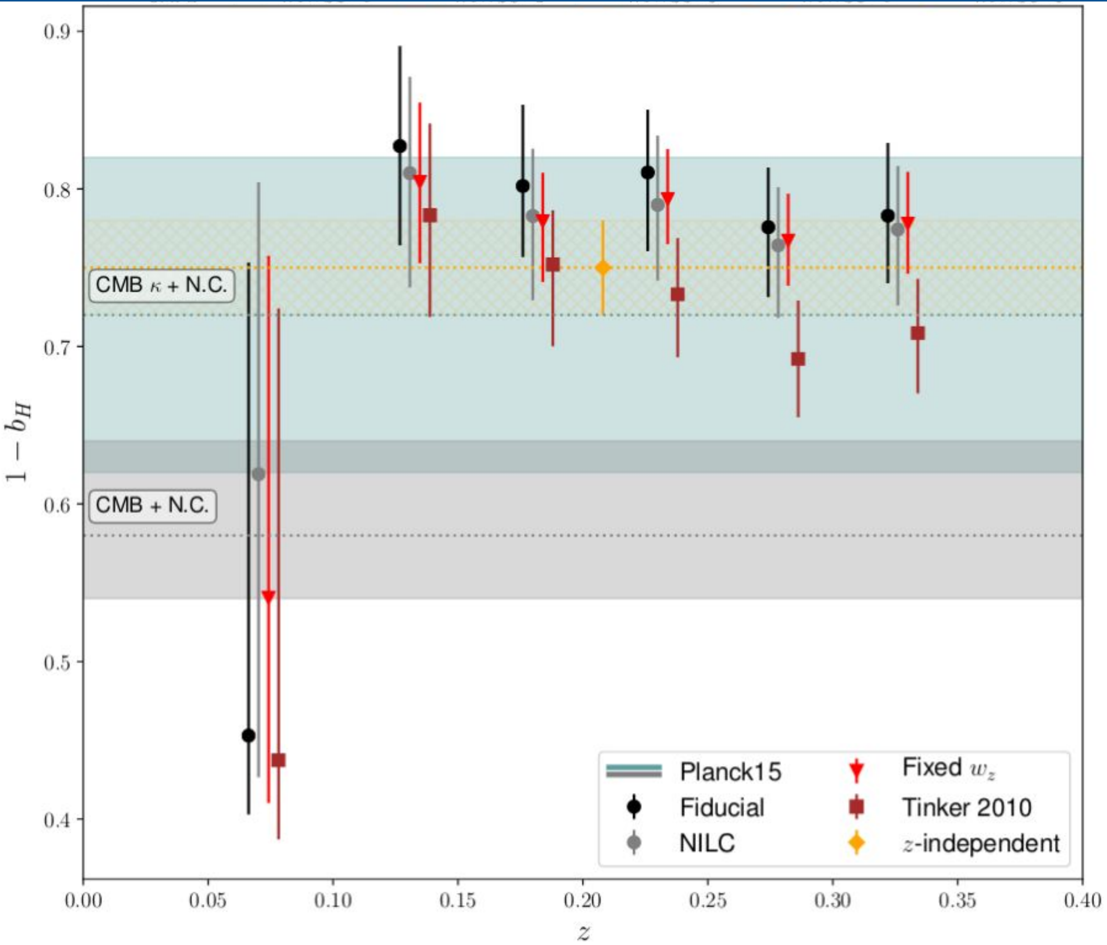
$$C_\ell^{gg} \propto b_g^2$$

$$C_\ell^{gy} \propto b_g \left(1 - b_H\right)^\alpha$$
$$\propto b_g \langle bP_e \rangle$$

Tomographic reconstruction: tSZ

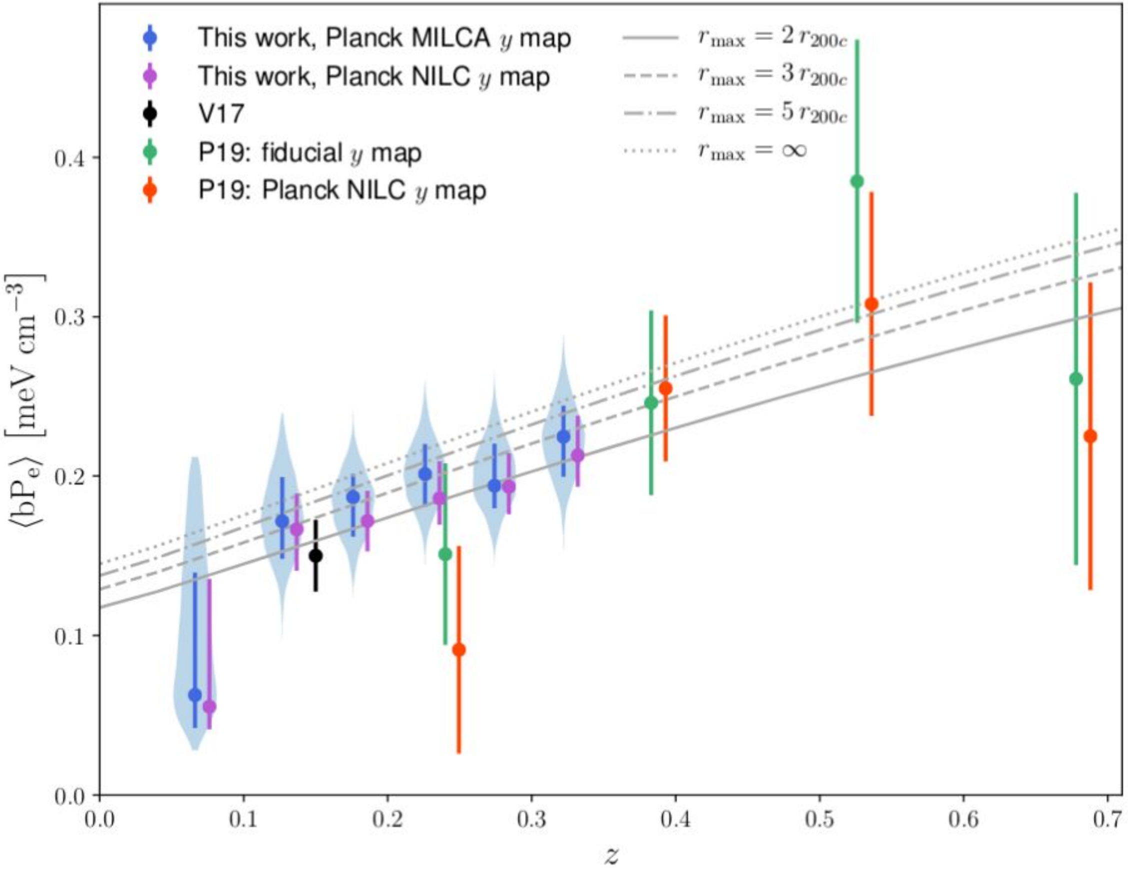
Koukoufilippas et al. 2019

(1-b) ~ 0.78
compatible with hydro sims



Tomographic reconstruction: tSZ

Koukoufilippas et al. 2019

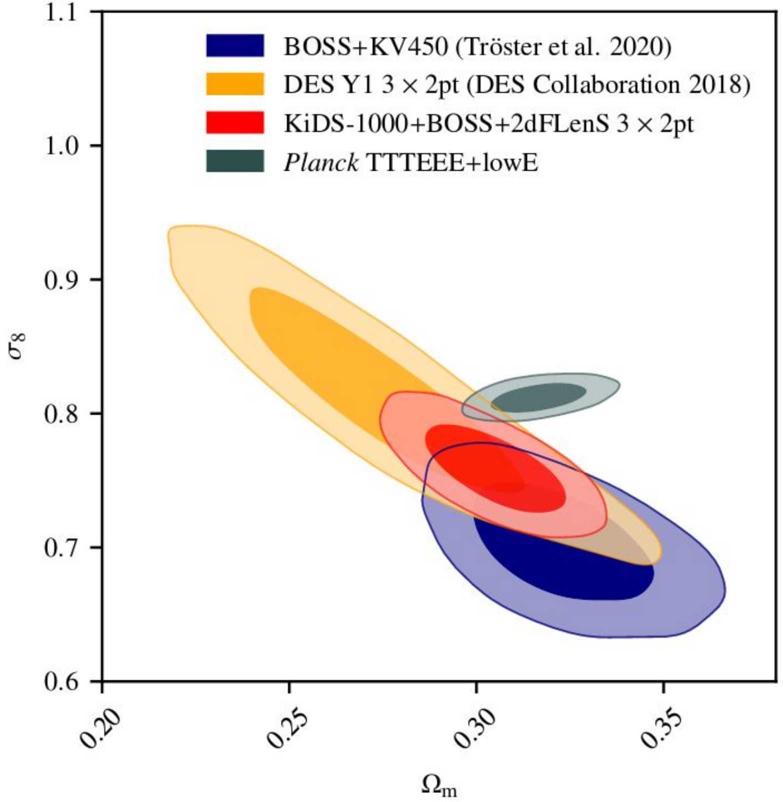


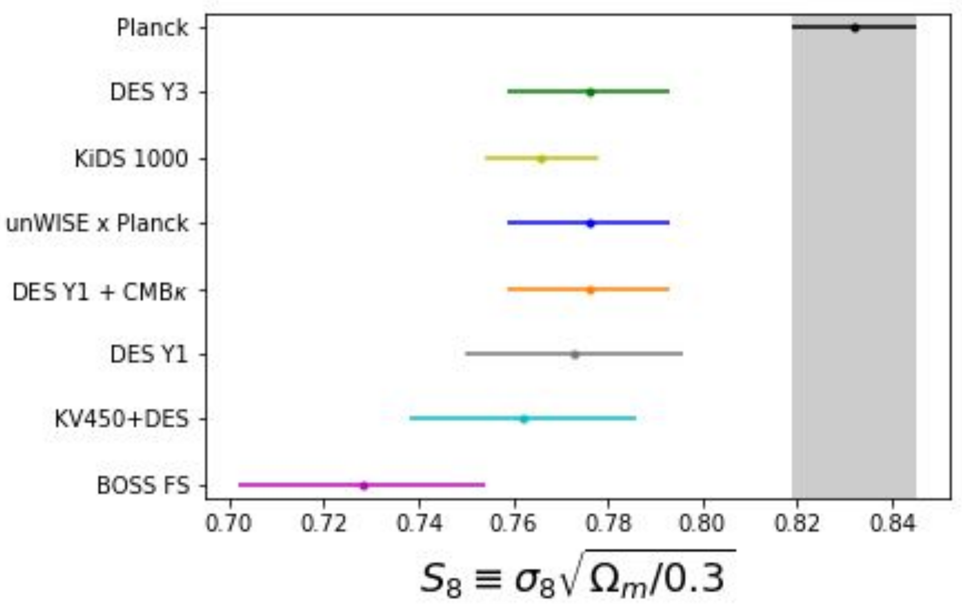
Tightest constraints on mean pressure evolution at low-z.

Tomographic reconstruction: growth

[Garcia-Garcia et al. 2021](#)

The S_8 conundrum





[Troster et al. 2020](#)
[Abbott et al. 2017](#)
[Abbott et al. 2018](#)
[Joudaki et al. 2019](#)

[Heymans et al. 2020](#)
[Krolewski et al. 2021](#)
[Abbott et al. 2021](#)

Tomographic reconstruction: growth

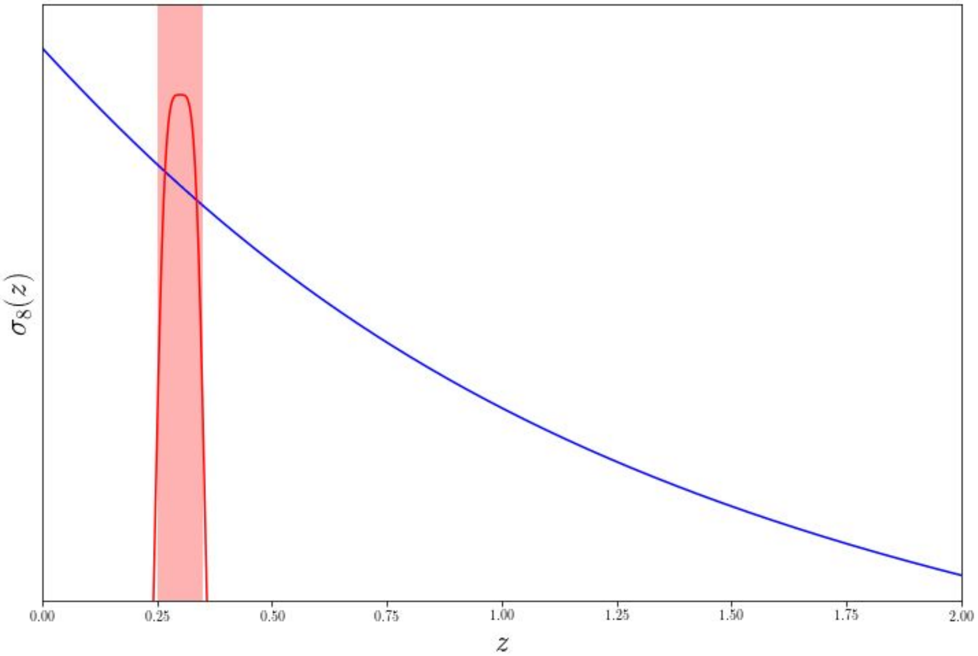
Garcia-Garcia et al. 2021

3x2pt as tomography

- Cosmic shear traces amplitude of perturbations directly. **What do we need clustering for?**

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

- Photometric clustering is not great for BAO… but it can help reconstruct growth history!



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?

Tomographic reconstruction: growth

Garcia-Garcia et al. 2021

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- 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

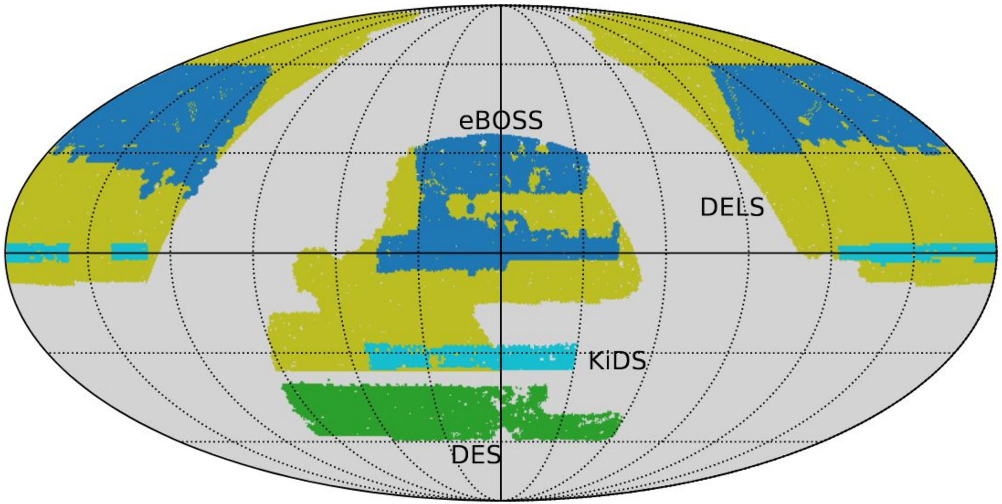
Growth reconstruction: the data

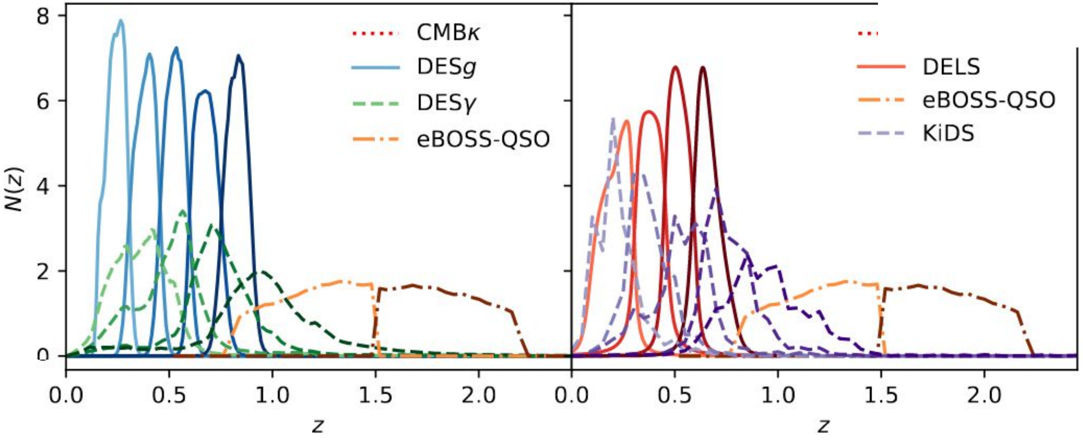
Shear:

- DES Y1
- KiDS-1000
- Planck CMB lensing

Clustering:

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





South Data (SD) North Data (ND)

CMB lensing:

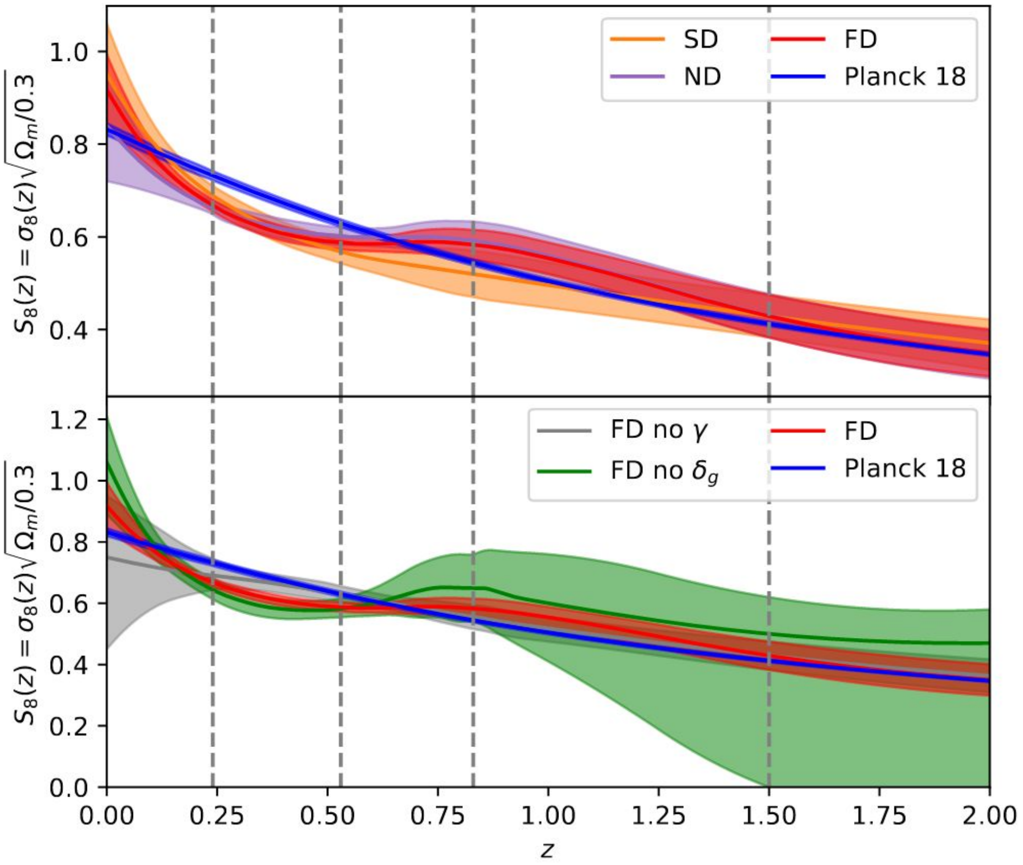
- Planck 2018 convergence map

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: results



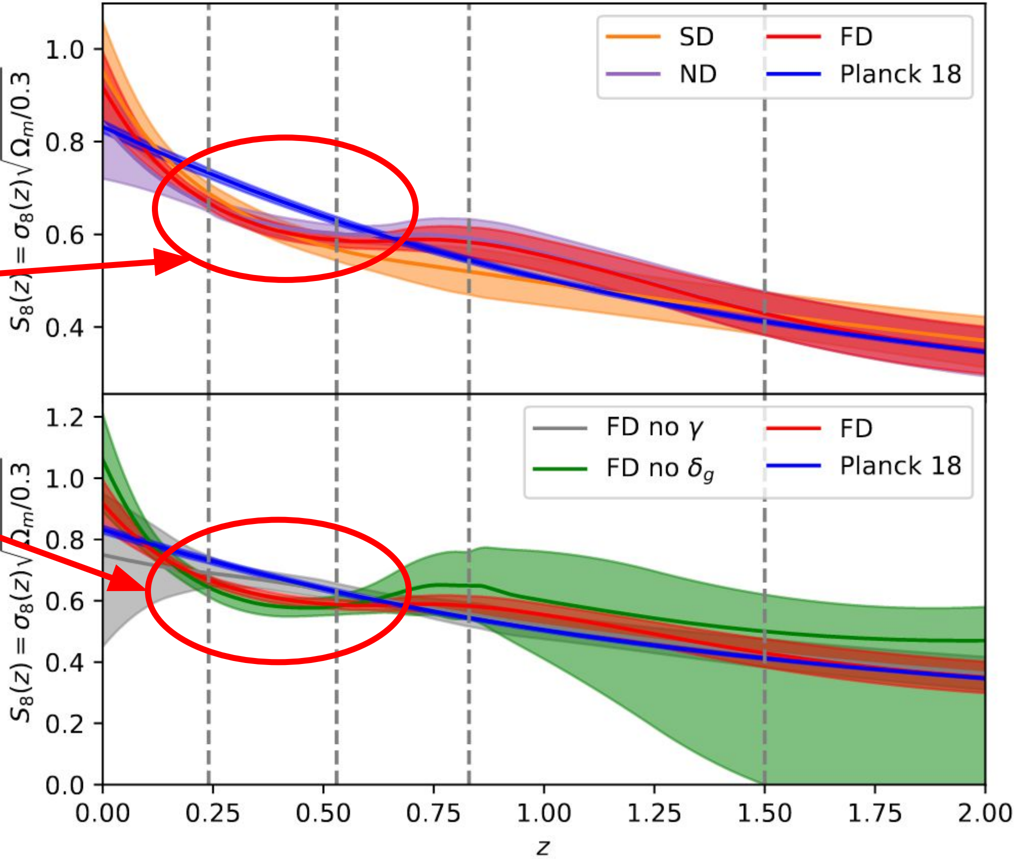
Tomographic reconstruction: growth

Garcia-Garcia et al. 2021

Growth reconstruction: results

Results:

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



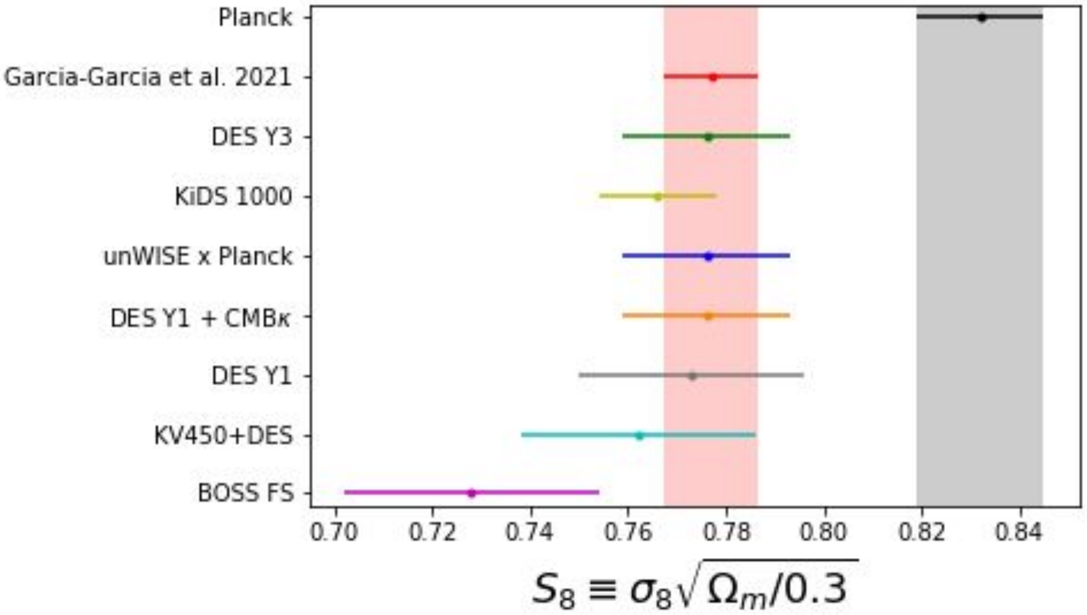
Tomographic reconstruction: growth

Garcia-Garcia et al. 2021

Growth reconstruction: ΛCDM constraints

Results:

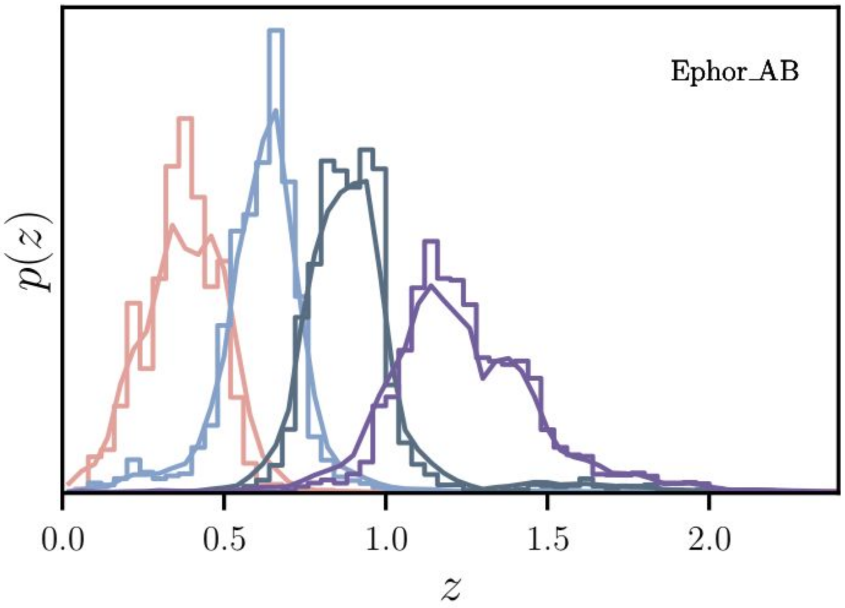
- ΛCDM is an excellent fit to the low-z data
- North and South data compatible
- 3.5σ tension with Planck on S_8
- Driven by cosmic shear data



Part 2
Calibrating N(z)

N(z) calibration

Nicola et al. 2020



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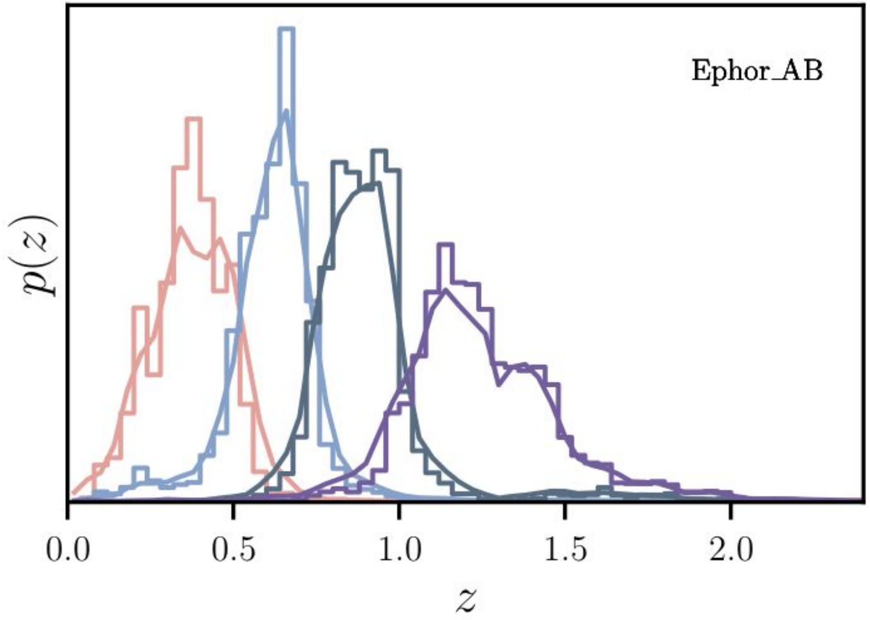

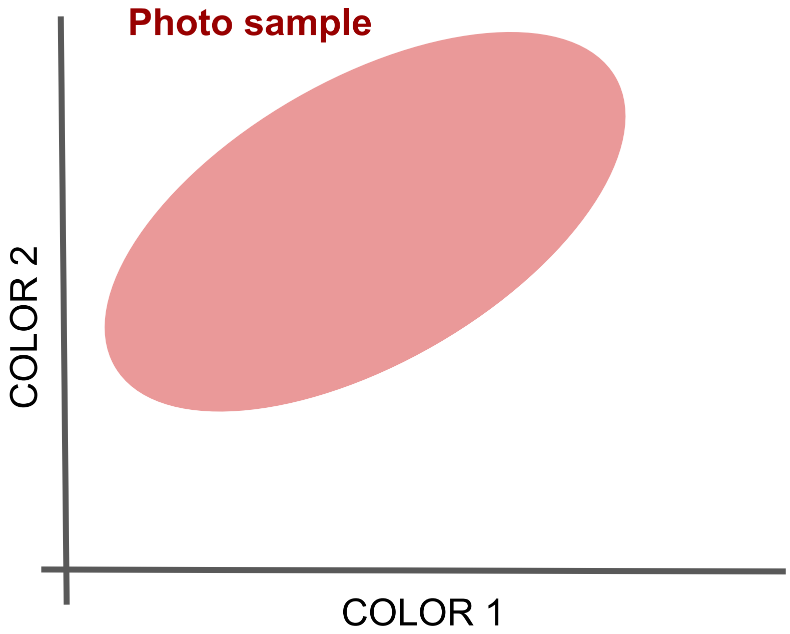

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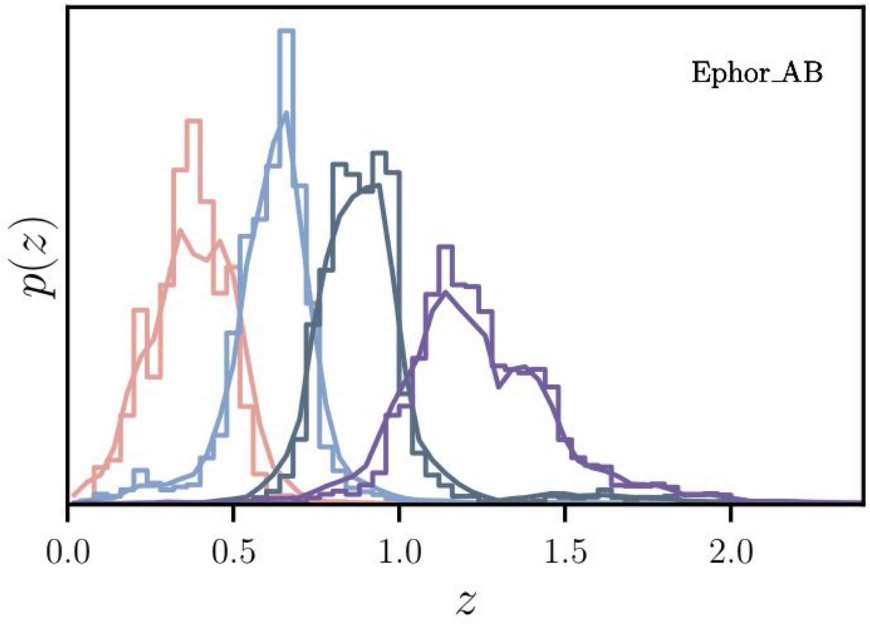

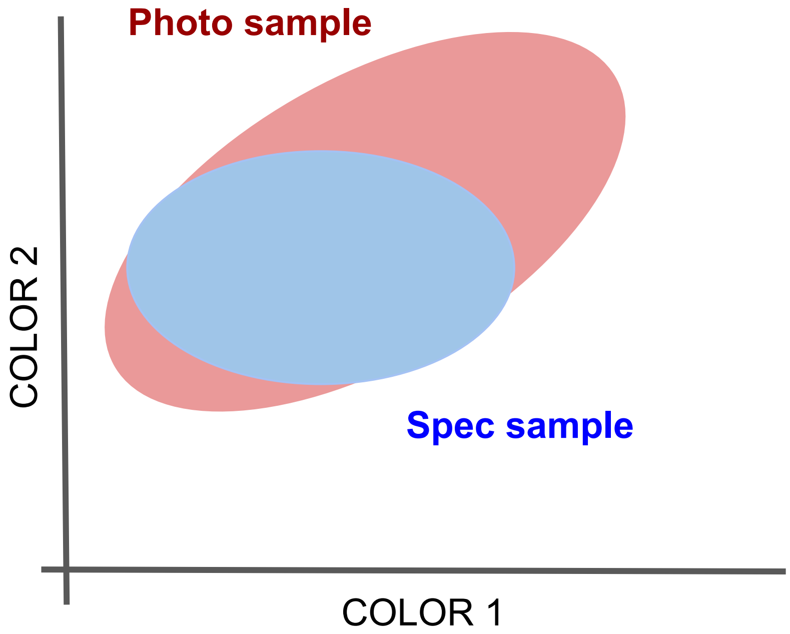

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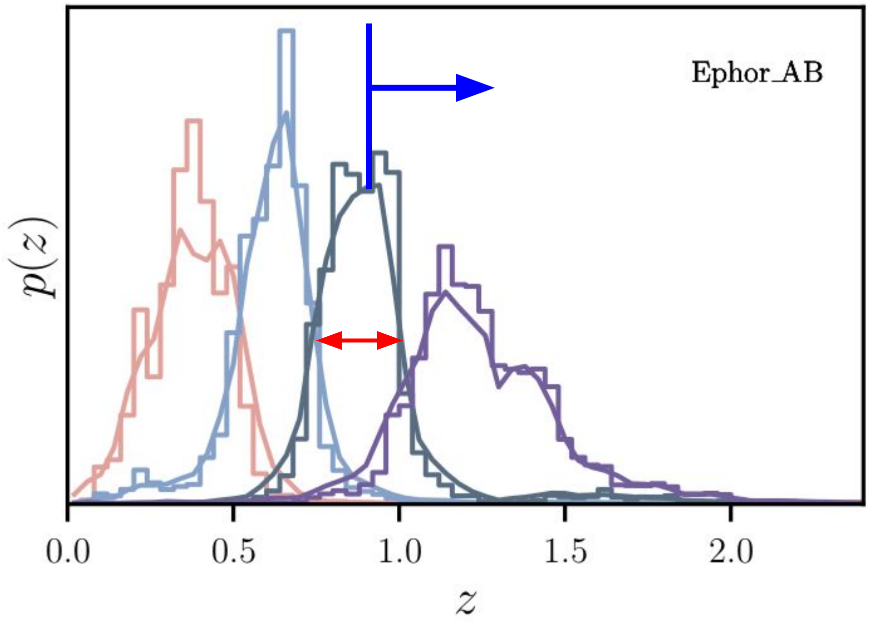
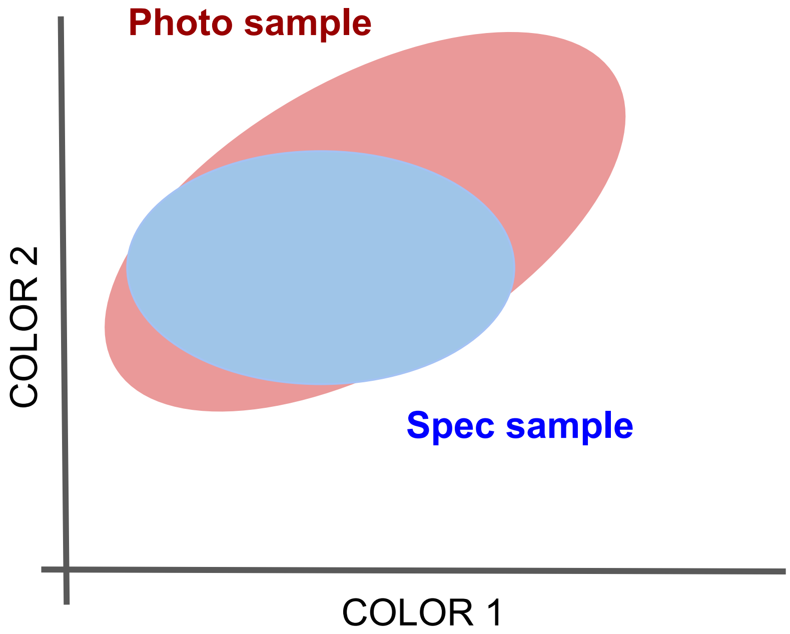


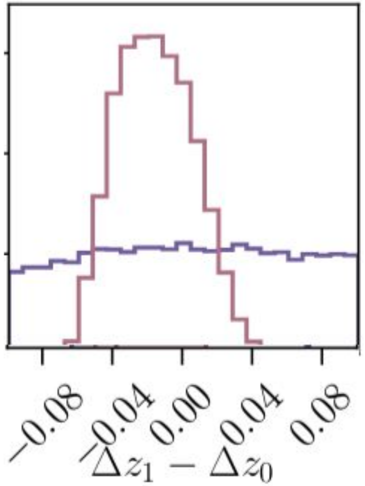


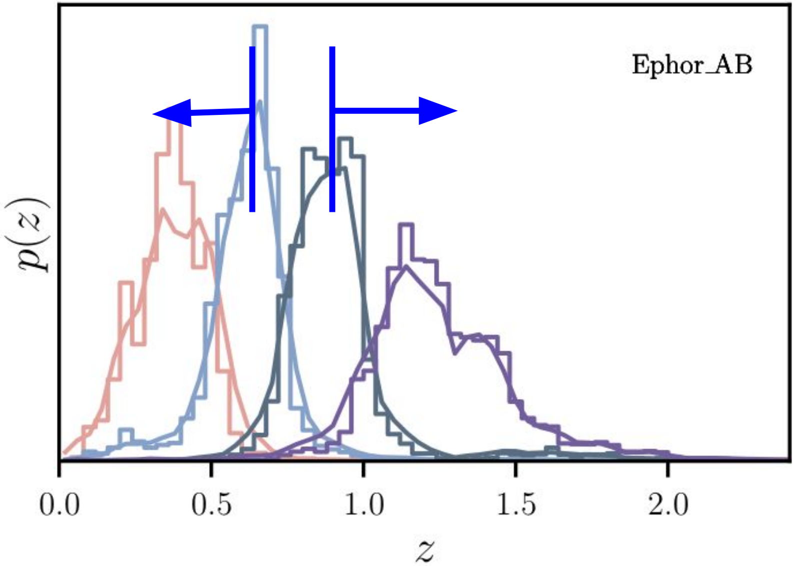
N(z) calibration

Nicola et al. 2020

Self-calibration:

- Cross-bin correlations are sensitive to the overlap between N(z)s
- Constrain relative bin separations!



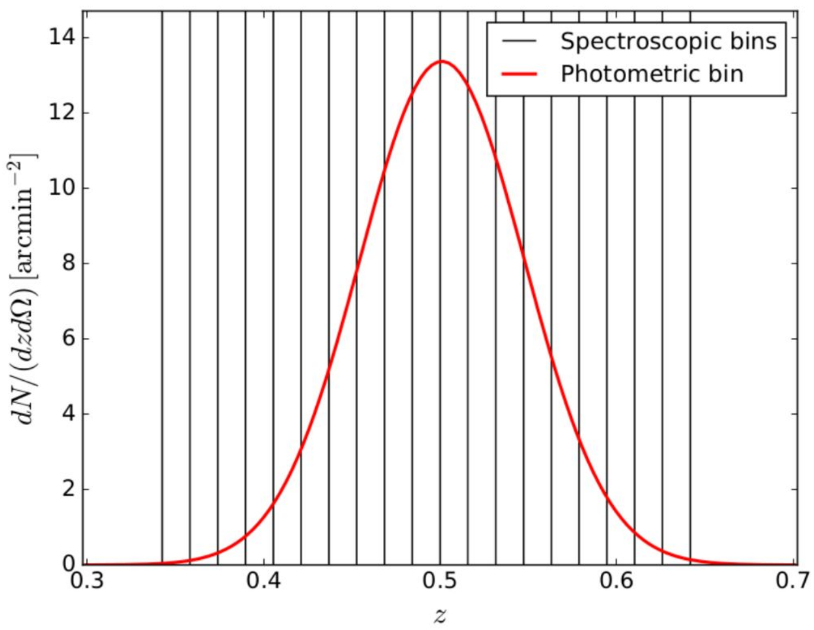


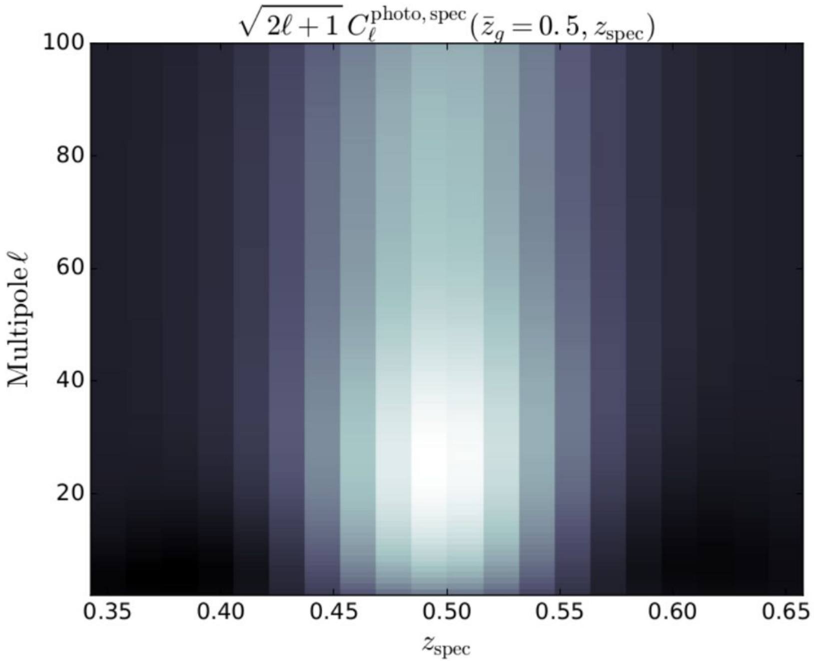
See also Schaan et al. 2020

N(z) calibration

Cross-correlation redshifts:

- x-corr with spec sample proportional to N(z)
- Spec sample does not have to be representative!
  Just lie at the same redshift





N(z) calibration

Guandalin et al. 2021

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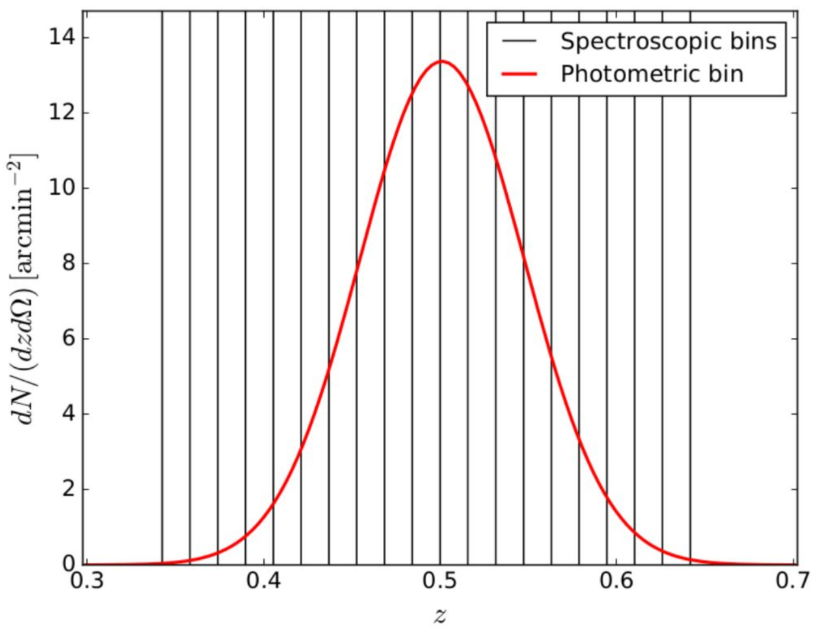
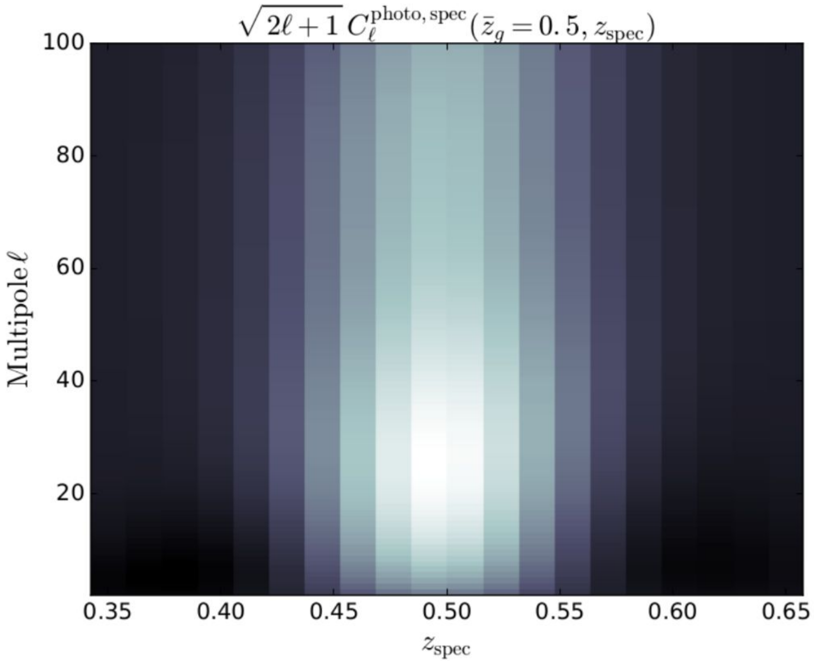
- **Can we do this with 21cm?**





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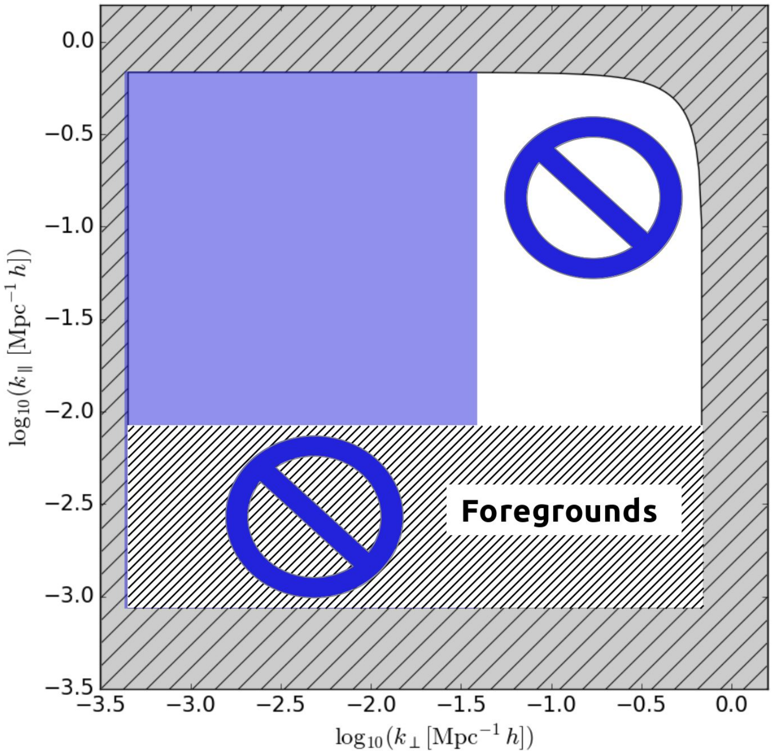

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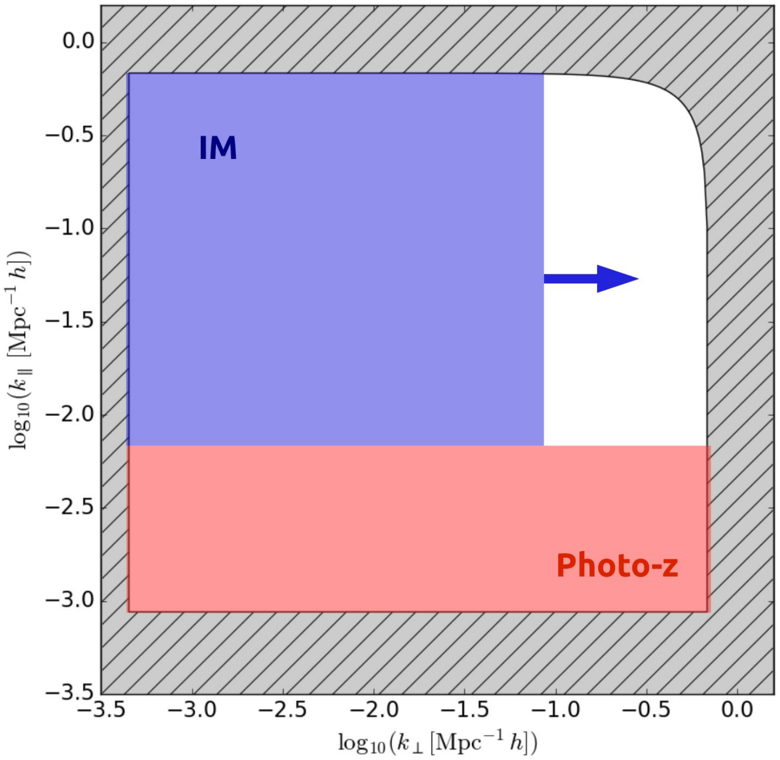
$$\langle \delta_g(k_g) \delta_{\rm HI}(k_{\rm HI}) \rangle \propto \delta^D(k_{\rm HI} + k_g)$$



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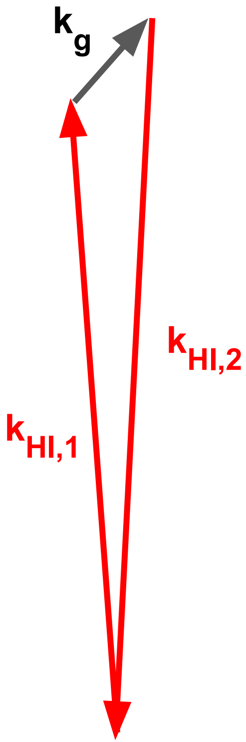
$$\langle \delta_g(k_g)\delta_{\rm HI}(k_{\rm HI,1})\delta_{\rm HI}(k_{\rm HI,2})\rangle$$
$$\propto \delta^D(k_{\rm HI,1} + k_{\rm HI,2} + k_g)$$



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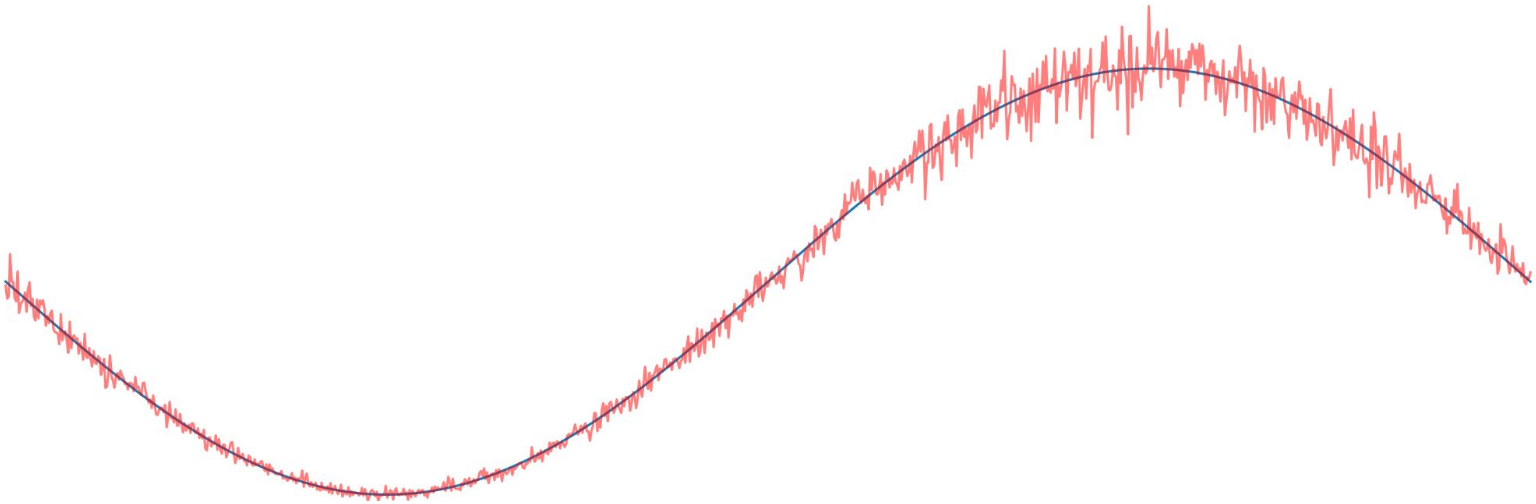

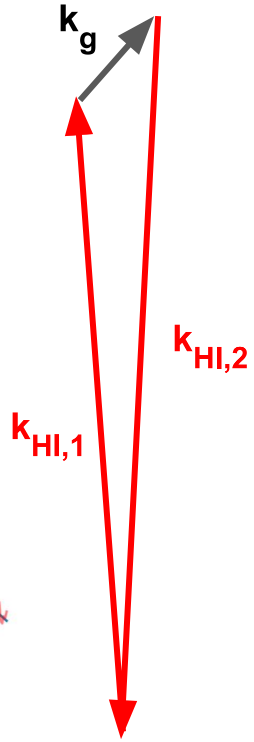

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Guandalin et al. 2021

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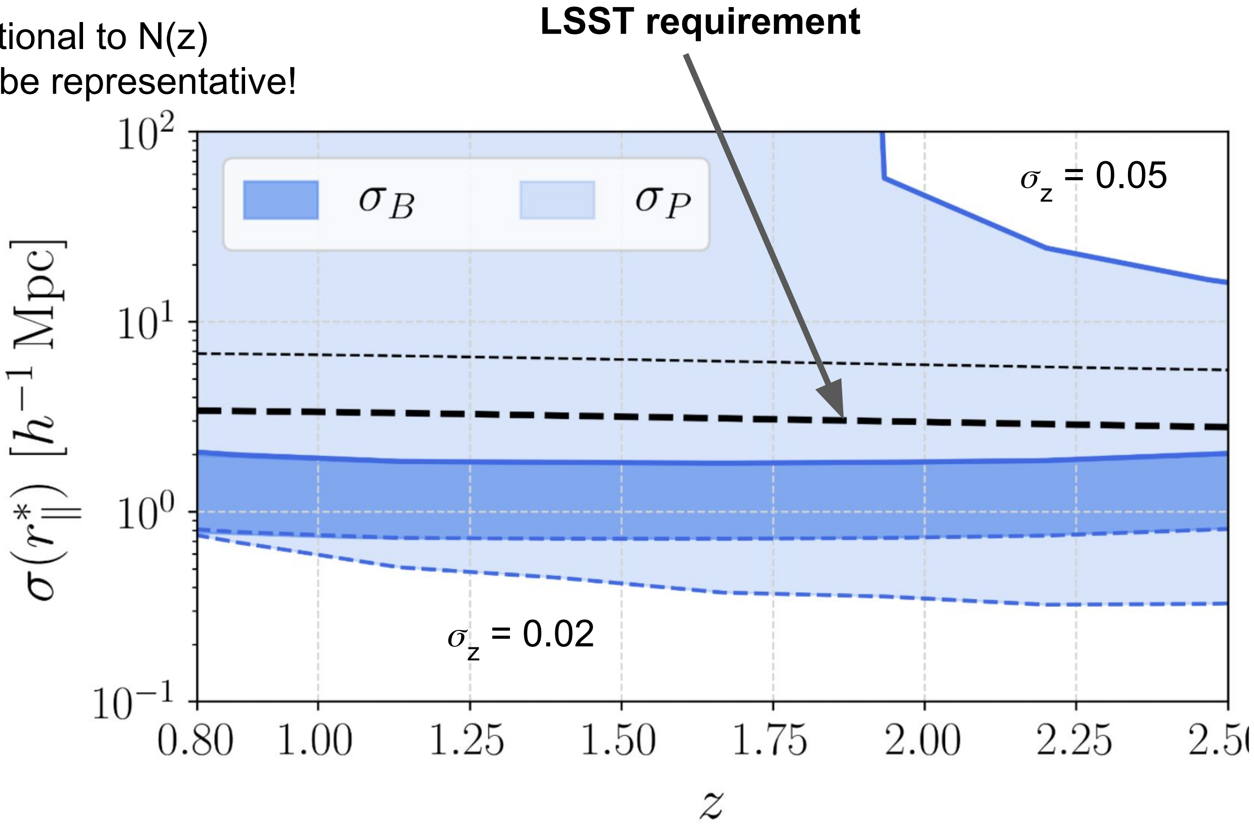

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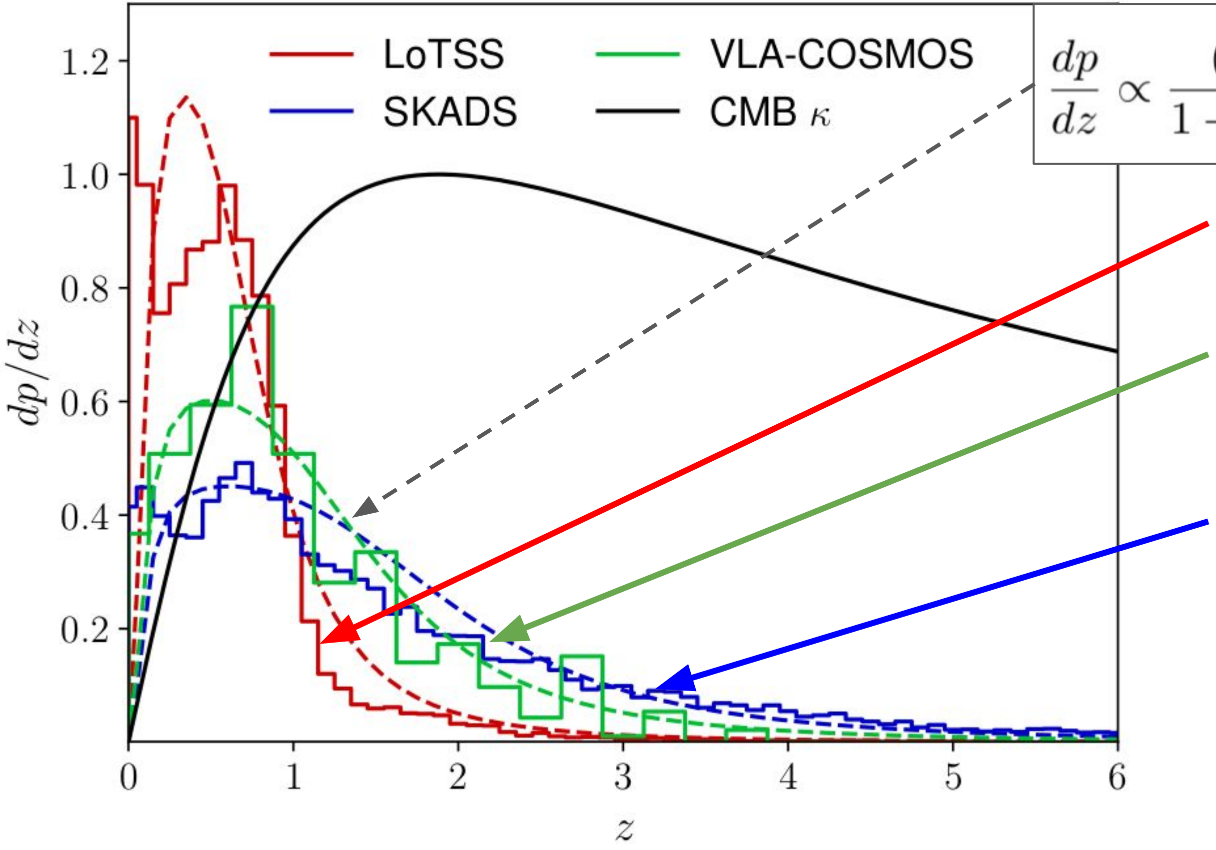
  Solution: bispectra

Similar principle:

- f_{NL} from g x HI x HI squeezed limit
- Clustering redshifts with Lya forest
- Reconstruction of super-sample density fluctuations

N(z) calibration: CMB lensing

Alonso, Bellini et al. 2021



$$\frac{dp}{dz} \propto \frac{(z/z_0)^2}{1+(z/z_0)^2}\,\frac{1}{1+(z/z_{\rm tail})^\gamma}$$

Direct measurement from PanSTARRs photo-zs.

Spec-z data from COSMOS field (different sample, ~500 galaxies).

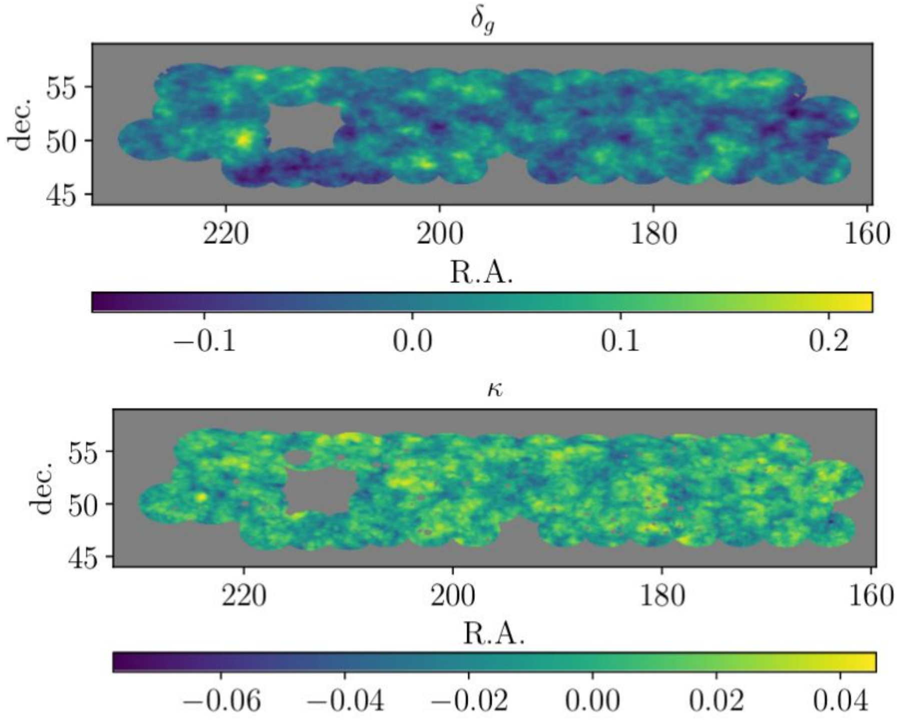
Prediction from SKA simulation (S-cubed).

N(z) calibration: CMB lensing

Alonso, Bellini et al. 2021

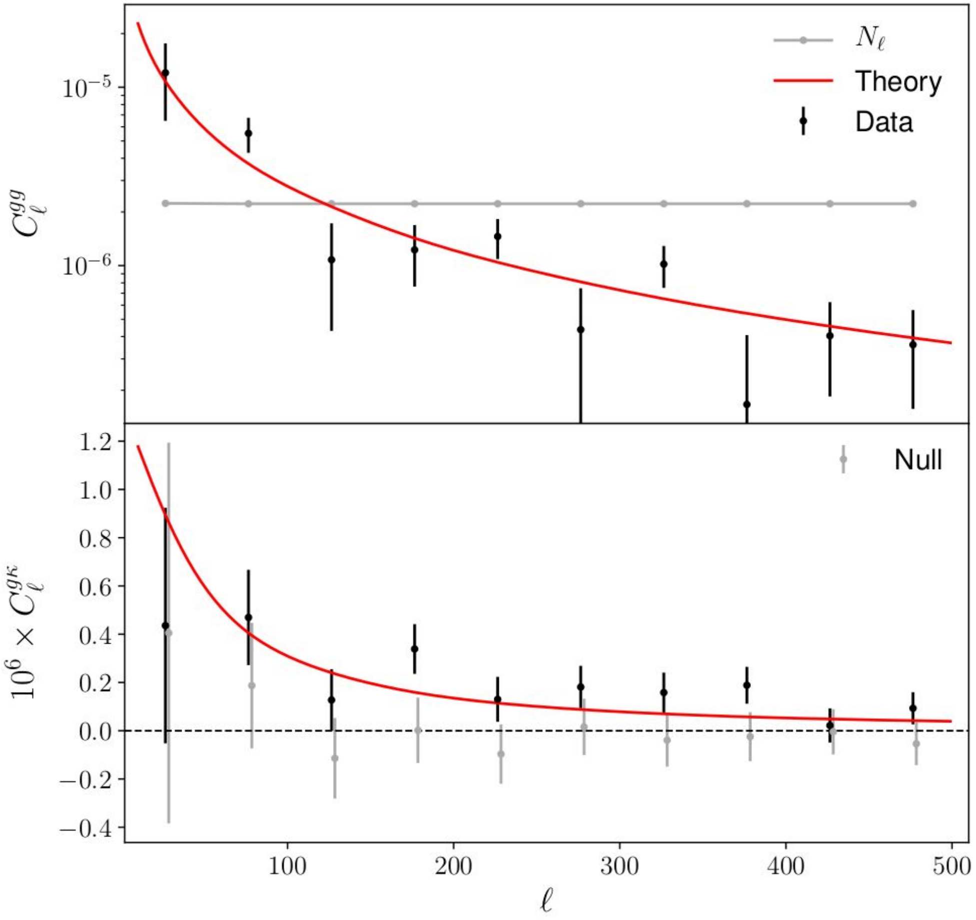
The LOFAR Two-metre Sky Survey

- Cont. Survey at ~150 MHz.
- DR1: ~424 deg2, ~320k objects @ I > 2mJy (as in Siewert et al.)
- Photo-zs from PanSTARRs matches (++)
- Large uncertainties over high-redshift tail.
- Think of a faint LSST sample with bad photo-zs and lots of outliers.
- Good overlap with CMB-κ kernel.
- Cross-correlation with Planck 2018 convergence maps.



N(z) calibration: CMB lensing

Alonso, Bellini et al. 2021



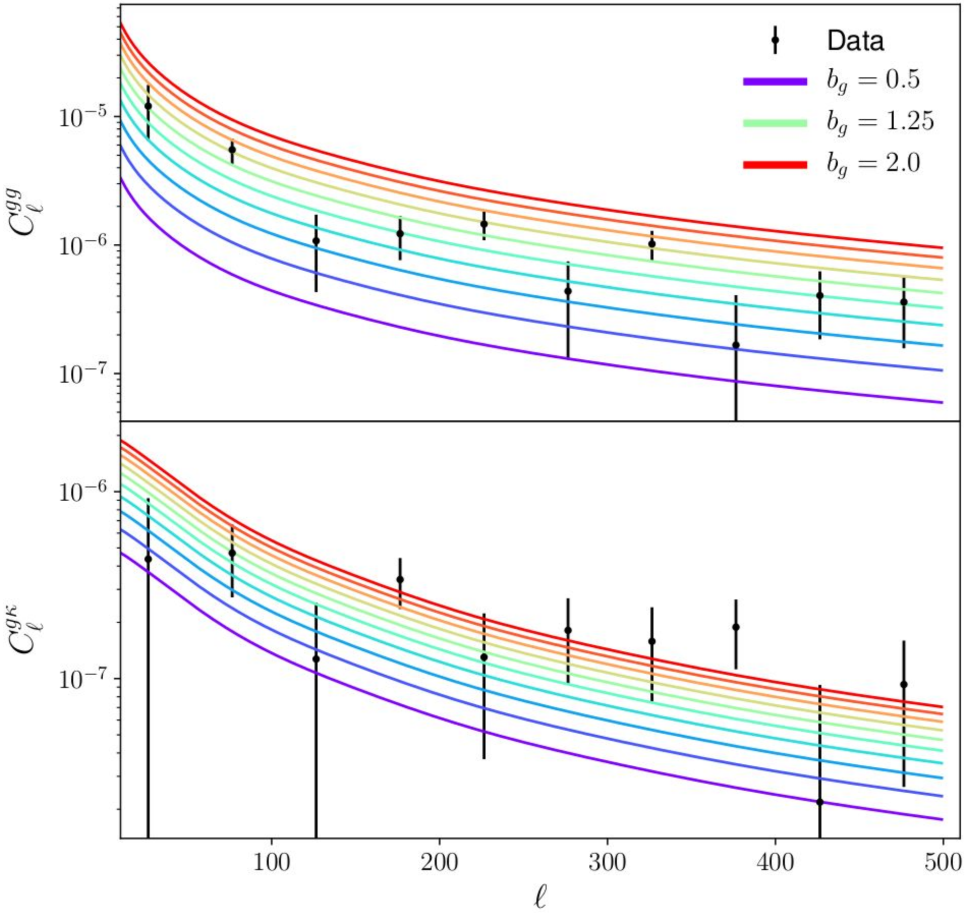
~ 5σ detection of x-correlation.

Main factors affecting g-g and g-κ amplitudes:

- Galaxy bias
- N(z) width/tail.
- σ_8

N(z) calibration: CMB lensing

Alonso, Bellini et al. 2021



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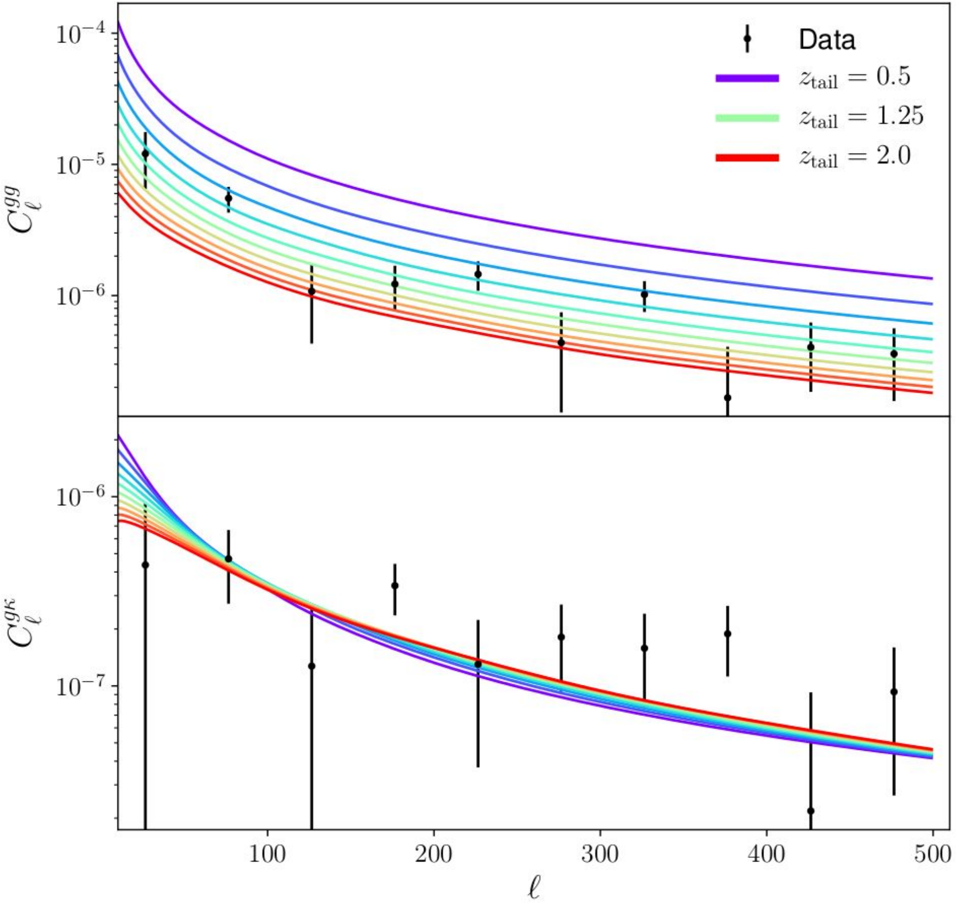
Alonso, Bellini et al. 2021



~ 5σ detection of x-correlation.

Main factors affecting g-g and g-κ amplitudes:

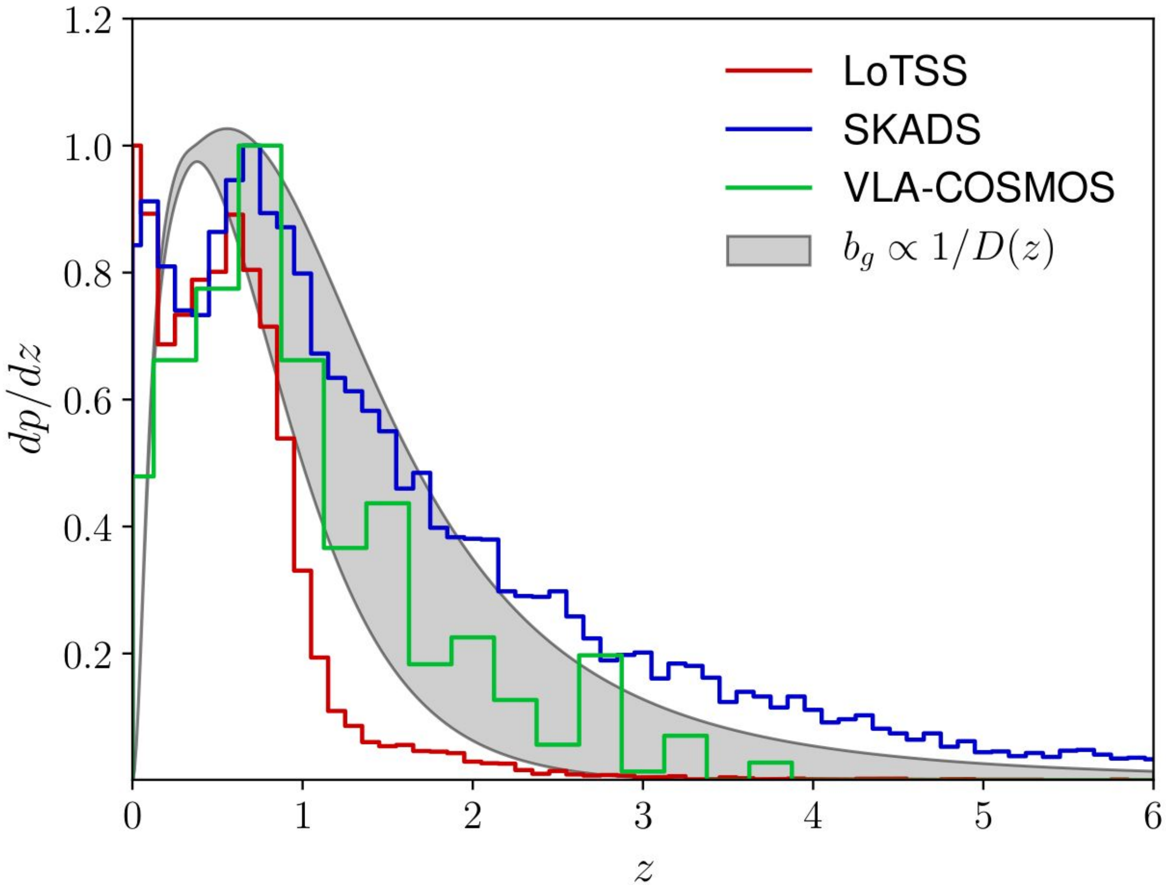
- Galaxy bias
- **N(z) width/tail.**
- σ_8

You can constrain z_{tail}!

Also, CMB-κ x-corr quite insensitive to width-like systematics.

N(z) calibration: CMB lensing

Alonso, Bellini et al. 2021



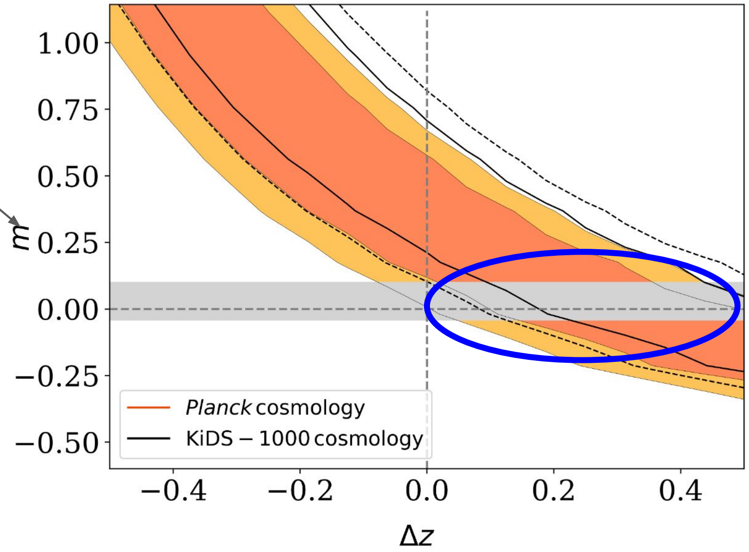
N(z) calibration: CMB lensing

Robertson et al. 2021

Same logic for κxγ (especially at high-z)

Naomi Robertson - Cambridge

Planck/ACT x KiDS



Part 3
Detecting new effects

Detecting new effects

$$a_{\ell m}^1 = s_{\ell m}^1 + n_{\ell m}^1 \qquad s^1 << n^1$$

$$a_{\ell m}^2 = s_{\ell m}^2 + n_{\ell m}^2 \qquad s^2 >> n^2$$

Low S/N

High S/N

Detecting new effects

$$a^1_{\ell m} = s^1_{\ell m} + n^1_{\ell m} \qquad s^1 << n^1$$

Low S/N

$$a^2_{\ell m} = s^2_{\ell m} + n^2_{\ell m} \qquad s^2 >> n^2$$

High S/N

$$(S/N)^{11}_\ell \simeq \frac{C^{11}_\ell}{N^1_\ell}\sqrt{\ell}$$

Detecting new effects

$$a^1_{\ell m} = s^1_{\ell m} + n^1_{\ell m} \qquad s^1 << n^1$$ **Low S/N**

$$a^2_{\ell m} = s^2_{\ell m} + n^2_{\ell m} \qquad s^2 >> n^2$$ **High S/N**

$$(S/N)^{11}_\ell \simeq \frac{C^{11}_\ell}{N^1_\ell}\sqrt{\ell}$$

$$(S/N)^{12}_\ell \simeq r^{12}\sqrt{\frac{C^{11}_\ell}{N_\ell}}\sqrt{2\ell}$$

$$r^{12} \equiv \frac{C^{12}_\ell}{\sqrt{C^{11}_\ell C^{22}_\ell}}$$

- Signal-dominated tracer
- Well-correlated tracers

Detecting new effects: HI properties and DLAs

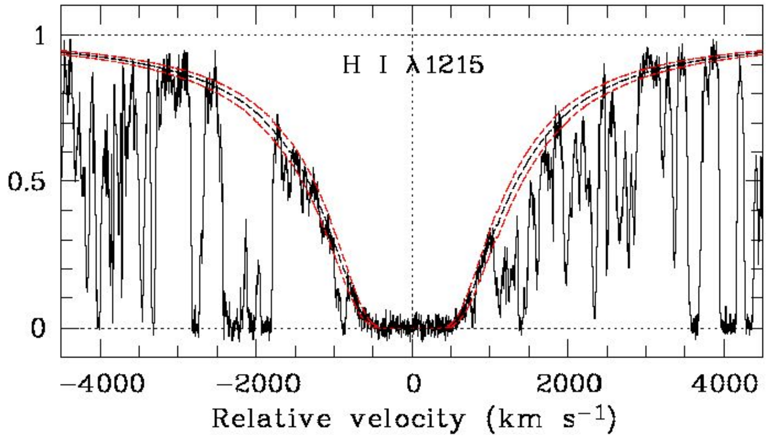
Alonso et al. 2018

HI at low redshifts

- After EoR, most HI in pockets
- Known as Damped Lyman-alpha systems (DLAs)
- Found as huge troughs in quasar spectra
- Bias measured by x-corr with quasars

$$b_{\mathrm{DLA-QSO}} \sim 2.0 \pm 0.1$$

Perez-Rafols et al. 2018



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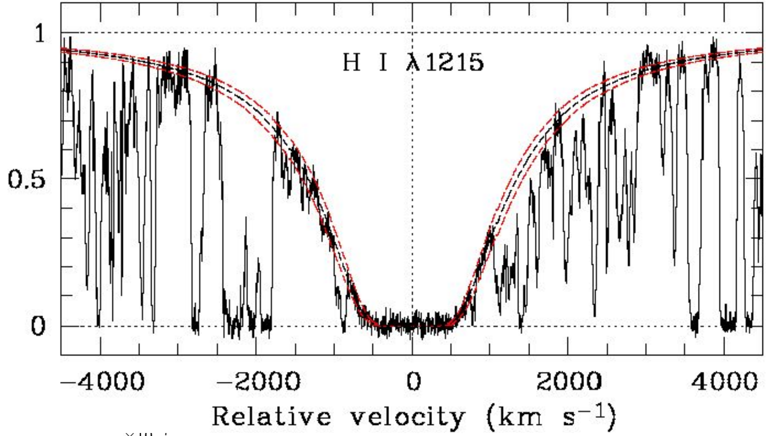
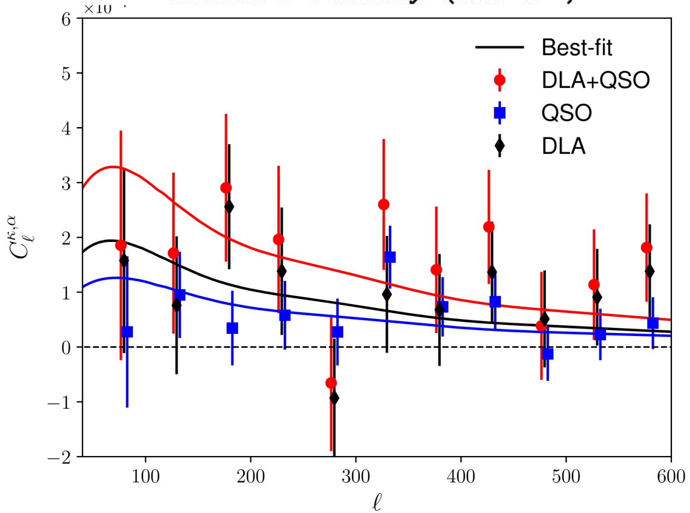
Perez-Rafols et al. 2018

- Check with x CMB-lensing:

$$b_{\rm DLA-\kappa} \sim 2.6 \pm 0.9$$





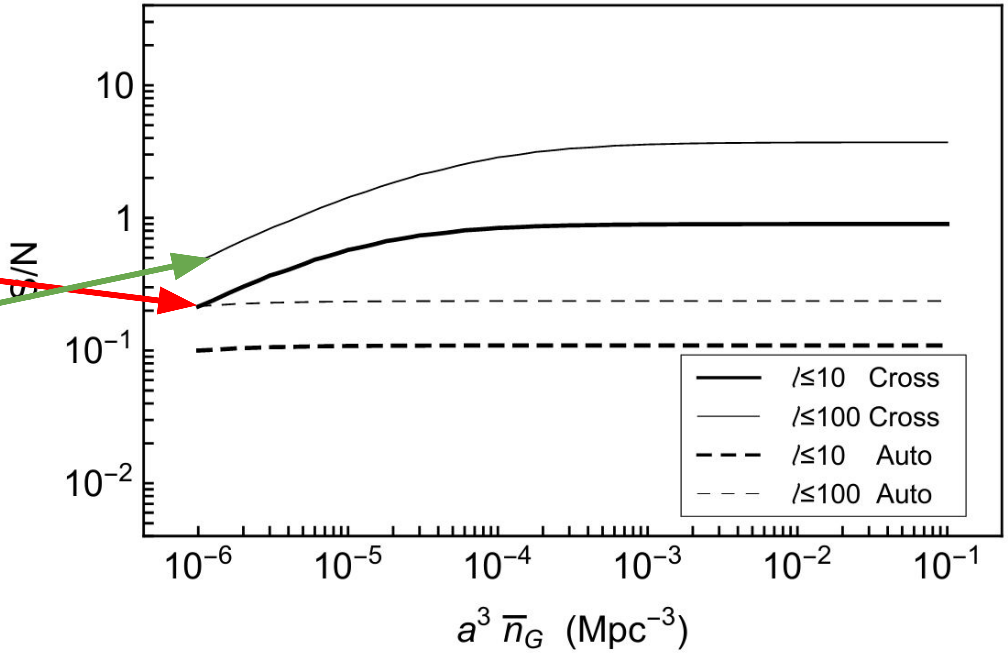
Detecting new effects: SGWB anisotropies

Alonso et al. 2020A

- SGWB likely dominated by unresolved astrophysical events
- Signal heavily dominated by few events at low-redshift (high shot-noise)
- Slice in redshift?

Unobservable in auto-correlation

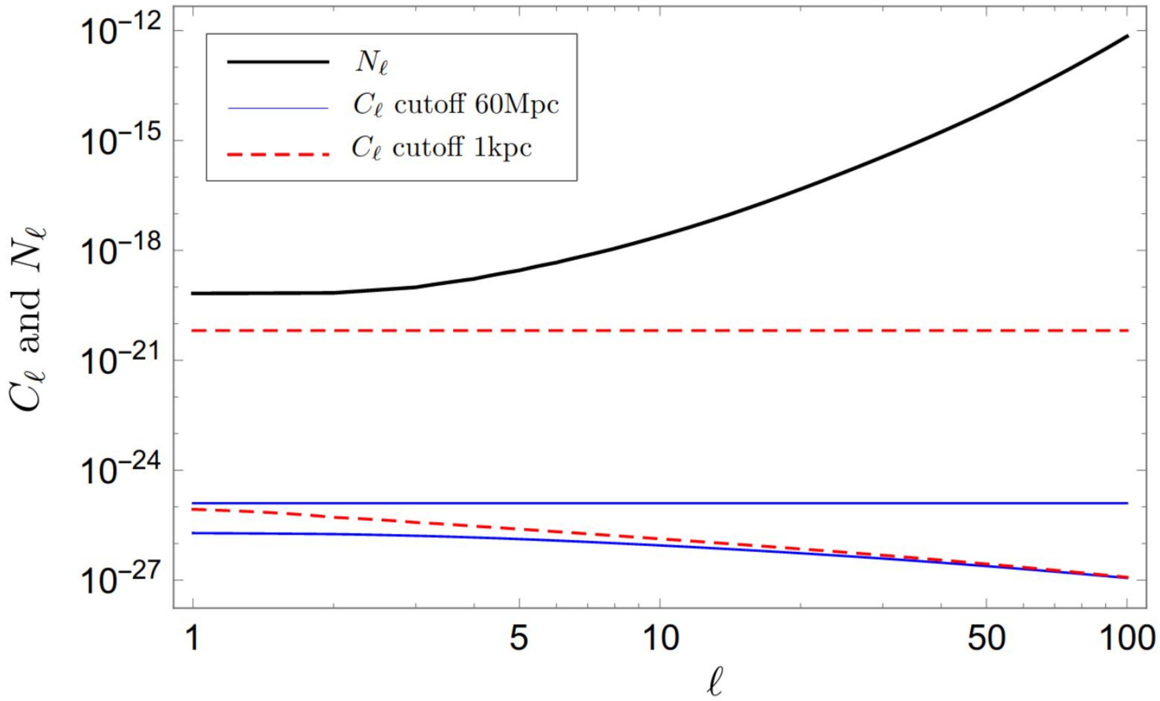
Potentially detectable with sufficiently dense sample



Detecting new effects: SGWB anisotropies

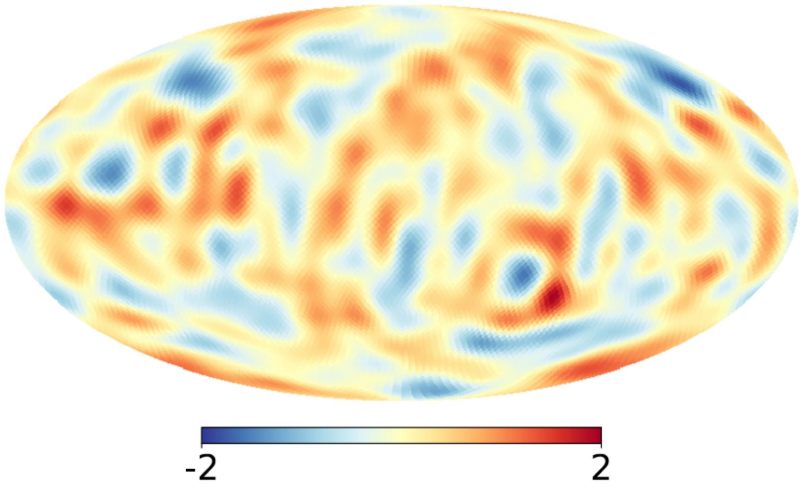
Alonso et al. 2020B

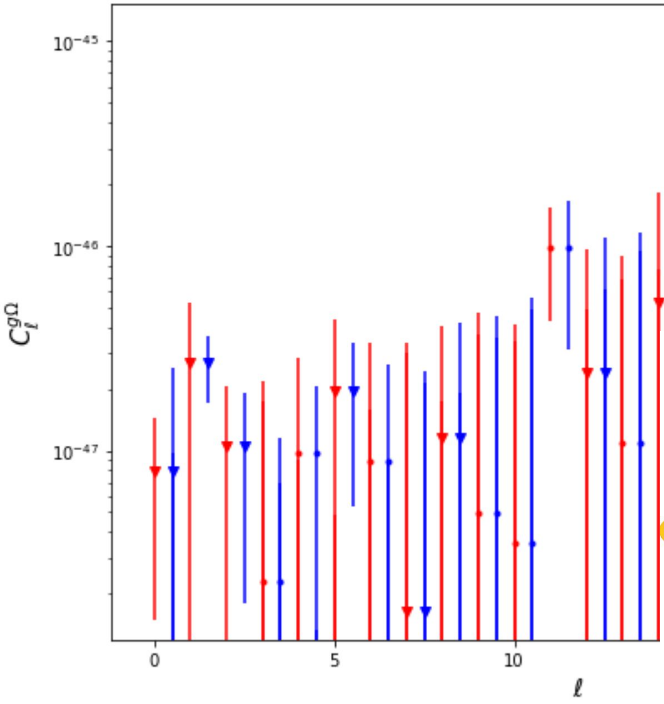
Instrumental noise likely too large to detect anything any time soon:

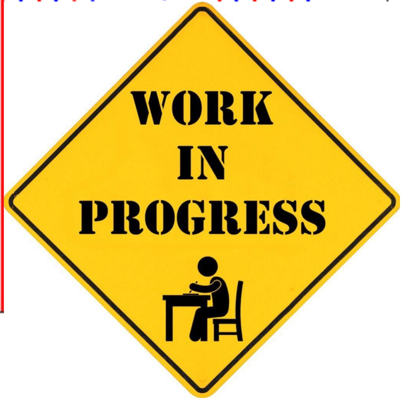


Detecting new effects: SGWB anisotropies

But you can still have fun :-)



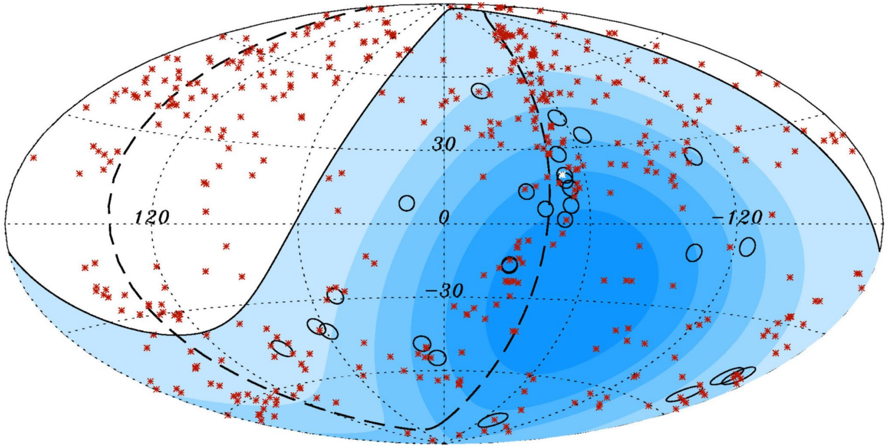


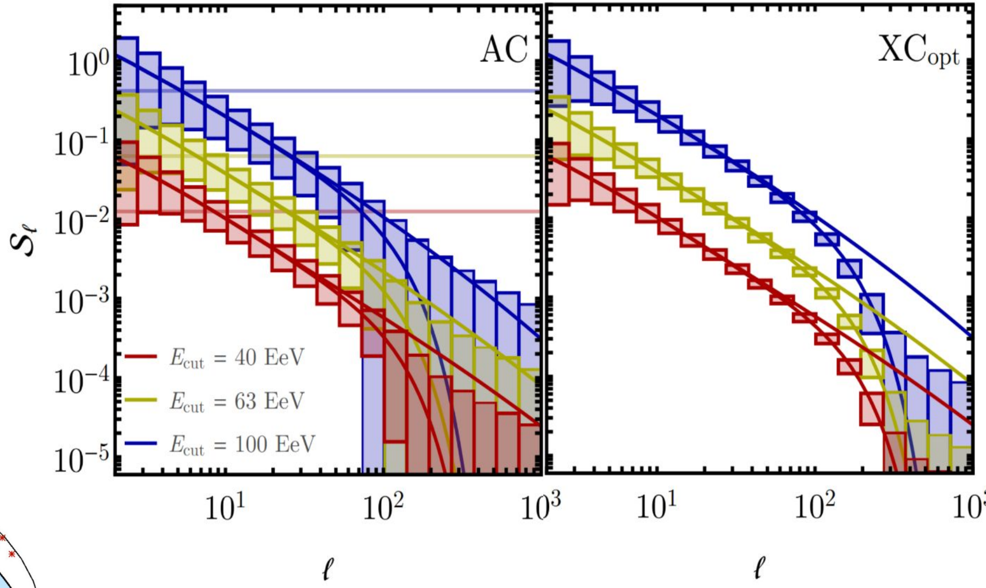


Detecting new effects: UHECRs

Urban et al. 2020

Ultra-high-energy cosmic rays:
- Not many of them
- Deflected by GMF
- Plagued by systematics





X-corr with galaxies probably better!

Summary

Tomographic reconstruction:

- Use localized tracers to reconstruct background quantities
  E.g. 1: gas pressure from tSZ x δ_g
  E.g. 2: structure growth from lensing x δ_g

Calibrate redshift distributions:

- Cross-correlate with spec-like sample:
  E.g. 3: 21cm through bispectra
- Uncertain kernel width?
  E.g. 4: x-correlate with CMB lensing

Detect new effects:

- Noise suppression in x-correlation:
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  E.g. 6: SGWBs with galaxies
  E.g. 7: UHECRs with galaxies

Thanks!

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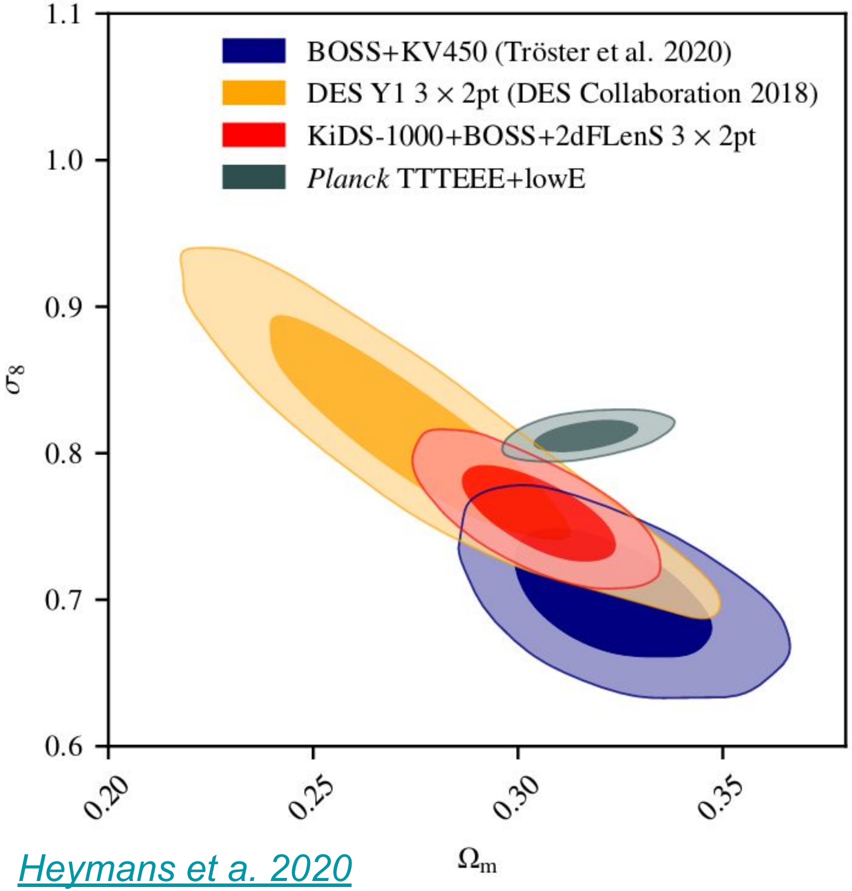
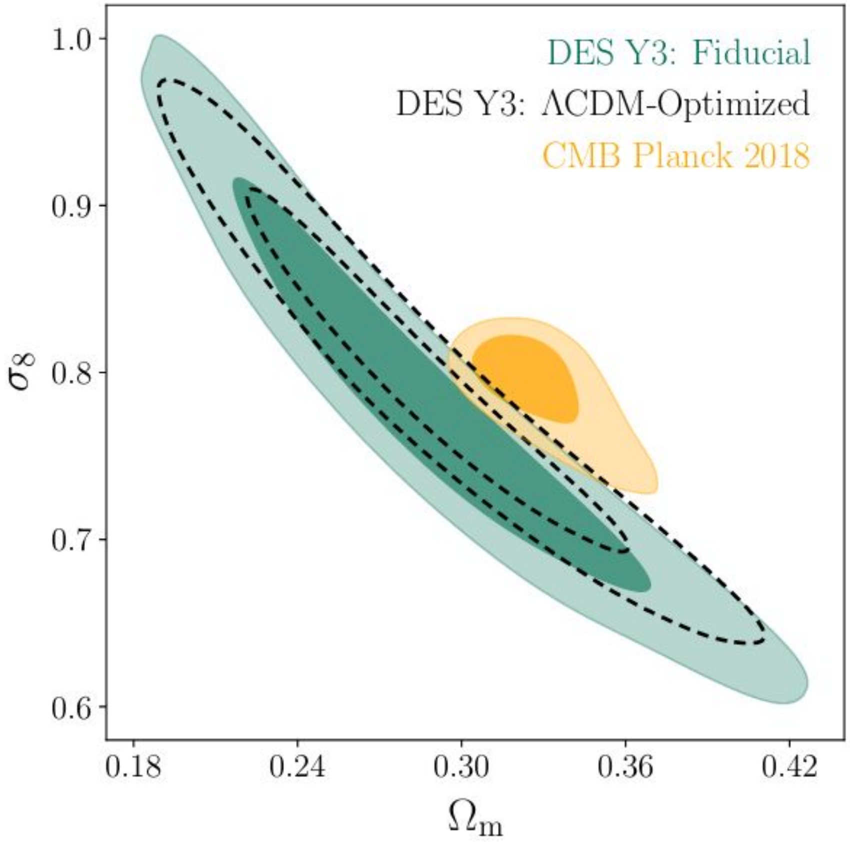
Thanks!

Projected tracers: “3x2-point”



Heymans et a. 2020



Abbot et al. 2021

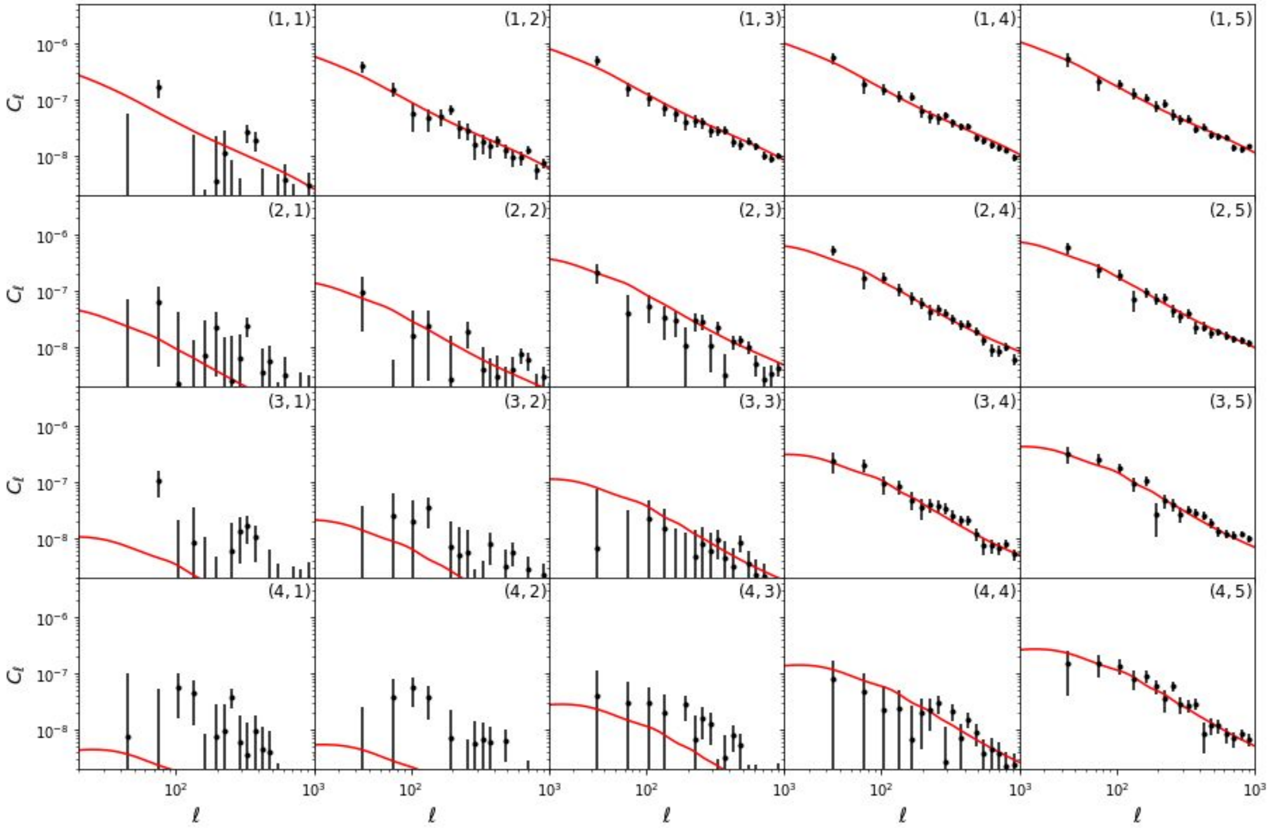
Tomographic reconstruction: growth

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

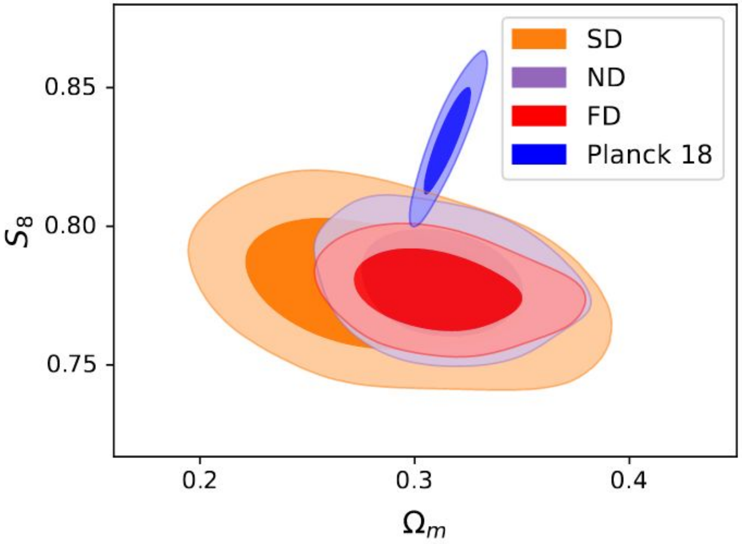
Tomographic reconstruction: growth

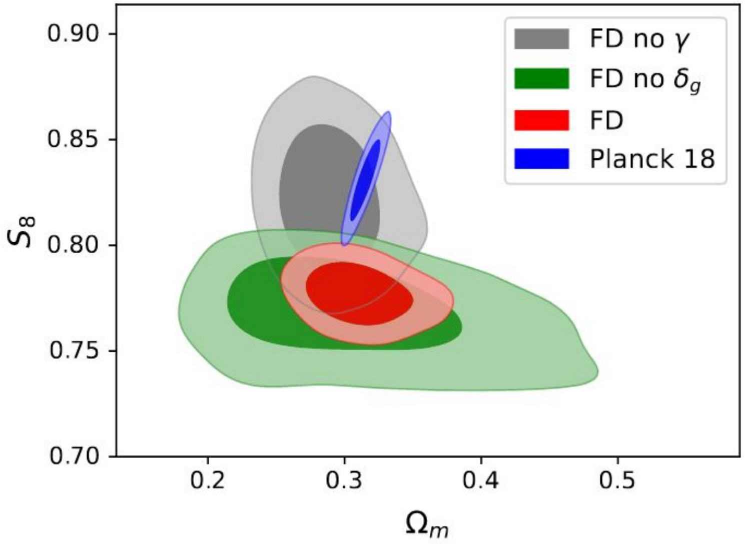
Garcia-Garcia et al. 2021

Growth reconstruction: ΛCDM constraints

Results:

- ΛCDM is an excellent fit to the low-z data
- North and South data compatible
- 3.5σ tension with Planck on S_8
- Driven by cosmic shear data





Tomographic reconstruction: growth

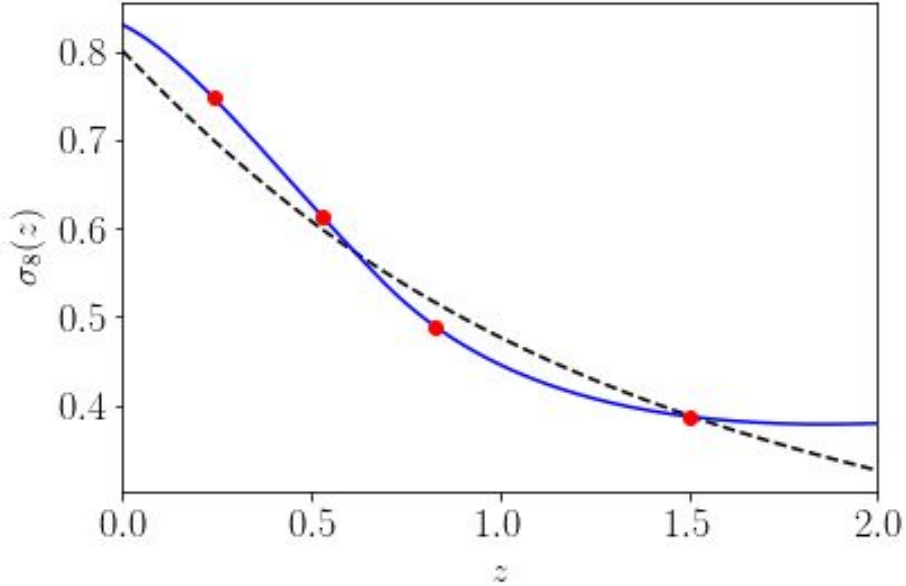
Garcia-Garcia et al. 2021

Growth reconstruction: the analysis

Model:

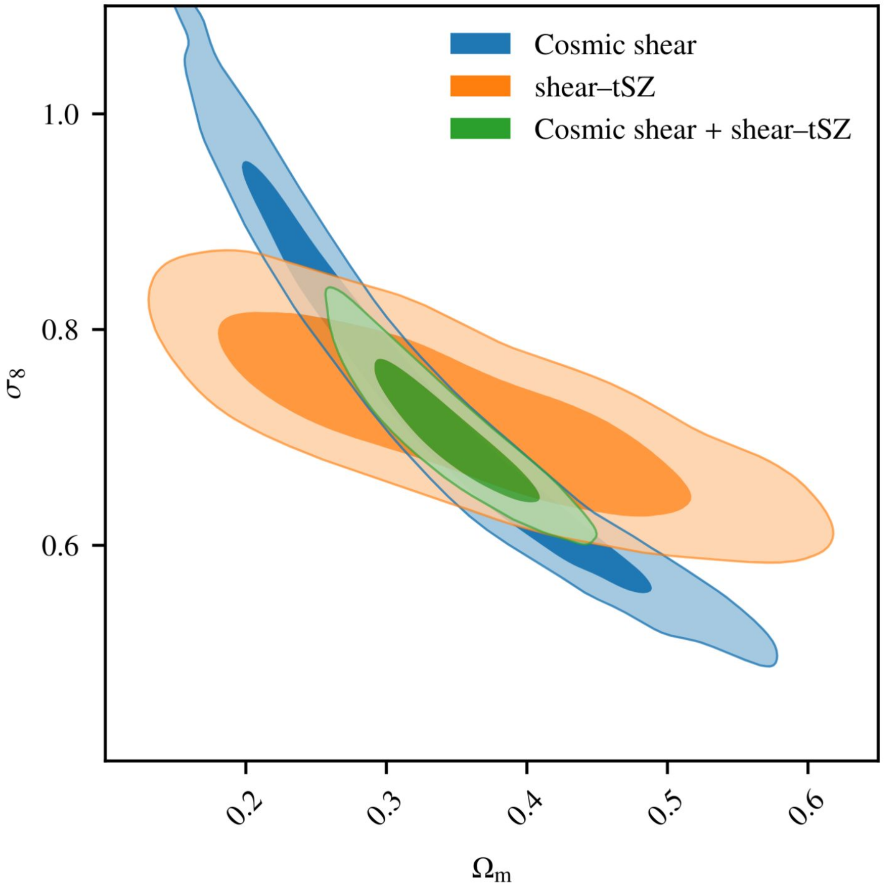
- Background: ΛCDM
- Power spectrum at z=0: ΛCDM
- Growth history: quadratic spline with free nodes
- Non-linear matter P.S.: HALOFIT
- Galaxy bias: linear (k_{max} = 0.15 Mpc^{-1})

$$P_L(k, z) = D^2(z)\, P_L(k, 0)$$



Tomographic reconstruction: tSZ

Koukoufilippas et al. 2019



Constraints on baryonic physics:
Troster et al. 2021

See also:

- Hojjati et al. 2015
- Hurier & Angulo 2017
- Gatti et al. 2021