CMB and LSS as seen by large experiments: cross-correlation, status and future prospects

Carlo Baccigalupi
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KASI Conference, April 16th, 2014

Outline

- Meeting each other
- CMB-LSS cross-correlation effects
- Evidences and implications
- The B-modes
- Planck 2013
- Planck 2014
- Euclid 2020
- More CMB from space
- Work at SISSA
- Conclusions

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April 16th

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April 23rd

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CMB and LSS groups at SISSA

- SISSA is located in Trieste, Italy
- Within Astrophysics, the CMB group is made of 5 post-docs (Basak, Bielewicz, Castex, Fabbian, Paci), 2 PhD student (Krachmalnicoff, Puglisi), the LSS group is made of 2 post-docs (Martinelli, Silvestri), 5 PhD studens (Antolini, Bianchini, Calabrese, Frusciante, Raveri)
- It constitutes the Planck Low Frequency Instrument Data Processing Centre together with the Astronomical Observatory with responsibility mainly on:
  - Production of Planck maps at 30, 44, 70 GHz
  - Production of CMB maps
- It is involved in the EBEX, PolarBear sub-orbital CMB experiments
- It is involved in Euclid for coordinating the activity in preparation to the Cross-Correlation with CMB

CMB-LSS Cross-Correlation effects

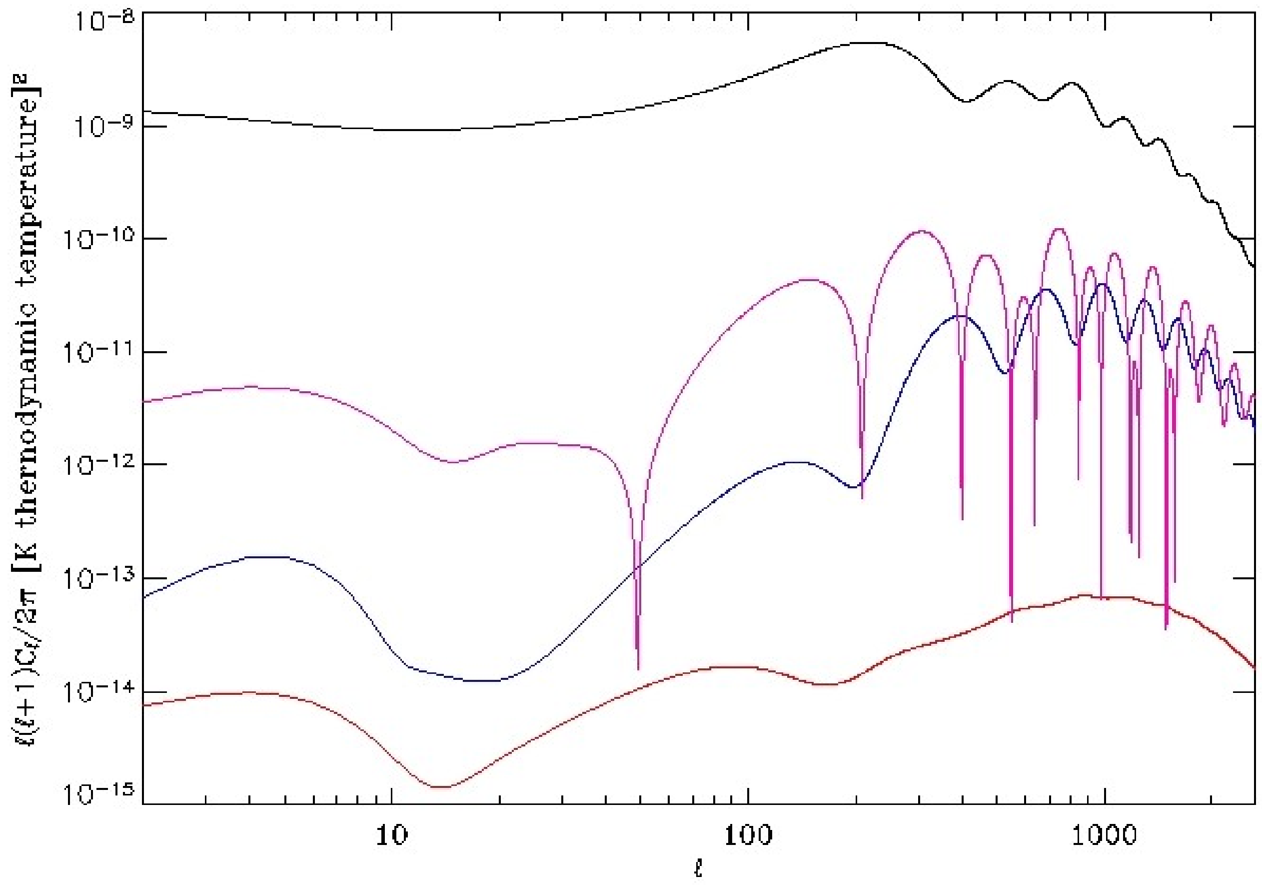
LSS effects on CMB

- Re-scattering
- Gravitation

LSS effects on CMB

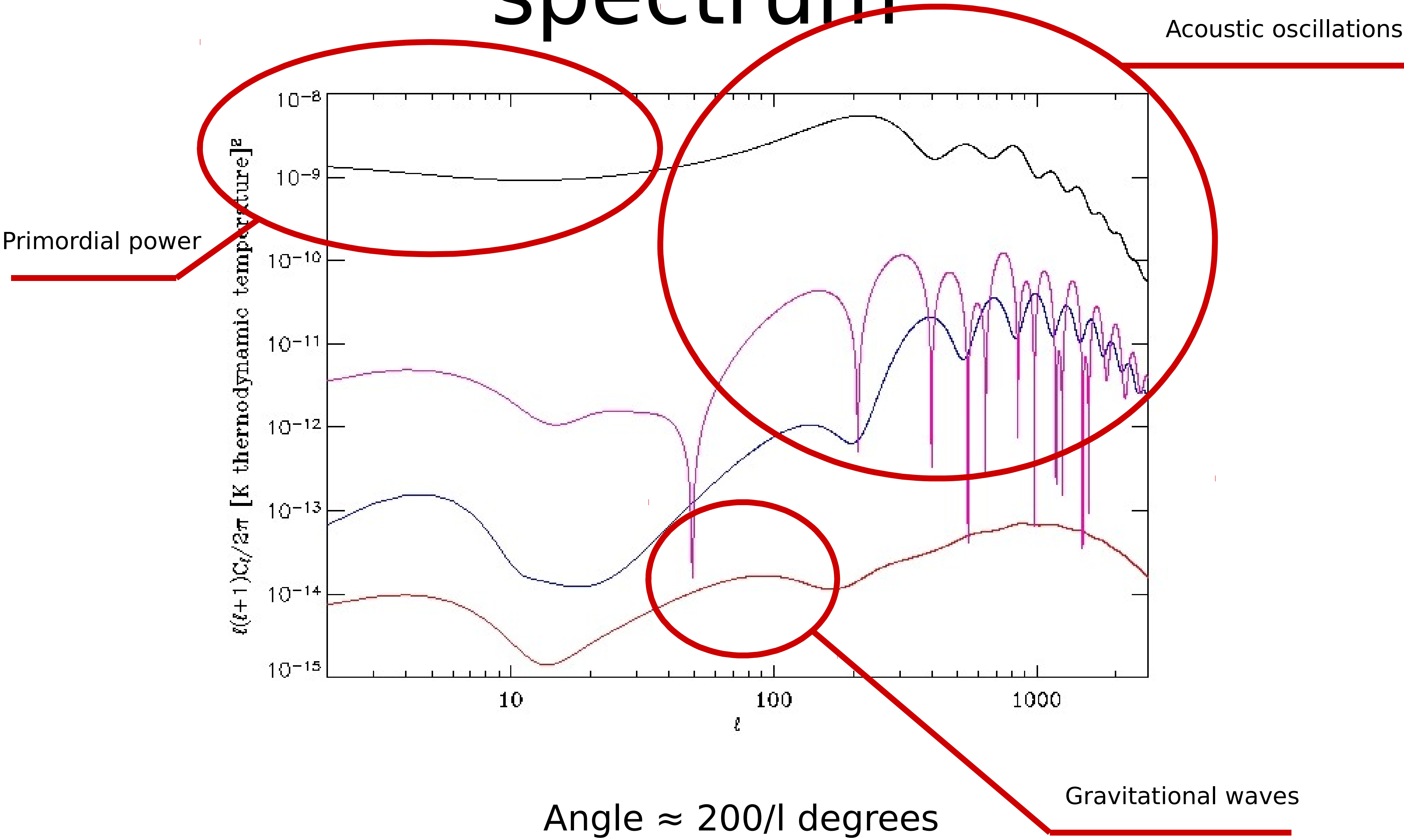
- Re-scattering
  - Re-ionization
- Gravitation
  - Time evolution of the metric tensor
  - Deflection

CMB angular power spectrum



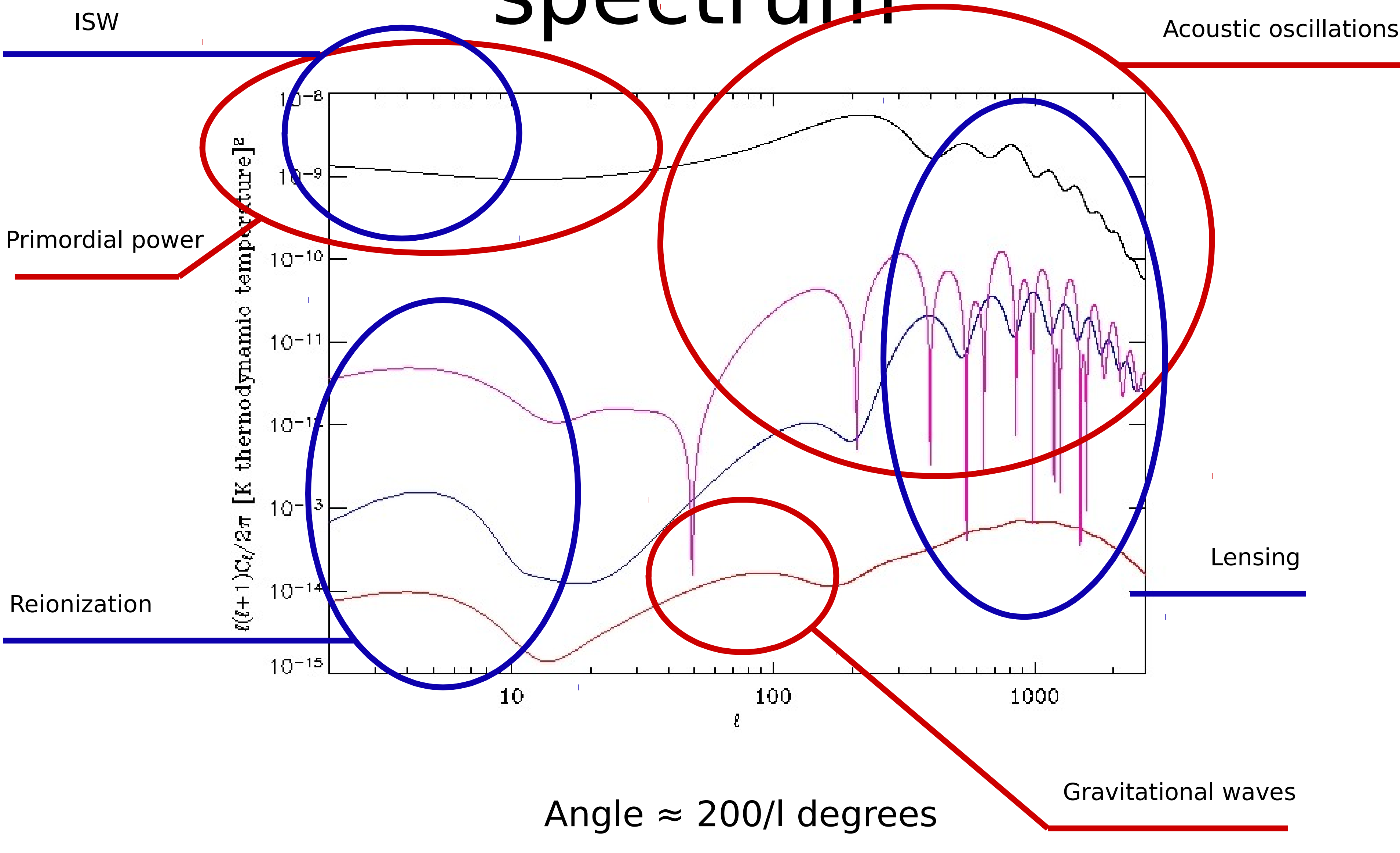
Angle ≈ 200/l degrees

CMB angular power spectrum



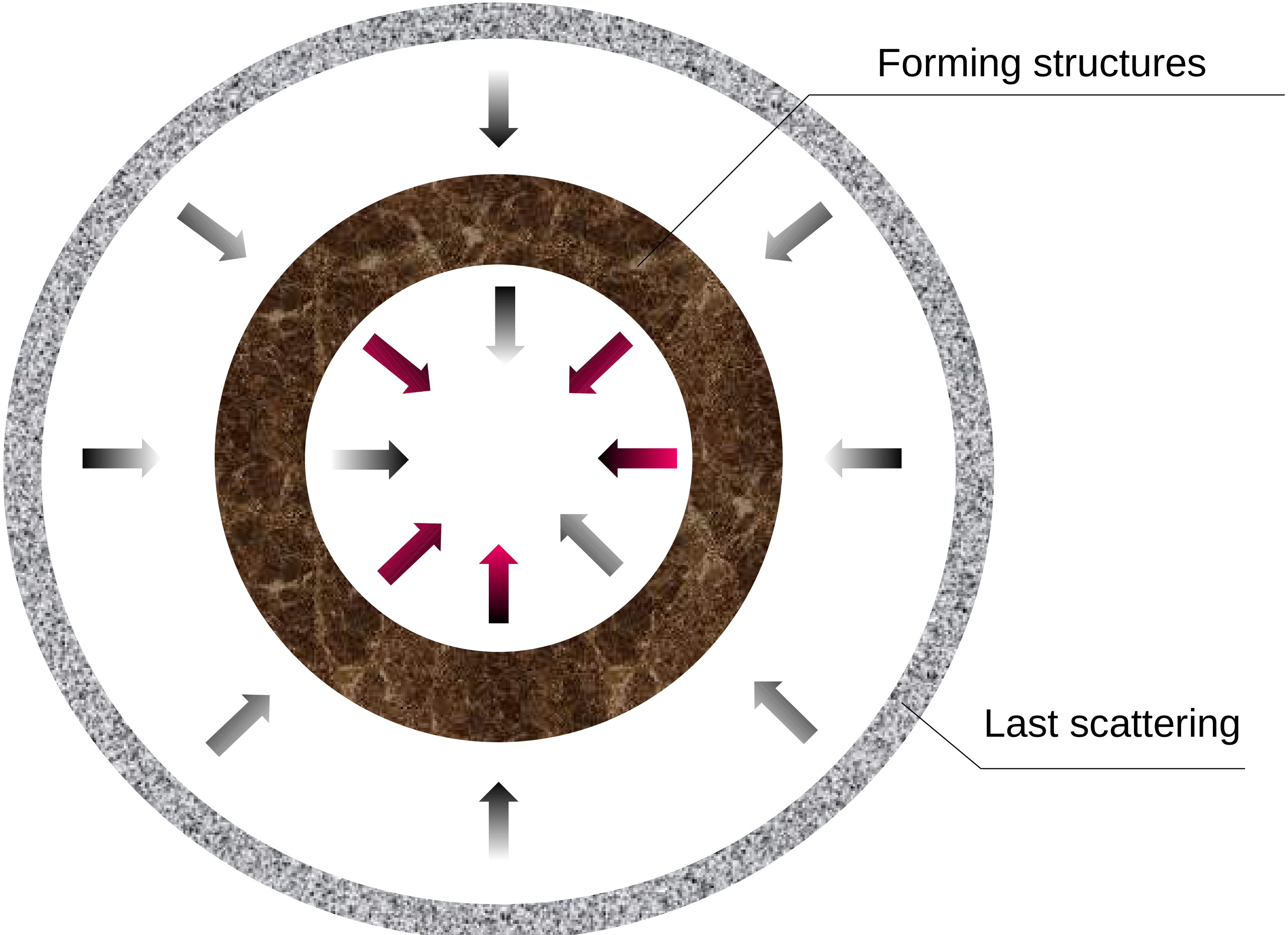
Angle ≈ 200/l degrees

CMB angular power spectrum



Angle ≈ 200/l degrees

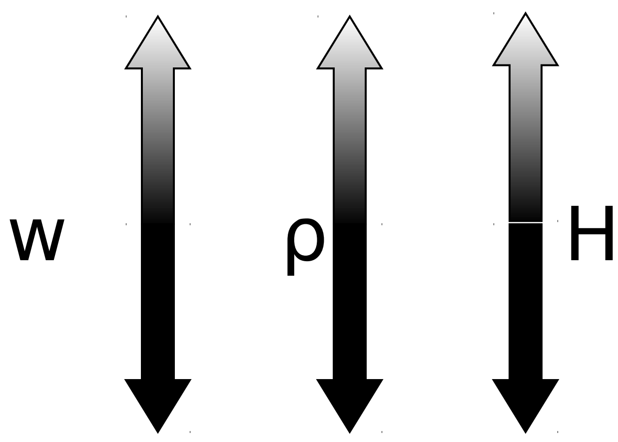
Integrated Sachs-Wolfe

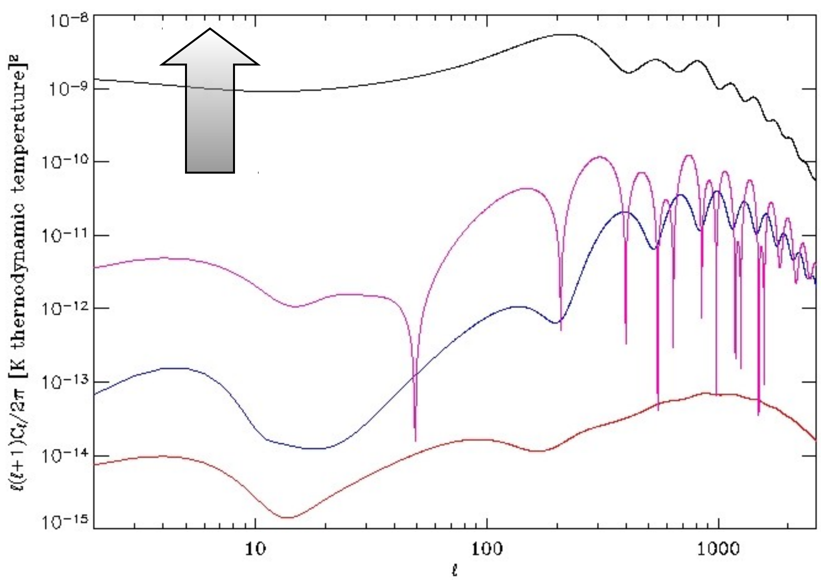


Sachs & Wolfe 1967

Integrated Sachs-Wolfe

Cosmological friction for cosmological perturbations∝H





Cross-correlating with LSS

$$\frac{\Delta T}{T}^{\rm ISW}(\hat{\mathbf{n}}) = -2\int \dot{\Phi}[\eta, \hat{\mathbf{n}}(\eta_0 - \eta)]d\eta \qquad \delta_{\rm g}(\hat{\mathbf{n}}_1) = \int f(z)\delta_{\rm m}(\hat{\mathbf{n}}_1, z)dz = \int b_{\rm g}(z)\frac{dN}{dz}(z)\delta_{\rm m}(\hat{\mathbf{n}}_1, z)dz$$

$$C^{\rm gT}(\theta) \equiv \left\langle \frac{\Delta T}{T}(\hat{\mathbf{n}}_1)\delta_{\rm g}(\hat{\mathbf{n}}_2)\right\rangle = \sum_{\ell=2}^{\infty}\frac{2\ell+1}{4\pi}C_\ell^{\rm gT}P_\ell[\cos(\theta)]\exp[-0.5(\theta_s\ell)^2]$$

$$C_\ell^{\rm gT} = \frac{2}{\pi}\int k^2 dk P(k) I_\ell^{\rm ISW}(k) I_\ell^{\rm g}(k)$$

$$I_\ell^{\rm ISW}(k) = -2\int \frac{d\Phi(k)}{dz} j_\ell[k\chi(z)]dz \qquad I_\ell^{\rm g}(k) = \int b_{\rm g}(z)\frac{dN}{dz}(z)\delta_{\rm m}(k, z) j_\ell[k\chi(z)]dz$$

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Perturbation **statistics and dynamics** → early Universe

Cross-correlating with LSS

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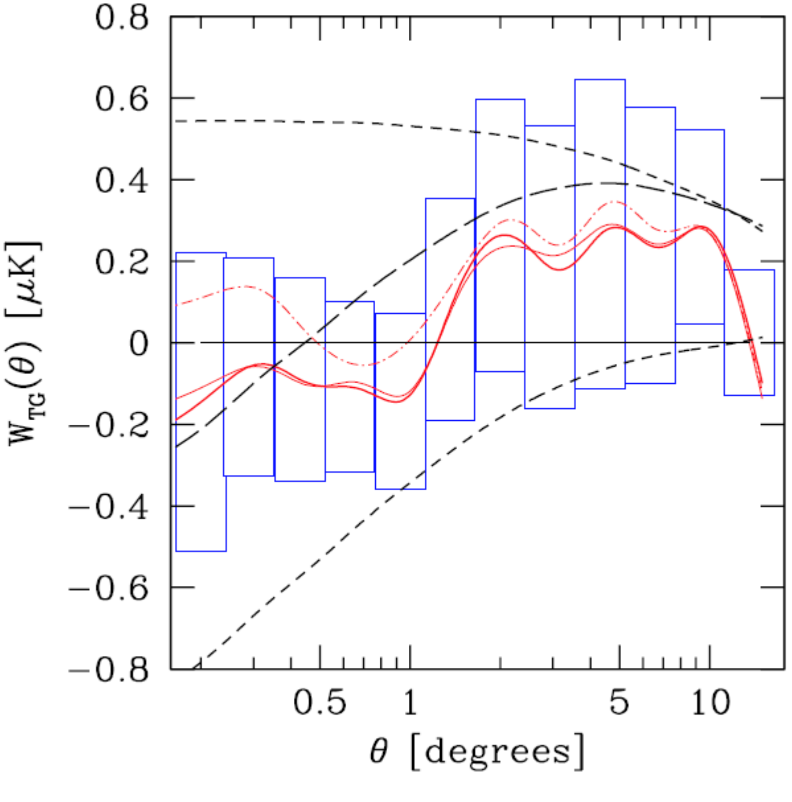
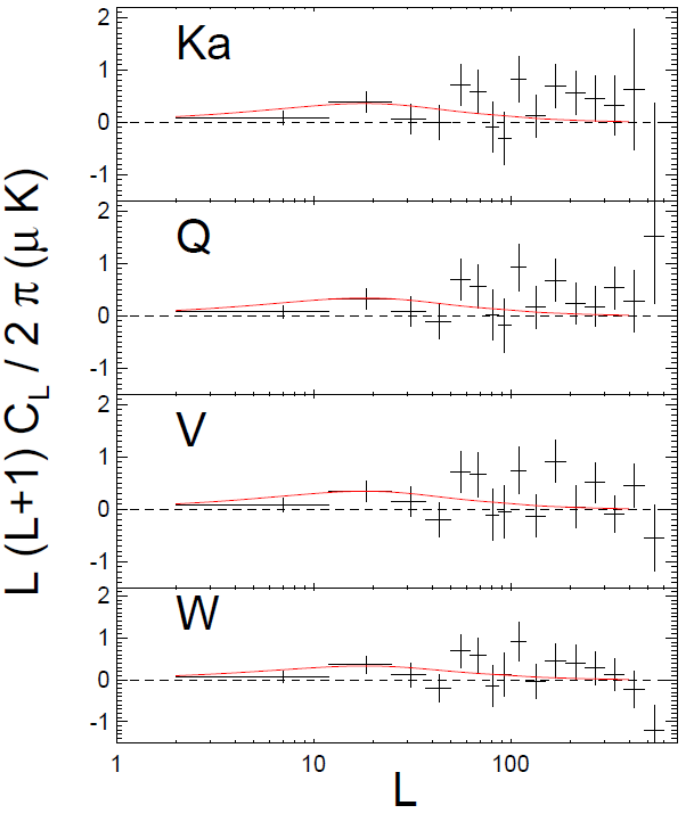
Geometry and **perturbation dynamics** → dark energy effects

ISW-LSS correlation detection

Fosalba, Gaztagnaga 2003

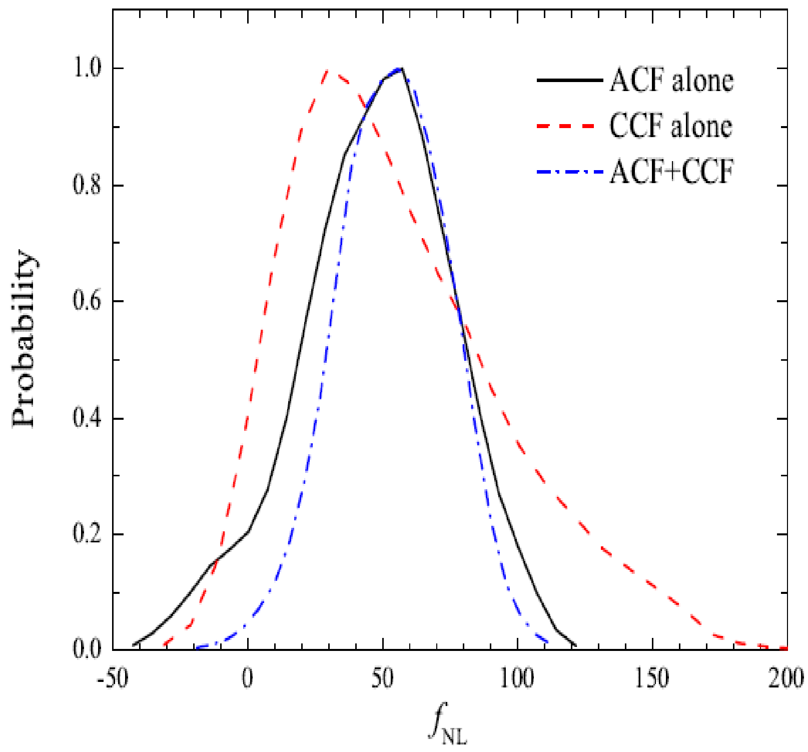


Padmanabhan et al. 2005

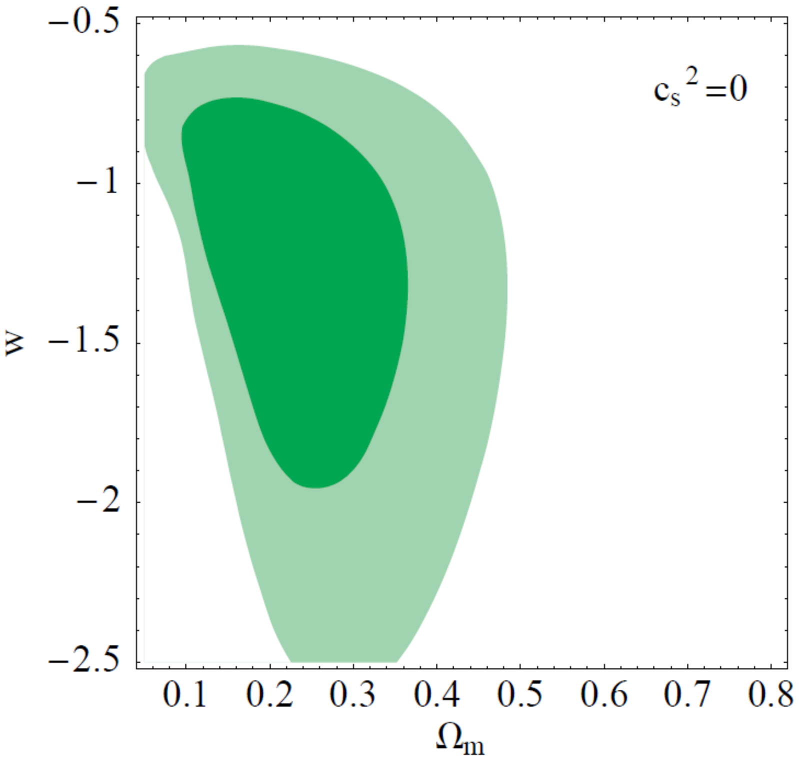


ISW-LSS impact on cosmology

Xia et al. 2010, 2011, 2012

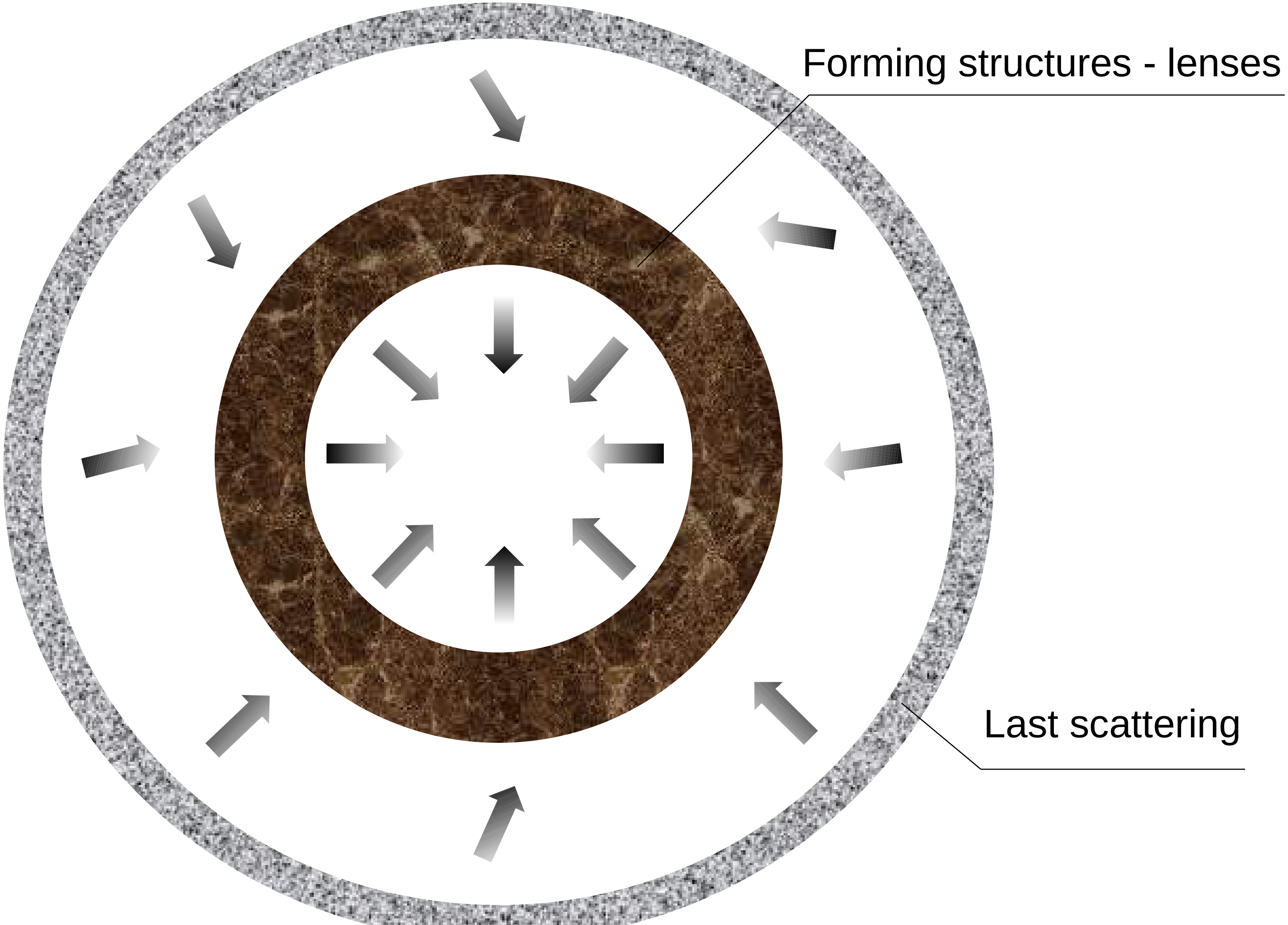


Giannantonio et al. 2008



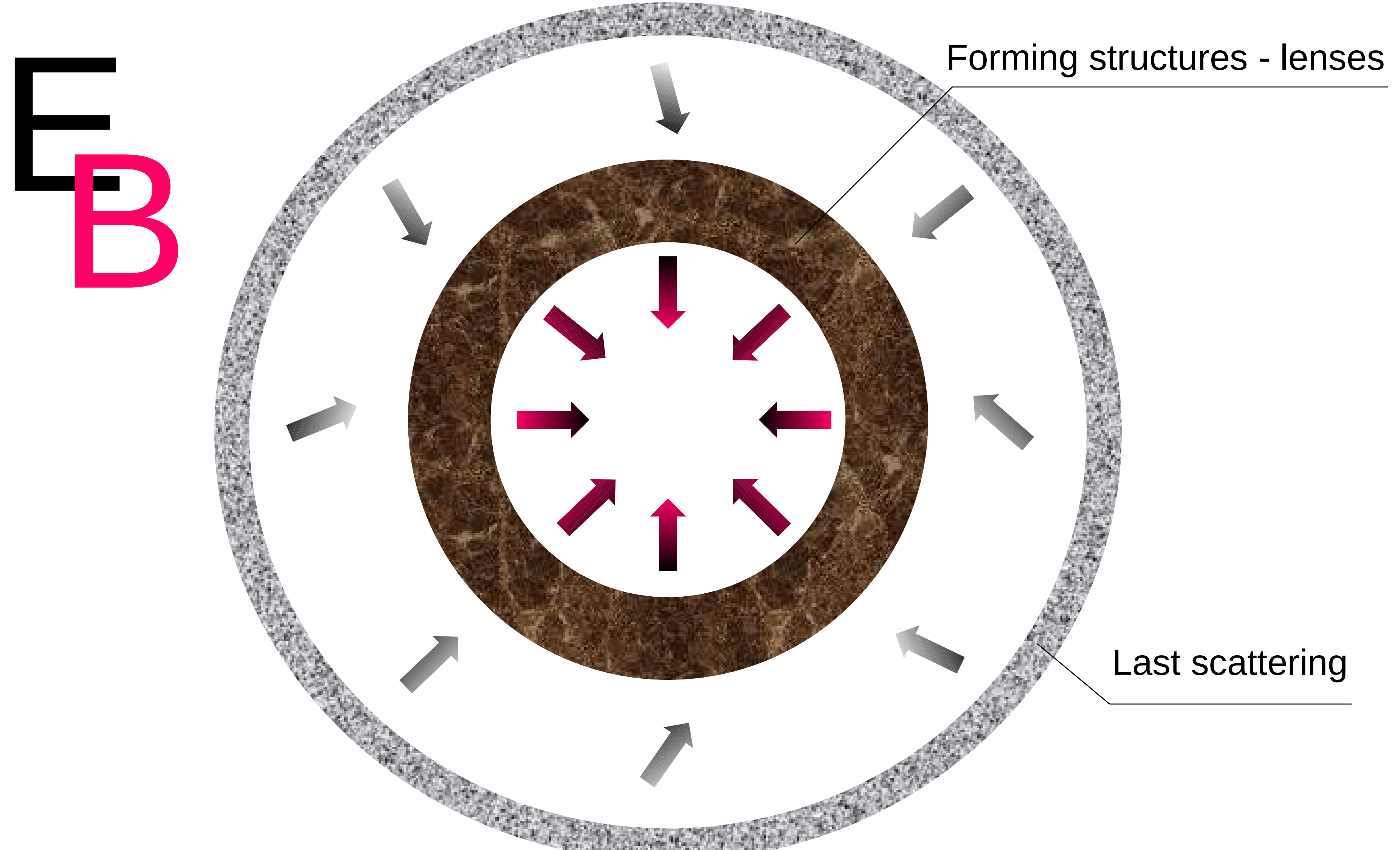
CMB lensing

T



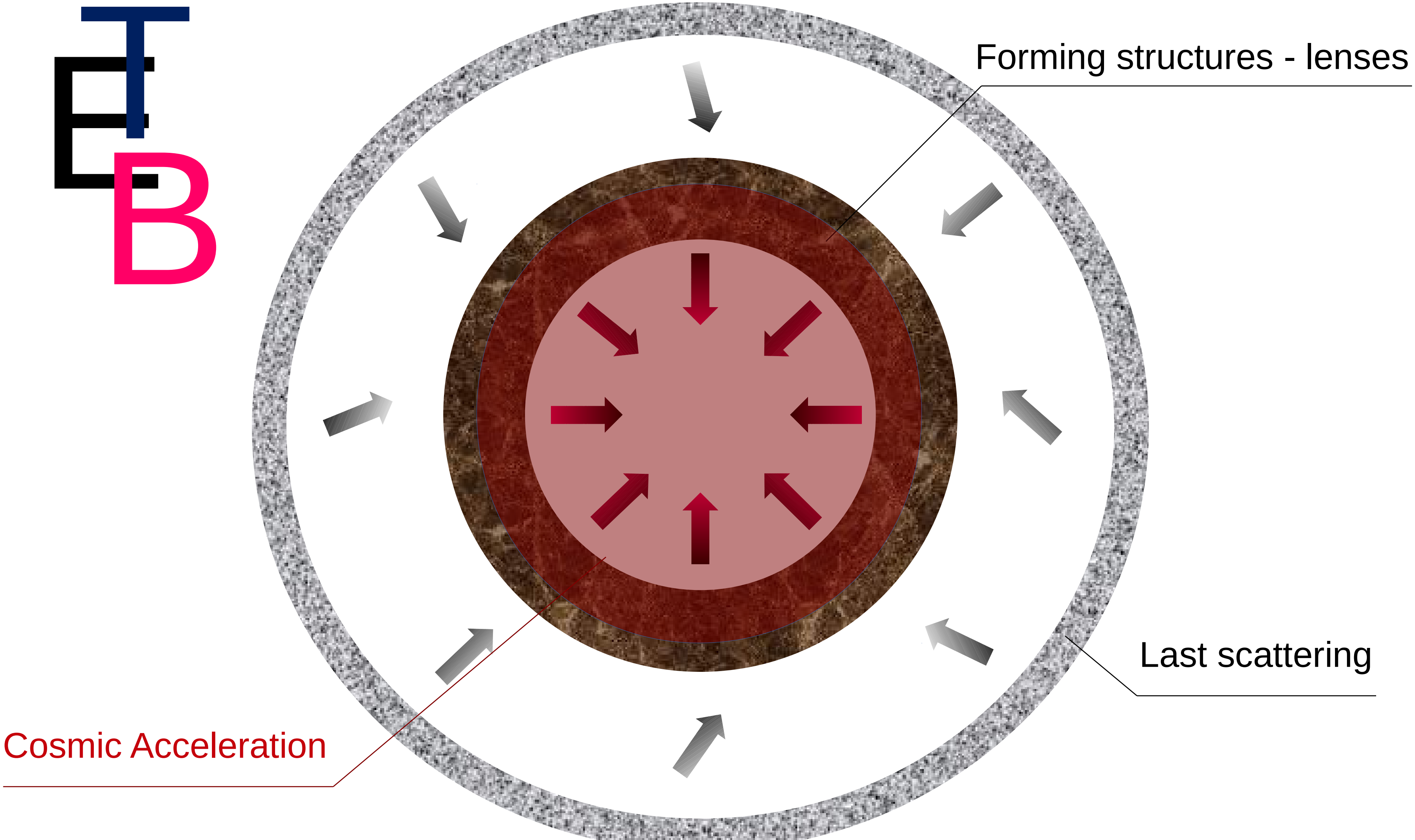
Bartelmann, Schneider 2001, Hu 2000

CMB lensing



Kamionkowski, Kosowsky & Stebbins, Zaldarriaga & Seljak1998

CMB lensing



Kamionkowski, Kosowsky & Stebbins, Zaldarriaga & Seljak1998

CMB lensing

$$\phi(\hat{n}) = \int_0^{\chi_\infty} d\chi D(\chi) \left[\Psi(\hat{n},\chi) - \Phi(\hat{n},\chi)\right] \int_\chi^{\chi_\infty} d\chi' \frac{D(\chi'-\chi)}{D(\chi')} g(\chi')$$

$$C_l^{\phi\phi} = \frac{32}{\pi} \int_0^{\chi_\infty} d\chi\, g'(\chi) \int_0^{\chi_\infty} d\chi' g'(\chi') \int k^2 dk\, u_l[k\,D(\chi)] u_l[k\,D(\chi')] \cdot$$
$$\cdot \left[\frac{1}{4}\langle\Psi(k,\chi)\Psi(k,\chi')\rangle + \frac{1}{4}\langle\Phi(k,\chi)\Phi(k,\chi')\rangle - \frac{1}{2}\langle\Psi(k,\chi)\Phi(k,\chi')\rangle\right]$$

$$C_l^{\Theta\phi} = \frac{2}{\pi} \int_0^{\chi_\infty} d\chi\, g'(\chi) \int_0^{\chi_\infty} d\chi' \int k^2\, dk\, u_l(k\,D(\chi)) u_l(k\,D(\chi')) \cdot$$
$$\cdot \left[\langle\Psi(k,\chi)\dot{\Psi}(k,\chi')\rangle + \langle\Phi(k,\chi)\dot{\Phi}(k,\chi')\rangle - \langle\Psi(k,\chi)\dot{\Phi}(k,\chi')\rangle - \langle\dot{\Psi}(k,\chi')\Phi(k,\chi)\rangle\right]$$

Acquaviva et al. 2004

CMB lensing

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Geometry

Acquaviva et al. 2004

CMB lensing

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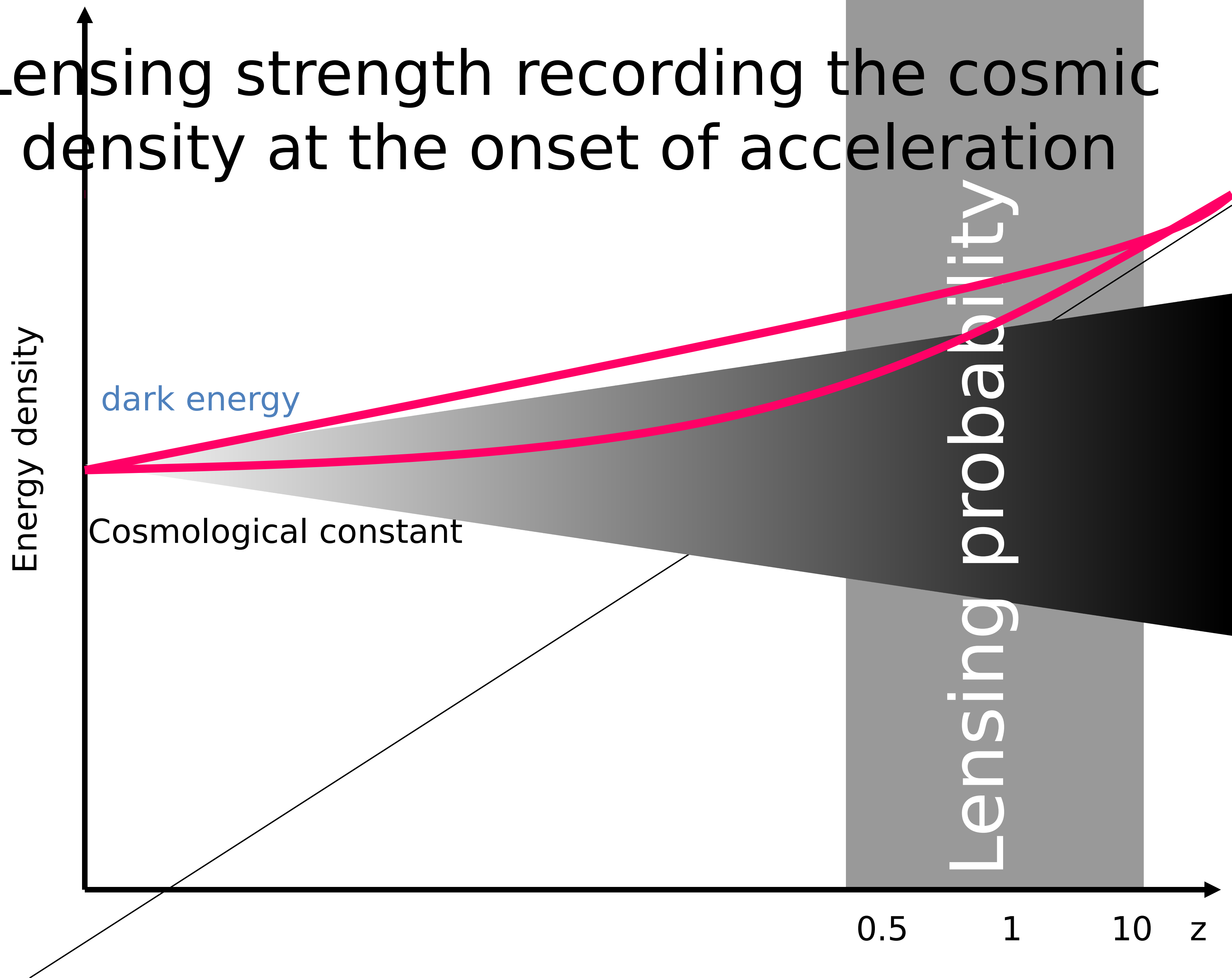
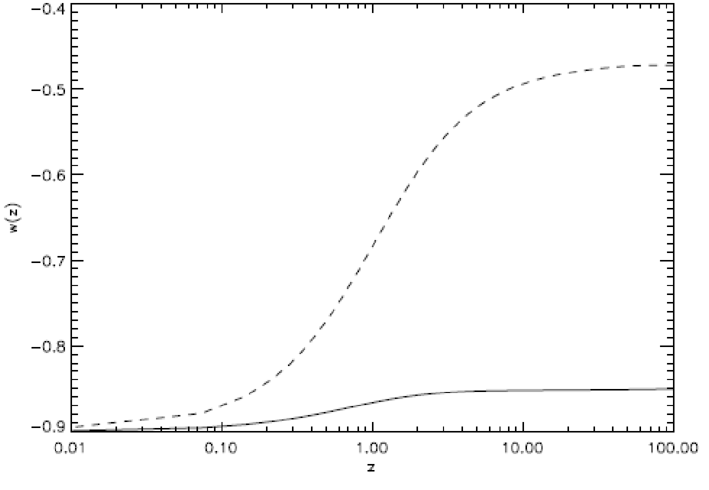
Perturbation dynamics

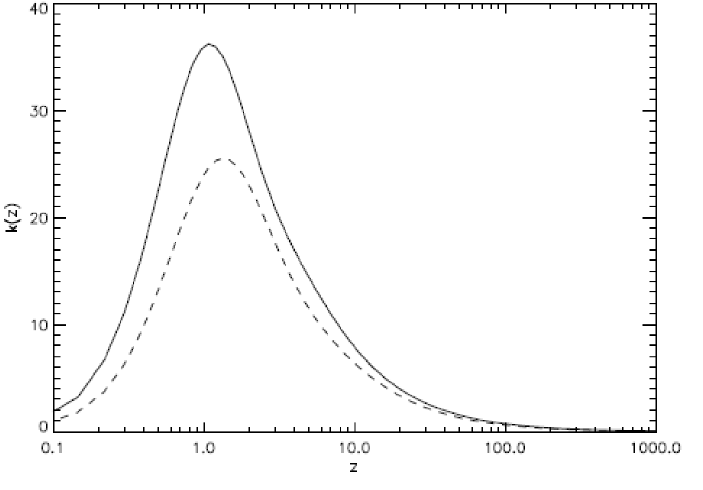
Acquaviva et al. 2004

Lensing strength recording the cosmic density at the onset of acceleration



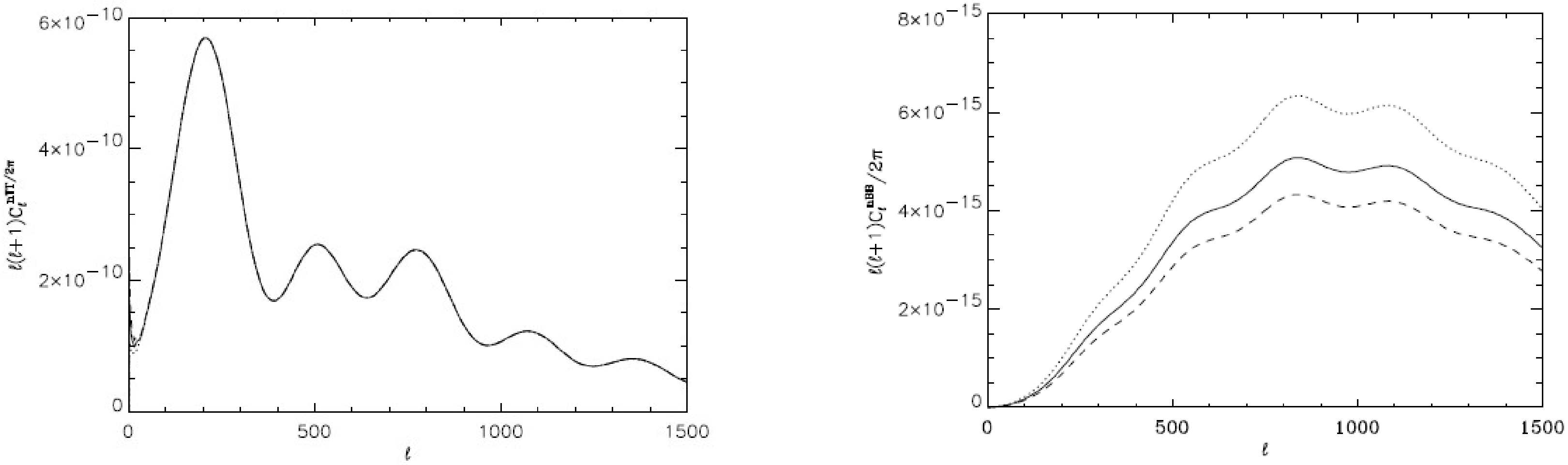
Early dark energy and CMB lensing





Acquaviva & Baccigalupi 2006

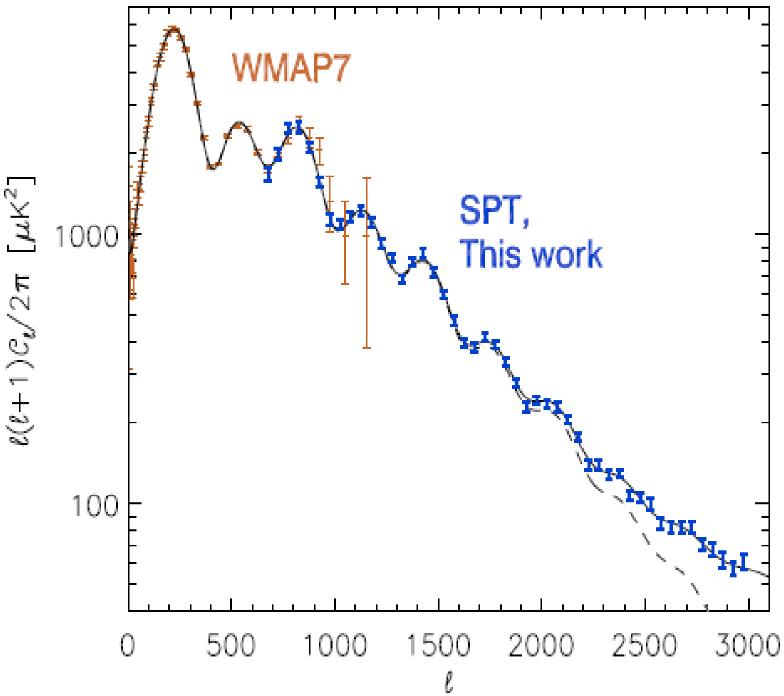
CMBreaking projection degeneracy

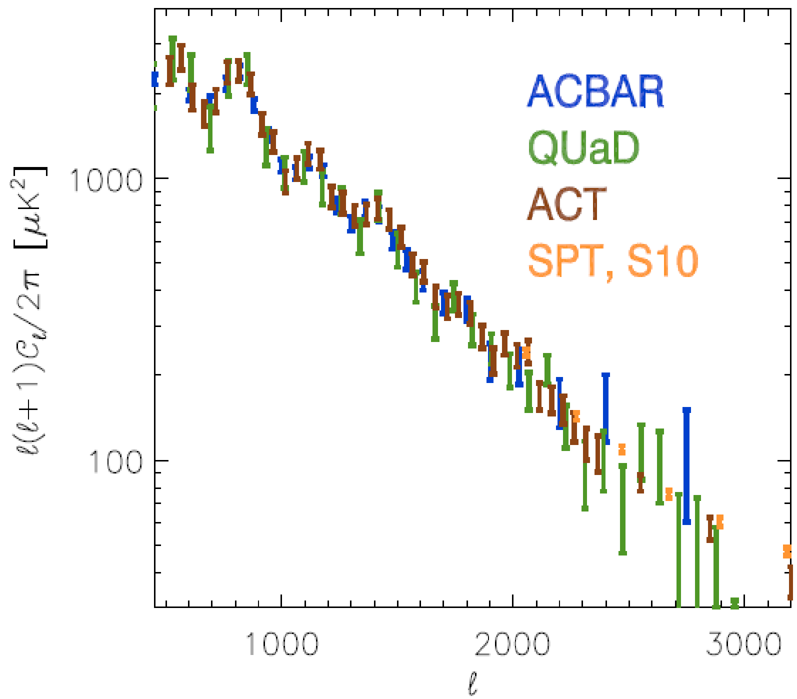


Acquaviva & Baccigalupi 2006

CMB lensing detection

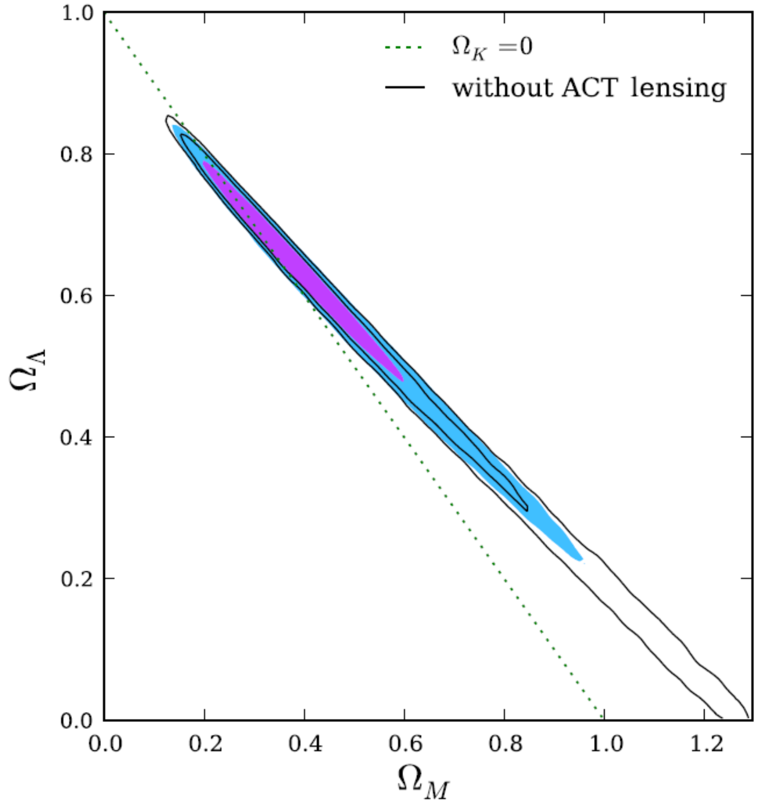
Keisler et al. 2011

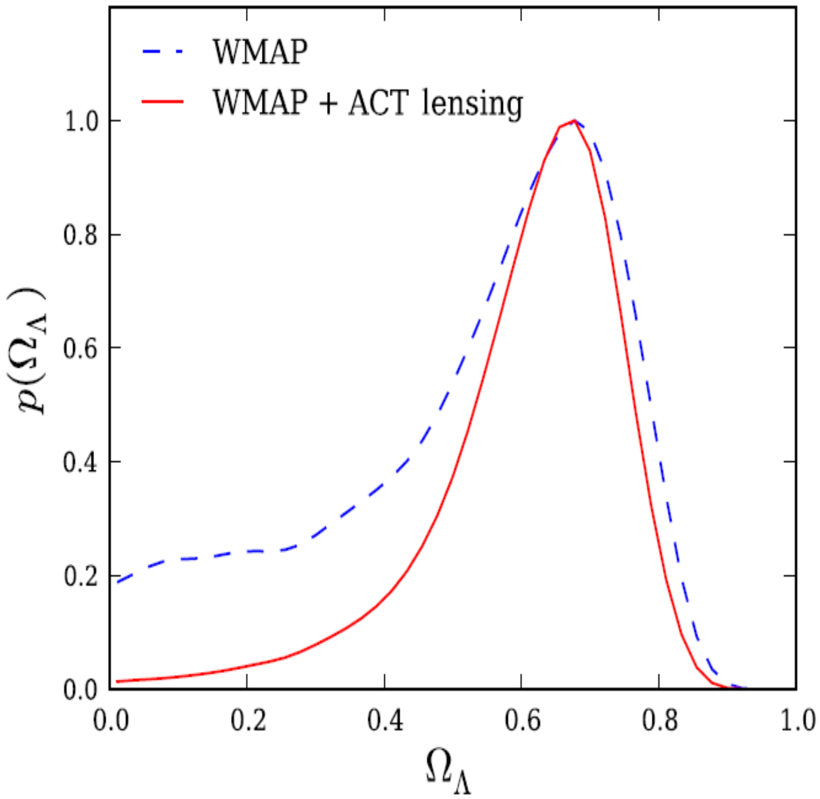




CMBroken degeneracy

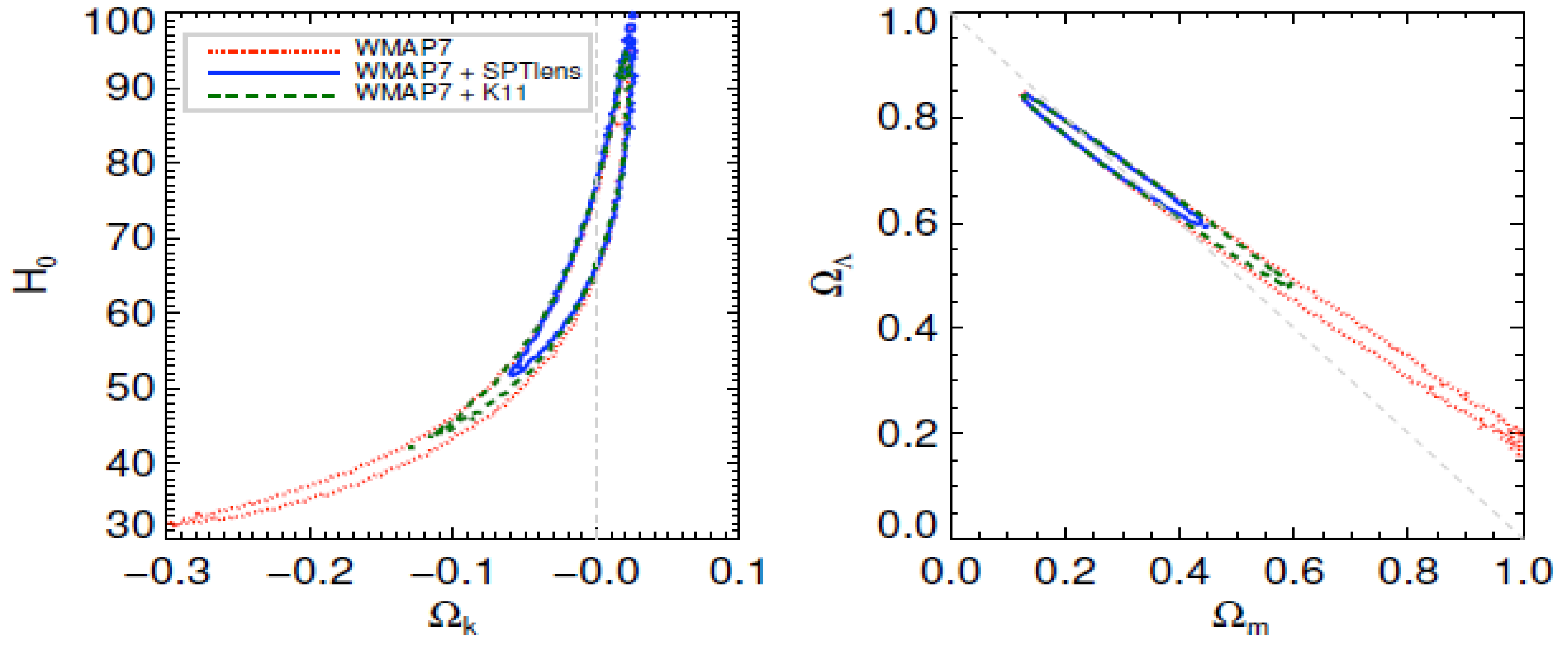
Sherwin et al. 2011





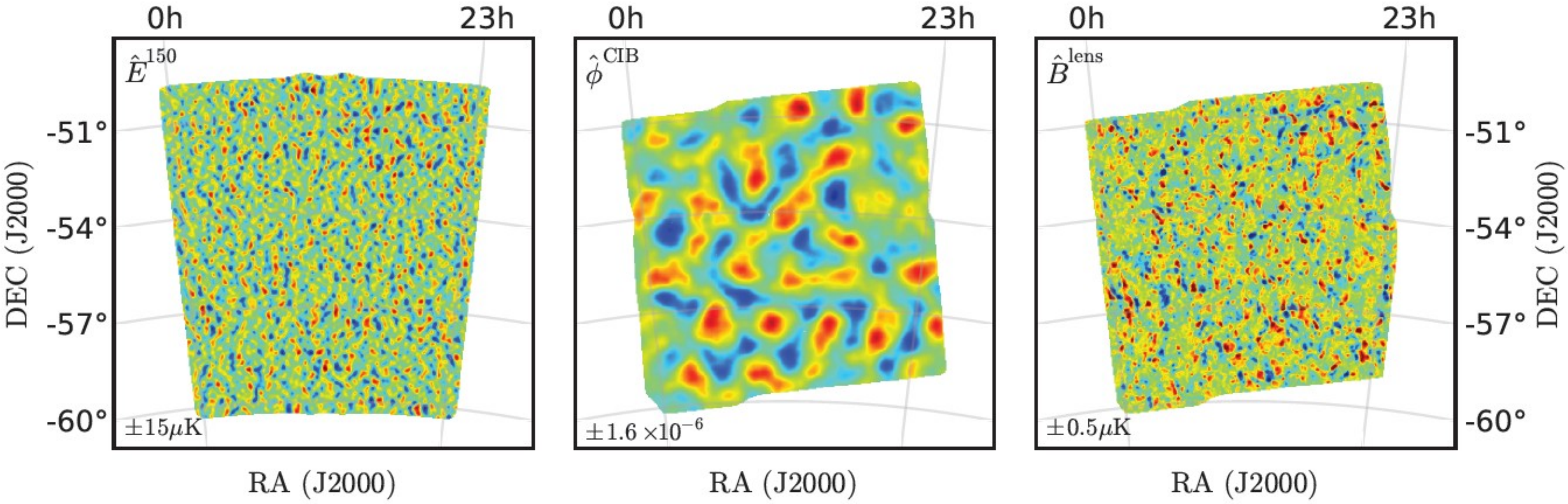
CMBroken degeneracy

Van Engelen et al. 2012



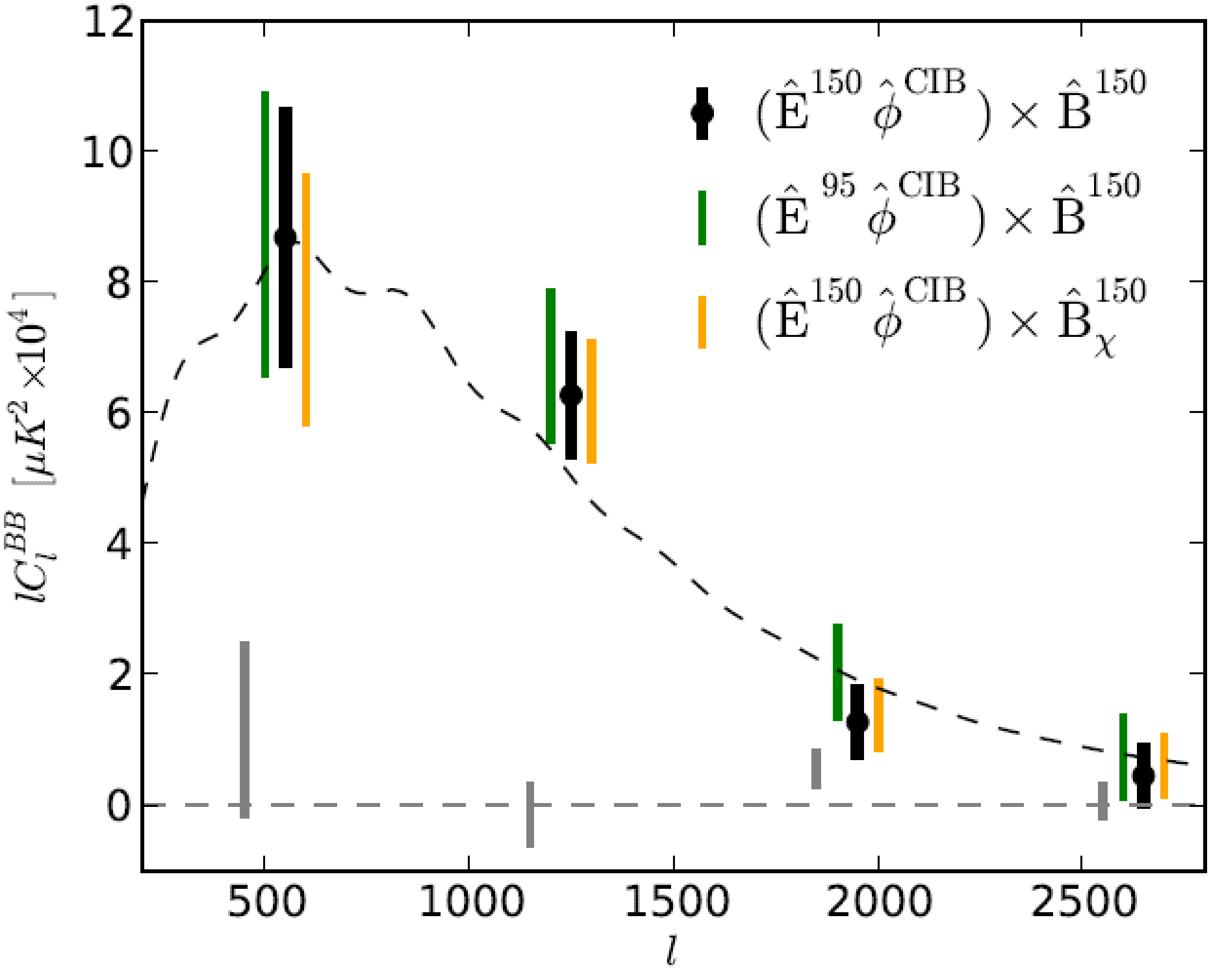
The B-modes

The first cross-evidence of lensing B modes



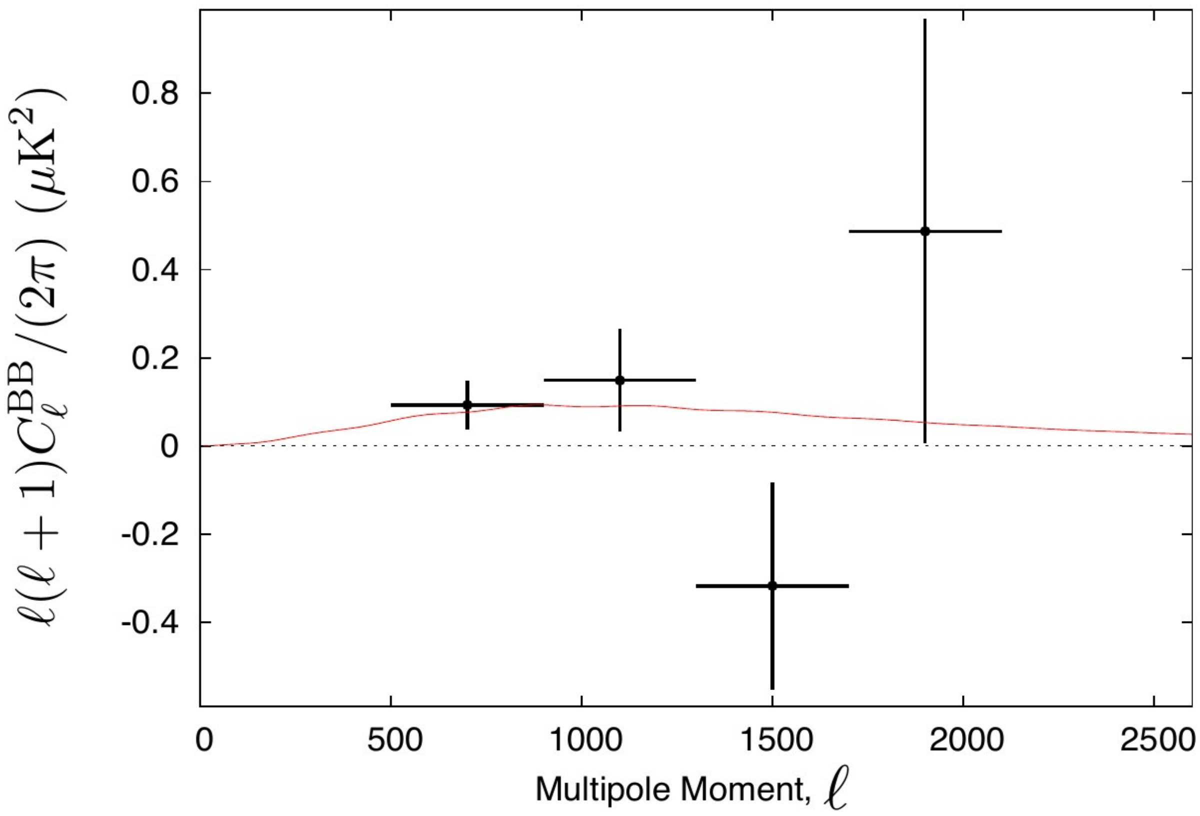
Hanson et al. 2013

The first cross-evidence of lensing B modes



Hanson et al. 2013

The first auto-evidence of lensing B-modes



Ade et al. 2013

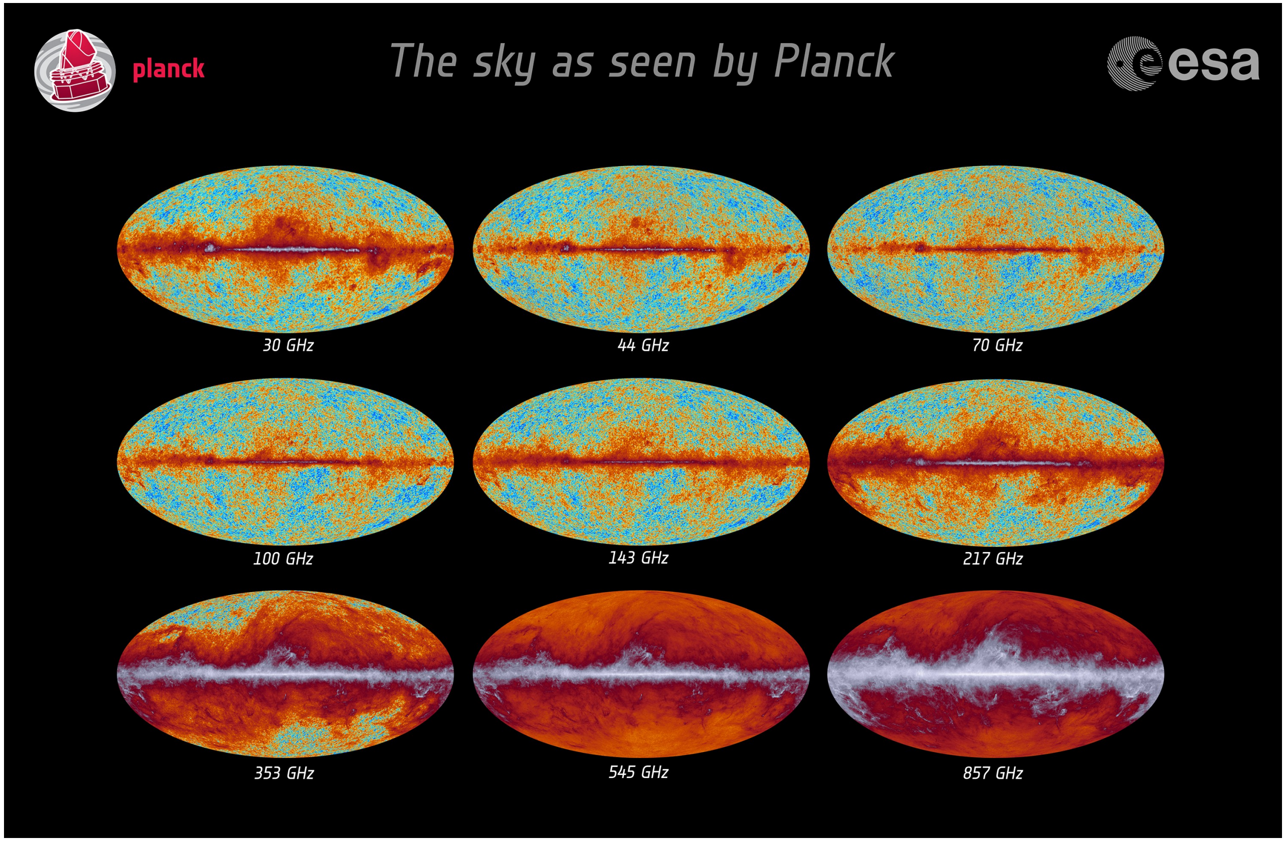
Planck 2013

Planck

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

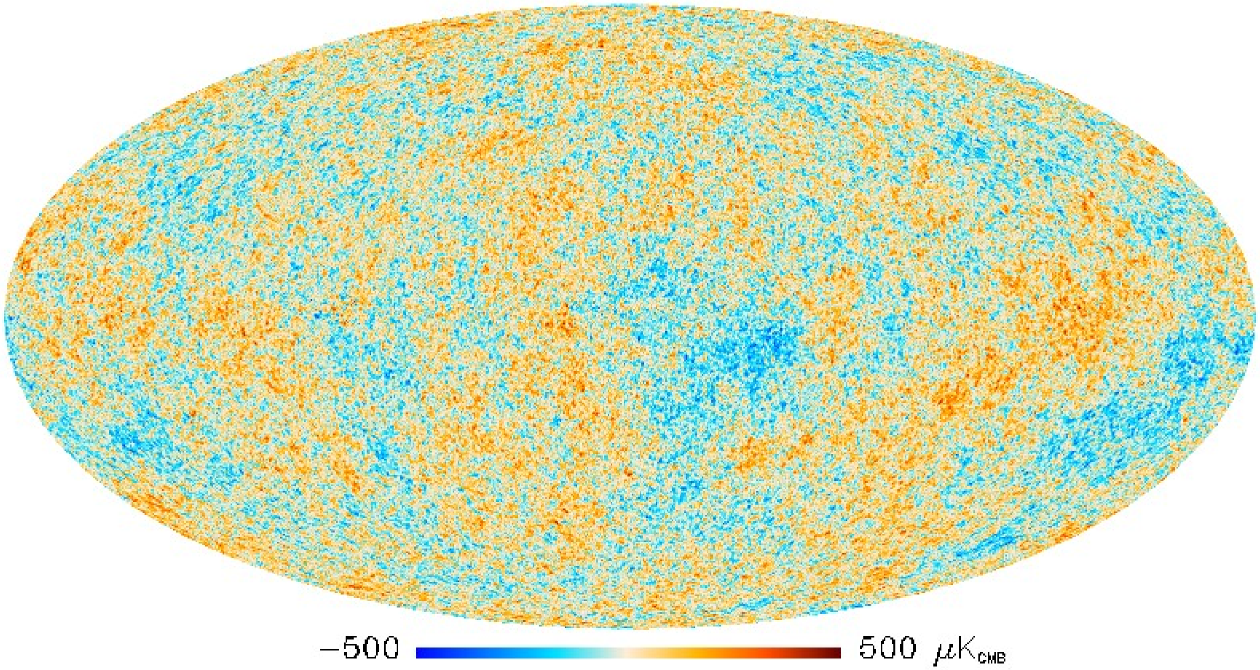
Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

The sky at Planck frequencies



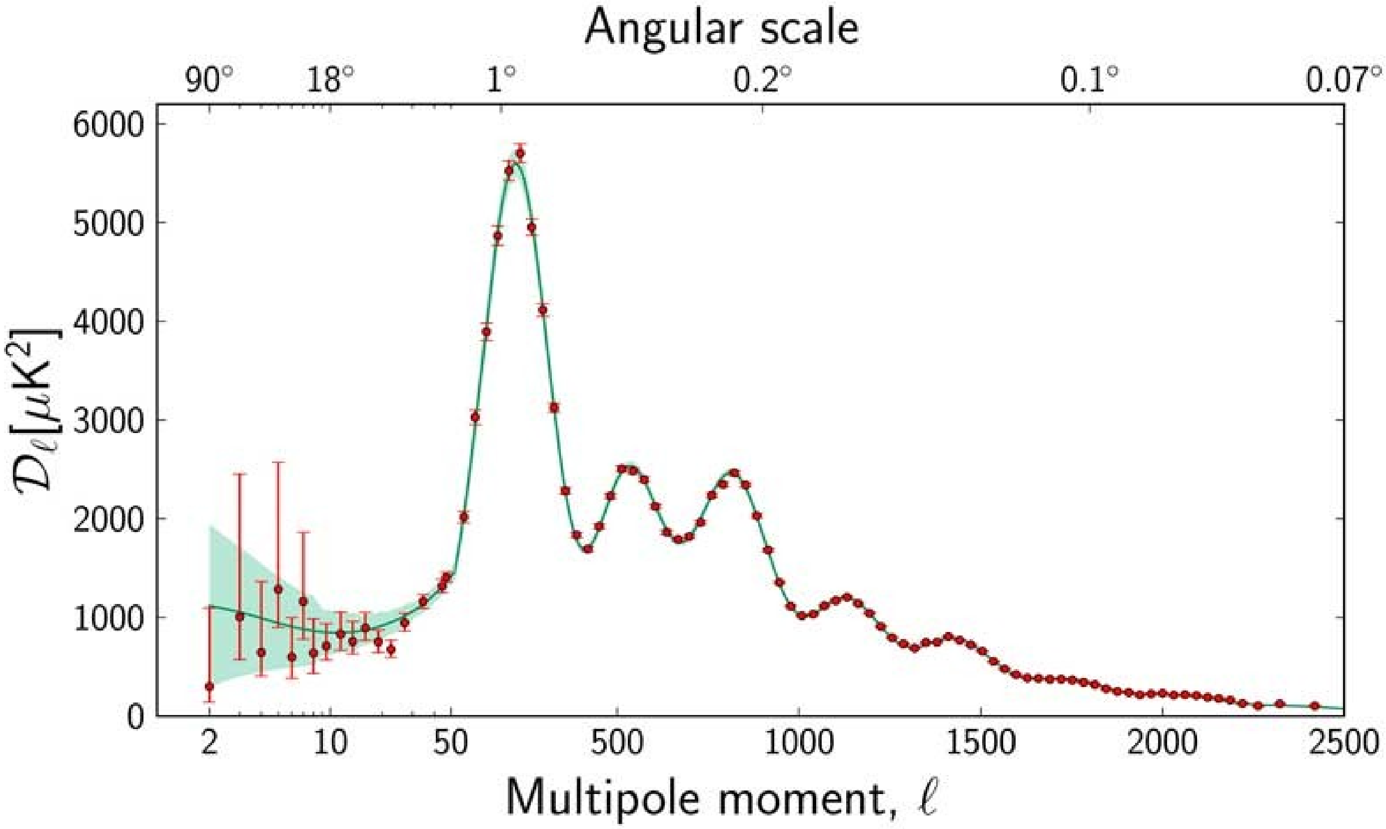
Planck 2013

The Planck CMB anisotropies



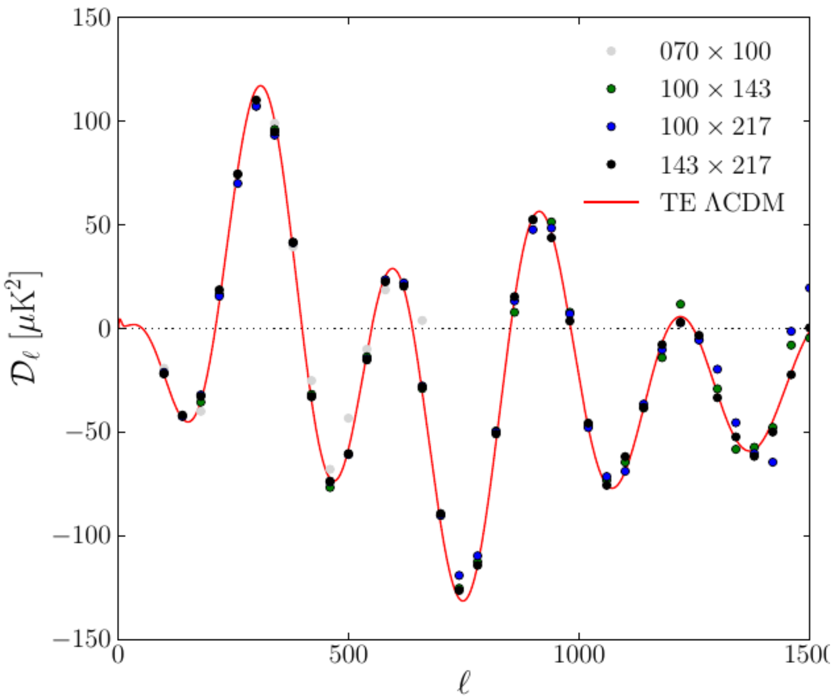
Planck 2013

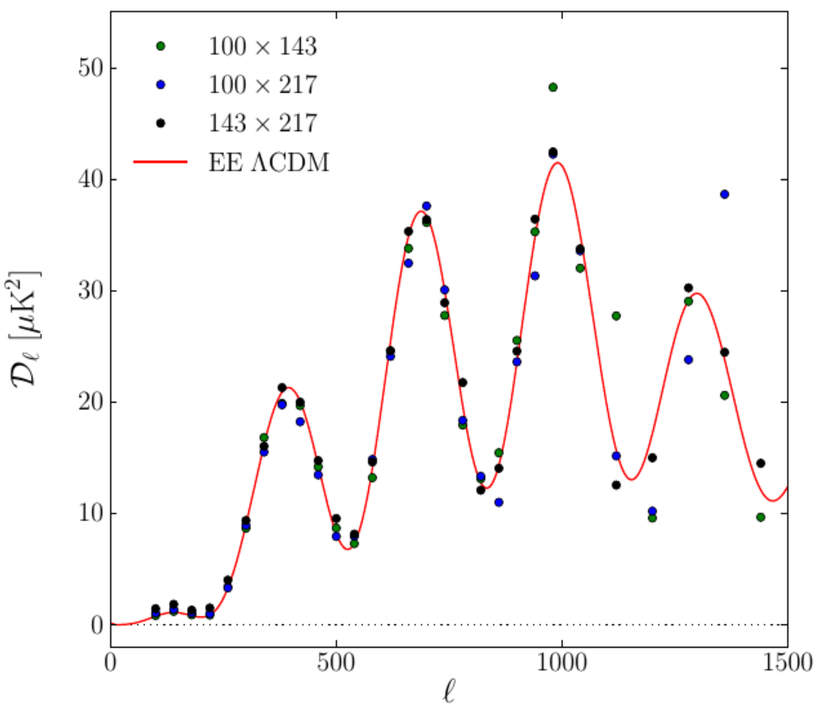
The Planck CMB power spectrum



Planck 2013

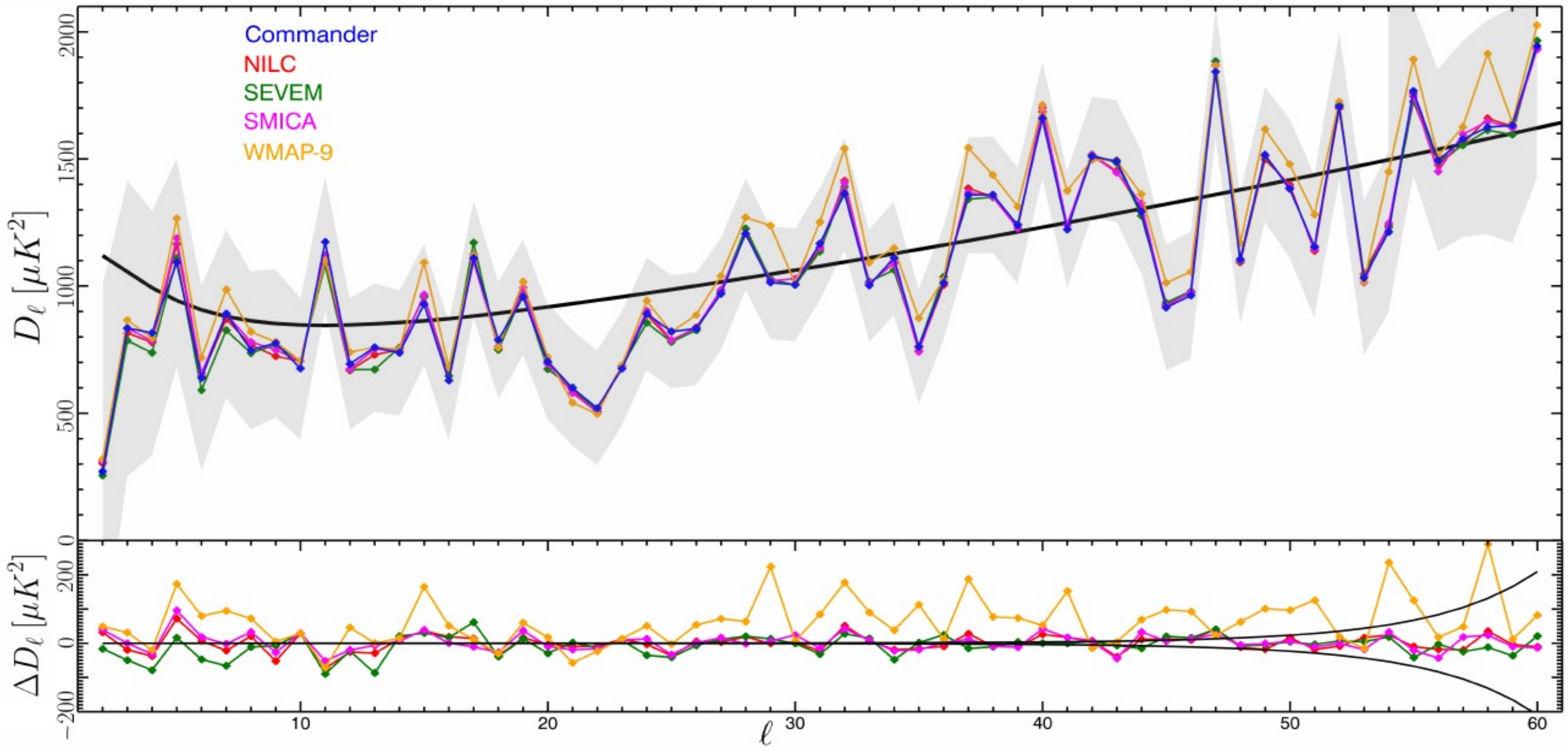
The Planck CMB power spectrum





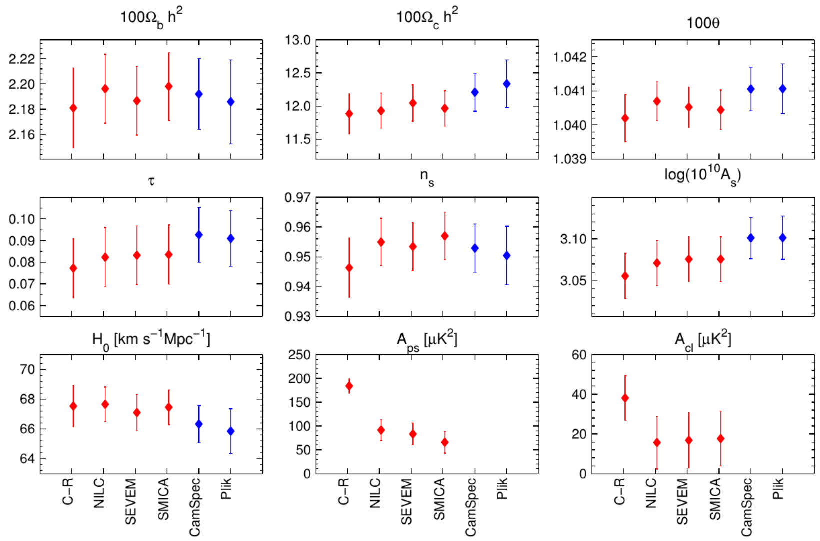
Planck 2013

The low l CMB T spectrum



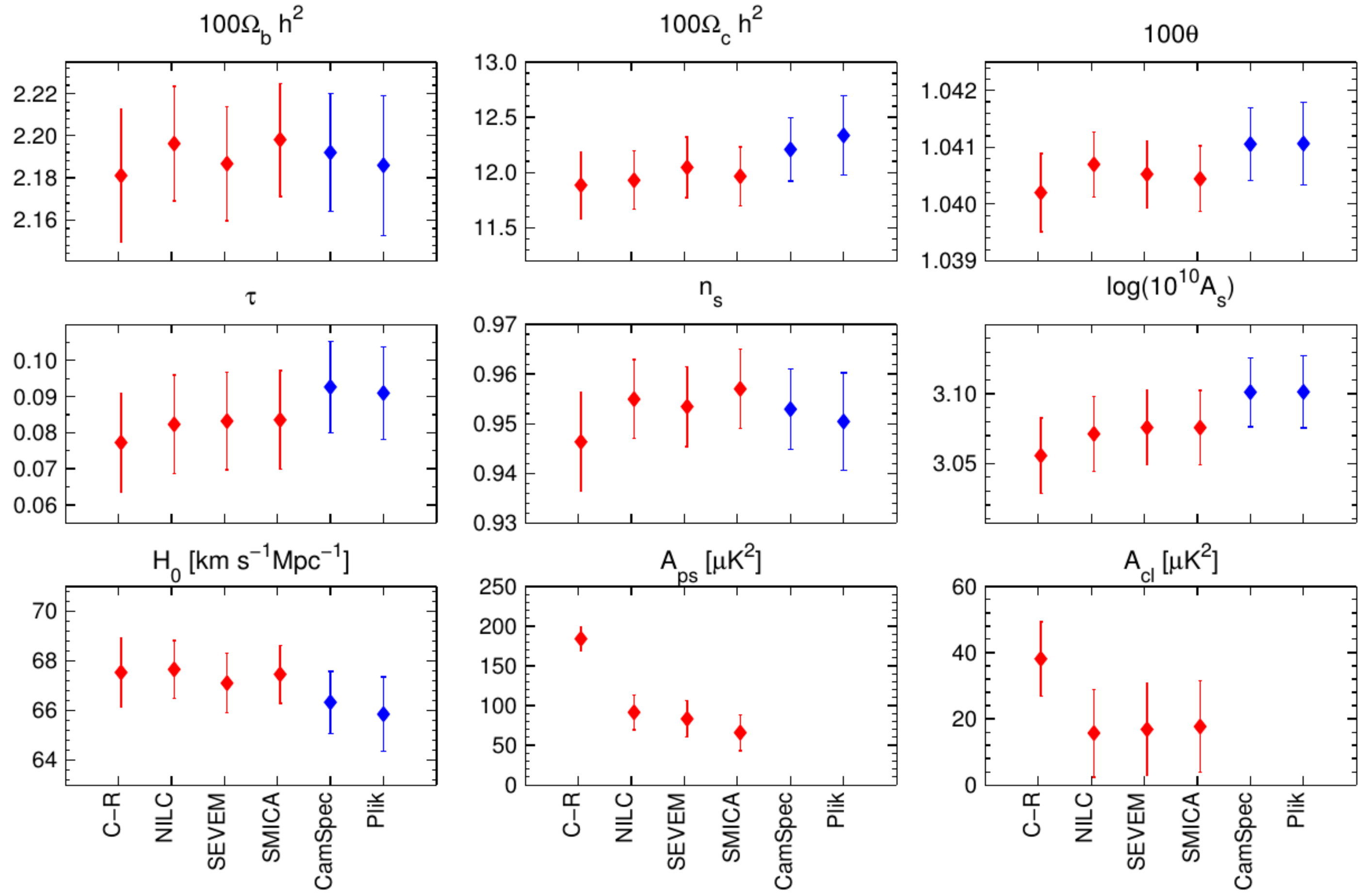
Planck 2013

Cosmological parameters



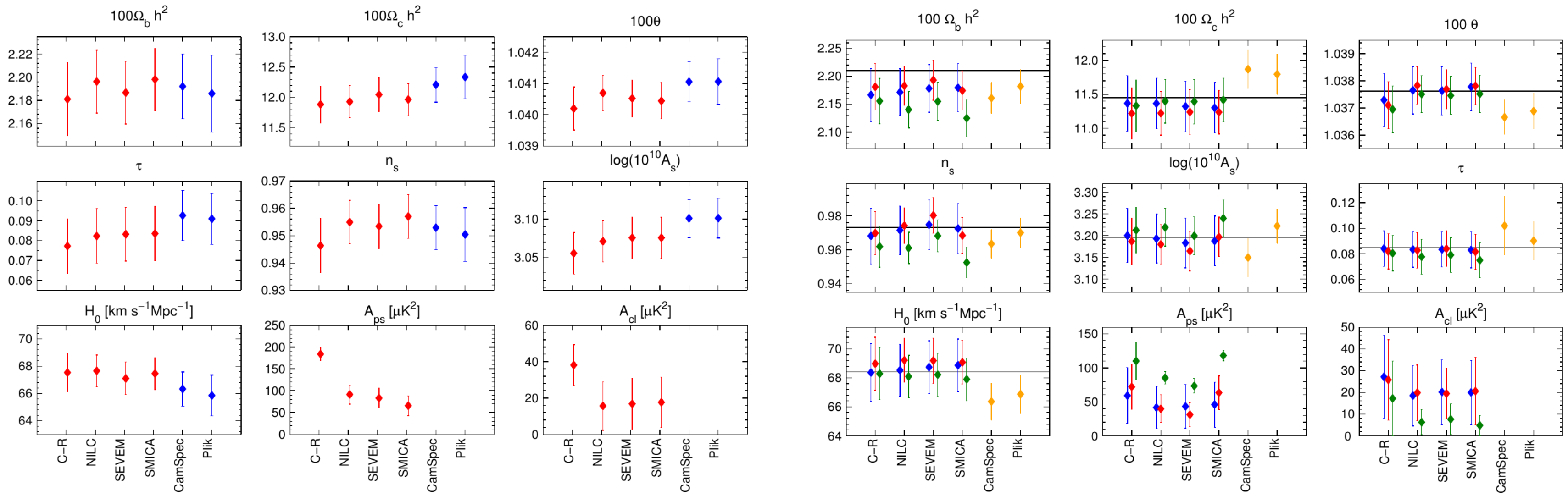
Planck 2013

Cosmological parameters



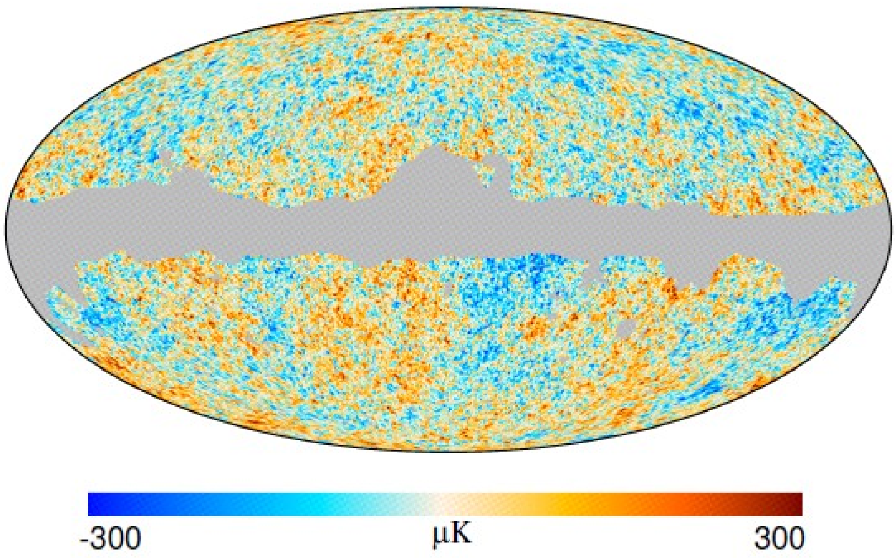
Planck 2013

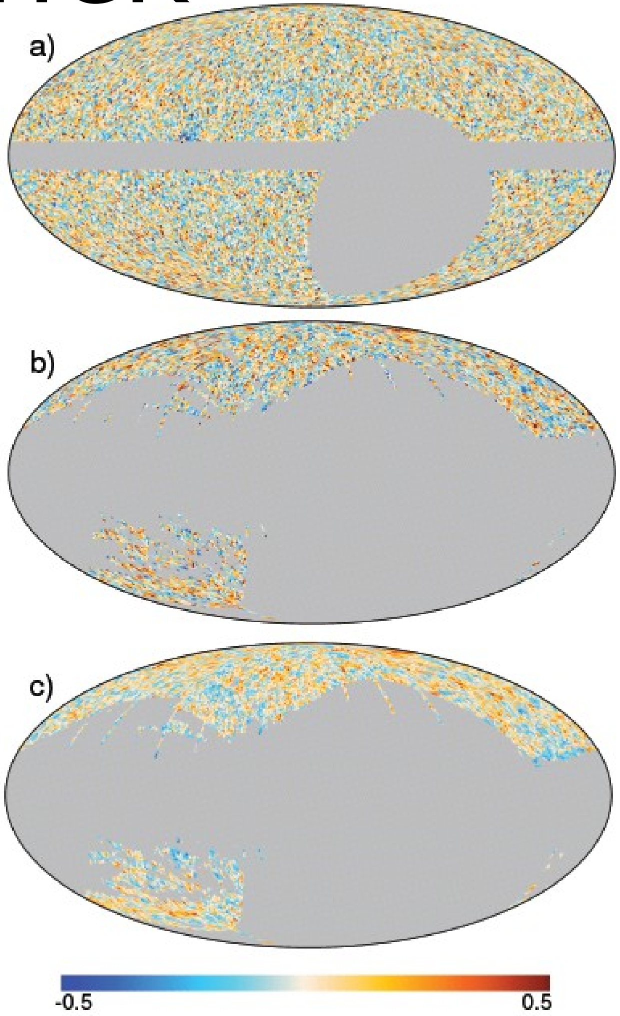
Cosmological parameters



Planck 2013

ISW-LSS cross-correlation from Planck





Planck 2013

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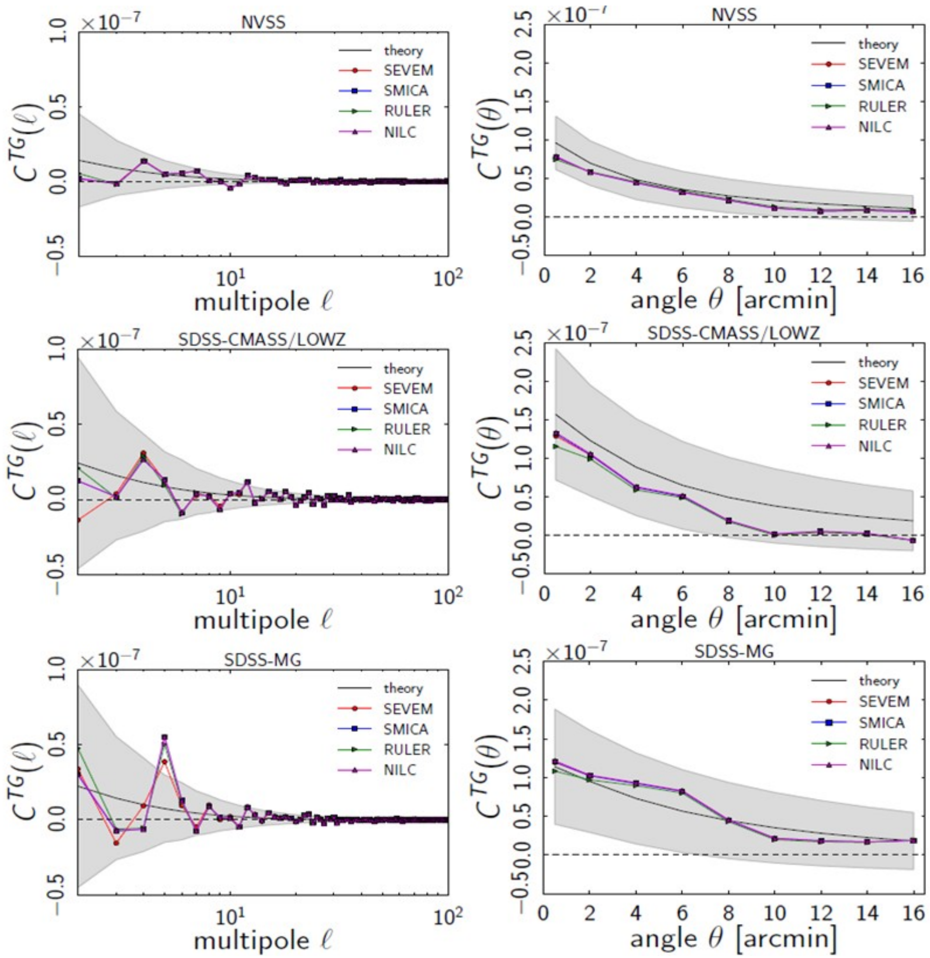
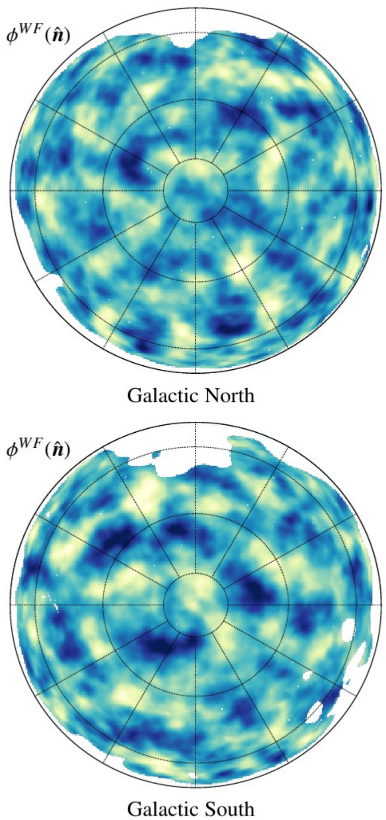
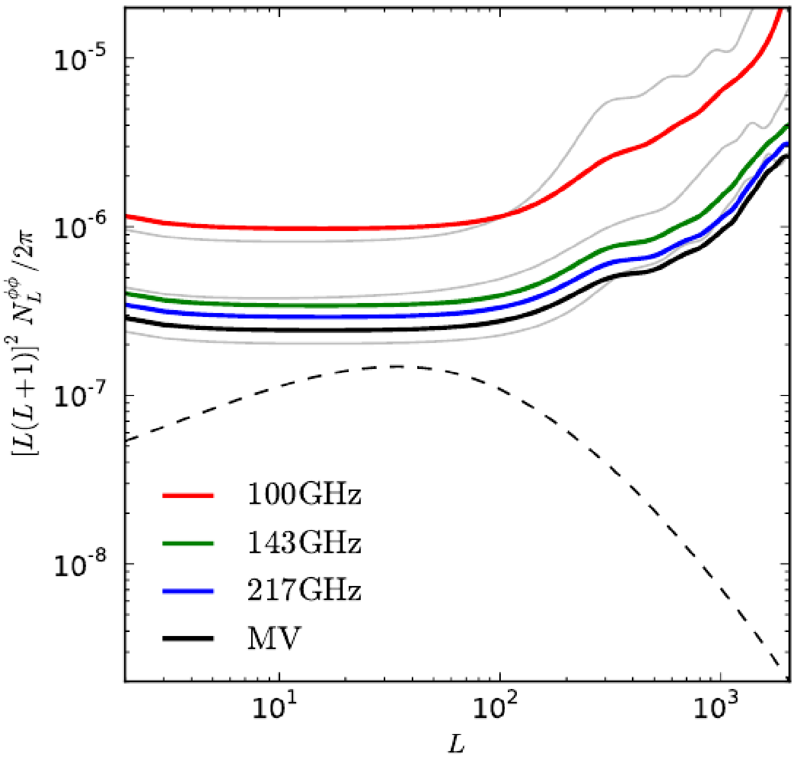


Planck 2013

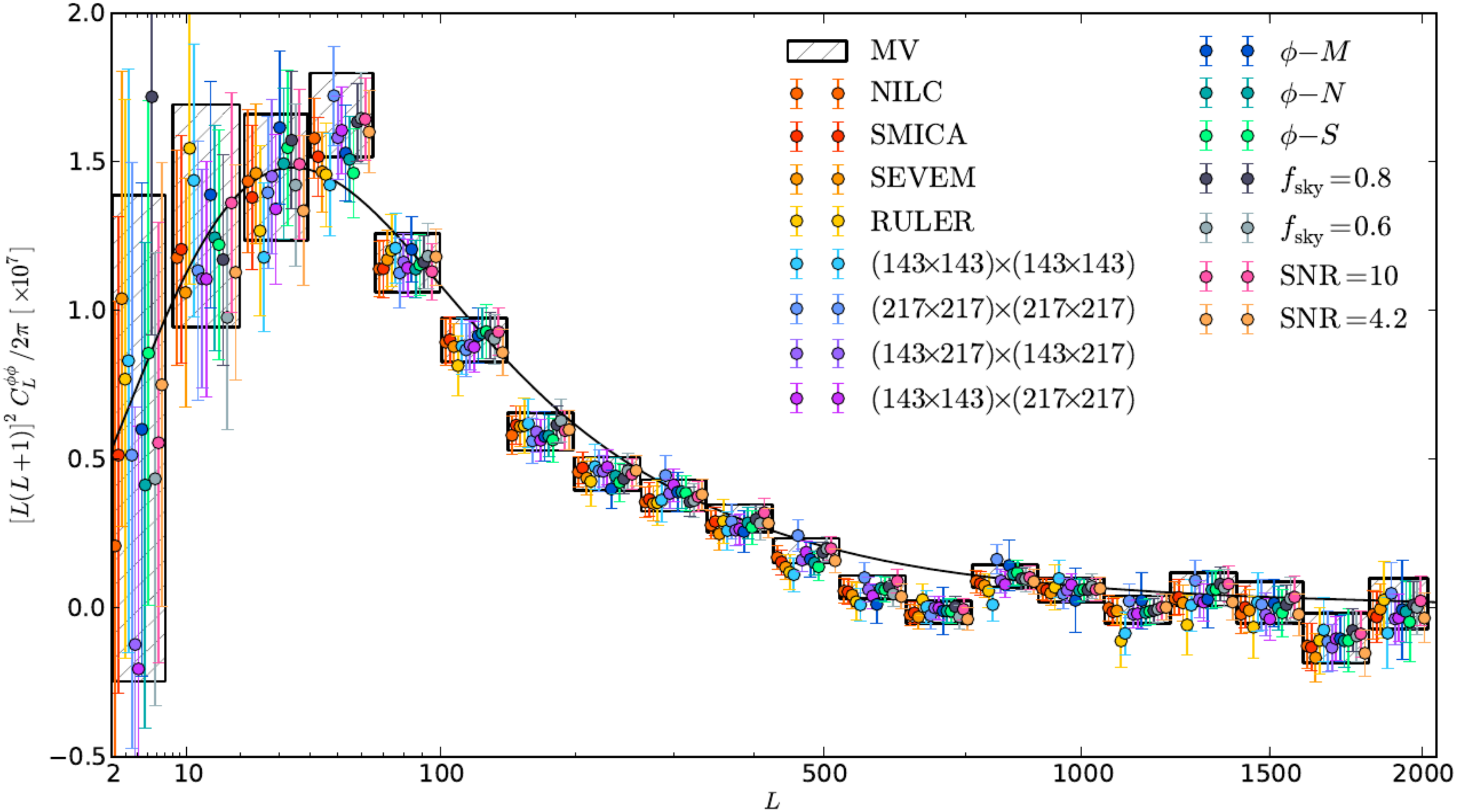
Gravitational lensing from Planck





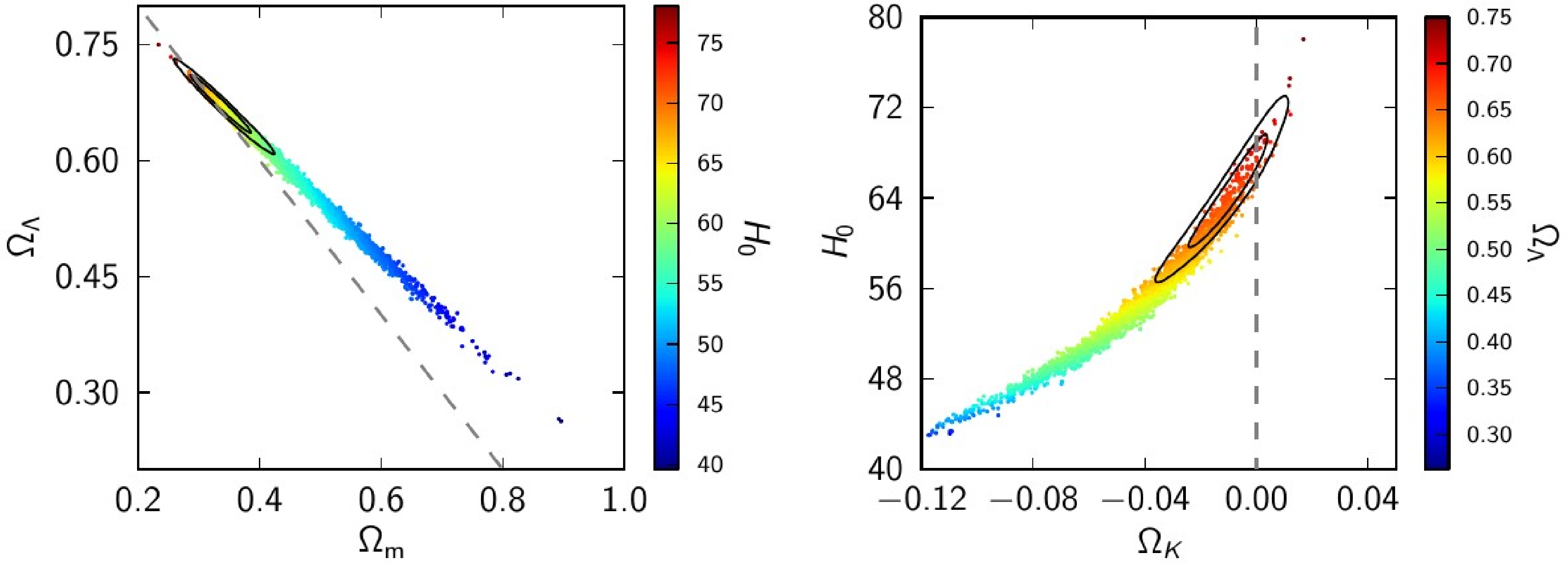
Planck 2013

Gravitational lensing from Planck



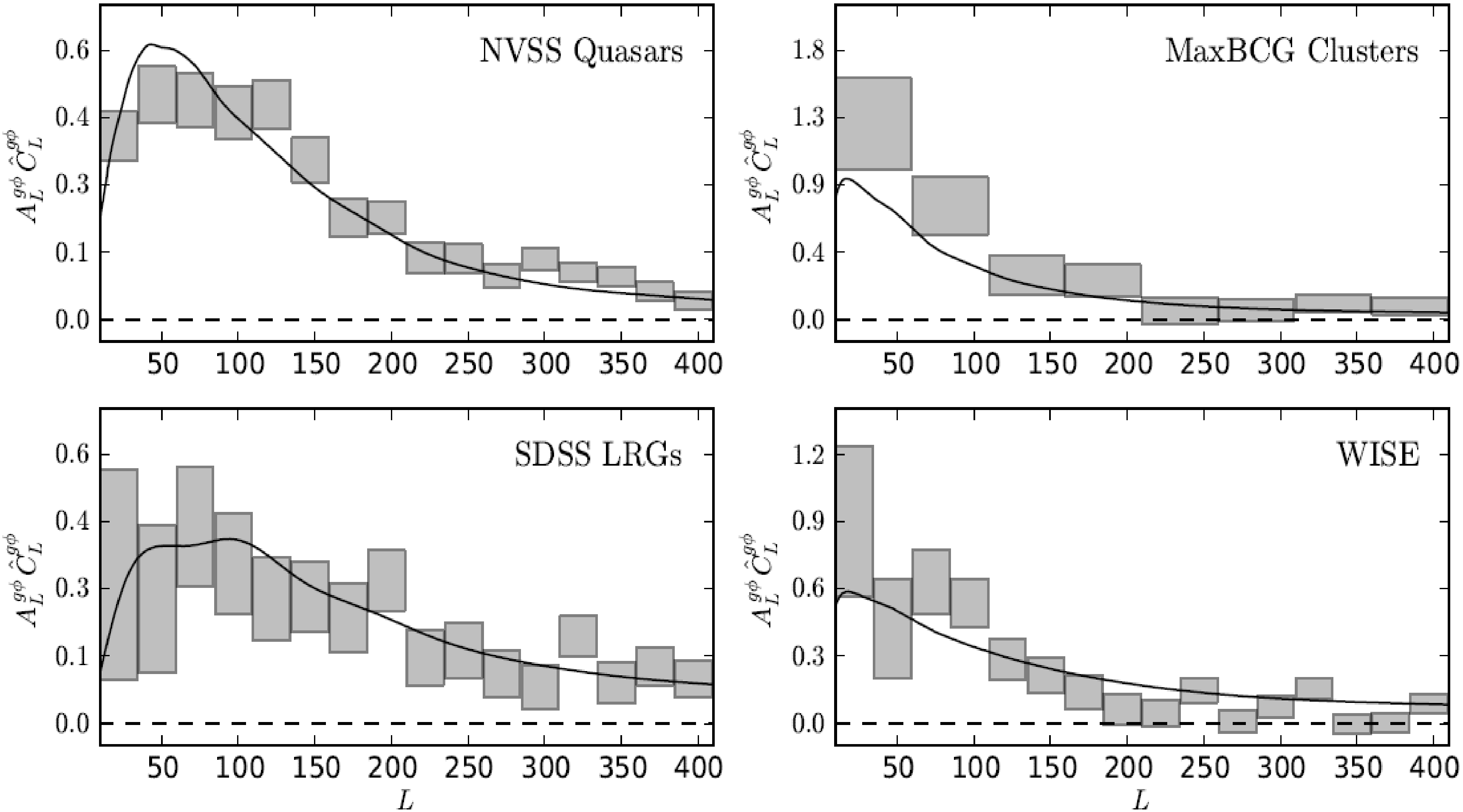
Planck 2013

Gravitational lensing from Planck



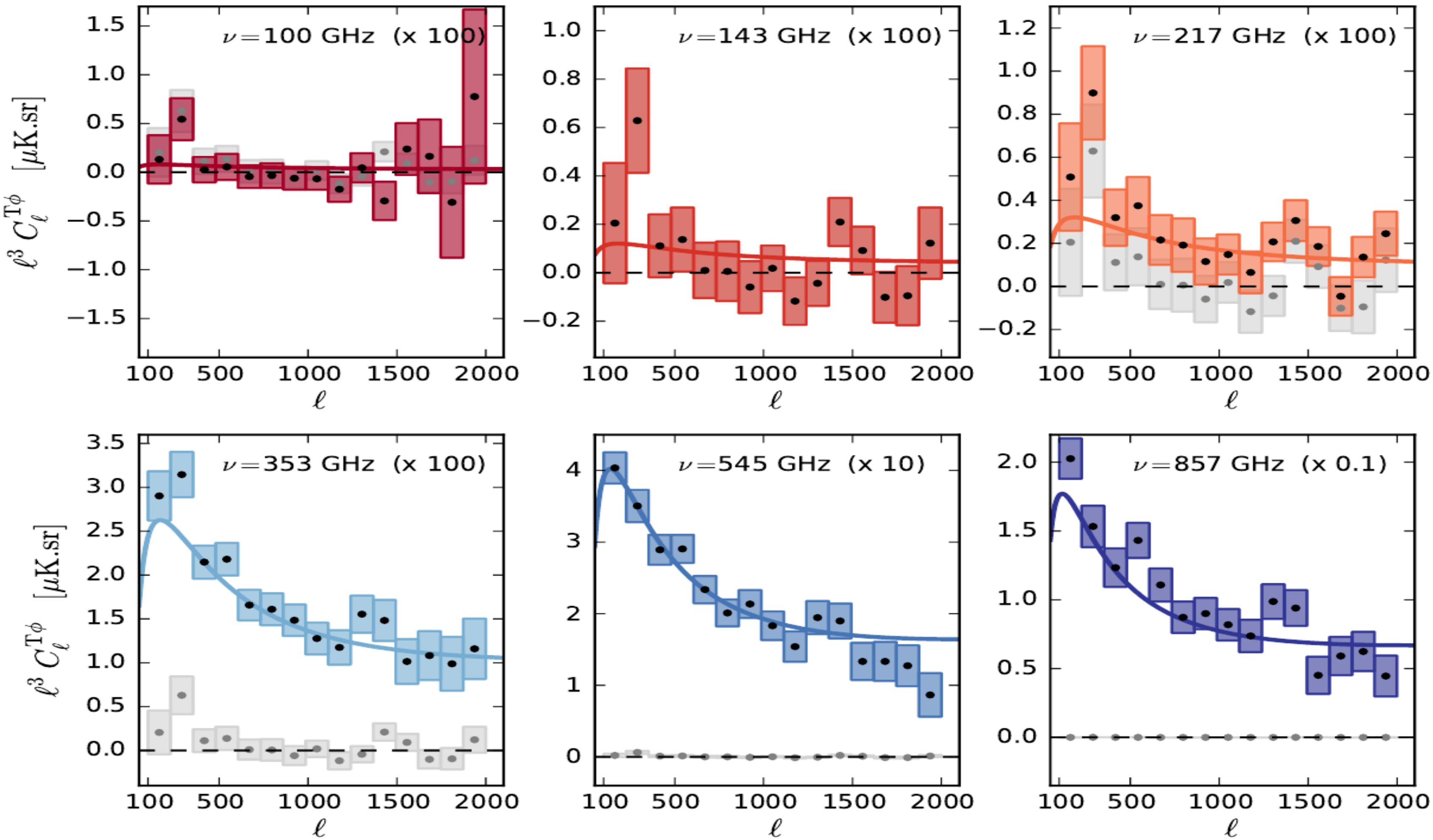
Planck 2013

Gravitational lensing from Planck



Planck 2013

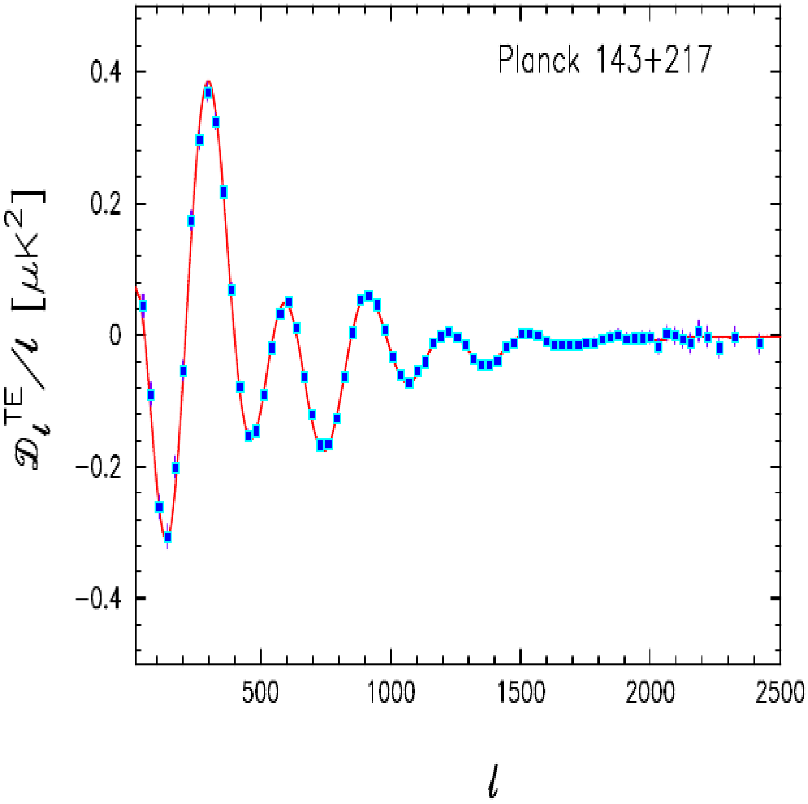
Gravitational lensing-CIB

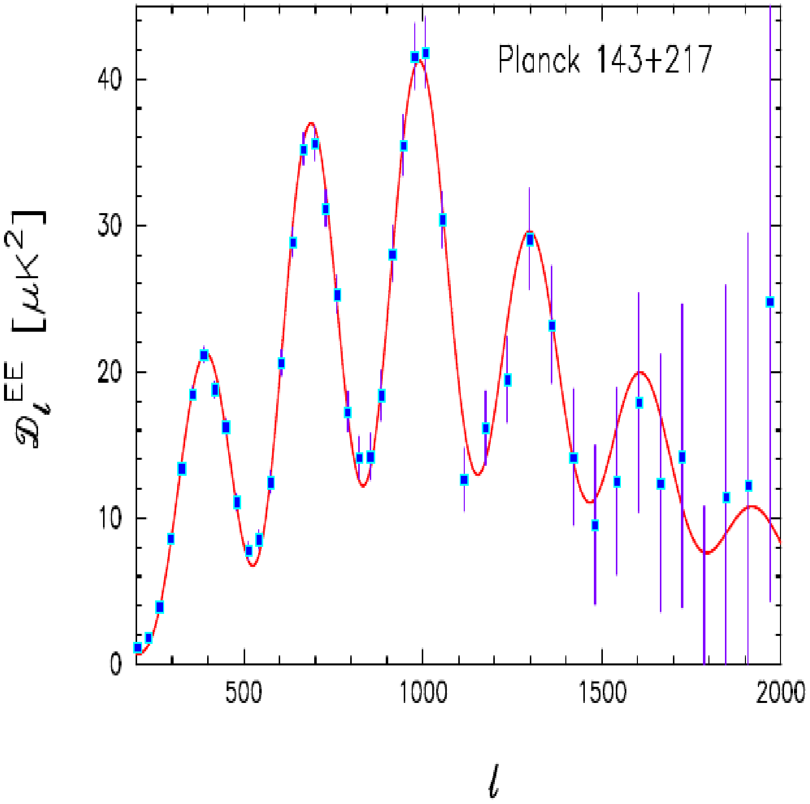


Planck 2013

Planck 2014

Expectations from Planck 2014





Planck 2013

Expectations from Planck 2014

- Total intensity:
  - Cosmology from 2.5 years of data rather than 1
  - Improved foreground modeling
- Polarisation:
  - High l spectra and likelihood for E modes
  - Cross-Correlation of large scale E modes and LSS data
  - Issues being tackled for constaints on B modes from cosmological gravitational waves:
    - Low l foreground cleaning
    - Low l noise covariance control
    - Low l systematics control

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    - Low l foreground cleaning
    - Low l noise covariance control
    - Low l systematics control
    - New: study data in regions surveyed by sub-orbitals, gain information on background and foregrounds

Euclid 2013

Euclid Facts

- 2011: selection
- 2012: adoption
- 2013: prime industrial contractor selected
- 2014-2020: working groups preparing for data analysis
- 2020: launch
- 7 years of data

Euclid Galaxy Clustering

Req. ID	Parameter	Requirement	Goal
GC.1-3	Redshift accuracy	σ(z)<0.001(1+z)	
GC.1-4	Systematic offset in redshift	<1/5 redshift accuracy	
GC.1-5	Redshift range	0.7<z<2.05	also gals z<0.7
GC.1-6	Median of redshift distribution	>1	>1.1
GC.1-7	Upper quartile of redshifts	>1.35	
GC.1-10	fraction of catastrophic failures	f<20%	
GC.1-11	fraction of catastrophic failures	known to 1%	
GC.1-12	mean redshift in 0.1 redshift bin	known to 0.1%	
GC.2.1-4	Spectral range: lower limit Spectral range: upper limit	less than 1.1 micron greater than 2.0 micron	
GC.2.1-5	Spectral resolution	>250	
GC.2.1-6	Resolution element	sampled by > 2 pixels	
GC.2.1-7	Wavelength error	line sampling f < 0.25	

Euclid Weak Lensing

Req. ID	Parameter	Requirement	Goal
WL.1-5	Redshifts error ($\sigma(z)/(1+z)$)	$\leq$ 0.05	$\leq$ 0.03
WL.1-6	Catastrophic failures	10%	5%
WL.1-7	Error in mean redshift in bin	<0.002	
WL.2.1-17	NIR wavelength range	920 to ≥1600nm	
WL.2.1-18	NIR number of filters:	≥3	
WL.2.1-19	NIR PSF size:	EE50 and EE80 Y: (<0.30”, <0.62”) J: (<0.30”, <0.63”) H: (<0.33”, <0.70”)	
WL.2.1-20	NIR Pixel scale:	0.3±0.03 arcsec	
WL.2.1-21	Relative Photometric Accuracy	<1.5%	

Euclid Forecasts

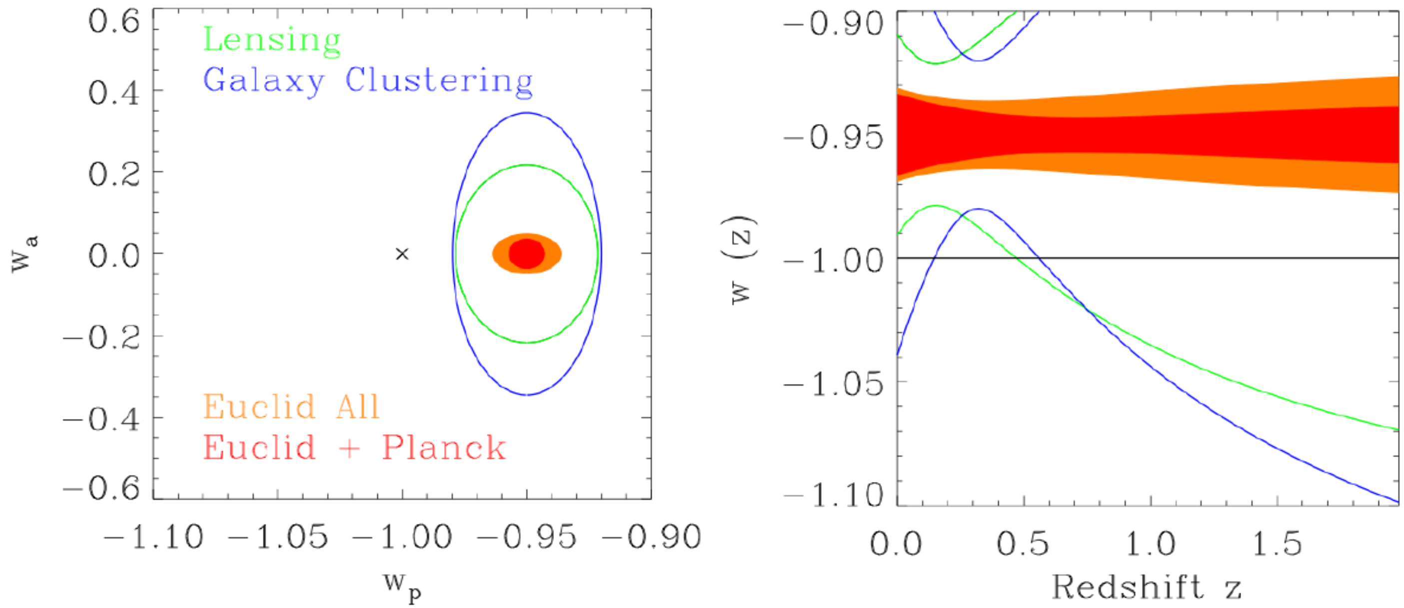


Figure 2.4: The expected constraints from Euclid in the dynamical dark energy parameter space. We show lensing only (green), galaxy clustering only (blue), all the Euclid probes (lensing+galaxy clustering+clusters+ISW; orange) and all Euclid with Planck CMB constraints (red). The cross shows a cosmological constant model. Left panel: the expected 68% confidence contours in the (w_p, w_a). Right panel: the 1σ constraints on the function w(z) parameterised by (w_p, w_a) as a function of redshift (green-lensing alone, blue-galaxy clustering alone, orange-all of the Euclid probes, red-Euclid combined with Planck).

Euclid Forecasts

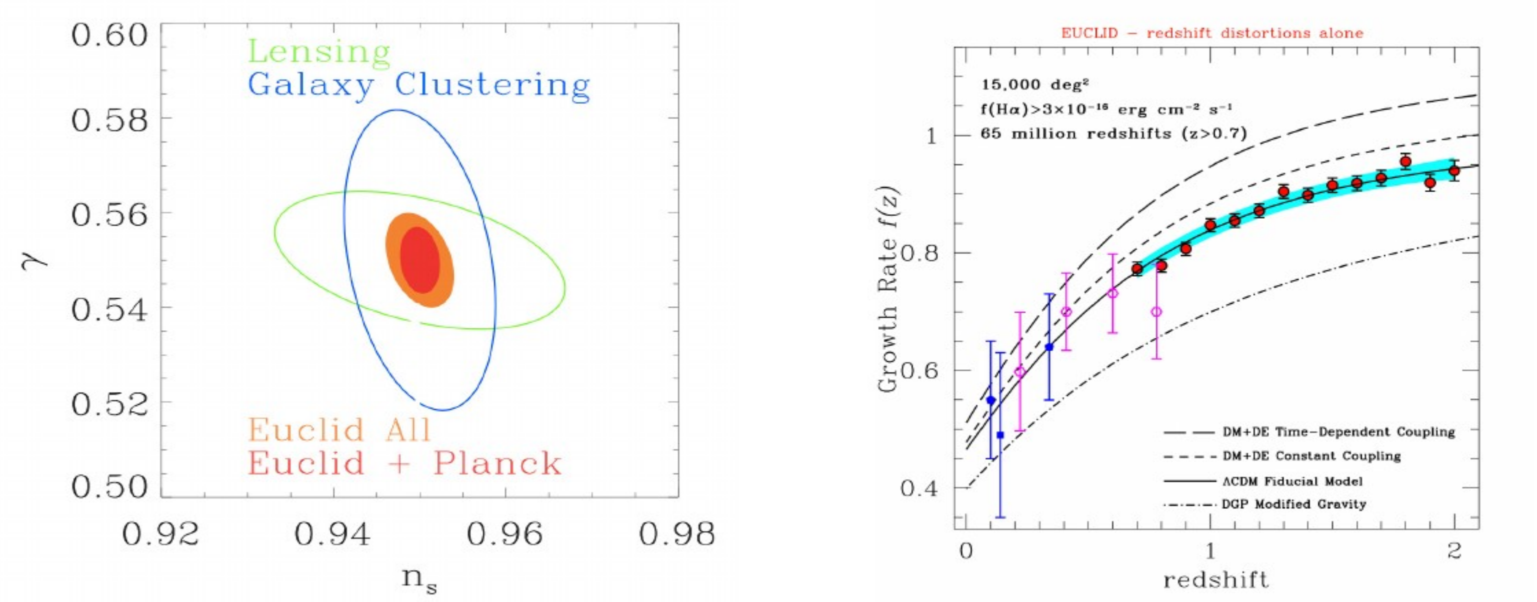
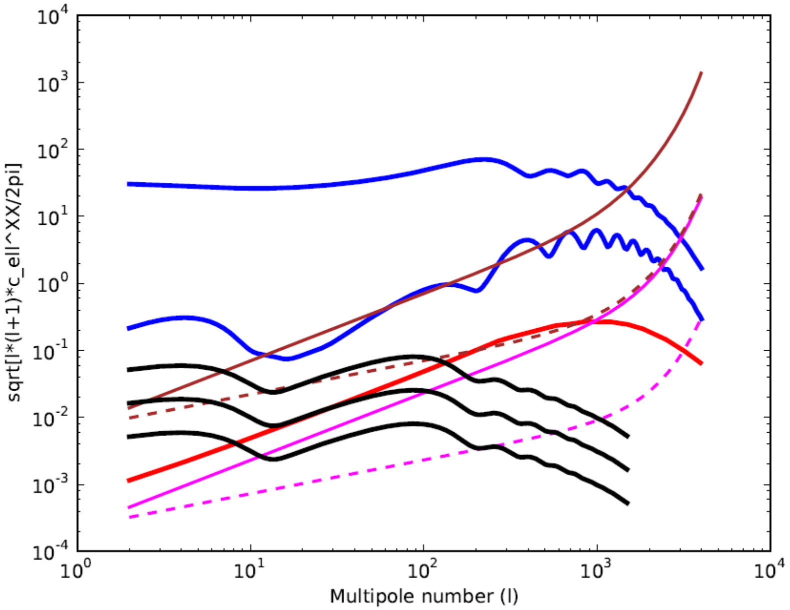


Figure 2.5: In the left panel we show the parameter space constraints on the γ parameter describing the growth factor and the scalar spectral index. Green is lensing, blue galaxy clustering, orange includes the primary and secondary Euclid probes and red is combined with Planck. These errors are marginalised over all other parameters. Right panel: Predicted Euclid measurements of the growth rate of structure f(z) using redshift-space distortions alone. The cyan (shaded) area gives the expected 1σ error, with the red points illustrating a corresponding simulated observation. Current state-of-the-art measurements by the SDSS (filled pentagons), 2dF (filled square, Hawkins et al., 2003) and Wigglez (open hexagons, Blake et al. 2011) are also shown. The lines show predictions for f(z) by the concordance model and by three alternative models in which DE couples with DM (Di Porto & Amendola, 2007) or gravity is generalised to a 5-dimensional brane-world (DGP, Dvali et al., 2000).

More CMB from space

COsmic oRigin Explorer

[White paper: arxiv.org/abs/1102.2181](http://arxiv.org/abs/1102.2181)

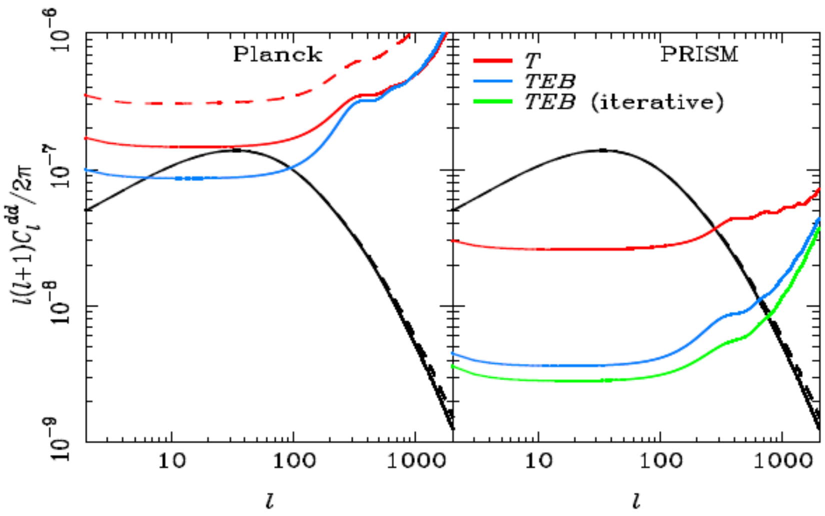


ν	$\Delta\nu$	n_{det}	θ^{arcmin}_{fwhm}	(ΔP)/arcmin			Pixel sensitivity		$(\Delta P)^{forecast}_{A(V)=1}$	$(S/N)^{pix}_{pol}$
				$(\mu K)_{thermo}$	$(\mu K)_{RJ}$	MJy/st	$(\mu K)_{RJ}$	MJy/st	MJy/st	
255	15	575	4.10	1.05×10^1	2.43	4.85×10^{-3}	0.59	1.18×10^{-3}	6.30×10^{-3}	5.33
285	15	375	3.70	1.74×10^1	2.94	7.33×10^{-3}	0.79	1.98×10^{-3}	8.20×10^{-3}	4.13
315	15	100	3.30	4.66×10^1	5.62	1.71×10^{-2}	1.70	5.19×10^{-3}	1.13×10^{-2}	2.20
375	15	64	2.80	1.19×10^2	7.01	3.03×10^{-2}	2.50	1.08×10^{-2}	2.12×10^{-2}	2.00
435	15	64	2.40	2.58×10^2	7.12	4.14×10^{-2}	2.97	1.72×10^{-2}	3.82×10^{-2}	2.20
555	185	64	1.90	6.26×10^2	3.39	3.21×10^{-2}	1.78	1.69×10^{-2}	7.53×10^{-2}	4.47
675	185	64	1.60	3.64×10^3	3.52	4.92×10^{-2}	2.20	3.08×10^{-2}	1.28×10^{-1}	4.13
795	185	64	1.30	2.22×10^4	3.60	6.99×10^{-2}	2.77	5.38×10^{-2}	1.65×10^{-1}	3.07
795**	185	64	1.30	1.00×10^4	1.61	3.13×10^{-2}	1.24	2.41×10^{-2}	1.65×10^{-1}	6.86

Polarised Radiation Imaging and Spectroscopic Mission

White Paper

arxiv.org/abs/1306.2259



ν_0 GHz	Range GHz	$\Delta\nu/\nu$	n_{det}	θ_{fwhm}	σ_I per det 1 arcmin		$\sigma_{(Q,U)}$ per det 1 arcmin		Main molec. & atomic lines
					μK_{RJ}	μK_{CMB}	μK_{RJ}	μK_{CMB}	
30	26-34	.25	50	17'	61.9	63.4	87.6	89.7	
36	31-41	.25	100	14'	57.8	59.7	81.7	84.5	
43	38-48	.25	100	12'	53.9	56.5	76.2	79.9	
51	45-59	.25	150	10'	50.2	53.7	71.0	75.9	
62	54-70	.25	150	8.2'	46.1	50.8	65.2	71.9	
75	65-85	.25	150	6.8'	42.0	48.5	59.4	68.6	
90	78-100	.25	200	5.7'	38.0	46.7	53.8	66.0	HCN & HCO^+ at 89 GHz
105	95-120	.25	250	4.8'	34.5	45.6	48.8	64.4	CO at 110-115 GHz
135	120-150	.25	300	3.8'	28.6	44.9	40.4	63.4	
160	135-175	.25	350	3.2'	24.4	45.5	34.5	64.3	
185	165-210	.25	350	2.8'	20.8	47.1	29.4	66.6	HCN & HCO^+ at 177 GHz
200	180-220	.20	350	2.5'	18.9	48.5	26.7	68.6	
220	195-250	.25	350	2.3'	16.5	50.9	23.4	71.9	CO at 220-230 GHz
265	235-300	.25	350	1.9'	12.2	58.5	17.3	82.8	HCN & HCO^+ at 266 GHz
300	270-330	.20	350	1.7'	9.6	67.1	13.6	94.9	
320	280-360	.25	350	1.6'	8.4	73.2	11.8	103	CO, HCN & HCO^+
395	360-435	.20	350	1.3'	4.9	107	7.0	151	
460	405-520	.25	350	1.1'	3.1	156	4.4	221	CO, HCN & HCO^+
555	485-625	.25	300	55"	1.6	297	2.3	420	C-I, HCN, HCO^+, H_2O, CO
660	580-750	.25	300	46"	0.85	700	1.2	990	CO, HCN & HCO^+
					nK_{RJ}	kJy/sr	nK_{RJ}	kJy/sr	
800	700-900	.25	200	38"	483	9.5	683	13.4	
960	840-1080	.25	200	32"	390	11.0	552	15.6	
1150	1000-1300	.25	200	27"	361	14.6	510	20.7	
1380	1200-1550	.25	200	22"	331	19.4	468	27.4	N-II at 1461 GHz
1660	1470-1860	.25	200	18"	290	24.5	410	34.7	
1990	1740-2240	.25	200	15"	241	29.3	341	41.5	C-II at 1900 GHz
2400	2100-2700	.25	200	13"	188	33.3	266	47.1	N-II at 2460 GHz
2850	2500-3200	.25	200	11"	146	36.4	206	51.4	
3450	3000-3900	.25	200	8.8"	113	41.4	160	58.5	O-III at 3393 GHz
4100	3600-4600	.25	200	7.4"	98	50.8	139	71.8	
5000	4350-5550	.25	200	6.1"	91	70.1	129	99.1	O-I at 4765 GHz
6000	5200-6800	.25	200	5.1"	87	96.7	124	136	O-III at 5786 GHz

Work at SISSA

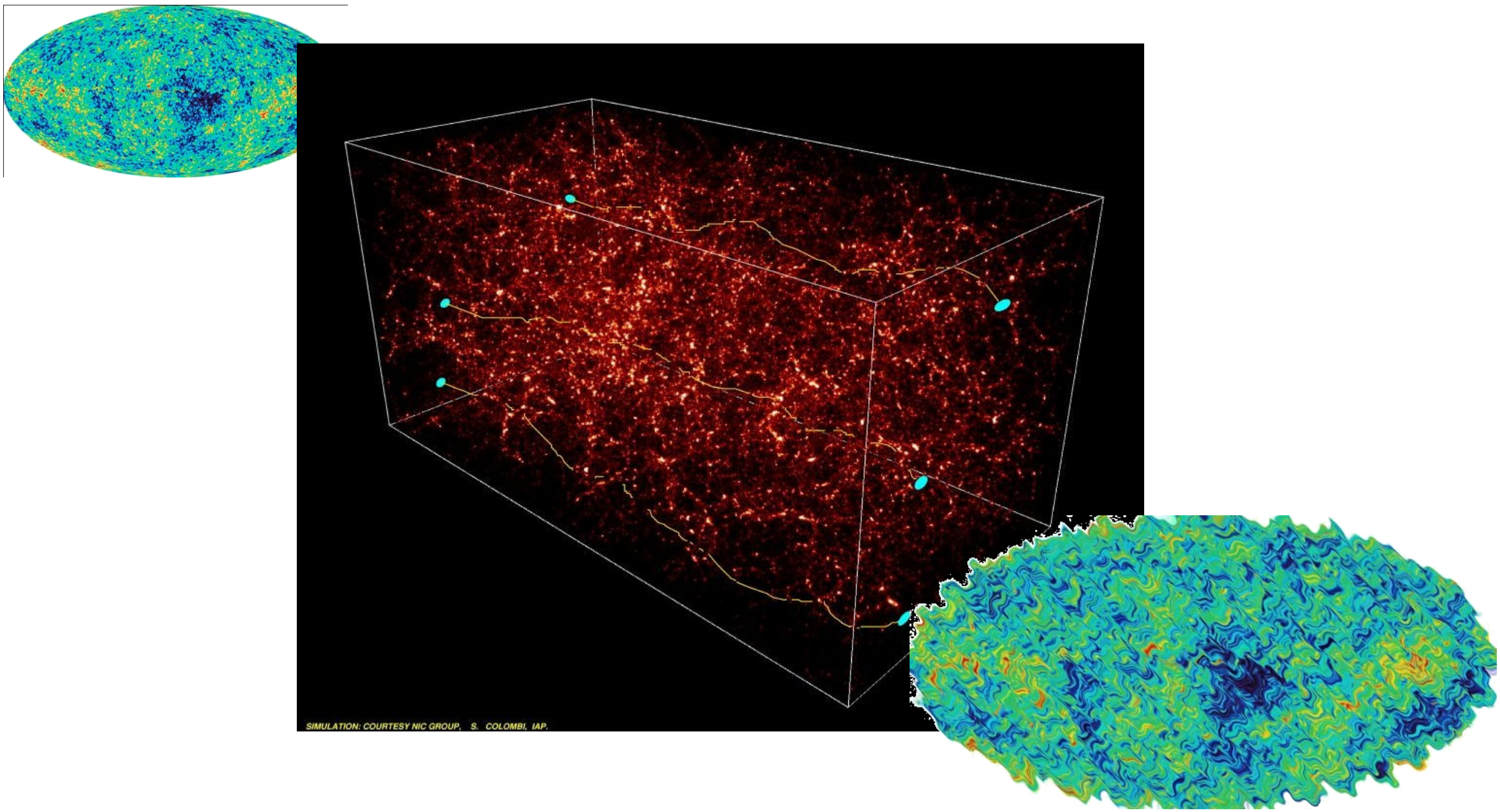
Main lines

- CMB-N-body lensing
- Component Separation
- Herschel-Planck Cross-Correlation
- Theory & Forecasts

Main lines

- CMB-N-body lensing
  - Sub-orbital CMB
  - Euclid
  - Carbone et al. 2013, Antolini et al. 2014
- Component Separation
  - Sub-orbital CMB
  - Planck
  - Fantaye et al. 2012, Stivoli et al. 2010, Stompor et al. 2009
- Herschel-Planck Cross-Correlation
  - Bianchini et al., 2014, in preparation
- Theory & Forecasts
  - Effective Field Theory
  - Hu et al. 2013, Raveri et al. 2013

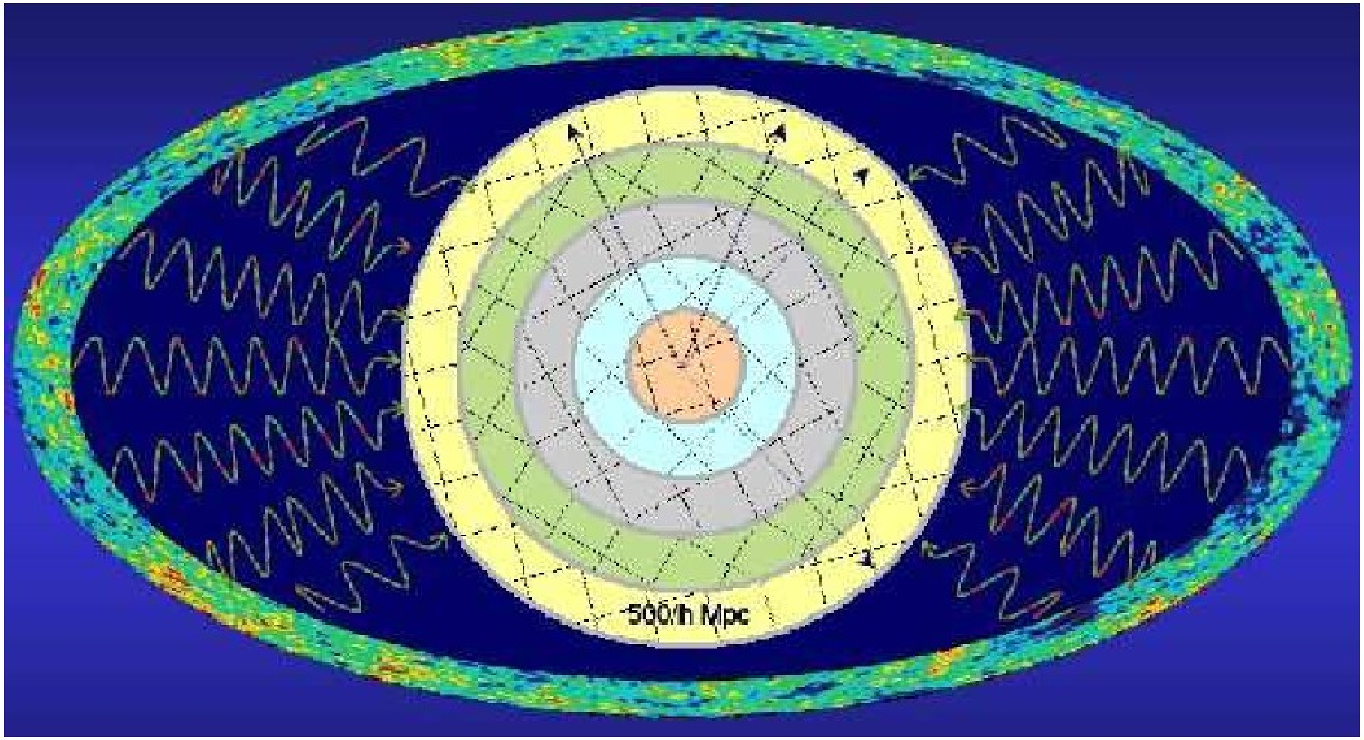
CMB-N-Body lensing



CMB-N-body lensing: do we really need it?

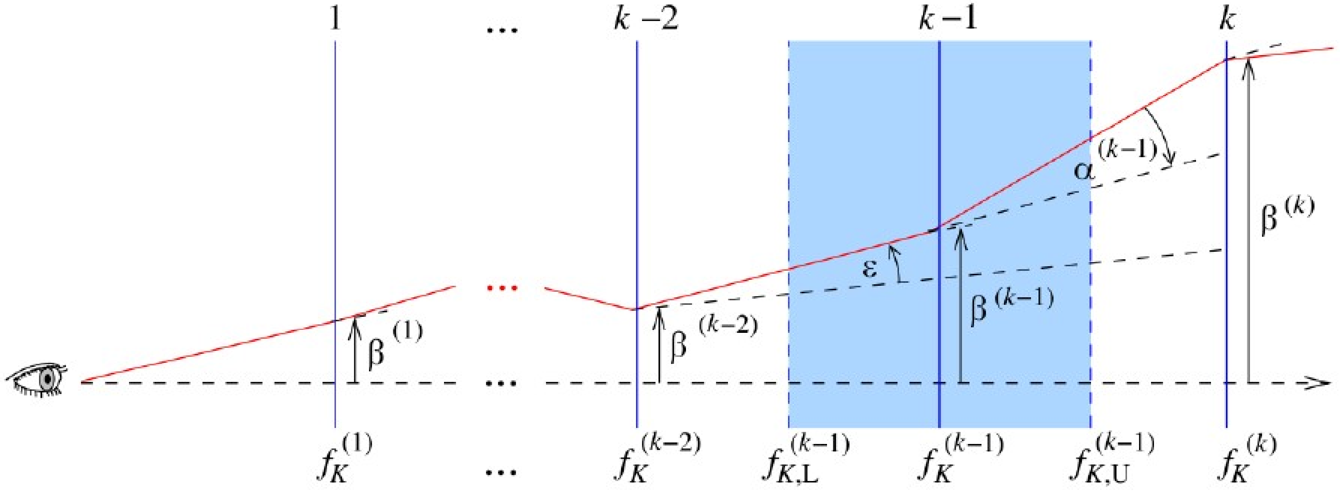
- Do we have a satisfactory statistics in semi-analytic prescriptions for CMB lensing?
- Do we have an understanding of mildly and full non-linear Dark Matter clustering in Dark Energy models?
- Can we learn about simulations trying to get the signal right in particular at high resolution?
- Do we need simulations for understanding cross-correlation studies?
- …

CMB-N-body lensing



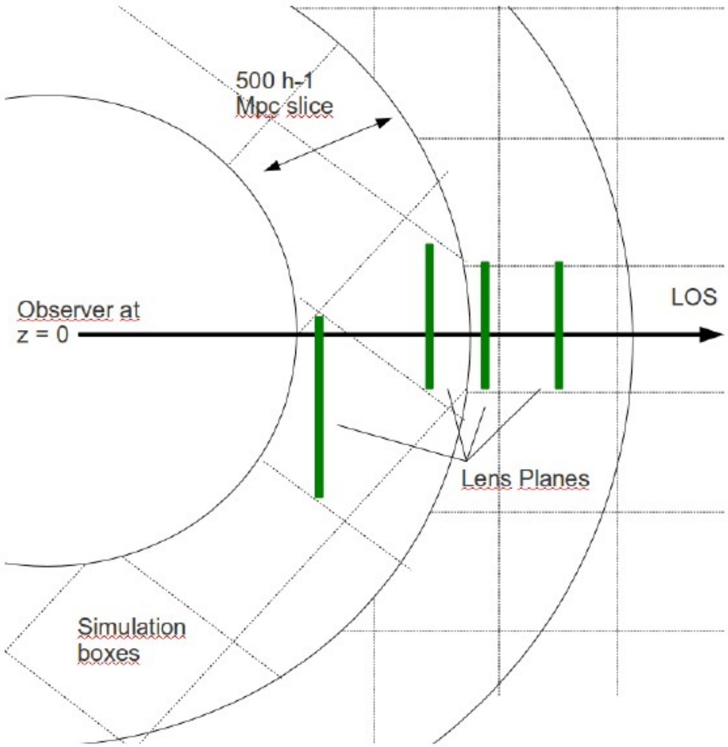
Carbone et al. 2008, 2009, 20

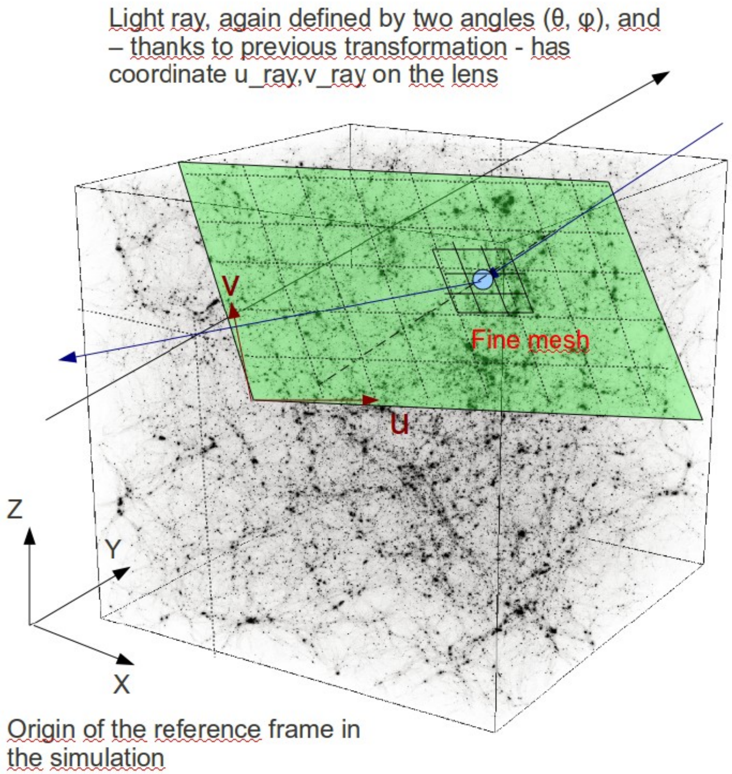
CMB-N-body lensing ray-tracing: Born or non-Born?



Hilbert et al. 2009

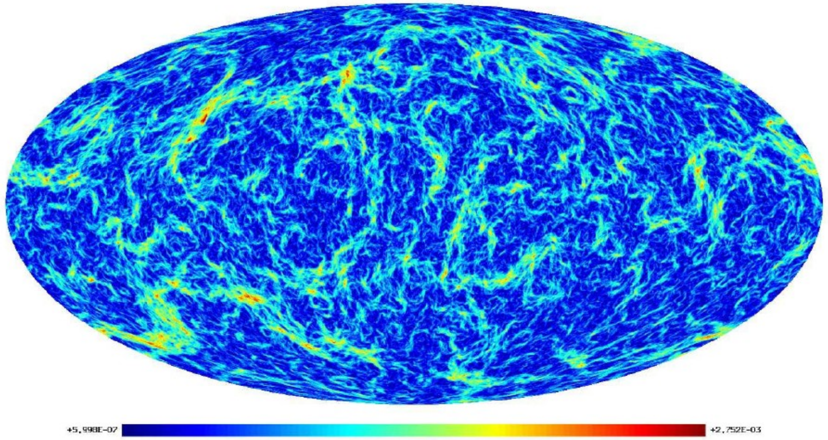
CMB-N-body lensing ray tracing

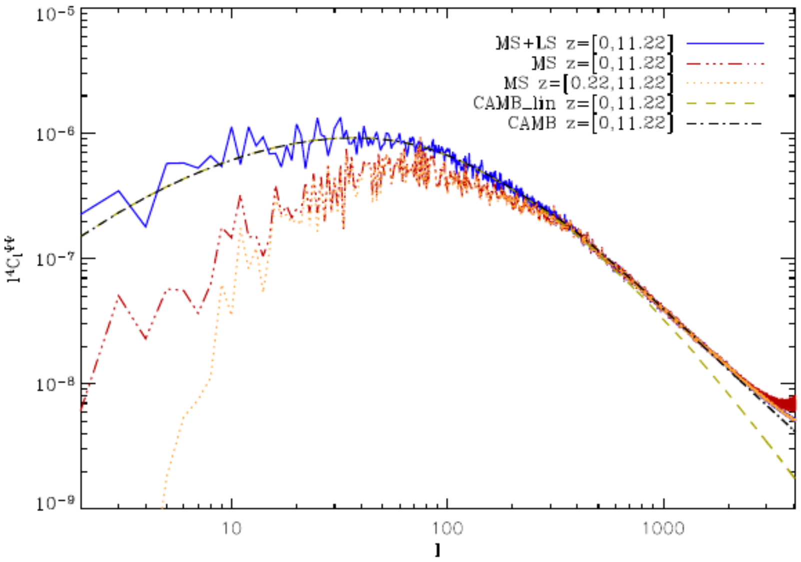




Hilbert et al. 2009, Calabrese et al. 2014, in preparation

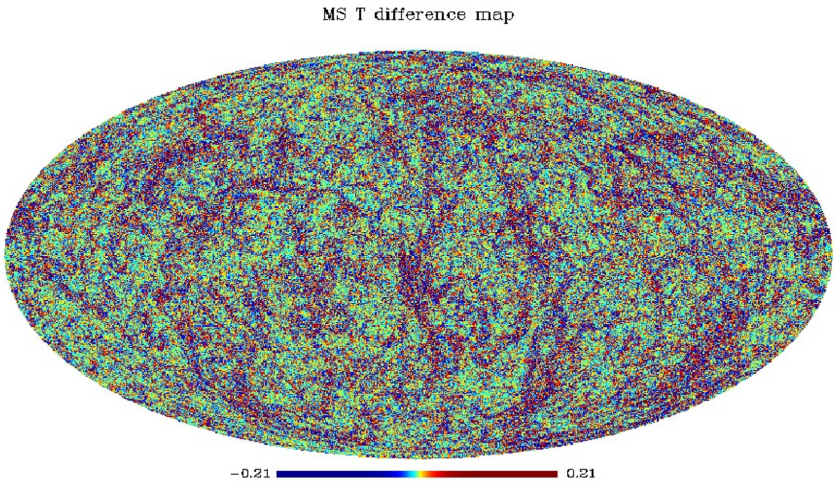
CMB-N-body lensing

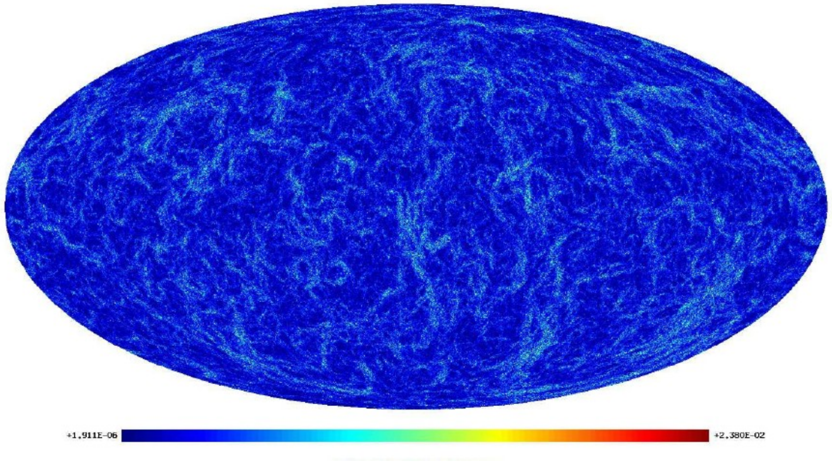




Carbone et al. 2008, 2009, 2013

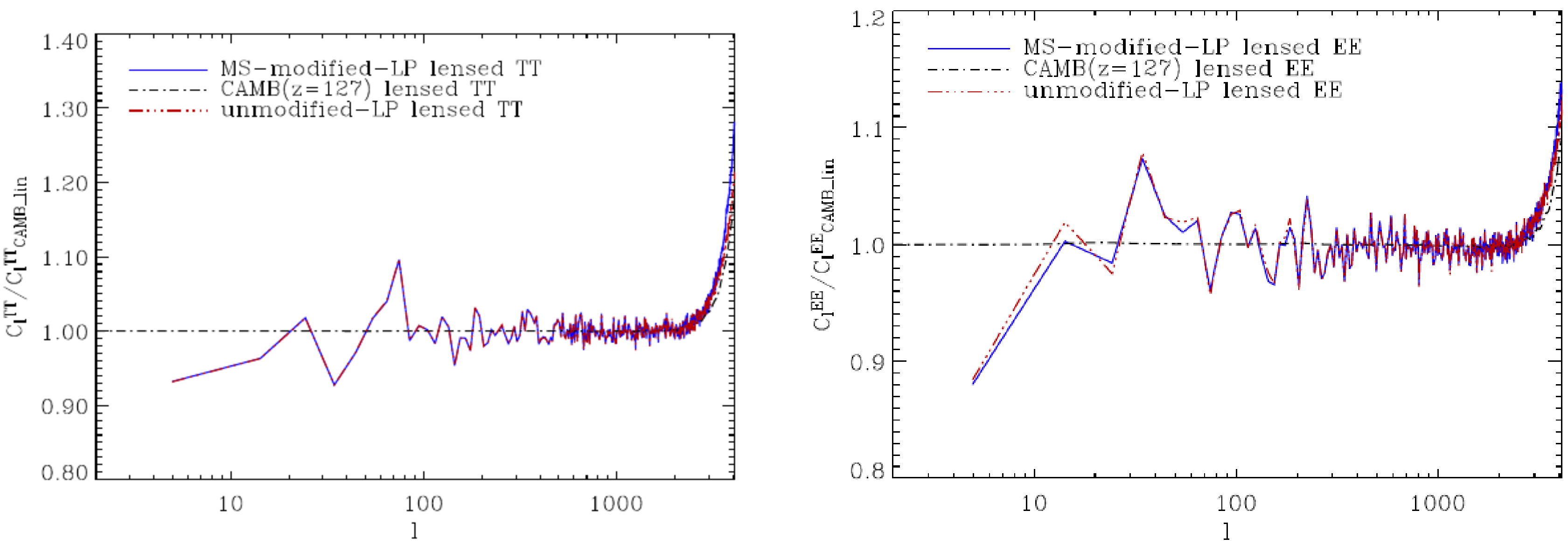
CMB-N-body lensing





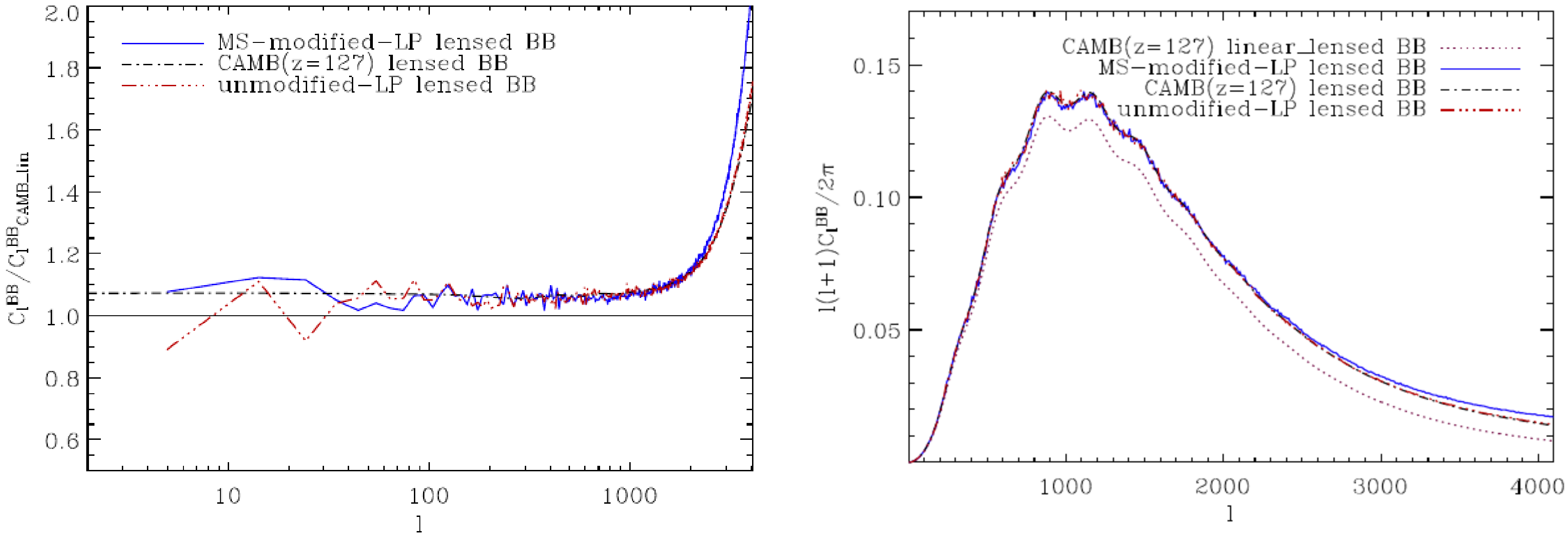
Carbone et al. 2008, 2009, 20

CMB-N-body lensing



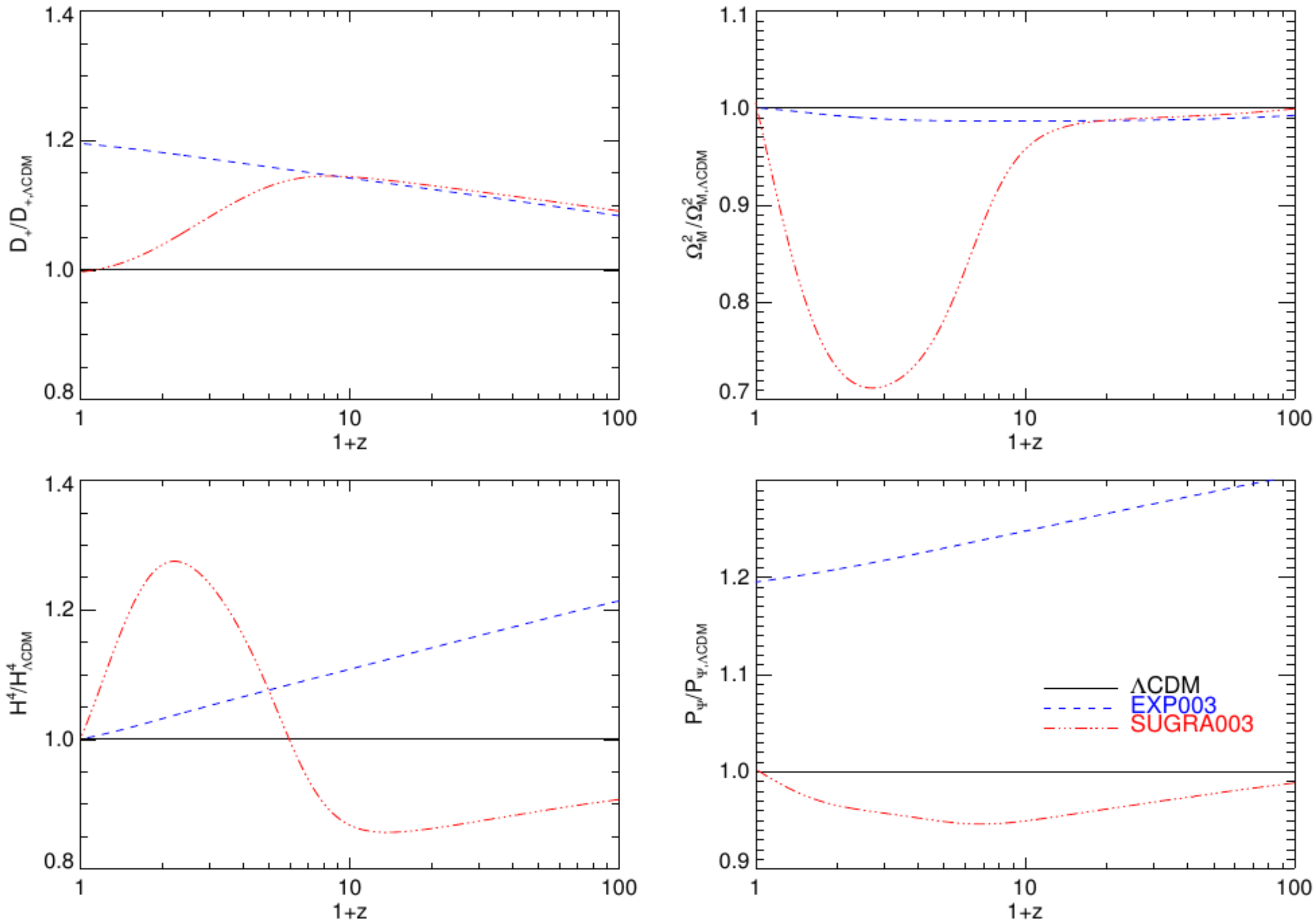
Carbone et al. 2008, 2009, 20

CMB-N-body lensing



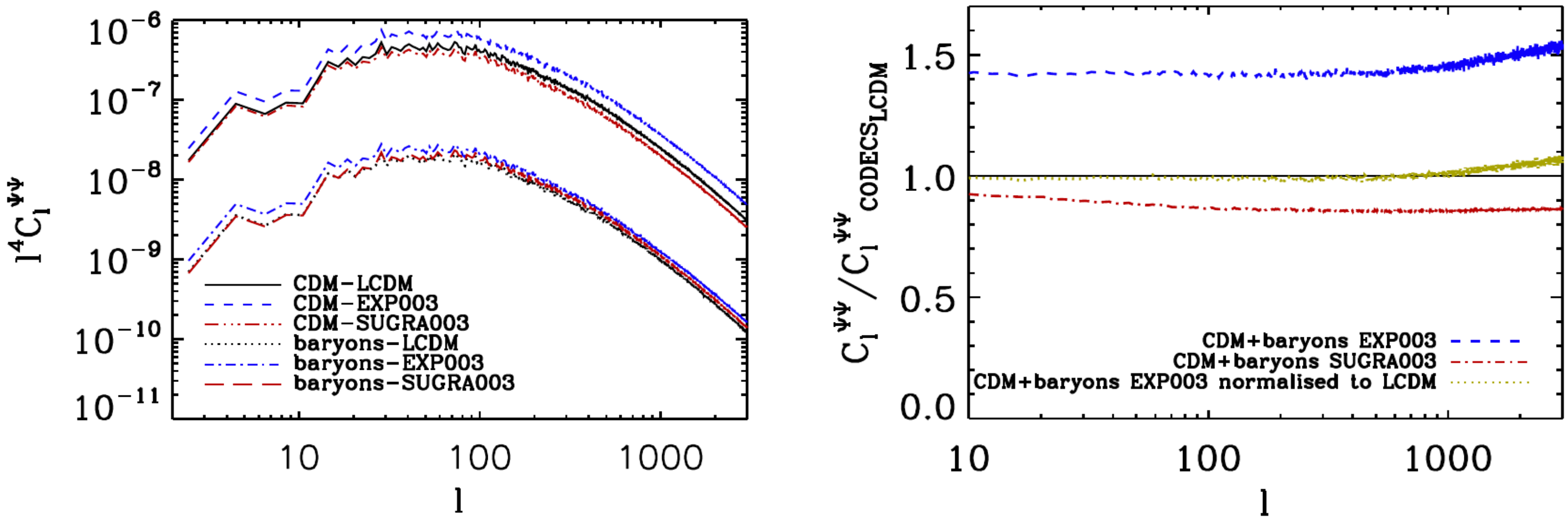
Carbone et al. 2008, 2009, 20

CMB-N-body lensing: first non-ΛCDM runs



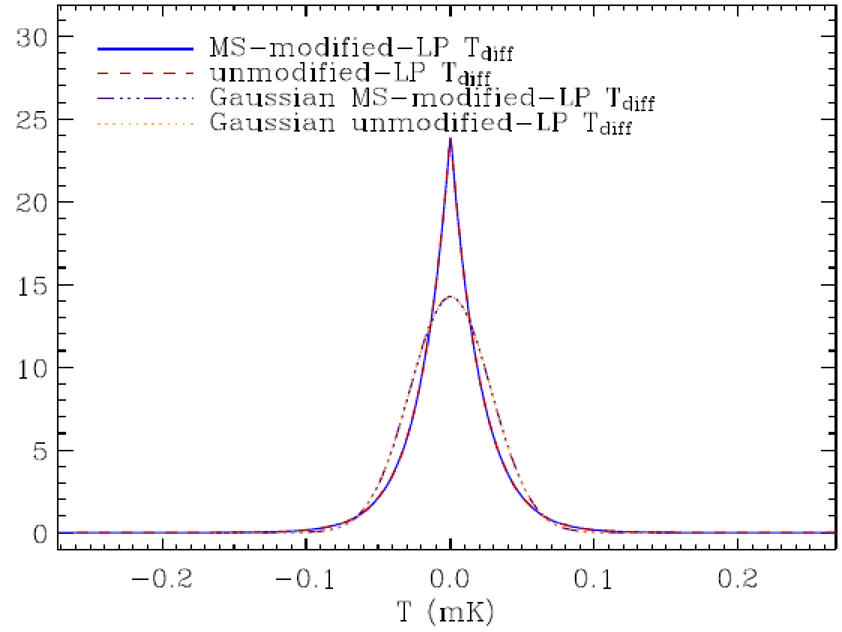
Baldi et al. 2012, Carbone et al. 2013

CMB-N-body lensing: first non-ΛCDM runs



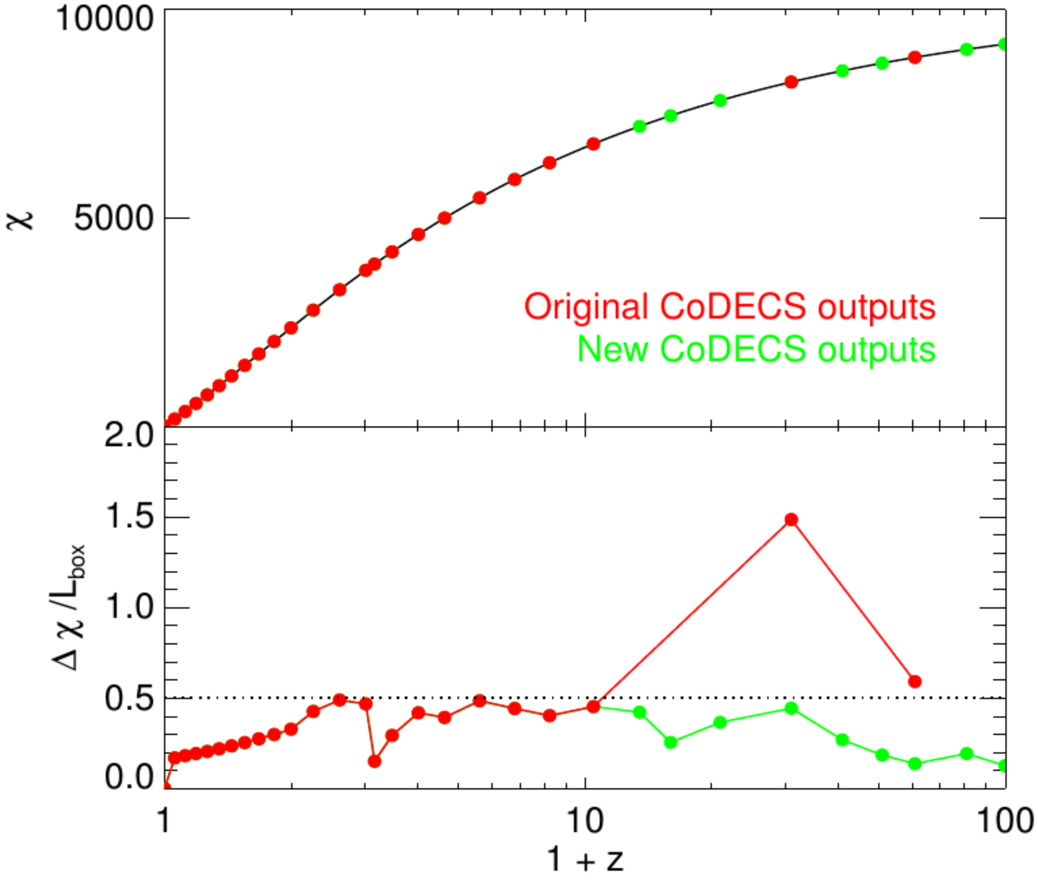
Baldi et al. 2012, Carbone et al. 2013

CMB-N-body lensing: skewed statistics in lensed CMB



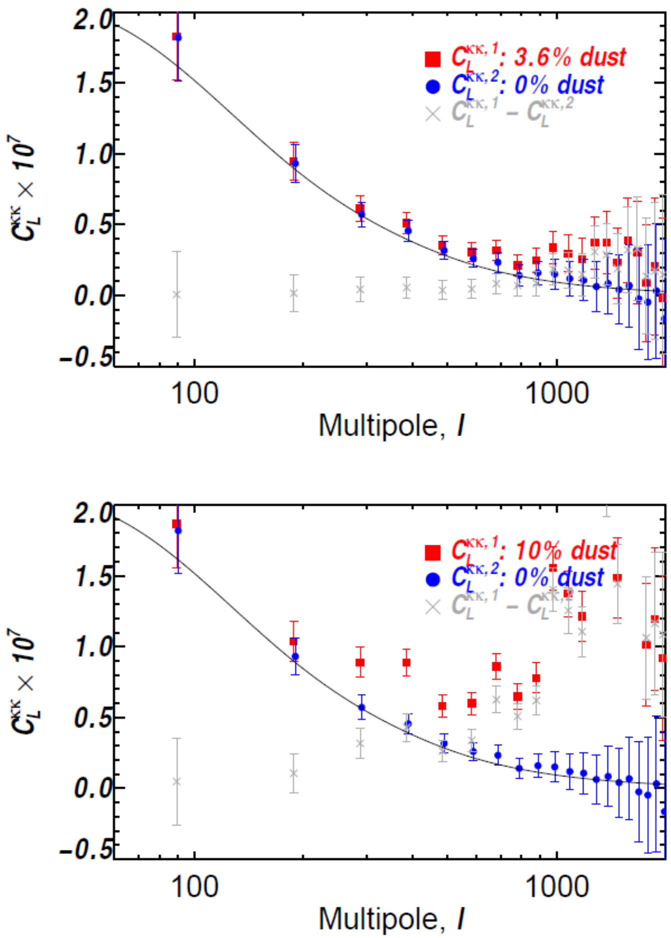
Carbone et al. 2008, 2009, 20

CMB-N-body lensing: learning lessons on N-body

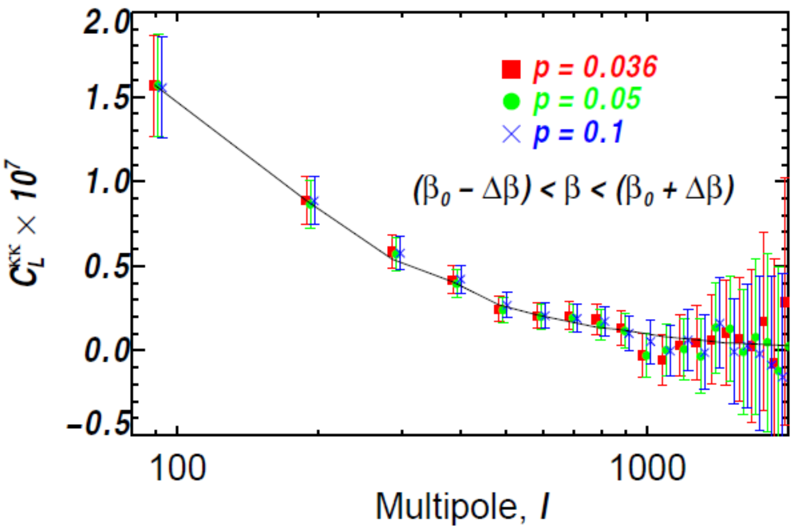


Carbone et al. 2008, 2009, 20

CMB N-body lensing recostruction



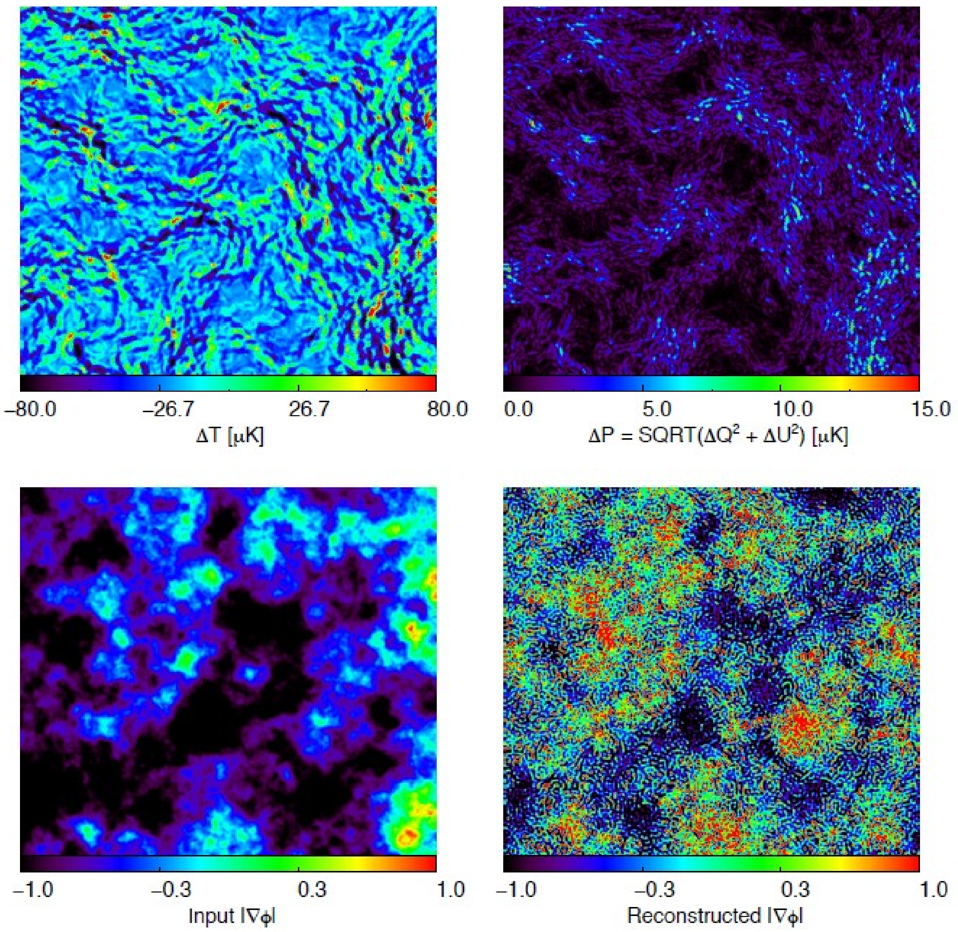
Convergence estimation
Without foreground cleaning



Convergence estimation
With foreground cleaning

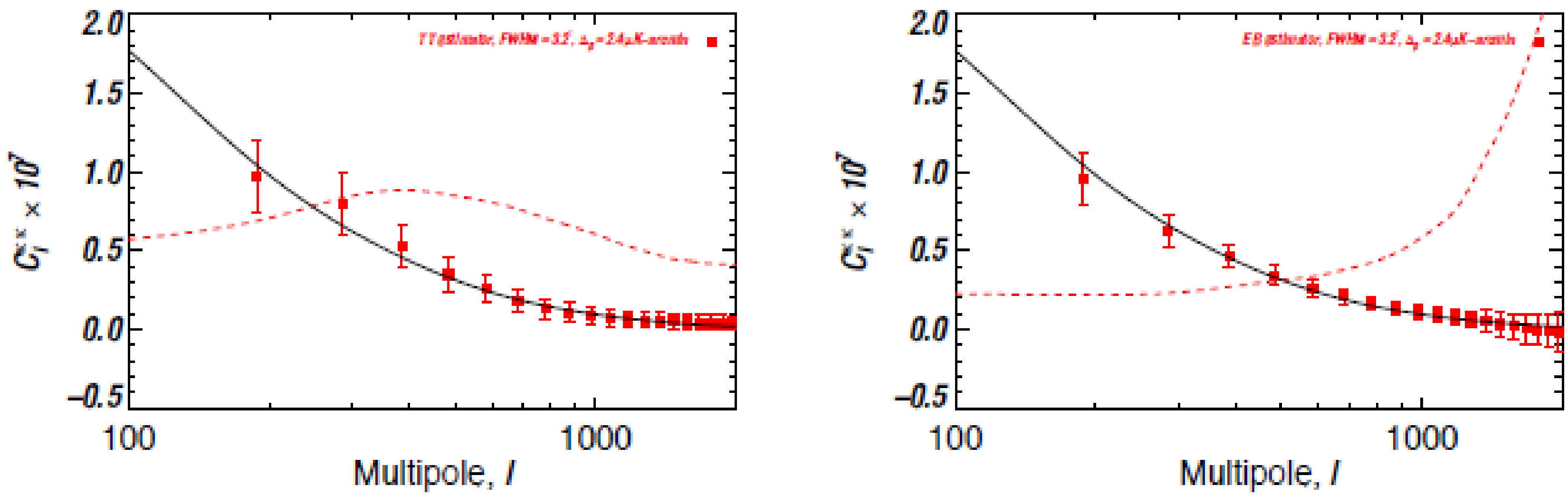
Fantaye et al. 2012

CMB-N-body lensing reconstruction



Antolini, et al. 2013

CMB-N-body lensing reconstruction



Antolini, et al. 2013

Cosmology goes…

$$\overrightarrow{\boldsymbol{Cosmology\ Obervation\ Vector}}$$

$$(CMB,\quad Infrared\ surveys,\quad Radio\ surveys,$$
$$Optical\ surveys,\quad Gravitational\ Lensing,\quad Baryonic\ Acoustic\ Oscillations, \ldots)$$

Cosmology goes off diagonal

$$(CMB, IR, R, Opt, GL, BAOs, \ldots)$$

$$(CMB, IR, R, Opt, GL, BAOs, \ldots) \begin{pmatrix} & \cdots & \\ \vdots & \ddots & \vdots \\ & \cdots & \end{pmatrix}$$

Cosmology goes off diagonal and also…

$$
\begin{matrix}
 & (CMB, IR, R, Opt, GL, BAOs, \ldots) \\
(CMB, IR, R, Opt, GL, BAOs, \ldots) & \begin{pmatrix} & \cdots & \\ \vdots & \ddots & \vdots \\ & \cdots & \end{pmatrix}
\end{matrix}
$$

Cosmology goes off diagonal and also statistical and systematic errors do

$(CMB, IR, R, Opt, GL, BAOs, \ldots)_{obs}$ $\Delta(CMB, IR, R, Opt, GL, BAOs, \ldots)_{stat}$

$$\begin{pmatrix} & \cdots & \\ \vdots & \ddots & \vdots \\ & \cdots & \end{pmatrix} = \begin{pmatrix} & \cdots & \\ \vdots & \ddots & \vdots \\ & \cdots & \end{pmatrix} + \begin{pmatrix} & \cdots & \\ \vdots & \ddots & \vdots \\ & \cdots & \end{pmatrix} + \begin{pmatrix} & \cdots & \\ \vdots & \ddots & \vdots \\ & \cdots & \end{pmatrix}$$

$(CMB, IR, R, Opt, GL, BAOs, \ldots)_{true}$ $\Delta(CMB, IR, R, Opt, GL, BAOs, \ldots)_{sys}$

Concluding remarks

- Planck 2013 and the other experiments confirm ΛCDM as a satisfactory fit to the data
- Lots of experiments, CMB sub-orbitals being extended and improved, CMB satellites being proposed, Euclid under construction
- Leap forward in the accuracy of ΛCDM expected from Planck 2014 and sub-orbital CMB, next LSS experiments, allowing to measure off-diagonal cosmology
- Celebration time for cross-correlation detection will be over soon, and precision cosmology from it will require the control of an entirely new set of systematics effects