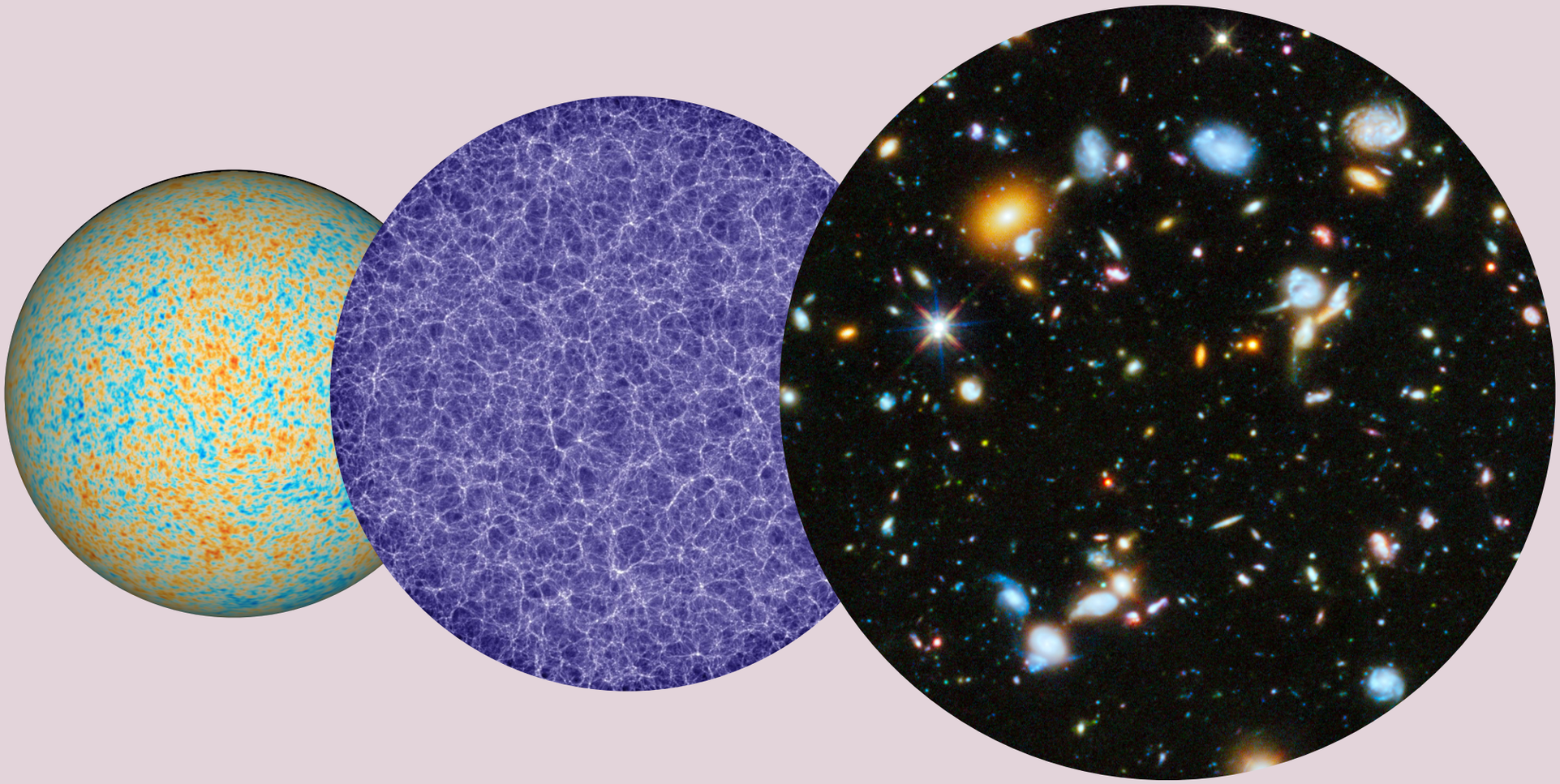
Integrated approach to cosmology



Andrina Nicola (ETH Zürich)
with Alexandre Refregier and Adam Amara

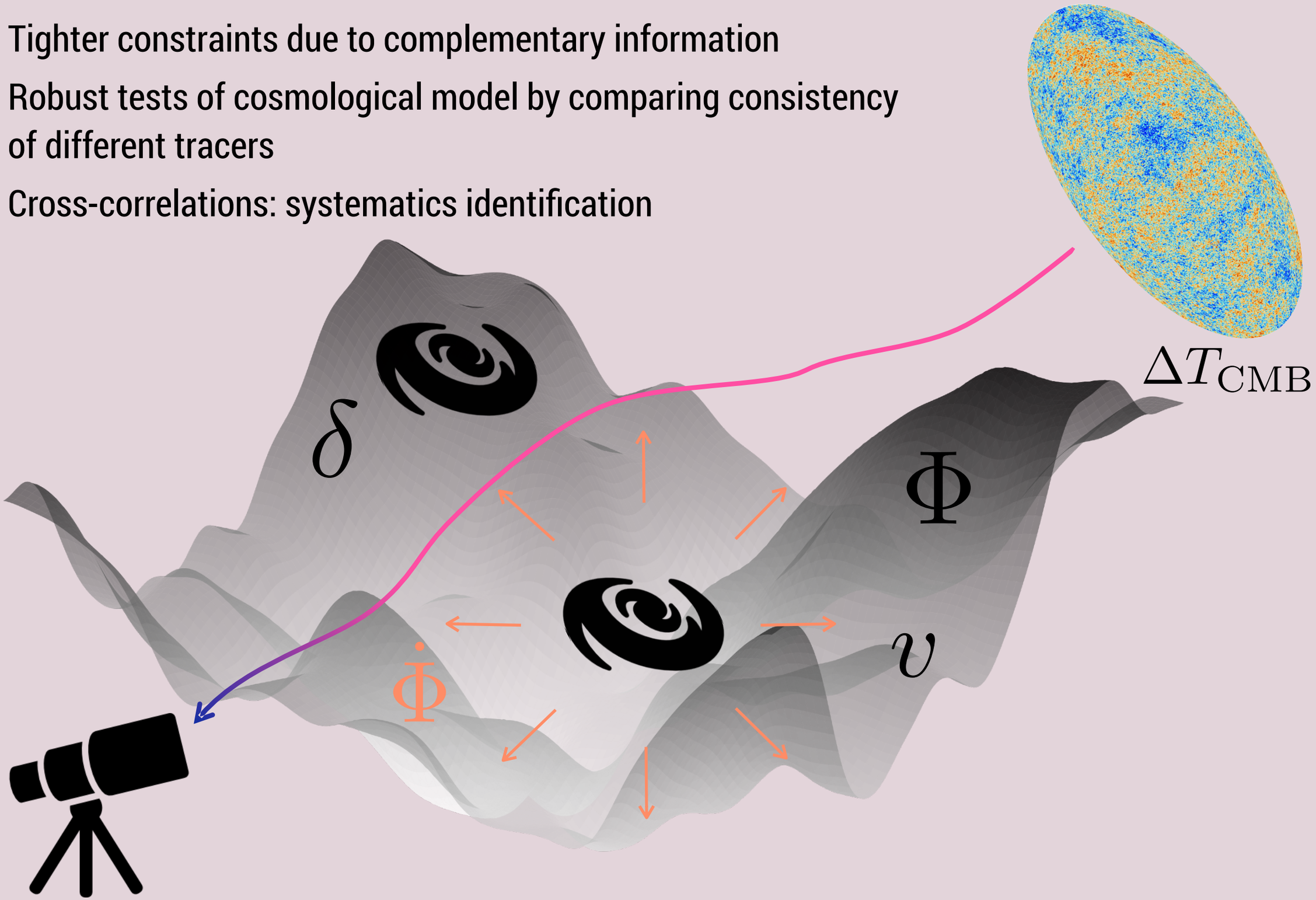
SCD @ CERN
February 6th, 2018

Cosmological probes

Tighter constraints due to complementary information

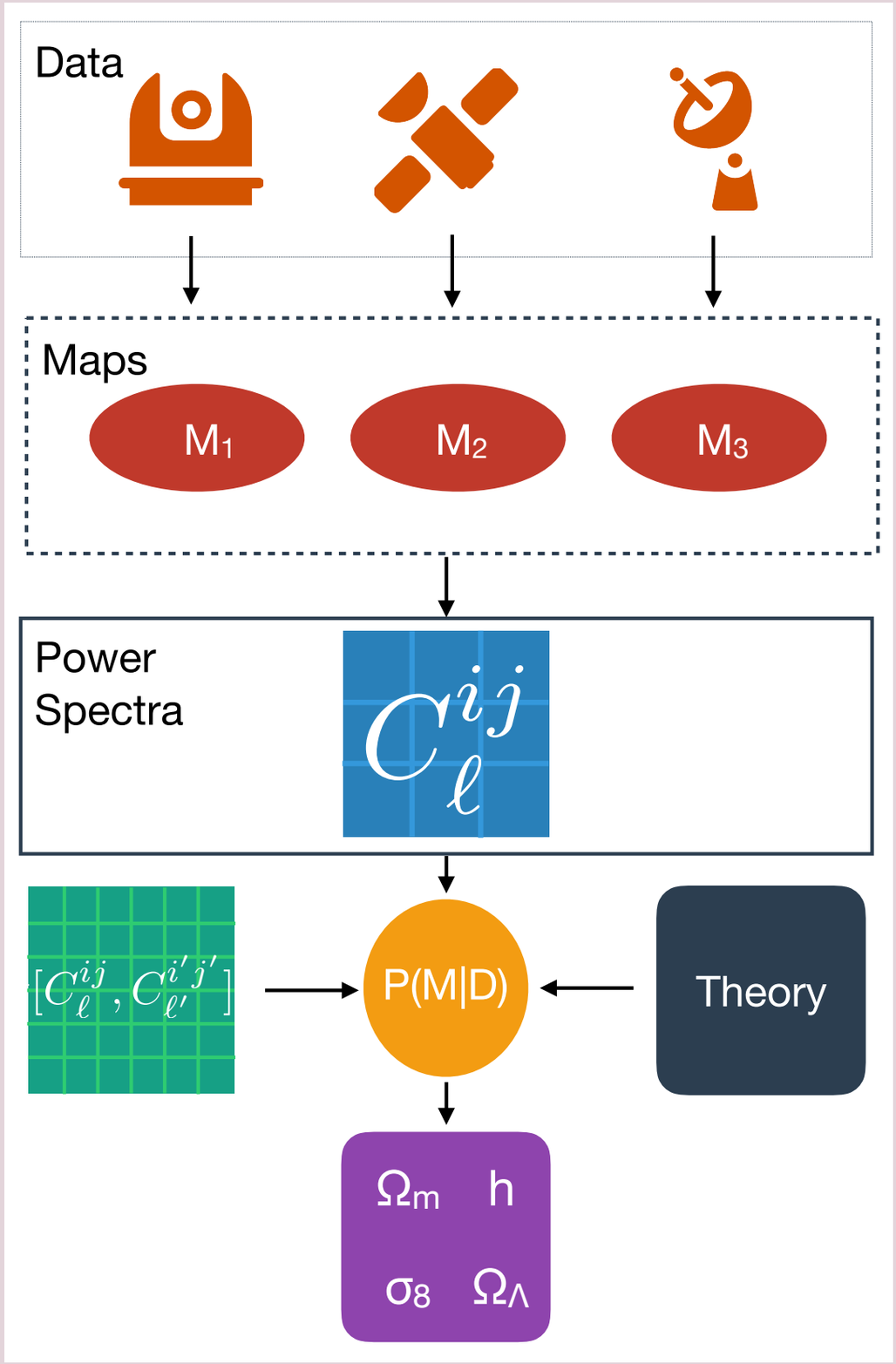
Robust tests of cosmological model by comparing consistency of different tracers

Cross-correlations: systematics identification



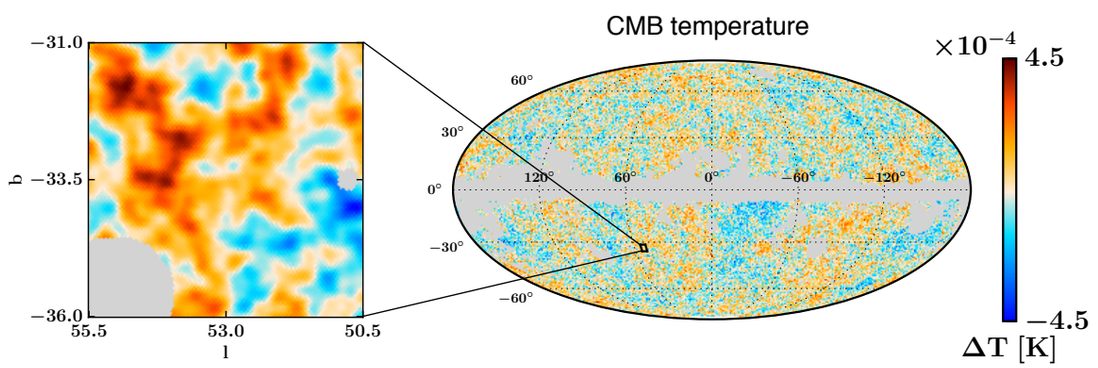
Images: Planck, Science, icons made by Freepik from www.flaticon.com

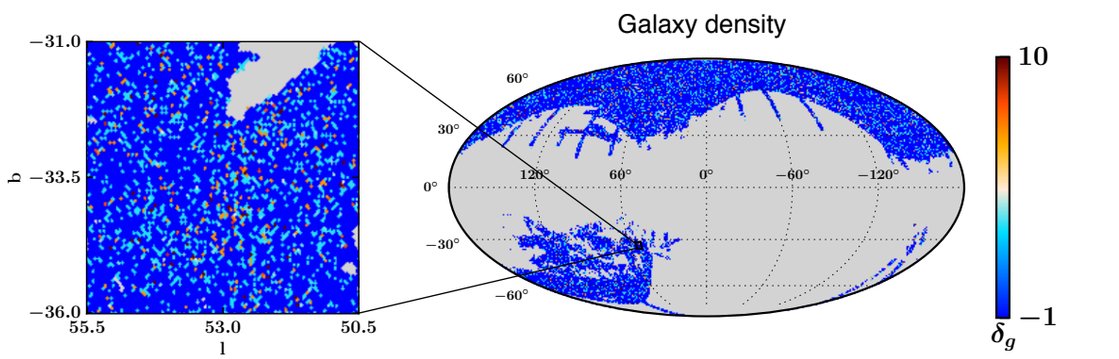
FRAMEWORK

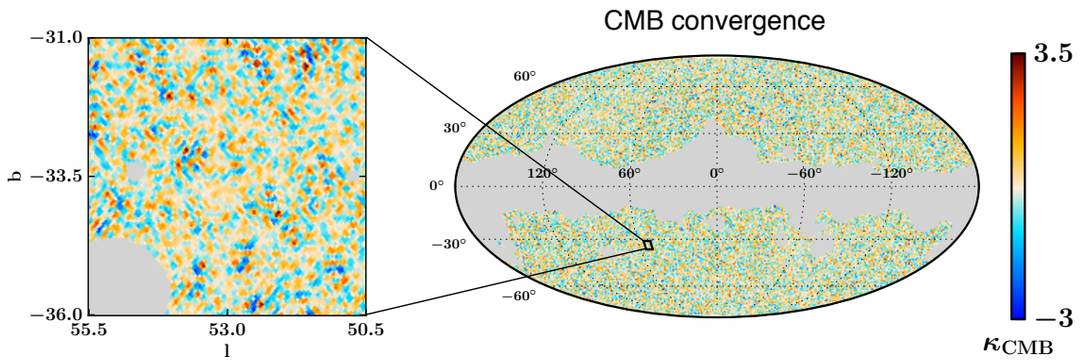


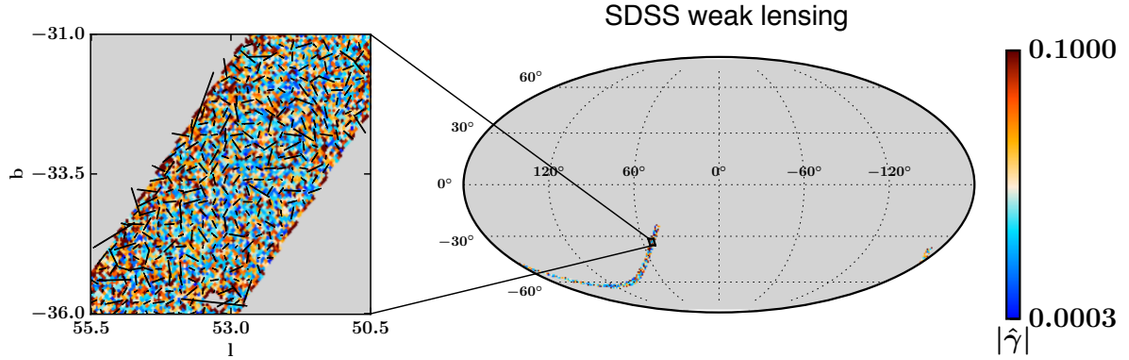
Nicola et al., 2016, 2017a

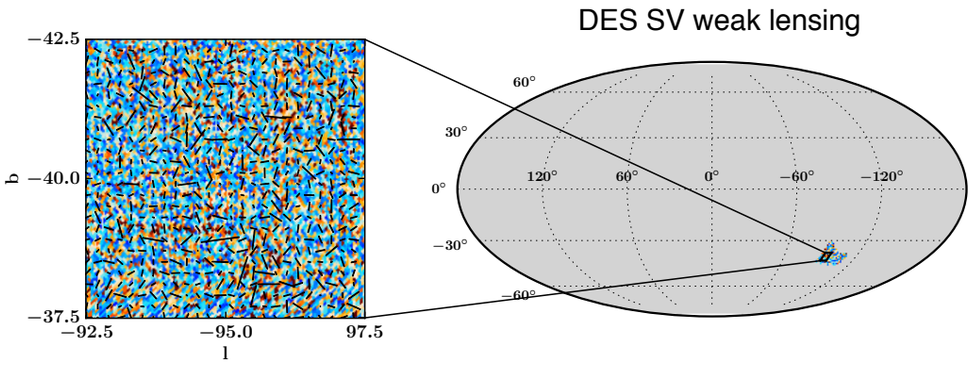
MAPS & BACKGROUND PROBES

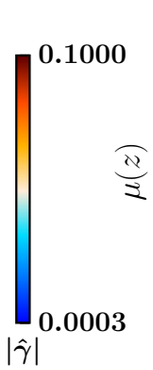


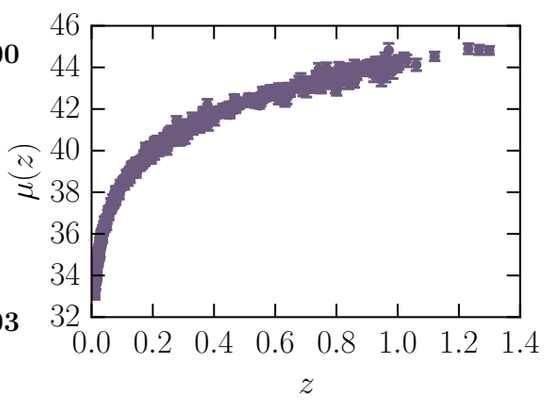


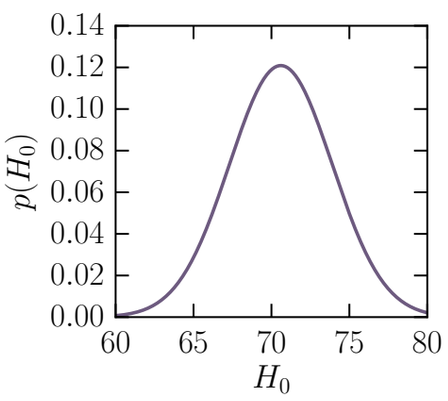






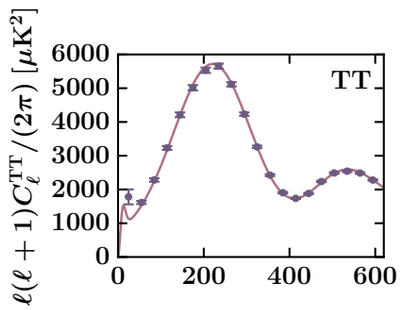


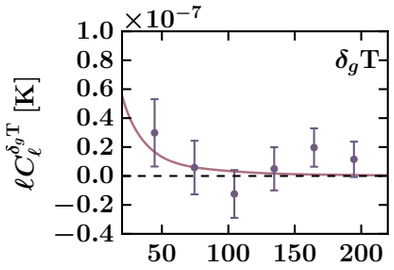


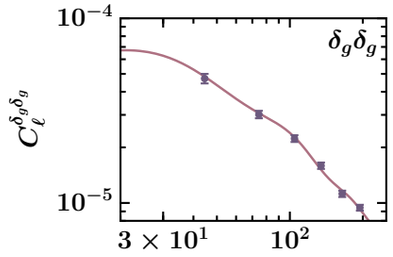


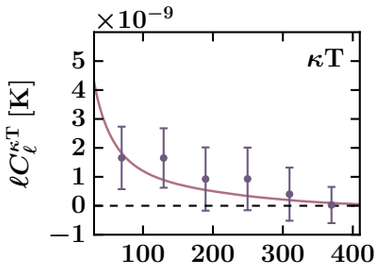
Nicola et al., 2016, 2017a

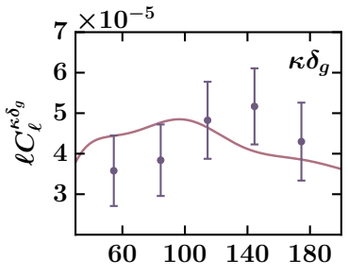
SPHERICAL HARMONIC POWER SPECTRA

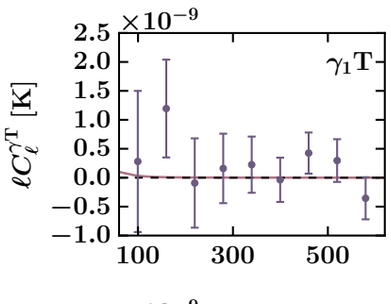


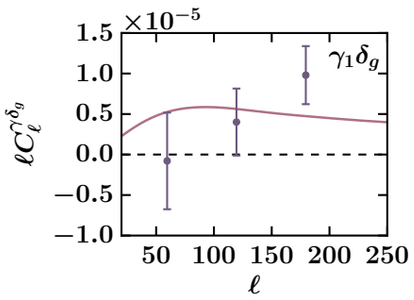


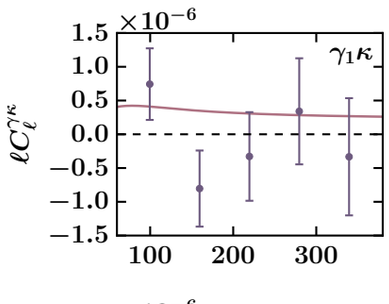


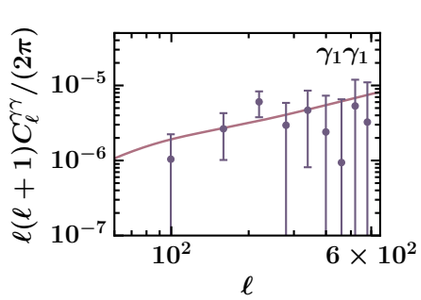


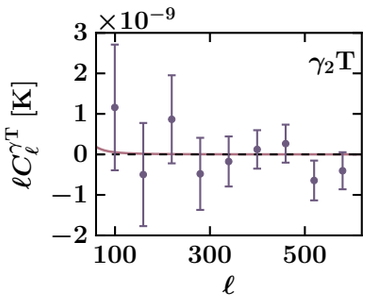


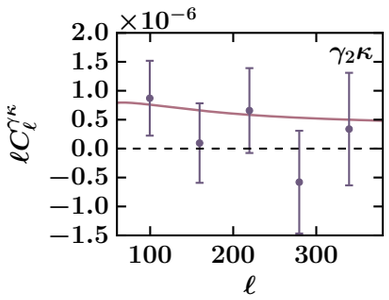


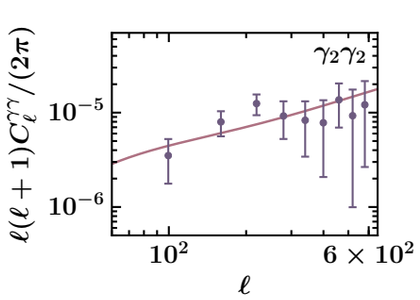




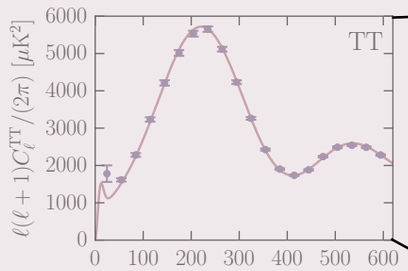


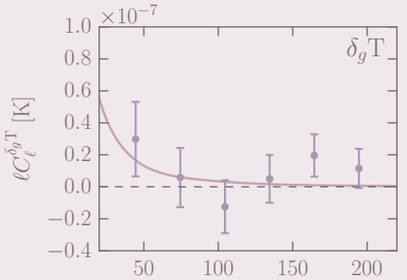


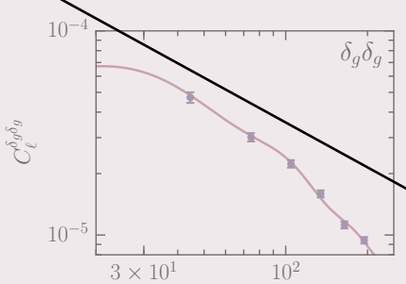


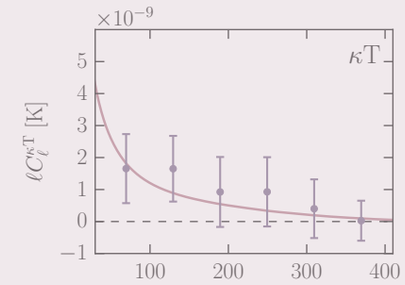


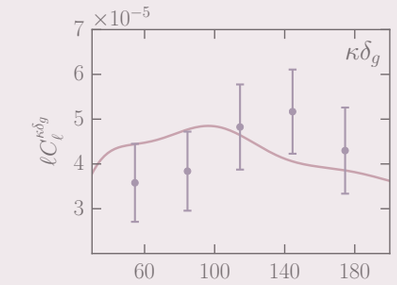
CMB TEMPERATURE ANISOTROPIES FROM PLANCK 2015

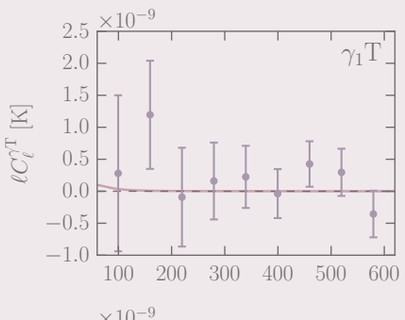


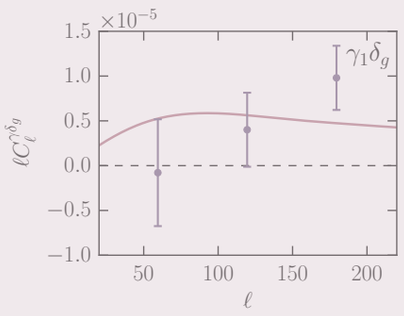


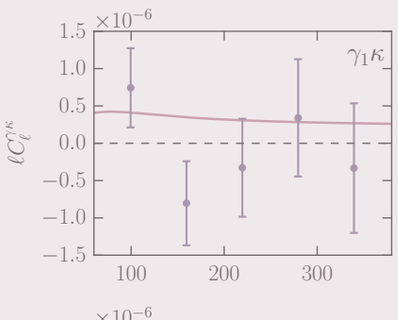


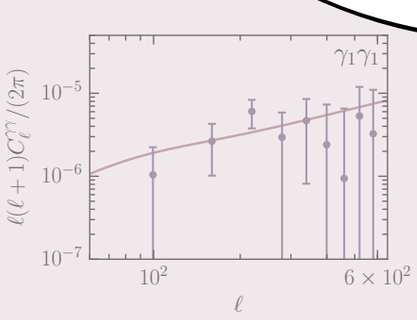


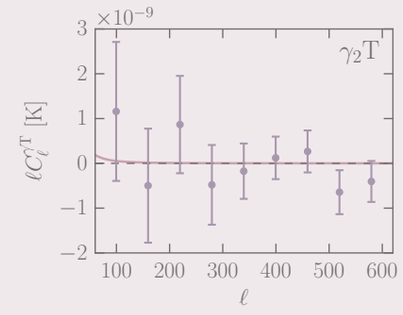


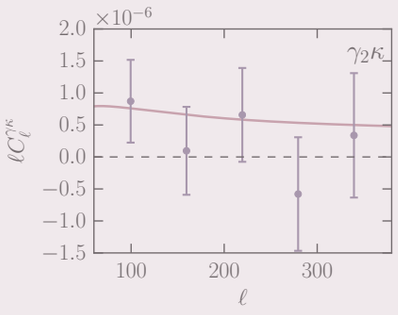


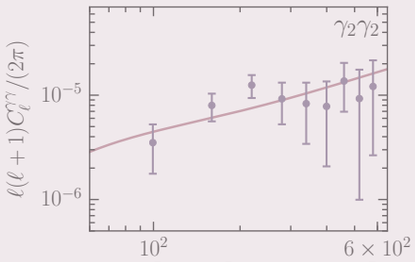


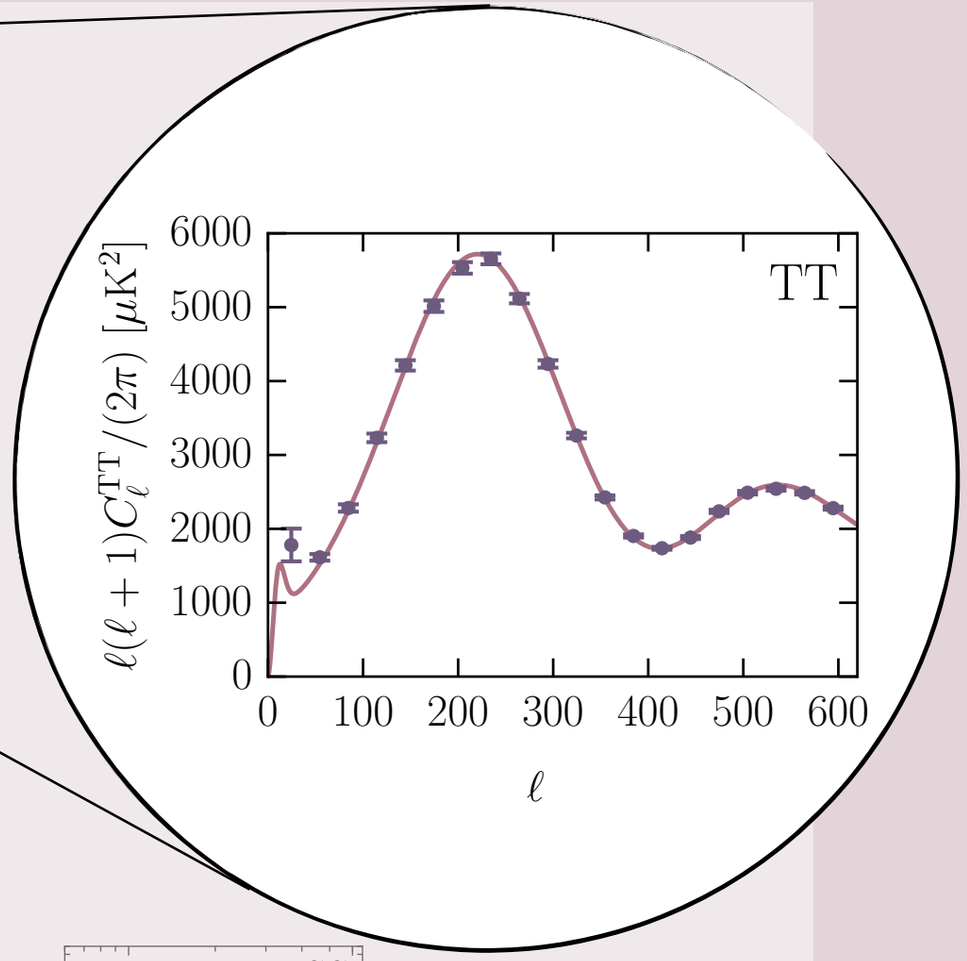






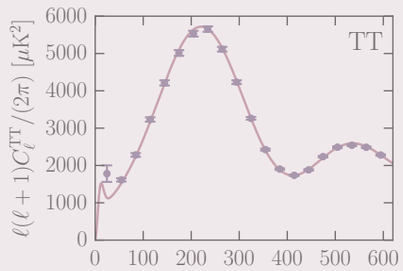


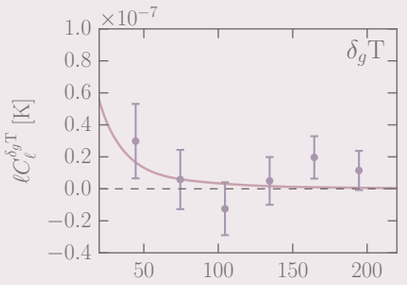


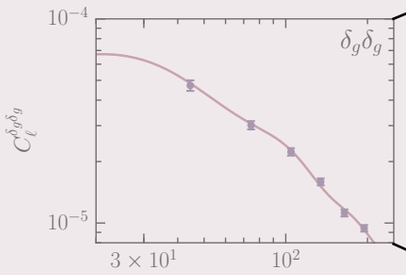


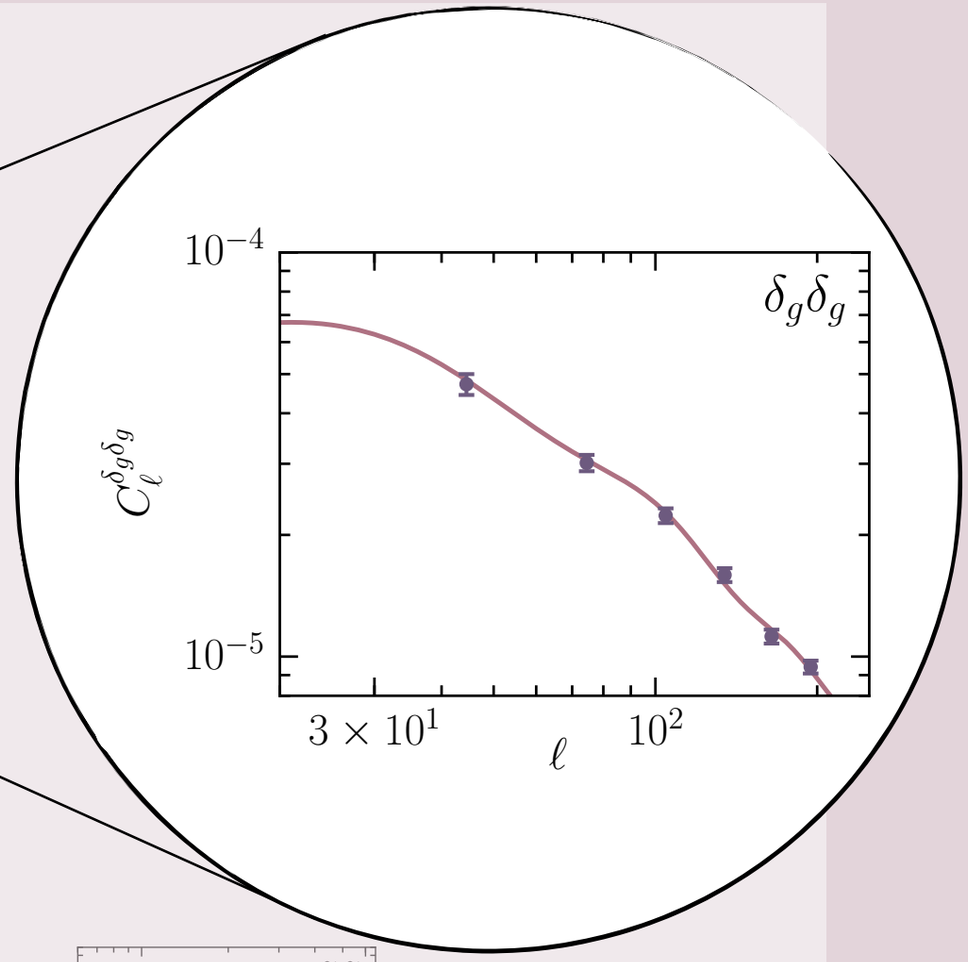
Nicola et al., 2017a

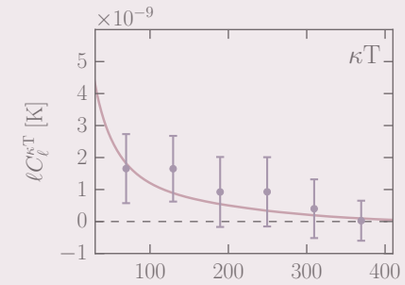
GALAXY CLUSTERING FROM SDSS DR8

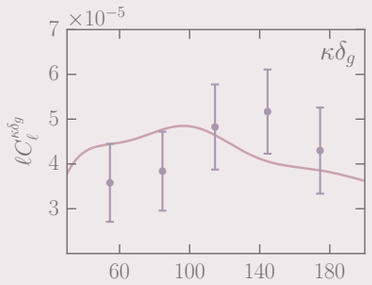


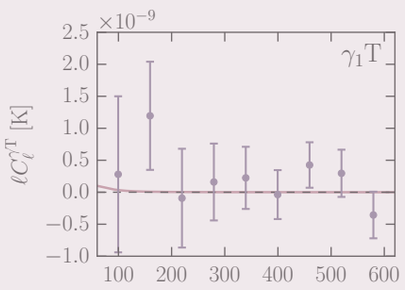


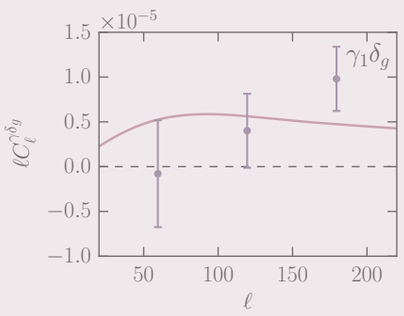


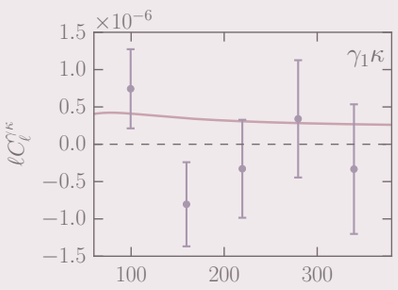


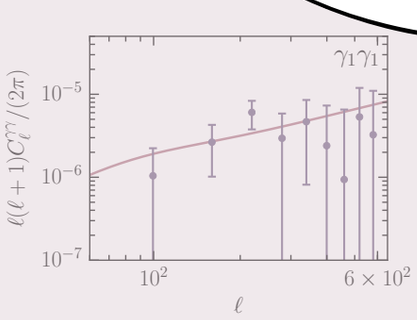


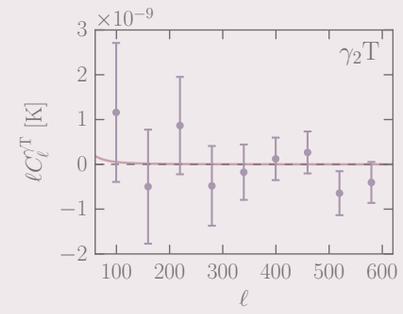


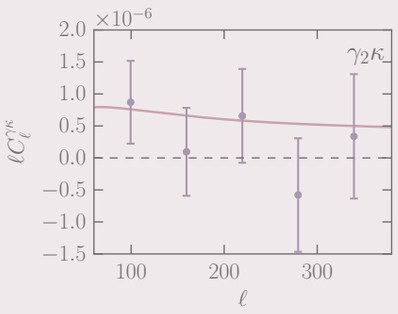


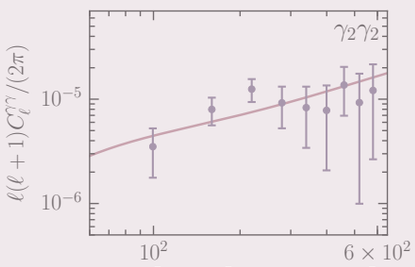






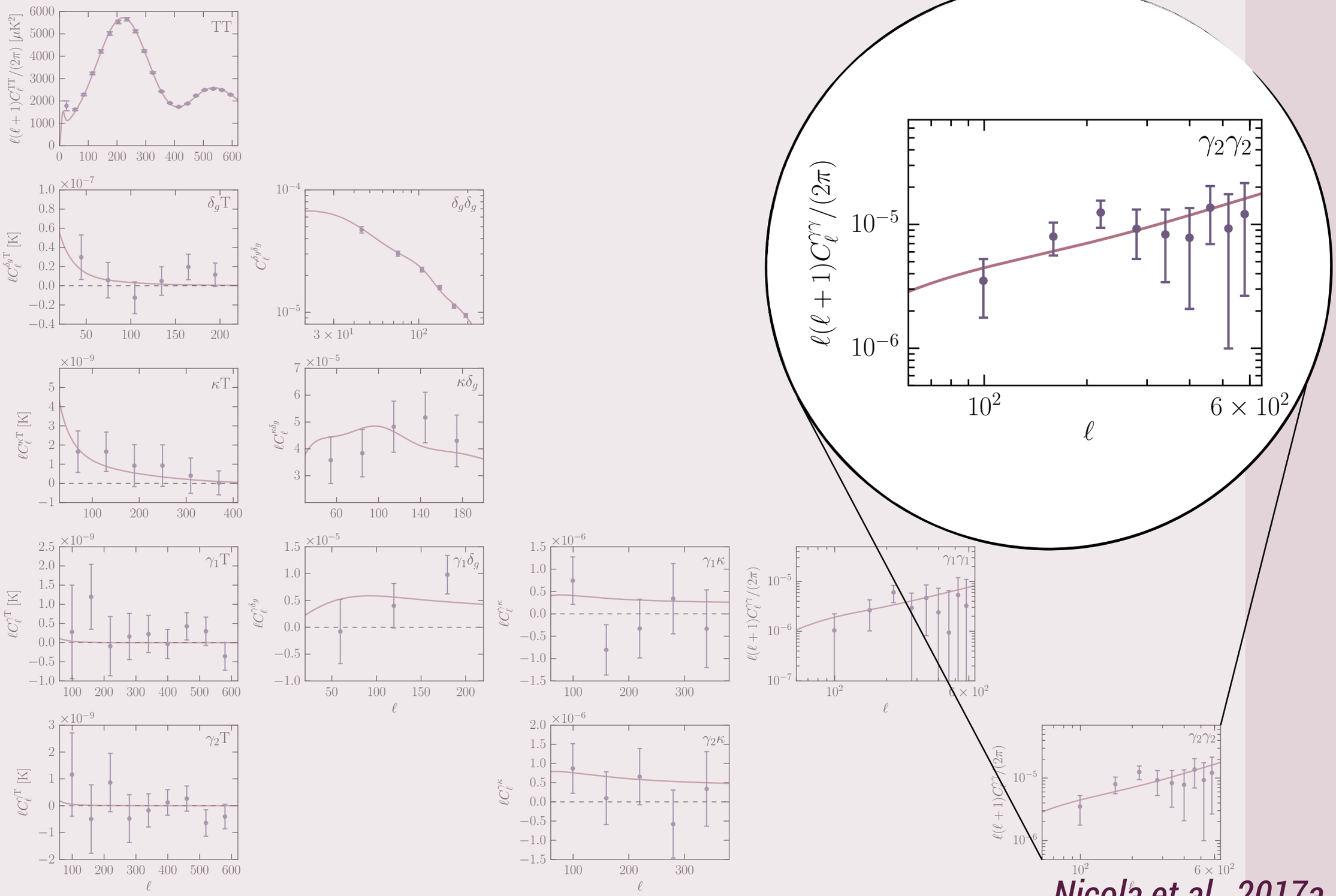






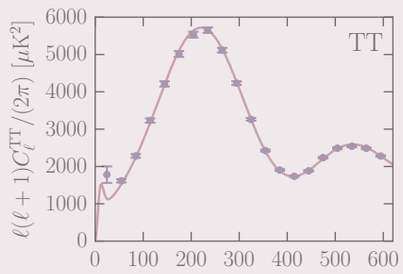
Nicola et al., 2017a

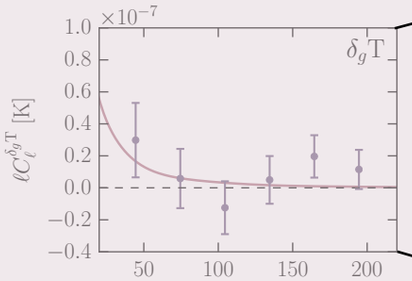
DES SV COSMIC SHEAR

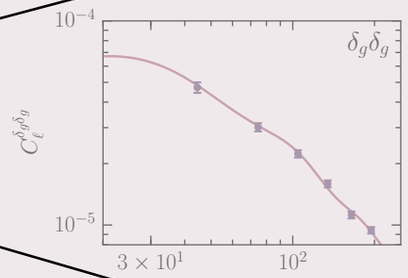


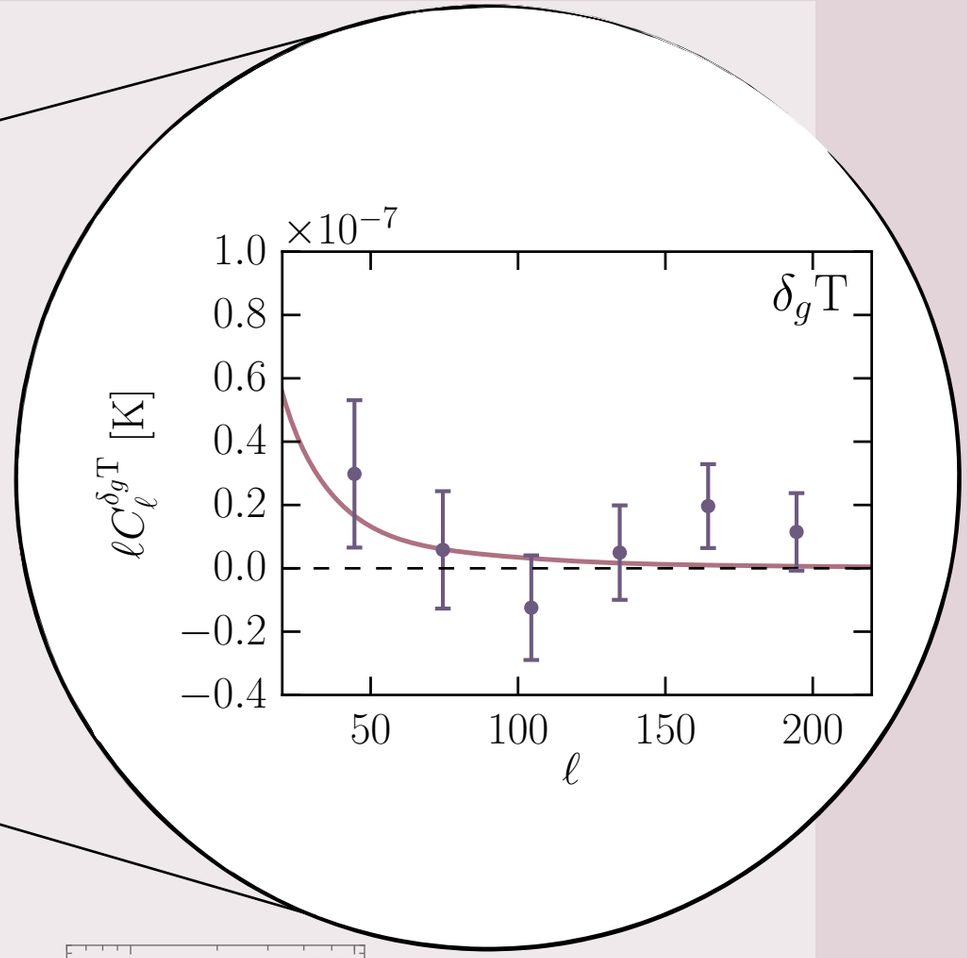
Nicola et al., 2017a

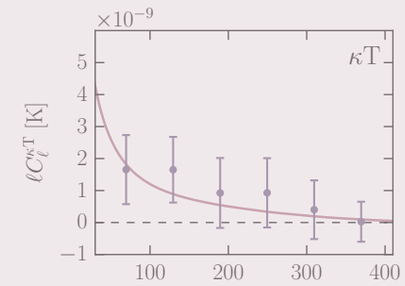
ISW FROM GALAXY OVERDENSITY

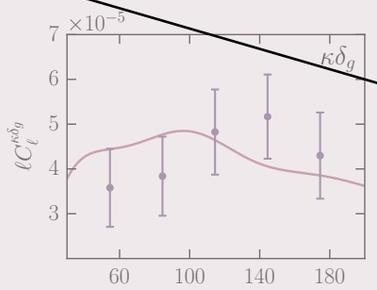


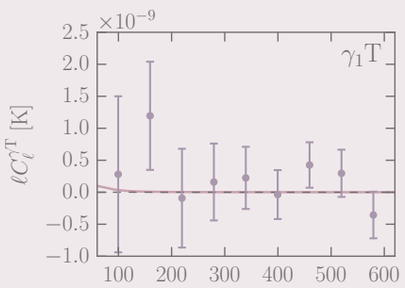


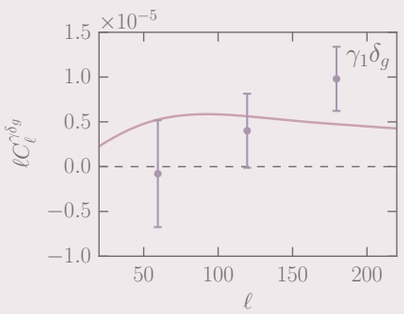


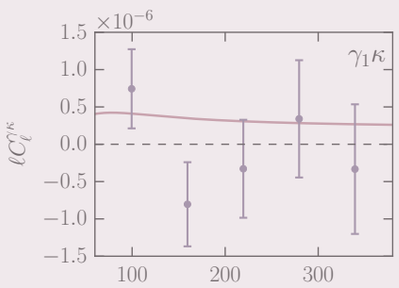


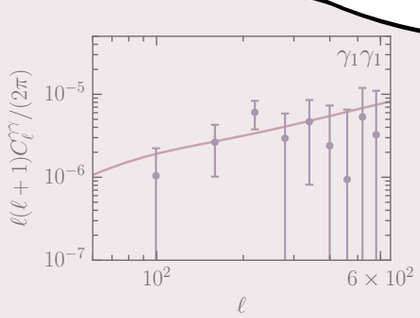


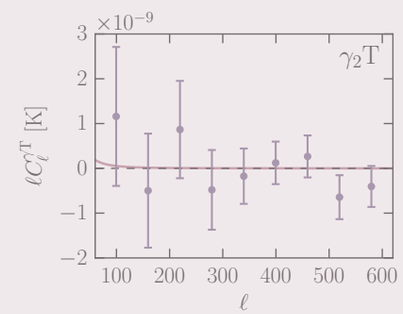


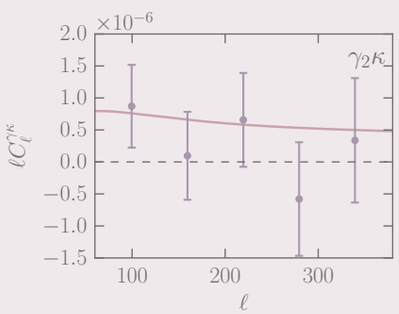


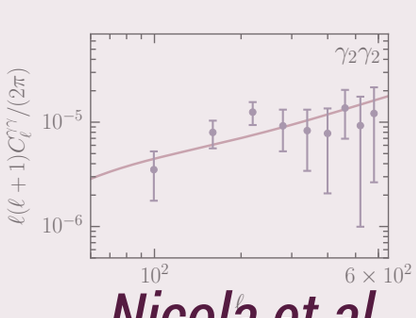






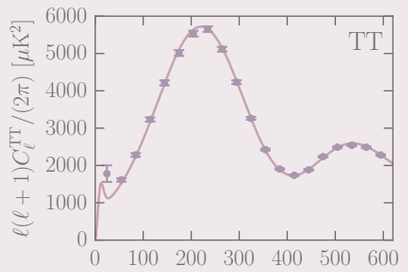


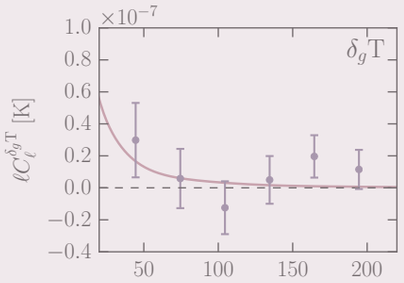


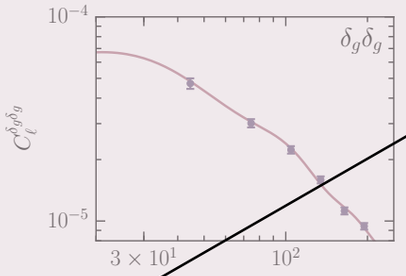


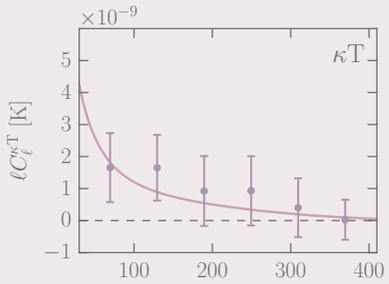
Nicola et al., 2017a

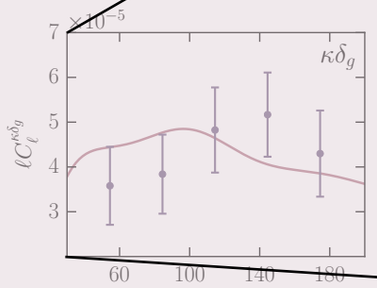
CROSS-CORRELATION GALAXY OVERDENSITY CMB LENSING

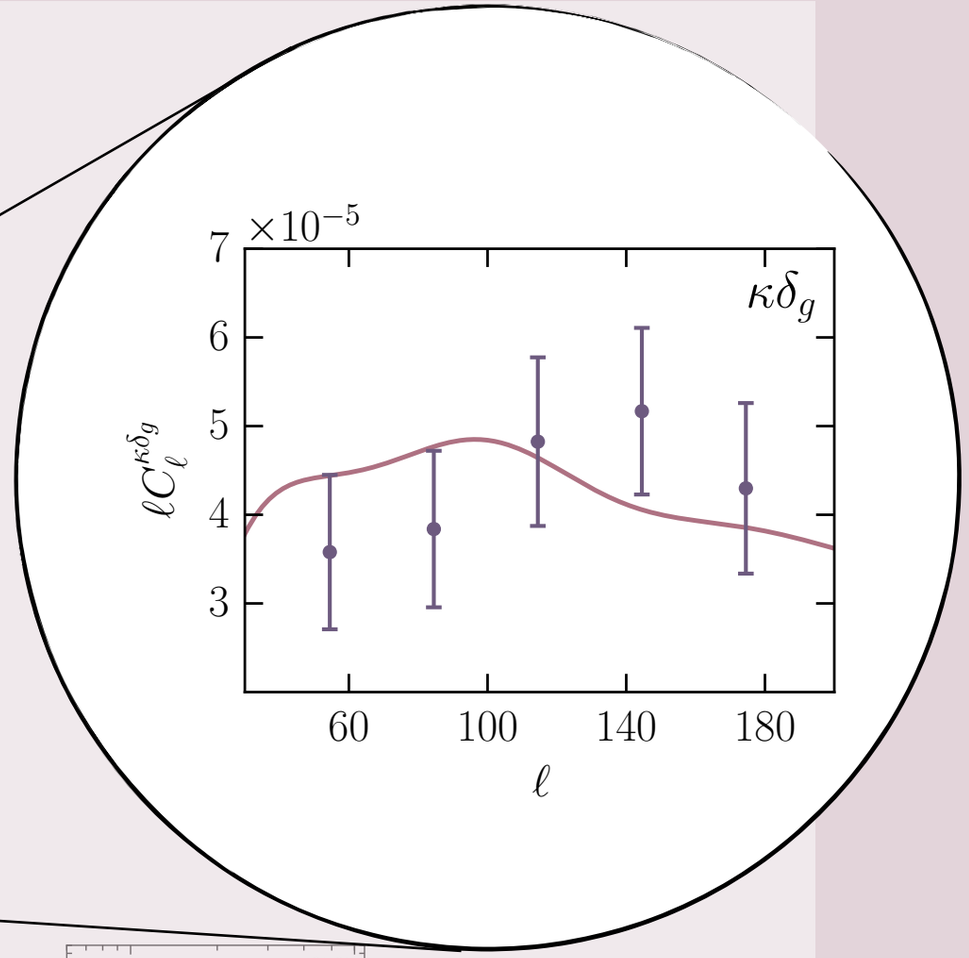


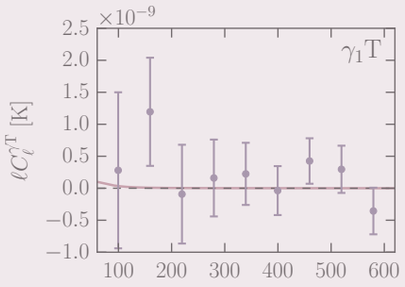


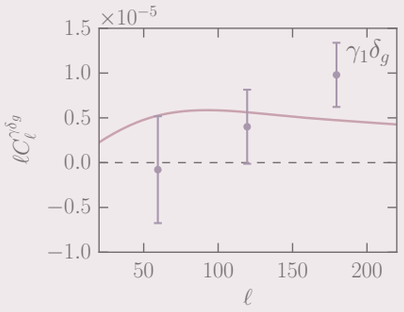


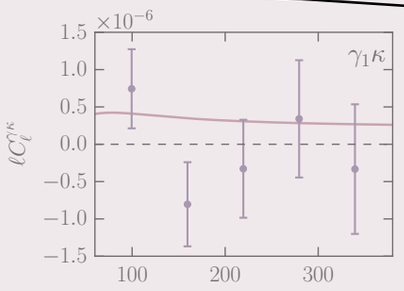


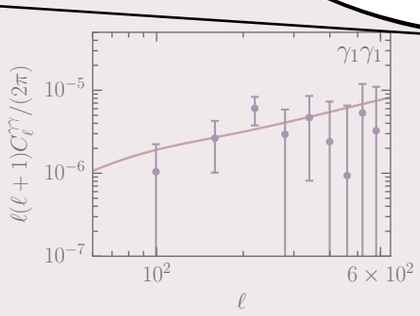


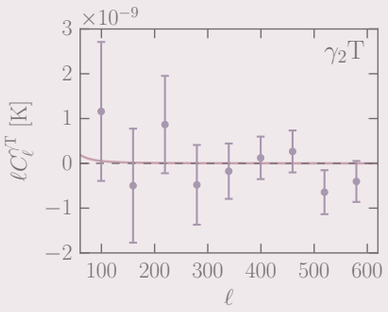


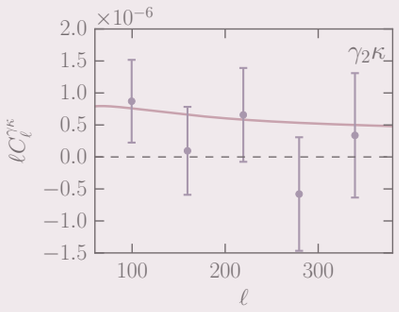


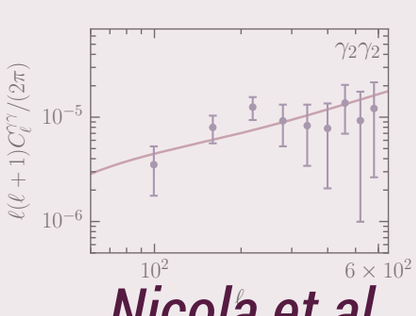






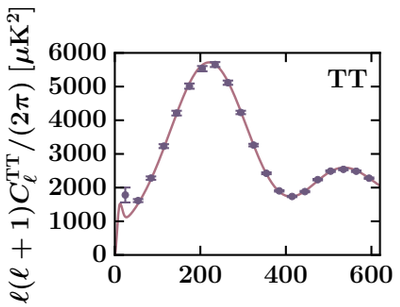


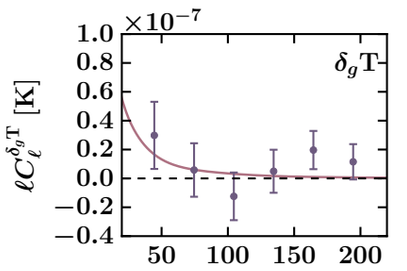


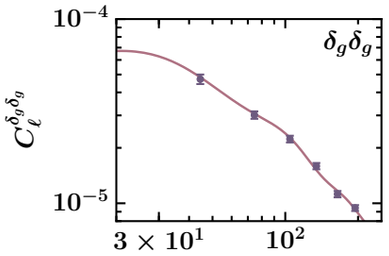


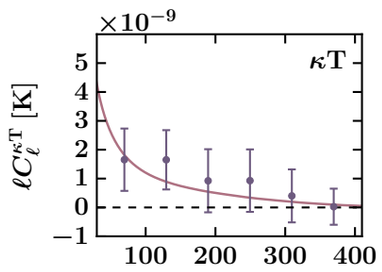
Nicola et al., 2017a

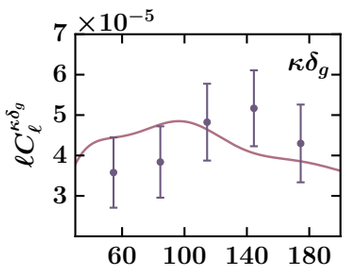
Data

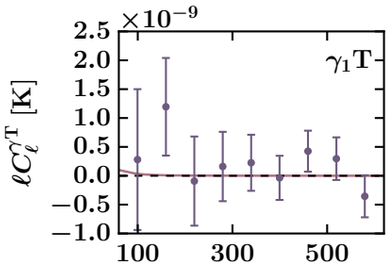

TT
$\ell(\ell+1)C_\ell^{\rm TT}/(2\pi)$ [μK^2]

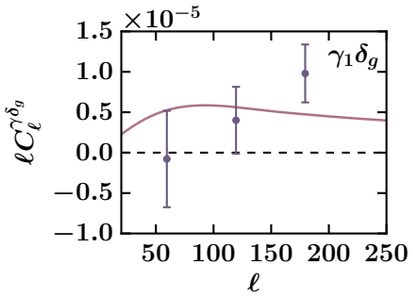

δ_gT
$\ell C_\ell^{\delta_g {\rm T}}$ [K]

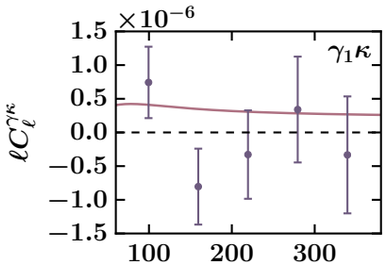

$\delta_g\delta_g$
$C_\ell^{\delta_g\delta_g}$

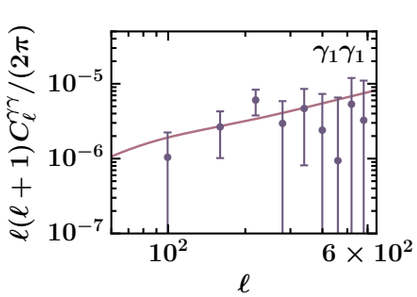

κT
$\ell C_\ell^{\kappa {\rm T}}$ [K]

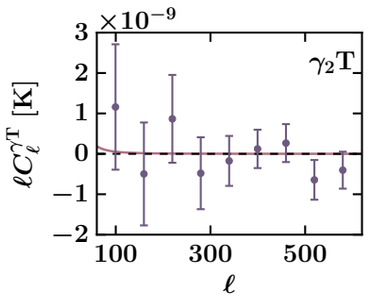

$\kappa\delta_g$
$\ell C_\ell^{\kappa\delta_g}$

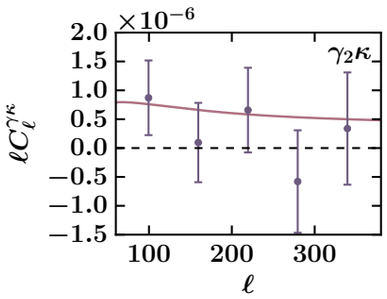

γ_1T
$\ell C_\ell^{\gamma {\rm T}}$ [K]

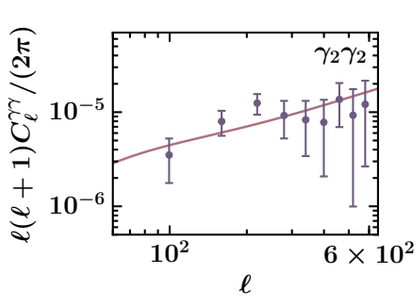

$\gamma_1\delta_g$
$\ell C_\ell^{\gamma\delta_g}$
ℓ

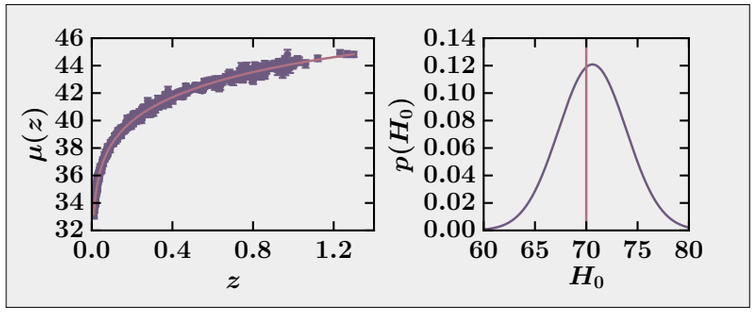

$\gamma_1\kappa$
$\ell C_\ell^{\gamma\kappa}$


$\gamma_1\gamma_1$
$\ell(\ell+1)C_\ell^{\gamma\gamma}/(2\pi)$
ℓ

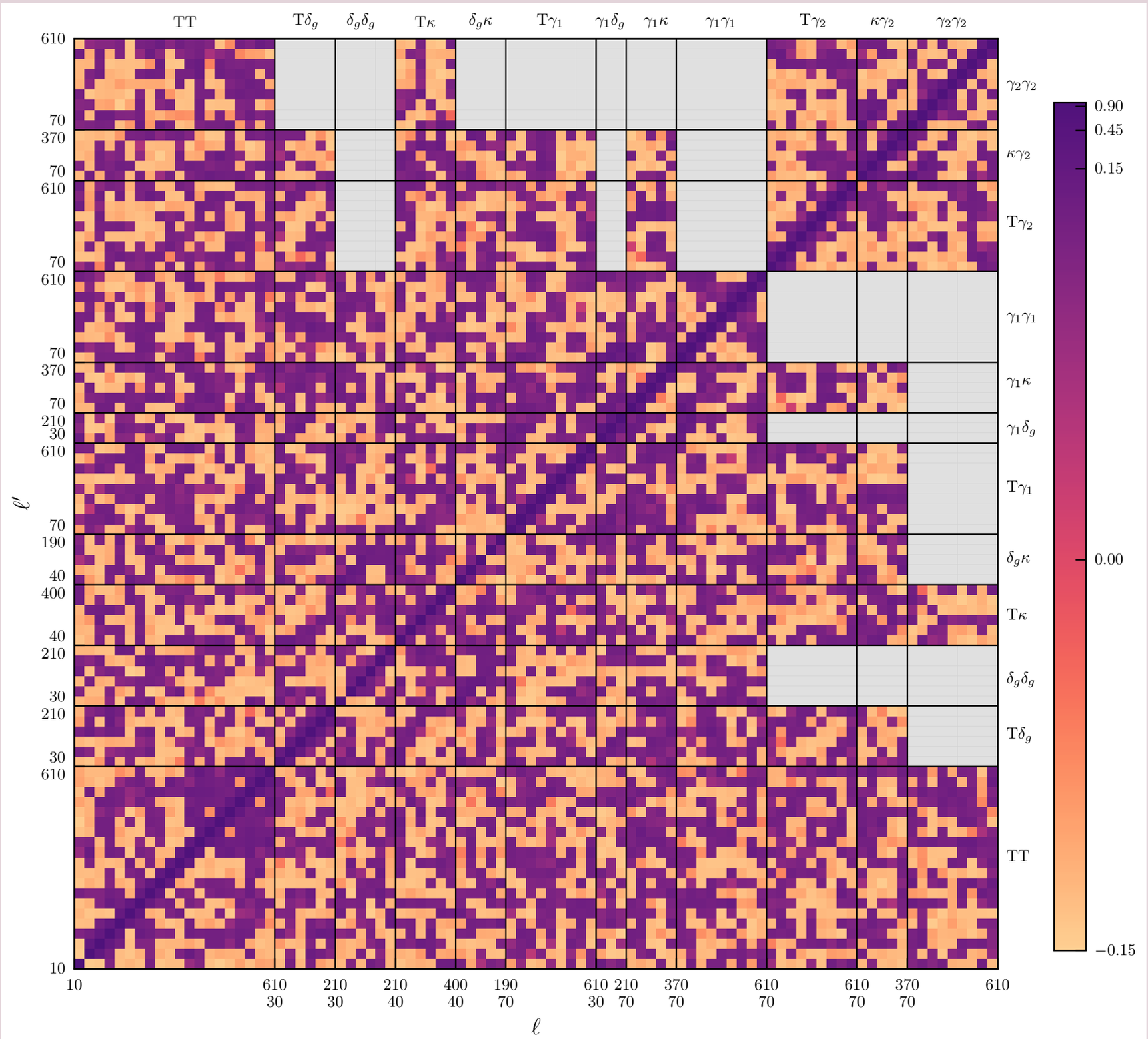

γ_2T
$\ell C_\ell^{\gamma {\rm T}}$ [K]
ℓ


$\gamma_2\kappa$
$\ell C_\ell^{\gamma\kappa}$
ℓ


$\gamma_2\gamma_2$
$\ell(\ell+1)C_\ell^{\gamma\gamma}/(2\pi)$
ℓ


$\mu(z)$
z
$p(H_0)$
H_0

COVARIANCE MATRIX



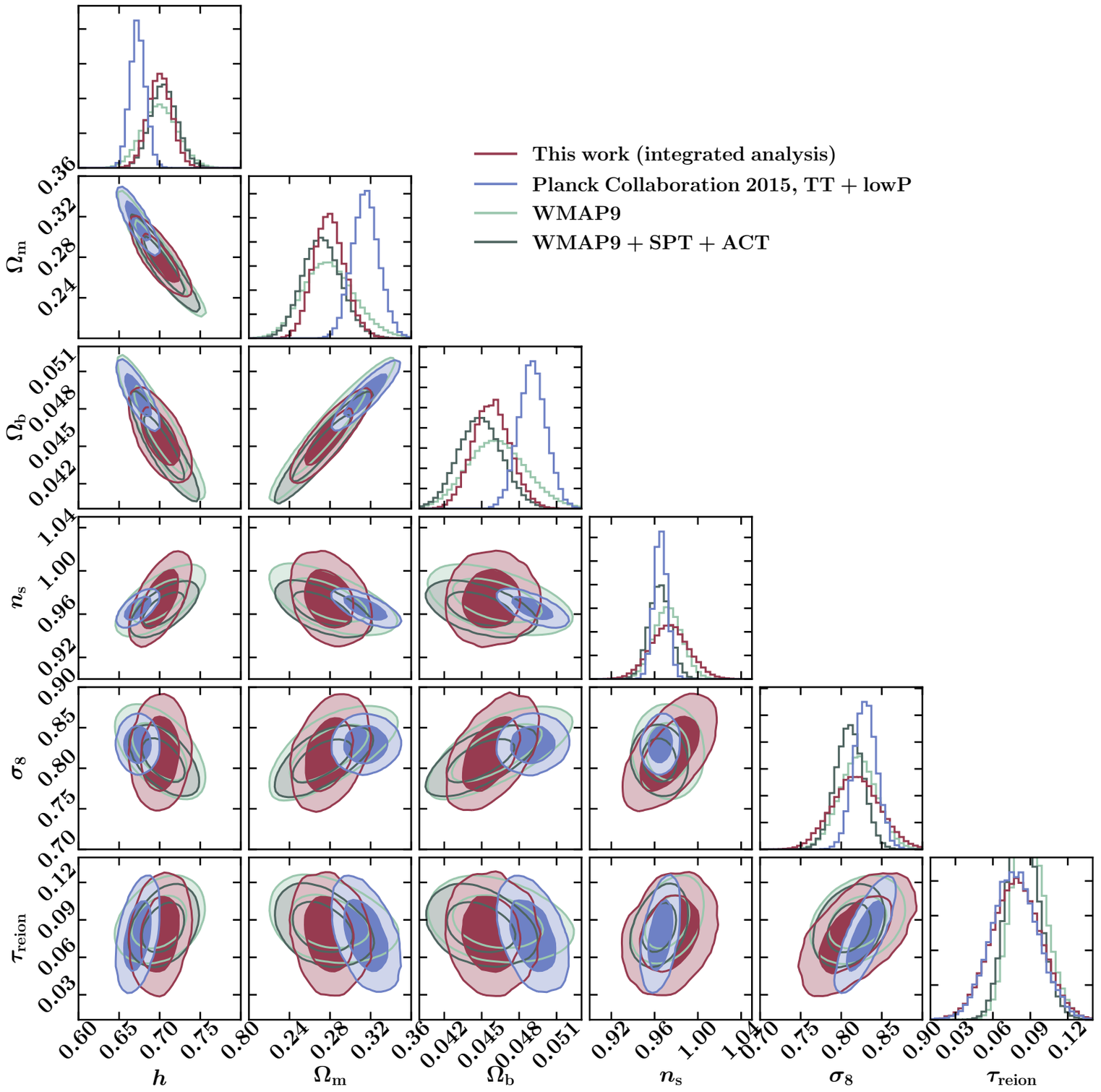
Nicola et al., 2017a

Model parameters

Parameter	
h	ΛCDM
$\Omega_{\rm m}$	
$\Omega_{\rm b}$	
$n_{\rm s}$	
σ_8	
$\tau_{\rm reion}$	
b	nuisance parameters
$m_*^{\rm SDSS}$	
$m_*^{\rm DES}$	
$m_{\kappa_{\rm CMB}}$	
α	
β	
$M_{\rm B}^1$	
ΔM	

Nicola et al., 2017a

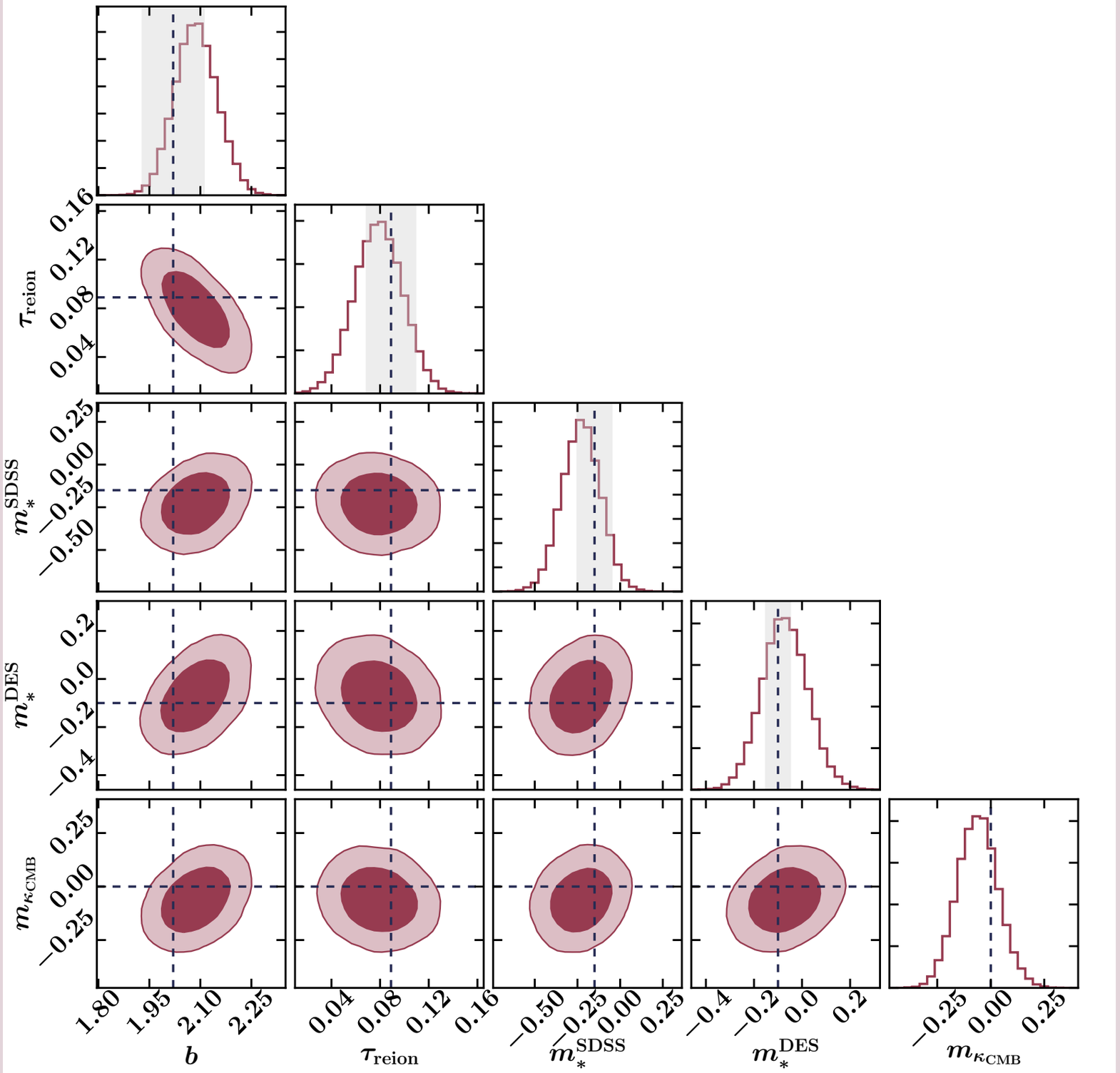
COSMOLOGICAL PARAMETER CONSTRAINTS



Concordance with Planck 2015 quantified in *Nicola et al., 2017b*: no sign for tensions

Nicola et al., 2017a

PROBE CALIBRATIONS



Nicola et al., 2017a

SUMMARY & CONCLUSIONS

Developed an integrated framework for cosmological probe combination

- Break parameter degeneracies
- Robust test of cosmological model
- Identification, understanding and calibration of systematics

Implementation with CMB temperature, CMB lensing, galaxy clustering, weak lensing from SDSS and DES SV and background probes leads to 12 power spectra

Derived constraints consistent with ΛCDM and no sign of tensions between probes

Quantification of possible tensions with relative entropy

Current: galaxy clusters with collaborators at USM

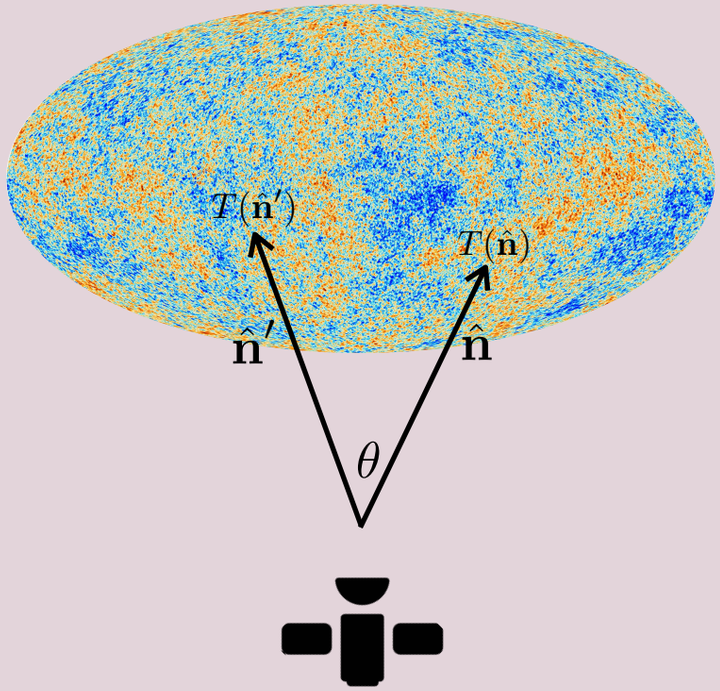
Future: tests of ΛCDM, application to current surveys

Thank you!

Backup

COSMOLOGICAL PROBES

Cosmic Microwave Background

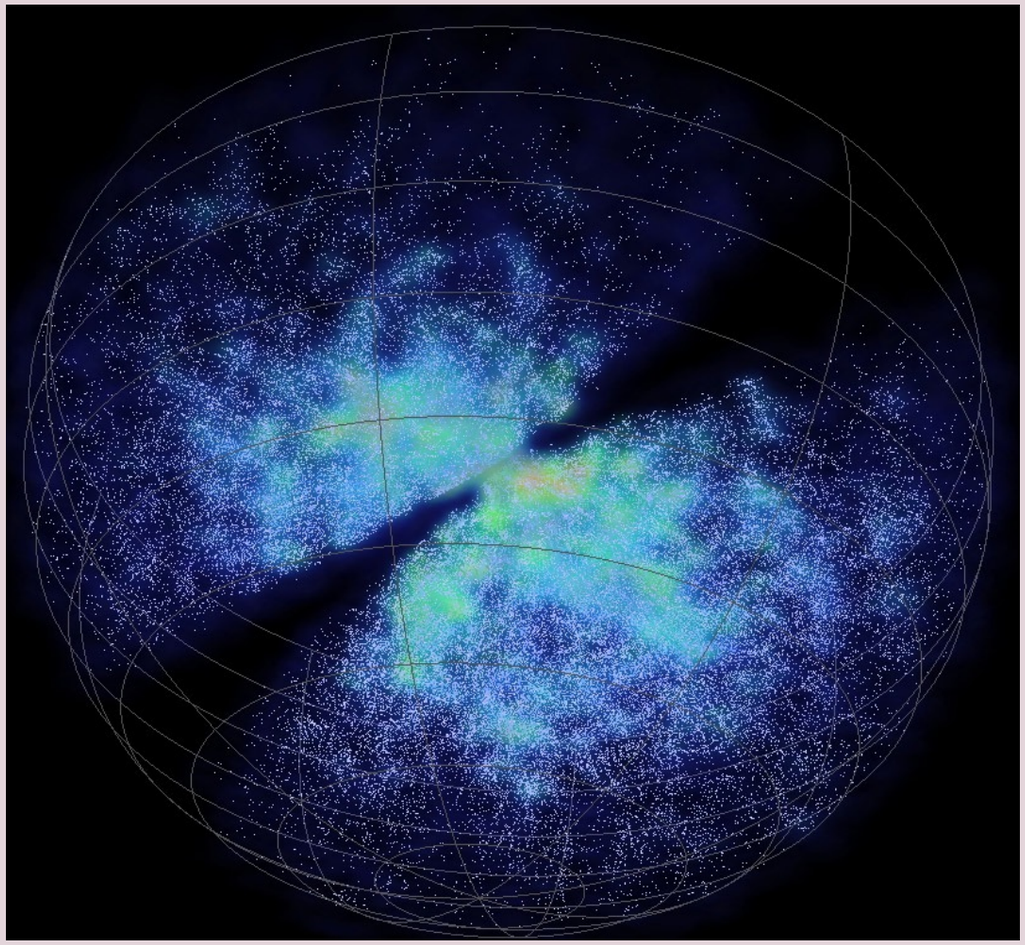


$$C(\theta) = \langle \frac{\Delta T(\hat{\mathbf{n}})}{\bar{T}} \frac{\Delta T(\hat{\mathbf{n}}')}{\bar{T}} \rangle \qquad C_\ell = \langle a_{\ell m} a_{\ell m} \rangle$$

Images: Planck,
Planck (Damien P. George)

COSMOLOGICAL PROBES

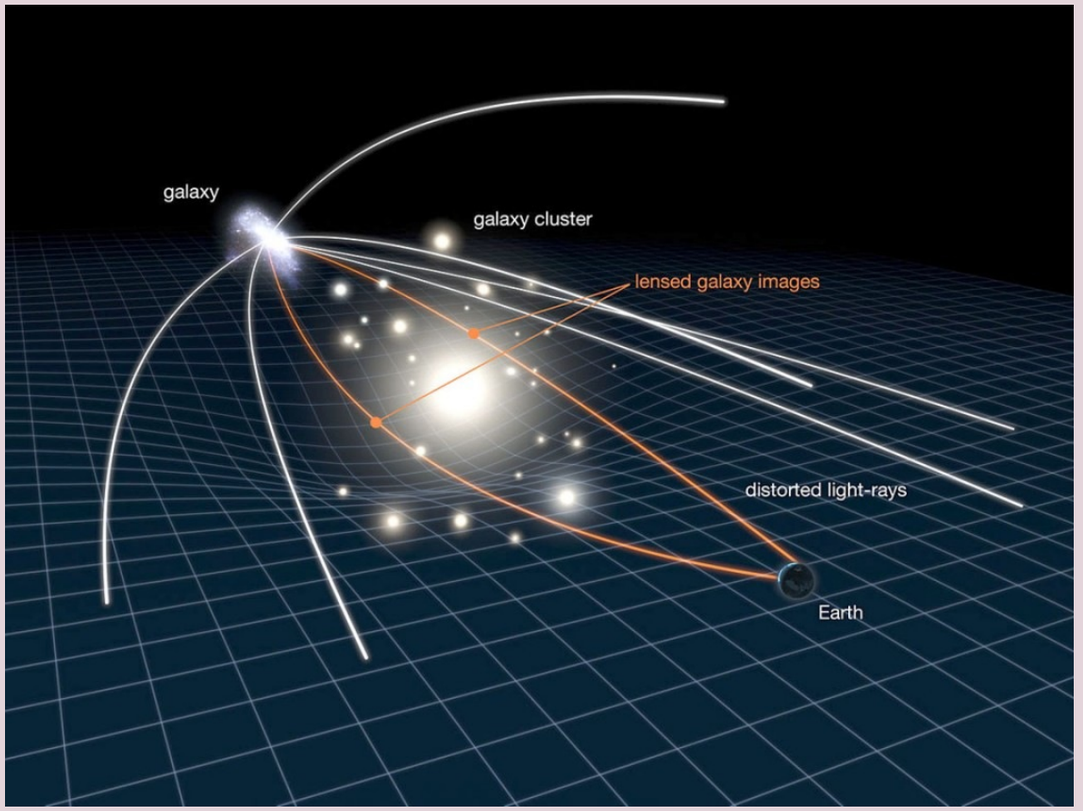
Galaxy clustering



Images: 6dF, Science News

COSMOLOGICAL PROBES

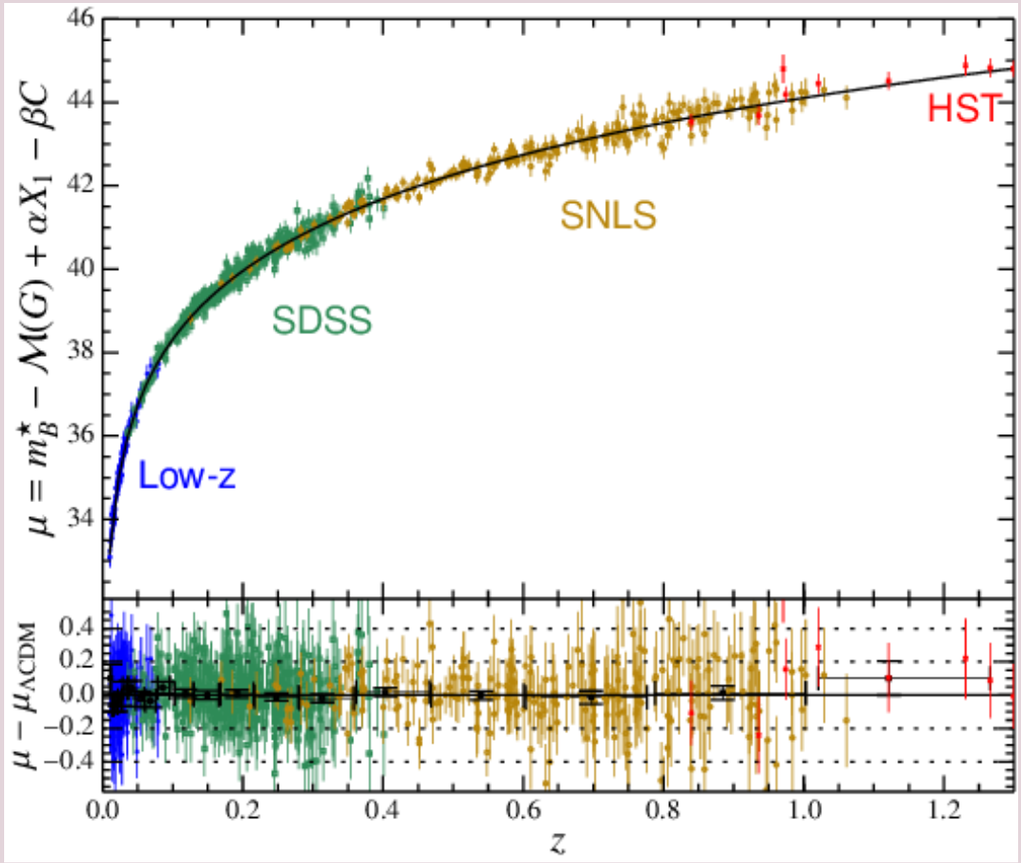
Weak gravitational lensing



Images: NASA/ESA, radioGREAT

COSMOLOGICAL PROBES

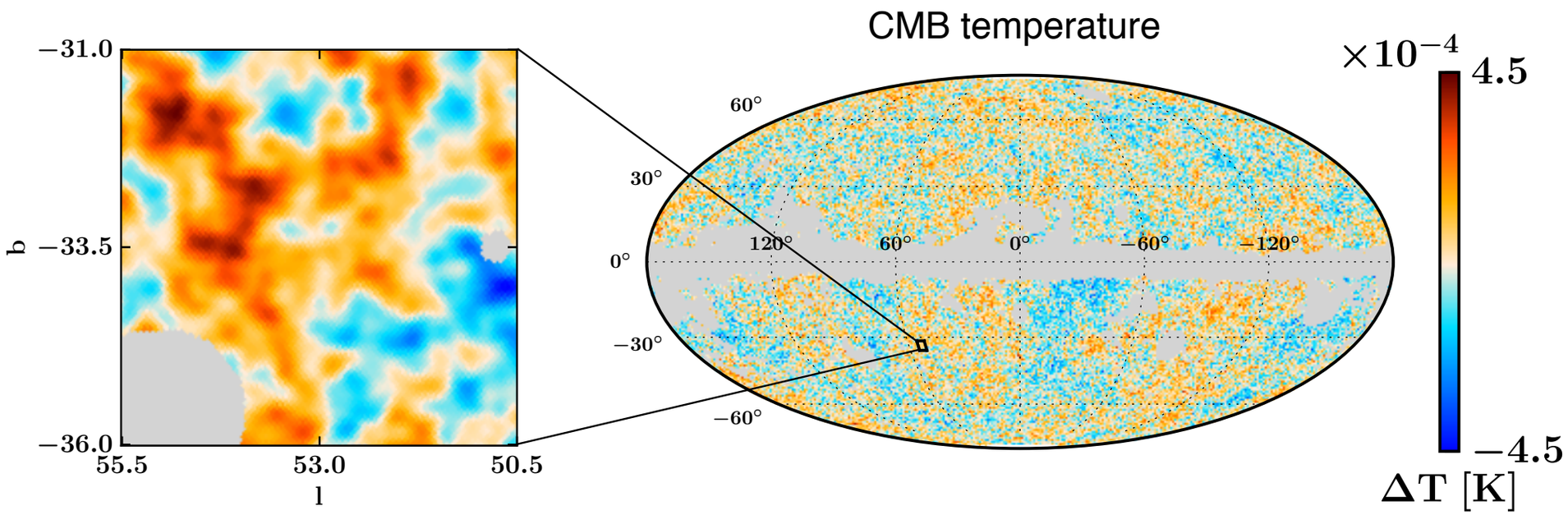
Supernovae

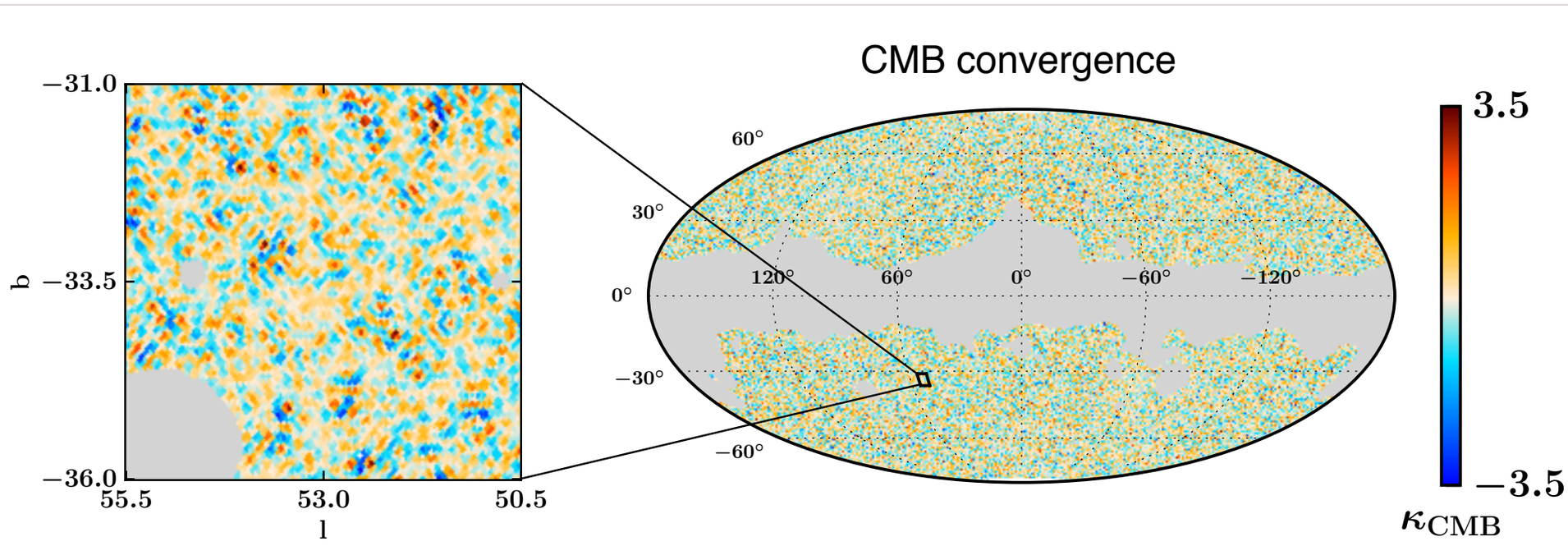


Images: HST, JLA

Cosmic Microwave Background

Data set: Planck 2015, *Planck Collaboration, 2015*

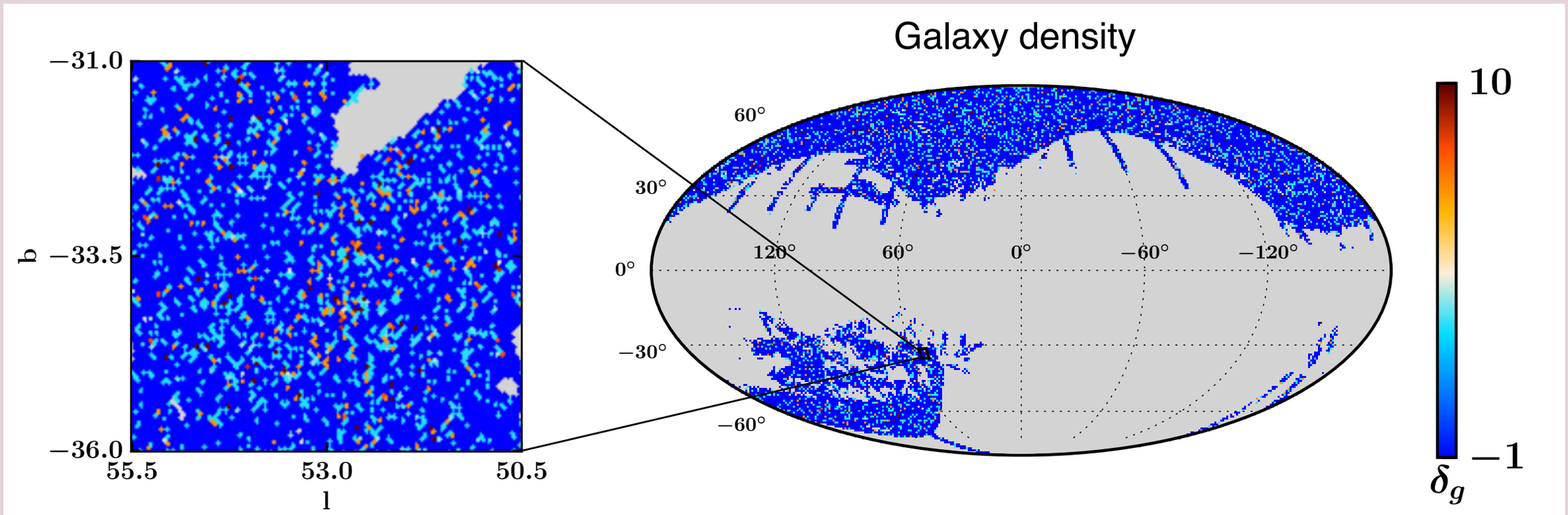




Nicola et al., 2016, 2017a

GALAXY DENSITY

Data set: SDSS DR8 CMASS1-4, *Aihara et al., 2011, Ho et al., 2012*



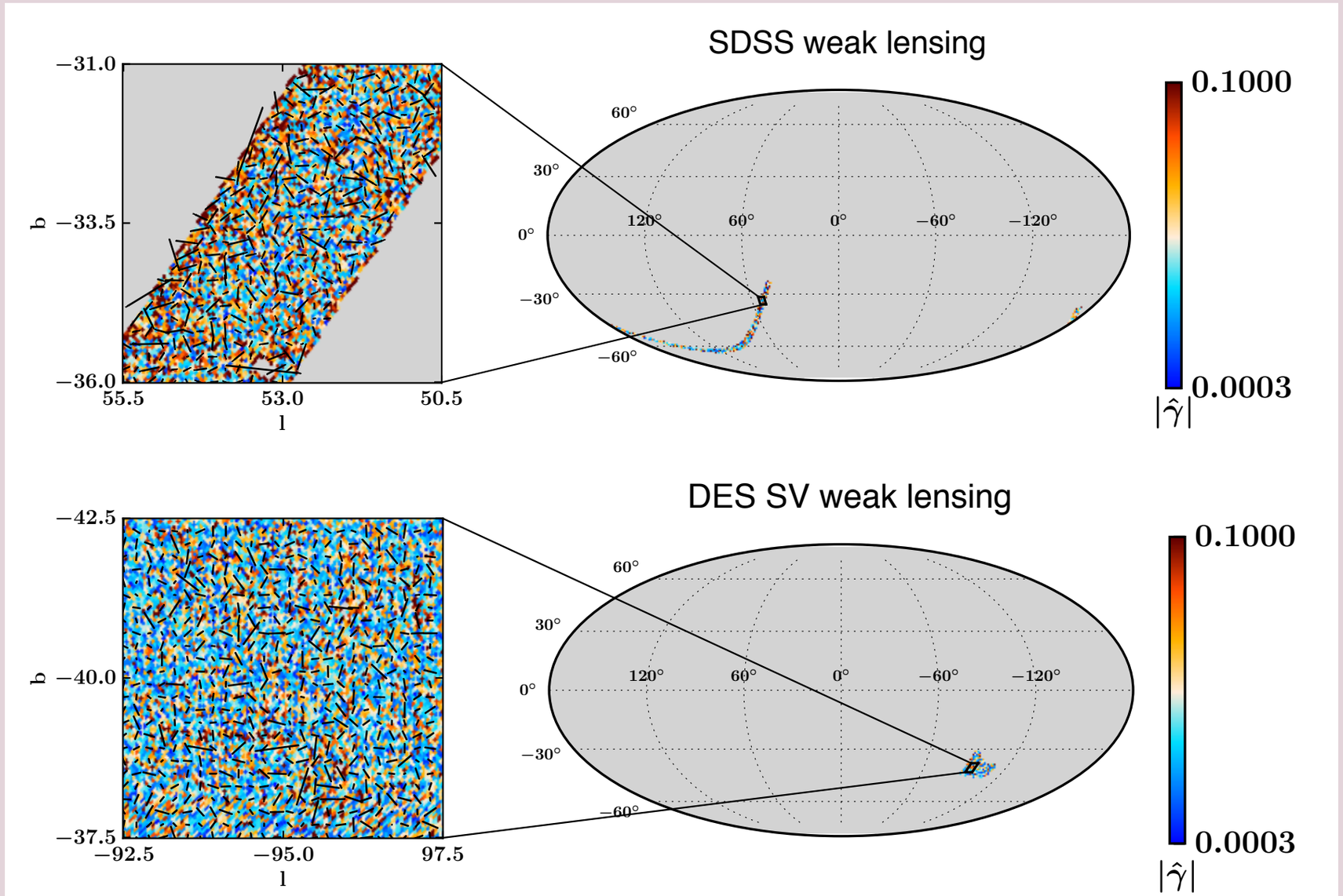
Nicola et al., 2016, 2017a

WEAK LENSING

Data sets:

SDSS Stripe 82 co-add, *Annis et al., 2014, Lin et al., 2012*

DES SV, *Jarvis et al., 2016, Becker et al., 2016*

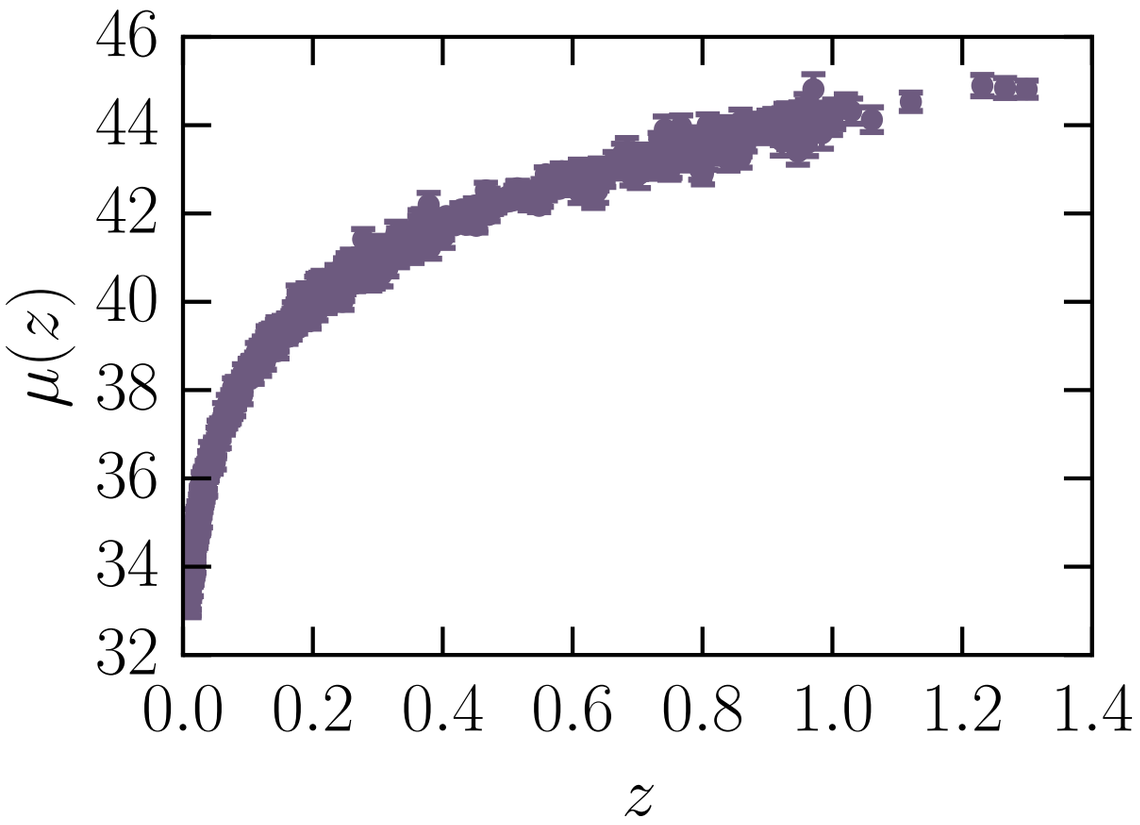


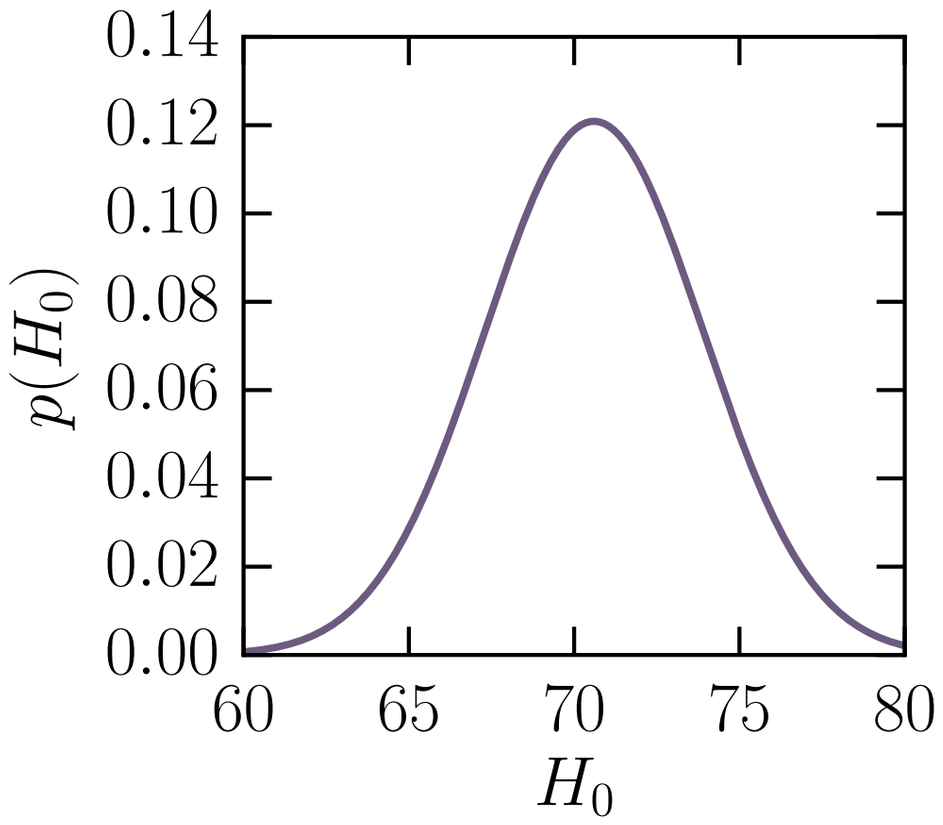
Nicola et al., 2016, 2017a

Background probes

Data sets:

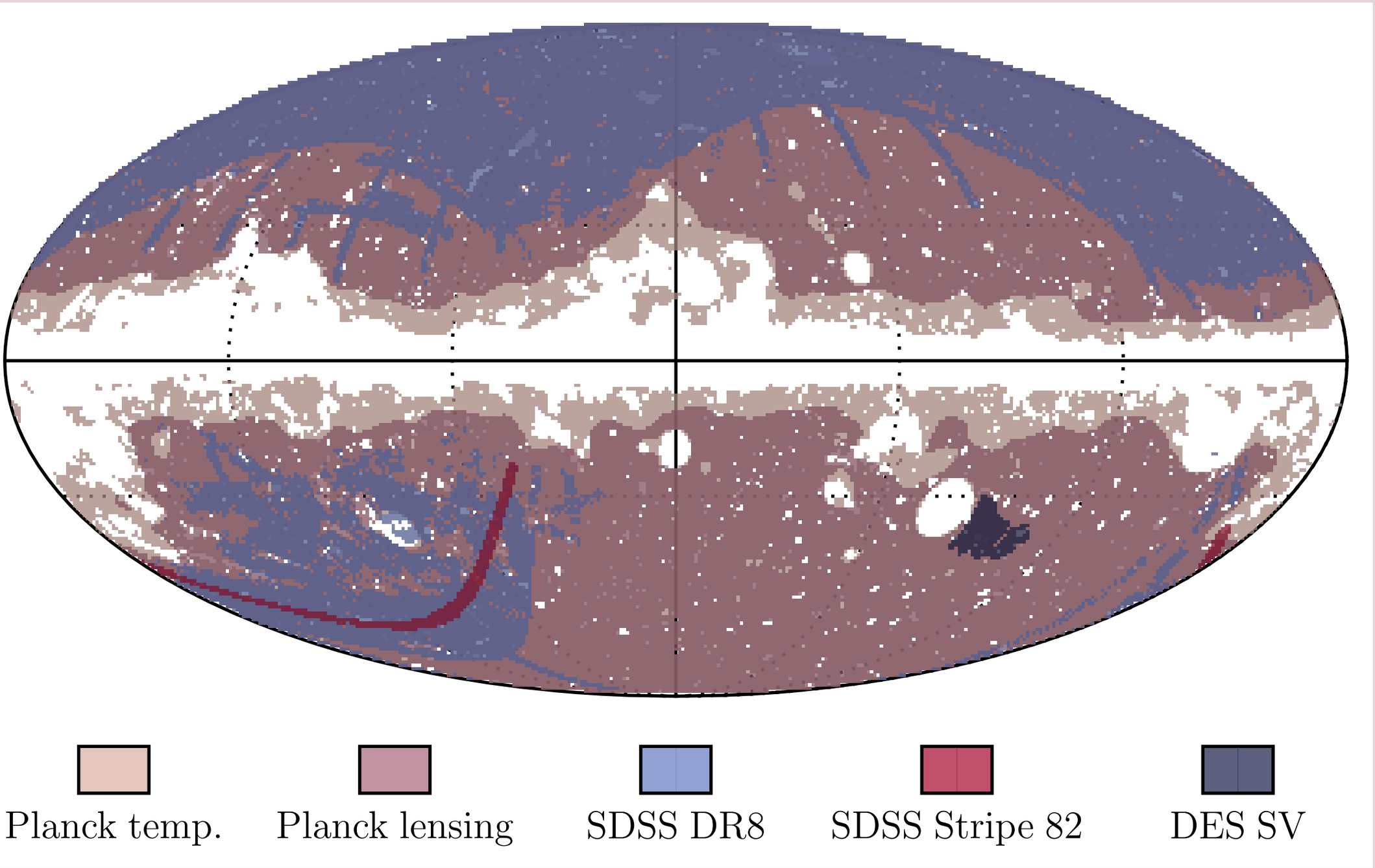
Joint Lightcurve Analysis (JLA), *Betoule et al., 2014*
H0, *Riess et al., 2011, Efstathiou, 2014*





Nicola et al., 2016, 2017a

Sky coverage



Nicola et al., 2017a

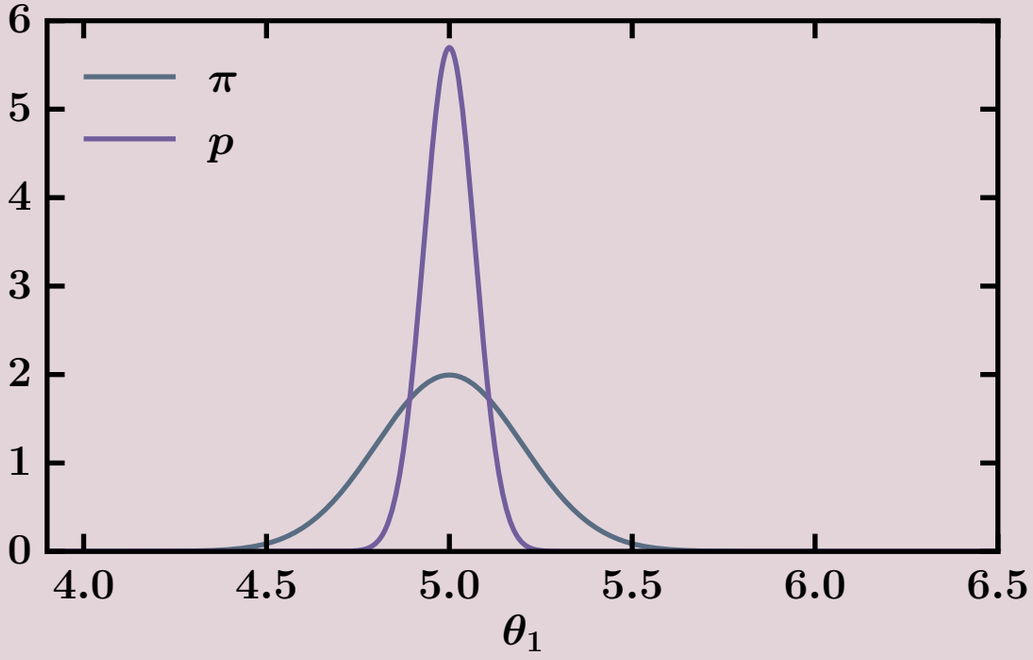
Relative entropy

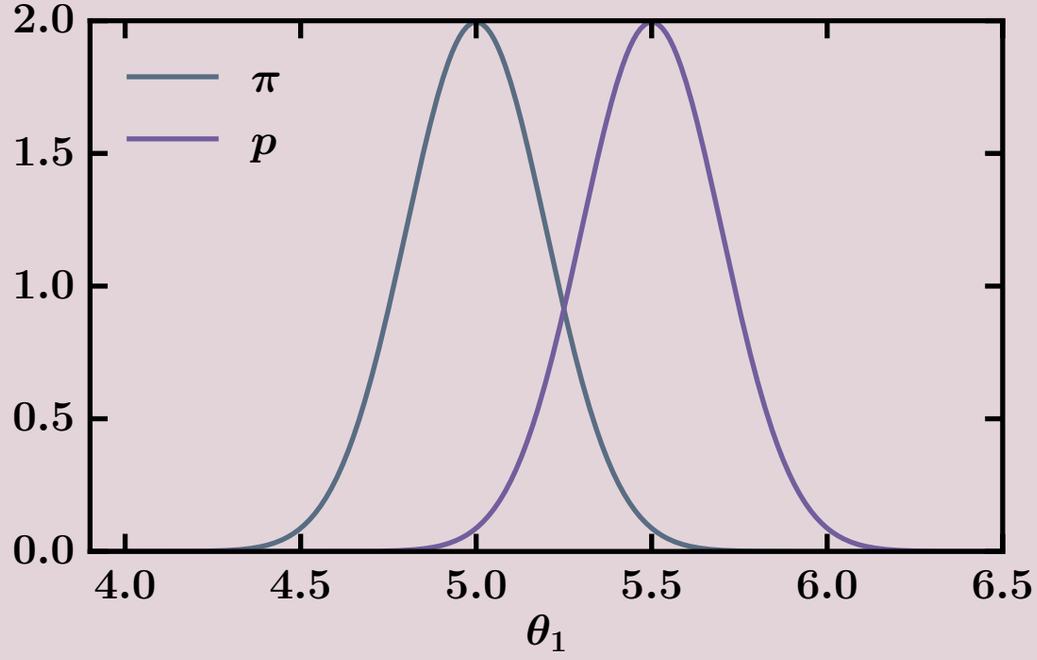
Measure for distance between

$\pi(\boldsymbol{\theta})$: prior

$p(\boldsymbol{\theta})$: posterior

$$D(p||\pi) = \int \mathrm{d}\boldsymbol{\theta}\; p(\boldsymbol{\theta}) \log \frac{p(\boldsymbol{\theta})}{\pi(\boldsymbol{\theta})}$$





Kullback & Leibler, 1951

SURPRISE - CONSISTENCY MEASURE

Measure for distance between

$\pi(\boldsymbol{\theta})$: prior

$p(\boldsymbol{\theta})$: posterior

$$D(p||\pi) = \int \mathrm{d}\boldsymbol{\theta}\; p(\boldsymbol{\theta}) \log \frac{p(\boldsymbol{\theta})}{\pi(\boldsymbol{\theta})}$$

observed

$$S = D(p||\pi) - \langle D \rangle$$

Surprise = observed - expected

Kullback & Leibler, 1951
Seehars et al., 2014, 2016
Grandis et al., 2016a, 2016b

QUANTIFICATION OF CONCORDANCE

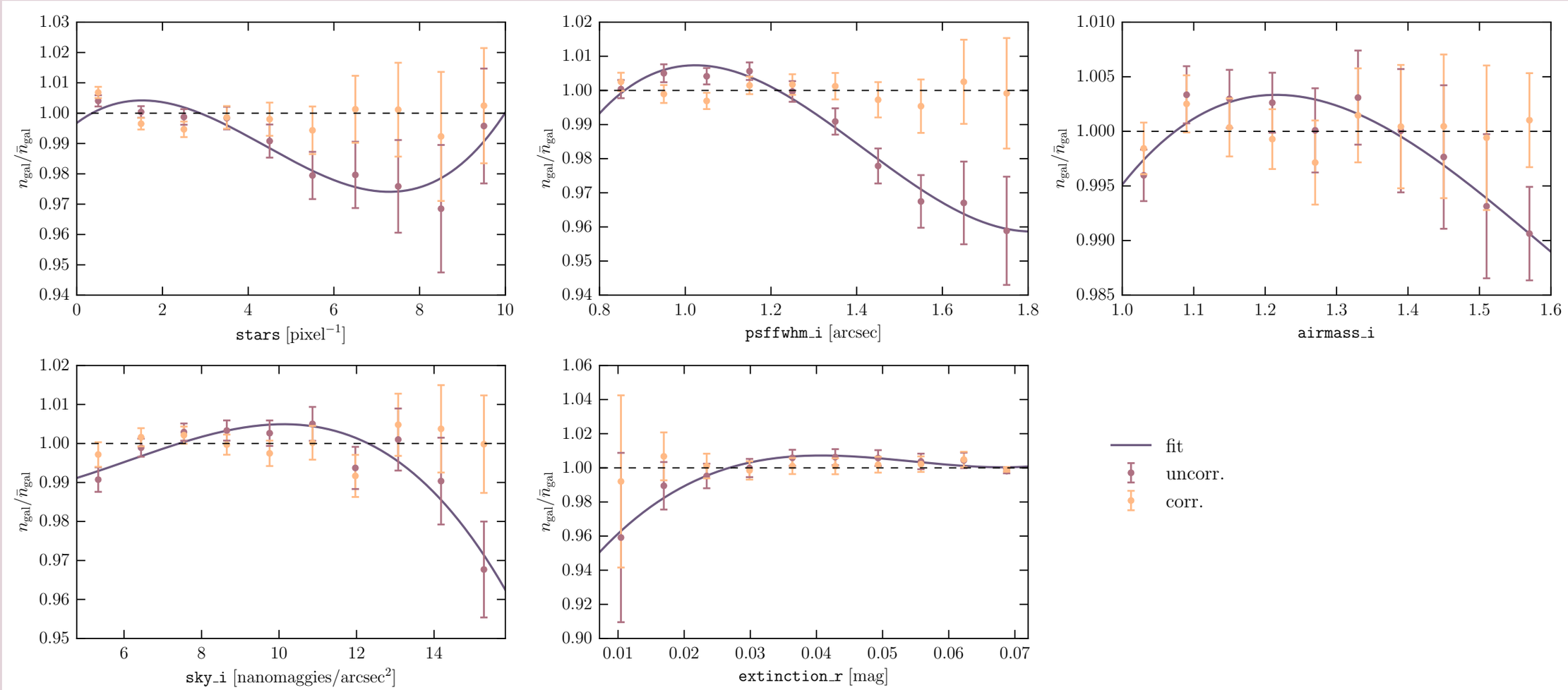
Data combination			Updating scheme	D	$\langle D \rangle$	S	$\sigma(D)$	p-value
CMB set	$\rightarrow$	P15	replace	9.1 (17.5) (8.3)	11.5 (12.4) (11.6)	-2.3 (5.1) (-3.3)	5.5 (4.5) (5.5)	0.4 (0.1) (0.3)
CMB set*	$\rightarrow$	P15	replace	13.7 (13.1) (12.6)	12.6 (13.4) (12.1)	1.1 (-0.4) (0.5)	6.5 (7.1) (6.1)	0.3 (0.6) (0.4)
CMB set*	$\rightarrow$	P15*	replace	9.6 (10.1)	9.7 (10.4)	-0.1 (-0.3)	4.7 (5.2)	0.6 (0.6)
IA	$\rightarrow$	IA+P15** hi-ℓ, massless ν	add	8.3 (8.3)	8.2 (8.1)	0.1 (0.2)	1.7 (1.7)	0.4 (0.4)
IA*	$\rightarrow$	IA*+P15** hi-ℓ, massless ν	add	10.7 (10.6)	9.3 (9.5)	1.5 (1.2)	1.8 (1.9)	0.2 (0.2)
IA	$\rightarrow$	IA+P15** hi-ℓ, massive ν	add	8.9 (-)	8.2 (-)	0.7 (-)	1.7 (-)	0.3 (-)

Nicola et al., 2017b

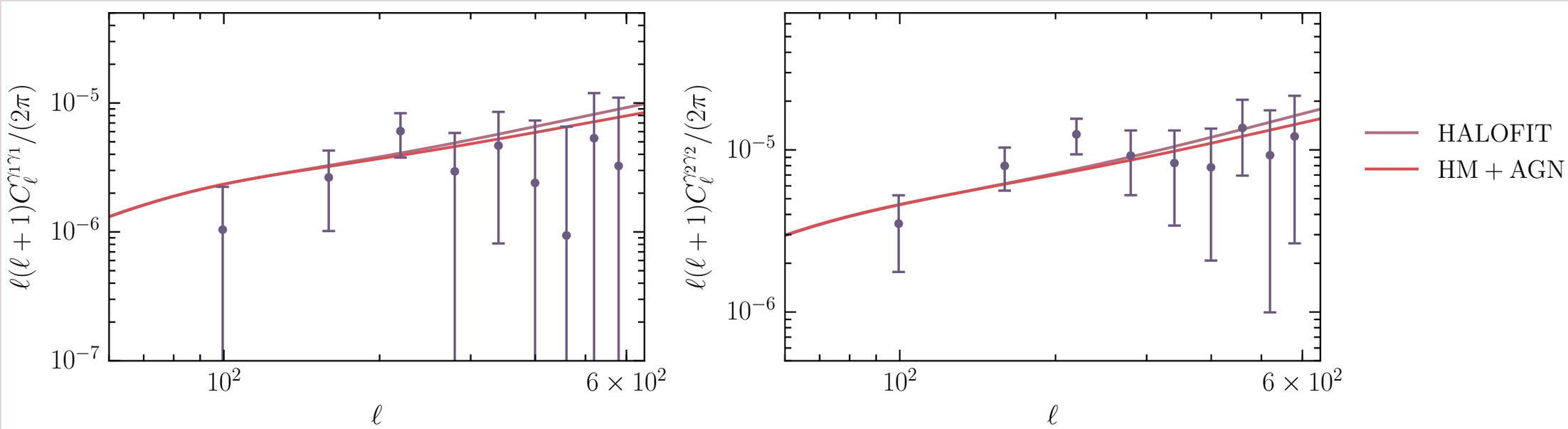
OVERVIEW OF DATA SETS

CMB temperature		Survey: Planck 2015 Fiducial foreground-reduced map: `Commander` Sky coverage: $f_{\rm sky} = 0.776$
Galaxy density		Survey: SDSS DR8 Sky coverage: $f_{\rm sky} = 0.27$ Galaxy sample: CMASS1-4 Number of galaxies: $N_{\rm gal} = 854\,063$ Photometric redshift range $0.45 \leq z_{\rm phot} < 0.65$
Weak lensing	SDSS Stripe 82	Survey: SDSS Stripe 82 co-add Sky coverage: $f_{\rm sky} = 0.0069$ Number of galaxies: $N_{\rm gal} = 3\,322\,915$ Photometric redshift range: $0.1 \lesssim z_{\rm phot} \lesssim 1.1$ r.m.s. ellipticity per component: $\sigma_e \sim 0.43$
	DES	Survey: DES SV Sky coverage: $f_{\rm sky} = 0.0039$ Number of galaxies: $N_{\rm gal} = 3\,279\,967$ Photometric redshift range: $0.3 < z_{\rm phot} < 1.3$ r.m.s. weighted ellipticity per component: $\sigma_e \sim 0.24$
CMB lensing		Survey: Planck 2015 Sky coverage: $f_{\rm sky} = 0.67$
SNe Type Ia		Compilation: JLA Number of SNe: $N_{\rm SNe} = 740$ Redshift range: $0.01 < z < 1.3$
Hubble parameter		Distance anchor: NGC 4258 Number of Cepheids: $N_{\rm Ceph.} = 600$ Number of SNe: $N_{\rm SNe} = 8$ Analysis: Efstathiou, 2014

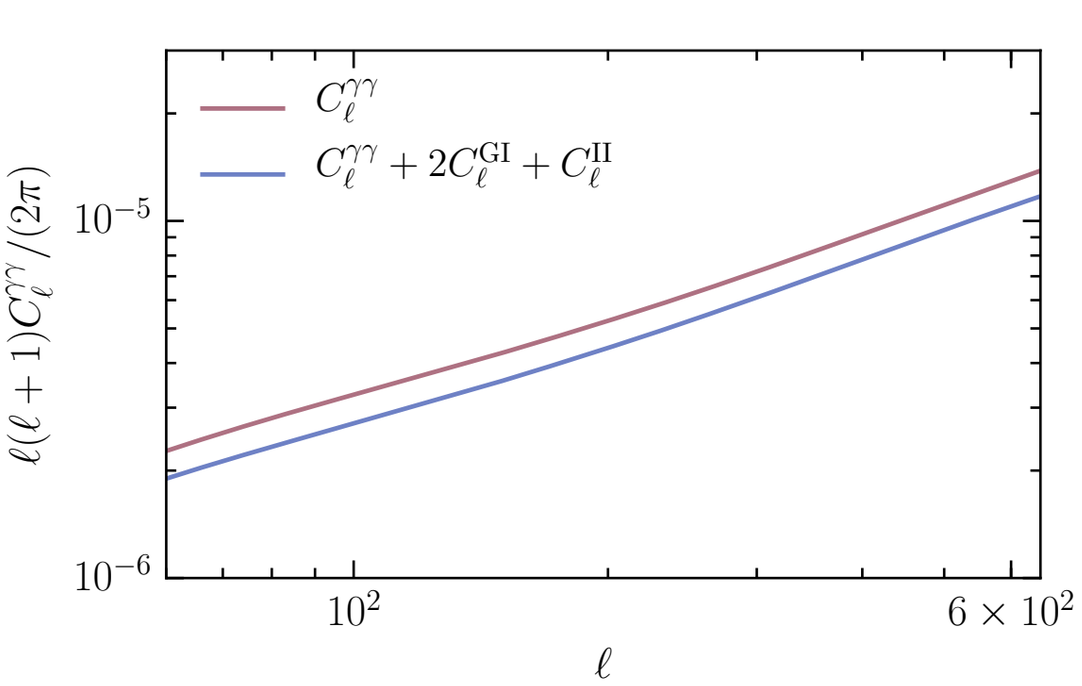
SYSTEMATICS CORRECTION FOR GALAXY CLUSTERING

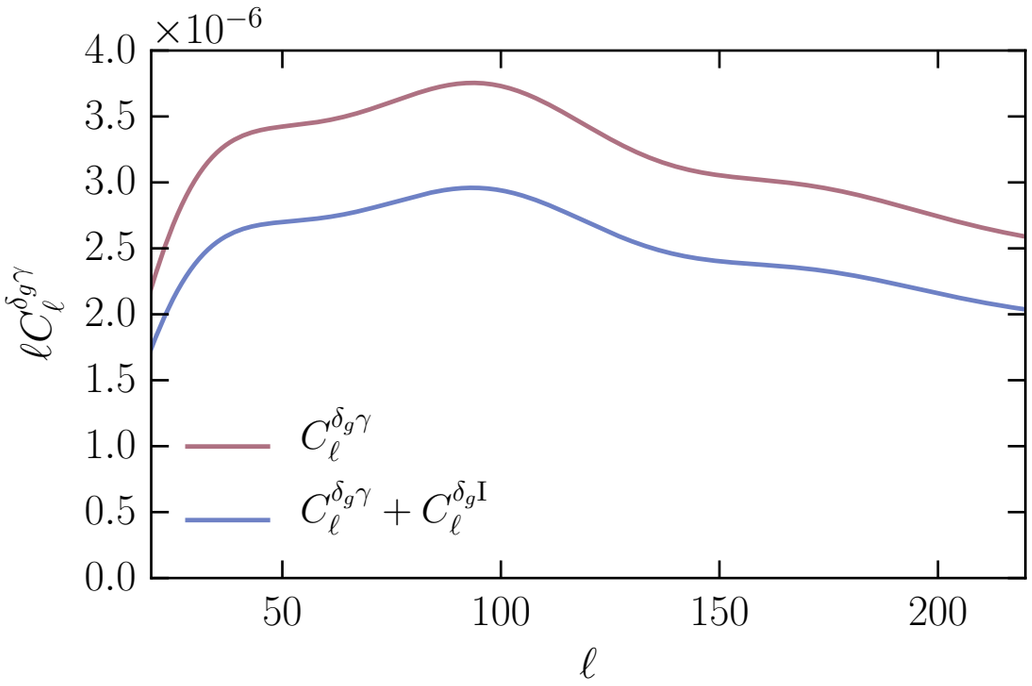


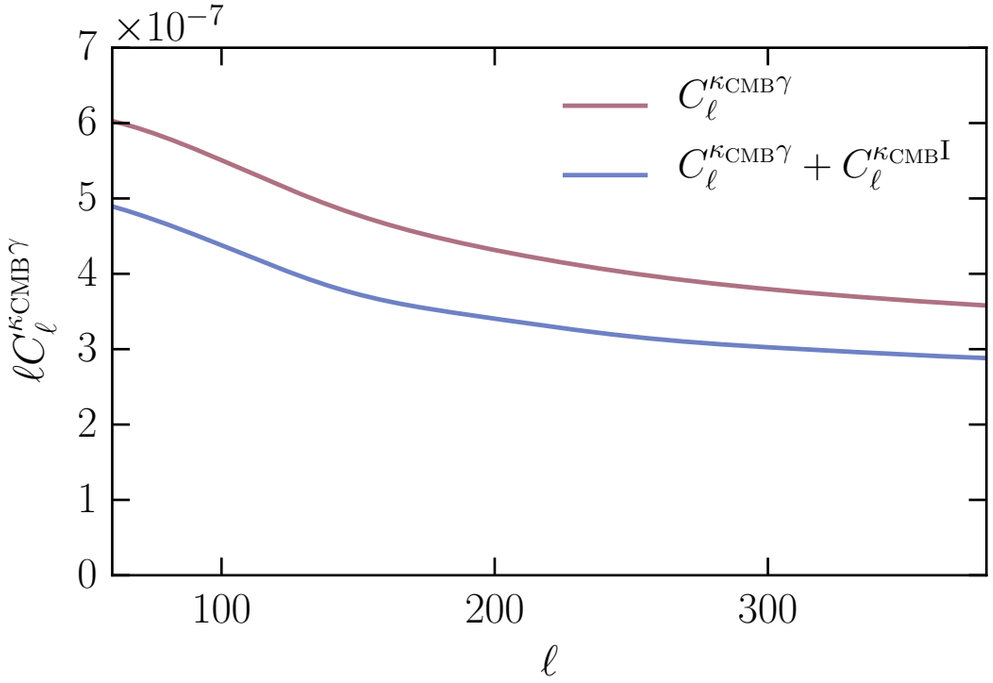
BARYONIC CORRECTIONS TO THE MATTER POWER SPECTRUM



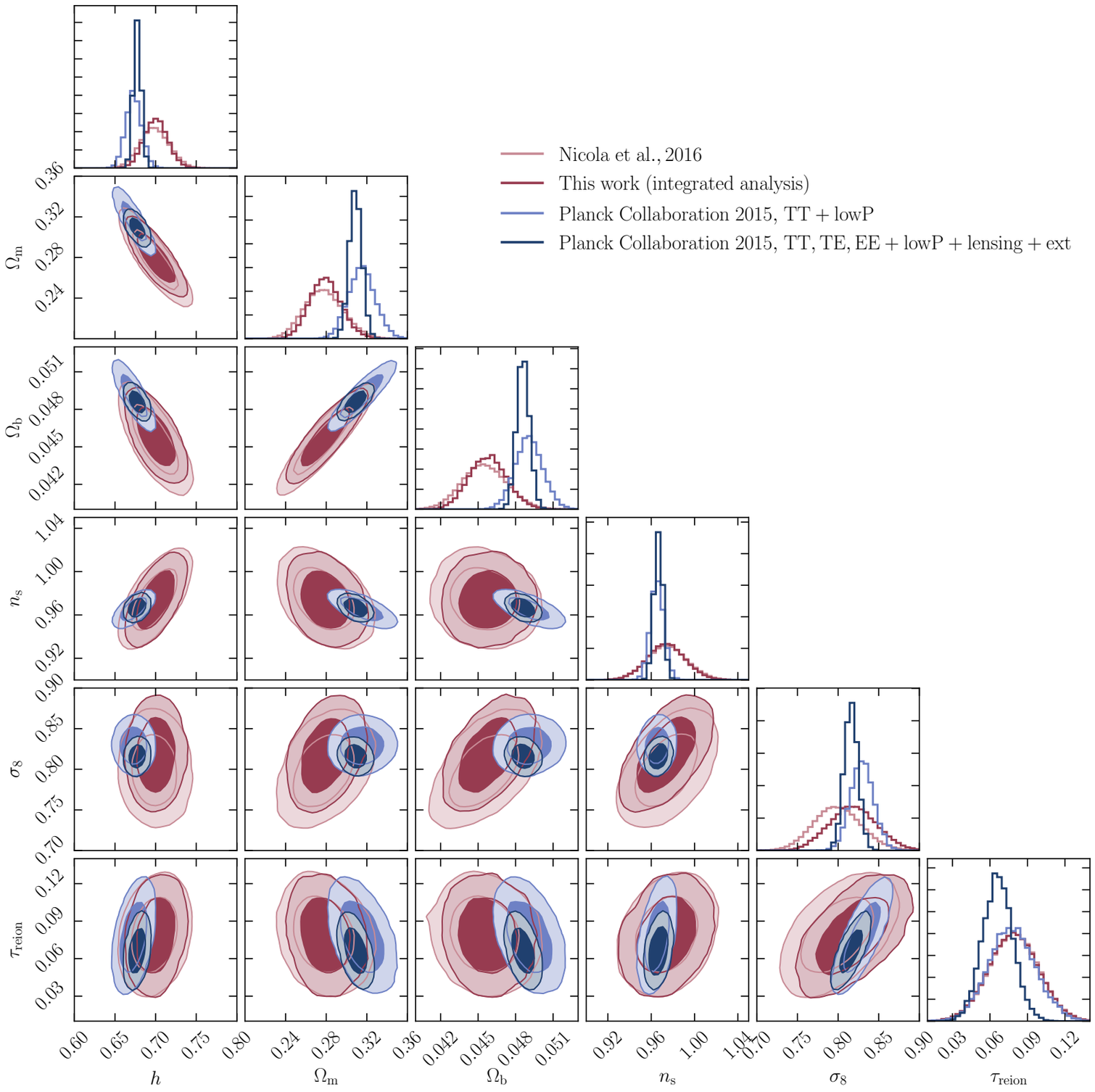
TREATMENT OF INTRINSIC ALIGNMENTS



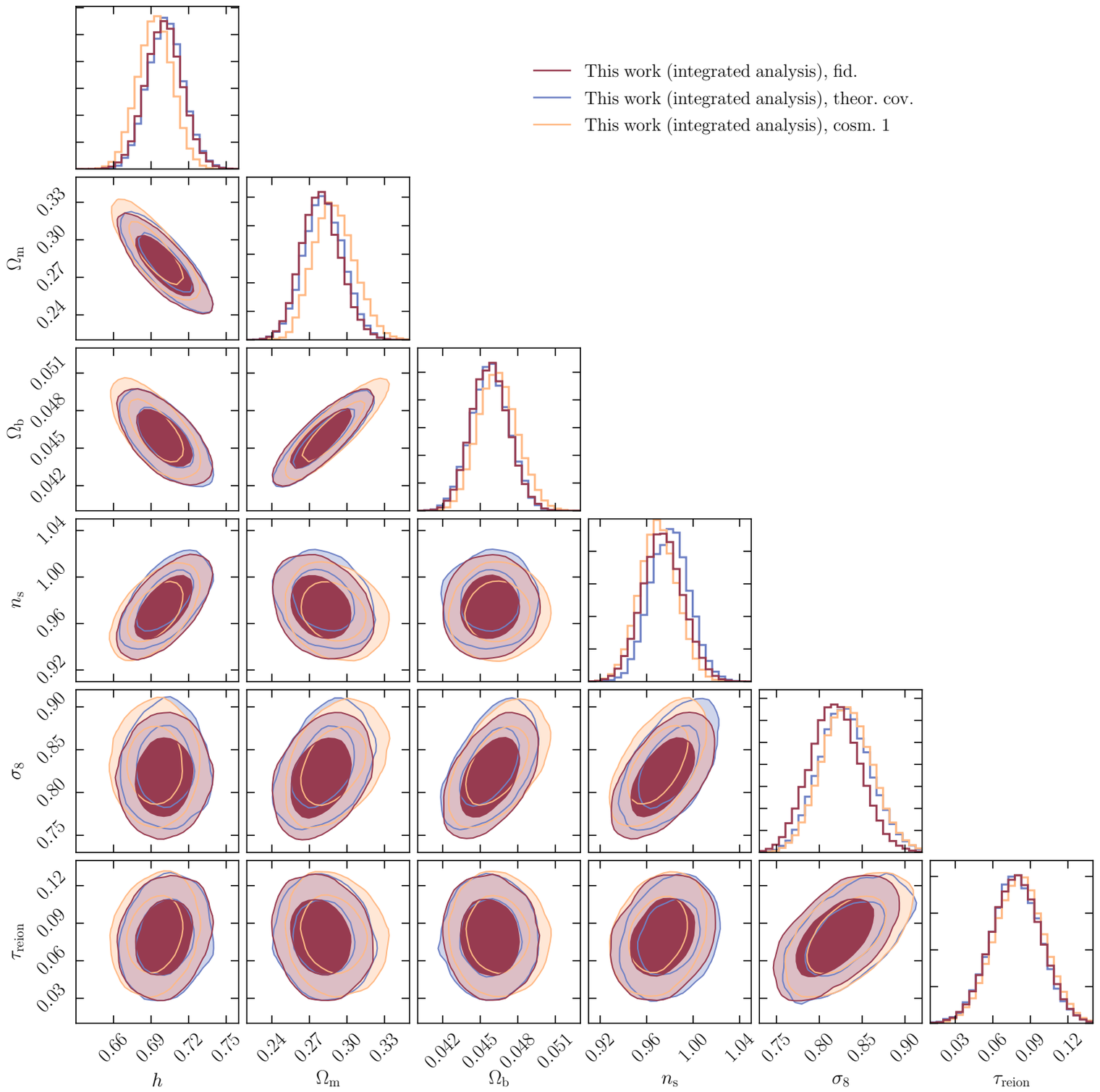




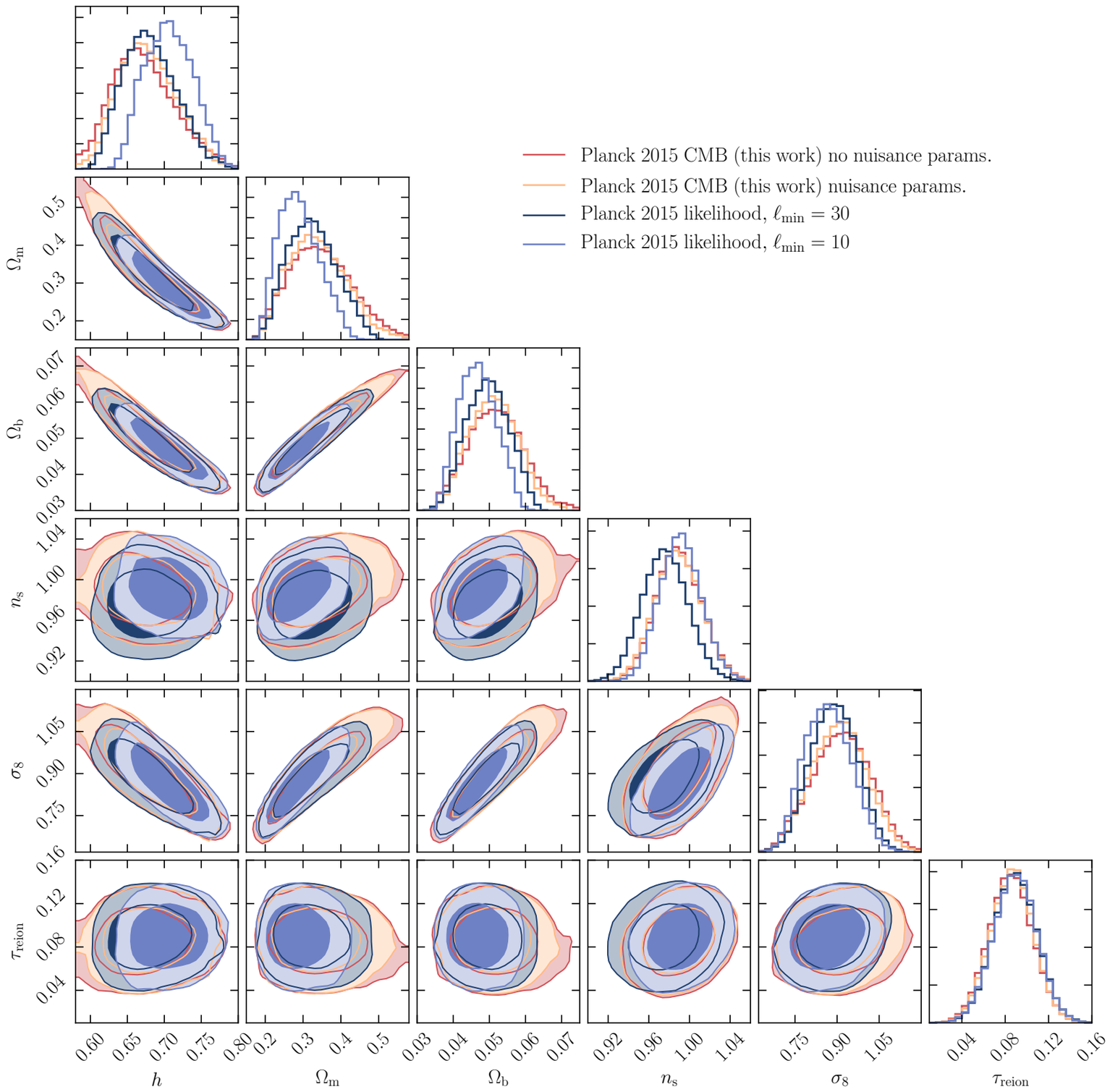
COMPARISON EXTENDED TO ORIGINAL IA



Sensitivity of cosmological constraints



Comparison to Planck 2015



COSMOLOGICAL PARAMETER CONSTRAINTS

Parameter	Prior	Posterior mean
h	flat $\in [0.2, 1.2]$	0.700 ± 0.014
$\Omega_{\rm m}$	flat $\in [0.1, 0.7]$	0.279 ± 0.015
$\Omega_{\rm b}$	flat $\in [0.01, 0.09]$	0.0458 ± 0.0015
$n_{\rm s}$	flat $\in [0.1, 1.8]$	$0.974^{+0.018}_{-0.017}$
σ_8	flat $\in [0.4, 1.5]$	0.819 ± 0.029
$\tau_{\rm reion}$	Gaussian with $\mu = 0.089$, $\sigma = 0.02$	$0.0787^{+0.0200}_{-0.0199}$
b	flat $\in [1., 3.]$	2.09 ± 0.06
$m_*^{\rm SDSS}$	Gaussian with $\mu = 0.0$, $\sigma = 0.22$	-0.229 ± 0.113
$m_*^{\rm DES}$	Gaussian with $\mu = 0.0$, $\sigma = 0.22$	$-0.0708^{+0.0953}_{-0.0946}$
$m_{\kappa_{\rm CMB}}$	flat $\in [-0.5, 0.5]$	$-0.0598^{+0.0941}_{-0.0946}$
α	flat $\in [0.1, 0.2]$	0.142 ± 0.007
β	flat $\in [2., 4.]$	3.11 ± 0.08
$M_{\rm B}^1$	flat $\in [-25., -10.]$	-19.06 ± 0.02
ΔM	flat $\in [-0.13, -0.01]$	$-0.0711^{+0.0230}_{-0.0227}$